

CONDITIONS FOR THE FORMATION OF PRIMORDIAL BLACK HOLE DARK MATTER

Sam Young

University of Sussex

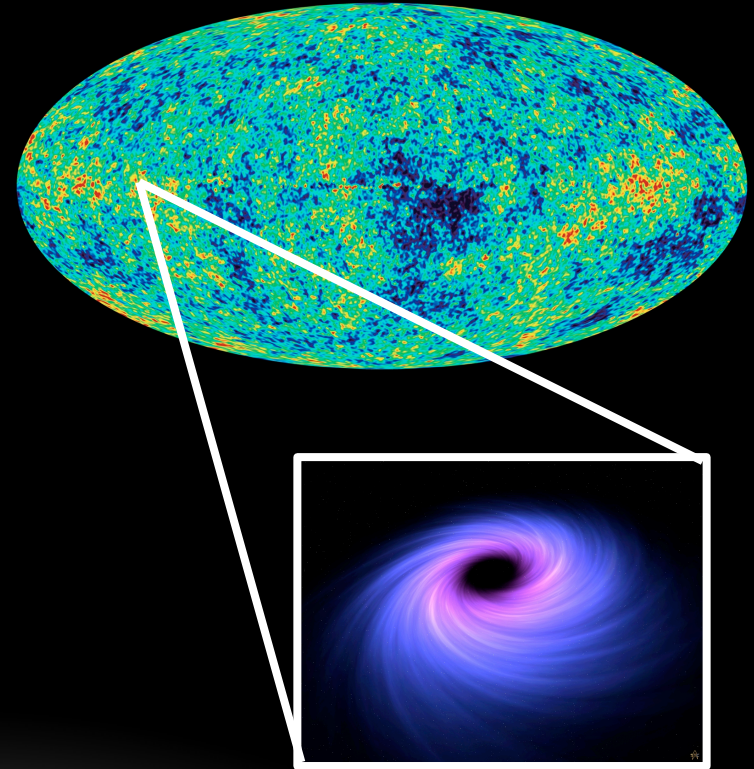
arXiv:1503.01505, SY, Christian Byrnes

Texas Symposium, 16th December 2015

What are the conditions that a cosmological model must satisfy such that dark matter can be made of primordial black holes?

OUTLINE

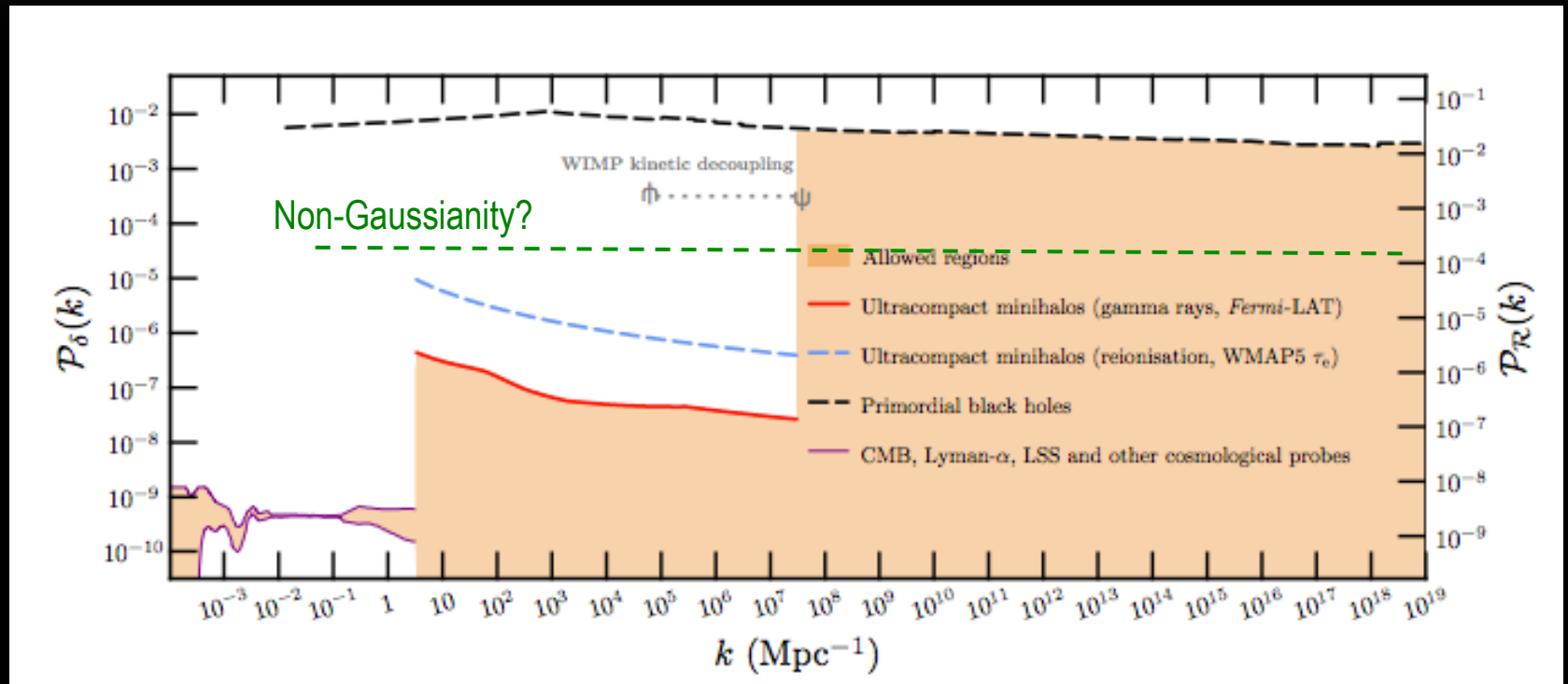
- What are PBHs?
- What is non-Gaussianity/modal coupling?
- What are isocurvature modes and how do they arise?
- Results
- Summary



WHAT ARE 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 ($>M_{\text{pl}}?$), but constraints on the abundance exist for PBHs of mass $\sim 10^8\text{g}$ to $\sim 10^{50}\text{g}$
- Can be used to constrain the power spectrum on a much greater range of scales than other sources
- A viable dark matter candidate (cold, collisionless, unobservable...)
- PBHs can provide non-linear seeds for structure growth, seed supermassive black holes, and provide a method for reheating using only gravitational interactions

CONSTRAINTS ON THE POWER SPECTRUM

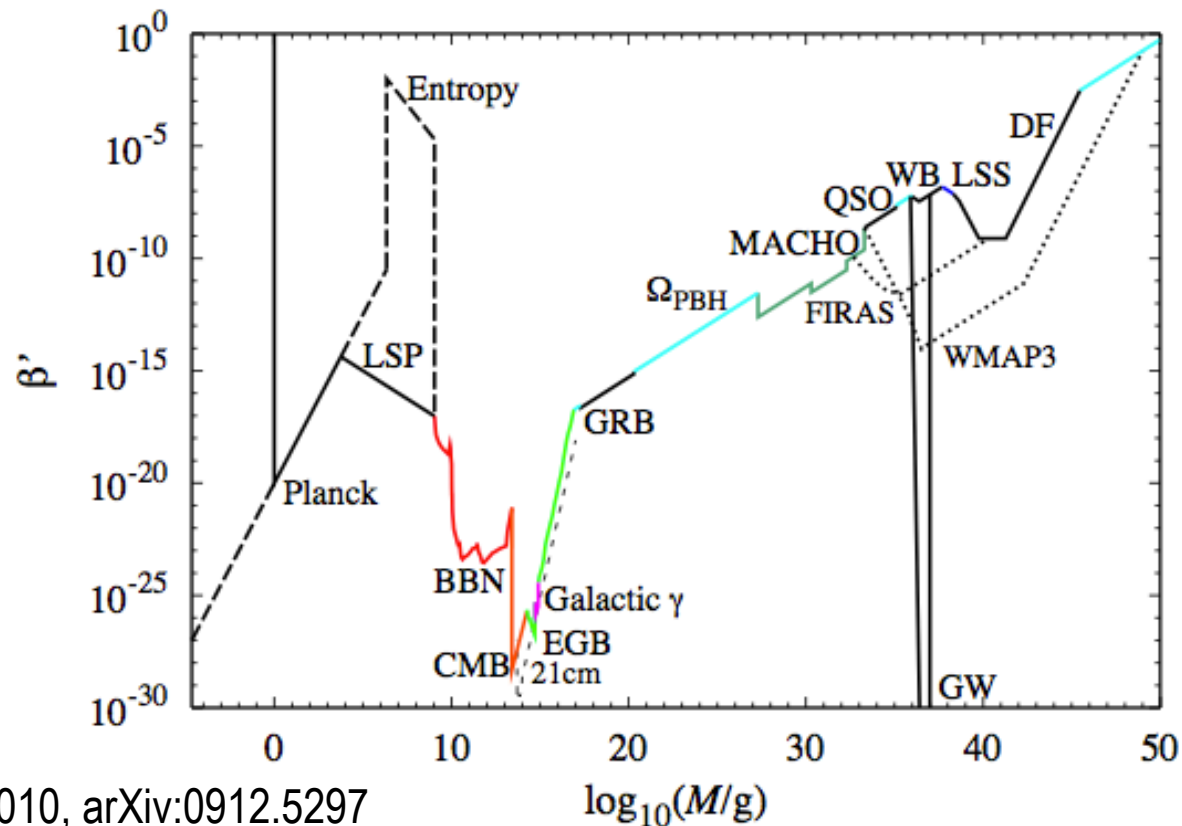


Bringmann, Scott, Akrami, 2013

KNOWN CONDITIONS FOR THE FORMATION OF PBH DARK MATTER

- Large super-horizon overdensity
 - Needs to be larger than some critical value at horizon crossing, $\delta_c \sim 0.45$
 - Exact value depends on profile of overdensity
- PBH must form before quark confinement during radiation domination
- To form a large enough number, power spectrum must be much larger on small scales (typically of order 10^{-2})
 - ...but only a very specific range of small scales (see next slide)
- Non-Gaussianity unconstrained on small scales
- Many models can predict these conditions

CONSTRAINTS ON PBHS – ONLY A NARROW RANGE OF MASSES FOR DM



Carr et al, 2010, arXiv:0912.5297

MODAL COUPLING AND NON-GAUSSIANITY

- Non-Gaussianity represents a coupling between different modes
 - Local-type non-Gaussianity has a strong signal in the squeezed limit – coupling modes of different scales

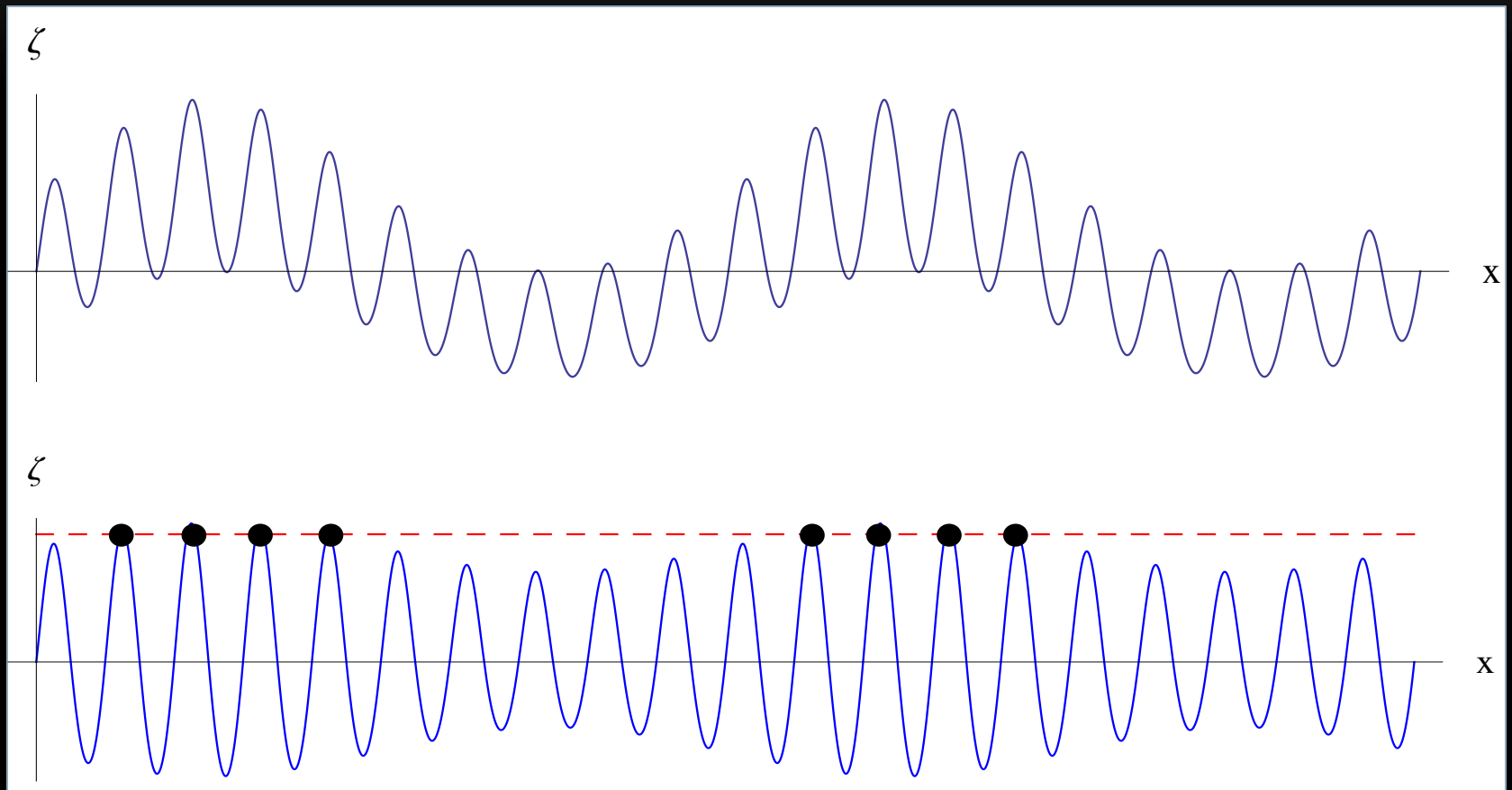
$$\zeta = \zeta_G + \frac{3}{5}f_{NL}(\zeta_G^2 - \sigma^2) + \frac{9}{25}g_{NL}\zeta_G^3 \dots$$

- Make use of peak-background split to separate Gaussian component into short and long components

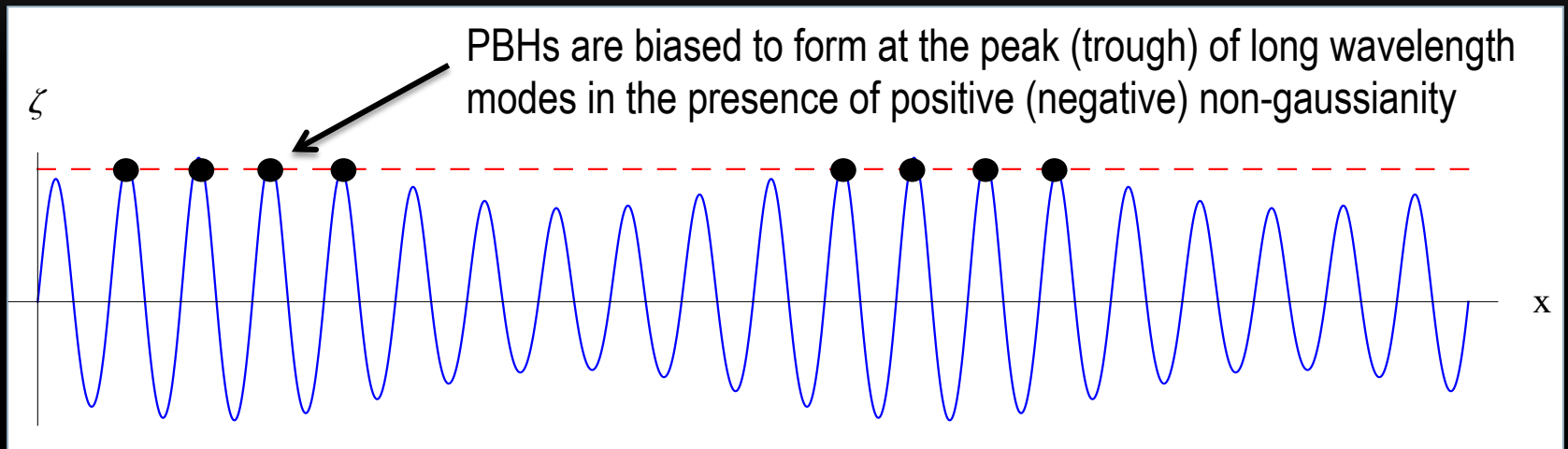
$$\zeta_G = \zeta_s + \zeta_l$$

- Super-horizon modes do not affect PBH formation
- Indirect effect due to modal coupling
- Coupling to super-horizon modes can affect local power spectrum and non-gaussianity
 - And the abundance of PBHs

MODAL COUPLING



PRIMORDIAL BLACK HOLE BIAS



- Does this biasing produce observable consequences on large scales?
- What would this tell us about the early universe?

PRIMORDIAL BLACK HOLE BIAS

- *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:

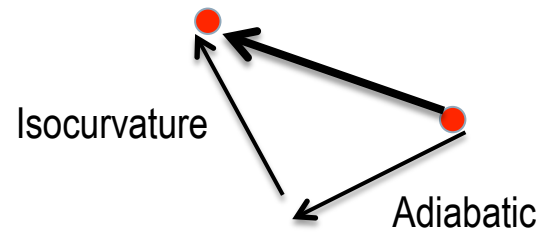
$$\Omega_{PBH} = (1 + 3\zeta + b\zeta) \bar{\Omega}_{PBH}$$

Background value

Adiabatic perturbation

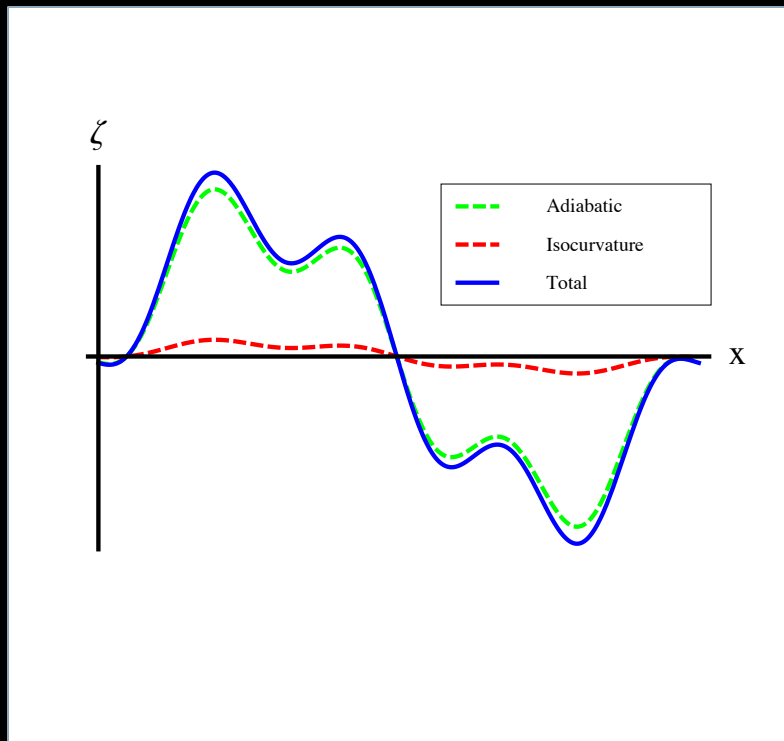
Isocurvature perturbation

WHAT ARE ISOCURVATURE MODES?

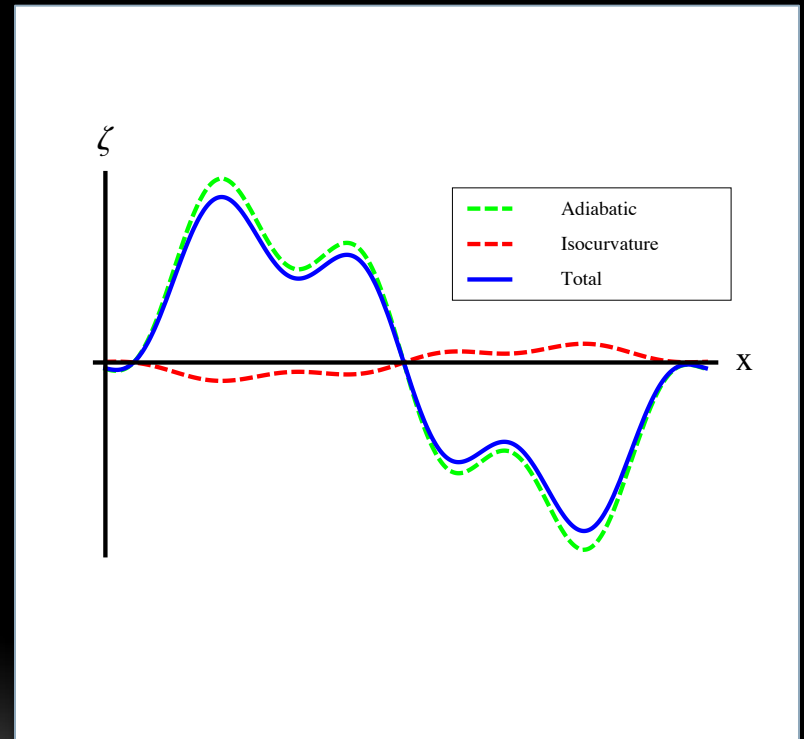


ISOCURVATURE PERTURBATIONS

Fully correlated – positive bias



Fully anti-correlated – negative bias



DERIVING THE BIAS FACTOR

- Abundance of PBHs is exponentially dependant on the power spectrum and non-Gaussianity parameters
- Large-scale modes can therefore have a significant effect on the abundance of PBHs in large regions of the universe

$$\beta(\mathcal{P}_\zeta, \zeta_l, f_{NL}, g_{NL}) = \int_{\zeta_c}^{\infty} P_{NG}(\zeta, \zeta_l, f_{NL}, g_{NL}) d\zeta$$

- At the time of PBH formation

$$\beta = (1 + \delta_\beta) \bar{\beta}$$

- At a later time, DM density is observed

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

- The expression for δ_β is then Taylor expanded to first order in ζ to give an expression for the bias factor

$$\delta_\beta = b\zeta$$

PLANCK CONSTRAINTS ON 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 $3/4$ - 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* creates isocurvature perturbations in the primordial distribution of PBH CDM in the presece of non-gaussianity
- Constraints from Planck: $-0.028 < b < 0.036$
- To first order in f_{NL} and g_{NL}

$$b_{f_{NL}} = \frac{6}{5} \left(1 + \frac{\zeta_c^2}{\sigma_s^2} \right) f_{NL}$$
$$b_{g_{NL}} = -\frac{27(\sigma_s^2 - \zeta_c^2)(\sigma_s^2 + \zeta_c^2)}{25\sigma_s^2\zeta_c} g_{NL}$$

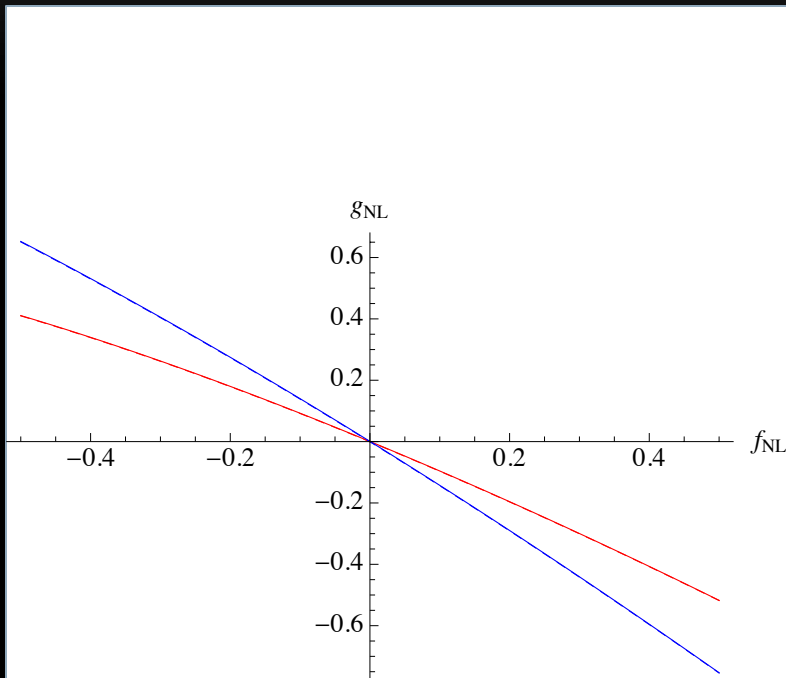
- Very tight constraints on the non-gaussianity parameters

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

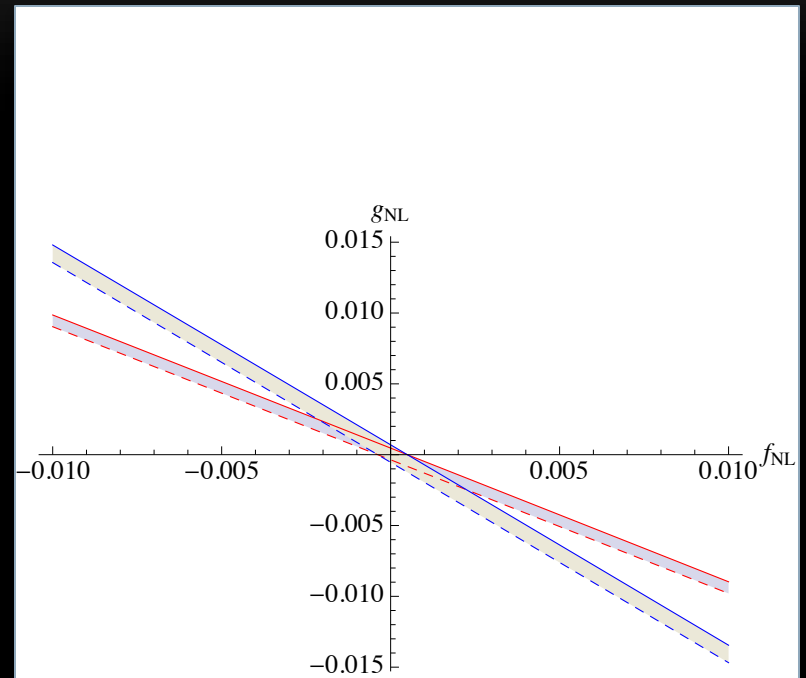
$$-6 \times 10^{-4} < g_{NL} < 7 \times 10^{-4}$$

- surprisingly strong!

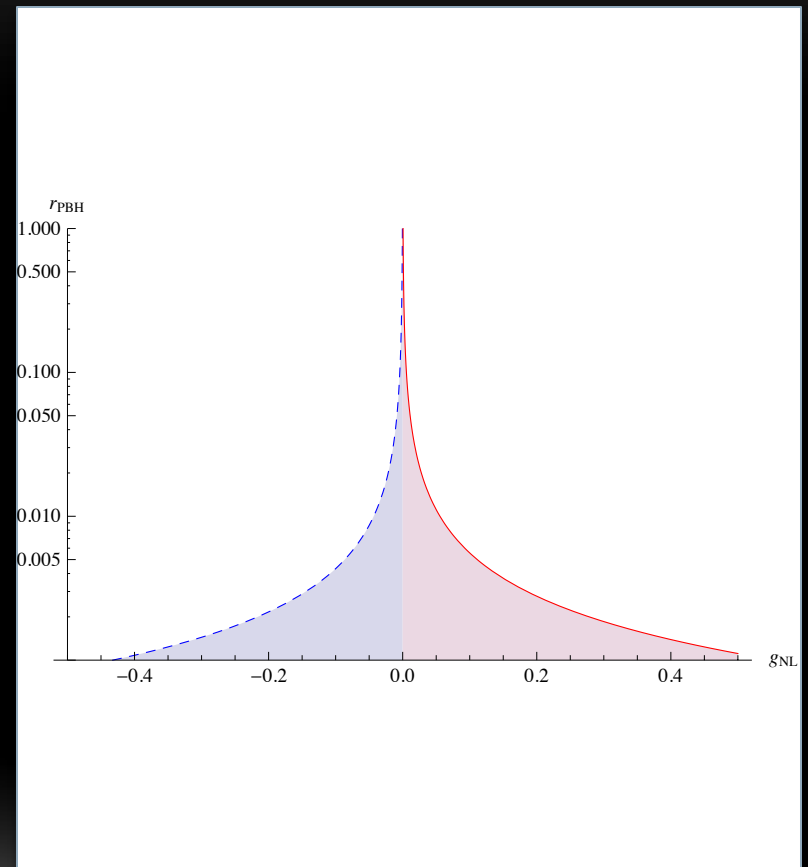
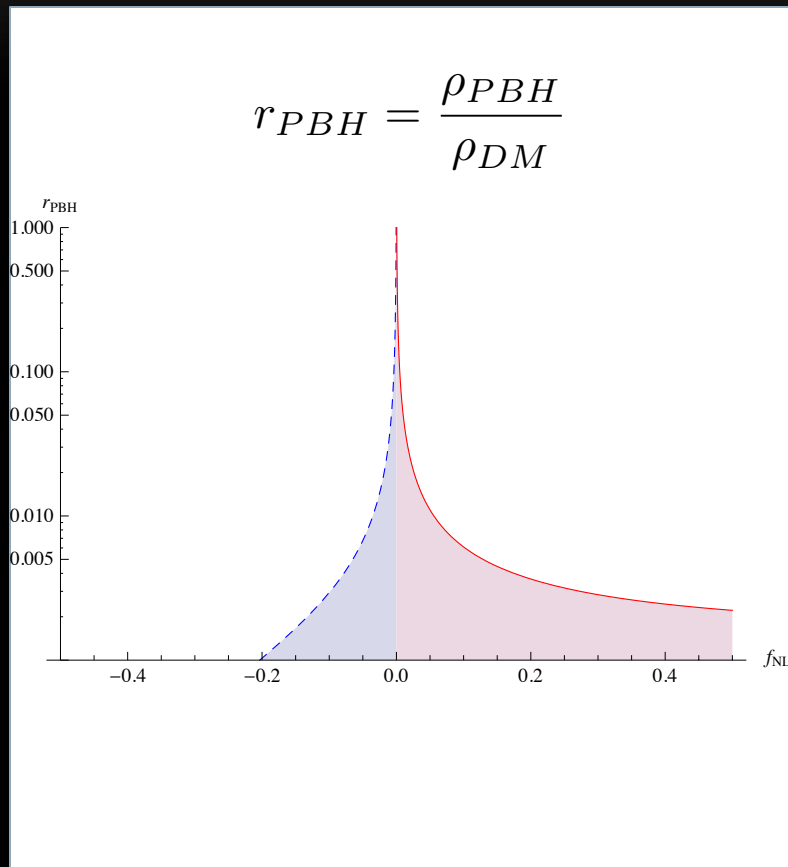
CAN g_{NL} OFFSET f_{NL} ?



Red and blue lines correspond to uncertainty in critical value for collapse



WHAT IF DARK MATTER IS ONLY PARTIALLY COMPOSED OF PBH'S?



COMING SOON ON PBHS

- Constraints on small scale power spectrum accounting for non-local types of non-Gaussianity, working with Donough Regan and Christian Byrnes
- Effects of super-horizon and sub-horizon modes on the formation of PBHs, working with Iliia Musco and Christian Byrnes



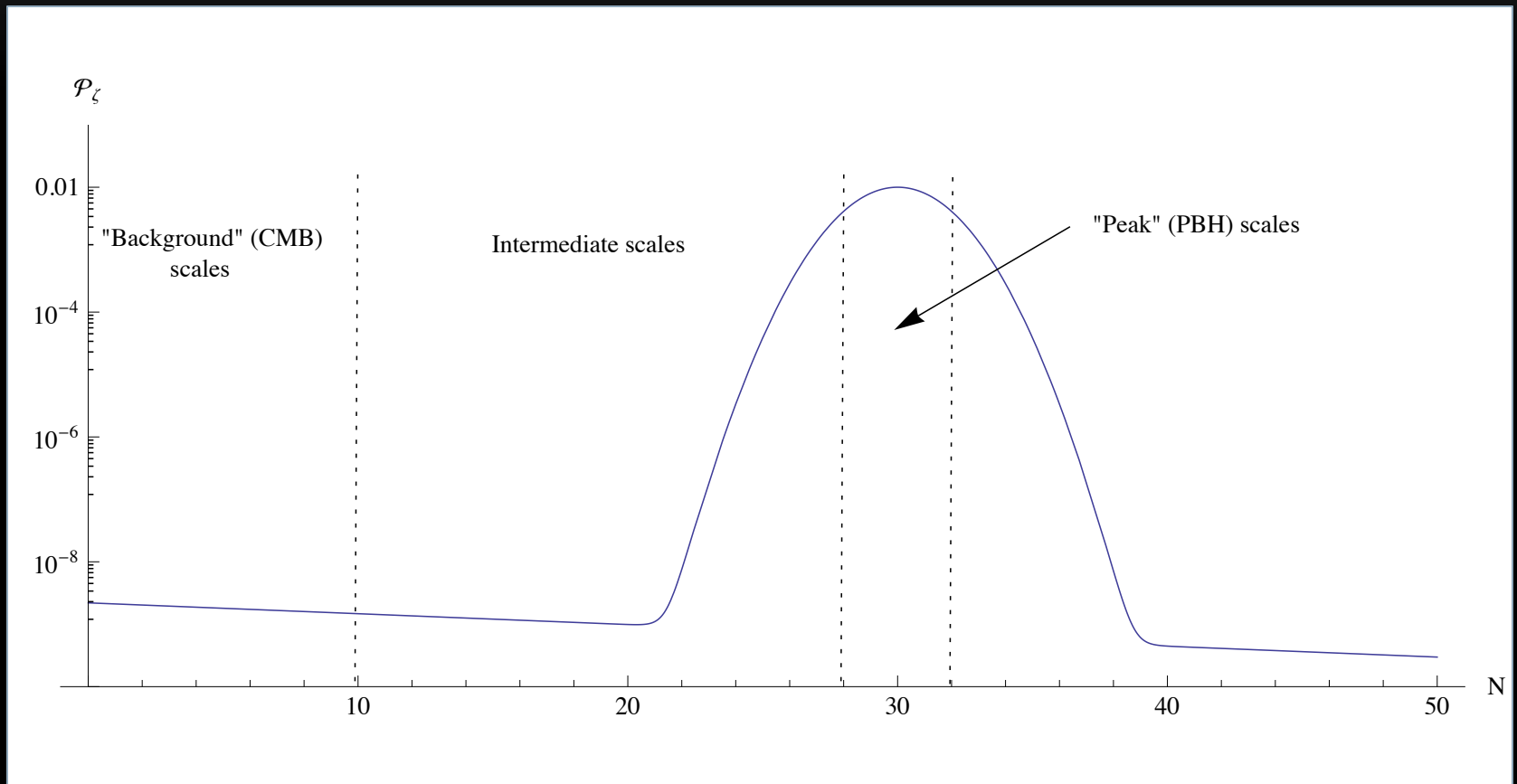
SUMMARY

- To produce PBHs the power spectrum needs to become much larger on small scales
 - ...but not too large
 - ...and only over a small range of scales
- If dark matter is made of PBHs, very tight constraints can be placed on the non-Gaussianity parameters
 - Nearly all models can be ruled out as a mechanism for producing PBH dark matter
 - Single field inflation not ruled out
- The future detection of PBHs, non-Gaussianity, or isocurvature modes can tell us a lot about the early universe

THANK YOU FOR LISTENING

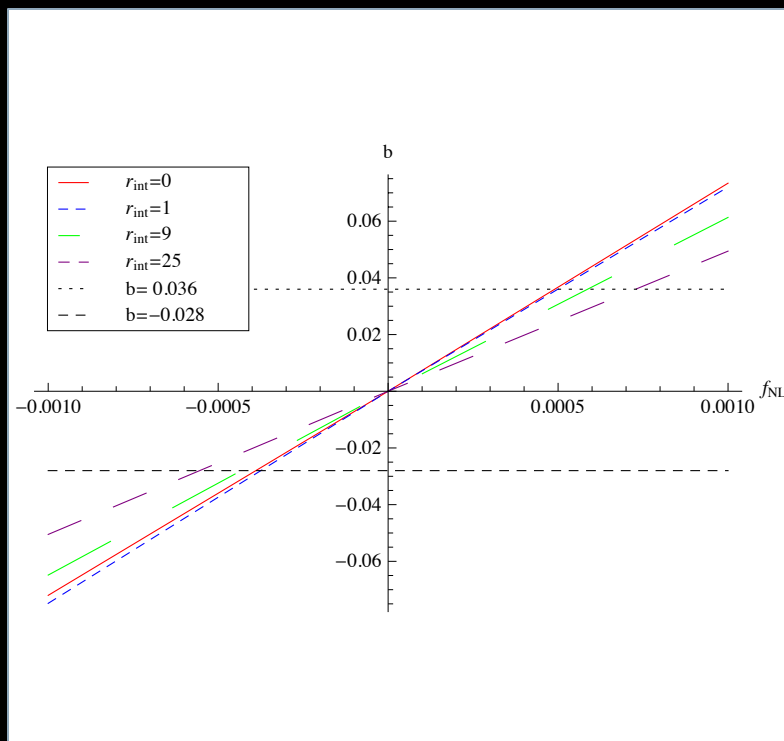
- Any questions?
- If you enjoyed the talk...

INTERMEDIATE MODES – POWER SPECTRUM



HOW IMPORTANT ARE THE INTERMEDIATE MODES?

Constraints on f_{NL}



Constraints on g_{NL}

