Title: Searching for Other Universes

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Abstract:

Searching for Other Universes

Matthew C. Johnson
York University and Perimeter Institute

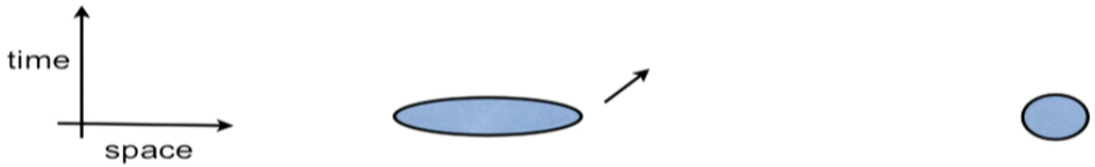

Movie: Anthony Aguirre

The Universe

Everything.

Far Out = Far Back in Time

Light has a constant speed.
Looking out is looking back in time.



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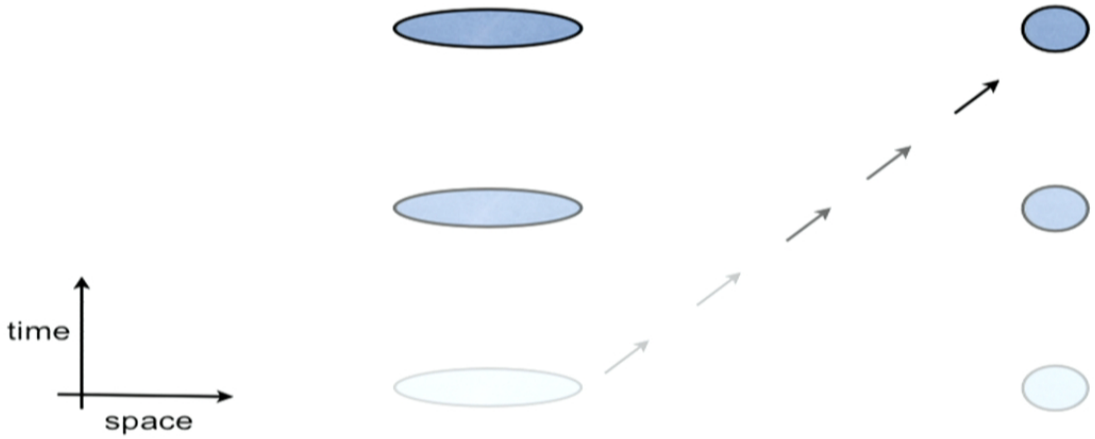

Cosmic Microwave Background (CMB) radiation

- The radiation released when neutral atoms were formed.

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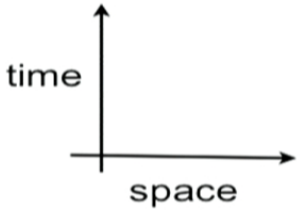
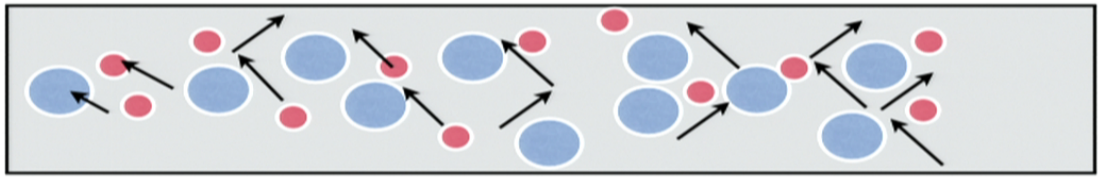


opaque



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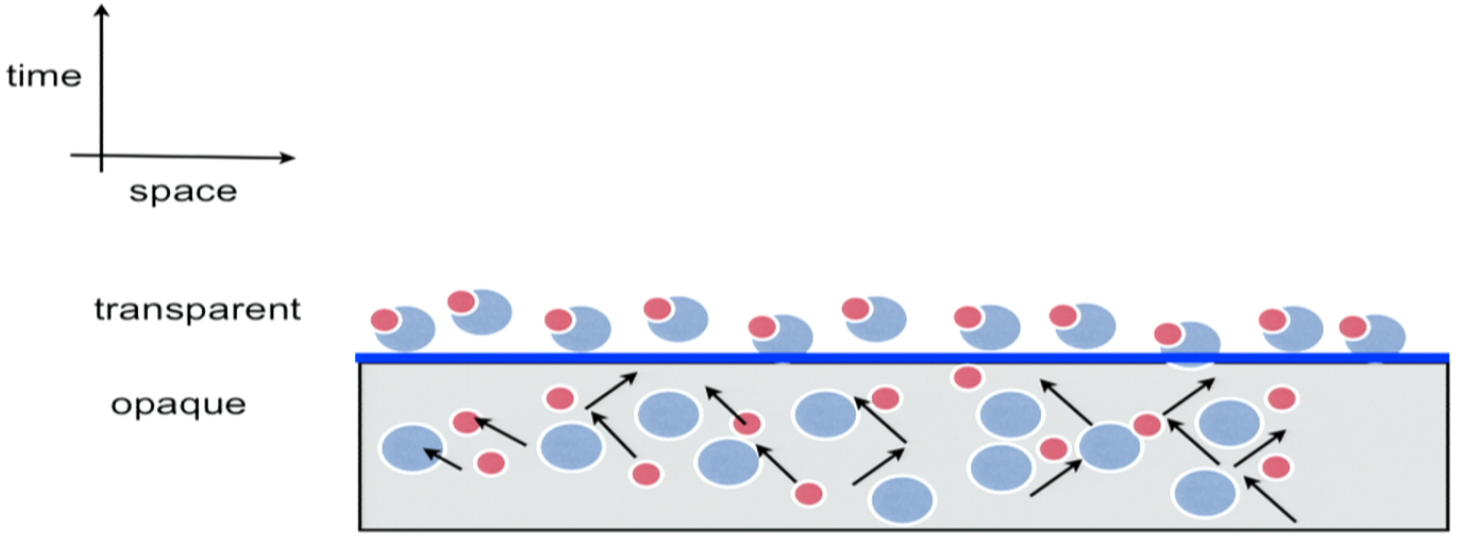

What is our best model?

- ``Our whole universe was in a hot dense state, then nearly 14 billion years ago expansion started.....” (The big bang theory)

(a time, not a place)

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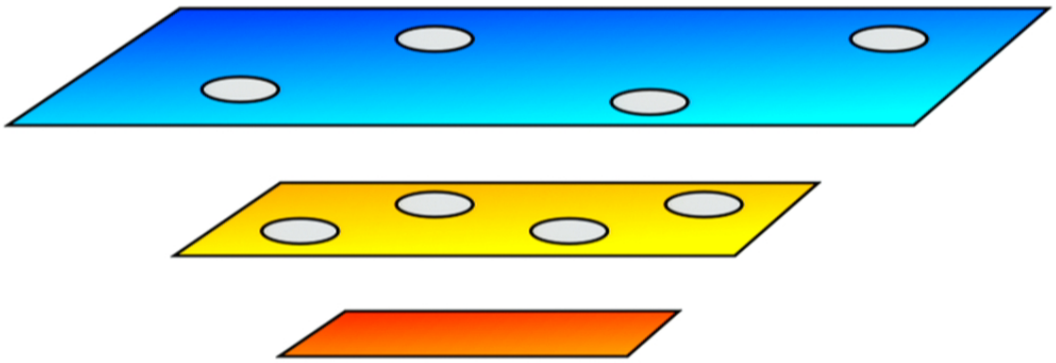

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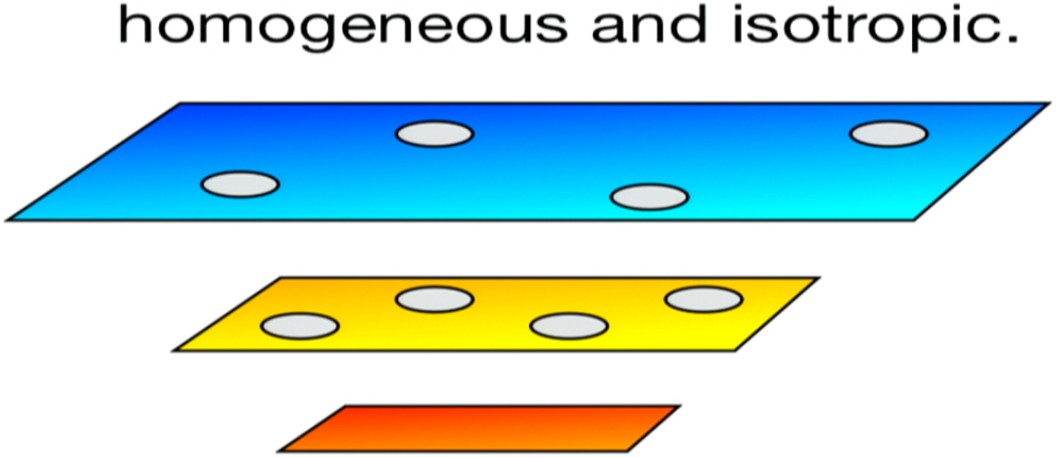

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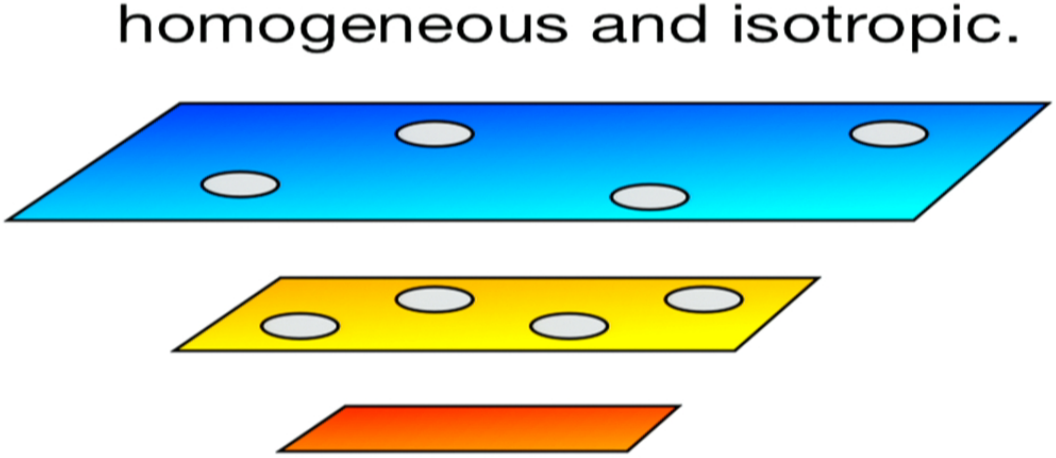

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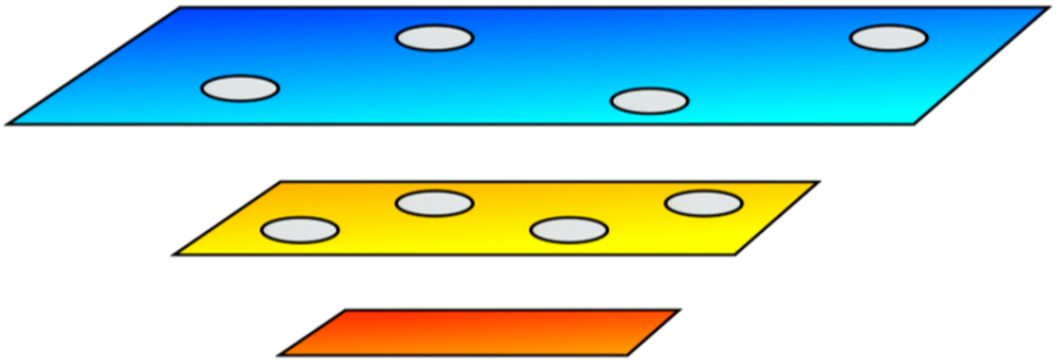

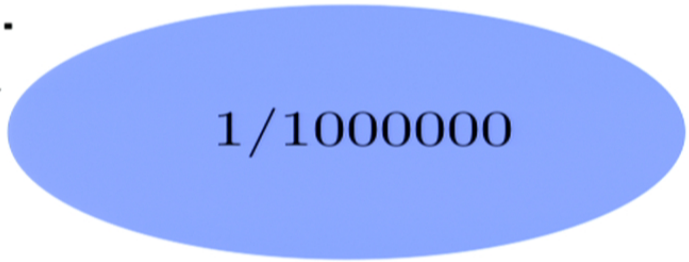

Nobel Prize 2006!

John Mather and George Smoot

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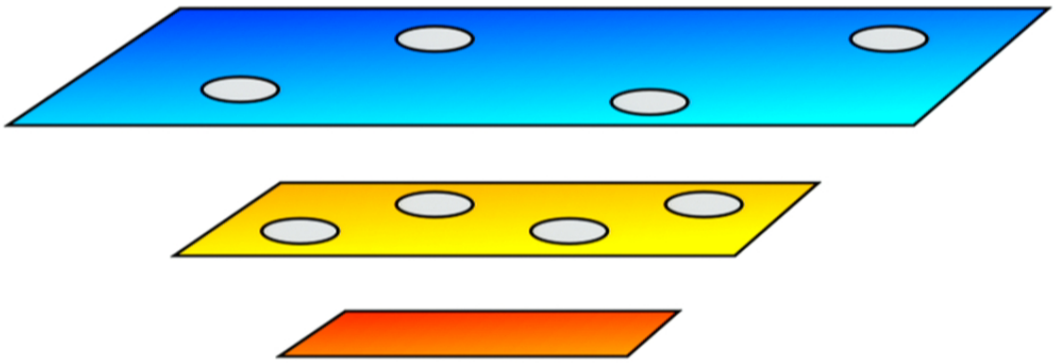
The expansion of the Universe is accelerating!



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Adam Riess, Saul Perlmutter, Brian Schmidt

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General Relativity

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$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Spacetime curvature

Matter & energy

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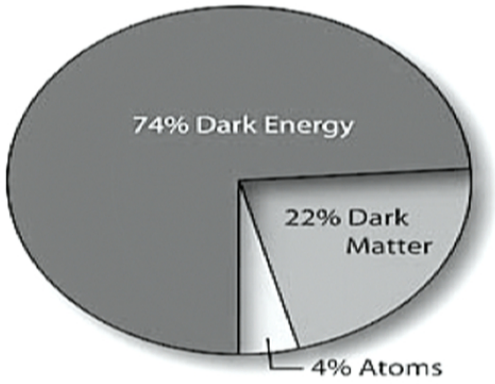

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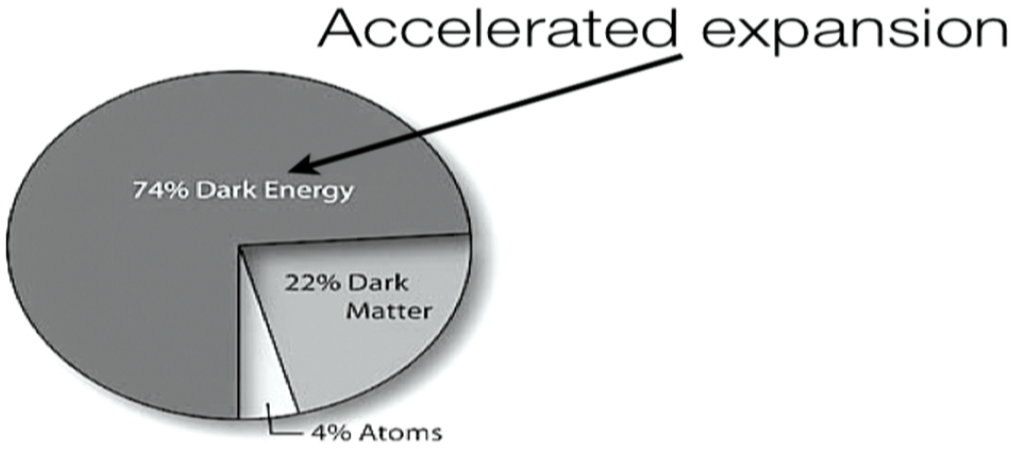

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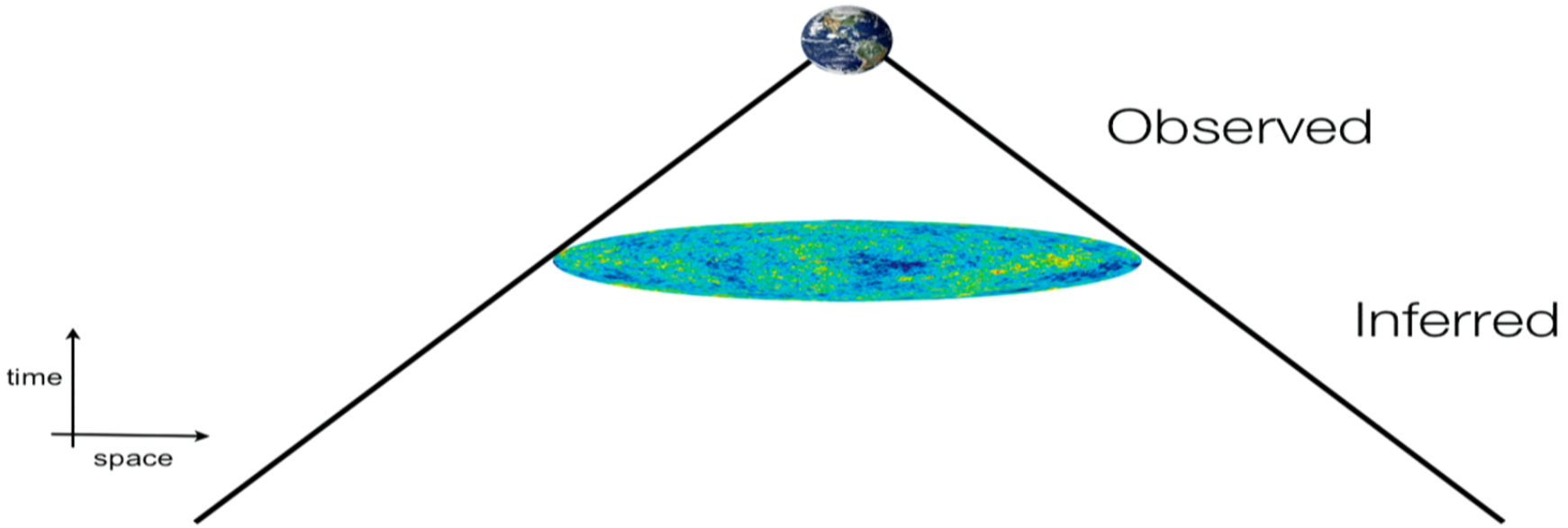
ΛCDM

The Inferred Universe

Everything that we think exists based on theoretical models.



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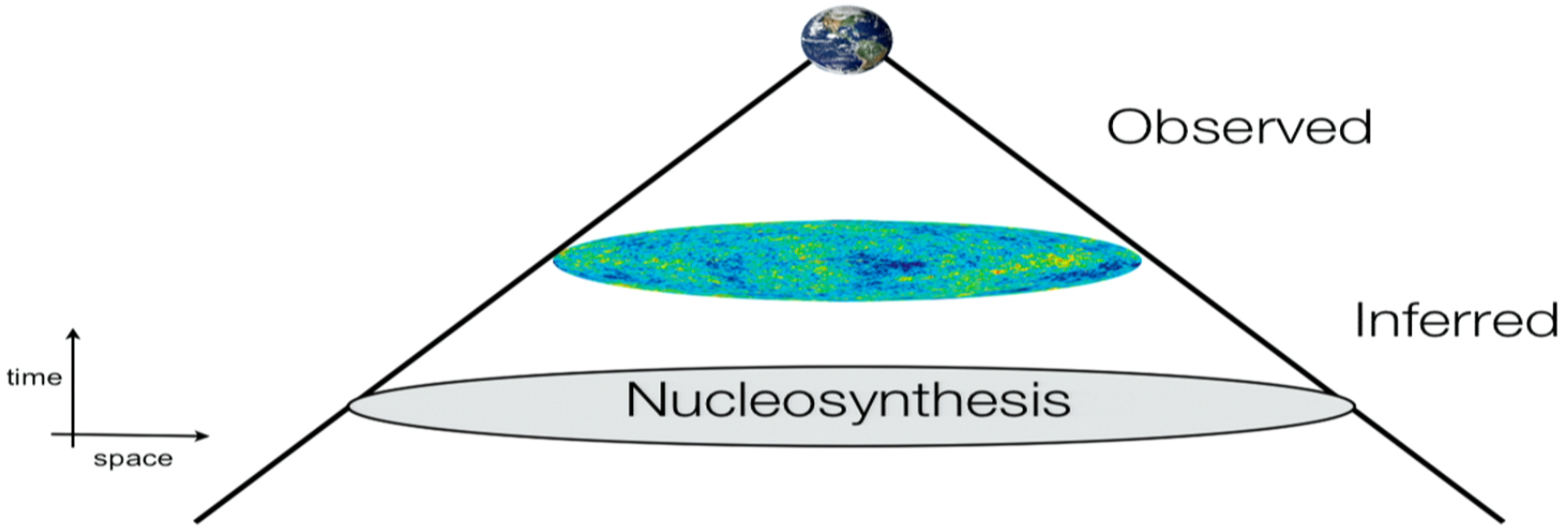

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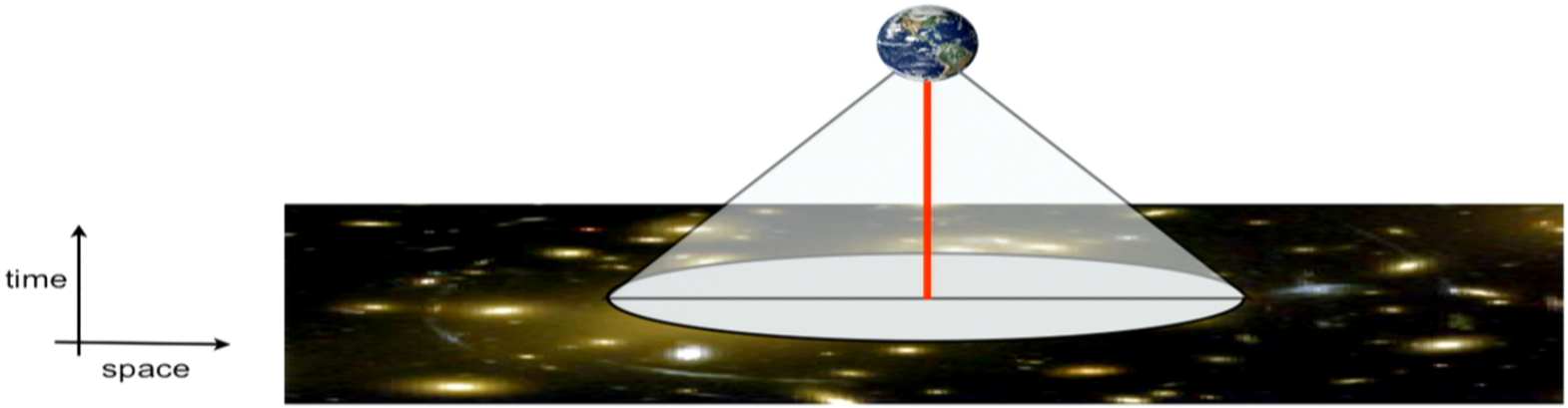

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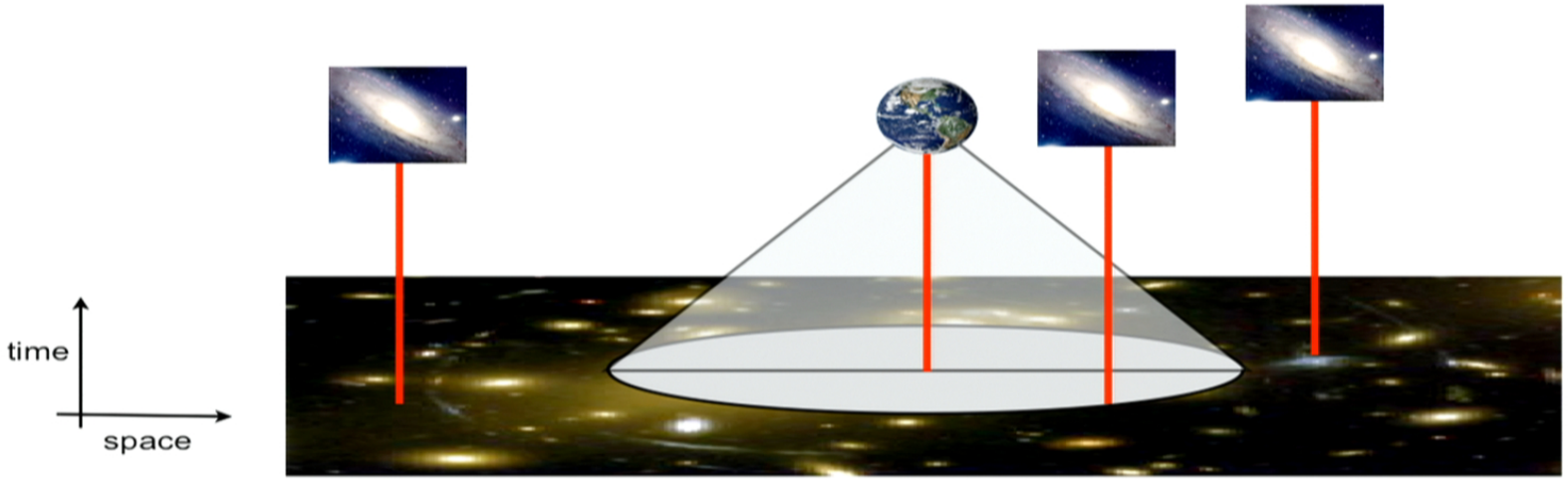

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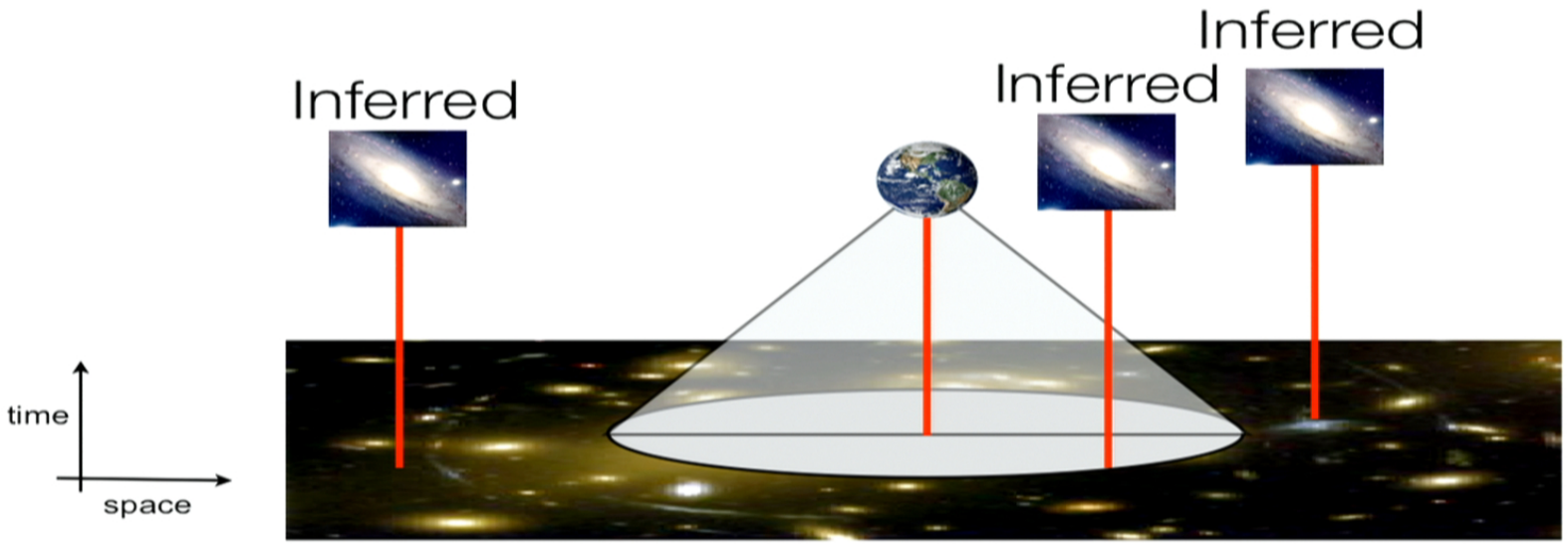
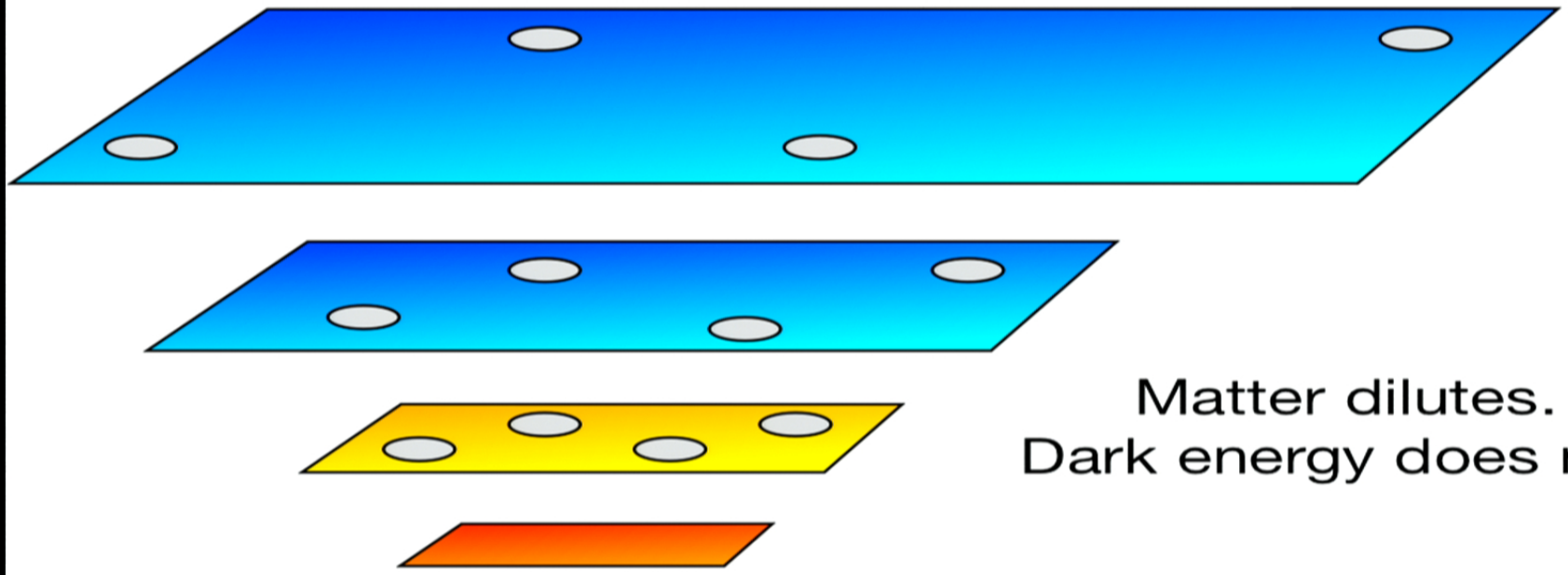
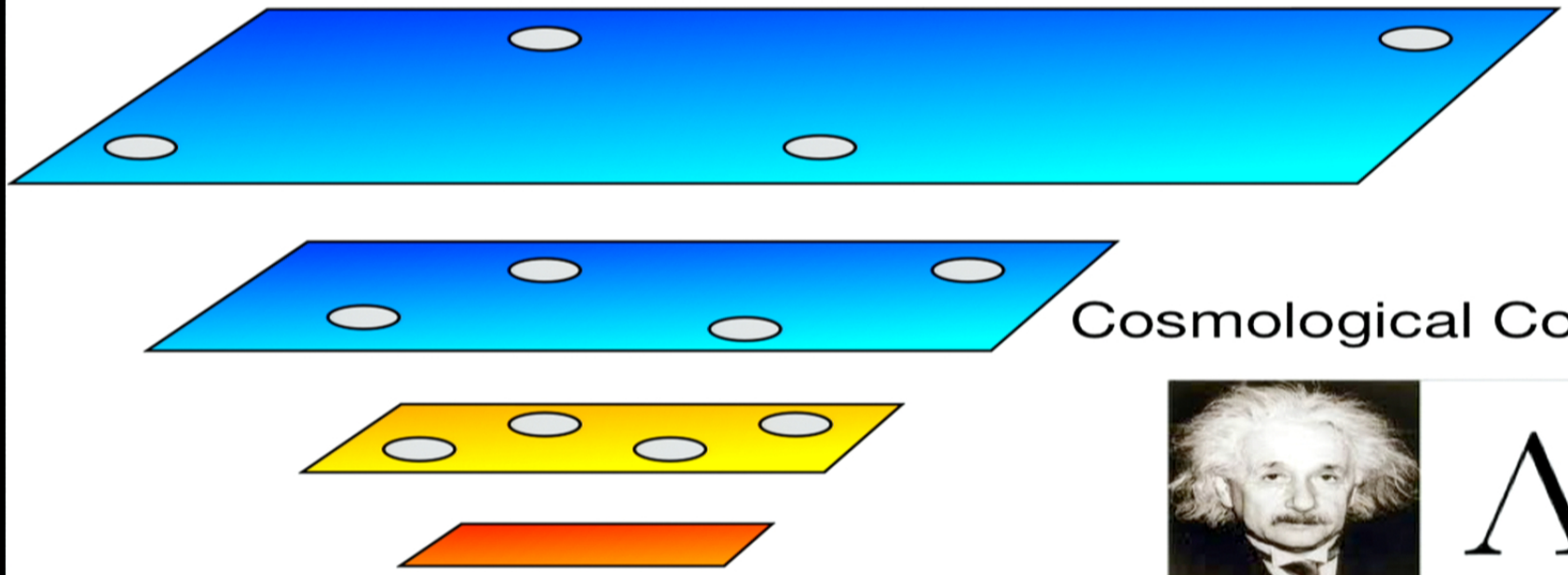


What is dark energy?



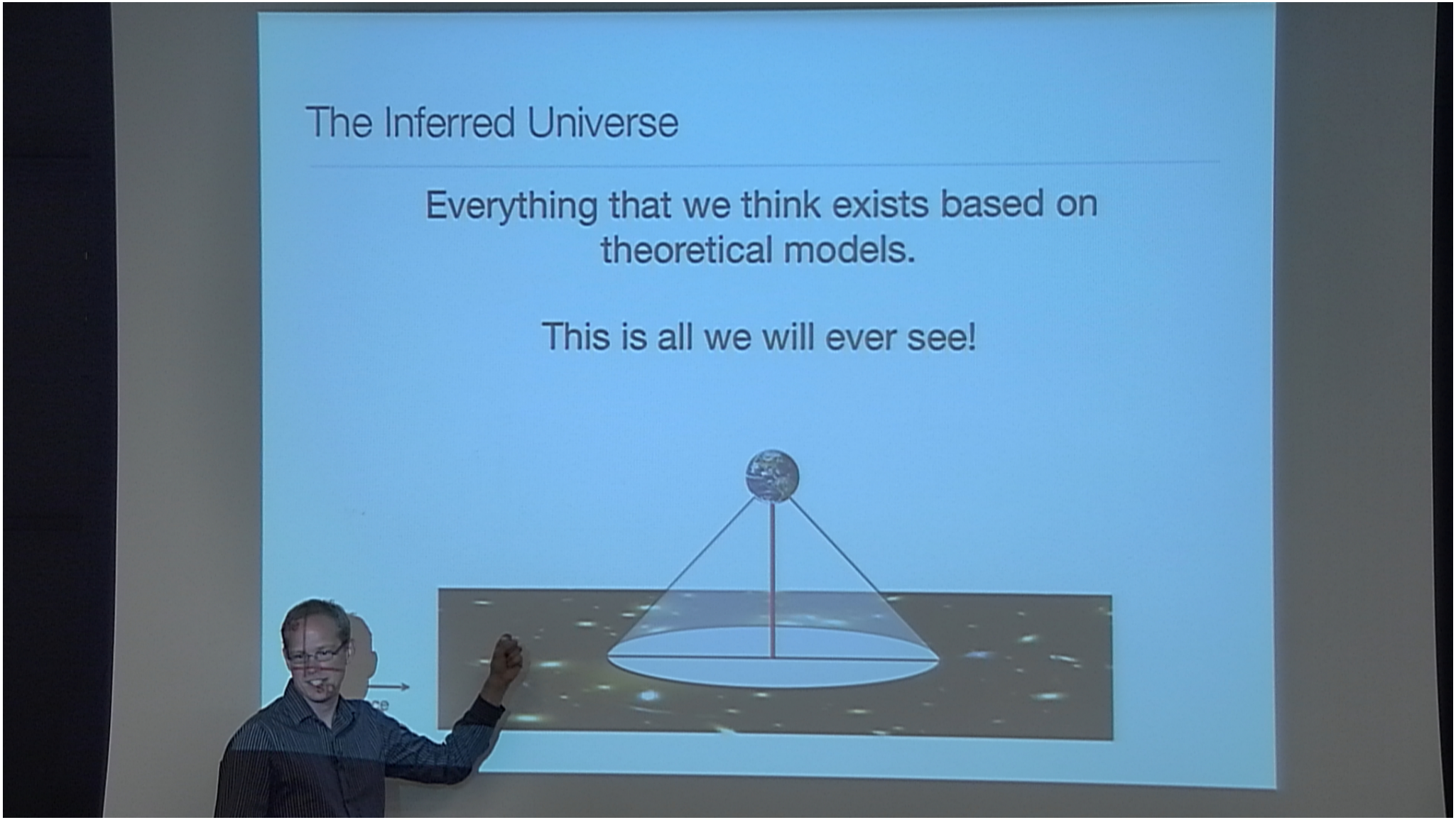
Matter dilutes.
Dark energy does not!

What is dark energy?



Cosmological Constant

Λ


The Inferred Universe
Everything that we think exists based on theoretical models.
This is all we will ever see!

The Inferred Universe

Everything that we think exists based on what we observe and theoretical models.

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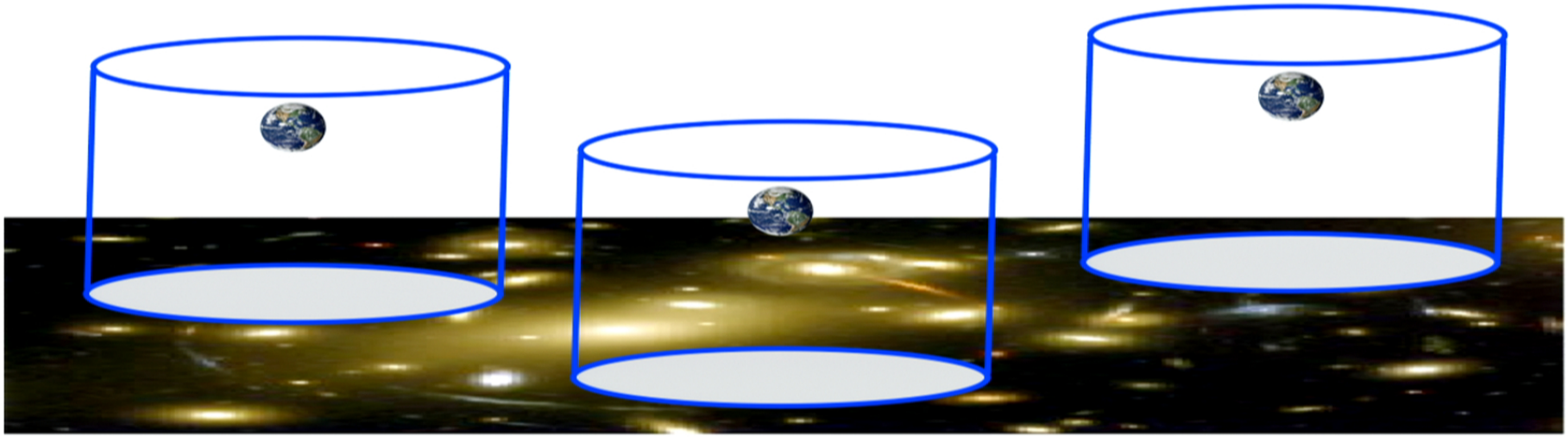
The Multiverse

A set of Observable Universes.

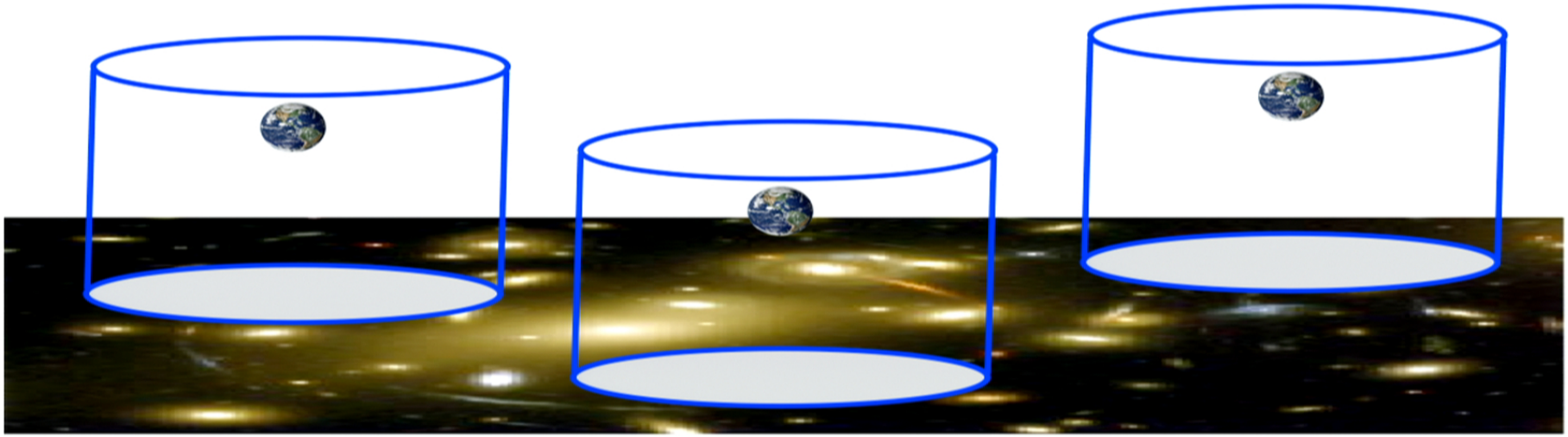


The Multiverse

A set of Observable Universes.

What can be different in the different Observable Universes?

Which one do we inhabit?



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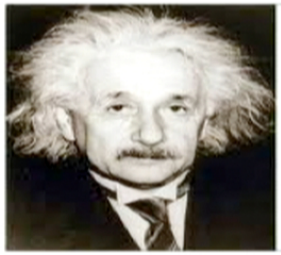


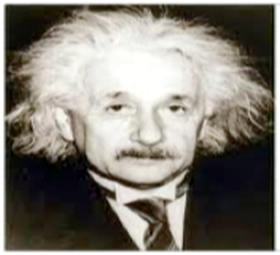
Λ

Prediction from
Quantum Field Theory

(zero-point energy)

What is dark energy?

Cosmological Constant



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Prediction from
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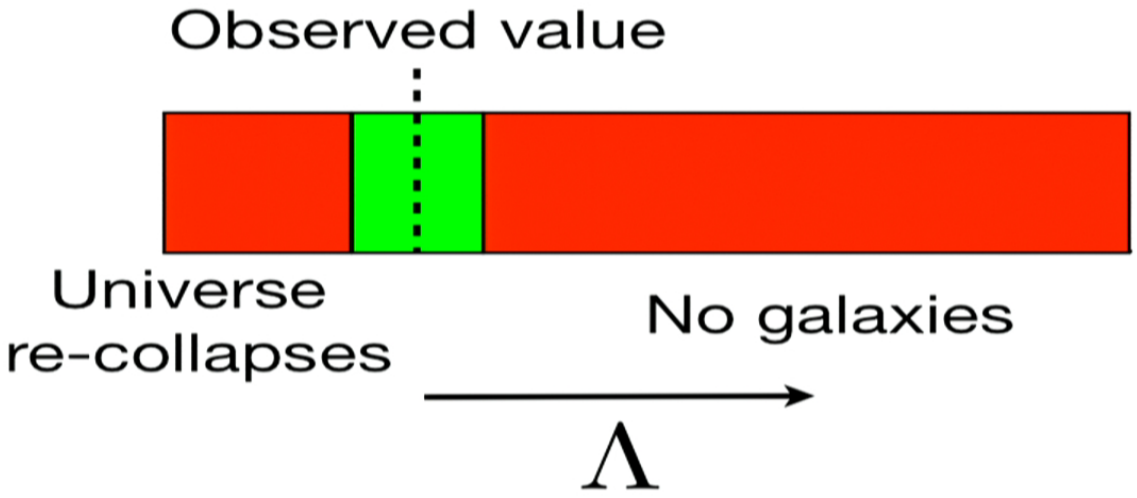
$$.000000000000000000000000$$
$$000000000000000000000000$$
$$000000000000000000000000$$
$$000000000000000000000000$$
$$00000000000000000001\%$$

Weinberg's Prediction of Λ

What if the cosmological constant varies between Observable Universes?



String Theory

(Graviton: particle associated with gravity)

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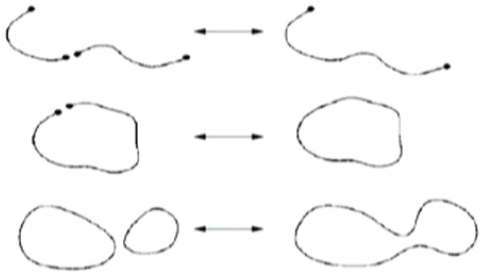
∞ The theory of gravitons does not work! ∞

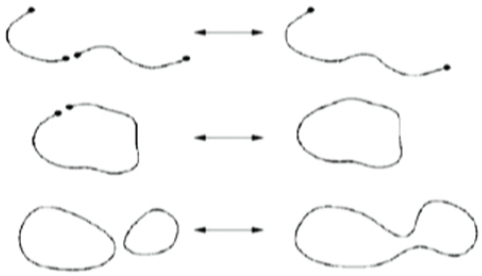
(not a good quantum theory of gravity)

String Theory



- String theory: A good theory of quantum gravity!
- Unifies all forces and fundamental particles!

String Theory



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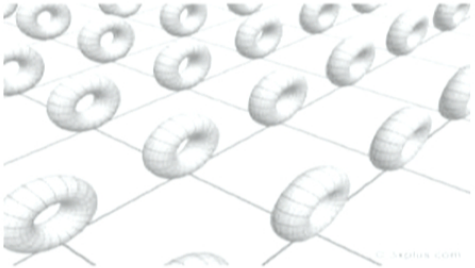
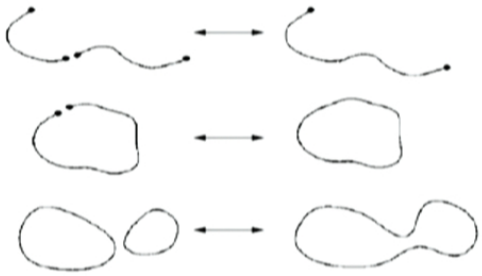
- This only works if there are 9 dimensions of space!



The solution: make the extra dimensions small!

String Theory



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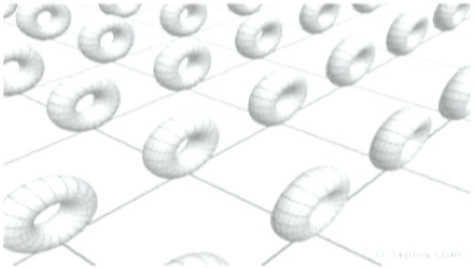

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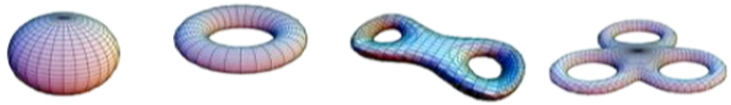

Many possible values of Λ !

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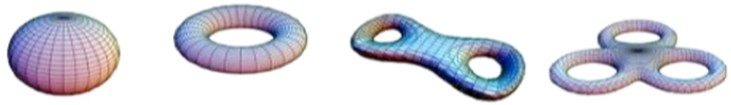
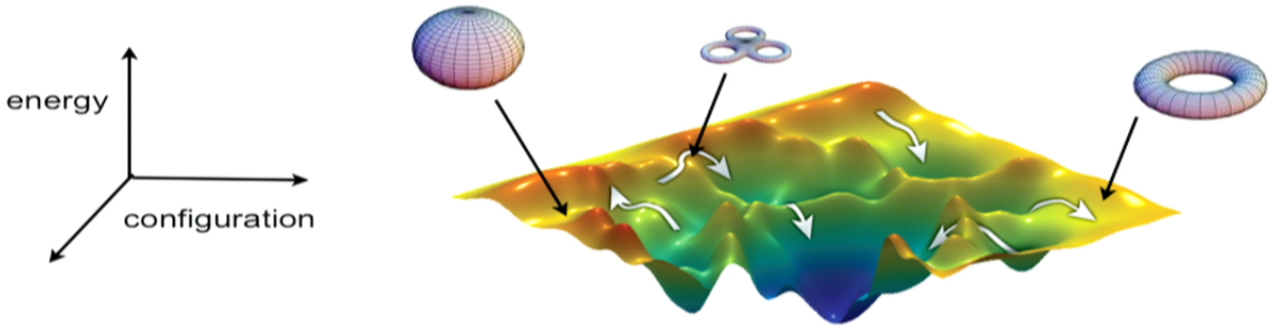


10^{500}

Many possible values of Λ!

The String Theory Landscape



- Configurations can be deformed into one another.
- Can each of these configurations be physically realized?

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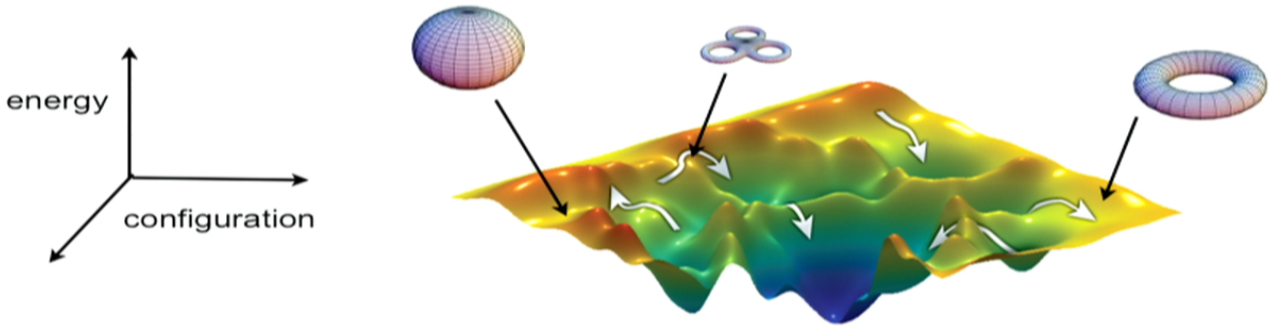

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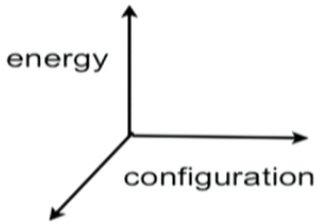

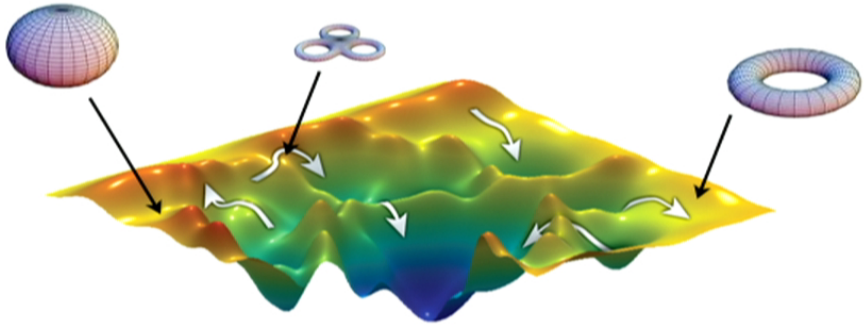

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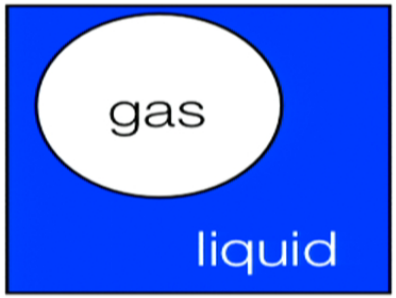
Cosmic Phase Transitions

Liquid water goes to steam by the formation of bubbles.



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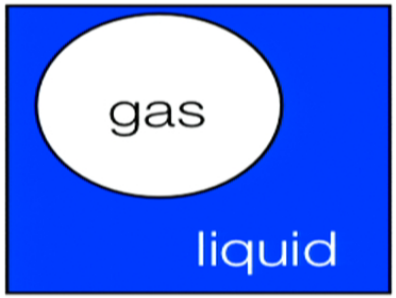

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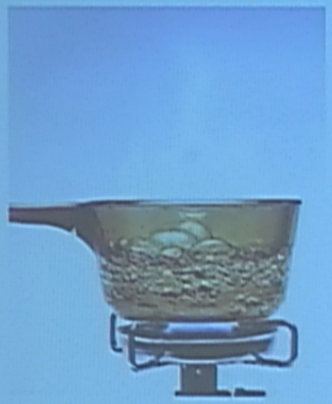
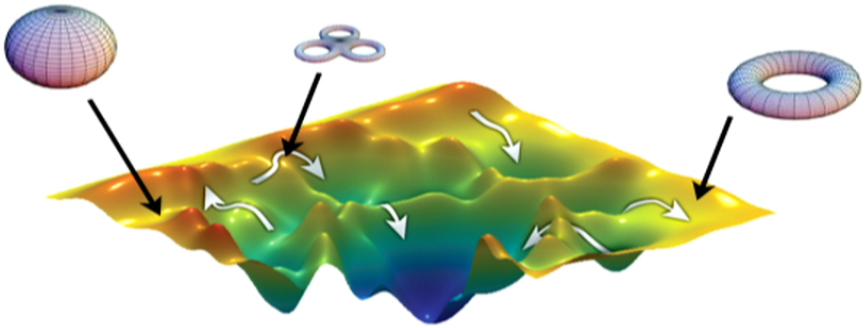


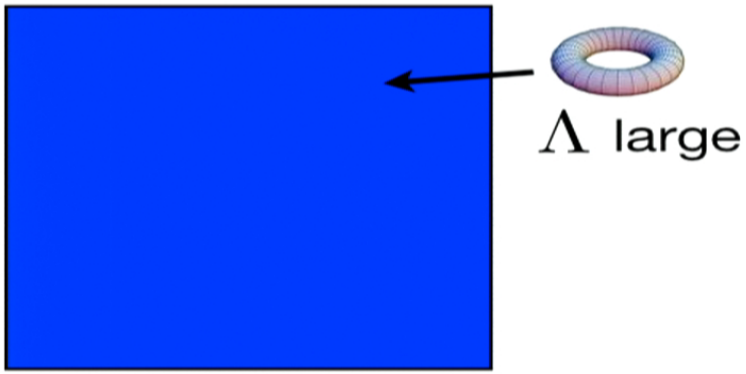
Liquid water goes to steam by the formation of bubbles.

Cosmological phase transitions are possible.

Happen even at zero temperature!

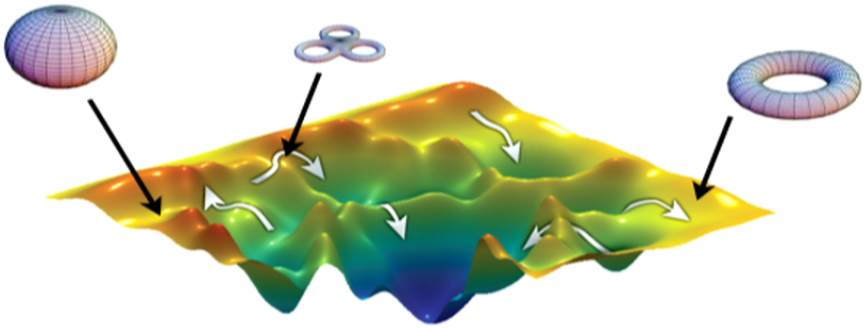
Cosmic Phase Transitions

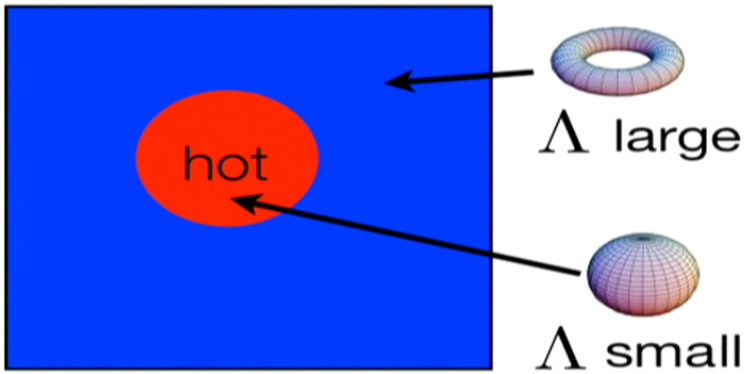




- The configuration of the extra dimensions can undergo phase transitions!
- This means Λ changes as well!

Cosmic Phase Transitions





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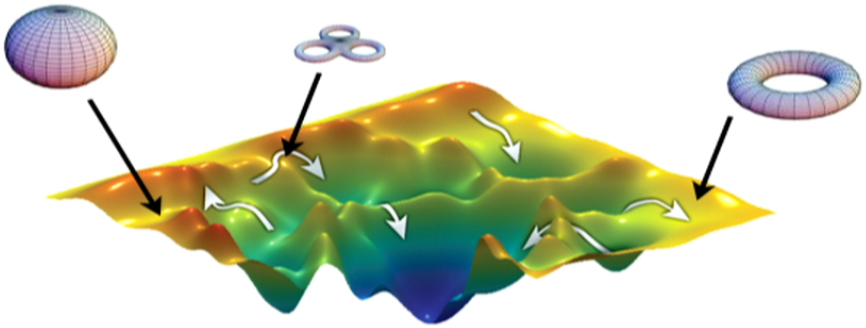

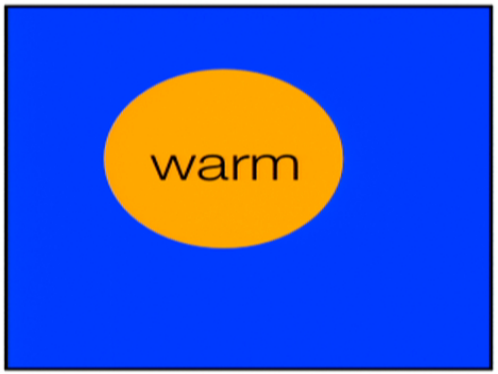

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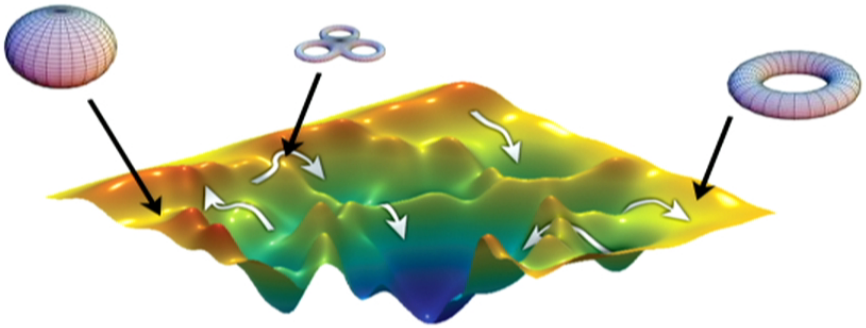
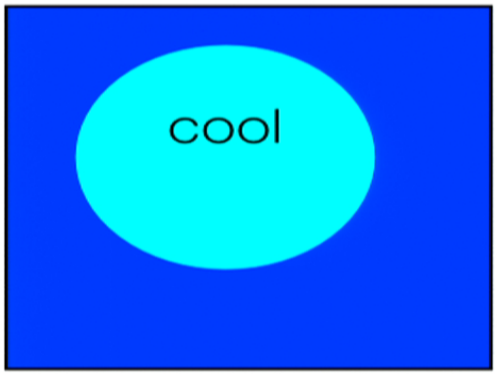
Cosmic Phase Transitions

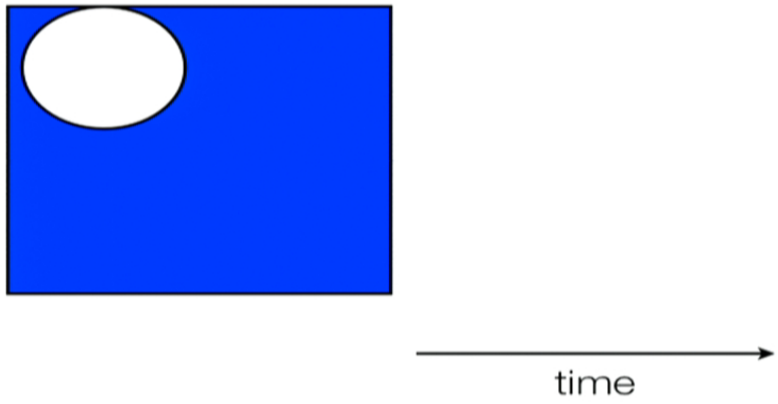




- The configuration of the extra dimensions can undergo phase transitions!
- This means Λ changes as well!
- Our Observable Universe is contained in a bubble.

Cosmic Phase Transitions

- In a static or decelerating universe:



Cosmic Phase Transitions

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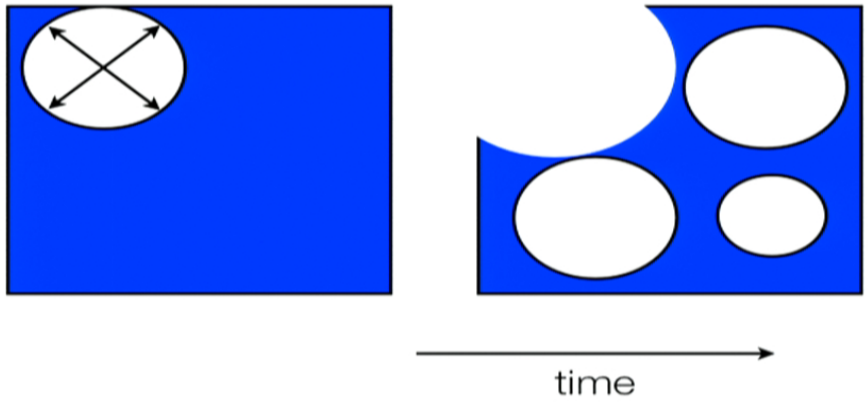

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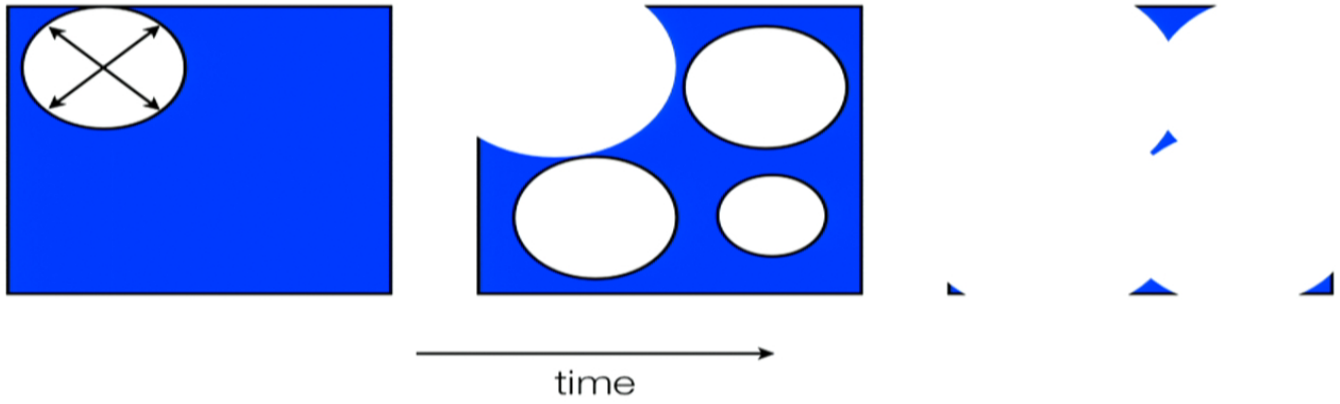
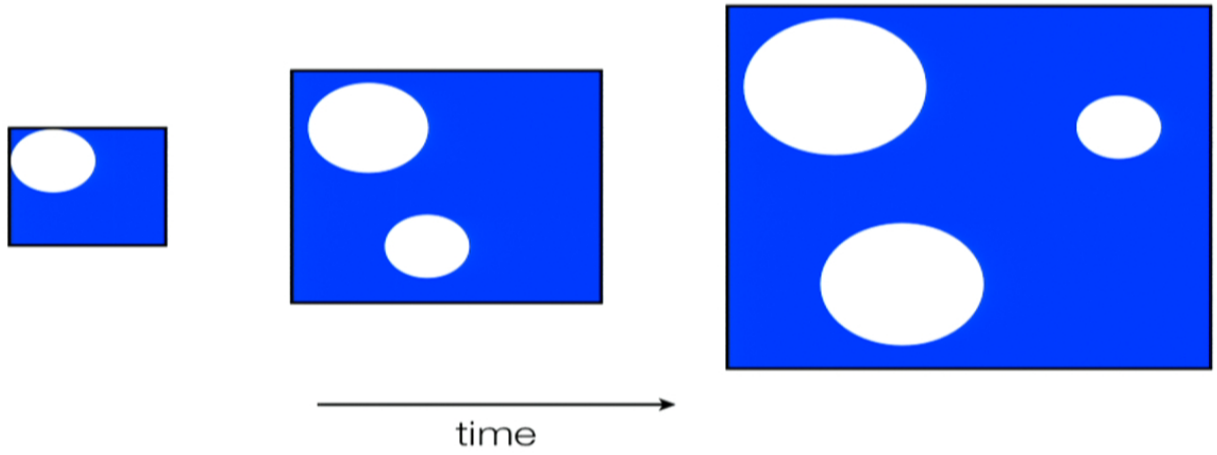


Cosmic Phase Transitions

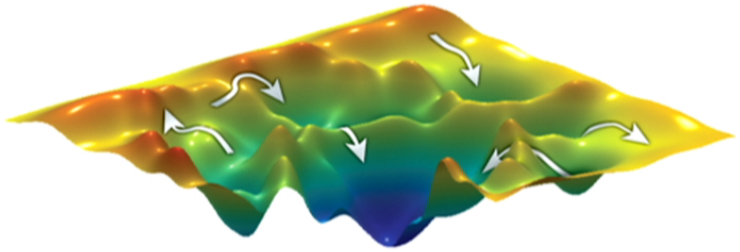
- In an accelerating universe:

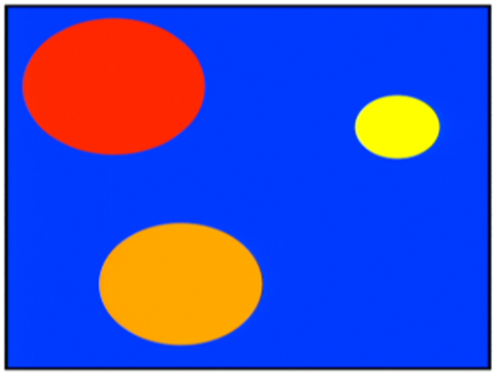


Eternal Inflation

When the rate of bubble formation is lower than the rate of expansion, accelerated expansion doesn't end everywhere!

Eternal Inflation



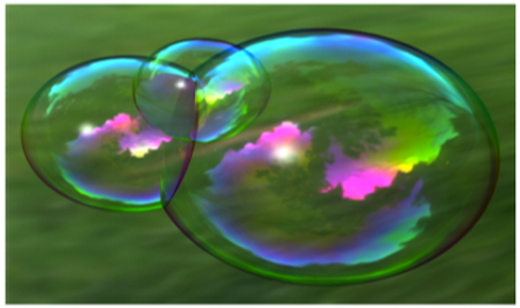


Many values of Λ are realized!

Observational Tests of Eternal Inflation

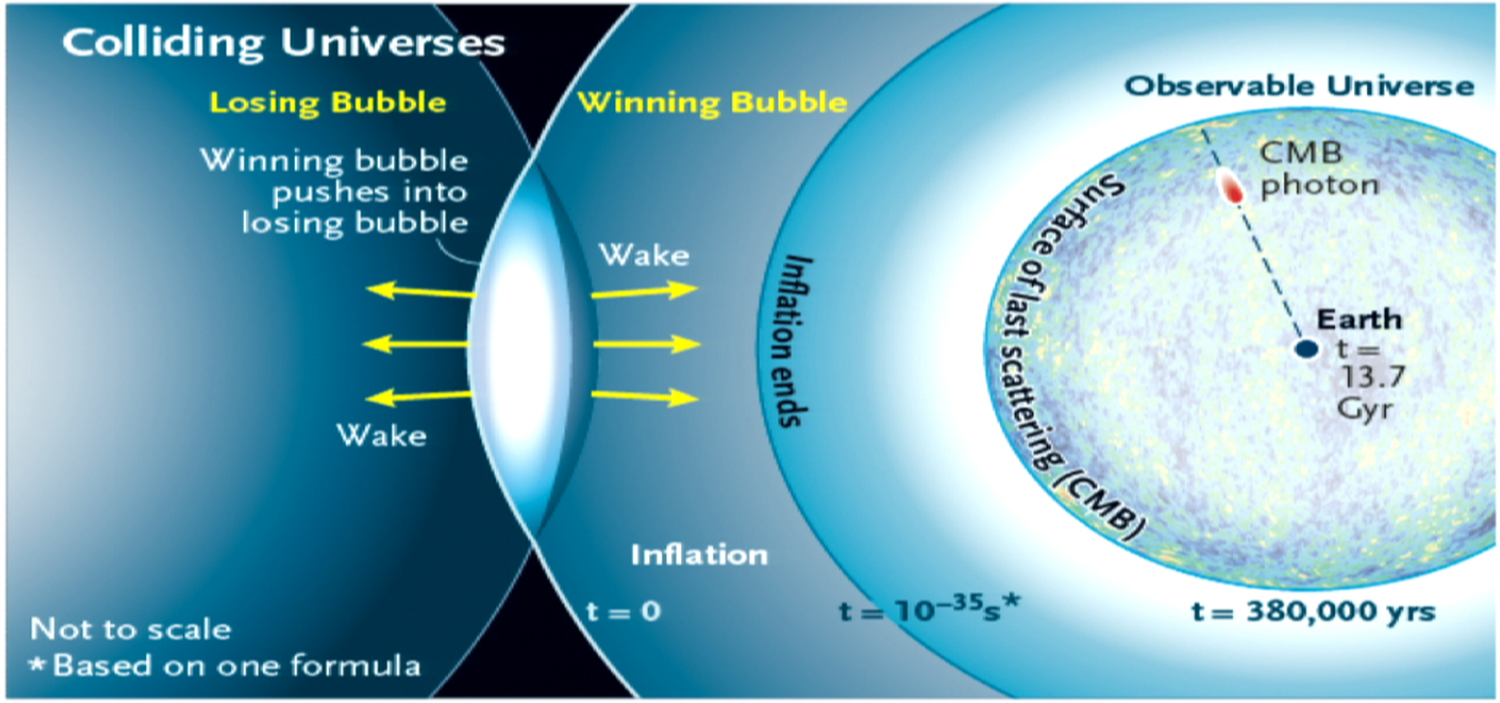
- But is eternal inflation experimentally verifiable?

Our bubble does not evolve in complete isolation....



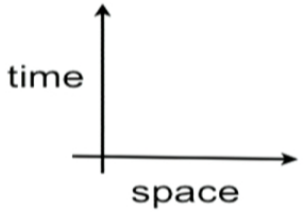
The collision of our bubble with others provides an observational test of the multiverse.

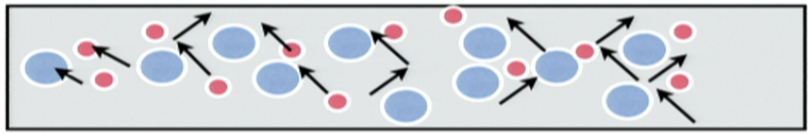
Observational Tests of Eternal Inflation



Cosmic Microwave Background (CMB) radiation

- Temperature anisotropies encode density perturbations.





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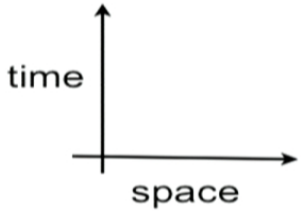

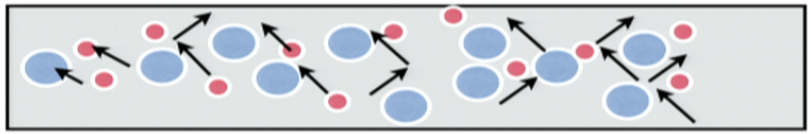

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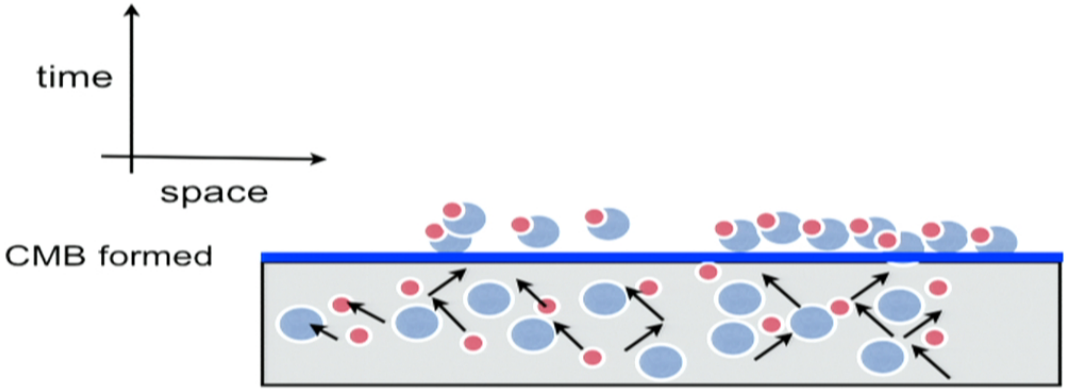

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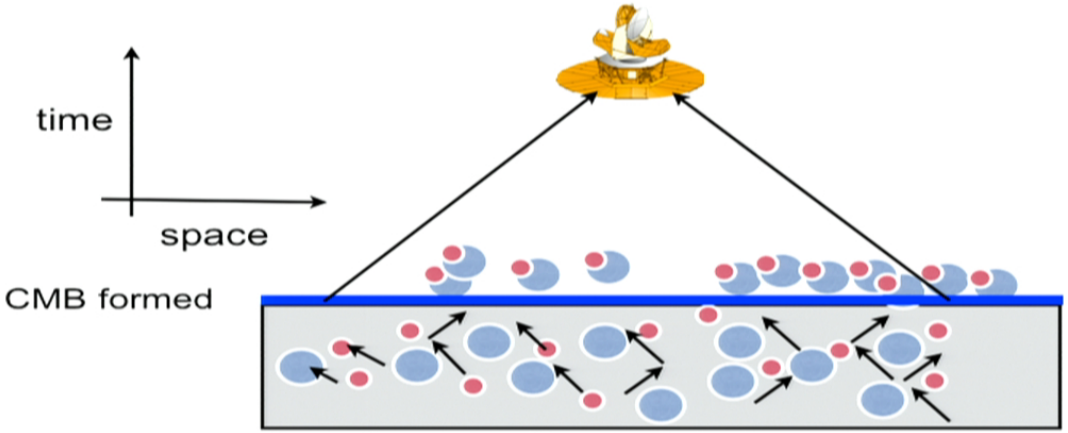

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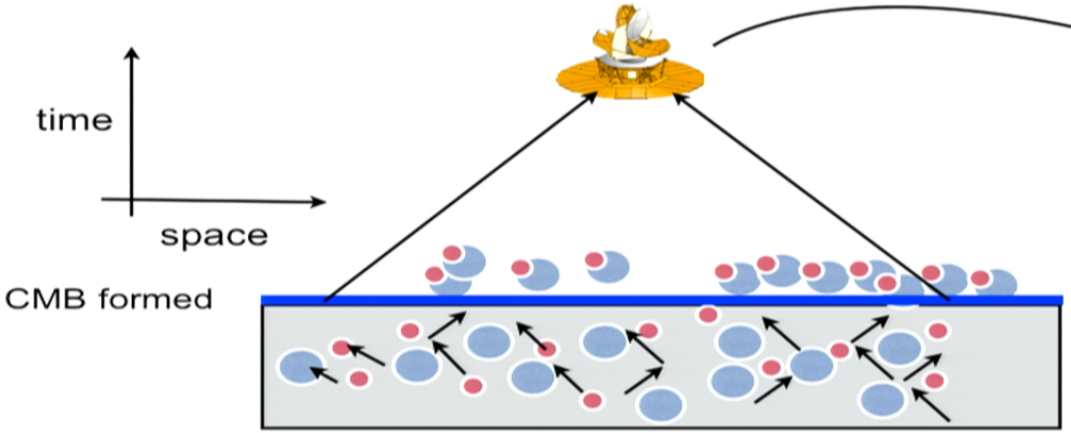

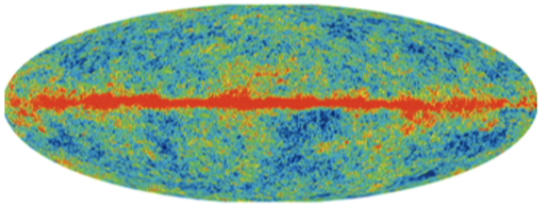

Hot and cold spots.

Cosmic Microwave Background (CMB) radiation

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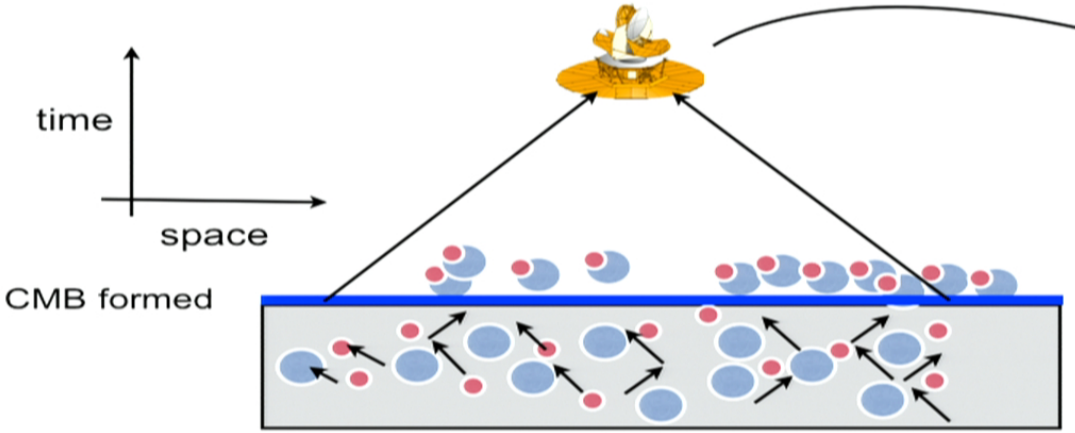
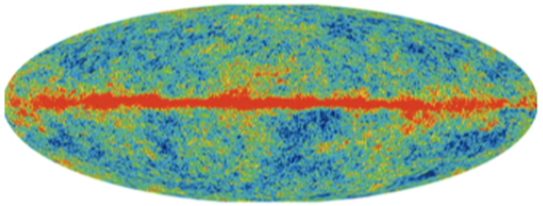
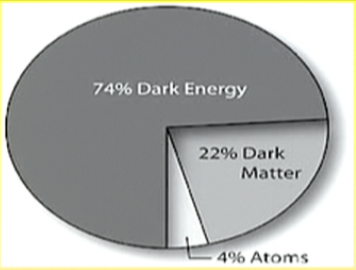




Hot and cold spots.

- We live in a nearly flat, accelerating universe, composed almost entirely of dark energy and dark matter.



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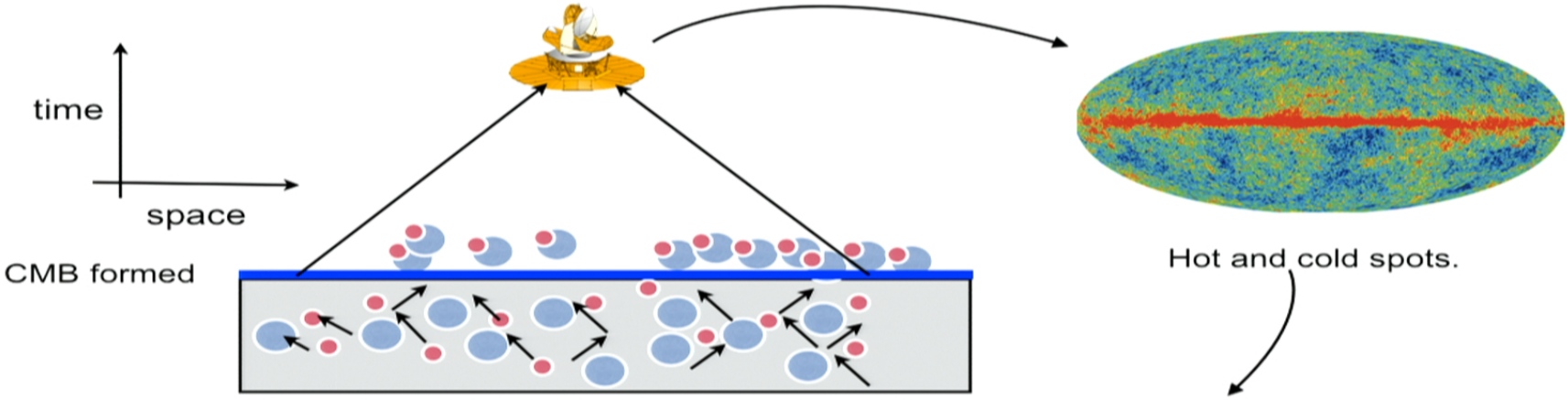

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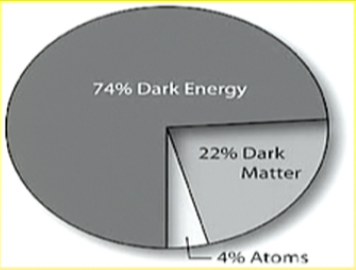
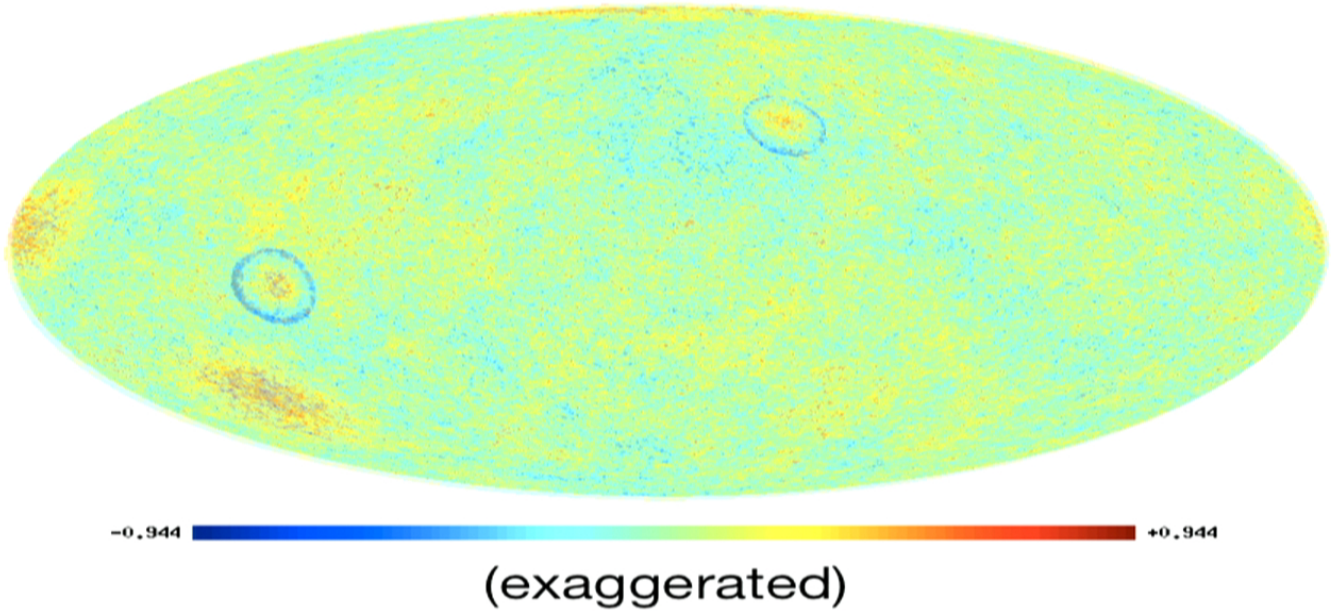


Bubble Collisions

- Bubble collisions induce extra features in the CMB:



(exaggerated)

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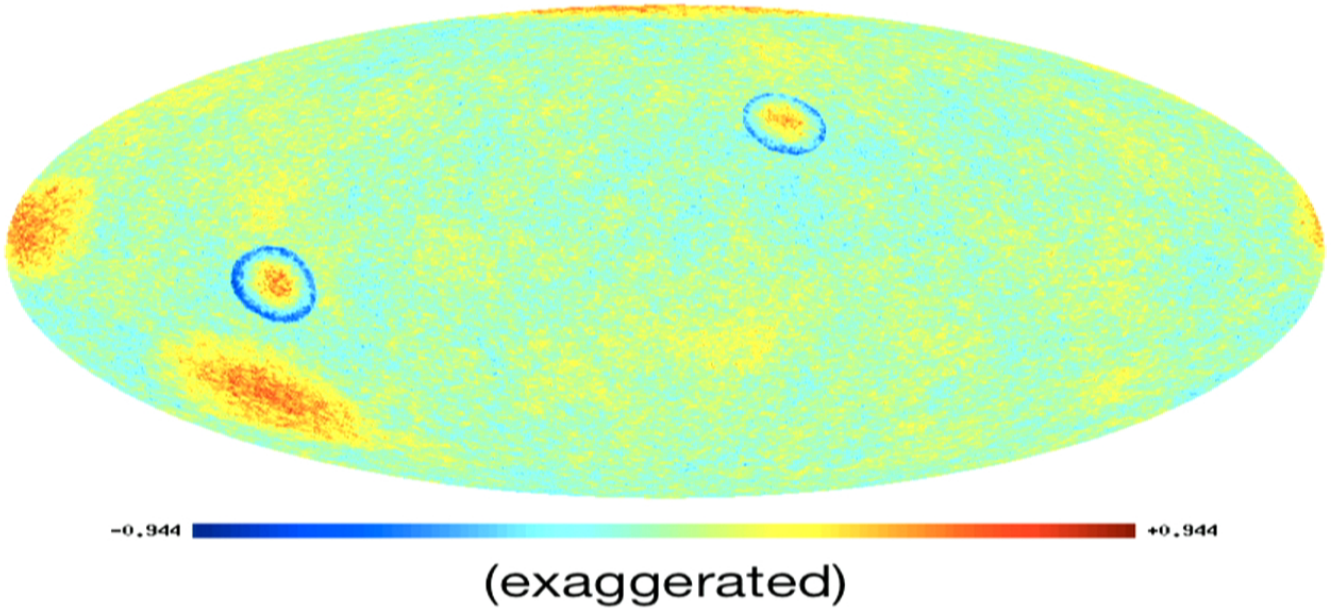
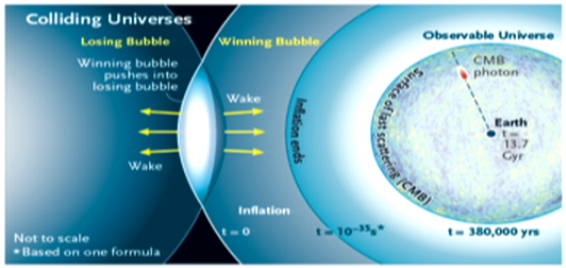
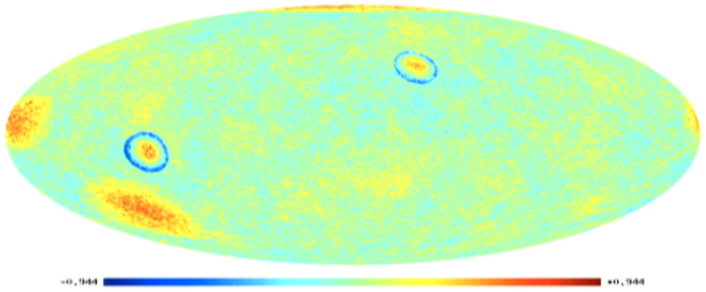


(exaggerated)

Bubble collisions model

- The model:



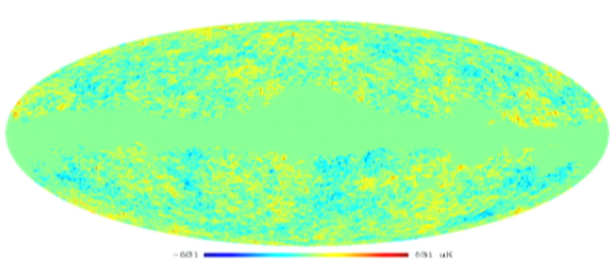


$\bar{N}_s$ expected number of collisions

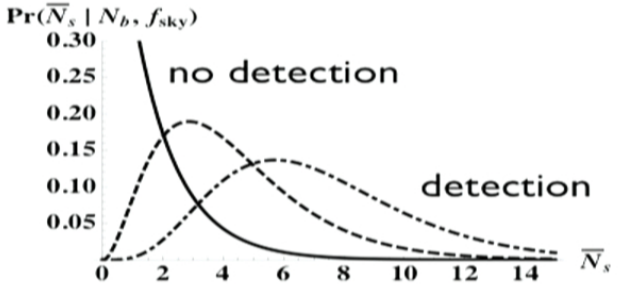
$\mathbf{m}$ parameters characterizing each collision

$\Pr(N_s, \mathbf{m})$ How many of each type do I expect to find?

Searching for collisions



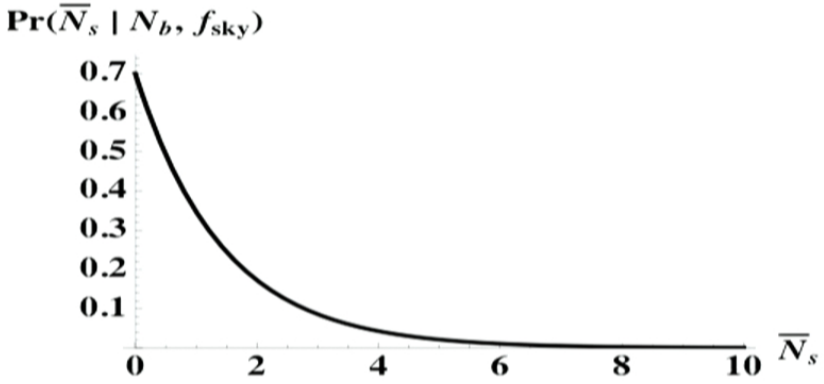
$$\longrightarrow \quad Pr(\bar{N}_s|\mathbf{d})$$



- To calculate this, need to test for:
  - Arbitrary number of collisions
  - Arbitrary position on the sky
  - Arbitrary amplitude, shape, and size (lying within prior $\Pr(N_s, \mathbf{m})$)

Observational Tests of Eternal Inflation

- Results using data from the WMAP satellite



$$\bar{N}_s < 1.6 \text{ at } 68\% \text{ CL}$$

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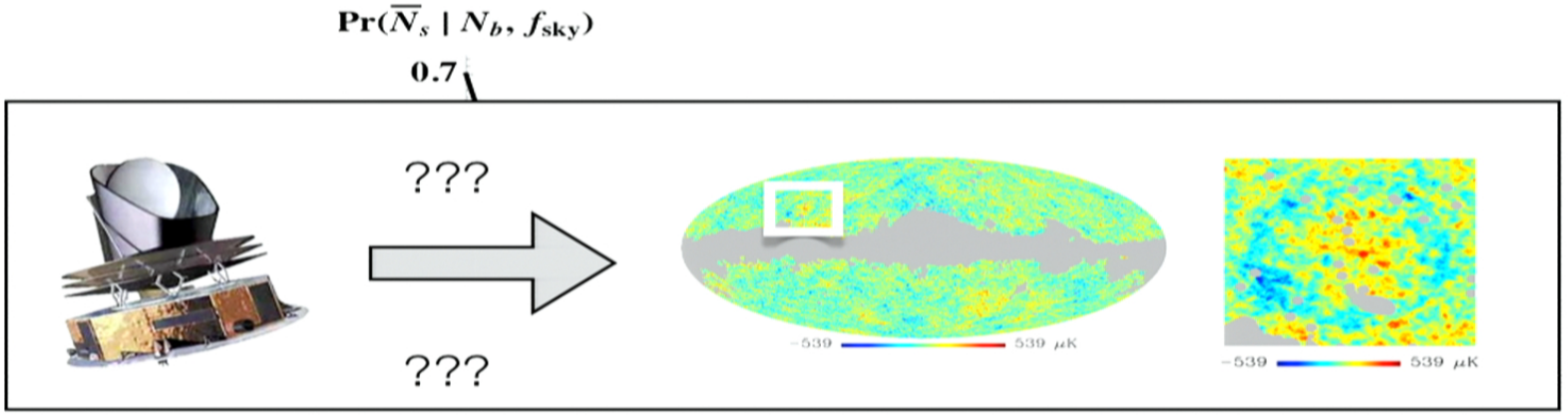

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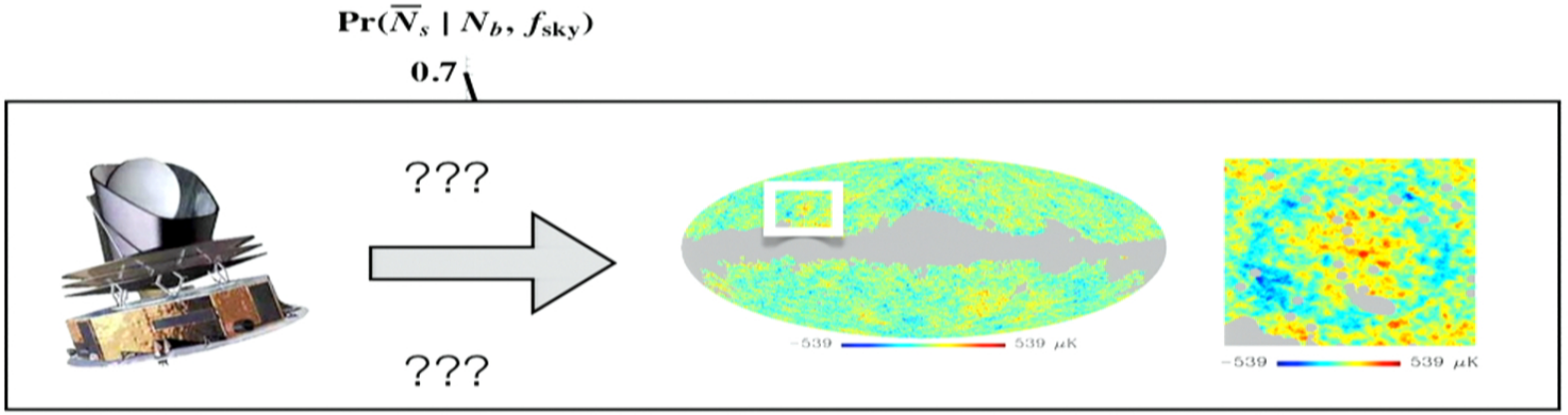

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Conclusions

We may inhabit a Multiverse.
We may know soon!