PRIMORDIAL BLACK HOLES AND NON-GAUSSIANITY

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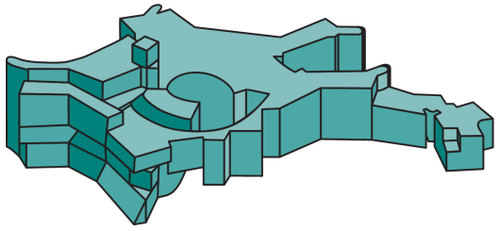
Work with: Christian Byrnes, Donough Regan, Ilia Musco

Workshop on the non-Gaussian universe. Cambridge, September 2019.



OVERVIEW

- Introduction
- Formation criterion and non-Gaussianity of δ
- Effects of primordial non-Gaussianity I: skewness and kurtosis
- Effects of primordial non-Gaussianity II: modal coupling
  - Clustering and isocurvature modes
  - Merger rate
- Summary

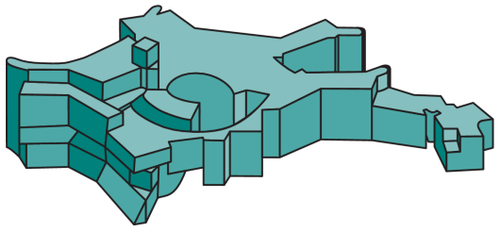
INTRODUCTION

- PBH Formation
  - We'll focus on PBHs formed from the collapse of large amplitude perturbations at horizon re-entry during radiation domination
  - Very rare events. Due to redshift of matter density, a very small initial number of PBHs can mean a large number today
- Viable dark matter candidate
- Unique constraints on small scale power spectrum
- Abundance calculation

INTRODUCTION

- PBH Formation
- Still a viable dark matter candidate
- Unique constraints on small scale power spectrum
- Basics of calculation

INTRODUCTION



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- Still a viable dark matter candidate
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INTRODUCTION

- PBH Formation
- Still a viable dark matter candidate
- Constraints from non-observation
- Abundance calculation
  - A Gaussian distribution is typically assumed

$$P(\delta) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{\delta^2}{2\sigma^2}\right)$$

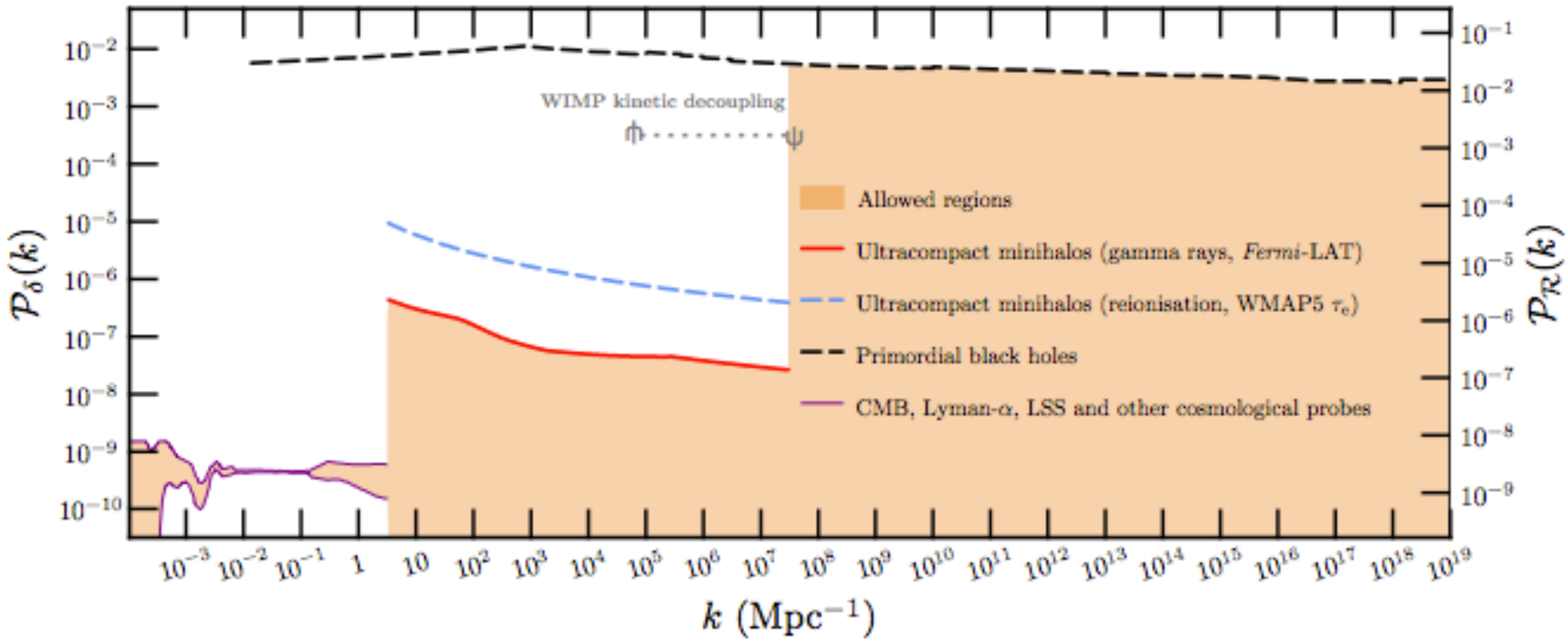
  - Mass fraction of the universe collapsing to form PBHs at the time of formation is

$$\beta \approx \mathrm{erfc}\left(\frac{\delta_c}{\sqrt{2}\sigma}\right)$$

    - δ_c is the threshold amplitude. Perturbations above this will collapse. Using the volume averaged density seems more robust.
  - σ^2 is proportional to the power spectrum, so β depends exponentially on the power spectrum

CONSTRAINTS ON THE POWER SPECTRUM

Constraints on β vary by many orders of magnitude, but constraints on $\mathscr{P}$ only vary by a factor of a few



Bringmann, Scott & Akrami, 2013

arXiv:1110.2484

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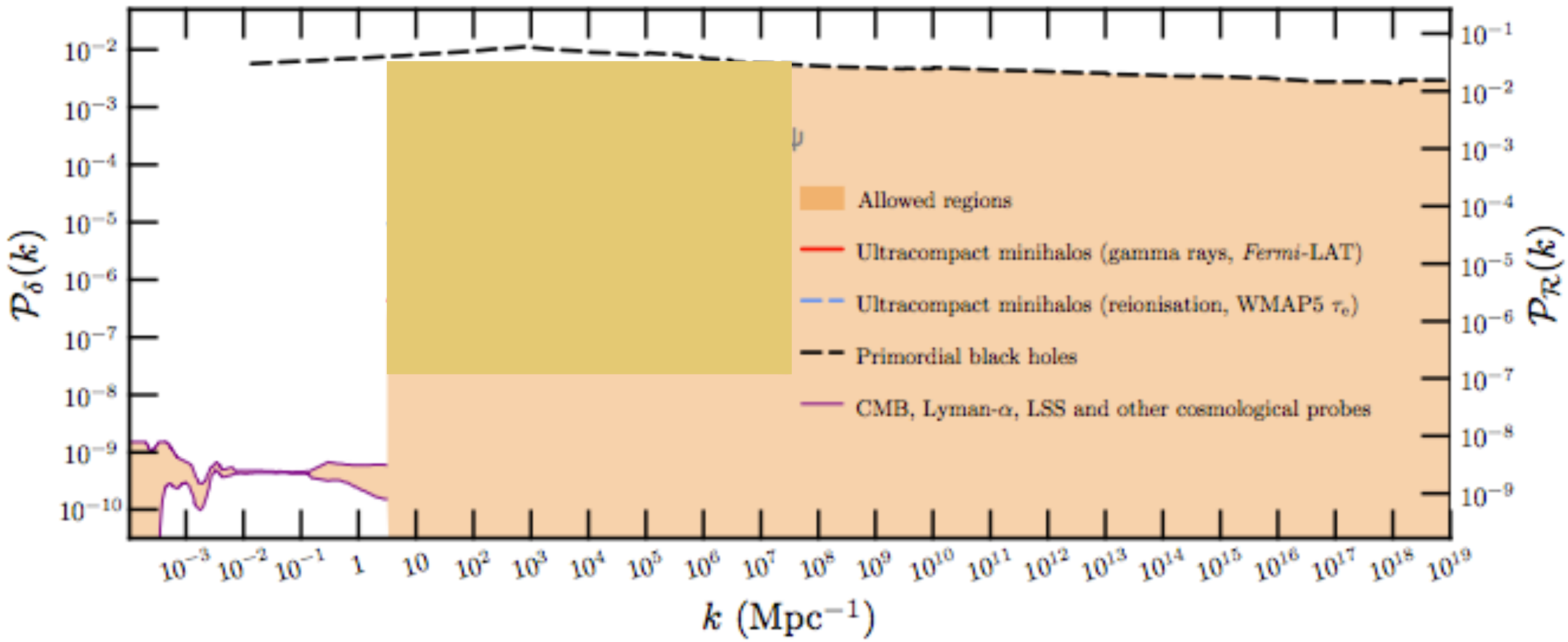

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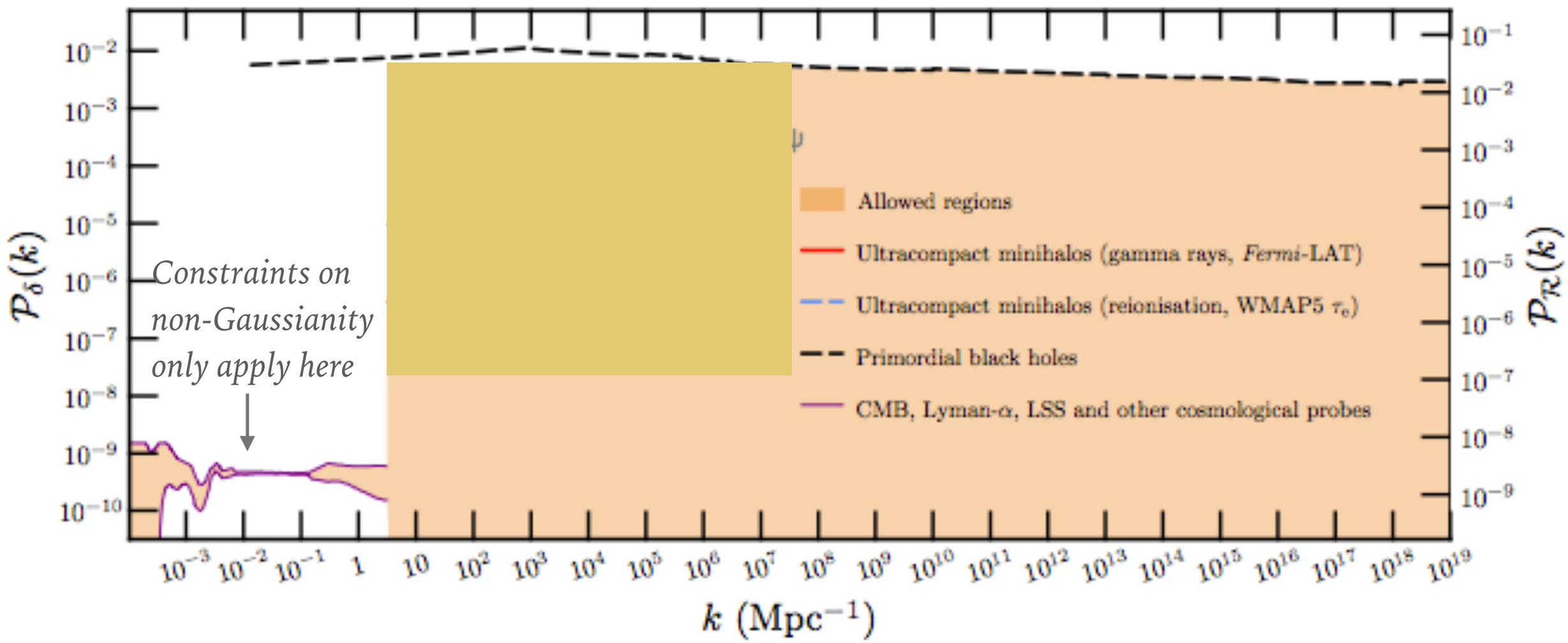

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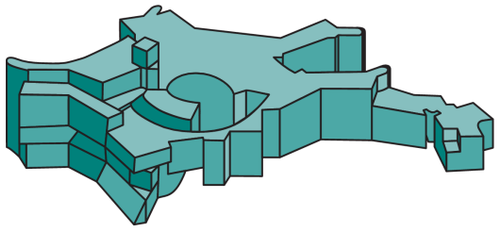
NON-GAUSSIANITY FROM THE DENSITY CONTRAST



- The relation between the curvature perturbation ζ and the density contrast δ is not linear

$$\delta(t) = -\frac{4(1+\omega)}{5+3\omega}\left(\frac{1}{aH(t)}\right)^2 \exp\left(-5\zeta\right)\nabla^2\left(\exp(\zeta/2)\right)$$

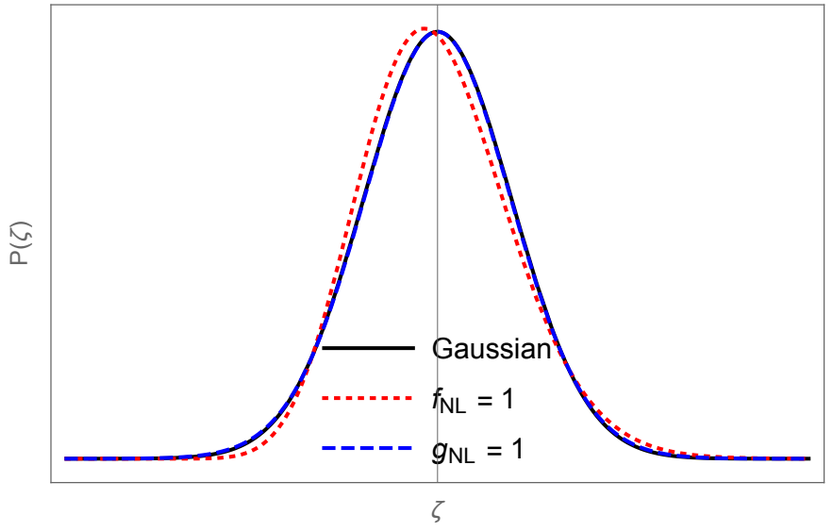
  - Exact, in the super-horizon limit, up to higher order terms in $(aH)^{-2}$. Quite messy.
- Integrate to find volume-average (smoothed) value

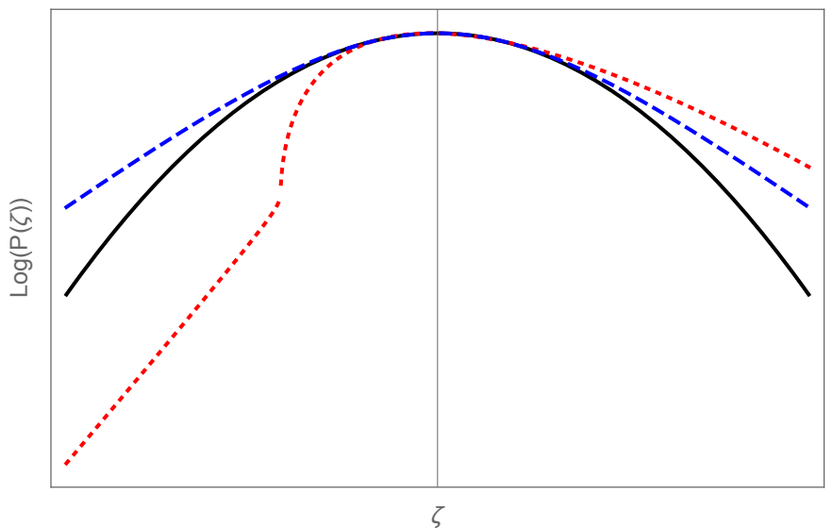
$$\delta_R = \frac{3}{r_m^3}\int_0^{r_m} \mathrm{d}R\delta(r,t)R^2$$

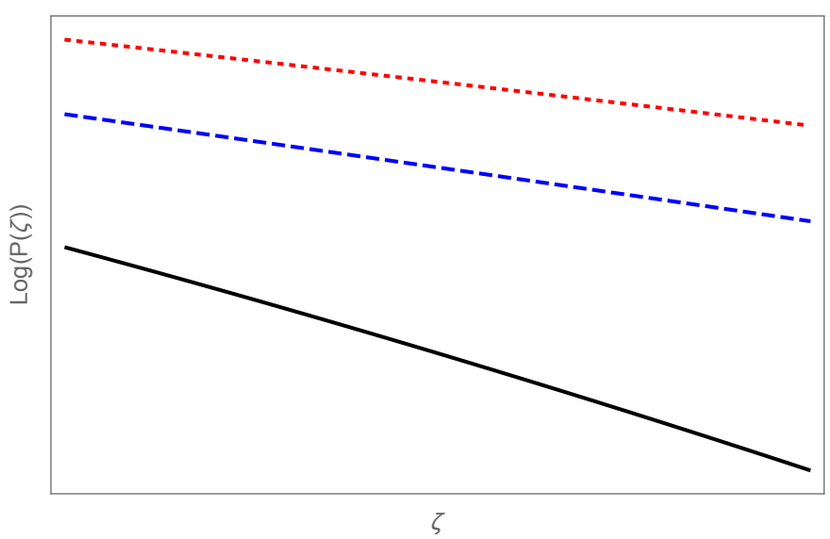
  - Where R is the areal radius, $R = e^{-\zeta(r)}r$

$$\delta_R = \delta_1 - \frac{3}{8}\delta_1^2$$

  - Where $\delta_1 = -\frac{2}{3}r_m\zeta'(r_m)$ is the value obtained from the linear calculation.
  - If ζ is Gaussian, δ_1 is Gaussian.
- Much easier to do calculations. Power spectrum needs to be 2-3 times larger to predict same number of PBHs as the linear case.
- arXiv:1905.01230







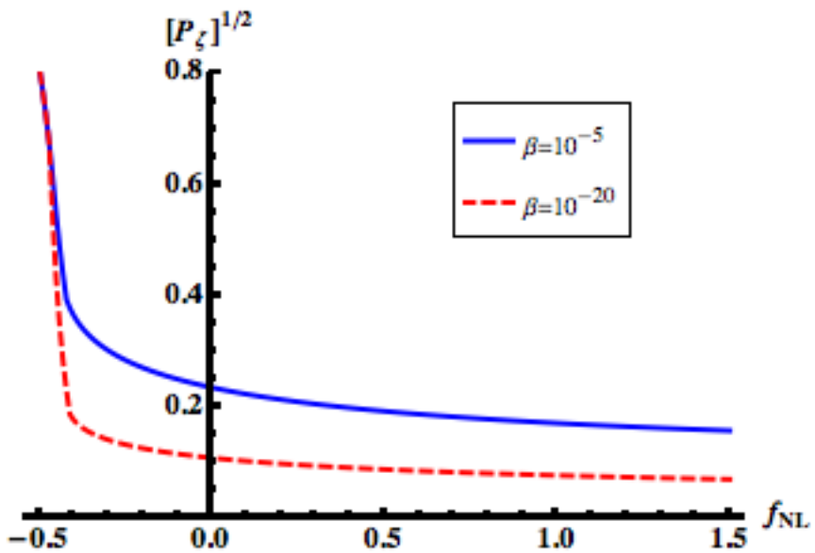
SKEWNESS AND KURTOSIS

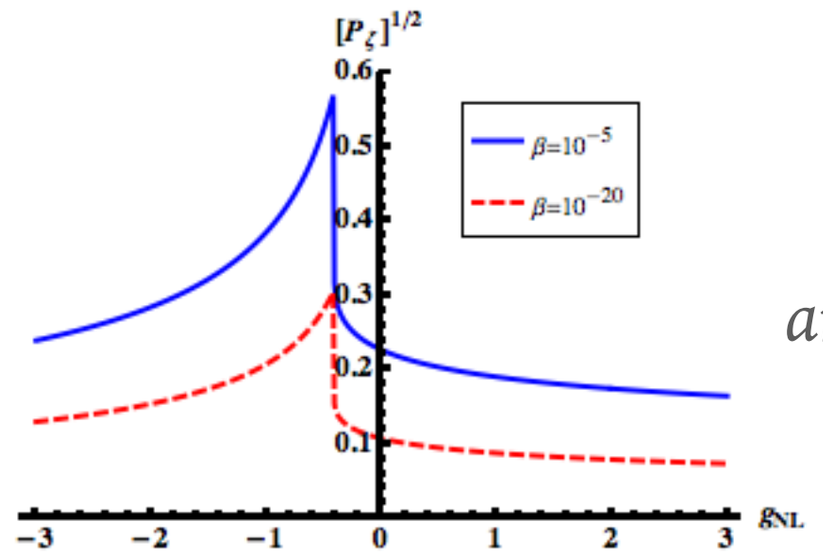
- Non-Gaussianity can introduce skewness and kurtosis to the distribution
- Here, assuming local-type non-Gaussianity

$$\zeta = \zeta_G + \frac{3}{5} f_{\rm NL} \zeta_G^2 + \frac{9}{25} g_{\rm NL} \zeta_G^3 + \dots$$

- Big effect on the tails of the distribution, where PBHs form
- Qualitatively similar results for other types of non-Gaussianity (arXiv:1512.07224)

POWER SPECTRUM CONSTRAINTS AND NON-GAUSSIANITY

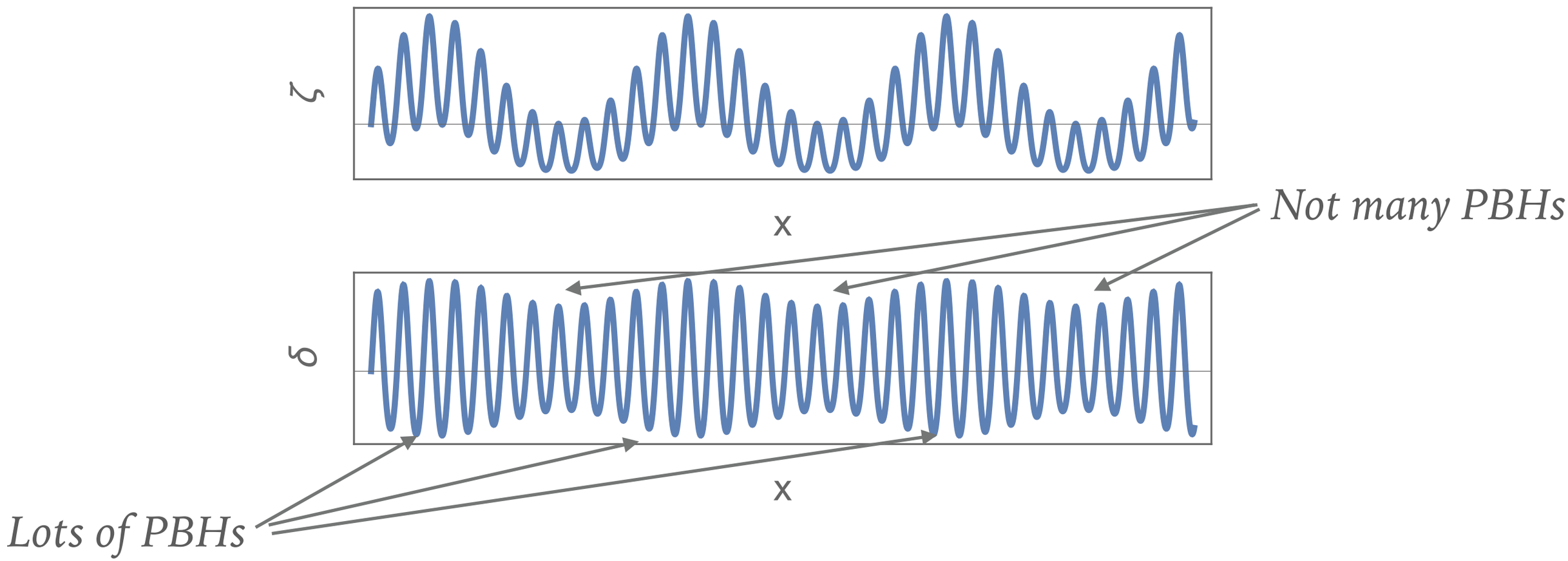




arXiv:1307.4995

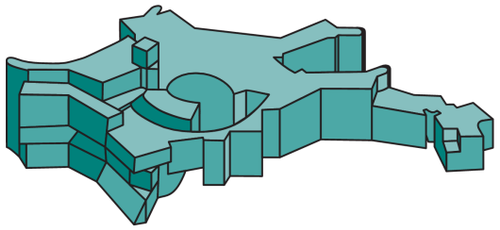
- Sensitive to non-Gaussianity, including high orders.
- Changing non-Gaussianity parameters by $\mathcal{O}(1)$ has a similar effect to changing constraints on β by many orders of magnitude
- More important to understand non-Gaussian effects than tighten constraints on β

MODAL COUPLING



- Due to the exponential dependance, a small linear change to the local power spectrum gives a big change to the local PBH abundance
- This also means accounting for modal coupling always increase the PBH abundance (or equivalently, constraints on $\mathscr{P}$ are tighter)
- arXiv:1411.4620

PRIMORDIAL CLUSTERING OF PBHS



- Modal coupling leads to an additional perturbation to the PBH number density on large scales, δ_β

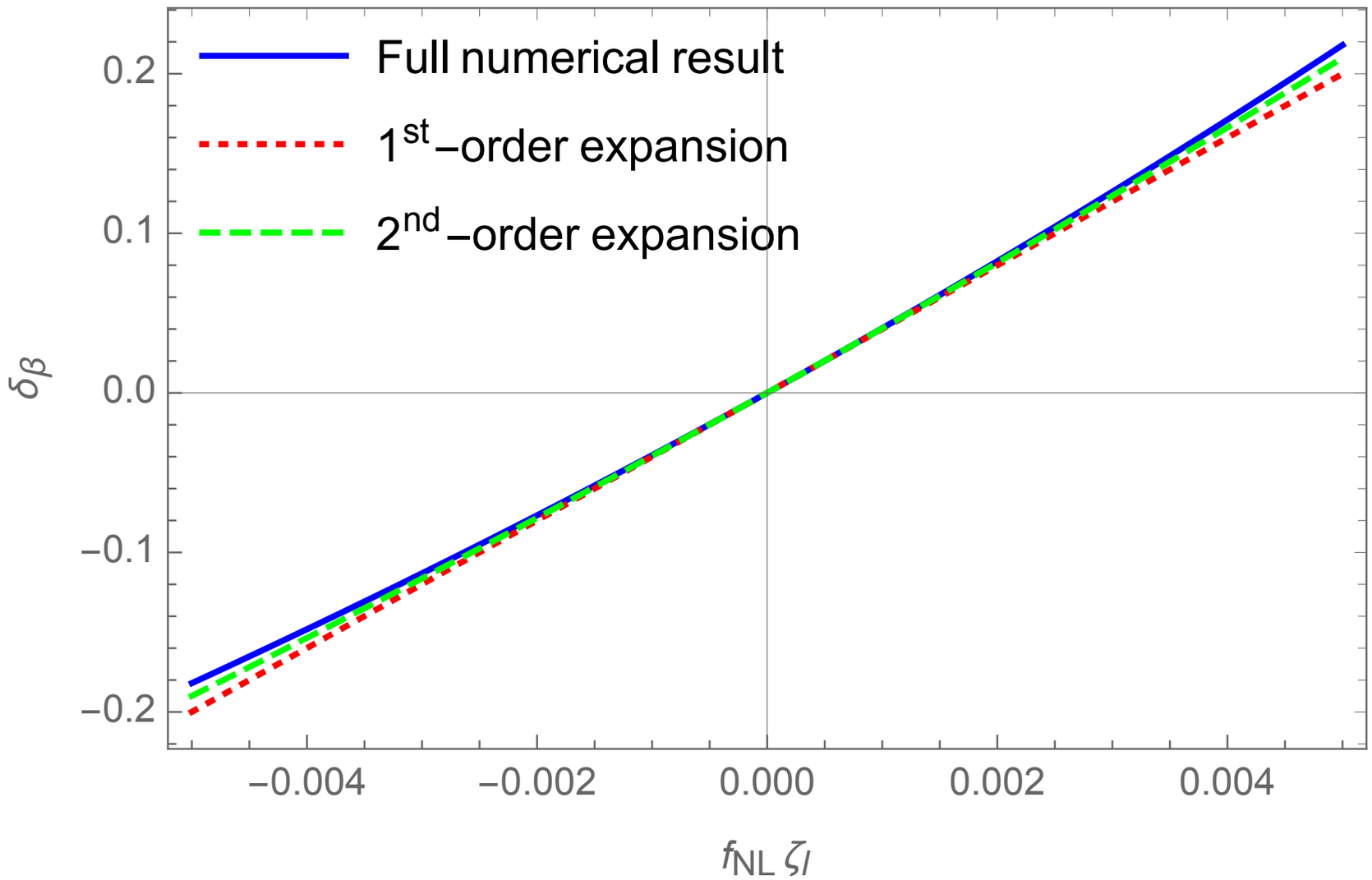
Note the factor $f_{\rm NL}\zeta$

$$\delta_\beta \approx \frac{6}{5}\nu_c^2 f_{\rm NL}\zeta + \mathcal{O}(\zeta^2)$$

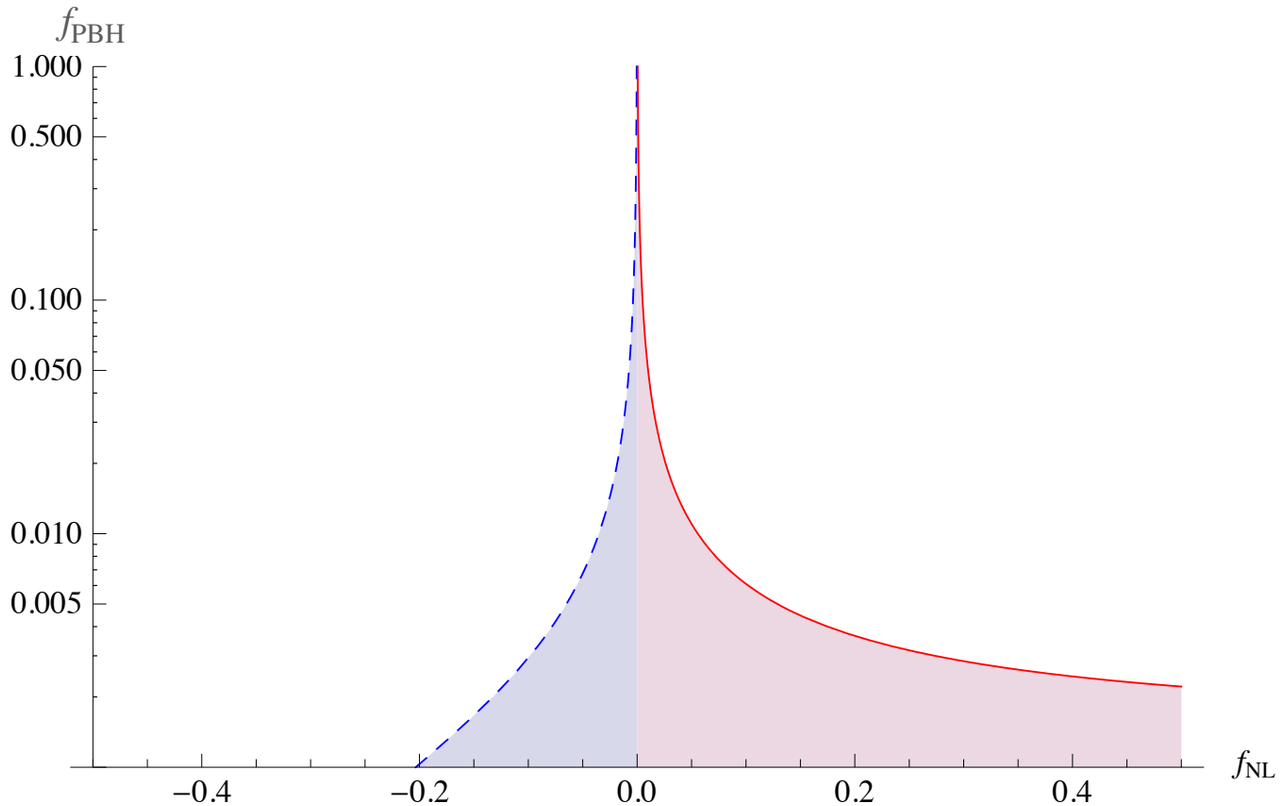
  - Where $\nu_c = \delta_c/\sigma$
- Which gives a contribution to the power spectrum, representing the primordial clustering

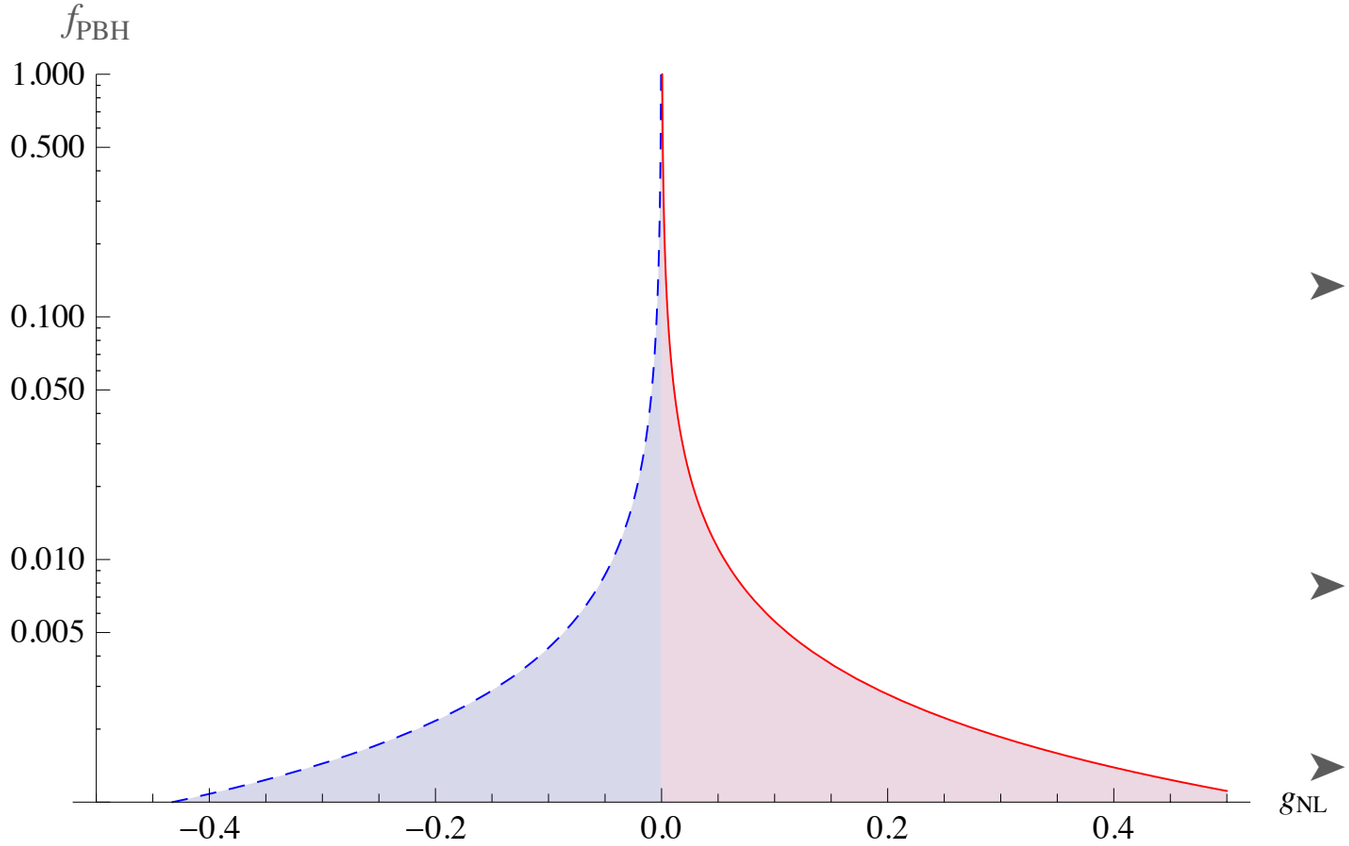
$$\mathcal{P}_{\rm PBH} \approx \frac{36}{25}\nu_c^4 f_{\rm NL}^2 \mathcal{P}_\zeta$$

  - (This can in principle be extended to any order. Here neglected Poisson noise and adiabatic perturbations)
- Calculation can be repeated for higher-order non-Gaussianity parameters



- The perturbations δ_β are much larger than the perturbations to $f_{\rm NL}\zeta$

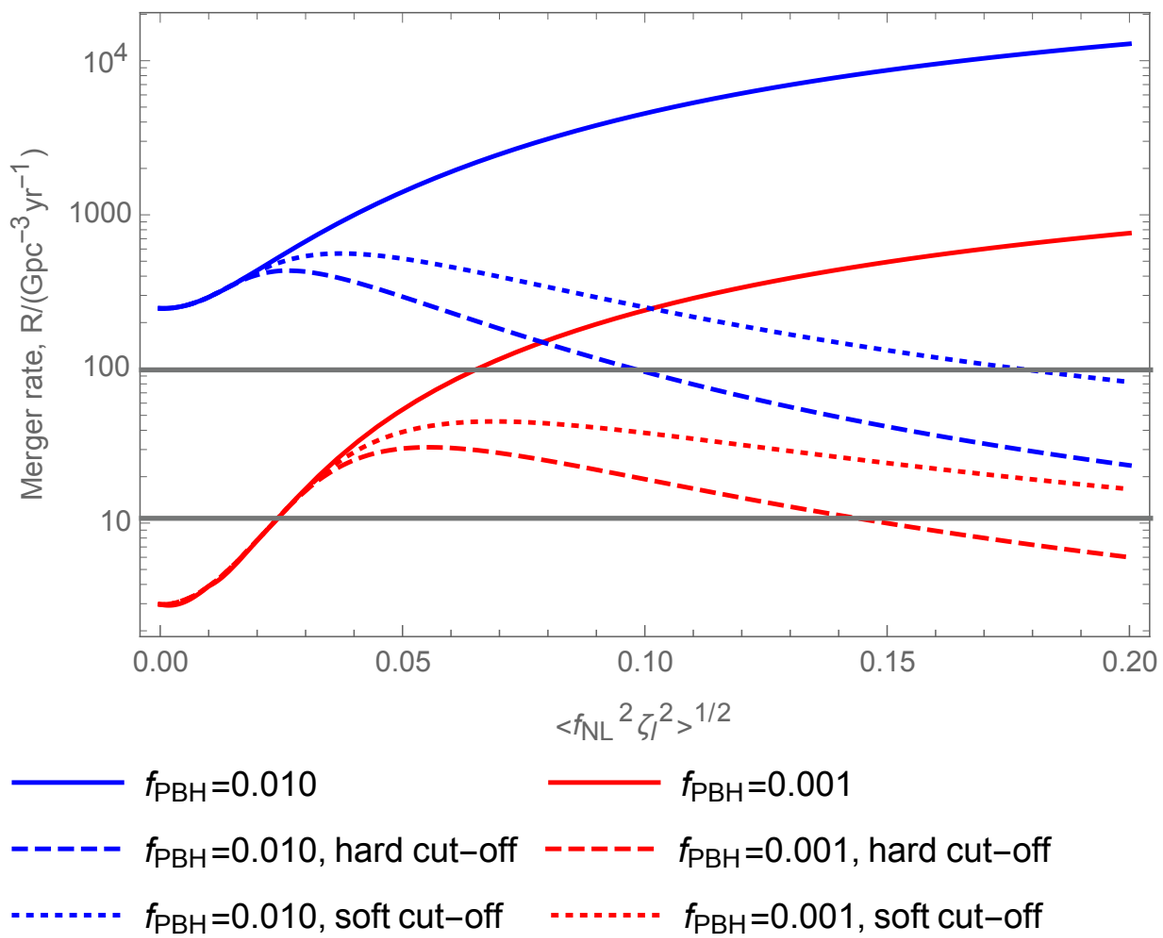




PBH ISOCURVATURE MODES

- If PBHs represent a significant fraction of dark matter, these modes represent isocurvature modes
- A difference between the (expected) adiabatic radiation and matter perturbations
- Strong constraints on isocurvature modes from Planck can be converted into strong constraints on the non-Gaussianity parameters
- Strong constraints on non-Gaussianity at all orders, $|f_{\rm NL}, g_{\rm NL}| < \mathcal{O}(10^{-3})$
- Caveats: only applicable to CMB scales, and only for local-type
- arXiv:1503.01505

BINARY FORMATION AND MERGER RATE



- Detections of merging BHs by LIGO, gives a (rough) measurement of the merger rate
- Possible (likely???) that these BHs may be primordial in origin - low spins and awkward masses (maybe)
- Merger rate is strongly dependent on the abundance on PBHs
  - But what if PBHs are not uniformly randomly distributed?
- Significant uncertainty due to uncertainty in disruption rate when PBH abundance is high*

*recent paper 1908.09752 may clear up some of the uncertainty

SUMMARY

- Thank you for listening

- PBH observables are extremely sensitive to even small amounts of non-Gaussianity
  - PBH abundance
  - Isocurvature modes
  - PBH merger rate
  - (Mass function - not discussed here)

- Keep an eye on arXiv.org!