PRIMORDIAL BLACK HOLES AND NON-GAUSSIANITY

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OVERVIEW

➤ Introduction

➤ Formation criterion and non-Gaussianity of $\delta$

➤ 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

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➤ Basics of calculation
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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

\[ \beta \approx \text{erfc} \left( \frac{\delta_c}{\sqrt{2}\sigma} \right) \]

➤ \( \delta_c \) is the threshold amplitude. Perturbations above this will collapse. Using the volume averaged density seems more robust.

➤ \( \sigma^2 \) is proportional to the power spectrum, so \( \beta \) depends exponentially on the power spectrum
Constraints on $\beta$ vary by many orders of magnitude, but constraints on $\mathcal{P}$ only vary by a factor of a few.

Bringmann, Scott & Akrami, 2013

arXiv:1110.2484
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Constraints on the power spectrum

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Bringmann, Scott & Akrami, 2013

$arXiv:1110.2484$
NON-GAUSSIANITY FROM THE DENSITY CONTRAST

- The relation between the curvature perturbation $\zeta$ and the density contrast $\delta$ 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

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

- 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 $\zeta$ is Gaussian, $\delta_1$ 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

\[ \zeta = \zeta_G + \frac{3}{5} f_{NL} \zeta_G^2 + \frac{9}{25} g_{NL} \zeta_G^3 + \ldots \]

- 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

➤ Sensitive to non-Gaussianity, including high orders.

➤ Changing non-Gaussianity parameters by $\mathcal{O}(1)$ has a similar effect to changing constraints on $\beta$ by many orders of magnitude.

➤ More important to understand non-Gaussian effects than tighten constraints on $\beta$.

arXiv:1307.4995
MODAL COUPLING

Due to the exponential dependence, 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 $\mathcal{P}$ are tighter).

arXiv:1411.4620
PRIMORDIAL CLUSTERING OF PBHS

Modal coupling leads to an additional perturbation to the PBH number density on large scales, $\delta_\beta$

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

Where $\nu_c = \delta_c / \sigma$

Which gives a contribution to the power spectrum, representing the primordial clustering

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

(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 $\delta_\beta$ are much larger than the perturbations to $f_{NL}\zeta$.
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, $|f_{\text{NL}}, g_{\text{NL}}| < \mathcal{O}(10^{-3})$.

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!