

# Are supermassive black holes primordial?

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arXiv:2404.18474 + 2404.18475



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# Supermassive BHs are:

- In the centres of many galaxies



- Hard to form but seen at high  $z$
- Pretty awesome - *Volonteri et al review 2021*

# Primordial black holes probe initial conditions and contents of the universe

- **Black holes are cold and dark**
- **Primordial (unlike astrophysical) BHs are a DM candidate and can form with any mass**
- **Pending *Primordial black holes* Springer textbook - edited by CB, Franciolini, Harada, Pani & Sasaki - thanks to many**

# Contents

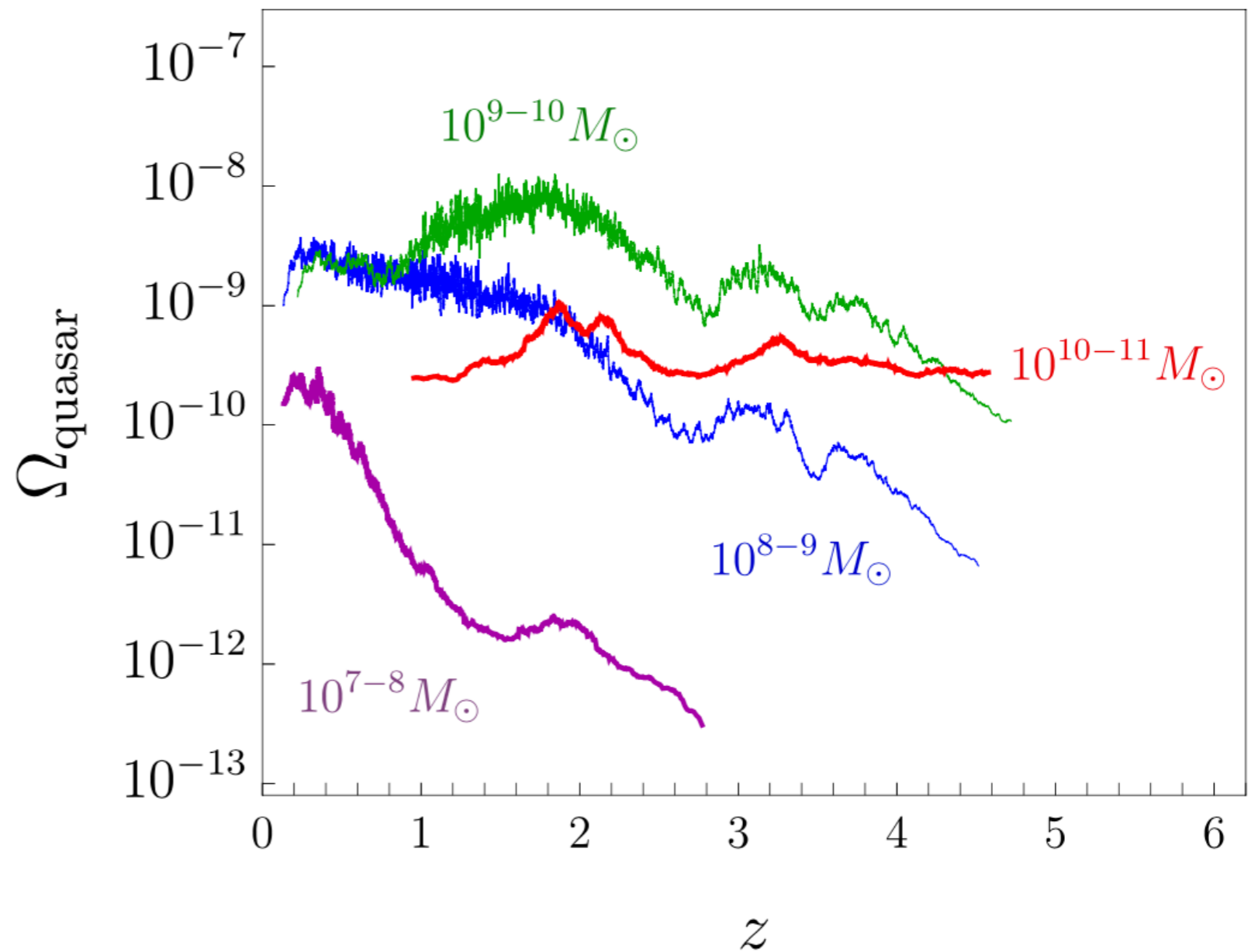
1. The mystery of SMBH formation
2. The challenge of cosmic  $\mu$ -distortions
3. More challenges

# SMBHs

- Are found in the centres of most large galaxies
- Have masses  $10^6$ - $10^{11} M_{\odot}$
- Observed even at redshifts  $>6-7$  (11???? JWST)
- How did they grow so massive in  $< 1$  Gyr?
- How did they start?
- Why two distinct BH mass populations with almost nothing in between?

# Accretion

- Is messy
- The Eddington limit suggests a  $10^2 M_{\odot}$  BH needs 1Gyr to grow to  $10^{10} M_{\odot}$ .
- SMBHs do not continuously accrete
- The maximum masses haven't changed much

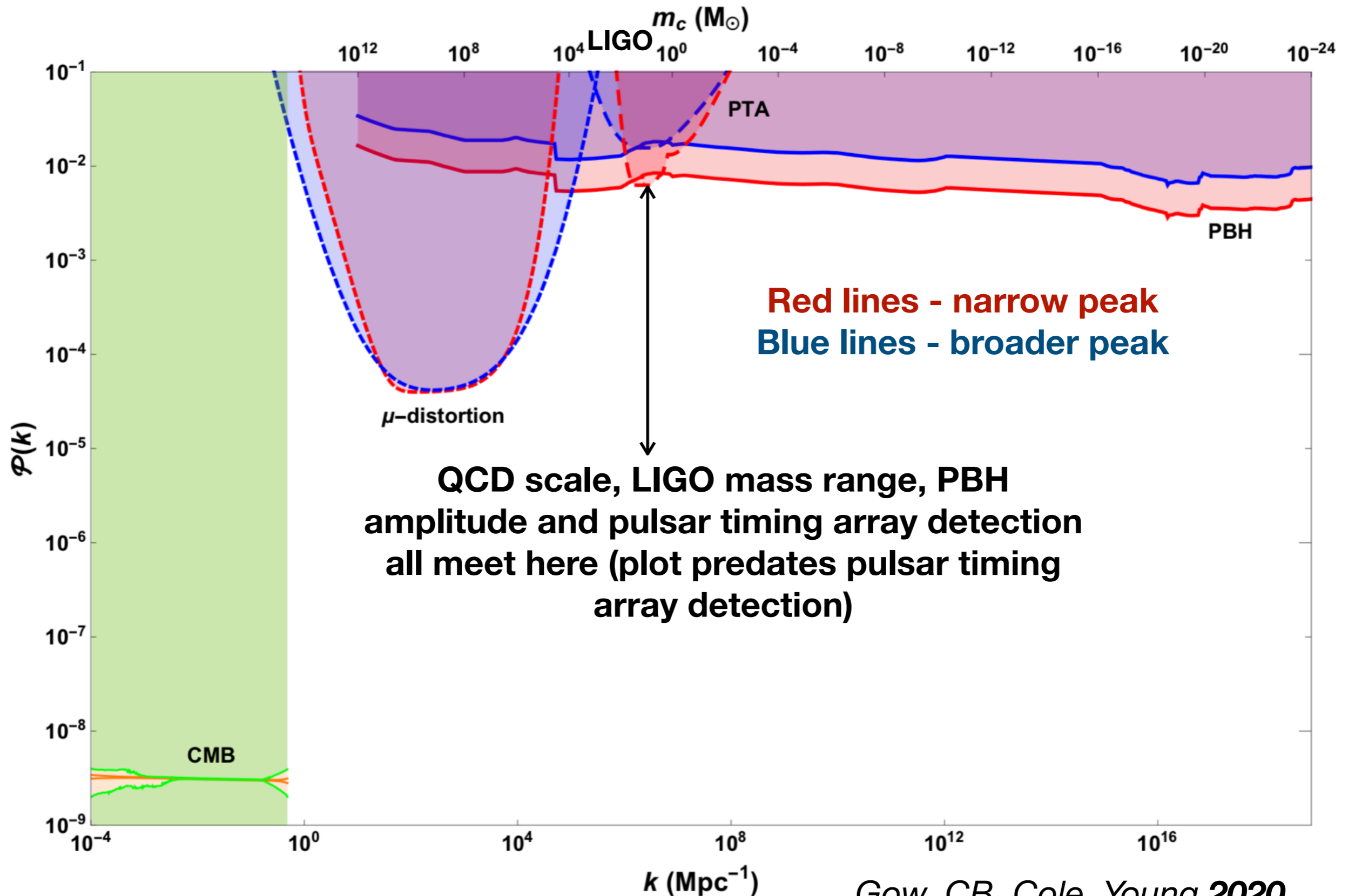


*Hooper et al 2023*

# SMBH formation

- Growth from collapsed Pop III stars isn't ruled out
- Needs super Eddington accretion
- Perhaps large gas clouds undergo direct collapse
- Runaway mergers
- Or SMBHs are primordial - Did the galaxy or SMBH come first?
- “In summary, low mass seeds are common, but high mass seeds are rare and depend on processes which we have not been observed yet”  
*Volonteri, Habouzit & Colpi 2021 review*

# The initial conditions of the universe

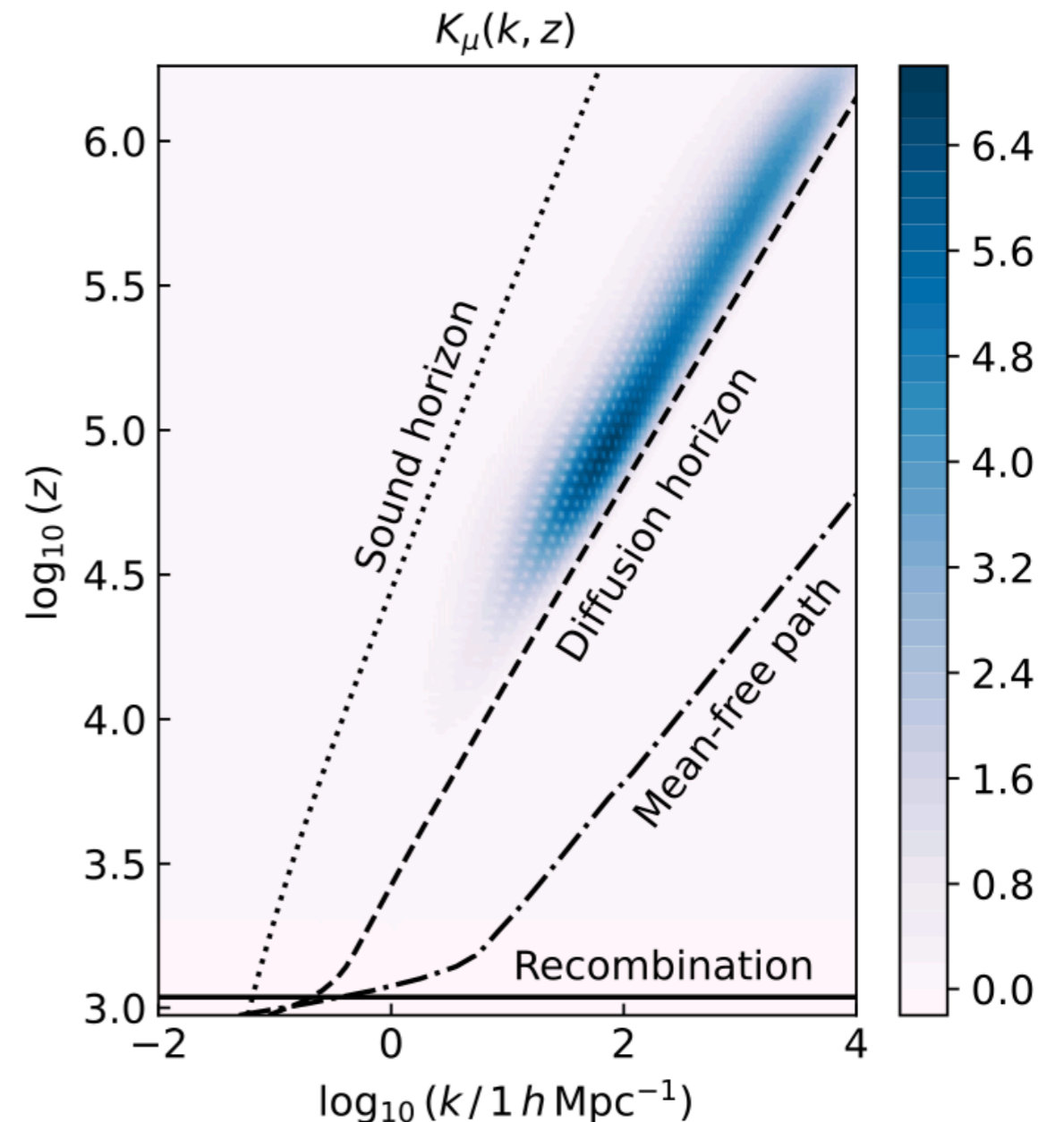




# CMB spectral distortions

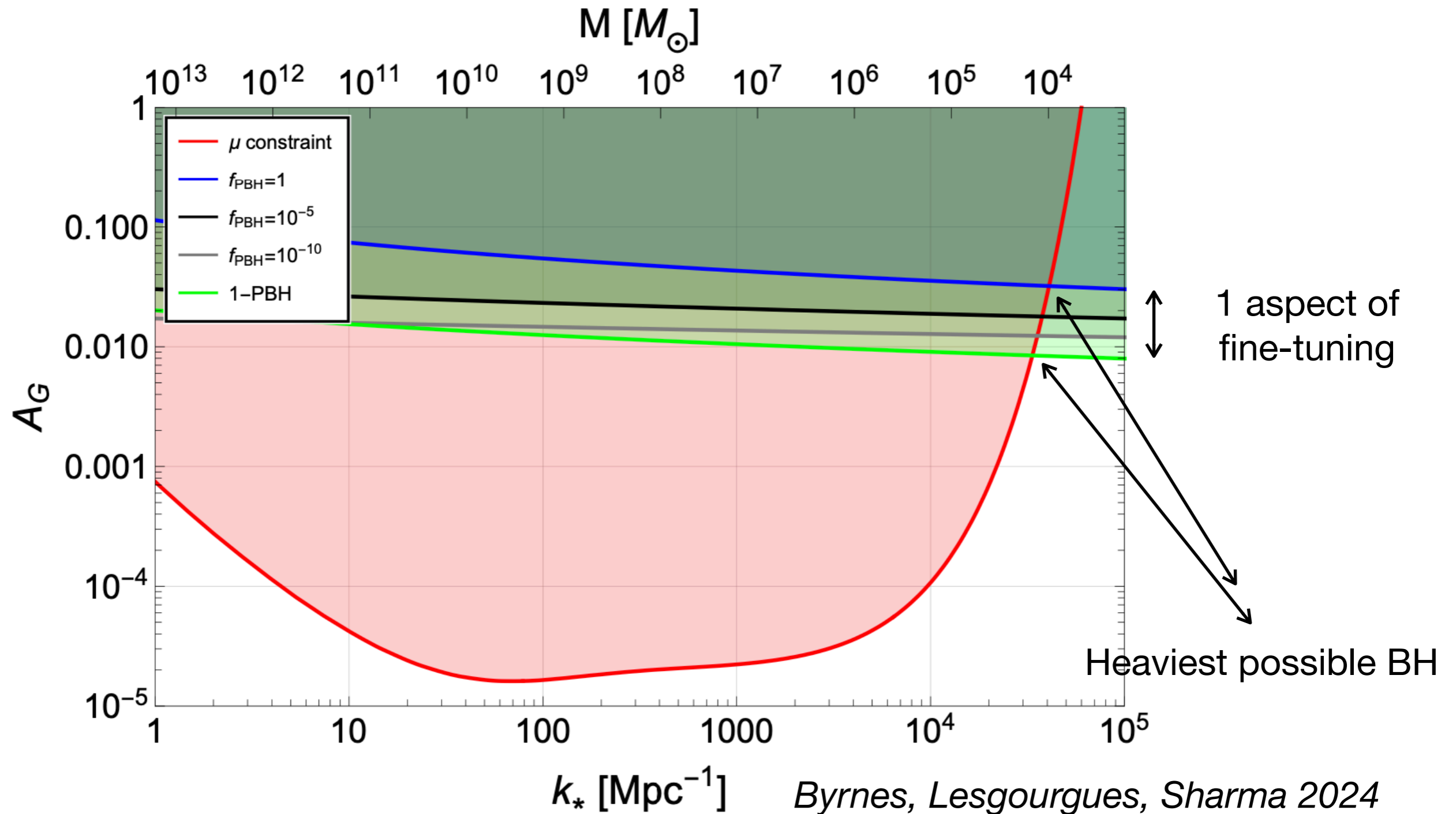
- The CMB is a nearly perfect black body, due to thermal equilibrium
- COBE FIRAS confirmed this to 0.01% precision
- The damping of perturbations acts like an energy injection into the baryon-photon plasma
- If this happens at low energies, thermal equilibrium cannot be maintained
- $\mu$ -distortions (chemical potential) probe the SMBH scales, with  $\mu$  being proportional to the power spectrum amplitude

## Contribution to $\mu$ distortion



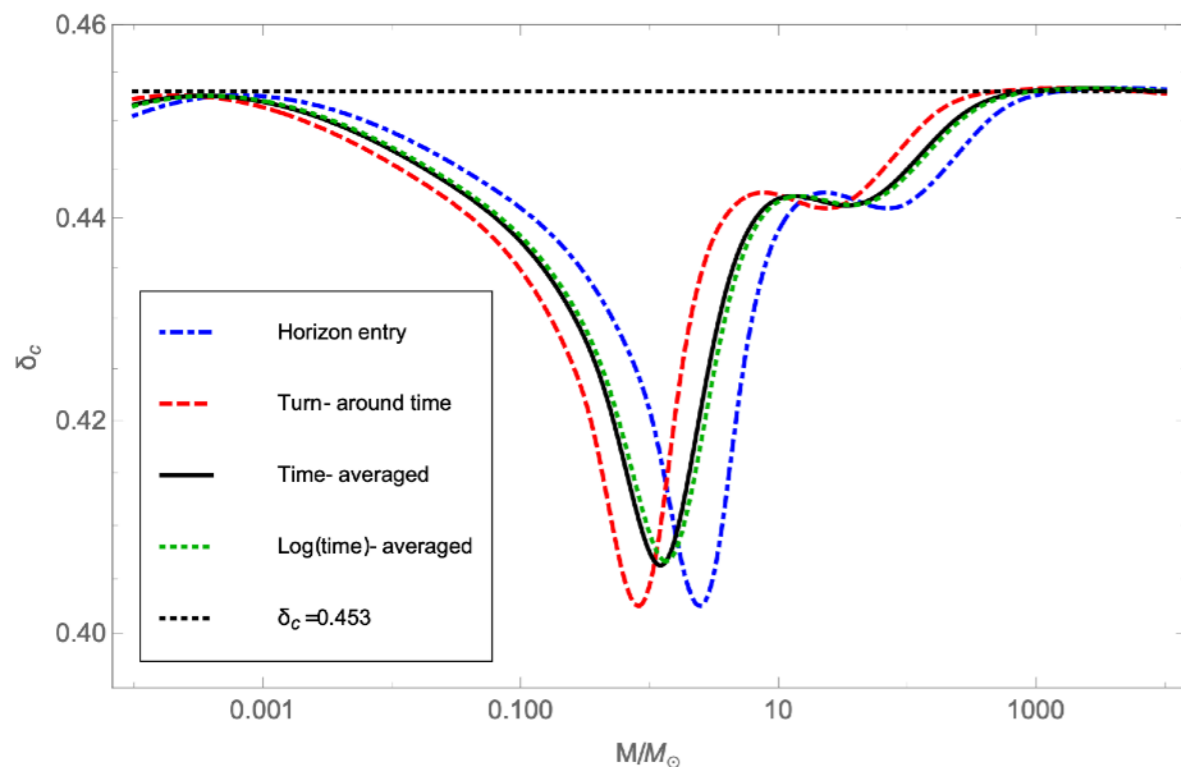
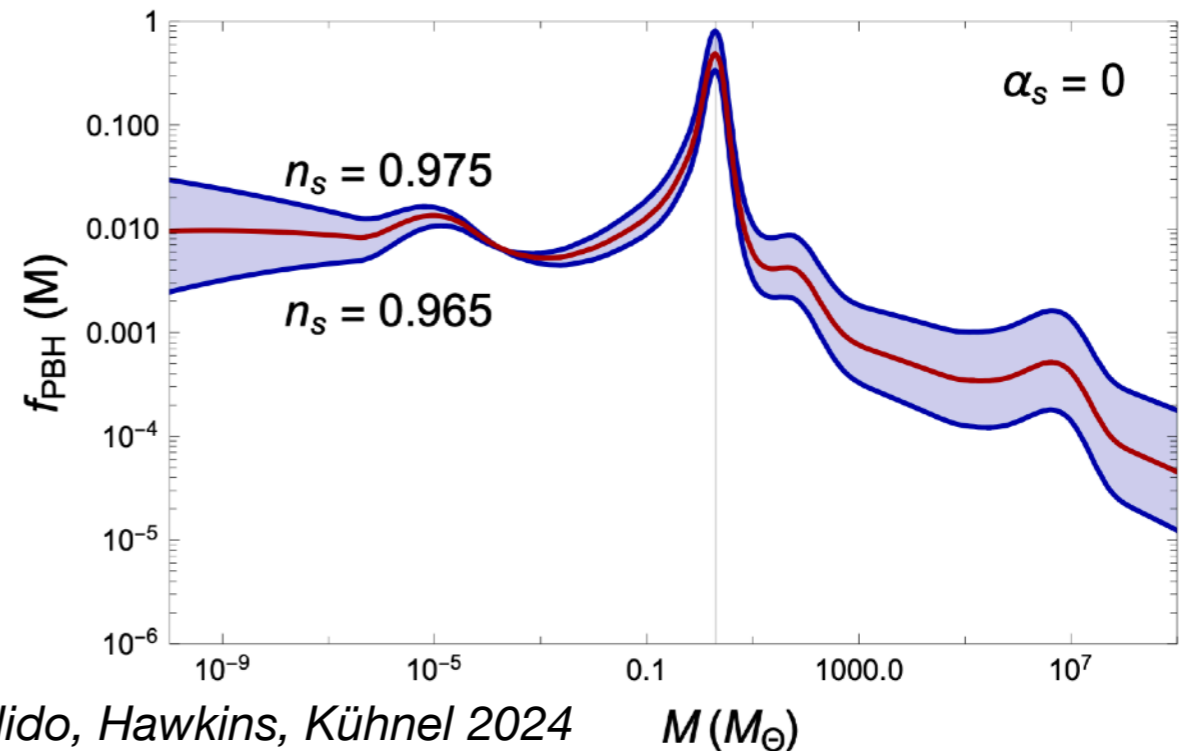
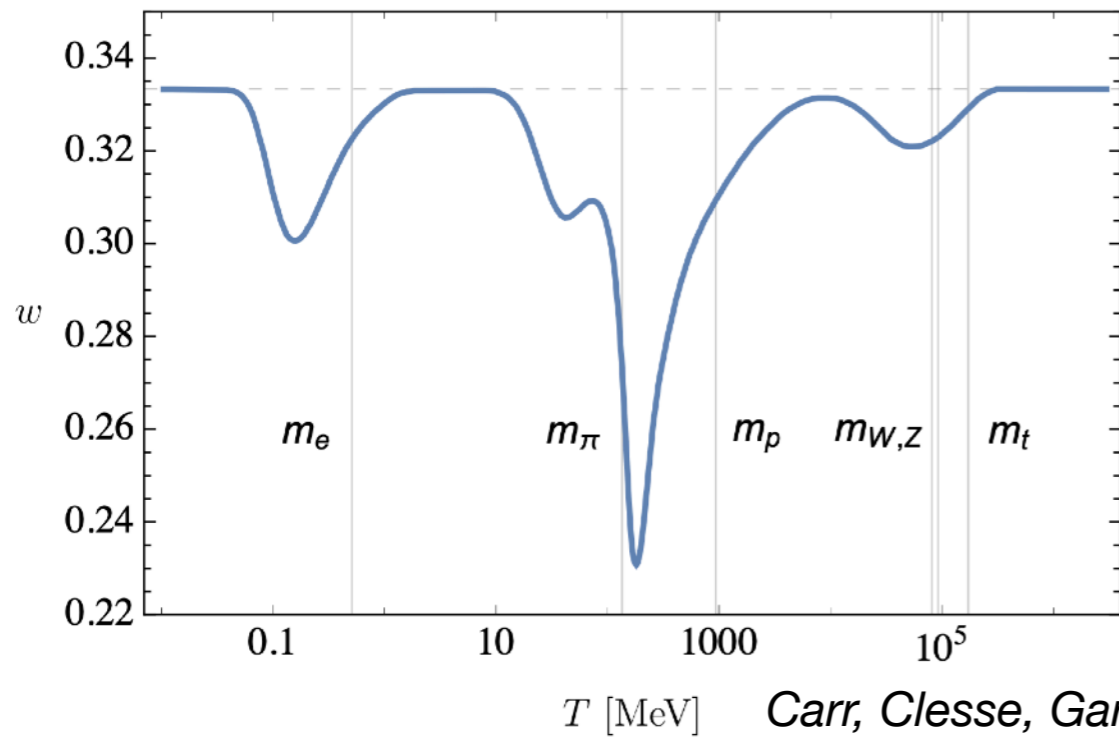
Sharma, Lesgourgues, Byrnes 2024

# The initial conditions of the universe



*$\mu$ -constraints are much tighter. Agrees with Chluba et al '12, Nakama et al '18, etc*

# Reduced pressure



*Byrnes, Hindmarsh, Young, Hawkins 2018*

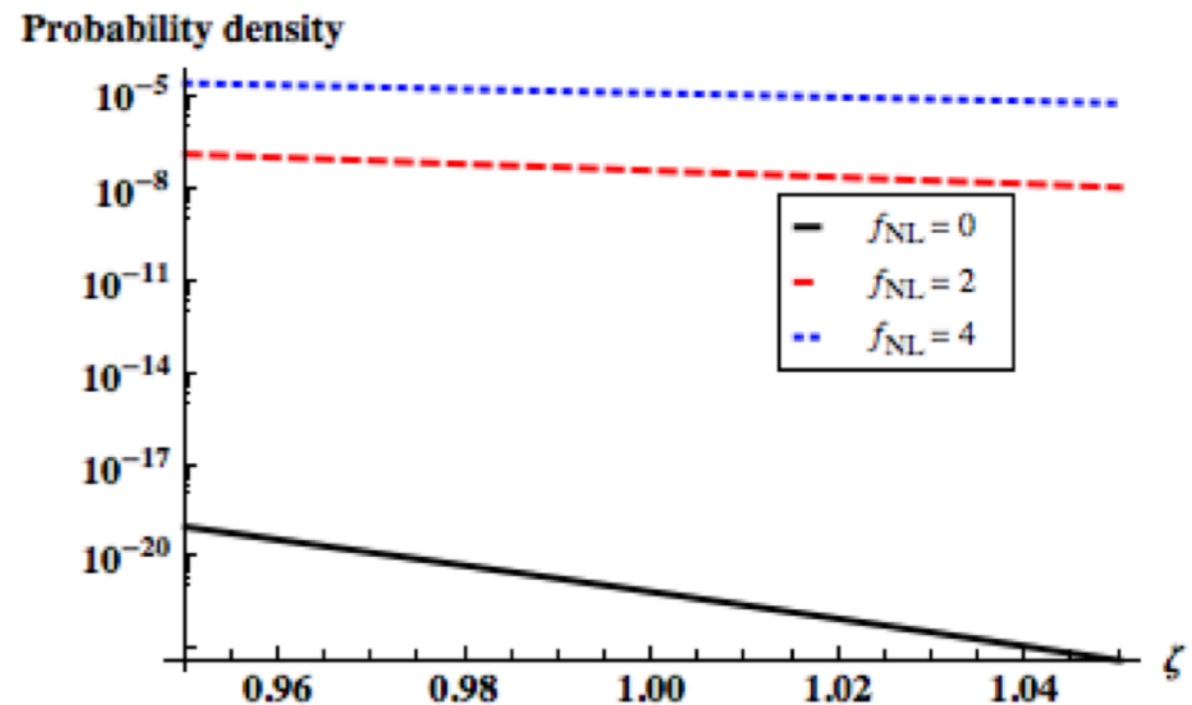
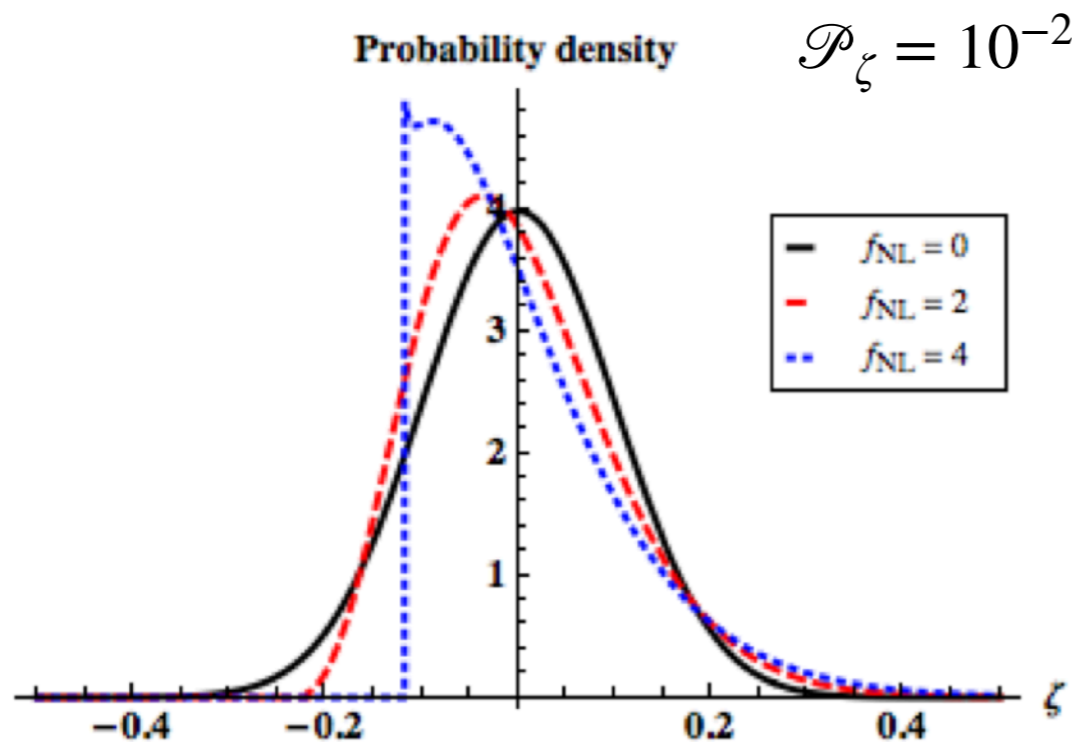
Overall impact of electron-positron annihilation on power spectrum amplitude only few %

Neutrino free streaming might make PBH formation harder: *Musco, Jedamzik, Young '23*

Florian Kühnel, Ilya Musco, Albert Escriva and Xav Pritchard talks

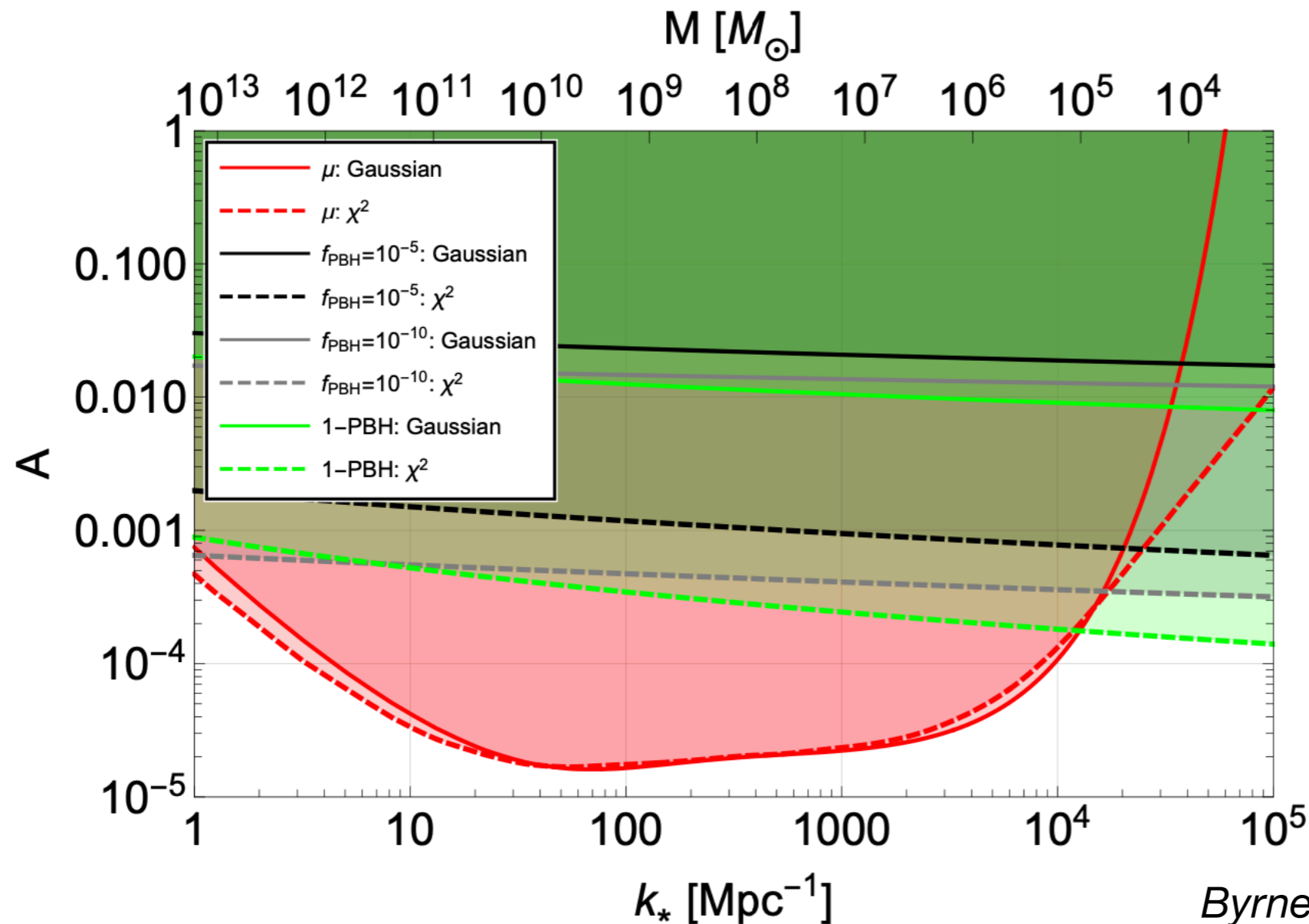
# Evading spectral distortions

- Primordial BHs are rare events which form deep in the pdf tail ( $\sim 7$  sigma fluctuations)
- Spectral distortions mainly form from the peak of the pdf
- Add positive skewness to boost the tail and suppress the peak



Young & Byrnes 2013

# Chi-squared non-Gaussianity



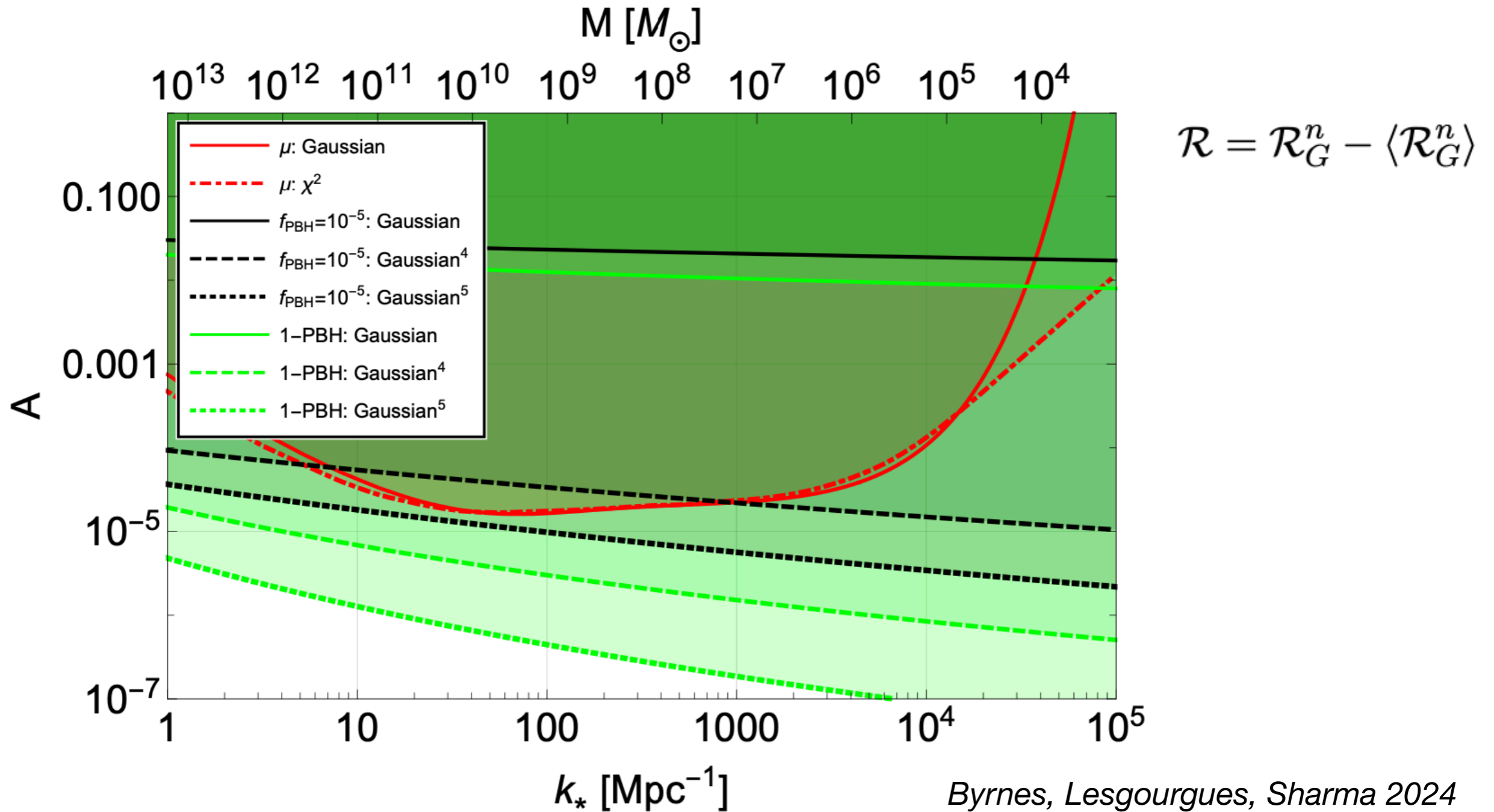
$$\mathcal{R}(\vec{x}) = \mathcal{R}_{\text{G}}^2(\vec{x}) - \langle \mathcal{R}_{\text{G}}^2 \rangle$$

Even the infinite  $f_{\text{NL}}$  limit is not nearly non-Gaussian enough - with exponential tail (matches tail of stochastic inflation)  
*Gow et al '22, Tomberg '23, Ballesteros et al '24*

*Byrnes, Lesgourgues, Sharma 2024*

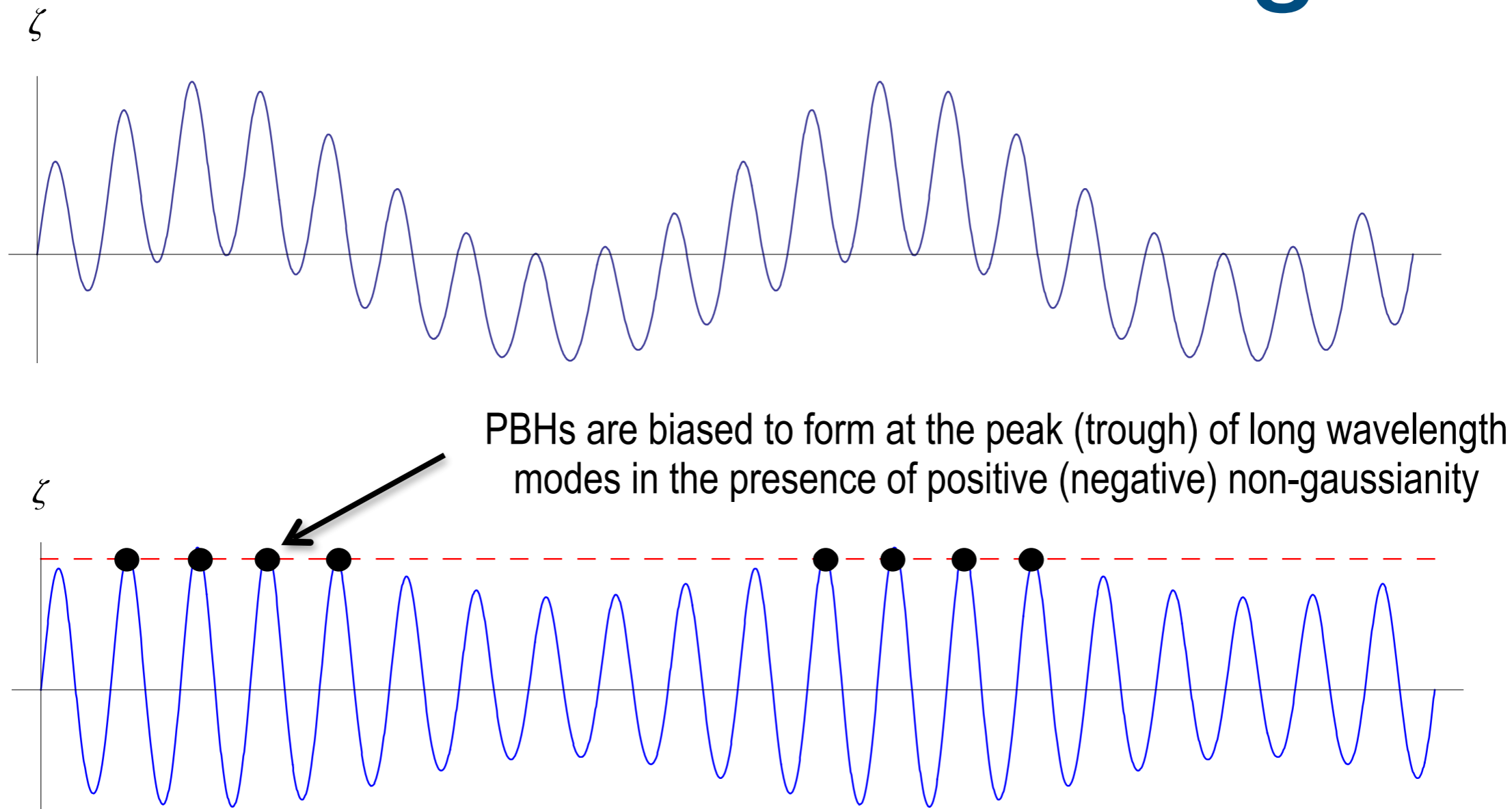
We determined mu-constraints with quadratic non-Gaussianity. Highly non-trivial that it remains so similar on the key scales: *Sharma, Lesgourgues, Byrnes 2024*

# Extreme non-Gaussianity



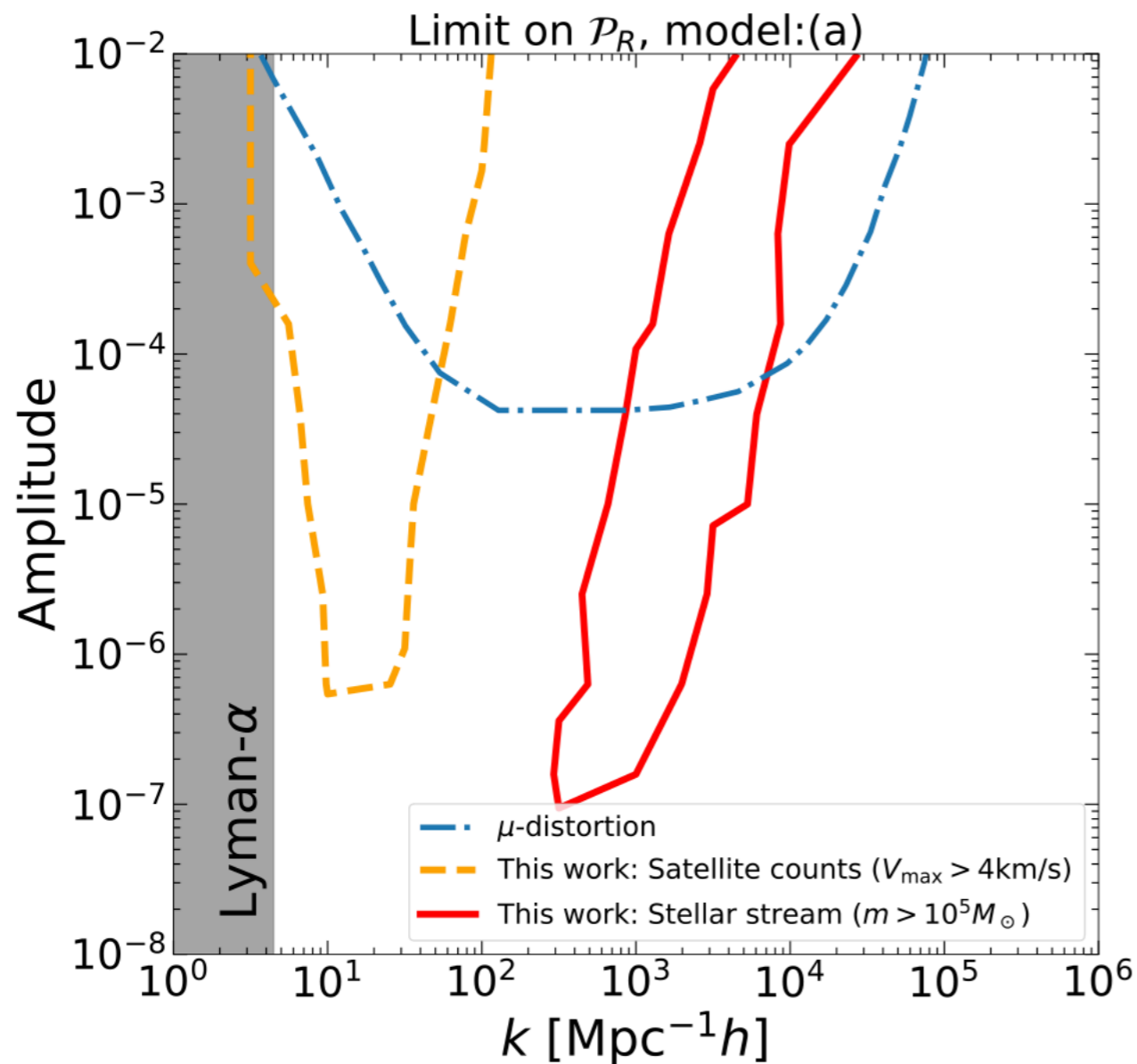
No model to generate such extremely non-Gaussian perturbations ( $n=4$  or  $5$ ) exists  
 See *Hooper et al '23* for ideas

# Non-Gaussian challenges



Clustered SMBHs may: 1) be incompatible with galaxy locations - *Shinohara et al '22, de Luca et al '22* 2) generate photon-DM isocurvature perturbation on CMB scales - *Tada & Yokoyama '19; Young & CB '19; van Laak & Young '23*  
3) generate  $\mu$ -T correlations - *Pajer & Zaldarriaga 2012, Chluba et al many papers*

# More challenges



*Ando, Hiroshima, Ishiwata 2022*

Flattened pdf tail requires type II PBH understanding - Tomohiro Harada talk

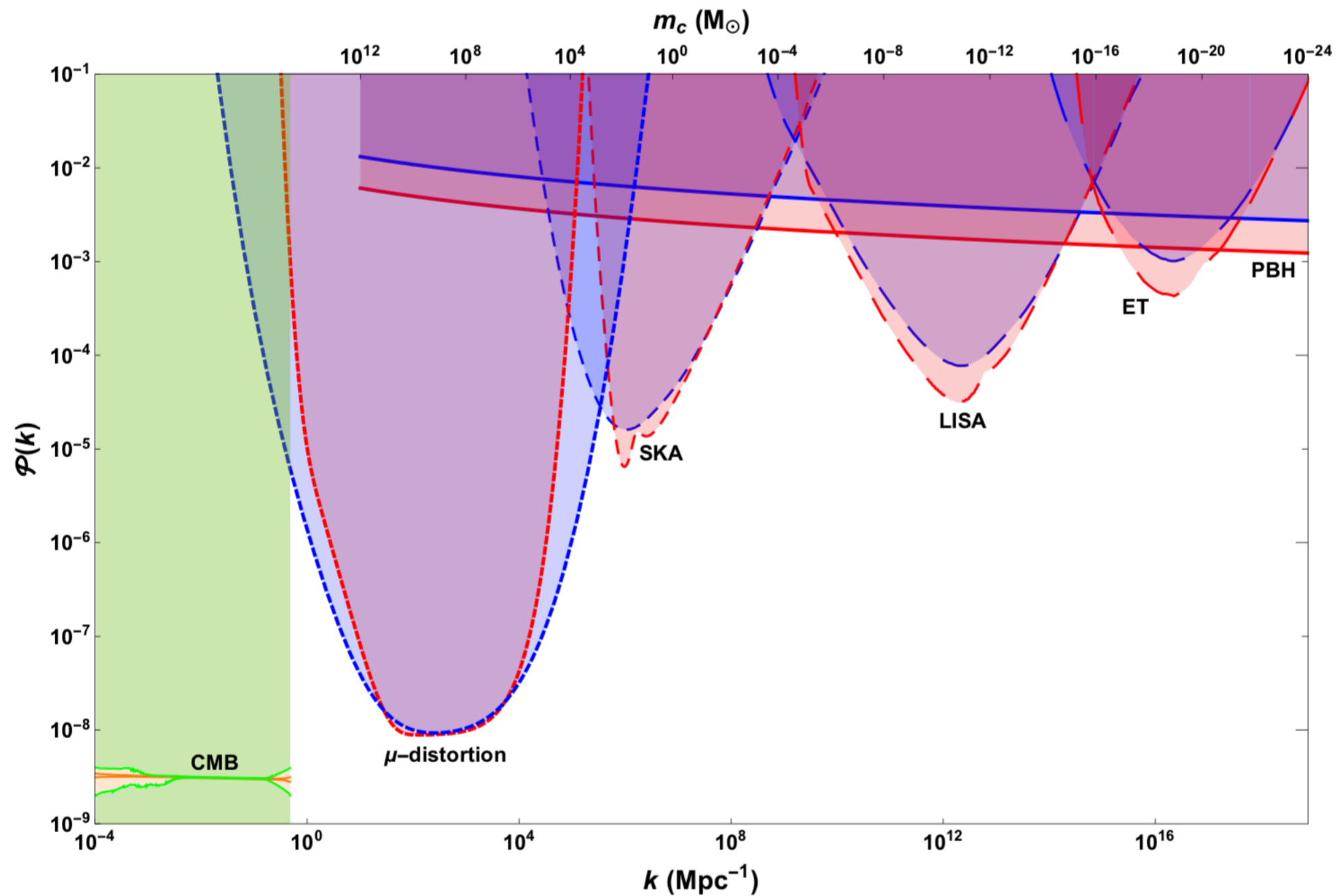
ultracompact minihalo constraints  
(model dependent)

Highly non-Gaussian models will be more Gaussian in local patches:  
Fine-tuning beyond that of Andrew Gow and Ioanna Stamou talks

An alternative PBH formation mechanism seems more promising -  
Hai-Long Huang talk



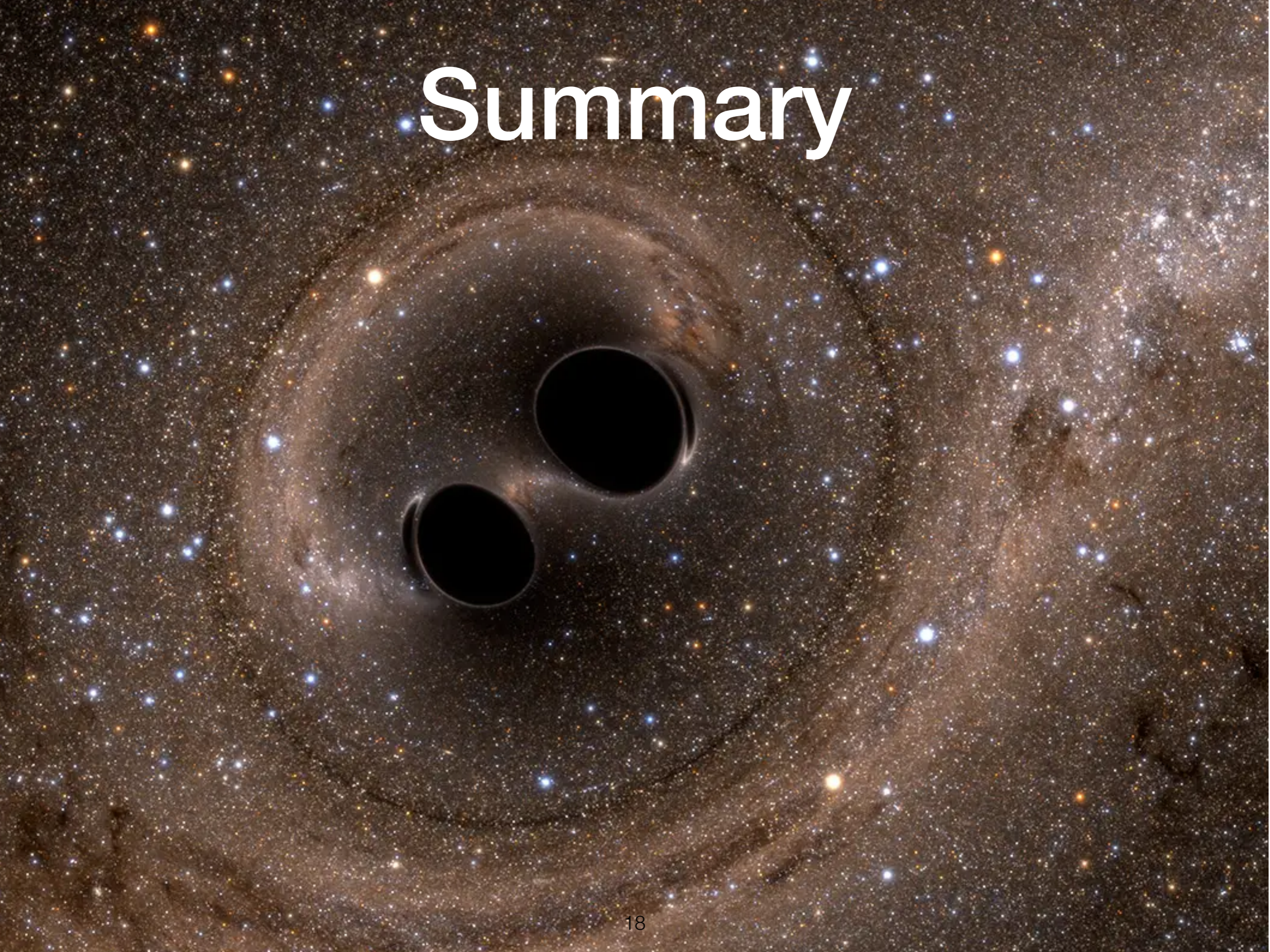
# A bright future (forecast)



The PBH lines correspond to zero PBHs  
*Cole & CB '17*

*Gow, CB, Cole, Young 2020*

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- **SMBHs exist but unknown formation**
- **PBHs might exist, formation hard but understood**
- **SM PBHs conflict with CMB spectral distortions for Gaussian or even for infinite  $f_{\text{NL}}$  or  $g_{\text{NL}}$**
- **More extreme non-G “works” but beware other issues**