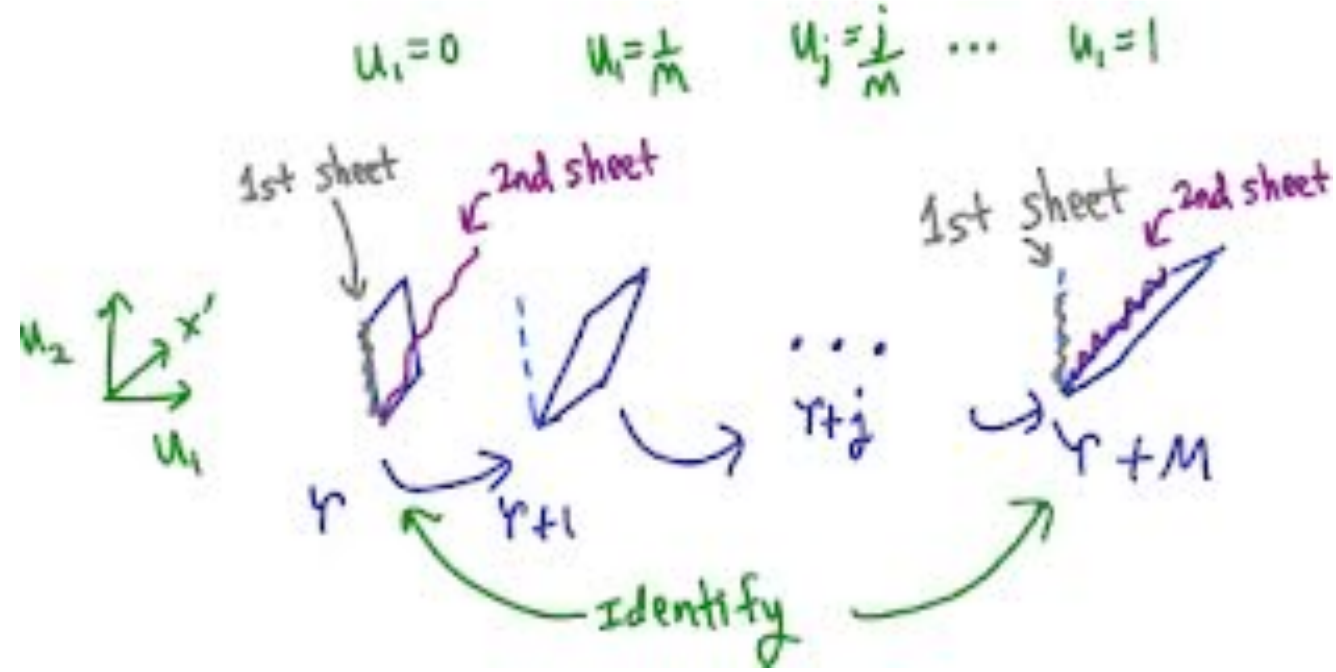
Leonardo Senatore
(Stanford & CERN)

Overview of the Bottom-Up approach

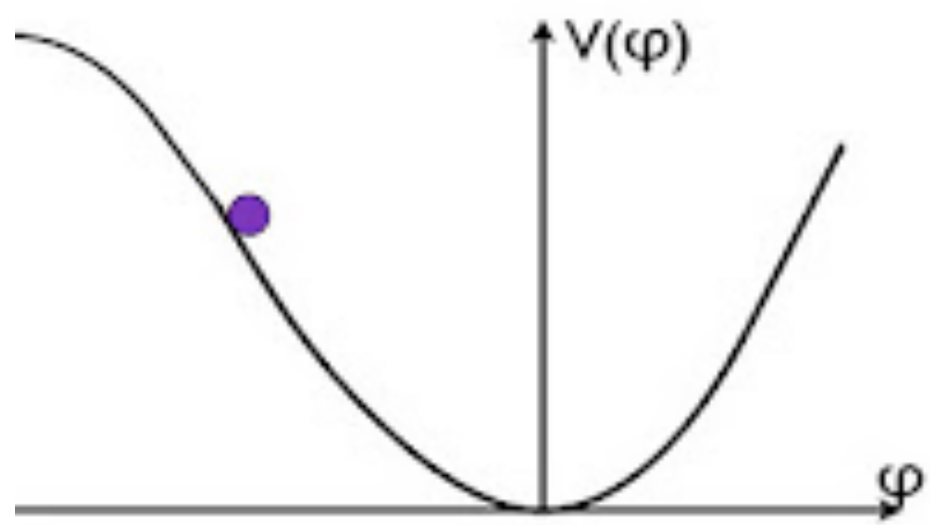
What is the bottom-up approach?

- We just saw the top-down approach



- Traditional this was the bottom-up

$$\int d^4x \left[(\partial\phi)^2 + V(\phi) \right]$$



- I will present the truly bottom-up approach (what we are really probing)

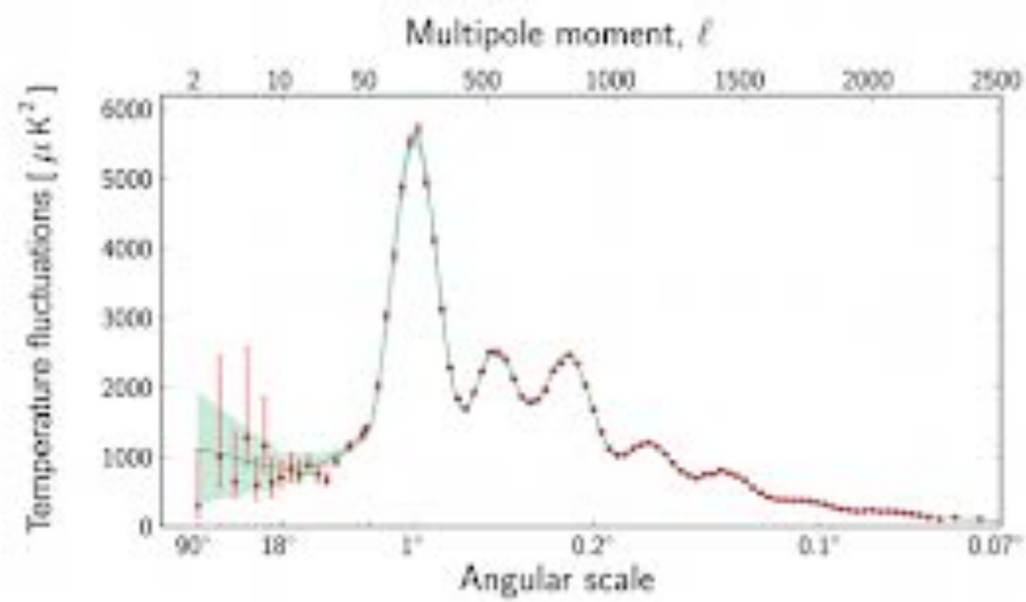
How do we probe Inflation?

What are we seeing?

- The only observable we are testing from the background solution is

  $\Omega_K \lesssim 3 \times 10^{-3}$

- All the rest, comes from the fluctuations



- For the fluctuations
  - they are primordial
  - they are scale invariant
  - they have a tilt $n_s - 1 \simeq -0.04 \sim \mathcal{O}\left(\frac{1}{N_e}\right)$
  - they are quite gaussian

$$\text{NG} \sim \frac{\langle \zeta^3 \rangle}{\langle \zeta^2 \rangle^{3/2}} \lesssim 10^{-3}$$

- Is this enough to buy slow-roll Inflation? or even Inflation?
  - and we even got anomalies!

An essential description

- We need a description that allows us
  - to state what we are really learning and what is assumed
  - in doing so, we will also explore all possible signatures
  - and allow us to know what we are swallowing when we say `it is slow-roll inflation'
    - how to get confident of slow-roll inflation, even in absence of additional information/detection

- To do that, link to observations.
  - therefore, link to the fluctuations

The bottom-up approach

- Turn to particles physics
  - If we are probing a system at energy E , we describe the system only with the degrees of freedom accessible up to that energy. Effects of inaccessible physics are encoded in a few higher dimension operators, that we call indeed irrelevant.
  - We change description, only when new degrees of freedom become accessible, and therefore relevant.

The bottom-up approach

- In Inflation
  - Fluctuations modes $E \sim H$
  - Background $\dot{\phi} \sim \left(\dot{H} M_{\rm Pl}^2\right)^{1/2} \sim 10^5 H^2 \gg H^2$
  - To describe obs, background is no needed!
- Higher energy effects: $$\int d^4x \left[(\partial\pi)^2 + \frac{1}{\Lambda_U^2}\pi^2(\partial\pi)^2 + \ldots\right]$$
  - Λ_U is unitarity bound: something happens by then.
  - By testing interactions (or their absence) limits Λ_U
  - If we could conclude that $\Lambda_U^4 \gtrsim \dot{H} M_{\rm Pl}^2 \sim \dot{\phi}^2_{\rm slow-roll}$
    - then we would know that slow-roll inflation is an allowed UV complition
    - but not guaranteed this is the one

The bottom-up approach

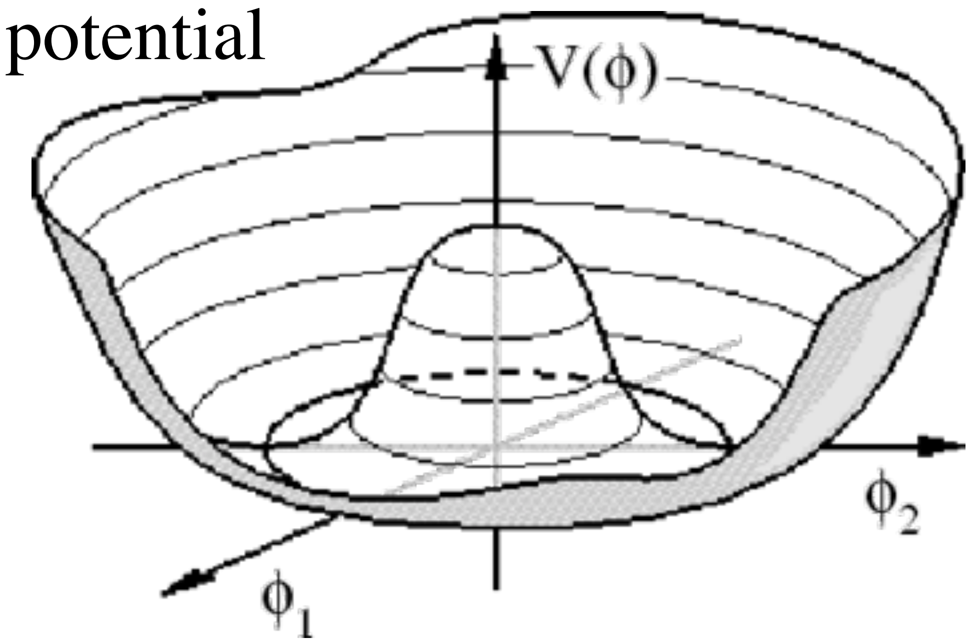
- $\cdot \quad \int d^4x \left[(\partial\pi)^2 + \frac{1}{\Lambda_U^2}\pi^2(\partial\pi)^2 + \ldots \right]$
- As I will show, currently $\quad \Lambda_U^2 \gtrsim \Lambda_{\rm min}^2 \simeq 10^4 H^2 \quad \Rightarrow \quad \Lambda_{\rm min}^2 \ll 10^5 H$
- We do not really know that the inflationary background is driven by a scalar field!
  – We will never know
  – But we really do not know now
- We just know that Inflation is a weakly coupled field theory

Particles Physics examples of fake scalars

- Fluctuations scalar $\neq$ fundamental scalar
  - As you change energies, the correct description can change radically
- Example: Pions

$$\int d^4x \left[(\partial\pi)^2 + \frac{1}{\Lambda_U^2}\pi^2(\partial\pi)^2 + \ldots \right]$$

  - Goldstone boson of $SU(2) \times SU(2) \rightarrow SU(2)$
  - Easy UV complition: scalar field with mexican hat potential



$$\int d^4x \left[(\partial\phi)^2 + (\partial\tilde{\phi})^2 + V(\phi, \tilde{\phi}) \right]$$

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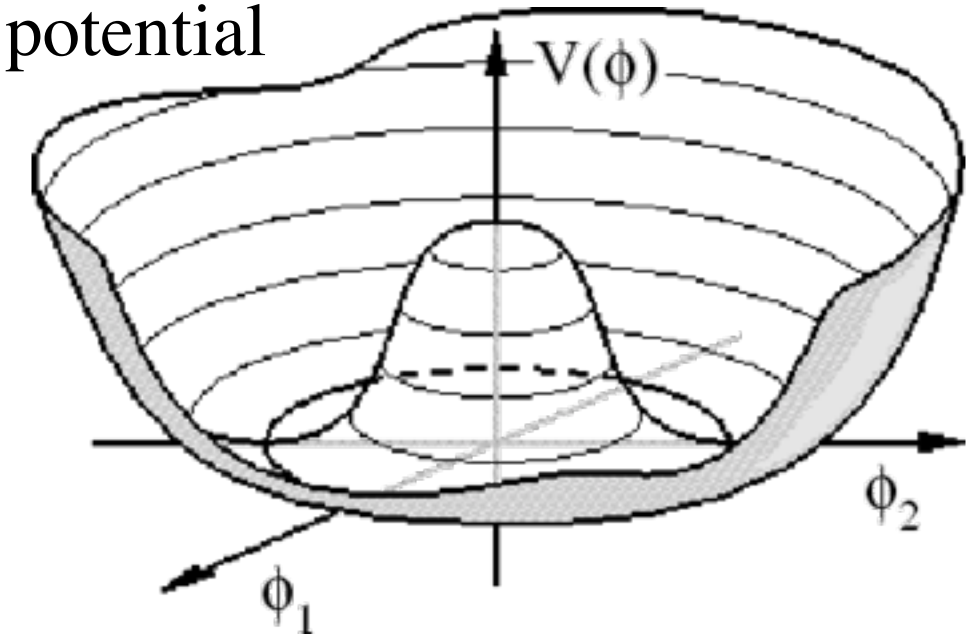

$$\int d^4x \left[(\partial\phi)^2 + (\partial\tilde{\phi})^2 + V(\phi, \tilde{\phi}) \right]$$

  - WRONG!!
  - There is no fundamental scalar field.
  - QCD is the UV complition, with Chiral Condensation of quarks $\pi \sim \langle u\bar{d}\rangle$

Particles Physics Example of fake scalars

- Longitudinal Polarization of Standard Model W, Z boson

$$S = \int d^4x \, \frac{1}{g_3^2} \mathrm{Tr}\left[F_{\mu\nu}F^{\mu\nu} + m_W^2 \, W^\mu W_\mu + m_Z^2 \, Z^\mu Z_\mu\right] \quad \rightarrow$$

$$\int d^4x \left[(\partial\pi)^2 + \frac{1}{\Lambda_U^2}\pi^2(\partial\pi)^2 + \ldots\right] \qquad \Lambda_U \sim 4\pi\frac{m_W}{g_2}$$

- Described by this Lagrangian by Goldstone Boson Equivalence Theorem
- Higgs: UV complition with fundamental scalar
- Technicolor: not scalar at all (same as Pions)

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- Described by this Lagrangian by Goldstone Boson Equivalence Theorem
- Higgs: UV complition with fundamental scalar
- Technicolor: not scalar at all (same as Pions)
- Higgs was correct!
  - But he was lucky (in a sense). The Higgs particle could have not been the right UV complition.
- and in fact the Higgs could be composite itself.
- What is fundamental... it's all relative

Particles Physics Example of fake scalars

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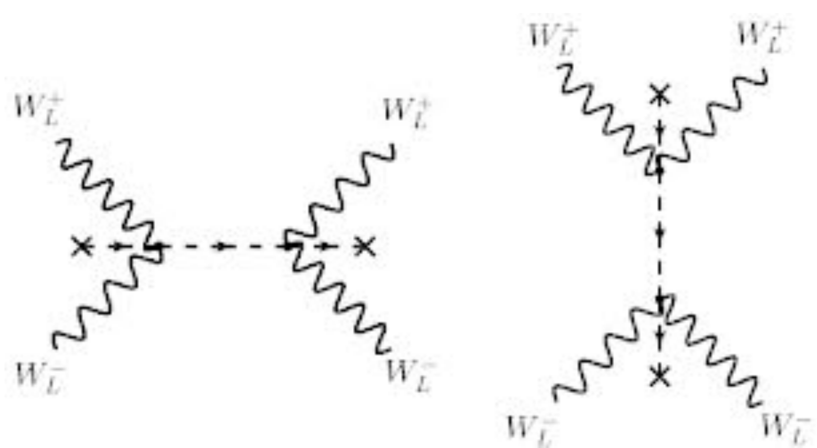
- A weakly coupled UV complition

$$\Rightarrow \quad m_{\text{new degree of freedom}} \sim g \times \Lambda_U \ll \Lambda_U$$

- .



$$\frac{g_2^2}{m_h^2} \sim \frac{1}{\Lambda_U^2} \quad \Rightarrow \quad m_h \sim g_2 \times \Lambda_U \ll \Lambda_U$$

- In Inflation we are in this situation? We do not know yet at all.

The general theory of the fluctuations

The Effective Field Theory of Inflation
(Inflation as the Theory of a Goldstone Boson)

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

The Effective Field Theory

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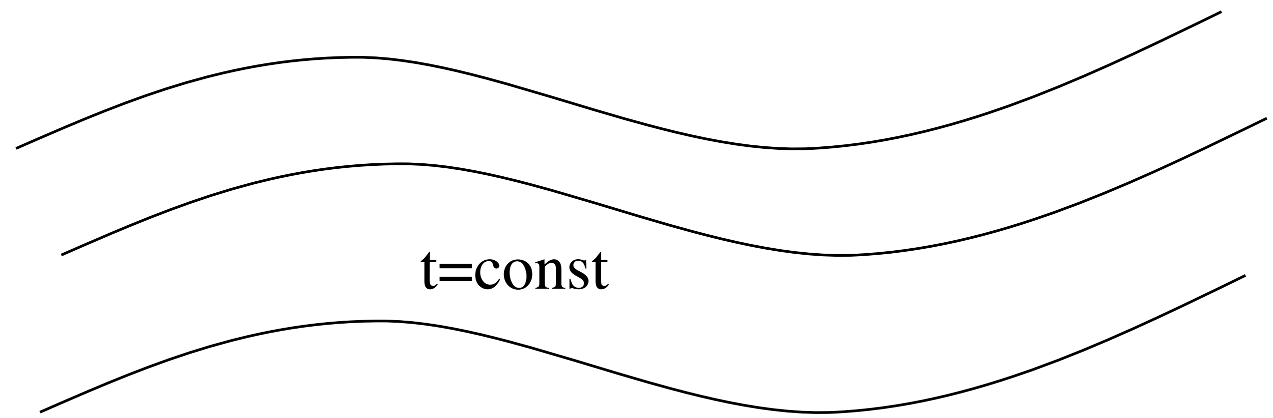
Inflation. Quasi dS phase with a privileged spatial slicing

Unitary gauge. This slicing coincide with time.

$$\delta\phi(\vec{x},t) = 0$$



Most 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 $K_{\mu\nu}$ and covariant derivatives

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

The Effective Field Theory of Inflation

Inflation: quasi dS phase with a privileged spacial slicing:

Inflation: the Theory of the Goldstone Boson of time translations

Reintroduce the Goldstone. $g^{00} \rightarrow g^{\mu\nu}\partial_\mu(t+\pi)\partial_\nu(t+\pi)$

$\pi \longrightarrow \pi + \delta t$

Cosmological perturbations probe the theory at E ~ H

$$S_\pi = \int d^4x\sqrt{-g}\left[-\frac{M_{\rm Pl}^2\dot{H}}{c_s^2}\left(\dot{\pi}^2 - c_s^2\frac{1}{a^2}(\partial_i\pi)^2\right)\right.$$
$$+\frac{\dot{H}M_{\rm Pl}^2}{c_s^2}(1-c_s^2)\dot{\pi}\frac{1}{a^2}(\partial_i\pi)^2 - \frac{\dot{H}M_{\rm Pl}^2}{c_s^2}(1-c_s^2)\left(1+\frac{2}{3}\frac{\tilde{c}_3}{c_s^2}\right)\dot{\pi}^3$$
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$$\left.+\ \ldots\right],$$

• Analogous of the Chiral Lagrangian for the Pions and W bosons S.Weinberg **PRL 17, 1966**

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- Used in WMAP9 and Planck papers (thanks!, but attributed to Weinberg)
  - Maybe because Weinberg is the true scientific father of all of us?
- There is more than used by WMAP and Planck!
- The third line for example contains Galileon Inflation

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$$\left. + \ \dots \right],$$

- Dispersion relations

$$\omega^2 = c_s^2k^2 + \frac{k^4}{M^2}$$

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- Interactions

$$\dot\pi^3\ , \quad \dot\pi(\partial_i\pi)^2\ , \quad (\partial^2\pi)(\partial\pi)^2$$

- at leading order in derivatives and in fluctuations

Some Lessons

The tilt

$$S_\pi = \int d^4x \sqrt{-g} \left[-\frac{M_{\rm Pl}^2 \dot H}{c_s^2} \left(\dot\pi^2 - c_s^2 \frac{1}{a^2} (\partial_i \pi)^2 \right) \right.$$
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$$\left. + \ \ldots \ \right] ,$$

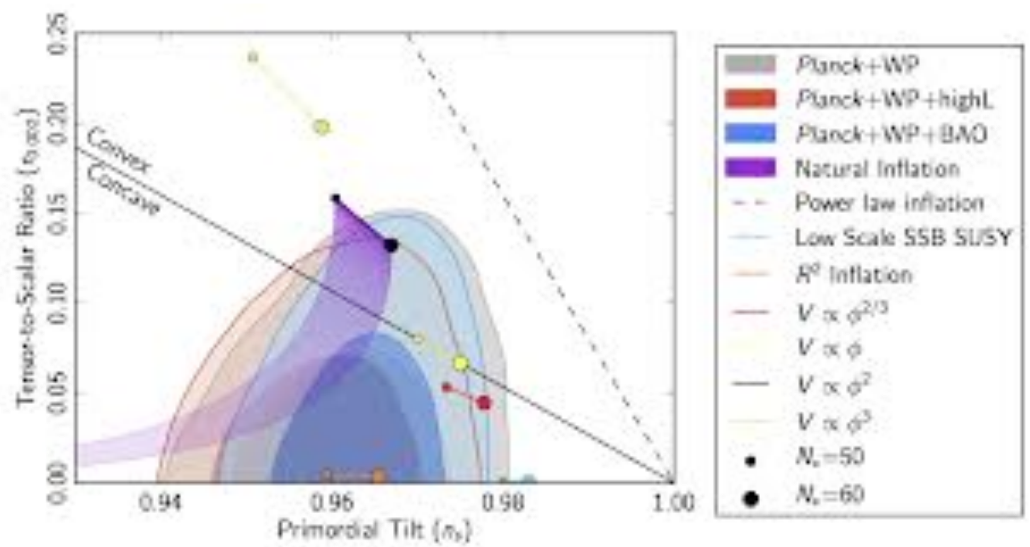
- This Lagrangian is fine to make all predictions
- The tilt

$$n_s - 1 = \frac{\dot H}{H^2} + \frac{\ddot H}{\dot H H} + \frac{\dot c_s}{c_s H}$$

- No potentials terms

$$M_{\rm Pl}^2 \left(\frac{V'}{V} \right)^2 , \quad M_{\rm Pl}^2 \frac{V''}{V}$$

  – just how history of a mode depends on time



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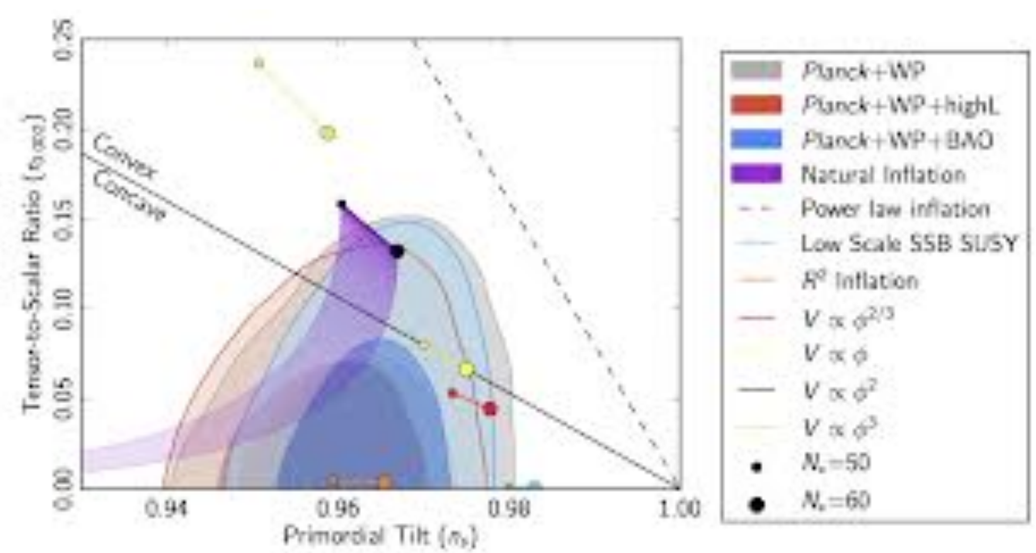

Technically Natural

$$S_\pi = \int d^4x \sqrt{-g} \left[-\frac{M_{\rm Pl}^2 \dot{H}}{c_s^2} \left(\dot{\pi}^2 - c_s^2 \frac{1}{a^2} (\partial_i \pi)^2 \right) \right.$$
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$$\left. + \ \ldots \right],$$

- The EFT is technically natural
  - time-independence of coefficients leads to $\pi \longrightarrow \pi + c$
    - $\Longrightarrow$ relevant operators are naturally small $H(t+\pi) \quad \Rightarrow \quad \ddot{H}\pi^2$
    - Only irrelevant operators $\frac{\dot{\pi}_c^3}{\Lambda_U^2}$, $\Lambda_U^4 \sim c_s^5 \dot{H} M_{\rm Pl}^2$
    - As natural as the theory of true pions.

    - $\Longrightarrow$ Inflation is not tuned (maybe some UV complition is, but not the EFT)

Non-Gaussianities

$$S_\pi = \int d^4x\sqrt{-g}\left[-\frac{M_{\rm Pl}^2\dot H}{c_s^2}\left(\dot\pi^2 - c_s^2\frac{1}{a^2}(\partial_i\pi)^2\right)\right.$$
$$+\frac{\dot H M_{\rm Pl}^2}{c_s^2}(1-c_s^2)\dot\pi\frac{1}{a^2}(\partial_i\pi)^2 - \frac{\dot H M_{\rm Pl}^2}{c_s^2}(1-c_s^2)\left(1+\frac{2}{3}\frac{\tilde c_3}{c_s^2}\right)\dot\pi^3$$
$$-\frac{d_1}{4}HM^3\left(6\,\dot\pi^2+\frac{1}{a^2}(\partial_i\pi)^2\right) - \frac{(d_2+d_3)}{2}M^2\frac{1}{a^4}(\partial_i^2\pi)^2 - \frac{1}{4}d_1M^3\frac{1}{a^4}(\partial_j^2\pi)(\partial_i\pi)^2$$
$$\left.+\ \ldots\right],$$

- Large non-Gaussianities are possible and technically natural

$$\dot\pi^3\ ,\quad \dot\pi(\partial_i\pi)^2\ ,\quad (\partial^2\pi)(\partial\pi)^2$$

  – Having these operators large is not in contrast with de Sitter epoch

  – Demystification of non-Gaussianities (after 25 years!)

    - NG do not need to be tiny, but just small

      – Smallness of NG simply corresponds to weakly coupled field theory at $E\sim H$

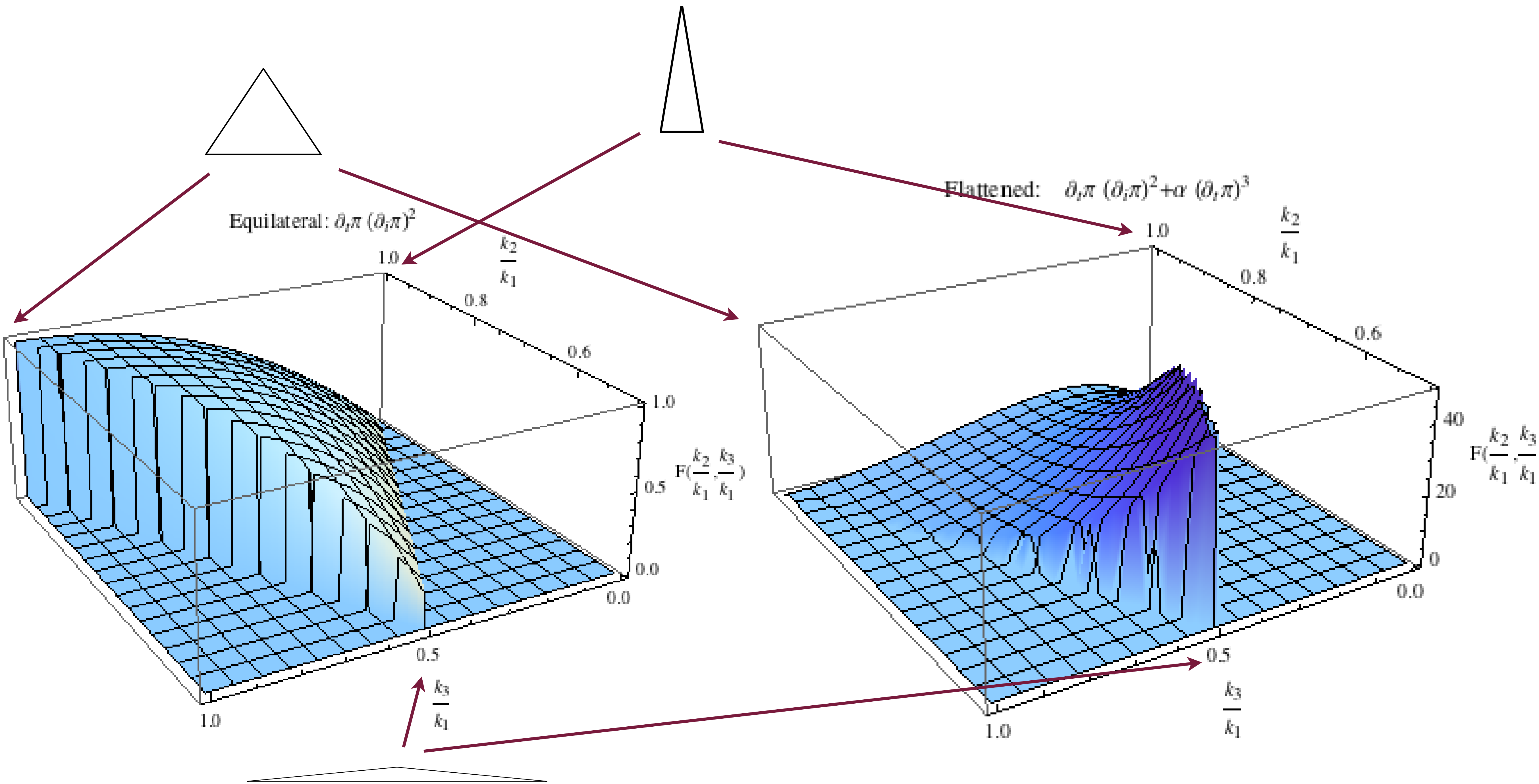
  – EFT automatically gives operators and size:

    - Canonically normalize, and get NG: Example: $\dfrac{\dot\pi_c^3}{\Lambda_U^2} \quad\Rightarrow\quad \text{NG} \simeq f_{\rm NL}\zeta \sim \dfrac{H^2}{\Lambda_U^2}$

      » as for dim=6 operators

Large non-Gaussianites

with Smith and Zaldarriaga, **JCAP2010**



A function of two variables: like a scattering amplitude

There are two templates

With this, we could prove inflation

Symmetries

$$S_\pi = \int d^4x \sqrt{-g} \left[-\frac{M_{\rm Pl}^2 \dot{H}}{c_s^2} \left(\dot{\pi}^2 - c_s^2 \frac{1}{a^2} (\partial_i \pi)^2 \right) \right.$$
$$+ \frac{\dot{H} M_{\rm Pl}^2}{c_s^2} (1 - c_s^2) \dot{\pi} \frac{1}{a^2} (\partial_i \pi)^2 - \frac{\dot{H} M_{\rm Pl}^2}{c_s^2} (1 - c_s^2) \left(1 + \frac{2}{3} \frac{\tilde{c}_3}{c_s^2} \right) \dot{\pi}^3$$
$$- \frac{d_1}{4} H M^3 \left(6 \dot{\pi}^2 + \frac{1}{a^2} (\partial_i \pi)^2 \right) - \frac{(d_2 + d_3)}{2} M^2 \frac{1}{a^4} (\partial_i^2 \pi)^2 - \frac{1}{4} d_1 M^3 \frac{1}{a^4} (\partial_j^2 \pi)(\partial_i \pi)^2$$
$$\left. + \ldots \right],$$

- Connection between speed of sound and non-Gaussianities
  - Invariant block
    $$\text{Invariant block N.1} \sim \dot{\pi}^2 - (\partial_i \pi)^2$$
    $$\text{Invariant block N.2} \sim \dot{\pi}^2 + \dot{\pi}^3 + \dot{\pi} (\partial_i \pi)^2 + (\partial_i \pi)^4$$
  - If dispersion relation is non-relativistic, non-linear terms account for it
    - with interaction term: $$f_{\rm NL}^{\rm equil.,\, orthog.} \sim \frac{1}{c_s^2}$$
  - This has nothing to do with Quantum Mechanics, just Lorentz symmetry.

Consistency Condition

$$S_\pi = \int d^4x \sqrt{-g} \left[-\frac{M_{\rm Pl}^2 \dot{H}}{c_s^2} \left(\dot{\pi}^2 - c_s^2 \frac{1}{a^2} (\partial_i \pi)^2 \right) \right.$$
$$+ \frac{\dot{H} M_{\rm Pl}^2}{c_s^2} (1 - c_s^2) \dot{\pi} \frac{1}{a^2} (\partial_i \pi)^2 - \frac{\dot{H} M_{\rm Pl}^2}{c_s^2} (1 - c_s^2) \left(1 + \frac{2}{3} \frac{\tilde{c}_3}{c_s^2} \right) \dot{\pi}^3$$
$$- \frac{d_1}{4} H M^3 \left(6 \dot{\pi}^2 + \frac{1}{a^2} (\partial_i \pi)^2 \right) - \frac{(d_2 + d_3)}{2} M^2 \frac{1}{a^4} (\partial_i^2 \pi)^2 - \frac{1}{4} d_1 M^3 \frac{1}{a^4} (\partial_j^2 \pi)(\partial_i \pi)^2$$
$$\left. + \ \ldots \right],$$

- Connection between 3-point function and 4-point function

  $$\text{Invariant block} \sim \dot{\pi}^2 + \dot{\pi}^3 + \dot{\pi}(\partial_i \pi)^2 + (\partial_i \pi)^4$$

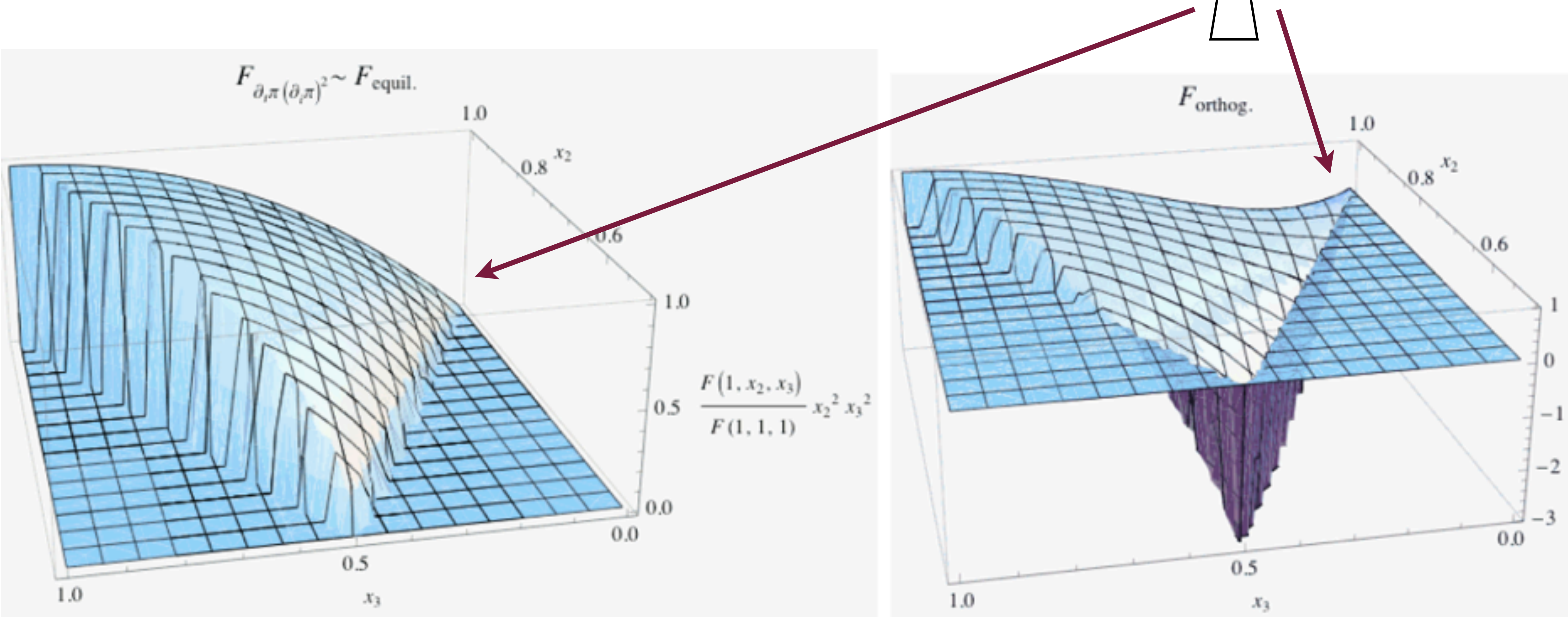
  – If we see $\dot{\pi}(\partial_i \pi)^2 \implies$ predicted $(\partial_i \pi)^4$

Leonardo Senatore
unpublished yet

- A new consistency condition

  – In principle positively testable

Small squeezed limit



- In single clock inflation long mode is locally un-observable

$$ds^2 = -N^2 + a^2(t)e^{2\zeta(x,t)}(dx^i + N^i dt)(dx^j + N^j dt)$$

Maldacena **2003**
Creminelli and Zaldarriaga **2004**
....
Khoury et al **2013** (see Justin Talk)

- Physical effect in $\frac{\dot{\zeta}}{H}$, $\frac{\partial^2\zeta}{a^2H^2}$ and so small

- Series of only-falsifiable (non-positively verifiable) consistency conditions

- Originate from EFT, by using spatial diff. invariance on slice where clock is uniform

Consistent w<-1

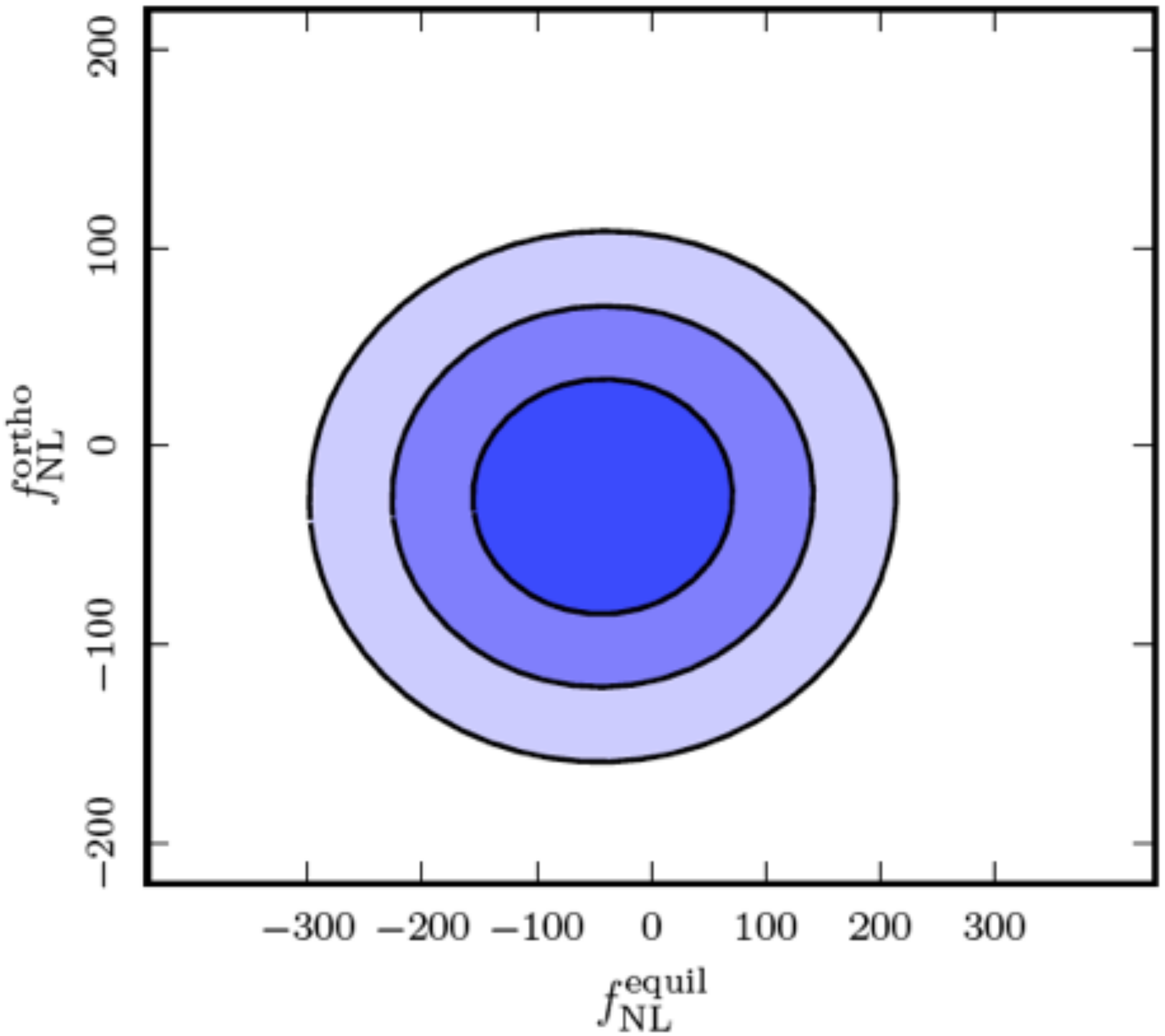
$$S=\int d^4x\sqrt{-g}\left[-\dot{H}M_{\rm Pl}^2(\partial_\mu\pi)^2+M^4\dot{\pi}^2+\bar{M}^3H(\partial_i\pi)^2+\tilde{M}^2(\partial^2\pi)^2\right]$$

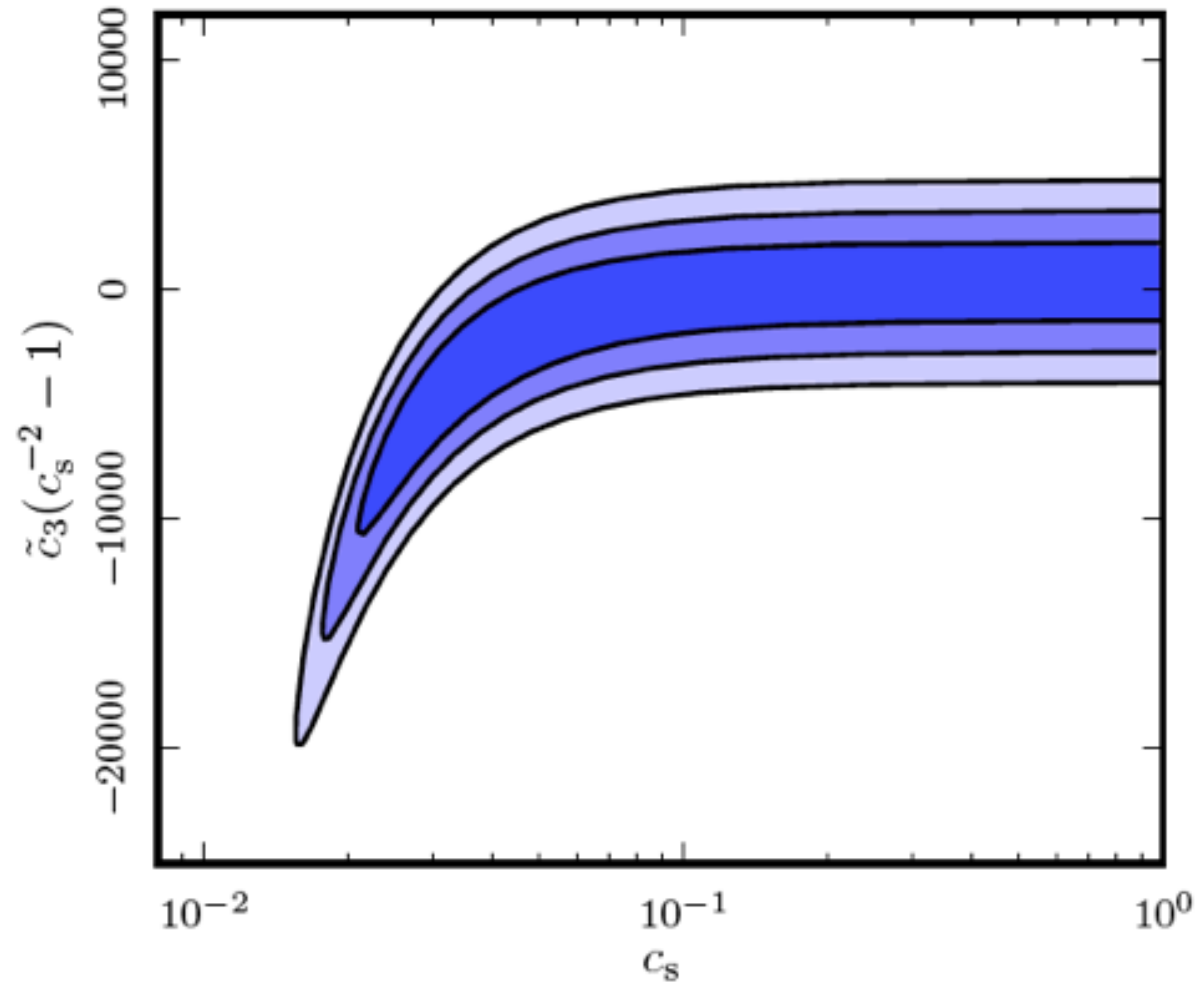
- Phantom dark energy is not consistent
- w<-1 is consistent, but only with the above theory
- w<-1 is not theoretically impossible (from low energy point of view)
- Null Energy Condition can be violated
  - and all ways found in this context
- If possible, let us not call it phantom. Call it `w<-1-dark-energy' or anything you like.

Then Planck came...

Limits in terms of parameters of a Lagrangian

- $$S = \int d^4x \sqrt{-g}\left[-\frac{M_{\rm Pl}^2 \dot{H}}{c_s^2}\left(\dot{\pi}^2 - c_s^2\frac{(\partial_i\pi)^2}{a^2}\right) + (M_{\rm Pl}^2\dot{H})\frac{1-c_s^2}{c_s^2}\left(\frac{\dot{\pi}(\partial_i\pi)^2}{a^2} + \frac{A}{c_s^2}\dot{\pi}^3\right) + \cdots\right]$$





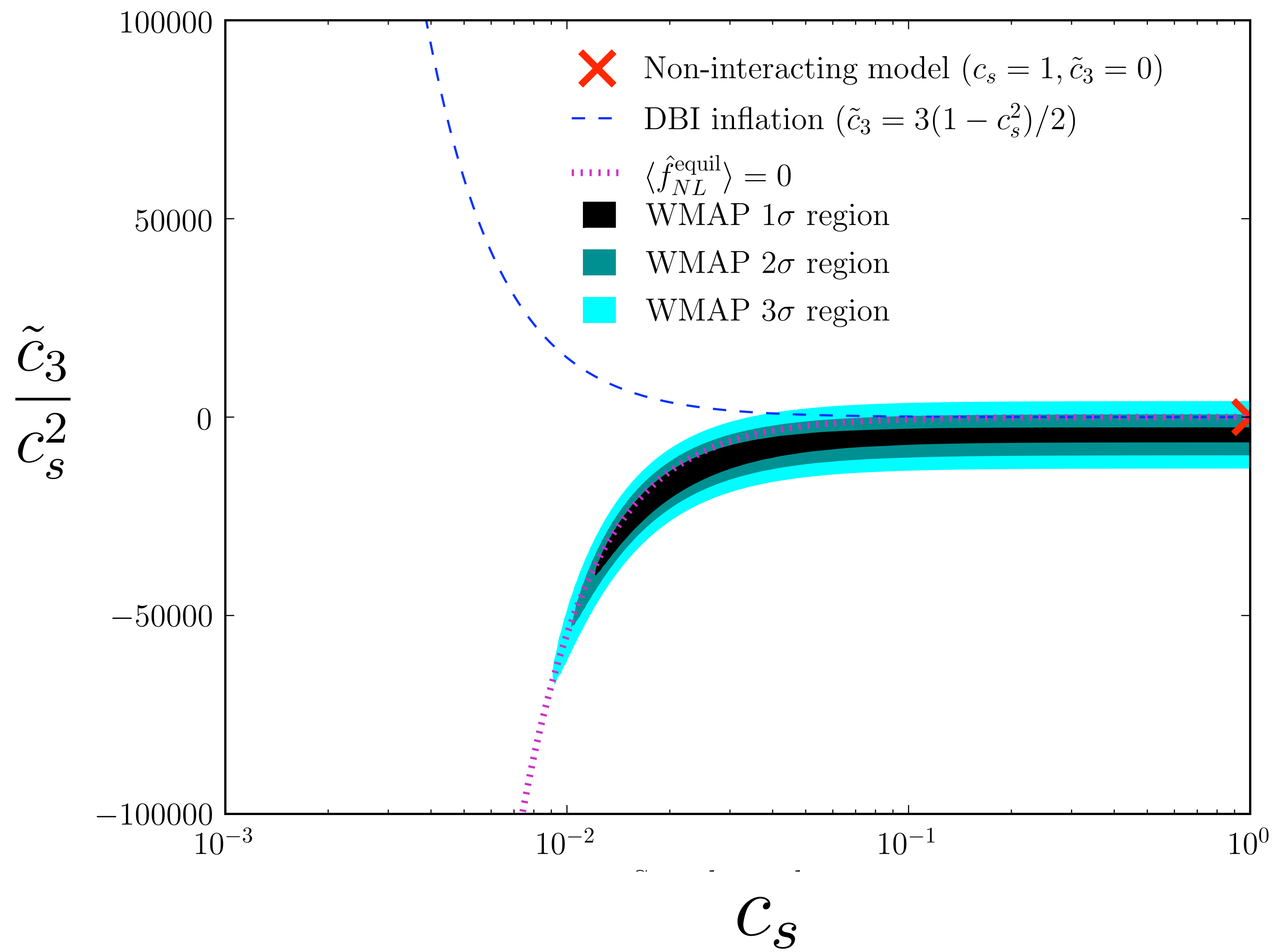
- These are contour plots of parameters of a fundamental Lagrangian
- Same as in particle accelerator Precision Electroweak Tests.
- Thanks to the EFT: A qualitatively new (and superior) way to use the cosmological data
- Universal limit $c_s \gtrsim 0.02$

with Smith and Zaldarriaga, **JCAP2010**
Planck Collaboration **2013**

(Optimal) Limits on the parameters of the Lagrangian

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

- Limits on f_{NL}'s get translated into limits on the parameters



With Smith and Zaldarriaga, **JCAP2010**

Very similar in spirit to **Precision Electroweak Tests** **(Complete Connection to Particle Physics)**

$$\frac{1}{c_s^2}\dot\pi(\partial_i\pi)^2+\frac{\tilde c_3}{c_s^2}\dot\pi^3$$

- Bound on speed of sound $c_s \gtrsim 0.011$!

(Optimal) Limits on the parameters of the Lagrangian

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

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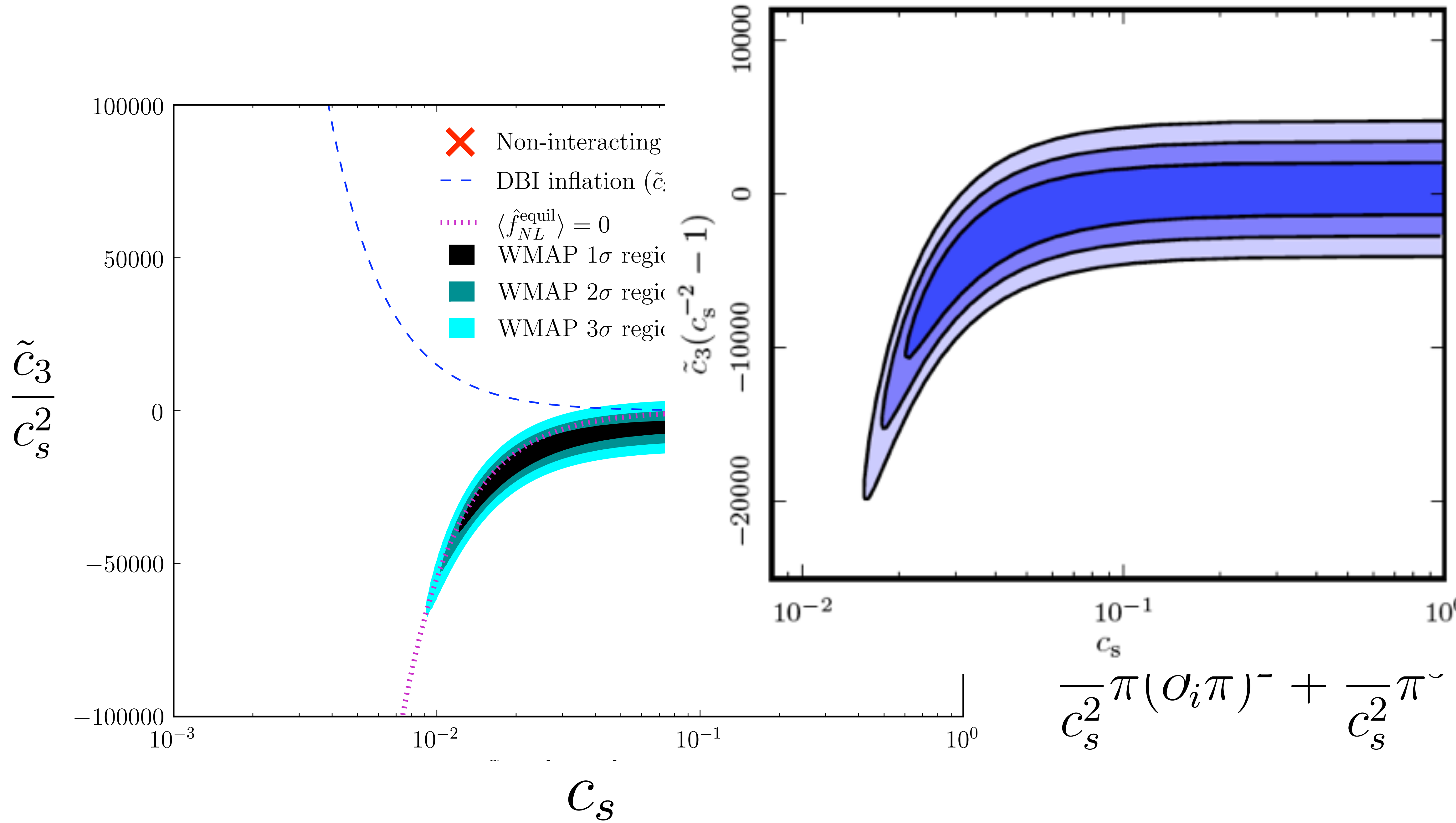
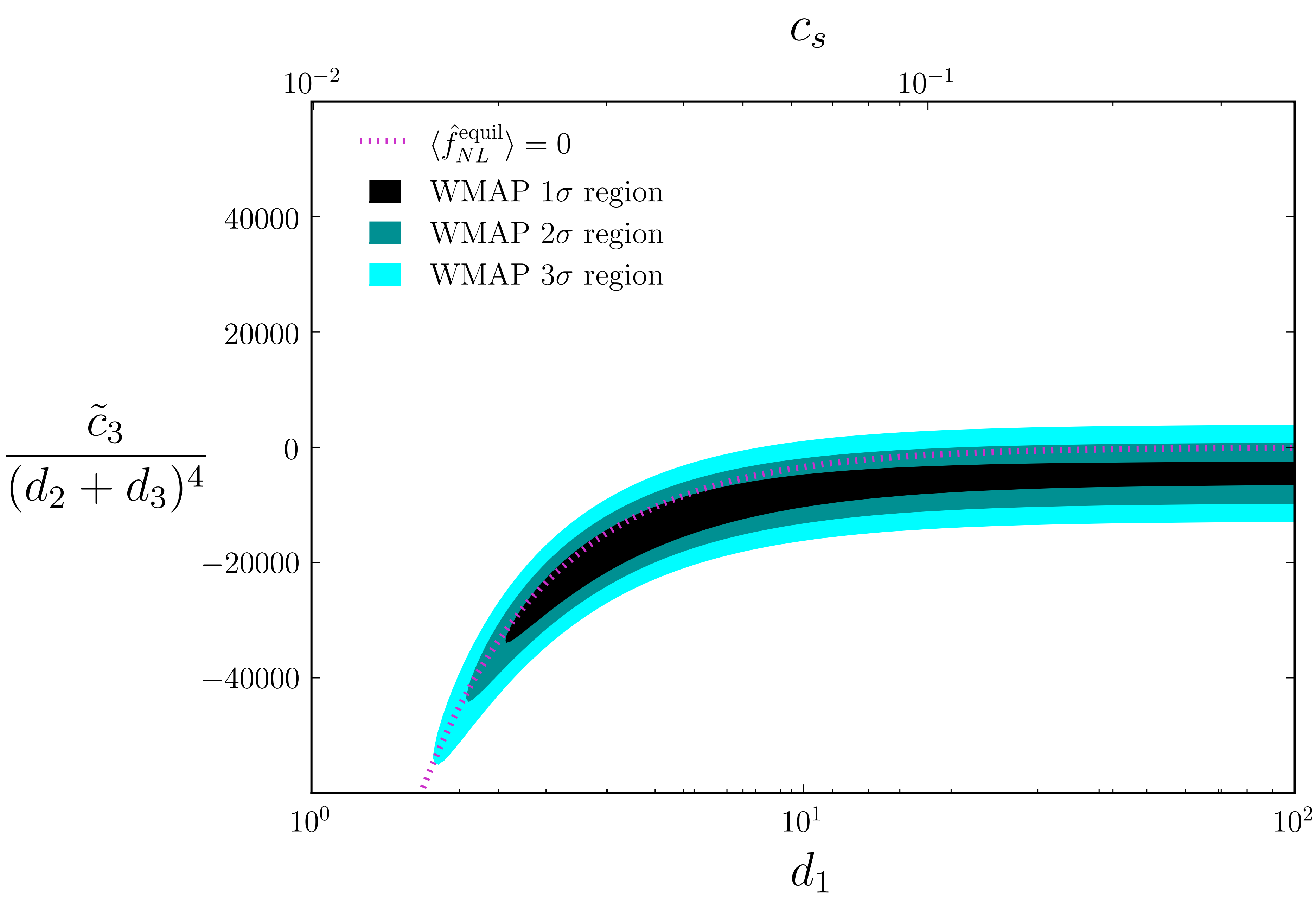


- Bound on speed of sound $c_s \gtrsim 0.011$!

(Optimal) Limits on the parameters of the Lagrangian

- Close to de Sitter. $d_1\,\delta g^{00}\delta K_i^i$
- Dispertion relation: $\omega^2 = c_s^2 k^2 \qquad c_s^2 = d_1 \frac{H}{M} \ll 1$



With Smith and Zaldarriaga, **JCAP2010**

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(Optimal) Limits on the parameters of the Lagrangian

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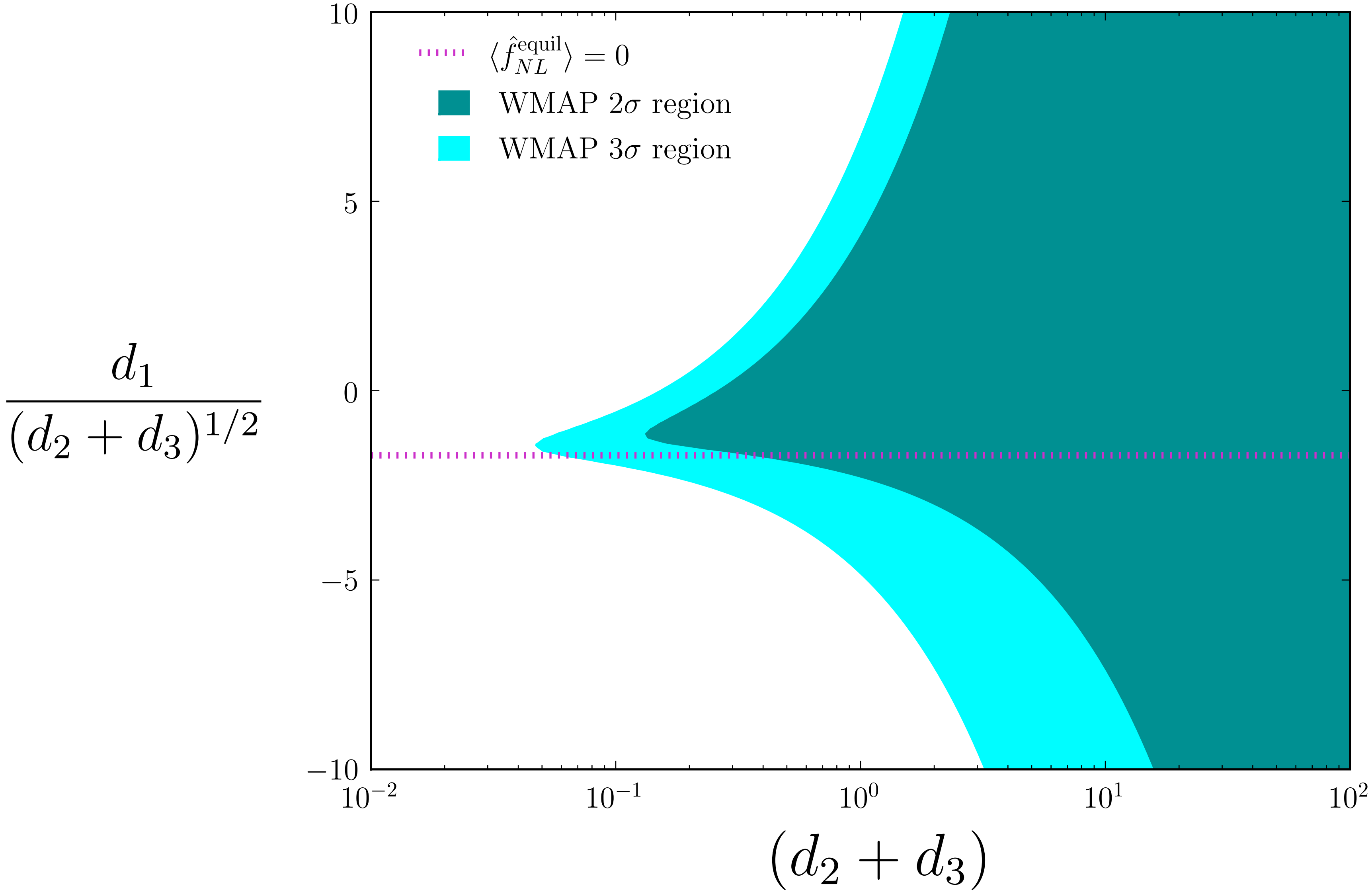
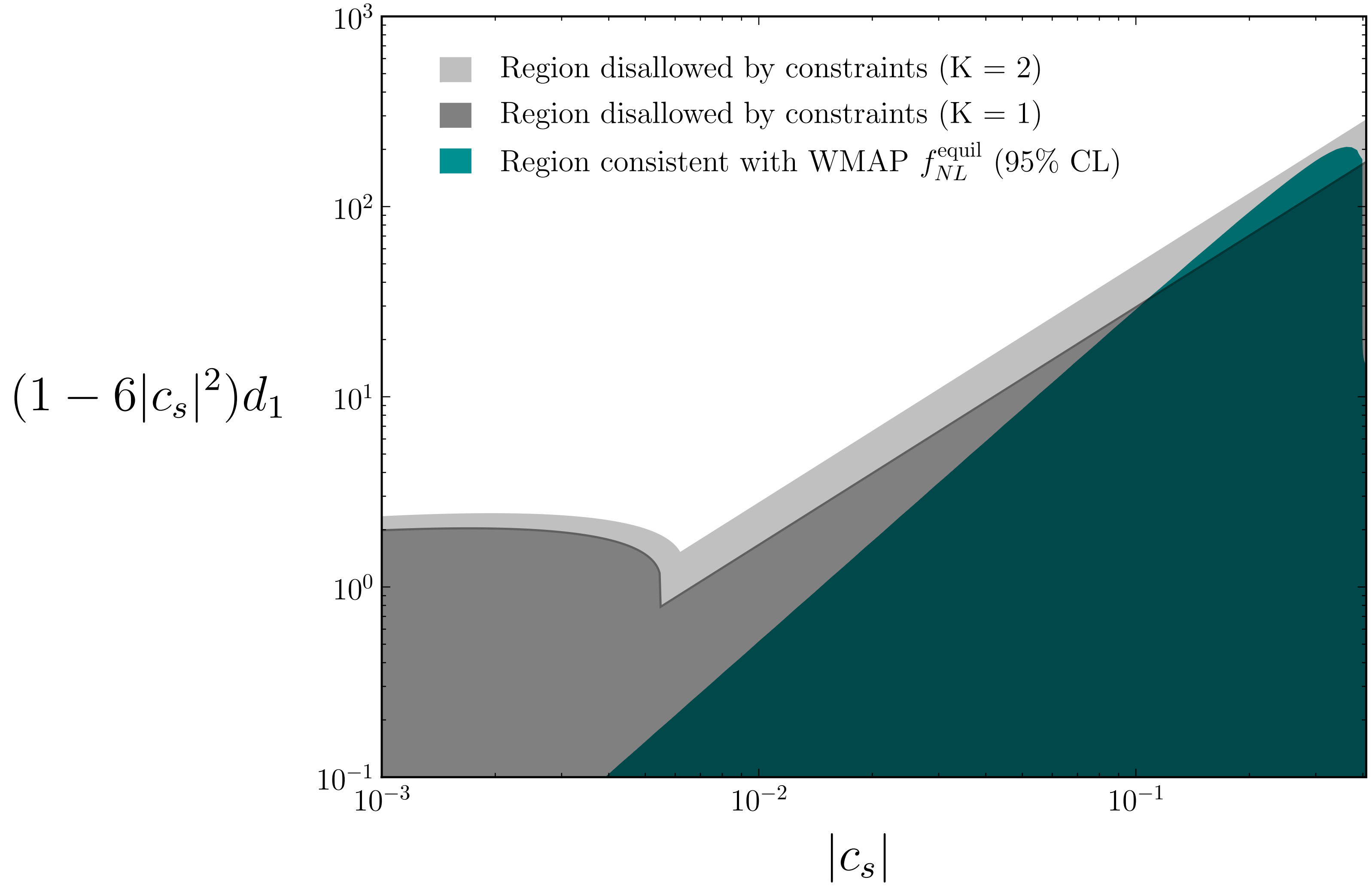


With Smith and Zaldarriaga, **JCAP2010**

Very similar in spirit to **Precision Electroweak Tests** **(Complete Connection to Particle Physics)**

(Optimal) Limits on the parameters of the Lagrangian

- Close to de Sitter.
- Negative c_s^2 due to $d_1 < 0$ $\qquad c_s^2 = d_1 \frac{H}{M} \ll 1$
- Ruled out at 95% CL.

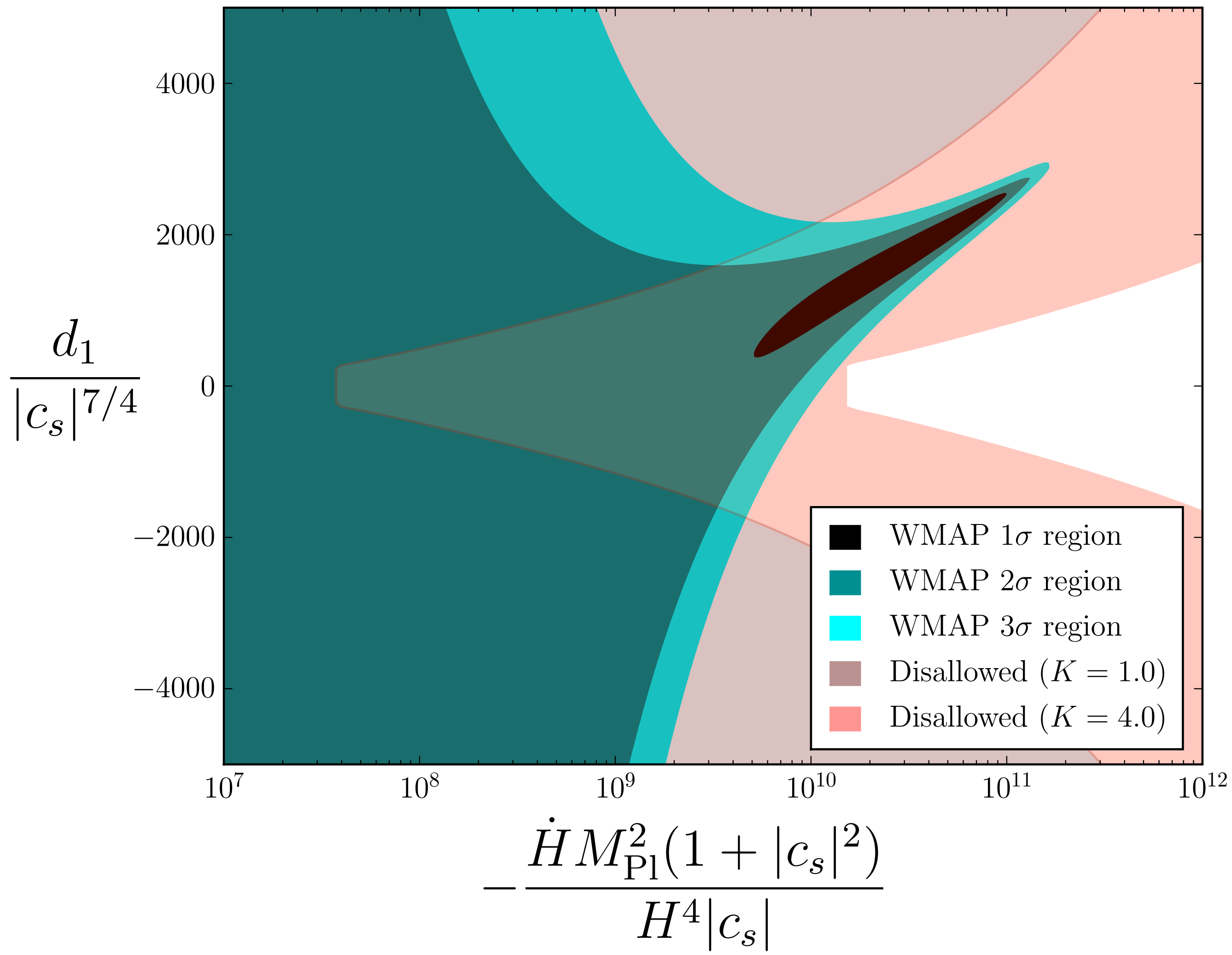


With Smith and Zaldarriaga, **JCAP2010**

Very similar in spirit to **Precision Electroweak Tests** **(Complete Connection to Particle Physics)**

(Optimal) Limits on the parameters of the Lagrangian

- Close to de Sitter.
- Negative c_s^2 due to $\dot{H} > 0$ $\quad\quad \dot{H} M_{\rm Pl}^2 (\partial_i \pi)^2$
- Ruled out at 95% CL.



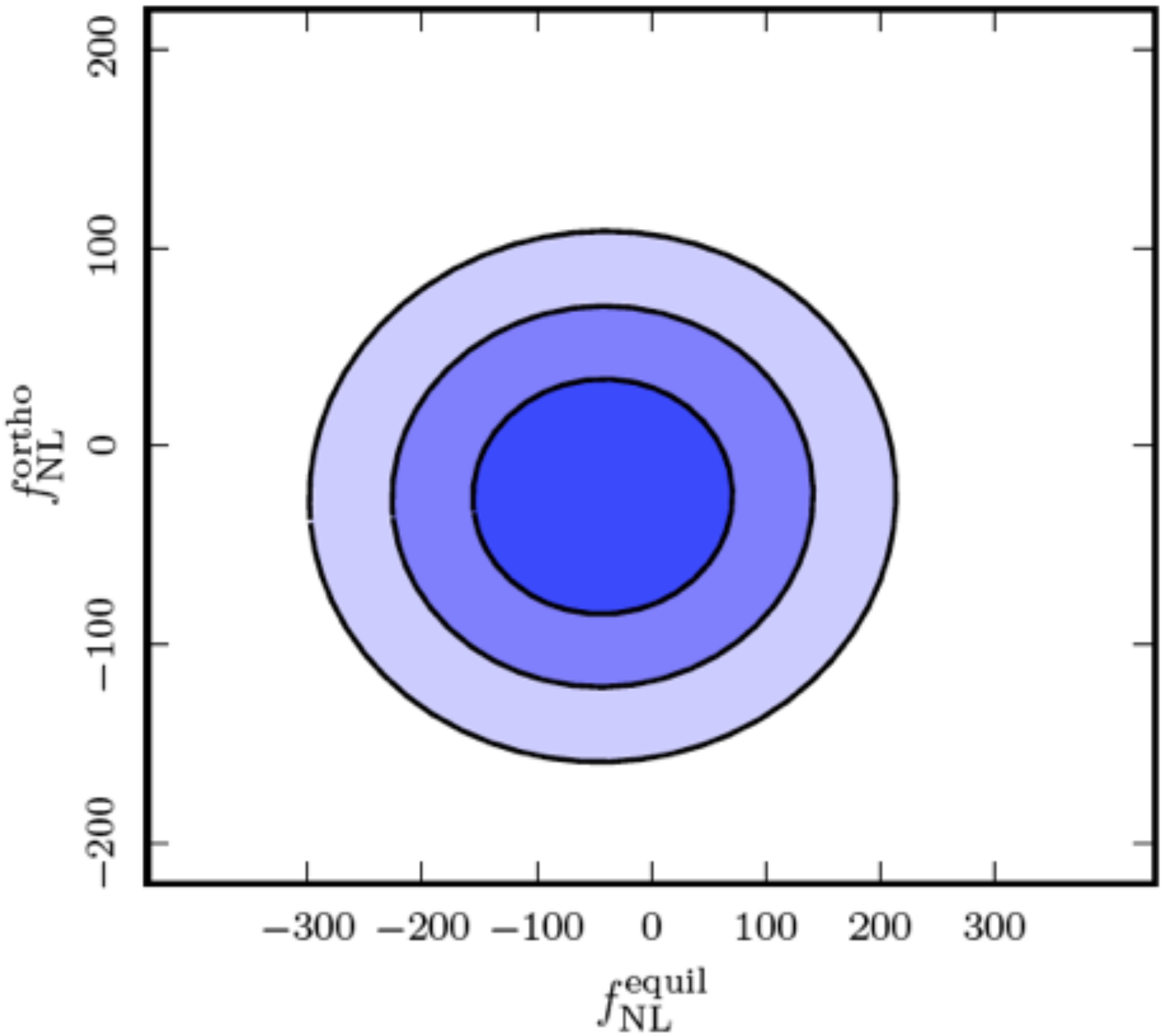
With Smith and Zaldarriaga, **JCAP2010**

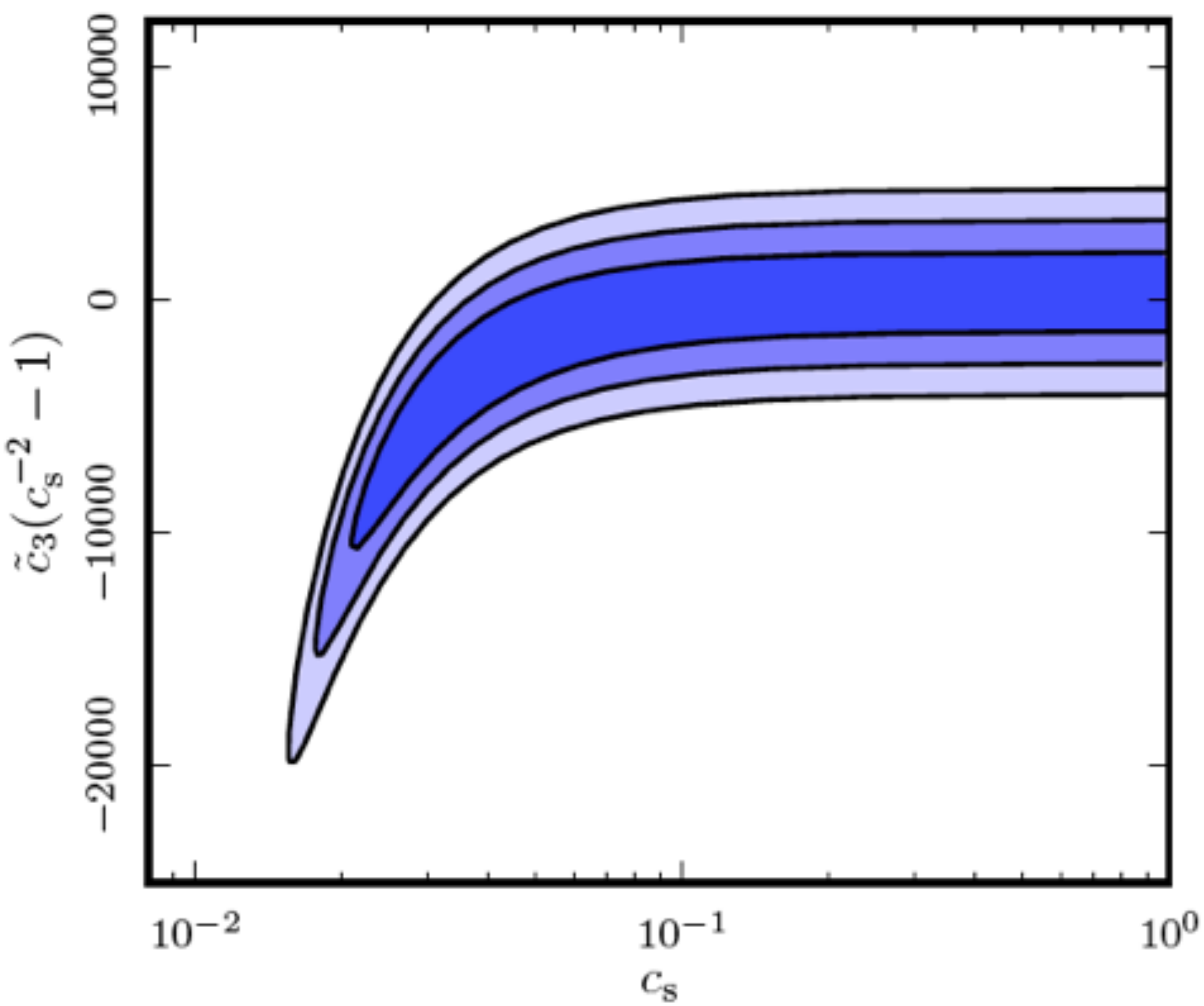
Very similar in spirit to **Precision Electroweak Tests** **(Complete Connection to Particle Physics)**

Limits in terms of parameters of a Lagrangian

- The Effective Field Theory of Inflation

$$S=\int d^4x\,\sqrt{-g}\left[-\frac{M_{\rm Pl}^2\dot H}{c_s^2}\left(\dot\pi^2-c_s^2\frac{(\partial_i\pi)^2}{a^2}\right)+(M_{\rm Pl}^2\dot H)\frac{1-c_s^2}{c_s^2}\left(\frac{\dot\pi(\partial_i\pi)^2}{a^2}+\frac{A}{c_s^2}\dot\pi^3\right)+\cdots\right]$$





with Smith and Zaldarriaga, **JCAP2010**
Planck Collaboration **2013**

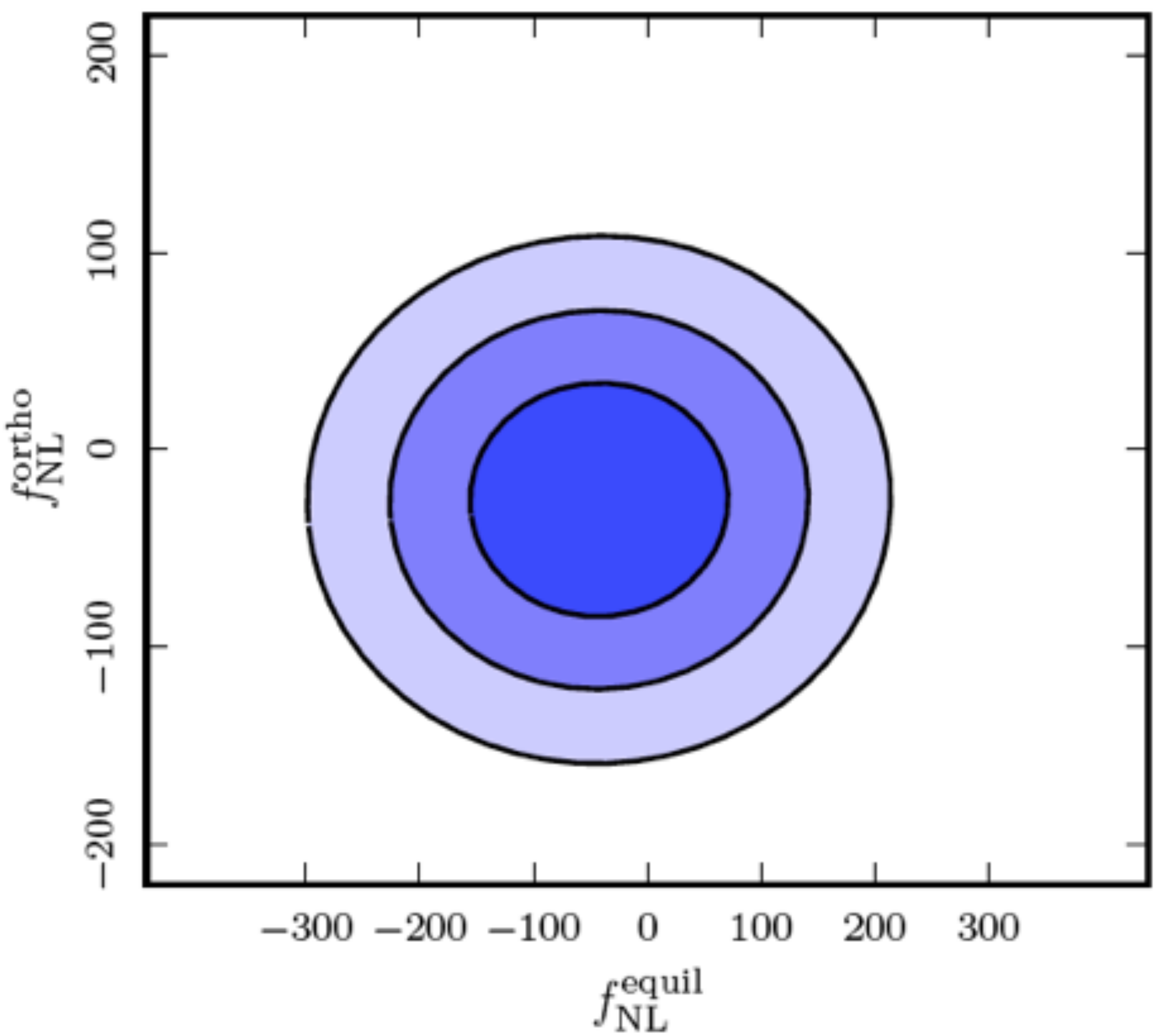
- This is great, but the phenomenology is reacher
- Cutoff $\quad \frac{\dot\pi_c^3}{\Lambda_U^2} \quad \Rightarrow \quad {\rm NG}\simeq f_{\rm NL}\zeta\sim\frac{H^2}{\Lambda_U^2}$

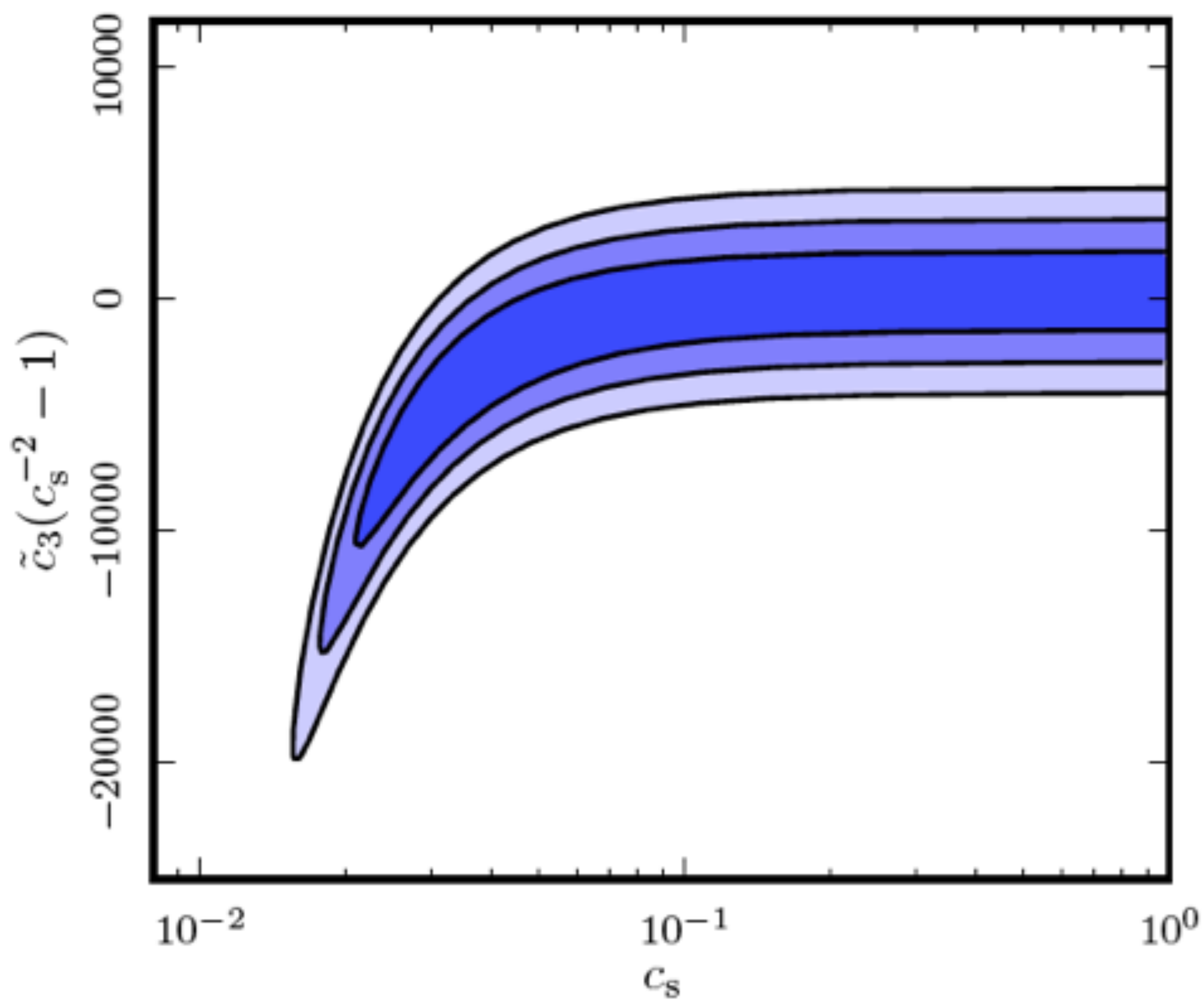
$$\Lambda_U^2\gtrsim\Lambda^2_{\rm min}\simeq 10^4H^2$$

Limits in terms of parameters of a Lagrangian

- The Effective Field Theory of Inflation

$$S = \int d^4x\,\sqrt{-g}\left[-\frac{M_{\rm Pl}^2\dot H}{c_s^2}\left(\dot\pi^2 - c_s^2\frac{(\partial_i\pi)^2}{a^2}\right) + (M_{\rm Pl}^2\dot H)\frac{1-c_s^2}{c_s^2}\left(\frac{\dot\pi(\partial_i\pi)^2}{a^2} + \frac{A}{c_s^2}\dot\pi^3\right) + \cdots\right]$$





with Smith and Zaldarriaga, **JCAP2010**
Planck Collaboration **2013**

- This is great, but the phenomenology is reacher
- Cutoff $\quad \frac{\dot\pi_c^3}{\Lambda_U^2} \quad \Rightarrow \quad \text{NG} \simeq f_{\rm NL}\zeta \sim \frac{H^2}{\Lambda_U^2}$

$$\Lambda_U^2 \gtrsim \Lambda_{\rm min}^2 \simeq 10^4 H^2$$

What has Planck done to NG?

(that is to one of two main ways to test inflation)

Let us look at LHC

- Two thresholds for detection. Awesome!

- By unitarity of WW scattering

$$\Lambda_U \sim \frac{m_W}{g} \lesssim 1\ \text{TeV} \quad \Rightarrow \quad m_{\text{Higgs}} \sim g_{\text{weak}} \times 1\ \text{TeV} \ll 1\ \text{TeV}$$

  – Something was guaranteed

- If Higgs found, then tuning problem:

$$\delta m_{\text{Higgs, quantum}} \sim \Lambda_U^{\text{new}} \quad \Rightarrow \quad \text{New Physics (or new principle) guaranteed}$$

- So, with LHC (or SSC), huge learning guaranteed

  – $1\ \text{TeV}$ is a threshold for discovery

Let us go to NG

- Threshold for detections $\frac{\dot{\pi}_c^3}{\Lambda_U^2} \quad \Rightarrow \quad \text{NG} \simeq f_{\rm NL}\zeta \sim \frac{H^2}{\Lambda_U^2}$

$$\Lambda_U \lesssim \Lambda_{U,\,\text{threshold}} \quad \Rightarrow \quad f_{\rm NL} \gtrsim \frac{H^2}{\Lambda^2_{U,\,\text{threshold}}}$$

- We do not have a compelling threshold (we just make them possible!)
- We have lower bound: $\Lambda_{U,\,\text{threshold}} \gtrsim H \quad \Rightarrow \quad f_{\rm NL} \lesssim 10^5$
  - This is the only correct prediction of Inflation on NG: weakly coupled field theory
- Minimal size of NG: from gravity

Maldacena
JCAP2003

$$f_{\rm NL,\,minimal} \sim \epsilon \sim 10^{-2} \ll 10 \sim f_{\rm NL,\,Planck}$$

- Another threshold is

$$f_{\rm NL}^{\text{equil., orthog.}} \sim 1 \quad \Rightarrow \quad \Lambda_U^4 \gtrsim \dot{H} M_{\rm Pl}^2 \sim \dot{\phi}^2_{\rm slow-roll}$$

  - With this we would be allowed to glue the EFT to slow-roll inflation
    - the bottom-up `verification' of slow-roll inflation (with assumption)
  - this is more than a factor of 10 far away.

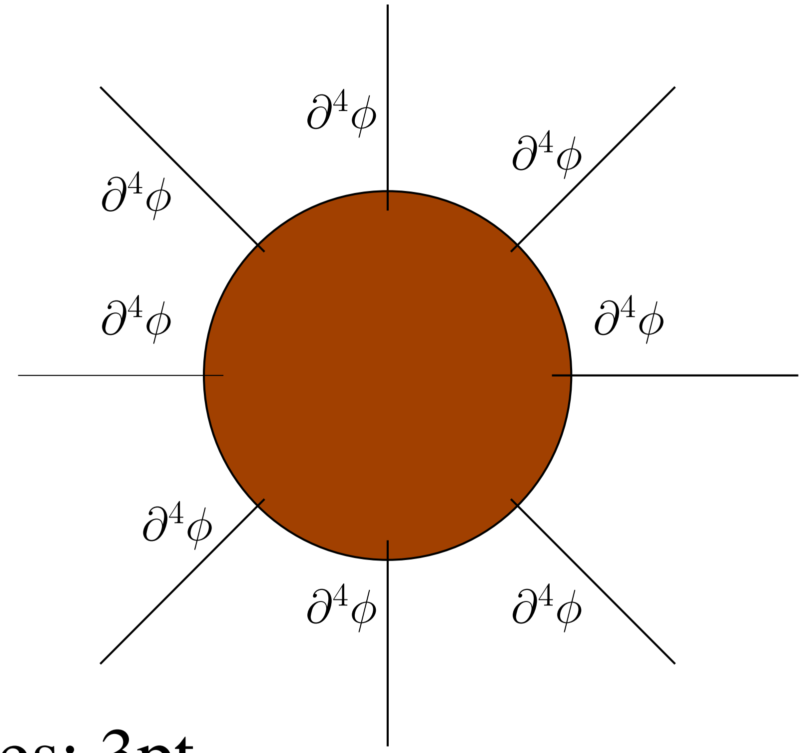
What has Planck done to theory?

- Planck improve limits wrt WMAP by a factor of ~3.
- Since $$\mathrm{NG} \sim \frac{H^2}{\Lambda_U^2} \quad \Rightarrow \quad \Lambda_U^{\mathrm{min,\,Planck}} \simeq 2\,\Lambda_U^{\mathrm{min,\,WMAP}}$$
- Given the absence of known or nearby threshold, this is not much.
- Planck is great
- but Planck is not good enough
  - not Plank's fault, but Nature's faults
    - Please complain with Nature
- Planck was an opportunity for a detection, not much an opportunity to change the theory in absence of detection
- On theory side, little changes
  - contrary for example to LHC, where any result is changing the theory

Are we done with Planck?

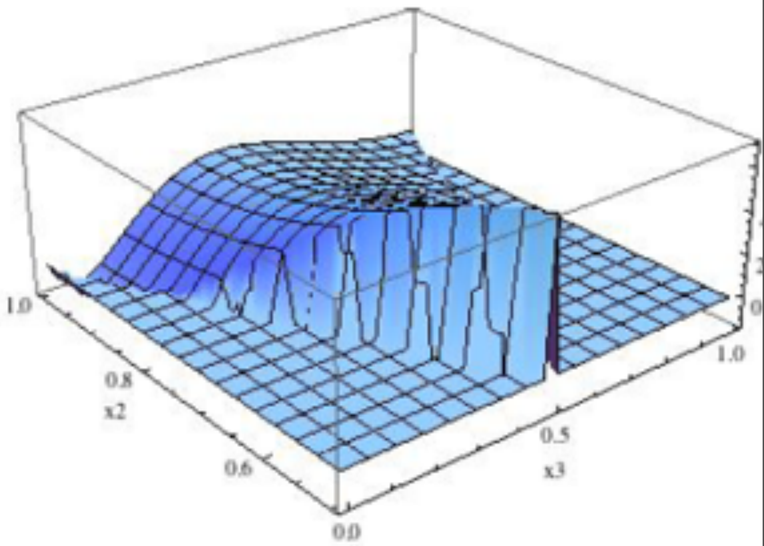
There is more to look for!

- Apart for improvement from polarization
- More 3-point functions
  - This theory is technically natural



$$\int d^3x \left[(\partial\phi)^2 + \frac{1}{M^{4n}}(\partial^n\phi)^4\right]$$

  - Apply this to the EFT of Inflation: many new shapes: 3pt (i.e. different for not-small part of parameter space).



With Berbabany, Mibabaye, and Smith
in completion

- One 4-point function $\dot{\pi}^4$ With Zaldarriaga **JCAP2010**
  - huge information

- Any of these changes Planck press release

What about additional fields?

The EFT of multifield inflation

- If they are observed, just couple to the Inflaton

$$S \sim \int (\partial\sigma)^2 + \dot\sigma^3 + \dot\pi(\partial\sigma)^2 + \ldots$$

With Zaldarriaga,
JHEP2012

- Find signatures
  - large quartic interactions

MultiField

Operator	Dispersion		Type	Origin	Squeezed L.
	$w = c_s k$	$w \propto k^2$			
$\dot\sigma^4$, $\dot\sigma^2(\partial_i\sigma)^2$, $(\partial_i\sigma)^4$	X		Ad., Iso.	Ab., non-Ab.	
$(\partial_\mu\sigma)^4$	X		Ad., Iso.	Ab., non-Ab.	
σ^4	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$, S.*	X
$\dot\sigma\sigma^3$	X	X	Ad., Iso.	Ab.$_s^\dagger$, non-Ab.$_s^\dagger$.	X
$\sigma^2\dot\sigma^2$, $\sigma^2(\partial_i\sigma)^2$	X	X†*	Ad.†*, Iso.	non-Ab, Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$,	X
$\sigma^2(\partial_\mu\sigma)^2$	X		Ad.†*, Iso.	non-Ab, Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$, S.*	X
$\sigma(\partial\sigma)^3$	X		Iso.	non-Ab.$_s^\star$.	X
$\dot\sigma^3$, $\dot\sigma(\partial_i\sigma)^2$	X		Ad., Iso.	Ab., non-Ab.	
$\dot\sigma(\partial_i\sigma)^2$, $\partial_j^2\sigma(\partial_i\sigma)^2$		X	Ad., Iso.	Ab.	
σ^3	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$, S, R	X
$\dot\sigma\sigma^2$	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$	X
$\sigma\dot\sigma^2$, $\sigma(\partial_i\sigma)^2$	X	X	Ad., Iso.	Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$	X
$\sigma(\partial_\mu\sigma)^2$	X		Ad., Iso.	Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$.	X

Single Field

Operator	Dispersion		Squeezed L.
	$w = c_s k$	$w \propto k^2$	
$\dot\pi^4$	X		
$(\partial_j^2\pi)^4$, $\dot\pi(\partial_j^2\pi)^3$, ...		X	
$\dot\pi^3$, $\dot\pi(\partial_i\pi)^2$	X		
$\dot\pi(\partial_i\pi)^2$, $\partial_j^2\pi(\partial_i\pi)^2$		X	

data analysis

with Smith, Zaldarriaga,
in progress

The EFT of multifield inflation

- If they are observed, just couple to the Inflaton

$$S \sim \int (\partial\sigma)^2 + \dot{\sigma}^3 + \dot{\pi}(\partial\sigma)^2 + \dots$$

With Zaldarriaga,
JHEP2012

- Find signatures
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MultiField

Operator	Dispersion		Type	Origin	Squeezed L.
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σ^4	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$, S.*	X
$\dot{\sigma}\sigma^3$	X	X	Ad., Iso.	Ab.$_s^\dagger$, non-Ab.$_s^\dagger$.	X
$\sigma^2\dot{\sigma}^2$, $\sigma^2(\partial_i\sigma)^2$	X	X†*	Ad.†*, Iso.	non-Ab, Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$,	X
$\sigma^2(\partial_\mu\sigma)^2$	X		Ad.†*, Iso.	non-Ab, Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$, S.*	X
$\sigma(\partial\sigma)^3$	X		Iso.	non-Ab.$_s^\star$.	X
$\dot{\sigma}^3$, $\dot{\sigma}(\partial_i\sigma)^2$	X		Ad., Iso.	Ab., non-Ab.	
$\dot{\sigma}(\partial_i\sigma)^2$, $\partial_j^2\sigma(\partial_i\sigma)^2$		X	Ad., Iso.	Ab.	
σ^3	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$, S, R	X
$\dot{\sigma}\sigma^2$	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$	X
$\sigma\dot{\sigma}^2$, $\sigma(\partial_i\sigma)^2$	X	X	Ad., Iso.	Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$	X
$\sigma(\partial_\mu\sigma)^2$	X		Ad., Iso.	Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$.	X

Single Field

Operator	Dispersion		Squeezed L.
	$w = c_s k$	$w \propto k^2$	
$\dot{\pi}^4$	X		
$(\partial_j^2\pi)^4$, $\dot{\pi}(\partial_j^2\pi)^3$, ...		X	
$\dot{\pi}^3$, $\dot{\pi}(\partial_i\pi)^2$	X		
$\dot{\pi}(\partial_i\pi)^2$, $\partial_j^2\pi(\partial_i\pi)^2$		X	

data analysis

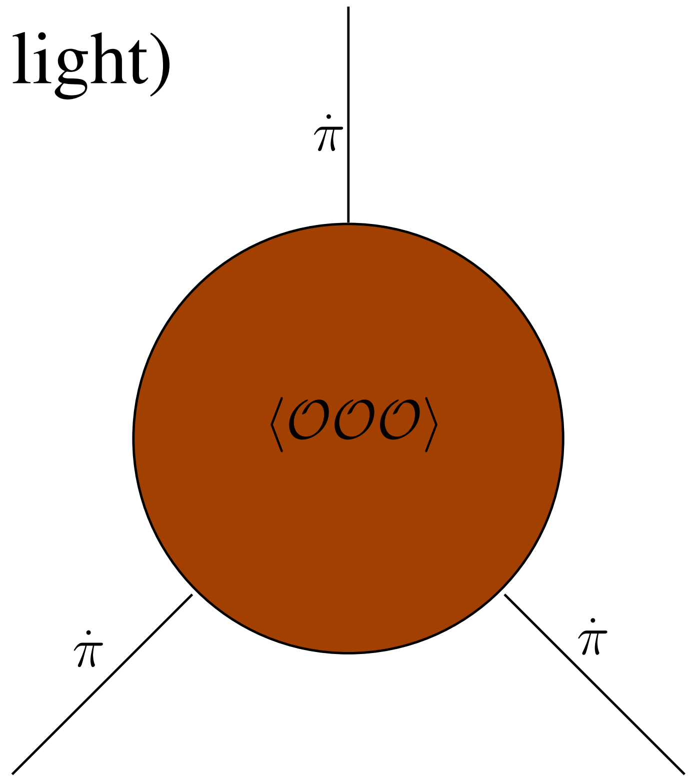
with Smith, Zaldarriaga,
in progress

The EFT of multifield inflation

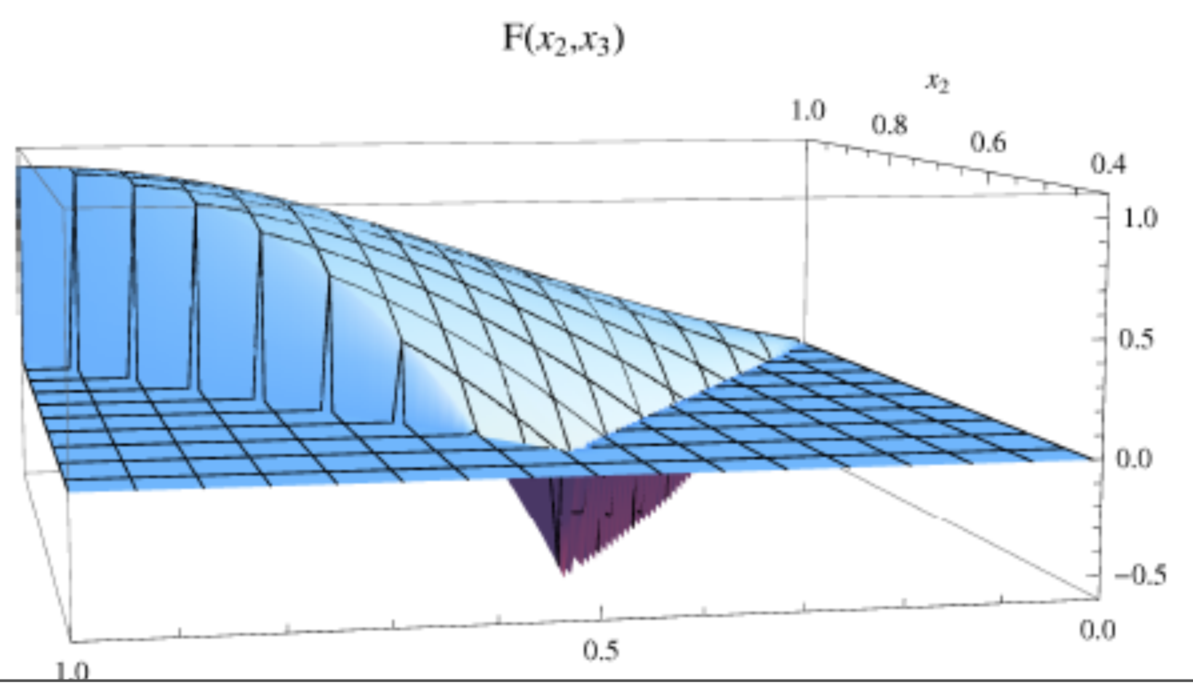
with Nacir, Porto, and Zaldarriaga
JHEP2012

- If they are not observed (but they are light)

$$S_{int} \sim \int \dot{\pi}\, \mathcal{O}$$



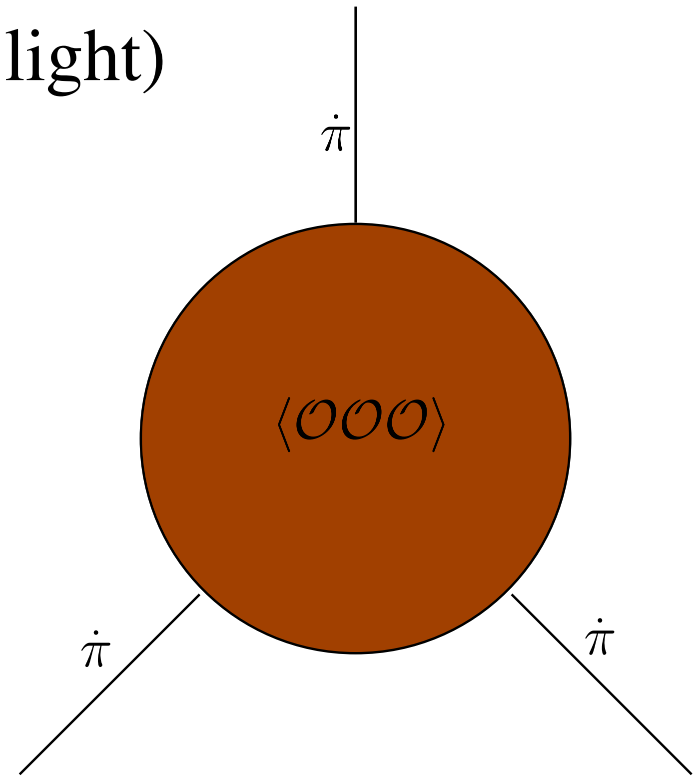
- Dissipative Effects
  - Usual relation $\gamma\dot{\pi} \to \gamma(\partial_i \pi)^2 \quad \Rightarrow \quad f_{\rm NL} \sim \frac{\gamma}{H}$
  - ~orthogonal template



The EFT of multifield inflation

- If they are not observed (but they are light)

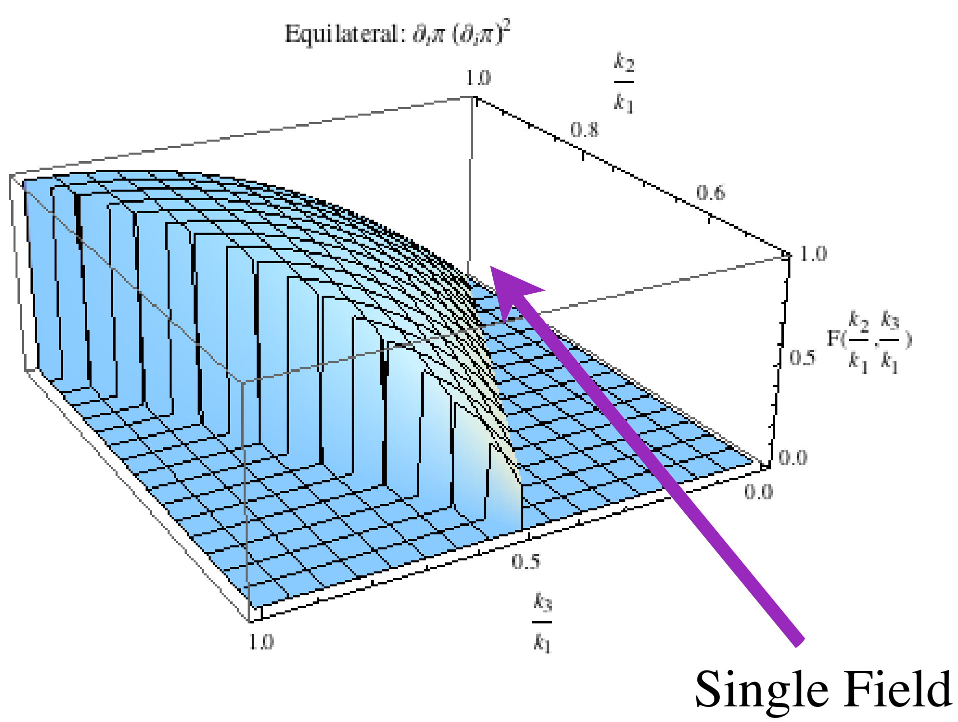
$$S_{int} \sim \int \dot{\pi}\, \mathcal{O}$$

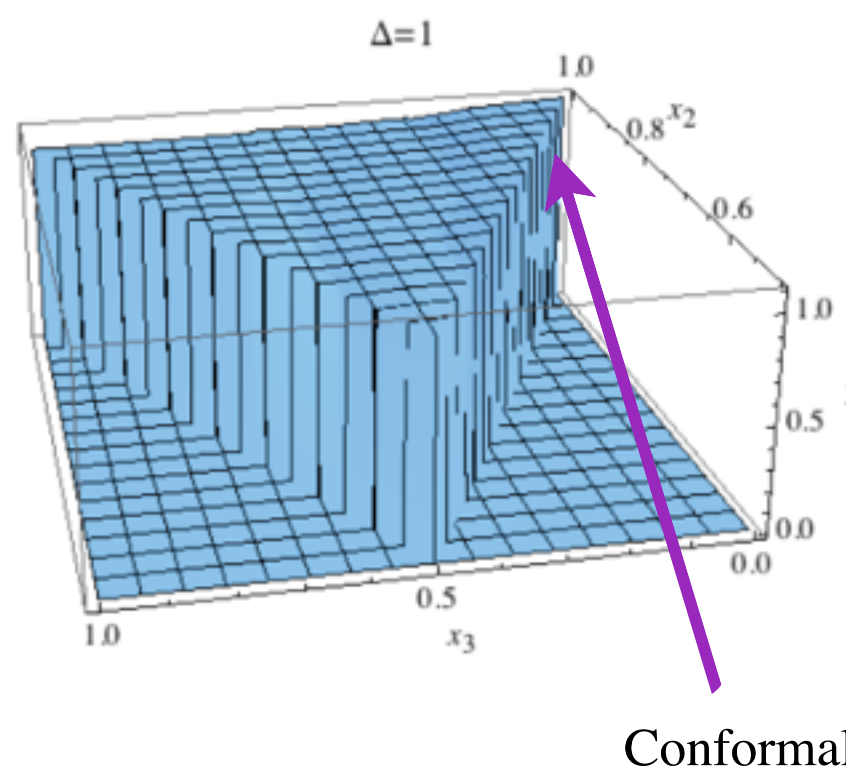


with Nacir, Porto, and Zaldarriaga **JHEP2012**

- Conformally coupled sector (strong coupling)

with Green, Lewandowski, Silverstein, and Zaldarriaga **1301**



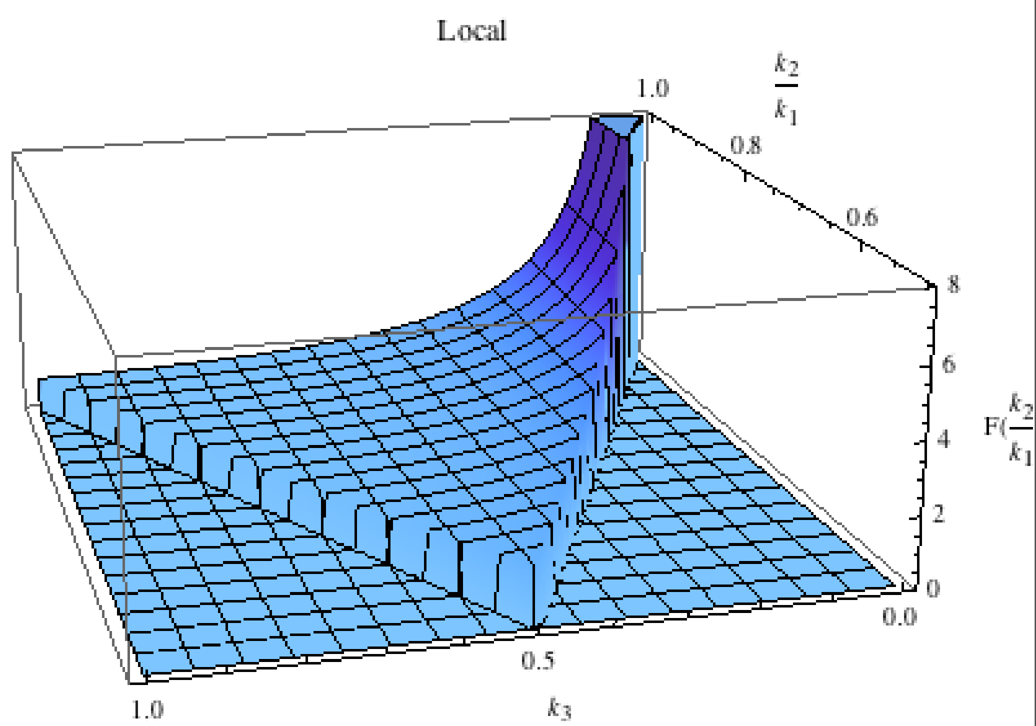


Conversion to adiabatic mode

- Conversion mechanism usually happens when all modes are outside of the horizon
  - modulation of reheating temperature
  - modulation of eq. of state
  - modulation of length of inflation
  - ...

$$\zeta(\vec{x}) = \epsilon_{\text{efficiency}} \left(\frac{\sigma(\vec{x})}{M} + c_2 \left(\frac{\sigma(\vec{x})}{M} \right)^2 + \dots \right) \quad \Rightarrow \quad f_{\text{NL}}^{\text{loc.}} \sim \frac{1}{\epsilon_{\text{efficiency}}} \gtrsim 1$$

- This is threshold to `rule-out' natural multi-field inflation
  - we should target it!



Developing the Phenomenology of Inflation

- Higher derivative interactions, ex: $(\partial^4\pi)^3$ — Bartolo, Fasiello, Matarrese, Riotto **2010,2010**; with Behbahani, Mirbabayi **in progress**
- Discrete shift-symmetry — with Behbahani, Mirbabayi **2012**
- Collective Breaking — Behbahani, Green **2012**
- Soft limits — with Cheung, Fitzpatrick, Kaplan **2008**; Creminelli, Norena, Simonovic **2012**; Baumann and Green **2011, 2012**
- Effects of massive fields — with Zaldarriaga **2012**; Acucarro, Palma, Patil **2012**; Noumi, Yagamuchi, Yokoyama **2012**
- Susy — with Zaldarriaga **2010**; Baumann and Green **2011**
- Loops — with Zaldarriaga **2010,2012,2012**
- EFT of acceleration — with Creminelli, Luty and Nicolis **2007**; Vernizzi and Piazza **2012**

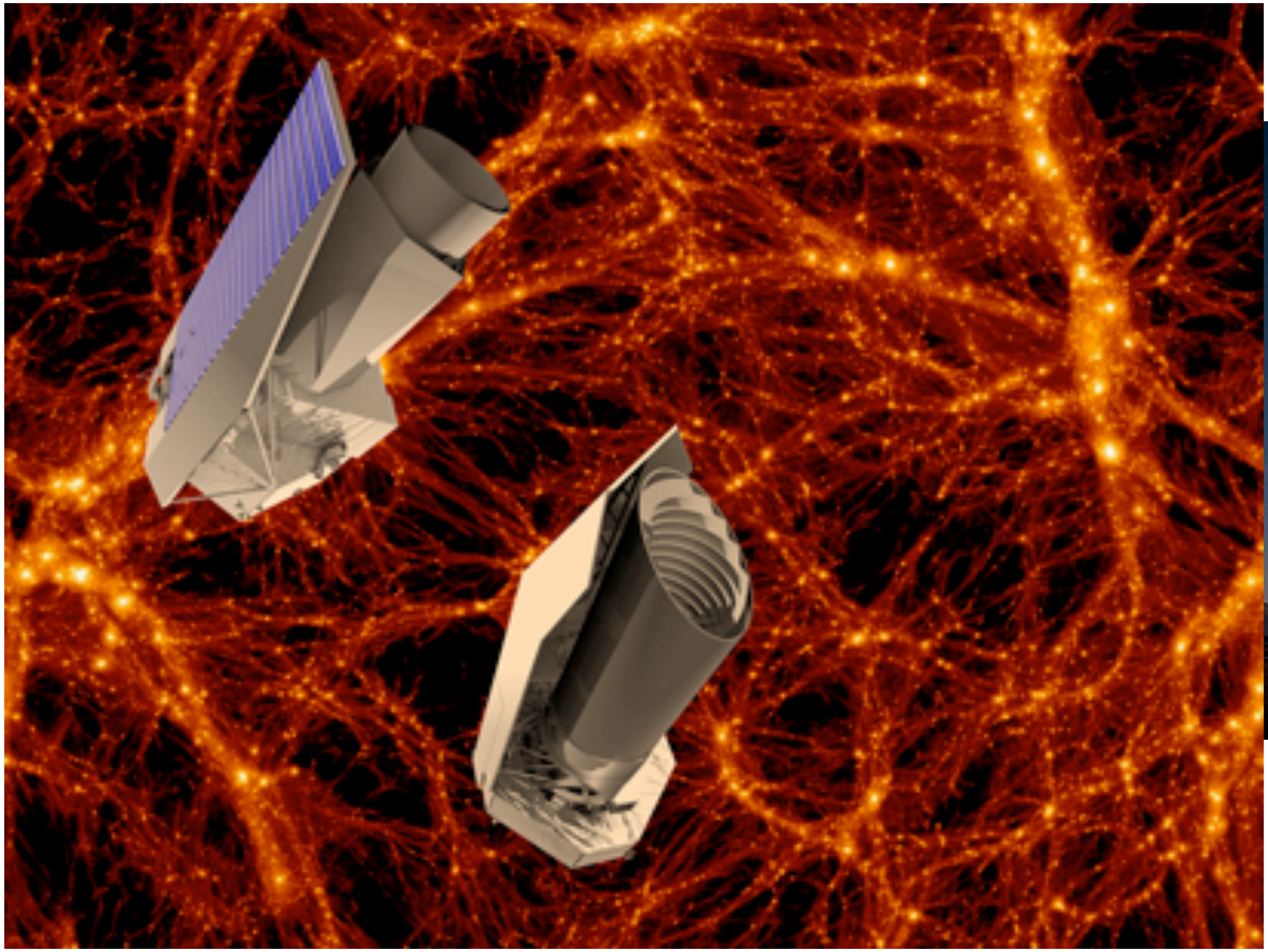
Becoming mainstreaming?

- Workshops on Effective Field Theory in Inflation
- Other groups joining in (Princeton, Stanford, Geneva, Paris, Cambridge, Amsterdam, Japan, UCSD...)
- Already taught in Summer Schools and Graduate Classes at Harvard, Princeton, Stanford, TASI (Arkani-Hamed, Silverstein, Zaldarriaga, ...)

Are we done with Cosmology?

What is next?

- Plank will increase by a factor of less than 2.
- Next are Large Scale Structures
- Like moving from LEP to LHC



What is next?

- Forecasts

$$\Delta f_{\rm NL}^{\rm equil.\,,orthog.}({\rm Planck}) \sim 75$$
$$\Delta f_{\rm NL}^{\rm equil.\,,orthog.}({\rm Euclid}) \sim 30$$

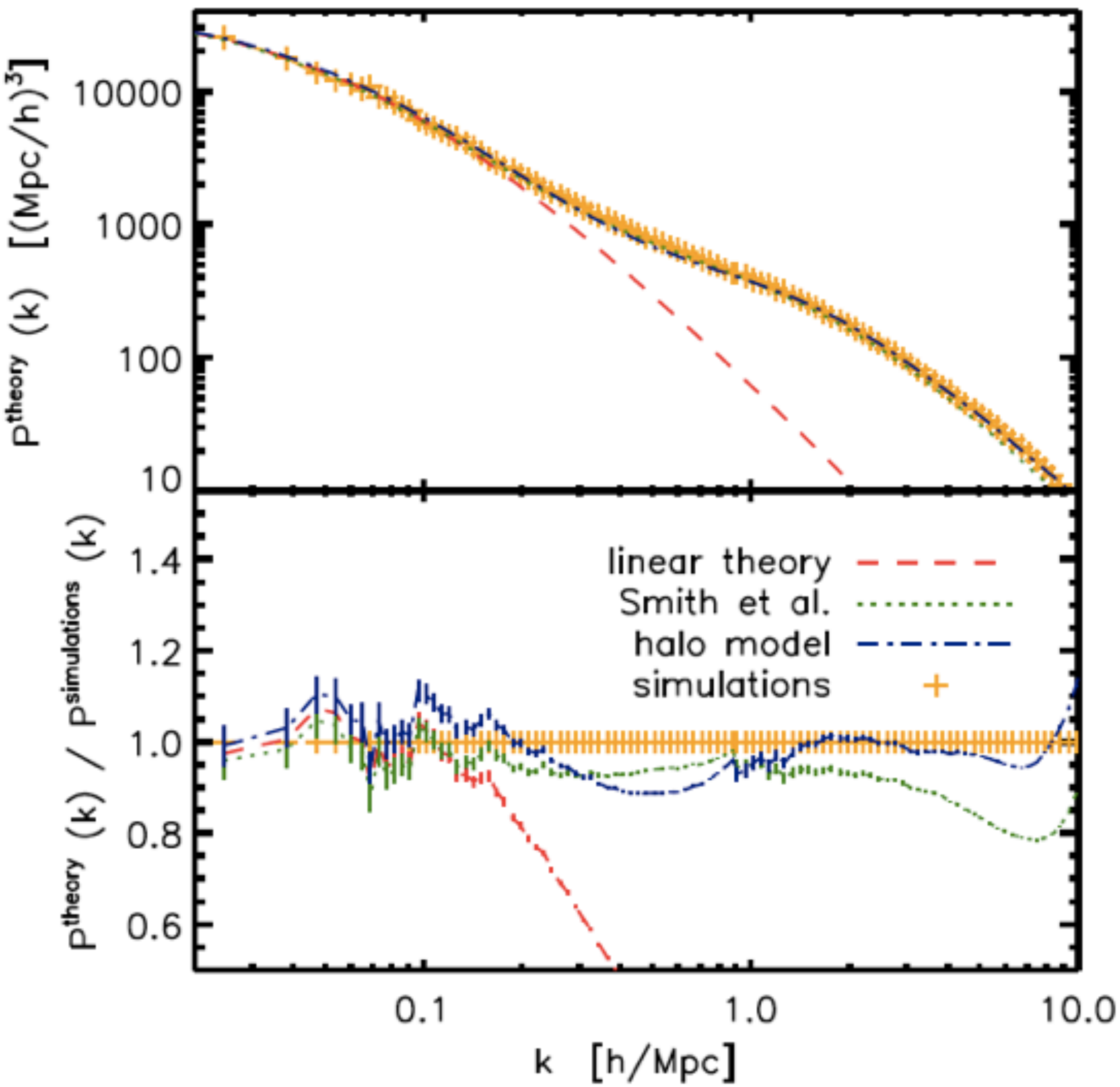
$$\text{Improvement} \simeq \frac{75}{30} \sim 2.5$$

- They use

$$k_{\rm max} \simeq 0.15\, h\, {\rm Mpc}^{-1}$$

- But the theory is probably wrong

Giannantonio, Porciani, Carron, Amara, Pillepich **1109**



The Effective Field Theory
of
Cosmological Large Scale Structures

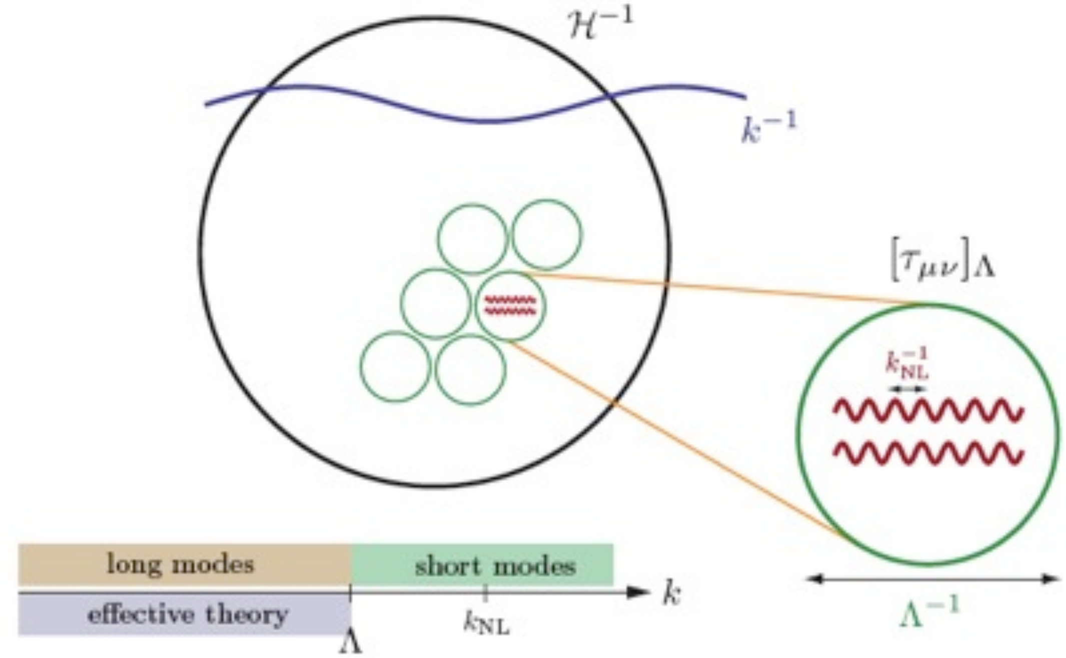
(from BSM to perturb. QCD)

with Bauman, Nicolis, Zaldarriaga **JCAP 2012**
with Carrasco, Hertzberg **JHEP 2012**
Pajer and Zaldarriaga **1301**
with Carrasco, Foreman, Green **1304**
with Carrasco, Foreman, Green **in completion**
with Porto, Tassev, Zaldarriaga **in progress**

Our Universe as a Chiral Lagrangian

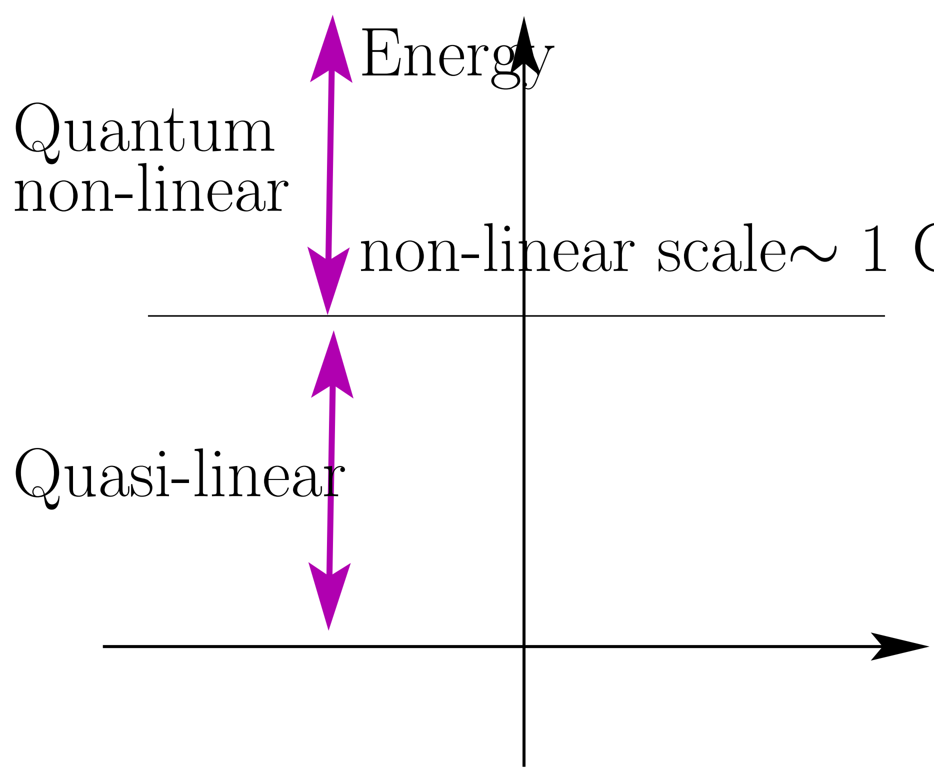
- How does our universe looks like?
- Non-linear on short scales $\lambda_{NL} \sim 1 - 10$ Mpc
  $\delta\rho/\rho \gg 1$
- Linear on large-scales

  $H^{-1} \sim 14000$ Mpc $\qquad \delta\rho/\rho \ll 1$

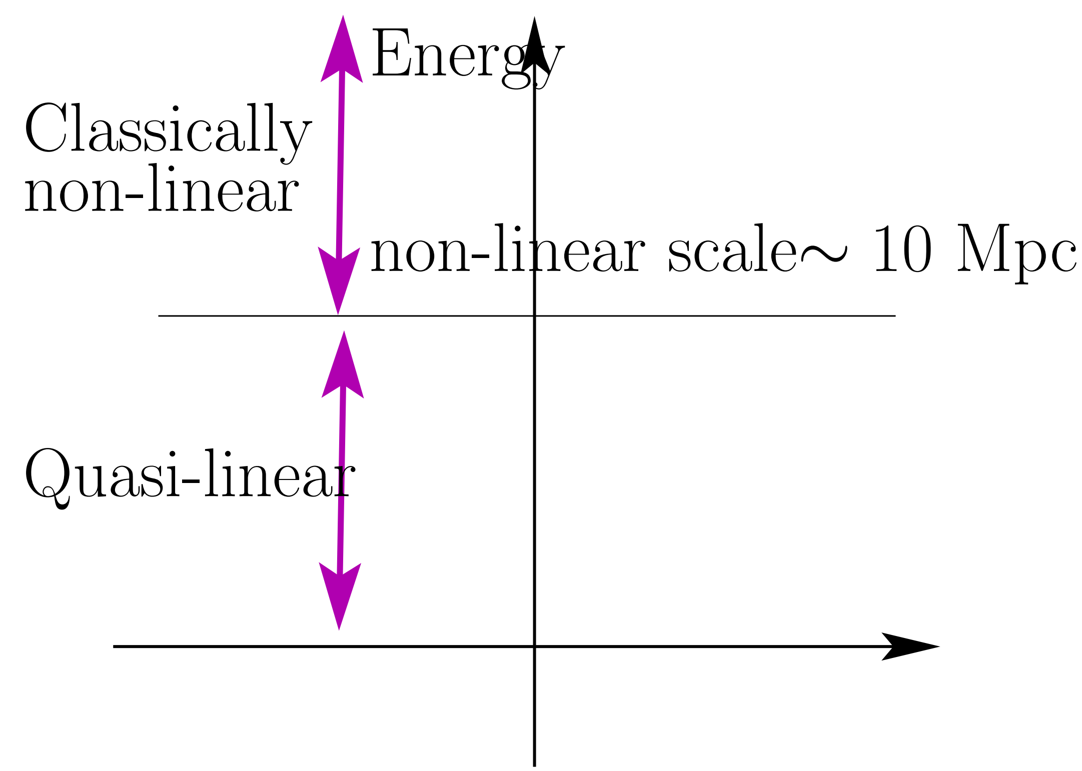


- Similar to Chiral Lagrangian

Chiral Lagrangian



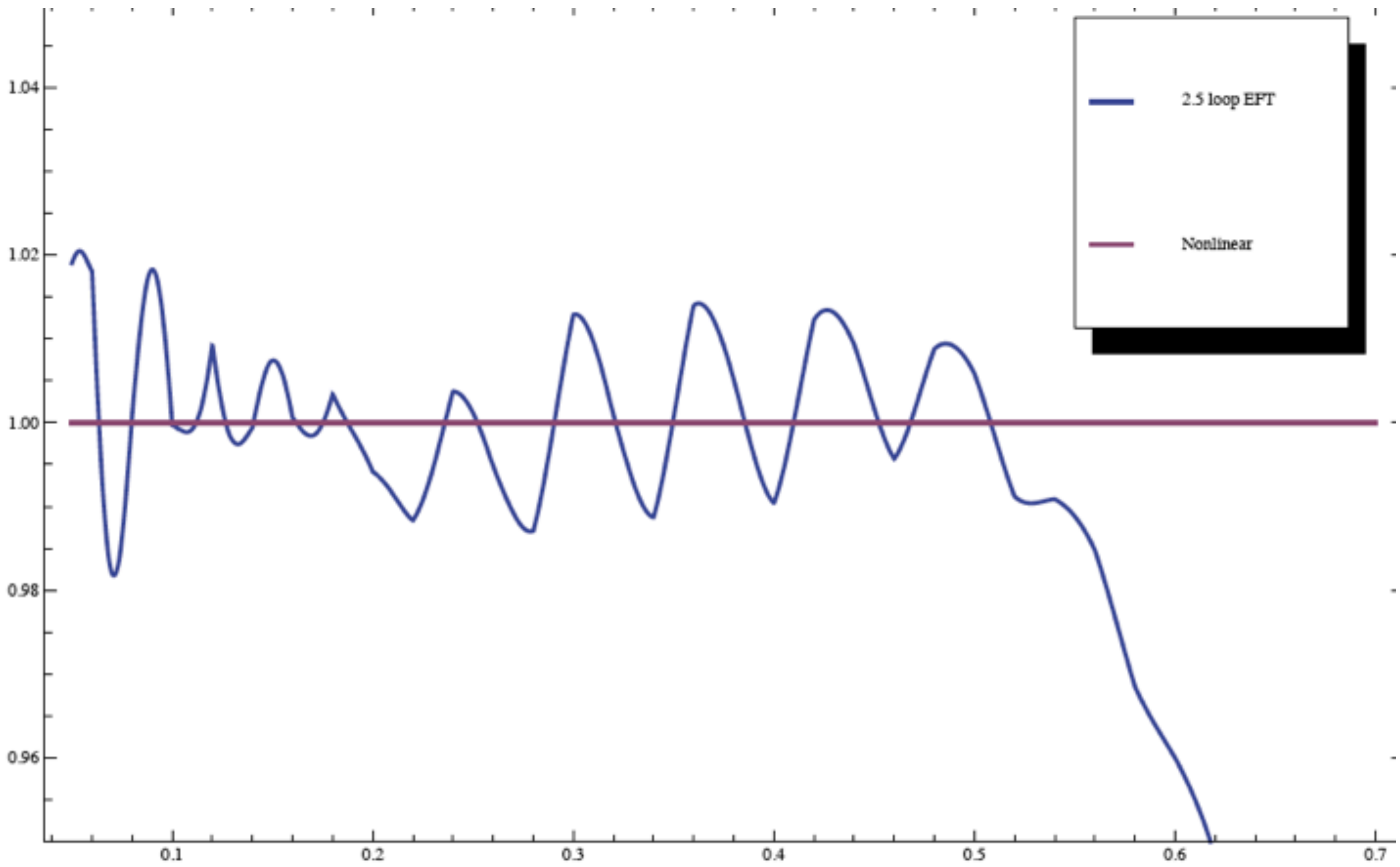
Universe



- Universe as an Effective Fluid with higher derivative stress-tensor in expansion in $k/k_{\rm NL}$

A much higher kmax

- So far predictions studied with the wrong theory
- At 2.5 loops (using loops, counterterms, matching, etc.)



- We reach

$$k_{\text{max}} \simeq 0.5\, h\, \text{Mpc}^{-1}$$

Big Improvement!

- So far predictions studied with the wrong theory
- Next are Large Scale Structures

$$\Delta f_{\rm NL}^{\rm equil.\,,orthog.}({\rm Planck}) \sim 75$$

Giannantonio, Porciani, Carron, Amara, Pillepich **1109**

$$\Delta f_{\rm NL}^{\rm equil.\,,orthog.}({\rm Euclid}) \sim 30$$

$$\text{Improvement} \simeq \frac{75}{30} \sim 2.5$$

- They use

$$k_{\rm max} \simeq 0.15\, h\, {\rm Mpc}^{-1}$$

- If I rescale by $\left(\frac{{k_{\rm max}}^{\rm EFT}}{{k_{\rm max}}^{\rm old}}\right)^{\frac{3}{2}} \sim \left(\frac{0.5}{0.15}\right)^{\frac{3}{2}} \simeq 6$
- We get $\text{New Improvement} \simeq 2.5 \quad \to \quad 15$
- And this is good. This is a lot

Big Improvement!

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Giannantonio, Porciani, Carron, Amara, Pillepich **1109**

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- And this is good. This is a lot.

Big Improvement!

- With $\text{New Improvement} \simeq 2.5 \quad \rightarrow \quad 15$
- We get
  - With no detection:
    - . $f_{\rm NL}^{\rm loc.} \simeq 1$
      - Good for testing multifield
    - .$f_{\rm NL}^{\rm equil.\,,orthog.} \sim 5 \qquad \Rightarrow \qquad c_s \gtrsim 0.2$
      - Making the speed of sound order 1
      - Making $\Lambda_U \sim \dot H M_{\rm Pl}^2 \sim \dot\phi^2_{\rm slow\ \ roll}$
        - » We would be allowed to believe in slow-roll
- And most importantly,
  - A very decent shot at a detection!
  - which of course is revolutionary
- With this, we improve even with DES, HEDTEX.

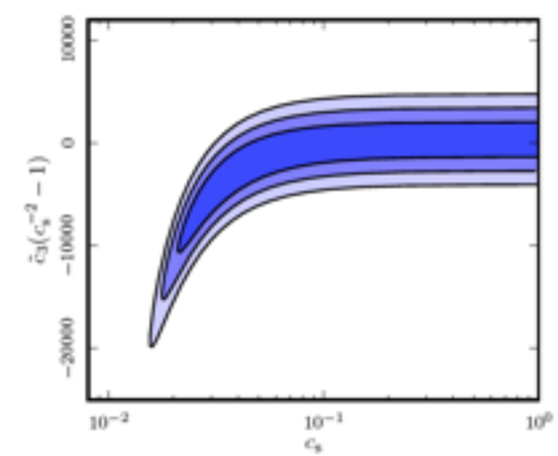
A challenge for you, theorists!

- This is the potential $\text{New Improvement} \simeq 2.5 \quad \to \quad 15$
  - If not more.
- The problem of Dark Matter clustering is being successfully addressed
  - Thanks to the EFT of LSS
- Can we manage the other ASTRO problems:
  - Halo Bias, Galaxy Bias, non-local Bias, Finger of God, Baryons, etc, etc, etc, etc, etc, etc, etc, etc, etc, etc, etc, etc, etc, etc, etc, etc, etc, etc, etc, etc, etc, etc, etc, etc, etc.
- A lot to understand, but this is what is at stakes
- This is a challenge for you.

Conclusions

- Thank you Planck, thank you Planck team.
  - the universe is clearly understandable, and so very beautiful.
- What are we learning of inflation?
  - initial perturbations are super-Hubble
  - the tilt is perfect
- The the EFT of Inflation, allows to to talk only of relevant information
- B-modes: great, but we have not seen them
- Non-Gaussianities
  - they would really prove inflation
  - not seen, and could have shown up, constrain couplings

$$S = \int d^4x \sqrt{-g}\left[-\frac{M_{\rm Pl}^2 \dot{H}}{c_s^2}\left(\dot{\pi}^2 - c_s^2 \frac{(\partial_i \pi)^2}{a^2}\right) - M_{\rm Pl}^2 \dot{H}(1-c_s^{-2})\dot{\pi}\frac{(\partial_i \pi)^2}{a^2} + \left(M_{\rm Pl}^2 \dot{H}(1-c_s^{-2}) - \frac{4}{3}M_3^4\right)\dot{\pi}^3\right]$$



- LSS offers a great window of potential improvement.
  - how much information is there for us to extract? possible factor of 15!
  - The answer if we can .... to the theorists.