Title: Solid of Inflation: An alternative symmetry breaking pattern for an EFT of inflation

Date: Nov 15, 2012 11:00 AM

URL: http://pirsa.org/13010005

Abstract: In this talk I will discuss a cosmological model where primordial inflation is driven by a `solid', defined as a system of three derivatively coupled scalar fields obeying certain symmetries and spontaneously breaking a certain subgroup of these. The symmetry breaking pattern differs drastically from that of standard inflationary models: time translations are unbroken. This prevents our model from fitting into the standard effective field theory description of adiabatic perturbations. Consequently, it exhibits a novel non-Gaussian `shape'.

Solomon Endlich
Columbia University

Solid Inflation:

An alternative symmetry breaking pattern for an EFT of inflation

w/ Alberto Nicolis and Junpu Wang (hep-th, 1210.0569)

(also Gruzinov: astro-ph/0404548
and Bucher and Spergel: astro-ph/9812022)

EFT of Inflation

- The early universe: homogenous, isotropic, and time dependent
- Inflation driven by $\psi_a = \bar{\psi}_a(t)$
- Time-translations spontaneously broken

⇒ Goldstone boson = adiabatic perturbations

$$\psi_a = \bar{\psi}_a(t + \pi(x)) \simeq \bar{\psi}_a(t) + \partial_t \bar{\psi}_a(t) \cdot \pi(x)$$

- Construct a systematic effective field theory

(Creminelli, Luty, Nicolis, Senatore 2006
Cheung, Creminelli, Fitzpatrick, Kaplan, Senatore 2007)

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Try a different breaking pattern

- x-dependent background solutions:

$$\phi_a = \phi_a(\vec{x})$$

time-translations unbroken,
spacial-translations broken

1) universe is homogenous
and isotropic

?

2) “clock”

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1) universe is homogenous and isotropic ⇨ Internal symmetries

2) "clock" ⇨ Metric

Internal symmetries

- try a single scalar field $\phi = x$
- w/ internal shift symmetry $\phi \to \phi + a$
- unbroken diagonal translation

$$\begin{cases} x \to x - a \\ \phi \to \phi + a \end{cases}$$

⇨ homogeneity

? isotropy need three fields

Internal symmetries, continued

- three scalar fields $\phi^I = x^I$
- internal SO(3) symmetry $\phi^I \to \mathcal{O}^I_J \phi^J$
- unbroken diagonal rotation

$$\begin{cases} x^I \to \left(\mathcal{O}^{-1}\right)^I_J x^J \\ \phi^I \to \mathcal{O}^I_J \phi^J \end{cases}$$

⇒ isotropy describes a solid (jelly)

(Dubovsky, Gregoire, Nicolis, Rattazzi: arXiv:hep-th/0512260)

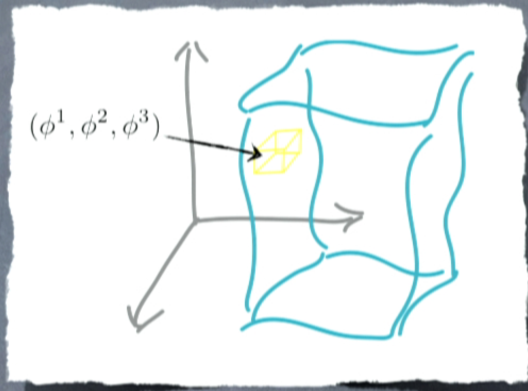
Solid: degrees of freedom

volume elements

$$\vec{x}(\phi^I, t)$$

or

$$\phi^I = \phi^I(\vec{x}, t)$$



Poincare scalars

Perfect fluid

- same dof: $\phi^I, \quad I = 1, 2, 3$
- same symmetries:

$$\phi^I \to \phi^I + a^I, \quad \phi^I \to \mathcal{O}^I_J \phi^J, \quad \text{L.I.}$$

- plus volume preserving diffeomorphism

$$\phi^I \to \xi^I(\phi^J) \qquad \text{with} \qquad \det\left(\frac{\partial \xi^I}{\partial \phi^J}\right) = 1$$

⇒ $\det\left(B^{IJ}\right)$ very symmetric solid

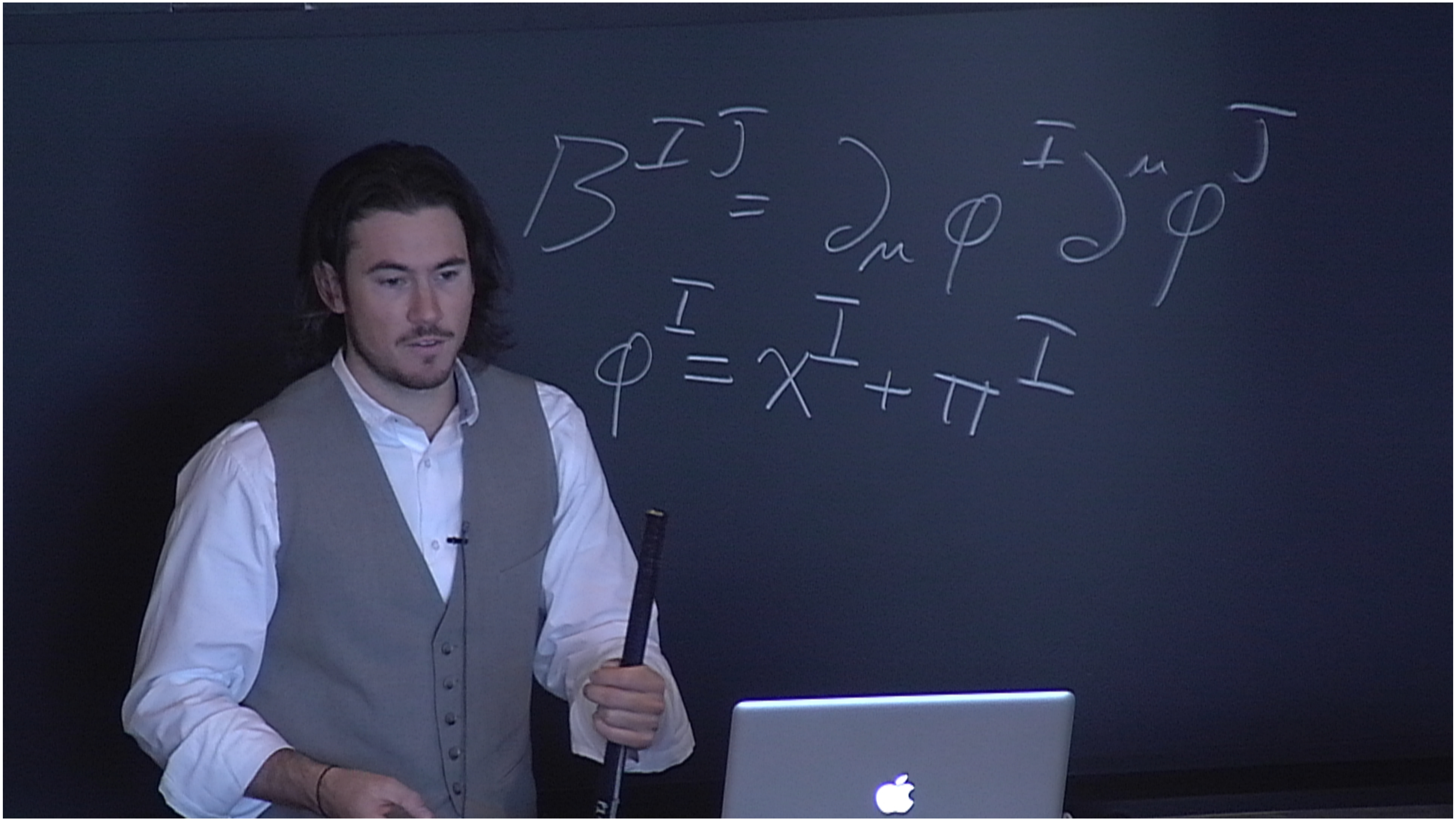
Solid action

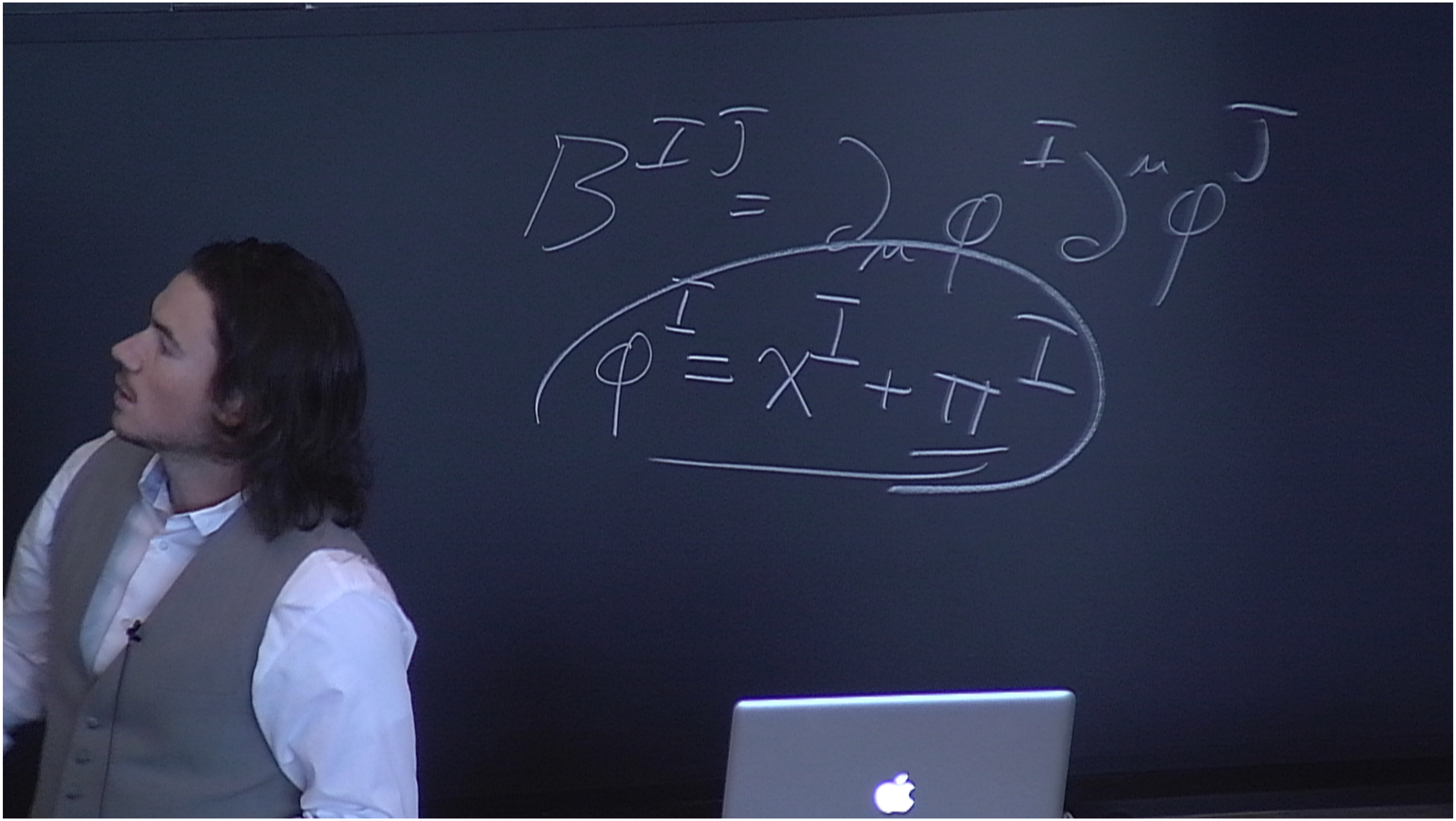
$$S = \int d^4x \, F\left([B], \frac{[B^2]}{[B]^2}, \frac{[B^3]}{[B]^3}\right)$$

$$(X, Y, Z)$$

- couple to gravity

$$B^{IJ} = g^{\mu\nu}\partial_\mu\phi^I\partial_\nu\phi^J \qquad d^4x \to d^4x\sqrt{-g}$$


$B^{IJ} = \partial_\mu \varphi^I \partial^\mu \varphi^J$
$\varphi^I = x^I + \pi^I$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Stress-energy tensor

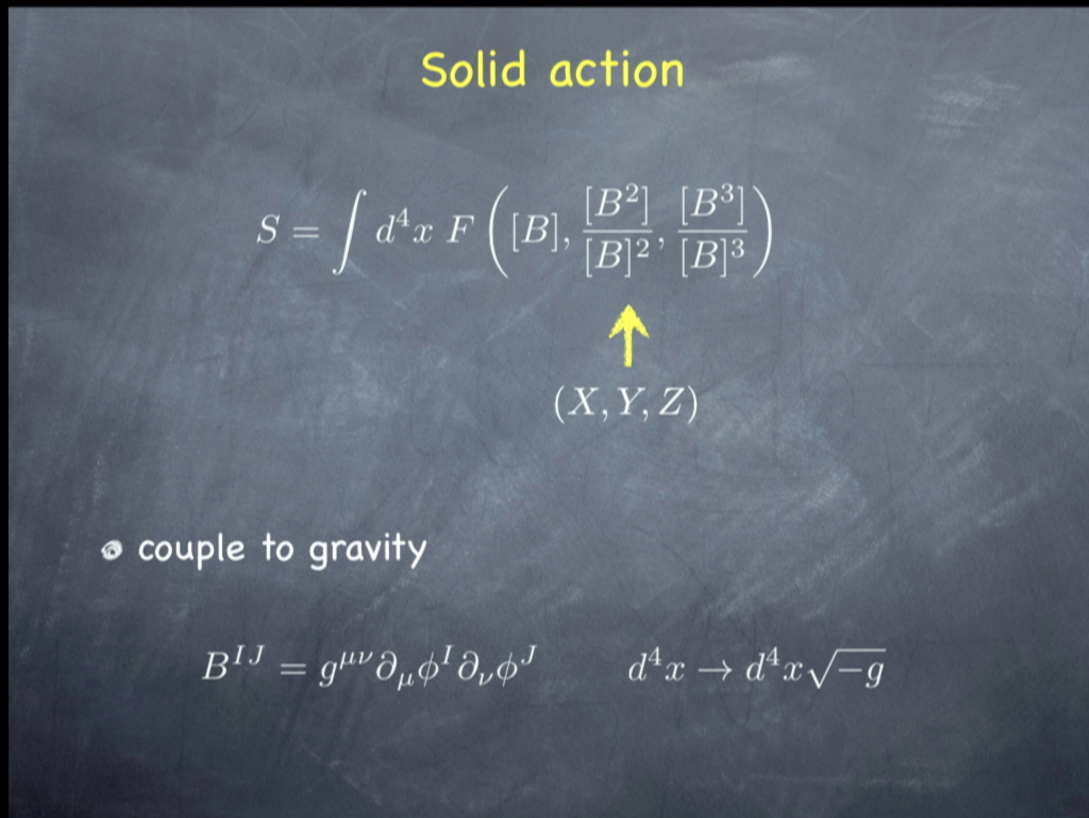
On the background $B^{IJ} = \frac{1}{a(t)^2}\delta^{IJ}$

$$T_{\mu\nu} \to \begin{cases} \rho = -F \\ \rho + p = -\frac{2}{3} F_X X \end{cases}$$

$$H^2 = \frac{1}{3M_{Pl}^2}\rho$$
$$\dot{H} = -\frac{1}{2M_{Pl}}(\rho + p)$$

Slow roll ⇨ $\frac{F_X X}{F} = \epsilon$

⇨ protected by approximate **internal** scale invariance $\phi^I \to \lambda \phi^I$



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(X, Y, Z)
couple to gravity
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Excitations in the solid (sound)

3 Goldstone bosons $\phi^I = x^I + \pi^I$

$$\mathcal{L} \to -\frac{F_X X}{3}\left[\dot{\vec{\pi}}^2 - c_T^2(\partial_i \pi_T^j)^2 - c_L^2(\partial_i \pi_L^i)^2\right] + \text{interactions}$$

$$c_L^2 = 1 + \frac{2}{3}\frac{F_{XX}X^2}{F_X X} + \frac{8}{9}\frac{(F_Y + F_Z)}{F_X X}$$

$$c_T^2 = 1 + \frac{2}{3}\frac{(F_Y + F_Z)}{F_X X}$$

$\text{interactions} \sim f^n \cdot (\partial\pi)^n$

2 possible issues

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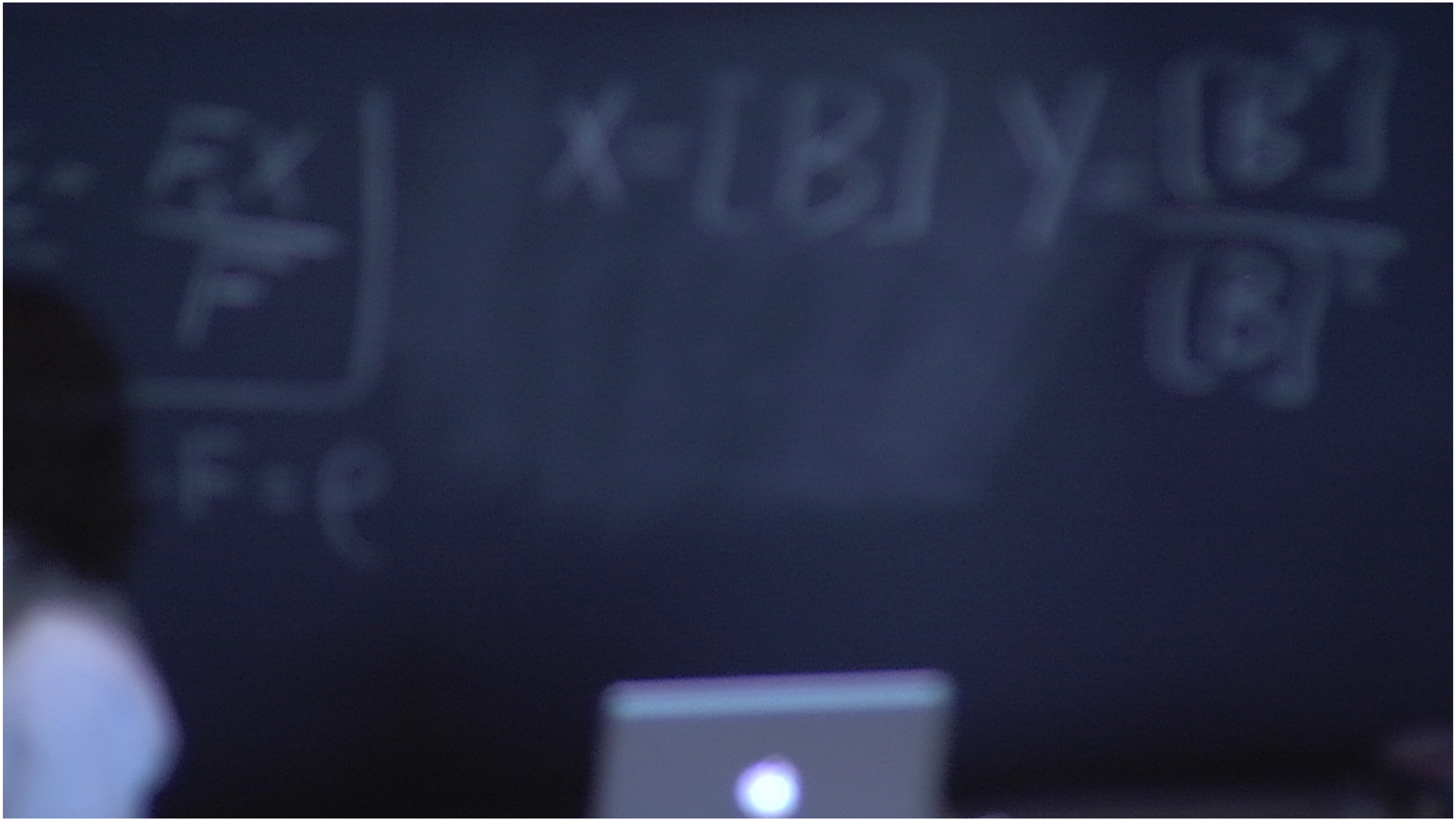
2 possible issues

Superluminality?

impose $\eta = \frac{\dot{\epsilon}}{H\epsilon} \ll 1$

$c_L^2 \simeq \frac{1}{3} + \frac{8}{9}\frac{(F_Y + F_Z)}{F_X X}$ and $c_T^2 \simeq 3/4 \cdot (c_L^2 + 1)$



Strong coupling?

$\Lambda_{strong} \gg H$ $\qquad$ $\mathcal{L} \sim \epsilon |F| \dot{\vec{\pi}}^2 + ...$

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If $F_Y, F_Z \sim F$ and $c_L, c_T \sim 1$

$\Rightarrow$ $\Lambda_{strong} \sim F^{1/4}\epsilon^{3/4} \sim (HM_{Pl})^{1/2}\epsilon^{3/4}$

much larger than H if ϵ is not too small

($\epsilon \cdot c_L^3 \gg (H/M_{Pl})^{2/3}$)

Why not a fluid?

set $c_T = 0$ what goes wrong?

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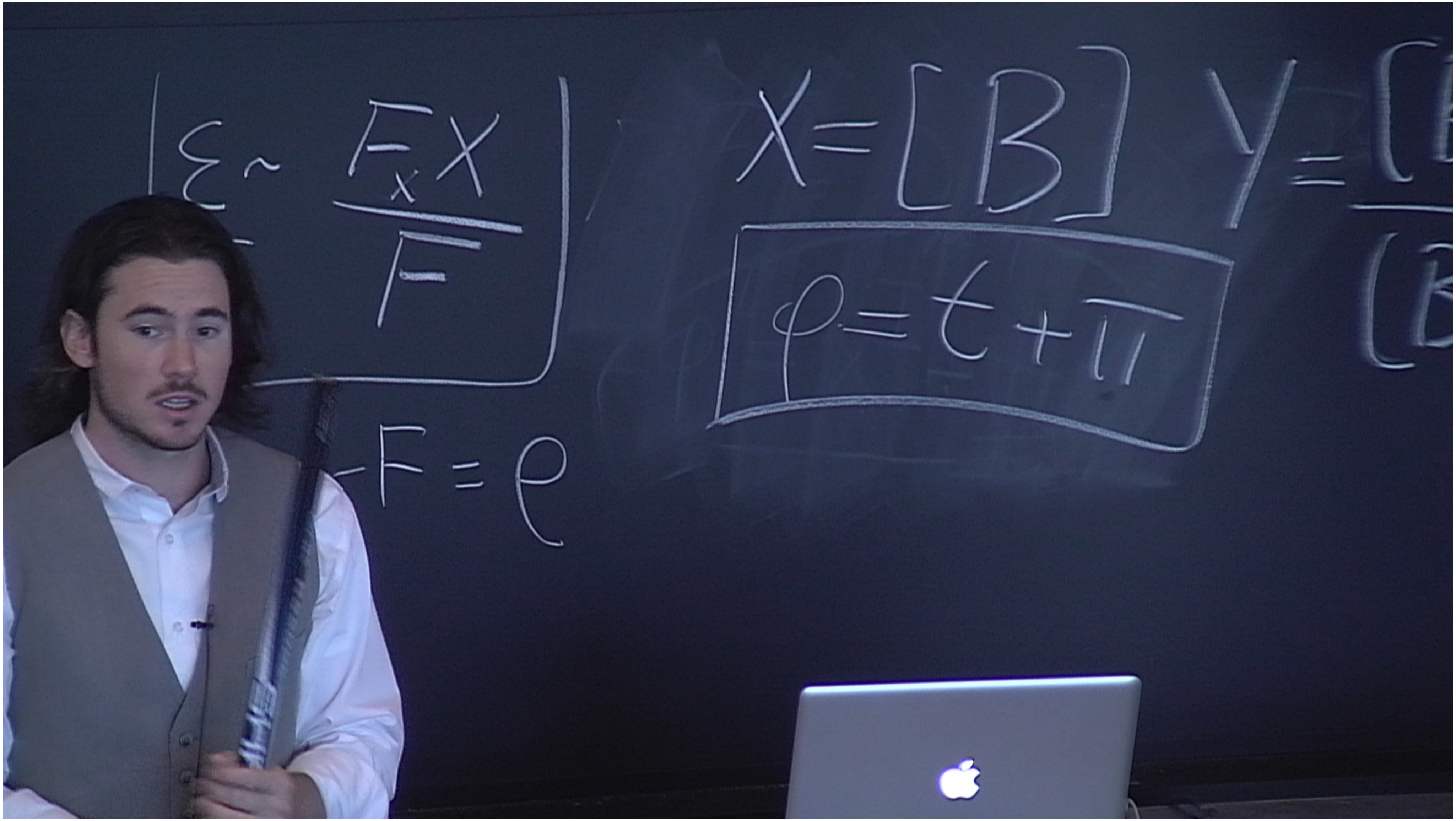
$$\Rightarrow \quad \eta = \frac{\dot{\epsilon}}{H\epsilon} \sim -1 \qquad c_T^2 = \frac{3}{4}\left(1 + c_L^2 - \frac{2}{3}\epsilon + \frac{1}{3}\eta\right)$$


$\varepsilon \sim \frac{F_x X}{F}$
$X = [B]$
$\varphi = t + \pi$
$F = e$

Try a different breaking pattern

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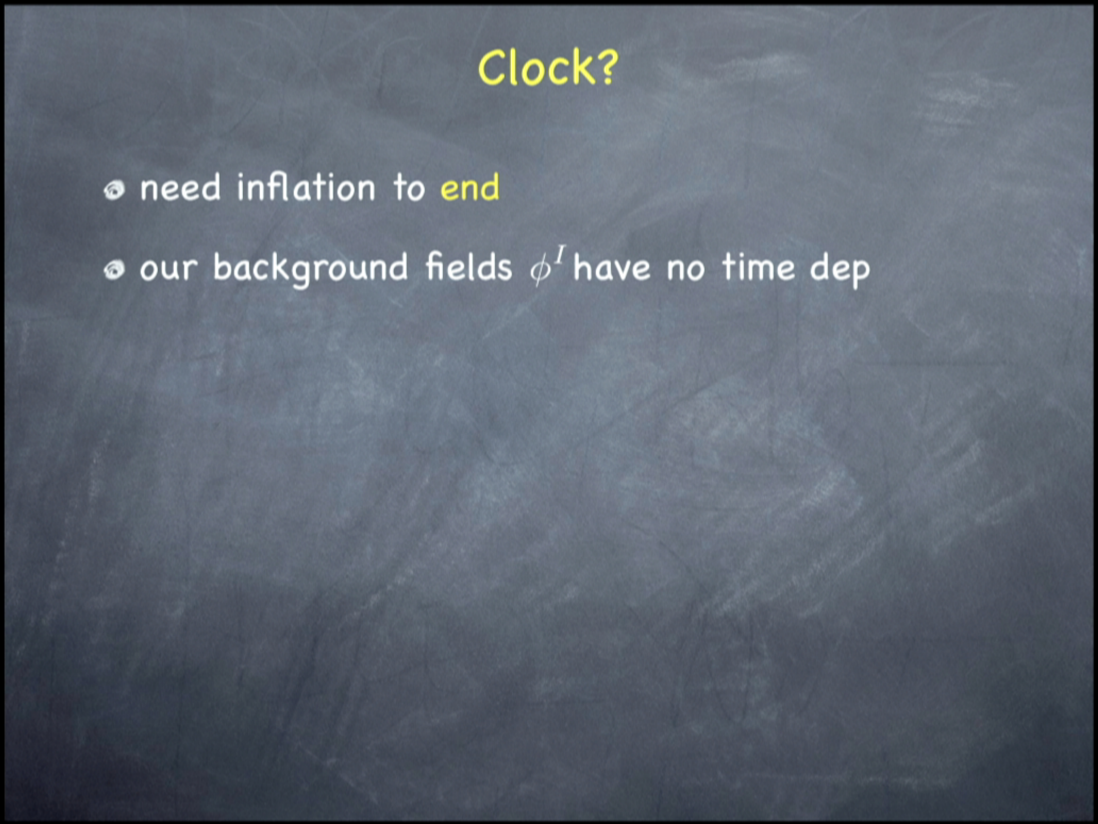
2) "clock" ⇒ Metric


Clock?
need inflation to end
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Clock?

- need inflation to end
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But the metric is time dep

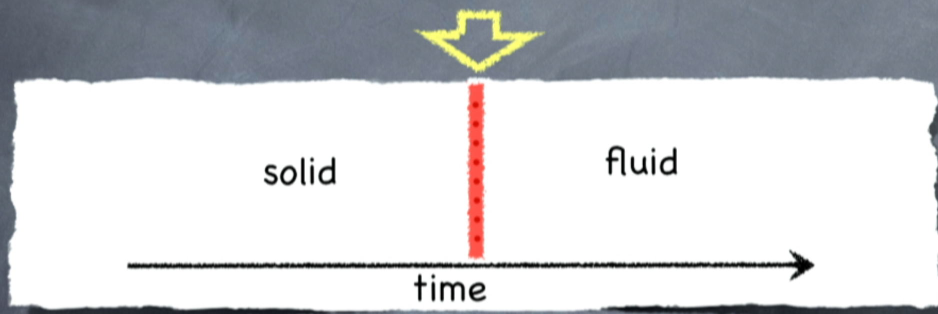
$$\Rightarrow \quad X = g^{\mu\nu}\partial_\mu\phi^I\partial_\nu\phi^I, \quad \rho(t), \quad p(t)$$

Postulate that reheating happens at

$$\det(B^{IJ}) = B_{critical}$$

Reheating

symmetry enhancement



- share the same degrees of freedom
- dof continuous across the boundary
- ΔEOS => equations of motion discontinuous

Postulate
- much faster than a Hubble time

Reheating, continued

ζ vs $\mathcal{R}$

- outside of horizon, no difference (usual story)

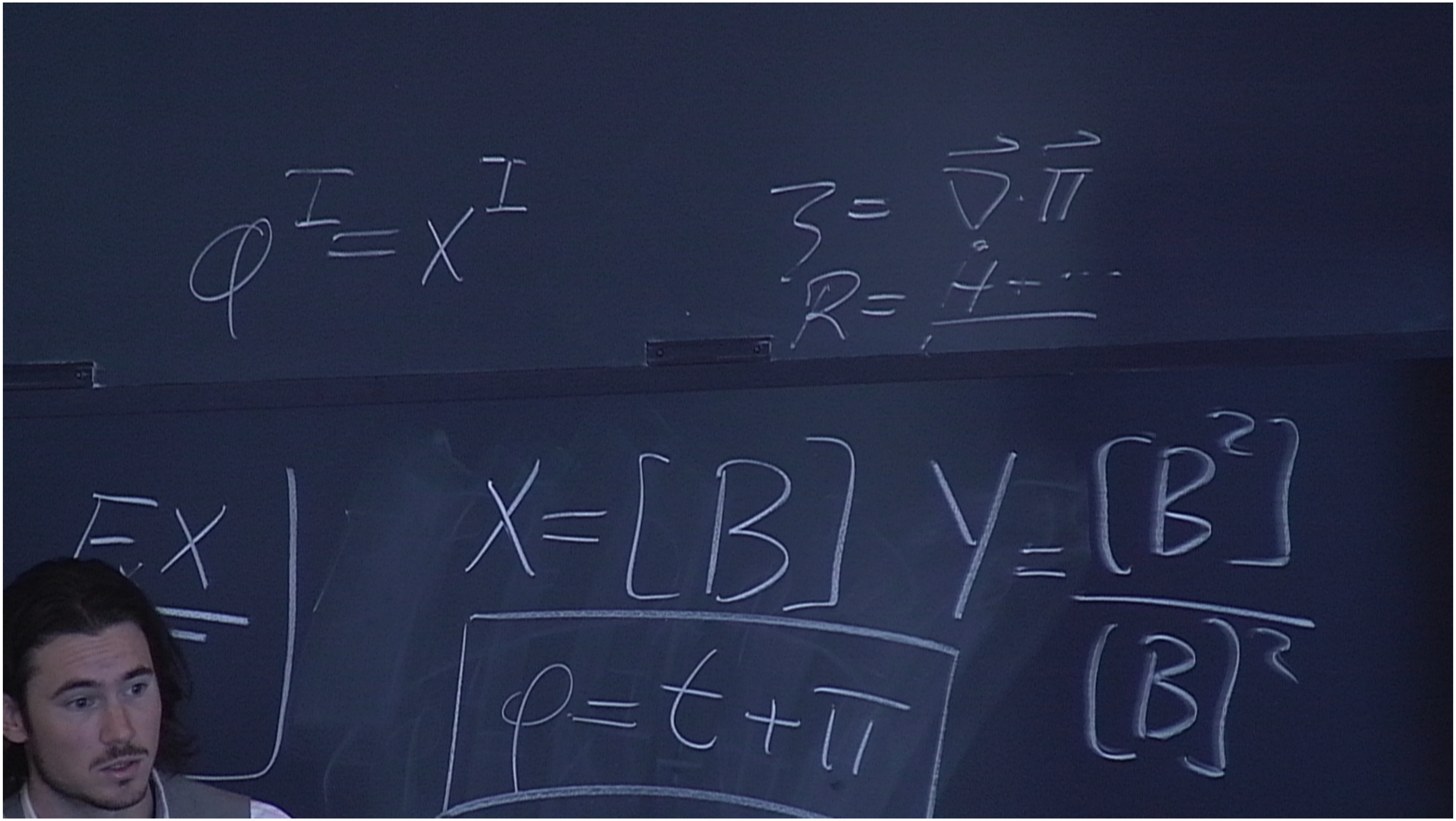
Reheating, continued

ζ vs $\mathcal{R}$

- outside of horizon, no difference (usual story)
- NOT true in our model

$$\mathcal{R} \neq \zeta$$

⇒ $\mathcal{R}$ is discontinuous across the reheating surface


φ^I = X^I
ζ = ∇·π
R =
X = [B]
Y = [B^2] / [B]^2
φ = t + π

Perturbations

work in SFSG:

$$\phi^I = x^I + \pi^I$$

$$g_{ij} = a(t)^2 \exp(\gamma_{ij})$$

$$\zeta = \frac{1}{3}\nabla \cdot \vec{\pi}$$

calculate: 2pt functions $\langle \zeta\zeta \rangle$ $\langle \gamma_{ij}\gamma_{kl} \rangle$

3pt function $\langle \zeta_{k_1}\zeta_{k_2}\zeta_{k_3} \rangle$

Perturbations: 2pt functions

First thing we notice:

$\dot{\zeta} \neq 0, \dot{\gamma} \neq 0$ No Adiabatic Modes!

$$\langle \gamma\gamma \rangle \sim \frac{H^2}{M_{Pl}^2} \cdot (\tau/\tau_c)^{8c_T^2\epsilon/3}$$

$$\langle \zeta\zeta \rangle \sim \frac{H^2}{\epsilon c_L^5 M_{Pl}^2} \cdot (\tau/\tau_c)^{8c_T^2\epsilon/3}$$

- scalar tilt: $n_s - 1 \simeq 2\epsilon c_L^2 - 5s - \eta$
- tensor tilt: $n_T - 1 \simeq 2\epsilon c_L^2 > 0$ blue shifted
- tensor-scalar ratio: $r \sim \epsilon c_L^5$

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Perturbations: 3pt function

Newtonian potential during matter domination $\Phi = \frac{3}{5}\zeta$

$$\langle \Phi\Phi \rangle = (2\pi)^3 \delta^3(k_1 + k_2) \frac{\Delta_\Phi}{k_1^3}$$

Observation:

$\Delta_\Phi \simeq 2 \times 10^{-8}$

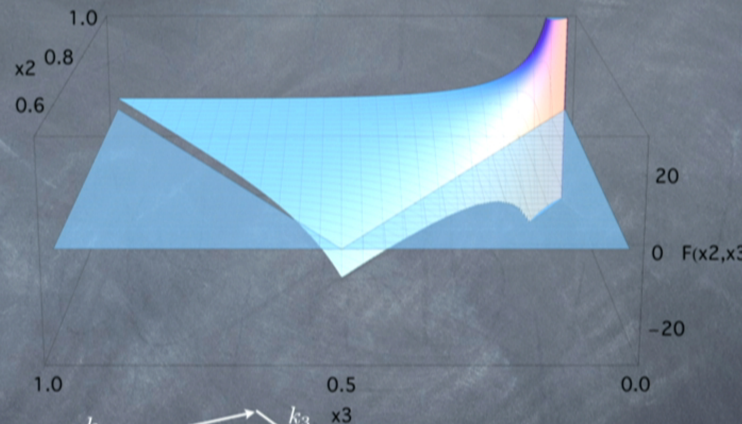
$$\langle \Phi\Phi\Phi \rangle = (2\pi)^3 \delta^3(k_1 + k_2 + k_3) \cdot f(k_1, k_2, k_3)$$

$$f(k, k, k) = f_{NL} \frac{6\Delta_\Phi^2}{k^6}$$

$$f_{NL} \simeq -\frac{F_Y}{F} \cdot \frac{1}{\epsilon c_L^2}$$

potentially huge

3pt function novel shape



squeezed limit

$$f(k_1, k_2, k_3 \to 0) \propto \frac{1 - 3\cos^2\theta}{k_1^3 k_3^3}$$

2% overlap w/ "local" shape
39% w/ "equilateral"
32% w/ "orthogonal"

Highlights

- Novel symmetry breaking pattern (in the context of inflation)
- Single scalar field but no adiabatic modes
- Blue shifted tensor tilt
- (Possibly) Huge non-Gaussianities
- Non-Gaussianities have novel shape which does not overlap much with standard shapes
- Tension between tilt and f_{NL} (both have ϵc_L^2 dependence)

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