STUDYING THE SMALL SCALE UNIVERSE WITH PRIMORDIAL BLACK HOLES

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ACP-YITP Collaboration: Mini-Workshop on Cosmology and Gravitation

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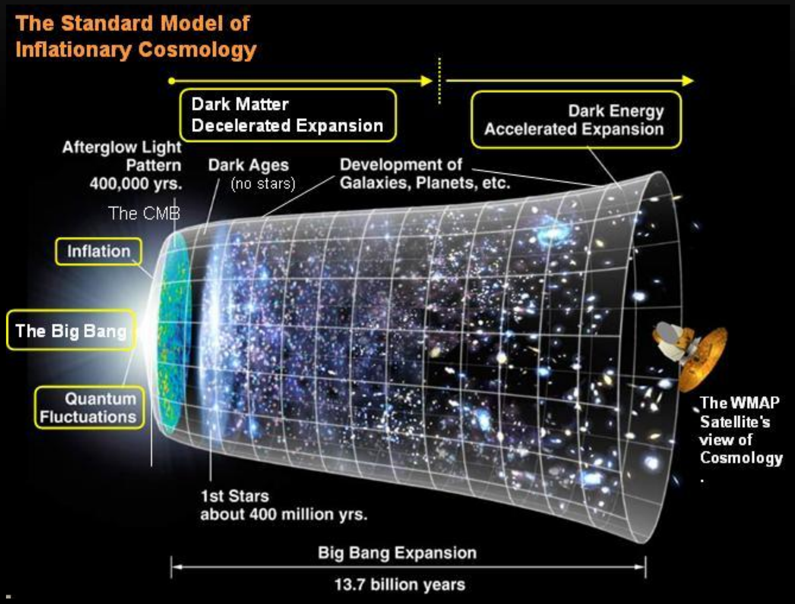
CONTENTS

- Introduction
- Constraints from PBHs
- The effect of non-Gaussianity
- The curvaton model
- Inhomogeneities from non-Gaussianity
- Conclusion



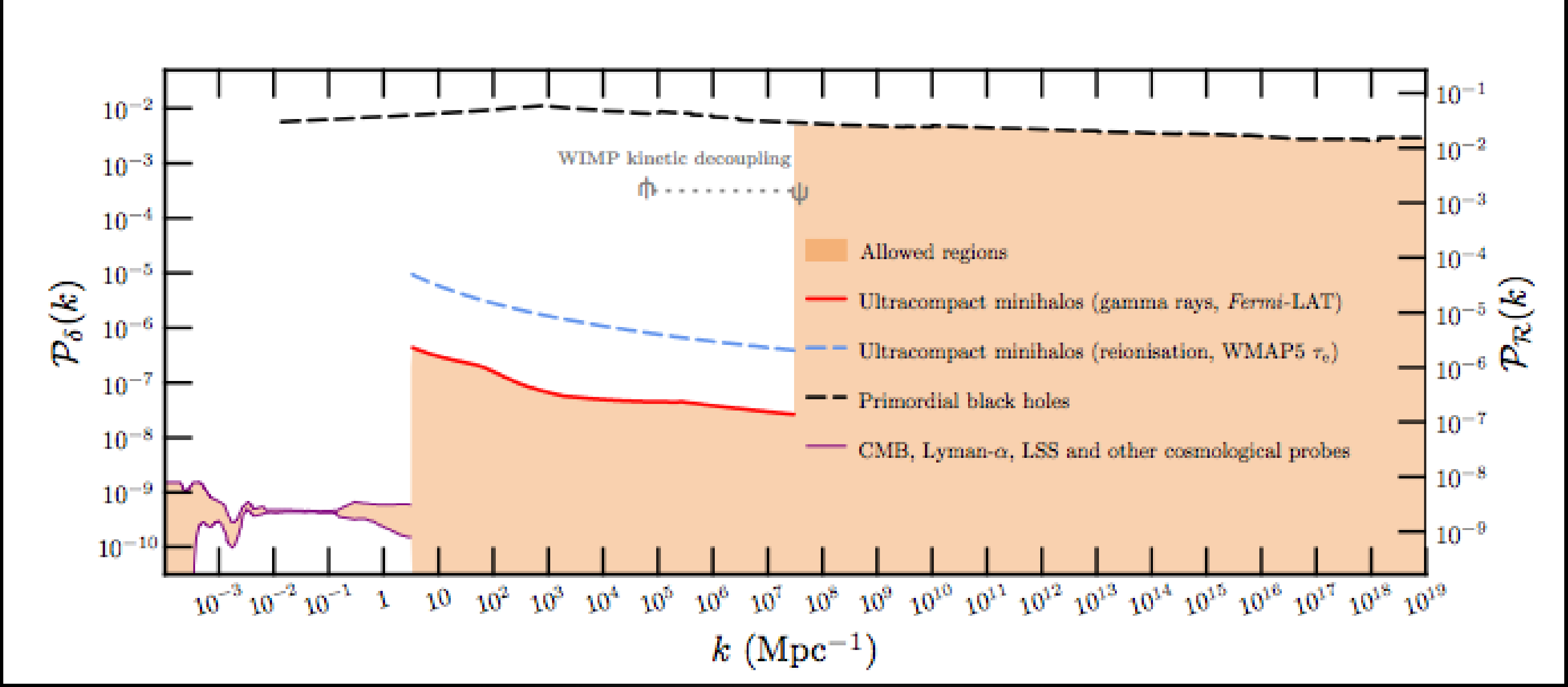
WHAT ARE PBH'S?

- During inflation, quantum fluctuations provide the seeds for density perturbations in the early universe.
- While the Universe is undergoing inflation, the Hubble horizon shrinks, but after inflation, the Hubble horizon begins to grow.
- If a region is dense enough, it will collapse to form a PBH as soon as it reenters the horizon.
- The critical value for collapse is normally stated in terms of the density contrast or the curvature perturbation – where larger perturbations are assumed to form PBHs. Although this is sensitive to the shape of the overdensity.
- Theoretically, PBHs of any mass can be formed – but PBH abundances in the range ~10^5g-10^{50}g grams are constrained by observations.

WHY SHOULD I CARE ABOUT PBH'S?

- Density perturbations from quantum fluctuations are visible in the cosmic microwave background (CMB) and in large scale structure (LSS) in the universe.
- Inflation is believed to have lasted at least 50-60 e-foldings, but the information from CMB and LSS only covers the largest 5-10 e-foldings.
- What about the small scales? Information in small scale structure will have been wiped out.
- Primordial black holes (PBHs) form in extremely overdense regions, however, the power spectrum on small scales needs to be significantly larger in order for a significant number of PBHs to form.
- We can constrain the early universe using the fact that PBHs have not been observed.

CONSTRAINTS ON THE POWER SPECTRUM



Bringmann, Scott, Akrami, 2013

CONSTRAINTS ON PBH ABUNDANCE

For low mass PBHs the constraints tpyically come from the effects of the radiation from evaporation, for example:

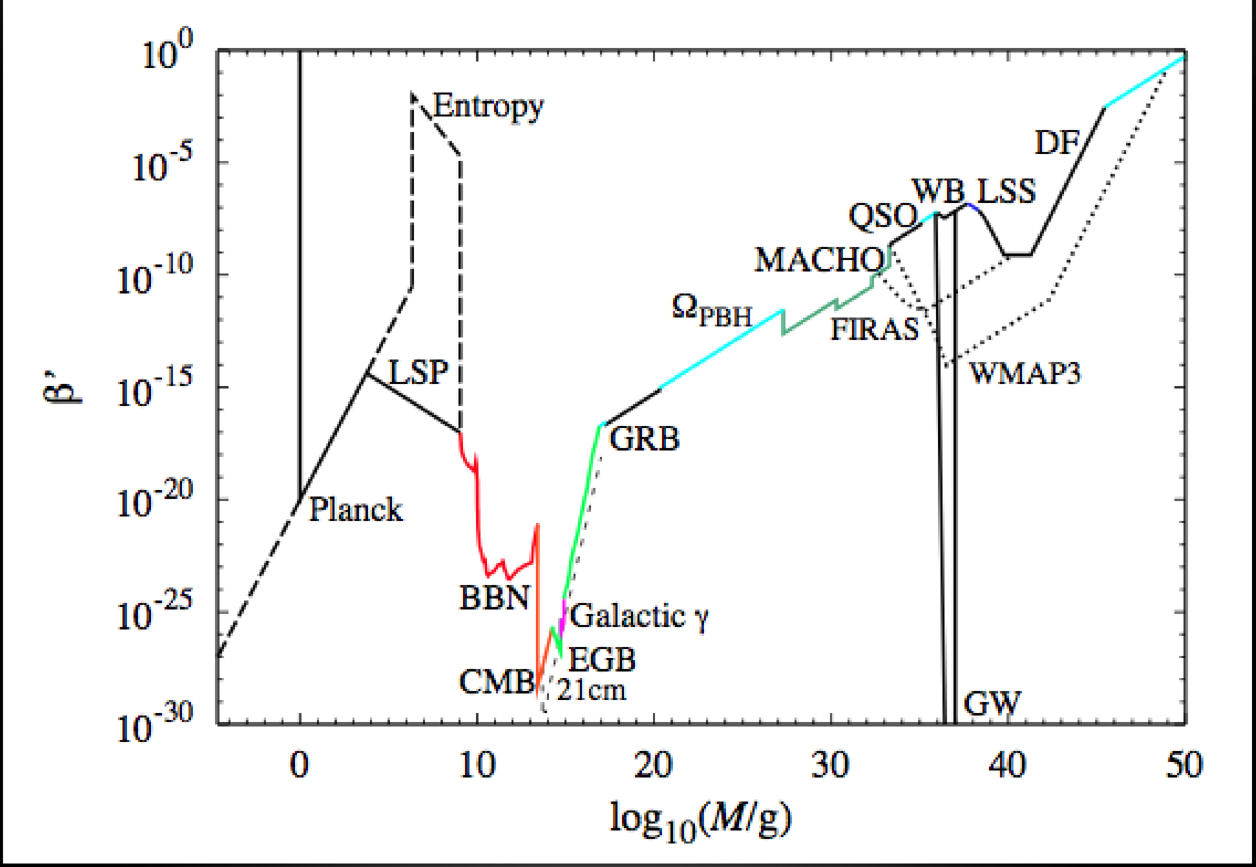
- Spectral distortions in the CMB
- Effects on nucleosynthesis
- Abundance of cosmic rays

For high mass PBHs, the constraints typically come from their gravitational effects, for example:

- Present day density must be less than the dark matter content of the universe
- Lensing of cosmological sources

For a review, see Josan, Green and Malik (2009), and Carr et al (2010)

REVIEW OF CONSTRAINTS



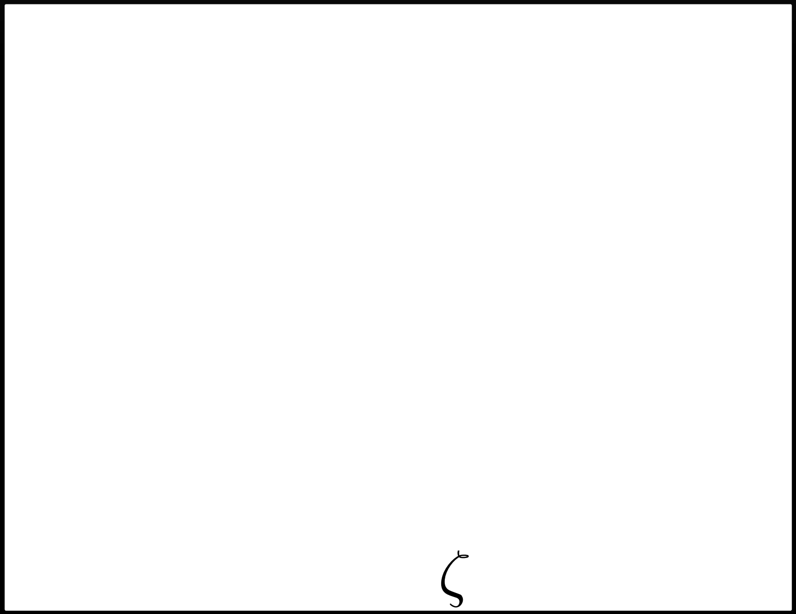
Carr et al (2010)

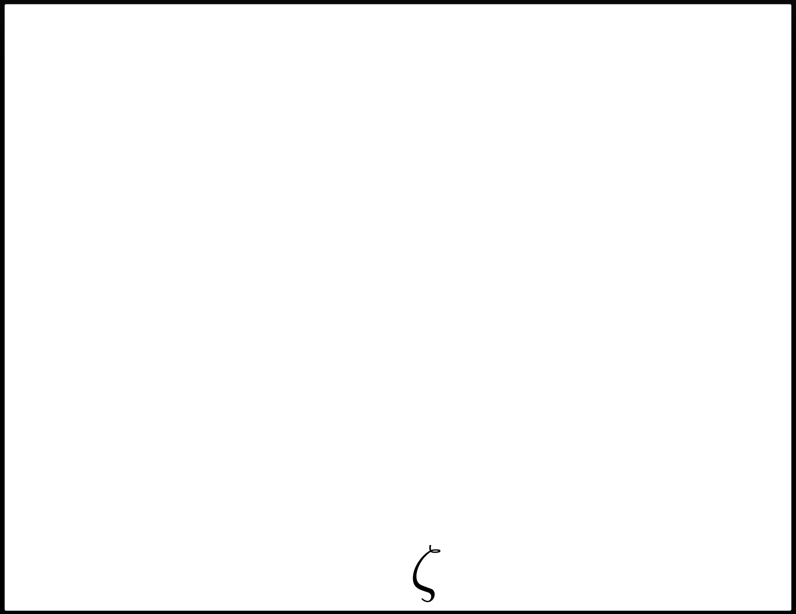
THE GAUSSIAN CASE

- $$P(\zeta) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{\zeta^2}{2\sigma^2}\right)$$
- Using a Press-Schechter approach
  $$\beta = 2\int_{\zeta_c}^{\infty} P(\zeta)\, d\zeta$$
- σ is given by the approximate analytical solution
  $$\sigma \approx \zeta_c \sqrt{\frac{1}{2\ln(1/\beta)}}$$
- Shibata & Sasaki (1999) found
  $$0.7 < \zeta_c < 1.2$$
- For definiteness, we will take
  $$\zeta_c = 1$$

QUADRATIC NON-GAUSSIANITY

$$\zeta = \zeta_g + \frac{3}{5} f_{NL} \left(\zeta_g^2 - \sigma^2 \right)$$

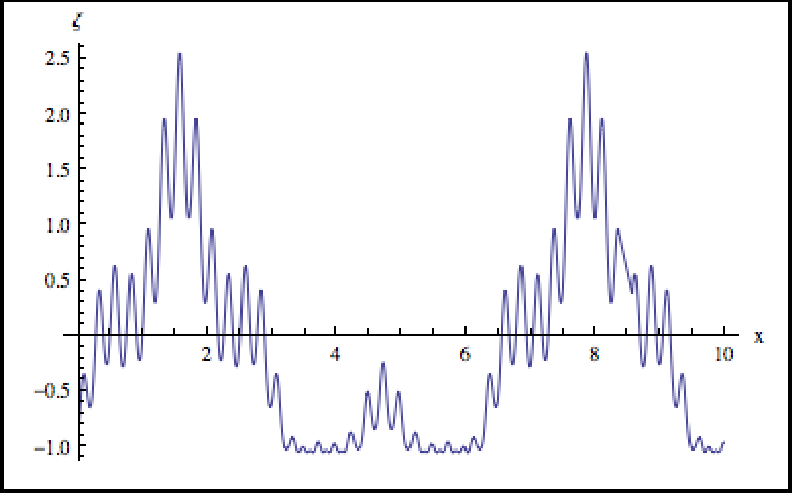




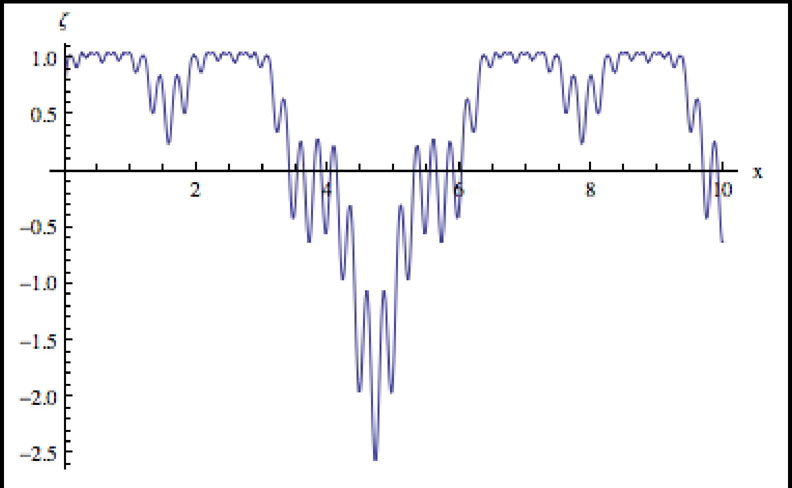
- Introducing a quadratic term skews the distribution (positive f_{NL} gives positive skew)
- Note also that for positive (negative) f_{NL} then ζ is bound from below (above)
- All graphs have the same variance
- See Byrnes et al, 2012

WHAT DOES A UNIVERSE WITH QUADRATIC NON-GAUSSIANITY LOOK LIKE?

Positive f_{NL}



Negative f_{NL}



QUADRATIC NON-GAUSSIANITY

CUBIC NON-GAUSSIANITY

$$\zeta = \zeta_G + \frac{9}{25} g_{NL} \zeta_G^3$$

- The addition of a cubic term to the curvature pertubation introduces kurtosis – typically negative kurtosis, increasing PBH production.
- Small negative values of g_{NL} can introduce positive kurtosis, decreasing PBH formation.

CUBIC NON-GAUSSIANITY

HIERARCHICAL SCALING

$$g_{NL} = f_{NL}^2, h_{NL} = f_{NL}^3, i_{NL} = f_{NL}^4,$$

$\beta=10^{-5}$

- This type of relation can occur in, for example, multi-brid inflation. See Lin and Wang (2010)

PDF'S IN THE CURVATON MODEL

- In the curvaton model there is a second field, which decays after reheating, which is responsible for perturbations. It can cause significant non-Gaussianity
- The free parameter in the pdf is the density parameter of the curvaton at the time of decay, $\Omega_{\chi,decay}$
- Changing $\Omega_{\chi,decay}$ adds both skew and kurtosis to the pdf

CONSTRAINTS IN THE CURVATON MODEL

INHOMOGENEITIES FROM NON-GAUSSIANITY

- Rather than considering perturbations coming from a single spike in the power spectrum, we will now consider the effect of a long wavelength mode.
- The Gaussian curvature perturbation, ζ_G, is split into a short wavelength component and a long wavelength component

$$\zeta_G = \zeta_L + \zeta_S$$

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

- The long wavelength modes are considered to be in the super-horizon regime, and do not contribute the local evolution of the Hubble patch (they do not affect PBH formation).
- Focusing on only the small scale perturbations relevant for PBH formation, we see that the distribution depends on the large scale perturbation:

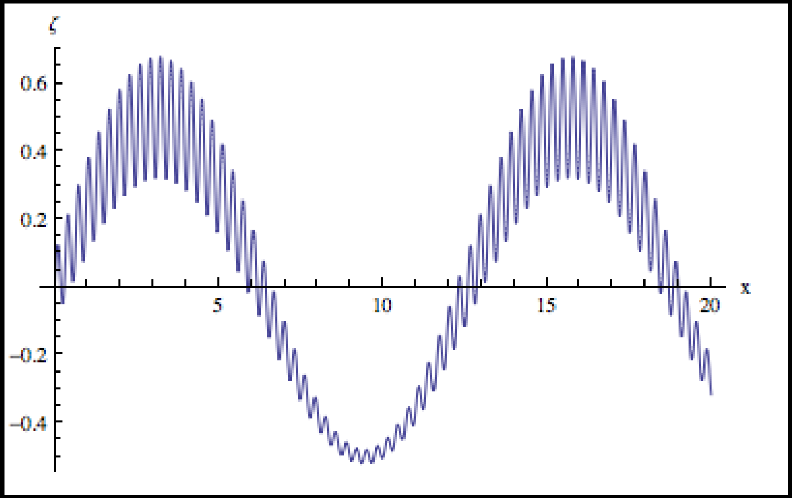
$$\tilde{\zeta} = \tilde{\zeta}_G + \frac{3}{5} \tilde{f}_{NL} \left(\tilde{\zeta}_G^2 - \langle \tilde{\zeta}_G^2 \rangle \right)$$

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

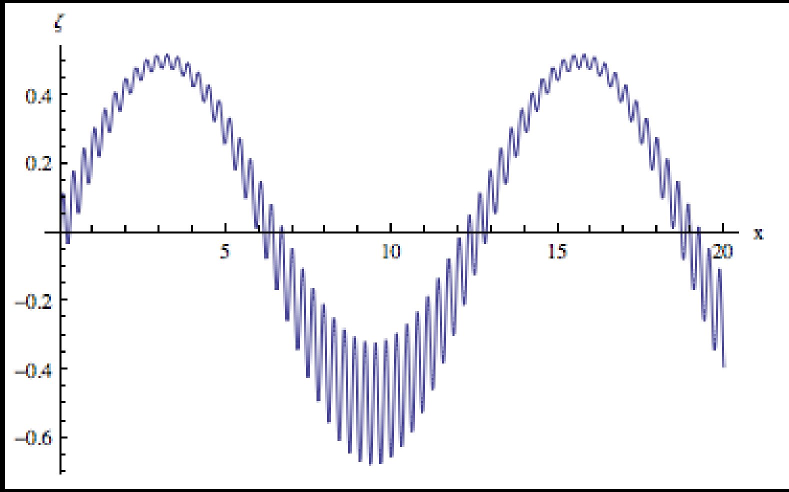
- See Byrnes et al (2011)

WHAT EFFECT DOES THIS HAVE?

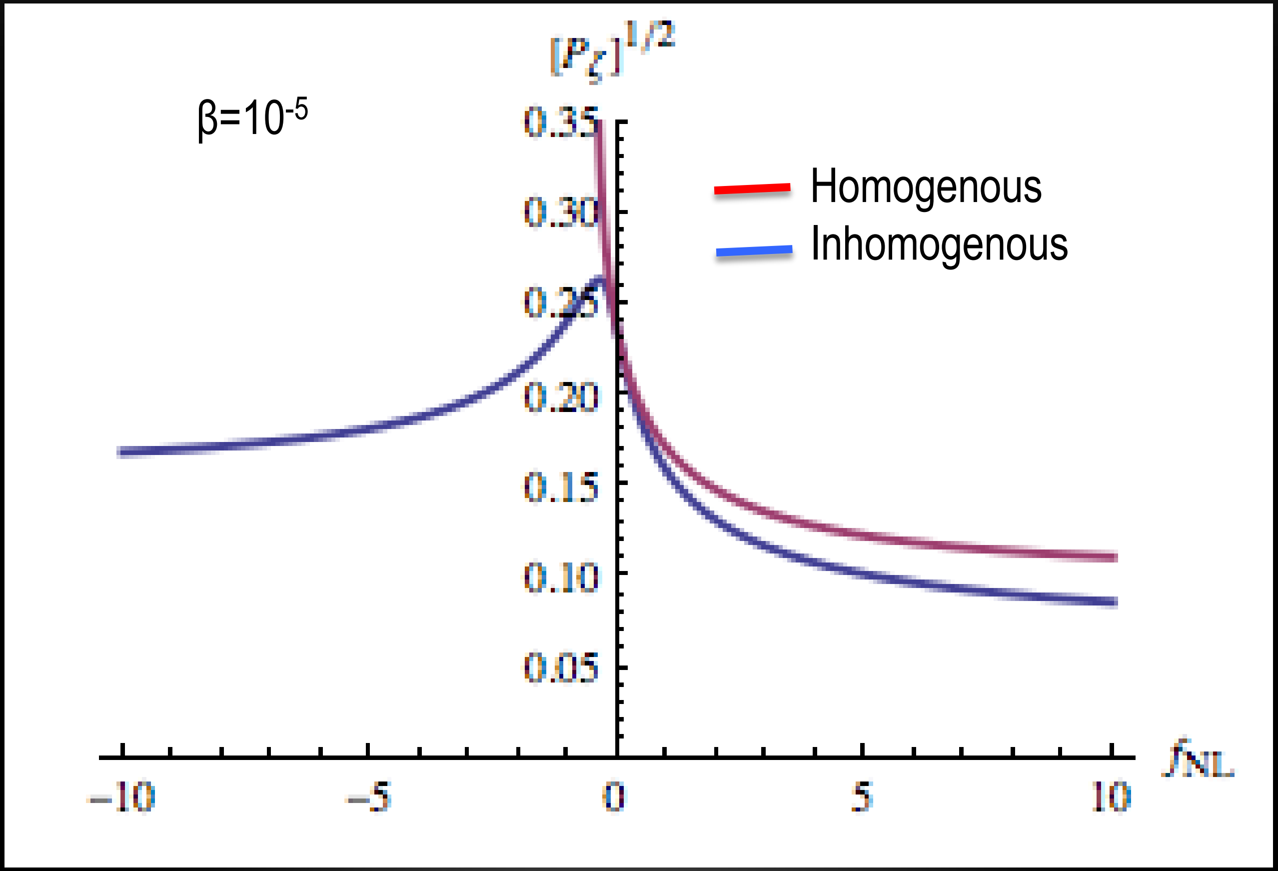
Positive f_{NL}



Negative f_{NL}



CONSTRAINTS FROM INHOMOGENEITIES



CONCLUSIONS

- The “precision” constraints on primordial cosmology come from a relatively small range of scales, about 6 e-foldings.
- PBHs allow us to probe a much larger range of scales in the early universe.
- However, the constraints are much weaker.
- Because PBHs form in the extreme tail of the pdf, their formation rate is highly sensitive to any non-Gaussianity.
- The constraints on the power spectrum typically become much tighter when non-Gaussianity is considered.
- If PBHs form in a given model, it is important to take into account the non-Gaussianity, even if this is irrelevant on CMB and LSS scales.