Fun With Dark Energy

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UC Davis

KITP Colloquium

Jan 11 2006

Outline

Intro

Part I

Cosmic equilibrium

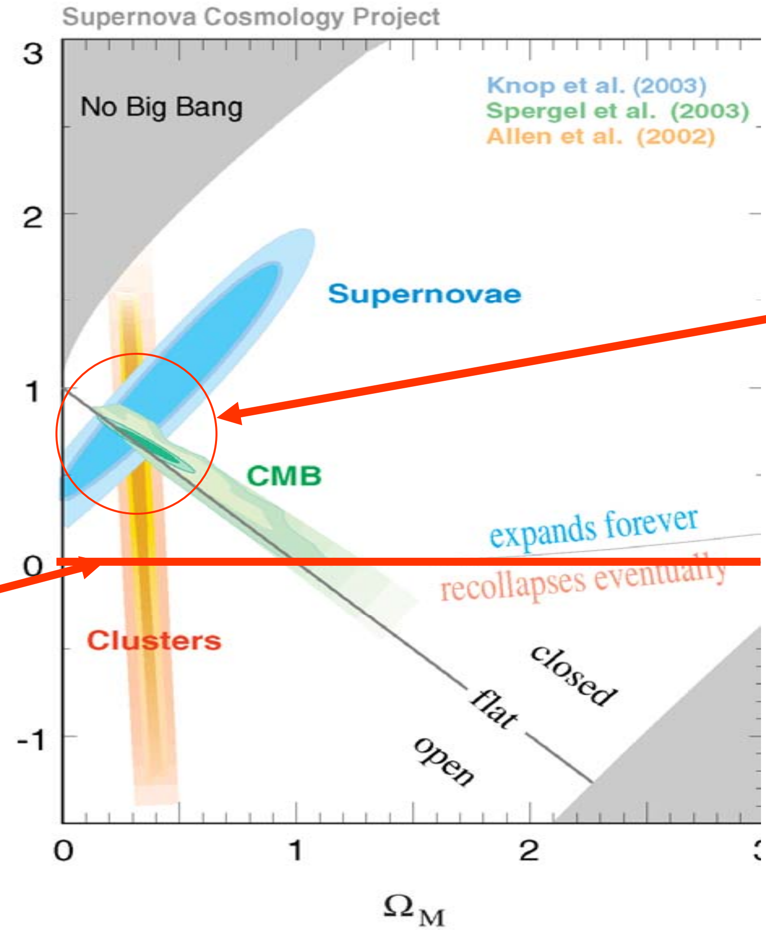
Equilibrium & Cosmology

Boltzmann's Brain

Part II Probing "Dark Energy"

Introduction

Evidence for cosmic acceleration



Amount of accelerating matter

Preferred by modern data

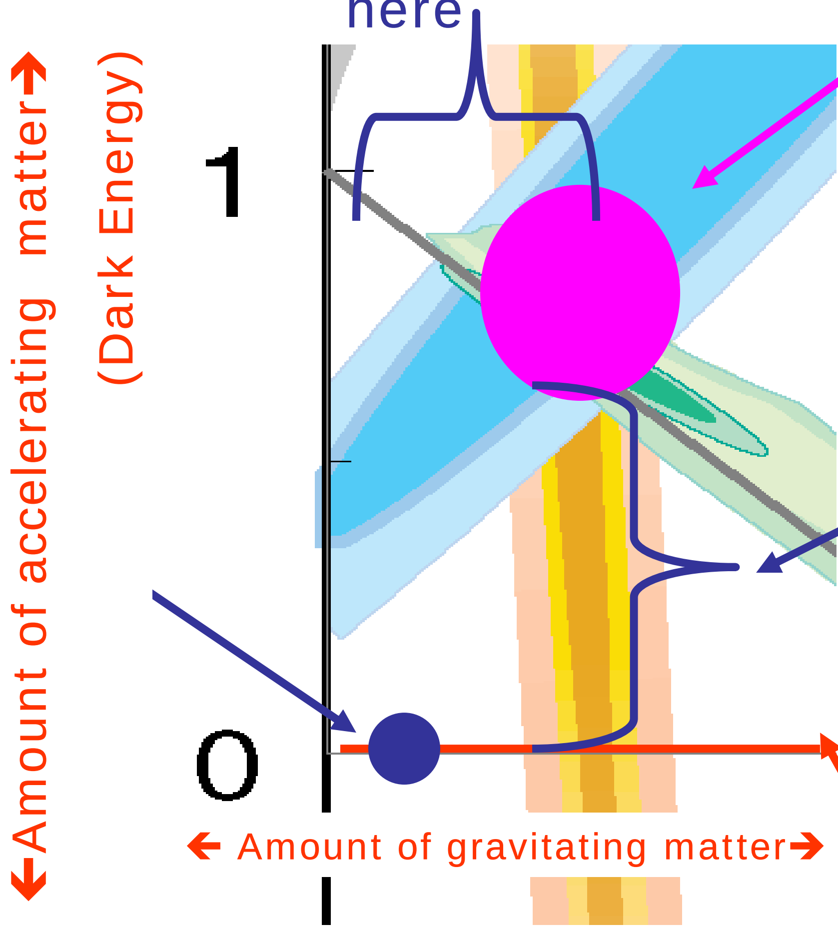
“Ordinary” non accelerating matter

Amount of gravitating matter

Need to add dark matter here

Preferred by modern data

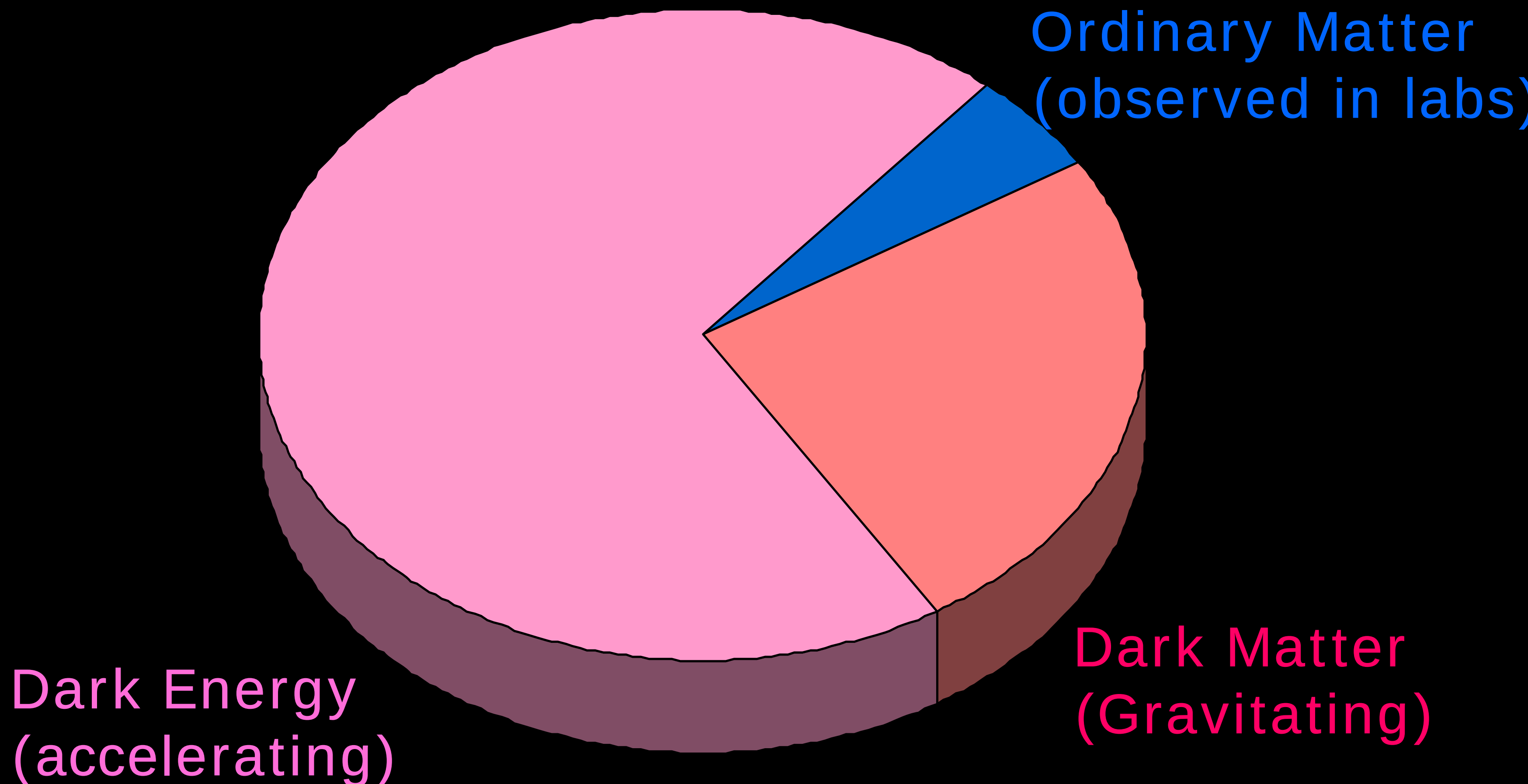
Mass-Energy of the a Universe made *only* matter we know form the lab ('standard model matter")



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:

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

The Numbers

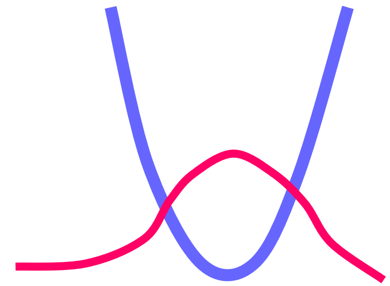
$$\rho_{DE} \approx 10^{-120} M_P^4 \approx \left(10^{-3} eV\right)^4$$

or

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

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

4) Why Now?

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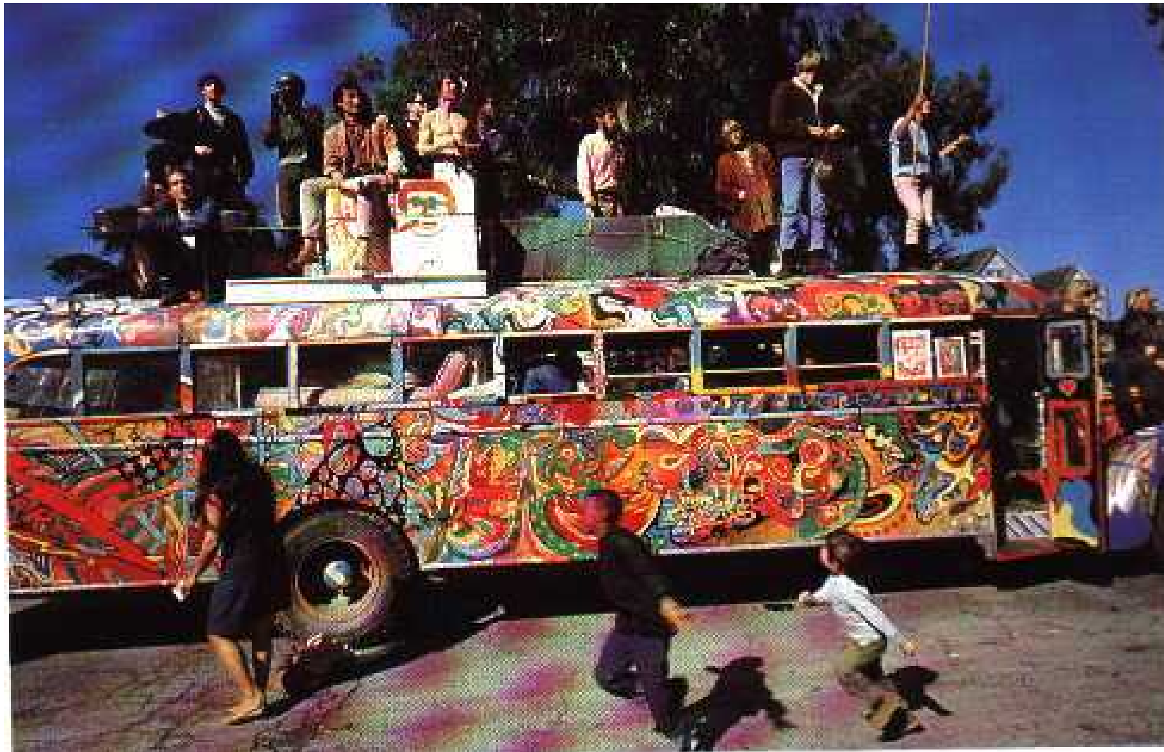

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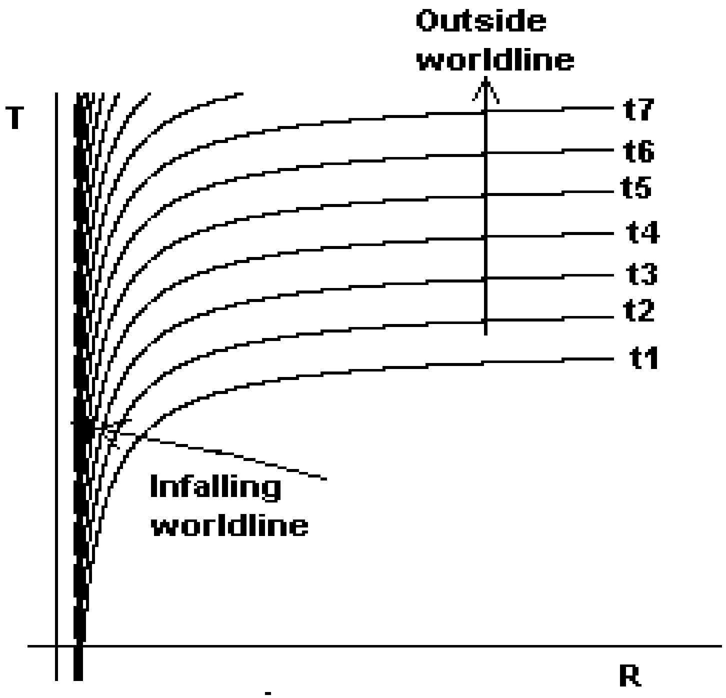
Part I

Some implications for physics and cosmology

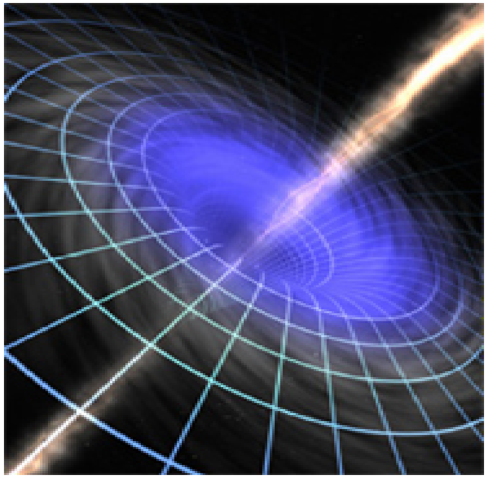
Cosmic equilibrium

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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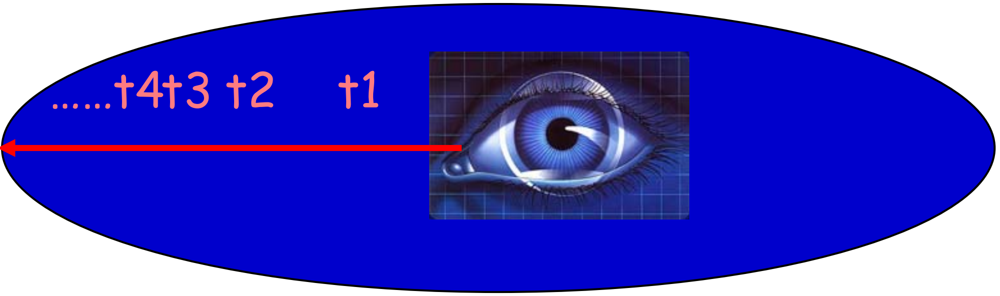
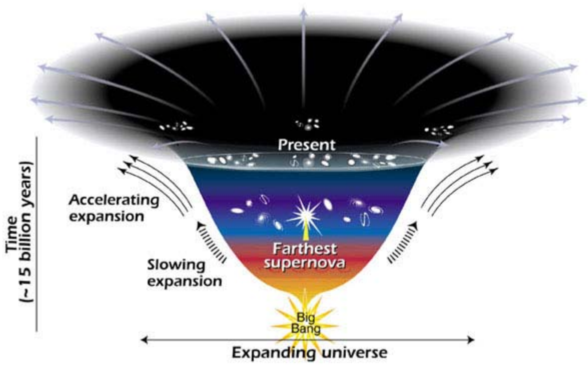
Dark Energy Event Horizon (schematic):



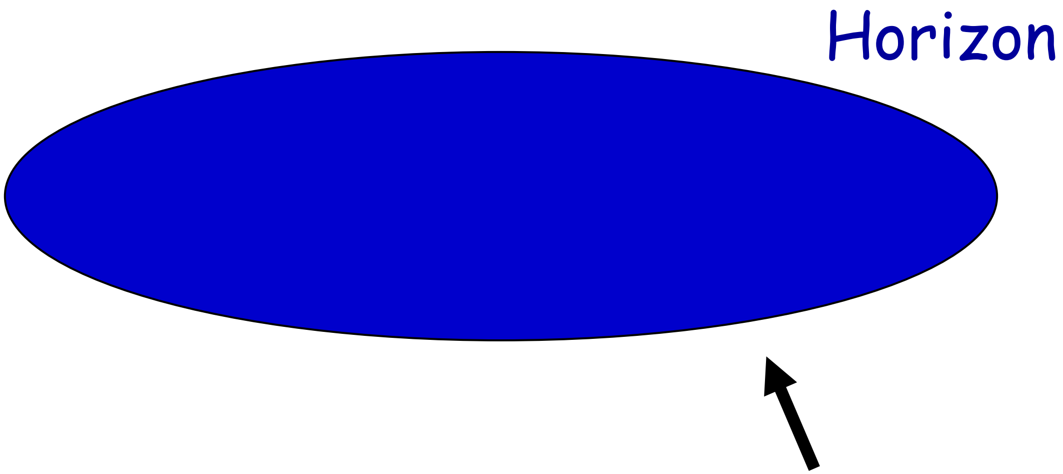
$$S \propto A = H^{-2} = \Lambda^{-1}$$

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

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

Quantum effects: Hawking Temperature

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

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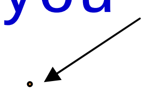
Needs a scheme for assigning probabilities (back to 1)?)

Only way out: In Eqm, nature tells you how to assign probabilities.

Problems with 1.

(State what the initial conditions "must be")

you



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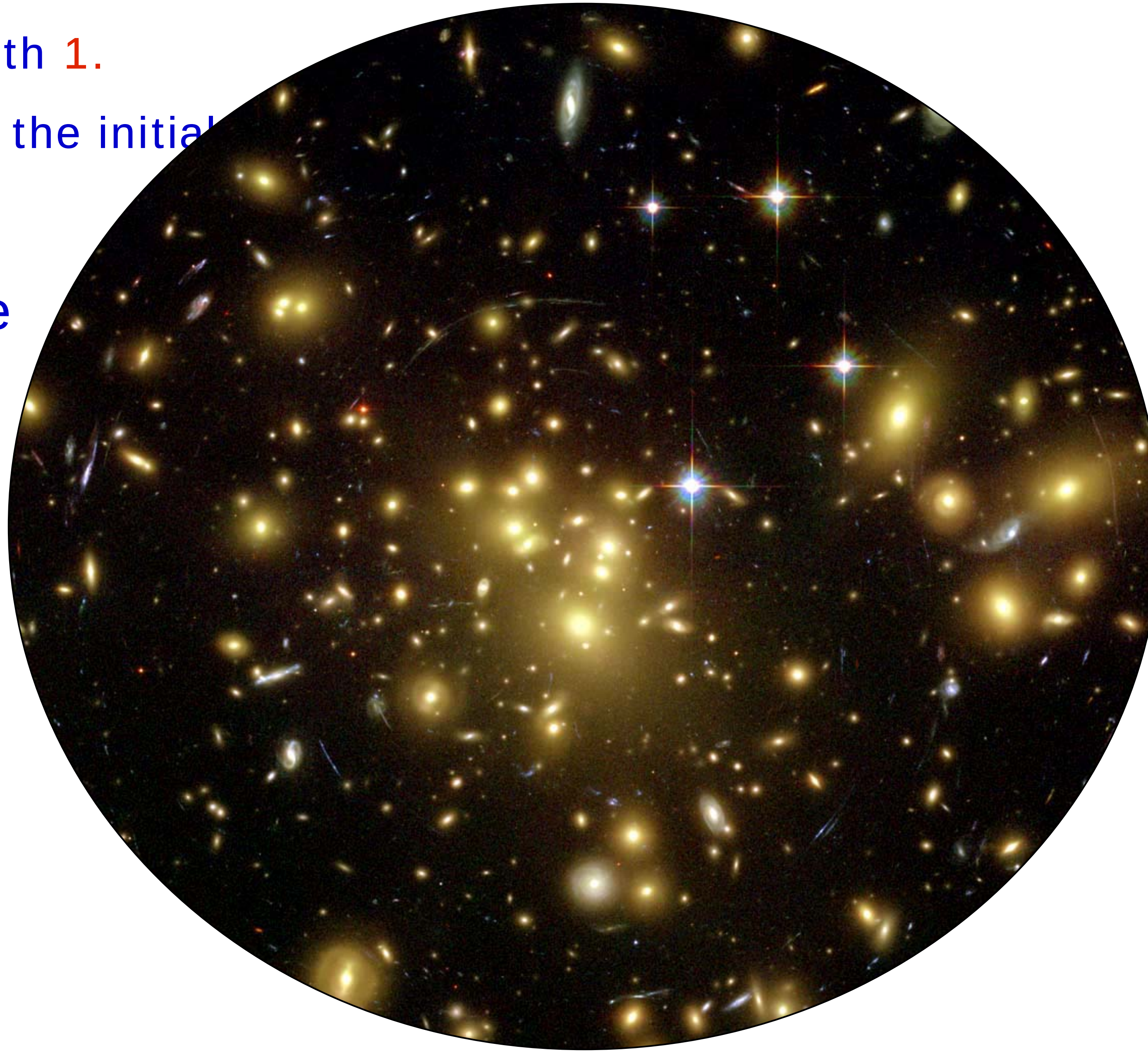

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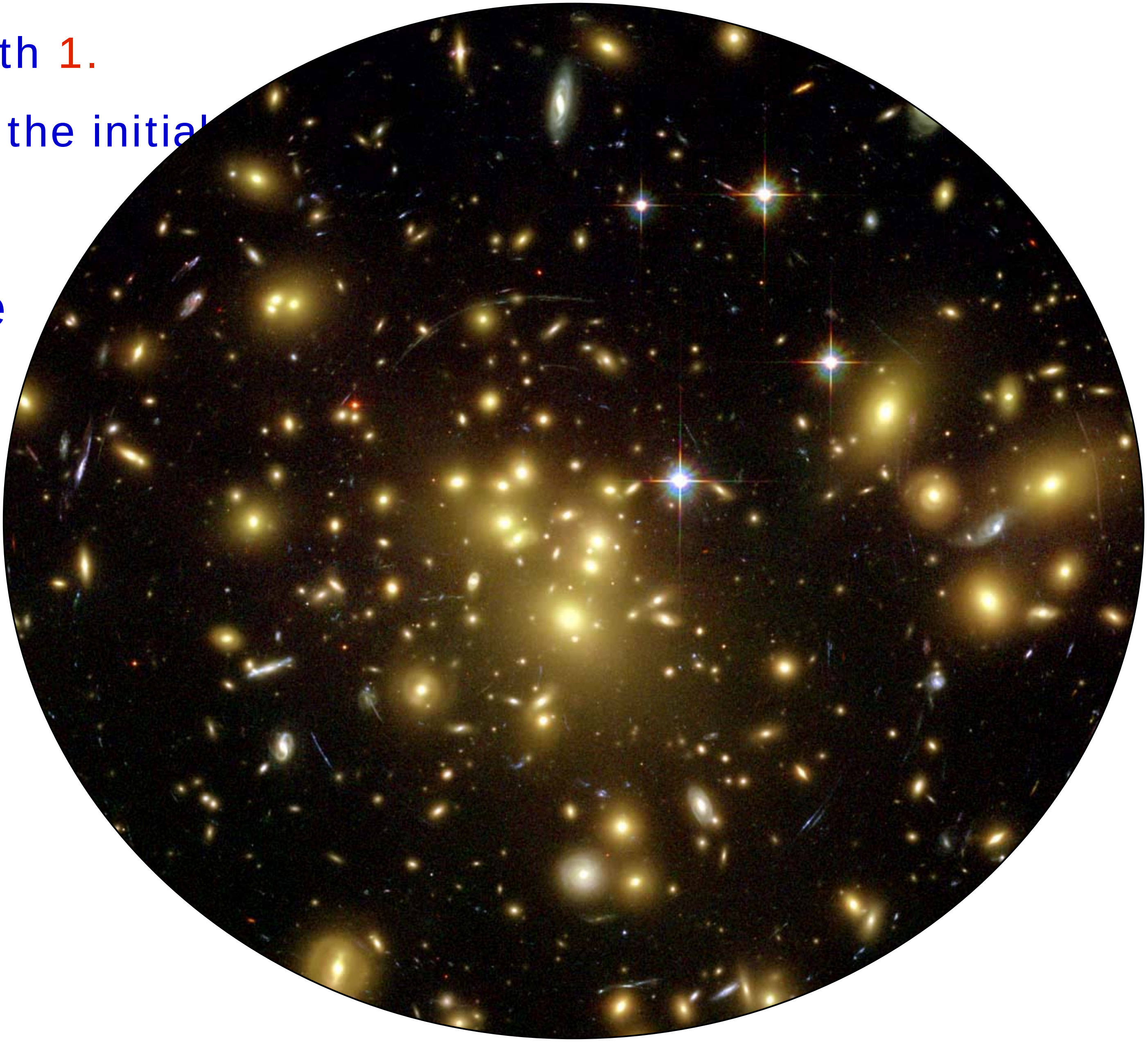
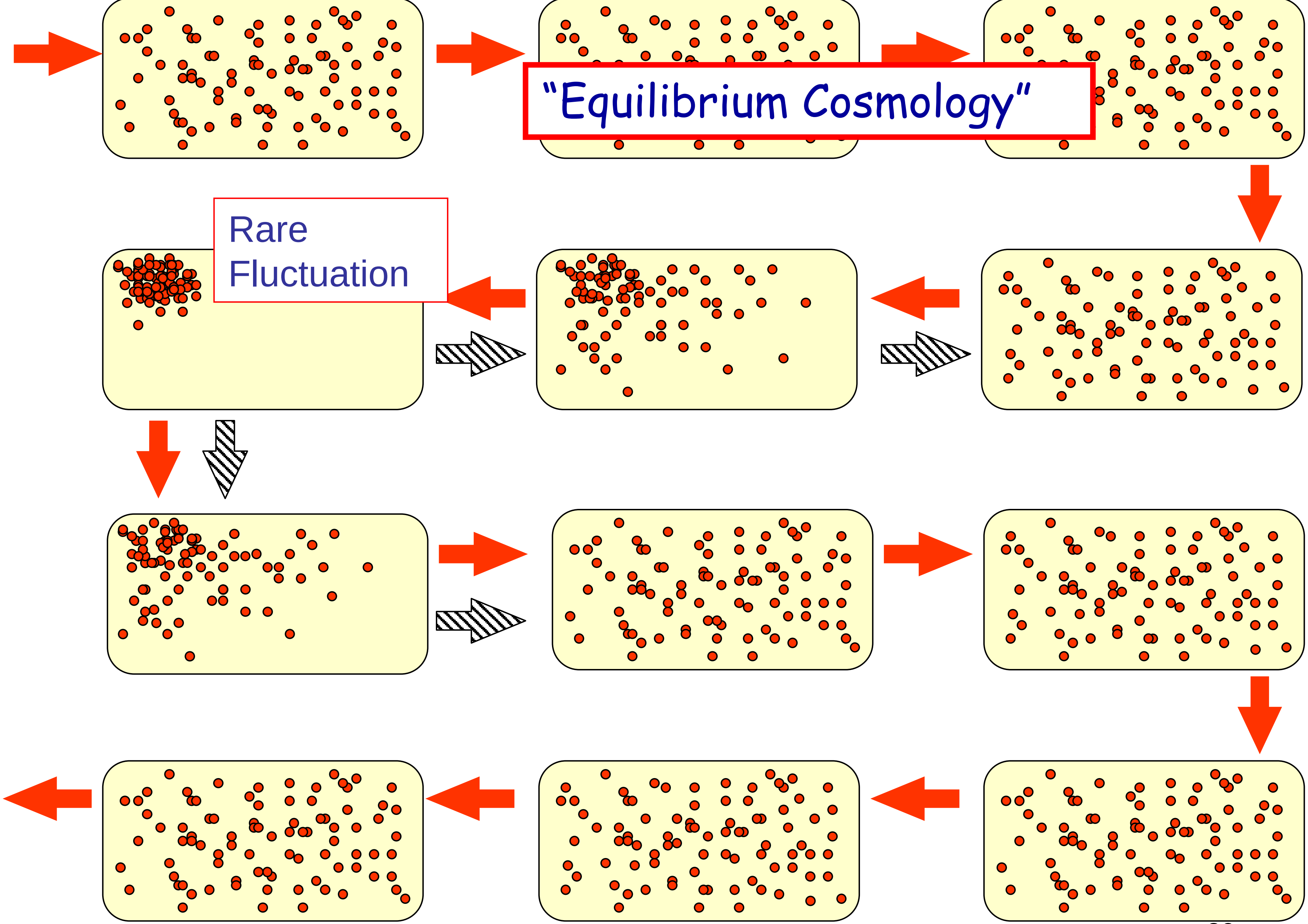


the universe

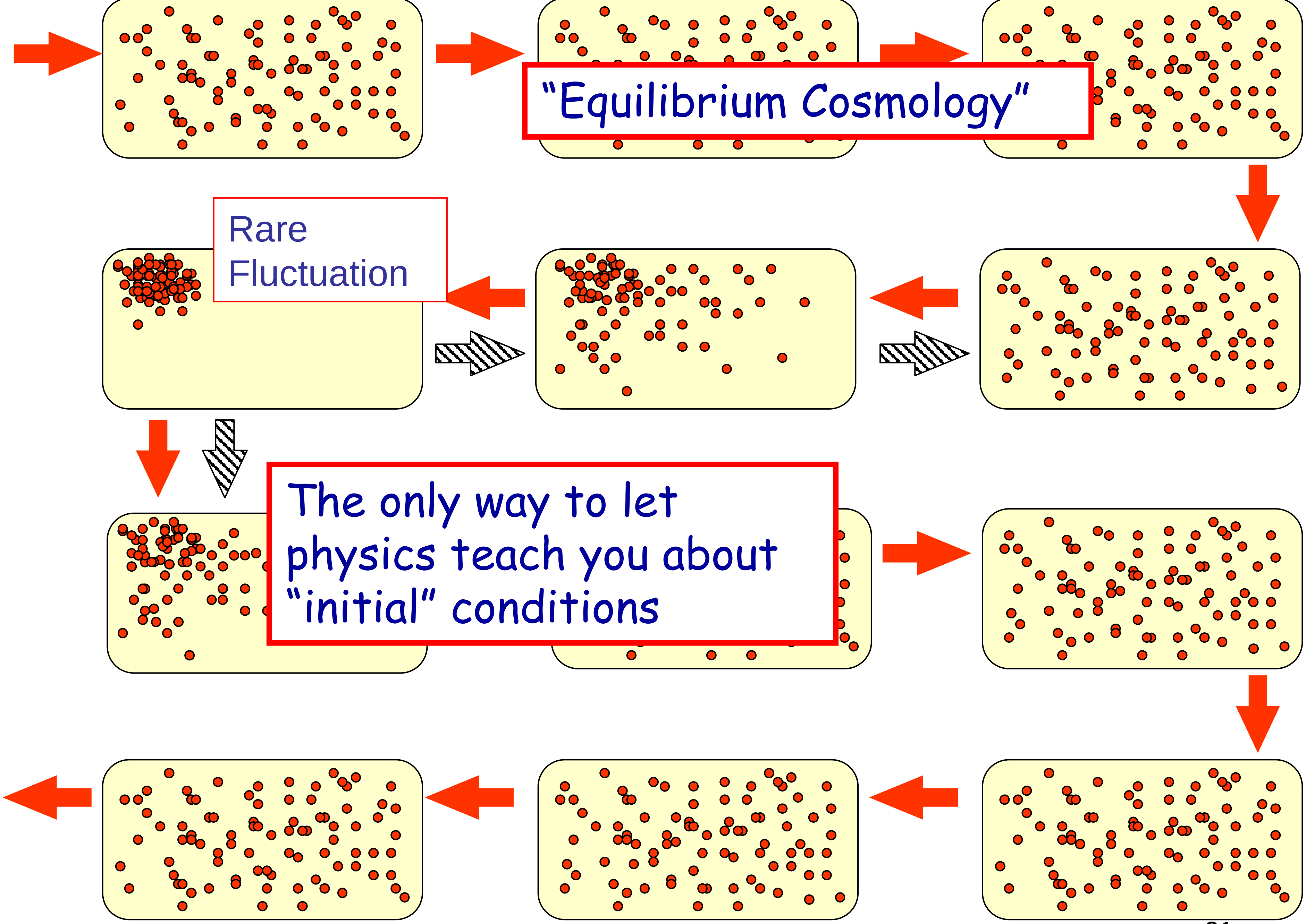
Is the universe listening?

you

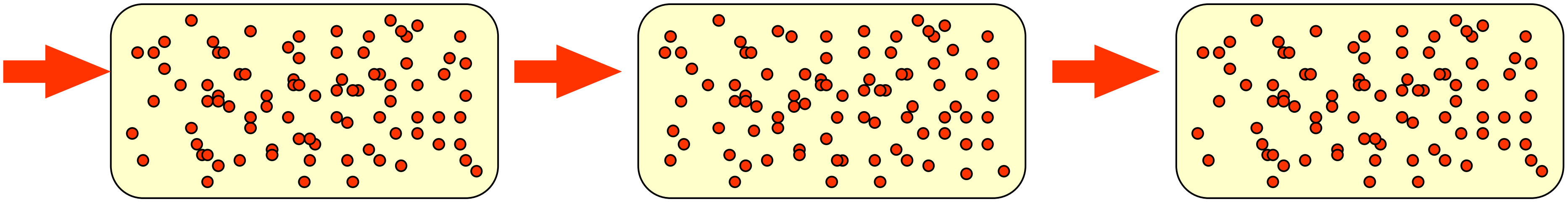
de Sitter equilibrium gives the one chance I know to use eqm as a basis for cosmology



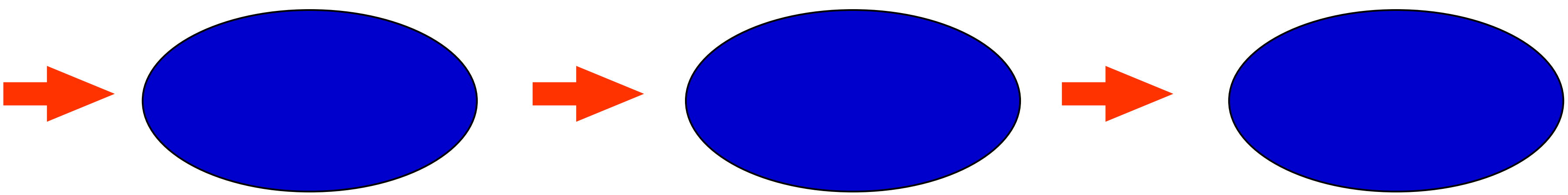
“Equilibrium Cosmology”
Rare Fluctuation


"Equilibrium Cosmology"
Rare Fluctuation
The only way to let physics teach you about "initial" conditions

Concept:



Realization:



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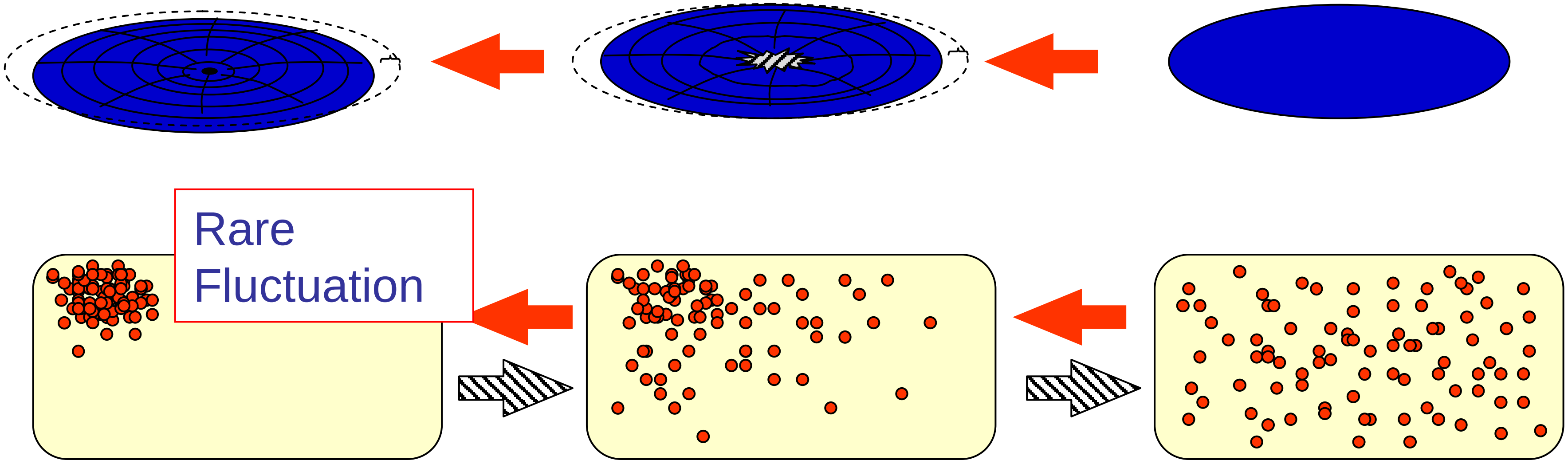

Rare
Fluctuation

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)

➔<u>This is as least as important as the other successes of inflation!</u>

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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Very Serious Problem

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AA & Sorbo

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Dyson Kleban & Susskind

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Blau Farhi Guth Guendleman Gueven

AA & Sorbo

Fischler Morgan & Polchinski

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Hertog & Horowitz

Dyson Kleban & Susskind

Banks

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}

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Dyson Kleban & Susskind

Aguirre and Johnson Dec 05

Guendleman Gueven

Fischler Morgan & Polchinski

Banks

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”

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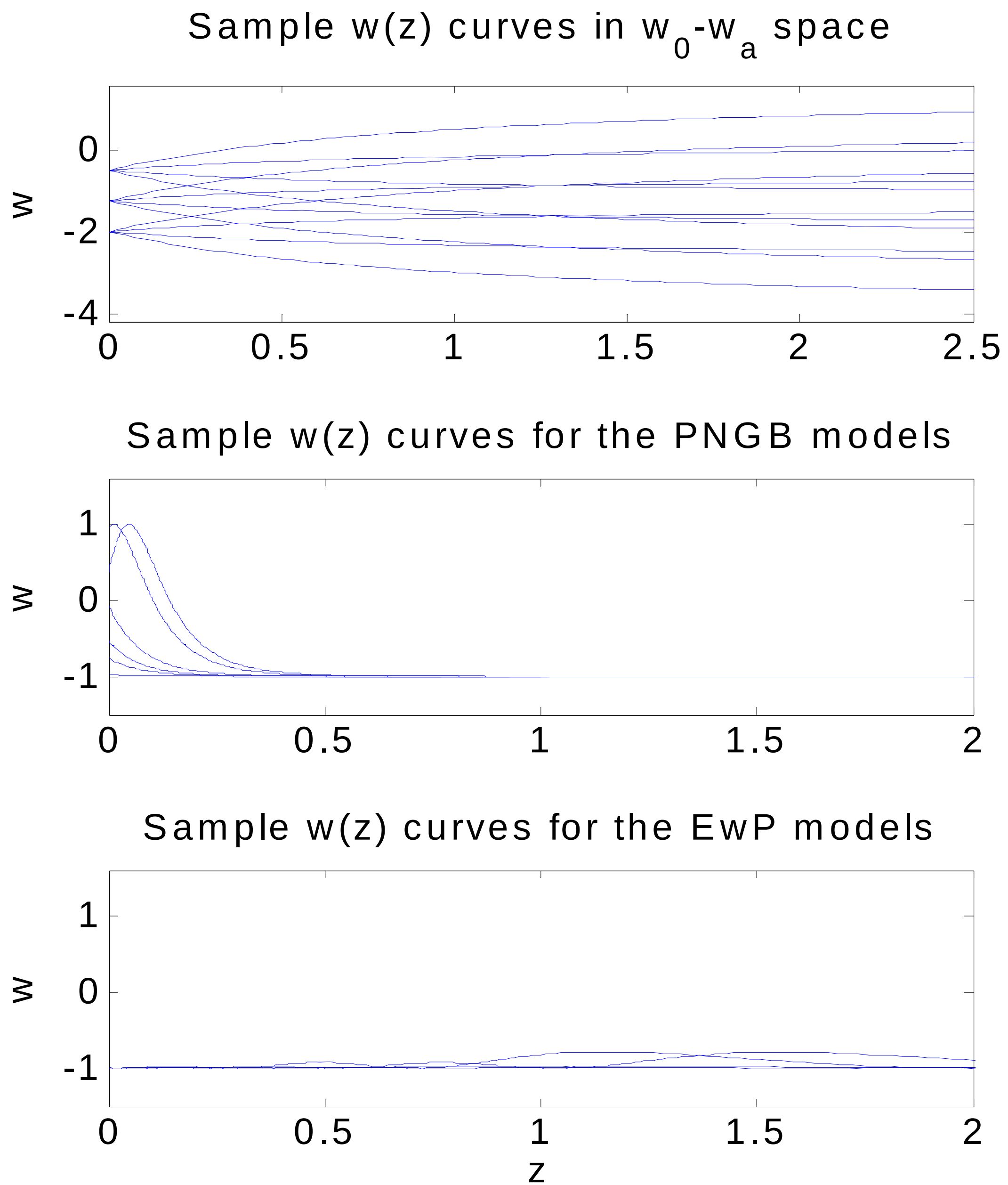
Probing “Dark Energy”

If we are clueless about dark energy, how do we devise good probes?

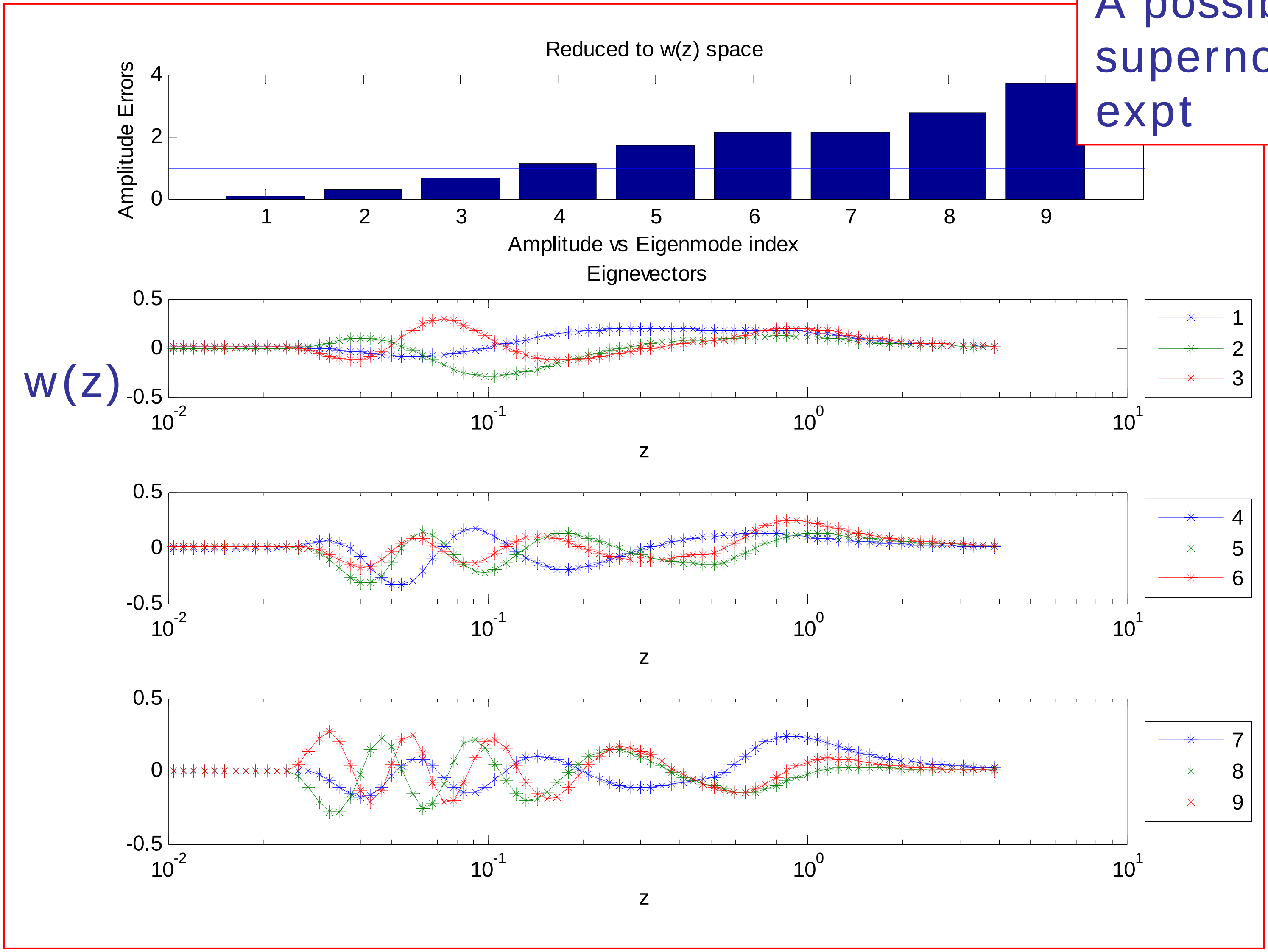
Consensus approach:

- ➔ If the acceleration is due to some new smooth matter component (dark energy) it can be characterized by pressure p and density ρ
- ➔ The critical characterization of the dark energy is the equation of state $p = w\rho$
- ➔ Use new observations to constrain $w(z)$
- ➔ Any deviation from $w(z) = -1$ is evidence against a cosmological constant
- ➔ Use different data (such as cosmic structure vs cosmic expansion) to constrain $w(z)$
- ➔ Inconsistencies between $w(z)$ from different data could signify deviations from Einstein gravity.


Sample w(z) curves in w_0-w_a space
w
0
-2
-4
0
0.5
1
1.5
2
2.5
Sample w(z) curves for the PNGB models
w
1
0
-1
0
0.5
1
1.5
2
Sample w(z) curves for the EwP models
w
1
0
-1
0
0.5
1
1.5
2
z

Each experiment is sensitive to its own best measured components of $w(z)$ (eigenstates of the Fisher matrix)

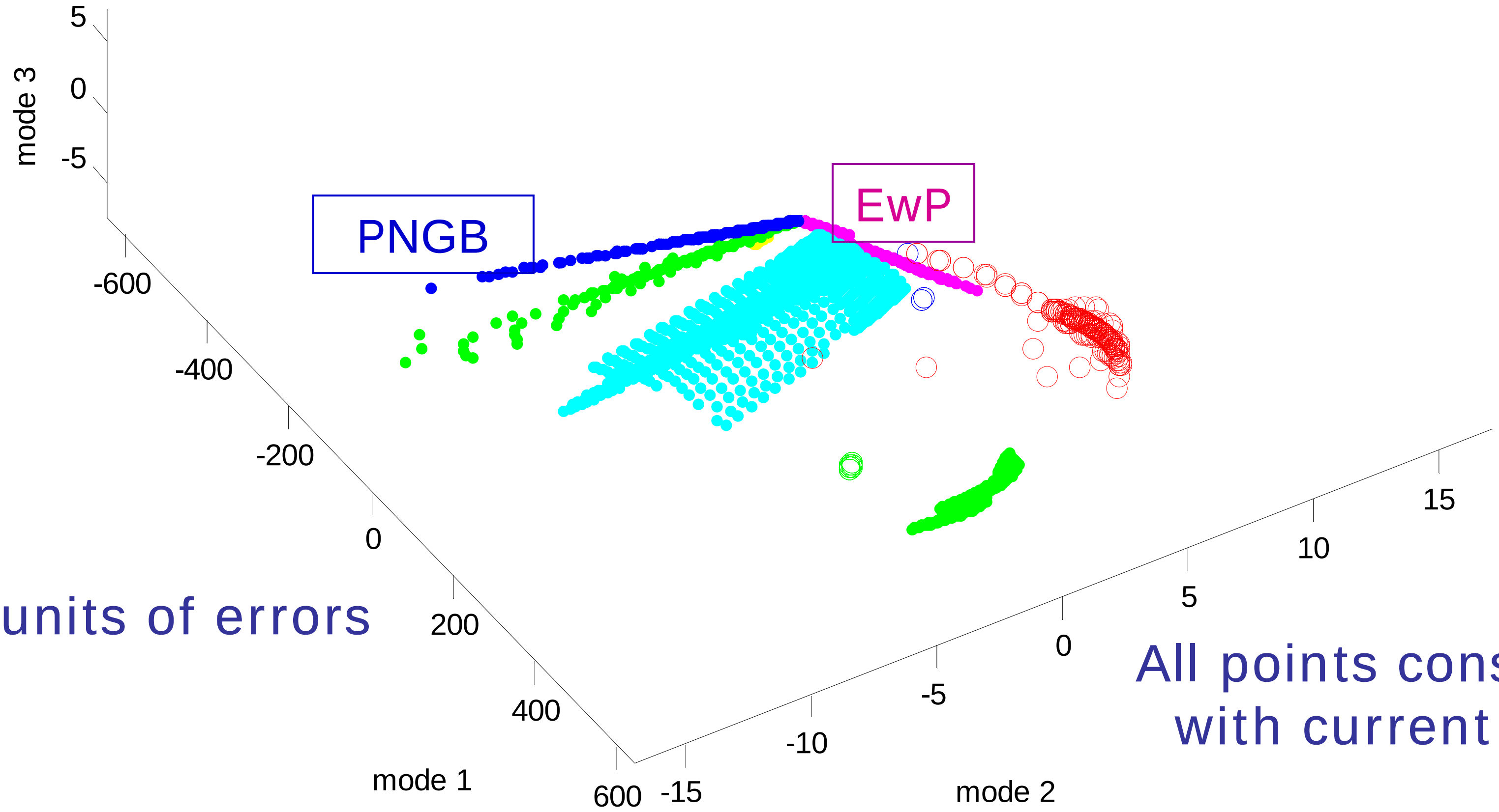
A possible supernova expt



Very powerful discrimination among Dark Energy models is possible

Using simulated data:

A possible supernova expt



In units of errors

All points consistent with current data

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