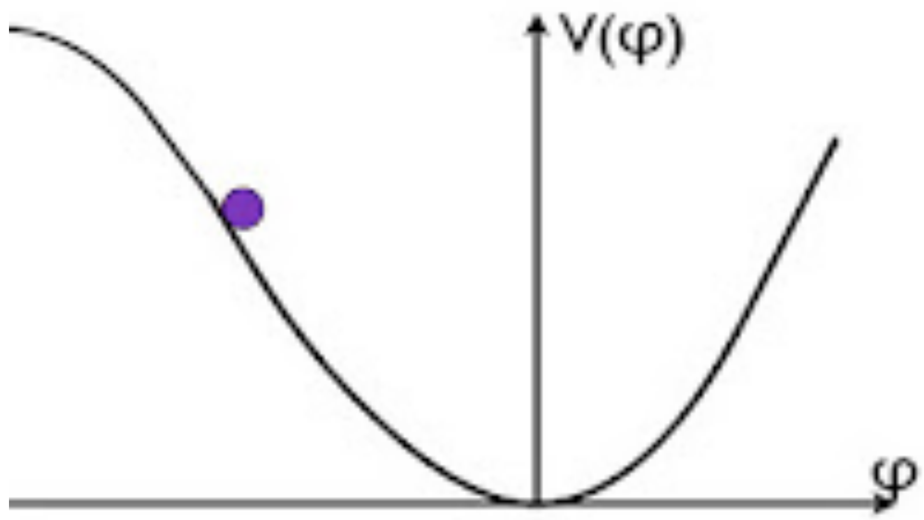
Leonardo Senatore
(Stanford & CERN)

Lessons on Inflation from Planck

Traditional talk

- Traditional this would have been the talk

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



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

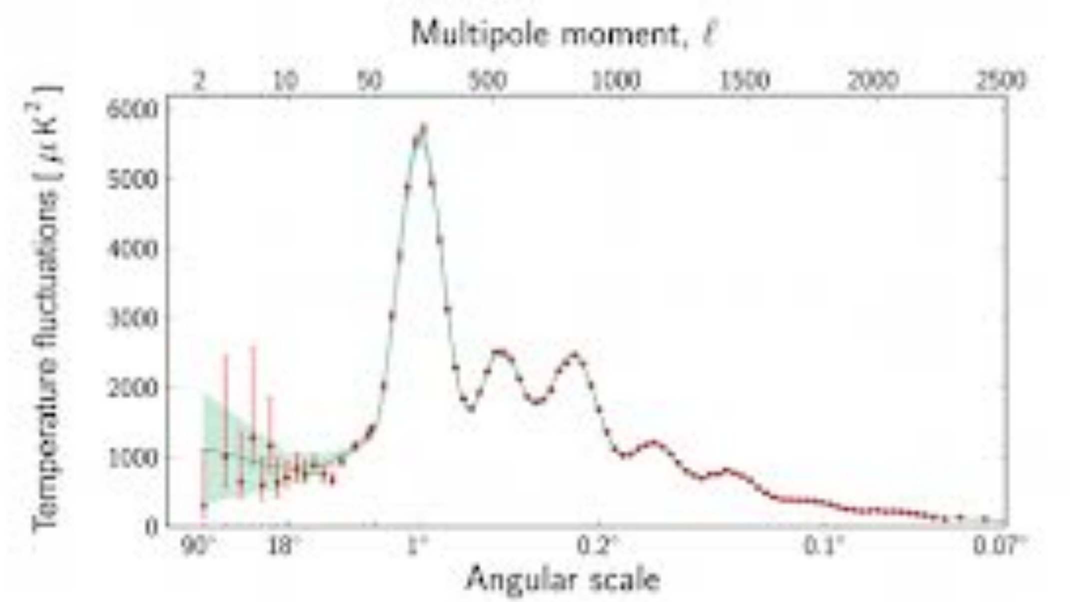
How do we probe Inflation?

What are we seeing?

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

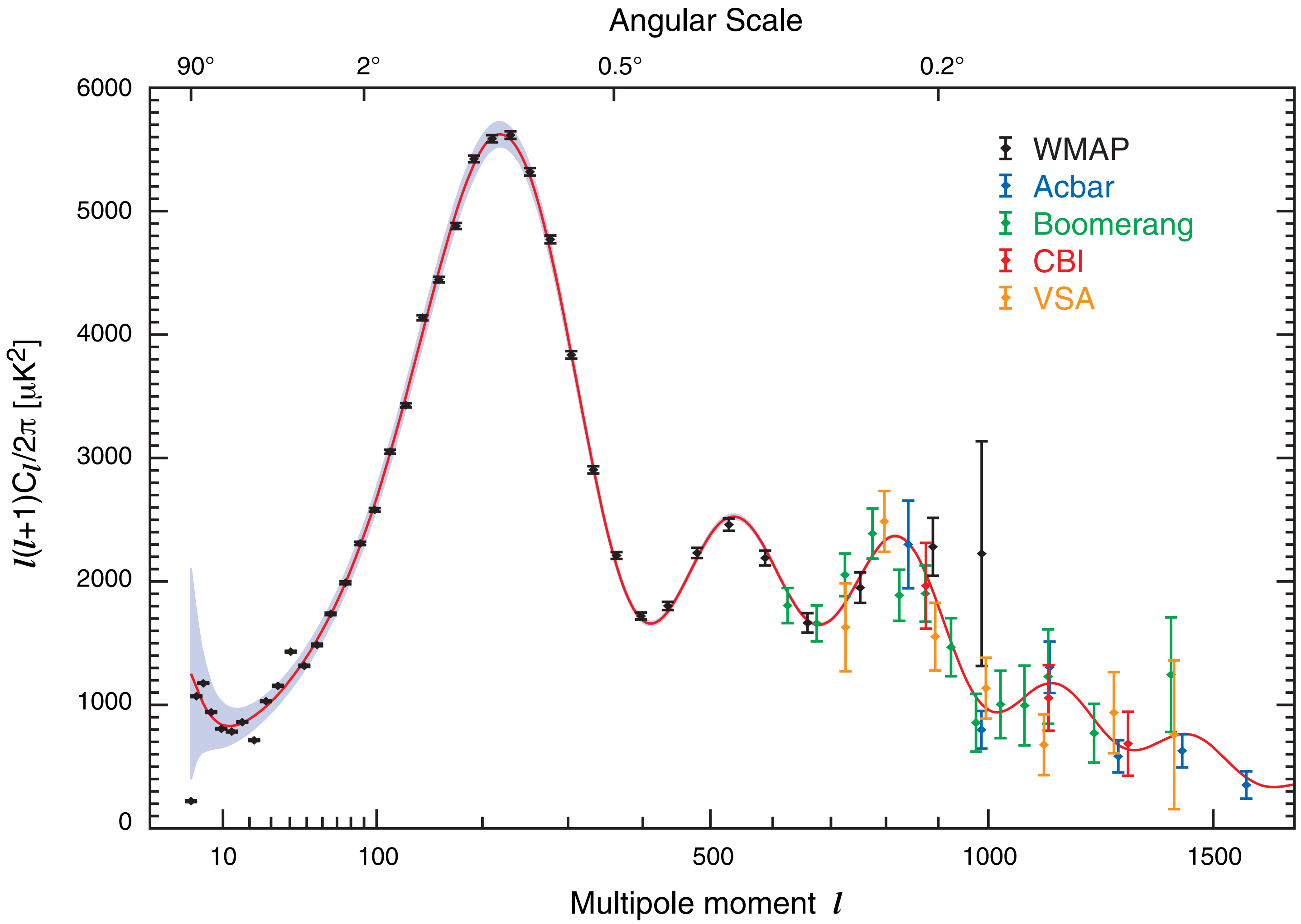
$$\Omega_K \lesssim 3 \times 10^{-3}$$

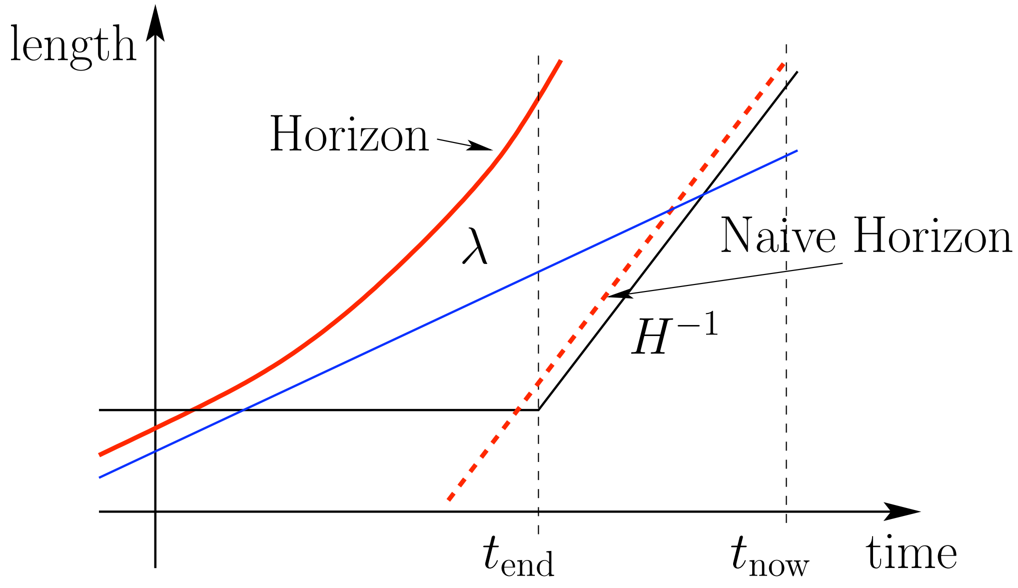
- All the rest, comes from the fluctuations
- For the fluctuations
  - they are primordial



What have we verified so far about Inflation?

- Qualitative: all the modes are in phase, perturbations from superhubble scale





$k\eta \lesssim 1$ modes are longer than H^{-1}

$k\eta \gtrsim 1$ modes are shorted than H^{-1}

$$\delta T(\vec{k},\eta) = \delta T_{in}(\vec{k}) \times \cos(k\,\eta + \phi_{\vec{k}}) \quad \Rightarrow \quad \delta T(\vec{k},\eta_{\rm now}) = \delta T_{in}(\vec{k}) \times \cos(k\,\eta_{\rm rec} + \phi_{\vec{k}})$$

$$\langle \delta T(\vec{k},\eta_{\rm rec})^2 \rangle \sim \delta T_k^2 \cos^2(k\eta_{rec})$$

- But the quantitative part of the peaks is not high-energy physics.

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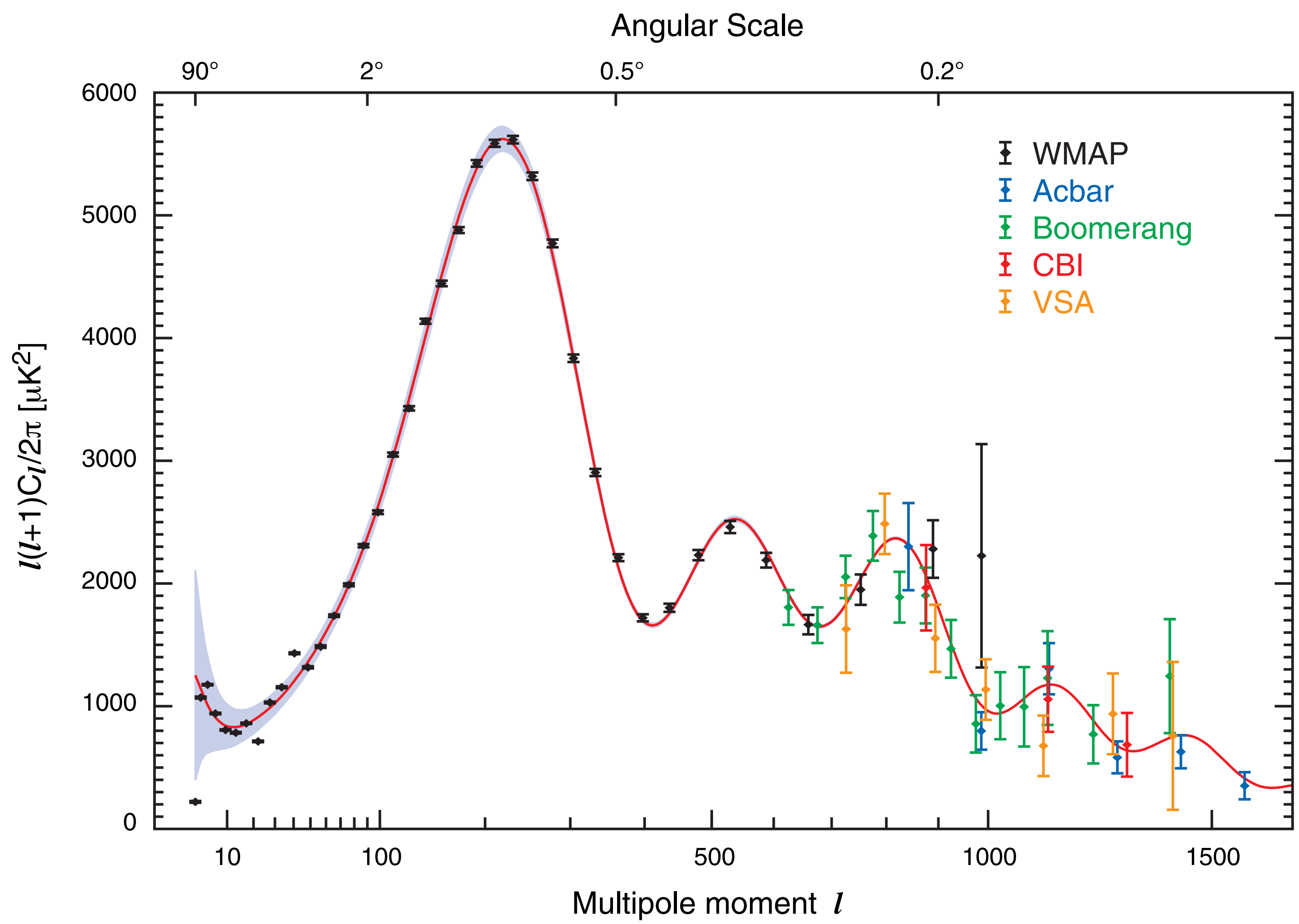

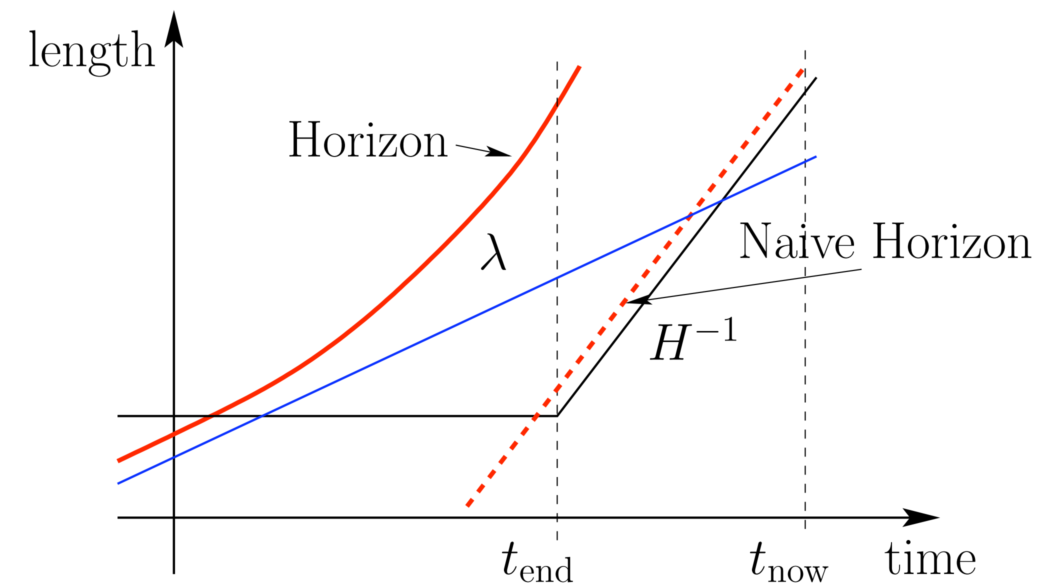

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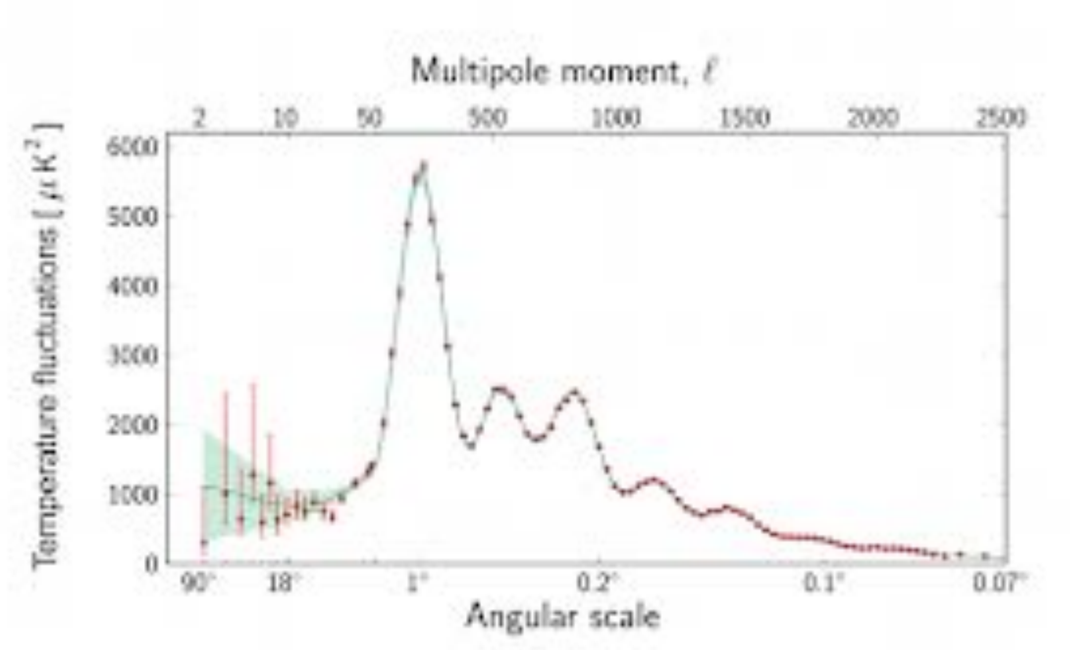


- For the fluctuations
  - they are primordial
  - they are scale invariant
  - they have a tilt $\quad n_s - 1 \simeq -0.04 \sim \mathcal{O}\left(\frac{1}{N_e}\right)$
  - they are quite gaussian
  $$\mathrm{NG} \sim \frac{\langle \zeta^3 \rangle}{\langle \zeta^2 \rangle^{3/2}} \lesssim 10^{-3}$$

- 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 from data 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

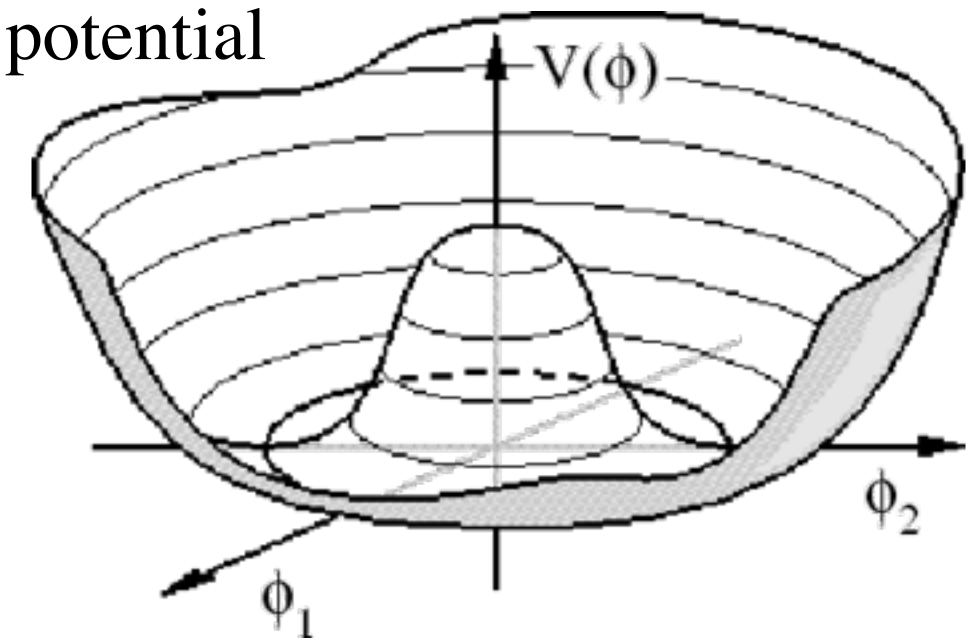
- We just know that Inflation is a weakly coupled field theory

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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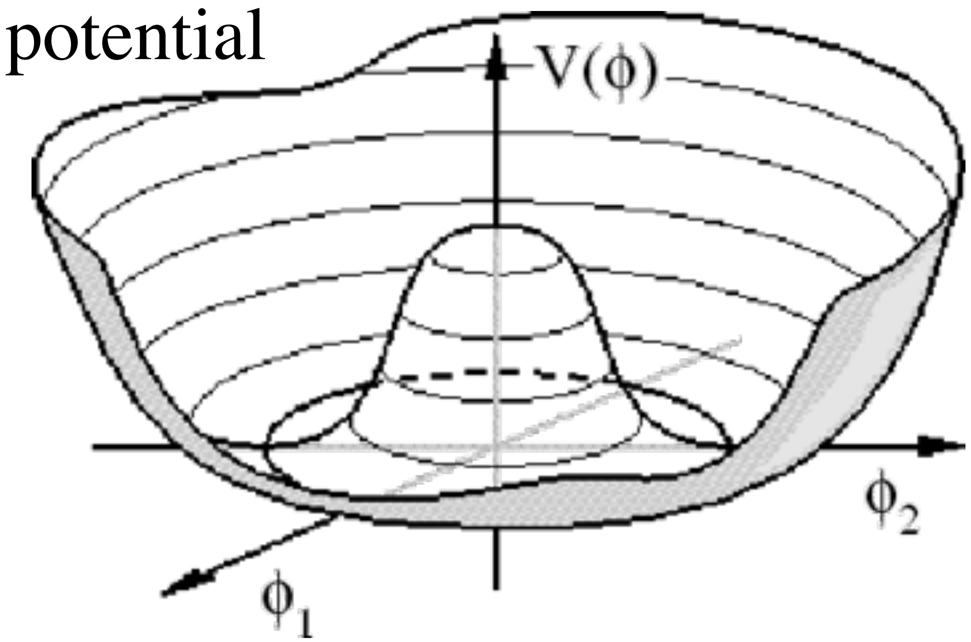

$$\int d^4x \left[(\partial\phi)^2 + (\partial\tilde{\phi})^2 + V(\phi, \tilde{\phi}) \right]$$

  - 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.
- Indeed, for superconductivity we do not have a scalar UV complition
- What is fundamental... it's all relative

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

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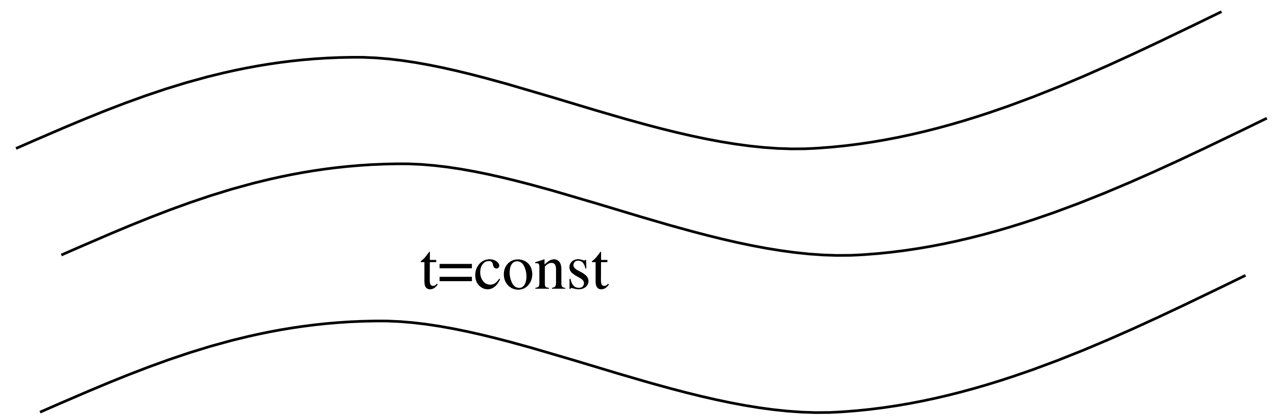
Inflation. Quasi dS phase with a privileged spatial slicing

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

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

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. $g^{00} \;\to\; g^{\mu\nu}\partial_\mu(t+\pi)\partial_\nu(t+\pi)$

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

Cosmological perturbations probe the theory at E ~ H

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

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

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

- 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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$$\left. + \ \ldots \ \right],$$

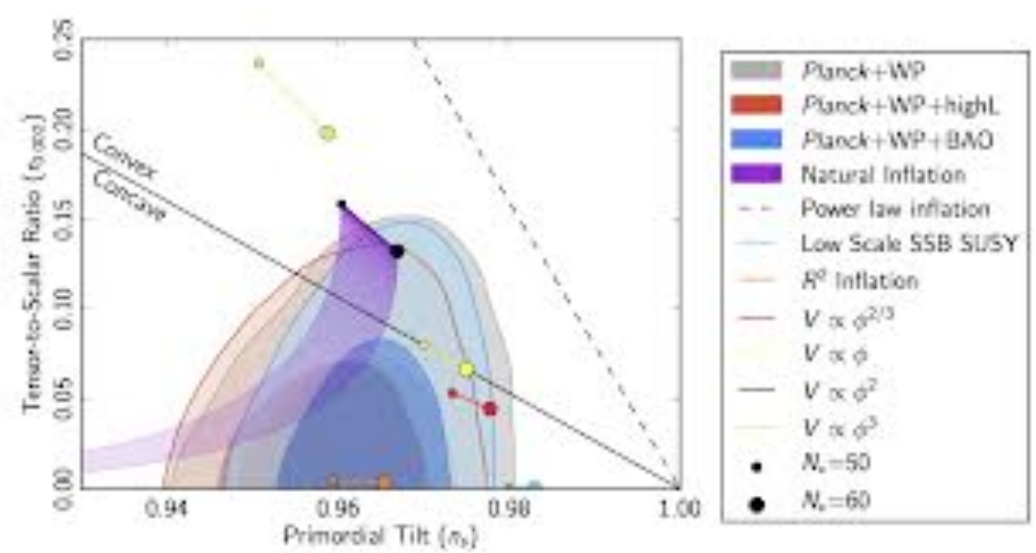
- This Lagrangian is fine to make all predictions
- The tilt

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

- 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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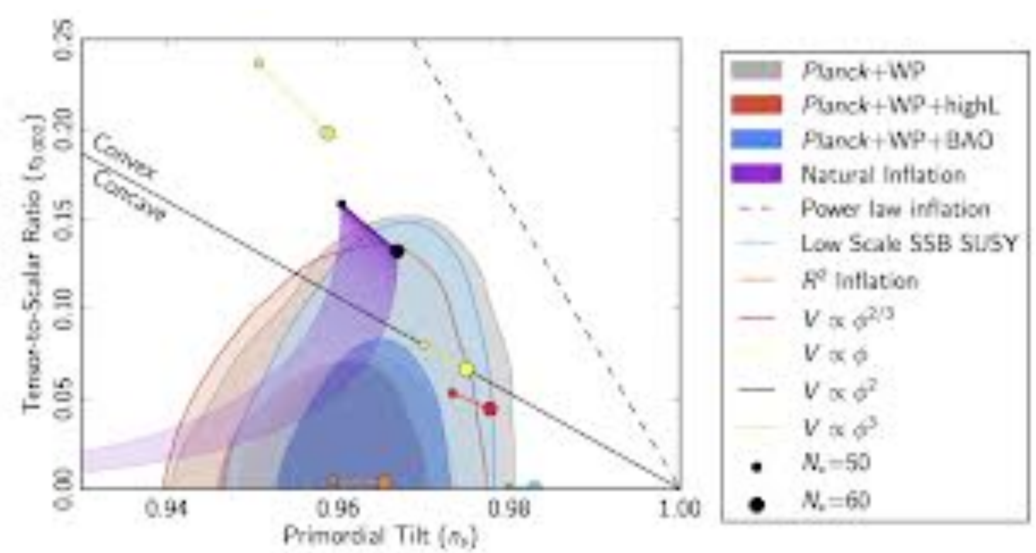


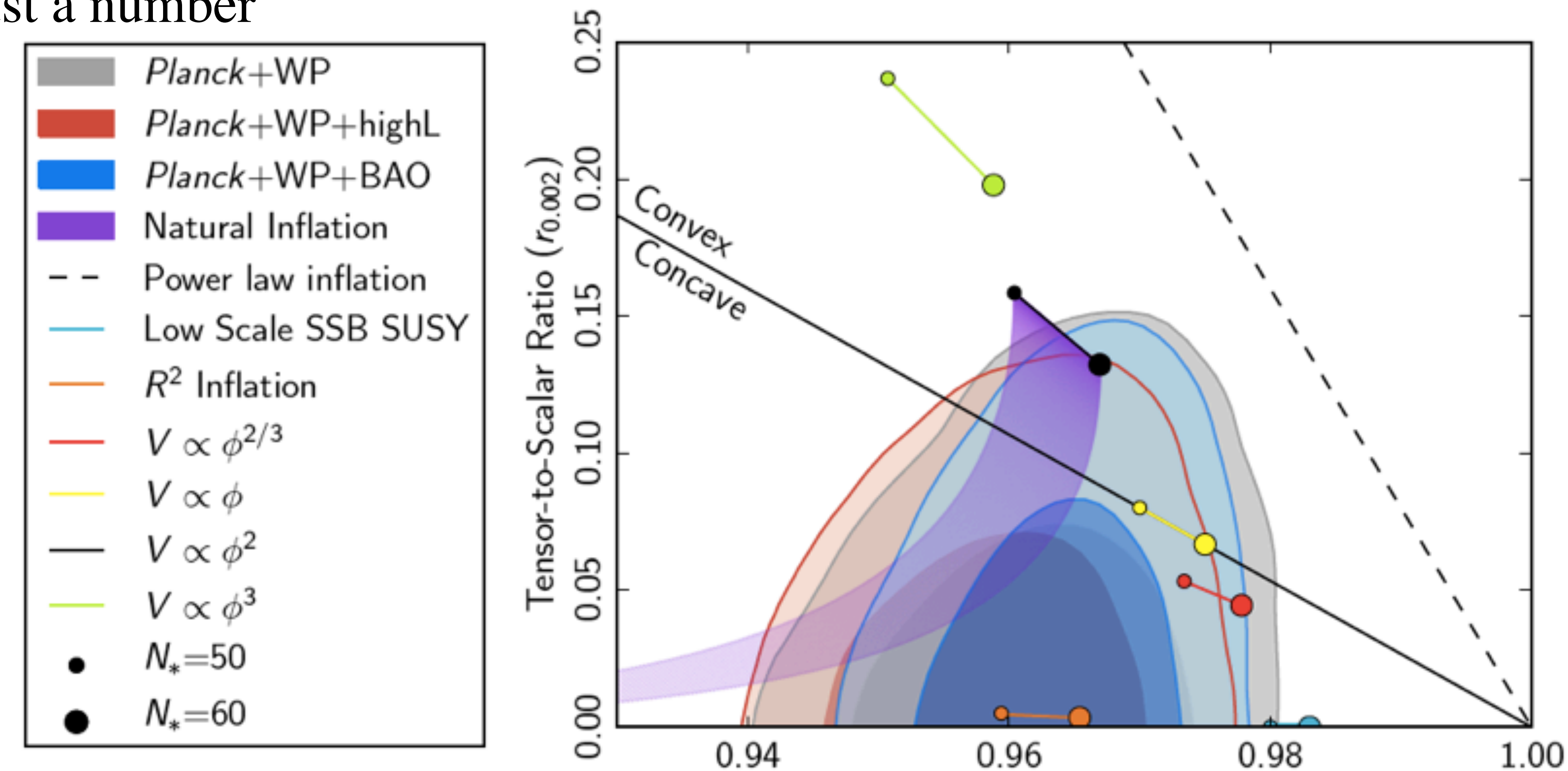
The tilt

- The tilt has been discovered $$n_s - 1 \simeq -0.04 \sim \mathcal{O}\left(\frac{1}{N_e}\right)$$

- This is what we learned: $$n_s - 1 = \frac{\dot{H}}{H^2} + \frac{\ddot{H}}{\dot{H}H} + \frac{\dot{c}_s}{c_s H}$$
  – the history during inflation

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

- Parametrically right! Huge success
  – but still, just a number



Technically Natural

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

- 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 $\dfrac{\dot\pi_c^3}{\Lambda_U^2}\,, \quad \Lambda_U^4 \sim c_s^5 \dot H M_{\rm Pl}^2$
    - As natural as the theory of true pions.

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

Non-Gaussianities

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

- Large non-Gaussianities are possible and technically natural

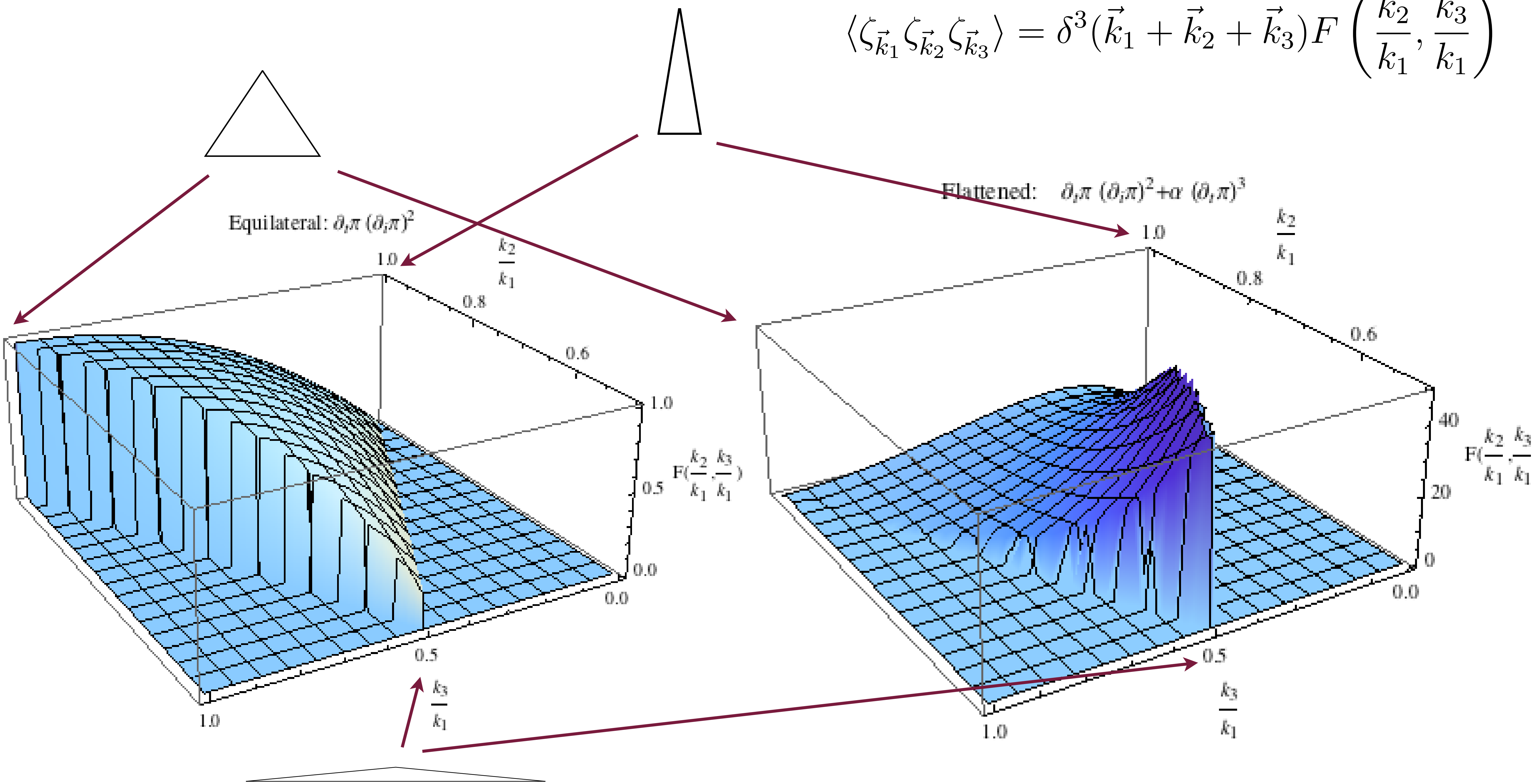
$$\dot\pi^3\ ,\qquad \dot\pi(\partial_i\pi)^2\ ,\qquad (\partial^2\pi)(\partial\pi)^2$$

  - 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

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



A function of two variables: like a scattering amplitude

There are two templates

With this, we could prove inflation

Symmetries

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

- 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: $$f_{\rm NL}^{\text{equil., orthog.}} \sim \frac{1}{c_s^2}$$
  - This has nothing to do with Quantum Mechanics, just Lorentz symmetry.

Consistency Condition

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

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

  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

Then Planck came...

☹ ~No detection ☹

With Smith and Zaldarriaga,
JCAP2009
JCAP2010

Optimal analysis of Planck data are ~ compatible with Gaussianity

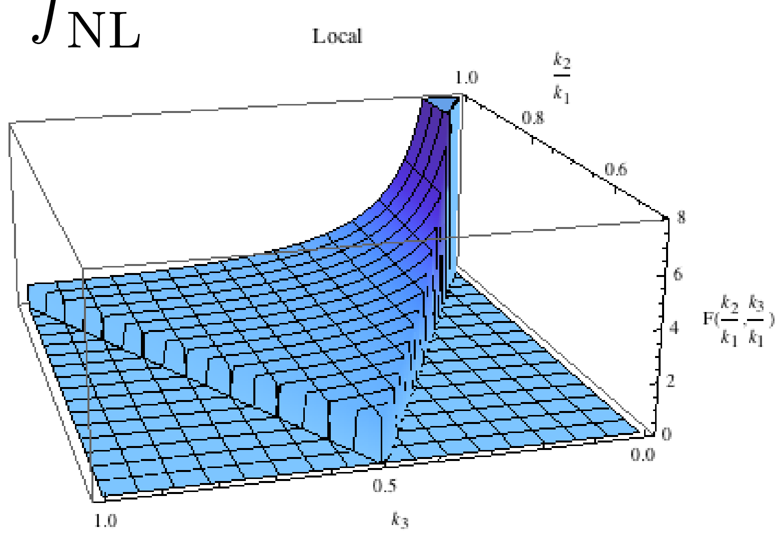
$$-1 < f_{NL}^{local} < 20 \quad \text{at } 95\% \text{ C.L.}$$

$$-187 < f_{NL}^{equil.} < 113 \quad \text{at } 95\% \text{ C.L.}$$

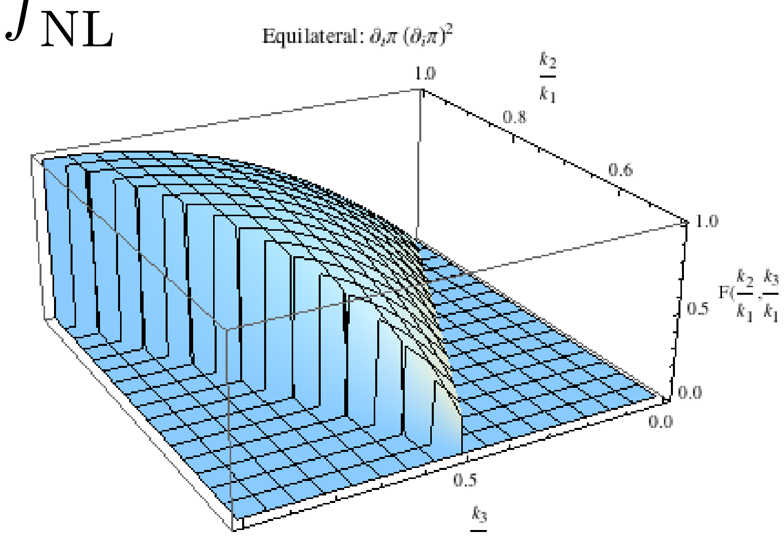
$$-124 < f_{NL}^{orthog.} < 32 \quad \text{at } 95\% \text{ C.L.}$$

Planck team 2013

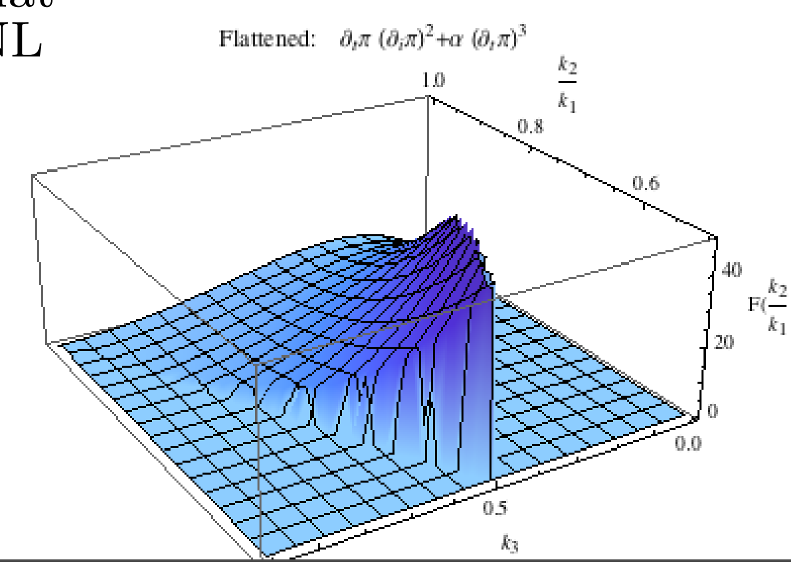
$f_{NL}^{loc.}$



$f_{NL}^{equil.}$

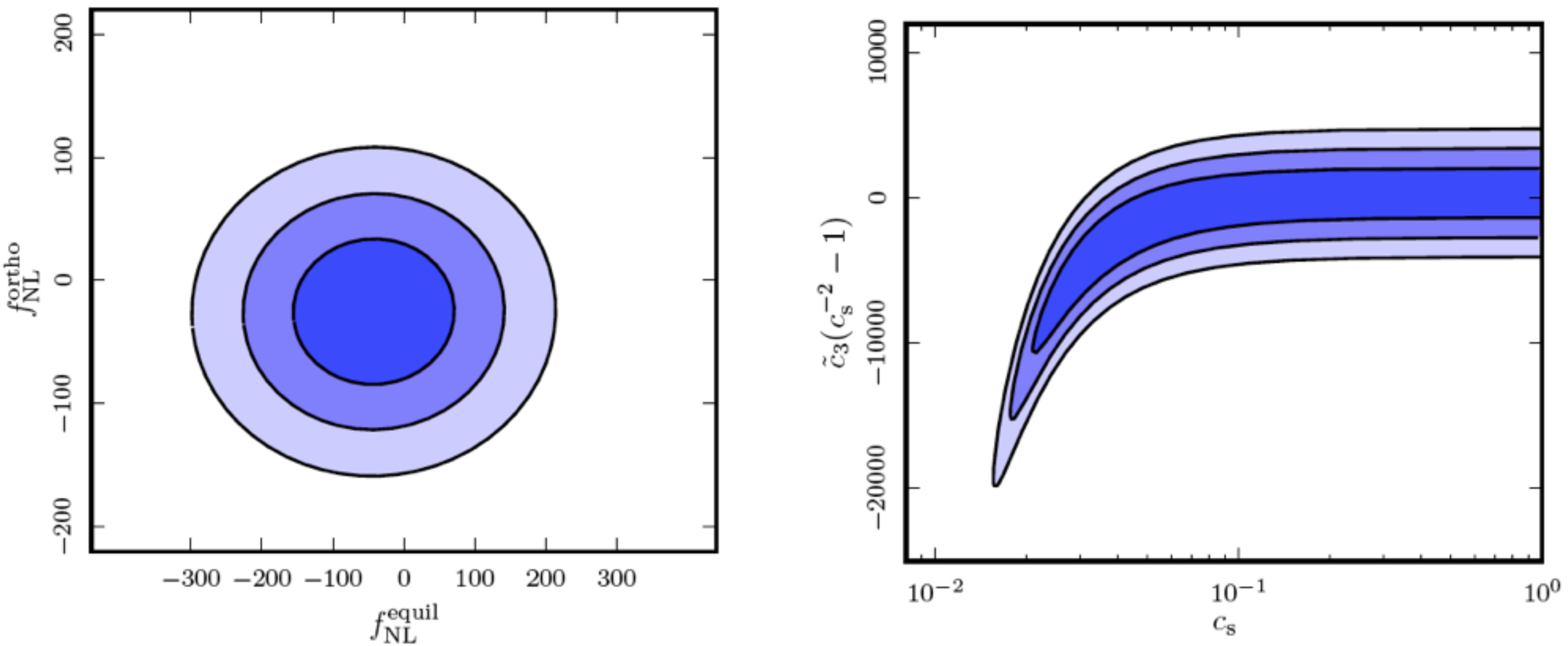


f_{NL}^{flat}



Limits in terms of parameters of a Lagrangian

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



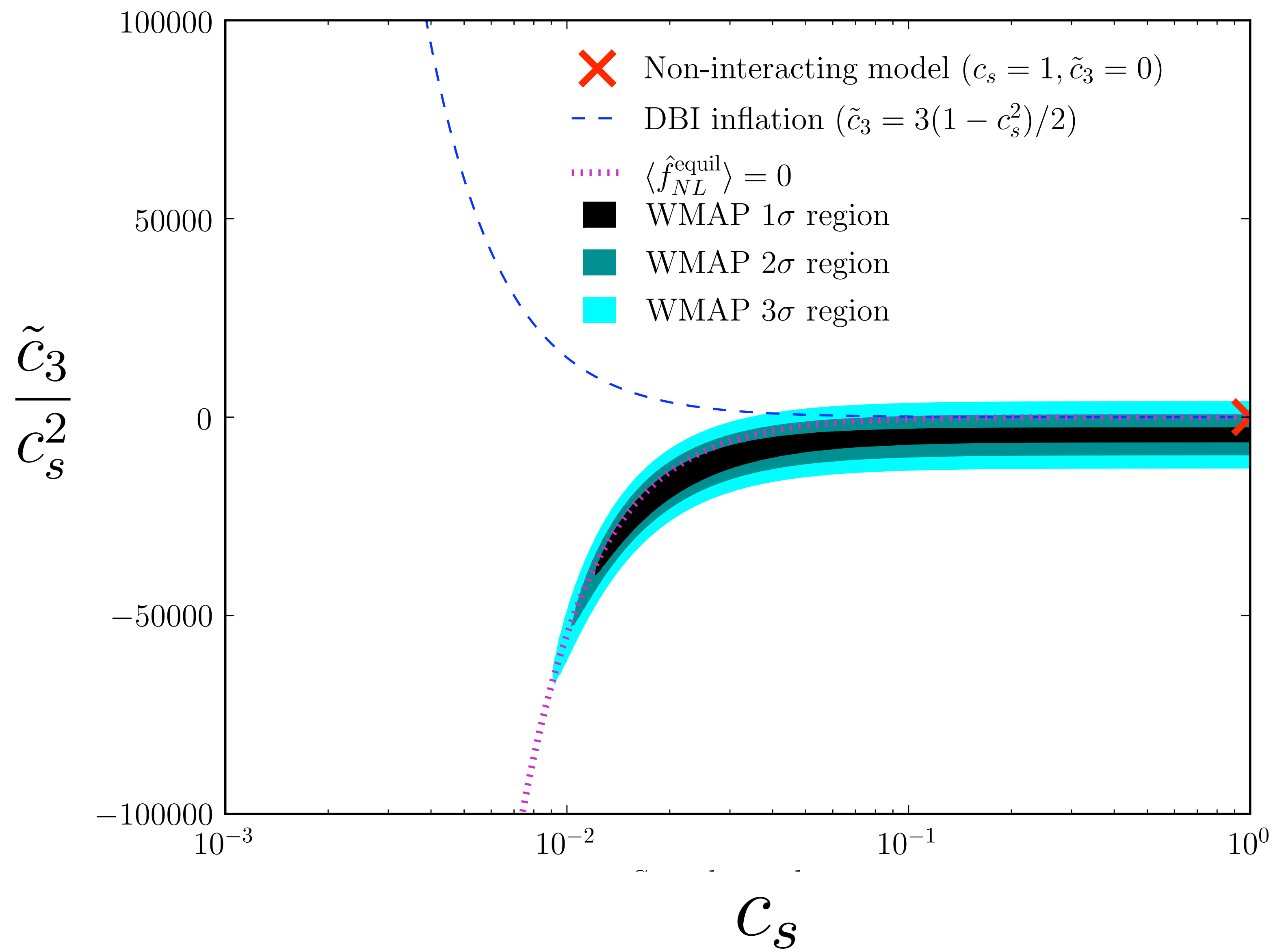
- These are contour plots of parameters of a fundamental Lagrangian
- Same as in particle accelerator Precision Electroweak Tests.
- Thanks to the EFT: A qualitatively new (and superior) way to use the cosmological data
- Universal limit $c_s \gtrsim 0.02$

with Smith and Zaldarriaga, **JCAP2010**
Planck Collaboration **2013**
see Barbieri, Giudice, Rattazzi ...

(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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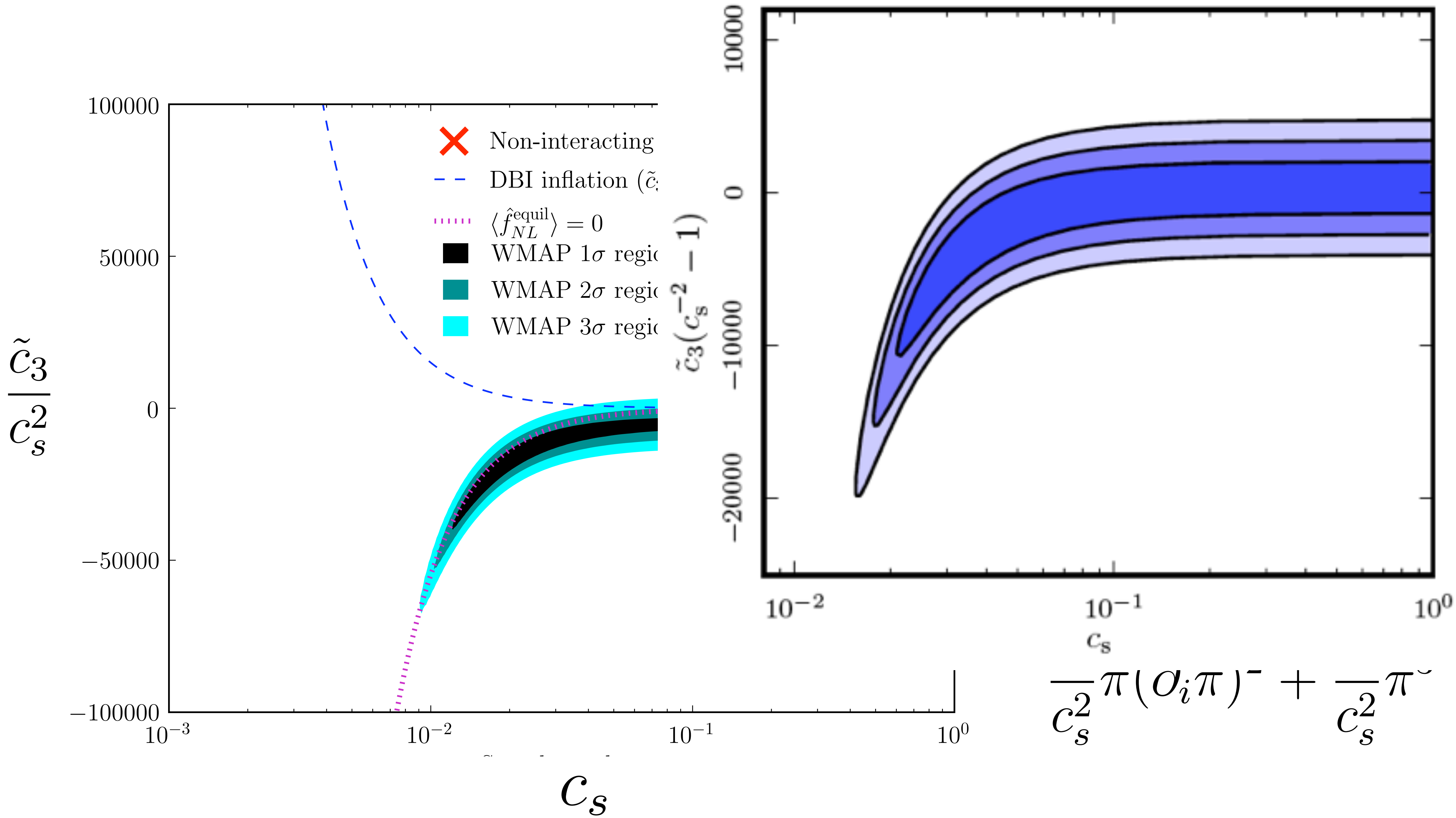
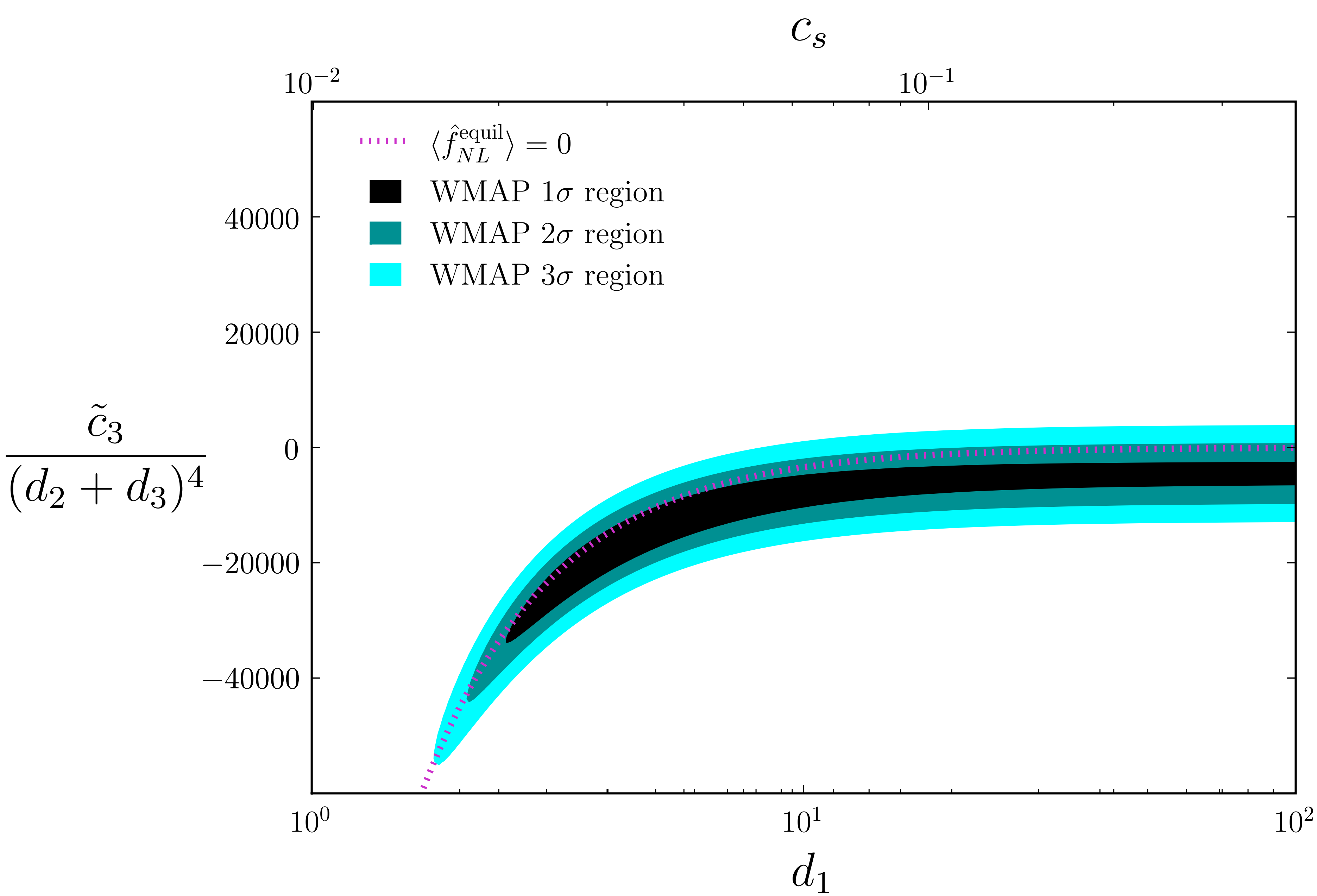


- Bound on speed of sound $c_s \gtrsim 0.011$!

(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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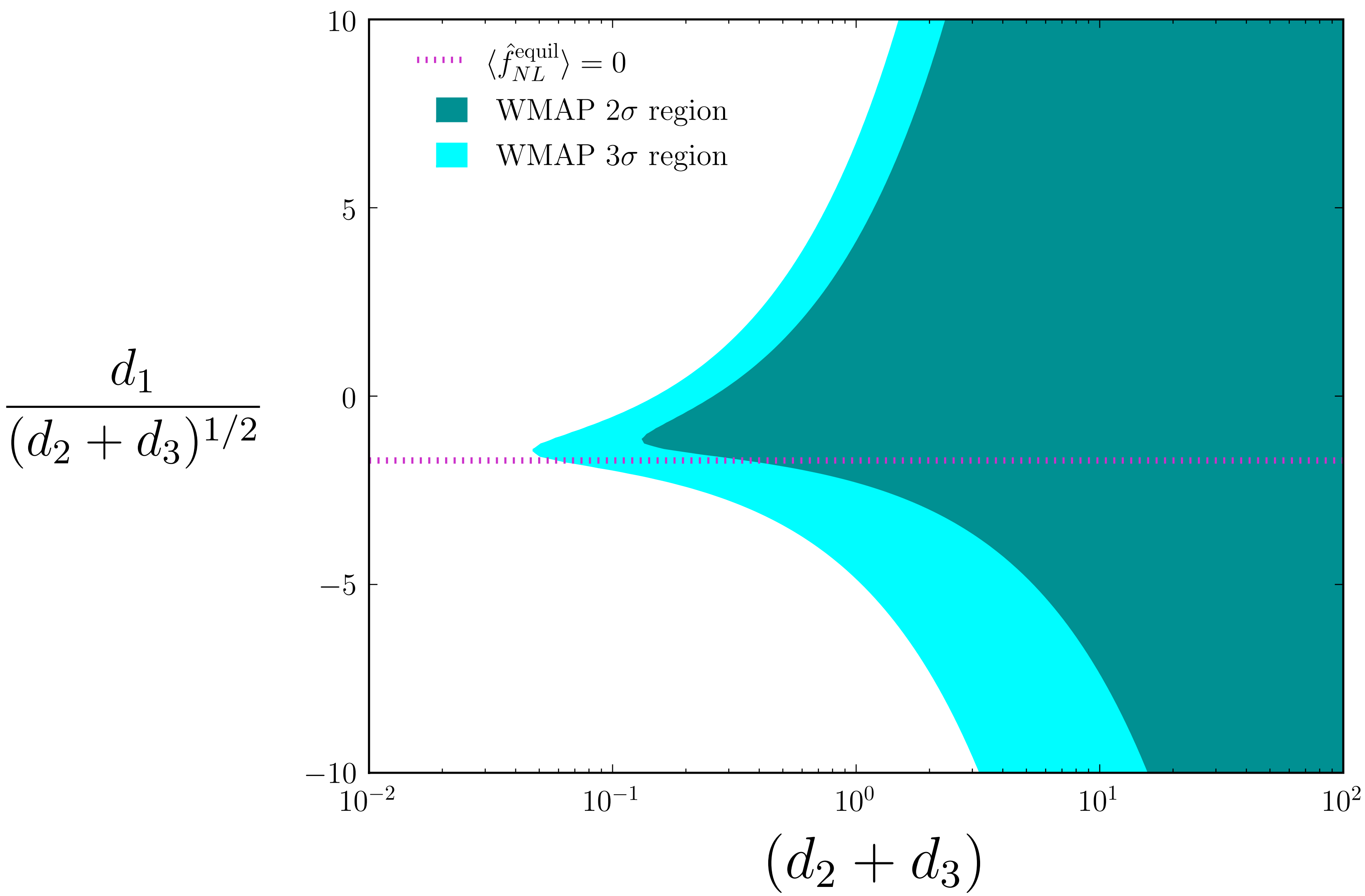
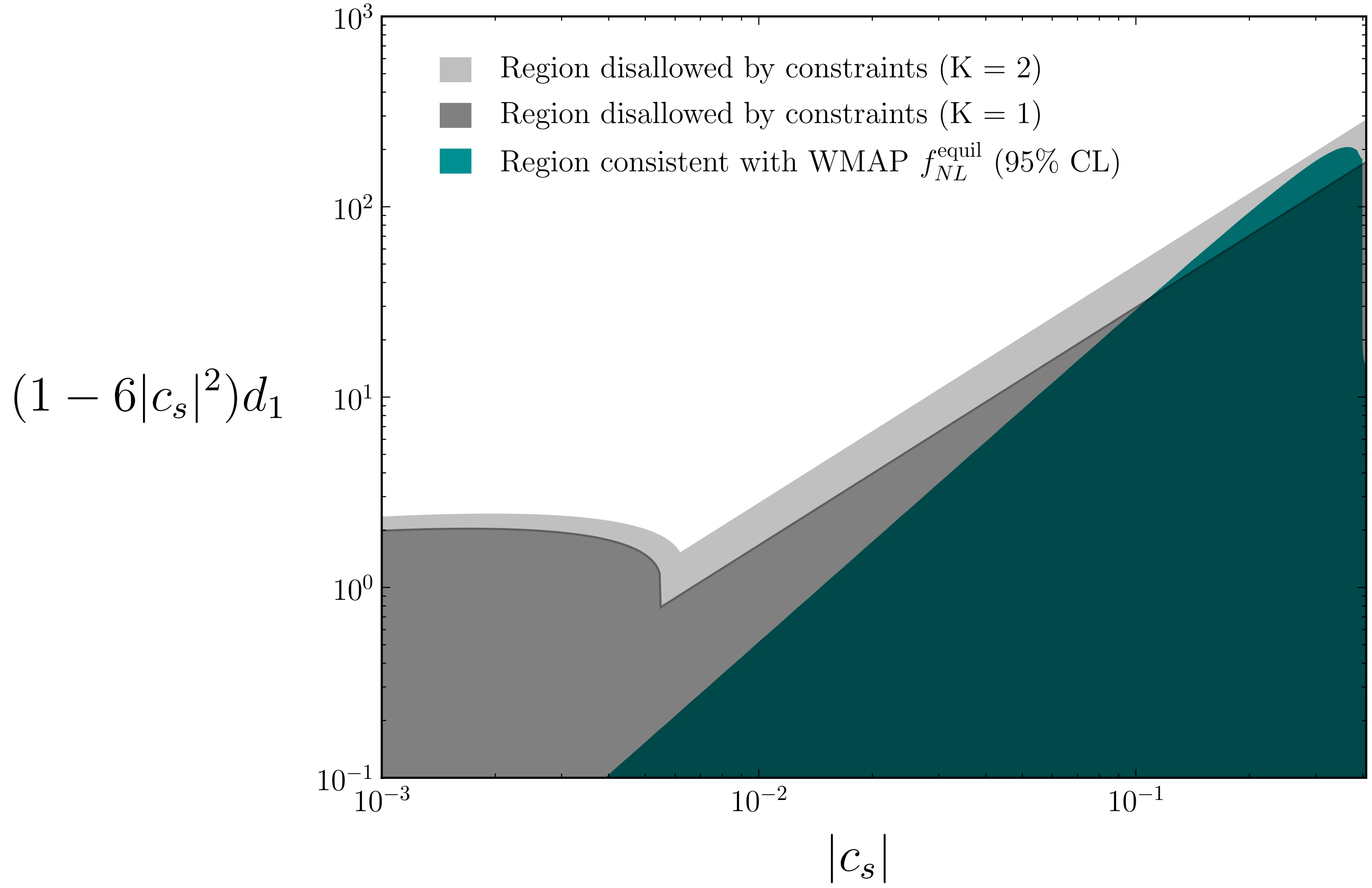


With Smith and Zaldarriaga, **JCAP2010**

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.

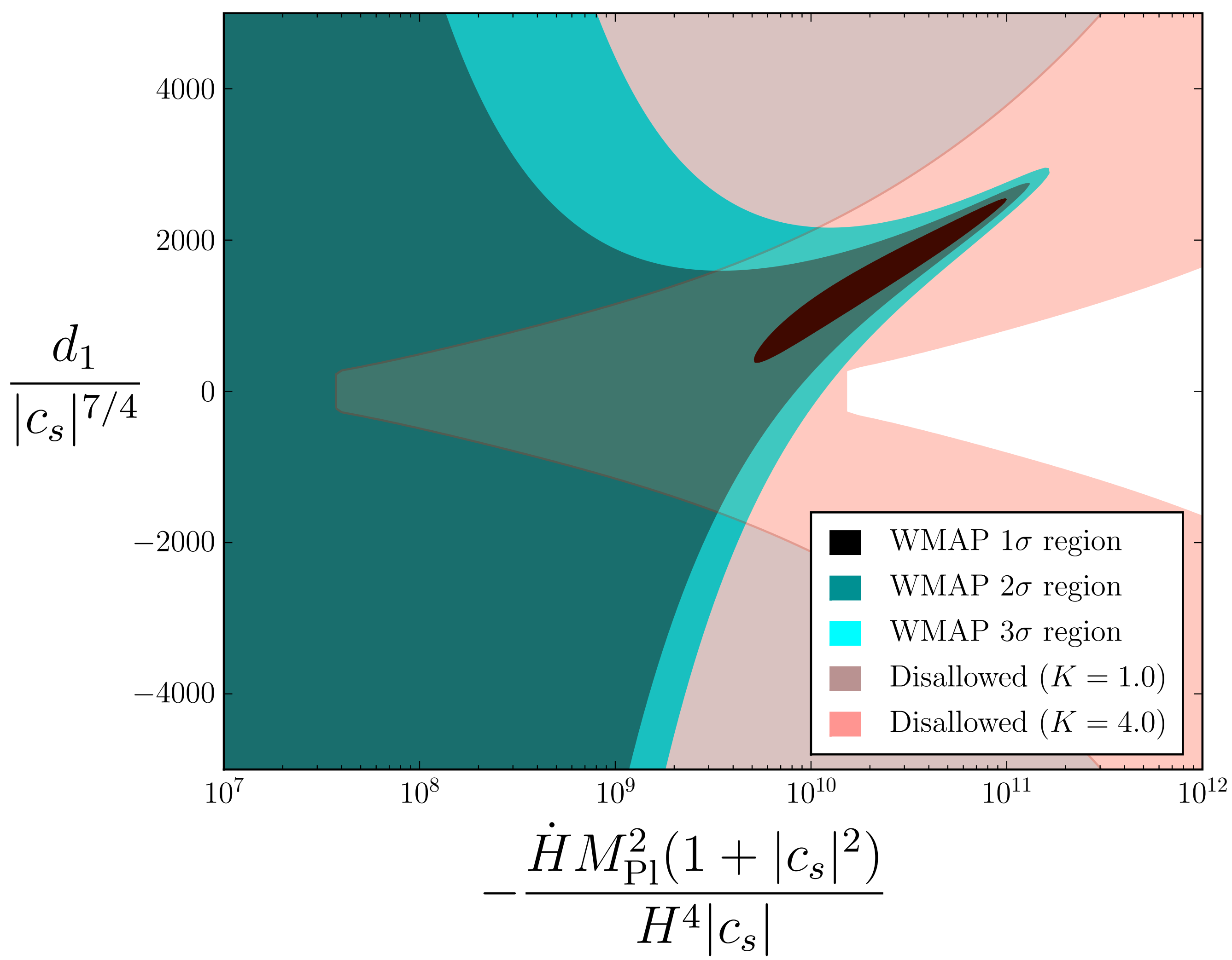


With Smith and Zaldarriaga, **JCAP2010**

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.



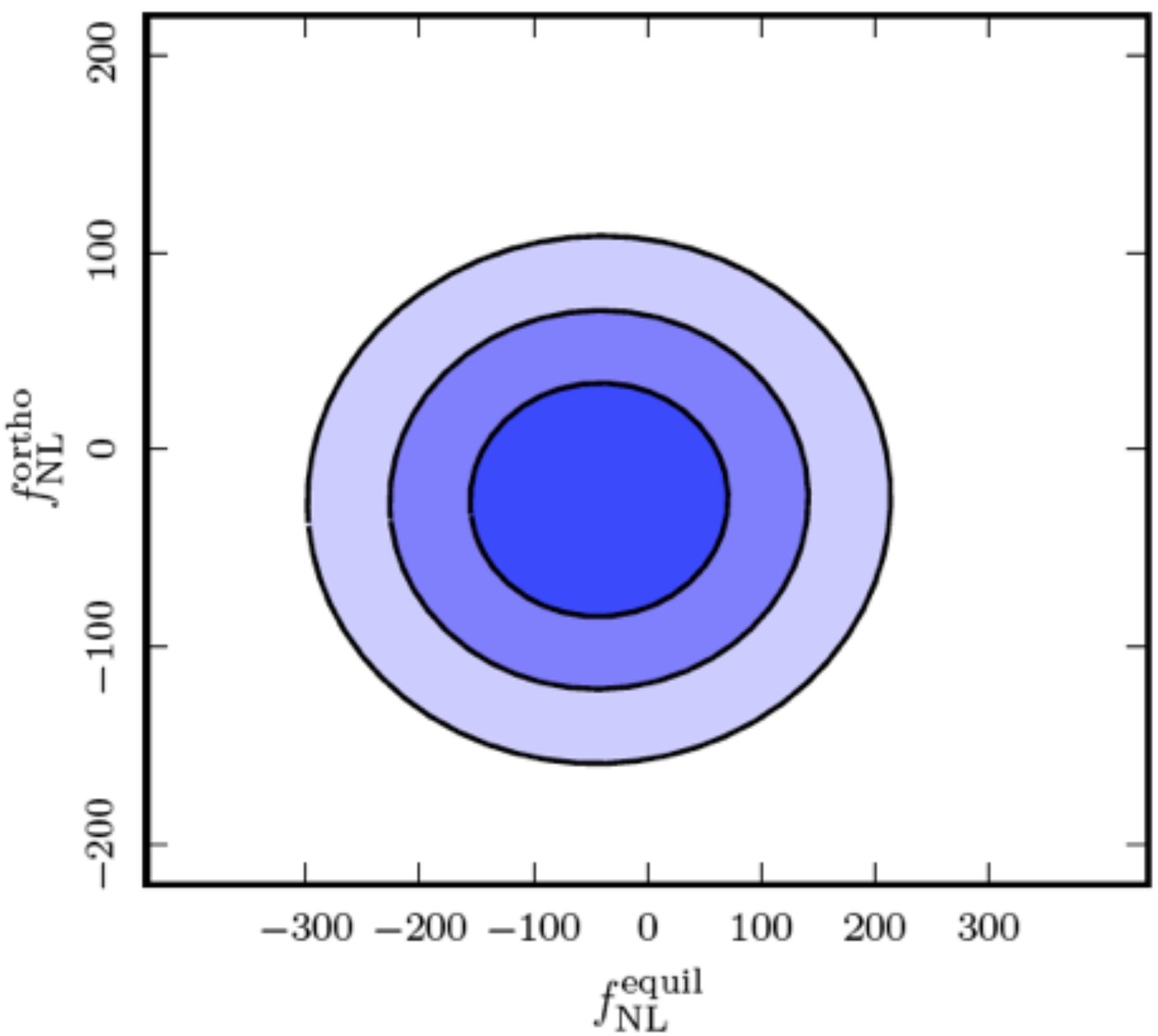
With Smith and Zaldarriaga, **JCAP2010**

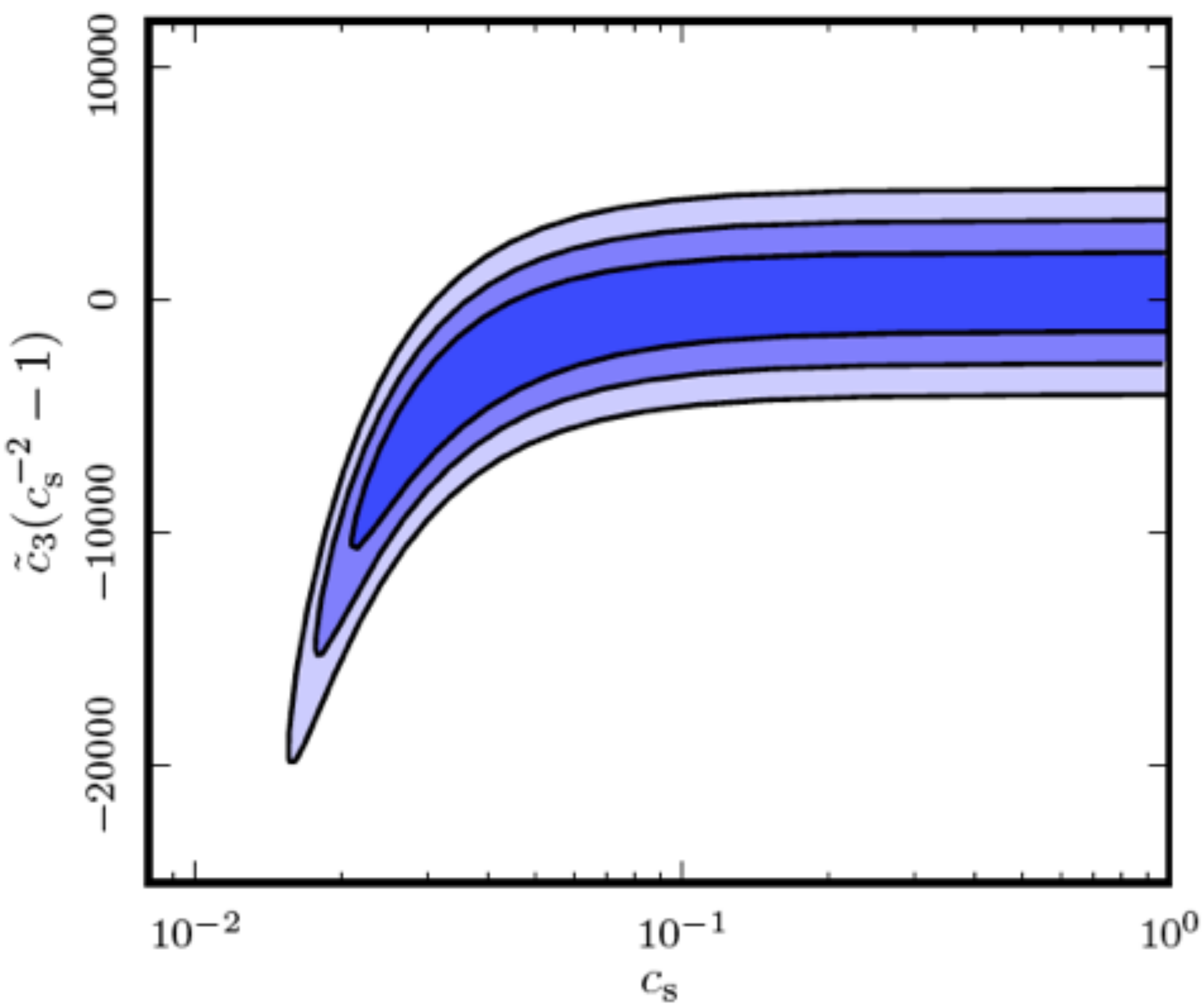
Very similar in spirit to **Precision Electroweak Tests (Complete Connection to Particle Physics)**

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 $\quad \dfrac{\dot\pi_c^3}{\Lambda_U^2} \quad\Rightarrow\quad \mathrm{NG}\simeq f_{\rm NL}\zeta\sim\dfrac{H^2}{\Lambda_U^2}$

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

Limits in terms of parameters of a Lagrangian

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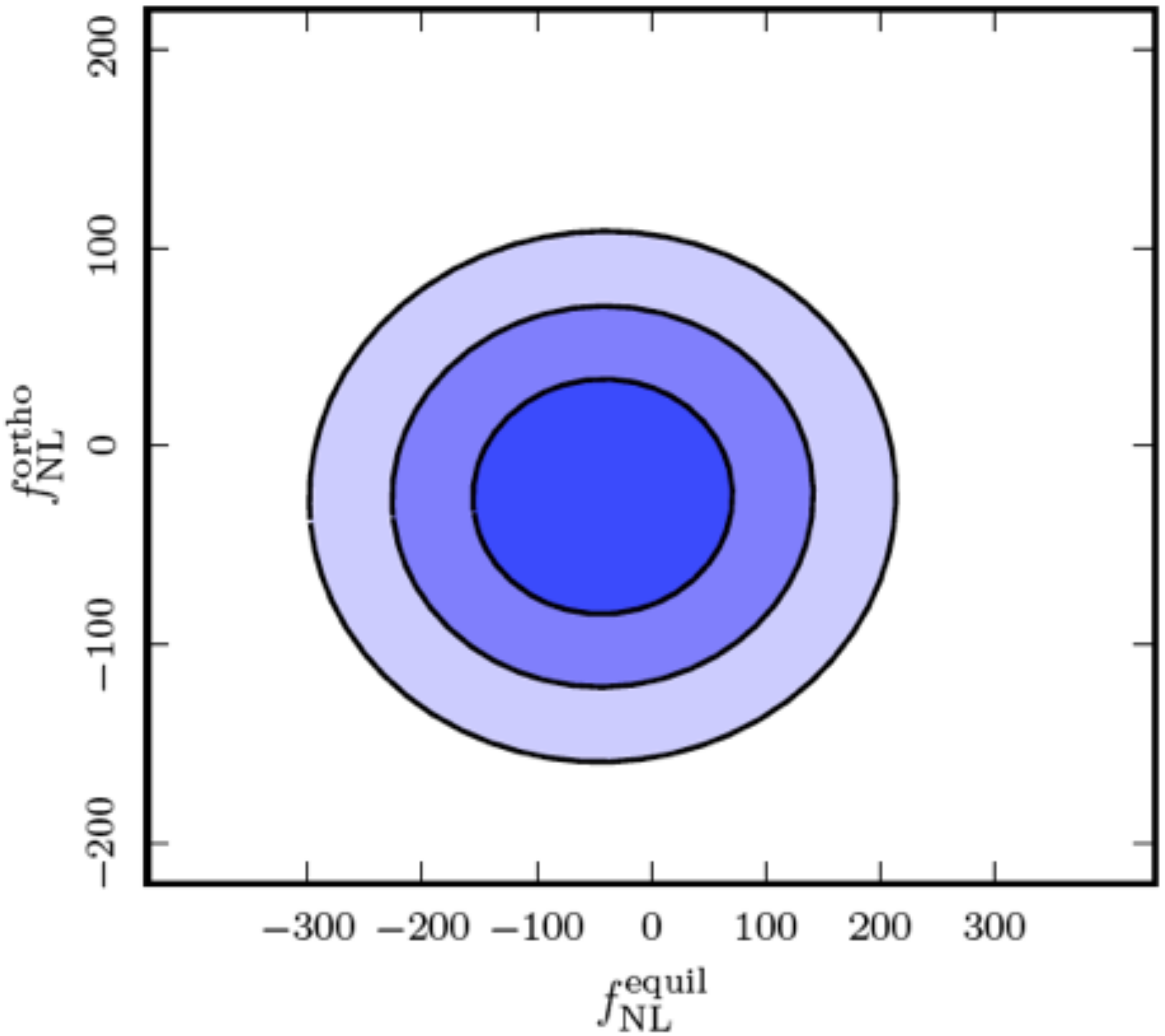

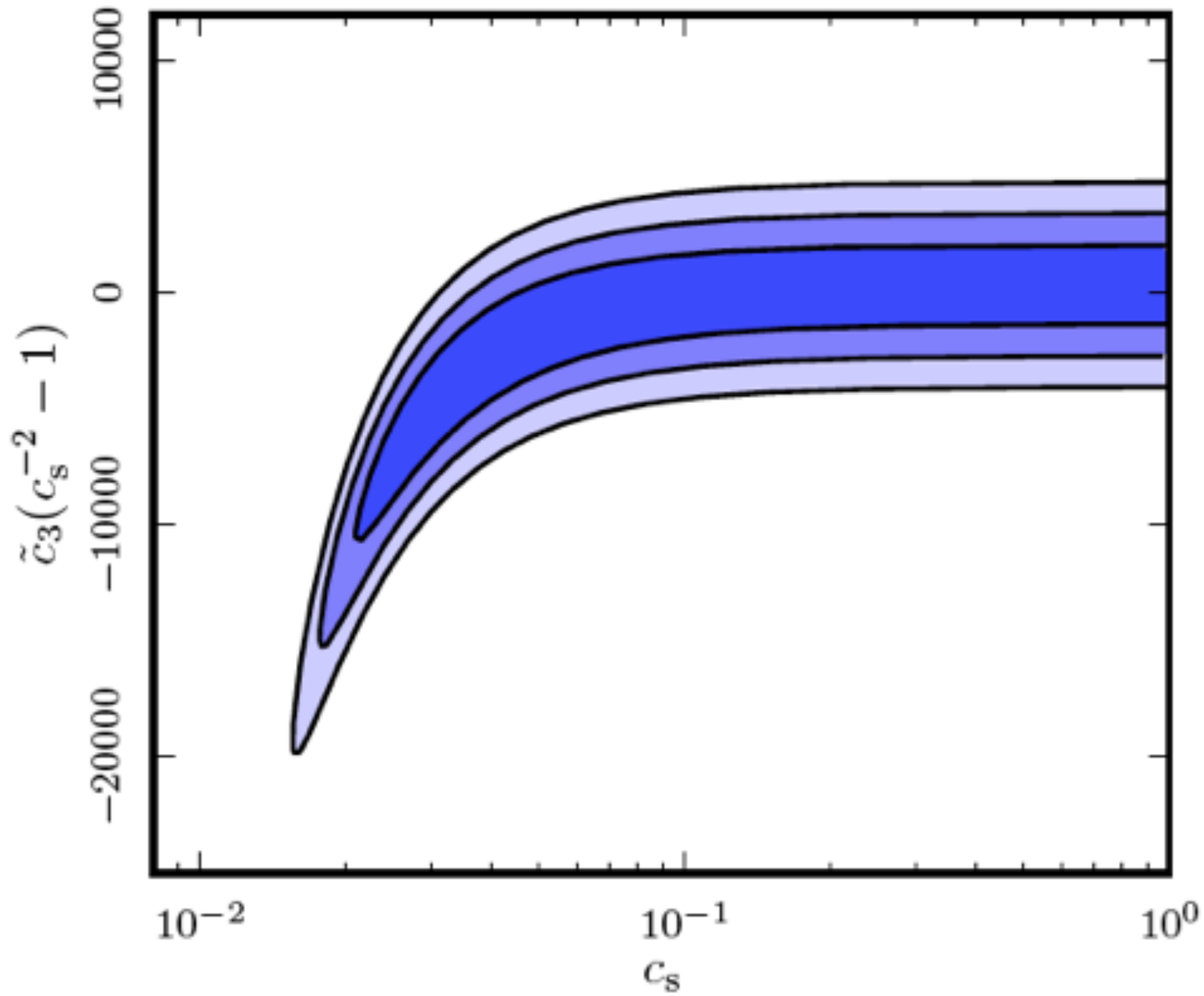

with Smith and Zaldarriaga, **JCAP2010**
Planck Collaboration **2013**

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

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 TeV is a threshold for discovery

Let us go to NG

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

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

- We do not have a compelling threshold (we just make them possible!)
- We have lower bound: $\Lambda_{U,\,\rm threshold} \gtrsim H \quad \Rightarrow \quad f_{\rm NL} \lesssim 10^5$
  – 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

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

  – 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?

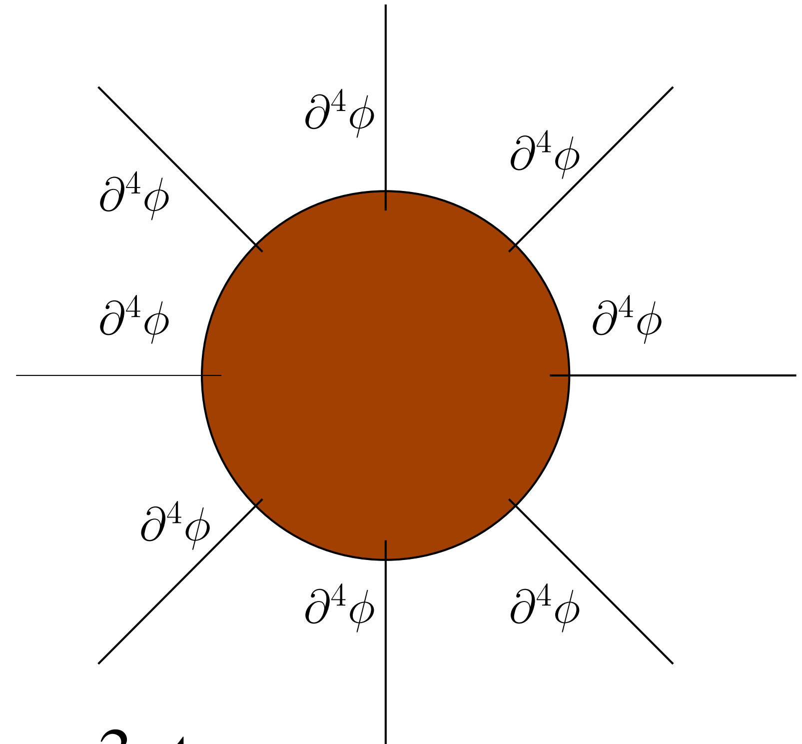
- Planck improve limits wrt WMAP by a factor of ~3.
- Since $\mathrm{NG} \sim \frac{H^2}{\Lambda_U^2} \quad \Rightarrow \quad \Lambda_U^{\mathrm{min,\,Planck}} \simeq 2\,\Lambda_U^{\mathrm{min,\,WMAP}}$
- Given the absence of known or nearby threshold, this is not much.
- Planck is great
- but Planck 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!

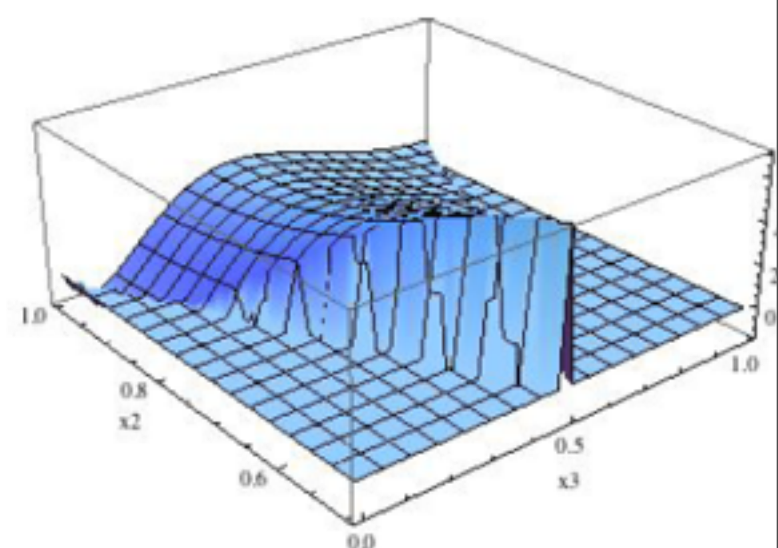
- Apart for improvement from polarization
- More 3-point functions
  - This theory is technically natural

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



  - 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
  - large quartic interactions

MultiField

Operator	Dispersion		Type	Origin	Squeezed L.
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$(\partial_\mu\sigma)^4$	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

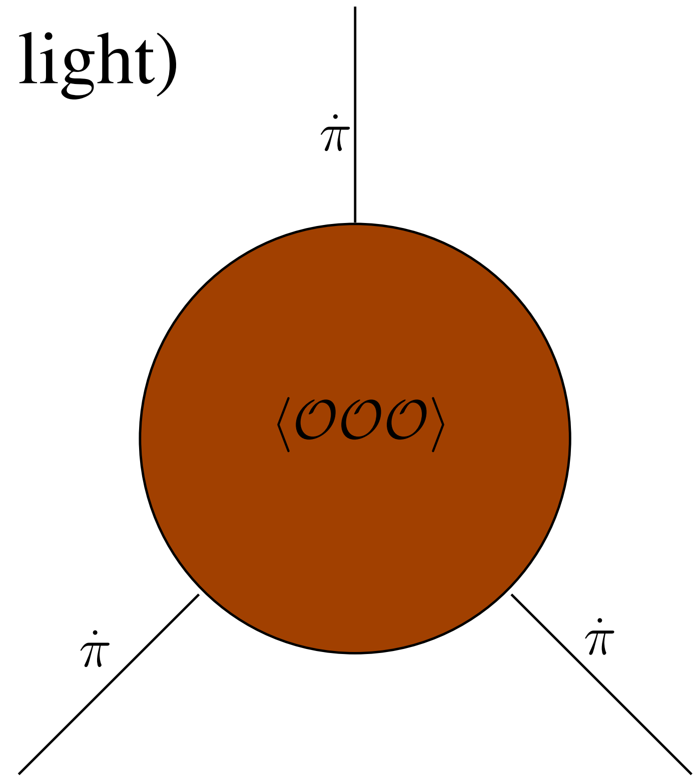
with Smith, Zaldarriaga,
in progress

The EFT of multifield inflation

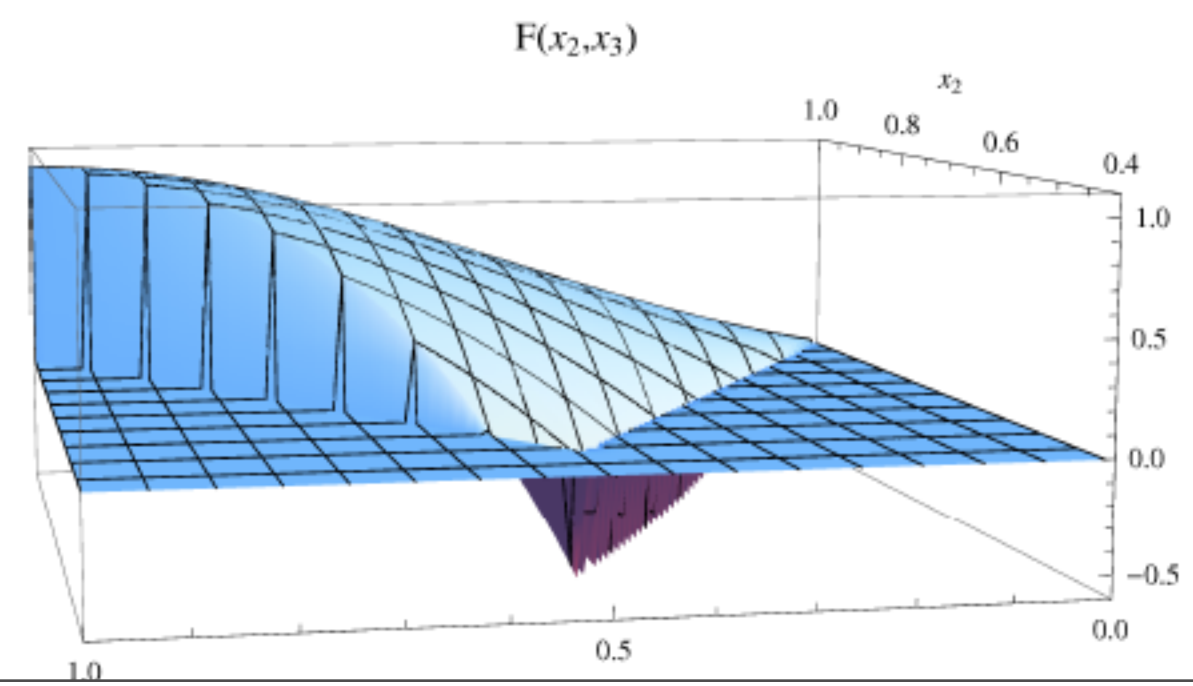
- If they are not observed (but they are light)

with Nacir, Porto, and Zaldarriaga
JHEP2012

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



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



The EFT of multifield inflation

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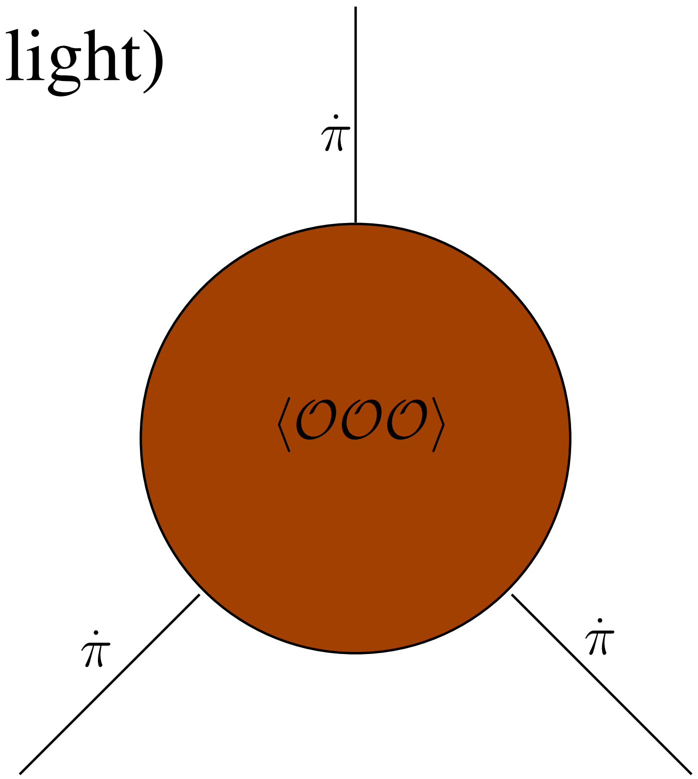
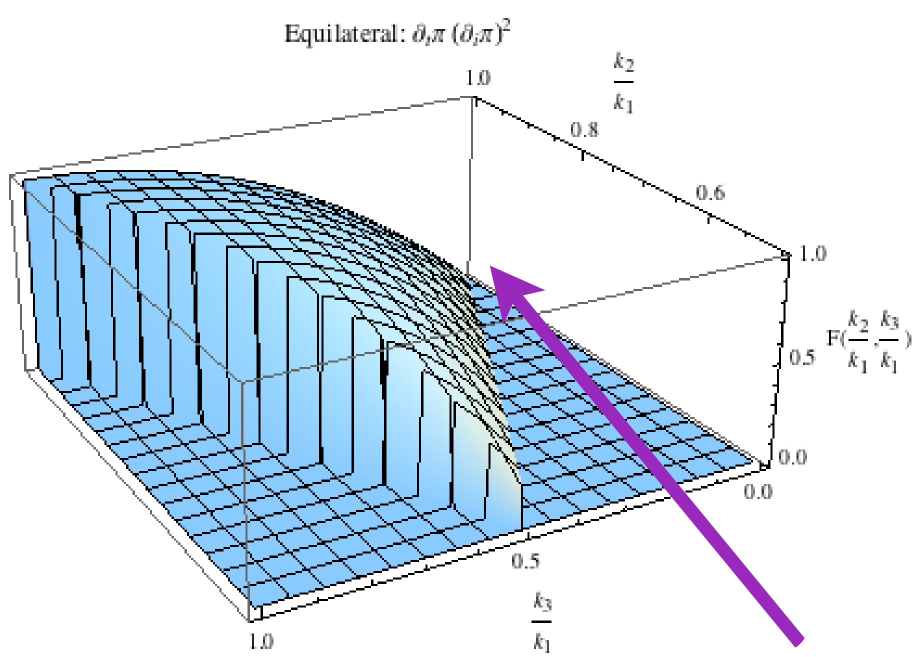
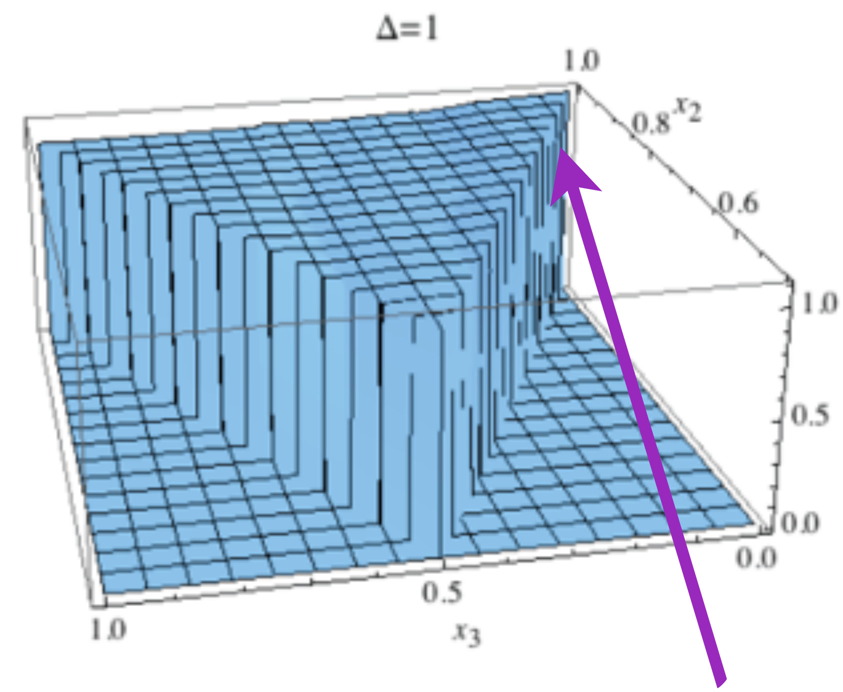


- Conformally coupled sector (strong coupling)

with Green, Lewandowski, Silverstein, and Zaldarriaga
1301



Single Field



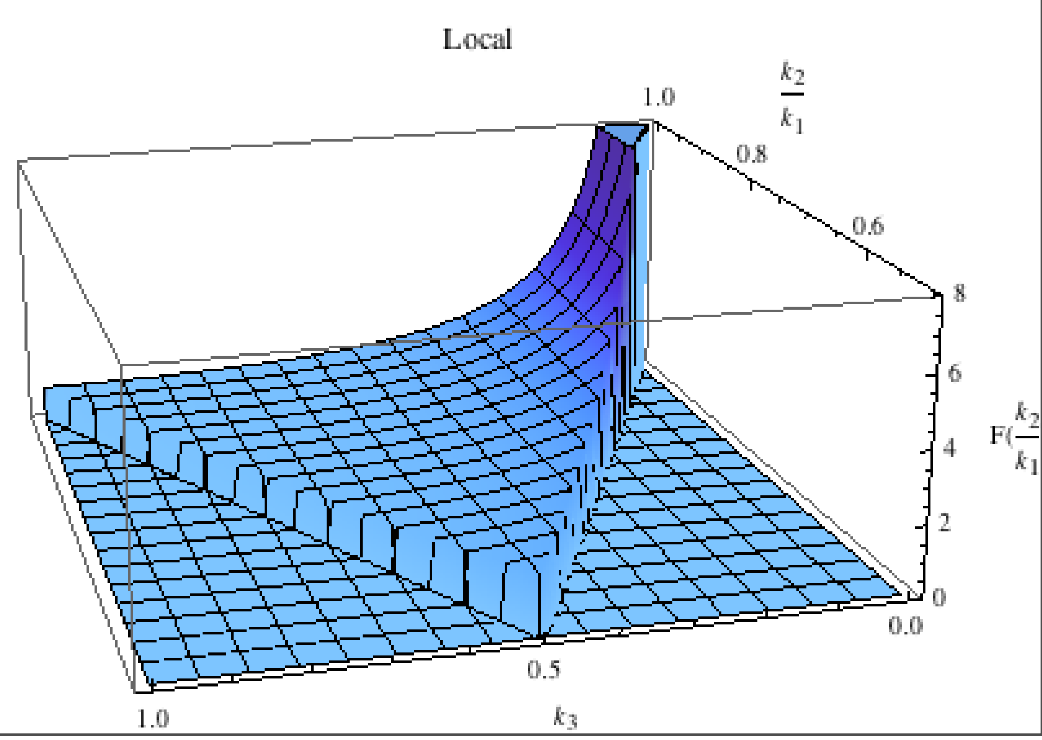
Conformal sector

Multifield 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
  - ...

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

- 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**
- Effects of massive fields — Baumann and Green **2011, 2012**; 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**
- conformal sector

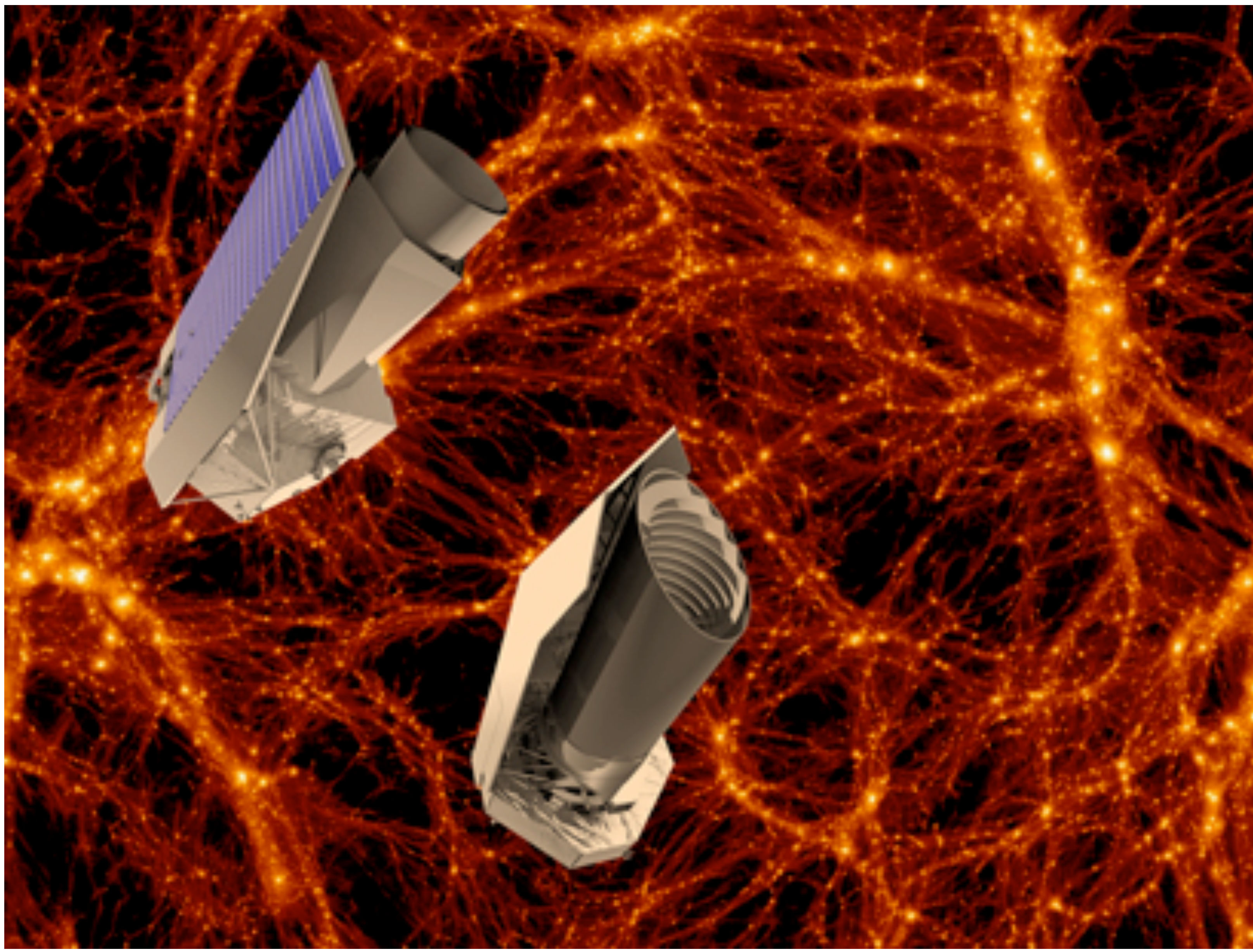
Becoming mainstreaming?

- 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

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

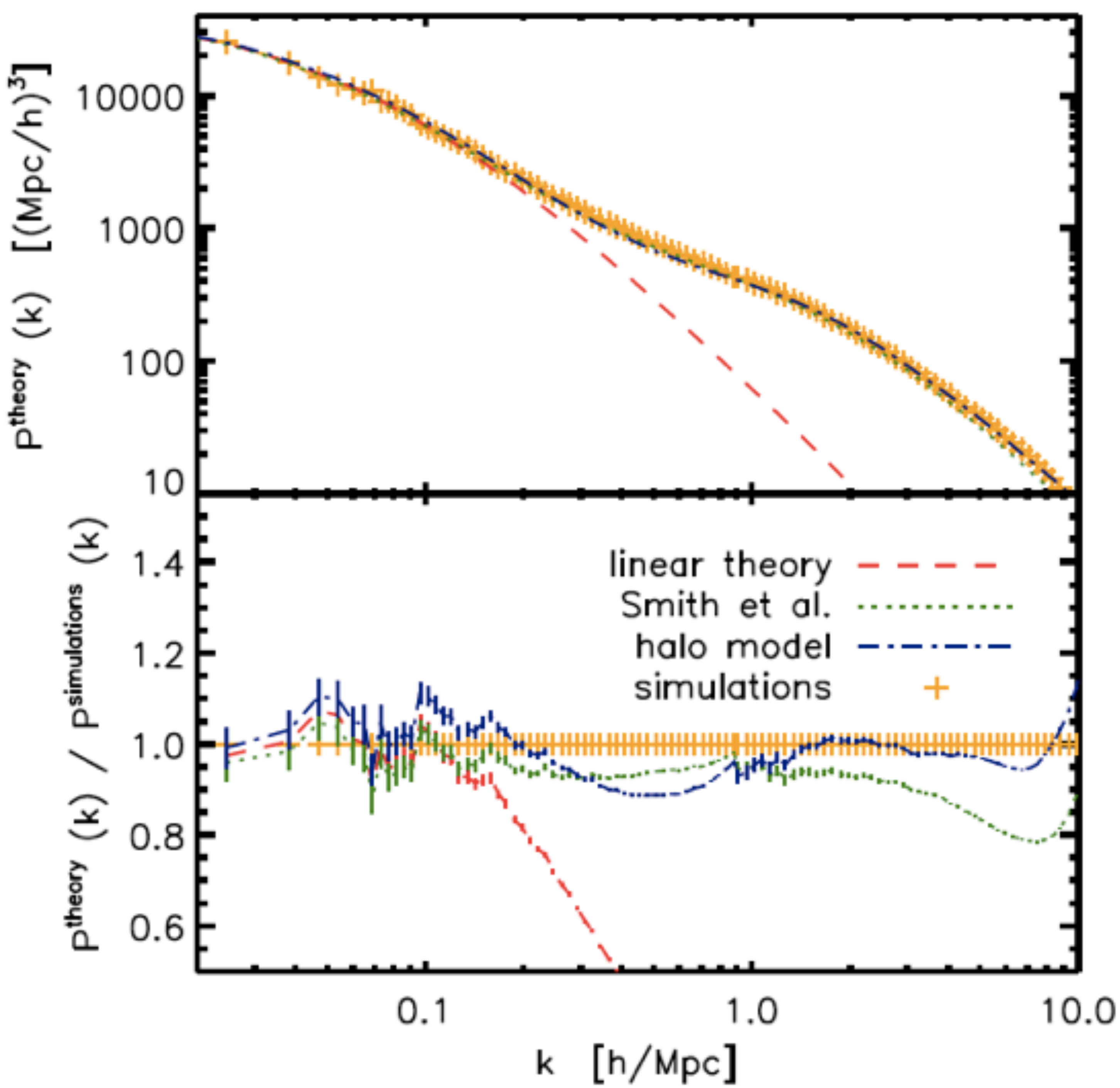
$${\rm Improvement} \simeq \frac{75}{30} \sim 2.5$$

- 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

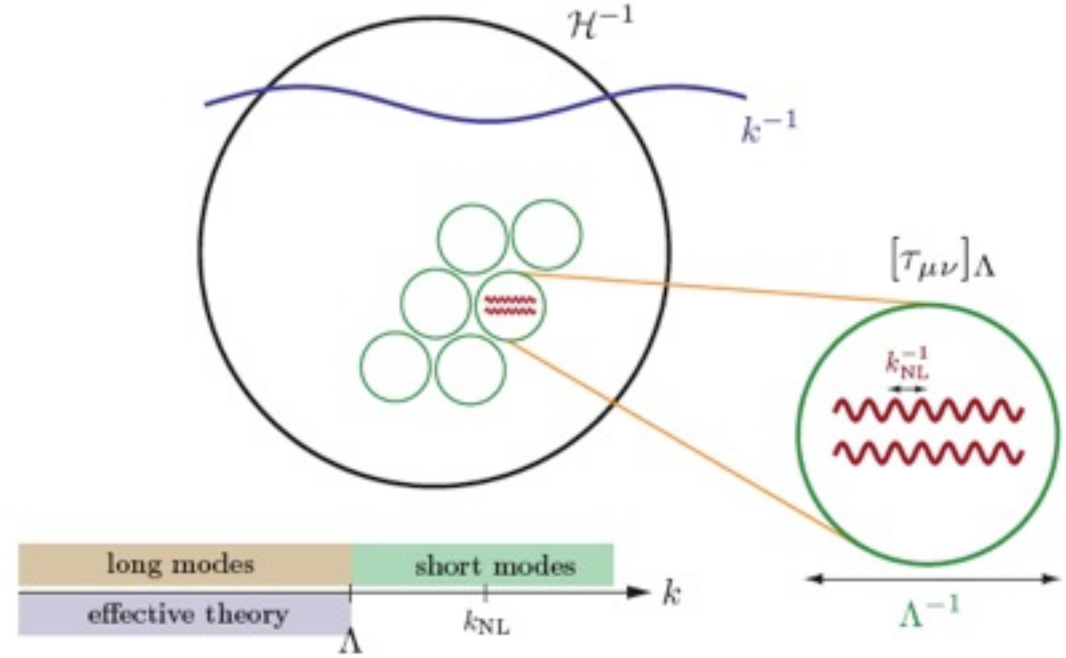
(from BSM to perturb. QCD)

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, Zaldarriaga **in progress**
....

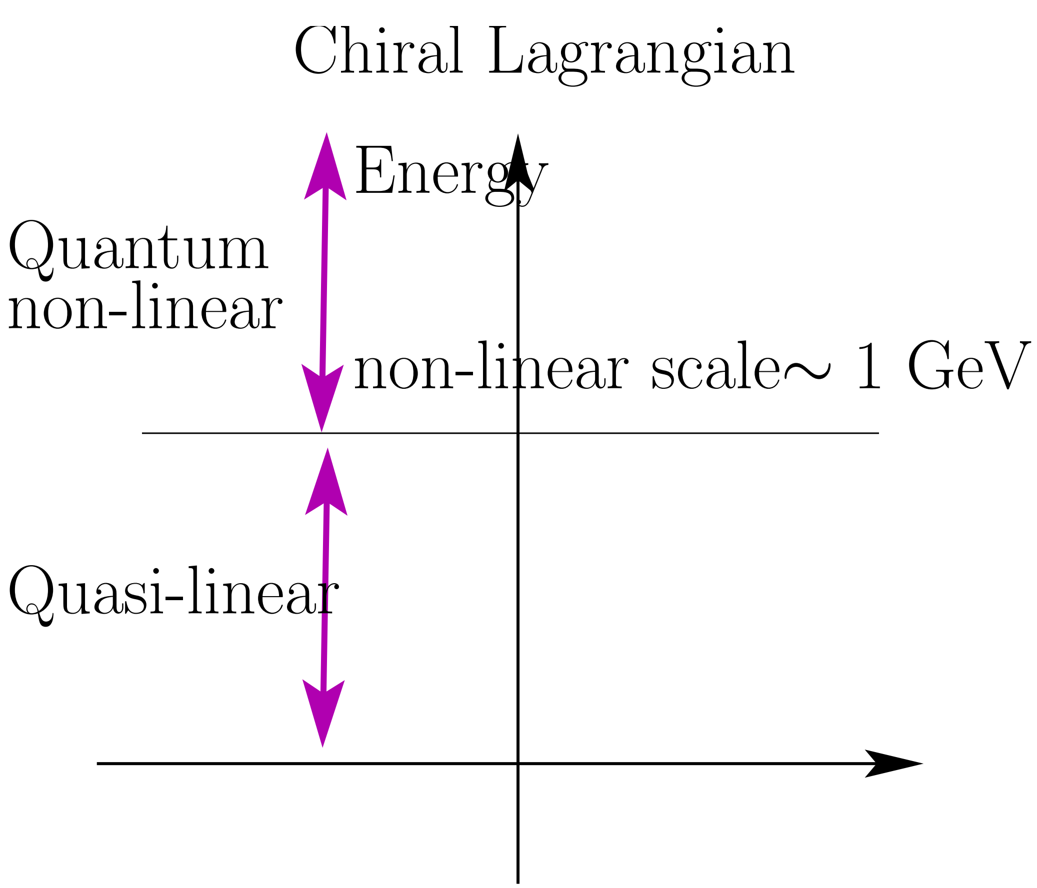
Our Universe as a Chiral Lagrangian

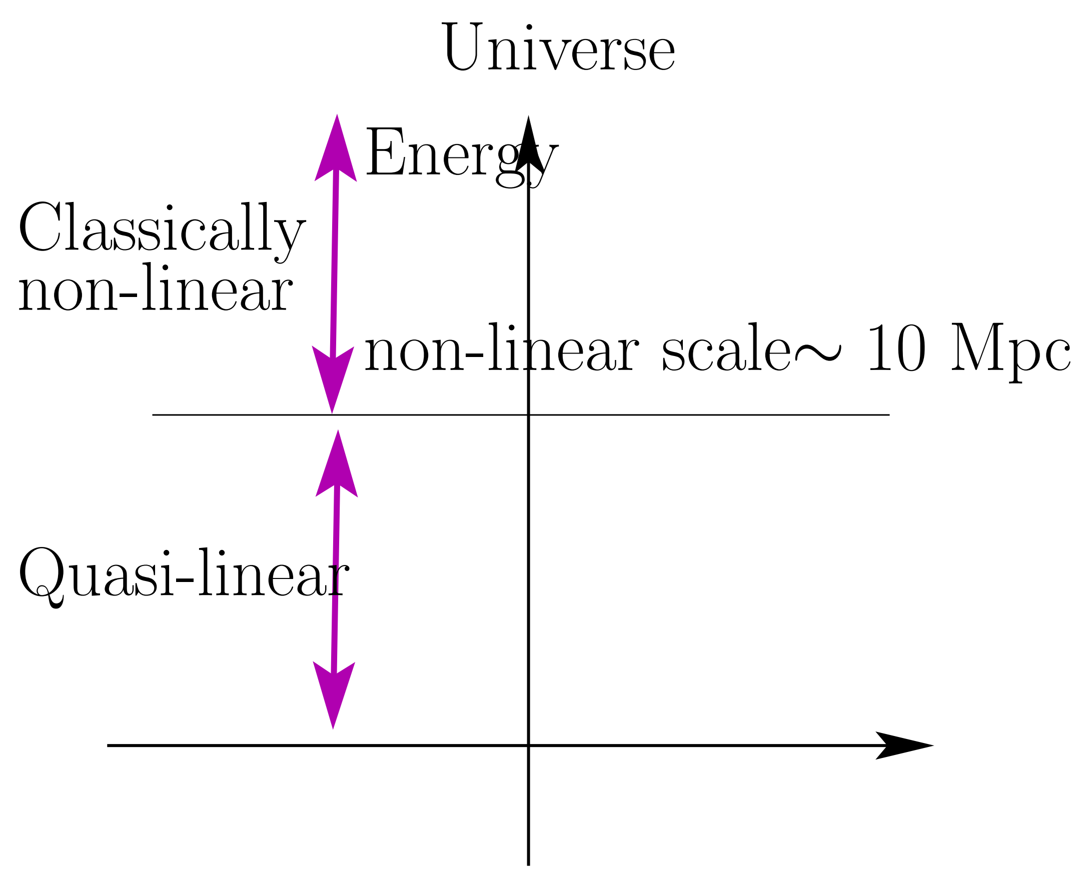
- How does our universe looks like?
- Non-linear on short scales $\lambda_{NL} \sim 1 - 10$ Mpc $\quad \delta\rho/\rho \gg 1$
- Linear on large-scales

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



- Similar to Chiral Lagrangian

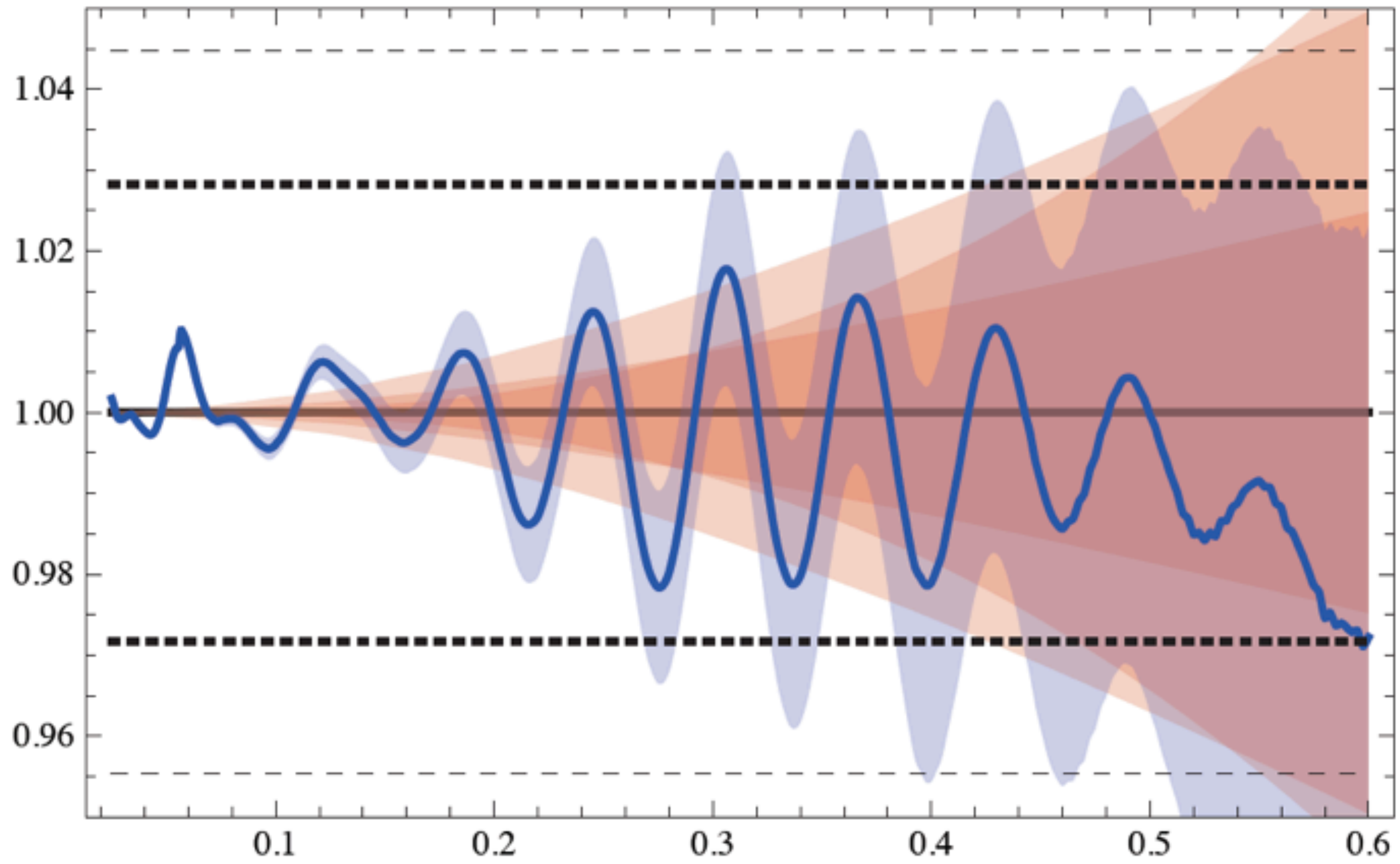




- Universe as an Effective Fluid with higher derivative stress-tensor in expansion in $k/k_{\rm NL}$

A much higher kmax

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



- We reach

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

Big Improvement!

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

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

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

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

- 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 $\text{New Improvement} \simeq 2.5 \quad \rightarrow \quad 15$
- And this is good. This is a lot

Big Improvement!

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- And this is good. This is a lot.

Big Improvement!

- With $\text{New Improvement} \simeq 2.5 \quad \to \quad 15$
- We get
  - With no detection:
    - . $f_{\rm NL}^{\rm loc.} \simeq 1$
      - Good for testing multifield
    - .$f_{\rm NL}^{\rm equil.,orthog.} \sim 5 \quad \Rightarrow \quad c_s \gtrsim 0.2$
      - 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, that are happening now.

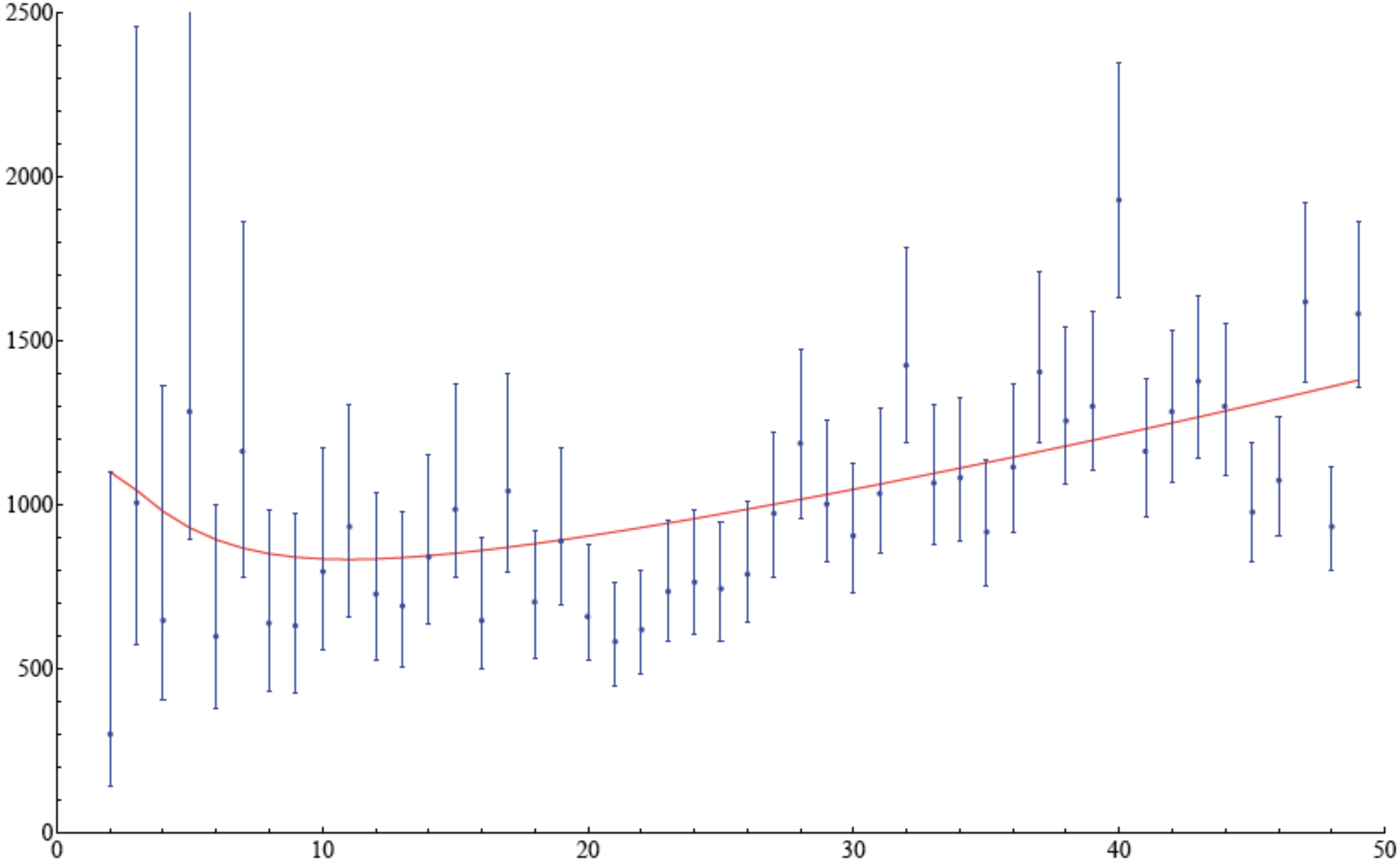
A challenge for the astro theorists!

- This is the potential $\text{New Improvement} \simeq 2.5 \quad \rightarrow \quad 15$
  - 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.
- A lot to understand, but this is what is at stakes.
- It an opportunity
  - and a challenge

But we got
anomalous surprises!

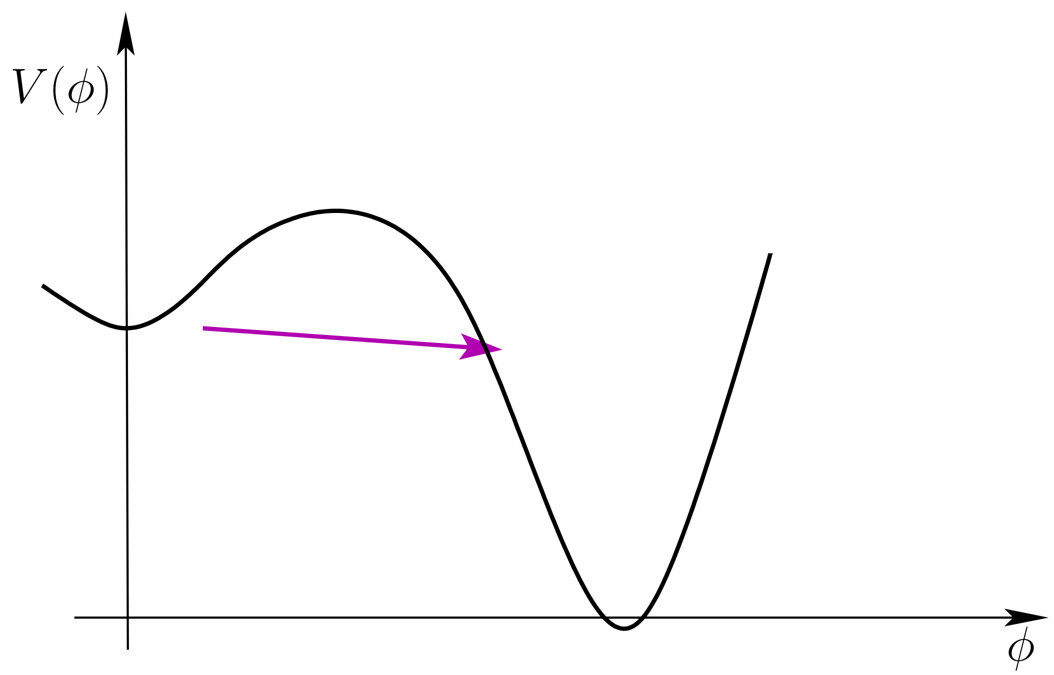
Planck signal

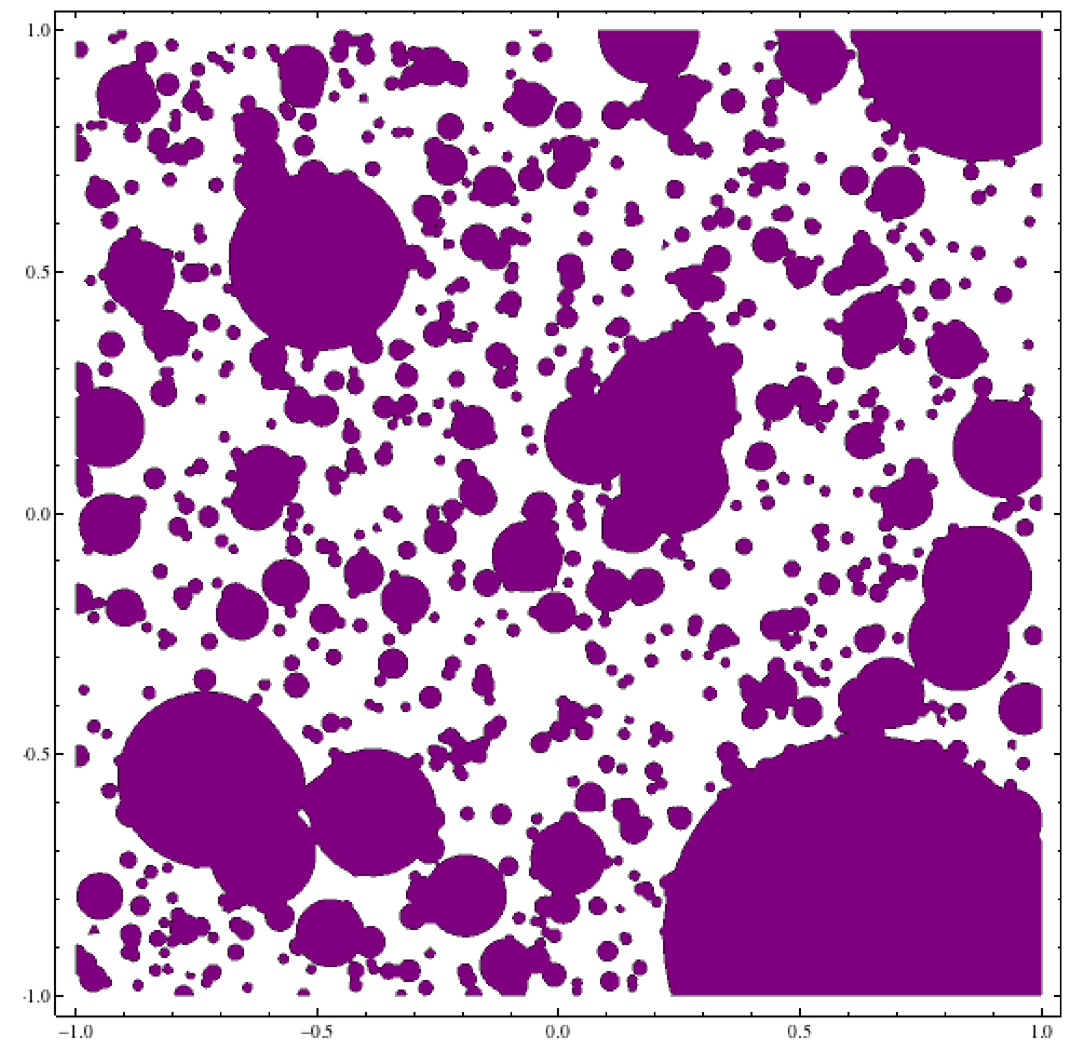
- Plank signal is low at low l at $2,3\ \sigma$



Eternal Inflation and the CC

- Anthropic bound on cosmological constant S. Weinberg **1984**
  - If Λ is too large, structures do not form
  - If you have a landscape of vacua, you can get Λ small enough
  - String theory has a landscape
  - Eternal Inflation populates this landscape
  - In this setup Λ was correctly predicted





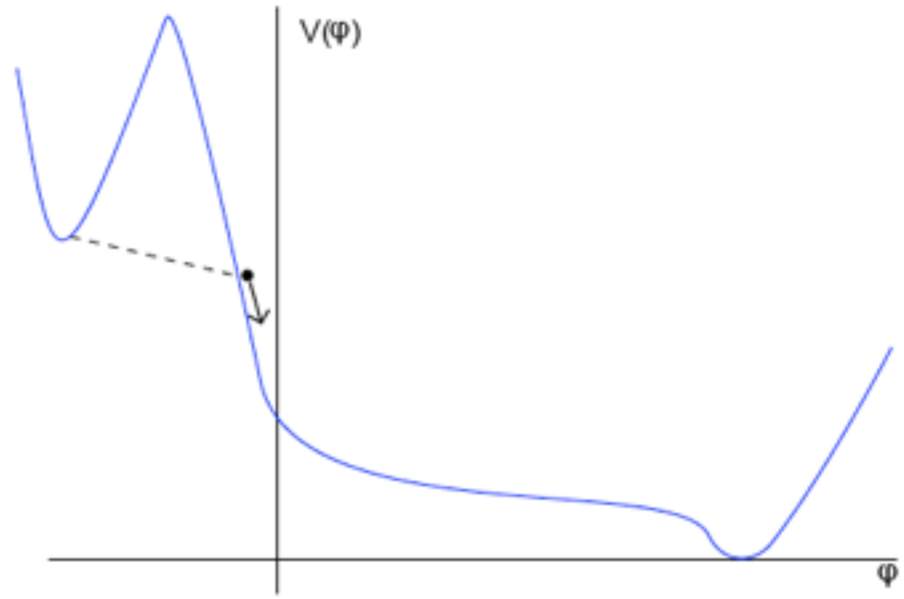
A nucleation in our past

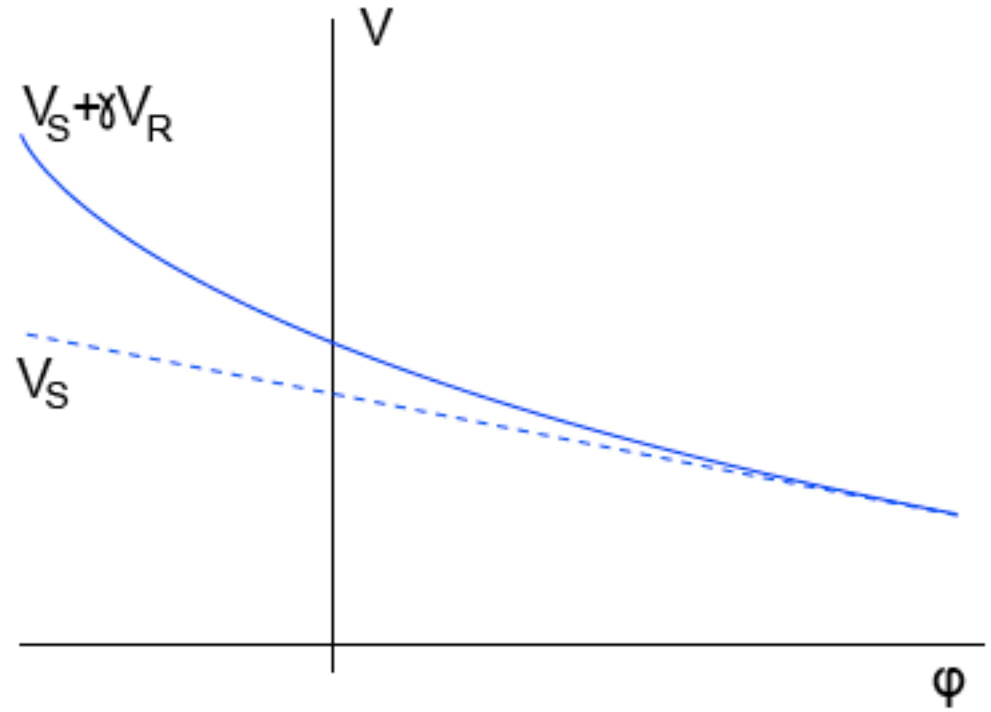
with Bousso and Harlow **to appear**

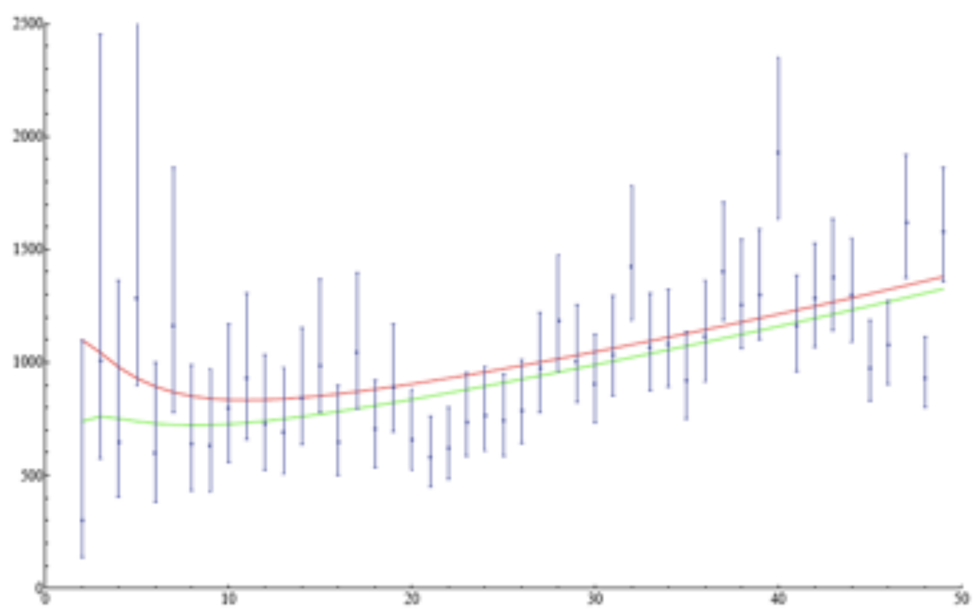
- If we come from a nucleation
  - . $\Omega_K \sim e^{-2N_{\rm e,tot}} > 0$
  - Steepening in our past

$$\epsilon = \epsilon_S \left[1 + 2\gamma \left(\frac{V_R'}{V_S'} - \frac{V_R}{V_S}\right) + O(\gamma^2)\right]$$

    - we increase ϵ parametrically
  - Since $P_{\delta T} \sim \frac{H^2}{M_{\rm Pl}^2} \cdot \frac{1}{\epsilon}$
    - $\Longrightarrow$ decrease low-l power
    - without having to see Ω_K

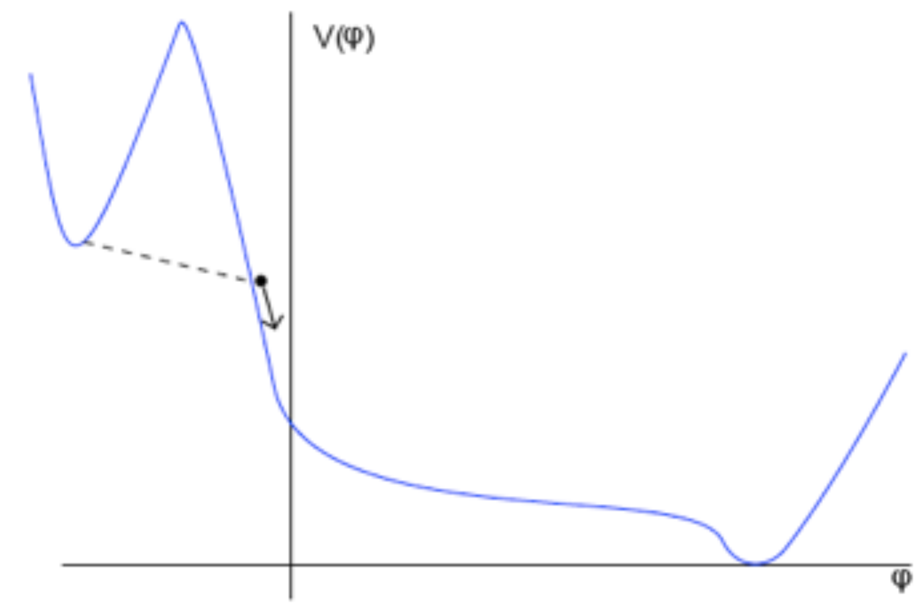




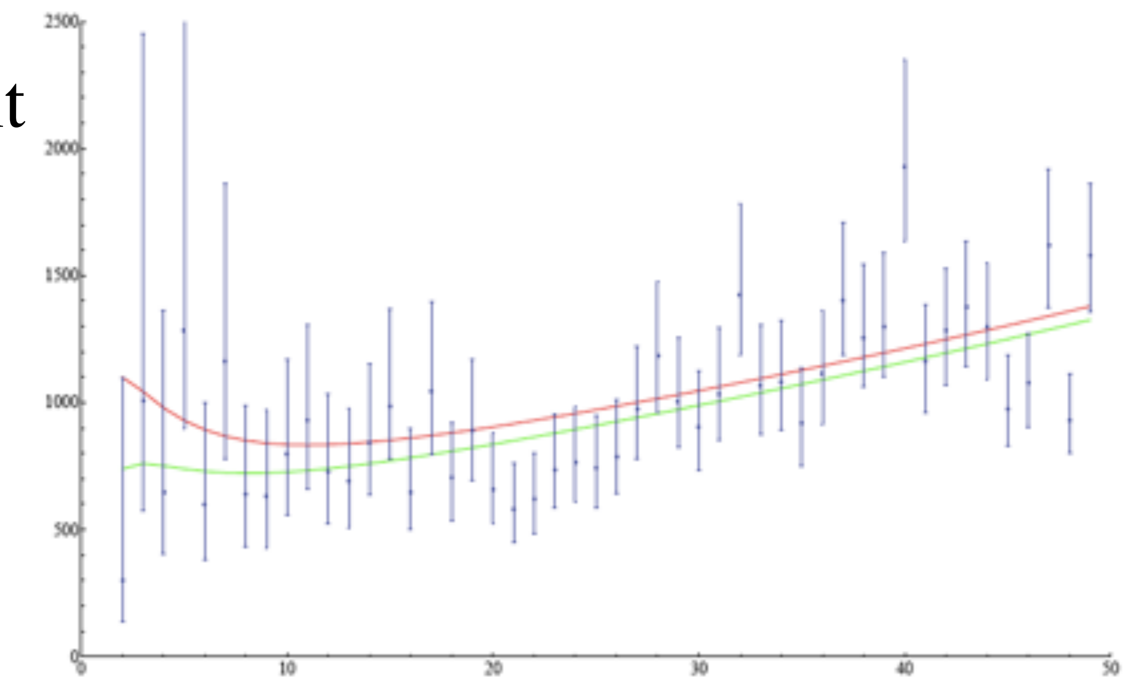


We will be able to tell! with Bousso and Harlow **to appear**

- Currently at $2, 3\,\sigma$
  - E-mode polarization
    - improve by ~30%



- Large scale structures will see these modes
  - Improve by 500%
  - Largely unexplored if we can actually do it
    - systematics
    - never looked before

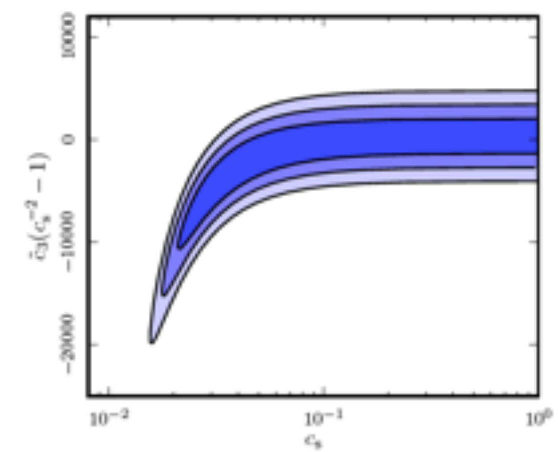


- We have hope and work to do

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.
- Maybe surprises from anomalies (eternal inflation and Λ)