Title: Prospects for cosmological collider physics

Date: Oct 25, 2016 11:00 AM

URL: http://pirsa.org/16100068

Abstract: <p>If heavy fields are present during inflation, they can leave an imprint in late-time cosmological observables. The main signature of these fields is a small amount of distinctly shaped non-Gaussianity, which if detected, would provide a wealth of information about the particle spectrum of the inflationary Universe. Here we investigate to what extent these signatures can be detected or constrained using futuristic 21-cm surveys. This part of my talk is based on 1610.06559. In the second part of my talk I will discuss how non-adiabatic production of heavy particles, as recently studied in 1606.00513, can generate an interesting and so far unconstrained class of non-Gaussianity in the CMB. </p>

Prospects for cosmological collider physics

Moritz Münchmeyer, Perimeter Institute

From inflation interactions to cosmology

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**

$$\mathcal{L}_{\rm infl}(\Phi, g_{\mu\nu}, ..) \xrightarrow{\text{Step 1}} \zeta(\mathbf{x}, \tau_0) \xrightarrow{\text{Step 2}} \begin{matrix} LSS \\ T_{\rm CMB} \\ 21cm \end{matrix}$$

Primordial curvature perturbations

QFT correlators in the sky (in principle)!!!

Bispectrum basics

Here we are mostly interested in the 3-point function (bispectrum) of curvature perturbations

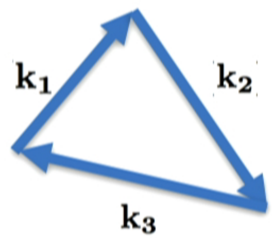
$$\langle \zeta(\mathbf{k_1})\zeta(\mathbf{k_2})\zeta(\mathbf{k_3})\rangle = (2\pi)^3 \delta(\mathbf{k_{1,2,3}}) B(k_1, k_2, k_3)$$

We also define the bispectrum "shape function"

$$S(k_1, k_2, k_3) = \frac{1}{N}(k_1 k_2 k_3)^2 B(k_1, k_2, k_3)$$

Statistical isotropy and homogeneity forces k1,k2,k3 to form a triangle.

equilateral triangles



"equilateral non-Gaussianity"

squeezed triangles

"local non-Gaussianity"

So far, all primordial bispectrum searches are consistent with zero.

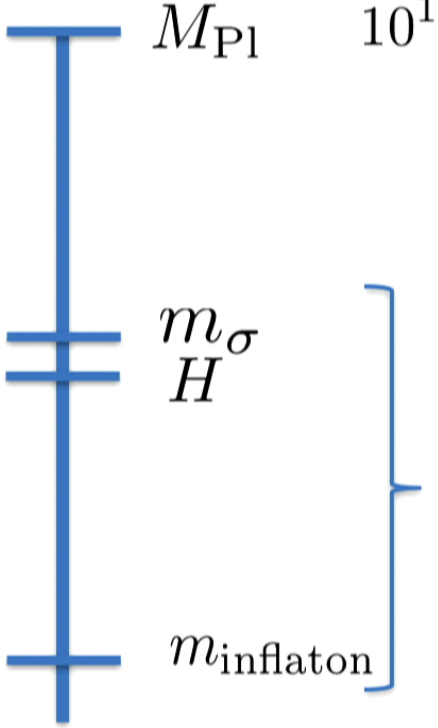
COSMOLOGICAL COLLIDER PHYSICS

Based on **1610.06559** with Daan Meerburg, Julian Munoz, Xingang Chen

4

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_{Pl} $10^{19}\mathrm{GeV}$

Much closer to GUT or even string scale than any other probe.

m_σ

H

Particles produced from vacuum fluctuations

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

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

Theoretical Motivation

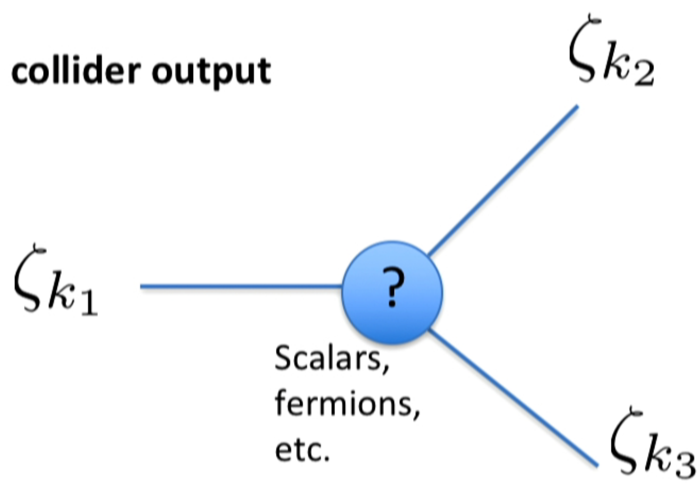
The inflationary particle collider in principle probes several orders of magnitude in energy from m_inflation to > H.

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

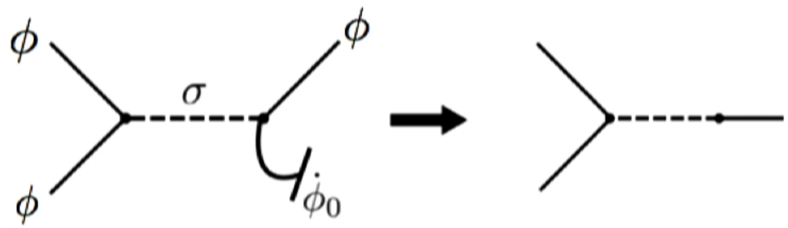
$$\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle =$$



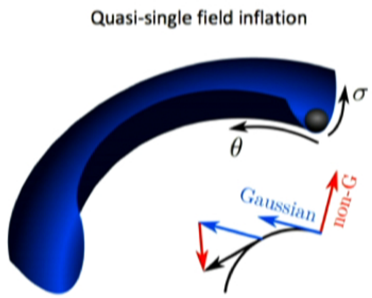
Two example processes

Derivative 3pt vertex: Arkani-Hamed, Maldacena 2015

$$\lambda(\nabla\phi)^2\sigma$$



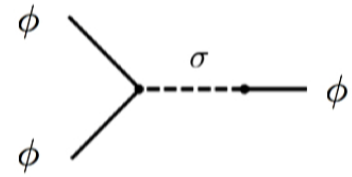
Bilinear term mediates large self-interactions of σ (quasi single field inflation, Chen/Wang 2010).



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

Primordial bispectrum for AHM model

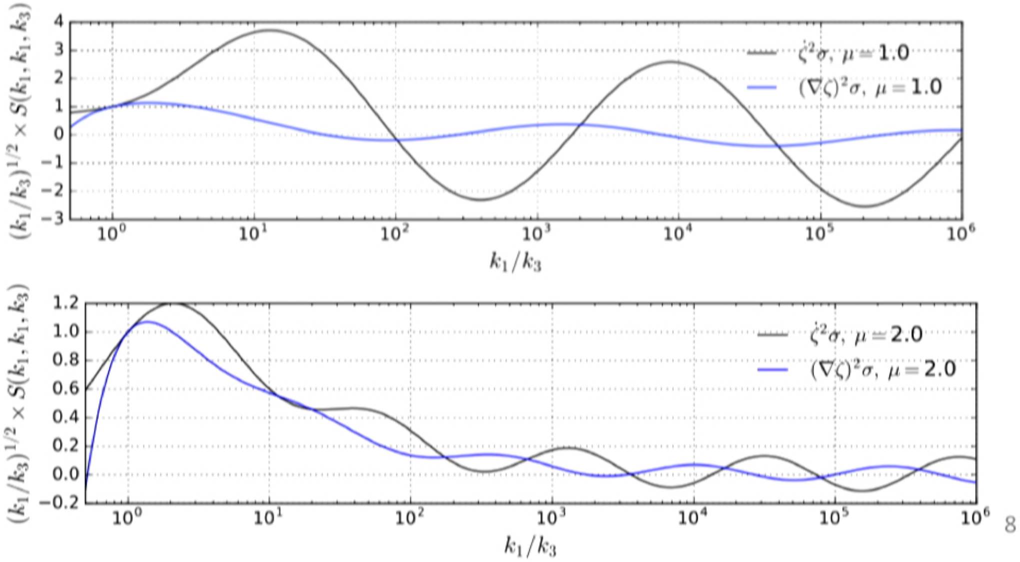
Basis: 2nd order in-in perturbation theory



Contains double integrals over Hankel functions, e.g.

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

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



Mass parameter

$$\mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$$

Model independent squeezed limit

Basic physical reason for squeezed limit behavior

After horizon crossing, massive fields decay and for large m also oscillate:

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

Therefore when the short modes cross the horizon, the amplitude of the long mode is suppressed in a specific way.

Squeezed limit encodes the mass spectrum

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

$$S_{\text{squeezed}} \propto \left(\frac{k_{\text{long}}}{k_{\text{short}}}\right)^{1/2\pm i\mu}$$

2 cases: μ **real or imaginary** → **oscillation or scaling**

Squeezed limit is more generic than equilateral contribution and contains a mass measurement. Acts like a "cosmological collider".

High mass oscillating template

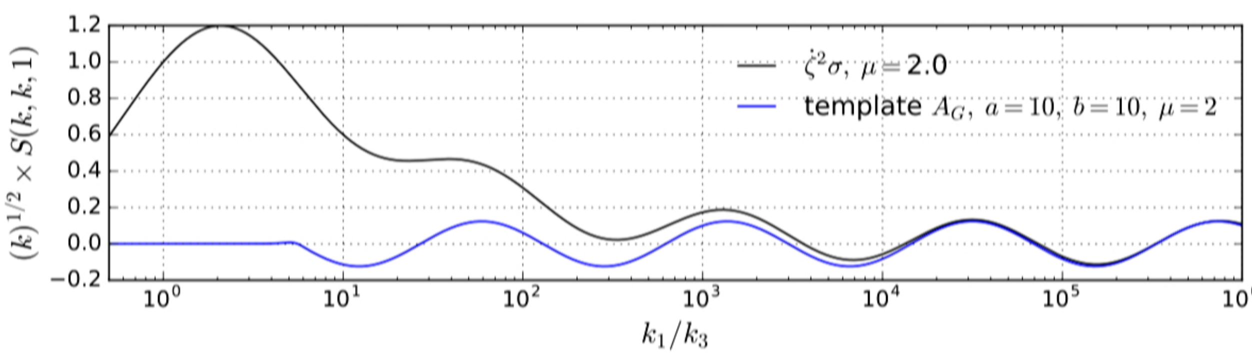
$$S^{\rm clock}(k_1,k_2,k_3) = \underbrace{f_{\rm NL}A}_{\text{amplitude}} \underbrace{\left(\frac{k_1+k_2}{k_3}\right)}_{\text{Gauss-type window function to cut off equilateral contribution}} \underbrace{\left(\frac{k_1+k_2}{k_3}\right)^{-1/2} \times \sin\left(\mu \ln\left(\frac{k_1+k_2}{2k_3}\right)+\delta\right)}_{\text{Squeezed limit oscillations}} + 2\,{\rm perm}$$

amplitude

Gauss-type window function to cut off equilateral contribution

Squeezed limit oscillations

Mass parameter $\mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$



10

Low mass scaling template

Low mass "intermediate" template was given by Chen&Wang in 0909.0496

$$S^{\mathrm{int}}(k_1,k_2,k_3) = f_{\mathrm{NL}} A(k_1,k_2,k_3) \frac{3^{\frac{9}{2}-3\nu}}{10} \frac{k_1^2+k_2^2+k_3^2}{(k_1+k_2+k_3)^{\frac{7}{2}-3\nu}} (k_1k_2k_3)^{\frac{1}{2}-\nu}$$

Mass parameter $\nu \equiv \sqrt{(9/4)-(m/H)^2} = -i\mu \qquad 0<\nu<3/2$

$$\text{squeezed limit } k_3 \ll k_1 = k_2,\ S^{\mathrm{int}} \sim (k_3/k_1)^{\frac{1}{2}-\nu}$$

Scaling regions:

– For small m: scales like local NG (as multi-field inflation should)

$$S^{\mathrm{loc.}} \sim (k_3/k_1)^{-1}$$

– For larger m: interpolates towards equilateral NG

$$S^{\mathrm{equi.}} \sim k_3/k_1$$

11

Low mass scaling template

Low mass "intermediate" template was given by Chen&Wang in 0909.0496

$$S^{\rm int}(k_1,k_2,k_3) = f_{\rm NL} A(k_1,k_2,k_3) \frac{3^{\frac{9}{2}-3\nu}}{10} \frac{k_1^2+k_2^2+k_3^2}{(k_1+k_2+k_3)^{\frac{7}{2}-3\nu}} (k_1k_2k_3)^{\frac{1}{2}-\nu}$$

Mass parameter $\nu \equiv \sqrt{(9/4)-(m/H)^2} = -i\mu \qquad 0<\nu<3/2$

$$\text{squeezed limit } k_3 \ll k_1 = k_2,\ S^{\rm int} \sim (k_3/k_1)^{\frac{1}{2}-\nu}$$

Scaling regions:

- For small m: scales like local NG (as multi-field inflation should)

$$S^{\rm loc.} \sim (k_3/k_1)^{-1}$$

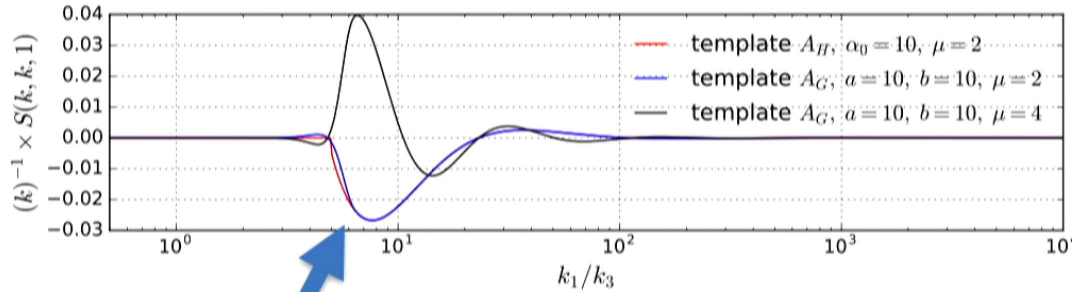
- For larger m: interpolates towards equilateral NG

$$S^{\rm equi.} \sim k_3/k_1$$

How much phase space to cut off?

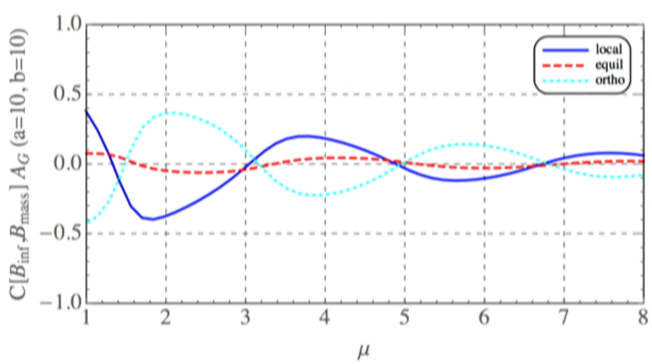
Objectives: Avoid equilateral bump, keep template accurate, get as much signal as possible

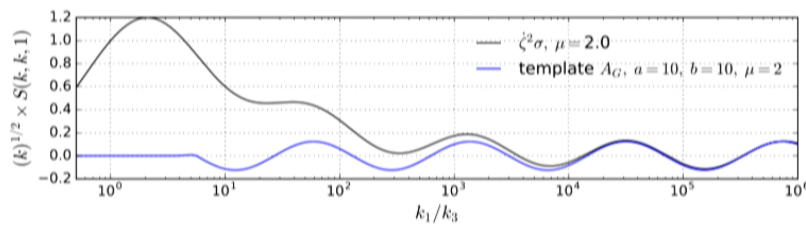
Cutoff depends on NG from self interactions. We chose a compromise.



S/N weighted

Most signal is in the first peak.





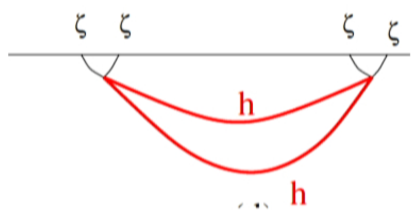
Outlook: Detecting spin

The squeezed limit also tells us about the spin of massive particles!

$$S \propto \left(\frac{k_{\text{long}}}{k_{\text{short}}}\right)^{1/2\pm\mu} P_s(\cos\Theta)$$

spin   Angle between k_l and k_s

Arkani-Hamed, Maldacena 2015 . Extended in Lee, Baumann, Pimentel 2016



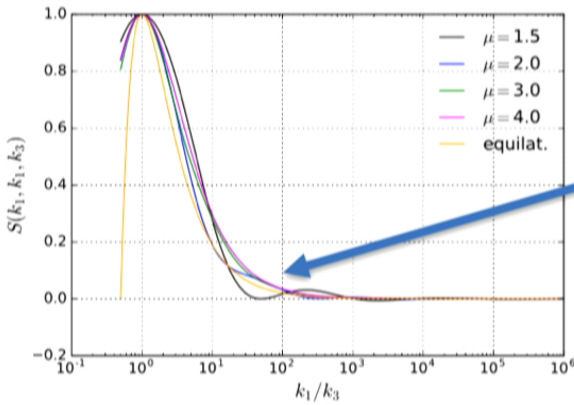
String theorists dream: Find a particle with spin>2.

Not generally predicted by string inflation, but we are way closer to the string energy scale than with any other probe.

How about a CMB analysis?

- For the non-oscillating case, this has already been done in Planck NG 2015
- For the oscillating case the overlap of the full shape with equilateral is large (C ~ 0.9).
- Therefore for the oscillating shape a search for the collider signal only makes sense **after equilateral non-Gaussianity has been detected**.

AHM example



Oscillations are Boltzmann suppressed

$$e^{-\frac{\mu}{H}}$$

This does not look good in the near term. But given the very exciting signal we won't give up that quickly. We need a much better probe than CMB!

A FORECAST FOR 21CM FROM THE DARK AGES

21 cm signal from the dark ages

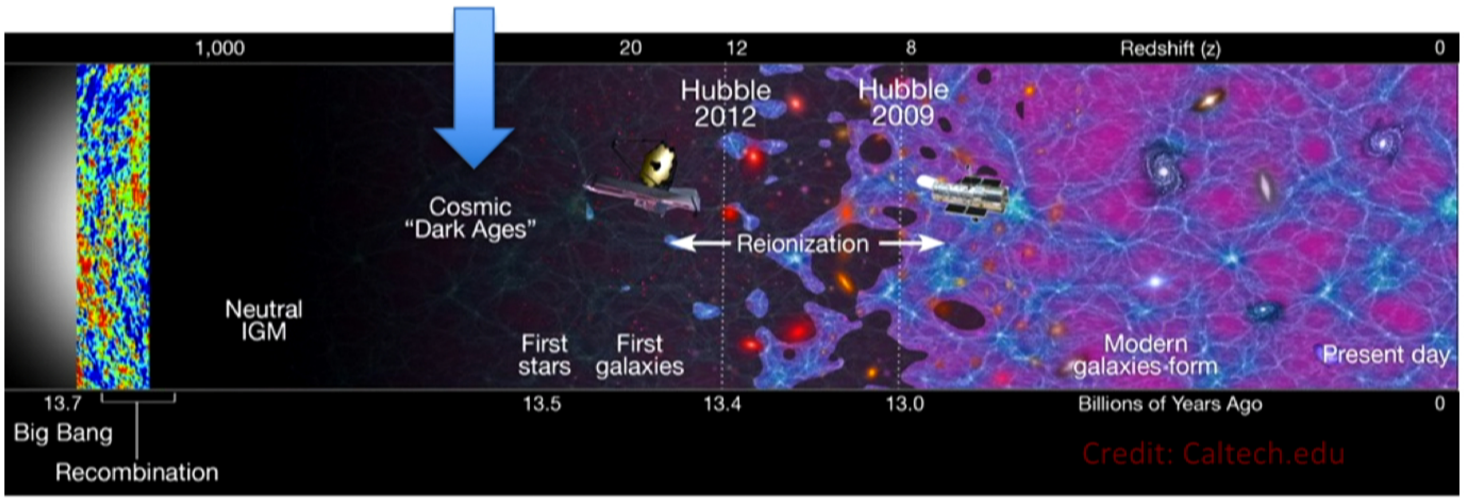
21cm tomography prior to structure formation

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 $21.12[(1+z)/100]m$



What kind of experiment would we need?

Mode counting

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

$$\sigma_a \sim \sqrt{\left(\frac{k_{\min}}{k_{\max}}\right)^3}$$

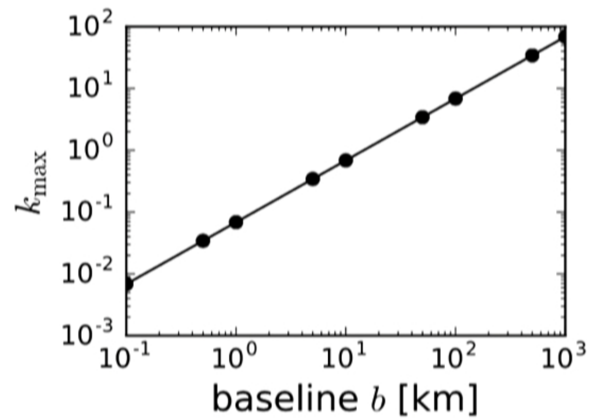
Radial (Frequency) resolution

We assume 30<z<100

$$\frac{\delta\nu}{\nu} = \frac{\Delta z}{z+1}$$

Angular resolution limited by size (baseline) of experiment

$$k_{\max} \simeq 2\pi\nu_0 b \frac{1}{d(z)(1+z)}\frac{1}{c}$$



We assume that the radial resolution matches the angular resolution

Projecting to the 21cm signal

We use linear perturbation theory and assume that the 21cm signal traces the matter perturbations.

$$\langle \delta T_{21}(\boldsymbol{k}_1)\delta T_{21}(\boldsymbol{k}_2)\delta T_{21}(\boldsymbol{k}_3)\rangle = (2\pi)^3\delta_{\rm D}(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3)\times B_{\delta T}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)$$

Secondary Non-Gaussianity

- Main sources
  - 21cm temperature depends non-linearly on baryon density and velocity
  - Gravitational interactions create non-Gaussianity
- **Our approach**: We used **templates** from Munoz et al 2015 that parametrize these effects to second order in delta_b and delta_v. We found O(1) changes in sensitivity for test cases.
- In principle N-body sims can determine these effects well (no complicated feedback mechanisms).

Noise and foregrounds

Foregrounds

- **Atmosphere partially opaque** at these frequencies

  → Often the moon is advocated as a possible location

- Noise amplitude many orders of magnitude larger than signal amplitude. Especially **galactic synchrotron radiation.**

- But: **synchrotron is much more smooth in frequency than signal**. Component separation is theoretically possible.

- We assume that one can completely subtract the foregrounds.

We do a cosmic variance limited forecast
(a very futuristic assumption)

Rough size of non-Gaussianities

Gravitational coupling (minimal case)

Heavy fields couple to inflaton only through gravity. $f_{\rm NL} \ll 10^{-2}$

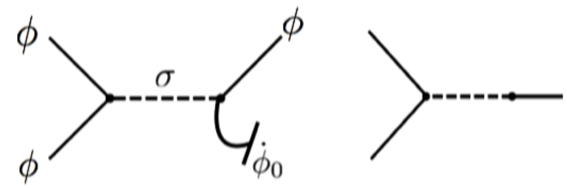
Loop corrections to the bispectrum.

Direct coupling of heavy fields and inflaton

In principle up to $f_{\rm NL} < \mathcal{O}(1)$

(limited by perturbative control)

AHM $f_{\rm NL} \sim \epsilon M_{Pl}^2 \lambda^2$

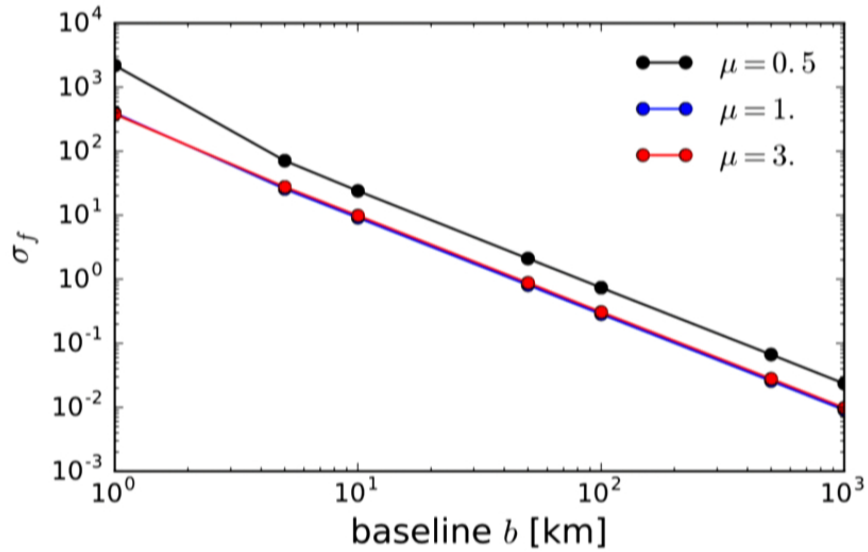


Self interactions of heavy fields and direct coupling

e.g. Chen/Wang QSFI $f_{\rm NL} \gtrsim \mathcal{O}(1)$

This is valid for $\text{mass} \lesssim \mathcal{O}(H)$. Above that there is a **Boltzmann factor,** giving exponential suppression. $e^{-\frac{\mu}{H}}$

Results for the oscillating template m>H



We assume fixed cosmology and do not marginalize over secondary non-Gaussianity.

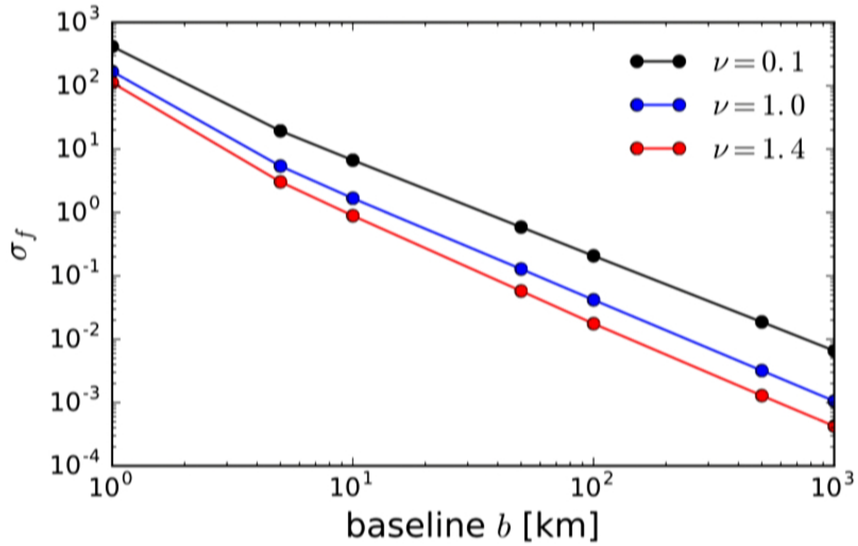
Red shift range: 30<z<100

$$\mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$$

Rough interpretation:

- Sensitivity almost mass independent (no Boltzmann suppression in our template)
- With an array of O(10) km one can probe O(1) self interactions.
- With an array of O(100) km, one can probe models with direct coupling.
- The AHM amplitude is only realistic if the operator is not Planck suppressed

Results for the non-oscillating template m<H



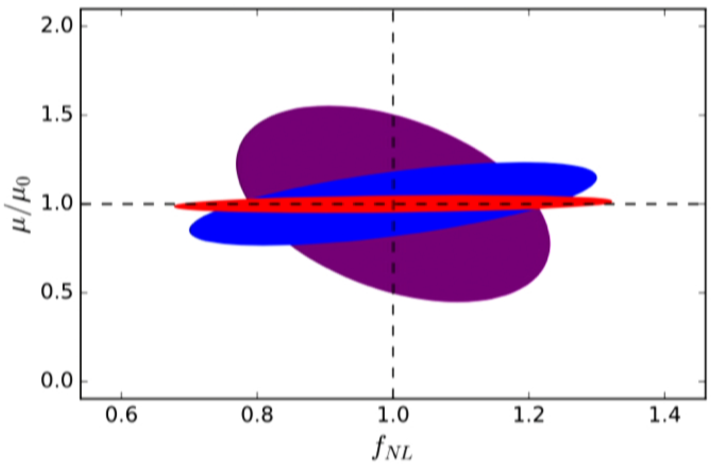
$$\nu \equiv \sqrt{(9/4) - (m/H)^2}$$

Smaller v means larger mass

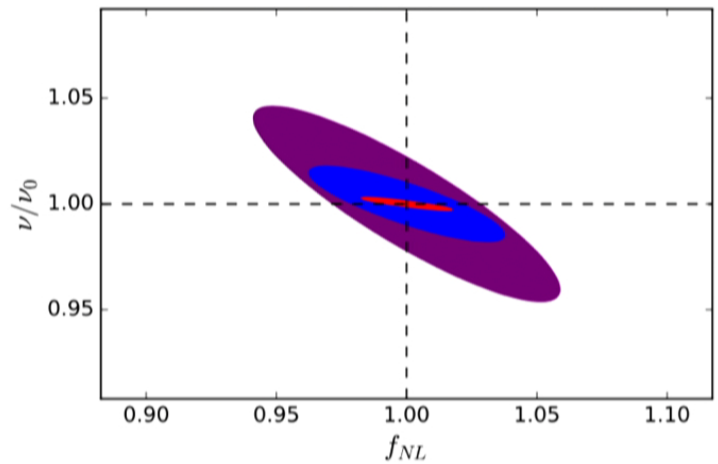
Rough interpretation:

- Sensitivity is mass dependent because scaling because the scaling in the squeezed limit is mass dependent
- Sensitivity can be 1-2 orders of magnitude better than in the oscillating case.
- For low masses a 10 km array would already give interesting constraints

Mass determination



$\mu = 0.7$ (purple), $\mu = 1.0$ (blue), $\mu = 3.0$ (red)



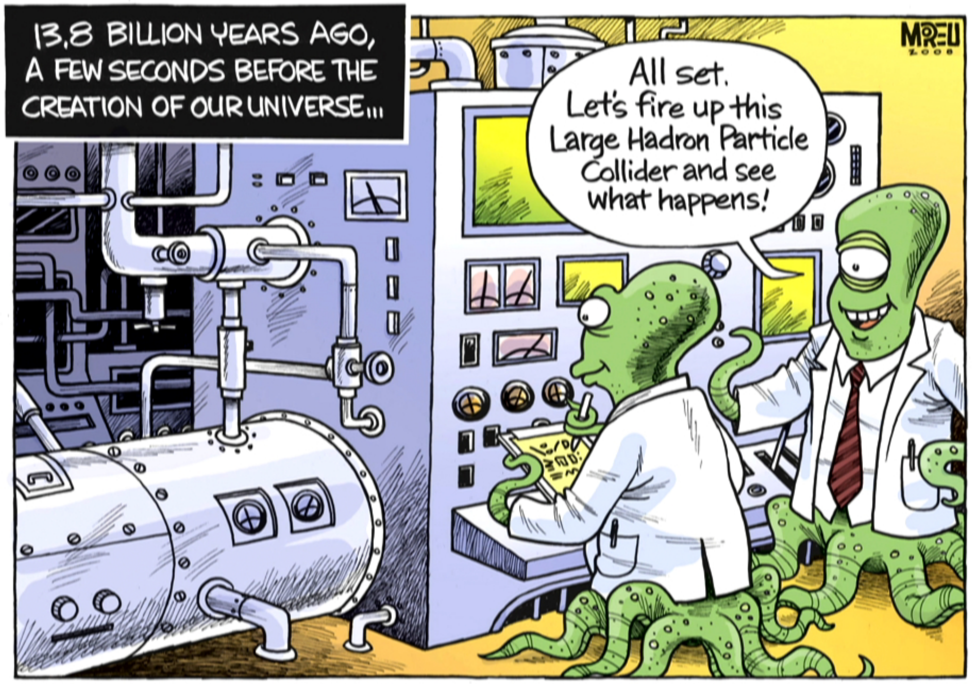
$\nu = 0.8$ (purple), $\nu = 1.0$ (blue), $\nu = 1.4$ (red)

Test case: fnl = 1, baseline = 100 km

Under these fortunate assumptions one could measure even a spectrum of particles with well determined masses.

Prospects for cosmological collider physics?

It seems that in the time frame of decades there is a fair chance, but in the near term there is little chance, because of known limits on local and equilateral NG.



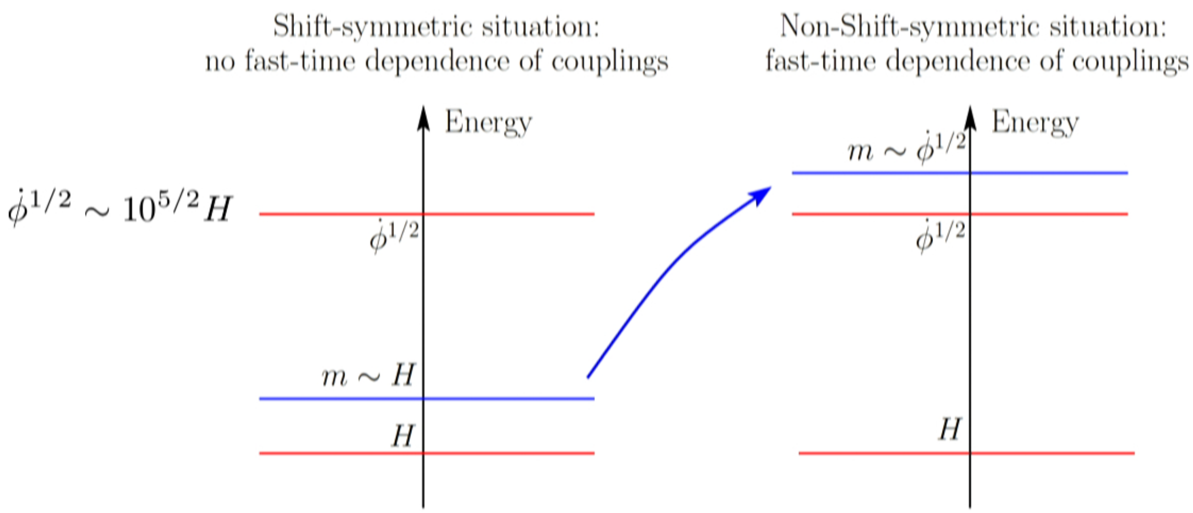
24

NON-ADIABATIC HEAVY PARTICLE PRODUCTION

Theoretical model **1606.00513** by Flauger, Mirbabayi, Senatore, Silverstein
Data analysis ideas from unpublished work MM, Senatore, Silverstein

Non-adiabatic particle production

- **Previous part of the talk: slow-roll background and time independent coupling constants.**
- If we relax these assumptions, we get very a different phenomenology.
- **This section of the talk: heavy particles with time dependent mass functions, but inflaton background dynamics are still slow roll.**



Source: Flauger et al 2016

26

2 classes of mass functions m_χ

Regular case (discrete shift symmetry)

- Shift symmetry $\Phi \to \Phi + \mathrm{const.}$ to protect inflaton potential from corrections

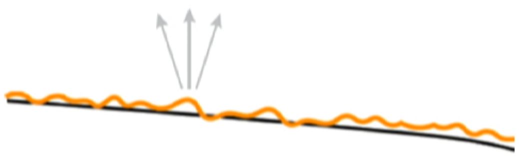
$$\Delta\mathcal{L} = \frac{\mathcal{O}_\Delta}{\Lambda^{\Delta-4}} \qquad \Lambda : \mathrm{UV\ scale} \qquad \Delta : \mathrm{Operator\ dimension}$$

- Discrete version $\varphi \to \varphi + 2\pi f$. e.g small sine one top of potential

- In our case e.g.: $m_\chi^2 = m_0^2 + g^2 \sin\left(\frac{\phi}{f}\right)$ or more "Fourier components"

Disordered case

Maybe the microphysics in the UV is very complicated, masses and couplings fluctuate stochastically



Source: Amin, Baumann 2016

27

Non-adiabatic particle production

Inflaton background (or time) 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

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

In this case the **adiabatic vacuum (WKB) is no longer valid** and the particle number n_k not conserved. (**as in preheating**)

> If UV physics is complicated, with many fields and couplings, this condition might arrive generically.
>
> A concrete UV model where this happens is axion monodromy.

Concrete example from axion monodromy

Coupling **heavy fields via field dependent mass**

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

Axion monodromy includes two sectors of this type:

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

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

Source: Flauger et al 2016

Near production: $\quad m_\chi^2 = m_0^2 + g^2\dot{\phi}^2(t - t_n)$

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

Concrete example from axion monodromy

Coupling **heavy fields via field dependent mass**

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

Axion monodromy includes two sectors of this type:

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

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

Source: Flauger et al 2016

Near production: $\quad m_\chi^2 = m_0^2 + g^2\dot{\phi}^2(t - t_n)$

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

Calculating n-point functions

Particle production + coupling term --> curvature perturbation source J

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

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

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

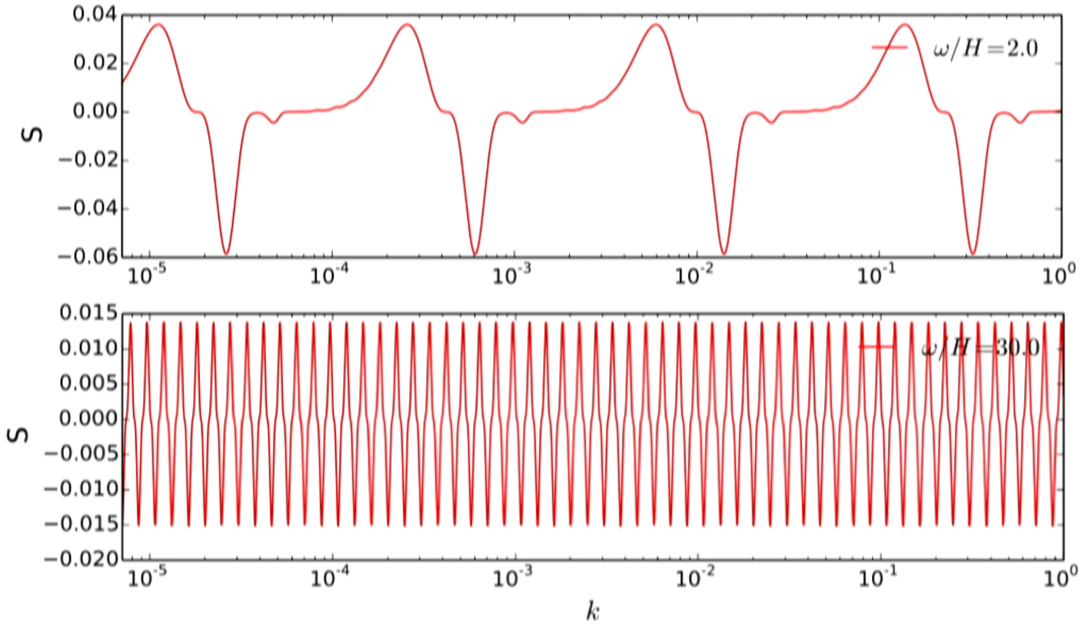
$$\langle \delta\phi_{\mathbf{k}_1} \dots \delta\phi_{\mathbf{k}_N} \rangle \sim (2\pi)^3 \delta(\sum \mathbf{k}_i) \frac{\bar{n}_\chi}{H^3} H^{N+3} \sum_n (H\eta_n)^{-3} \Pi_{i=1}^N \frac{\hat{h}(k_i \eta_n)}{k_i^3}$$

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

Interesting extension: produce fermions with this mechanism

Unexplored phenomenology

Primordial bispectrum example (for k1=k2=k3=k):



No significant overlap with previously examined bispectrum shapes, including resonance and feature shapes.

Can have large amplitude.

CMB analysis needed!

Inverted signal to noise hierarchy possible

- **Normal case:** Higher N-point functions are smaller because they involve higher powers of the coupling constants (more vertices) or higher order vertices (more suppressed in EFT).

- **Present case:** In part of the parameter space the signal to noise can grow with N. This is possible because non-adiabatic production already modifies the free theory of the heavy particles.

- Roughly: $(S/N)_N \sim \epsilon x^N$ (x>1, epsilon <1) up to some N, e.g. O(100)

- **Interesting from a data analysis point of view**: higher N-point functions have been much less constrained. One could easily have a detection in WMAP data.

32

N-point CMB estimator

- **Potential problems**: combinatoric explosion of terms in shape function, contamination by lower N-point functions (especially power spectrum), combinatoric explosion of MC estimator correction terms

- None of these are fatal for this shape (for odd N).

- Schematically

Senatore, MM, unpublished

$$M^N_{\{\ell,m\}} = M^{\ell_1\ell_2\ldots\ell_N}_{m_1m_2\ldots\ell_N} \;=\; \langle a_{\ell_1m_1}a_{\ell_2m_2}\ldots a_{\ell_Nm_N}\rangle_c$$

$$\mathcal{E} \;=\; \frac{1}{N!F}\sum_{\ell_im_i} M^{N*}_{\{\ell,m\}}\left[(C^{-1}a)_{\ell_1m_1}(C^{-1}a)_{\ell_2m_2}\ldots(C^{-1}a)_{\ell_Nm_N}\right]$$

- Old KSW trick

$$\mathcal{E} \;=\; \frac{1}{N!F}\sum_q \int dr\, r^2 \int d\Omega\, \left(M^{N,q}(\mathbf{r},\widehat{\mathbf{r}})\right)^N$$

$$M^{N,q}(r,\widehat{\mathbf{r}}) = \sum_{\ell_im_i}(C^{-1}a)_{\ell_1m_1}M^{N,q}_\ell(\mathbf{r})Y_{\ell m}(\widehat{\mathbf{r}})$$

N-point CMB estimator

- **Potential problems**: combinatoric explosion of terms in shape function, contamination by lower N-point functions (especially power spectrum), combinatoric explosion of MC estimator correction terms

- None of these are fatal for this shape (for odd N).

- Schematically

Senatore, MM, unpublished

$$M^N_{\{\ell,m\}} = M^{\ell_1\ell_2\ldots\ell_N}_{m_1m_2\ldots\ell_N} = \langle a_{\ell_1m_1}a_{\ell_2m_2}\ldots a_{\ell_Nm_N}\rangle_c$$

$$\mathcal{E} = \frac{1}{N!F}\sum_{\ell_im_i} M^{N*}_{\{\ell,m\}}\left[(C^{-1}a)_{\ell_1m_1}(C^{-1}a)_{\ell_2m_2}\ldots(C^{-1}a)_{\ell_Nm_N}\right]$$

- Old KSW trick

$$\mathcal{E} = \frac{1}{N!F}\sum_q \int dr\, r^2 \int d\Omega\left(M^{N,q}(\mathbf{r},\widehat{\mathbf{r}})\right)^N$$

$$M^{N,q}(r,\widehat{\mathbf{r}}) = \sum_{\ell_im_i}(C^{-1}a)_{\ell_1m_1}M^{N,q}_\ell(\mathbf{r})Y_{\ell m}(\widehat{\mathbf{r}})$$

33

Monte Carlo Planck maps

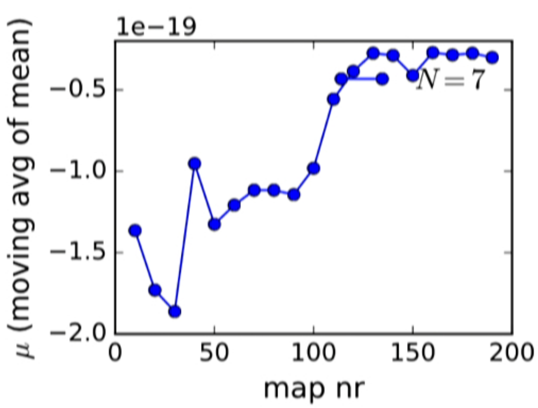
- **Shape function**

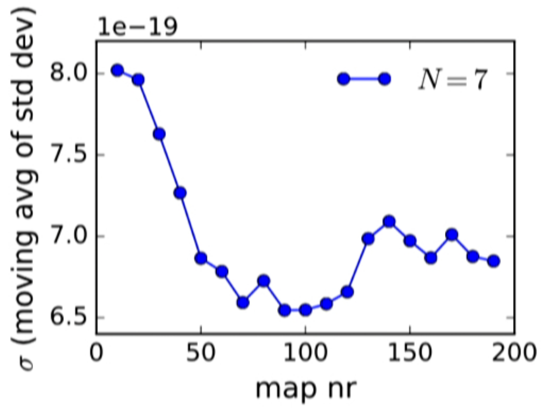
$$S^N(k_1, k_2, k_3, \dots) = \frac{k_1^{i\omega/H} k_2^{i\omega/H} k_3^{i\omega/H} \dots}{(k_1 k_2 k_3 \dots)^{3(N-1)/N}}$$

(approximation of the full shape)

- Need to scan over frequency and phase (look elsewhere effect).

- **Run estimator on Planck sims**





- **Data results upcoming. First N>4 analysis.**

Outlook: Searching for time dependent couplings

- How to search for non-Gaussianity systematically?
- Well established in the case of slow roll inflation with constant couplings. EFTI action

$$S = \int d^4x \sqrt{-g} \left[M_{\rm Pl}^2 \dot{H}(t+\pi) \left(\dot{\pi}^2 - \frac{(\partial_i \pi)^2}{a^2} \right) + \right.$$
$$\left. + M_1^4(t+\pi)\left(\dot{\pi}^2 + \dot{\pi}^3 + \ldots\right) + M_2^4(t+\pi)\left(\dot{\pi}^3 + \ldots\right) + M_3^4(t+\pi)\left(\dot{\pi}^4 + \ldots\right) \right]$$

- Less well understood: How to look systematically for time dependent masses/couplings.
- Basic Idea (Flauger et al.): Fourier expand couplings

$$M_I^4(t) = \int d\omega \, e^{i\omega t} \, \tilde{M}_I^4(\omega) \simeq \sum_{J=-J_{\rm max}}^{J_{\rm max}} e^{i\,\Delta\omega\, J\, t} \, \tilde{M}_{I,J}^4$$

- BUT: large look elsewhere effect. Adiabatic and non-adiabatic effects. Higher N point functions etc. Can we be systematic?

Conclusions

The good side

- The weakly non-linear modes contained in the observable universe may well allow the detection of heavy particles m~H.
- Heavy particles are very common in UV models of inflation
- Cosmological perturbations have access to 3-5 orders of magnitude in energy, lots of room for discoveries.
- We have reviewed adiabatic and non-adiabatic particle production. The latter has unexplored phenomenology with CMB data.

The bad side

- CMB sensitivity on equilateral non-Gaussianity will not be significantly beaten any time soon.
- 21cm mapping of the dark ages is decades away.

We are at the beginning of cosmological collider physics.