SIGNATURES OF NON-GAUSSIANITY IN THE ISOCURVATURE MODES OF PRIMORDIAL BLACK HOLE DARK MATTER

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Based on work with Chris Byrnes 1503.01505,

And previous work with Chris Byrnes and Misao Sasaki 1411.4620, 1405.7023, 1307.4995

IberiCos, Aranjuez, 2015

CONTENTS

- Introduction to primordial black holes (PBHs)
- Modal coupling and the peak-background split
- Bias factors
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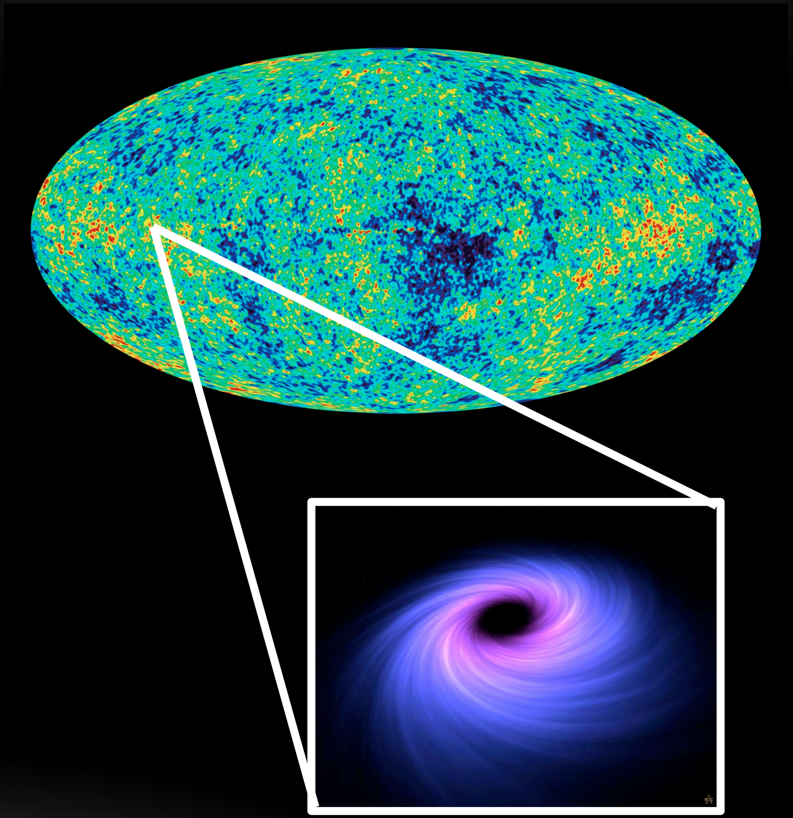


MOTIVATION

- PBHs are a viable DM candidate, requiring no extensions to the standard model
- Many models predict a large amount of PBHs – and typically, these models also produce non-gaussianity

PRIMORDIAL BLACK HOLES

- Form very early on in the history of the universe from the collapse of density fluctuations
- They can theoretically have any mass (>M_{Pl}?), but constraints on the abundance exist for PBHs of mass ~10^8g to ~10^{50}g
- A perturbation will collapse if above a certain critical value, $\zeta_c \approx 1$ (Shibata and Sasaki, 1999), when it re-enters the horizon
- Still a viable DM candidate – there exists a narrow range of mass scales which are not constrained by observations, roughly 10^{20}g (we will assume DM is PBHs)
- Traditionally used to constrain the small scale power spectrum
- But can the very small PBHs can produce observable consequences in the very large CMB?

CALCULATING THE ABUNDANCE OF PBH'S

- The abundance has can be calculated using a Press-Schechter (PS) approach, integrating over the probability density function (pdf)

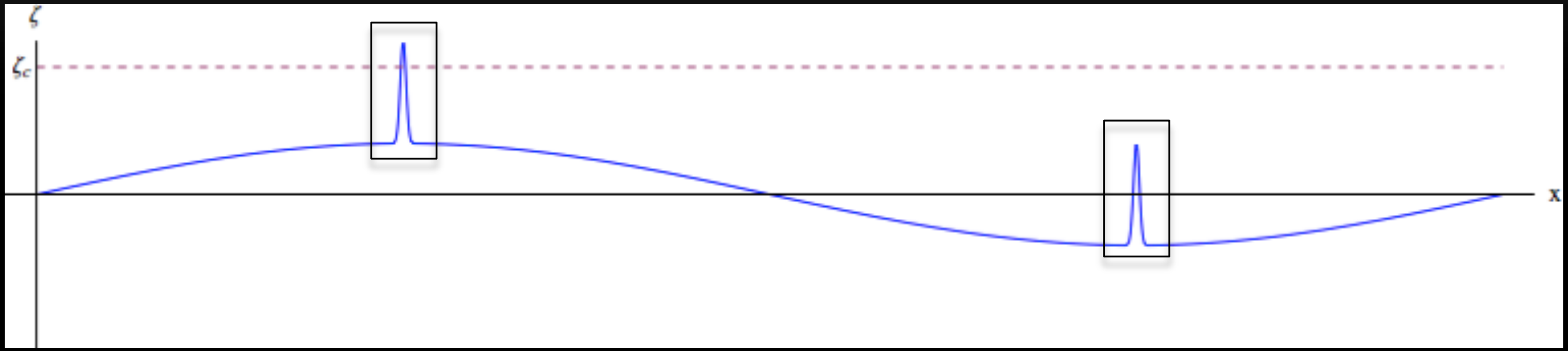
$$\beta = \int_{\zeta_c}^{\infty} P(\zeta) d\zeta$$

- The theory of peaks can also be used (see arXiv:1405.7023)
- The pdf is normally assumed to be gaussian

$$P(\zeta) = \frac{1}{\sqrt{2\pi\mathcal{P}_\zeta}} \exp\left(\frac{\zeta^2}{2\mathcal{P}_\zeta}\right)$$

- (The power spectrum can be used instead of the variance, $\langle\zeta^2\rangle$, because super-horizon modes can be neglected)
- β is exponentially sensitive to the power spectrum (and non-gaussianity parameters)

THE CURVATURE PERTURBATION AND SUPER-HORIZON MODES



- Naively expect first perturbation to collapse, but not the second
- However, horizon is small at time of formation, and both universes look the same locally
- They should both collapse, or neither should collapse
- (Extremely) super-horizon modes can be neglected

MODAL COUPLING DUE TO NON-GAUSSIANITY

- In the local model of non-gaussianity

$$\zeta = \zeta_G + \frac{3}{5} f_{NL} \left(\zeta_G^2 + \langle \zeta_G^2 \rangle \right)$$

- Split perturbations into “peak” and “background”

$$\zeta_G = \zeta_s + \zeta_l$$

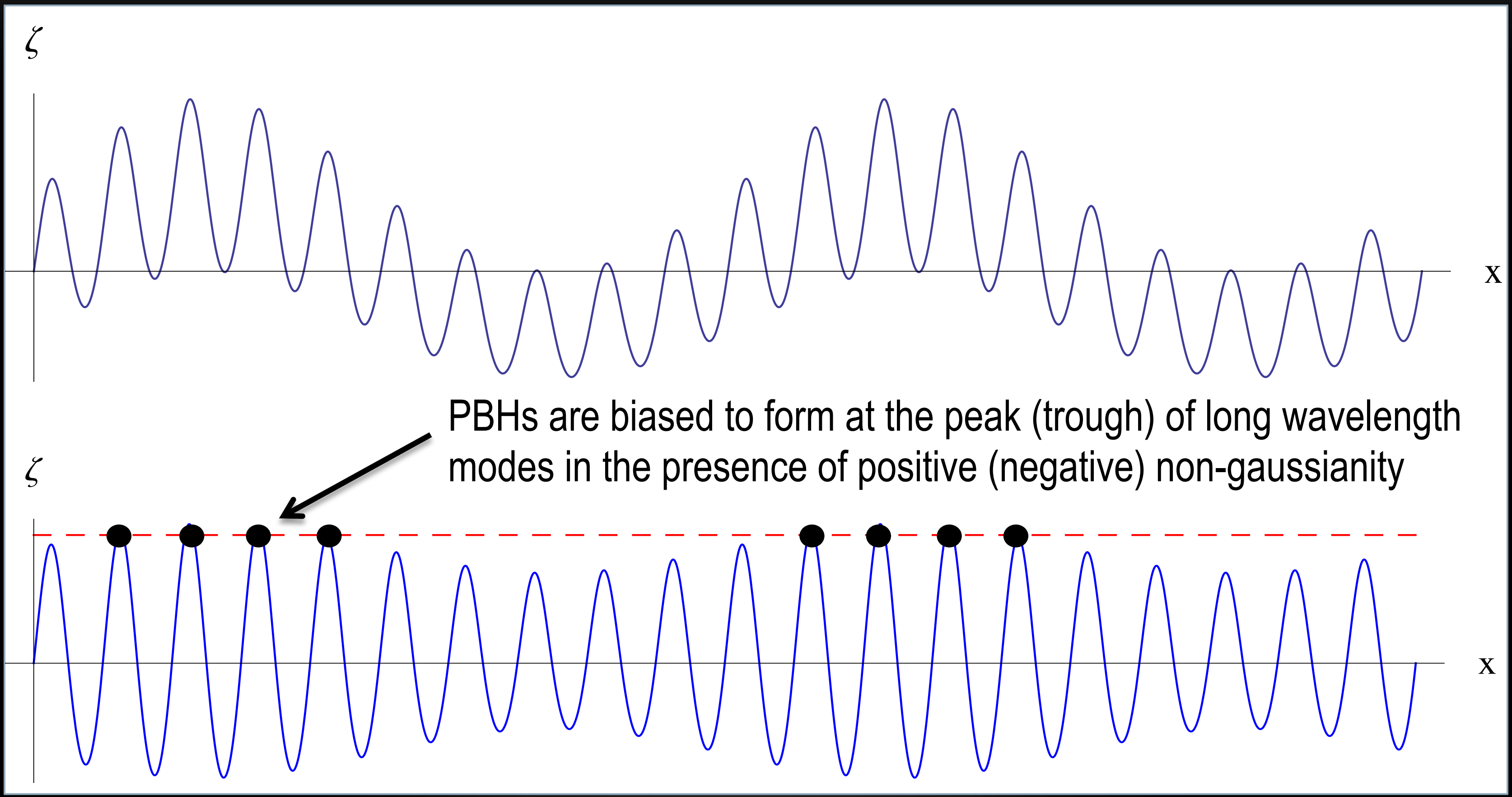
$$\zeta = \left(1 + \frac{6}{5} f_{NL} \zeta_l \right) \zeta_s + \frac{3}{5} f_{NL} \left(\zeta_s^2 - \langle \zeta_s^2 \rangle \right) + \zeta_l + \frac{3}{5} f_{NL} \left(\zeta_l^2 - \langle \zeta_l^2 \rangle \right)$$

- ζ can then be rewritten in terms of new perturbed variables

$$\zeta = \tilde{\zeta}_G + \frac{3}{5} \tilde{f}_{NL} \left(\tilde{\zeta_G}^2 - \langle \tilde{\zeta}_G^2 \rangle \right)$$

$$\tilde{\zeta}_G = \left(1 + \frac{6}{5} f_{NL} \zeta_l \right) \zeta_s, \;\; \tilde{f}_{NL} = \frac{f_{NL}}{\left(1 + \frac{6}{5} f_{NL} \zeta_l \right)^2}$$

MODAL COUPLING



BIAS FACTORS

- *Scale-independent bias*: a perturbation (halo) is more likely to collapse if it is in the middle of a larger-scale over-density (a bigger halo)
  - Not relevant for PBHs as larger super-horizon density modes are strongly suppressed
- *Scale-dependant bias*: arises from the modal coupling due to non-gaussianity
  - Extremely relevant for PBHs
- To first order:

$$\Omega_{PBH} = (1 + 3\zeta + b\zeta)\bar{\Omega}_{PBH}$$

Background value

Adiabatic perturbation

Isocurvature perturbation

ISOCURVATURE MODES

- In the standard picture of single field inflation, all perturbations are adiabatic – and can be explained by the difference in expansion of a region due to ζ
  - $\rho_r \propto a^{-4} \rightarrow \delta_r \sim 4\zeta$
  - $\rho_m \propto a^{-3} \rightarrow \delta_m \sim 3\zeta$
- Adiabatic modes in the matter and radiation fluids are therefore related by a factor ¾ - and deviation from this ratio is considered to be an isocurvature perturbation
- Very tight constraints from Planck on fully-, or fully anti-, correlated isocurvature modes in CDM

$$100\beta_{iso} = \begin{cases} 0.13 & \text{, fully correlated} \\ 0.08 & \text{, fully anti-correlated,} \end{cases}$$

$$\beta_{iso} = \frac{\mathcal{P}_{iso}}{\mathcal{P}_{iso} + \mathcal{P}_\zeta}$$

CONSTRAINTS ON NON-GAUSSIANITY IN THE PBH DM SCENARIO

- The *scale-dependant bias* therefore creates isocurvature perturbations in the primordial distribution of CDM in the presece of non-gaussianity
- Constraints from Planck: $-0.028 < b < 0.036$
- To first order in f_{NL} and g_{NL}

$$b_{f_{NL}} = \frac{6}{5}\left(1+\frac{\zeta_c^2}{\sigma_s^2}\right) f_{NL}$$

$$b_{g_{NL}} = -\frac{27(\sigma_s^2-\zeta_c^2)(\sigma_s^2+\zeta_c^2)}{25\sigma_s^2\zeta_c} g_{NL}$$

- Very tight constraints on the non-gaussianity parameters

$$-4\times 10^{-4} < f_{NL} < 5\times 10^{-4}$$

$$-6\times 10^{-4} < g_{NL} < 7\times 10^{-4}$$ - surprisingly strong!

CONCLUSIONS

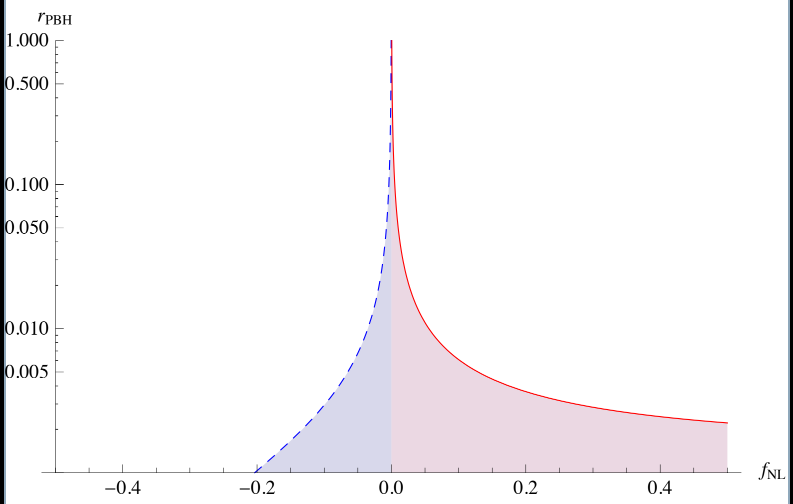
- Detection of PBHs would effectively rule out non-gaussianity, and vice versa
- Constraints are (almost) independent of PBH mass, and cannot be evaded if PBHs span a large range of masses
- Most PBH producing models can be ruled out as a mechanism for producing PBH DM
- Calculation can be extended to exclude higher order terms as well
- Not accounted for scale dependant NG, but would not weaken constraints significantly (though distribution is free to become strongly NG on small scales)

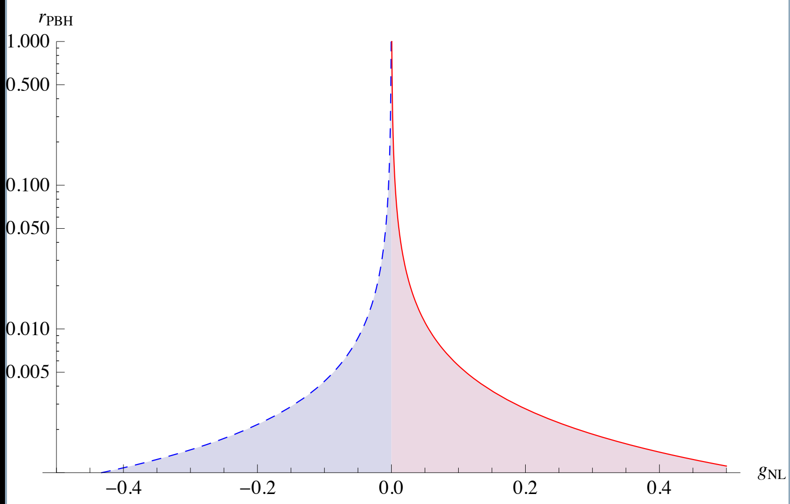
THANK YOU FOR LISTENING

- Any questions?
- Here are some suggestions (of things I didn't have time for):
  - Why does non-gaussianity have such a strong effect on the abundance of PBHs?
  - What if dark matter is only partially composed of PBHs?
  - Why are the constraints on g_{NL} so similar to the constraints on f_{NL}?
  - Can a positive g_{NL} cancel the effect of a negative f_{NL}?
  - What about higher order terms?

PARTIAL PRIMORDIAL BLACK HOLE DARK MATTER

$$r_{PBH} = \frac{\rho_{PBH}}{\rho_{DM}}$$

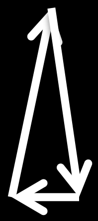




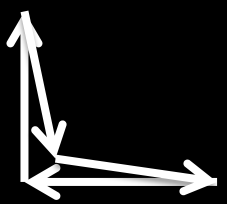
WHAT IS NON-GAUSSIANITY?

- The bispectrum $\mathcal{B}$ is the fourier transform of the 3-point correlation function
- The trispectrum $\mathcal{T}$ is the fourier transform of the 4-point correlation function
- Non-zero non-gaussianity implies a coupling between modes
- In the local model of non-gaussianity

$$\zeta = \zeta_G + \frac{3}{5} f_{NL} \left(\zeta_G^2 - \sigma^2 \right) + \frac{9}{25} g_{NL} \zeta_G^3 + \ldots$$



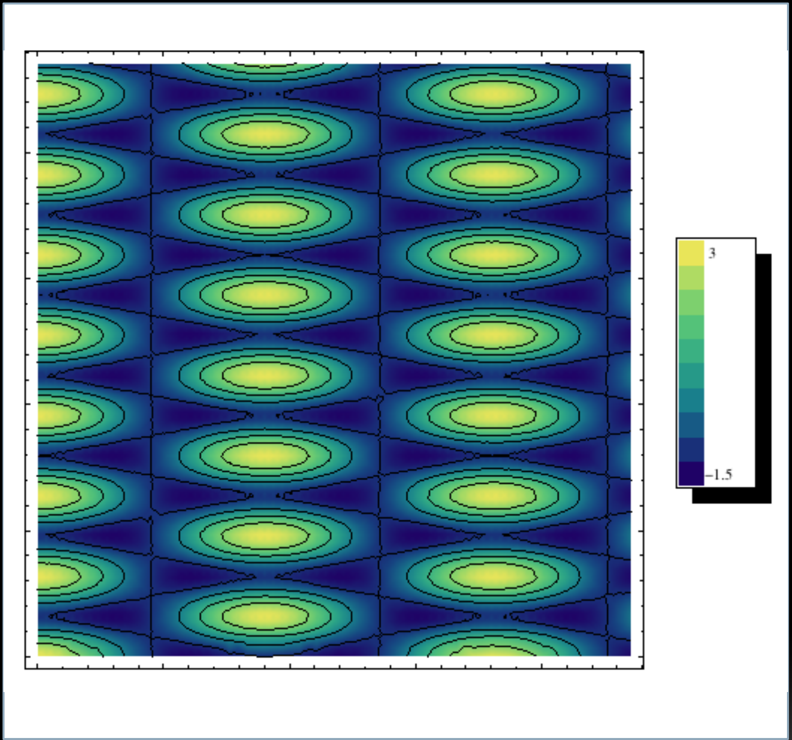
Squeezed bispectrum



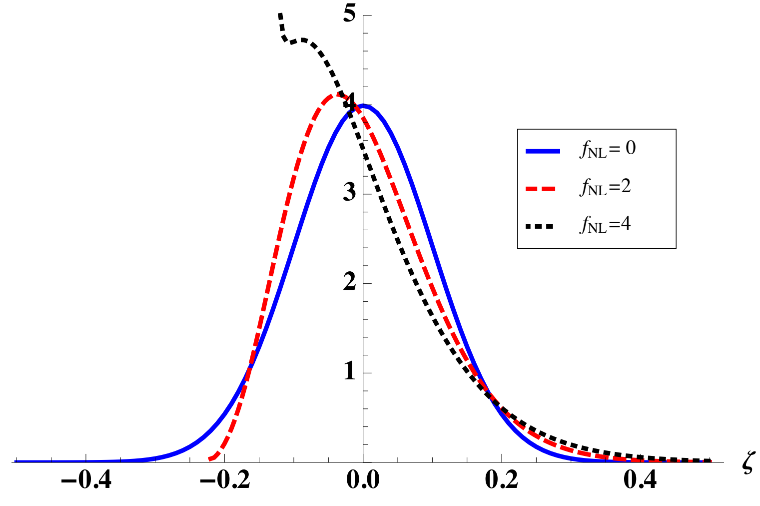
Trispectrum

A POSITIVE BISPECTRUM

Density distribution



Probability density

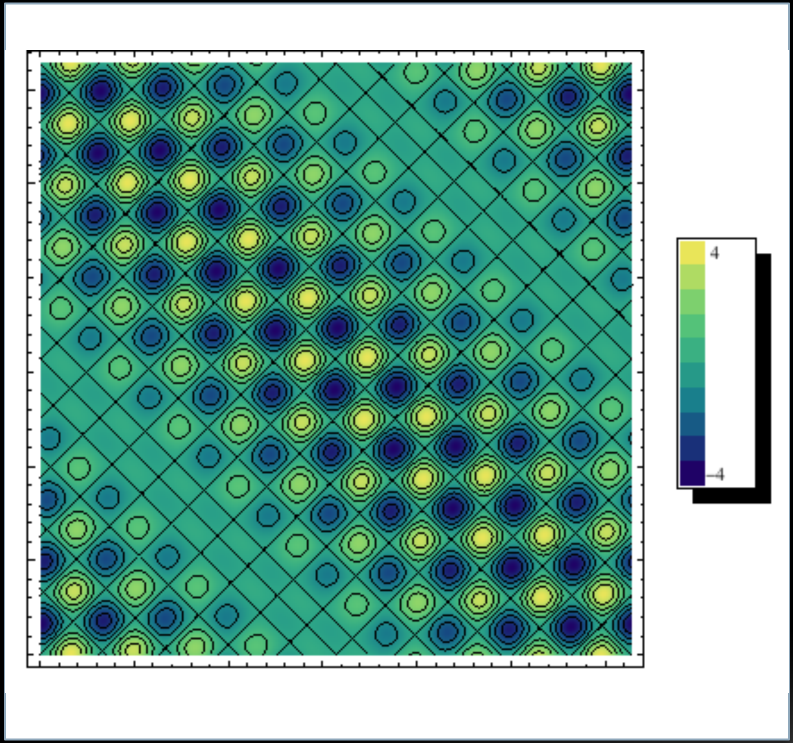


$$\sigma^2 = 0.01$$

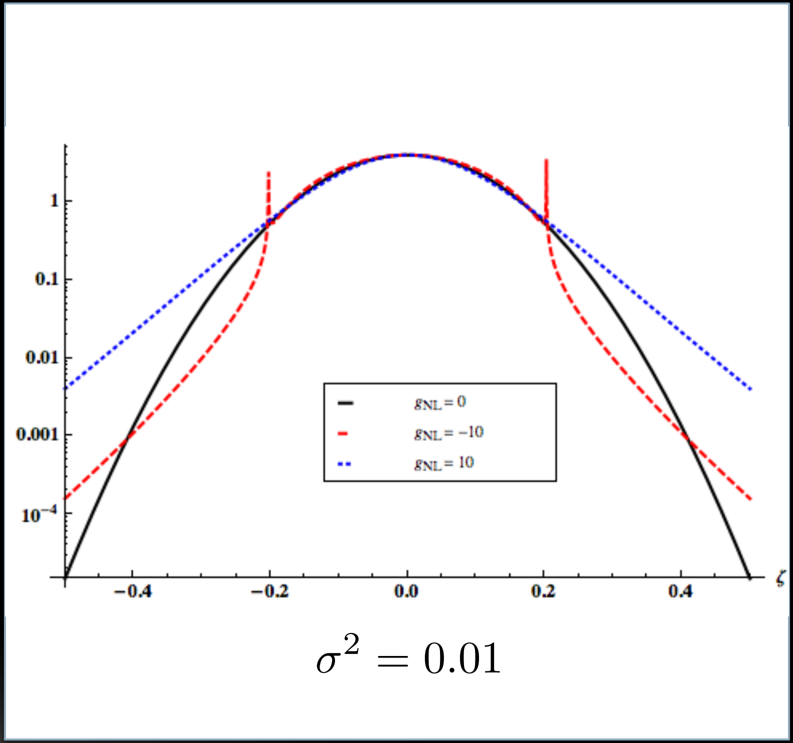
NB. Small f_{NL} has a large effect on distribution

THE TRISPECTRUM

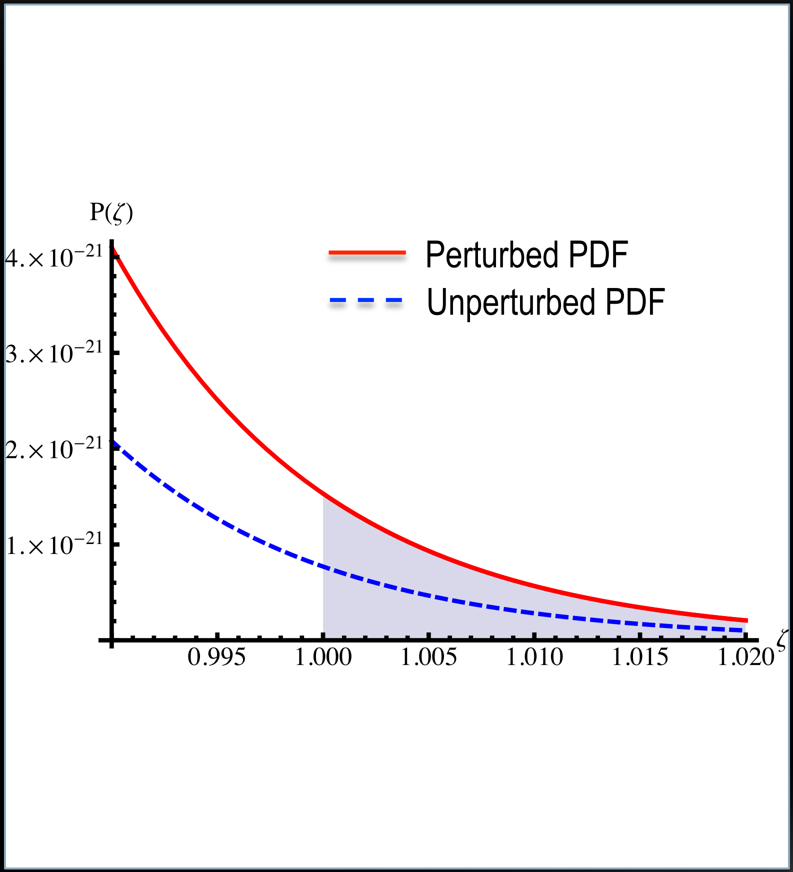
Density distribution



Probability density



CONSTRAINTS ON F_{NL}



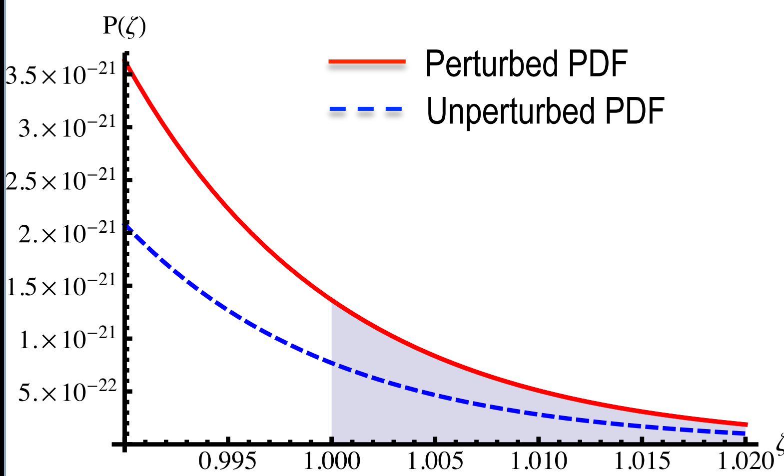
- Small change in the parameters means a large change to the tail of the distribution
- The f_{NL} term has a linear effect on the amplitude of perturbation

$$\tilde{\sigma} = \left(1 + \frac{6}{5} f_{NL} \zeta_l\right) \sigma$$

$$f_{NL} \sim 10^{-3}, \zeta_l \sim 10^{-5}$$
$$\rightarrow \tilde{\sigma} \sim (1 + 10^{-8})\sigma$$

- (Difference has been amplified by 10^5)

CONSTRAINTS ON G_{NL}



- Constraints on g_{NL} are naively expected to be ~10^{-5} weaker

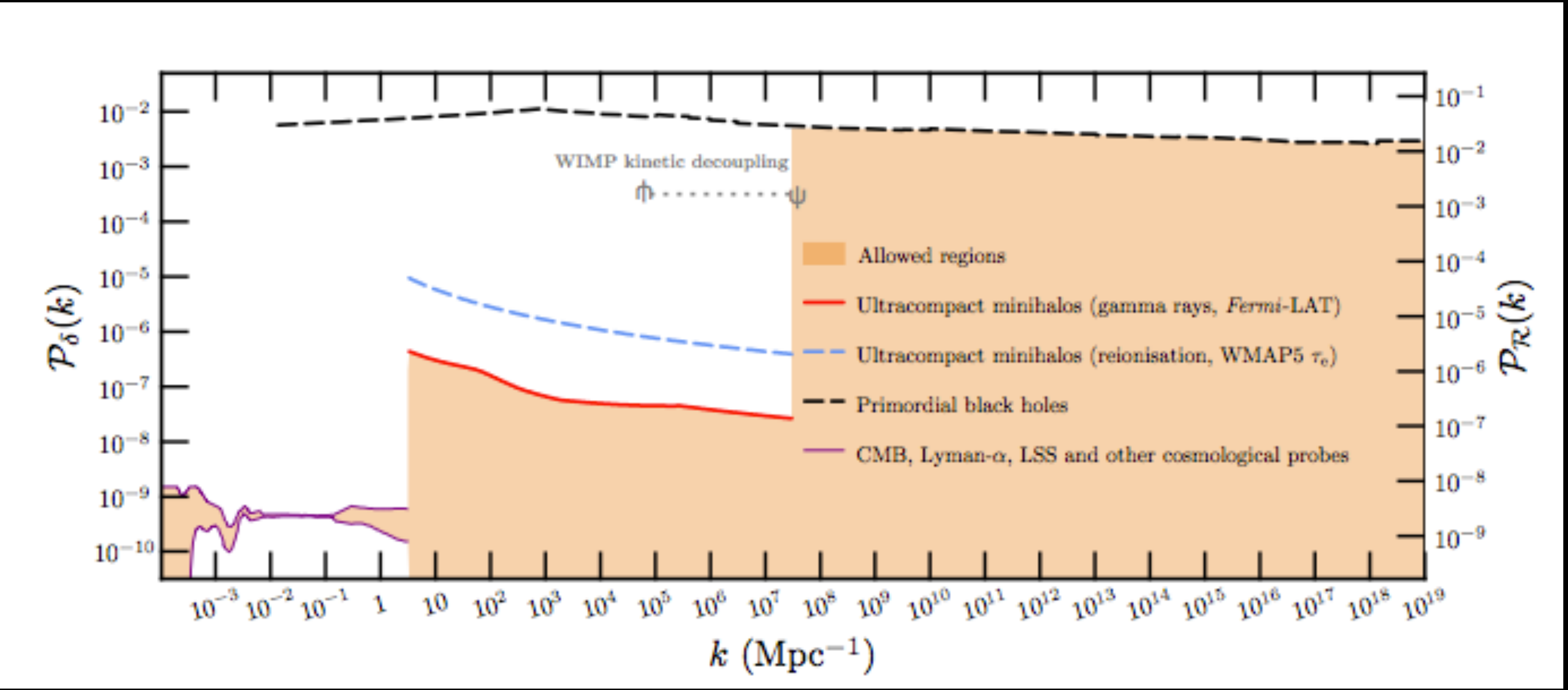
$$\tilde{\sigma} = \left(1 + \frac{27}{25} g_{NL} \zeta_l^2\right) \sigma$$

- g_{NL} term has a linear effect on the f_{NL} term

$$\tilde{f}_{NL} \sim \left(f_{NL} + \frac{9}{5} g_{NL} \zeta_l\right)$$

$$f_{NL} = 0, g_{NL} = 10^{-3}, \zeta_l \sim 10^{-5}$$
$$\rightarrow \tilde{f}_{NL} \sim 10^{-8}$$

CONSTRAINTS ON THE POWER SPECTRUM



Bringmann, Scott, Akrami, 2013