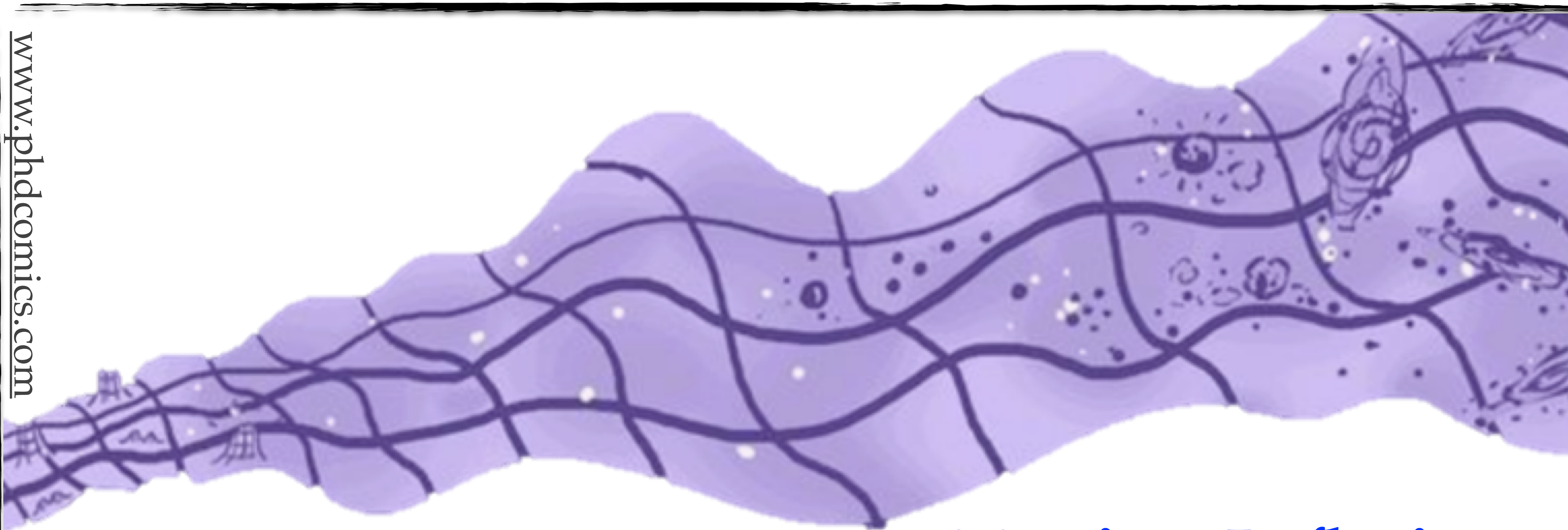
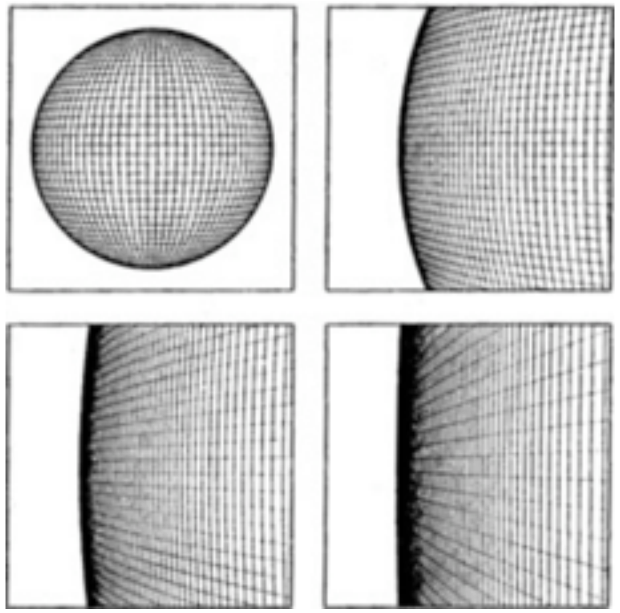


Testing Inflation

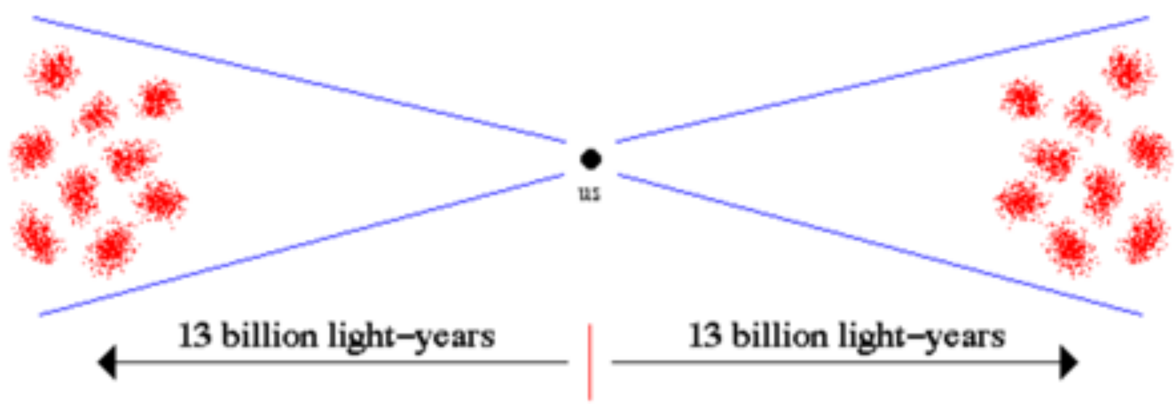
Basic principles
How to generate Inflation ?
Predictions and observations

Sophie Henrot-Versillé

1-Basic principles



university of Oregon



The problems of standard Big Bang cosmology:

The flatness problem
The horizon problem
The monopole problem
…

+ one additional thing to explain:
where do the fluctuations
that seeded the CMB anisotropies
and the LSS come from ?

That's why **Inflation** was introduced !

What is Inflation ?

Period of accelerated expansion in the early Universe

+ it must have an end to allow gravity to form galaxies (reheating)

A.H. Guth, Phys. Rev. D23, 347, 1981

1-Basic principles

In equations (classical dynamics)…

NB: everywhere « comoving » is implicit and a is the scale factor

An Accelerated Expansion !

$$\ddot{a} > 0.$$

Using the FRW equations, one gets:

$$-\frac{4}{3}\pi(\rho + 3p) = \frac{\ddot{a}}{a} > 0.$$

$$\Leftrightarrow \quad p < -\frac{1}{3}\rho,$$

The stress-energy responsible for inflation has negative pressure

It corresponds to a period where the Hubble radius decreases:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{1}{aH}\right) < 0.$$

Introducing:

$$\mathrm{d}N \equiv \mathrm{d}\ln a = H\mathrm{d}t,$$

N being the number of e-fold

This also implies that:

$$\varepsilon \equiv -\frac{\dot{H}}{H^2} = -\frac{d\ln H}{dN} < 1\ .$$

The fractional change of H per e-fold is small

Why Inflation ?

Inflation was introduced to solve the problems of standard Big Bang cosmology:

The horizon problem ✓

The flatness problem

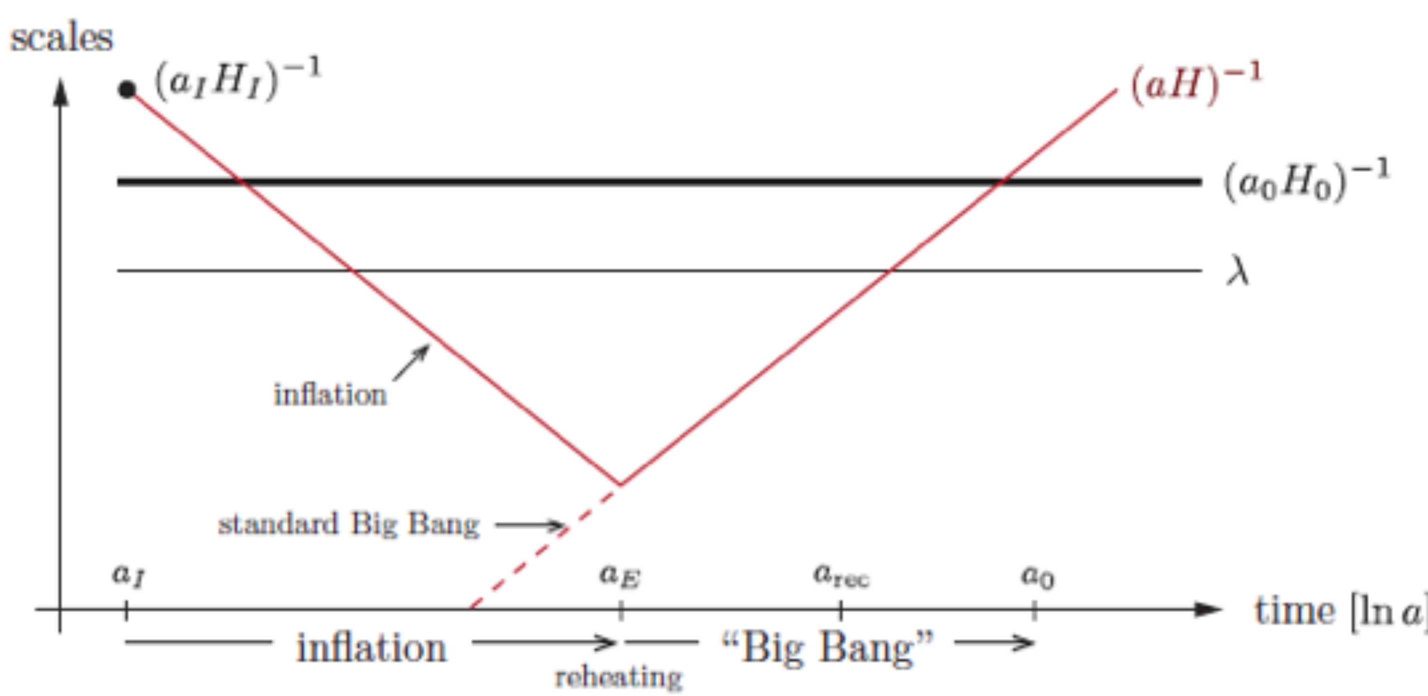
The monopole problem

…

1-Basic principles

Horizon problem and e-folds

We want the Hubble radius today (0) to fit in the Hubble radius at the time of inflation (I):



$$(a_0 H_0)^{-1} < (a_I H_I)^{-1} \, .$$

at first order, with a simple back of the enveloppe calculation, it can be shown that this is equivalent to:

$$\frac{a_E}{a_I} > 10^{28} \quad \Rightarrow \quad \ln\left(\frac{a_E}{a_I}\right) > 64 \, .$$

solved….given such constraint ! and this is where comes the

« about 60e-folds are required to solve the horizon problem »

lectures from D.D. Baumann

1-Basic principles

Why Inflation ?

Inflation was introduced to solve the problems of standard Big Bang cosmology:

The horizon problem ✓

The flatness problem ✓

The monopole problem ✓

…

Flatness and monopoles problems

Flatness problem

Total energy density and curvature:

$$1 - \Omega(a) = \frac{-k}{(aH)^2} \,,$$

But we have seen that, during inflation: $(aH)^{-1}$ decreases !

The Universe is driven towards flatness !

The Monopole Problem:

Inflation allows for magnetic monopoles to exist as long as they were produced prior to the period of inflation. During inflation, their density drops exponentially,

Their abundance drops to undetectable levels.

2-Which mechanism for Inflation ?

1- The simplest way: **homogeneous scalar field** driven out of equilibrium

Consider a scalar field ϕ , the inflaton, minimally coupled to Einstein gravity:

$$S=\int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_{\rm pl}^2}{2}\mathcal{R}-\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi-V(\phi)\right],$$

The evolution equation of the scalar field is governed by the Klein Gordon equation:

$$\ddot{\phi}+3H\dot{\phi}=-V' \quad \text{with} \quad V'\equiv dV/d\phi.$$

Here: the **potential acts like a force**, V',
while the **expansion of the universe adds friction:** $H\dot{\phi}$.

NB: From Friedmann equations, we have:

$$\dot{H}=-\frac{1}{2}\frac{\dot{\phi}^2}{M_{\rm pl}^2} \qquad H^2=\frac{1}{3M_{\rm pl}^2}\left[\frac{1}{2}\dot{\phi}^2+V\right]$$

2-Which mechanism for Inflation ?

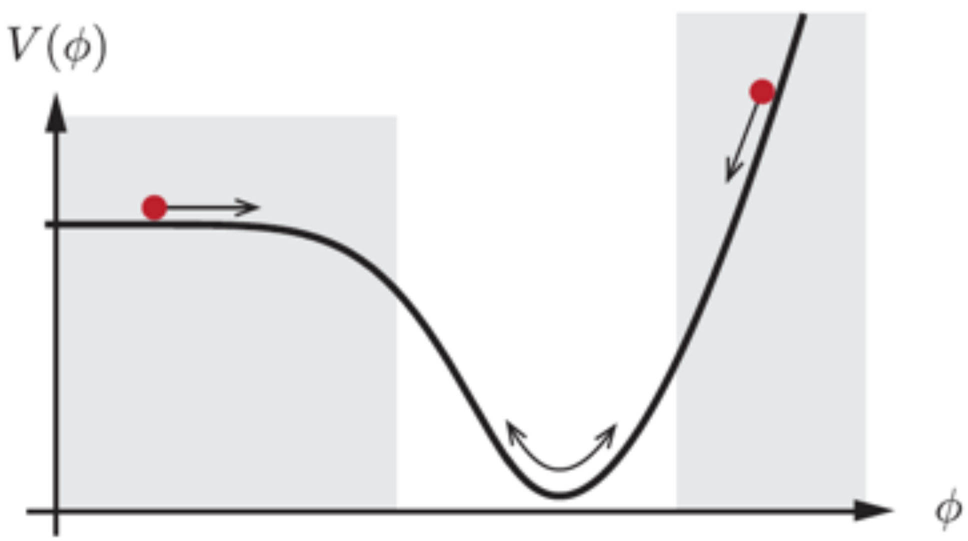
2- Even simpler: slow-roll

We can make ε explicit:

$$\varepsilon \equiv -\frac{\dot{H}}{H^2} = \frac{\frac{1}{2}\dot{\phi}^2}{M_{\rm pl}^2 H^2} < 1$$

Inflation occurs if the kinetic term only makes a small contribution of the total energy

This is what is called the **slow-roll inflation** (no approximation so far!)



In order for this condition to persist the acceleration of the scalar field has to be small, we often define:

$$\eta = \frac{\dot{\varepsilon}}{H\varepsilon} = 2\frac{\ddot{\phi}}{H\dot{\phi}} - 2\frac{\dot{H}}{H^2}$$

which has to be small too !

To make sure that inflation occurs and persists (here is the approximation!):

$$\{\varepsilon, |\eta|\} \ll 1.$$

slow-roll parameters

$$\epsilon_{\rm v} \equiv \frac{M_{\rm pl}^2}{2}\left(\frac{V'}{V}\right)^2 \quad , \quad |\eta_{\rm v}| \equiv M_{\rm pl}^2 \frac{|V''|}{V}$$

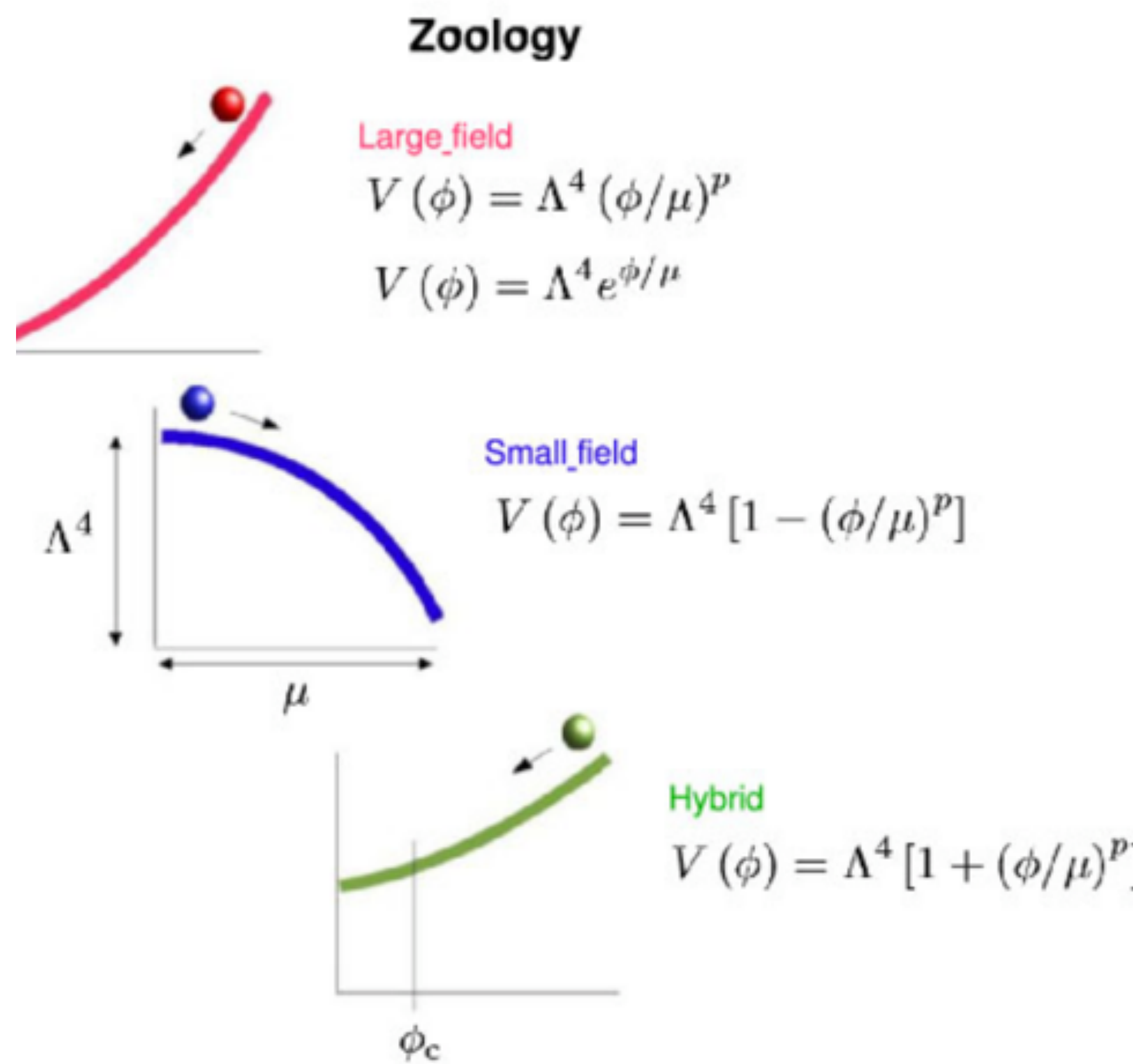
$V' = dV/d\phi,$

2-Which mechanism for Inflation ?

3- But…there a lot of different inflation models !

old, new, pre-owned,
chaotic, quixotic, ergodic,
ekpyrotic, autoerotic,
faith-based, free-based,
brane, braneless, brainless,
supersymmetric, supercilious,
natural, supernatural, *au natural,*
hybrid, low-bred, white bread,
one-field, two-field, left-field,
eternal, internal, infernal,
self-reproducing, self-promoting,

[adapted from R. Kolb]



[adapted from W.H. Kinney]

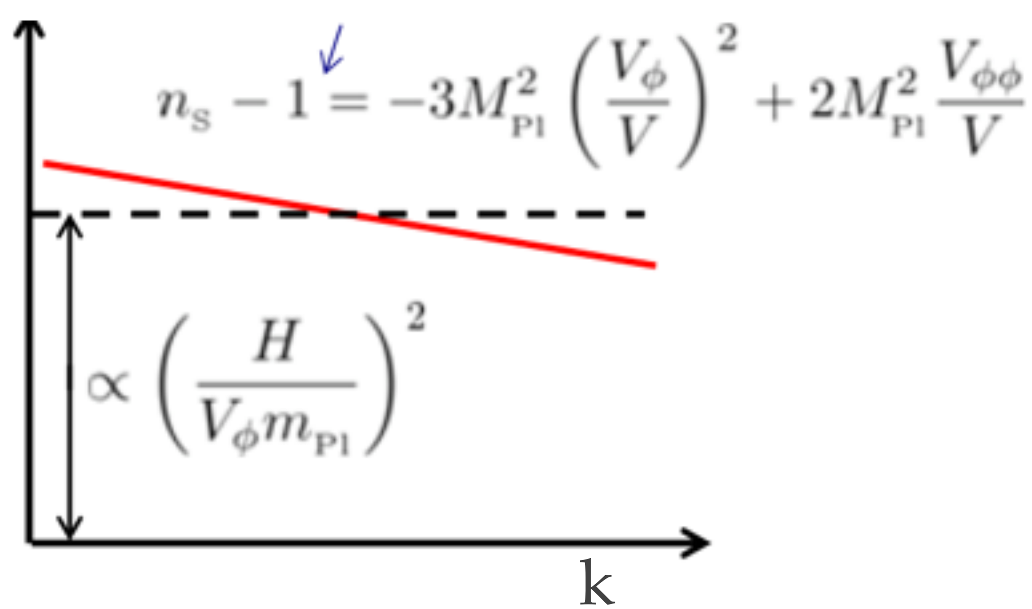
3-Predictions of Inflation

Scalar and Tensor Perturbations

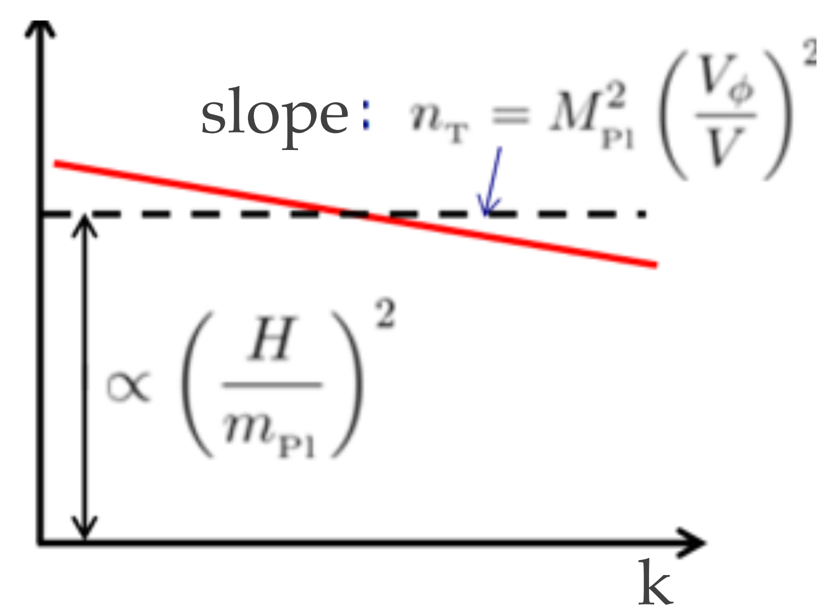
Inflation does predict the existence of two types of perturbations:

- fluctuations of the scalar inflaton field: **scalar perturbations**
- fluctuations of the gravitational field: **tensor perturbations** (or primordial gravitational waves, those are the **B-modes !**)

Scalar Perturbations Power Spectrum



Tensor Perturbations Power Spectrum



[adapted from J. Martin]

The tensor to scalar ratio, r, is given by:

$$\boxed{r = \frac{T}{S} = 8M_{Pl}^2 \left(\frac{V_\phi}{V}\right)^2 < 1}$$

This is what we are trying to tackle in the **search for CMB B-modes !**

3-Predictions of Inflation

- Spatial flatness
- Adiabatic initial Conditions
- Nearly Gaussian initial fluctuations
- Almost (but not exactly) scale-invariant scalar perturbations
- Background of primordial gravitational waves
- Tensor to scalar ratio

4- Tests and Results

[Planck 2015 results, XIII, ArXiv:1502.01589]

spatial flatness

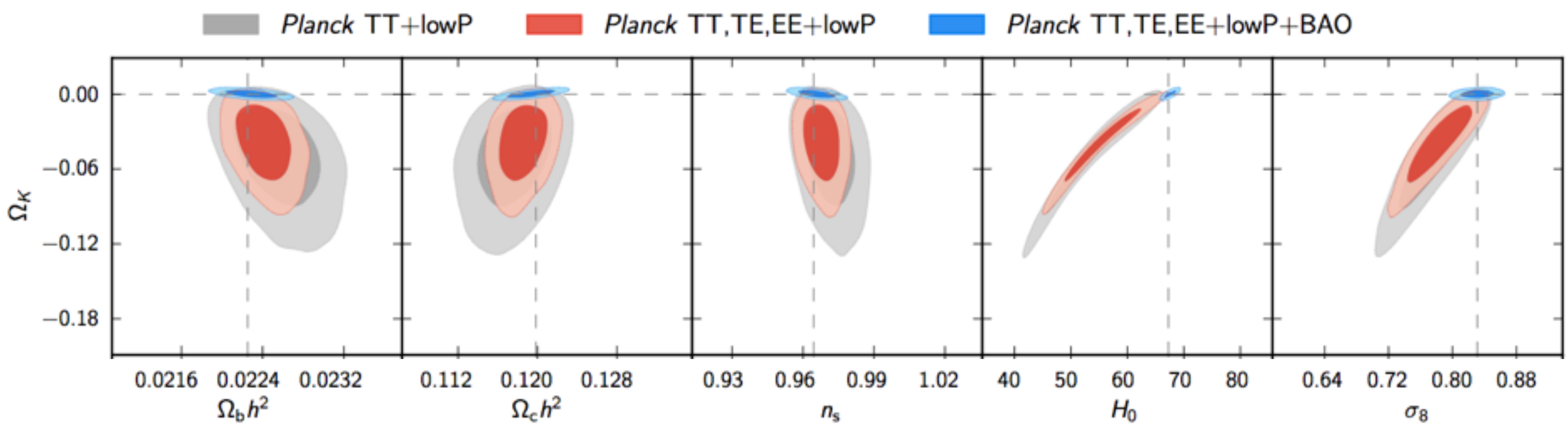


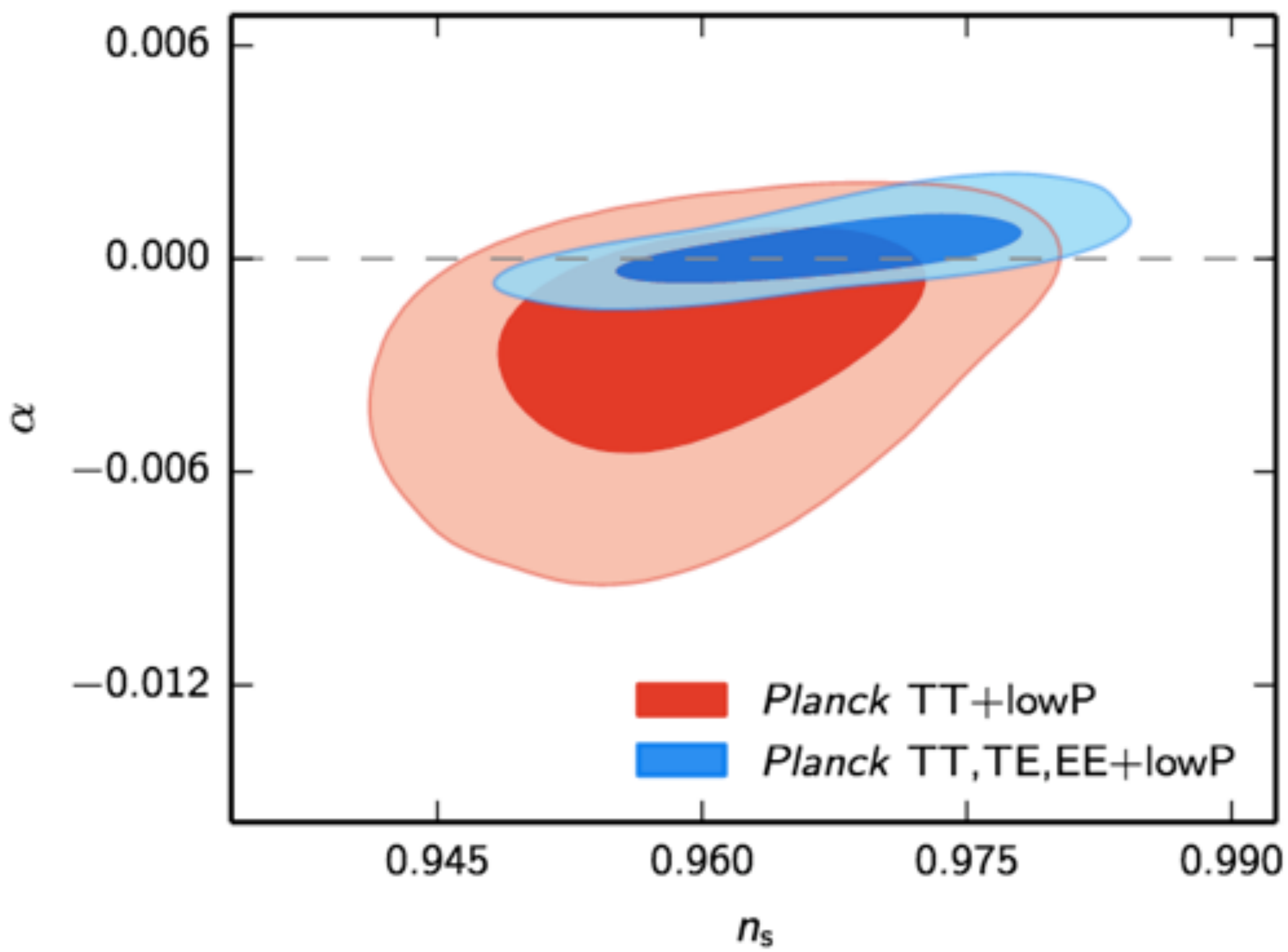
Table 5. Constraints on 1-parameter extensions to the base ΛCDM model for combinations of *Planck* power spectra, *Planck* lensing, and external data (BAO+JLA+H_0, denoted "ext"). All limits and confidence regions quoted here are 95 %.

Parameter	TT	TT+lensing	TT+lensing+ext	TT, TE, EE	TT, TE, EE+lensing	TT, TE, EE+lensing+ext
Ω_K	$-0.052^{+0.049}_{-0.055}$	$-0.005^{+0.016}_{-0.017}$	$-0.0001^{+0.0054}_{-0.0052}$	$-0.040^{+0.038}_{-0.041}$	$-0.004^{+0.015}_{-0.015}$	$0.0008^{+0.0040}_{-0.0039}$

4- Tests and Results

[Planck 2015 results. XX, arXiv :1502.02114]

adiabaticity



Constraints on the correlated matter isocurvature mode amplitude parameter α, where $\alpha = 0$ corresponds to purely adiabatic perturbations.

4- Tests and Results

[Planck 2015 results. XVII, arXiv :1502.01592]

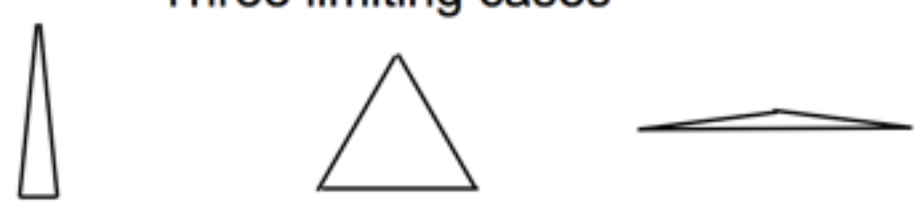
<u>search for non-gaussianity</u>

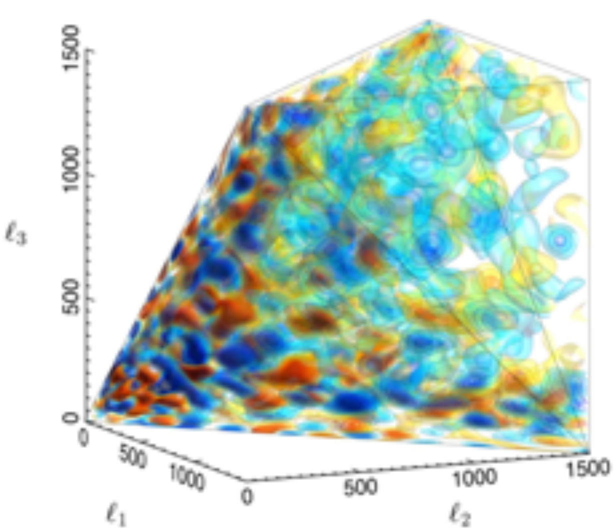
estimated with the 3-points correlation function

$$\underbrace{\langle \Phi(\vec{k}_1)\Phi(\vec{k}_2)\Phi(\vec{k}_3)\rangle}_{\text{Three-point correlation}} = (2\pi)^3\,\delta^{(3)}(\vec{k}_1+\vec{k}_2+\vec{k}_3)\;\underbrace{f_{\rm NL}\;F(k_1,k_2,k_3)}_{\text{Bispectrum}}$$

enforces triangular configurations

Three limiting cases



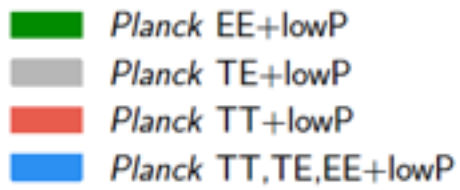


Shape and method	ISW-lensing subtracted
SMICA (T)	
Local	**2.5** ± **5.7**
Equilateral	**−16** ± **70**
Orthogonal	**−34** ± **33**
SMICA (T+E)	
Local	**0.8** ± **5.0**
Equilateral	**−4** ± **43**
Orthogonal	**−26** ± **21**

The structure we observe today was sourced by adiabatic, passive, Gaussian and primordial seed perturbations

4- Tests and Results

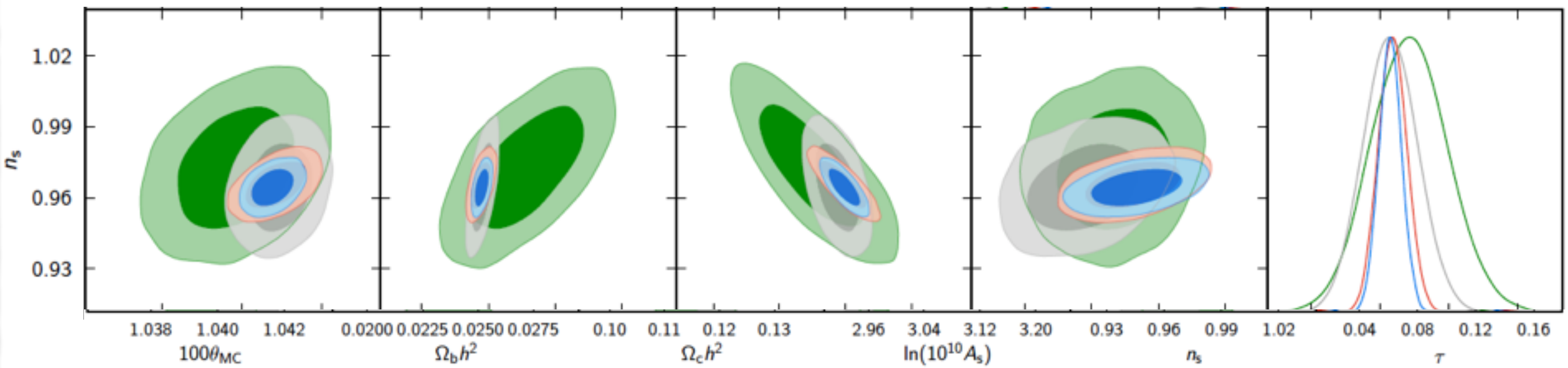
[Planck 2015 results, XIII, ArXiv:1502.01589]



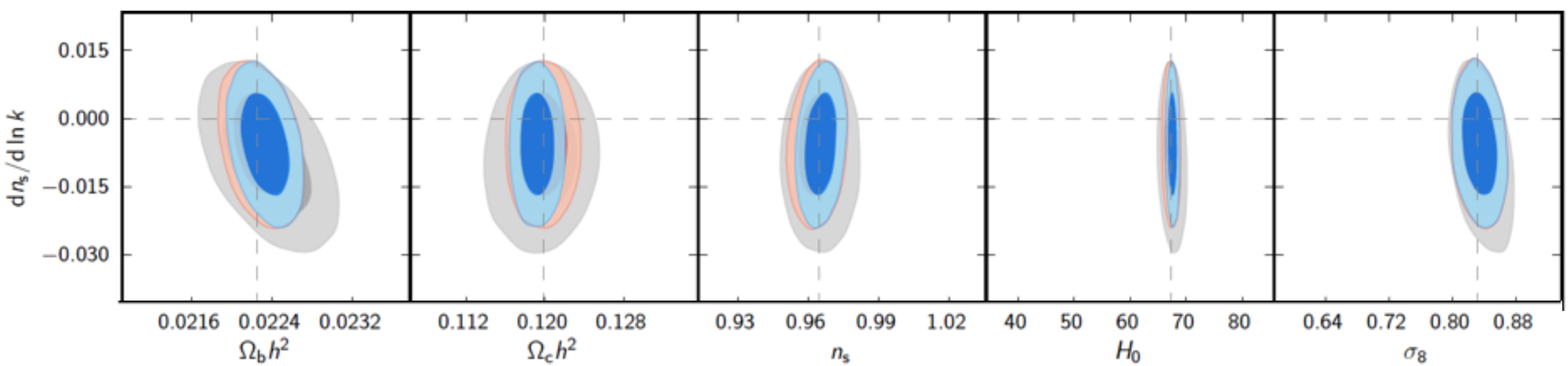
Almost (but not exactly)
scale-invariant scalar perturbations

NB: $n_S = 1 - 4\epsilon - 2\delta$ [slow-roll]

n_S should be slightly smaller than 1



+ No hint for anything more complicated than power-law : no running

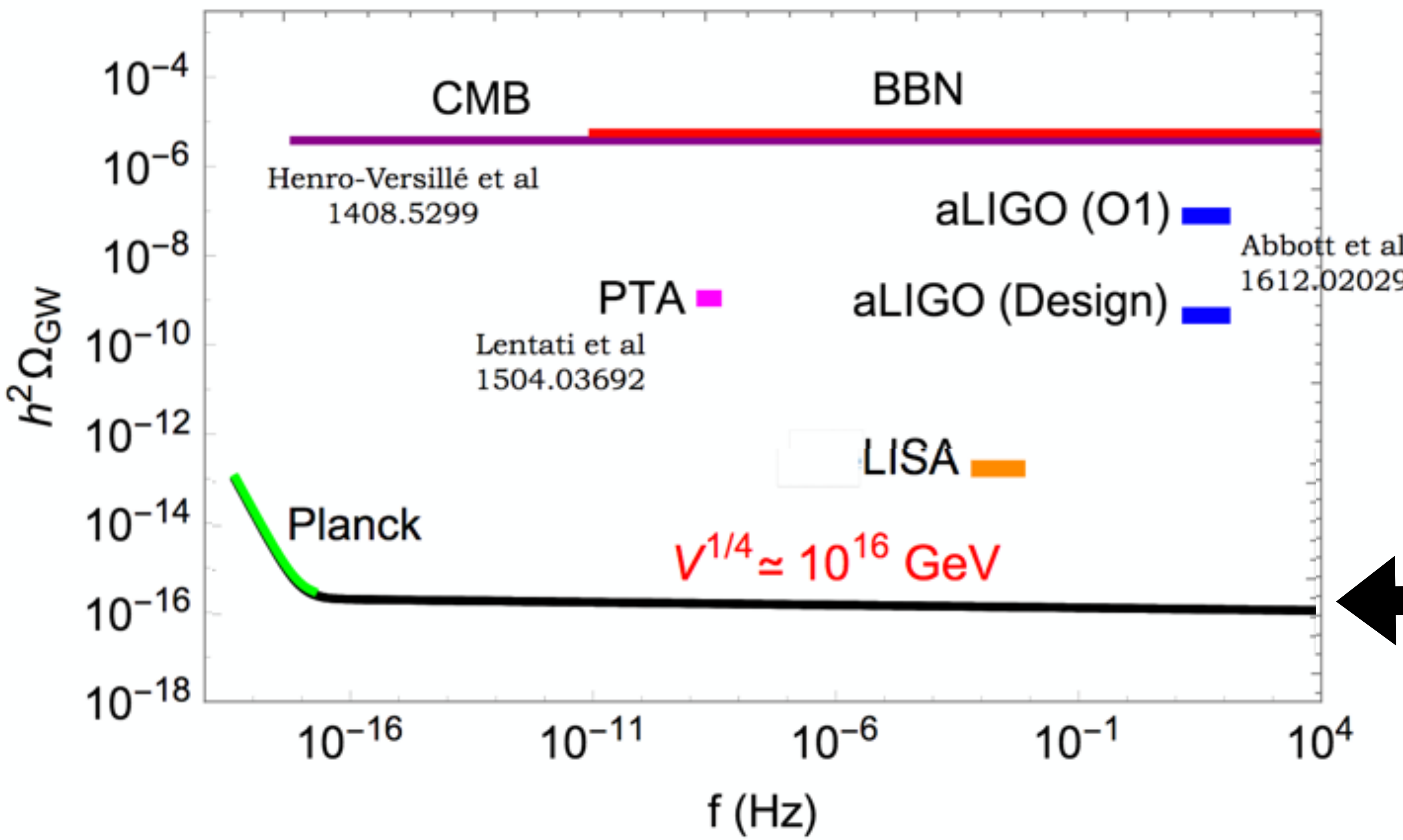


4- Tests and Results

C. Caprini

<u>primordial gravitational wave background</u>

Observational bounds/sensitivities for SGWB



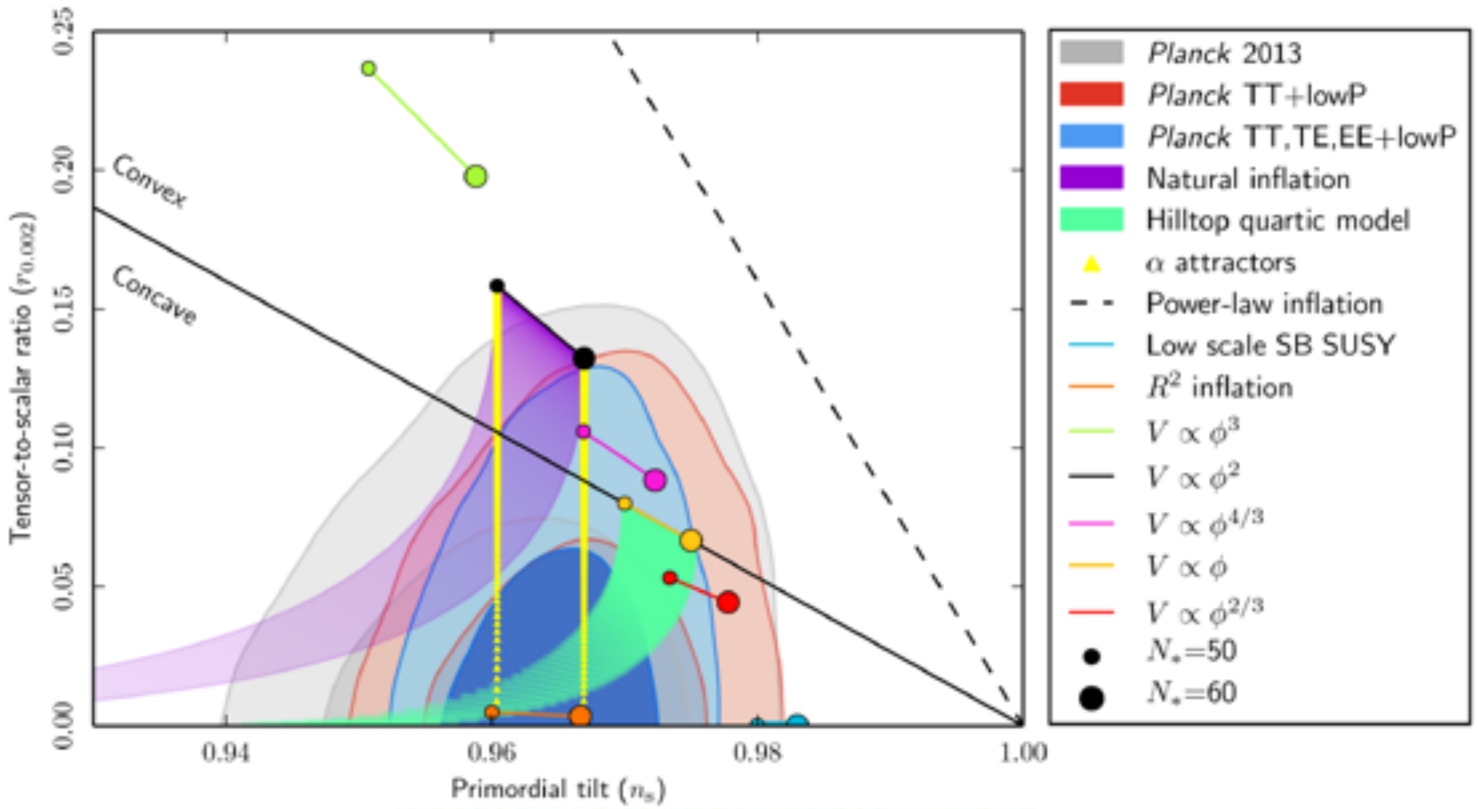
expected from standard inflation

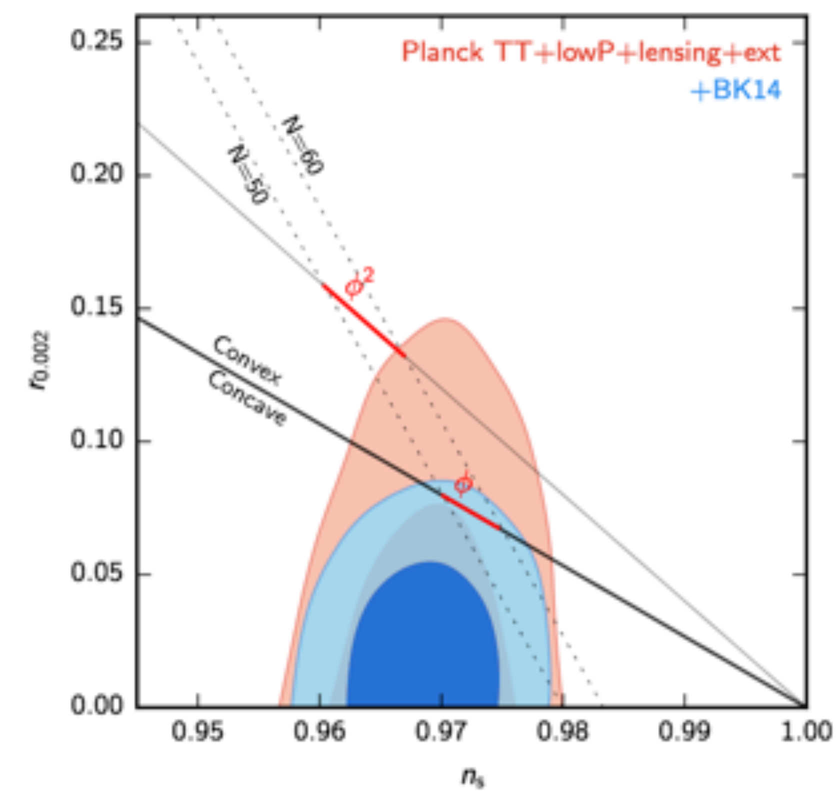
4- Tests and Results

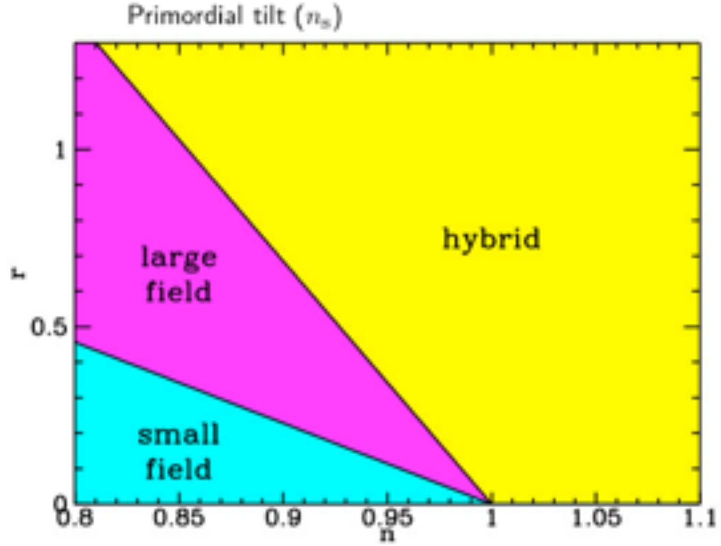
[Planck 2015 results. XVII, arXiv :1502.01592]

[Bicep2/KeckArray, arXiv:1510.09217]

<u>tensor to scalar ratio</u>

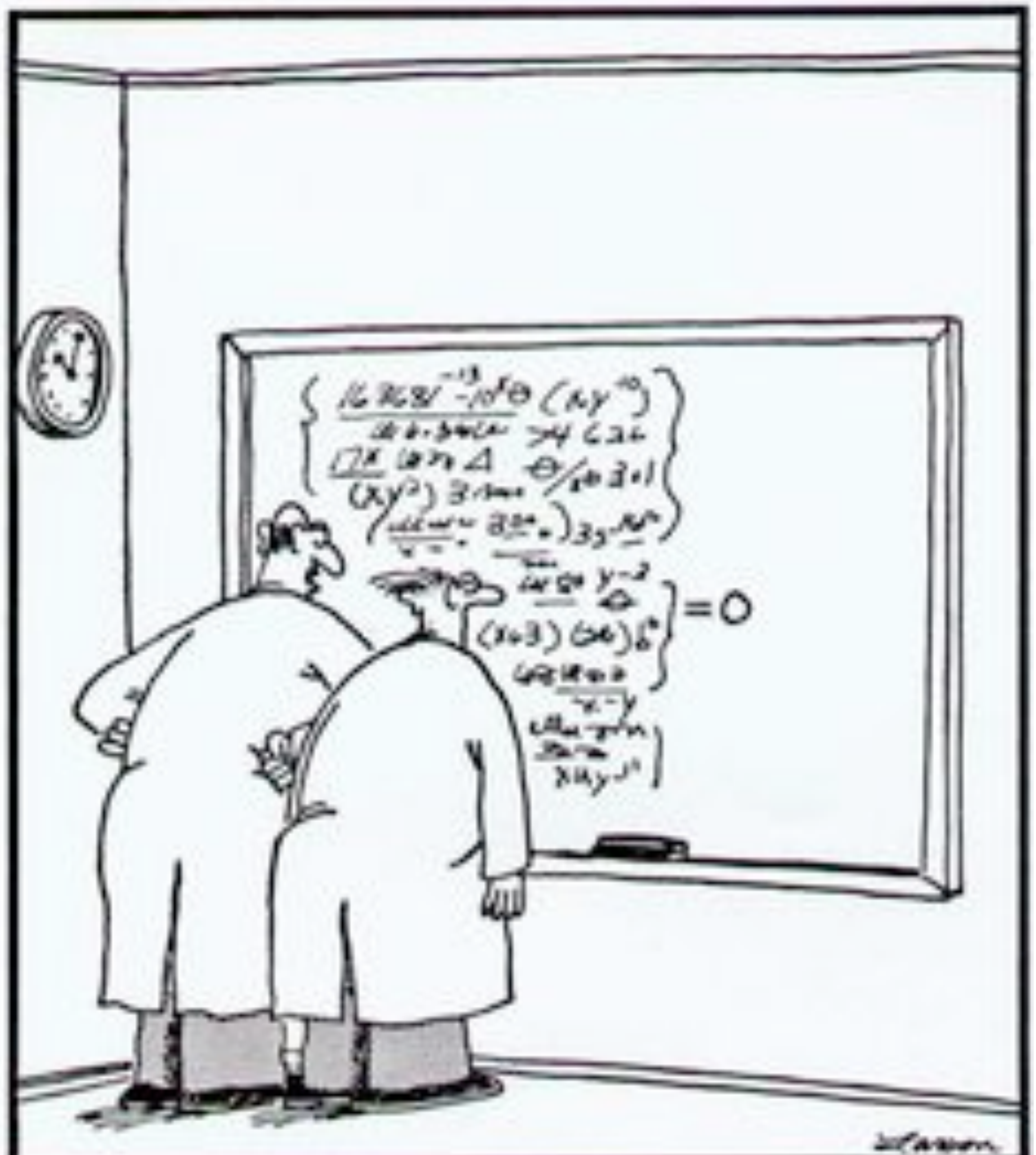






=> Adding Bicep
tends to disfavor models with a $V(\phi) \propto \phi^2$ potential

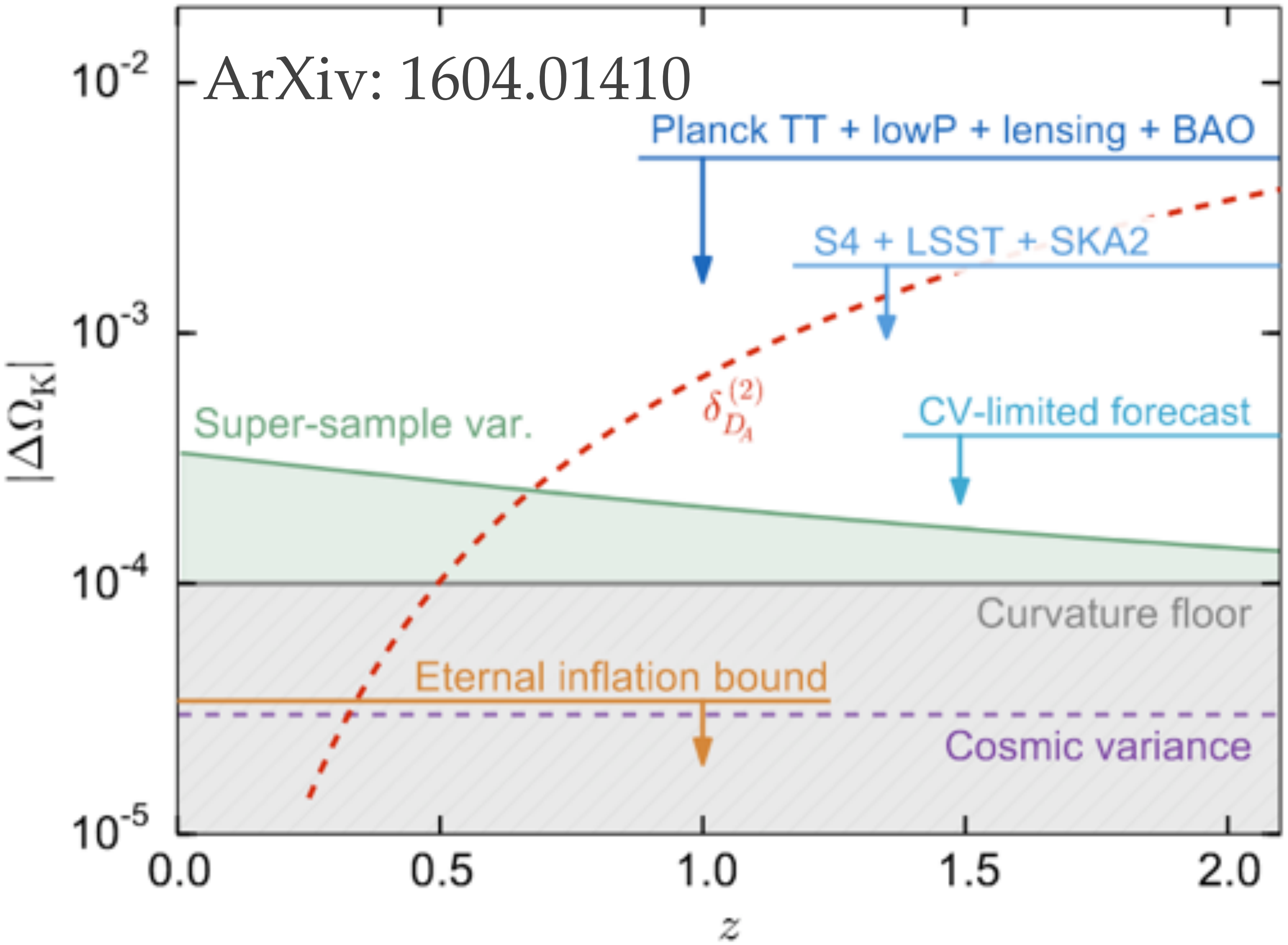
Still a long road to probe inflation


"No doubt about it, Ellington—we've mathematically expressed the purpose of the universe. God, how I love the thrill of scientific discovery!"

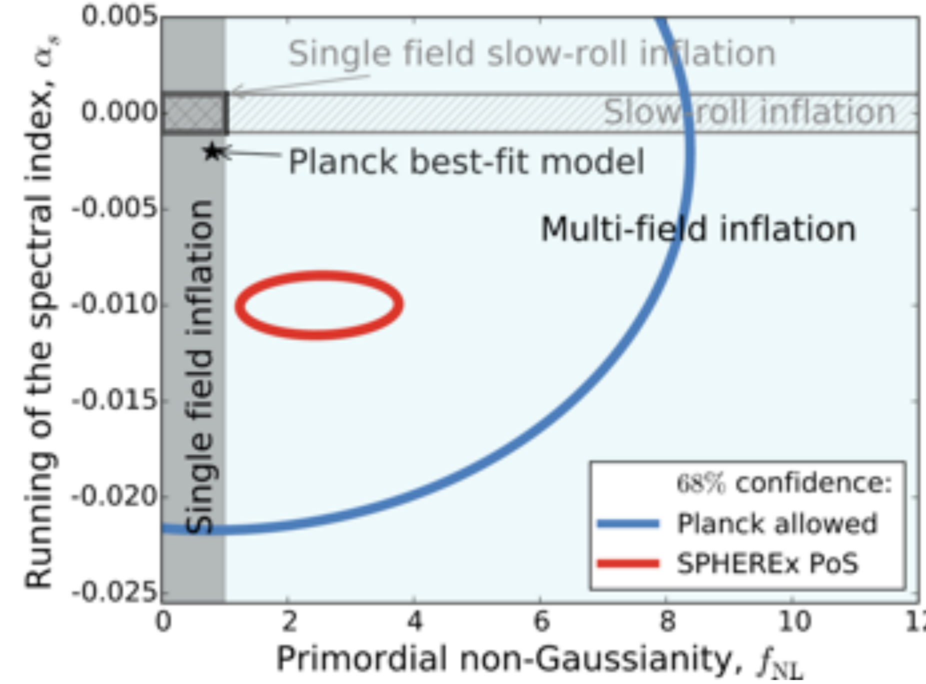
- Of course we are expecting a (short-term) measurement of primordial gravitational waves (through B-modes detection) !

- Then still a long road to definitely state which mechanism led to Inflation and characterize its parameters (shape of the potential…)

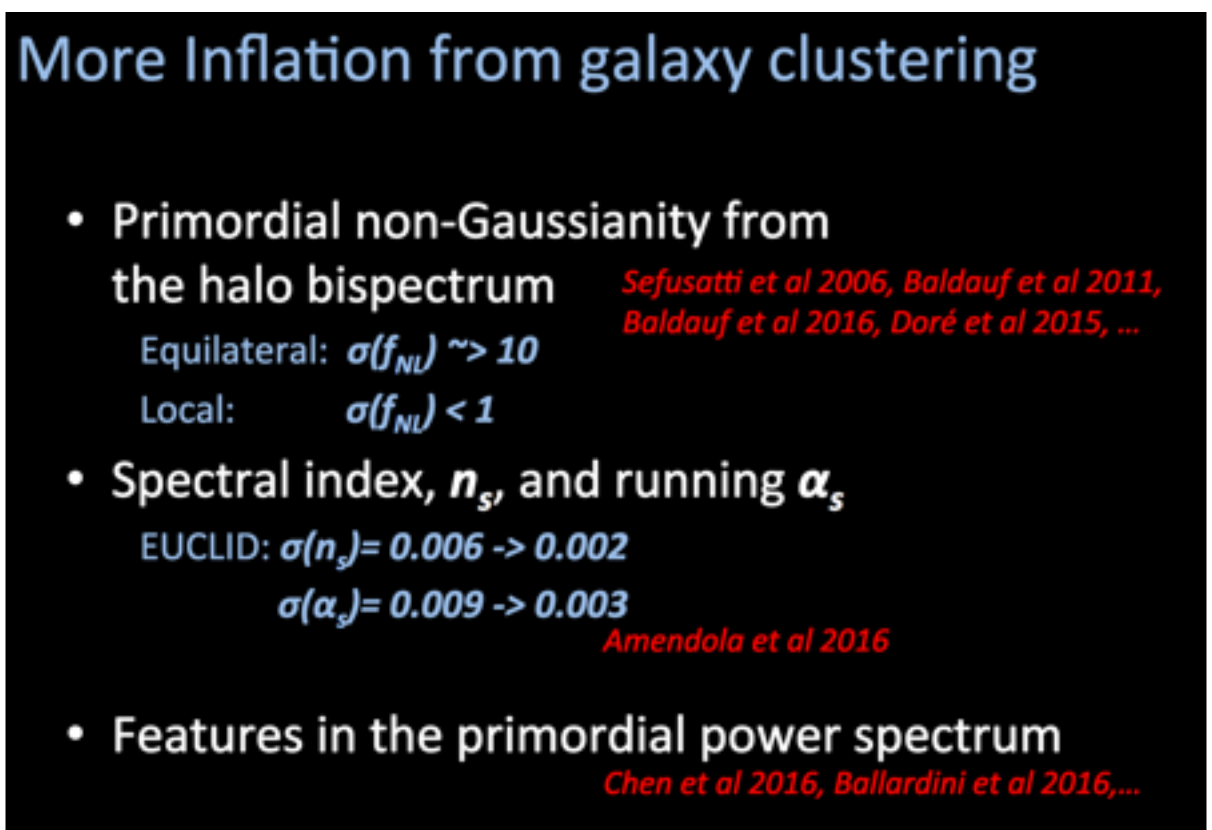
- We will need all the cosmo data to get the overall picture (more accurate Ω_K ,f_{NL},n_s…)
  S4/LiteBIRD/LSST/Euclid/LISA/SKA
  +cross-correlations (…)



SPHEREx galaxy clustering can reach $\sigma(f_{NL})< 1$



(ArXiv: 1412.4872)



[DePutter IPA 2016]