Title: Acceleration in our past, present, and future

Date: Mar 20, 2009 11:00 AM

URL: http://pirsa.org/09030038

Abstract: The great advances in observational cosmology in the last few years have delivered us an unprecedented amount of new data. They begin to indicate with confidence that in the past our universe underwent a phase of acceleration, called inflation, and that it is currently undergoing a similar phase, usually thought of as a consequence of a cosmological constant. I will show how inflation can be probed, using to this purpose a very general effective field theory description. In particular, I will concentrate on the new and powerful signal of the non-gaussianity of the primordial density perturbations, explaining its theoretical motivation, the techniques to look for it in the data, and the current constraints from the WMAP experiment. This signature is very important not only to identify the precise mechanism that drove inflation, but also to shed light on possible alternatives, such as the recently proposed bouncing cosmology. I will describe how these alternative theories can be consistently formulated and be predictive, and how similar theories may have interesting implications for the current acceleration of the universe. If inflation happened in our past, it might actually have been eternal. The presence of such a phase offers a new way to address the problem of the cosmological constant and of the current acceleration of the universe. This will lead us to explain in precise terms what eternal inflation is.

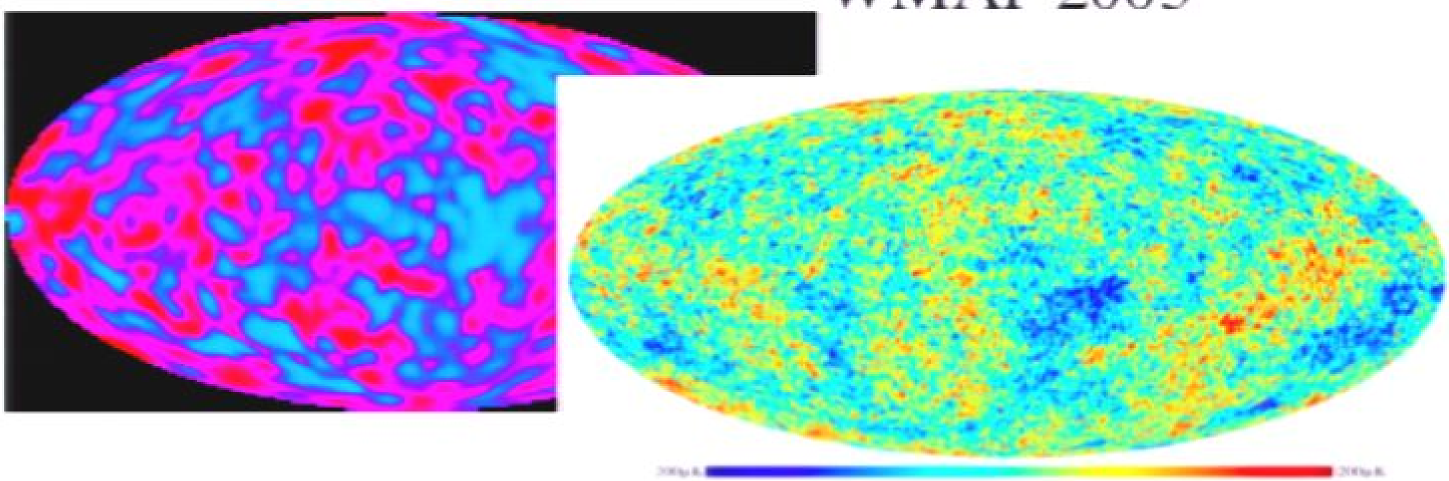
Outline

- Today's Cosmology
- Moving towards two discoveries
  - Inflation: acceleration in our past
  - Dark Energy: acceleration in our present
- Huge Theoretical Implications
  - The CC, the Landscape and Eternal Inflation
  - Probing Inflation
    - Theory: Effective Field Theory description
    - Experiment: non-Gaussianities in WMAP 5yr
    - and its alternatives.
  - What if not a CC...
  - Eternal Inflaton

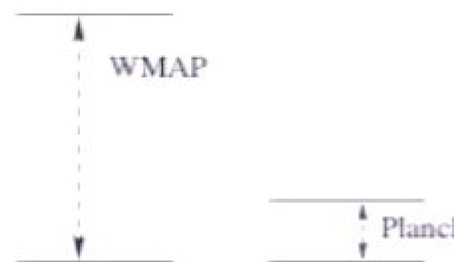
A data driven subject

Cobe 1992

WMAP 2003



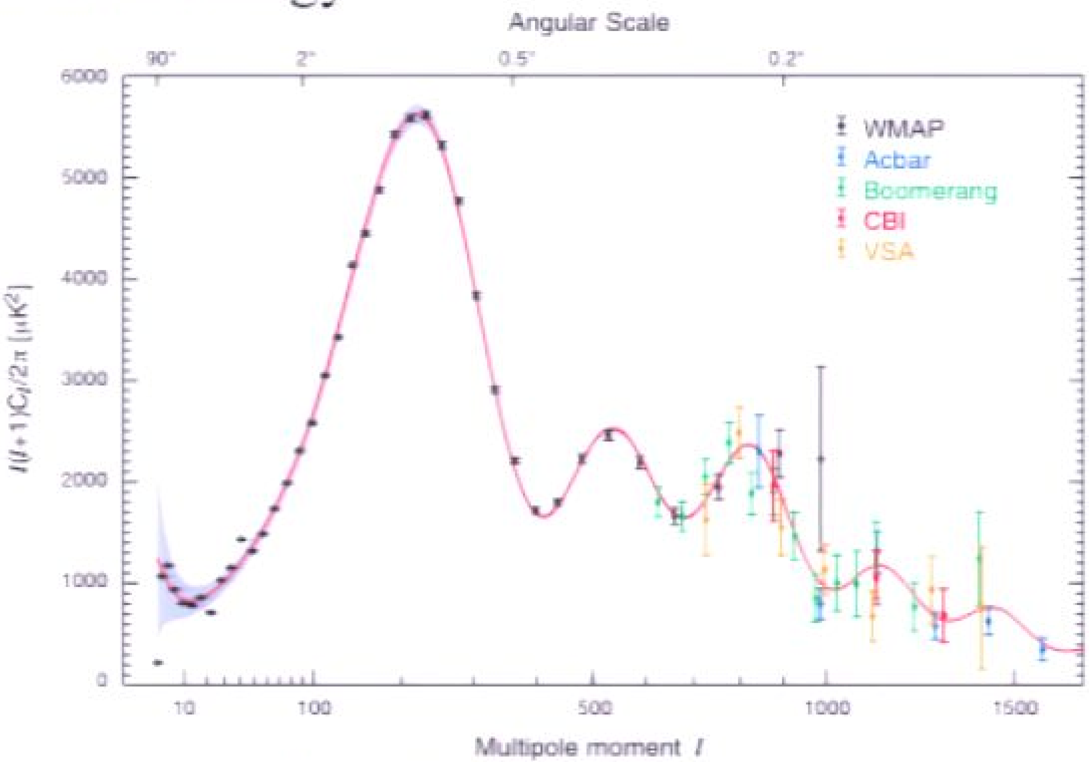
Planck 2010



- Galaxies, Supernovae, ...
- Are we learning something new?

1 and 1/2 important discoveries

- Concordance model: 6 parameters explain all:
  - 5% Baryons
  - 25% Dark Matter
  - 70% Dark Energy



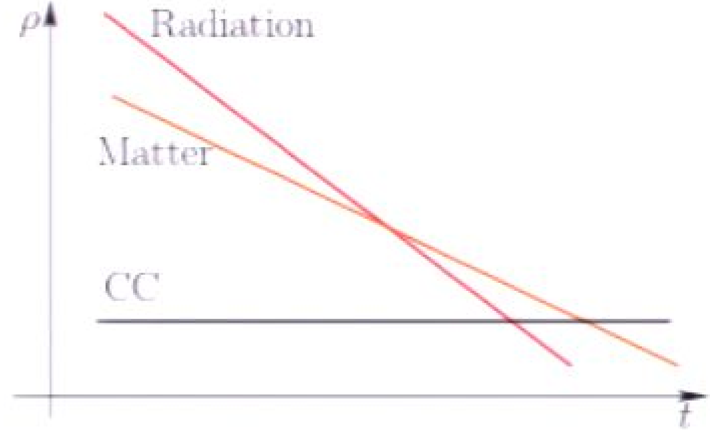
- Dark Energy: acceleration in our present
- Inflation: acceleration in our past

Impact on Theoretical Physics

Something beyond the SM

Weinberg's speculative solution

– We have a CC: S. Weinberg **PRL59:2607, 1987**



Impact on Structure Formation

– If you have many vacua ...

Needs:

- Large CC: OK
- Many Vacua: Landscape of String Theory
- A way to populate them
  - We seem to Inflation in our past, ...
  - We can populate through Eternal Inflation

Arkani-Hamed, Bousso, Dimopoulos, Susskind, Shenker, Kachru, Vilenkin, Hall, Denef, Vafa, Polchinski, Guth, Taylor, Tegmark, Wilczek, Turok, Cachazo ...

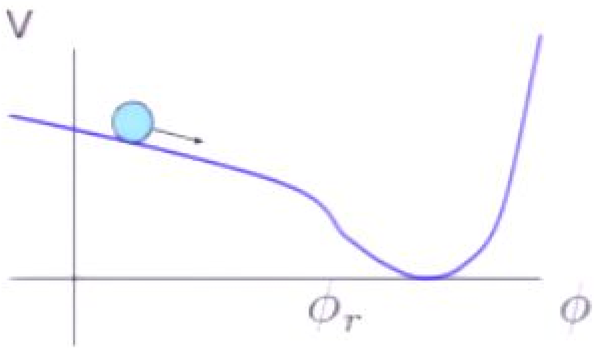
How do we probe Inflation?

How do we probe inflation?

- Simple Models

$$a \sim e^{Ht}$$

$$\dot{\phi} \sim \frac{V'}{H}$$



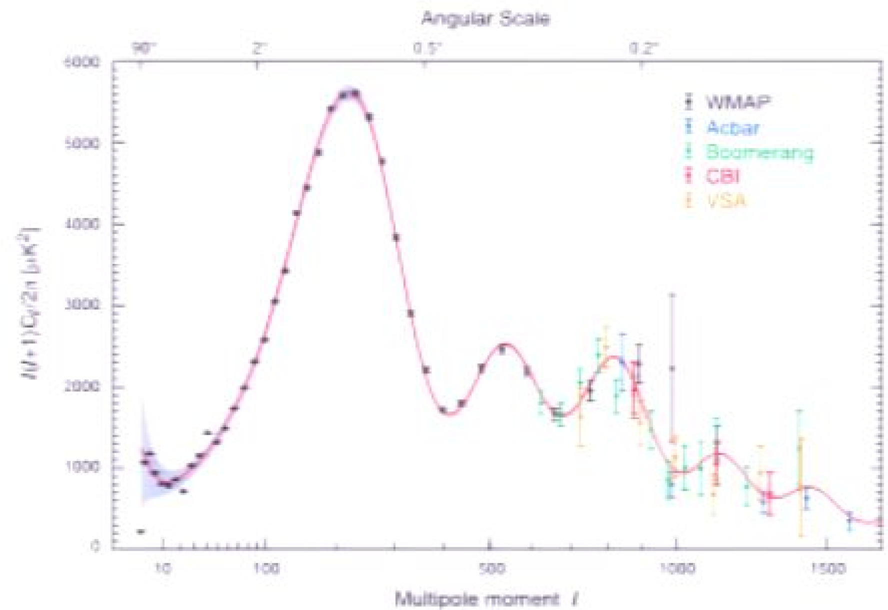
$$\epsilon \simeq \frac{\dot{\phi}^2}{V(\phi)} \ll 1$$

- Standard predictions

$$\zeta \sim \frac{\delta T}{T} \sim \frac{\delta \rho}{\rho}$$

$$\langle \zeta^2 \rangle \sim \frac{1}{\epsilon} \frac{H^2}{M_{\rm Pl}^2}$$

$$\langle \gamma^2 \rangle \sim \frac{H^2}{M_{\rm Pl}^2}$$



- WMAP, Planck, SDSS, ... Now we can look for more!
  - Is it there something more?

Large non-Gaussianities

- Standard slow-roll infl.: very Gaussian

Maldacena, **JHEP 0305:013,2003**

$$\frac{\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \rangle}{\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \rangle^{3/2}} \simeq f_{\rm NL} \langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \rangle^{1/2} \sim 10^{-7} \quad . \qquad f_{\rm NL} \sim 10^{-2}$$

So far undetectable

- DBI inflation

$$\mathcal{L} = \phi^4 \sqrt{1 - \lambda \frac{\dot{\phi}^2}{\phi^4}}$$

Alishahiha, Silverstein and Tong, **Phys.Rev.D70:123505,2004**

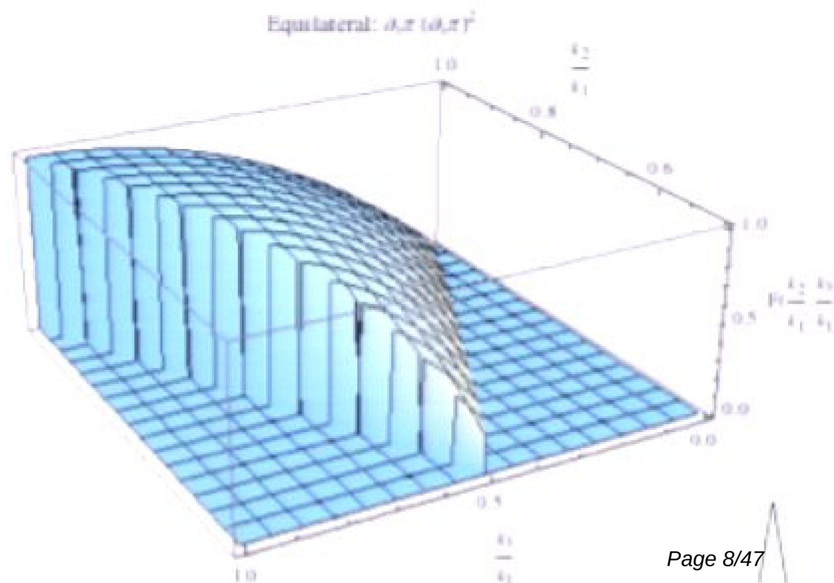
- Large non-Gaussianities

$$f_{\rm NL} \sim 10^2$$

Currently Detectable!

- Shape of non-Gaussianities

$$\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \rangle = (2\pi)^3 \delta^{(3)}(\sum_i \vec{k}_i) F\left(\frac{k_2}{k_1}, \frac{k_3}{k_1}\right)$$

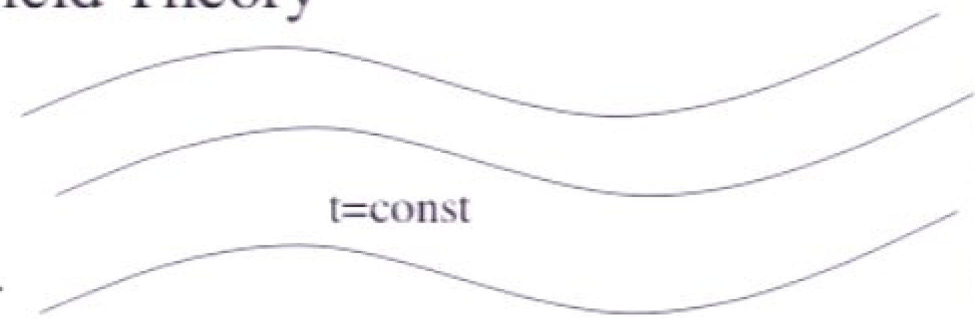


- What are the generic signatures?

What is Inflation?

with C. Cheung, P. Creminelli,
L. Fitzpatrick, J. Kaplan
JHEP 0803:014,2008

The Effective Field Theory



Inflation. Quasi dS phase with a privileged
spacial slicing

Unitary gauge. This slicing coincide with time.

$$\delta\phi(\vec{x},t) = 0 \quad \left(\delta\phi(\vec{x},t) \to \delta\phi(\vec{x},t) - \dot{\phi}(t)\,\delta t(\vec{x},t) \right)$$

Iost generic Lagrangian built by metric operators invariant only under $x^i \to x^i + \xi^i(t,\vec{x})$

Generic functions of time

Upper 0 indices are ok. E.g. g^{00} R^{00}

Geometric objects of the 3d spatial slices: e.g. extrinsic curvature K_{ij} and
ovariant derivatives

$$S = \int d^4x\sqrt{-g}\left[M_{\rm Pl}^2 R + M_{\rm Pl}^2\dot{H}(-1+\delta g^{00}) - M_{\rm Pl}^2(H^2+\dot{H}) + M_2^4(t)(\delta g^{00})^2 + M_3^4(t)(\delta g^{00})^3 \right.$$
$$\left. -\bar{M}_1^3(t)\delta g^{00}\delta K_i^i - \bar{M}_2^2(t)\delta K_i^{i\ 2} + \ldots\right]$$

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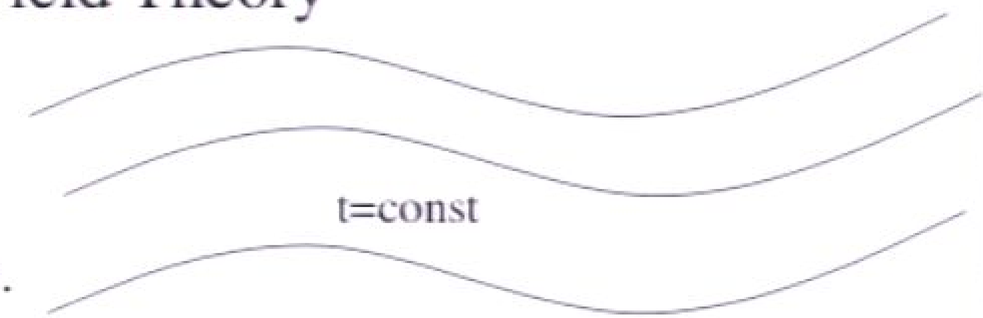

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JHEP 0803:014,2008

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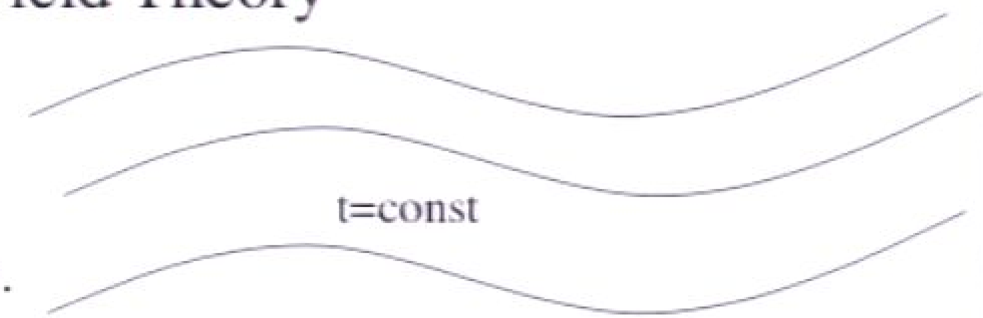

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All single field models are unified

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$$= \int d^4x \sqrt{-g}\Big[M_{\rm Pl}^2 R + M_{\rm Pl}^2 \dot{H}(-1+\delta g^{00}) - M_{\rm Pl}^2(H^2+\dot{H}) + \cancel{M_2^4(t)(\delta g^{00})^2} \cancel{+ M_3^4(t)(\delta g^{00})^3}$$

$$\cancel{-\bar{M}_1^3(t)\delta g^{00}\delta K^i_i - \bar{M}_2^2(t)\delta K^{i\,2}_i} + \ldots\Big]$$

- Slow Roll Inflation: $\int d^4x\,\sqrt{-g}\left[-\frac{1}{2}(\partial\phi)^2 - V(\phi)\right] \to \int d^4x\,\sqrt{-g}\left[-\frac{\dot{\phi}_0(t)^2}{2}g^{00} - V(\phi_0(t))\right]$

All single field models are unified

$$= \int d^4x\sqrt{-g}\,\Big[M_{\rm Pl}^2 R + \cancel{M_{\rm Pl}^2\dot{H}(-1+\delta g^{00})} - M_{\rm Pl}^2(H^2+\cancel{\dot{H}}) + M_2^4(t)(\delta g^{00})^2 + \cancel{M_3^4(t)(\delta g^{00})^3}$$
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- k-inflation, DBI inflation $\mathcal{L} = \phi^4\sqrt{1-\lambda\frac{\dot{\phi}^2}{\phi^4}}$

Alishahiha, Silverstein and Tong,
Phys.Rev.D70:123505,2004

- Ghost Inflation $\underline{\underline{-(\partial\phi)^2}} + \frac{1}{M^4}(\partial\phi)^4 + \ldots$

WRONG SIGN

Arkani-Hamed, Creminelli, Mukohyama and Zaldarriaga,
JCAP 0404:001,2004

Leonardo Senatore
Phys. Rev. D71:043512,2005

- Something else

A simplifying limit

$$S=\int d^4x\sqrt{-g}\left[M_{\rm Pl}^2R+M_{\rm Pl}^2\dot{H}(-1+\delta g^{00})-M_{\rm Pl}^2(H^2+\dot{H})+M_2^4(t)(\delta g^{00})^2+M_3^4(t)(\delta g^{00})^3\right.$$
$$\left.-\bar{M}_1^3(t)\delta g^{00}\delta K_i^i-\bar{M}_2^2(t)\delta K_i^{i\ 2}+\ldots\right]$$

Spontaneously Broken Gauge Symmetry

Reintroduce the Goldstone boson

Reintroducing the Goldstone

At sufficiently high energy the Goldstone mode decouples.

$$S = \int d^4x \; -\frac{1}{4}\mathrm{Tr}\, F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m^2 \mathrm{Tr}\, A_\mu A^\mu \qquad \text{where } A_\mu = A_\mu^a T^a.$$

Gauge transformation:

$$A_\mu \to U A_\mu U^\dagger + \frac{i}{g} U \partial_\mu U^\dagger \equiv \frac{i}{g} U D_\mu U^\dagger \; . \qquad S = \int d^4x \; -\frac{1}{4}\mathrm{Tr}\, F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\frac{m^2}{g^2}\mathrm{Tr} D_\mu U^\dagger D_\mu U \; .$$

Gauge invariance is "restored" introducing the Goldstones:

$$U = \exp\left[iT^a \xi^a(t,\vec{x})\right] \quad \Rightarrow \quad U = \exp\left[iT^a \pi^a(t,\vec{x})\right]$$

Under a gauge trans. Λ we impose: $\quad e^{iT^a\tilde{\pi}^a(t,\vec{x})} = \Lambda(t,\vec{x})\, e^{iT^a\pi^a(t,\vec{x})} \qquad e^{i\tilde{\pi}} = e^{i(\pi+\alpha)}$

Going to canonical normalization: $\quad \pi_c \equiv m/g \cdot \pi \qquad \pi^2(\partial\pi)^2 \quad \Rightarrow$ Cutoff: $\quad 4\pi m/g$

Mixing with transverse component: $\quad \frac{m^2}{g} A_\mu^a \partial^\mu \pi^a = m A_\mu^a \partial^\mu \pi_c^a \qquad$ Irrelevant for $\quad E \gg m$

In the window: $\quad m \ll E \ll 4\pi m/g \qquad$ The physics of the Goldstones is perturbative and decoupled from transverse modes

Doing the same for Inflation

Reintroduce the Goldstone: $g^{00} \to g^{\mu\nu}\partial_\mu\pi\partial_\nu\pi$
Decoupling limit:
At high energy, no mixing with gravity.

Cosmological perturbations probe the theory at E ~ H

$$S_\pi = \int d^4x \sqrt{-g}\left[M_{\rm Pl}^2\dot H(\dot\pi^2 - (\partial_i\pi)^2) + M_2^4\left(\dot\pi^2 + \dot\pi^3 - \dot\pi(\partial_i\pi)^2\right) - M_3^4\dot\pi^3 + \dots\right]$$

- All single field models are unified (Ghost Inflation, DBI inflation, ...); prove theorems on signal.

- The systematic way of parametrizing high energy effects on inflation. Experiments set limits on these operators (NG, GWs,...).

- What is forced by symmetries and large signatures are explicit:
  - The spatial kinetic term: pathologies for : $\dot H > 0$, ... not always ...

with Creminelli, Luty and Nicolis
JHEP 0612:080,2006

  - Connection between c_s and Non-Gaussianities: $\dot\pi^2 - c_s^2(\partial_i\pi)^2$, $\dfrac{1}{c_s^2} = 1 - \dfrac{M_2^4}{M_{\rm Pl}^2\dot H}$

  non-local NG: $f_{\rm NL}^{\rm non-loc.} \sim \dfrac{1}{c_s^2}$

(see also Chen, Huang, Kachru and Shiu **JCAP 0701:002,2007**)

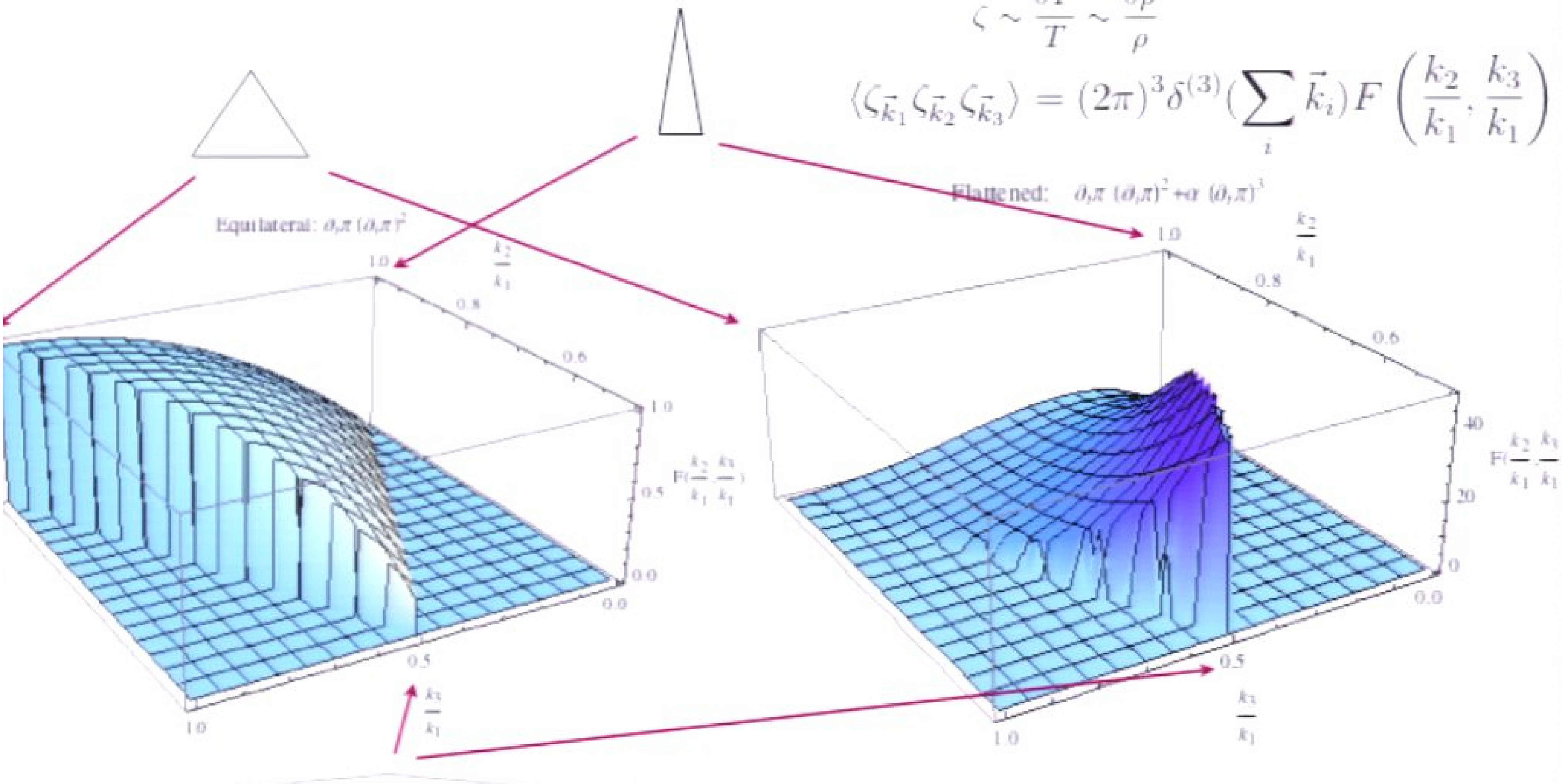
- The number of relevant operators is explicit. Large non-Gaussianities!: $\dot\pi(\nabla\pi)^2$ and $\dot\pi^3$

Large non-Gaussianites

with Smith and Zaldarriaga.
in progress

$$\zeta \sim \frac{\delta T}{T} \sim \frac{\delta\rho}{\rho}$$

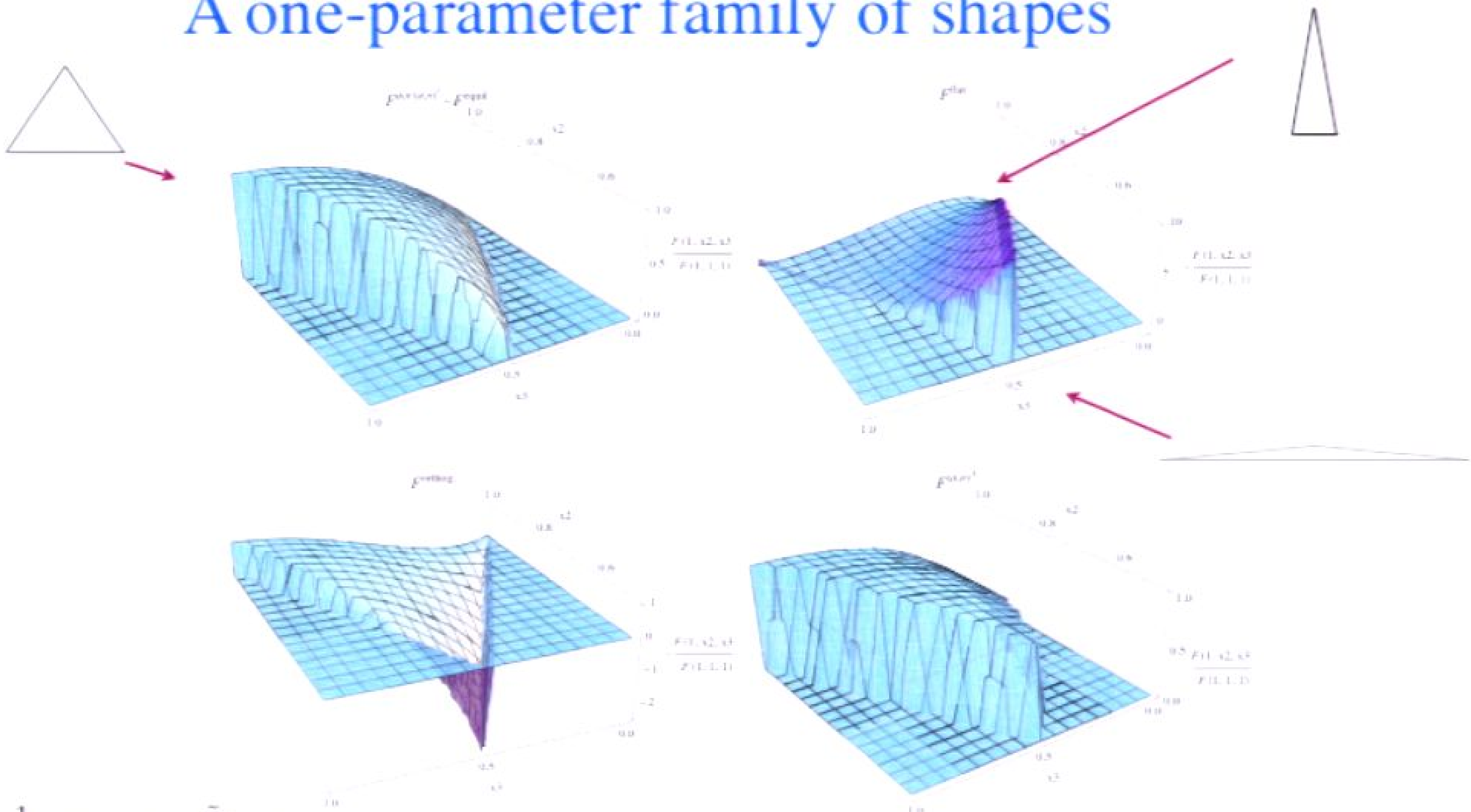
$$\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \rangle = (2\pi)^3 \delta^{(3)}\left(\sum_i \vec{k}_i\right) F\left(\frac{k_2}{k_1}, \frac{k_3}{k_1}\right)$$



$$\frac{1}{c_s^2}\dot{\pi}(\partial_i\pi)^2 + \frac{\tilde{c}_3}{c_s^2}\dot{\pi}^3$$

A function of two variables: we are measuring the interactions!
(and the coefficient of the Lagrangian!)

A one-parameter family of shapes



$$\frac{1}{c_s^2}\dot{\pi}(\partial_i\pi)^2 + \frac{\bar{c}_3}{c_s^2}\dot{\pi}^3$$

- Single field consistency condition:

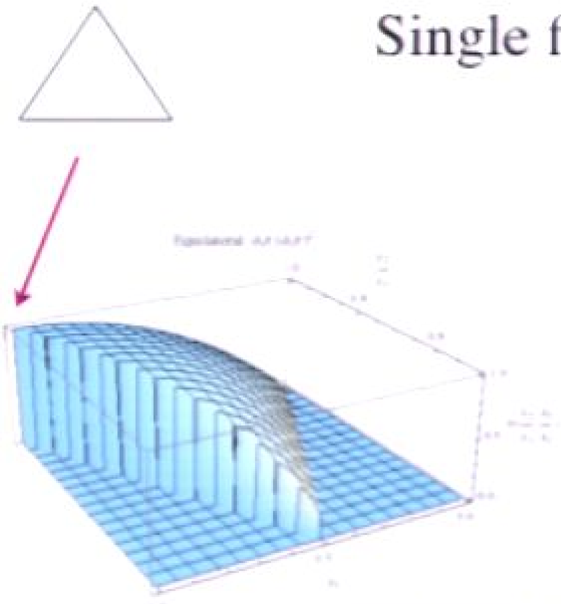
$$\lim_{k_1\to 0}\langle\zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\zeta_{\vec{k}_3}\rangle = -(2\pi)^3\delta^3\left(\sum\vec{k}_i\right)\overline{\langle\zeta_{\vec{k}_1}\zeta_{\vec{k}_1}\rangle}\ \overline{\langle\zeta_{\vec{k}_2}\zeta_{\vec{k}_2}\rangle}(n_s-1) \quad\Rightarrow\quad f_{\rm NL}\sim 10^{-2}$$

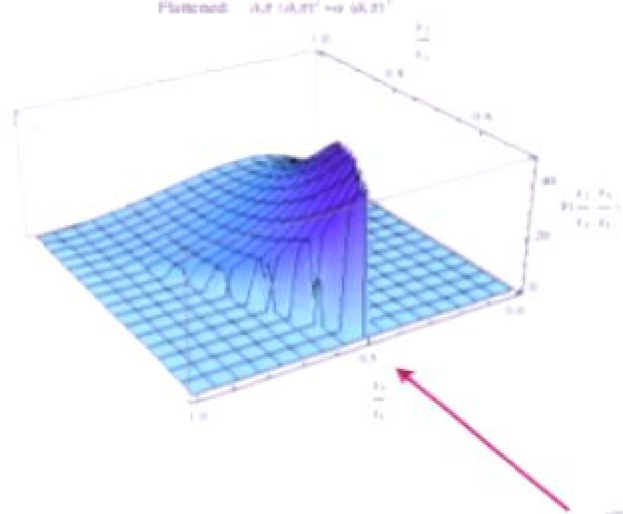
J. Maldacena, **JHEP 0305:013,2003**.

P. Creminelli, M. Zaldarriaga, **JCAP 0410:006, 2004**.

Shape of NG

Single field



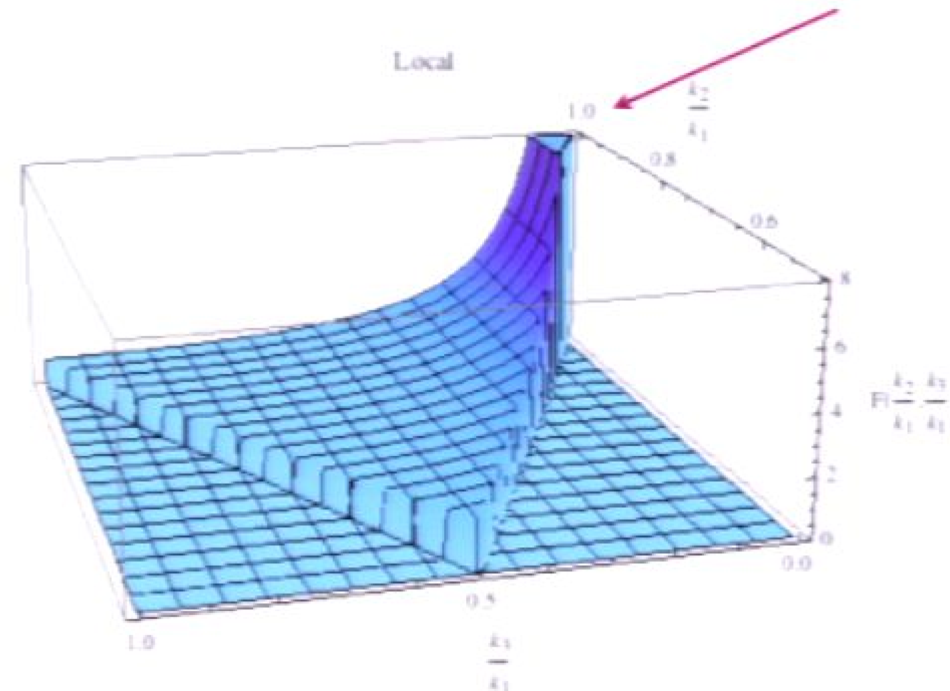


Multi field

Dvali, Gruzinov and Zaldarriaga **Phys.Rev.D69:023505,2004**

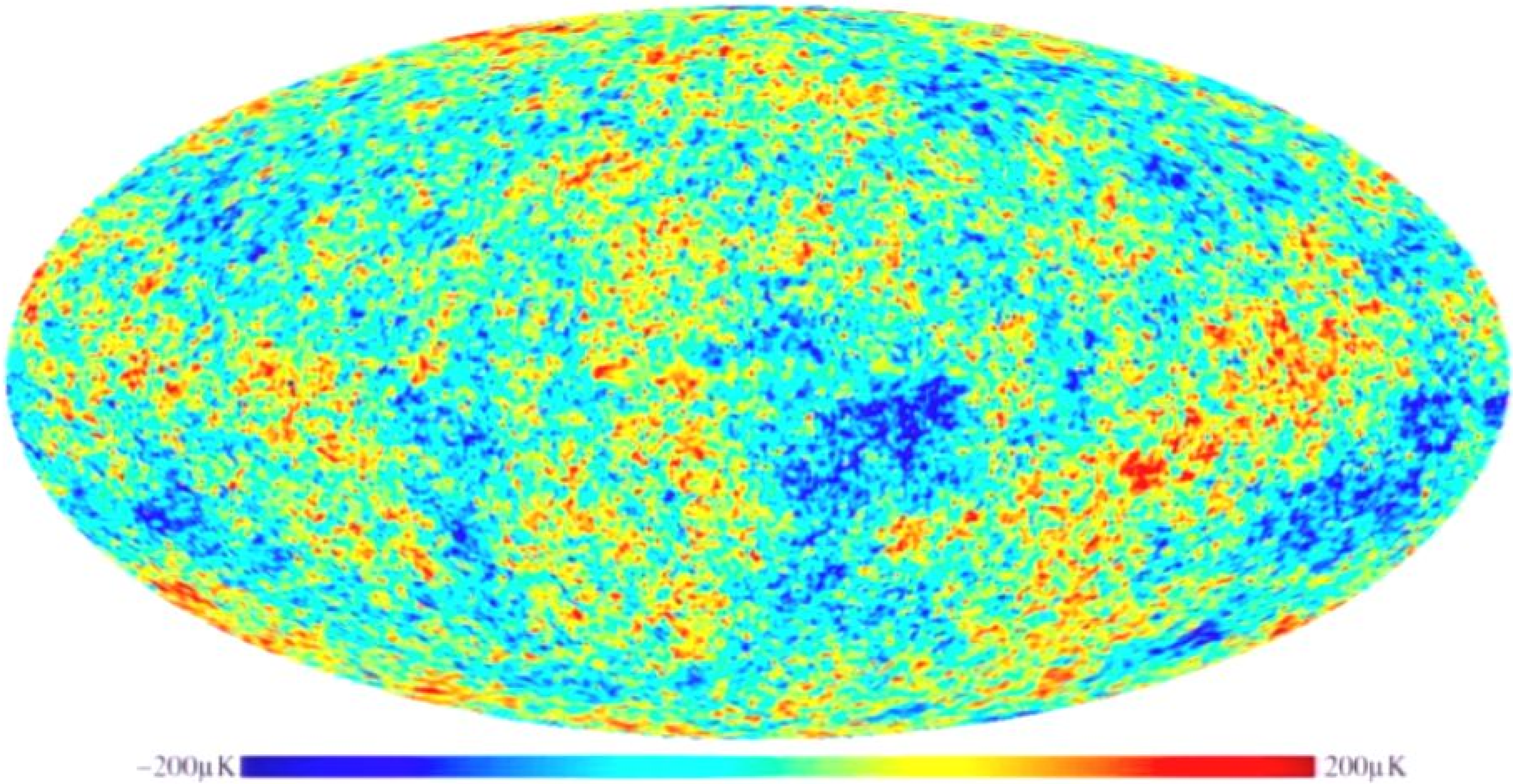
with Creminelli **JCAP 0711:010,2007**

$$\zeta(x) = \zeta_g(x) + f_{\rm NL}^{\rm loc.}\zeta_g(x)^2$$



- Theoretically motivated
- Wealth of information: 3 shapes $\Rightarrow$ interactions
- They need to be analyzed in the data

Is there some non-Gaussianity now?
We are ready!



Claimed $2.9\,\sigma$ detection of $f_{\rm NL}^{\rm loc.}$ Yadav and Wandelt **PRL100:181301,2008**

Analysis of the WMAP data

With Creminelli, Nicolis, Tegmark and Zaldarriaga, **JCAP 0605:004,2006**

With Smith and Zaldarriaga, **0901.2572** [astro-ph]
and in progress

$$\frac{\Delta T}{T}(\theta,\phi) = \sum_{lm} a_{lm} Y_{lm}(\theta,\phi) \qquad C_{l_1 m_1, l_2, m_2} = \langle a_{l_1 m_1} a_{l_2 m_2} \rangle$$

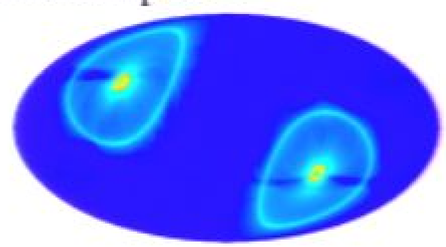
$$\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle = (2\pi)^3 \delta^{(3)}(\sum_i \vec{k}_i) F(k_1, k_2, k_3) \;\Rightarrow\; \langle a_{l_1 m_1} a_{l_2 m_2} a_{l_3 m_3} \rangle$$

Minimum variance estimator for three shapes:

$$\mathcal{E}_{\rm lin}(a) = \frac{1}{N} \sum_{l_i m_i} \Big(\langle a_{l_1 m_1} a_{l_2 m_2} a_{l_3 m_3} \rangle_1 \; C^{-1}_{l_1 m_1, l_4 m_4} C^{-1}_{l_2 m_2, l_5 m_5} C^{-1}_{l_3 m_3, l_6 m_6} a_{l_4 m_4} a_{l_5 m_5} a_{l_6 m_6}$$

CMB signal diagonal in Fourier space (without NG!!). Foreground and noise in real space.

Non-diagonal error matrix + linear term in the estimator



It saturates Cramers-Rao bound. With Creminelli and Zaldarriaga
Nothing else is necessary **JCAP 0703:019,2007**

Reduces variance wrt WMAP coll. analysis (~ 60%), generalize to the other two shapes, foreground marginalization.

Technique progressively adopted by the WMAP collaboration: linear term, shapes, inverse matrix.

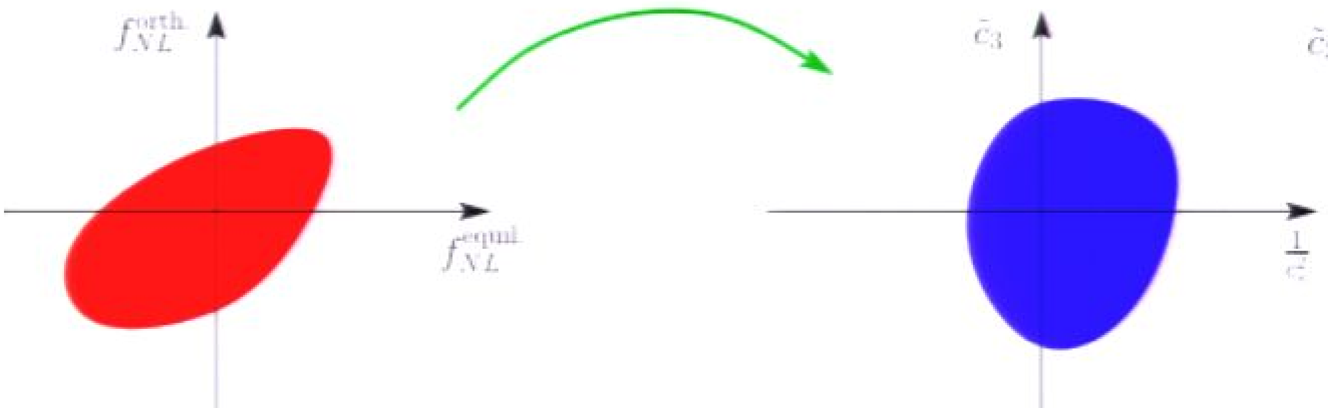
Limits on the parameters of the Lagrangian

$$F^{\text{singl. field}}(k_1,k_2,k_3,c_s,\tilde{c}_3) = f_{NL}^{\text{equil.}} F^{\text{equil.}}(k_1,k_2,k_3) + f_{NL}^{\text{orthog.}} F^{\text{orthog.}}(k_1,k_2,k_3)$$

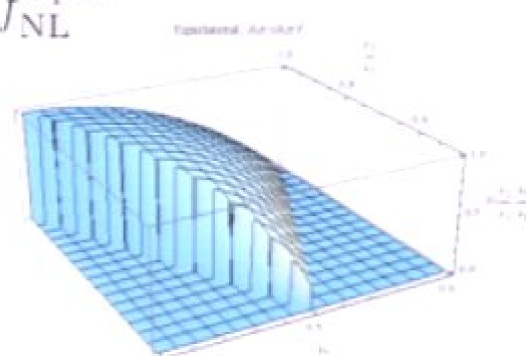
- Limits on f_{NL}'s get translated into limits on the parameters c_s and $\tilde{c}_3$:

$$\frac{1}{c_s^2} \simeq -1.05\, f_{NL}^{\text{equil.}} - 6.59\, f_{NL}^{\text{orthog.}}\ ,$$

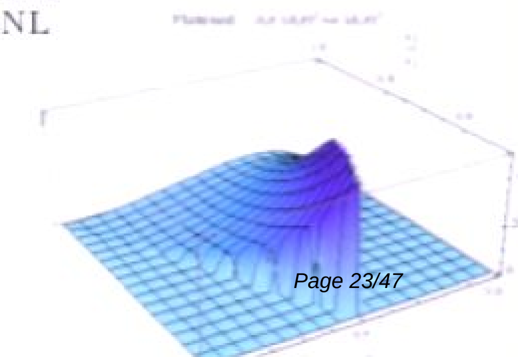
$$\tilde{c}_3 \simeq -5.48 + \frac{0.658\, f_{NL}^{\text{equil.}}}{0.160\, f_{NL}^{\text{equil.}} + f_{NL}^{\text{orthog.}}}$$



$f_{\rm NL}^{\rm equil.}$



$f_{\rm NL}^{\rm flat}$



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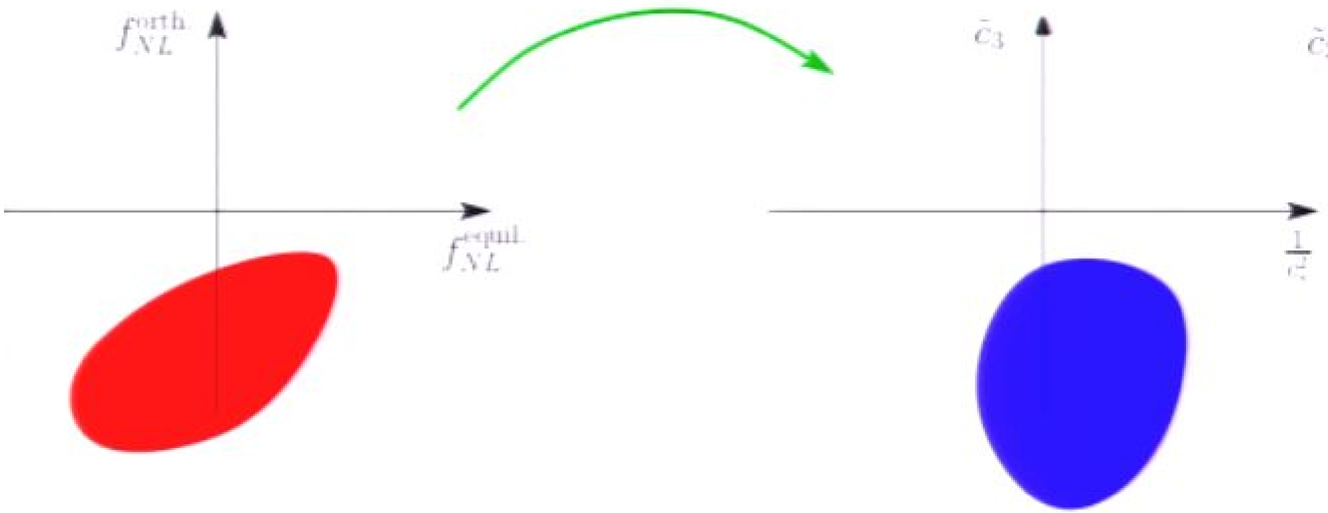
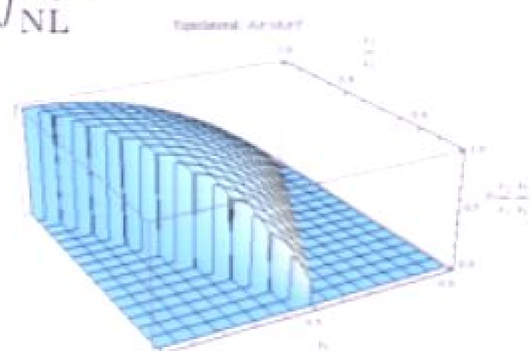
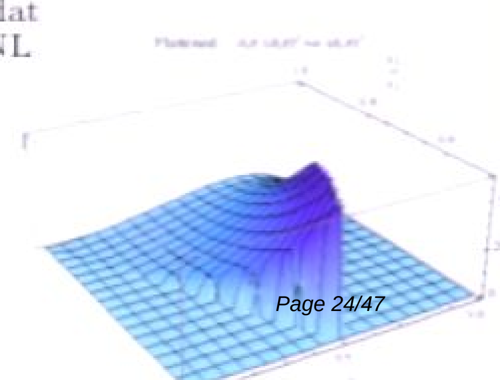


$f_{\text{NL}}^{\text{equil.}}$



$f_{\text{NL}}^{\text{flat}}$



⍨ ~No detection ⍨

With Smith and Zaldarriaga.
0901.2572 [astro-ph]
in progress

Optimal analysis of WMAP data (foreground template corrections) are ~ compatible with Gaussianity

We have the best limits on NG

$$-4 < f_{NL}^{\text{local}} < 80 \quad \text{at } 95\% \text{ C.L.}$$

$$(-1 < f_{NL}^{\text{local}} < 63 \quad \text{at } 95\% \text{ C.L.})$$

after combining with LSS
Slosar *et al*. **JCAP 0808:031, 2008**

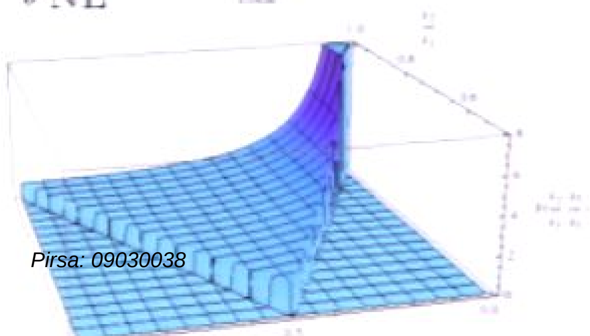
- 7% prob. gaussian signal gives larger
- We do not agree with the $2.9\,\sigma$ detection (!) of Wandelt and Yadav **PRL 100: 181301, 2008**

$$-125 < f_{NL}^{\text{equil.}} < 435 \quad \text{at } 95\% \text{ C.L.}$$

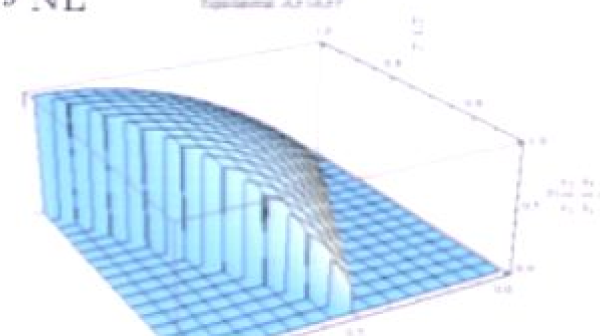
$$-369 < f_{NL}^{\text{orthog.}} < 71 \quad \text{at } 95\% \text{ C.L.}$$

Preliminary

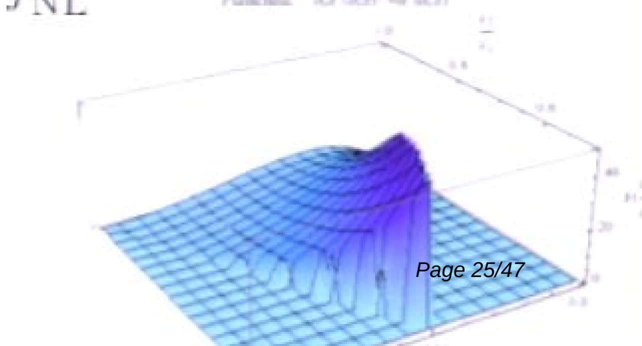
$f_{NL}^{\text{loc.}}$



$f_{NL}^{\text{equil.}}$



f_{NL}^{flat}

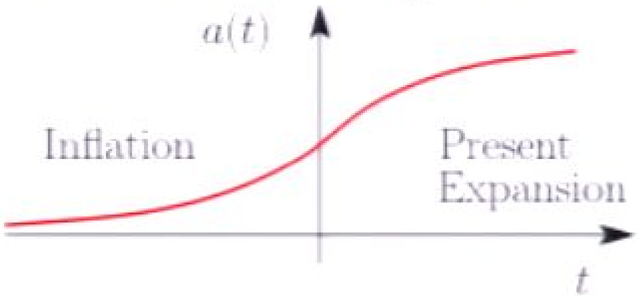


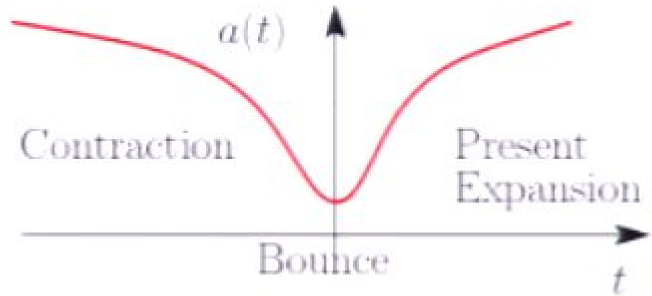
Why do we need to probe inflation more?

A Working Bouncing Cosmology

with Creminelli
JCAP 0711:010,2007

- Are we sure inflation took place?





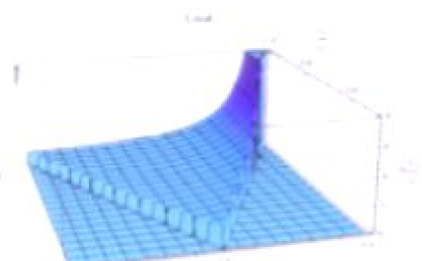
- Two important problems of formerly proposed bouncing models:
  - Bounce requires $\dot{H} > 0$: violation of NEC: $T_{\mu\nu}n^\mu n^\nu > 0$

    Violation usually associated to instabilities.

  - Generation of scale-invariant perturbations.
    - Isocurvature scalar: a second scalar moving down an exponential potential
    - Signatures:
      - No gravitational waves
      - Large level of local non-Gaussianities

Lehners, McFadden, Turok, Steinhardt
Phys.Rev.D76:103501,2007

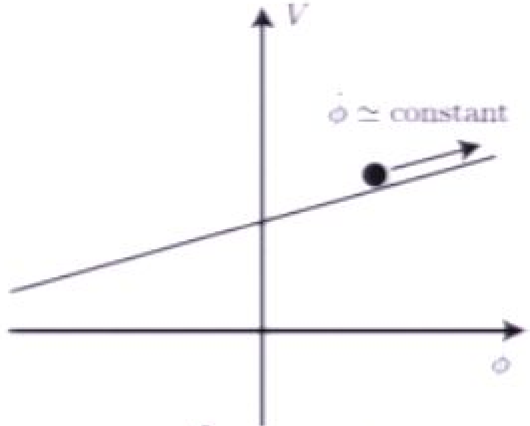
with Creminelli
JCAP 0711:010,2007



Stable Violation of NEC: bounce and current acc.

with P. Creminelli, M. Luty, A.Nicolis,
JHEP 0612:080,2006

Is $\dot{H} > 0$ possible ?



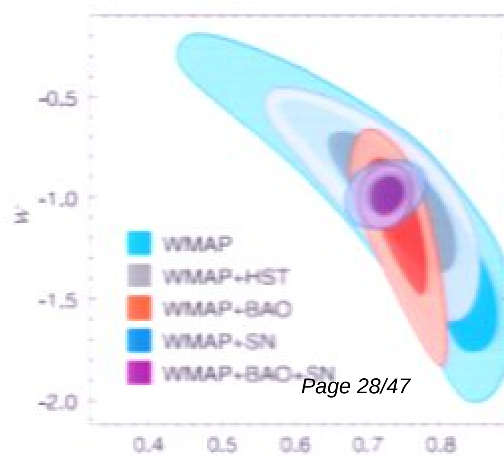
Low Energy Effective Action: $S_\pi = \int d^4x \left[M_{\rm Pl}^2 \dot{H} (\partial_\mu \pi)^2 + M^4 \dot{\pi}^2 - \bar{M} (\partial_i^2 \pi)^2 \right]$

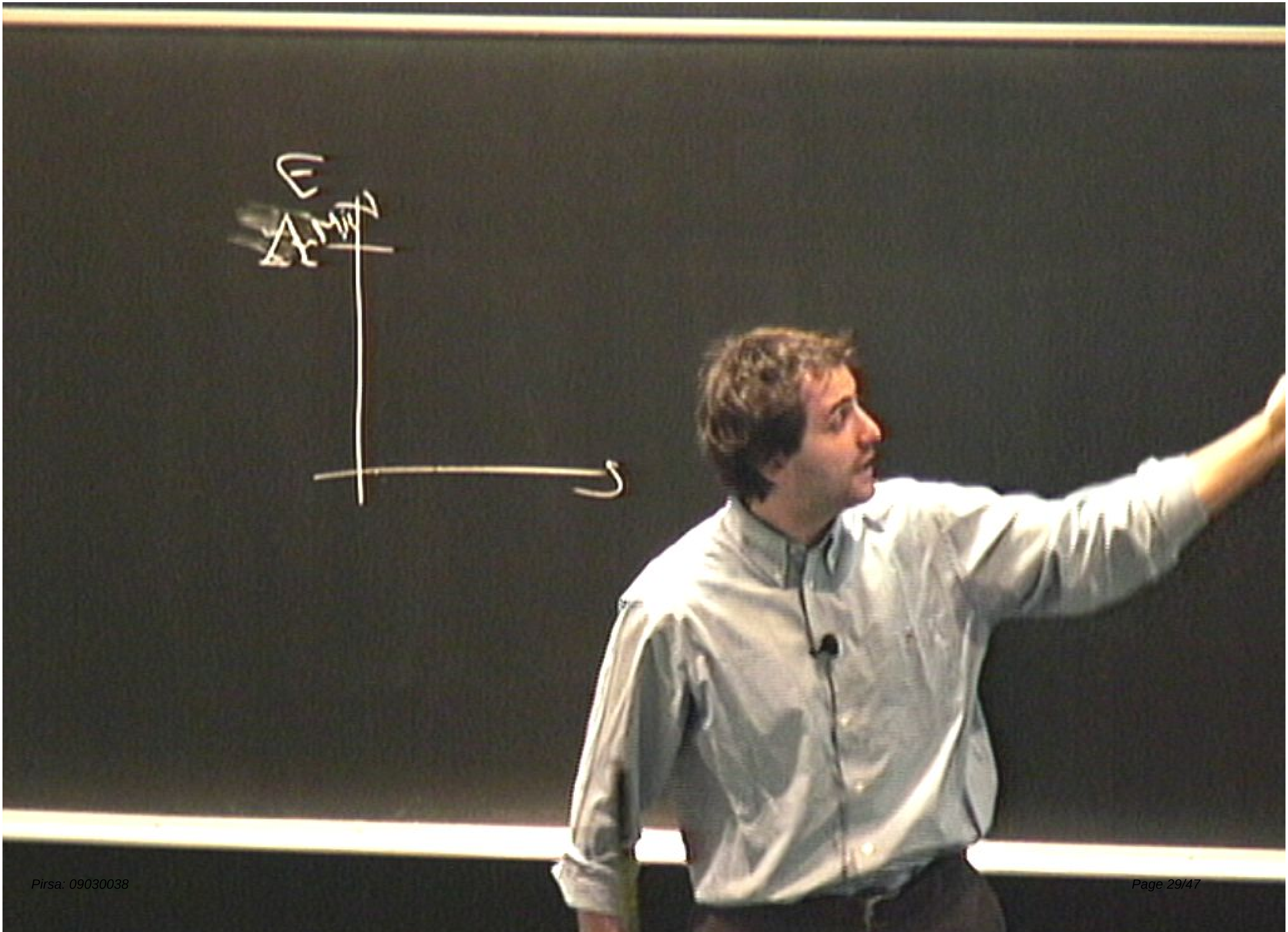
Dispersion relation: $\omega^2 = -\frac{M_{\rm Pl}^2 \dot{H}}{M^4} k^2 + \frac{\bar{M}^2}{M^4} k^4$ Freezing at: $\omega \sim H$

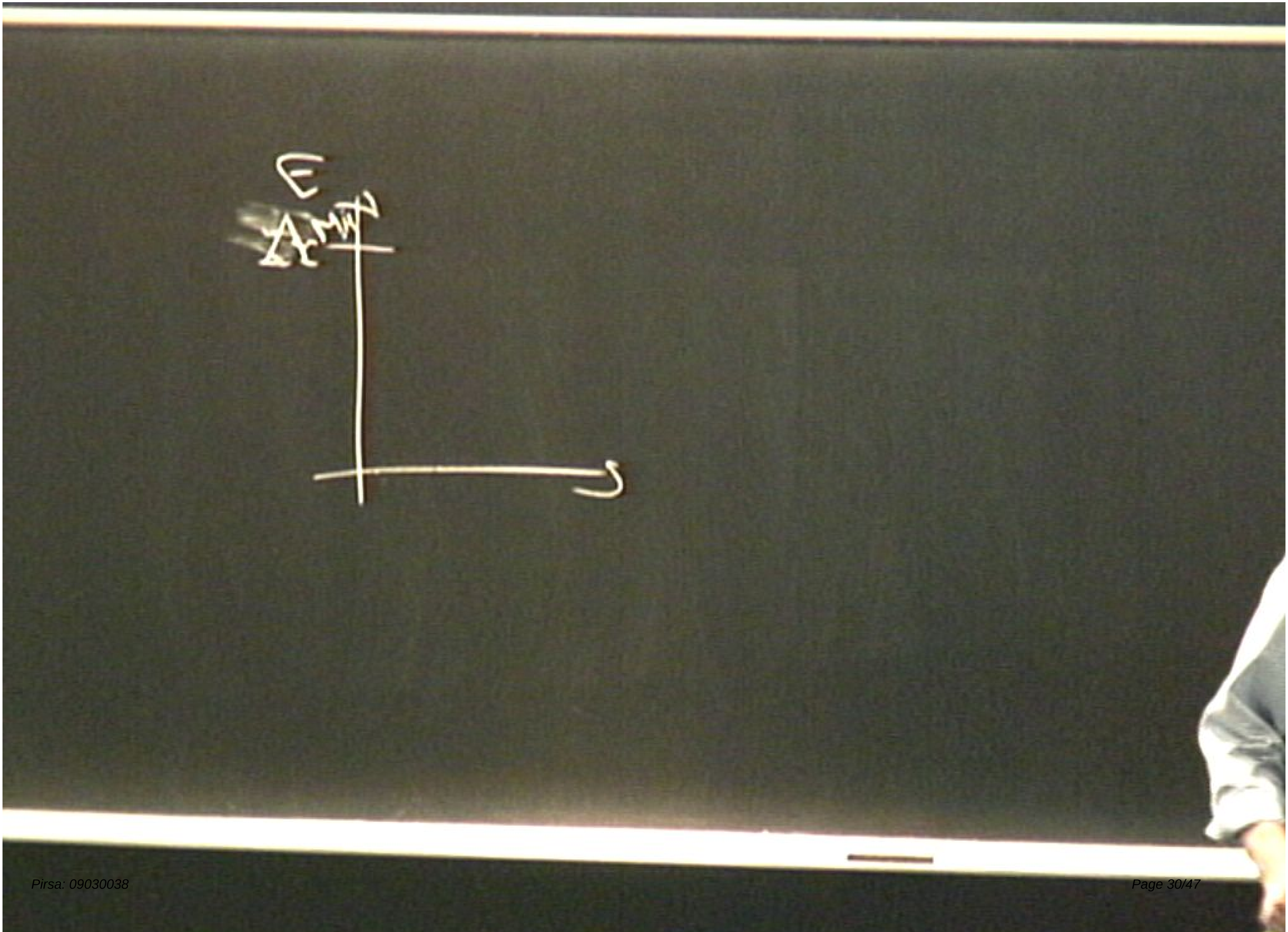
- Stable for $\frac{\dot{H}}{H} \lesssim \frac{\bar{M} M^2}{M_{\rm Pl}^2} \lesssim H$
- Stable bounce solution (but still less compelling than Inflation)

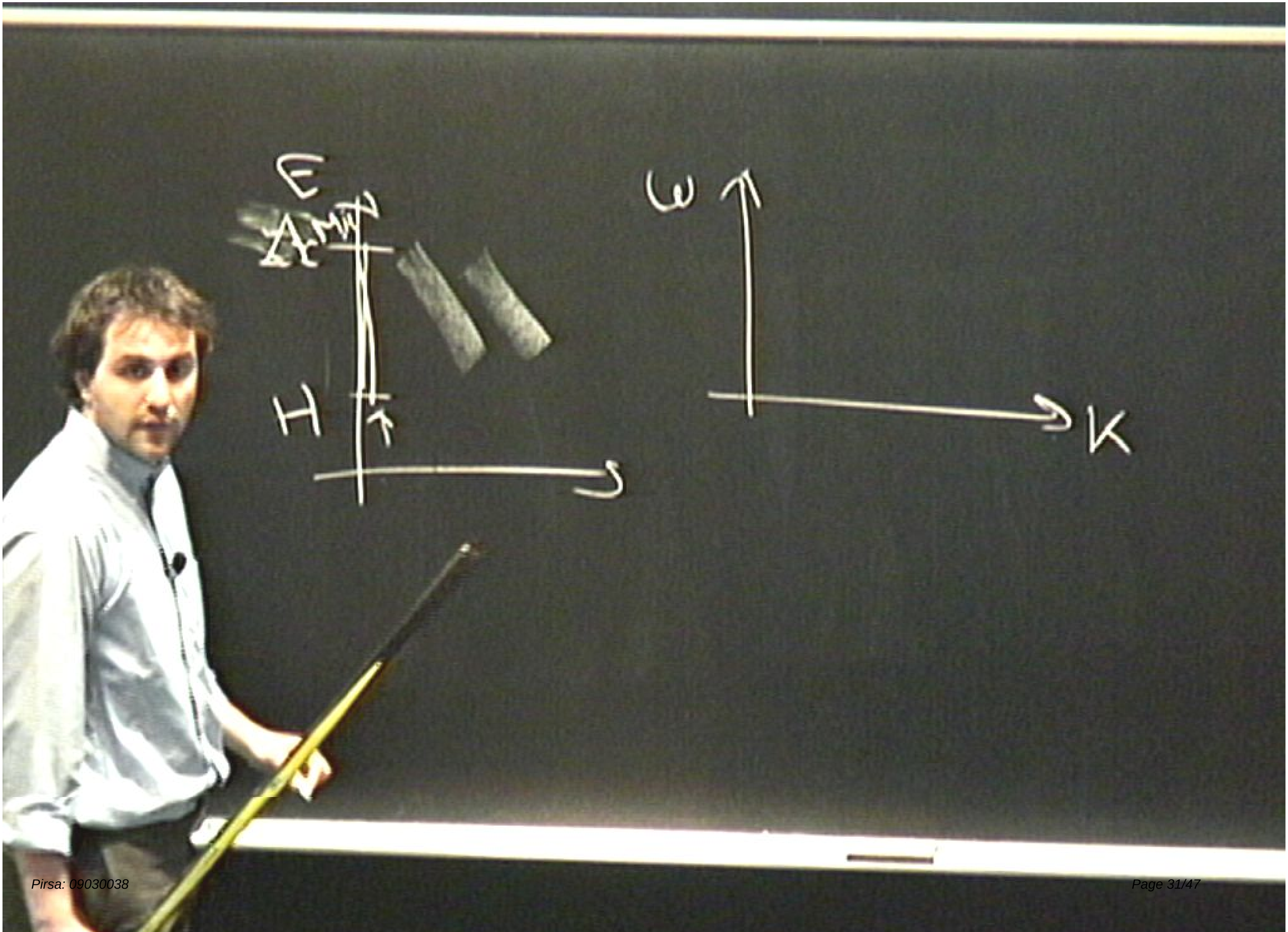
$p = w\rho$

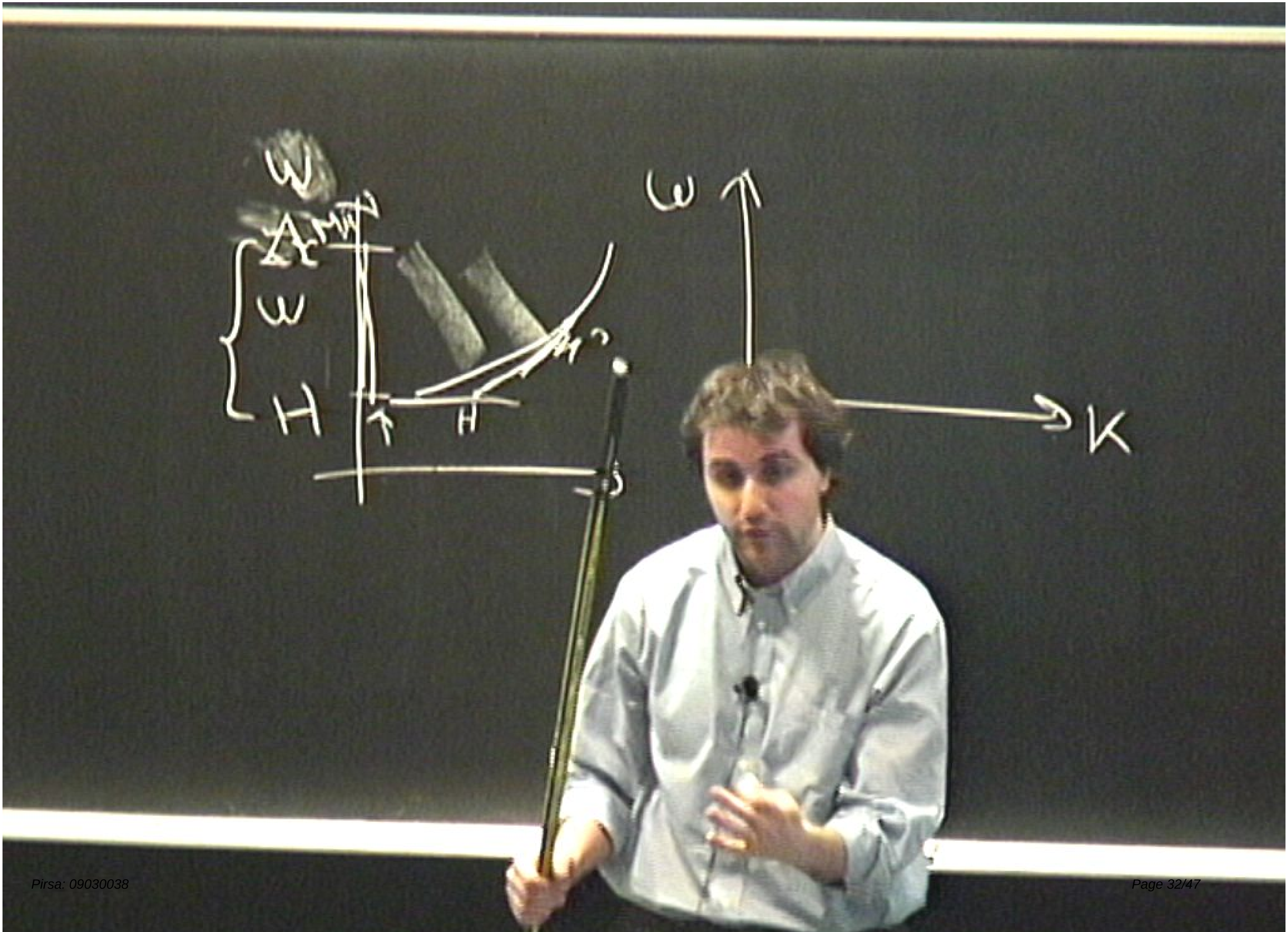
- Unique low energy prediction for current acceleration having $w < -1 \quad (\dot{H} > 0)$






E
J


E
H
ω
K


ω
A
ω
H
H
ω
K

Stable Violation of NEC: bounce and current acc.

with P. Creminelli, M. Luty, A.Nicolis,
JHEP 0612:080,2006

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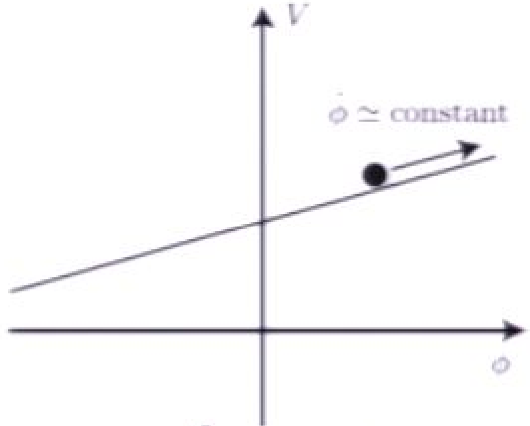

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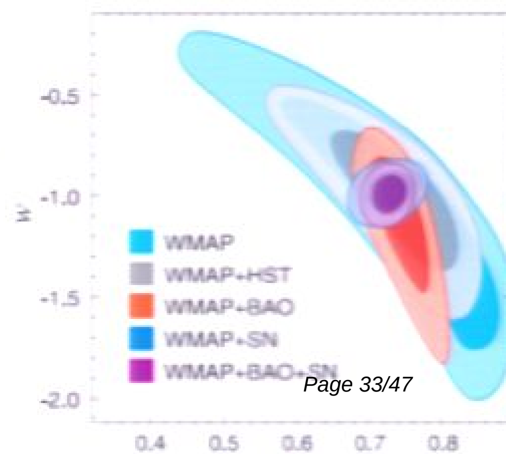


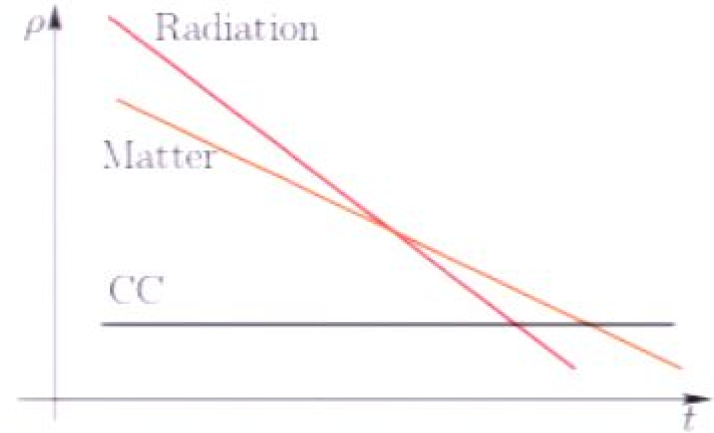
Impact on Theoretical Physics

Something beyond the SM

Weinberg's speculative solution

– We have a CC: S. Weinberg **PRL59:2607, 1987**

Impact on Structure Formation



– If you have many vacua ...

Needs:

- Large CC: OK
- Many Vacua: Landscape of String Theory
- A way to populate them
  - We seem to Inflation in our past, ...
  - We can populate through Eternal Inflation

Arkani-Hamed, Bousso, Dimopoulos, Susskind, Shenker, Kachru, Vilenkin, Hall, Denef, Vafa, Polchinski, Guth, Taylor, Tegmark, Wilczek, Turok, Cachazo ...

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with P. Creminelli, M. Luty, A.Nicolis,
JHEP 0612:080,2006

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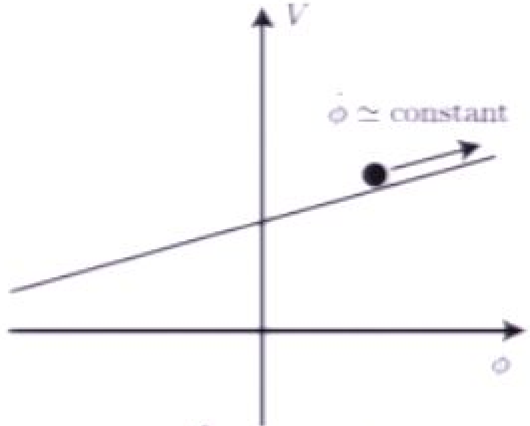

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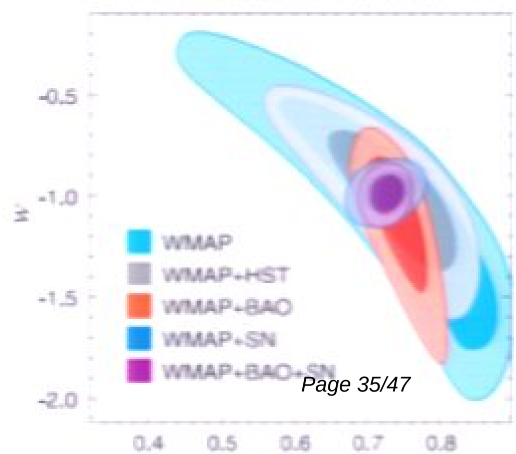

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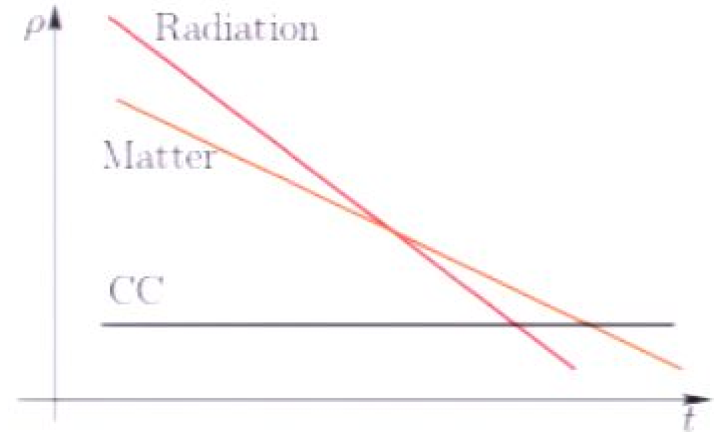

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Arkani-Hamed, Bousso, Dimopoulos, Susskind, Shenker, Kachru, Vilenkin, Hall, Denef, Vafa, Polchinski, Guth, Taylor, Tegmark, Wilczek, Turok, Cachazo ...

What is Eternal Inflation?

What is Eternal Inflation?

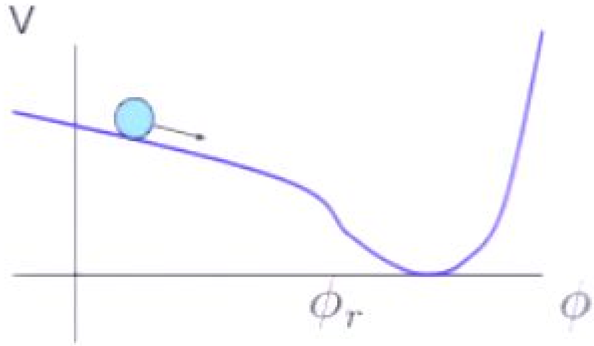
with P. Creminelli, S. Dubovsky, A. Nicolis, M. Zaldarriaga, **JHEP 0809:036**

with S. Dubovsky and G. Villadoro **0812.2246 [hep-th]**

- What is Inflation?

$$a \sim e^{Ht}$$

$$\dot{\phi} \sim \frac{V'}{H}$$



- What is Eternal Inflation?

  Classical Motion Vs Quantum Motion

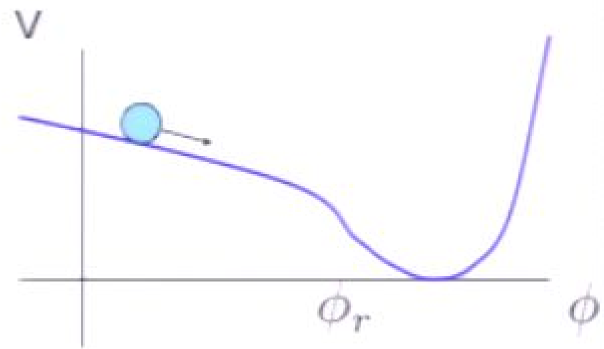
  $\Delta\phi_{\rm Cl} \sim \dot{\phi}\, H^{-1}$ Vs $\Delta\phi_{\rm Q} \sim H$

  Reproduction of space

  Quantum dominates for $\dfrac{\dot{\phi}}{H^2} \lesssim 1 \Rightarrow$ Slow Roll Eternal Inflation

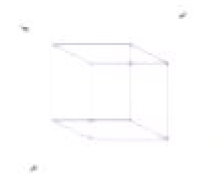
- Make Eternal Inflation sharp? Calculable?
  - No Semiclassical
  - No FRW $\delta\rho/\rho \sim H^2/\dot{\phi} \sim 1$

Perturbativity of the system

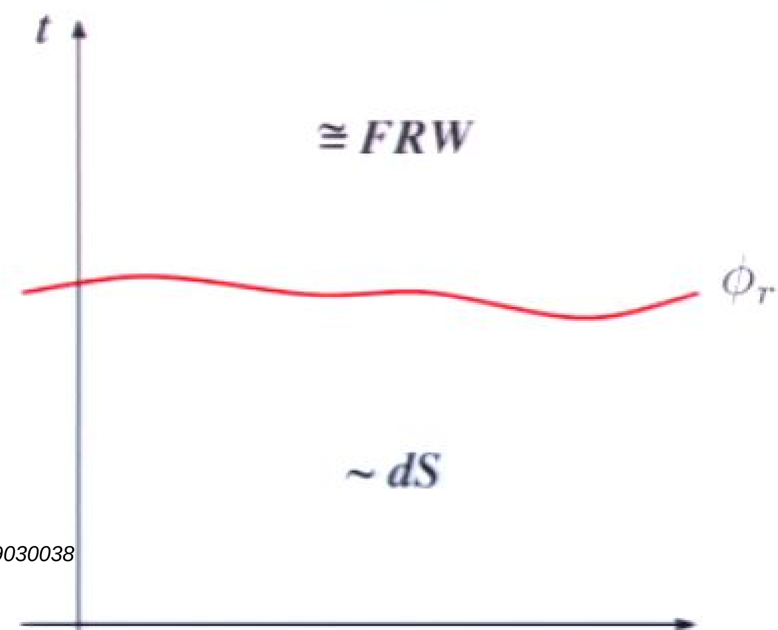


- Close to de-Sitter $\quad \epsilon \simeq \dfrac{\dot{\phi}^2}{V(\phi)} \ll 1$
  - Still unperturbed before reheating: $\delta g \sim \sqrt{\epsilon}\dfrac{H}{M_{\rm Pl}}$
- No big interactions: $\quad \dfrac{S_3}{S_2} \sim \sqrt{\epsilon}\dfrac{H}{M_{\rm Pl}}$

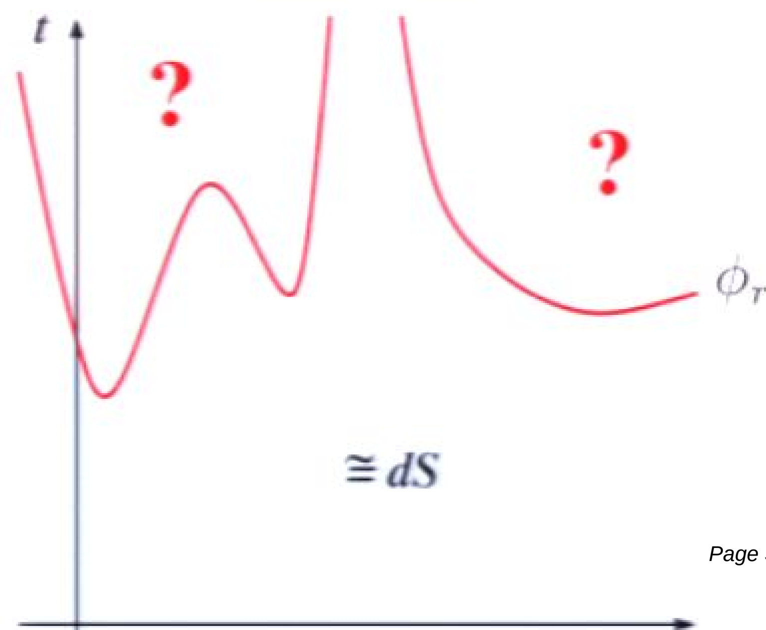
- $\Longrightarrow$ Study the volume of the Reheating surface $\phi = \phi_r$



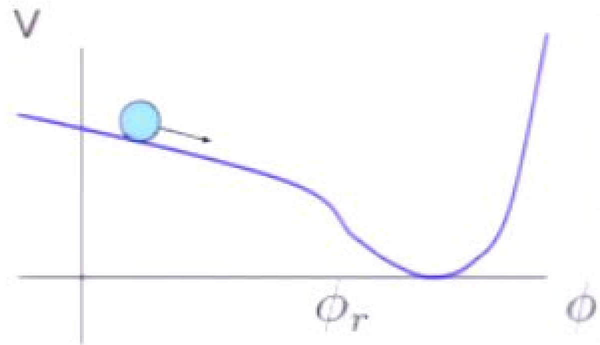
Standard Infl.



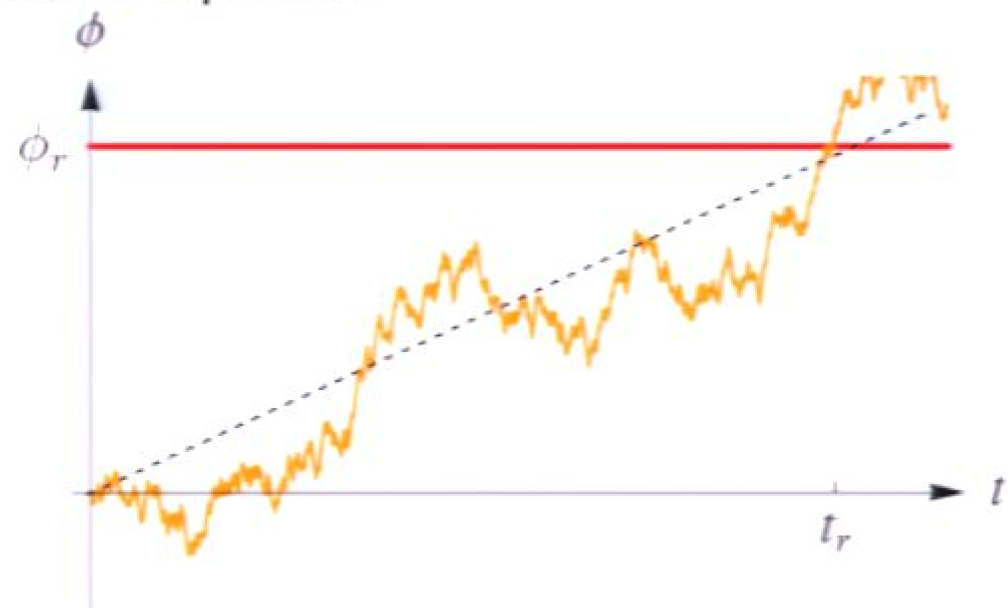
Eternal Infl.



A random walk



- Smoothing the field: $\Lambda \ll H$
  - » $\Delta t \gtrsim H^{-1}$ for reheating
  - » . $[\delta\phi_k, \dot{\delta\phi}_{-k}] \to 0$
- Inflaton ~ Classical stochastic system with Gaussian statistics
- Probability distribution follows a diffusion equation



$$\delta\phi = \phi - \phi_{cl}(t)$$

$$\langle \delta\phi(x,t)^2 \rangle_\Lambda \sim H^3 t$$

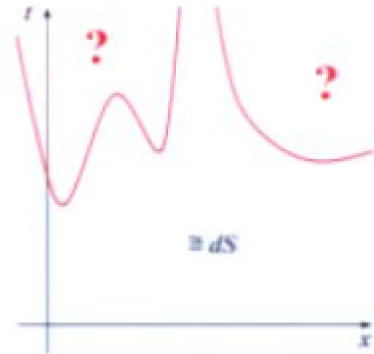
$$\frac{\partial P(\delta\phi, t)}{\partial t} = H^3 \frac{\partial^2 P(\delta\phi, t)}{\partial \delta\phi^2}$$

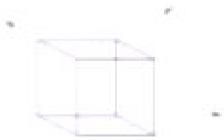
$$P(\delta\phi, t) \sim e^{-\frac{\delta\phi^2}{H^3 t}}$$

- Probability to reheat at time t :

$$P_r(t) \simeq P(\delta\phi = \phi_r - \phi_{cl}(t), t) \sim e^{-\frac{(\phi_r - \phi_{cl}(t))^2}{H^3 t}} \sim e^{-\frac{\dot{\phi}^2}{H^3} t}$$

Volume statistics



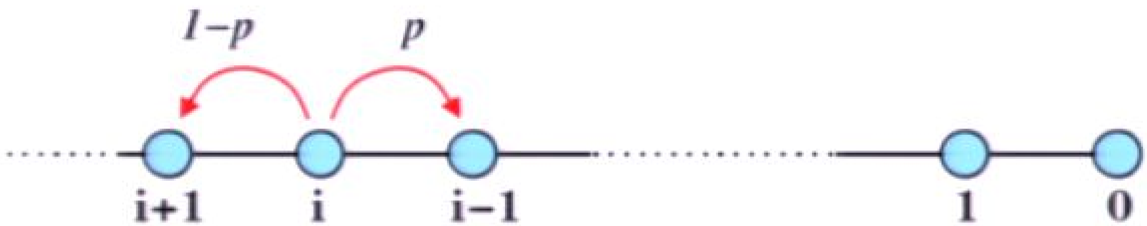
- Start with a box 
- Critical value of $\dot{\phi}^2/H^4$ for phase transition in $\rho(V)$
- The Average $\langle V \rangle = \int d^3x \langle e^{3Ht_r(x)} \rangle = L^3 \int dt P_r(t) e^{3Ht}$
  - Using the probability for the reheating time $P_r(t) \sim e^{-\frac{\dot{\phi}^2}{H^3}t}$

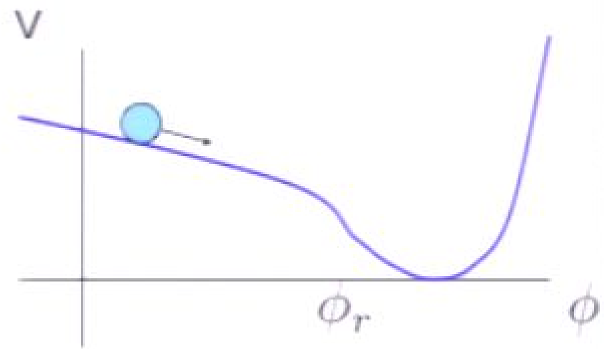
$$\langle V \rangle \sim \int dt \; e^{(3H - \frac{\dot{\phi}^2}{H^3})\,t}$$

  - Diverges for $\underline{\underline{\Omega \equiv \frac{2\pi^2}{3}\frac{\dot{\phi}^2}{H^4} < 1}}$ $\qquad \Omega \simeq 2\pi^2 \frac{M_{\rm Pl}^6 V'^2}{V^3} < 1$
- The same for all $\langle V^n \rangle$
- But what about $\rho(V)$?

Ex: $\rho(V) \propto \frac{1}{1+V^2}$: Normalizable, and $\langle V^n \rangle = \infty$, but $\rho(V = \infty) = 0$

Bacteria Model: a discretization





$$i = \frac{\phi}{\Delta\phi} \quad , \quad n = \frac{t}{\Delta t}$$

Classical motion $\quad \dot{\phi} \quad \Rightarrow \quad p - \frac{1}{2}$.

Reproduction $\quad N \quad \Rightarrow \quad \sim e^3$ New Hubble volumes

Number of dead bacteria $\Rightarrow$ Reheated Volume

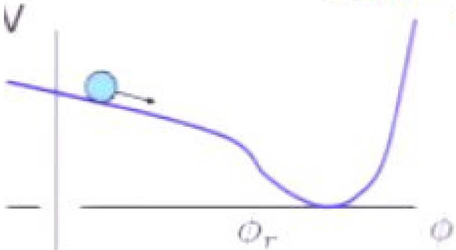
Continuum Limit Identifications:

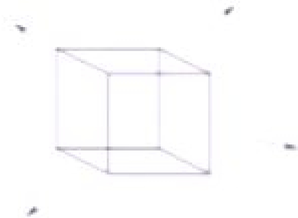
$$-(1-2p)\frac{\Delta\phi}{\Delta t} = \dot{\phi} \quad , \quad \frac{4\pi^2}{H^3}\frac{\Delta\phi^2}{\Delta t} = 1 \; , \quad N = 1 + 3H\Delta t$$

It matches $\langle V^n \rangle = \infty$ for $\frac{1}{2} < p < p_c \quad \left(\Omega = \frac{2\pi^2}{3}\frac{\dot{\phi}^2}{H^4} < 1\right)$

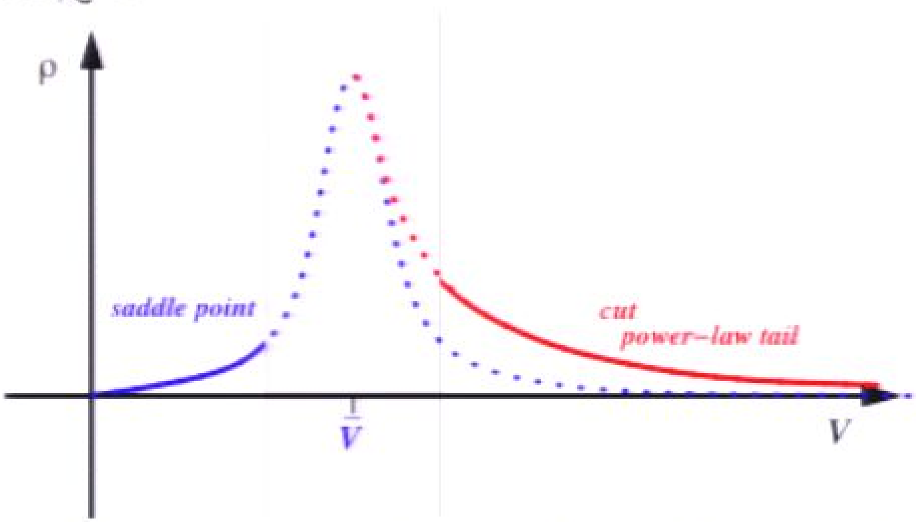
Theorem: for $p < p_c \;\Rightarrow\; p_{\text{extinction}} \neq 1 \;\Rightarrow\; \rho(V=\infty) \neq 0$

The probability distribution of the Volume

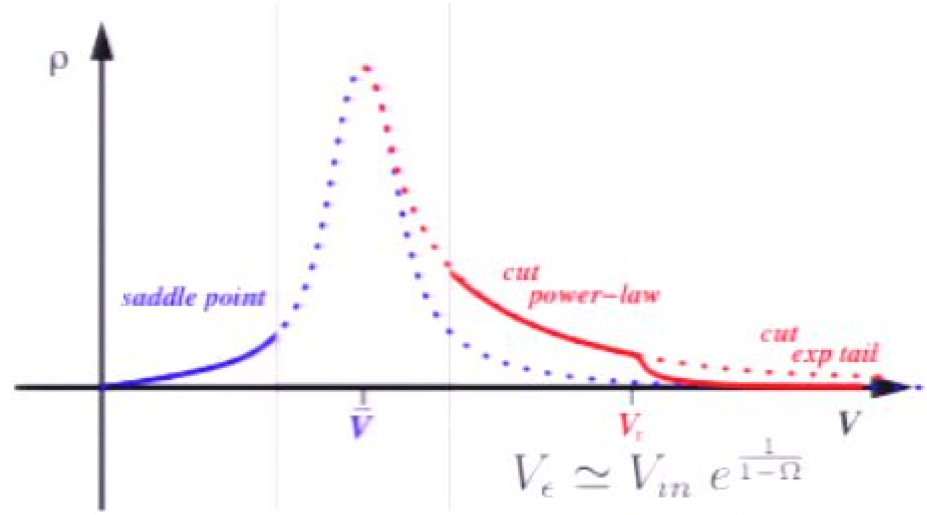




$\Omega \gtrsim 1$



$\Omega \lesssim 1$

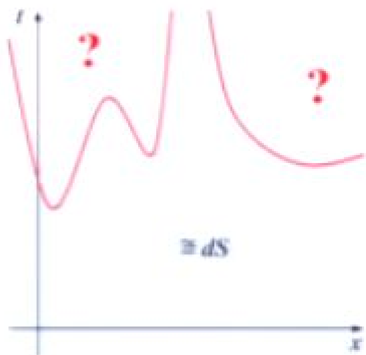


- Map to a mechanical problem of ball in a potential, and solve for $\rho(V)$
- Average of the volume

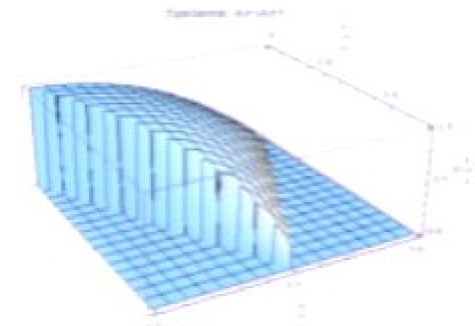
$$\bar{V} \simeq V_{cl} \qquad \text{for} \quad \Omega \gg 1$$

$$\bar{V} \simeq \frac{V_{cl}}{V_{in}} V_{cl} \qquad \text{for} \quad \Omega \simeq 1$$

- Exponential tail in eternal regime
- Eternal Inflation: gives new way to study it, opens new questions



What is next?



Theory

- Eternal Inflation
- Generic predictions of inflation and its alternatives
- Effective Field Theory for multifield inflation (in progress)

Foregrounds

Planck will reach $f_{\rm NL} \sim 3$

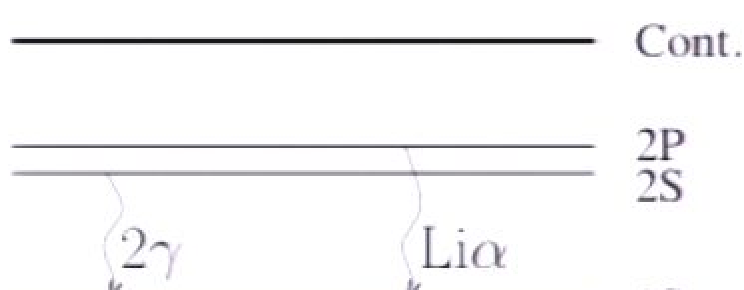
$$\Phi = \Phi^{(g)}(x) + f_{\rm NL}^{\rm loc.}\left(\Phi^{(g)}(x)^2 - \langle \Phi^{(g)}(x) \rangle^2\right)$$

Non linearities in gravity and in plasma physics: $f_{\rm NL} \sim 1$. They also contain information!

$\Longrightarrow$ Possible background for Planck $\Longrightarrow$ Need to compute them

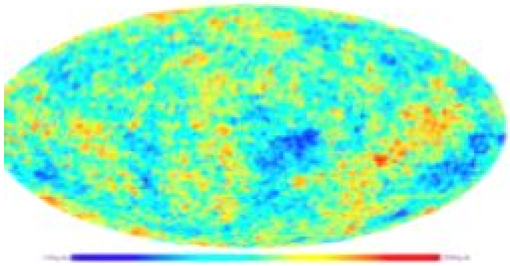
Ex: non linearities from H recombination $\Longrightarrow$ Perturbation in last scattering surface:

Peebles, **Astr. J. 153, 1968**



With Tassev, Zaldarriaga,
0812.3652 [astro-ph]
0812.3658 [astro-ph]

$f_{\rm NL} \simeq 4$



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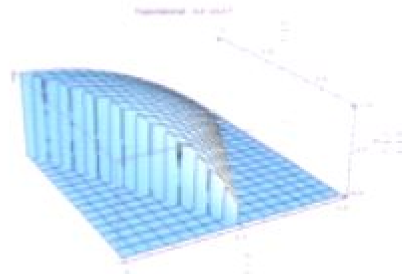
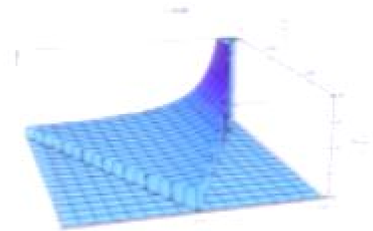




Experiments: CMB and Large Scale Structures

CMB: WMAP 7yr: $\Delta f_{\rm NL}^{\rm loc.} \simeq 20$

Planck: $\Delta f_{\rm NL}^{\rm loc} \simeq 3$ Clean the 2σ

Galaxies 3-point funct.: $\Delta f_{\rm NL}^{\rm loc.} \sim 10 - 20$ HETDEX Sefusatti and Komatsu. **PRD 76:083004,2007**

$\Delta f_{\rm NL}^{\rm loc} \sim 3$ CIP

Scale dependent bias: $\Delta f_{\rm NL}^{\rm loc.} \sim 20$ SDSS Dalal et al. **Phys.Rev.D77:123514,2008**
Slosar et al. **JCAP 0808:031,2008**
(already applied to data!)

$\Delta f_{\rm NL}^{\rm loc} \sim 1$ LSST Carbone, Verde, Matarrese **0806.1950** [astro-ph]

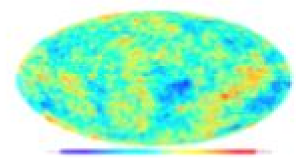
Mass function: $\Delta f_{\rm NL}^{\rm loc} \sim 10's$ SPT Dalal et al. **Phys.Rev.D77:123514,2008**

21 cm line: $\Delta f_{\rm NL} \sim 10^{-2}$ (?) ; Slow-roll Infl.
Loeb and Zaldarriaga. **PRL 92:211301,2004**

a few years: $f_{\rm NL} \gtrsim 1$ either ruled out $\Longrightarrow$ ~confirmation of slow-roll inflation
or detected $\Longrightarrow$ rule-out standard slow-roll and find non-trivial interaction

Conclusions

Cosmology



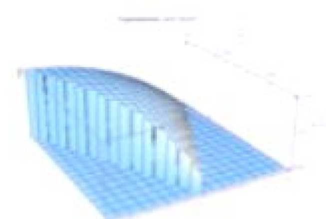
- A data driven subject
- dS phase in our past and our present
- Huge theoretical implications (The CC, the Landscape and Eternal Inflation)

Our Past and our Present

Probing Inflation

- An Effective Lagrangian to see all what is possible and what we learn from exp.
- Non-Gaussianities:
  - What they teach us
  - How we analyze them

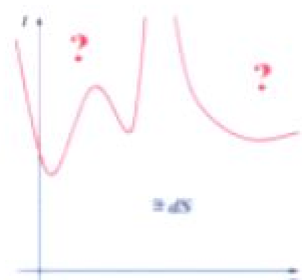
$$\frac{1}{c_s^2}\dot{\pi}(\partial_i\pi)^2 + \frac{\tilde{c}_3}{c_s^2}\dot{\pi}^3$$



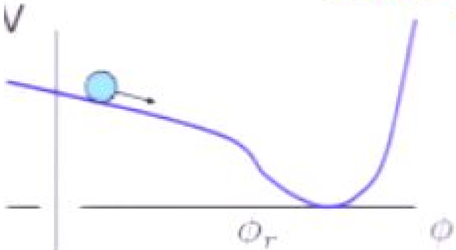
- and its alternatives: a working bouncing cosmology
- and the unique testable model with $w < -1 \quad (\dot{H} > 0)$

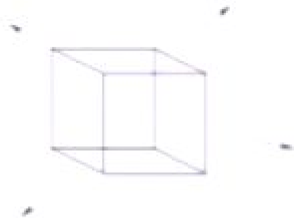
Eternal Inflation

- A sharp and quantitative characterization

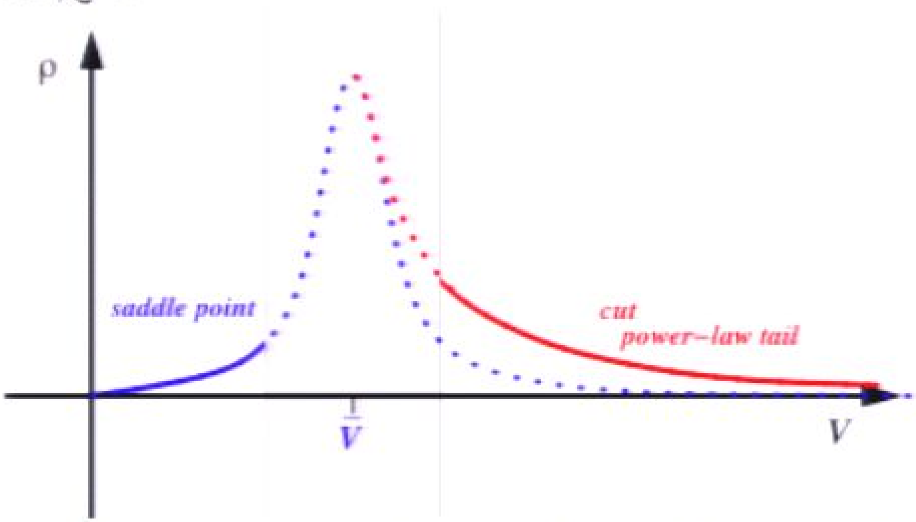


The probability distribution of the Volume

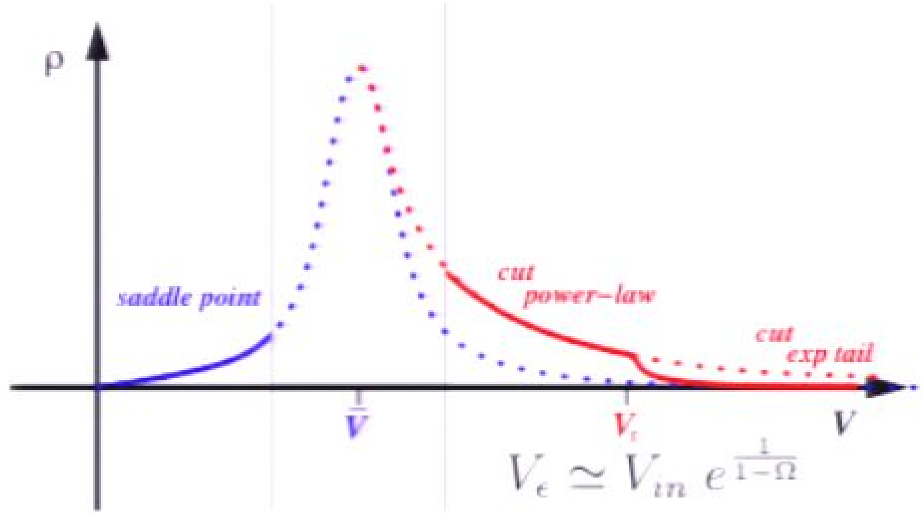




$\Omega \gtrsim 1$



$\Omega \lesssim 1$



- Map to a mechanical problem of ball in a potential, and solve for $\rho(V)$
- Average of the volume

$$\bar{V} \simeq V_{cl} \qquad \text{for} \quad \Omega \gg 1$$

$$\bar{V} \simeq \frac{V_{cl}}{V_{in}} V_{cl} \qquad \text{for} \quad \Omega \simeq 1$$

- Exponential tail in eternal regime
- Eternal Inflation: gives new way to study it, opens new questions