Early Universe Cosmology

Matthew C. Johnson
York University and Perimeter Institute

YORK
UNIVERSITÉ
UNIVERSITY
redefine THE POSSIBLE

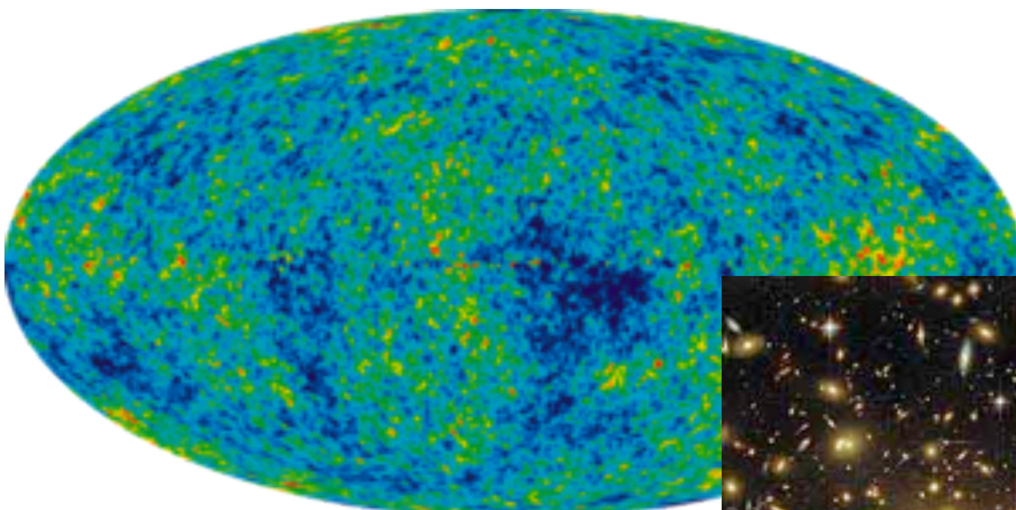
PERIMETER INSTITUTE
FOR THEORETICAL PHYSICS

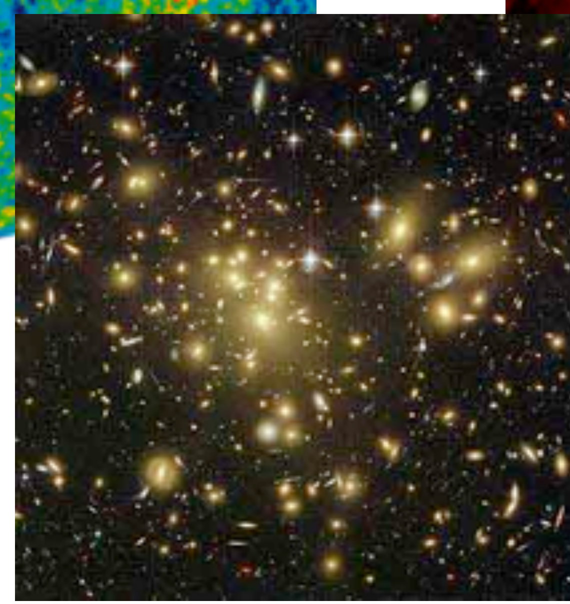
Early Universe Cosmology

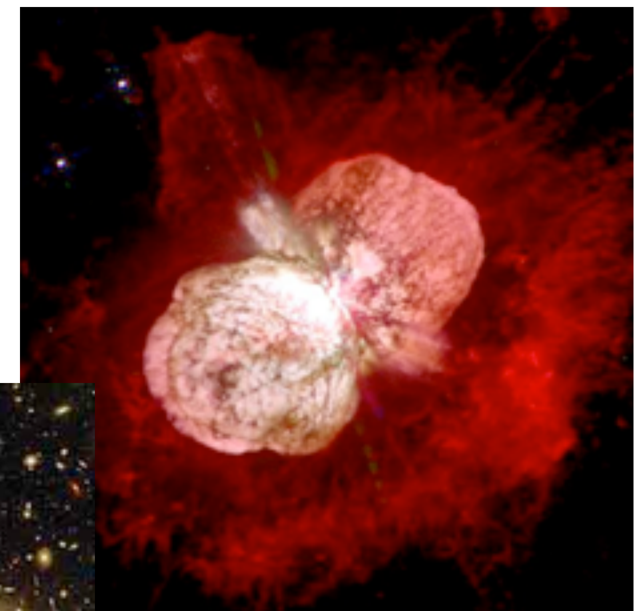
- Testing fundamental theories using limited and imperfect records of the past.

Early Universe Cosmology

- Testing fundamental theories using limited and imperfect records of the past.







Early Universe Cosmology

What can we know?

One paradigm: Inflation

Extremes: Eternal Inflation

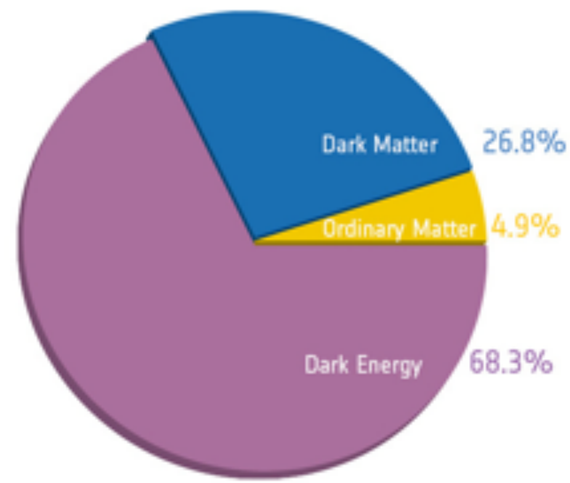
What can we know?

What we can know about the early Universe depends on what happens in the late Universe.

What can we know?

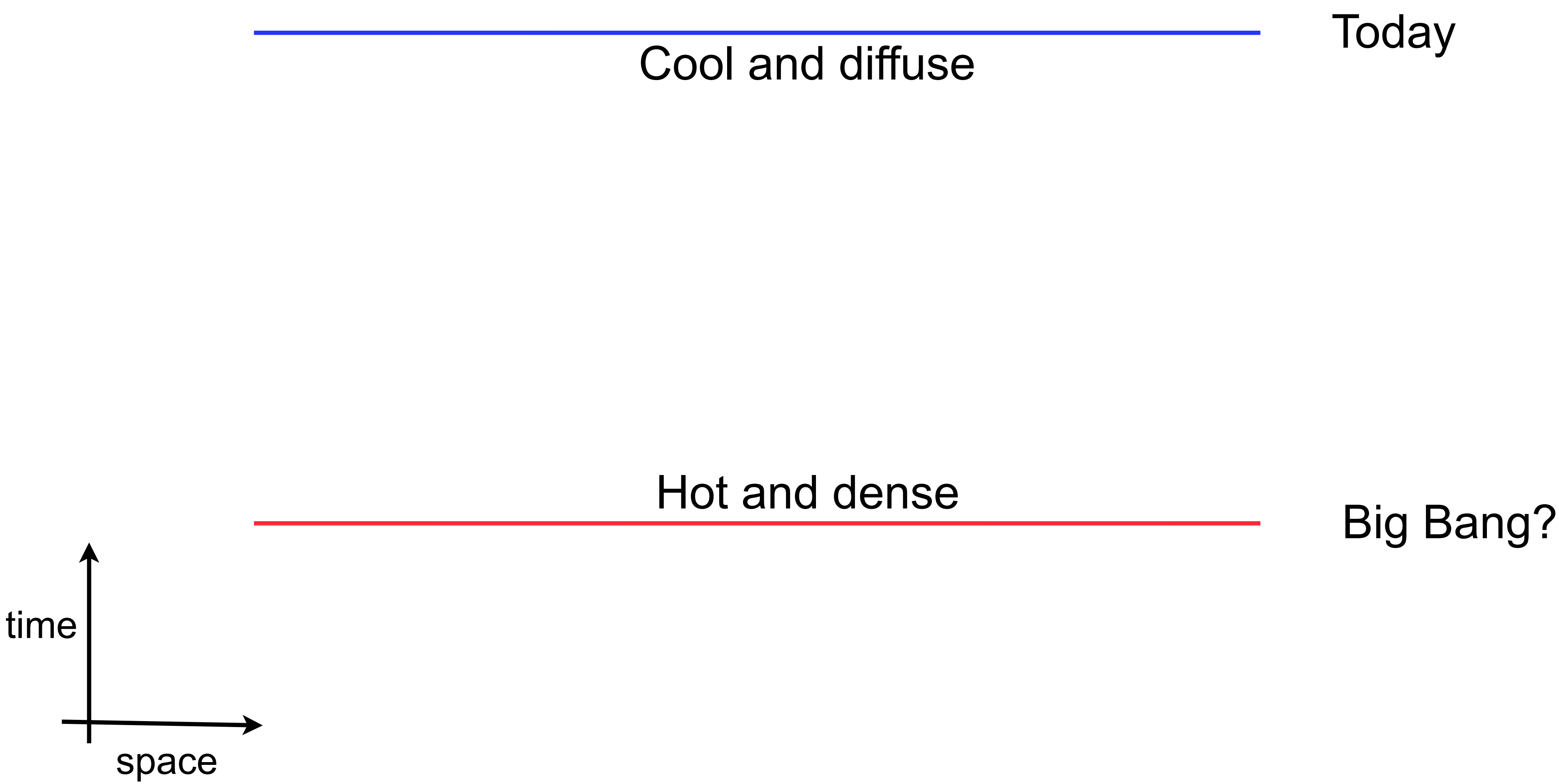
The best theoretical model for the late Universe:

$$\Lambda\mathrm{CDM}$$

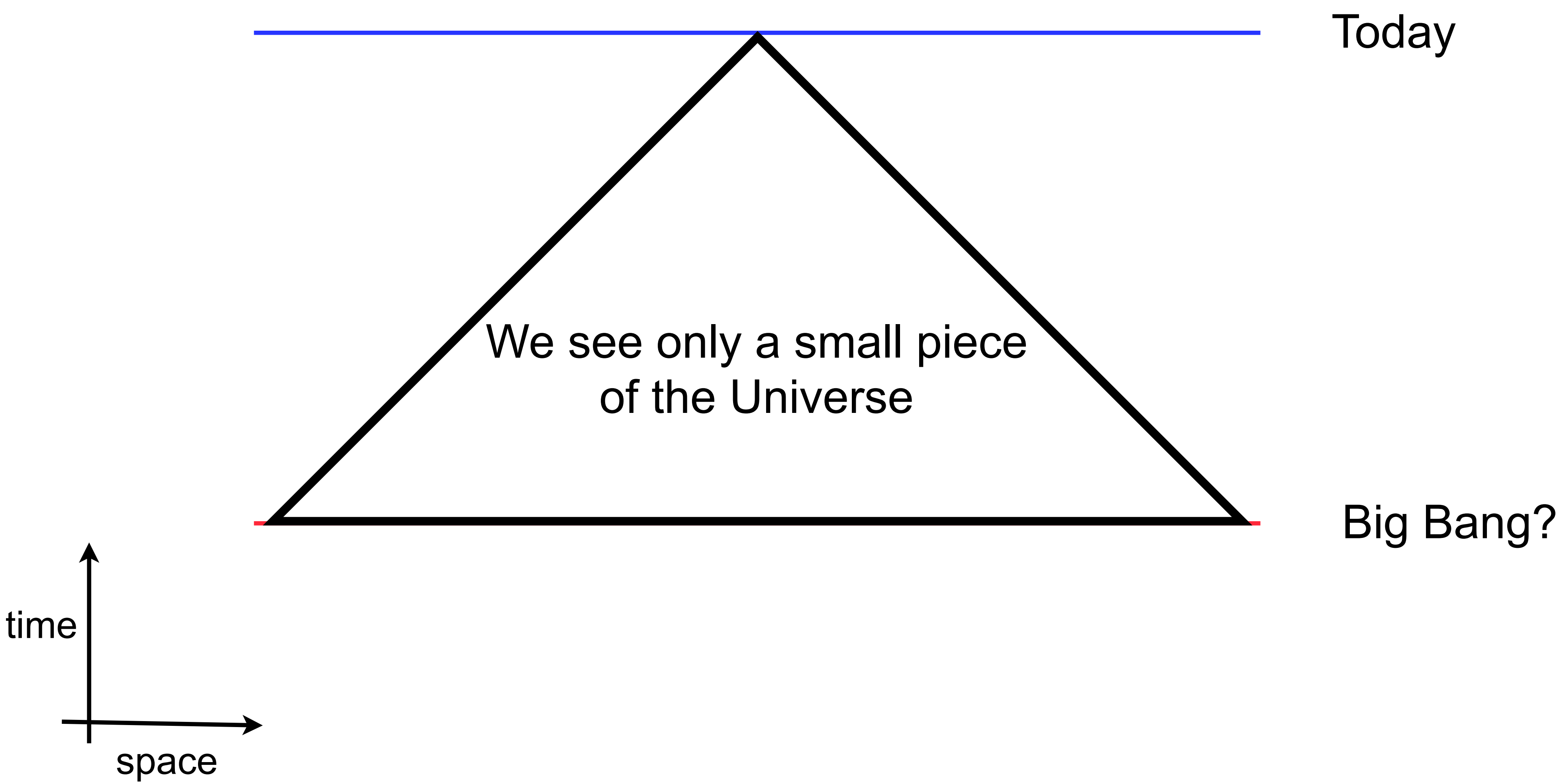


$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

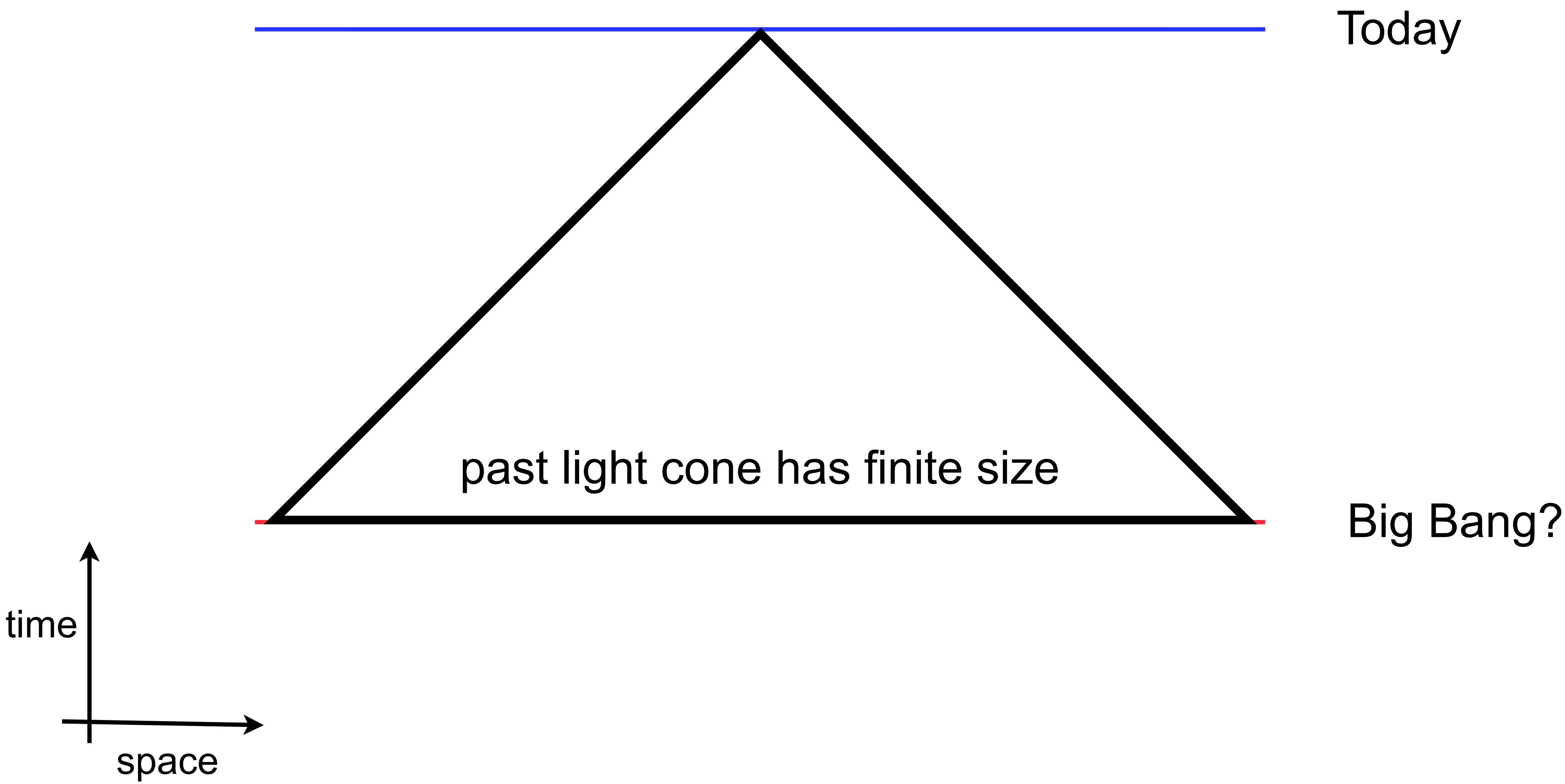
What can we know?



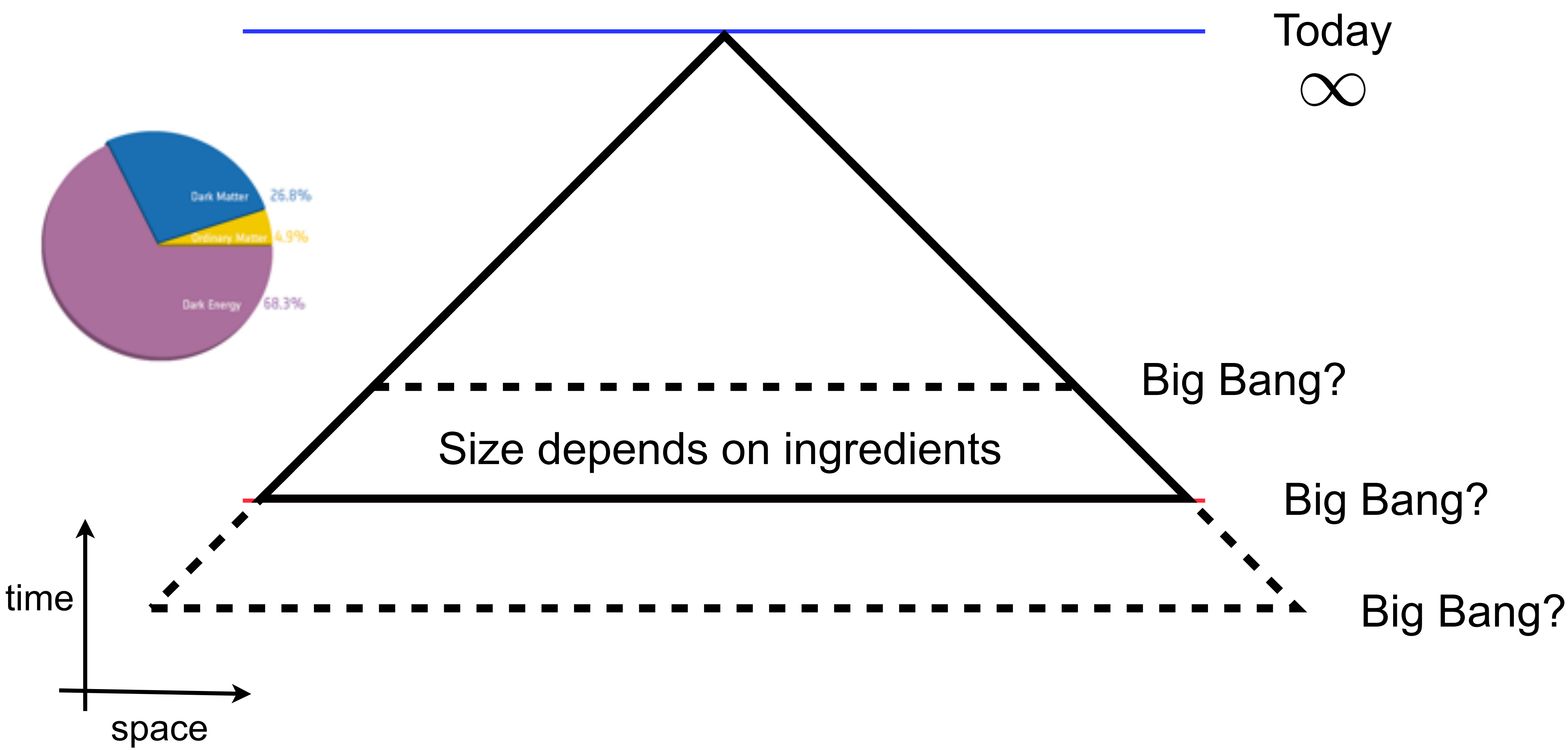
What can we know?



What can we know?

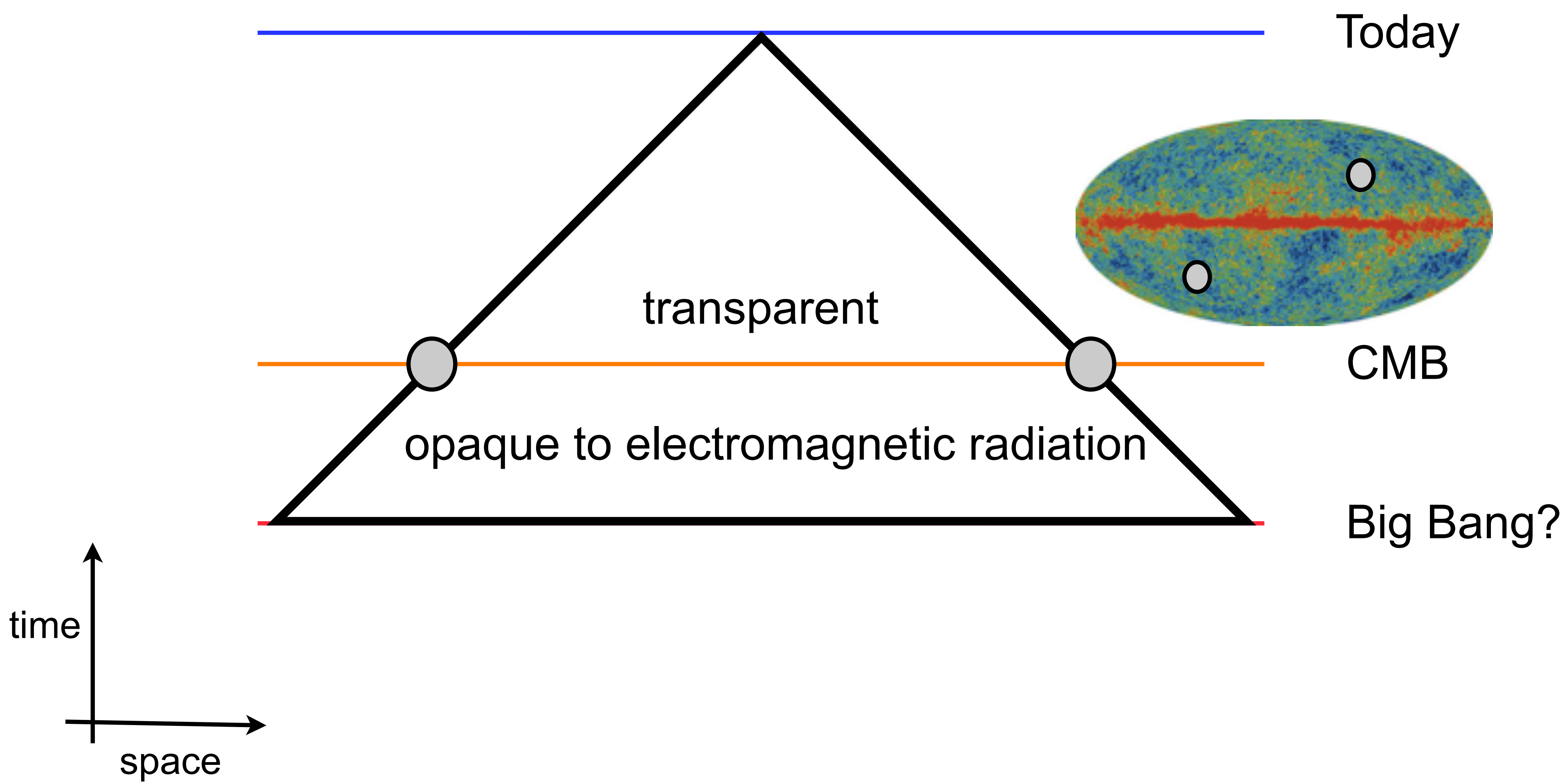


What can we know?



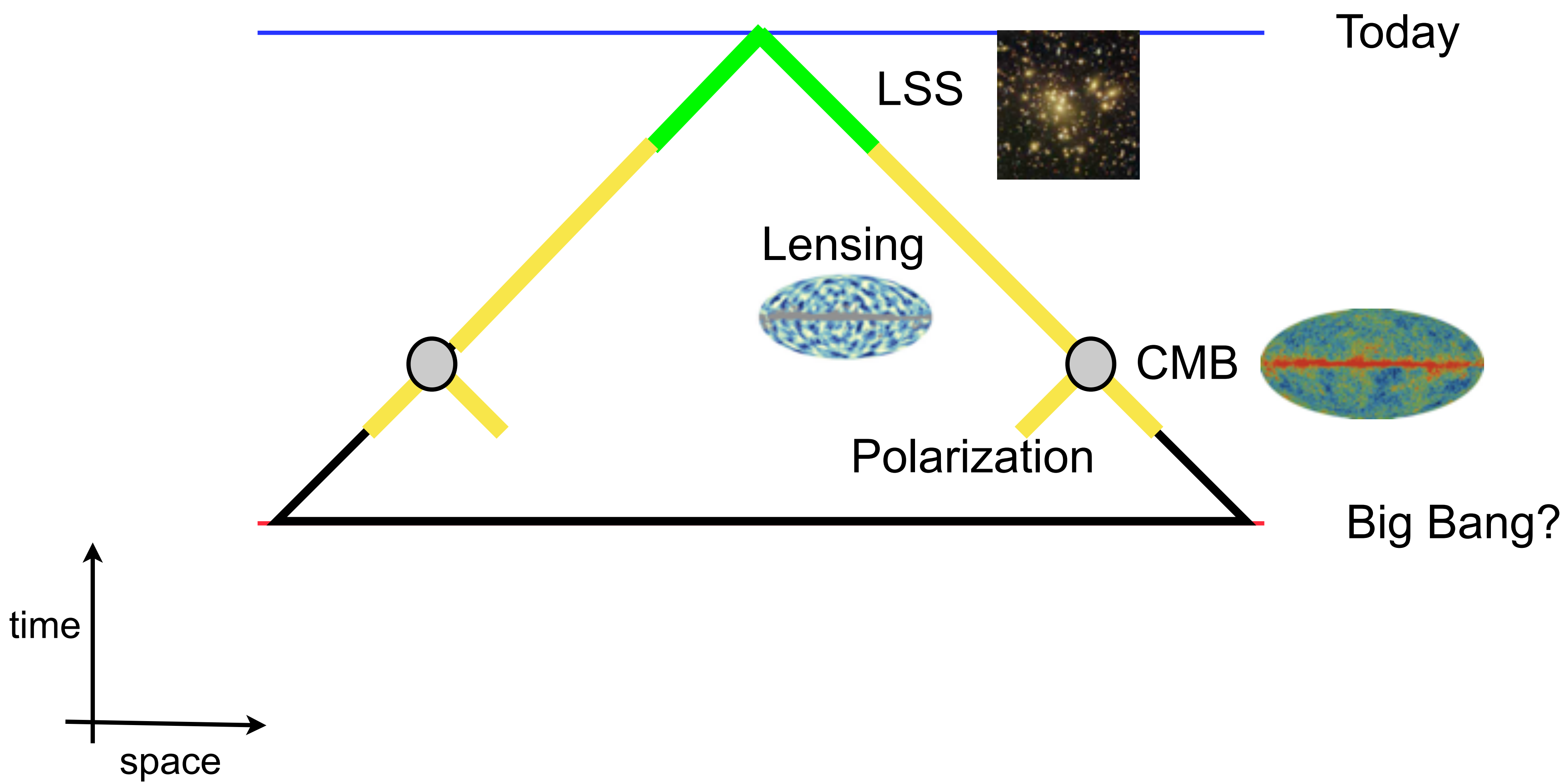
What can we know?

- We can't directly see arbitrarily far into the past!



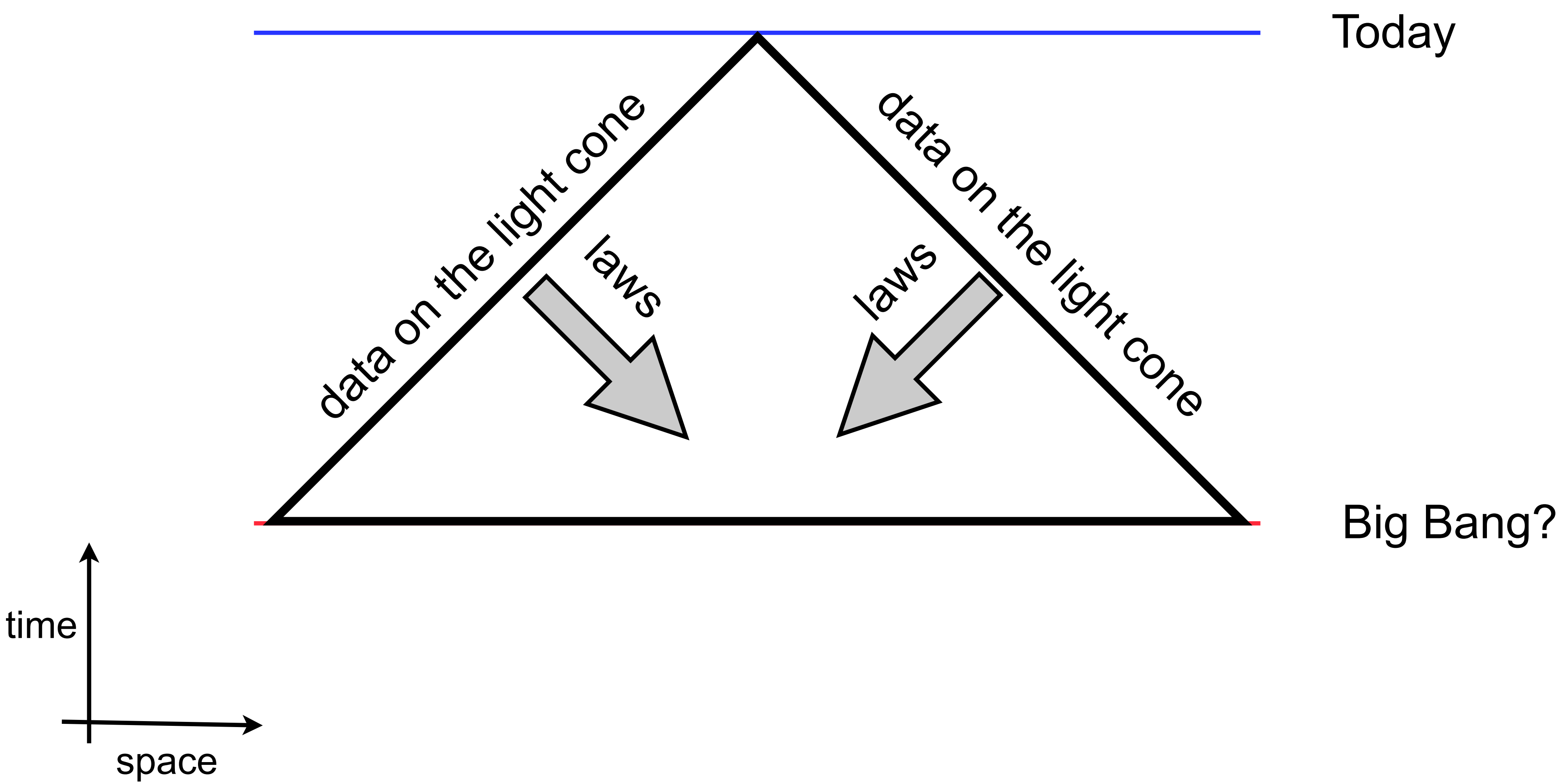
What can we know?

- We (almost) only measure what is on the light cone!

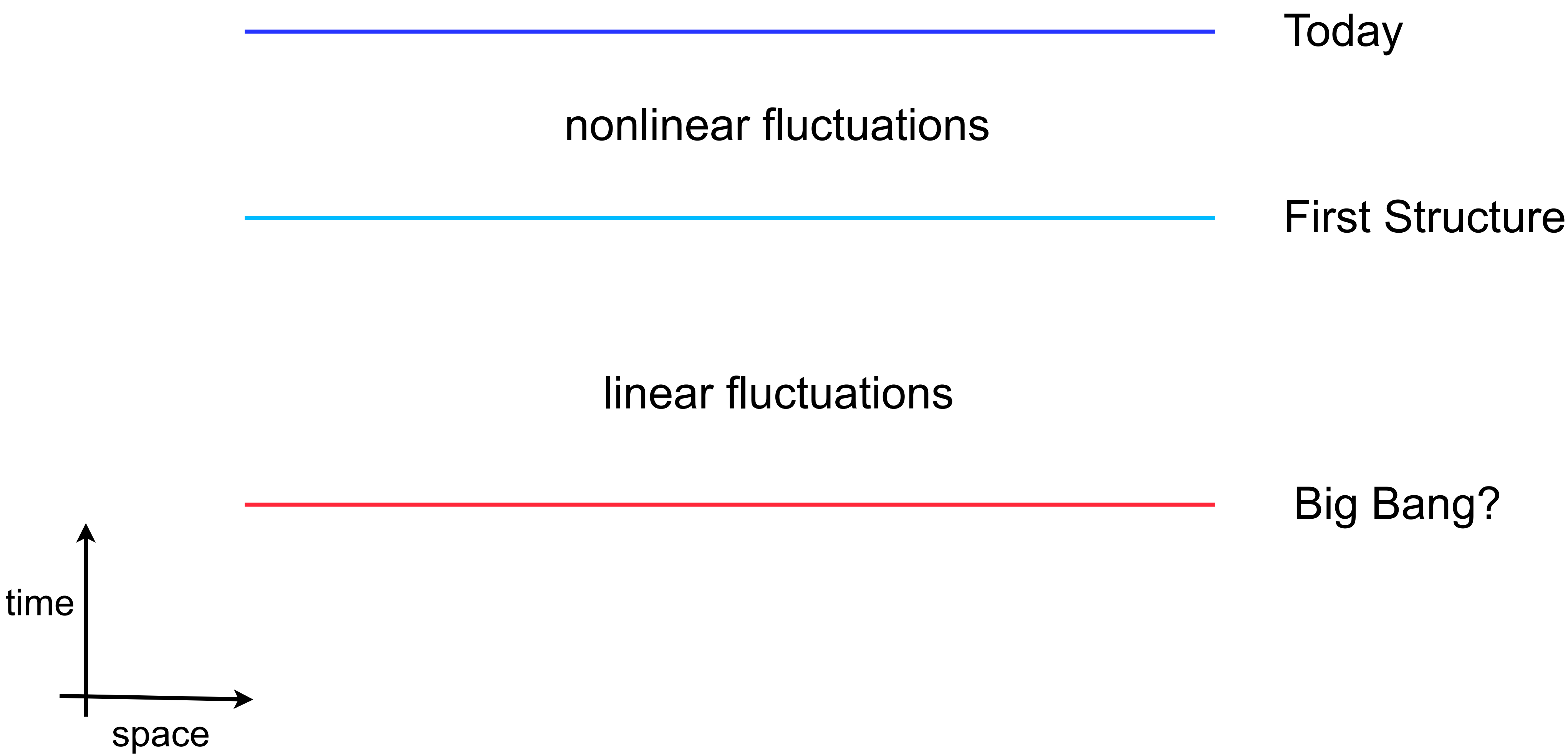


What can we know?

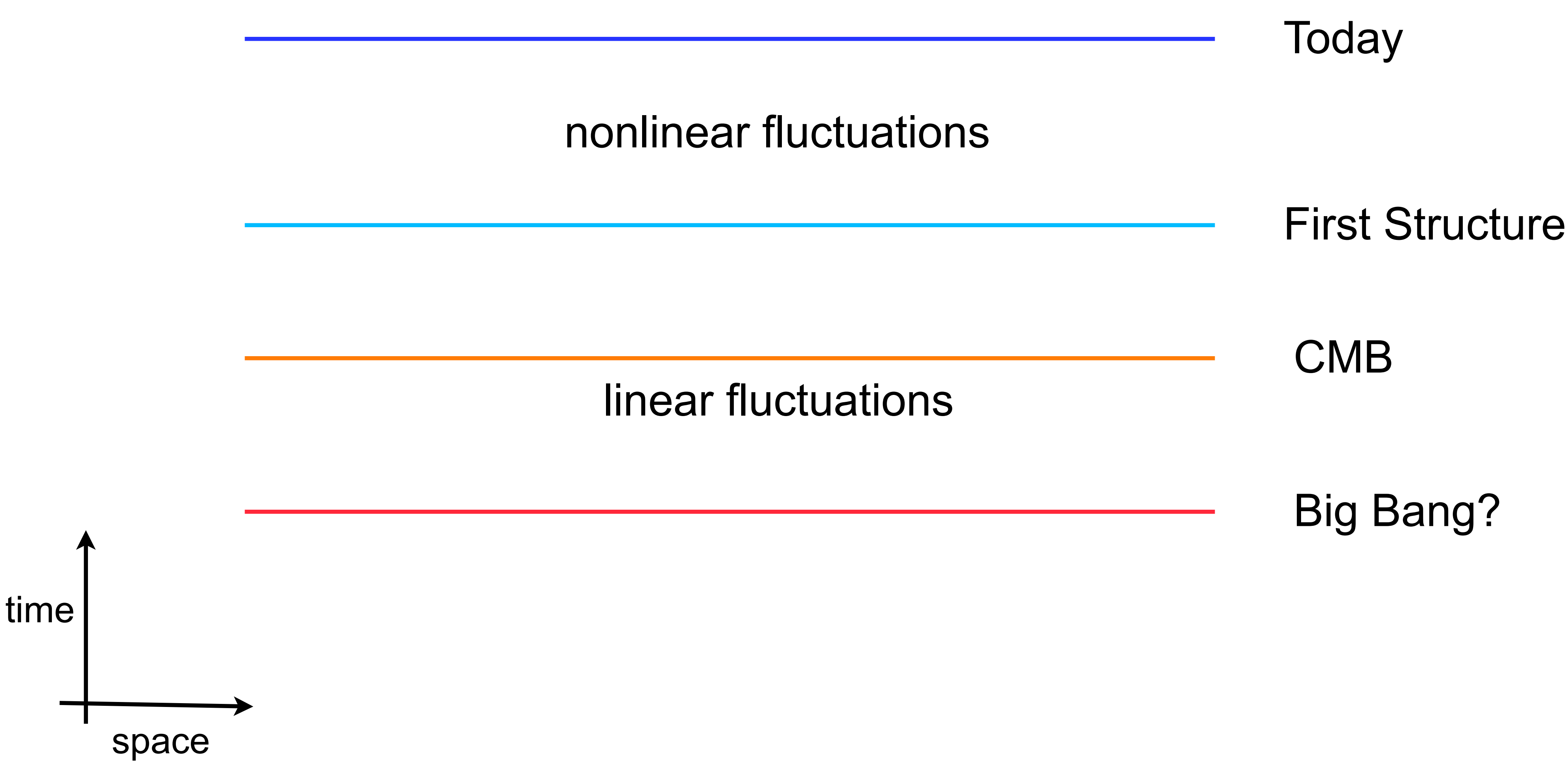
- In principle, we can infer what is inside the light cone.



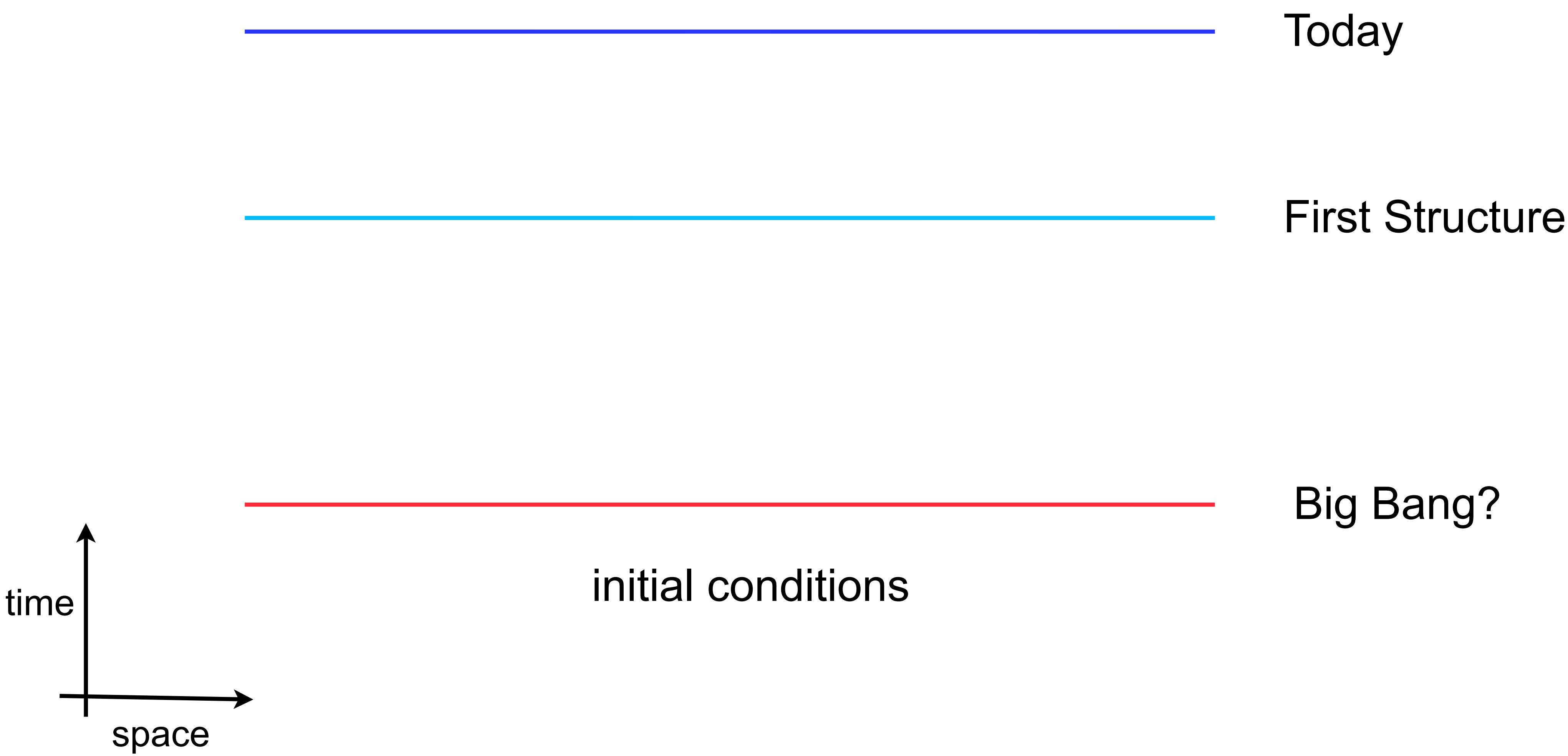
What can we know?



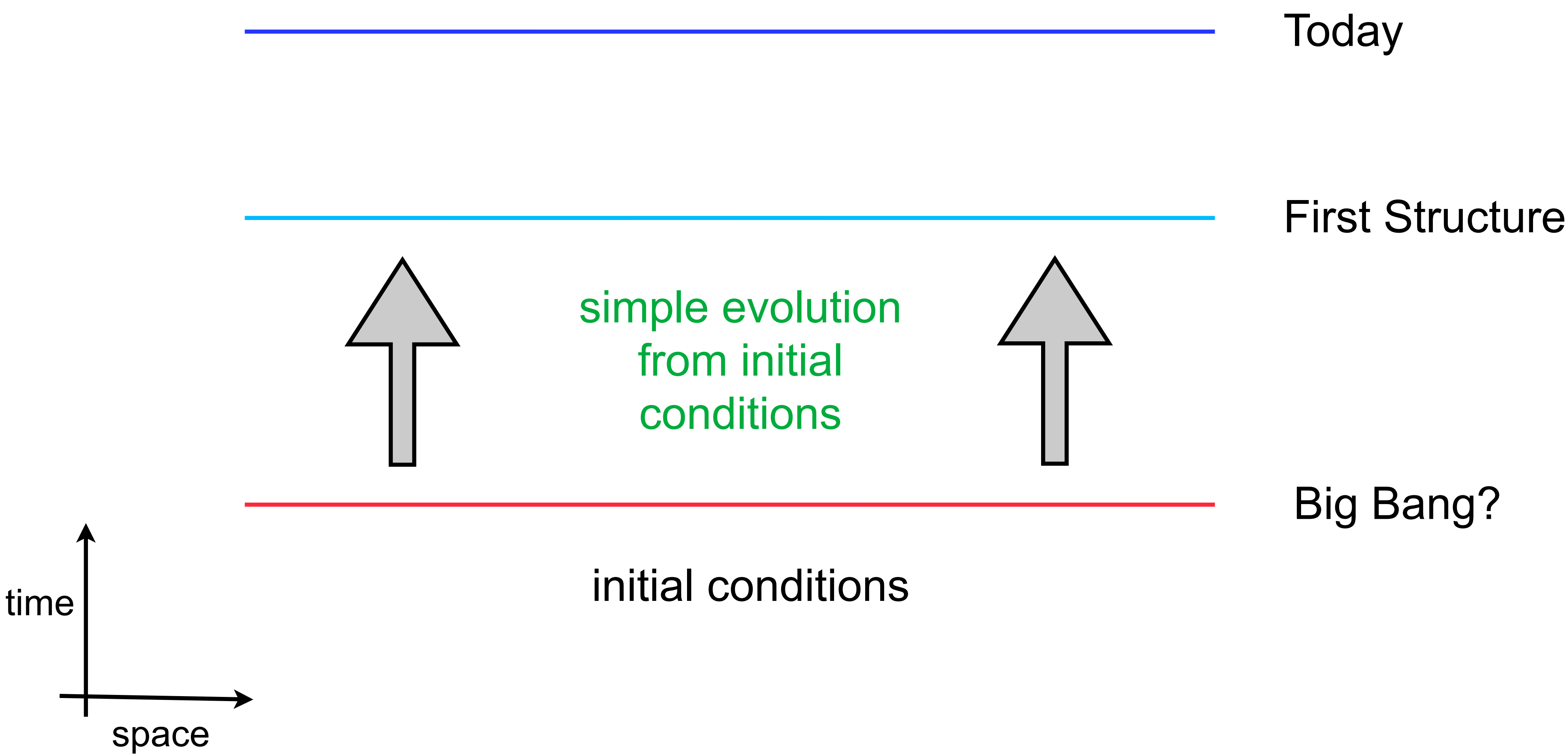
What can we know?



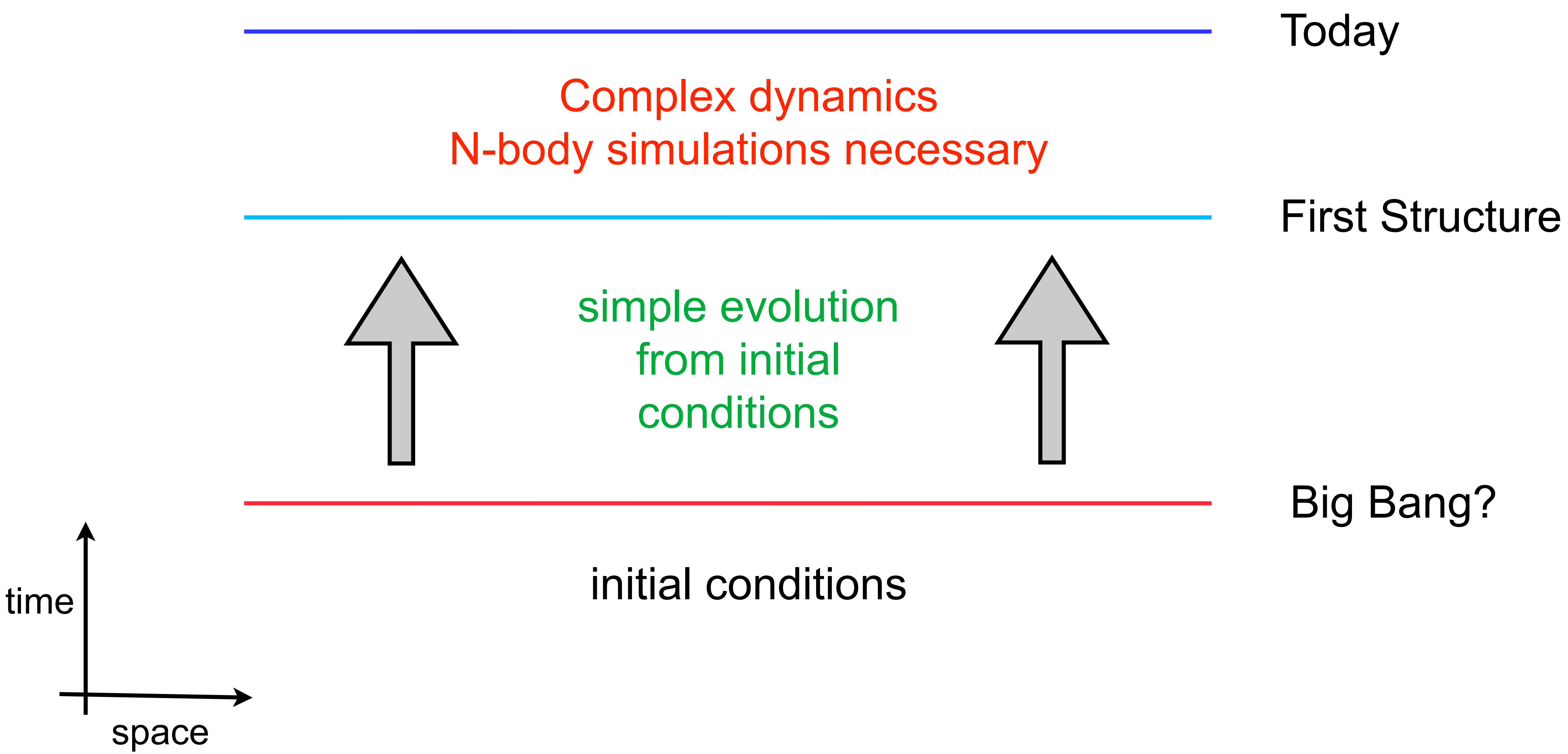
What can we know?



What can we know?

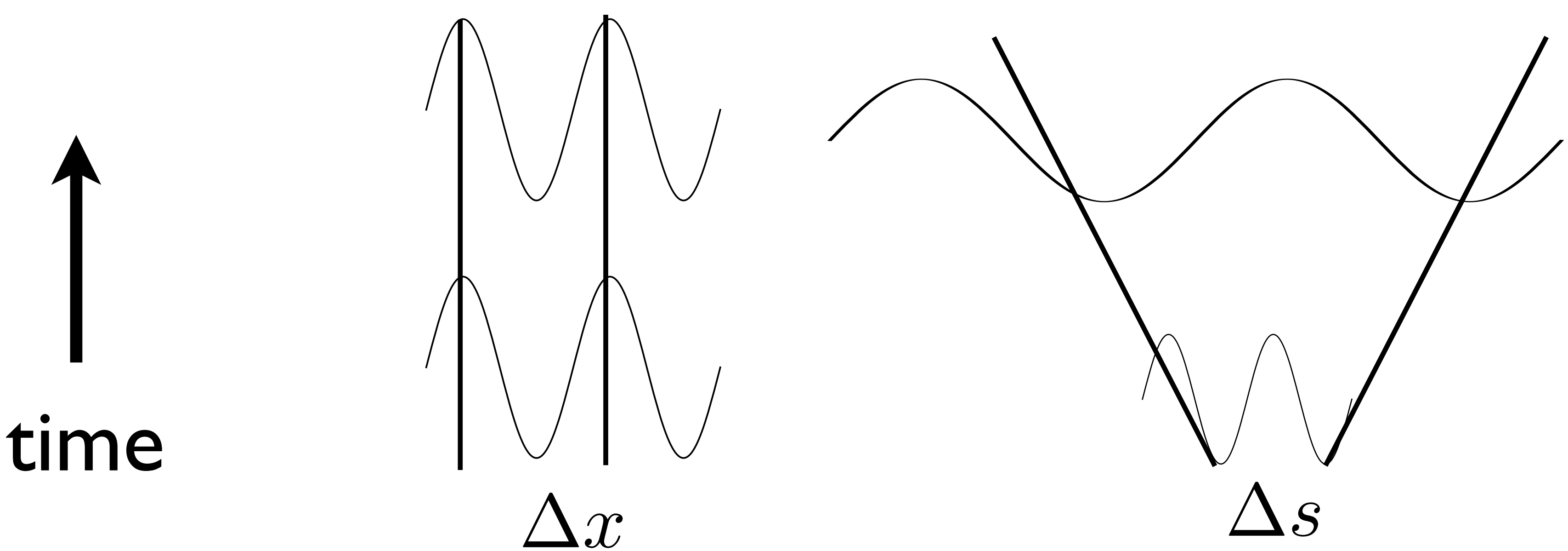


What can we know?



What can we know?

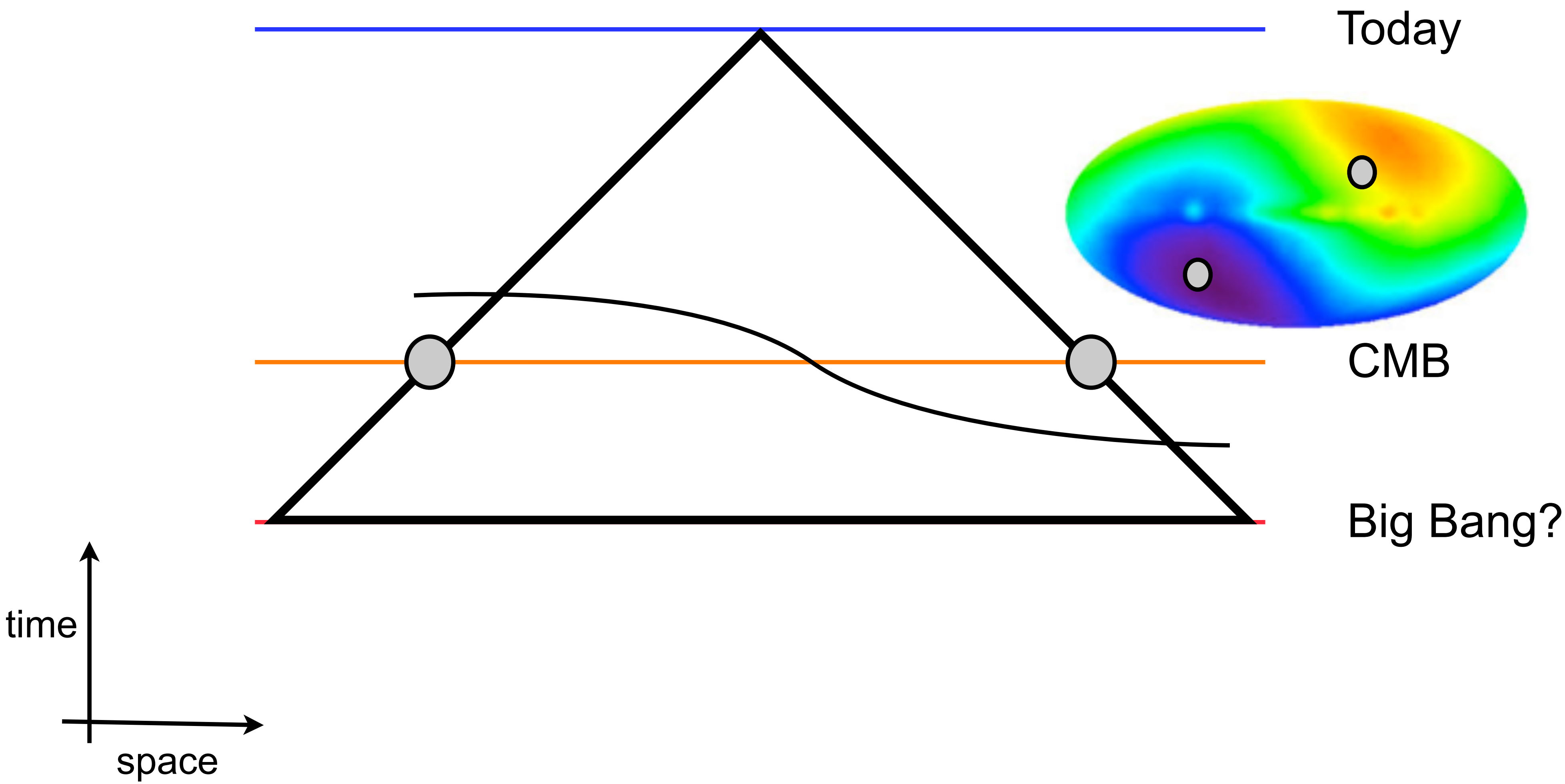
- Small scale modes are stretched into large scale modes.



$$\lambda_{\rm ph} = a(t)\lambda_{\rm com}$$

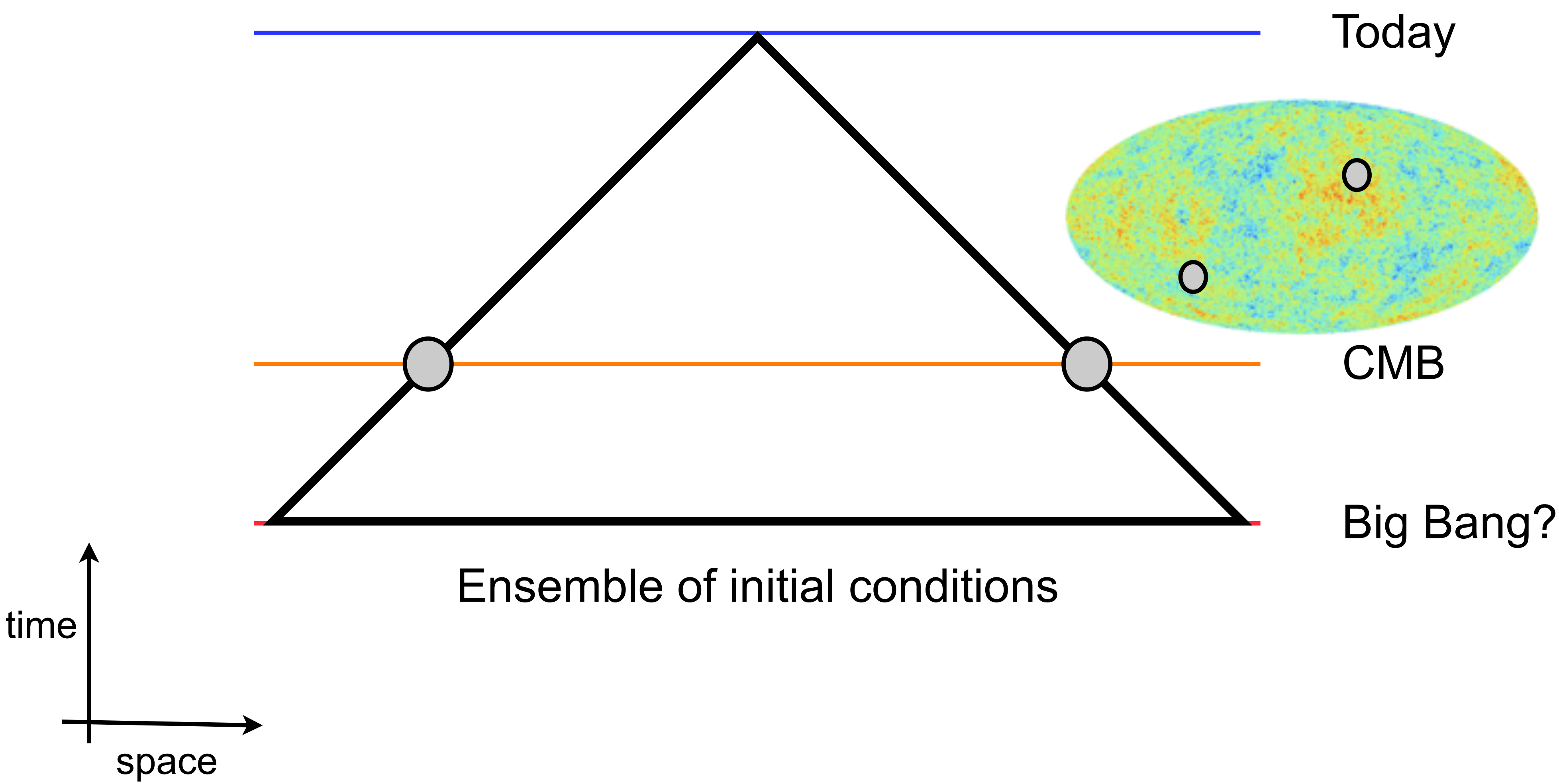
What can we know?

- There is an upper limit on observable wavelengths:



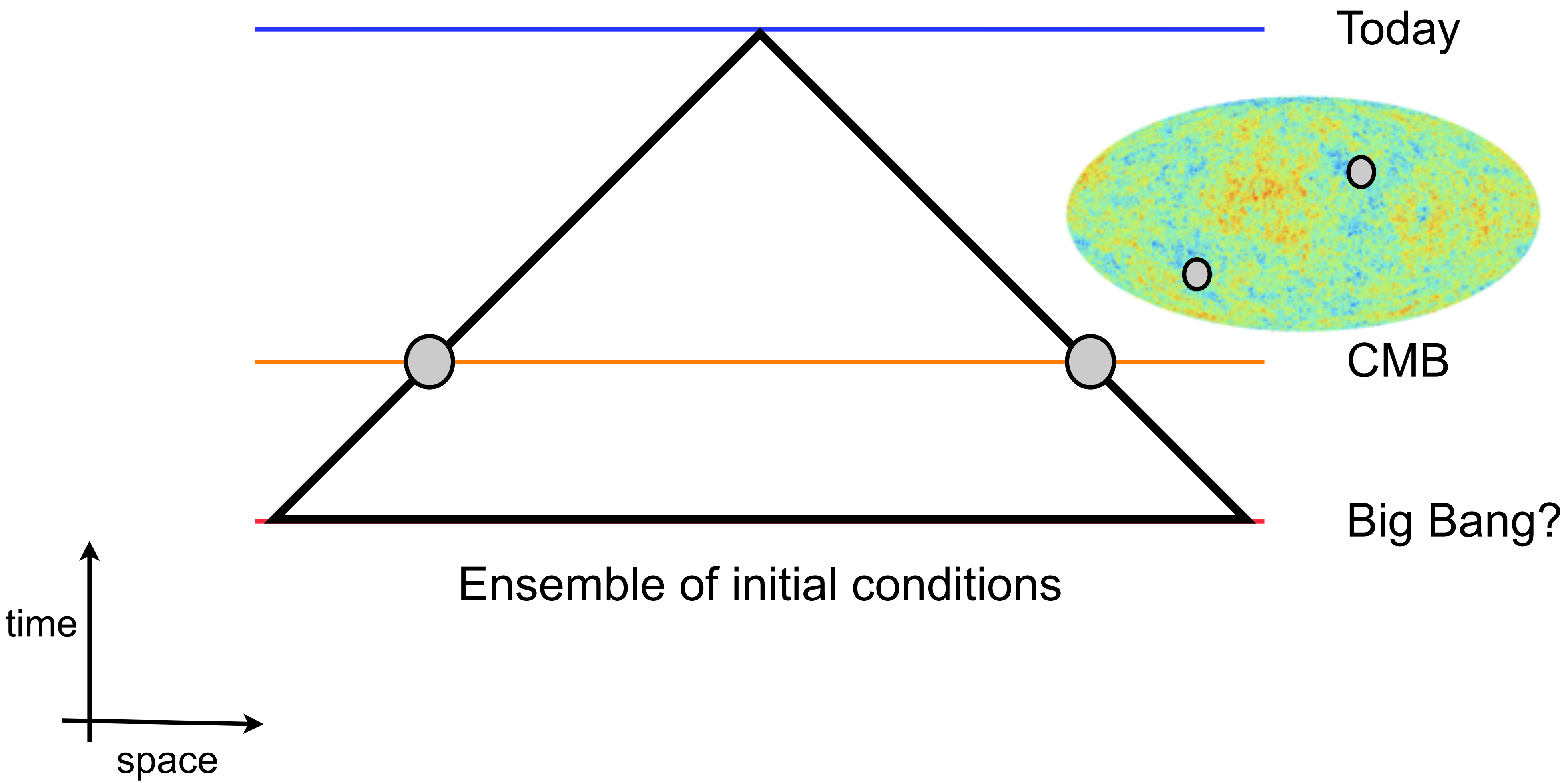
What can we know?

- We are typically interested in statistics



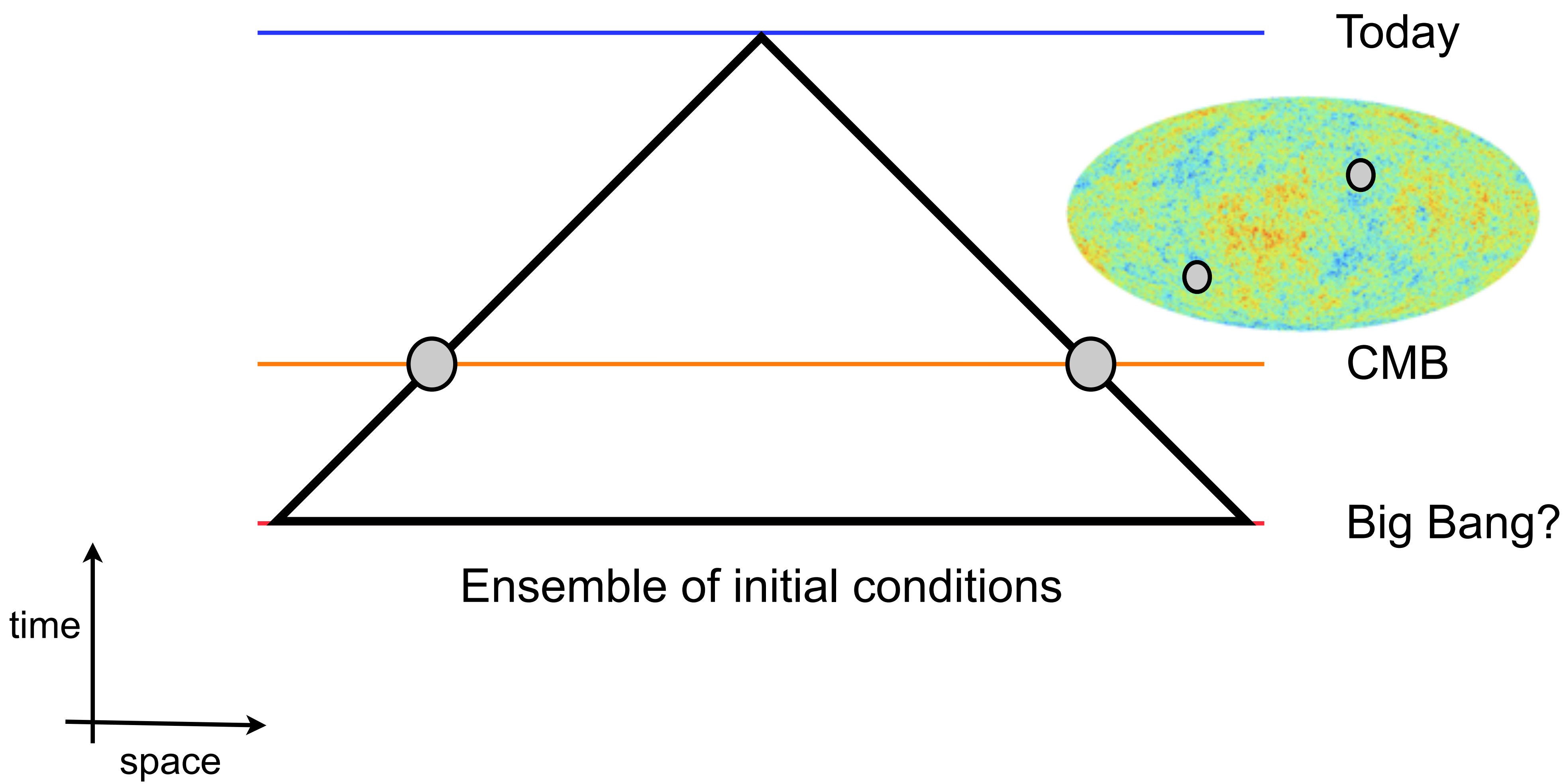
What can we know?

- We are typically interested in statistics



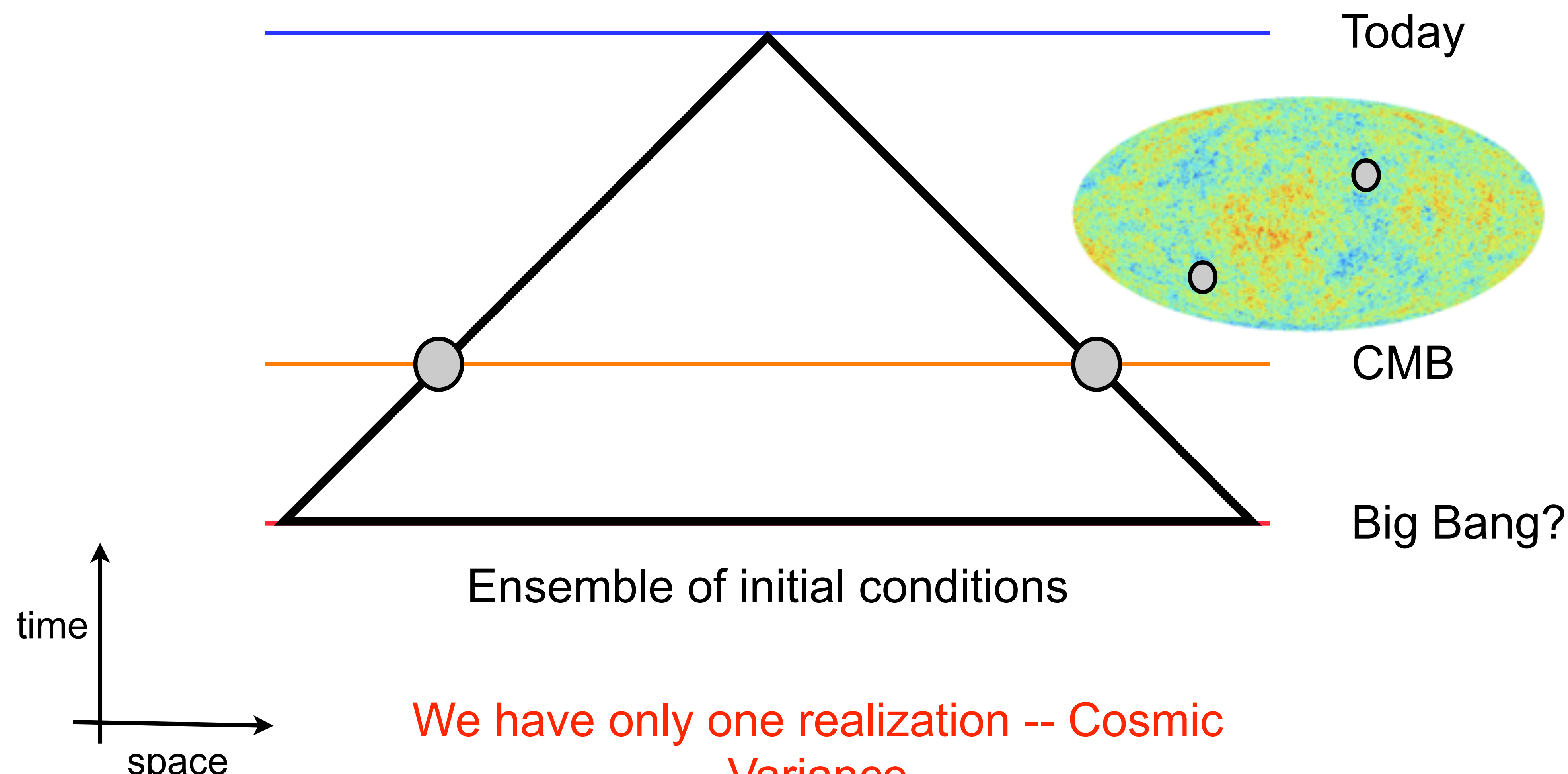
What can we know?

- We are typically interested in statistics



What can we know?

- We are typically interested in statistics



We have only one realization -- Cosmic Variance

What can we know?

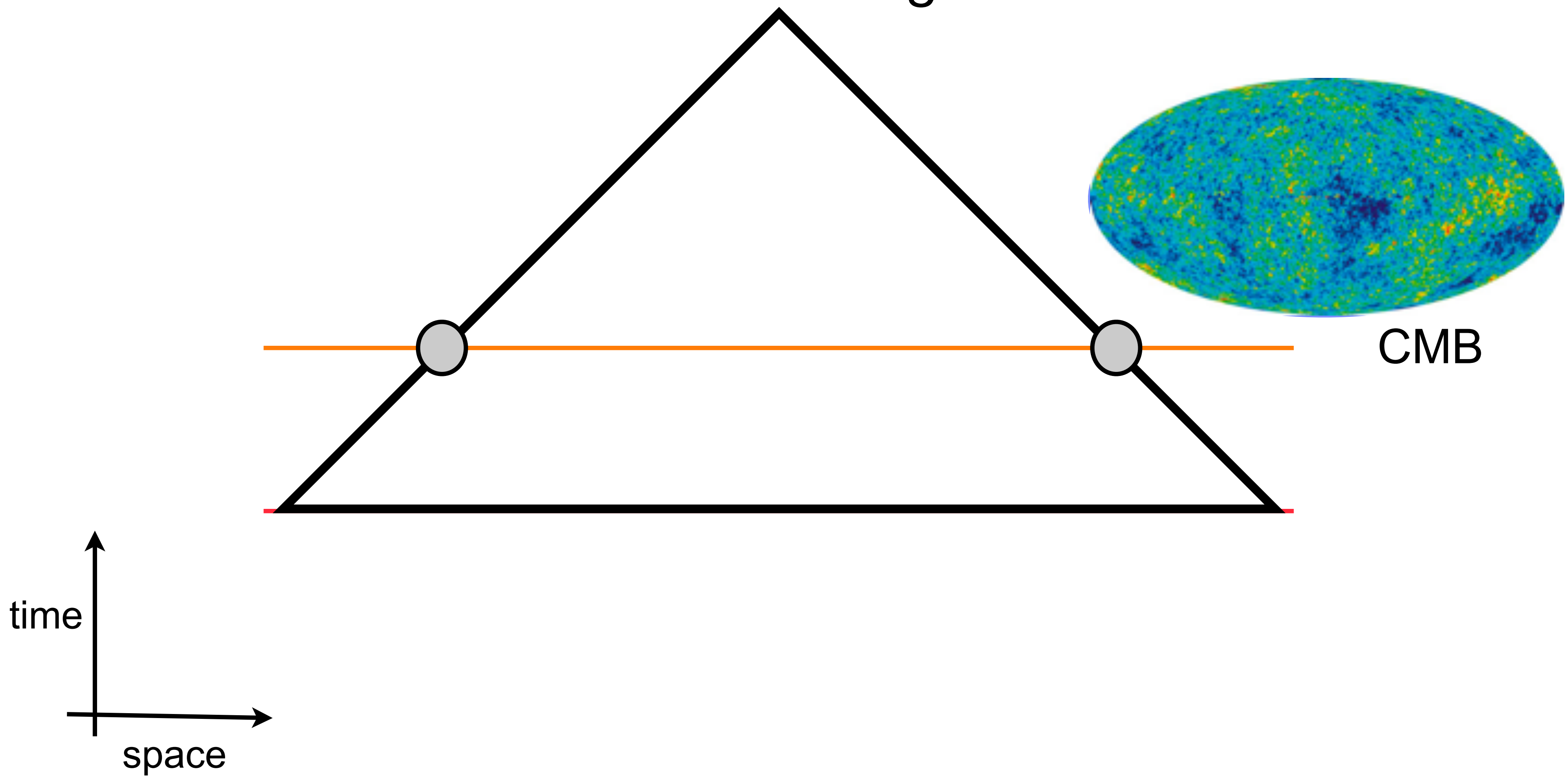
- In practice restrictions:
    - We are limited to a few snapshots on the light cone.
    - We are limited by our ability to understand non-linear evolution.

What can we know?

- In practice restrictions:
    - We are limited to a few snapshots on the light cone.
    - We are limited by our ability to understand non-linear evolution.
- In principle restrictions:
    - Finite size past light cone.
    - Maximum wavelength.
    - Cosmic variance.

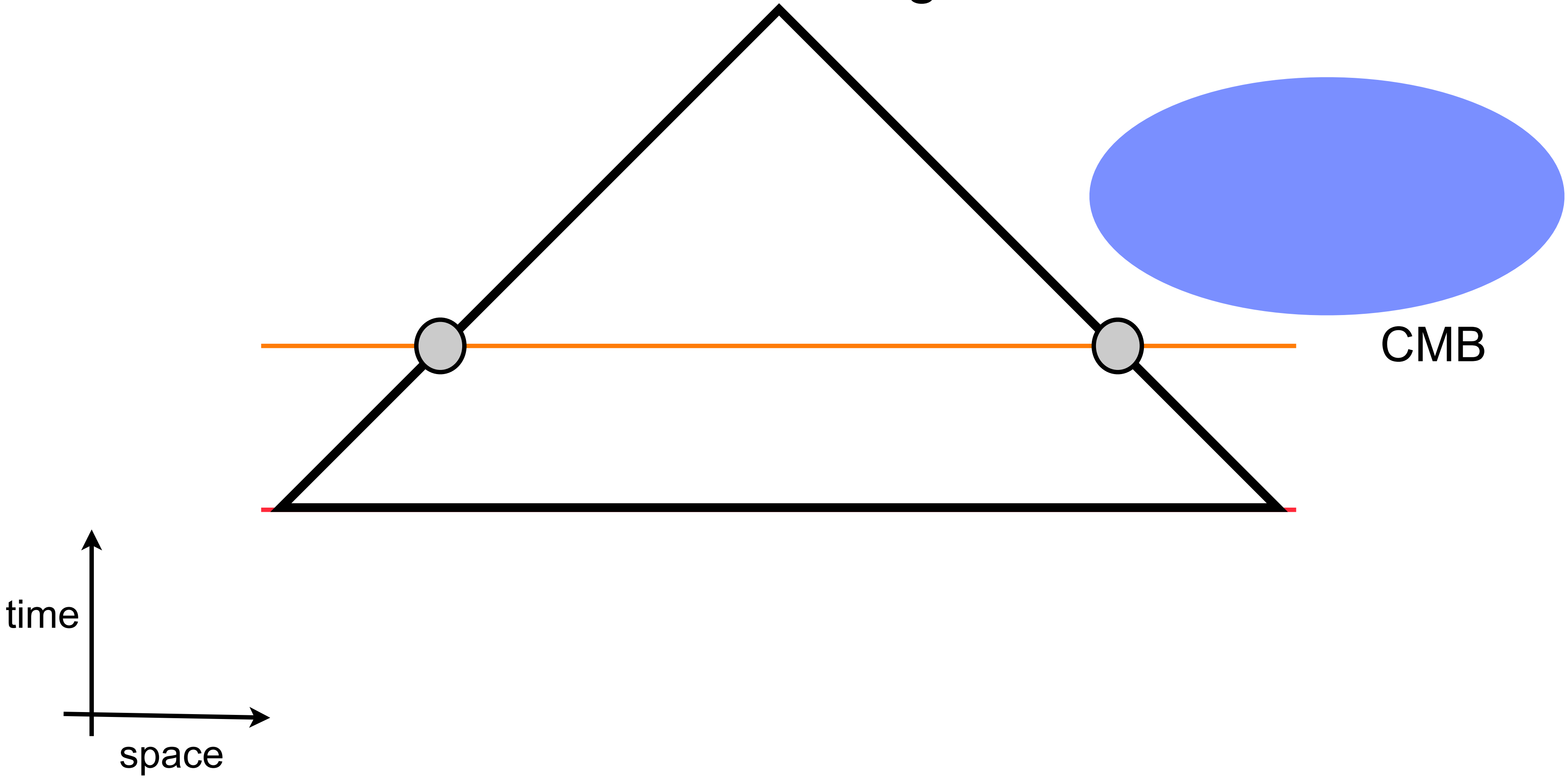
Strange Initial Conditions

- A first look at the CMB indicates that the initial conditions must be rather strange.



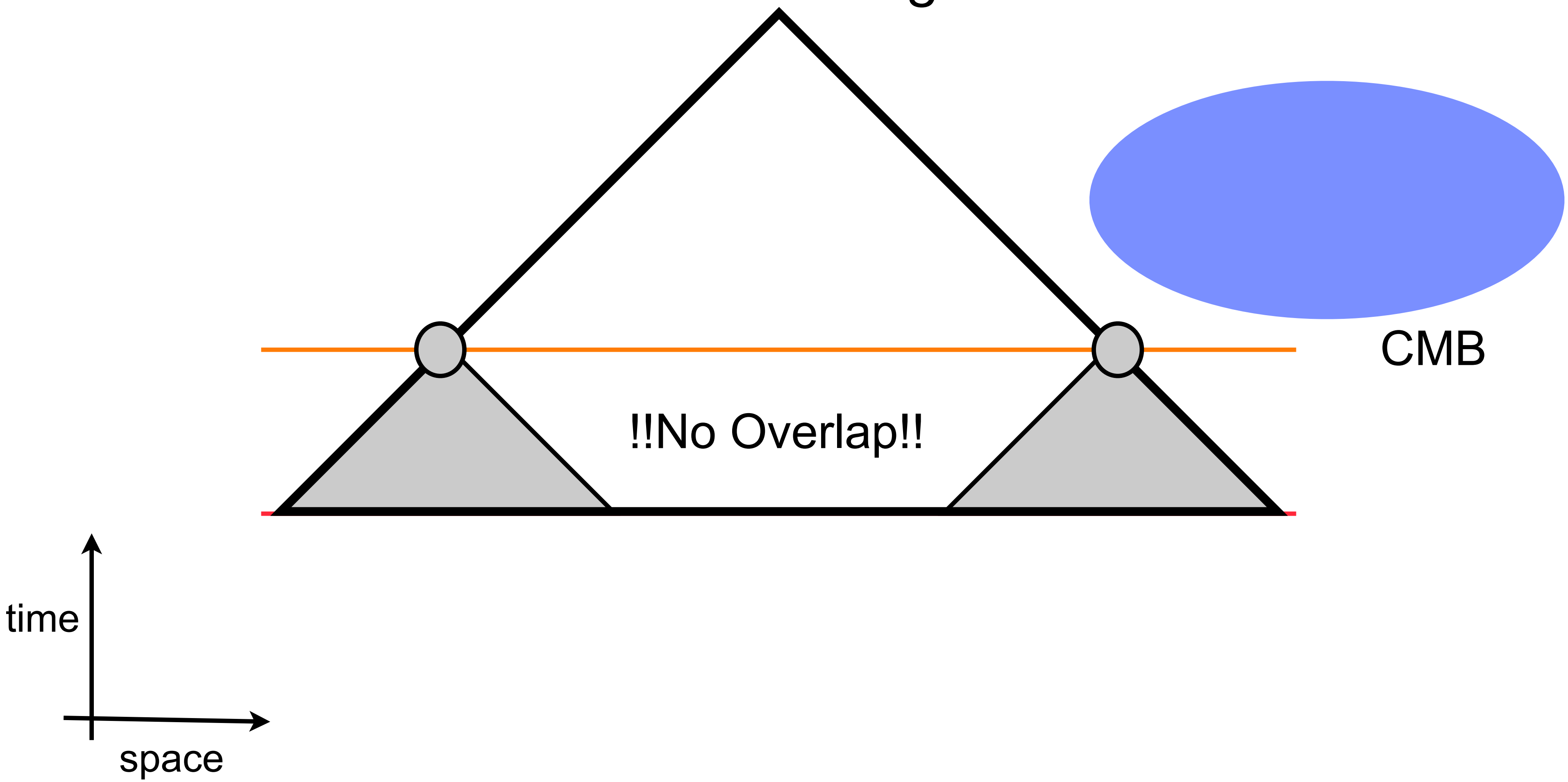
Strange Initial Conditions

- A first look at the CMB indicates that the initial conditions must be rather strange.



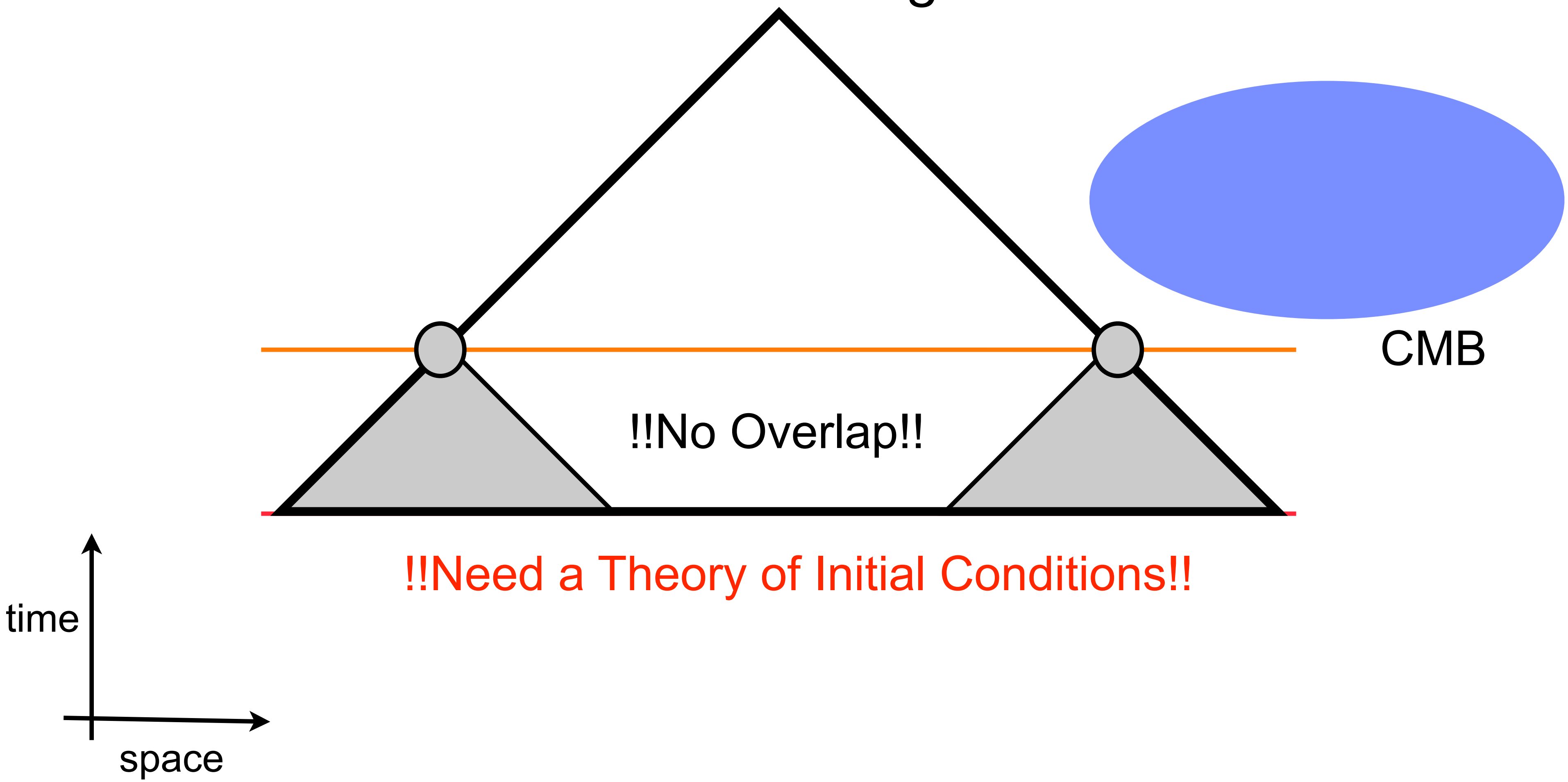
Strange Initial Conditions

- A first look at the CMB indicates that the initial conditions must be rather strange.



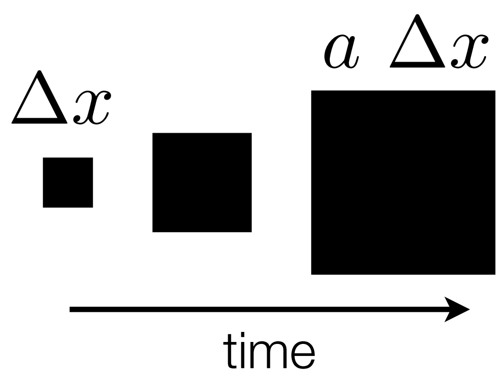
Strange Initial Conditions

- A first look at the CMB indicates that the initial conditions must be rather strange.



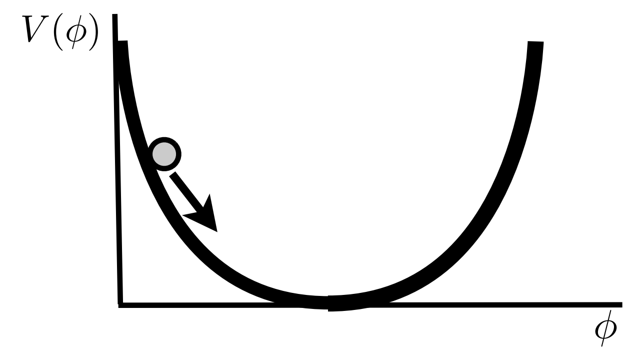
Inflation

- A non-diluting perfect fluid - Inflation!
- Grows the observable universe from a causally connected primordial patch.



$$a \propto \exp\left[\sqrt{\frac{8\pi G_N}{3}\rho}\ \ t\right]$$

$$\rho \simeq 10^{85}\ \mathrm{kg/m^3}$$



Perfect candidate: potential energy of a scalar field!

Inflationary Seeds of Density Perturbations

- An inflating Universe has thermodynamic properties:

$$T = \frac{H}{2\pi} \qquad\qquad S = \frac{Area}{4G_N} = \frac{\pi}{H^2 G_N}$$

Inflationary Seeds of Density Perturbations

- An inflating Universe has thermodynamic properties:

$$T = \frac{H}{2\pi} \qquad\qquad S = \frac{Area}{4G_N} = \frac{\pi}{H^2 G_N}$$

- The Universe is a small/hot system, so fluctuations likely:

$$H^{-1} \simeq 10^{-28} m \qquad T \simeq 10^{12}\ \mathrm{GeV} \qquad S \simeq 10^{14}$$

Inflationary Seeds of Density Perturbations

- An inflating Universe has thermodynamic properties:

$$T = \frac{H}{2\pi} \qquad\qquad S = \frac{Area}{4G_N} = \frac{\pi}{H^2 G_N}$$

- The Universe is a small/hot system, so fluctuations likely:

$$H^{-1} \simeq 10^{-28} m \qquad T \simeq 10^{12}\ \mathrm{GeV} \qquad S \simeq 10^{14}$$

- Fluctuations in the inflaton source scalar perturbations in the metric.

Inflationary Seeds of Density Perturbations

- An inflating Universe has thermodynamic properties:

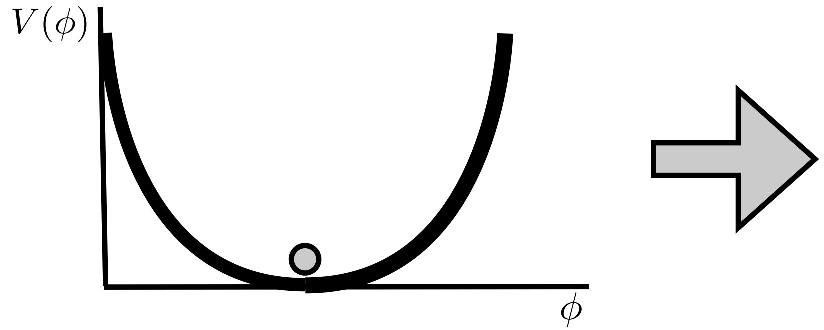
$$T = \frac{H}{2\pi} \qquad\qquad S = \frac{Area}{4G_N} = \frac{\pi}{H^2 G_N}$$

- The Universe is a small/hot system, so fluctuations likely:

$$H^{-1} \simeq 10^{-28} m \qquad T \simeq 10^{12}\ \mathrm{GeV} \qquad S \simeq 10^{14}$$

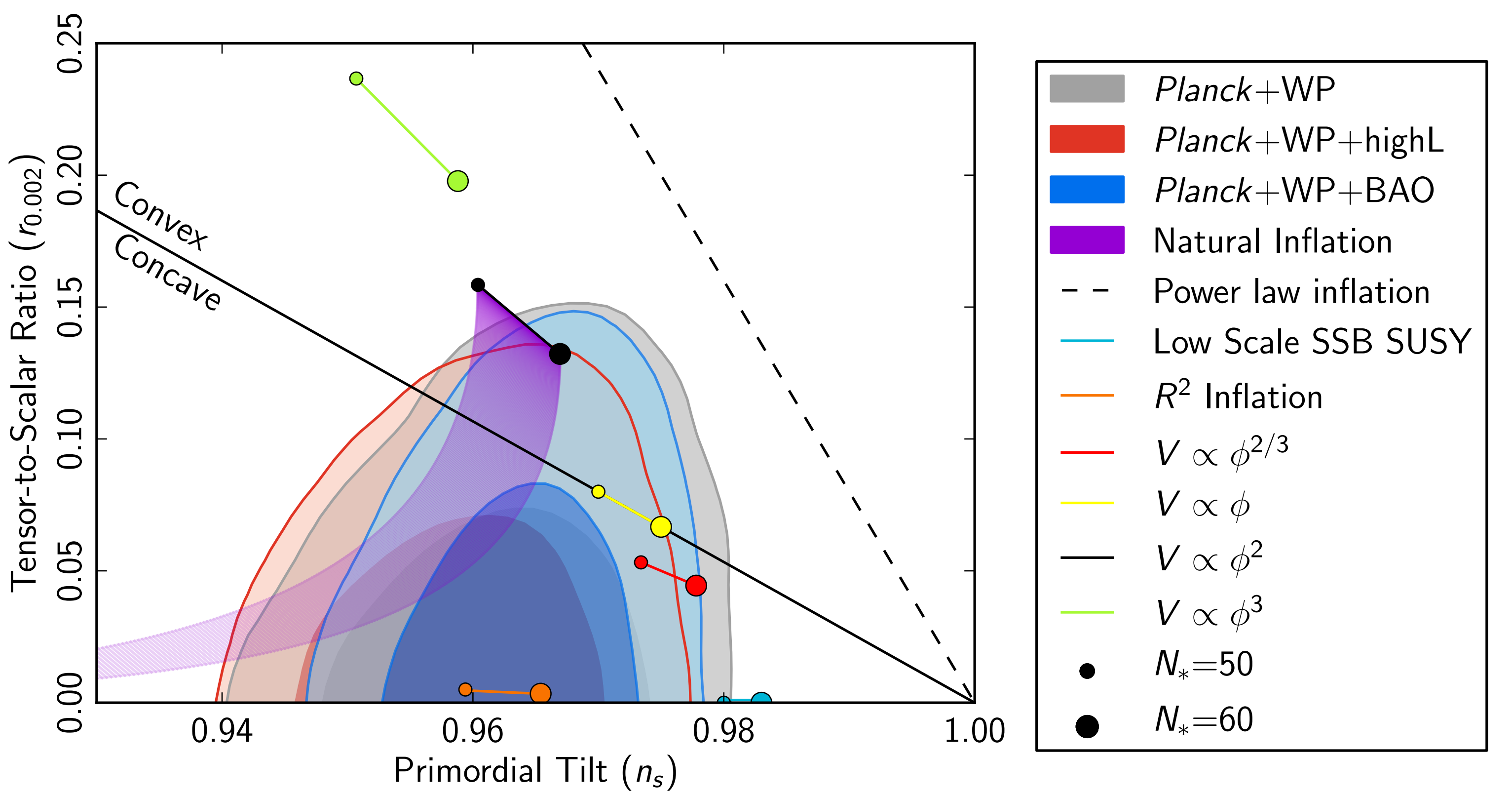
- Fluctuations in the inflaton source scalar perturbations in the metric.
- All light fields fluctuate - gravitational waves!

Predictions from Models of Inflation

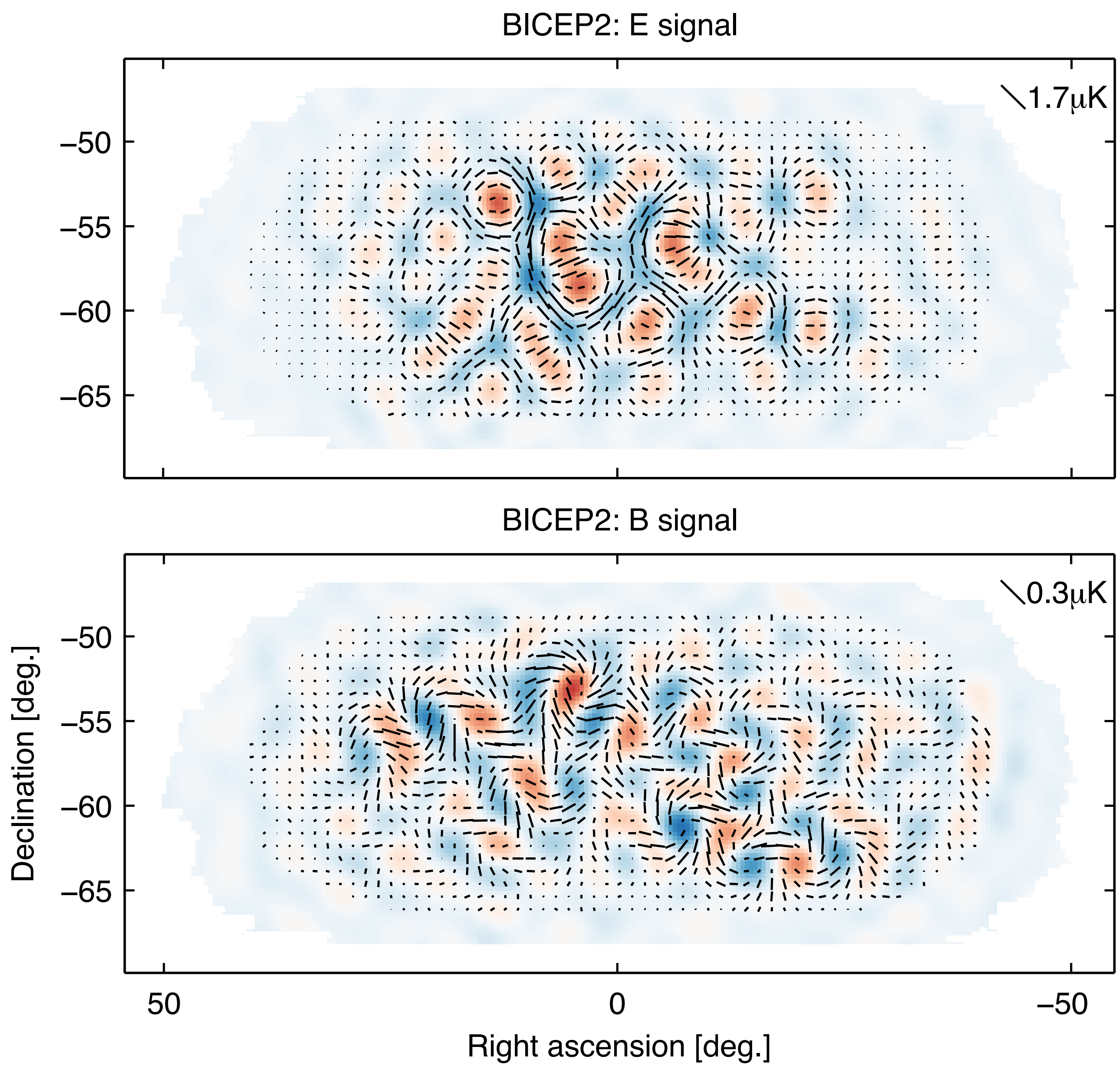


$$P_S(k) = A_S \; k^{n_s - 1}$$

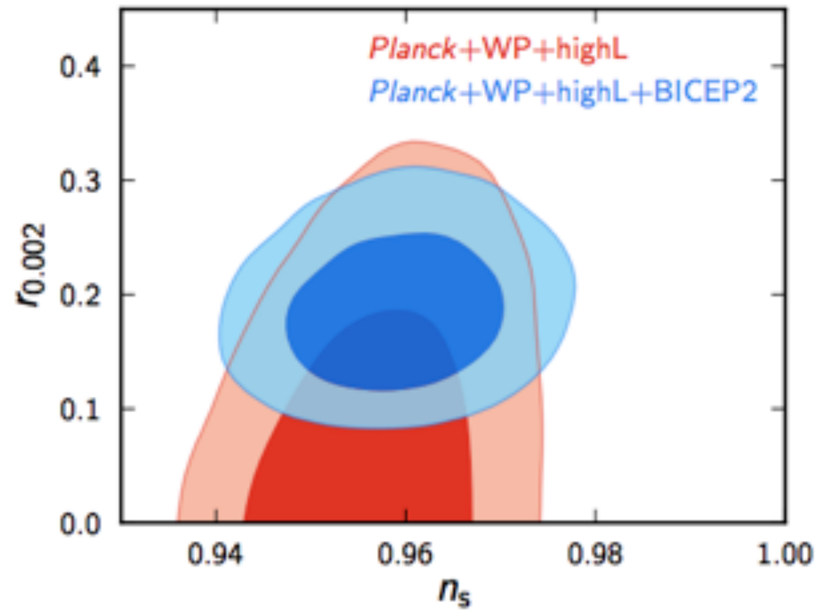
$$P_T(k) = A_T \; k^{n_T}$$



???Discovery of Primoridal Tensors????



Discriminating Between Models



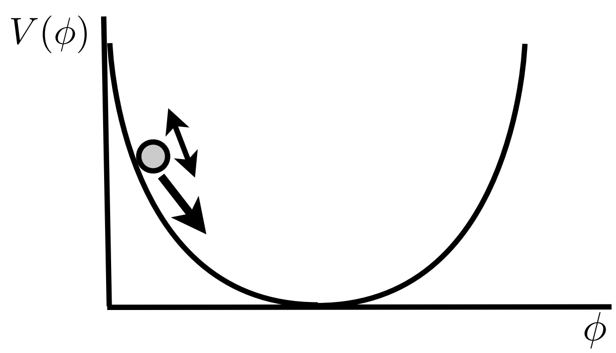
- Powerful discriminator for different models.
- Interesting tension with temperature power spectrum may hint at non-vanilla inflationary history.
- Can distinguish alternatives to inflation (Ekpyrotic Universe, string gas cosmology, etc.)

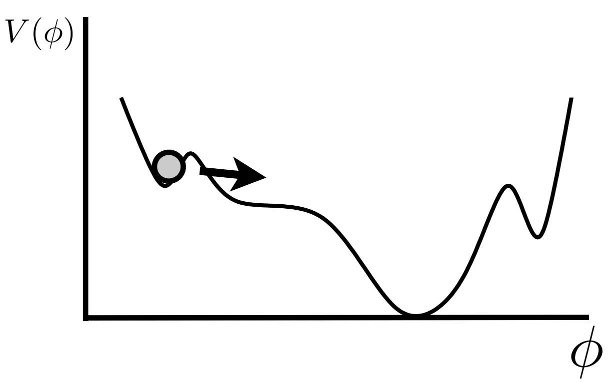
Inflationary Baggage

- Inflation has a lot of baggage:
  - Potential is sensitive to Quantum Gravity corrections.
  - Is the horizon problem really solved?
  - Still need to resolve the initial singularity.
  - Inflation can become future eternal.

Inflationary Baggage

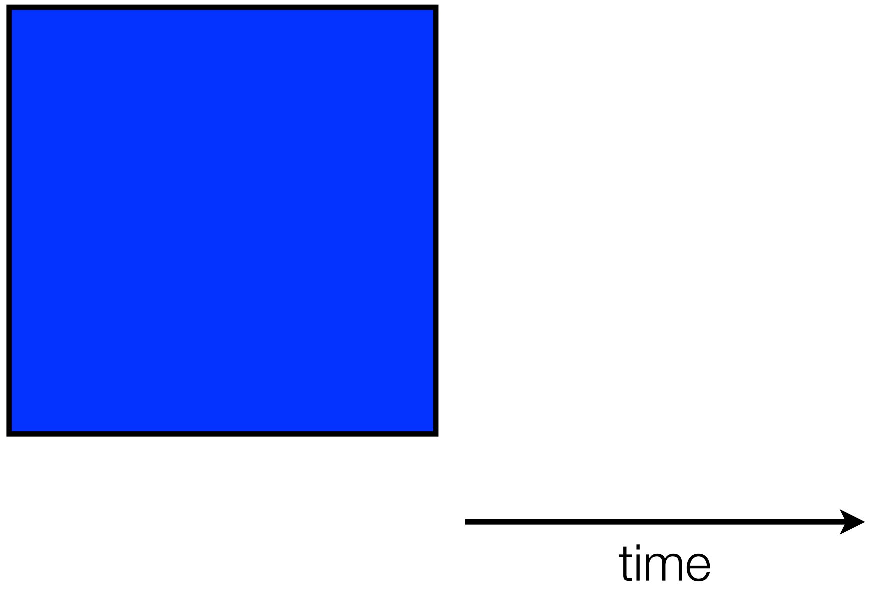
- Inflation has a lot of baggage:
  - Potential is sensitive to Quantum Gravity corrections.
  - Is the horizon problem really solved?
  - Still need to resolve the initial singularity.
  - Inflation can become future eternal.





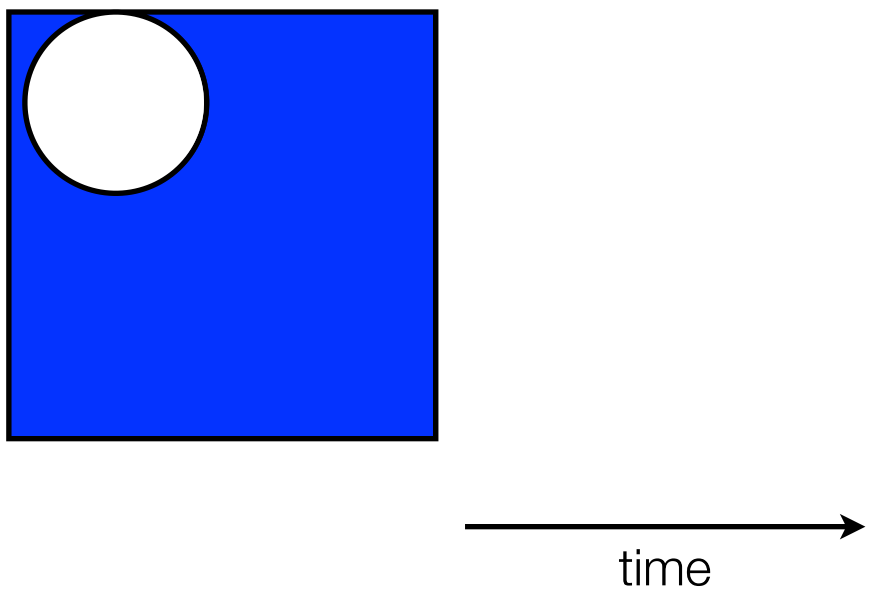
Does the accelerated expansion ever end?

- In a static or decelerating universe:



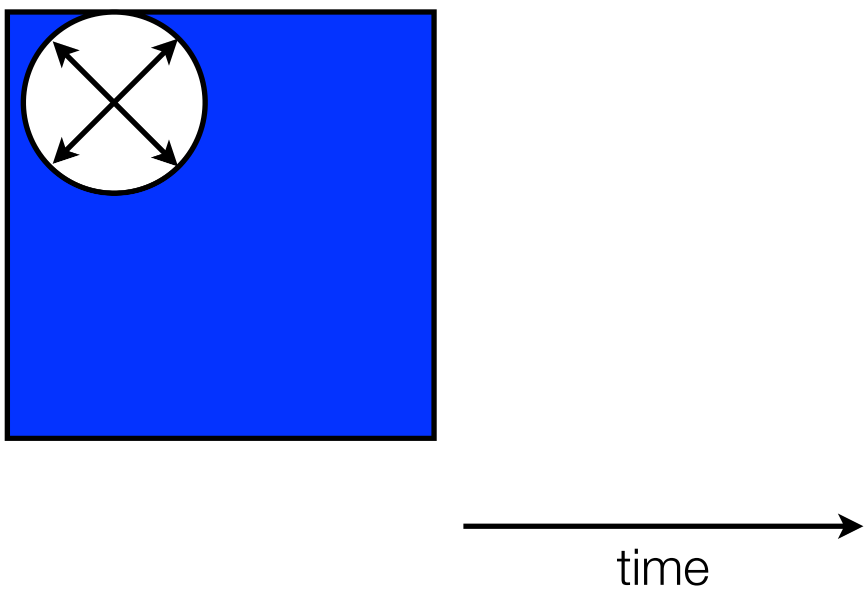
Does the accelerated expansion ever end?

- In a static or decelerating universe:



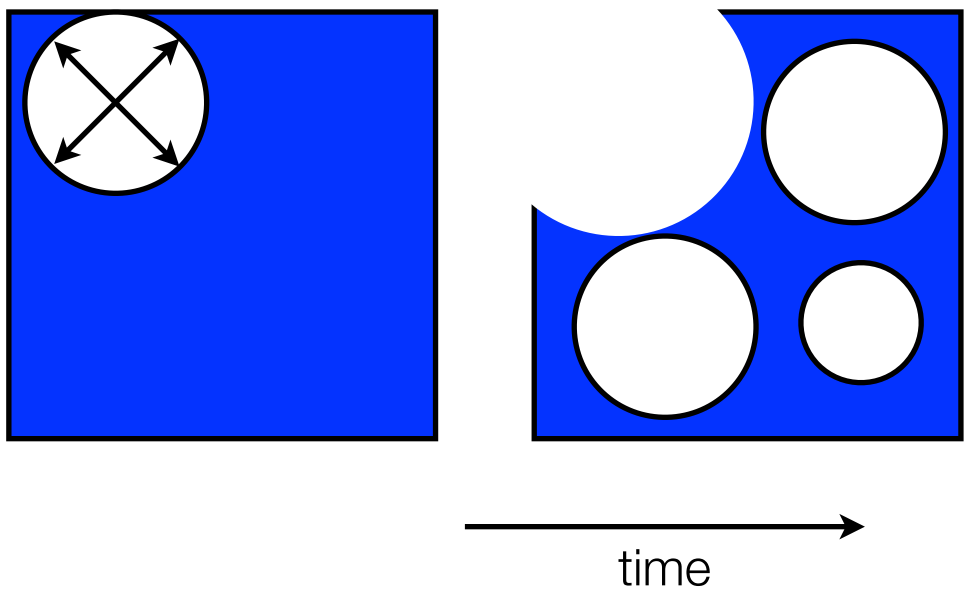
Does the accelerated expansion ever end?

- In a static or decelerating universe:



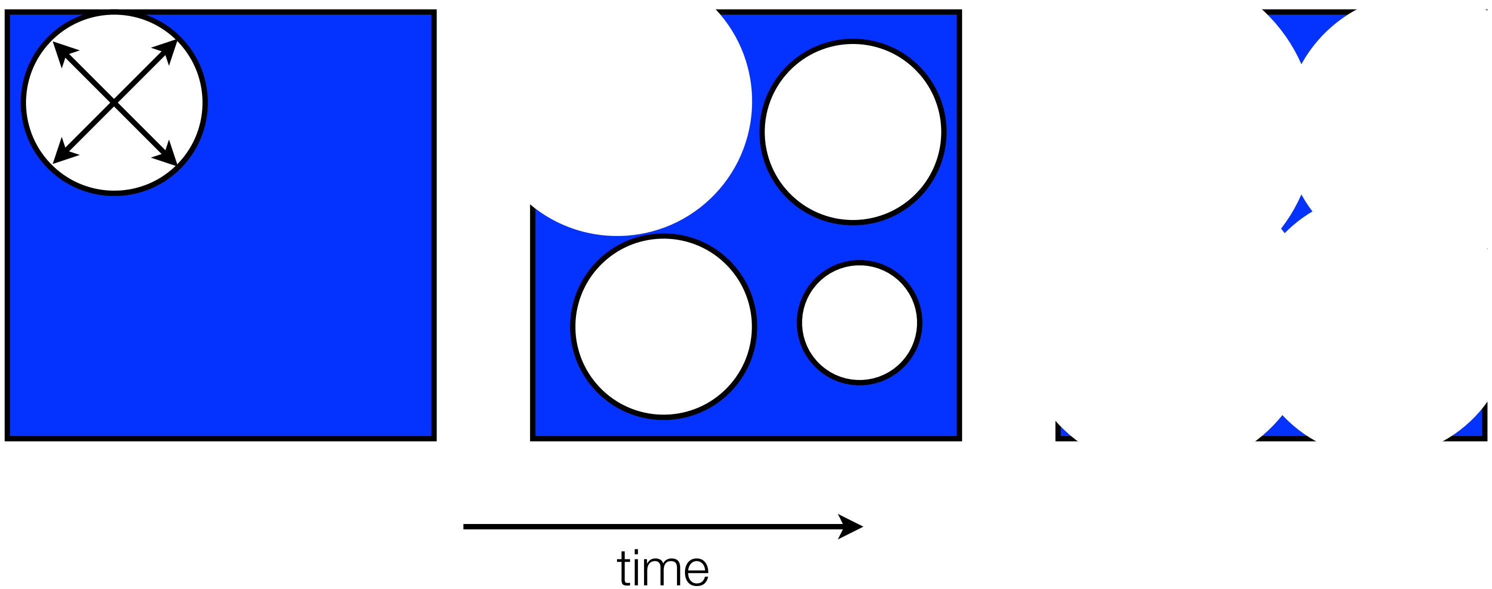
Does the accelerated expansion ever end?

- In a static or decelerating universe:



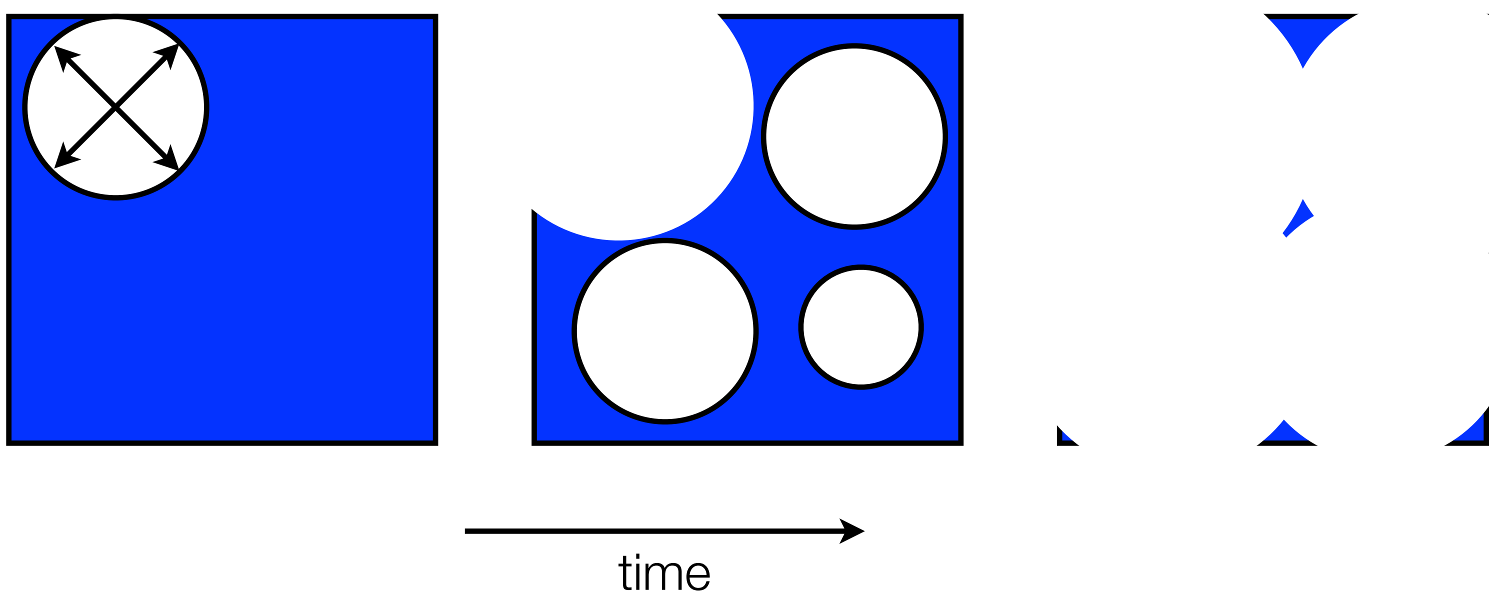
Does the accelerated expansion ever end?

- In a static or decelerating universe:



Does the accelerated expansion ever end?

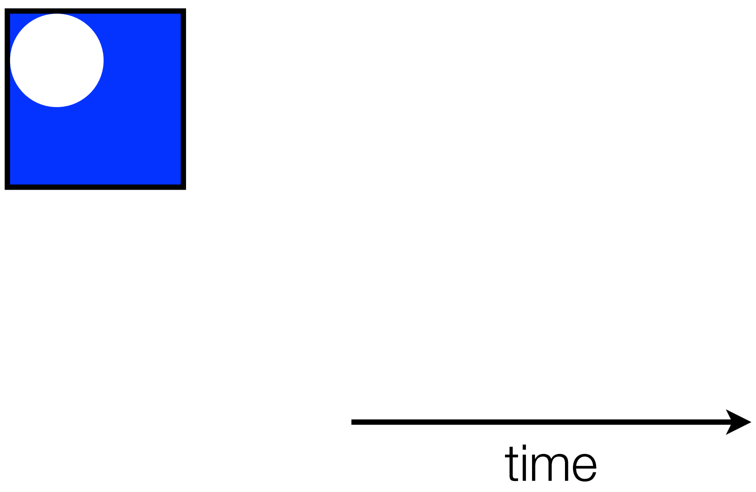
- In a static or decelerating universe:



No matter how slow, the phase transition always completes!

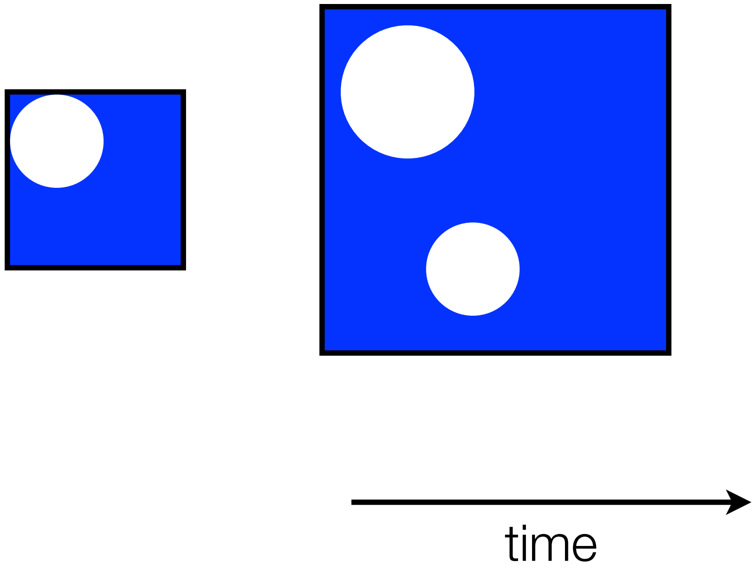
Does the accelerated expansion ever end?

- In an accelerating universe:



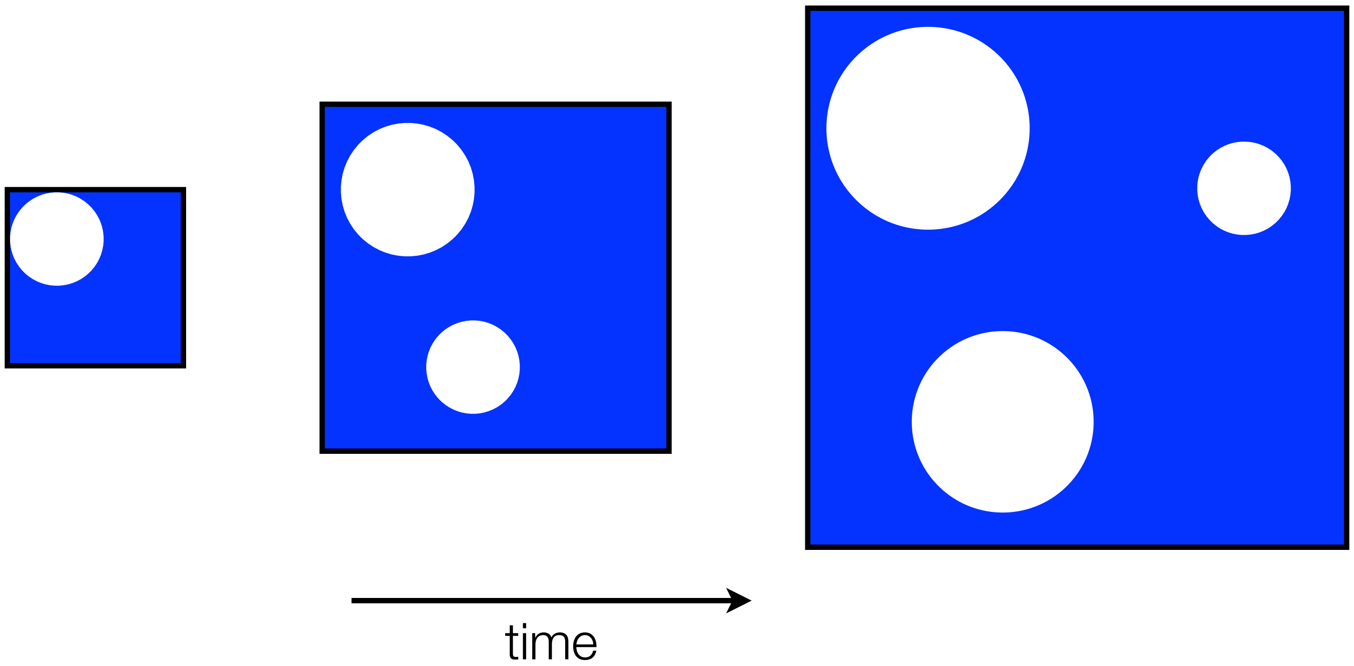
Does the accelerated expansion ever end?

- In an accelerating universe:



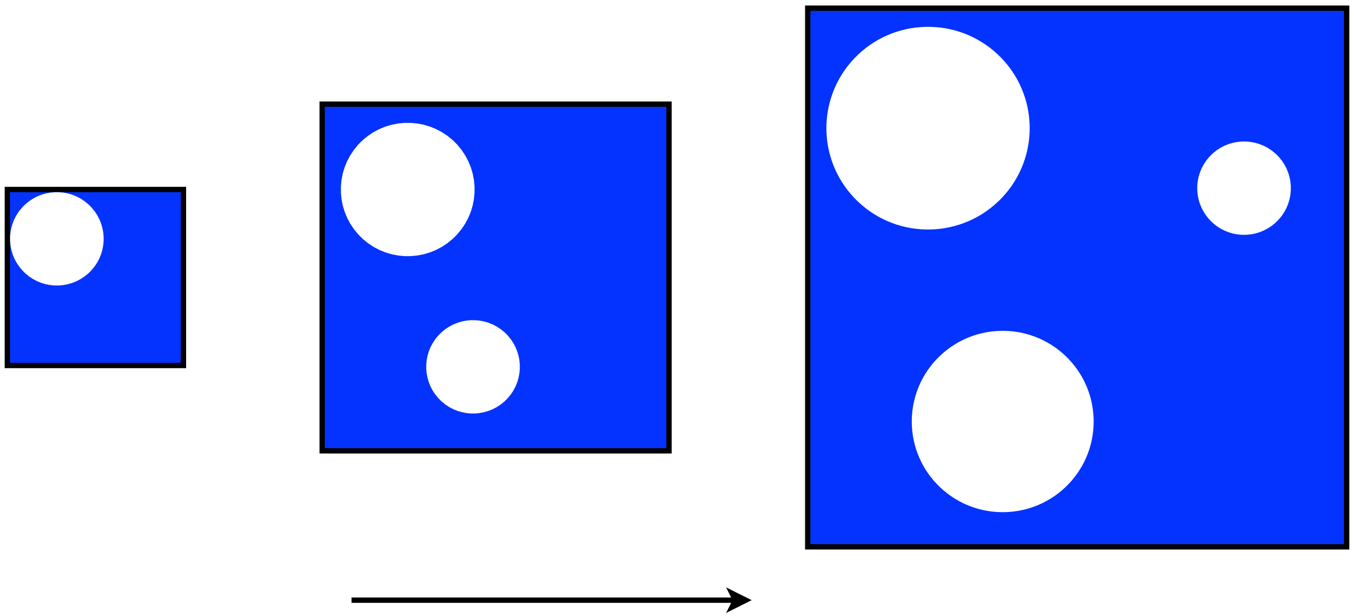
Does the accelerated expansion ever end?

- In an accelerating universe:



Does the accelerated expansion ever end?

- In an accelerating universe:



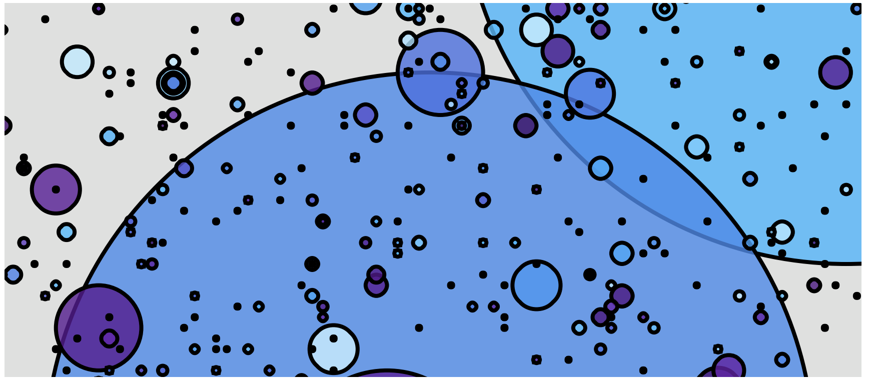
Eternal Inflation Vilenkin, Linde, Guth

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

Testing Eternal Inflation

- Do we live in an eternally inflating Universe?

Our bubble does not evolve in isolation....

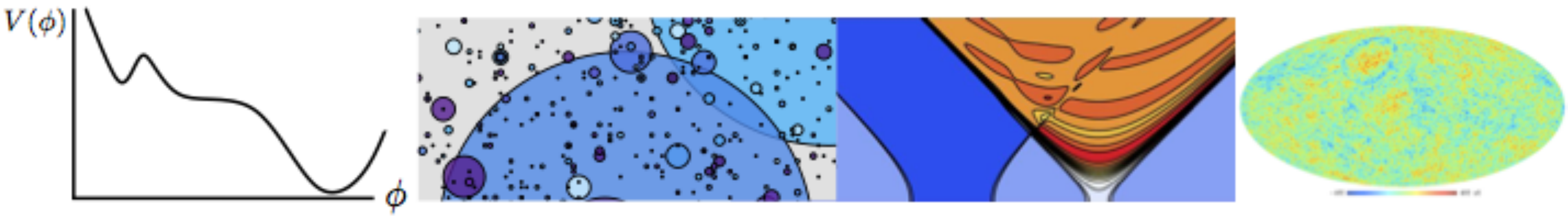


The collision of our bubble with others provides an observational test of eternal inflation.

Aguirre, MCJ, Shomer

Observational Tests of Eternal Inflation

Predictions

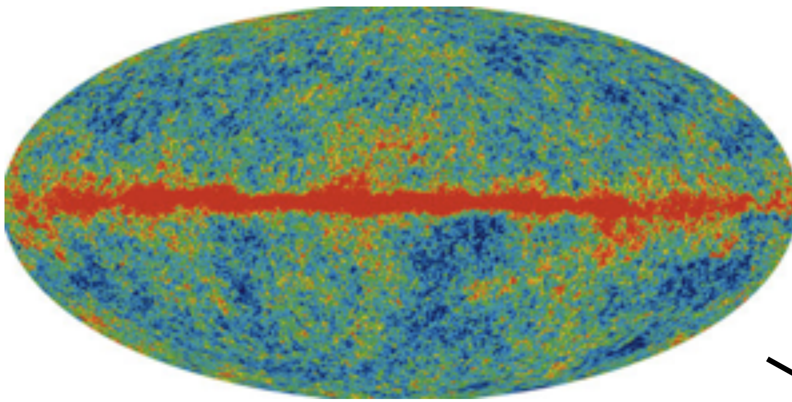


Constraints

Scalar field Lagrangian	**Eternal inflation**	**Bubble collisions**	**Observational signatures**
Possible models? Motivation from theory? Constraints from observation?	Probabilities and inferences? Relation to other versions of the multiverse? How are model parameters manifest?	Predictions from specific models? Phenomenology? Perturbations inside the bubble?	Detailed signature for temperature and polarization? Best data analysis strategies?

The data

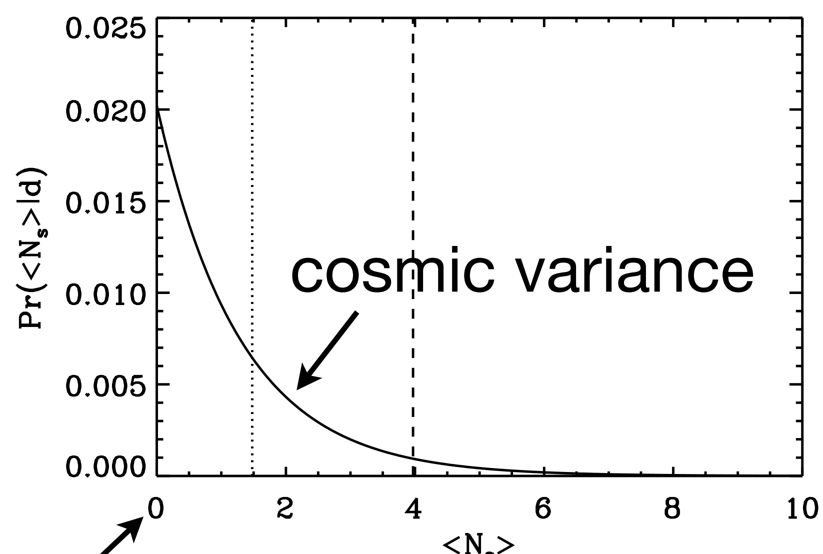
WMAP7 W-Band data.......



Feeney, MCJ, McEwan, Mortlock, Peiris

Osbourne, Senatore, Smith

Posterior over the total number of observable collisions in a generic model (various assumptions in prior)



ΛCDM

Closing Remarks

- In practice restrictions:
  - We are limited to a few snapshots on the light cone.
  - We are limited by our ability to understand non-linear evolution.

HUGE progress coming in the near future!!!!

CMB polarization, LSS surveys, lensing, 21 cm, N-body codes, analytic handles on non-linear evolution

Closing Remarks

- In principle restrictions:
    - Finite size past light cone.
    - Maximum wavelength.
    - Cosmic variance.

Raises some thorny questions:

If it can't be observed in principle, is it real?

How large is the fundamental degeneracy between models?

Fundamental connection between early and late Universe?

Thank you!