NON-GAUSSIANITY: TESTING INFLATION THROUGH INTERACTIONS

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With N. Dalal, D. Huterer (1010.3722)
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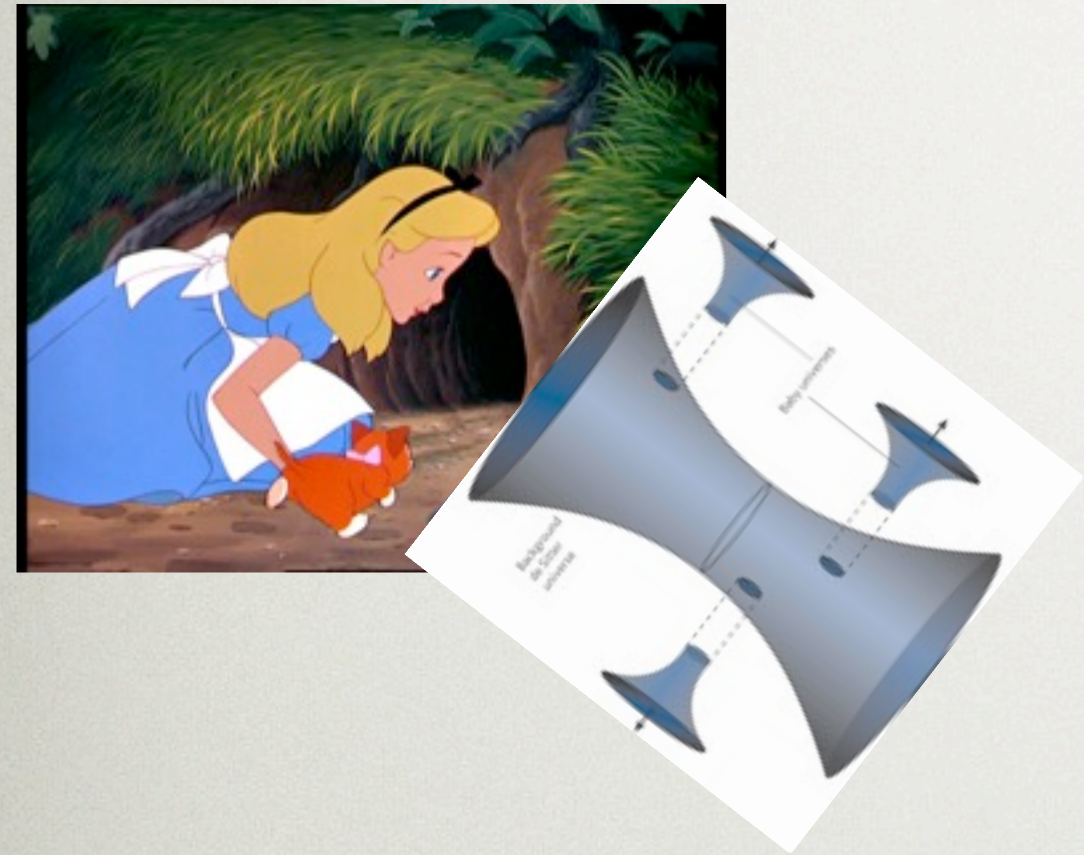
with N. Barnaby (1109.2985)

27 Oct 2011

INFLATION IN THEORY LAND



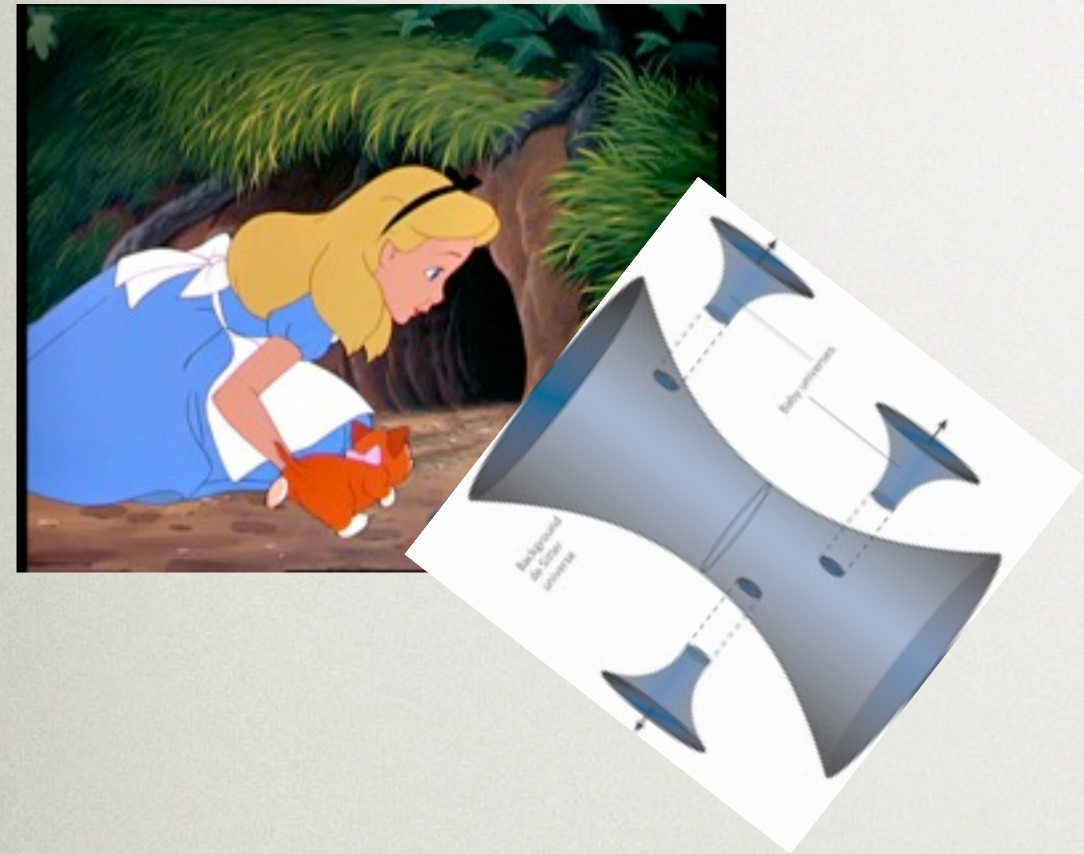
Better observations have theorists (re)asking:

(1) What particle physics is behind inflation?

(2) Is inflation right?

Shandera; RPM; Oct 27, 2011

Inflation in Theory Land



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Interactions

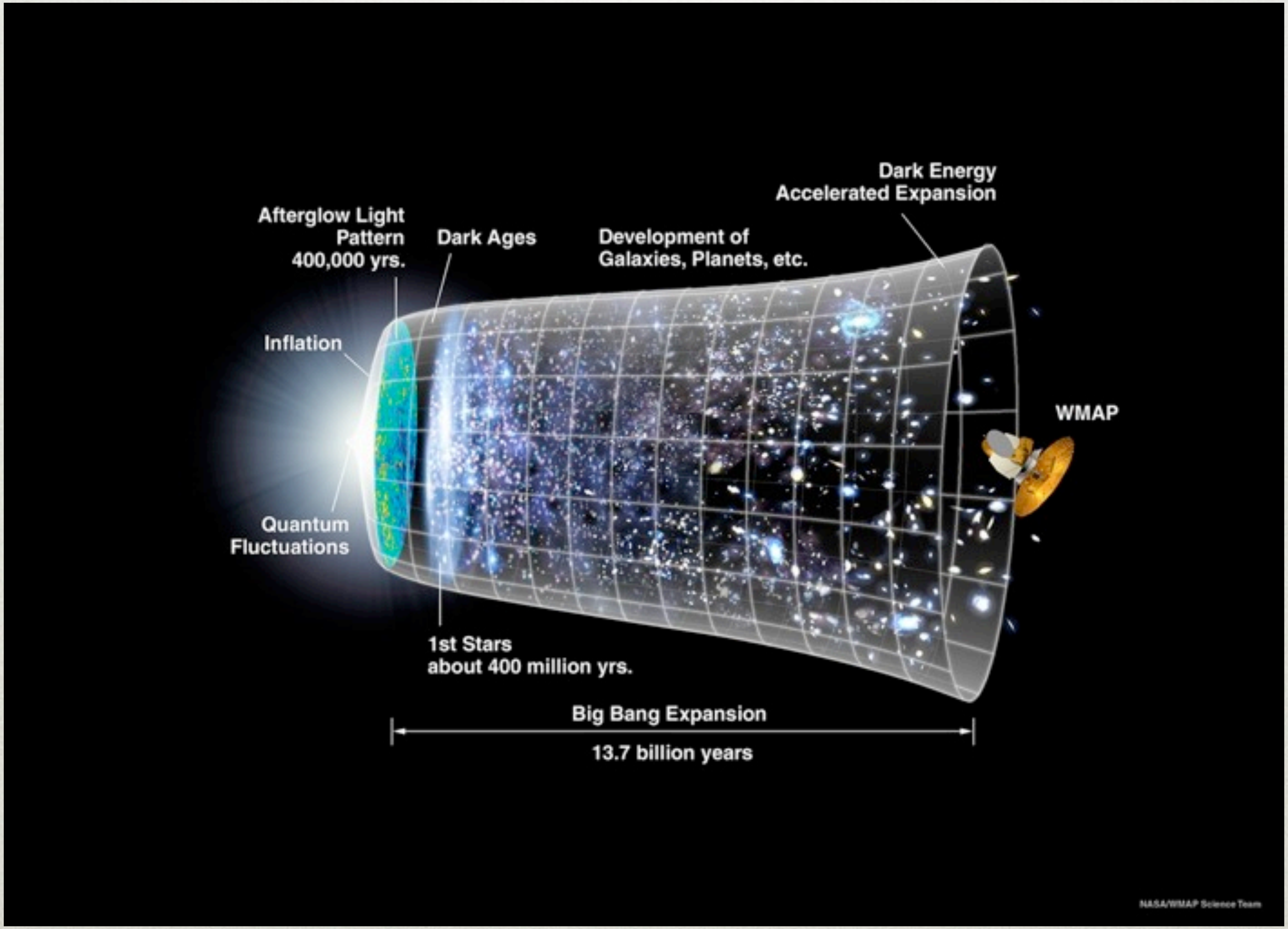
Non-Gaussianity

WHAT HAS CHANGED?

- Promise of better, and new, observations; realization that we can extract much more information
- Shift in consensus about what is 'natural' or likely for inflation
- New calculational tools to test the framework itself

I. REVIEW OF THE STANDARD STORY

THE UNIVERSE OBSERVED



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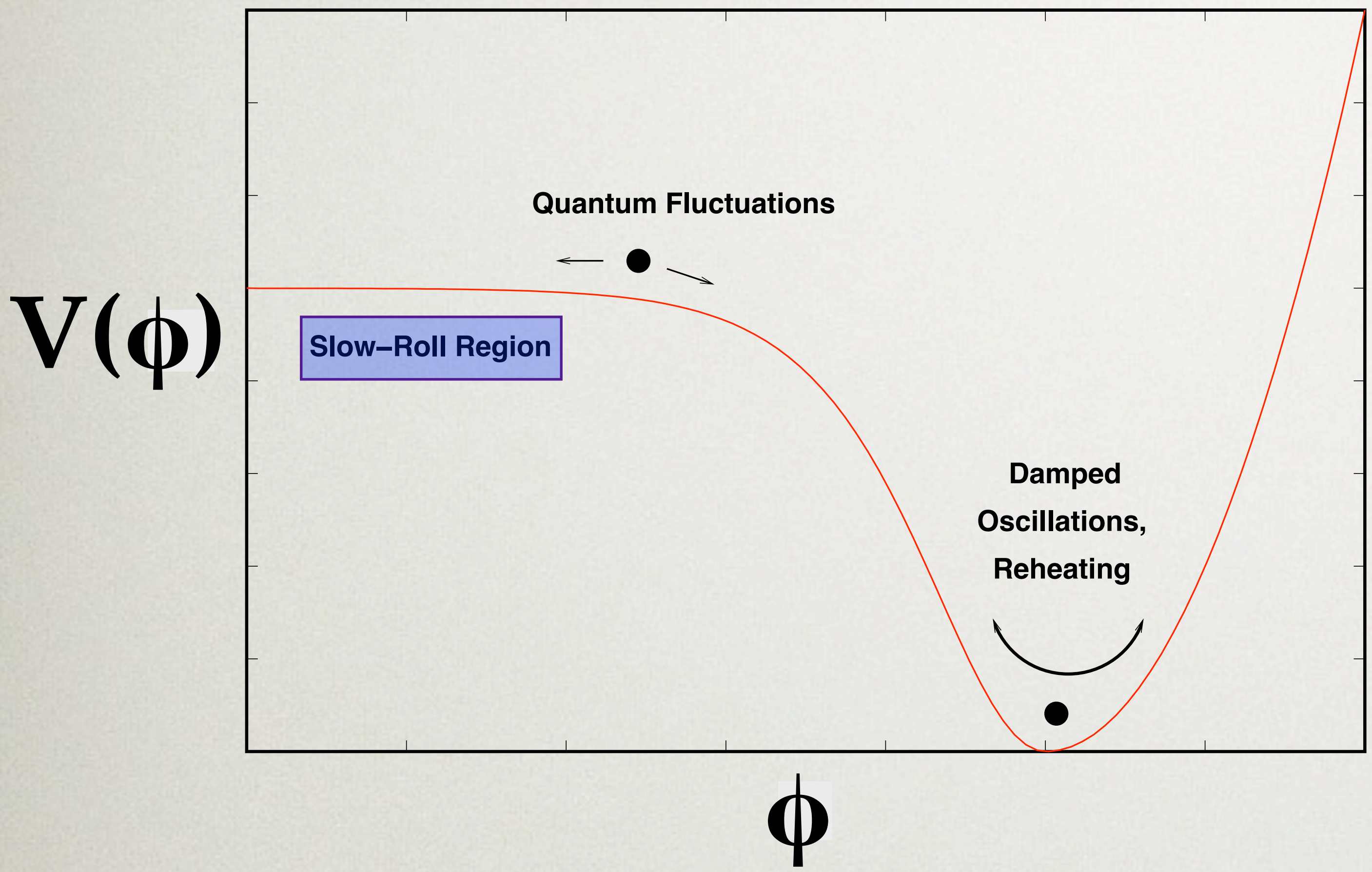
QUESTIONS INFLATION IS SUPPOSED TO ANSWER:

- Why and How is the observed universe
  - Nearly homogeneous on current horizon scales
  - Nearly flat
  - Filled with small density inhomogeneities at an early time
  - Cooling from a high temperature

THE TRADITIONAL 'HOW':
A SCALAR INFLATON



- Classical motion of inflaton drives uniform accelerated expansion

Albrecht, Steinhardt,
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Shandera; RPM; Oct 27, 2011

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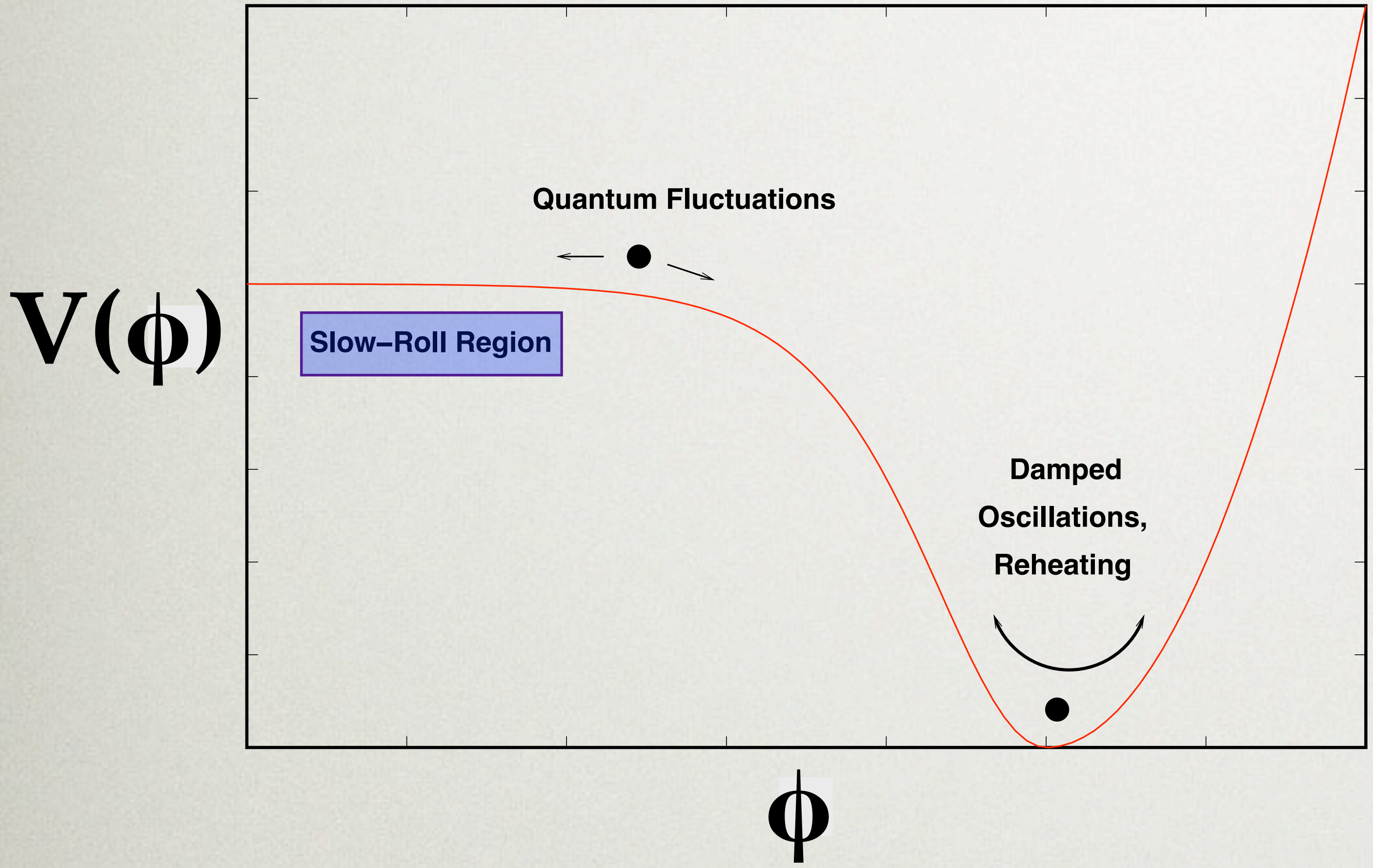

- Classical motion of inflaton drives uniform accelerated expansion

Equation of motion: $\boxed{\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0}$

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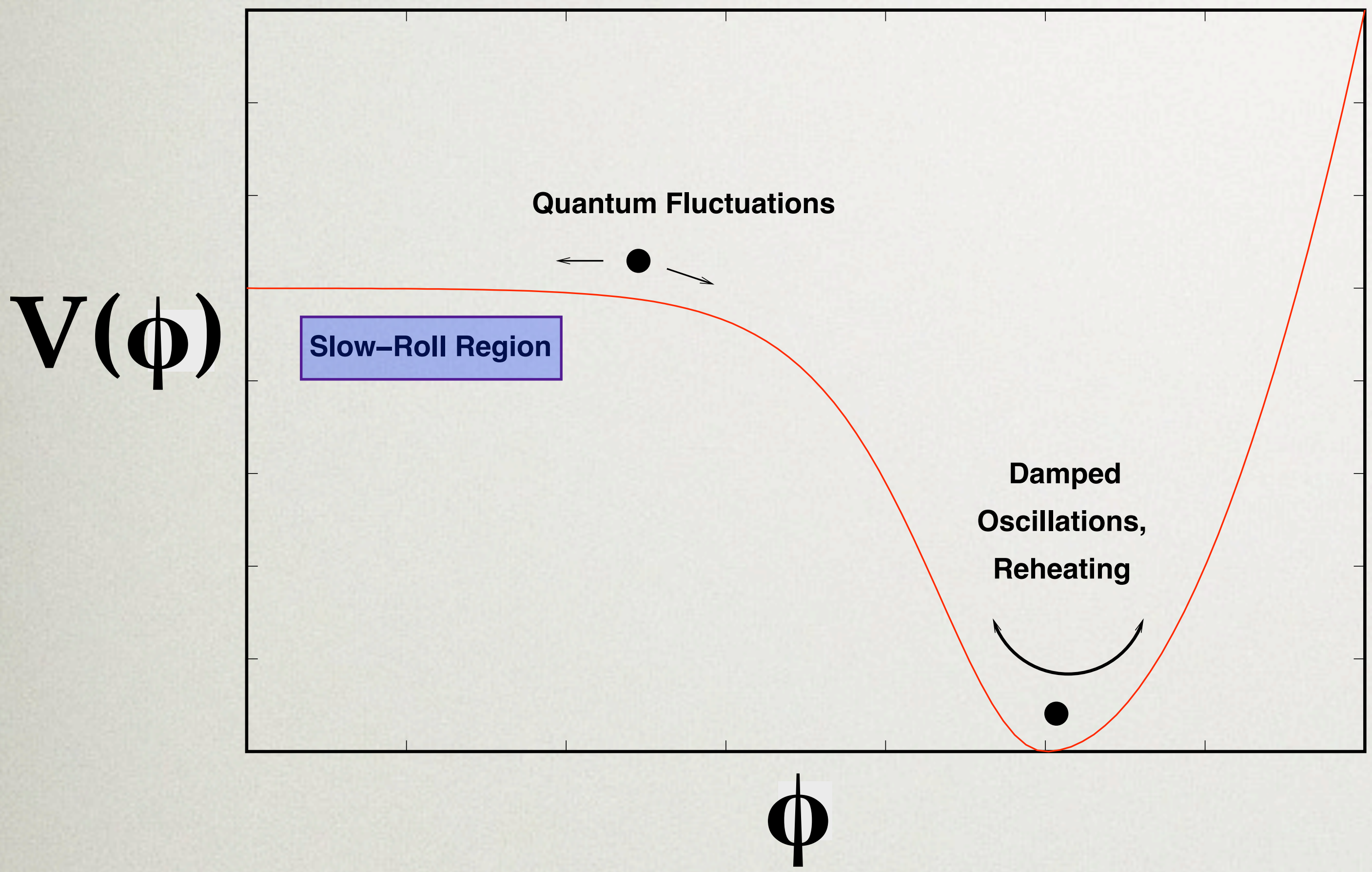

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Einstein: $\boxed{3M_p^2H^2 = \rho \approx V(\phi)}$

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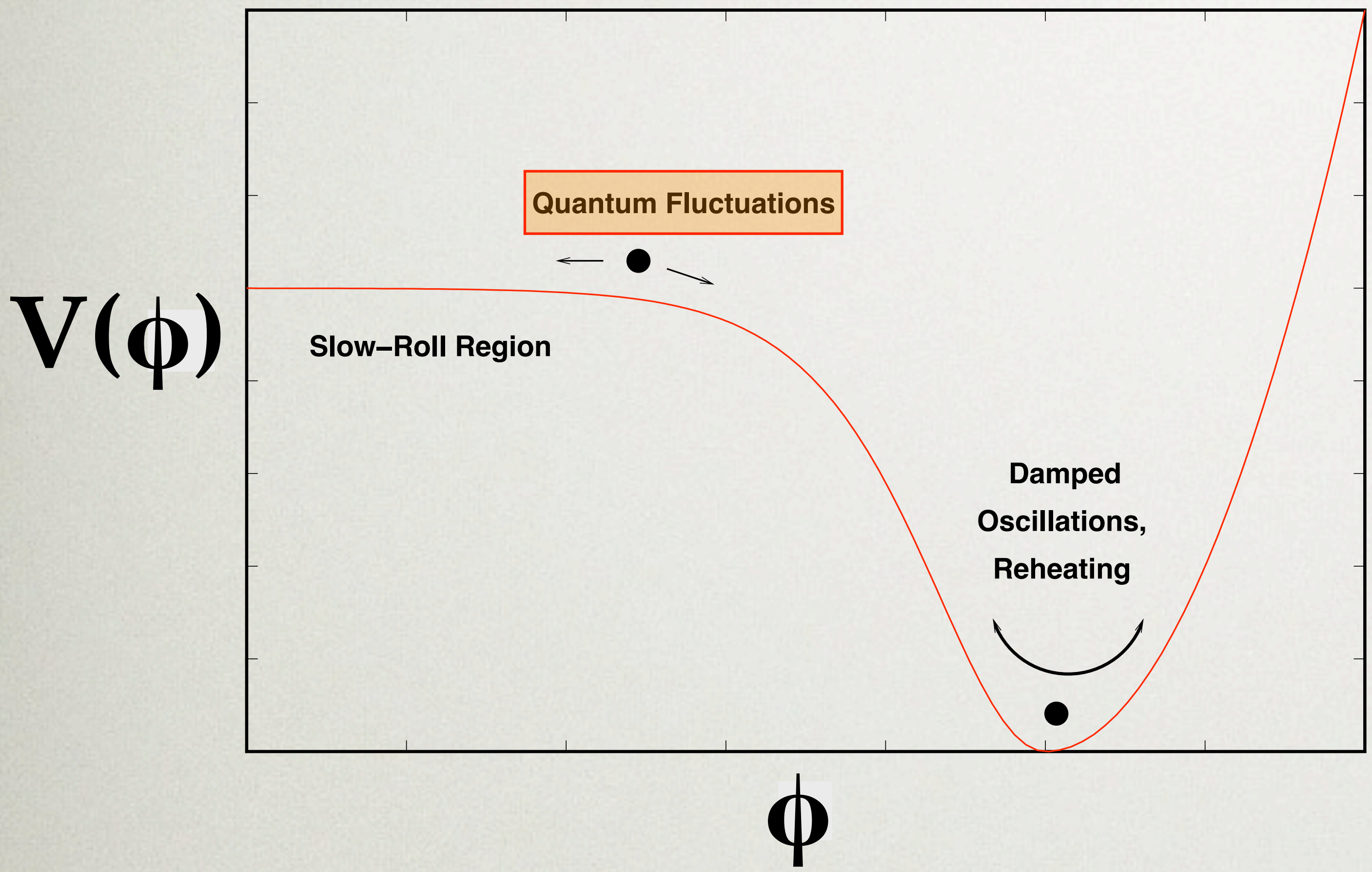
The traditional 'how':
A Scalar Inflaton



- Small (quantum) fluctuations of the field generate curvature fluctuations at the end of inflation

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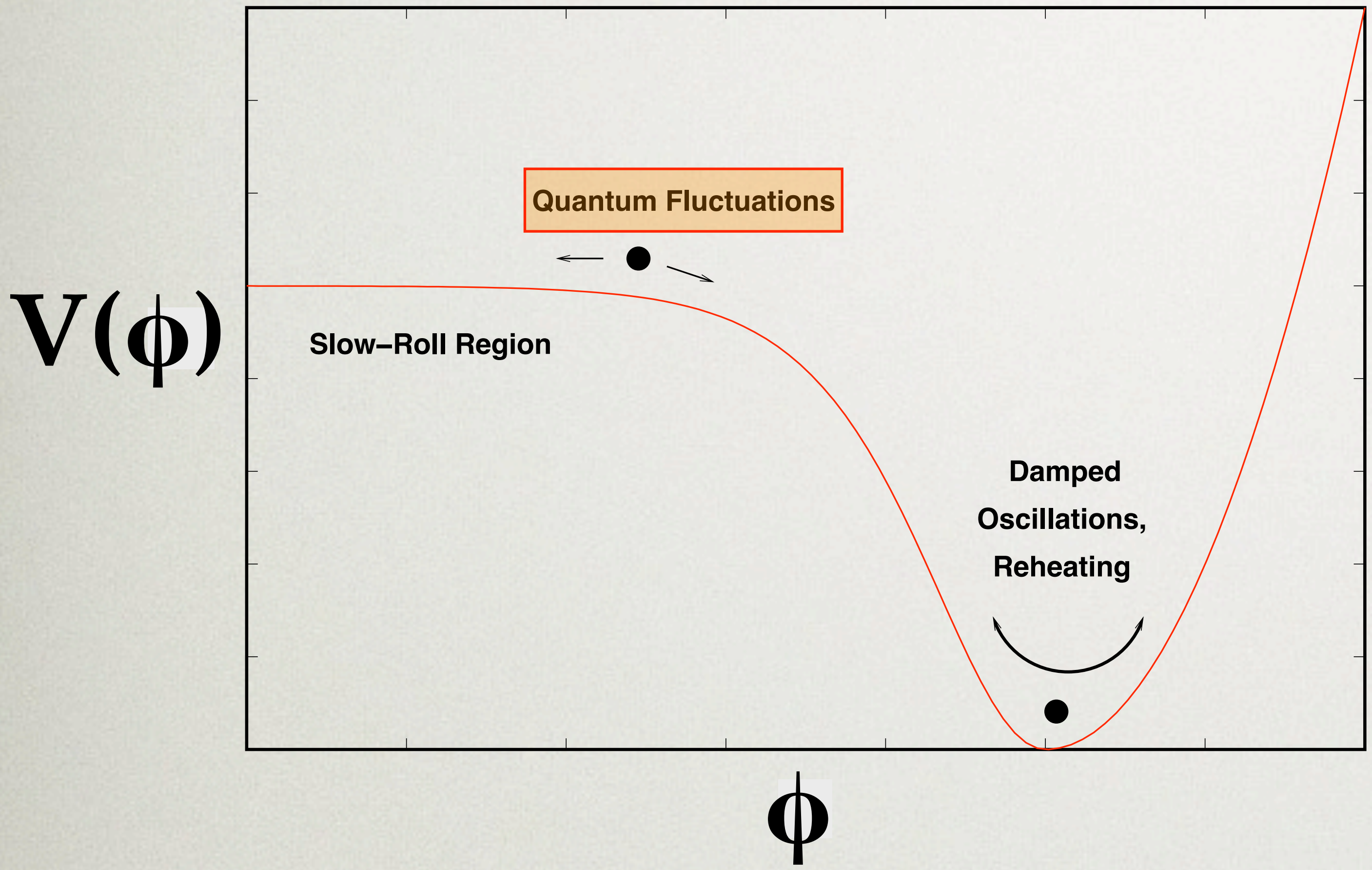

- Small (quantum) fluctuations of the field generate curvature fluctuations at the end of inflation

$$\boxed{\phi = \phi_0 + \delta\phi}$$

$$\boxed{\delta\phi = \frac{H}{2\pi}}$$

Albrecht, Steinhardt,
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DESCRIBING THE FLUCTUATIONS

Grav. Potential

$$\boxed{\langle\Phi(\mathbf{k}_1)\Phi(\mathbf{k}_2)\rangle \propto \delta^3_D(\mathbf{k}_1+\mathbf{k}_2)k^{-3}P_\Phi(k)}$$

Shandera; RPM; Oct 27, 2011

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$$n_s - 1 \approx -0.04$$

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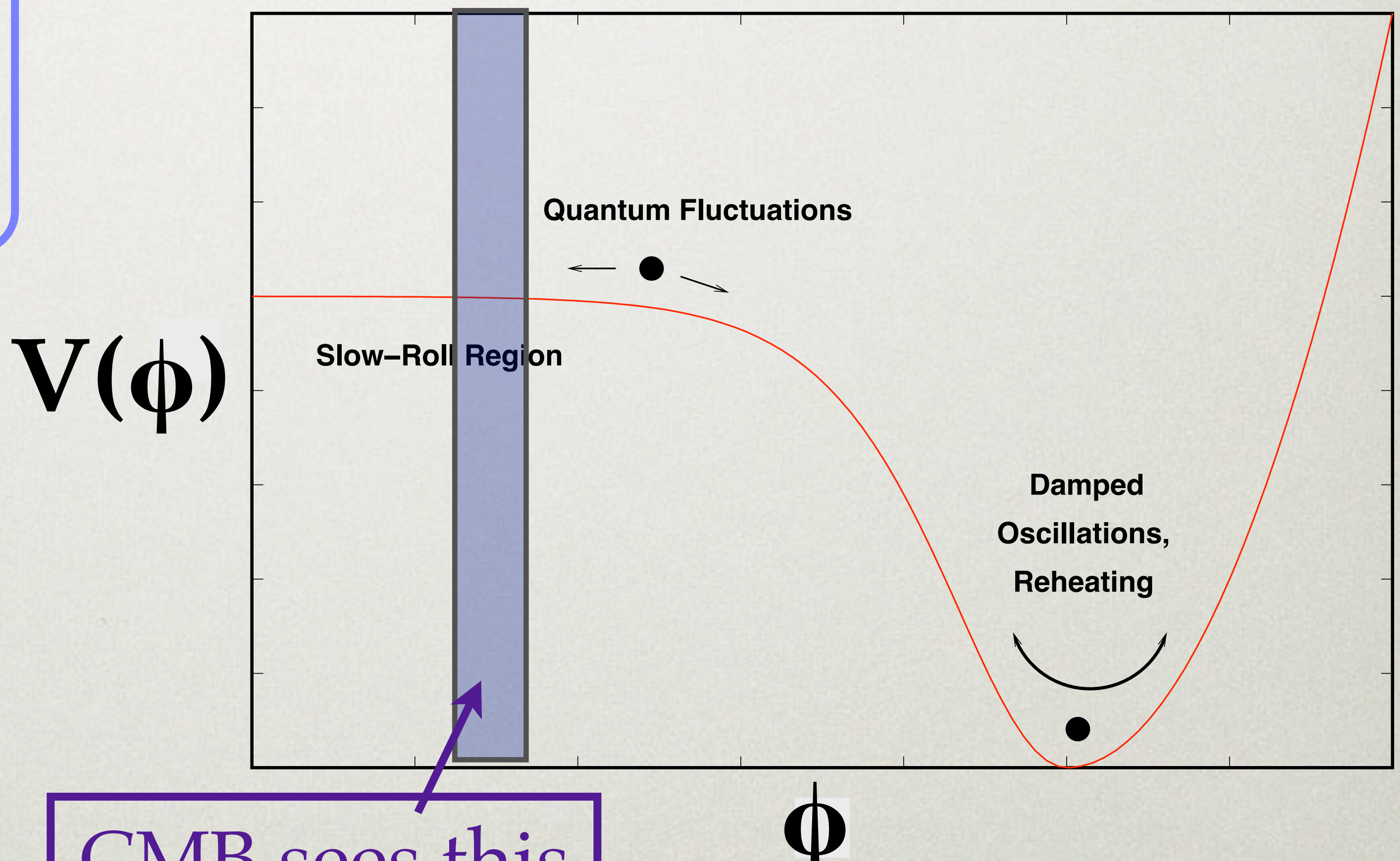

CMB sees this

Shandera; RPM; Oct 27, 2011

Describing the Fluctuations

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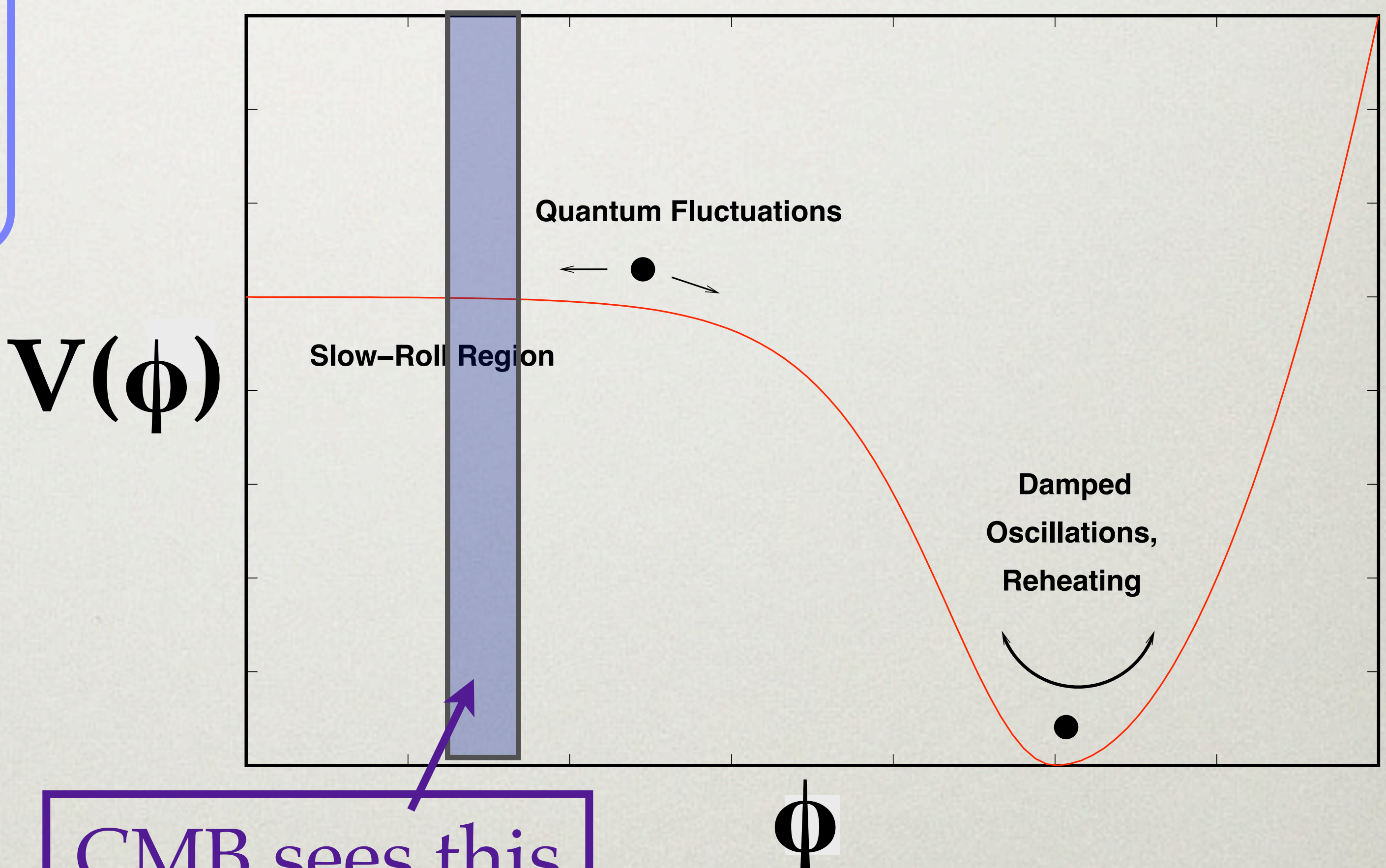

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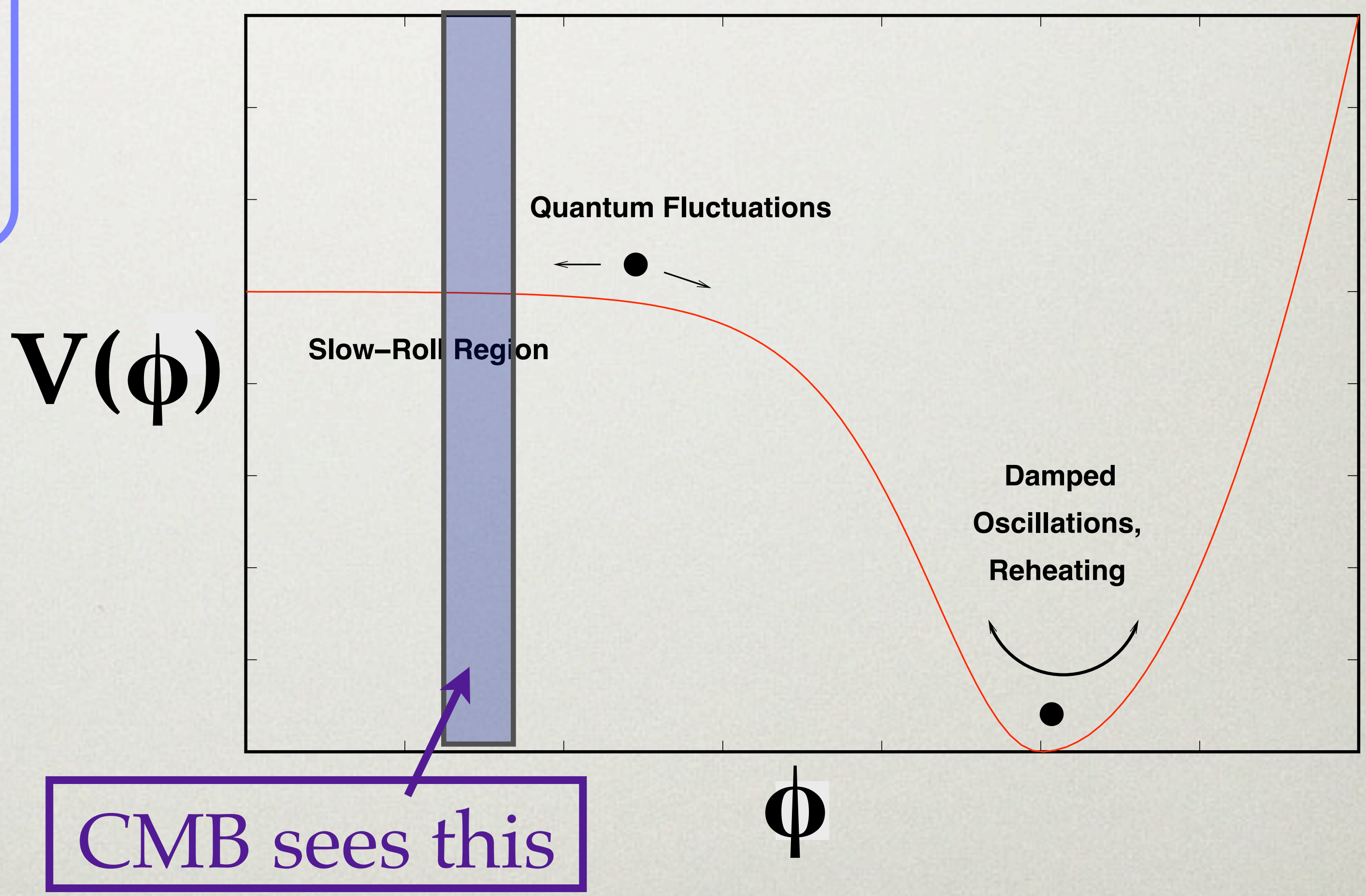

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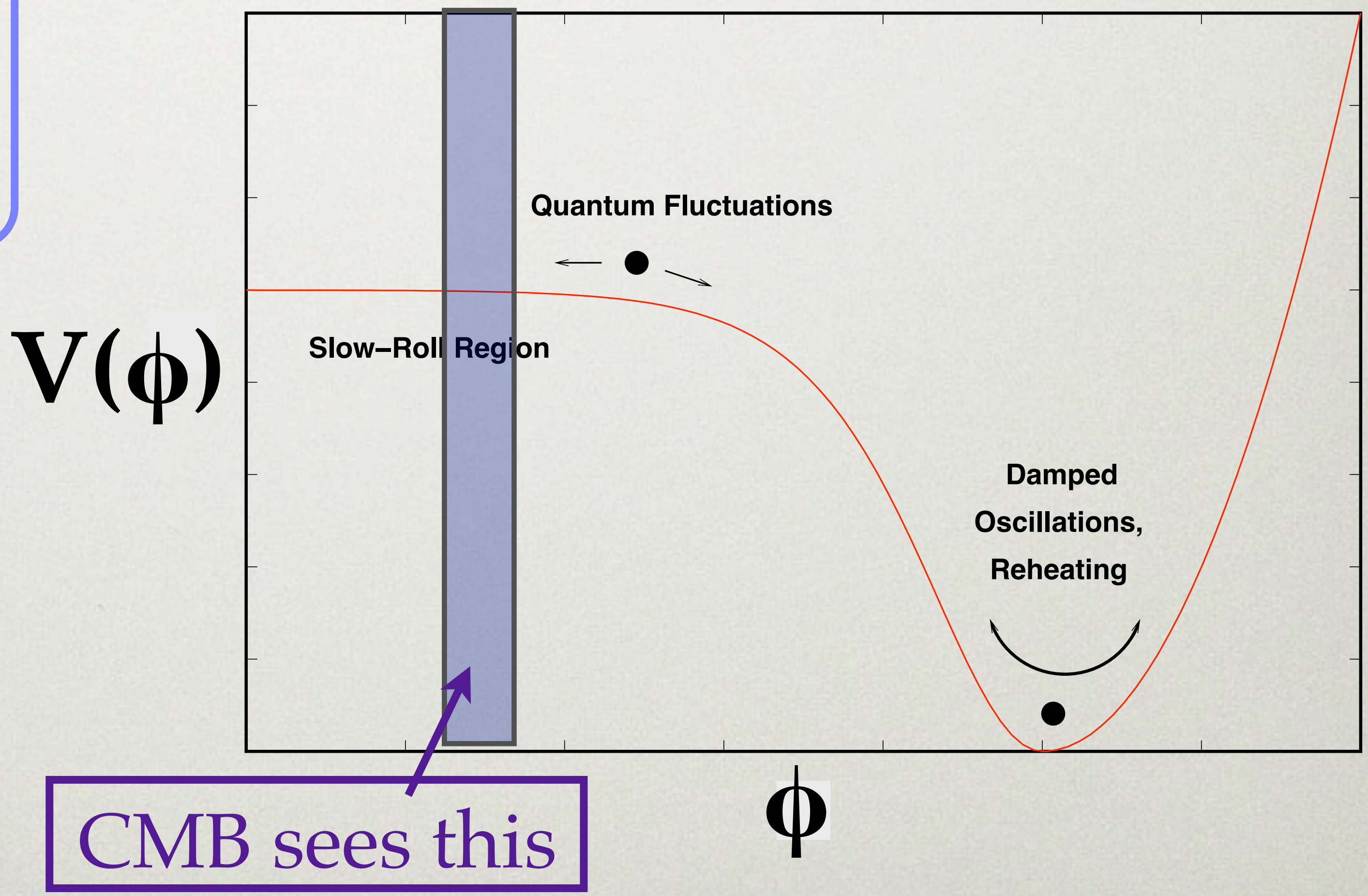
$$n_s - 1 \propto \epsilon$$



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Consistent with Observations

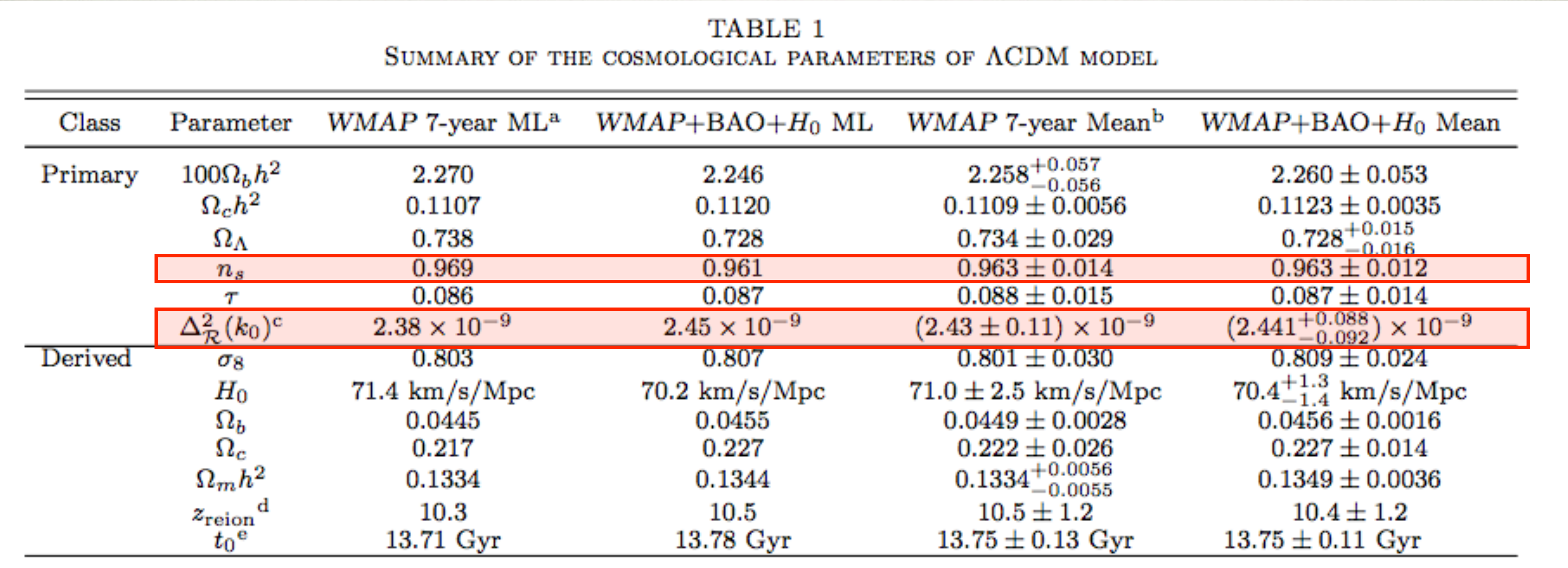

TABLE 1
Summary of the cosmological parameters of ΛCDM model

Class	Parameter	*WMAP* 7-year ML[a]	*WMAP*+BAO+H_0 ML	*WMAP* 7-year Mean[b]	*WMAP*+BAO+H_0 Mean
Primary	$100\Omega_b h^2$	2.270	2.246	$2.258^{+0.057}_{-0.056}$	2.260 ± 0.053
	$\Omega_c h^2$	0.1107	0.1120	0.1109 ± 0.0056	0.1123 ± 0.0035
	Ω_Λ	0.738	0.728	0.734 ± 0.029	$0.728^{+0.015}_{-0.016}$
	n_s	0.969	0.961	0.963 ± 0.014	0.963 ± 0.012
	τ	0.086	0.087	0.088 ± 0.015	0.087 ± 0.014
	$\Delta^2_{\mathcal{R}}(k_0)$[c]	2.38×10^{-9}	2.45×10^{-9}	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.441^{+0.088}_{-0.092}) \times 10^{-9}$
Derived	σ_8	0.803	0.807	0.801 ± 0.030	0.809 ± 0.024
	H_0	71.4 km/s/Mpc	70.2 km/s/Mpc	71.0 ± 2.5 km/s/Mpc	$70.4^{+1.3}_{-1.4}$ km/s/Mpc
	Ω_b	0.0445	0.0455	0.0449 ± 0.0028	0.0456 ± 0.0016
	Ω_c	0.217	0.227	0.222 ± 0.026	0.227 ± 0.014
	$\Omega_m h^2$	0.1334	0.1344	$0.1334^{+0.0056}_{-0.0055}$	0.1349 ± 0.0036
	$z_{\rm reion}$[d]	10.3	10.5	10.5 ± 1.2	10.4 ± 1.2
	t_0[e]	13.71 Gyr	13.78 Gyr	13.75 ± 0.13 Gyr	13.75 ± 0.11 Gyr

WMAP 7
Komatsu et al
1001.4538

THE OBSERVED FEATURE: AN APPROX SYMMETRY

- Fluctuations are nearly scale invariant

$$\boxed{0.001 \text{ Mpc}^{-1} < k < \mathcal{O}(1) \text{ Mpc}^{-1}}$$

Shandera; RPM; Oct 27, 2011

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→ Near time-translation invariance

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OBSERVATIONAL LANDSCAPE

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   CMBPol *($>$ 2020?)*

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OBSERVATIONAL LANDSCAPE

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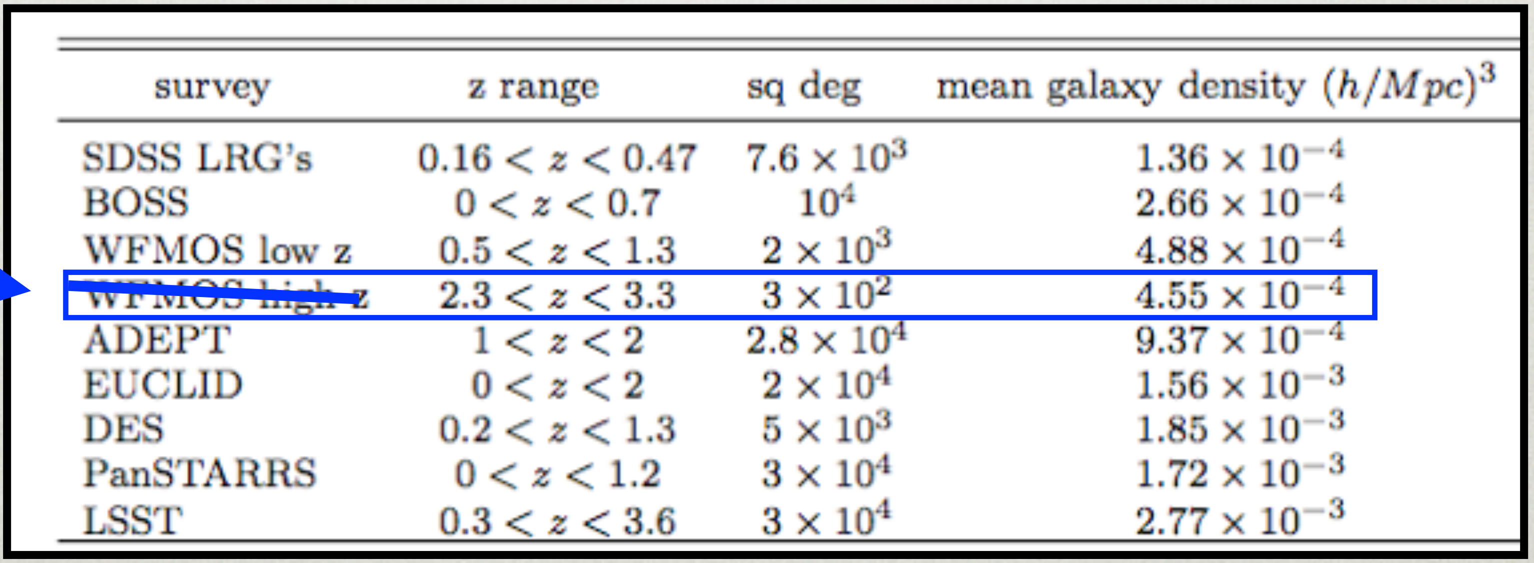
2. Large Scale Structure Surveys:

HETDEX



survey	z range	sq deg	mean galaxy density $(h/Mpc)^3$
SDSS LRG's	$0.16 < z < 0.47$	7.6×10^3	1.36×10^{-4}
BOSS	$0 < z < 0.7$	10^4	2.66×10^{-4}
WFMOS low z	$0.5 < z < 1.3$	2×10^3	4.88×10^{-4}
~~WFMOS high z~~	$2.3 < z < 3.3$	3×10^2	4.55×10^{-4}
ADEPT	$1 < z < 2$	2.8×10^4	9.37×10^{-4}
EUCLID	$0 < z < 2$	2×10^4	1.56×10^{-3}
DES	$0.2 < z < 1.3$	5×10^3	1.85×10^{-3}
PanSTARRS	$0 < z < 1.2$	3×10^4	1.72×10^{-3}
LSST	$0.3 < z < 3.6$	3×10^4	2.77×10^{-3}

Carbone, Verde, Matarrese

Shandera; RPM; Oct 27, 2011

INTERACTIONS AND NON-GAUSSIANITY

EVIDENCE OF INFLATION FROM THE SCALAR SECTOR?

VANILLA FRAMEWORK:

- One field does it all:
  - Classical source for inflationary background $\boxed{\dot{H} < 0}$
  - *Inevitable* Quantum fluctuations → primordial perturbations
- Gravitational waves, red tilt

BUT WHAT CONTEXT?

- Single field: doesn't (can't!) mean no other fields are in there somewhere

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* Single field: doesn't (can't!) mean no other fields are in there somewhere

- Only one degree of freedom?
- No physics between H and M_P?
- Pre-inflationary state?
- Reheating?

THE INFLATON, "IN A VACUUM"

Simplest model:

$$\boxed{\begin{gathered} V(\phi) = \frac{1}{2}m^2\phi^2 \\ r \approx 0.1 \\ V^{1/4} \sim 10^{16}\ \mathrm{GeV} \end{gathered}}$$

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$\Longrightarrow$ Look for field in particle spectrum at high energies

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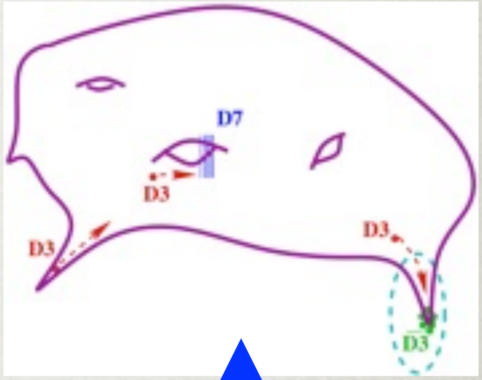
LESSONS FROM INFLATION IN SUGRA, STRINGS, ETC

- Hard to get flat potentials ("right" inflaton mass)
- Lots of other fields generically in the game
- Other scales: SUSY breaking scale, string scale, geometric scales, etc
- Suggestions for symmetries and interactions that preserve them



↑

Lots of Moving Parts!

BEYOND THE POWER SPECTRUM

- *Non-Gaussianity*: any higher order connected correlation different from zero
- Interactions: $\boxed{S = S_0 + S_2 + S_3 + \ldots}$

  - Gravity
  - Self-interactions
  - Multiple fields

Qualitatively distinguishable!

DIFFICULTY AS AN OPPORTUNITY...

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DIFFICULTY AS AN OPPORTUNITY...

- Interactions $\Longrightarrow$ Non-Gaussianity
- N-point functions beyond the power spectrum
- N-point functions likely have some structure
- Amplitude of new correlations related to some scale of new physics

$$\boxed{H < M < M_p}$$

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WHY INTERACTIONS GIVE NON-GAUSSIANITY

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Quadratic action/Free Field

$$\boxed{S = \frac{1}{2}\int d^4x\, a(t)^3 \left[M_p^2 R + \dot{\phi}^2 - m^2\phi^2\right]}$$

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Independent equation for each Fourier mode:

$$\boxed{(\phi_k)'' + \left(k^2 + m^2 a^2 - \frac{a''}{a}\right)\phi_k = 0}$$

$$\boxed{\langle \phi_k^2 \rangle = \sigma_k^2}$$

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✱ Interactions $\Longrightarrow$ Non-Gaussianity

THE THREE-POINT (BISPECTRUM)

- Genericaly:

$$\boxed{\langle\zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\rangle = (2\pi)^3\delta^3_D(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)B(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)}$$

- Slow-roll result (Aquaviva et al; Maldacena)

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"f$_{\rm NL}$"

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HOW NON-GAUSSIAN IS THAT?

$$\boxed{f_{NL} \sim 0.05 \ll 5 \sim 5 \ll \mathcal{O}(100) \ll 10^{9/2}}$$

How Non-Gaussian is that?

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Slow-roll

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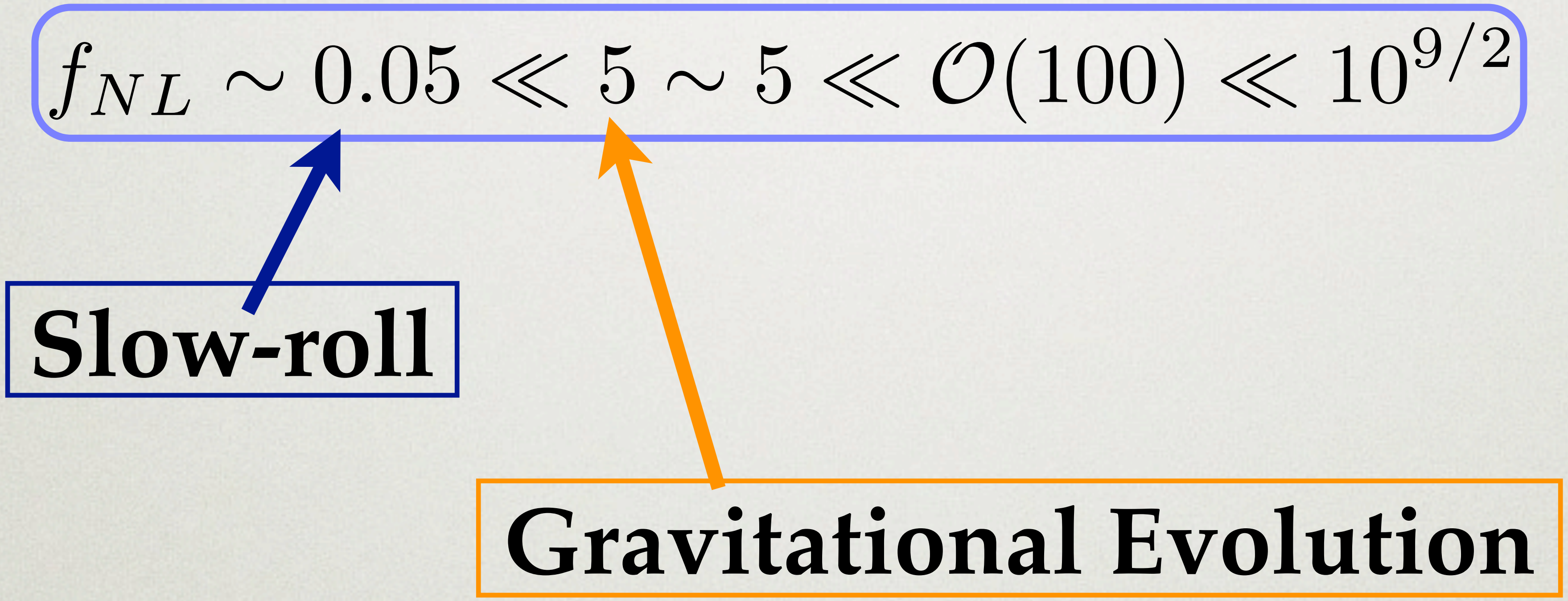

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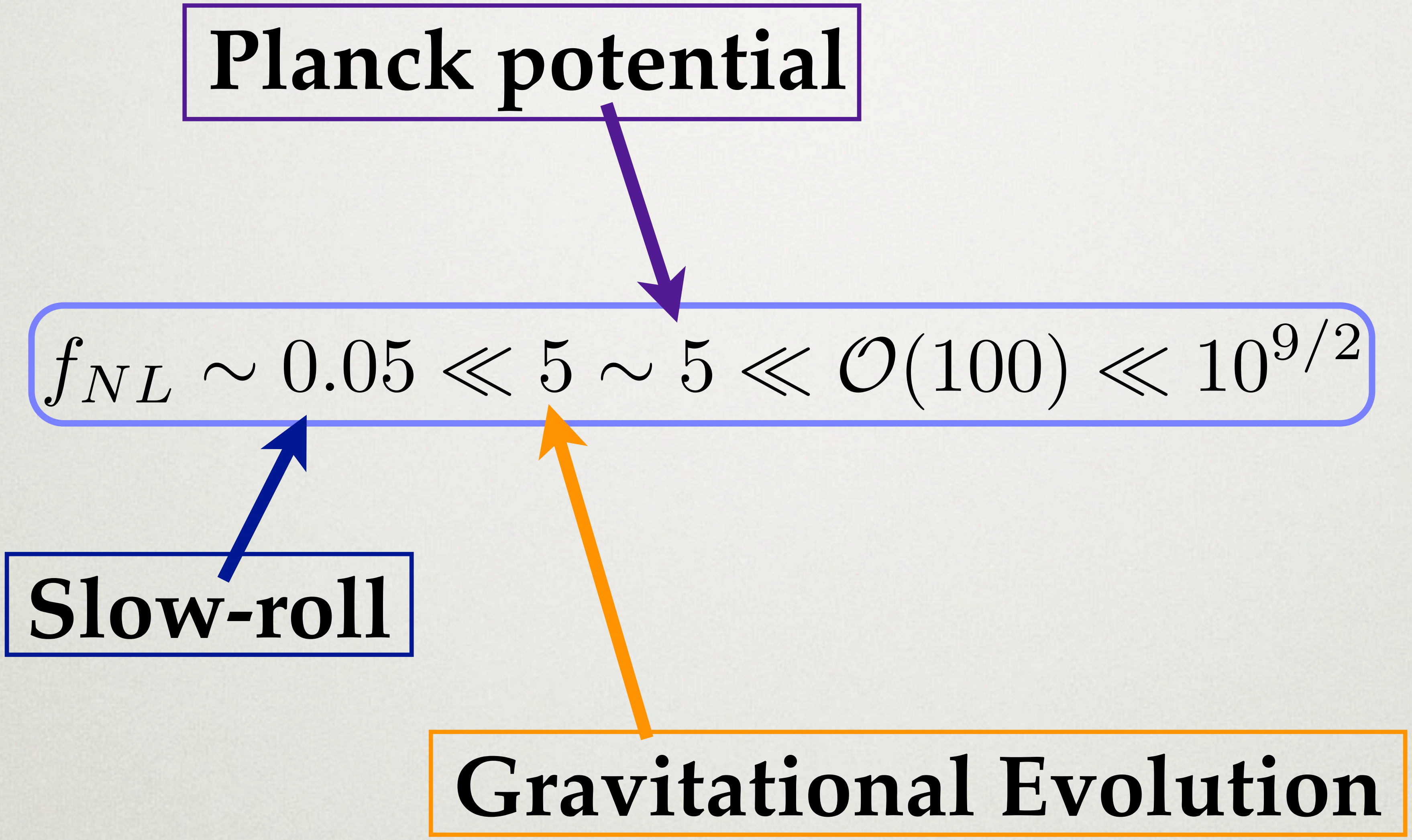
Slow-roll

Gravitational Evolution

How Non-Gaussian is that?



Planck potential

$$f_{NL} \sim 0.05 \ll 5 \sim 5 \ll \mathcal{O}(100) \ll 10^{9/2}$$

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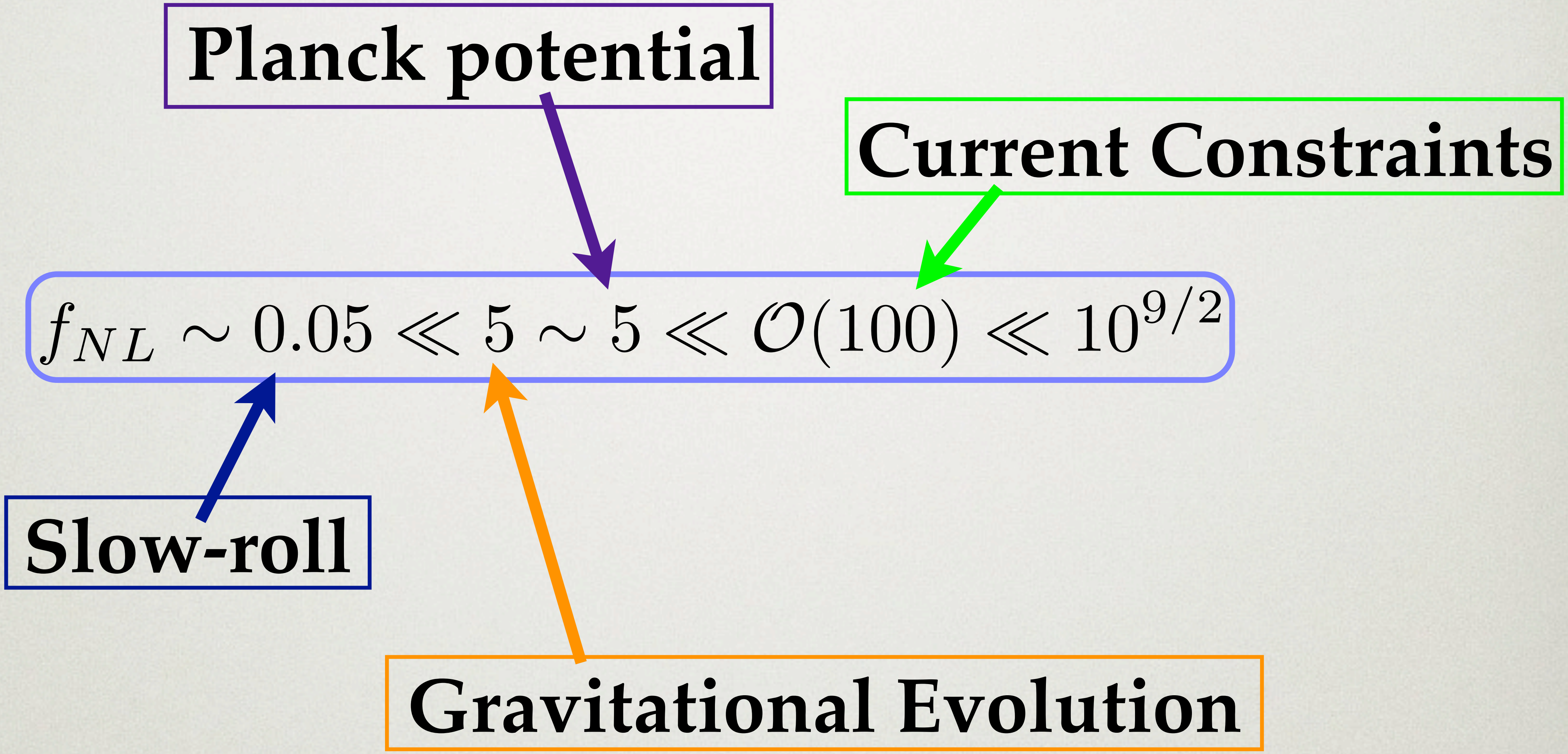

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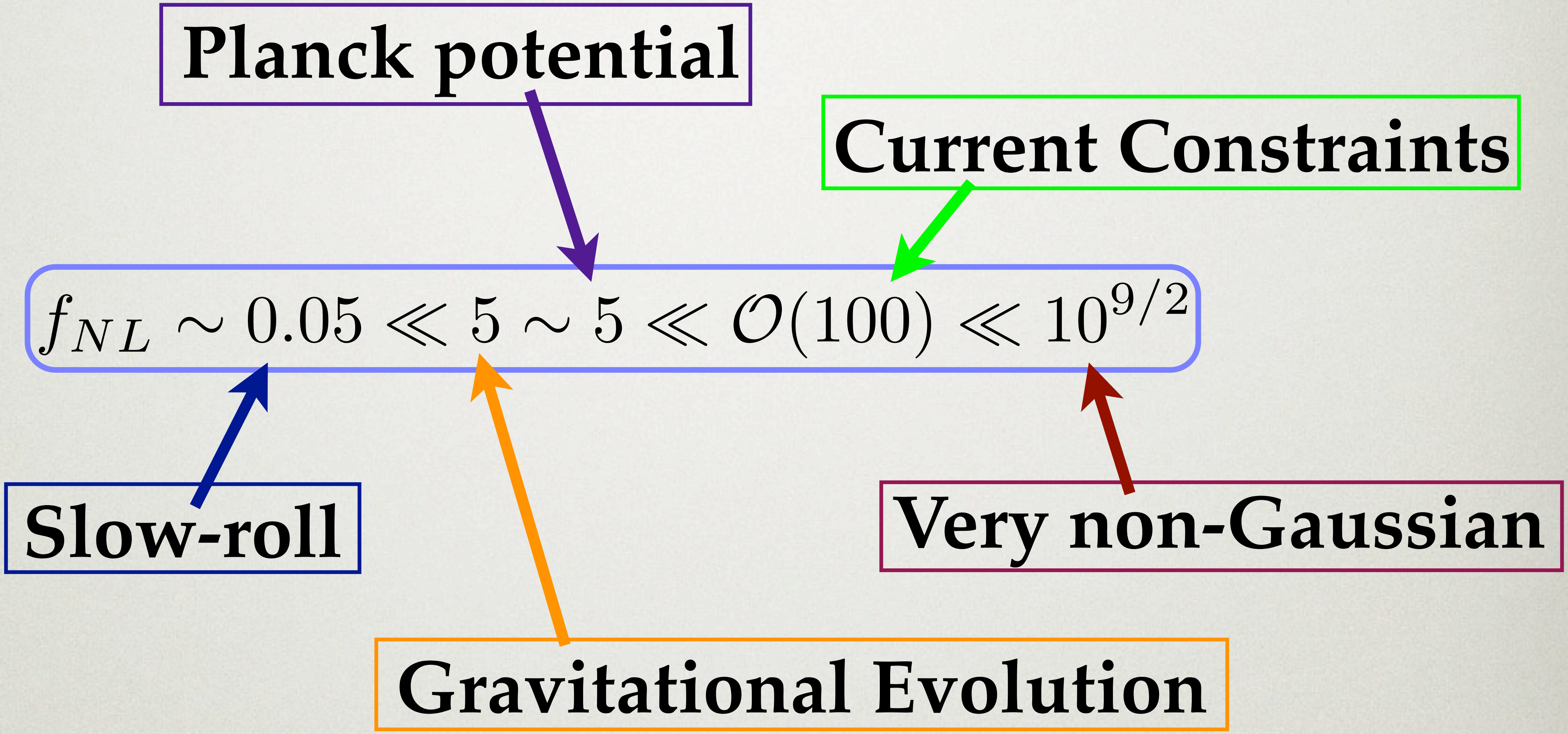

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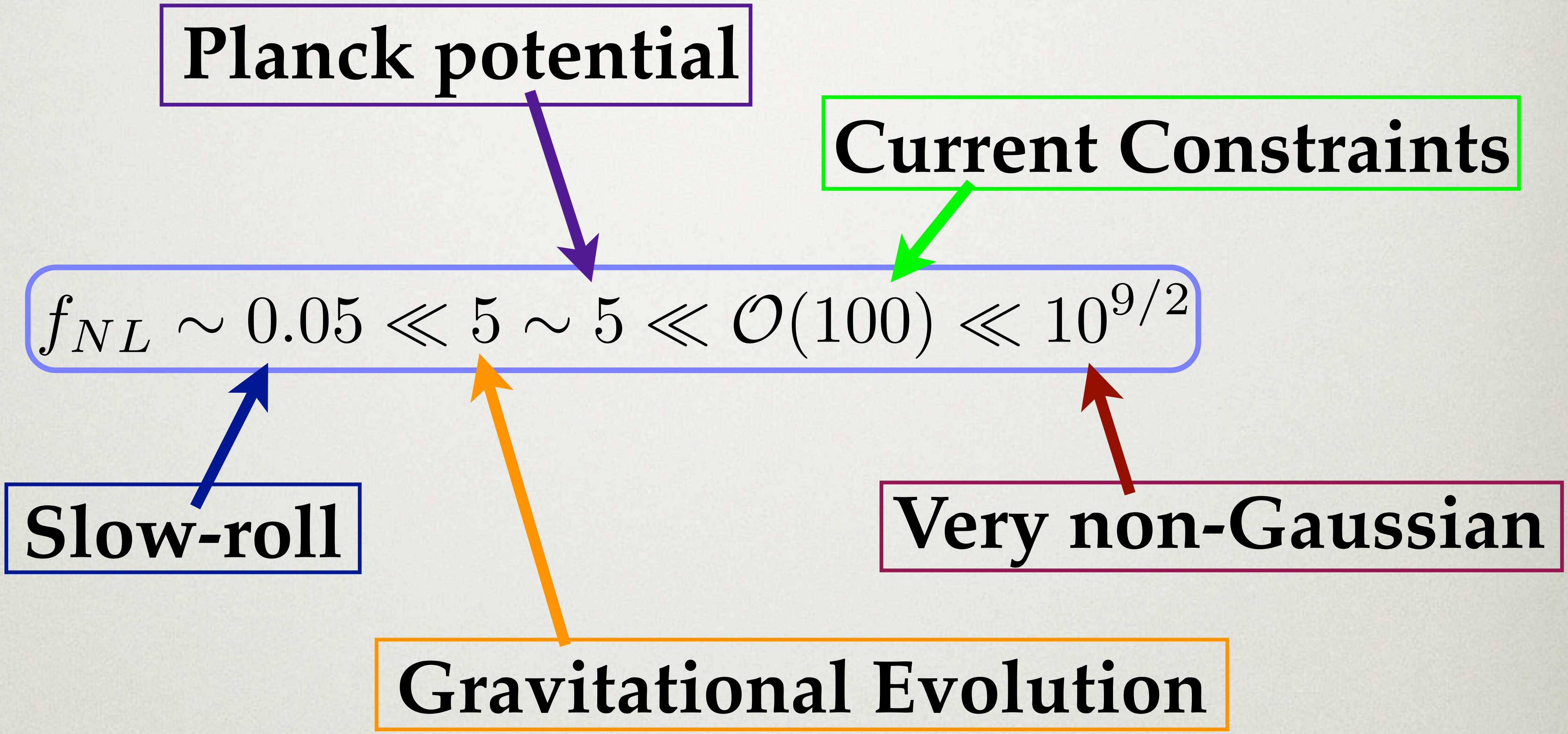

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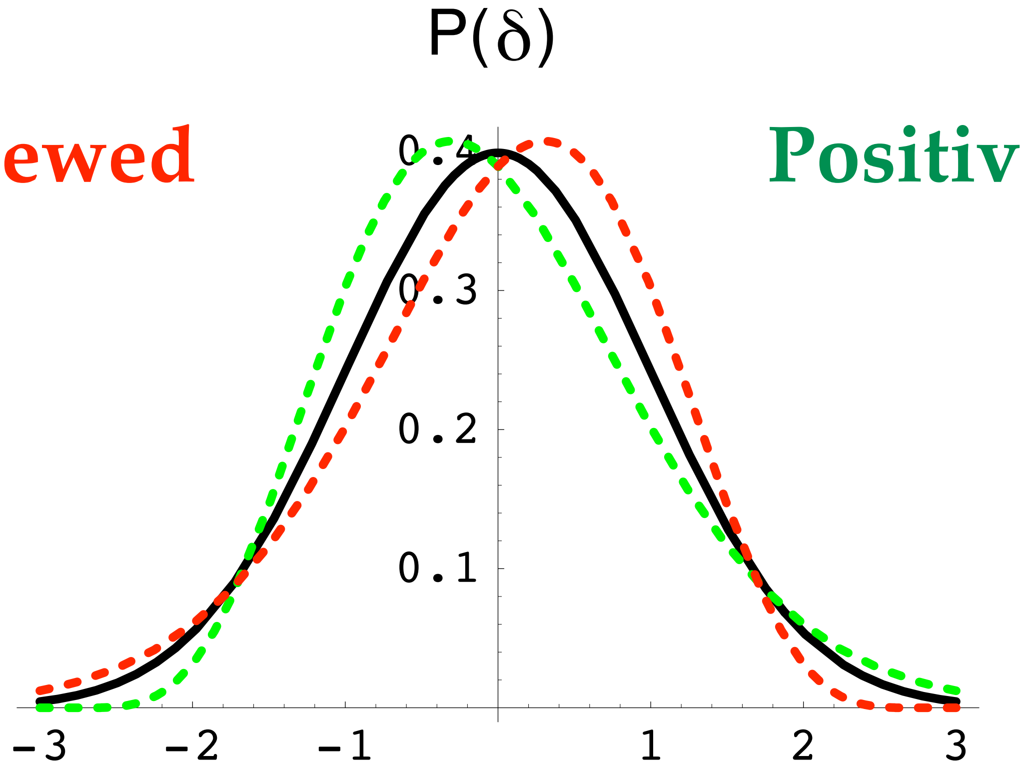
Gravitational Evolution

- Lots of room for discovery
- Detection now rules out 99% of models

THE LOCAL ANSATZ

- One parameter: $\boxed{\langle\zeta^n\rangle \propto f_{NL}^{n-2}\mathcal{P}_\zeta^{n-1}}$



Negatively skewed

Positively skewed

$f_{NL} = \pm 0.1$

$\sigma^2 = 1$

Shandera; RPM; Oct 27, 2011

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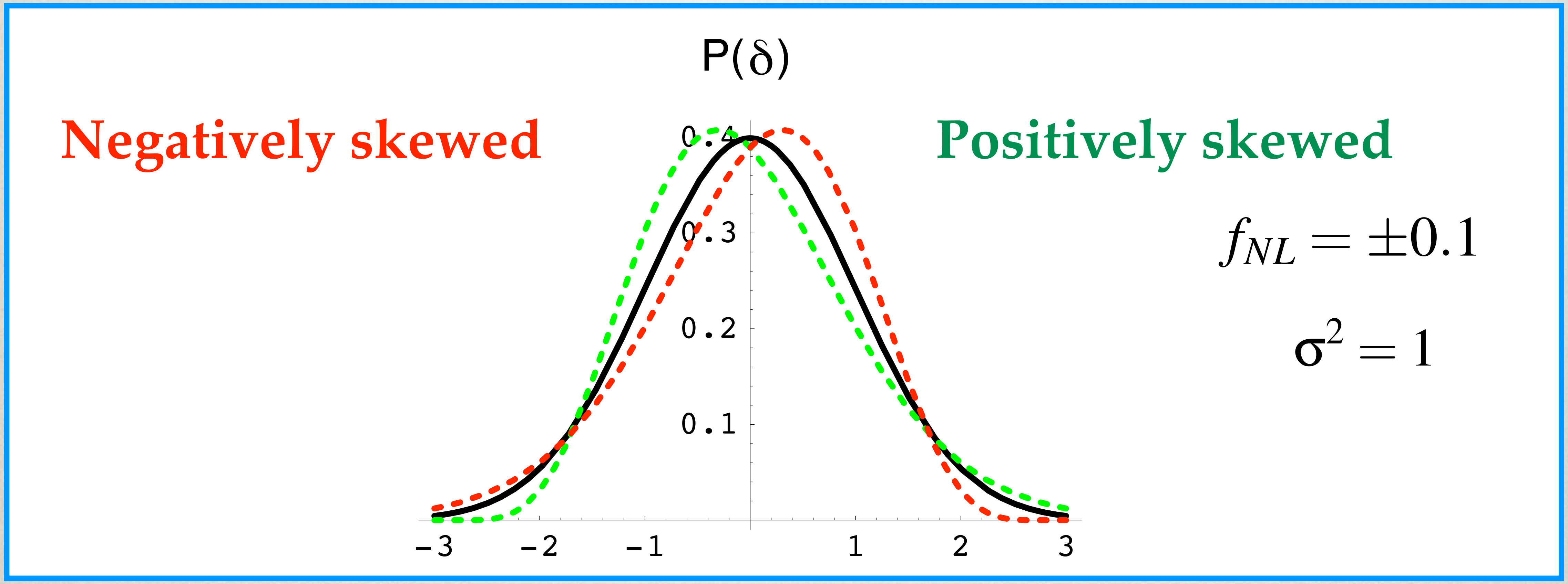


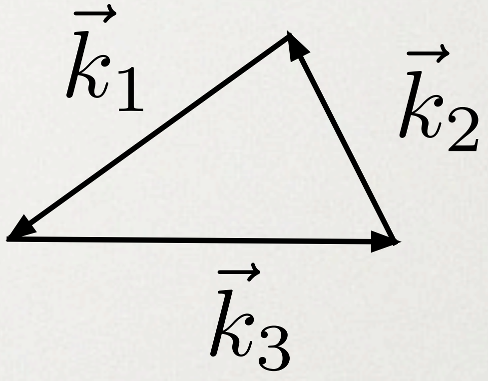
- Easy for N-body simulations (defined from a real space Gaussian)

MORE GENERALLY...

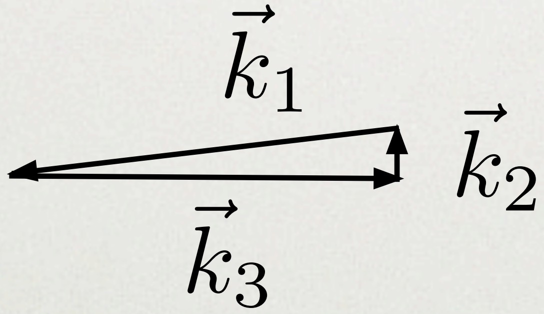
- Interactions that don't screw up inflation are allowed:
  - ✱ Self-interactions with symmetry
  - ✱ Multi-field inflation
  - ✱ Interactions with spectator fields
- Different interactions ⇒ Different shapes in bispectrum

3-POINT TRIANGLES

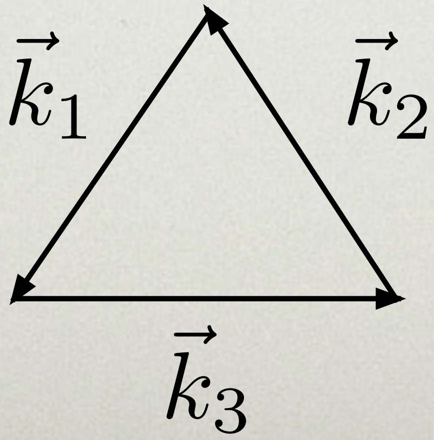
$$\delta_D^3(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) \Rightarrow$$



- Squeezed



- Equilateral



(Babich, Creminelli, Zaldarriaga;)

Information in higher statistics

	Power Spectrum	Bispectrum	Beyond...
Information			
Amplitude			
Sign			
Scale Dependence			

Shandera; RPM; Oct 27, 2011

Information in higher statistics

	Power Spectrum	Bispectrum	Beyond...
Information	$\frac{\lvert\vec{k}\rvert}{}$		
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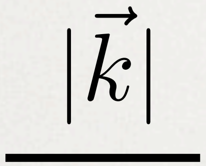
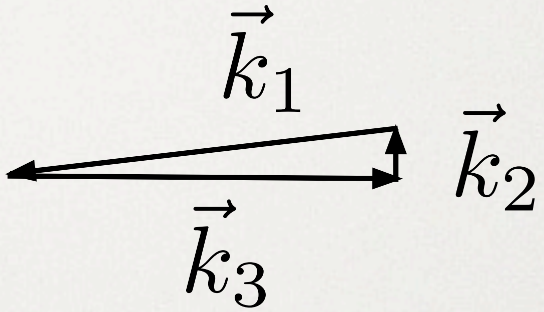
Information			
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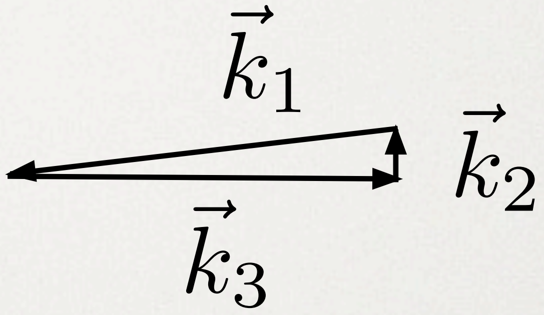
Information	$\|\vec{k}\|$		
Amplitude	$\frac{H^2}{\epsilon M_p^2}$	$\frac{H}{M} < 1$	
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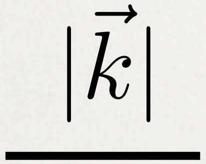
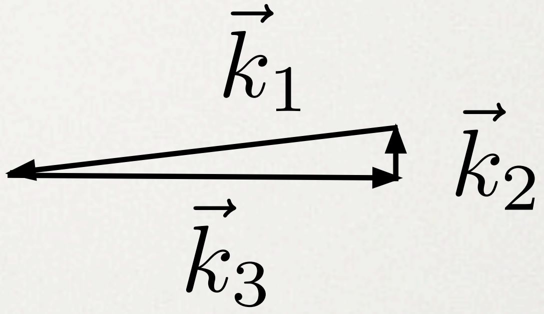
Information			
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Shandera; RPM; Oct 27, 2011

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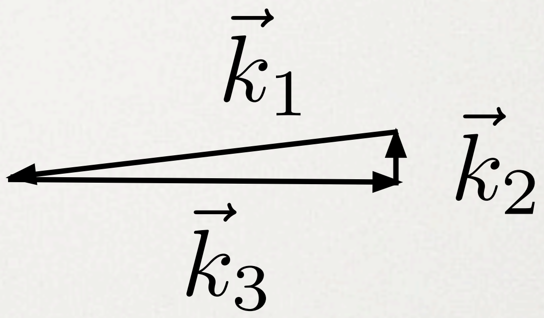
Information	$|\vec{k}|$		
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Scale Dependence	$n_s - 1$ not exact dS	Difference between fields	

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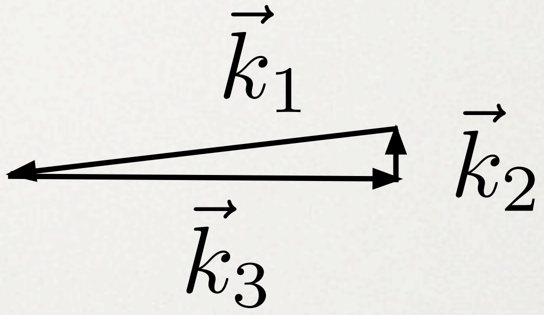
Information	$\underline{\|\vec{k}\|}$		
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Shandera; RPM; Oct 27, 2011

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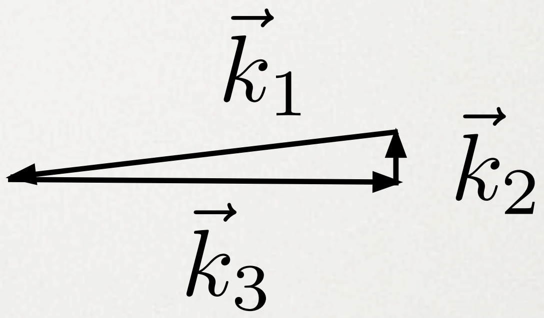
Information	$\underline{\;|\vec{k}|\;}$		N-gon
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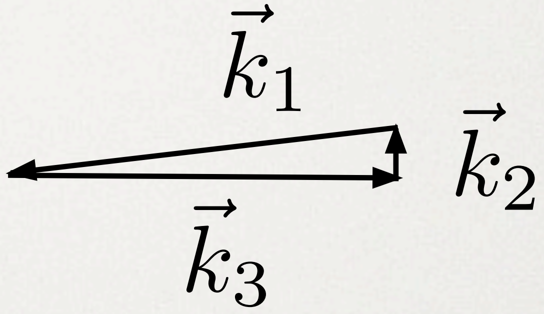
Information	$\underline{\vert\vec{k}\vert}$		N-gon
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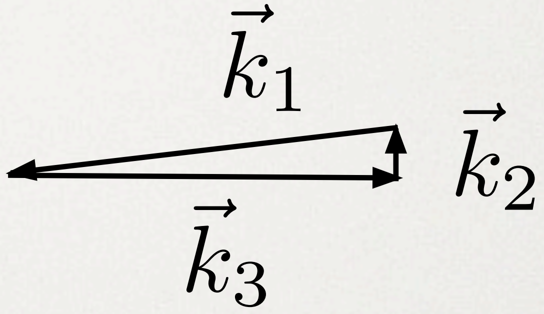
Information	$\underline{\lvert\vec{k}\rvert}$		N-gon
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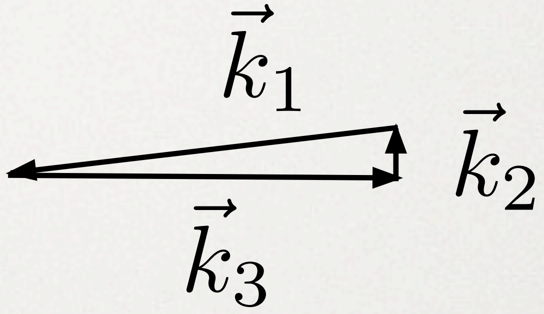
Information	$\underline{\lvert\vec{k}\rvert}$		N-gon
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WHY ALL THE EXCITEMENT?

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Data!

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WMAP 7

$$f_{NL}^{\rm local} : \ 32 \pm 21$$

$$f_{NL}^{\rm equil} : \ 26 \pm 140$$

$$f_{NL}^{\rm orthog} : \ -202 \pm 104$$

Sloan (SDSS)

$$-29 < f_{NL}^{\rm local} < 69$$

(all 1 σ; Komatsu et al;
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Shandera; RPM; Oct 27, 2011

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* A lot going on behind one number...

(all 1 σ; Komatsu et al;
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WAYS TO MEASURE INTERACTIONS

- n-point functions (CMB, LSS)
    - detailed shapes distinguish interactions
- non-linear effects in LSS: *halo bias*
    - sensitive to just some correlations
- other statistics: cluster number counts

Ways to Measure Interactions

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*When are we convinced the theory beats just setting initial conditions?

EXAMPLE: SYMMETRY FOR THE INFLATON

$$\boxed{\phi \rightarrow \phi + c}$$

Standard Model: Any allowed interactions appear....

(Freese; Silverstein, Westphal; Barnaby, Peloso; Anber, Sorbo; Chen et al; Flauger, Pajer; Leblond, Pajer)

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$$\mathcal{L}_0 = -\frac{1}{2}(\partial\varphi)^2 - \frac{1}{4f}\varphi G^a\tilde{G}^a - \frac{\alpha}{4f}\varphi F\tilde{F} + \sum_{n=1}^{\infty} c_n \frac{(\partial\varphi)^{2n+2}}{f^{4n}} + \cdots$$

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- Moments Scale Differently

(AT LEAST) TWO EQUILATERAL TYPES

(Barnaby, Shandera; 1109.2985)

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(At least) Two equilateral types

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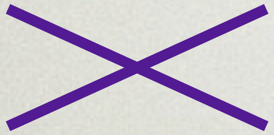

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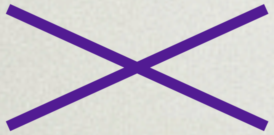

Hierarchical: $\boxed{\mathcal{M}_n \propto \left(\mathcal{I}\mathcal{P}_\zeta^{1/2}\right)^{n-2}}$

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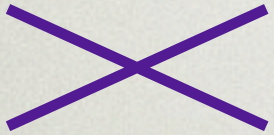

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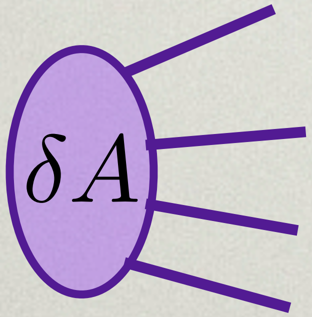

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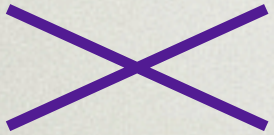

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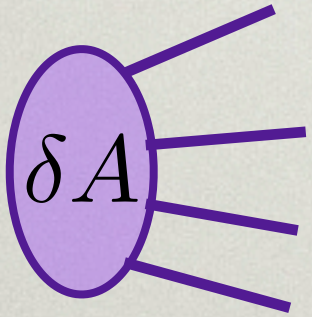

Feeder: $\boxed{\mathcal{M}_n \propto \mathcal{I}^n}$

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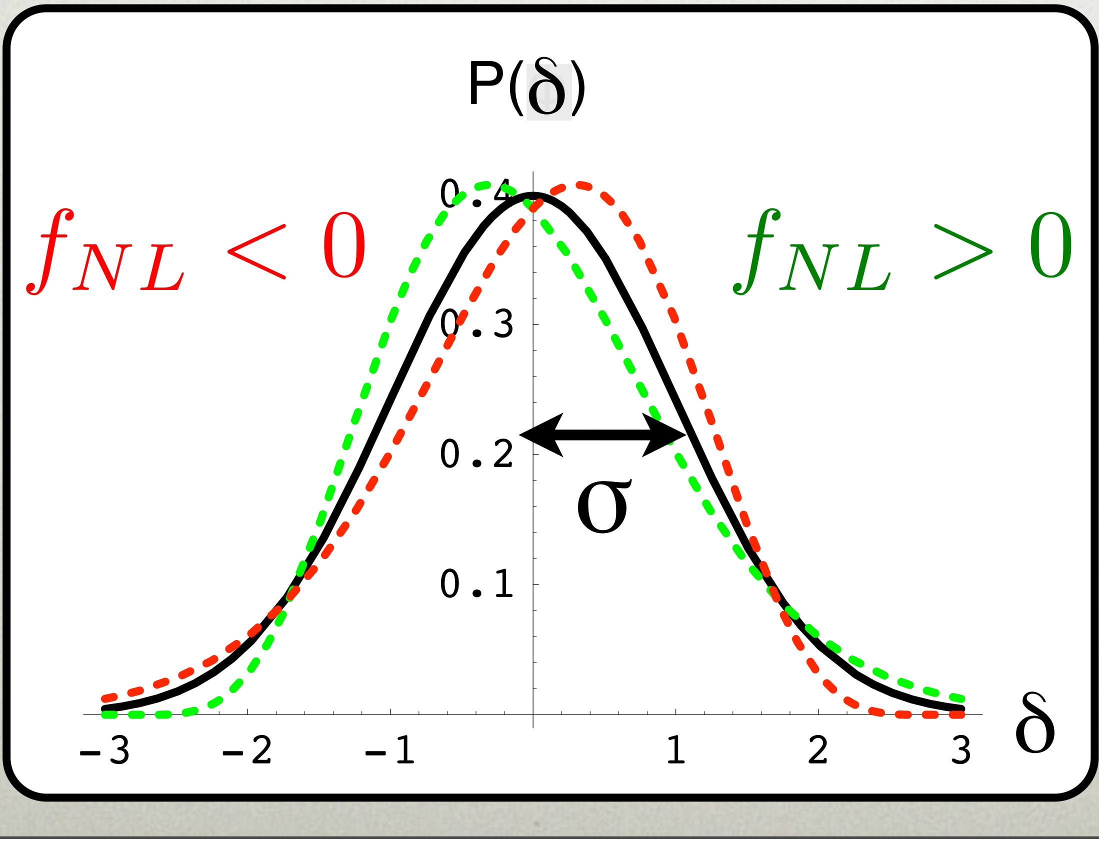
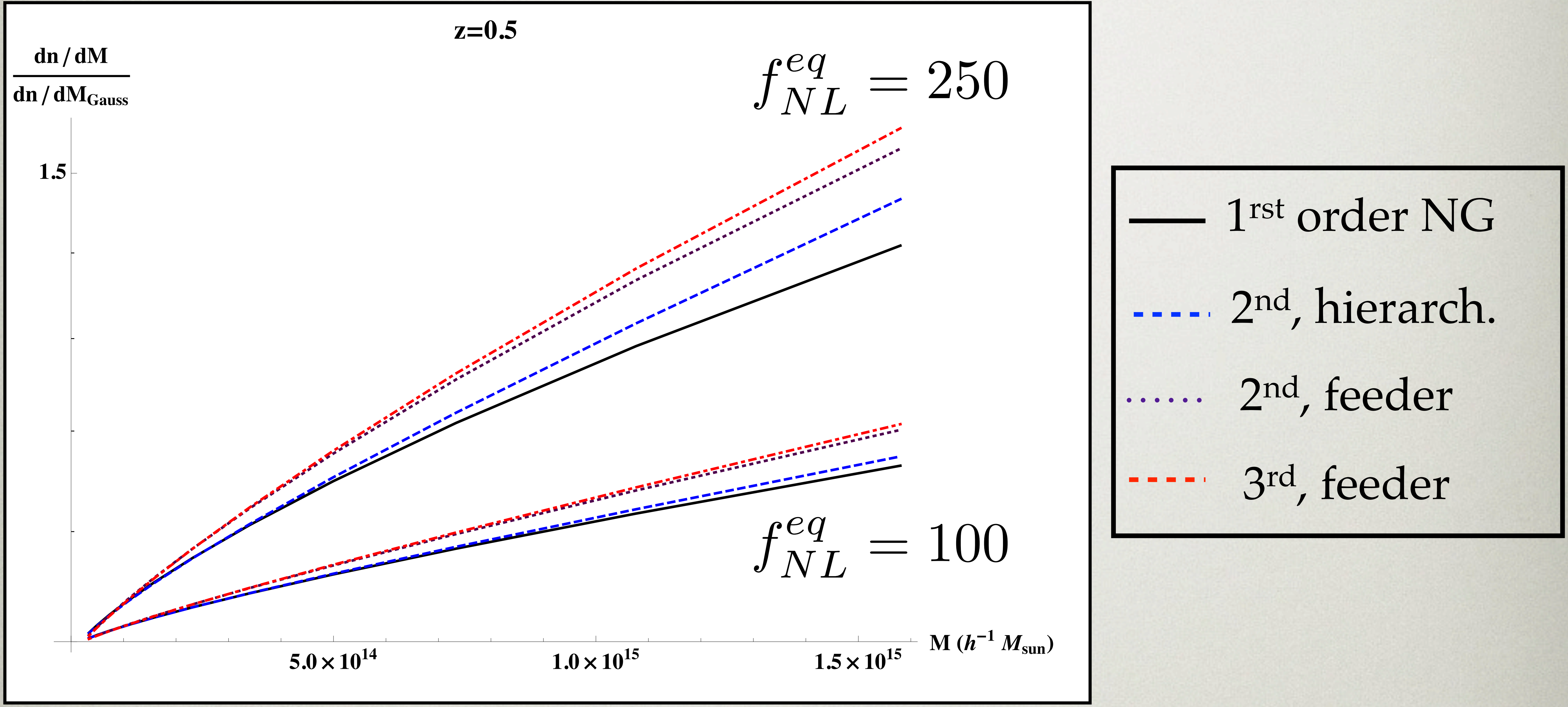
DIFFERENT SCALING?

- Relative importance of higher order moments is greater for *fixed amplitude* of three point
- Skewness isn't everything...



Shandera; RPM; Oct 27, 2011

NG Mass Function



✱What can we learn from rare objects?

(Barnaby, Shandera; 1109.2985)

DISTINGUISHING MULTI-FIELD MODELS

- Break correlation between background evolution and fluctuations
- Anything goes?

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Multi-field → Local shape → Halo Bias

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Multi-field → Local shape → Halo Bias

$$\boxed{-29 < f_{NL}^{\text{local}} < 69}$$

(Slosar et al)

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- Local density and local σ_8 determine where halos form

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- Two or more fields contribute to curvature:

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Scale-dependence from changing ratio of contribution to $\mathcal{P}_\zeta$

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- and -

- The field has self-interactions beyond quadratic

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HOW NATURAL?

- Theoretically, are multiple fields likely?? Hard to say, but:
- IF we find observably large local non-Gaussianity, as natural as the spectral index different from one
- IF we are constraining local non-Gaussianity, this is more honest

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- Effect of local and generalized local NG:

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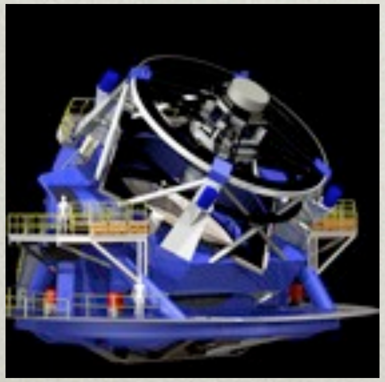

LSST can distinguish multi-field models at level comparable to spectral index!

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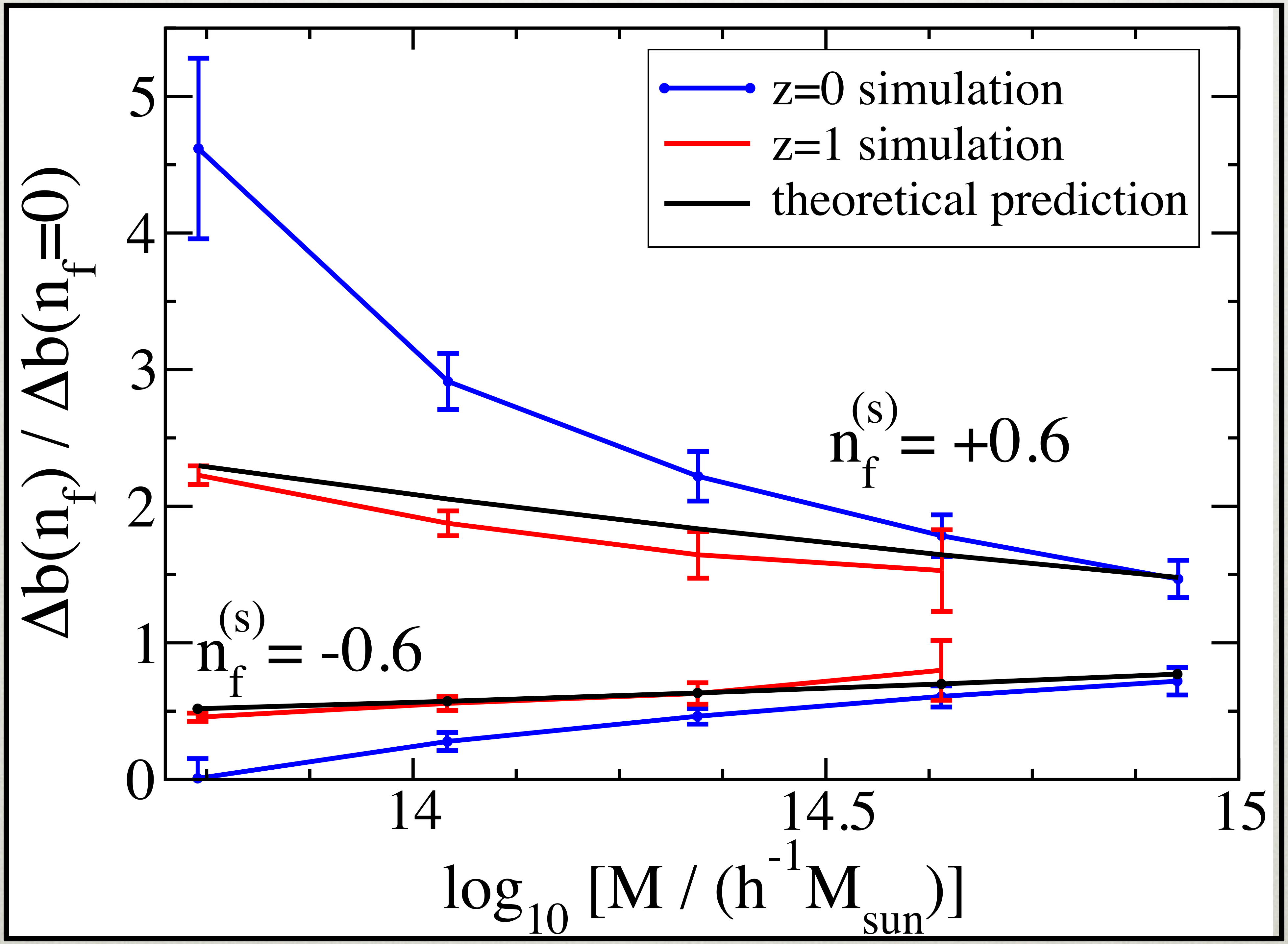
SIMULATION RESULTS



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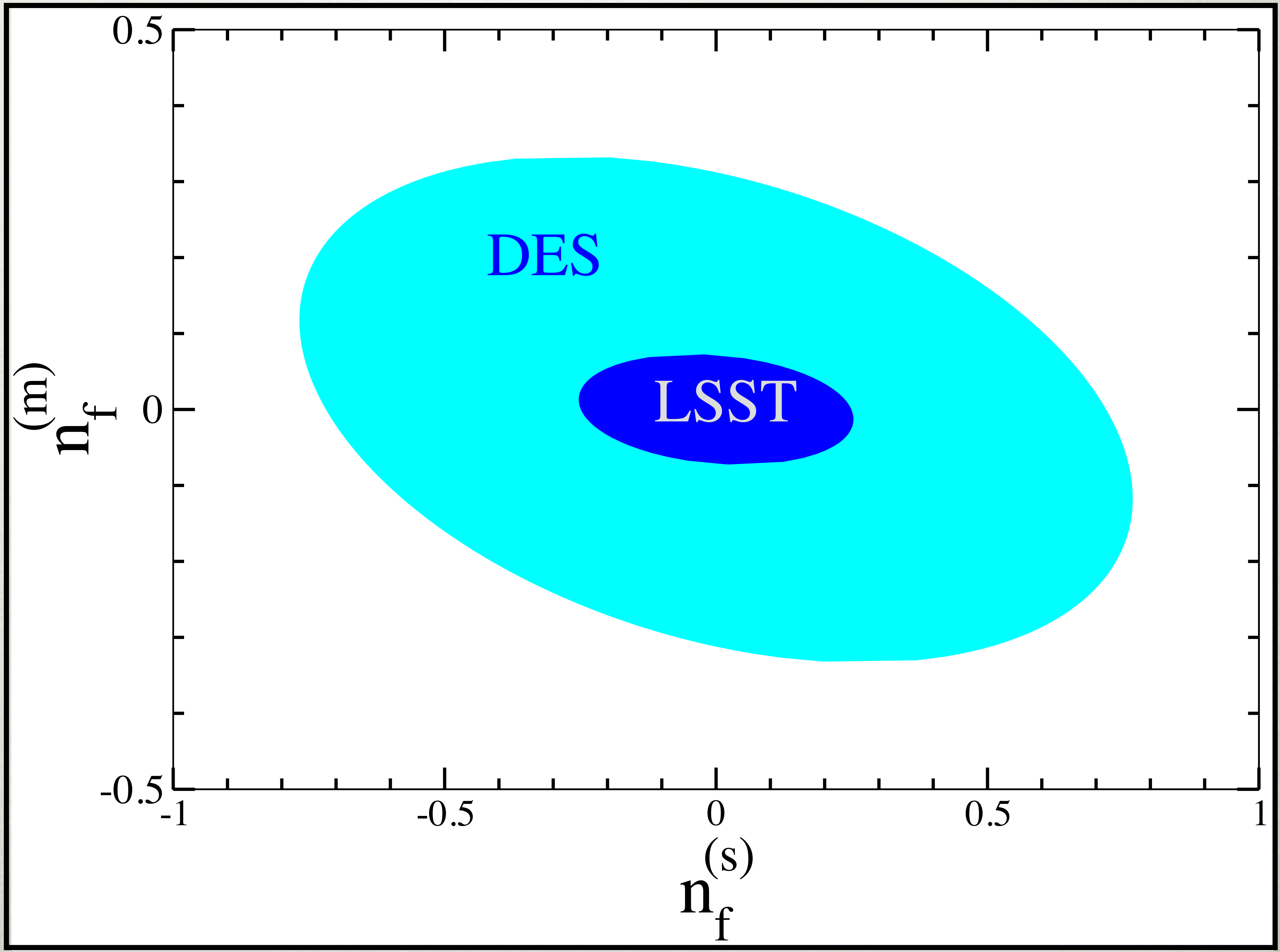
DISTINGUISHING BETWEEN THE EFFECTS (STRONGER THAN THIS!)

Using old, wrong, analytic ansatz!



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- Generic:

If: $$B(k_1, k_2 \gg k_3) \propto \frac{1}{k_3^{p_{div}}}$$

Then: $$\Delta b_{NG} \propto \frac{k^{3-p_{div}}}{k^2}$$

Forecasts

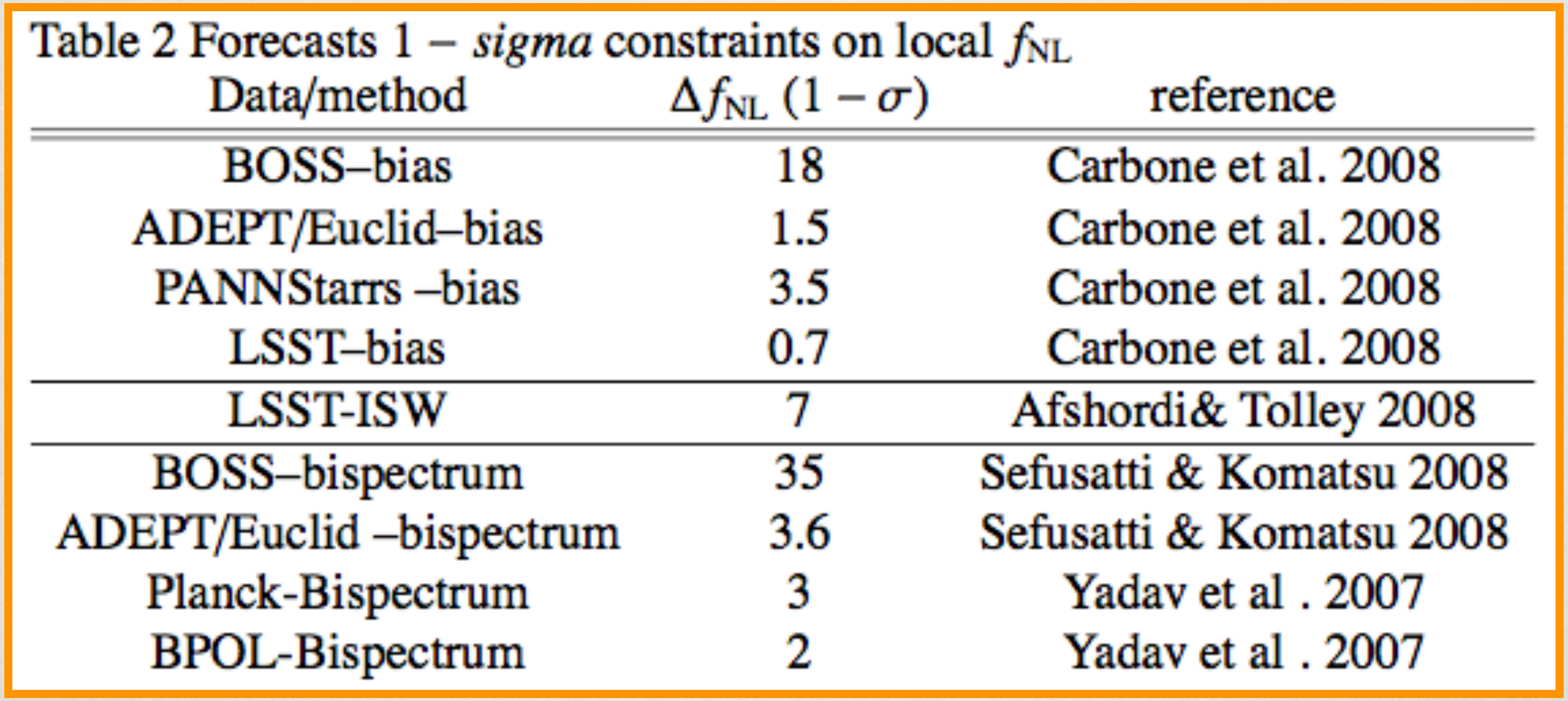

Table 2 Forecasts 1 – *sigma* constraints on local $f_{\rm NL}$

Data/method	$\Delta f_{\rm NL}$ $(1-\sigma)$	reference
BOSS–bias	18	Carbone et al. 2008
ADEPT/Euclid–bias	1.5	Carbone et al. 2008
PANNStarrs –bias	3.5	Carbone et al. 2008
LSST–bias	0.7	Carbone et al. 2008
LSST-ISW	7	Afshordi& Tolley 2008
BOSS–bispectrum	35	Sefusatti & Komatsu 2008
ADEPT/Euclid –bispectrum	3.6	Sefusatti & Komatsu 2008
Planck-Bispectrum	3	Yadav et al . 2007
BPOL-Bispectrum	2	Yadav et al . 2007

Table compiled by Licia Verde

Future: Large Scale Structure

And if Inflation
is not
This picture?

OTHER APPROACHES

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OTHER APPROACHES

- If we see no non-Gaussianity, no tensors...what then?
- Or, what if we see a bizarre pattern?
- Model fluctuations alone: *Effective Field theory for the fluctuations* (Cheung et al: 0709.0293)
- Or, parametrize sensitivity of data? Find a basis for higher order correlation functions (Fergusson and Shellard)

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- If the standard picture is right:
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  - Need more simulations!
- A new push to understand (quasi) de Sitter space *(if we see no tensors, no NG?)*
- Observables tell us what's physical