Title: Bubble Nucleation and Eternal Inflation

Date: Dec 05, 2006 10:30 AM

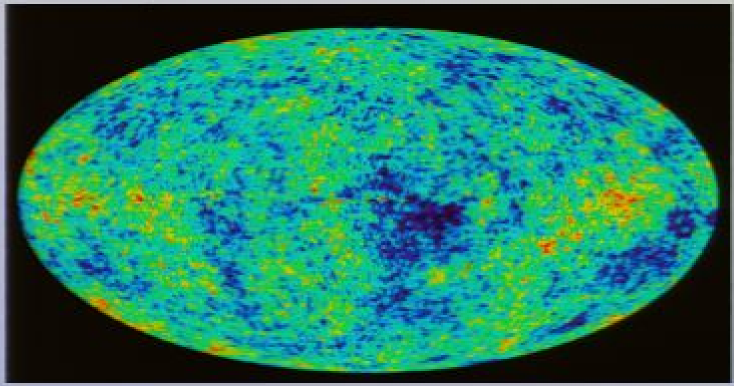
URL: http://pirsa.org/06120021

Abstract: A number of mechanisms have been introduced in previous literature that might be responsible for transitions between metastable minima in a scalar field theory coupled to gravity. The connection between these transition mechanisms has remained unclear, and current formulations of eternal inflation only include a subset of the allowed processes. In the first part of this talk, I will discuss how a number of transition mechanisms can be unified in the thin-wall limit, with interesting consequences for quantum cosmology and eternal inflation. I will then discuss making predictions in an eternally inflating universe, and introduce a measure for eternal inflation that is based on transitions rather than vacua.

Inflation:

An epoch of exponential accelerated expansion.

- Good experimental/theoretical evidence for inflation (though not proven):



    - Solves flatness problem, horizon problem, monopole abundance, etc.
    - Produces a homogenous universe with gaussian, ~scale-invariant perturbations (that agree with data).

- But, serious problems with interpretation and initial conditions.

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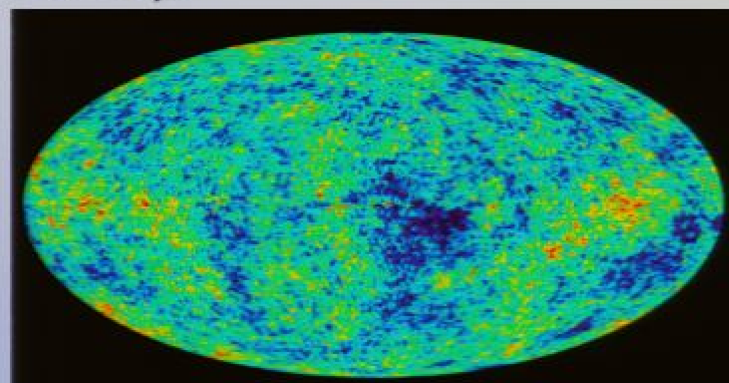

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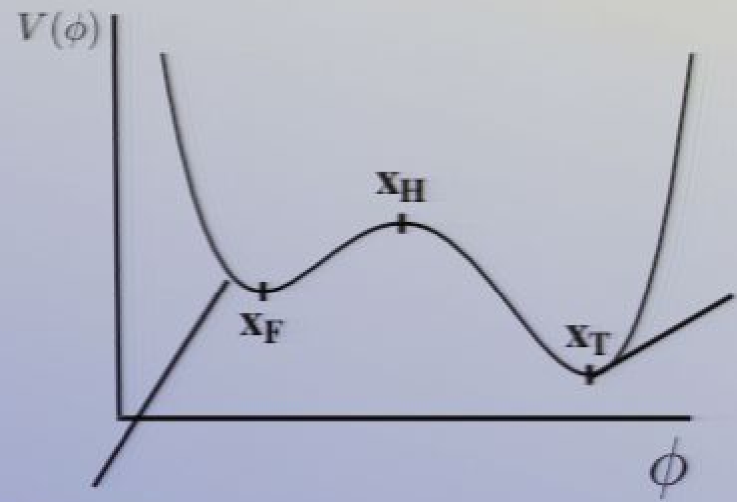
Metastable Minima



True Vacuum:
lower energy state

False Vacuum:
higher energy state

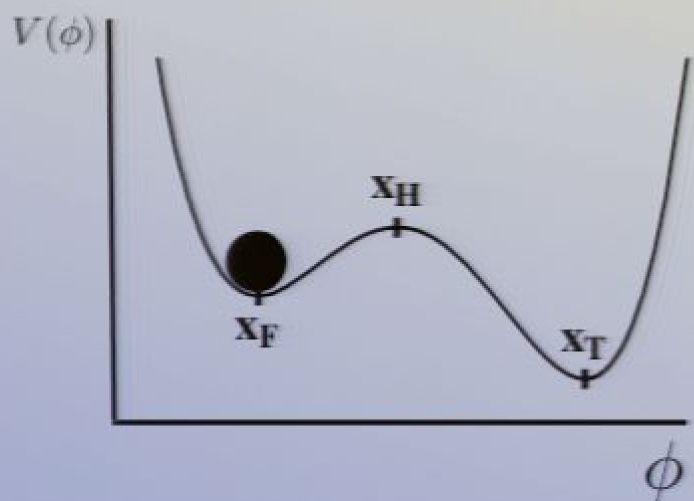
- Good experimental evidence that we are evolving towards dS.
- In the context of string theory, dS is metastable.
- We may be in a metastable state: what states are we connected to?

CDL Vacuum Bubbles

Coleman 1977

Callan and Coleman 1977

Coleman and De Luccia 1980



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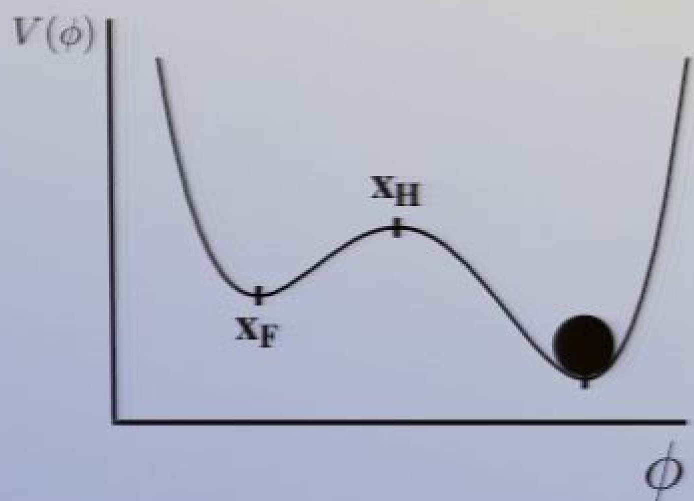
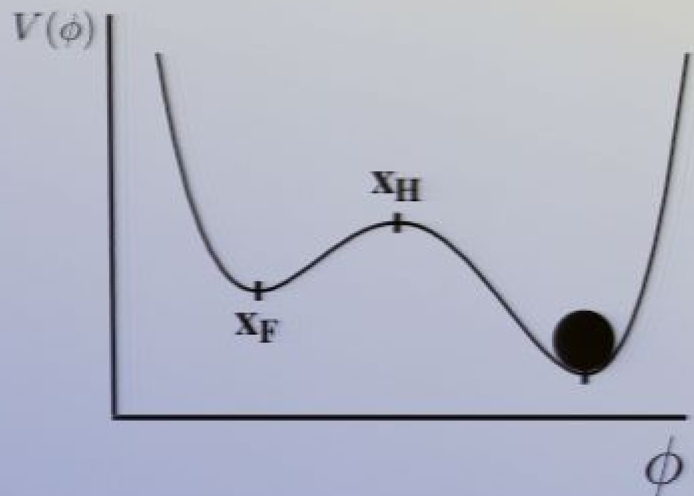


Tunneling = Bubble Nucleation

- If the nucleation rate is small compared to the dS expansion in the false vacuum, then inflation is eternal.
- Need a period of slow-roll after tunneling.....
- Also slow-roll eternal inflation: not considered today.

CDL Vacuum Bubbles



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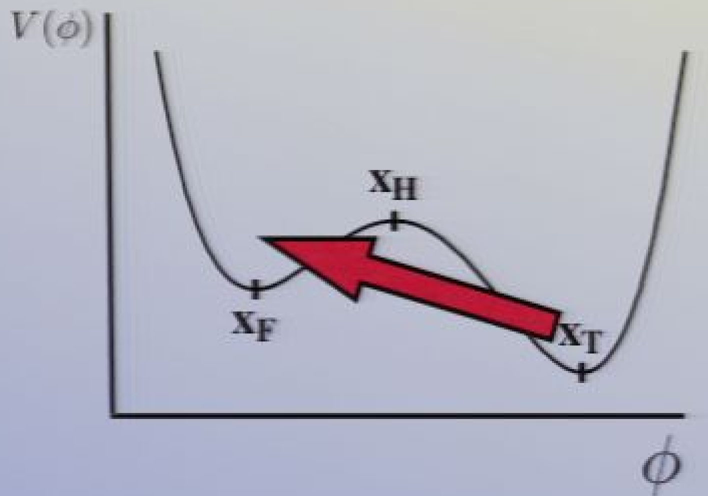
Pandora's Box

- Eternal Inflation + string theory landscape => low-energy physics is not unique.
- Different spatiotemporal regions have different low-energy observables (particle physics + cosmological parameters).
- Is it possible to predict low energy physics from the high energy theory?
  - If so, then predictions become statistical.
- If not, then there are side-benefits from asking these questions:
  - Naturalness.
  - Initial conditions for inflation.
  - Makes anthropic questions well-defined.

Eternal Inflation: what to do?

- Understand the dynamics:
  - What transitions are allowed?
  - What does the multiverse look like?
- Is it possible to make (statistical) predictions for a model using eternal inflation?
  - What are the necessary ingredients?
  - What sort of observations could we hope to make predictions for?

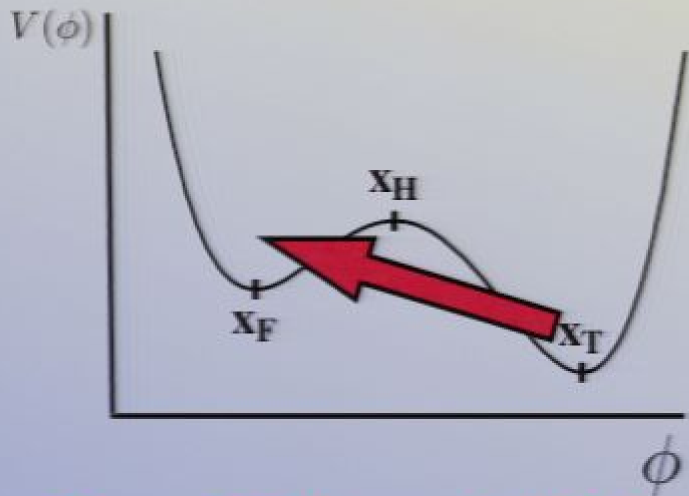
Dynamics of eternal inflation



Can we tunnel up? Lee and Weinberg 1987

L(ee)W(einberg) Bubbles

Dynamics of eternal inflation



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But, CDL and LW are not the only ways to transition...

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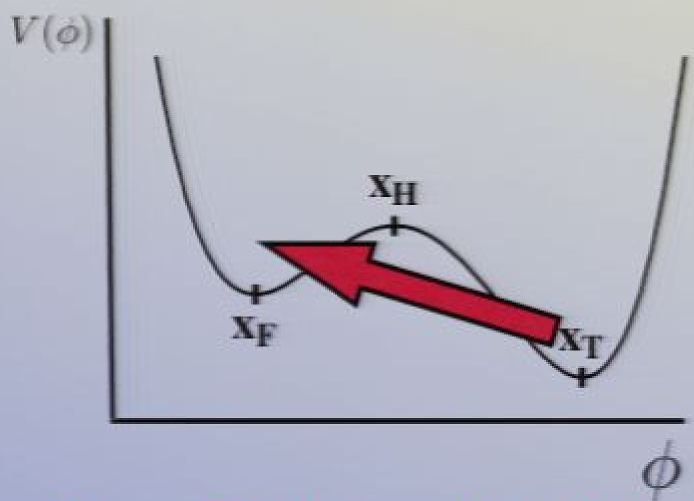

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FGG Mechanism

Farhi, Guth, Guven 1990

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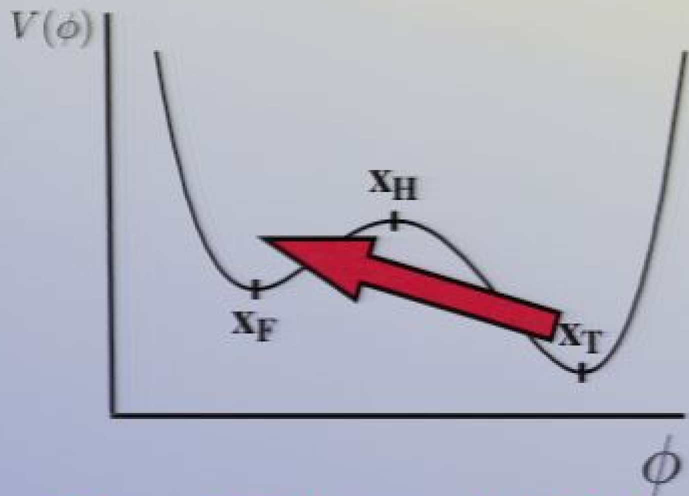

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Creation of a universe from nothing

Vilenkin 1982

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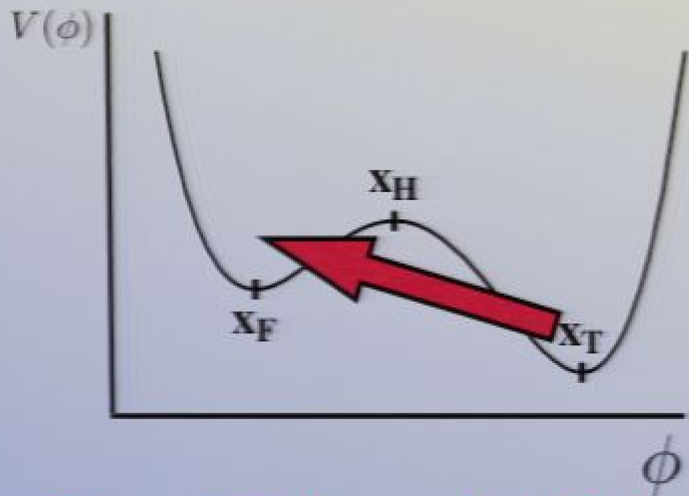

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Hawking-Moss Instanton

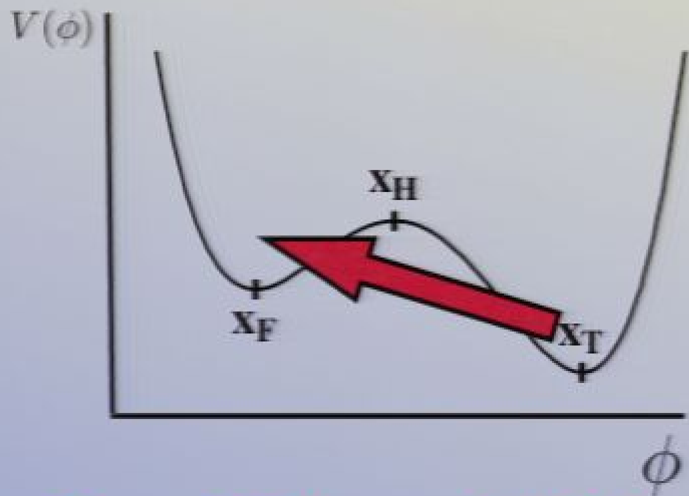
Hawking and Moss 1982

Stochastic Fluctuations

Starobinski
Linde

Others?

Dynamics of eternal inflation



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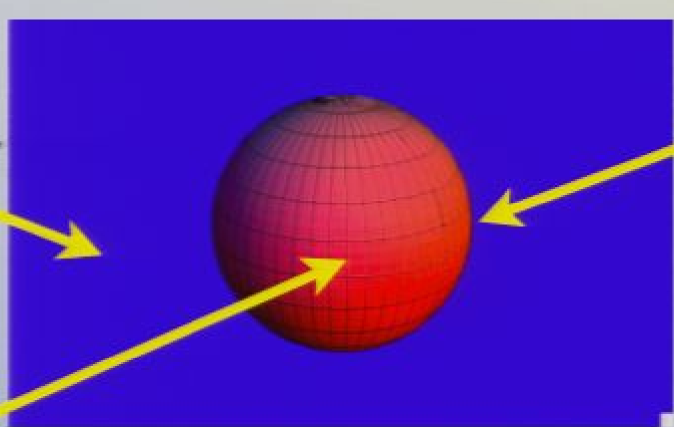
Four can be unified in the Thin-wall limit!

There are implications for Eternal Inflation

Vacuum Bubbles

3 Ingredients for Classical Dynamics



True or False
Vacuum exterior

Bubble Wall
Tension
k

True or False
Vacuum interior

Vacuum Bubbles

3 Ingredients for Classical Dynamics

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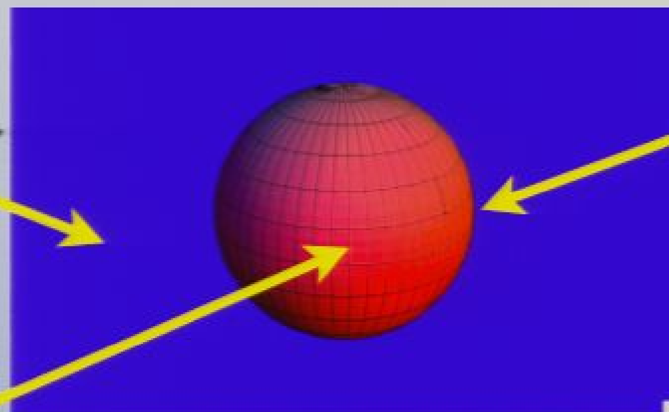

Bubble Wall
Tension
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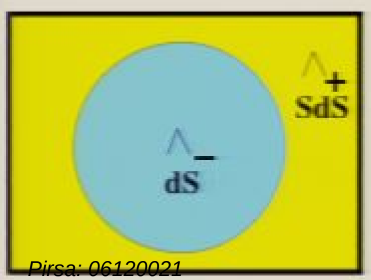
True or False
Vacuum interior

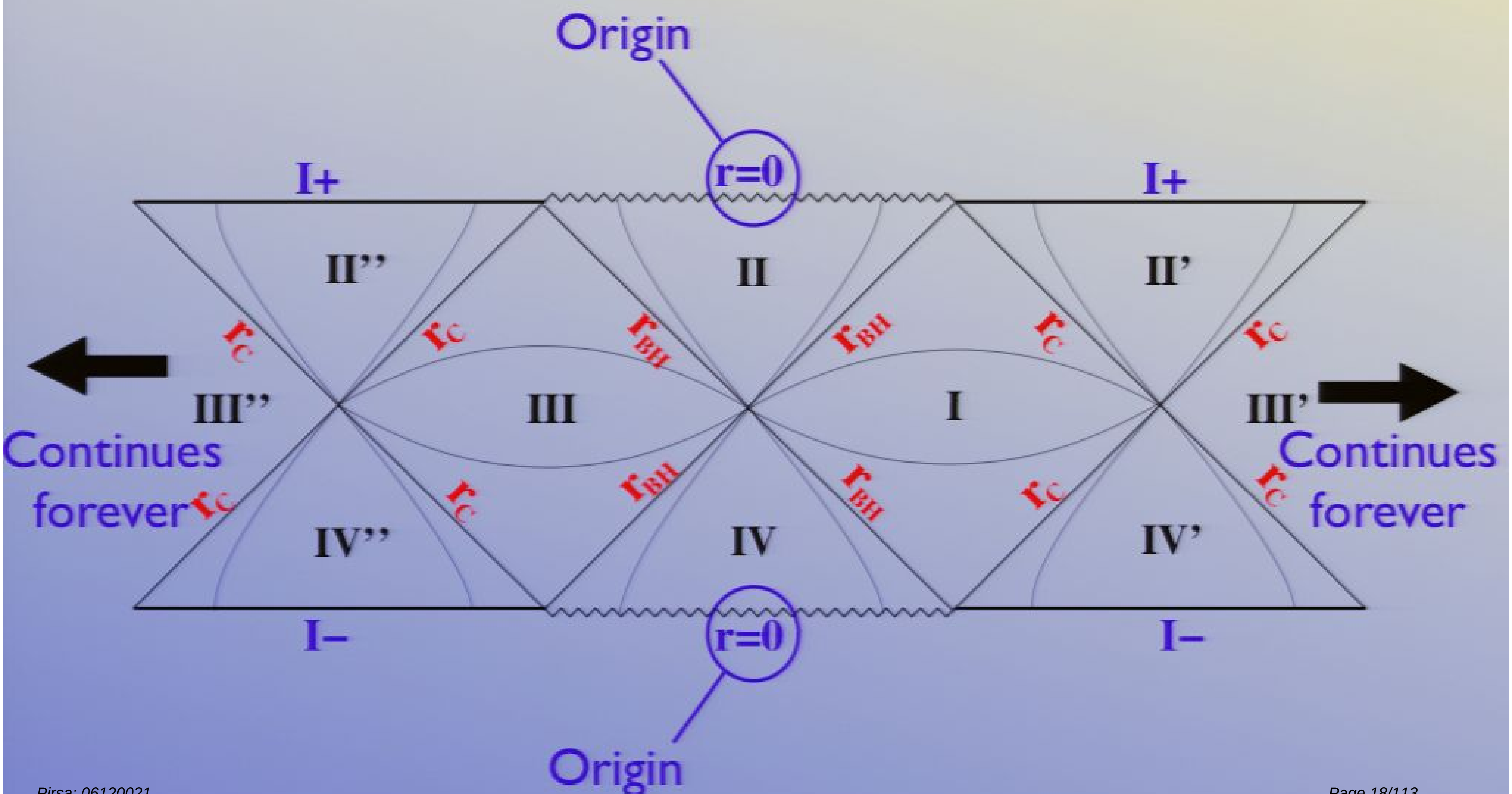
CDL/LW: wall and volume energy cancels, so M=0.



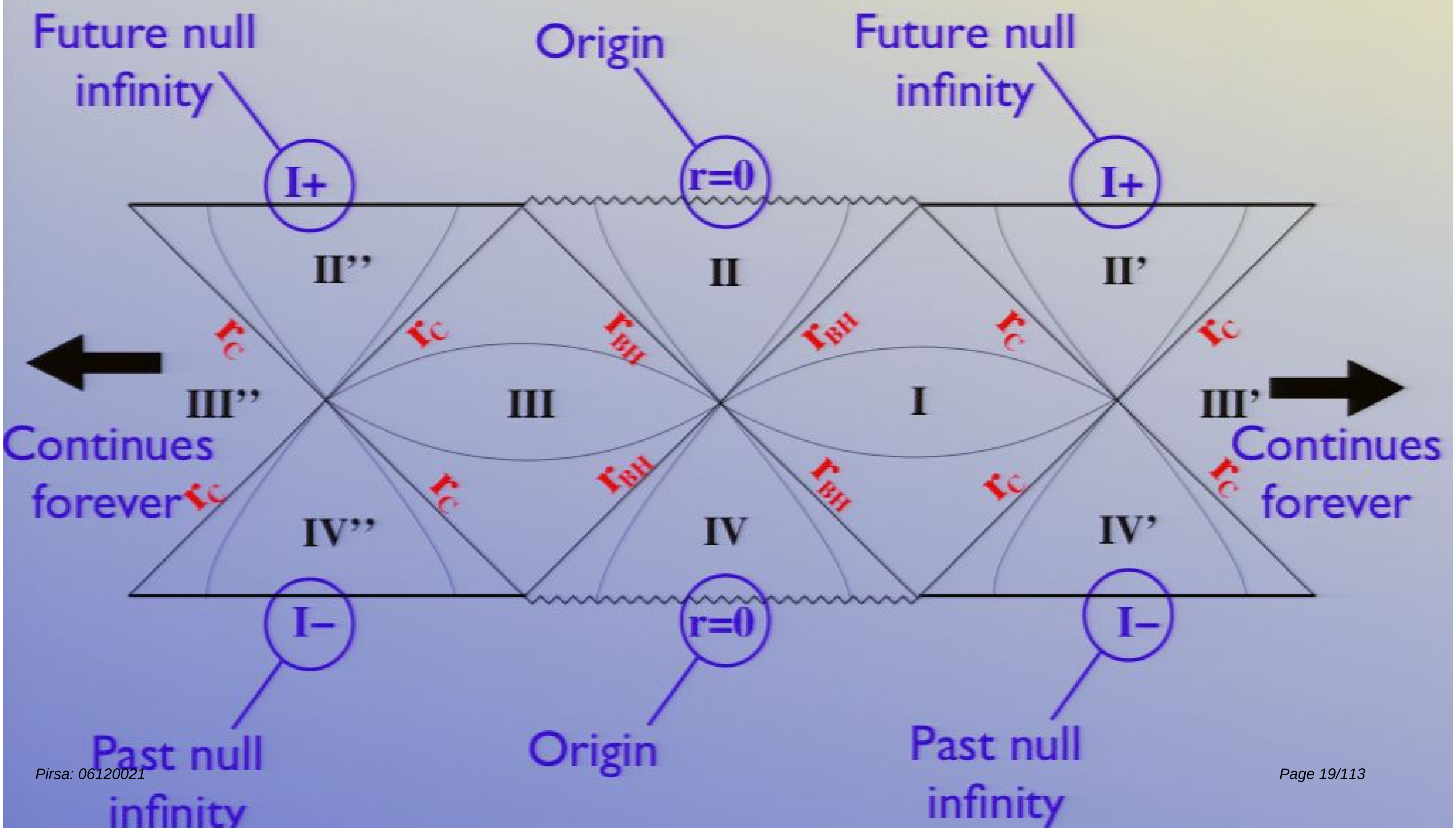
Can also consider massive bubbles:

Birkhoff's Theorem: exterior Schwarzschild-de Sitter.

Schwarzschild-de Sitter



Schwarzschild-de Sitter



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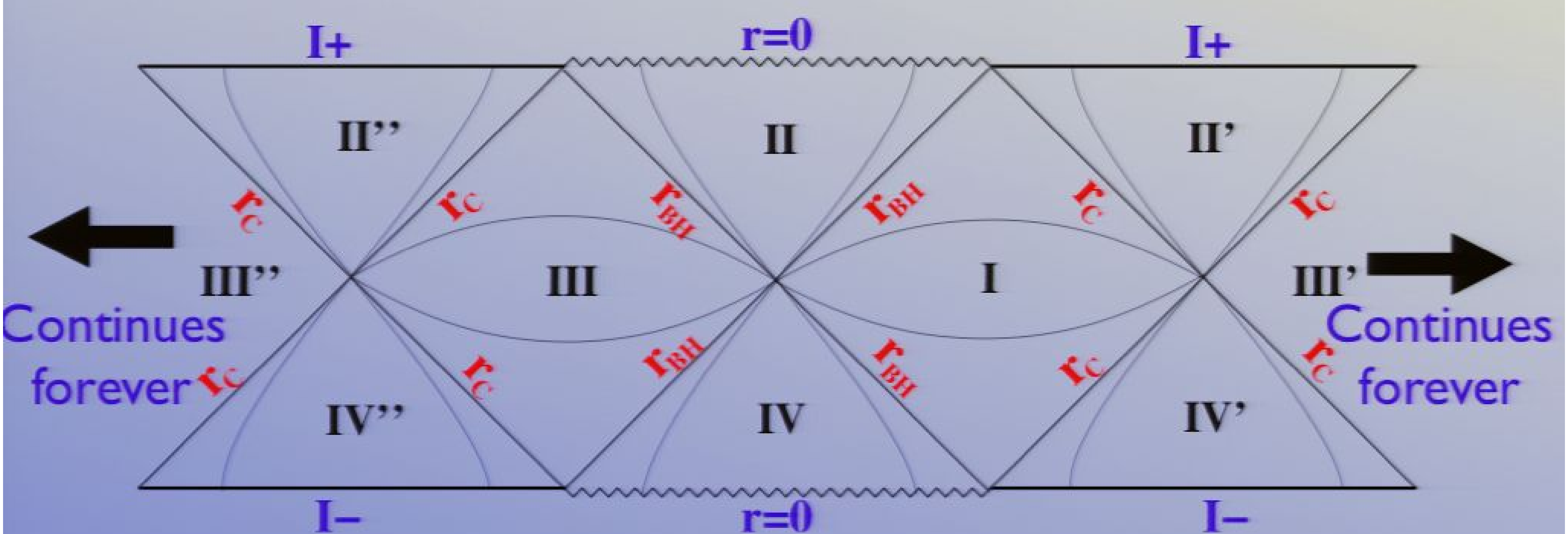

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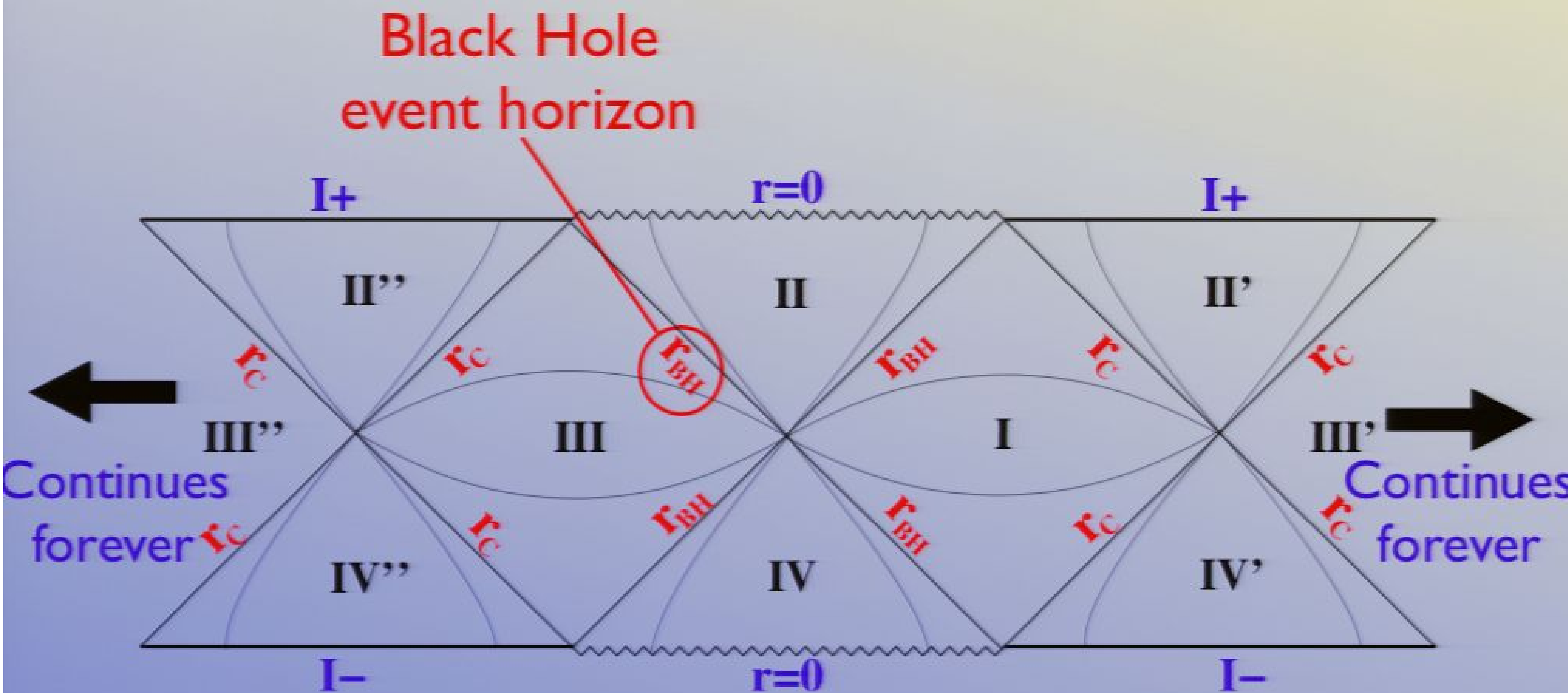

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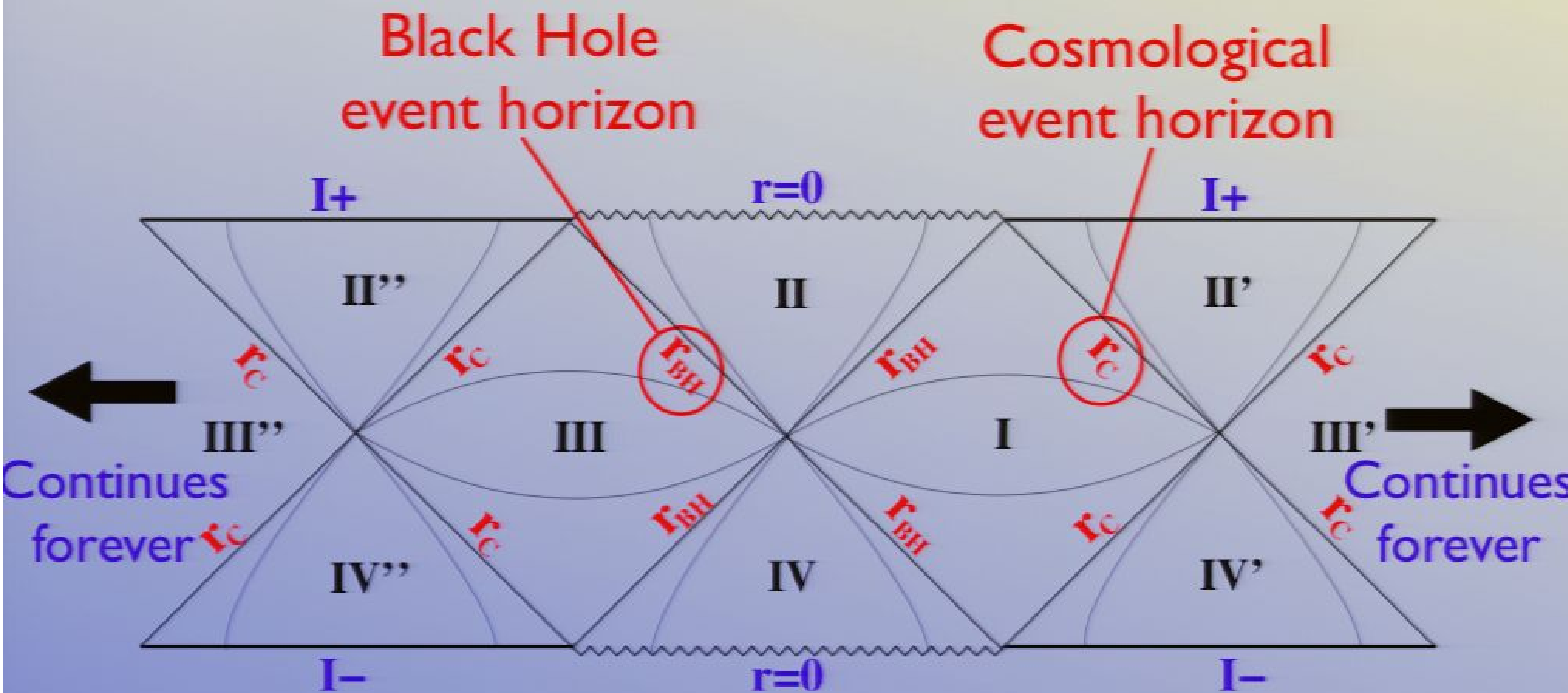
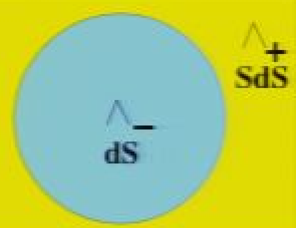
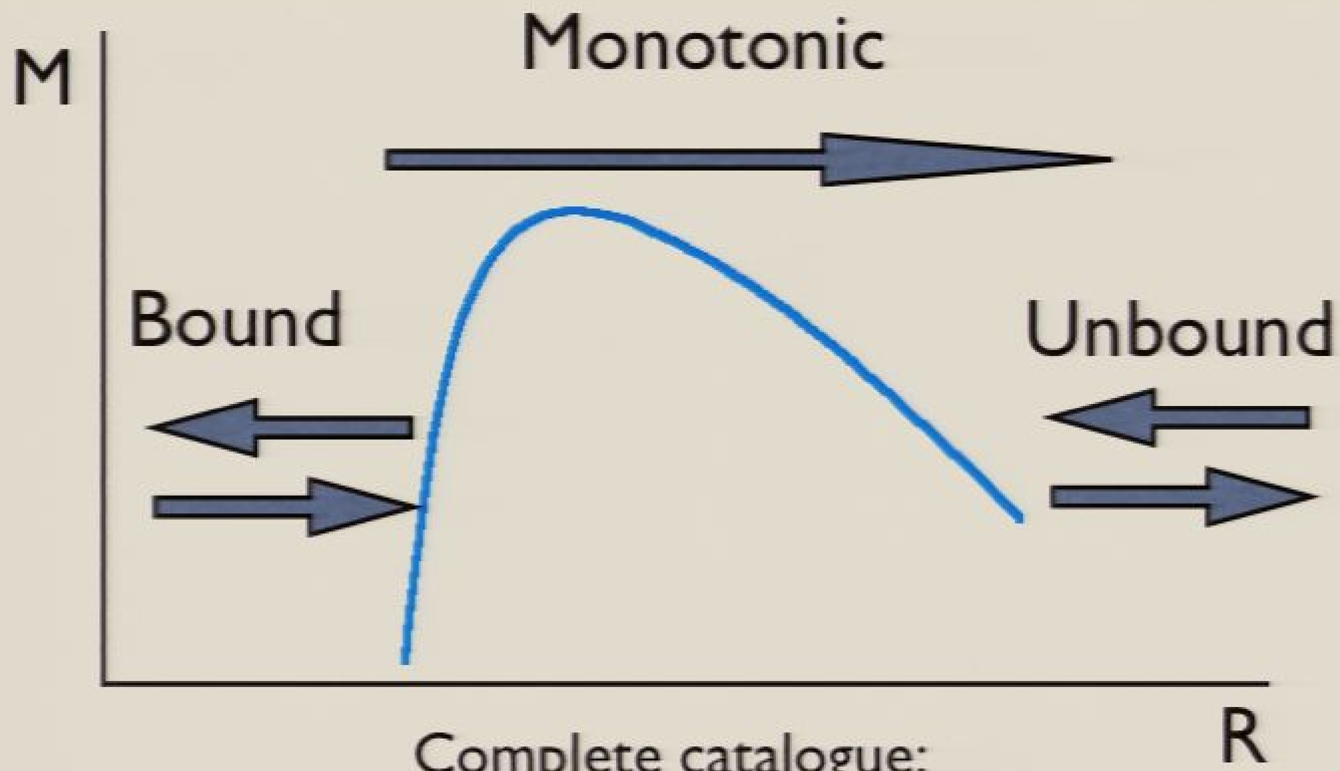


Israel Junction Conditions

Israel 1966, 1967
Blau et. al 1987
Aurilia et. al. 1989
Berezin et. al 1983, 1987
Sato 1986



Wall Dynamics from
1-D potential:



Complete catalogue:
Aguirre and Johnson gr-qc/0508093 and gr-qc/0512034

Classical Dynamics

Metric on bubble wall worldsheet $\gamma_{\mu\nu}$: $ds^2 = -d\tau^2 + R(\tau)^2 d\Omega^2$

Full 4-D metric $g_{\mu\nu}$: $ds^2 = g_{\tau\tau}(\tau,\eta)d\tau^2 + d\eta^2 + r(\tau,\eta)^2 d\Omega^2$

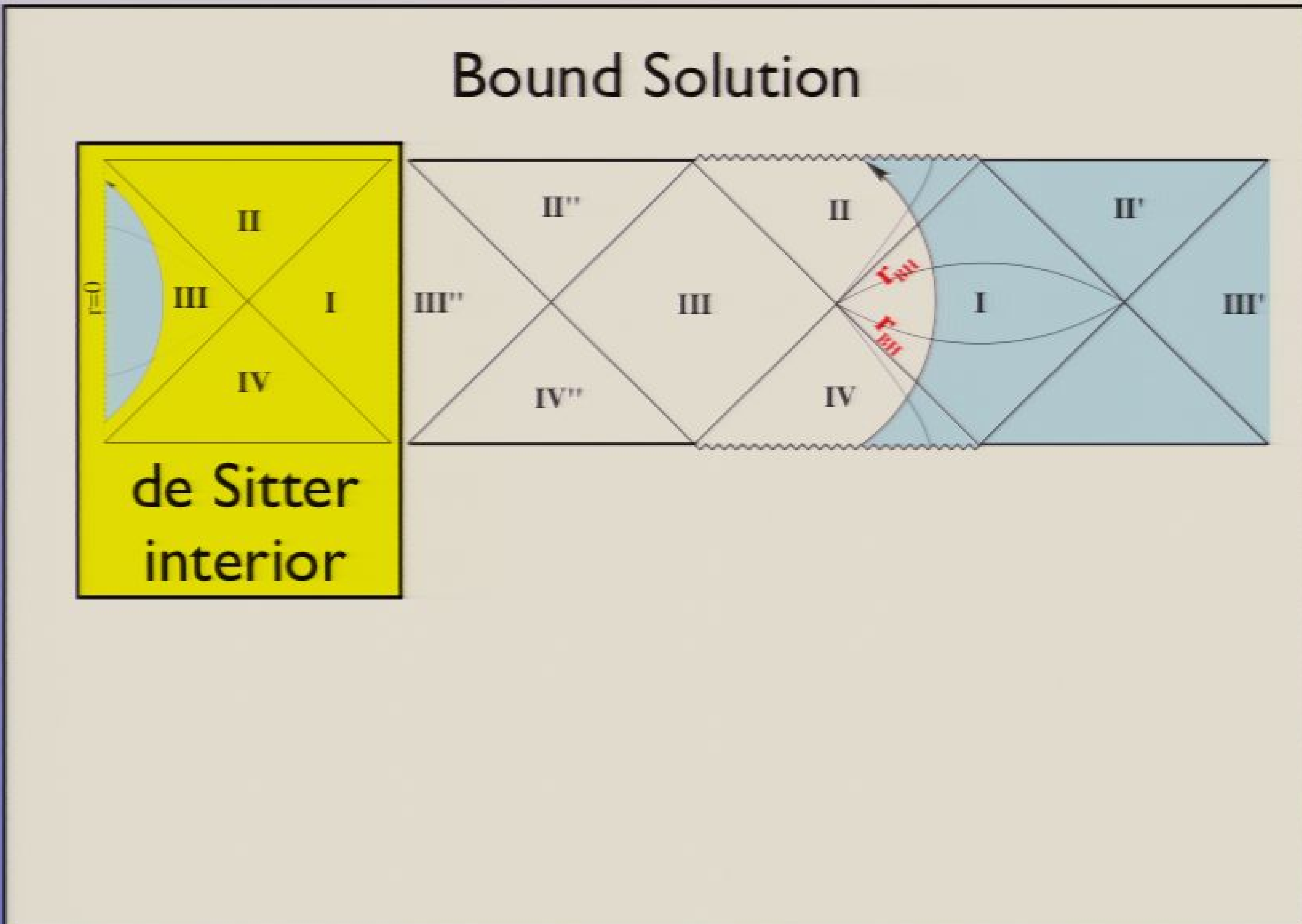
Wall EM tensor: $T^{\mu\nu}_{\text{wall}} = -\sigma\gamma^{\mu\nu}\delta(\eta)$

Einstein's Equations: $K^i_j(\eta_+) - K^i_j(\eta_-) = -4\pi\sigma R\delta^i_j$

$$K_{ij} = \frac{1}{2}\frac{d}{d\eta}g_{ij}$$

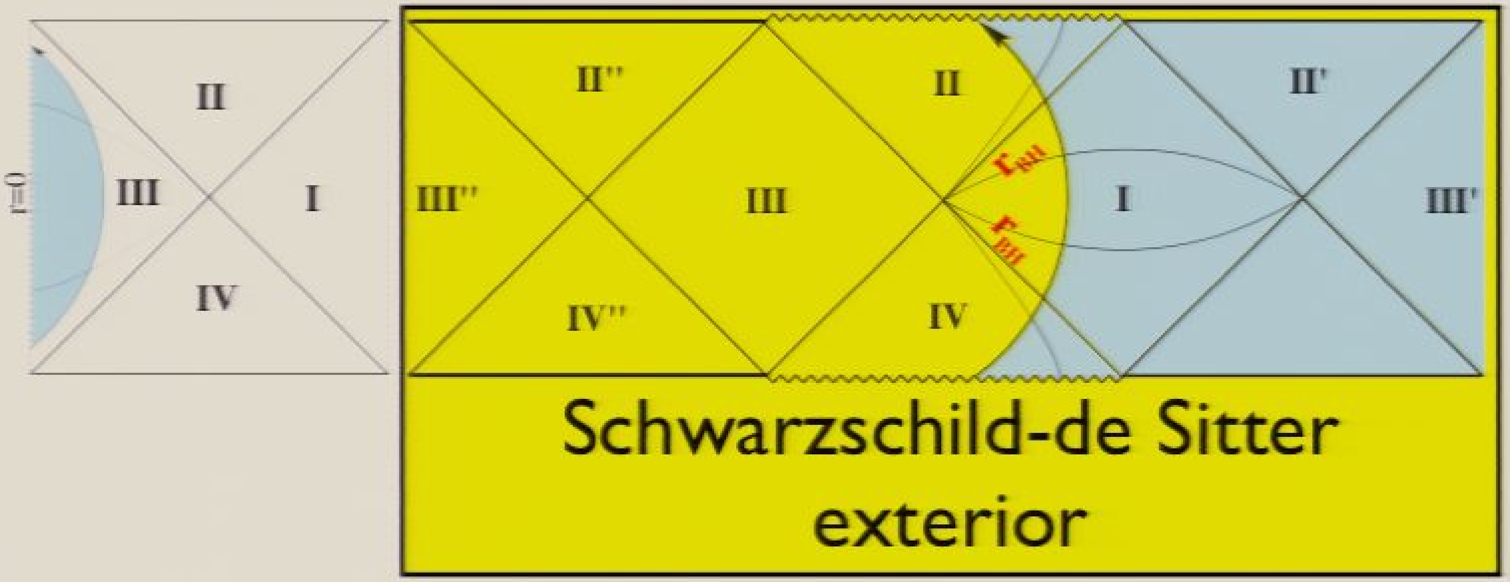
$$\dot{R}^2 + V(R,M) = -1$$

Allowed Spacetimes



Allowed Spacetimes

Bound Solution



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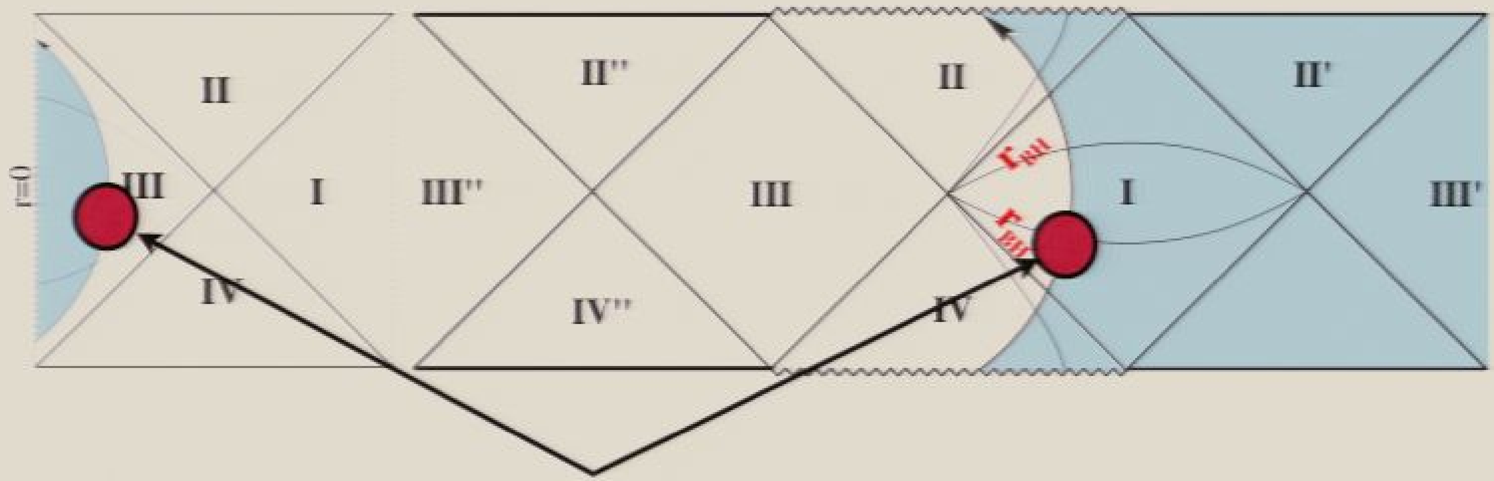
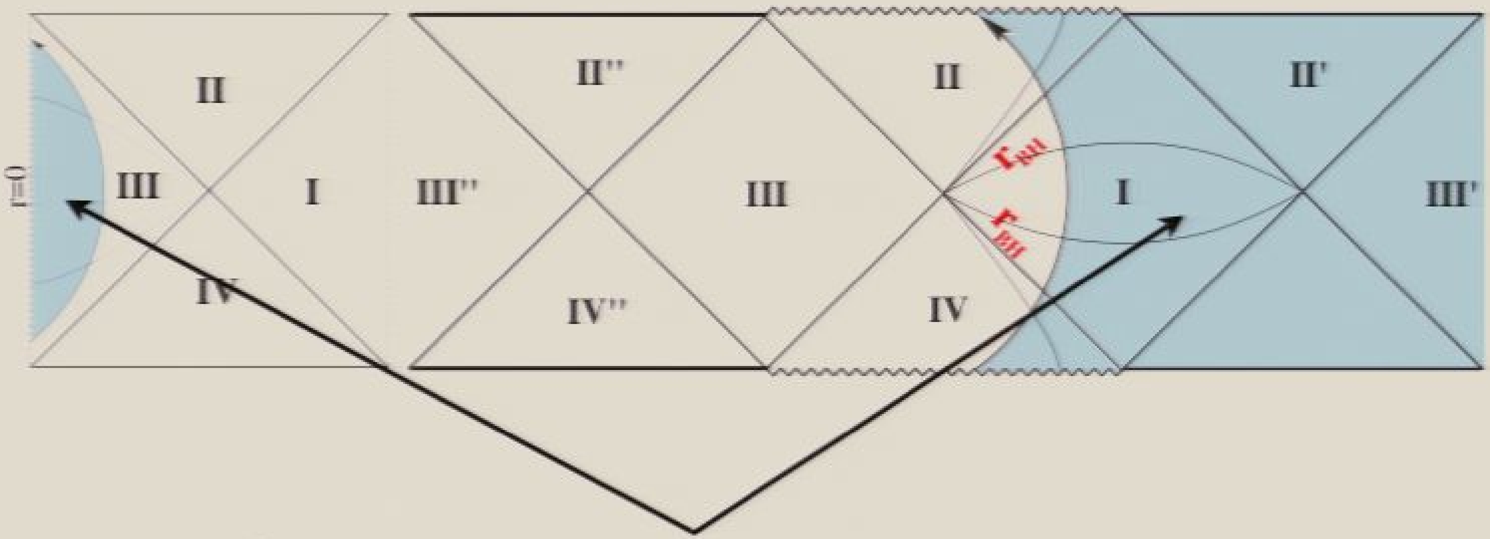


Bubble wall:
identify these points

Allowed Spacetimes

Bound Solution



Only shaded regions physical!

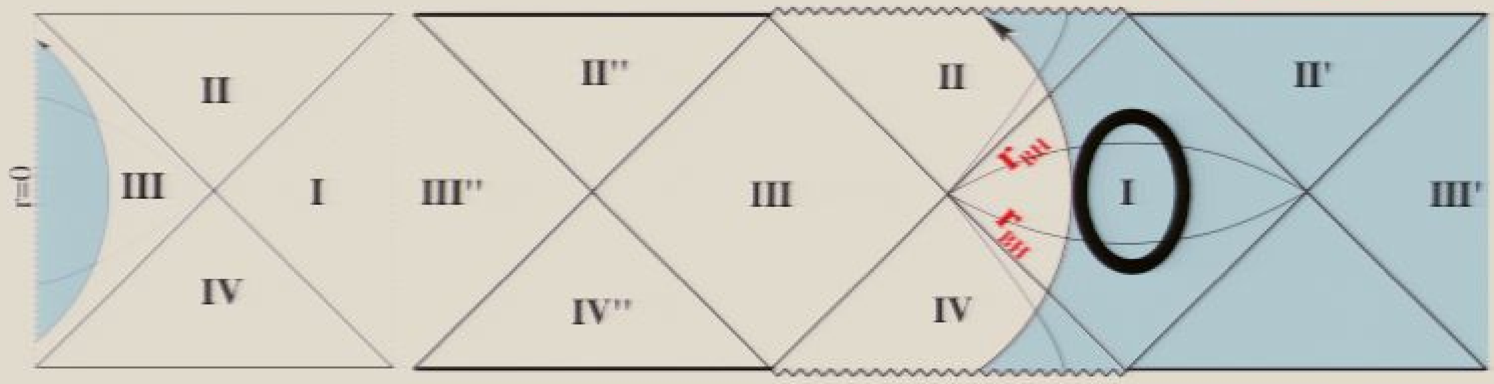
Concentrate on False Vacuum Bubbles for now.

Allowed Spacetimes

Bound Solution

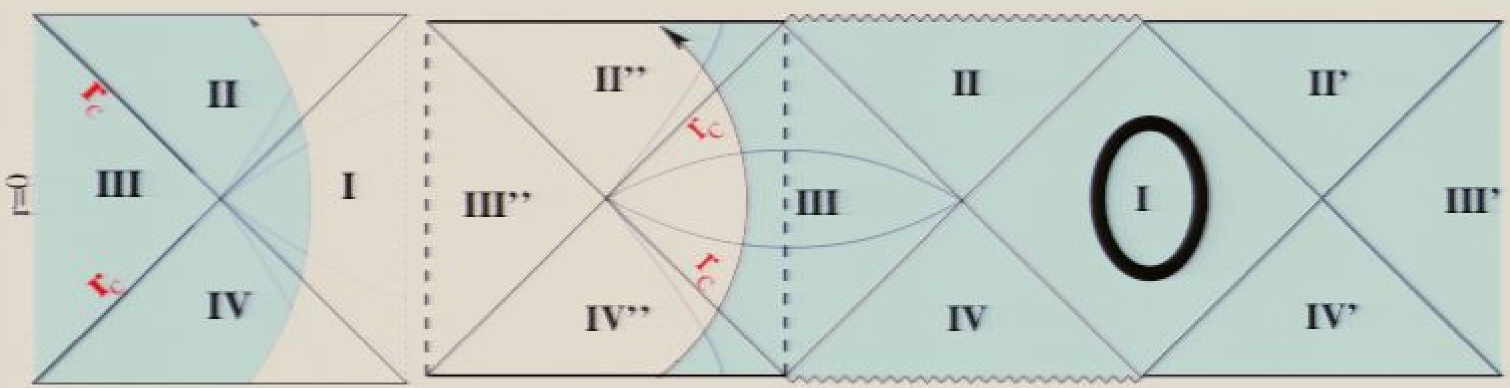
classically buildable

Farhi and Guth 1987



Unbound Solution

Not
classically buildable!

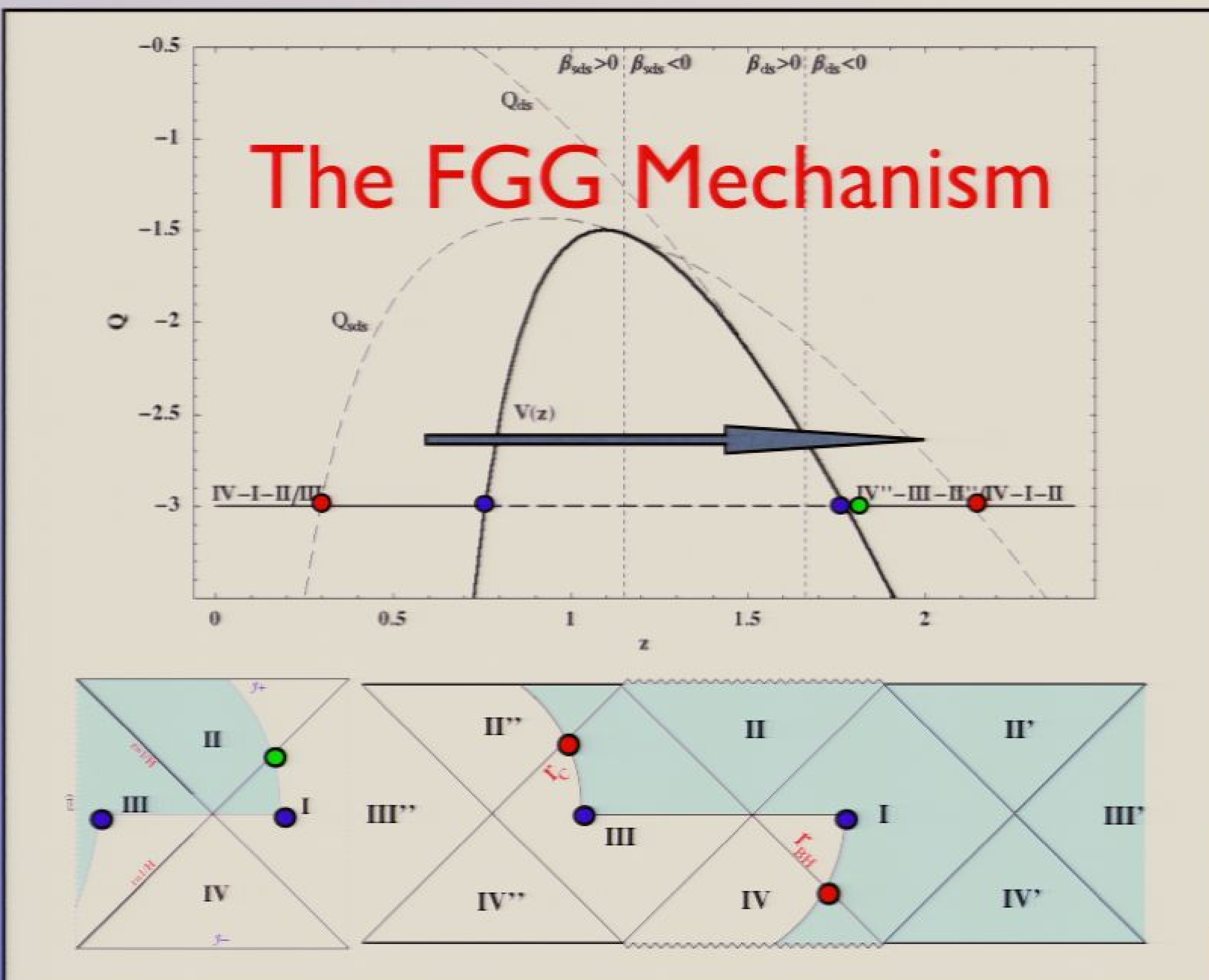


Got Tunneling?

Farhi, Guth, Guven 1990

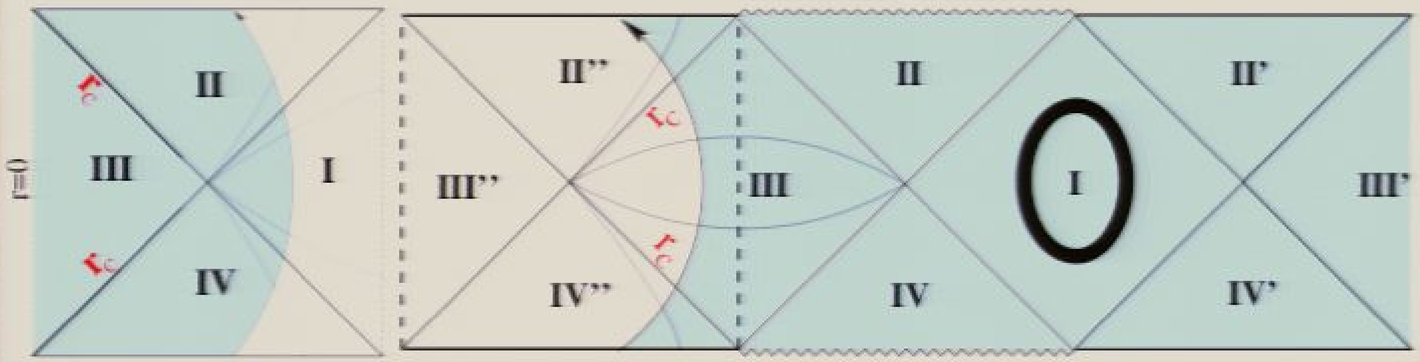
Fischler et. al. 1990

The FGG Mechanism

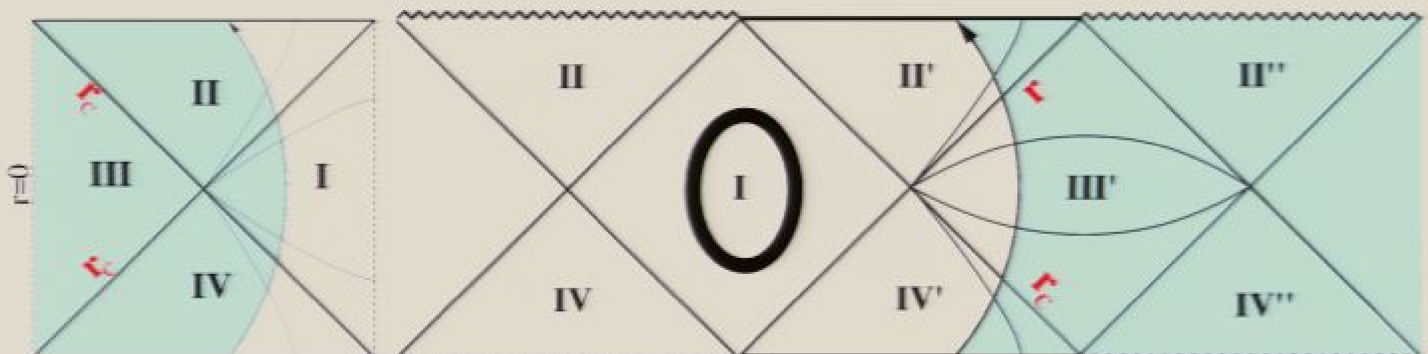


An Observation

For every unbound solution behind a worm hole,



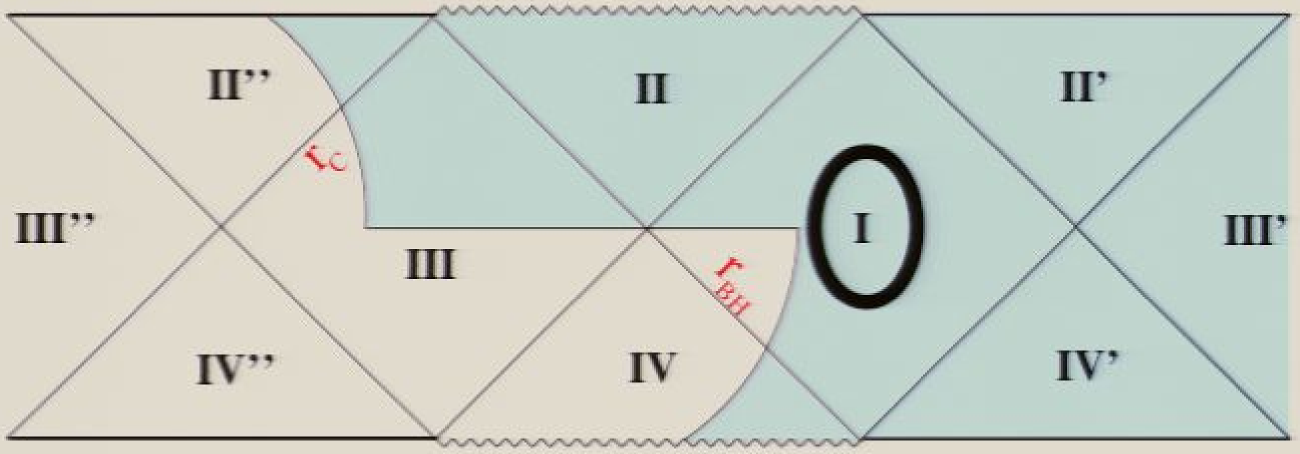
there is an identical solution outside the cosmological horizon (SdS non-compact).



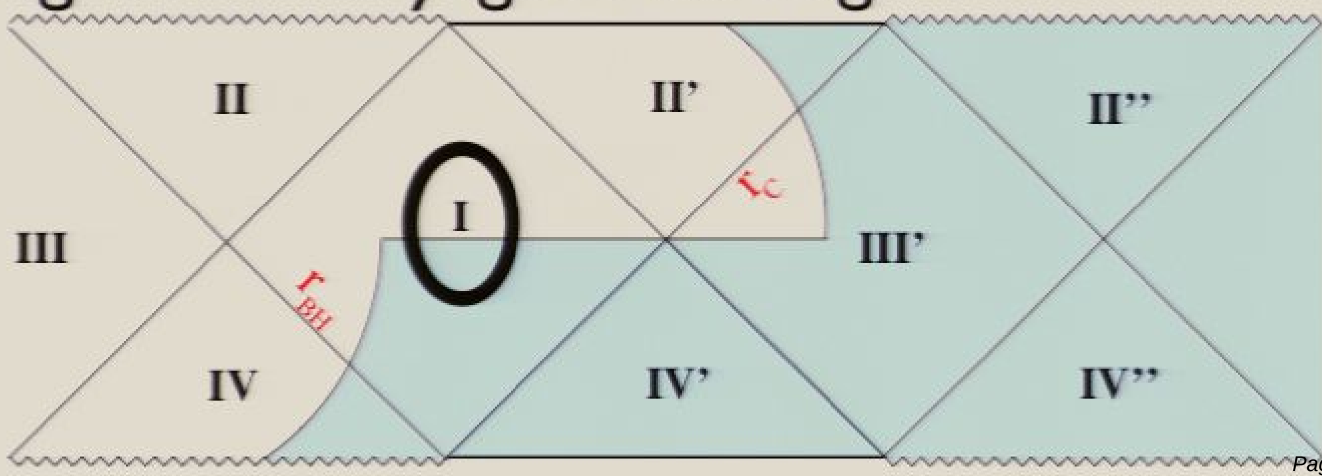
Two Tunnels

A. Aguirre and M. C. Johnson (2005), gr-qc/0512034.

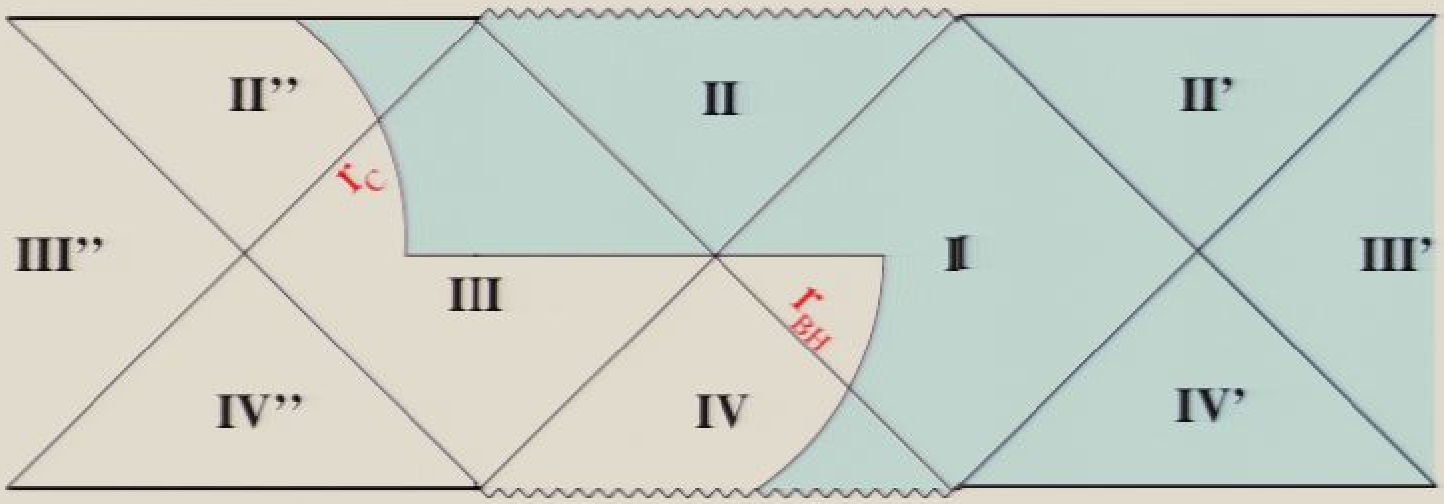
L Tunneling Geometry: goes through wormhole.



R Tunneling Geometry: goes through dS horizon.



Zero Mass Limit: L Geometry



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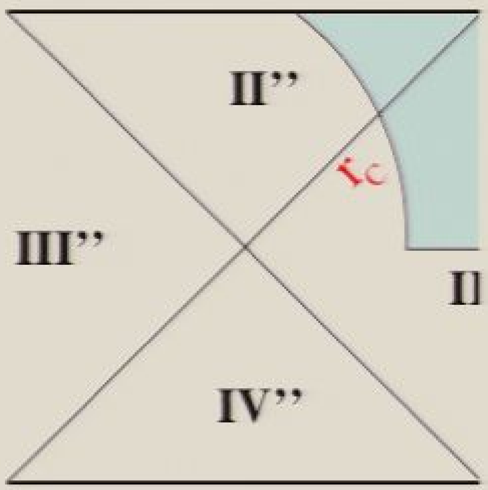
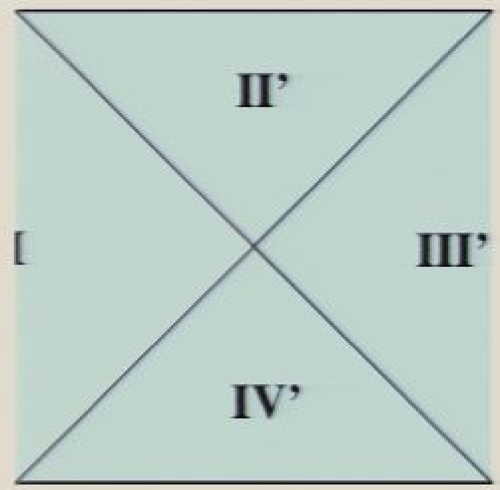
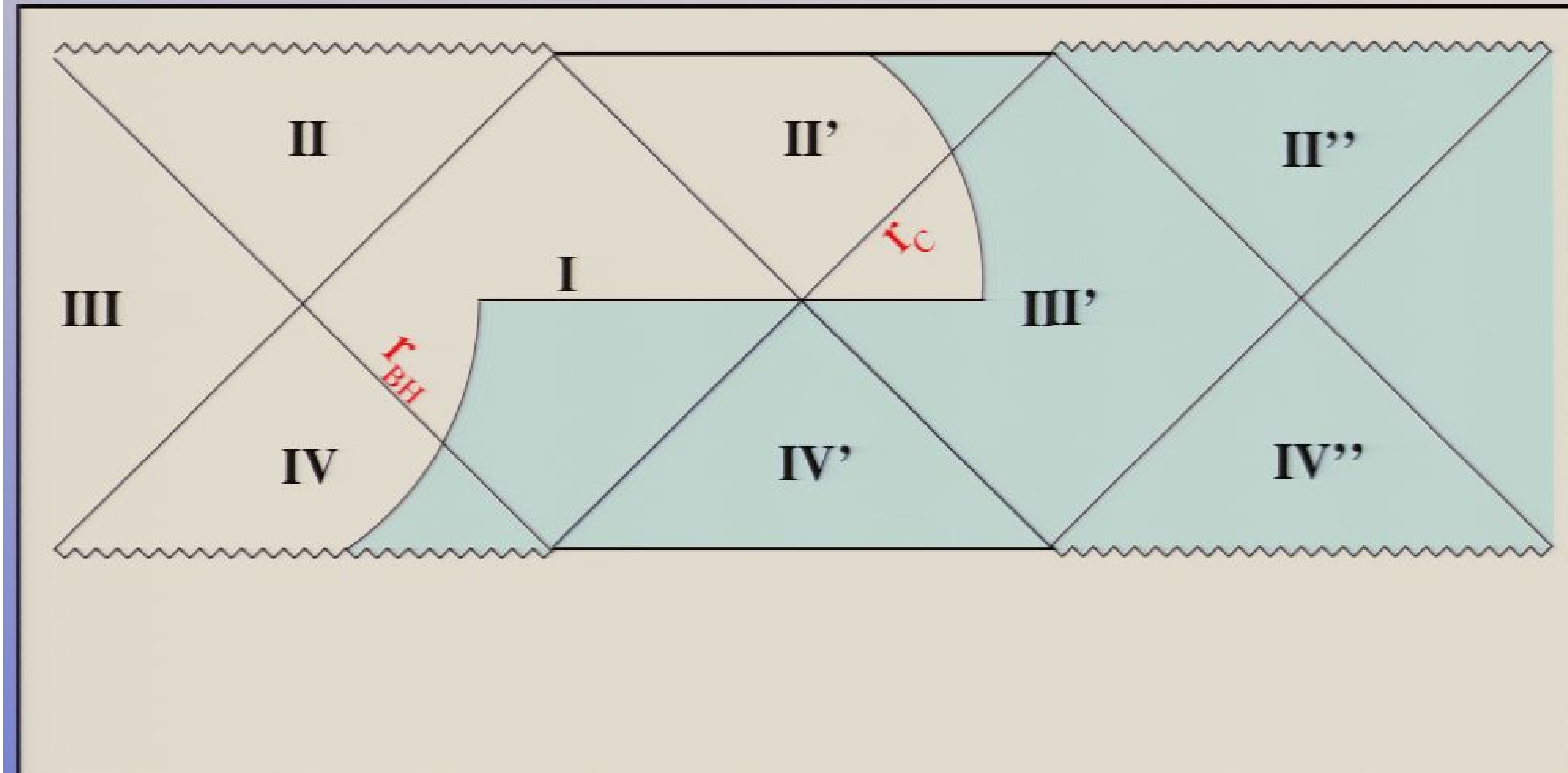


Universe "from nothing" containing a LW bubble



Undisturbed universe

Zero Mass Limit: R Geometry



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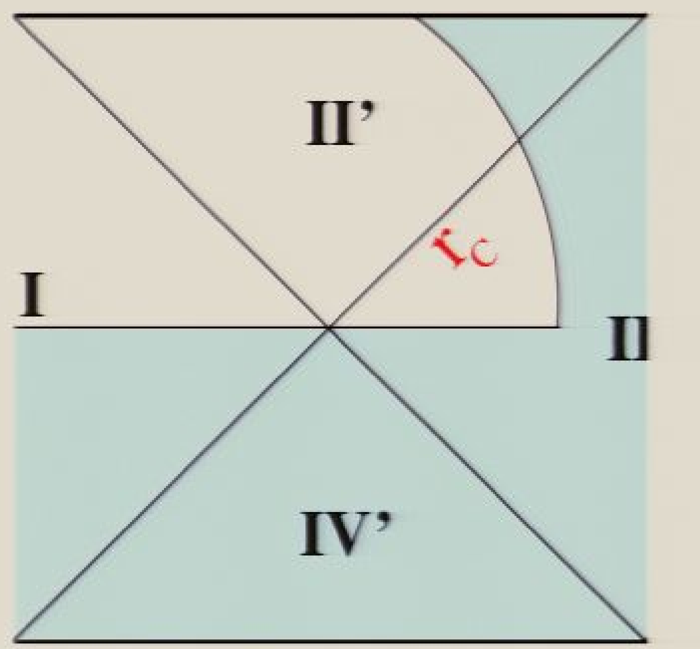

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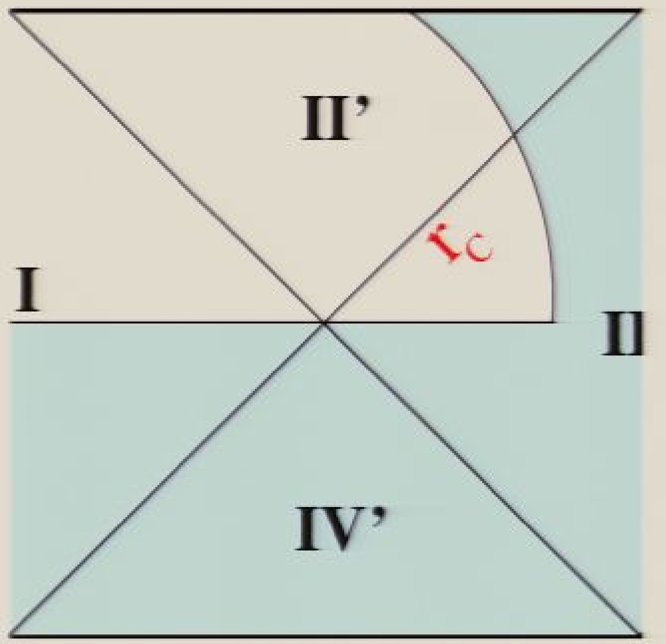
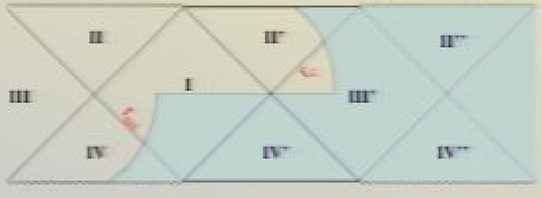


LW bubble

dS to Bubble Spacetime

Three step process:



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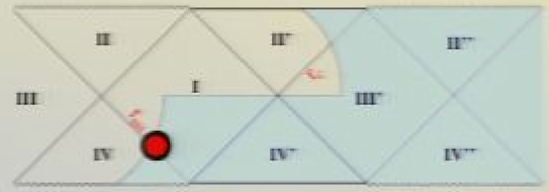

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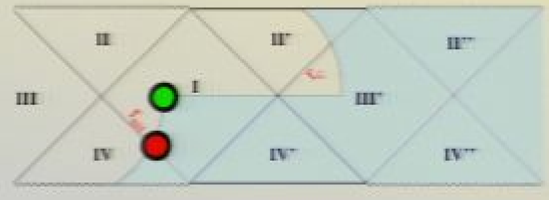

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Bound solutions are unstable. (Aguirre & Johnson, Phys. Rev. D72, 103525)

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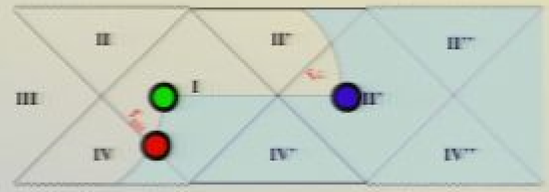

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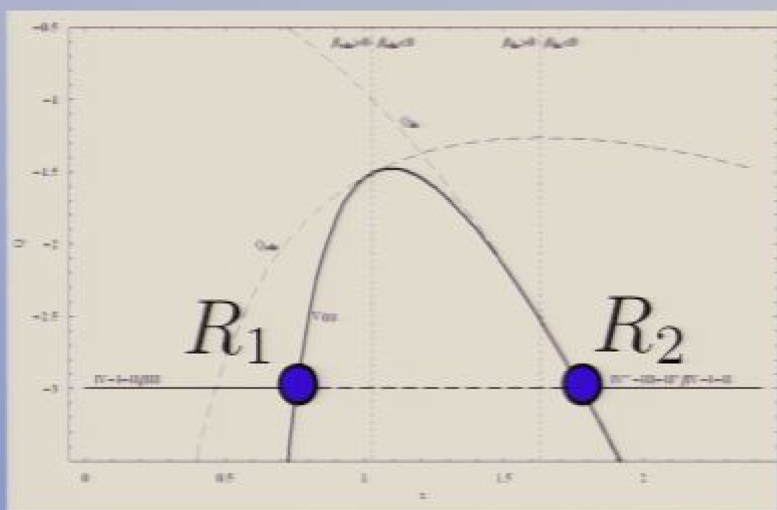
dS to Bubble Spacetime

- Tunneling rate calculated using Dirac quantization in the WKB approximation, assuming a spherically symmetric mini-superspace. Fischler et. al. 1990



$$P(R_1 \to R_2) = \left| \frac{\Psi(R_2)}{\Psi(R_1)} \right|^2 \simeq e^{2i\Sigma_0[R_2 - R_1]}$$

(Note: we neglect a pre-factor. Unclear how to calculate this.)

Parametrized Systems

- ⇒ Particle in motion: $S\left[q\left(t\right)\right]=\int_{t_1}^{t_2}dtL\left(q,\frac{dq}{dt}\right)$

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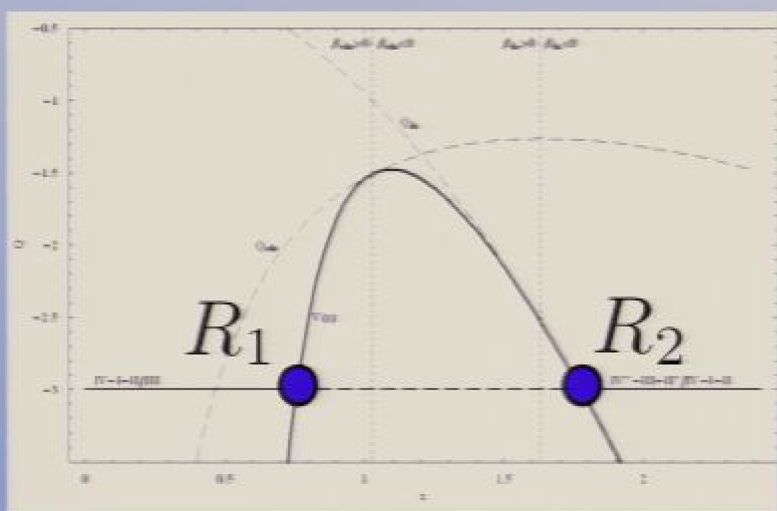

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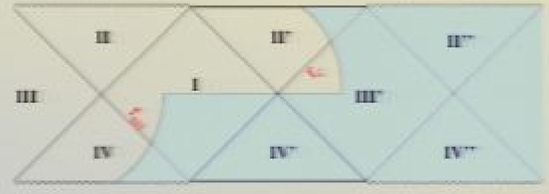
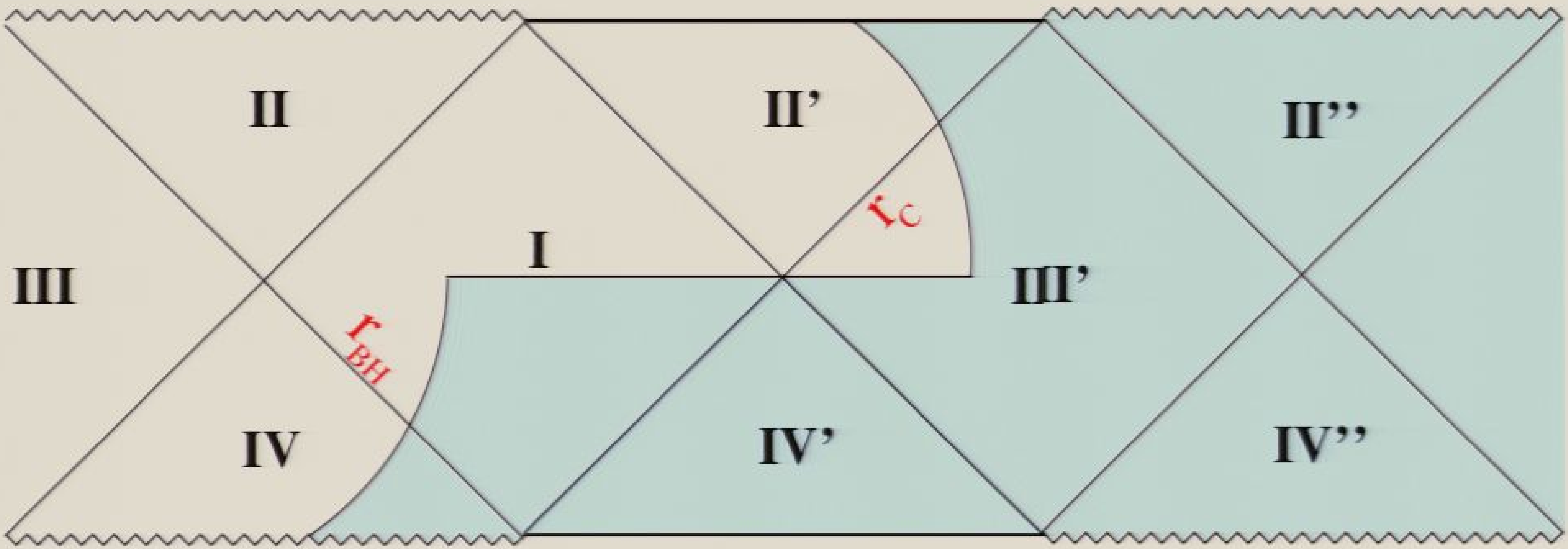


Zero Mass Limit:
R Geometry



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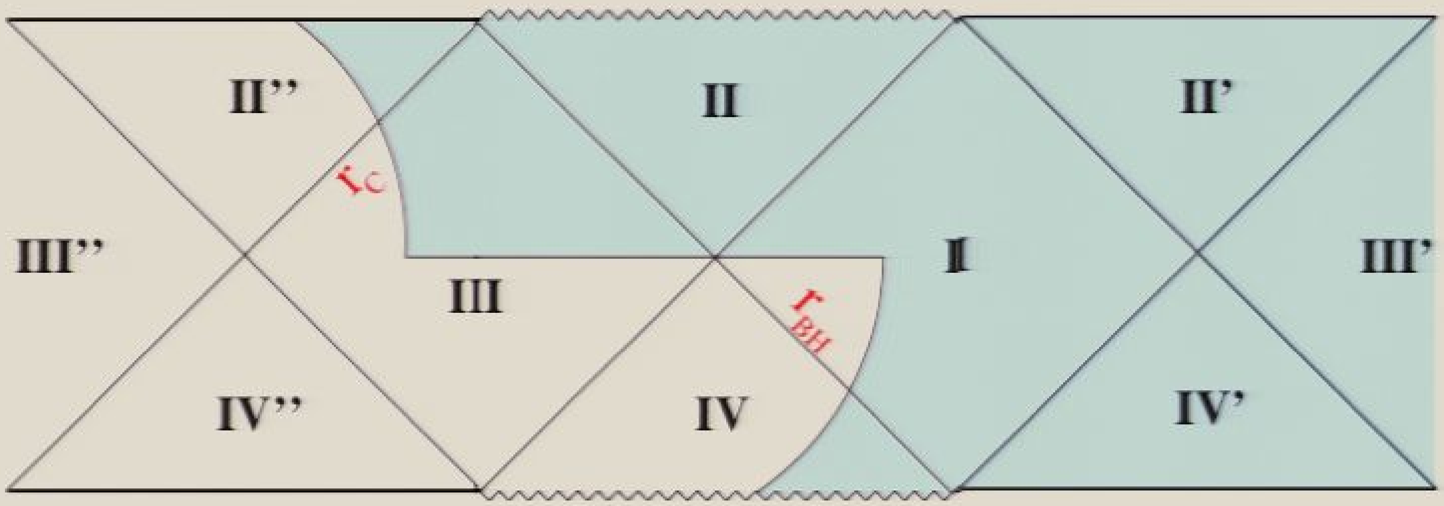

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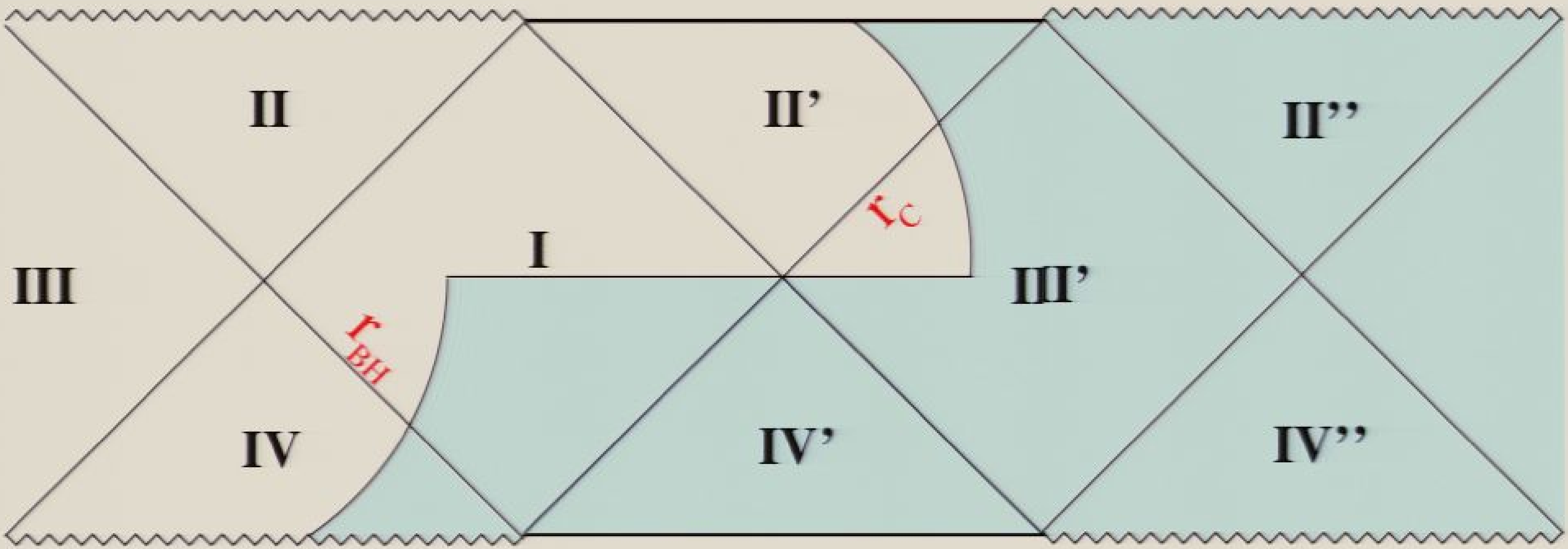

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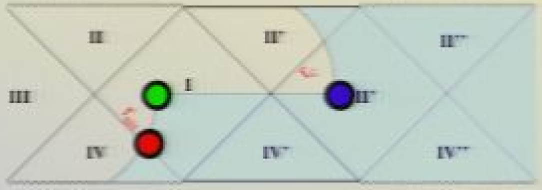

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- ⇨ Particle in motion: $S\left[q\left(t\right)\right]=\int_{t_1}^{t_2}dtL\left(q,\frac{dq}{dt}\right)$

The trick: $S\left[q,t\right]=\int_{\tau_1}^{\tau_2}d\tau\tilde{L}\left(q,\dot{q},\dot{t}\right)\qquad\tilde{L}\equiv\dot{t}\;L$

$$\tilde{H}=\tilde{p}_q\dot{q}+\tilde{p}_t\dot{t}-\tilde{L}\qquad\tilde{p}_t=\frac{\partial\tilde{L}}{\partial\dot{t}}\quad\tilde{p}_q=\frac{\partial\tilde{L}}{\partial\dot{q}}$$

Parametrized Systems

- ⇒ Particle in motion: $S[q(t)] = \int_{t_1}^{t_2} dt L\left(q, \frac{dq}{dt}\right)$

The trick: $S[q,t] = \int_{\tau_1}^{\tau_2} d\tau \tilde{L}(q,\dot{q},\dot{t}) \quad \tilde{L} \equiv \dot{t}\, L$

$$\tilde{H} = \tilde{p}_q \dot{q} + \tilde{p}_t \dot{t} - \tilde{L} \qquad \tilde{p}_t = \frac{\partial \tilde{L}}{\partial \dot{t}} \quad \tilde{p}_q = \frac{\partial \tilde{L}}{\partial \dot{q}}$$

Constraint

$$\Longrightarrow \tilde{H} = \dot{t}\left(\tilde{p}_t + H\right) = 0$$

Parametrized Systems

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Constraint

$$\Longrightarrow \tilde{H} = \dot{t}\left(\tilde{p}_t + H\right) = 0$$

Quantize!

$$\tilde{p}_t \longrightarrow -i\hbar\frac{\partial}{\partial t} \Rightarrow \left(\hat{H} - i\hbar\frac{\partial}{\partial t}\right)\Psi = 0$$

Full Hamiltonian

$$ds^2 = -N^t(t,r)^2\,dt^2 + L(t,r)^2\left[dr + N^r(t,r)\,dt\right]^2 + R(t,r)^2\left(d\theta^2 + \sin^2\theta d\phi^2\right),$$

$$S = \int dt\ p\ \dot{q} + \int dr\ dt\ \left(\pi_L \dot{L} + \pi_R \dot{R} - N^t H_t - N^r H_r\right)$$

$$\hat{H}_t \Psi = \hat{H}_r \Psi = \hat{\pi}_{N^t} \Psi = \hat{\pi}_{N^r} \Psi = 0$$

$$\begin{aligned} H_t &= \frac{L\pi_L^2}{2R^2} - \frac{\pi_L \pi_R}{R} \\ &+ \frac{1}{2}\left[\left[\frac{2RR'}{L}\right]' - \frac{R'^2}{L} - L + \Lambda_+ L R^2\right] \\ &+ \Theta(r_w - r)\frac{(\Lambda_- - \Lambda_+)}{2} L R^2 \\ &+ \delta(r_w - r)\left(L^{-2} p_w^2 + k^2 R_w^4\right)^{1/2}, \end{aligned}$$

$$H_r = R'\pi_R - L\pi_L' - \delta(r_w - r)\, p_w,$$

WKB Approximation

$$H = \sum_{n=0}^{\infty} a_n (q) p^n$$

WKB Approximation

Quantize!

$$H = \sum_{n=0}^{\infty} a_n(q)\, p^n \quad \Rightarrow \quad \hat{H} = \sum_{n=0}^{\infty} \left[a_n(\hat{q})\, \hat{p}^n + O(\hbar) + \ldots.. \right]$$

WKB Approximation

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Ansatz: $$\boxed{\Psi(q) = e^{\frac{i\sigma(q)}{\hbar}}}$$

$$\left(\hat{H} - E\right)\Psi(q) = 0$$

WKB Approximation

Quantize!

$$H=\sum_{n=0}^{\infty}a_n(q)\,p^n \quad \Rightarrow \quad \hat{H}=\sum_{n=0}^{\infty}\left[a_n(\hat{q})\,\hat{p}^n+O(\hbar)+.....\right]$$

Ansatz: $\Psi(q)=e^{\frac{i\sigma(q)}{\hbar}}$

$$\left(\hat{H}-E\right)\Psi(q)=0$$

To lowest order in $\hbar$ $\Rightarrow$

$$\sum_{n=0}^{\infty}a_n(q)\left(\frac{d\sigma}{dq}\right)^n=H(q,\frac{d\sigma}{dq})=E$$

WKB Approximation

Quantize!

$$H = \sum_{n=0}^{\infty} a_n(q)\, p^n \quad \Rightarrow \quad \hat{H} = \sum_{n=0}^{\infty} \left[a_n(\hat{q})\, \hat{p}^n + O(\hbar) + \ldots.. \right]$$

Ansatz: $\Psi(q) = e^{\frac{i\sigma(q)}{\hbar}}$

$$\left(\hat{H} - E\right)\Psi(q) = 0$$

To lowest order in $\hbar$ ⇒

$$\sum_{n=0}^{\infty} a_n(q) \left(\frac{d\sigma}{dq}\right)^n = H\left(q, \frac{d\sigma}{dq}\right) = E$$

Solution: $\sigma(q) = \int^{q} p(\bar{q})\, d\bar{q}$

With constraint H = E

Full Hamiltonian

$$\Psi\left(L,R,r\right)=\exp\left[i\Sigma_0\left(L,R,r\right)/\hbar+O\left(\hbar\right)\right]$$

1 true degree of freedom.

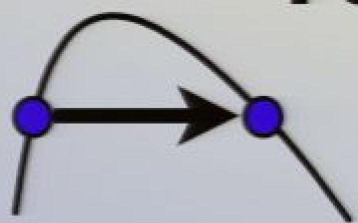
$$H_{r,t}\left(r,L,R,\frac{\delta\Sigma_0}{\delta r},\frac{\delta\Sigma_0}{\delta L},\frac{\delta\Sigma_0}{\delta R}\right)=0$$

Perform functional integral between the classical turning points:

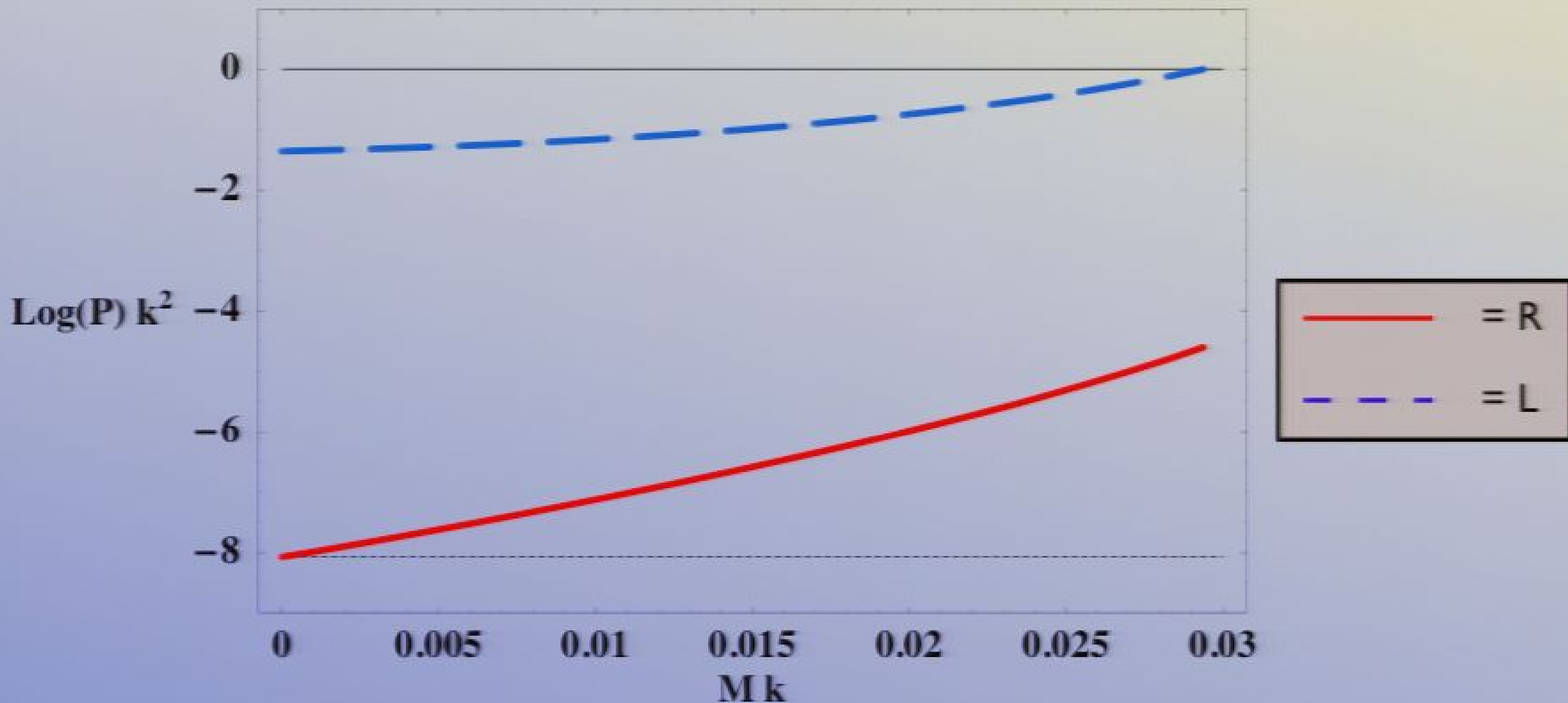
$$\delta\Sigma_0=\hat{p}\delta\hat{r}+\int_0^\infty dr\left[\pi_L\delta L+\pi_R\delta R\right]$$

(subject to constraints...)

Tunneling Exponents



$$P(R_1 \to R_2) = \left| \frac{\Psi(R_2)}{\Psi(R_1)} \right|^2 \simeq e^{2i\Sigma_0[R_2 - R_1]}$$

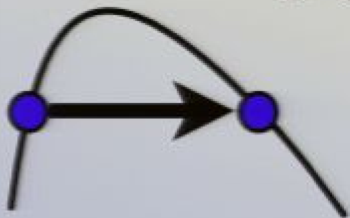


False Vacuum Bubbles

$10^{-50} < k < 10^{-5}$

weak ~Planck

Tunneling Exponents



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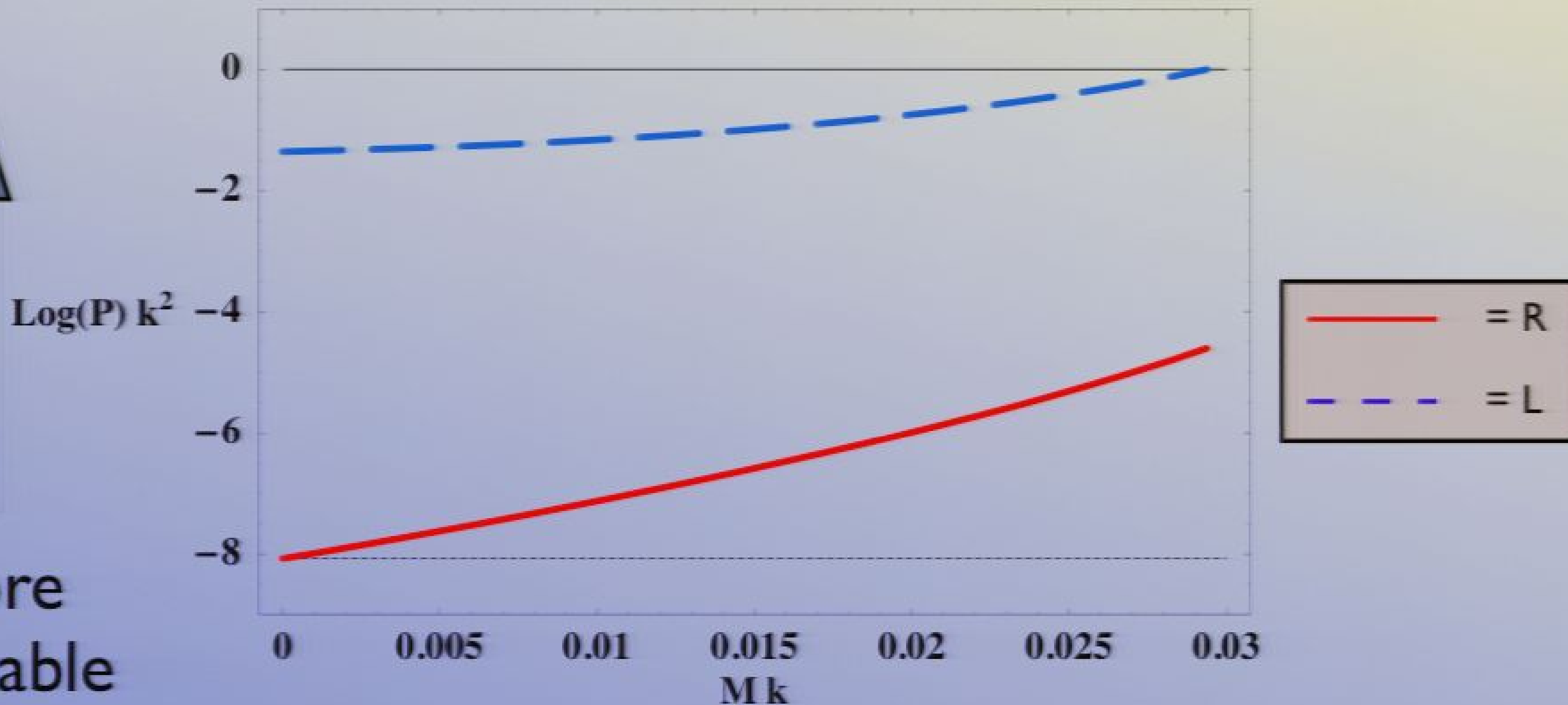
More Probable



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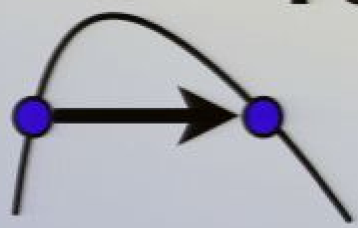
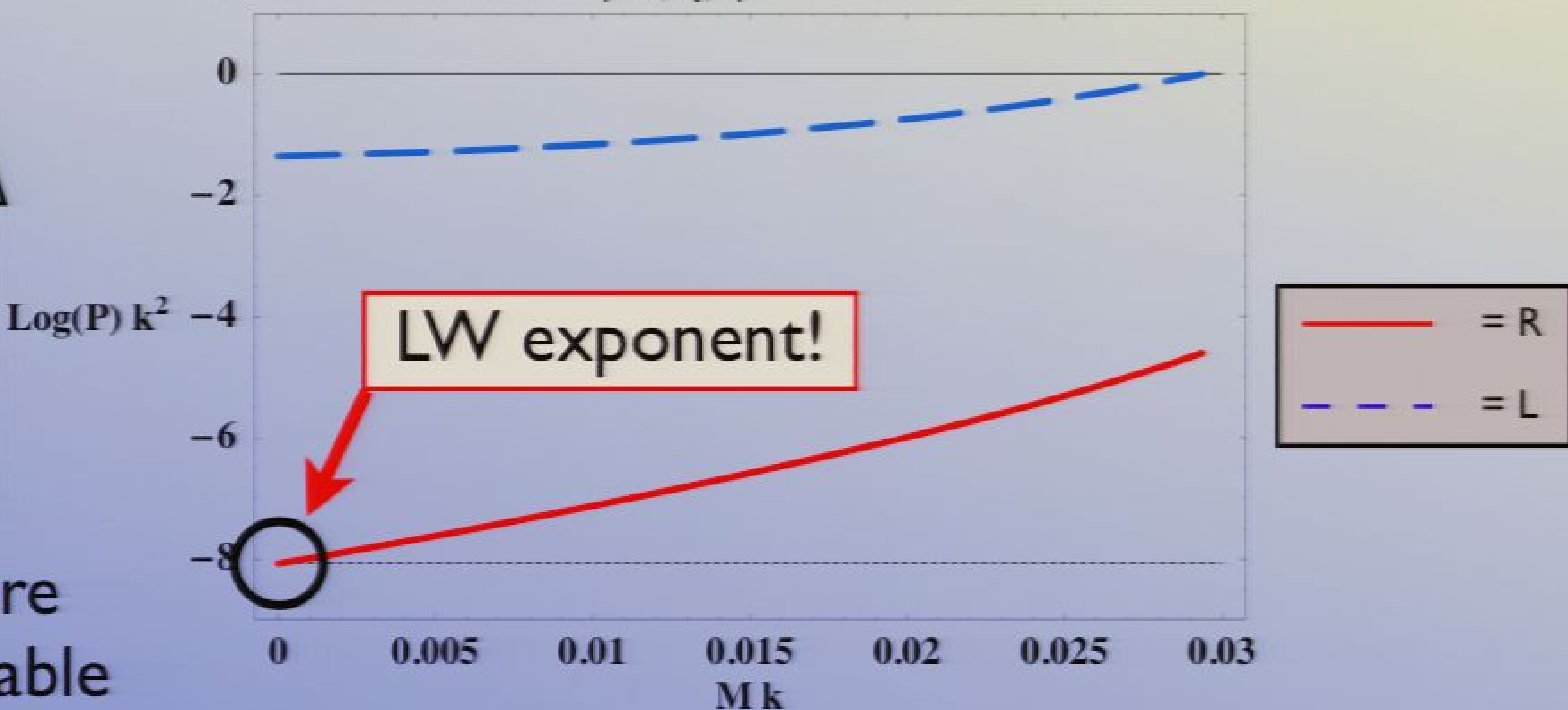


$$P(R_1 \rightarrow R_2) = \left|\frac{\Psi(R_2)}{\Psi(R_1)}\right|^2 \simeq e^{2i\Sigma_0[R_2 - R_1]}$$



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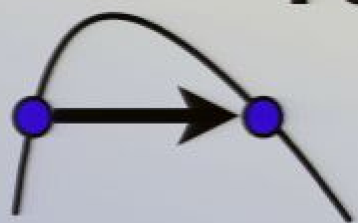

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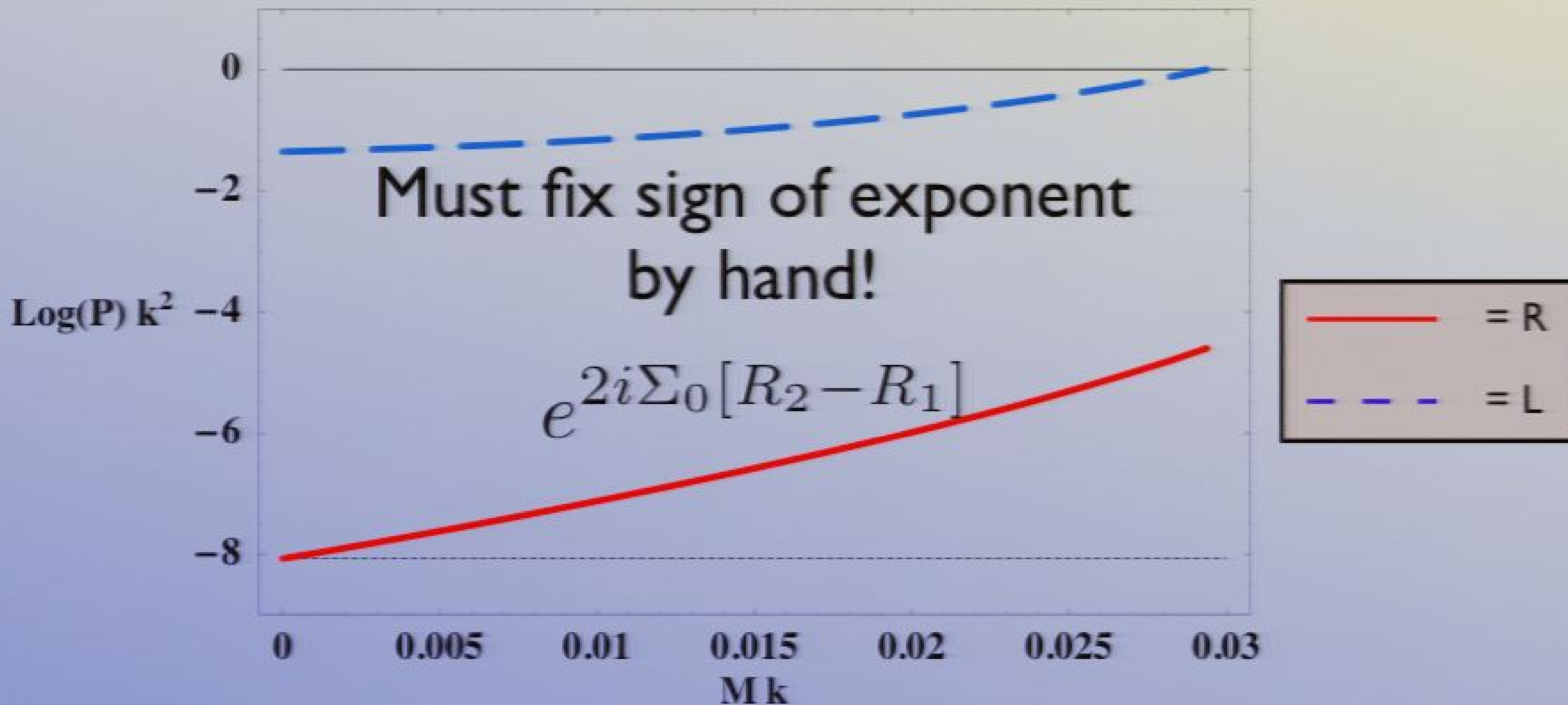
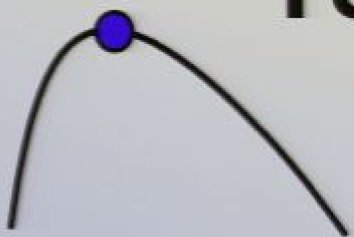


Must fix sign of exponent by hand!

$$e^{2i\Sigma_0[R_2 - R_1]}$$

False Vacuum Bubbles

Tunneling Exponents



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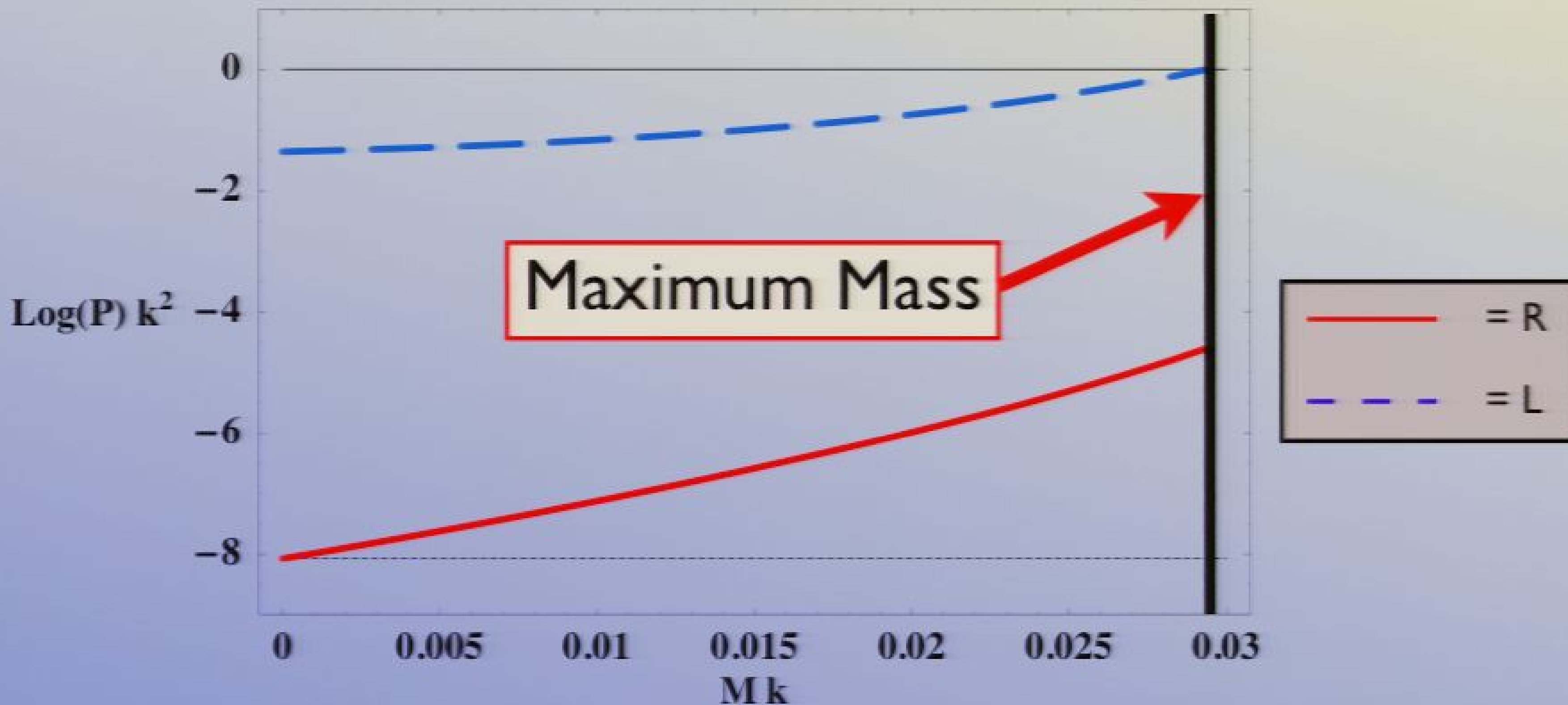
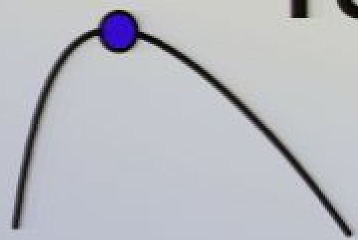


False Vacuum Bubbles

Tunneling Exponents



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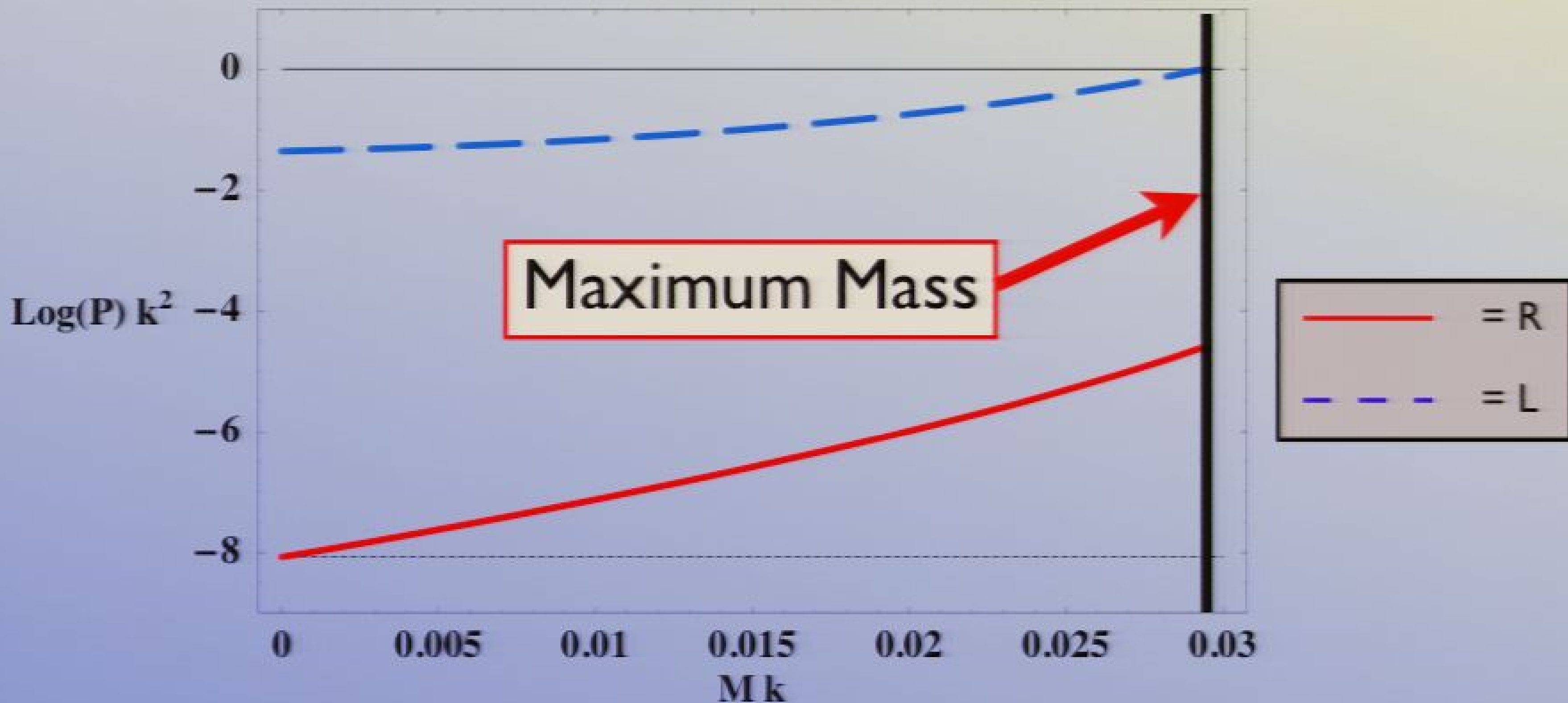
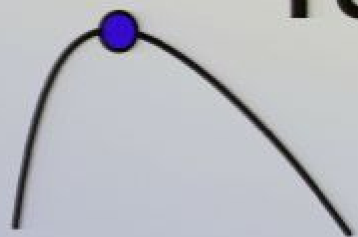


False Vacuum Bubbles

Tunneling Exponents



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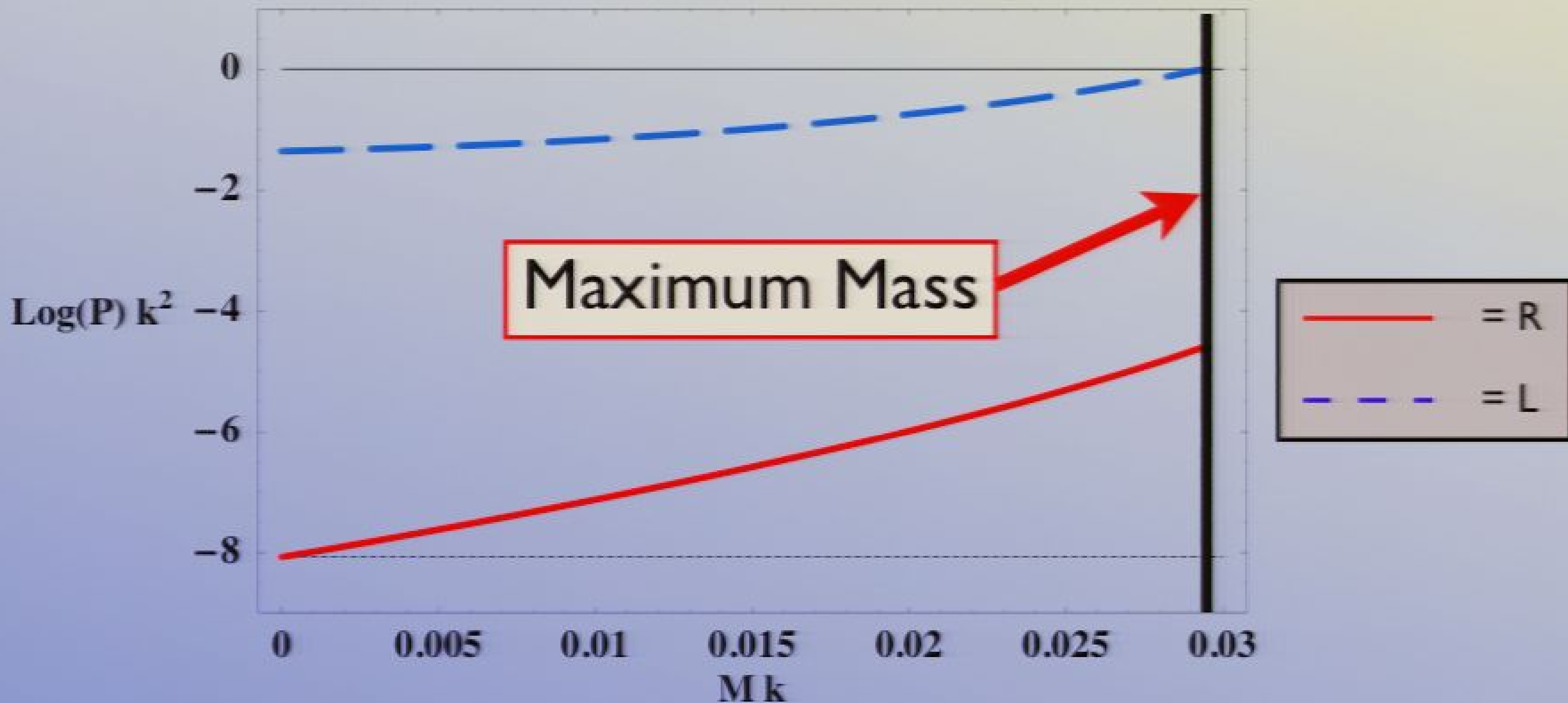
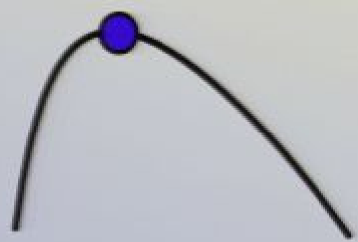
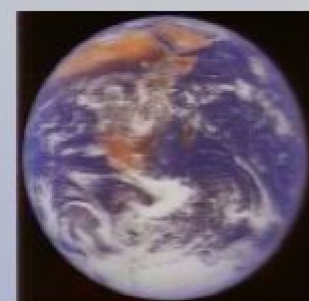


False Vacuum Bubbles

Maximum Mass

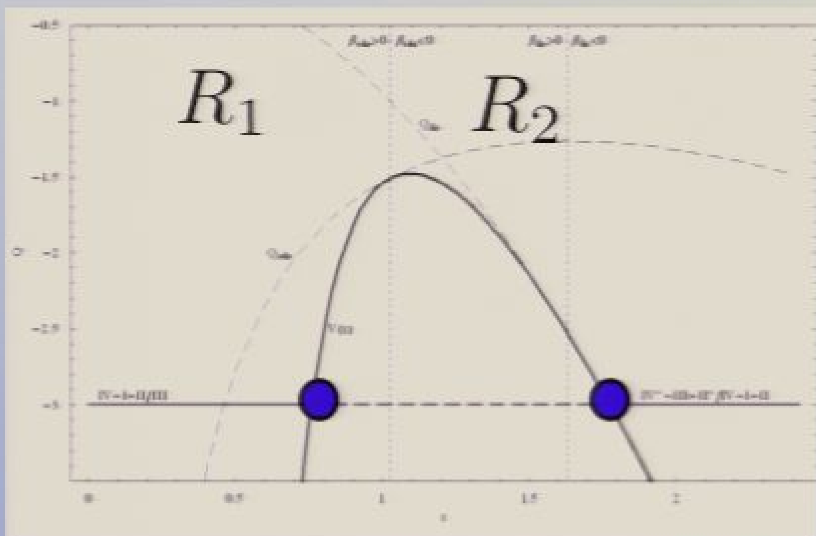


 $< M_{max} <$ 

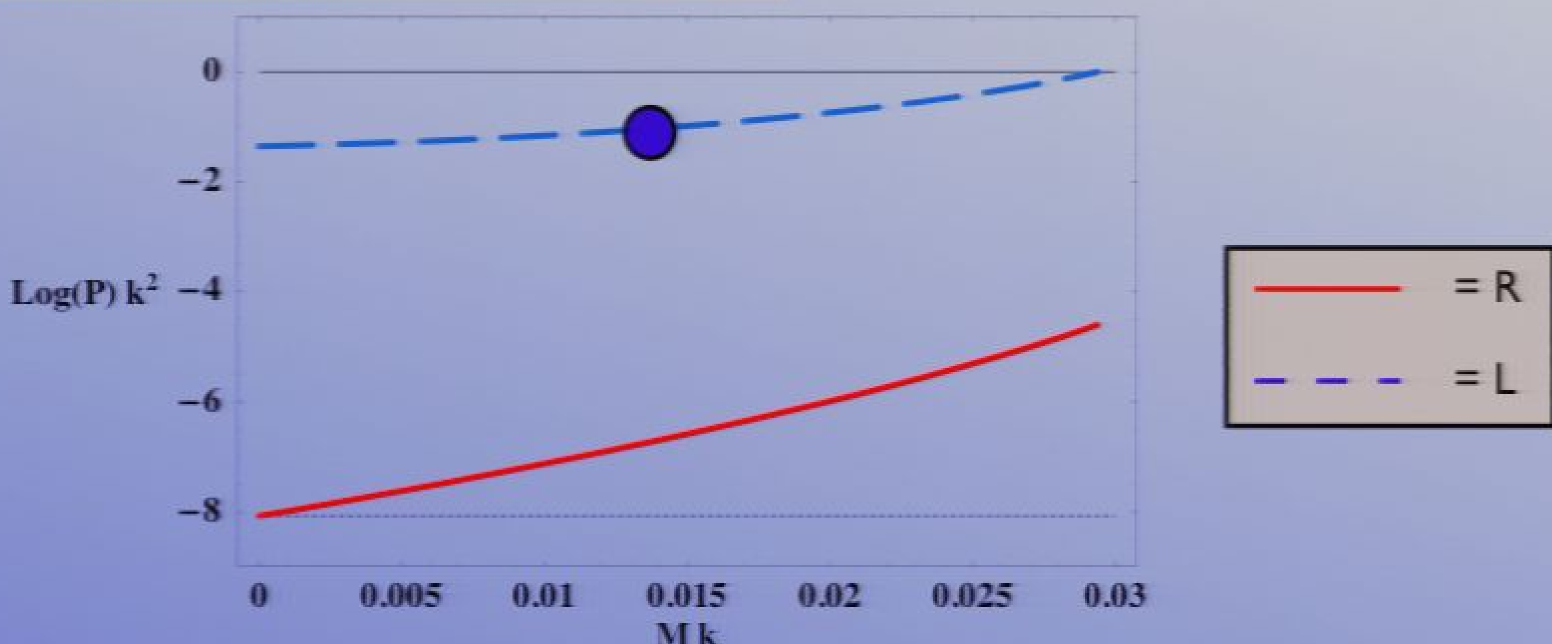
Planck Scale
FV

Weak Scale
FV

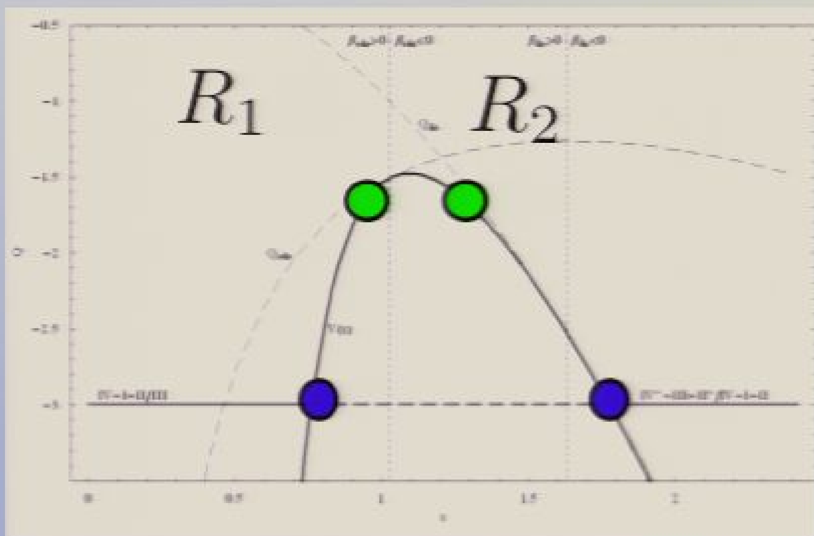
High-Mass Limit: FV Bubbles



L Geometry



High-Mass Limit: FV Bubbles



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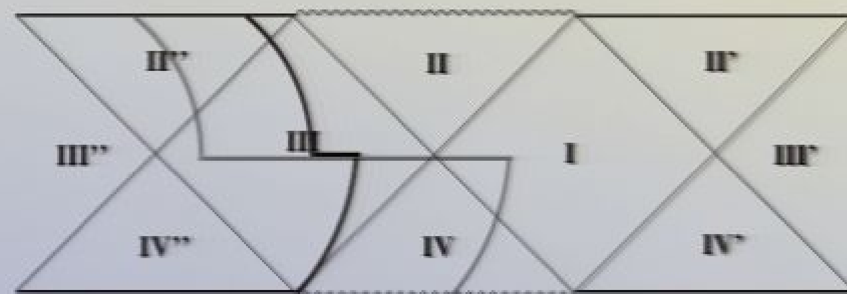
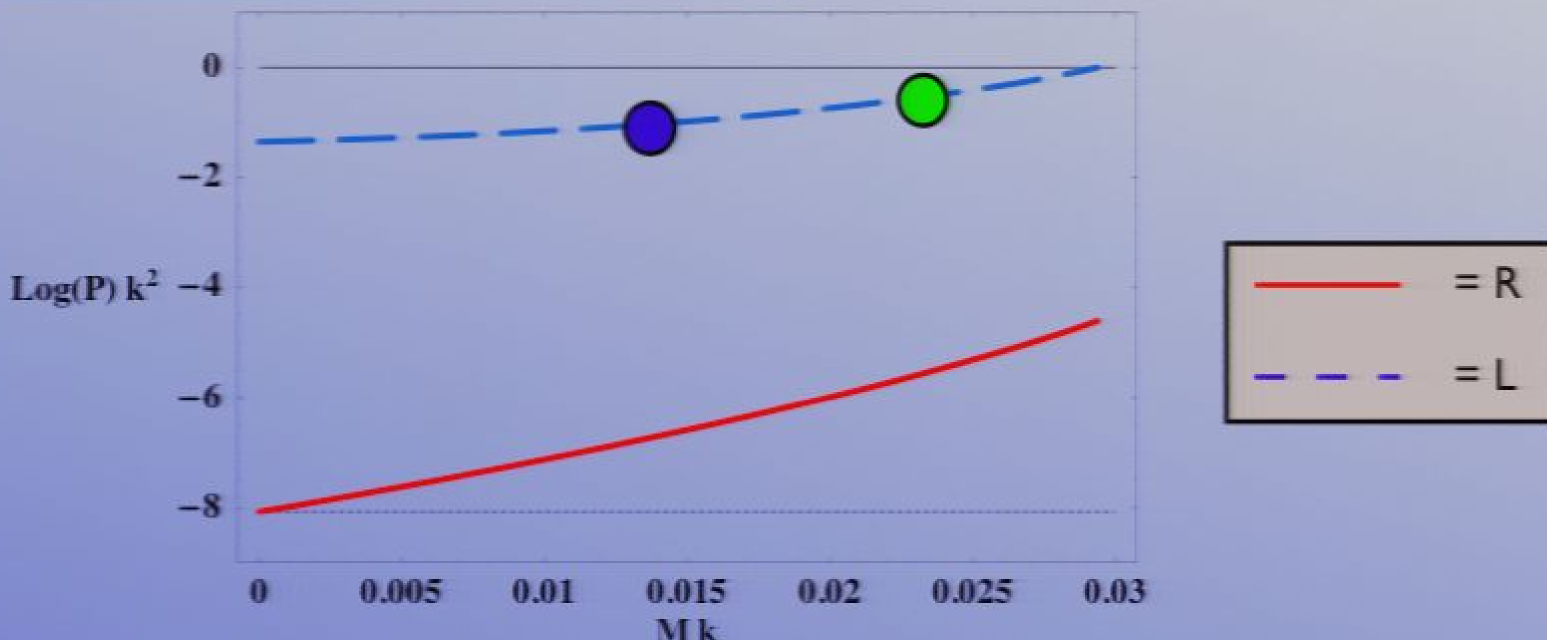
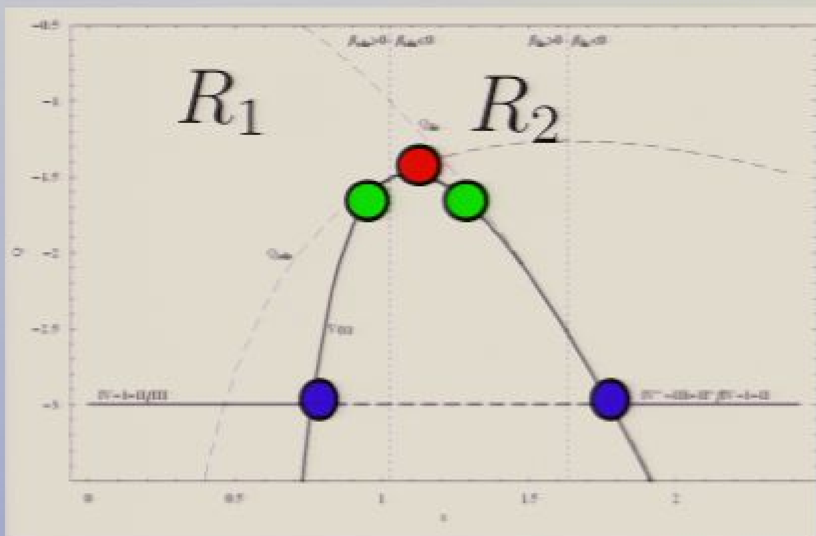




High-Mass Limit: FV Bubbles



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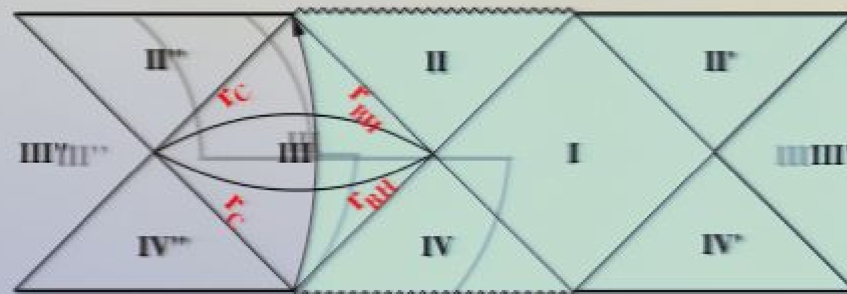
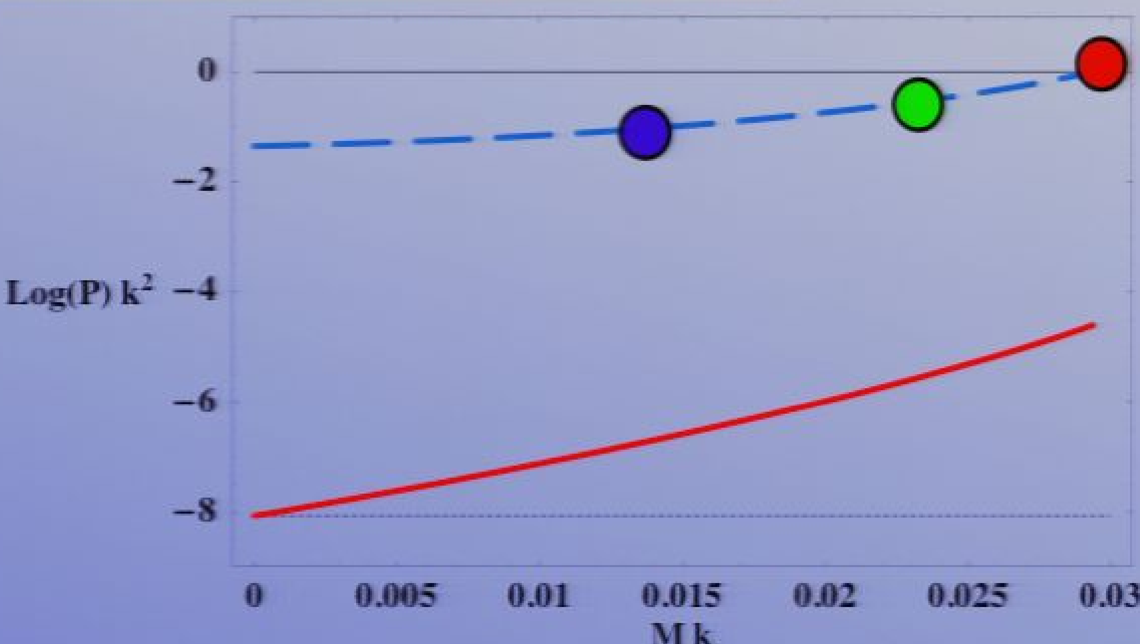
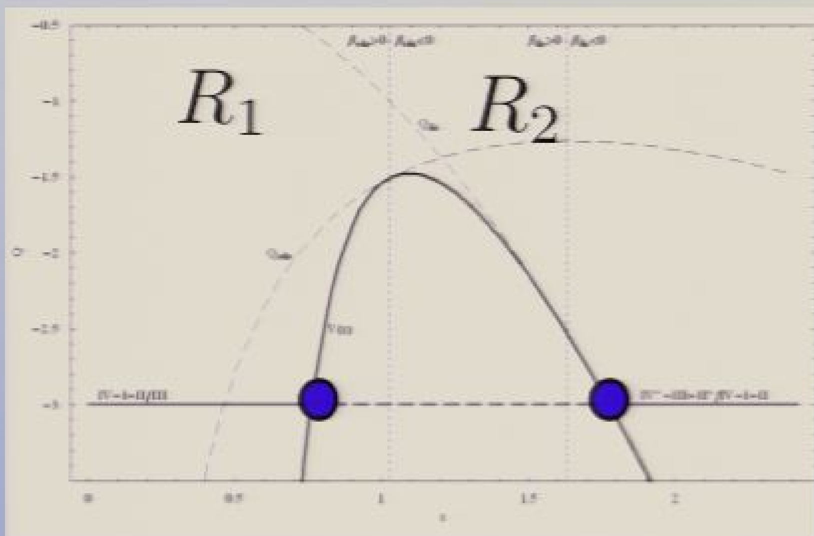


Thermal Activation

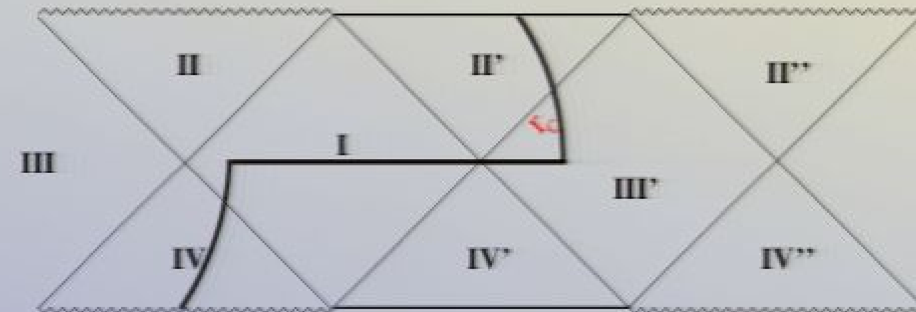
Garriga and Megevand 2004
Gomberoff et. al. 2004

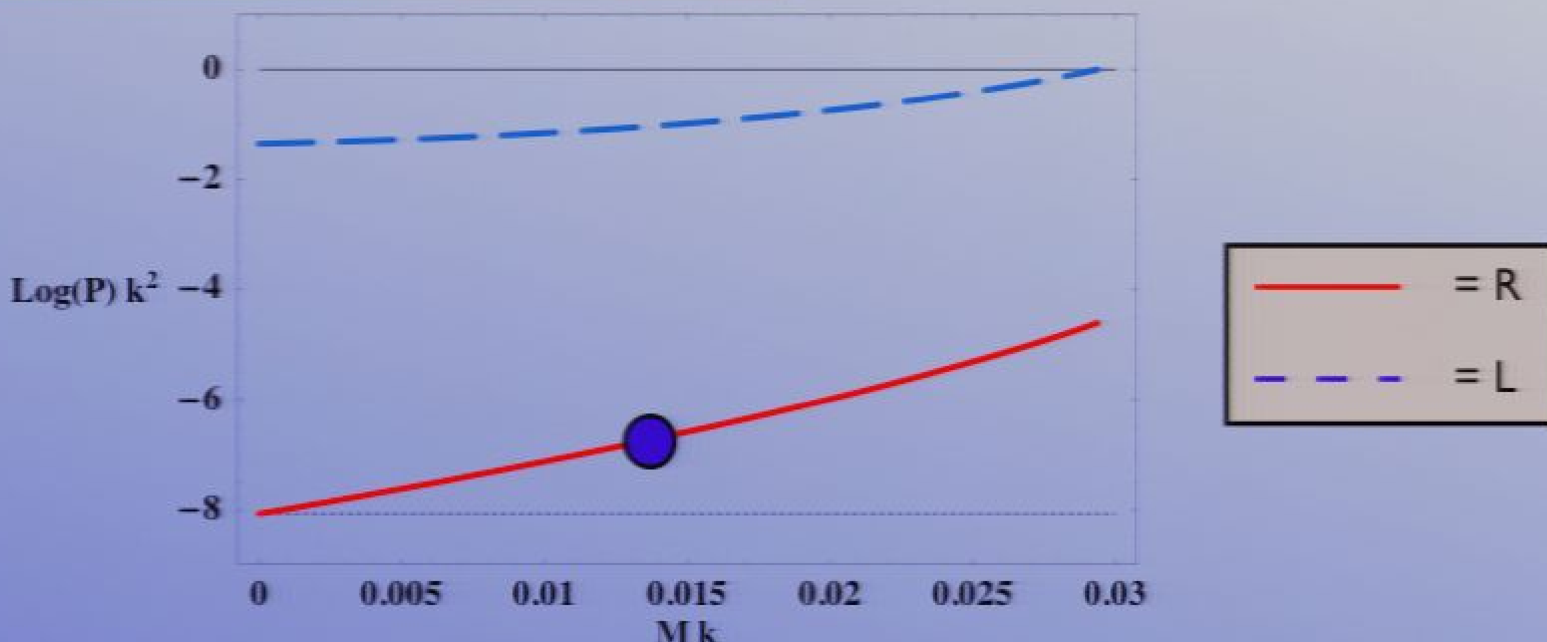


High-Mass Limit: FV Bubbles

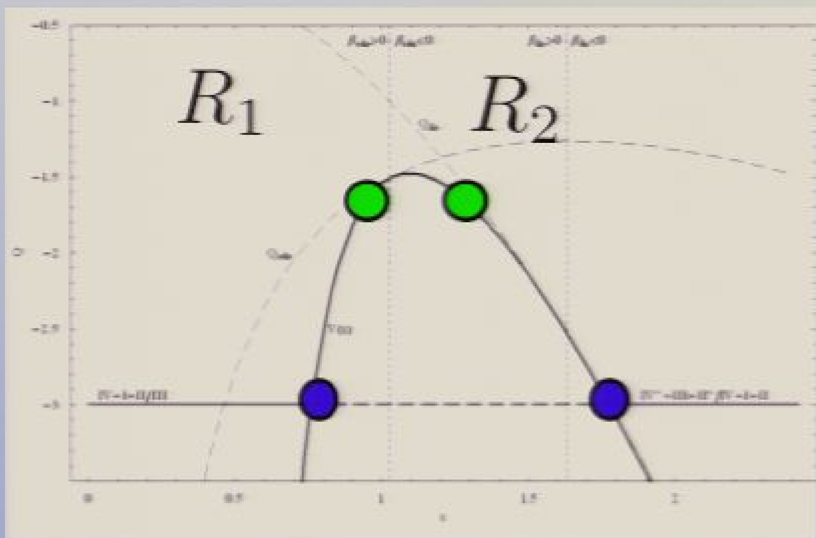


R Geometry

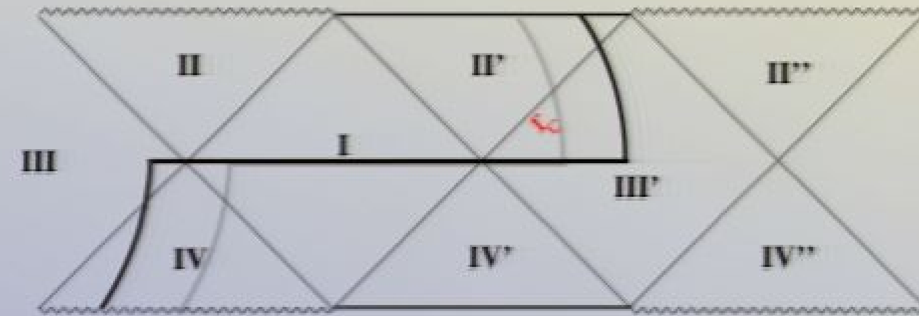


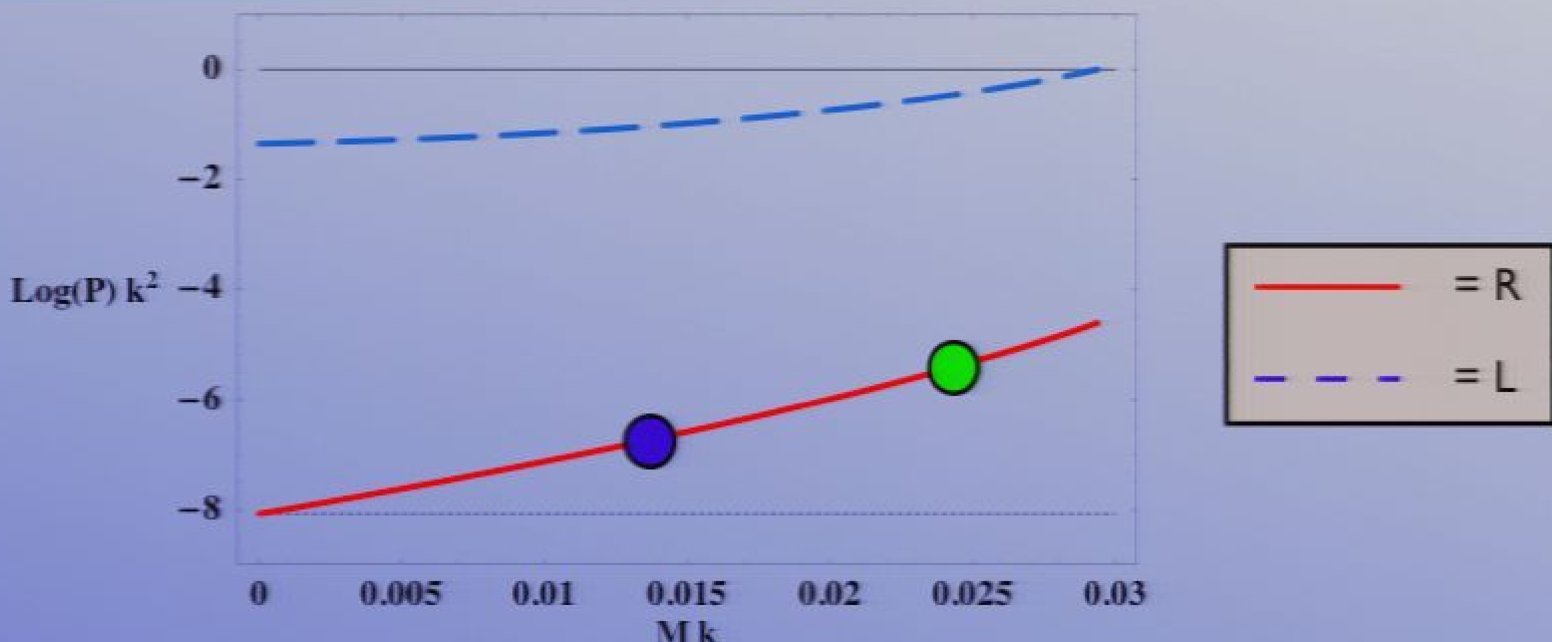


High-Mass Limit: FV Bubbles

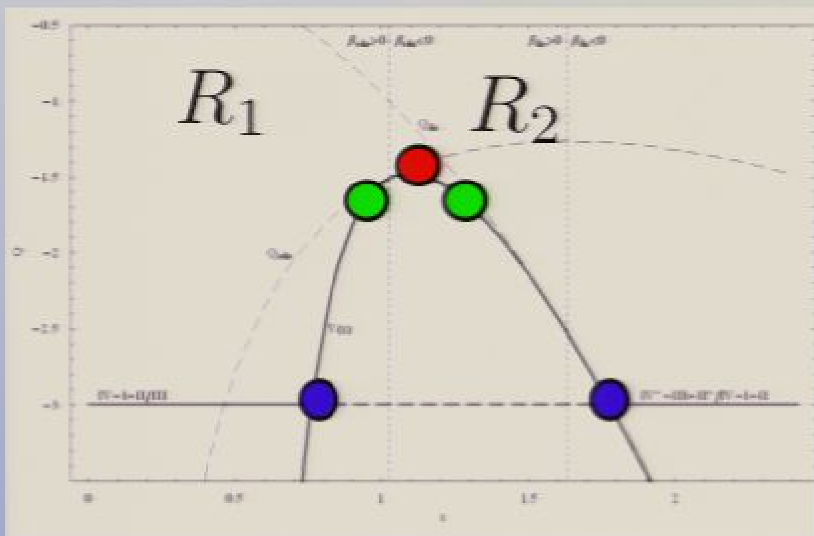


R Geometry



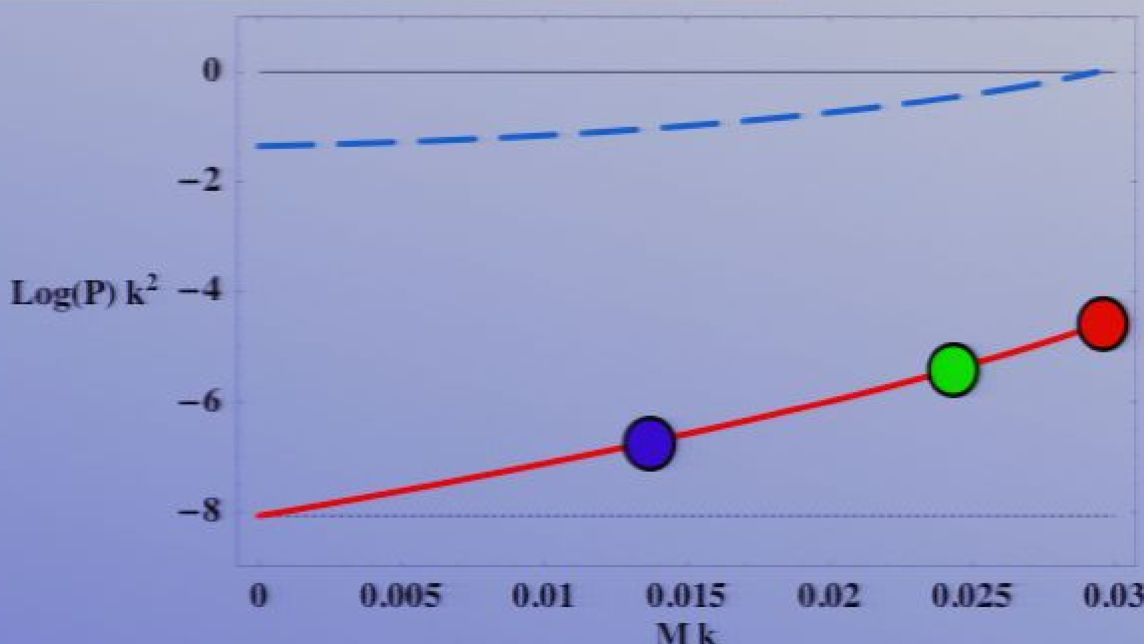


High-Mass Limit: FV Bubbles

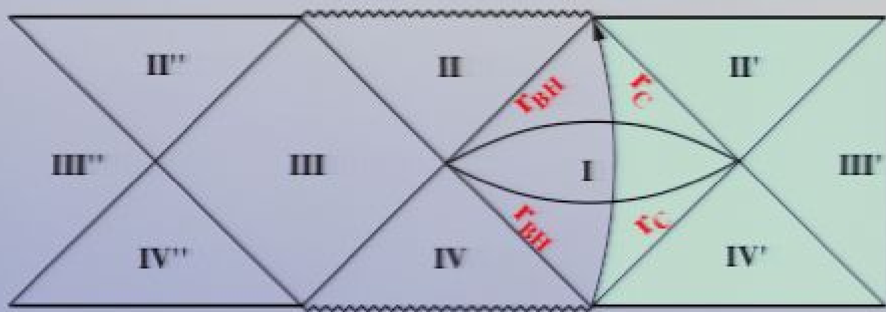


R Geometry

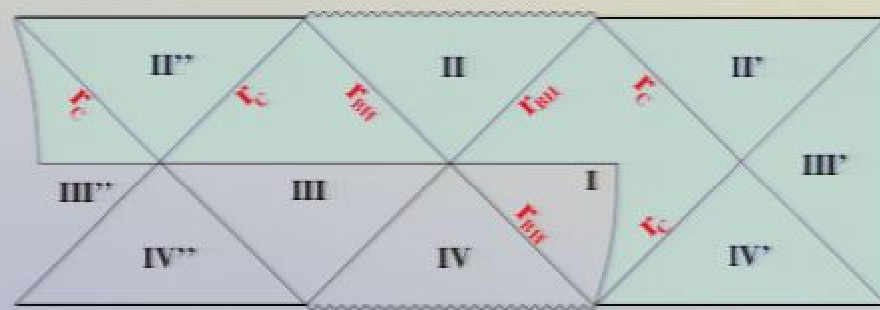
"Destroys" a huge region!



High-Mass Limit: TV Bubbles

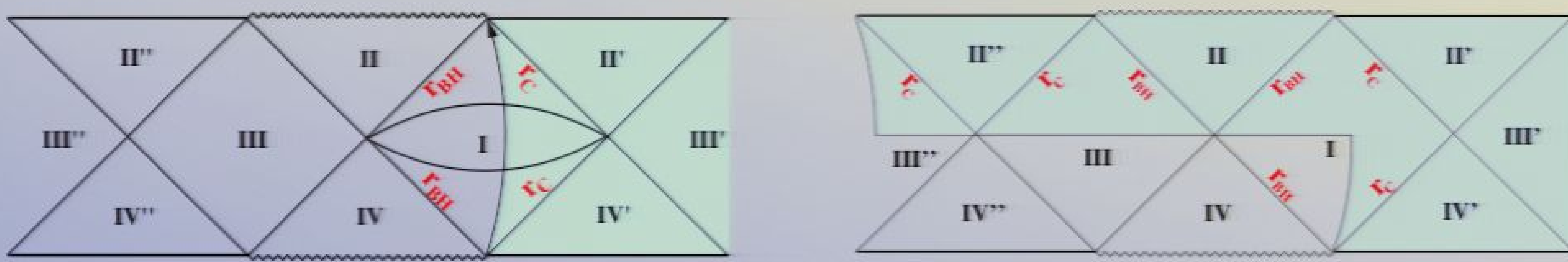


R Geometry



L Geometry

High-Mass Limit: TV Bubbles



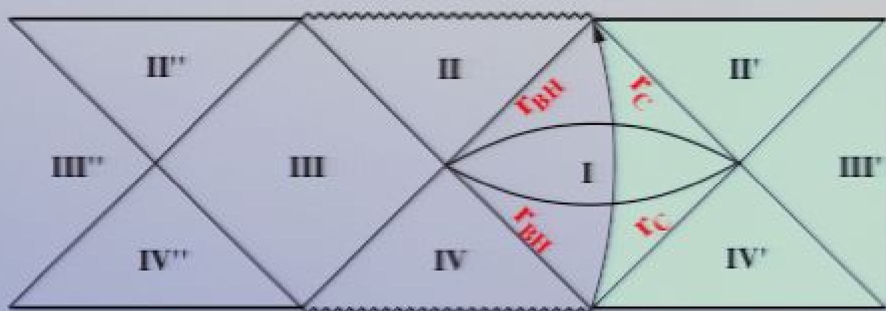
R Geometry

L Geometry

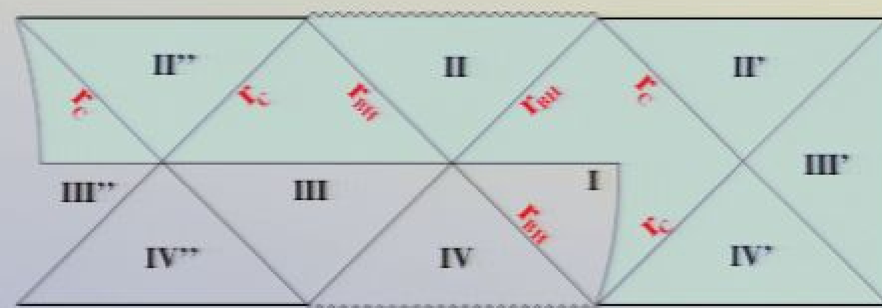
FV Bubbles: L geometry continuous.

TV Bubbles: R geometry continuous.

High-Mass Limit: TV Bubbles



R Geometry



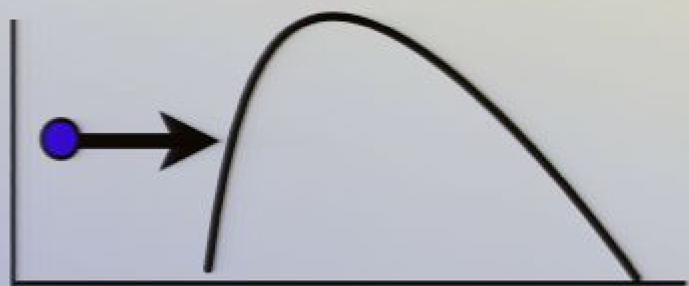
L Geometry

FV Bubbles: L geometry continuous.

TV Bubbles: R geometry continuous.

Both L and R Geometries have QC aspects.

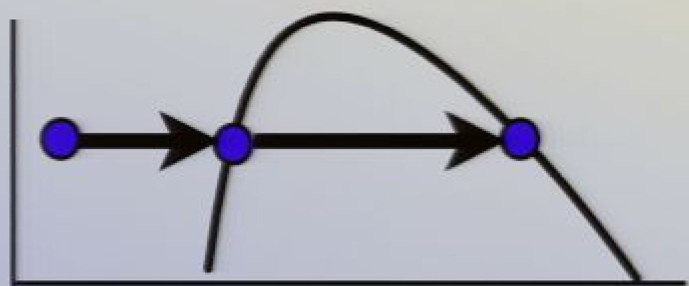
Nucleation Probability



$$P \simeq C P_{\text{seed}} e^{2i\Sigma_0} \equiv C e^{-S_E}$$

$$P_{\text{seed}} = \exp\left[-\pi\left(\frac{3}{\Lambda_+} - R_C^2\right)\right]$$

Nucleation Probability



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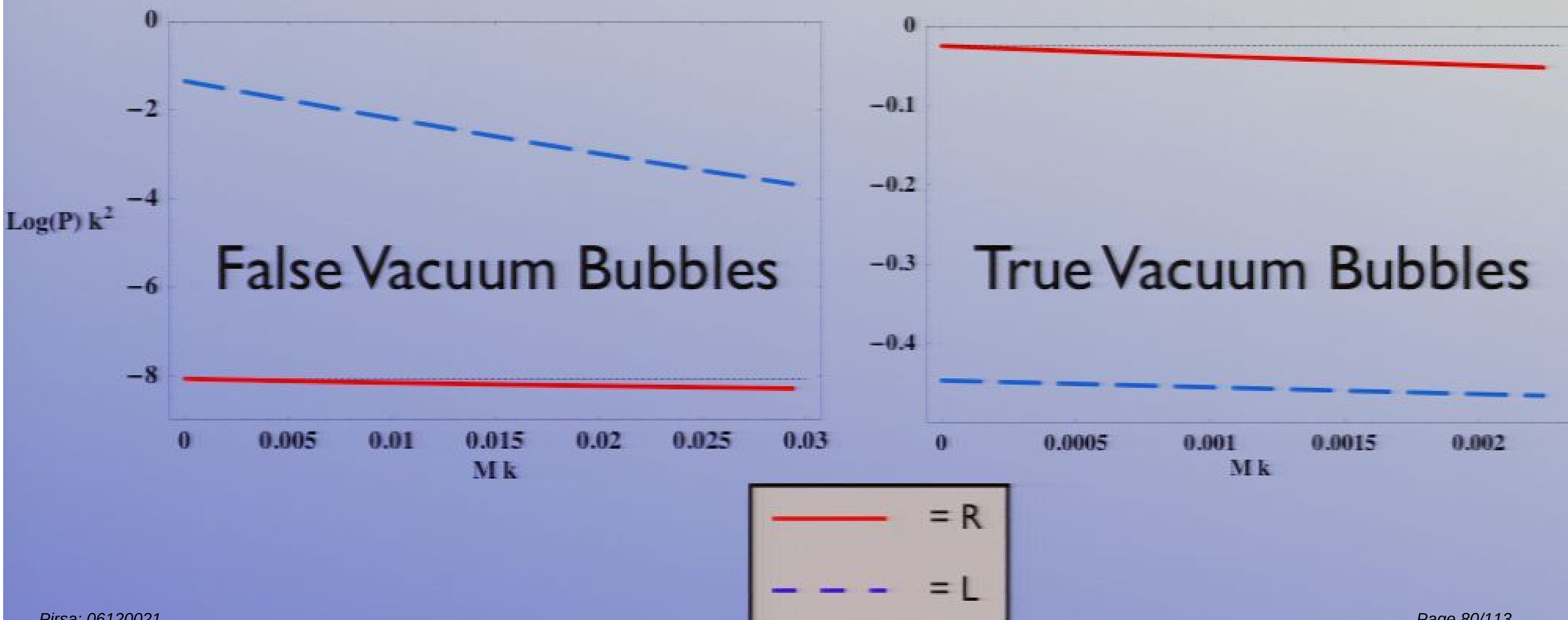
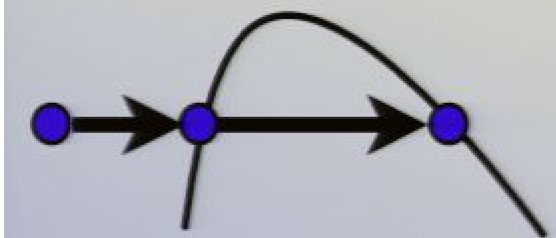
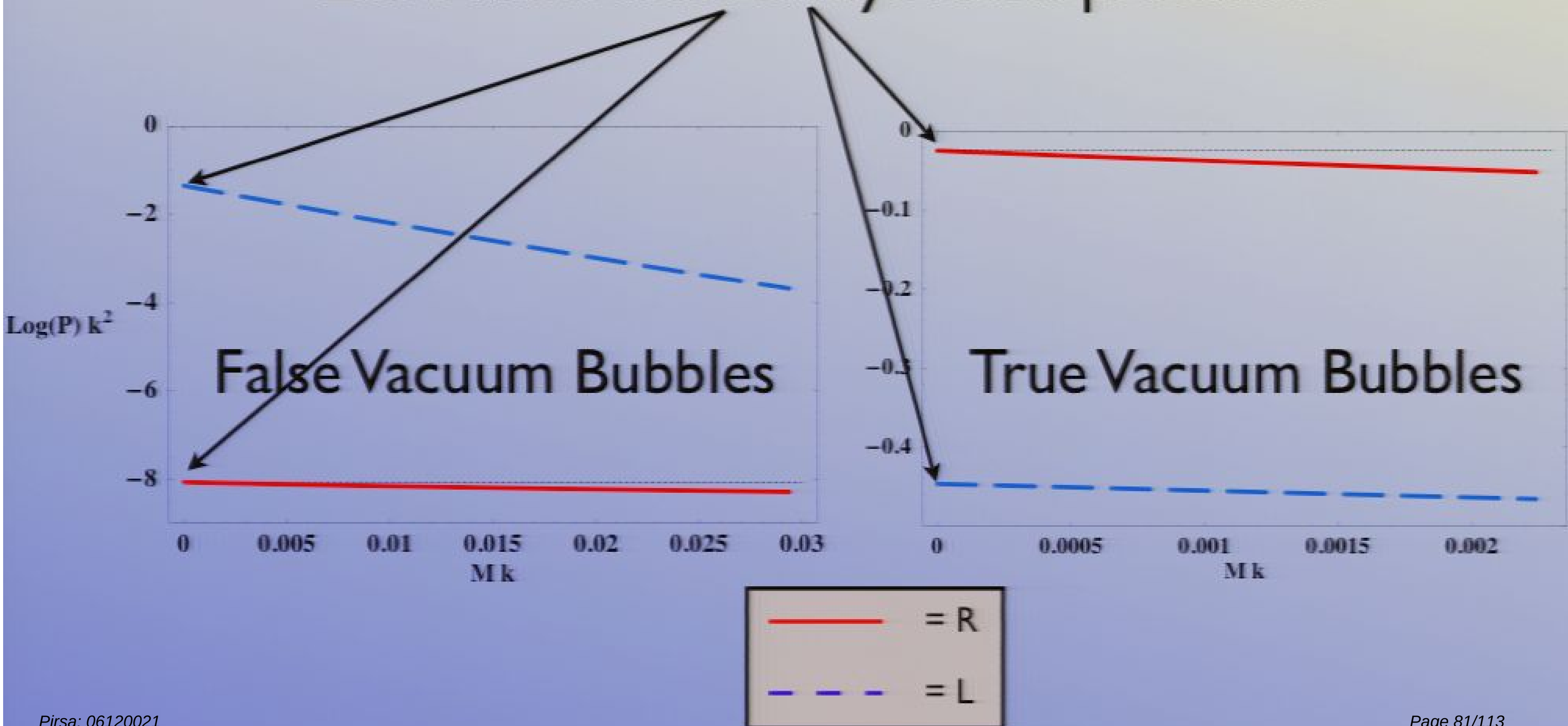


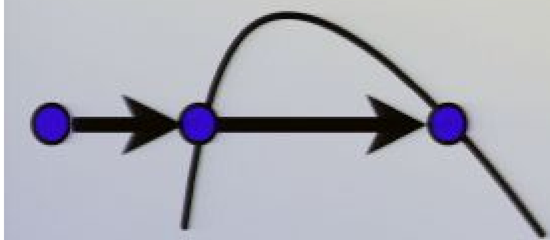
Nucleation Probability

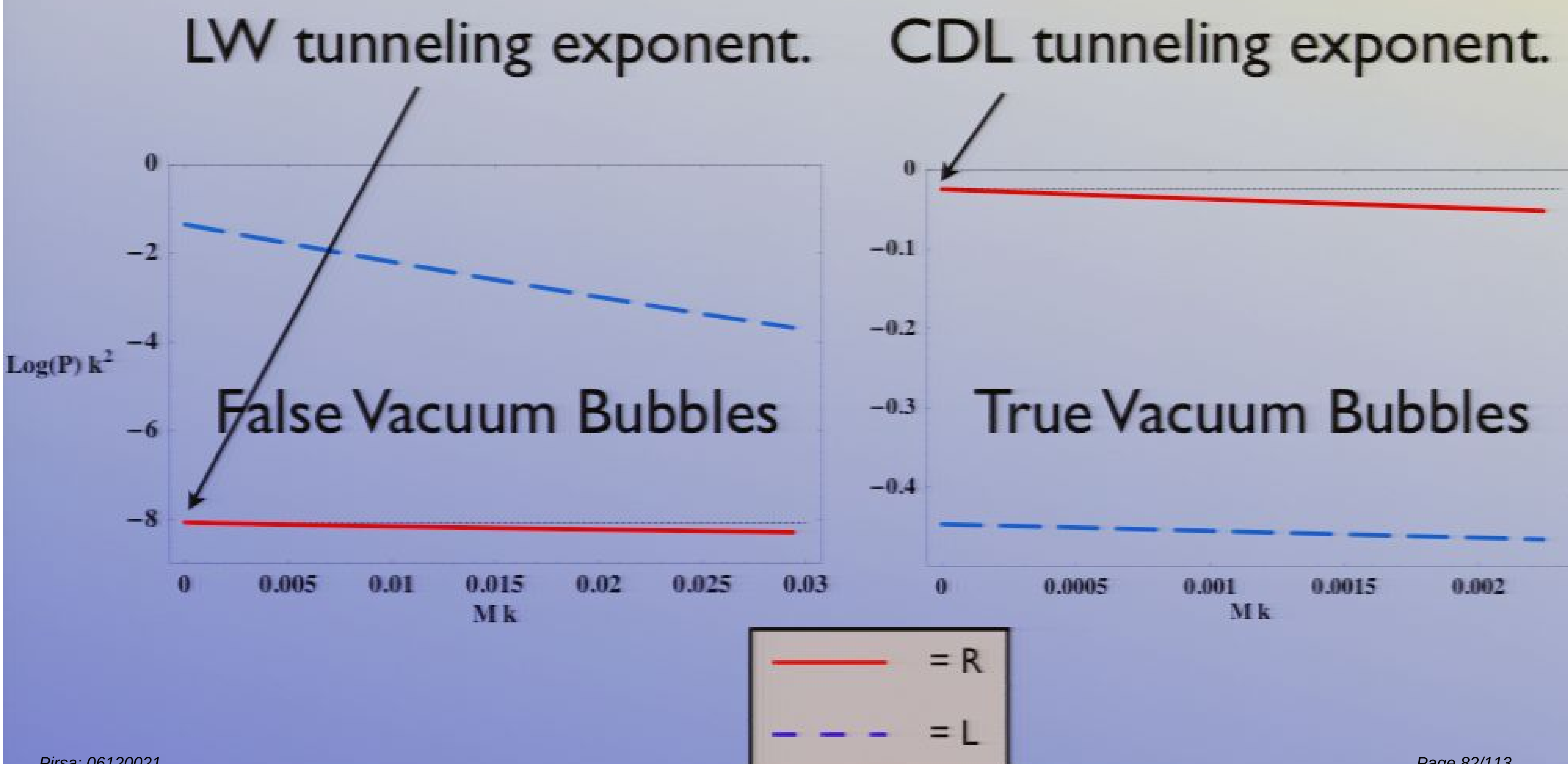


Zero mass limit always most probable!

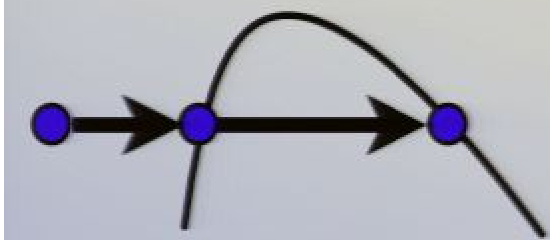


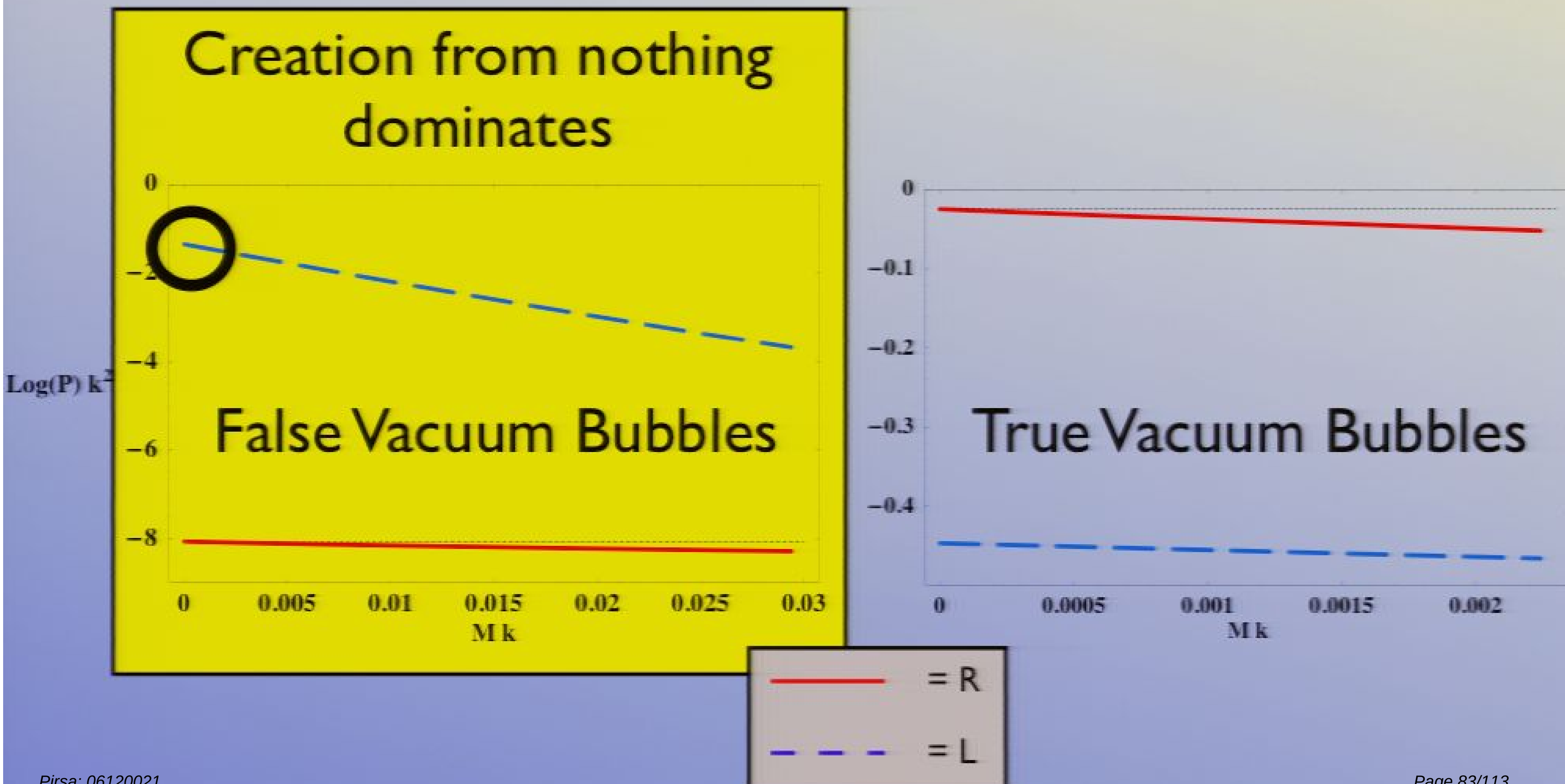
Nucleation Probability





Nucleation Probability





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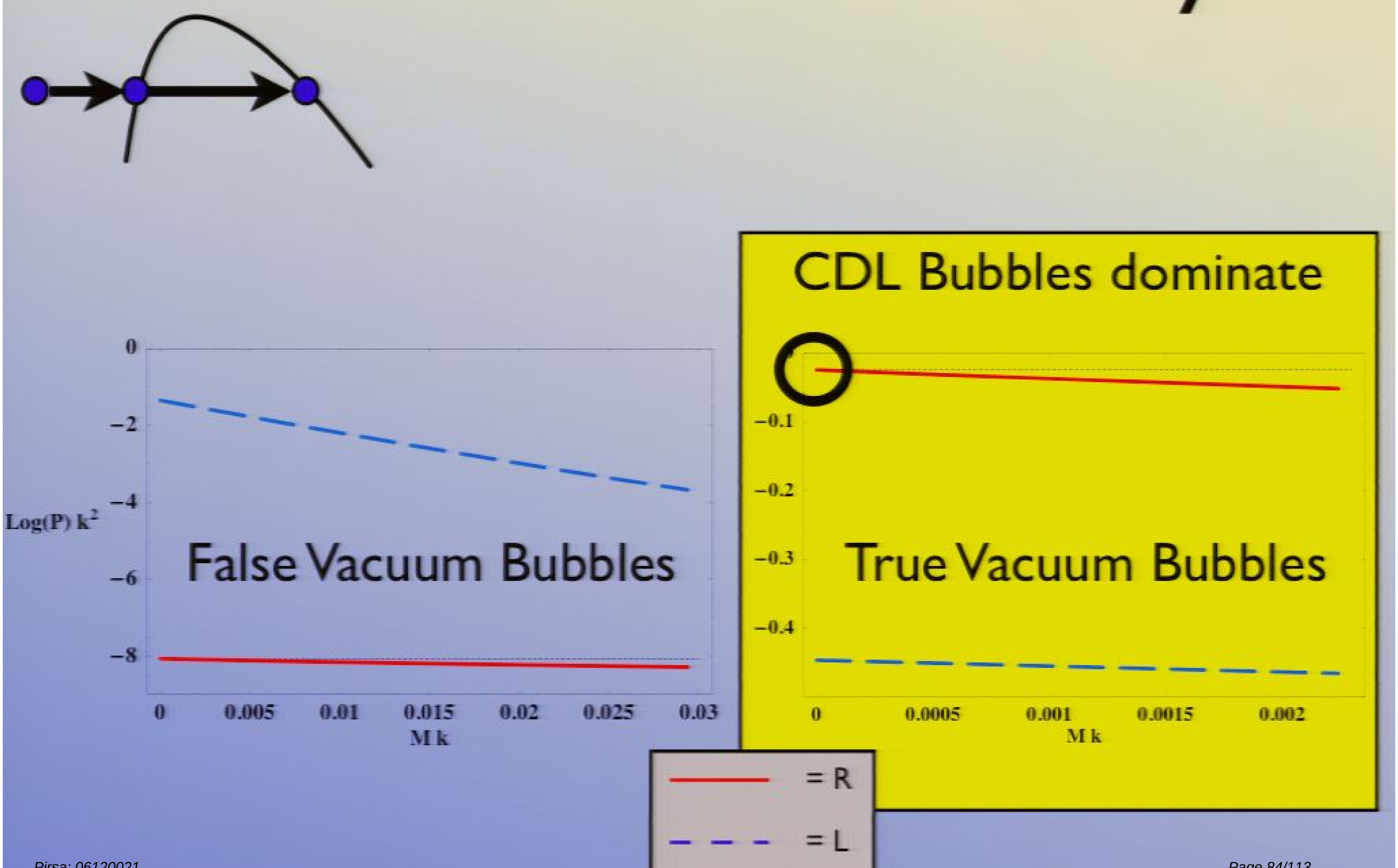
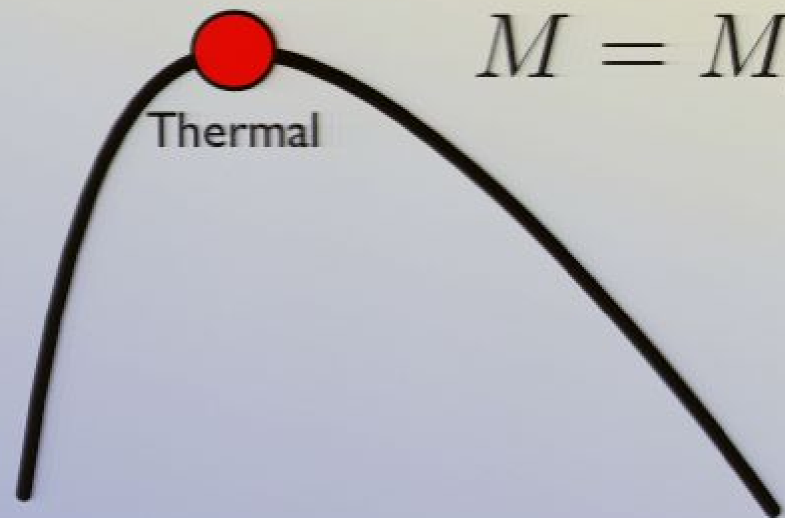


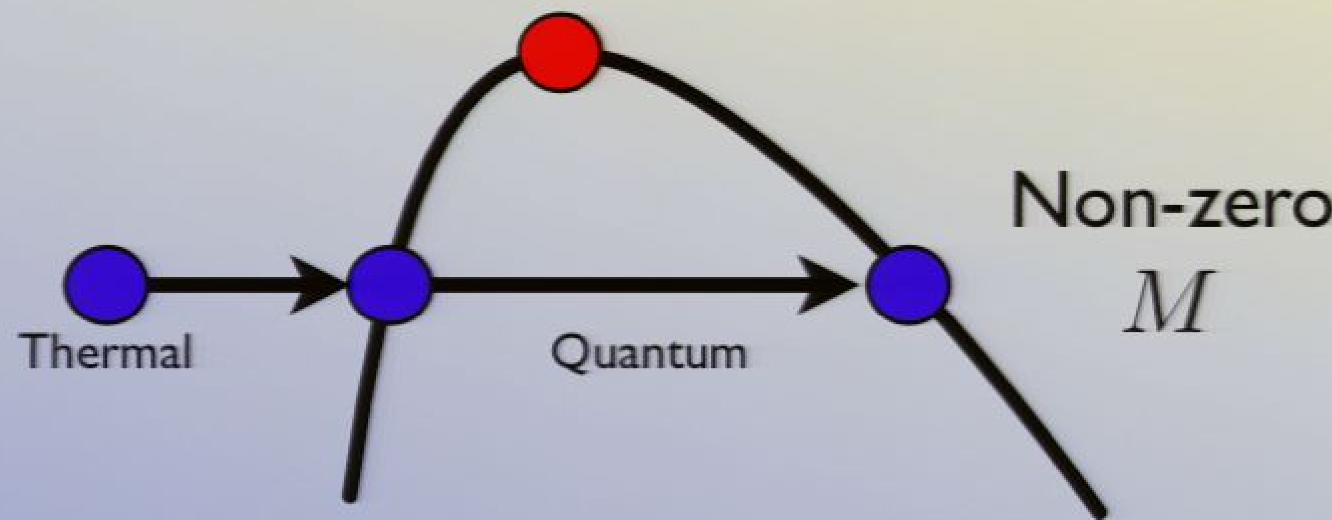
Two Tunnels



$$M = M_{max}$$

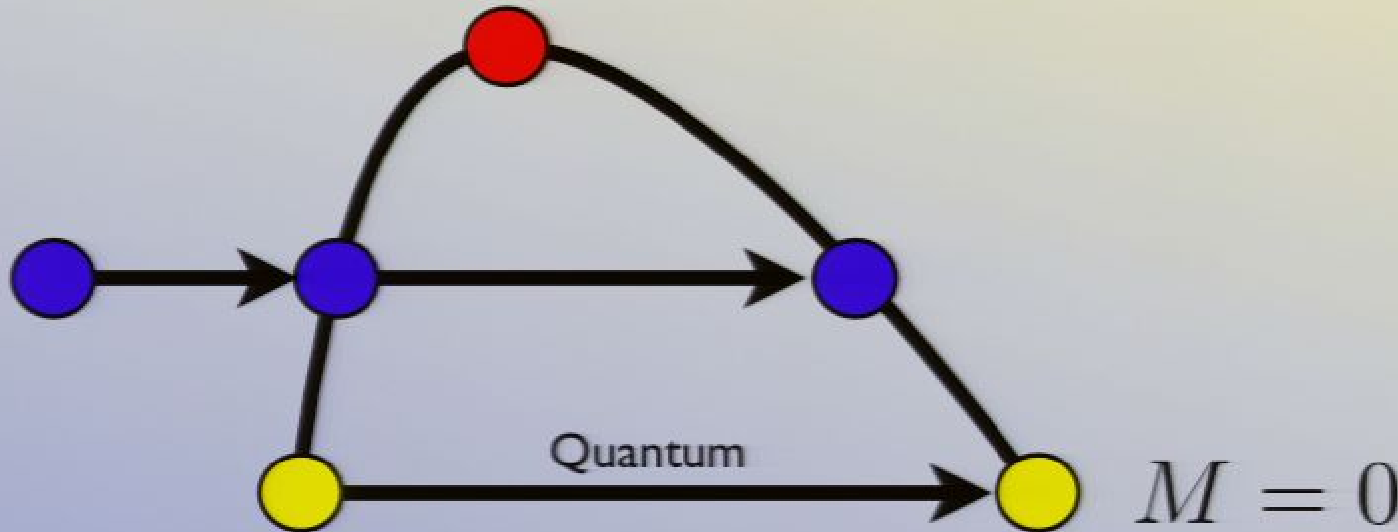
Thermal activation or ...	... or Thermal activation

Two Tunnels



Thermal activation or ...	... or Thermal activation
L tunneling geometry	R tunneling geometry

Two Tunnels



Thermal activation or ...	... or Thermal activation
L tunneling geometry	R tunneling geometry
Creation of a universe from nothing	CDL/LW bubbles

What are the Rules?

- Sign convention of tunneling exponent.
- Are CDL and LW bubbles more "reasonable" than creation of a universe from nothing?
- But.... High mass limit.
- Interpolating geometry.....

In conclusion:

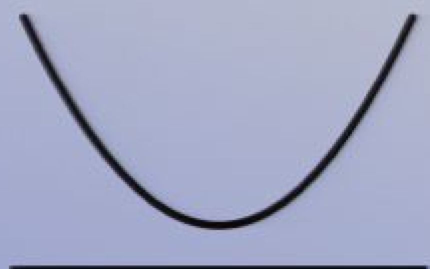
It is Unclear which processes are allowed!

We need more than semi-classical methods!

What are the Rules?

Two types of vacua:

Recycling



L and R geometries

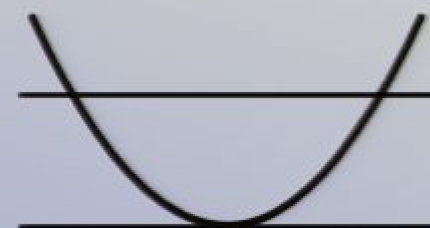
Hawking-Moss

Creation from nothing

Thermal activation

Stochastic dynamics

Terminal



L geometries?

Stochastic dynamics?

Predictions?

- How do we use these dynamics to talk about what an observer would see?
- To connect with observations, we have to assume the principle of mediocrity: What are we most likely to observe given that we are a typical observer?
    - Many problems: what is a typical observer? What if we are not typical? How large a role do anthropics play?

Predictions?

$$\mathcal{P}_X(\alpha) \propto P_p(\alpha) n_{X,p}(\alpha)$$

Probability that a randomly chosen X will observe the parameters $\vec{\alpha}$

Prior:

$P_p(\alpha)$ Probability that a randomly chosen p has parameters $\vec{\alpha}$

Conditionalization:

$n_{X,p}(\alpha)$ The number of X associated with each p that experience the parameters $\vec{\alpha}$

Prior Distributions

Prior specified by object p

Linde, Vilenkin, Garriga, Winitzki — $p =$ Unit of comoving or physical volume

Vilenkin et. al., Easther et. al. — $p =$ Bubbles of a given type.

Bousso — $p =$ Segment of a worldline between transitions.

$P_p(\alpha)$ is then proportional to :

Ratio of volume in $\vec{\alpha}$ to the total volume

Number of bubbles containing $\vec{\alpha}$

Frequency of entry into a vacuum with $\vec{\alpha}$

Counting Transitions

Need a new p in our toolbox:

$p =$ Transition of a given type.

Many cosmological observables depend on HOW you get to a state, not the properties of the state itself.

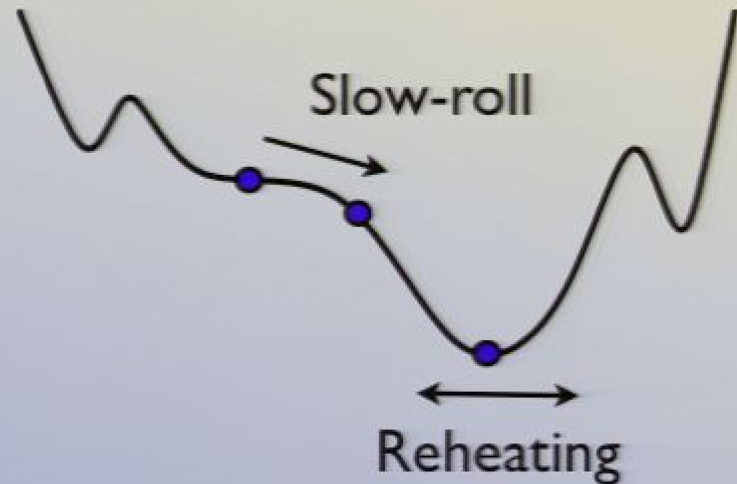
- Spectral index.
- Amplitude of scalar perturbations.
- Tensor to scalar ratio.
- Curvature scale.

Counting Transitions

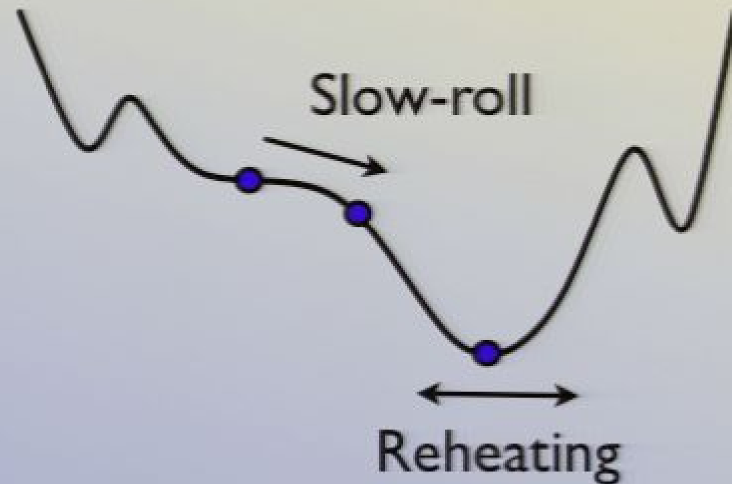
The end-points of the instanton determine subsequent evolution.

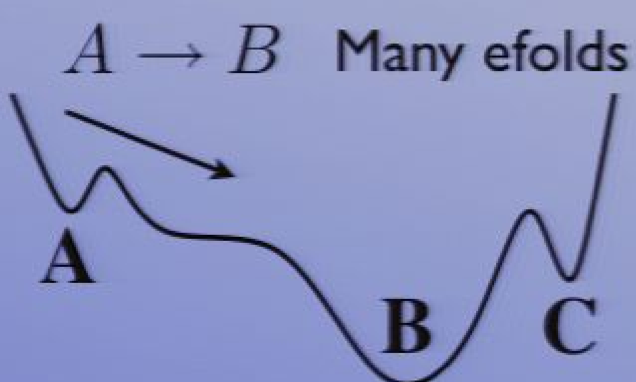
Counting Transitions

Counting Transitions



Counting Transitions



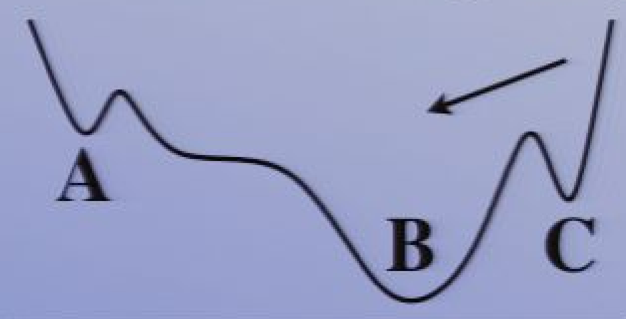


Counting Transitions

Counting Transitions

Counting Transitions

$C \rightarrow B$ Few efolds



Counting Transitions

May be important for determining which transitions are allowed:

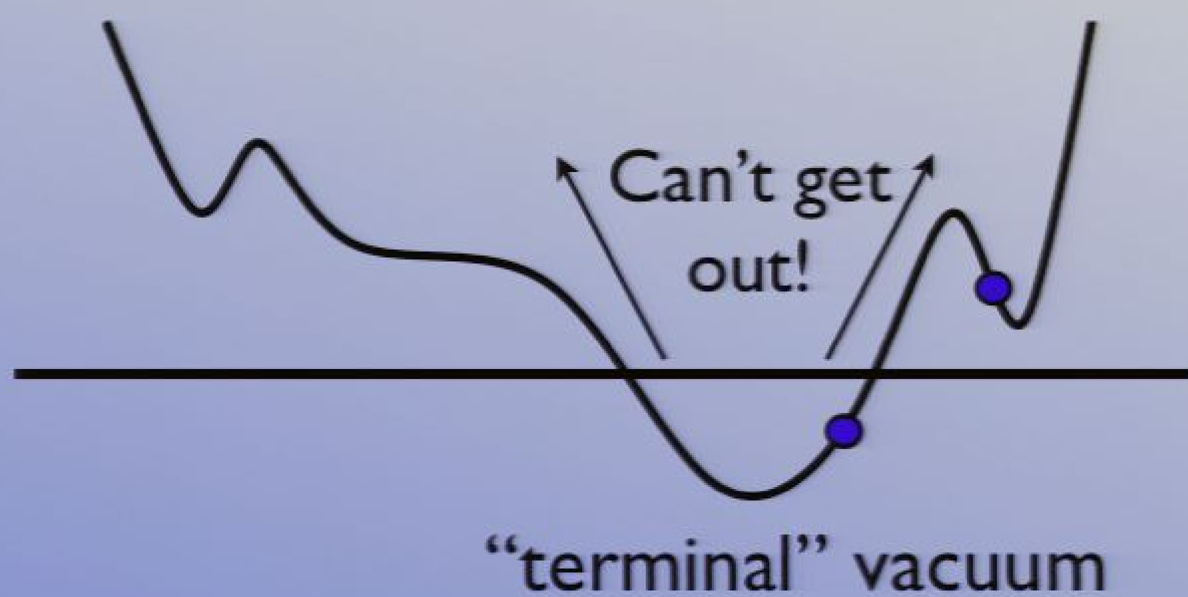
What if terminal vacua are not exactly terminal?

“terminal” vacuum

Counting Transitions

May be important for determining which transitions are allowed:

What if terminal vacua are not exactly terminal?



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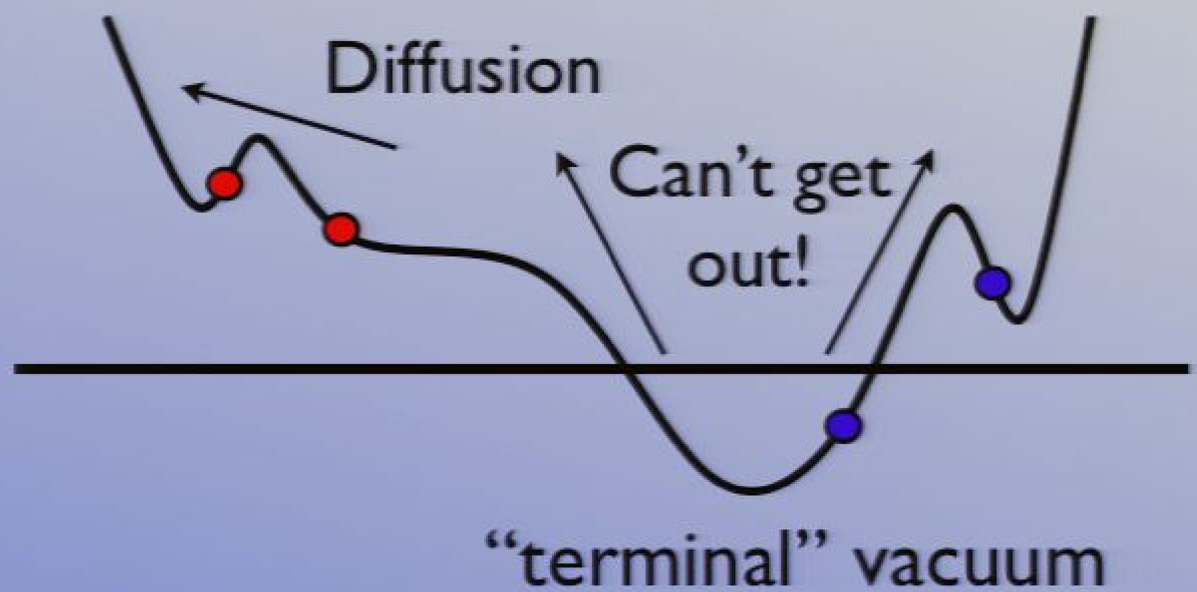

Counting Transitions

Markov chain of transitions between transitions.

$$(A \to B) \bigcirc\!\!\!\!\!\to (B \to C) \bigcirc\!\!\!\!\!\to (C \to D) \ldots$$

Counting Transitions

Markov chain of transitions between transitions.

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Probability of a transition depends on previous transition.

$$p^{\alpha}_{i+1} = \sum_{\beta} \mu^{\alpha}{}_{\beta}\, p^{\beta}_{i} \qquad \left(p^{B\to A}_{i+1} = \sum_{J} \mu^{B\to A}{}_{J\to B}\;\; p^{J\to B}_{i} \right)$$

$$\mu^{\alpha}{}_{\beta} = \frac{\kappa^{\alpha}_{\beta}}{\sum_{\alpha} \kappa^{\alpha}_{\beta}} \qquad \sum_{\alpha} \mu^{\alpha}{}_{\beta} = 1$$

Matrix of relative transition rates.

Counting Transitions

Markov chain of transitions between transitions.

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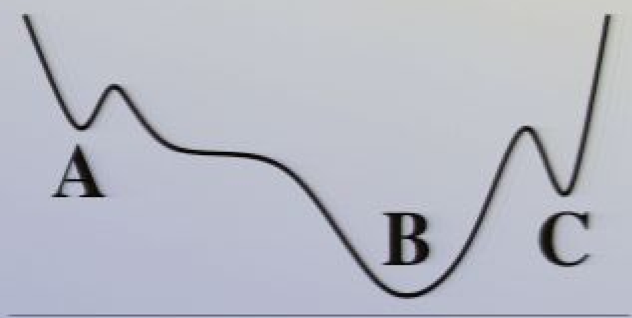
Matrix of relative transition rates.

$$\mathbf{n} = \sum_{i=1}^{\infty} (\mu)^{i}\, \mathbf{p_0}$$

Expected number of transitions.

Counting Transitions



6 nearest-neighbor transitions.

4 normalization conditions.

2 free parameters.

$$\mu = \begin{pmatrix} 0 & \mu^{B\to A}_{A\to B} & 0 & \mu^{B\to A}_{C\to B} \\ \mu^{A\to B}_{B\to A} & 0 & 0 & 0 \\ 0 & \mu^{B\to C}_{A\to B} & 0 & \mu^{B\to C}_{C\to B} \\ 0 & 0 & \mu^{C\to B}_{B\to C} & 0 \end{pmatrix} = \begin{pmatrix} 0 & \epsilon & 0 & \delta \\ 1 & 0 & 0 & 0 \\ 0 & 1-\epsilon & 0 & 1-\delta \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

Start with an $A \to B$ Normalizing, we obtain:

$$P(A \to B) = P(B \to A) = \frac{\delta}{2(1-\epsilon+\delta)}$$

$$P(B \to C) = P(C \to B) = \frac{1-\epsilon}{2(1-\epsilon+\delta)}$$

Counting Transitions

If the rates are determined by CDL and LW instantons:

$$\frac{P(C \to B)}{P(A \to B)} = \frac{1-\epsilon}{\delta} \propto \frac{e^{-(S_I^{CB} - S_{BG}^{B})}}{e^{-(S_I^{AB} - S_{BG}^{B})}} = e^{S_I^{AB} - S_I^{CB}}$$

In the absence of fine-tuning, $\frac{P(C \to B)}{P(A \to B)} \gg 1$ or $\frac{P(C \to B)}{P(A \to B)} \ll 1$

What are the issues that come with this?

Issues

Need to know transition rates to very good accuracy.

Need to know properties of vacua to very good accuracy.

The end-points of the instanton determine subsequent evolution.

If correlations can be made between cosmological observables and transitions, then we can make (potentially sharp) predictions!

Issues

Prior-dominated predictions:

Consider parameters $\vec{\alpha}$ not dependent on conditions for life. Then, for example, $X =$ galaxies.

- Cosmological Constant (Weinberg + others).
- Axions and dark matter (Tegmark et al).

P_p

$n_{X,p}$

$\mathcal{P}_X$

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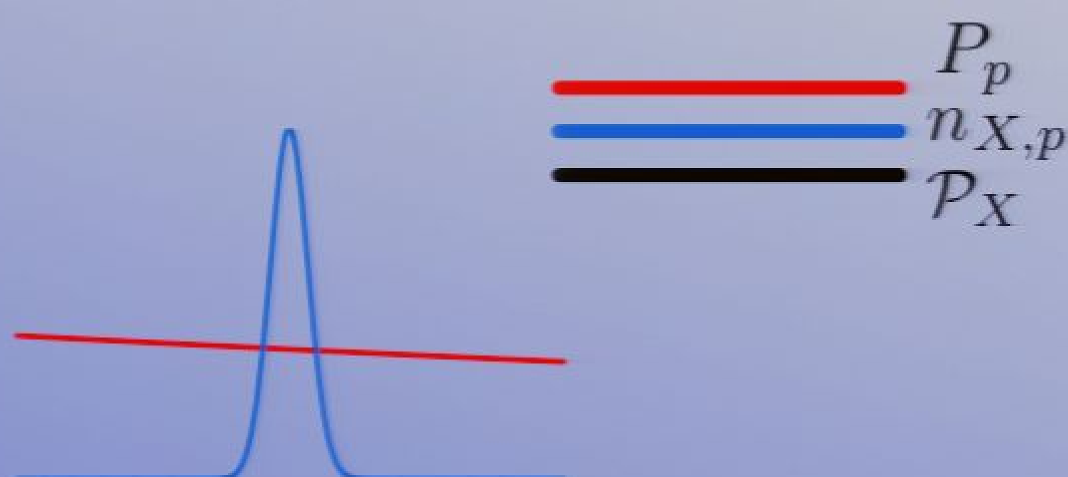

Conditionalization factor dominates predictions.

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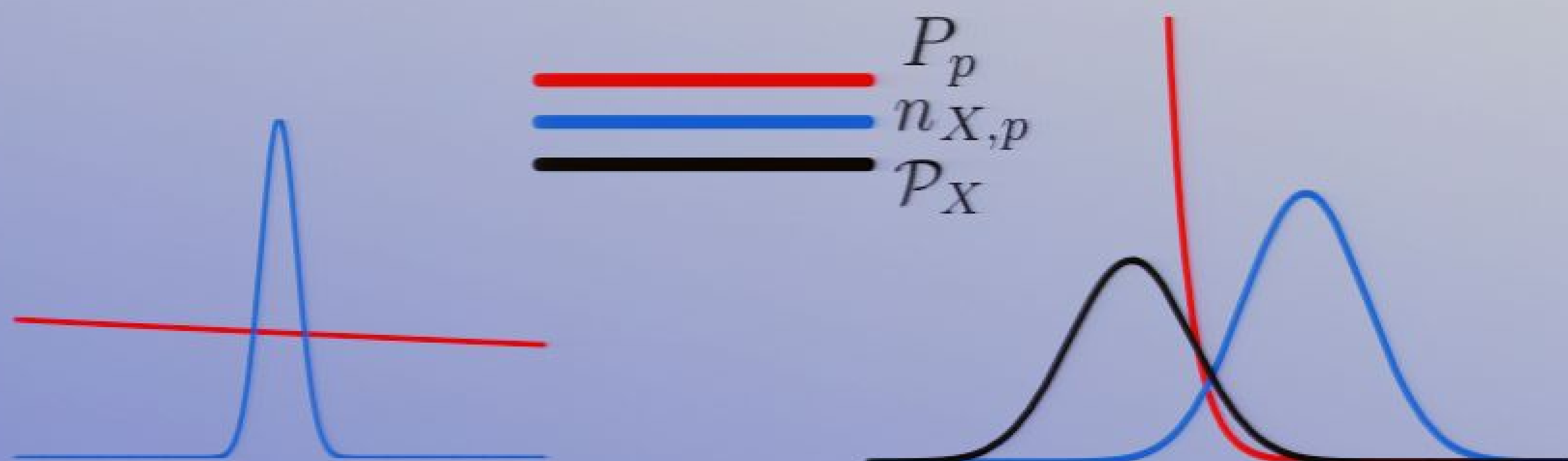

Conditionalization factor dominates predictions.

Prior dominates predictions.

Conclusions

- There are a variety of transition mechanisms!
- We may need more than semi-classical methods to find the answer.
  - Detailed balance and quantum gravity. Banks 2002; Banks and Johnson 2005
  - ADS/CFT and holography. Frievogel et. al. 2005; Bousso 2005
  - Initial conditions for inflation. Albrecht and Sorbo 2004; Dyson et. al. 2002
- This has implications for eternal inflation.
- Transition-based measures can be applied to cosmological parameters with potentially troubling effects.