Non-Gaussianities

November 2012

The Aftermath of the Bang

"Although it is called the Big Bang Theory, it is not really the theory of a bang at all. It is only the theory of the aftermath of a bang."
Alan Guth

CMB

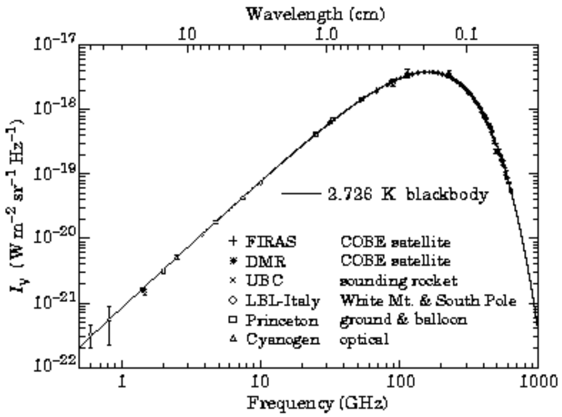
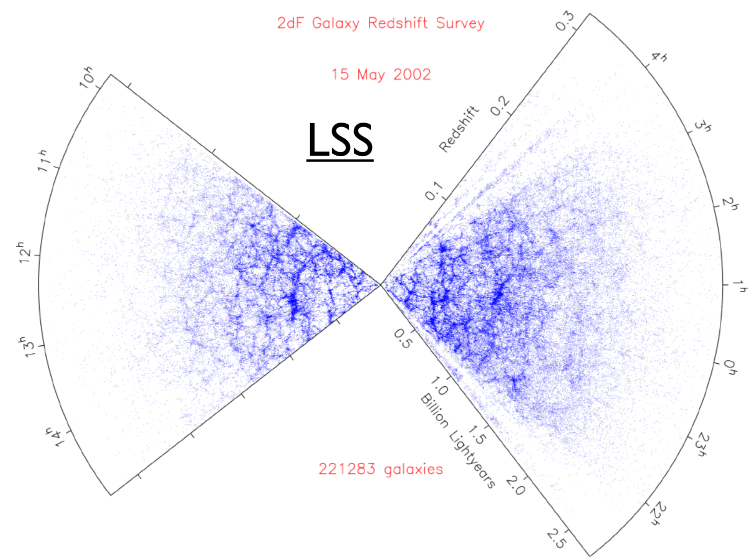
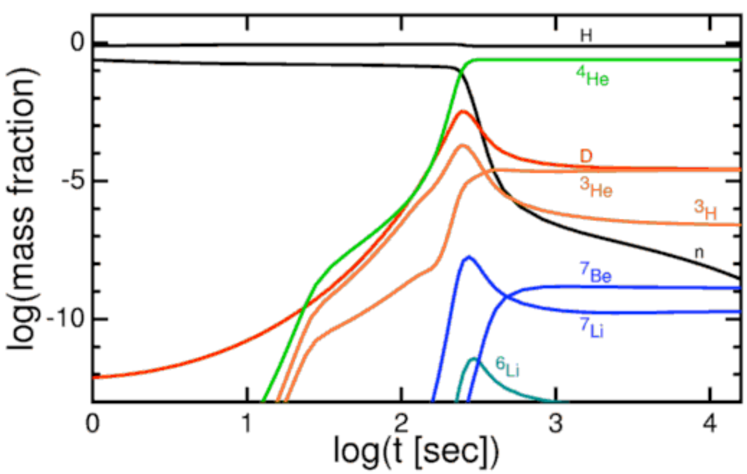


Figure 1. Precise measurements of the CMB spectrum. The line represents a 2.73 K blackbody, which describes the spectrum very well, especially around the peak of intensity. The spectrum is less well constrained at frequencies of 3 GHz and below (10 cm and longer wavelengths). (References for this figure are at the end of this section under "CMB Spectrum References.")

LSS



BBN:



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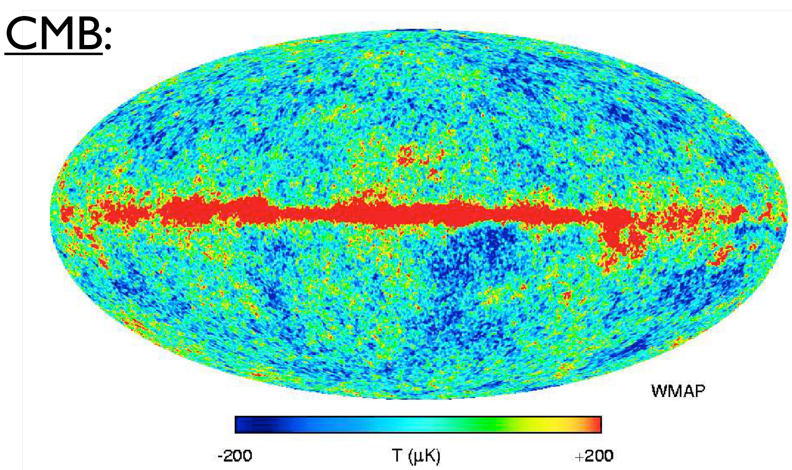
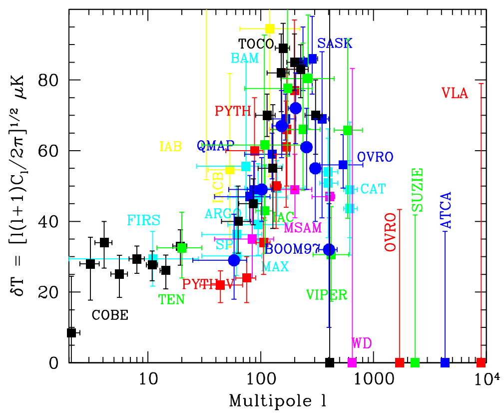
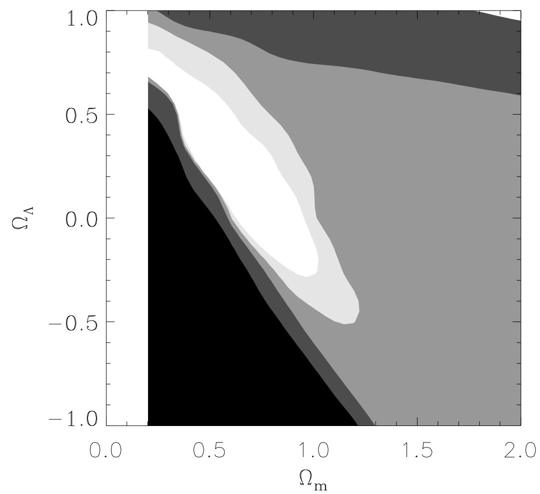


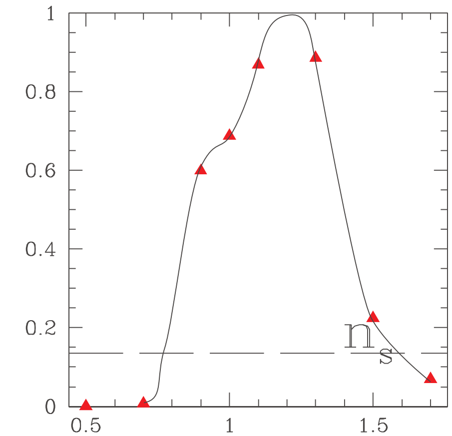
Progress



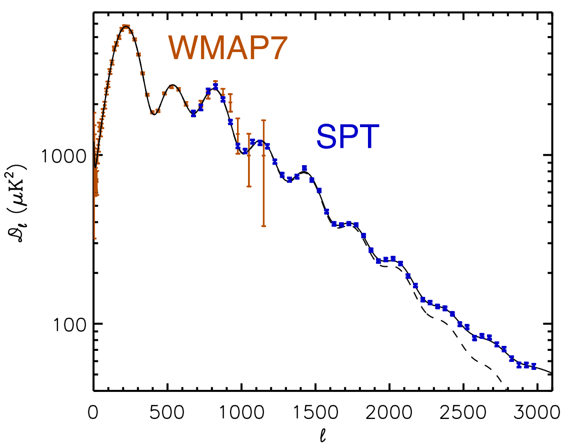
δT = [l(l+1)C_l/2π]^{1/2} μK
Multipole l
COBE
FIRS
TEN
PYTH
IAB
QMAP
TOCO
BAM
SASK
OVRO
CAT
SUZIE
ATCA
VLA
MSAM
BOOM97
MAX
VIPER
WD



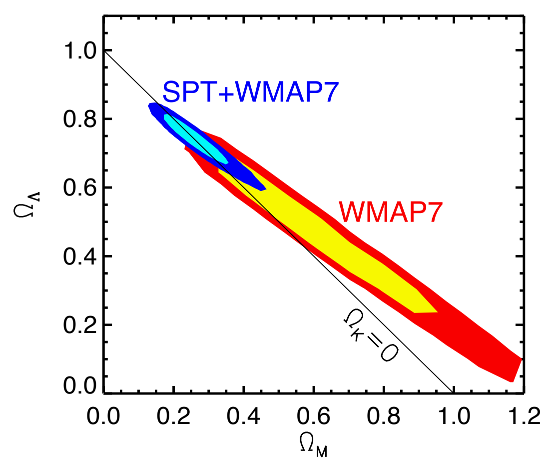
Ω_Λ
Ω_m



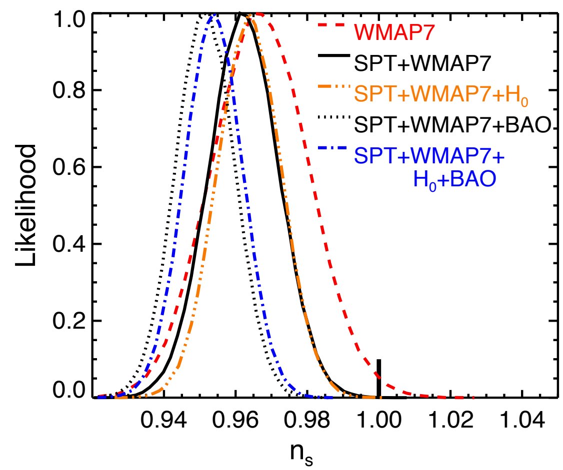
n_s



WMAP7
SPT
ℓ



SPT+WMAP7
WMAP7
Ω_k=0
Ω_Λ
Ω_M

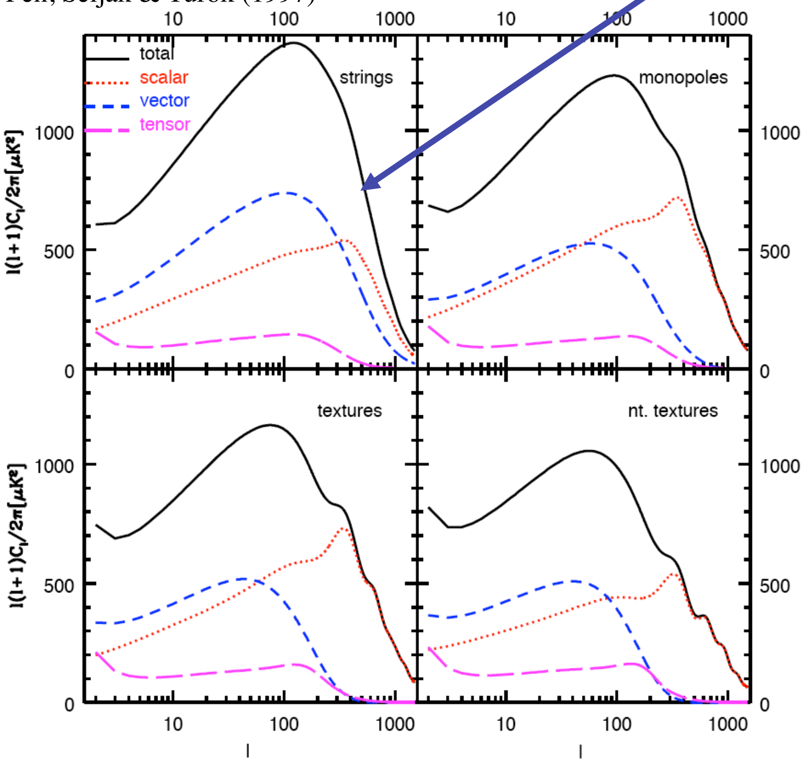


WMAP7
SPT+WMAP7
SPT+WMAP7+H0
SPT+WMAP7+BAO
SPT+WMAP7+H0+BAO
Likelihood
n_s

The Seeds for structure

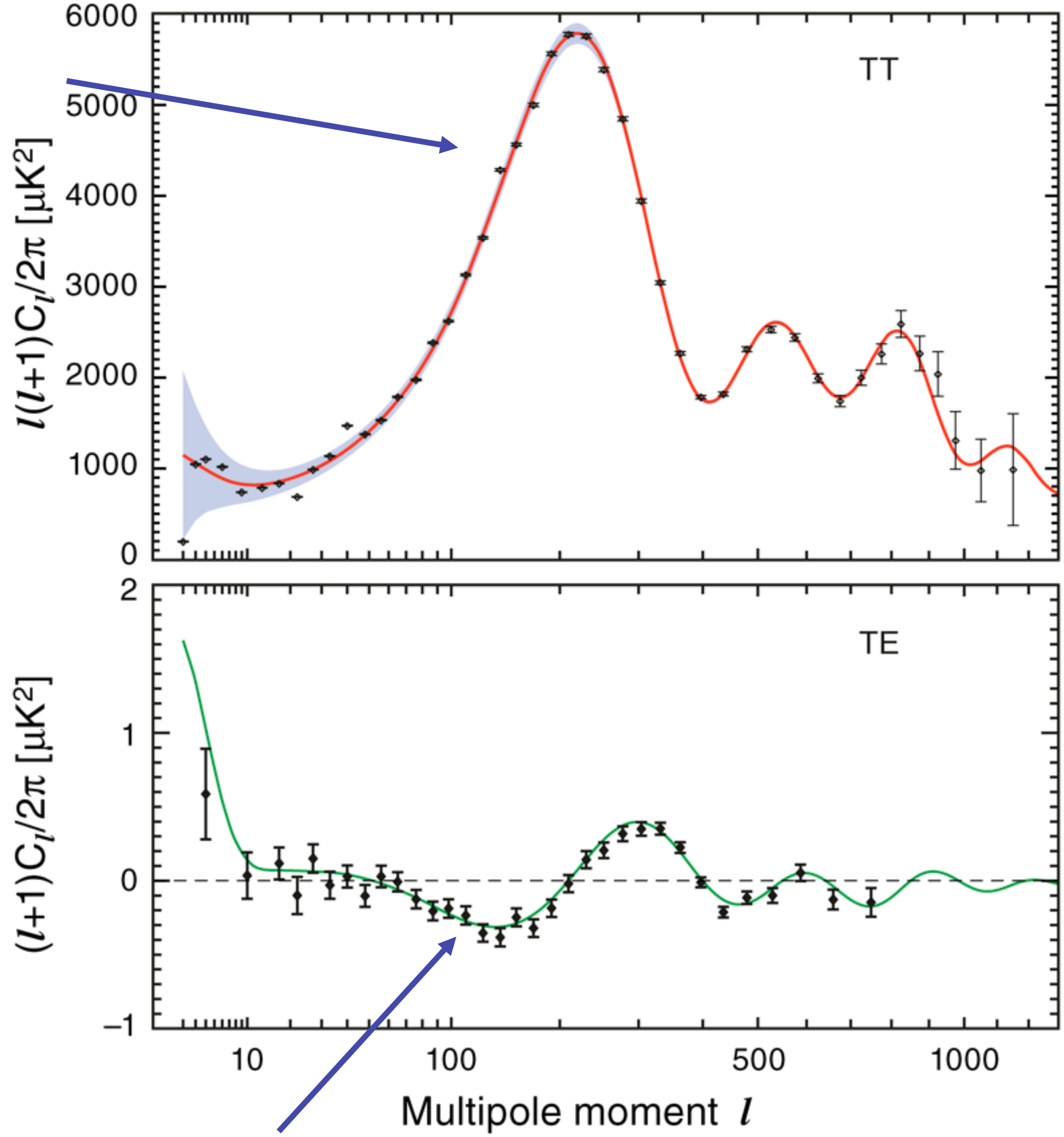
Causal Seeds

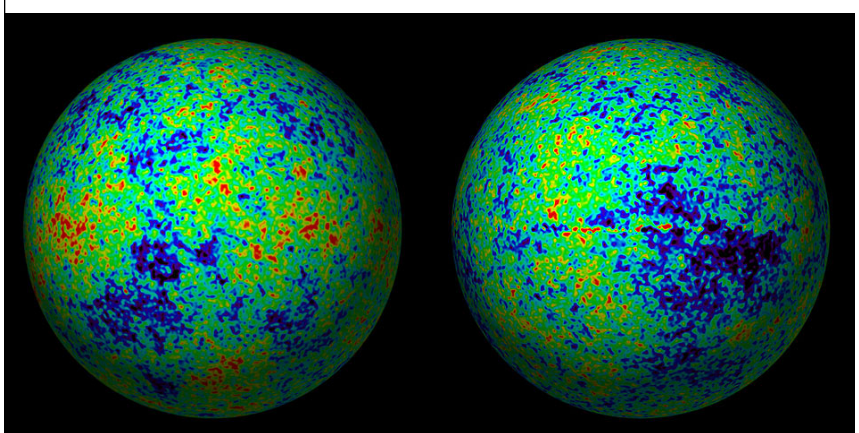
Pen, Seljak & Turok (1997)



Sharp acoustic peaks are difficult to create without inflation

WMAP 7yrs

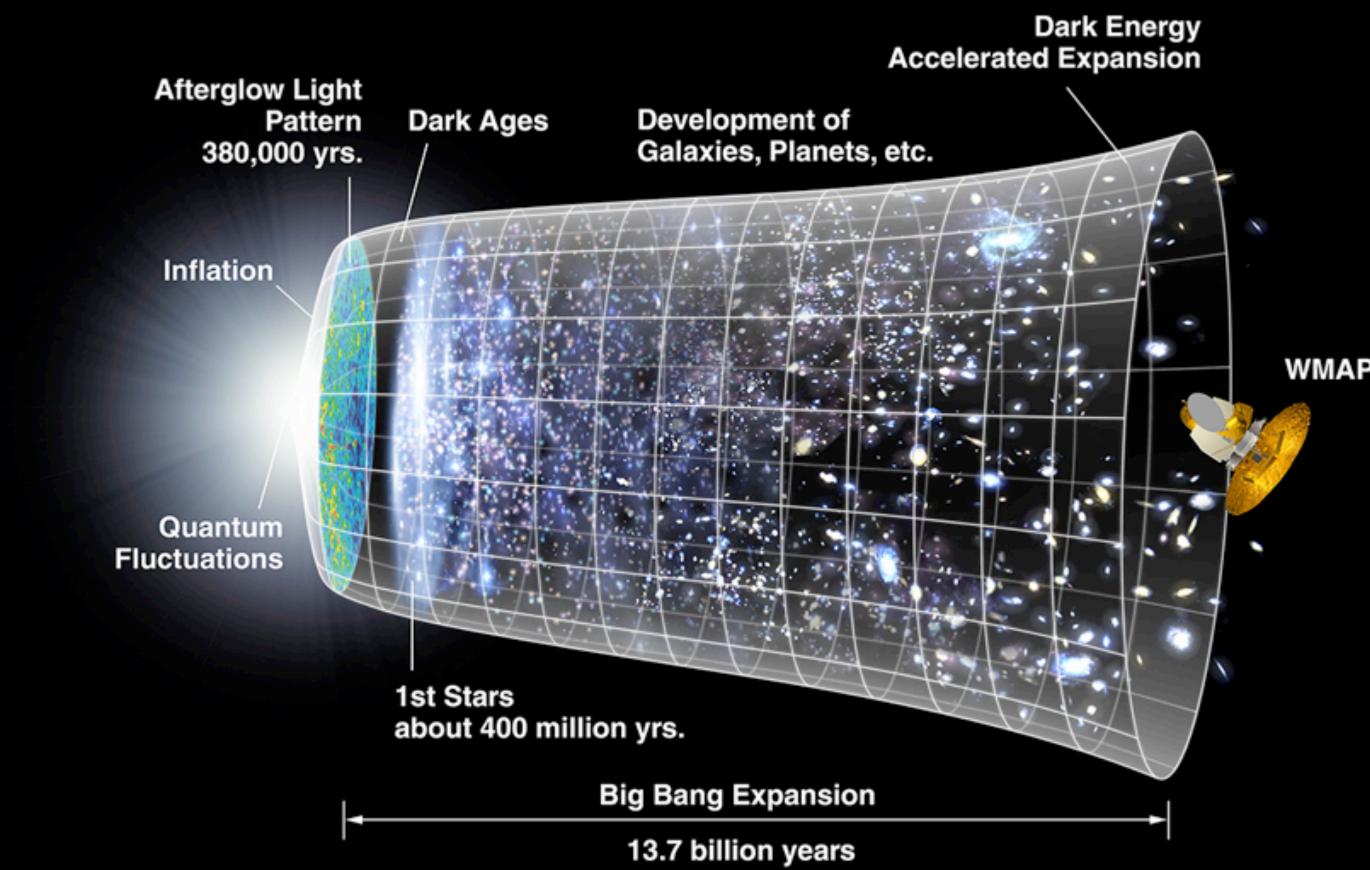




Negative peak imply fluctuations come from outside horizon

Hu & White (1996)
Spergel & MZ (1997)
Pieris et al WMAP (2003)

The history of the Universe



Understanding the origins of the Universe requires physics not yet tested in the Laboratory.

The theory for the initial seeds

Abracadabra vs extrapolation of known physics

Inflation is by far our best "non-abracadabra" model

Basic inflation

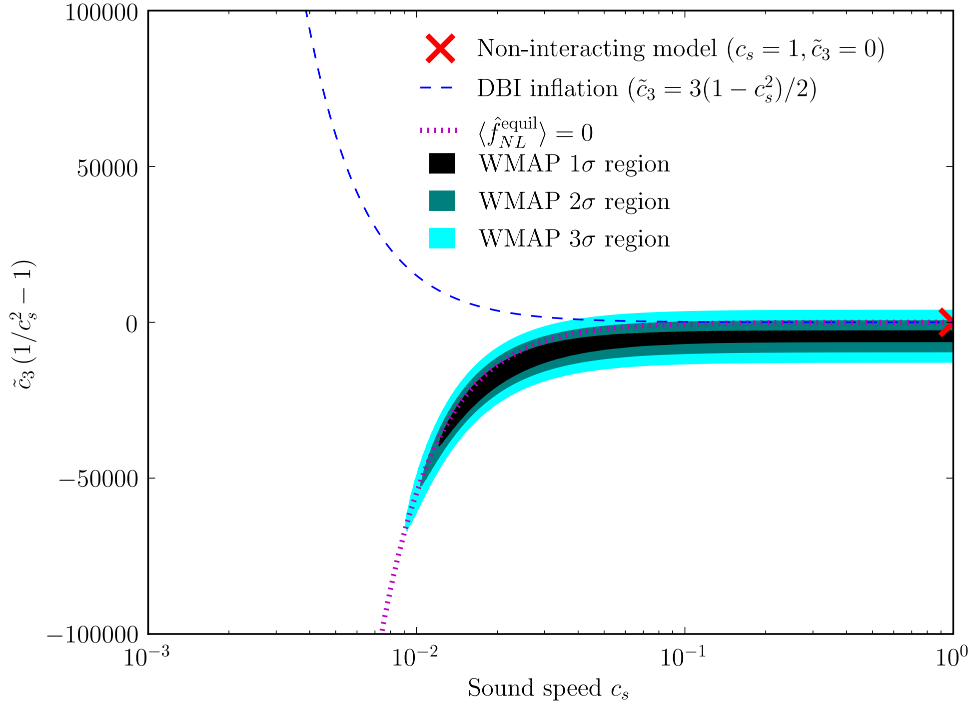
- Inflation needs to end so there is a clock, time translations are spontaneously broken
- Dynamics of the fluctuations of the clock are very constrained by symmetries, "EFT of inflation"
- What is the speed of propagation of the fluctuations?
- Connection between speed of sound and non-Gaussianities.
- Shape of non-Gaussianities very constrained and go to zero in the "squeezed-limit".

$$S = \int d^4x \, \sqrt{-g} \;\; \Big[\;\; \frac{1}{2} M_{\rm Pl}^2 R + M_{\rm Pl}^2 \dot{H} g^{00} - M_{\rm Pl}^2 (3H^2 + \dot{H}) + \\ + \frac{1}{2!} M_2(t)^4 (g^{00}+1)^2 + \frac{1}{3!} M_3(t)^4 (g^{00}+1)^3 + \\ - \frac{\bar{M}_1(t)^3}{2} (g^{00}+1) \delta K^\mu{}_\mu - \frac{\bar{M}_2(t)^2}{2} \delta K^\mu{}_\mu{}^2 - \frac{\bar{M}_3(t)^2}{2} \delta K^\mu{}_\nu \delta K^\nu{}_\mu + ... \Big]$$

Predictions of these model are in perfect agreement with the data

The connection between cs and non-Gaussianity

$$S_\pi = \int d^4x\sqrt{-g}\Bigg[-\frac{M_{\rm Pl}^2\dot H}{c_s^2}\left(\dot\pi^2 - c_s^2\frac{1}{a^2}(\partial_i\pi)^2\right) \tag{8}$$
$$+\frac{\dot H M_{\rm Pl}^2}{c_s^2}(1-c_s^2)\dot\pi\frac{1}{a^2}(\partial_i\pi)^2 - \frac{\dot H M_{\rm Pl}^2}{c_s^2}(1-c_s^2)\left(1+\frac{2}{3}\frac{\tilde c_3}{c_s^2}\right)\dot\pi^3$$
$$-\frac{d_1}{4}HM^3\left(6\,\dot\pi^2+\frac{1}{a^2}(\partial_i\pi)^2\right) - \frac{(d_2+d_3)}{2}M^2\frac{1}{a^4}(\partial_i^2\pi)^2 - \frac{1}{4}d_1M^3\frac{1}{a^4}(\partial_j^2\pi)(\partial_i\pi)^2$$
$$+\ \dots\Bigg]\,,$$



0905.3746

Even within this framework there are less explored corners

<u>Opening the box</u>

Should we?

Are there additional degrees of freedom relevant for the creation the perturbations?

- Heavy (m >> H)
- Masses of order Hubble
- Light (m << H)

Light fields

- Local type non-Gaussianities
- Different shapes than those that can be produced by single field
- 4-pt functions with large signal to noise

EFT of multifield inflation 1009.2093

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.	
$\dot\sigma^p(\partial_i\partial_j\sigma)^{(4-p)}$		X	Ad., Iso.	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

Table 1: Signatures in Multi-field Inflation. In the first column we give the operator generating the non-Gaussian signal: operators quartic in the σ's lead to a four-point function, operators cubic in the σ's lead to a three-point function. In the second and third columns we explain with which dispersion relation the signal can be generated. In the third we explain if the signal can appear in the Adiabatic (Ad.) or the Isocurvature (Iso.) fluctuations. In the fourth we state the potential origin of the signal. Here Ab. stands for Abelian; non-Ab. stands for non-Abelian, S stands for supersymmetry, and R stands for generated by non-linearities at reheating. The subscript $_s$ indicates that the term is generated by soft-breaking terms. The symbol † represents that such a signal can be generated in the case the soft symmetry breaking term is such that it forbids some of the lowest dimensional terms. The symbol * represents the fact that the signal is in general subleading, but still possibly detectable. In the last column we explicitly mention if the induced signal has a non-vanishing squeezed limit and is therefore detectable also in clustering statistics of collapsed objects.

Local non-Gaussianty

Masses of order Hubble

Heavy modes

Other symmetry breaking patterns

<u>Opening the box</u>

Where should we stop?

Abracadabra
Simplicity
Naturalness
UV-Abracadabra

Summary