Title: What Happens When Entropy Decreases

Date: Jul 16, 2011 09:00 AM

URL: http://pirsa.org/11070012

Abstract: Closed systems never evolve to lower entropy states -- except when they do, which is if one waits a time that is exponential in the entropy change. Thus macroscopic decreases in entropy are 'never' observed. Yet in cosmology there are eternal systems in which downward entropy fluctuations of any magnitude eventually happen. What is the nature of such fluctuations? I will argue that these can be understood in a simple and general way that sheds light on our understanding of various interesting cosmological processes such as bubble nucleation, black/white hole formation, eternal stochastic inflation, Boltzmann brain formation, and other processes.

What Happens when Entropy Decreases?

PI Meeting: Challenges for Early Universe Cosmology

Anthony Aguirre, UC Santa Cruz
(Work with Matt Johnson and occasionally Sean Carroll)

See ArXiv, any day now.

"...The law that entropy always increases holds, I think, the supreme position among the laws of Nature.... if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation."

- Eddington

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Experimental Demonstration of Violations of the Second Law of Thermodynamics for Small Systems and Short Time Scales

G. M. Wang,[1] E. M. Sevick,[1] Emil Mittag,[1] Debra J. Searles,[2] and Denis J. Evans[1]
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(Received 4 March 2002; published 15 July 2002)

We experimentally demonstrate the fluctuation theorem, which predicts appreciable and measurable violations of the second law of thermodynamics for small systems over short time scales, by following the trajectory of a colloidal particle captured in an optical trap that is translated relative to surrounding water molecules. From each particle trajectory, we calculate the entropy production/consumption over the duration of the trajectory and determine the fraction of second law–defying trajectories. Our results show entropy consumption can occur over colloidal length and time scales.

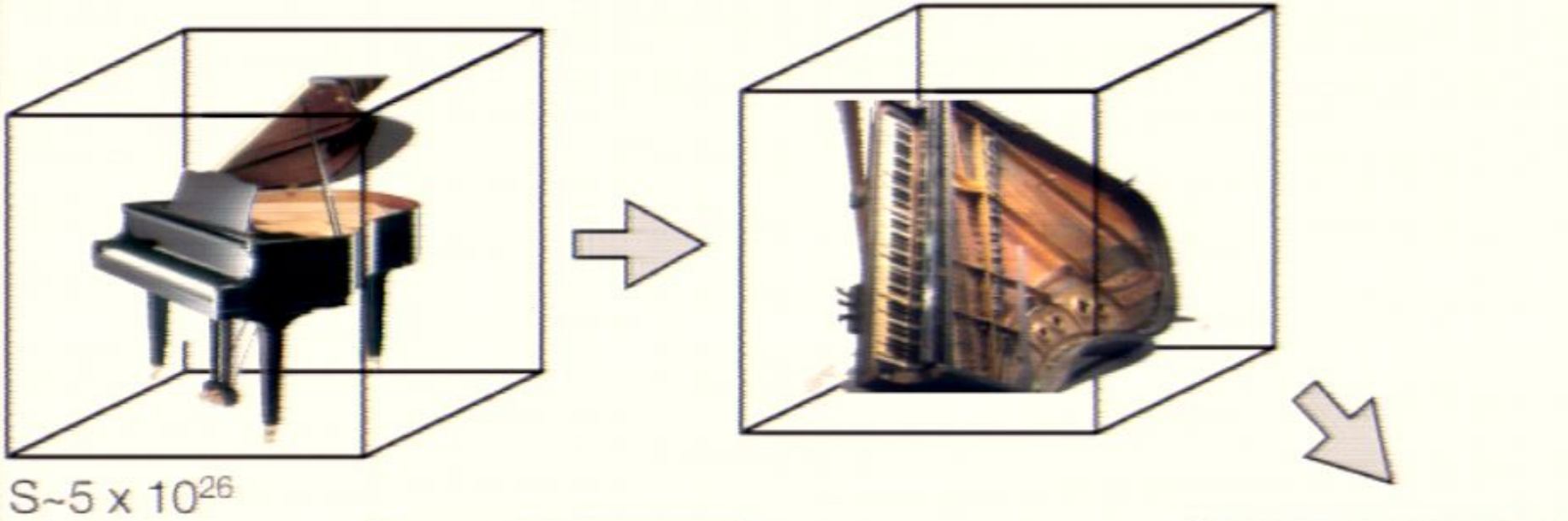
DOI: 10.1103/PhysRevLett.89.050601 PACS numbers: 05.70.Ln, 05.40.–a

Entropy decreasing processes in cosmology

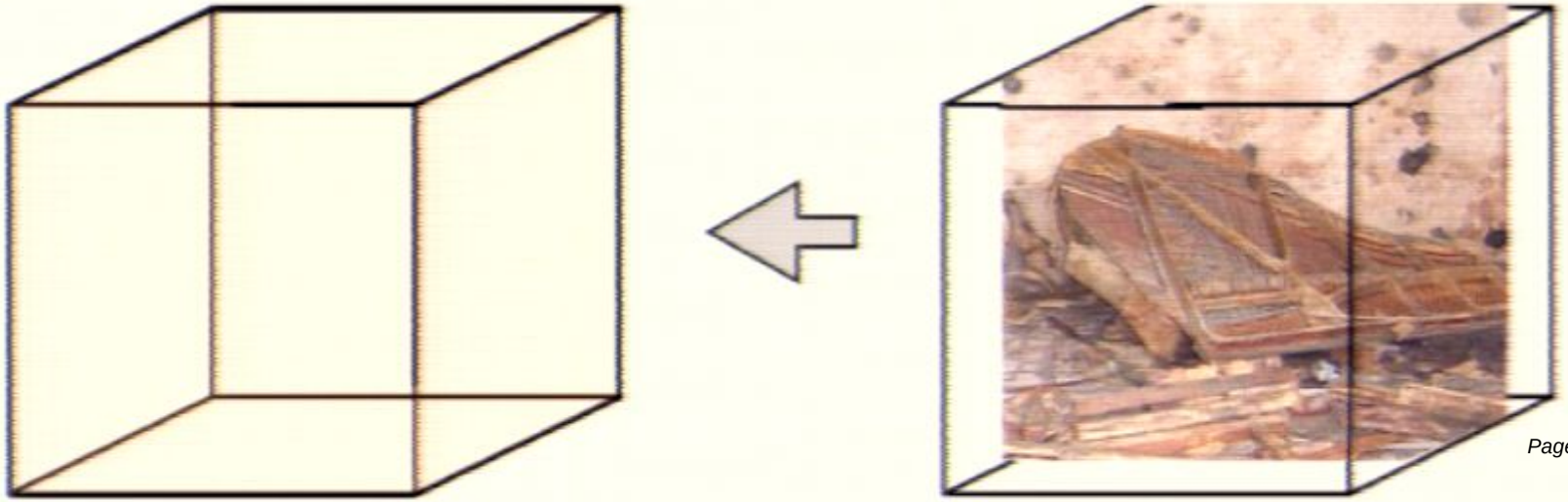
- **Transitions between inflationary vacua:**
  - Hawking-Moss transitions
  - (Part of) Coleman-DeLuccia
  - Lee-Weinberg
  - Stochastic eternal inflation uphill fluctuations
- **Nucleation of things in thermal spaces:**
  - Black holes
  - Localized blobs
  - Boltzmann Brains
  - Universes

Piano in a box

Piano in a box



$S \sim 5 \times 10^{26}$



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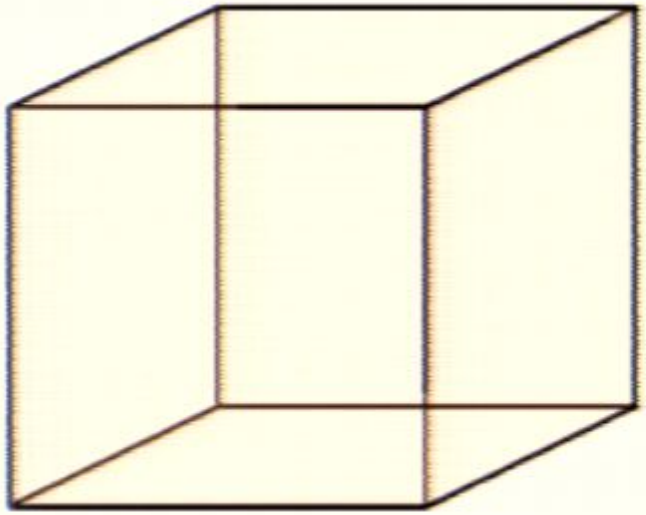

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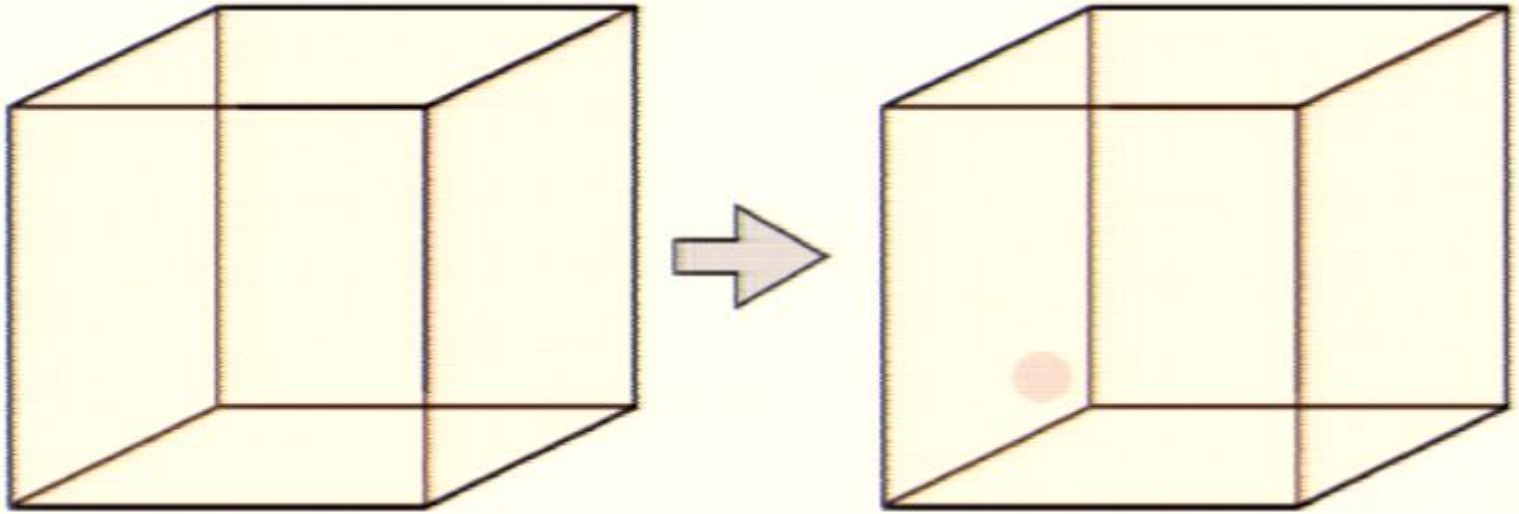

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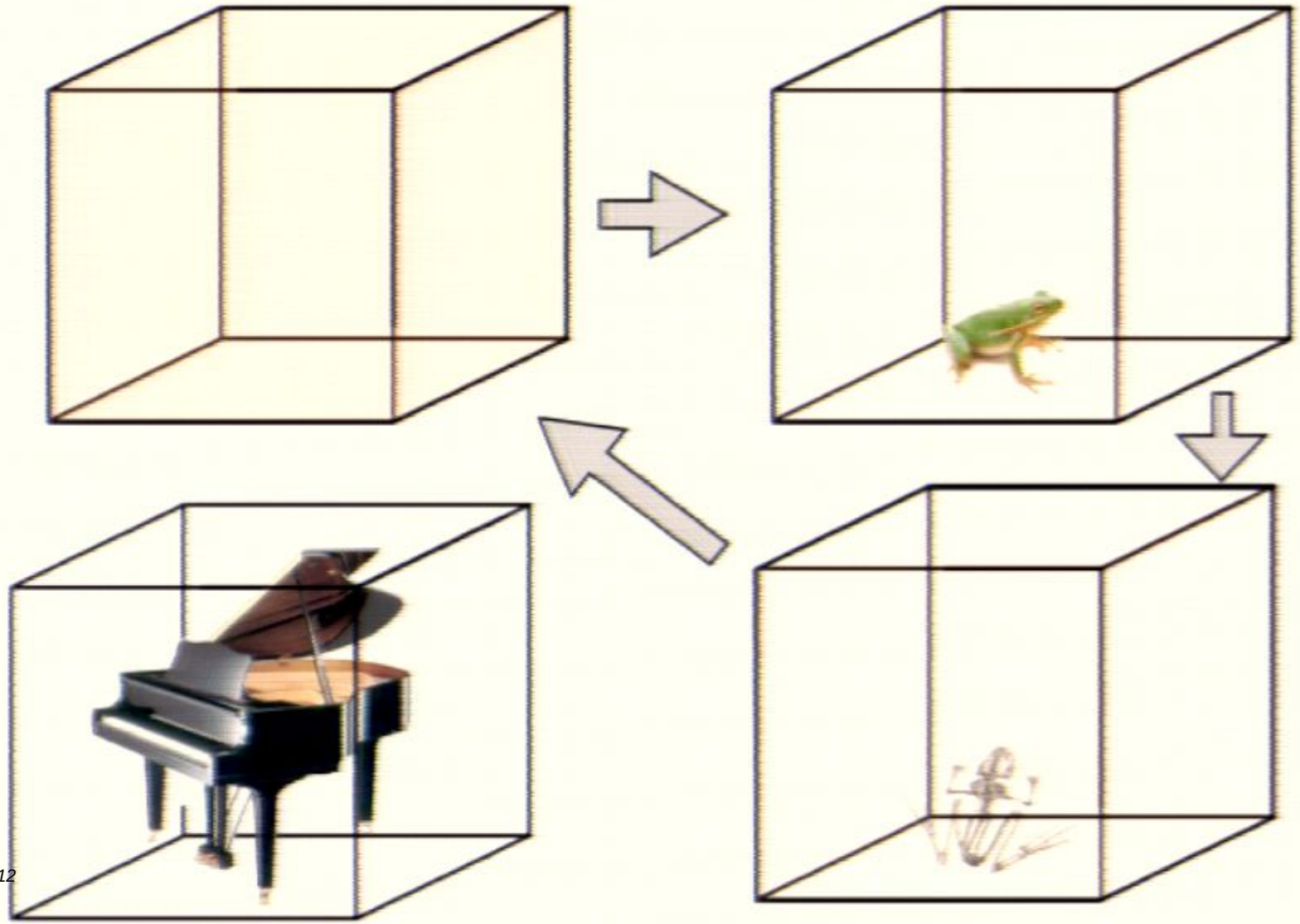

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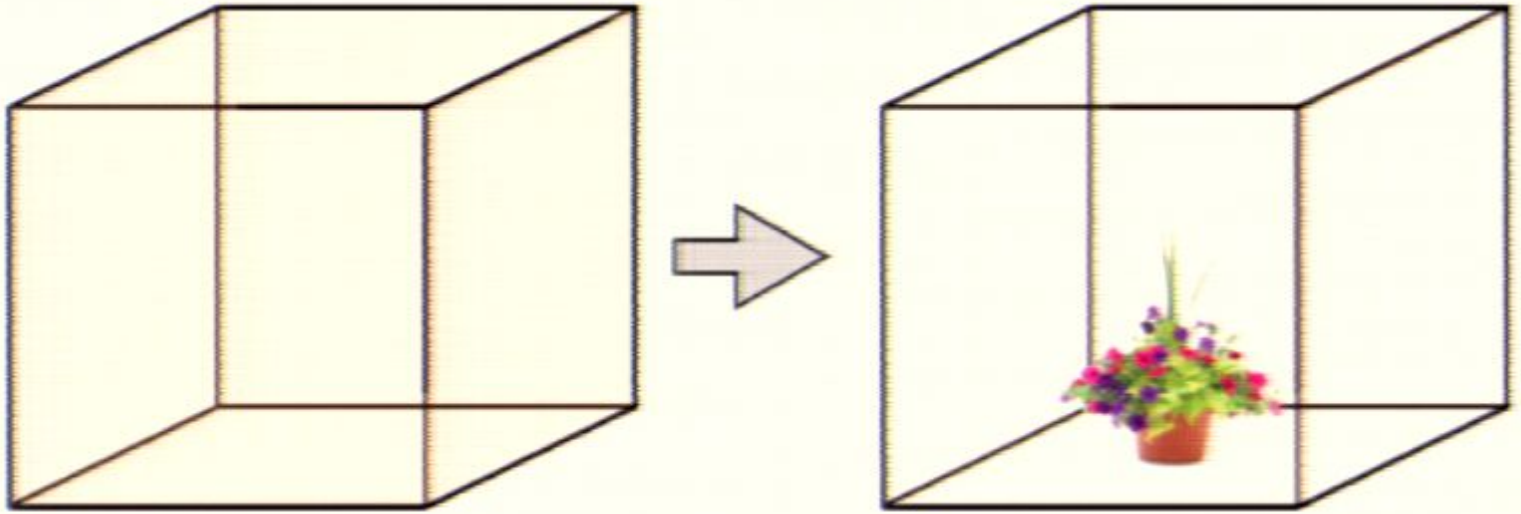

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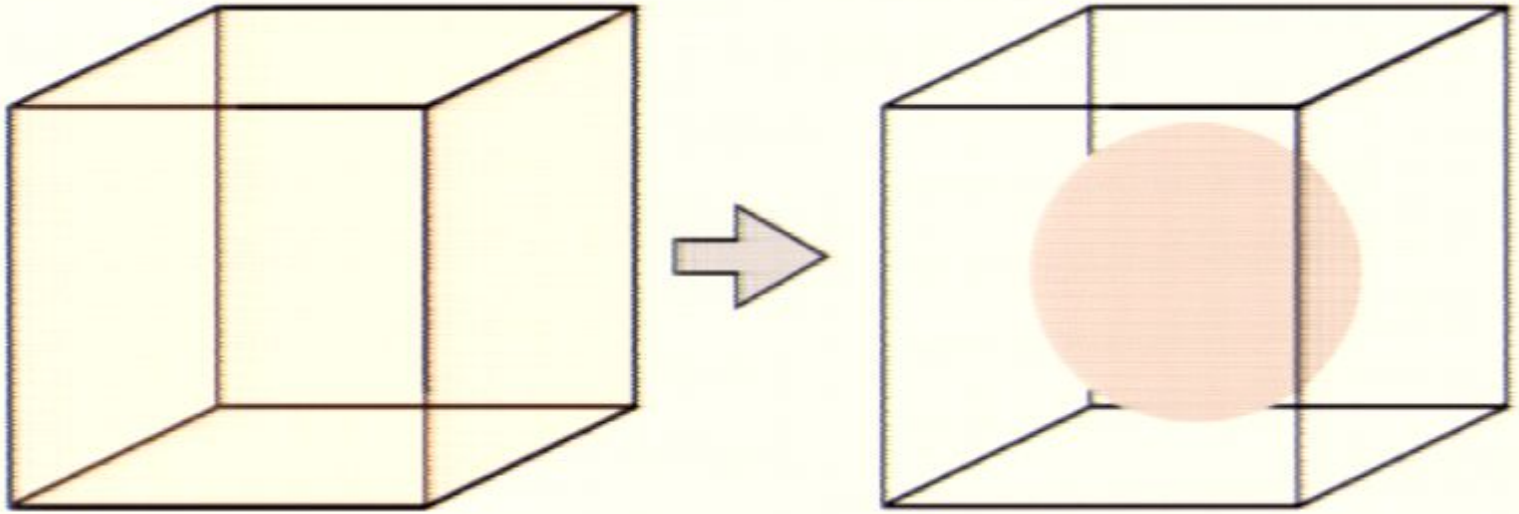

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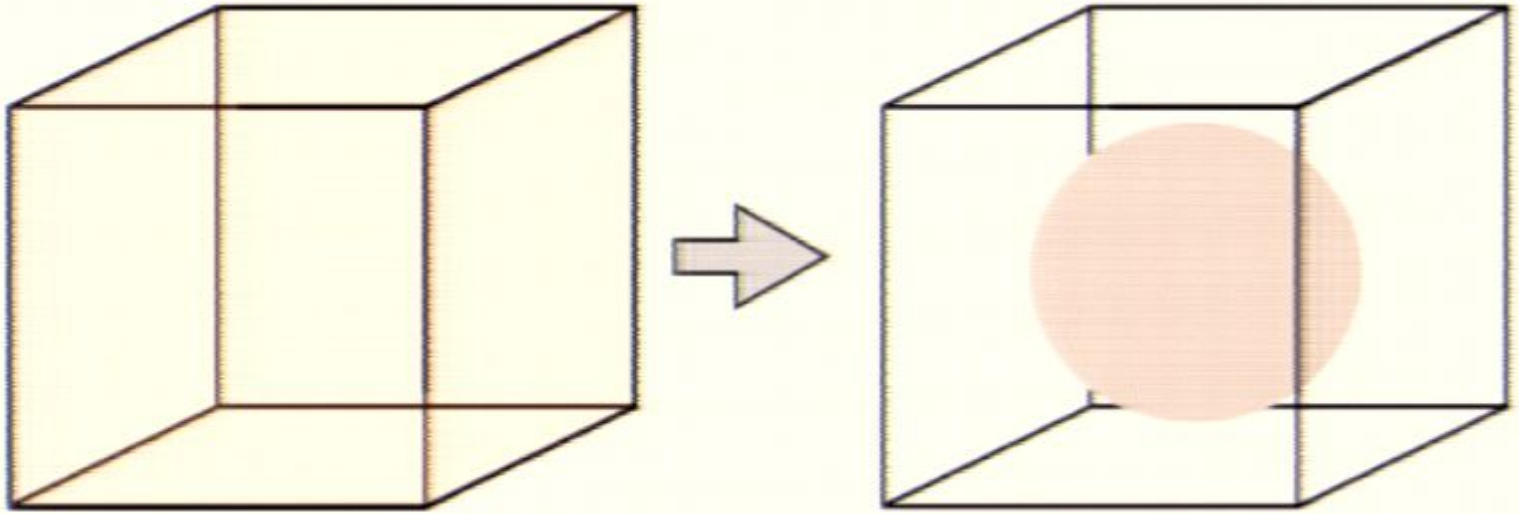

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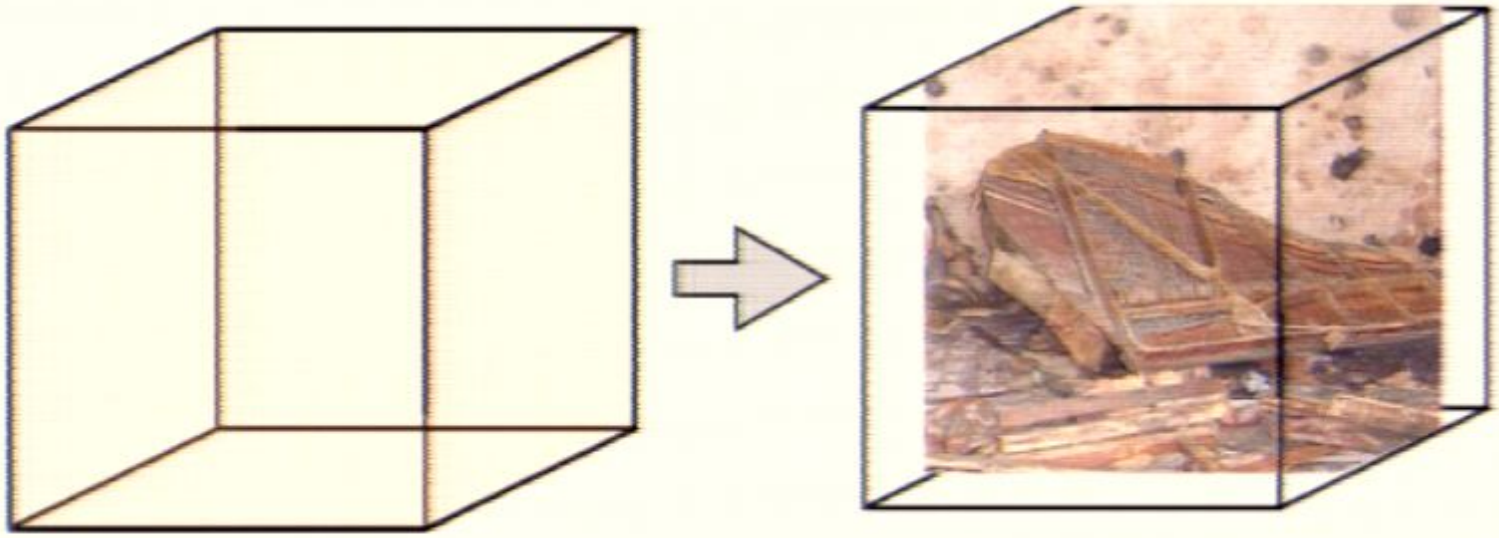

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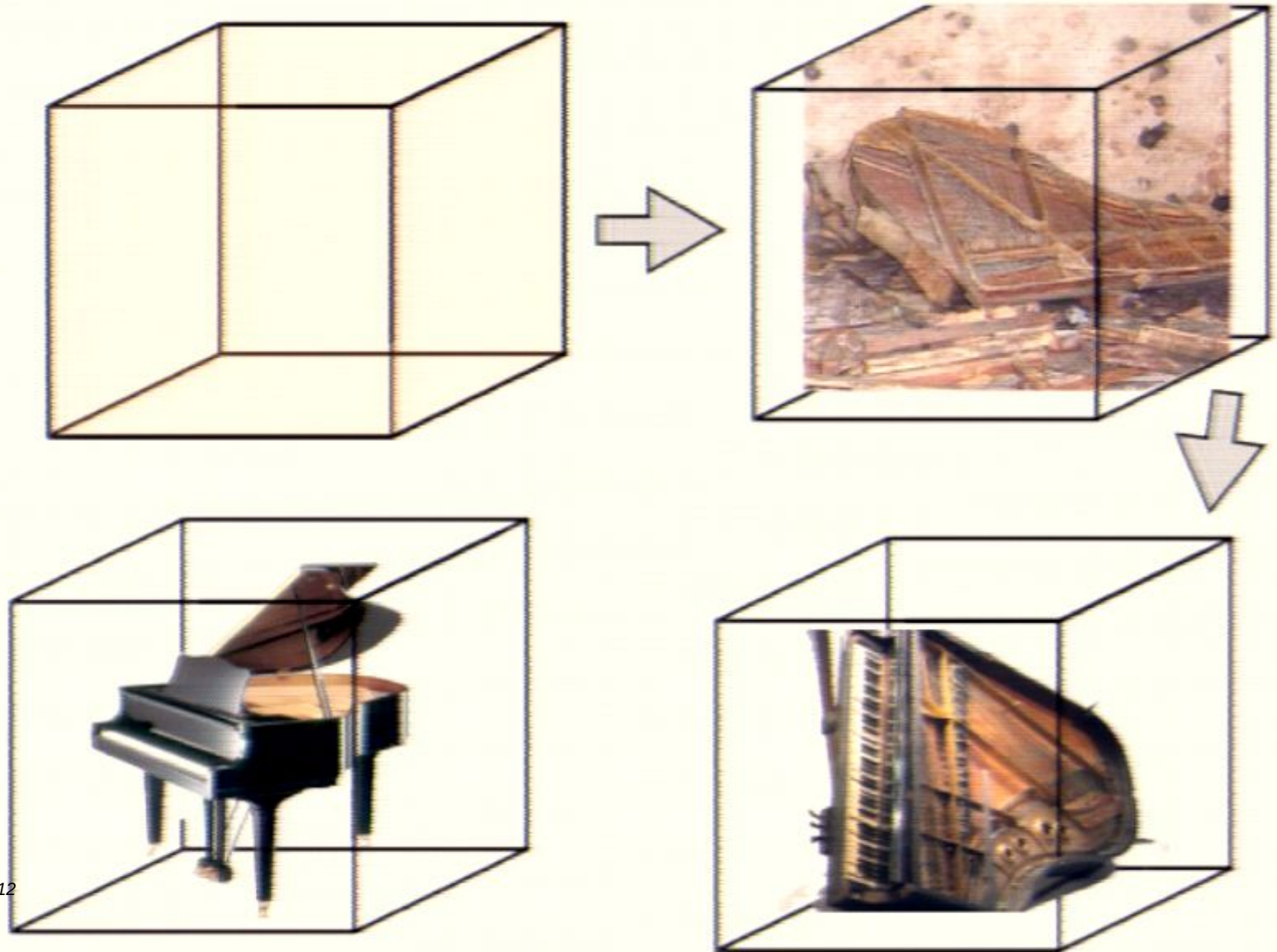
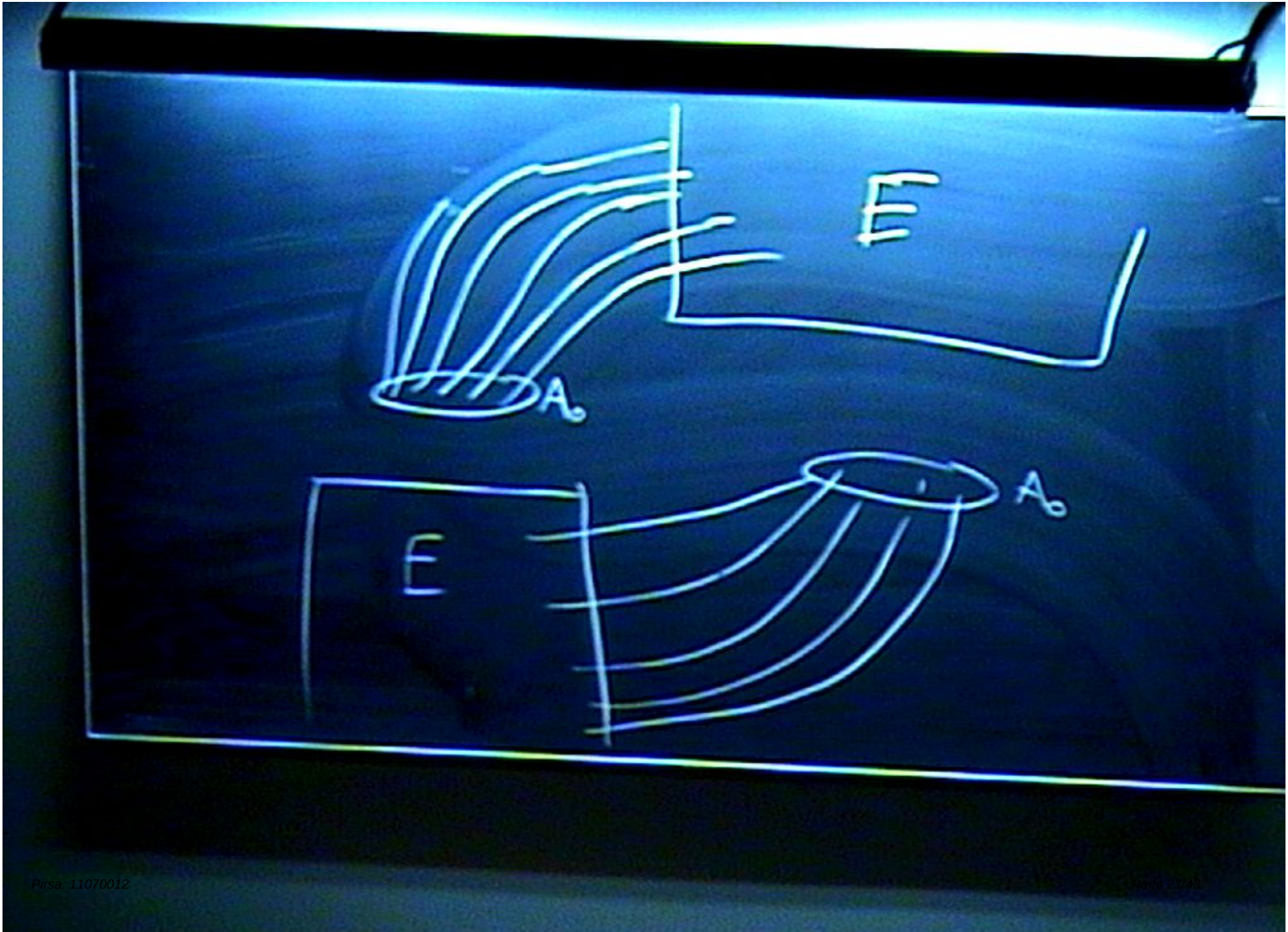


Plan:

- Hand-wavy argument
- More rigorous argument
- Storytime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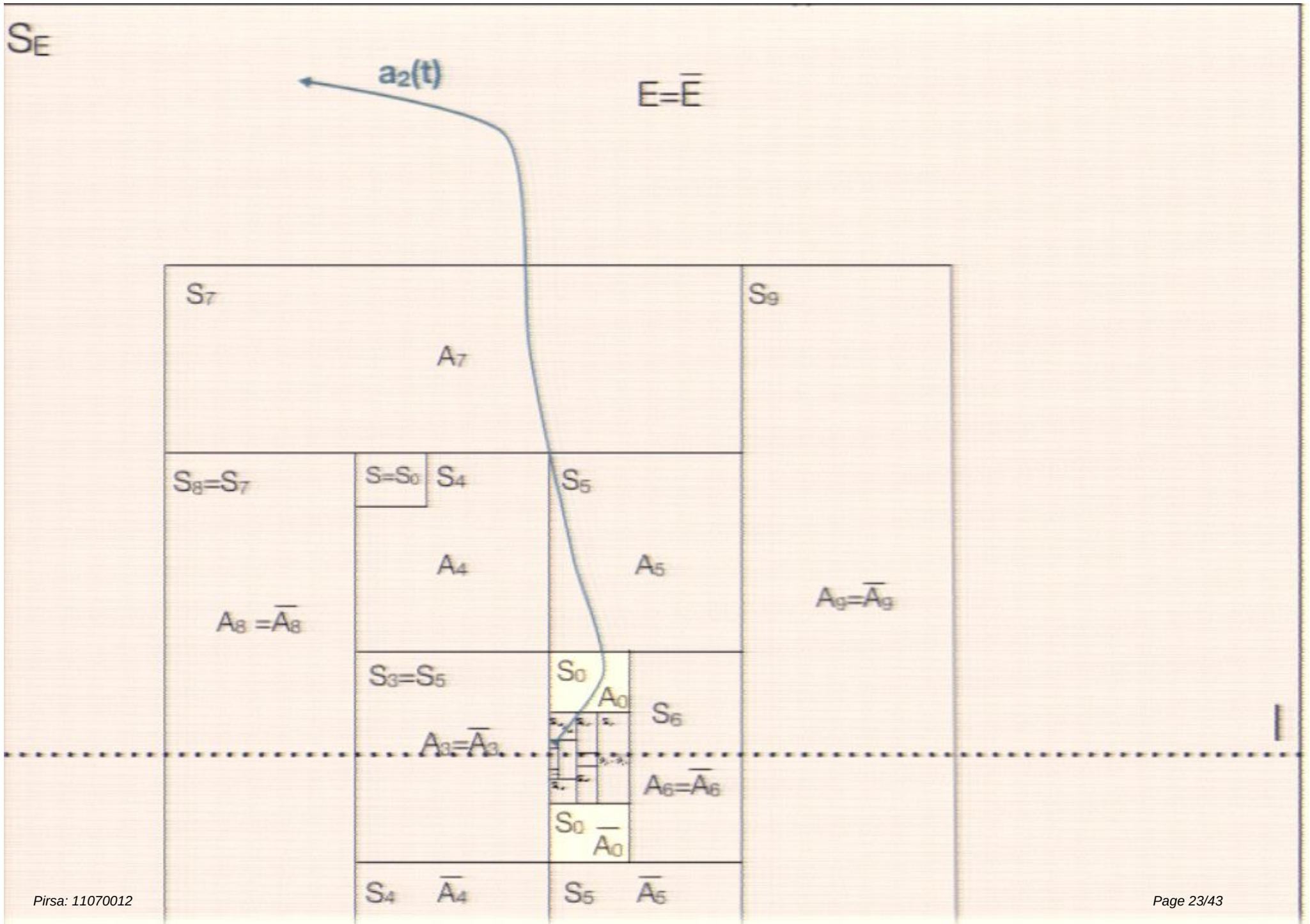
The classical/toy model argument

- Fixed set of microstates a_i with probabilities p_i.
- Partition these into macrostates A_j with probabilities $P_j = \sum_{a_i \in A_j} p_i$
- Microstates evolve via $a(t)=U(t-t_0)a(t_0)$ where U is unitary:
  - In particular, for each $a(t)$, there is an $\bar{a}(-t)$ that is a solution, where 'bar' is an involution that maps the state space onto itself, and $a=\bar{\bar{a}}$
- Then U induces evolution $p_i(t)$,
- and $p_i(t)$ induces evolution $P_i(t)$.
- We can also accord (micro) and (course-grained) statistical entropies to these:

$$S^a = -\sum_i p_i \log p_i$$

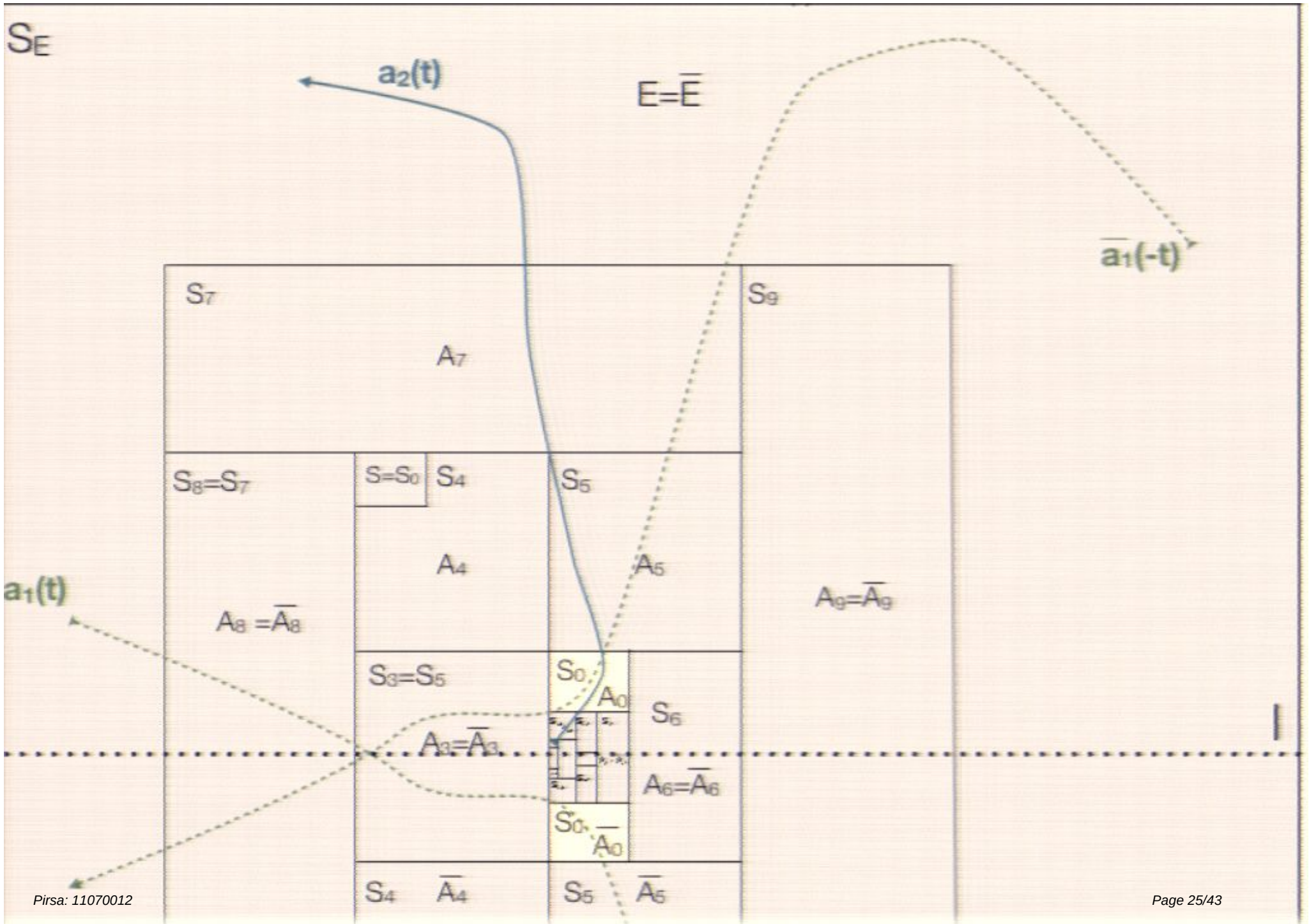
$$S^A = -\sum_j P_j \log P_j$$

- S^a is fixed; S^A dislikes decreasing.


S_E
$a_2(t)$
$E=\bar{E}$
S_7
A_7
S_9
$S_8=S_7$
$S=S_0$
S_4
S_5
A_4
A_5
$A_8=\bar{A}_8$
$A_9=\bar{A}_9$
$S_3=S_5$
S_0
A_0
S_6
$A_3=\bar{A}_3$
$A_6=\bar{A}_6$
S_0 $\bar{A}_0$
S_4 $\bar{A}_4$
S_5 $\bar{A}_5$

The classical/toy model argument

- Start in equilibrium (which may be metastable).
- Wait until macrostate A_0 is realized; call this time t=0.
- What is $P_j(t)$ such that:
  - $P_j(t_0) = \delta_{j0}$ (the macrostate is the one we want), and
  - $p_i(t_0) = 1/N$ for the N microstates in j, zero otherwise ("democracy")
- Answer:
  - Consider $\bar{A}_0$, composed of $\bar{a}_i$, $i \in j=0$. (*Assume* $\bar{A}_0 = A_k$ for some k. If $\bar{A}_0 = A_0$ denote "bounce" state).
  - Let this naturally evolve to equilibrium to get $P_j(t)$.
  - Now 'bar' the whole evolution.
  - This is a set of macro-probabilities describing macrostates leading up to A_0 such that each microstate making up A_0 is equally probable.


S_E
$a_2(t)$
$E=\bar{E}$
$\bar{a}_1(-t)$
S_7
A_7
S_9
$S_8=S_7$
$S=S_0$
S_4
S_5
A_4
A_5
$a_1(t)$
$A_8=\bar{A}_8$
$A_9=\bar{A}_9$
$S_3=S_5$
S_0
A_0
S_6
$A_3=\bar{A}_3$
$A_6=\bar{A}_6$
S_0
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S_4
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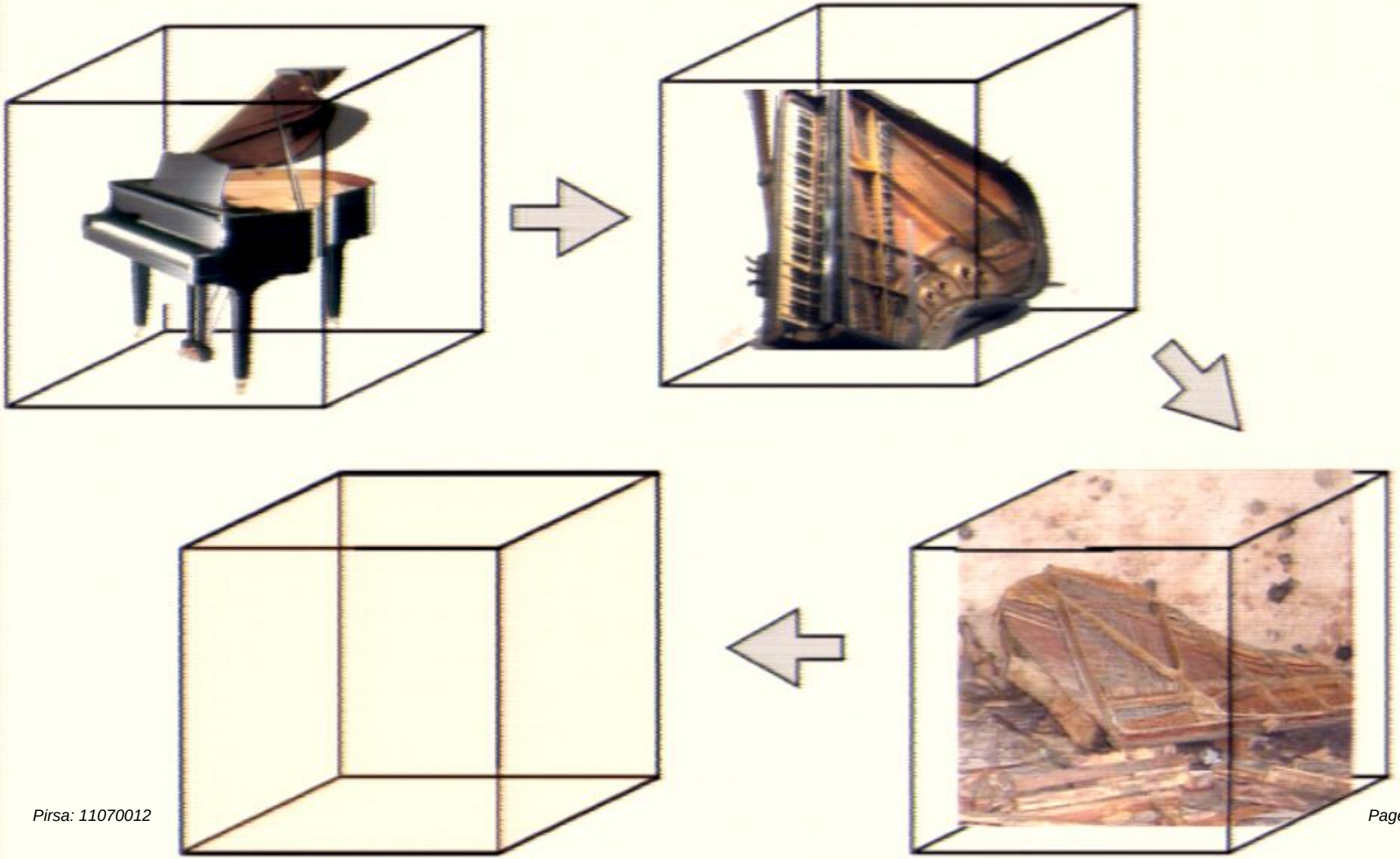
S_5
$\bar{A}_5$

Anti-piano

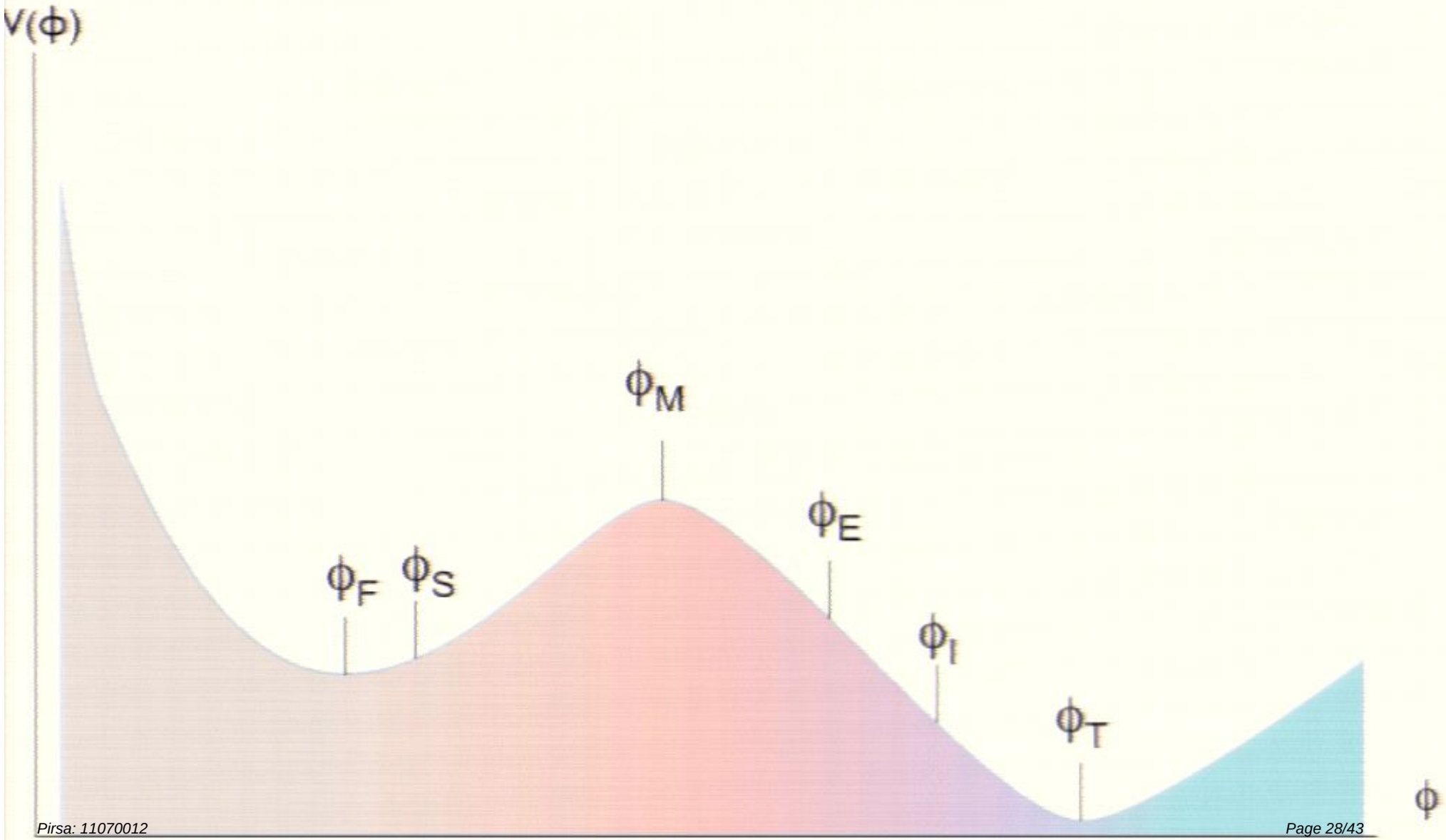


Assumptions

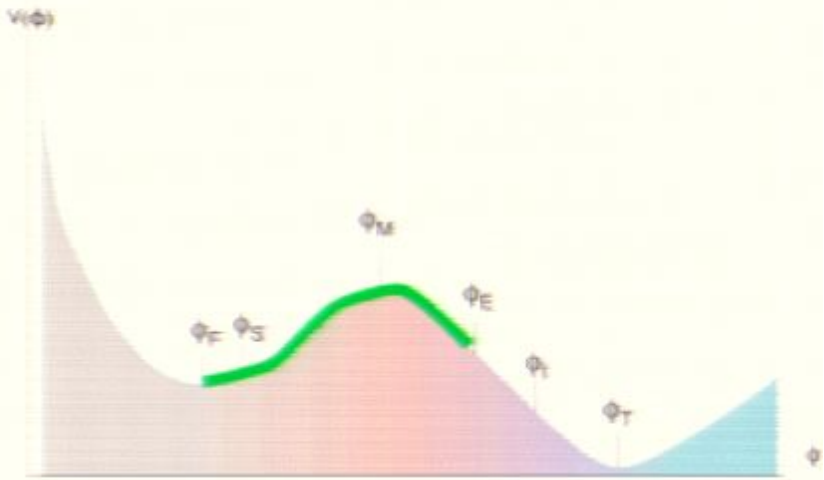
- System with a fixed set of microstates.
- Unitary evolution operator (for each microstate history: there is a conjugate history that is time-reversed.)
- Denumerable set of macrostates based on them.
- Democracy of microstates given a choice of coarse-grained macrostates.

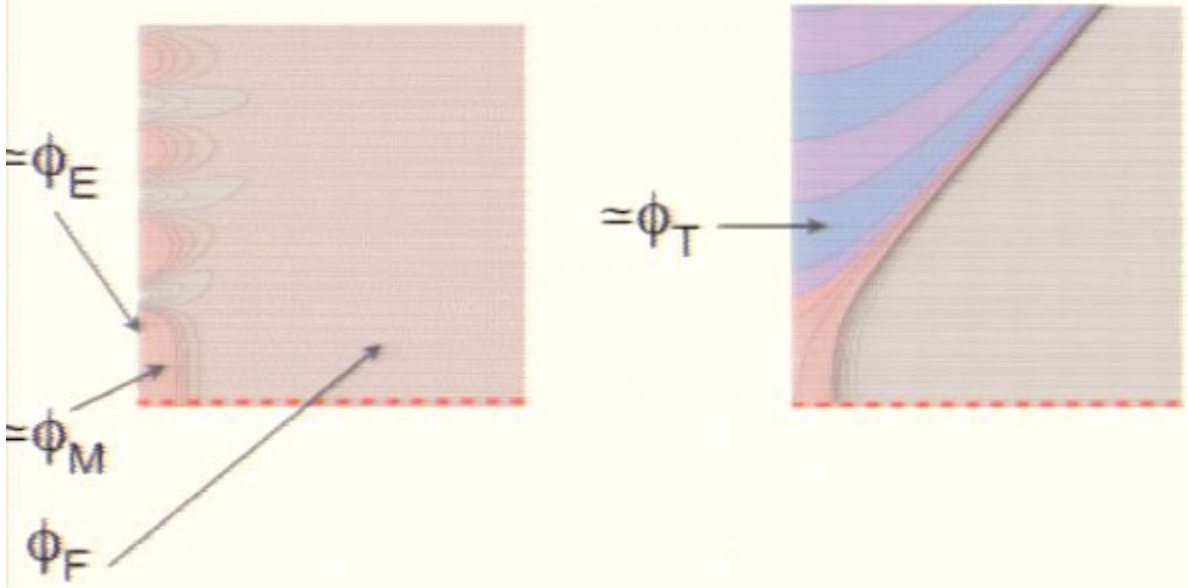
- **Assumptions concerning gravitating/spacetime systems**
  - Fixed systems including gravity also obey the same assumptions.
  - In the processes to be discussed, we can treat the interior of the causal diamond of a timelike observer as a closed gravitating system with a fixed set of states.

Multipurpose Potential



The "Thermalon"





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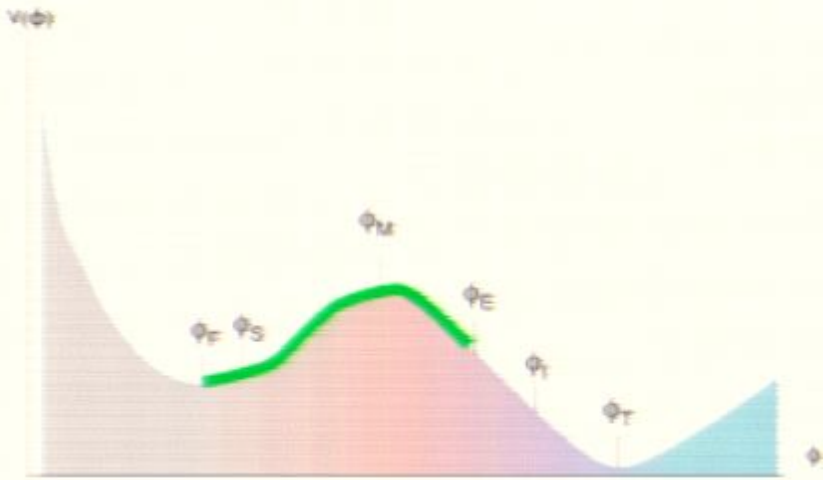
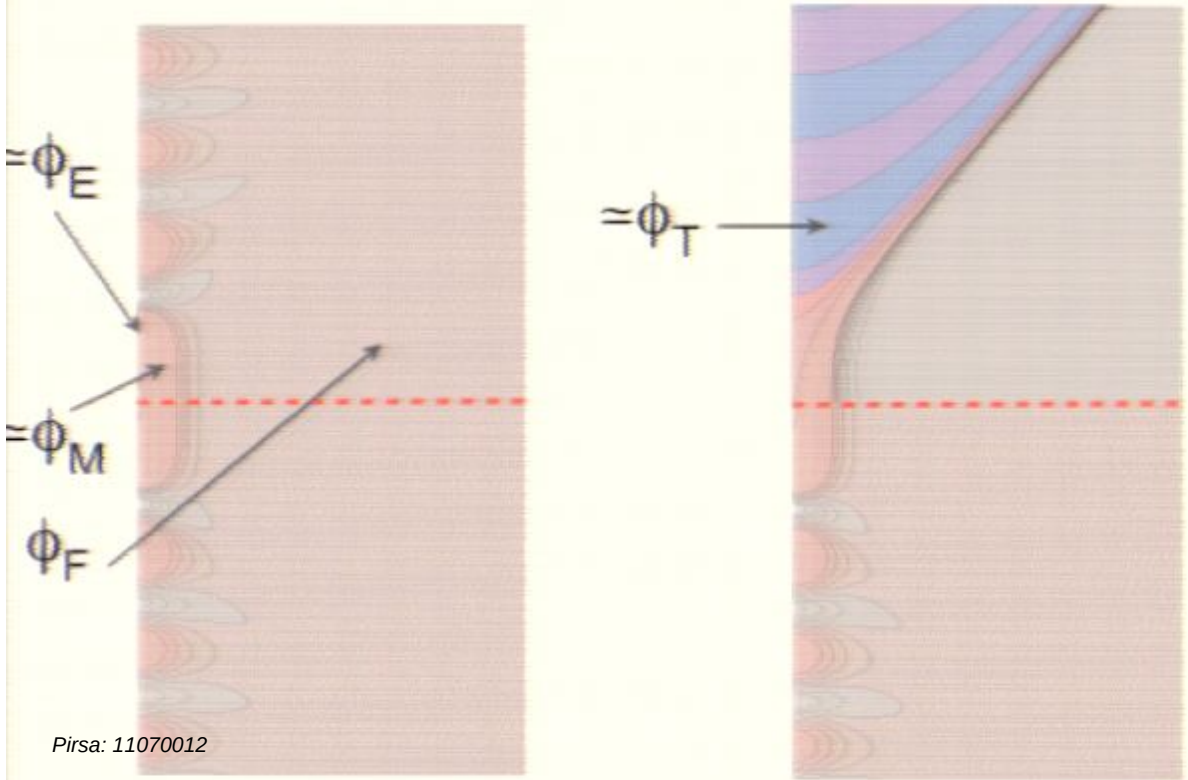
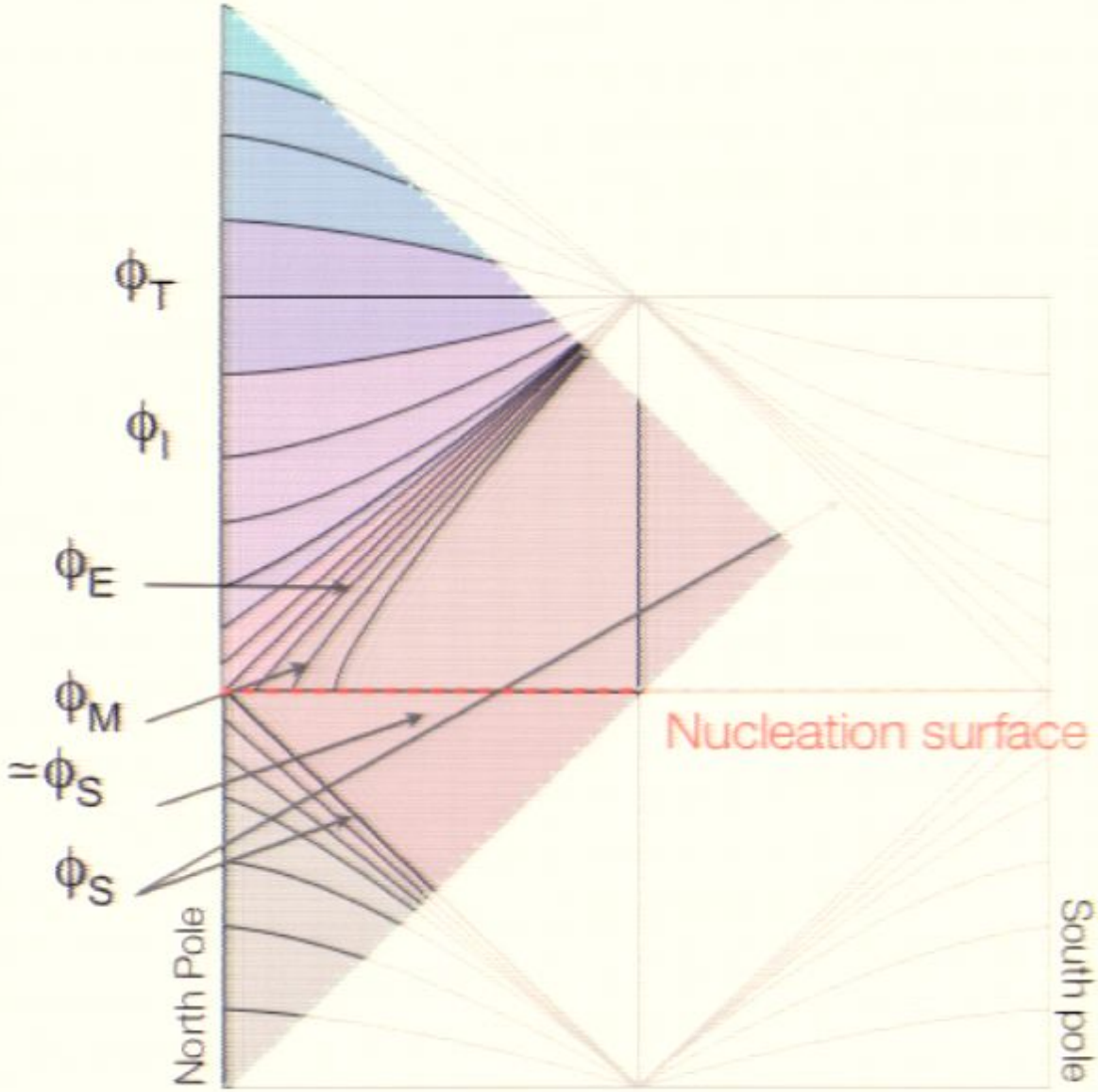
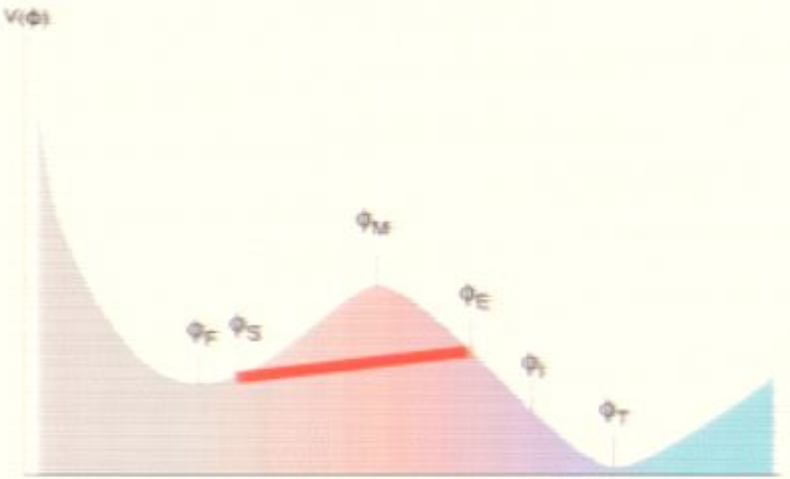


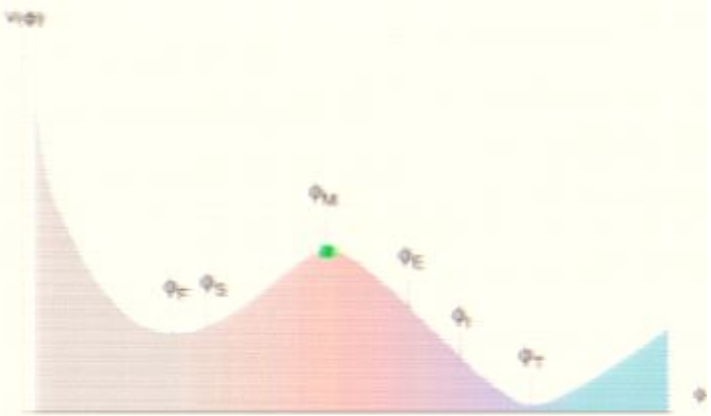


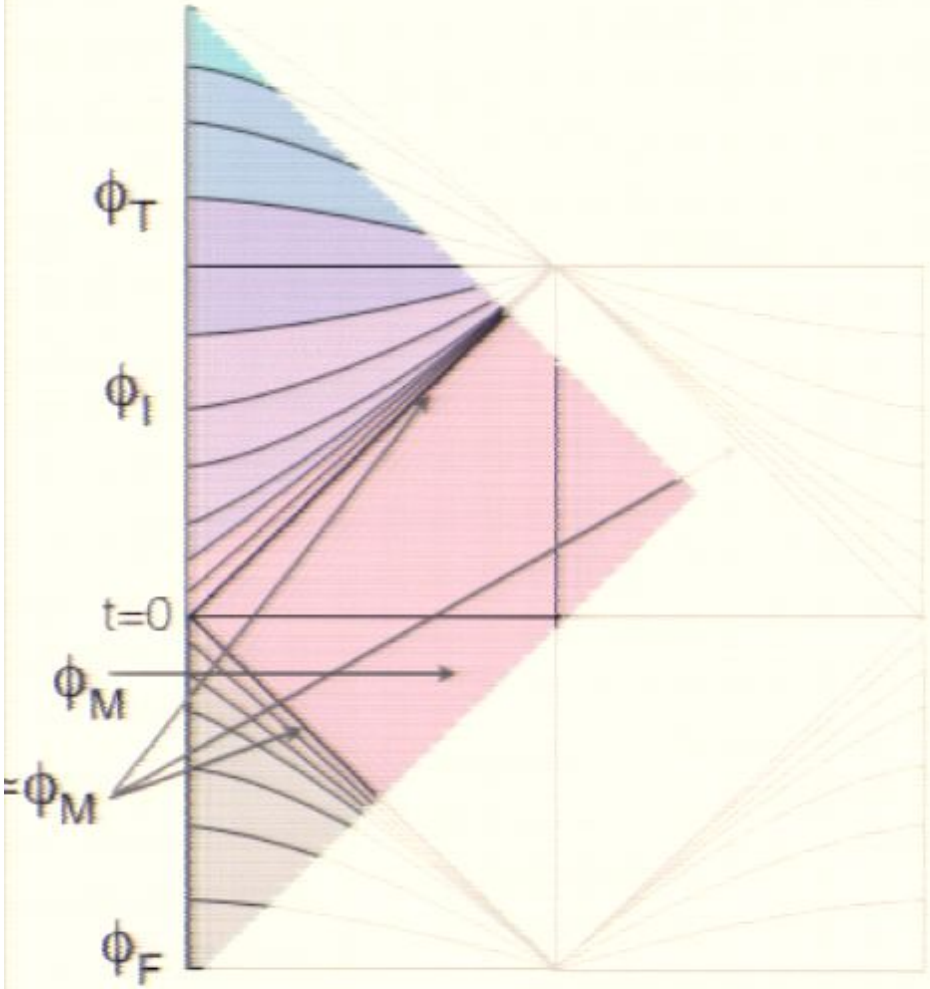
Coleman-DeLuccia tunneling

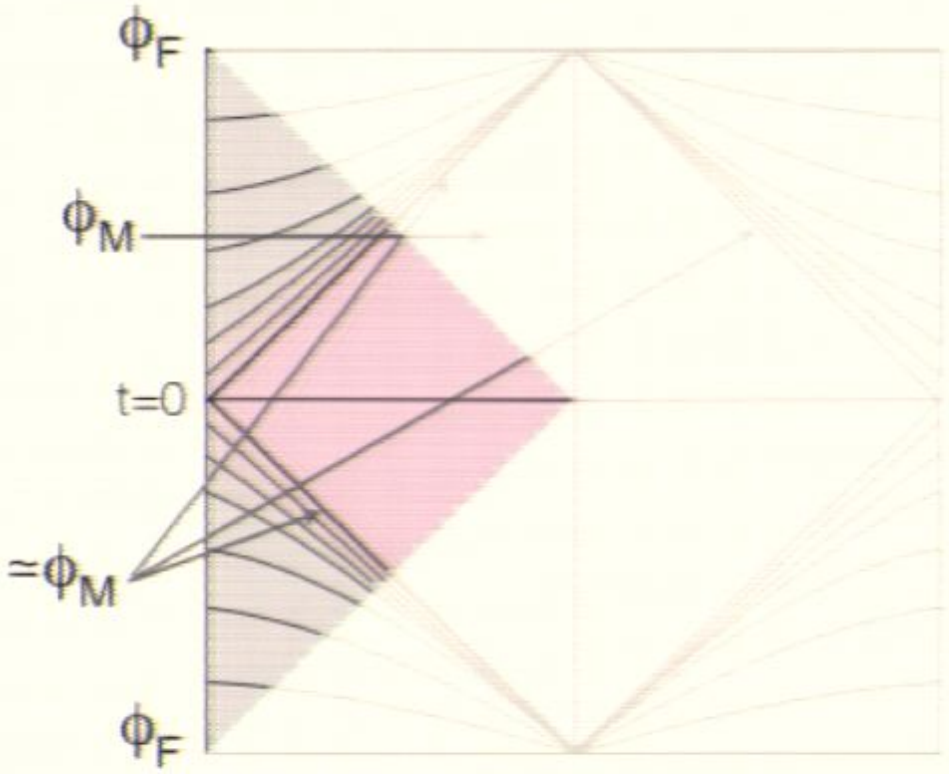




Hawking-Moss as a limit of CDL



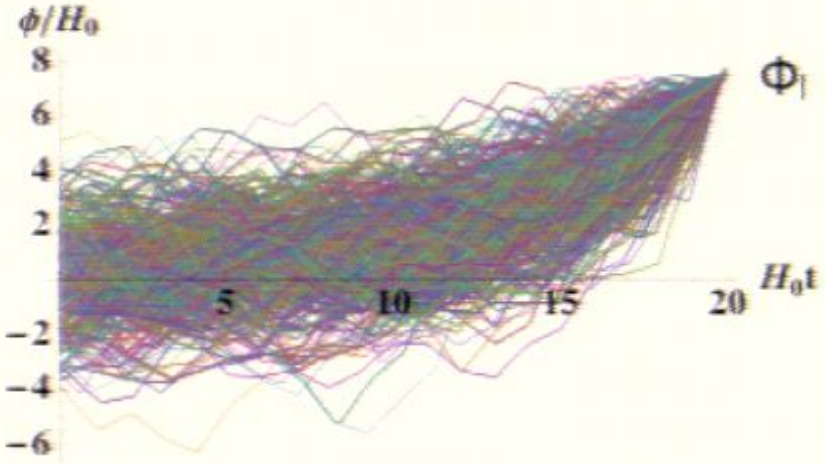


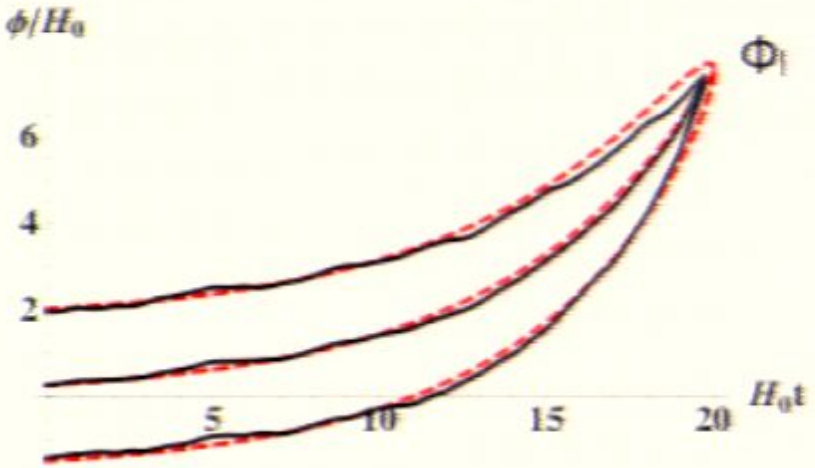


Stochastic eternal inflation

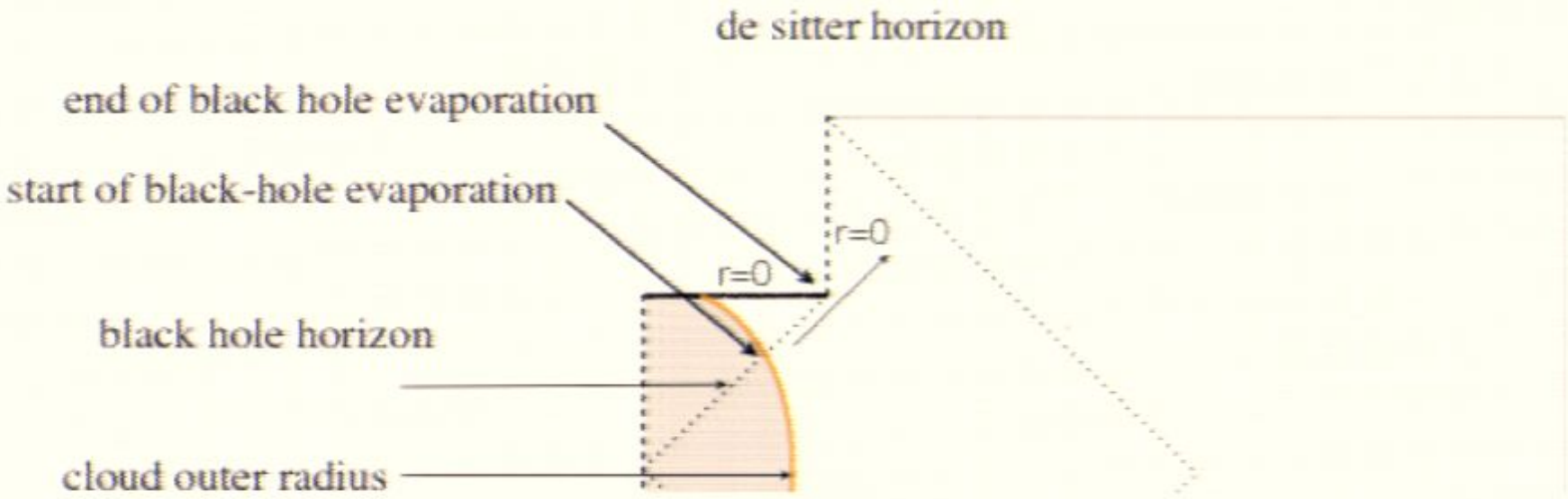
Langevin approach:

$$3H_0\dot{\phi} = \frac{3H_0^{5/2}}{2\pi} n(t) - m^2\phi(t)$$

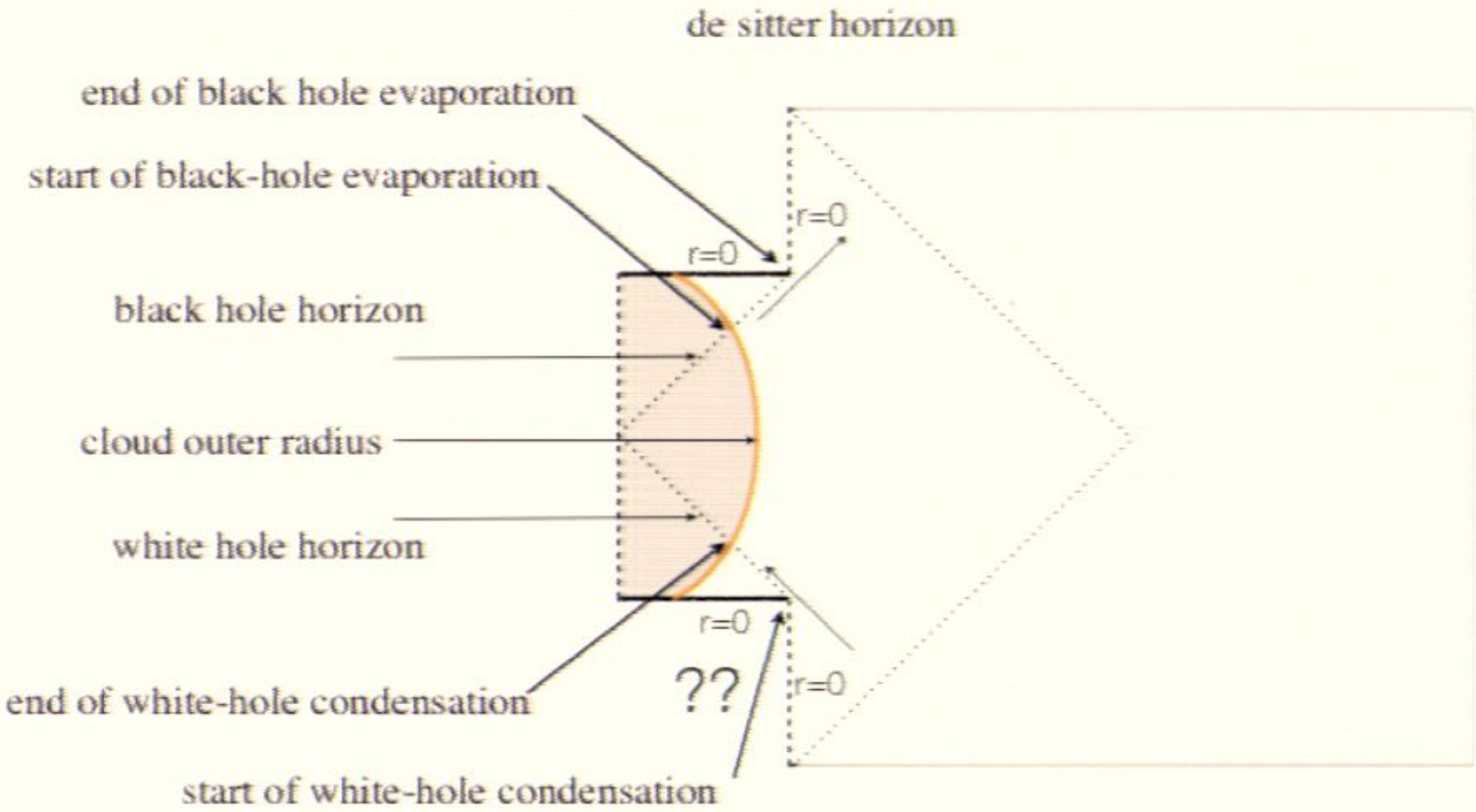




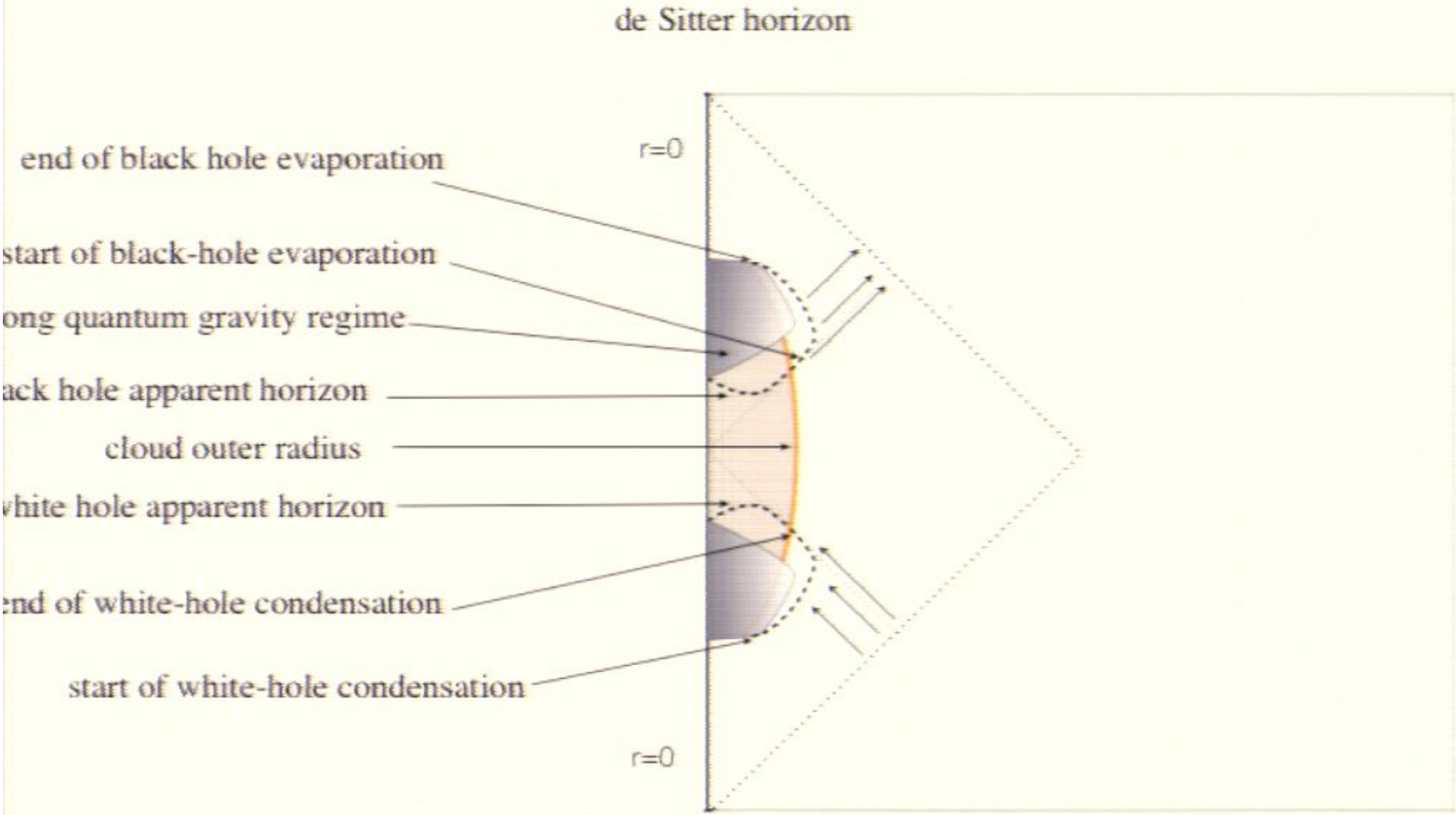
Black+white hole, traditional version



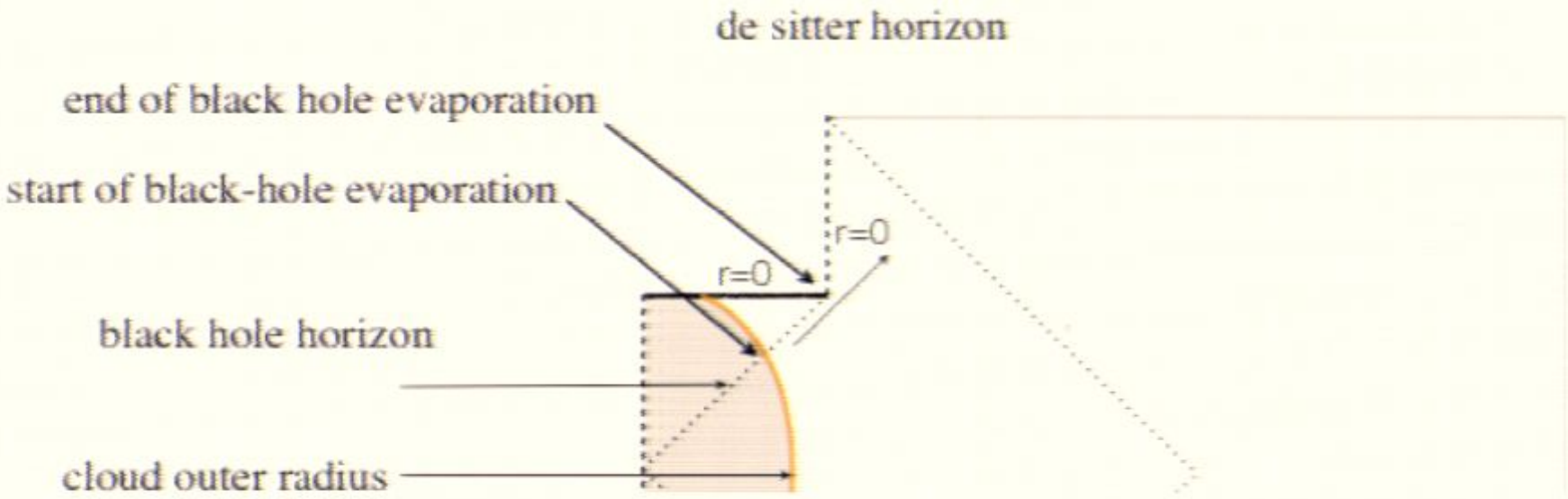
Black+white hole, traditional version



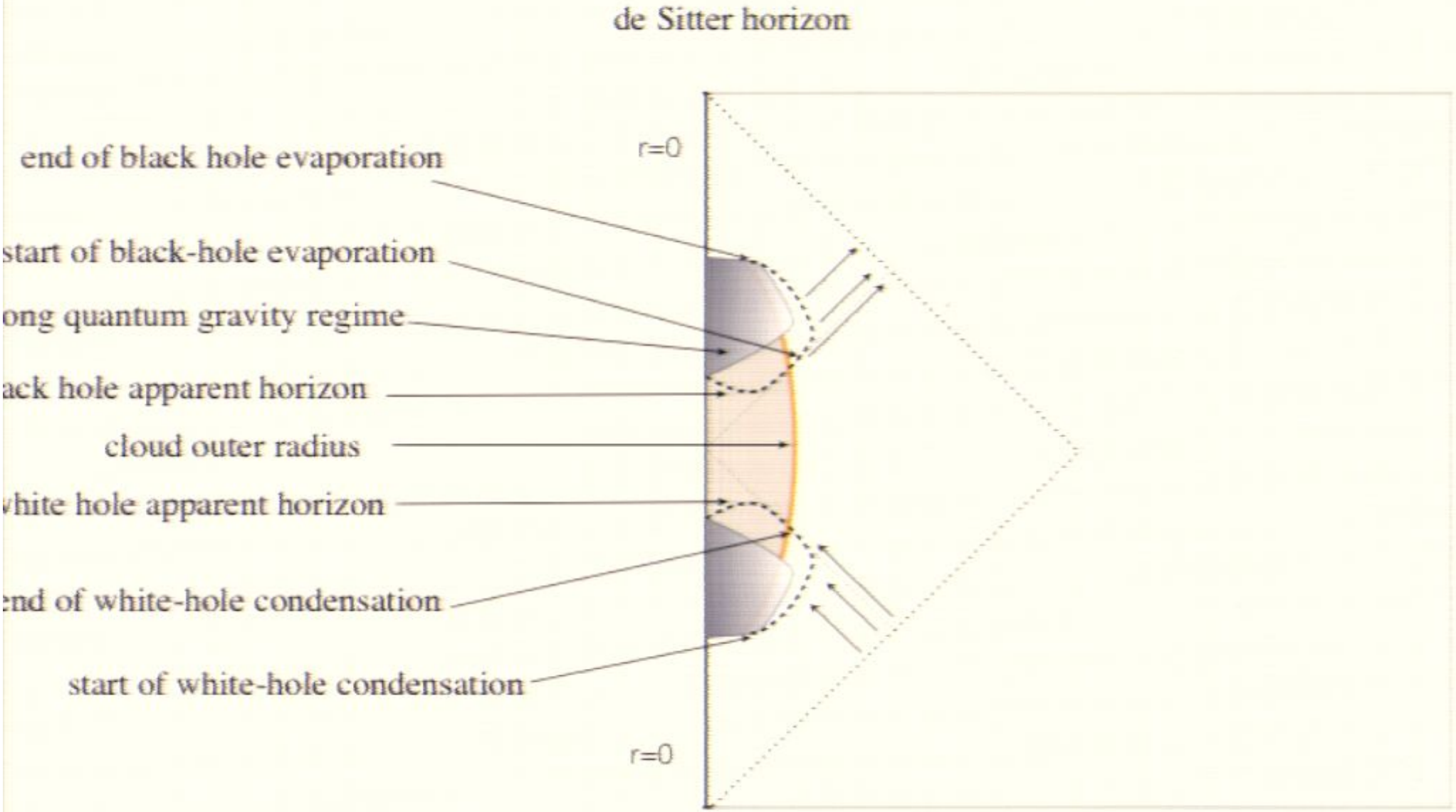
Black+white hole, unitary version

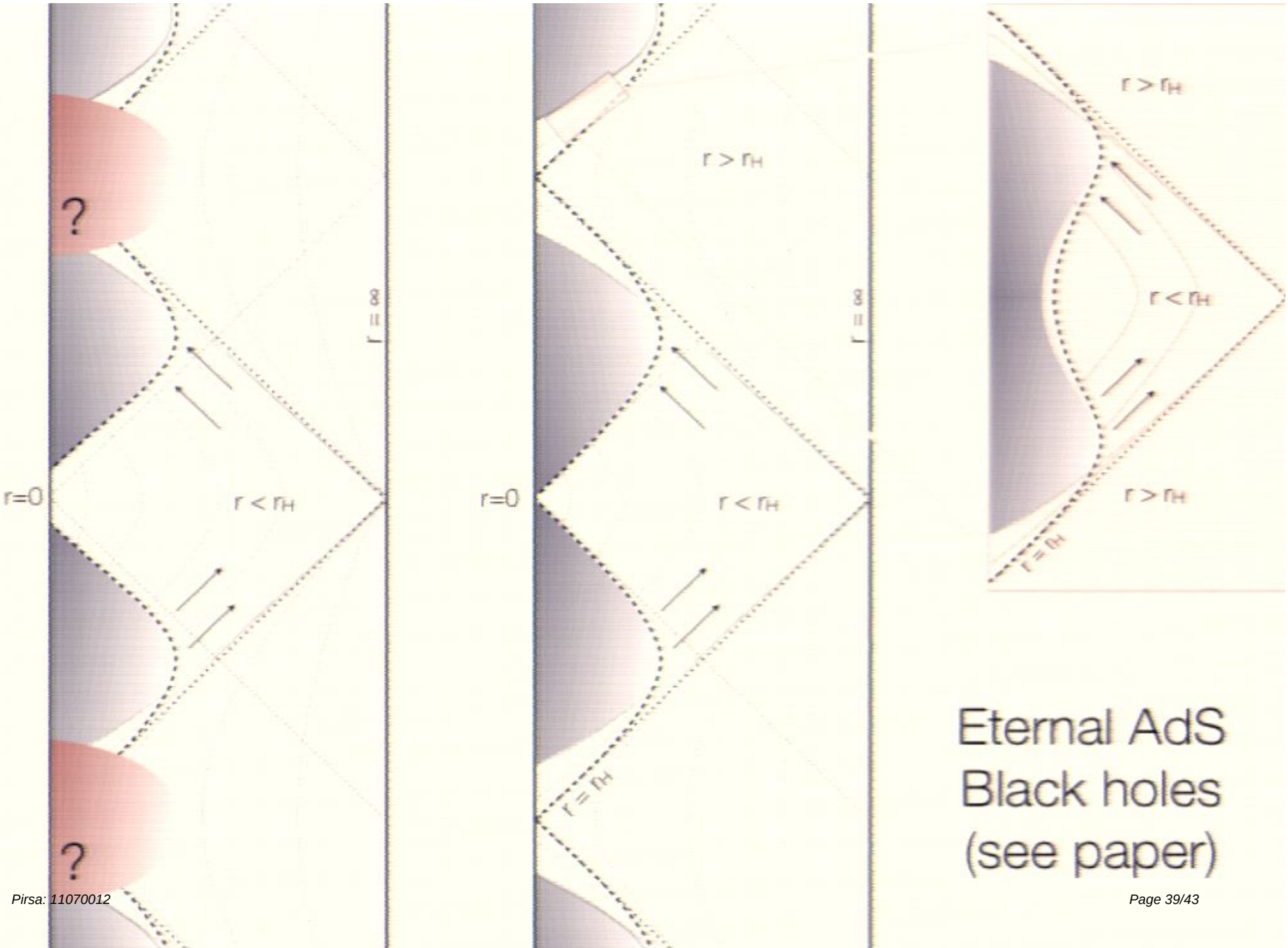


Black+white hole, traditional version



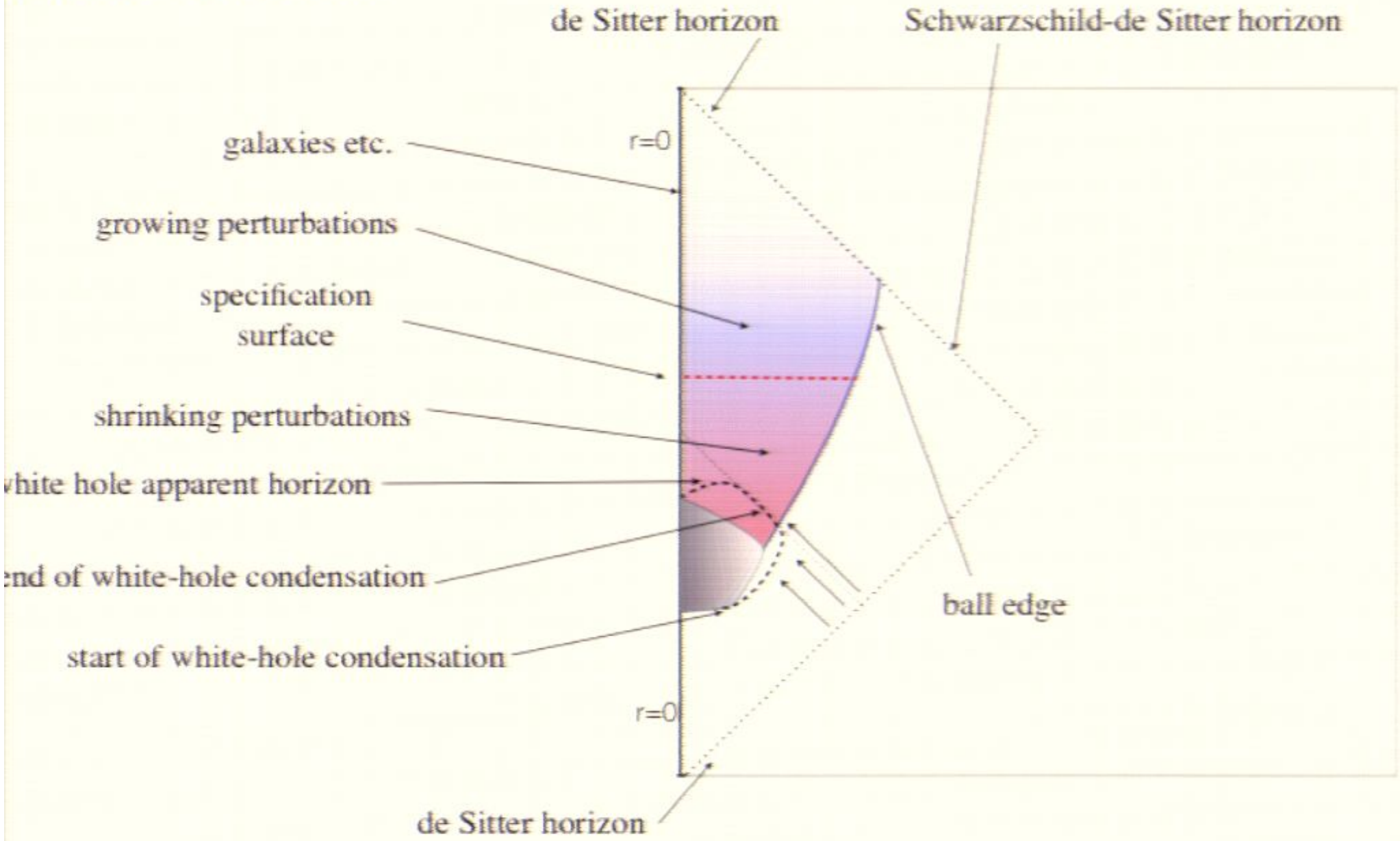
Black+white hole, unitary version



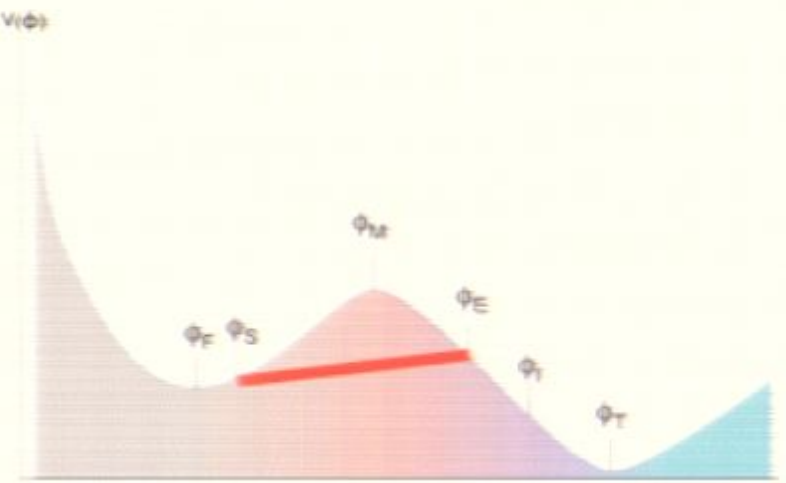


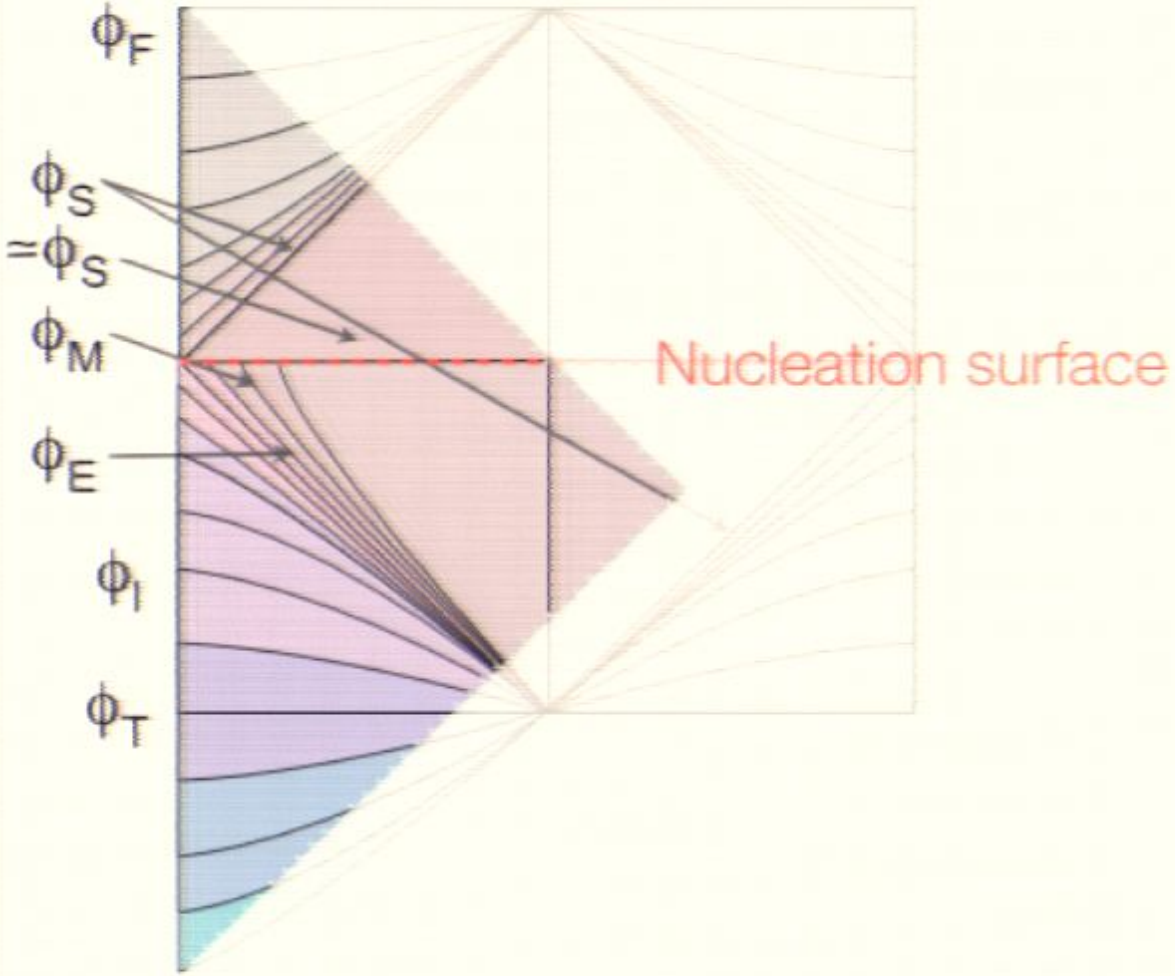
Eternal AdS Black holes (see paper)

Island Universe



Lee-Weinberg "up-tunneling"





Notes on cosmology

- We should not really think of 'upward tunneling' as just like downward tunneling but less probable.
- Seems likely that probabilities determined by a 'dominant vacuum' will be quite similar to those coming from equilibrium.
- Going beyond our assumptions:
  - Eternal inflationists tend to reward inflation for producing infinite volume out of a false vacuum created, but not charge an infinite price to create the false vacuum. Unclear whether this makes sense.
  - But how exactly to think about things beyond the horizon is generally unclear.

Summary

Evolution* from equilibrium[♂] to a chosen macrostate A is[♆] the time-reverse[♆] of the evolution from A's time reverse to equilibrium.[☺]

* That is, the evolution of the probability distribution over macrostates.

[♂] Or metastable equilibrium that is attained more quickly than, but does not decay more quickly than, the typical time it takes to fluctuate A.

[♆] Under assumptions of a unitary time evolution and democracy of microstates.

[♆] Where this is the involution under which the theory is symmetric, and includes time-reversal.

[☺] Even if it seems weird.

This allows us to understand various processes in ultra-long-lived (or microscopic) systems, and might lead to useful new insights. Give it a try!