Primordial non-Gaussianities

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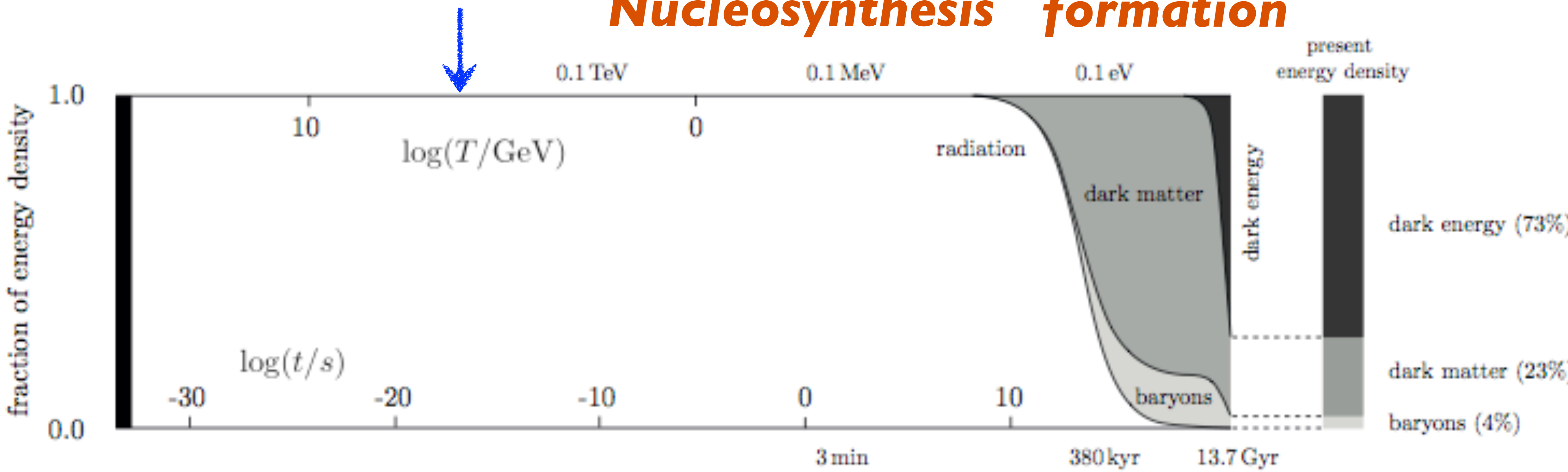
Cosmic history

LHC

Big Bang Nucleosynthesis

Structure formation



Inflation

Cosmic Microwave Background

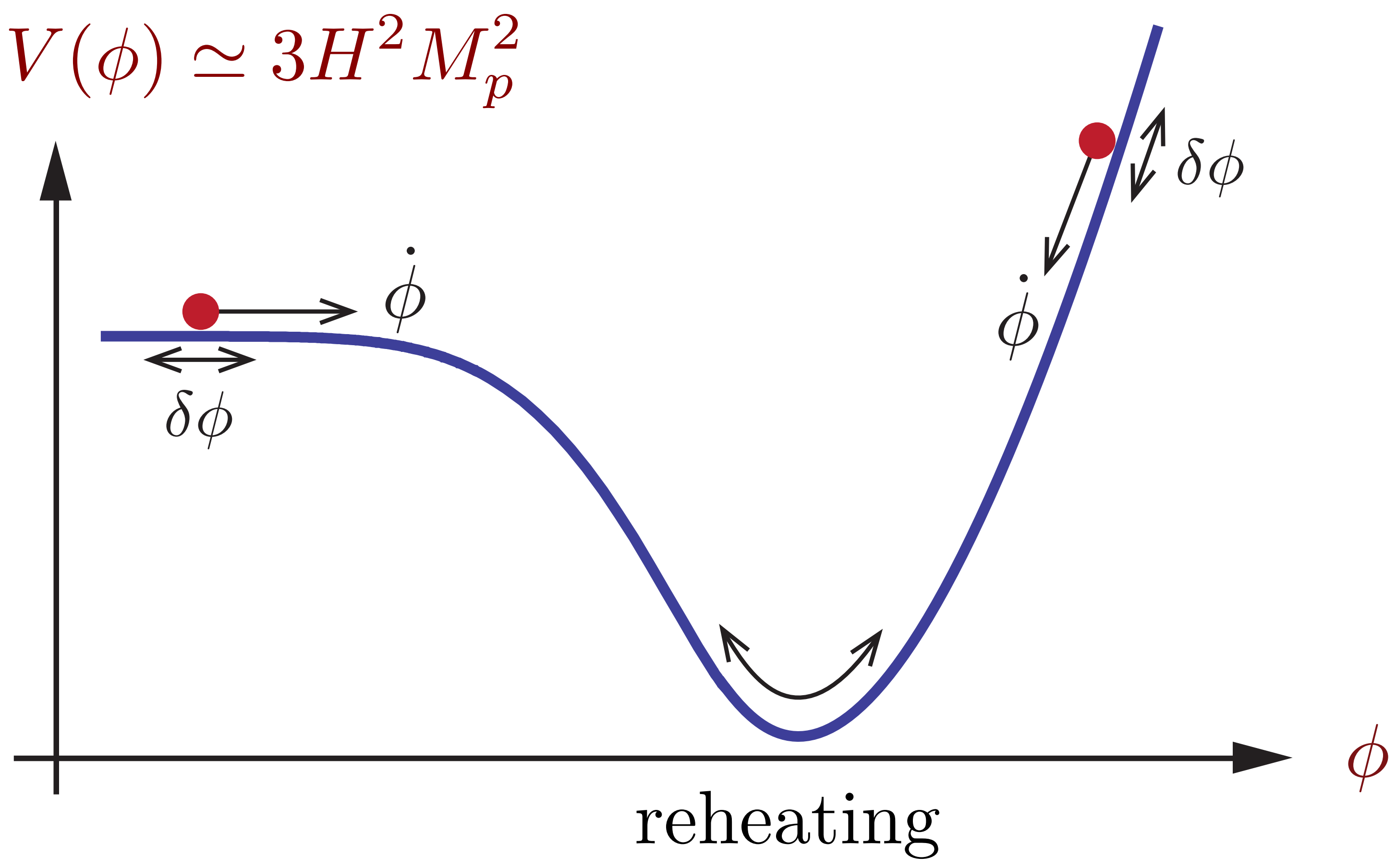
Inflation: a phase of accelerated expansion before the radiation era, that:

- solves the problems of the Hot Big Bang model
- generates the seeds of the large scale structures.

Slow-roll single field inflation

- Simplest set-up for prolonged phase of accelerated expansion: scalar field with flat potential in Planck units

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



$$\epsilon \equiv \frac{M_{\rm pl}^2}{2} \left(\frac{V_{,\phi}}{V} \right)^2 \ll 1$$

$$\eta \equiv M_{\rm pl}^2 \frac{V_{,\phi\phi}}{V} \ll 1$$

Inflation generates

scalar (density) fluctuations	***tensor fluctuations (Gravitational Waves)***
$$P_\zeta \sim \frac{H^4}{M_{\rm pl}^2 \dot{H}}$$	$$P_h \sim \frac{H^2}{M_{\rm pl}^2}$$

power spectra (2-point correlations) measure:

$$H(t) \equiv \frac{\dot{a}(t)}{a(t)}$$

Power spectra measurements constrain

Scale-dependence of scalar fluctuations

Tensor-to-Scalar ratio

$$n_s - 1 \equiv \frac{\mathrm{d}\ln P_\zeta}{\mathrm{d}\ln k} \propto \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{H^4}{M_{\mathrm{Pl}}^2 \dot{H}}\right)$$

$$r \equiv \frac{P_h}{P_\zeta}$$

Planck constraints

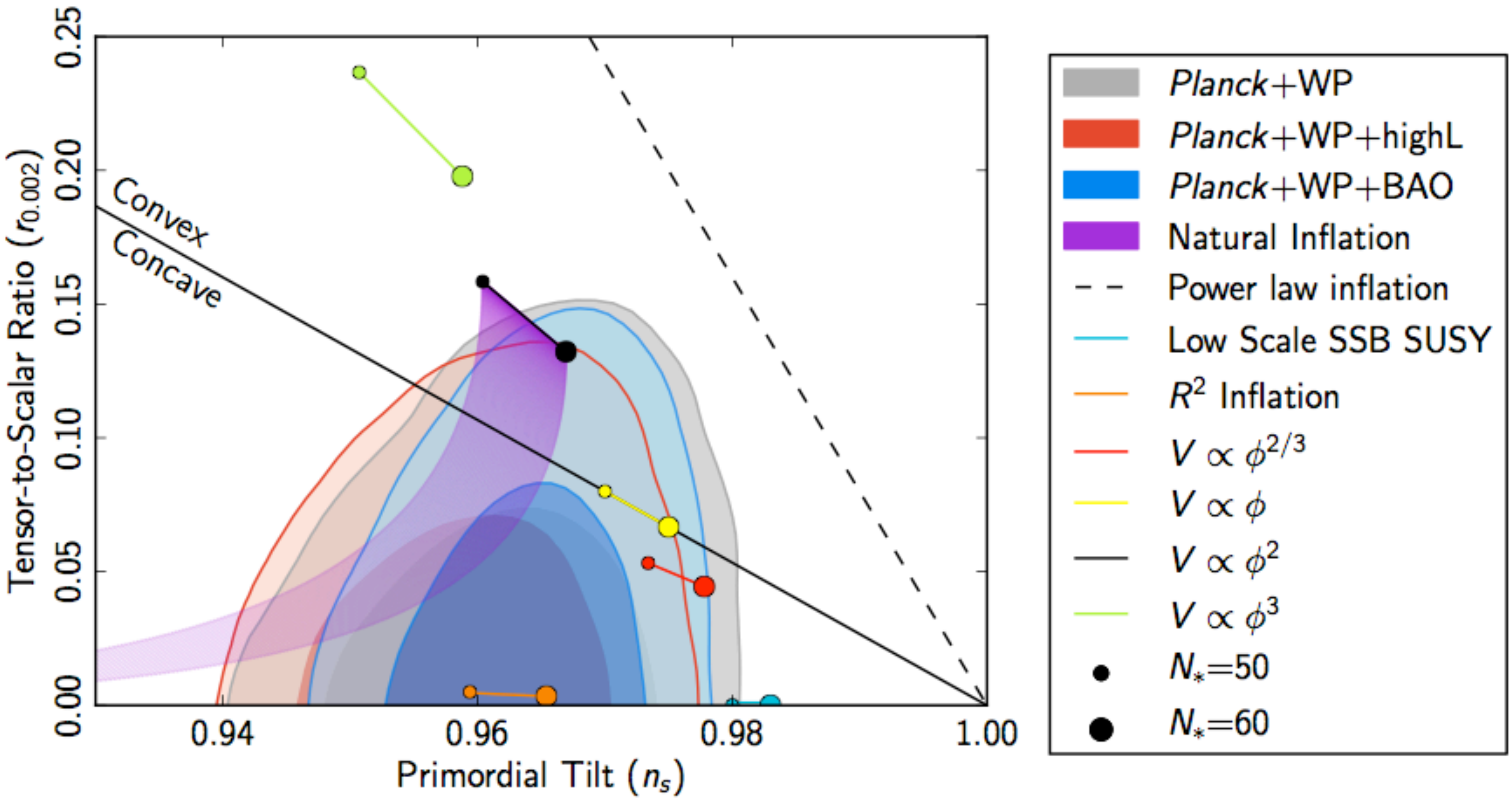


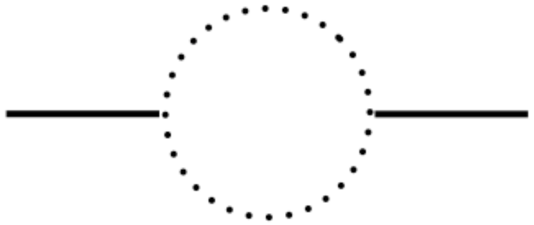
Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets compared to the theoretical predictions of selected inflationary models.

Microphysical origin of inflation?

• Physics at the energy scale of inflation is unknown!
Observational probe of very high-energy physics

• Candidate physical theories motivate much more complicated dynamics than the simplest scenarios:

- ***eta-problem*** (like Higgs hierarchy problem)
- ***multiple fields***
- ***non-standard kinetic terms***
- ***modified gravity***
- alternatives to inflation, e.g. curvaton



$$m_\phi^2 \sim \Lambda_{\rm uv}^2 \gg H^2$$

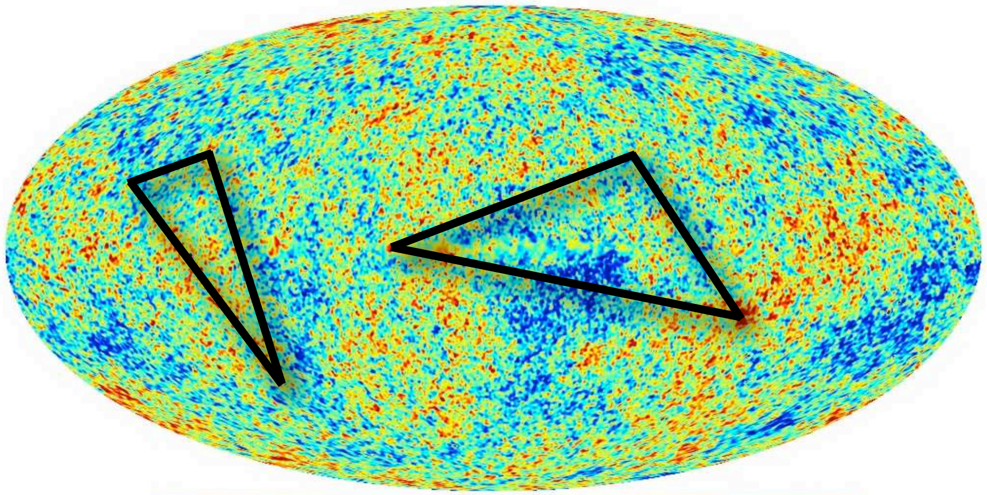
• Plethora of inflationary models. How can we learn more?

Non-Gaussianity

probes physics beyond

$$H(t)$$

3-point correlations



$\longrightarrow$

direct measurement of
inflaton interactions

Primordial non-Gaussianities

- Gaussian approximation: freely propagating particles

- Non-Gaussianities measure the ***interactions*** of the field(s) driving inflation. ***Discrimination amongst models*** which are degenerate at the linear level

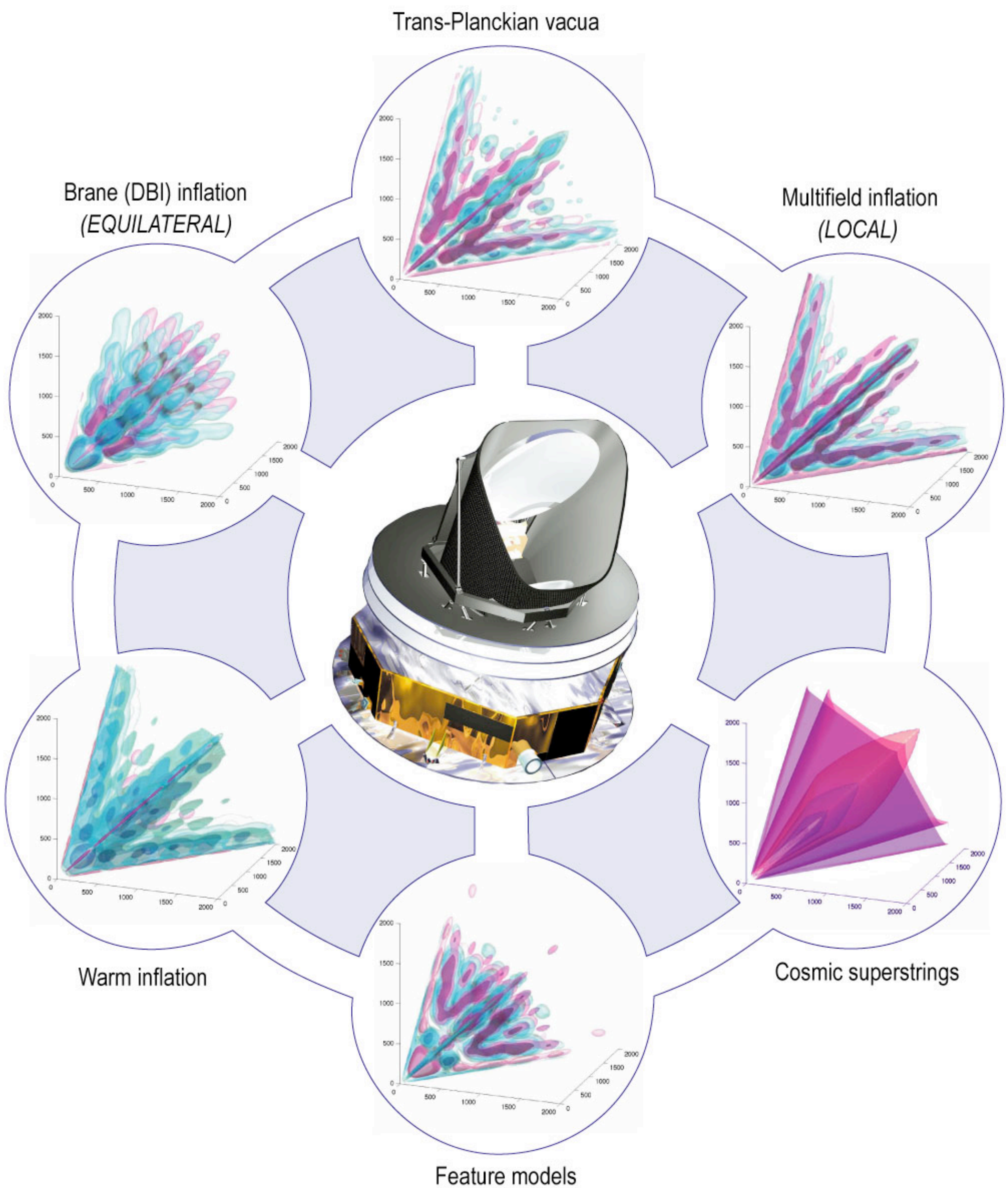
Particle physics

Cosmology

Primordial non-Gaussianities

'Happy families are all alike; every unhappy family is unhappy in its own way.'

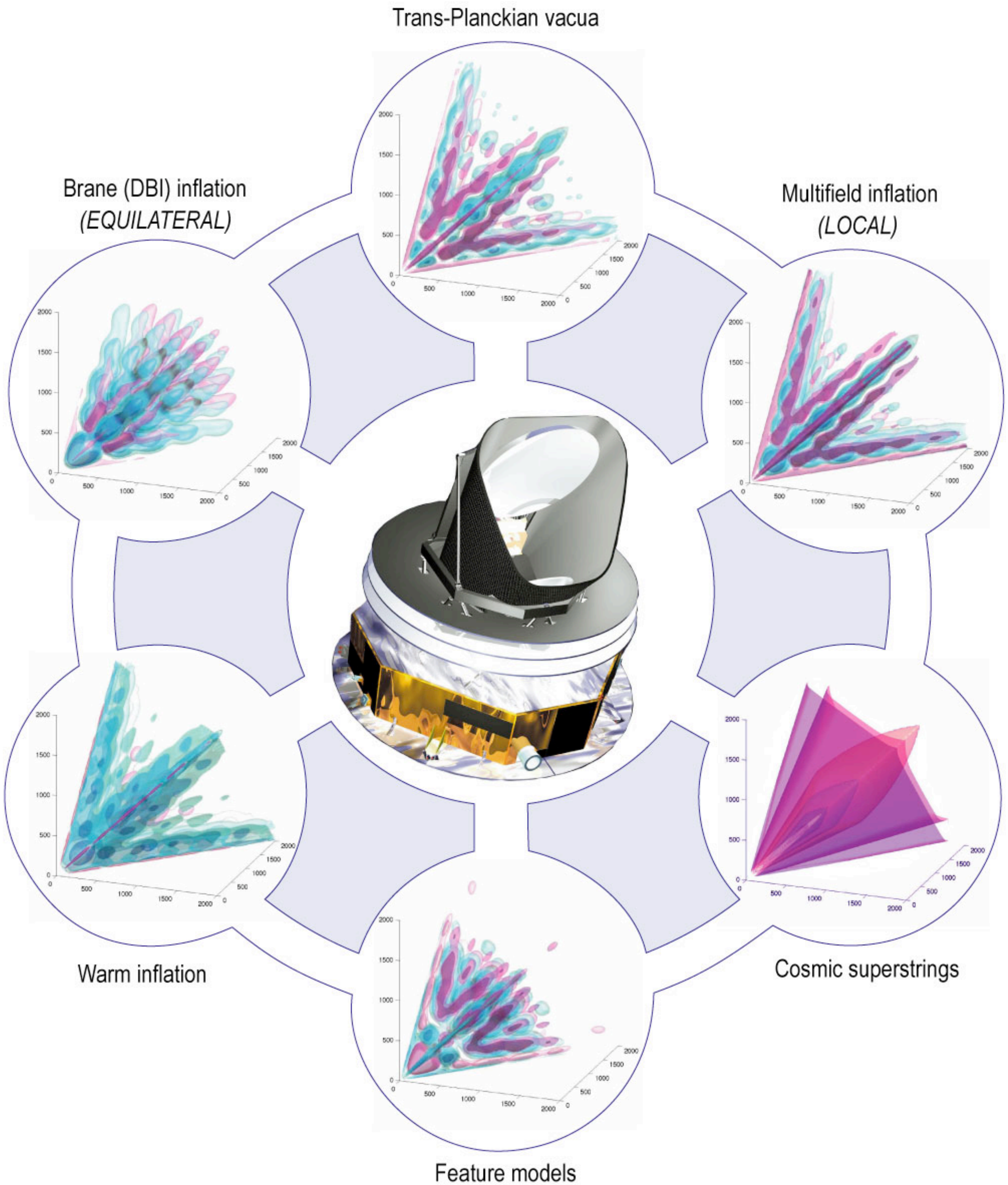
Anna Karénine, Tolstoï



Primordial non-Gaussianities

Gaussian distribution are all alike; every non-Gaussian distribution is non-Gaussian in its own way.

Cosmologist.



Maldacena's 2003 result

Very small non-Gaussianities (much more quantitative statement actually!)

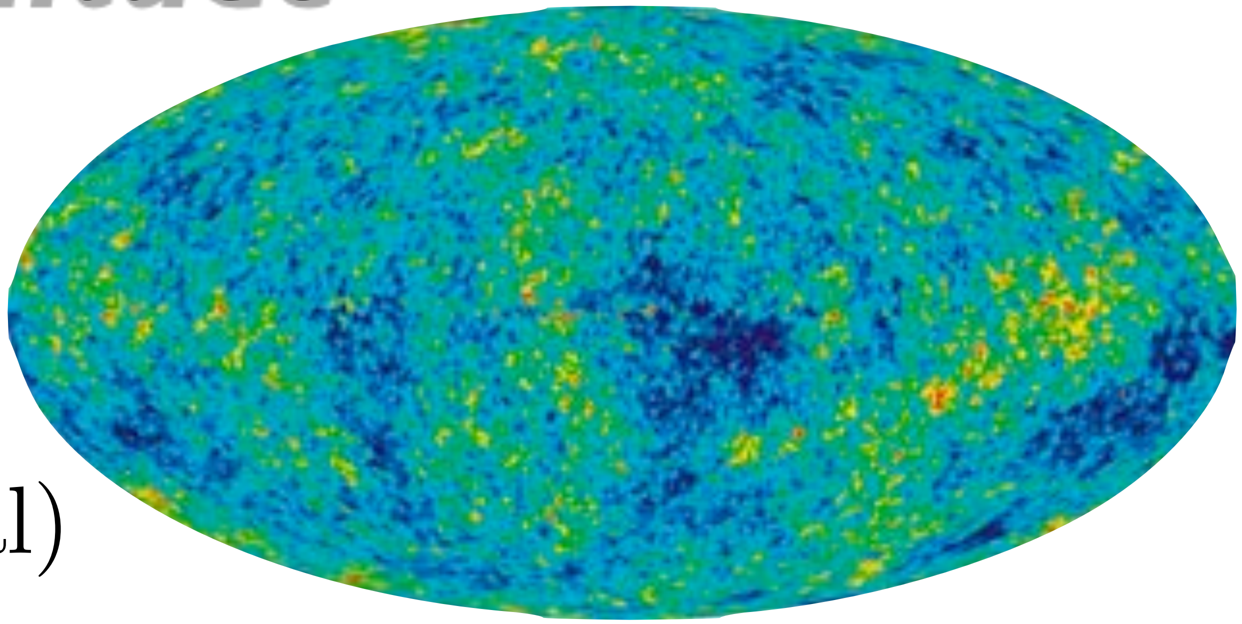
UNDER HYPOTHESES

- Single field
- Standard kinetic term
- Slow-roll
- Initial vacuum state
- Einstein gravity

It is now clear that violating any of these assumptions might lead to observably large NGs.

A simple example and orders of magnitude

$$\frac{\delta T}{T} \sim \zeta \sim 10^{-5}$$



$$\zeta = \zeta_G + \frac{3}{5} f_{NL}^{loc} \zeta_G^2 \qquad \text{(local)}$$

- Constraints: $f_{NL}^{loc} = 37.2 \pm 19.9\,(68\%\,CL)$ WMAP 9

Gaussianity already tested to better than 0.1%

- Planck: $f_{NL}^{loc} = 2.7 \pm 5.8\,(68\%\,CL)$

- Slow-roll single field prediction: $f_{NL}^{loc} = \mathcal{O}(\epsilon, \eta) \approx 10^{-2}$

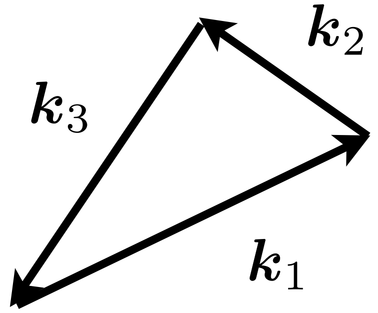
Non-Gaussianities

- Beyond the power spectrum: $$\langle \zeta_{\boldsymbol{k}_1} \zeta_{\boldsymbol{k}_2} \rangle = P_\zeta(k_1)(2\pi)^3 \delta^3(\boldsymbol{k}_1 + \boldsymbol{k}_2)$$

- Higher-order connected, n-point functions:

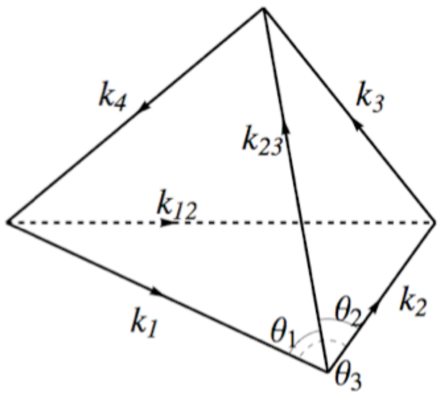
3 point: bispectrum

$$\langle \zeta_{\boldsymbol{k}_1} \zeta_{\boldsymbol{k}_2} \zeta_{\boldsymbol{k}_3} \rangle = B_\zeta(k_1, k_2, k_3)(2\pi)^3 \delta^3(\boldsymbol{k}_1 + \boldsymbol{k}_2 + \boldsymbol{k}_3)$$



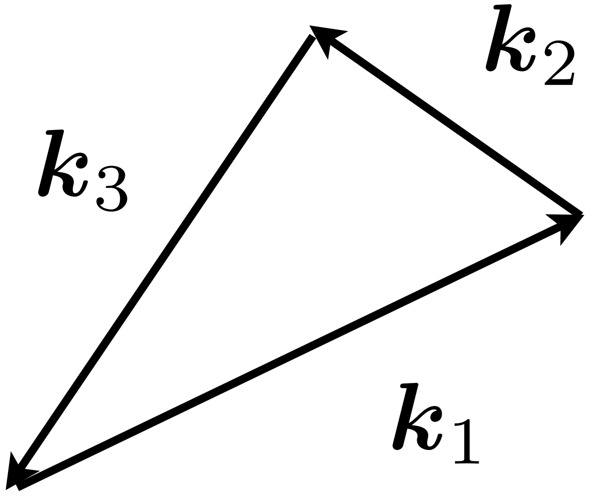
4 point: trispectrum

$$\langle \zeta_{\boldsymbol{k}_1} \zeta_{\boldsymbol{k}_2} \zeta_{\boldsymbol{k}_3} \zeta_{\boldsymbol{k}_4} \rangle_c = T_\zeta(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3, \boldsymbol{k}_4)(2\pi)^3 \delta^3(\sum_i \boldsymbol{k}_i)$$



The bispectrum

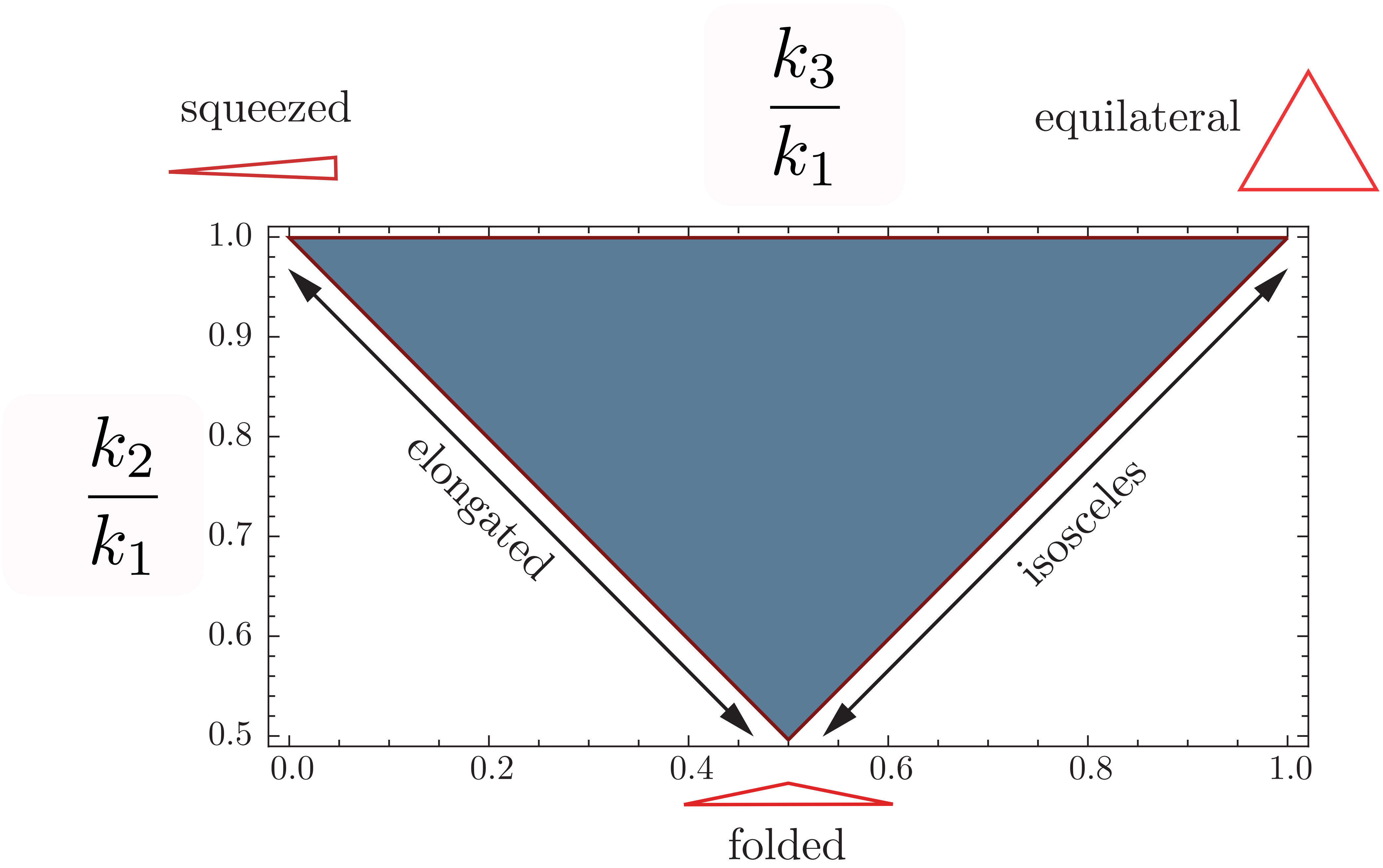
$$\langle \zeta(\boldsymbol{k}_1)\zeta(\boldsymbol{k}_2)\zeta(\boldsymbol{k}_3)\rangle = (2\pi)^7 \delta(\sum_{i=1}^{3} \boldsymbol{k}_i)\mathcal{P}_\zeta^2 \frac{\boxed{S(k_1, k_2, k_3)}}{(k_1 k_2 k_3)^2}$$



- $\boxed{f_{NL} \sim S}$ dimensionless measure of the **amplitude** of the bispectrum
- **Scale-dependence** (growing or shrinking on small scales?)
- **Sign** (more or less cold spots?)
- **Shape** (dependence on the configuration of triangles)

Each of these features can rule out large classes of models

The shape of the bispectrum



$$k_3 \leq k_2 \leq k_1$$

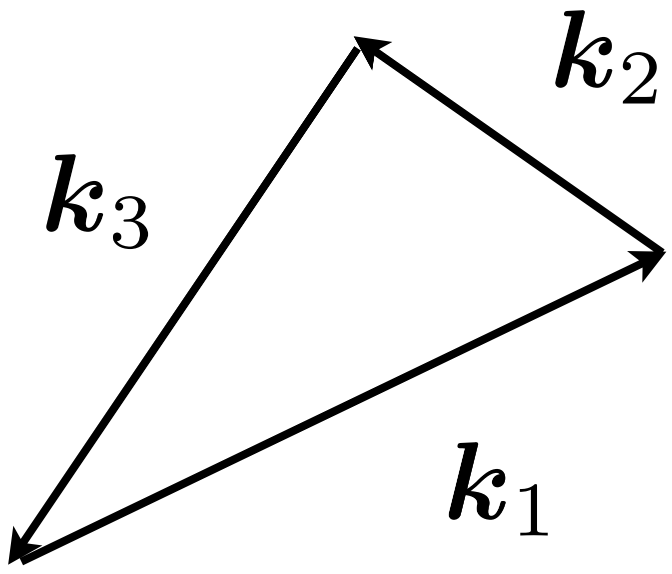
The shape of the bispectrum

In most (almost scale-invariant) models

$$S(k_1, k_2, k_3)$$

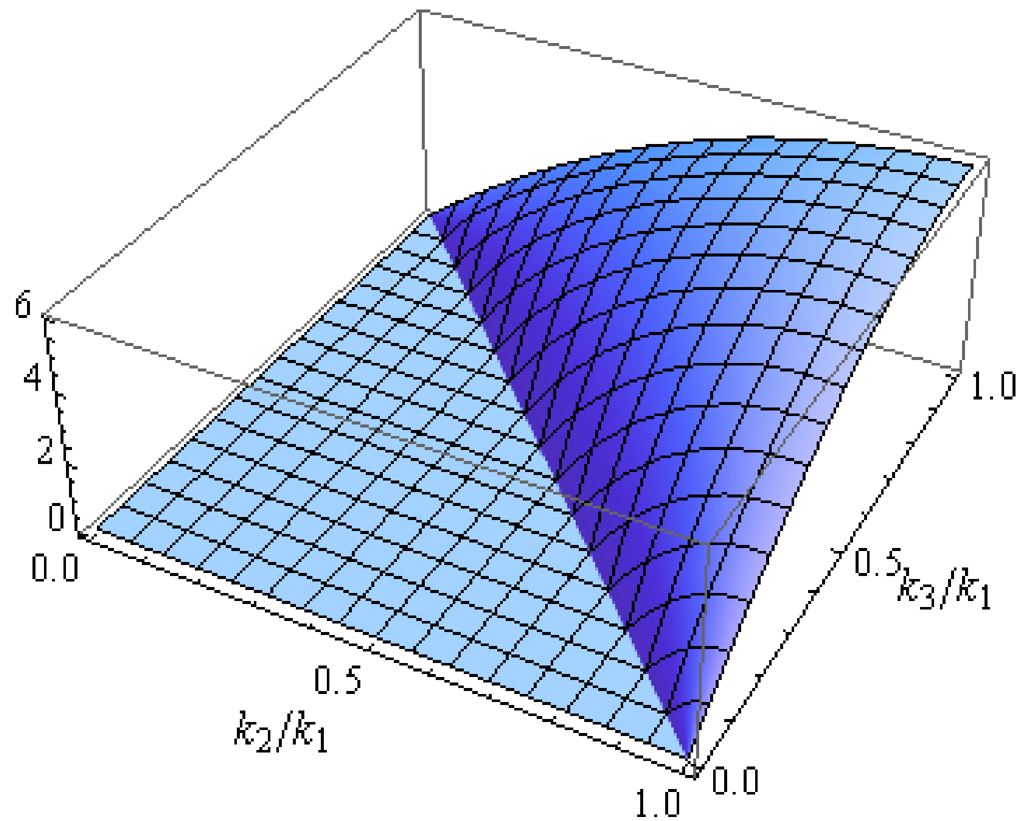
- only depends on the ratios between the norms of the wavevectors

- has the same properties than the observed angular bispectrum

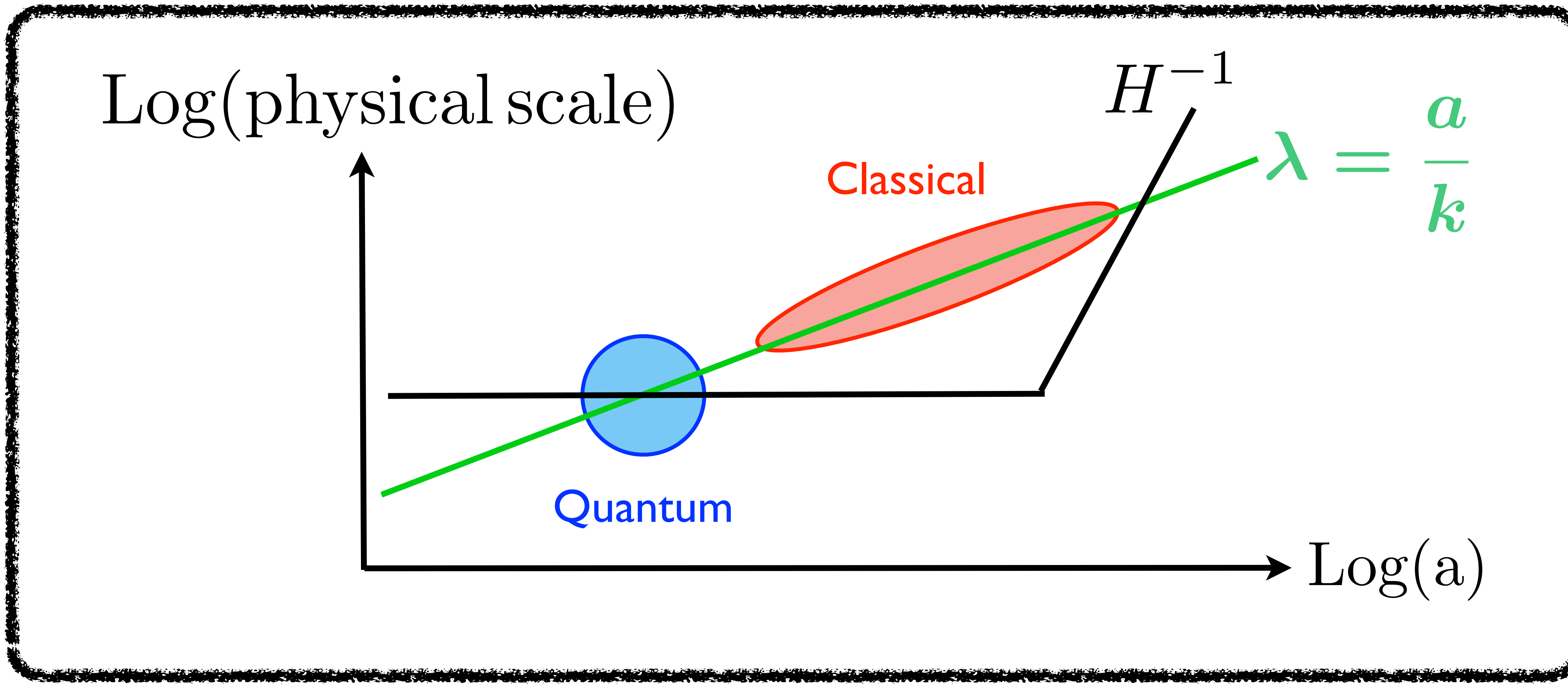


Babich et al (04)

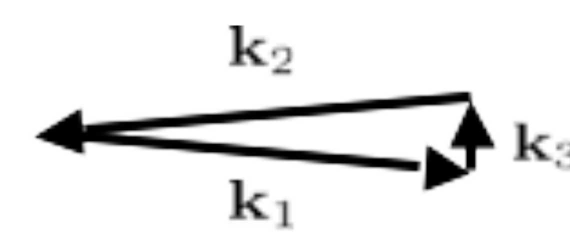
Fergusson & Shellard (08)

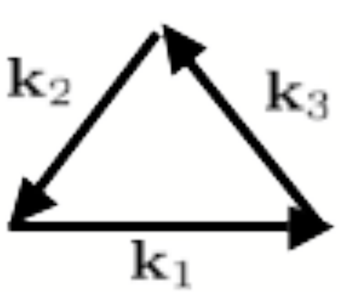


Inflationary physics and shapes of non-Gaussianities



$$S(k_1,k_2,k_3) = f_{NL}^{loc}\left(\frac{k_1^2}{k_2k_3} + 2\,\text{perm.}\right)$$

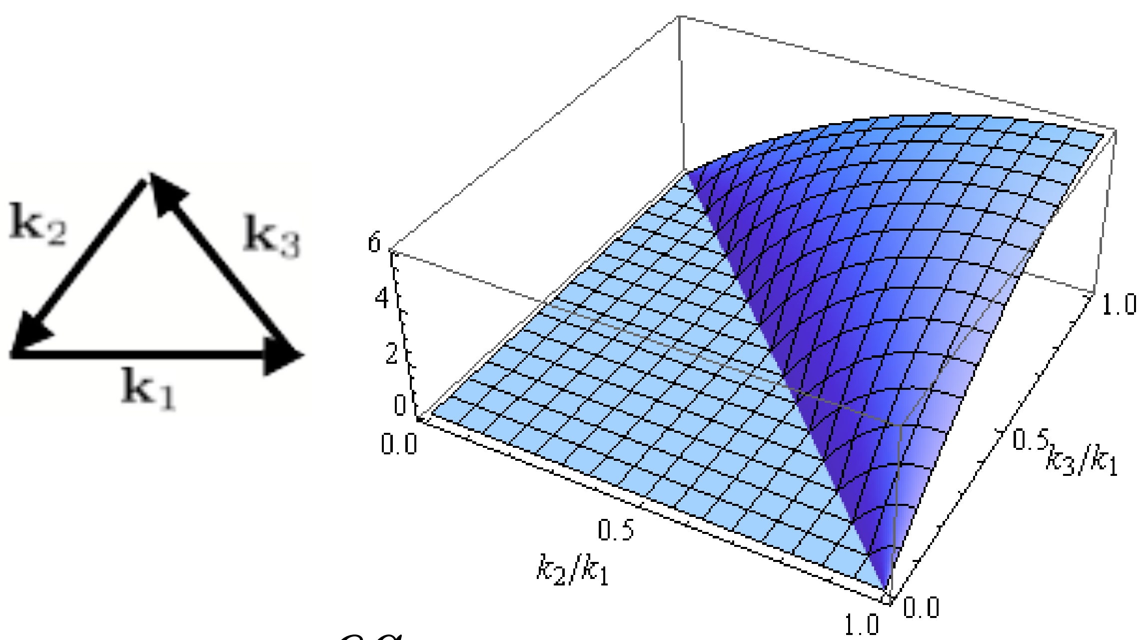




$$+ \quad 3f_{NL}^{eq}\left(-\left(\frac{k_1^2}{k_2k_3}+2\,\text{perm.}\right)+\left(\frac{k_1}{k_2}+5\,\text{perm.}\right)-2\right)$$

Inflationary physics and shapes of non-Gaussianities

Equilateral type (quantum)



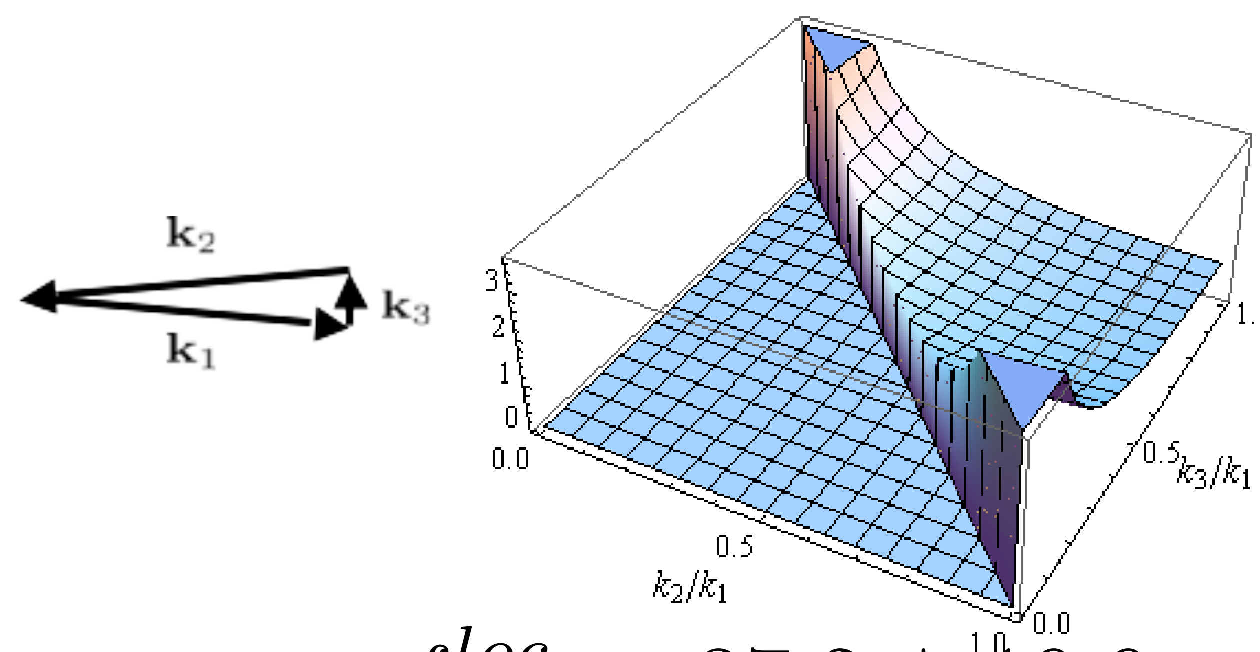
WMAP $f_{NL}^{eq} = 51 \pm 136$

Planck $f_{NL}^{eq} = -42 \pm 75$

Non-standard kinetic terms:
DBI, low sound speed models.

Good understanding with EFT of inflation

Local type (classical)



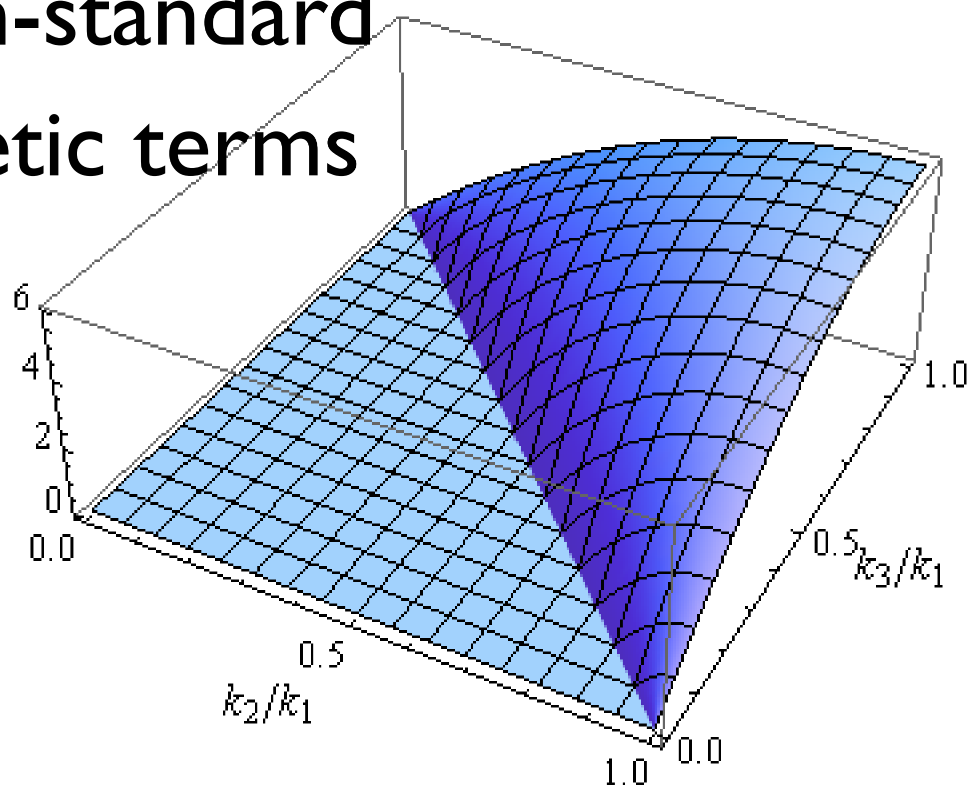
WMAP $f_{NL}^{loc} = 37.2 \pm 19.9$

Planck $f_{NL}^{loc} = 2.7 \pm 5.8$

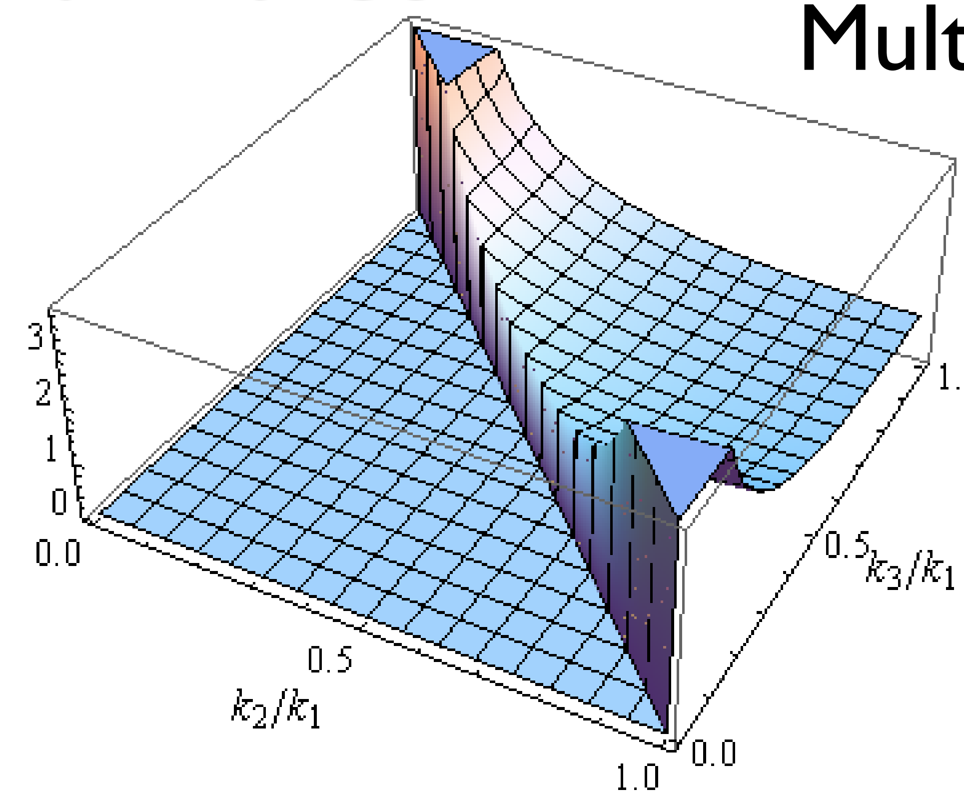
Multiple degrees of freedom:
Multified inflation, curvaton, ekyprotic...

Inflationary physics and shapes of non-Gaussianities

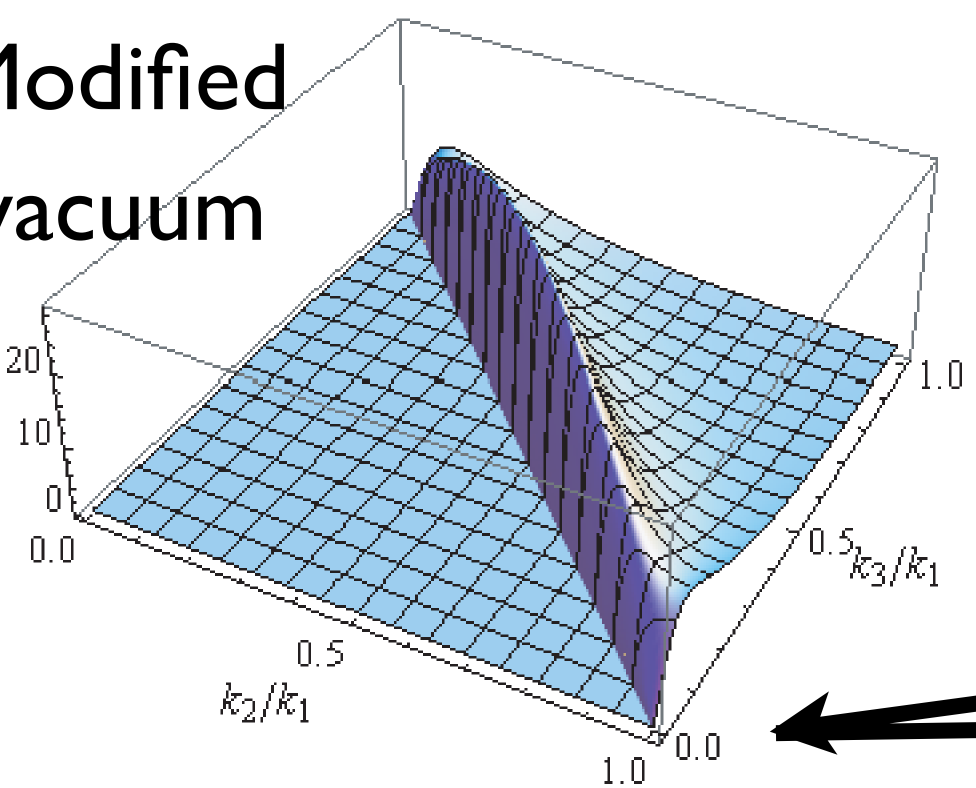
Non-standard kinetic terms



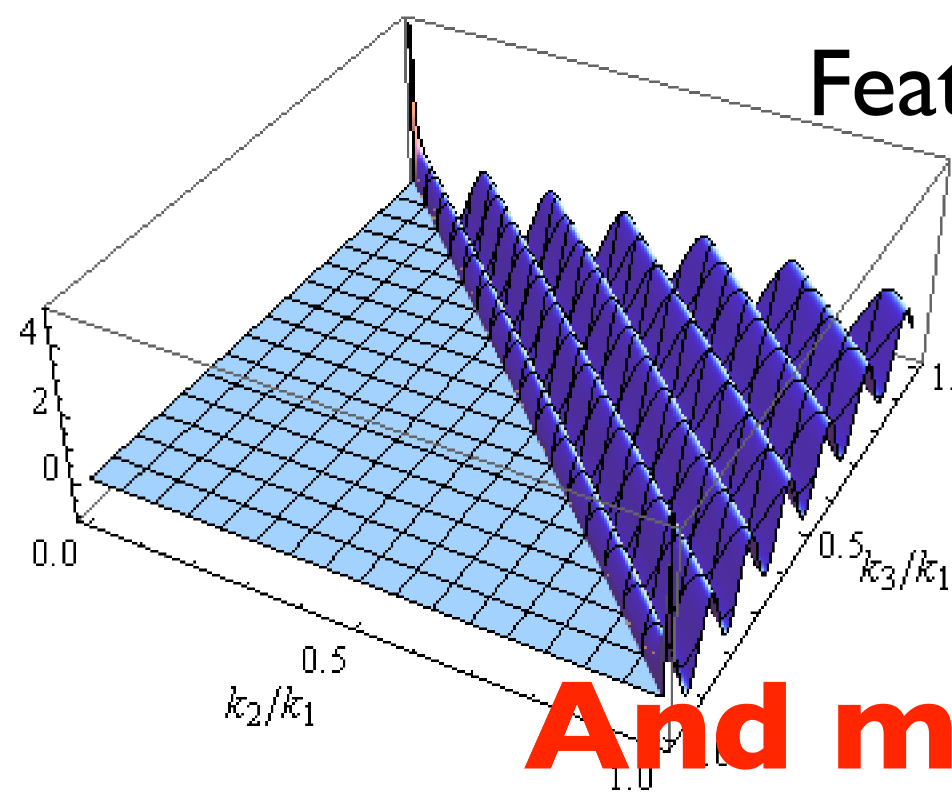
Multifield



Modified vacuum



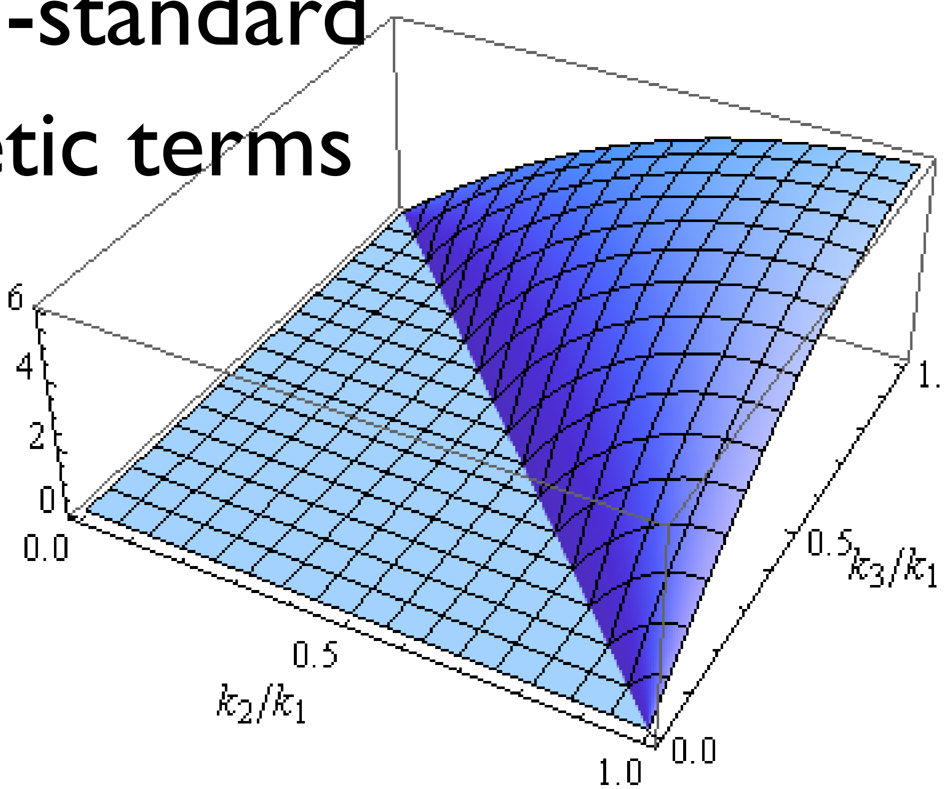
Features



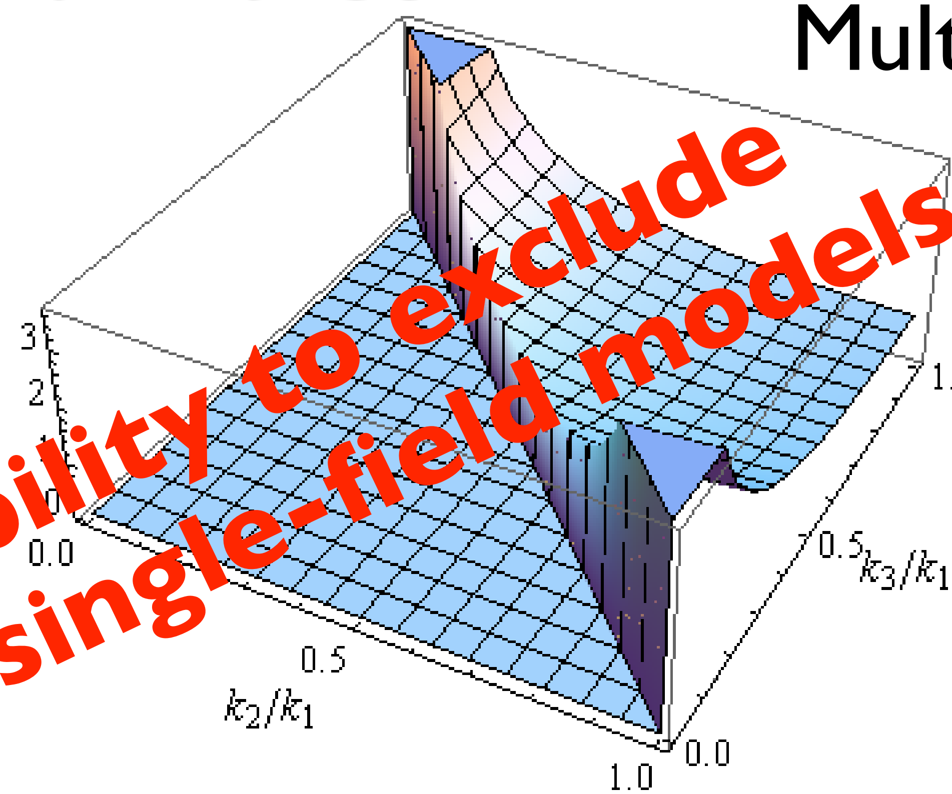
And more!

Inflationary physics and shapes of non-Gaussianities

Non-standard kinetic terms

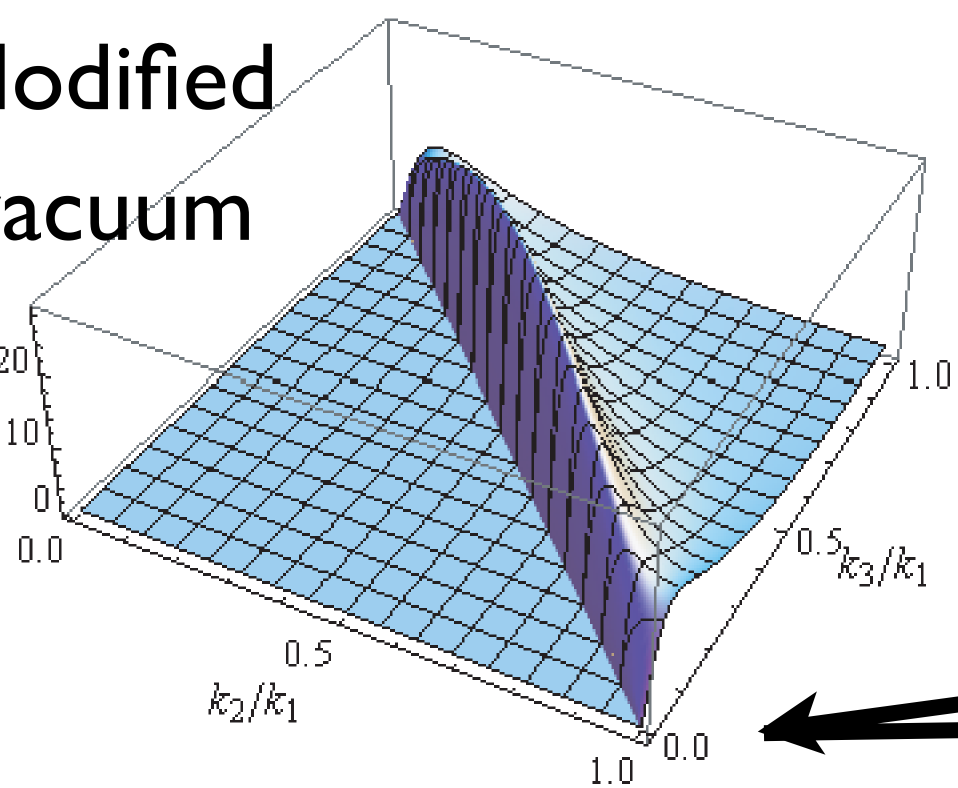


Multifield

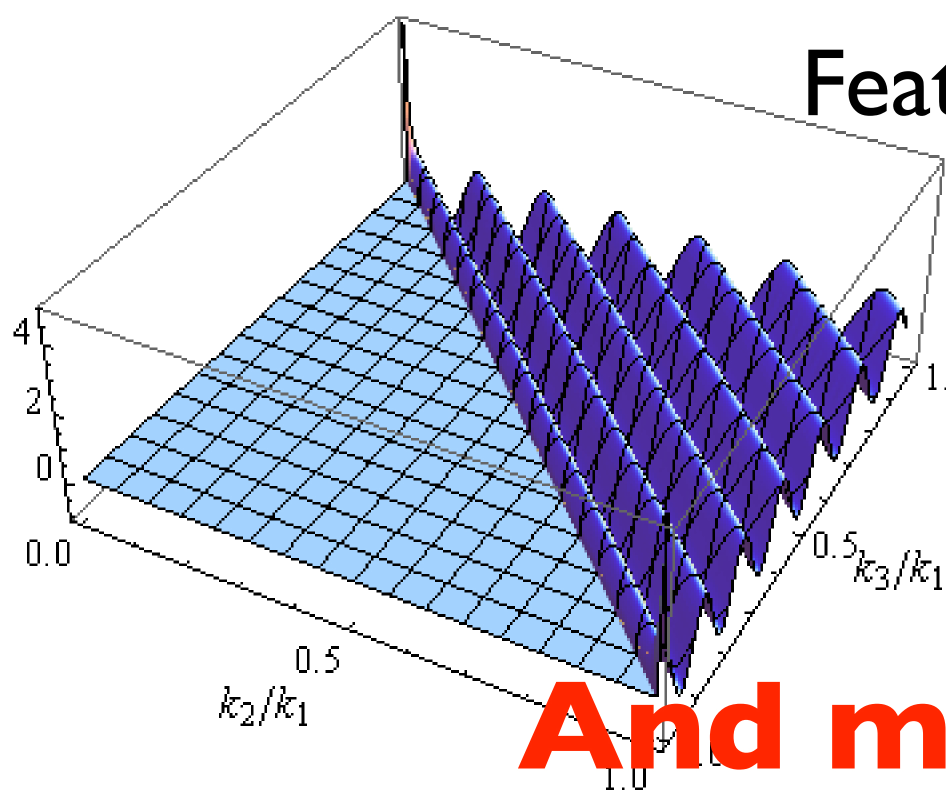


Ability to exclude all single-field models

Modified vacuum



Features



And more!

Single field consistency relation

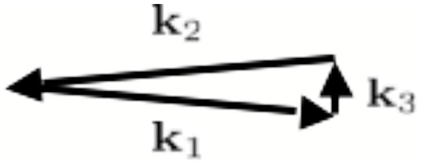
Any single-clock inflation (irrespective of kinetic terms, potential etc)

Maldacena (03), Creminelli & Zaldarriaga (04)

$$\boxed{f_{NL}^{sq}(k_1) = \frac{5}{12}(1 - n_s(k_1))}$$

with

$$f_{NL}^{sq}(k_1) \equiv \lim_{k_3 \to 0} f_{NL}(k_1, k_2, k_3)$$



Remember $n_s = 0.9603 \pm 0.0073 \ (68\% \ \mathrm{CL})$ Planck

If $f_{NL}^{sq} \gtrsim 1$ of primordial origin is robustly detected,
all single field models would be ruled out!

Planck implications

$f_{NL}^{loc} = 2.7 \pm 5.8$ → Constrain multi-field effects

$f_{NL}^{eq} = -42 \pm 75$

$f_{NL}^{orth} = -25 \pm 39$

→ Lower bound on the inflaton speed of sound

$c_s \geq 0.02 \, (95\% \, \mathrm{CL})$

Strong constraints on light hidden sector fields coupled to the inflaton via operators suppressed by a high mass scale.

Assassi et al, 2013.

$\Lambda > 10^5 H$ $\qquad$ $\Lambda > 10^2 H$

depending on assumptions on the hidden sector

The simplest inflationary models are in full agreement with data and have passed very stringent tests.