Title: Infinity, Finiteness and Inflationary Cosmology

Date: Jul 14, 2011 09:00 AM

URL: http://pirsa.org/11070039

Abstract: I analyze the various roles of infinity in current thinking about cosmology. Topics include initial conditions, attractor behavior, inflation and the precision and meaning of quantum measurements. I review the de Sitter equilibrium cosmology as an example of a finite cosmology, and present some new predictions that permit observable tests.

Infinity, Finiteness and Inflationary Cosmology

Andreas Albrecht
UC Davis
Challenges for Early Universe Cosmology
Perimeter Institute
July 14, 2011

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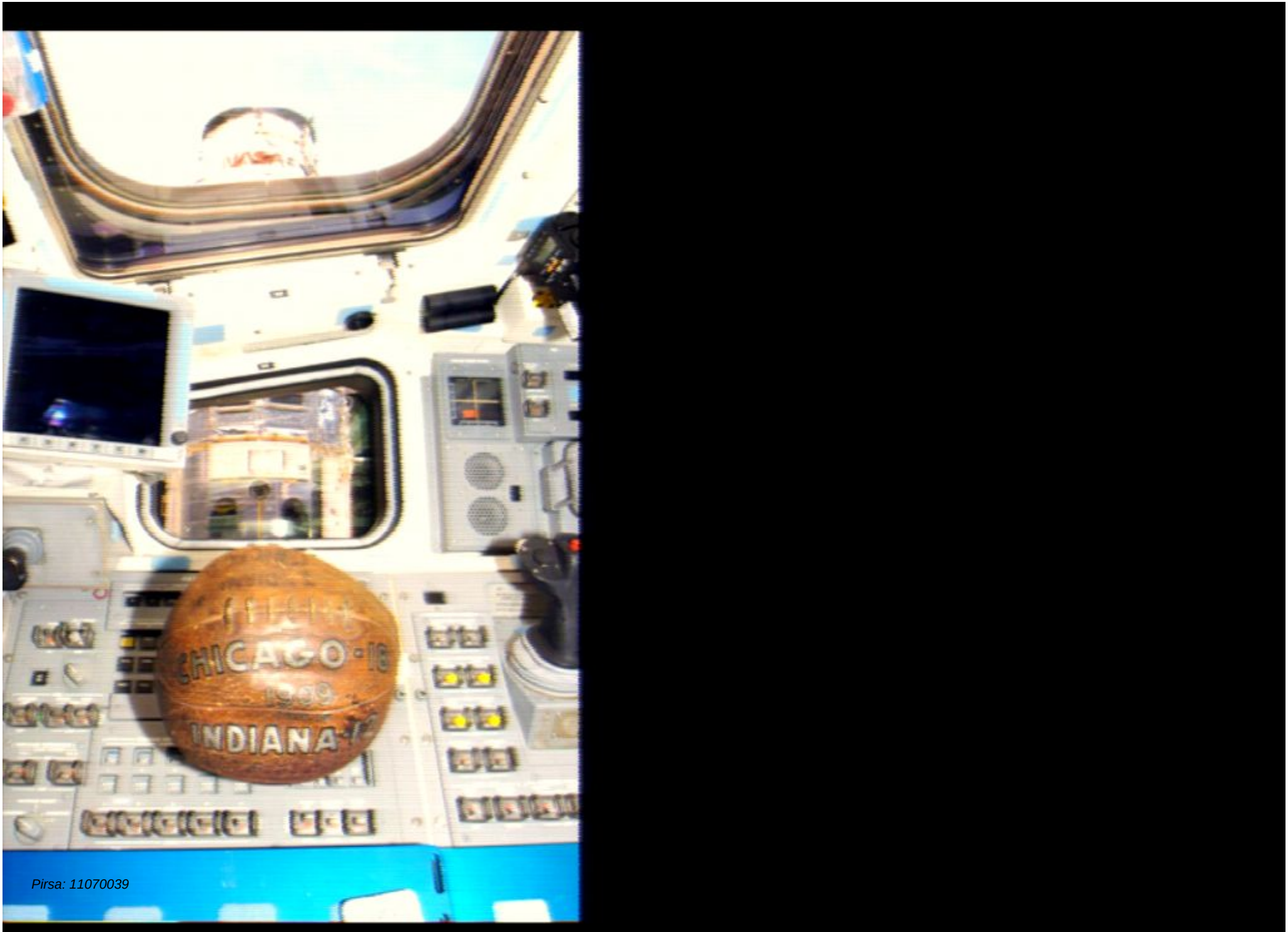

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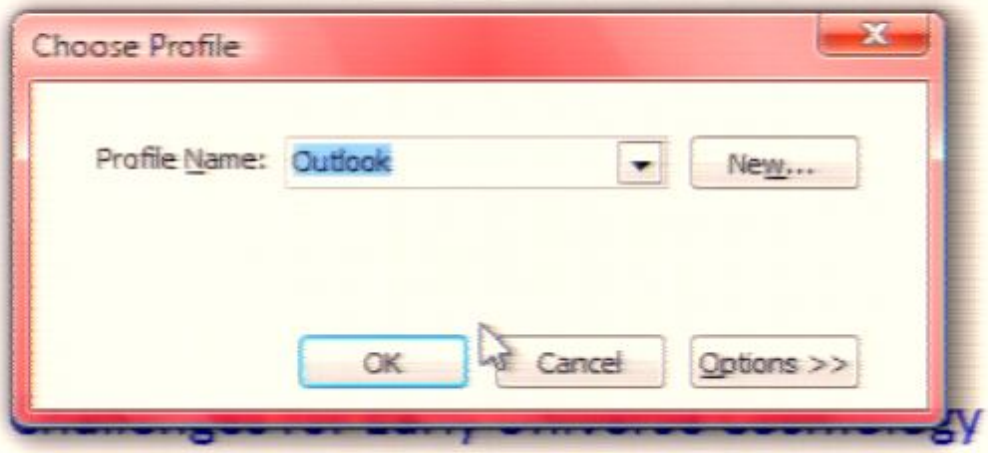


Perimeter Institute

July 14, 2011

OUTLINE

1) Ideas and Principles

2) A technical point about ergodicity

3) de Sitter Equilibrium

4) Cosmic curvature from de Sitter Equilibrium

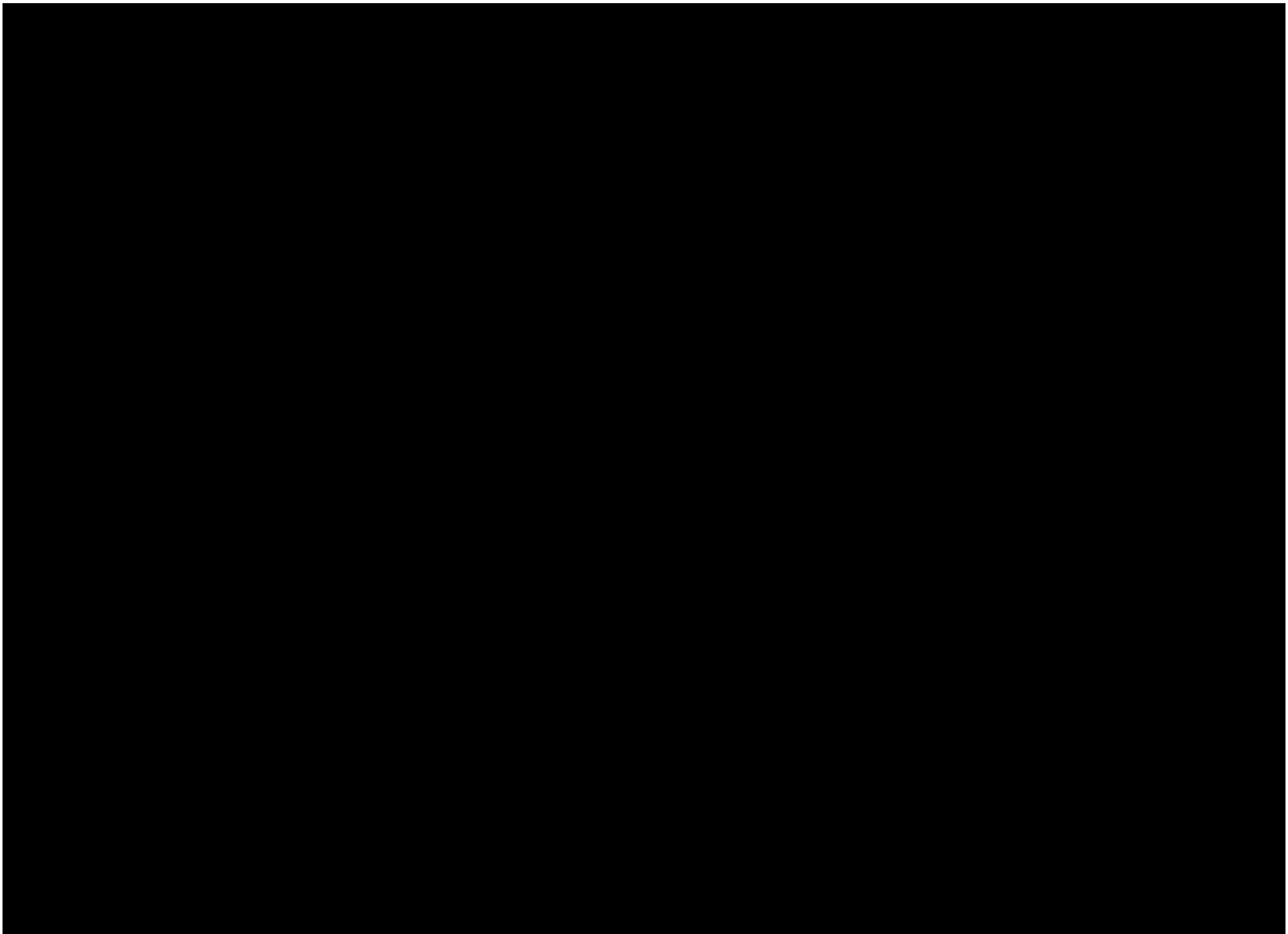
OUTLINE

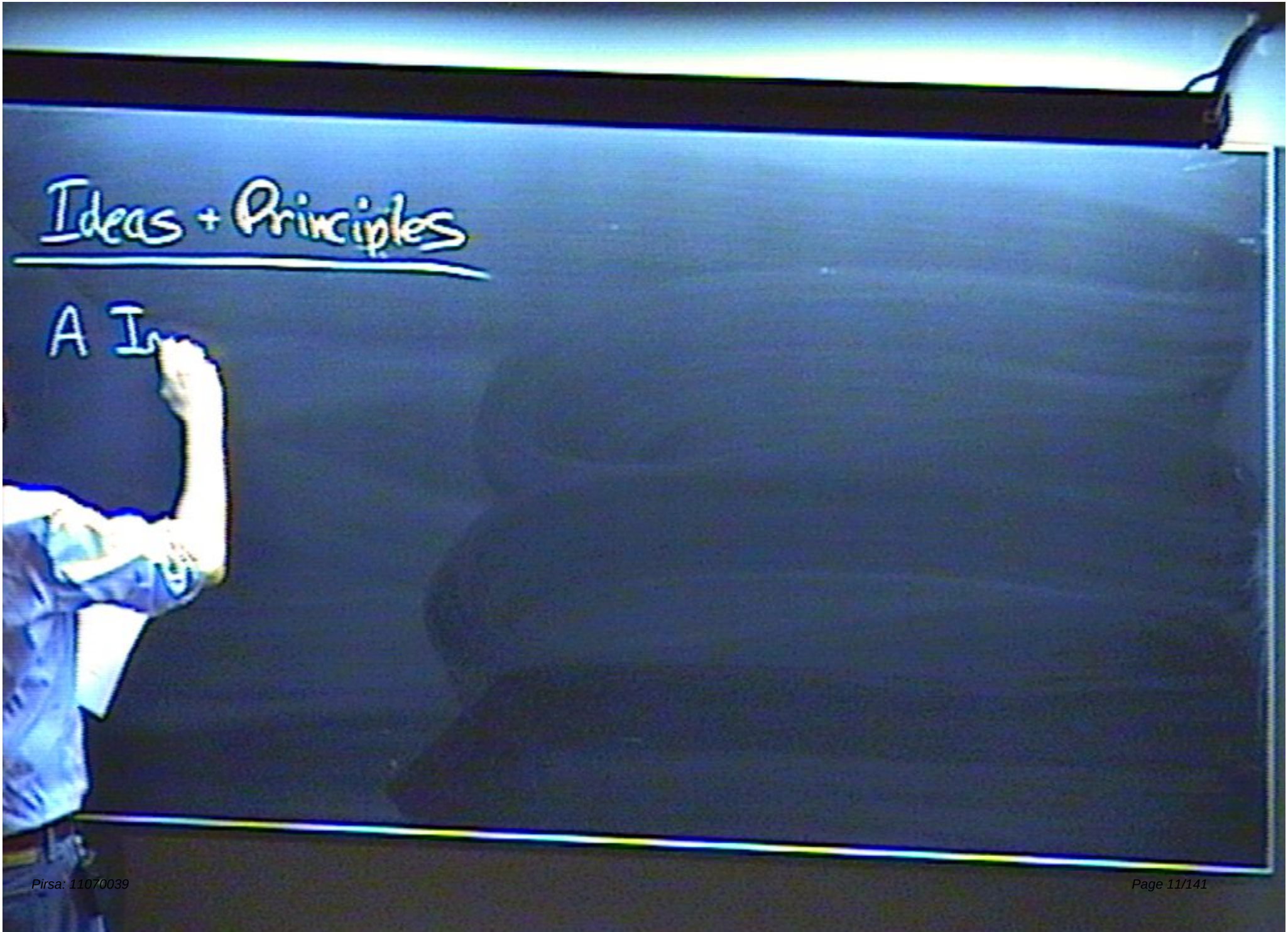
1) Ideas and Principles

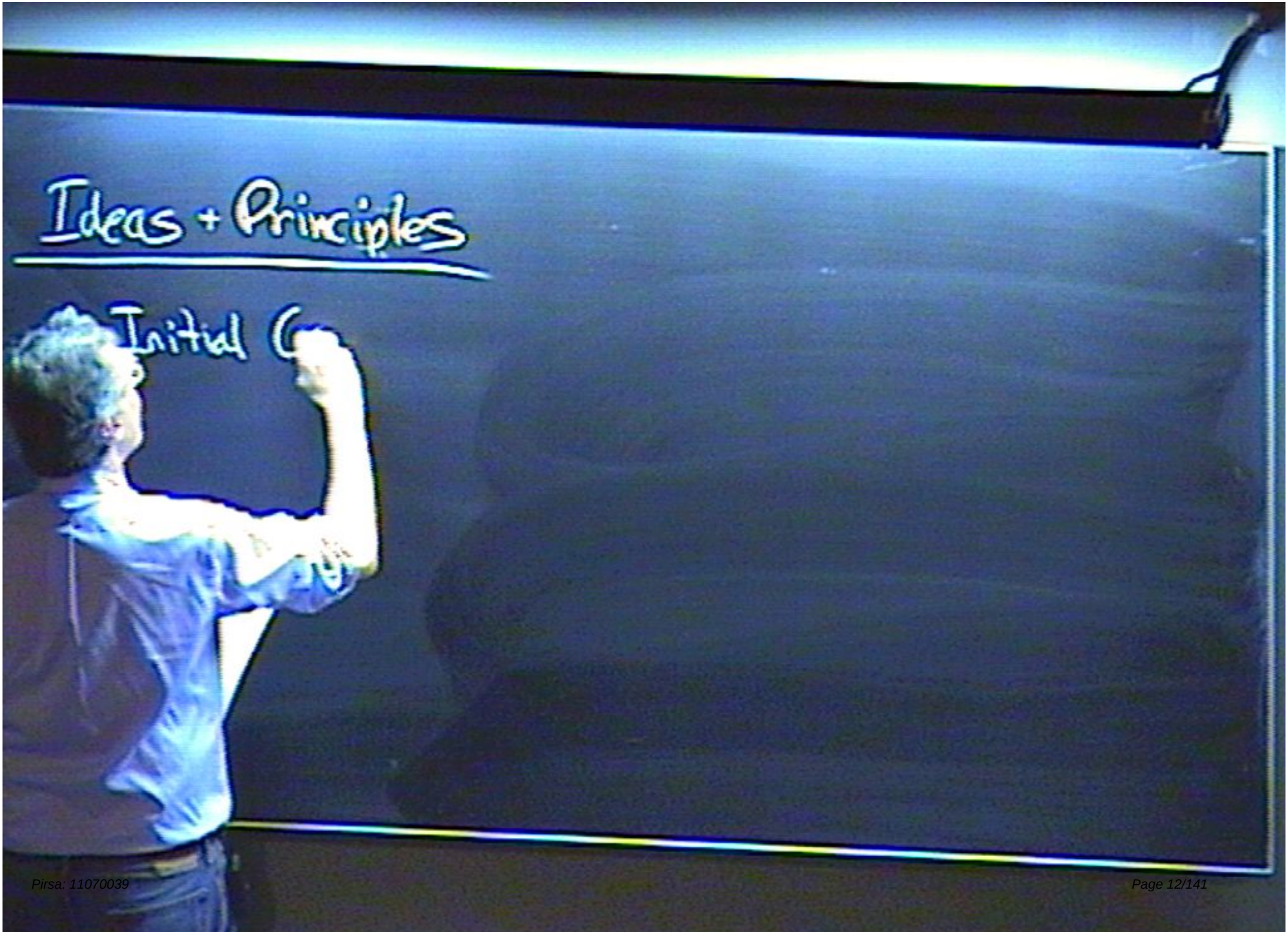
2) A technical point about ergodicity

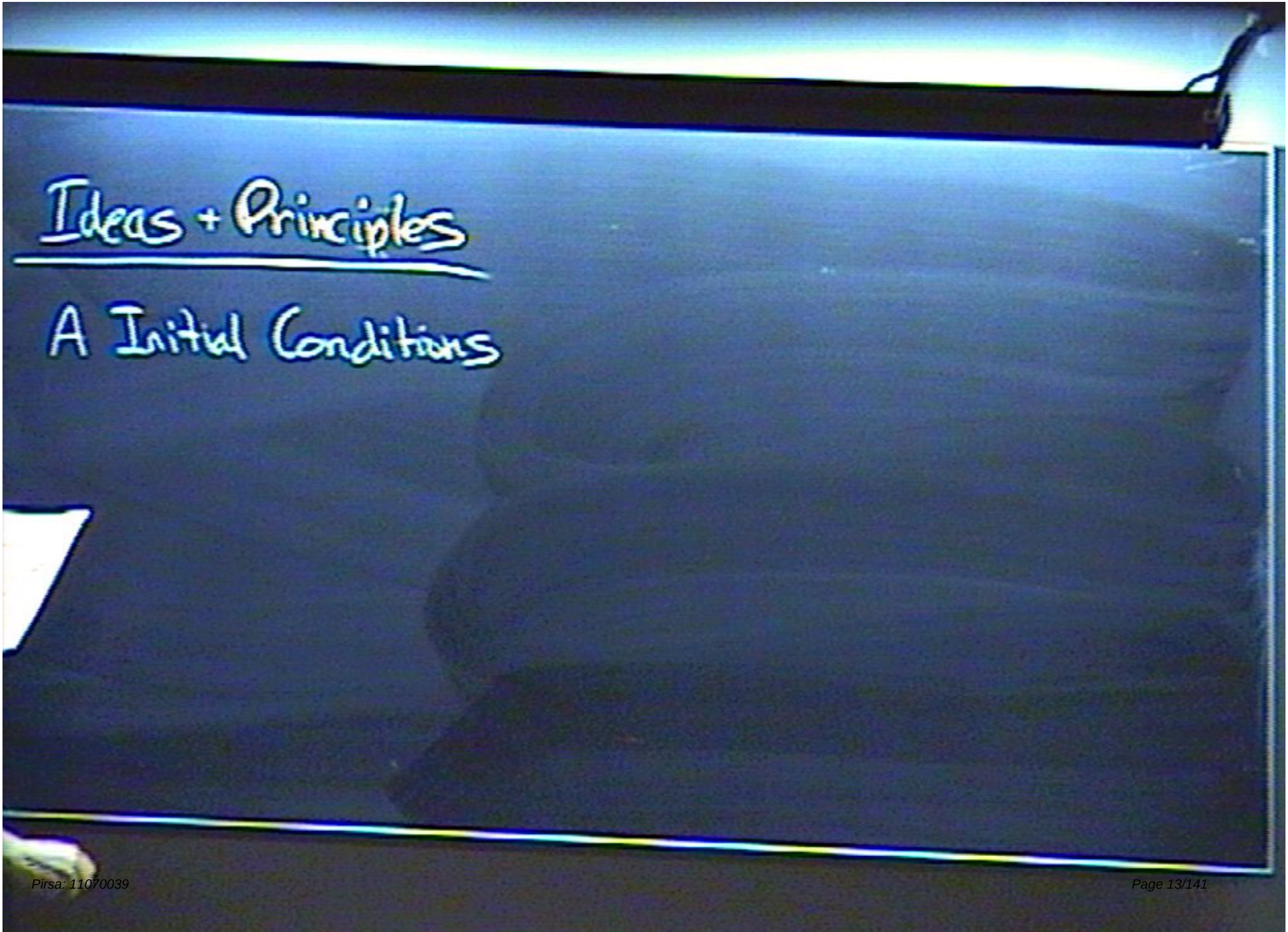
3) de Sitter Equilibrium

4) Cosmic curvature from de Sitter Equilibrium




Ideas + Principles
A I


Ideas + Principles
Initial C


Ideas + Principles
A Initial Conditions

Ideas + Principles

A Initial Conditions

i) Inflation hope: depend less on these

Ideas + Principles

A Initial Conditions

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ii)

Ideas + Principles

A Initial Conditions

i) Inflation hope: depend less on these

ii) Competition: SFB, right state at $t = t_{RH} \in$ (no inflation)

Ideas + Principles

A Initial Conditions

i) Inflation hope: depend less on these

ii) Competition: SFB, right state at $t = t_{end}$ (no inflation)

iii) 2nd law

Ideas + Principles

A Initial Conditions

i) Inflation hope: depend less on these

ii) Competition: SSB, right state at $t = t_{PT} \in$ (no inflation)

iii) 2nd law → unnatural early universe

Ideas + Principles

A Initial Conditions

i) Inflation hope: depend less on these

ii) Competition: SBB, right state at $t_{BB} \in$ (no inflation)

iii) 2nd law → unnatural early universe

iv) Past hypothesis

Ideas + Principles

A Initial Conditions

i) Inflation hope: depend less on these
ii) Competition: SBB, right state at $t = t_{BB} \in$ (no inflation)
iii) 2nd law → unnatural early universe
iv) Past hypothesis

} BB's

Ideas + Principles

A Initial Conditions

i) Inflation hope: depend less on these

ii) Competition: SBB, right state at $t_{BB} \in$ (no inflation)

iii) 2nd law → unnatural early universe } BB's

iv) Past hypothesis

v)

Ideas + Principles

A Initial Conditions

i) Inflation hope. depend less on these

ii) Competition: SBB, right state at $t = t_{BB} \in$ (no inflation)

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v) No one else cares about IC's

Ideas + Principles etc.

A Initial Conditions

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Ideas + Principles etc.

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Ideas + Principles etc.

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vii) No entitlement to large initial ρ

Ideas + Principles etc.

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Ideas + Principles etc.

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ii) Competition: SBB, right state at $t \sim \epsilon$ (no inflation)

iii) 2^{nd} law → unnatural early universe } BB's

iv) Past hypothesis

v) No one else cares about IC's

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vii) No entitlement to large initial ρ in meta picture

Ideas + Principles etc.

A Initial Conditions

i) Inflation hope: depend less on these ←

ii) Competition: SBB, right state at $t_{BB} \in$ (no inflation)

iii) 2nd law → unnatural early universe

iv) Past hypothesis

} BB's

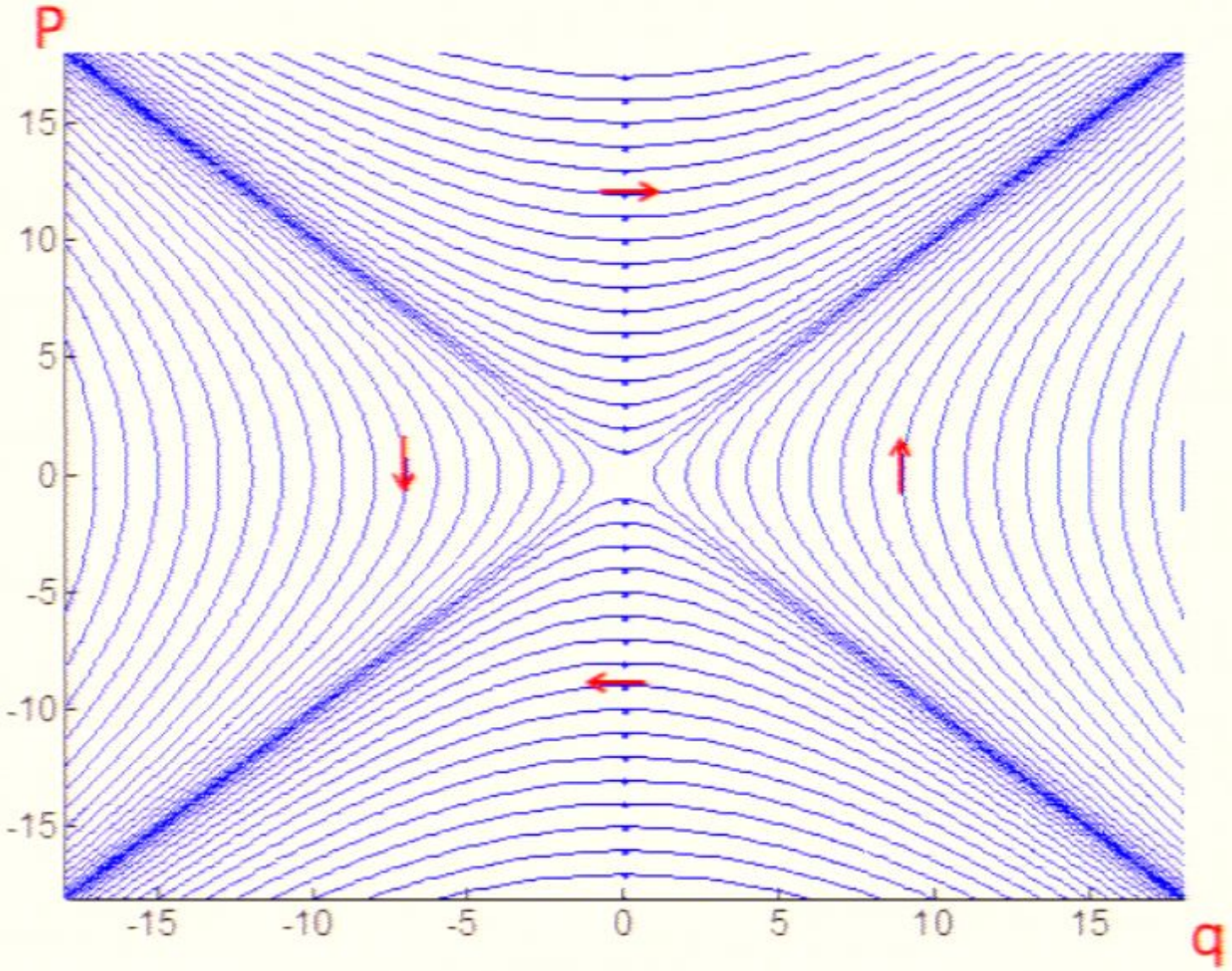
v) No one else cares about IC's

vi) Egm exception

vii) No entitlement to large initial ρ in meta picture

B Finite as Infinite

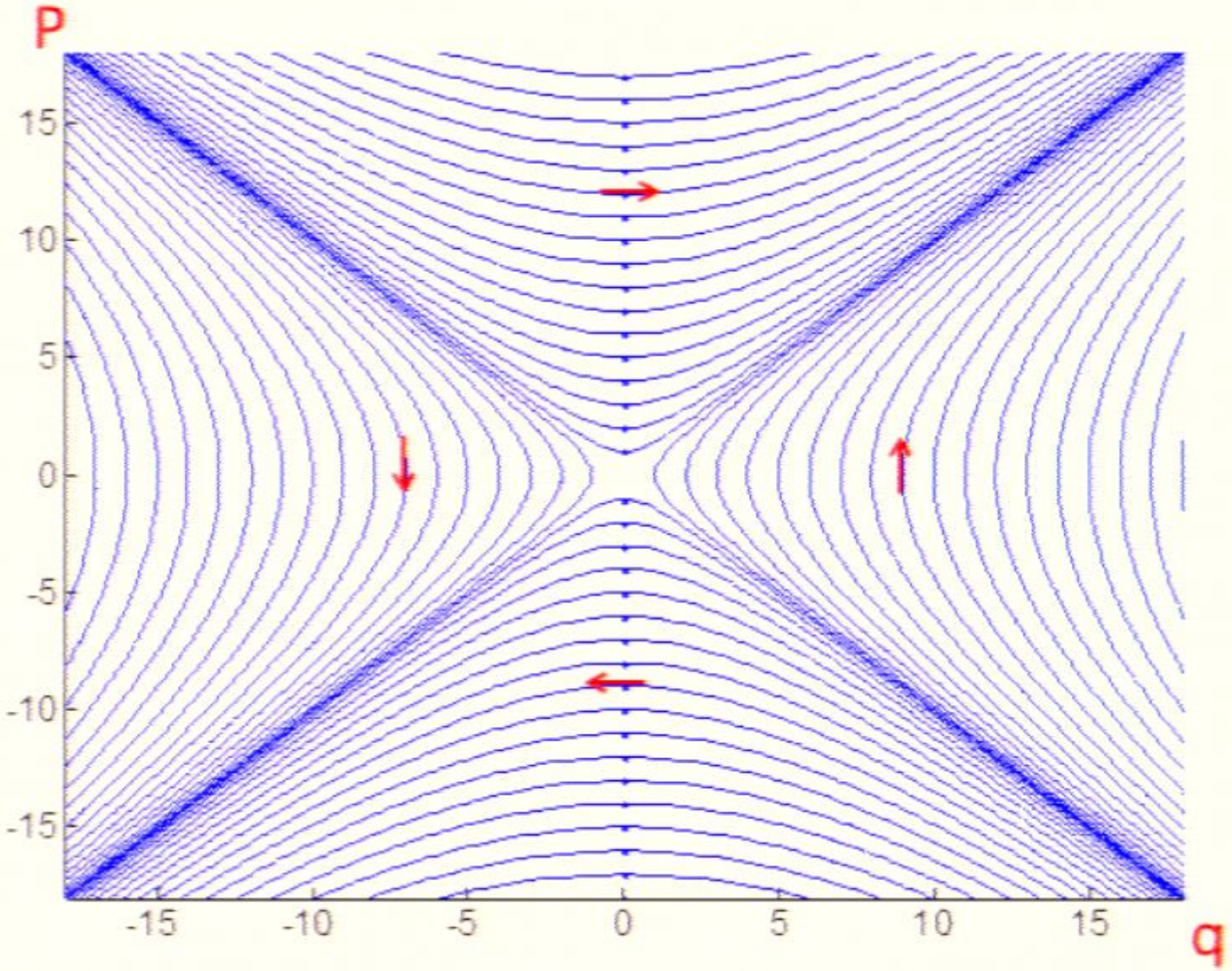
Phase space trajectories of Upside-down Harmonic Oscillator

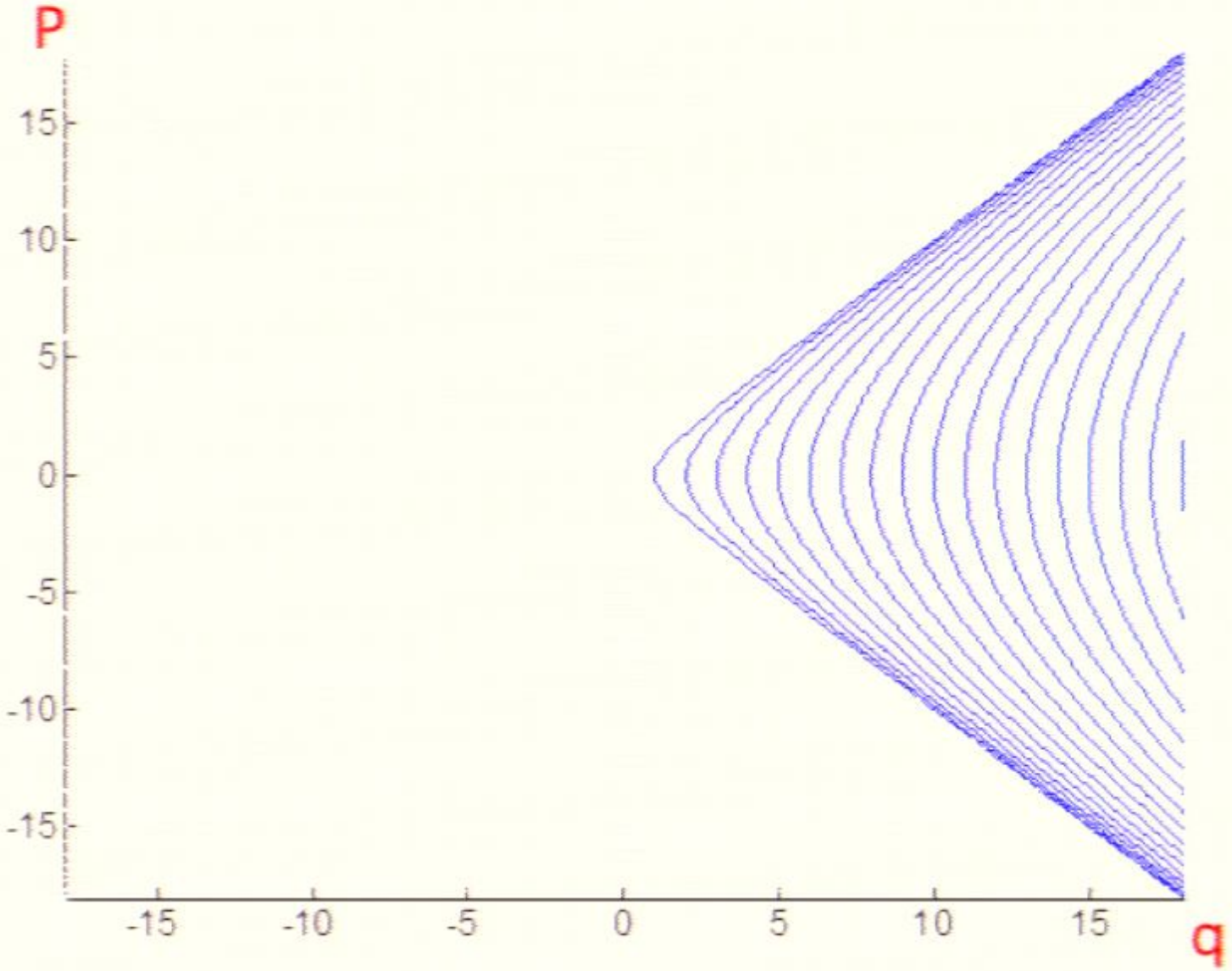


B Finite vs Infinite

USHO

Phase space trajectories of Upside-down Harmonic Oscillator




P
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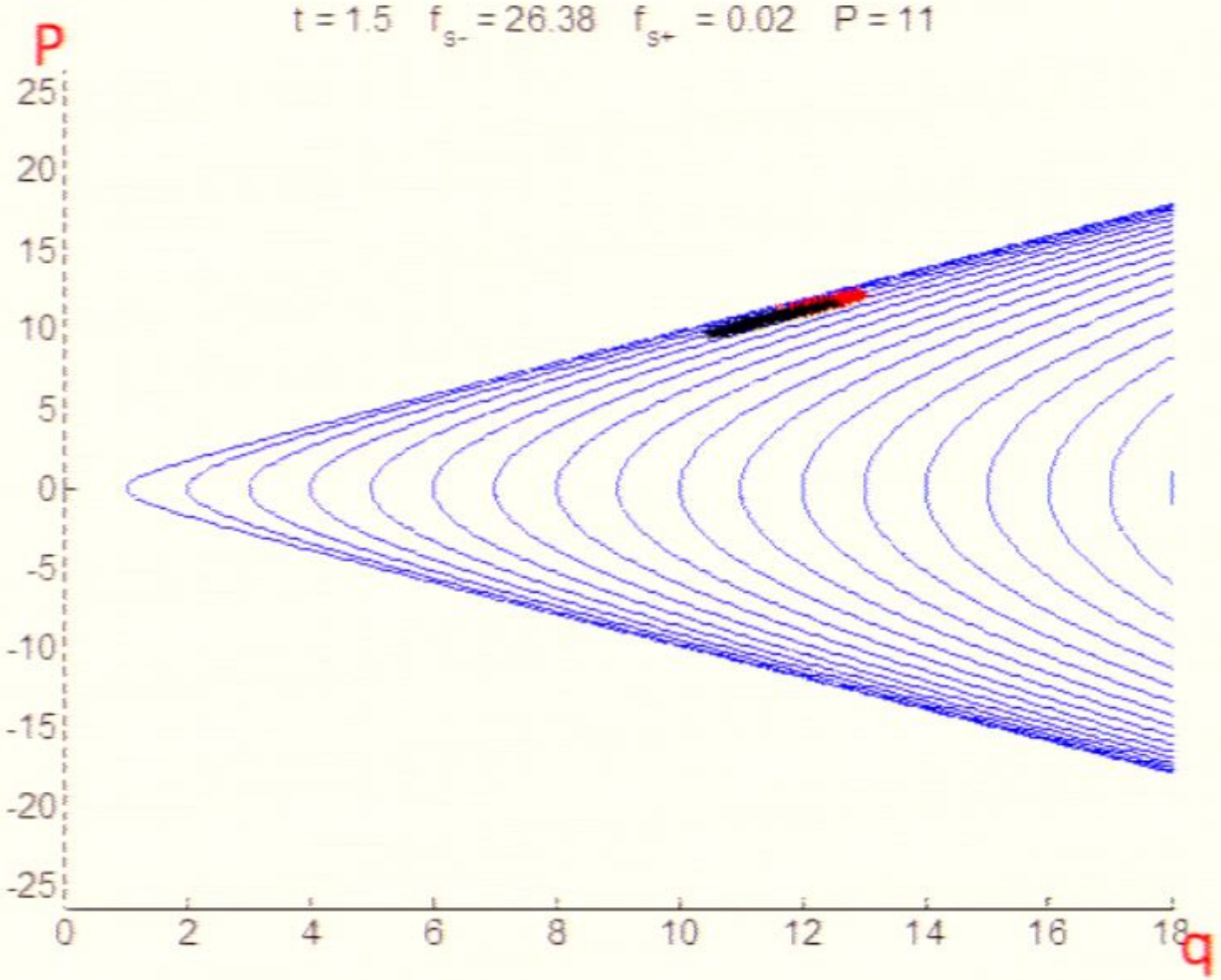
15
q


t = 1.5 f$_{s-}$ = 26.38 f$_{s+}$ = 0.02 P = 11
P
25
20
15
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-25
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2
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6
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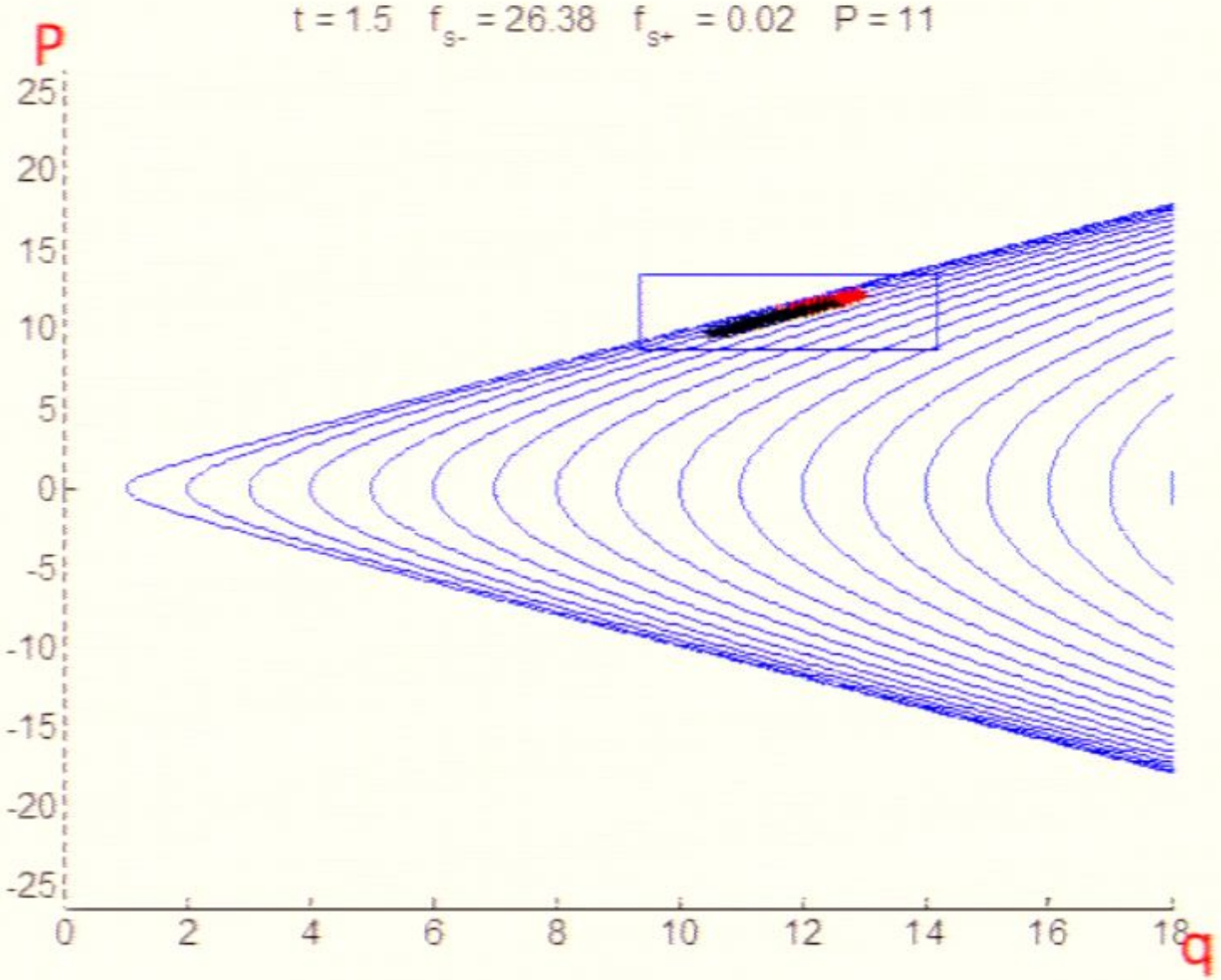
14
16
18
q


t = 1.5 f_{s-} = 26.38 f_{s+} = 0.02 P = 11
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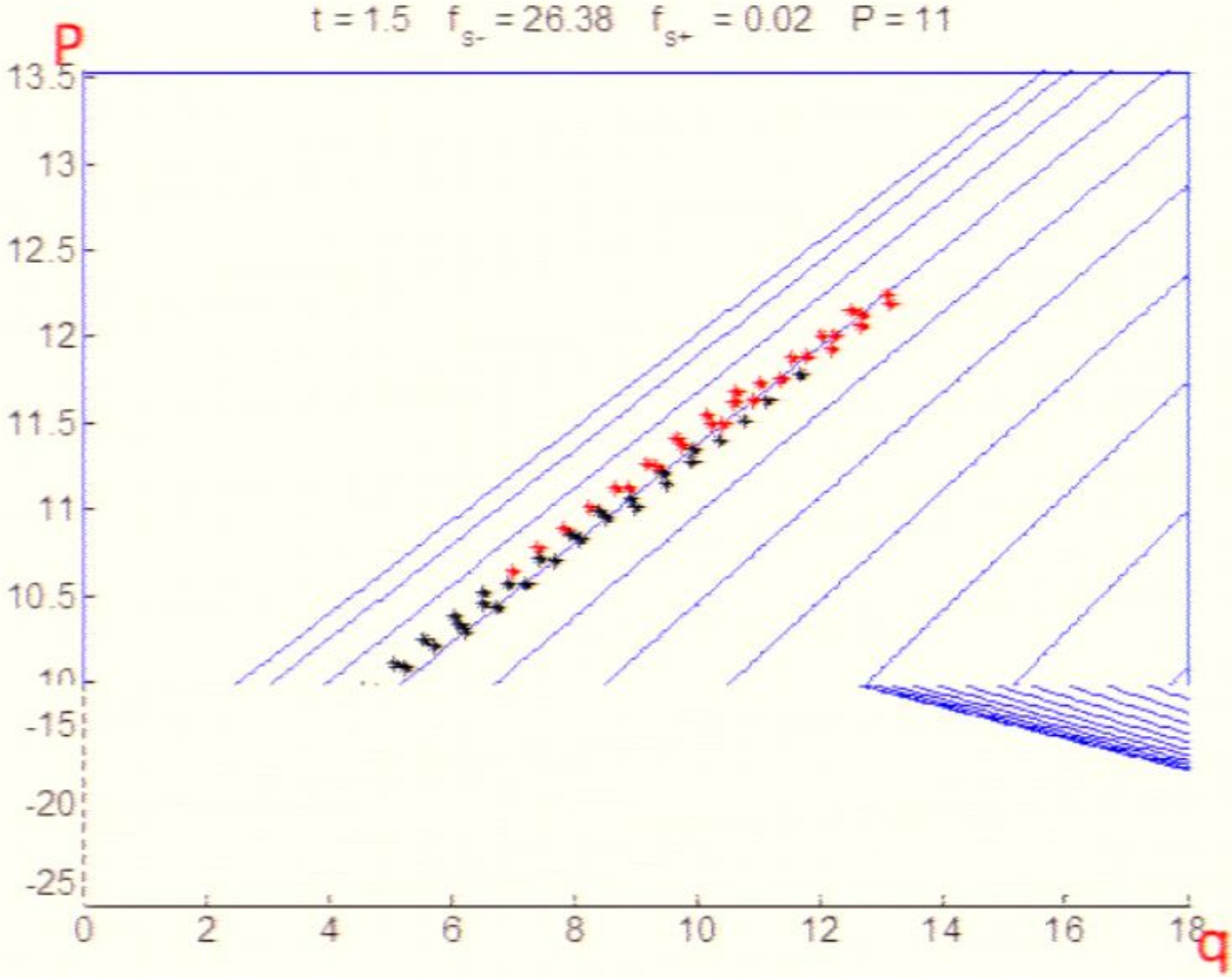
t = 1.5 f$_{s-}$ = 26.38 f$_{s+}$ = 0.02 P = 11
P
13.5
13
12.5
12
11.5
11
10.5
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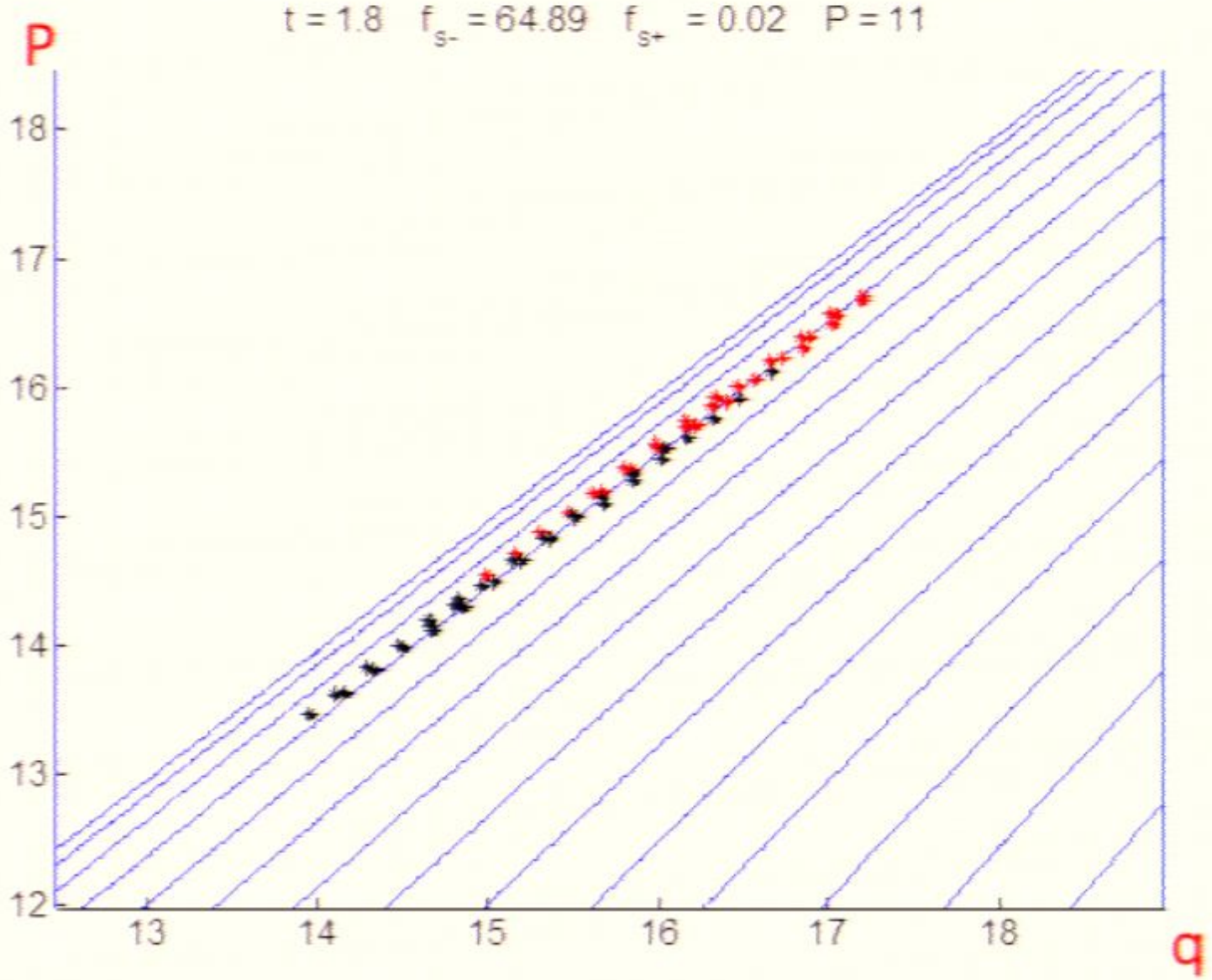
t = 1.8 f$_{s-}$ = 64.89 f$_{s+}$ = 0.02 P = 11
P
18
17
16
15
14
13
12
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14
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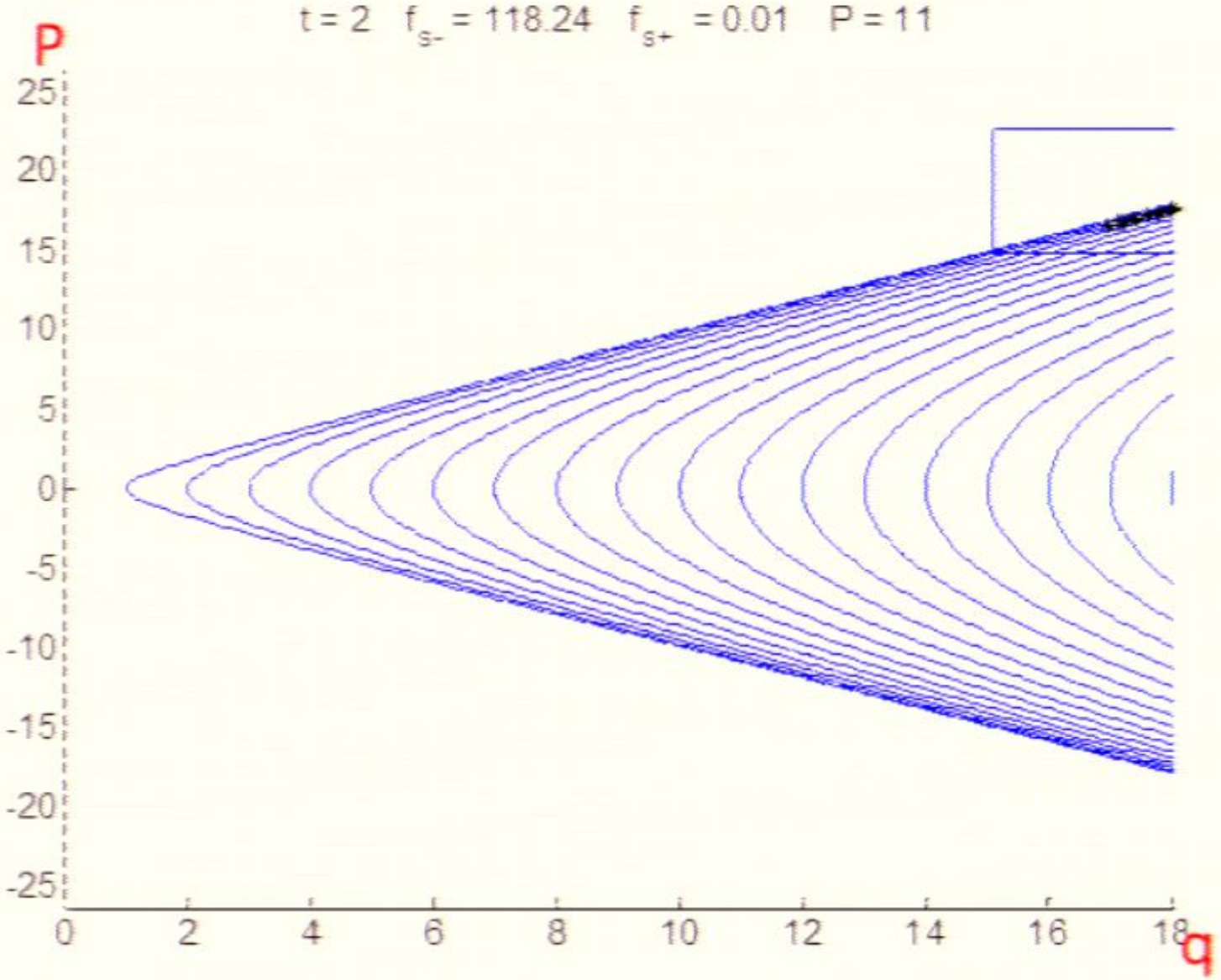
16
17
18
q


t = 2 f$_{s-}$ = 118.24 f$_{s+}$ = 0.01 P = 11
P
25
20
15
10
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-20
-25
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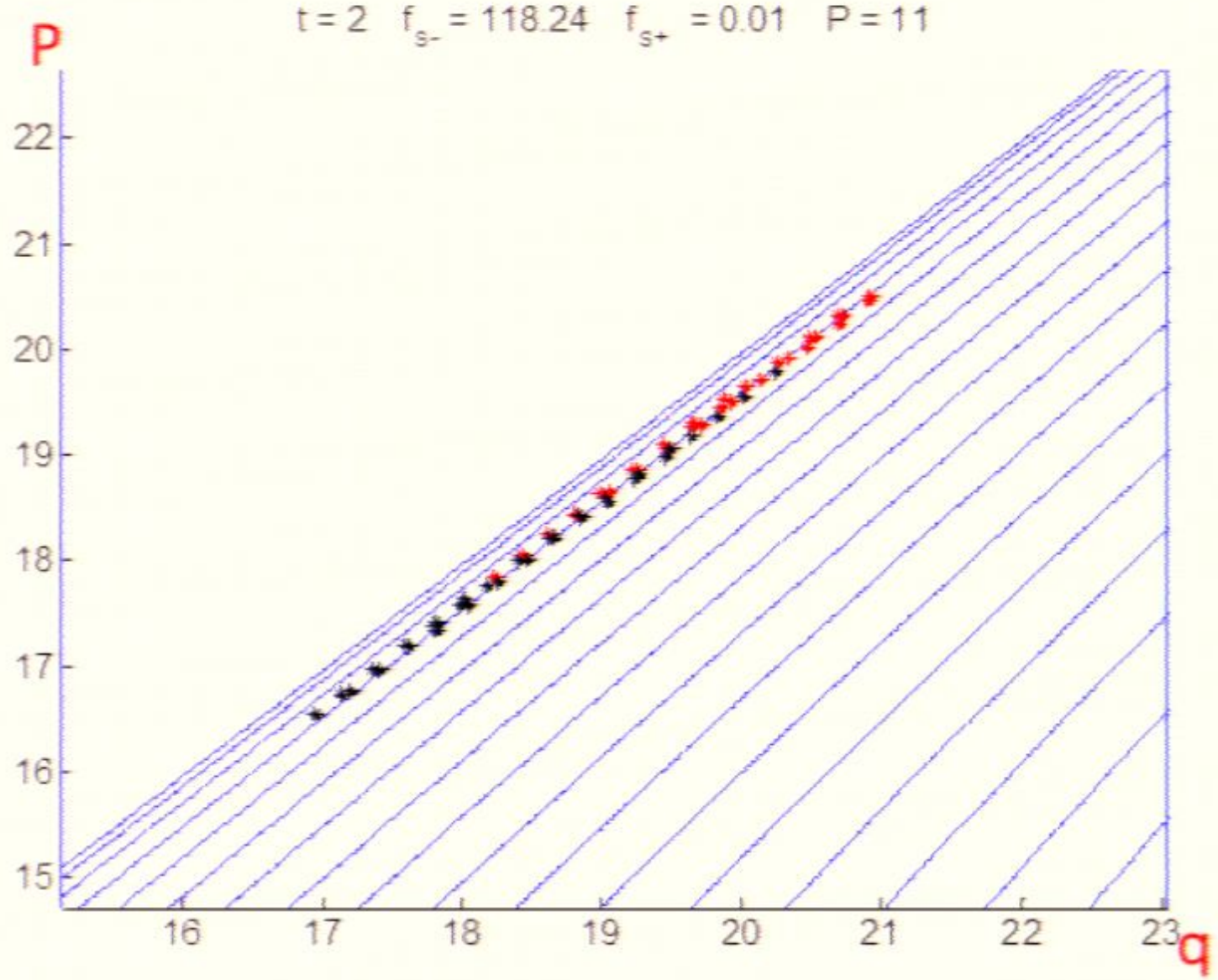
t = 2 f_{s-} = 118.24 f_{s+} = 0.01 P = 11
P
22
21
20
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18
19
20
21
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23
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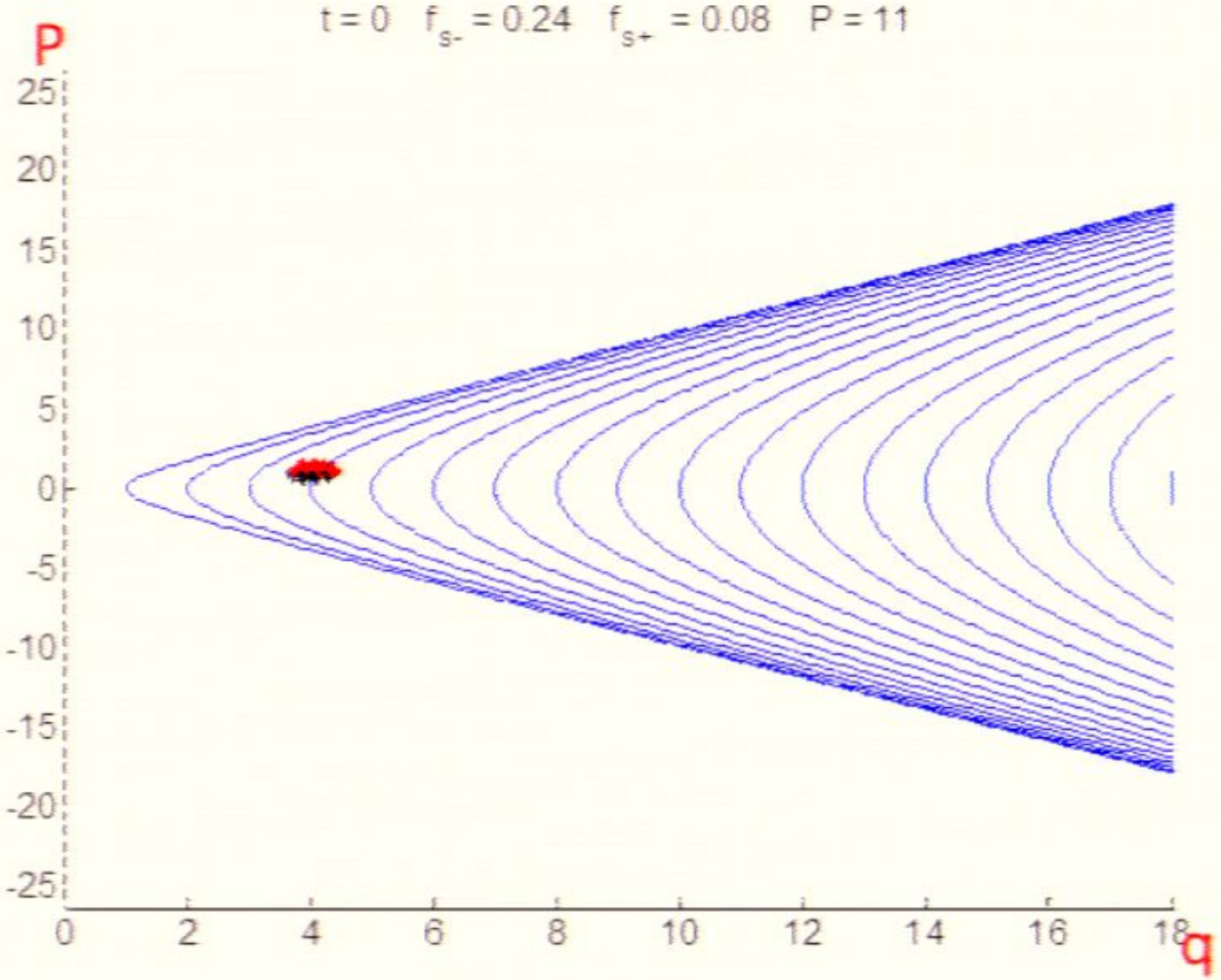
t = 0 f_{s-} = 0.24 f_{s+} = 0.08 P = 11
P
25
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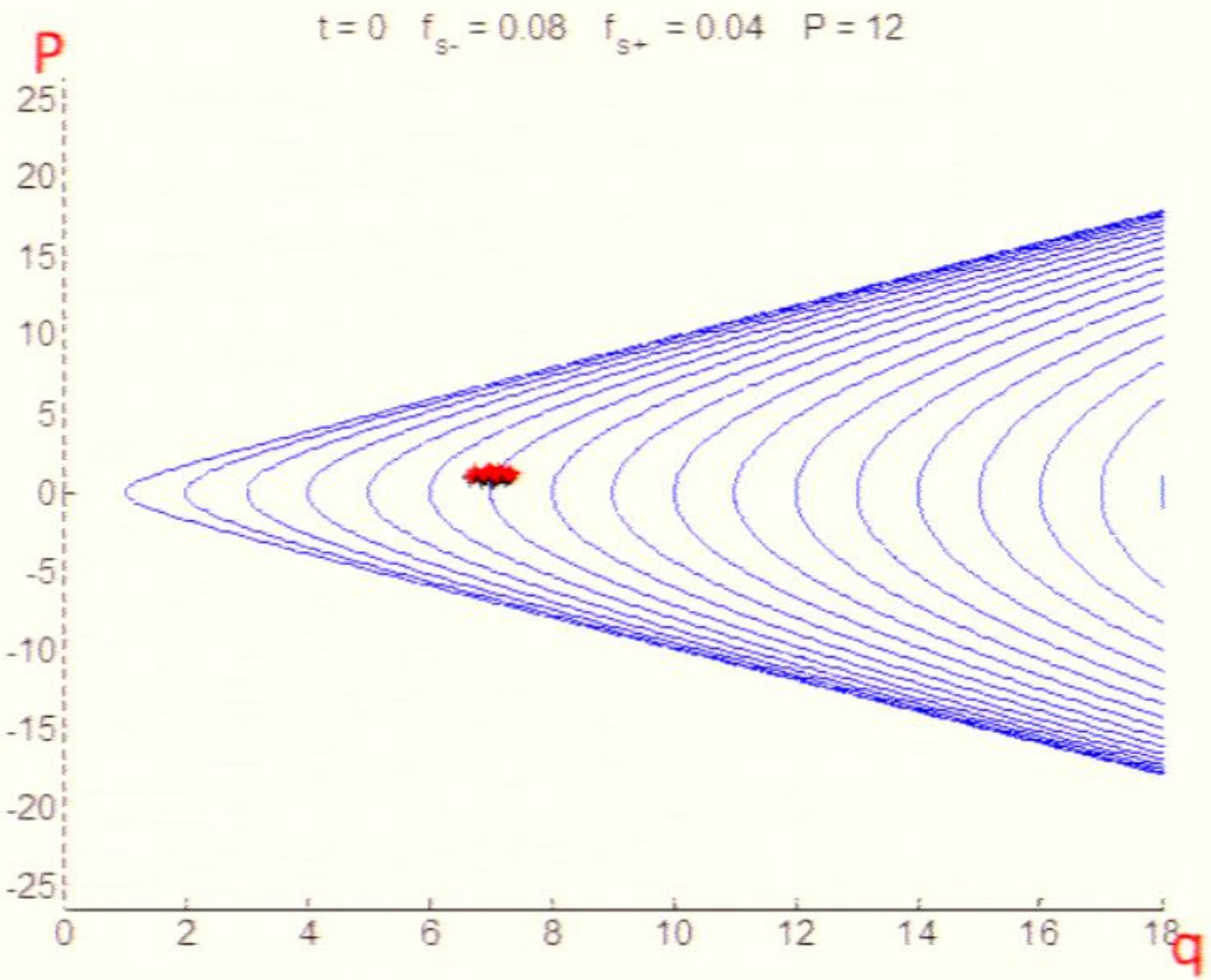
t = 0 f$_{s-}$ = 0.08 f$_{s+}$ = 0.04 P = 12
P
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-20
-25
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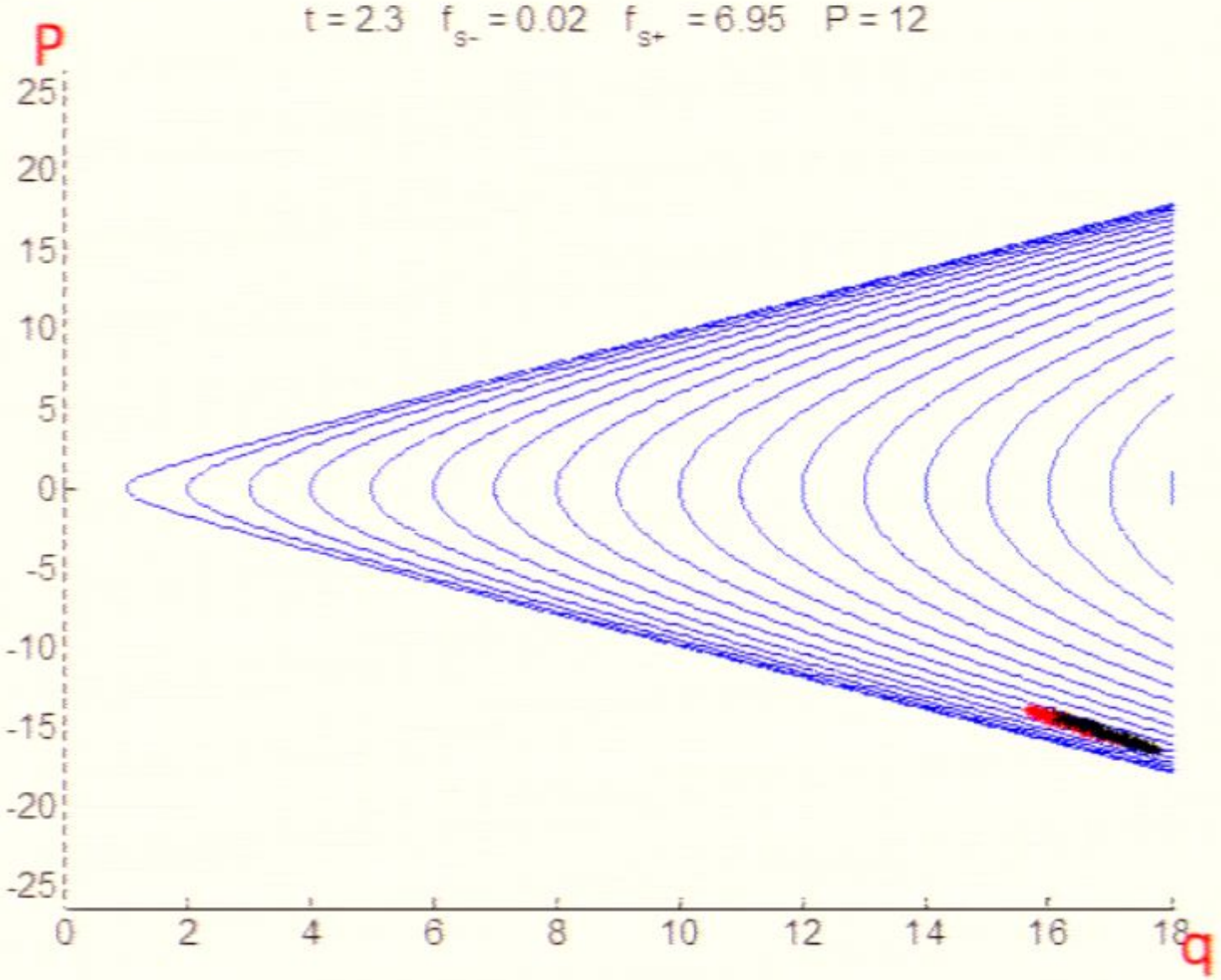
t = 2.3 f$_{s-}$ = 0.02 f$_{s+}$ = 6.95 P = 12
P
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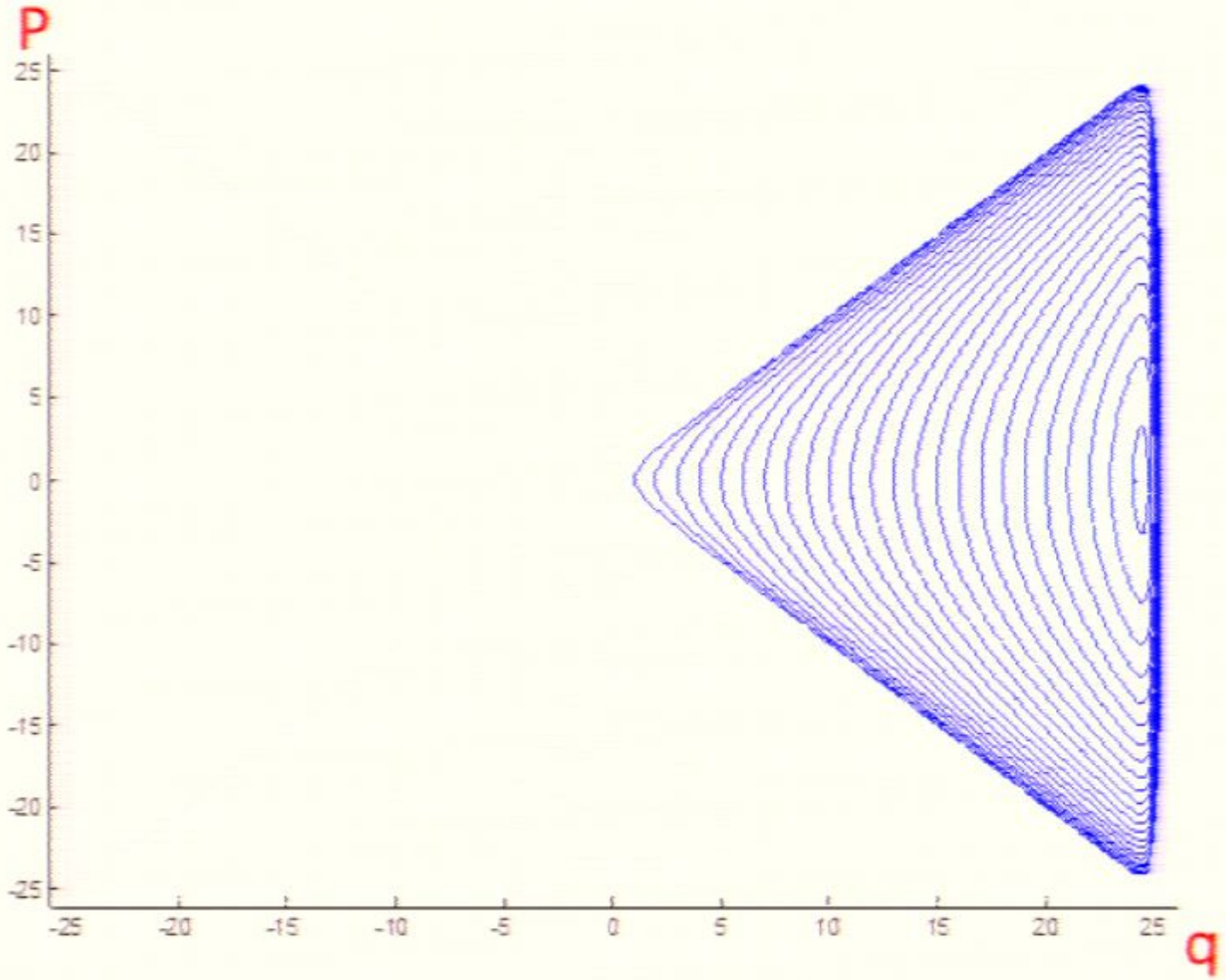
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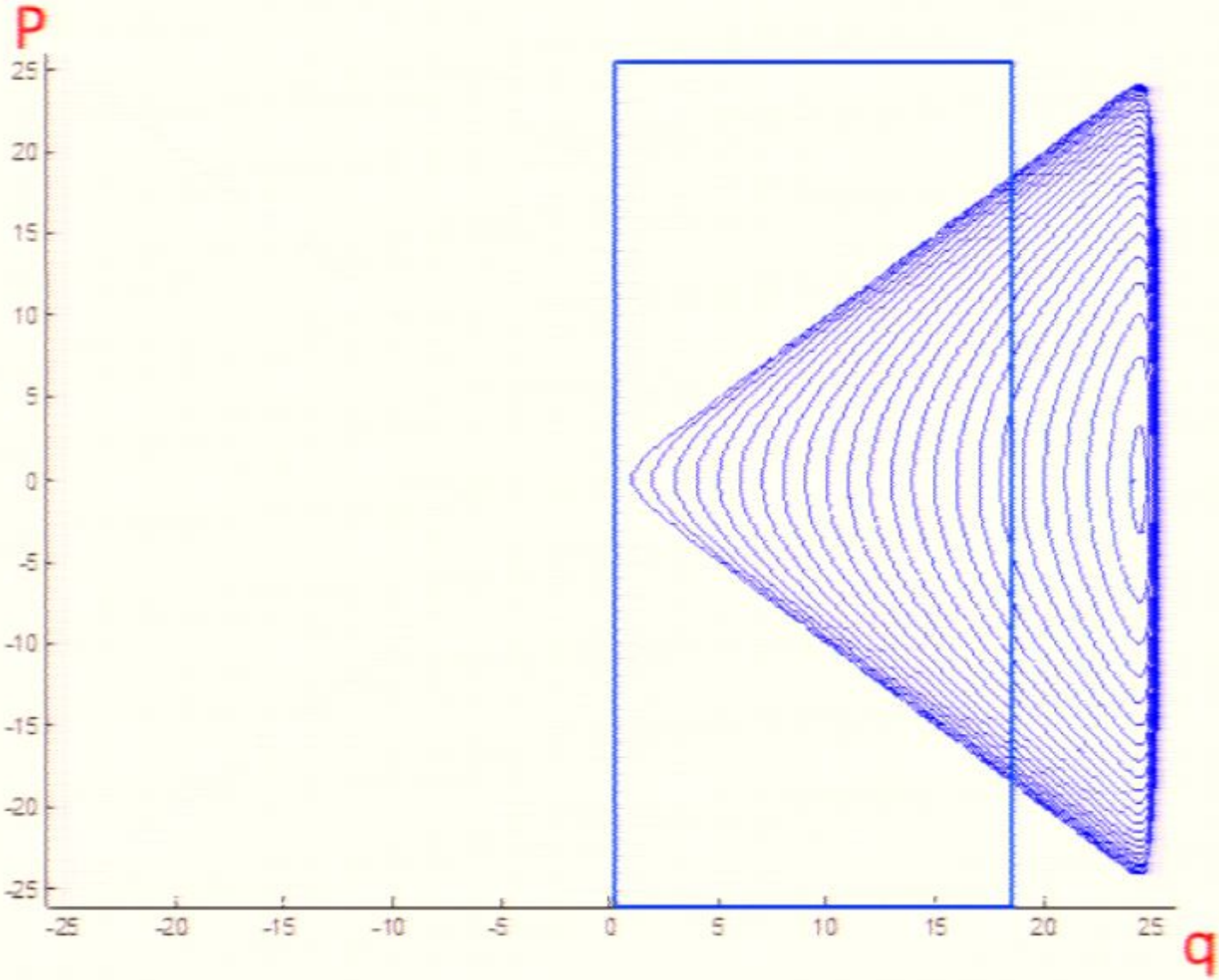
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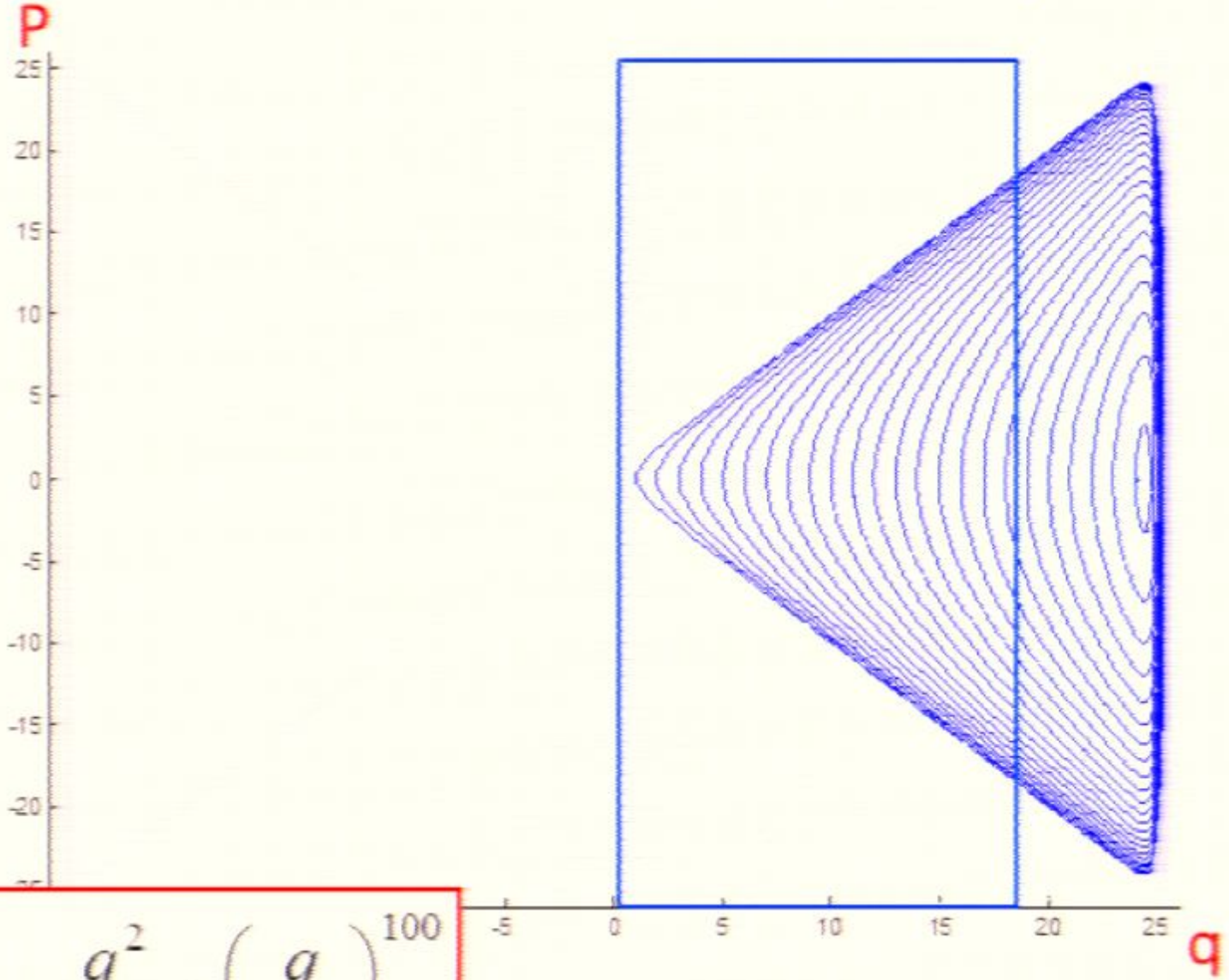
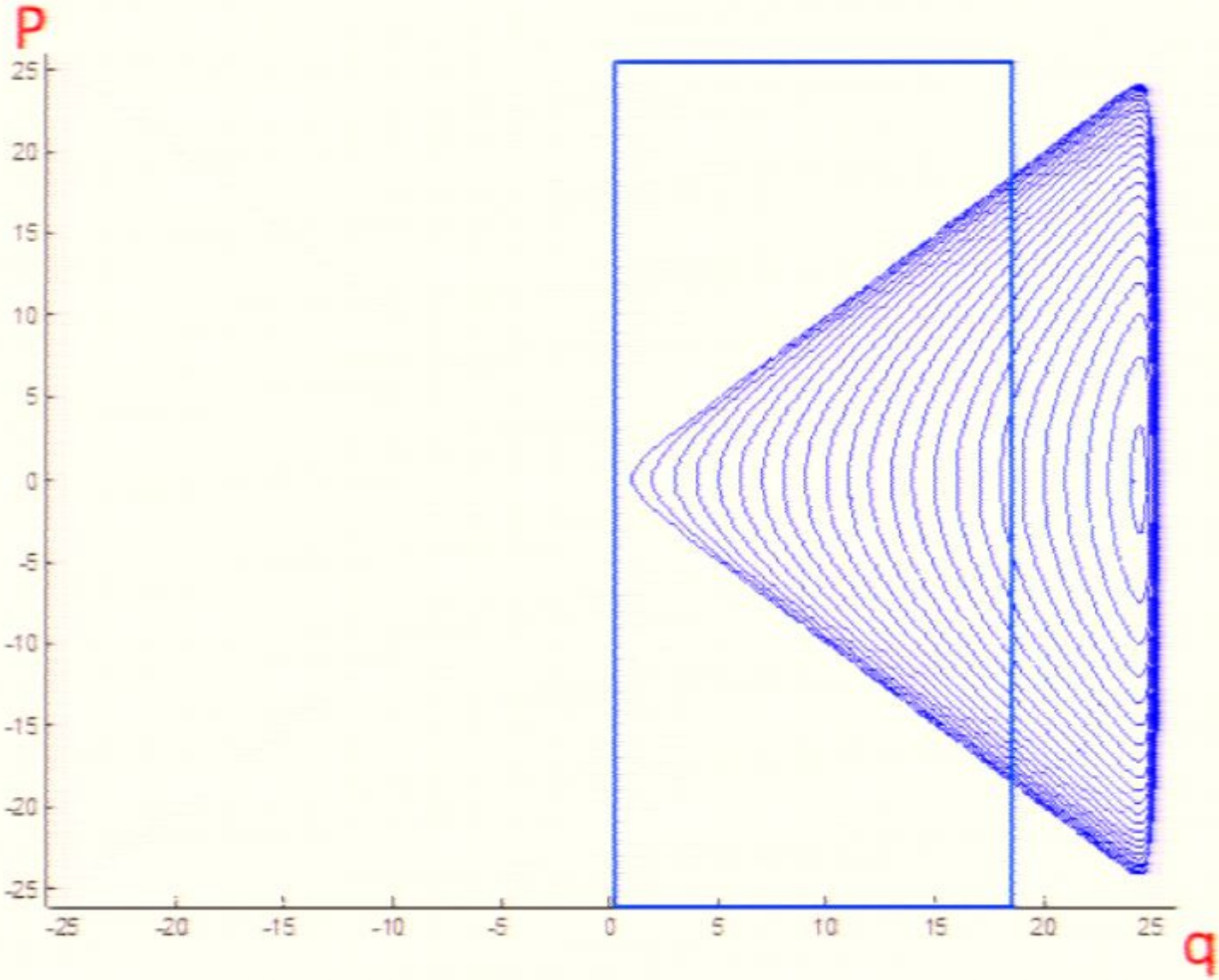
I've put a barrier in the USHO to make a finite system



$$V(q) \to -\frac{q^2}{2} + \left(\frac{q}{24}\right)^{100}$$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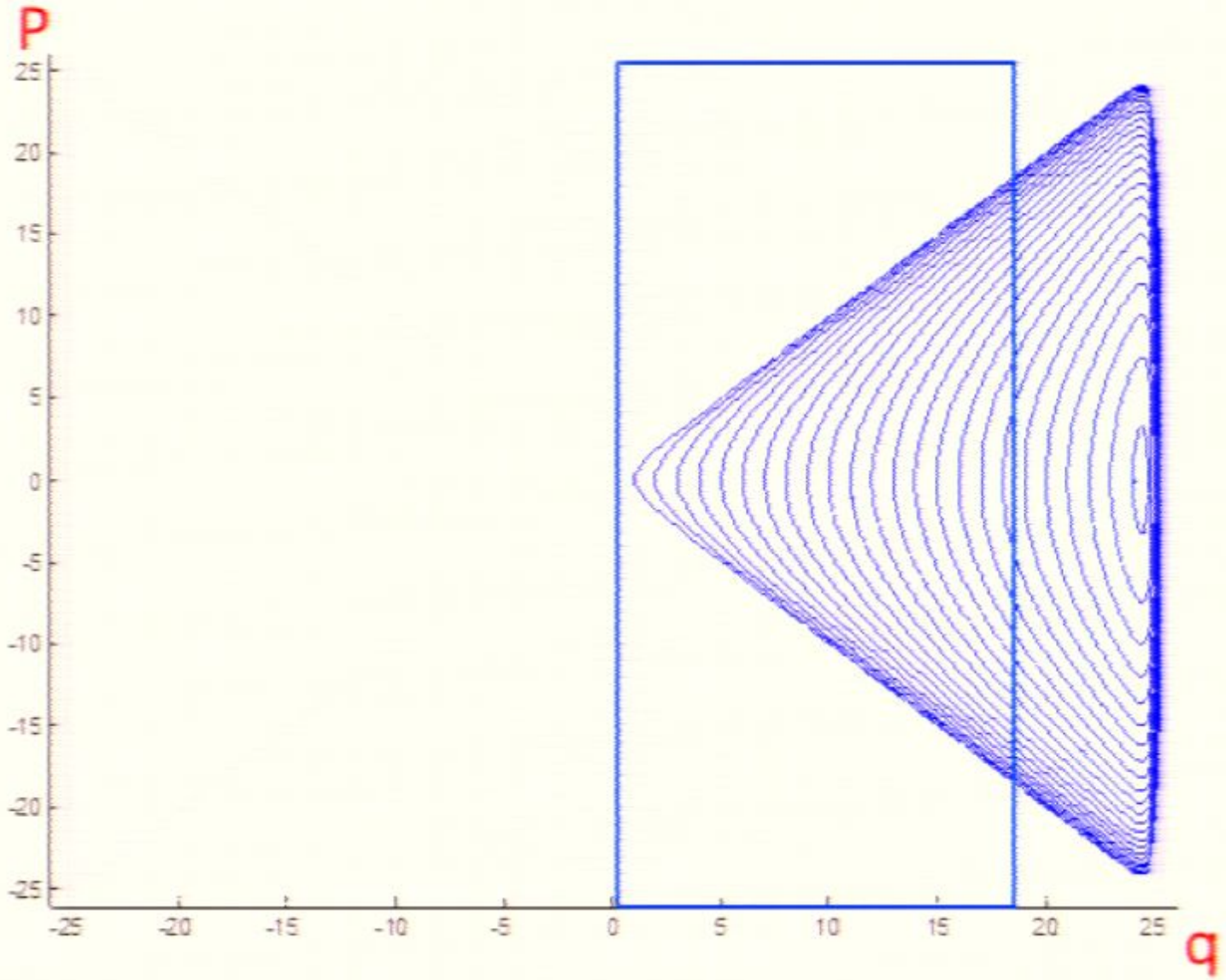
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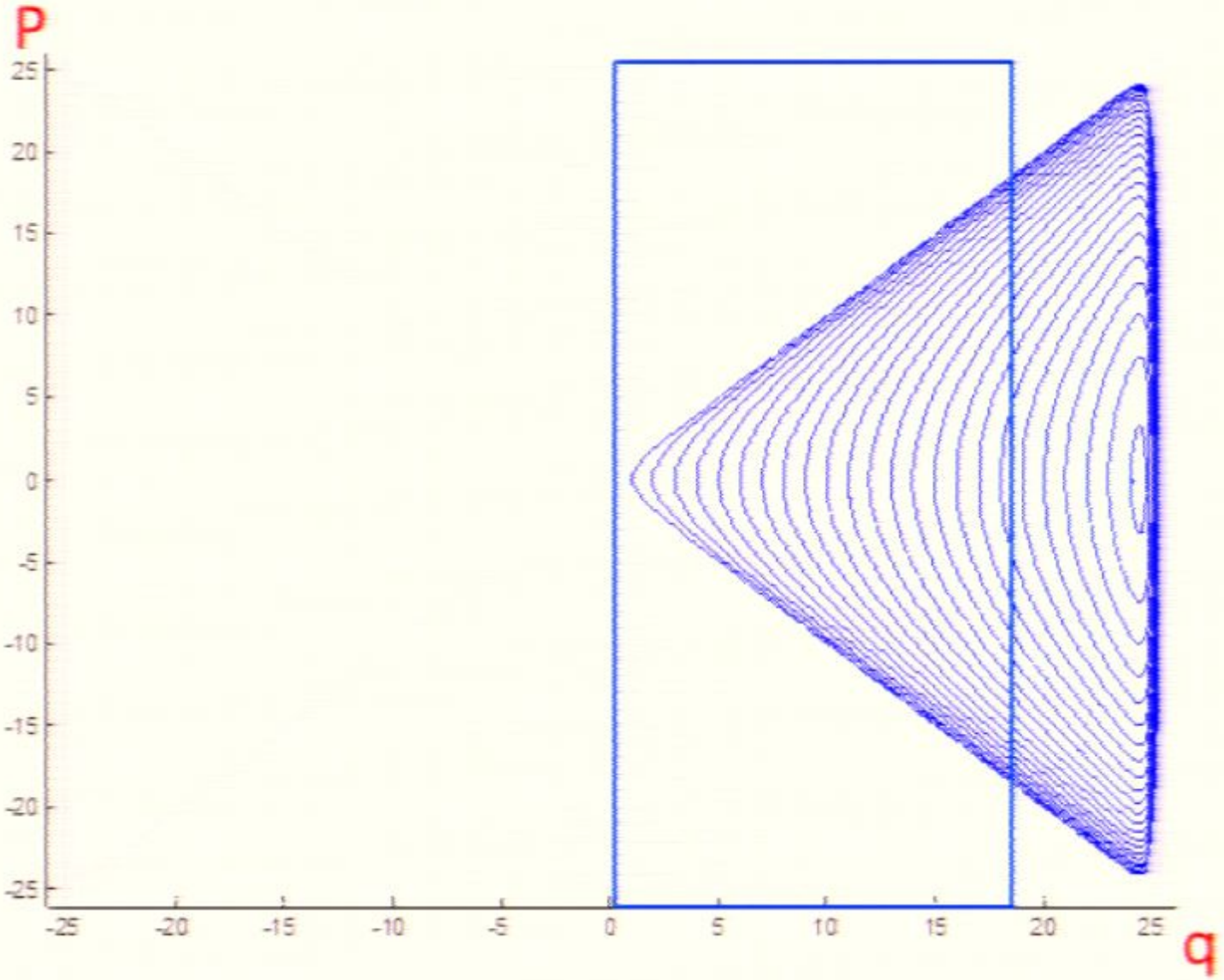
P
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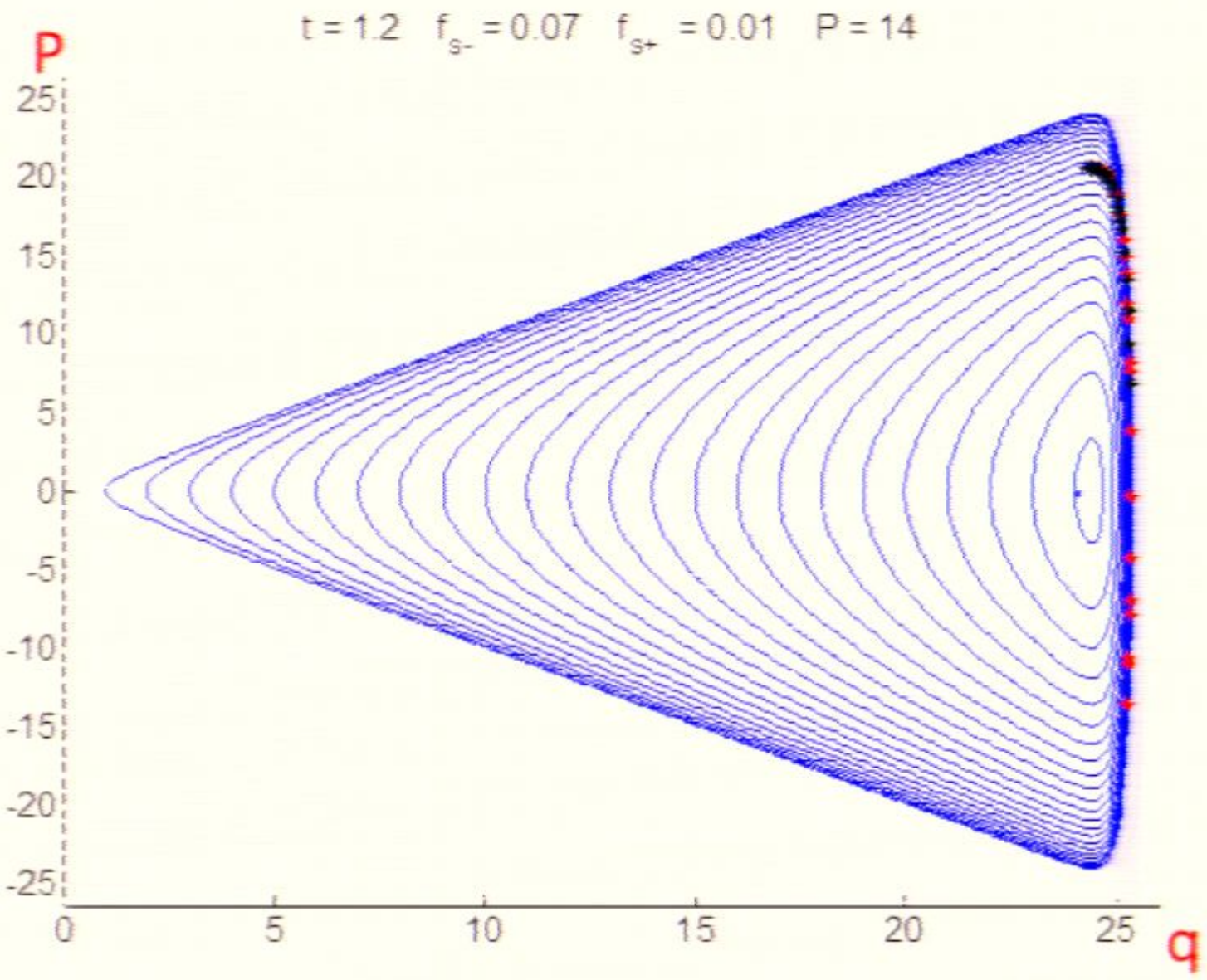
25
q

B Finite vs Infinite

USHO

$$V = -\frac{q^2}{2} + \left(\frac{q^4}{24}\right)^{100}$$


t = 1.2 f$_{s-}$ = 0.07 f$_{s+}$ = 0.01 P = 14
P
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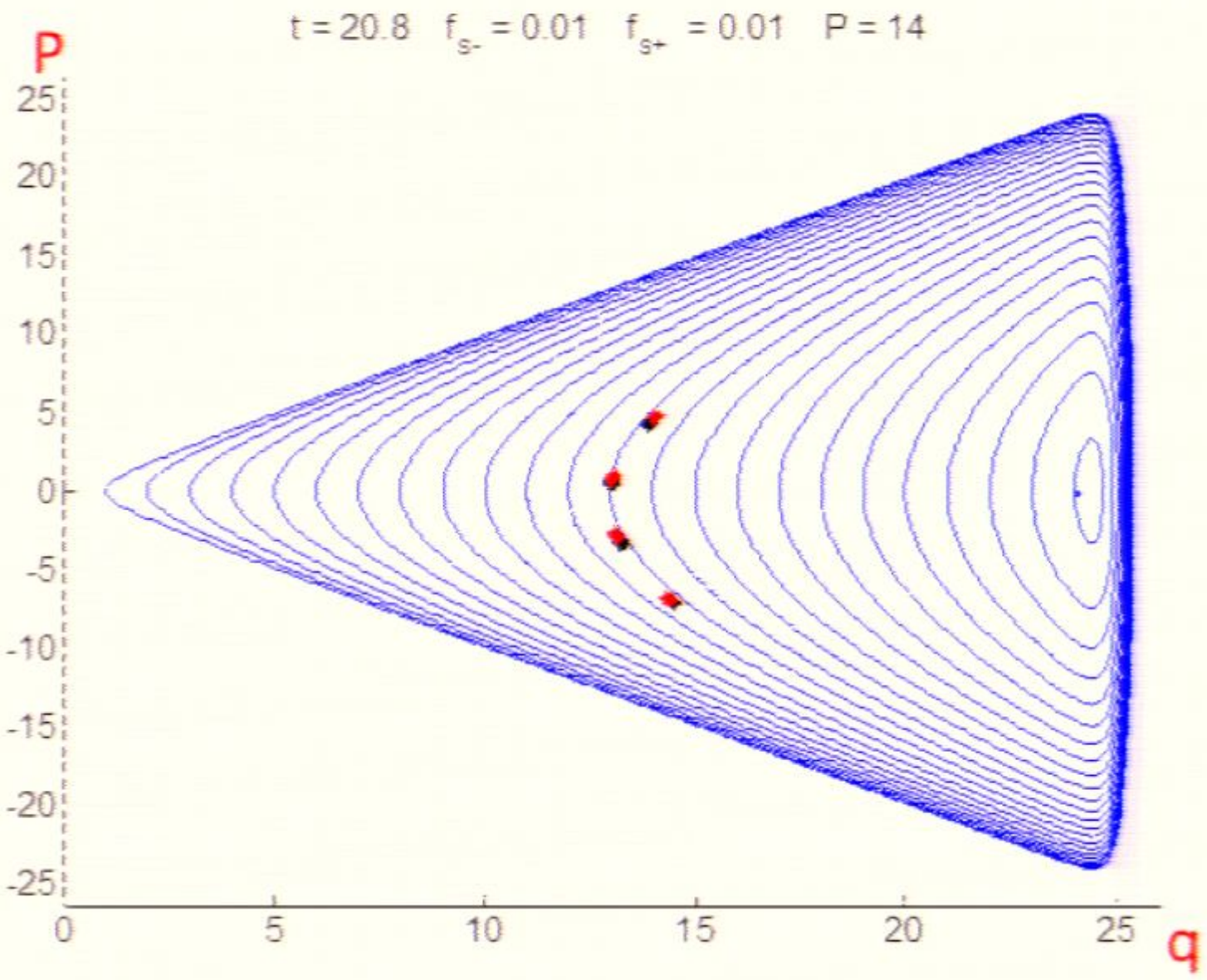
t = 20.8 f$_{s-}$ = 0.01 f$_{s+}$ = 0.01 P = 14
P
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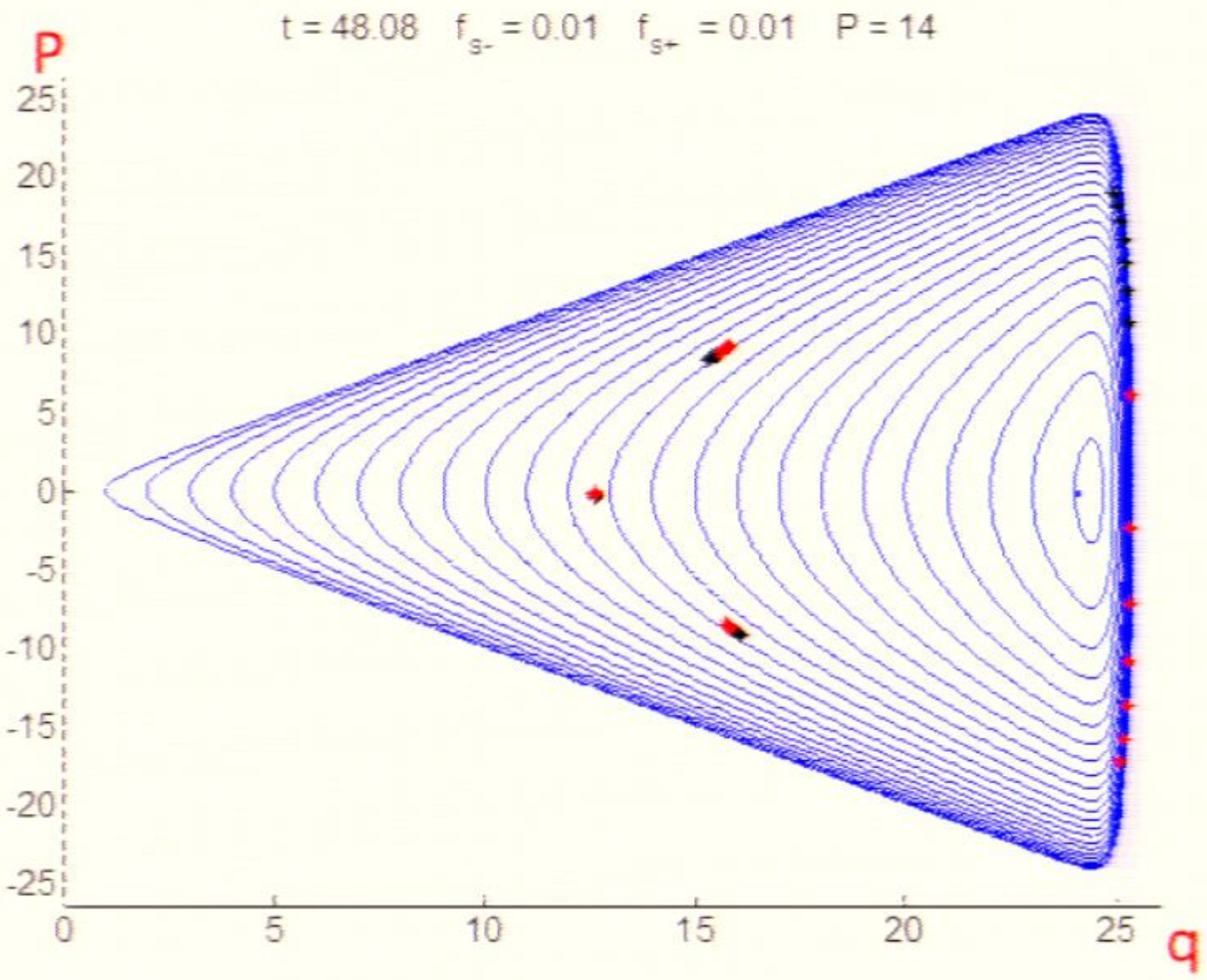
t = 48.08 f$_{s-}$ = 0.01 f$_{s+}$ = 0.01 P = 14
P
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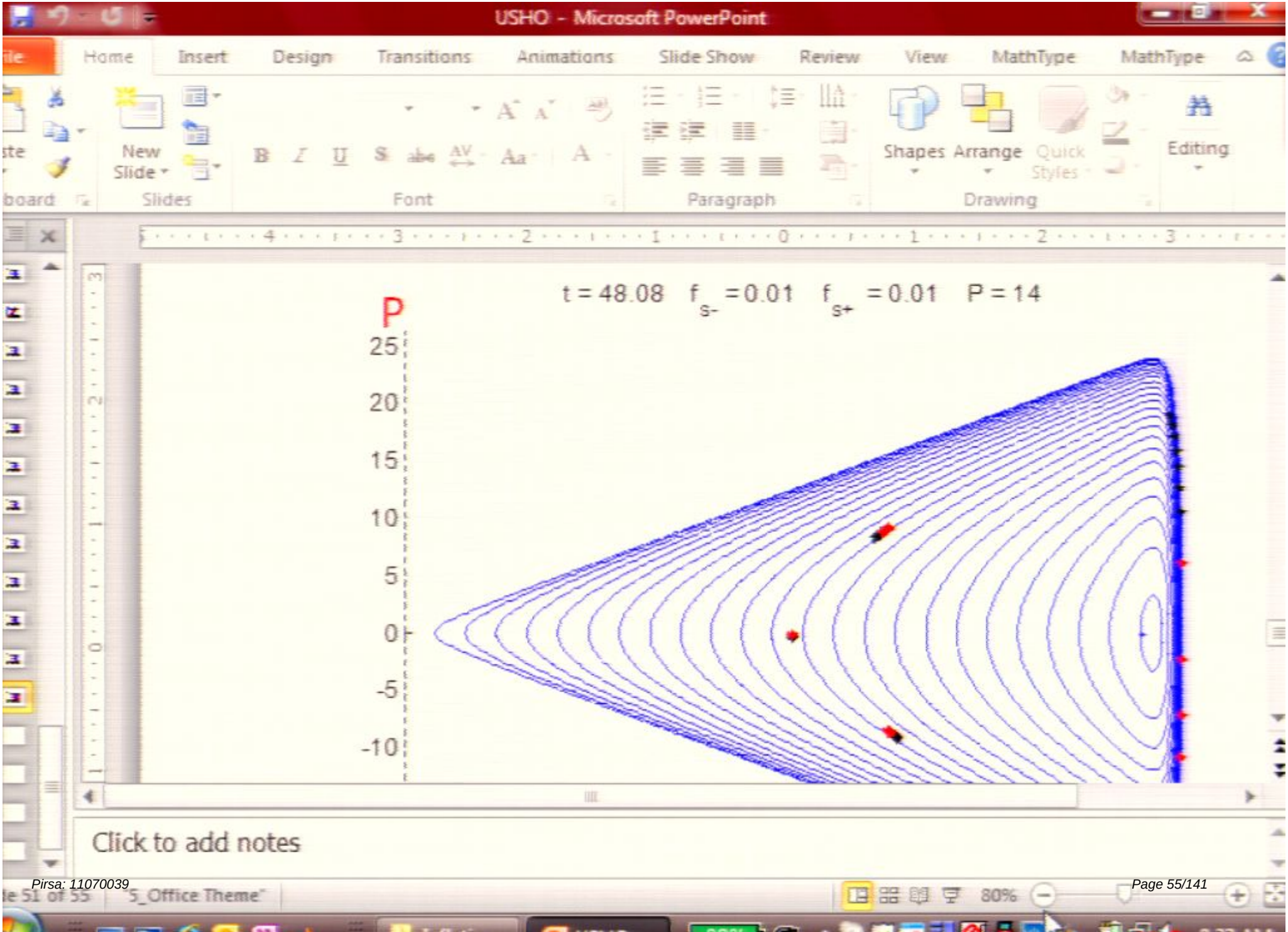
USHO - Microsoft PowerPoint
Home
Insert
Design
Transitions
Animations
Slide Show
Review
View
MathType
MathType
New Slide
Slides
Font
Paragraph
Shapes
Arrange
Quick Styles
Editing
Drawing
t = 48.08 f s- = 0.01 f s+ = 0.01 P = 14
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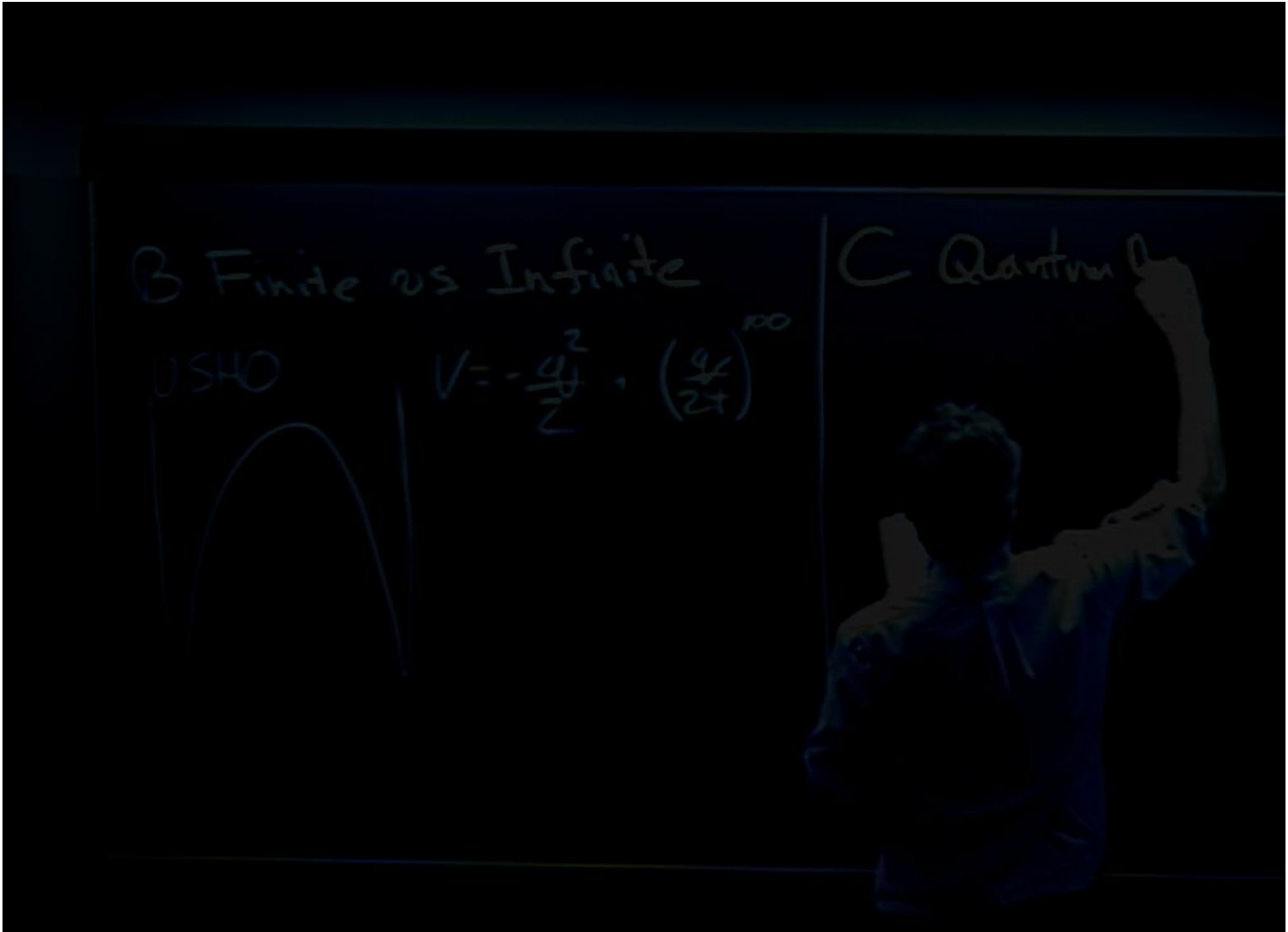
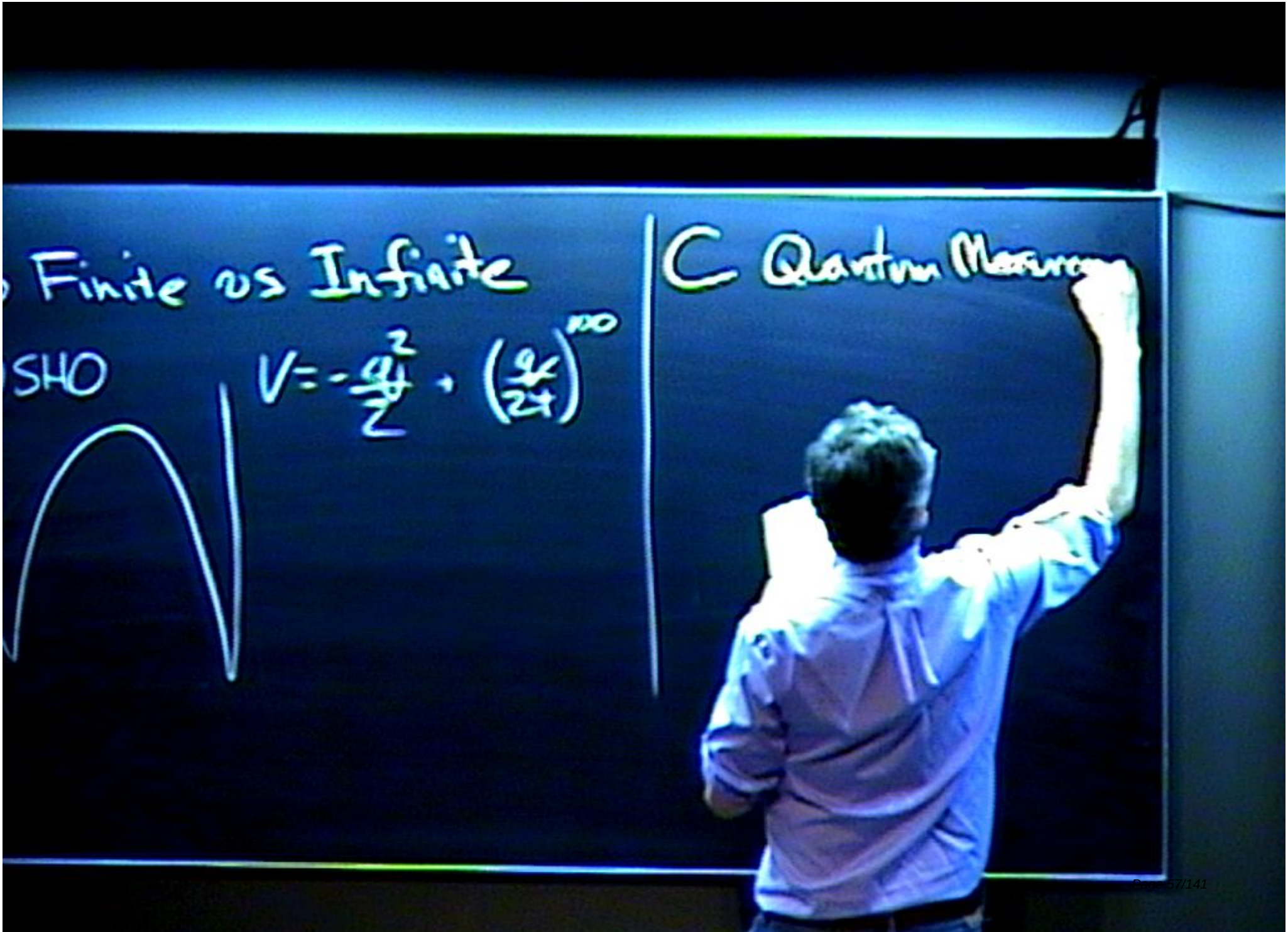
Click to add notes
80%


B Finite vs Infinite
USHO
$V = -\frac{q^2}{2} \cdot \left(\frac{q}{24}\right)^{100}$
C Quantum

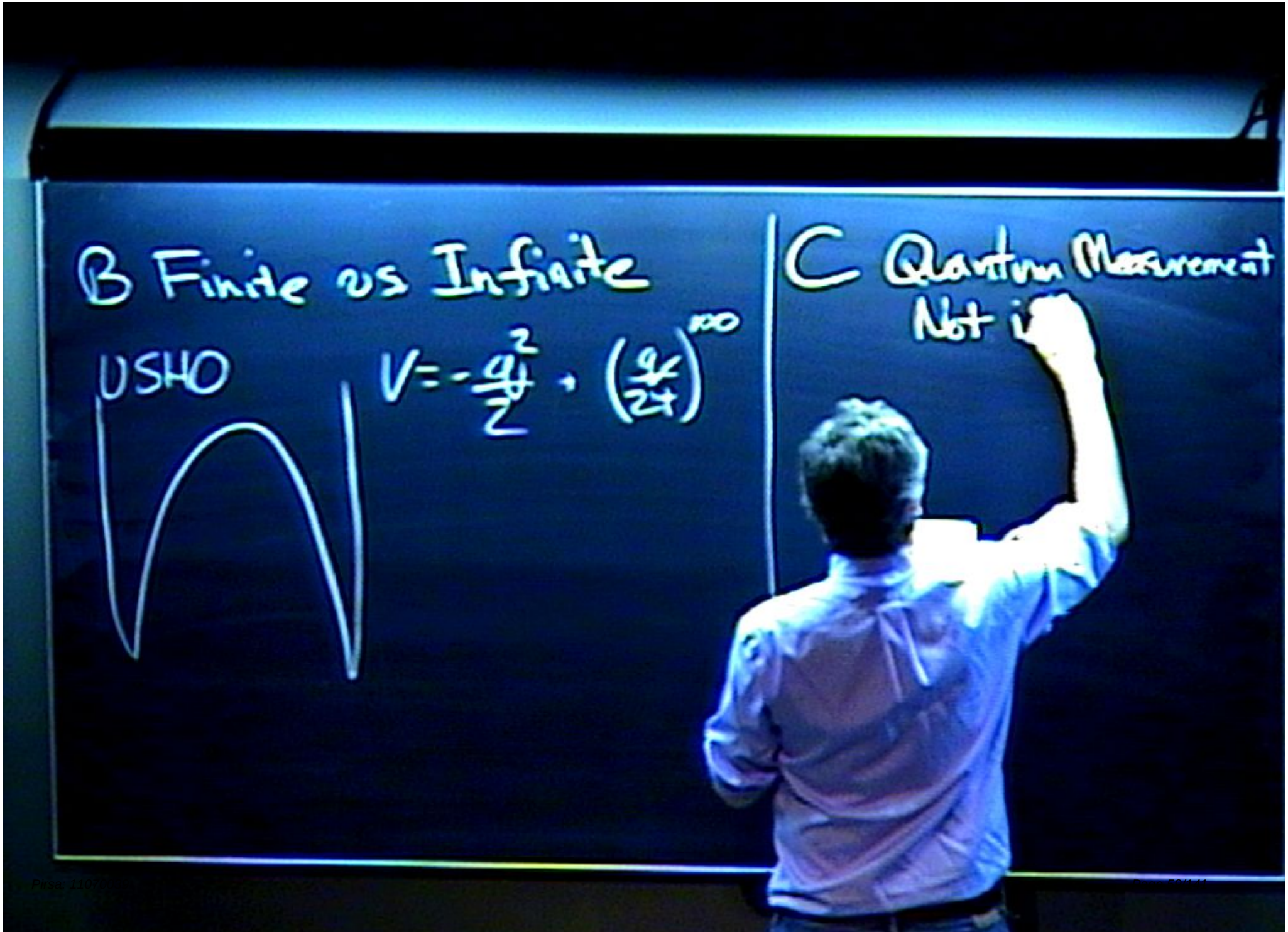

Finite vs Infinite
SHO
$V = -\frac{q^2}{2} + \left(\frac{q^4}{24}\right)^{100}$
C Quantum

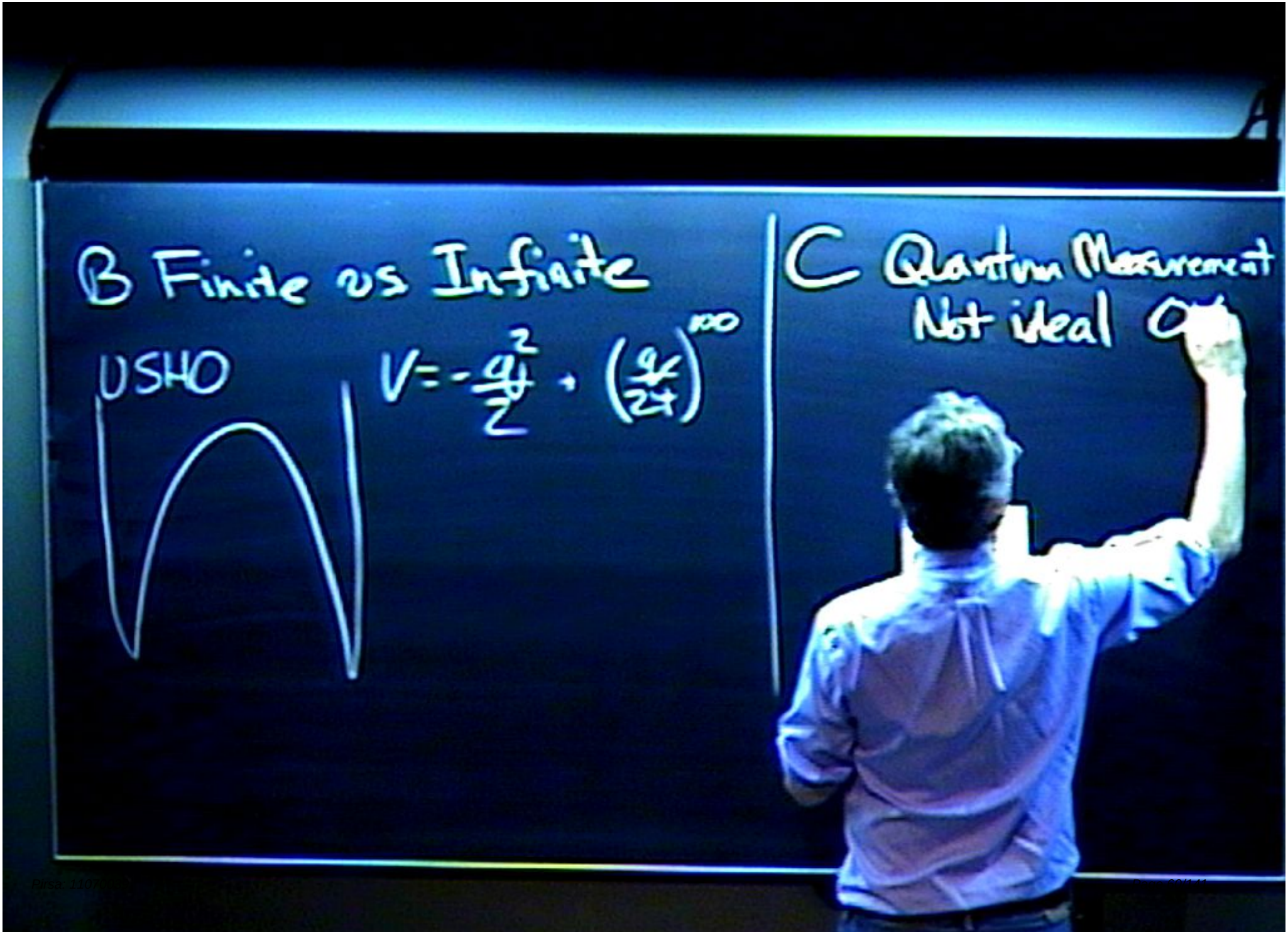
B Finite vs Infinite

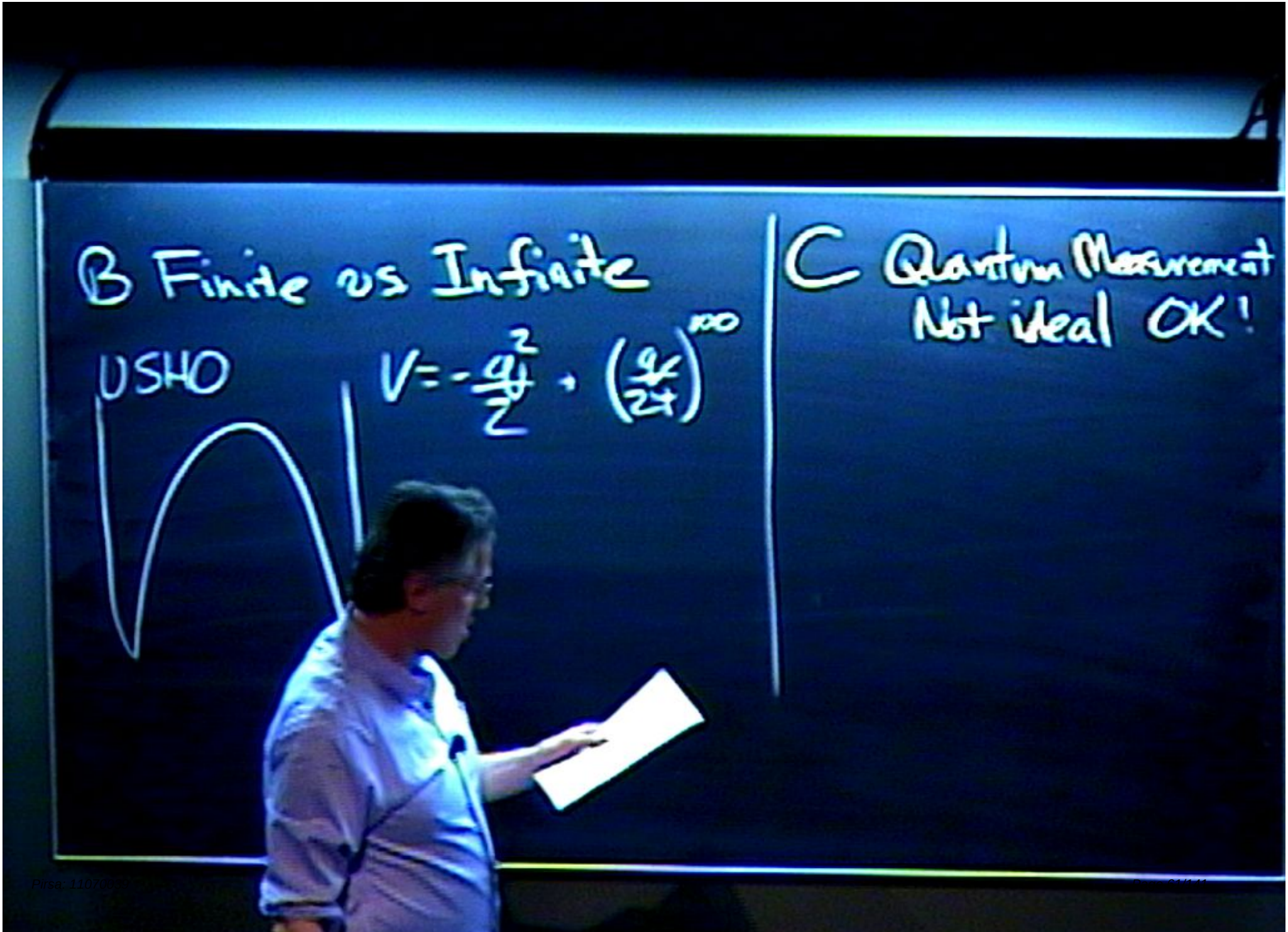
USHO

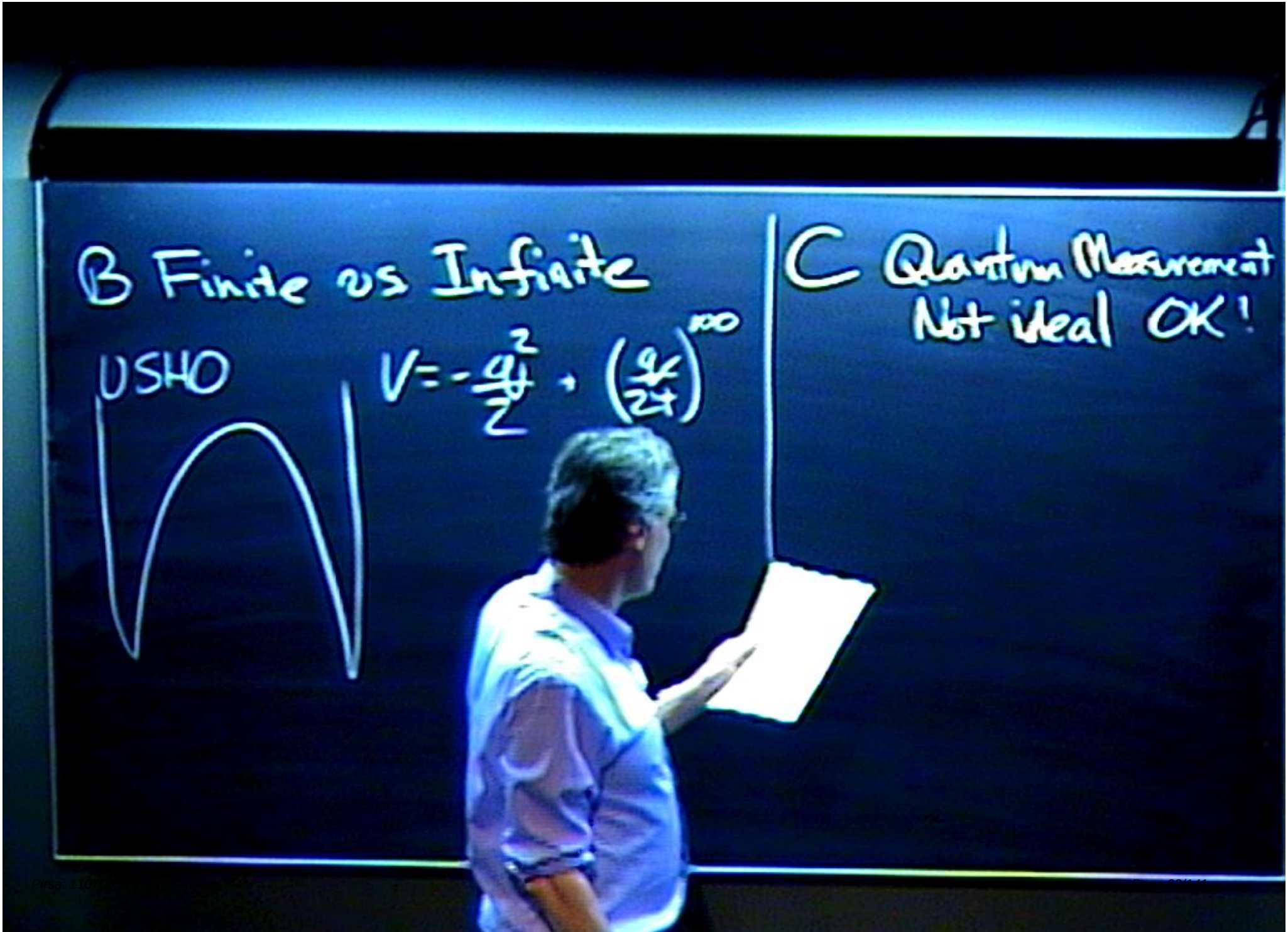
$V = -\frac{q^2}{2} + \left(\frac{q^4}{24}\right)^{100}$

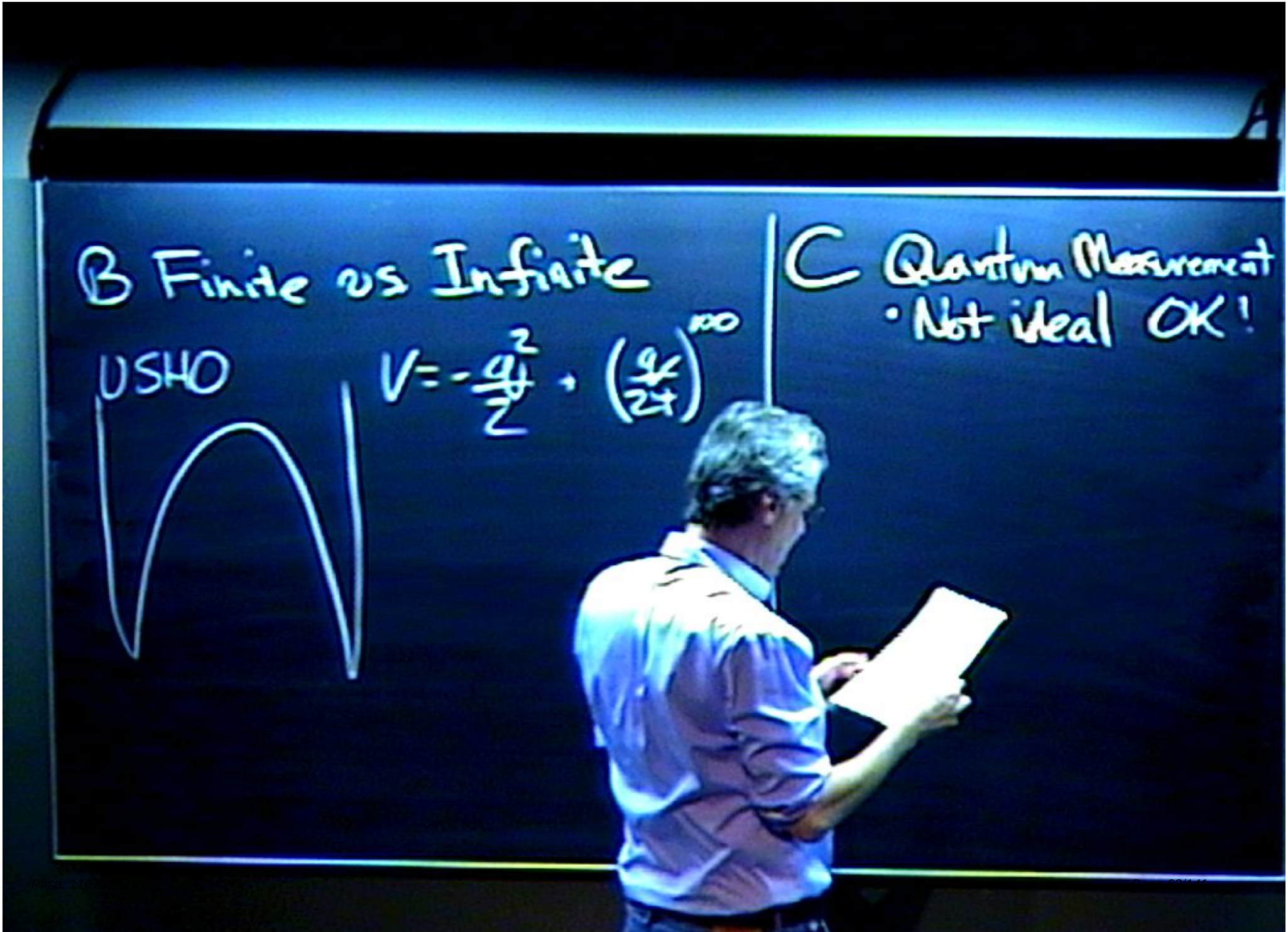
C Quantum Measurement


B Finite vs Infinite
USHO
$V = -\frac{q^2}{2} + \left(\frac{q^4}{24}\right)^{\infty}$
C Quantum Measurement
Not i


B Finite vs Infinite
USHO
$V = -\frac{q^2}{2} \cdot \left(\frac{q}{24}\right)^{100}$
C Quantum Measurement
Not ideal


B Finite vs Infinite
USHO
$V = -\frac{q^2}{2} \cdot \left(\frac{q}{24}\right)^{\infty}$
C Quantum Measurement
Not ideal OK!


B Finite vs Infinite
USHO
$V = -\frac{q^2}{2} + \left(\frac{q}{24}\right)^{100}$
C Quantum Measurement
Not ideal OK!


B Finite vs Infinite
USHO
$V = -\frac{q^2}{2} + \left(\frac{q^4}{24}\right)^{\infty}$
C Quantum Measurement
• Not ideal OK!

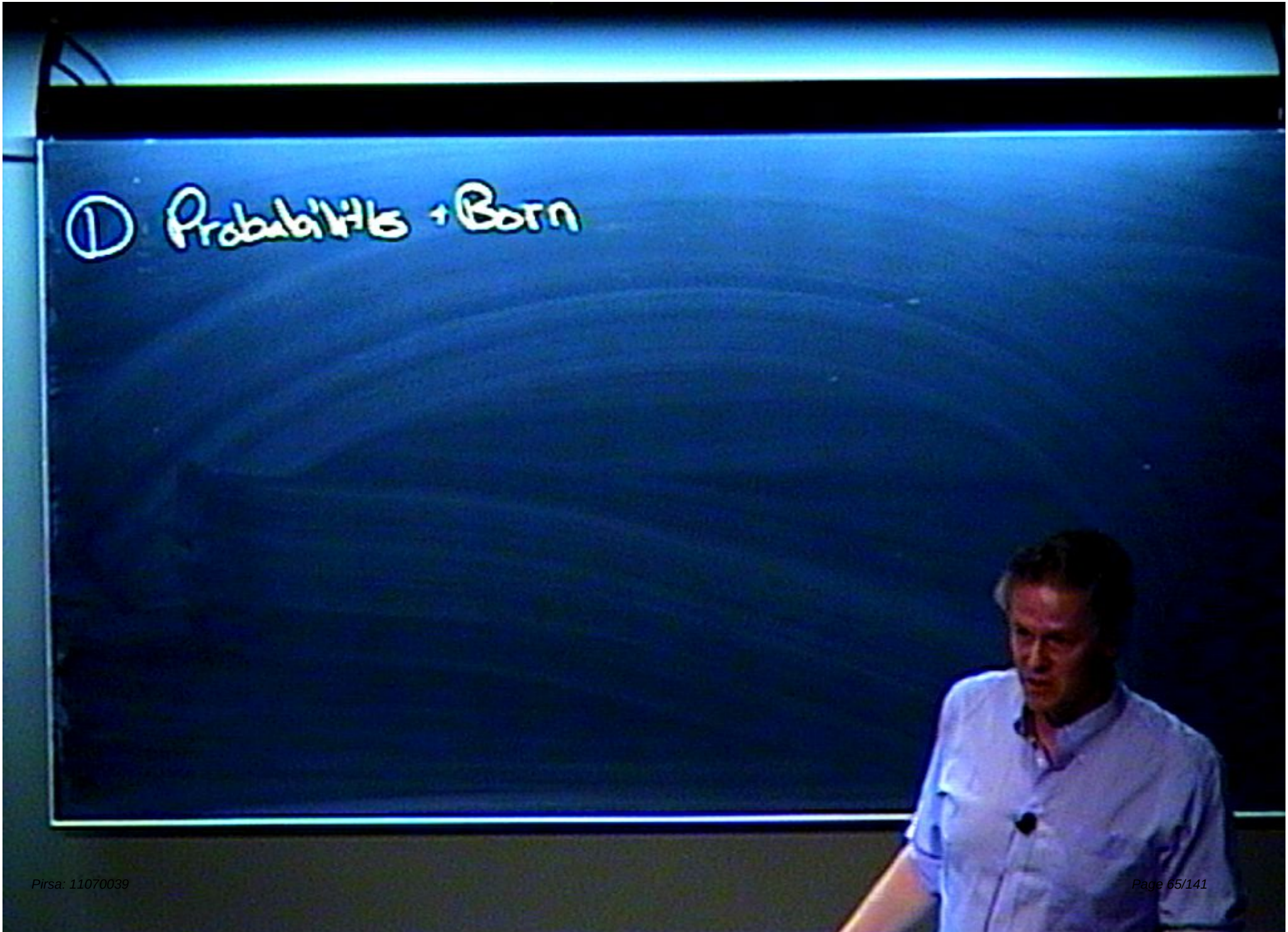
B Finite vs Infinite

USHO

$V = -\frac{q^2}{2} + \left(\frac{q^4}{24}\right)^{\infty}$

C) Quantum Measurement

- Not ideal OK!
- Experimental Errors OK
- Things Un-happening OK


① Probability + Born

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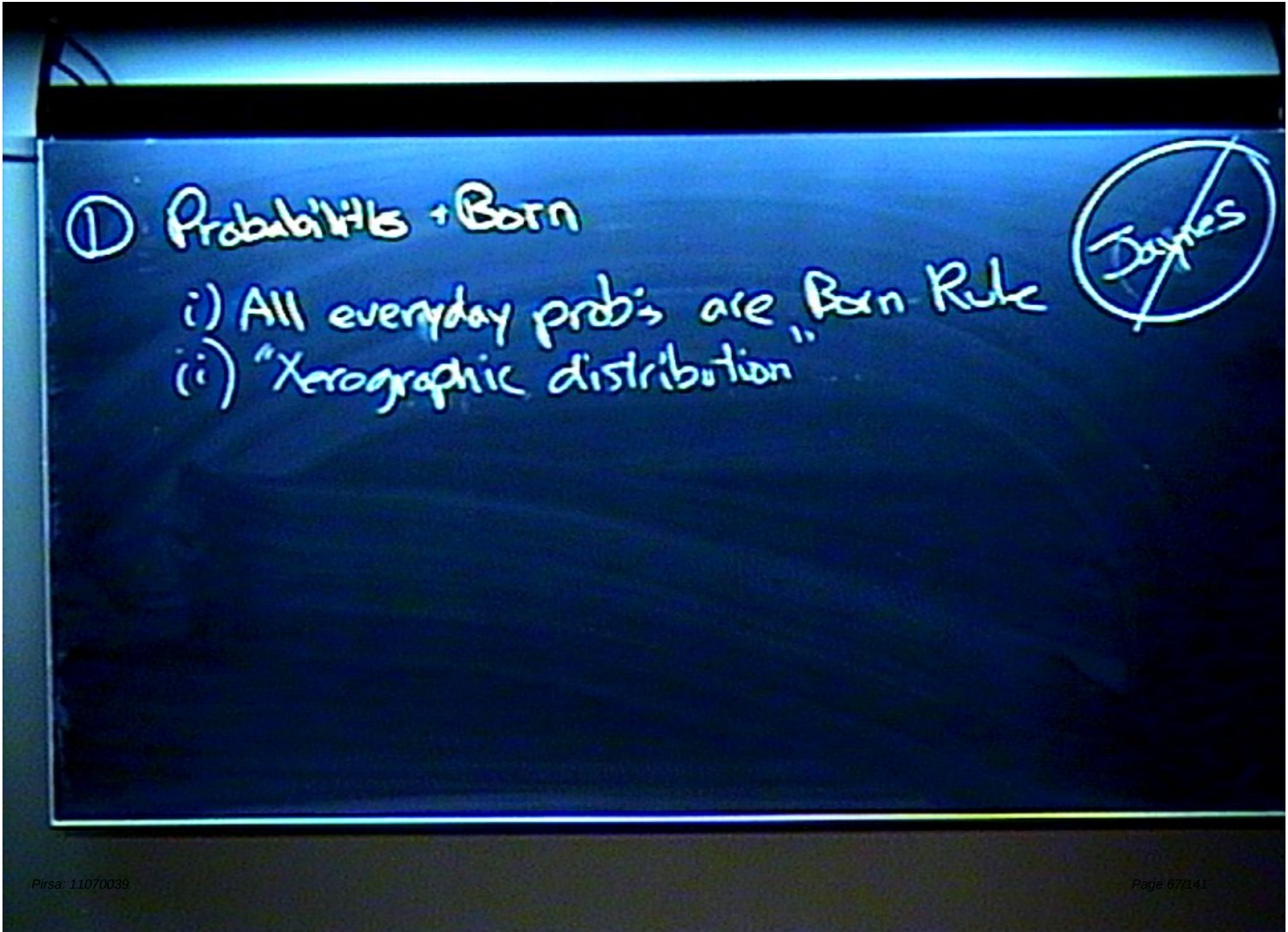
i) All everyday prob's are Born Rule


① Probability + Born
i) All everyday prob's are Born Rule
ii) "Xerographic distribution"
Bayes

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Ergodicity

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de Sitter Equilibrium (dSE) cosmology

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AA: arXiv:1104.3315
AA: arXiv:0906.1047
AA & Sorbo: hep-th/0405270

mplications of the de Sitter horizon

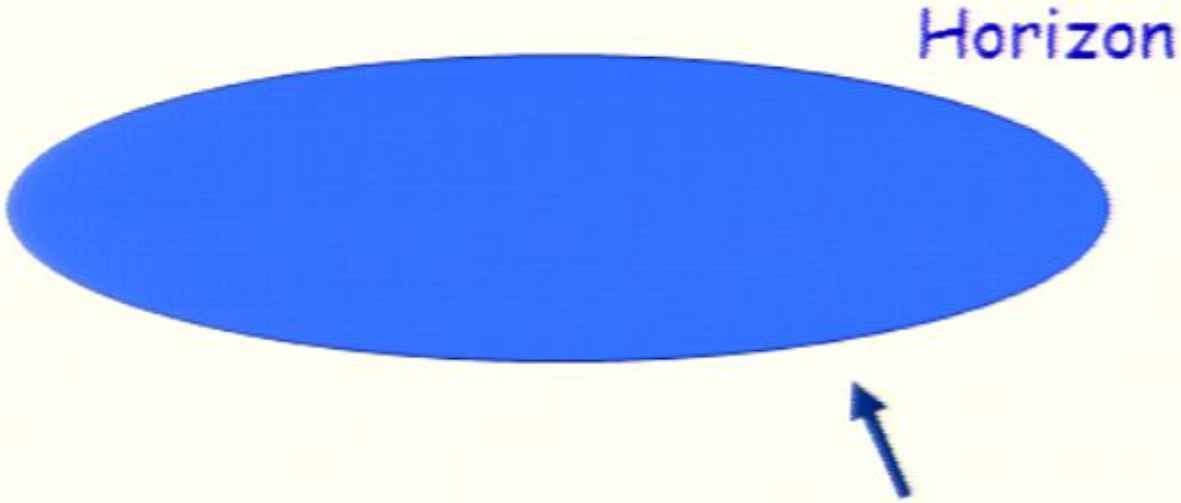
- Maximum entropy

$$S_\Lambda \propto A = H_\Lambda^{-2} = \left(\frac{\Lambda}{3}\right)^{-1}$$

- Gibbons-Hawking Temperature

$$T_{GH} = H_\Lambda = \sqrt{\frac{8\pi G}{3}\rho_\Lambda}$$

"De Sitter Space: The ultimate equilibrium for the universe?



$$S \propto A = H^{-2} = \Lambda^{-1}$$

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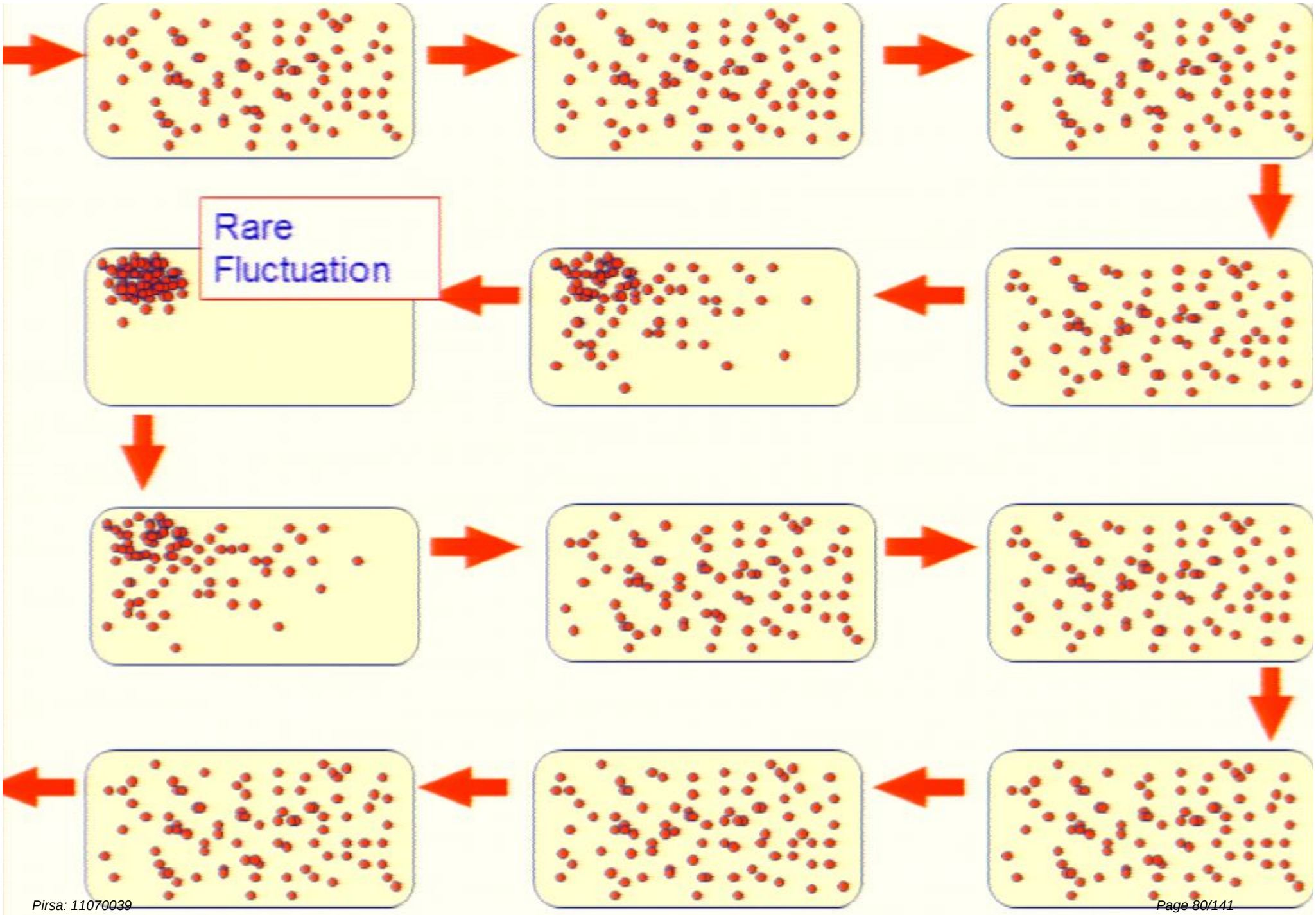
- Only a finite volume ever observed

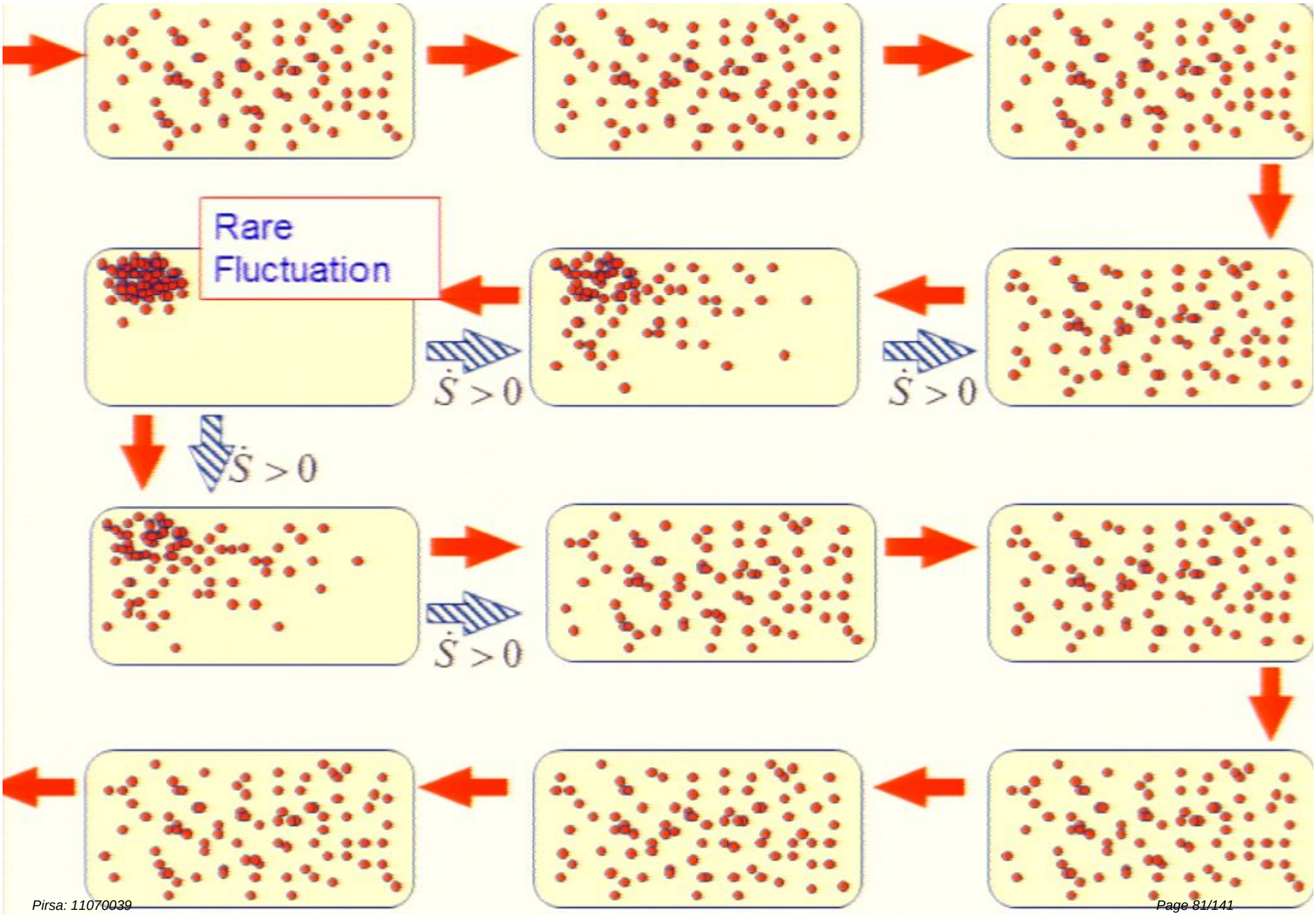
- If Λ is truly constant: Cosmology as fluctuating Eqm.

- Maximum entropy $\longrightarrow$ finite Hilbert space of dimension $N = e^{S_\Lambda}$

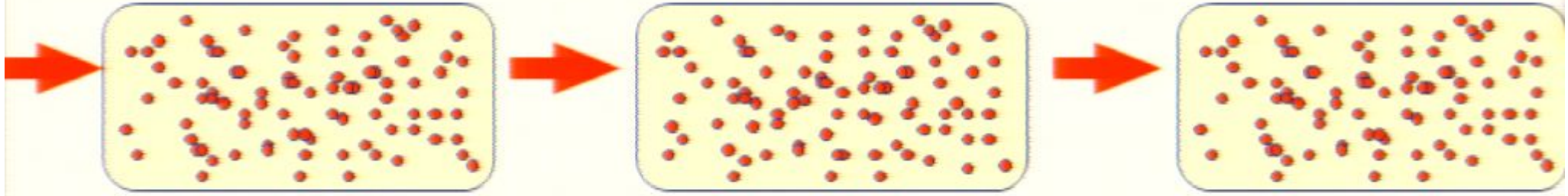
Banks & Fischler; Dyson et al.

Equilibrium Cosmology

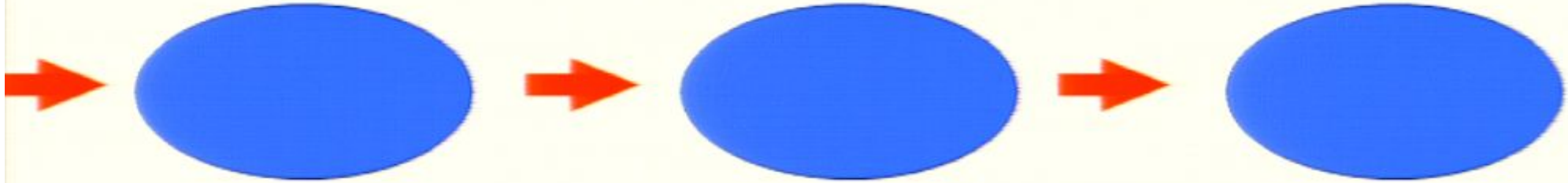

Rare
Fluctuation


Rare
Fluctuation
$\dot{S} > 0$
$\dot{S} > 0$
$\dot{S} > 0$
$\dot{S} > 0$

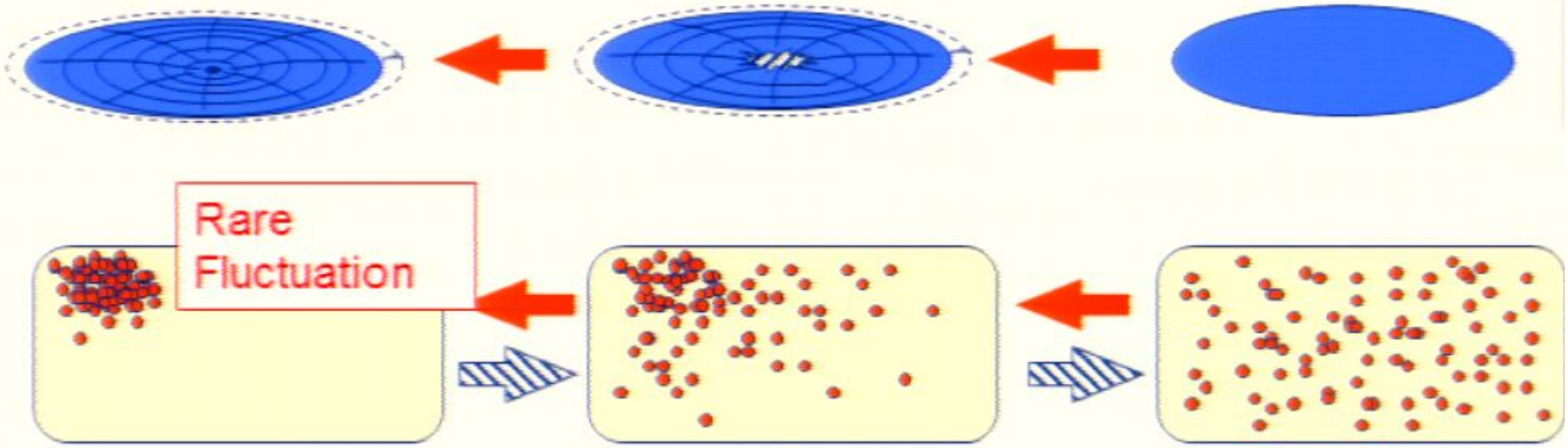
Concept:



Realization:



"de Sitter Space"


Rare
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Fluctuating from dSE to inflation:

- The process of an inflaton fluctuating from late time de Sittter to an inflating state is dominated by the "Guth-Farhi process"
- A "seed" is formed from the Gibbons-Hawking radiation that can then tunnel via the Guth-Farhi instanton.
- Rate is well approximated by the rate of seed formation:

$$\propto e^{-\frac{m_s}{T_{GH}}} = e^{-\frac{m_s}{H_\Lambda}}$$

- Seed mass:

$$m_s = \rho_I \left(cH_I^{-1}\right)^3 = 0.0013kg\left(\frac{\left(10^{16}GeV\right)^4}{\rho_I}\right)^{1.2}$$

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Small seed can produce an entire universe → Evade "Boltzmann Brain" problem

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New work on G-F process by Andrew Ulvestad & AA: No problematic $m \to 0$ limit

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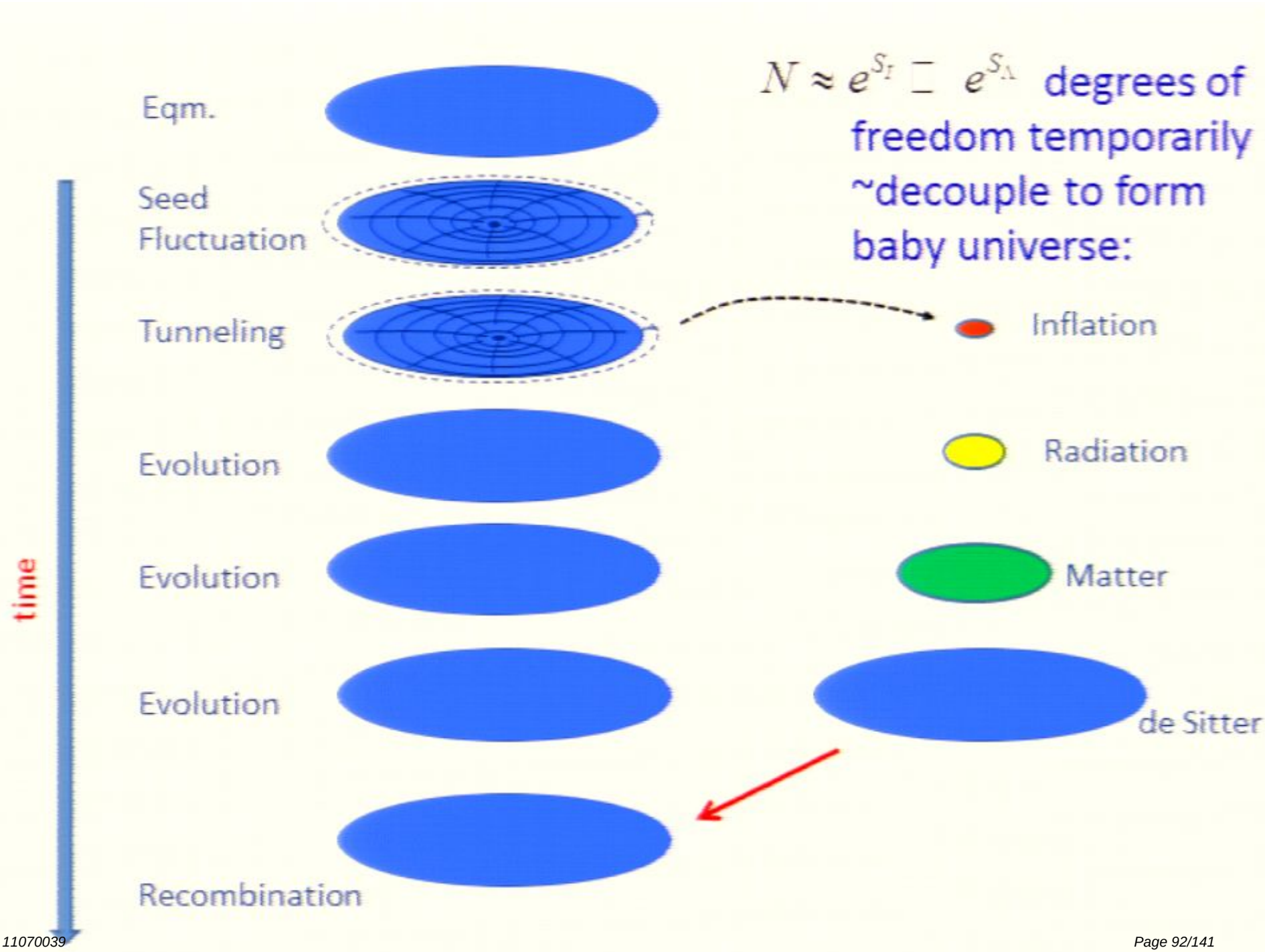
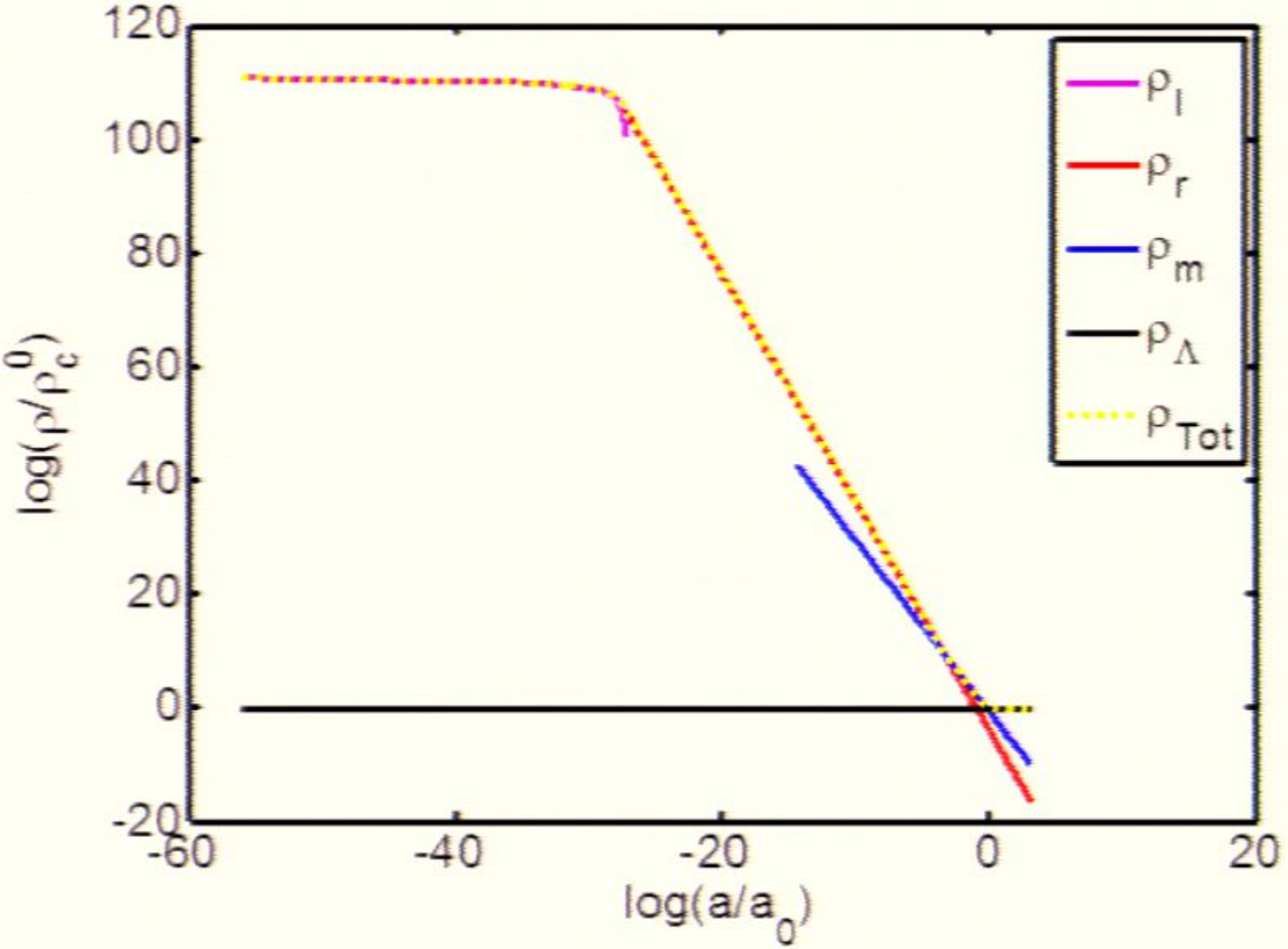
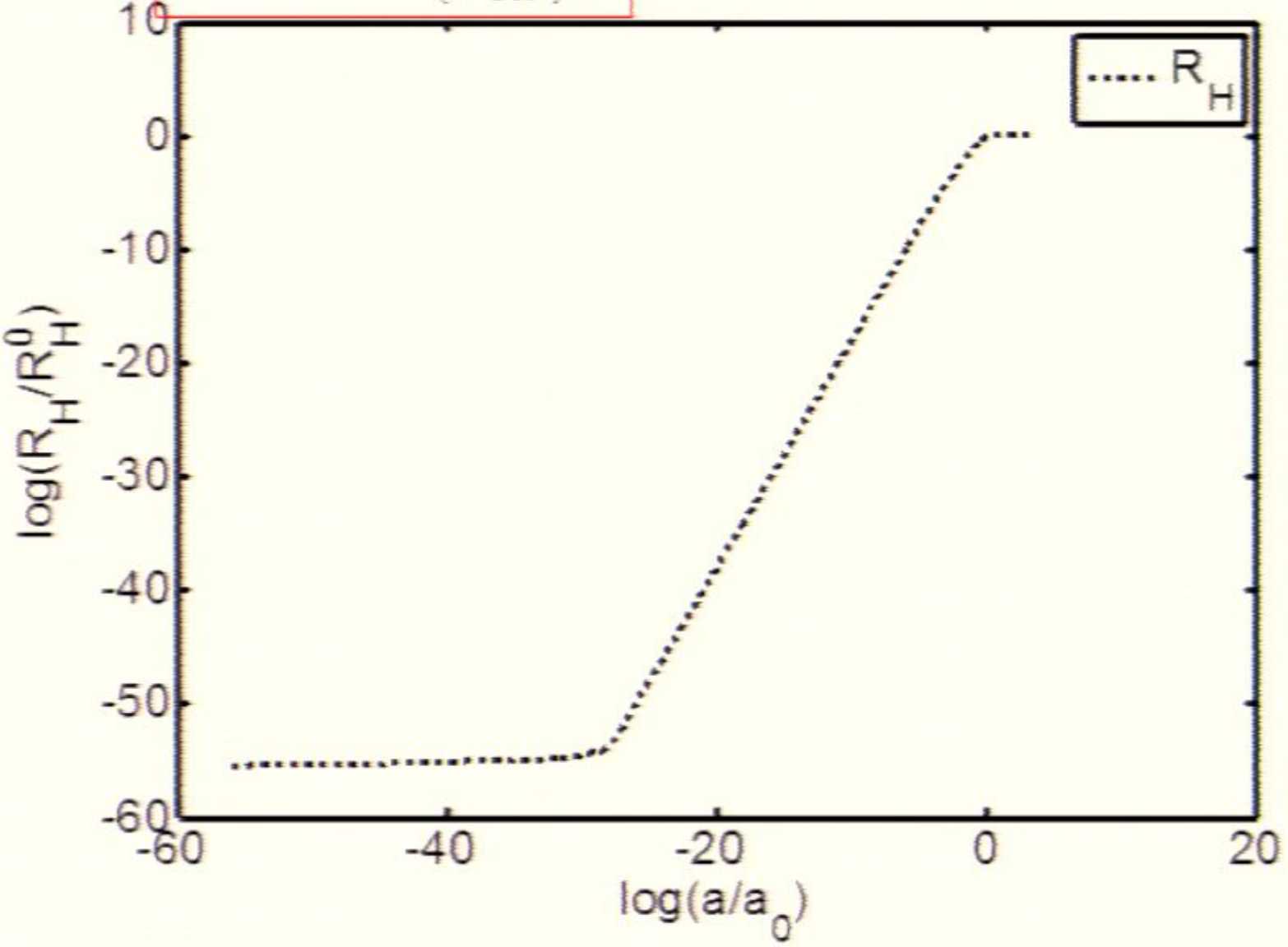

$N \approx e^{S_I} \sqsupset e^{S_\Lambda}$ degrees of freedom temporarily ~decouple to form baby universe:
Eqm.
Seed Fluctuation
Tunneling
Inflation
Evolution
Radiation
Evolution
Matter
Evolution
de Sitter
Recombination
time

Implications of finite Hilbert space $N = e^{S_\Lambda}$

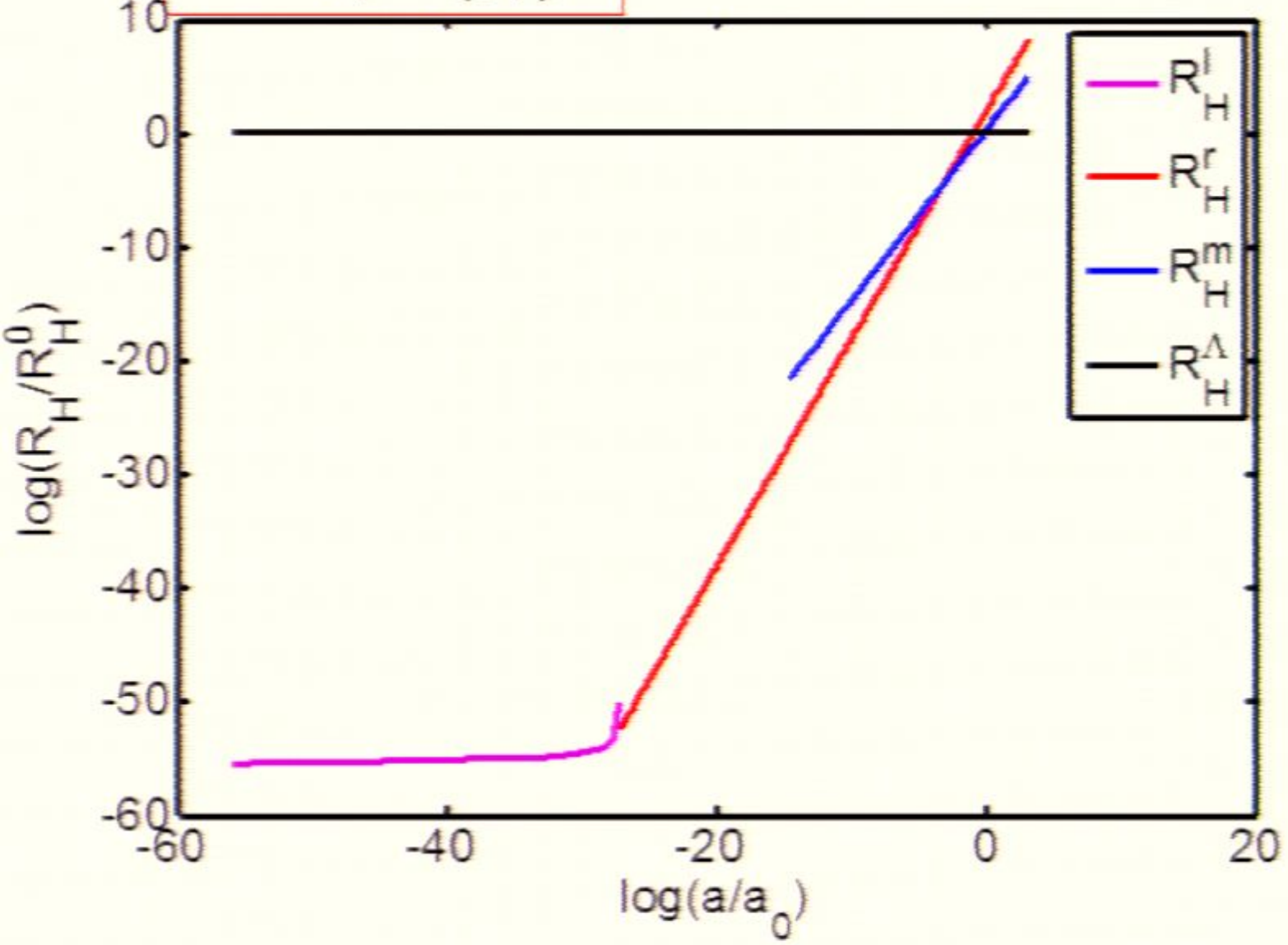
- Recurrences
- Eqm.
- Breakdown of continuum field theory


120
100
80
60
40
20
0
-20
-60
-40
-20
0
20
log(ρ/ρc0)
log(a/a0)
ρl
ρr
ρm
ρΛ
ρTot

$$R_H \equiv \frac{c}{H} \propto \left(\frac{1}{\rho_{Tot}} \right)^{1/2}$$



$$R_H^i \equiv \frac{c}{H_i} \propto \left(\frac{1}{\rho_i}\right)^{1/2}$$



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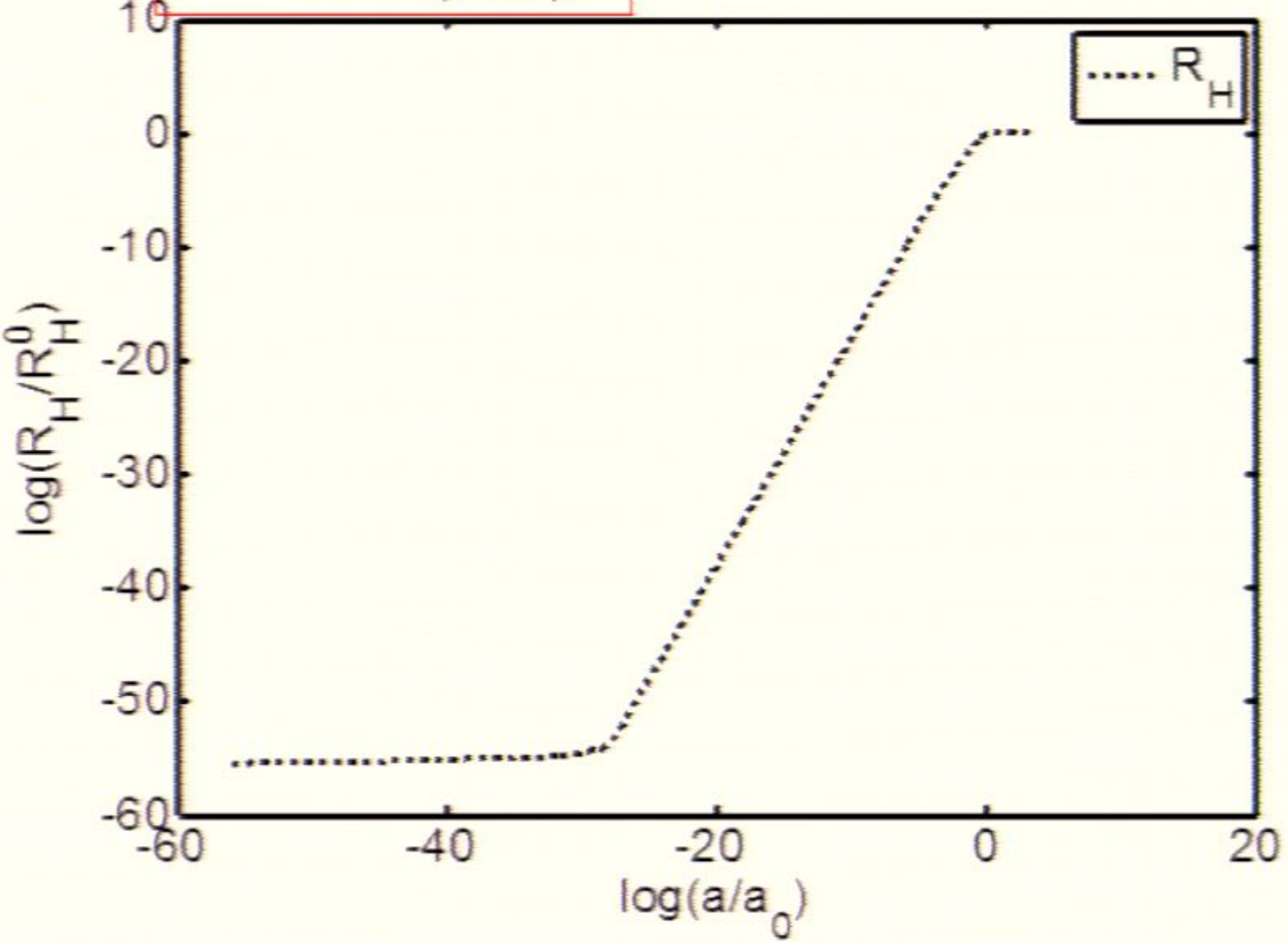
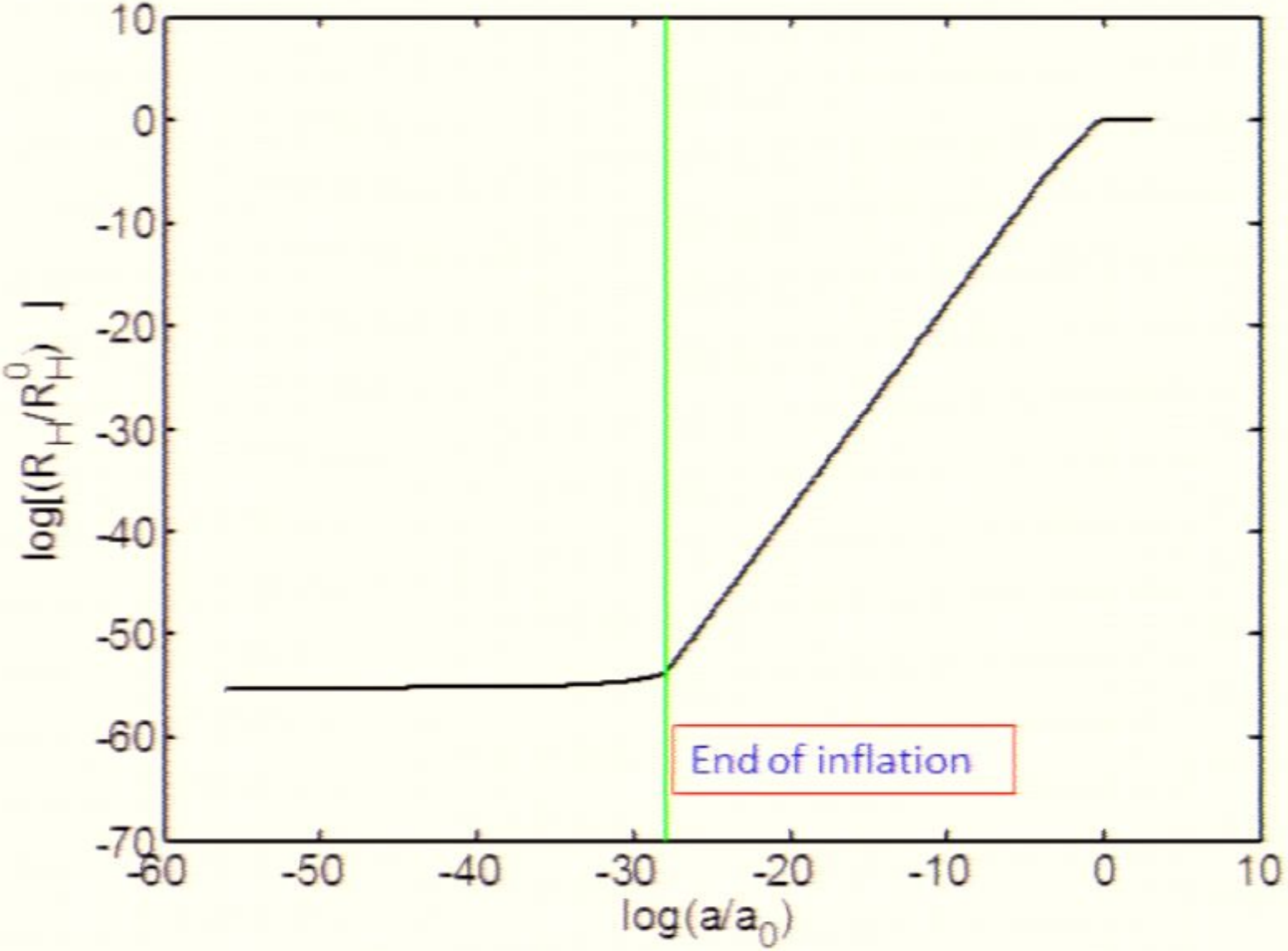
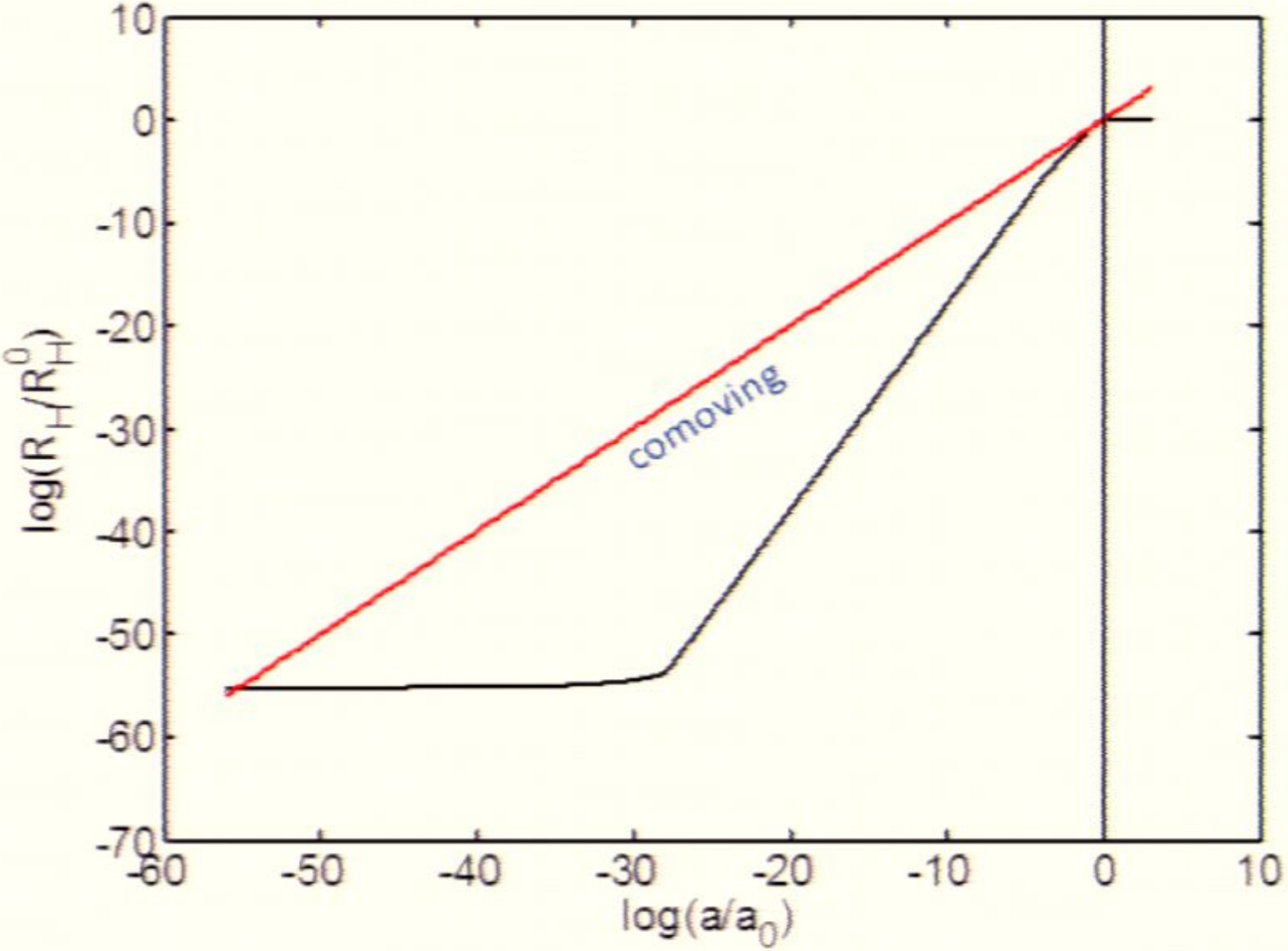
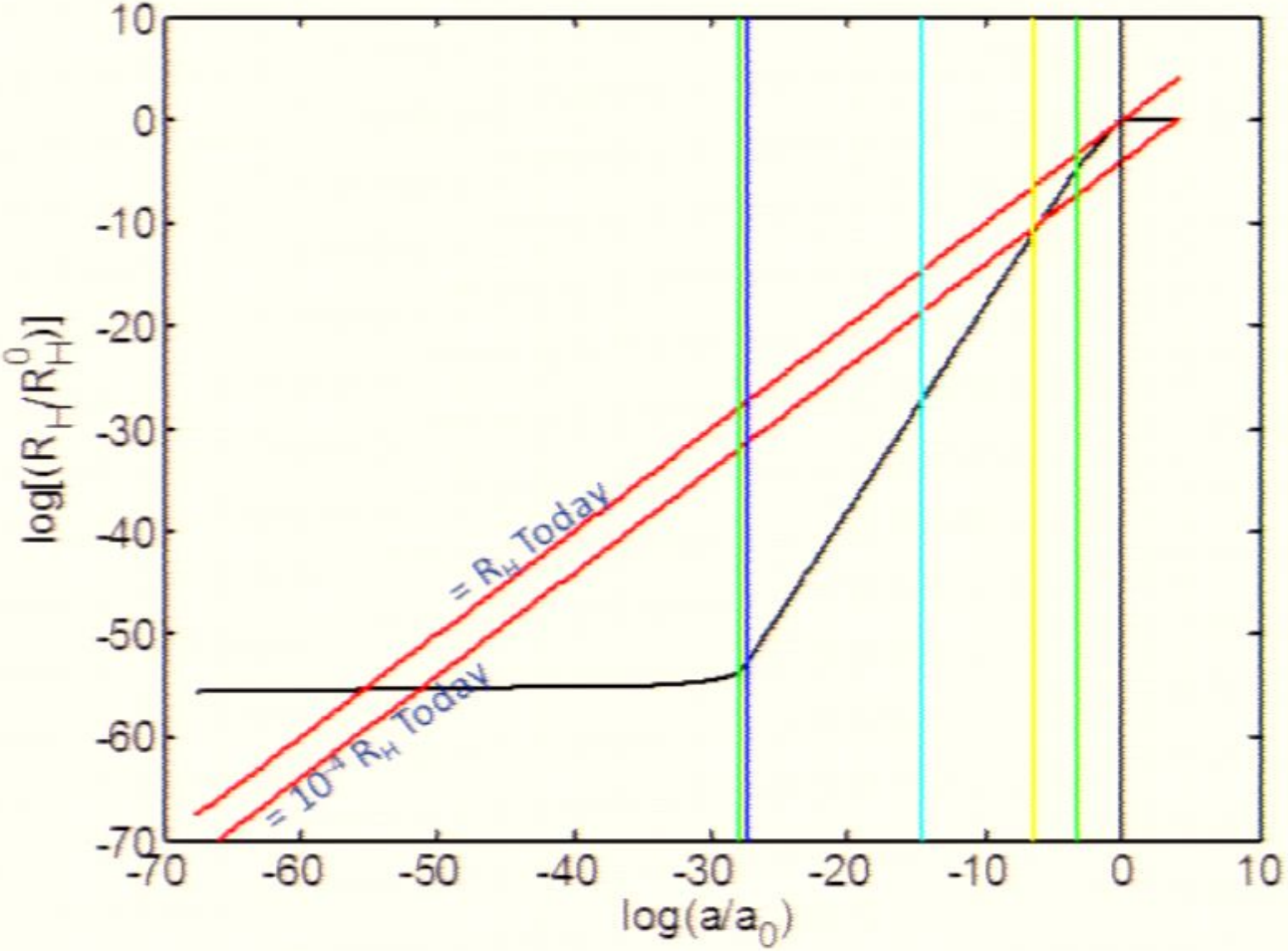
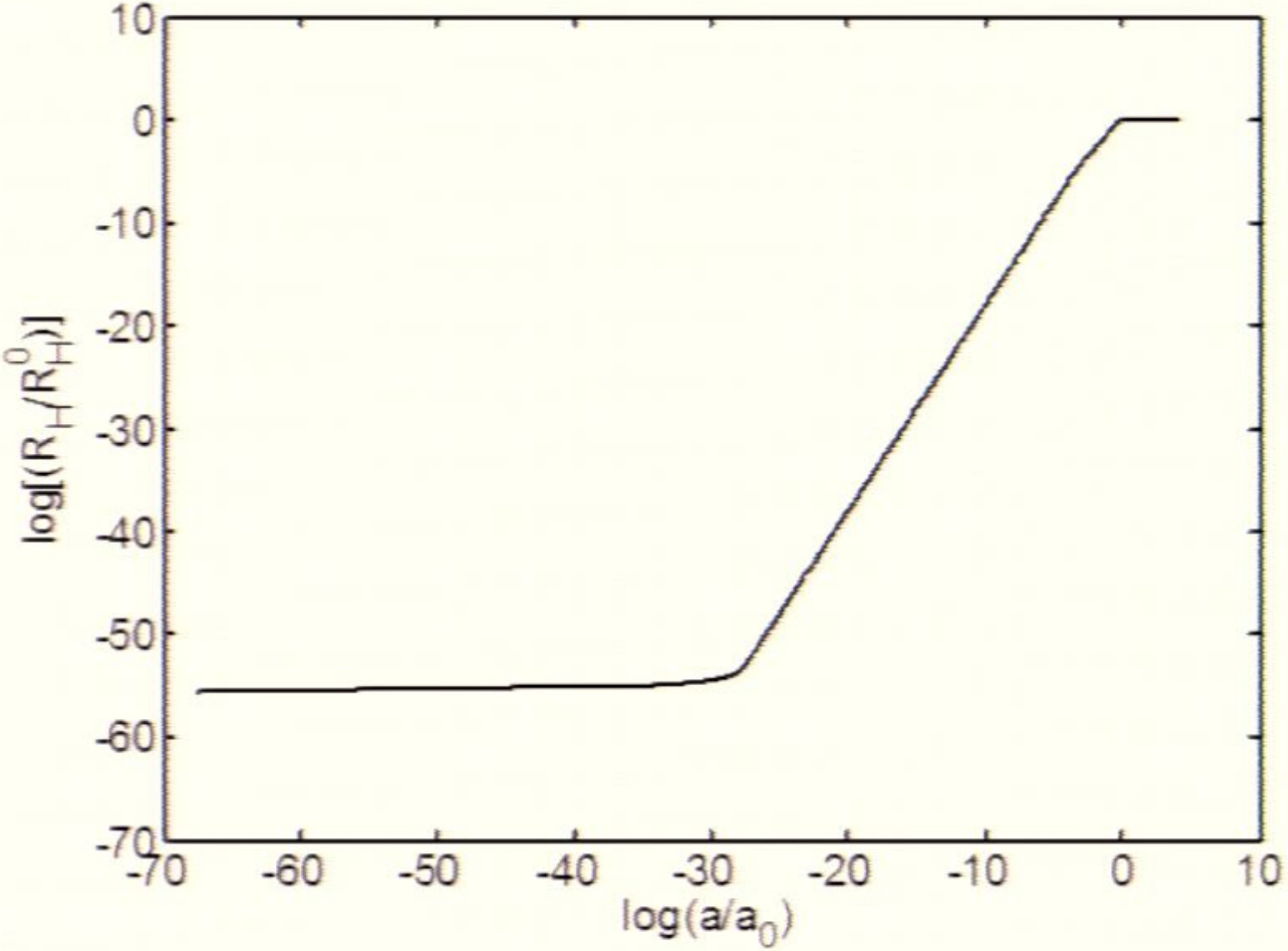
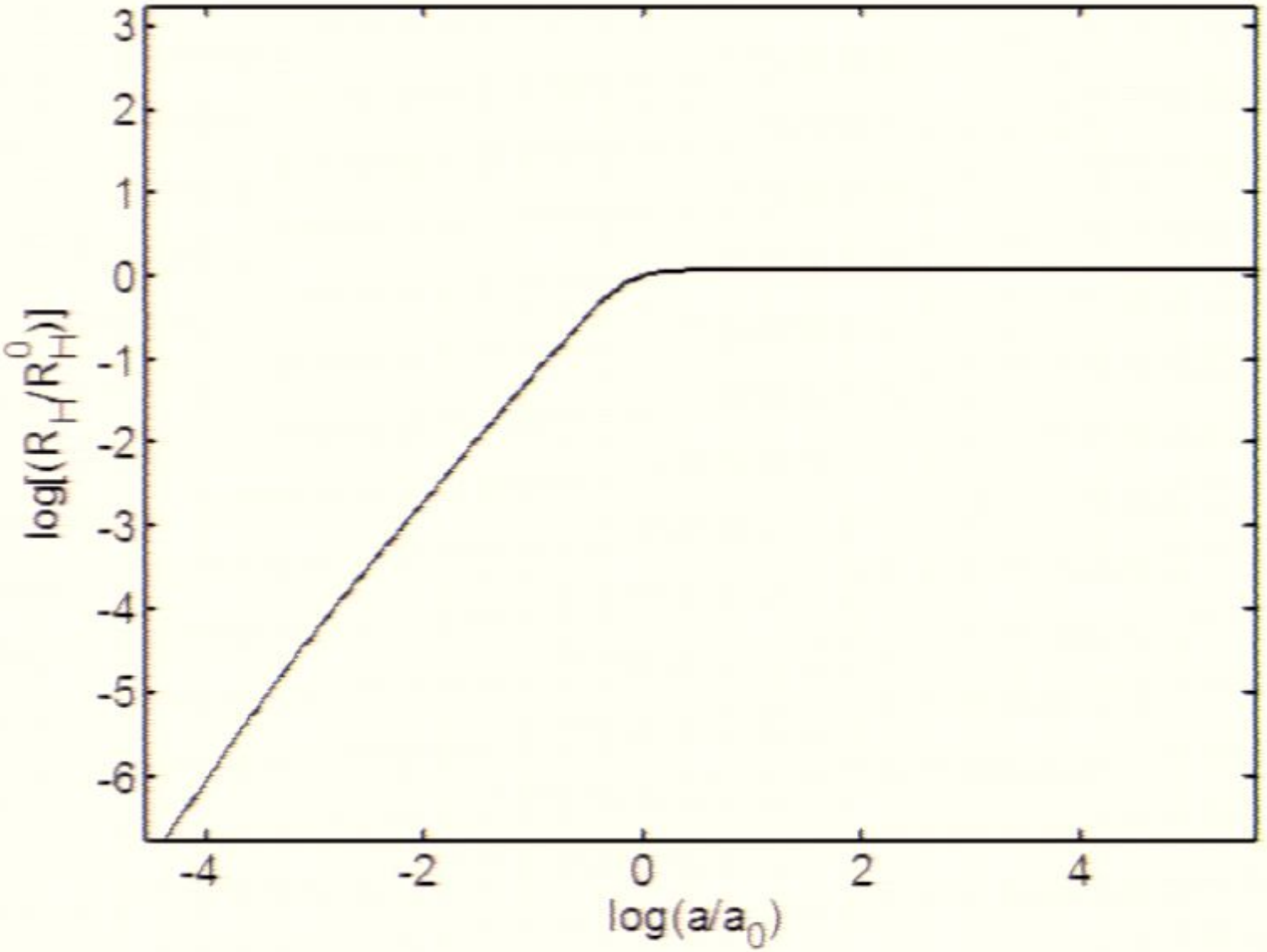


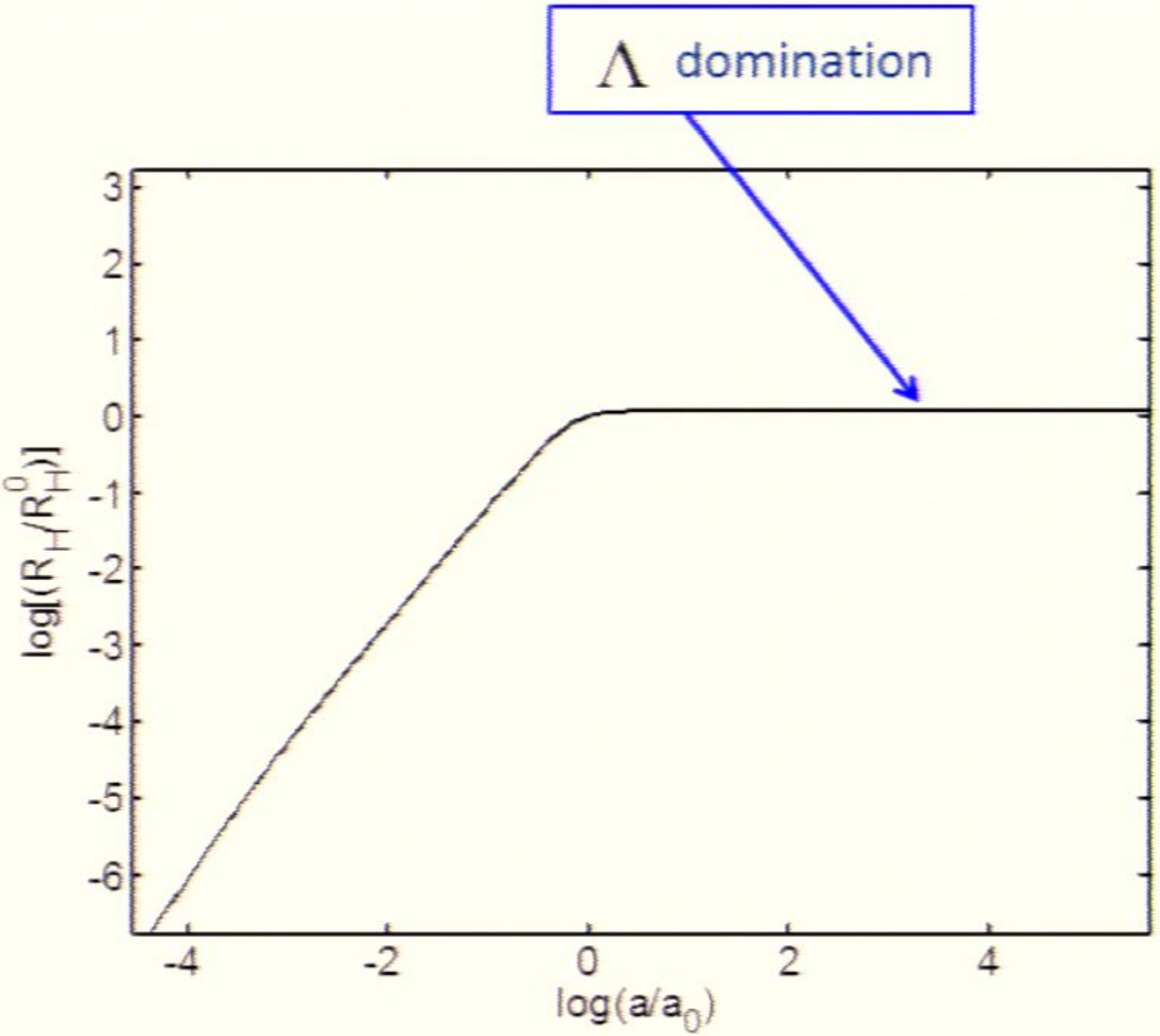

10
0
-10
-20
-30
-40
-50
-60
-70
-60
-50
-40
-30
-20
-10
0
10
log[(R_H/R_H^0) - 1]
log(a/a_0)
End of inflation


10
0
-10
-20
-30
-40
-50
-60
-70
-60
-50
-40
-30
-20
-10
0
10
log(R_H/R_H^0)
log(a/a_0)
comoving

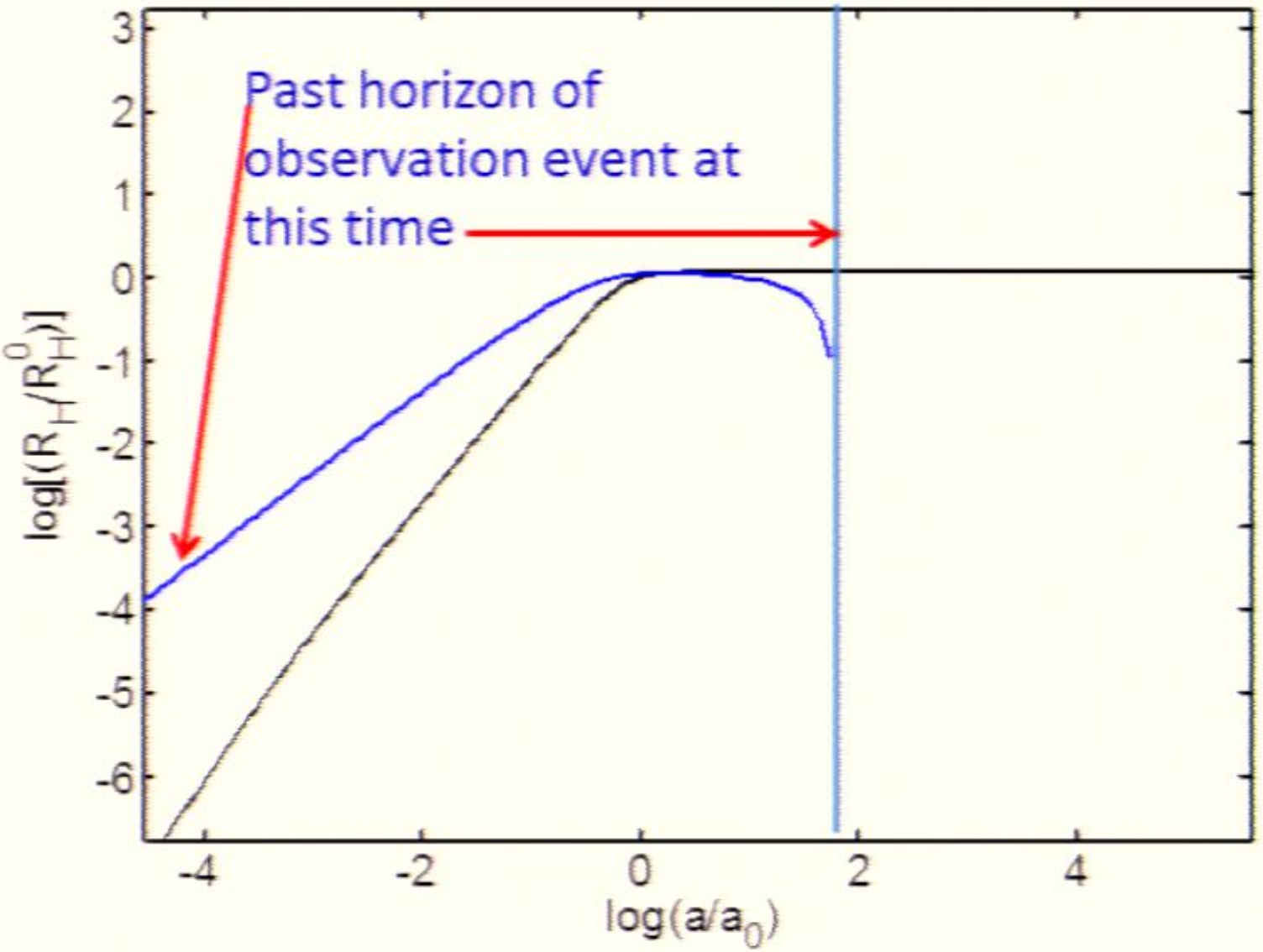

10
0
-10
-20
-30
-40
-50
-60
-70
-70
-60
-50
-40
-30
-20
-10
0
10
log[(R_H/R_H^0)]
log(a/a_0)
= R_H Today
= 10^-4 R_H Today


10
0
-10
-20
-30
-40
-50
-60
-70
log[(R_H/R_H^0)]
-70
-60
-50
-40
-30
-20
-10
0
10
log(a/a_0)


3
2
1
0
-1
-2
-3
-4
-5
-6
-4
-2
0
2
4
log[(R_H/R_H^0)]
log(a/a_0)

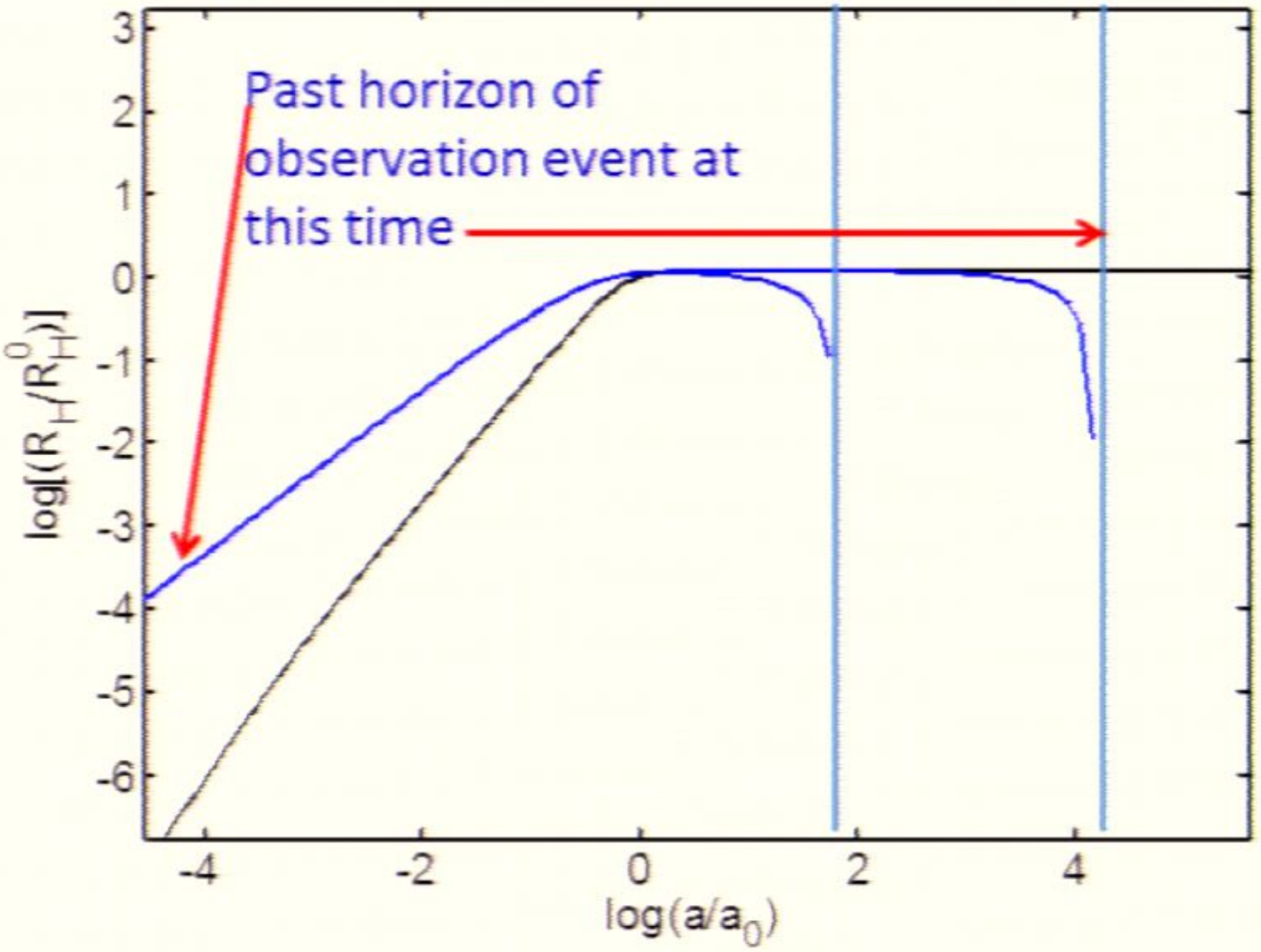

Λ domination
log[(R_H/R_H^0)]
log(a/a_0)
3
2
1
0
-1
-2
-3
-4
-5
-6
-4
-2
0
2
4

The de Sitter horizon



Past Horizon: Physical distance from (comoving) observer of a photon that will reach the observer at the time of the observation

The de Sitter horizon



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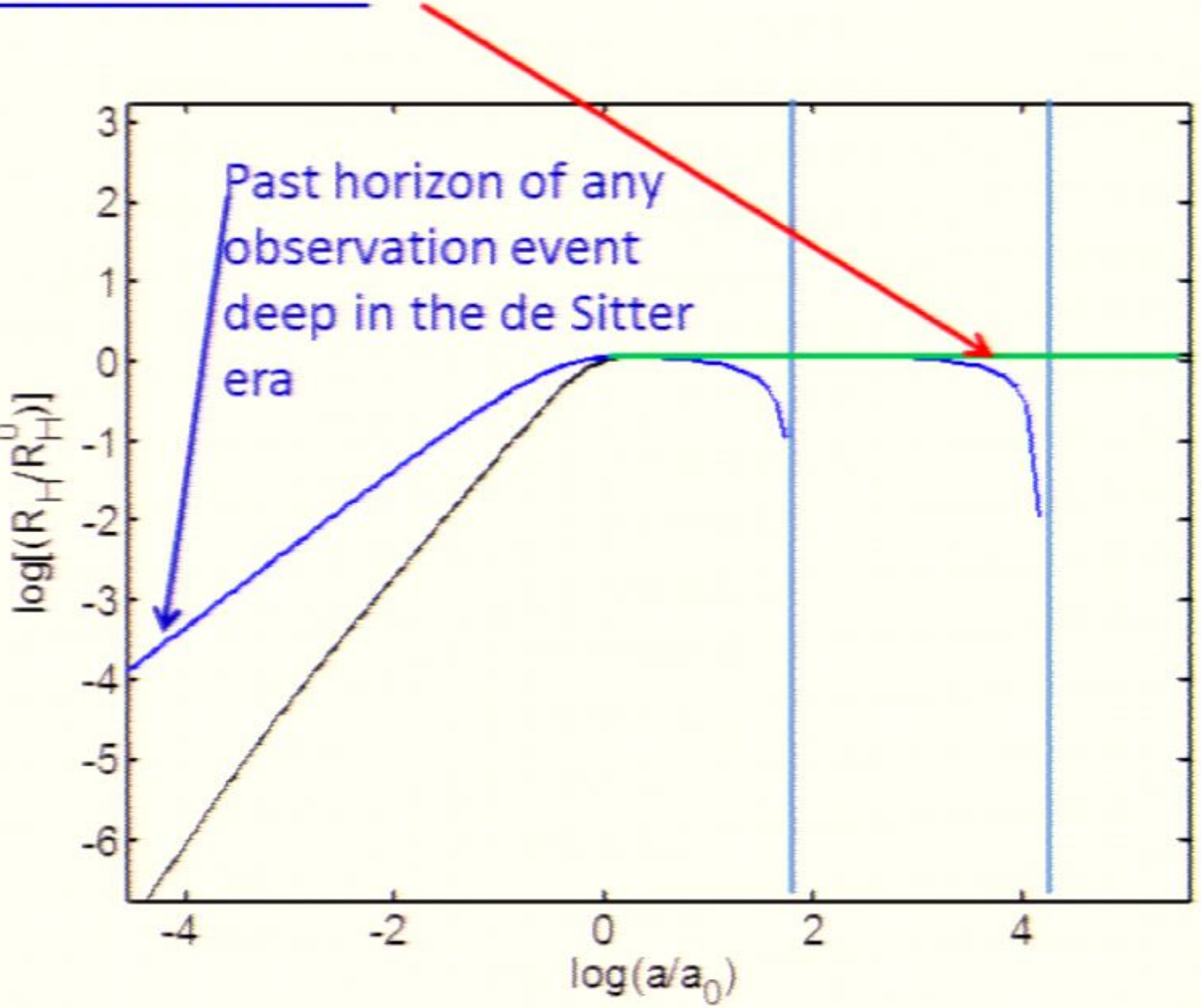

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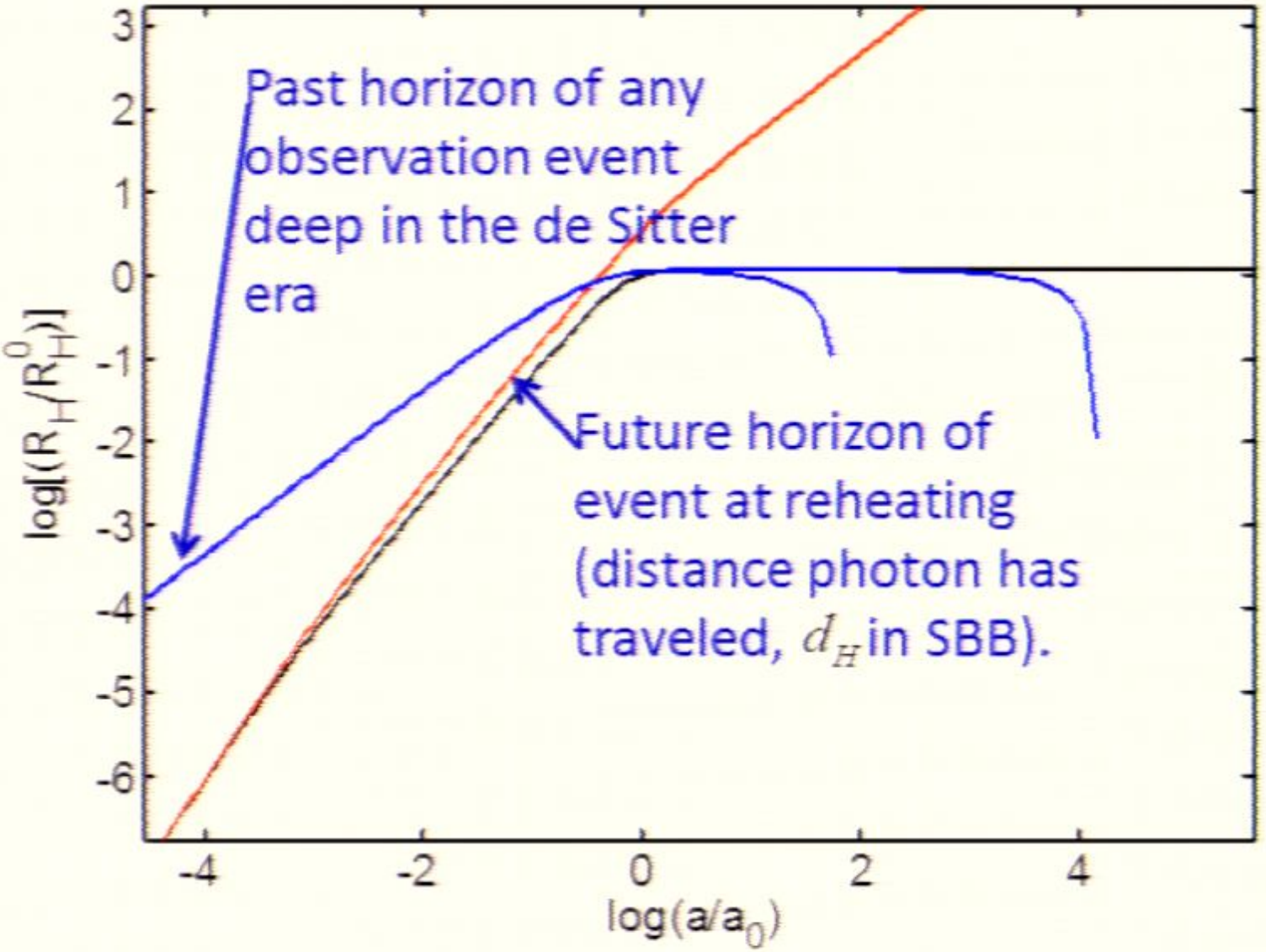

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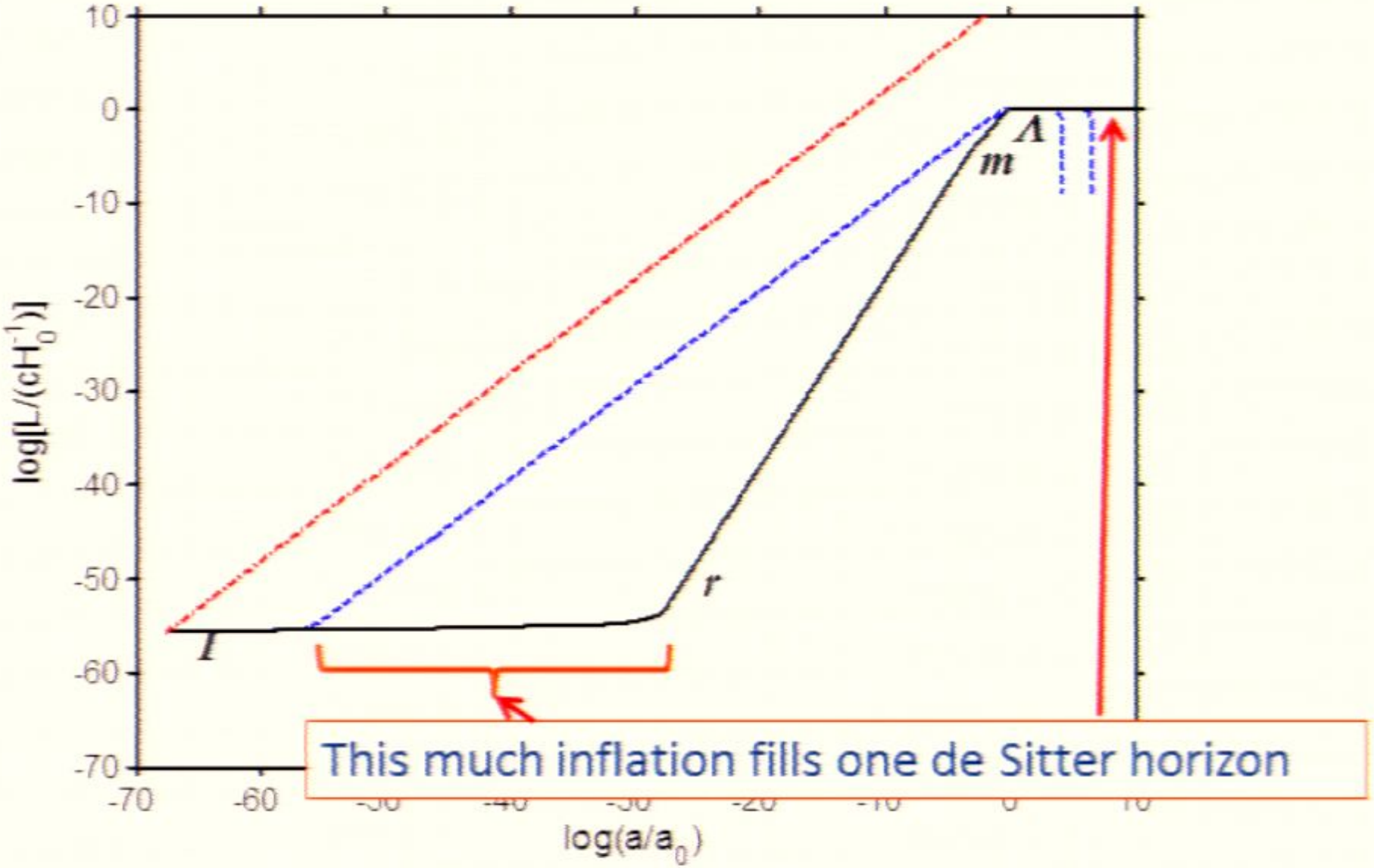
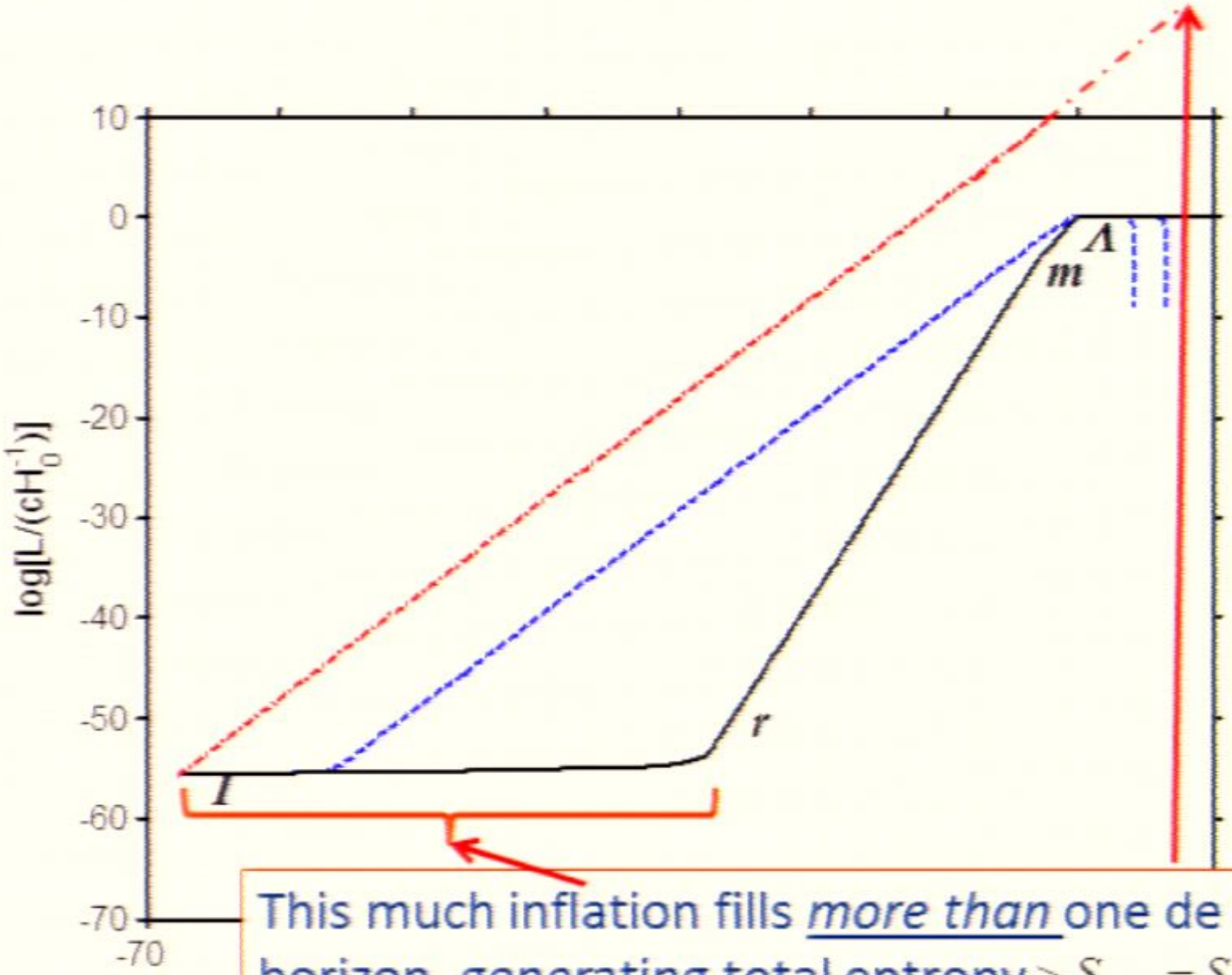
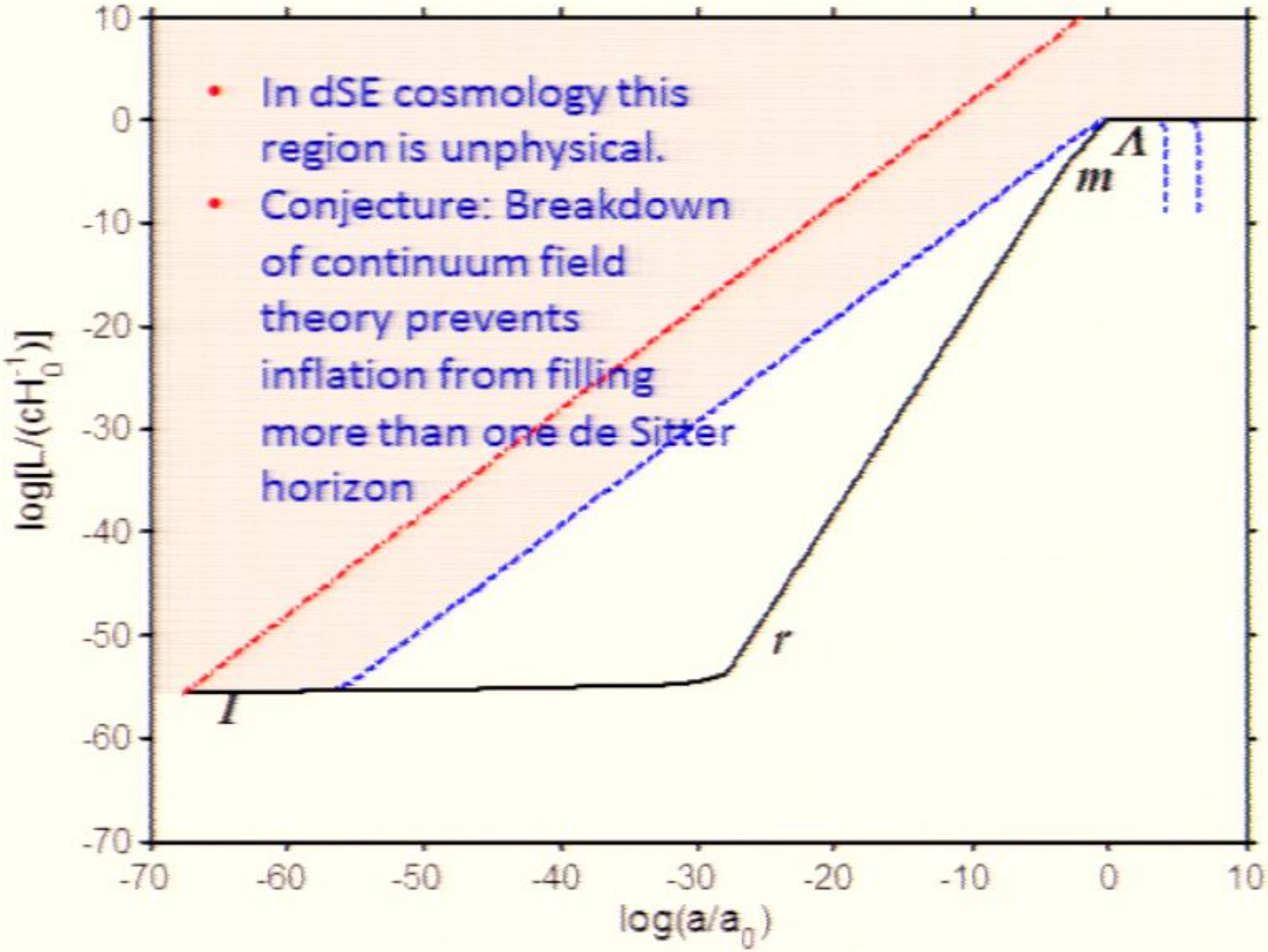

10
0
-10
-20
-30
-40
-50
-60
-70
-70
-60
log[L/(cH$_0^{-1}$)]
log(a/a$_0$)
Λ
m
r
I
This much inflation fills one de Sitter horizon



This much inflation fills *more than* one de Sitter horizon, generating total entropy $> S_{Max} = S_{\Lambda}$ and affecting regions beyond the horizon of the observer


In dSE cosmology this region is unphysical.
Conjecture: Breakdown of continuum field theory prevents inflation from filling more than one de Sitter horizon
I
r
m
Λ
log[L/(cH0-1)]
log(a/a0)
10
0
-10
-20
-30
-40
-50
-60
-70

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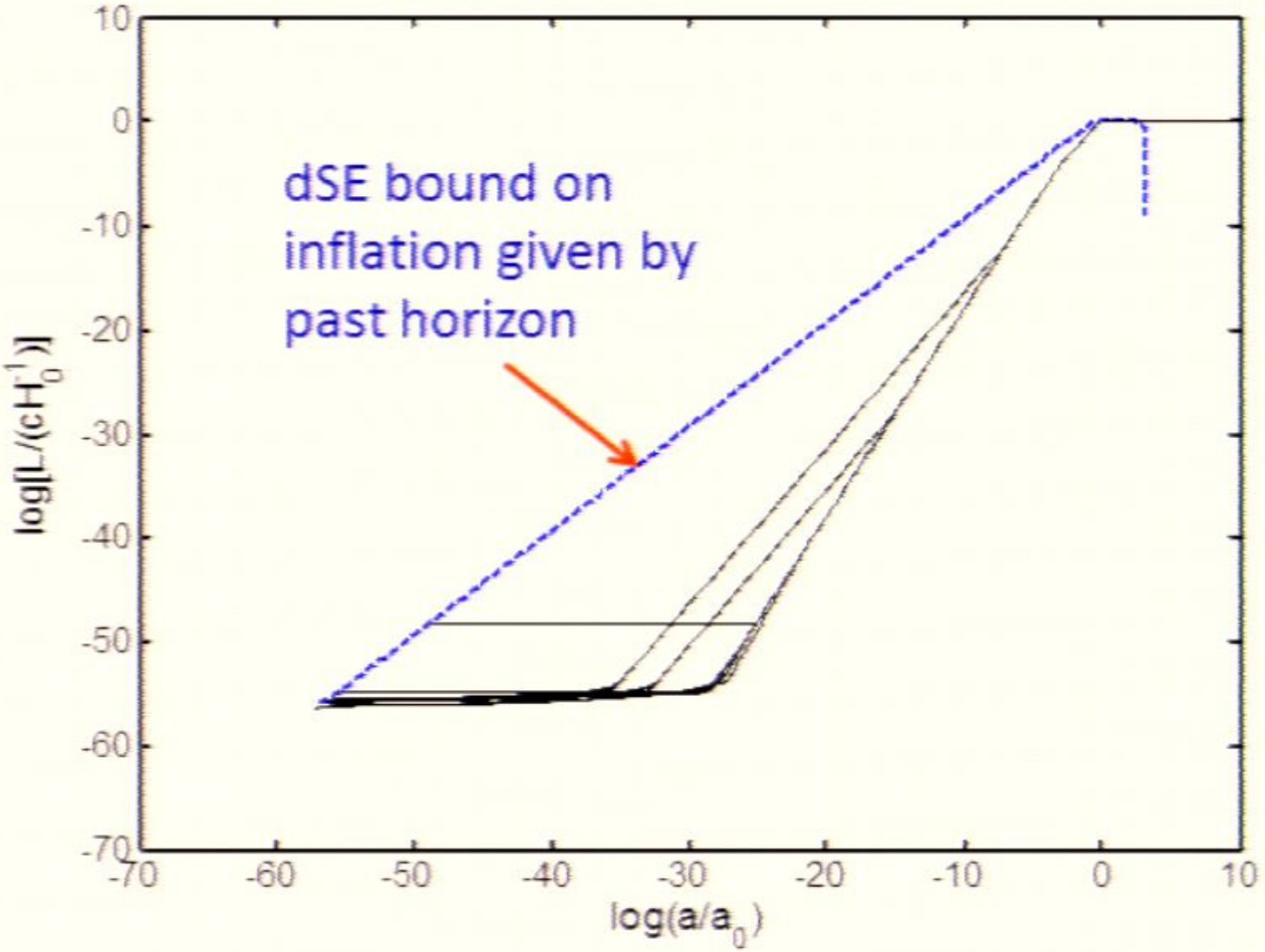
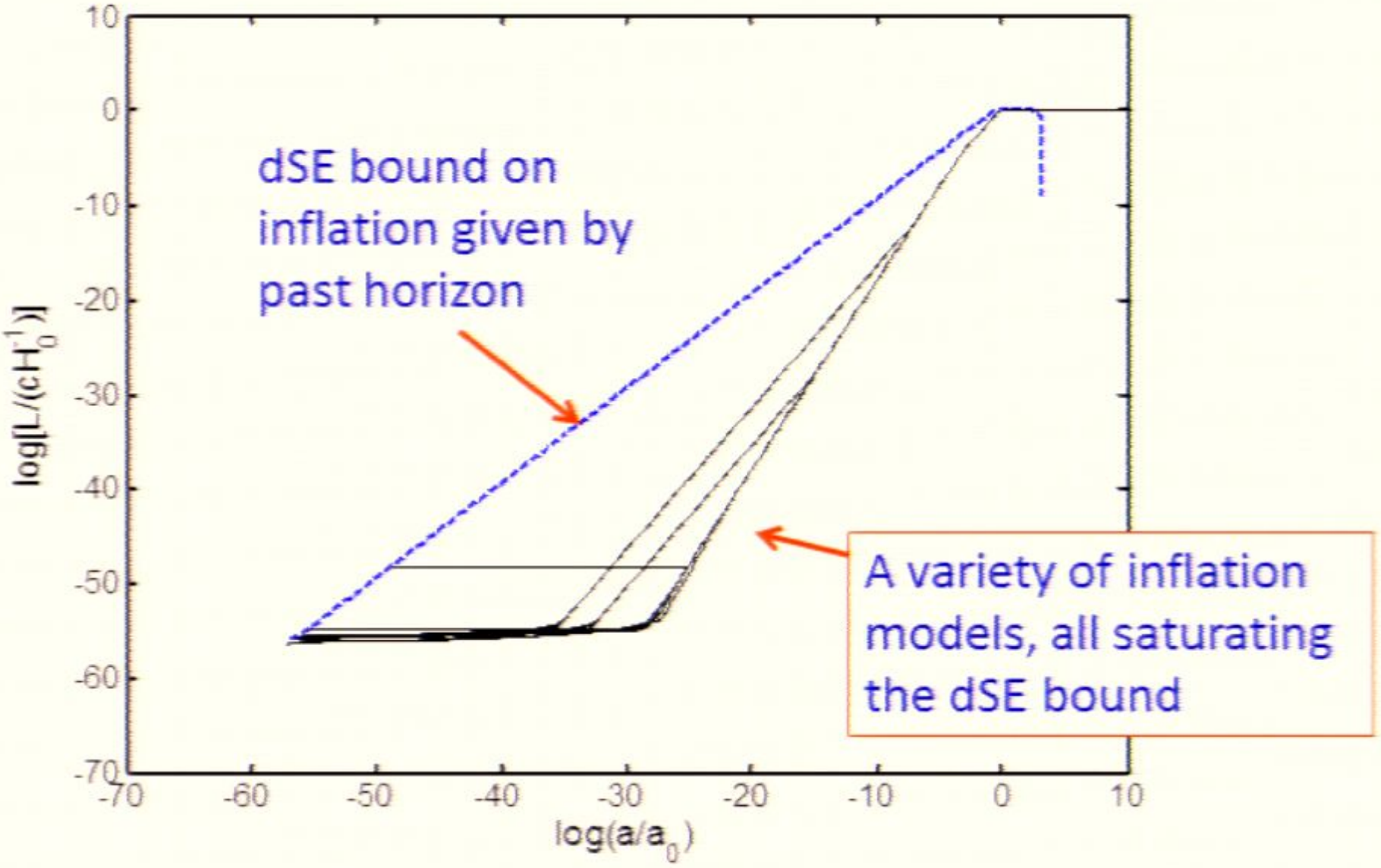
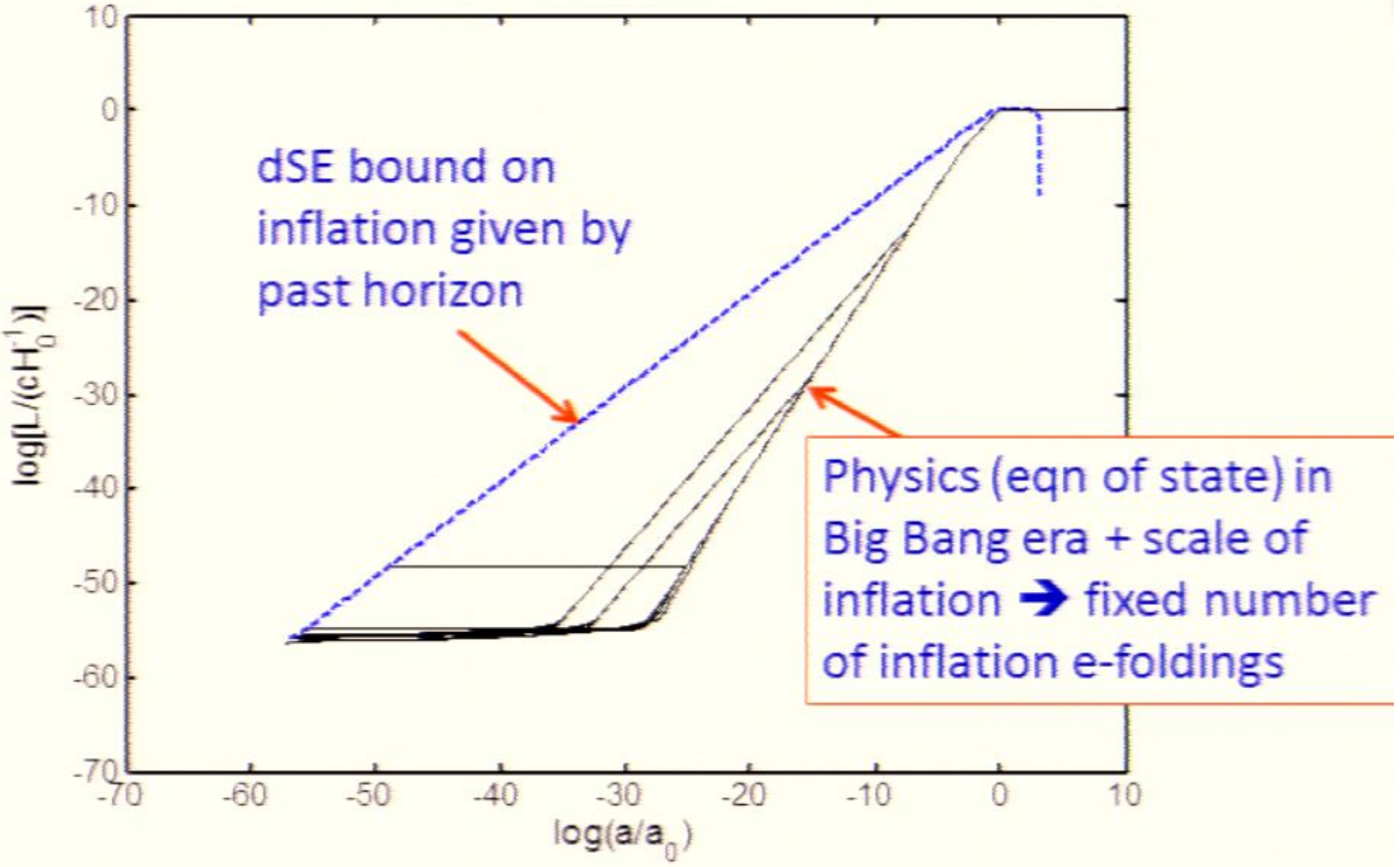
Large ρ_I exponentially favored ➔ saturation of dSE bound


dSE bound on
inflation given by
past horizon
log[L/(cH$_0^{-1}$)]
log(a/a$_0$)
10
0
-10
-20
-30
-40
-50
-60
-70
-70
-60
-50
-40
-30
-20
-10
0
10


dSE bound on
inflation given by
past horizon
A variety of inflation
models, all saturating
the dSE bound
log[L/(cH$_0^{-1}$)]
log(a/a$_0$)
10
0
-10
-20
-30
-40
-50
-60
-70
-70
-60
-50
-40
-30
-20
-10
0
10


dSE bound on inflation given by past horizon
Physics (eqn of state) in Big Bang era + scale of inflation ➔ fixed number of inflation e-foldings
log[L/(cH$_0^{-1}$)]
log(a/a$_0$)
10
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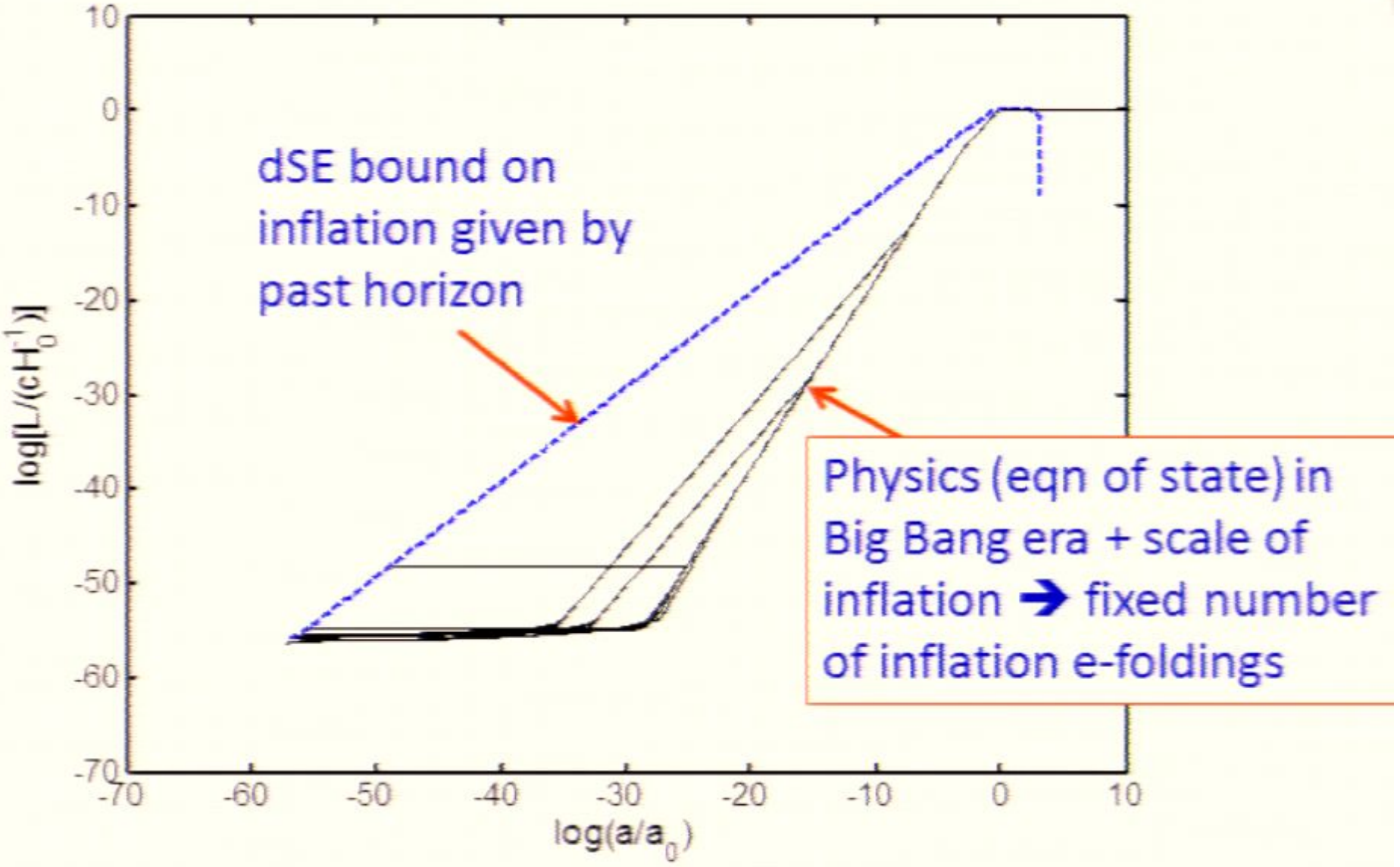
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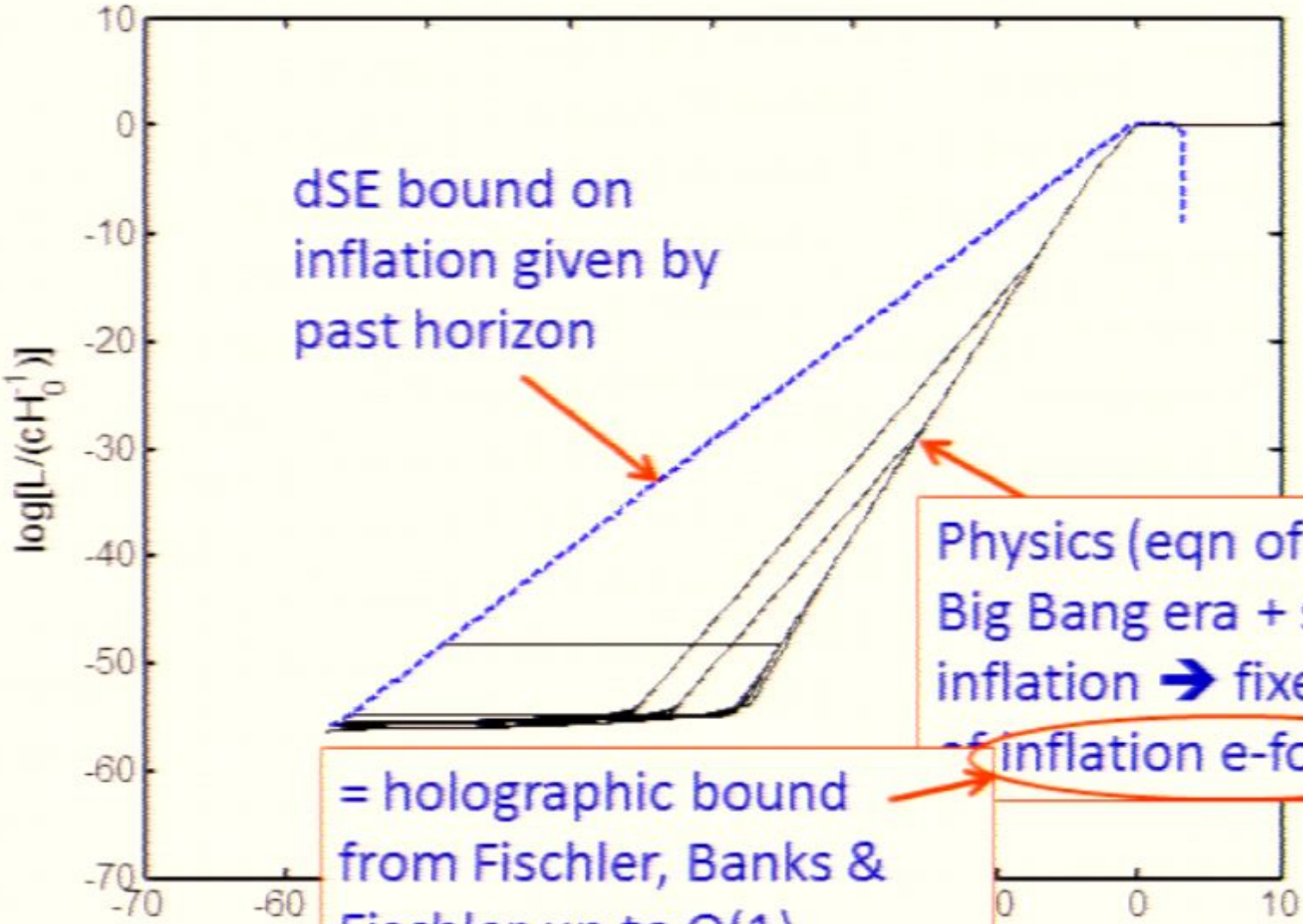
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dSE bound on inflation given by past horizon
Physics (eqn of state) in Big Bang era + scale of inflation → fixed number
inflation e-foldings
= holographic bound from Fischler, Banks & Fischler up to O(1) factors. (Dan Phillips & AA in prep)

OUTLINE

1) Ideas and Principles

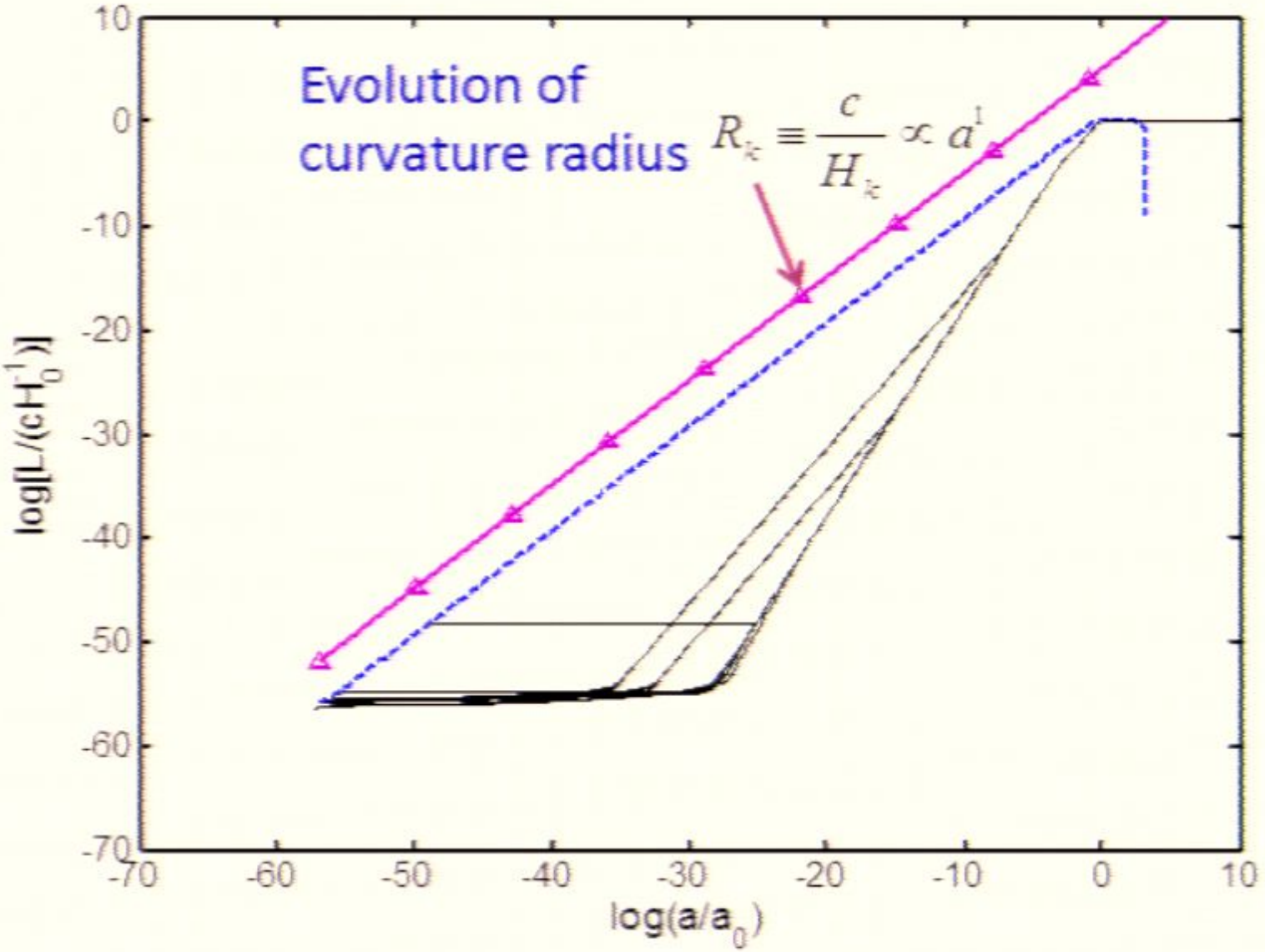
2) A technical point about ergodicity

3) de Sitter Equilibrium ⟸

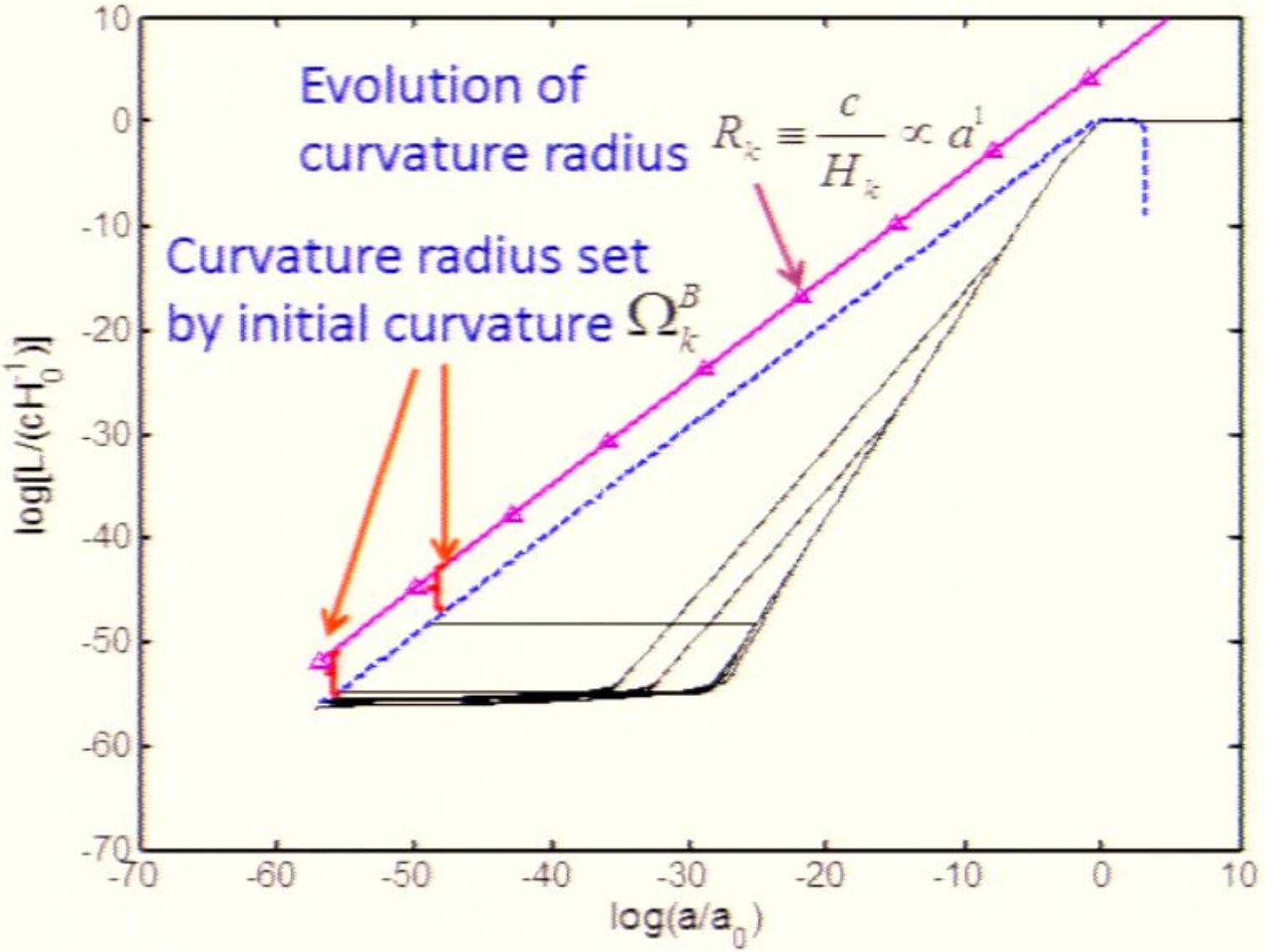
4) Cosmic curvature from de Sitter Equilibrium

dSE Cosmology and cosmic curvature

- The Guth-Farhi process starts inflation with an initial curvature set by the curvature of the Guth-Farhi Bubble Ω_k^B
- Inflation dilutes the curvature, but dSE cosmology has a minimal amount of inflation



AA: arXiv:1104.3315



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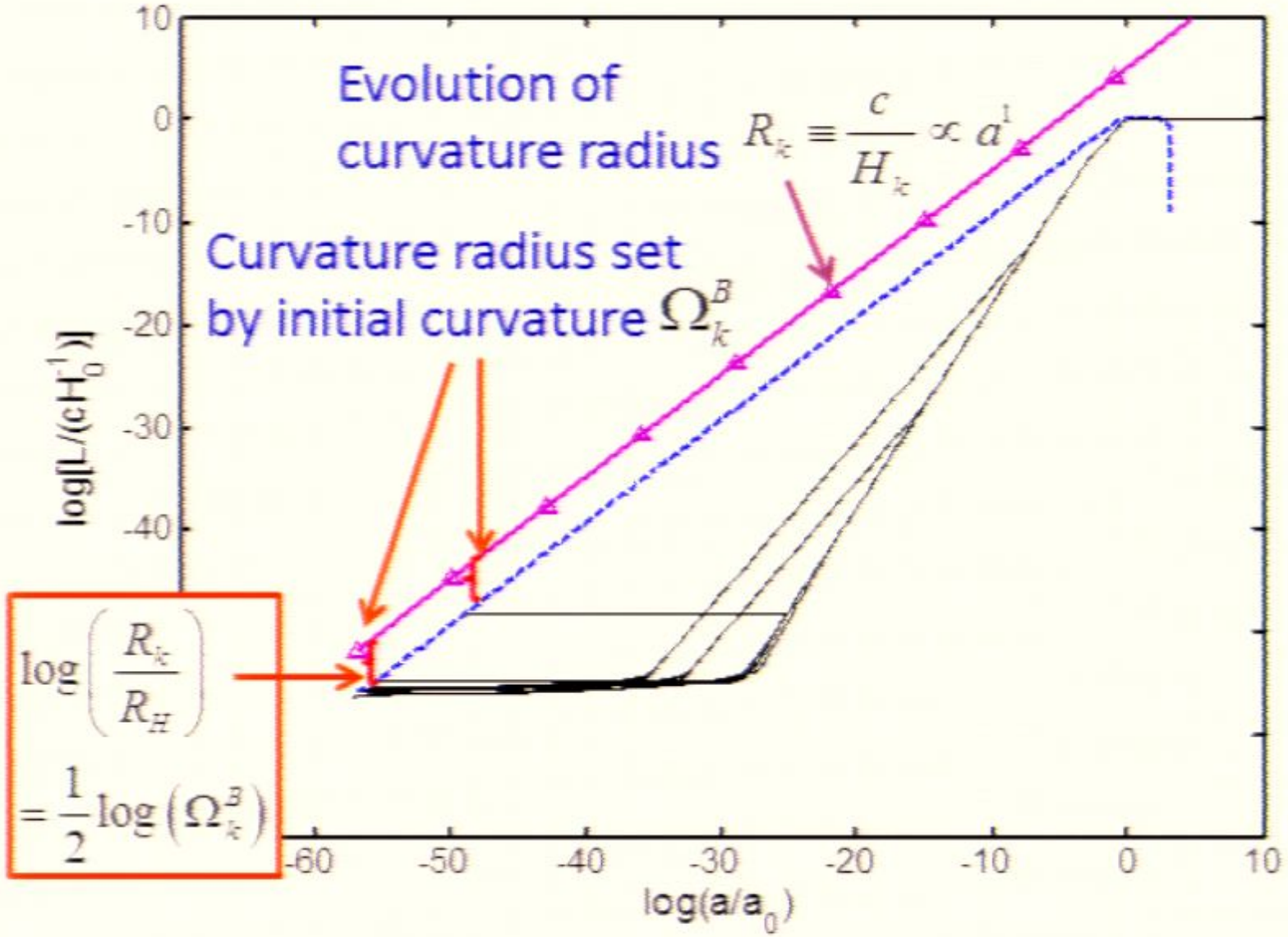

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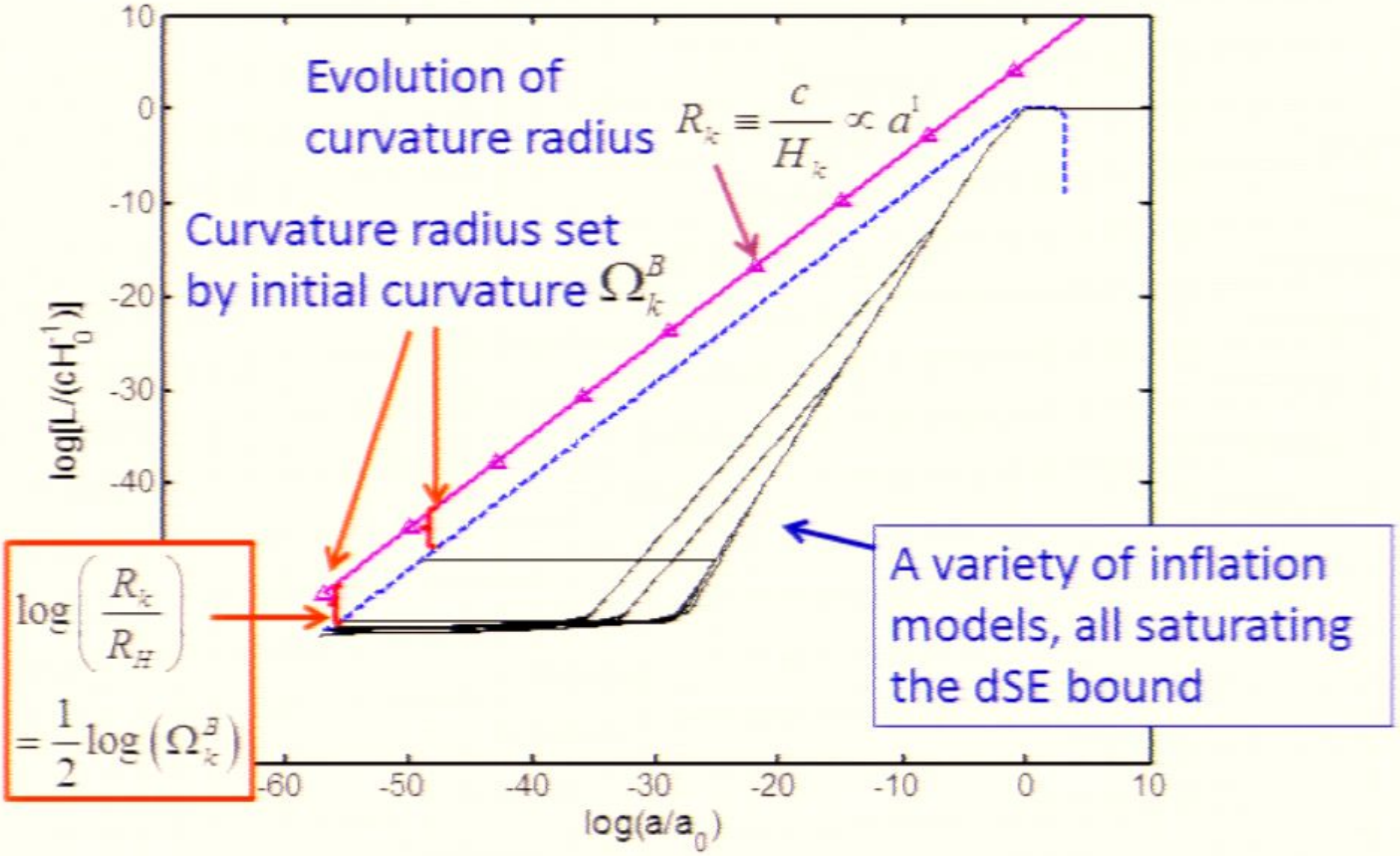

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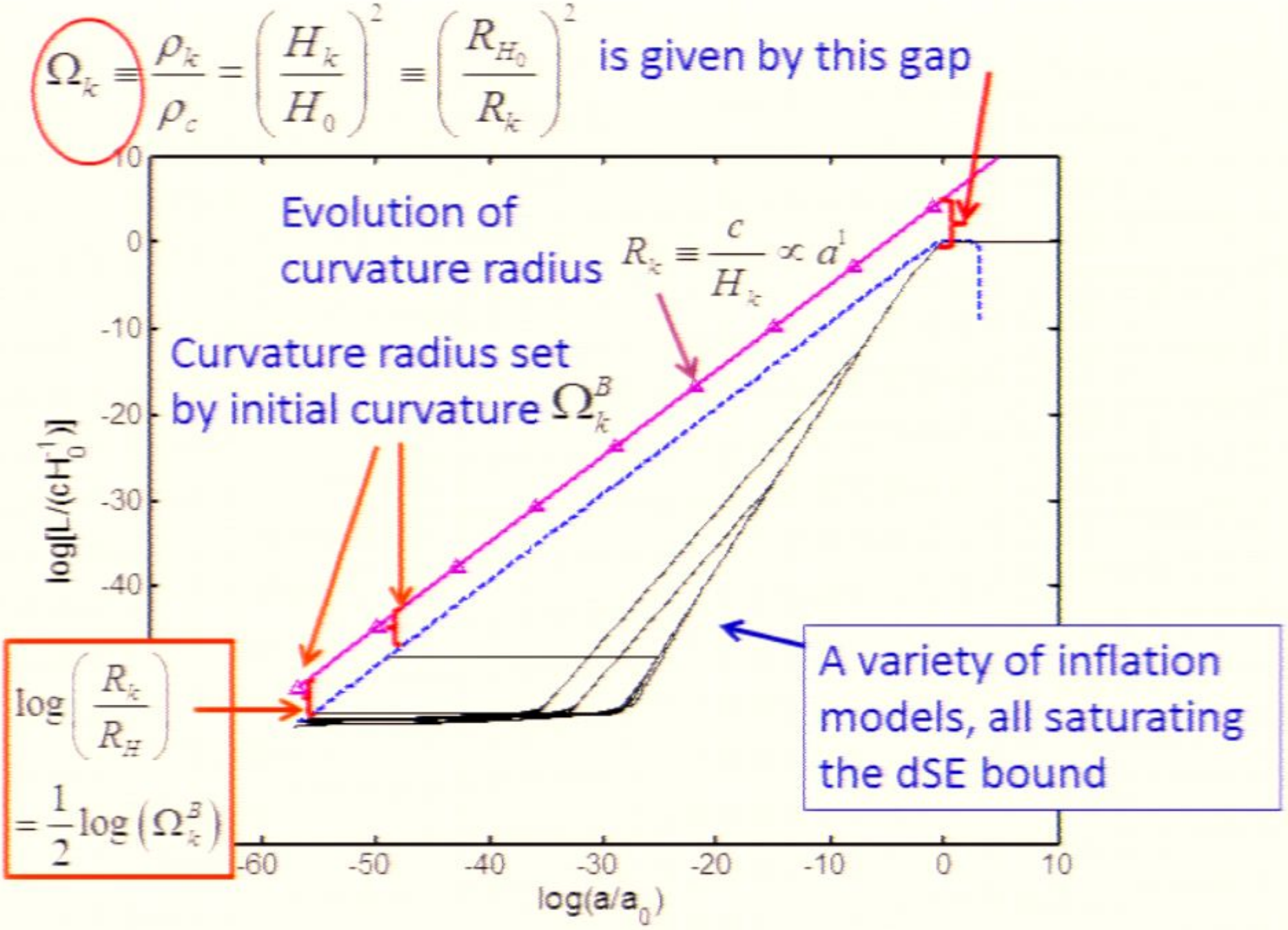
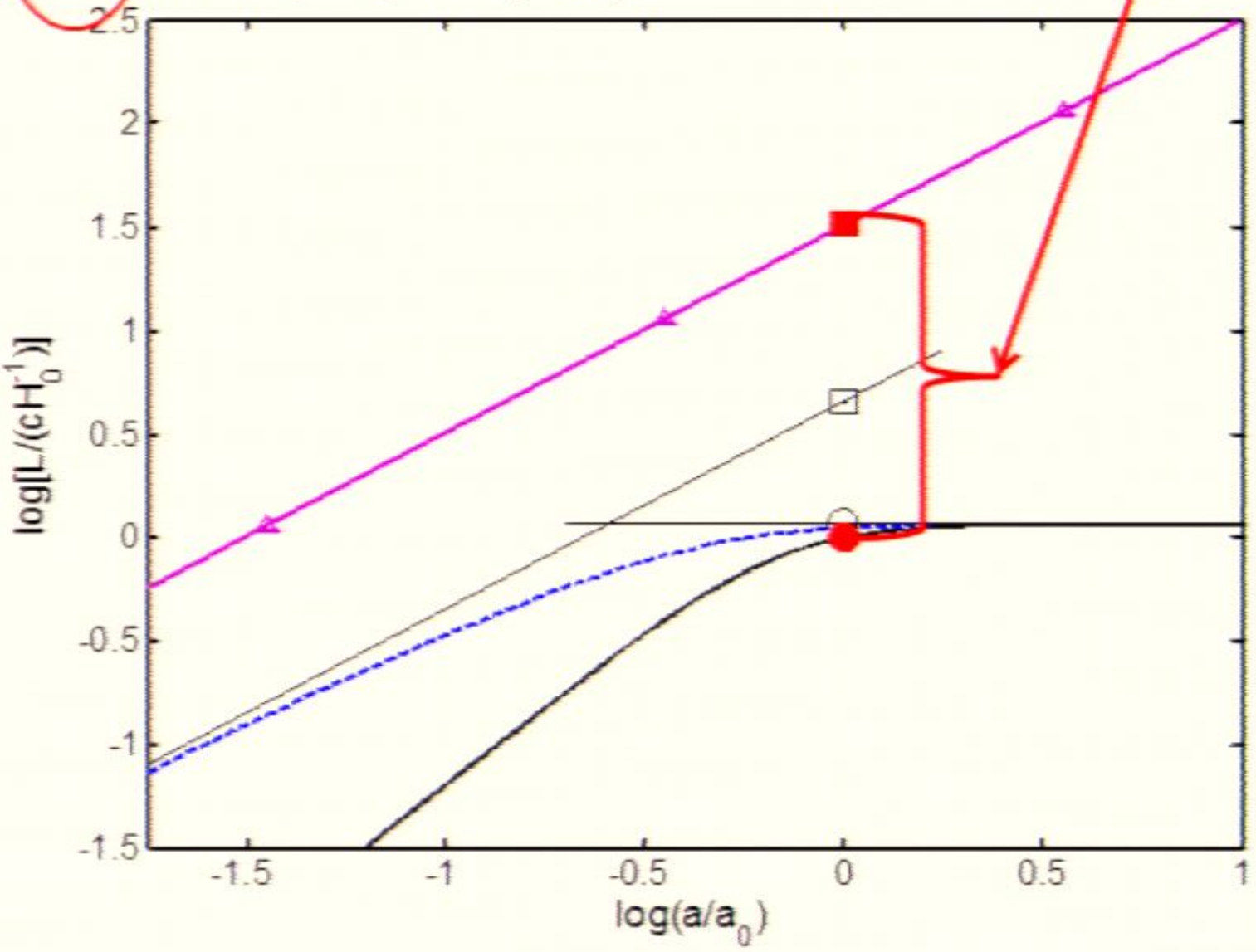


AA: arXiv:1104.3315

$$\Omega_k \equiv \frac{\rho_k}{\rho_c} = \left(\frac{H_k}{H_0}\right)^2 \equiv \left(\frac{R_{H_0}}{R_k}\right)^2$$ is given by this gap



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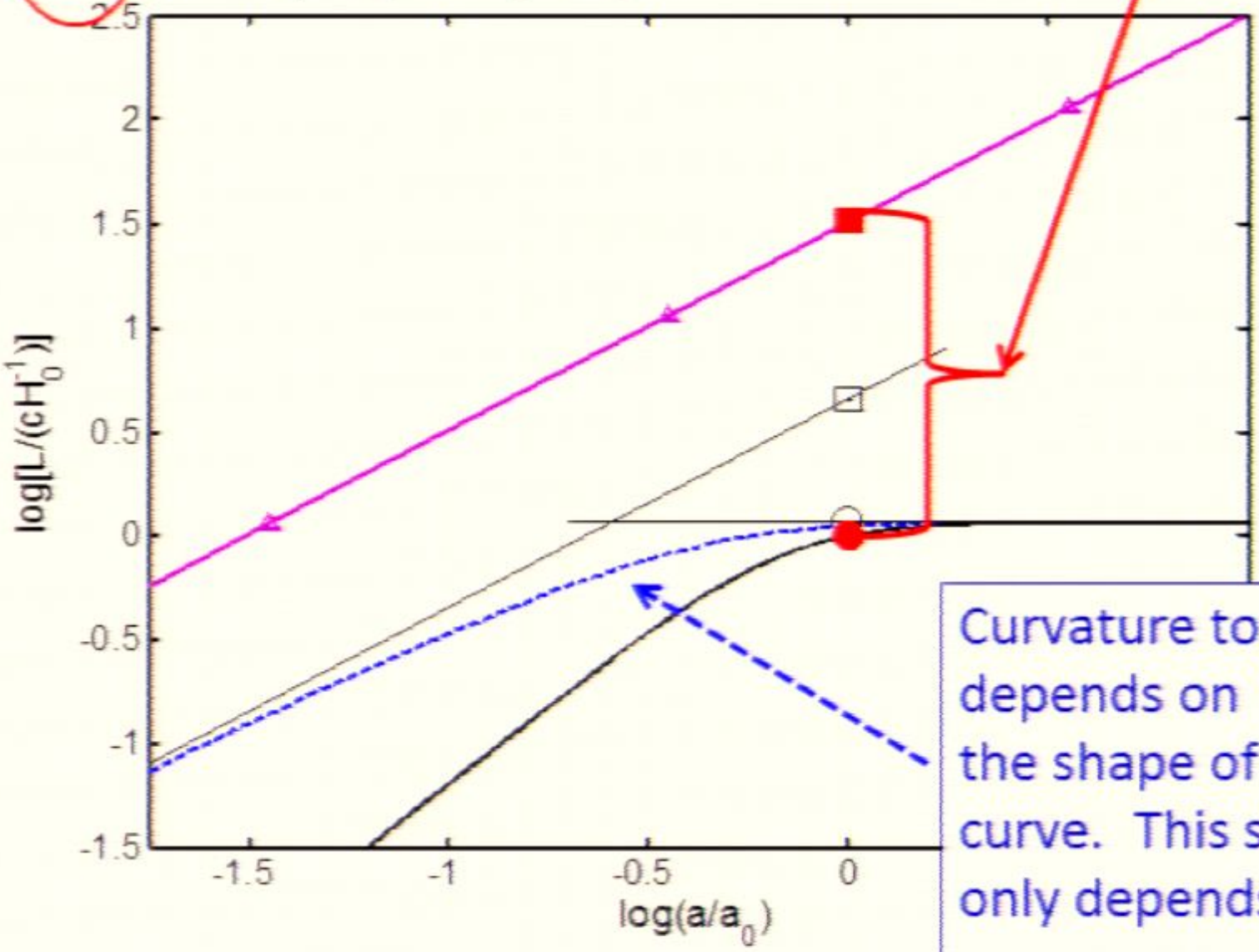


Curvature today only depends on Ω_k^B and the shape of this curve. This shape only depends on $\frac{\rho_m^0}{\rho_\Lambda}$

AA: arXiv:1104.3315

dSE Cosmology and cosmic curvature

- The Guth-Farhi process starts inflation with an initial curvature set by the curvature of the Guth-Farhi bubble Ω_k^B
- Inflation dilutes the curvature, but dSE cosmology has a minimal amount of inflation

$$\Omega_k = \frac{1}{g^2} \frac{\Omega_k^B}{\left(\frac{\rho_m^0}{\rho_\Lambda} + \frac{\rho_k^0}{\rho_\Lambda} + 1 \right)}$$

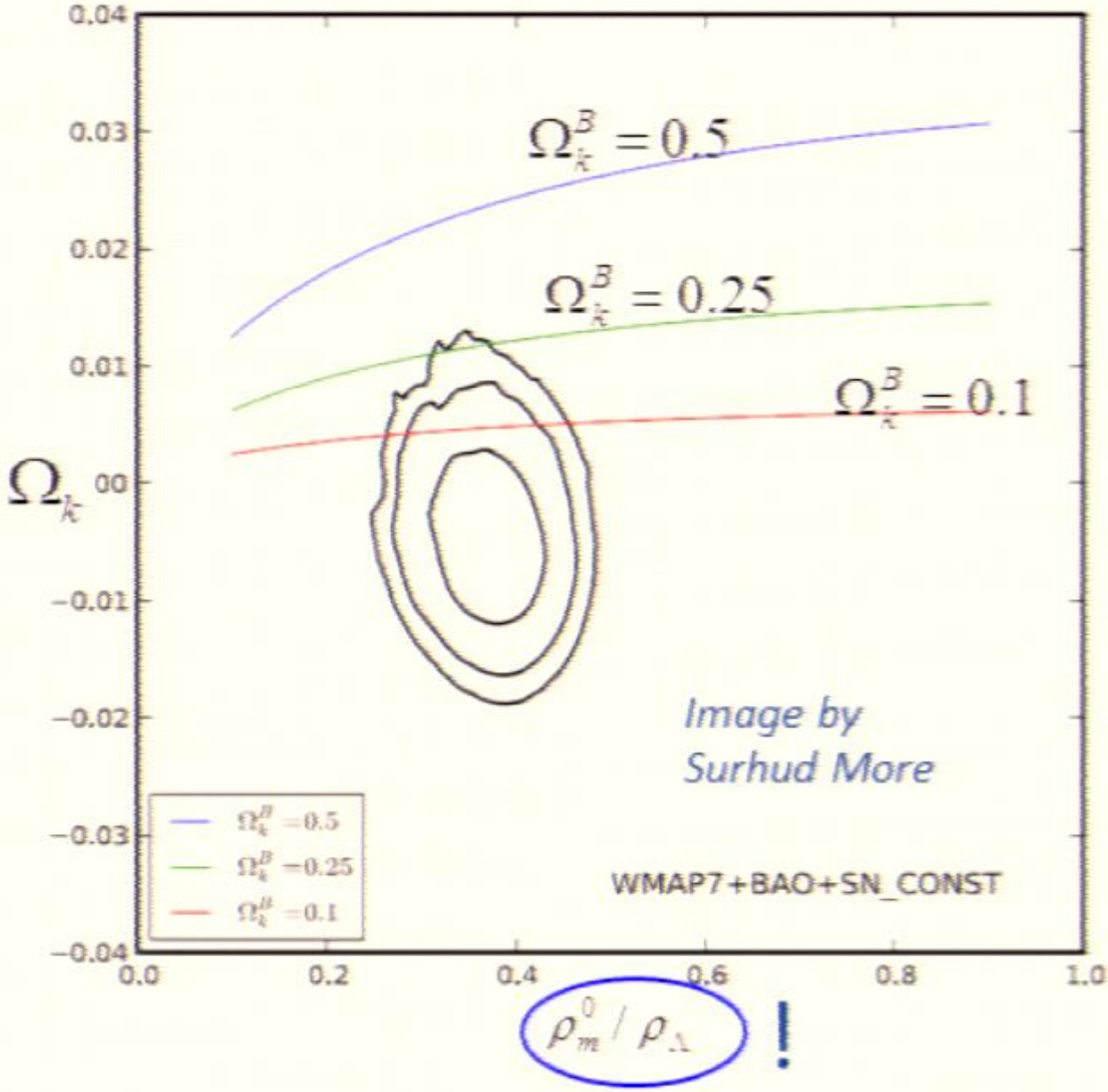
where

$$g\left(\frac{\rho_m^0}{\rho_\Lambda}, \frac{\rho_k^0}{\rho_\Lambda} \right) \equiv \int_0^\infty \frac{dx}{x^2 \sqrt{x^{-3} \frac{\rho_m^0}{\rho_\Lambda} + x^{-2} \frac{\rho_k^0}{\rho_\Lambda} + 1}}$$

AA: arXiv:1104.3315

Predicted Ω_k from dSE cosmology is:

- Independent of almost all details of the cosmology
- Just consistent with current observations
- Will easily be detected by future observations



!

Work in progress on expected values of Ω_k^B (Andrew Ulvestad & AA)

Conclusions

- The search for a "big picture" of the Universe that explains why the region we observe should take this form has proven challenging, but has generated exciting ideas.
- We know we can do science with the Universe
- It appears that there is something right about cosmic inflation
- dSE cosmology offers a finite alternative to the extravagant (and problematic) infinities of eternal inflation
- Predictions of observable levels of cosmic curvature from dSE cosmology will give an important future test

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