Title: Fun with dark energy

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Abstract: The discovery of cosmic acceleration has generated tremendous excitement among researchers in fundamental physics and cosmology. Most experts agree that nothing short of a revolution will be required to fully integrate the observed cosmic acceleration (which many attribute to a mysterious "dark energy") with established physics. Currently this discovery is driving very exciting research in both the theoretical and observational domain. I will present two of these topics that particularly interest me: 1) Dark Energy and Cosmic Equilibrium: How a cosmological constant could make the universe look like a box of gas (and what this could mean for cosmology). 2) Probes of Dark Energy: A host of new probes promise to tell us more about dark energy, but what do we really want to know?

Fun With Dark Energy

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Mar 7 2006

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Outline

Intro

Part I

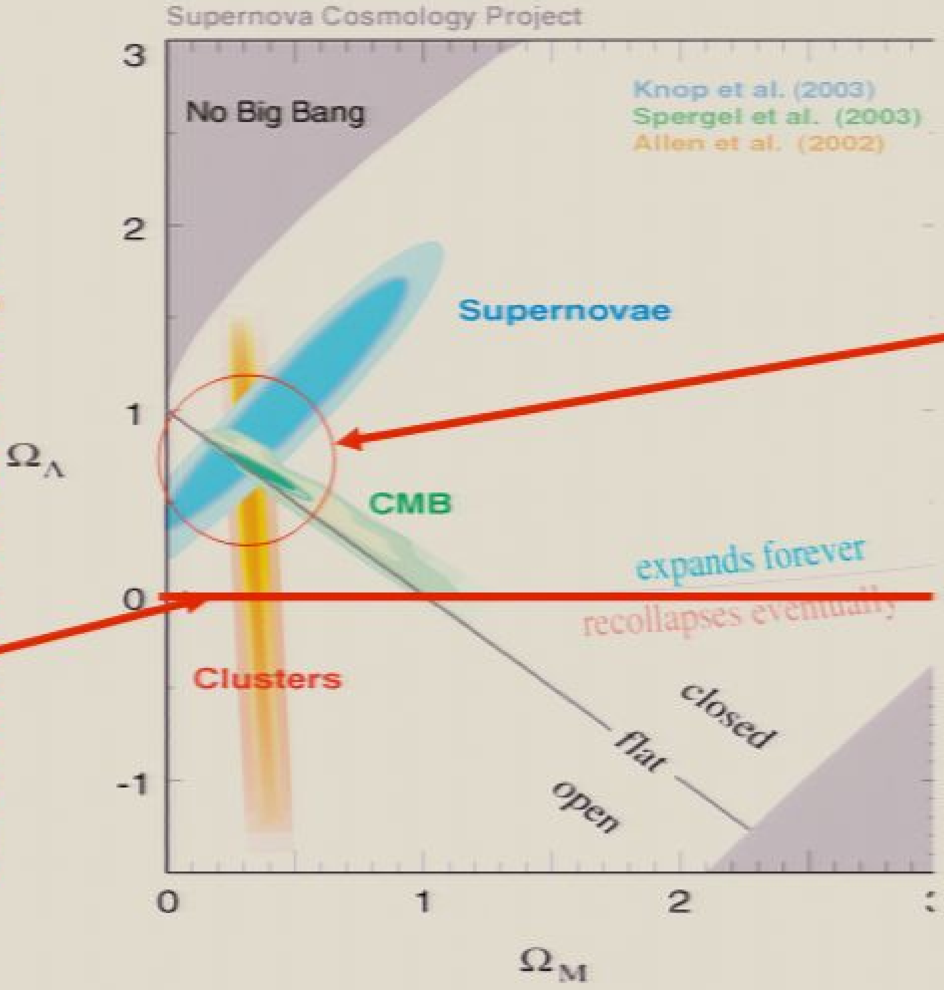
- Cosmic equilibrium
- Equilibrium & Cosmology
- Boltzmann’s Brain

Part II Probing “Dark Energy”

Introduction

Evidence for cosmic acceleration

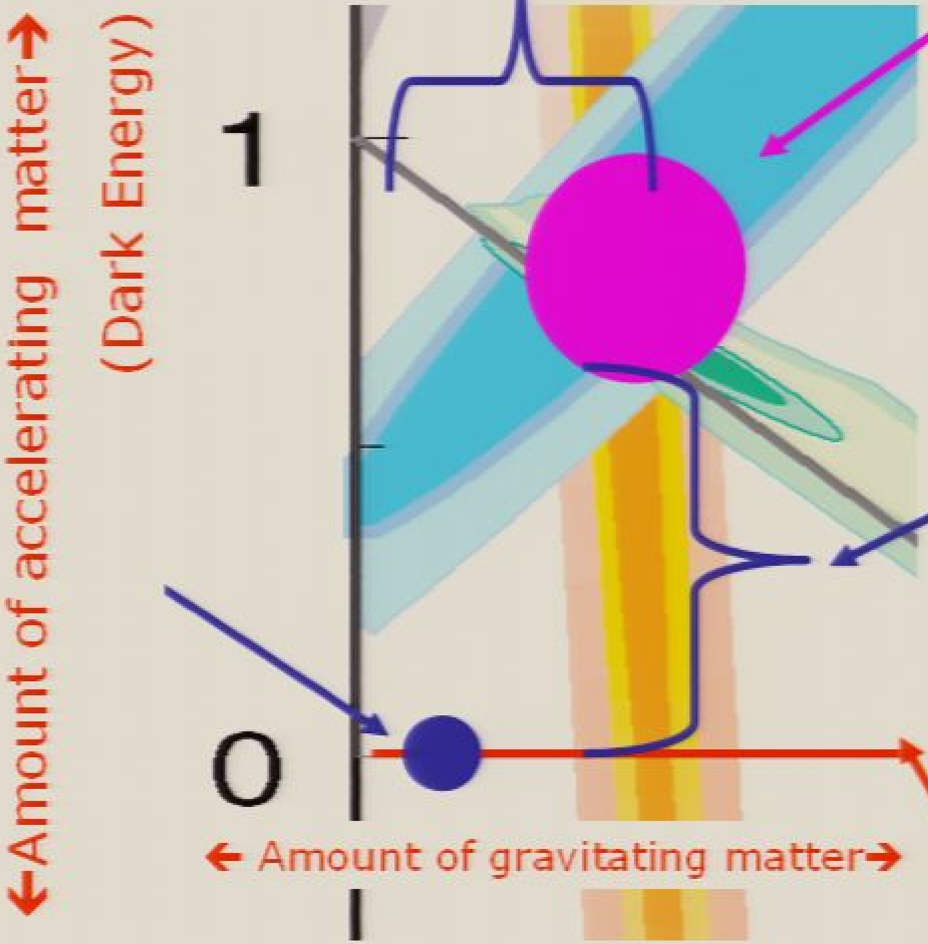
↑ Amount of accelerating matter ↓



Preferred by modern data

"Ordinary" non accelerating matter

← Amount of gravitating matter →



Need to add dark matter here

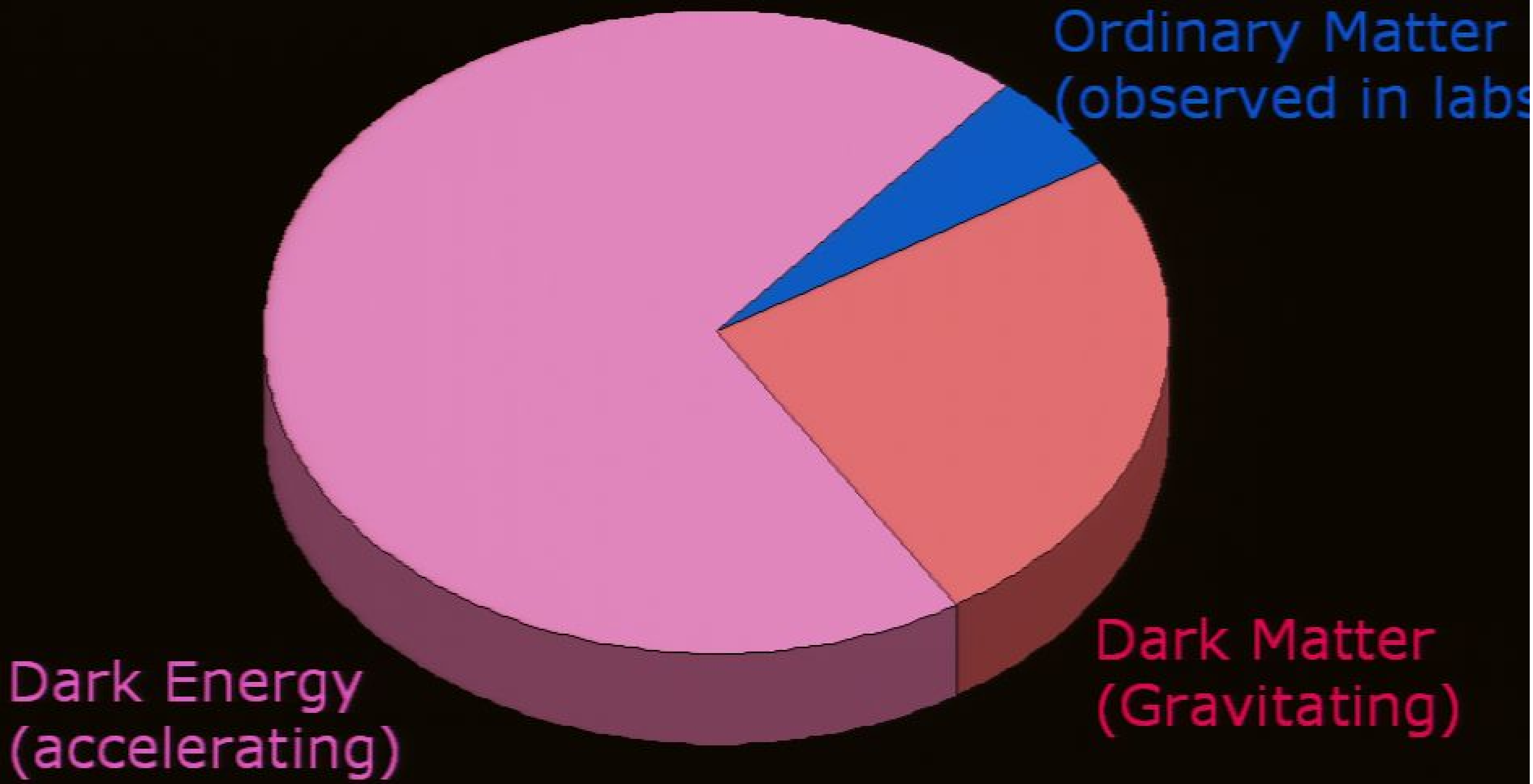
Preferred by modern data

Mass-Energy of the a Universe made *only* matter we know form the lab (‛standard model matter”)

Need to add “dark energy” here

Red line: No accelerating matter

95% of the cosmic matter/energy is a mystery. It has never been observed even in our best laboratories



Dark Matter:

➔ Plausible Candidates in modern particle theories

Dark Energy:

➔ Many theories, NONE are compelling

Dark Matter:

→ Plausible Candidates in modern particle theories

Dark Energy:

→ Many theories, NONE are compelling

Ego test: Number of people who are not authors on their favorite explanation of acceleration ~ 0

The Numbers

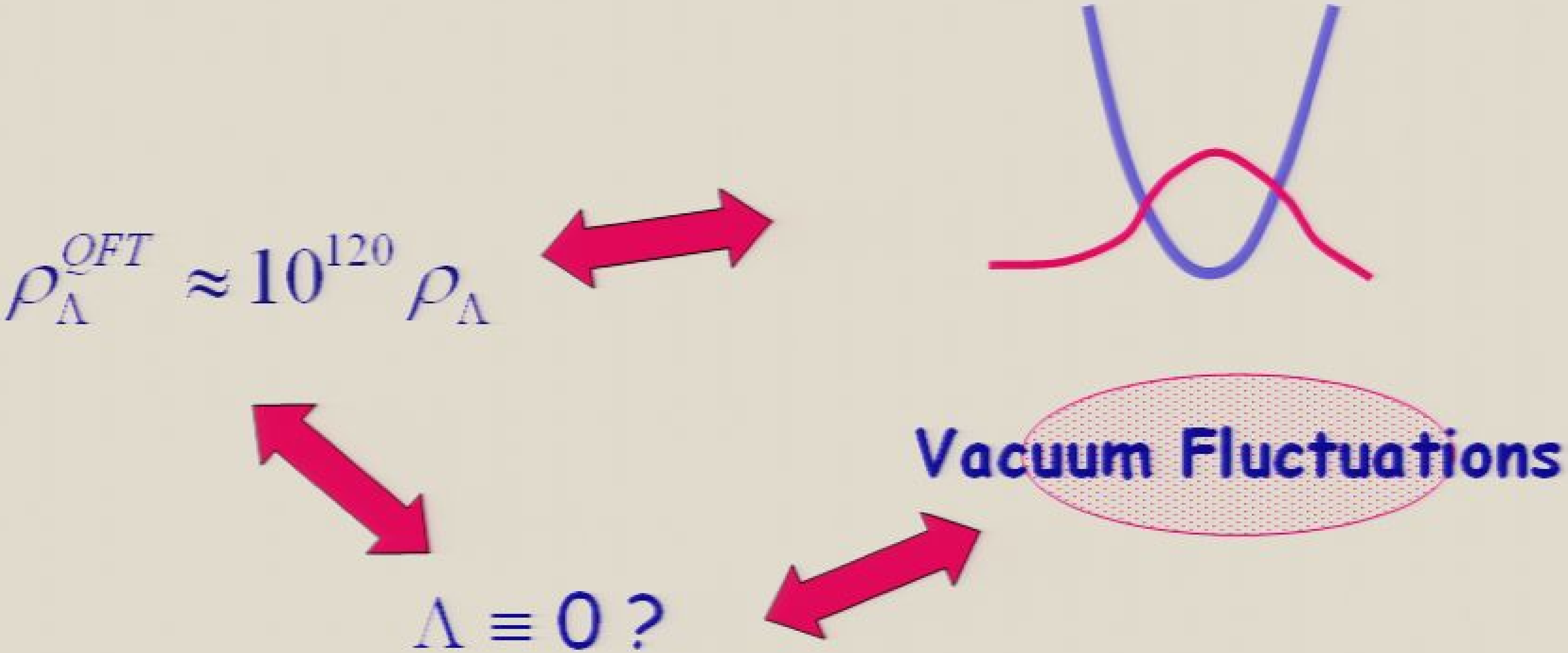
$$\boxed{\rho_{DE} \approx 10^{-120} M_P^4 \approx \left(10^{-3} eV\right)^4}$$

or

$$\boxed{\rho_{DE} \approx M^2 \varphi^2 \approx M^2 M_P^2} \rightarrow \boxed{M \approx 10^{-32} eV}$$

Great unsolved problem in physics:

Why is $\rho_\Lambda \leq 10^{-120}\,\rho_\Lambda^{QFT}$



$$\rho_\Lambda^{QFT} \approx 10^{120}\,\rho_\Lambda$$

Vacuum Fluctuations

$\Lambda \equiv 0$?

Issues

1) Where do these strange numbers come from?

2) How are they protected from quantum corrections?

3) How do unresolved quantum vacuum/quantum gravity problems impact your explanation.

4) Why Now?

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Most experts expect nothing short of a revolution in our understanding of fundamental physics is required to really understand the cosmic acceleration

Issues

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2) How are they protected from quantum corrections?

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Not there yet, but we’re having a lot of fun

4) Why Now?

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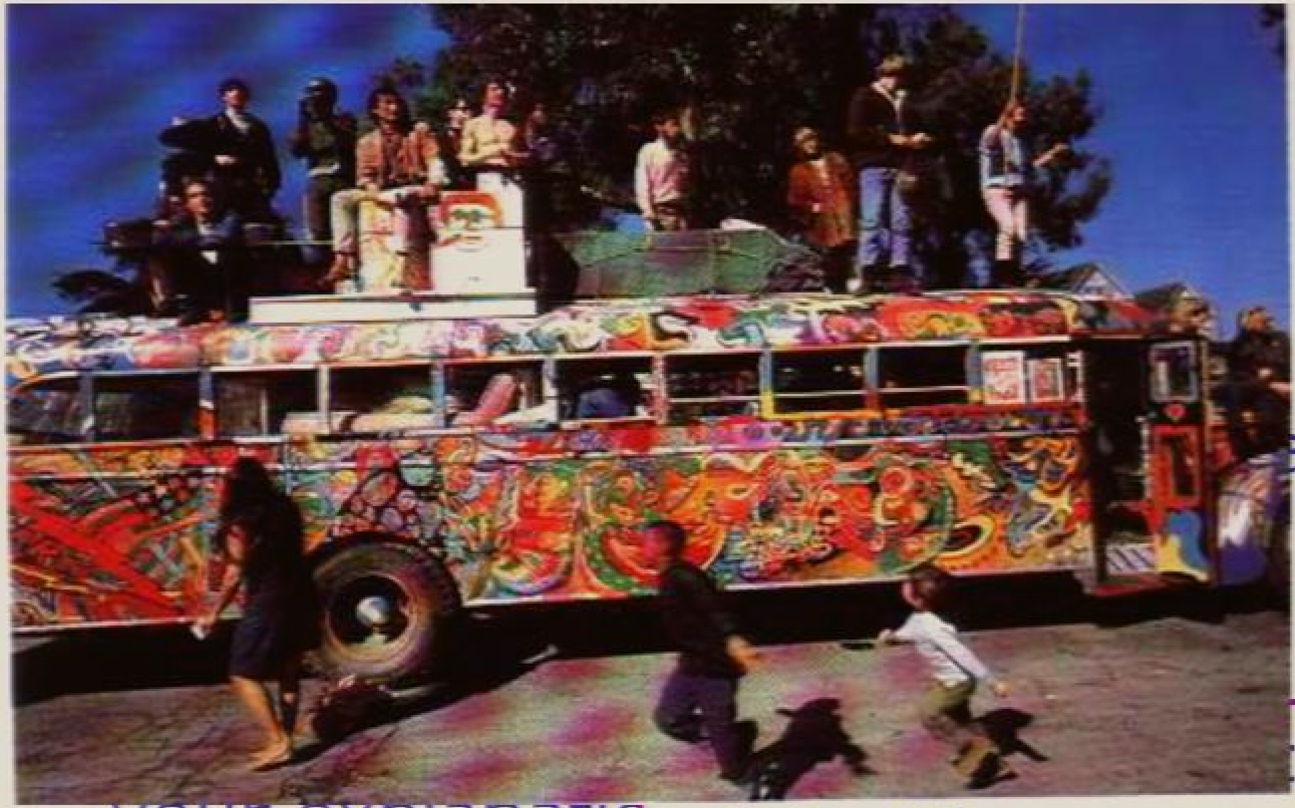

come from?

antum

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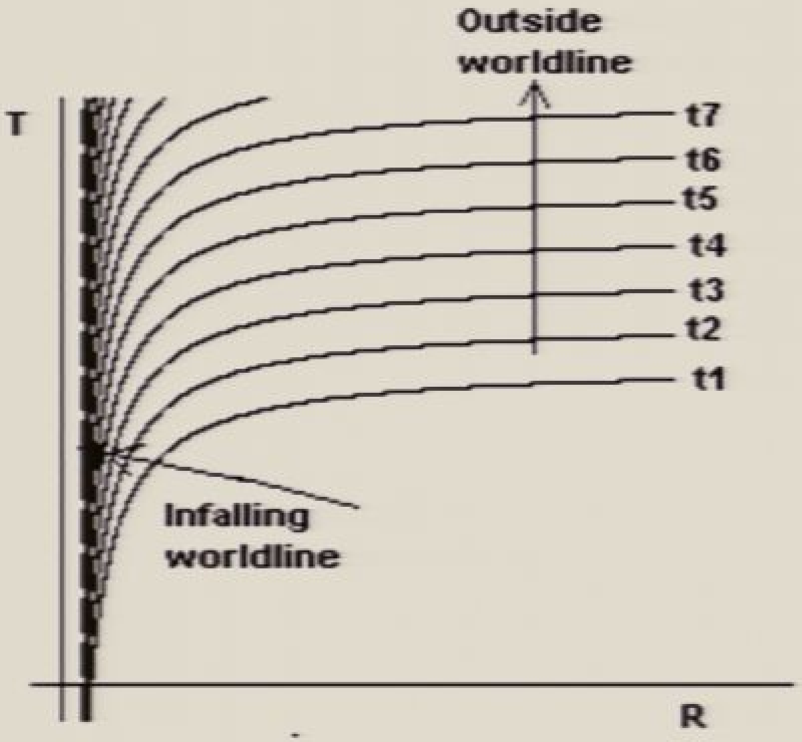
Part I

Some implications for physics and cosmology

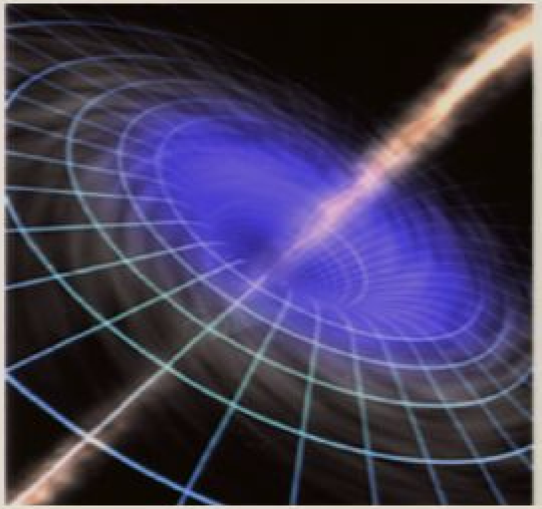
Cosmic equilibrium

An interesting property of some types of dark energy (including a w=-1 cosmological constant): Formation of an event horizon:

Black Hole Event Horizon (schematic):



Outside observer sees in-falling object take infinite time to reach the horizon ("never reaches the horizon")



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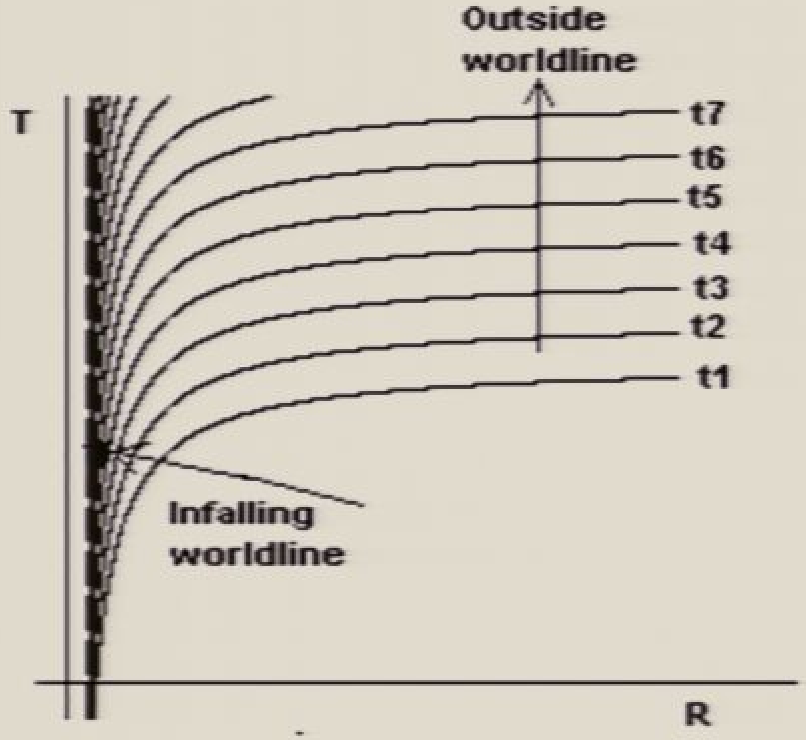

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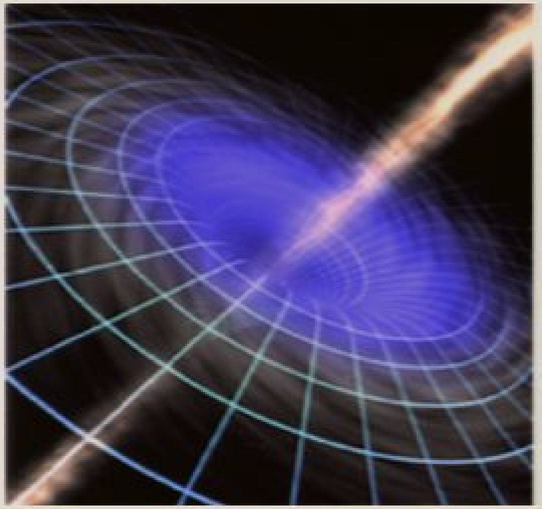

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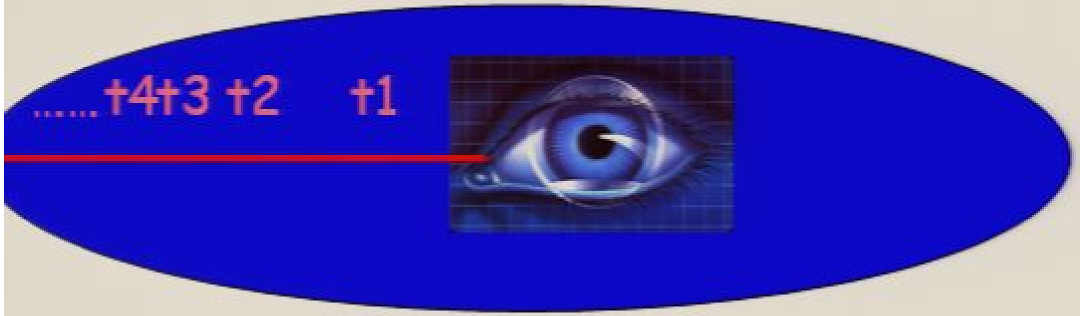
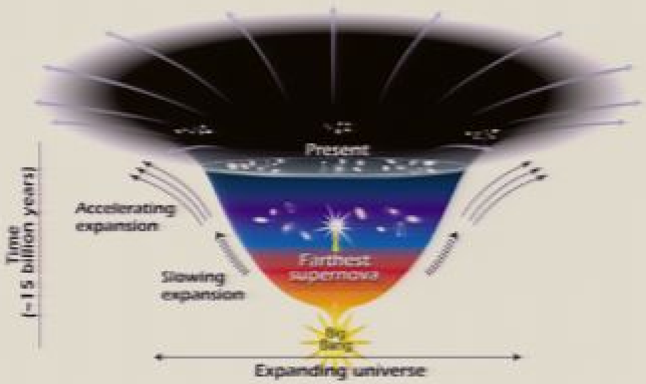


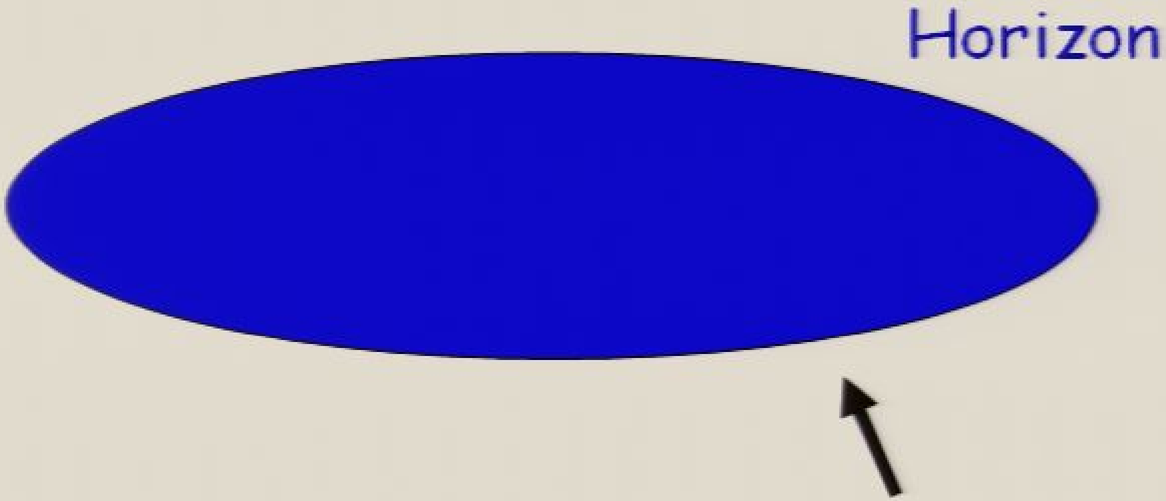
$$S \propto A = H^{-2} = \Lambda^{-1}$$

INSIDE observer sees OUT-flying object take infinite time to reach the horizon ("never reaches the horizon")



"de Sitter Space"

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



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

Quantum effects: Hawking Temperature

Gibbons &
Hawking

$$T = H = \sqrt{\frac{8\pi G}{3}\rho_{DE}} \approx 10^{-28} K$$

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

One consequence: If $S_{deS} = S_{MAX} \geq S = \text{"} \ln N \text{"}$

Should N be finite? Does this mean we must abandon all known fundamental theories?

Banks & Fischler

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Equilibrium & Cosmology

Darwinian Cosmology

Two approaches to the state of the universe (initial conditions for the observed FRW universe)

1. State what the initial condition "must be" (play god)

2. Darwinian: Let all possible states compete. Most probable = your prediction

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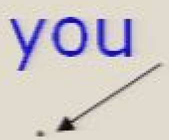
2. Darwinian: Let all possible states
   Most probable = your prediction

Needs a scheme for assigning probabilities (back to 1)?)

Only way out: In Eqm, nature tells <u>you</u> how to assign probabilities.

Problems with 1.

(State what the initial conditions "must be")



Problems with 1.

(State what the initial

the universe

you

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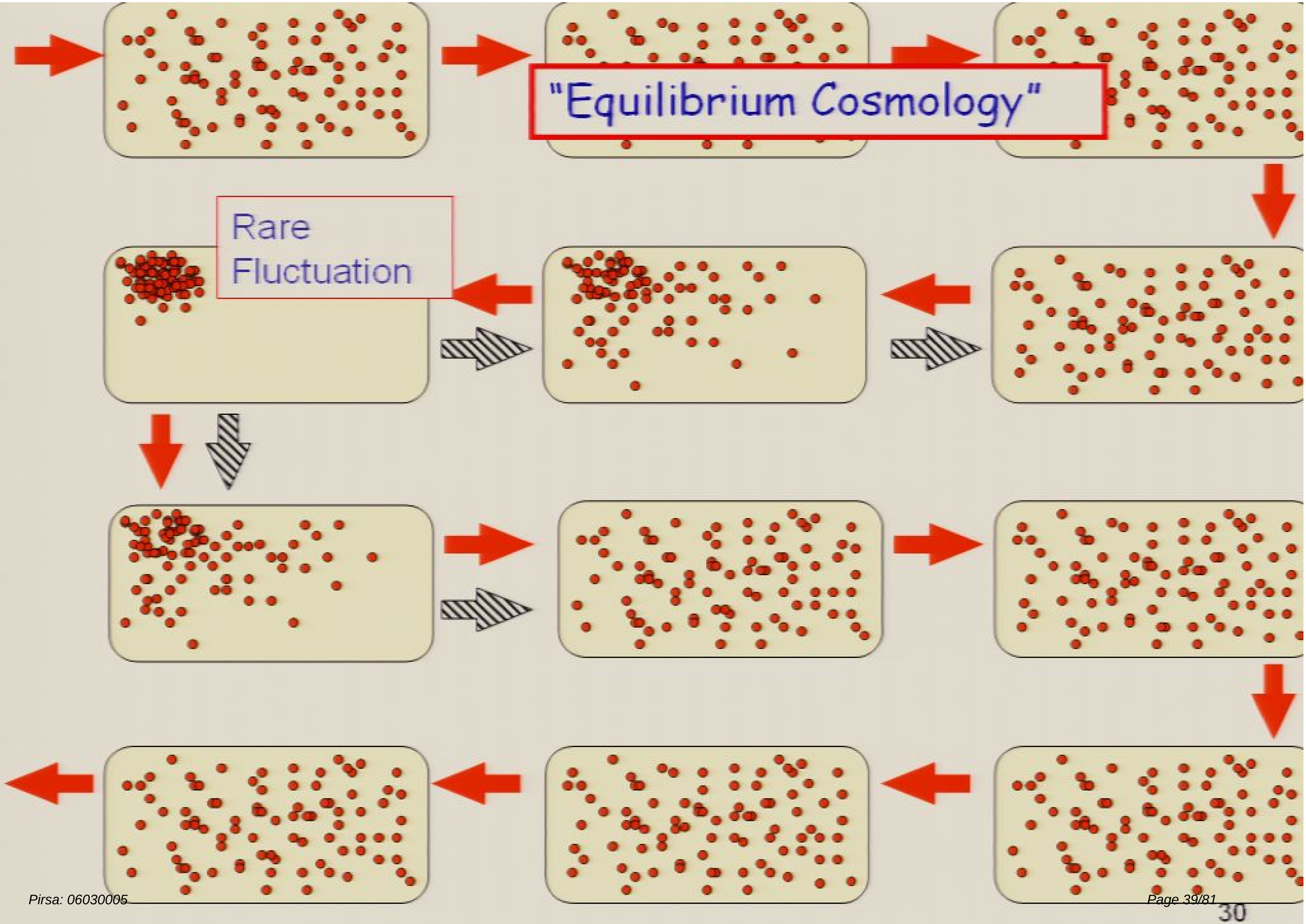
(State what the initial

the universe

Is the universe listening?

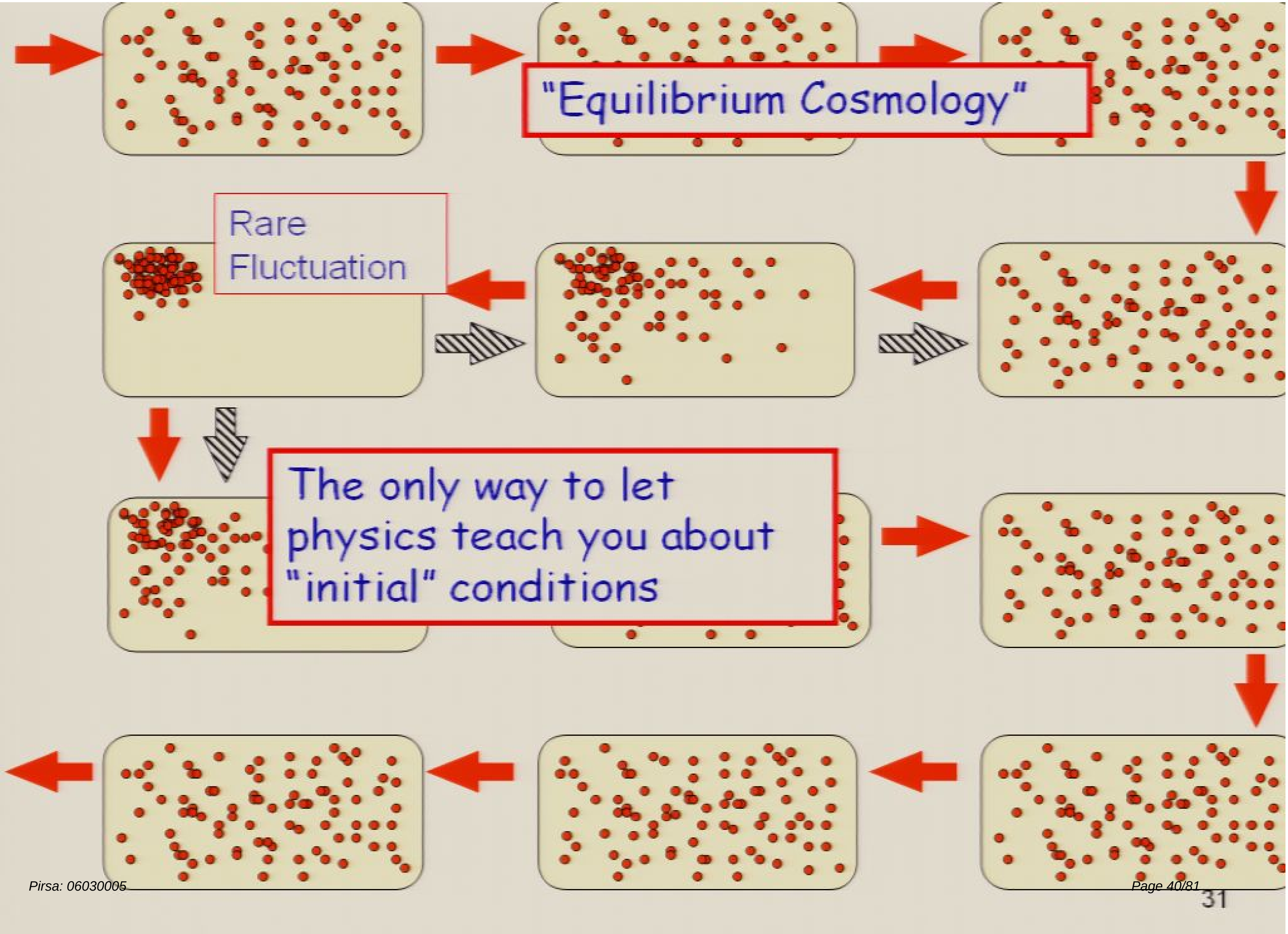
you

de Sitter equilibrium gives the one chance I know to use eqm as a basis for cosmology



"Equilibrium Cosmology"

Rare Fluctuation

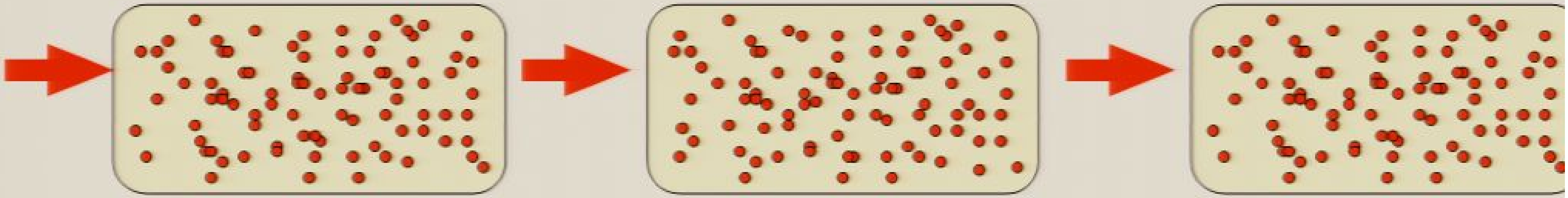


"Equilibrium Cosmology"

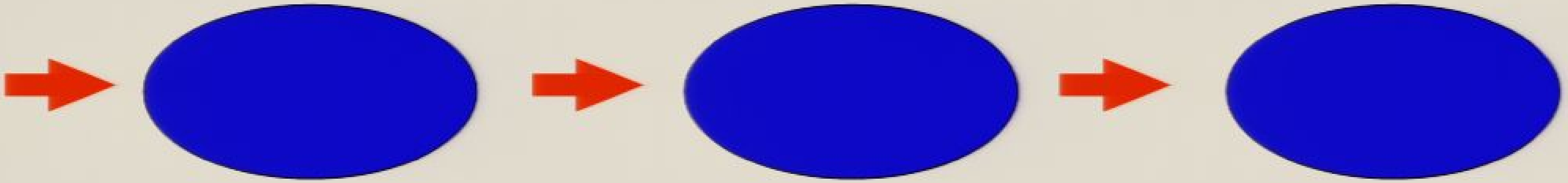
Rare Fluctuation

The only way to let physics teach you about "initial" conditions

Concept:



Realization:



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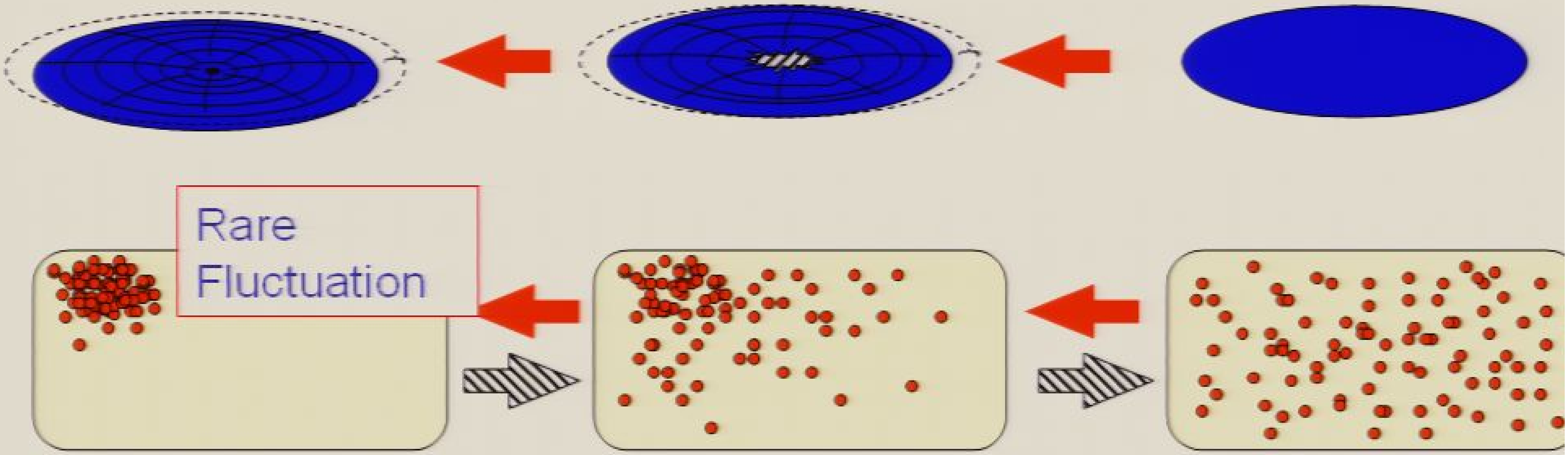


Rare Fluctuation

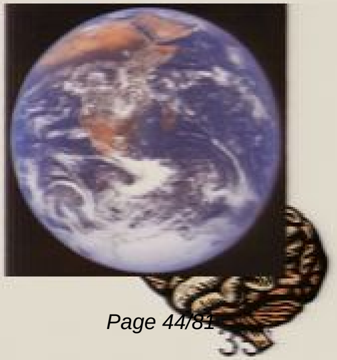
Boltzmann’s Brain

- Boltzmann’s Brain paradox:

➔The most likely fluctuation consistent with everything you know is your world (actually just your brain) fluctuating out of chaos and immediately re-equilibrating.

➔ Only inflation has an answer to this paradox. With inflation, most probable way to create one brain (or planet) comes packaged with a huge flat universe (+body, fellow creatures etc)

➔This is as least as important as the other successes of inflation!



But

Two versions of the story

Version 1

- Initial fluctuations that start inflation are a small perturbation on Eqm and are thus "cheap".
- Inflation much more likely than the whole universe "fluctuating directly"
- Solve "Boltzmann's Brain" problem and have predictive power in cosmology

Version 2

- Initial fluctuations that start inflation are much more "expensive" the universe (or a brain) fluctuating directly.
- AND standard big bang as we know it is LESS LIKELY than other junk (Boltzmann's brain problem not resolved)

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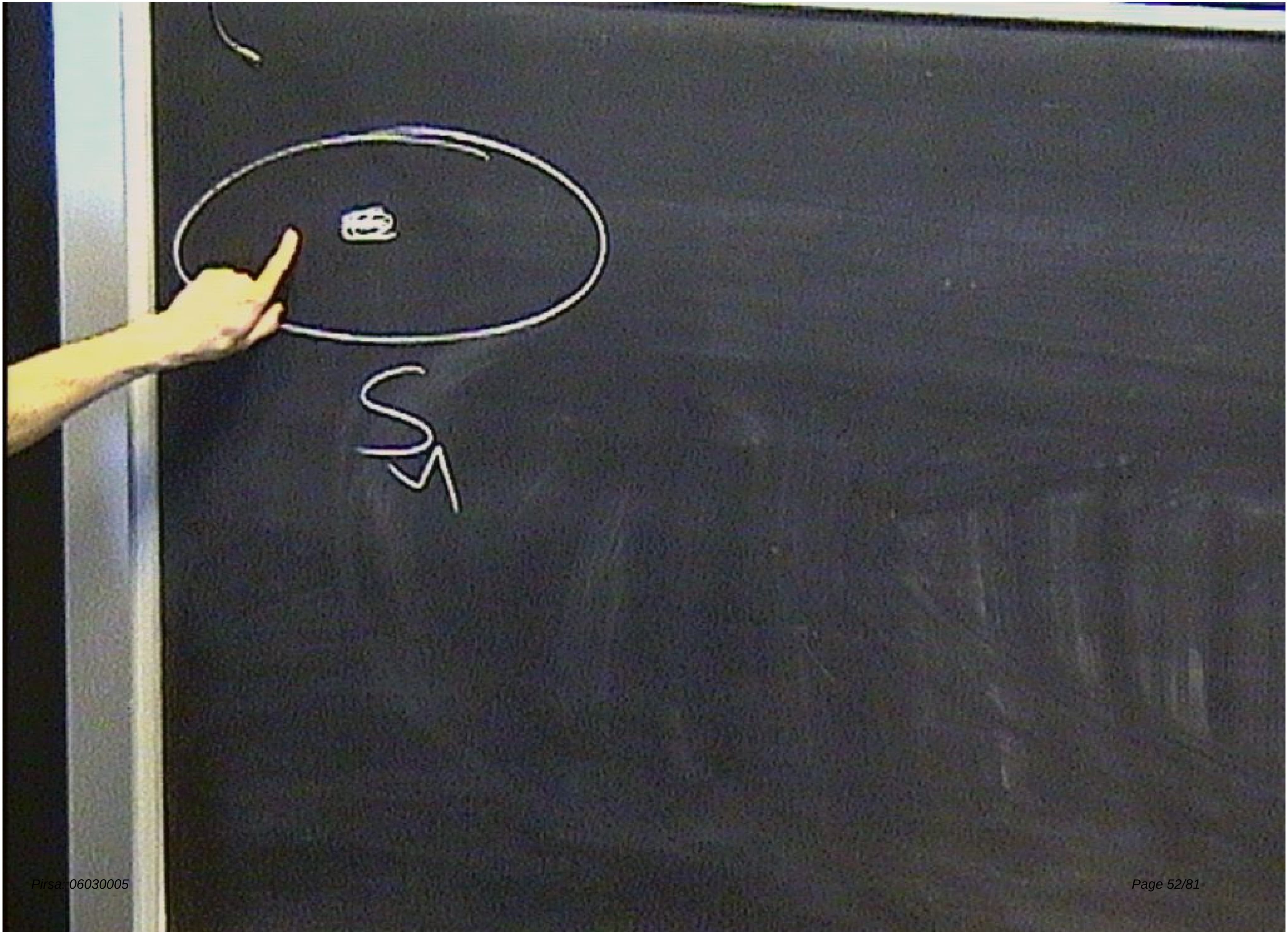
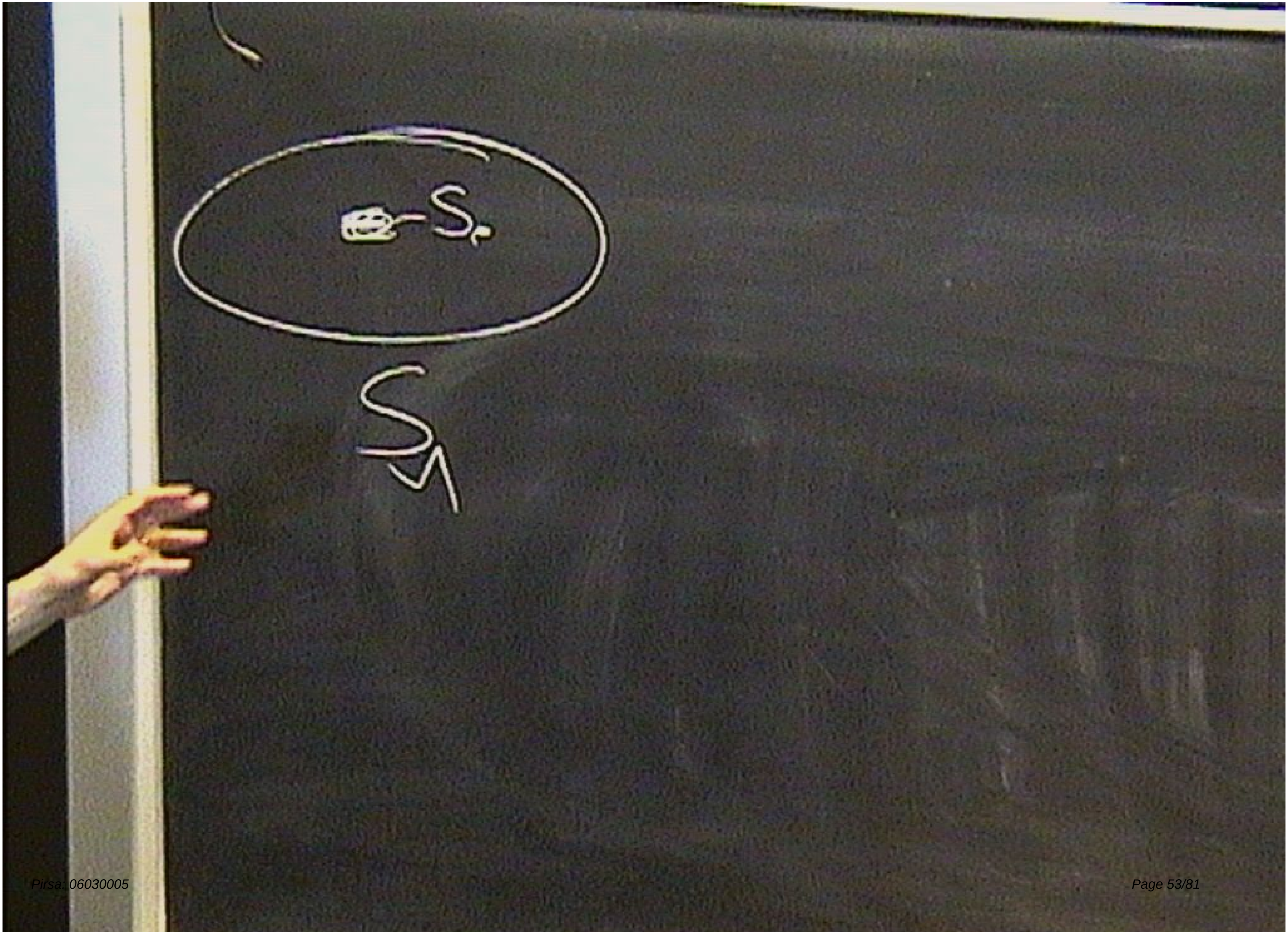
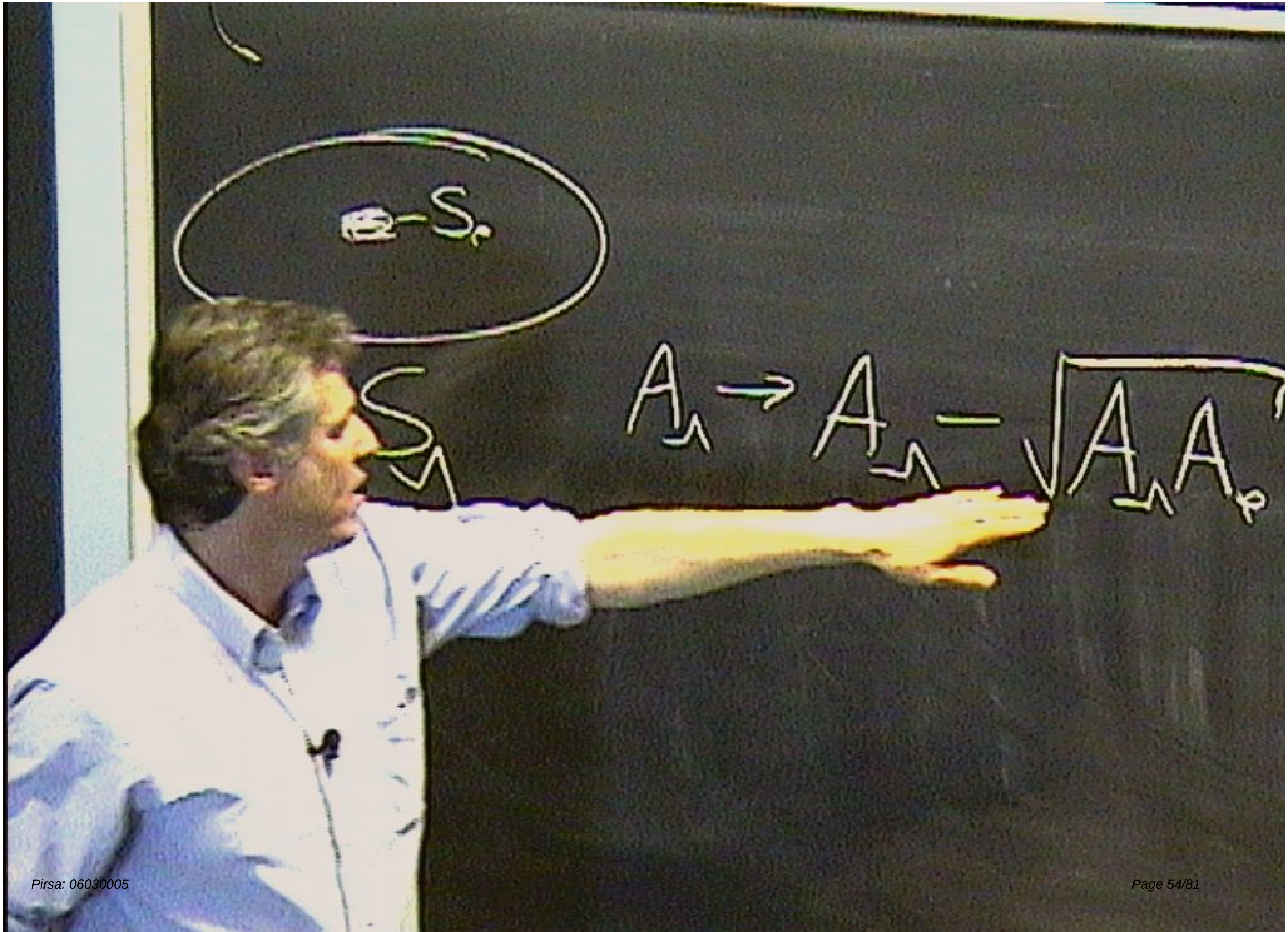
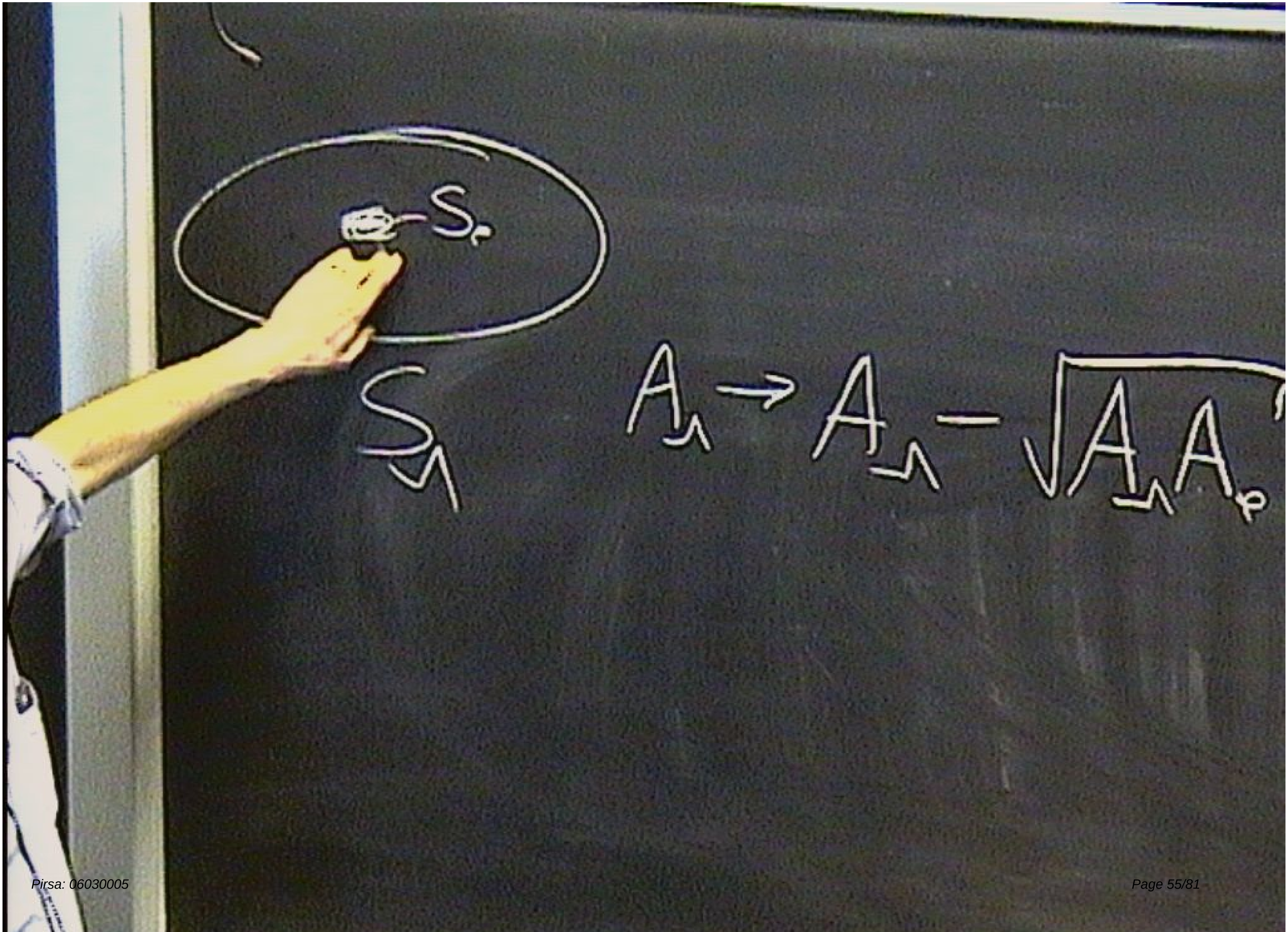


SM


S_e
S_M


$-S_\rho$
S_M
$A_1 \rightarrow A_1 - \sqrt{A_1 A_\rho}$



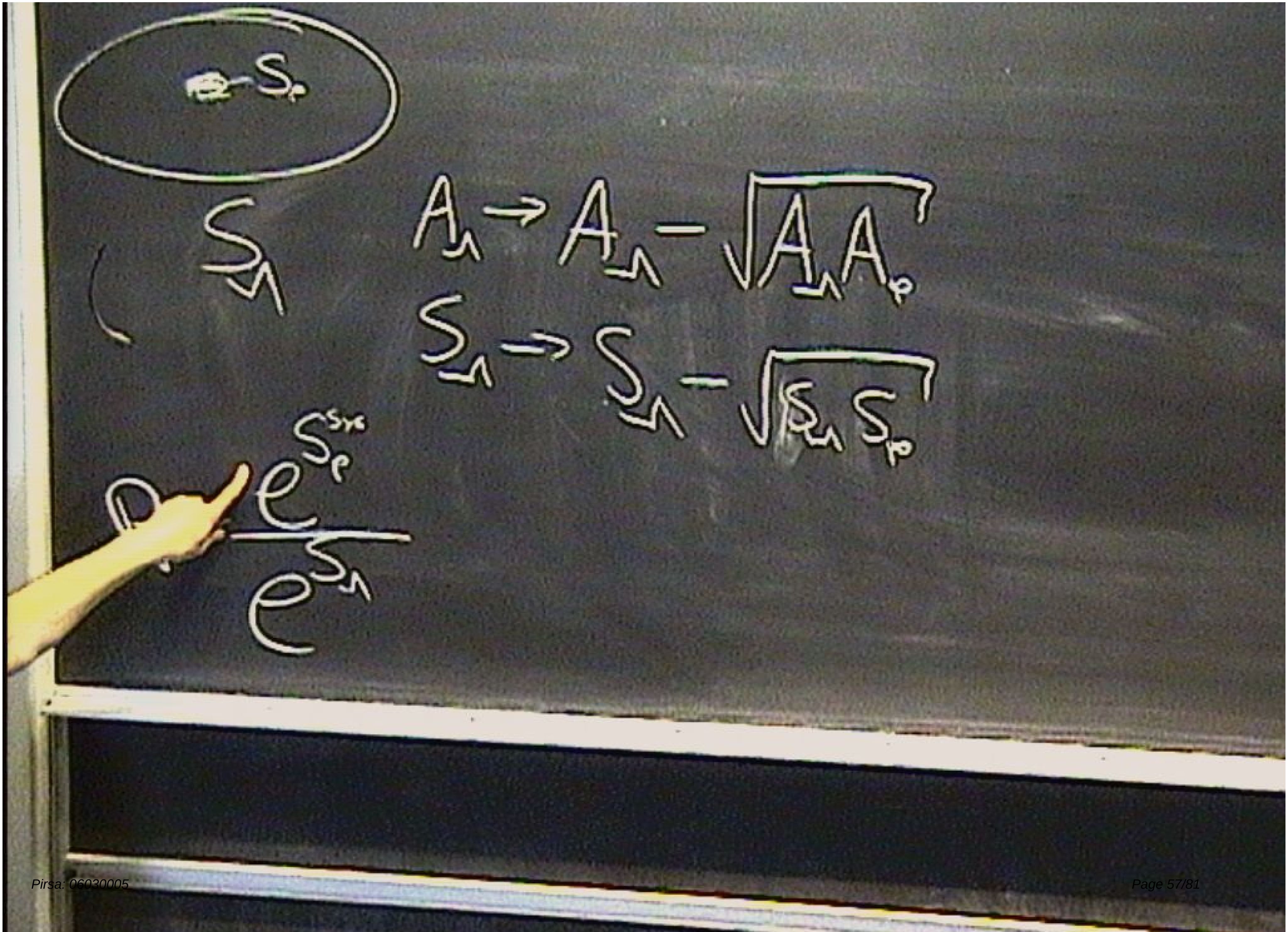
$$A_\Lambda \to A_\Lambda - \sqrt{A_\Lambda A_e}$$

$$\boxed{e-S_\varphi}$$

$$S_\lambda$$

$$A_\lambda \to A_\lambda - \sqrt{A_\lambda A_\varphi}$$

$$S_\lambda \to S_\lambda - \sqrt{S_\lambda S_\varphi}$$



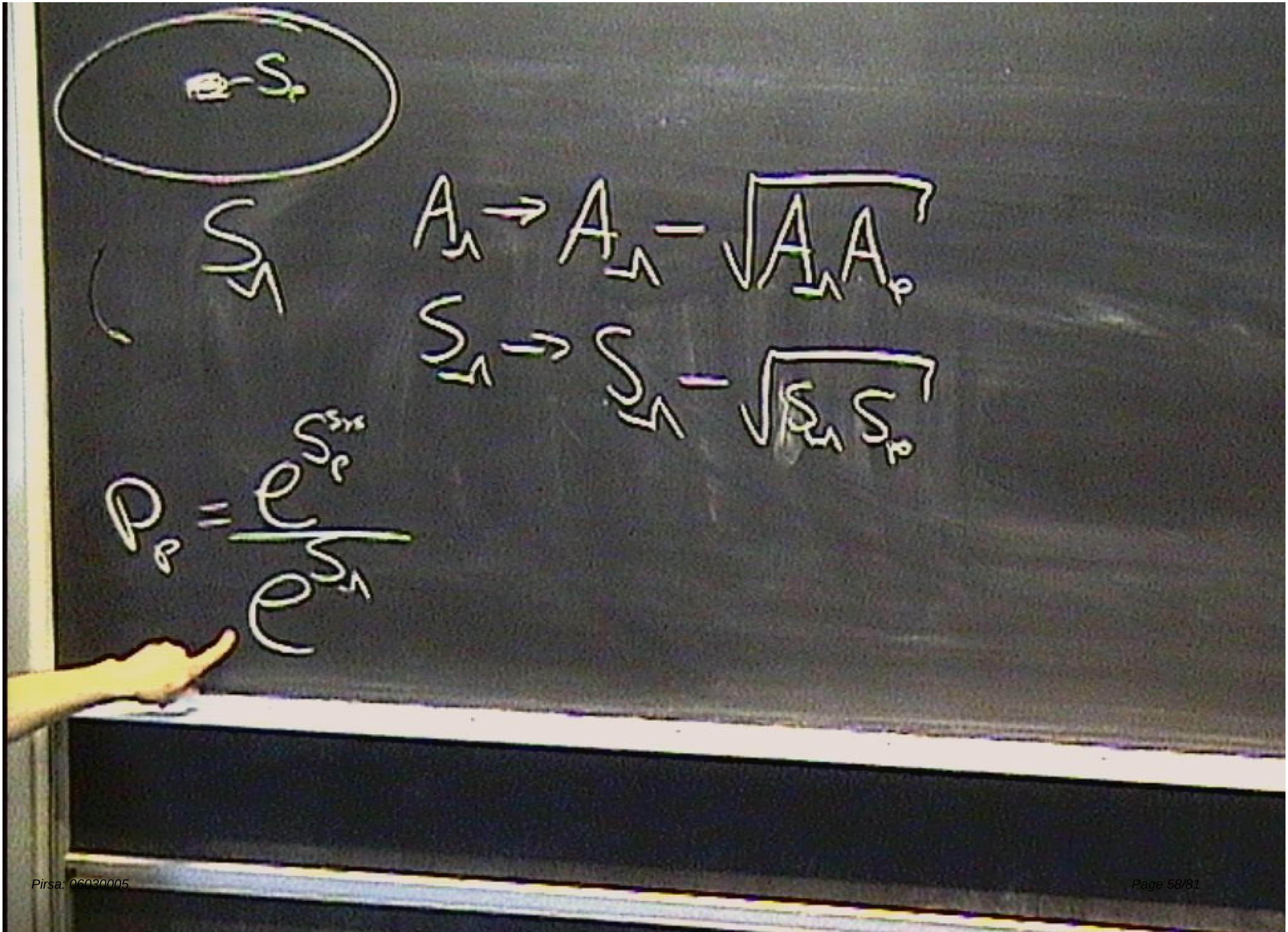
$-S_p$

S_n

$A_n \to A_n - \sqrt{A_n A_p}$

$S_n \to S_n - \sqrt{S_n S_p}$

$\frac{e^{S_p^{sys}}}{e^{S_n}}$



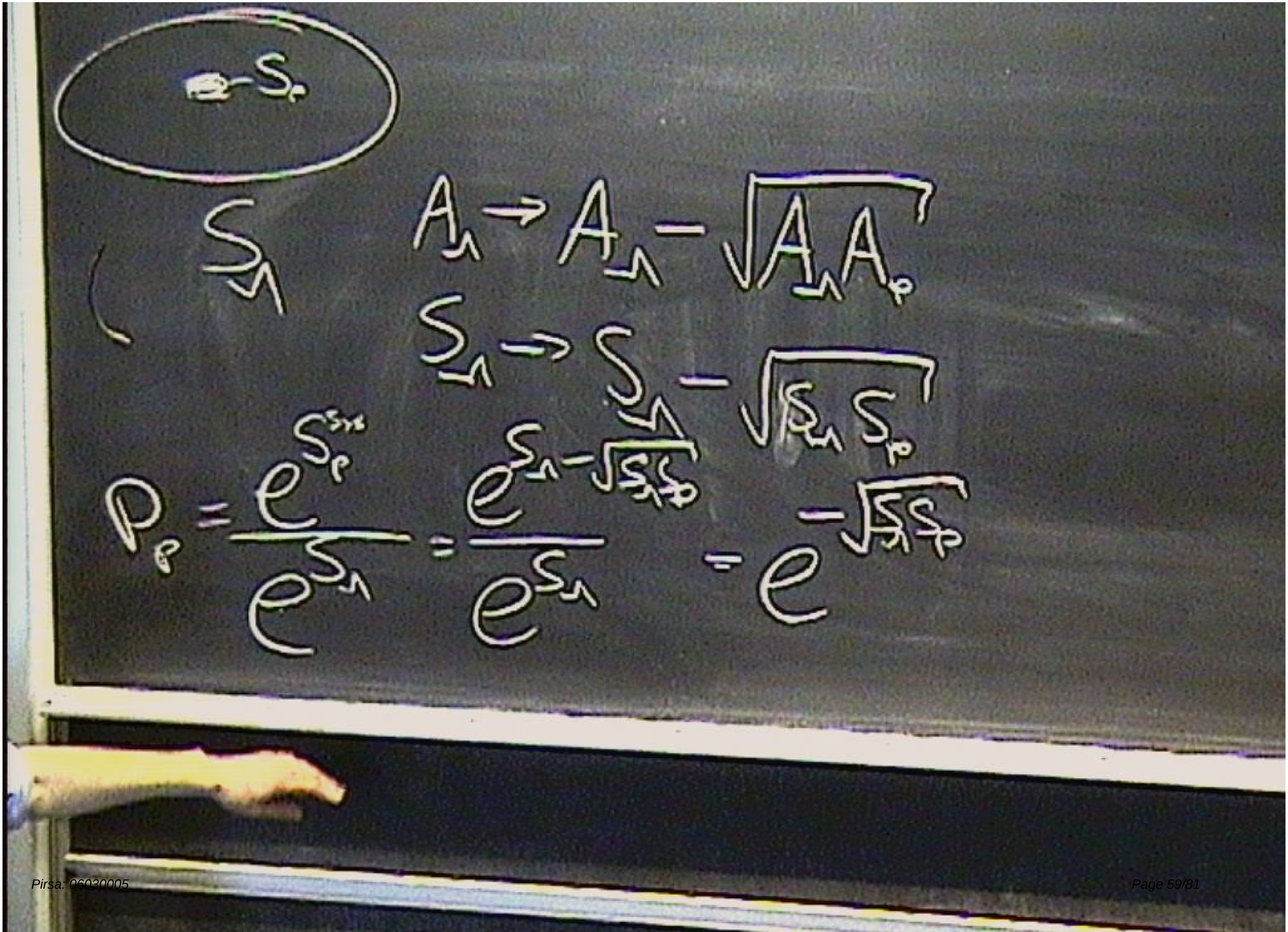
$$-S_p$$

$$S_\lambda$$

$$A_\lambda \to A_\lambda - \sqrt{A_\lambda A_p}$$

$$S_\lambda \to S_\lambda - \sqrt{S_\lambda S_p}$$

$$\rho_p = \frac{e^{S_p^{sys}}}{e^{S_\lambda}}$$



$$-S_p$$

$$S_\Lambda$$

$$A_\Lambda \rightarrow A_\Lambda - \sqrt{A_\Lambda A_p}$$

$$S_\Lambda \rightarrow S_\Lambda - \sqrt{S_\Lambda S_p}$$

$$P_p = \frac{e^{S_p^{S_{1+2}}}}{e^{S_\Lambda}} = \frac{e^{S_\Lambda - \sqrt{S_\Lambda S_p}}}{e^{S_\Lambda}} = e^{-\sqrt{S_\Lambda S_p}}$$

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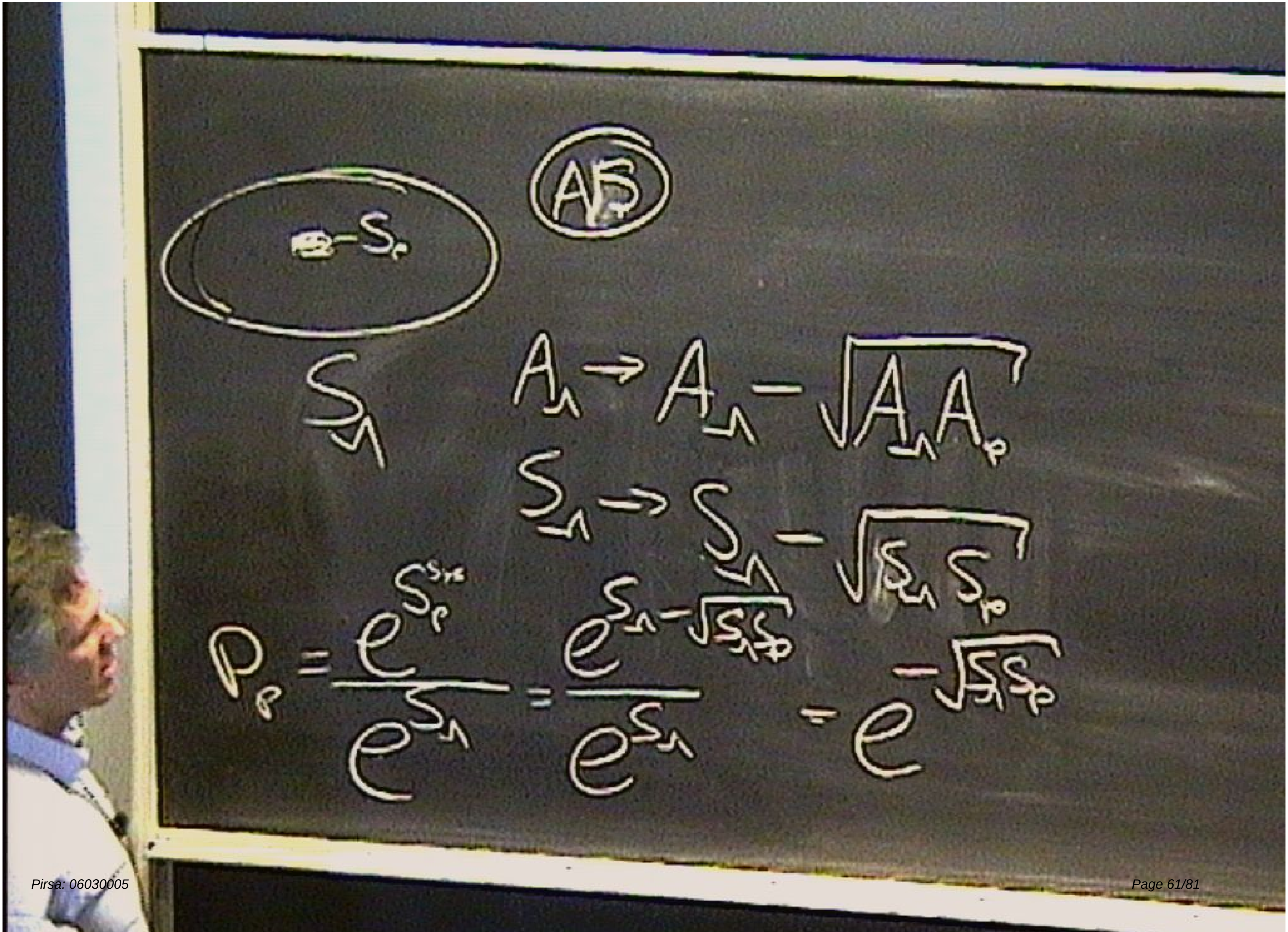

[illegible]$-S_p$

A_S

S_Λ

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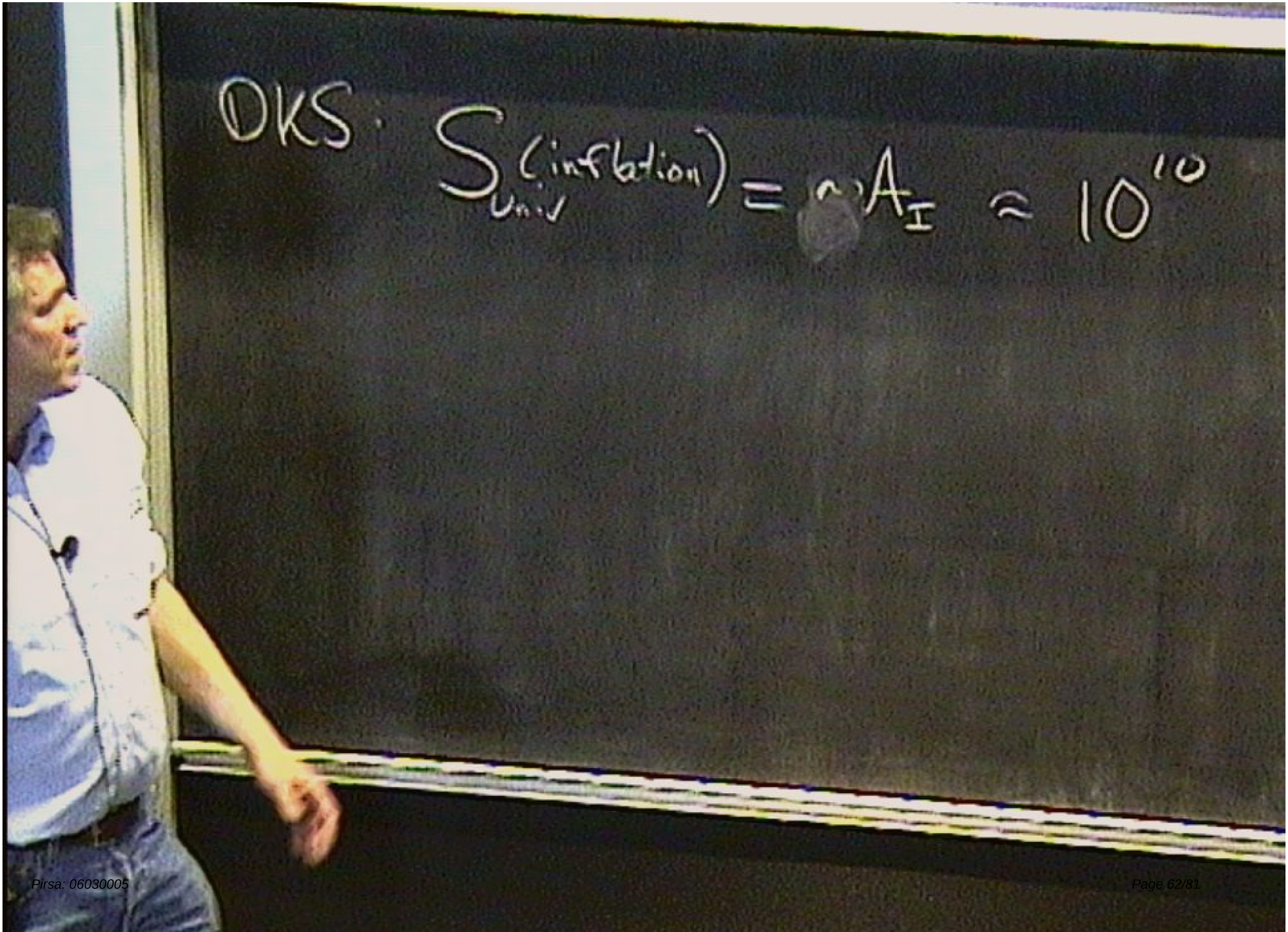
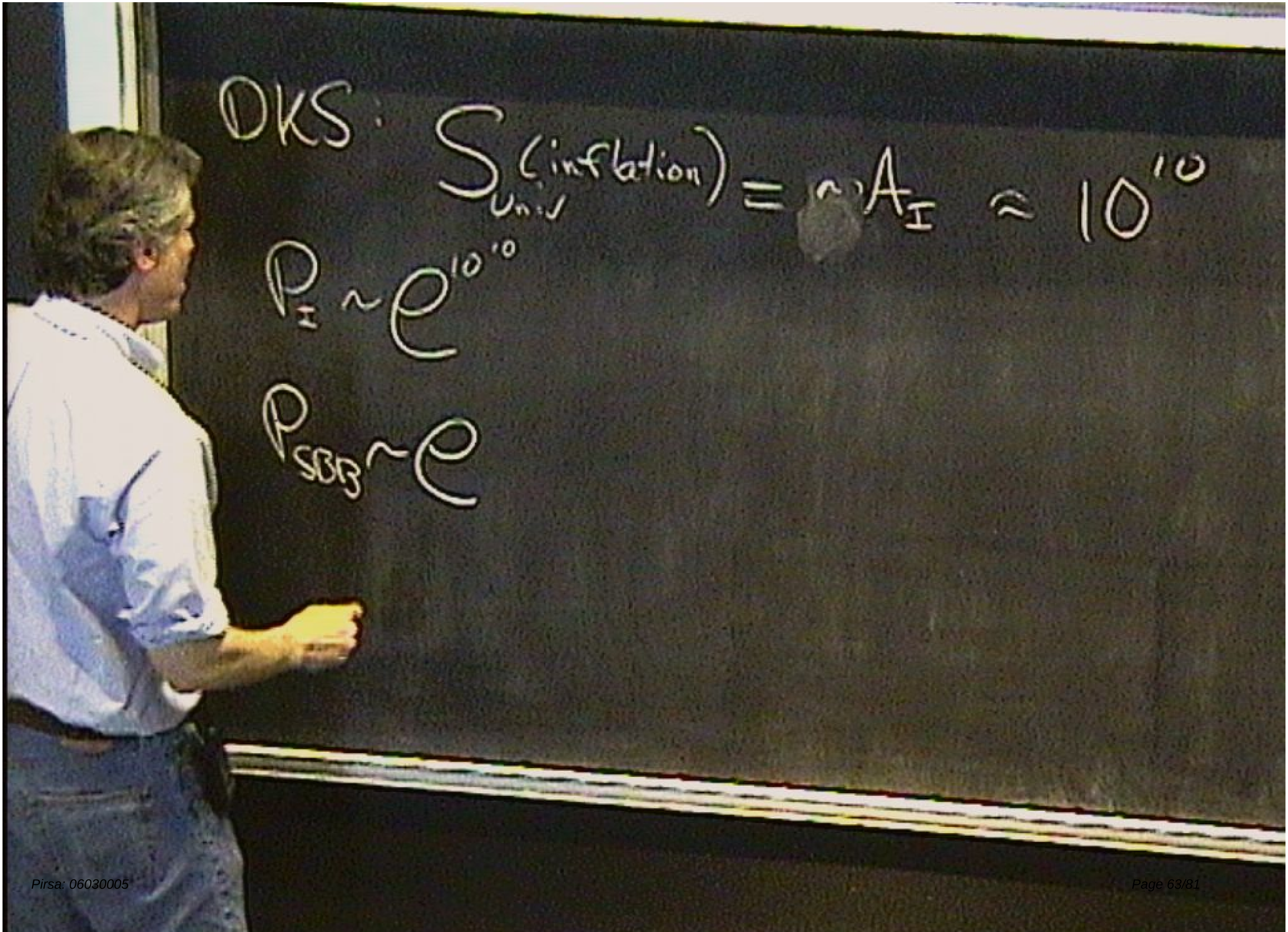
$$S_\Lambda \to S_\Lambda - \sqrt{S_\Lambda S_p}$$

$$P_p = \frac{e^{S_p^{sys}}}{e^{S_\Lambda}} = \frac{e^{S_\Lambda - \sqrt{S_\Lambda S_p}}}{e^{S_\Lambda}} = e^{-\sqrt{S_\Lambda S_p}}$$



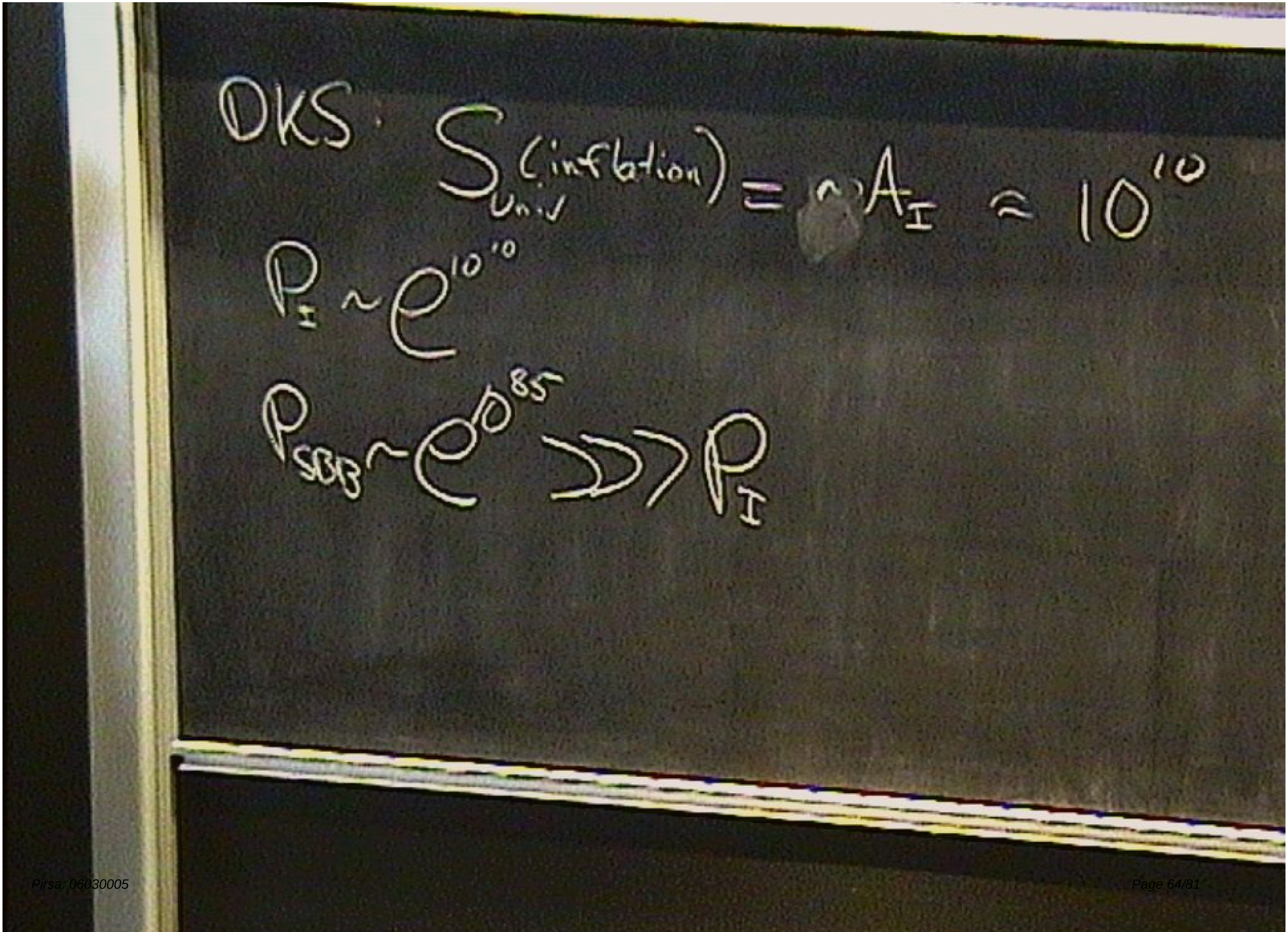
DKS: $S_{Univ}^{(inflation)} = A_I \approx 10^{10}$



DKS: $S_{Univ}^{(inflation)} = \sim A_I \approx 10^{10}$

$P_I \sim e^{10^{10}}$

$P_{SBB} \sim e$



DKS: $S_{\text{Univ}}(\text{inflation}) = \sim A_I \approx 10^{10}$

$P_I \sim e^{10^{10}}$

$P_{SBB} \sim e^{10^{85}} \ggg P_I$

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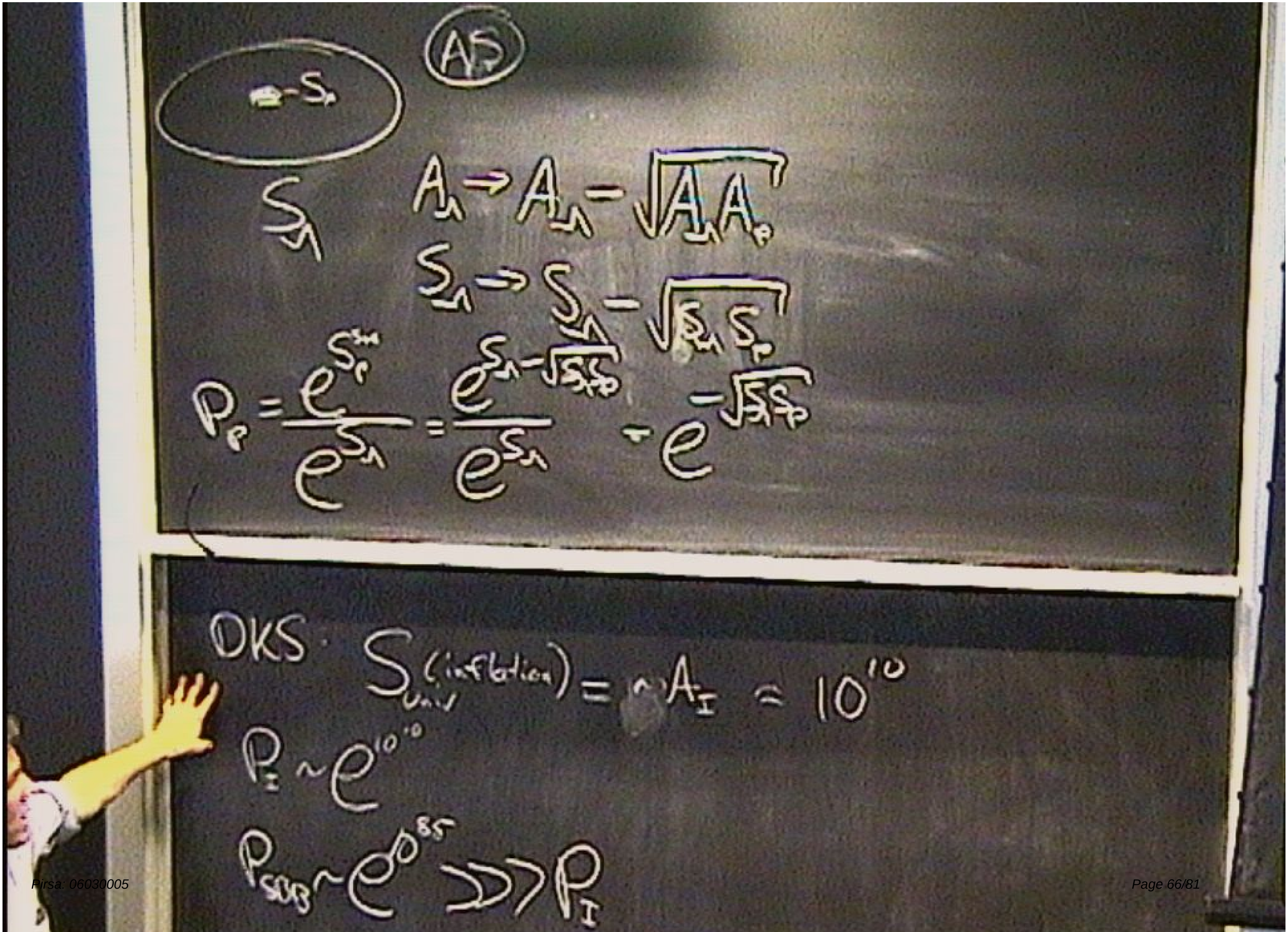


AS

$-S_e$

S_h

$A_h \rightarrow A_h - \sqrt{A_h A_e}$

$S_h \rightarrow S_h - \sqrt{S_h S_e}$

$$P_e = \frac{e^{S_e^{int}}}{e^{S_h}} = \frac{e^{S_h - \sqrt{S_h S_e}}}{e^{S_h}} = e^{-\sqrt{S_h S_e}}$$

DKS: $S_{univ}^{(inflation)} = \sim A_I \approx 10^{10}$

$P_I \sim e^{10^{10}}$

$P_{SDB} \sim e^{0^{85}} >>> P_I$

Discuss calculations at blackboard here

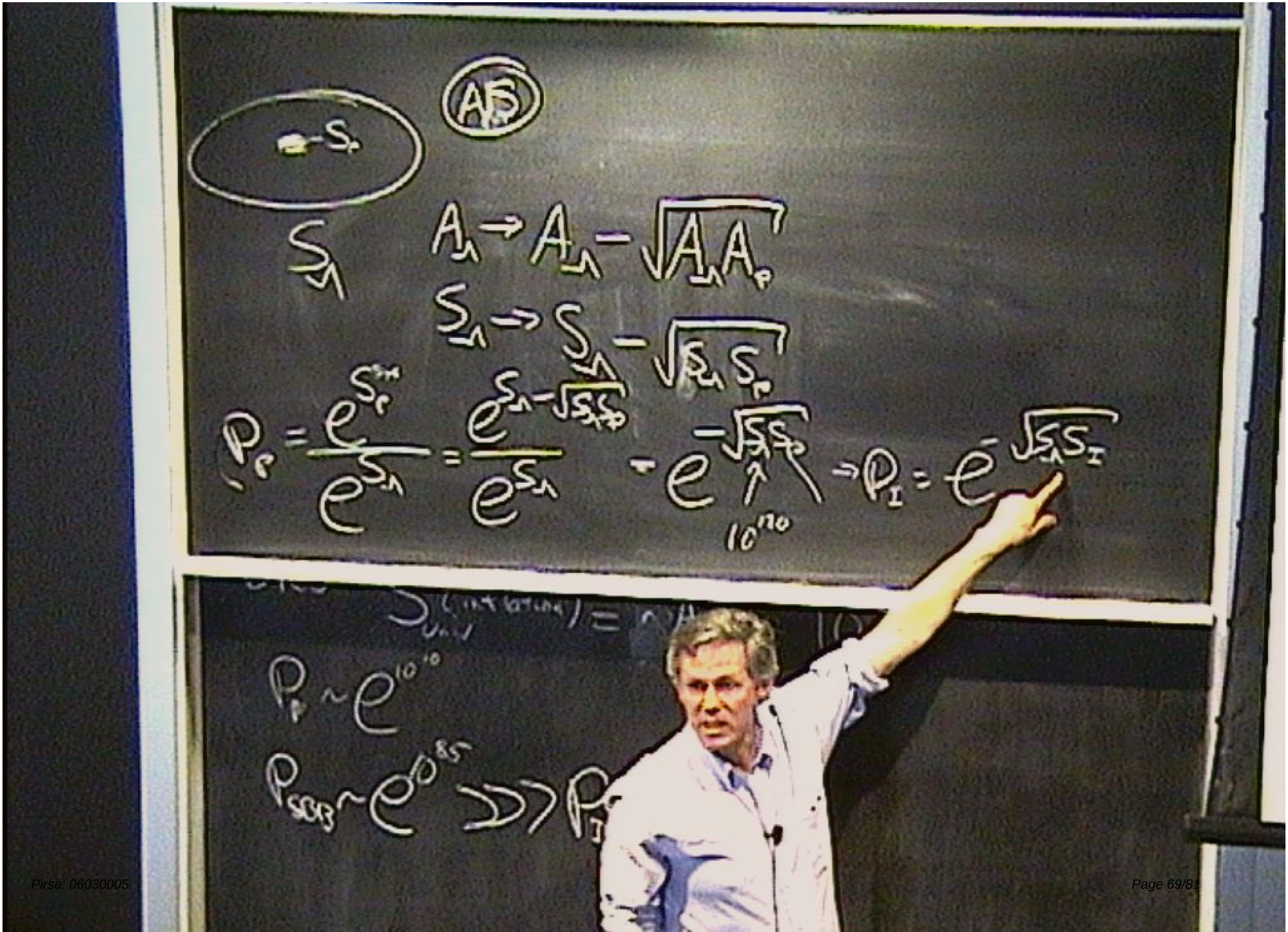
Version 1

Inflation requires only a small fluctuation "out of the bath" to get started.

it is much easier to start inflation than start the whole big bang directly.

Version 2

Because of the horizon (similar to the de Sitter horizon) during inflation, there is no "bath". The entropy of the entire universe must reduce down to 10^{10} to start inflation. Much more expensive than going directly to the big bang with entropy of 10^{85}



AS

$\bullet - S_e$

S_Λ

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$S_\Lambda \to S_\Lambda - \sqrt{S_\Lambda S_e}$

$$P_e = \frac{e^{S_e}}{e^{S_\Lambda}} = \frac{e^{S_\Lambda - \sqrt{S_\Lambda S_e}}}{e^{S_\Lambda}} = e^{-\sqrt{\underset{\underset{10^{120}}{\uparrow}}{S_\Lambda} S_e}} \to P_I = e^{-\sqrt{S_\Lambda S_I}}$$

$S_{univ}^{(\text{inflation})} =$

$P_e \sim e^{10^{10}}$

$P_{SSB} \sim e^{10^{85}} \ggg P_I$

$$S_\Lambda \to S_\Lambda - \sqrt{S_\Lambda S_p}$$

$$P_p = \frac{e^{S_p^{sm}}}{e^{S_\Lambda}} = \frac{e^{S_\Lambda - \sqrt{S_\Lambda S_p}}}{e^{S_\Lambda}} = e^{-\sqrt{\underset{\substack{\uparrow \\ 10^{120}}}{S_\Lambda} S_p}} \to P_I = e^{-\sqrt{S_\Lambda S_I}}$$

OKS: $S_{univ}^{(inflation)} = A_I \approx 10^{10}$

$P_p \sim e^{10^{10}}$

$P_{SUSB} \sim e^{10^{85}} \ggg P_I$

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Important:

If the entire universe has an entropy of 10^{10} during inflation, the problems with version 2 are NOT resolved by

1) Eternal Inflation

2) String theory landscape

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Version 2

- Initial fluctuations that start inflation are much more “expensive” the universe (or a brain) ating directly.
- AND standard big bang as we know it is LESS LIKELY than other junk (Boltzmann’s brain problem not resolved)

Hertog & Horowitz

Blau Farhi Guth Guendleman Gueven

AA & Sorbo

Fischler Morgan & Polchinski

Dyson Kleban & Susskind

Banks

Important:

If the entire universe has an entropy of 10^{10} during inflation, the problems with version 2 are NOT resolved by

1) Eternal Inflation

2) String theory landscape

Two versions of the story

Version 1

- Initial fluctuations that start inflation are a small perturbation on Eqm and are thus "cheap".
- Inflation much mo likely than the whole universe "fluctua directly"
- Solve "Bo Brain" prob predictive po co

Version 2

- Initial fluctuations that start inflation are much more "expensive" the universe (or a brain) ating directly.
- AND standard big bang as we know it is LESS LIKELY than other junk (Boltzmann's brain problem not resolved)

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Aguirre and Johnson Dec 05

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Conclusions of Part I

Taking a fundamental cosmological constant seriously:

- suggests radical changes to how we do fundamental physics and cosmology
- could form the basis for "equilibrium cosmology". A much stronger way of doing cosmology than "stating the state of the Universe".
- The depending on (deep) unresolved questions from quantum gravity, the eqm cosmology either puts the status quo on stronger footing or sends us back to the drawing board.

Part II

Probing “Dark Energy”

Dark Energy Task Force

Full report to appear soon

Key points already released (slides available):

- Quantitative figure of merit chosen
- "order of magnitude" progress only possibly through combinations of different data
- Major projects (ie Joint Dark Energy Mission or LST) required to achieve order of magnitude progress (mid-term projects critical to major projects).
- Combining "dark energy" data leads to extremely tight constraints on cosmological parameters such as

$$H_0, \Omega_k, \Omega_m$$

Conclusions

- Science Magazine #1 question in science!
- A revolution is needed to understand the cosmic acceleration
- Already driving very exciting ideas in physics and cosmology
- A whole new level of high-impact data is within reach