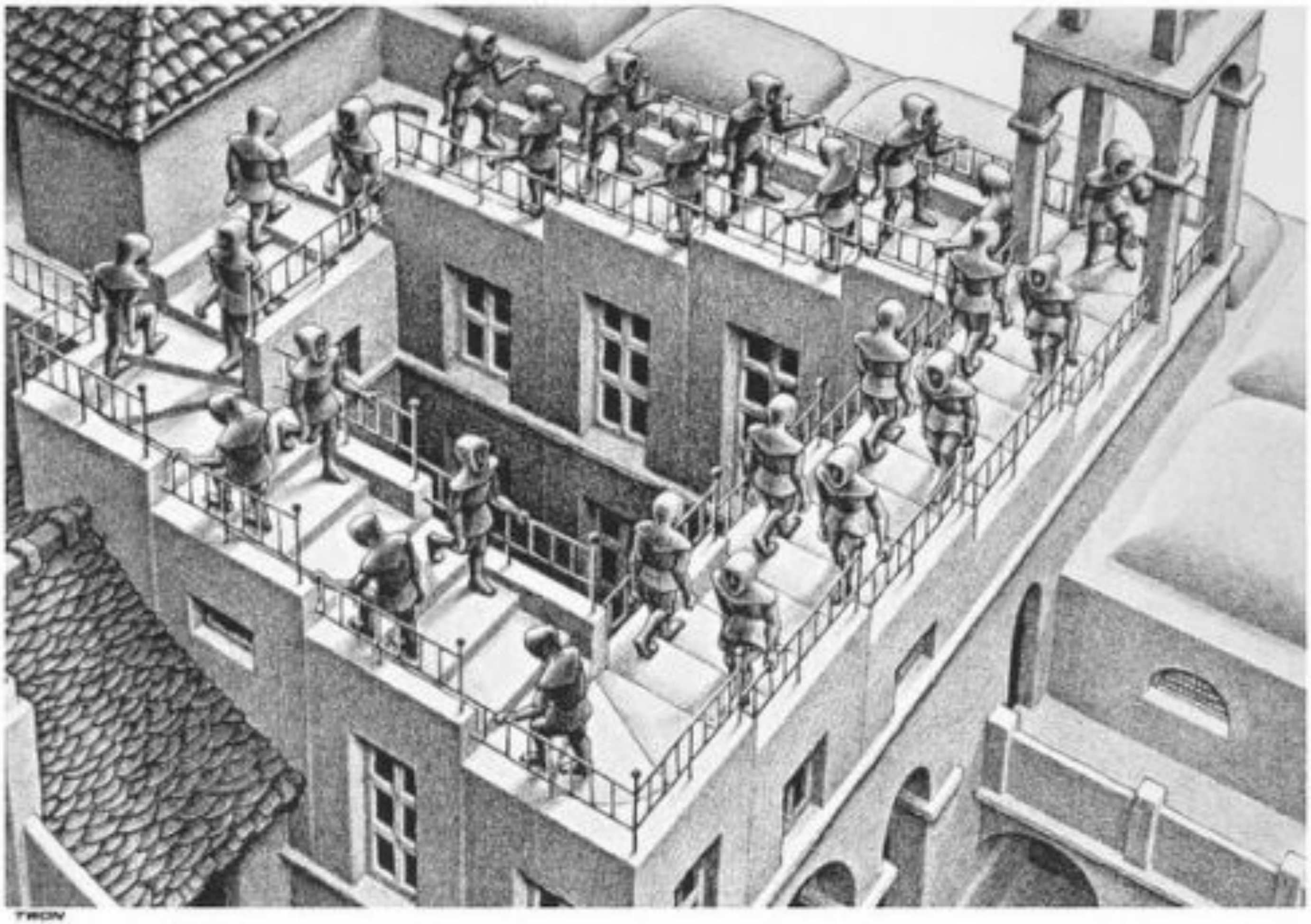
Raul Jimenez

Measuring the Energy Scale of Inflation with Large Scale Structures

with Nicola Bellomo, Nicola Bartolo, Sabino Matarrese & Licia Verde in **arXiv:1809. 07113** today



ΛCDM: The standard cosmological **model**

Just **7** numbers.....

describe the Universe composition and evolution

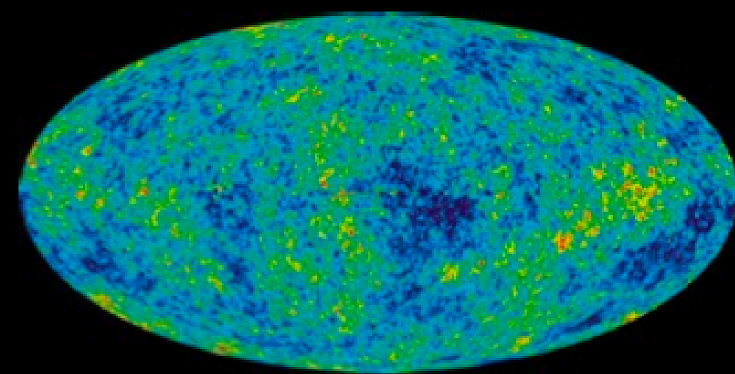
Homogenous background

$\Omega_b, \Omega_c, \Omega_\Lambda, H_0, \tau$

- atoms 4%
- cold dark matter 23%
- dark energy 73%

Λ? CDM?

Perturbations



A_s, n_s

- nearly scale-invariant
- adiabatic
- Gaussian

ORIGIN??

The **Inflationary Paradigm** has passed four major tests:

1. There are super-horizon perturbations, as shown for the first time by Peiris, Komatsu, Verde et al. 2003

2. The power spectrum of these fluctuations is nearly scale invariant (Spergel, Verde, Peiris et al. 2003) but deviates by a small amount from it, as first shown compellingly in Plank team 2013 results

3. The Universe is essentially spatially flat (WMAP 2013; Planck 2013 & 2015) and **appears** homogeneous and **IS** isotropic on large scales (WMAP 2011 & Planck 2013 & 2015)

4. Initial conditions are very nearly Gaussian (Planck 2013 & 2015)

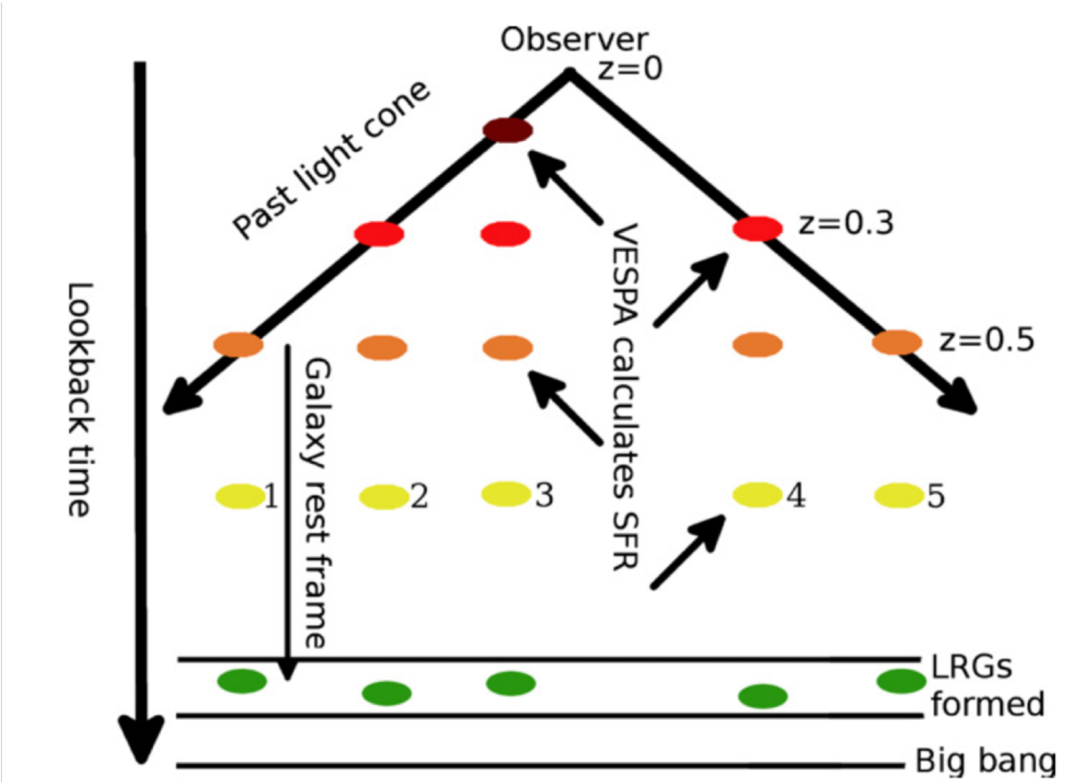
But there are three things we have not measured yet:

1. Tensor modes as proof of a period of accelerated expansion

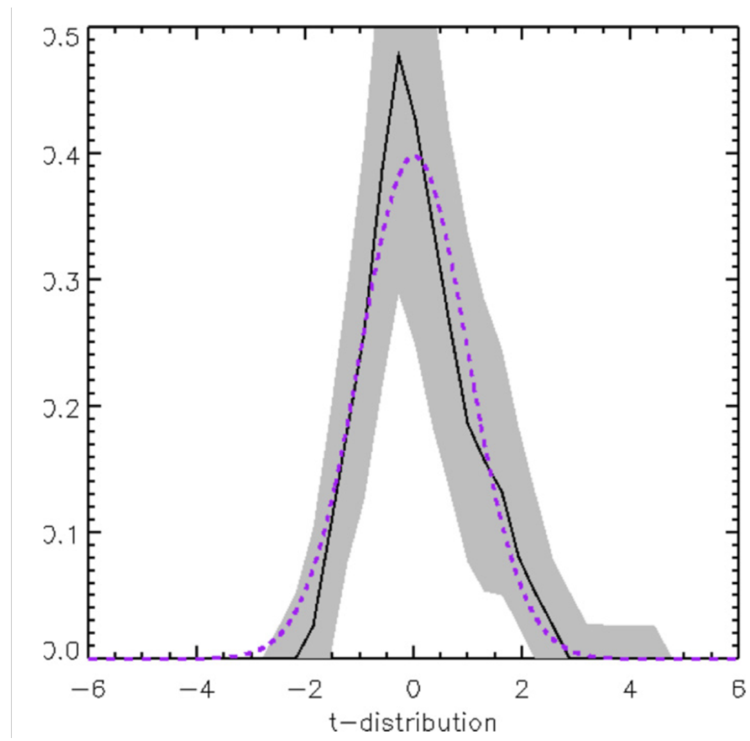
2. Tiny deviations from Gaussianity

3. We have **NOT YET** demonstrated homogeneity; **we have assumed it (ALTHOUGH THERE ARE NEW RESULTS)**

Current constraints on Homogeneity (Hoyle et al. 2013)



From SDSS, Universe homogeneous at > 94% at 95% confidence



Peering beyond the horizon with standard sirens and redshift drift.

JCAP 2017

Raul Jimenez,[1,2] Alvise Raccanelli*,[1] Licia Verde,[1,2] Sabino Matarrese[3,4,5,6]

$$d_L(z) = \frac{(1+z)}{H_0\sqrt{|\Omega_k|}} S_k\left[\sqrt{|\Omega_k|}\int_0^z \frac{H_0}{H(z')}dz'\right]$$

	No projection $\sigma\Omega_k$	With projection $\sigma\Omega_k$
redshift drift		
2.5% $\sigma(H_0)$	0.017	0.033
1% $\sigma(H_0)$	0.008	0.026
1% $\sigma(H_0)$ and $\sigma(d_L)/10$	0.001	–
1% $\sigma(H_0)$ and $\sigma(d_L)/10$ and $\sigma_{\delta v}/10$	0.0002	–
1% $\sigma(H_0)$ and $\sigma(d_L)/1000$ and $\sigma_{\delta v}/10$	3×10^{-5}	–
cosmic clocks		
2.5% $\sigma(H_0)$	0.019	0.05
1% $\sigma(H_0)$	0.008	0.02
1% $\sigma(H_0)$ and $\sigma(d_L)/10$	8×10^{-4}	
1% $\sigma(H_0)$ and $\sigma(d_L)/100$ and $\sigma_{H(z)}/10$	3×10^{-4}	–
1% $\sigma(H_0)$ and $\sigma(d_L)/1000$ and $\sigma_{H(z)}/10$	2×10^{-5}	–

Model-independent constraints on curvature

Energy Scale of Inflation

Energy scale of inflation is unknown, but in single field inflation

$$V^{1/4} \sim 3.3 \times 10^{16} r^{1/4}\,\mathrm{GeV}.$$

Tensor-to-scalar ratio

$$r = \mathcal{P}_T/\mathcal{P}_S \lesssim 10^{-1} \qquad \textit{Planck '15}$$

Different ways to measure *r*:

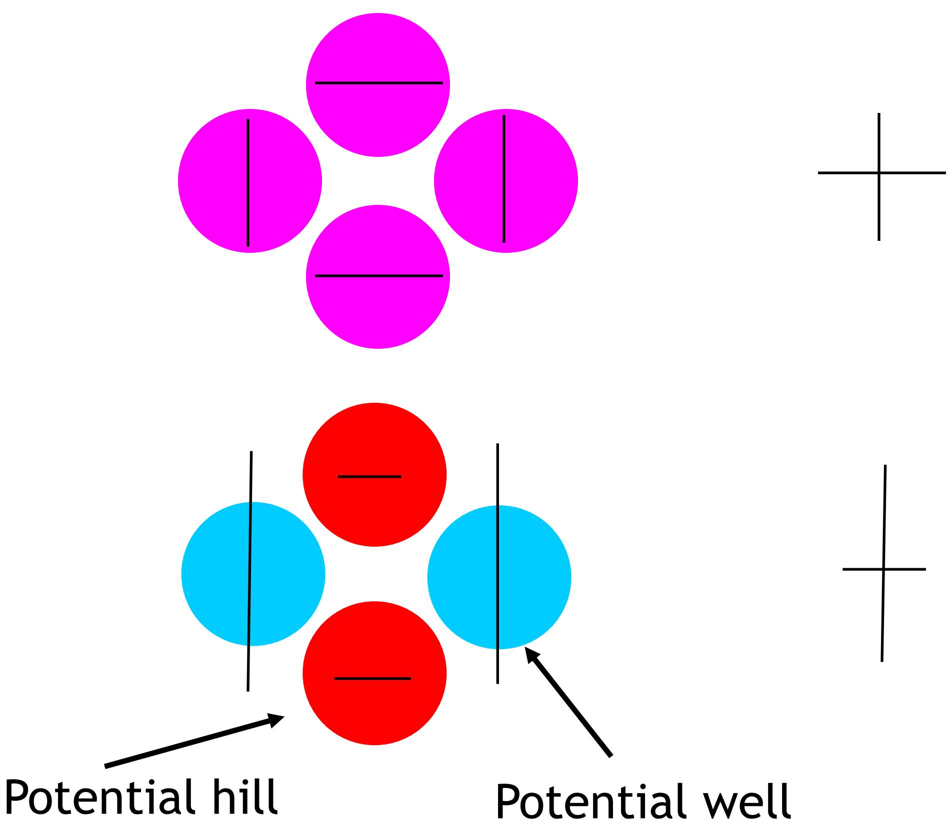
- CMB B-modes polarization.
- Gravitational Waves Background.
- Large Scale Structure.

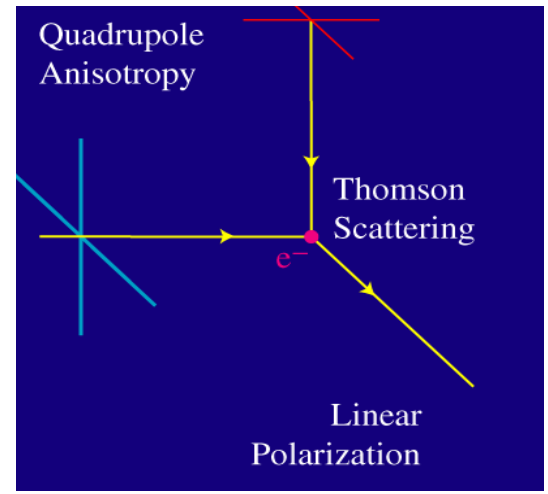
$$V^{1/4} = \left(\frac{3}{2}\pi^2 r \mathcal{P}_\zeta\right)^{1/4} M_P \sim 3.3 \times 10^{16}\ r^{1/4}\ \mathrm{GeV},$$

$$\mathcal{P}_\zeta = \frac{k^3}{2\pi^2} P_\zeta = \frac{1}{2M_P^2 \epsilon}\left(\frac{H_\star}{2\pi}\right)^2 \left(\frac{k}{aH_\star}\right)^{n_s - 1}$$

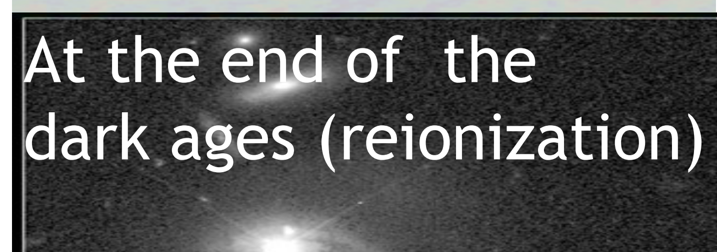
Generation of CMB polarization

- Temperature quadrupole at the surface of last scatter generates polarization.

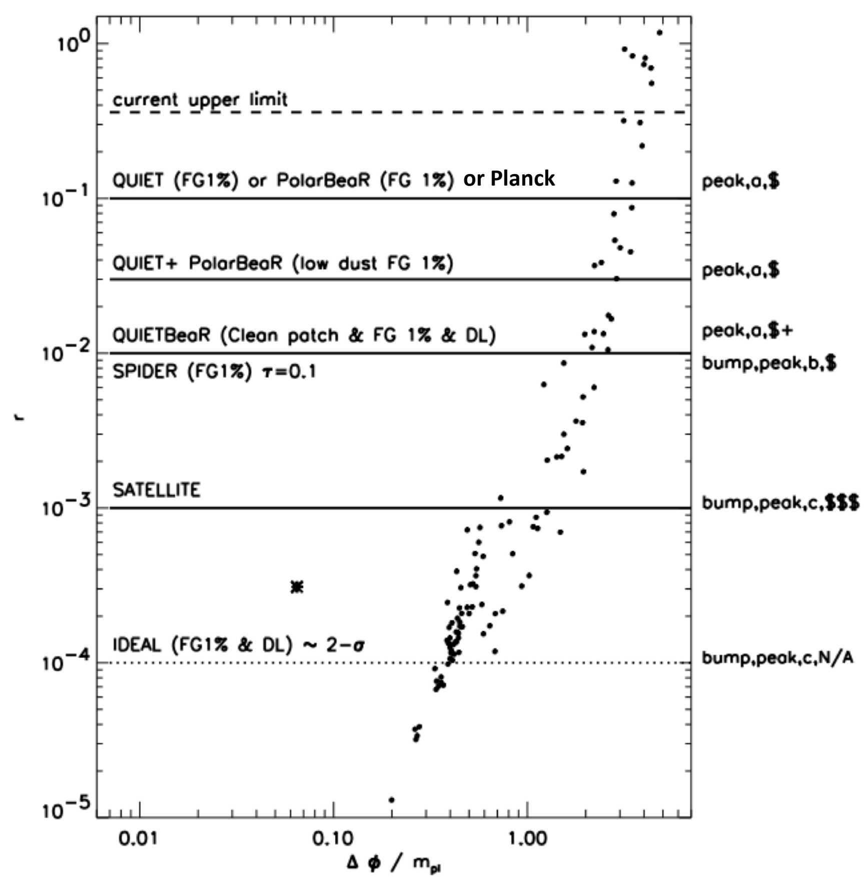




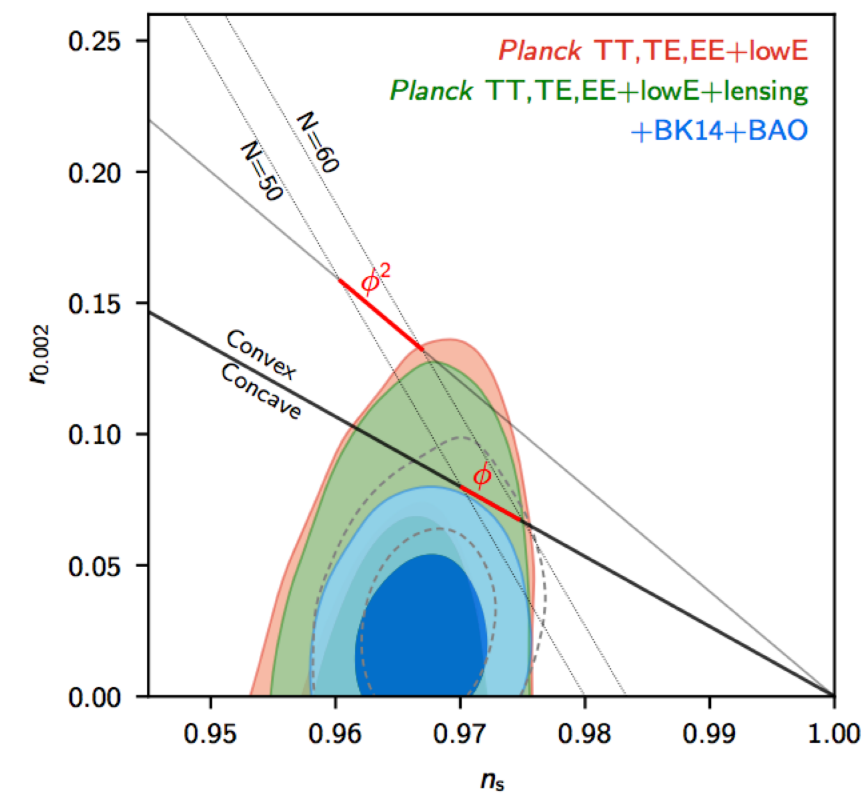
At the last scattering surface



Verde, Jimenez, Peiris JCAP 2005



Planck 2018

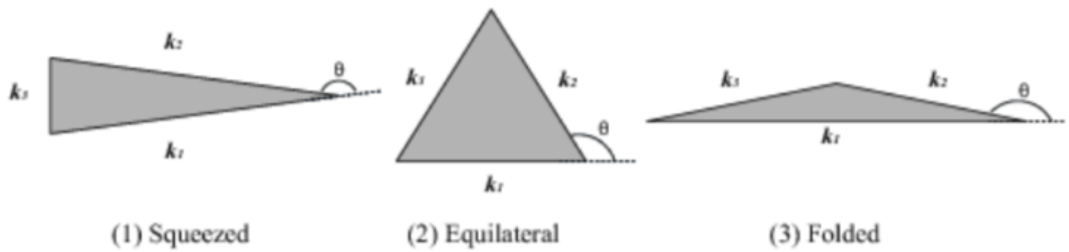


Only constraint we have is that $V^{1/4}$ > MeV as we have to make H and He

Coincidences (as told to me by Fergus Simpson)

NG and the Early Universe

Bispectrum (triangle) shapes yield information on early Universe physics.



- Local NG $\Longrightarrow$ Information on gravitational growth.
- Equilateral NG $\Longrightarrow$ Information on inflaton self-interaction.
- Folded NG $\Longrightarrow$ Information on initial state.

NG = Coupling of inflaton to Gravity

Inflationary predictions for f_{NL}

Models	$f_{\rm NL}$	Comments
Single–field inflation	$\mathcal{O}(\epsilon, \eta)$	ϵ, η slow-roll parameters
Curvaton scenario	$\frac{5}{4r} - \frac{5}{6}r - \frac{5}{3}$	$r \approx \left(\frac{\rho_\sigma}{\rho}\right)_{decay}$
Inhomogeneous reheating	$-\frac{5}{4} - I$	$I = -\frac{5}{2} + \frac{5}{12}\frac{\bar{\Gamma}}{\alpha \Gamma_1}$ "minimal case" $I = 0$ $(\alpha = \frac{1}{6}, \Gamma_1 = \bar{\Gamma})$
Multiple scalar fields	$\frac{\mathcal{P}_S}{\mathcal{P}_\mathcal{R}} \cos^2 \Delta \left(4 \cdot 10^3 \cdot \frac{V_{\chi\chi}}{3H^2}\right) \cdot 60 \frac{H}{\chi}$	order of magnitude estimate of the absolute value
Warm inflation	$-\frac{5}{6}\left(\frac{\dot{\varphi}_0}{H^2}\right)\left[\ln\left(\frac{\Gamma}{H}\right)\frac{V'''}{\Gamma}\right]$	Γ: inflaton decay rate
Ghost inflation	$-85 \cdot \beta \cdot \alpha^{-8/5}$	equilateral configuration
DBI	$-0.2\,\gamma^2$	equilateral configuration
Preheating scenarios	*e.g.* $\frac{M_{Pl}}{\varphi_0} e^{Nq/2} \sim 50$	N: number of inflaton oscillations
Inhomogeneous preheating and inhomogeneous hybrid inflation	*e.g.* $\frac{5}{6}\lambda_\varphi \left(\frac{M_{Pl}}{m_\chi}\right)^2 \sim 100$	λ_φ: inflaton coupling to the waterfall field χ
Generalized single-field inflation (including k-inflation and brane inflation)	$-\frac{35}{108}\left(\frac{1}{c_s^2} - 1\right) + \frac{5}{81}\left(\frac{1}{c_s^2} - 1 - 2\frac{\lambda}{\Sigma}\right)$	high when the sound speed $c_s \ll 1$ or $\lambda/\Sigma \gg 1$

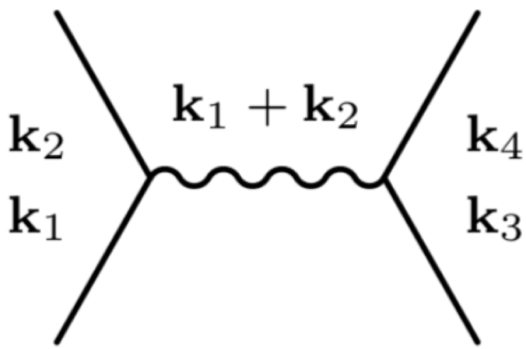
Look at Trispectrum

Non-Gaussianity results in non-trivial *n*-point functions:

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

$$\langle \delta\phi_{\mathbf{k}_1}\delta\phi_{\mathbf{k}_2}\delta\phi_{\mathbf{k}_3}\delta\phi_{\mathbf{k}_4}\rangle = (2\pi)^3\delta^D(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3+\zeta_{\mathbf{k}_4})T(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4)$$

Exchange contributions to 4-point functions:



Seery, Sloth, Vernizzi '08

Curvature 4-point function:

$$T_\zeta(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3\mathbf{k}_4) \propto r$$

This signal arises from correlations between inflaton fluctuations **mediated by a graviton and enters in the four-point function of scalar curvature perturbations**. The magnitude of this non-Gaussian effect is directly proportional to the tensor-to-scalar ratio r, therefore by isolating this contribution we can extract a direct information (or a stronger upper bound) on the energy scale of inflation. Moreover, this GE contribution contains much more information about inflationary dynamics, in particular on whether inflation is a strong isotropic attractor

NG signal generated by curvature perturbation is "passed" to matter perturbation.

$$\delta_m \propto \underbrace{\zeta}_{10^{-5}} + \underbrace{\text{NG Corrections}}_{\mathcal{O}(\zeta^2) \text{ or higher}}$$

Boosting the signal by looking to dark matter halos.

$$P_{\text{halo}}^{\text{NG}} - P_{\text{halo}}^{\text{G}} \propto \underbrace{B_{112}}_{\text{Bispectrum Contribution}} + \underbrace{T_{1112} + T_{1122}}_{\text{Trispectrum Contribution}} + \cdots$$

Since curvature perturbations are small (typically ζ ∼ O(10−5) at cosmological scales), it is naively believed that the (n + 1)-point function is just a small correction to the the n-point function, however this statement does not take into account the numerous possible mechanisms that can generate a non-Gaussian signal. Moreover, existing small non-Gaussianities can be boosted in the clustering of high density regions that underwent gravitational collapse, as the peaks of the matter density field, that today host virialized structures.

Look at the correlation of high excursion regions

Remember the **gist** behind this **NG bias**...

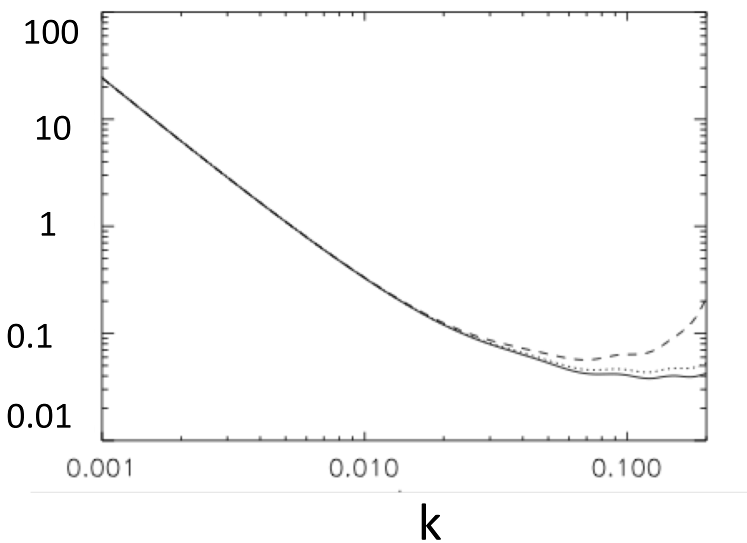
Local case

$$P_h(k,z) = \frac{\delta_c^2(z) P_{\delta\delta}(k,z)}{\sigma_R^4 D^2(z)} \left[1 + 4 f_{NL} \delta_c(z) \frac{\mathcal{F}_R(k)}{\mathcal{M}_R(k)} \right]$$

Gaussian bias (squared)
-can be improved...-

In general

$$\frac{\delta_c}{8\pi^2\sigma_R^2} \int dk_1 k_1^2 \mathcal{M}_R(k_1) \times \int_{-1}^{1} d\mu \mathcal{M}_R\left(\sqrt{\alpha}\right) \frac{B_\phi(k_1, \sqrt{\alpha}, k)}{P_\phi(k)}.$$



$$\frac{P_{NG} - P_G}{P_G}$$

Acts as a scale dependent (and z dependent) bias!

Important on large scales!

In this work we are mainly interested in the four-point function or trispectrum, in particular its connected part (the disconnected part is always present even in the purely Gaussian case). The complete form of the curvature perturbation trispectrum in single-field inflation, up to second order in slow-roll parameters is:

$$
\begin{aligned}
T_\zeta(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4) = {} & (\partial_\varphi N)^4 T_{\delta\varphi}(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4) \\
& + (\partial_\varphi^2 N)(\partial_\varphi N)^3 \left[P_{\delta\varphi}(k_1) B_{\delta\varphi}(k_{12},k_3,k_4) + (11 \text{ perms})\right] \\
& + (\partial_\varphi^2 N)^2(\partial_\varphi N)^2 \left[P_{\delta\varphi}(k_{13}) P_{\delta\varphi}(k_3) P_{\delta\varphi}(k_4) + (11 \text{ perms})\right] \\
& + (\partial_\varphi^3 N)(\partial_\varphi N)^3 \left[P_{\delta\varphi}(k_2) P_{\delta\varphi}(k_3) P_{\delta\varphi}(k_4) + (3 \text{ perms})\right],
\end{aligned}
$$

Graviton exchange is NOT suppressed by high-orders of slow-roll parameters

However, things are different when we consider the exchange of a graviton. In this case the interaction Lagrangian between a graviton and two scalars is not suppressed by any powers of slow-roll parameters at all, *i.e.*, $\mathcal{L}_{\gamma\zeta\zeta}/\mathcal{L}_{\zeta\zeta} \sim P_\gamma^{1/2}$ and therefore

$$\sim r^{1/2} \, .$$

Dark Matter Halos

We consider the alternative approach of looking at the effect of the GE trispectrum contribution in the halo two- and three-point functions. The trispectrum due to a graviton exchange is given by

$$\langle \zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}\zeta_{\mathbf{k}_4}\rangle^{\mathrm{GE}} = (2\pi)^3\delta(\mathbf{k}_{1234})\left(\frac{H_\star^2}{4\epsilon}\right)^3 \frac{r/4}{\prod_j k_j^3}\times$$
$$\times\left[\frac{k_1^2k_3^2}{k_{12}^3}\left[1-(\hat{\mathbf{k}}_1\cdot\hat{\mathbf{k}}_{12})^2\right]\left[1-(\hat{\mathbf{k}}_3\cdot\hat{\mathbf{k}}_{12})^2\right]\cos 2\chi_{12,34}\cdot(\mathcal{I}_{1234}+\mathcal{I}_{3412})+\right.$$
$$+\frac{k_1^2k_2^2}{k_{13}^3}\left[1-(\hat{\mathbf{k}}_1\cdot\hat{\mathbf{k}}_{13})^2\right]\left[1-(\hat{\mathbf{k}}_2\cdot\hat{\mathbf{k}}_{13})^2\right]\cos 2\chi_{13,24}\cdot(\mathcal{I}_{1324}+\mathcal{I}_{2413})+$$
$$\left.+\frac{k_1^2k_2^2}{k_{14}^3}\left[1-(\hat{\mathbf{k}}_1\cdot\hat{\mathbf{k}}_{14})^2\right]\left[1-(\hat{\mathbf{k}}_2\cdot\hat{\mathbf{k}}_{14})^2\right]\cos 2\chi_{14,23}\cdot(\mathcal{I}_{1423}+\mathcal{I}_{2314})\right],$$

All is left is to perform the corresponding integrals

In Fourier Space

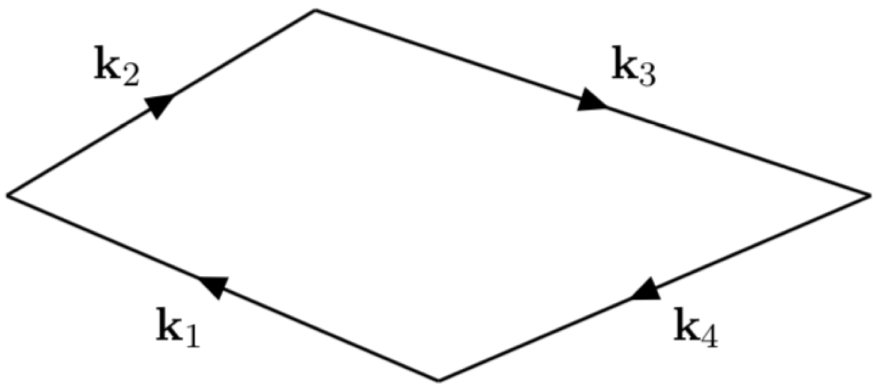
$$P^{NG}_{\text{halo}}(k,z) \approx P^{G}_{\text{halo}}(k,z) + B_{112}(k,z) + T_{1112}(k,z) + T_{1122}(k,z) + M_{12-112}(k,z).$$

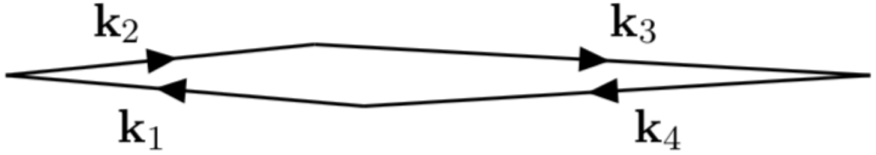
$$P^{G}_{\text{halo}}(k,z) \approx b_L^2(z) P_R(k,z) + \frac{b_L^4(z)}{2} \int \frac{d^3q}{(2\pi)^3} P_R(q,z) P_R(|\mathbf{k}-\mathbf{q}|,z)$$

$$\begin{aligned}
B_{112}(k,z) &= b_L^3(z)\,\mathrm{FT}\left\{\xi_R^{(3)}(\mathbf{x}_1,\mathbf{x}_1,\mathbf{x}_2)\right\} = \\
&= b_L^3(z) \int \frac{d^3q}{(2\pi)^3} \mathcal{M}_R(q,z)\mathcal{M}_R(|\mathbf{k}-\mathbf{q}|,z)\mathcal{M}_R(k,z) B_\zeta(\mathbf{q},\mathbf{k}-\mathbf{q},-\mathbf{k}), \\
T_{1112}(k,z) &= \frac{b_L^4(z)}{3}\,\mathrm{FT}\left\{\xi_R^{(4)}(\mathbf{x}_1,\mathbf{x}_1,\mathbf{x}_1,\mathbf{x}_2)\right\} = \\
&= \frac{b_L^4(z)}{3} \int \frac{d^3q_1}{(2\pi)^3}\frac{d^3q_2}{(2\pi)^3} \mathcal{M}_R(q_1,z)\mathcal{M}_R(q_2,z)\mathcal{M}_R(|\mathbf{k}-\mathbf{q}_{12}|,z)\mathcal{M}_R(k,z)\times \\
&\qquad \times T_\zeta(\mathbf{q}_1,\mathbf{q}_2,\mathbf{k}-\mathbf{q}_{12},-\mathbf{k}), \\
T_{1122}(k,z) &= \frac{b_L^4(z)}{4}\,\mathrm{FT}\left\{\xi_R^{(4)}(\mathbf{x}_1,\mathbf{x}_1,\mathbf{x}_2,\mathbf{x}_2)\right\} = \\
&= \frac{b_L^4(z)}{4} \int \frac{d^3q_1}{(2\pi)^3}\frac{d^3q_2}{(2\pi)^3} \mathcal{M}_R(|\mathbf{k}-\mathbf{q}_1|,z)\mathcal{M}_R(q_1,z)\mathcal{M}_R(q_2,z)\mathcal{M}_R(|\mathbf{k}+\mathbf{q}_2|,z)\times \\
&\qquad \times T_\zeta(\mathbf{k}-\mathbf{q}_1,\mathbf{q}_1,\mathbf{q}_2,-\mathbf{k}-\mathbf{q}_2),
\end{aligned}$$

$$\begin{aligned}
M_{12-112}(k,z) &= b_L^5(z)\,\mathrm{FT}\left\{\xi_R^{(2)}(\mathbf{x}_1,\mathbf{x}_2)\xi_R^{(3)}(\mathbf{x}_1,\mathbf{x}_1,\mathbf{x}_2)\right\} \\
&= b_L^5(z) \int \frac{d^3q_1}{(2\pi)^3}\frac{d^3q_2}{(2\pi)^3} P_R(|\mathbf{k}-\mathbf{q}_{12}|,z) B_R(q_1,q_2,q_{12},z).
\end{aligned}$$

Look at Graviton Exchange and “kite” shapes



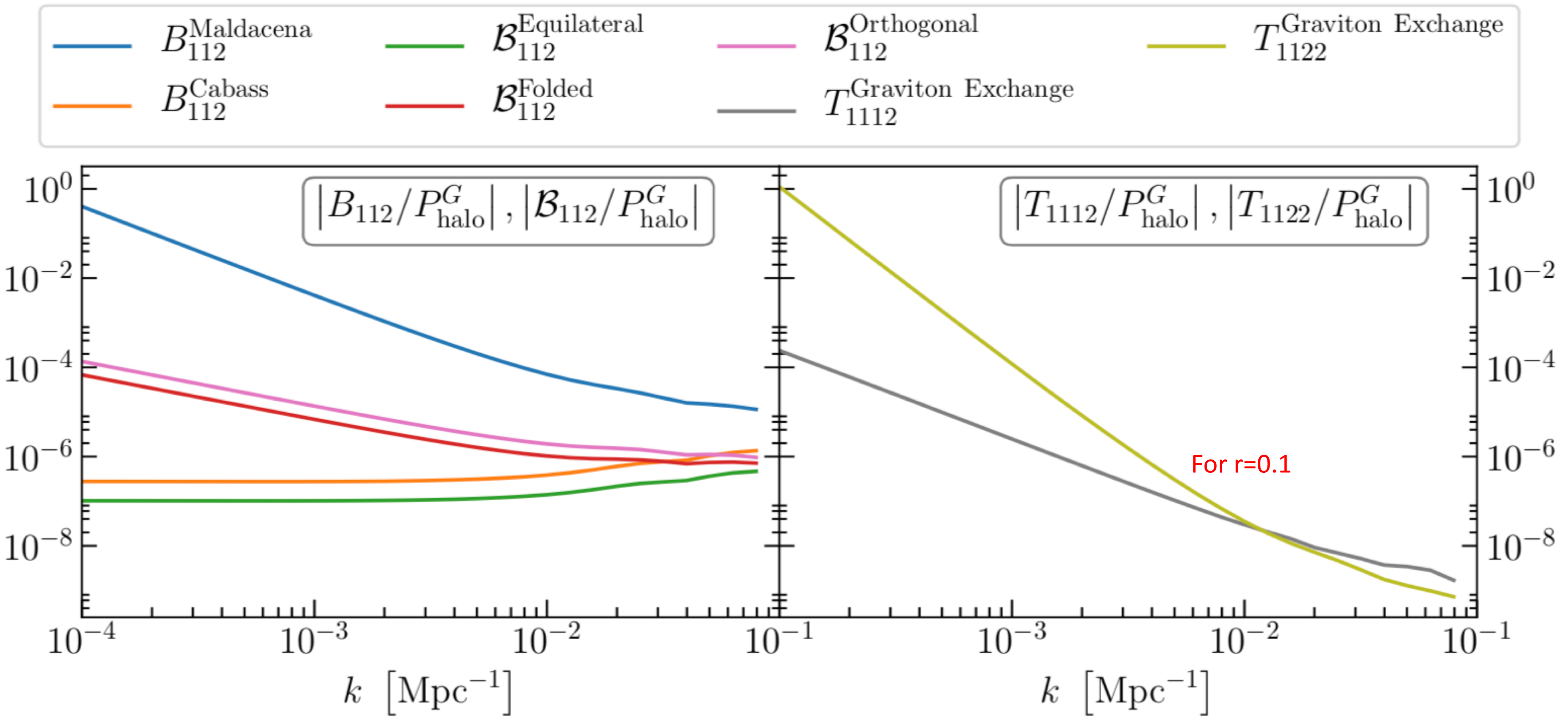


$k_{13} \ll k_1 \sim k_3, k_2 \sim k_4$

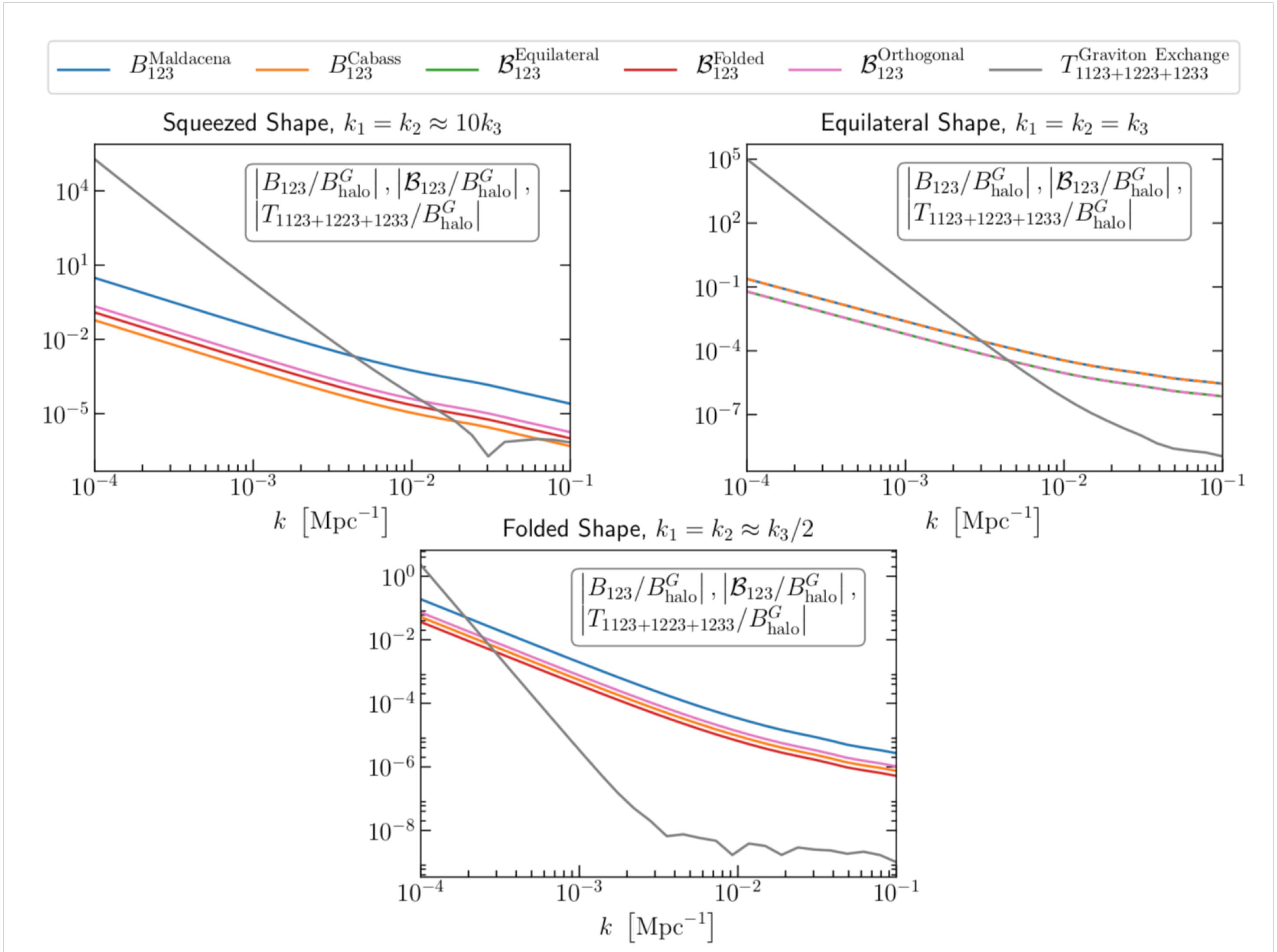
$k_{12} \ll k_1 \sim k_2, k_3 \sim k_4$

Signal in **Halo Power Spectrum**

ratio between different bispectra and the Gaussian halo power spectrum at redshift z = 0



Signal in the Halo Bispectrum



Conclusions

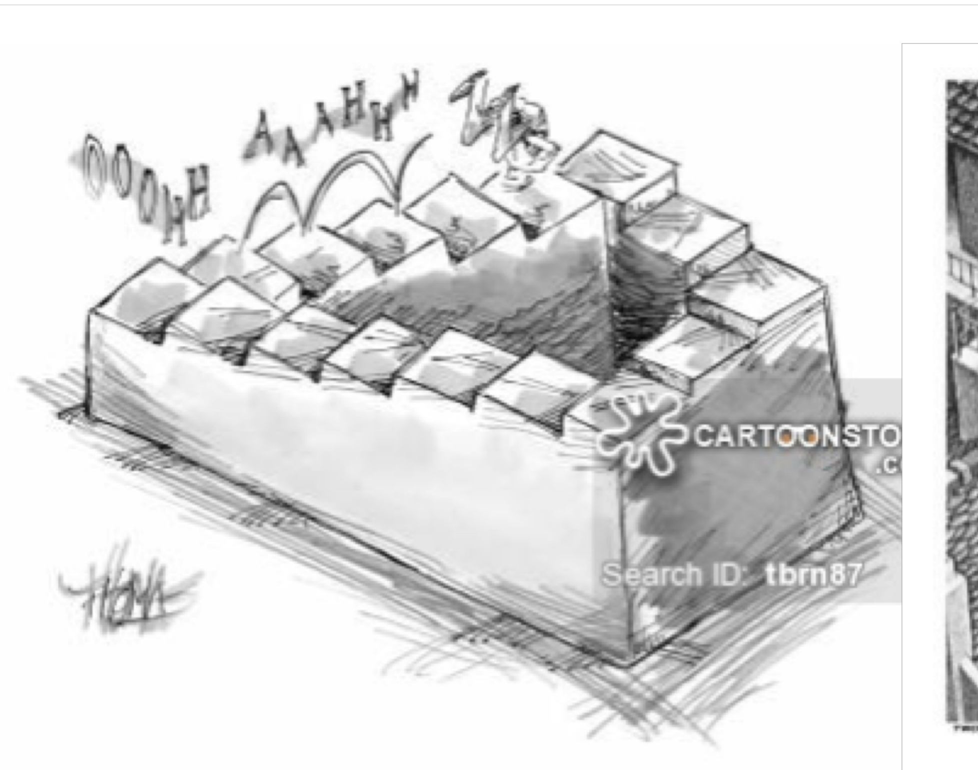
1. Determining the underlying physics of inflation is one of the big goals of Cosmology. A first step necessary to accomplish such a goal is **determining the inflationary energy scale.**

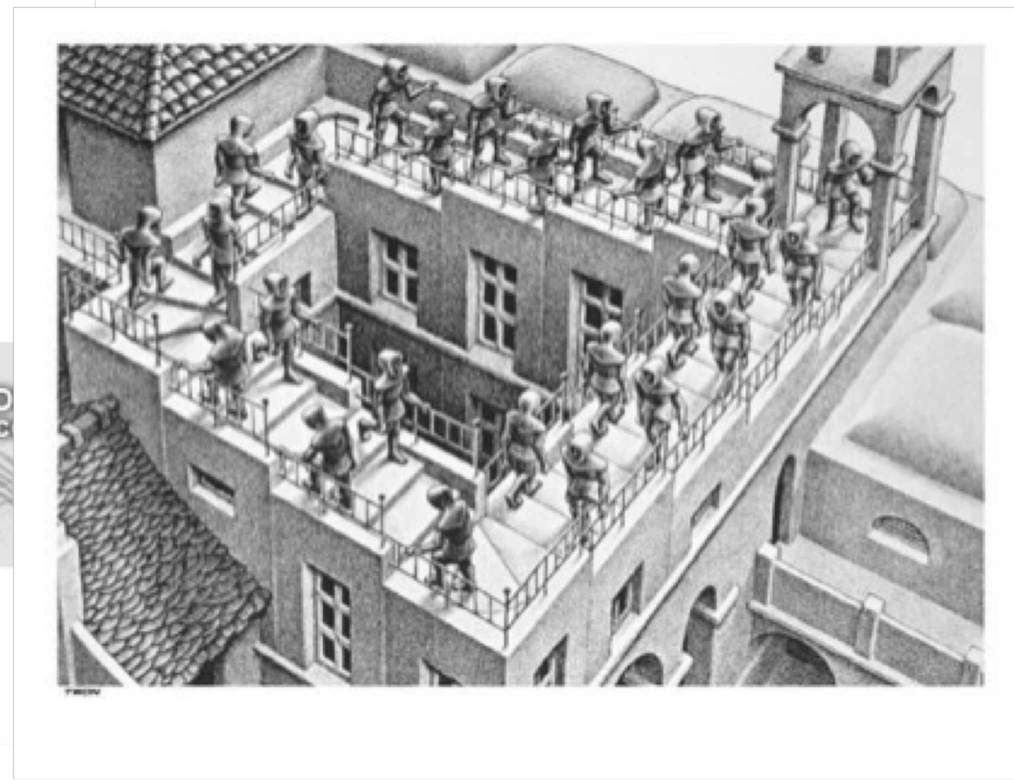
2. Non-Gaussianities are unavoidably produced during inflation and they constitute on their own a probe of the inflationary physics

3. We focused on the so-called graviton exchange, in particular on the specific non- Gaussianity generated by the interaction of scalar and tensor fluctuations at the horizon scale during the epoch of inflation. This contribution to the four-point function is that it is **suppressed only by one power of the slow-roll parameter**.

4. Here we proposed to look at the n-point function of gravitationally collapsed structures to further boost the signal coming from the primordial universe. We have shown that at large scales ($k \sim 10{-}4 - 10{-}3$ Mpc-1) the contribution due to graviton exchange to the power spectrum of rare **peaks is comparable to, if not dominant over, the one generated by the primordial three-point function expected from generic inflationary models** (e.g., Maldacena and Cabass bispectrum).

More Conclusions: which one? When is the next DISRUPTION going to happen? Which dataset? Which Theory?





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EXCELENCIA MARÍA DE MAEZTU

Oportunities @ ICC-UB (Barcelona)

http://icc.ub.edu/job/offers

Postdoctoral position(S) in Cosmology (see AAS jobs or link above)

Fellowship: Junior leader “la caixa” (deadline 26 Sept!!!)

Ask Hector Gil-Marin for practical info
and contact Licia Verde if you want to apply
Time is short!

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