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>

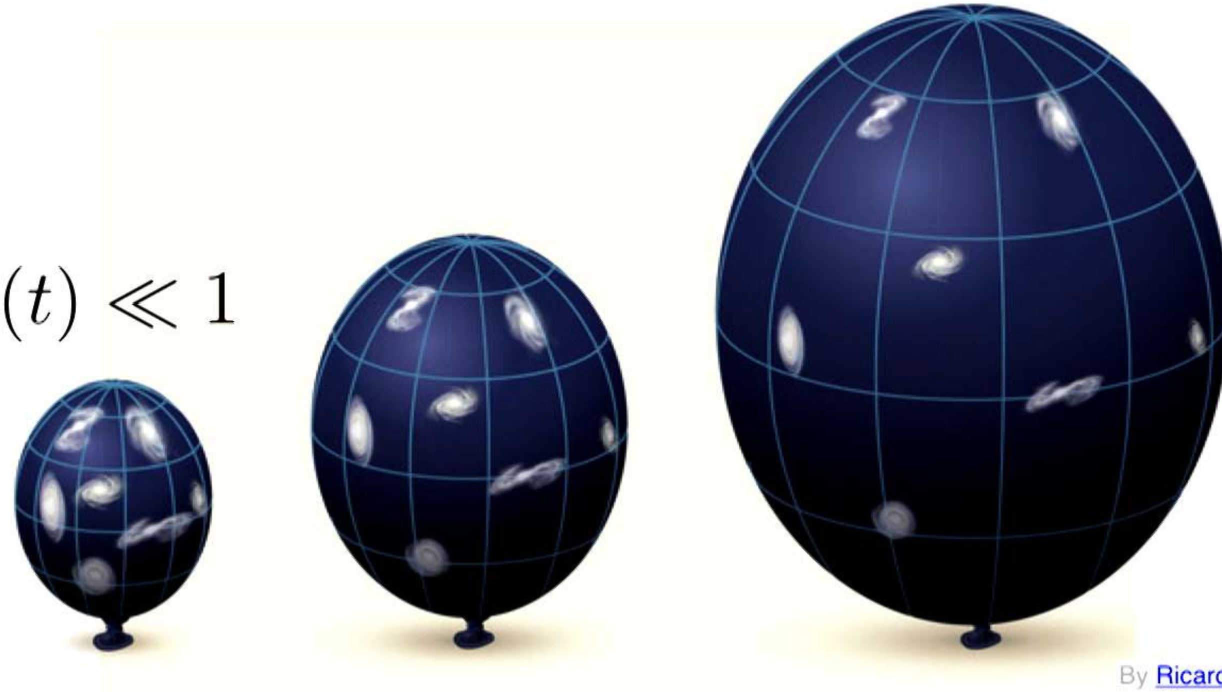
<div>universe and some of its mysteries.</div>

Cosmic Observations Meeting Fundamental Theory

Hubble Law

$a(t) = 1$

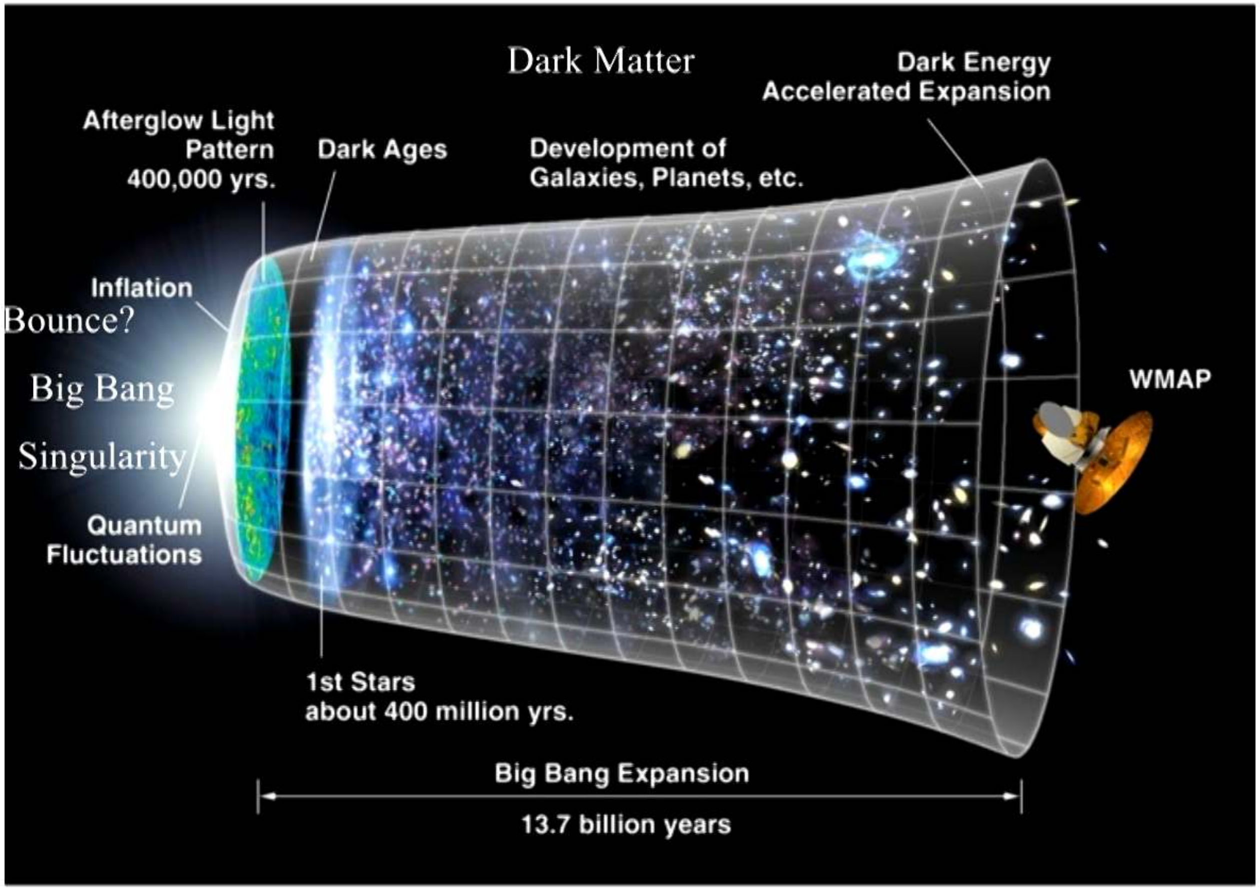
$a(t) \ll 1$



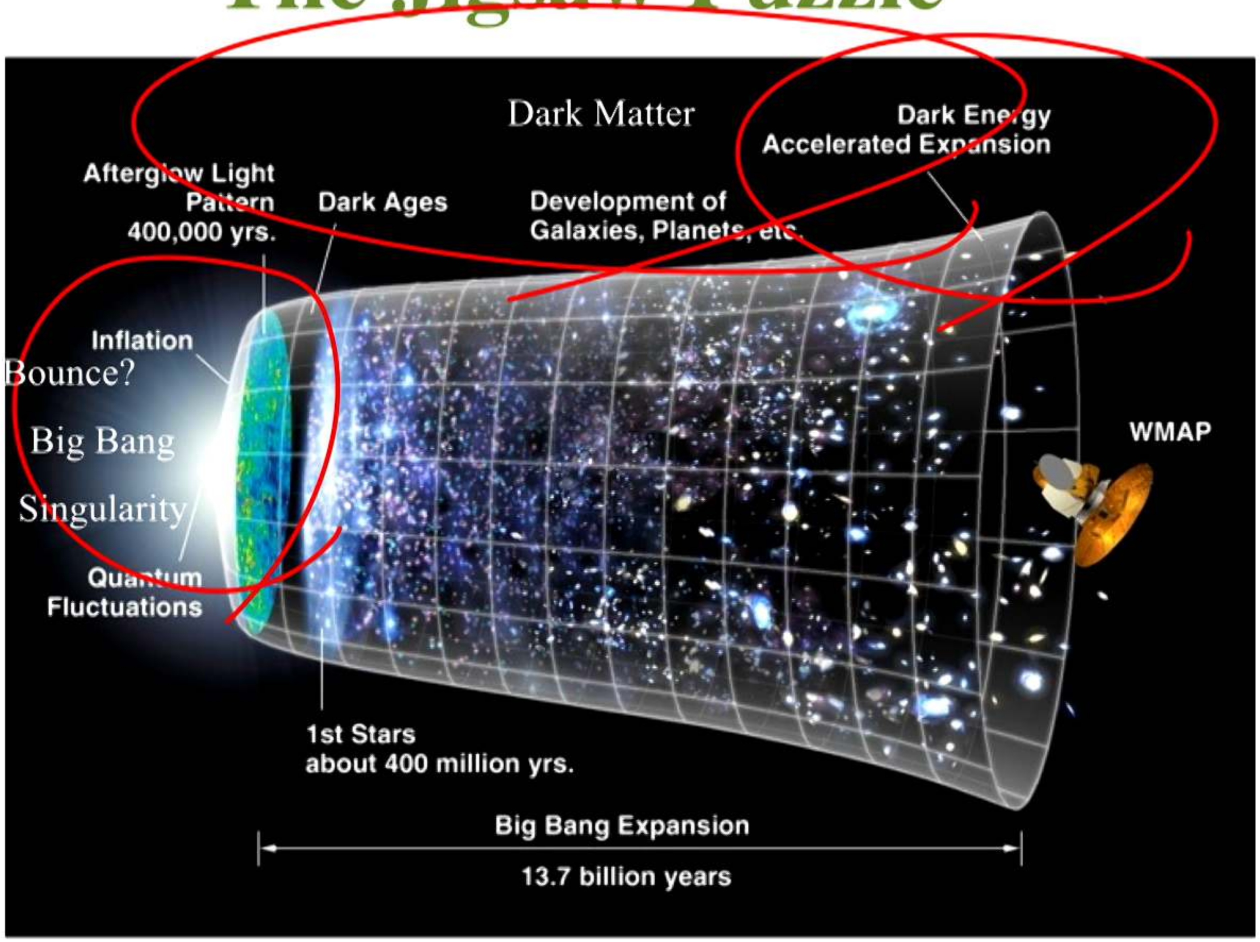
By Ricardo García

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

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,

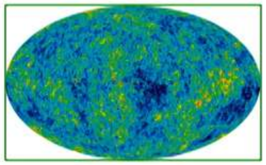
  first stars, galaxy formation, re-ionization …

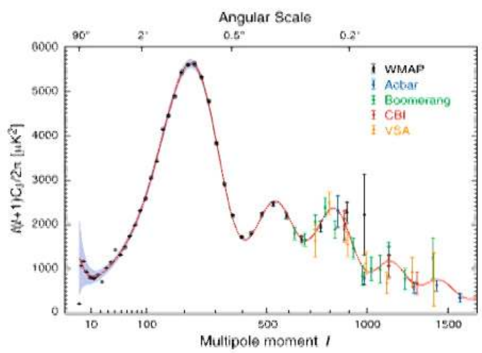
- **Late Time Acceleration:**

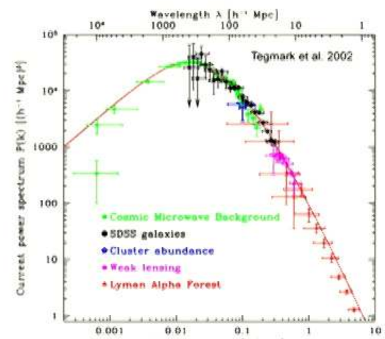
  Cosmological constant problem, Lambda/Dark Energy/Modified Gravity

  Observation: CMB, Supernovae, Gravitational waves

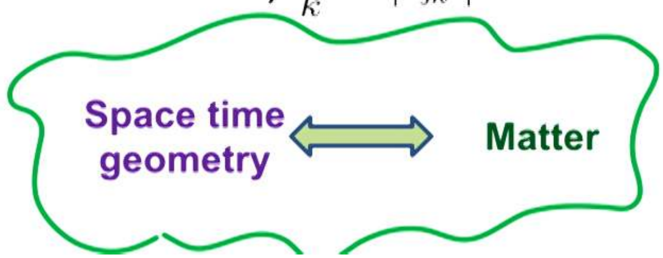
Anisotropies of order 10^(-5)!
Scale Invariant Power Spectrum



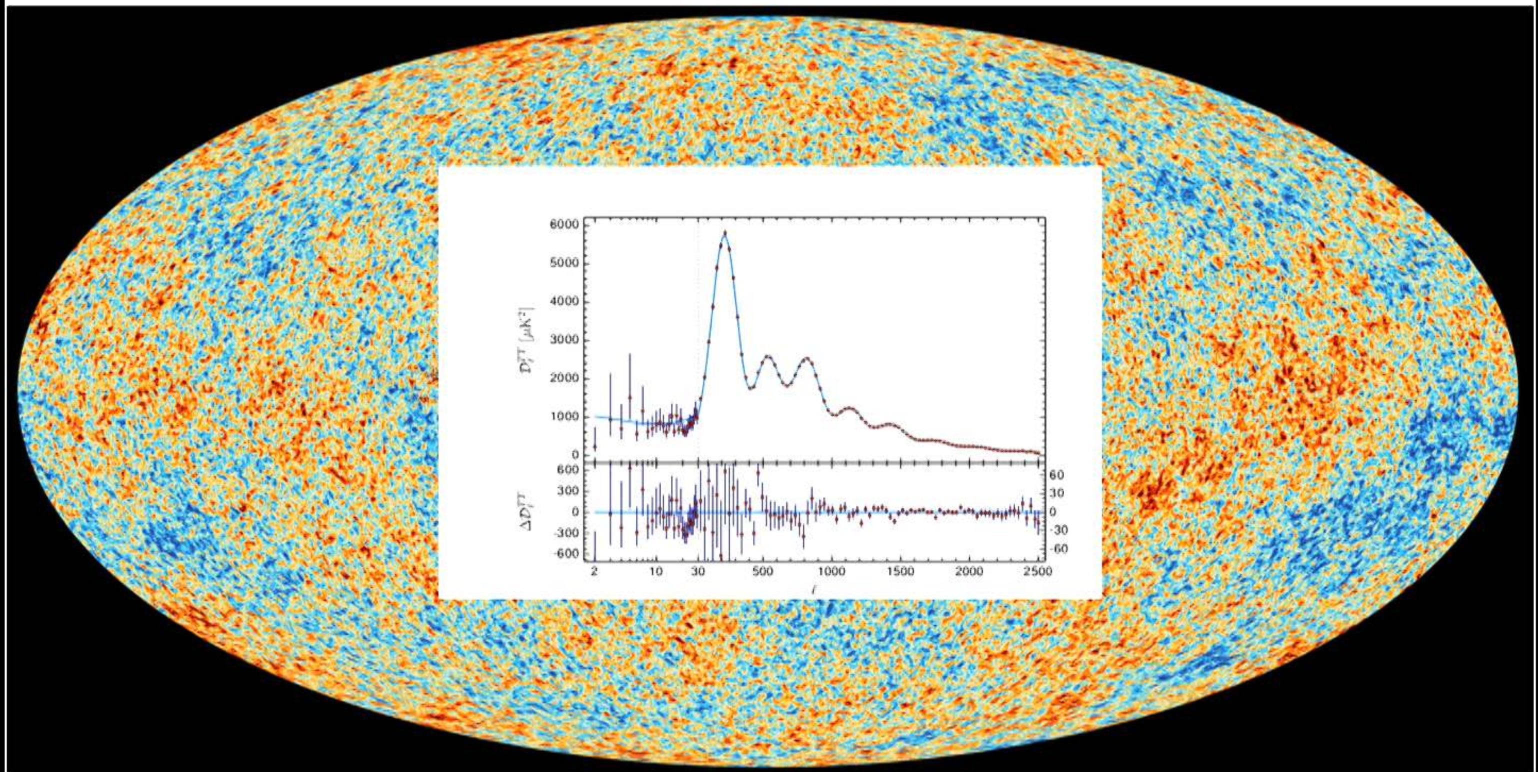




$$< \zeta(\mathbf{x})\zeta(\mathbf{x}+\mathbf{r}) > \longleftrightarrow \mathcal{P}_k^{\zeta} \equiv |\ \zeta_k\ |^2\ k^3 \longleftrightarrow k^{-1}|\delta\rho_k^2|$$

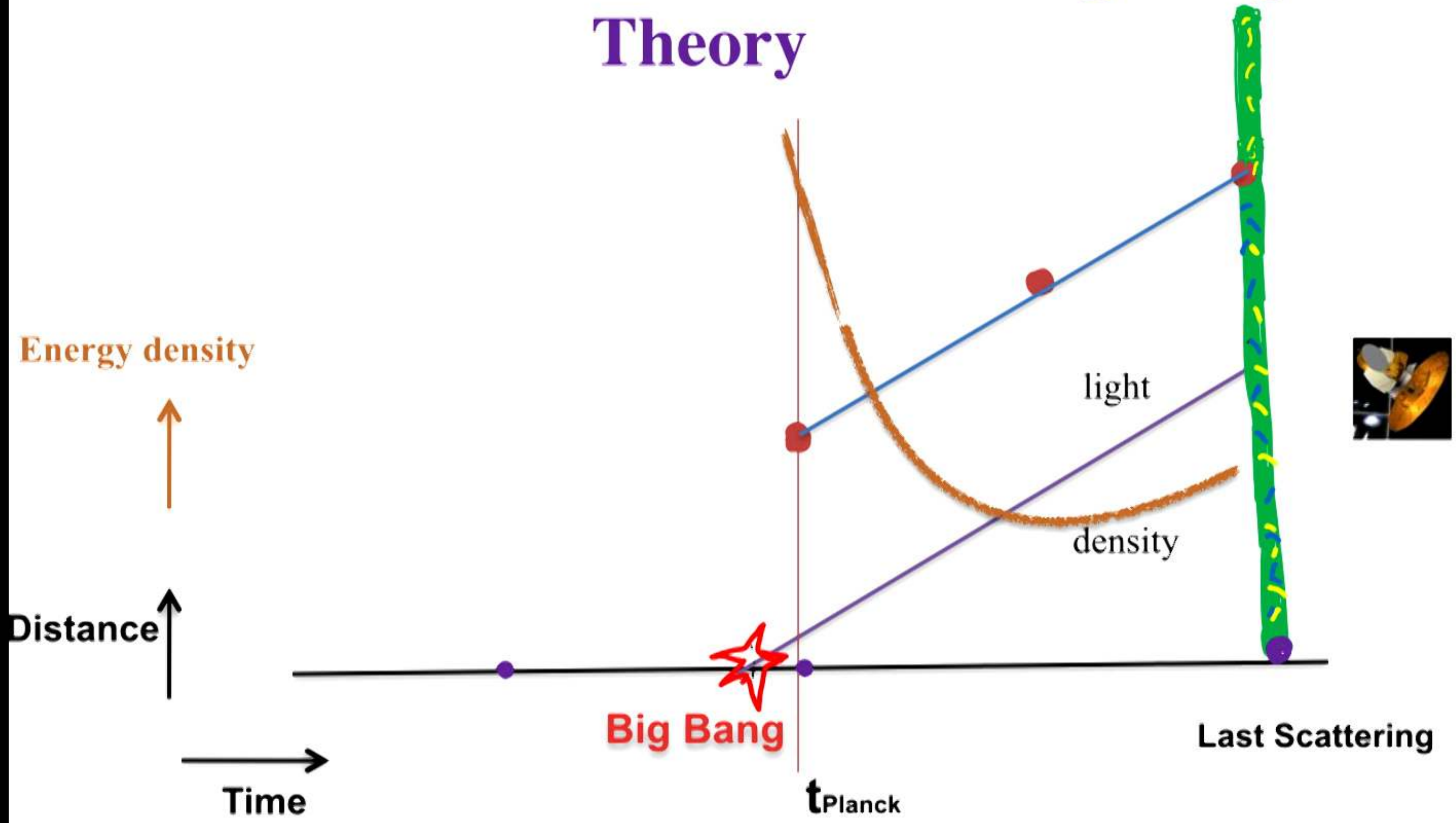


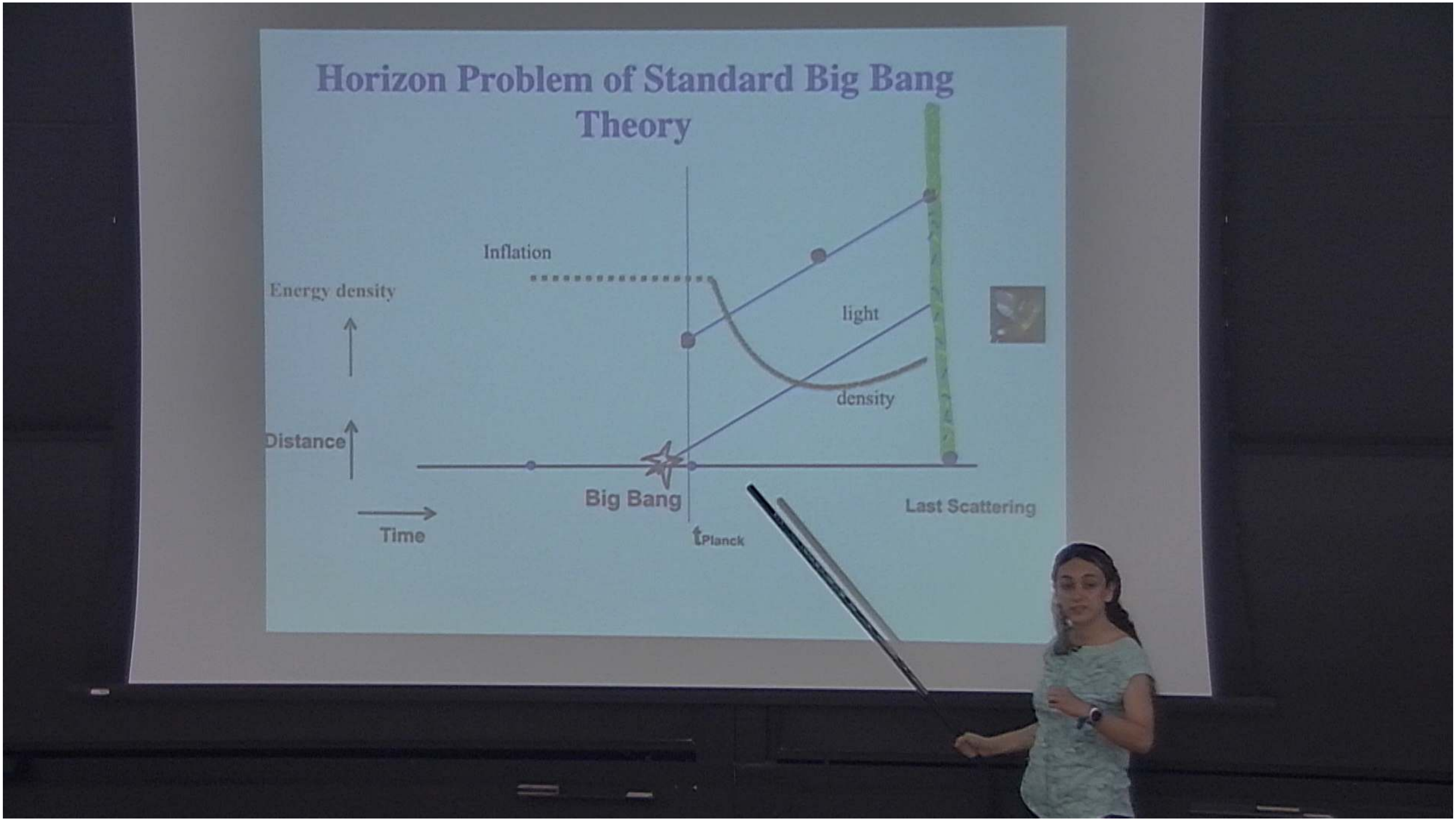
Most recent Picture of baby universe, released last week



- **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
tPlanck

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!

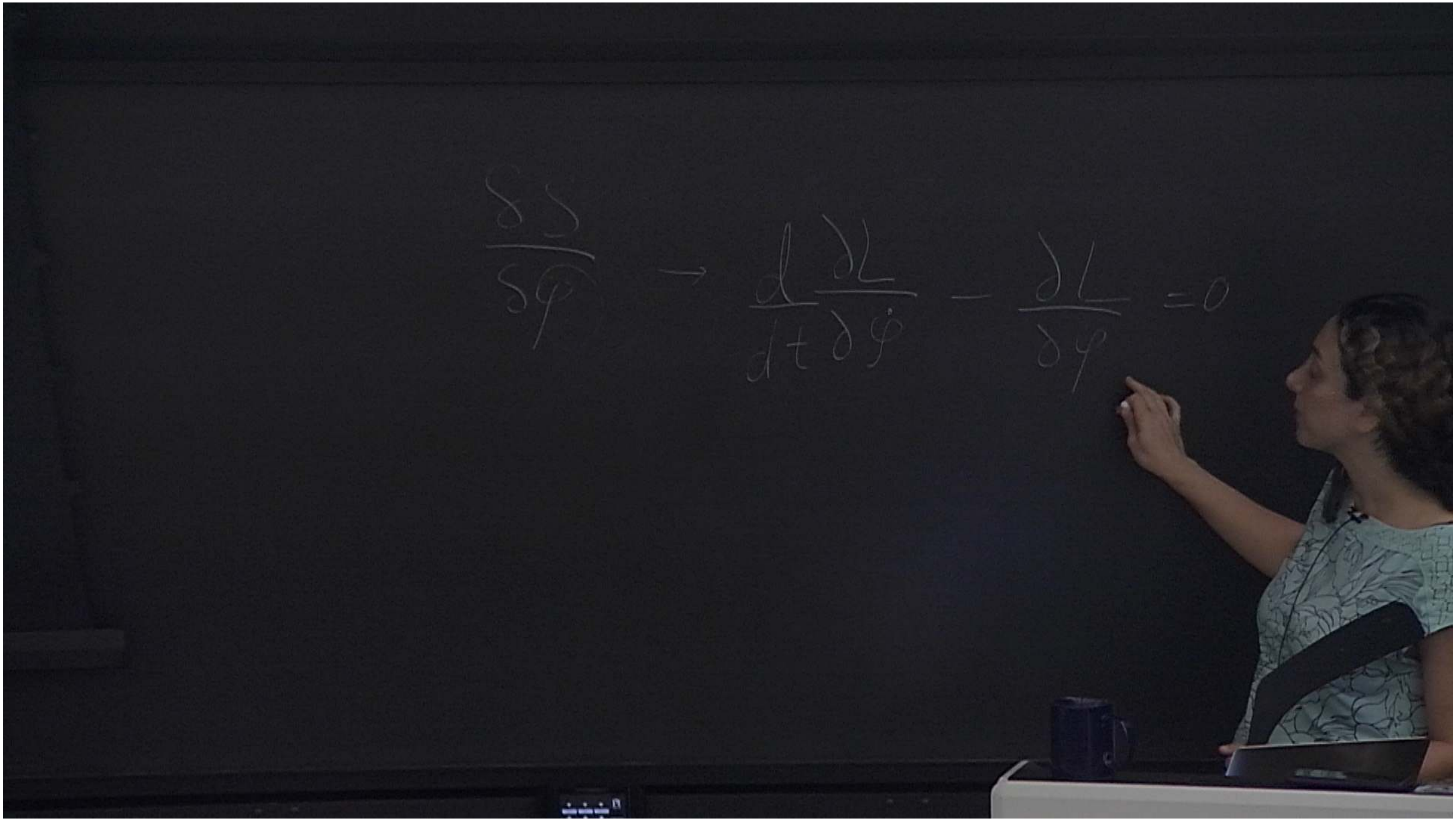
$$S = \int dx^4 \sqrt{-g}\mathcal{L}(X, \phi) \qquad X = \frac{1}{2}\partial_\mu \phi \partial^\mu \phi$$

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

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


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

Generalized Slow Roll Inflation

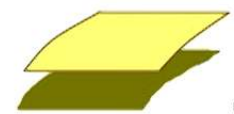
$$\mathcal{L}(X,\phi) \longleftarrow X = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi$$

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

Gravity

Space time geometry $\Longleftrightarrow$ **Matter**

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

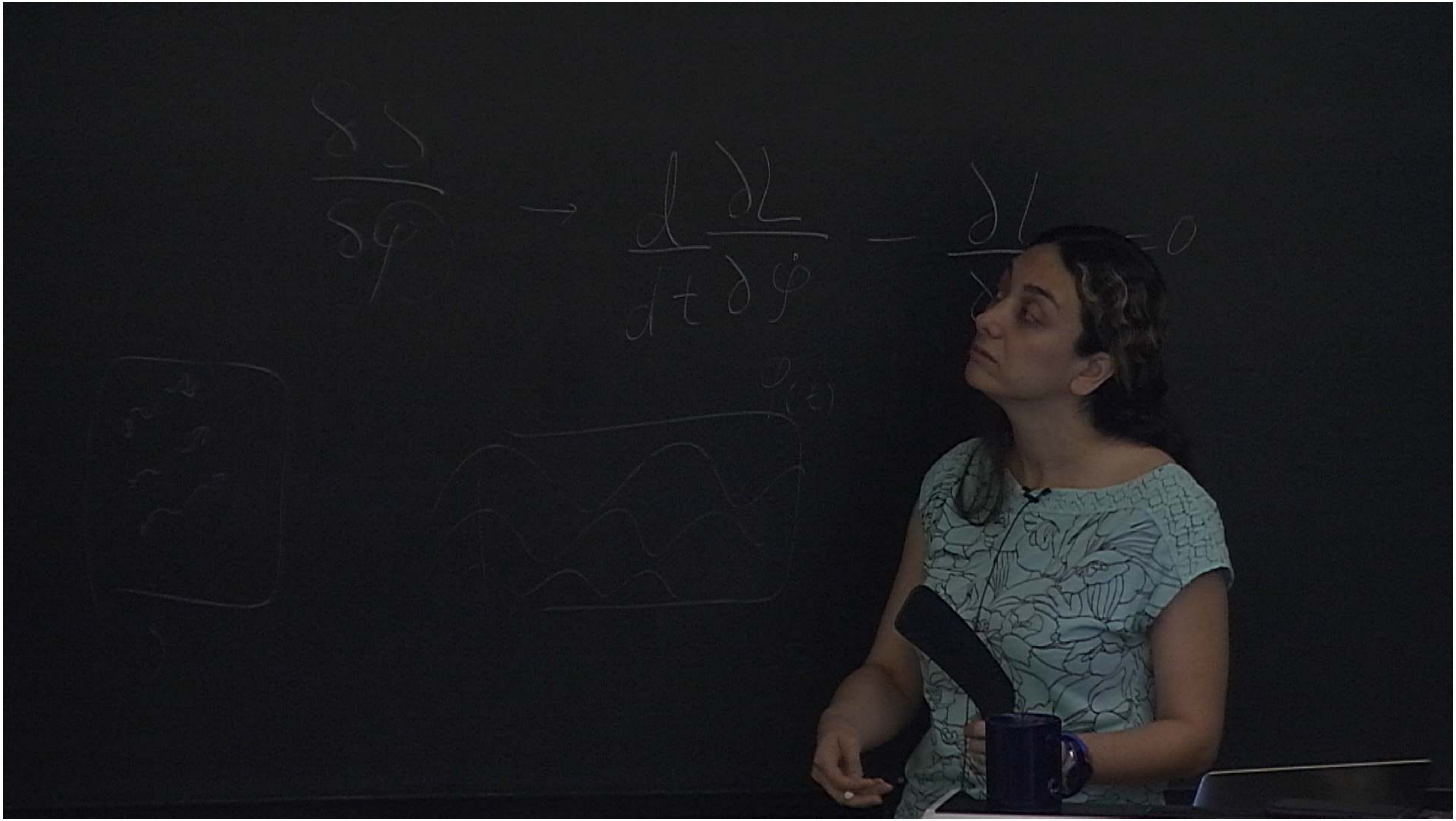


$g_0, \varphi_0, \ldots$

2. Linear perturbation for quantum fluctuations

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

$g, \varphi, \ldots$



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Gravity

Space time geometry $\Longleftrightarrow$ **Matter**

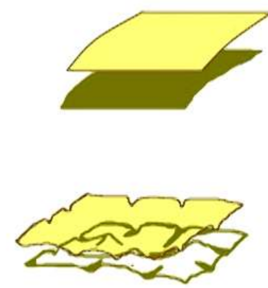
1. Friedmann equations for homogenous background $a(t), \quad H =$ $\longleftrightarrow$ $\rho(\phi(t))$

Accelerated Expansion

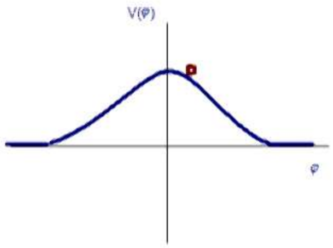
2. Linear perturbation for quantum fluctuations

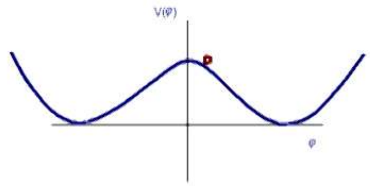
$$\zeta(x,t) \longleftrightarrow \delta\phi(x,t) \Longrightarrow \delta\rho$$

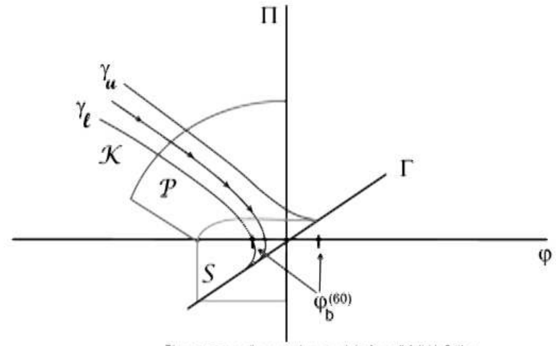
CMB anisotropies and Large scale structure



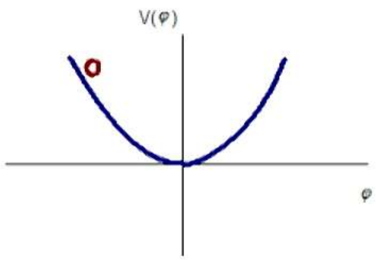
Examples:

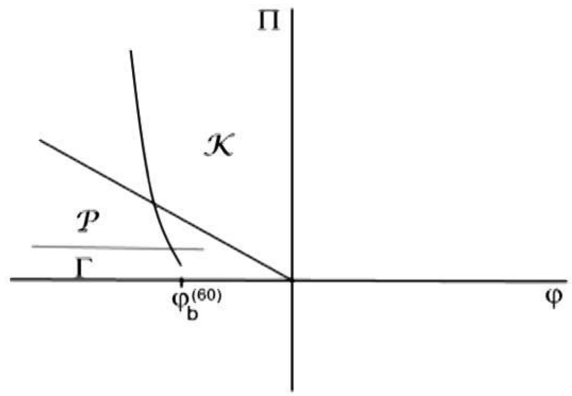






Phase-Space diagaram in a model of small feild inflation



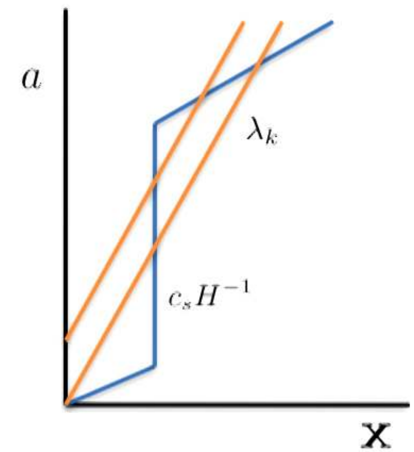


$$\frac{d^2 u_k}{d\tau^2} + \left(c_s^2 k^2 - 2(aH)^2\{(1+\frac{\eta}{2}+\kappa)(1-\frac{\epsilon}{2}+\frac{\eta}{4}+\frac{\kappa}{2}) + \frac{\dot\eta}{2H} + \frac{\dot\kappa}{H}\}\right)u_k = 0$$

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

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

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



A Bessel equation

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

Scalar spectral index:

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

$$n_s = 0.9665 \pm 0.0038$$

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

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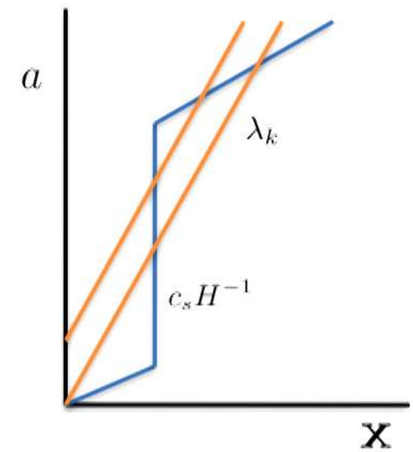
slow roll: $\epsilon = -\frac{\dot H}{H^2}, \eta, \frac{\dot\eta}{H}, \kappa, \frac{\dot\kappa}{H} << 1$

A Bessel equation



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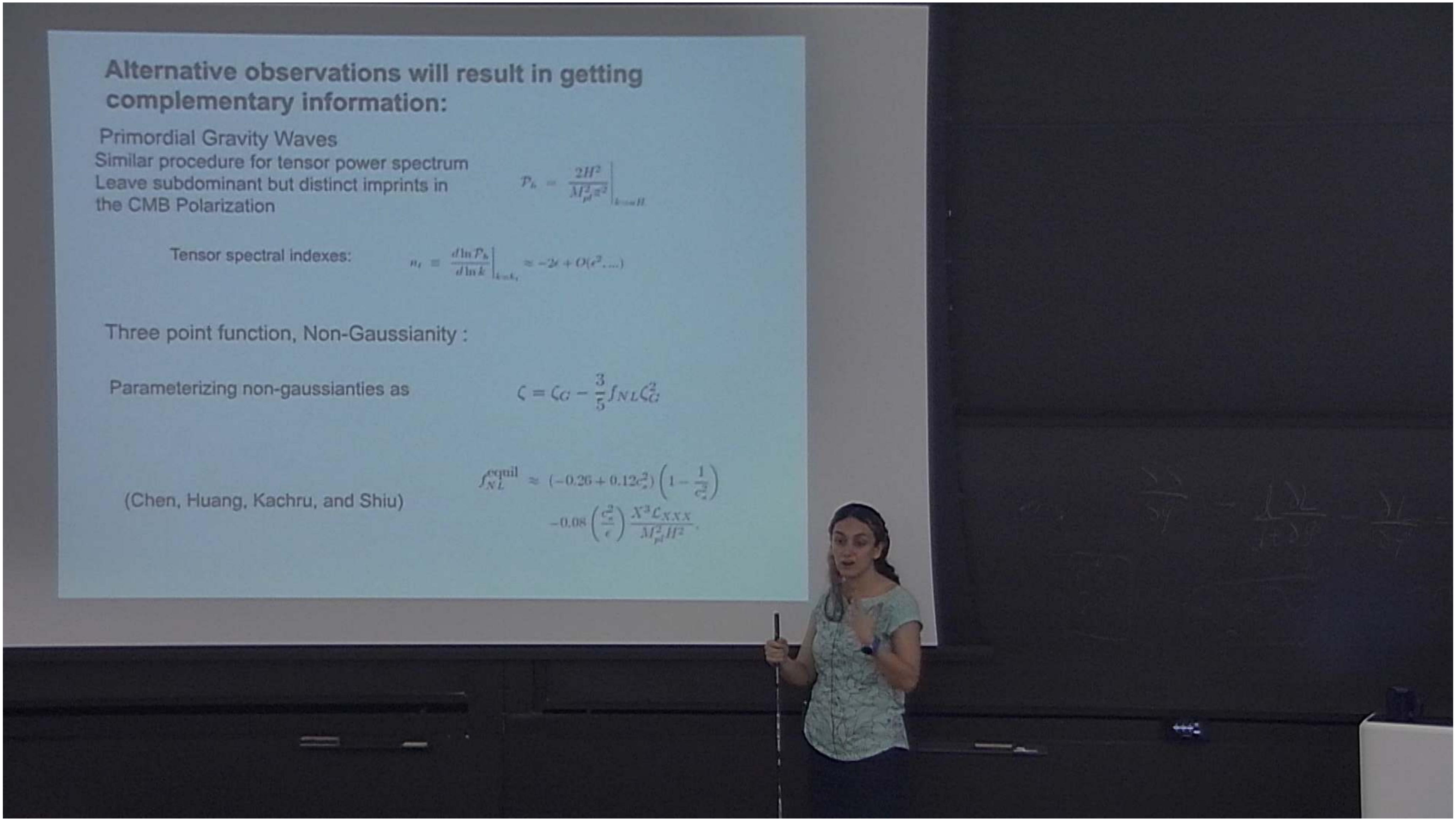
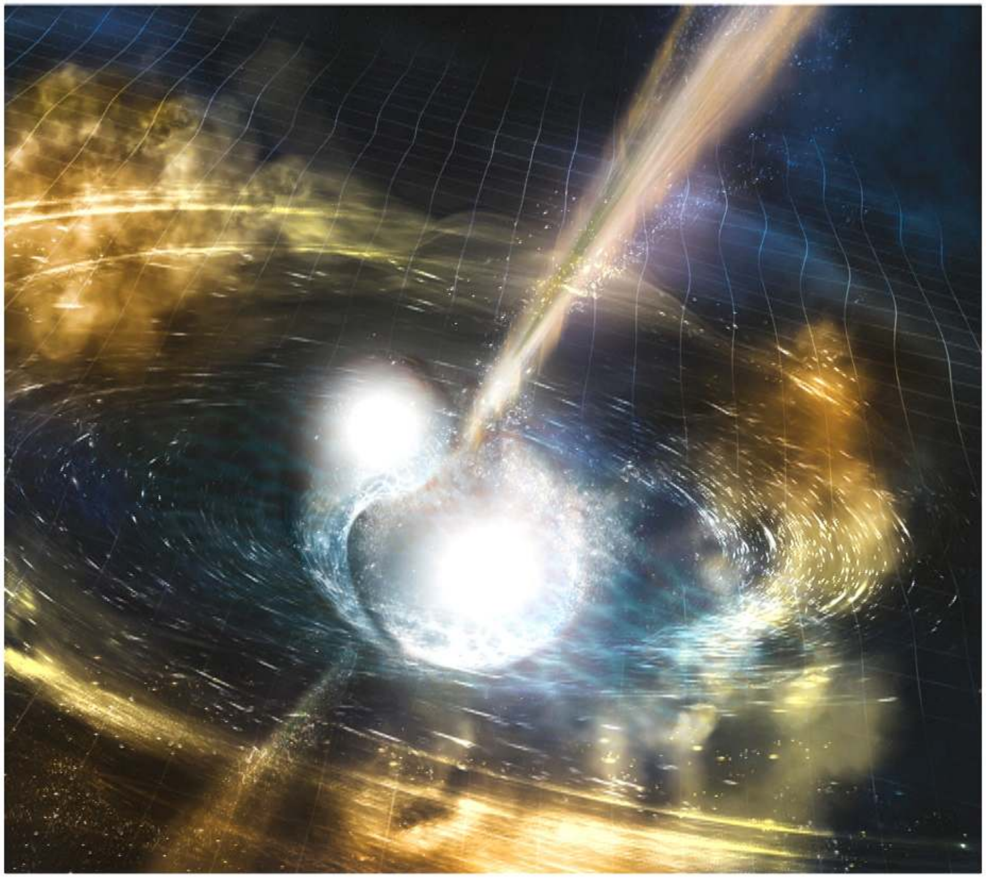
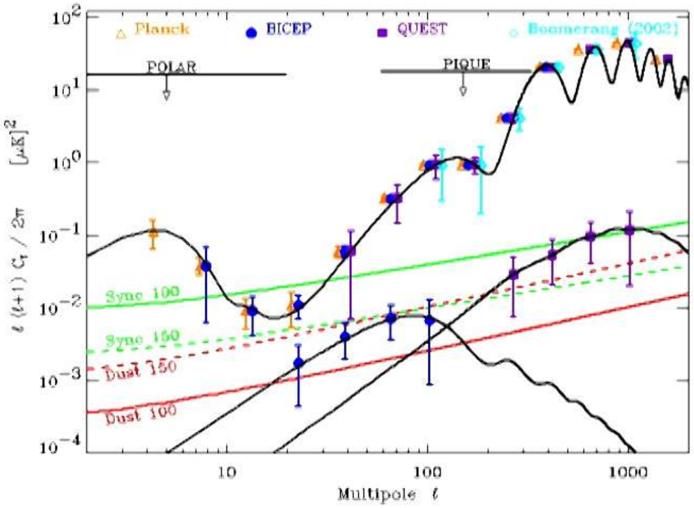

Alternative observations will result in getting complementary information:
Primordial Gravity Waves
Similar procedure for tensor power spectrum
Leave subdominant but distinct imprints in the CMB Polarization
$\mathcal{P}_h = \frac{2H^2}{M_{pl}^2\pi^2}\Big|_{k=aH}$
Tensor spectral indexes:
$n_t \equiv \frac{d\ln\mathcal{P}_h}{d\ln k}\Big|_{k=k_*} \simeq -2\epsilon + O(\epsilon^2, ...)$
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)
$f_{NL}^{\rm equil} \approx (-0.26 + 0.12c_s^2)\left(1 - \frac{1}{c_s^2}\right) - 0.08\left(\frac{c_s^2}{\epsilon}\right)\frac{X^3\mathcal{L}_{XXX}}{M_{pl}^2H^2}.$

Gravitational waves

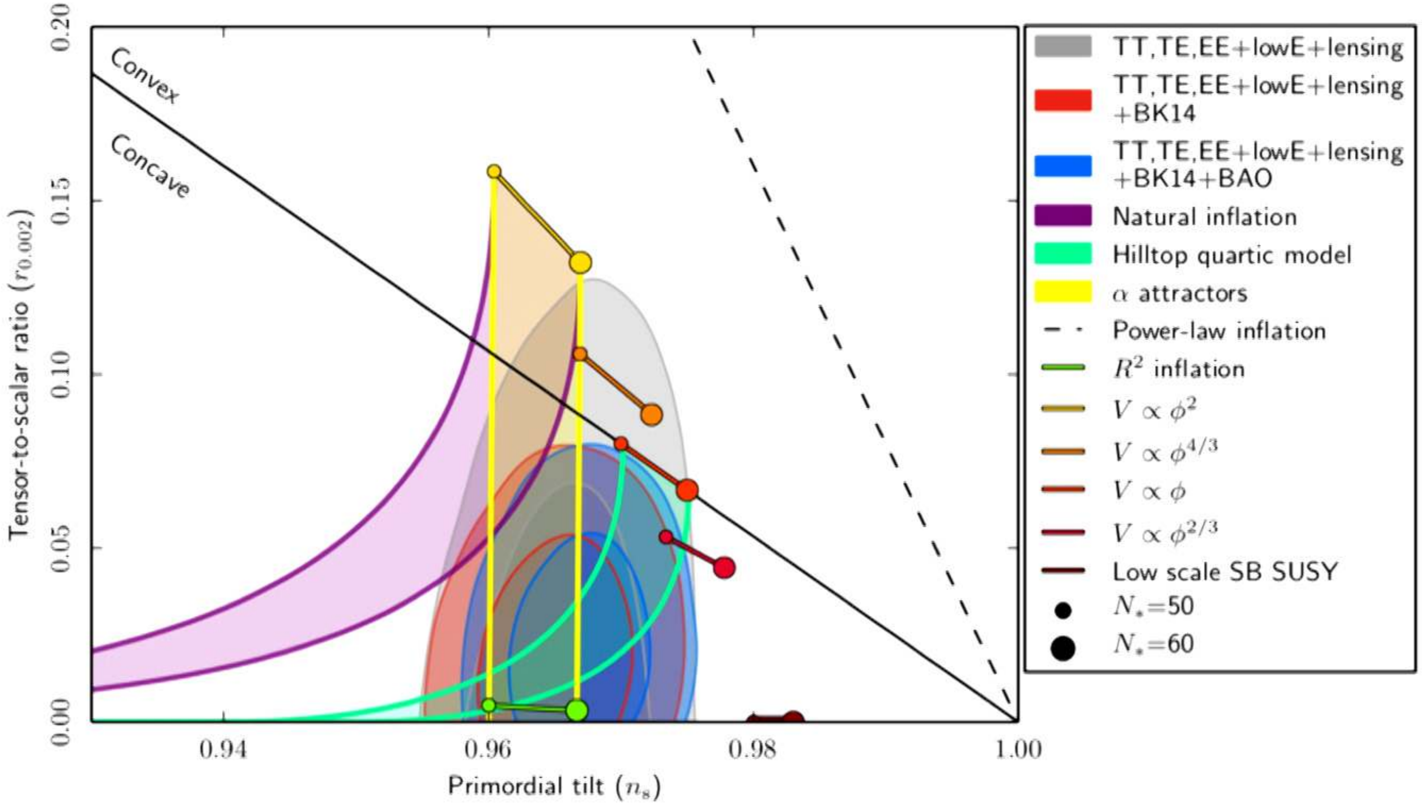


Credit
NSF/LIGO/Sonoma State University/A. Simonne

BICEP Experiment

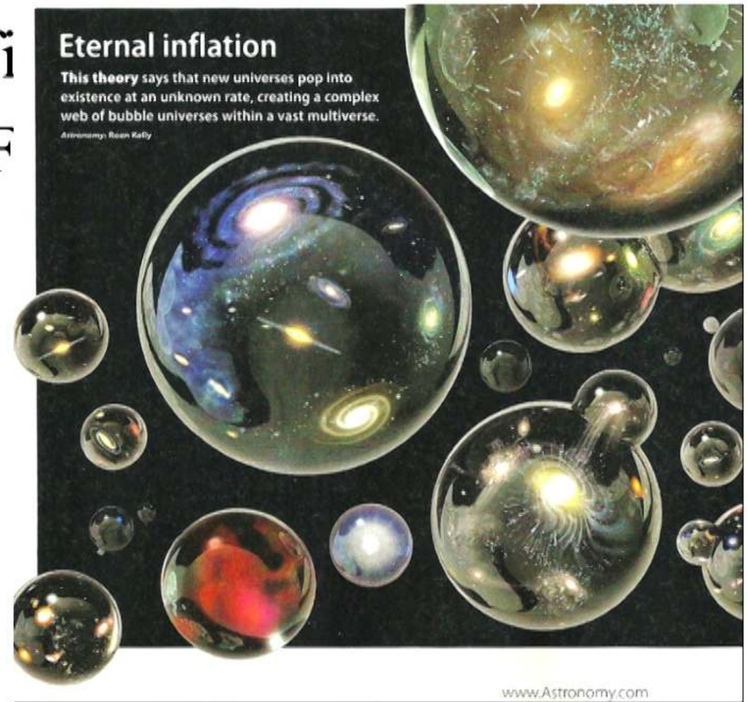


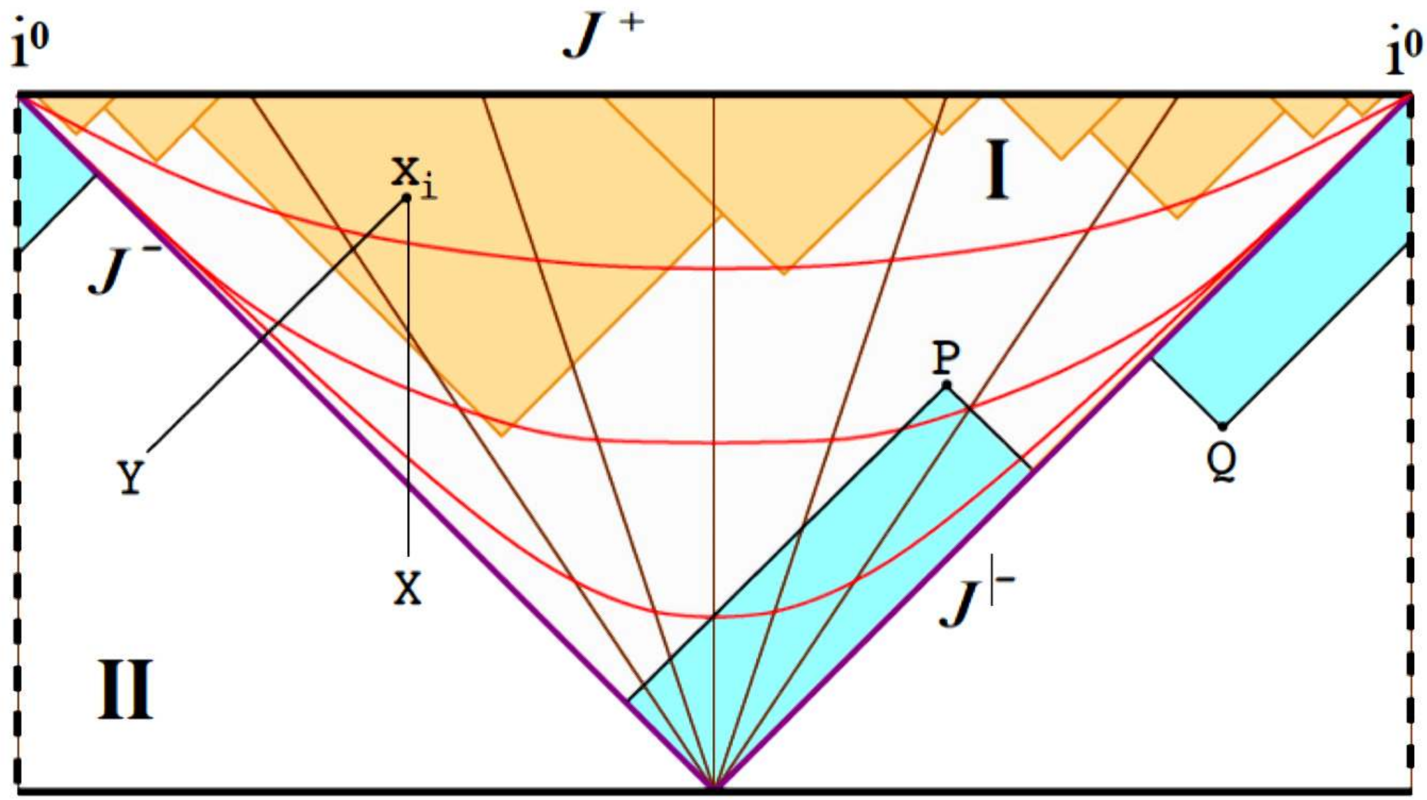
Planck Collaboration: Constraints on Inflation



What then?

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

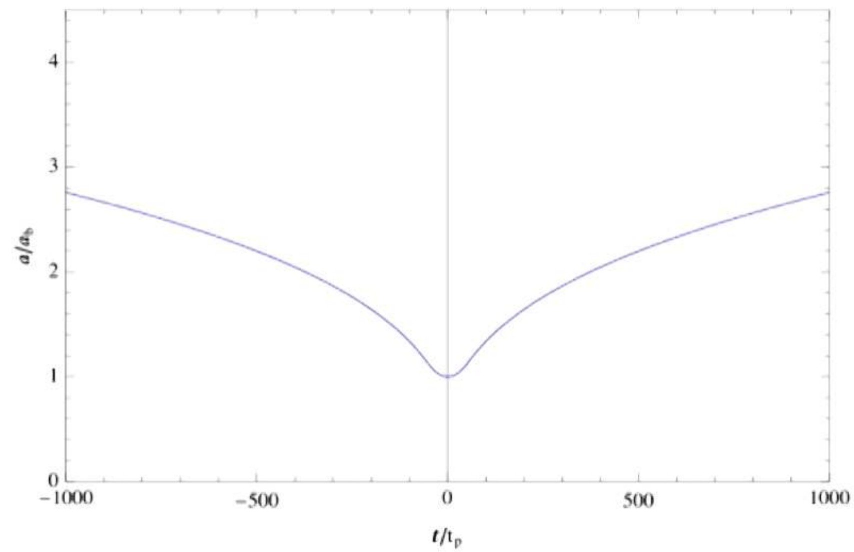


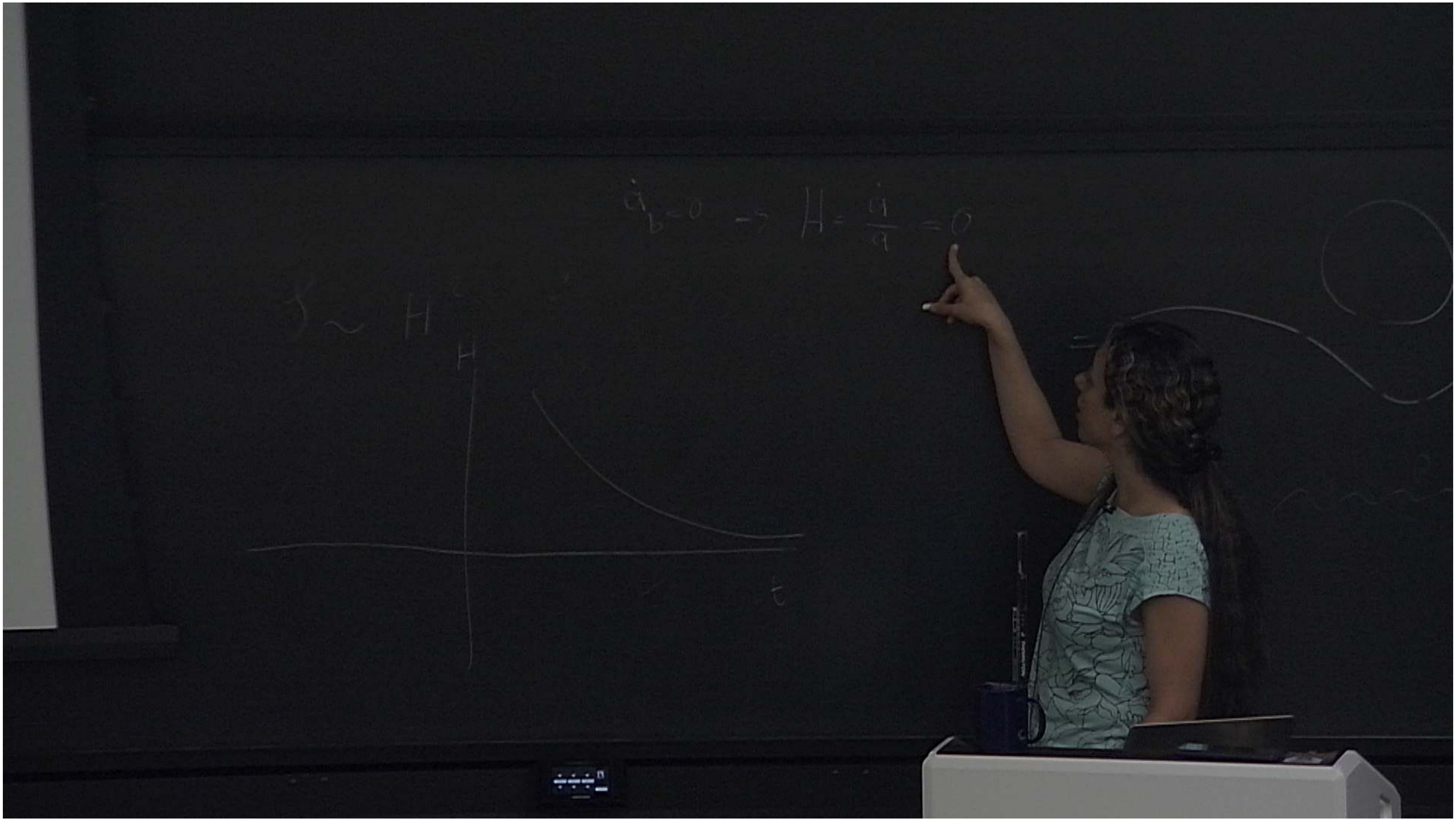


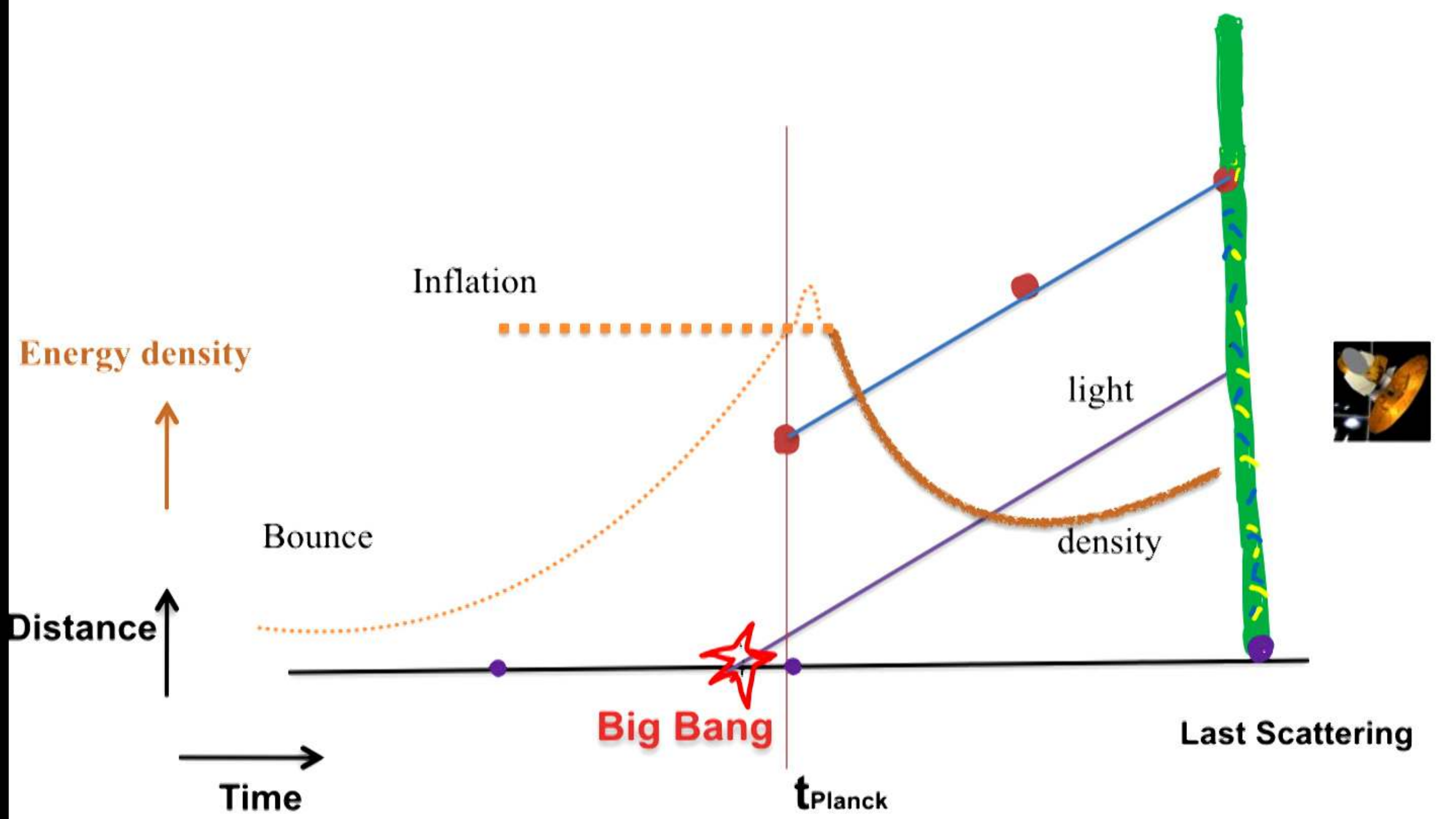
Aguirre & Gratton

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: $c_s = \infty$

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

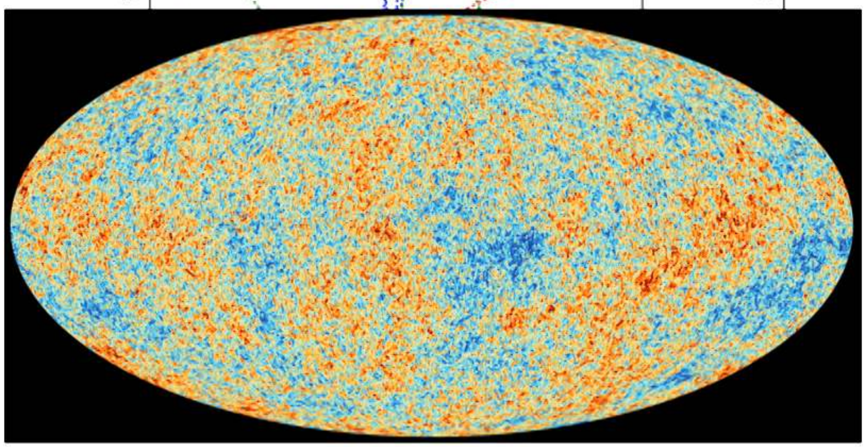
→ **Field equation becomes a constraint equation that uniquely determines Cuscuton as a function of metric**

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

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

Cuscuton Bounce: No Instabilities!

Can it produce anisotropies?



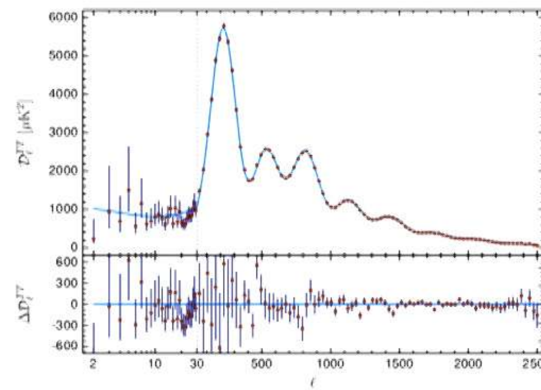


Illustration of NASA's Wide Field Infrared Survey Telescope (WFIRST).
Credits: NASA/GSFC/Conceptual Image Lab