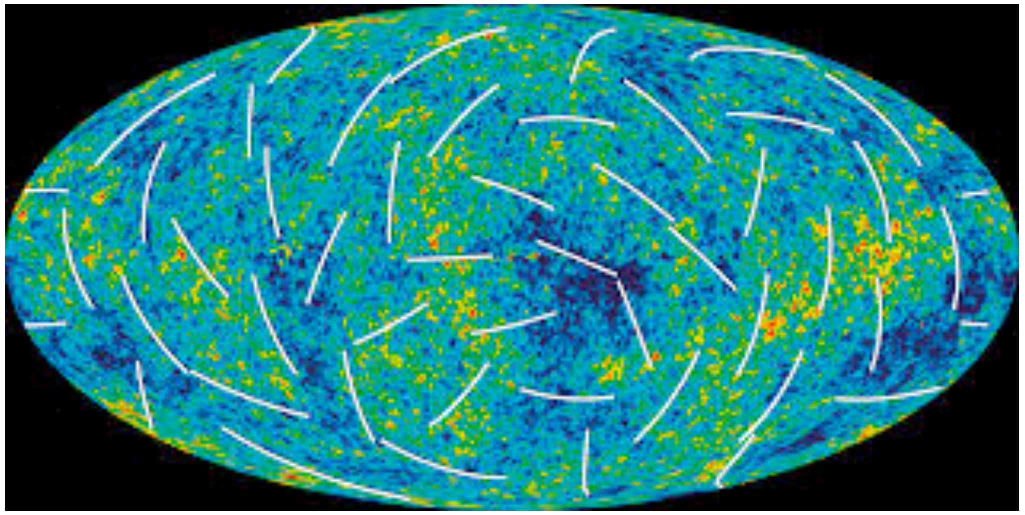
Leonardo Senatore (Stanford)

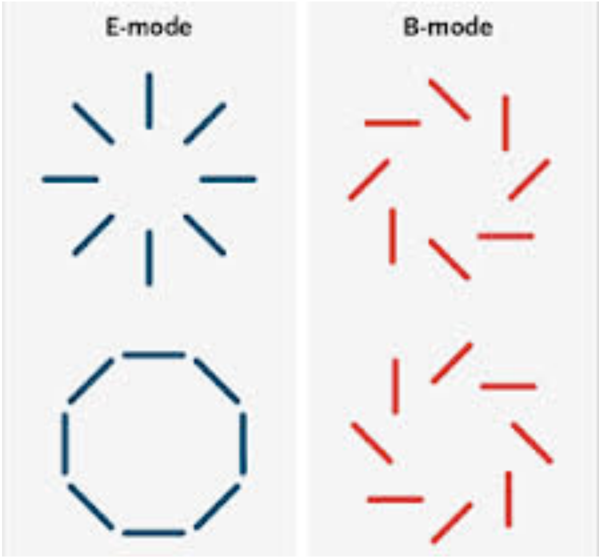
Some theoretical aspects of B-modes and Inflation

BICEP2 Announcement

- A detection of B-modes
  - what are them?
    - The CMB is polarized



- Can decompose it in E and B modes

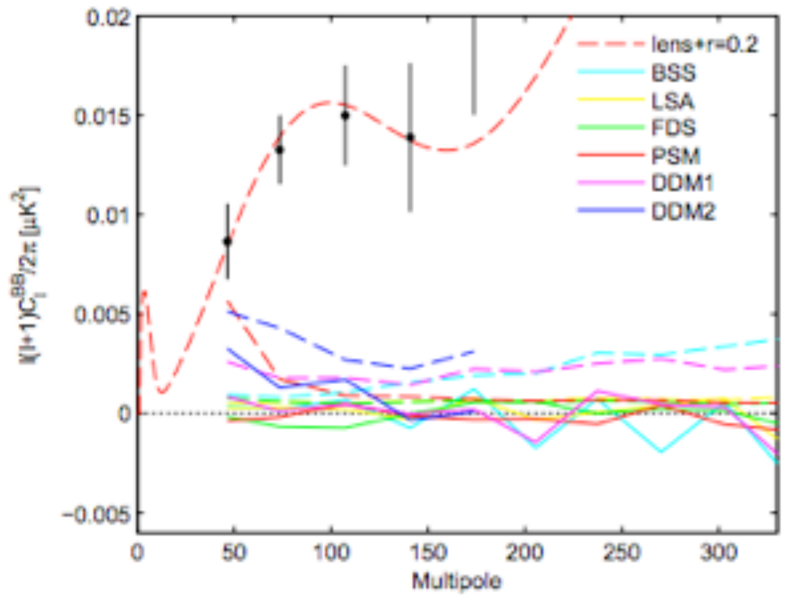


- Primordial E-modes are induced by scalar (normal temperature) fluctuations
  - detected since 2001 Dasi experiment **2001**
- Primordial B-modes can only be generated by primordial gravity waves

Seljak and Zaldarriaga **1996**
Kamionkowski, Kosowski, Stebbins **1996**

- Dust can generate both E and B modes at CMB frequencies

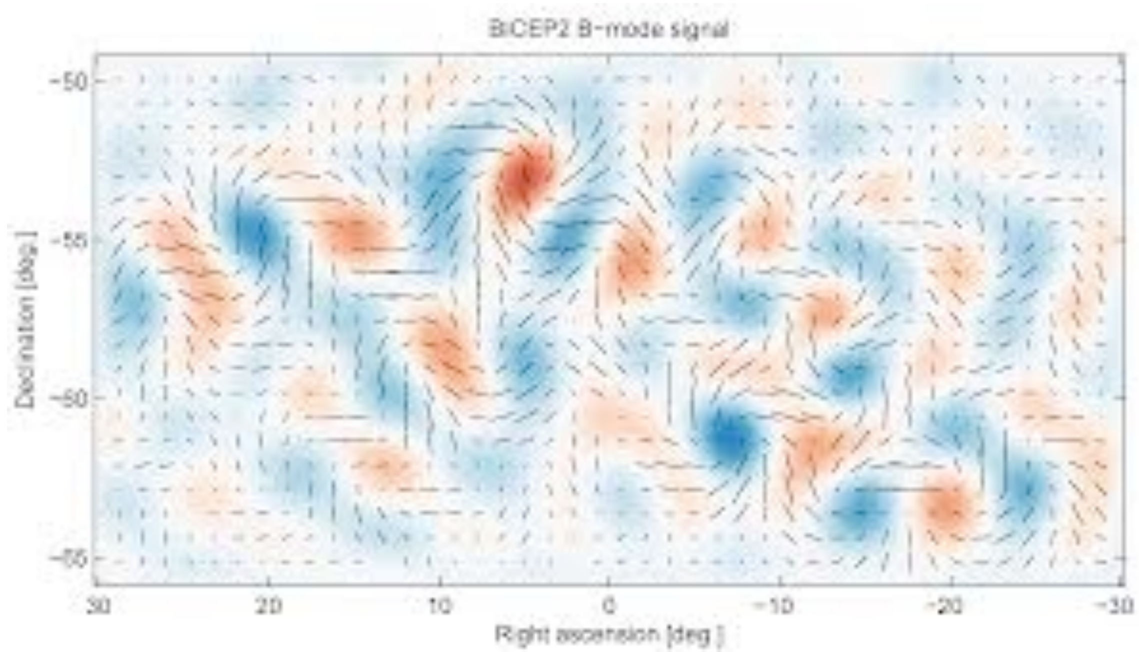
BICEP2 Announcement



- BICEP2 claimed their signal was primordial
  - with disclaimers!
  - by now, more careful analysis driven
    - by Planck, Princeton people and BICEP2
    - we do not know it is primordial, we do not know if it is dust
      - very uncertain situation

Mortonson and Seljak **now**
Flauger, Hill, Spergel **now**
BICEP2 paper V2 **now**

- If signal is primordial, this discovery represents
  - the first direct detection of gravitational waves
    - what we are seeing is the shape
      - gravity wave at one moment in time
      - Huge discovery



    - many implications for cosmology: very hot universe: milestone for mankind

BICEP2 Announcement

- If signal is all primordial, we will know in one-year
  - Planck releases in December
  - Keck 100 GHz array data in October
    - many many experiments trailing behind: Spider, SPT, ACT, Polarbear....
- If we forget the unjustified and glamourous claim of discovery, BICEP result tells us that an exquisite experimental sensitivity has been reached.
  - Huge progress is coming up
  - If signal is primordial, we will know the signal very well
    - implications for inflation: naively
      - a proof of inflation, transplanckian field excursion $\Delta\phi \sim M_{\rm Pl}\, 60\, r$
      - Surjeet will see it with gravity waves atom interferometry
        - » a measurement of the potential of inflation 20 e-folding further down
  - If signal is foreground: implications for inflation

The 10 year future of Cosmology

- Cosmology has been great in the last 20 years
- Cosmology probes the early universe by measuring the primordial fluctuations
  - like a low energy luminosity experiments
- To make progress we need more modes.
  - Planck will measure all scalar modes available in the CMB
  - If BICEP is primordial, we will explore primordial B-modes
  - Independently of BICEP (which is just a factor 2):
    - to get tilt, running, neutrino masses, oscillasions, dark energy, primordial non-Gaussianities $\Longrightarrow$ need more modes
  - Large Scale Structure surveys provide many $\left(\frac{l}{l_{\rm min}}\right)^2 \quad \rightarrow \quad \left(\frac{k}{k_{\rm min}}\right)^3$
    - experiments are coming: LSST, Euclid
    - need to understand the theory, very much as CMB was understood in the 90's

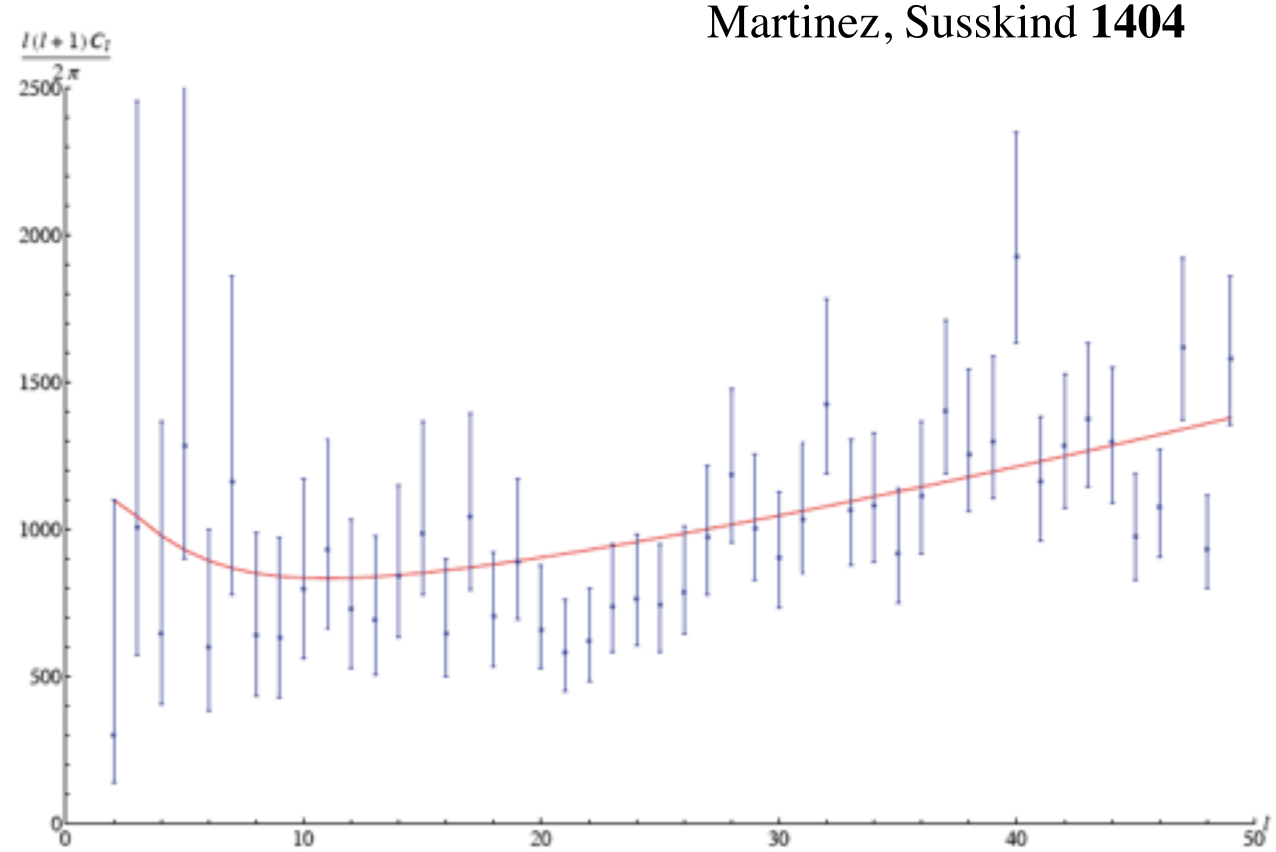
An outline of less-common ideas related to B modes and Inflation

The low-TT anomaly
and
the beginning of the universe

The TT low-l anomaly

with Bousso, Harlow **1309**
with Bousso, Harlow **1404**
see also Freivogel, Kleban, Martinez, Susskind **1404**

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



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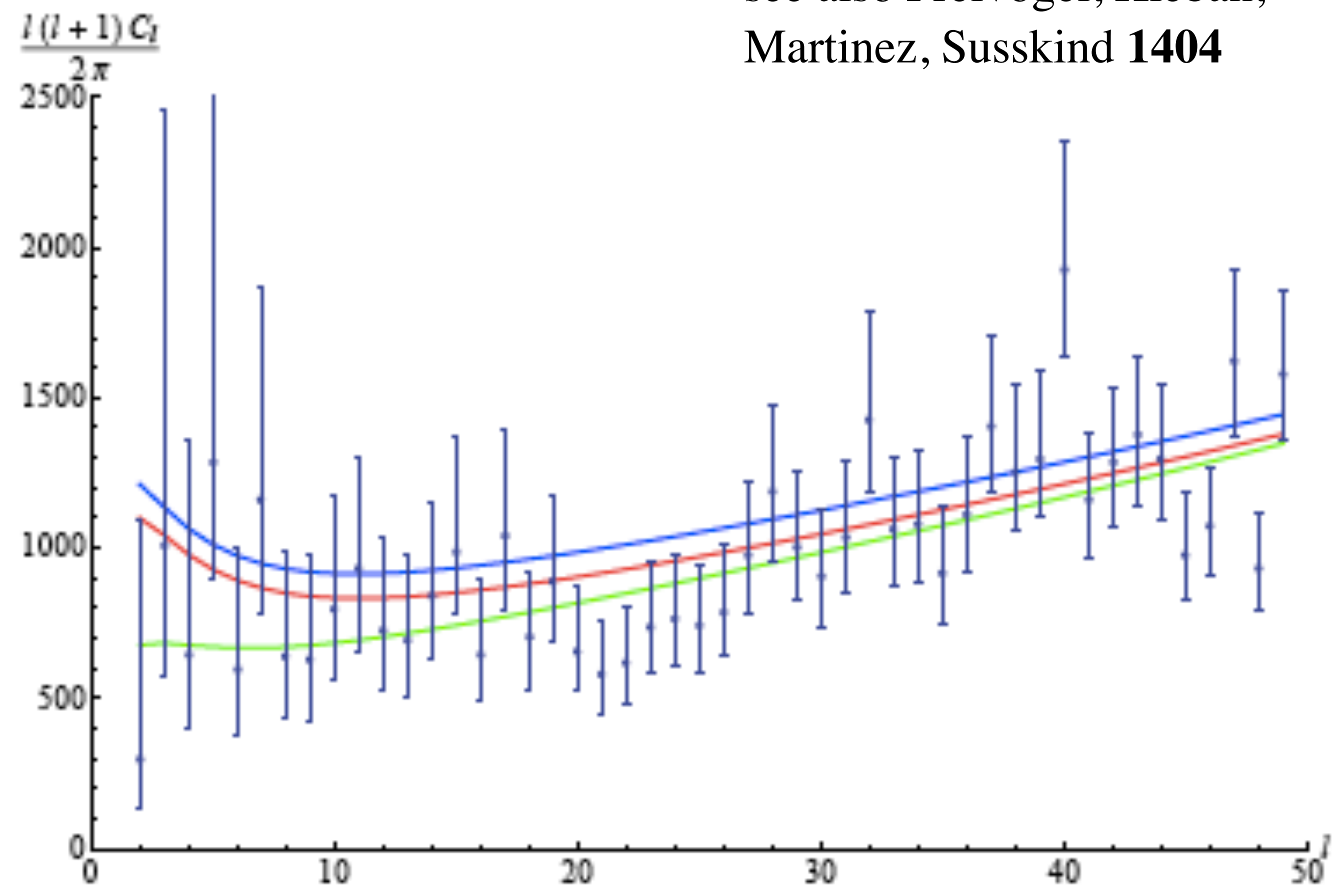
- Planck TT signal is low at low ell
  - $2, 3\sigma$
- After BICEP, even more
  - $3, 4\sigma$



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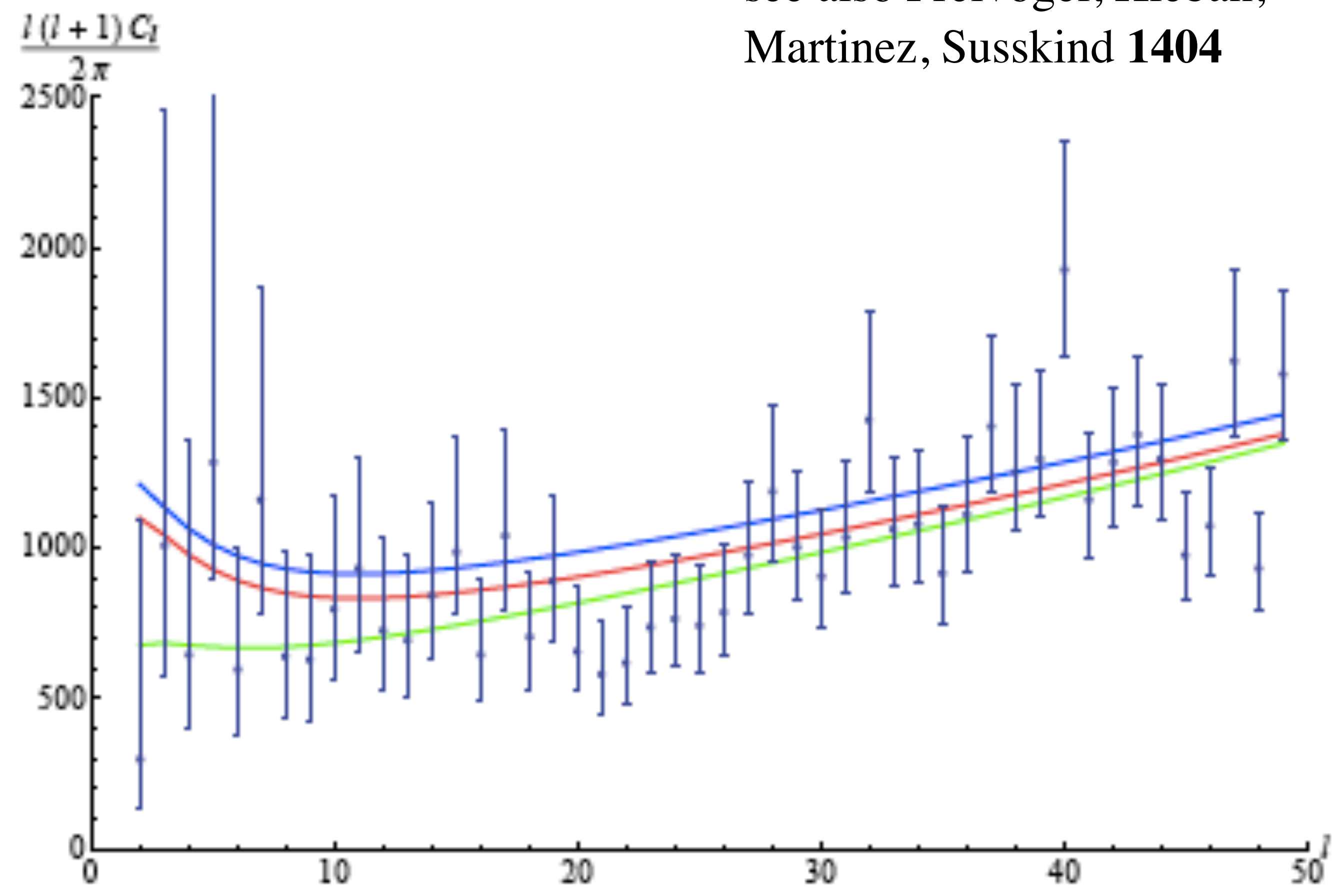
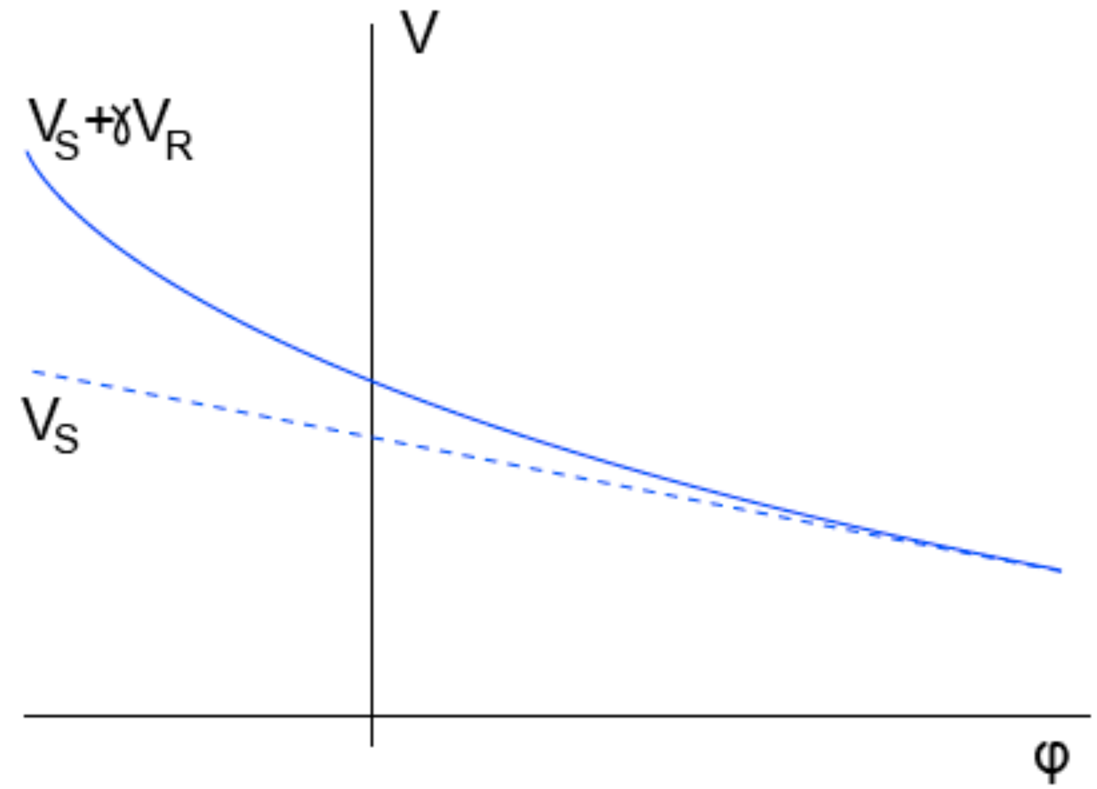


- Simple explanation:
  - Steepen the potential
    - by order slow-roll
  - Since

$$\langle \zeta^2 \rangle \sim \frac{H^4}{\dot{\phi}^2}$$

  - $\dot{\phi}^2$ is of order slow roll, very easy to change, while H^4 does not change
  - so, steepening $\Rightarrow$ low TT



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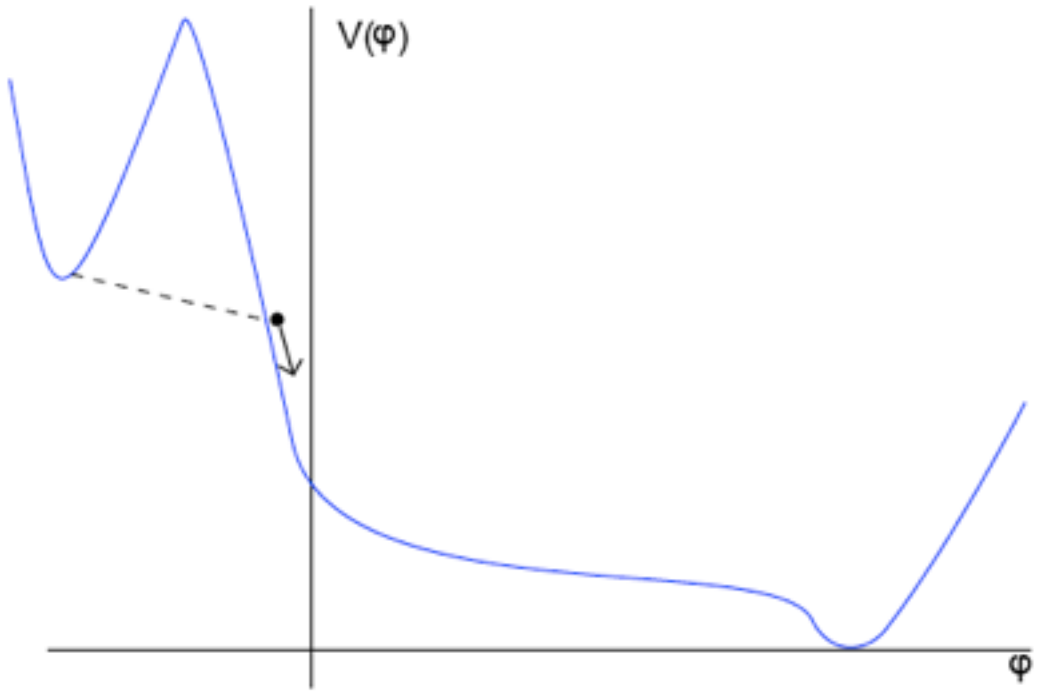
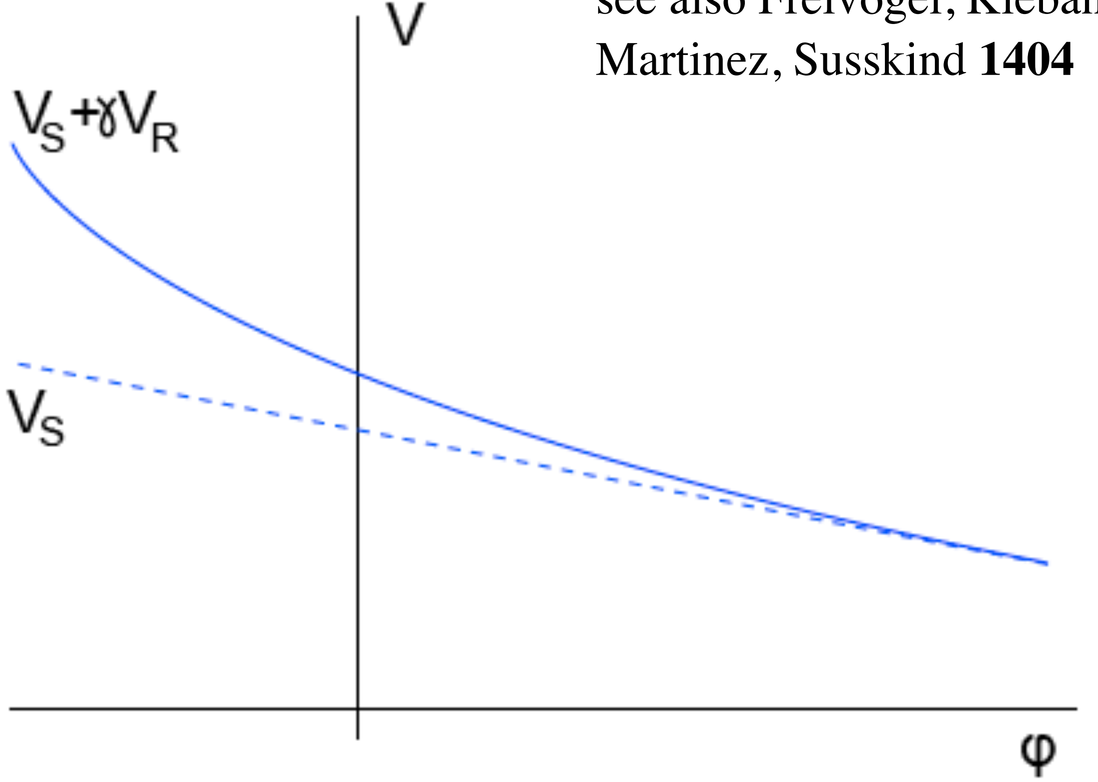
- Is this well motivated?
  - Yes, by this

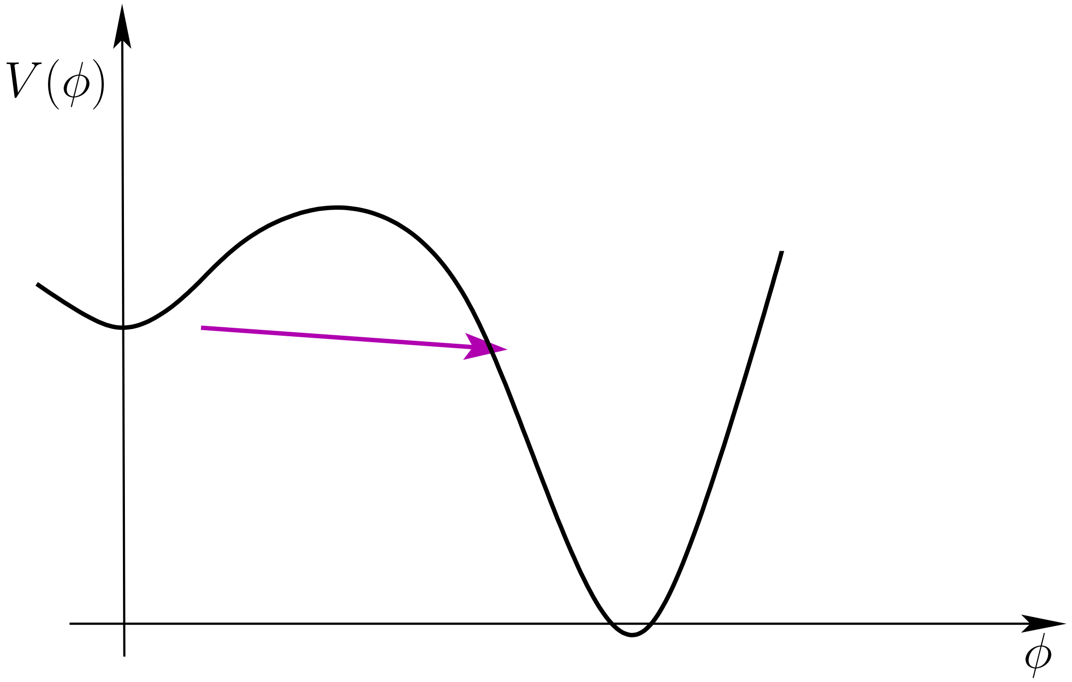


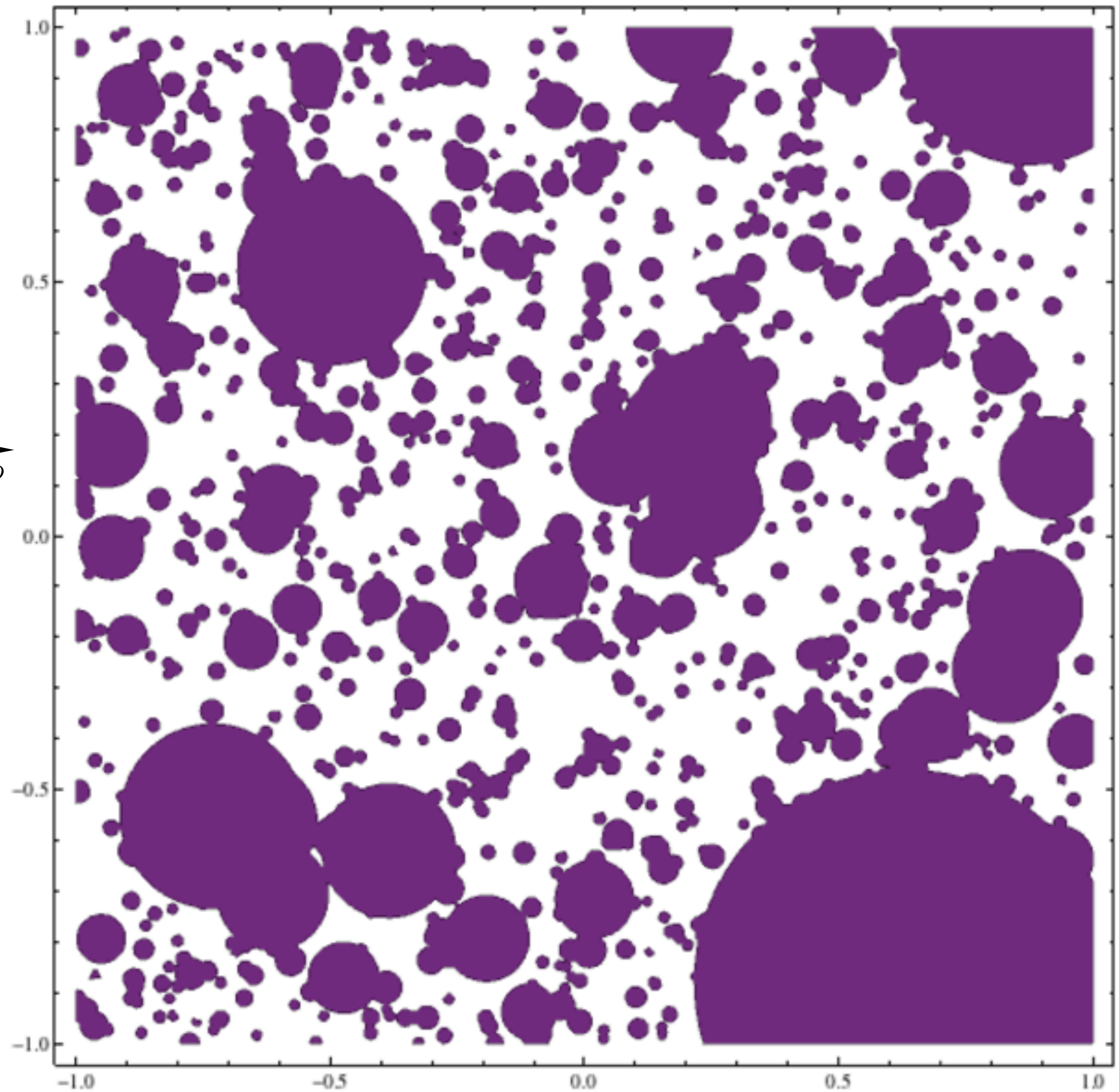


  - Eternal Inflation and the landscape offer the only available working solution of the cosmological constant: Weinberg's anthropic solution.
    - Appealing, but in desperate need of measure-safe observables

Eternal Inflation

- Our phase of slow roll inflation might have been preceded by a more global eternal inflation





- If $\Gamma \lesssim H^4$
  - Eternal Inflation

- You can see collisions.

$$\langle N_{\text{collisions}} \rangle \sim e^{-S_{\text{instanton}}} e^{-(N_e - 60)} \frac{H_f^2}{H_i^2}$$

Freivogel, Kleban, Nicolis, Sigurdson, **2009**

  - Low expectancy, but huge importance

Pictures from **M. Kleban**'s review

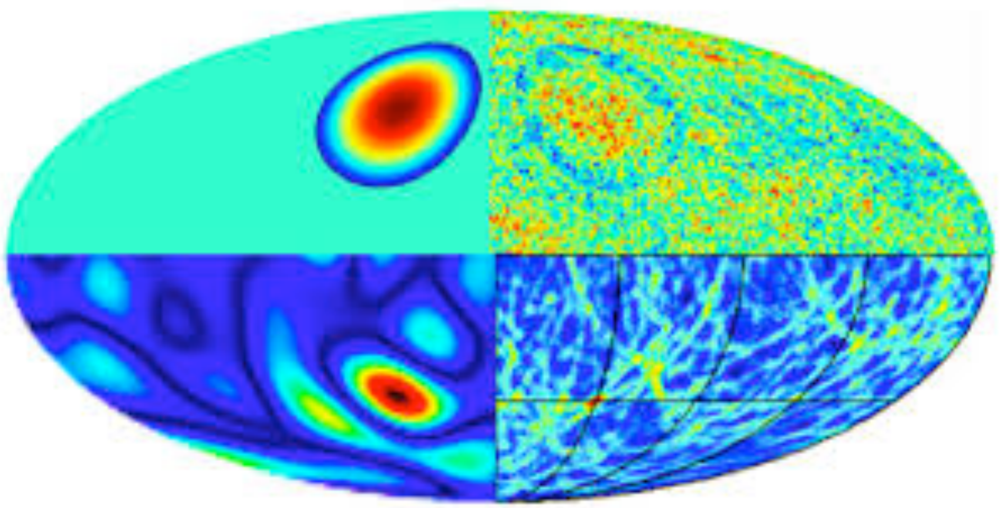
Eternal Inflation

with Osborne, Smith **1305**
with Osborne, Smith **1305**

- Bubble Shaped imprint in CMB

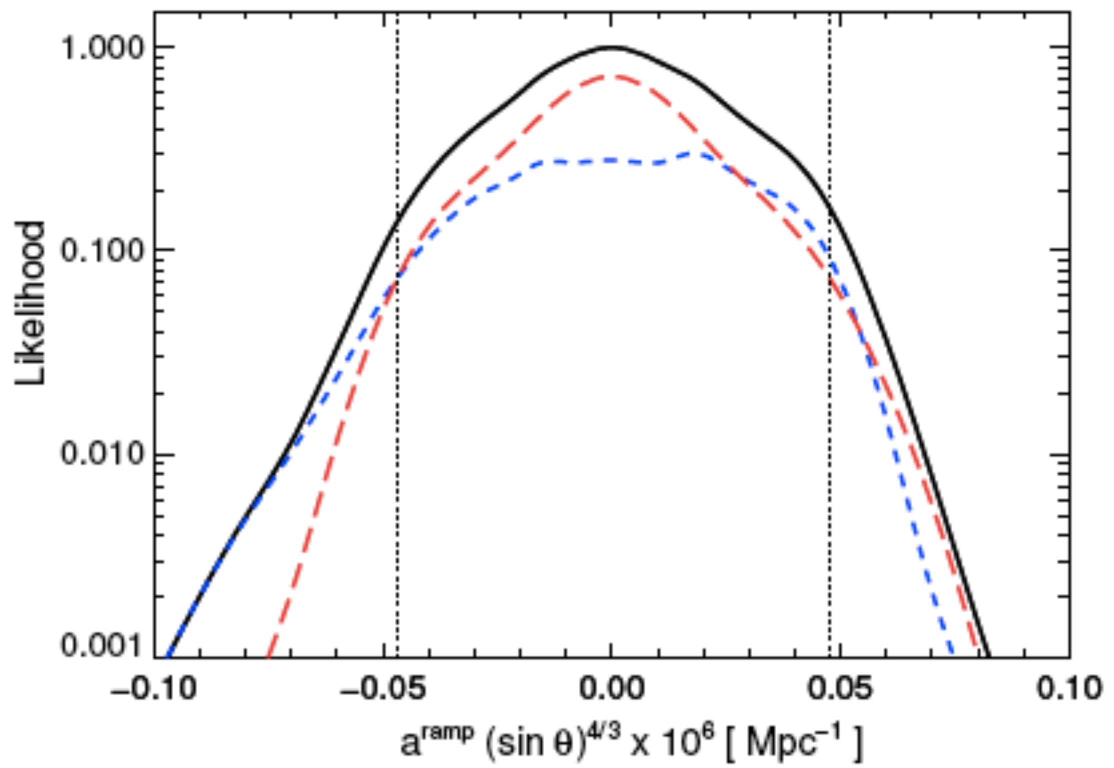
$$\text{Amplitude} \sim \cos(\theta) - \cos(\theta_{\text{Max}})$$

Kleban, Levi, Sigurdson, **2011**



- Series of suboptimal analysis detects `candidates'
- We perform the optimal analysis, by computing the
  - Likelihood of the data exactly.
- Results completely compatible with absence of a signal

Feeney, Johnson, Mortlock, Peiris,
2010 2011 2012



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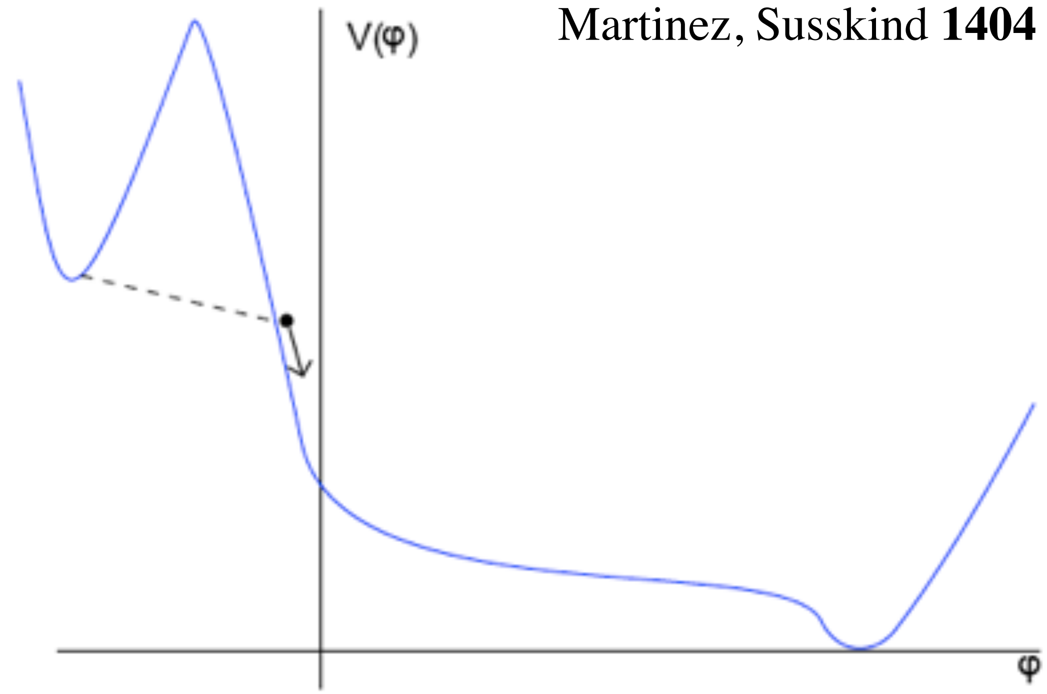
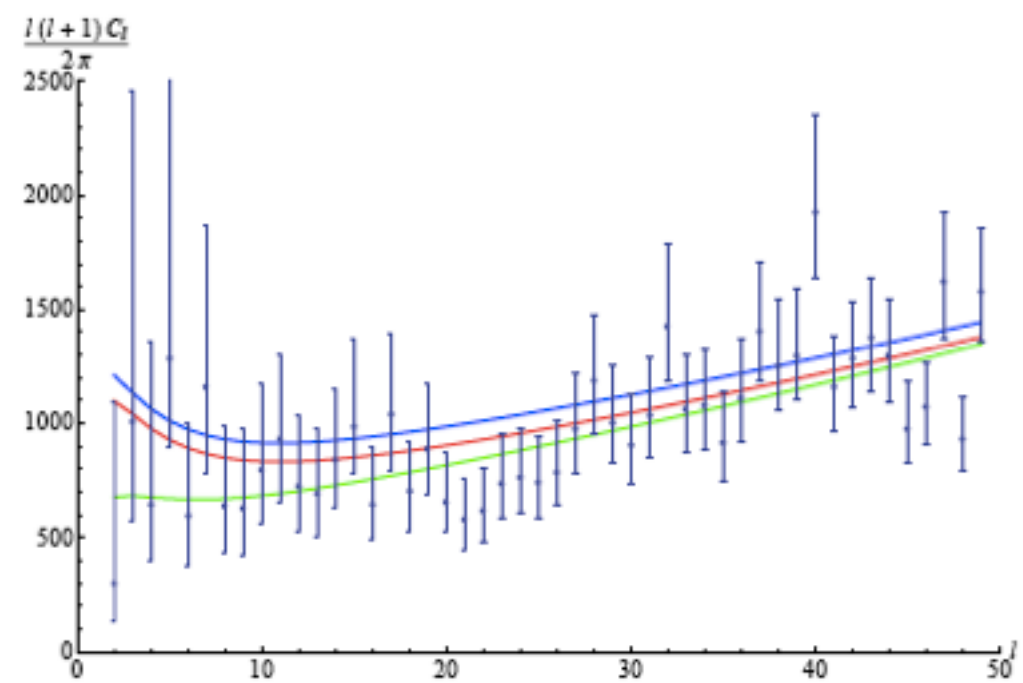
- Other signatures
  - $\Omega_K > 0$

    Linde **90'**
    Freivogel, Kleban, Martinez, Susskind **0505**
    - but it redshifts differently than steepening
  - ??



- More data?
  - with E-polarization we can gain a $\sqrt{2}$
  - B-modes will not decrease
    - . $\langle \gamma^2 \rangle \sim \frac{H^2}{M_{\rm Pl}^2}$



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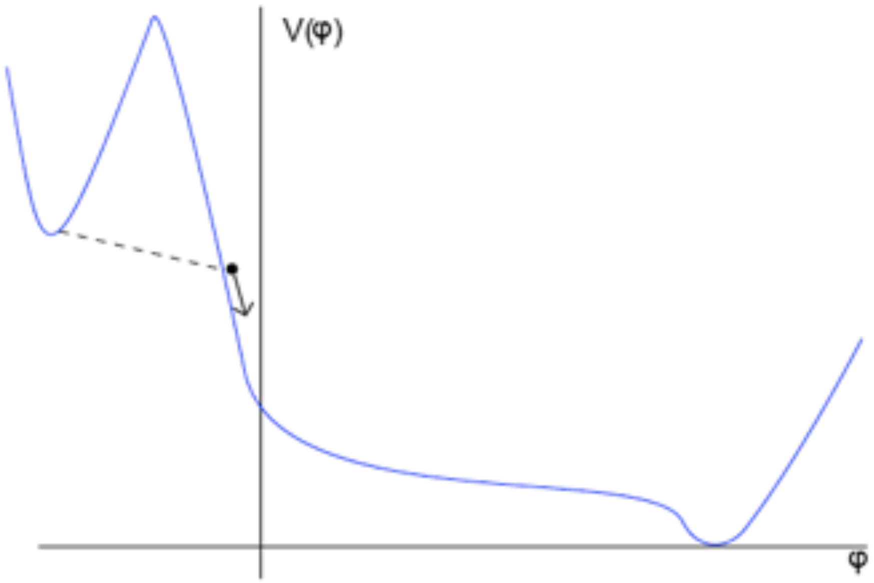
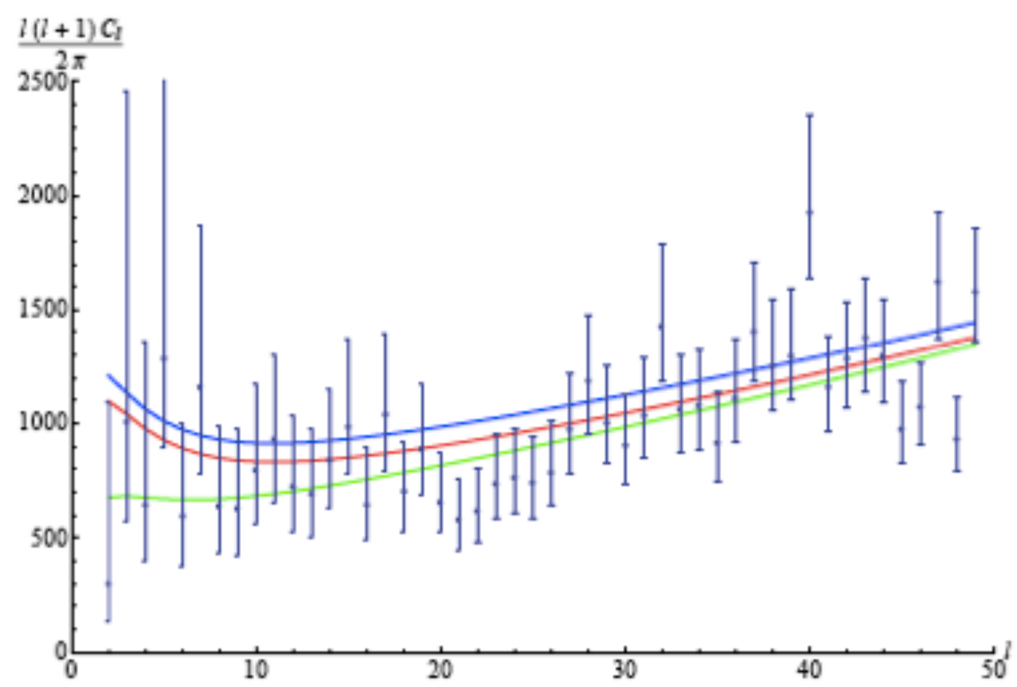


- This low-l anomaly is not low-l enough!
  - Large scale structure surveys will observe those modes
    - and they have much more modes!

$$N_\ell = 2\ell + 1 + 4\pi \frac{\ell^2}{\ell_z^3}$$



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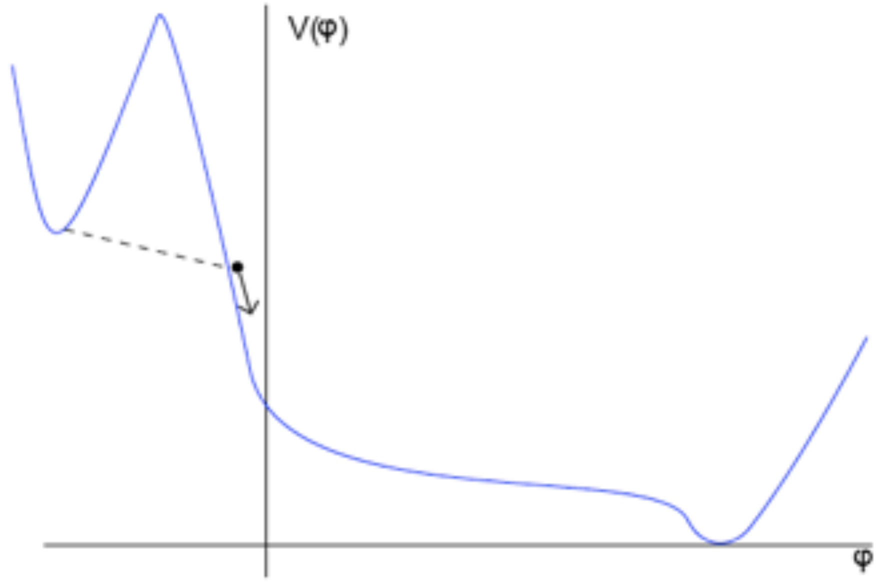

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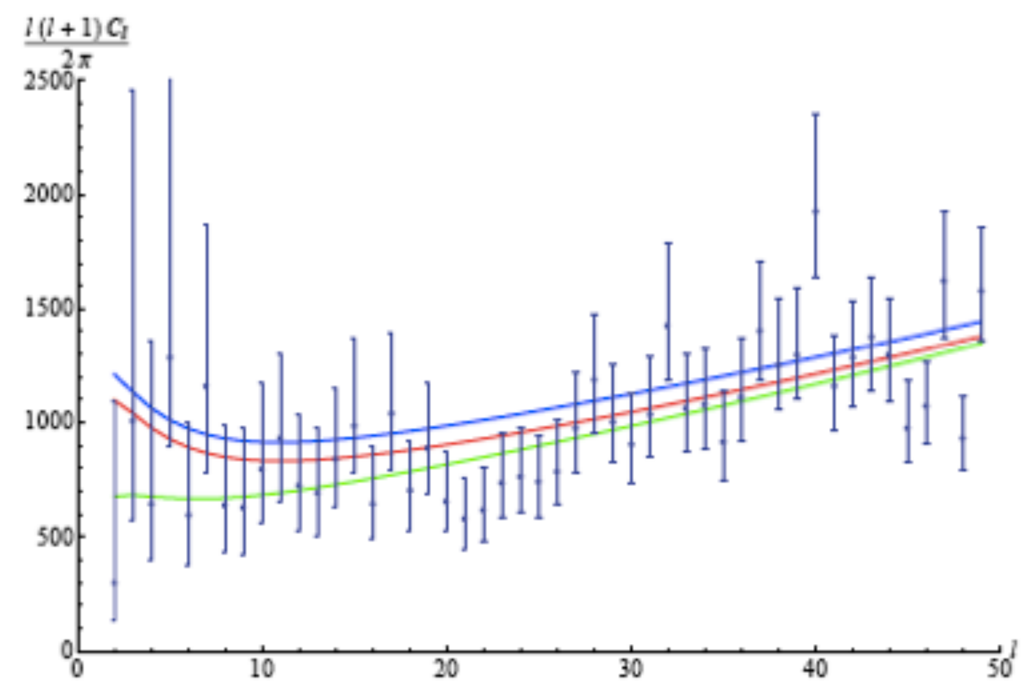
$$N_\ell = 2\ell + 1 \to 4\pi \frac{\ell^2}{\ell_z^3}$$

From CMB



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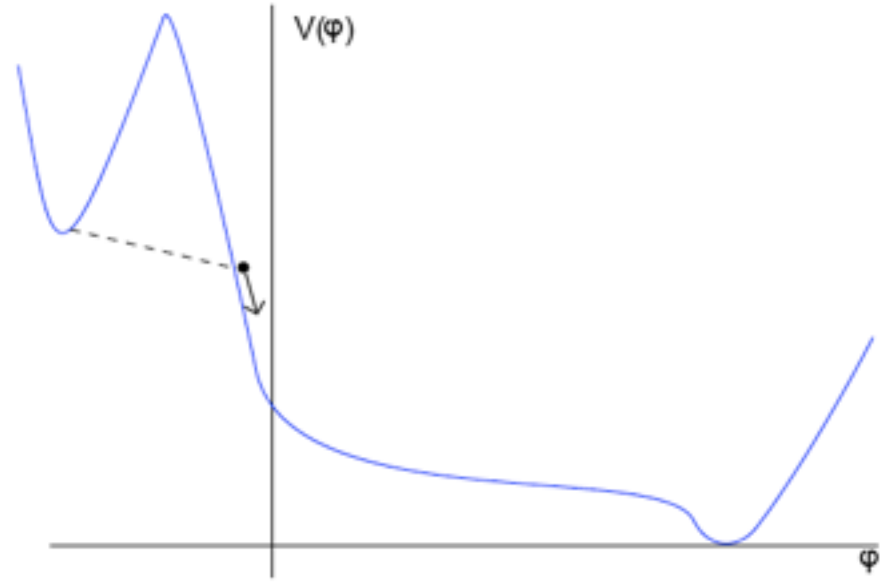

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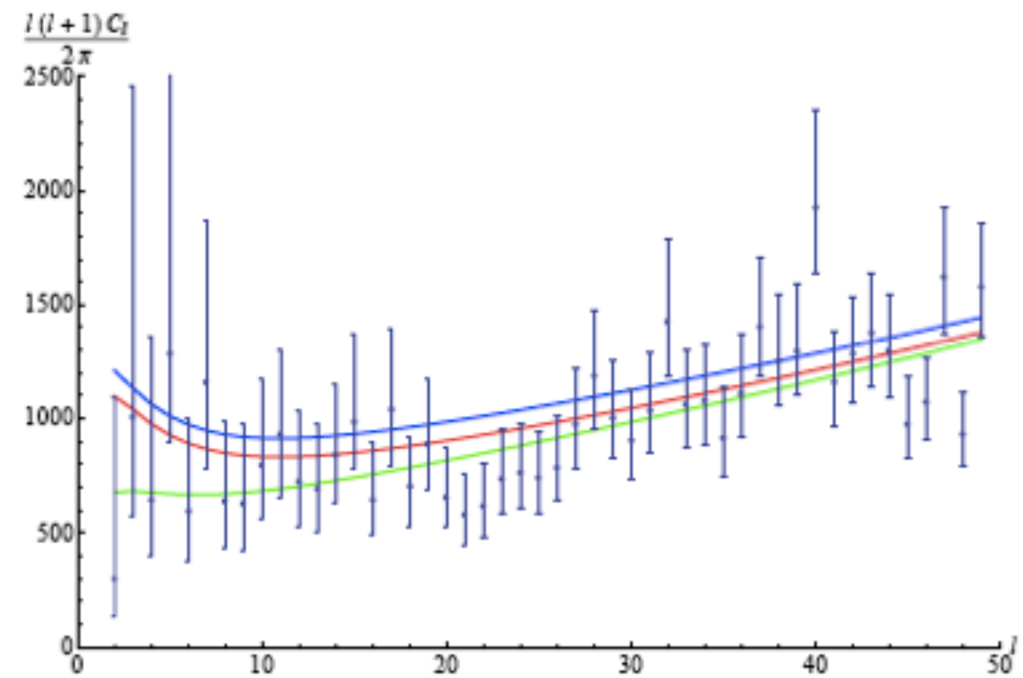
From LSS



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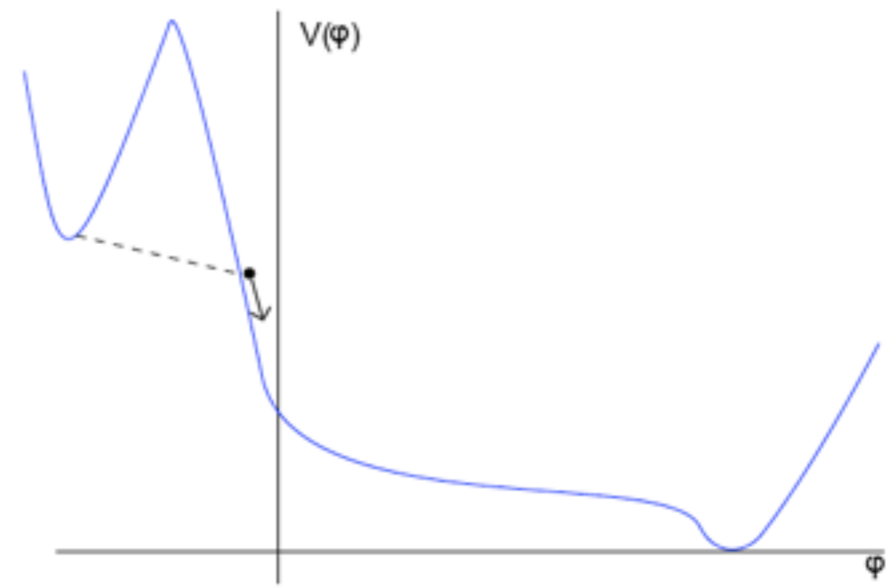

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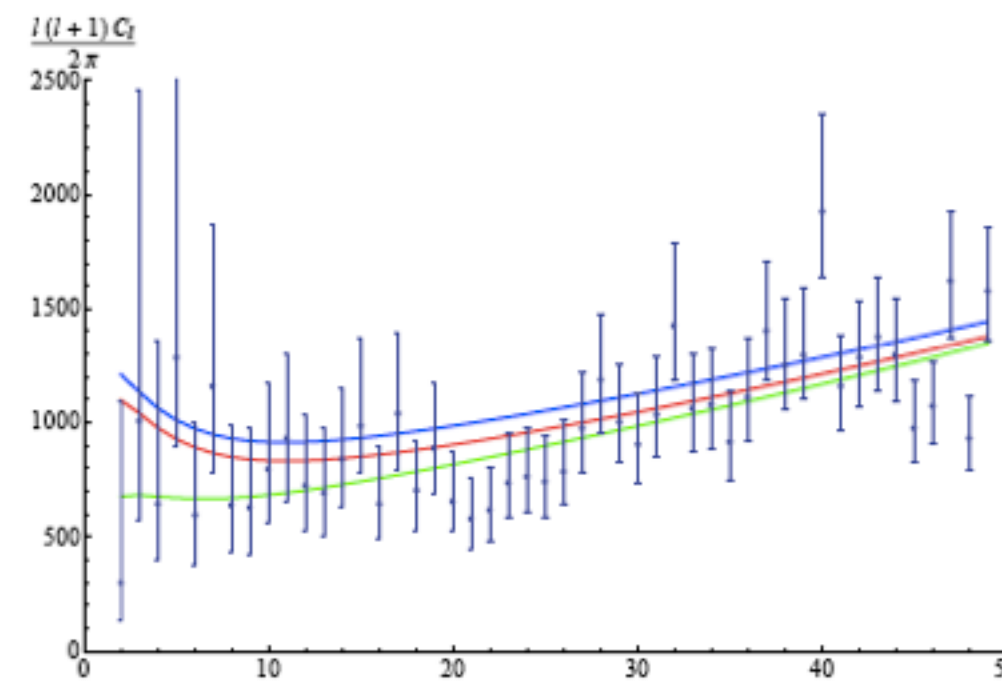


- This can become many many σ's.
  - It is one low-l anomaly that can become non-anomalous; and it is theory motivated

A more general look

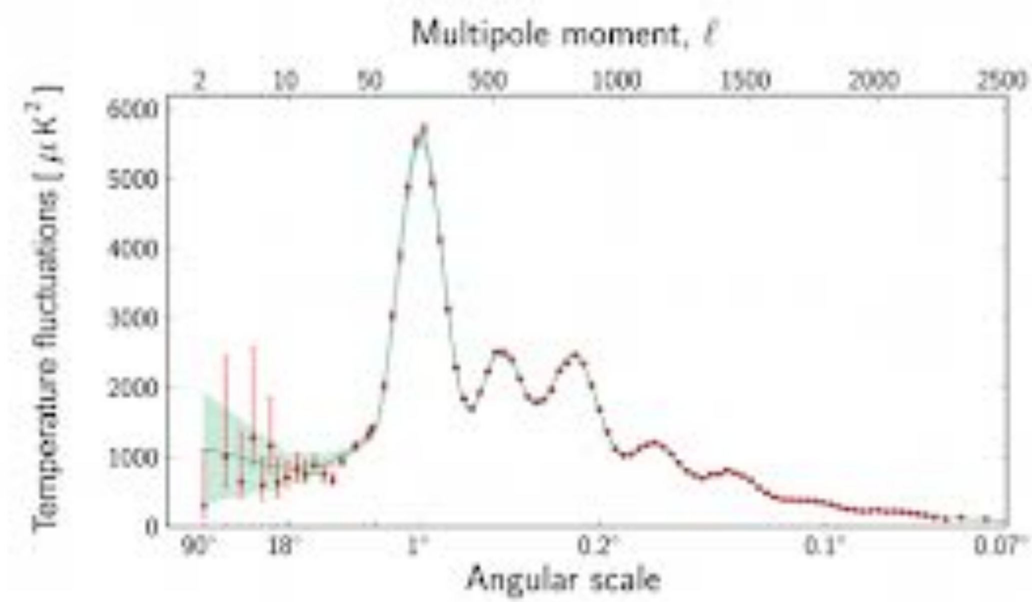
How do we probe Inflation?

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 $\quad n_s - 1 \simeq -0.04 \sim \mathcal{O}\left(\frac{1}{N_e}\right)$
  - they are quite gaussian

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

  - both tensors and scalar

- Is this enough to conclude it is slow-roll Inflation?
  - and in general, what is the dynamics of this inflaton?

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
- 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.

- 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!

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

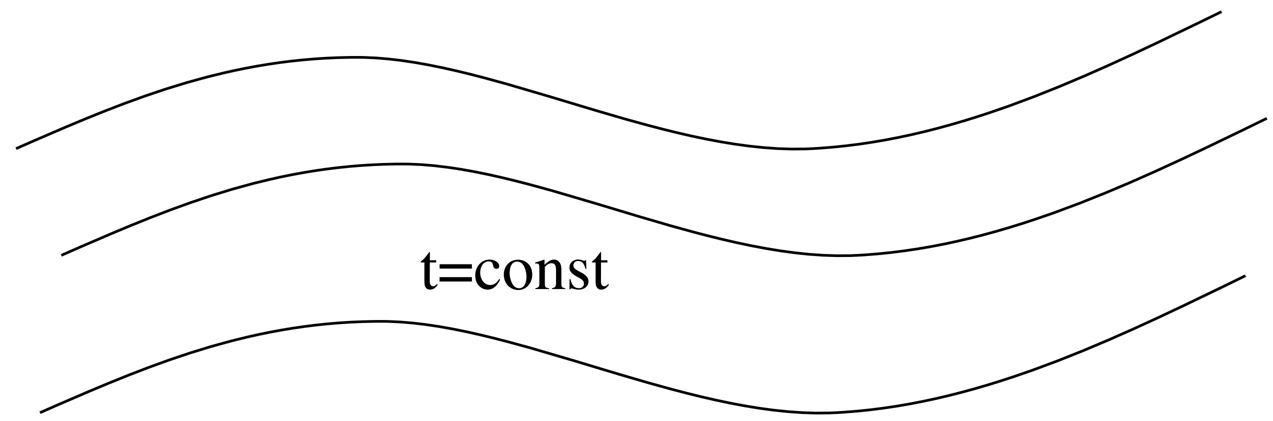
JHEP 2008

The Effective Field Theory

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

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}

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

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

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

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

Cosmological perturbations probe the theory at E ~ H

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

- Analogous to W-bosons in Standard Model (Goldstone boson equivalence principle)
- Analogous of the Chiral Lagrangian for the Pions and W bosons S. Weinberg **PRL 17, 1966**

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

- Used in WMAP9 and Planck papers (thanks!, but attributed to Weinberg)
  - Maybe because Weinberg is the true scientific father of all of us?

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Inflation: the Theory of the Goldstone Boson of time translations

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

- Dispersion relations

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

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

- 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

A lesson from B-modes

The amplitude and the tilt

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

- This Lagrangian is fine to make all predictions
- The Amplitude $$\langle \zeta^2 \rangle \sim \frac{H^4}{\dot H M_{\rm Pl}^2 c_s}\,, \qquad \langle \gamma^2 \rangle \sim \frac{H^2}{M_{\rm Pl}^2}$$
- 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
  - just symmetry

Even more general

Can we have scale invariance without Inflation?

Scale Invariance and Strong coupling

with Baumann and Zaldarriaga **1101**

- The trick of inflation is to generate a factor of e^{60} in length scales from the same energy scale H
  - this is clever because physics tends to change with energy
  - in inflation every correlation function is scale invariant:
    - scale invariance comes from time translation invariance
- Let us verify how hard it is to get scale invariance without inflation
- Let us engineer that the two point function is scale invariant even if H changes
  - From the EFT, if one dof, we have

$$S_2 = M_{\rm pl}^2 \int {\rm d}t\, {\rm d}^3x\, \frac{a^3 \epsilon}{c_s^2} \left[\dot{\zeta}^2 - \frac{c_s^2}{a^2}(\partial_i \zeta)^2\right]$$

    - it depends on parameters different than just a^3
    - scale invariance of $\langle \zeta^2 \rangle \Rightarrow$ diff. equation for a
      - solutions other than inflation exist, with $\epsilon(t),\ c_s(t)$ strongly time dependent

Scale Invariance and Strong coupling

with Baumann and Zaldarriaga **1101**

- The non-linear realization of time-diff induces self-couplings

$$\mathcal{L}_3 \subset \frac{a^3\epsilon}{c_s^2}\left[\frac{1}{c_s^2}\left(\epsilon-3(1-c_s^2)\right)\zeta\dot{\zeta}^2+\left(\epsilon-2\epsilon_s+1-c_s^2\right)\zeta\frac{(\partial\zeta)^2}{a^2}+\frac{1}{2c_s^2}\left(\dot{\eta}+H\eta-2H\epsilon_s\right)\zeta^2\dot{\zeta}\right],$$

– $\Rightarrow$ the 3pt function need to be scale invariant

- and when it is not scale invariant, it will blow up pretty soon.

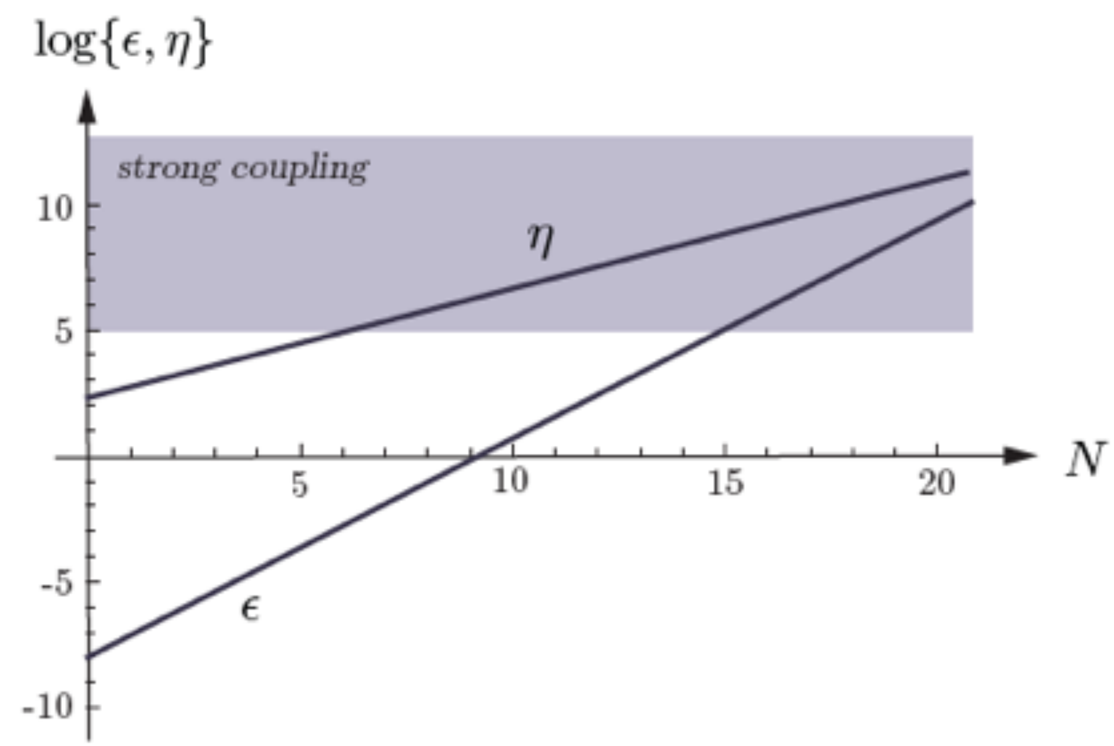
– We need to have

$$\boxed{X \equiv \frac{\mathcal{L}_3}{\mathcal{L}_2} \sim \mathcal{O}(\{1,\epsilon,\eta,\epsilon_s\})\,\frac{\zeta}{c_s^2}} \ll 1$$

– but it is fixed, and this does not happen:

- the solution becomes strongly coupled

– Generically, no more that 10 e-folds of scale invariance are allowed with one field



– But if we add more than one scalar, then theorem can be avoided

Scale Invariance and Strong coupling

with Perko, Silverstein and Zaldarriaga **in progress**

- Can we do the same for gravity waves?
  - Theorem: if we see scale-invariant gravity waves, then the universe was de Sitter
- Imagine we are not in dS and a second field is generating the scalar fluctuations
- Can we have scale invariant gravity waves?
- Consider the Unitary-gauge Lagrangian in gravity sector

$$S = \int d^4x \sqrt{-g}\left(\frac{1}{2} M_{\rm Pl} R - \frac{M_2(t)^2}{2} \delta K^\mu_\nu \delta K^\nu_\mu\right)$$

  - at quadratic level we have

$$S = \frac{M_{\rm Pl}^2}{8} \int d^3x d\eta \; a^2 \left(\frac{\gamma'_{ij}\gamma'^{ij}}{c^2_{s,\gamma}(\eta)} - \partial_l \gamma_{ij} \partial^l \gamma^{ij}\right) \qquad c^2_{s,\gamma}(\eta) = \left(1 - \frac{M_2(\eta)^2}{M_{\rm pl}^2}\right)^{-1}$$

  - $\Rightarrow$ can engineer $c_{s,\gamma}$ to have scale invariant $\langle \gamma^2 \rangle$ when non in dS
    - we can, by making $c_{s,\gamma} \to 0$ in a time dependent way

Scale Invariance and Strong coupling

with Perko, Silverstein and Zaldarriaga **in progress**

- As before, expect that interactions will violate this
- Look at 4pt function

$$\mathcal{L}_4 \sim \frac{M_{\rm Pl}^2}{H^2}\frac{1}{c_{s,\gamma}^6}\dot{\gamma}^4 \qquad \Longrightarrow \qquad \frac{\mathcal{L}_4}{\mathcal{L}_2} \sim \frac{\frac{M_{\rm Pl}^2}{H^2}\frac{1}{c_{s,\gamma}^6}\omega^4\gamma^4}{\frac{M_{\rm Pl}^2\omega^2\gamma^2}{c_{s,\gamma}^2}} \sim \frac{\gamma^2}{c_{s,\gamma}^4}$$

$$\Longrightarrow \qquad \frac{\mathcal{L}_4}{\mathcal{L}_2} \sim \frac{2\times 10^{-11}}{c_{s,\gamma}^4} \ll 1 \quad \Rightarrow \quad c_{s,\gamma} \gg 10^{-3}$$

- since $c_{s,\gamma} \longrightarrow 0$ in the scale invariant solution, the solution cannot last too long
  - theory becomes strongly coupled
- Summary: only dS can produce more that 10 e-folds of scale invariant gravity waves
  - no matter what.
  - scale invariance of 2pt function is related to inflation only thanks to interactions

The Scale of Inflation

Is it always true that ?

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

Energy Scale of Gravity Waves

- Energy of gravity waves:

$$\langle h^2 \rangle \sim \frac{H^2}{M_{\rm Pl}^2} \quad \Rightarrow \quad \rho_h \sim M_{\rm Pl}^2 \, (\partial h)^2 \big|_{\omega \sim H} \sim M_{\rm Pl}^2 H^2 \langle h^2 \rangle \sim H^4$$

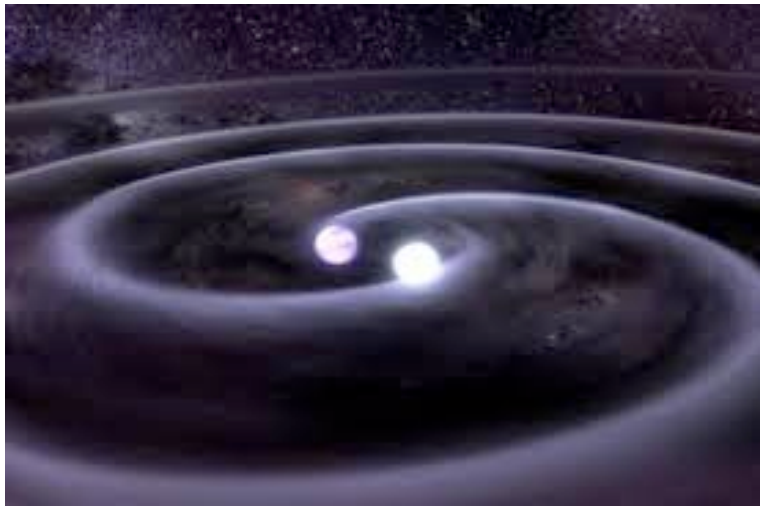
- This is minuscule
- For an harmonic oscillator with $\omega \sim H$, vacuum energy is $E_{\rm vac} \sim \omega \sim H$
- So

$$\rho_h \sim H^4 \quad \Rightarrow \quad \text{one quanta per Hubble volume} \quad \Rightarrow \quad \text{Minuscole!}$$

- One graviton with $\omega \sim H$ per Hubble volume
- Consider our universe, which is accelerating. One quanta in the whole universe.
  - Good luck with detecting it!

Energy Scale of Gravity Waves

- In fact, we normally look at other sources



Available Energy

- By definition, in Inflation there is a physical clock

$$\dot{\phi}^2 \sim \dot{H} M_{\rm Pl}^2 \sim \epsilon H^2 M_{\rm Pl}^2$$

- From the temperature power spectrum $\langle (\delta T/T)^2 \rangle \sim \dfrac{H^2}{\epsilon M_{\rm Pl}^2} \sim 10^{-10}$

$$\dot{\phi}^2 \sim 10^{10} H^4 \ggg\gg H^4$$

- So, there is enough energy (we cannot use the potential energy, just its gradients)

- Problem is that usually this energy sits there and does nothing
  – not converted in Gravity Waves
- It needs to be converted
- and not diluted away

Conversion and not-dilution

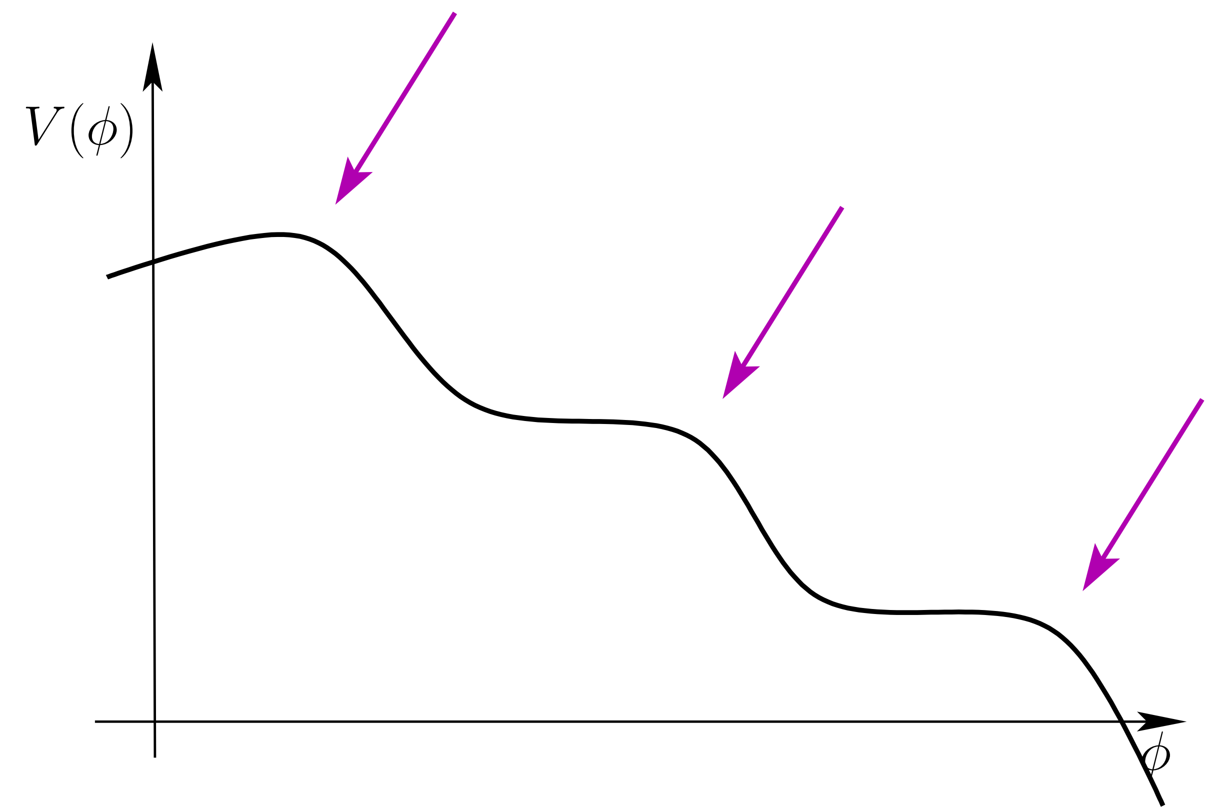
- A proof of principle

with Green, Horn, Silverstein **PRD 2009**

- Trapped Inflation
  - Consider wiggly potential
  - At each wiggle, coupling

$$V \sim \sum_n (\phi - \phi_n)^2 \chi_n^2$$

$$\Rightarrow \quad m_\chi^2(t) \sim \dot\phi^2 (t - t_n)^2$$



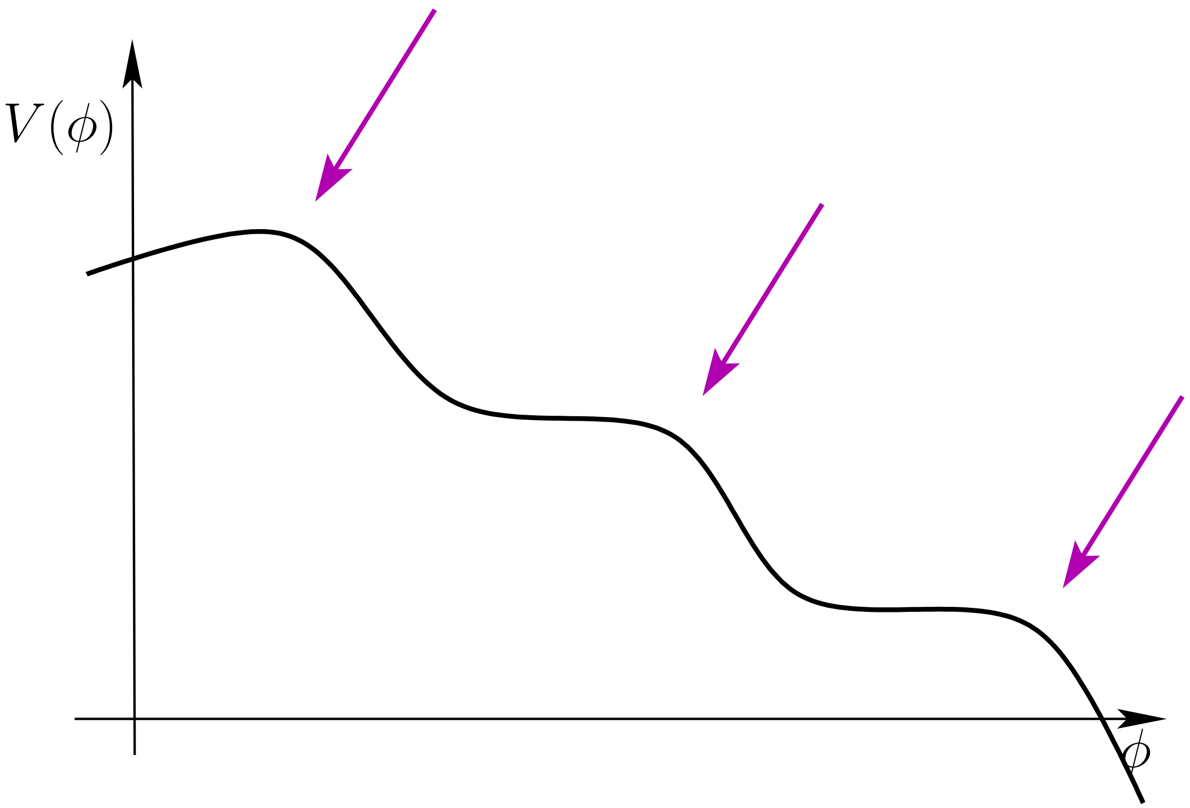
  - At $t \sim t_n$, adiabaticity for χ is broken $\Rightarrow$ many particles are produced

$$\Rightarrow \quad n_{\chi_n} \sim \dot\phi^{3/2}$$

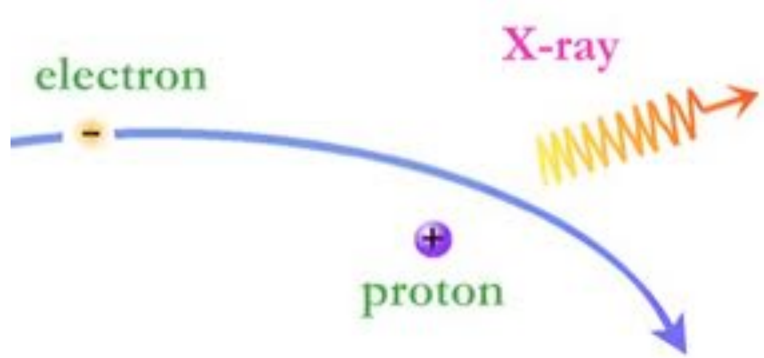
  - We achieved conversion of $\dot\phi^2$ energy in χ_n , and this happens continuously:
    - χ_n dilutes away, but gets replenished by χ_{n+1}
  - We now need to convert χ_n into Gravity Waves (continuously)

Conversion and not-dilution

with Silverstein and Zaldarriaga **1109**



- Conversion to Gravity Waves
- Imagine χ_n decay to ψ_n (out of many)
- In this decay,
  - gravitational bremsstrahlung is produced



$$\frac{dE_t}{d\Omega d\omega} \sim \frac{1}{(2\pi)^3}\frac{M^2}{M_{\rm Pl}^2} \Rightarrow$$

$$\langle h^2 \rangle \sim \frac{\rho_\chi}{\rho_{\rm total}}\frac{H M_\chi}{M_{\rm Pl}^2} \gg \frac{H^2}{M_{\rm Pl}^2}$$

  - How large can this be?
    - Detectable signal even with $H \simeq 10^{-5} H_{\text{min, vacuum}}$

Scalar Production

with Silverstein and Zaldarriaga **1109**
with Mirbabayi, Silverstein and Zaldarriaga **in progress**

- How can we tell?
- There are particles with time-dependent mass. In unitary gauge:

$$S_X = -\int d\tau M(t)\sqrt{g_{\mu\nu}\dot{x}^\mu_X \dot{x}^\nu_X}.$$

- Because of time-diff invariance, this is a coupling to π

$$S = -\int d^4x\sqrt{-g}M_{\rm Pl}^2\dot{H}[\dot{\pi}^2 - a^{-2}(\partial\pi)^2]$$
$$+\int d^4x M(t+\pi)\int dt_X \gamma^{-1}\delta^4(x^\mu - x^\mu_X(\tau)), \qquad \Longrightarrow \qquad g\equiv\frac{\dot{M}}{\sqrt{2\epsilon}M_{\rm Pl}H},$$

- π waves are produced $\quad \dfrac{dE_s}{d\Omega d\omega}\sim\dfrac{1}{(2\pi)^3}\dfrac{M^2}{\epsilon M_{\rm Pl}^2}$

- Notice that deviations from vacuum formulas tell us number of quanta

$$P_t = N_t\frac{H^2}{M_{\rm Pl}^2}\,, \qquad P_s = N_s\frac{H^2}{M_{\rm Pl}^2\epsilon}, \qquad \Rightarrow \qquad r = 16\epsilon\frac{N_t}{N_s}$$

Scalar Production

with Silverstein and Zaldarriaga **1109**
with Mirbabayi, Silverstein
and Zaldarriaga **in progress**

$$P_t = N_t \frac{H^2}{M_{\rm Pl}^2}\,, \qquad P_s = N_s \frac{H^2}{M_{\rm Pl}^2 \epsilon}, \qquad \Rightarrow \qquad r = 16\epsilon \frac{N_t}{N_s}$$

- From the formulas of production, we have

$$\frac{dE_t}{d\Omega d\omega} \sim \frac{1}{(2\pi)^3}\frac{M^2}{M_{\rm Pl}^2} \qquad\qquad \frac{dE_s}{d\Omega d\omega} \sim \frac{1}{(2\pi)^3}\frac{M^2}{\epsilon M_{\rm Pl}^2}$$

$$\frac{N_t}{N_s} \sim \epsilon \quad \Rightarrow \quad r \sim \epsilon^2$$

- This means that in this scenario the tensor modes can be larger than the standard,
  – but the scalar are also produced by this mechanism
- Both scalar and tensors produced *not* out of vacuum fluctuations
  – $\Rightarrow$ they will be non-Gaussian
    - standard fluctuations are Gaussian because are quantum vacuum fluct.s

Scalar non-Gaussianity

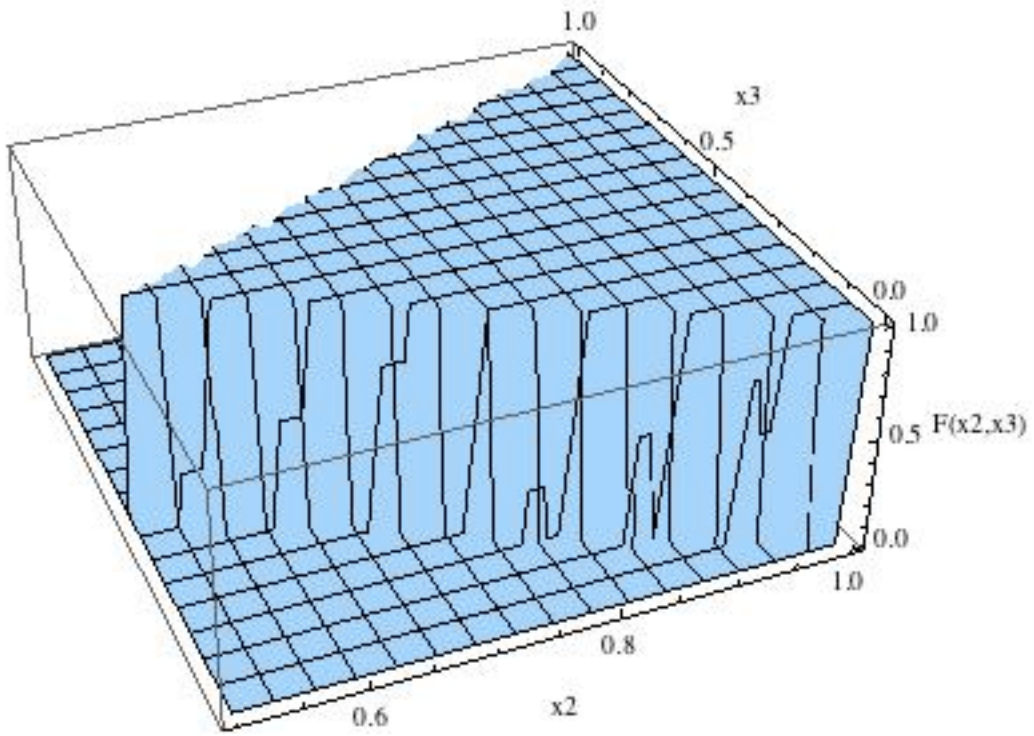
with Silverstein and Zaldarriaga **1109**
with Mirbabayi, Silverstein
and Zaldarriaga **in progress**

- Size of scalar NG
- Central limit $\Longrightarrow \quad f_{NL}\zeta \sim \frac{\langle \pi^3 \rangle}{\langle \pi^2 \rangle^{3/2}} \sim N_X^{-1/2},$
- But $\rho_X = n_X M \ll M_{\rm Pl}^2 H^2 \epsilon. \quad \Longrightarrow \quad N_X \frac{MH}{\epsilon M_{\rm Pl}^2} \ll 1. \quad \Longrightarrow \quad N_X \ll \frac{1}{\zeta^2}$

$$\Longrightarrow \quad f_{NL} \gtrsim 1$$

- So, the signature to observe these new mechanisms is to get to such low NG:
  – they seem to be rulable out!
- Shape of signal

$$F(k_1, k_2, k_3) = \frac{1}{(k_1 k_2 k_3)^2}$$



BICEP implications
for multifield inflation

The EFT of Multifield Inflation

with Zaldarriaga **1109**

- Multifield Inflation offers a plethora of interesting signatures. The multiple fields can be
  - goldstone bosons
    - abelian
    - non-abelian
  - Susy (introduced in the EFT to study NG for the first time)
    - unless coupled to inflaton sector, SUSY broken just by H, or $g_{\rm weak} H$
- But?! multiple fields must dominate the signal of π fluctuations
  - Call $\langle\zeta^2\rangle_\pi = \epsilon_\pi \langle\zeta^2\rangle_\sigma$ with $\epsilon_\pi \lesssim 1$
  - Since $r = 16\epsilon\,\epsilon_\pi = 0.2 \quad \Rightarrow \quad \epsilon \sim \frac{0.2}{16\epsilon_\pi} \lesssim \frac{1}{10}\,, \quad \Rightarrow \quad \epsilon_\pi \gtrsim \frac{1}{10}$
    - $\Longrightarrow$ some room left, but not very large

BICEP implications for non-Gaussianities

The c_s Operator

- One of the two leading opt is

$$S = \int d^4x\ \dot{H} M_{\rm Pl}^2 \left[(\partial\pi)^2 + \frac{1}{c_s^2}\dot{\pi}(\partial_i\pi)^2 \right] \qquad \Rightarrow \qquad f_{\rm NL}^{\dot{\pi}(\partial_i\pi)^2} \sim \frac{1}{c_s^2}$$

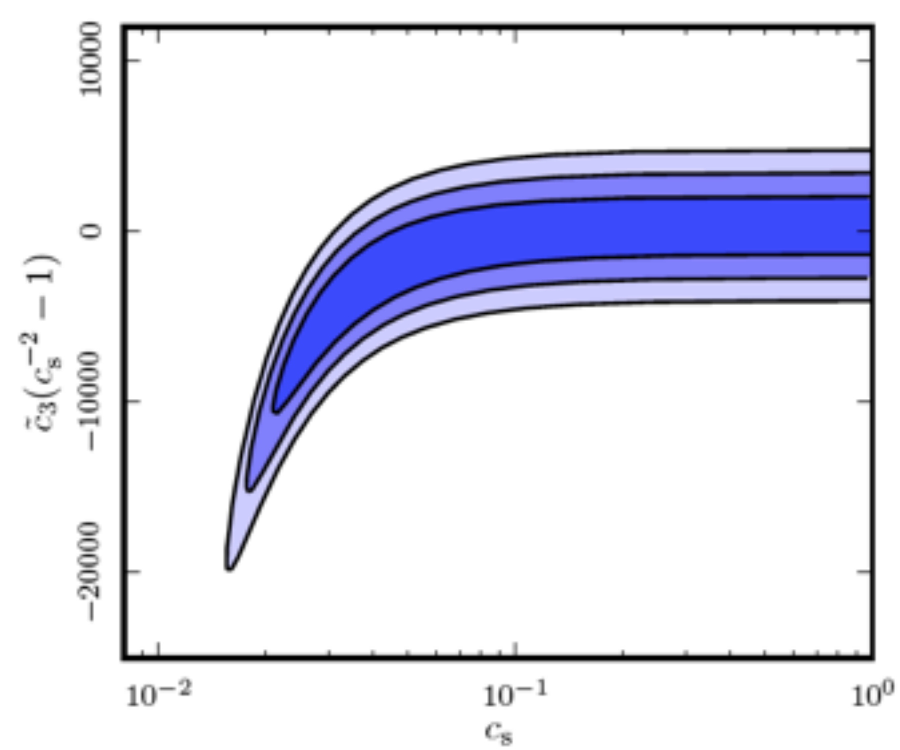
- But Bicep:

$$r = 16\epsilon c_s = 0.2 \quad \Rightarrow \quad c_s \gtrsim \frac{0.2}{16\epsilon}$$

- But the tilt

$$n_s - 1 \sim 6\epsilon - 4\eta + \frac{\dot{c}_s}{H c_s} \sim 4\times 10^{-2} \quad \overset{\text{no tuning}}{\Rightarrow} \quad c_s \sim 1$$

- Note this is an indirect limit from imposing no-tuning.
  – direct limit on c_s still comes from NG



Other possibilities

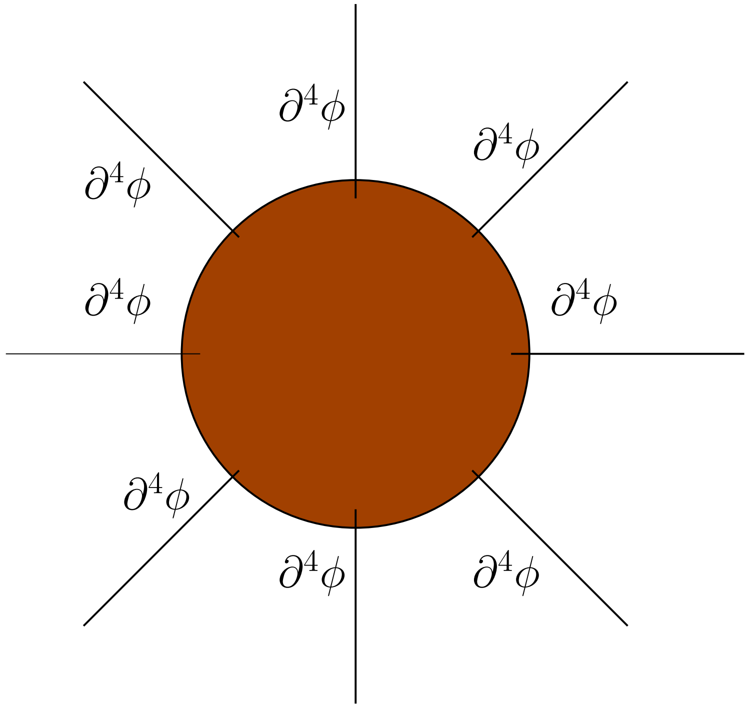
- multifield inflation ``The EFT of Multifield Inflation'' with Zaldarriaga **1109**
  - many many 3pt and 4pt functions

- 4pt function $\dot{\pi}^4$ with Zaldarriaga **1109**
- analysis in progress

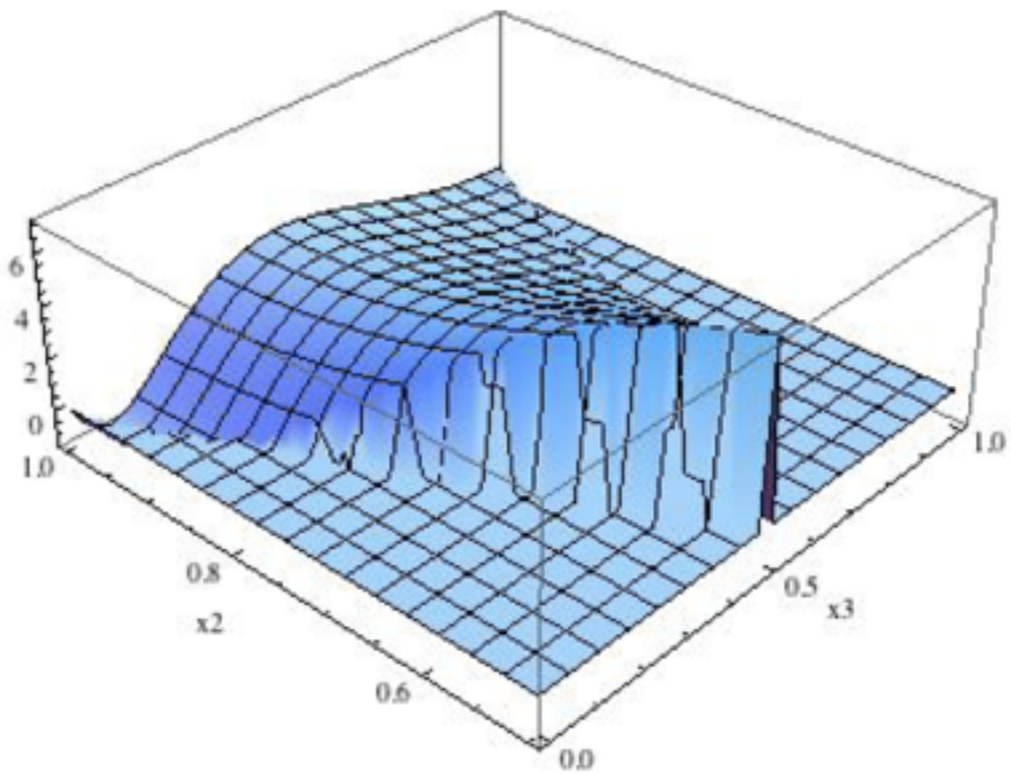
Enhanced Symmetries

with Behbahani, Mirbabayi, Smith
in completion

- Higher derivative opts can be the leading ones
  - QFT fact: the following theory is technically natural $S \sim \int d^4x \; (\partial_\mu \phi)^2 + \frac{1}{\Lambda^{4n}} (\partial^n \phi)^4$
    - loops do not generate lower derivative opts.
    - it could come from integrating out a high spin particle



- Apply this logic to the EFT of Inflation
  - we can start at very high number of derivatives
  - Many shapes are similar
    - field redefinition
    - just similar
  - The first non-trivial ones are at 7- and 9-derivs
    - $\frac{d^3\pi}{dt^3}(\partial_i\partial_j\pi)^2$ and $\frac{d^3\pi}{dt^3}\left(\partial_i \frac{d^2\pi}{dt^2}\right)^2$

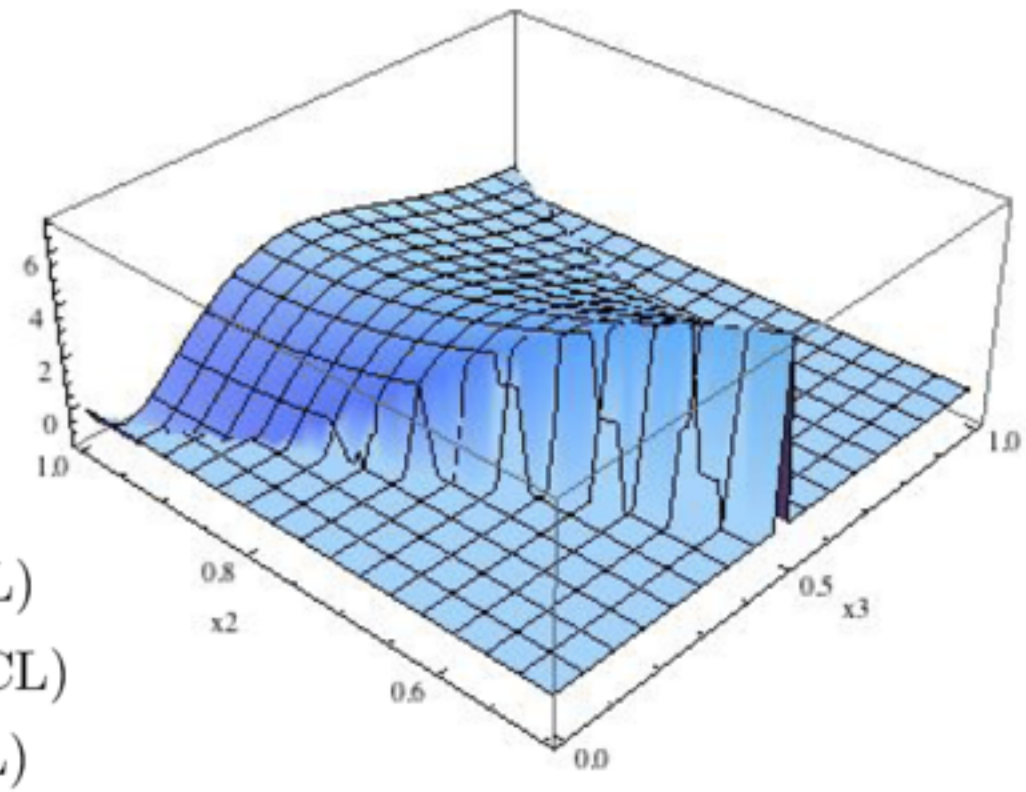


Enhanced Symmetries

with Behbahani, Mirbabayi, Smith
in completion

- Optimal analysis of WMAP9 (could not do Planck)

$$\frac{d^3\pi}{dt^3}(\partial_i\partial_j\pi)^2 \qquad \frac{d^3\pi}{dt^3}\left(\partial_i\frac{d^2\pi}{dt^2}\right)^2$$



- Results

$$\begin{aligned} f_{NL}^{\rm eq} &= 51 \pm 136 & (-221 < f_{NL}^{\rm eq} < 323 \text{ at } 95\% \text{ CL}) \\ f_{NL}^{\rm orth} &= -245 \pm 100 & (-445 < f_{NL}^{\rm orth} < -45 \text{ at } 95\% \text{ CL}) \\ f_{NL}^{\rm 7der} &= -34 \pm 56 & (-146 < f_{NL}^{\rm 7der} < 78 \text{ at } 95\% \text{ CL}) \\ f_{NL}^{\rm 9der} &= 30 \pm 16 & (-1 < f_{NL}^{\rm 9der} < 62 \text{ at } 95\% \text{ CL}) \end{aligned}$$

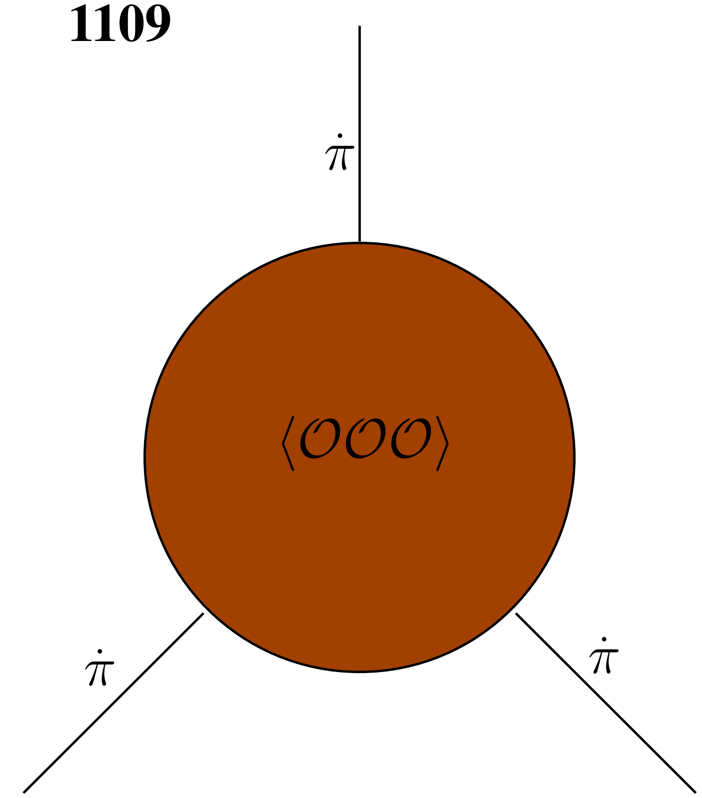
Parameter space	χ^2/(d.o.f.)	p-value
{Equil}	0.14 / 1	0.71
{Equil, Orth}	7.3 / 2	0.026
{Equil, Orth, 7der}	9.7 / 3	0.022
{Equil, Orth, 7der, 9der}	9.7 / 4	0.046

- About 2.5 σ
  - we know with Planck $f_{\rm NL}^{\rm orthog.}$ goes down,.... wait and see

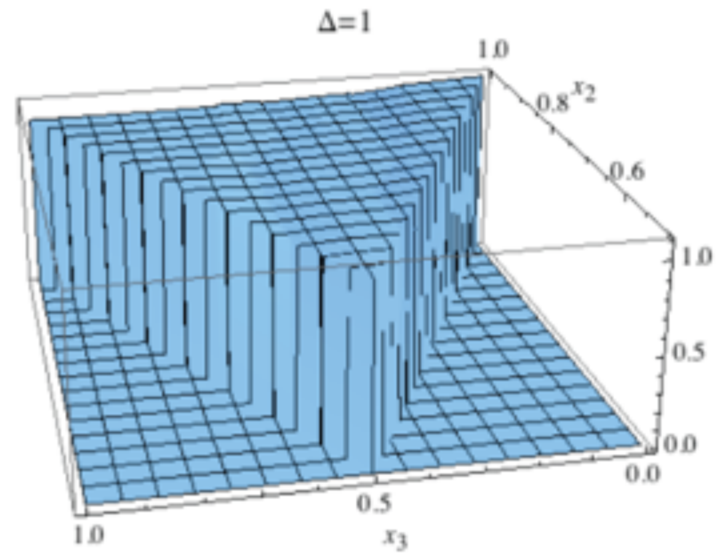
Particles in intermediate states

with Nacir, Porto, and Zaldarriaga **1109**

- Another option is to have particles in intermediate states
  - If they are not observed, but they are light
- Several examples $S = \int d^4x\, \dot\pi\, \mathcal{O}$
  - effective opts
  - Conformally coupled sector



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



  - Quasi single field Chen and Wand **0909**
    - a scalar $m \sim H$
      - protected as a Pseudo Goldstone Senatore **in progress**
      - protected by SUSY

Senatore and Zaldarriaga **1109**
Baumann and Green **1205**
Craig and Green **1404**

- All this quite unconstrained

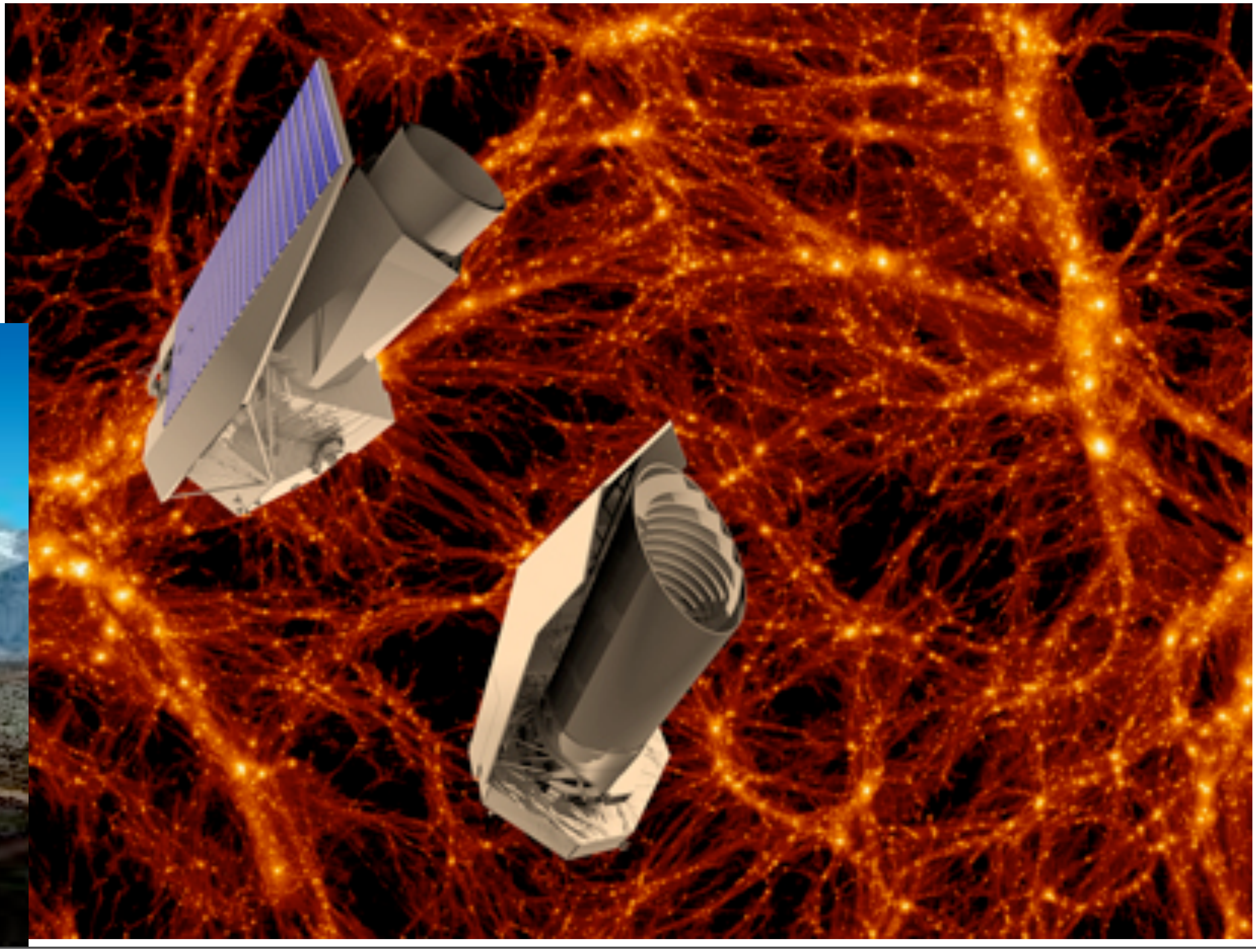
NG and the future

- No matter BICEP, non-Gaussianities crucial to increase our understanding

- In order to increase our knowledge of interactions in Inflation, we need more modes
  - Planck will not do it, nor BICEP
- Large Scale Structures offer the ideal place for hunting for more modes
  - I will show results from the EFTofLSS that, if verified and extended to all observable, can increase limits to $f_{\rm NL}^{\rm equil,\, orthog,\;\; loc.} \lesssim 1$
  - We can argue that absence of detection of NG up to this level implies observational proof of slow-roll inflation
    - Because every other theory gives larger non-Gaussianities
    - This is learning even without detection (like LHC for the hierarchy problem)
- This also offers us a way to study large scale structures (which are nice)

What is next?

- Plank will increase by a factor of less than 2.
- Next are Large Scale Structures
- Like moving from LEP to LHC:
  - much dirtier, but much more potential
- How many modes are there?
  - this is the question



Leonardo Senatore (Stanford)

The Effective Field Theory of Cosmological Large Scale Structures

The IR-resummed Effective Theory of Large Scale Structure — with Zaldarriaga **1304**

The Lagrangian-space Effective Theory of Large Scale Structure — with Porto and Zaldarriaga **1311**

The Effective Theory of Large Scale Structure at 2-loops — with Carrasco, Foreman and Green **1310**

The 2-loop power spectrum and the IR safe integrand — with Carrasco, Foreman and Green **1304**

The Effective Theory of Large Scale Structure — with Carrasco and Hertzberg **JHEP 2012**

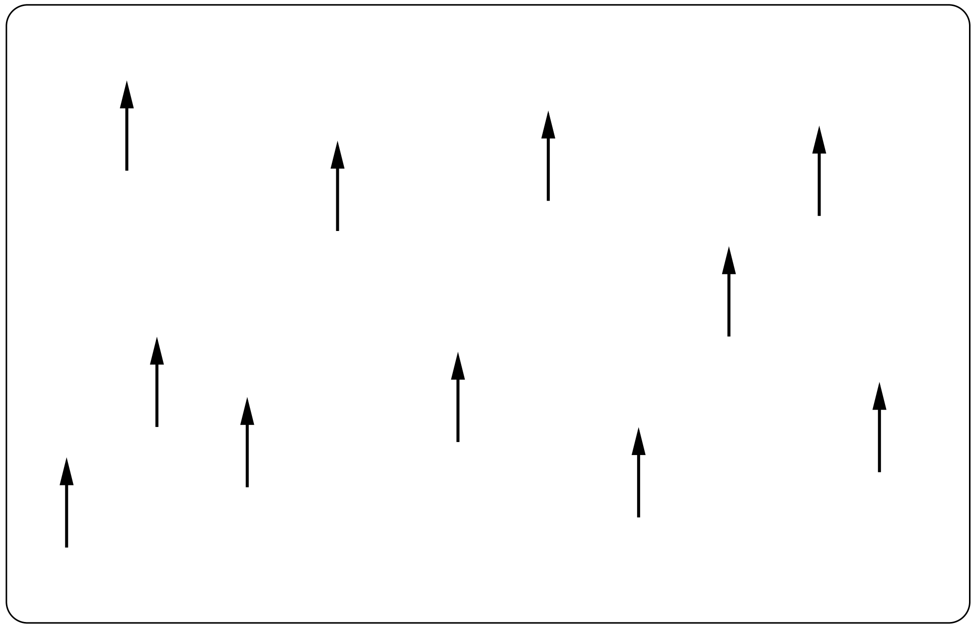
Cosmological Non-linearities as an Effective Fluid — with Baumann, Nicolis and Zaldarriaga **JCAP 2012**

Idea of the
Effective Field Theory

Main Idea

- Similar to a dielectric material
- For E&M waves with $d \gg d_{\rm atomic}$ with do not study Maxwell equations with many atoms, we study Dielectric Maxwell equations, where effect of atoms is in gross features as $\vec{d}_{\rm dipole} \sim \alpha\, \vec{E}_{\rm electric}$
- The universe looks like a dielectric, just replace
  - E&M with GR
  - atoms with galaxies

Dielectric Fluid



Main Idea

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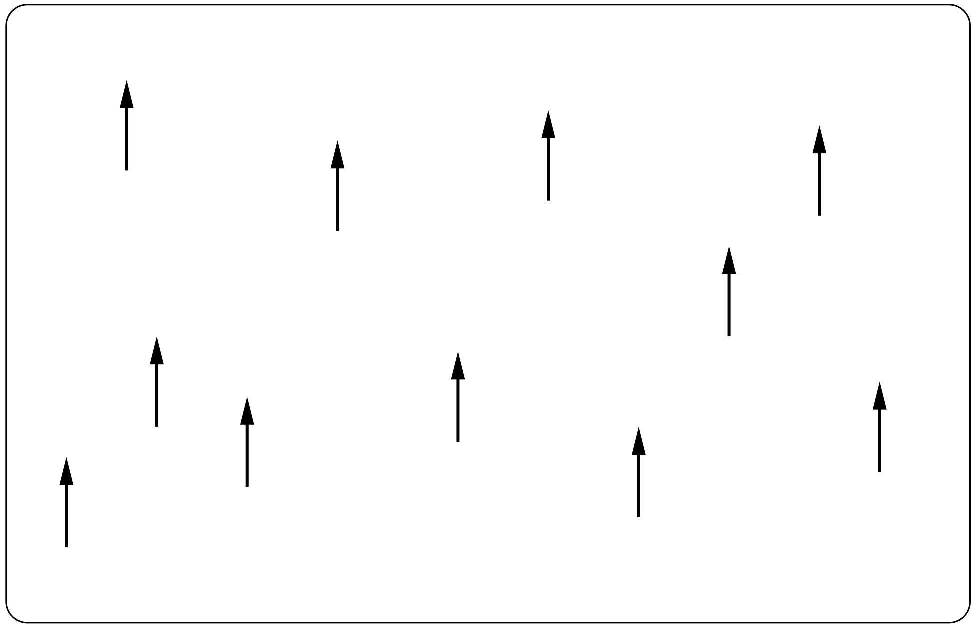
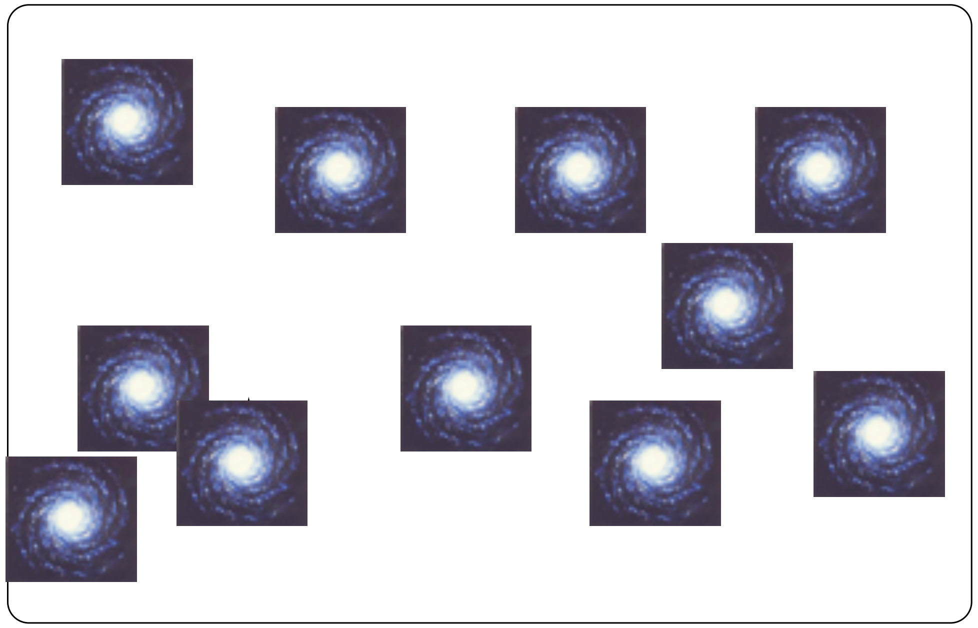
- The universe looks like a dielectric, just replace
  - E&M with GR
  - atoms with galaxies

$$\text{EM} \quad \longrightarrow \quad \text{GR}$$

Dielectric Fluid



Dielectric Fluid



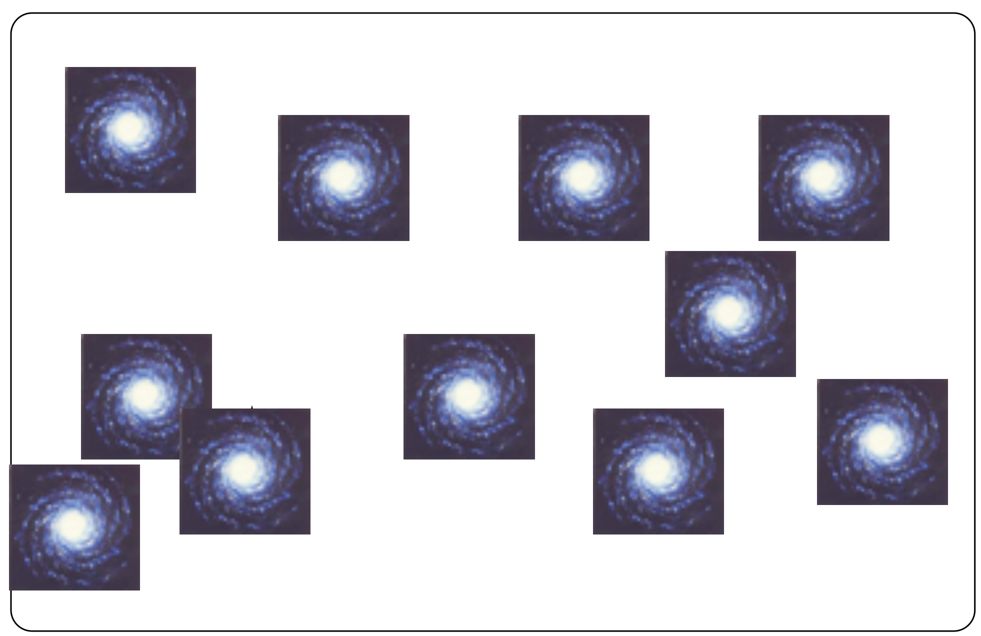
Main Idea

– Like Chiral Lagrangian

- weakly coupled at long distances
- strongly coupled at short distances

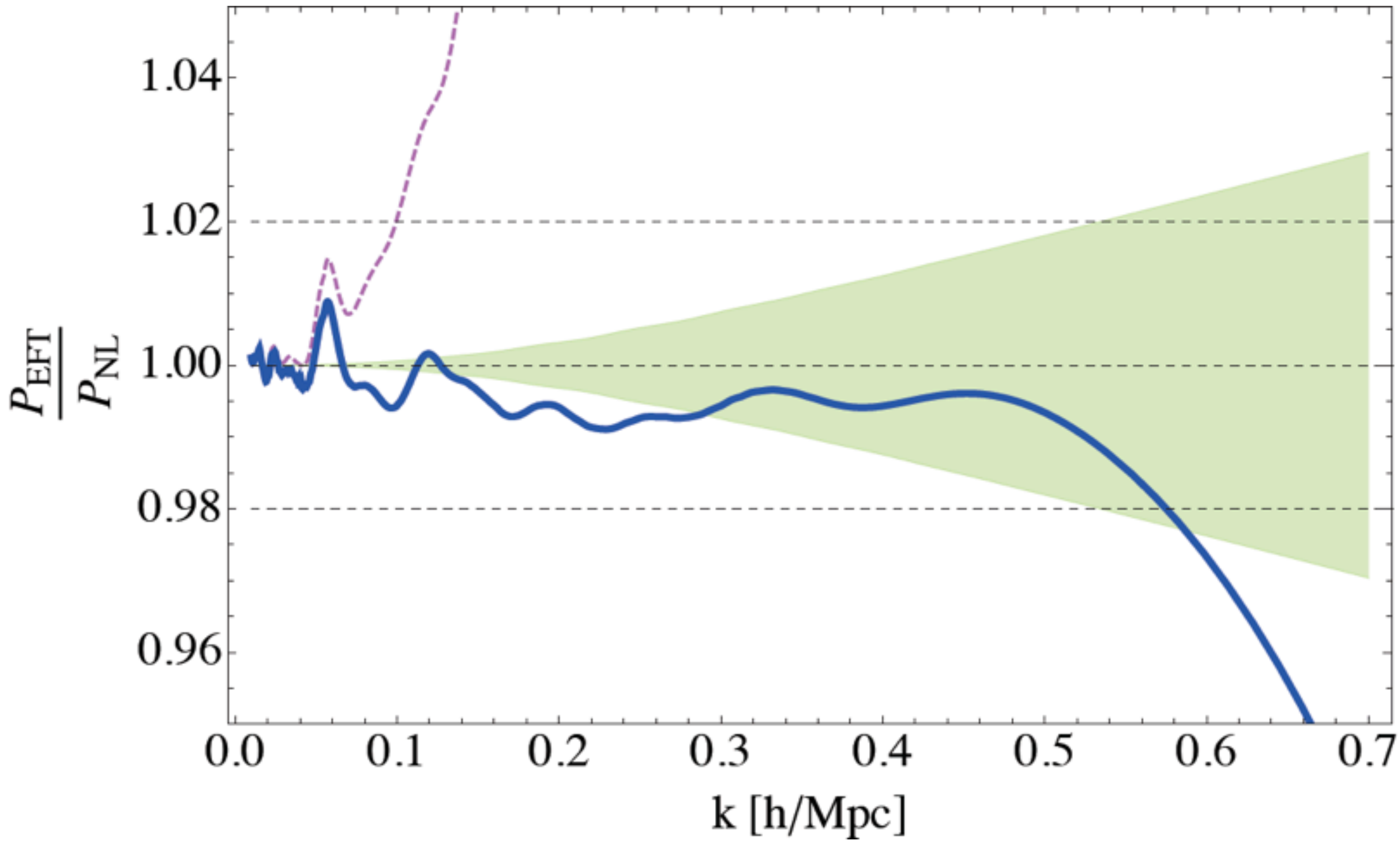
$$\text{EM} \quad \longrightarrow \quad \text{GR}$$

Dielectric Fluid



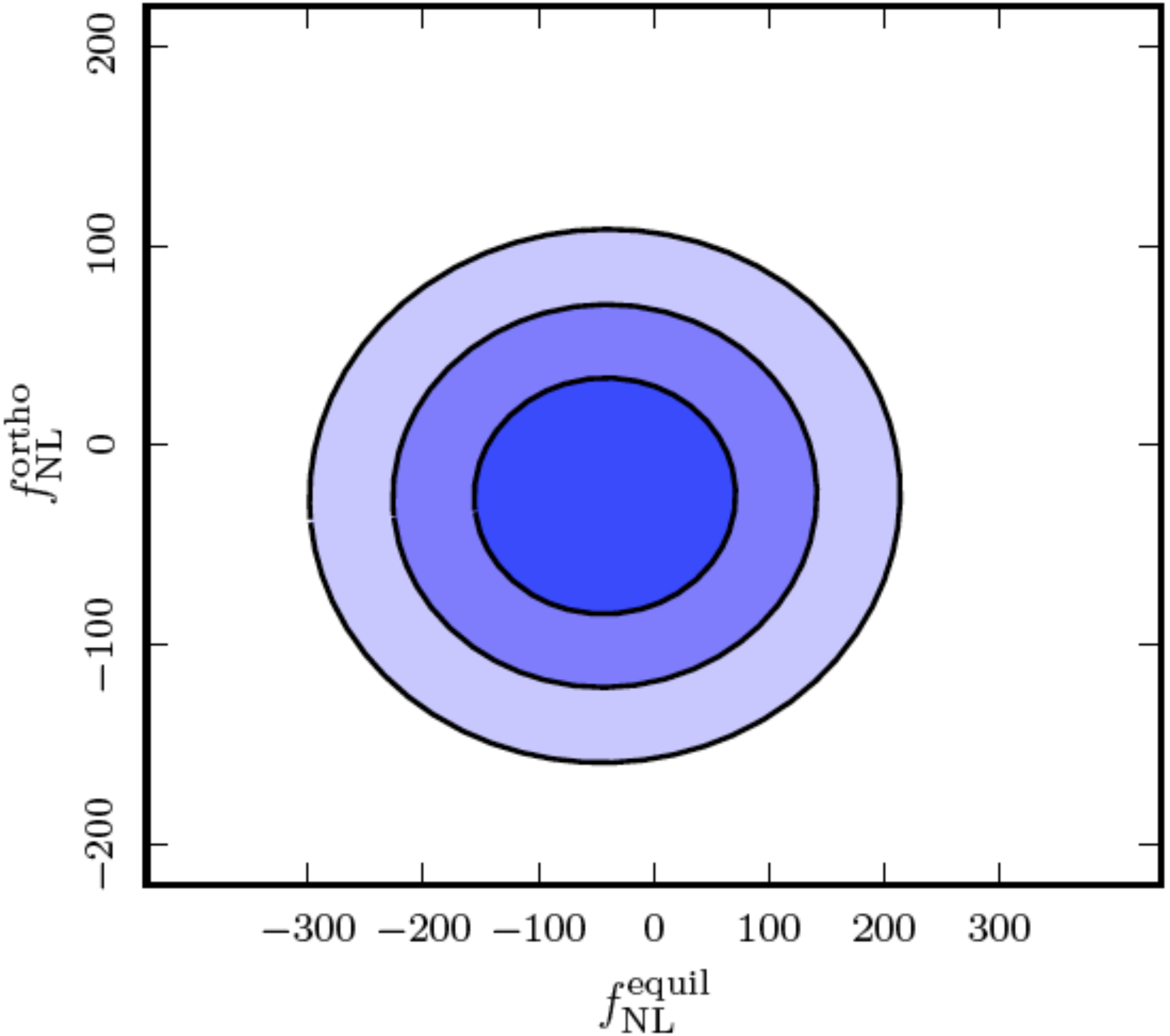
Bottom line result

- A well defined perturbation theory
- 2pt function at 2-loop in the EFT, with IR resummation



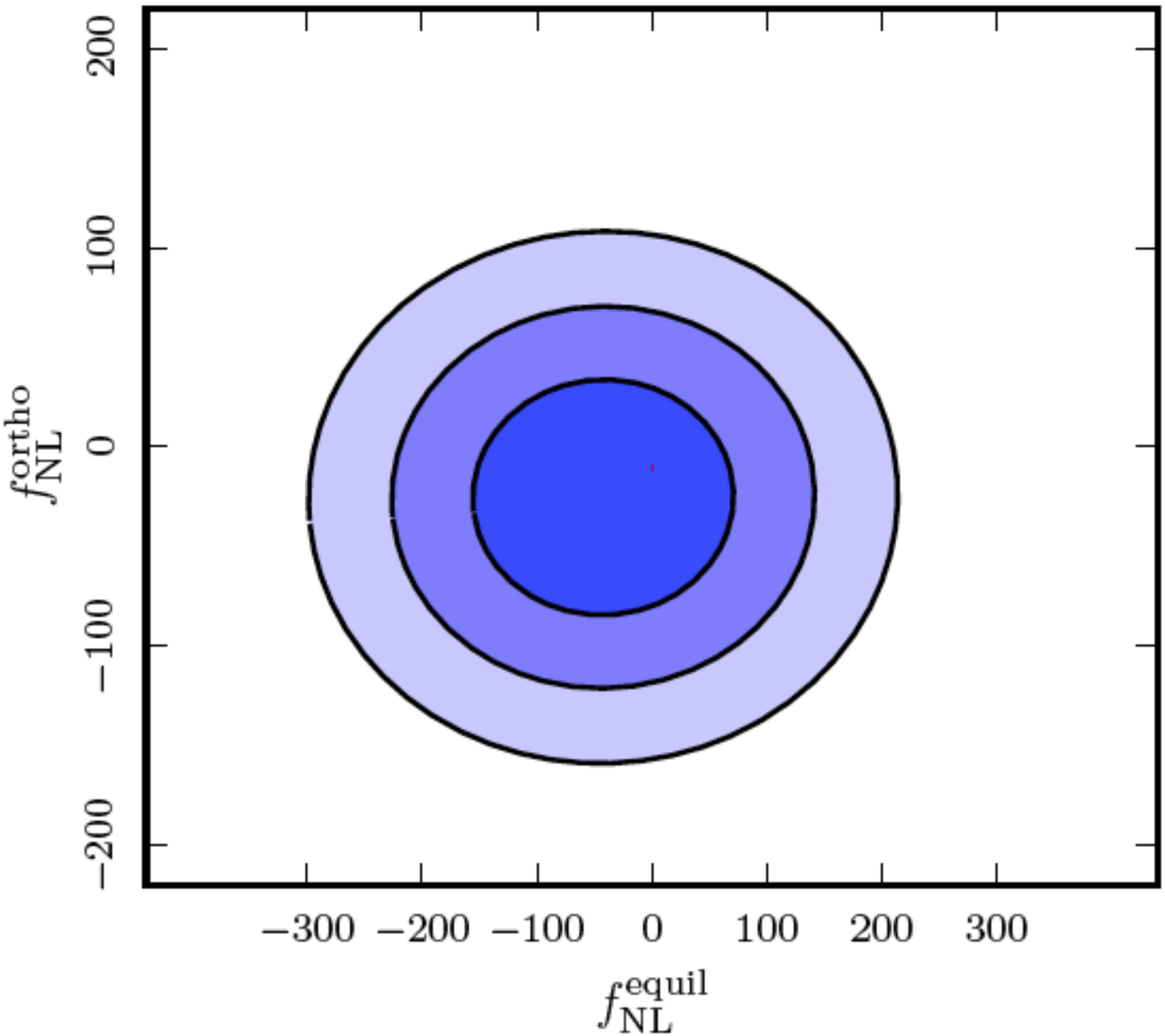
- agreement up to high k

With this



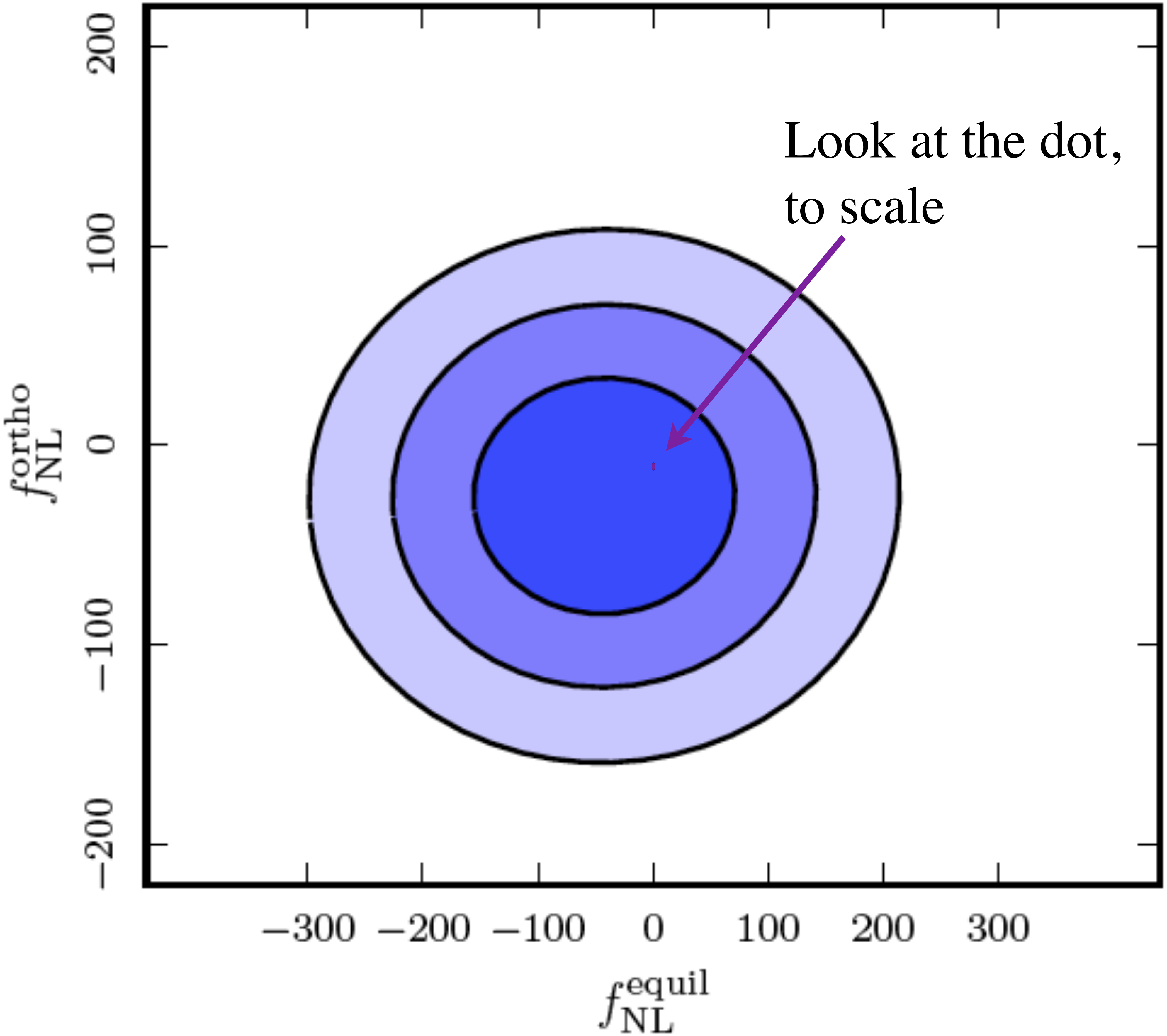
200
100
0
−100
−200
$f_{\rm NL}^{\rm ortho}$
−300
−200
−100
0
100
200
300
$f_{\rm NL}^{\rm equil}$

With this

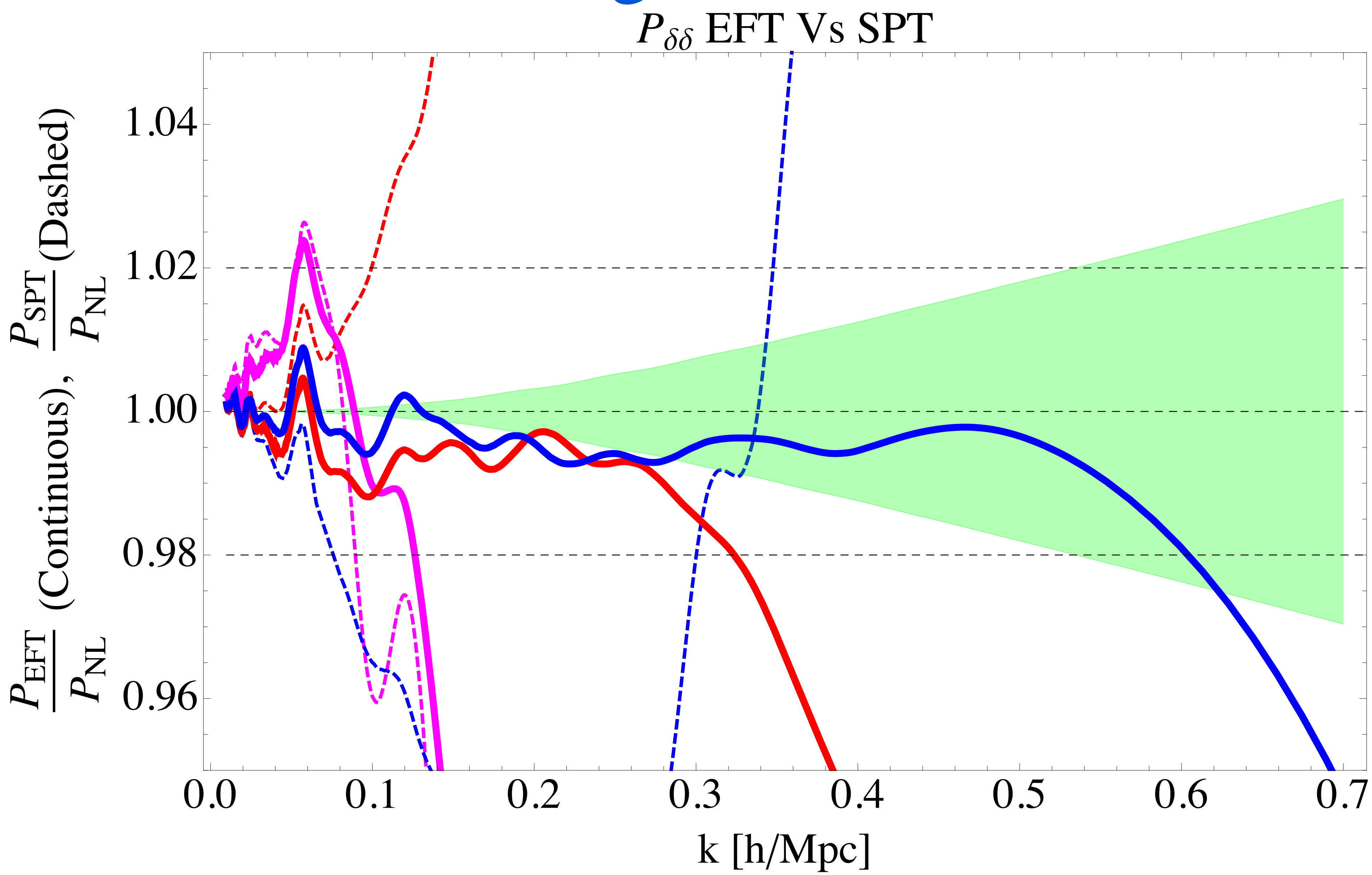


200
100
0
−100
−200
$f_{\rm NL}^{\rm ortho}$
−300
−200
−100
0
100
200
300
$f_{\rm NL}^{\rm equil}$

With this

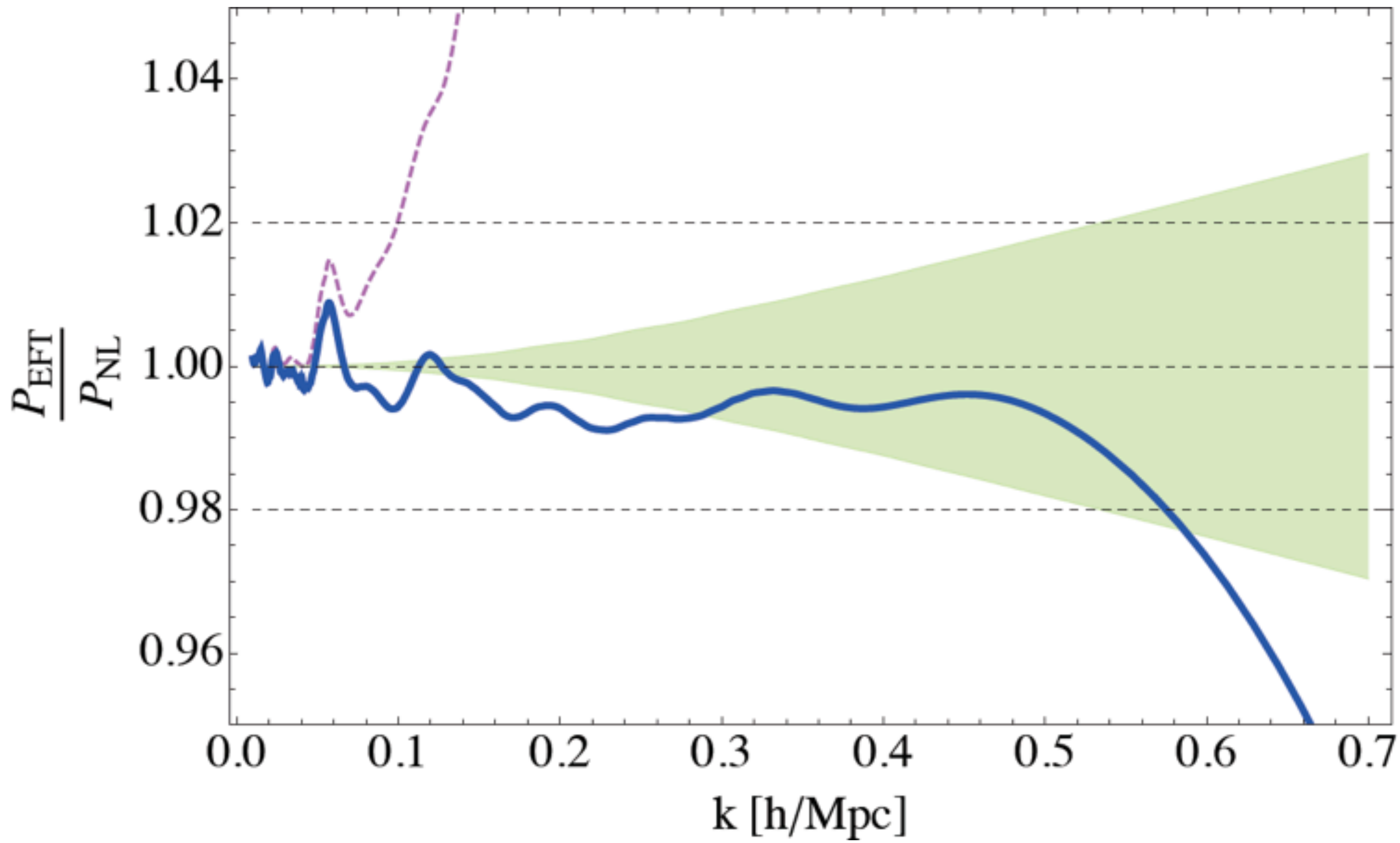

Look at the dot,
to scale
200
100
0
−100
−200
−300
−200
−100
0
100
200
300
f_{NL}^{ortho}
f_{NL}^{equil}

EFT of Large Scale Structures



- Comparison with Standard Treatment
  - no improvement order by order
  - we improve

EFT of Large Scale Structures



- Huge impact on possibilities for $f_{\rm NL}^{\rm equil.,\, orthog.} \lesssim 1$
- Can all of us handle it?! This is an huge opportunity and a challenge for us

Conclusions

- Overview of theoretical implications of B-modes and Inflation
  - nucleation and the beginning of inflation
  - The EFT and what we are really learning
    - Scale Invariance of tensors and Inflation
    - Amplitude of B-modes and the scale of Inflation
      - alternative mechanisms and non-Gaussianities
  - non-Gaussianities
    - i.e. everything but the 2pt function
    - to tell us about the physics of inflation (not just that it existed)
    - some models are constrained, some other are very free
      - prediction and analysis of new higher derivative shapes
  - The Effective Field Theory of Large Scale Structure
    - together with B-modes, the opportunity of a bright 10yr future for cosmology