UV signatures in cosmological data

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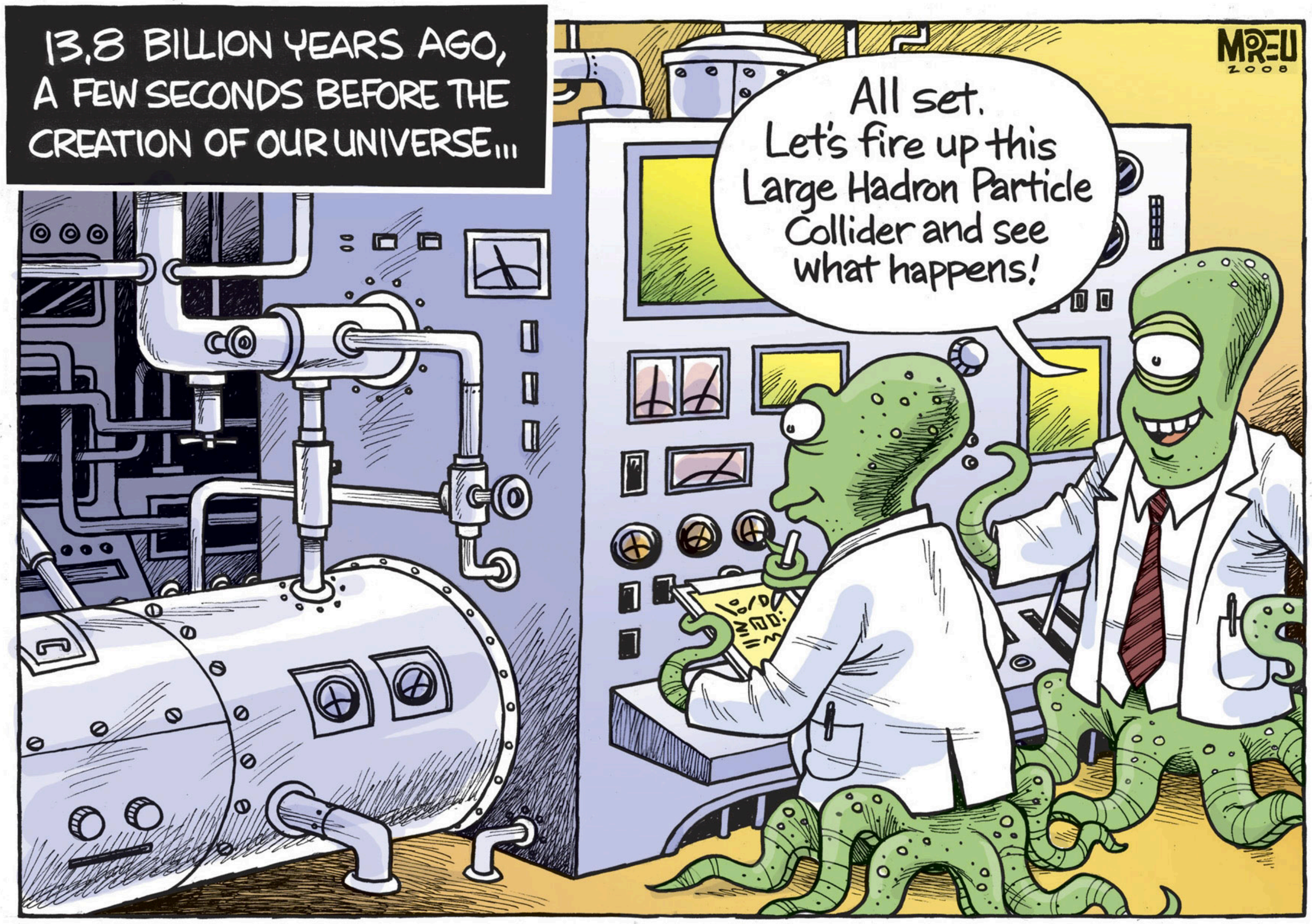
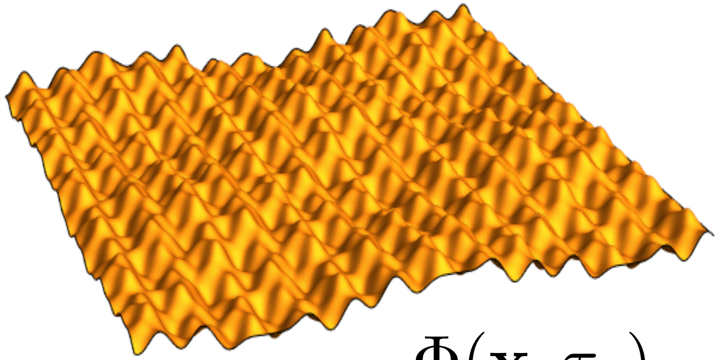


MREU 2008

INTRODUCTION TO NON-GAUSSIANITIES

Primordial density perturbations

Primordial density perturbations



$\Phi(\mathbf{x}, \tau_\mathbf{0})$

Time evolution

CMB, large scale structure

Hubble deep field

The physical properties of the field Φ are given by its n-point functions.

Power spectrum $$P(k) \propto \langle \Phi(k)\Phi(k) \rangle$$

Bispectrum $$B(k_1, k_2, k_3) \propto \langle \Phi(k_1)\Phi(k_2)\Phi(k_3) \rangle$$

Gaussian random field: all higher n-point functions are given by products of the 2-point function. **Otherwise we speak of "non-Gaussianity".**

From inflation interactions to the CMB

We assume that the primordial density fluctuations are created during inflation.

Primordial non-gaussianities are **a measure of interactions during inflation.**

non-Gaussianity ⟺ **Connected n-point functions** ⟺ **Interactions of primordial fields**

Predictions for cosmological measurements:

$$\mathcal{L}_{\text{infl}}(\Phi, g_{\mu\nu}, ..) \xrightarrow{\text{Step 1}} \Phi(\mathbf{x}, \tau_{\mathbf{0}}) \xrightarrow{\text{Step 2}} \begin{matrix} LSS \\ T_{\text{CMB}} \end{matrix}$$

Goal of primordial non-gaussianity search.

Step 1: Calculating primordial correlators

We want to calculate expectation values of field operators at equal time τ_0.

$$\langle \Phi_{\mathbf{k}_1}(\tau_0)\Phi_{\mathbf{k}_2}(\tau_0)\Phi_{\mathbf{k}_3}(\tau_0)\rangle$$

Perturbation theory similar to QFT correlation functions in particle physics.

At tree level:

First complete treatment: Maldacena 2002

$$\langle \Phi_{\mathbf{k}_1}\Phi_{\mathbf{k}_2}\Phi_{\mathbf{k}_3}\rangle \propto \int d\tau \langle \Phi^I_{\mathbf{k}_1}\Phi^I_{\mathbf{k}_2}\Phi^I_{\mathbf{k}_3} H_{\mathrm{I}}(\tau)\rangle$$

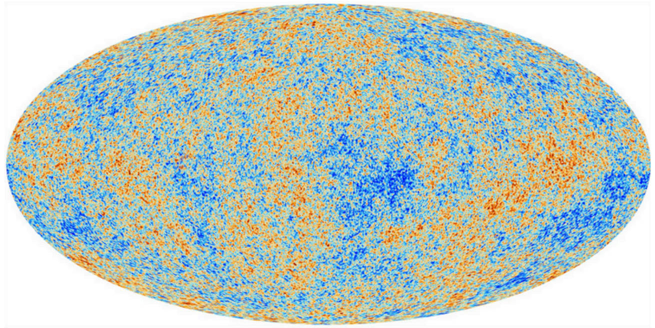
Interaction Hamiltonian of the model

With this calculation, one gets the map

$$\mathcal{L}_{\mathrm{inflation}} \Rightarrow B(k_1,k_2,k_3) \propto \langle \Phi_{\mathbf{k}_1}\Phi_{\mathbf{k}_2}\Phi_{\mathbf{k}_3}\rangle$$

In principle we could measure QFT correlators in the sky!

Step 2: calculate CMB bispectrum



From primordial potential to CMB multipoles

$$a_{lm}^{\mathrm{CMB}} = \int d^3\mathbf{k}\ \mathbf{\Phi}(\mathbf{k})\ \mathbf{\Delta}_{\mathrm{transfer}}(\mathbf{k})\ \mathbf{Y_{lm}}(\hat{\mathbf{k}})$$

From primordial bispectrum to CMB bispectrum

$$\langle \Phi(k_1)\Phi(k_2)\Phi(k_3)\rangle \xrightarrow{\mathbf{\Delta}_{\mathrm{transfer}}(\mathbf{k})} \langle a_{l_1m_1}a_{l_2m_2}a_{l_3m_3}\rangle \simeq B_{l_1l_2l_3}^{\mathrm{CMB}}$$

Summary: Each inflation model (Lagrangian + initial conditions) predicts a CMB bispectrum shape (although **often unmeasurably small**).

$$\mathcal{L}(\Phi, g_{\mu\nu}, \ldots) \longrightarrow B_{l_1l_2l_3}^{\mathrm{CMB}}$$

Bispectrum estimation in the CMB

In CMB non-Gaussianity search, we **estimate the amplitude f_{NL}** of theoretically well-motivated CMB bispectrum shapes.

$$\langle a_{l_1 m_1} a_{l_2 m_2} a_{l_3 m_3} \rangle_{\text{data}} \propto \hat{f}_{NL} B^{\text{theo}}_{l_1 l_2 l_3}$$

Some Planck 2015 contraints:

$$f_{NL}^{\text{local}} = 0.8 \pm 5.0$$

$$f_{NL}^{\text{equilateral}} = -4 \pm 43$$

Overlap (inner product) of CMB bispectrum shapes:

$$B^1 \cdot B^2 = \frac{1}{\mathcal{N}} \sum_{l_1 l_2 l_3} \frac{B^1_{l_1 l_2 l_3} B^2_{l_1 l_2 l_3}}{C_{l_1} C_{l_2} C_{l_3}}$$

The oscillating bispectrum shapes in this talk generally have little overlap with previously constrained shapes.

PART 1: AXION MONODROMY & RESONANCE NON-GAUSSIANITY

Shift symmetry

The slow roll potential of inflation **must be protected from quantum corrections** of form

$$\Delta\mathcal{L} = \frac{\mathcal{O}_\Delta}{\Lambda^{\Delta-4}}$$

Λ : UV scale $\qquad \Delta$: Operator dimension

Eta problem: η << 1 sensitive to Δ≤ 6 operators.

Large field models: Sensitivity to infinite series of operators of arbitrary dimension.

→ **We need a symmetry to control these corrections!**

Use a **shift symmetry** to make the potential exactly flat

$$\Phi \to \Phi + \mathrm{const.}$$

Slightly break the shift symmetry (e.g. by a small mass term) to get slow roll.

→ **radiatively stable, technically natural** theory

Axion monodromy and discrete shift symmetry

UV complete model with shift symmetry: **Axion monodromy inflation.**

$$V(\varphi) = \mu^3 \varphi^p + \Lambda^4 \cos\left(\frac{\varphi}{f}\right)$$

Silverstein et al.

Monodromy ("spiral staircase"): inflation over multiple circuits of a single periodic axion field.

discrete version of shift symmetry

$$\varphi \to \varphi + 2\pi f$$

Periodicity of the UV theory → approximate discrete shift symmetry

Oscillating potentials and resonances

Axion monodromy inflation motivates the search for observable consequences of oscillating potentials.

Oscillation in BG evolution → **Oscillations in the couplings**

Interaction Vertex → $$\int d\tau\ \tau\ \sin(\omega t)\ e^{i(k_1+k_2+k_3)\tau}$$

Chen et al. 2008

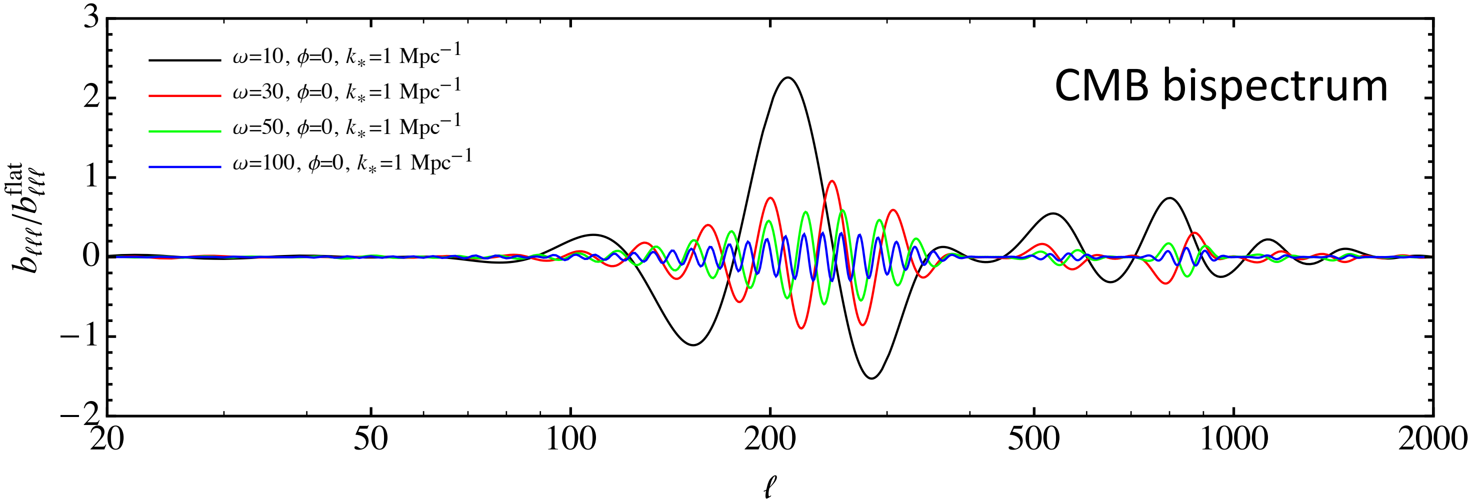
Resonance between couplings and modes

$$B(k_1, k_2, k_3) = \frac{f_{NL}}{(k_1 k_2 k_3)^2} \sin\left(\omega \ln(k_1 + k_2 + k_3) + \varphi\right)$$

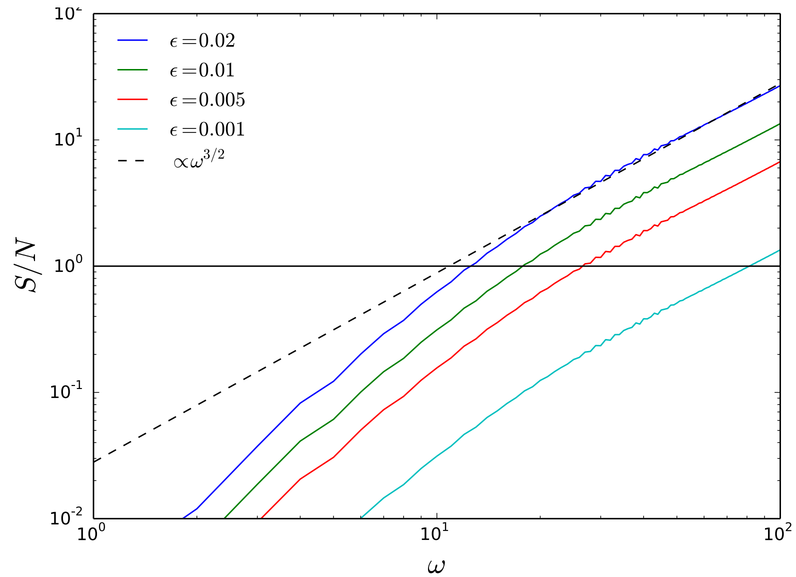
Non-gaussianity in these models could be observably large!

Projection to the CMB and forecast

$$B(k_1, k_2, k_3) \xrightarrow{\Delta_{\text{transfer}}(\mathbf{k})} B^{\text{CMB}}_{l_1 l_2 l_3}$$



EFTI prediction (*Behabani et al. 2013*) based signal-to-noise forecast:



Münchmeyer, Meerburg, Wandelt, PRD 2015

Estimator via separable expansion

Efficient estimation requires separability: *"KSW", Komatsu et. al 2003*

$$B(k_1, k_2, k_3) = f(k_1)g(k_2)h(k_3)$$

Resonance bispectrum is not separable!

Modal expansion *(Fergusson et al. 2009)*: Expand any shape as

$$B(k_1, k_2, k_3) = \sum_{p,r,s} c_{prs} q_p(k_1) q_r(k_2) q_s(k_3)$$

Problem: With a general basis, and ~1000 modes, **limited to ω<50**

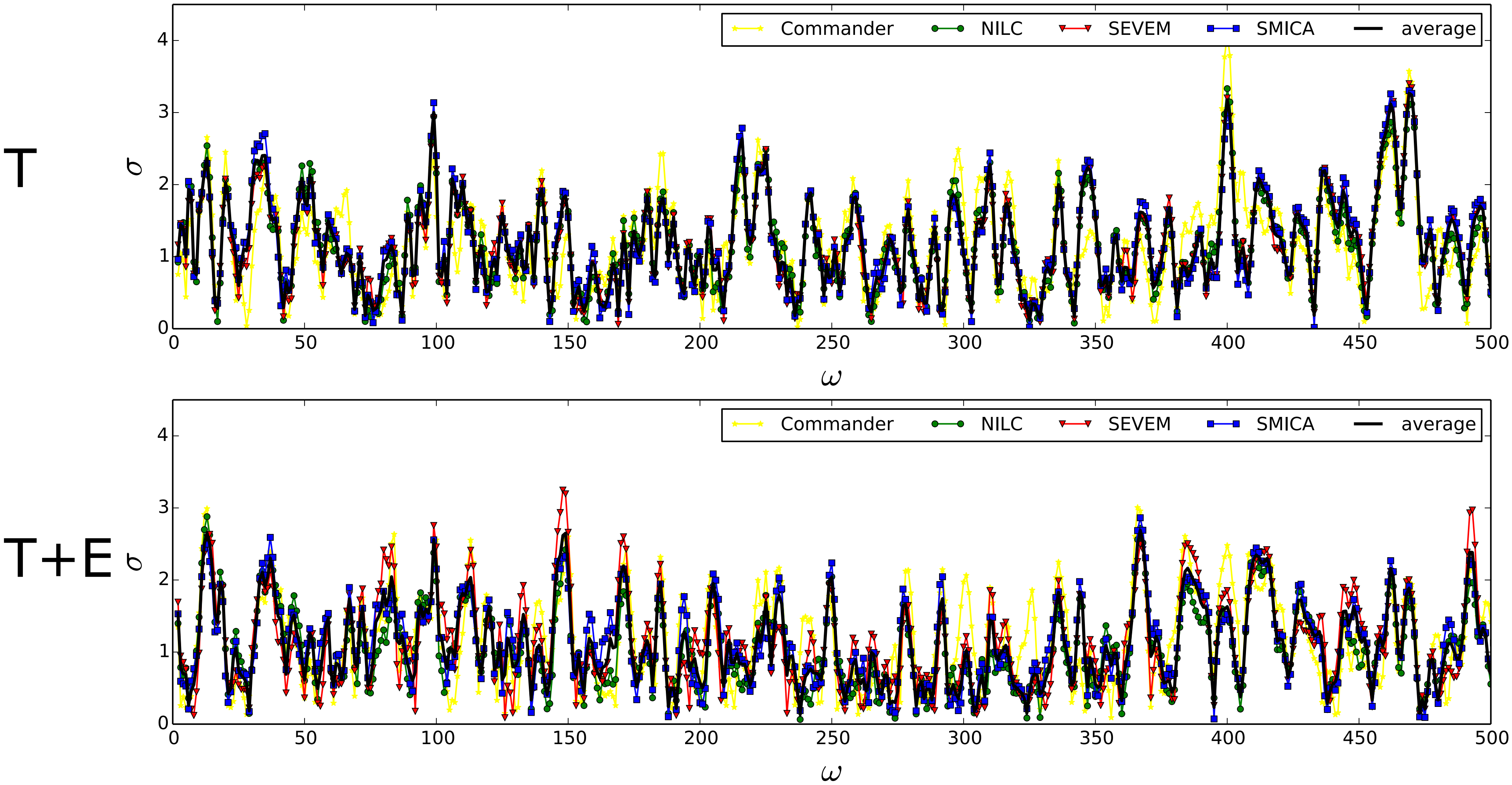
New idea *(Münchmeyer, Meerburg, Wandelt, PRD 2015)***:**

Exploit the effective 1d property of the shape

$$B(k_1, k_2, k_3) \propto \sin(\omega \ln(k_1 + k_2 + k_3)) = \sum_i \alpha_i \sin\left(\omega_i (k_1 + k_2 + k_3)\right)$$

Now 1000 modes cover full frequency range of interest **ω<1000**

Results from Planck



Y axis: local significance (maximized over phase).

Planck 2015 results. XVII. Constraints on primordial non-Gaussianity.

Look elsewhere effect

Standard method of Gaussian map simulation is computationally intractable.

Our method: **analytic approximation to the estimator PDF:**

$$P(\{\hat{A}^{\sin,\cos}_{\omega_i}\}) = \mathcal{N}(\mu = 0, \Sigma) \qquad\qquad \Sigma = \frac{F_{ij}}{F_{ii}F_{jj}}$$

Technical details of how to calculate this in

Meerburg, Münchmeyer, Wandelt 2015

Result for this class of bispectra:

Look-elsewhere corrected significances:

Single peak significance: 0.5σ

Multi peak significance: 0.6σ

Clearly no sign of non-Gaussianity.

Related shapes and analyses

Modified resonance bispectra have been tested at lower frequency with the modal expansion.

	SMICA		
	Raw	Single	Multi
Sin(Log) constant T-only	2.4	0.7	1.2
Sin(Log) constant T+E	2.4	0.7	1.7
Sin(Log) equilateral T-only	3.0	1.6	2.4
Sin(Log) equilateral T+E	3.5	2.2	3.5
Sin(Log) flattened T-only	2.5	0.7	1.8
Sin(Log) flattened T+E	2.9	1.4	2.9

Planck non-Gaussianity paper 2015

Weak hints, but not significant.

Another possibility: Need to take into account frequency drifting?

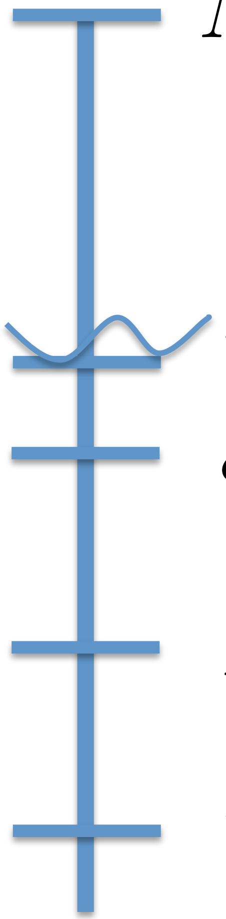
Flauger et al 2014: « Drifting Oscillations in Axion Monodromy »

Todo: combine power spectrum, bispectrum, trispectrum (?) analysis.

HEAVY PARTICLES AND AXION MONODROMY

Energy scales

Inflation is the highest energy particle collider (indirectly) available to us, probably forever. → We need to **read off the results as precisely as possible.**



$M_{\rm Pl}$ $10^{19}{\rm GeV}$

m_χ

These particles cannot be integrated out if masses are background field dependent!

$\dot\phi^{1/2} \sim 10^{5/2} H$

H e.g. $10^{14}{\rm GeV}$ Energy scale of inflation.

$m_{\rm inflaton}$ e.g. $10^{11}{\rm GeV}$

LHC energy $\sim 10^4{\rm GeV}$

Non-adiabatic particle production

Inflaton dependent mass term $m_\chi(\phi)^2\chi^2$

EOM of the massive field χ

$$\ddot{\psi}_k + 3H\dot{\psi}_k + \omega_k^2\psi_k = 0 \qquad \omega_k^2 = \mu^2 + \Delta m(t)^2 + (k/a)^2$$

Particle production happens when the evolution becomes non-adiabatic

$$|\dot{\omega}_k| > \omega_k^2$$

Number density of χ particles produced per production event

$$\langle n_\chi \rangle \equiv \bar{n}_\chi \sim (g\dot{\phi})^{3/2} \exp[-\frac{\pi\mu^2}{g\dot{\phi}}]$$

Flauger, Mirbabayi, Senatore, Silverstein, to appear

More favorable exponential suppression than that of vacuum fluctuations

$$e^{-\frac{\pi\mu^2}{\dot{\phi}}} \quad \text{compared to} \quad e^{-\frac{\mu}{H}}$$

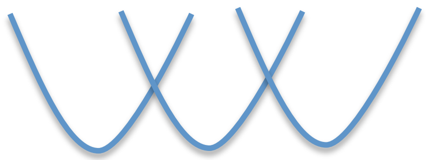
Oscillating masses from axion monodromy

Coupling **heavy fields via field dependent mass**

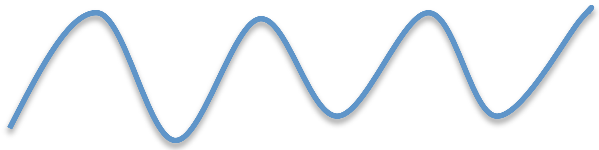
$$V(\chi_I, \phi) \simeq \sum_I \frac{1}{2} m_{\chi_I}(\phi)^2 \chi_I^2 + V_0(\phi)$$

Discrete shift symmetry also motivates a periodic mass function. Axion monodromy includes two sectors of this type:

- Case 2a $\mathcal{L}_m = \sum_n \frac{1}{2}\chi^2(\mu^2 + g^2(\phi - 2\pi n f)^2)$



- Case 2b $\mathcal{L}_m = \frac{1}{2}\chi^2(\mu^2 + 2g^2 f^2 \cos\frac{\phi}{f})$



Flauger, Mirbabayi, Senatore, Silverstein, to appear

These fields are generally included in the theory and their effects **can be large enough to be observable in the CMB, in particular with possible large bispectrum.**

Calculating power spectrum and bispectrum

Particle production sources inflaton/curvature perturbations

$$J = \chi^2 \frac{\delta}{\delta\phi} m_\chi^2$$

Calculate n-pt function of the sources, e,g $\langle JJJ \rangle$

and from that the **inflaton/curvature n-point functions**

$$\langle \delta\phi_{\mathbf{k}_1} \ldots \delta\phi_{\mathbf{k}_N} \rangle \sim (2\pi)^3 \delta(\sum \mathbf{k}_i) \frac{\bar{n}_\chi}{H^3} H^{N+3} \sum_n (H\eta_n)^{-3} \Pi_{i=1}^N \frac{\hat{h}(k_i \eta_n)}{k_i^3}$$

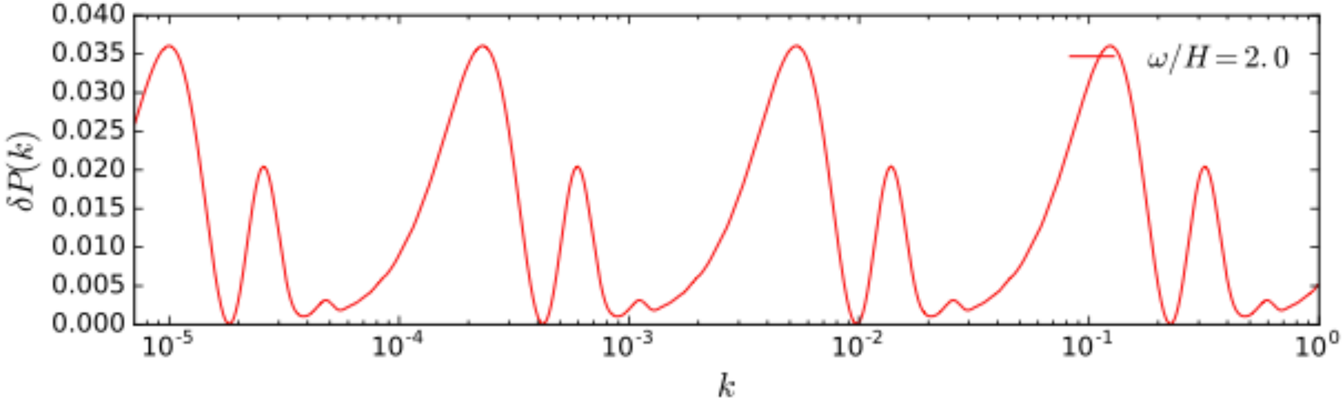
Flauger, Mirbabayi, Senatore, Silverstein, to appear

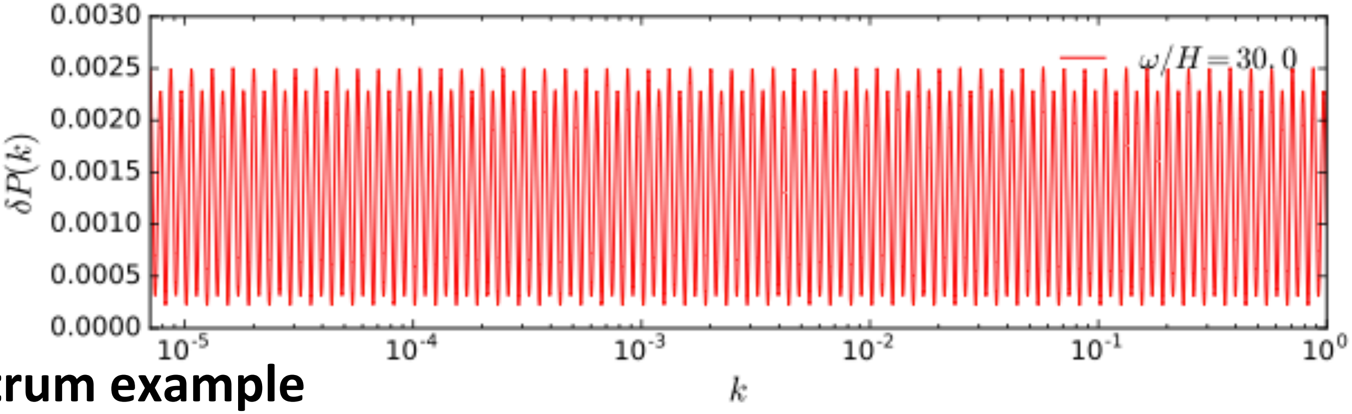
Power spectrum and bispectrum can have comparable signal-to-noise.

Besides these source terms, there are additional interference terms like X particle annihilation that also contribute.

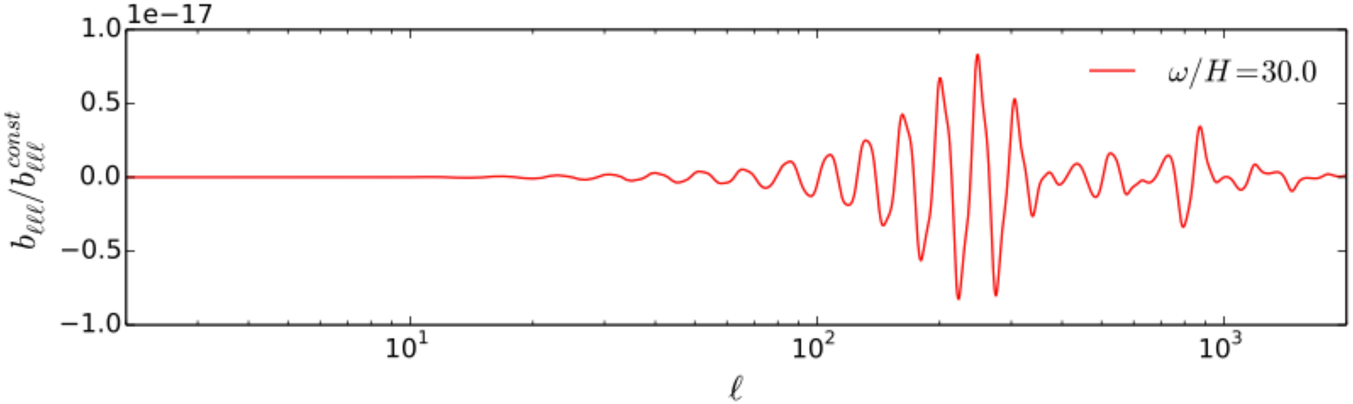
What does it look like?

Primordial power spectrum example:





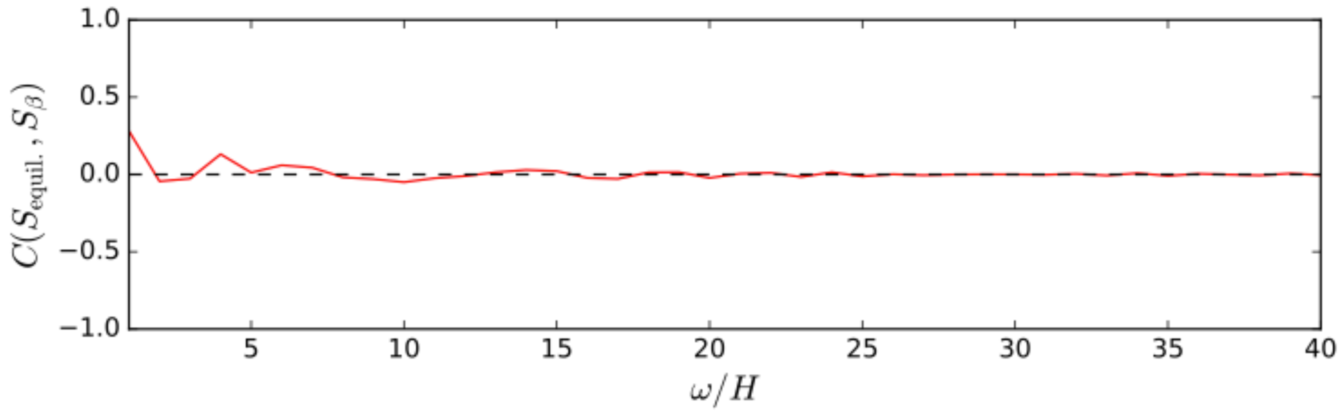
CMB bispectrum example



CMB analysis

No significant overlap with previously examined shapes

For example correlator with equilateral shape:



→ Needs dedicated analysis.

Work in progress. Challenges:

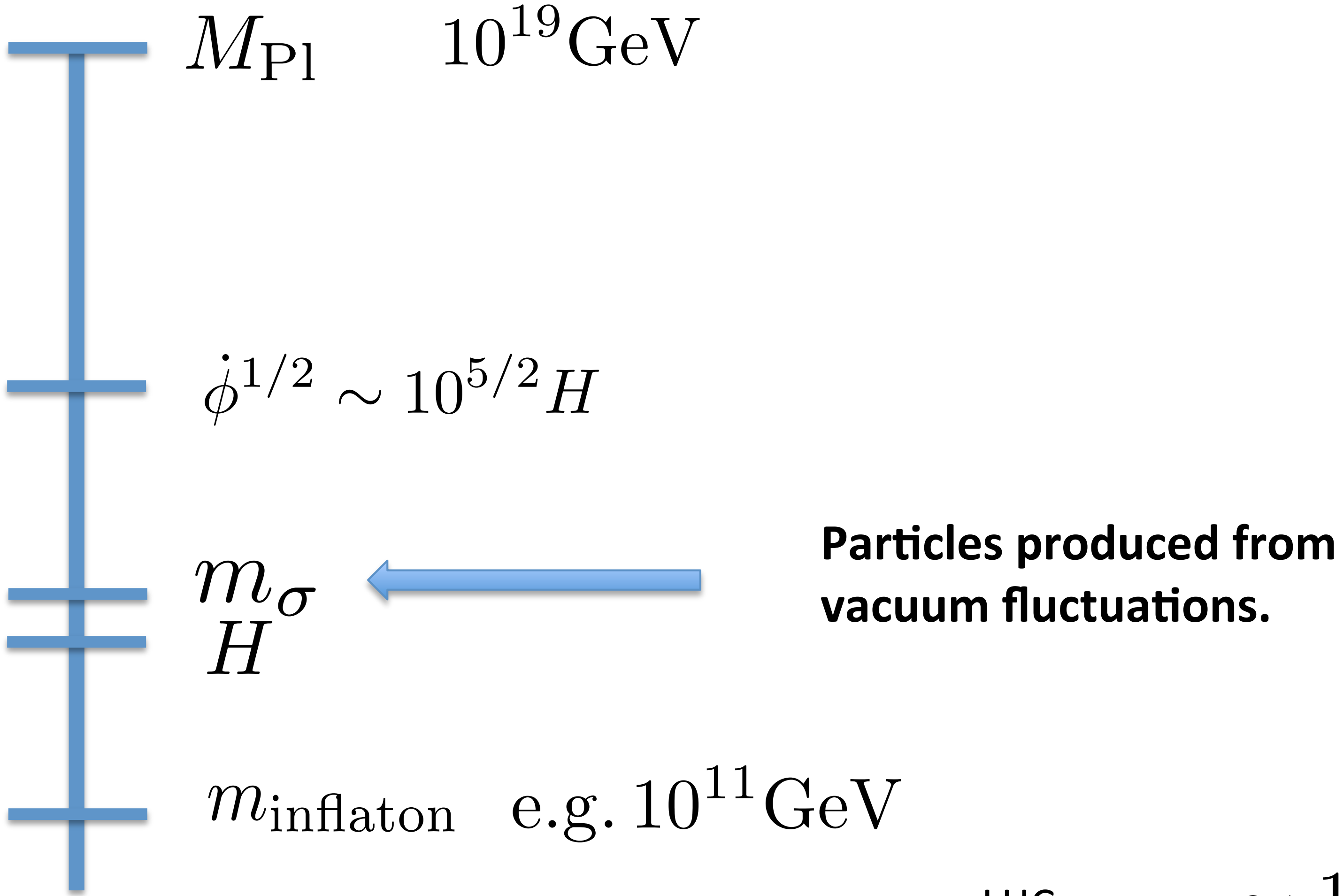
- Oscillations are easily orthogonal. Need large number of sampling points in frequency and phase parameter space.
- Sum over production events n needs many terms

→ Computationally harder than all previously analyzed shapes

PART 2: COSMOLOGICAL COLLIDER PHYSICS

Energy scales again

Inflation is the highest energy particle collider (indirectly) available to us, probably forever. → We need to **read off the results as precisely as possible.**



LHC energy $\sim 10^4 {\rm GeV}$

Theoretical Motivation

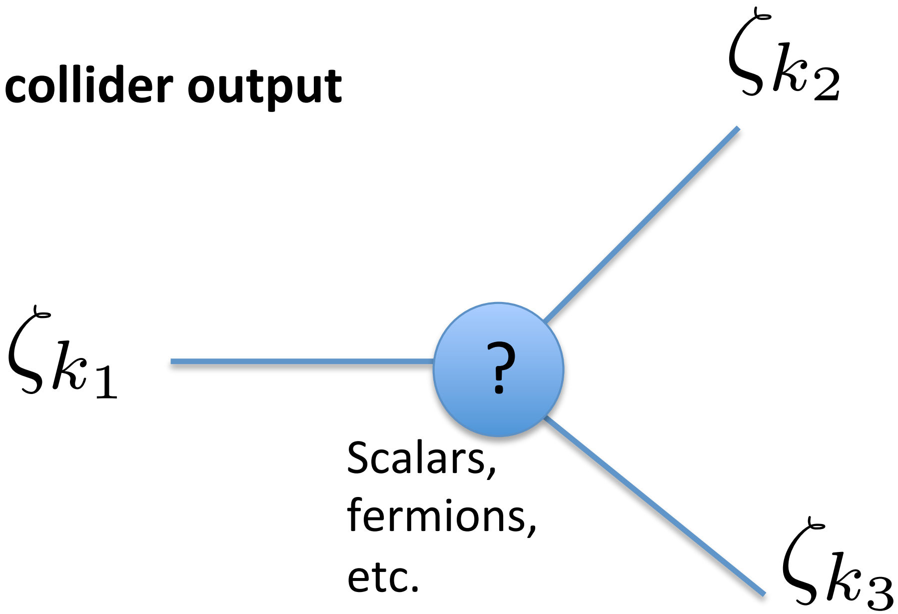
The inflationary particle collider in principle probes several orders of magnitude in energy from m_inf to > H. **There should be particles!**

String theory models strongly suggest many fields. Single field inflation is not natural in this sense.

Supersymmetry at order H to partially protect the slow roll potential suggests super-partners in this energy range.

Curvature bispectrum as particle collider output

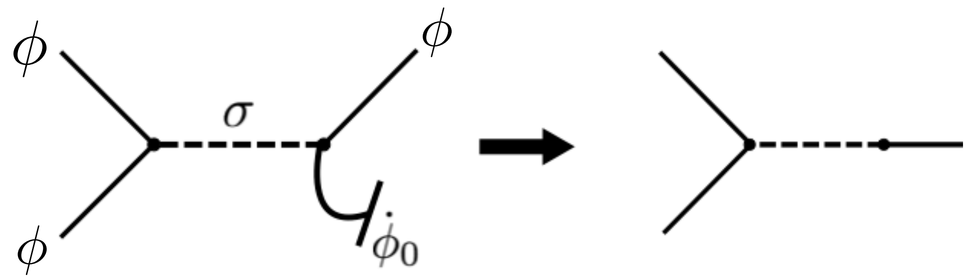
$$\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle =$$



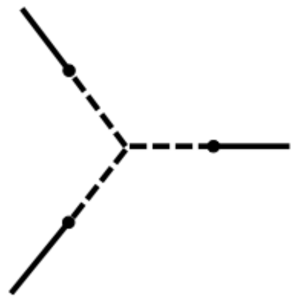
Scattering processes

Derivative couplings (shift symmetry) of inflaton to heavy field σ

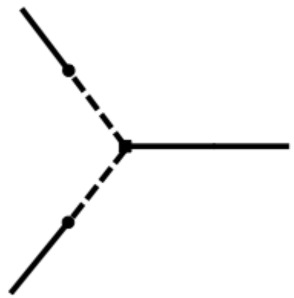
A



B



C



Arkani-Hamed,Maldacena 2015 considered **Diagram A** with:

$$\lambda(\nabla\phi)^2\sigma \qquad \text{with} \qquad \lambda M_{Pl} \sim 1 \qquad \text{or larger}$$

Diagram B: Bilinear term could mediate large self-interactions of σ (quasi single field inflation, Chen/Wang 2010).

More generally: all diagrams from cubic coupling and bilinear mixing term.

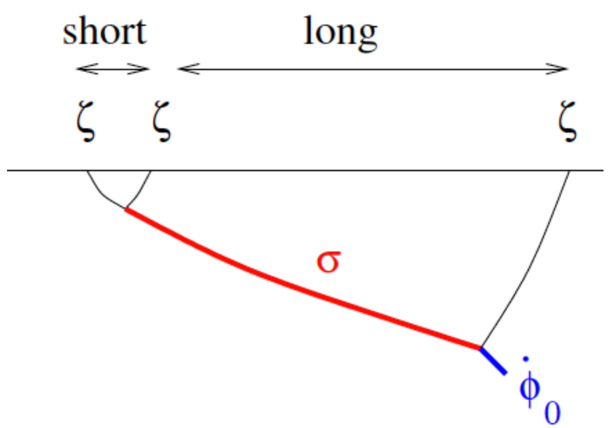
Primordial bispectrum

massive field mode function (EOM solutions)

Outside the horizon, modes decay and for large m also oscillate:

$$(-\tau)^{3/2-\mu} \text{ where } \mu = \sqrt{\frac{9}{4} - \frac{m_\sigma^2}{H^2}}$$

A-H/M



Squeezed limit encodes the mass spectrum

$$\frac{\langle\zeta\zeta\zeta\rangle}{\langle\zeta\zeta\rangle_{\rm short}\langle\zeta\zeta\rangle_{\rm long}} \sim \epsilon e^{-\pi\mu}|c(\mu)| \left[e^{i\delta(\mu)} \left(\frac{k_{\rm long}}{k_{\rm short}}\right)^{\frac{3}{2}+i\mu} + e^{-i\delta(\mu)} \left(\frac{k_{\rm long}}{k_{\rm short}}\right)^{\frac{3}{2}-i\mu} \right] P_s(\cos\theta)$$

A-H/M, Chen/Wang, Assassi/Baumann/Green

Contains mass spectrum and spin of the particles ☺

Exponential suppression factor (in addition to other small factors) ☹

IS there hope to measure it?

Full bispectrum: Numerical results

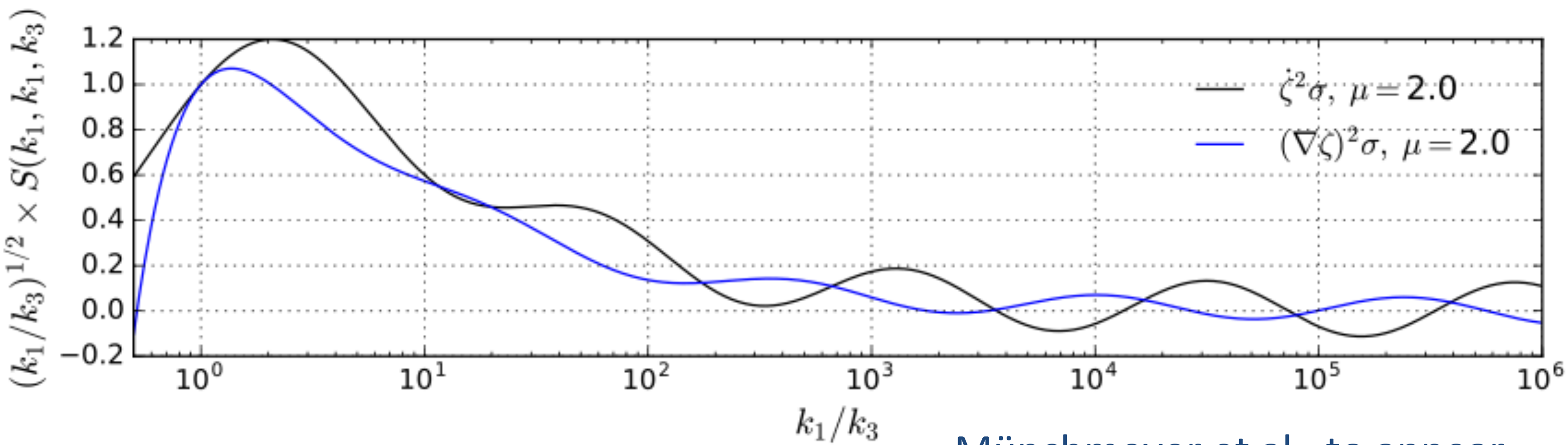
Basis: 2^{nd} order in-in perturbation theory

But no known complete analytic solution -> we evaluated the integrals numerically for our cosmological forecast.

Contains ugly double integrals over Hankel functions, e.g.

$$\int_{-\infty}^{0} dx\, x^{(3/2)} e^{\alpha x} H_{i\mu}^{(1)}(ix) \int_{-\infty}^{x} dy\, y^{(-1/2)} e^{y} H_{i\mu}^{(2)}(iy)$$

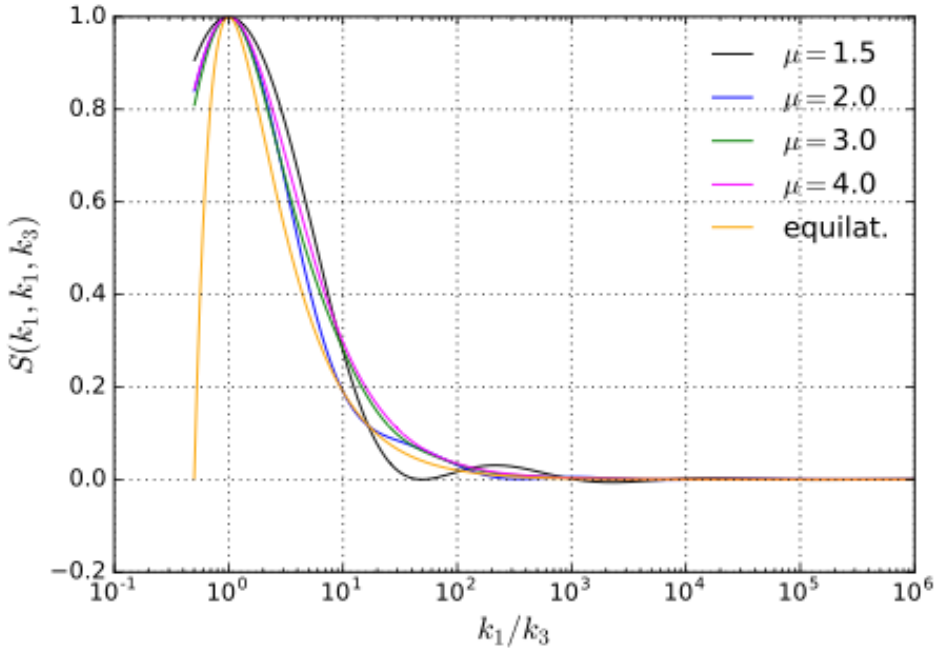
(use Wick rotation for numerical convergence (Chen/Wang 2015))

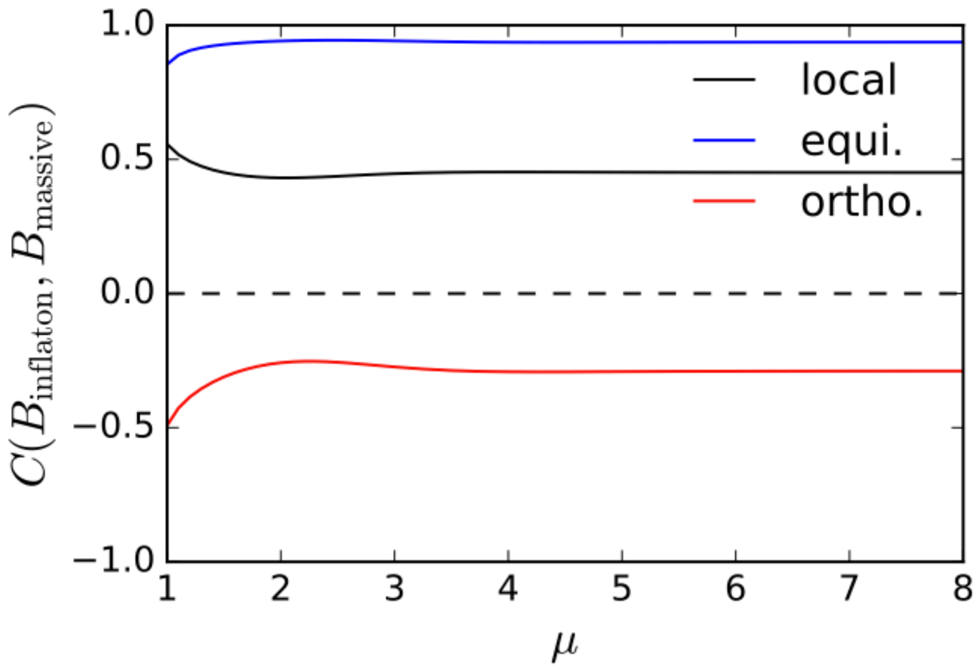


Scale invariant oscillations

Münchmeyer et al., to appear

Bispectrum correlator





Münchmeyer et al., to appear

Large overlap with self interaction NG (equilateral shape).

Conclusion: CMB search is hopeless (independent of the coupling size) because of known non-detection of equilateral NG.

COSMIC VARIANCE AND THE DARK AGES

21 cm signal from the dark ages

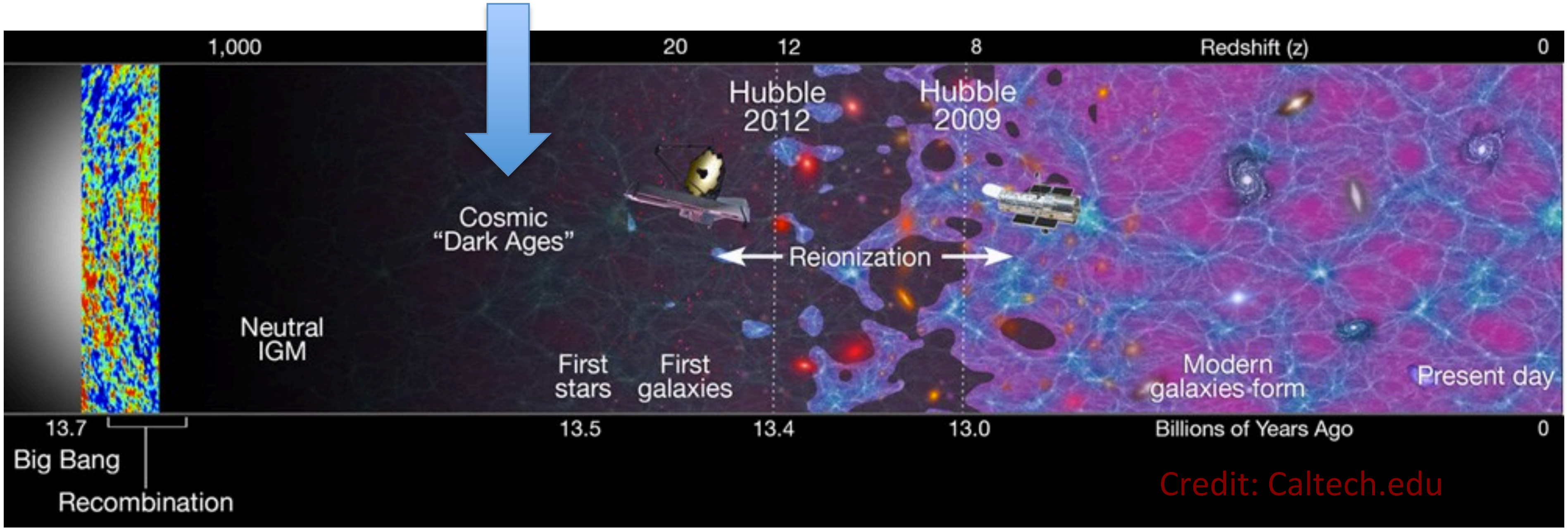
21cm tomography prior to structure formation

Ideal probe for inflationary physics: Very large number of Fourier modes, perturbative regime. Zaldarriaga, Loeb 2004

Origin: Cosmic neutral hydrogen prior to star formation maps the matter density.

→ Absorption of CMB photons at 21cm spin flip transition.

→ 21cm radiation anisotropies today at wave length $21.12[(1+z)/100]$ m



Credit: Caltech.edu

Cosmic variance of the 21 cm power spectrum

Red shift range

z = 30 to z = 200

Conformal k range

$$k \sim 10^{-4}\mathrm{Mpc}^{-1} \text{ to } k \sim 10^{2}\mathrm{Mpc}^{-1}$$

21cm: 3d, 6 orders of magnitude k VS CMB 2d, 3 orders of magnitude k

Example: measure a scale-invariant correction to the power spectrum

3d survey: $\sigma_a \sim \sqrt{\left(\frac{k_{\min}}{k_{\max}}\right)^3}$; **several 2d shells:** $\sigma_{a'} \sim \sqrt{\frac{1}{N_z}\left(\frac{1}{l_{\max}}\right)^2}$

21cm: e.g. N~10, l_max~10^5

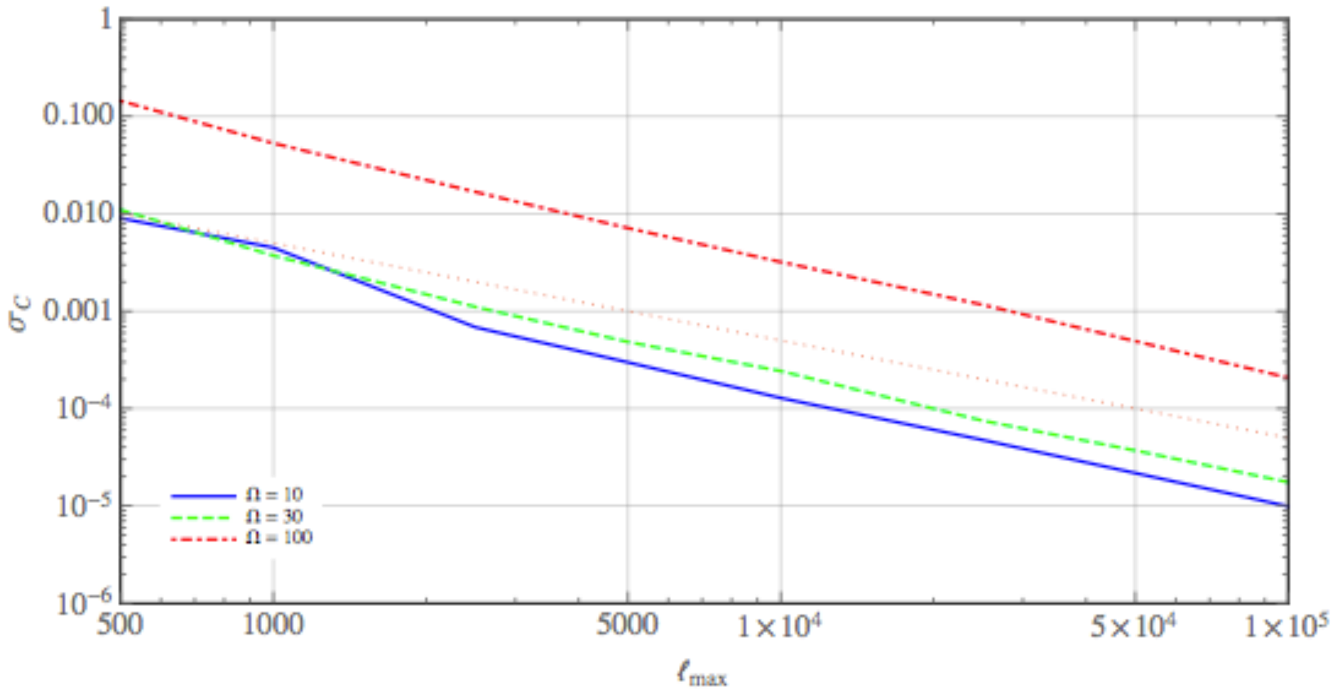
BUT experiments of that sort are probably several decades away.
Experimental sensitivity and foreground cleaning extremely difficult.

A 21cm power spectrum forecast

21cm signal can be calculated with **CAMBsources (Lewis, Challinor)**

We assume frequency resolution $$\Delta\nu = 0.1 \text{ MHz}$$

Example for resonance oscillations: $$\frac{\Delta P_\zeta}{P_{\zeta 0}} = C \sin\left[\Omega \log\left(2k\right) + \phi\right]$$



Also including other oscillating shapes: Chen, Meerburg, Münchmeyer, to appear

Cosmic variance of the "collider bispectrum"

The total signal-to-noise of the bispectrum in a cosmological volume is

$$\left(\frac{S}{N}(\langle\zeta^3\rangle)\right)^2 = V\int \frac{d^3\mathbf{k}_1}{(2\pi)^3}\frac{d^3\mathbf{k}_2}{(2\pi)^3}\frac{d^3\mathbf{k}_3}{(2\pi)^3}(2\pi)^6\delta^3(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)\frac{B^2(k_1,k_2,k_3)}{P(k_1)P(k_2)P(k_3)}$$

precision on f_nl scales as $\sigma_f \propto \sqrt{\left(\frac{k_{\min}}{k_{\max}}\right)^3}$

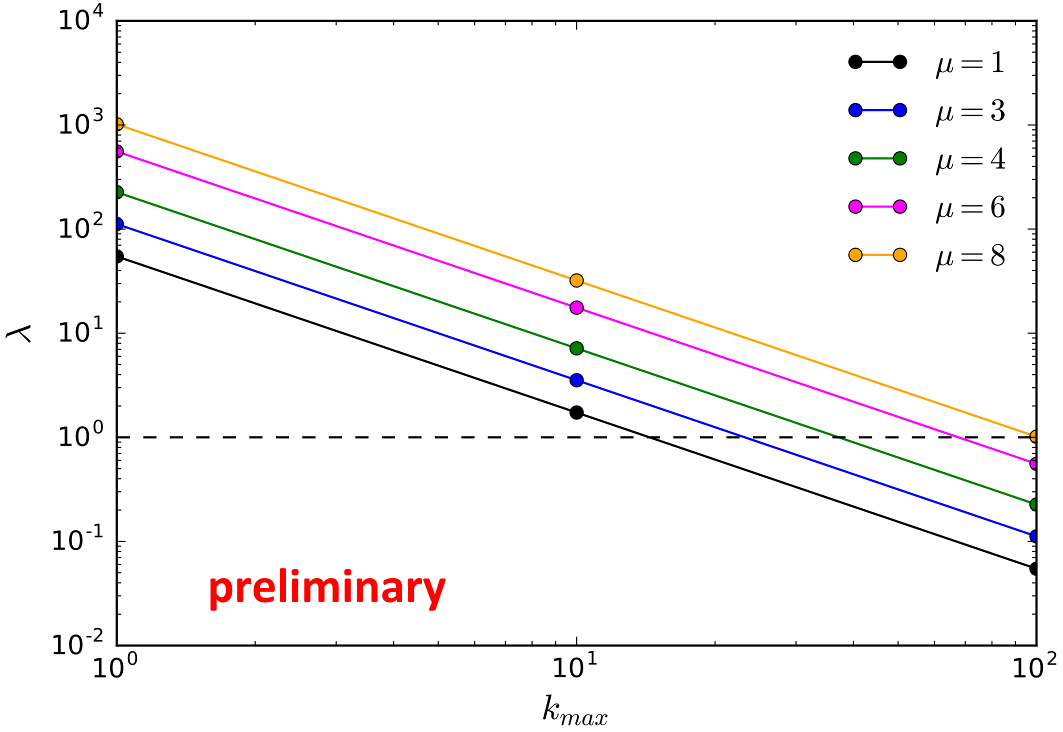
Plug in numerical solution

This integral answers:

Is the information needed for a detection even contained in the conformal volume probed by the 21cm signal?

Cosmological collider bispectrum

For an experiment that maps all mode from $k_{\min} = 10^{-4}\,\mathrm{Mpc}^{-1}$ to k_max



Plot of λ that could be detected as a function of kmax of the experiment.

λ ~ 1 is worst case scenario, could also be much larger.

Plot considers full signal (not just oscillations)

For this plot we used A-H/M shape with amplitude $C_B = 4A_s^2 \epsilon M_p^2 \lambda^2$

Decades from now heavy particles O(H) from "cosmological collider physics" may possibly be discovered with cosmological data.

CONCLUSION

Conclusion

Cosmological data allows to look for many different signatures motivated by UV physics.

First search for high frequency resonance bispectra. Results are fully compatible with Gaussianity.

Due to UV sensitivity of inflation some string theory models can be tested with CMB data. Certainly more such models will be found and tested.

Work on **more shapes and a combined analysis with the power spectrum** is in progress. **In particular for oscillating mass terms.**

The CMB could still be hiding sensations, but in the future we will retest these and related models with **LSS and 21cm astronomy with better precision.**

In the distant future "cosmological collider physics" may tell us the spectrum of particles around the Hubble scale.

Thank you!