Title: Eternal Inflation in the Light of Quantum Cosmology

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Abstract: If the universe is a quantum mechanical system it has a quantum state. This state supplies a probabilistic measure for alternative histories of the universe. During eternal inflation these histories typically develop large inhomogeneities that lead to a mosaic structure on superhorizon scales consisting of homogeneous patches separated by inflating regions. As observers we do not see this structure directly. Rather our observations are confined to a small, nearly homogeneous region within our past light cone. This talk will describe how the probabilities for these observations can be calculated from the probabilities supplied by the quantum state without introducing a further ad hoc measure. The talk will emphasize the principles behind this result --- a quantum state, quantum spacetime leading to an ensemble of classical histories, quantum observers, a focus in local observations, and the use of coarse-grainings adapted to these observations. The principles will be illustrated in simple models in particular using the no-boundary wave function as a model of the quantum state. Applied to a model landscape we obtain specific predictions for features of the CMB spectrum and improvements in the `anthropic' bounds on the cosmological constant.

Eternal Inflation in the Light of Quantum Cosmology

Stephen Hawking, DAMTP, Cambridge
Thomas Hertog, APC, UP7, Paris

Mark Srednicki, UCSB, Santa Barbara

Perimeter Institute, March 8, 2011

A Quantum Universe

If the universe is a quantum mechanical system it has a quantum state.
What is it?

Ψ

That is the problem of
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A Quantum Mechanics of Cosmological History

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It predicts probabilities for all possible alternative 4-d histories of the universe ---
what went on then
what goes on now
what will go on in the future.

Aims of this Talk

Understand the origin of
eternal inflation
in the context of
quantum cosmology.

Understand the implications of
eternal inflation
for predictions of our observations
in quantum cosmology.

Can the
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predict the probabilities for
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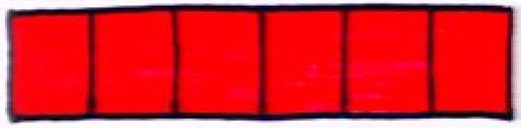
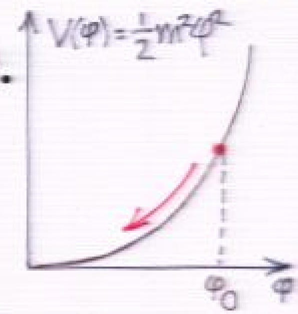
- Our Observations: Focus on probabilities for our observations in our Hubble volume which are conditioned on a description of the observational situation.
- Adapted Coarse Grainings: Use coarse grainings that follow observations and ignore unobservable features of the universe such as very large scale structure.

Parts of the Talk:

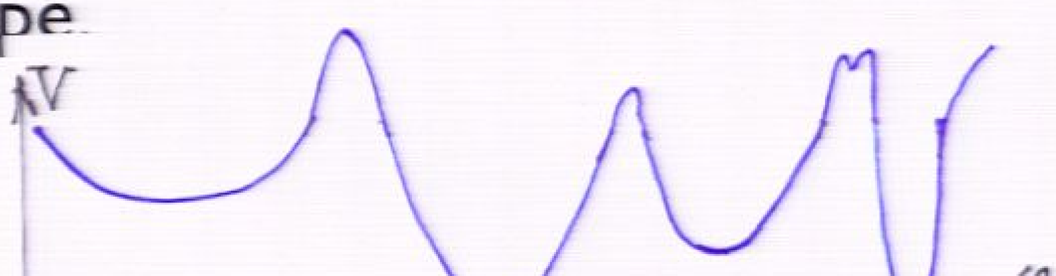
- Box Models: Where we will learn how a quantum theory of the observer can lead to top-down weighting for probabilities for observation.



- One minimum: Where we will learn how to calculate probabalities for histories exhibiting eternal inflation from a wave function of the universe.



- Landscapes: Where we will learn how to calculate the probabilities that we are in different minima in a toy landscape.

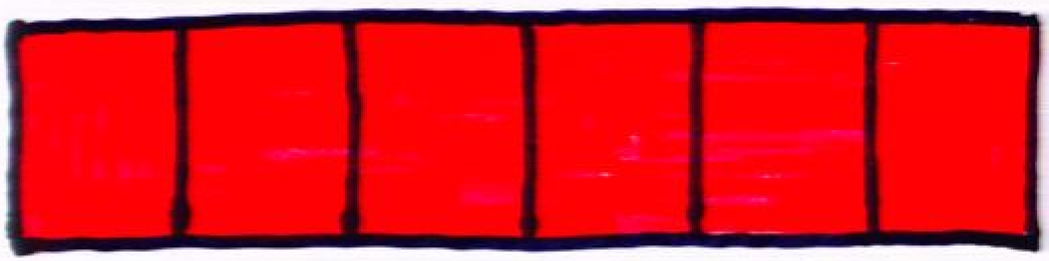


Box Models

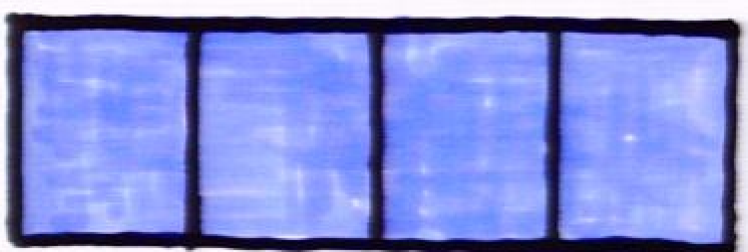
A Model Universe
Hubble Volumes

A universe with two possible configurations of Hubble volumes (1 and 2), with colors red and blue (CMB).

N_1 boxes, all red, occurring with probability p(1).



N_2 boxes, all blue, occurring with probability p(2)



Model Universe - Observers

- As observers we are physical systems within the universe with only a probability to have evolved in any Hubble volume.
- We are not certain to exist in any Hubble volume, and in a very large universe may be replicated elsewhere.
- This is modeled by assuming a probability p_E for an observer like us to exist (E) in any Hubble volume the same for all of them. (More realistic than most.)

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Model Universe - Observers

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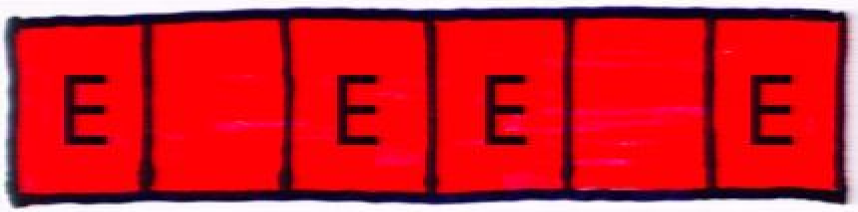
- We … ume, and … else…

p_E includes the probability of the accidents of 3 Gyr of biological evolution and is very, very small.

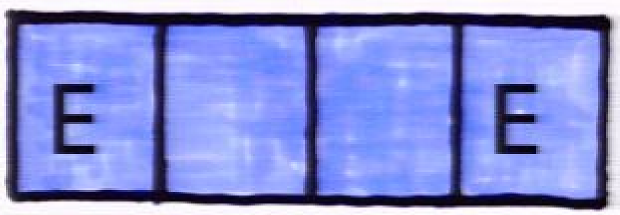
- This is modeled by assuming a probability p_E for an observer like us to exist (E) in any Hubble volume the same for all of them. (More realistic than most.)

Model Universe -- Histories

Alternative histories are defined by 1 or 2 and by which Hubble volumes are occupied by observers.



$$p(1)p_E^4(1-p_E)^2$$

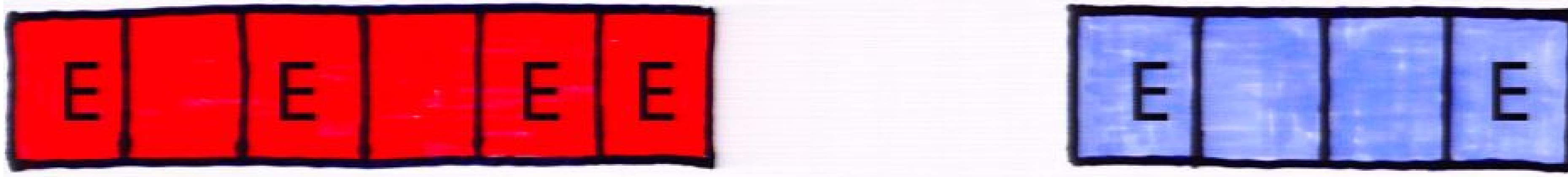


$$p(2)p_E^2(1-p_E)^2$$

More generally: $p(\mathrm{history}) = p(k)p_E^{n_E}(1-p_E)^{N_k-n_E}$

These are called bottom up (BU) probabilities.

What is the probability that we see red ?



- Assume we are equally likely to be any of the incidences of E (typicality assumption).
- The probability that we see red (WSR) is the probability that we are in the history with all red boxes.
- This is NOT the probability that the history 1 with all red boxes occurs, p(1), because that could happen with no observers.
- Rather the probability that we see red is proportional to the probability that 1 occurs with at least one instance of E , p(1, at least one E)

The probability that we see red (WSR)

The probability that there is at least one instance of E in the history k is

$$p(\text{at least one } E) = 1 - p(\text{no } E) = 1 - (1 - p_E)^{N_k}$$

$$p(WSR) \propto p(1)[1 - (1 - p_E)^{N_1}]$$

$$p(WSB) \propto p(2)[1 - (1 - p_E)^{N_2}]$$

$$p(WSR) = \frac{p(1)[1 - (1 - p_E)^{N_1}]}{\sum_k p(k)[1 - (1 - p_E)^{N_k}]}$$

Such conditional probabilities are called top-down (TD) probabilities and the factor $[1 - (1 - p_E)^{N_k}]$ is the top-down weighting.

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Important Limiting Cases

$N \ll 1/p_E$ We are rare, $N \gg 1/p_E$ We are common.

$$p(WSR) = \frac{p(1)[1-(1-p_E)^{N_1}]}{\sum_k p(k)[1-(1-p_E)^{N_k}]}$$

$$p_E N_1 \ll 1 \qquad p_E N_2 \ll 1 \qquad p(WSR) \approx \frac{N_1 p(1)}{N_1 p(1) + N_2 p(2)}$$

This is volume weighting --- favors large N.

$$p_E N_1 \gg 1 \qquad p_E N_2 \ll 1 \qquad p(WSR) \approx \frac{p(1)}{p(1) + N_2 p_E p(2)} \approx 1$$

Suppresses small N.

$$p_E N_1 \gg 1 \qquad p_E N_2 \gg 1 \qquad p(WSR) \approx p(1)$$

No top-down weighting.

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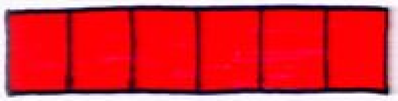
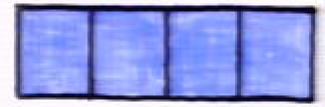
- Not particular to the NBWF -- required for any state.
- Not always volume weighting --- depends on p_E N.
- Not inconsistent with causality -- an observer at a given position is affected only by events in their past light cone. But we don't know our position and have to sum



Volume Weighting



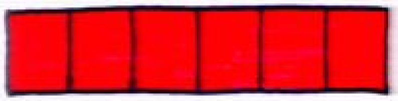
Vhen $p_E N_1 \ll 1$ and $p_E N_2 \ll 1$ we are rare in both histories

$$p(WSR) \approx \frac{N_1 p(1)}{N_1 p(1) + N_2 p(2)}$$

- Since we are rare, the weighting by N's can be understood as a sum over our unknown location according to the usual rules of QM.

- The probability that we observe red can differ significantly from the probability that the universe is red and favors large N.

- This difference does not arise from a perturbation by the observer (negligible) but rather because in a larger universe there are more places for us to be.



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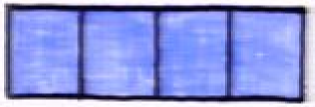

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Common Limit

f $p_E N_1 \gg 1$ and $p_E N_2 \gg 1$ we are common in both histories.

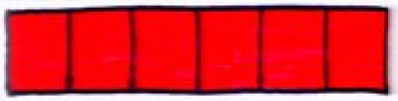
$$p(WSR) \approx p(1)$$

- This result for our observations in our Hubble volume is independent of the structure outside ---N's and patterns of E's. Top-down=Bottom-up.

- We derived it by first calculating the summing over the patterns of large scale structure E's and N's and letting the N's become large.

- But it can be derived directly by coarse-graining over all boxes outside ours. (later)

- That's important if the N's are infinite.



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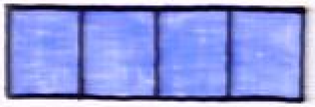

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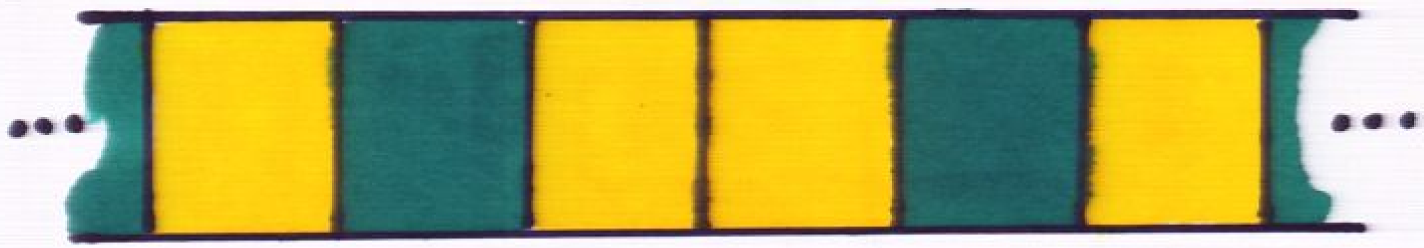
An Improved (Y,G) Model

- Two kinds of Hubble volumes k=1,2. Each has a probability p_Y^k to be yellow (Y) and $p_G^k = 1 - p_Y^k$ green (G). There are an infinite number of boxes in each kind (common limit). A fine-grained history is a configuration of Y's and G's for each k.

k 

- The probability of any particular fine-grained history is

$$p(k)(p_Y^k)^{n_Y}(p_G^k)^{n_G} = 0$$

- Physical alternatives are coarse-grainings of these histories. Their probabilities are sums of those for the infinite number of fine-grained histories in each

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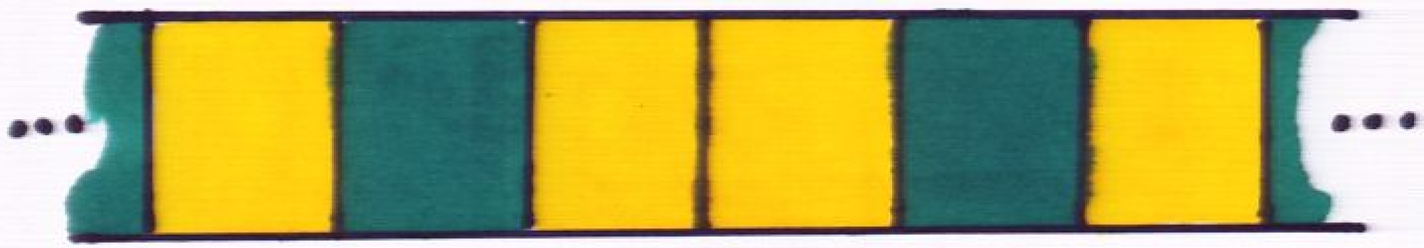

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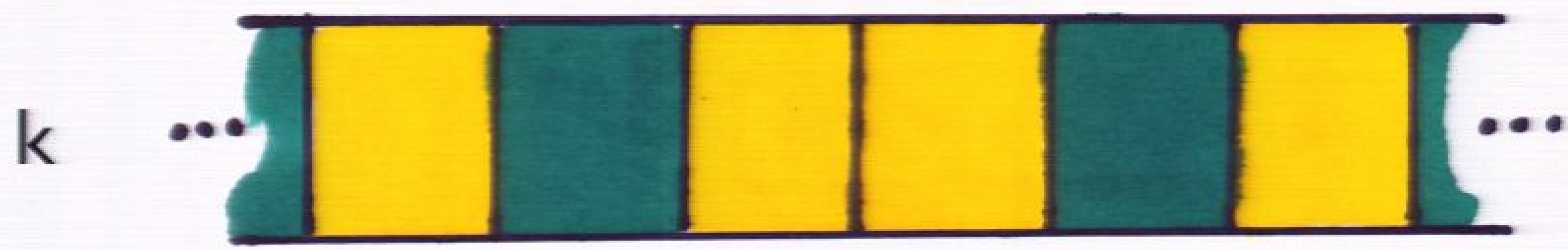

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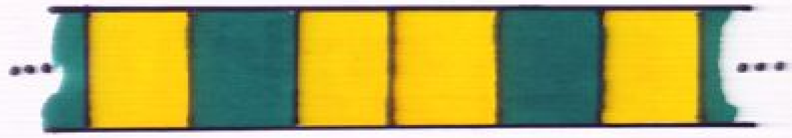
Coarse-graining



- What is the probability that we see Y?
- Calculating for finite N's (cutoffs) and taking limits (as before) leads to ambiguities from the ratio N_1/N_2.
- Rather calculate directly using a coarse-graining that follows the color in our box and ignores the others, summing over the probabilities of whether they others are Y or G.

- The result is

$$p(WSY) = \sum p_Y^k p(k)$$

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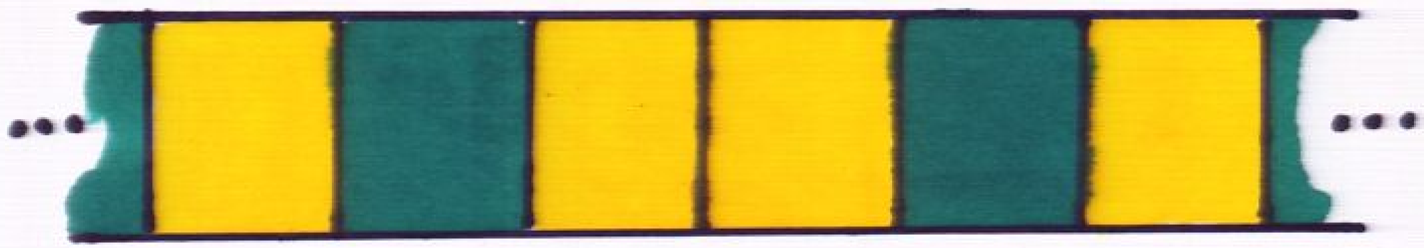

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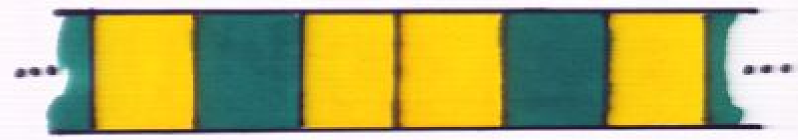

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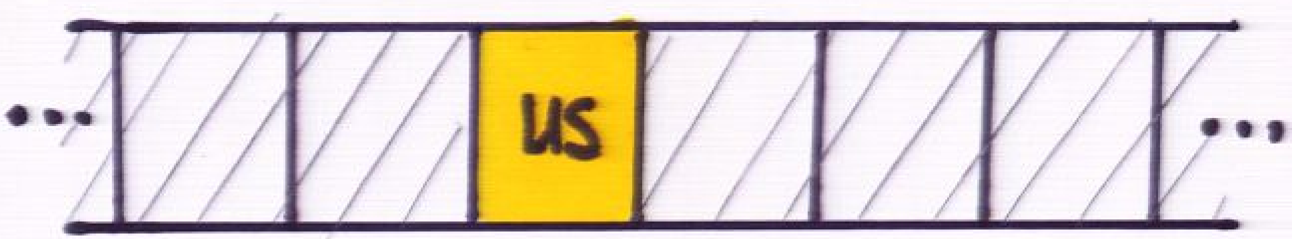
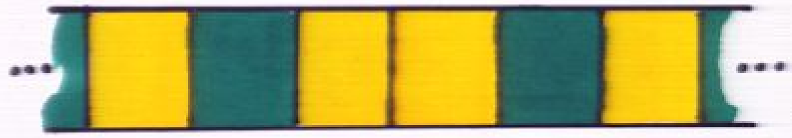


- The result is

$$p(WSY) = \sum p_Y^k p(k)$$

One Minimum

Coarse-graining



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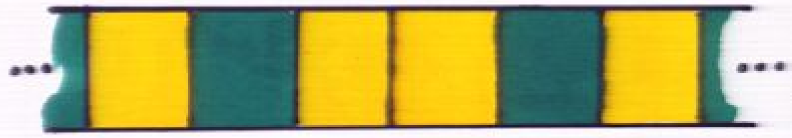

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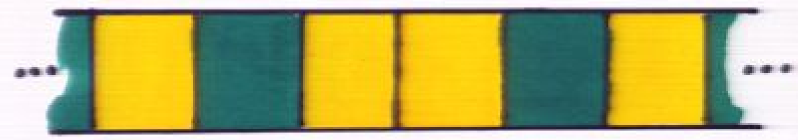

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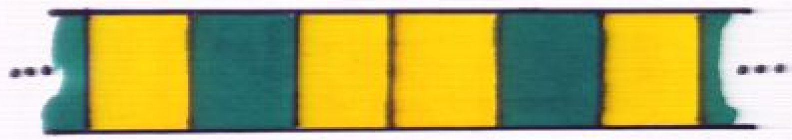

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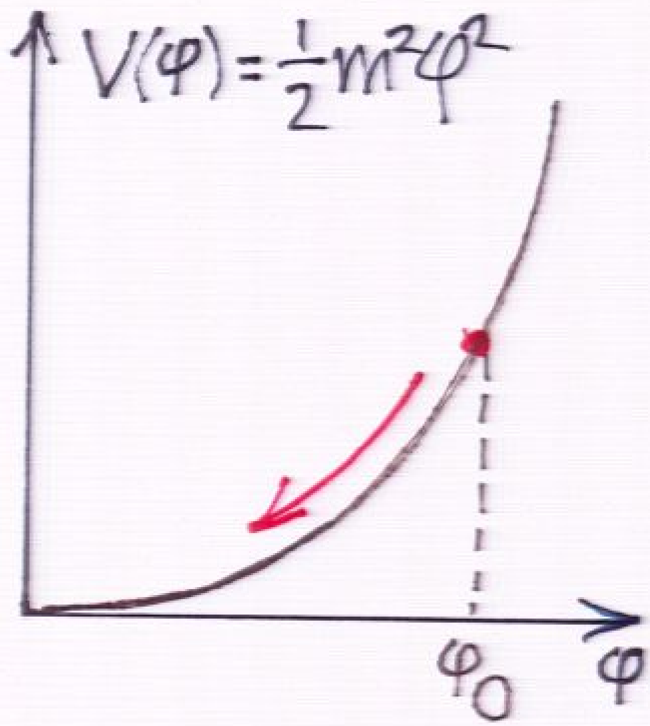
Qualitative EI



- A scalar field φ moving in a potential $V(\varphi) = (1/2)m^2\varphi^2$
- A quantum state Ψ (NBWF)
- From Ψ derive the (BU) probabilities for the ensemble of homo/iso classical background histories labeled by the value φ_0 at the start of roll down (the p(k)).
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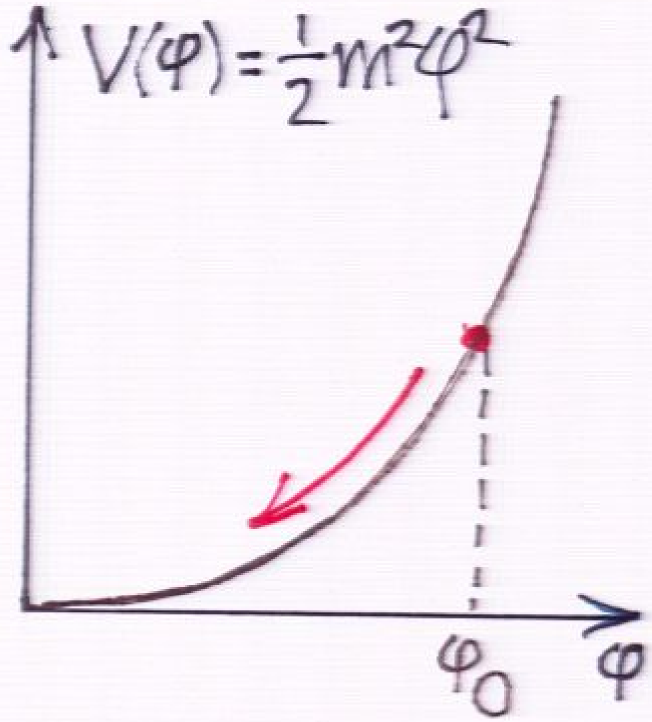

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Selection for EI

- Regime of eternal inflation $V^3 > (V')^2$

- Fluctuations that leave the horizon during EI grow large and make the universe inhomogeneous on superhorizon scales.

- Constant density surfaces become large. TD weighting suppresses histories that do not have EI.

$$p(WSR) \approx \frac{p(1)}{p(1) + N_2 p_E p(2)} \approx 1$$

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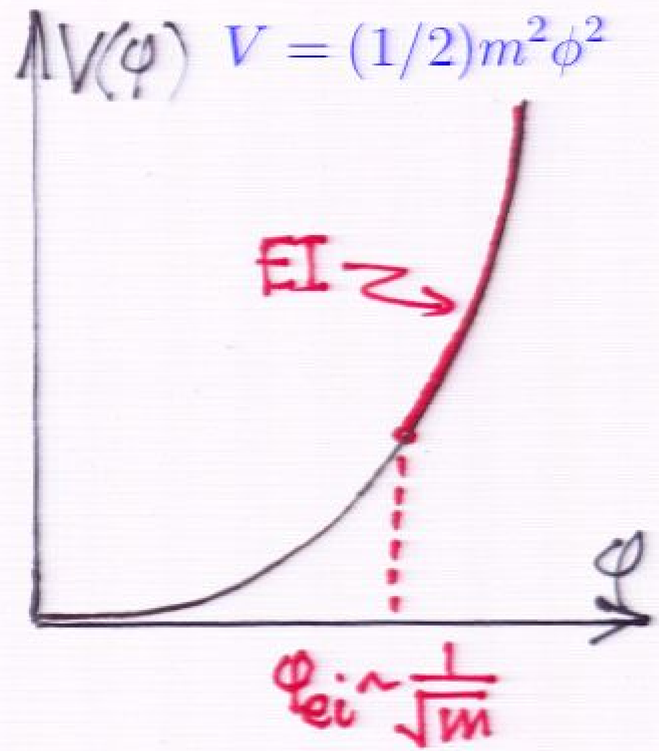

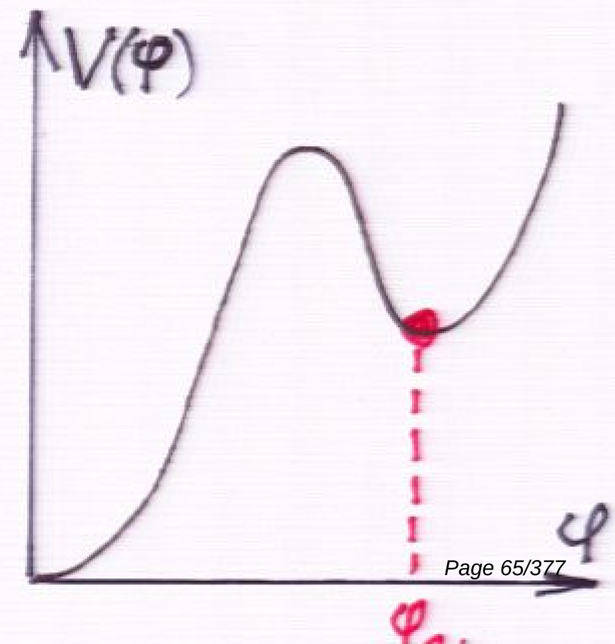

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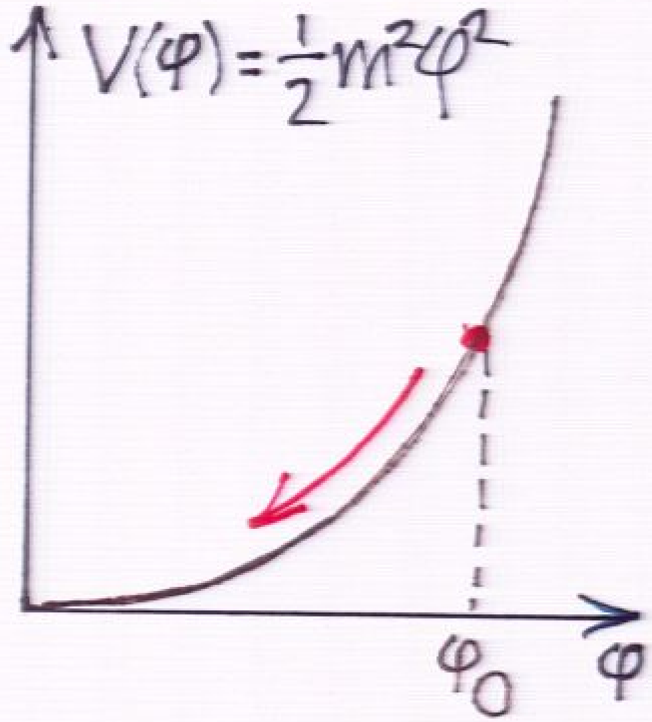

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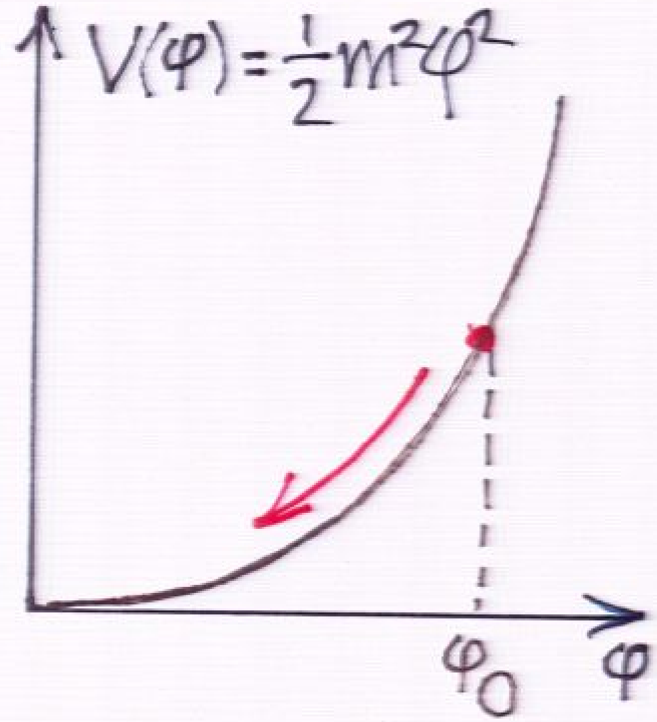

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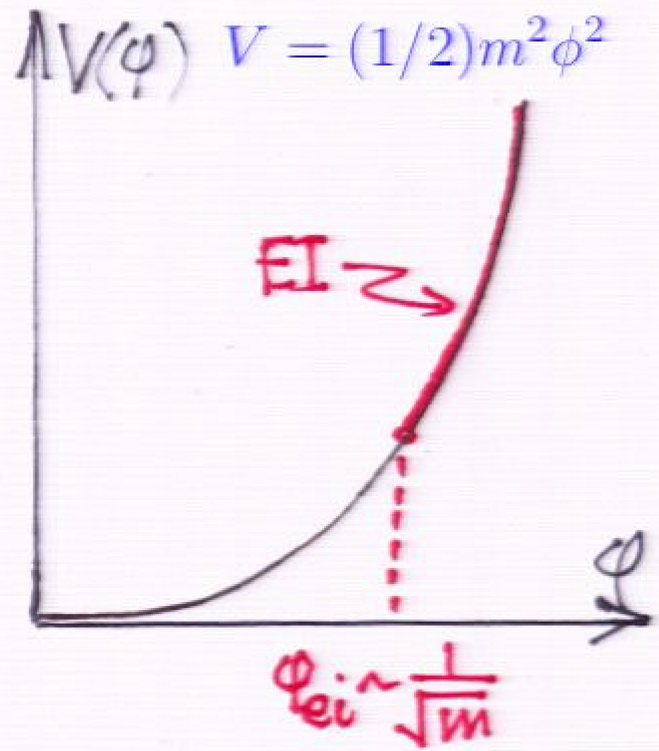

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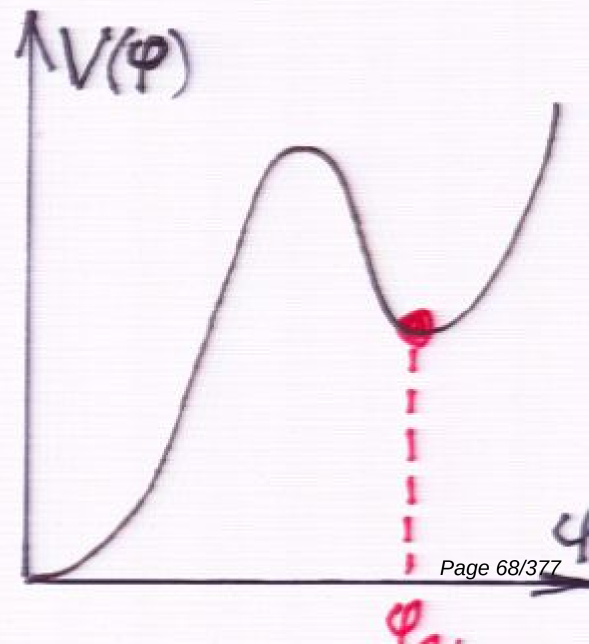

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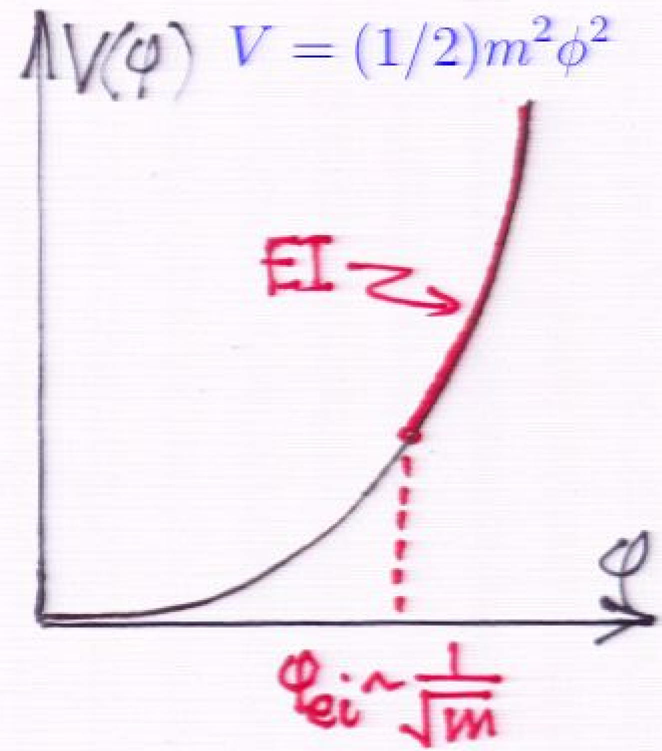

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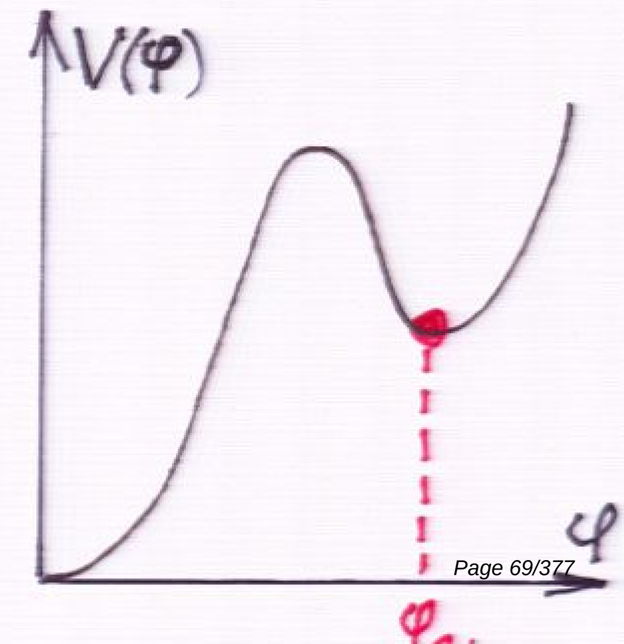

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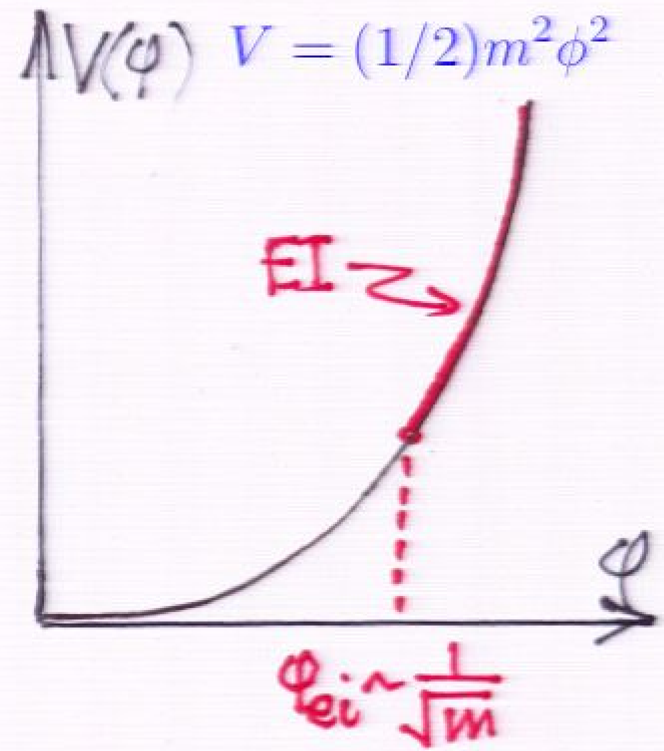

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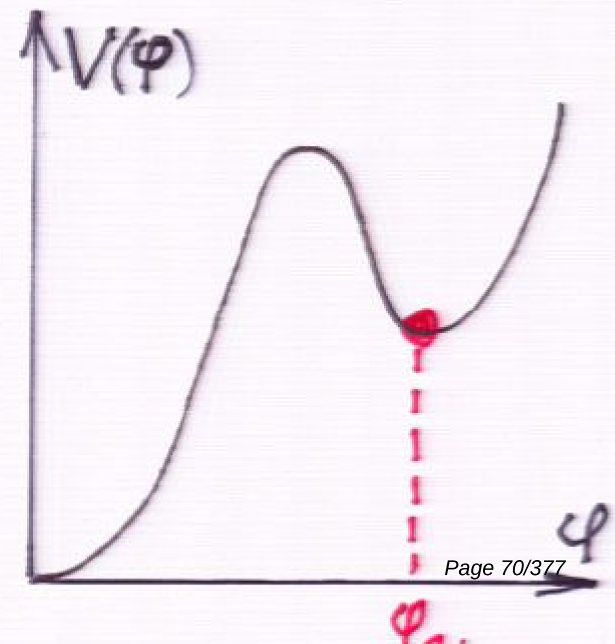

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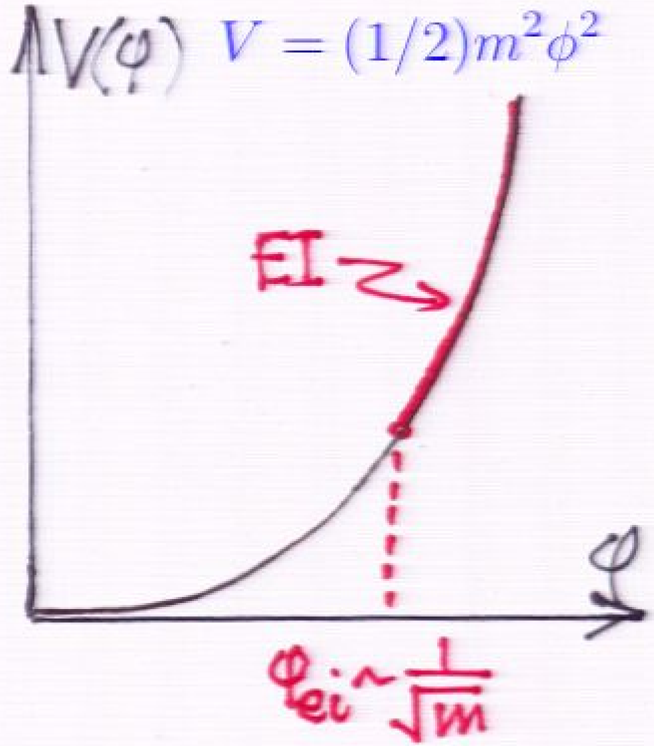

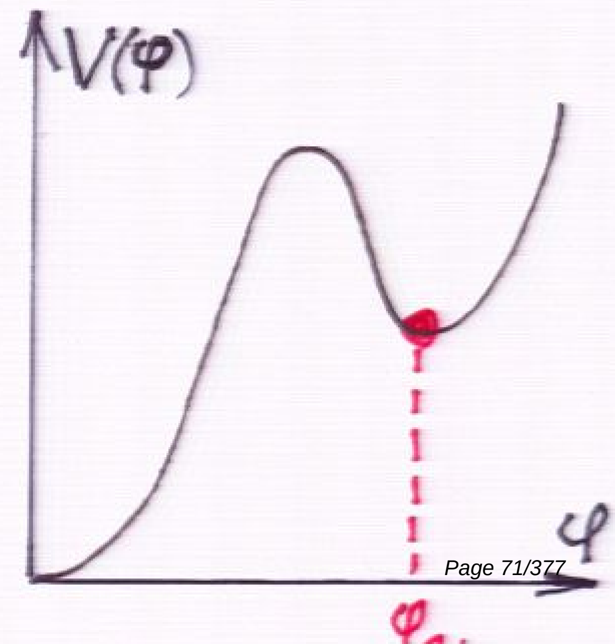

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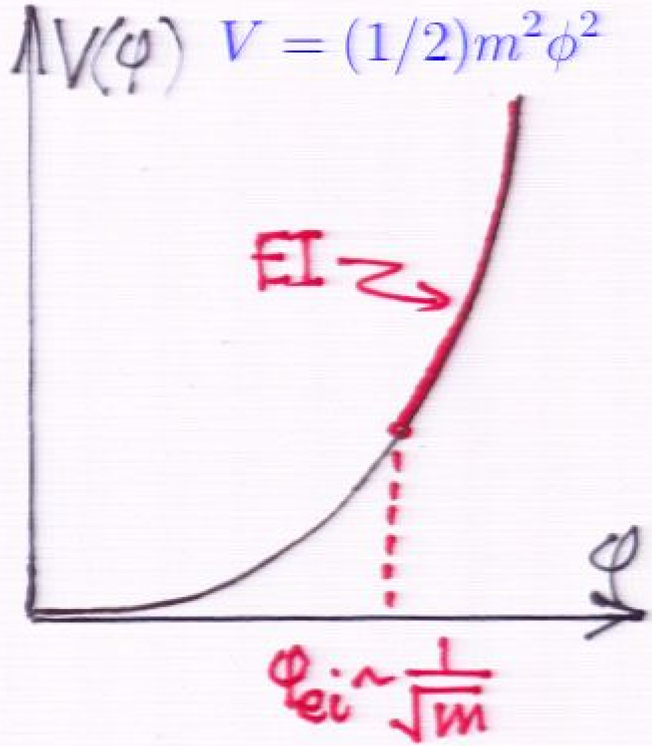

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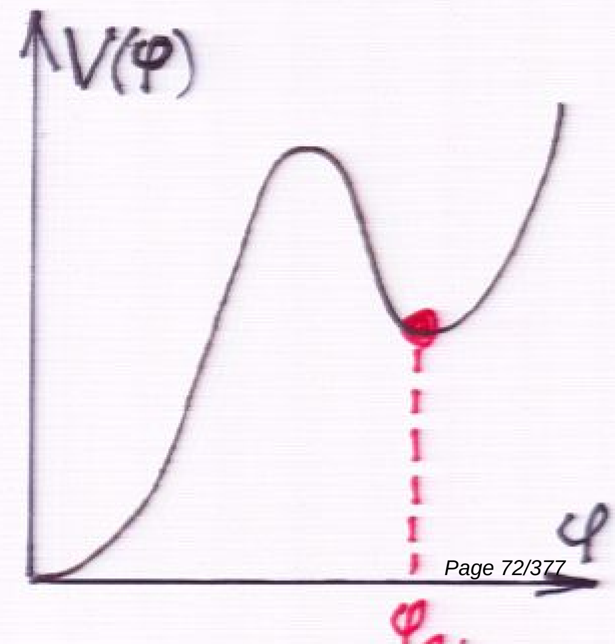

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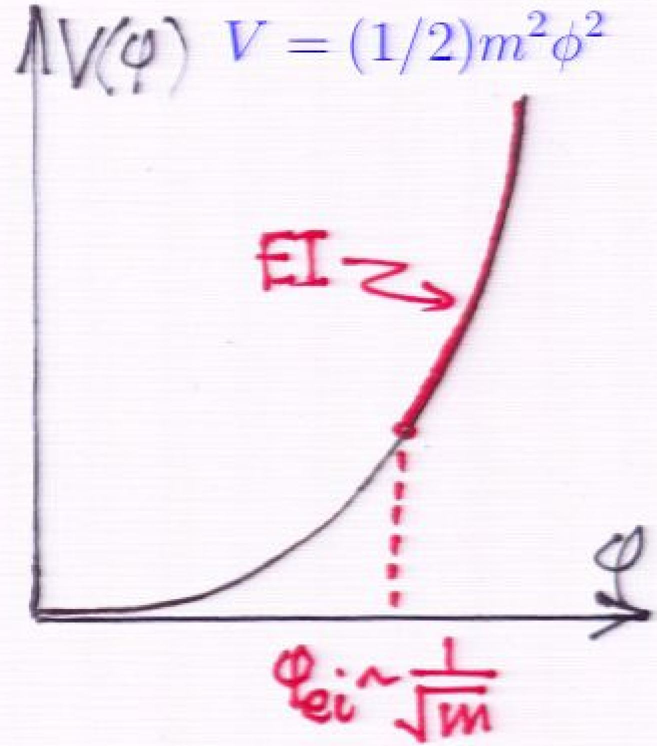

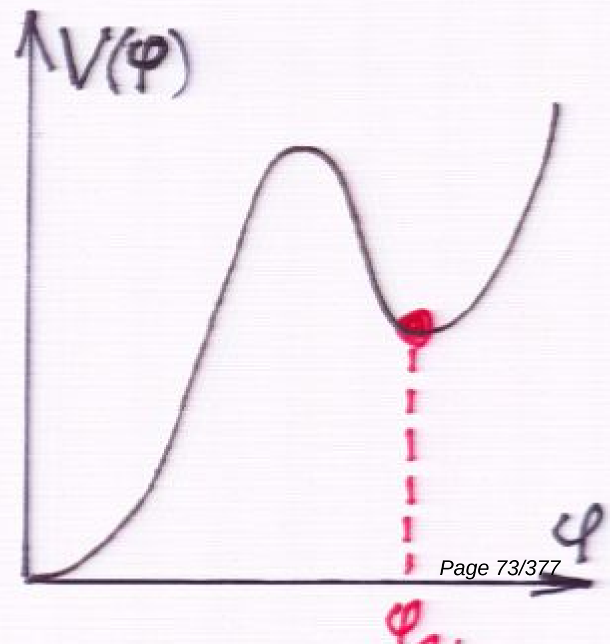

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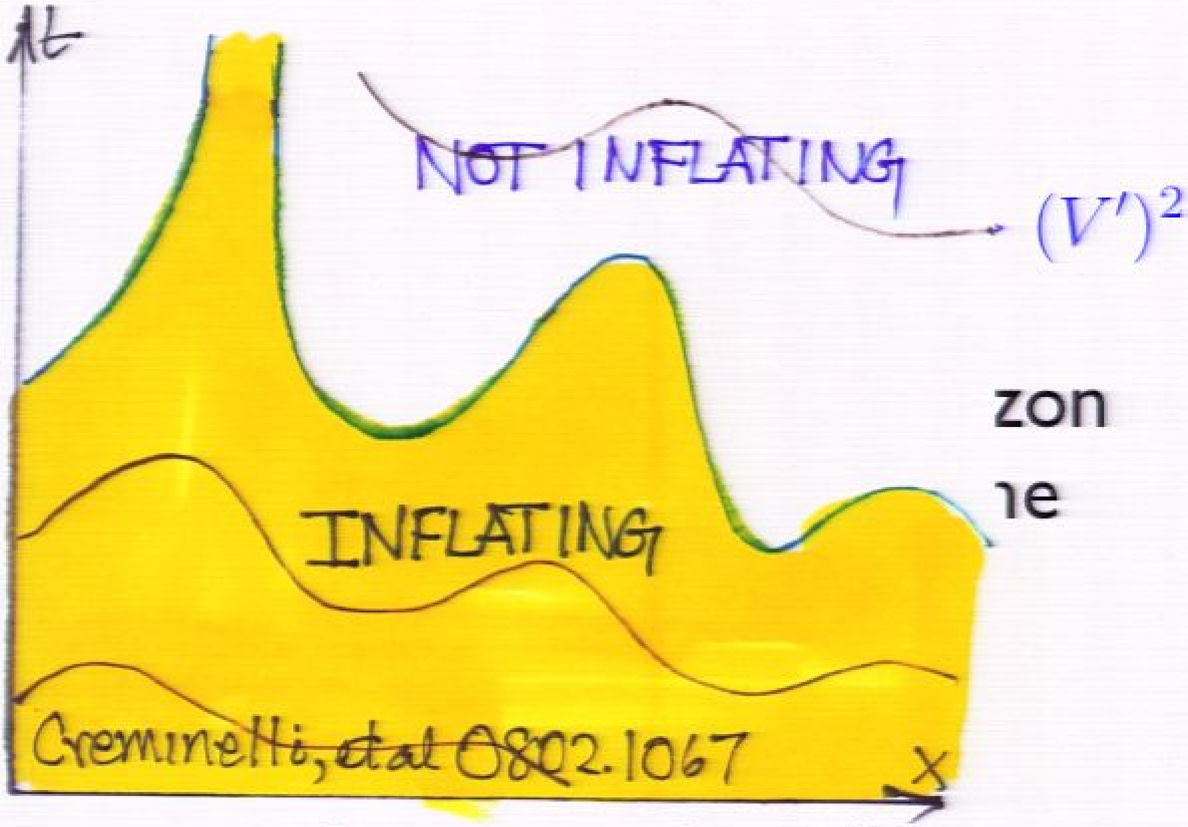

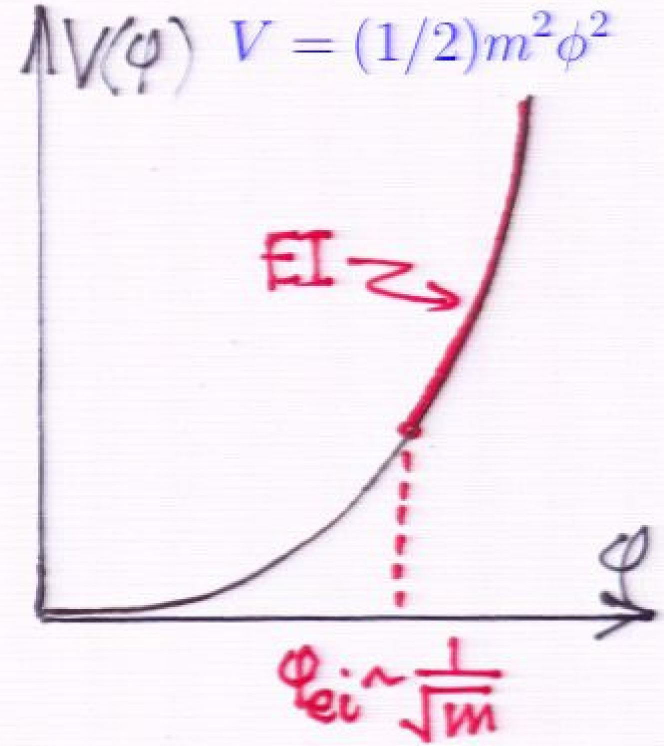

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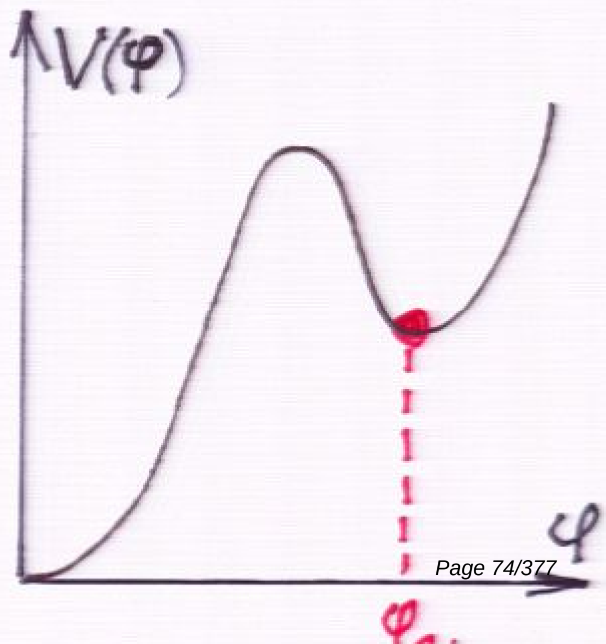

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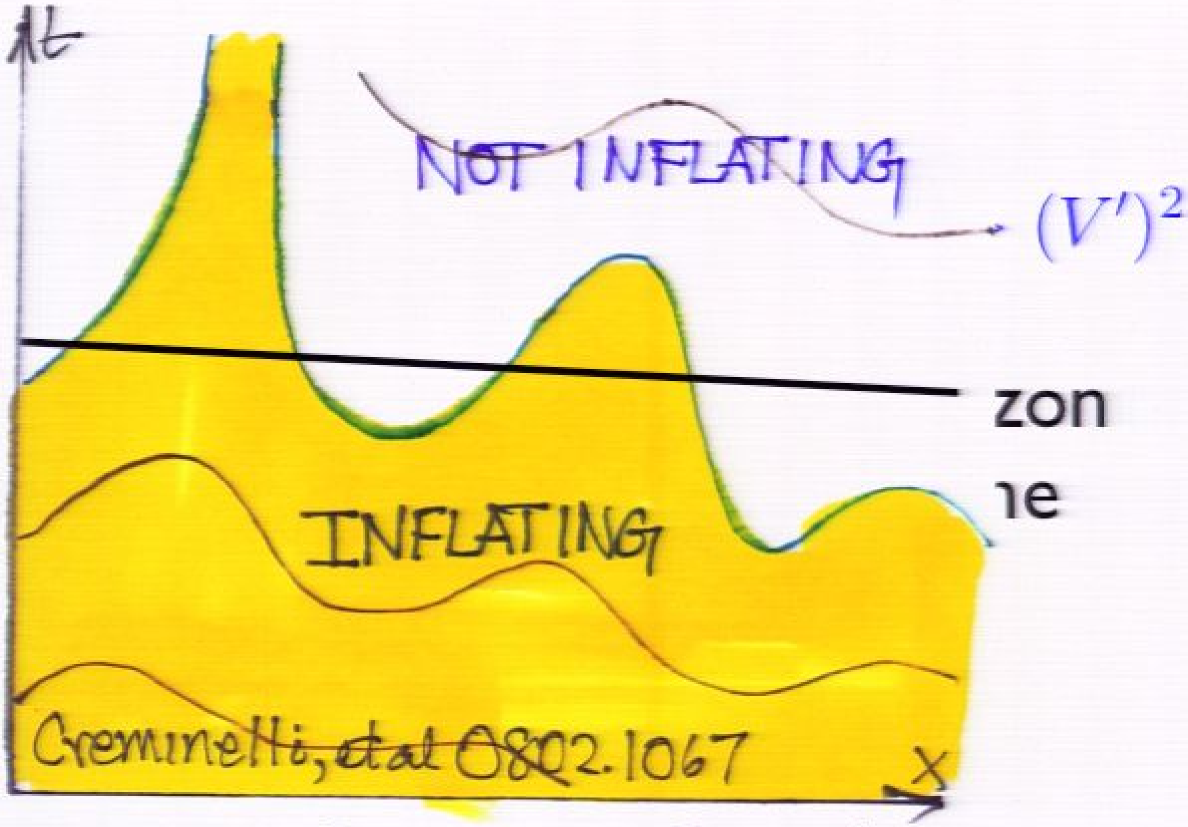

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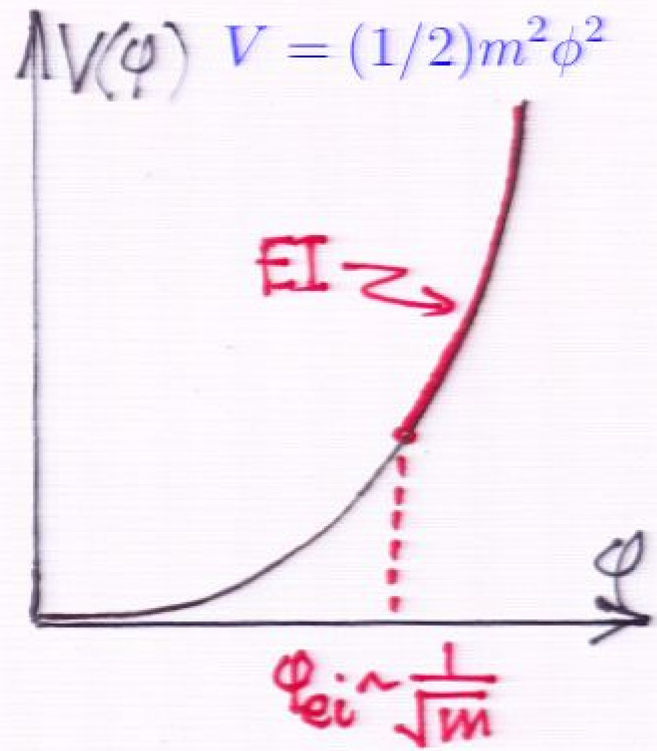

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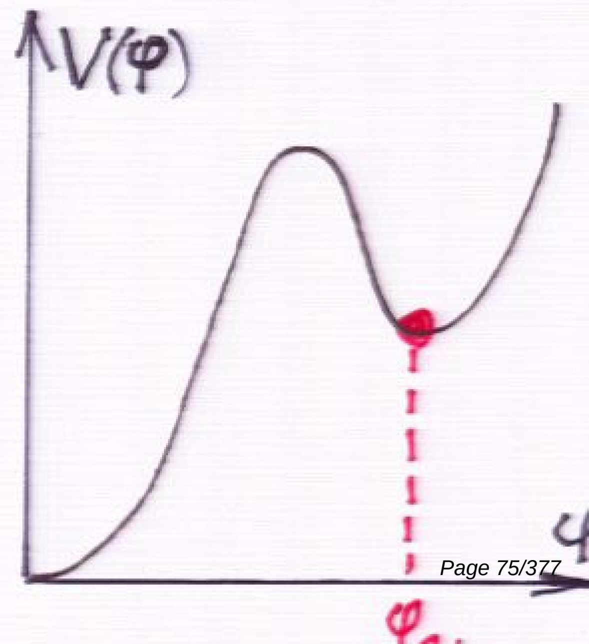

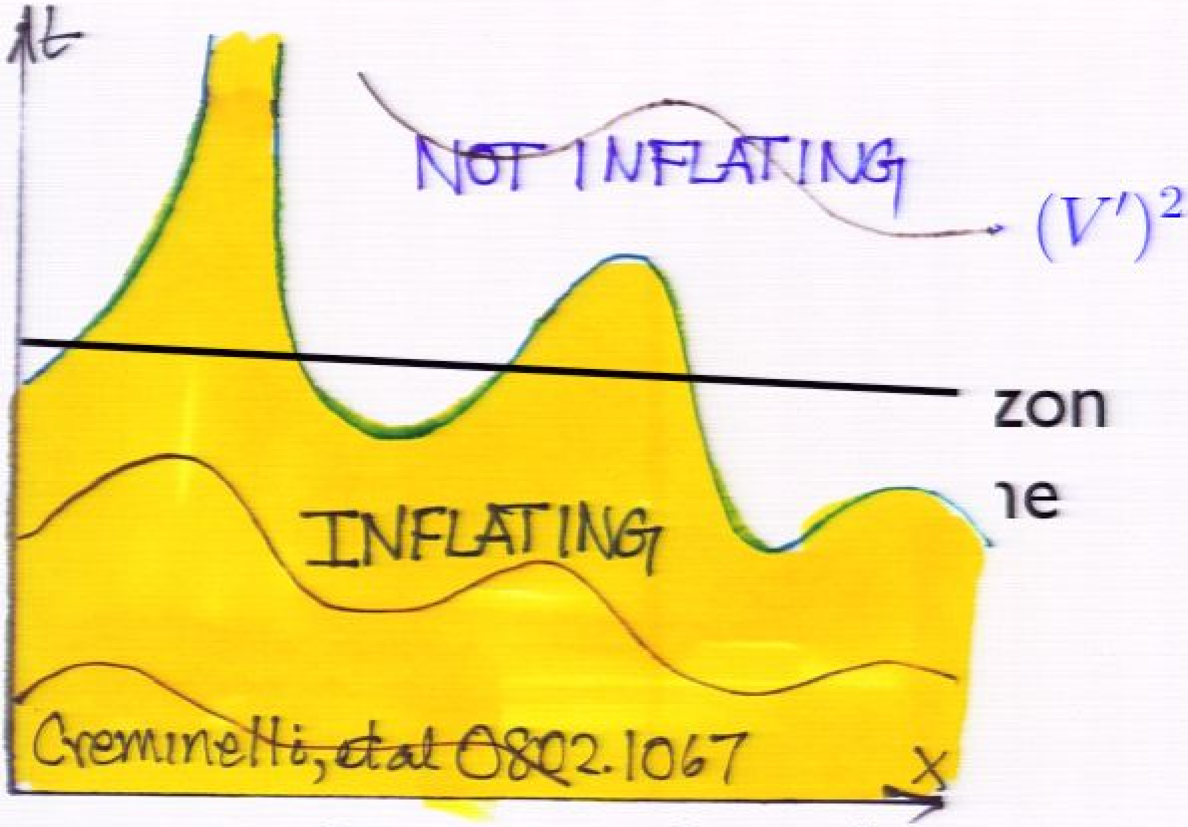

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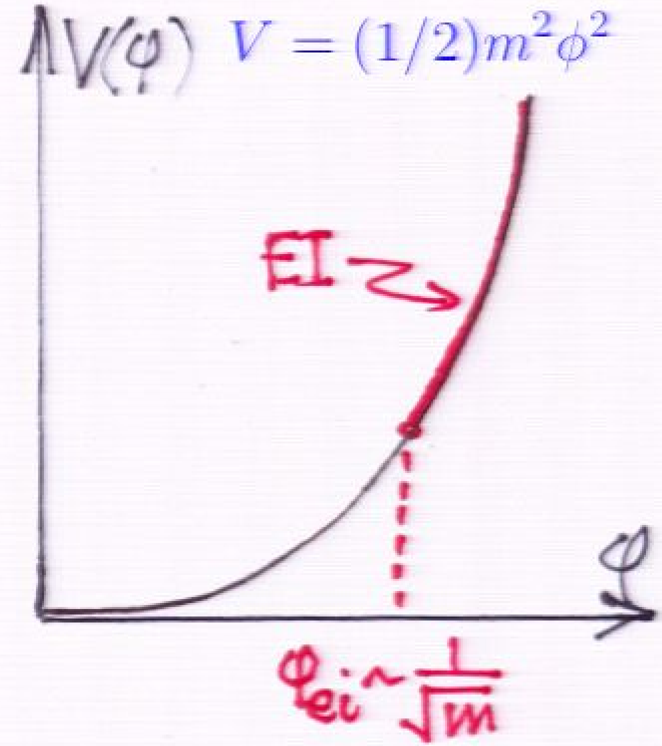

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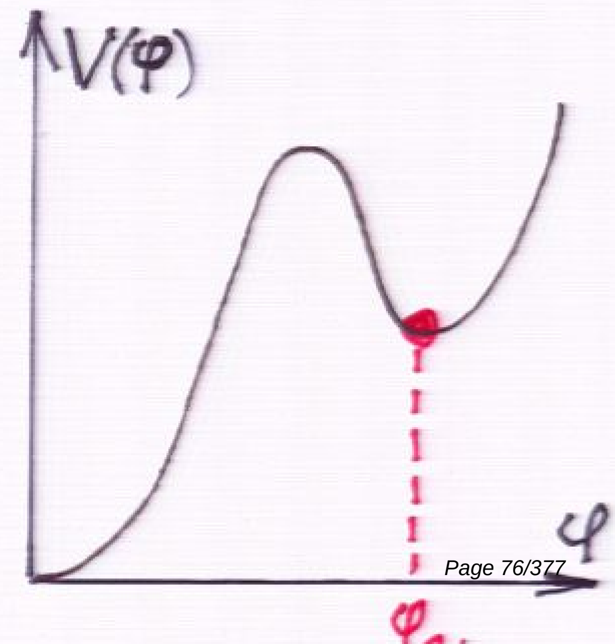

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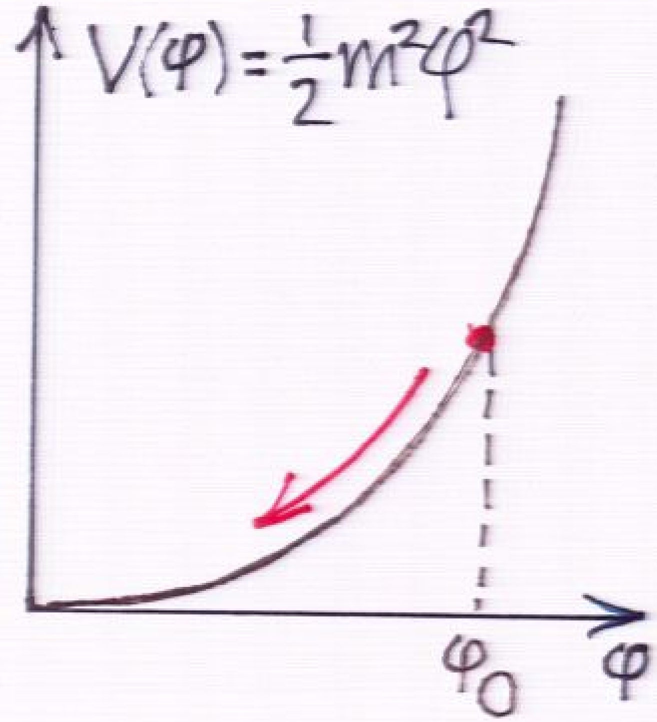

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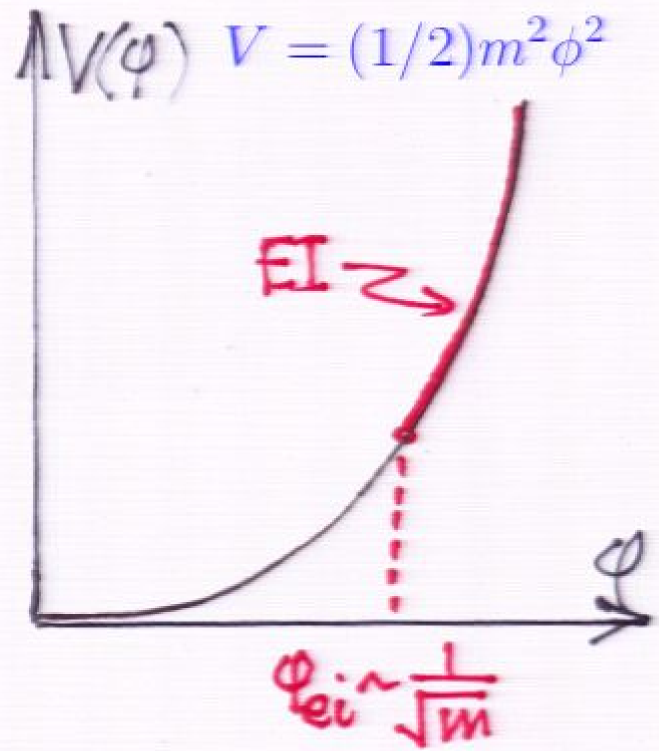

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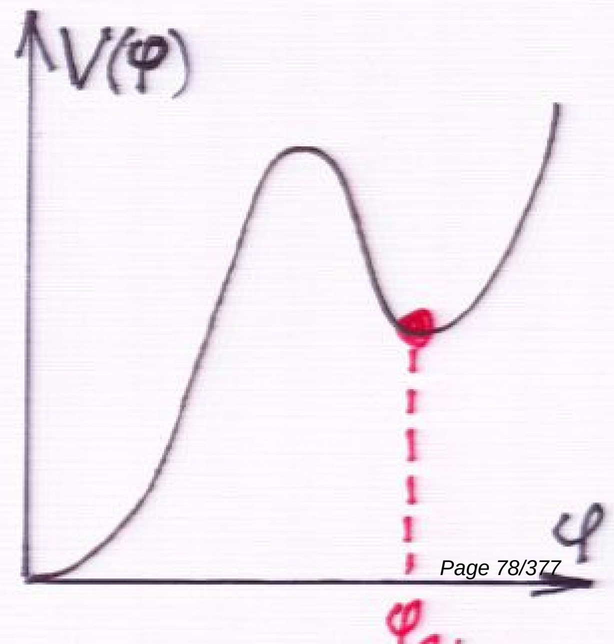

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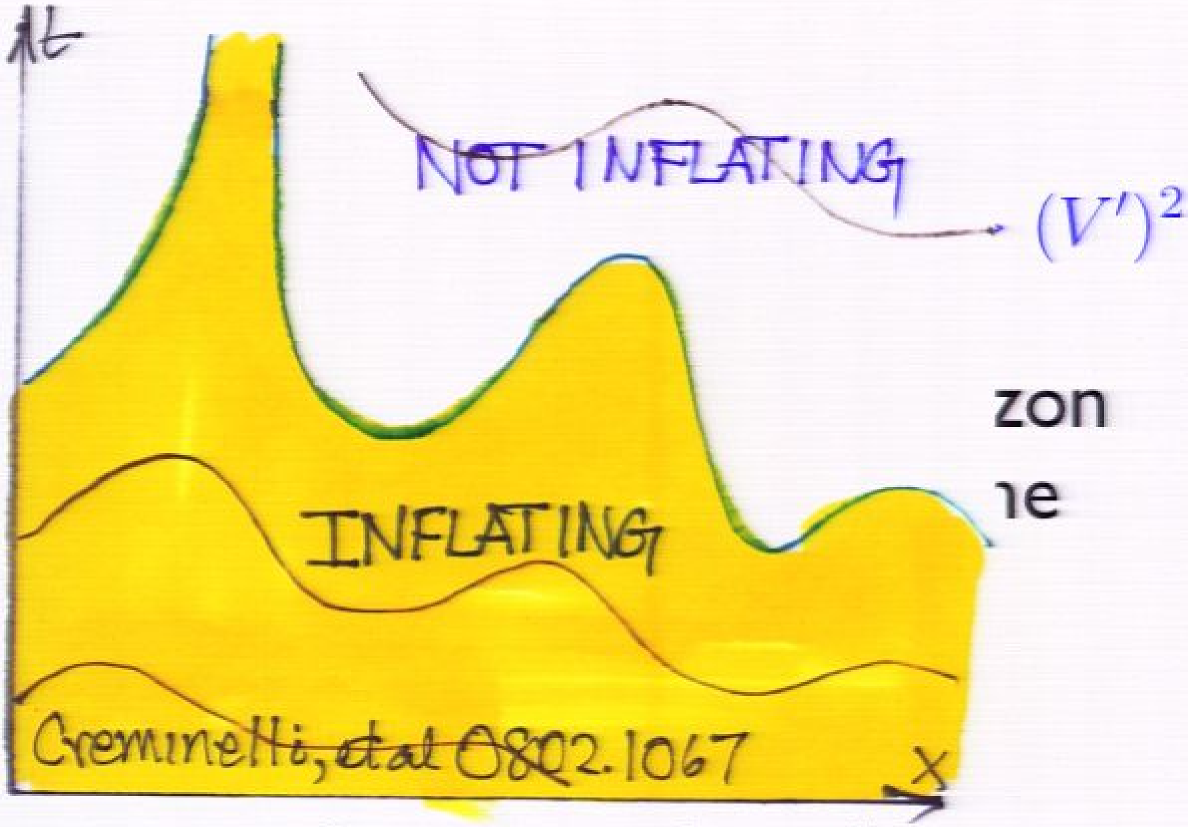

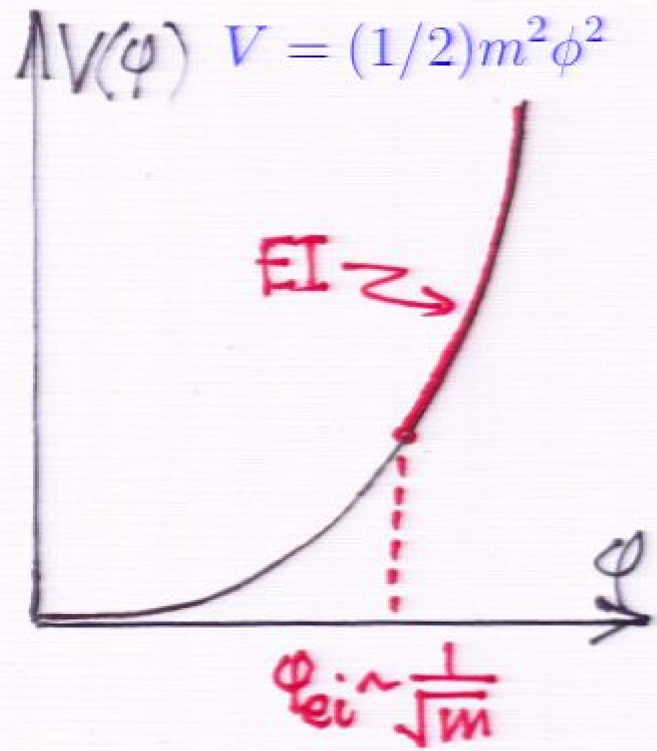

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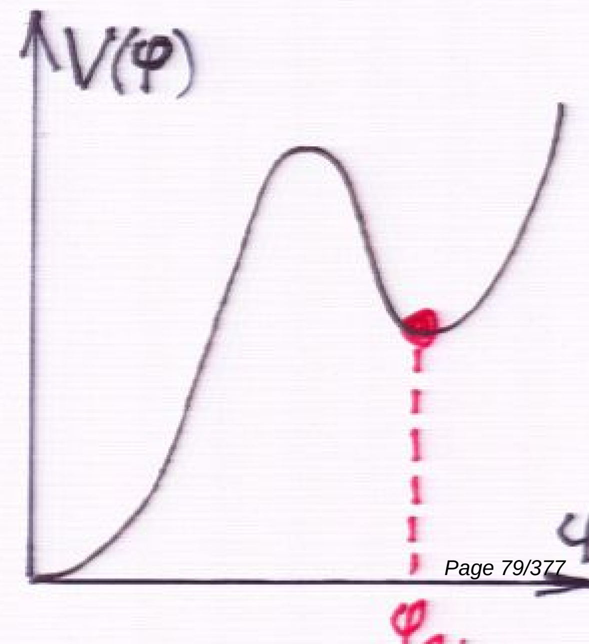

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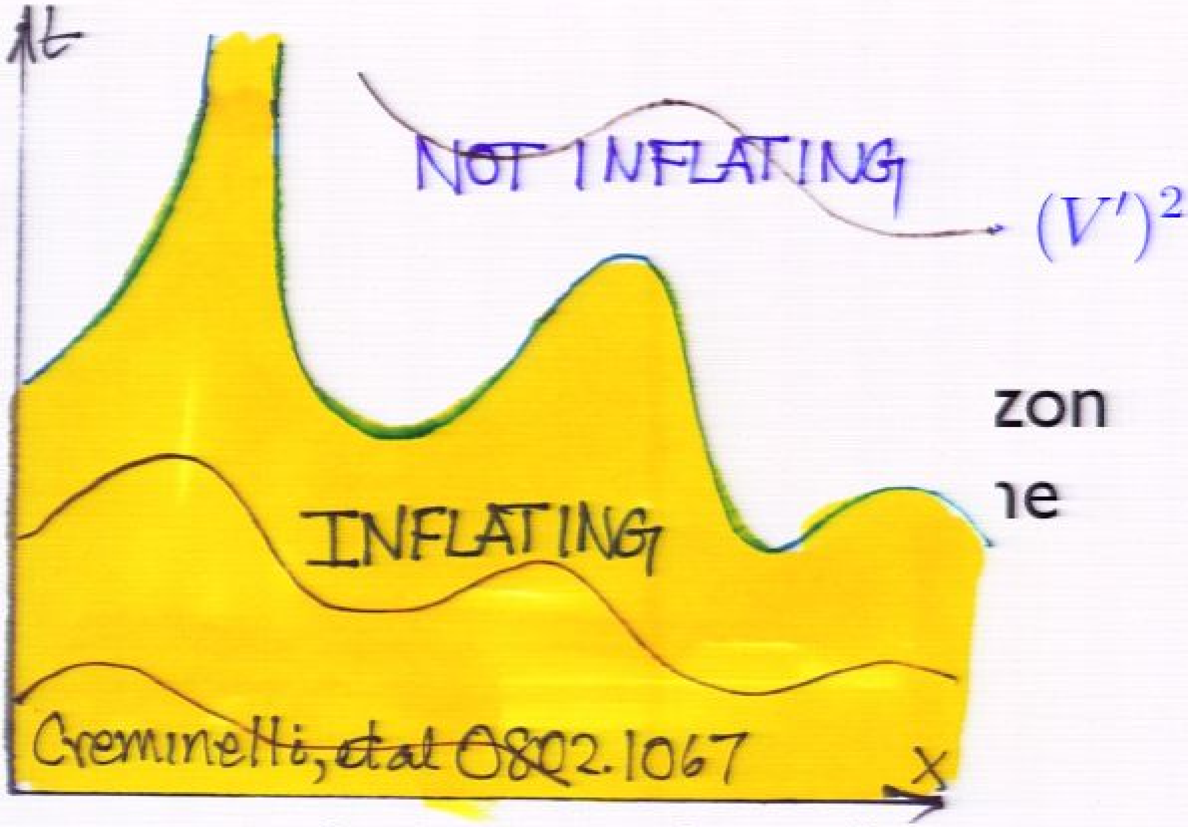

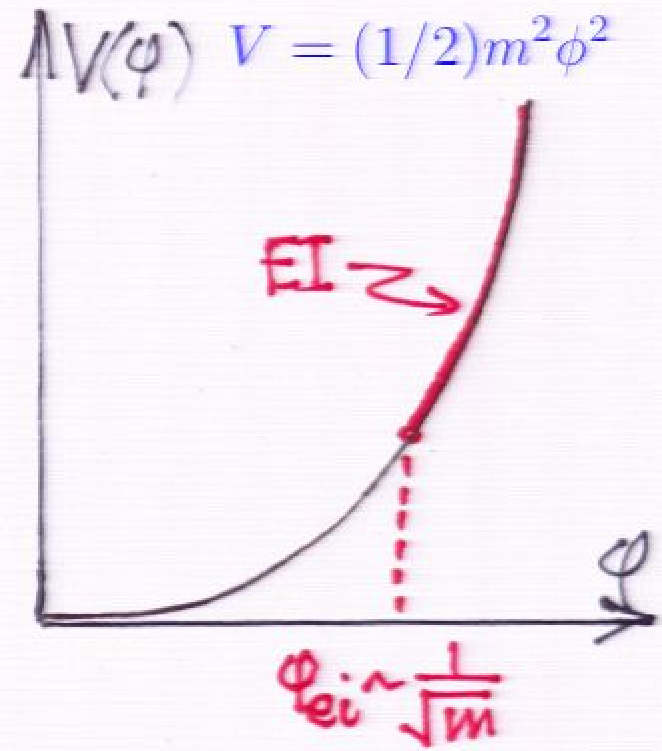

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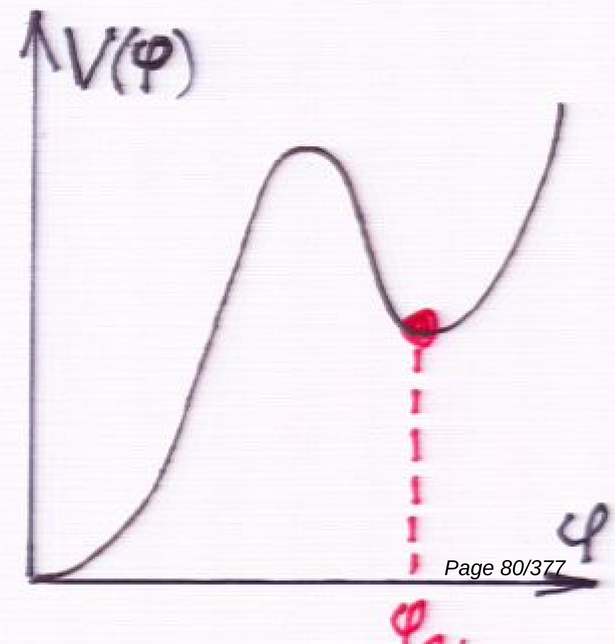

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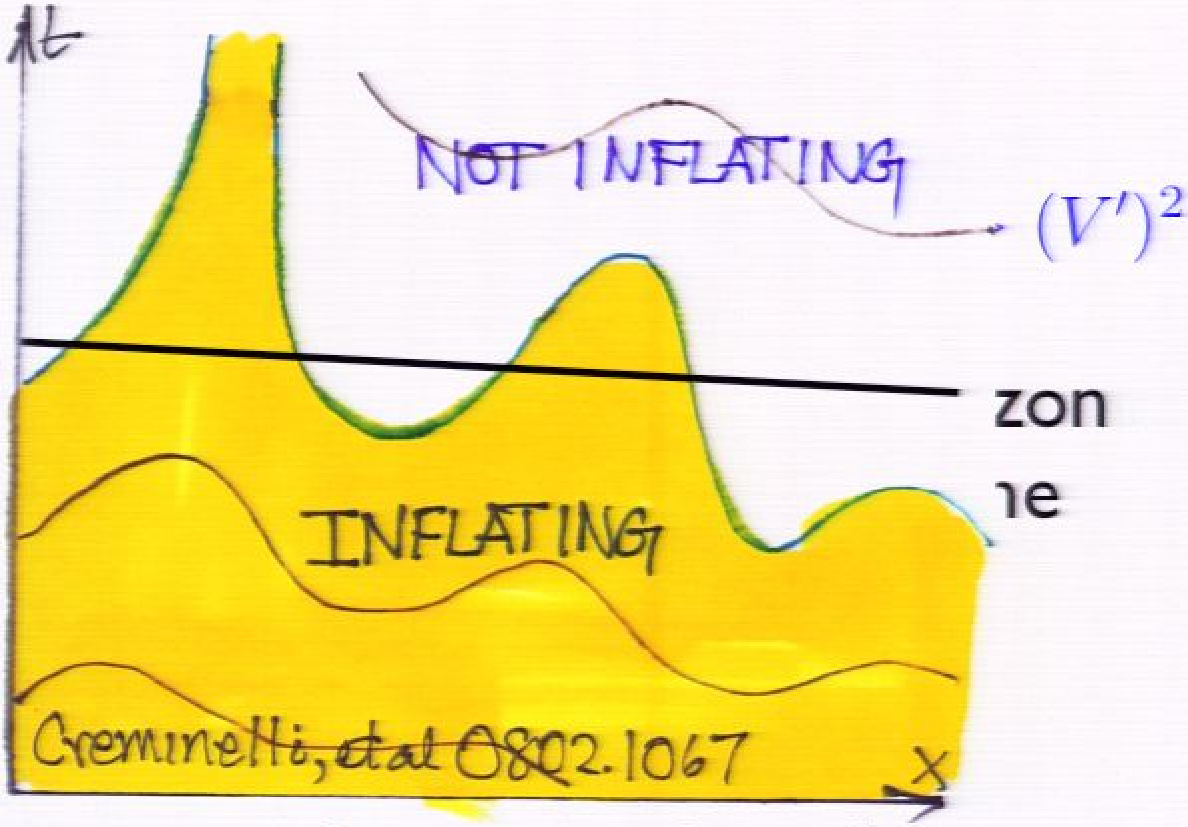

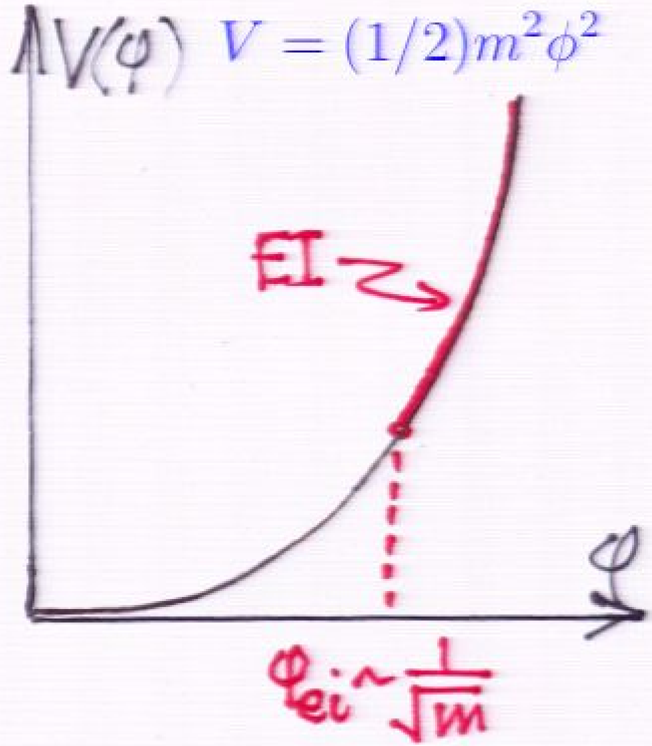

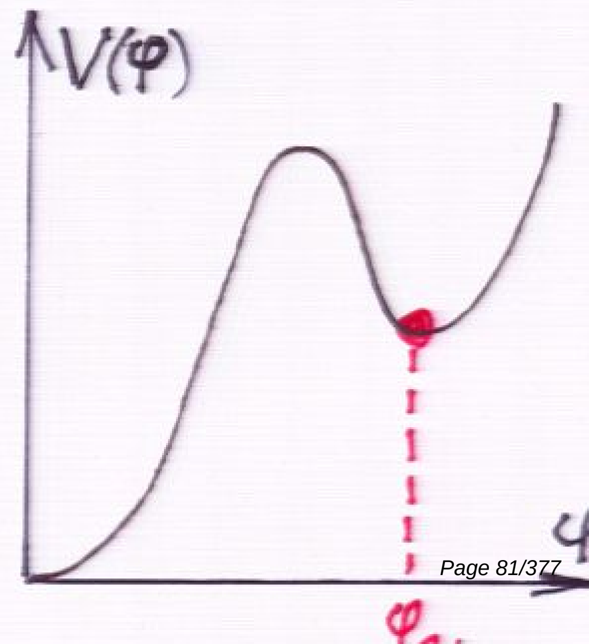

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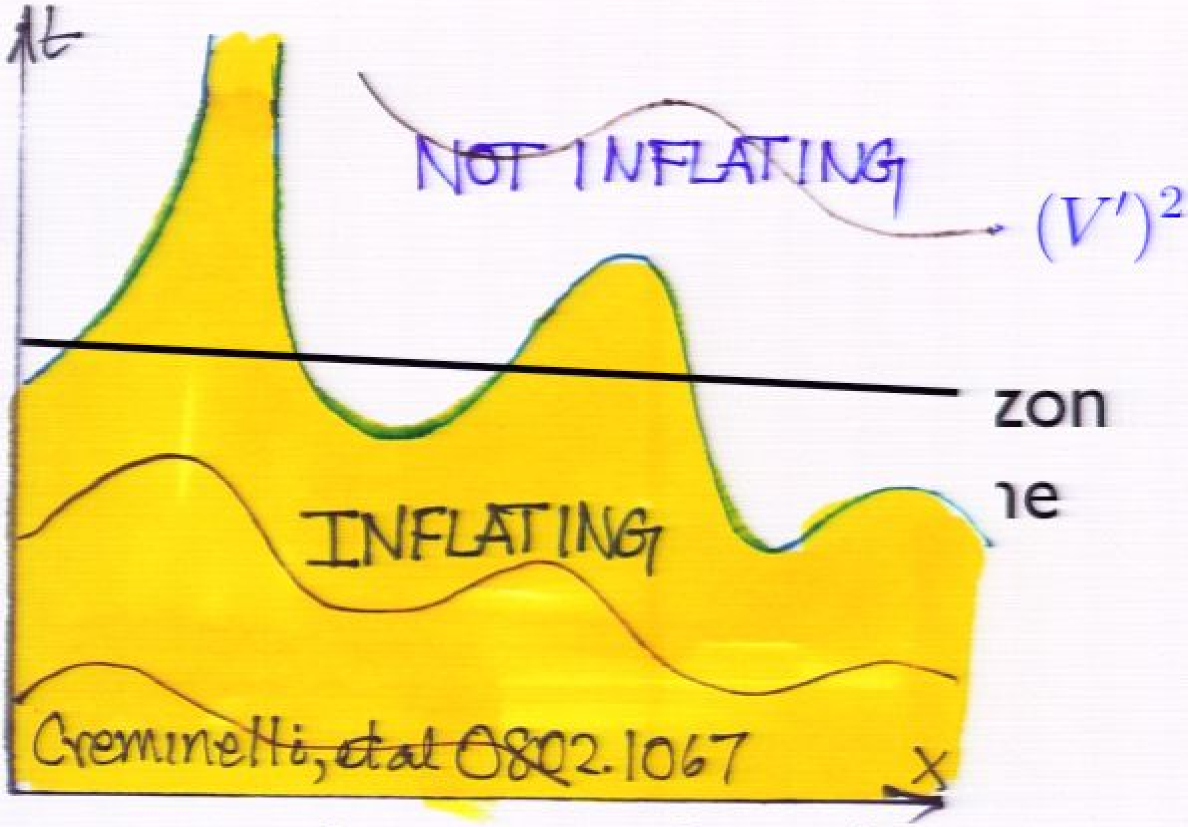

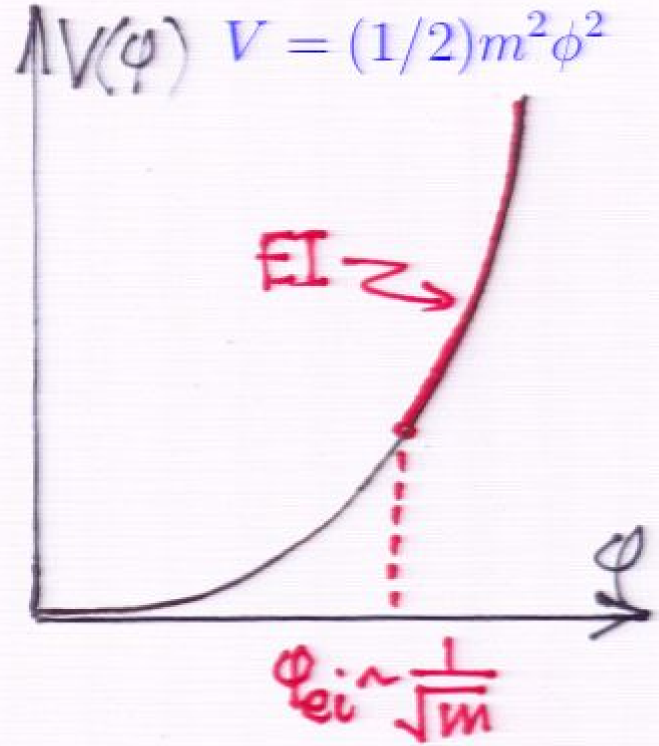

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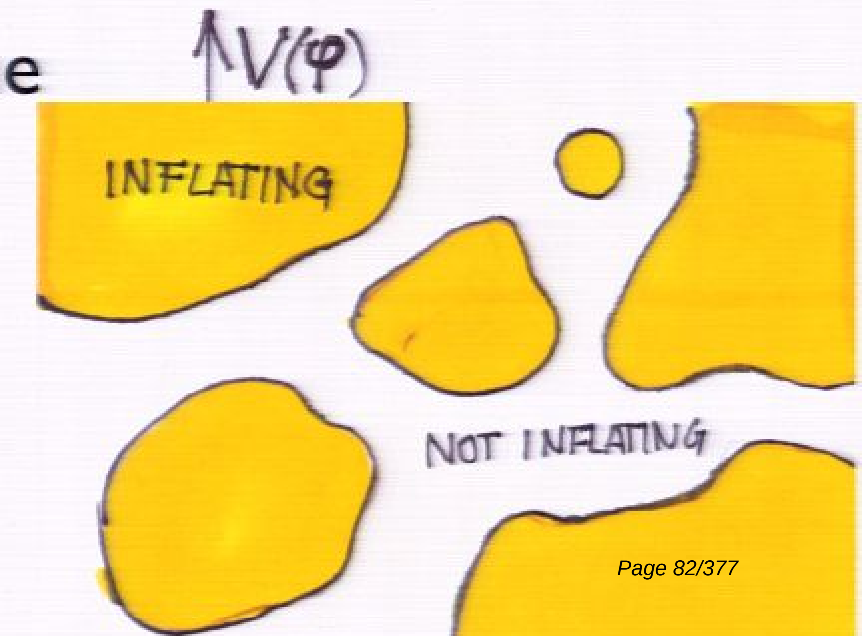

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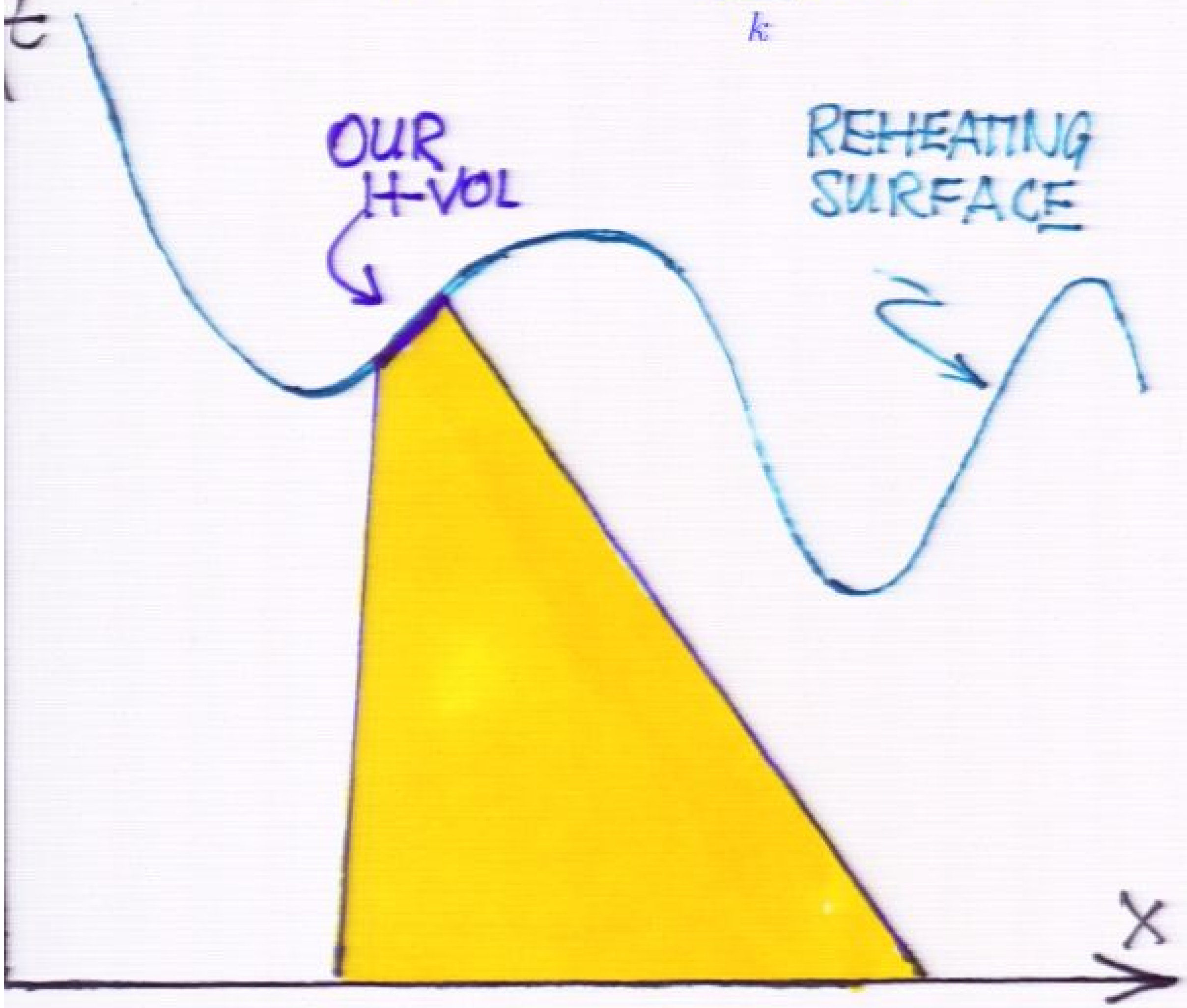
Coarse-Graining

$$p(WSY) = \sum_k p_Y^k p(k)$$



$$p(W S\ C_\ell^{\prime \rm obs}) = \int d\phi_0\ p(C_\ell^{\prime \rm obs}|\phi_0)p(\phi_0)$$

- Focus on probabilities for our observations in our H-vol, the same as others.
- Probabilities for our observations are determined by sums over relevant parts of history in our past light cone.
- Coarse-grain over everything outside the past light cone in particular the future

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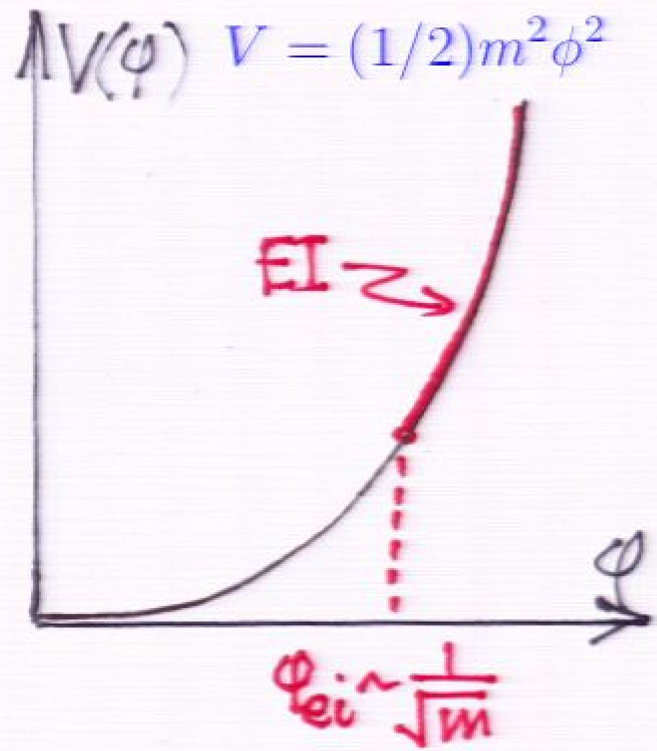

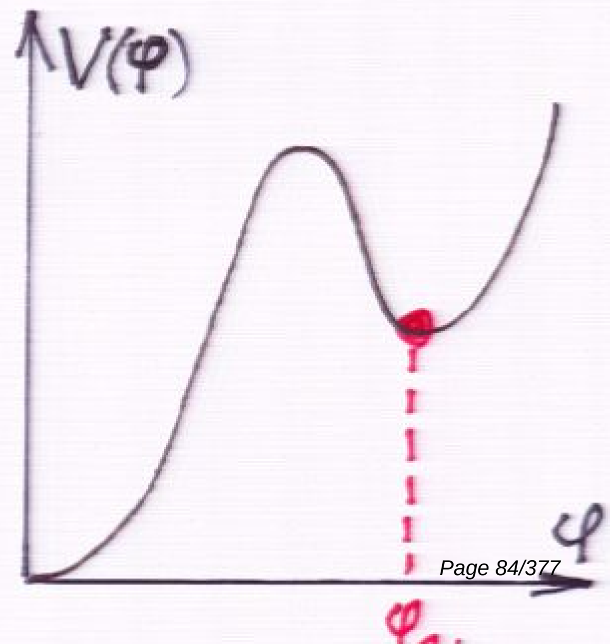

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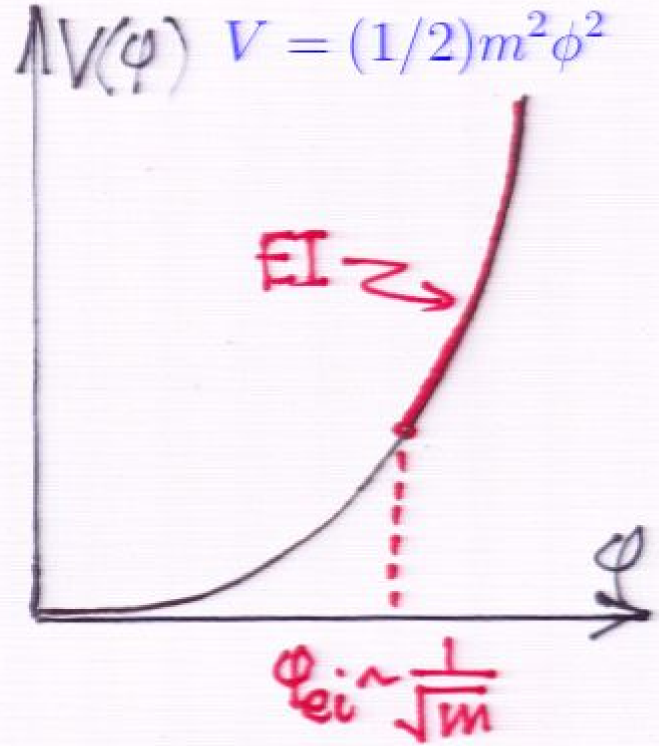
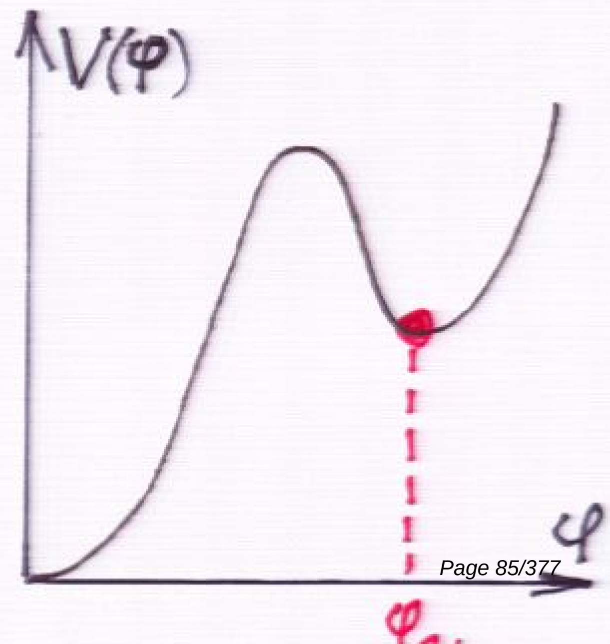


- Fluctuations that leave the horizon during EI grow large and make the universe inhomogeneous on superhorizon scales.

- Constant density surfaces become large. TD weighting suppresses histories that do not have EI.



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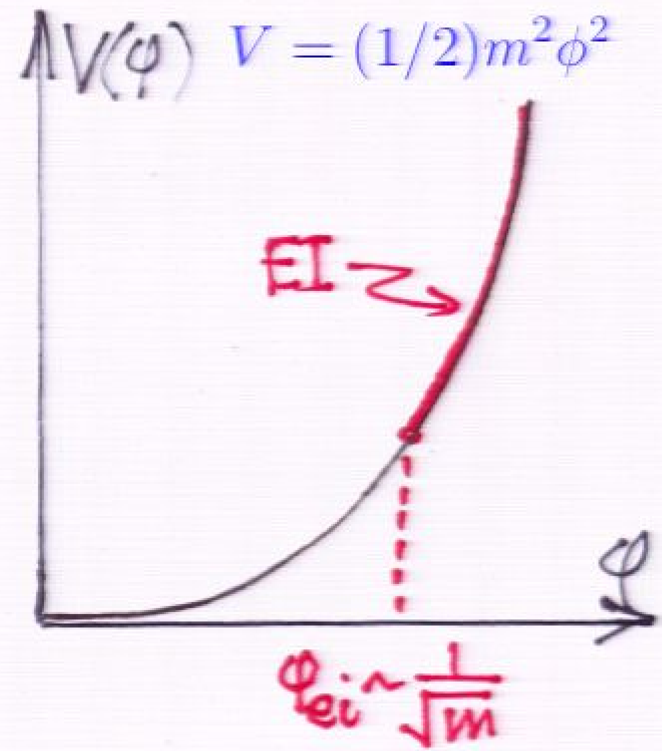

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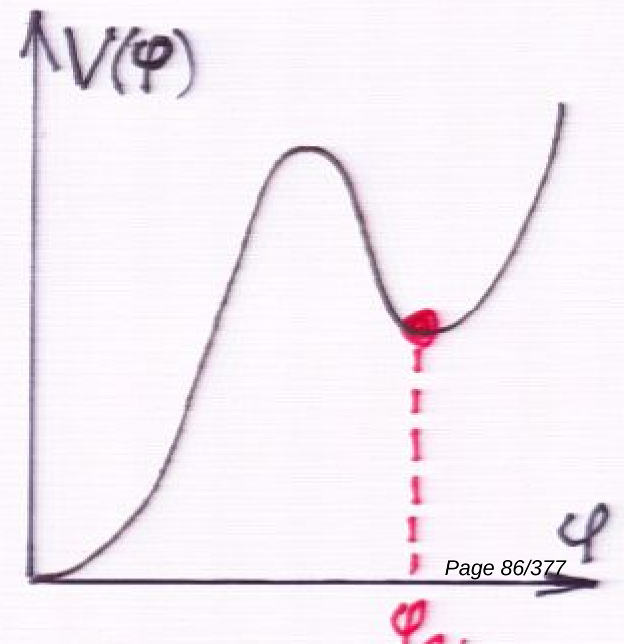

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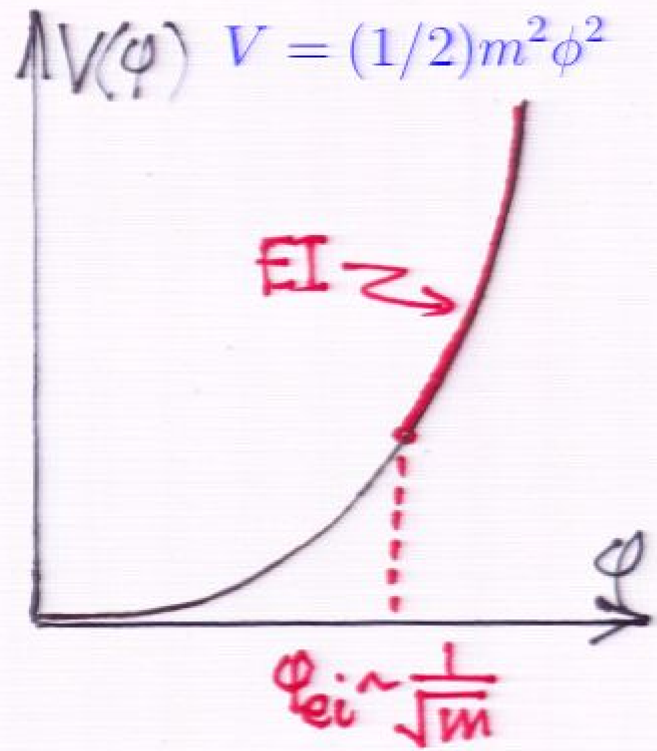

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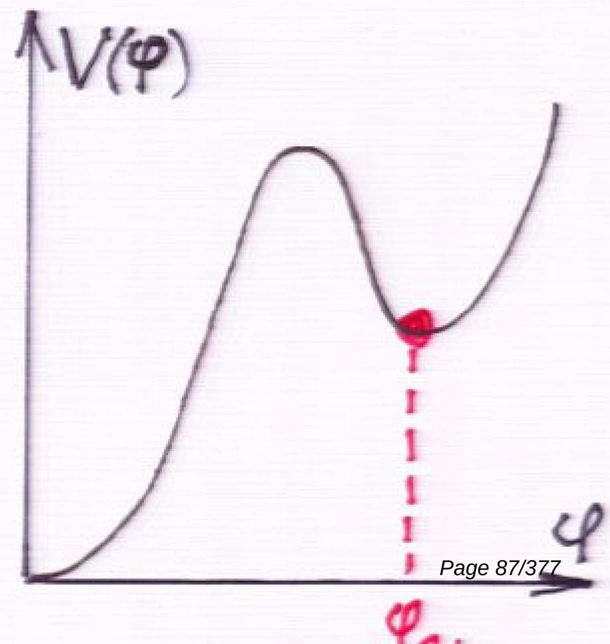

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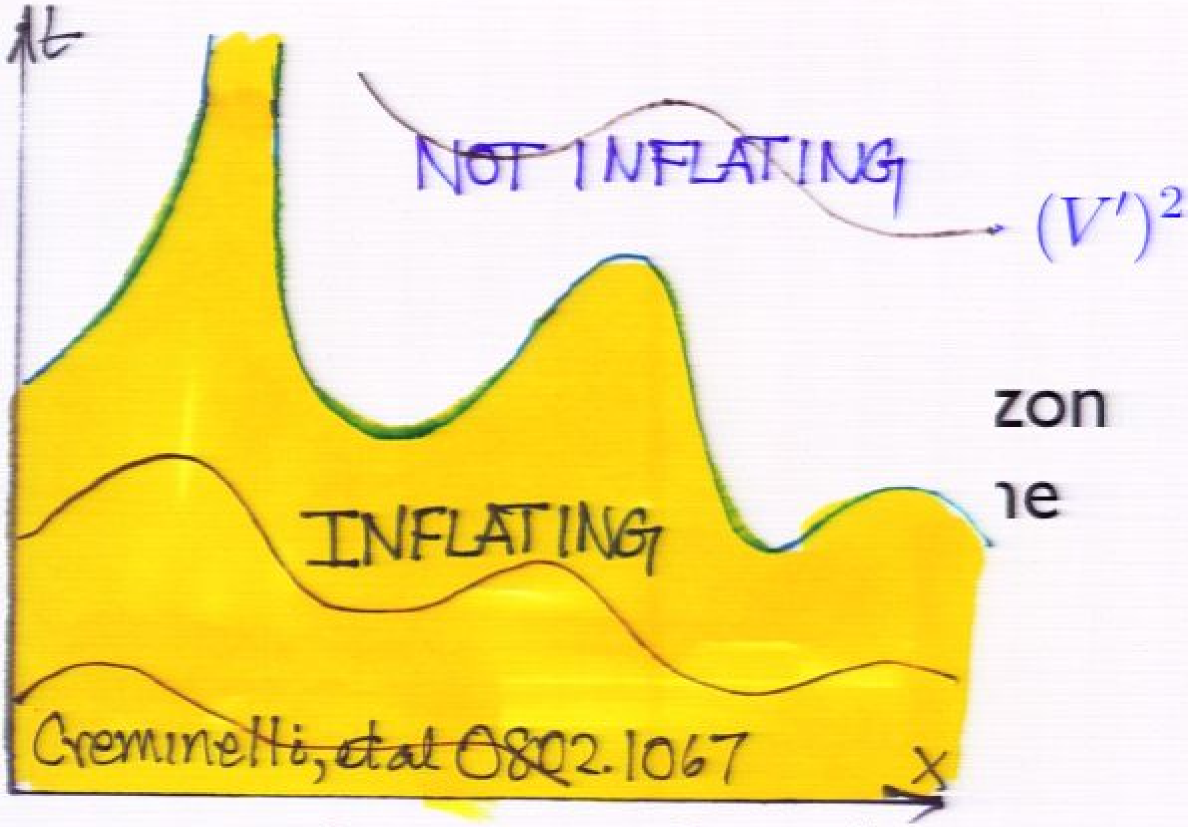

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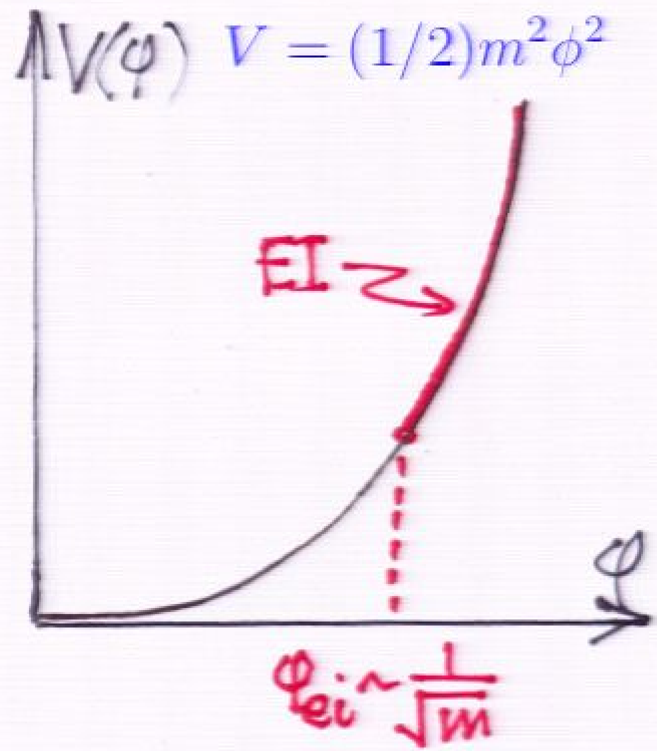

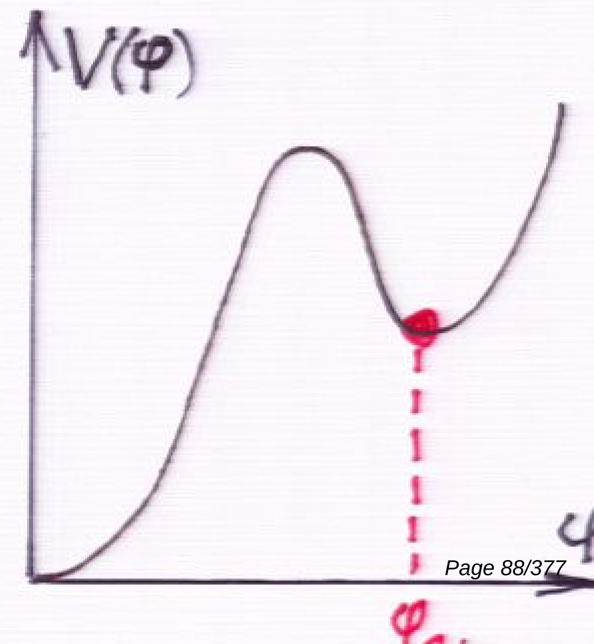

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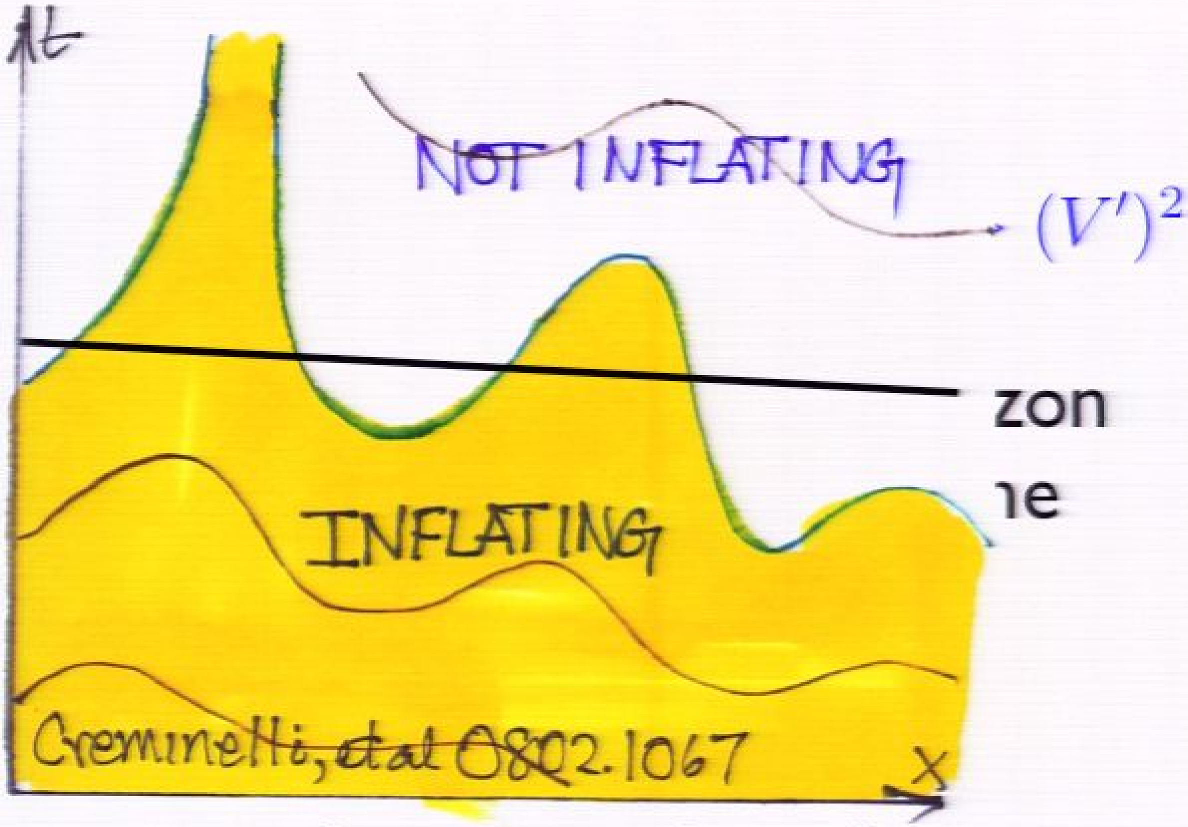

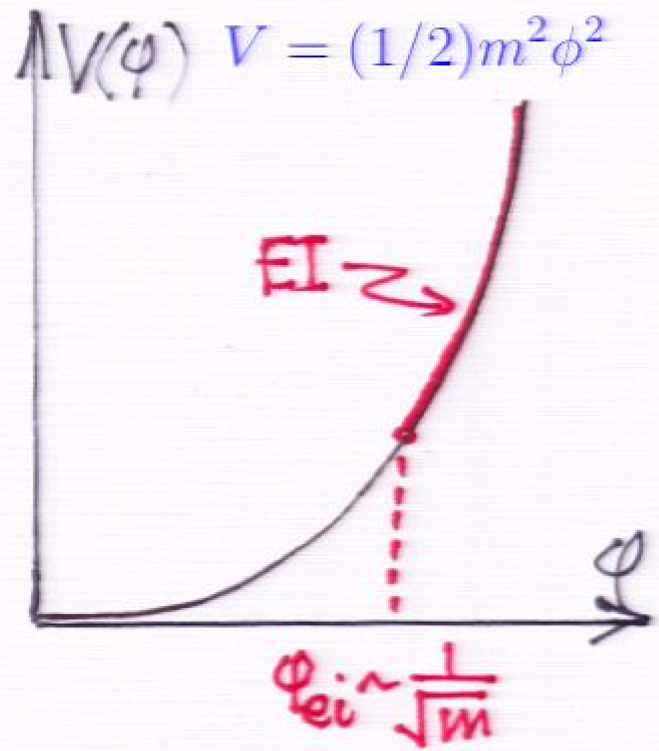

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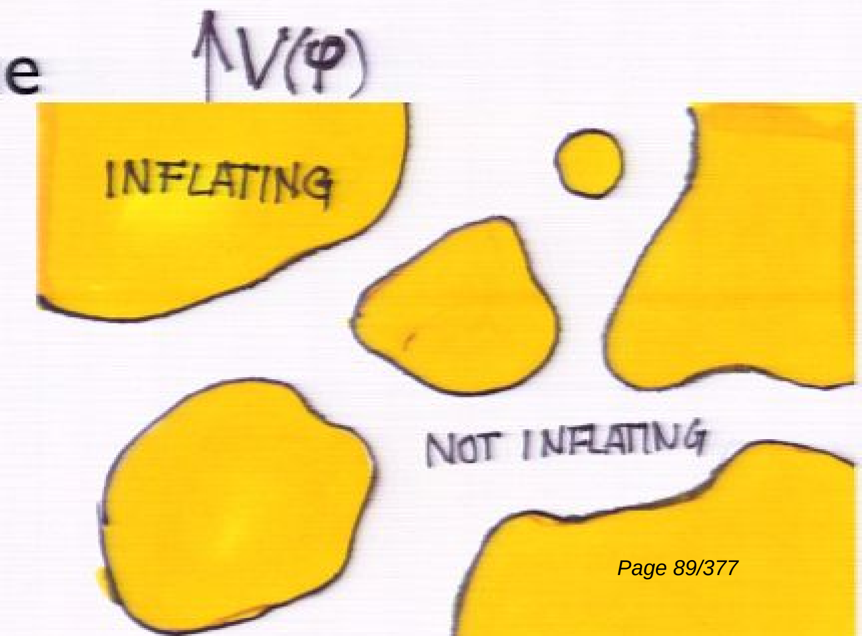

Coarse-Graining

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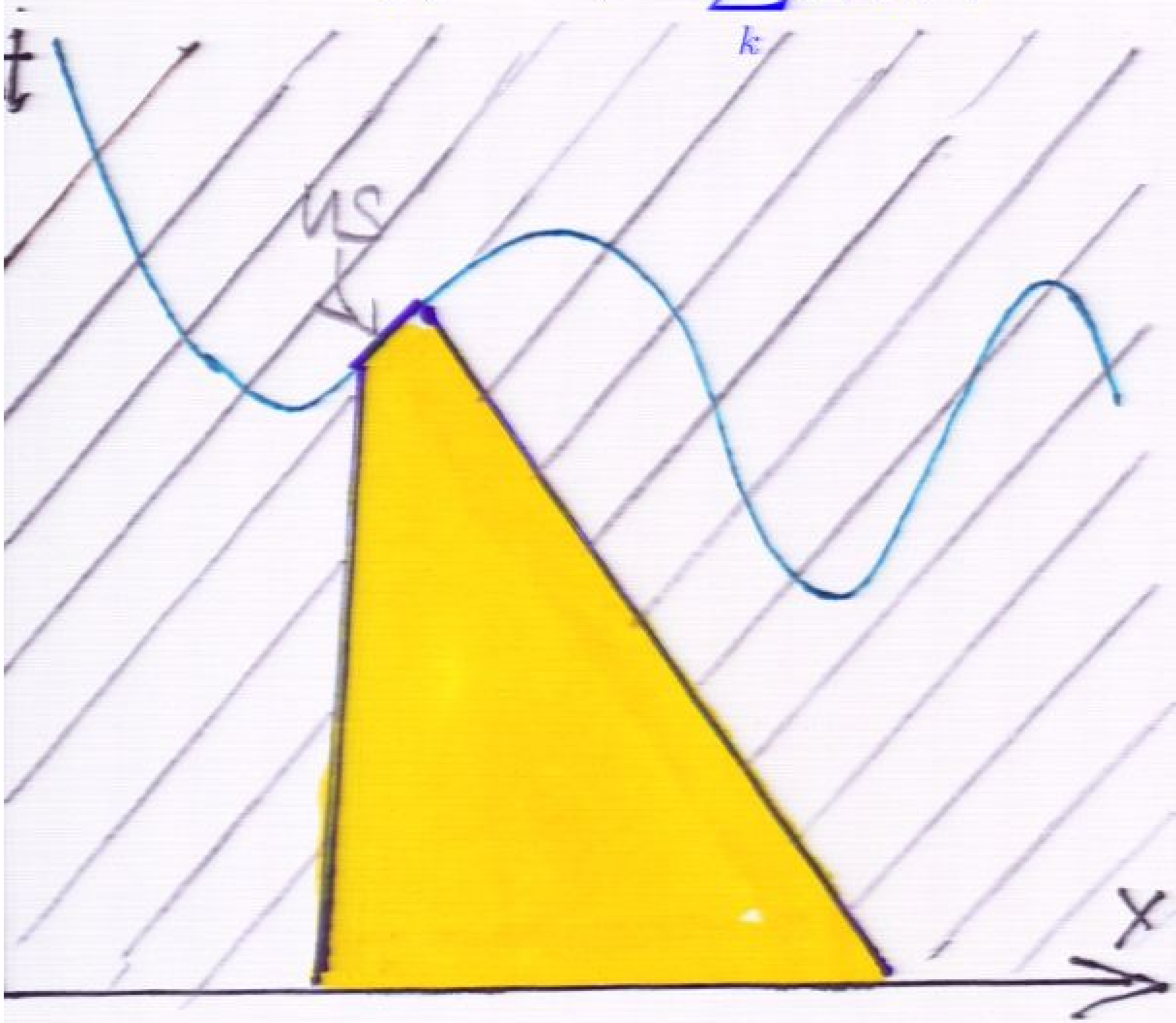

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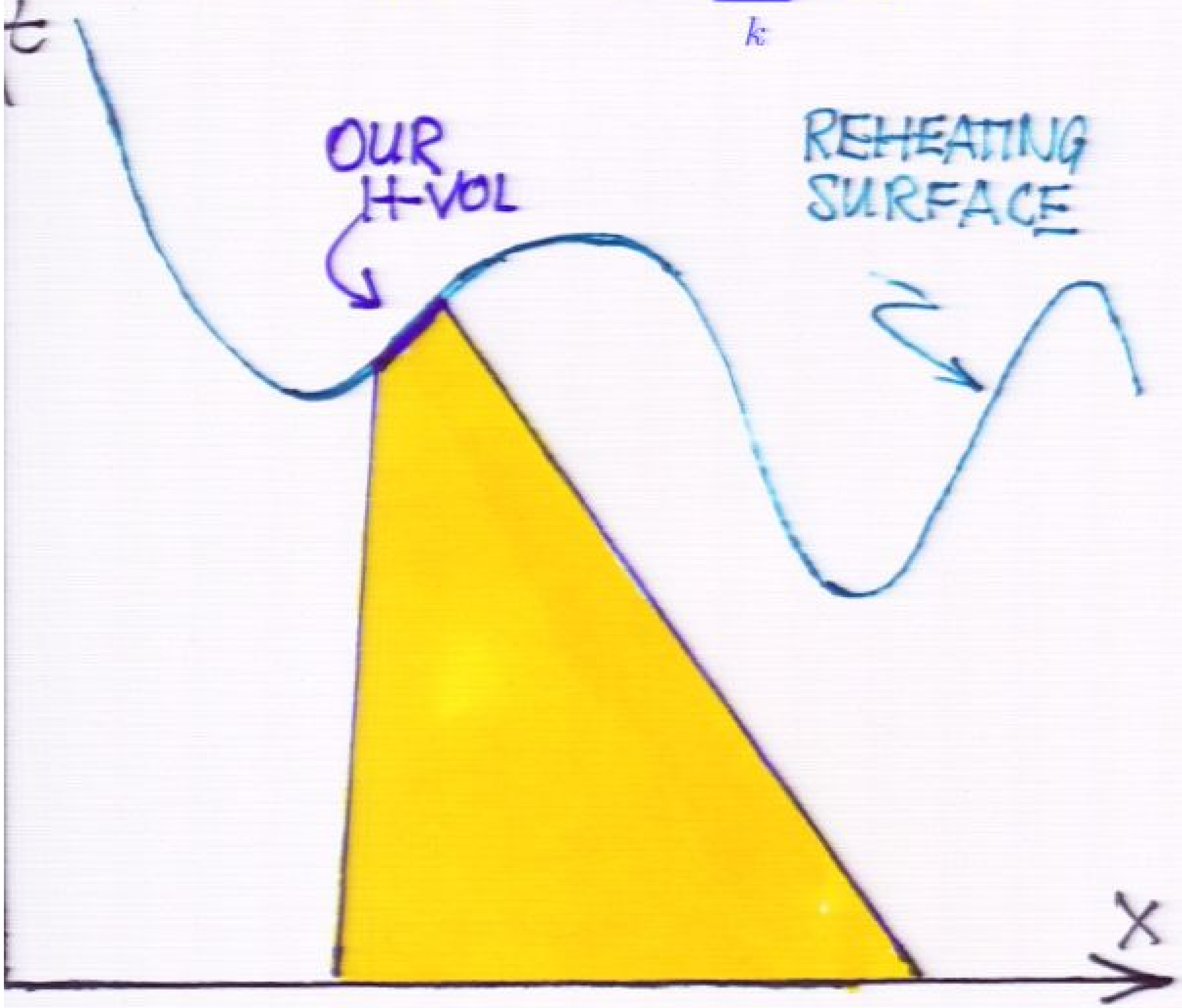

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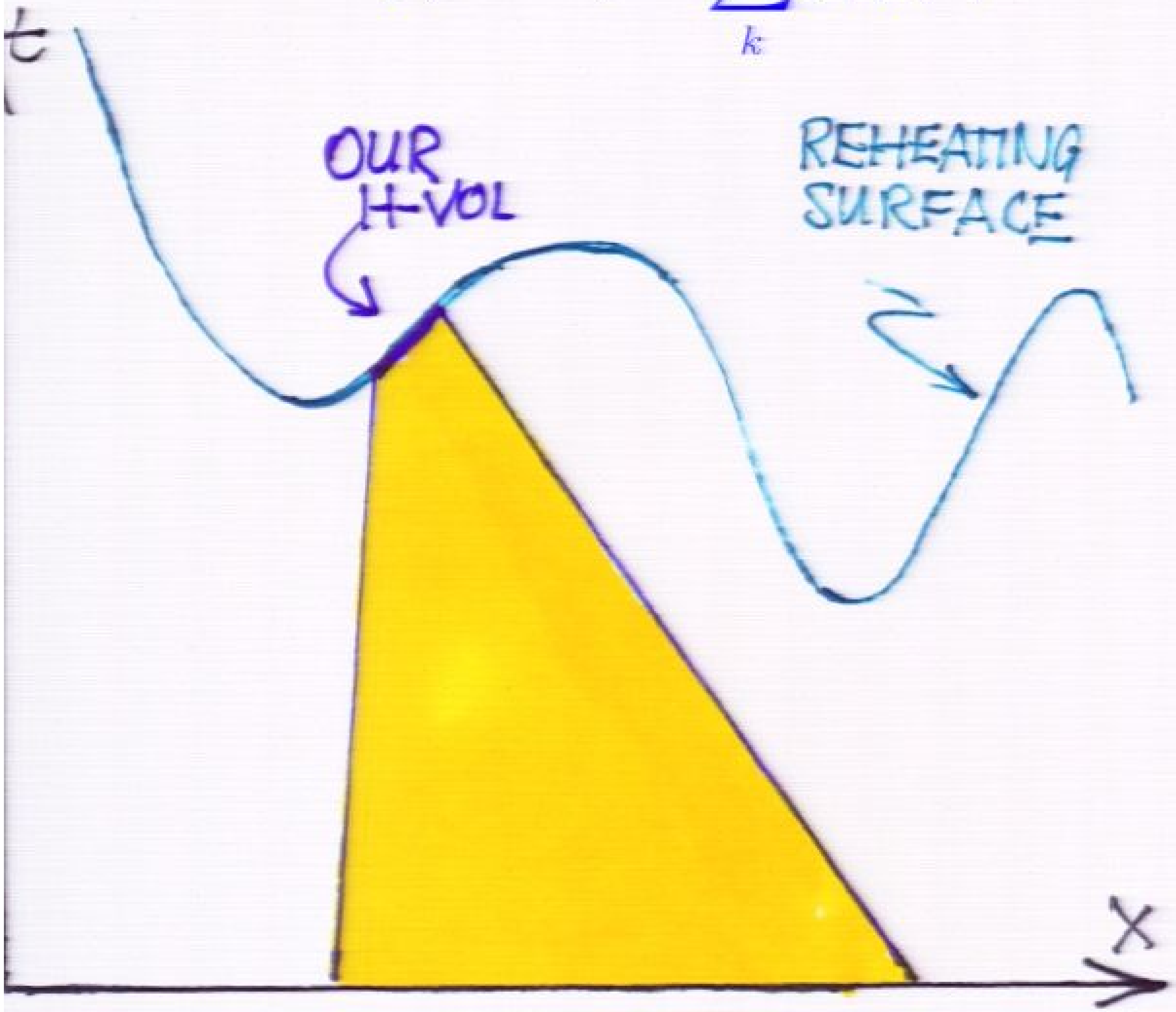

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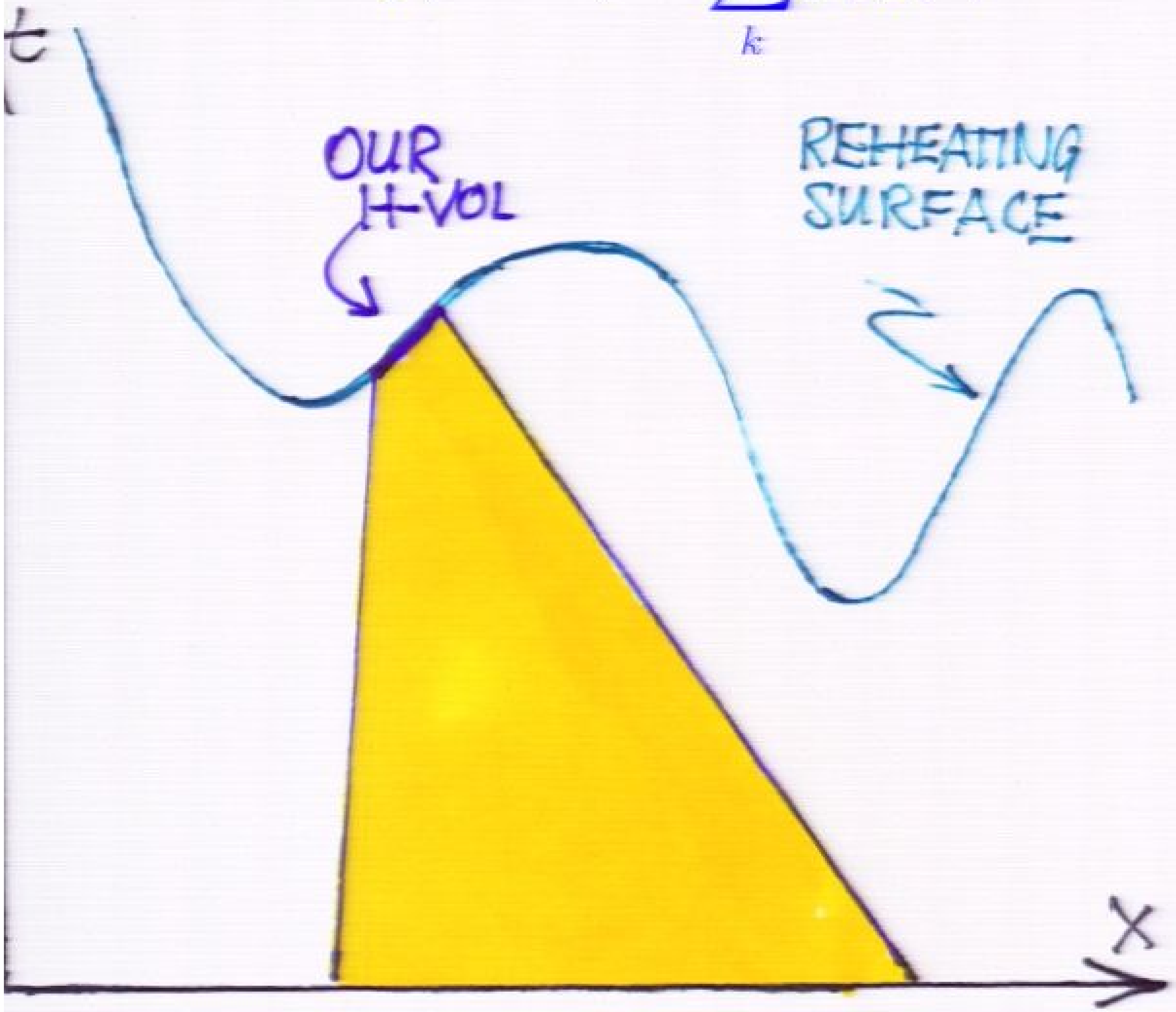

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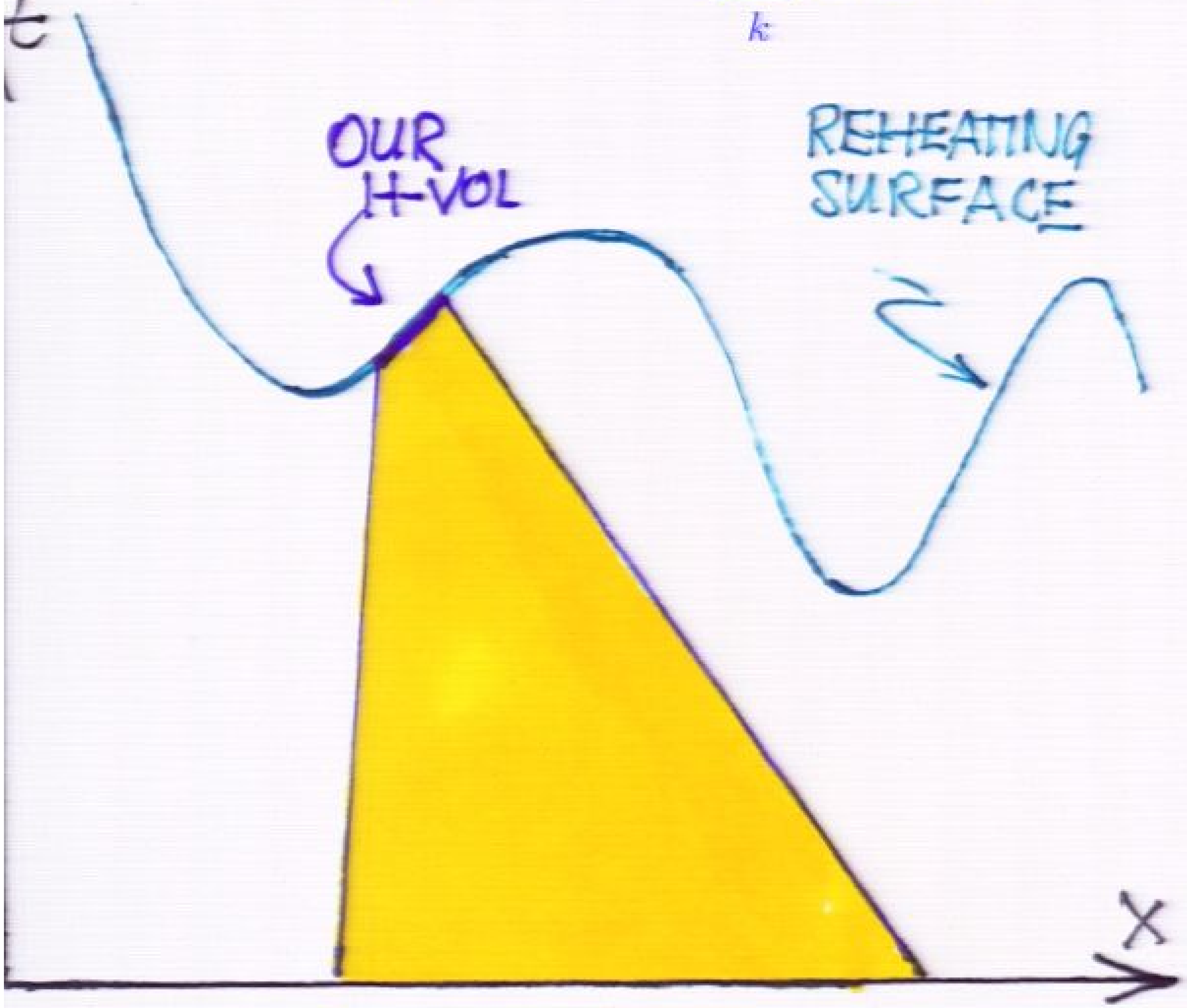

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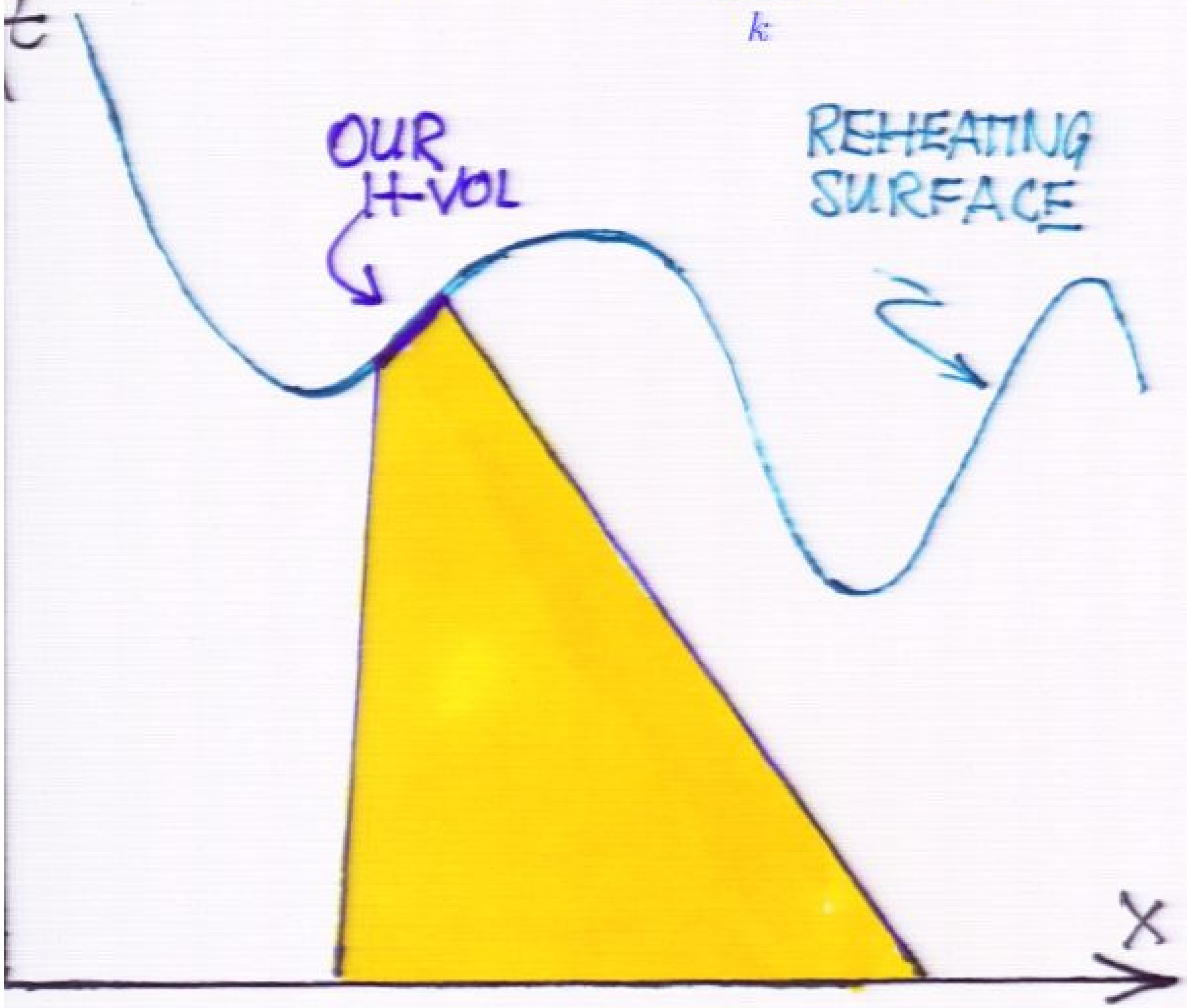

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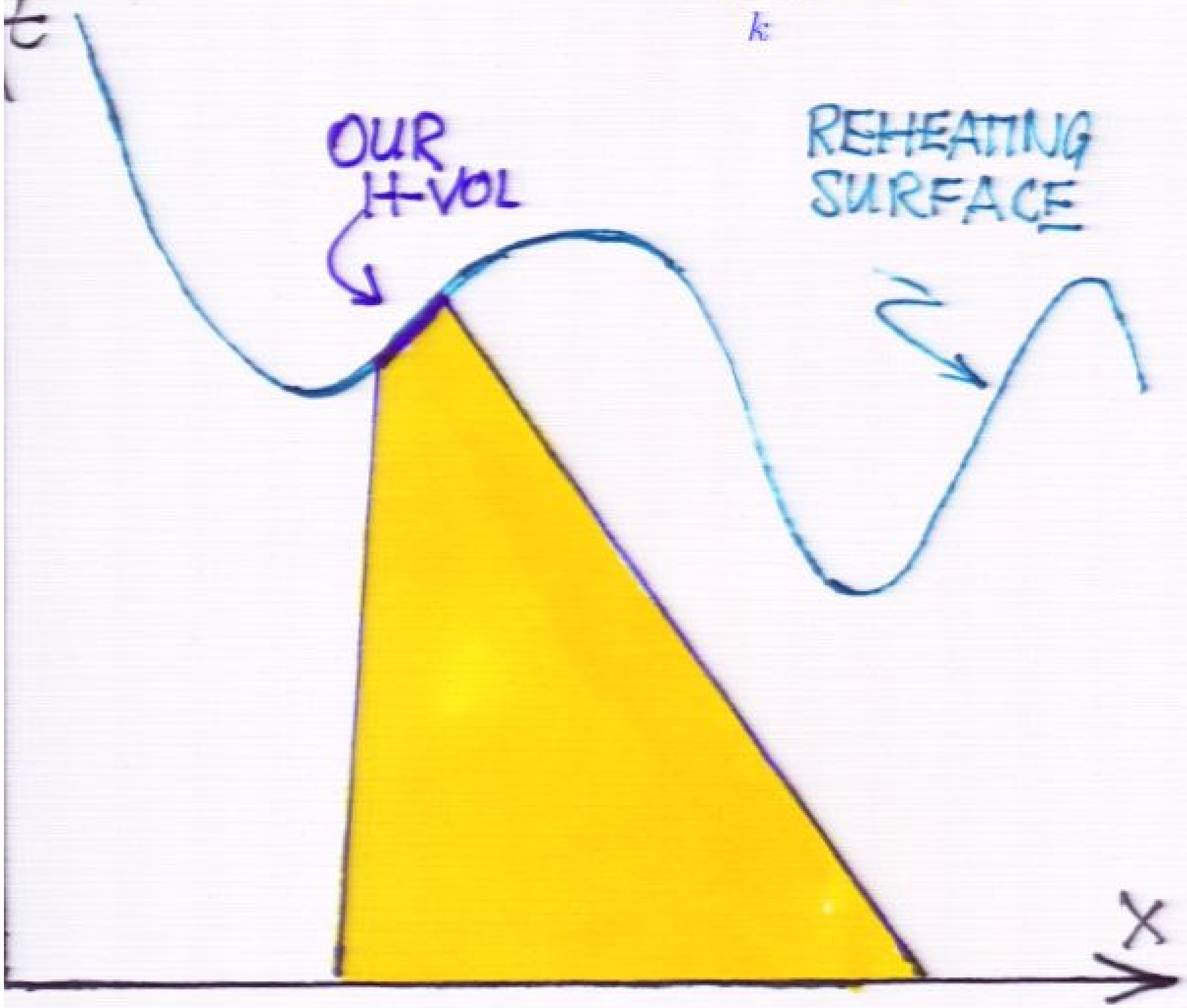

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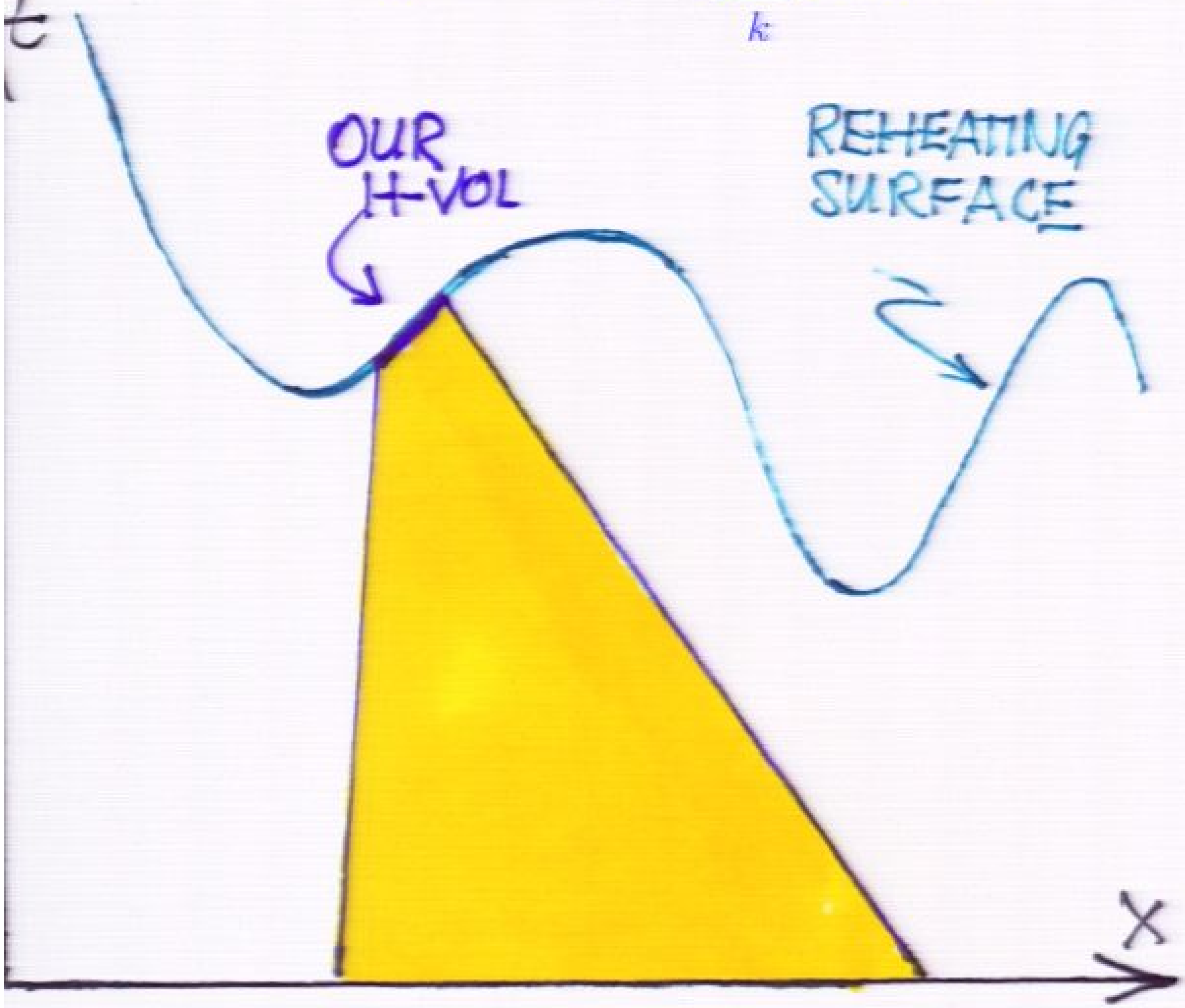

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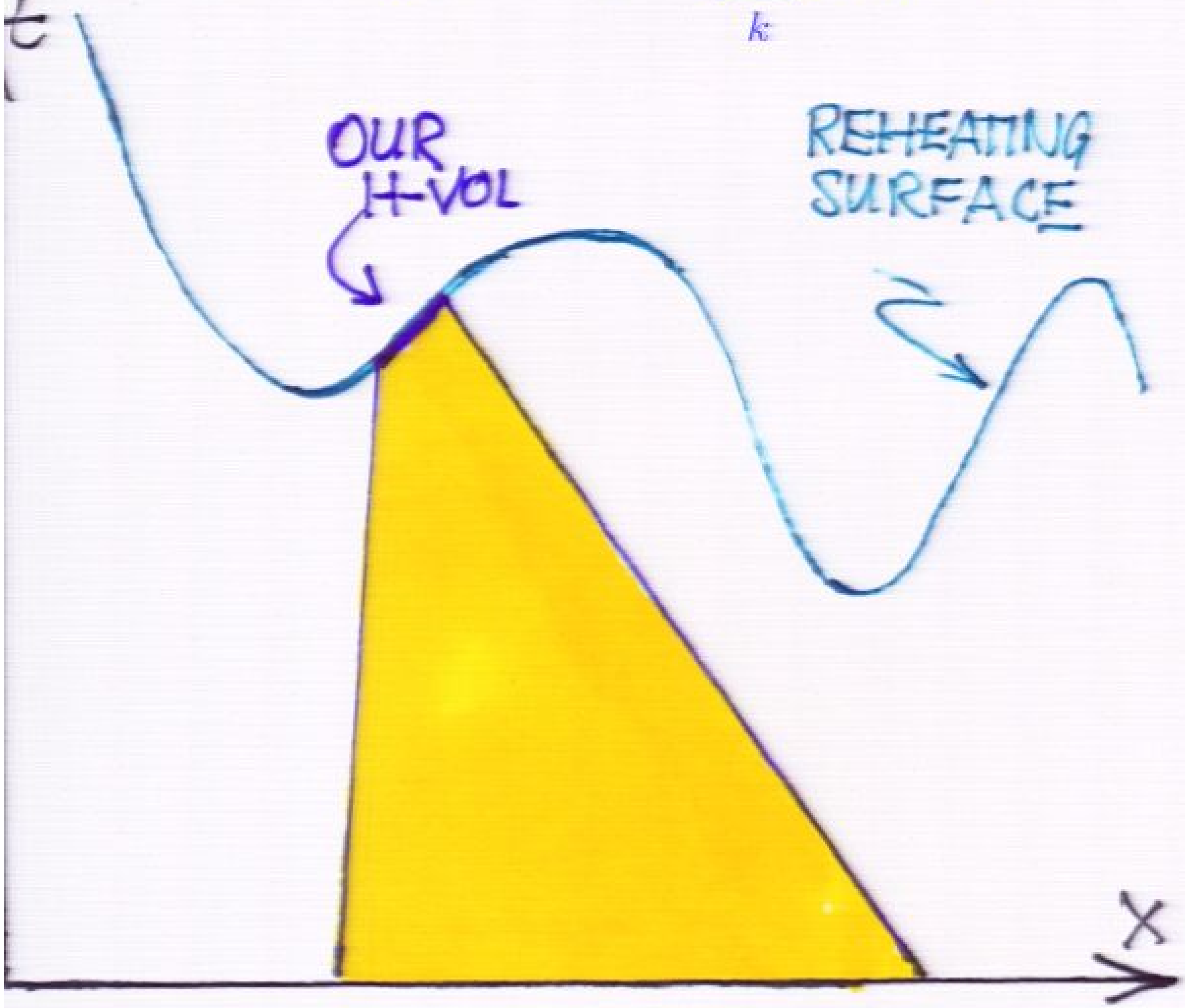

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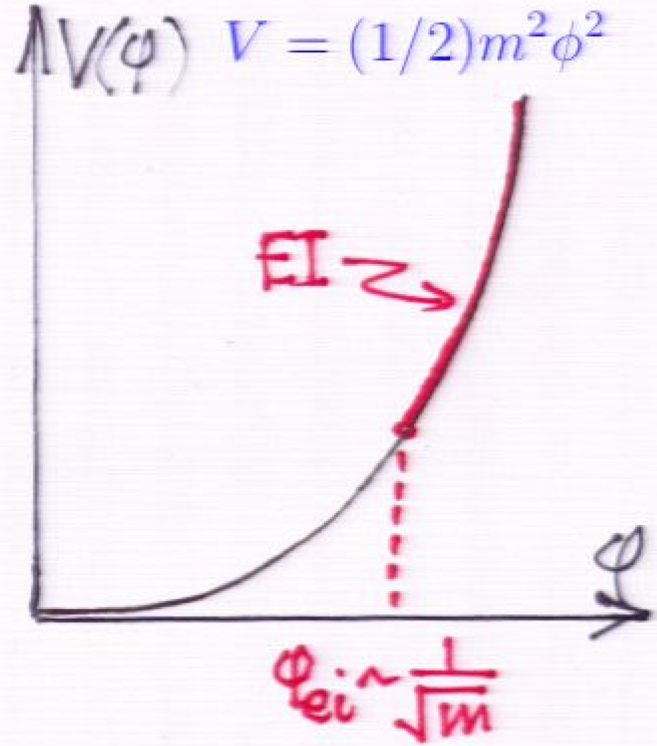

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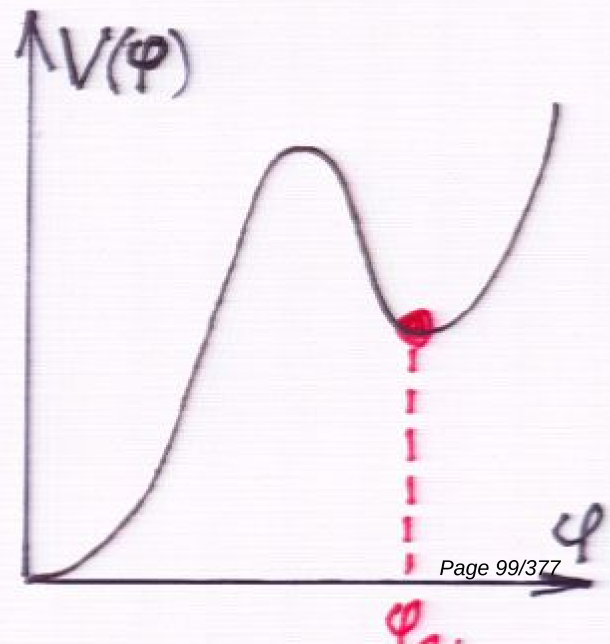
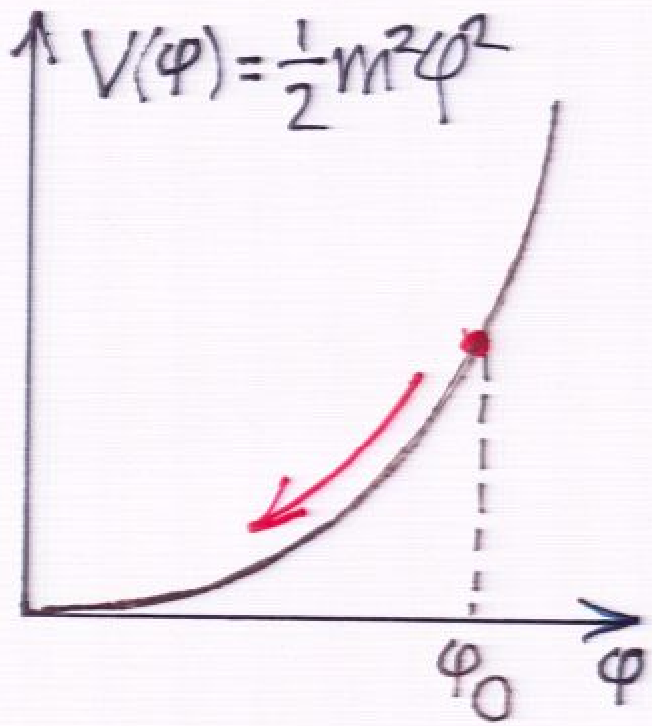


- For EI histories TD=BU.

Qualitative EI

- A scalar field φ moving in a potential $V(\varphi) = (1/2)m^2\varphi^2$



- A quantum state Ψ (NBWF)

- From Ψ derive the (BU) probabilities for the ensemble of homo/iso classical background histories labeled by the value φ_0 at the start of roll down (the p(k)).

- Add linear fluctuations in the scalar field and geometry.

One Minimum

Selection for EI

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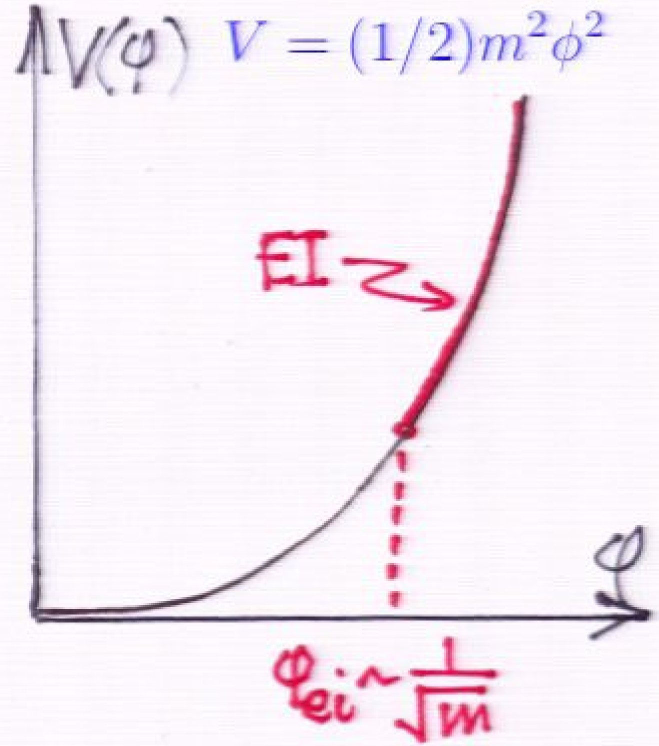

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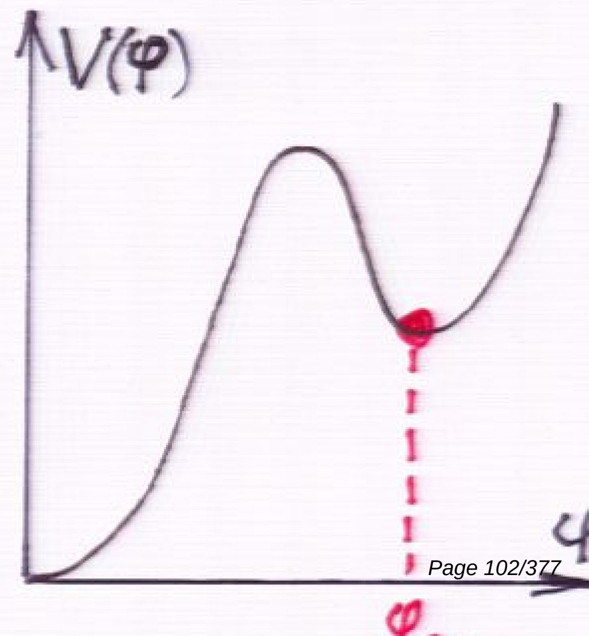

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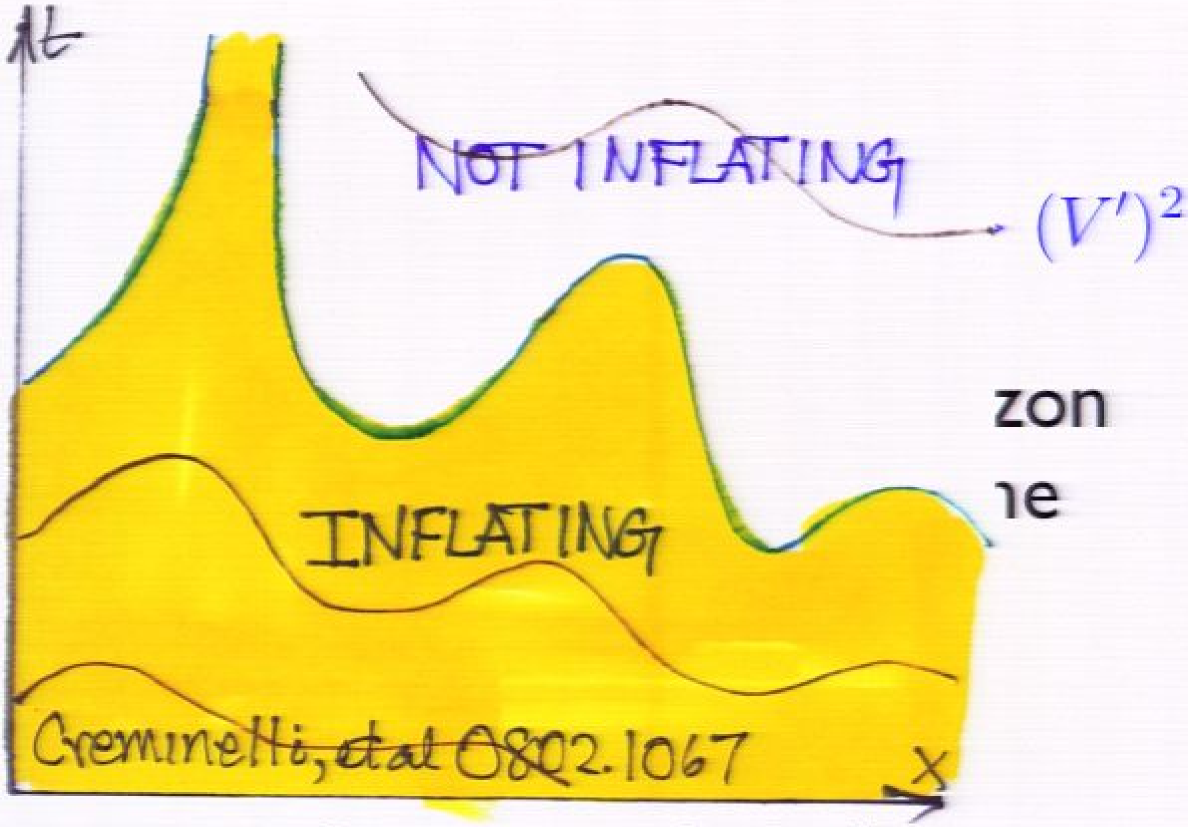

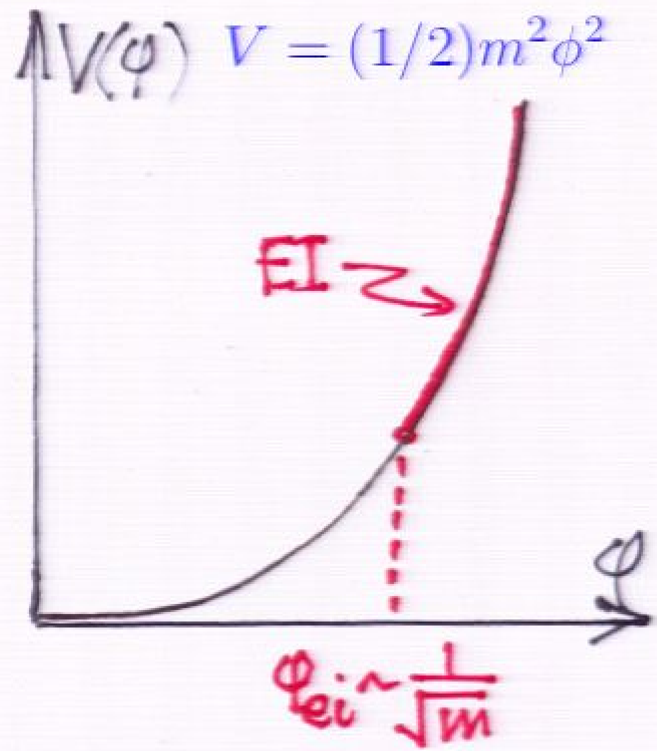

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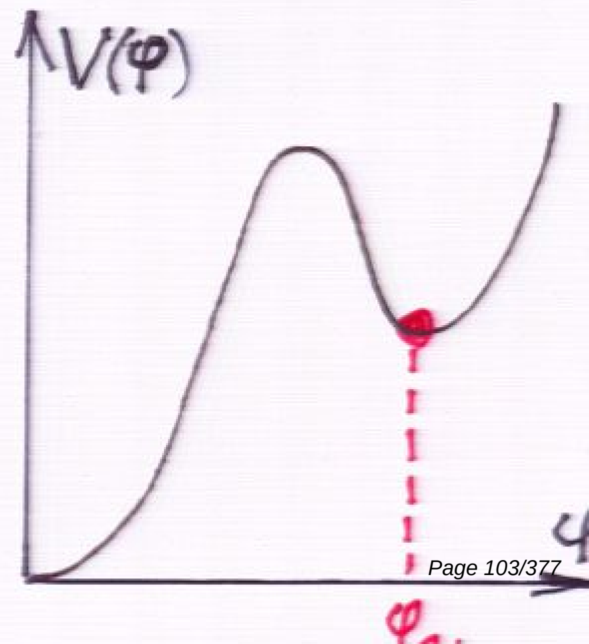

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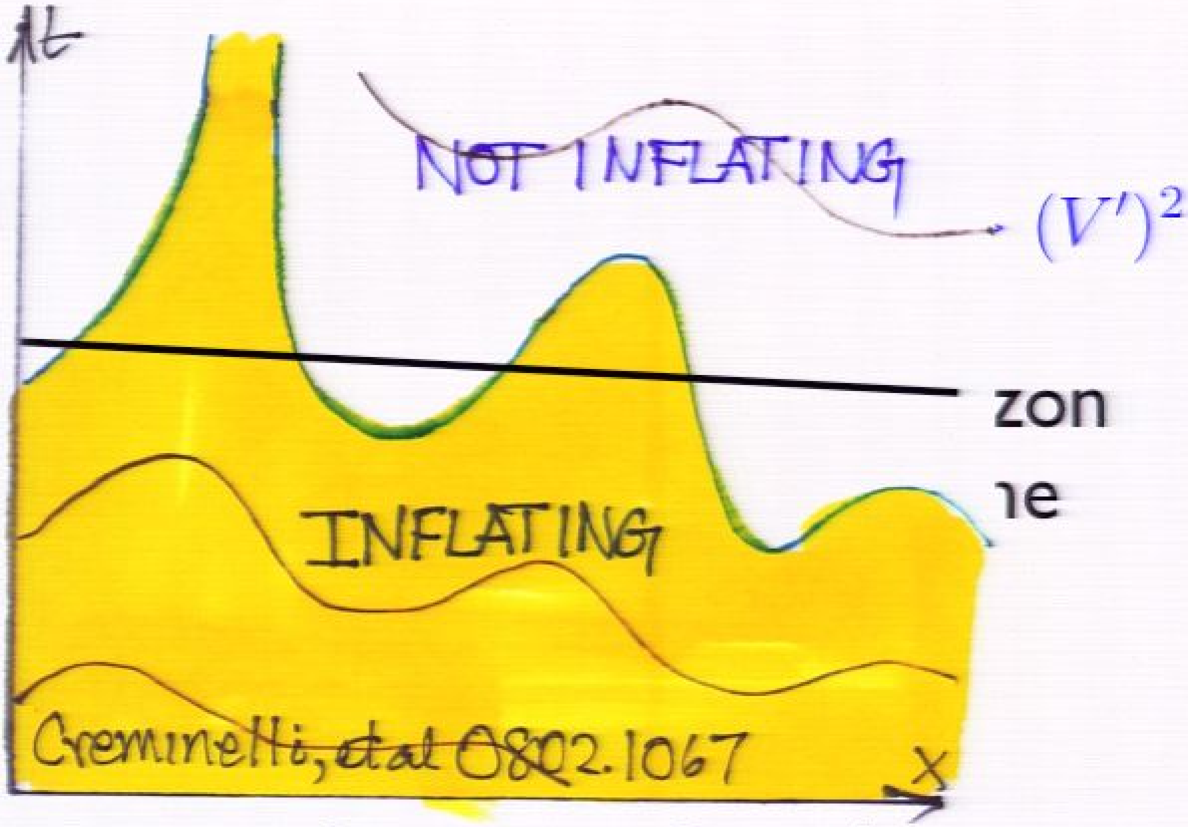

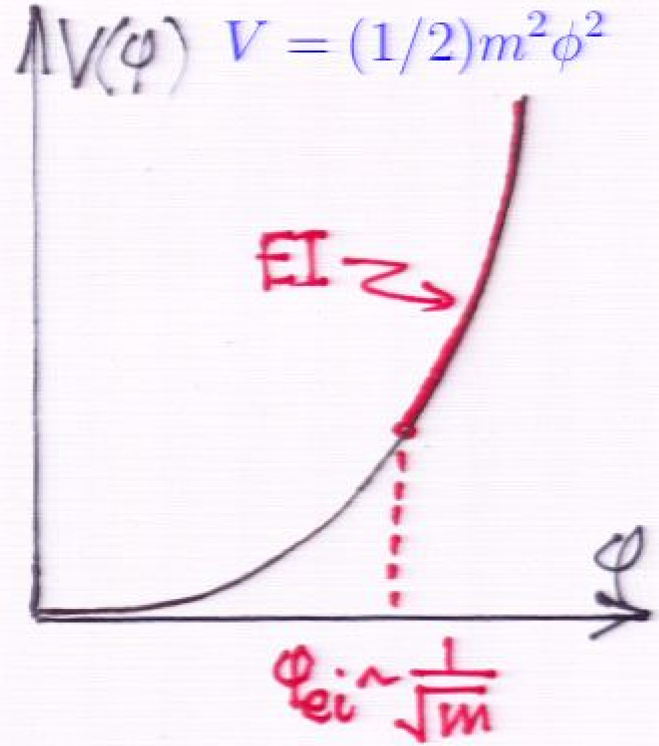

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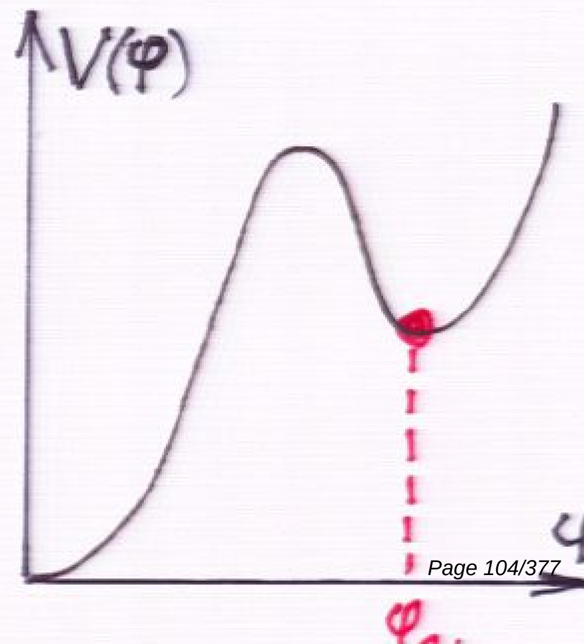

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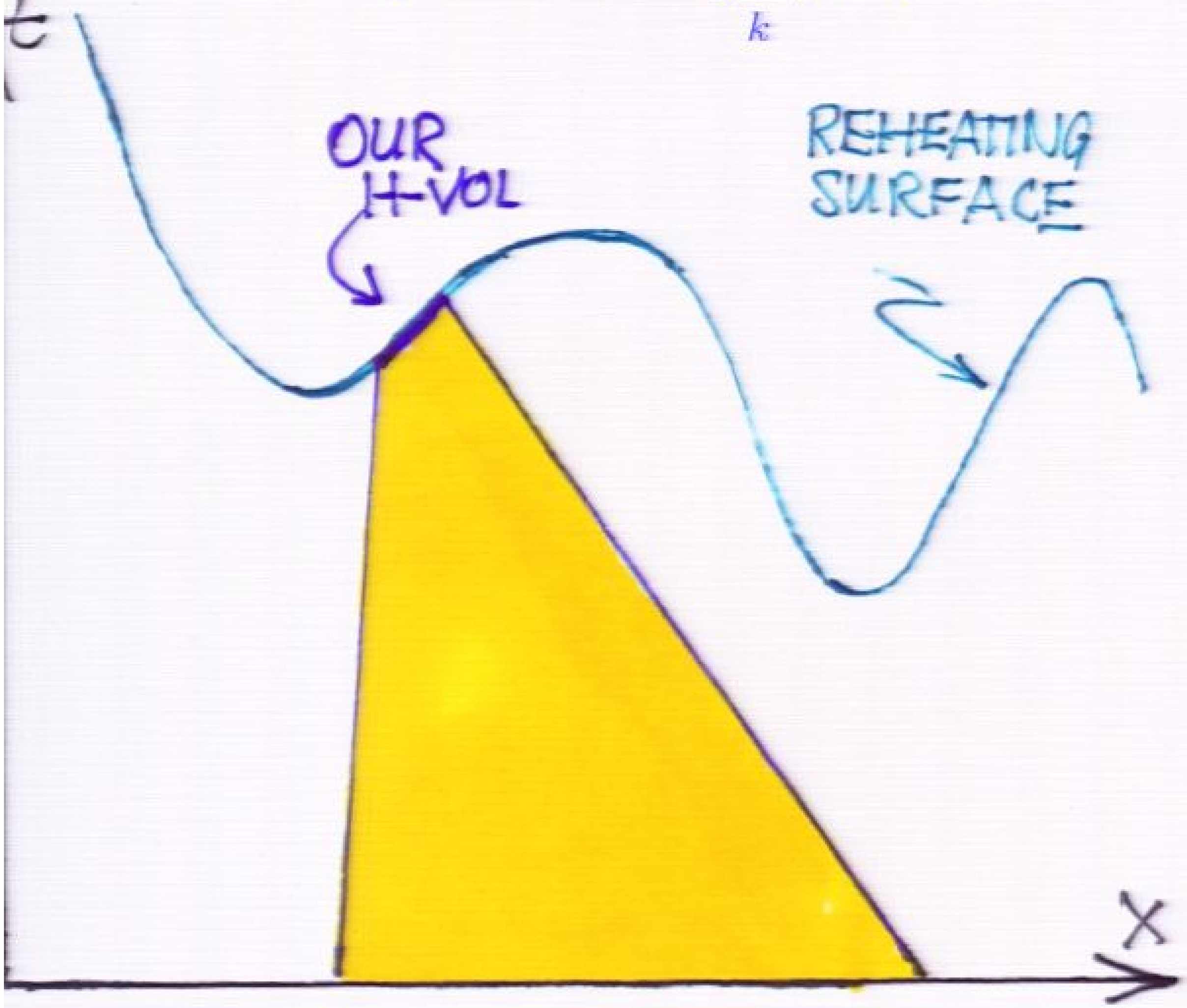

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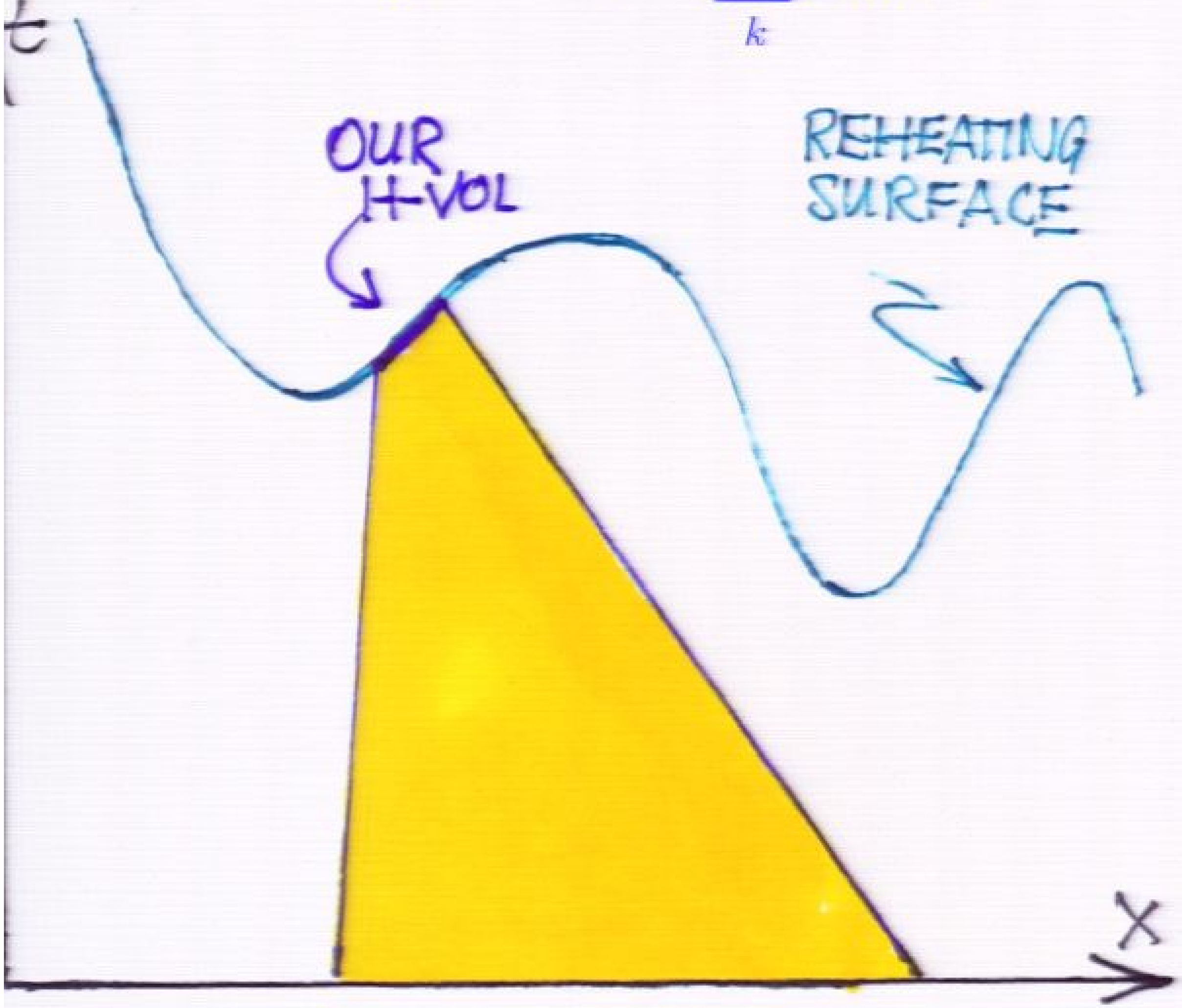

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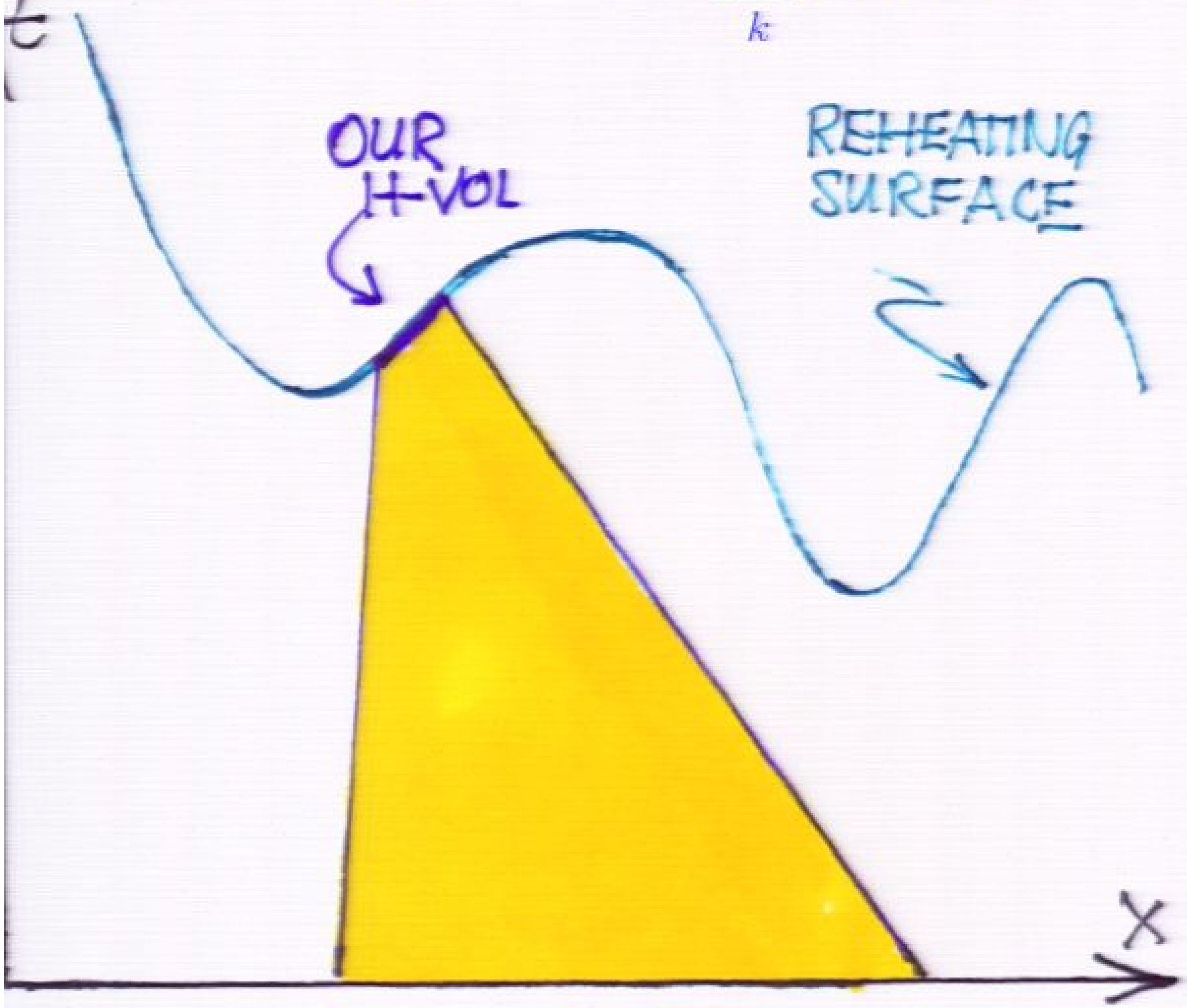

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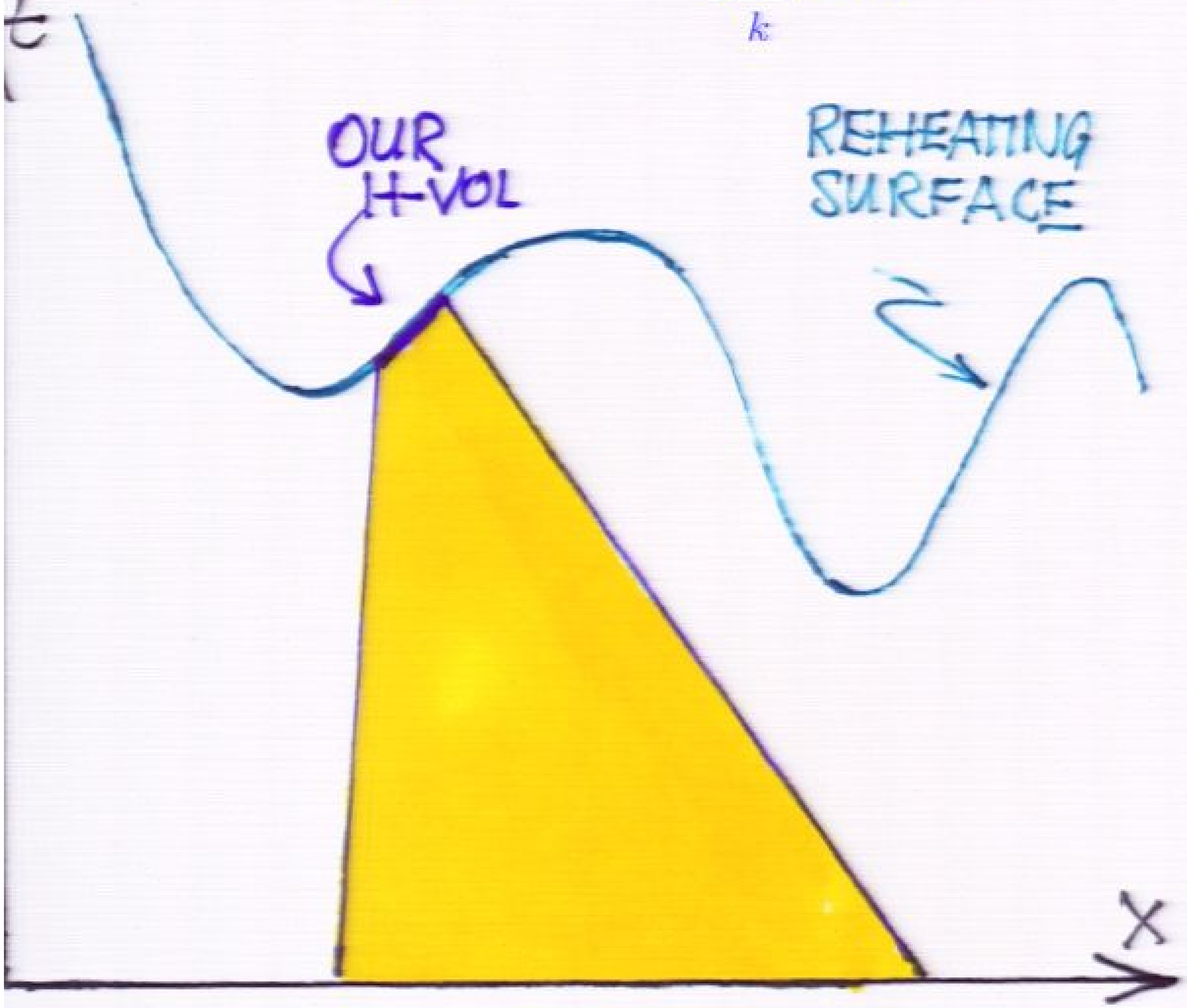

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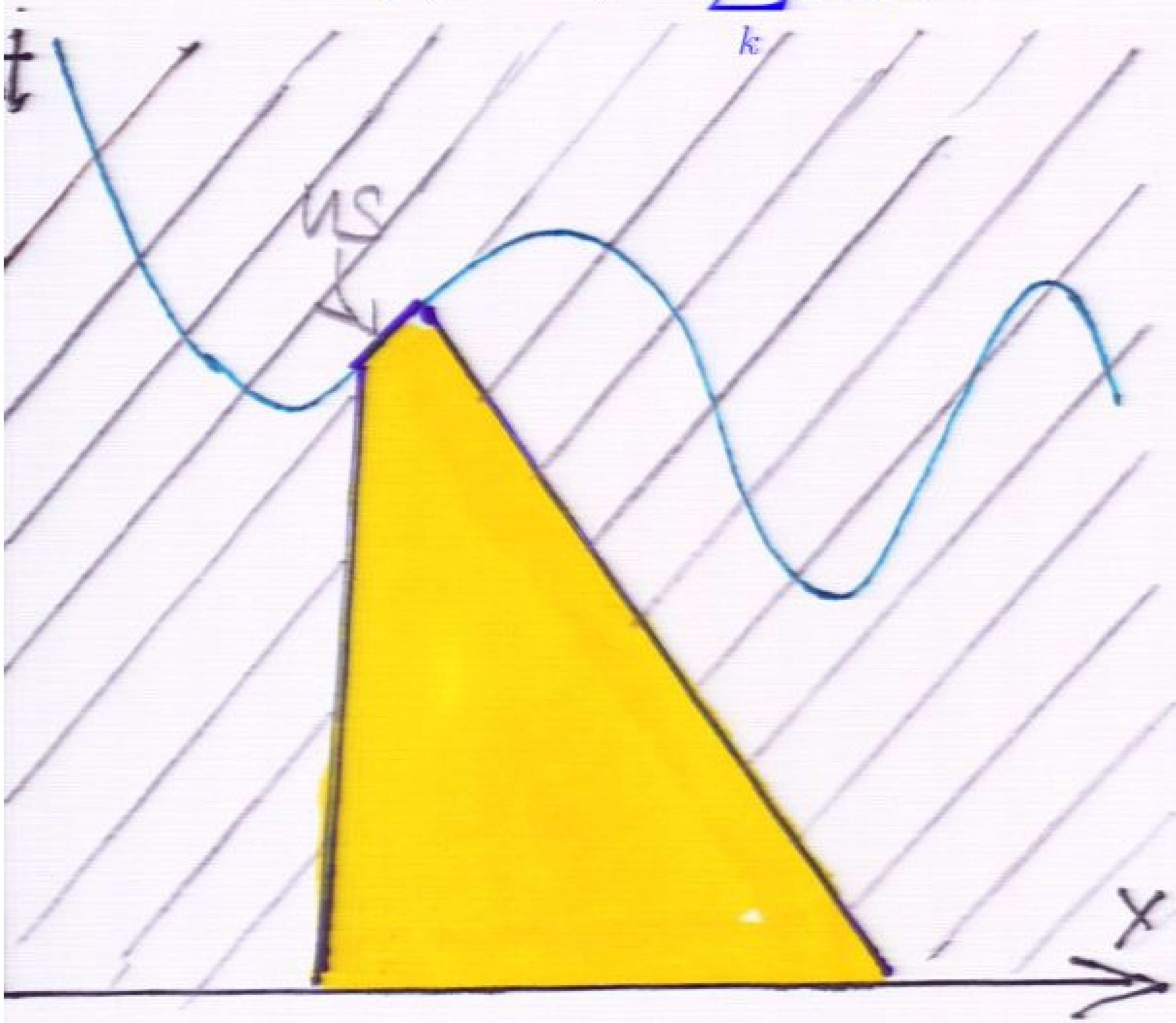

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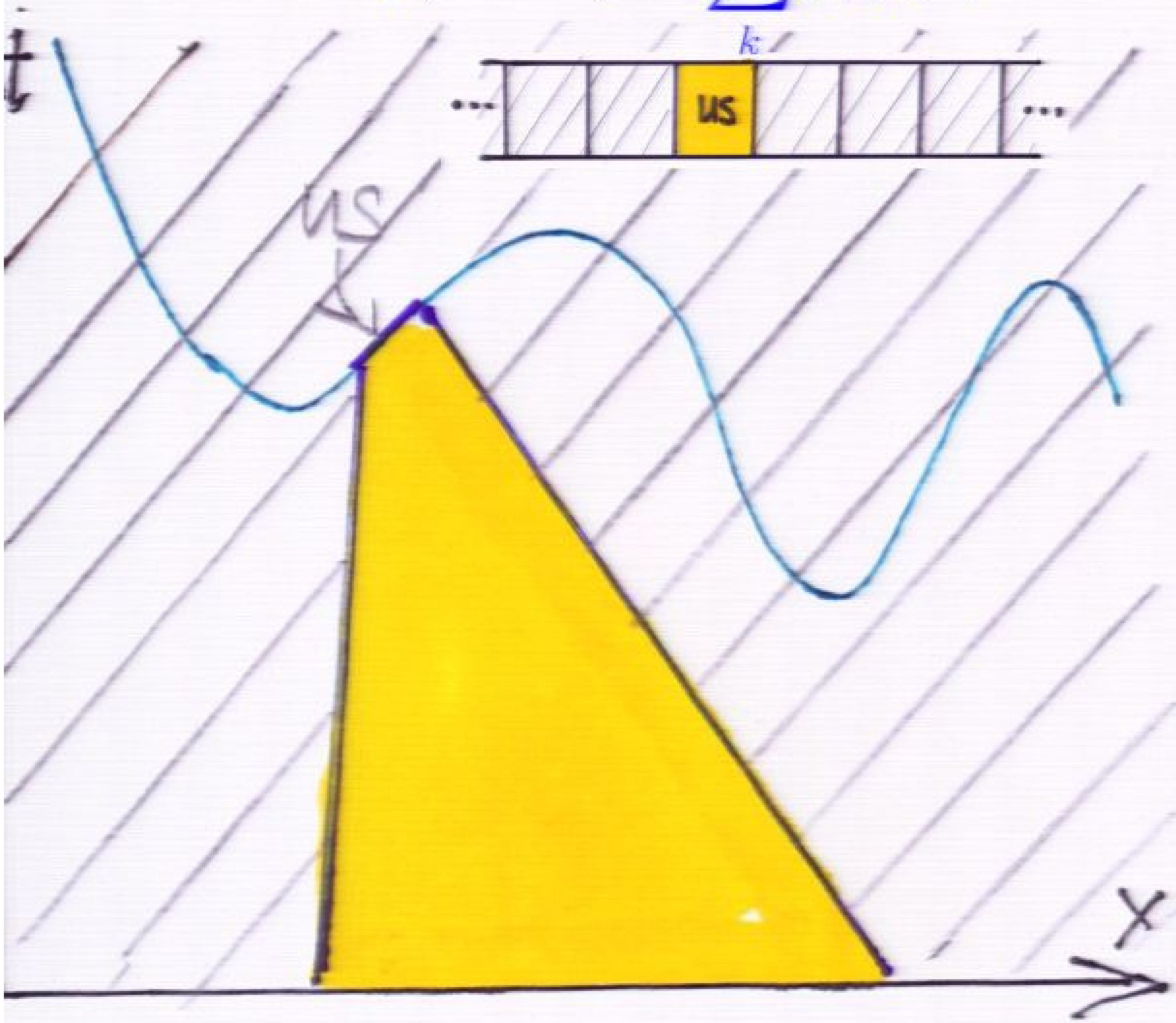

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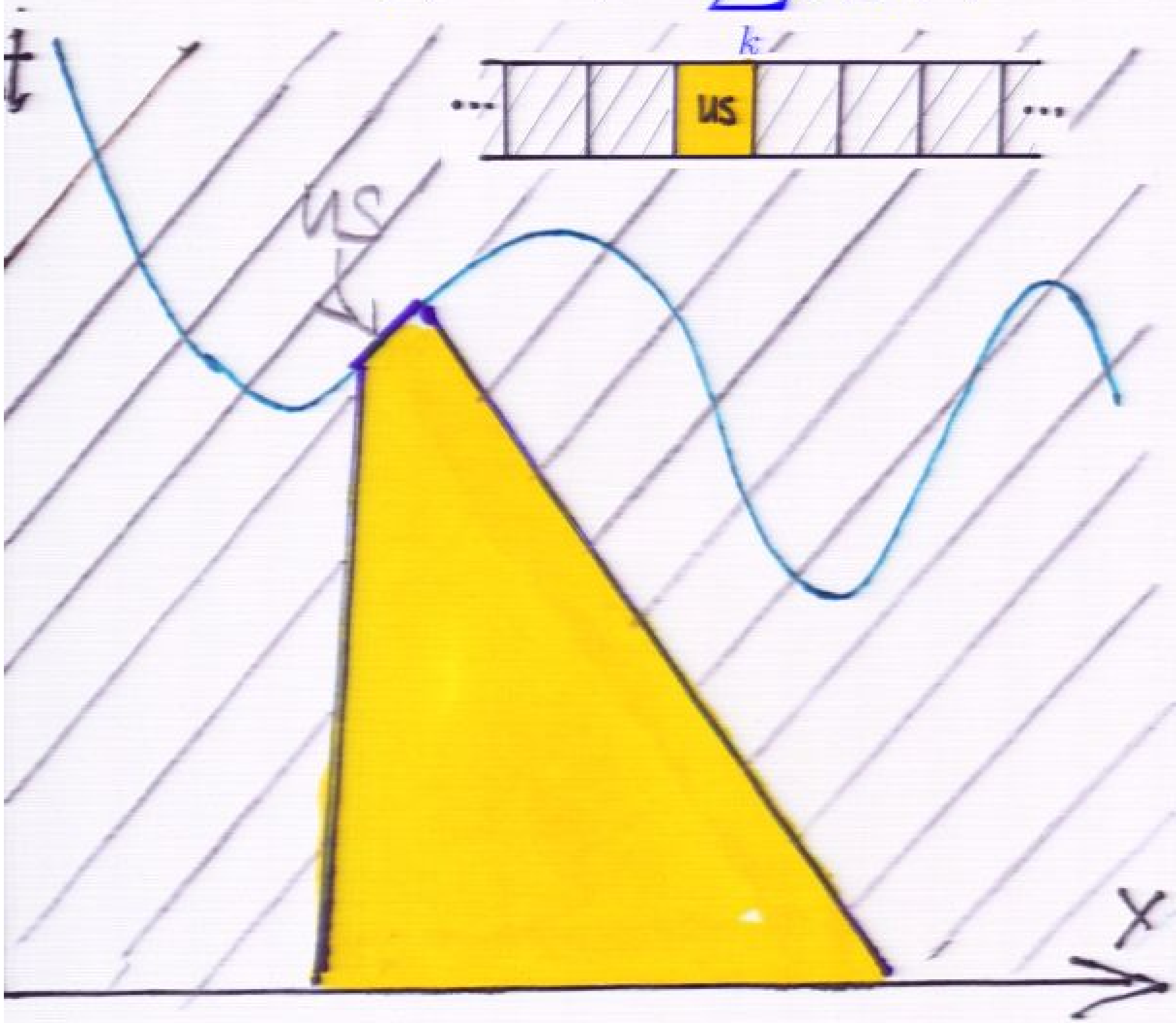

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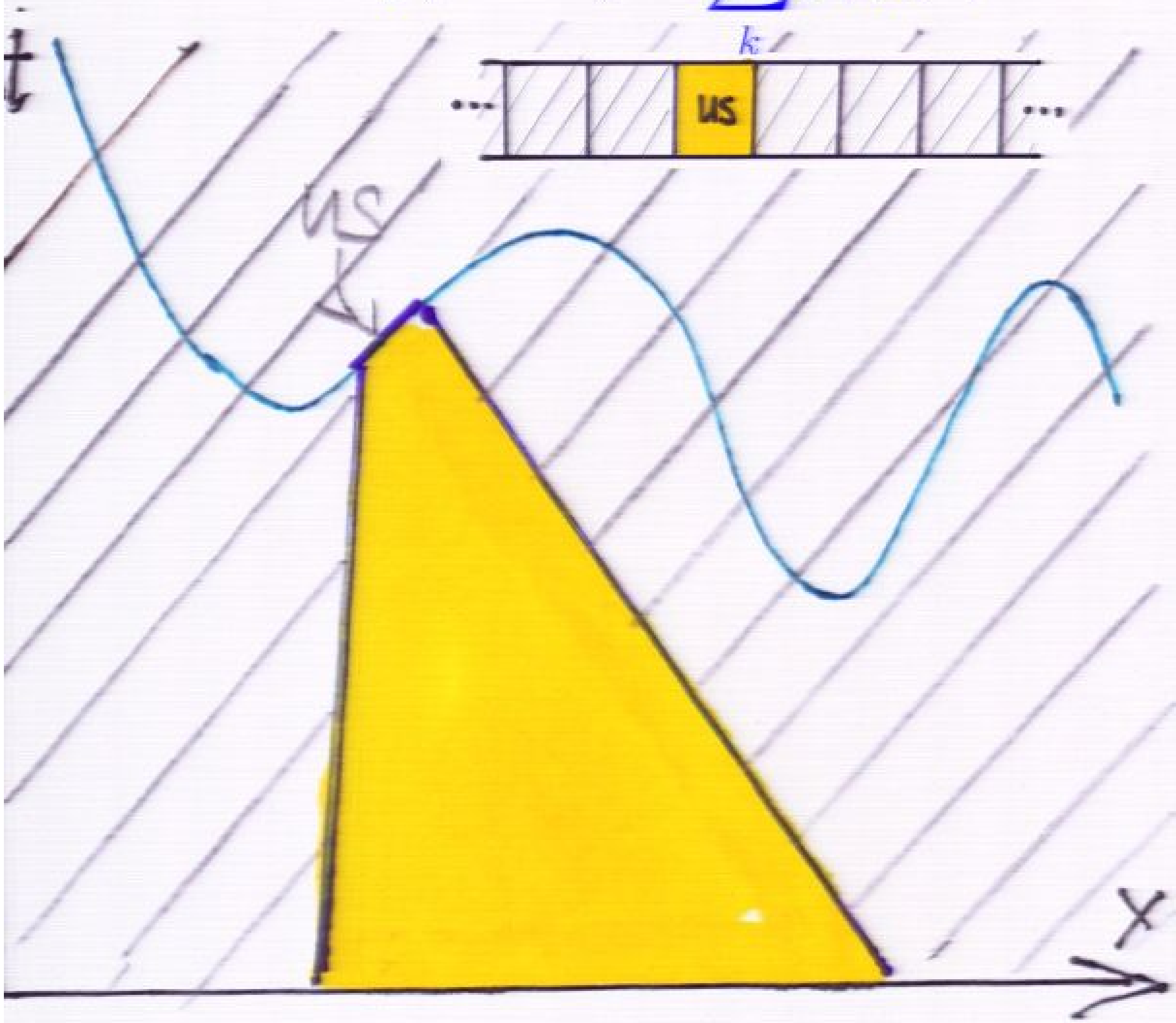

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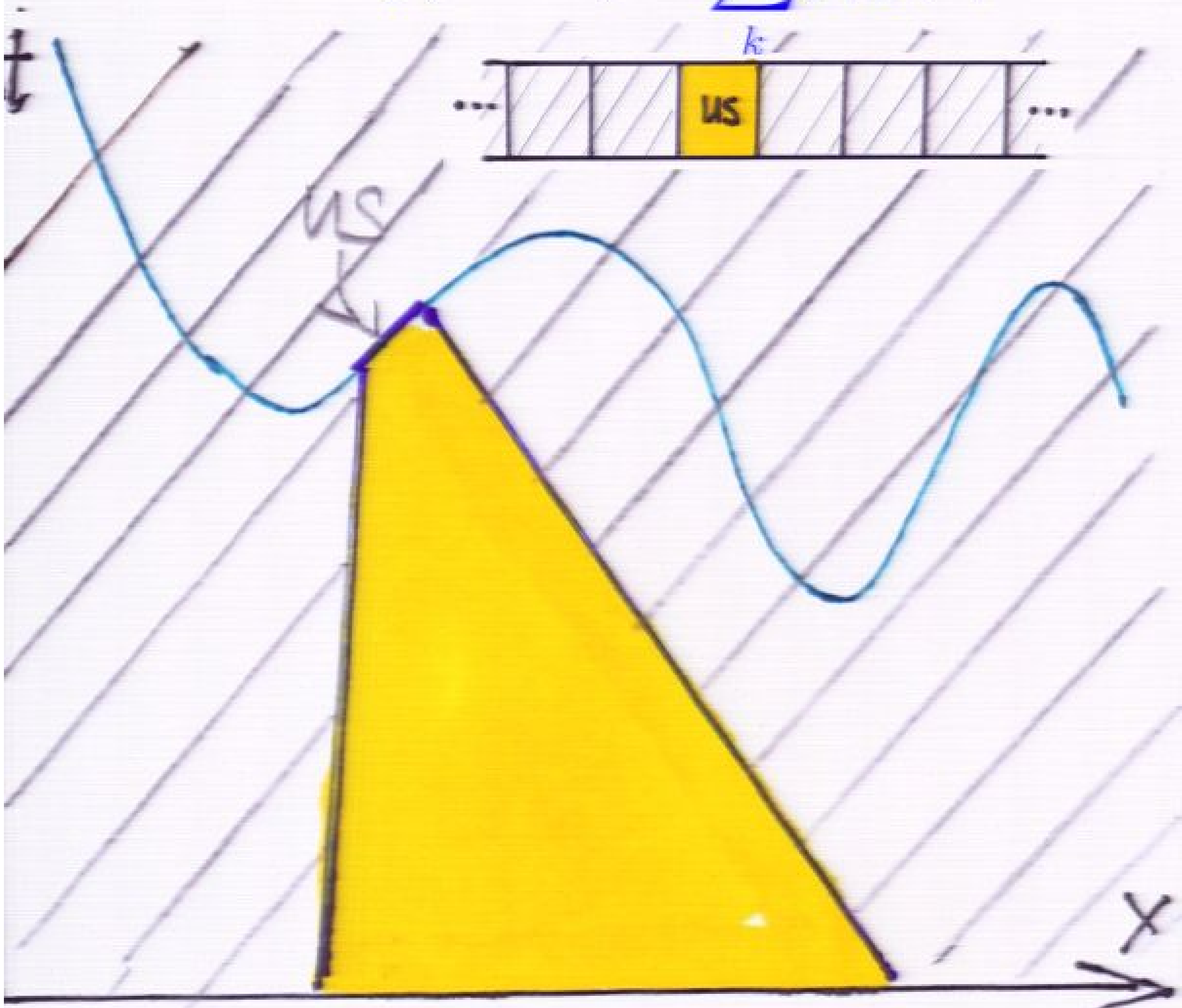

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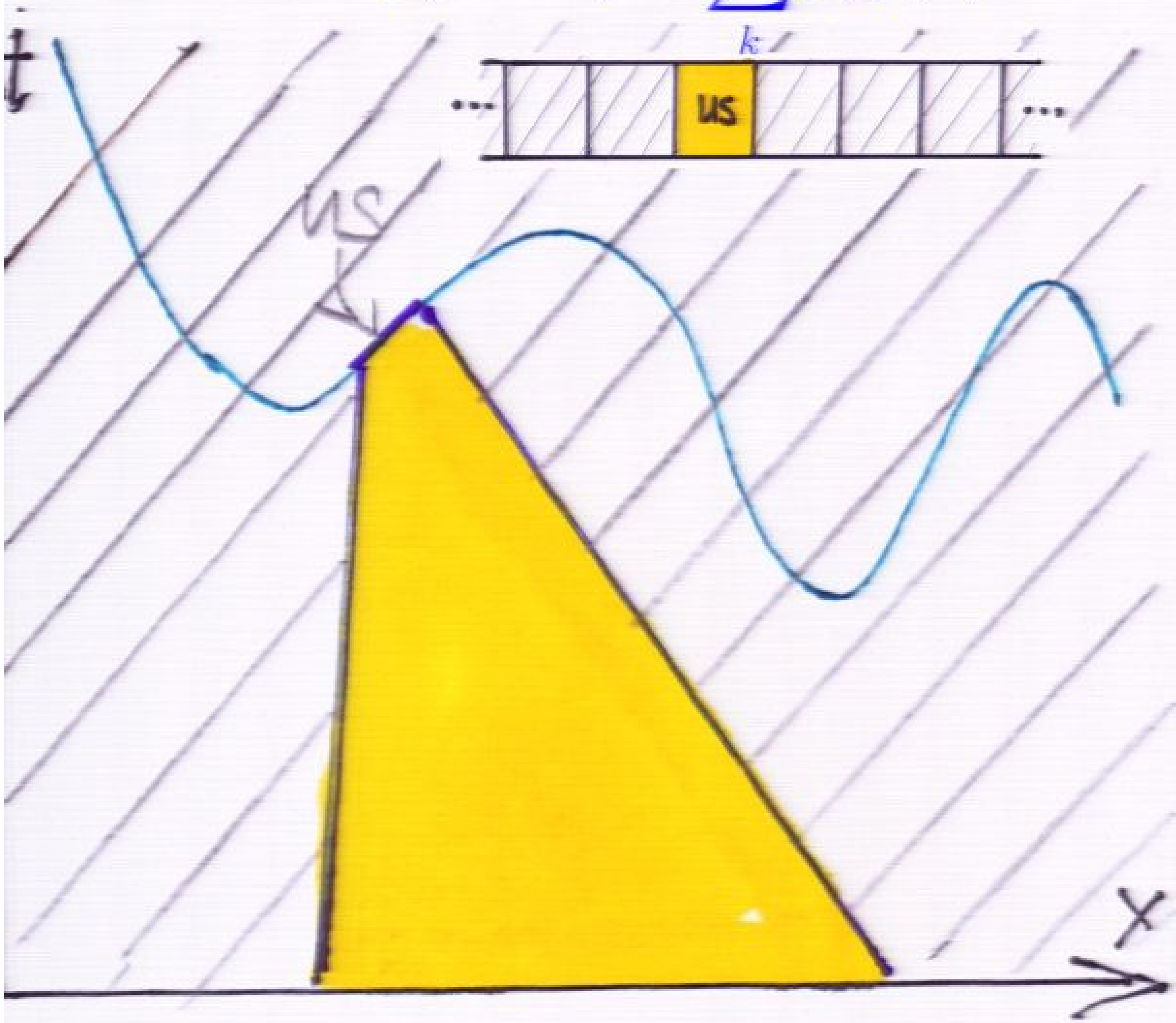

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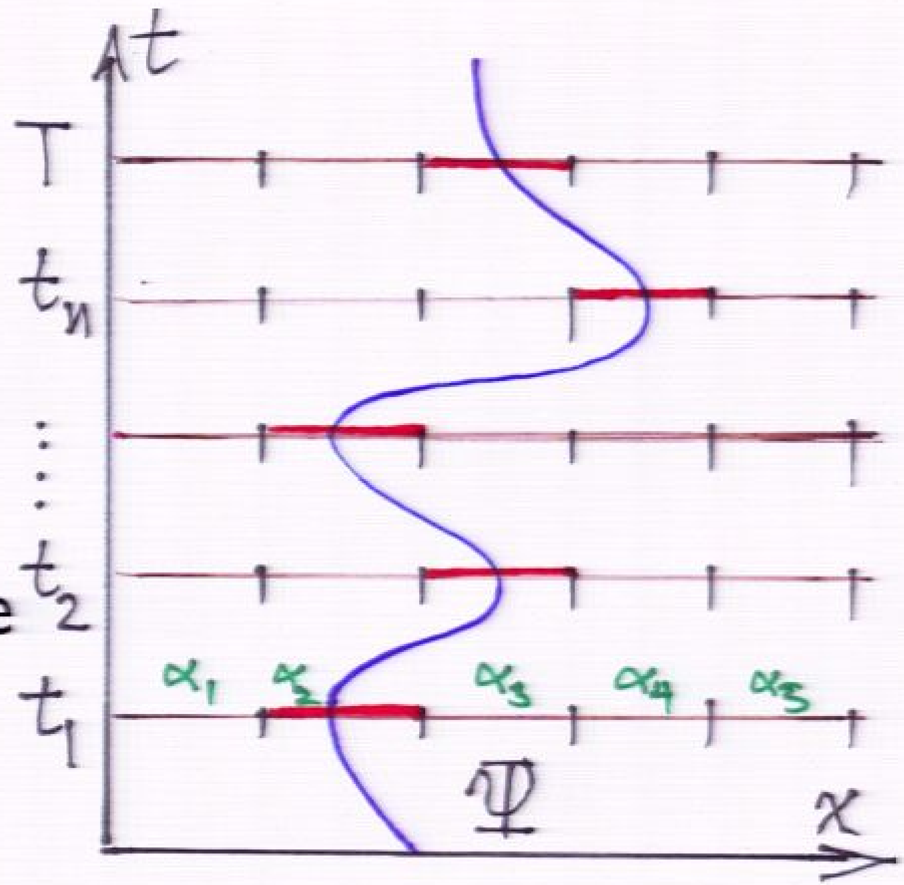
Coarse Graining the Future in NRQM



- Consider a state $|\Psi\rangle$ and projections $\{P_\alpha(t)\}$ onto a set of ranges of x, $\{\Delta_\alpha\}$
- The probability that the particle is in region α_1 at a time t_1

$$p(\alpha_1) = ||P_{\alpha_1}(t_1)|\Psi\rangle||^2$$

- We could calculate this probability by first calculating the probabilities of future histories and then summing

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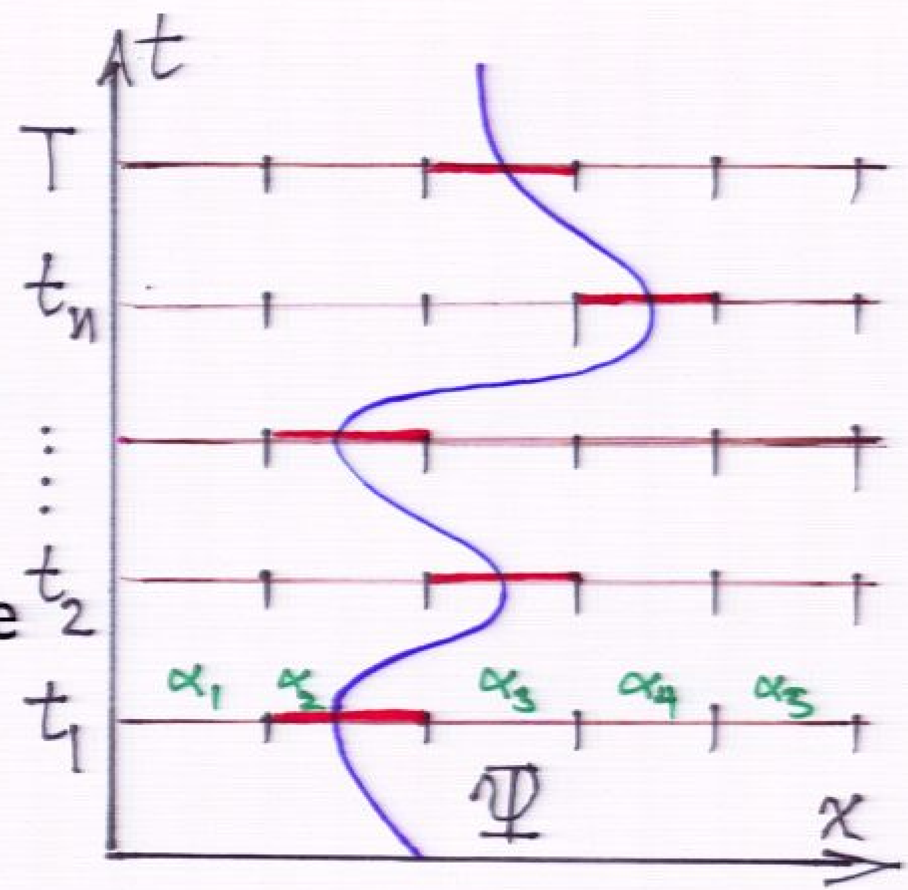

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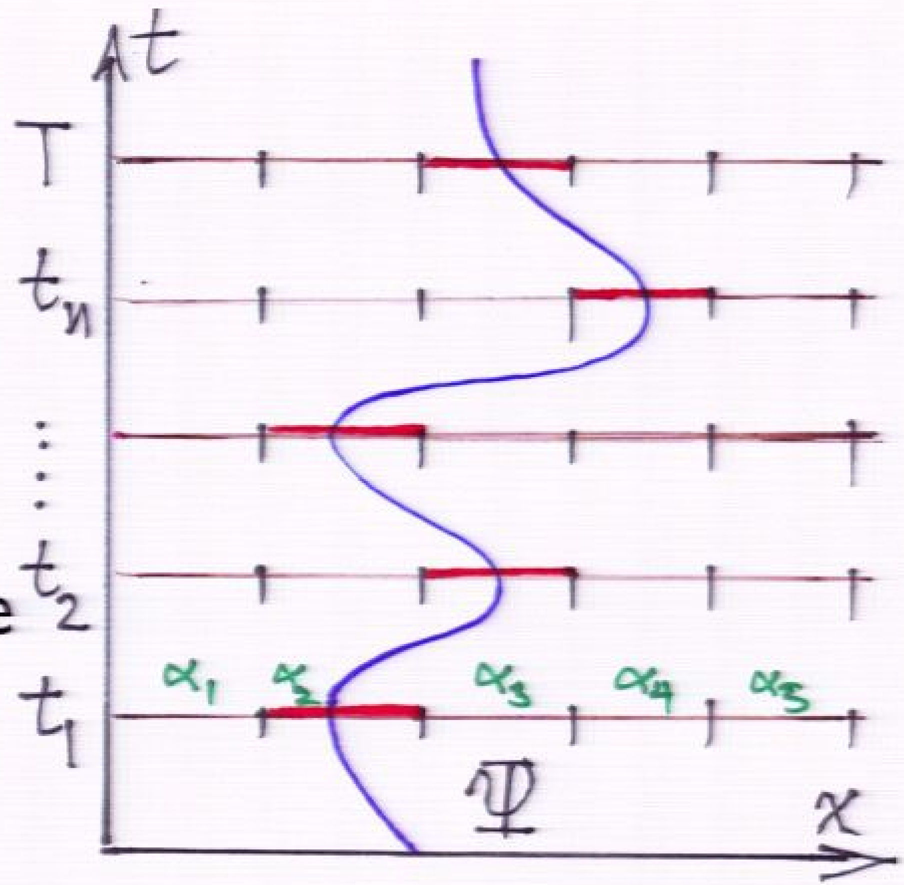

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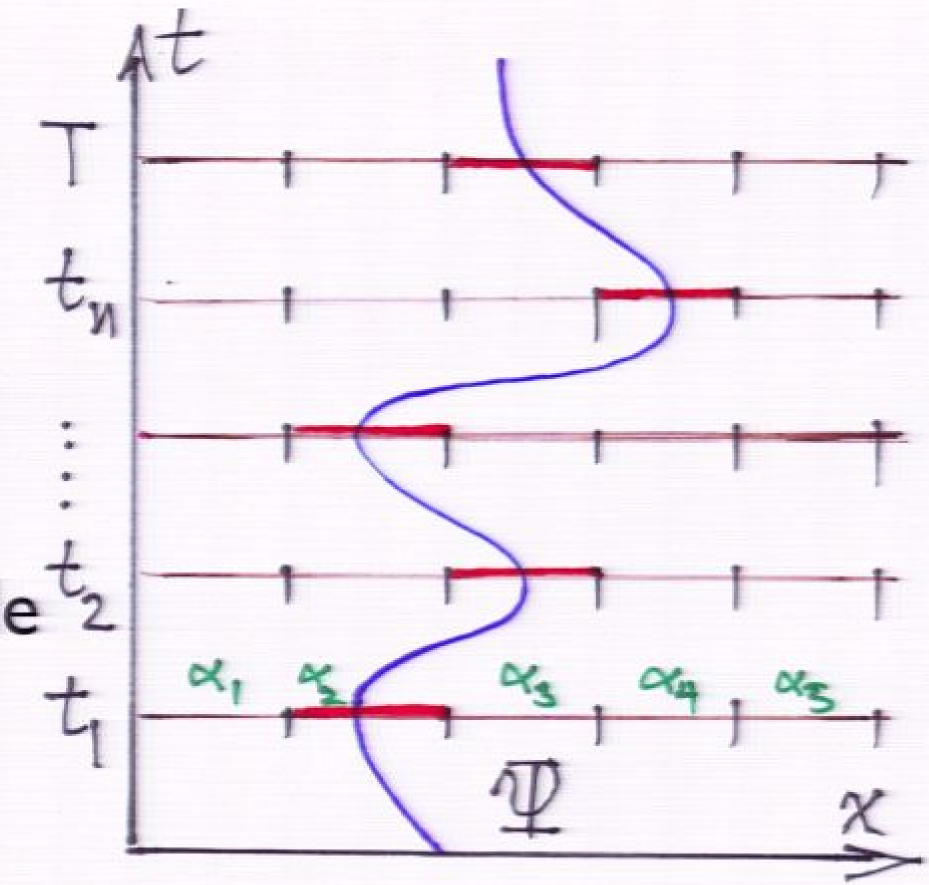

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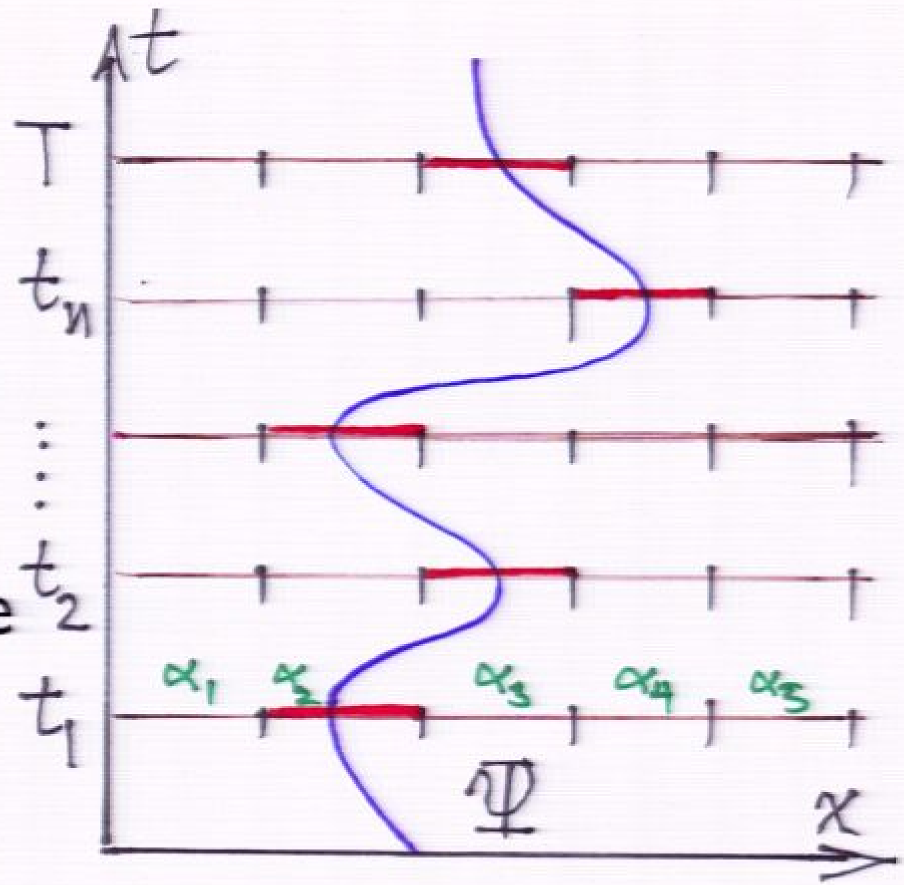

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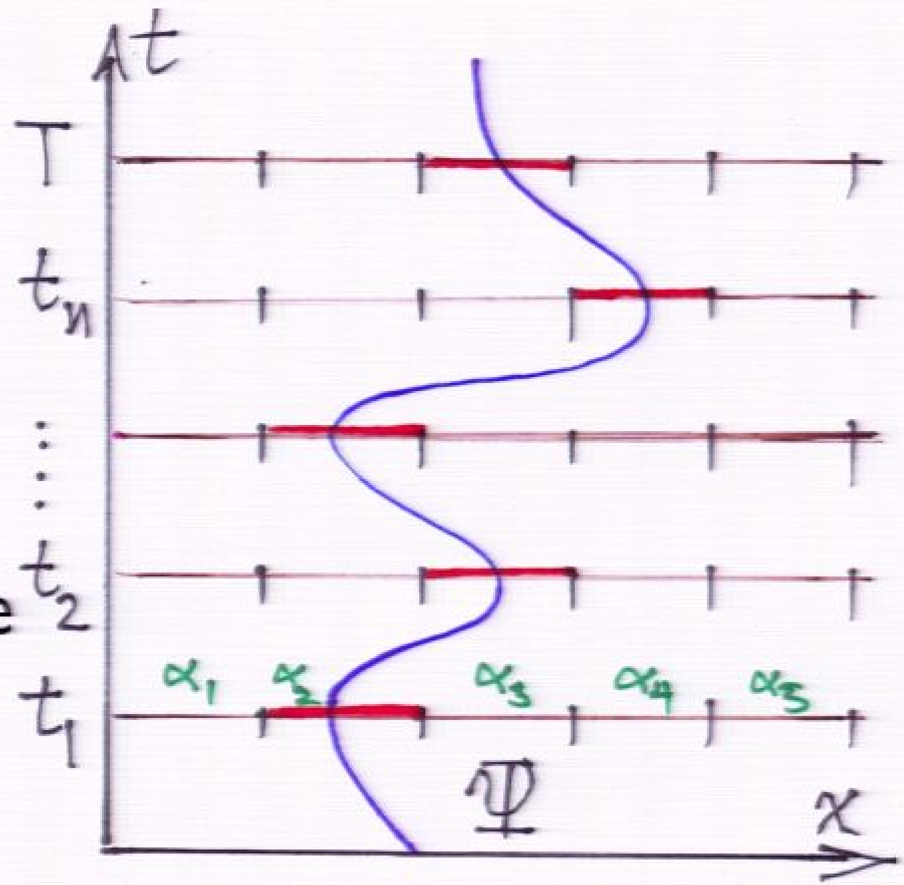

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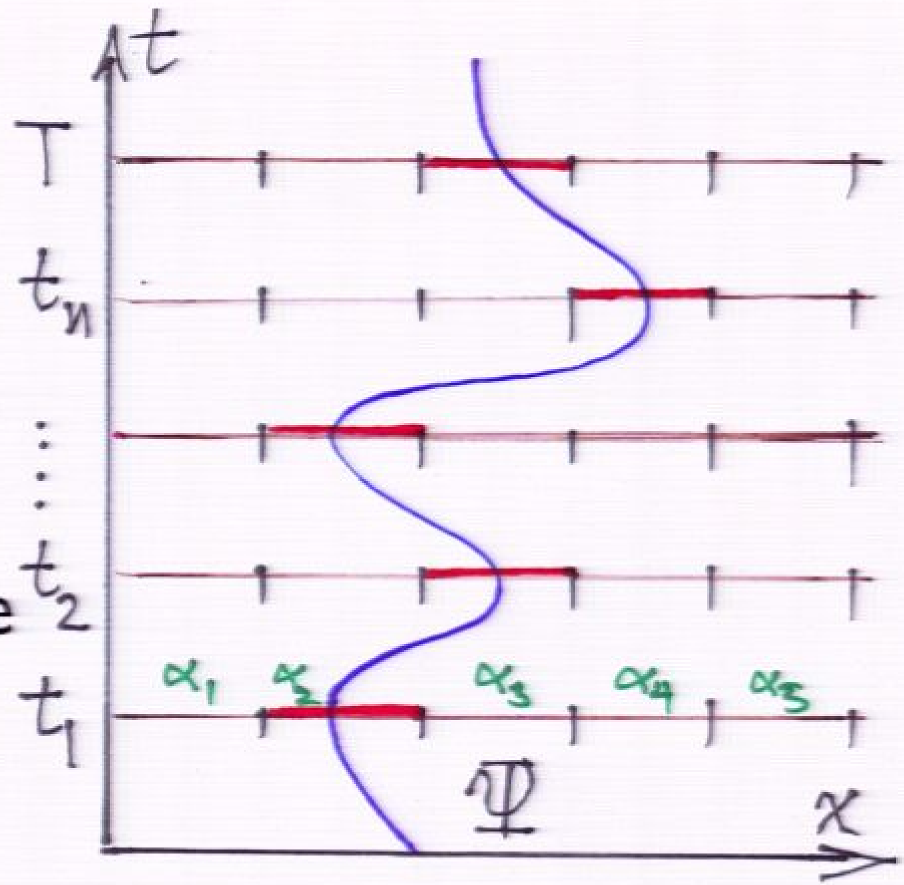

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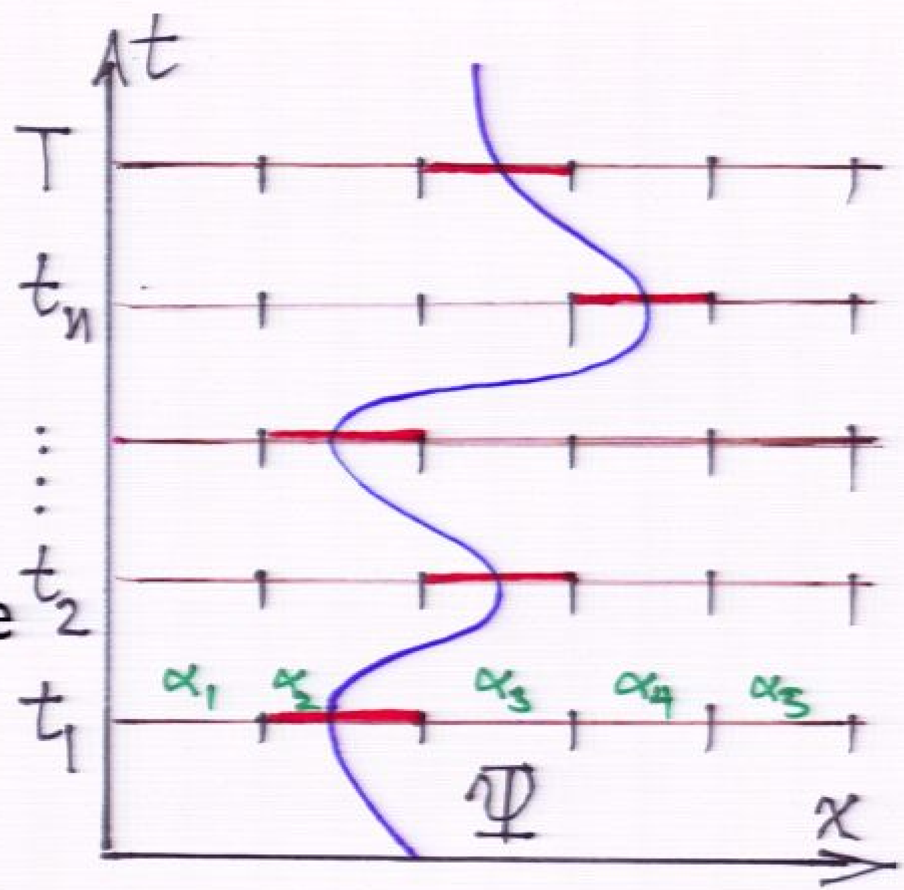

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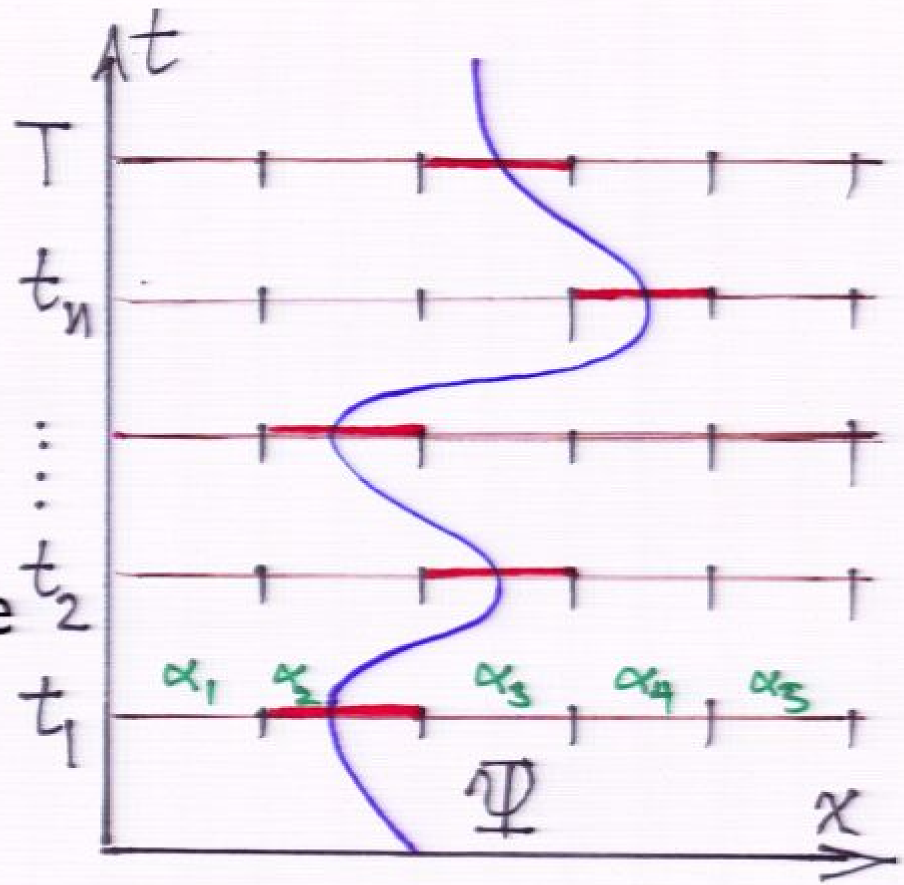

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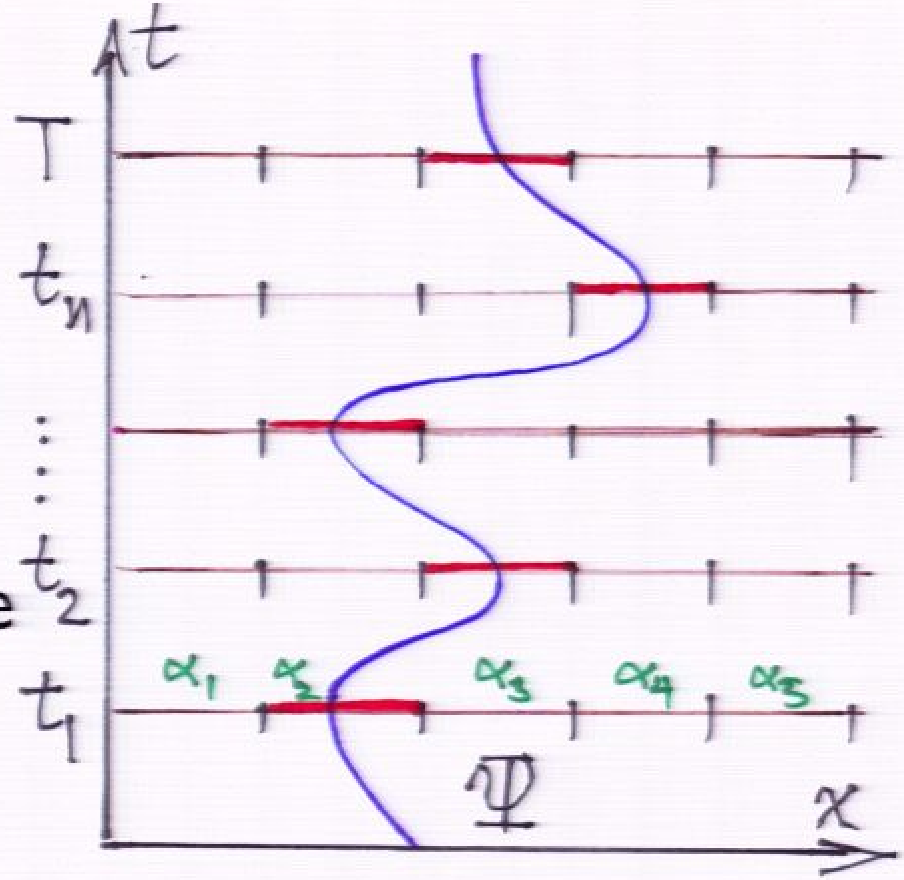

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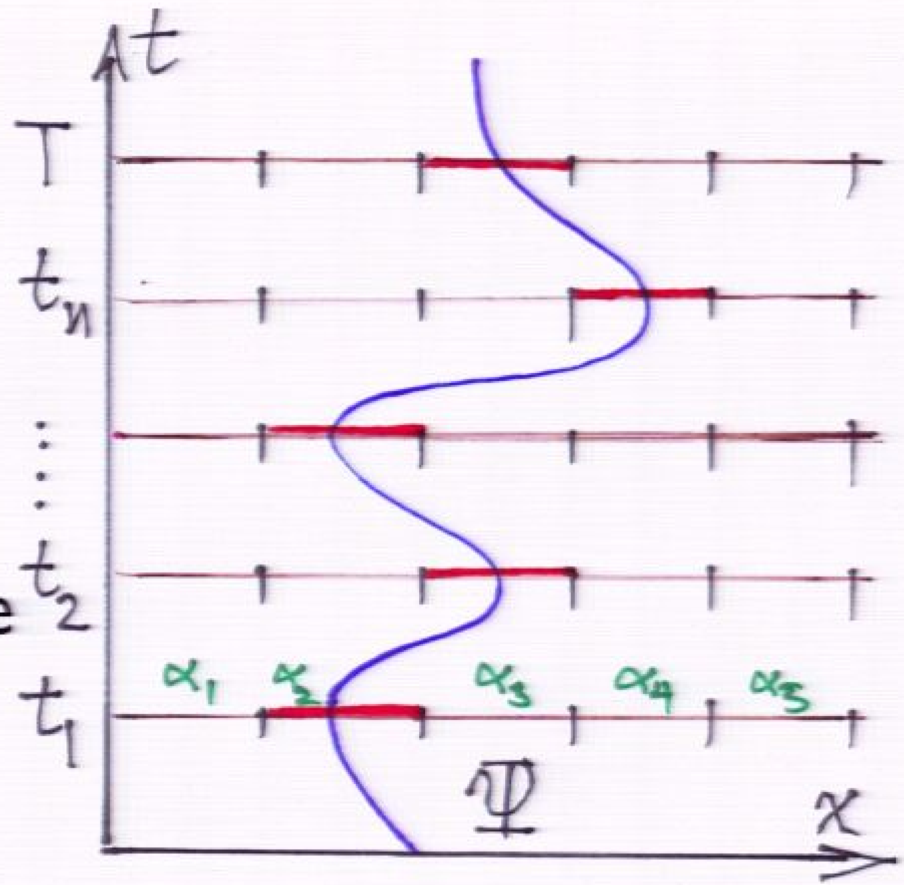

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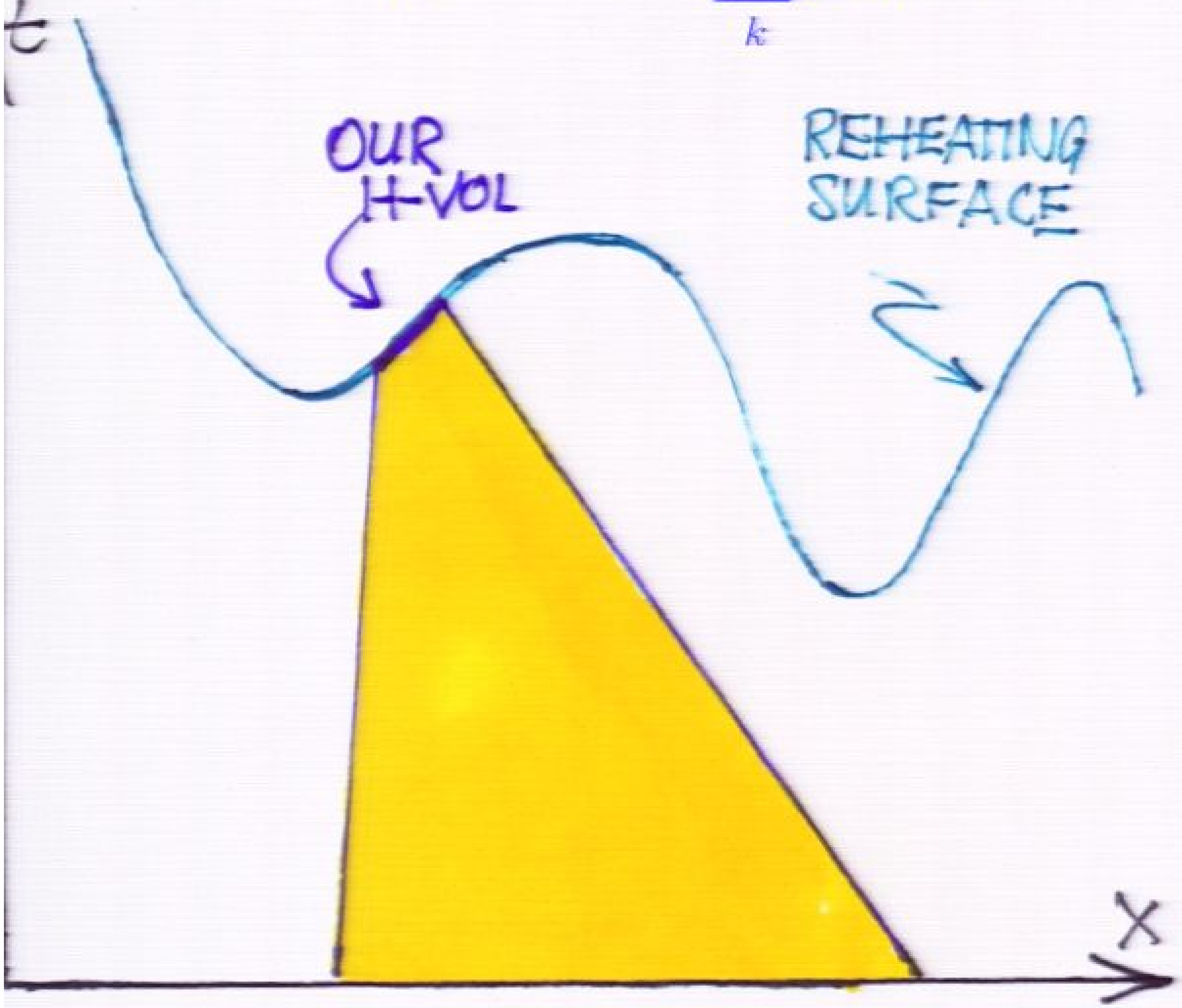

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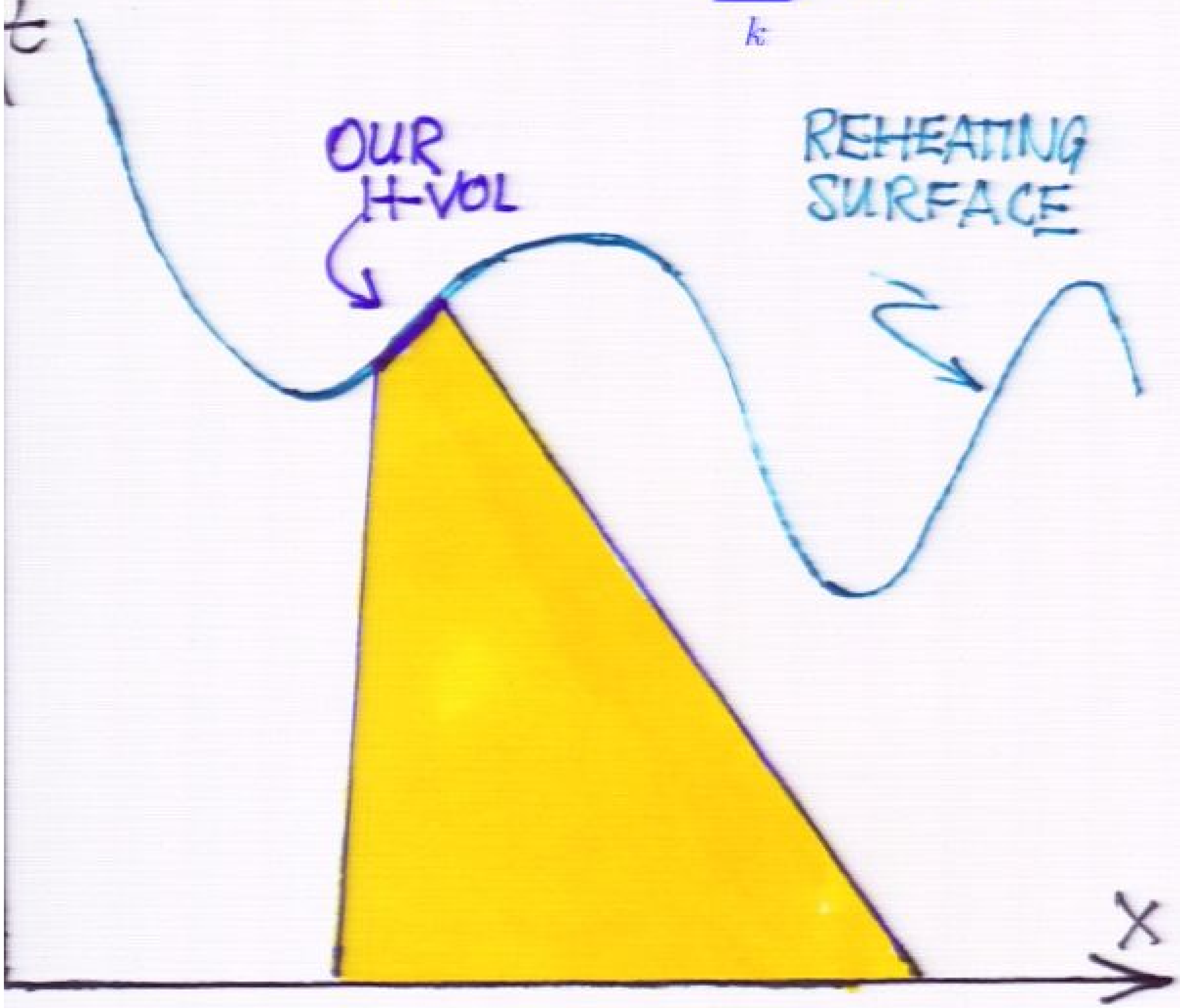

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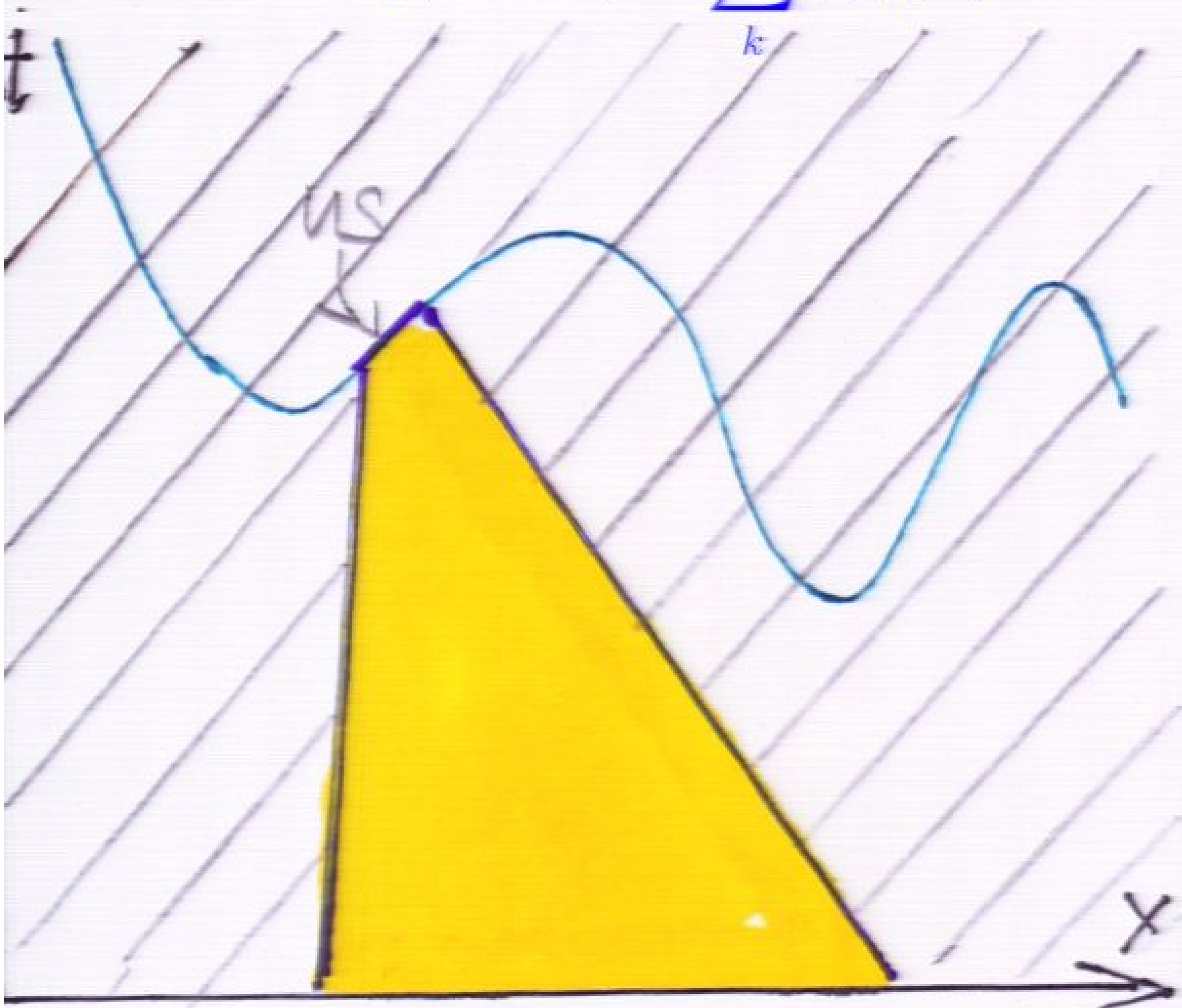

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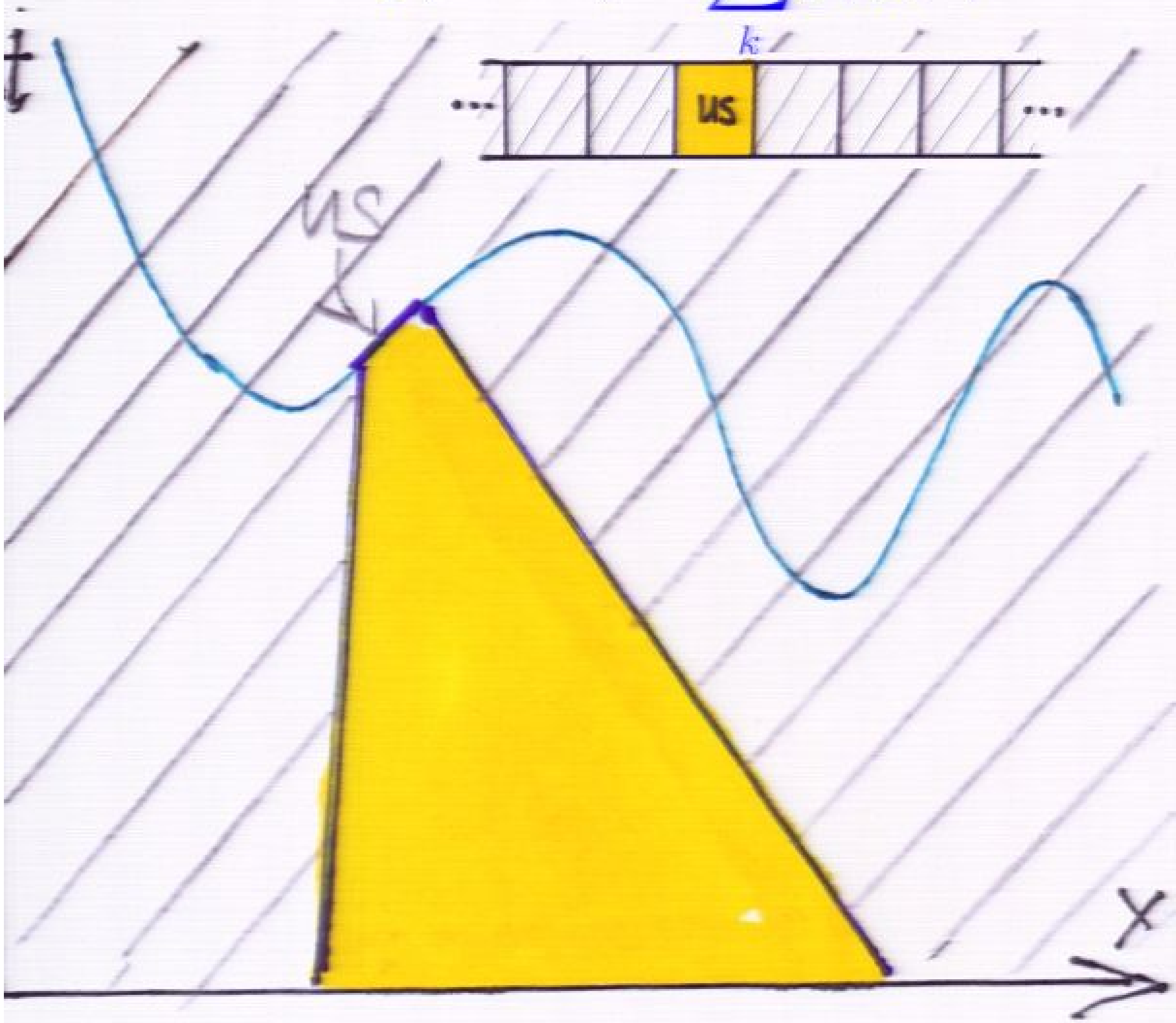

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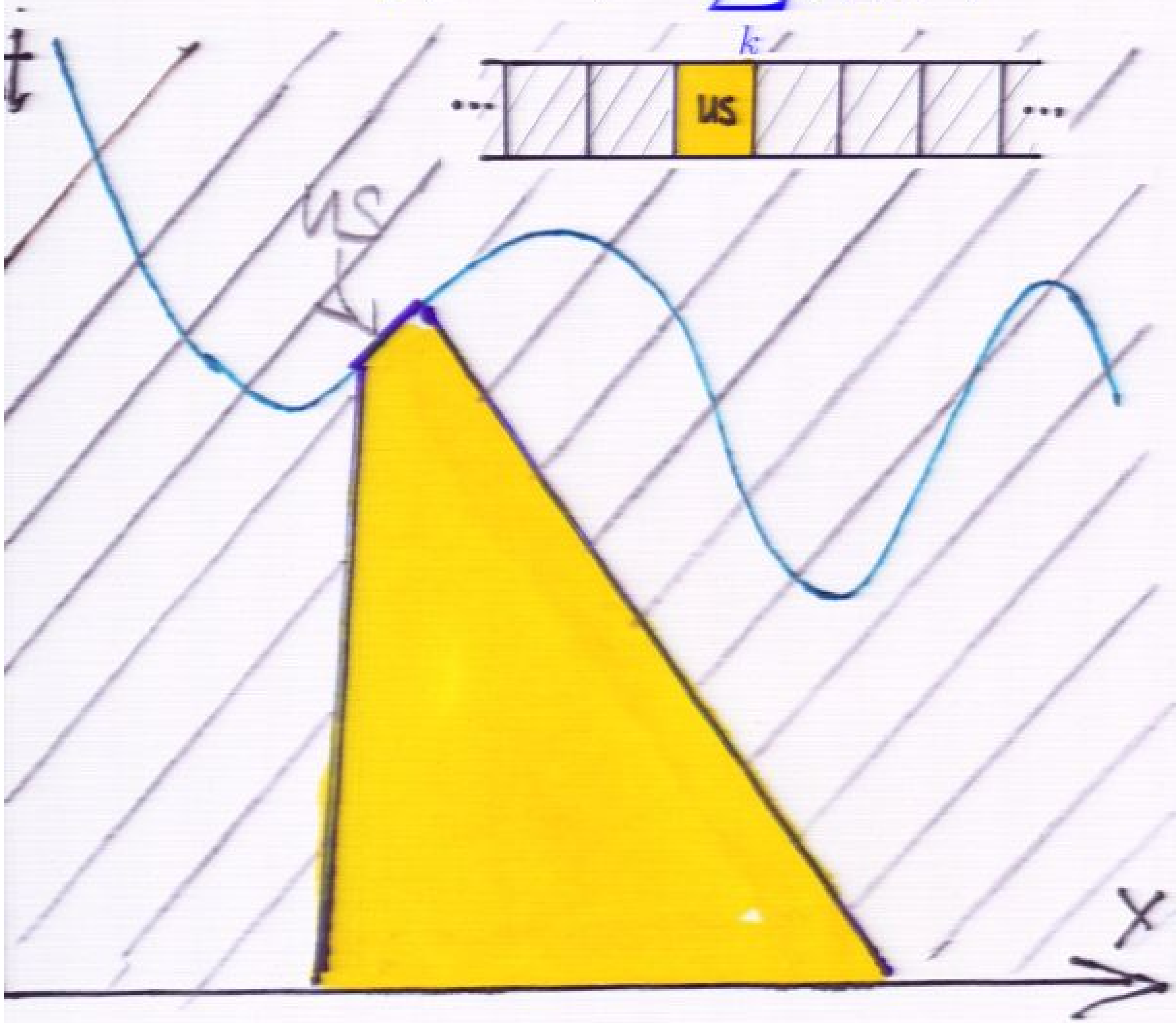

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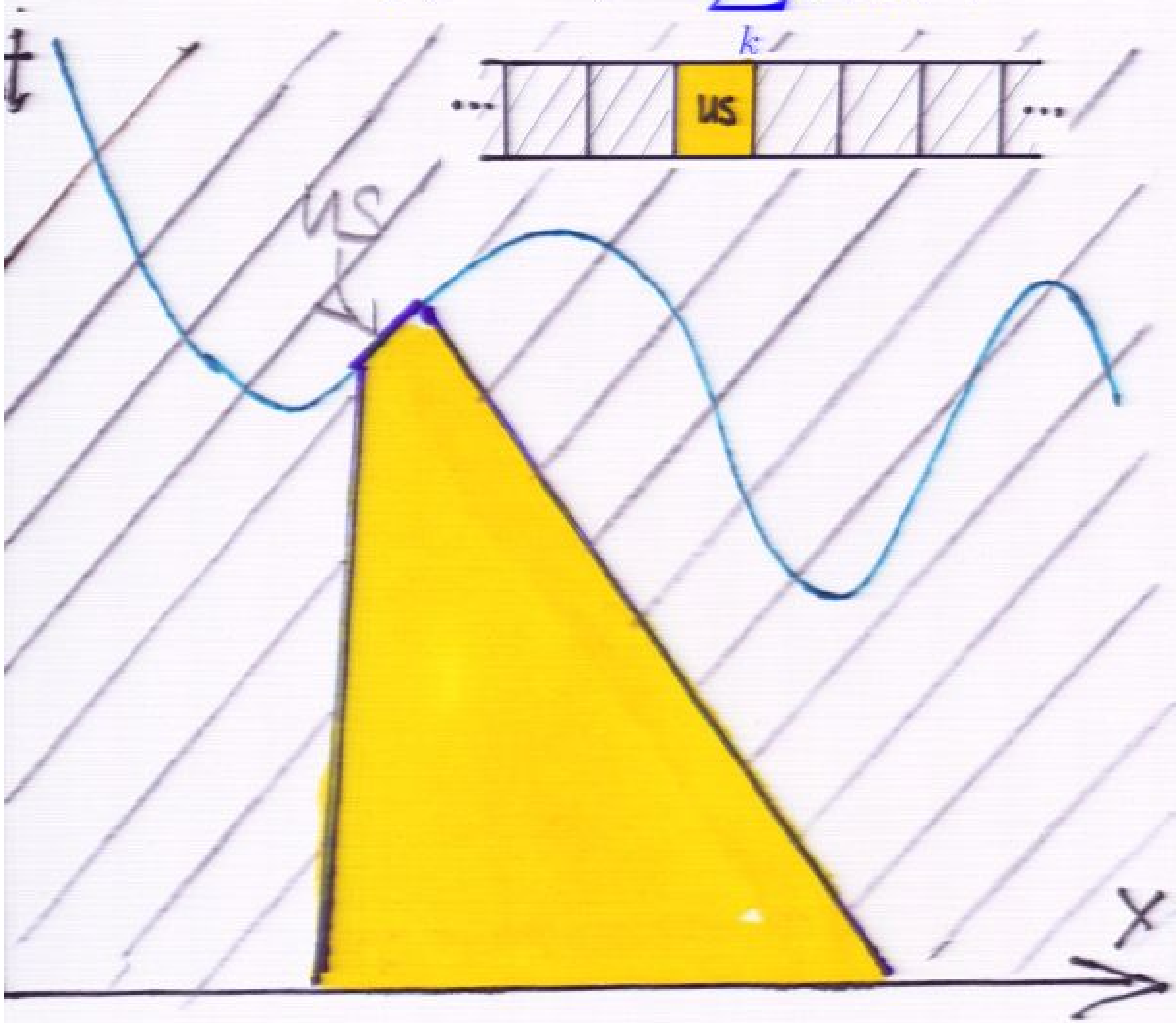

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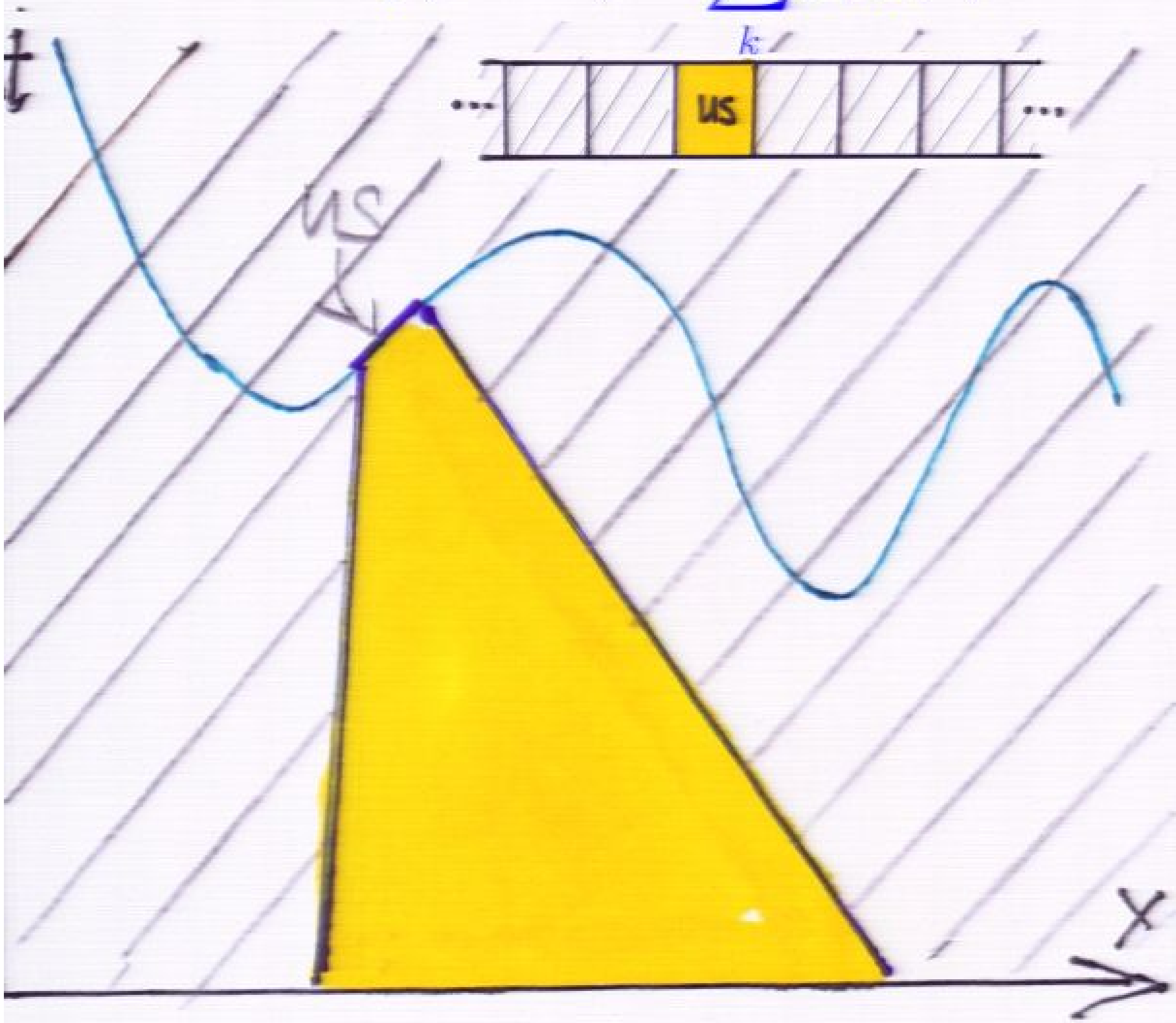

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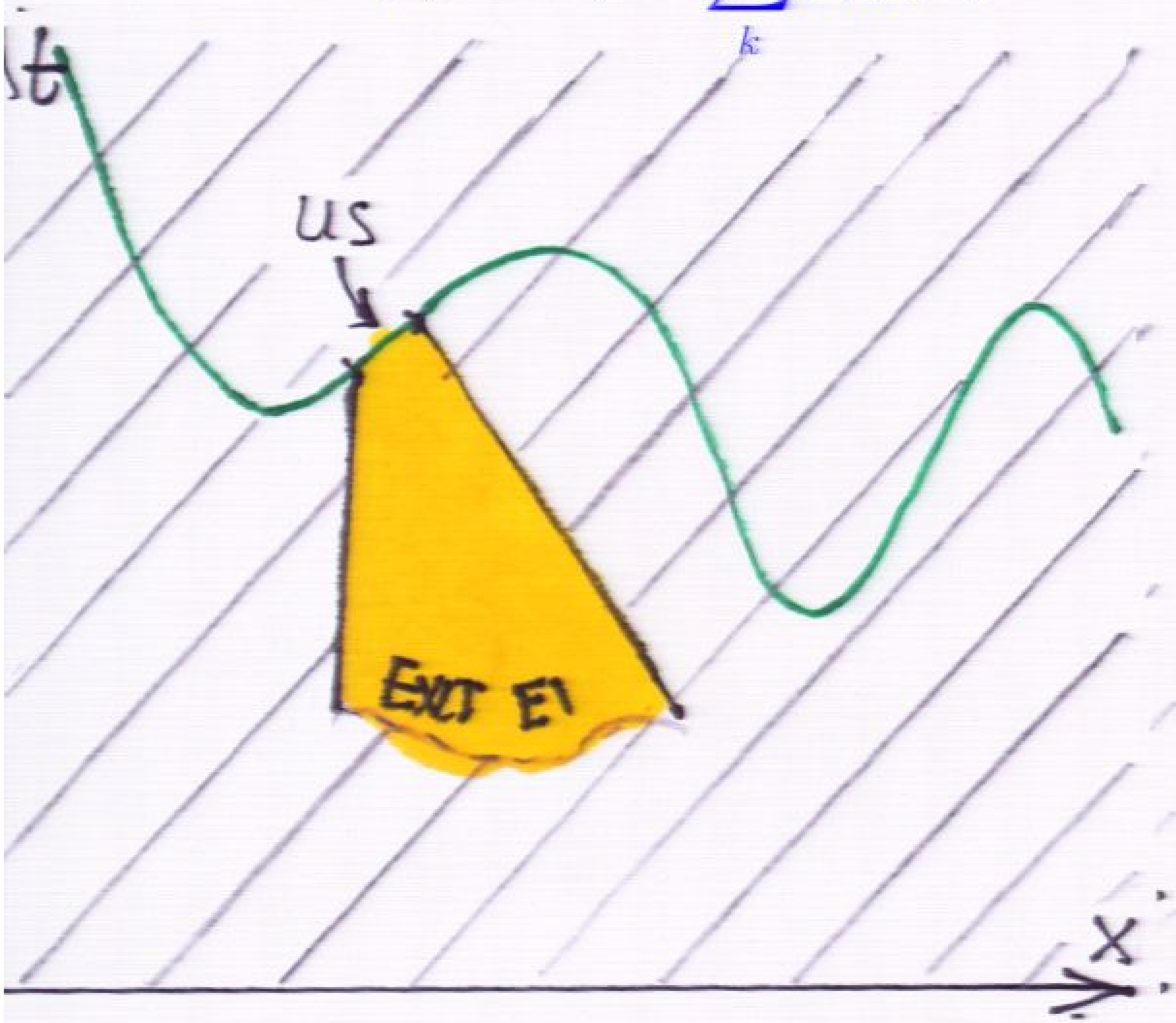

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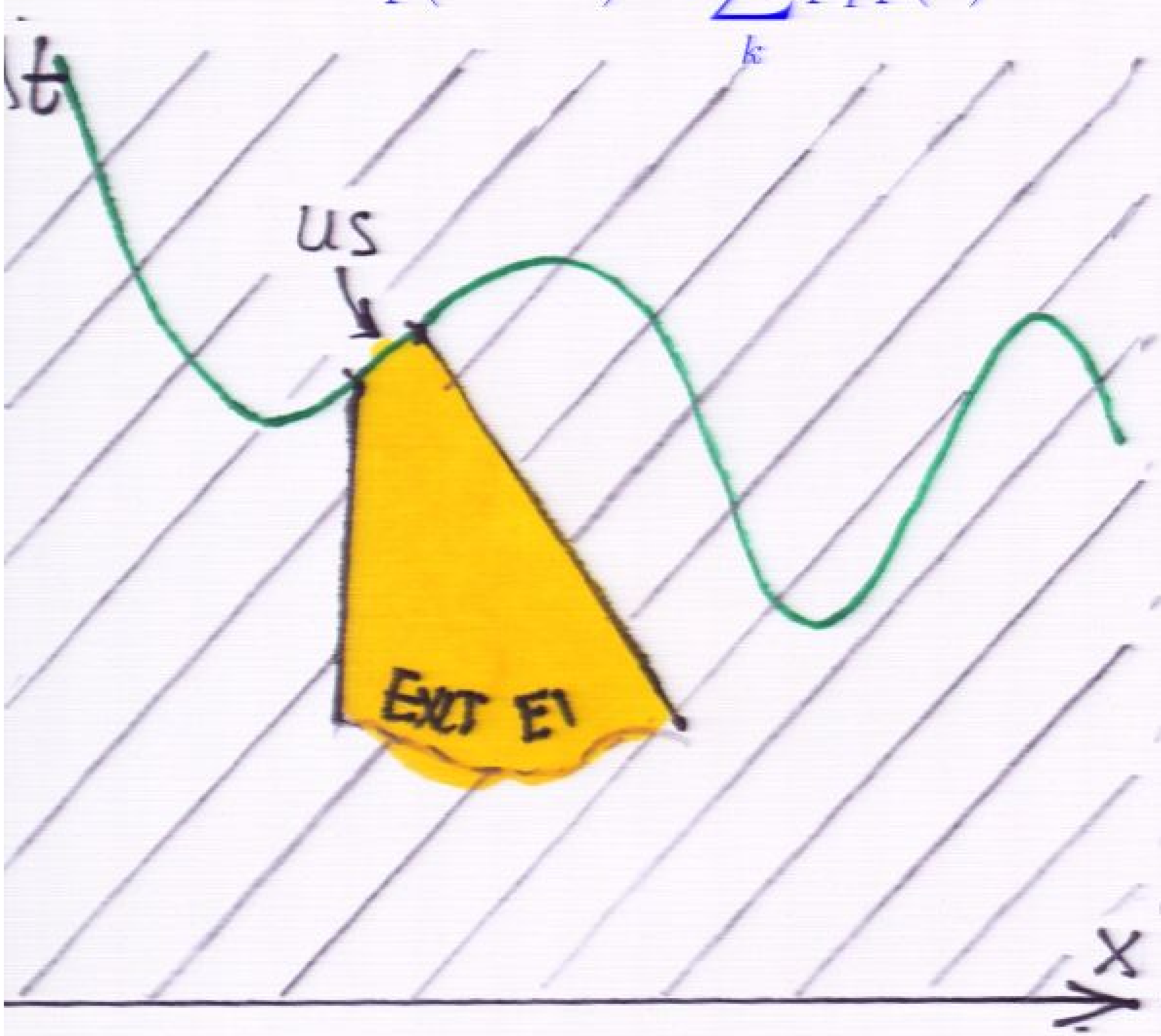

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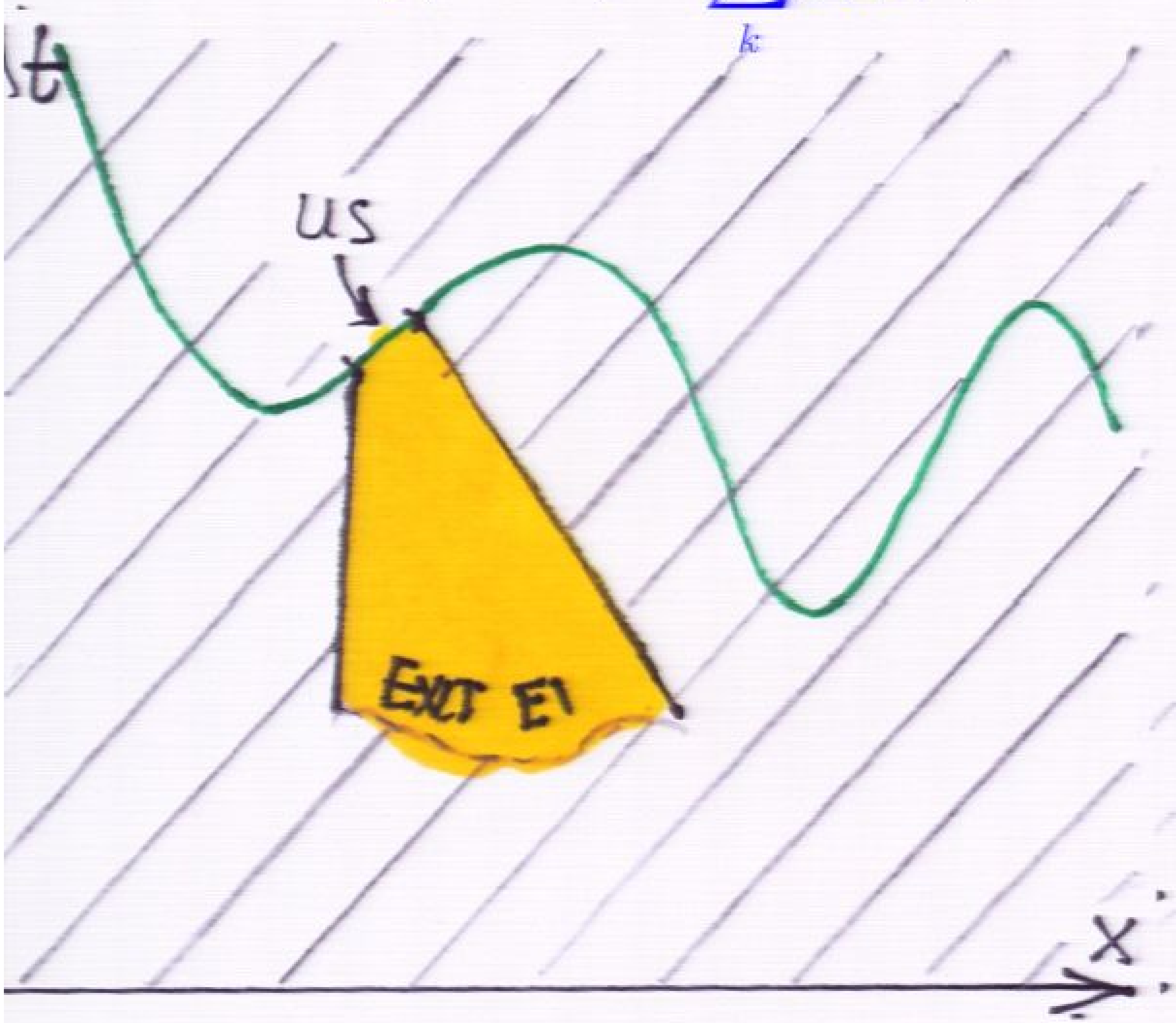

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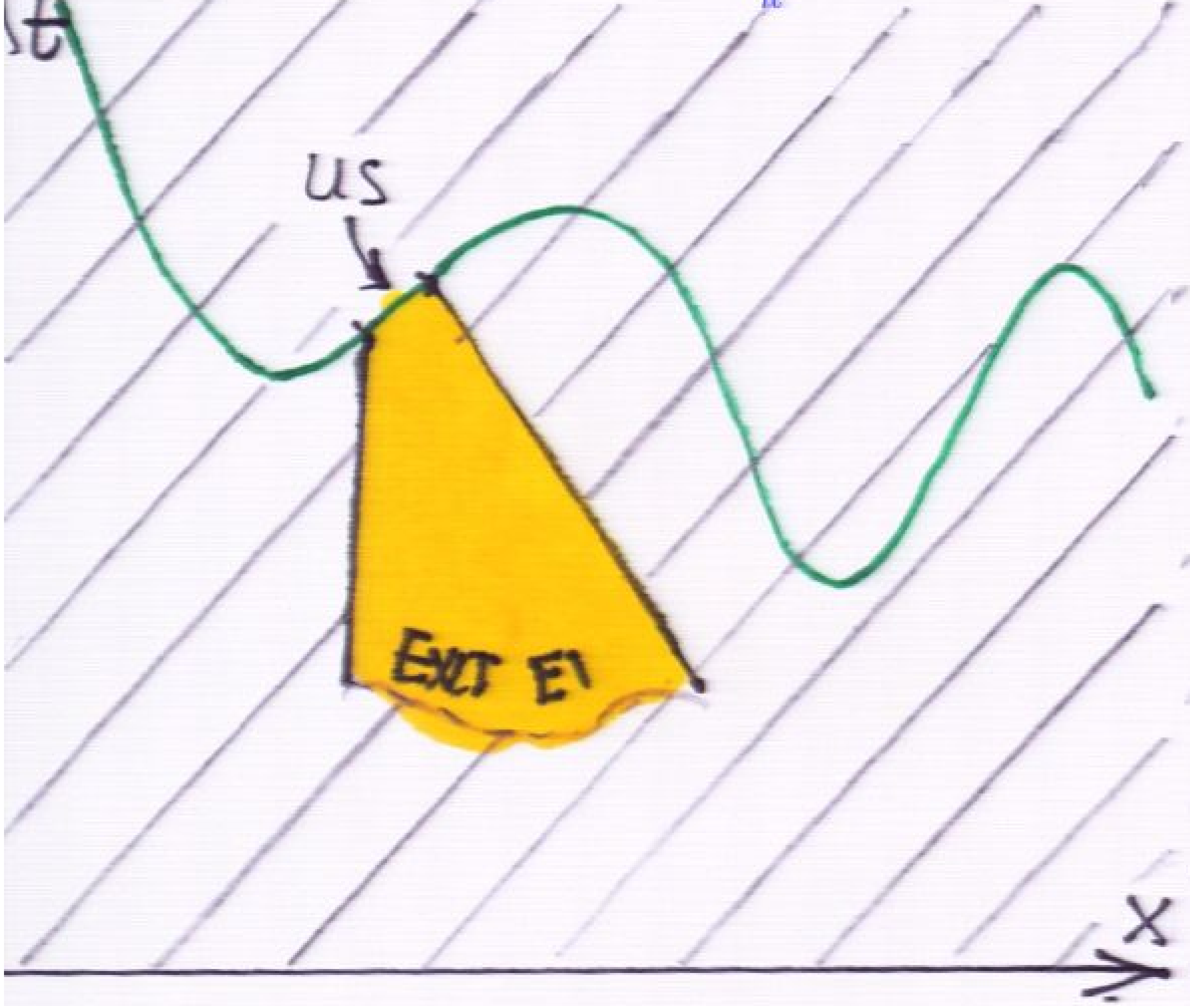

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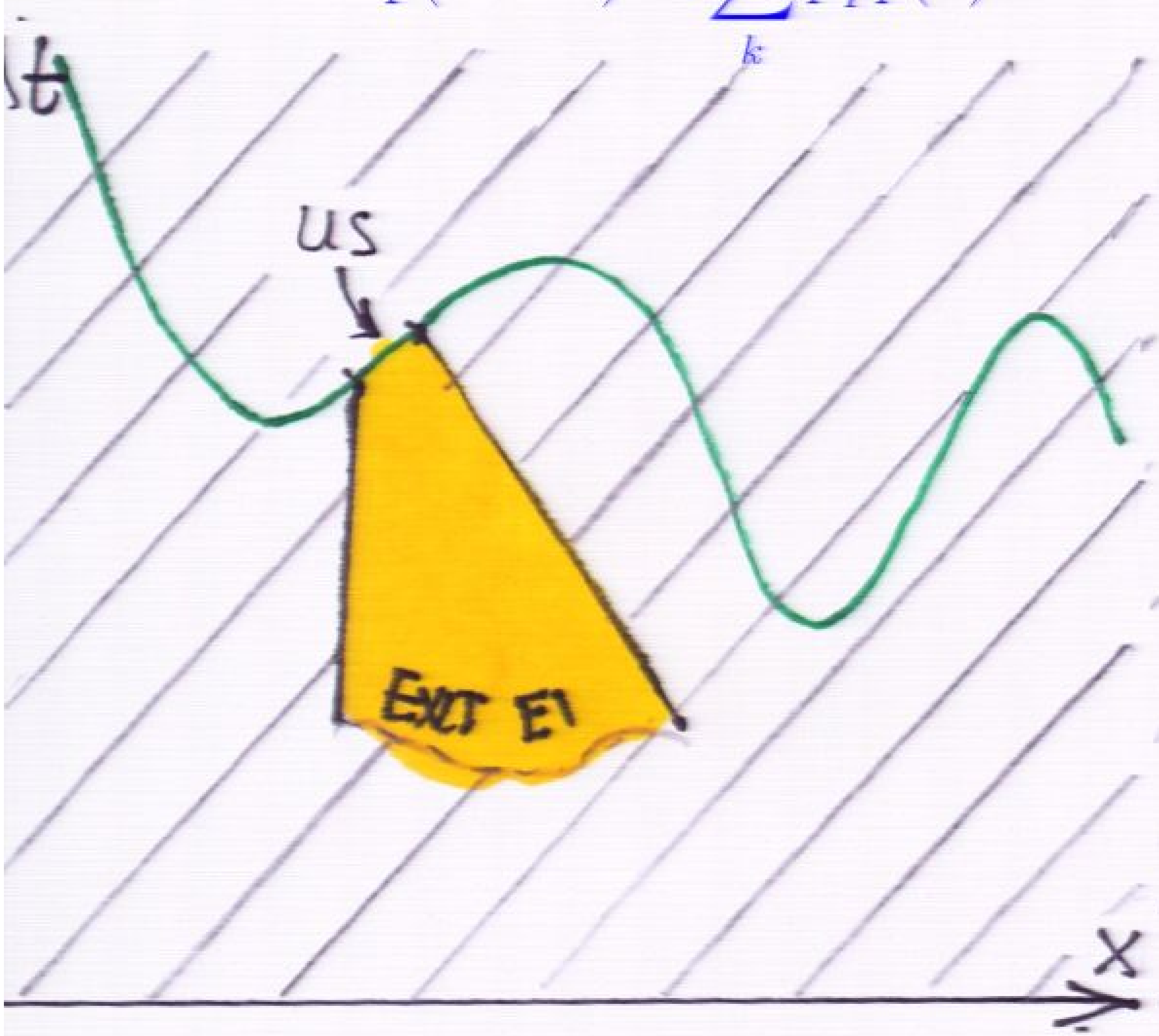

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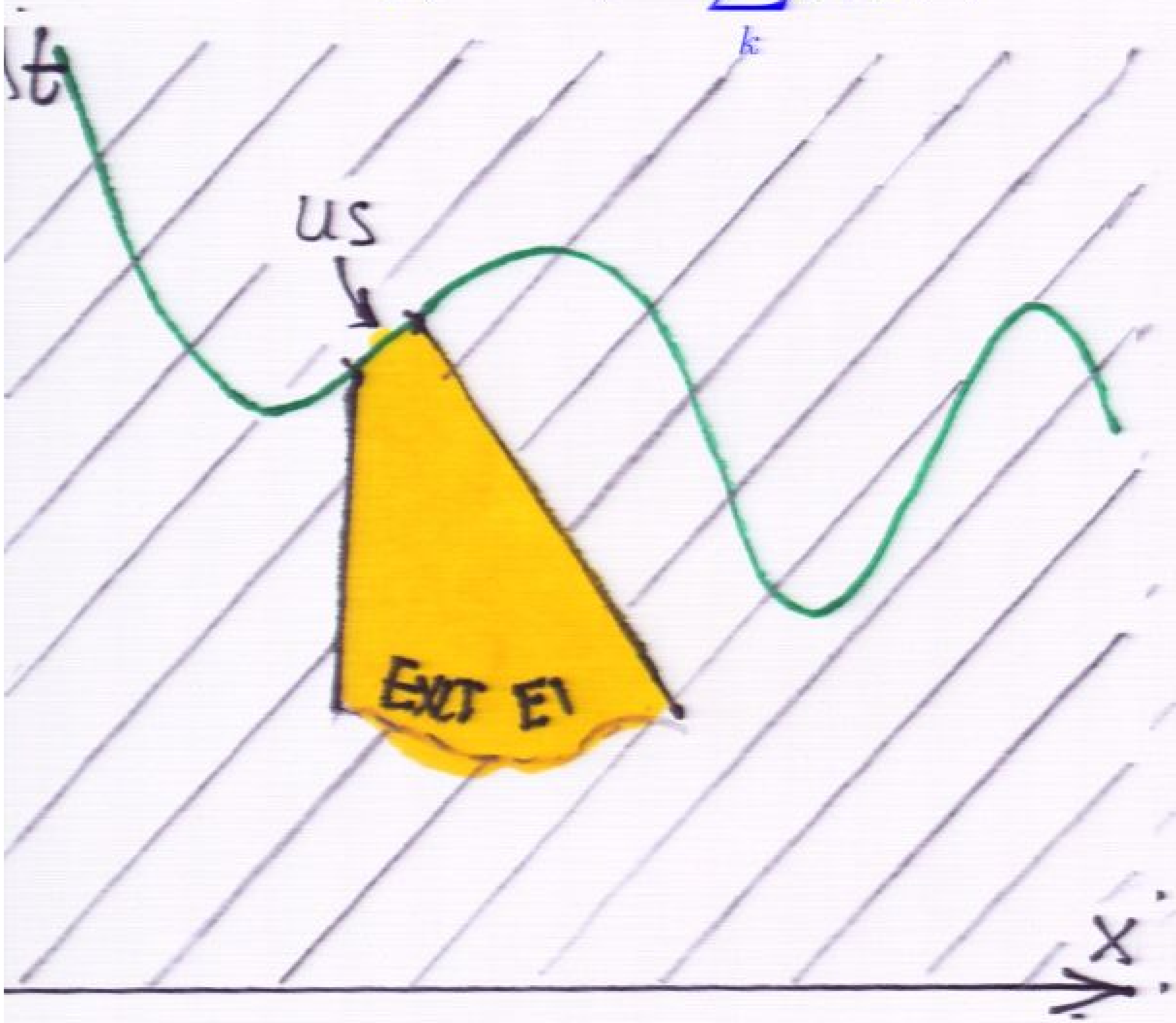

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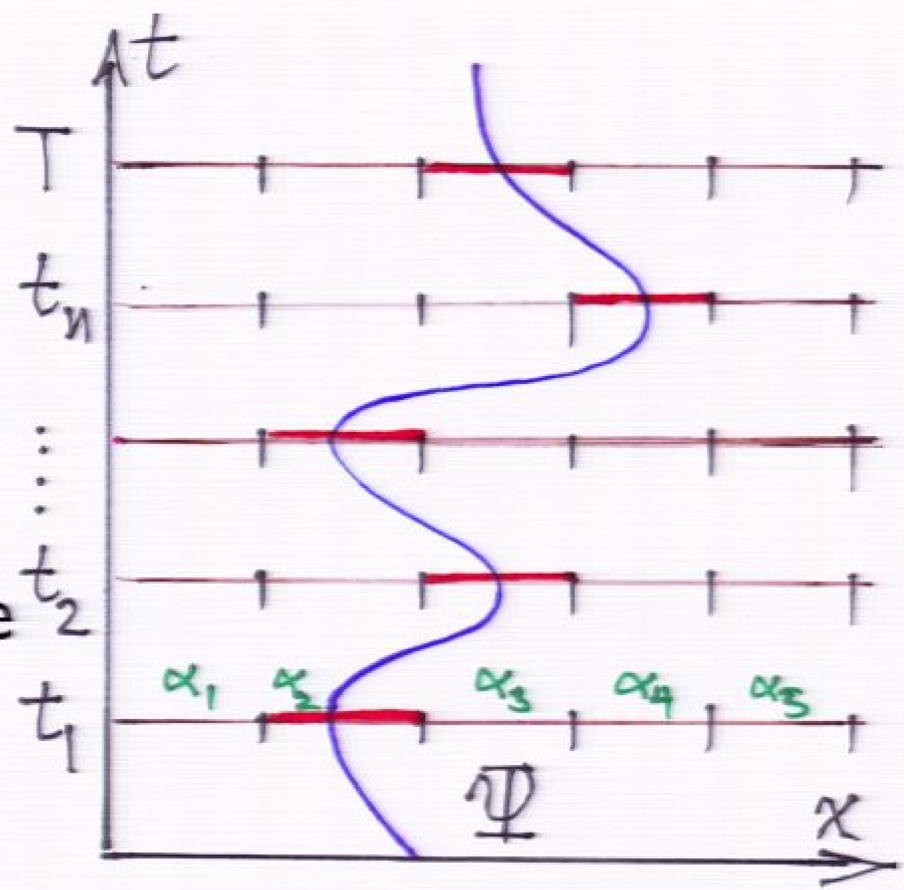

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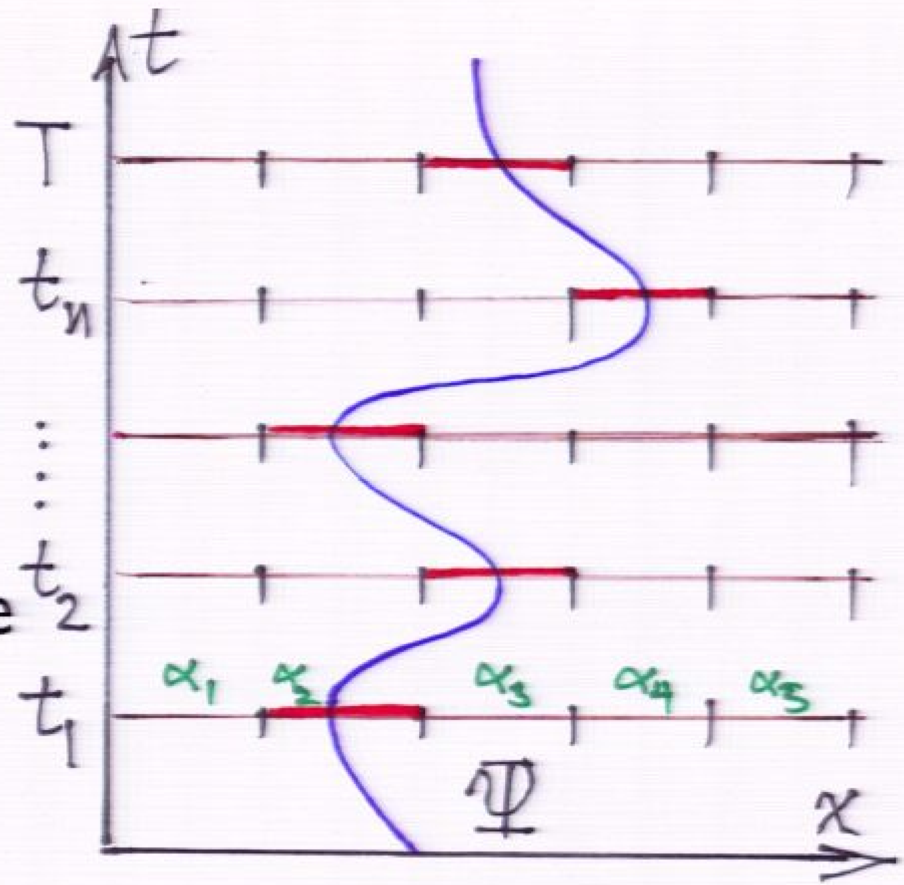

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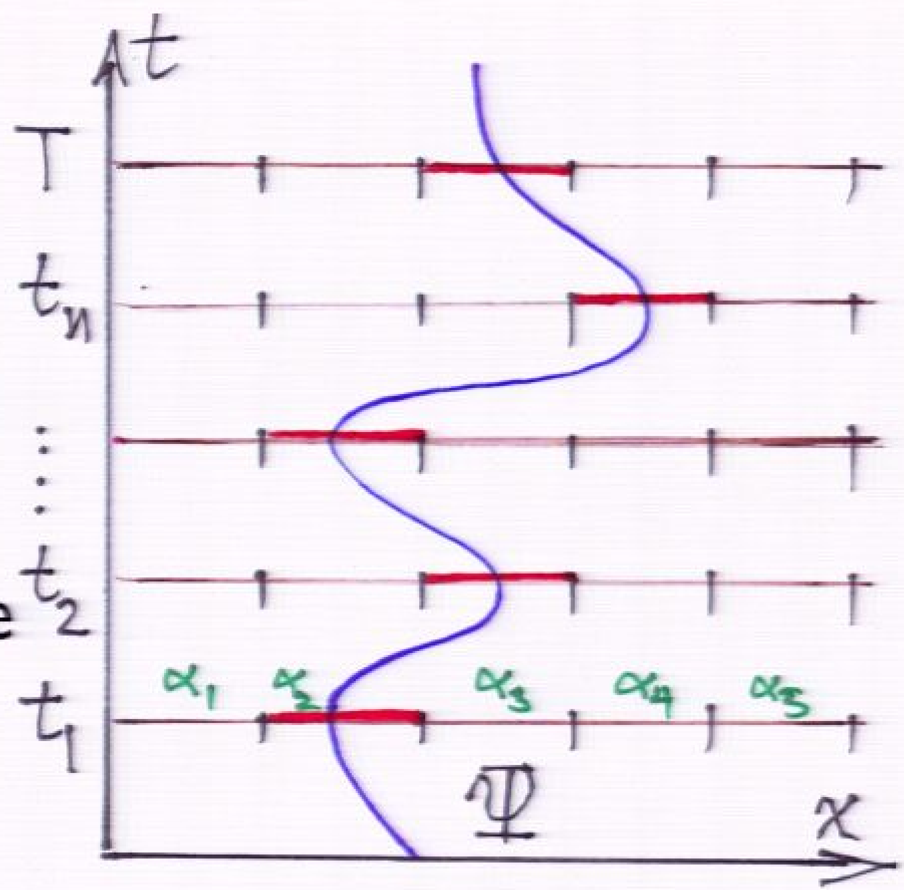

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Geometry: Homogeneous, isotropic, closed.

$$ds^2 = (3/\Lambda)\left[N^2(\lambda)d\lambda^2 + a^2(\lambda)d\Omega_3^2\right]$$

Matter: cosmological constant Λ plus homogeneous scalar field moving in a quadratic potential.

$$V(\Phi) = \frac{1}{2}m^2\Phi^2$$

Theory: Low-energy effective gravity.

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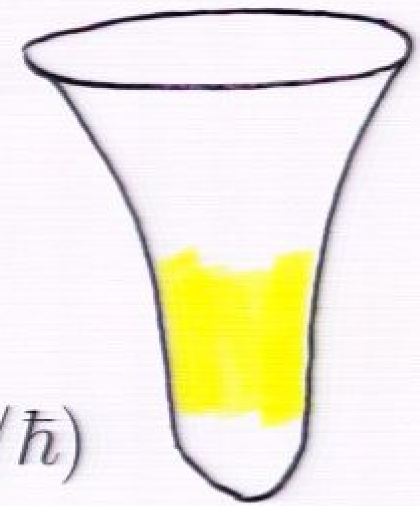

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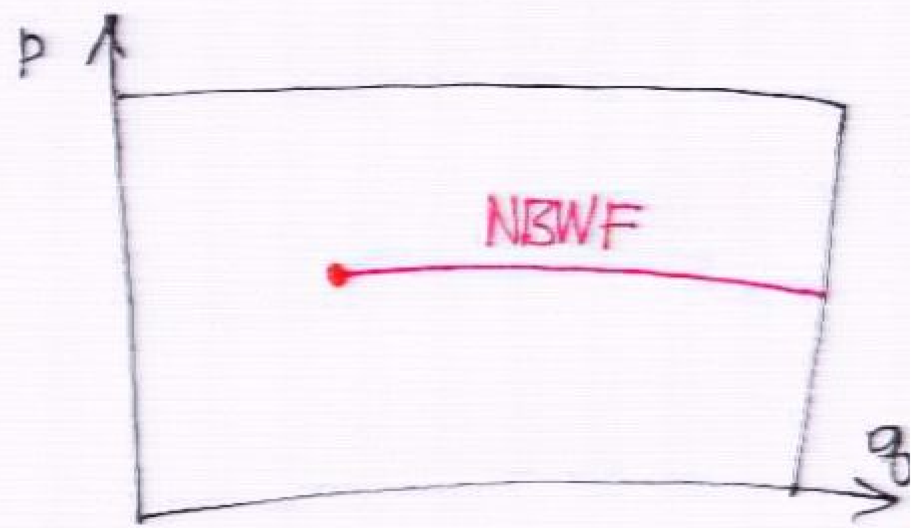

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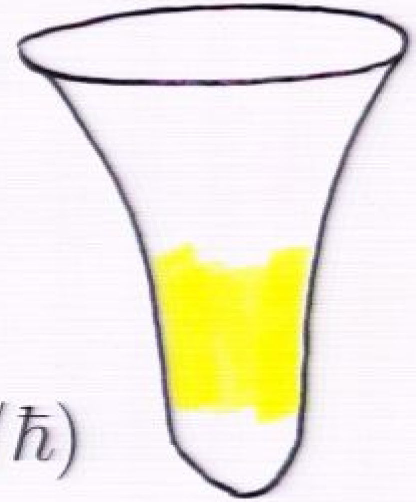

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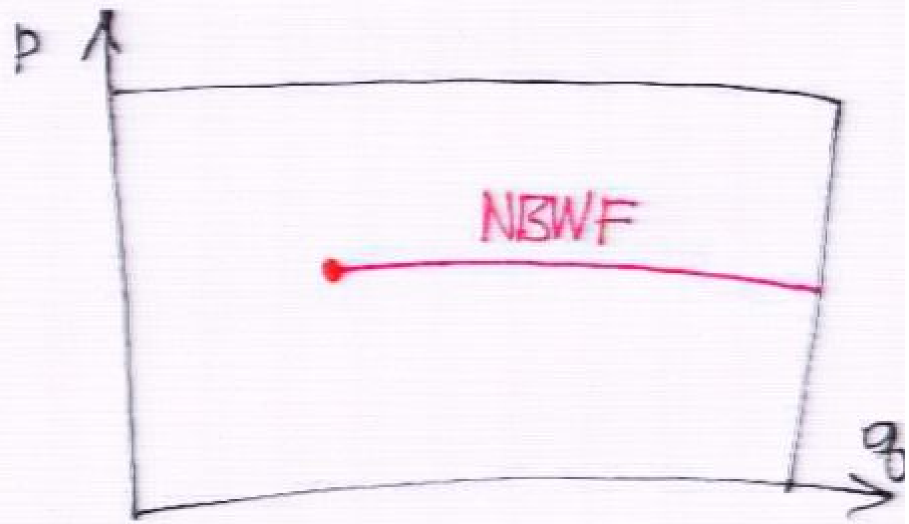

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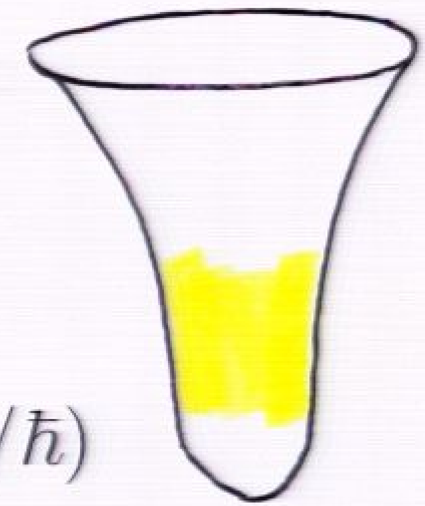

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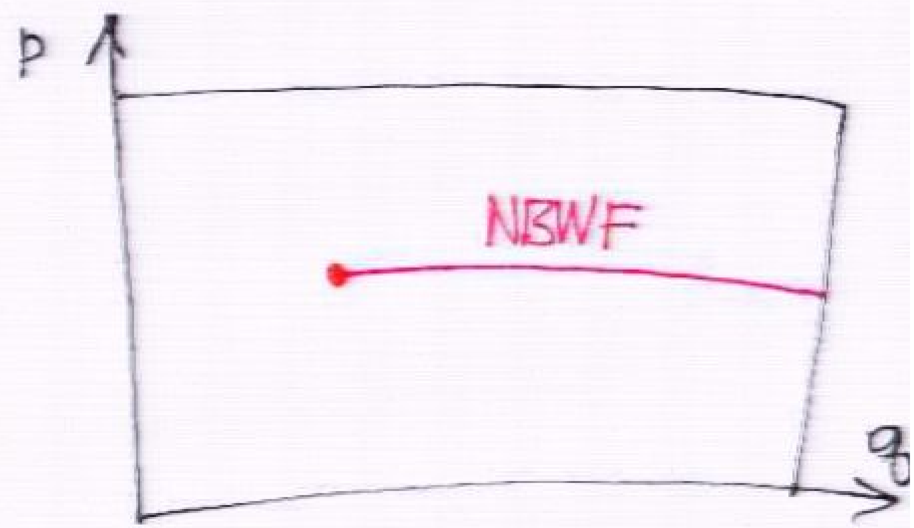

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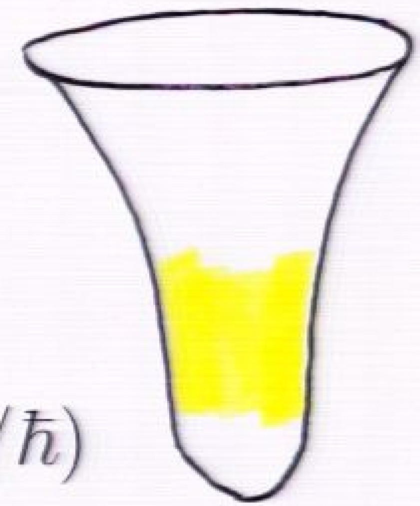

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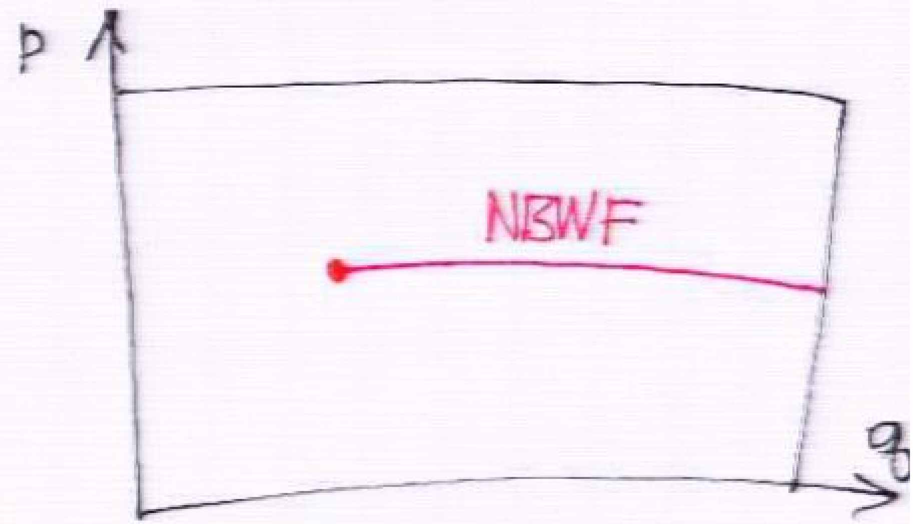

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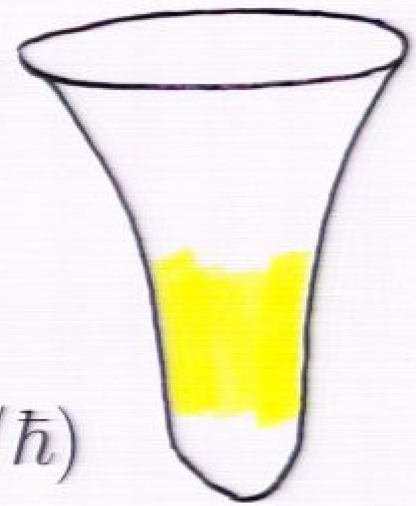

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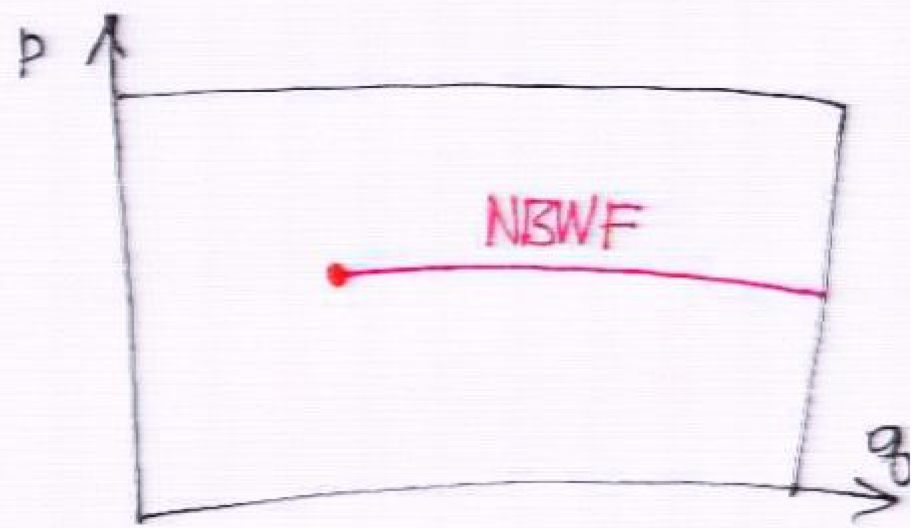

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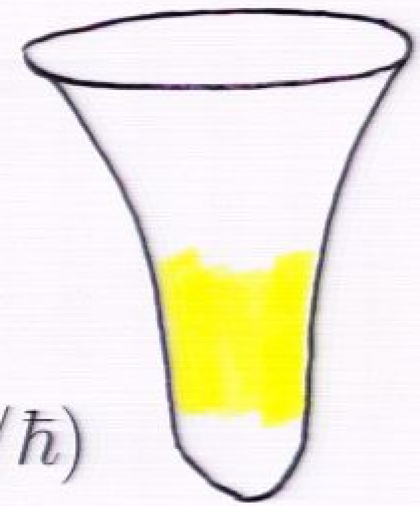

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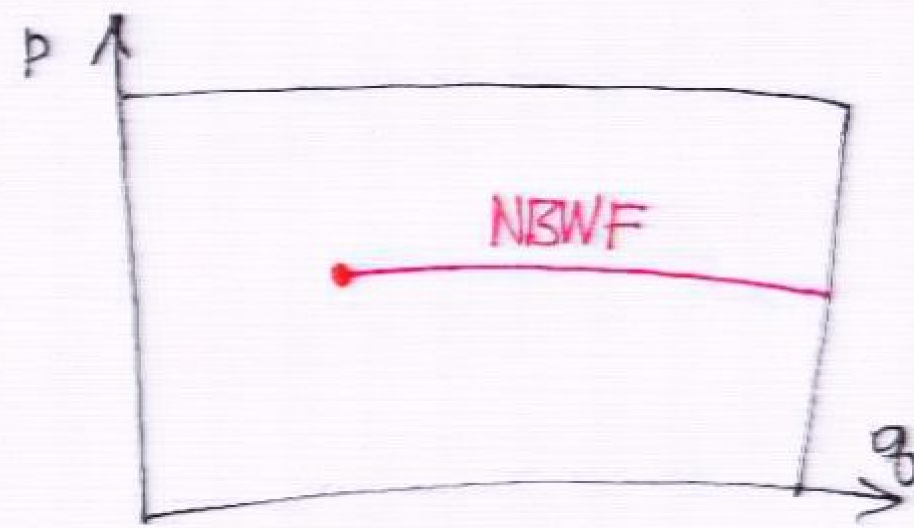

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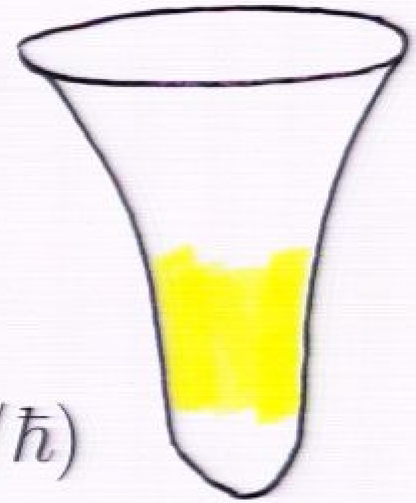

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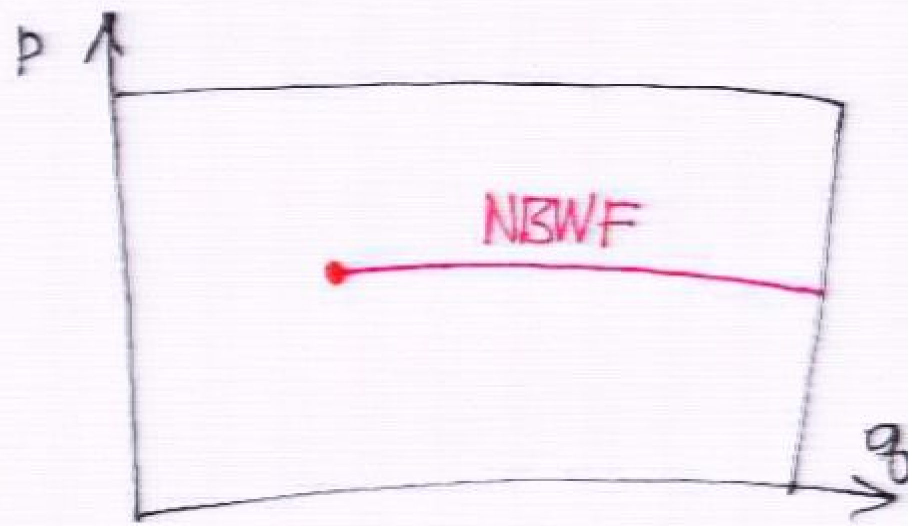

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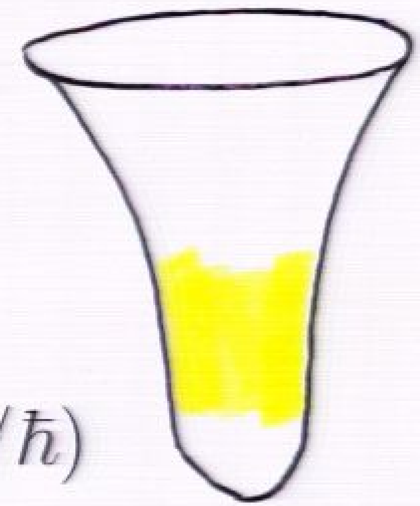

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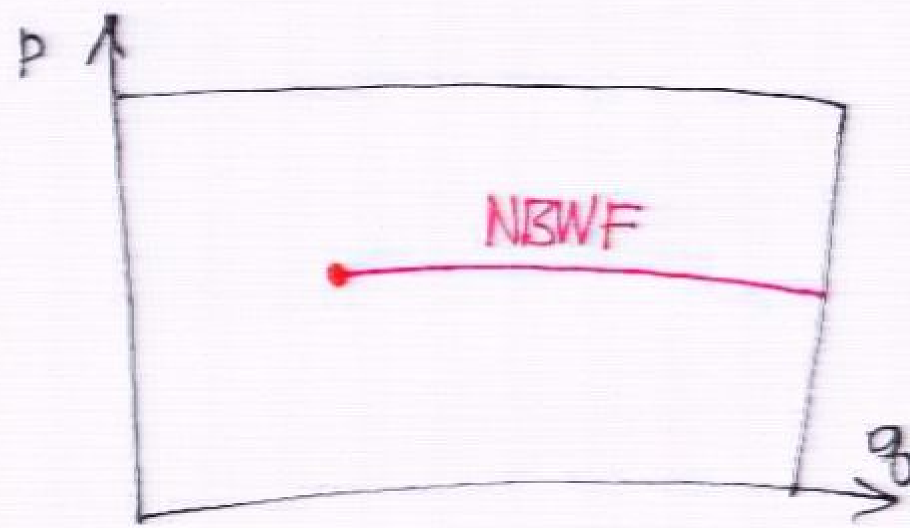

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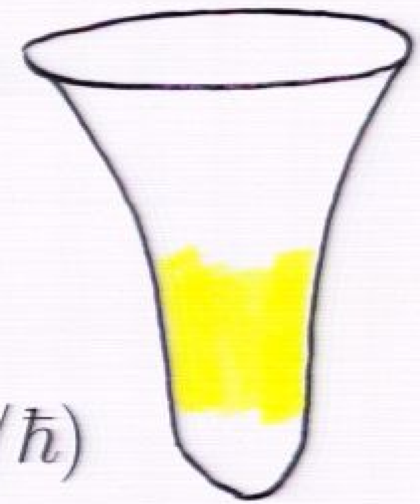

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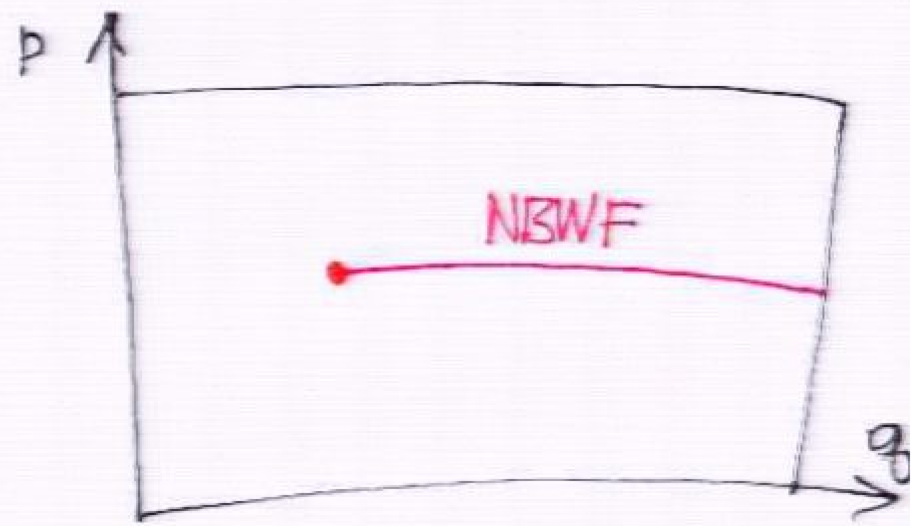

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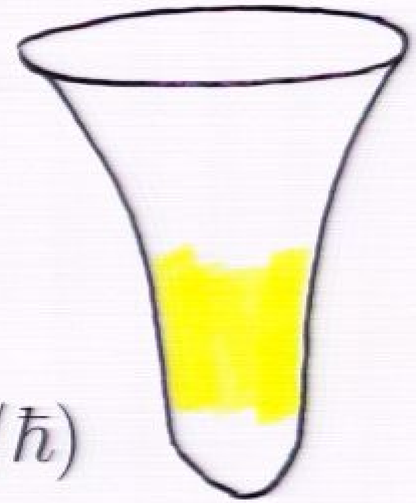

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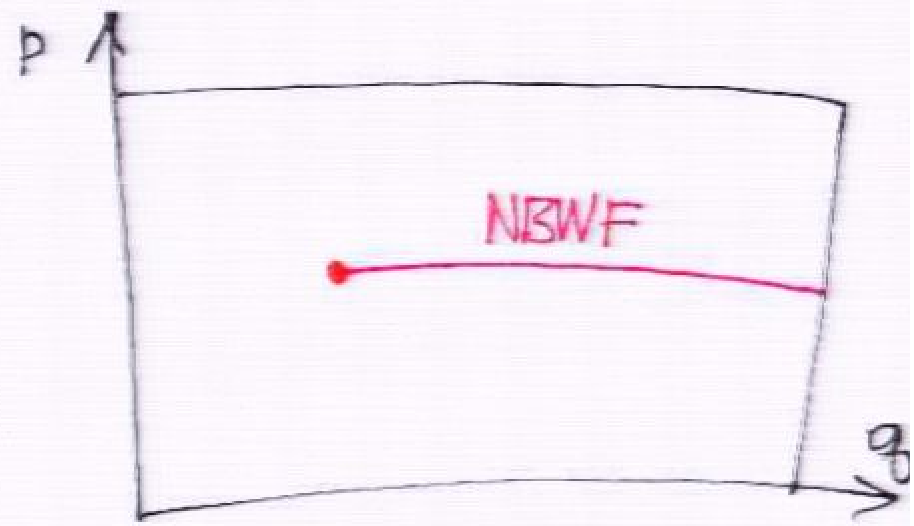

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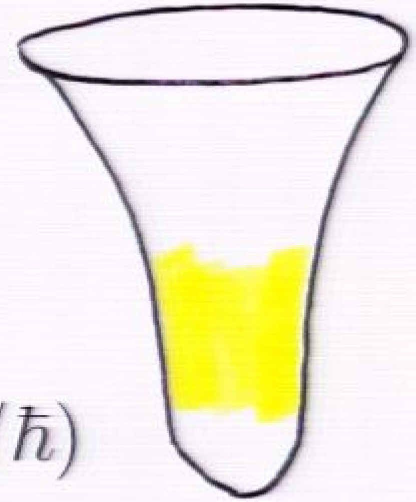

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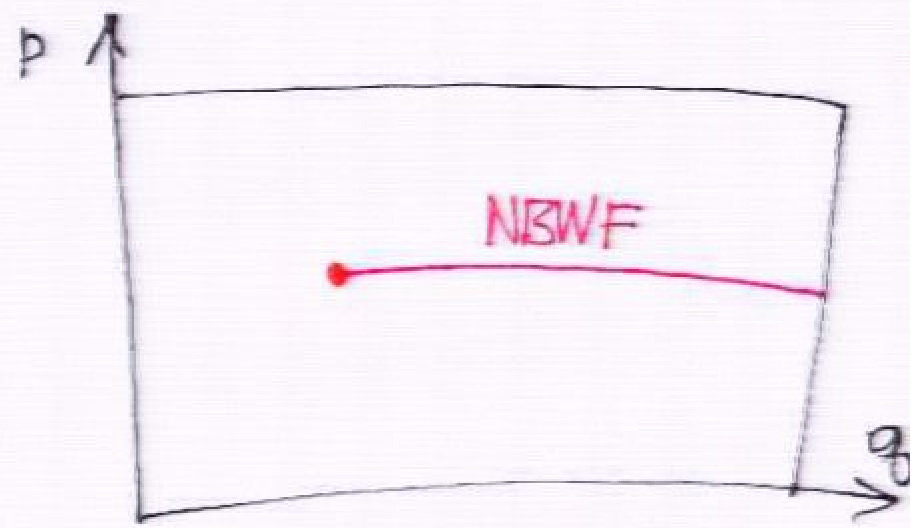

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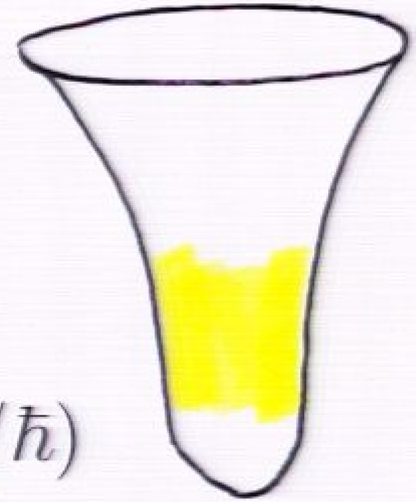

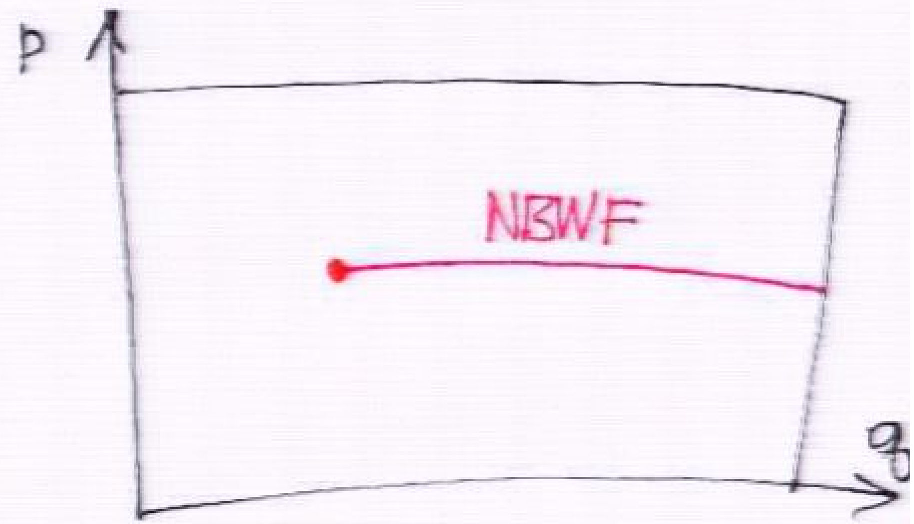

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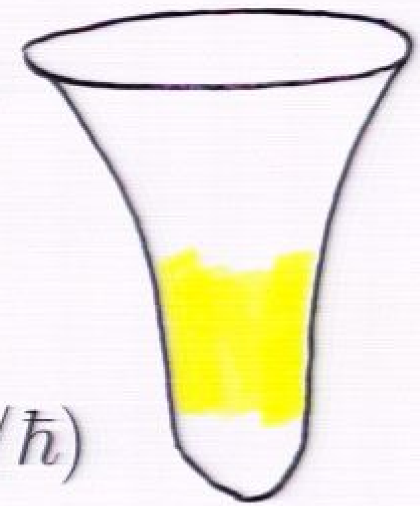

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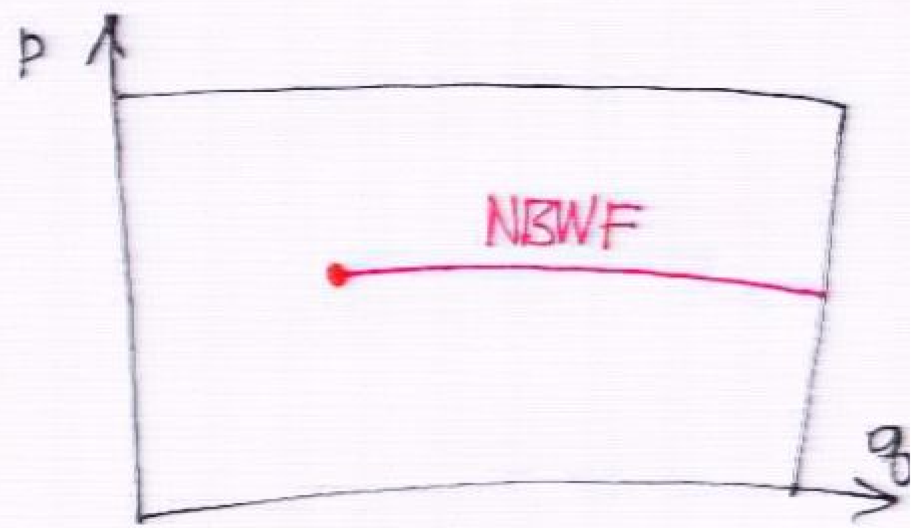

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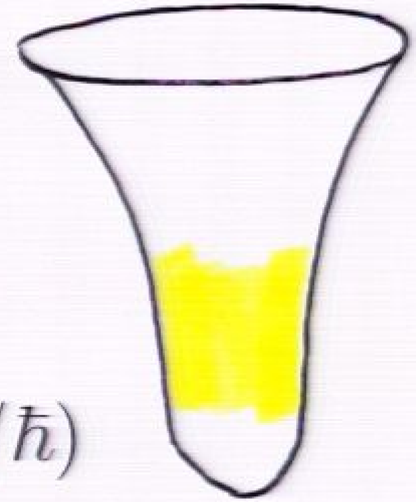

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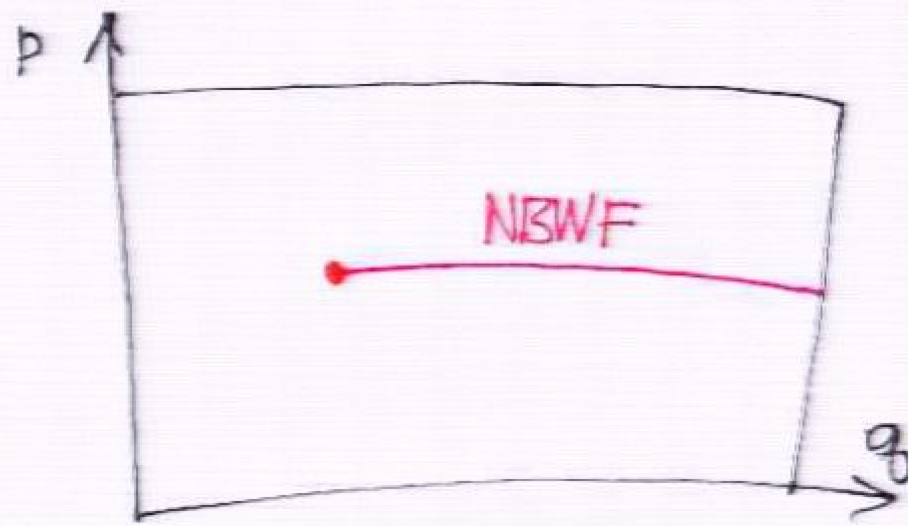

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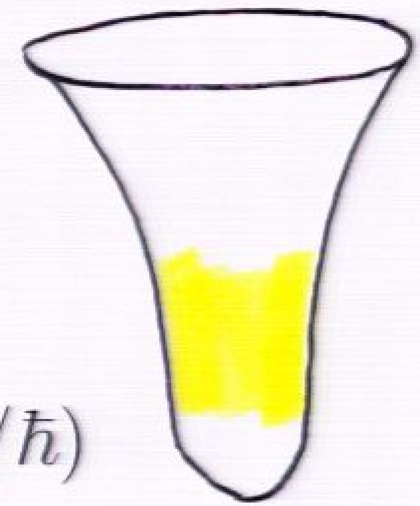

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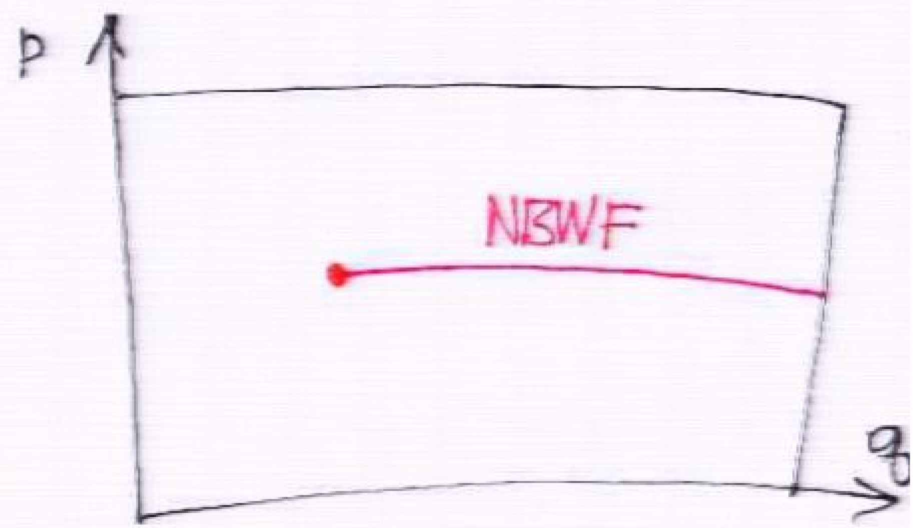

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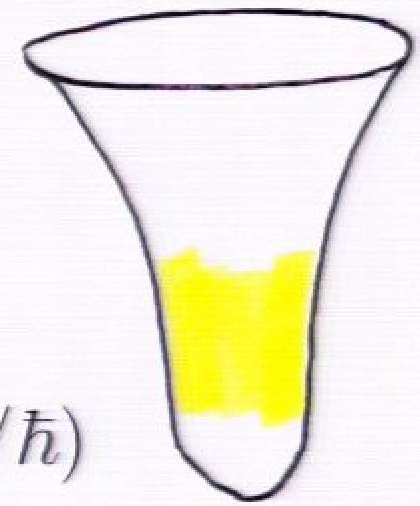

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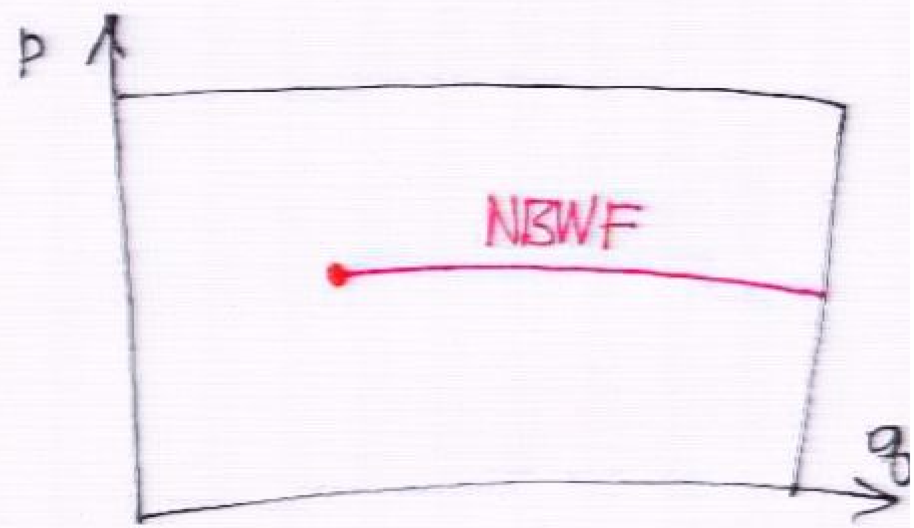

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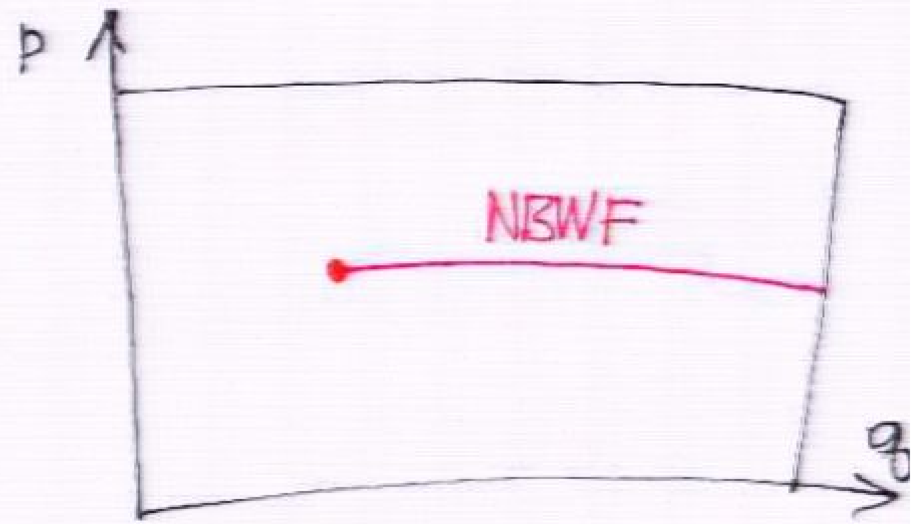

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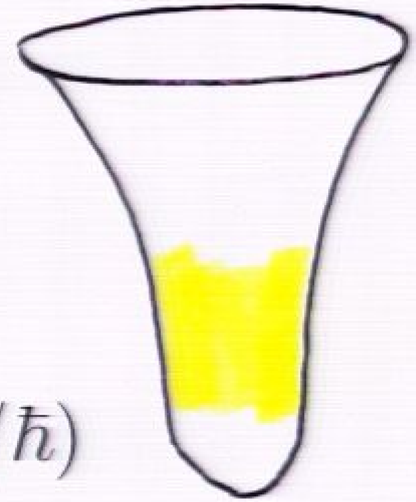

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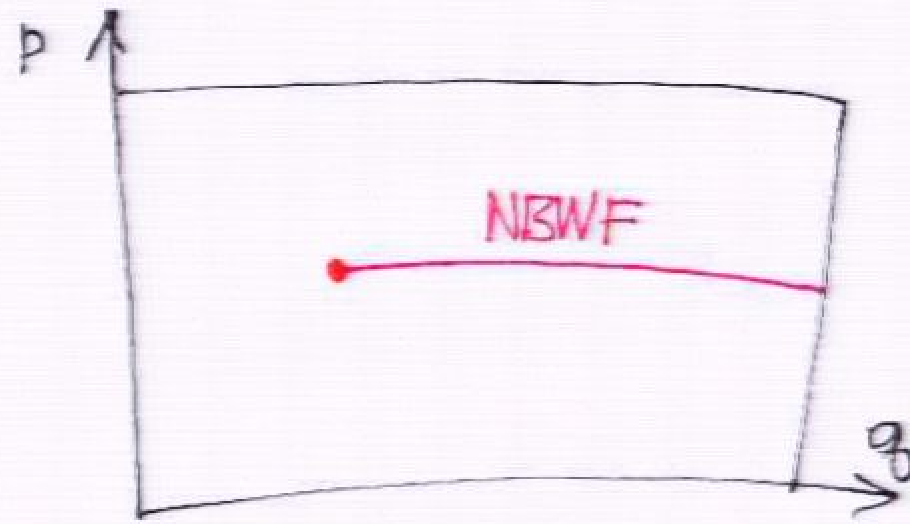

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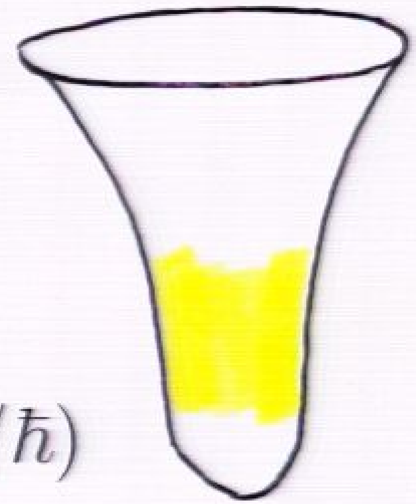

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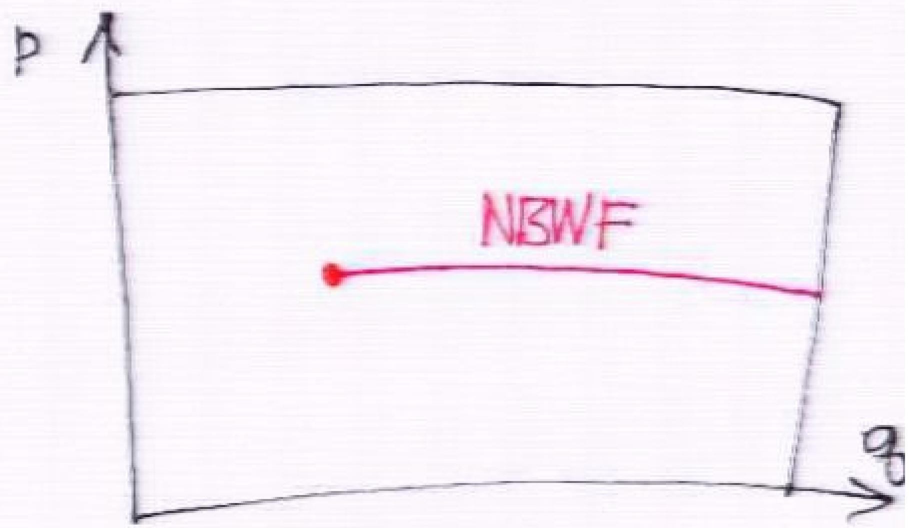

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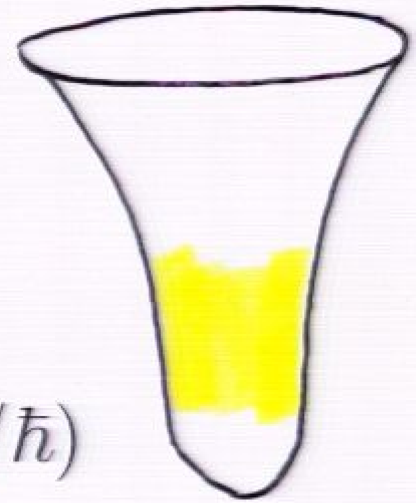

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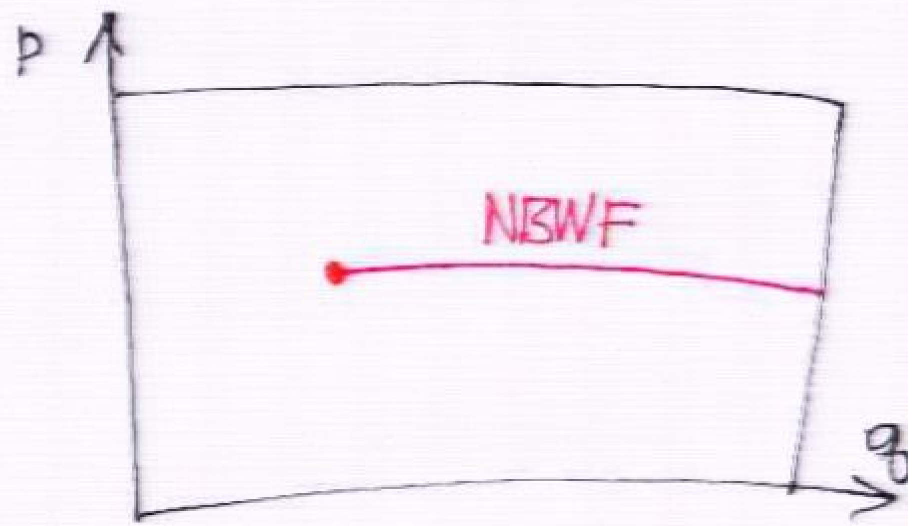

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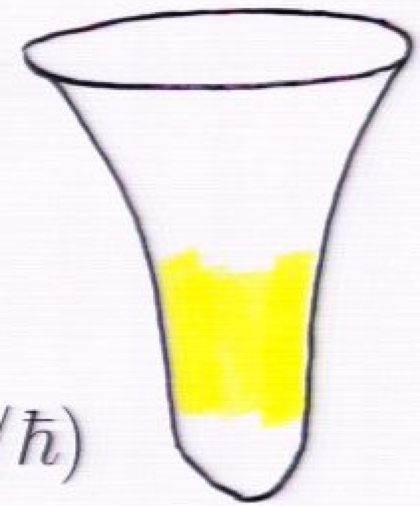

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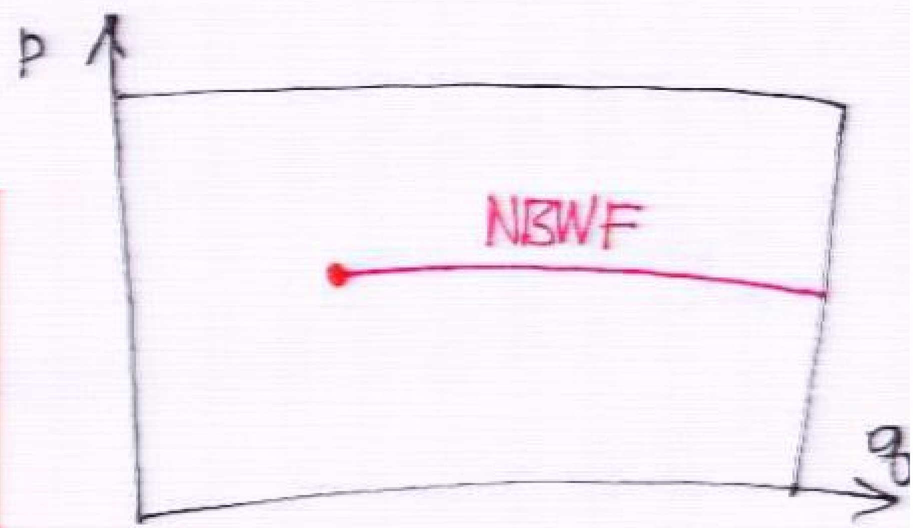

- No big empty universes.
- All histories exhibit scalar field driven inflation.

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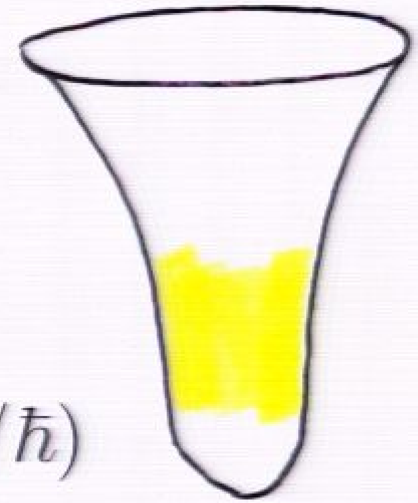

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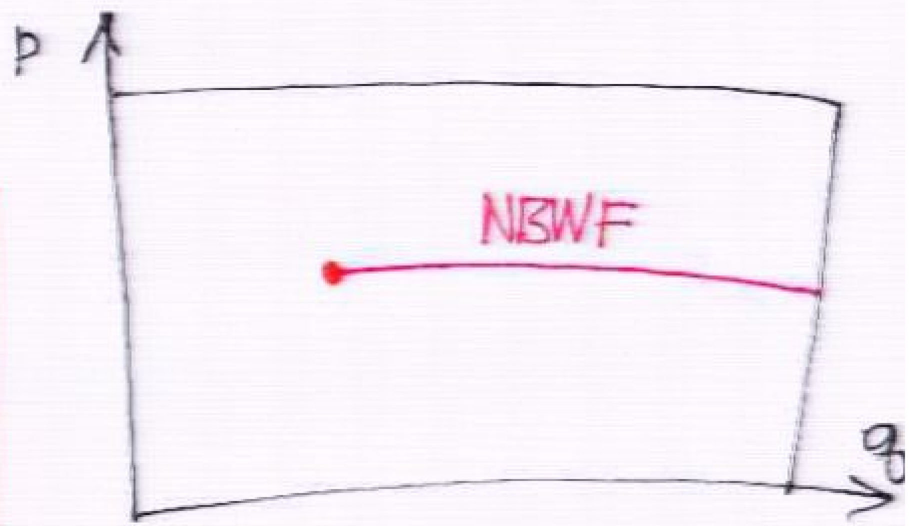

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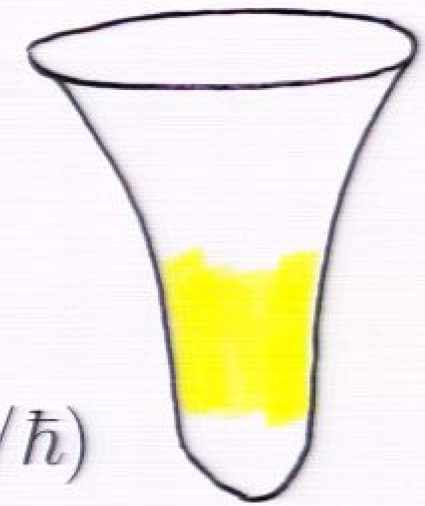

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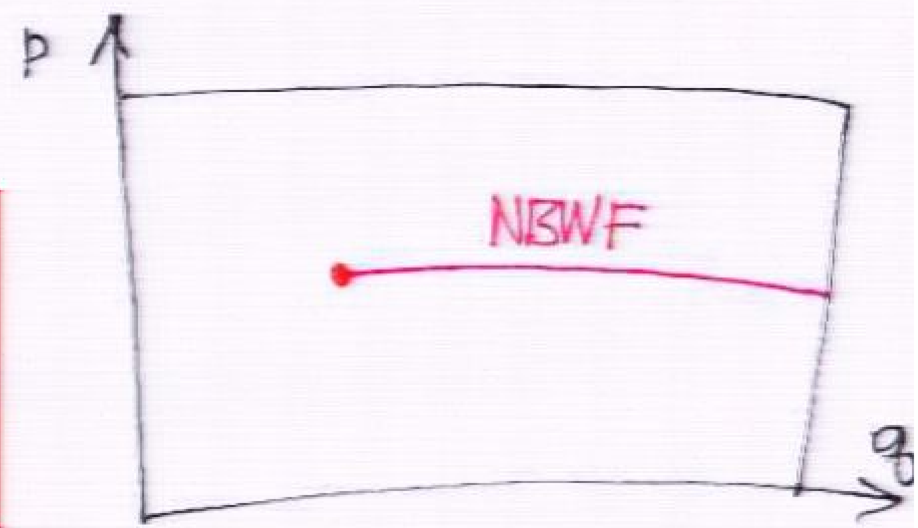

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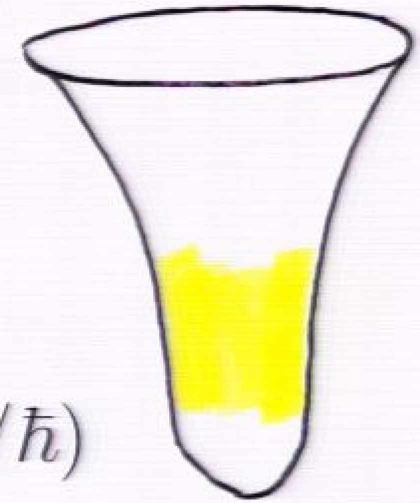

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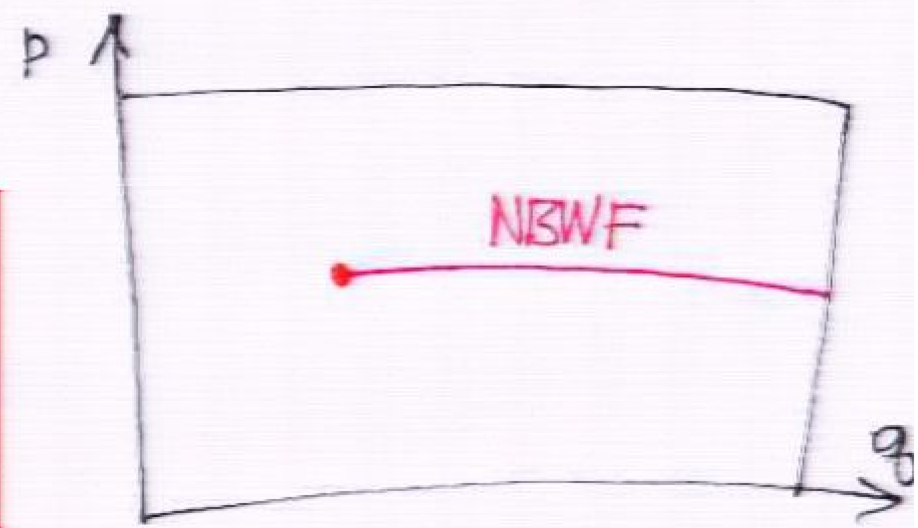

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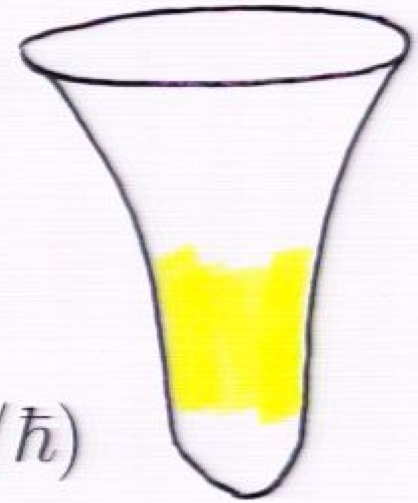

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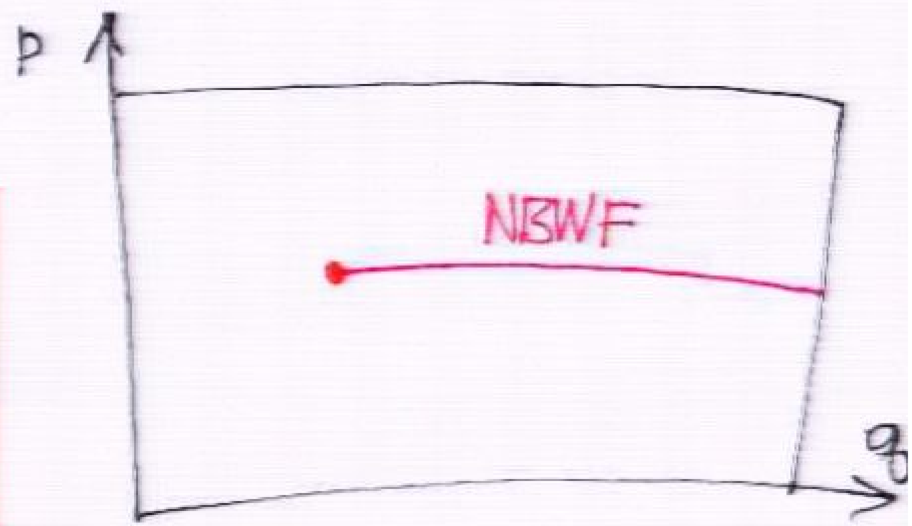

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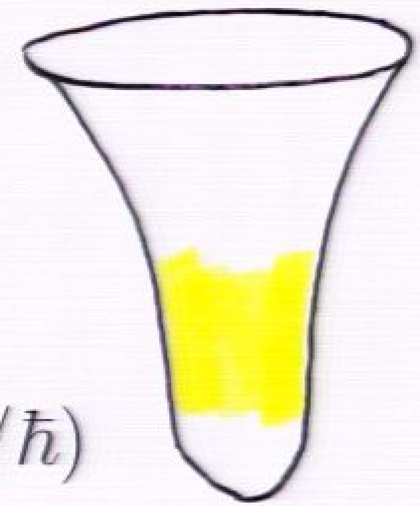

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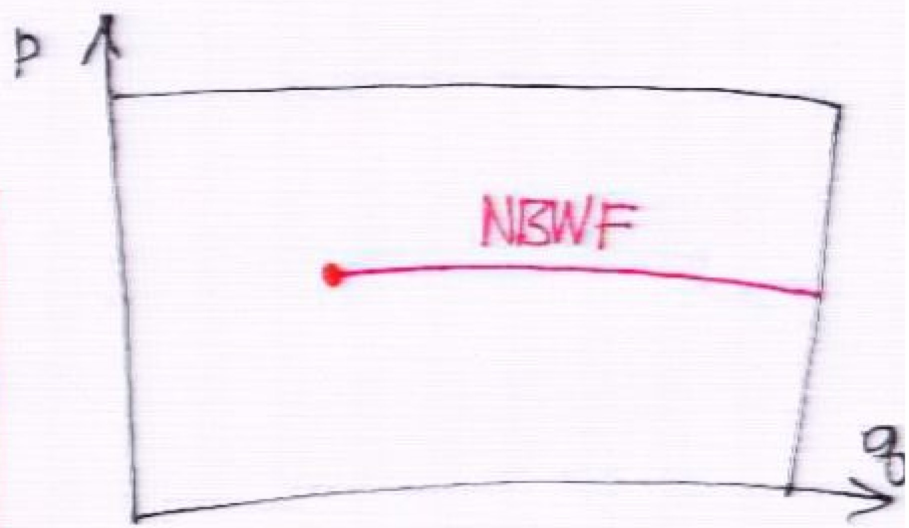

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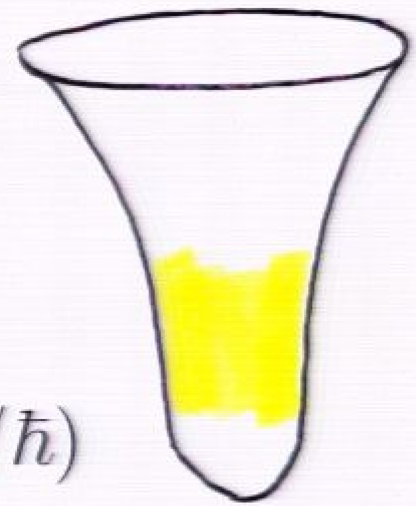

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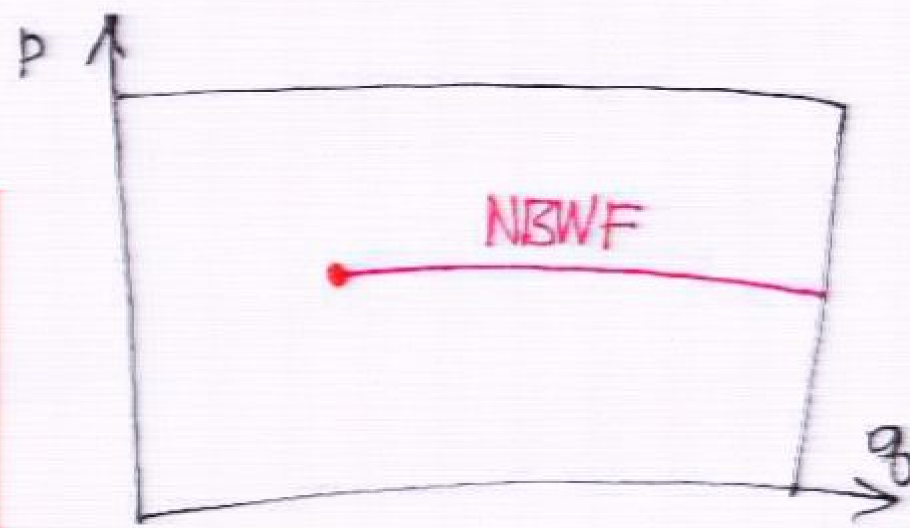

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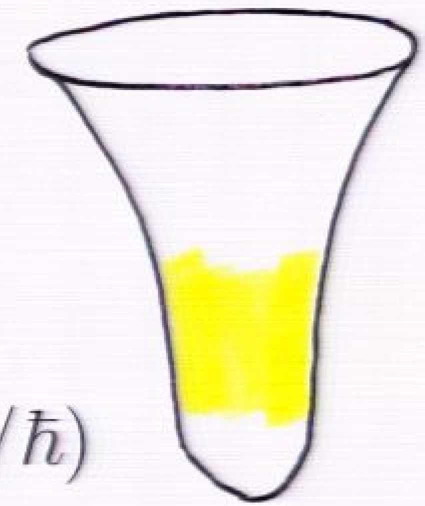

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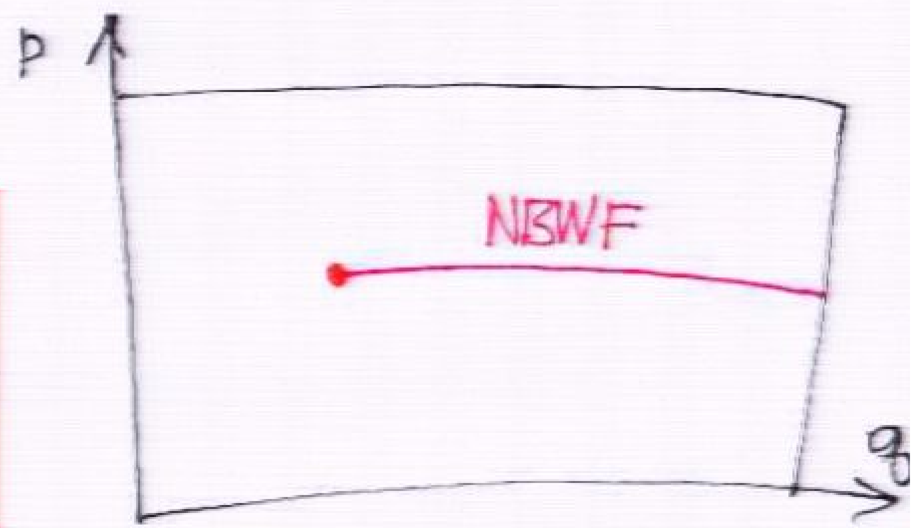

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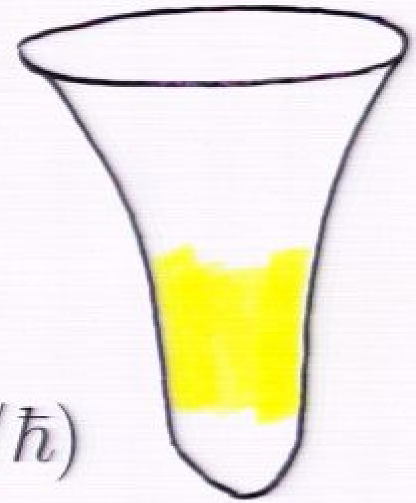

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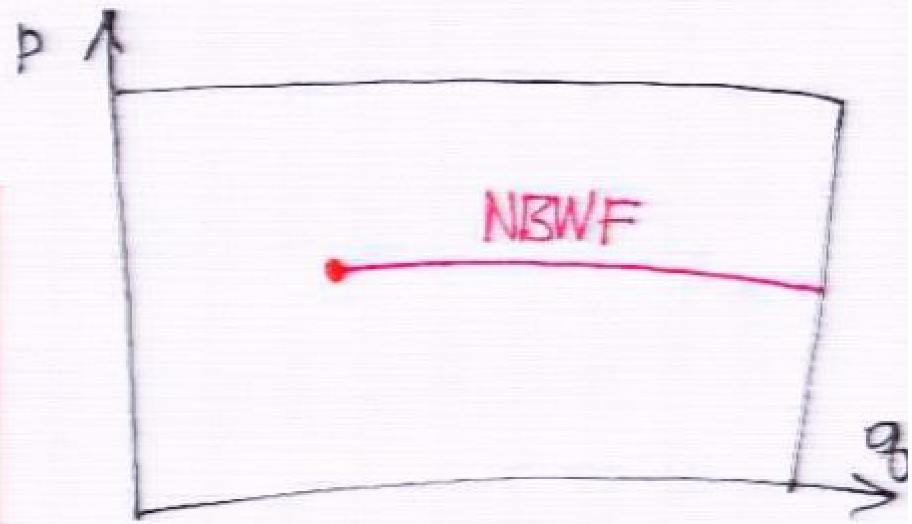

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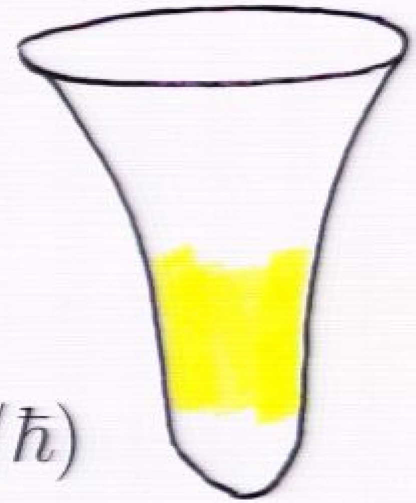

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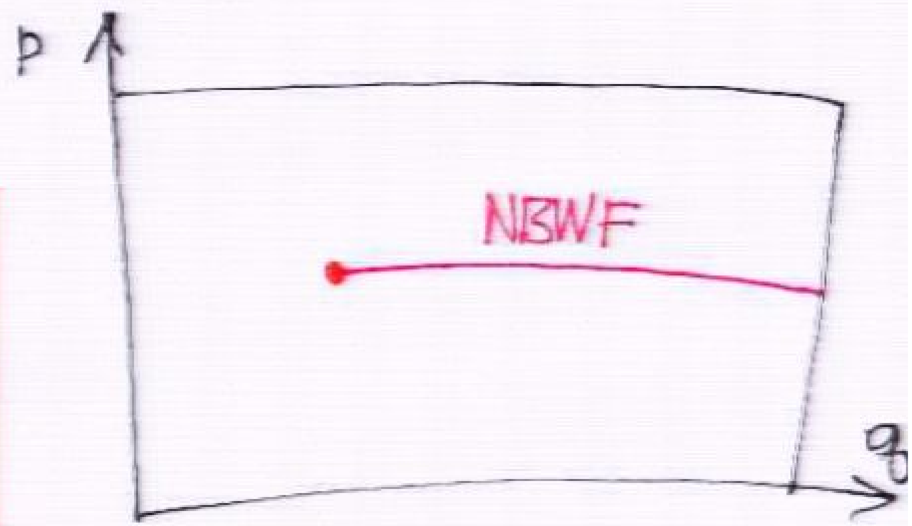

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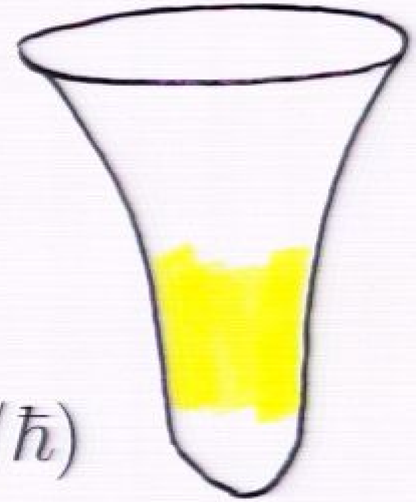

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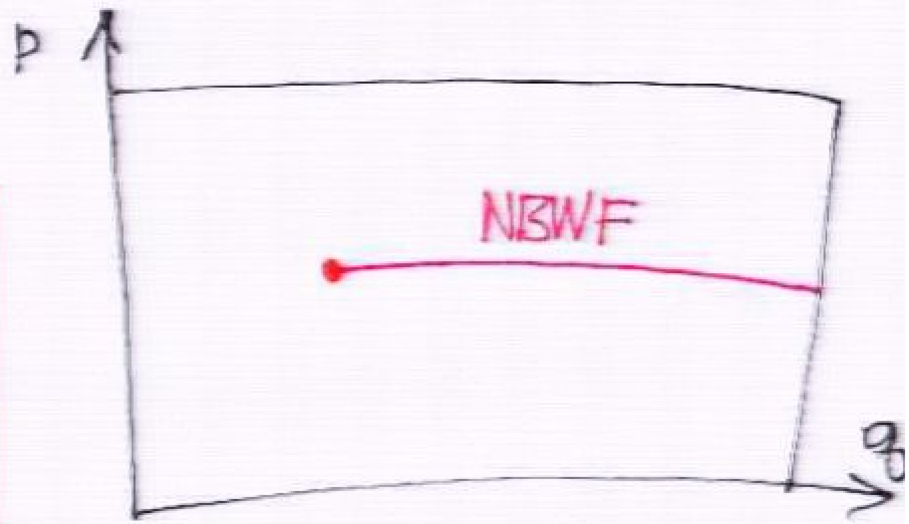

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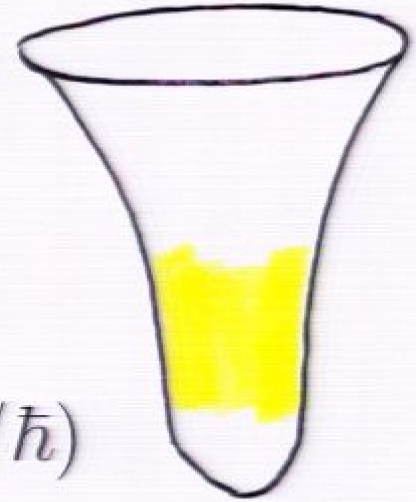

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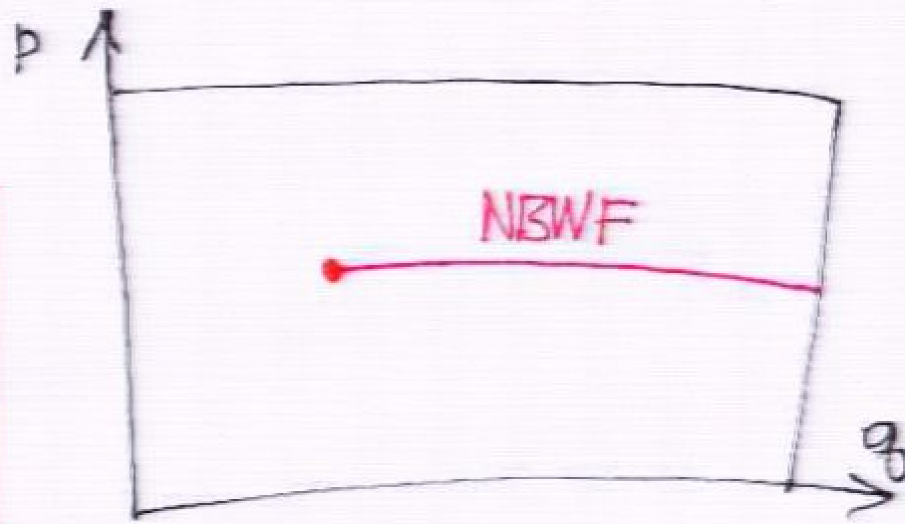

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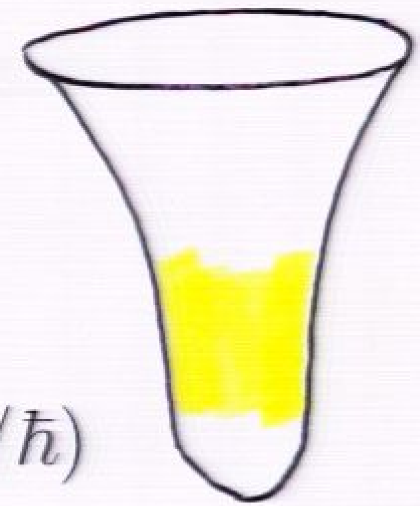

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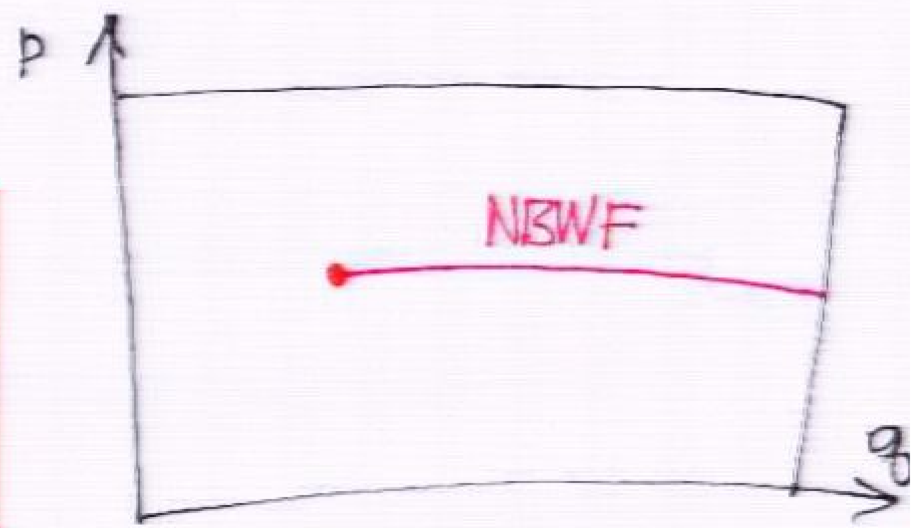

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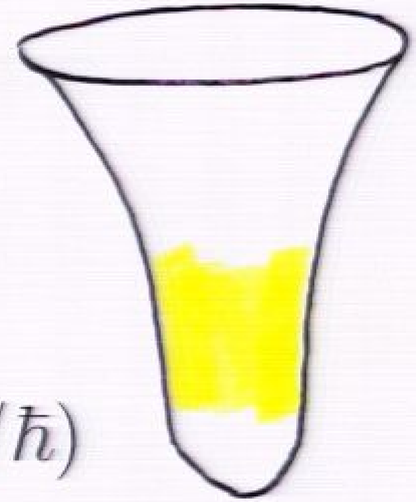

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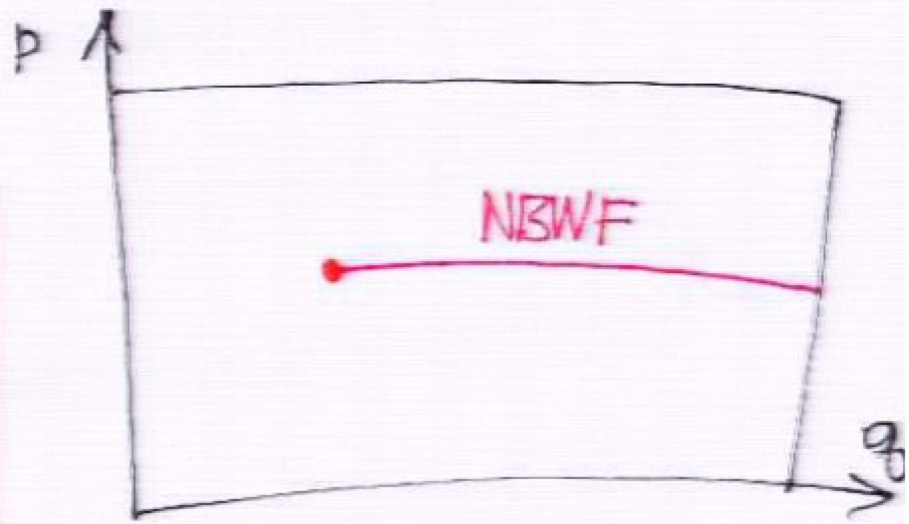

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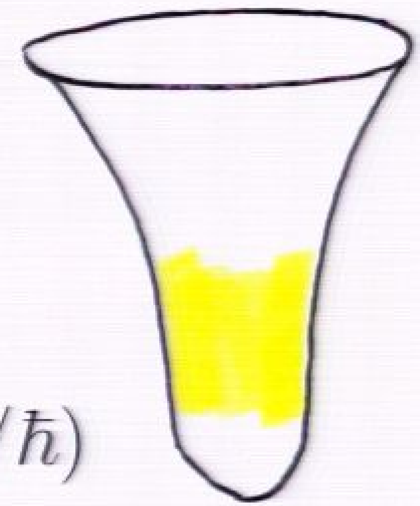

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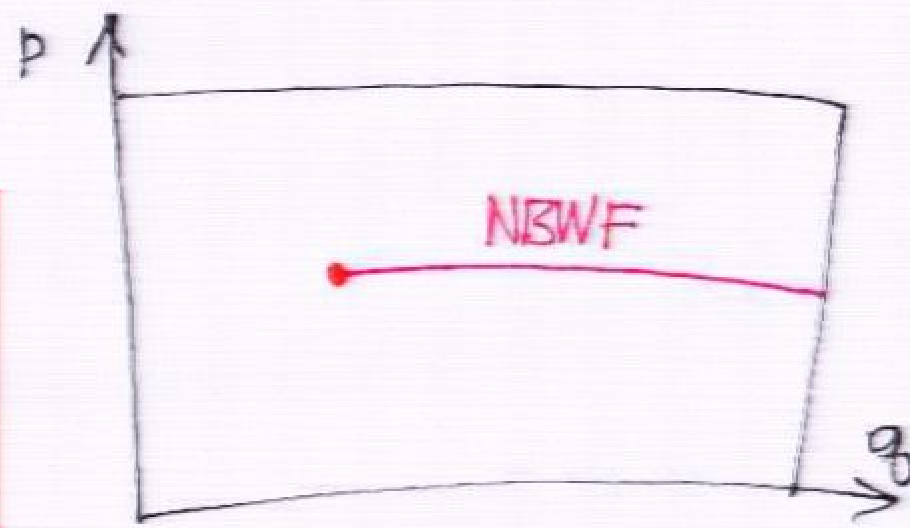

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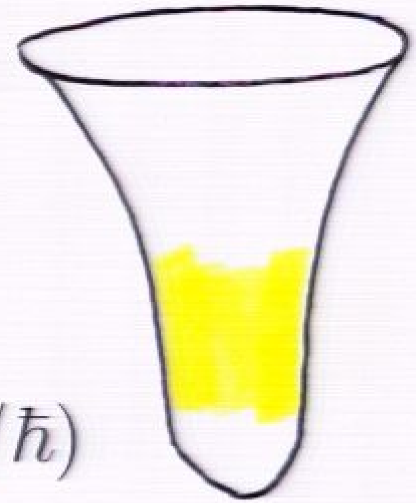

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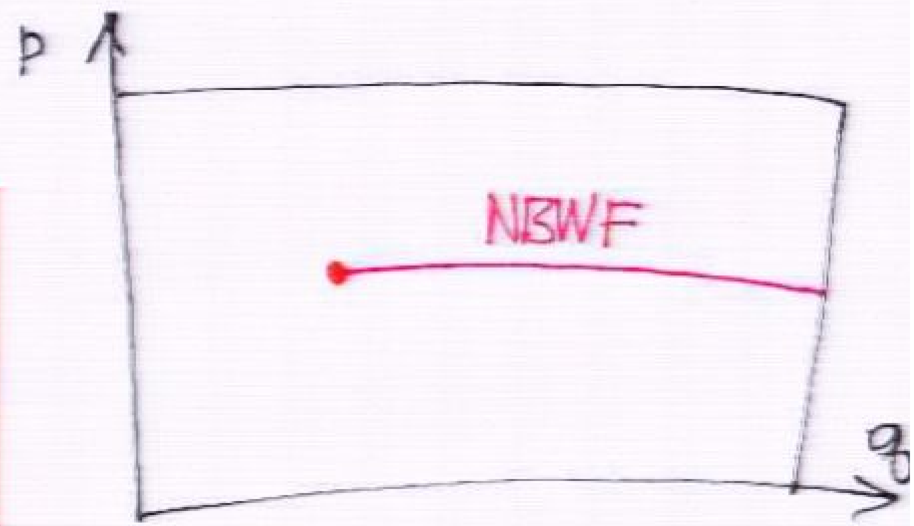

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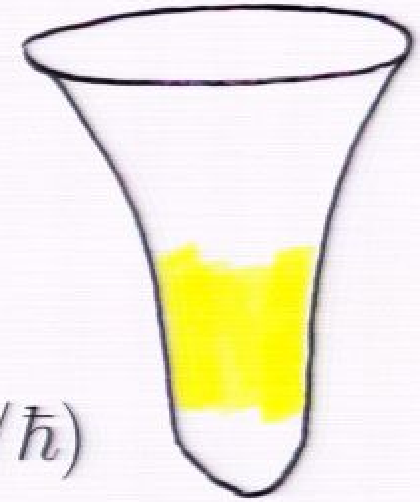

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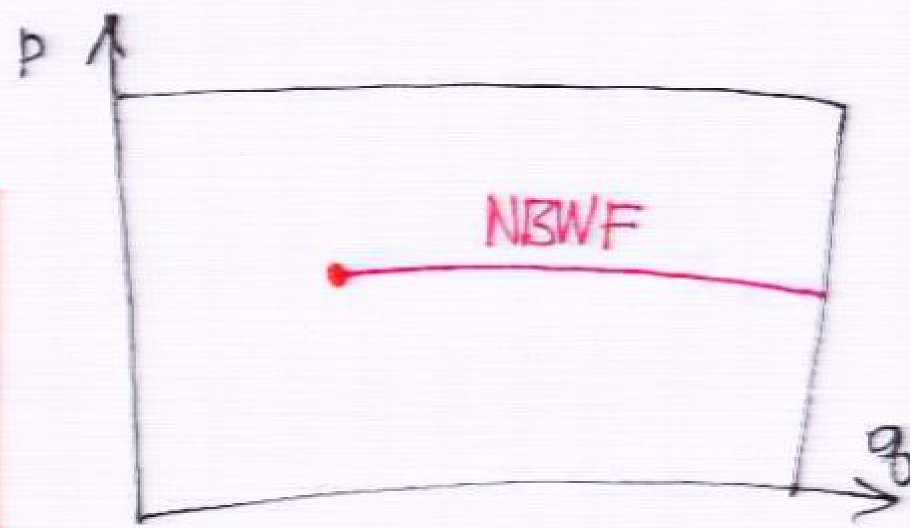

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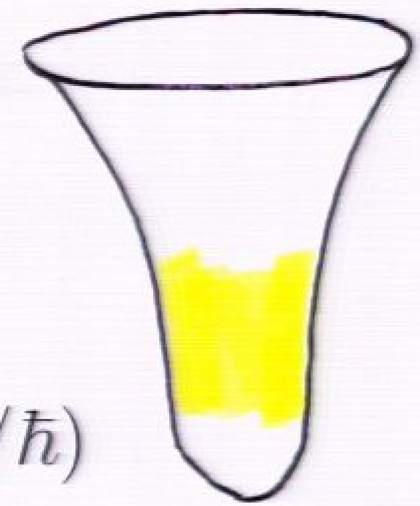

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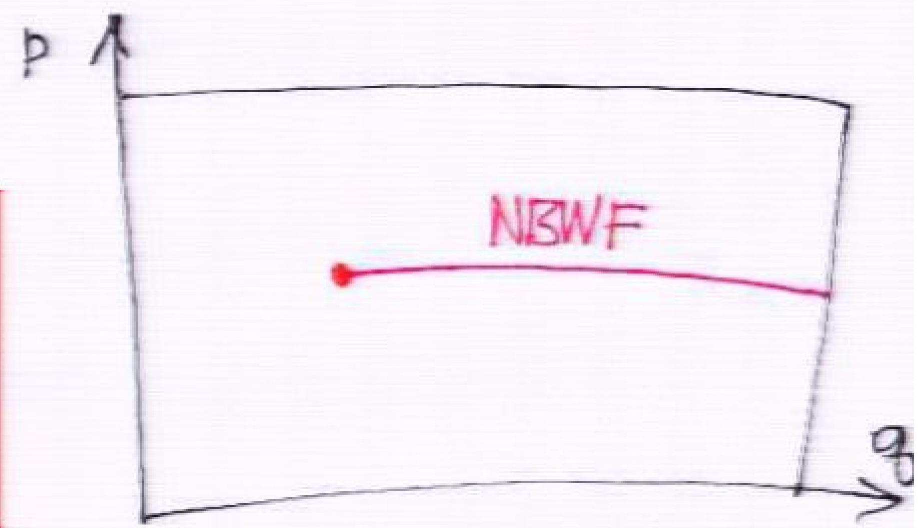

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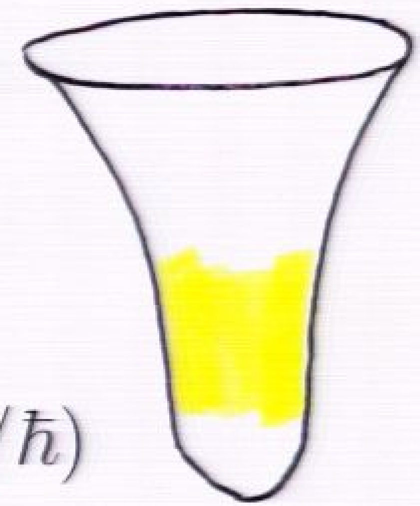

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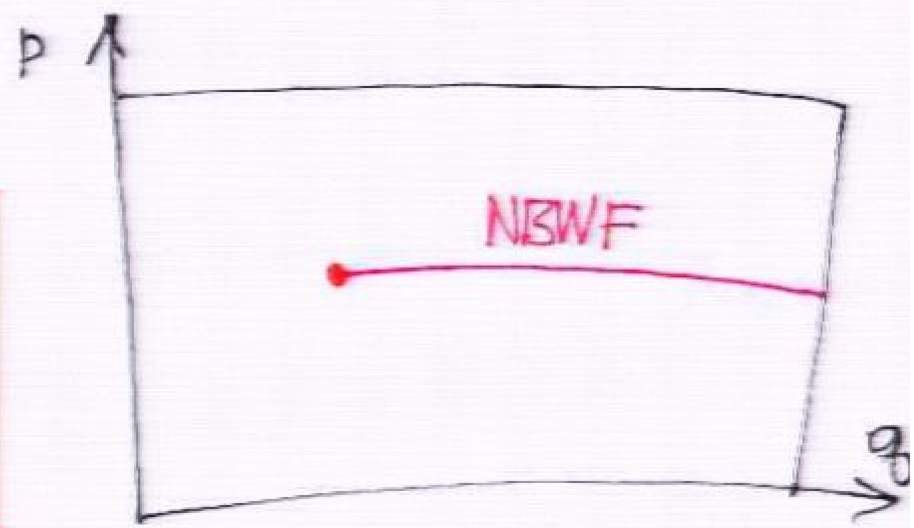

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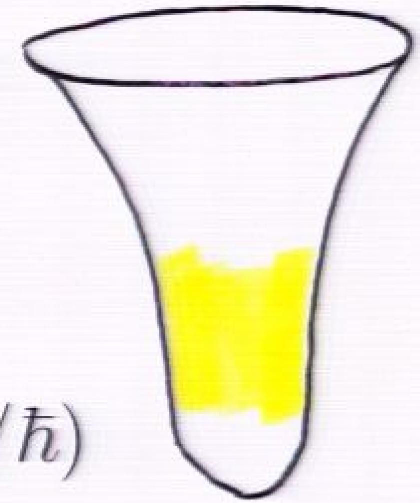

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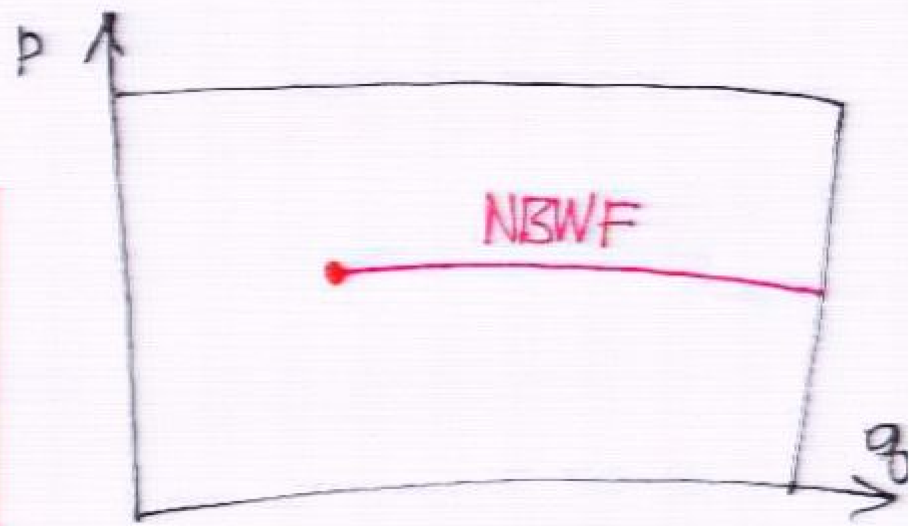

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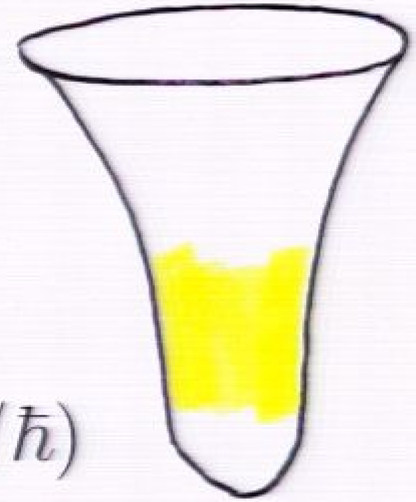

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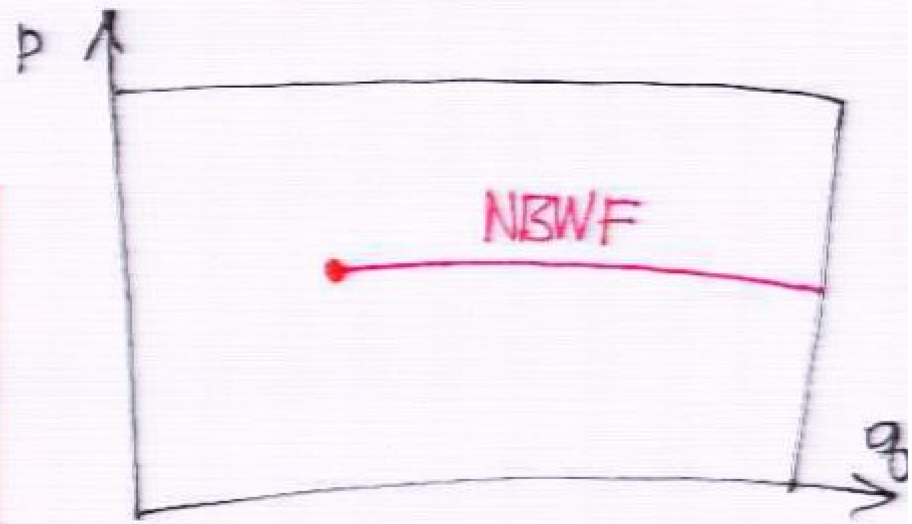

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Bottom Up Probability for Efolds

Minisuperspace Models

Geometry: Homogeneous, isotropic, closed.

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Matter: cosmological constant Λ plus homogeneous scalar field moving in a quadratic potential.

$$V(\Phi) = \frac{1}{2}m^2\Phi^2$$

Theory: Low-energy effective gravity.

$$I_C[g] = -\frac{m_p^2}{16\pi}\int_M d^4x(g)^{1/2}(R-2\Lambda) + \text{(surface terms)}$$

- One parameter (φ_0) family of classical histories with BU NBWF probabilities $p(\varphi_0)$.
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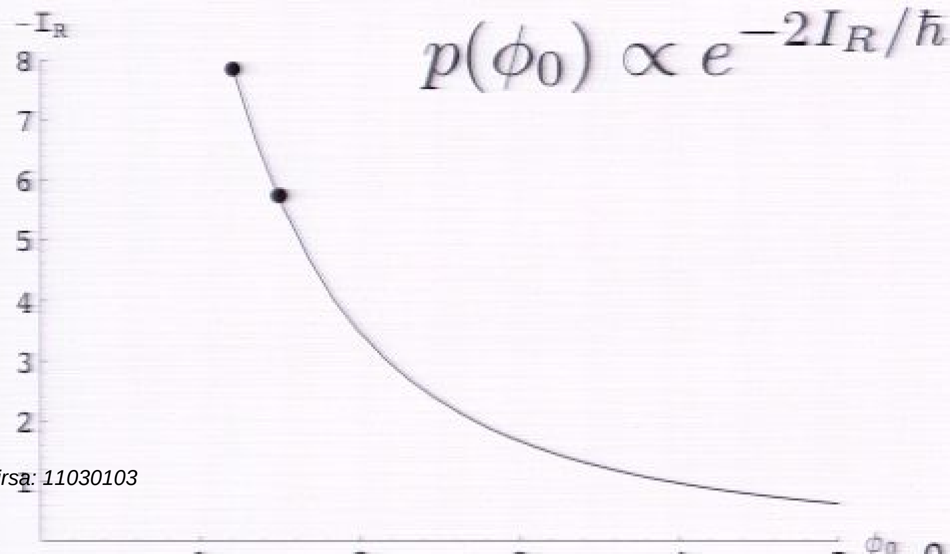
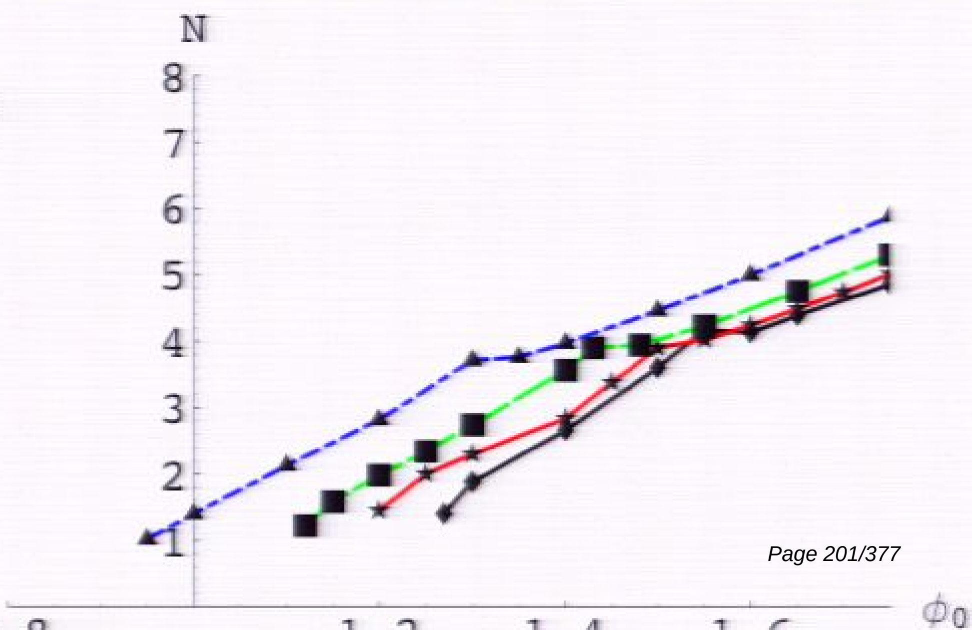
$$p(\phi_0) \propto e^{-2I_R/\hbar}$$





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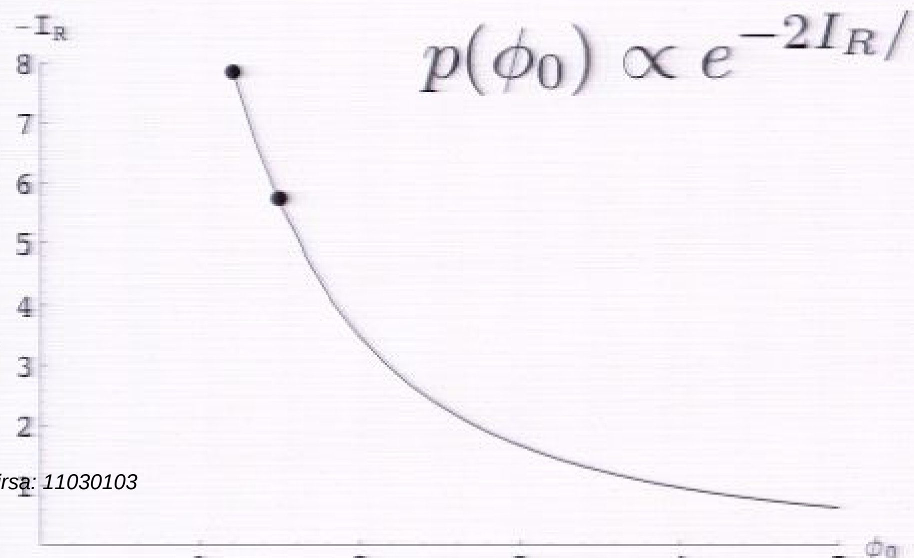

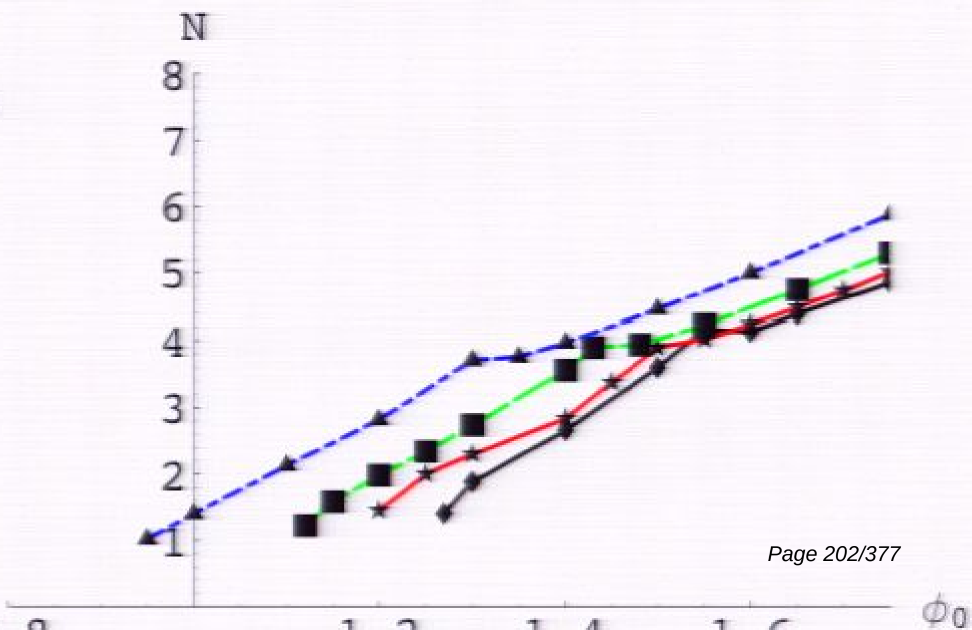

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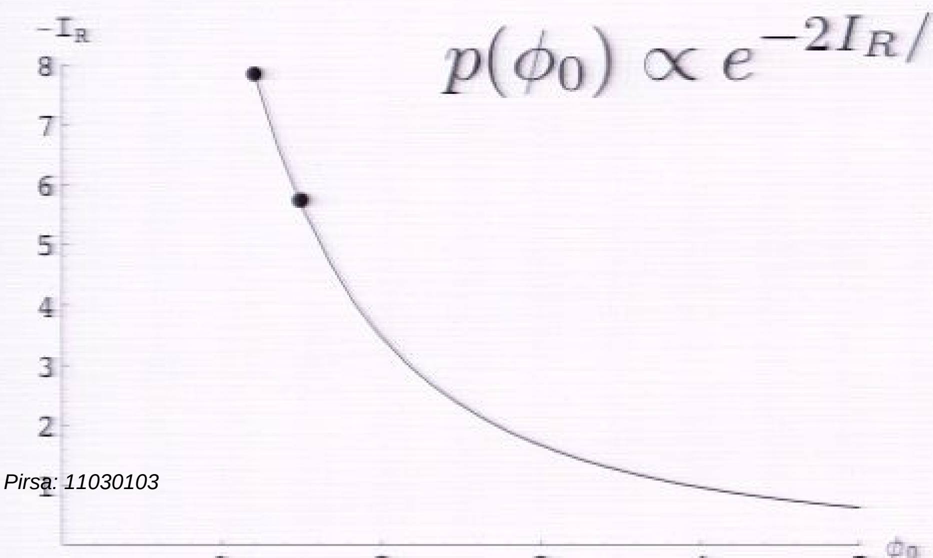

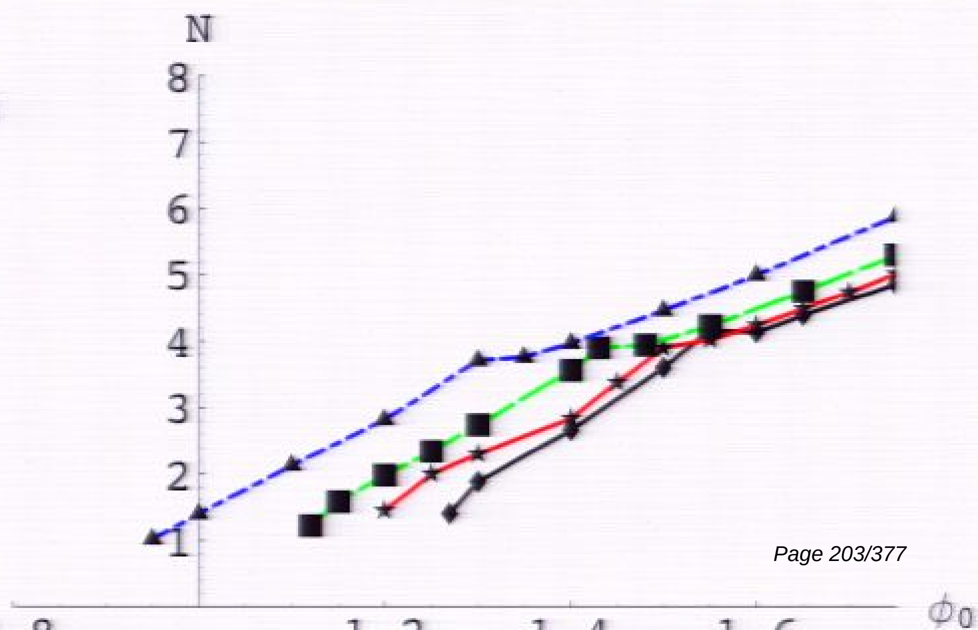

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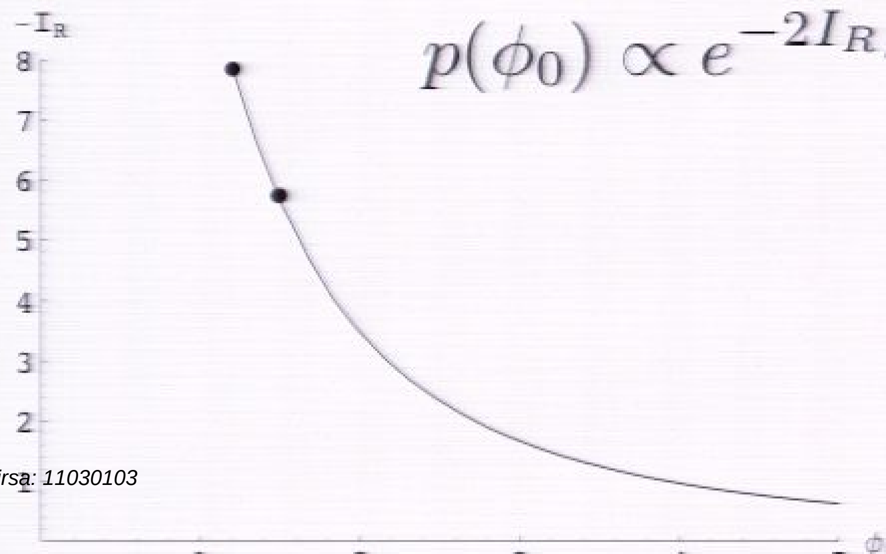

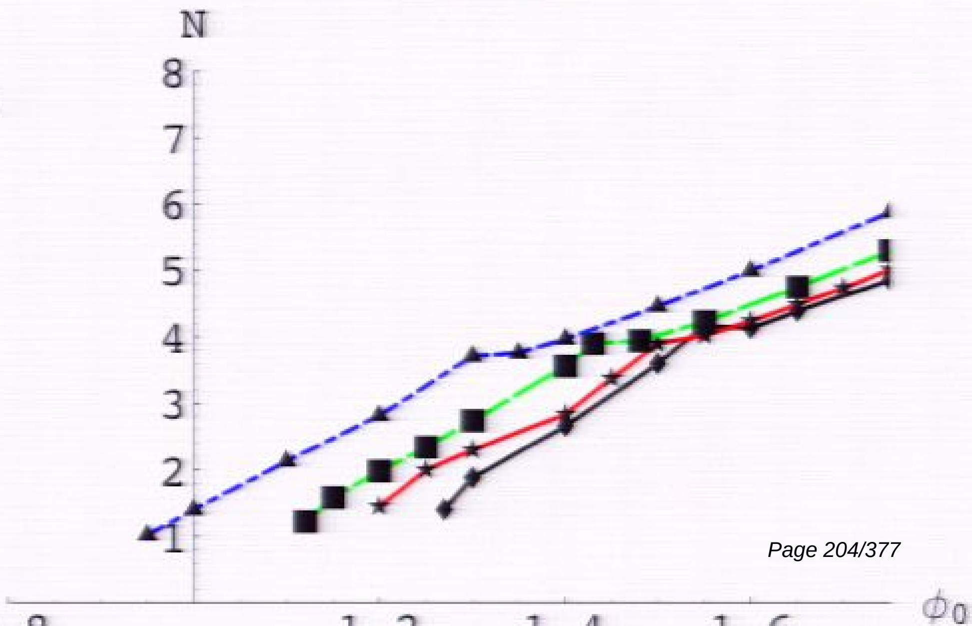

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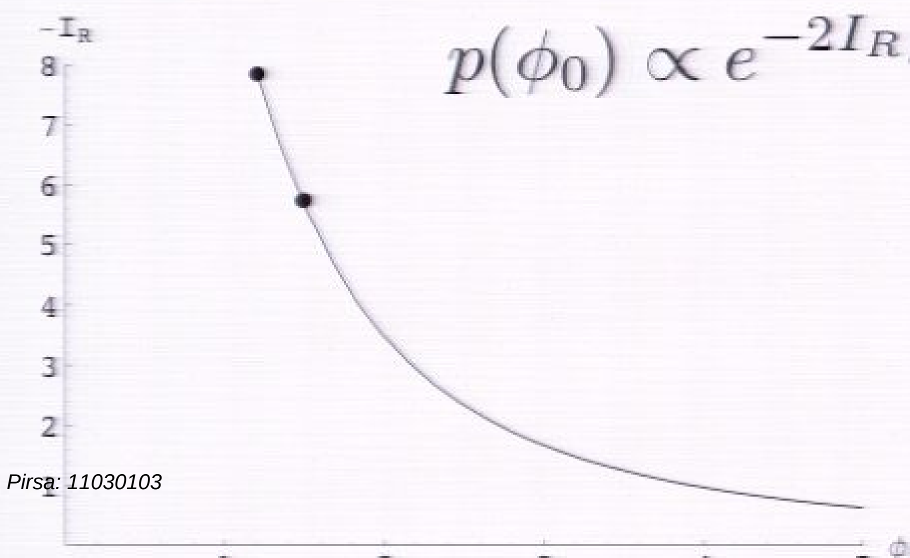

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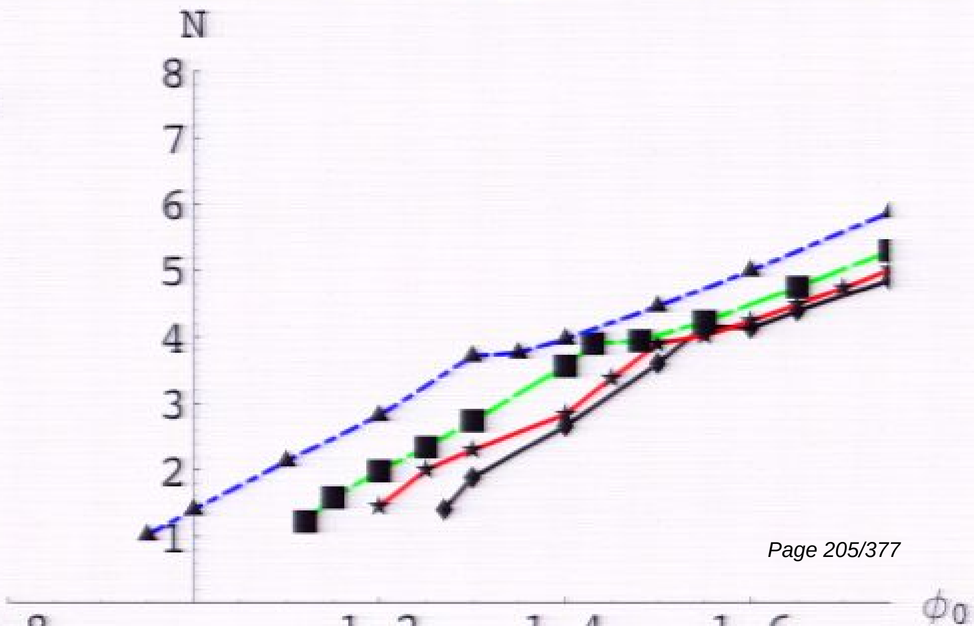

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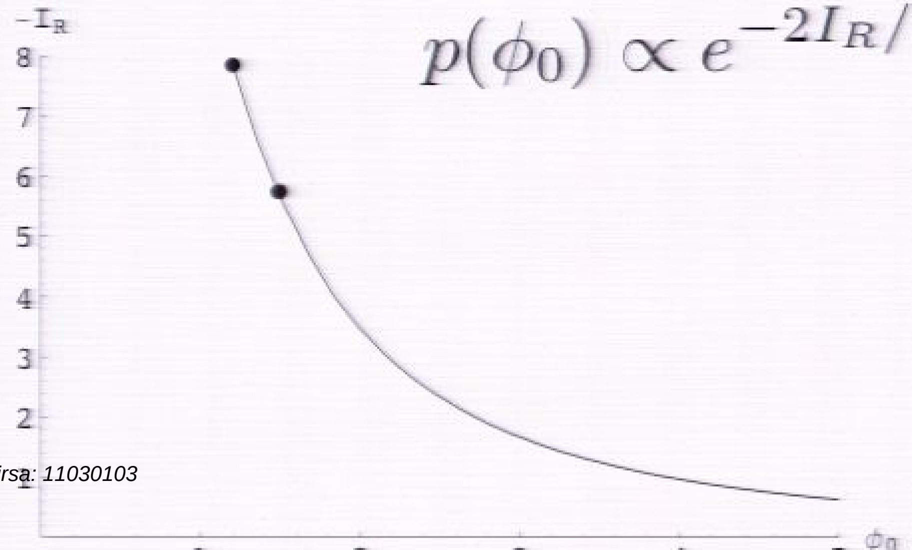

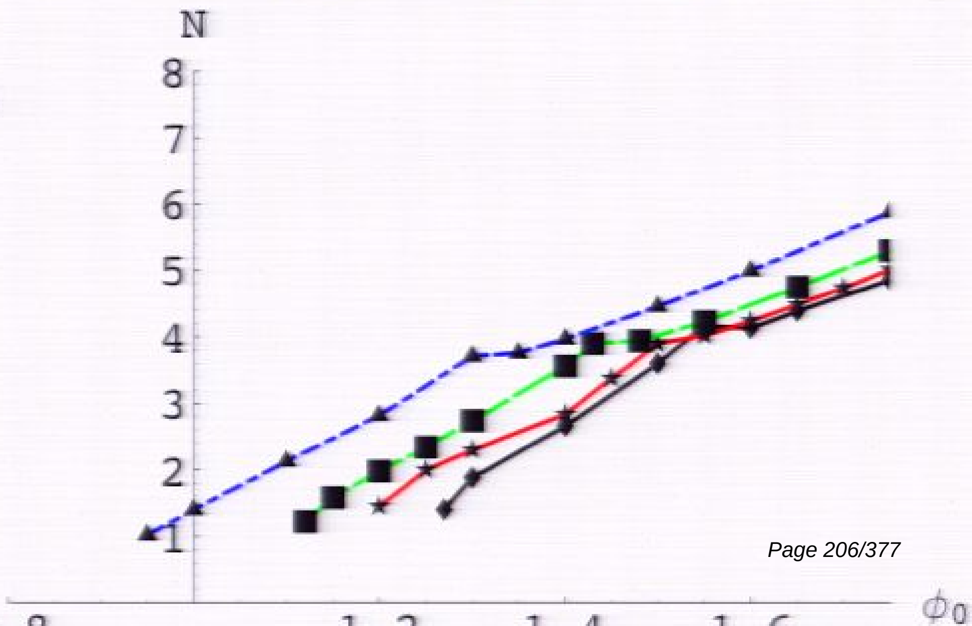

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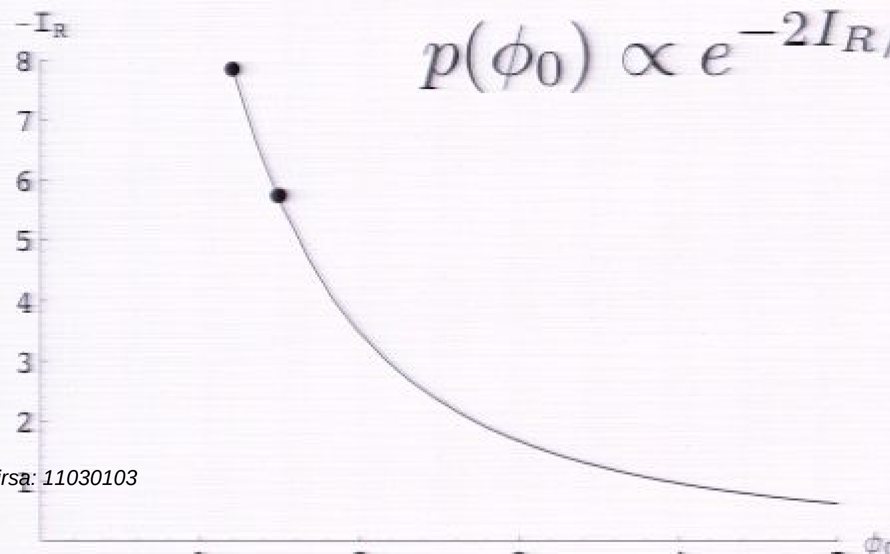

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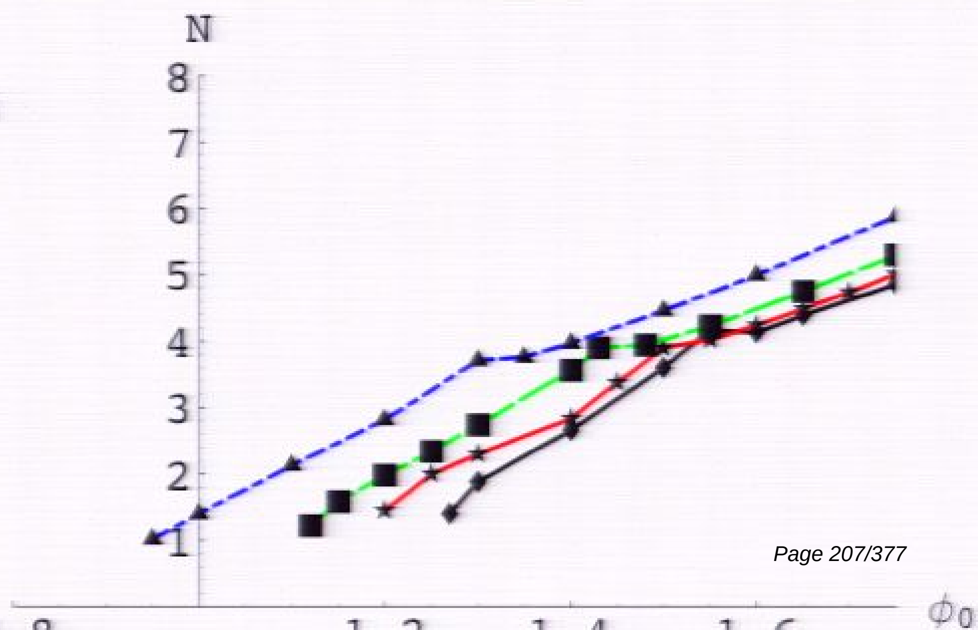

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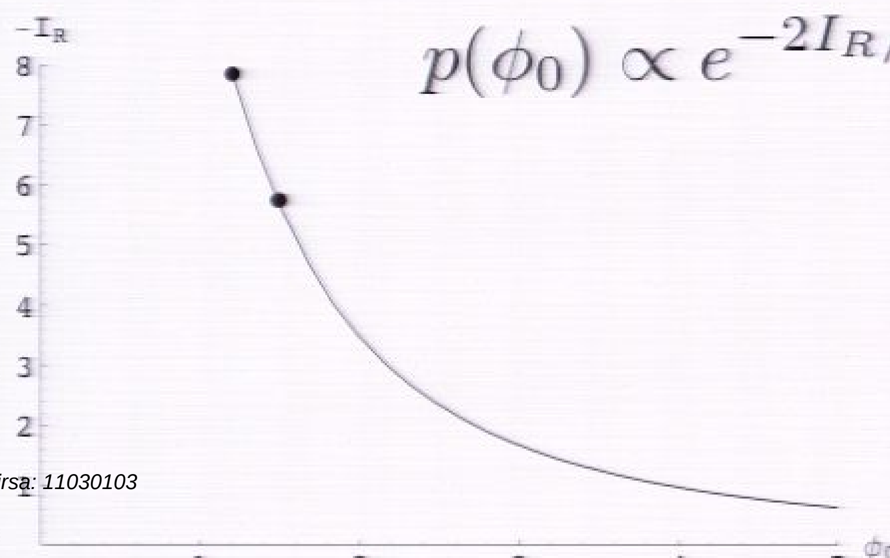
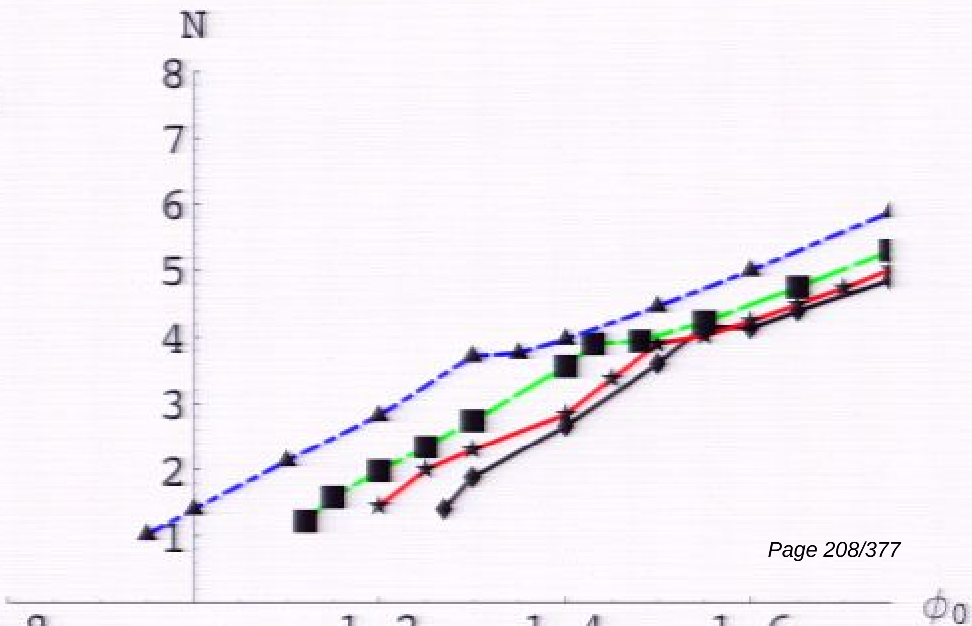
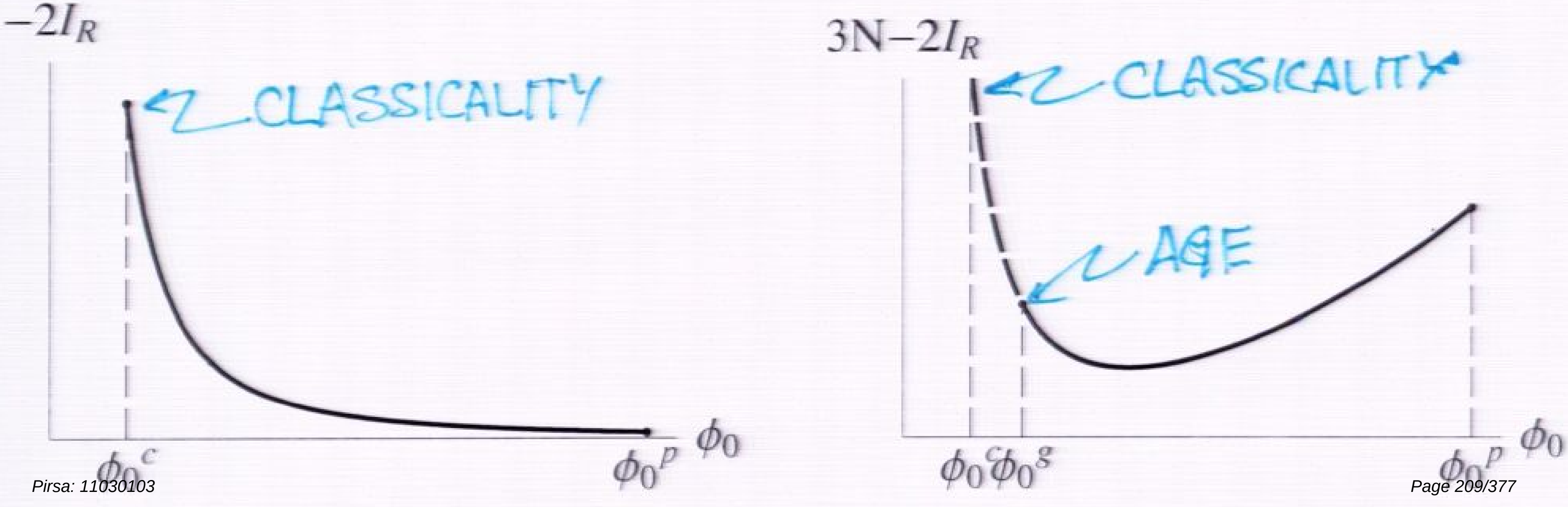




TD Weighting favors Inflation

By itself, the NBWF + classicality favor low inflation, but we are are more likely to live in a universe that has undergone more inflation, because there are more places for us to be.

$$p(\phi_0|H_0,\rho) \propto \exp(3N)p(\phi_0) \propto \exp(3N - 2I_R)$$



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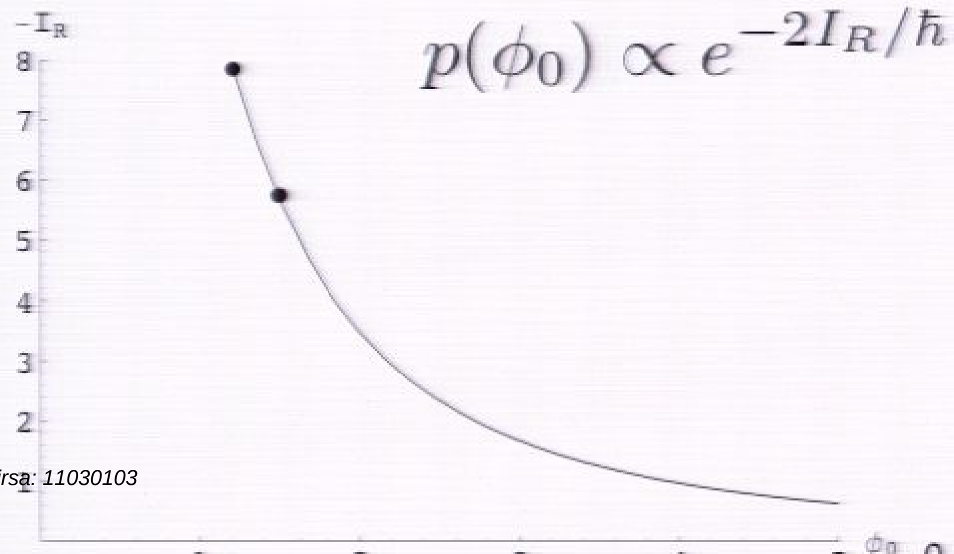

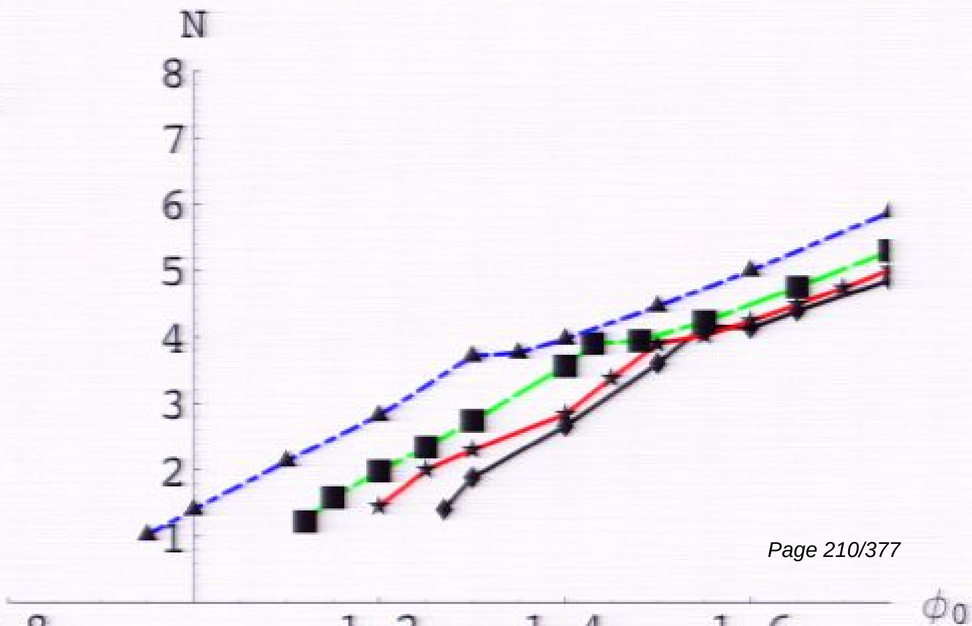

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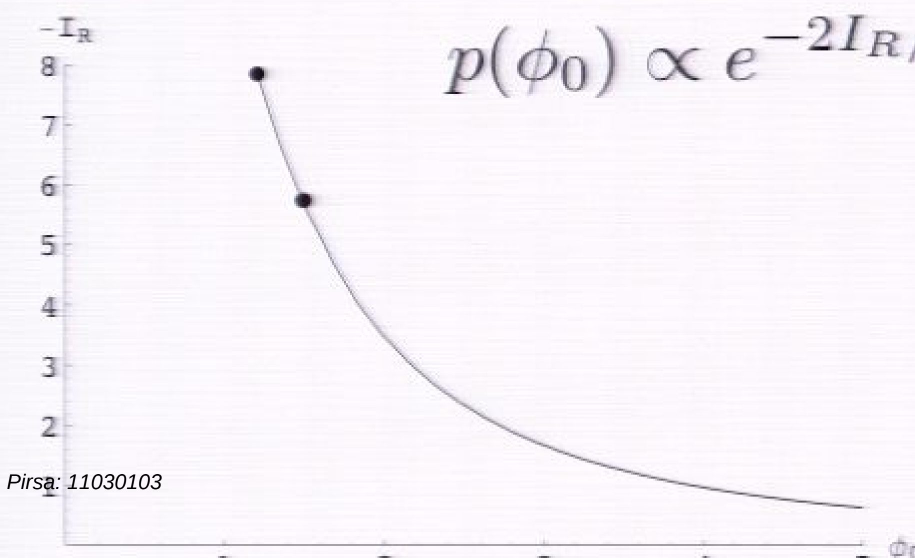

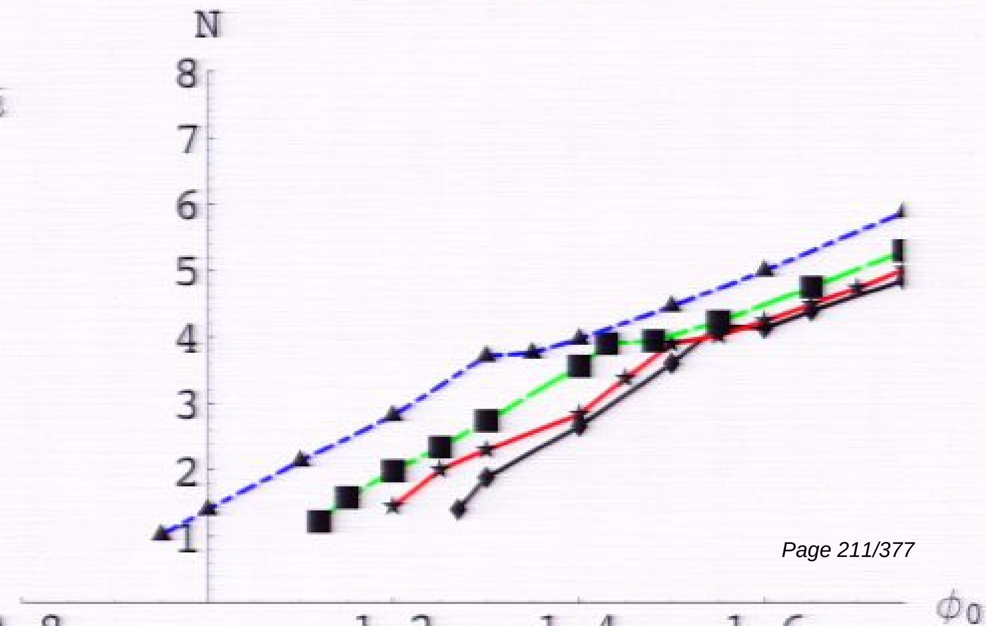

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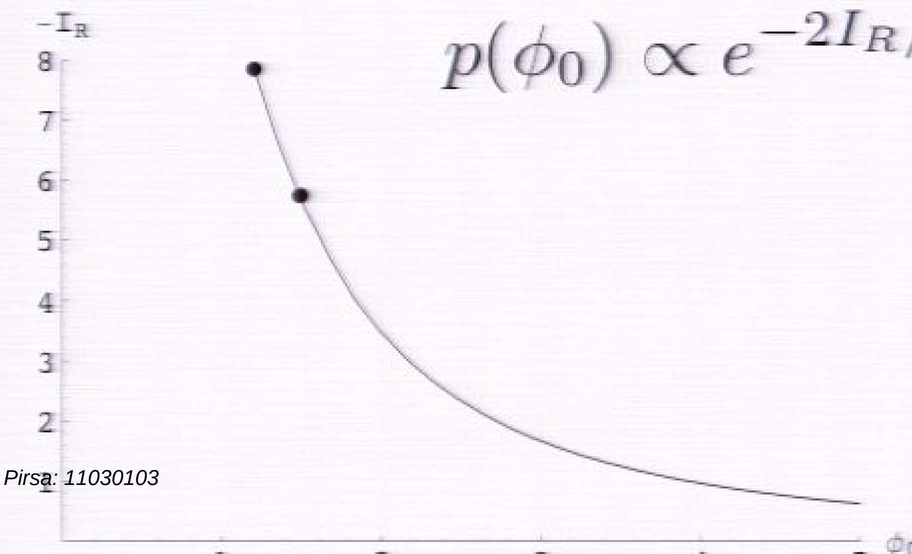

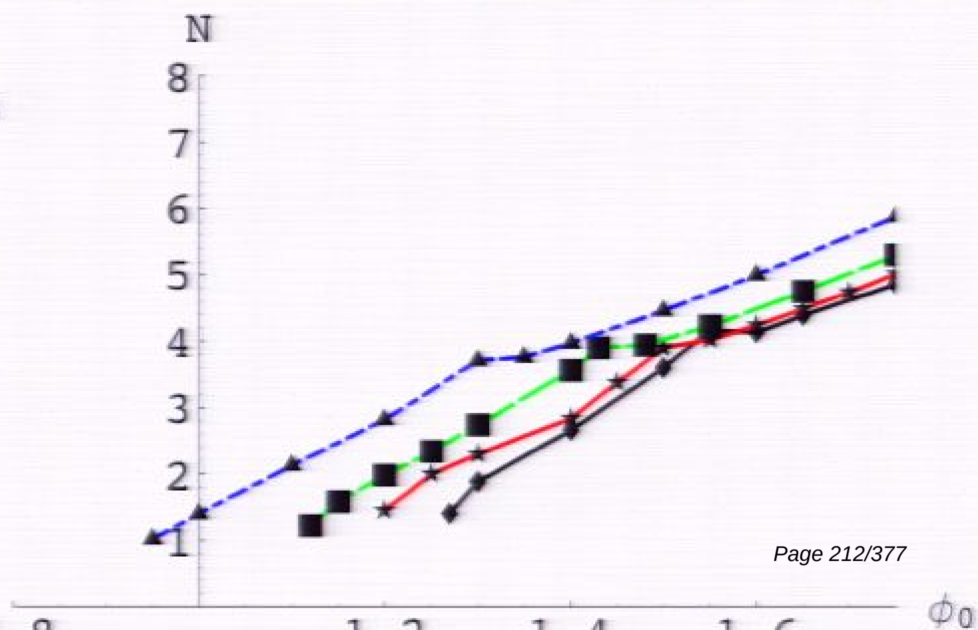

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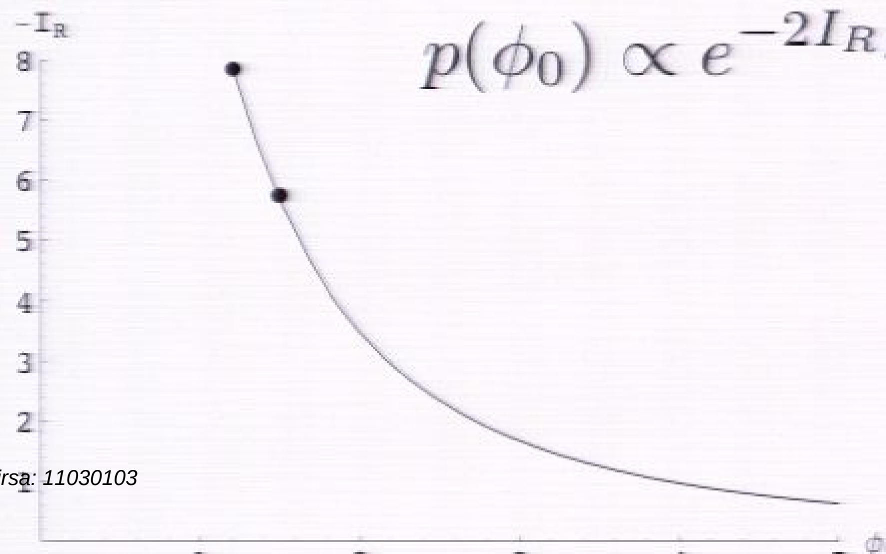

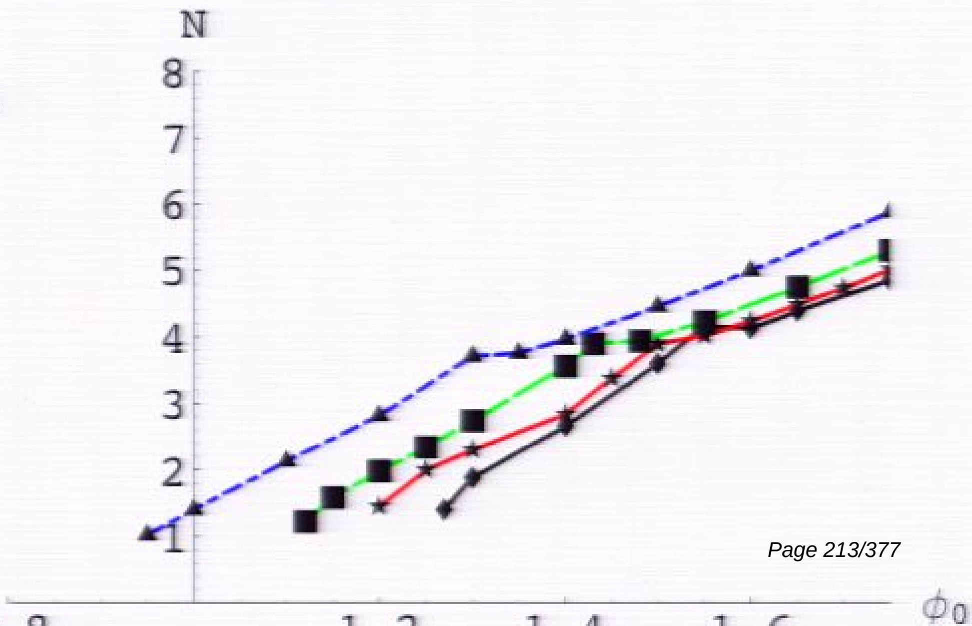

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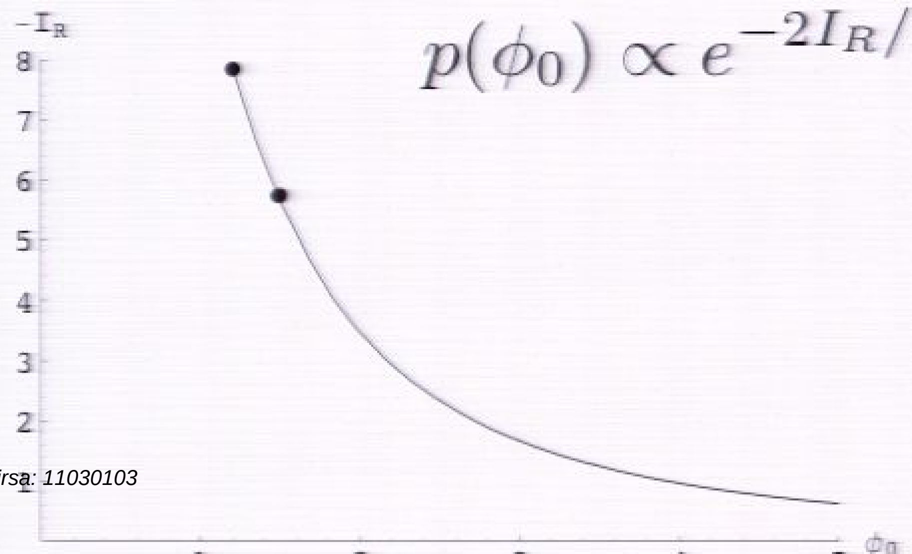

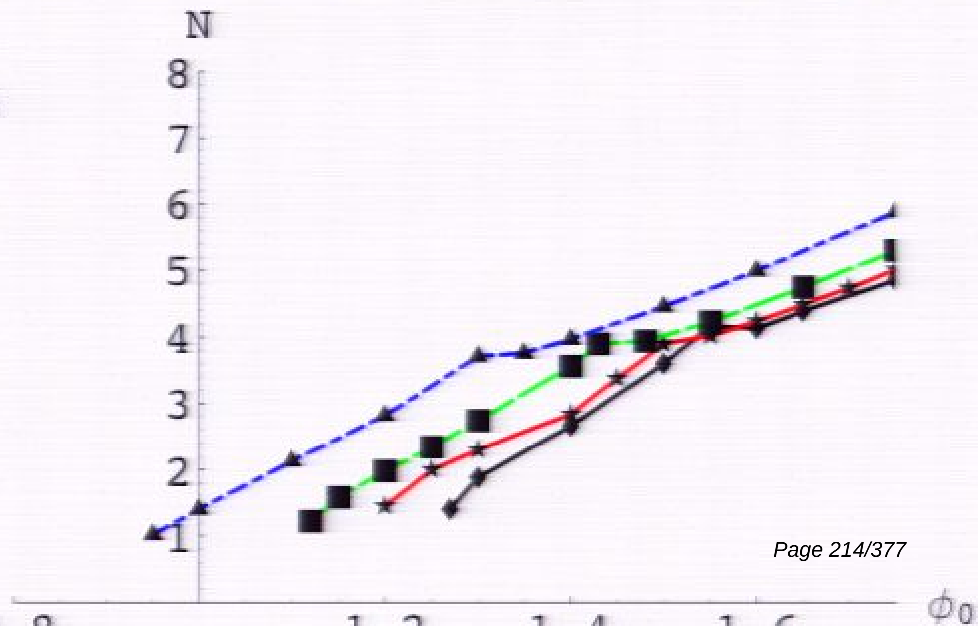

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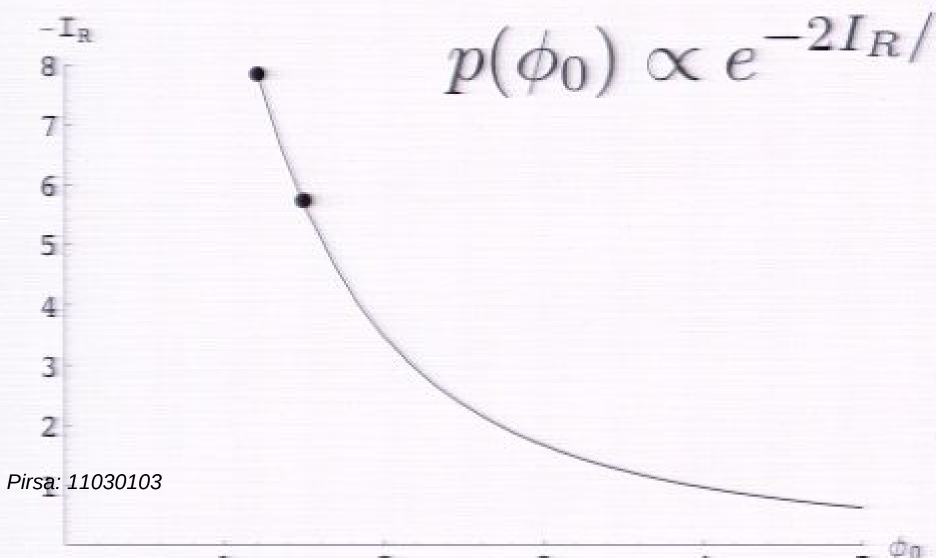

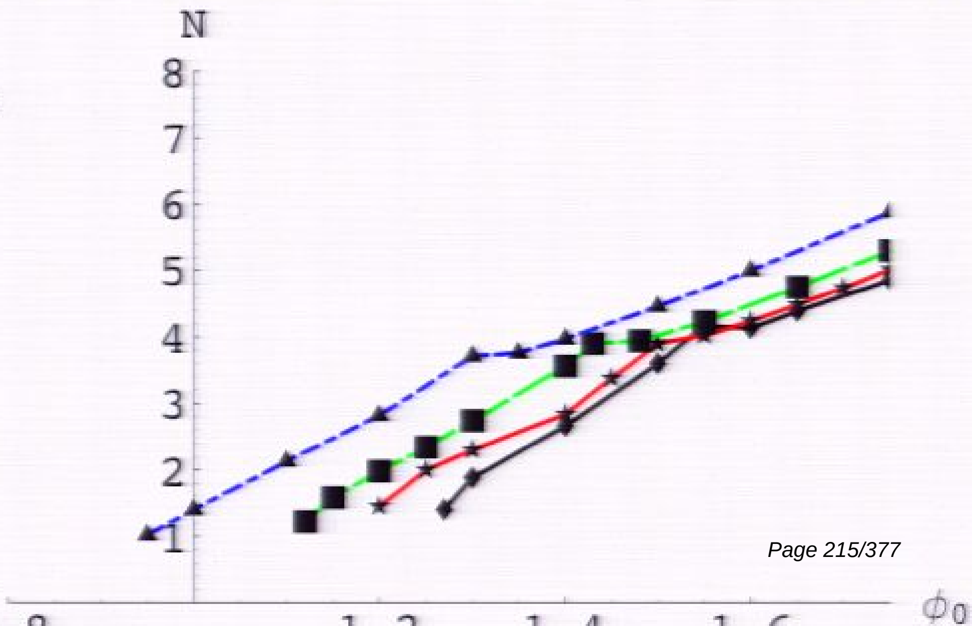

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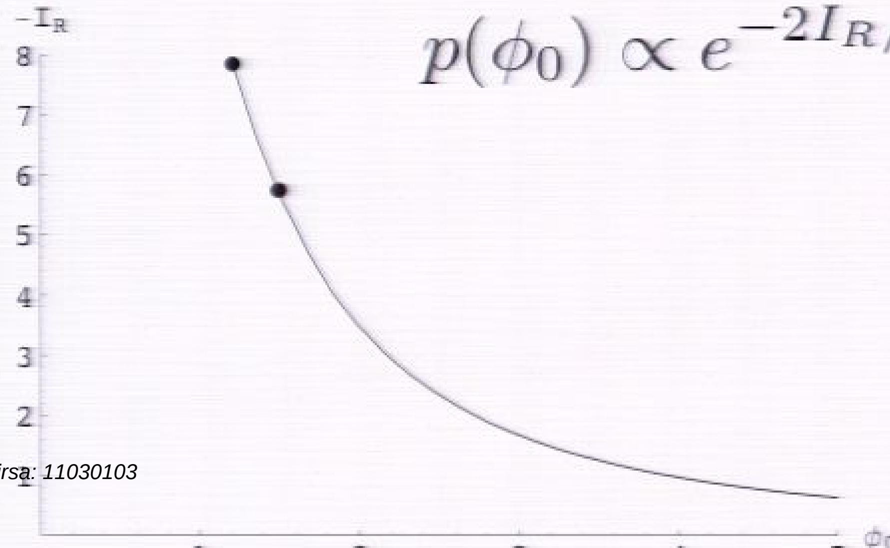

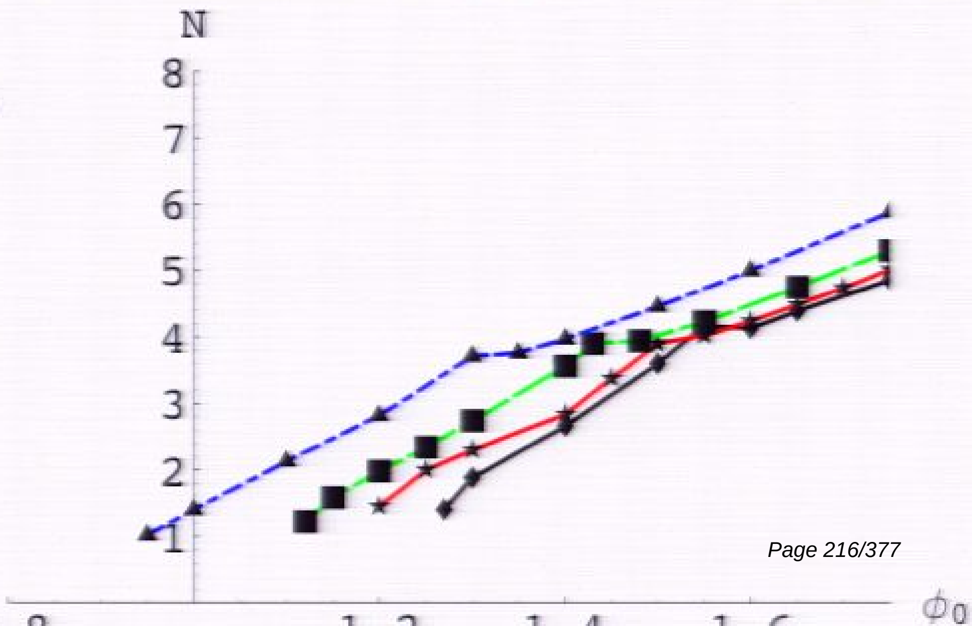

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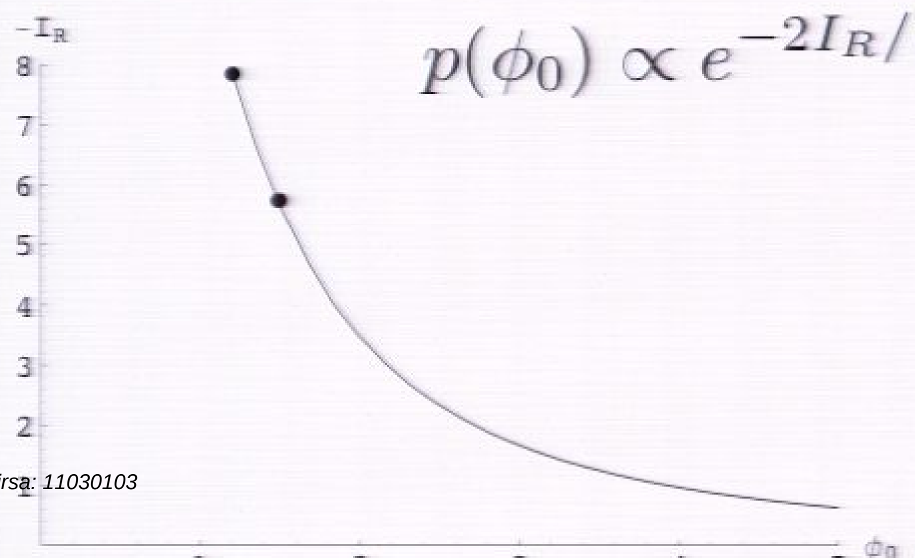

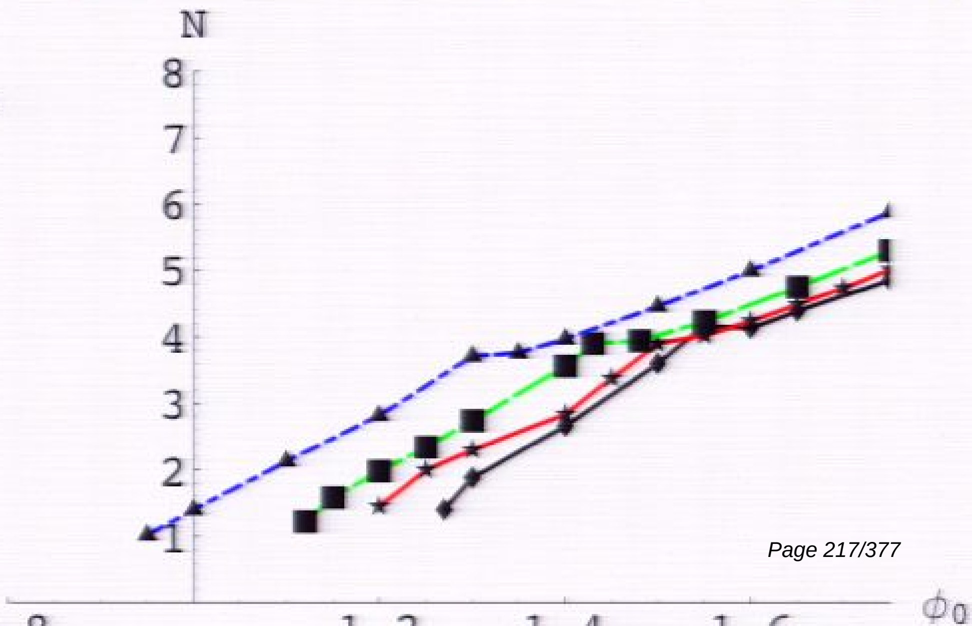

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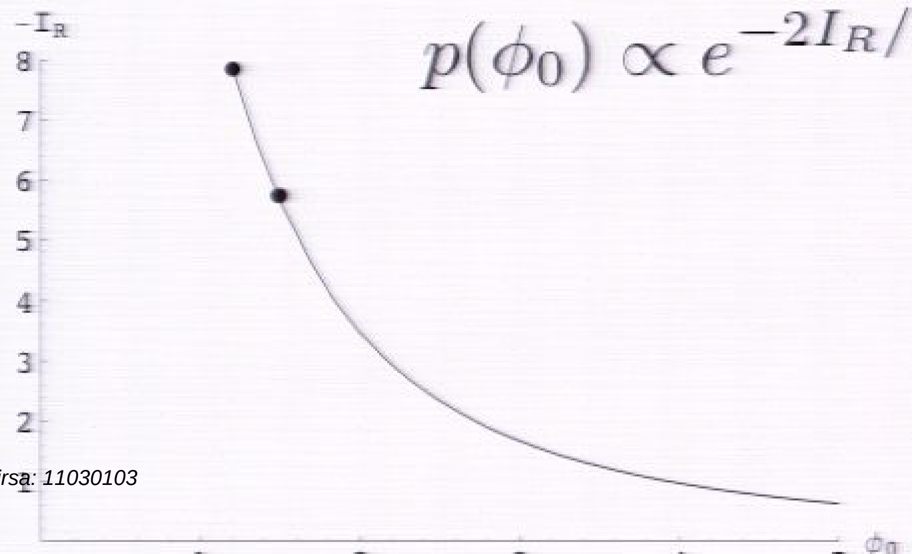

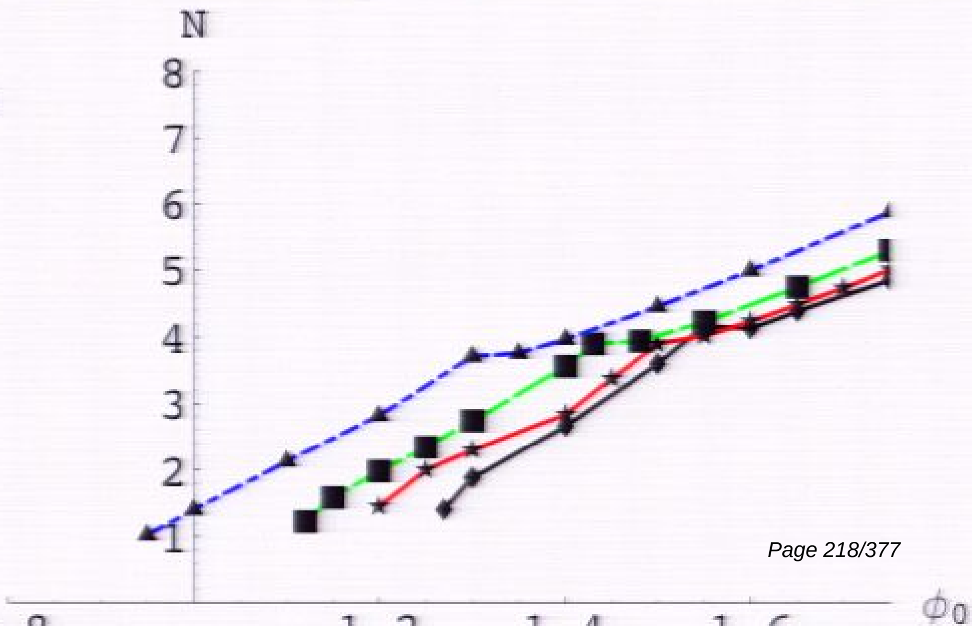

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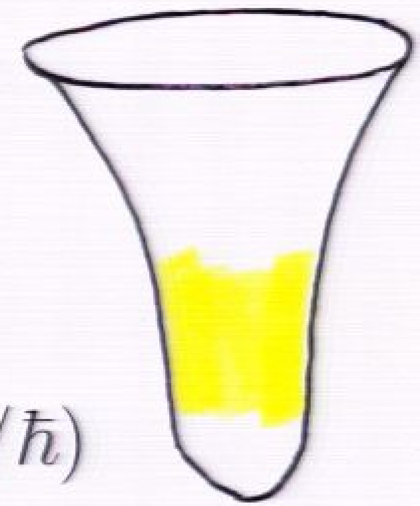

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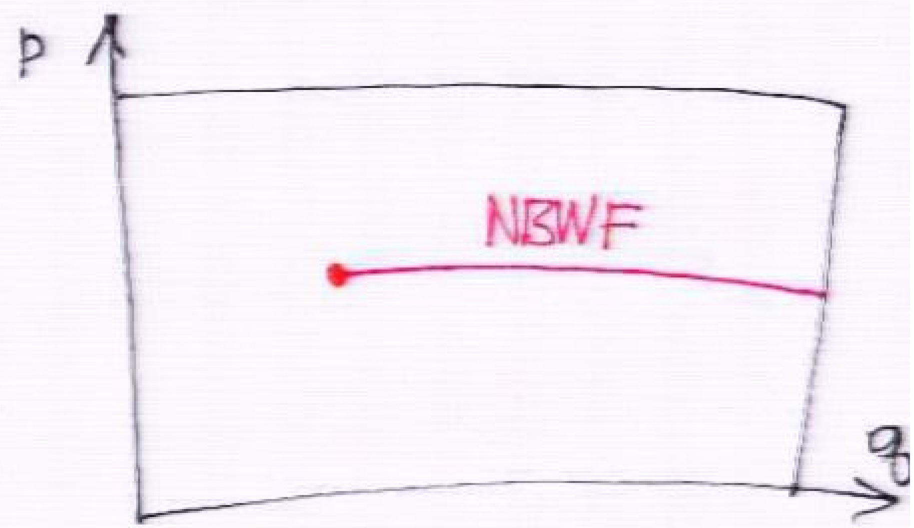
Predicted classical histories:

$$p_A = \nabla_A S \qquad \text{prob(class hist)} \propto \exp(-2I_R/\hbar)$$

Provided! $\quad |\nabla_A I_R| \ll |\nabla_A S|$



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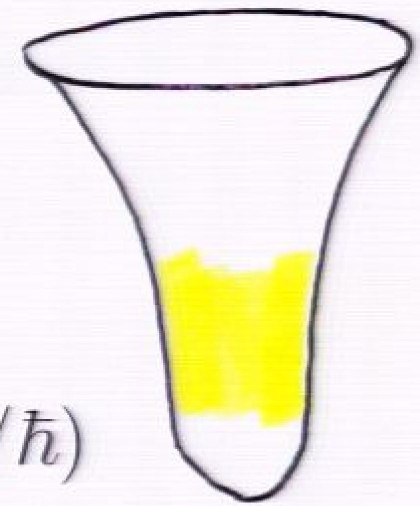

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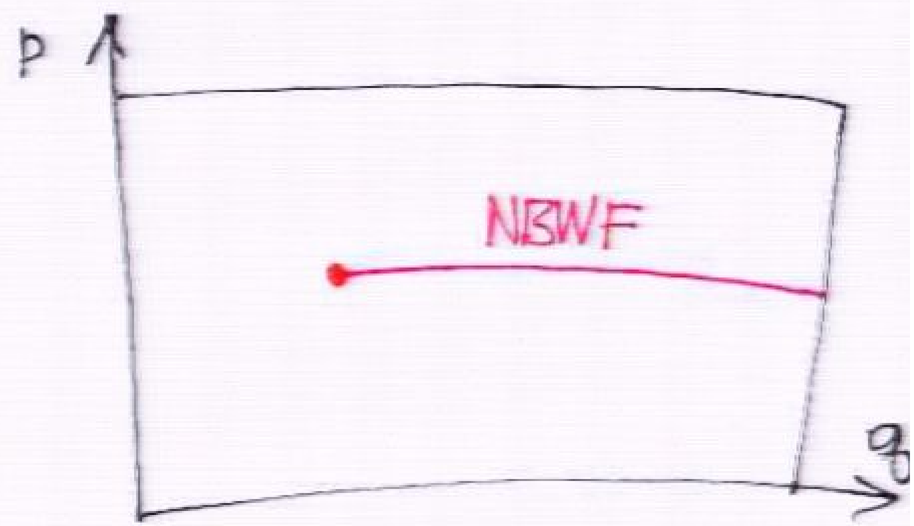

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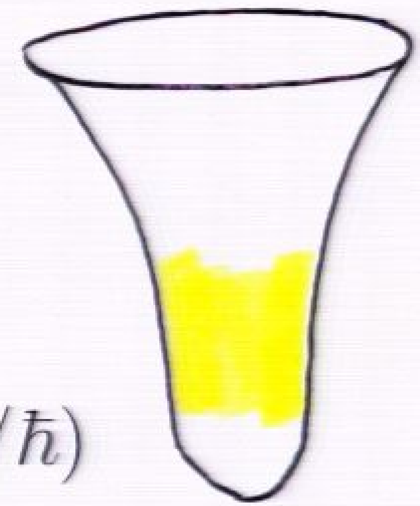

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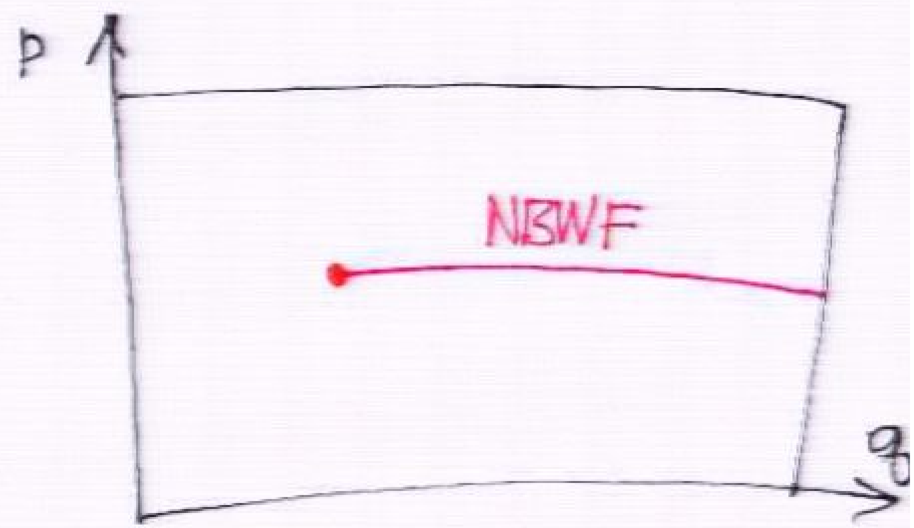

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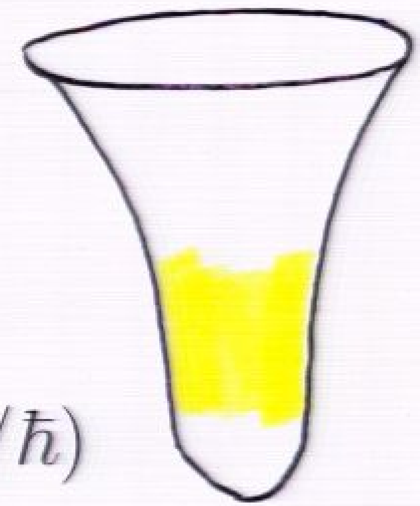

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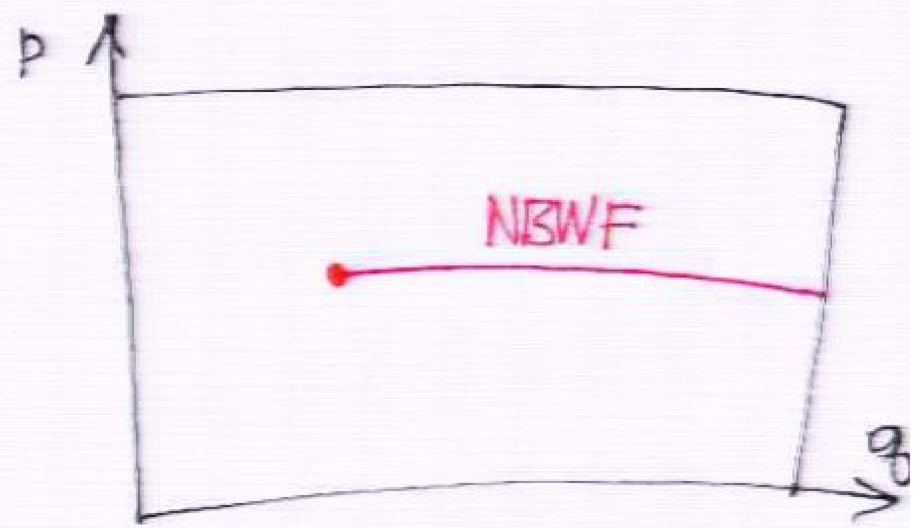

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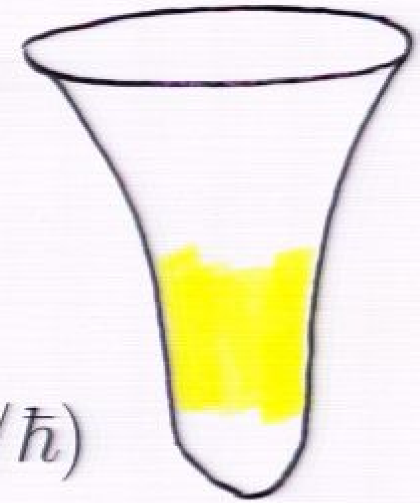

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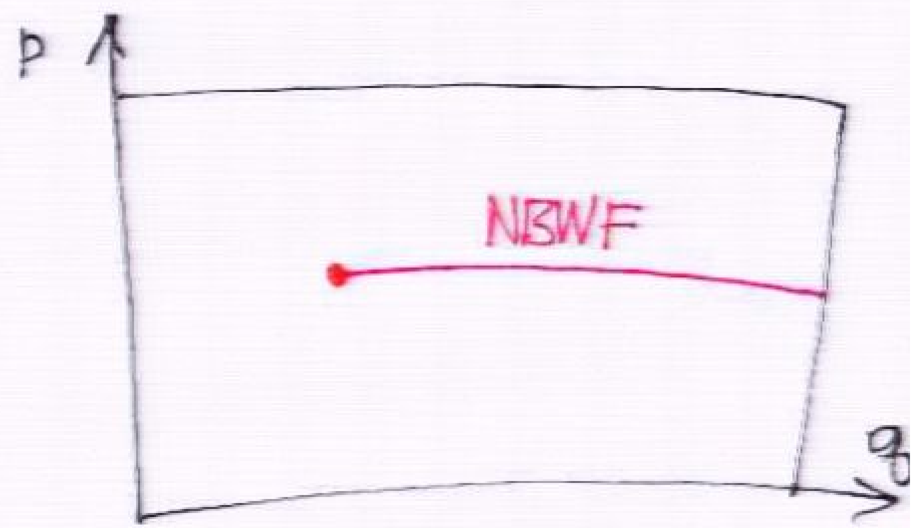

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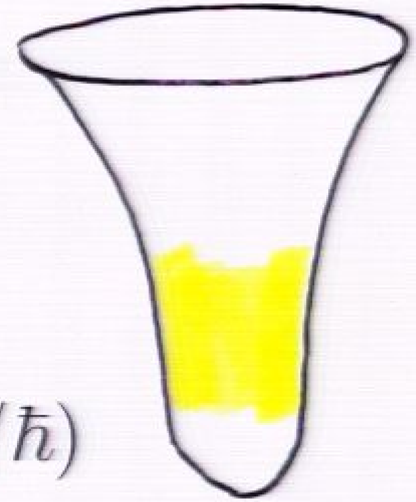

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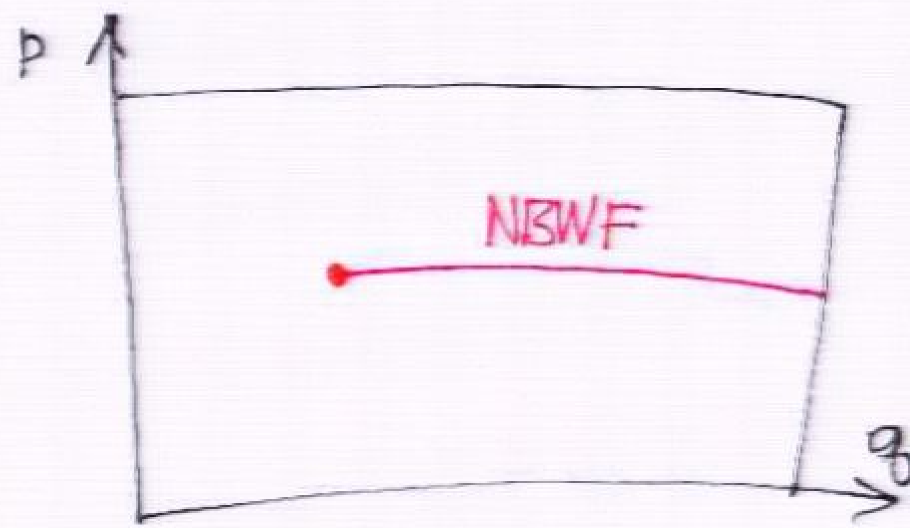

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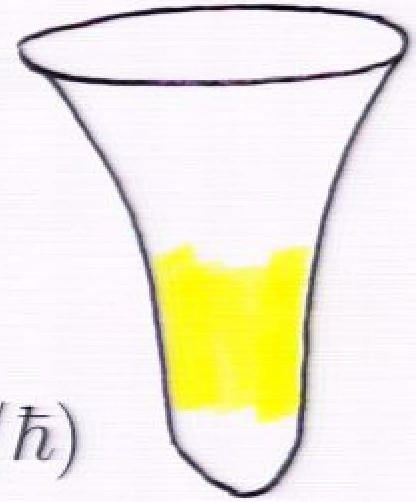

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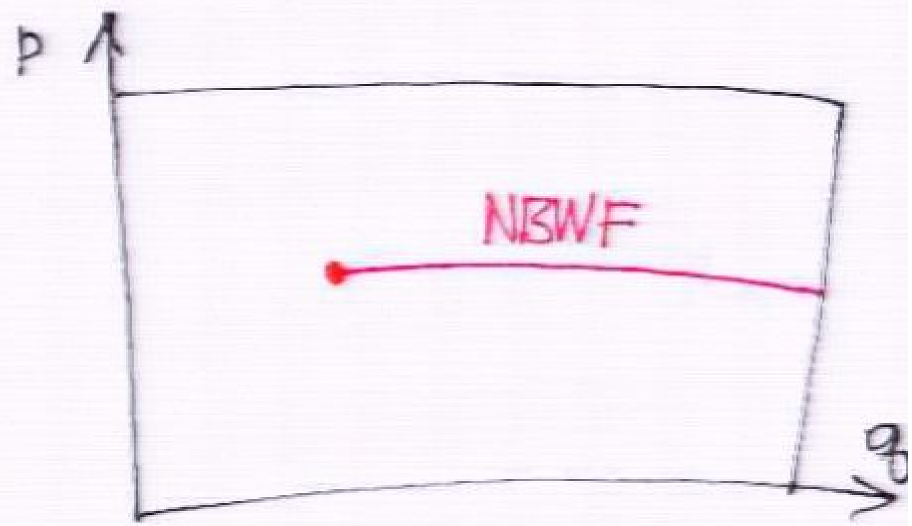

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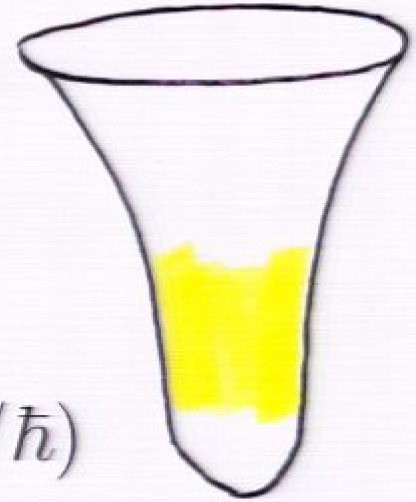

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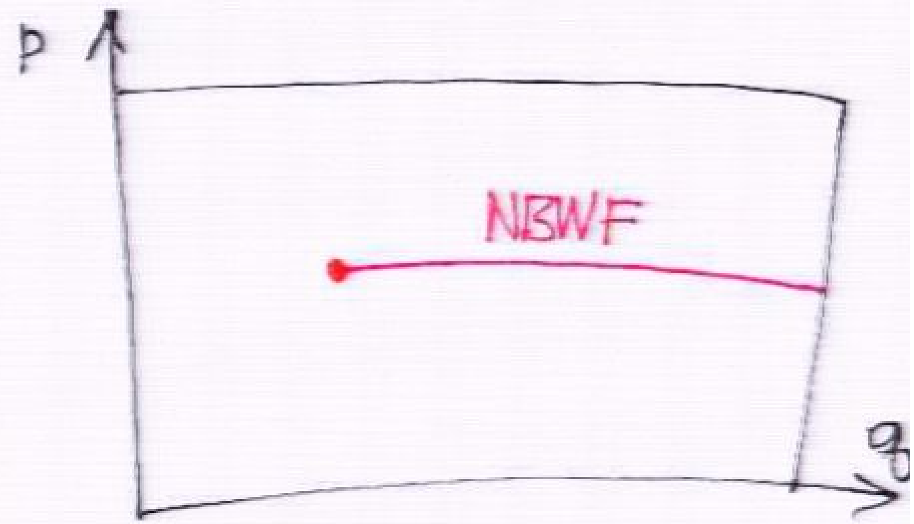

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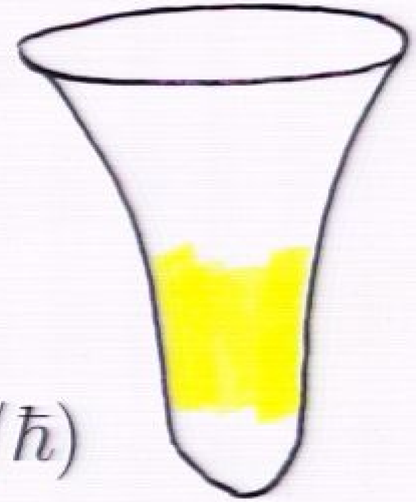

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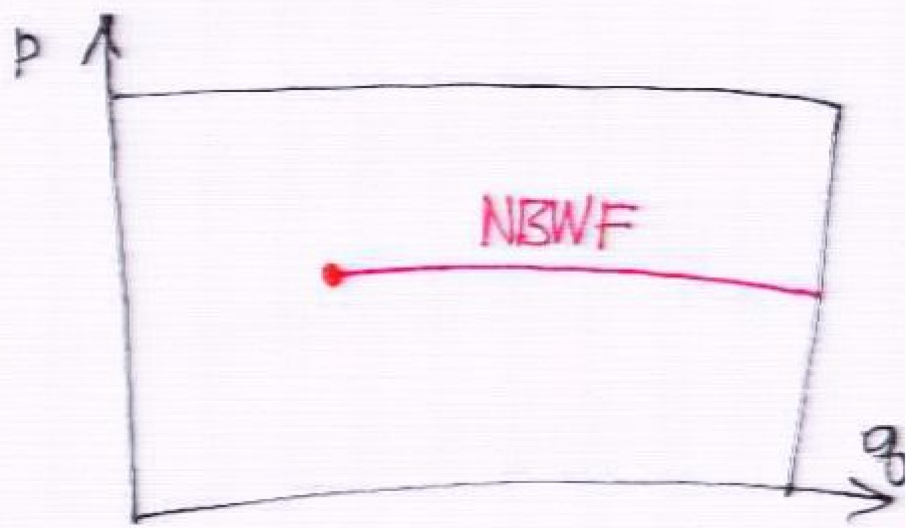

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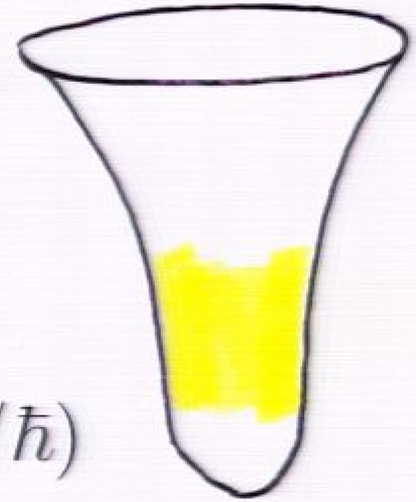

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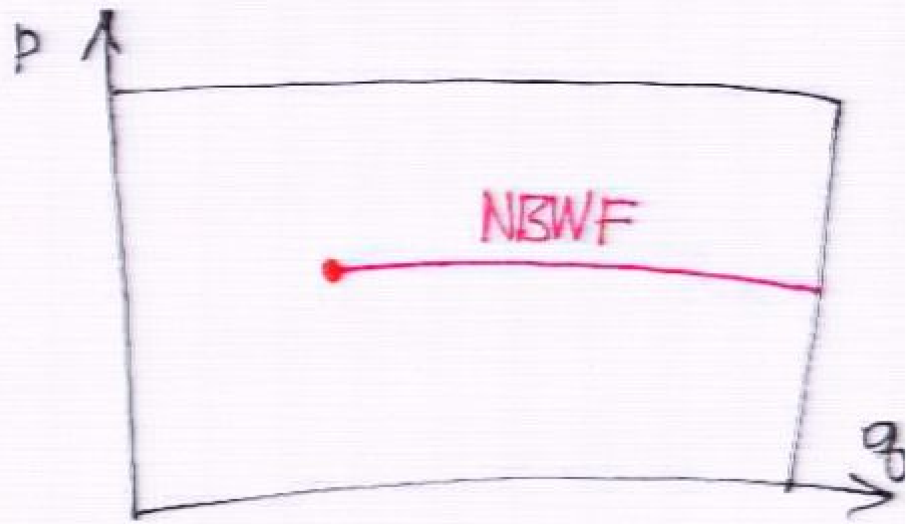

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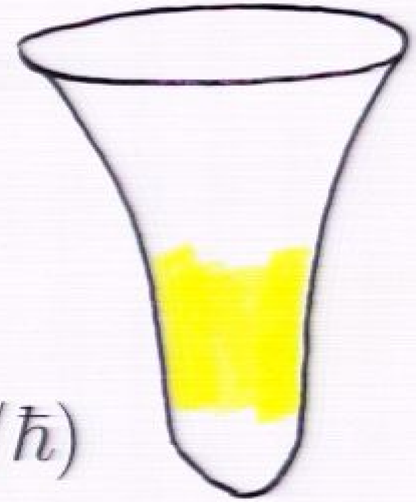

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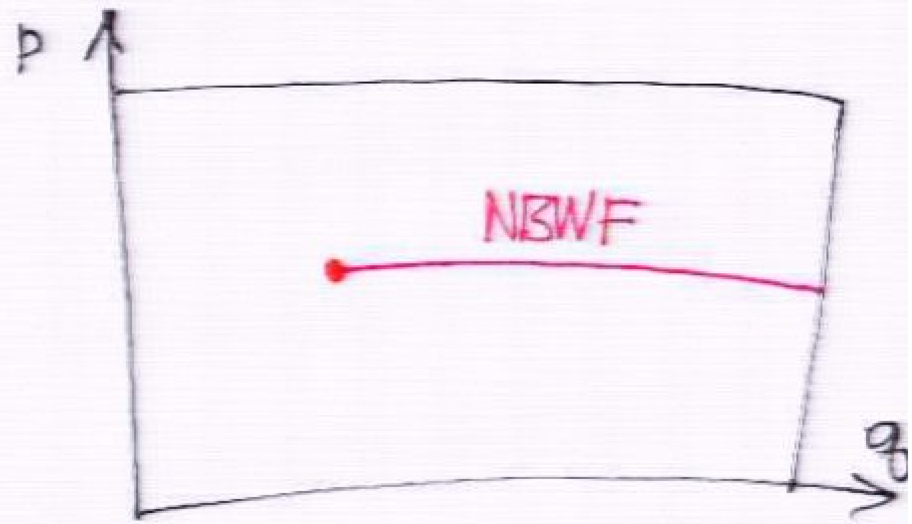

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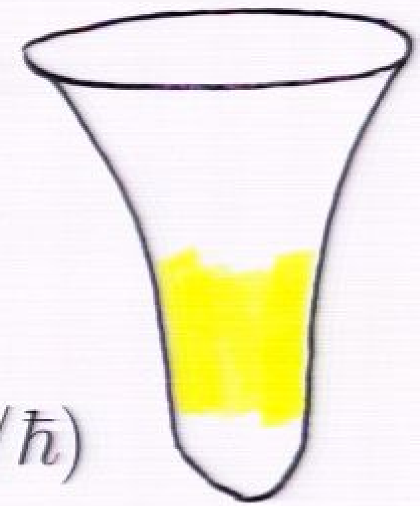

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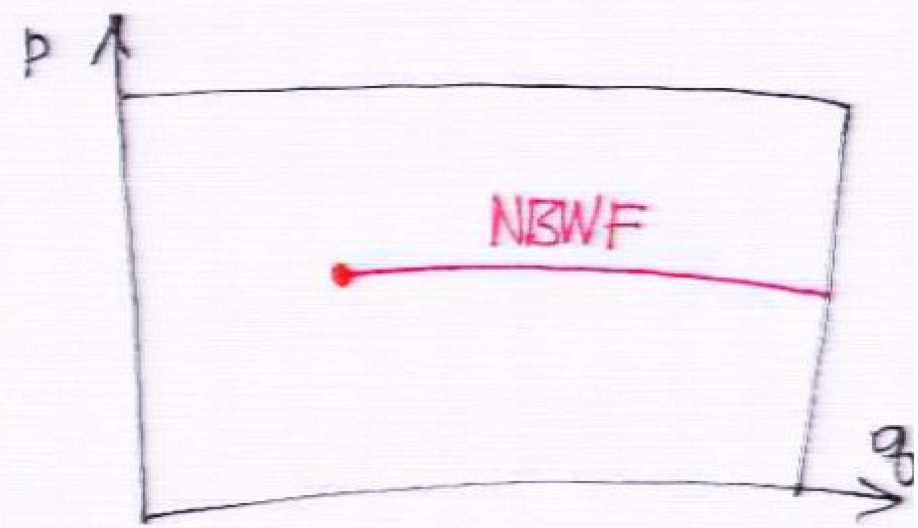

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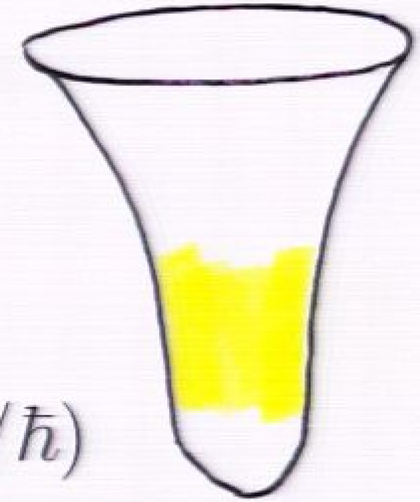

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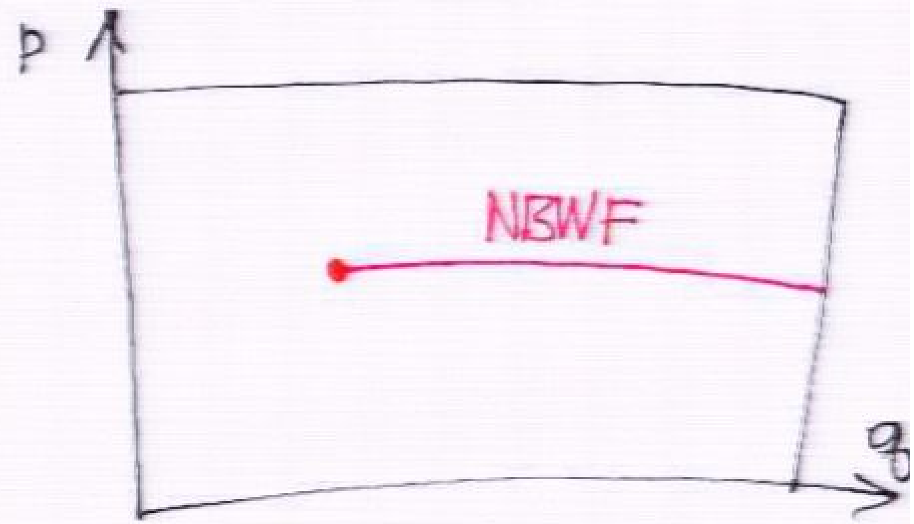

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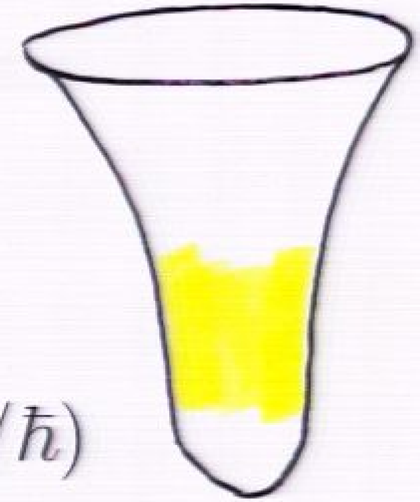

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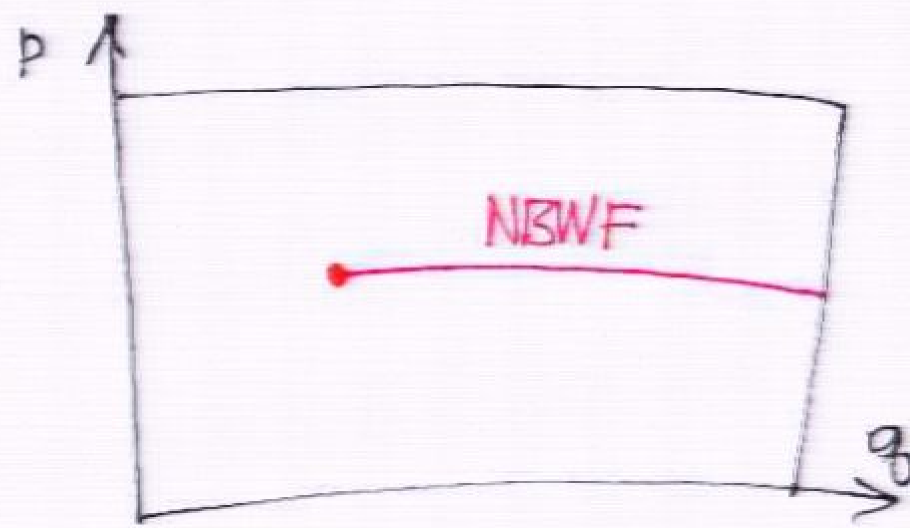

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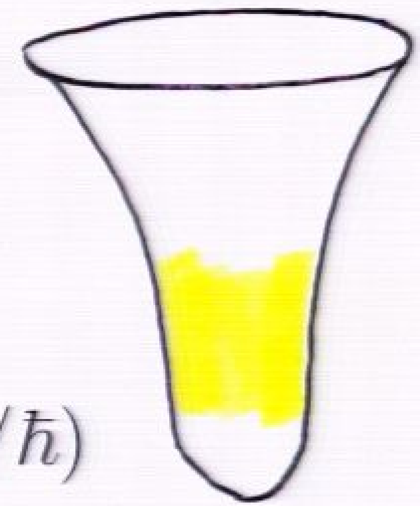

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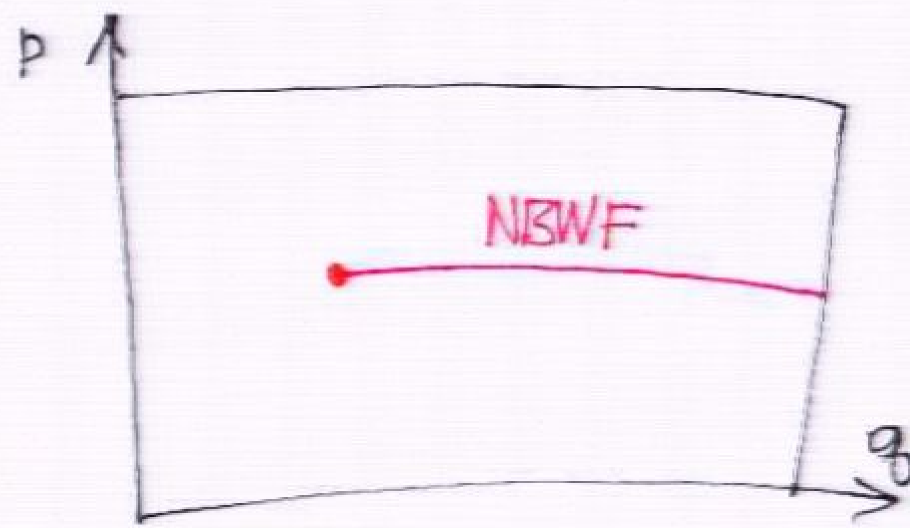

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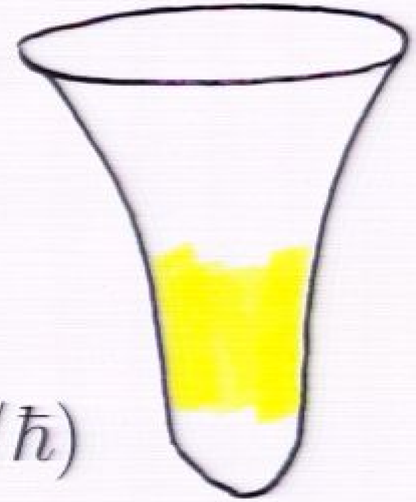

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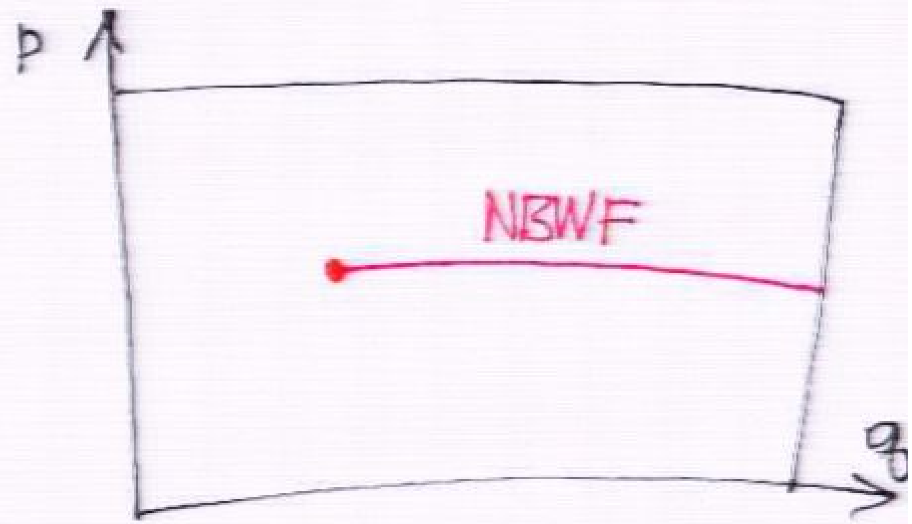

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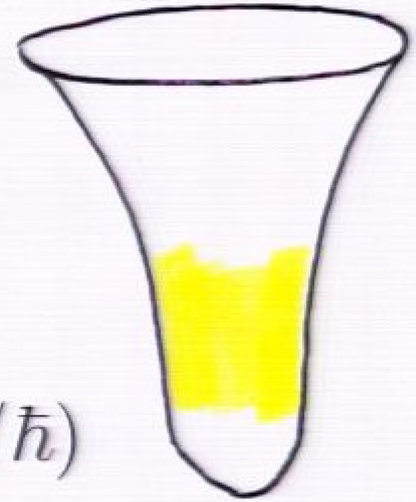

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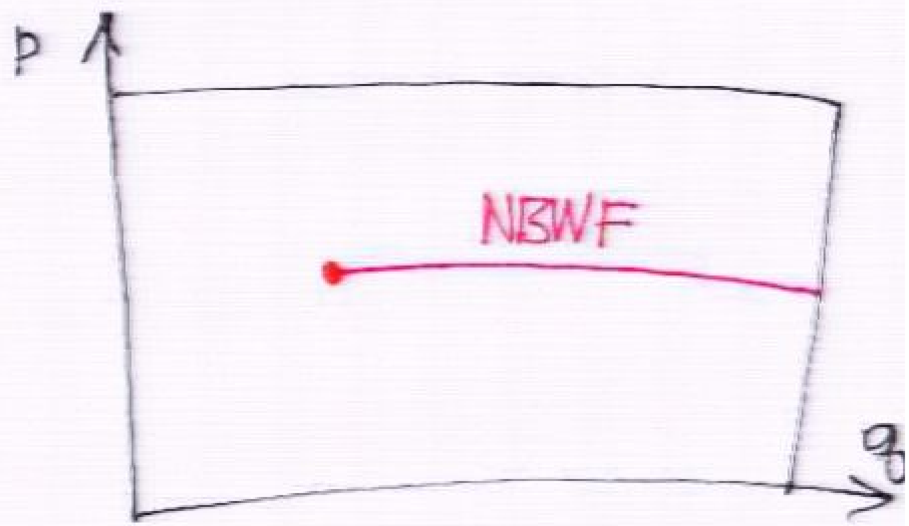

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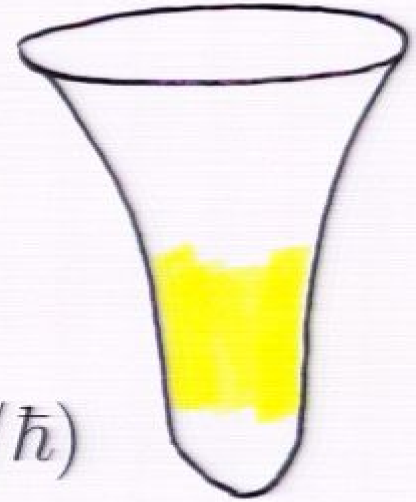

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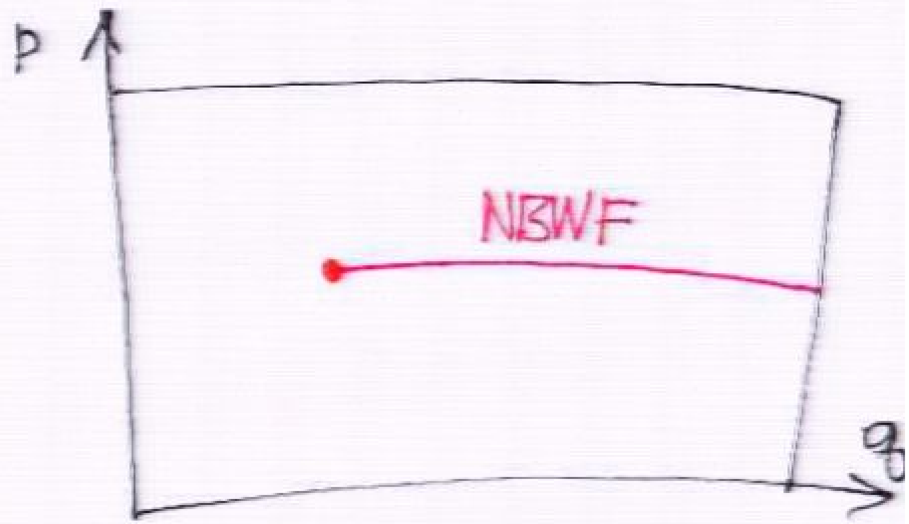

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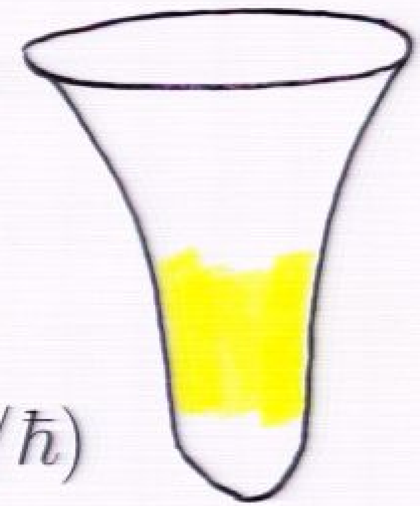

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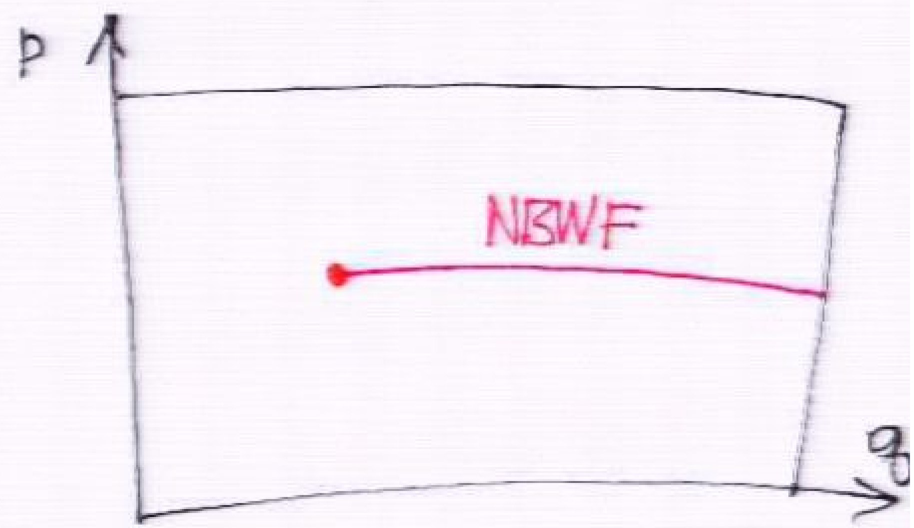

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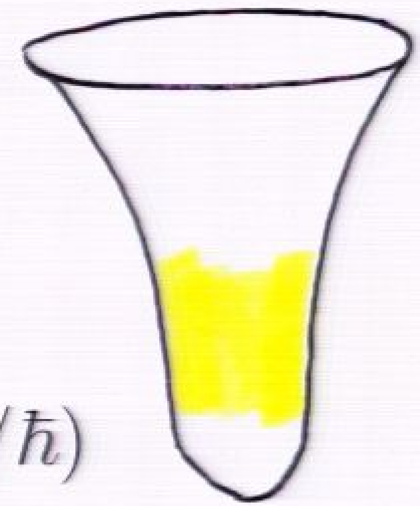

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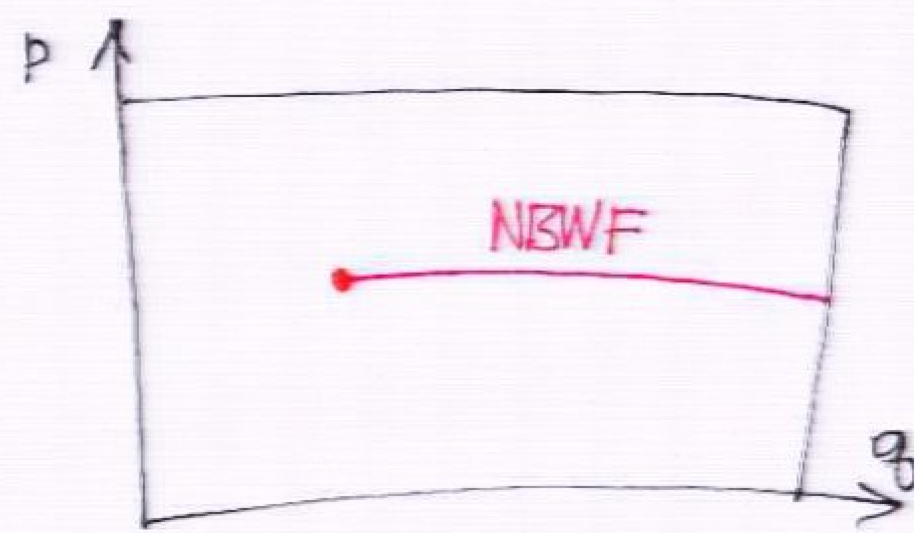

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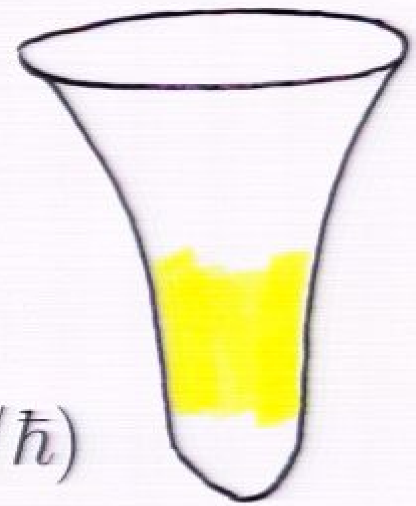

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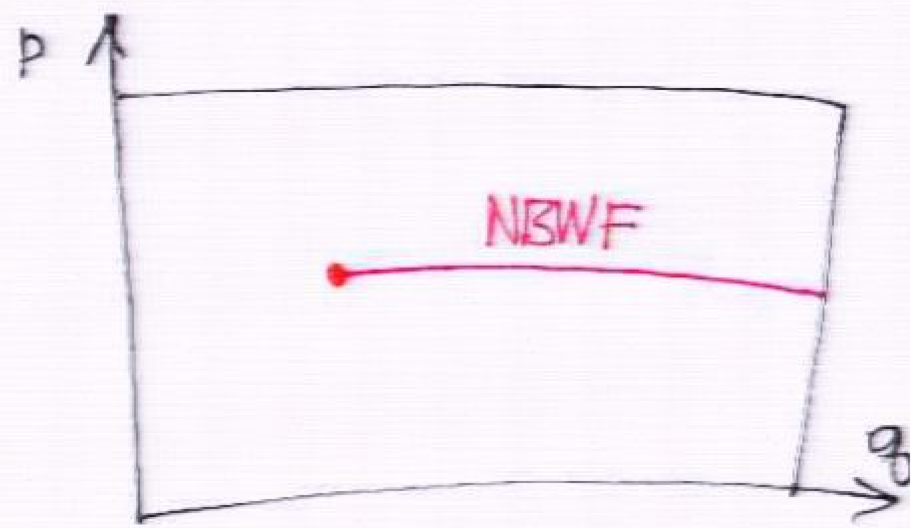

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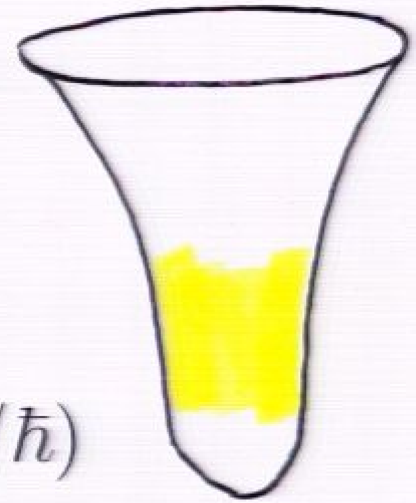

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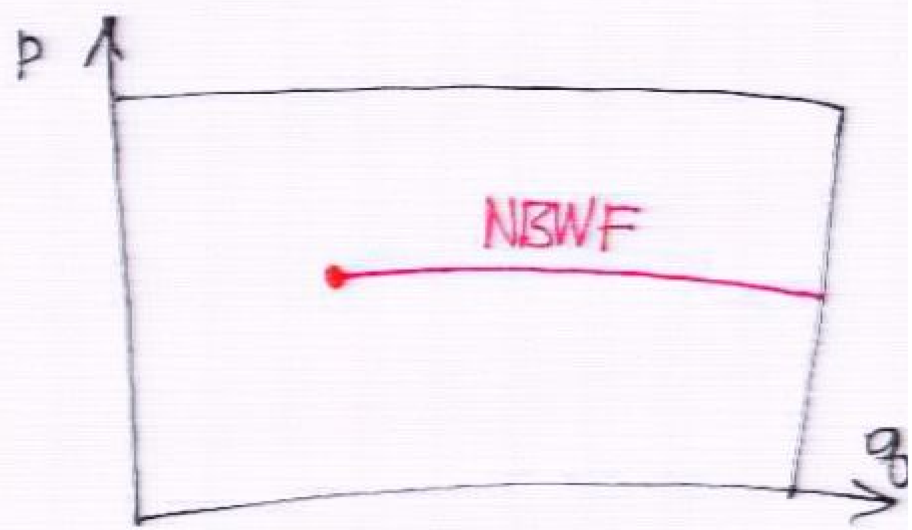

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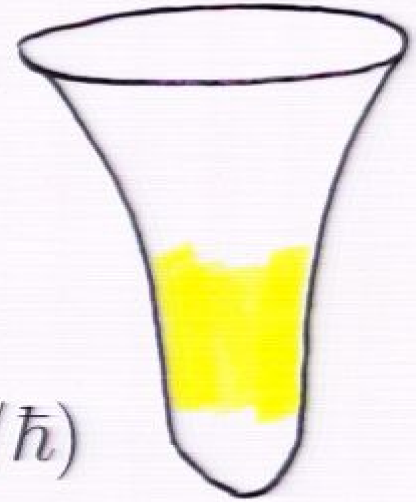

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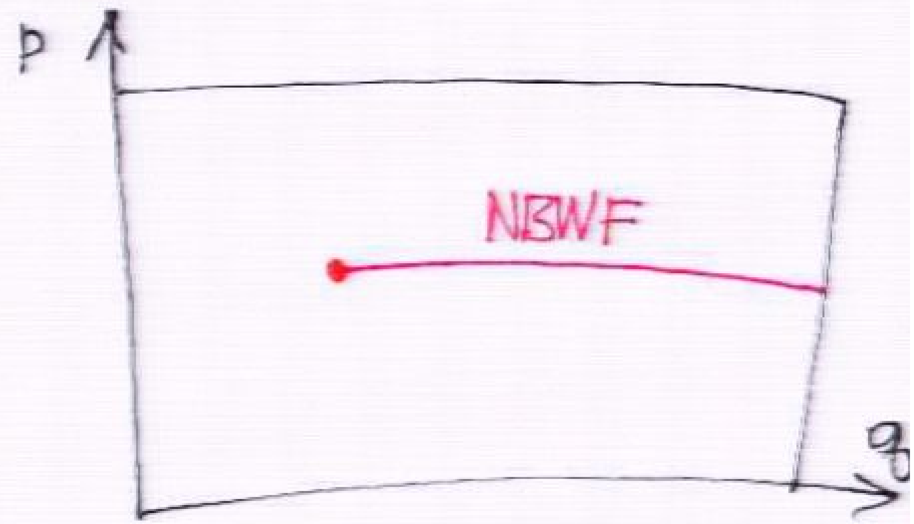

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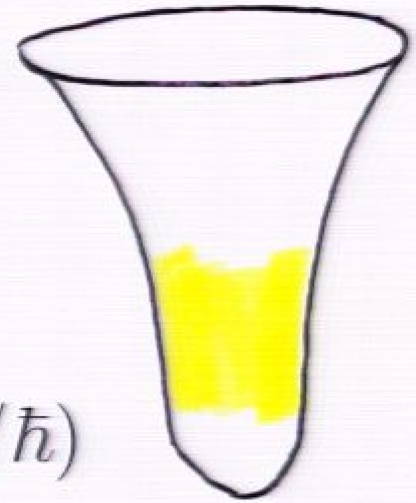

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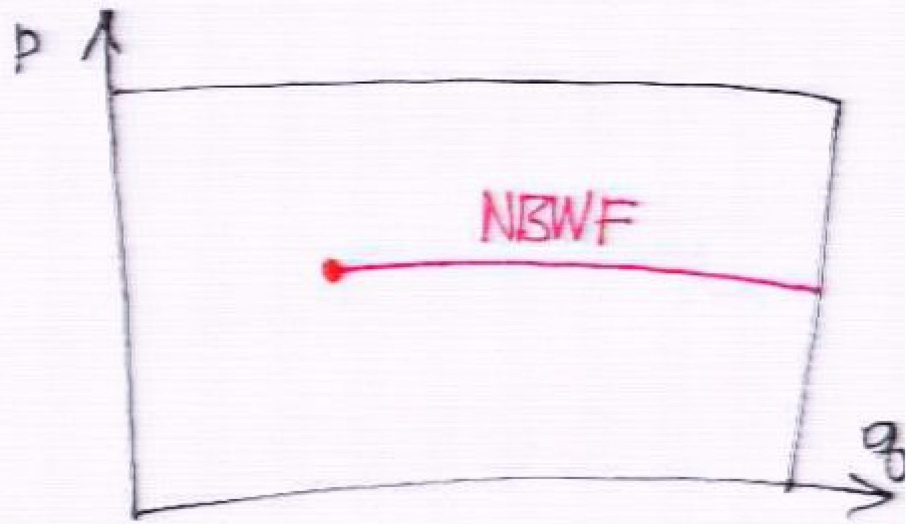

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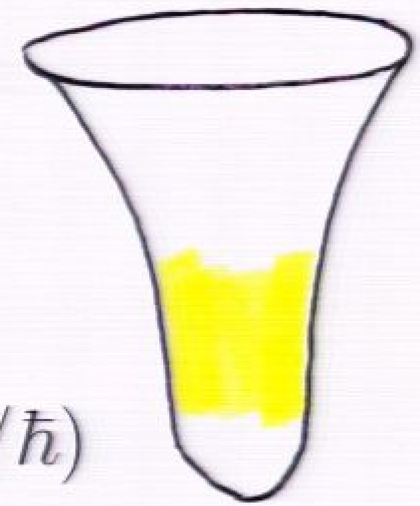

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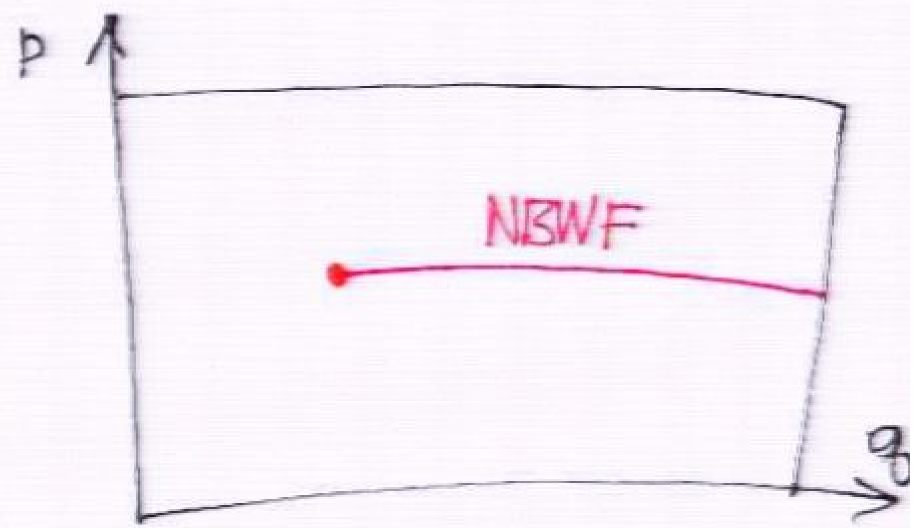

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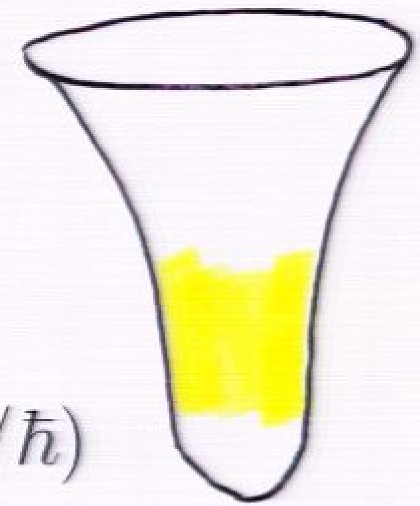

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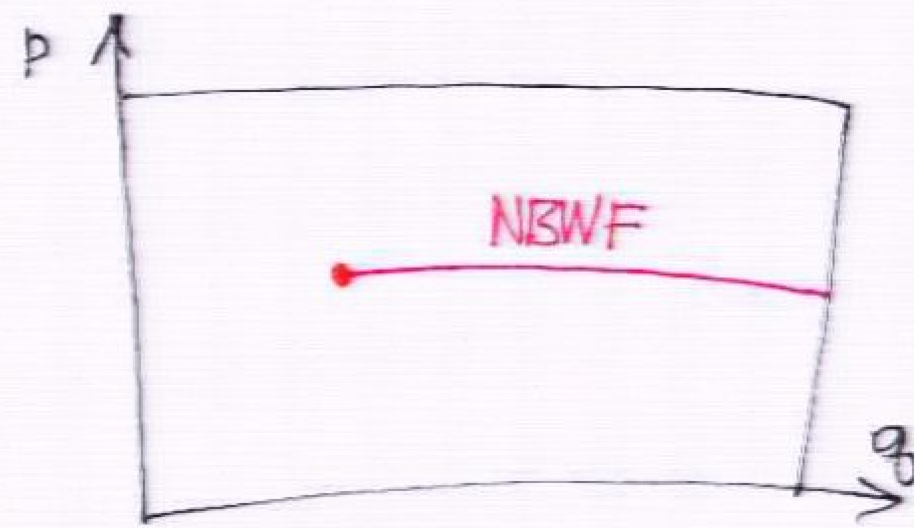

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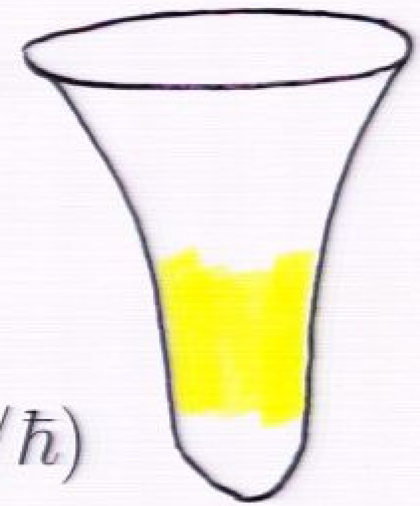

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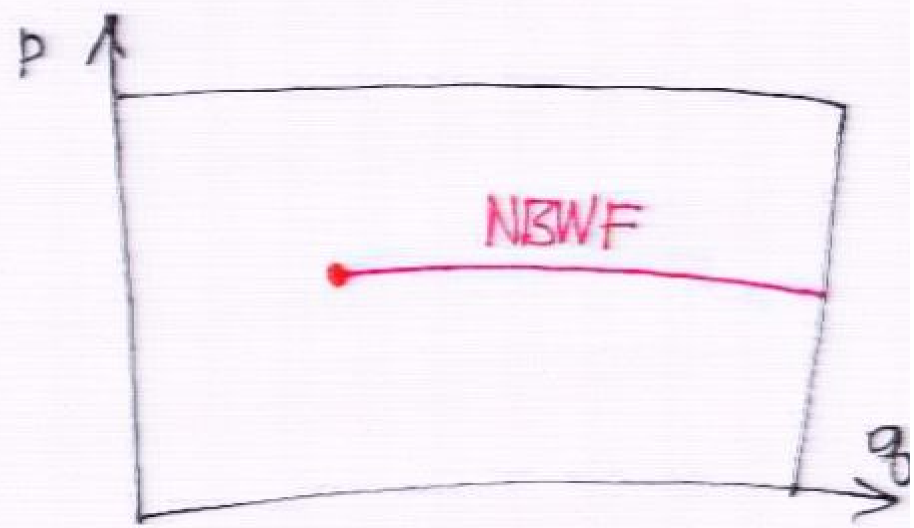

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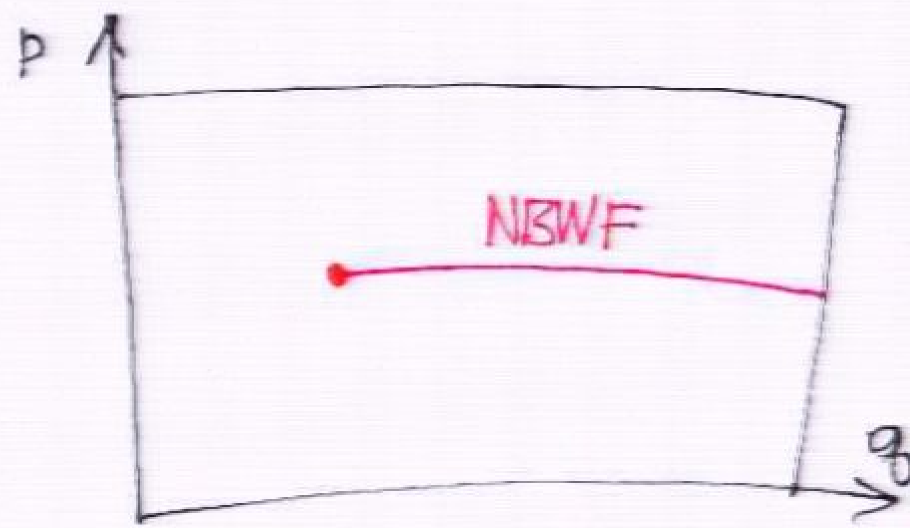

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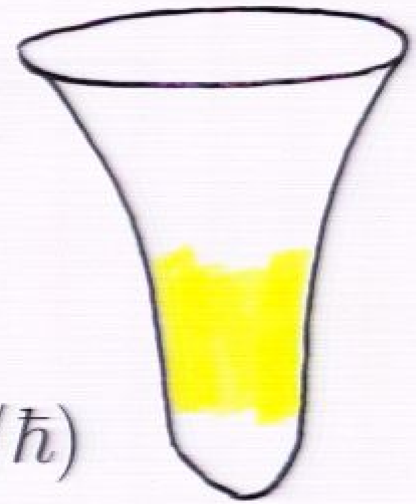

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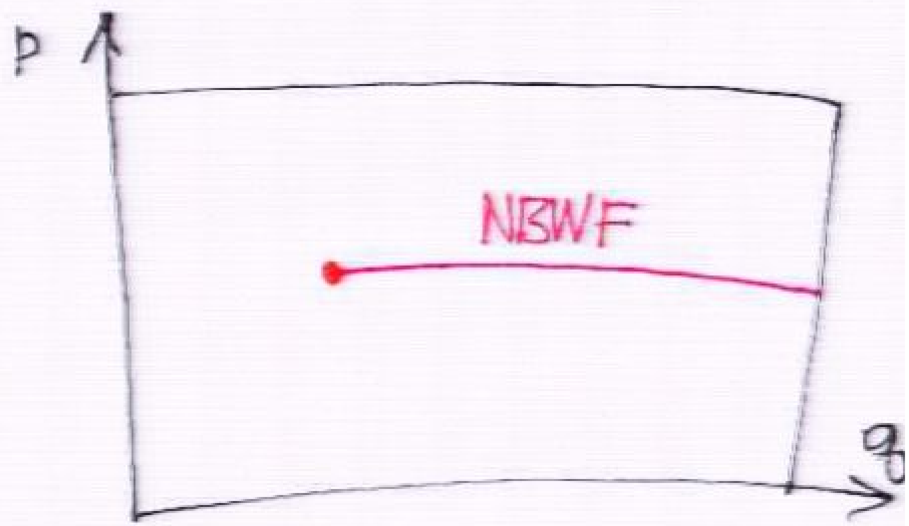

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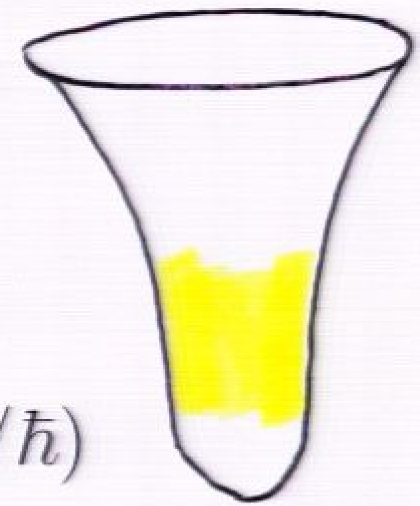

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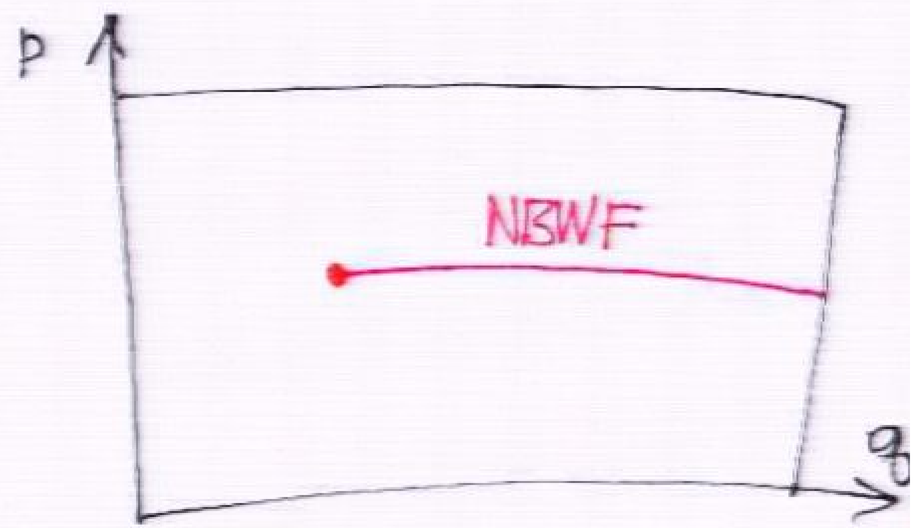

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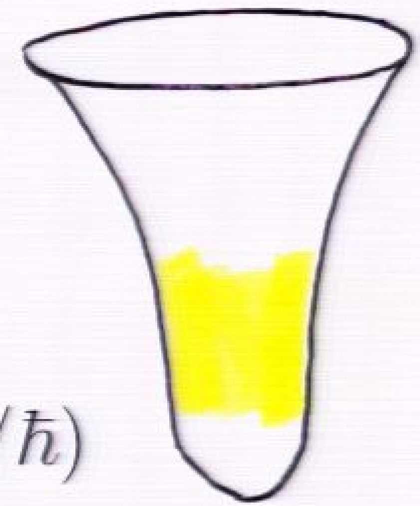

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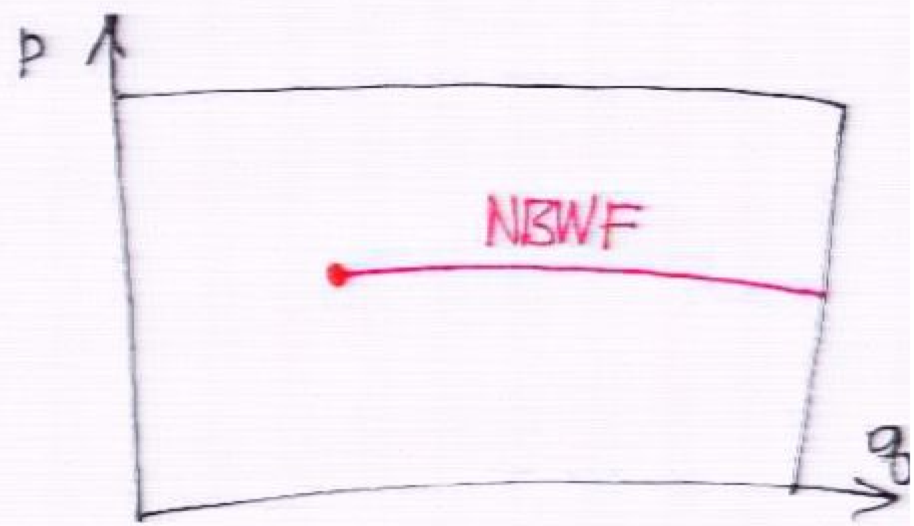

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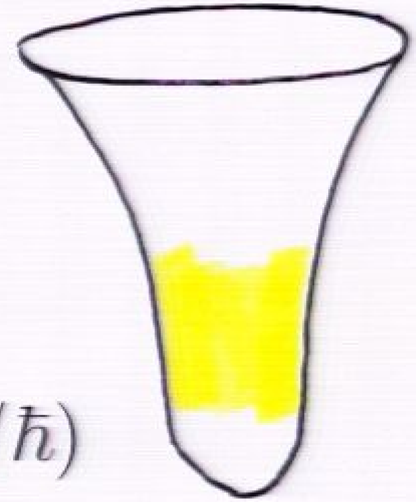

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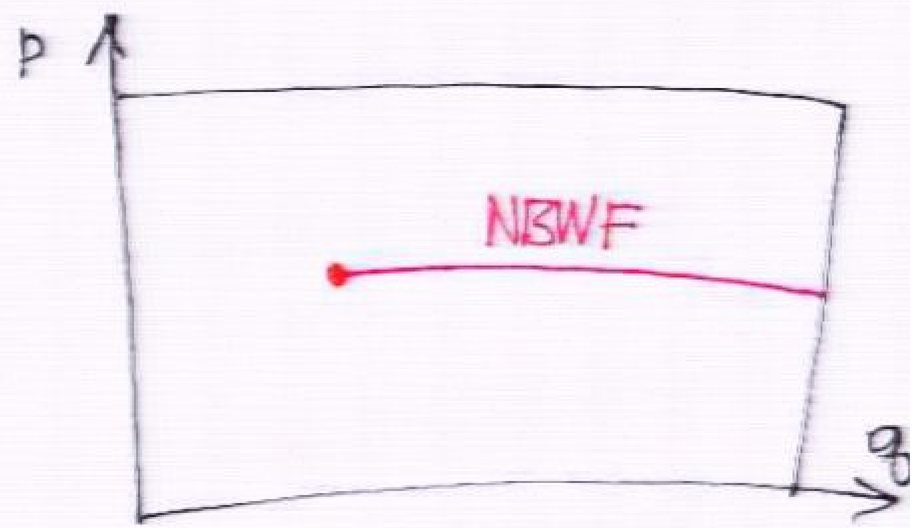

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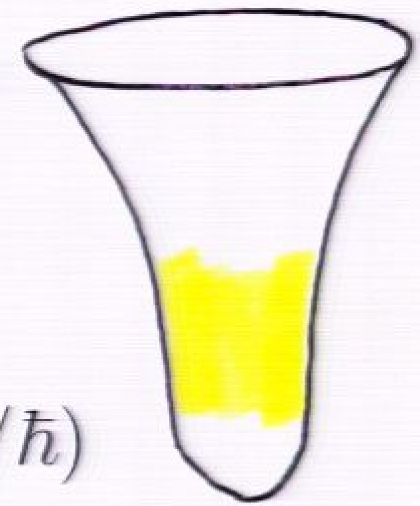

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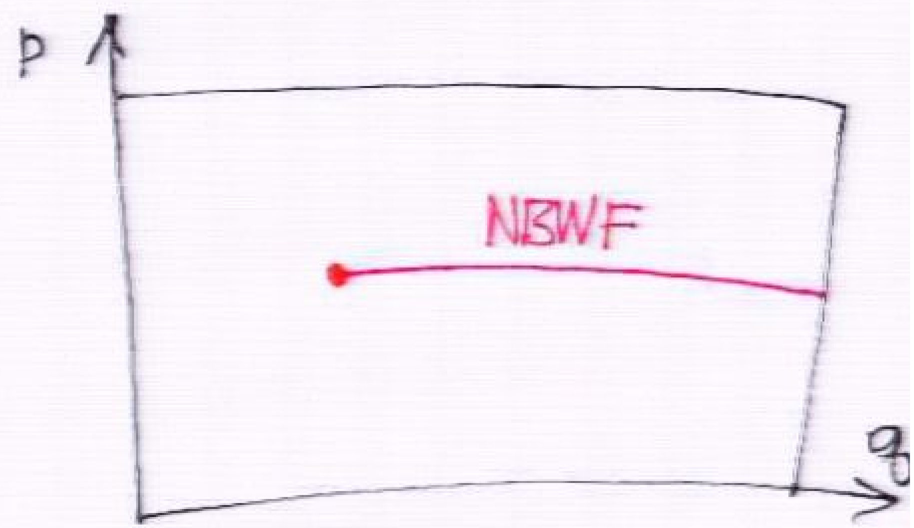

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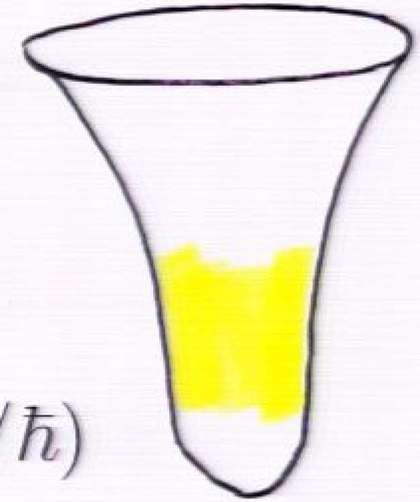

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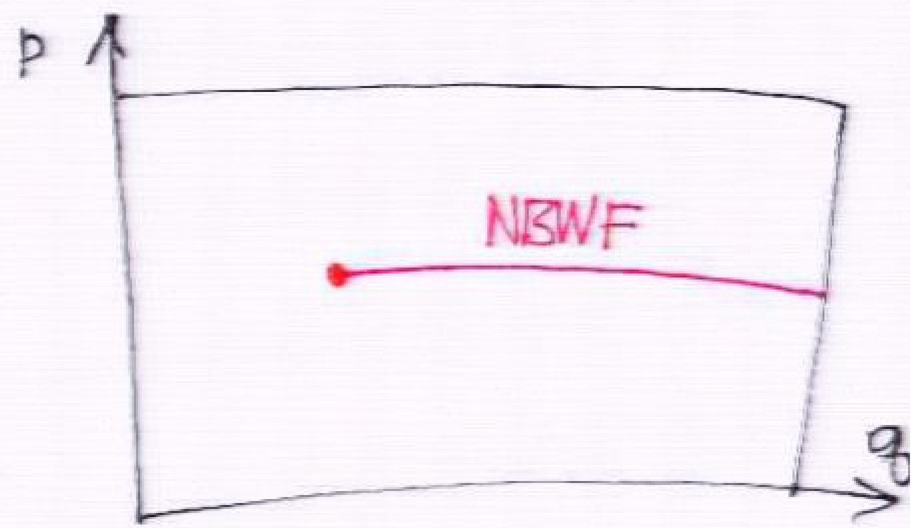

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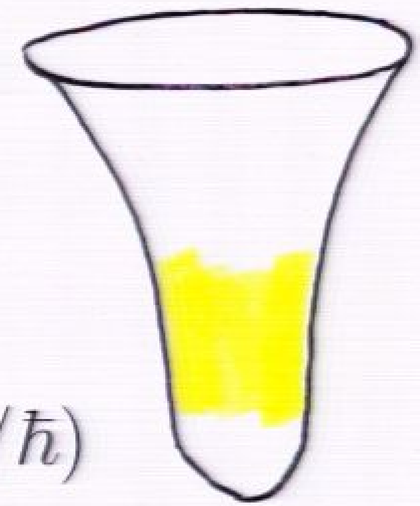

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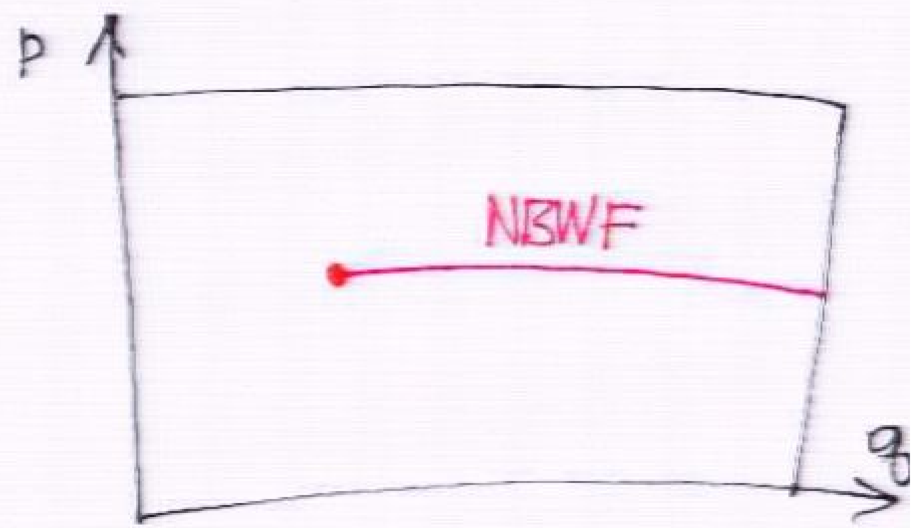

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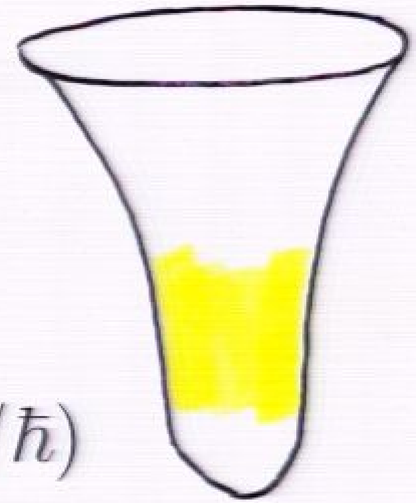

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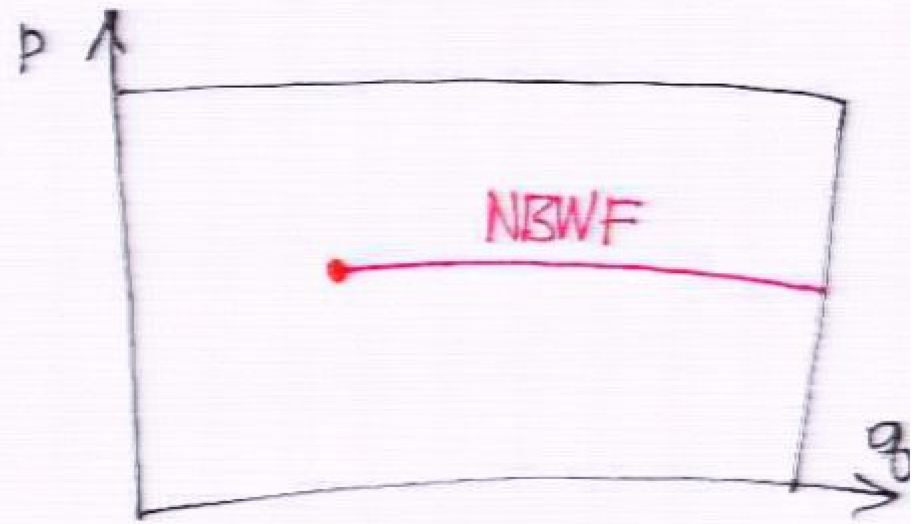

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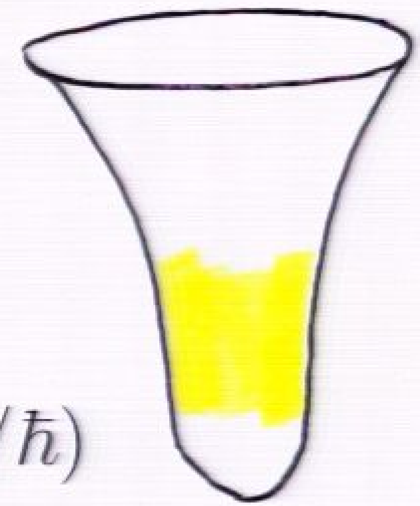

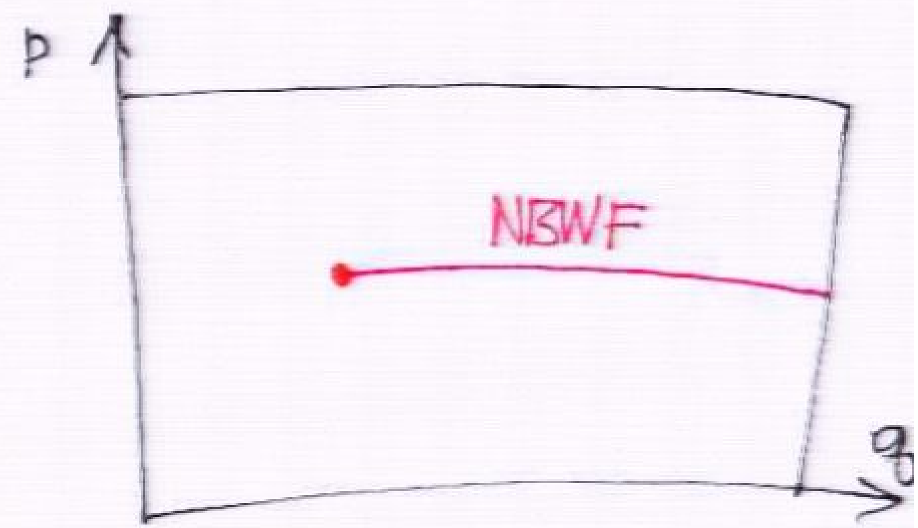

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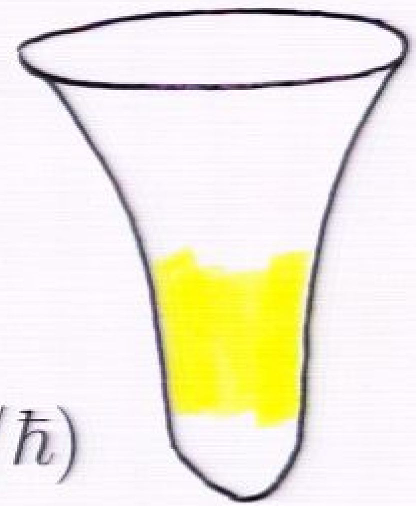

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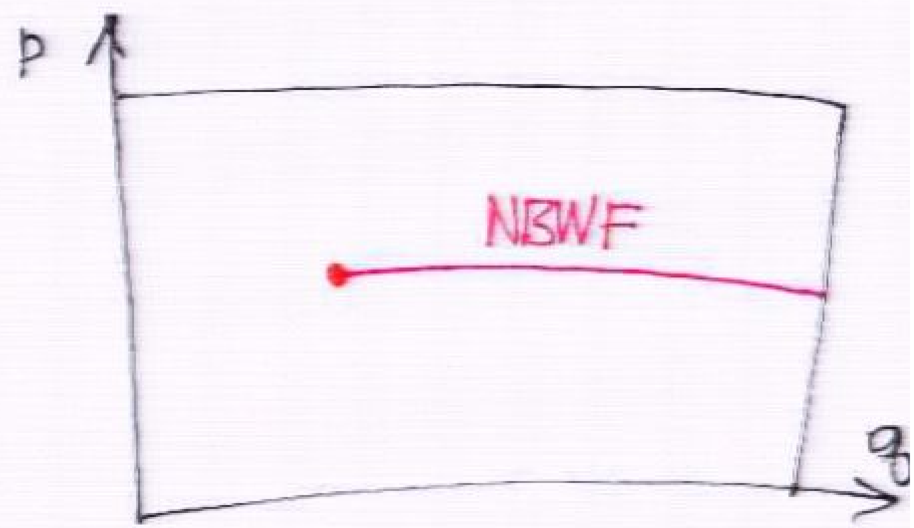

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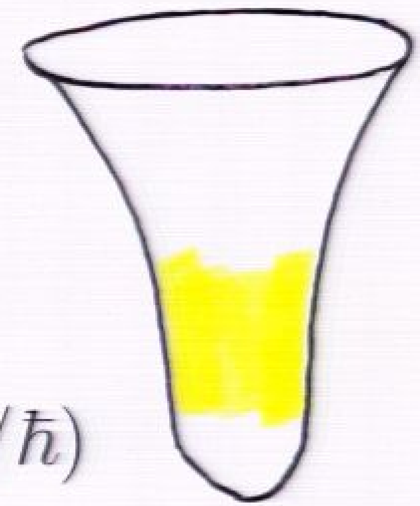

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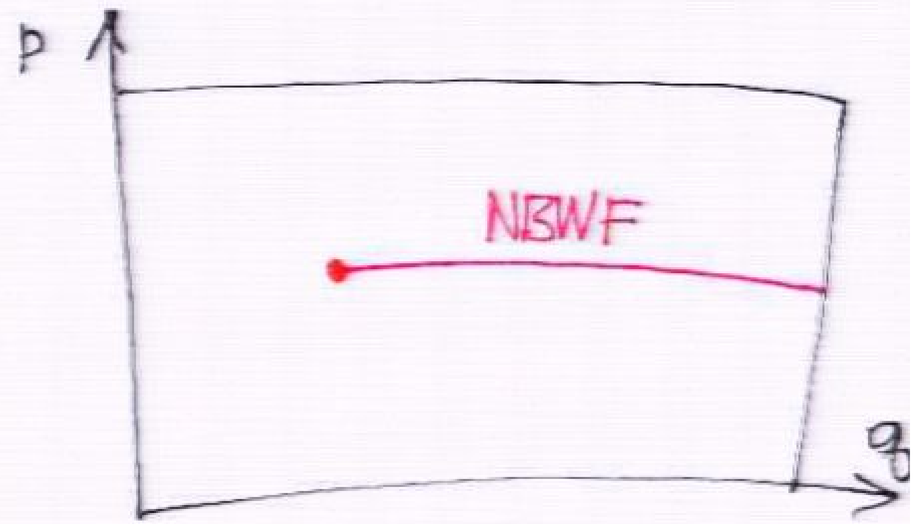

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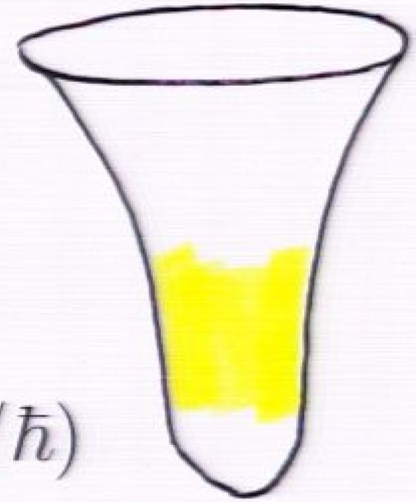

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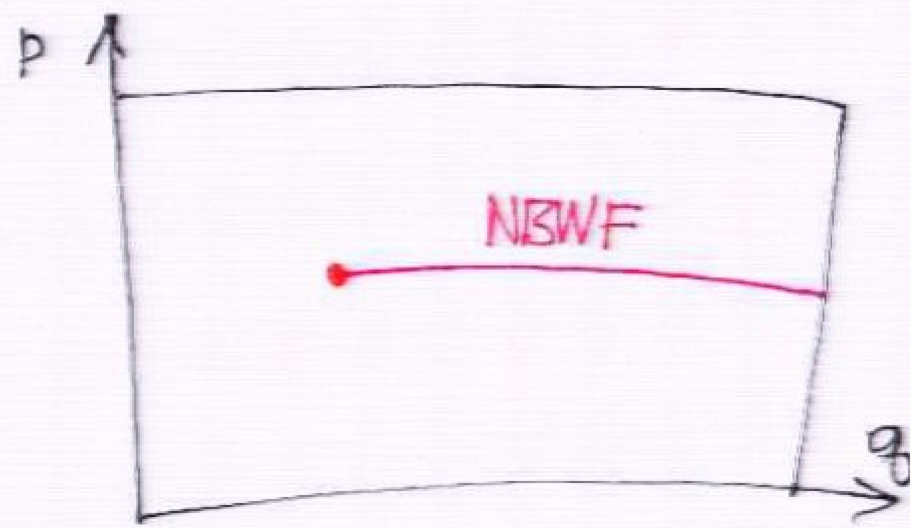

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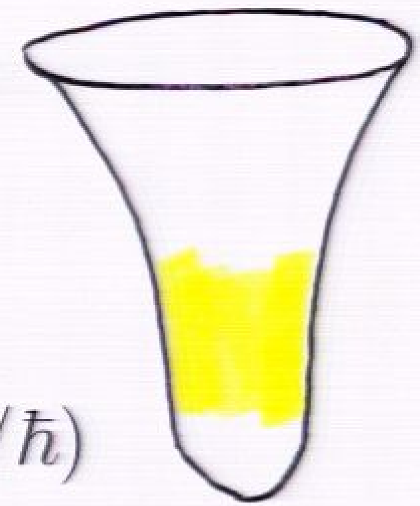

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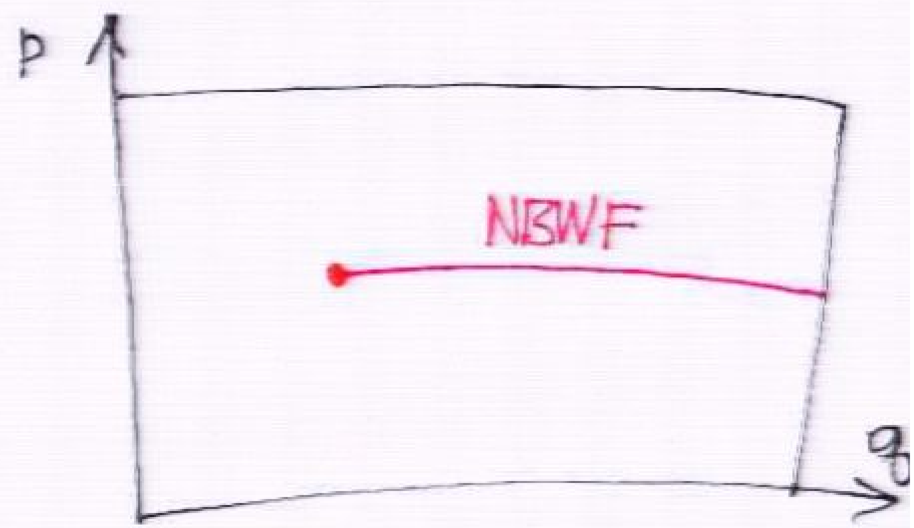

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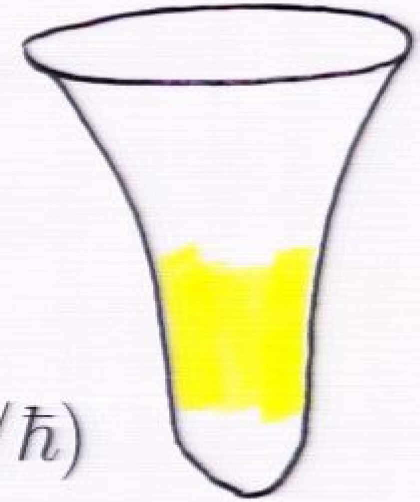

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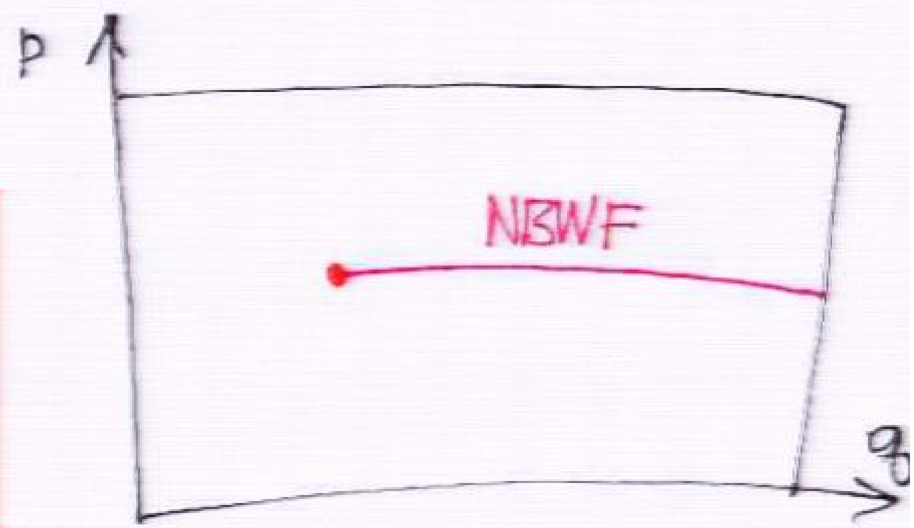


- No big empty universes.
- All histories exhibit scalar field driven inflation.

Bottom Up Probability for Efolds

- One parameter (φ_0) family of classical histories with BU NBWF probabilities $p(\varphi_0)$.

Minisuperspace Models

Geometry: Homogeneous, isotropic, closed.

$$ds^2 = (3/\Lambda)\left[N^2(\lambda)d\lambda^2 + a^2(\lambda)d\Omega_3^2\right]$$

Matter: cosmological constant Λ plus homogeneous scalar field moving in a quadratic potential.

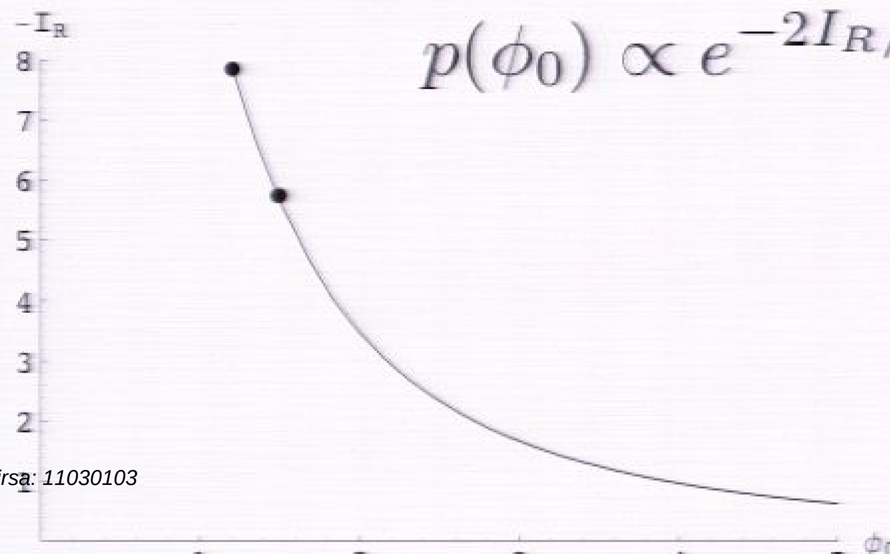
$$V(\Phi) = \frac{1}{2}m^2\Phi^2$$

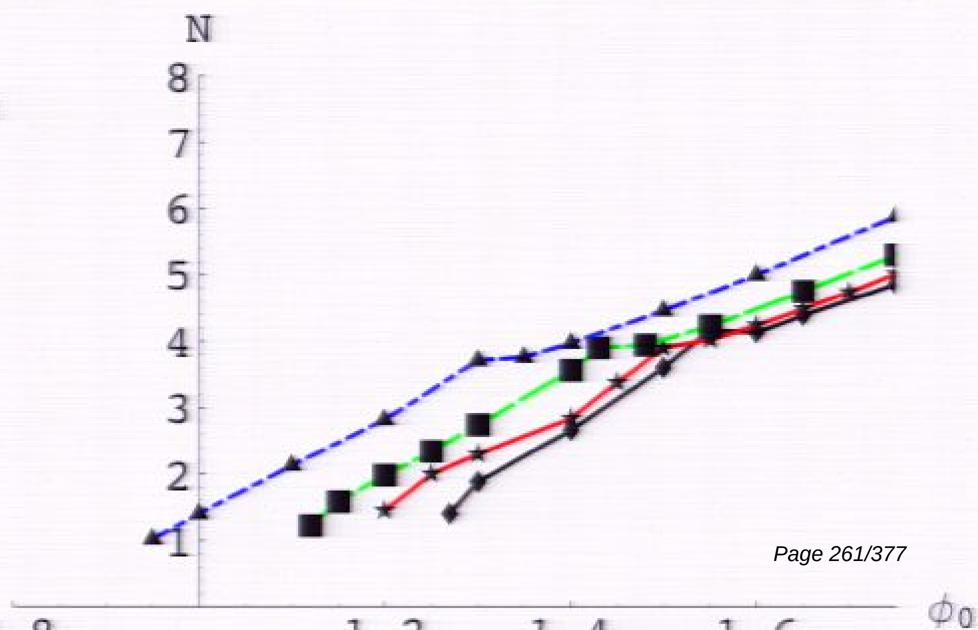
Theory: Low-energy effective gravity.

$$I_C[g] = -\frac{m_p^2}{16\pi}\int_M d^4x(g)^{1/2}(R-2\Lambda) + (\text{surface terms})$$

- $N(\varphi_0)$=number of efolds of field driven inflation.

$$p(\phi_0) \propto e^{-2I_R/\hbar}$$





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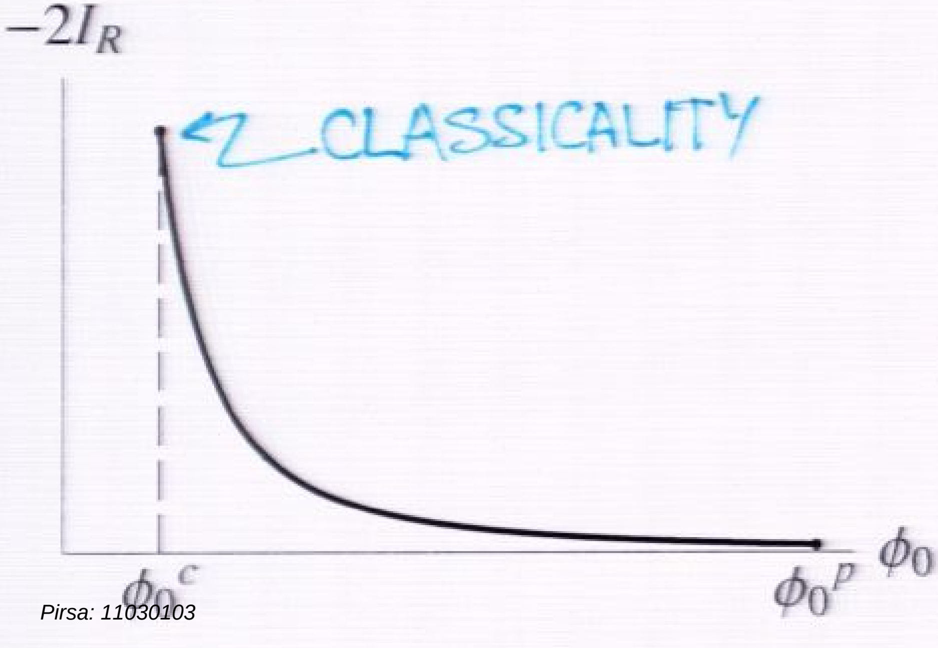

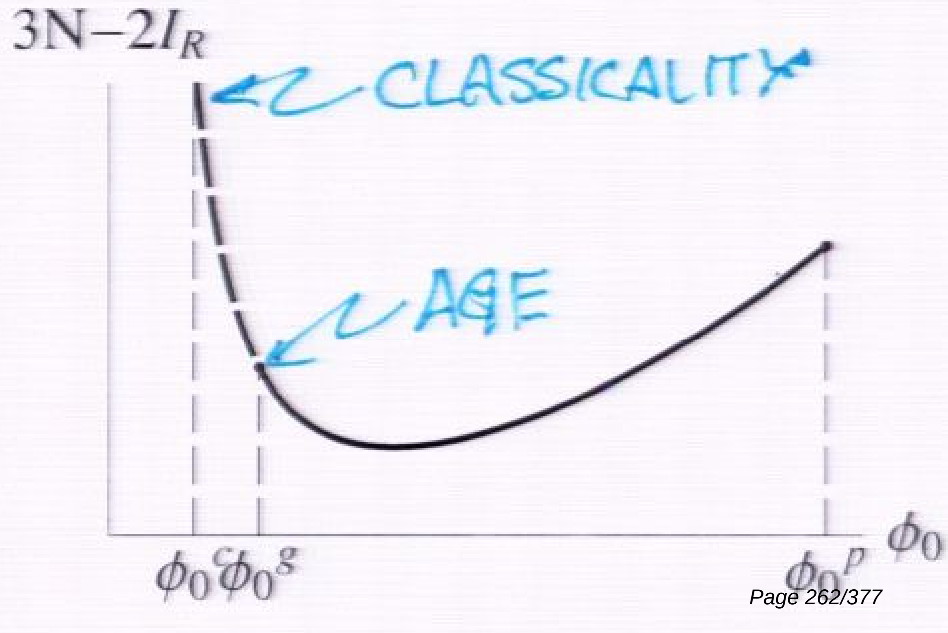

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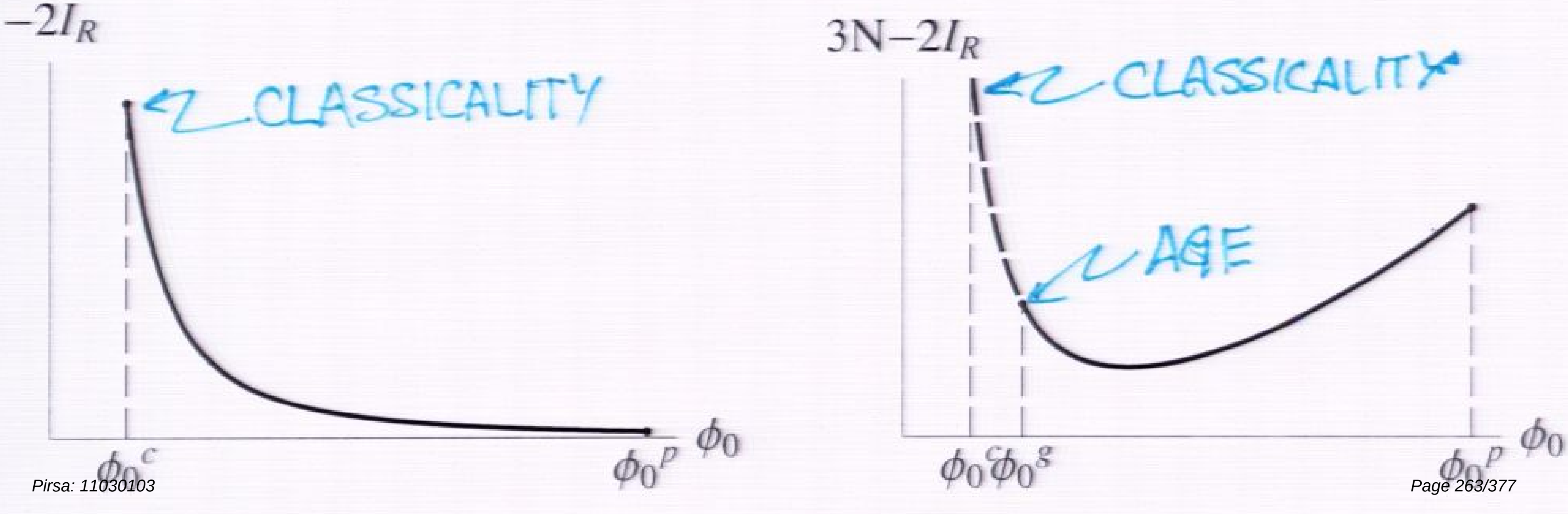

Fluctuations

- Scalar perturbations of metric and matter from homo/iso backgrounds labeled by φ_0 .
- Gauge+constraints leave one gauge-invariant combination ζ which can be expanded in S^3 harmonics.
- Action: $I = I^{(0)}[a(\tau), \phi(\tau)] + I^{(2)}[a(\tau), \phi(\tau), \zeta(\tau)]$.
- NBWF: $\Psi(b, \chi, z) \approx \exp\{[-I_R^{(0)}(b, \chi) + iS^{(0)}(b, \chi)]/\hbar\}\psi(b, \chi, z)$.

$$\psi(b, \chi, z) \equiv \int_{\mathcal{C}} \delta\zeta \exp(-I^{(2)}[a(\tau), \phi(\tau), \zeta(\tau)]/\hbar).$$

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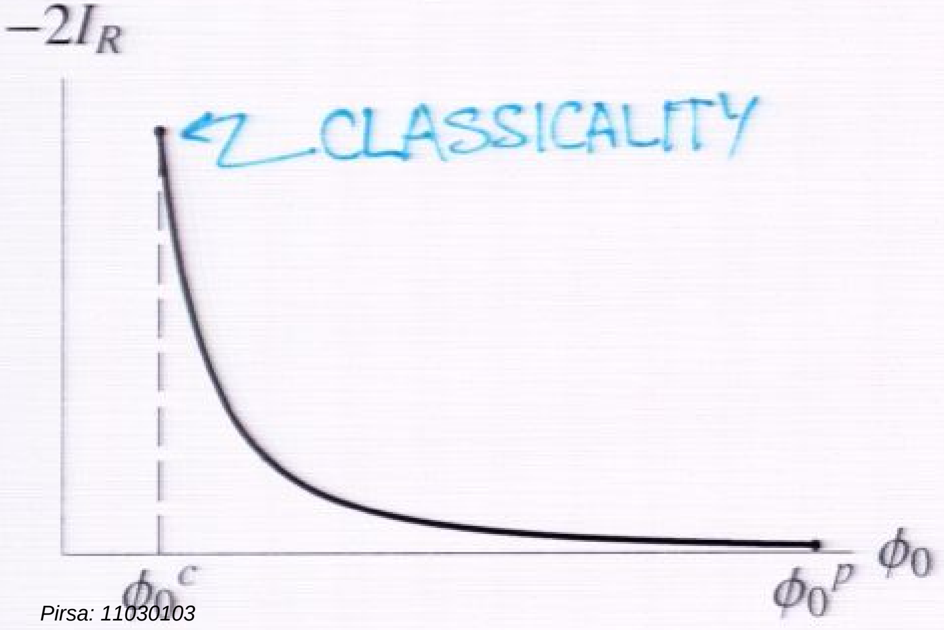

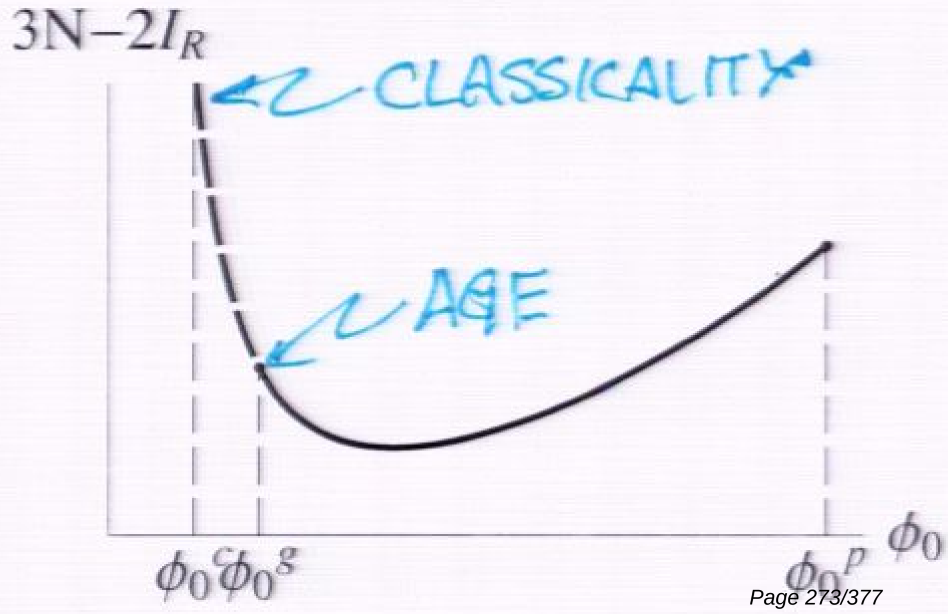

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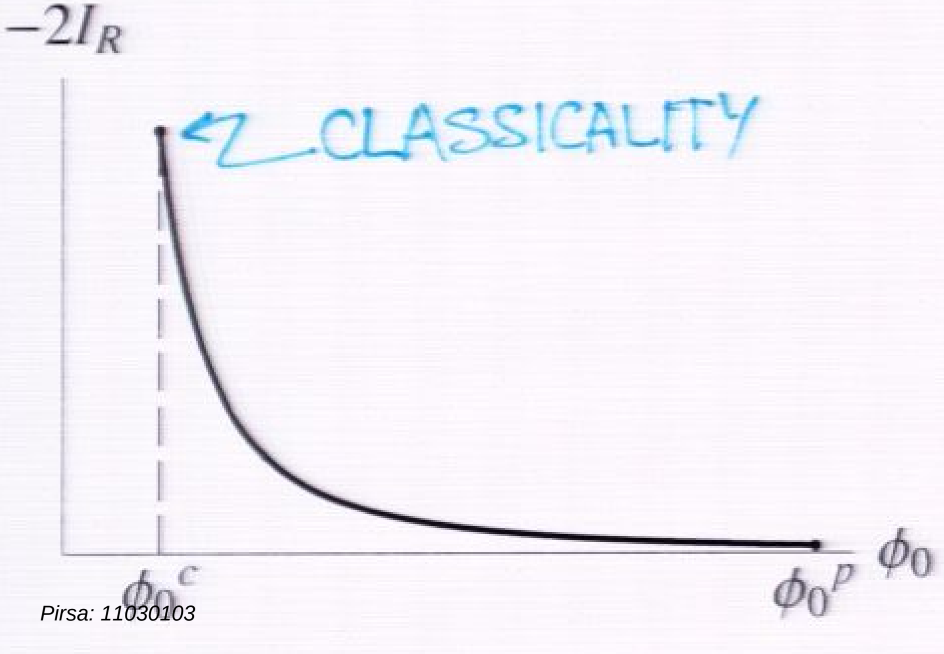

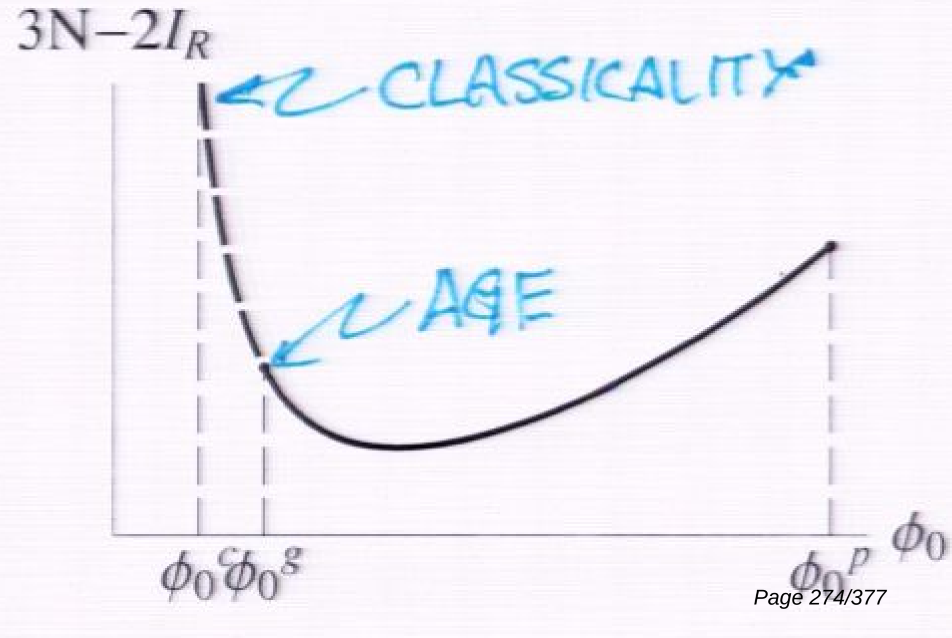

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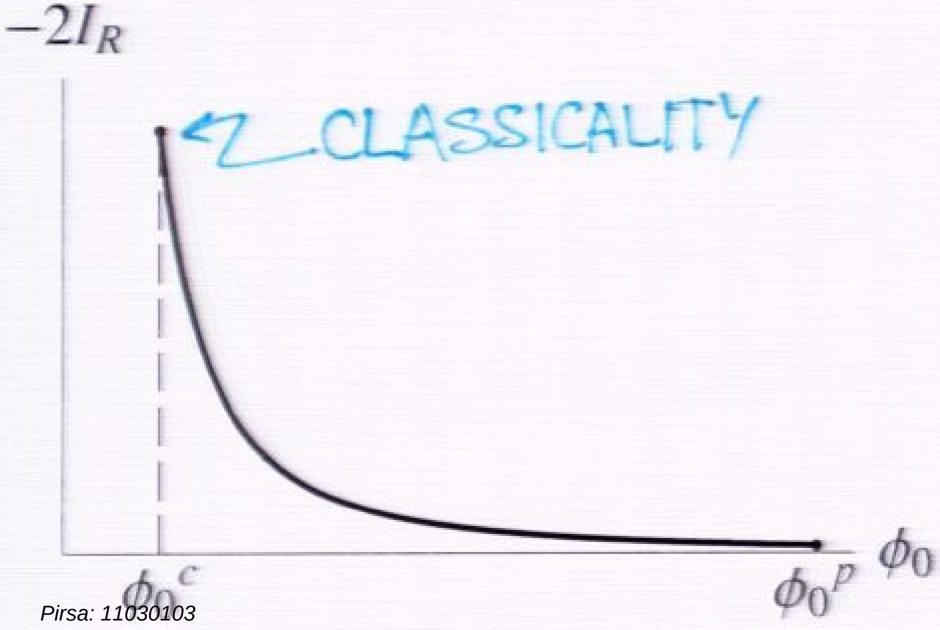

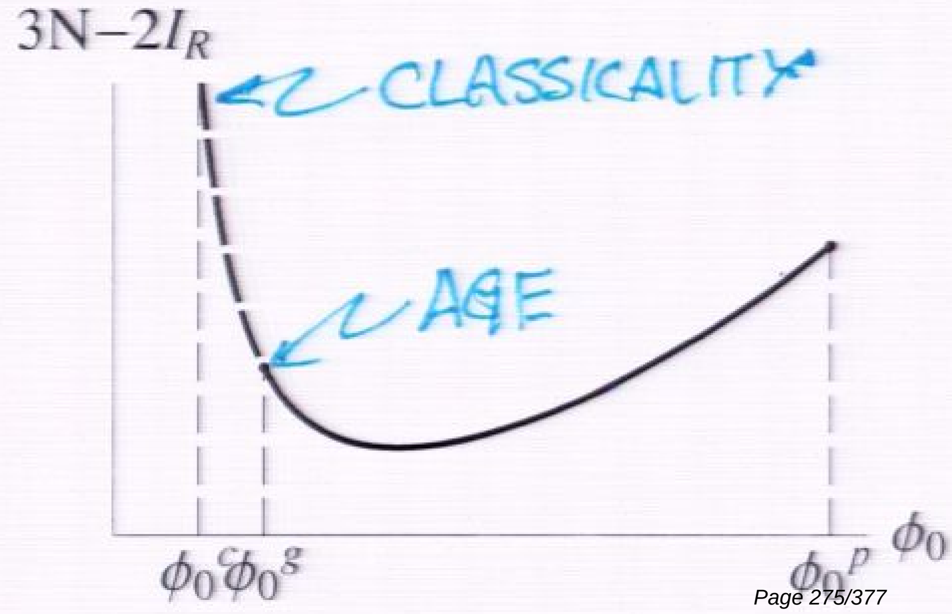

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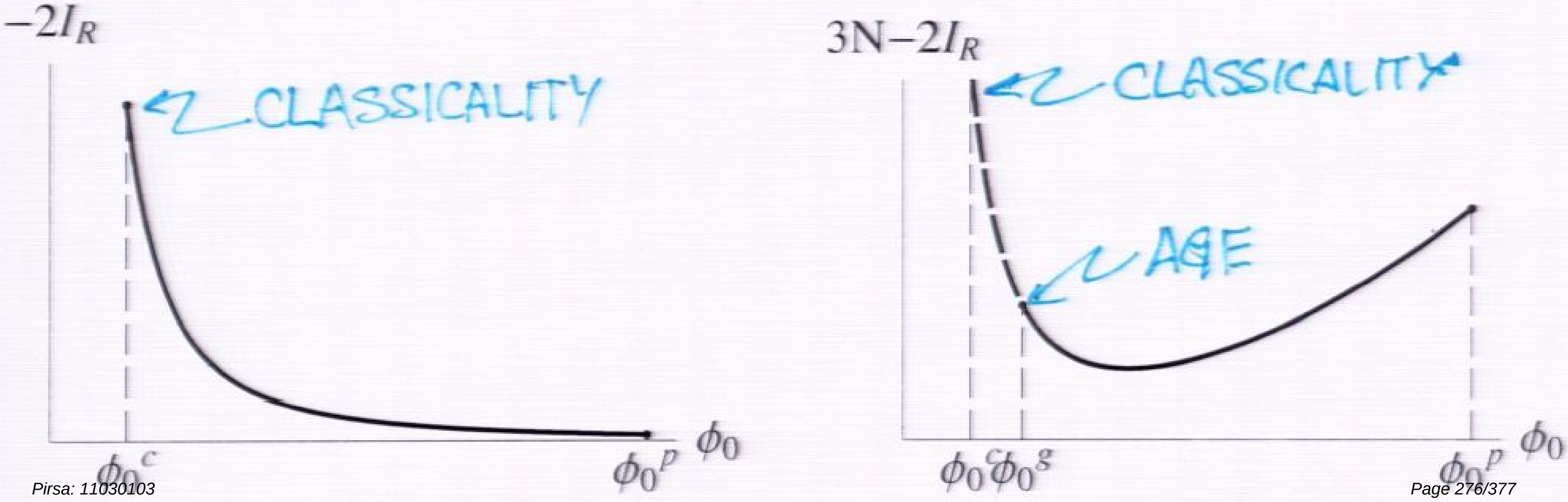

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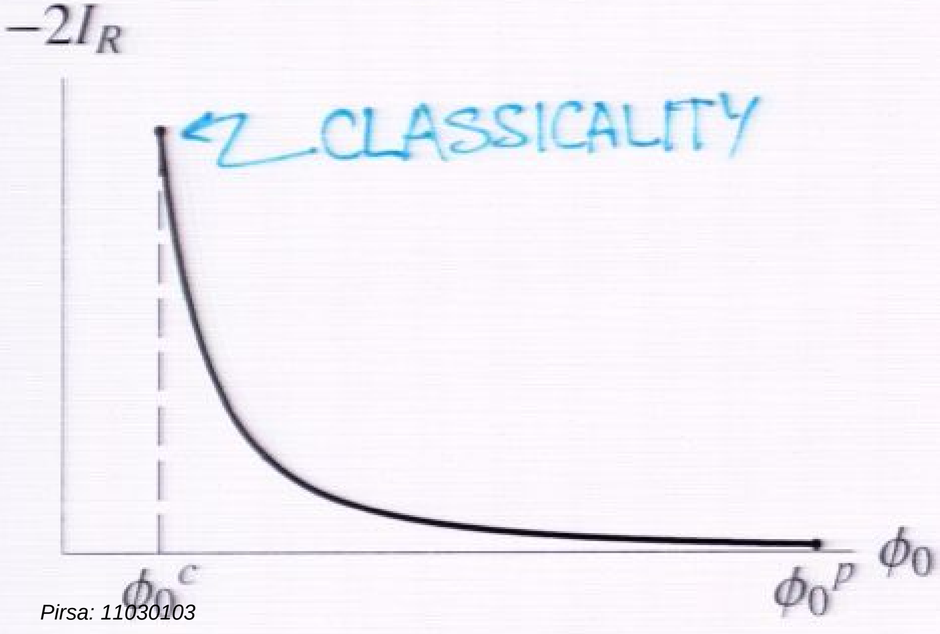

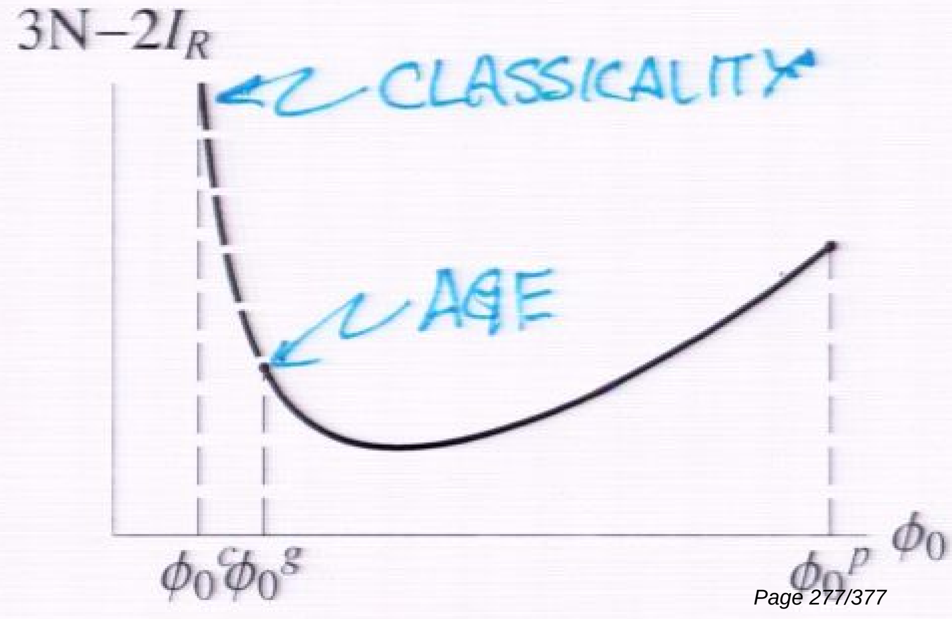

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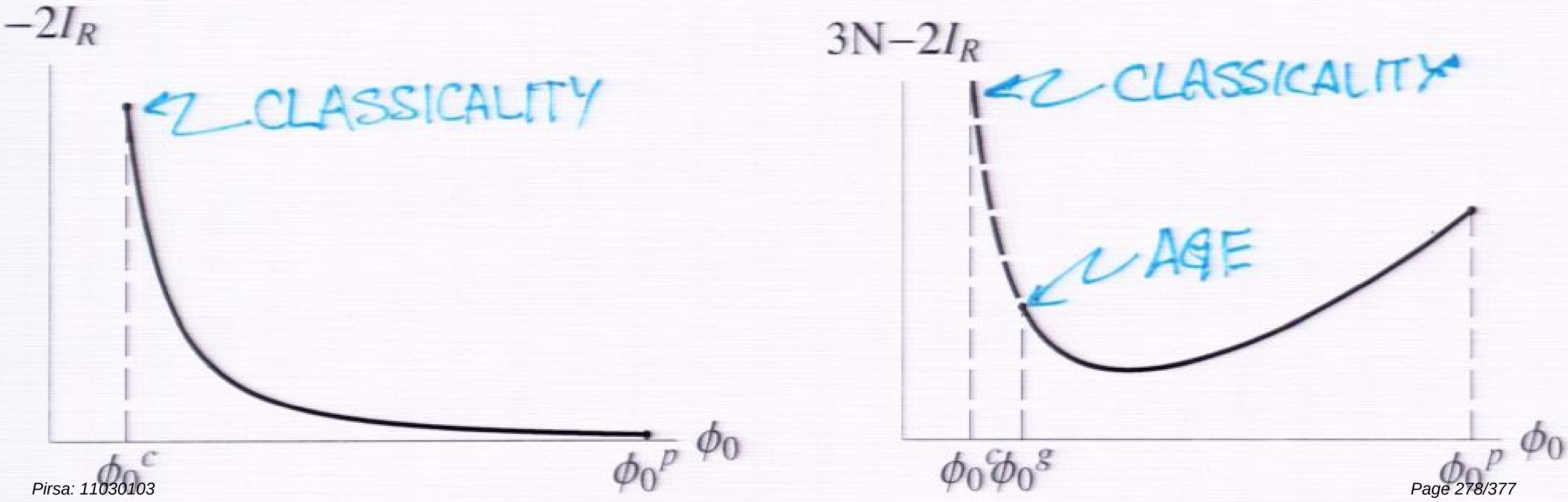

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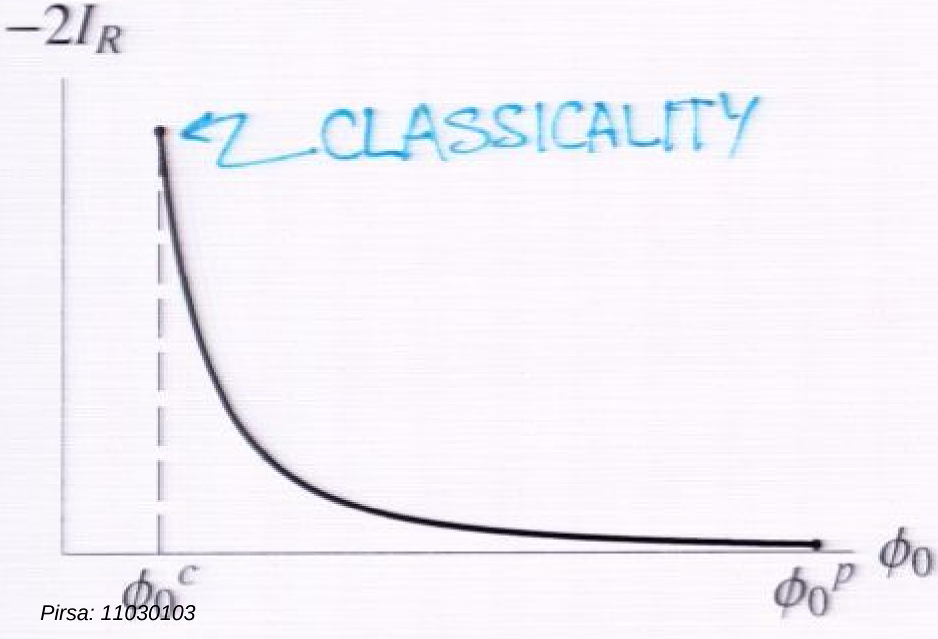

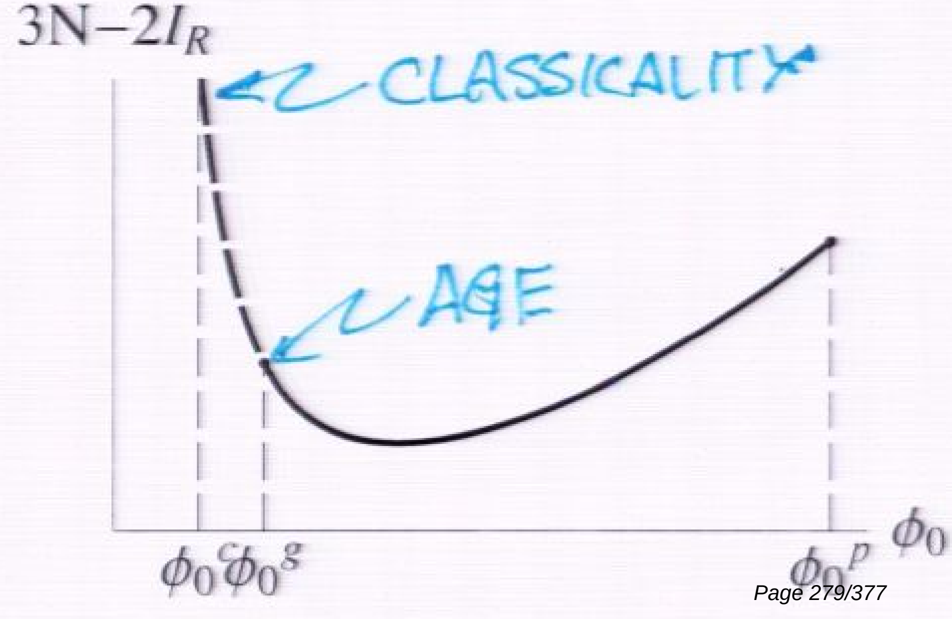

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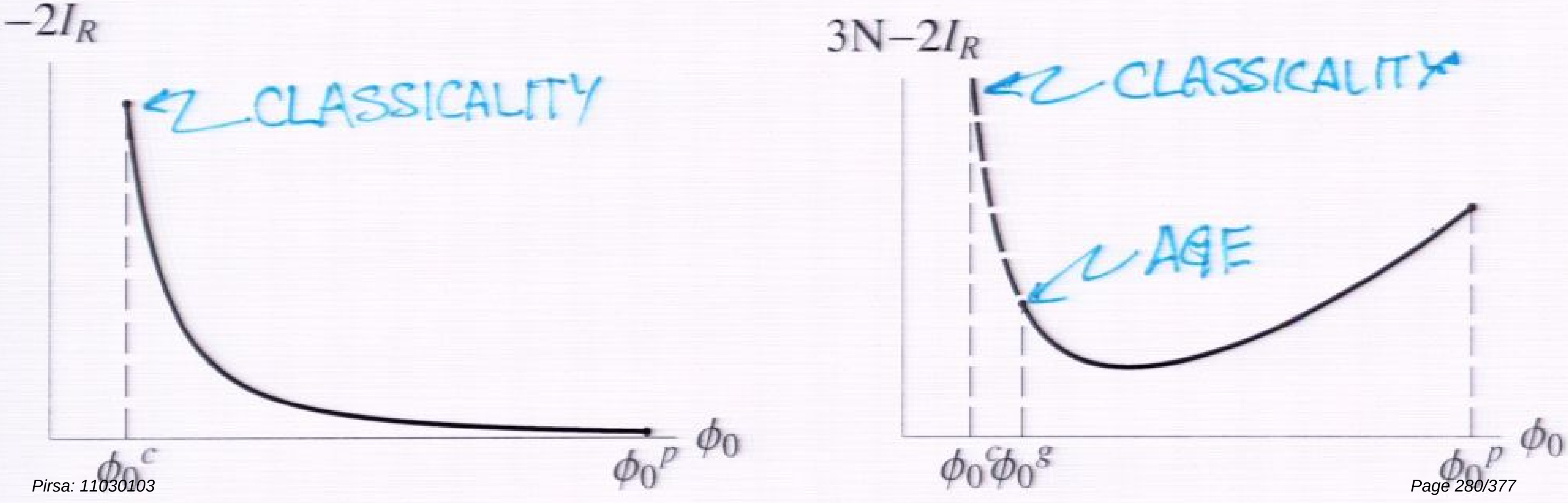

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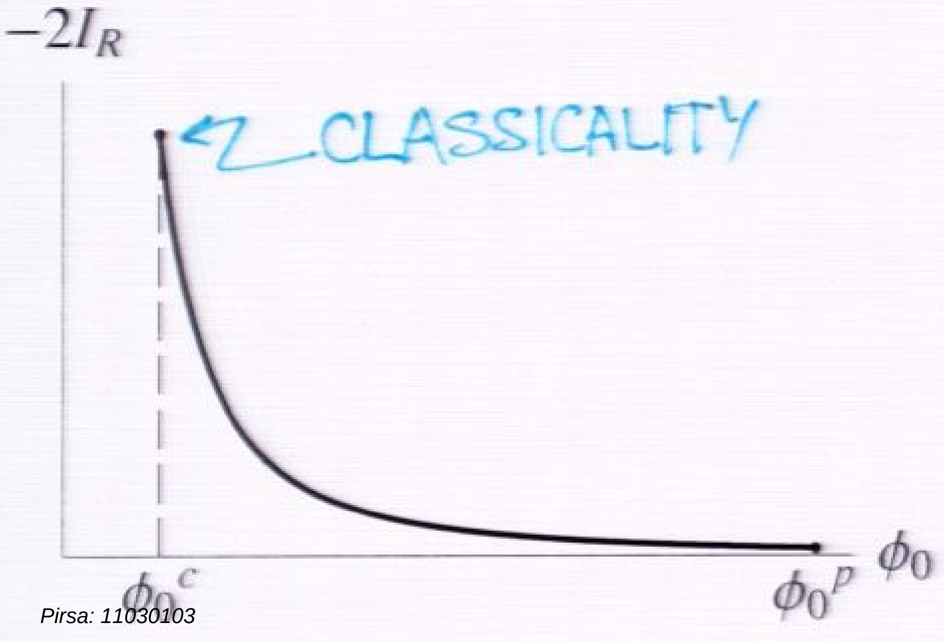

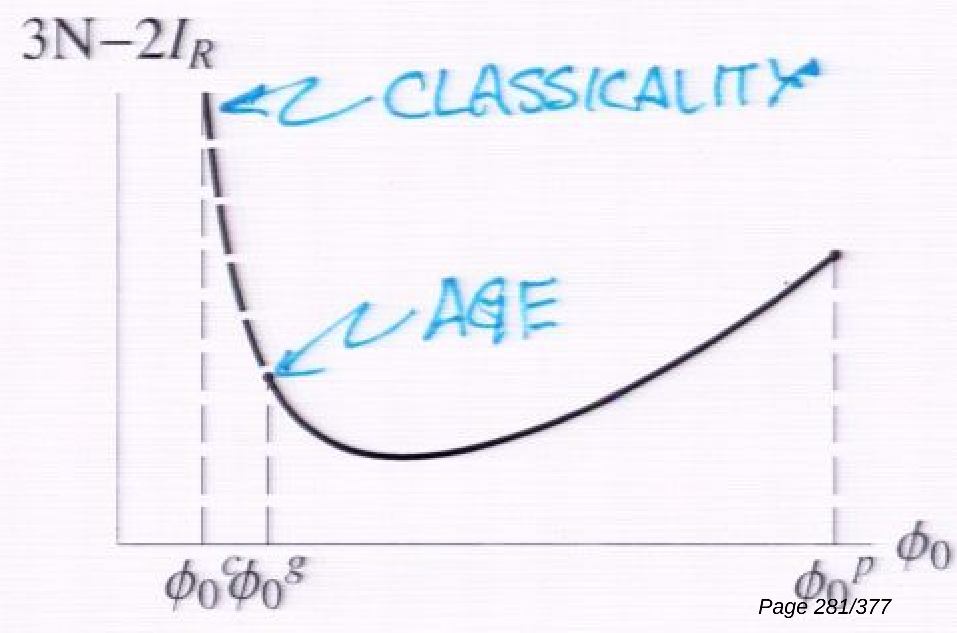

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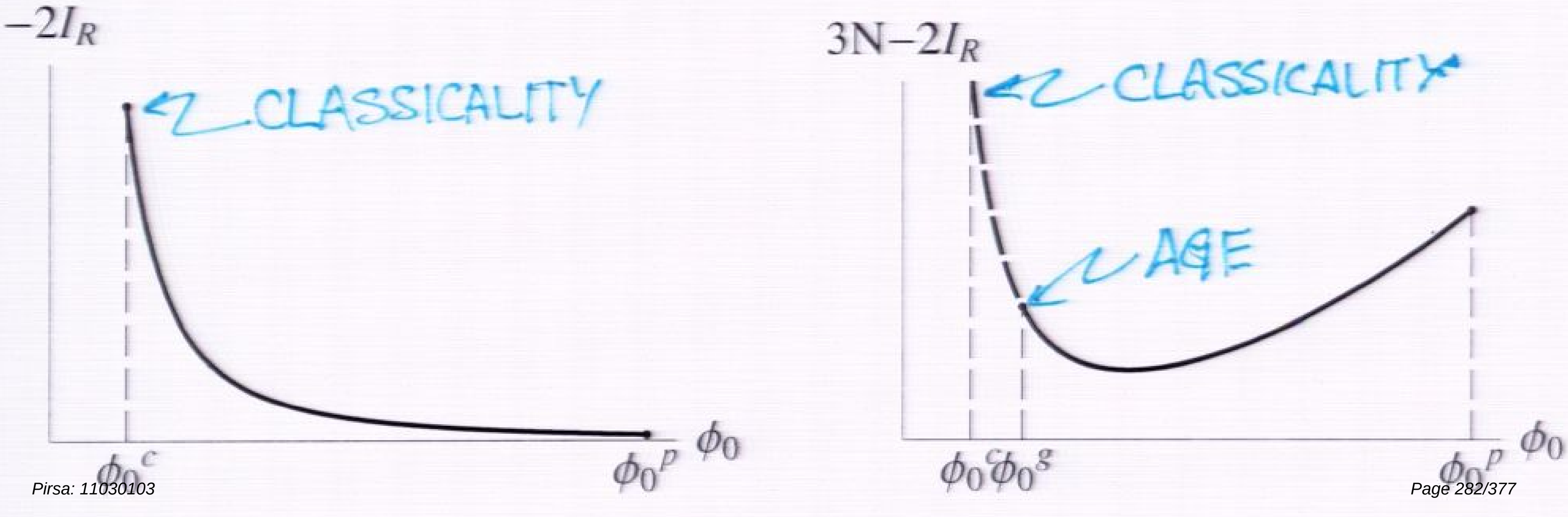

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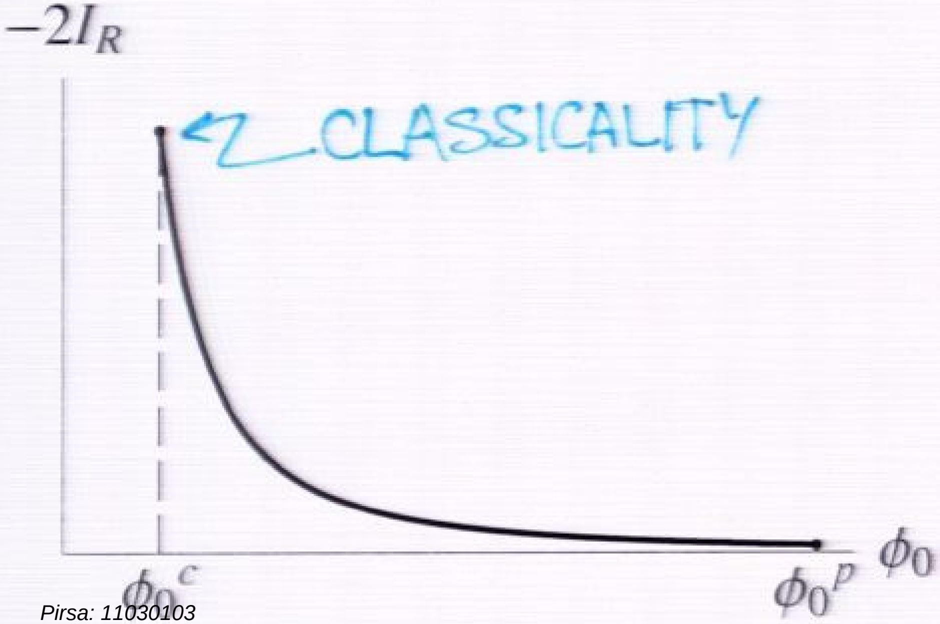

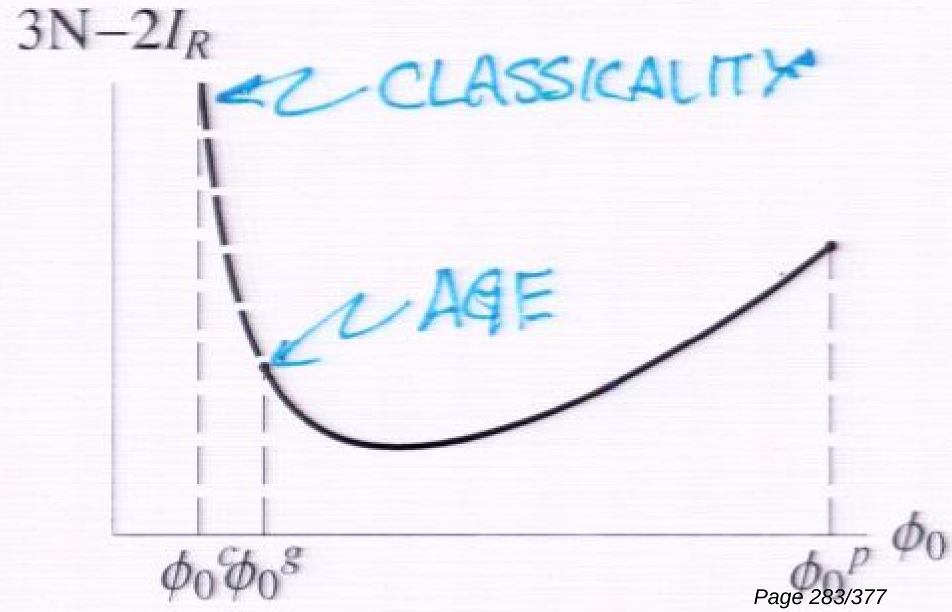

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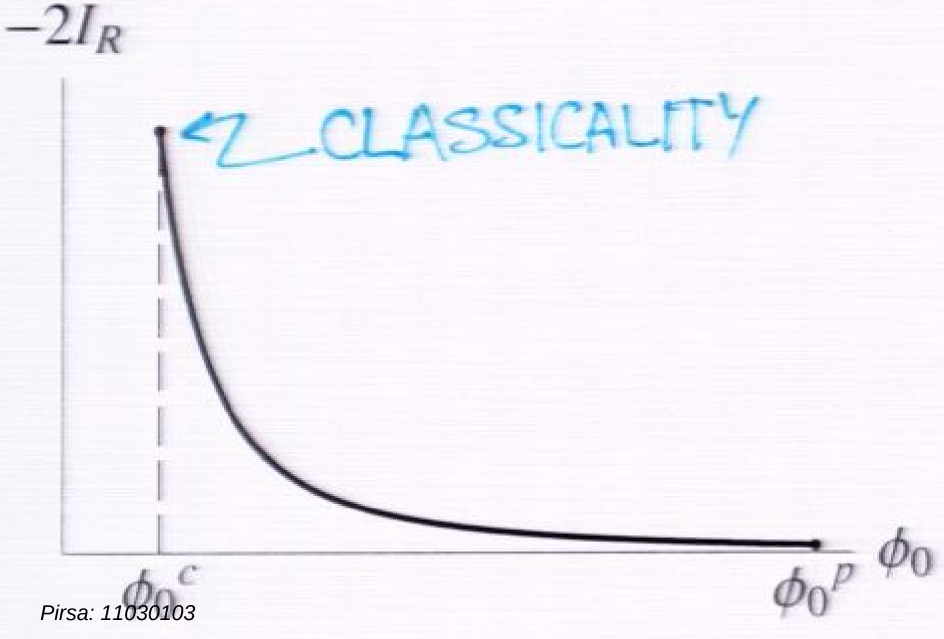

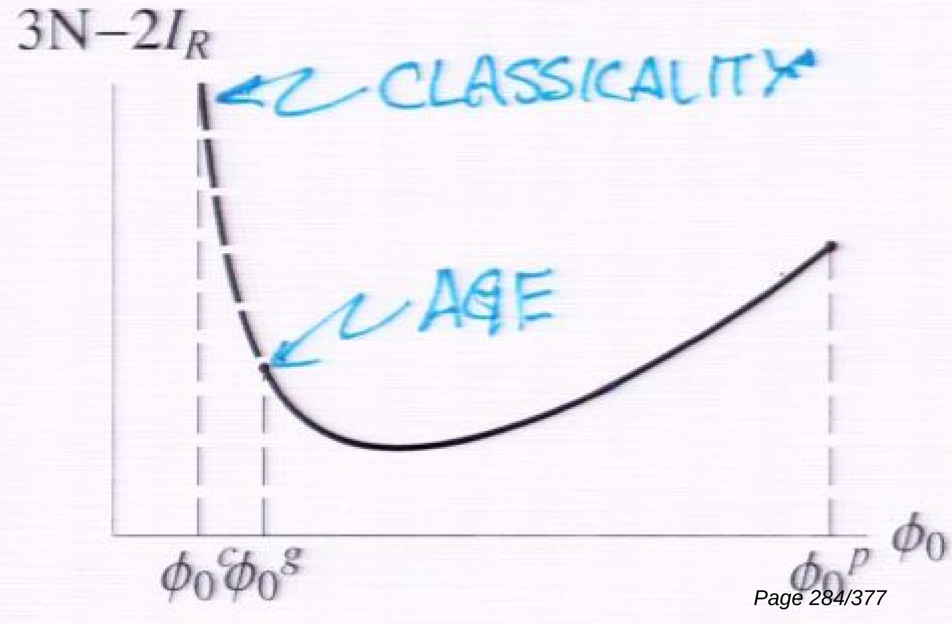

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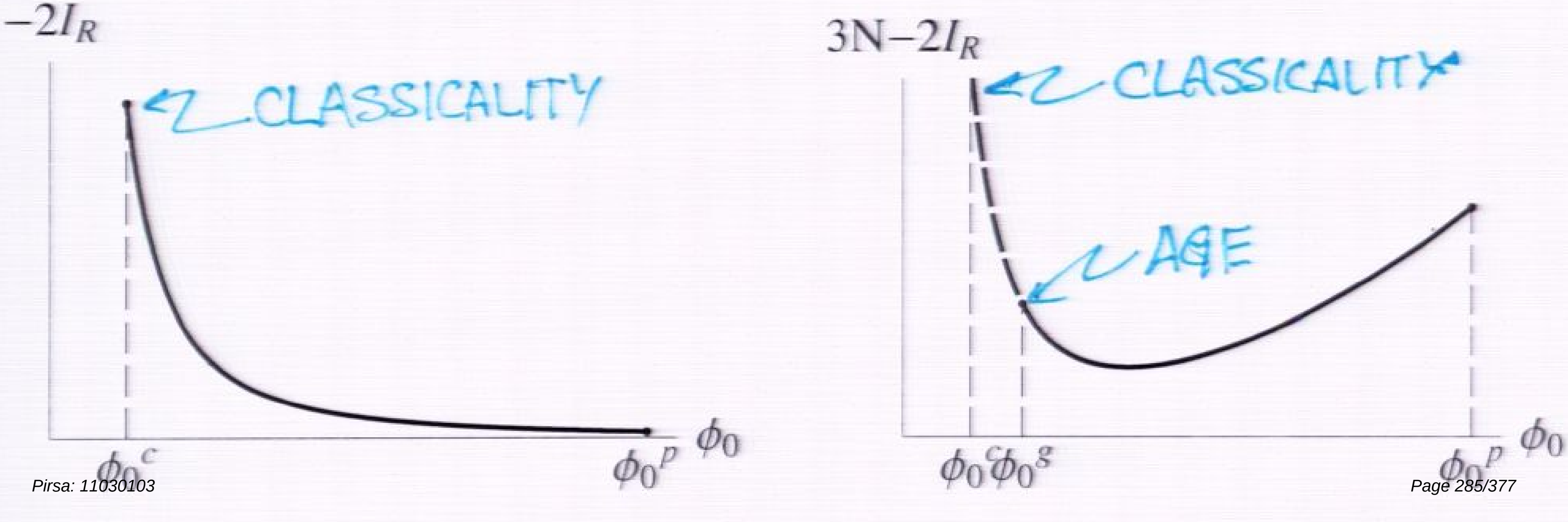

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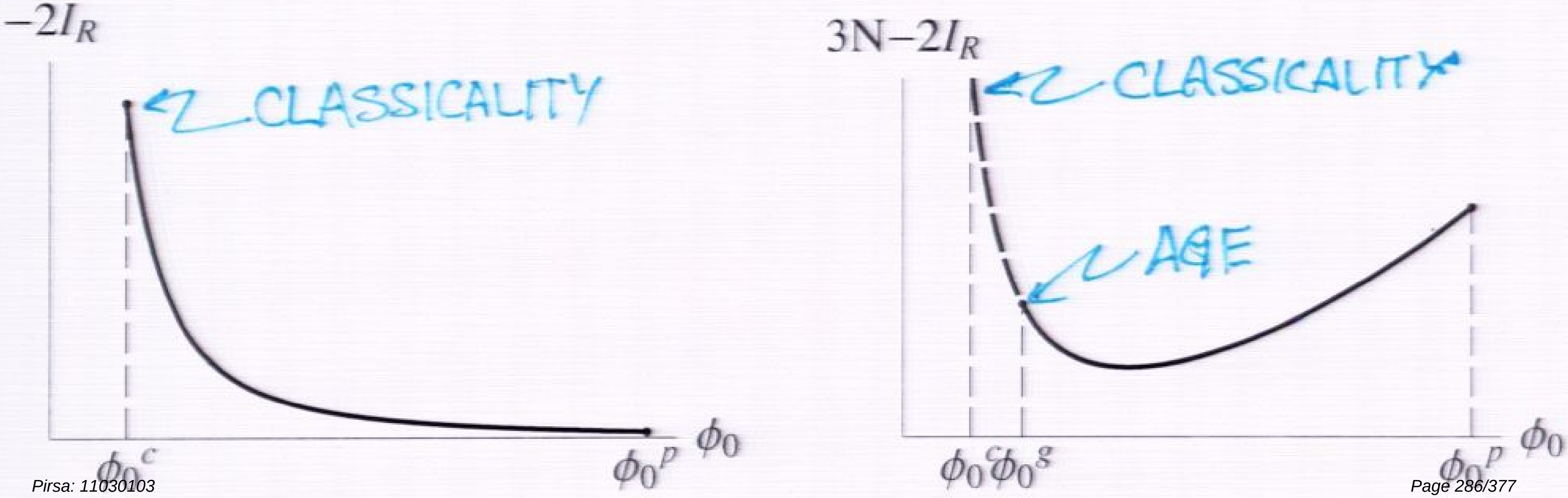

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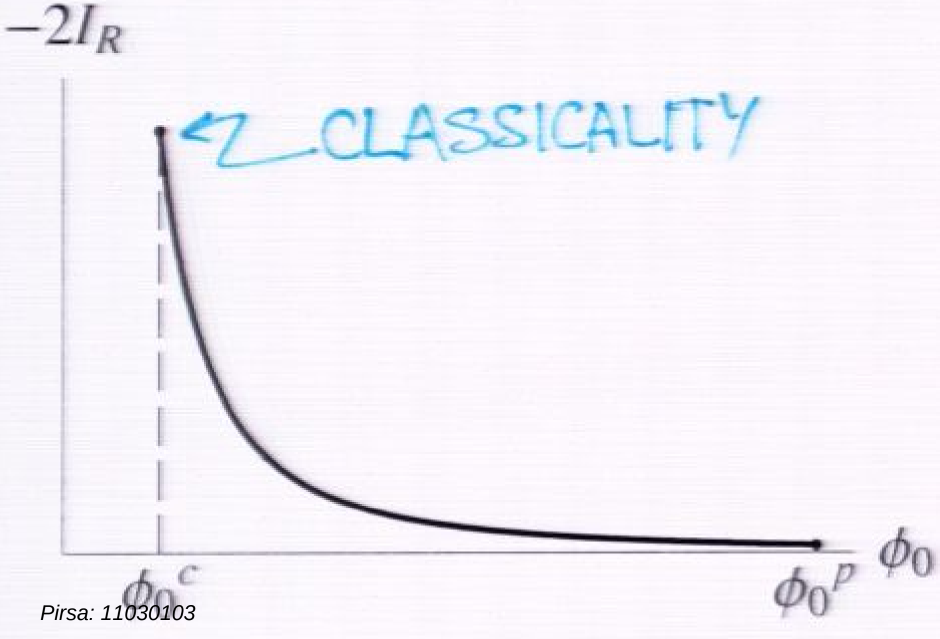

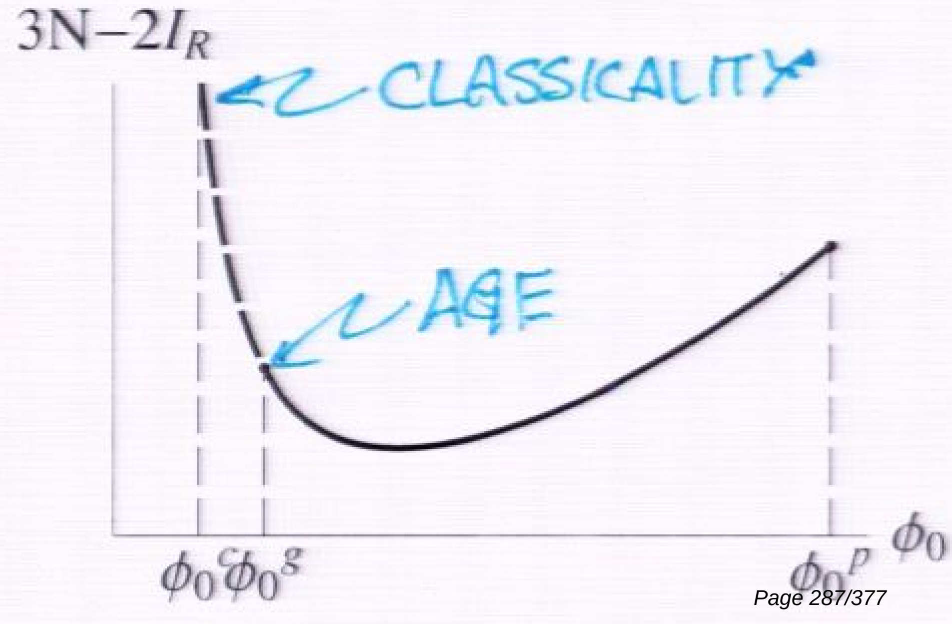

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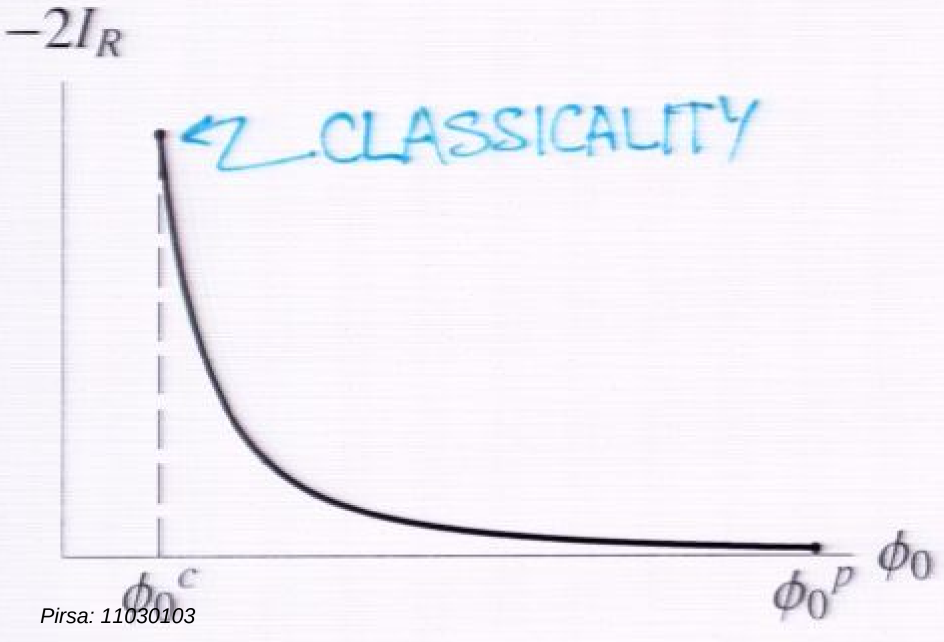

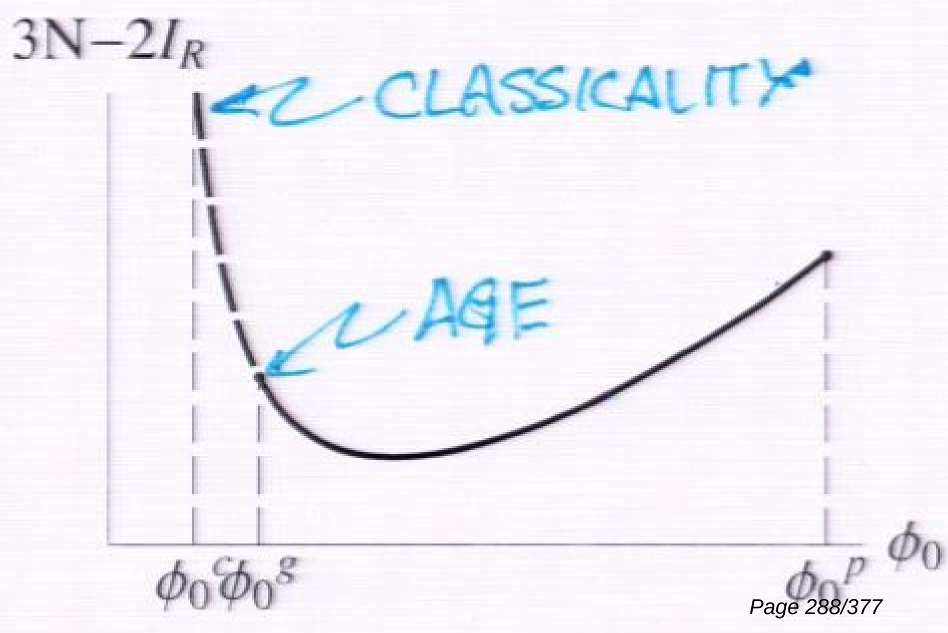

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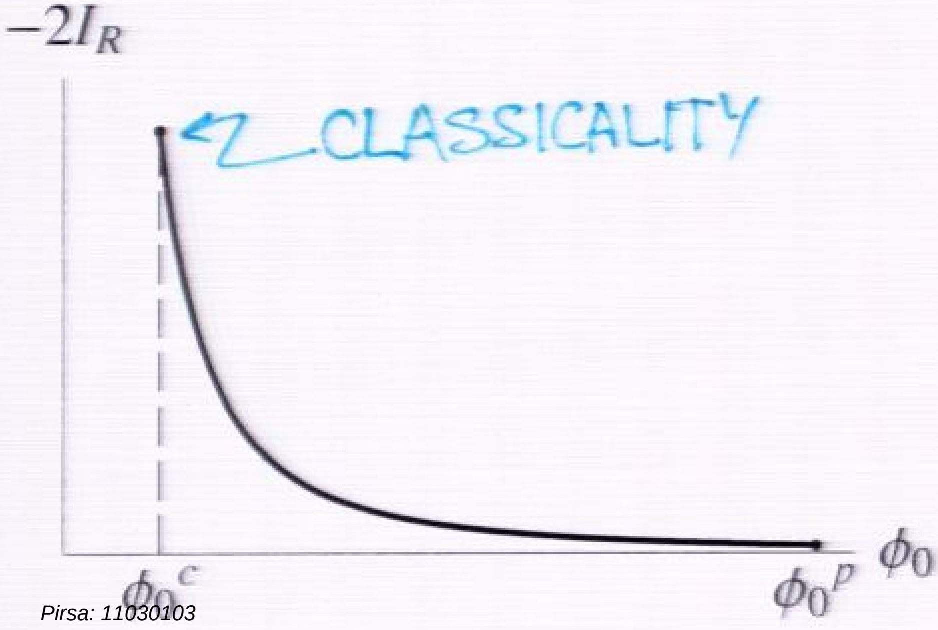

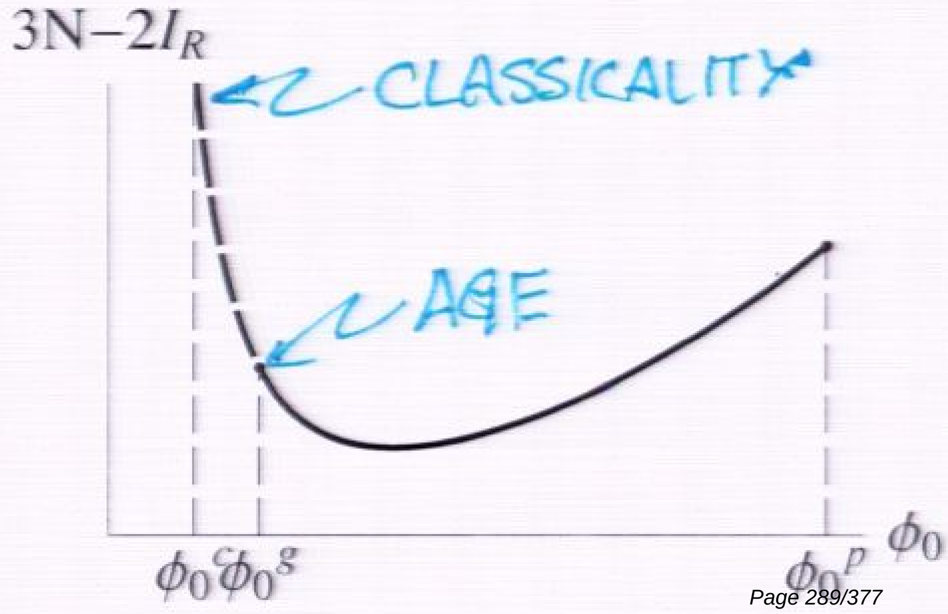

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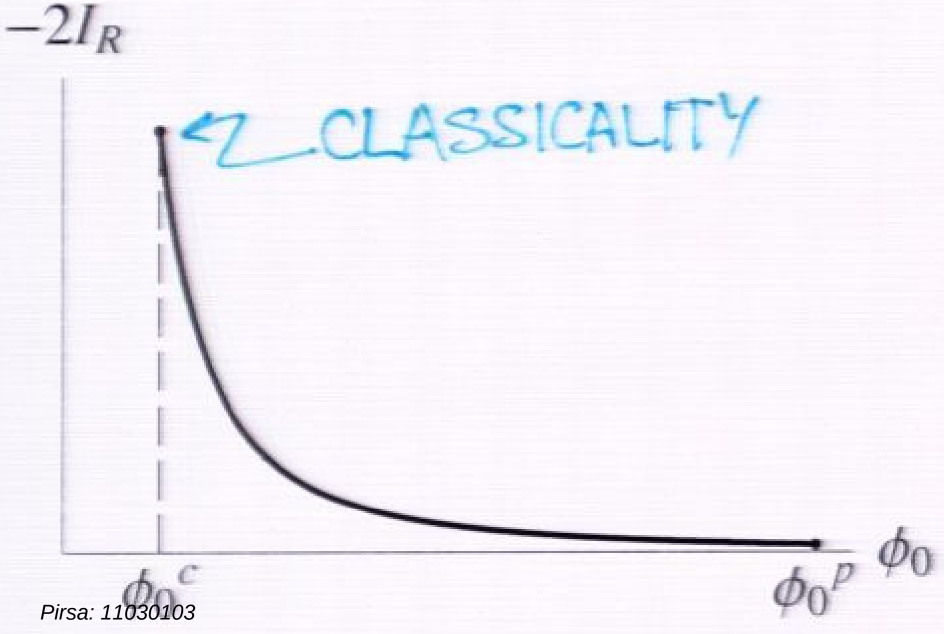

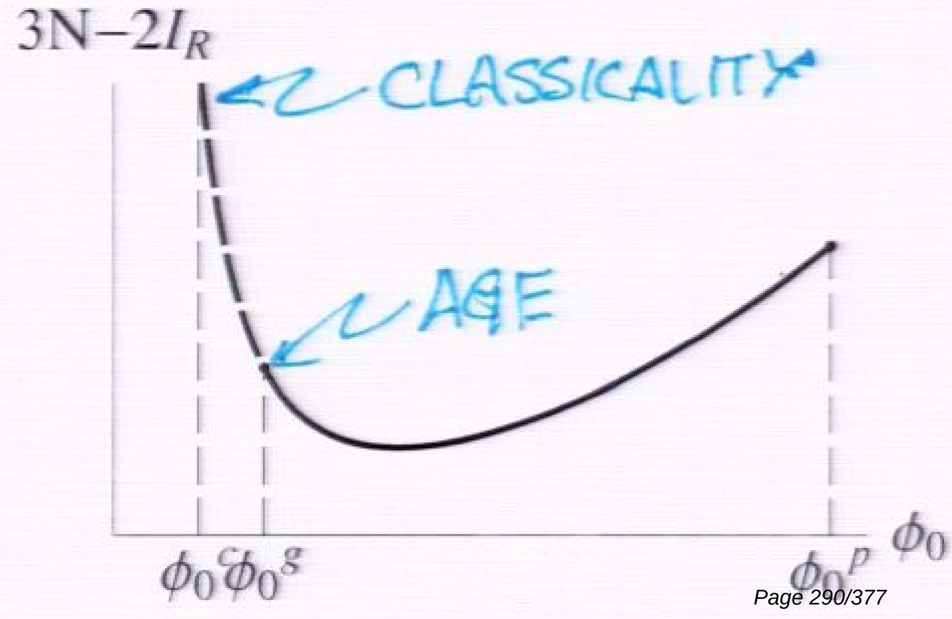

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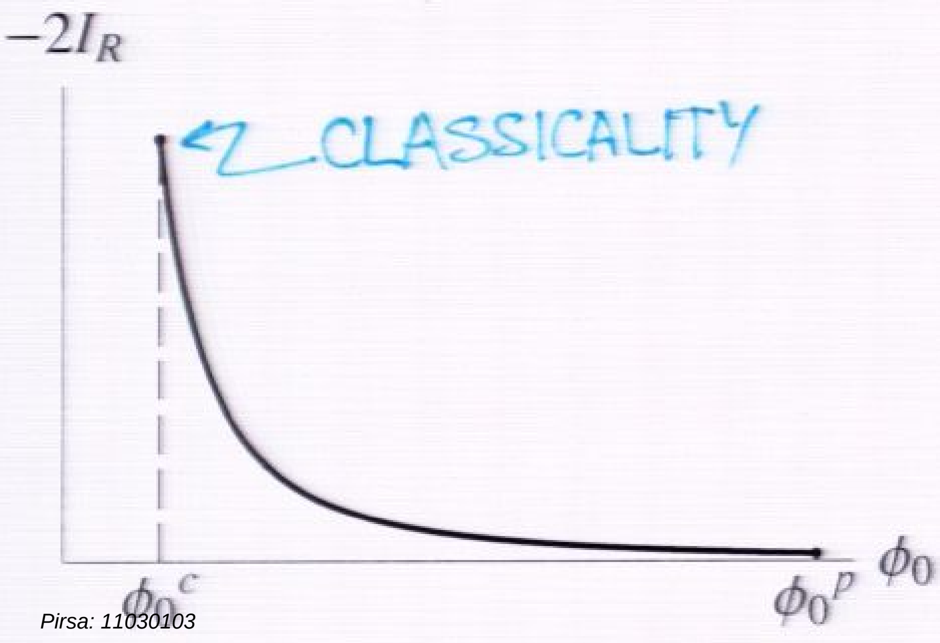

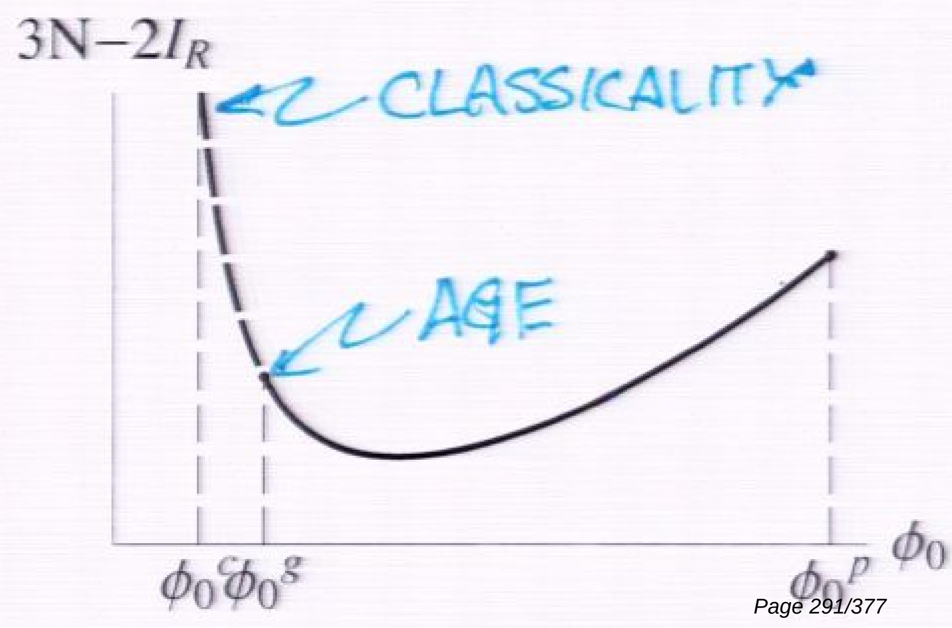

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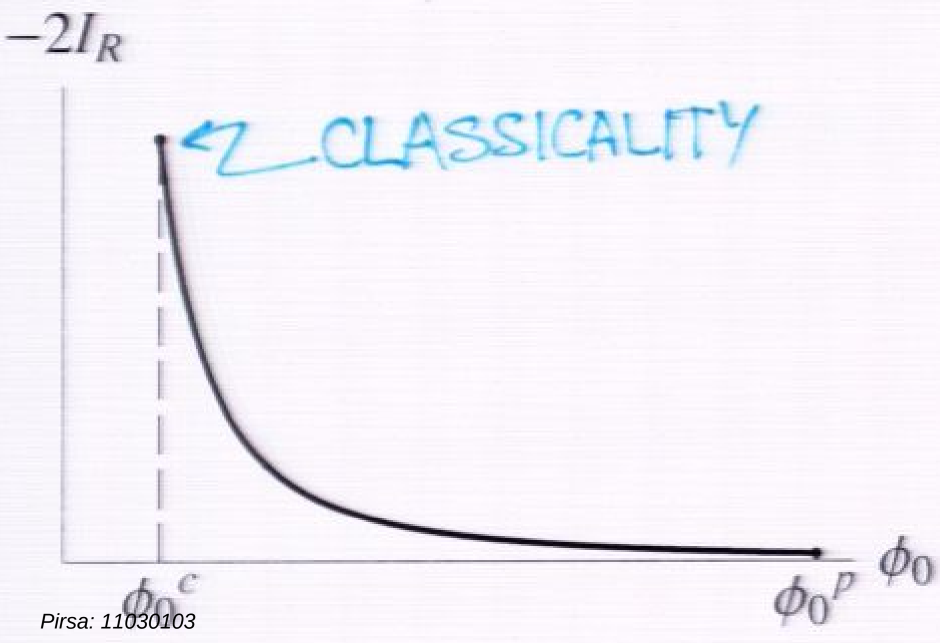

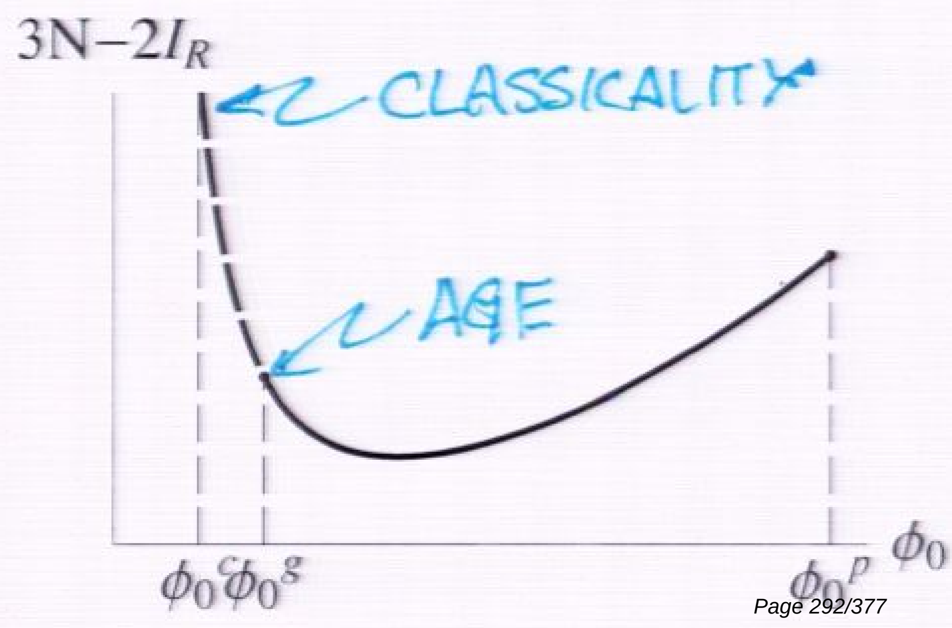

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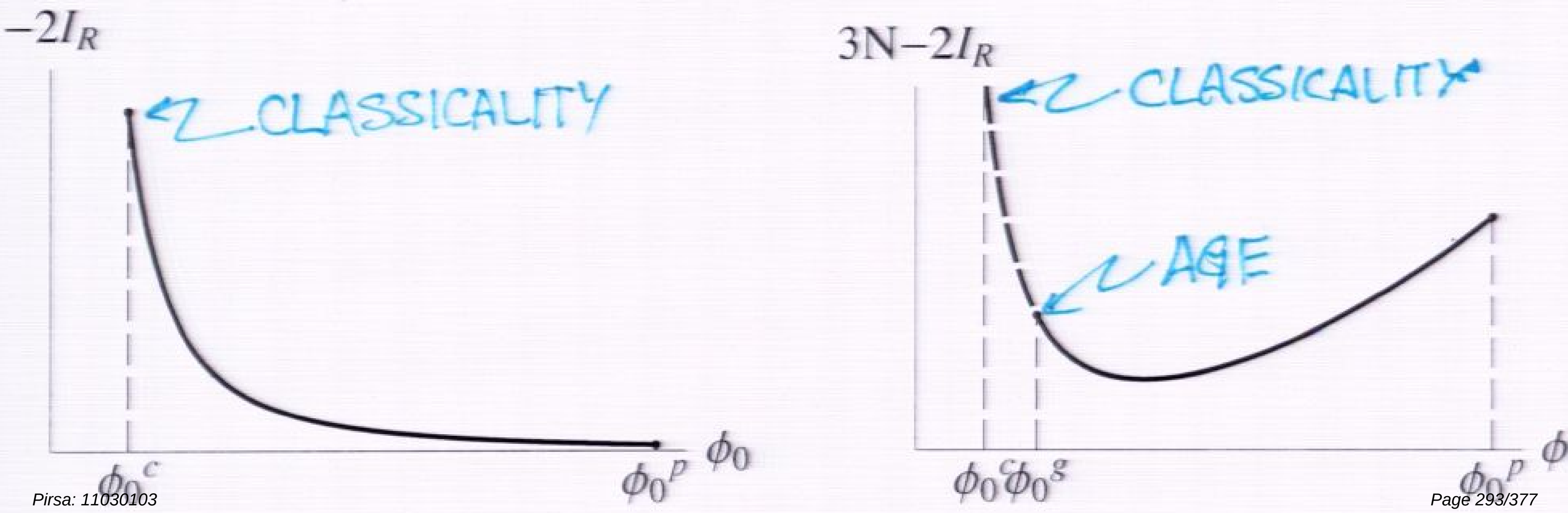

Fluctuations

- Scalar perturbations of metric and matter from homo/iso backgrounds labeled by φ_0 .
- Gauge+constraints leave one gauge-invariant combination ζ which can be expanded in S^3 harmonics.
- Action: $I = I^{(0)}[a(\tau), \phi(\tau)] + I^{(2)}[a(\tau), \phi(\tau), \zeta(\tau)].$
- NBWF: $\Psi(b, \chi, z) \approx \exp\{[-I_R^{(0)}(b, \chi) + iS^{(0)}(b, \chi)]/\hbar\}\psi(b, \chi, z).$

$$\psi(b, \chi, z) \equiv \int_{\mathcal{C}} \delta\zeta \exp(-I^{(2)}[a(\tau), \phi(\tau), \zeta(\tau)]/\hbar).$$

- This is QFTCST for the fluctuation fields in the homo/iso background.

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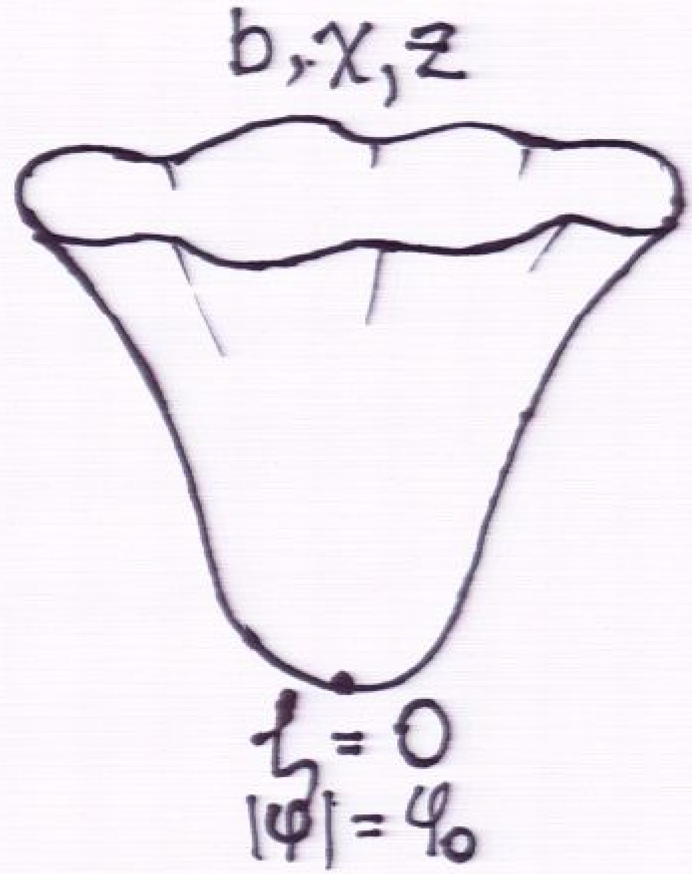
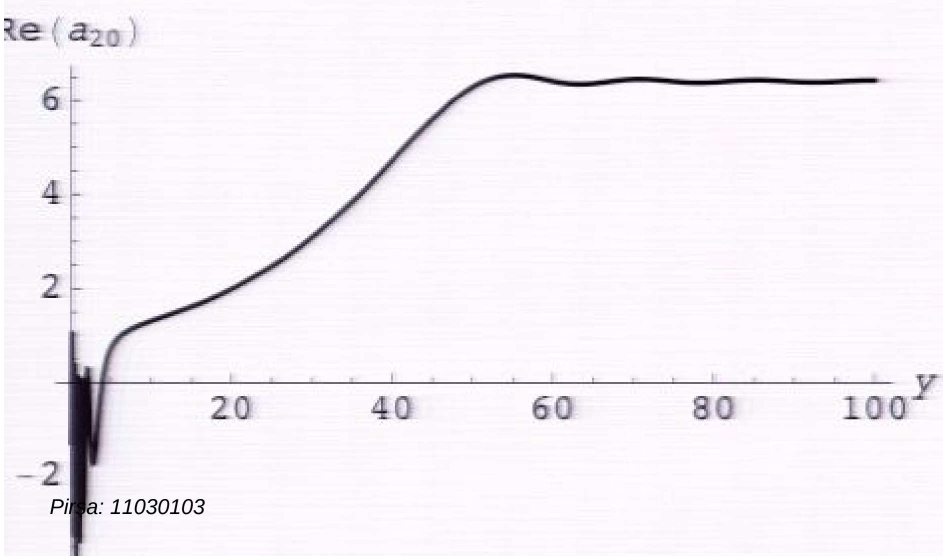
Regularity at the SP and matching at the boundary determine a unique complex fuzzy instanton giving the semiclassical approx to the NBWF path integral.





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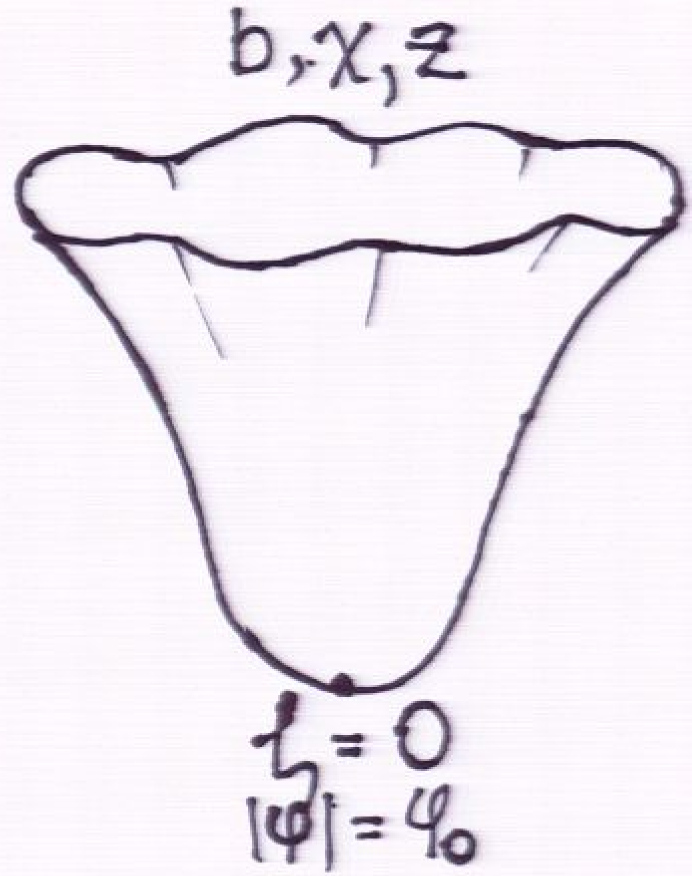

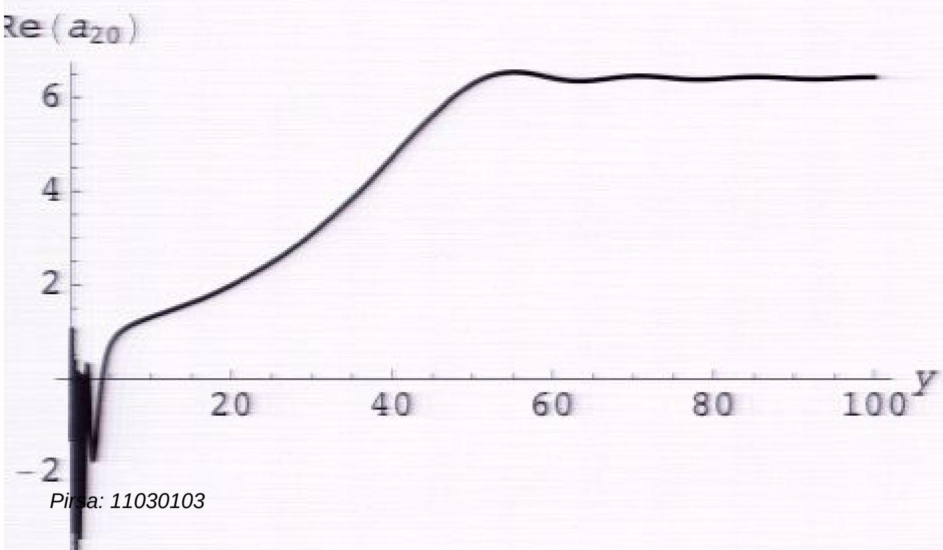

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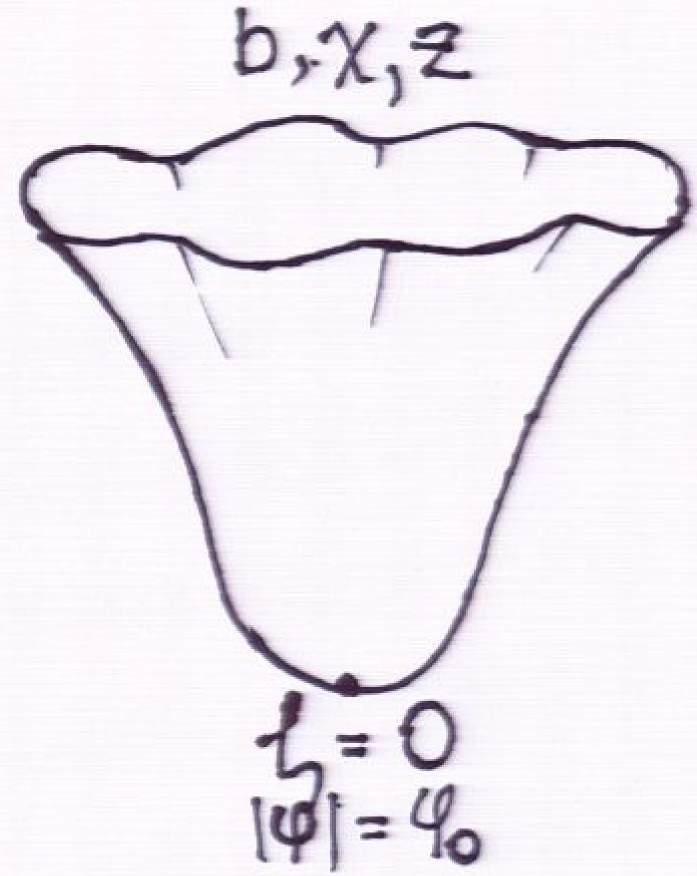

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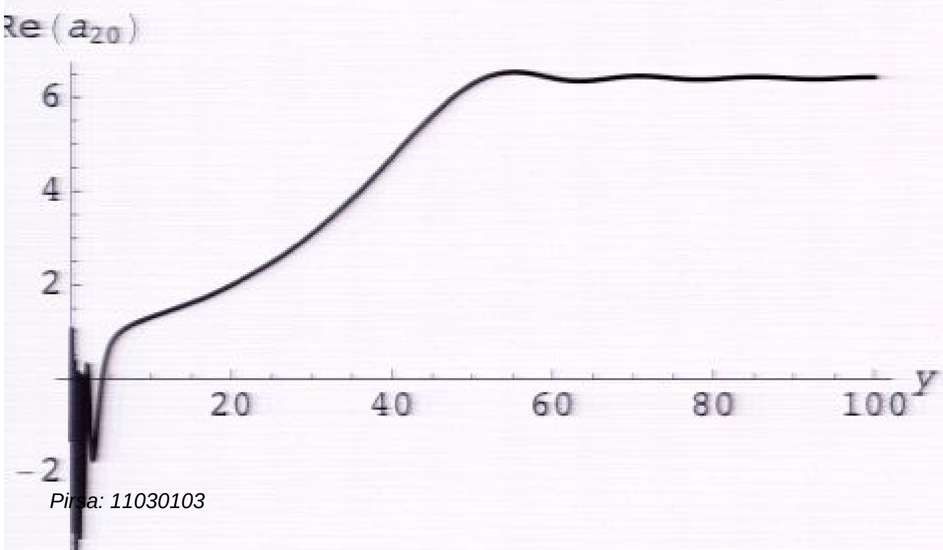

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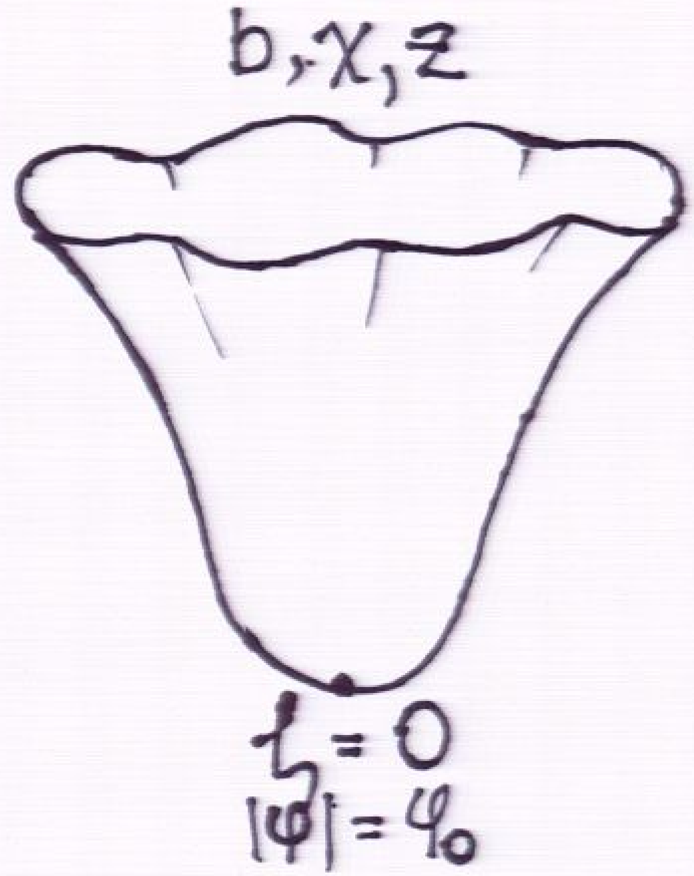

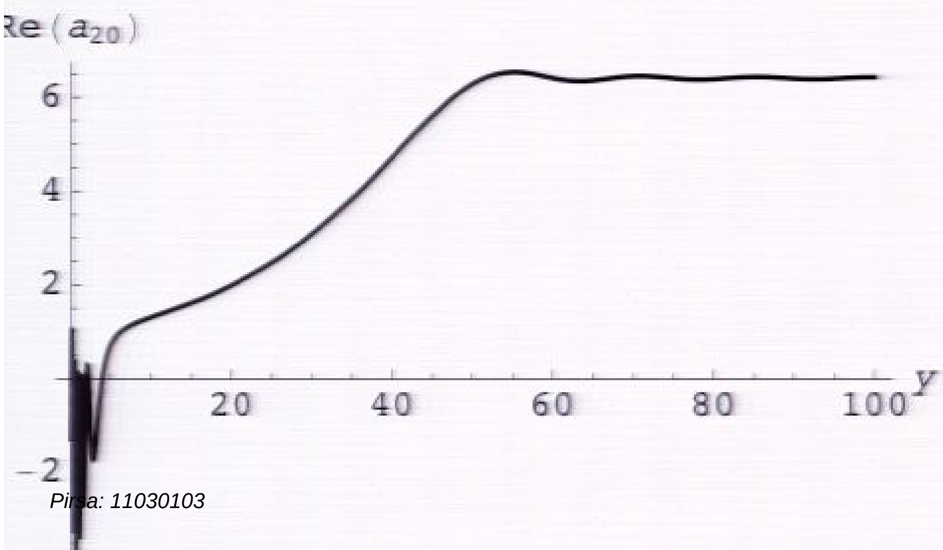

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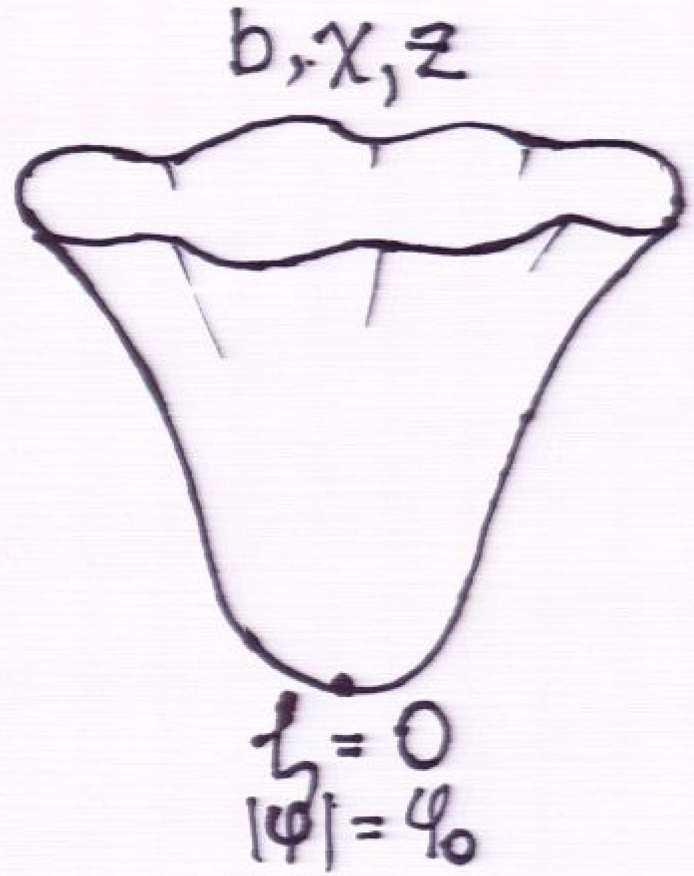

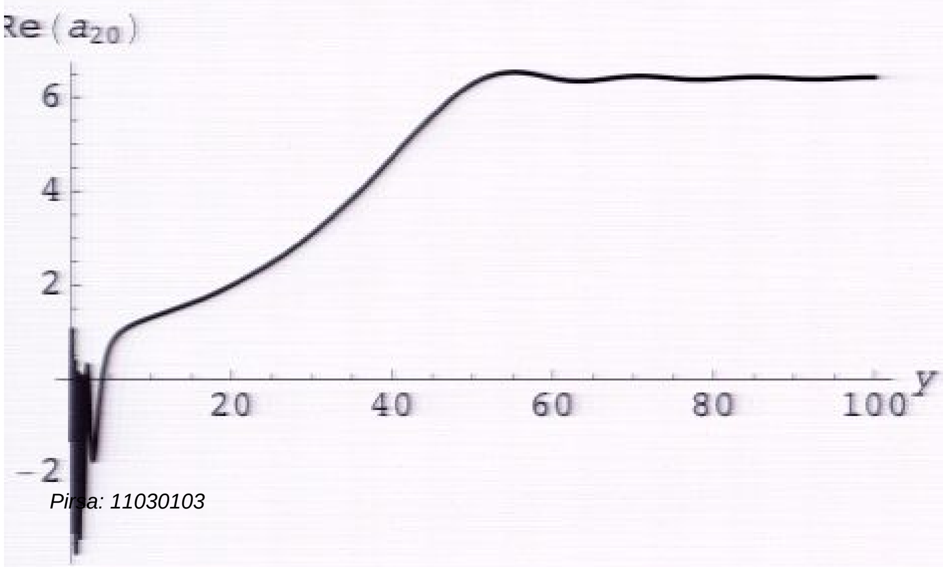

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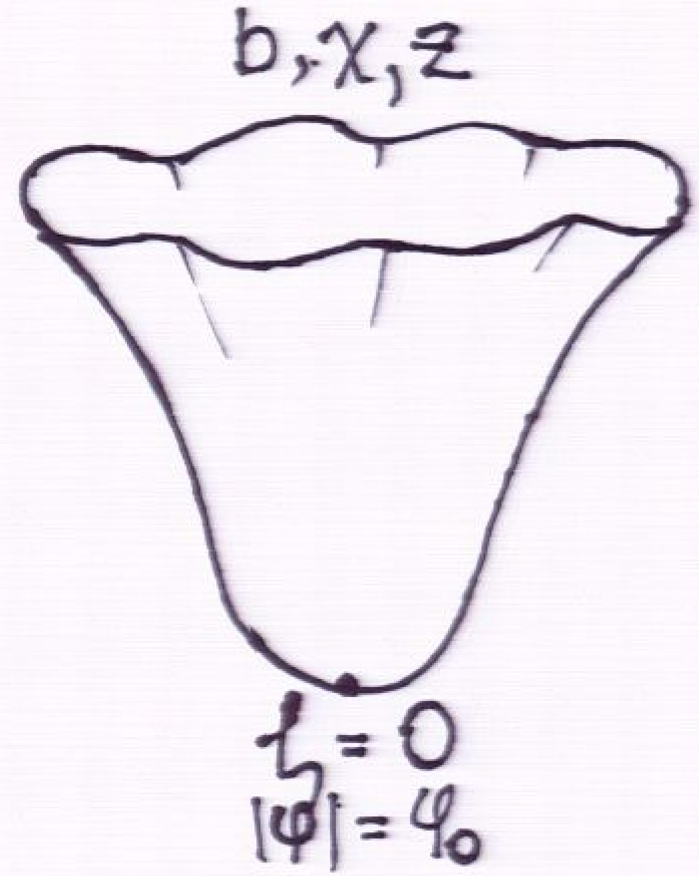

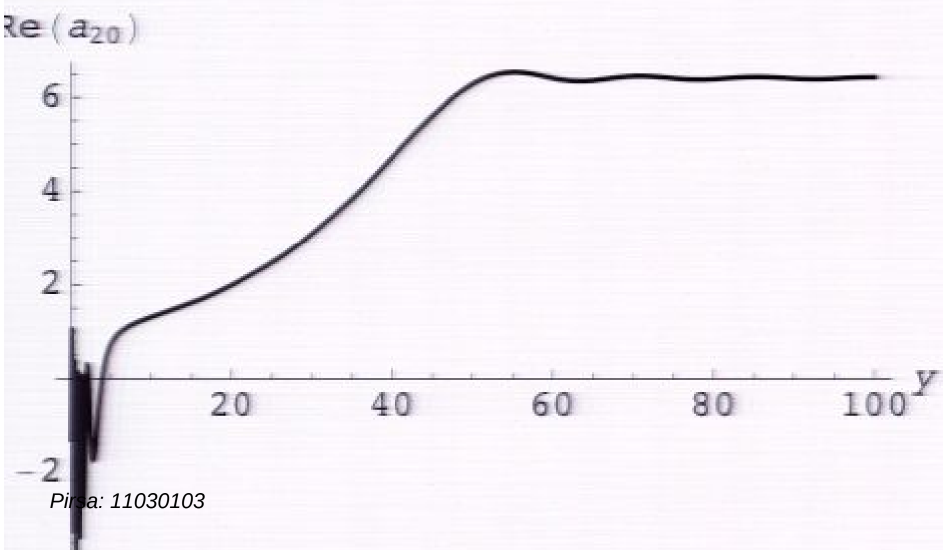

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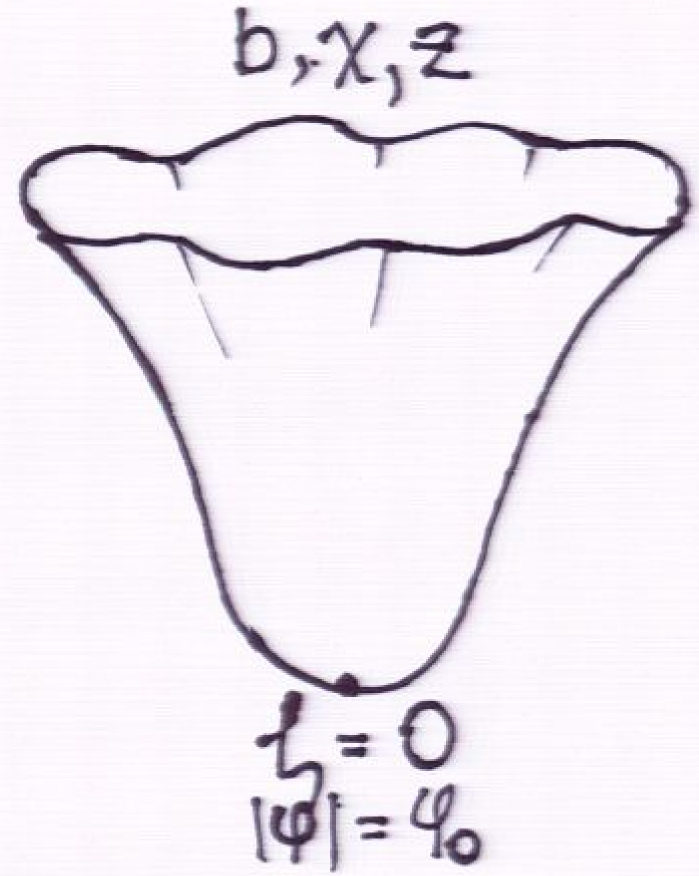

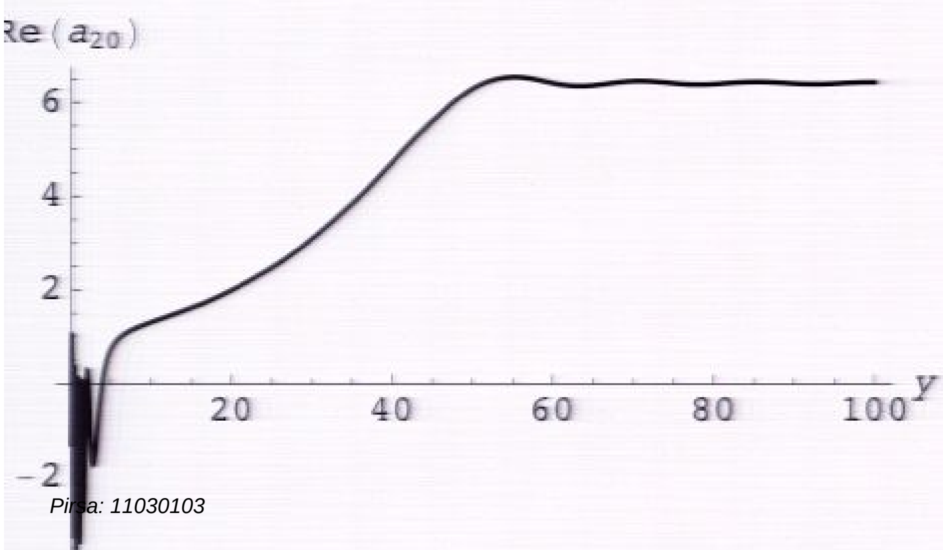

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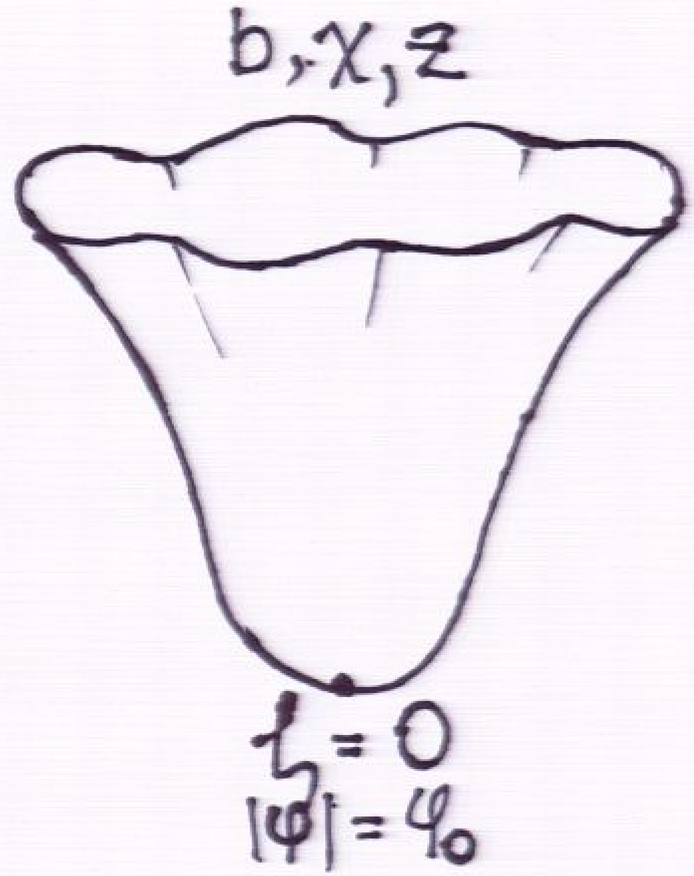

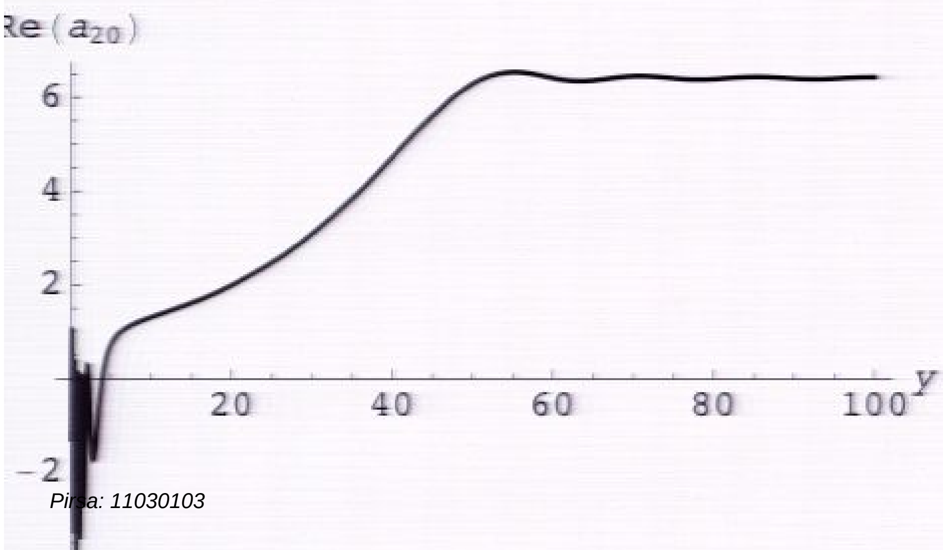

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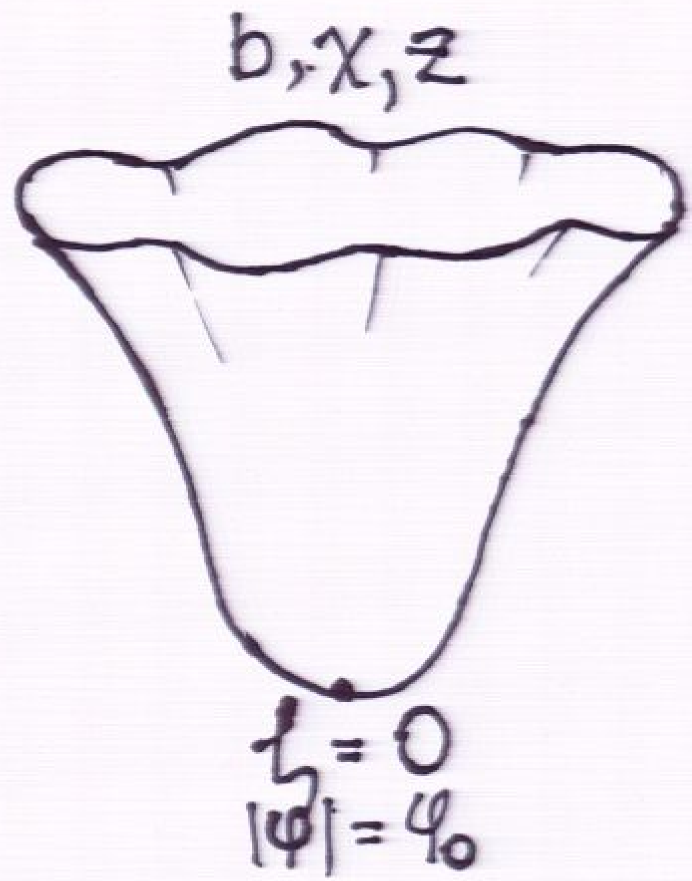

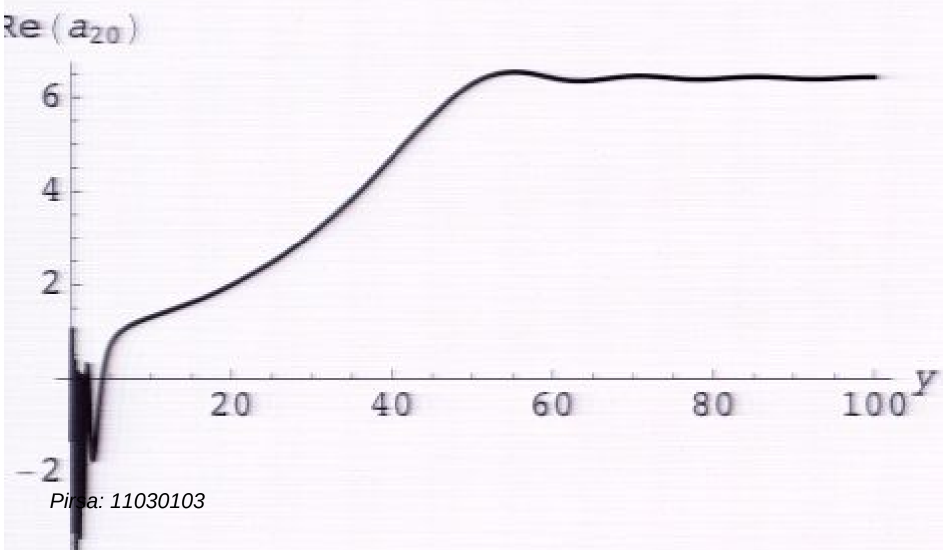

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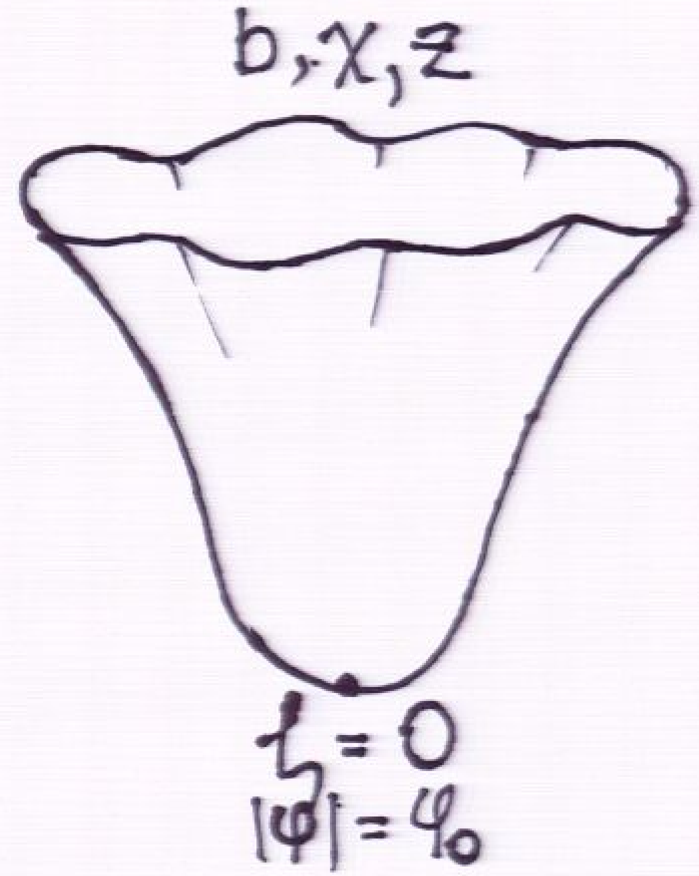

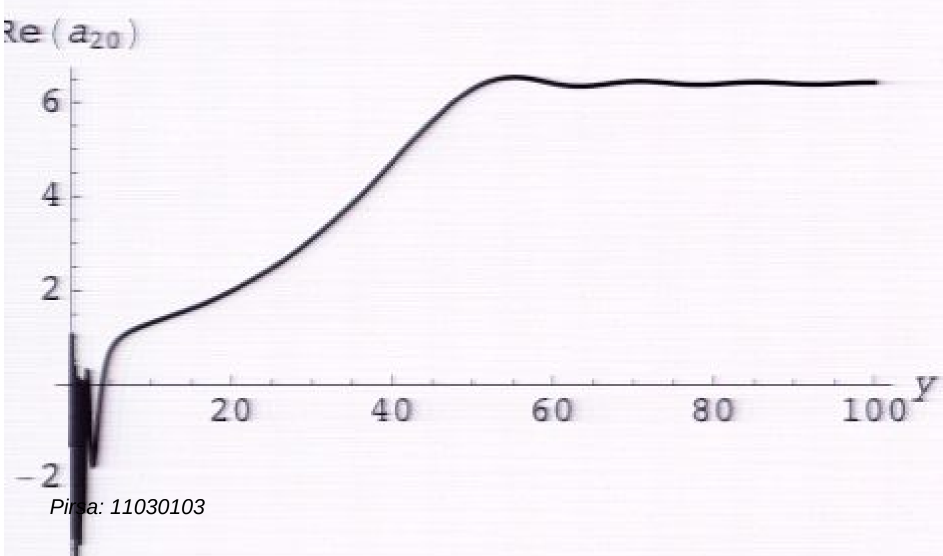

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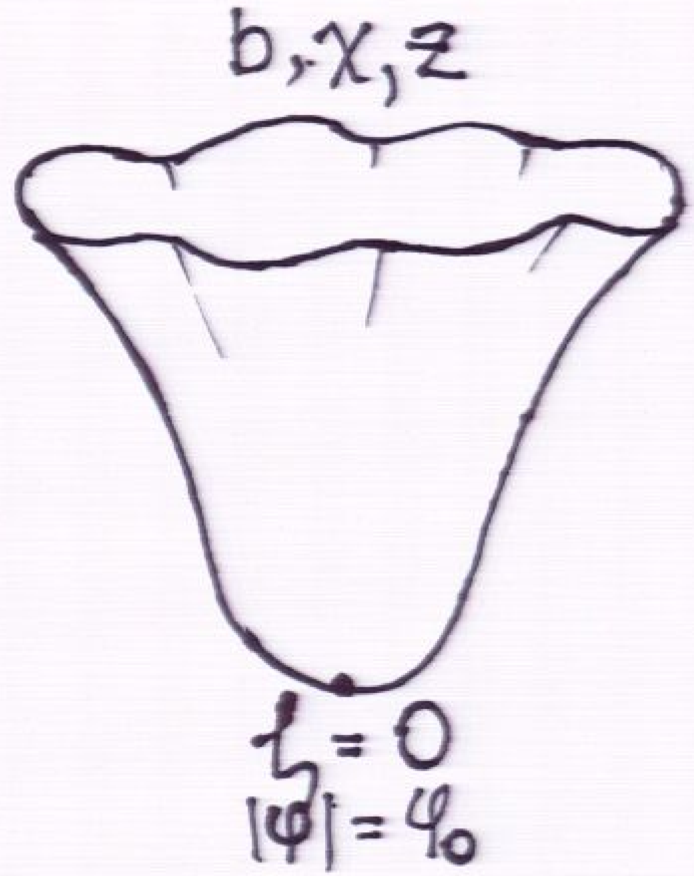

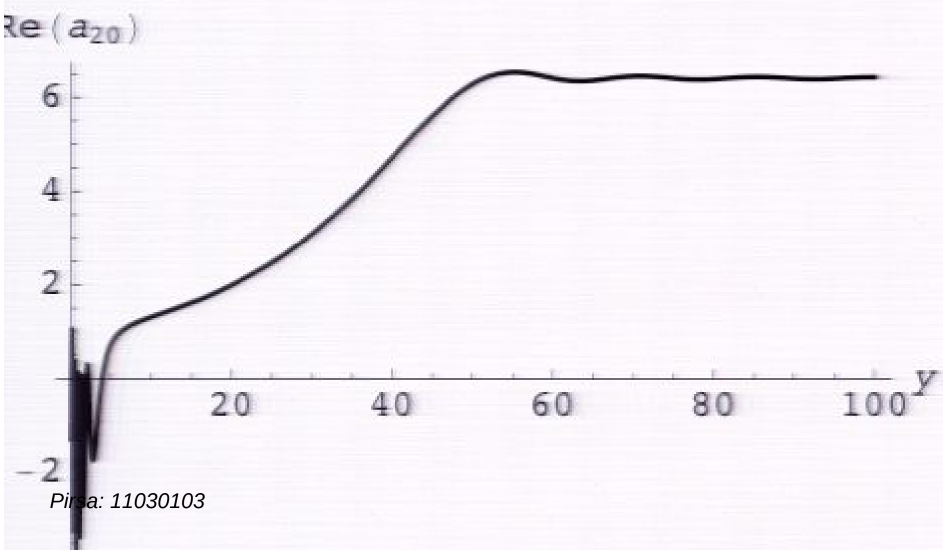

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where ϵ_* and H_* are the slow roll and expansion parameters when the mode leaves the horizon $n = a_* H_*$

- This is essentially the Bunch-Davis vacuum (not a surprise.)
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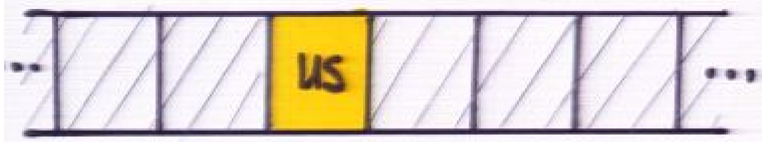

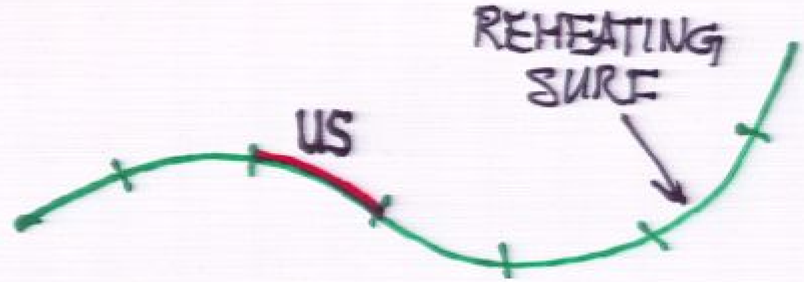

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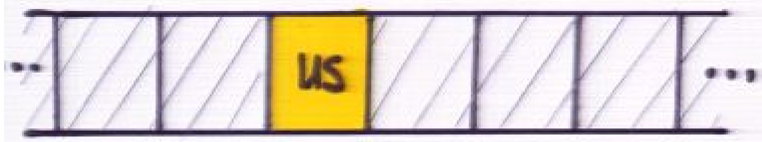

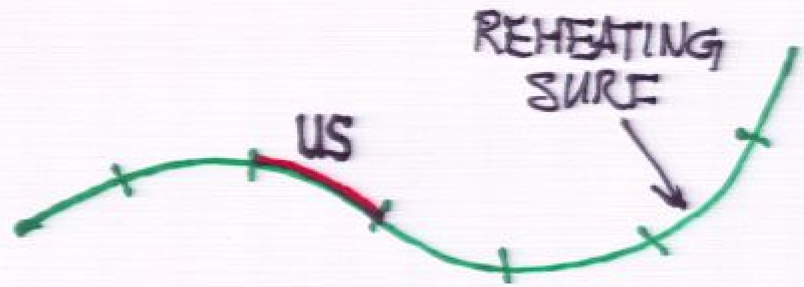

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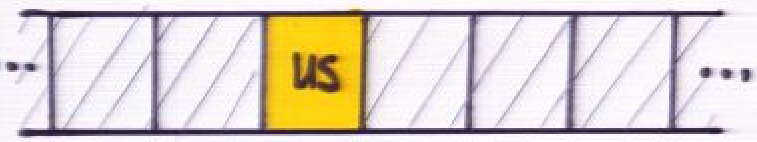

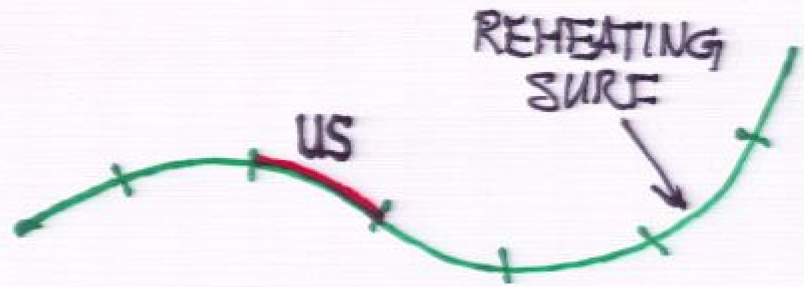

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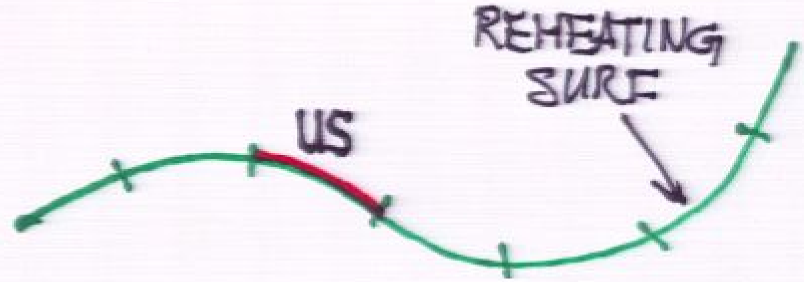

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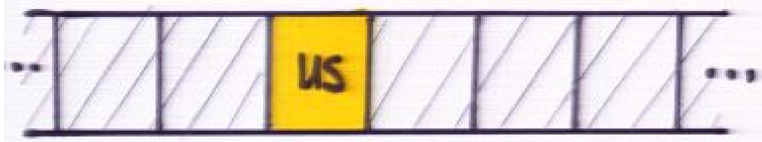

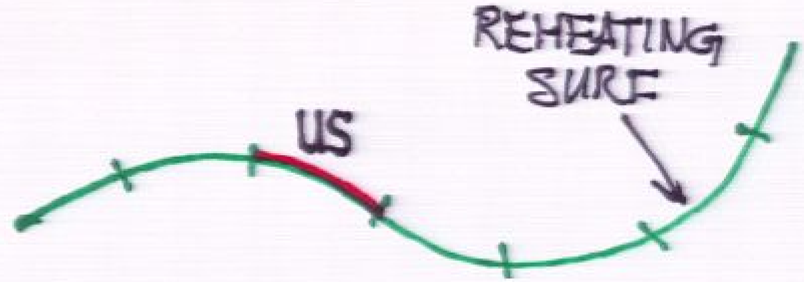

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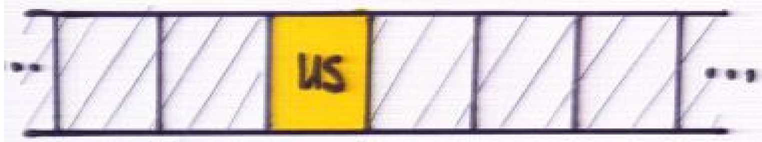

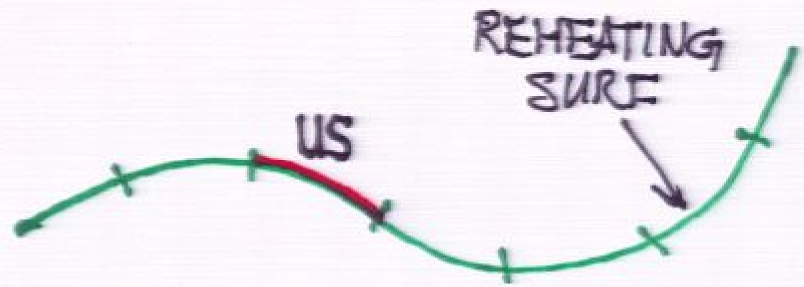

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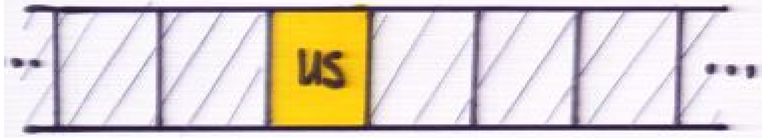

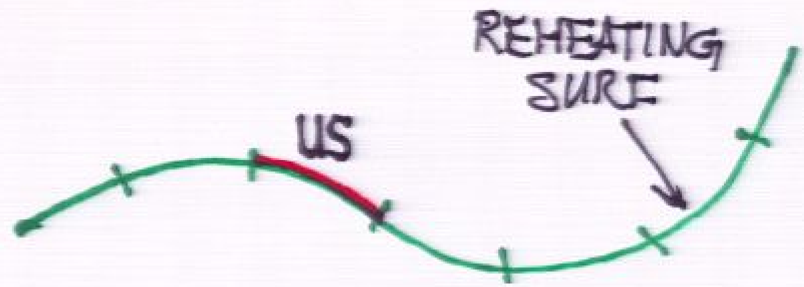

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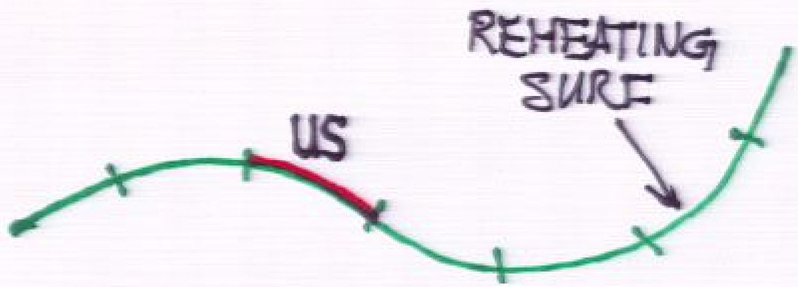

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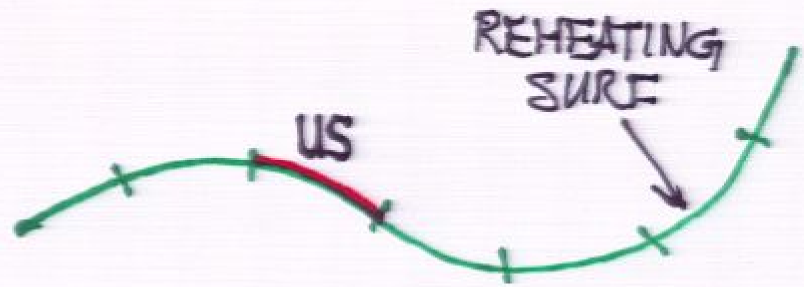

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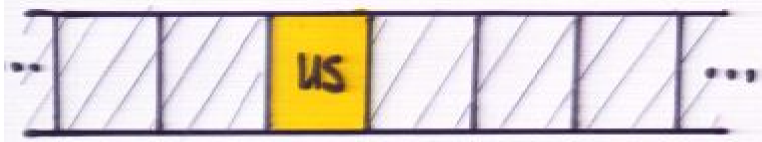

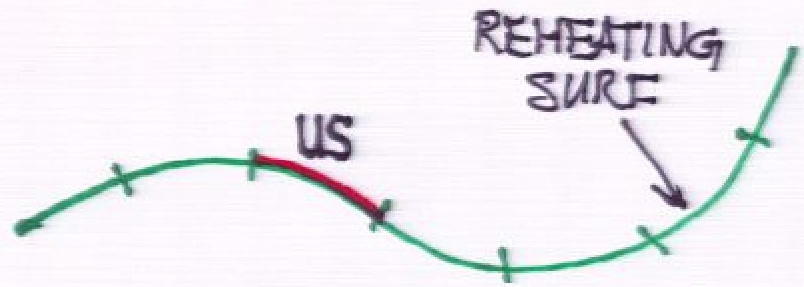

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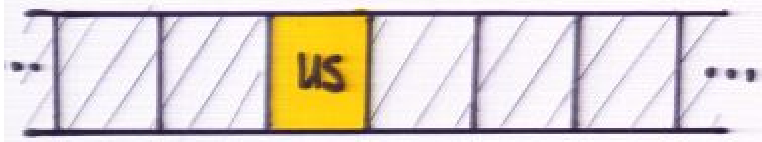

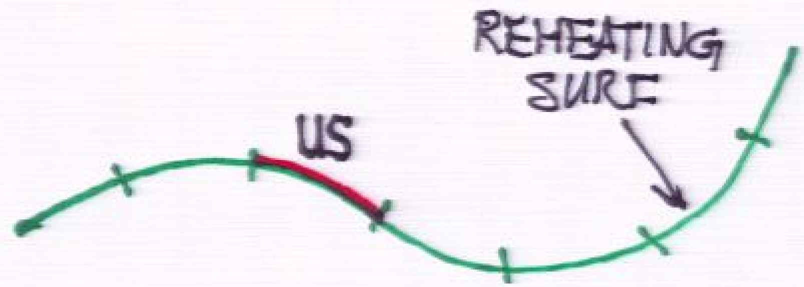

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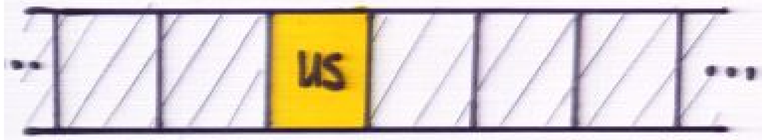

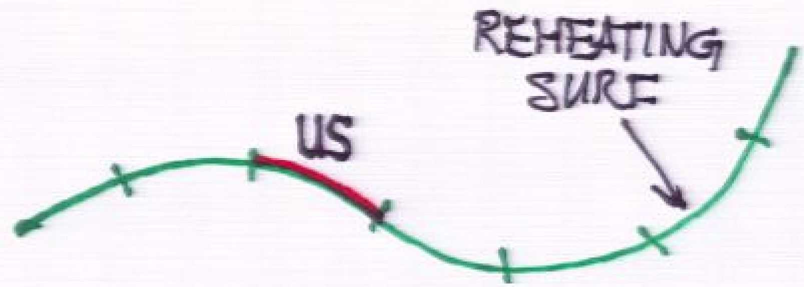

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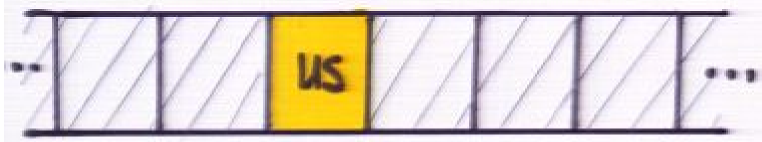

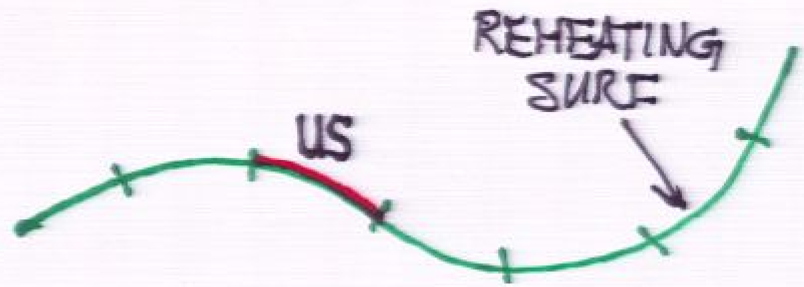

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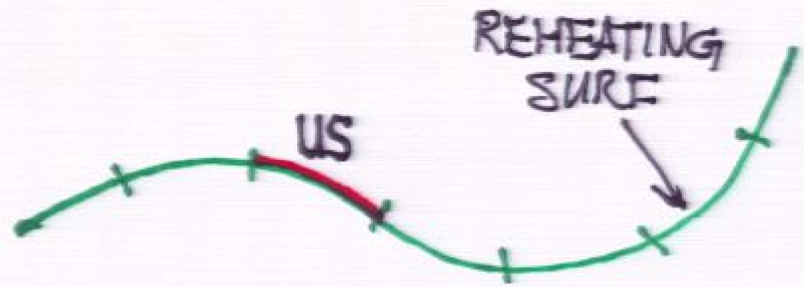

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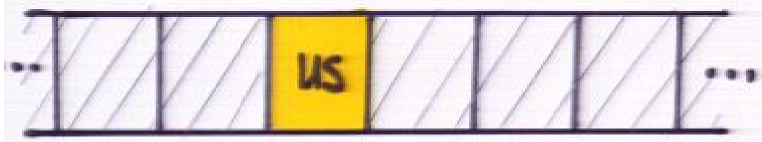

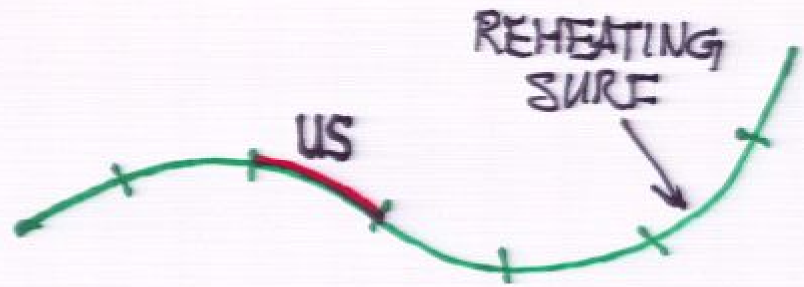

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$$p(WS\, C_\ell^{\rm obs}) = \sum_{\phi_0, F} p(C_\ell^{\rm obs}|\phi_0, F) p(\phi_0, F)$$

Denote superhorizon fluctuations by F. Consider the local observable $C_\ell^{\rm obs}$ in our Hubble volume and the ansatz:

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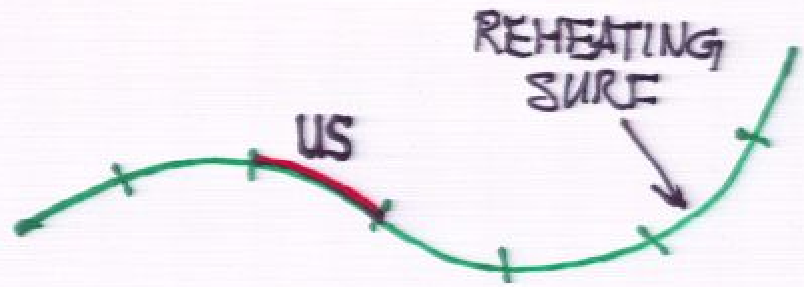
I.e. assume that for the purpose of calculating local observables we can ignore the back reaction on the reheating surface produced by large superhorizon modes that left their horizons during EI.

Every Hubble volume is then the same and coarse graining outside ours is easy as in the (YG) model

Probabilities for CMB



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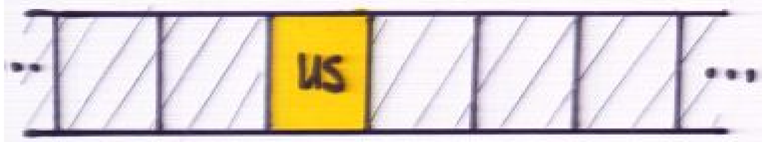

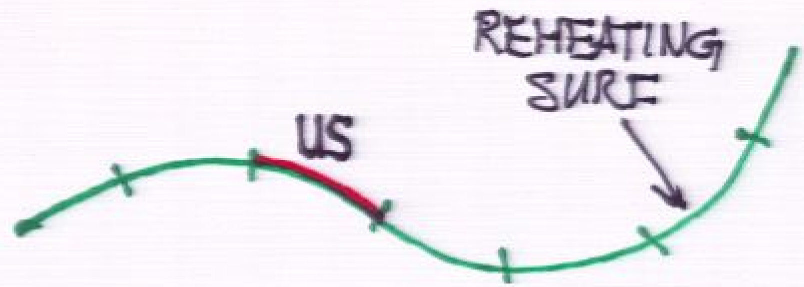

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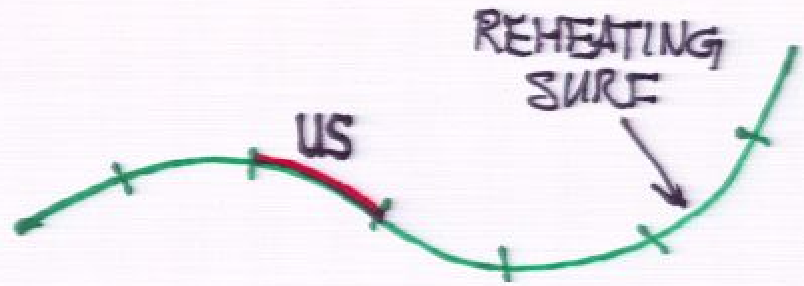

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Support for the Ansatz

$$p(C_\ell^{\rm obs}|\phi_0, F) \approx p(C_\ell^{\rm obs}|\phi_0, F=0)$$

- Cosmic no-hair theorems: These say just the ansatz provided there are a sufficient number of efolds after N the exit from EI. Since $N \sim 1/m \sim 10^6$ this condition seems ok.

- Explicit calculation in solutions with big inhomogeneities on large scales and linear fluctuations on small scales like the GHT bubble instanton.

- This ansatz is not a new principle of quantum mechanics or a further measure but a testable approximation.

Gratton and Turok Hertog and Turok

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Local Predictions of CMB

- From the NBWF calculate the fluctuation probabilities

$$p(z_{(n)}|\phi_0) \approx \sqrt{\frac{\epsilon_* n^3}{2\pi H_*^2}} \exp\left[-\frac{\epsilon_*}{2H_*^2} n^3 z_{(n)}^2\right]$$

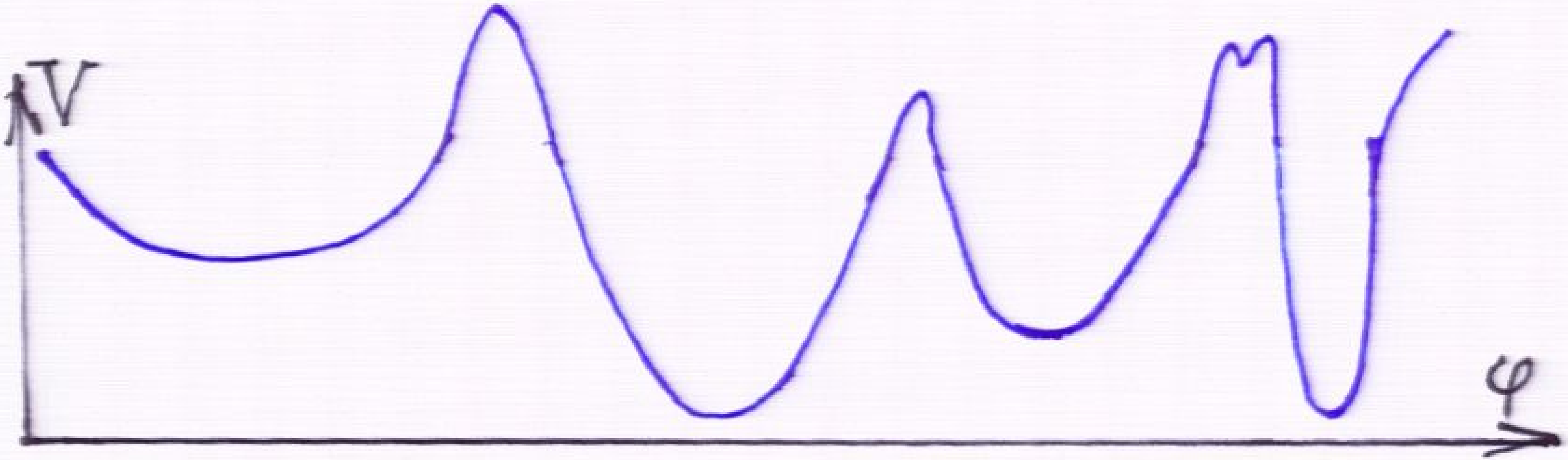
- From these probabilities calculate the correlators.

$$\langle z_{(n)} z_{(n')} \rangle$$

- From the correlators calculate the expected C_ℓ .
- The probabilities for the $C_\ell^{\rm obs}$ are a chi-squared distribution with the mean C_ℓ .
- The results for the $C_\ell^{\rm obs}$ will not differ significantly from the usual inflation story.

Landscapes

A Model Landscape



- Different minima K with

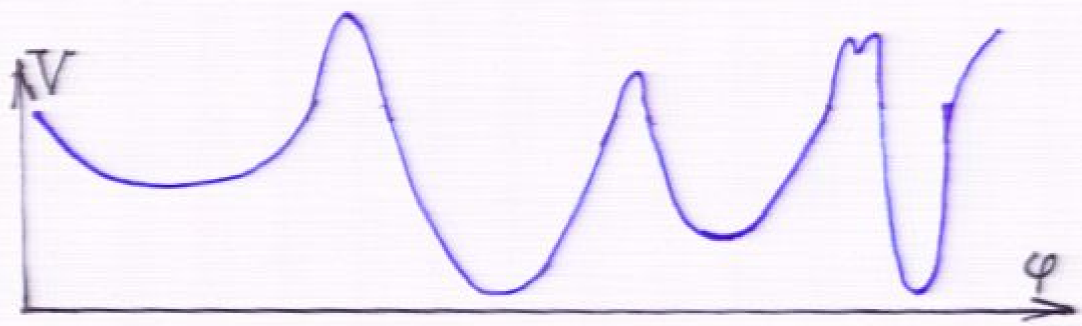
$$V_K(\phi) \approx \Lambda_K + \mu_K \phi^{n_K}$$

and big potential barriers between them (no tunnelling in leading order semiclassical.)

- Objective: The probability $p(n, \Lambda, \mu | D)$ for the parameters of our minimum given our data D.

- Assume the NBWF for illustration.

Mechanisms for the Selection of Landscape Regions (`Potentials')



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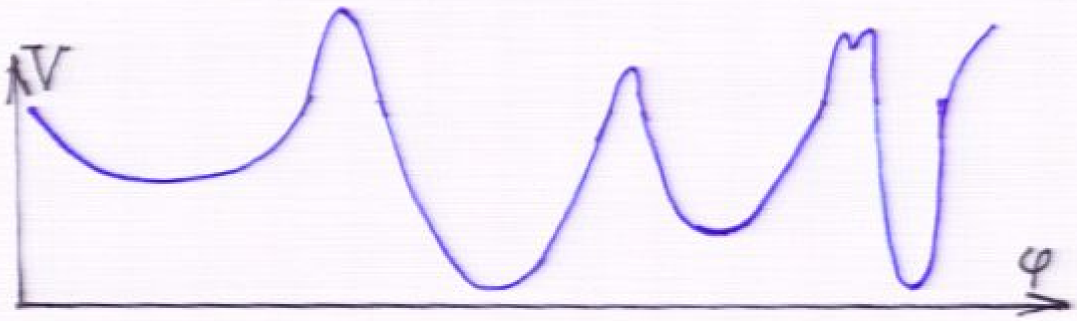

- Selection for potentials that allow a classical realm (an ensemble of classical histories.)

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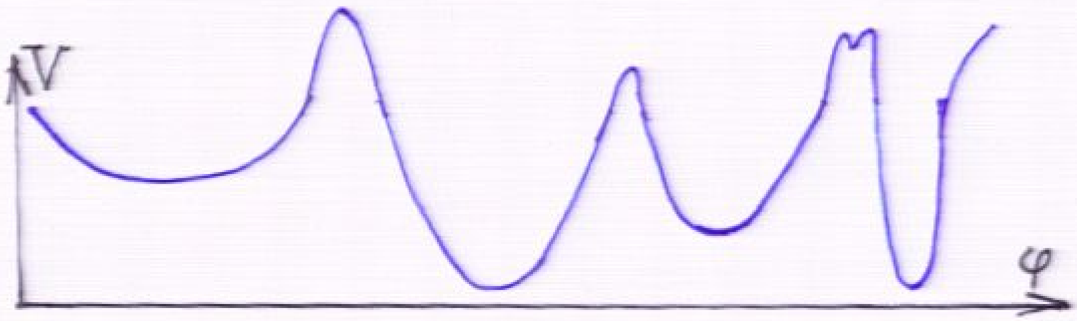

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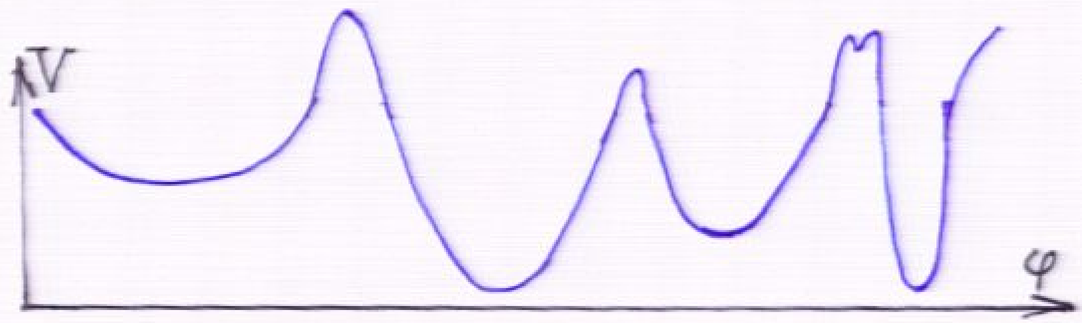

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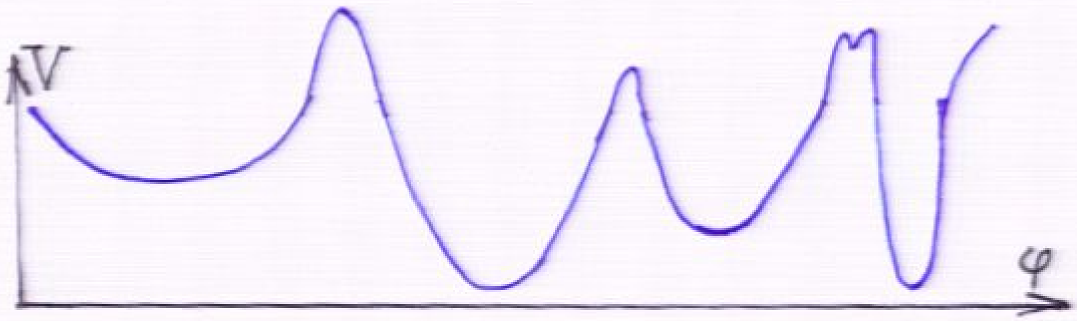

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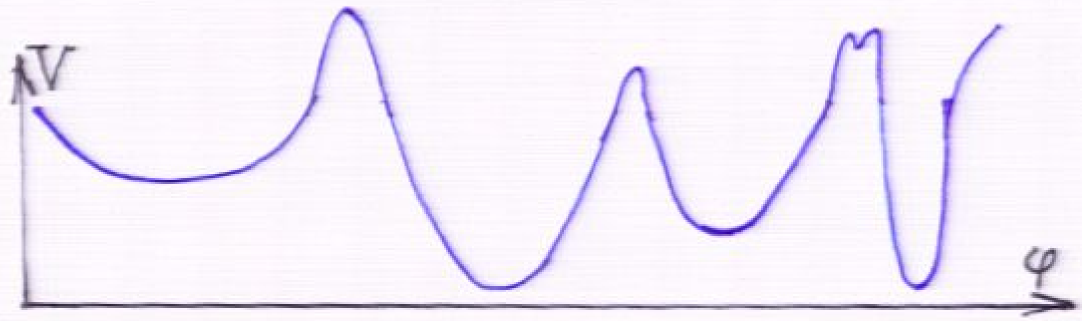

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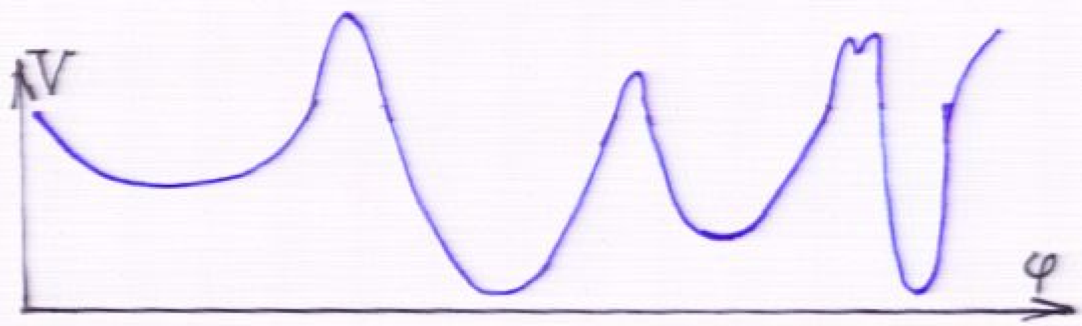
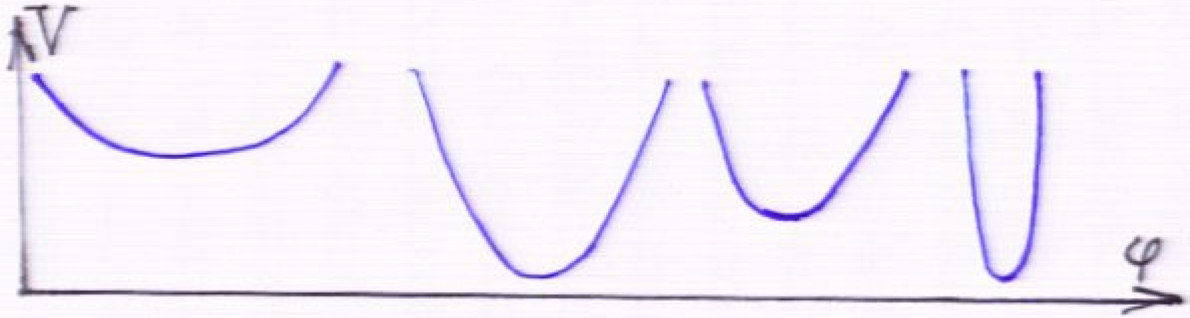


- Selection for potentials that allow a classical realm (an ensemble of classical histories.)
- Selection for potentials that allow eternal inflation.

Selection for a Classical Realm



- $\Psi(b,\chi) \approx \exp\{[-I_R(b,\chi) + iS(b,\chi)]/\hbar\}\,.$

- Require a potential that leads to

$$|\nabla_A I_R| \ll |\nabla_A S|$$

- Numerical evidence suggests that this happens when the potential allows for slow roll inflation (not too steep).

Selection for Eternal Inflation

Top-down weighting suppresses histories with small reheating surfaces compared to histories with the large (or infinite) reheating surfaces generated by eternal inflation.

$$p(WSR) \approx \frac{p(1)}{p(1) + N_2 p_E p(2)} \approx 1$$

Selection for the History with the Lowest Exit from Eternal Inflation

$$p(\phi_{0K}) \propto \exp\left(\frac{\pi}{\Lambda_K + V_K(\phi_{0K})}\right)$$

Among the selected set of eternally inflating histories with $\phi_0 > \phi_{ei}$ the one with $\phi_0 \approx \phi_{ei}$ will dominate.

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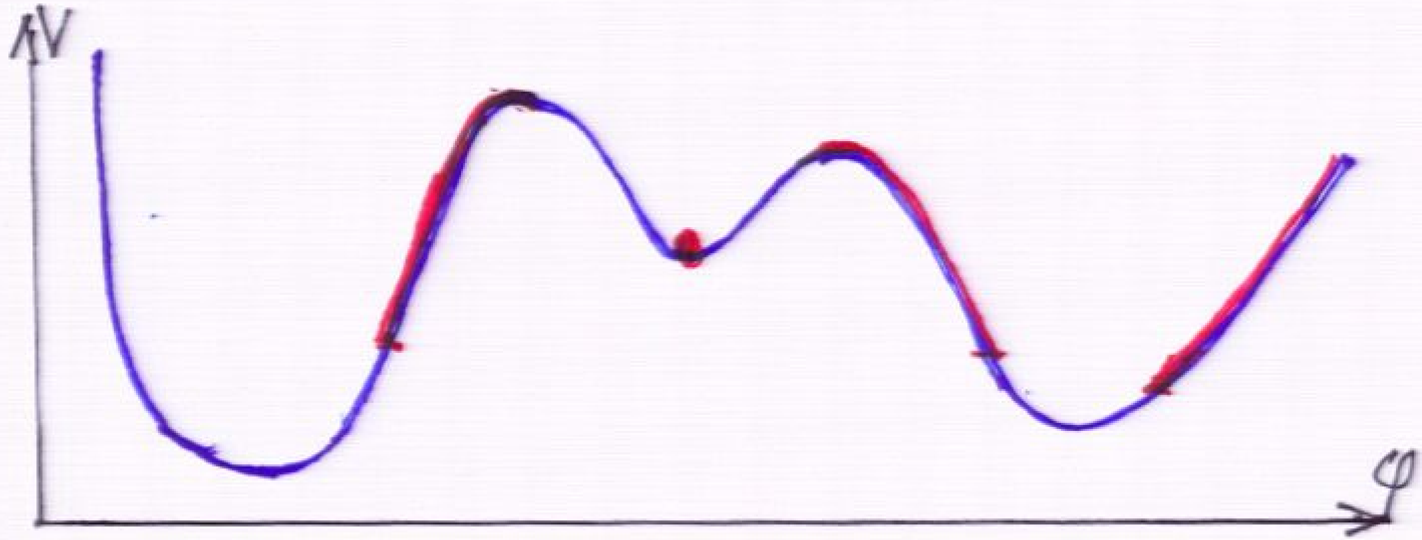

The dominance of the history with the lowest exit from eternal inflation means that the structure of the potential much above that is irrelevant for the prediction of local observations. That means the results hold for a more general class of models.

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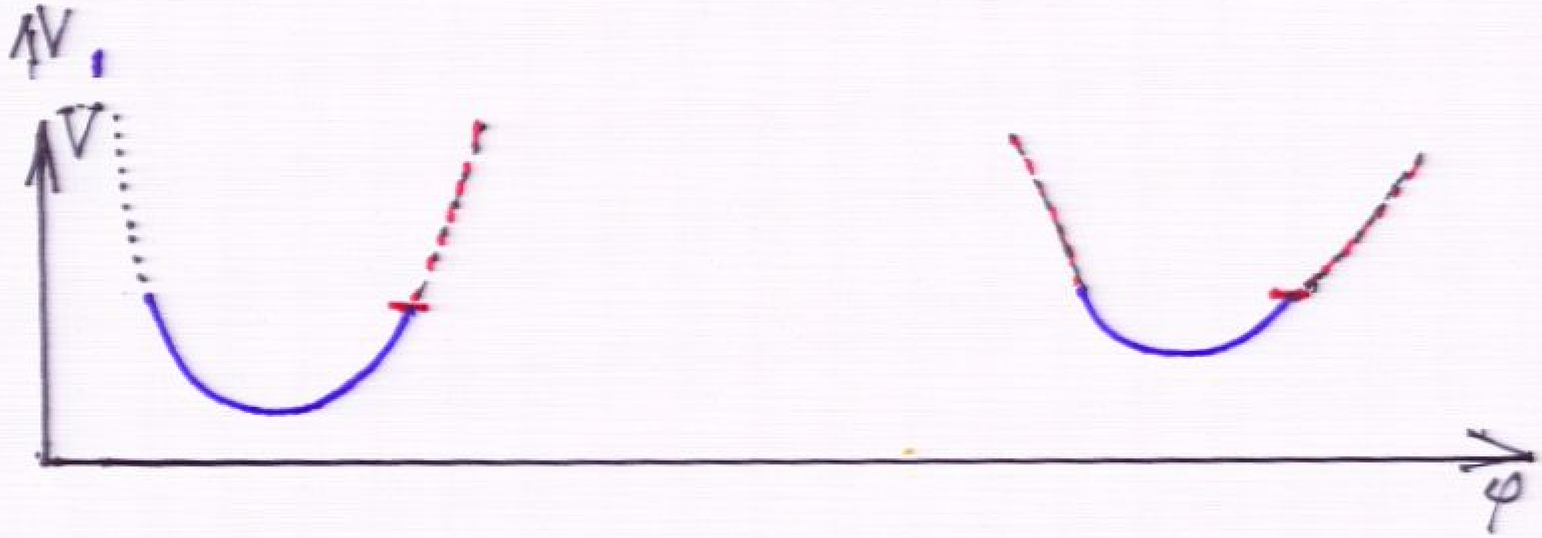

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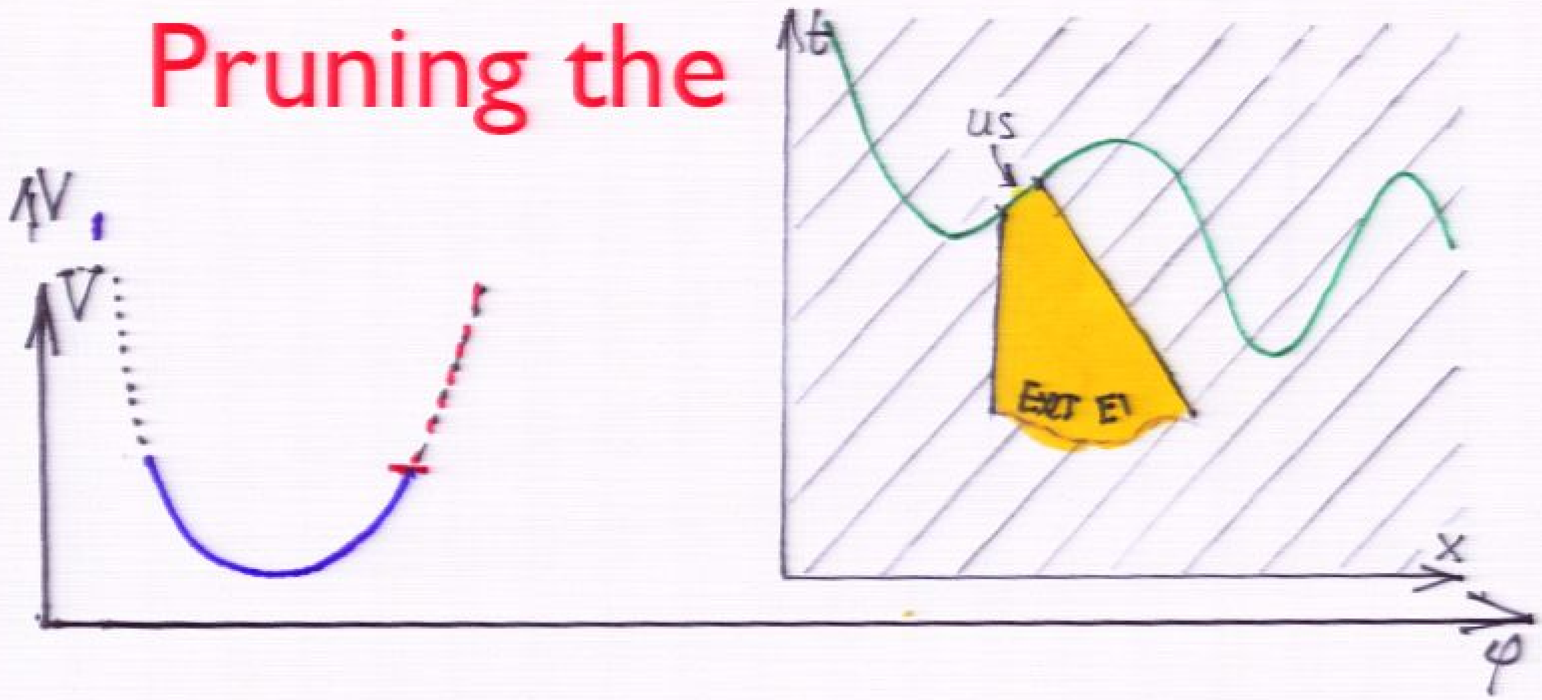

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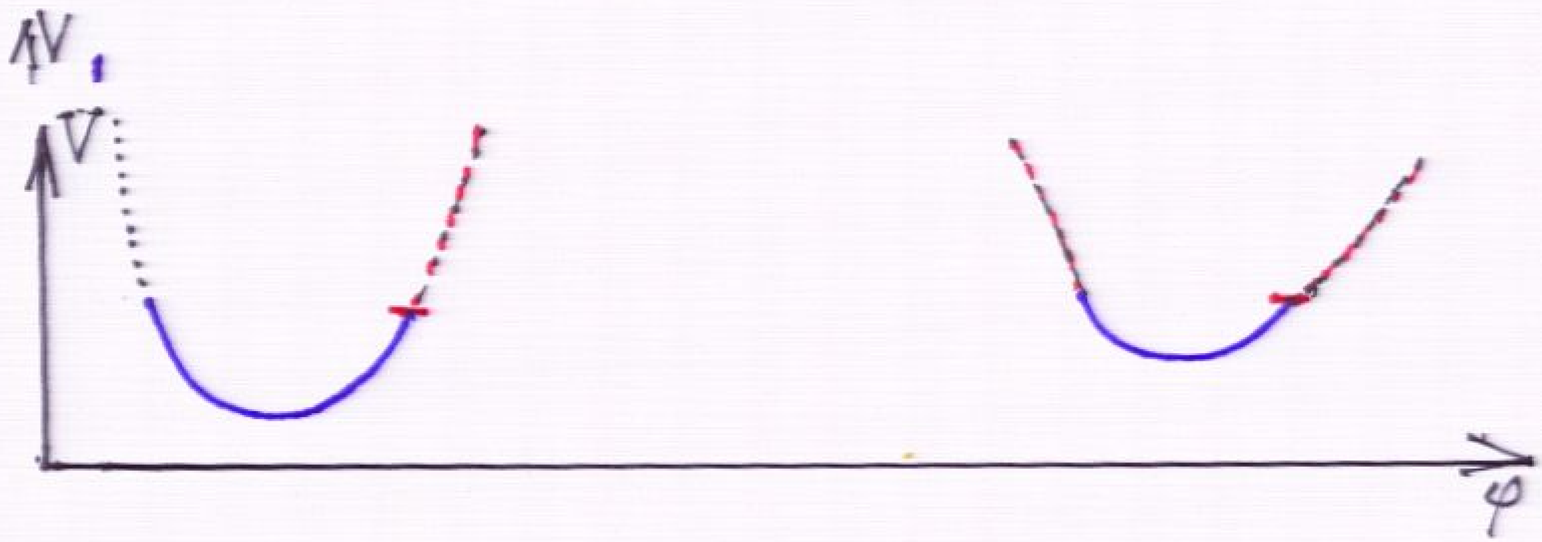

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Quadratic Minima Dominate

$$V_K(\phi) \approx \Lambda_K + \mu_K \phi^{n_K}$$

- Assume Λ's approx. zero and the μ's approx. comparable (to be justified self-consistently).
- In the region selected for classicality and EI. and for the dominant history at the exit of EI

$$p(n_K|\mu_K) \propto \exp\left[\pi/V(\phi_{ei})\right] \approx \exp(\mu_K^{-2/2+n_K})$$

- Assuming the μ's are comparable this implies that the lowest value of n_K =2 dominates.
- Standard CMB calculations mean that we predict a spectral index of .97 and a scalar

`Anthropic' Selection

(TD weight)= $1-(1-p_E)^N$

$$p_E = p(D|n, \Lambda, \mu)$$

- For parameters where the data can't exist $p_E = 0$ then TD weight =0 no matter what N is.
- This is traditional `anthropic' selection emerging at a fundamental level by including observers as quantum physical systems within the universe.
- It's not a choice. Just like TD weighting in general is not a choice.

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Predicting Λ m from NBWF

$$V = \Lambda + \frac{1}{2}m^2\phi^2$$

dropped sub K's

We are interested in the probability $p(\Lambda, m|D)$ for the parameters given some part of our data D.

$$p(\Lambda, m|D) = \frac{p(D|\Lambda, m)p(\Lambda, m)}{\sum_{\Lambda,m} p(D|\Lambda, m)p(\Lambda, m)}$$

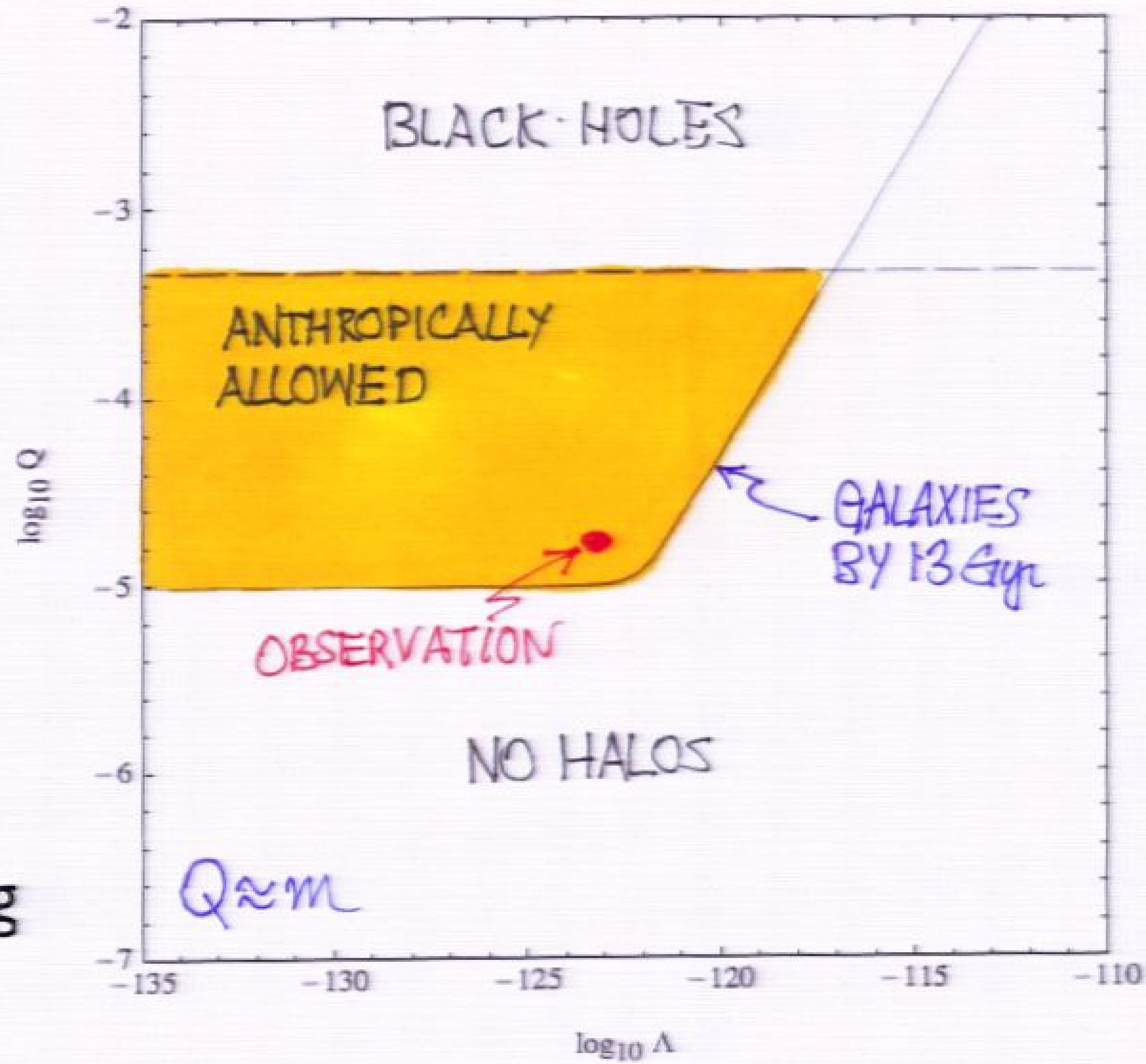
Take D to include the fact that we live in a Hubble volume of galaxies 13.7Gyr after the big bang.

$$p(D|\Lambda, m) \propto p_g \langle N_g(\Lambda, m)\rangle$$

$\langle N_g(\Lambda, m)\rangle$ is the expected number of galaxies in a Hubble volume in the state of the fluctuations. p_g is the probability that we evolved in one galaxy ---

Anthropic Selection

- $p(D|\Lambda, m)$ is the basis for traditional anthropic selection. Non-zero p is anthropically allowed.
- Weinberg got good results by putting in the observed m and assuming a uniform prior for Λ.



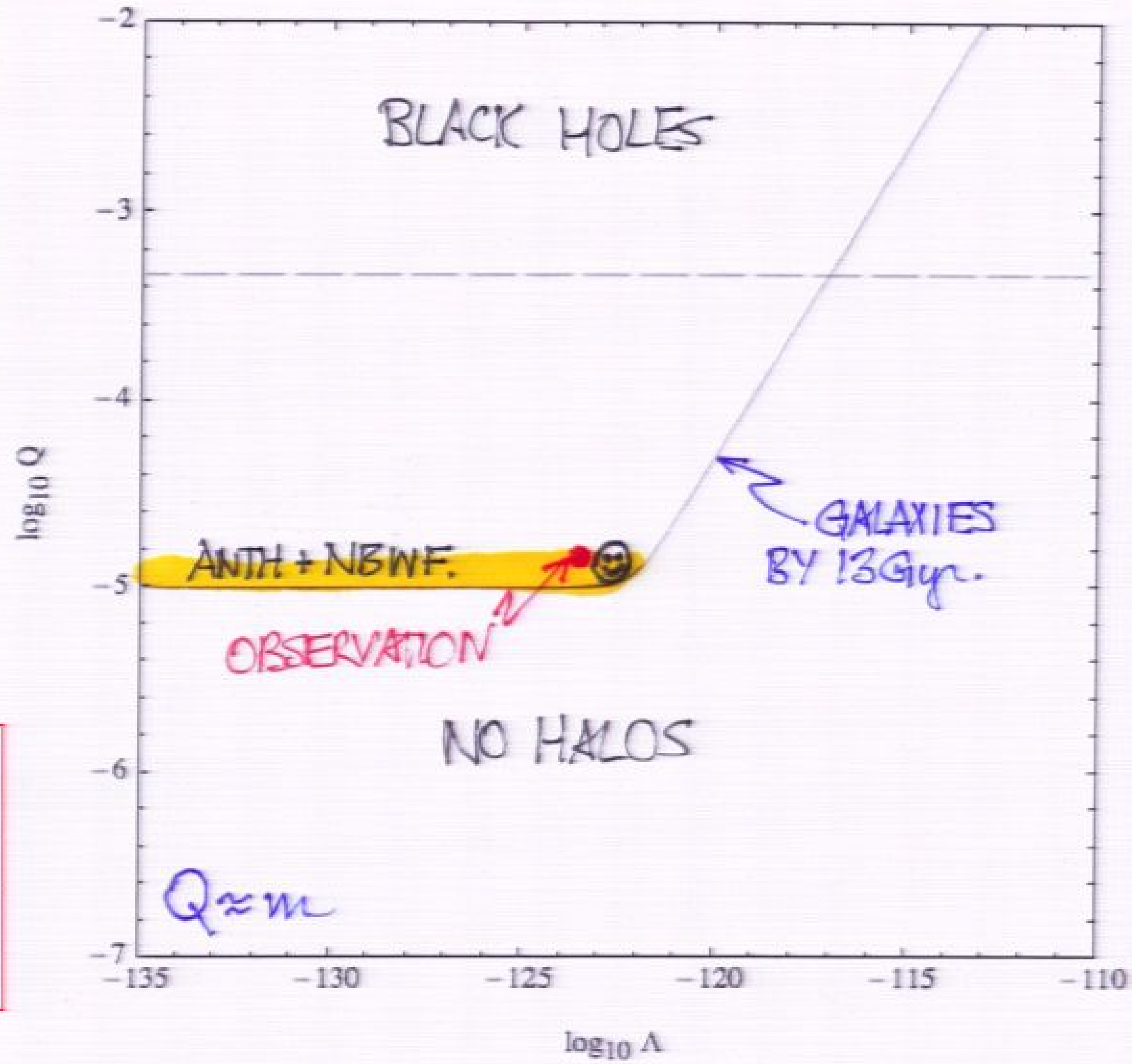
- But Livio & Rees, Tegmark & Rees etc showed the result got worse by letting Q scan with uniform priors.

NBWF Aided Anthropics

$$p(\Lambda, m|D) \propto p(D|\Lambda, m)p(\Lambda, m)$$

$$p(\Lambda, m) \approx \exp(\pi/V(\phi_{ei})) \approx \exp[\pi/(\Lambda + m/2)] \approx \exp(2\pi/Q)$$

NBWF favors the lowest value of Q in the anthrop. allowed range.



This restores Weinberg's anthropic argument for Λ.

$$Q \sim 10^{-5}, \quad \Lambda \sim 10^{-123}.$$

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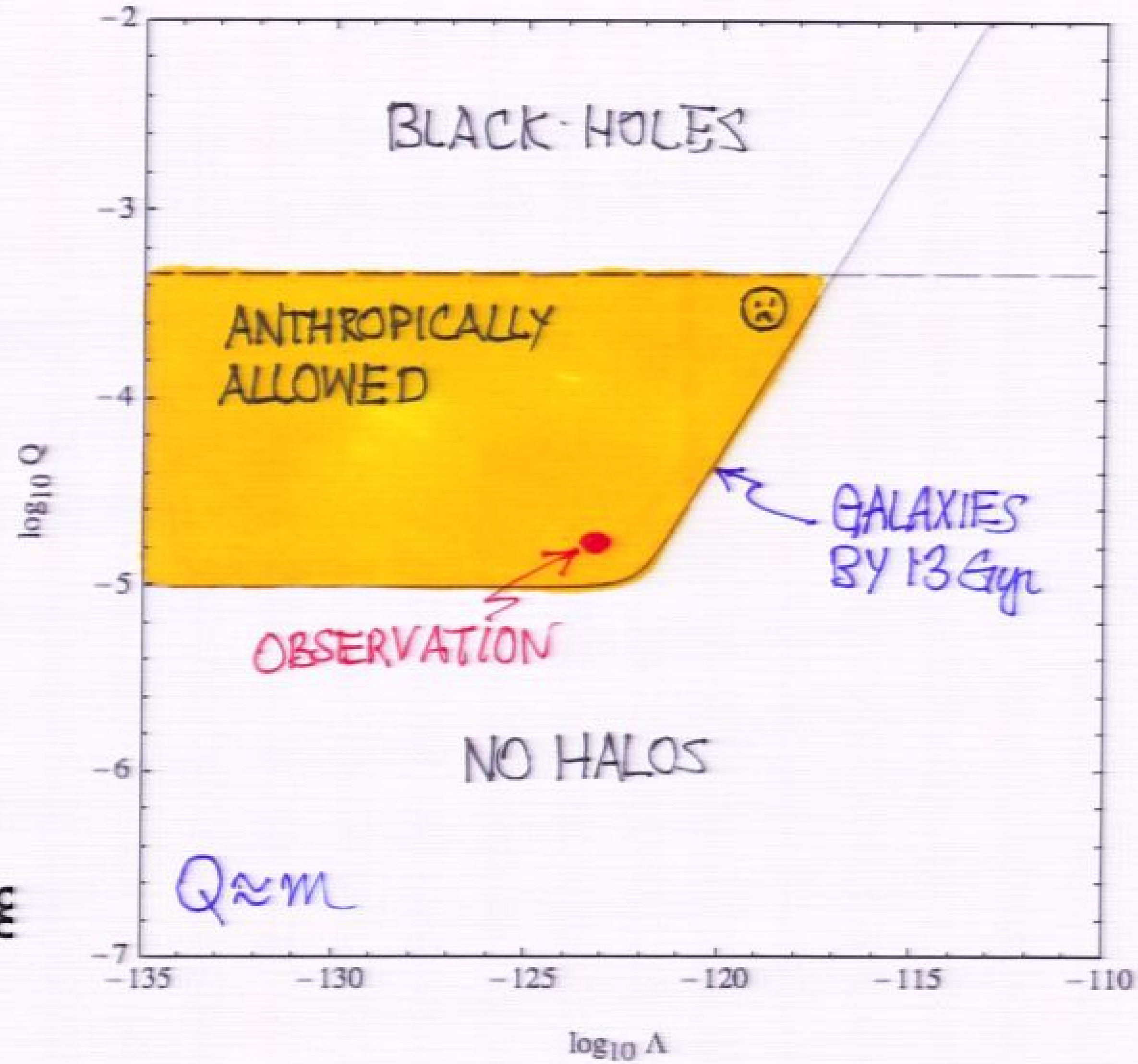

But Livio & Rees, Tegmark & Rees etc showed the result got worse by letting Q scan with uniform priors.

But the NBWF supplies the prior!

Assumptions and `Predictions'

- Quantum mechanics, the NBWF, quantum spacetime, and quantum observers.
- A toy landscape with power law potentials.
- A 13Gyr universe of galaxies.

- Inflation
- CMB: $n_S \sim .97, \quad S/T \sim .1$
- Parameters: $Q \sim 10^{-5}, \quad \Lambda \sim 10^{-123}.$

A landscape provides
a mechanism for
the parameters
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`Anthropic reasoning' is then
a necessary consequence of
realistic models of obsevers.

	Quantum Cosmology EI	Traditional EI
Target Probabilities	Probabilities for observations in our Hubble volume	Probabilities for observations in our Hubble volume
Spacetime	Ensemble of classical spacetime histories with quantum probabilities	One classical spacetime in which quantum events take place (eg. nucleation)
Observers like us	Quantum systems within the U with a probability pE to exist in any H-vol.	Classical -- assumed to exist in all hospitable environments
Observers -- rare or common?	Rare in sufficiently small universes, common (replicated) in very large ones	Rare
Origin of Probabilities	The quantum state	Ratios of numbers of environments for observers of different kinds defined by a sequence of cutoffs (measure)

The Main Points Again

- If the universe is a quantum system it has a quantum state. This supplies probabilities (BU) for alternative classical histories of the universe.
- Observers of the universe are physical systems within it with only a probability to exist in any Hubble volume.
- Probabilities for observation (TD) are necessarily conditioned on a description of the observational situation including what's doing the observing.
- TD probabilities favor large universes because there are more places for us to be. But the observer's details cancel.
- By coarse graining over everything outside the past light cone of our H-vol, probabilities for observation can be calculated even with the large inhomogeneities generated by EI without a further measure.

Put Quantum Mechanics to Work for Cosmology !

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0803.1663
0905.3877
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