Title: Cosmos, the beginnings...

Date: Jul 24, 2018 10:30 AM

URL: http://pirsa.org/18070060

Abstract: <div>Abstract: â€œHow did our universe begin?â€• is possibly one of the oldest questions that have</div>

<div>bewildered humans throughout history. As a theoretical cosmologist, our job is to find a</div>

<div>mathematically consistent picture for early universe that could explain observations, from</div>

<div>the largest to the smallest scales. The past thirty years have witnessed amazing progress,</div>

<div>both in developing technology for precision cosmological observations, and in perfecting</div>

<div>mathematical methodology to explain them. For example, ripples in cosmic geometry are</div>

<div>now measured with the precision of one part in a million. We also have sophisticated</div>

<div>mathematical frameworks such as general relativity and quantum theories that describe the</div>

<div>origin of these ripples in early universe. However, with all of these extraordinary</div>

<div>achievements, some old and new puzzles remain unsolved. For example we still have not</div>

<div>resolved the most crucial puzzle about the origin of cosmos, namely the Big Bang Singularity</div>

<div>problem. We will take a journey back in time to explore the fascinating realm of early</div>

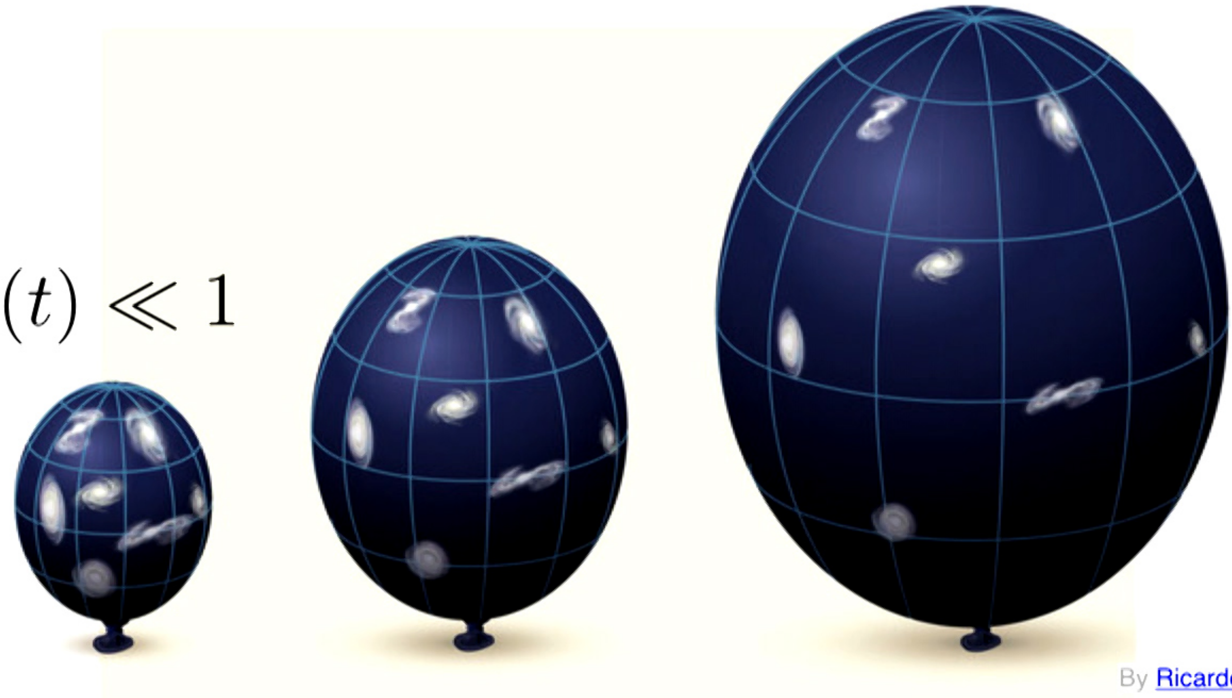
<div>universe and some of its mysteries.</div>

Cosmic Observations Meeting Fundamental Theory

Hubble Law

$a(t) = 1$

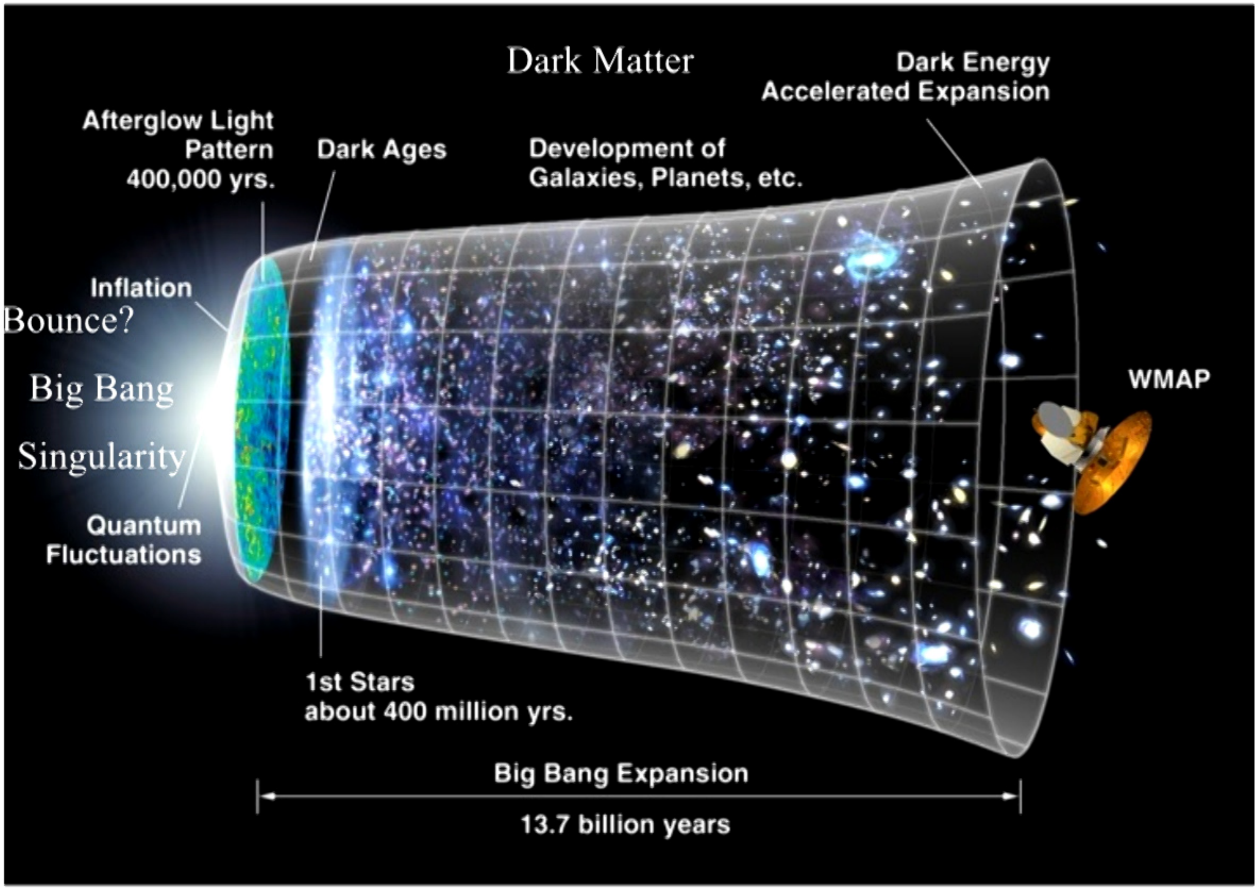
$a(t) \ll 1$



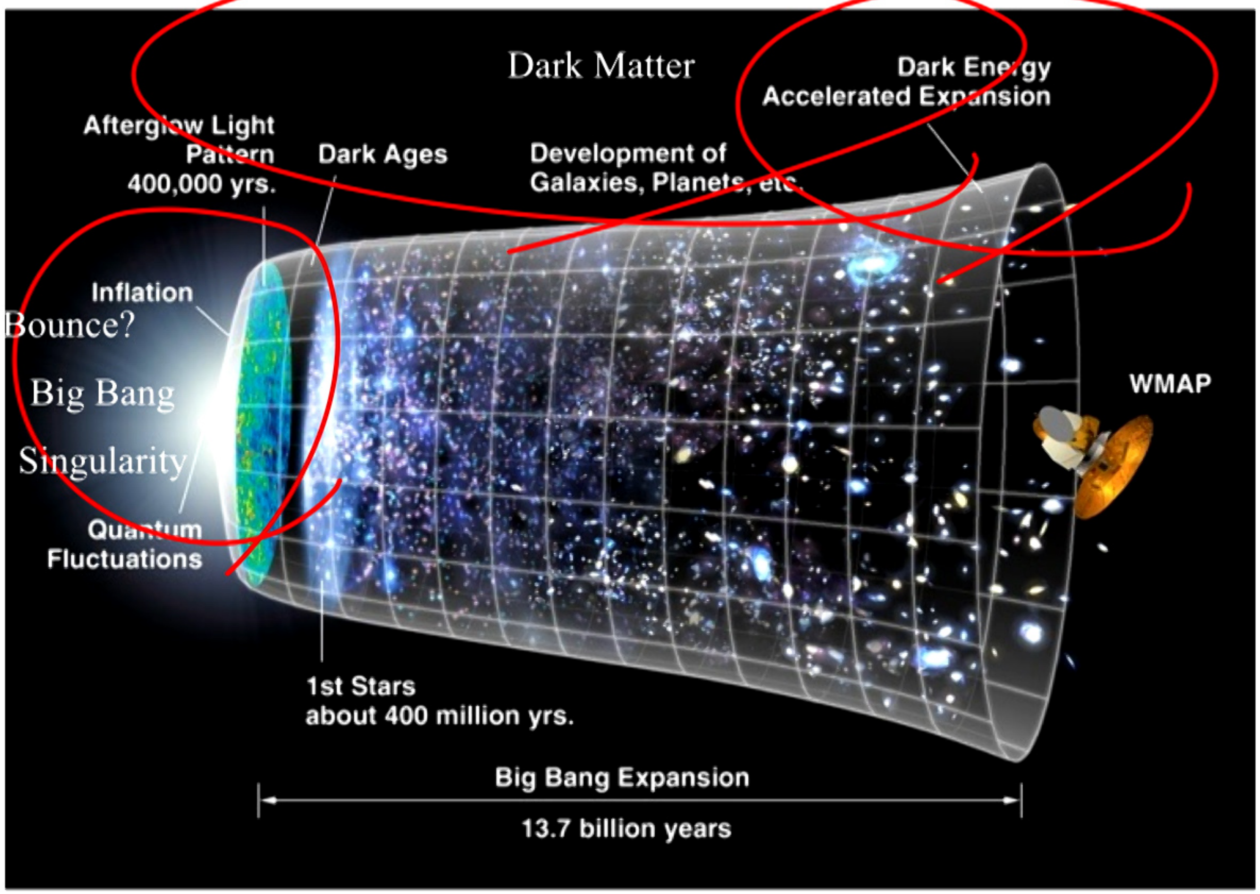
By Ricardo García

$$H = \frac{\dot{a}}{a} \qquad V = Hr$$

The Jigsaw Puzzle



The Jigsaw Puzzle



- **Early Time:**

  Big Bang Singularity, Quantum fluctuations, Generating seeds of Large scale structure, Big Bang nucleosynthesis, …

  Inflation, Bounce, Quantum gravity, New theories of particle Physics

  Observation: CMB and Matter Power Spectrum, Non-Gaussianity, Gravitational waves? Neutrinos?

- **Intermediate time:**

  Observations: Galaxy curves, lensing signal, CMB …

  Missing Matter: Dark Matter, Mond/TEVES/MUG,

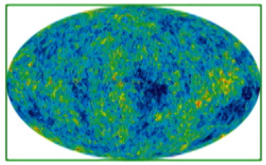
  first stars, galaxy formation, re-ionization …

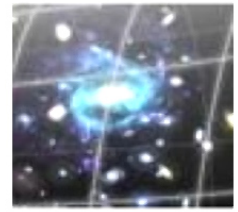
- **Late Time Acceleration:**

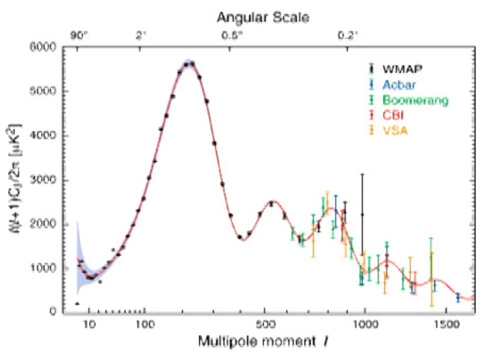
  Cosmological constant problem, Lambda/Dark Energy/Modified Gravity

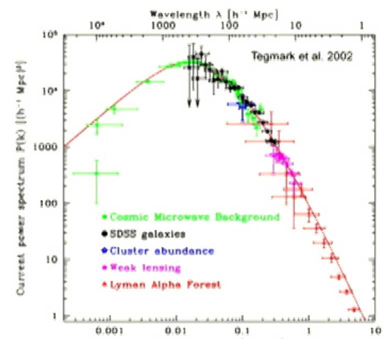
  Observation: CMB, Supernovae, Gravitational waves

Anisotropies of order 10^(-5)!
Scale Invariant Power Spectrum

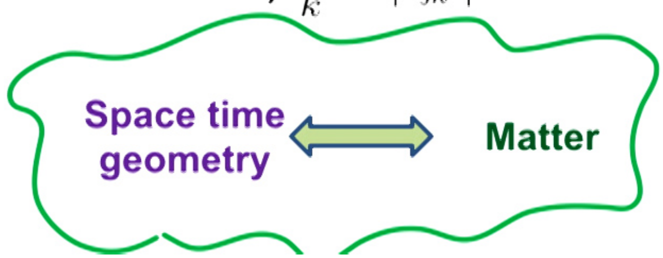




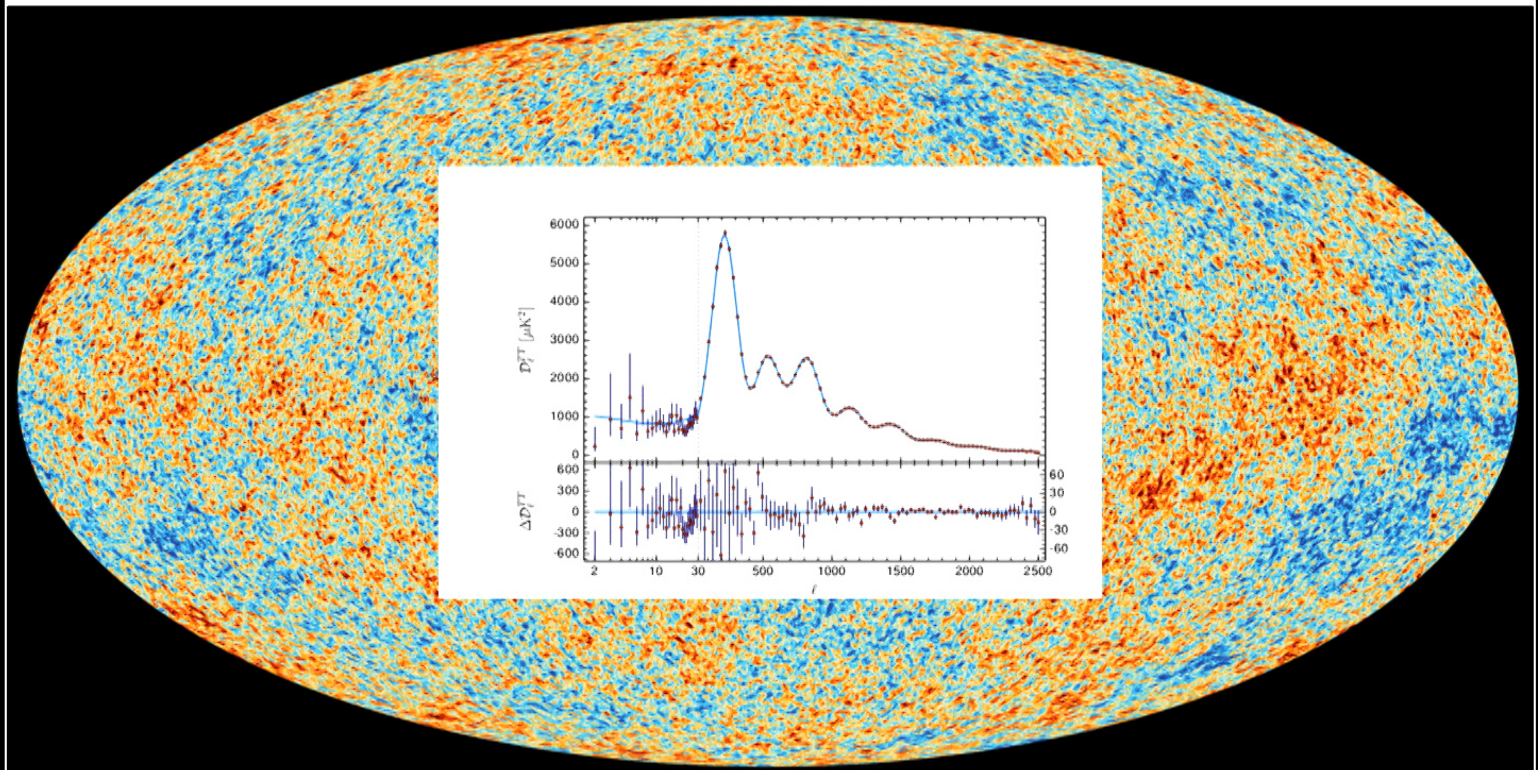




$$< \zeta(\mathbf{x})\zeta(\mathbf{x}+\mathbf{r}) > \longleftrightarrow \mathcal{P}_k^\zeta \equiv |\zeta_k|^2 k^3 \longleftrightarrow k^{-1}|\delta\rho_k^2|$$

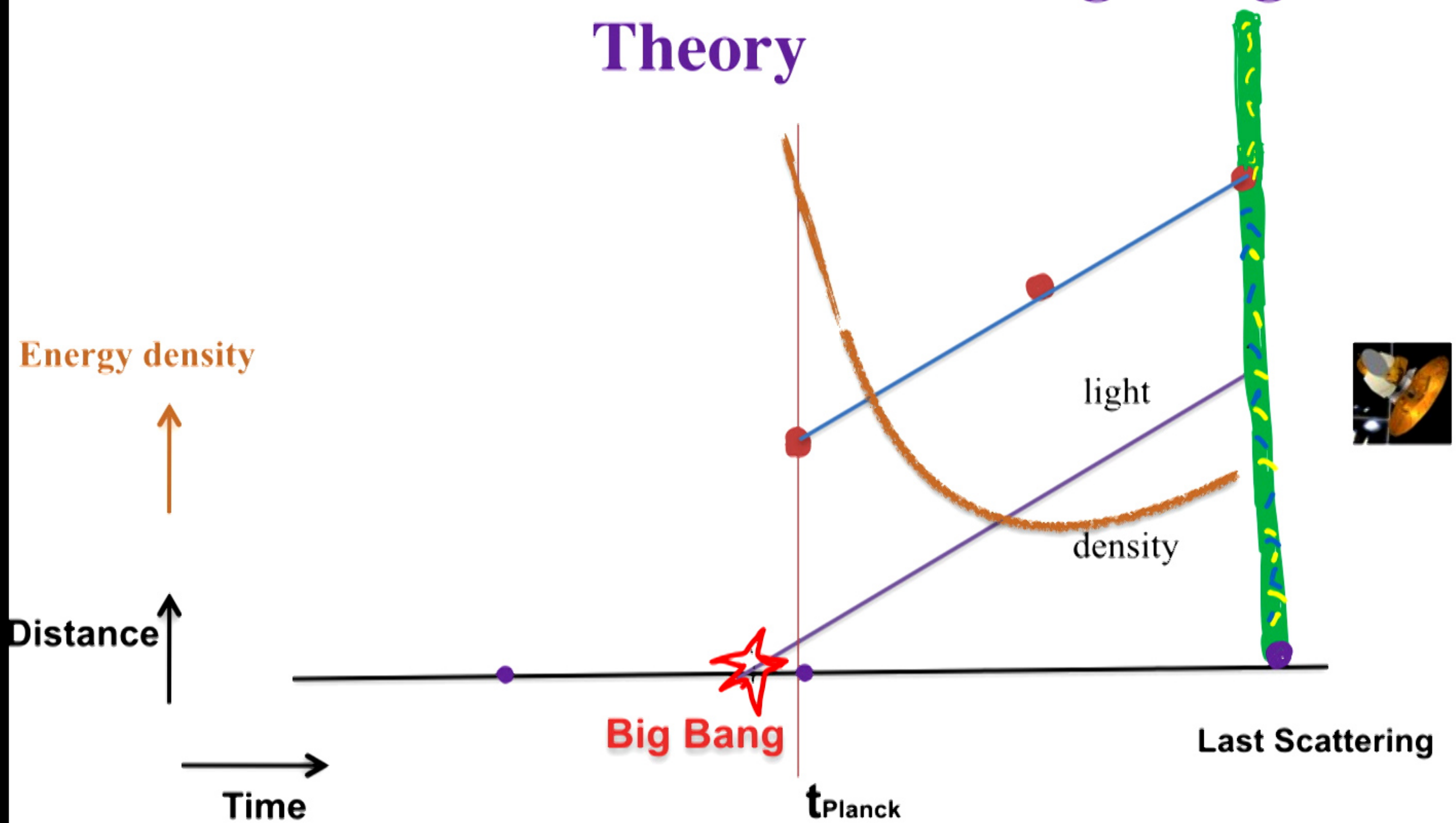


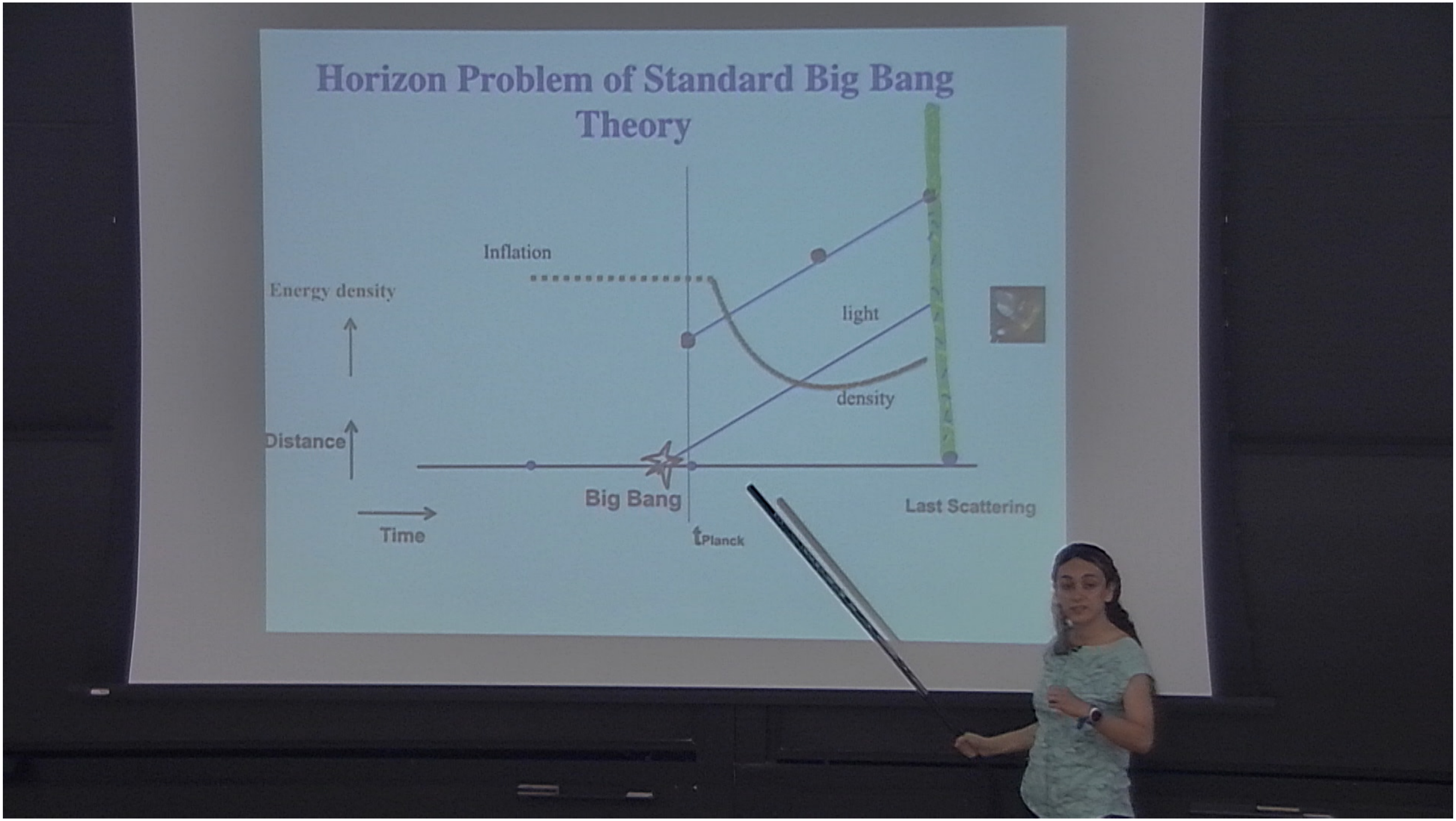
Most recent Picture of baby universe, released last week



- **Title** Planck's view of the cosmic microwave background
- **Released** 17/07/2018 3:00 pm
- **Copyright** ESA/Planck Collaboration

Horizon Problem of Standard Big Bang Theory




Horizon Problem of Standard Big Bang Theory
Inflation
Energy density
light
density
Distance
Big Bang
Last Scattering
Time
t_{Planck}

Motivation from Particle Physics and String Theory

Standard Action of a Scalar Field:

$$S_\phi = \int dx^4 \sqrt{-g}[\frac{1}{2}(\partial_\mu \phi \partial^\mu \phi) - V(\phi)]$$

However at high energies Scalar Fields may have non-canonical kinetic terms and they could also inflate the universe!

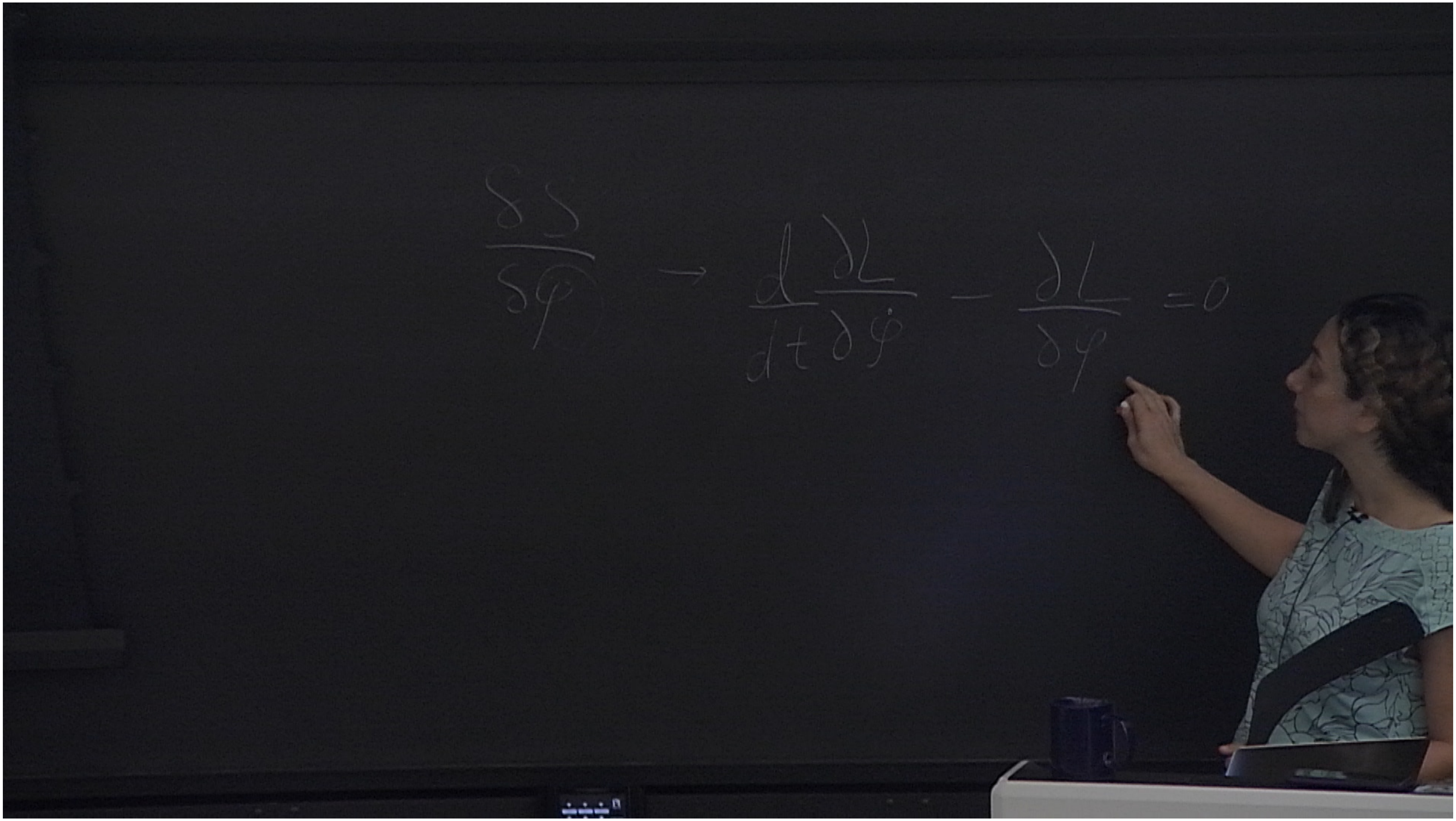
$$S = \int dx^4 \sqrt{-g}\mathcal{L}(X, \phi) \qquad X = \frac{1}{2}\partial_\mu \phi \partial^\mu \phi$$

Warped D-Brane Inflation

$$S_{DBI} = \int dx^4 \sqrt{-g}[-f(\phi)^{-1}\sqrt{1 - 2f(\phi)X} - (V(\phi) - f(\phi)^{-1})]$$

What are the general criteria other fields and particles

$$S = \int dx^4 L(\phi, \pi, \psi^i, \dots)$$


$\frac{\delta S}{\delta \varphi} \to \frac{d}{dt}\frac{\partial L}{\partial \dot{\varphi}} - \frac{\partial L}{\partial \varphi} = 0$

Generalized Slow Roll Inflation

$$\mathcal{L}(X,\phi) \leftarrow X = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi$$

The scalar field is very similar to a hydrodynamical fluid: $\Rightarrow$ $p(X,\phi)$ $\rho(X,\phi)$

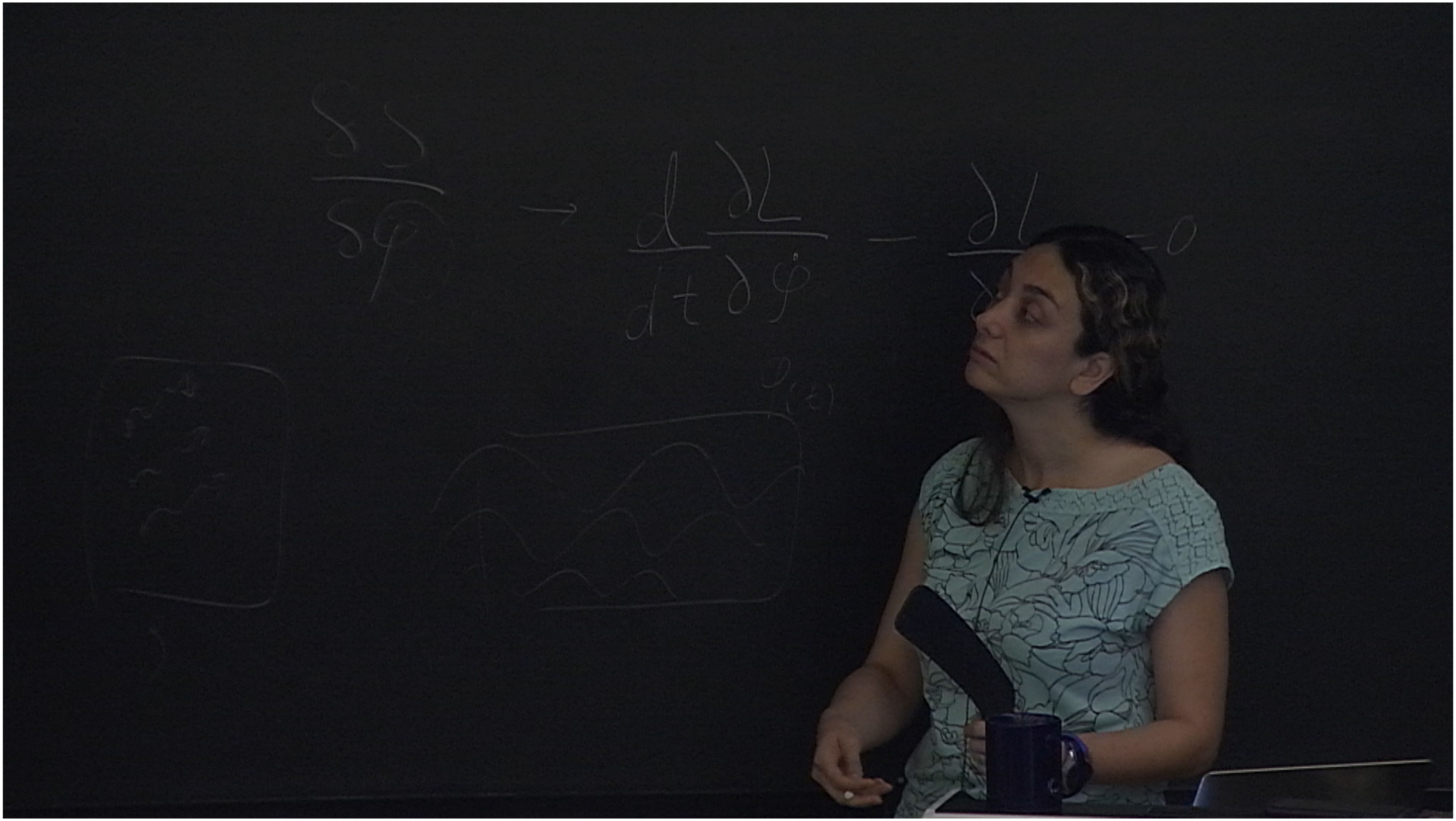
Gravity

Space time geometry $\Leftrightarrow$ Matter

1. Friedmann equations for homogenous background $a(t), \quad H = \frac{\dot{a}}{a} \longleftrightarrow \rho(\phi(t))$

2. Linear perturbation for quantum fluctuations

$$\zeta(x,t) \longleftrightarrow \delta\phi(x,t) \Rightarrow \delta\rho$$



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Space time geometry $\Leftrightarrow$ Matter

Gravity

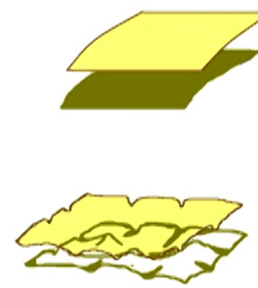
1. Friedmann equations for homogenous background $a(t),\ H = \frac{\dot{a}}{a} \longleftrightarrow \rho(\phi(t))$

Accelerated Expansion

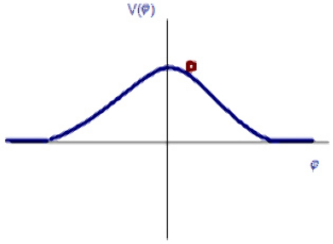
2. Linear perturbation for quantum fluctuations

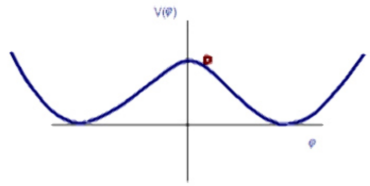
$$\zeta(x,t) \longleftrightarrow \delta\phi(x,t) \Rightarrow \delta\rho$$

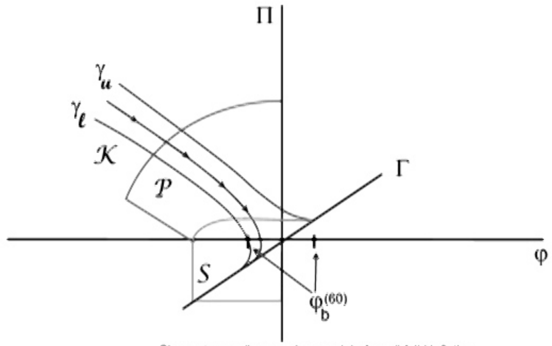
CMB anisotropies and Large scale structure



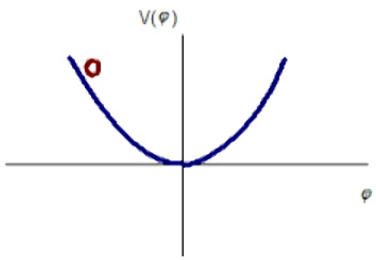
Examples:

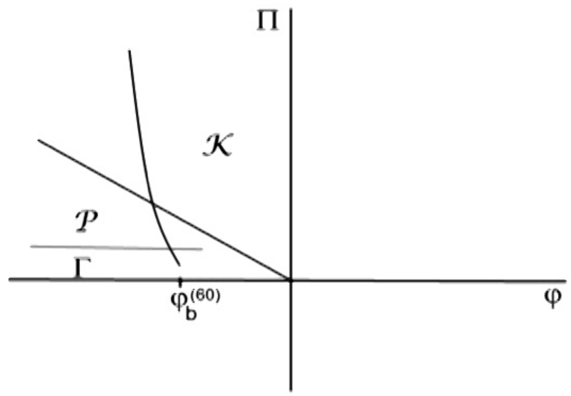






Phase-Space diagaram in a model of small feild inflation





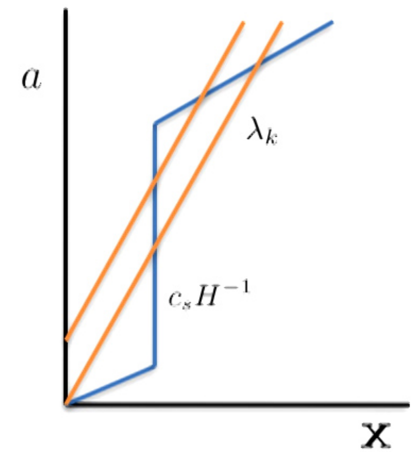
$$\frac{d^2u_k}{d\tau^2} + (c_s^2k^2 - 2(aH)^2\{(1+\frac{\eta}{2}+\kappa)(1-\frac{\epsilon}{2}+\frac{\eta}{4}+\frac{\kappa}{2}) + \frac{\dot\eta}{2H} + \frac{\dot\kappa}{H}\})u_k = 0$$

$$\eta \equiv \frac{\dot\epsilon}{H\epsilon}$$

$$\kappa \equiv \frac{\dot c_s}{Hc_s}$$

slow roll: $\epsilon = -\frac{\dot H}{H^2}, \eta, \frac{\dot\eta}{H}, \kappa, \frac{\dot\kappa}{H} << 1$

A Bessel equation



Scalar Power Spectrum $\mathcal{P}_k^\zeta \sim (\frac{1}{8\pi^2M_p^2})\frac{H^2}{c_s\epsilon}\Big|_{c_sk=aH}$

Scalar spectral index:

$$n_s - 1 \equiv \frac{d\ln\mathcal{P}_\mathcal{R}}{d\ln k}\Big|_{k=k_s},$$
$$\approx -(2\epsilon+\eta+\kappa) + O(\epsilon^2, \epsilon\eta, \kappa_N, ...)$$

$$n_s = 0.9665 \pm 0.0038$$

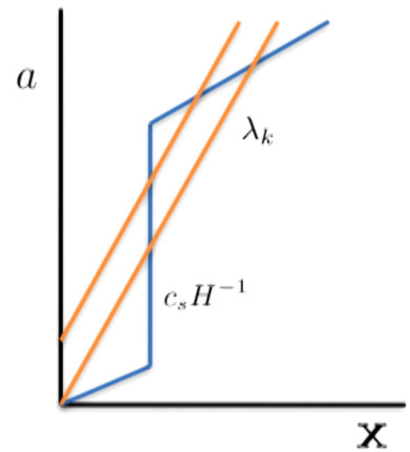
$$\frac{d^2u_k}{d\tau^2} + \left(c_s^2k^2 - 2(aH)^2\{(1 + \frac{\eta}{2} + \kappa)(1 - \frac{\epsilon}{2} + \frac{\eta}{4} + \frac{\kappa}{2}) + \frac{\dot{\eta}}{2H} + \frac{\dot{\kappa}}{H}\}\right)u_k = 0$$

$$\eta \equiv \frac{\dot{\epsilon}}{H\epsilon}$$

$$\kappa \equiv \frac{\dot{c_s}}{Hc_s}$$

slow roll: $\epsilon = -\frac{\dot{H}}{H^2}, \eta, \frac{\dot{\eta}}{H}, \kappa, \frac{\dot{\kappa}}{H} << 1$

A Bessel equation



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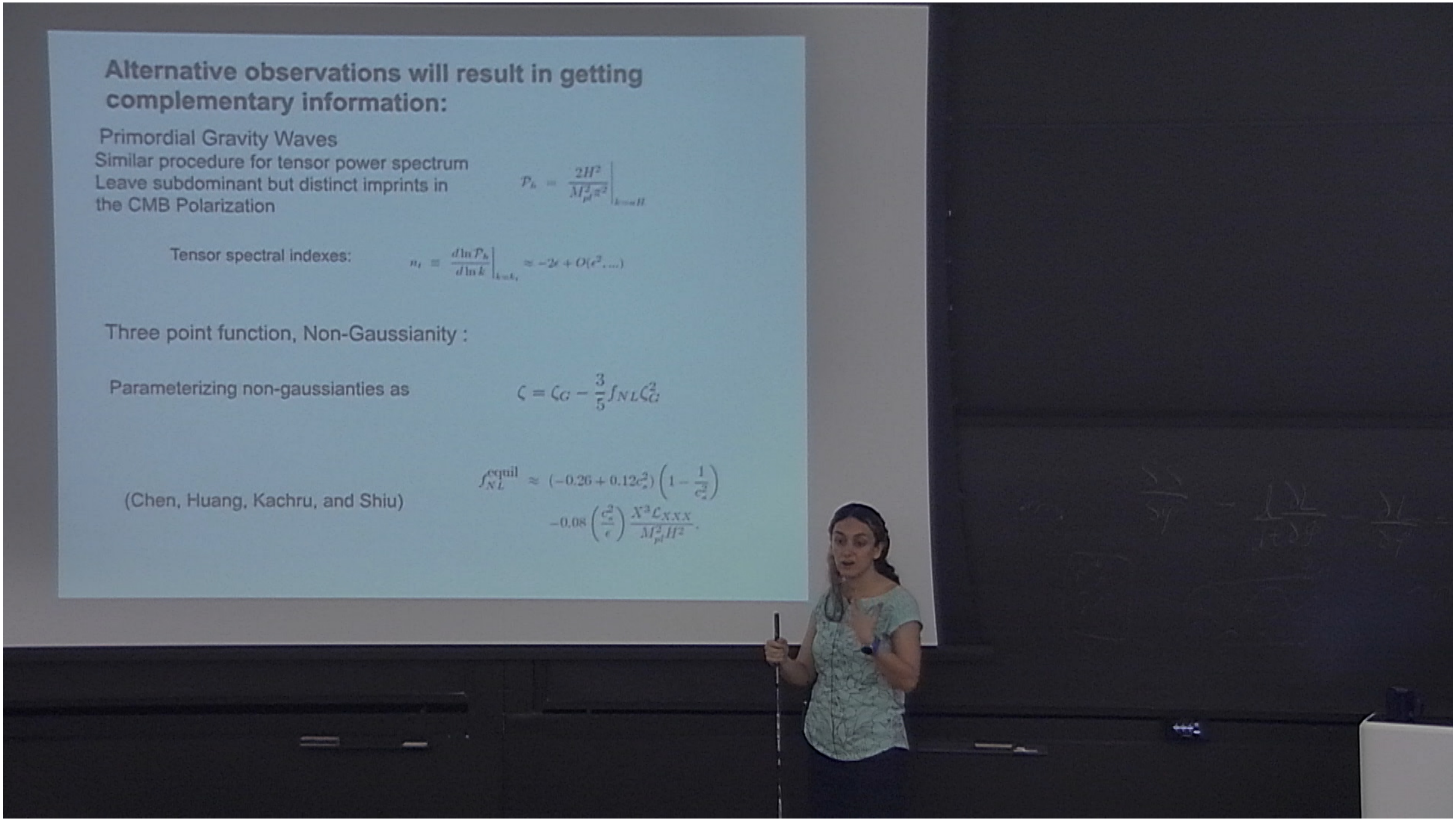
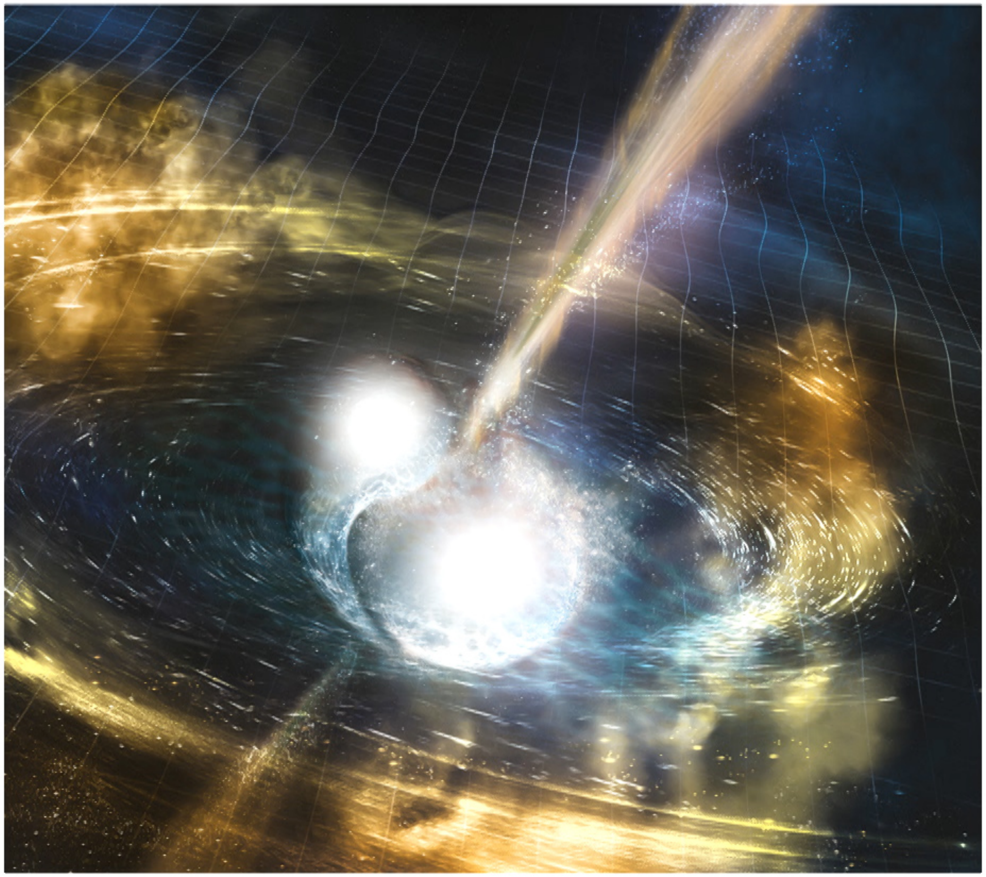
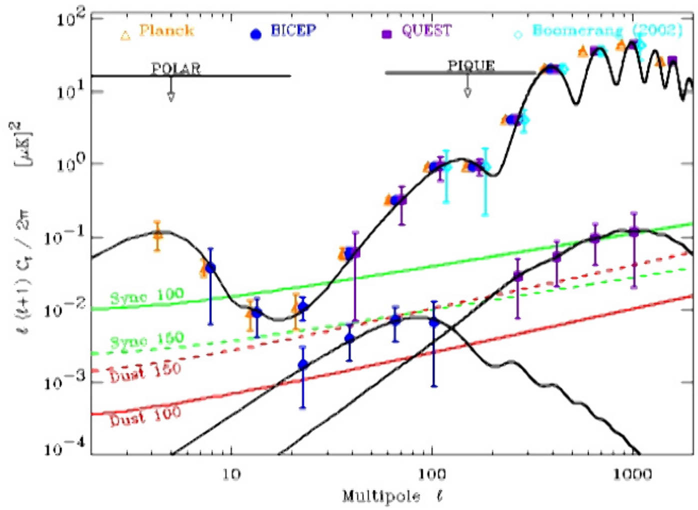

Alternative observations will result in getting complementary information:
Primordial Gravity Waves
Similar procedure for tensor power spectrum
Leave subdominant but distinct imprints in the CMB Polarization
Tensor spectral indexes:
Three point function, Non-Gaussianity :
Parameterizing non-gaussianties as
$\zeta = \zeta_G - \frac{3}{5} f_{NL} \zeta_G^2$
(Chen, Huang, Kachru, and Shiu)

Gravitational waves

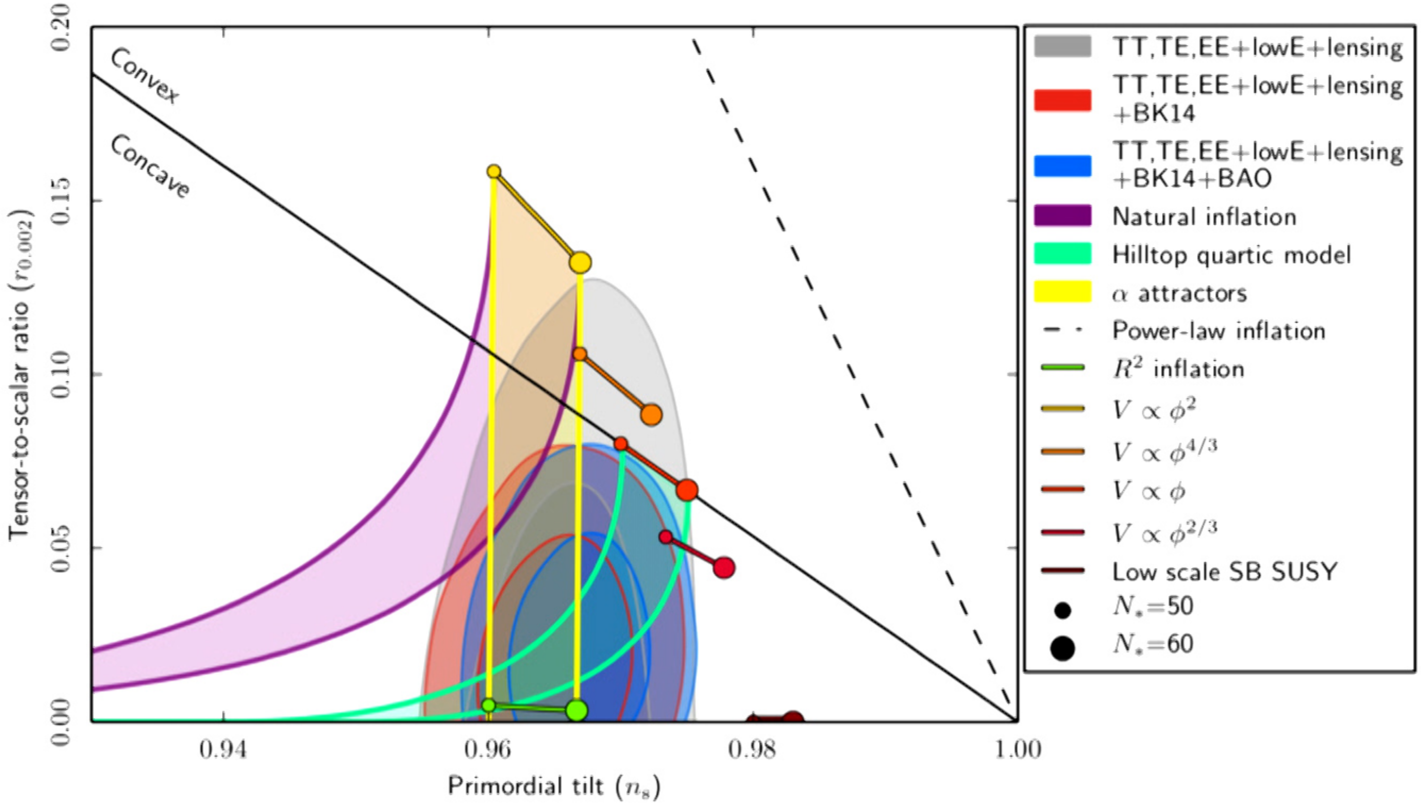


Credit
NSF/LIGO/Sonoma State University/A. Simonne

BICEP Experiment

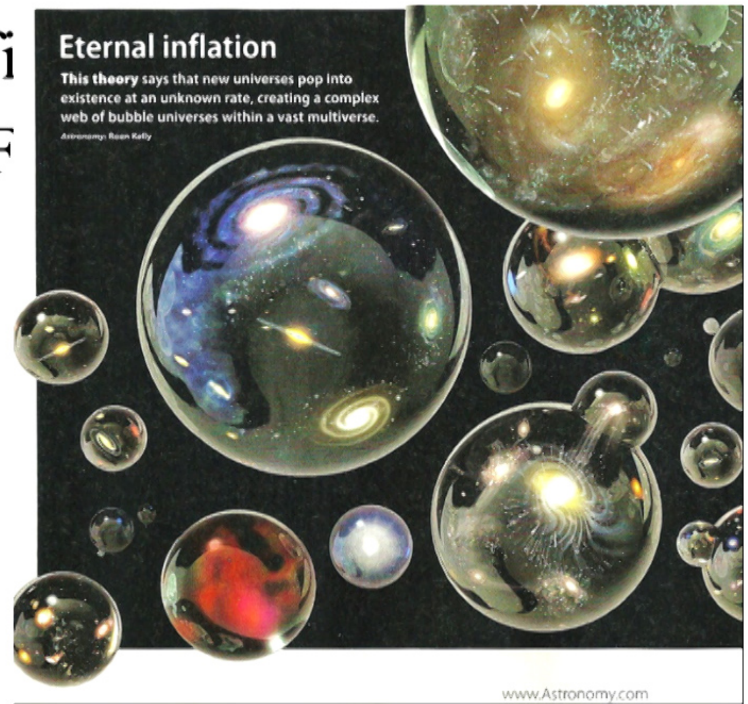


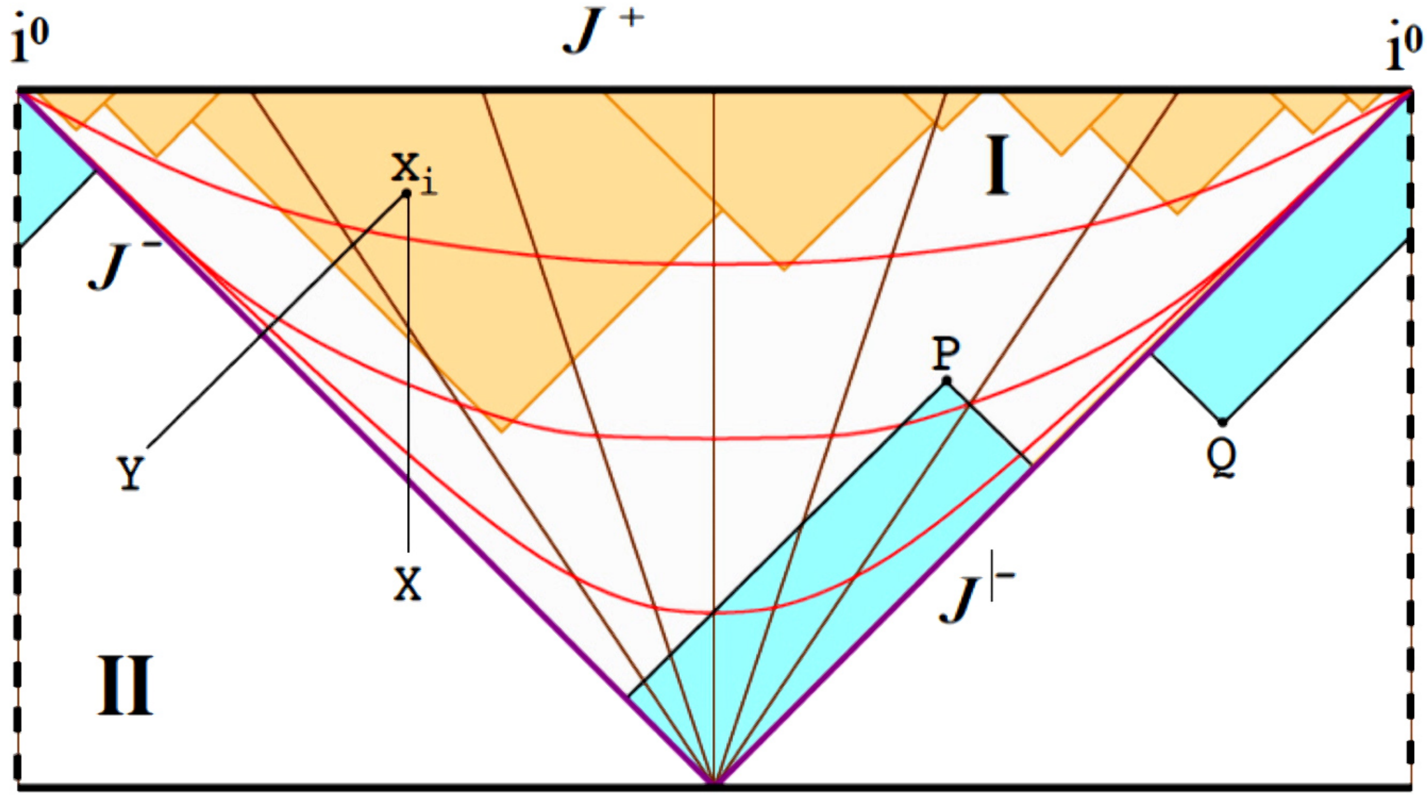
Planck Collaboration: Constraints on Inflation



What then?

- Falsifiable?
- What is Inflaton fi
- Eternal inflation/F

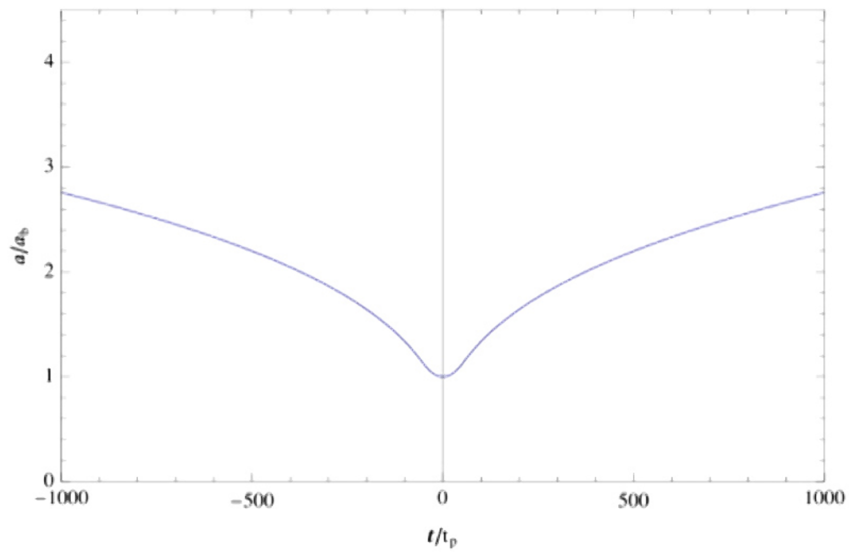


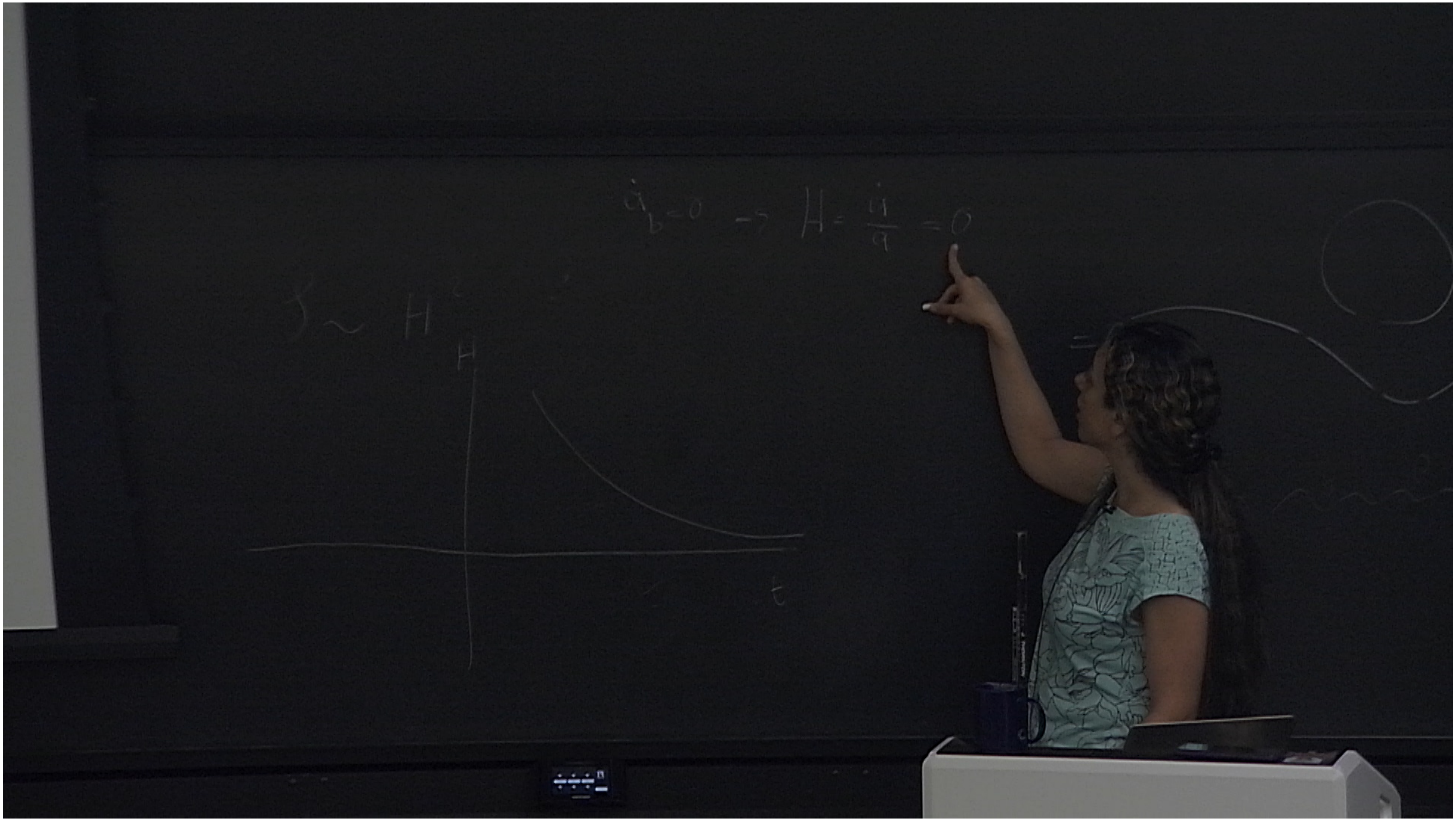


Aguirre & Gratton

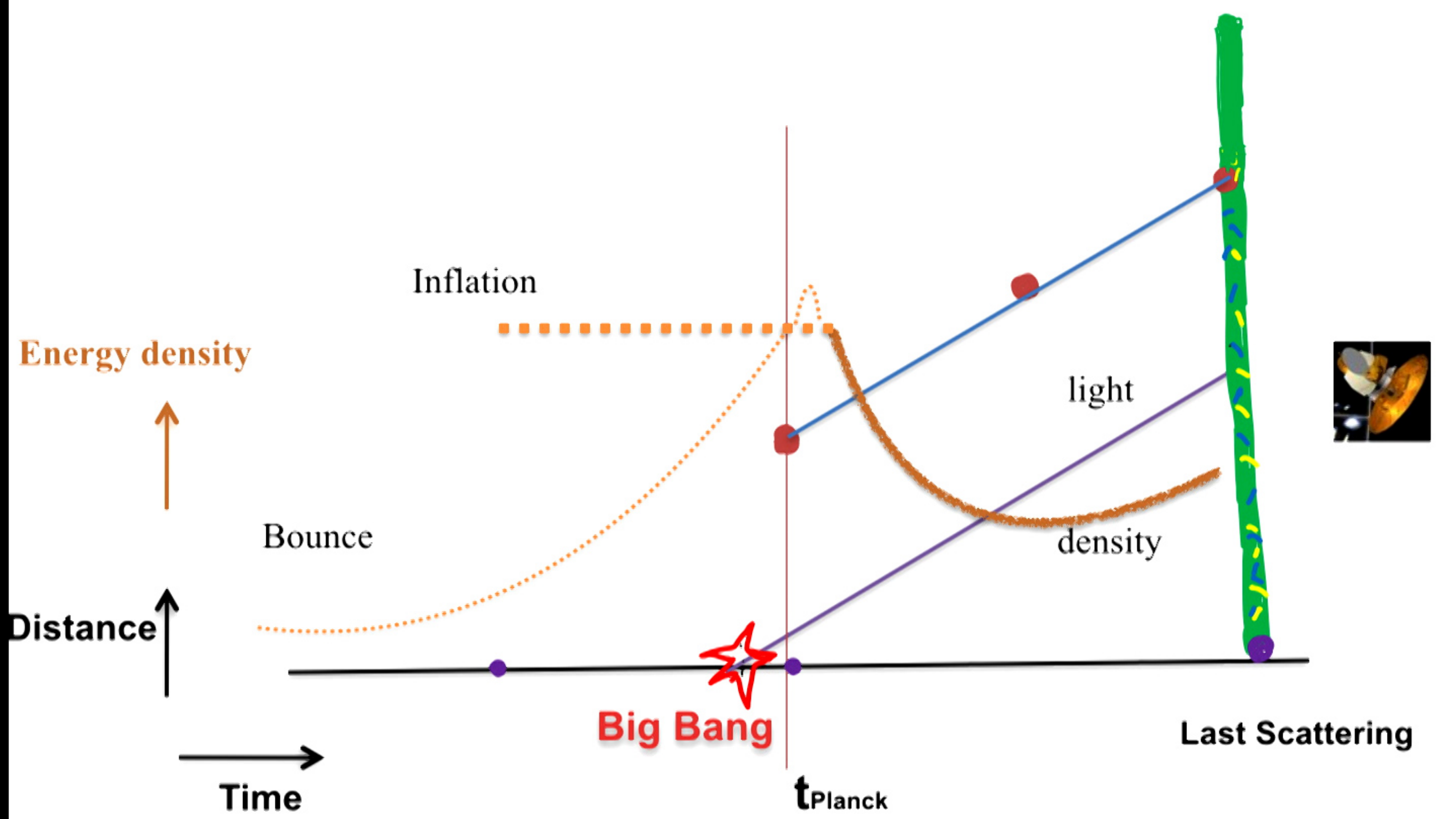
Alternatives: Bounce?

- Instabilities
- Getting the right spectrum
- What field?





H
t


Inflation
Energy density
light
Bounce
density
Distance
Big Bang
Last Scattering
Time
t_{Planck}

Getting a bounce cosmology through Cuscuton

Cuscuton **(G.G., N. Afshordi, D. Chung,07; G.G., N. Afshordi, D. Chung, M. Doran, 07)**

Specific limit of K-essence Action: $c_s = \infty$

$$\mathcal{L} = -\mu^2 \sqrt{\underbrace{|\partial^\mu \varphi \partial_\mu \varphi|}_{2X}} - V(\varphi) \qquad c_s^2 = \frac{p_{,X}}{\rho_{,X}} = \frac{1}{1 + 2\frac{X\mathcal{L}_{,XX}}{\mathcal{L}_{,X}}}$$

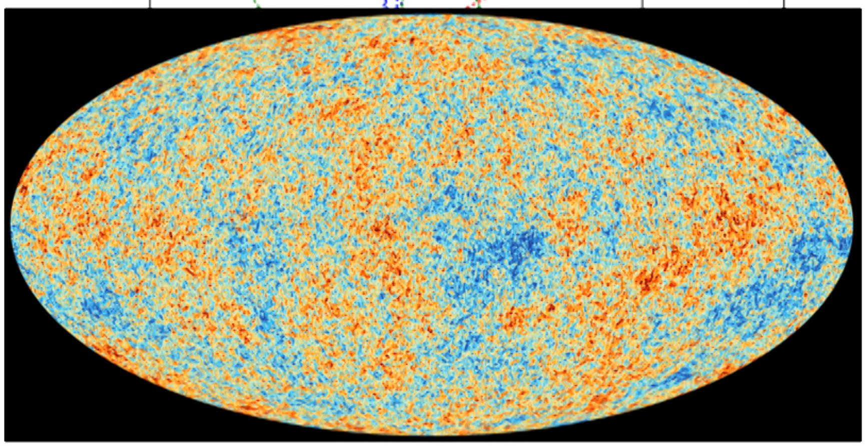
→ **Field equation becomes a constraint equation that uniquely determines Cuscuton as a function of metric**

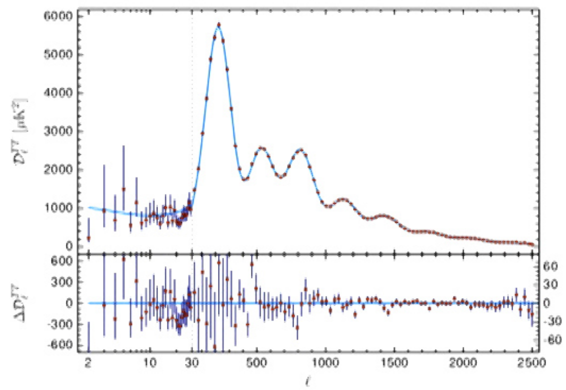
→ **No internal dynamics; only follows what it couples to**

→ *Cuscuton* (käs-kŭ-tän): **derived from the Latin name for the parasitic plant of dodder, "Cuscuta"**

Cuscuton Bounce: No Instabilities!

Can it produce anisotropies?





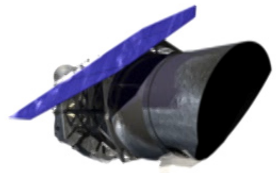


Illustration of NASA's Wide Field Infrared Survey Telescope (WFIRST).
Credits: NASA/GSFC/Conceptual Image Lab