CMB constraints on light primordial black holes

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Based on **work in progress**
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Primordial Black Holes (PBHs) as a Dark Matter candidate?

→ Misao Sasaki's talk this morning

- PBHs do not require a new particle to explain DM

- Formation of PBHs does require new physics
- Getting the right DM abundance requires careful tuning

Phenomenology of PBHs

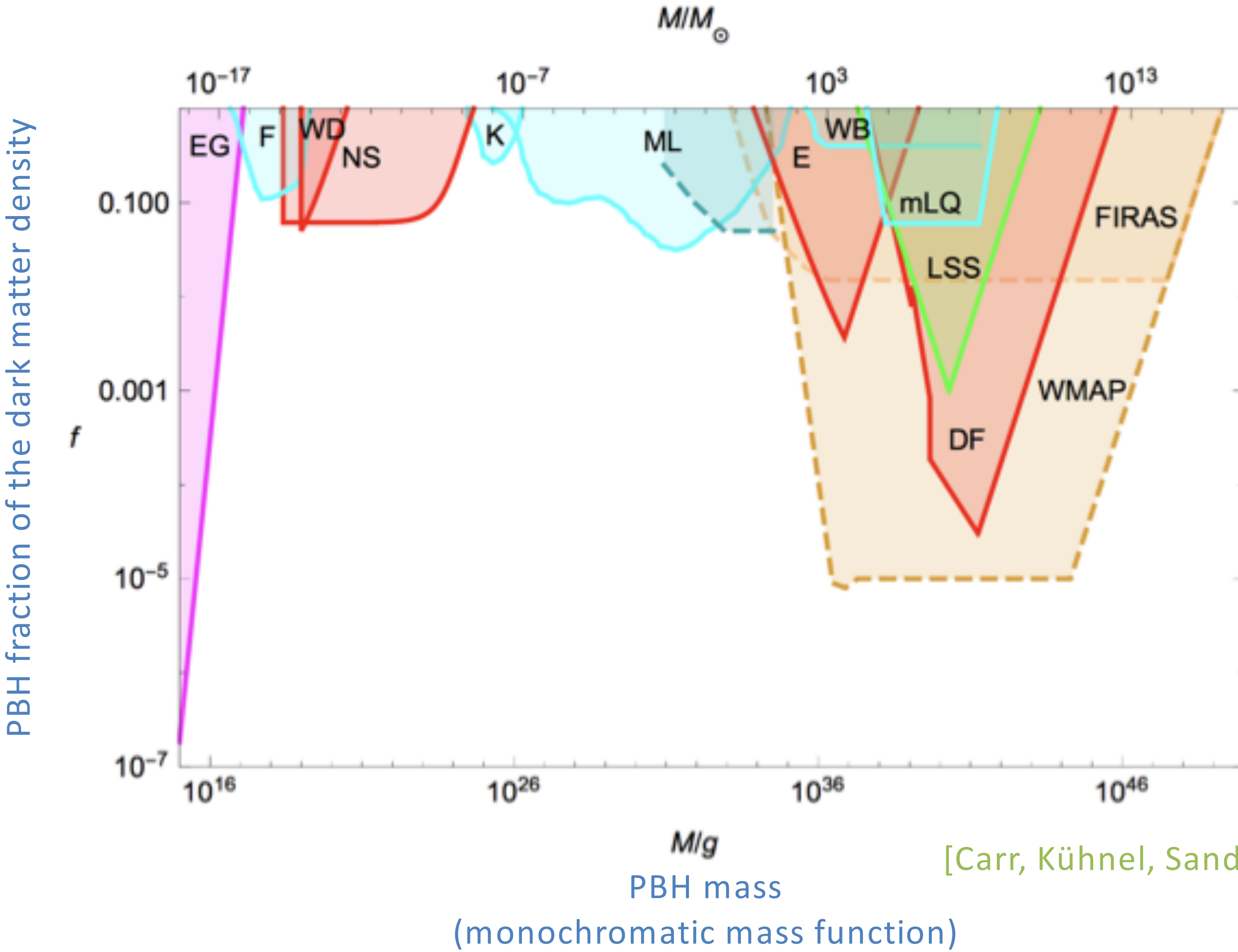
- Depending on their mass, PBHs can potentially lead to observable signatures via
  - Hawking radiation
  - Gravitational lensing
  - Kinematic effects
  - Capture by astrophysical objects
  - Accretion on PBH
  - Generation of additional large scale structure (Poisson)

Conceptual mass limits

- PBH lifetime should be longer than the age of the Universe
- At least one PBH per galaxy halo

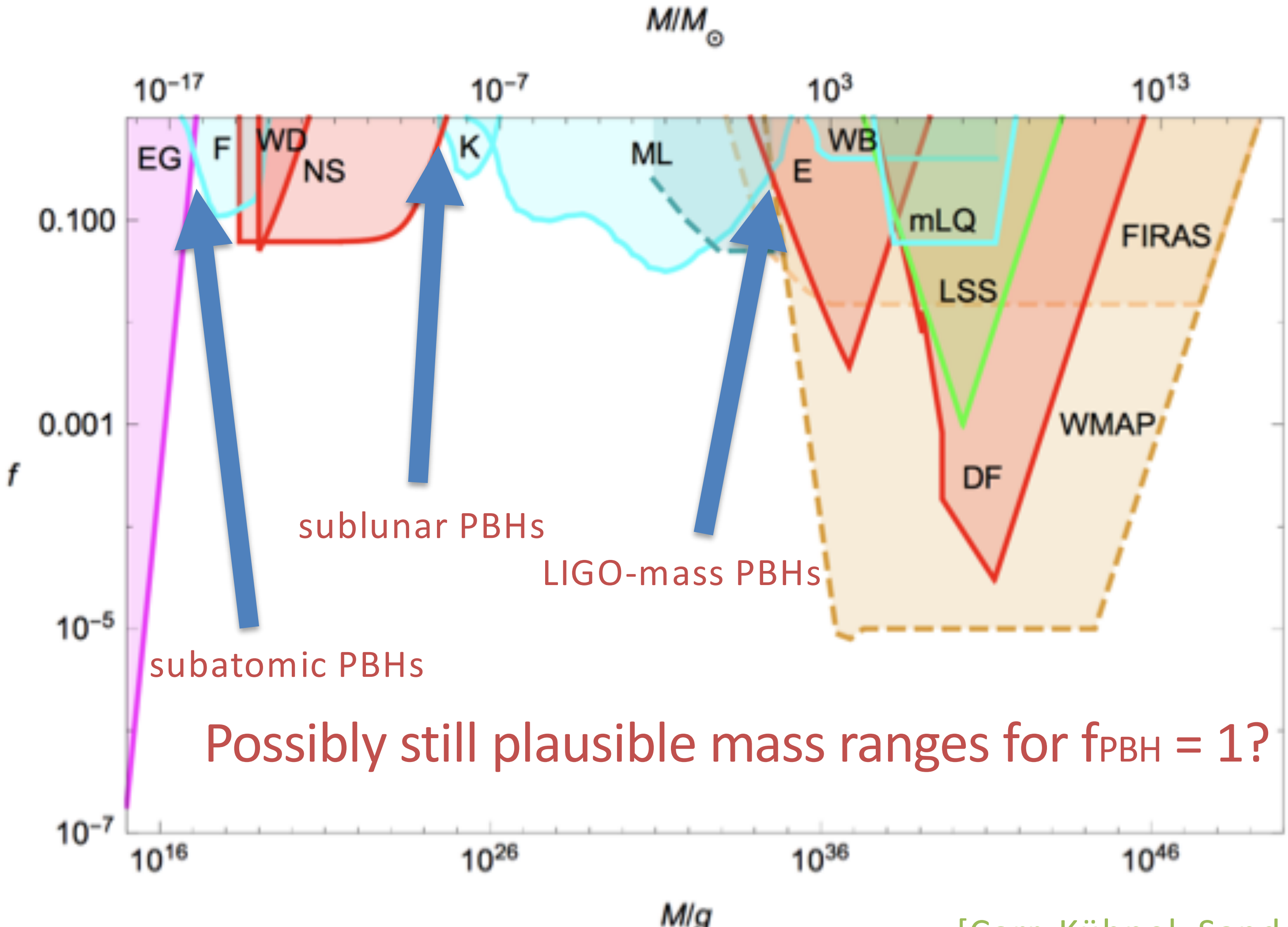
$$\Longrightarrow\ 10^{\sim 45}\mathrm{g} \gtrsim M_{\mathrm{PBH}} \gtrsim 10^{15}\mathrm{g}$$

Constraints on the PBH fraction



[Carr, Kühnel, Sandstad (2016)]

Constraints on the PBH fraction

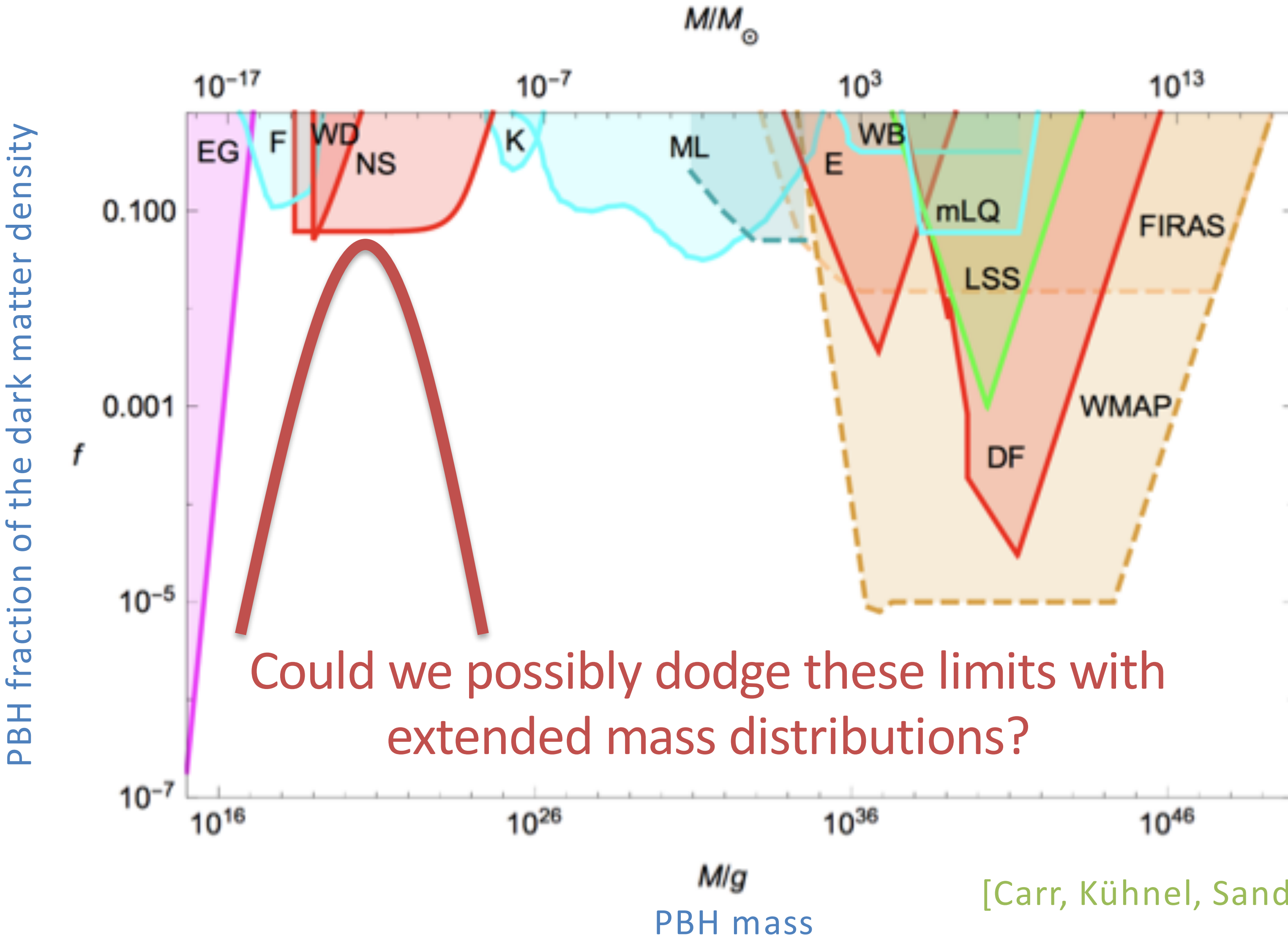


PBH fraction of the dark matter density

PBH mass
(monochromatic mass function)

[Carr, Kühnel, Sandstad (2016)]

Constraints on the PBH fraction

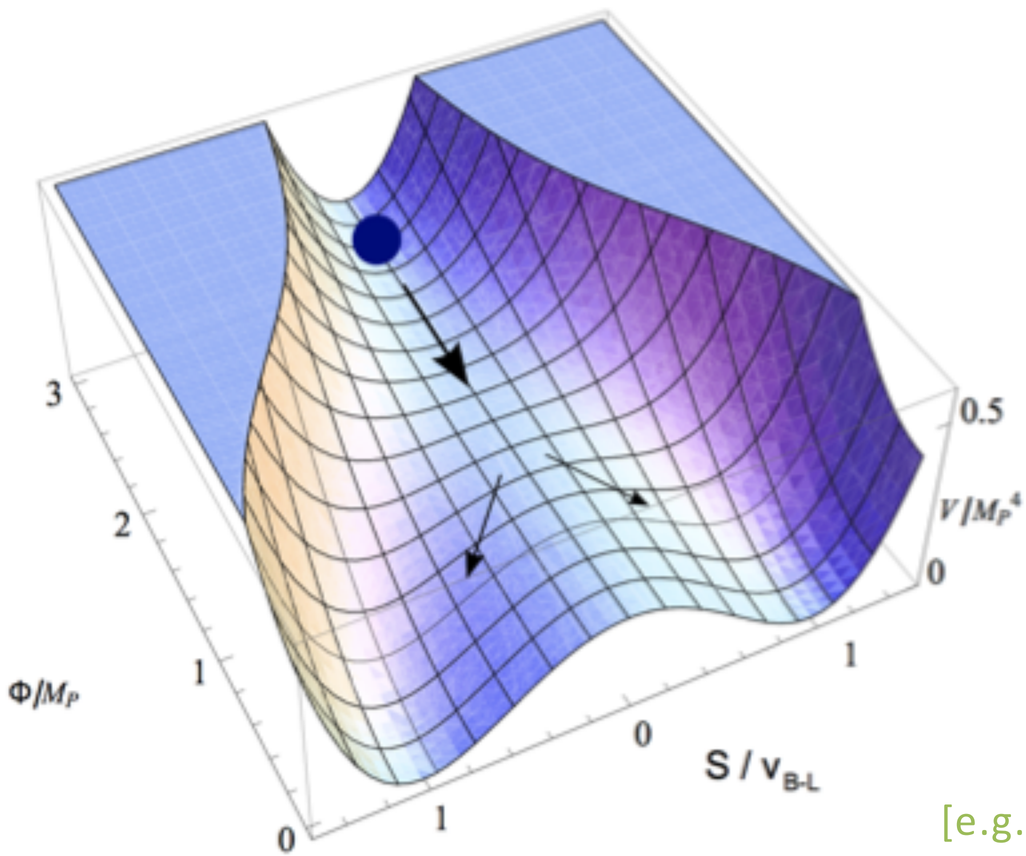


Could we possibly dodge these limits with extended mass distributions?

[Carr, Kühnel, Sandstad (2016)]

Extended PBH mass distributions from inflation

- Example: hybrid inflation

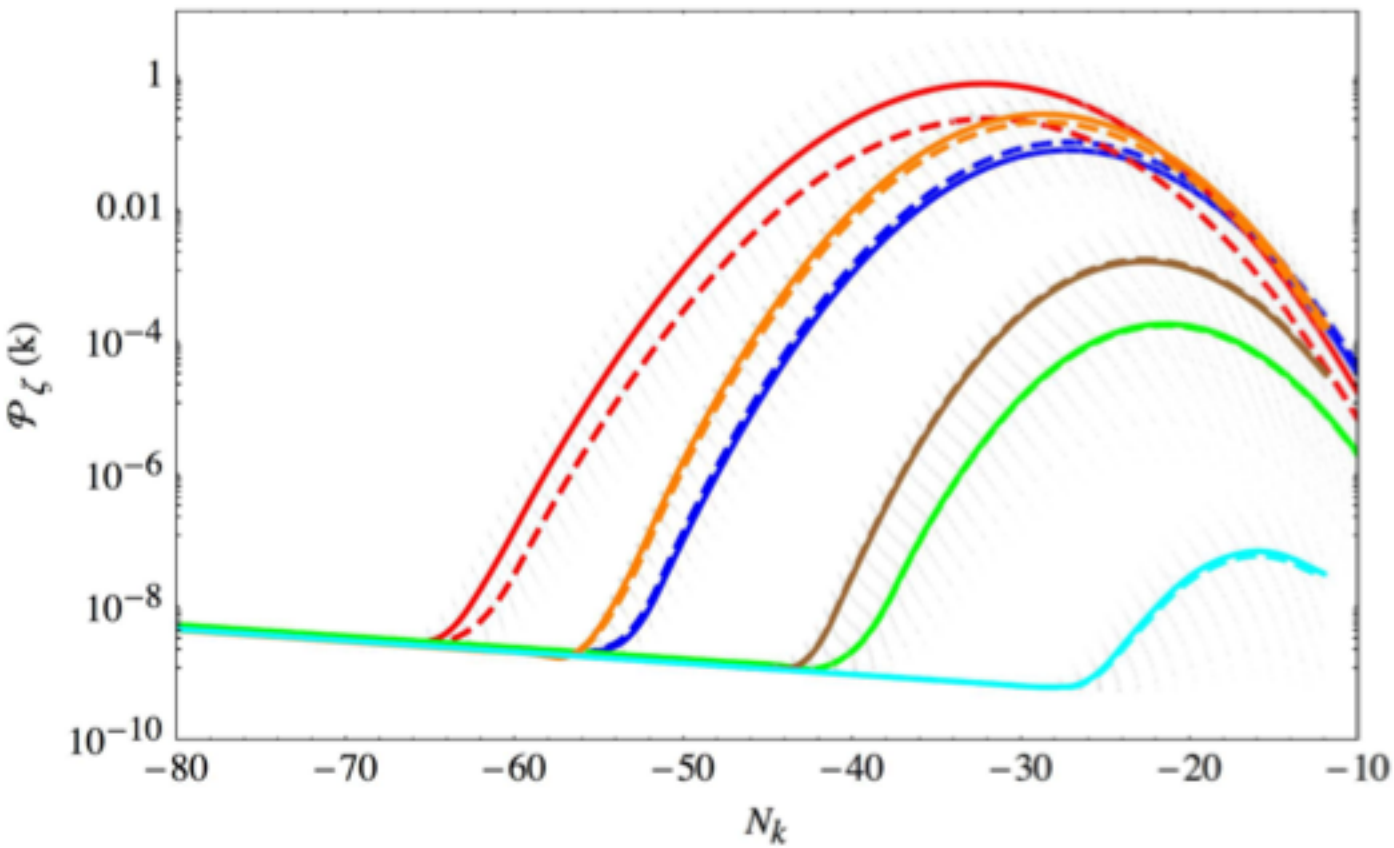


Can generate large amplitude fluctuations in “waterfall field” at the end of inflation

[e.g., Clesse, Garcia-Bellido (2015)]

Extended PBH mass distributions from inflation

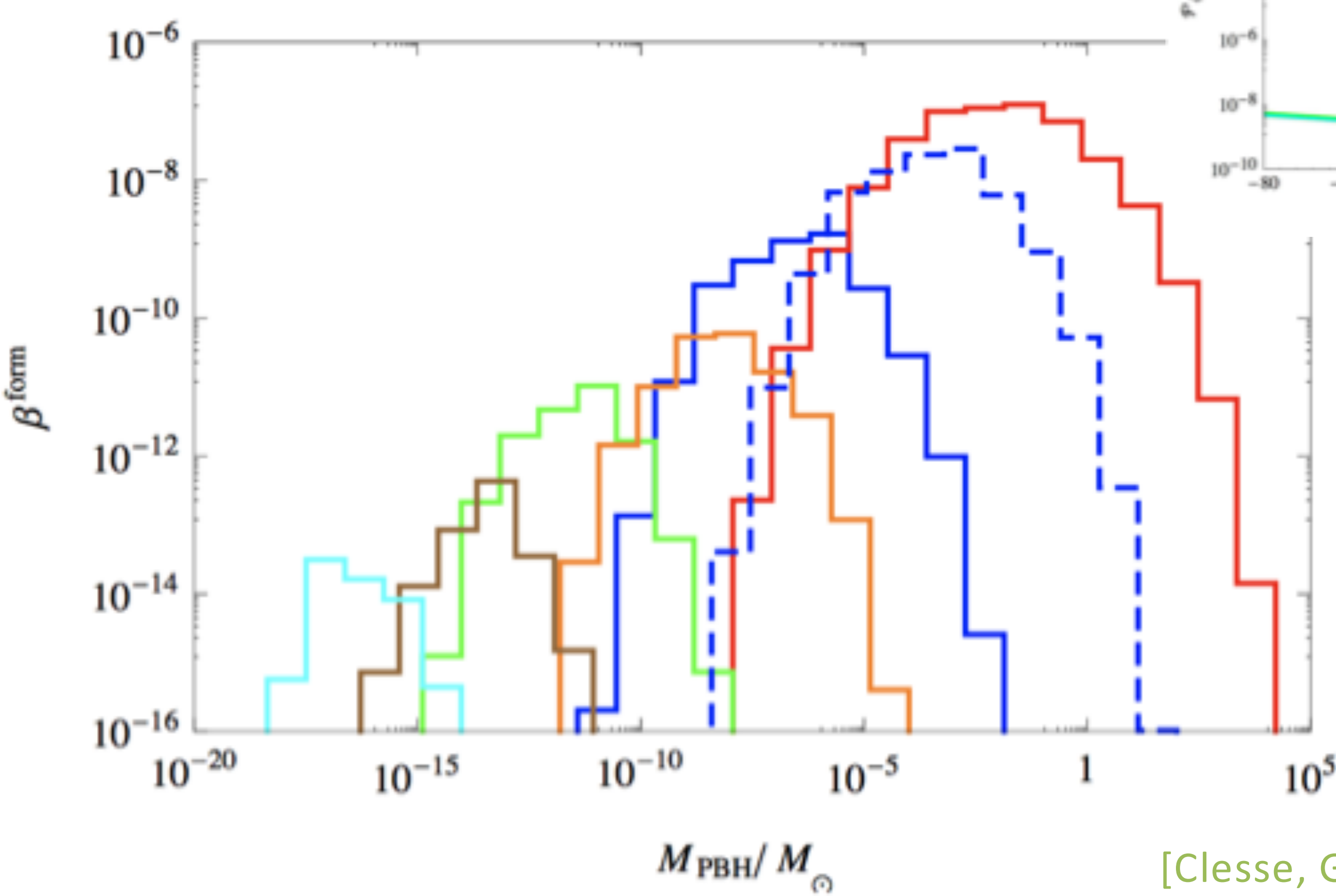
Primordial power spectrum
of curvature perturbations

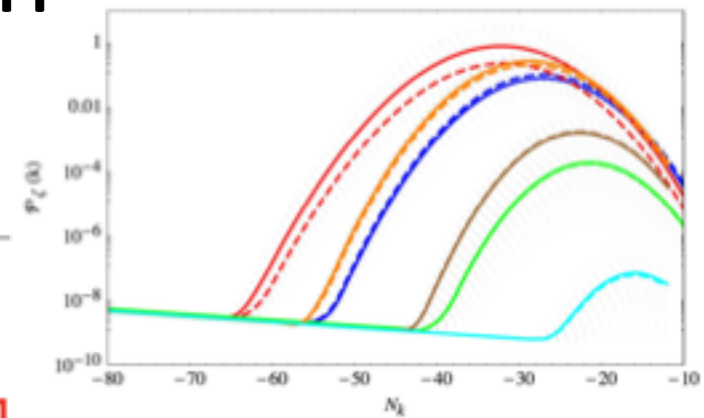


[Clesse, Garcia-Bellido (2015)]

Extended PBH mass distributions from inflation

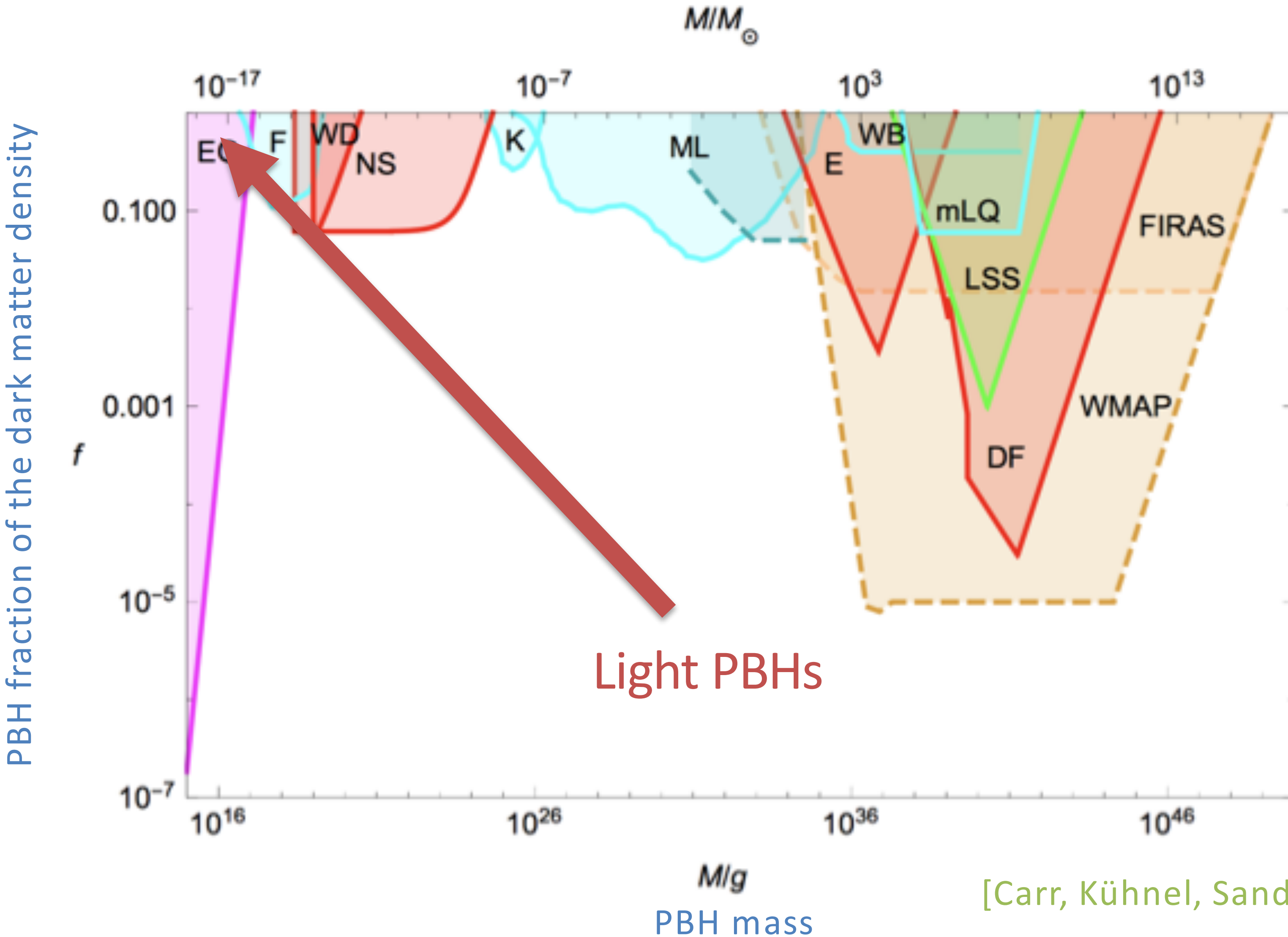
Mass distribution of PBHs at formation





[Clesse, Garcia-Bellido (2015)]

Constraints on the PBH fraction



[Carr, Kühnel, Sandstad (2016)]

Light PBHs:

$$10^{15}\text{ g} < M_{\text{PBH}} < 10^{17}\text{ g}$$

$$10^{-14}\text{ m} < r_{\text{PBH}} < 10^{-12}\text{ m}$$

[Hydrogen atom: $r = 5 \times 10^{-11}$ m]

Constraining light PBHs with the CMB

- PBHs with mass $M_{\mathrm{PBH}} < 10^{17}$ g deposit energy into plasma via Hawking radiation
- Changes recombination history of the Universe (free electron fraction $x_e(z)$)
- Affects the temperature and polarisation anisotropies of the CMB
- Compare with *Planck* data to constrain f_{PBH}

Phenomenology very similar to decaying dark matter scenario

Constraints on light PBHs

- Extragalactic γ-ray background

[Carr, Kohri, Sendouda, Yokoyama (2012)]

- CMB

[e.g., Carr, Kohri, Sendouda, Yokoyama (2012); Belotsky, Kirillov (2014); Clark, Dutta, Gao, Strigari, Watson (2016); Lesgourgues, Poulin, Serpico (2017)]

- Extended mass distributions (but not for this scenario)

[e.g., Kühnel, Freese (2017); Bellomo, Bernal, Raccanelli, Verde (2017); Carr, Raidal, Tenkanen, Vaskonen, Veermäe (2017)]

Hawking radiation

Black holes emit blackbody radiation with temperature

$$T_{\rm BH} = \frac{m_{\rm Pl}^2}{M_{\rm BH}} \sim \left(\frac{M_{\rm BH}}{10^{13}{\rm g}}\right)^{-1} {\rm GeV} \sim \left(\frac{M_{\rm BH}}{10^{26}{\rm g}}\right)^{-1} {\rm K}$$

implying an evaporation time* of

$$\tau_{\rm BH} \sim 10^{10} \left(\frac{M_{\rm BH}}{5\times 10^{14}{\rm g}}\right)^{3} {\rm a}$$

*this assumes an isolated black hole that does not accrete; given today's CMB temperature, only black holes with masses < $O(10^{26}$g) lose mass

PBH energy loss

- Total energy loss of PBHs per volume and time

$$\frac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t} = -\frac{\dot{M}_{\mathrm{PBH}}}{M_{\mathrm{PBH}}}\rho_{\mathrm{PBH}}(1+z)^3$$

- For 10^{15} g < M_{PBH} < 10^{17} g, Hawking radiation consists of gravitons, photons, neutrinos and $e^{\pm}$

only these can heat the plasma around CMB decoupling

PBH energy loss

- PBH mass loss

$$\dot{M}_{\rm PBH} \approx -5 \times 10^{-5} \left(f_{\rm grav} + f_\gamma + f_\nu + f_{e^\pm} \right) \left(\frac{M_{\rm PBH}}{10^{15} {\rm g}} \right)^{-2} {\rm g\, s^{-1}}$$

0.007 0.06 0.147 0.142

[MacGibbon, Webber (1990)]

  - Above 10^{17} g: no $e^{\pm}$, heating becomes inefficient
  - Below 10^{15} g: QCD phase transition, quark jets

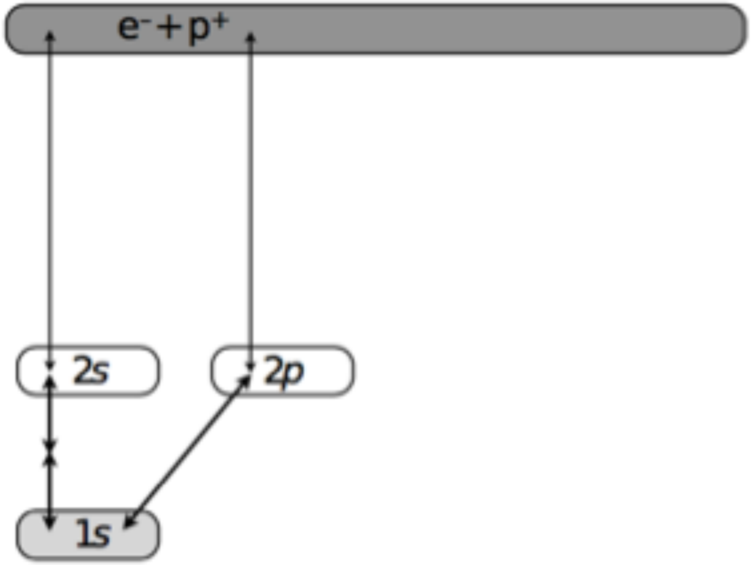
- Energy injected into the plasma

$$\frac{{\rm d}E_{\rm inj}}{{\rm d}V{\rm d}t} \propto f_{\rm PBH} M_{\rm PBH}^{-3} (1+z)^3$$

Recombination

Effective three-level atom

[Peebles (1968)]



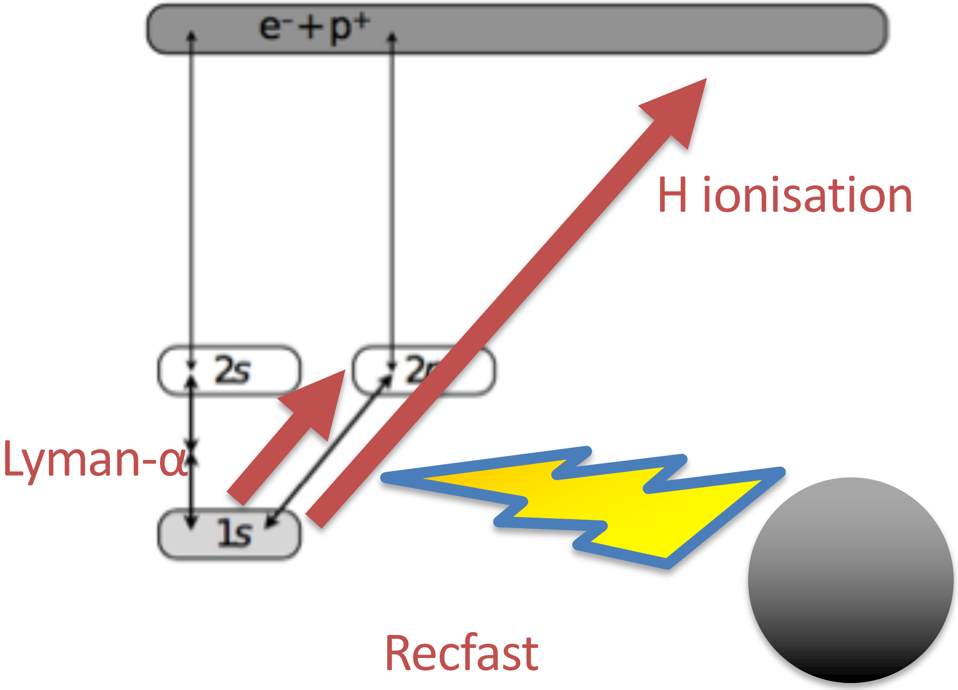
Recfast

[Seager, Sasselov, Scott (1999)]

Recombination

Effective three-level atom

[Peebles (1968)]



Recfast

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Recombination

Effective three-level atom

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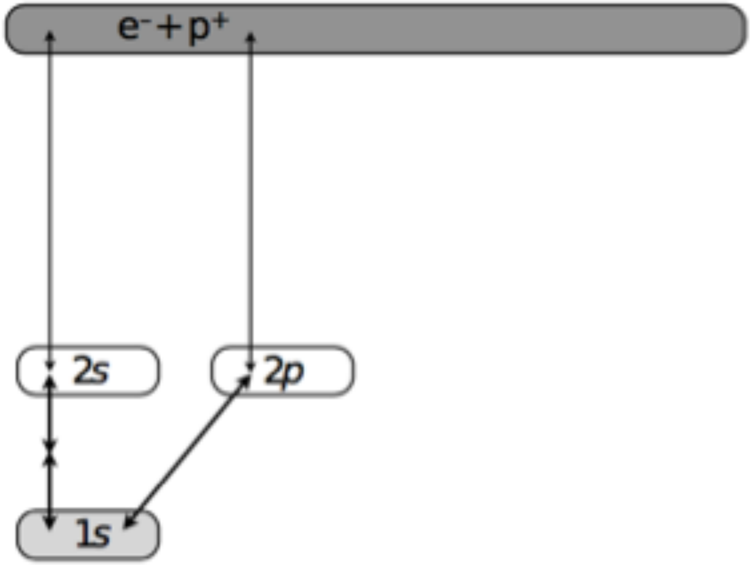
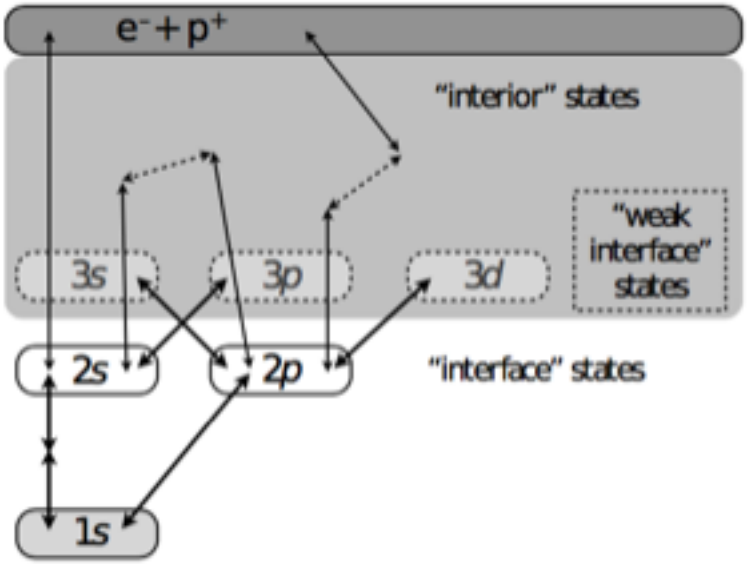


Recfast

[Seager, Sasselov, Scott (1999)]

Extended effective multi-level atom



HyRec

[Ali-Haïmoud, Hirata (2010)]

Modifications to recombination equations

- Coupled ODEs for free electron fraction x_e and baryon temperature T_b

H ionisation   Lyman-α

$$\frac{\mathrm{d}x_e}{\mathrm{d}z} = \left(\frac{\mathrm{d}x_e}{\mathrm{d}z}\right)_{\mathrm{std}} \boxed{- \frac{1}{(1+z)H(z)} \left[I_{X_\mathrm{i}}(x_e, T_\mathrm{b}, z) + I_{X_\alpha}(x_e, T_\mathrm{b}, z)\right]}$$

$$\frac{\mathrm{d}T_\mathrm{b}}{\mathrm{d}z} = \left(\frac{\mathrm{d}T_\mathrm{b}}{\mathrm{d}z}\right)_{\mathrm{std}} \boxed{- \frac{2}{3(1+z)H(z)} \frac{K_\mathrm{h}(x_e, T_\mathrm{b}, z)}{1 + f_\mathrm{He} + x_e}}$$

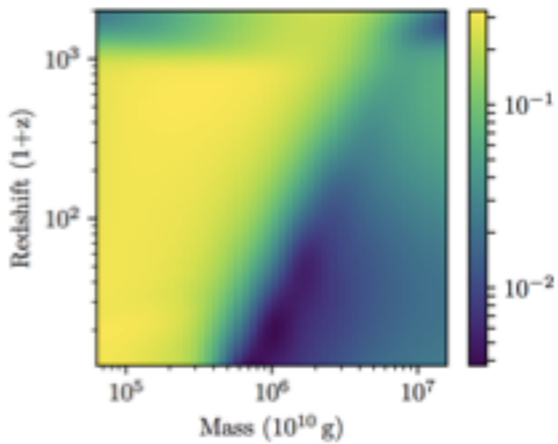
baryon heating

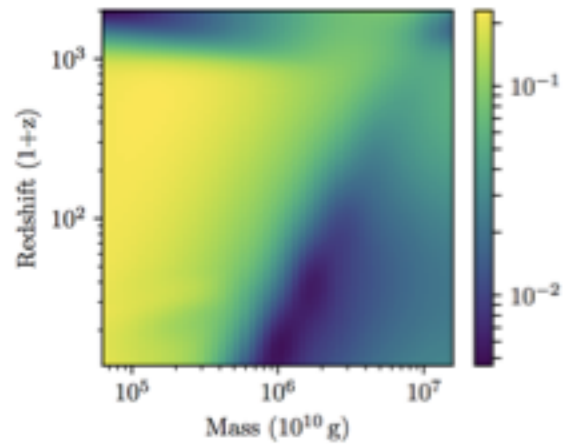
These extra terms depend on the hydrogen number density and the effective efficiencies of energy deposition in the different channels

Effect of injected energy on plasma

Effective efficiencies

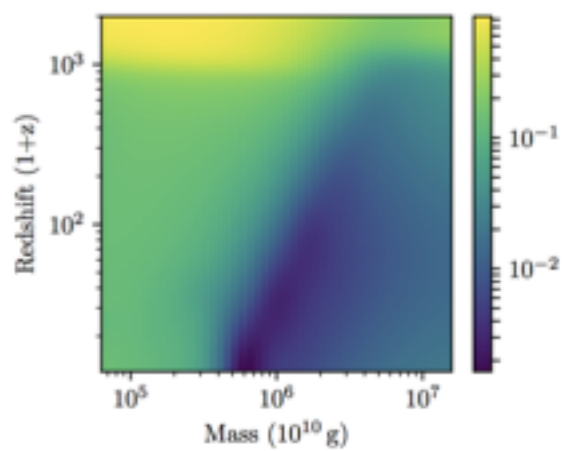
H ionisation





Lyman-α

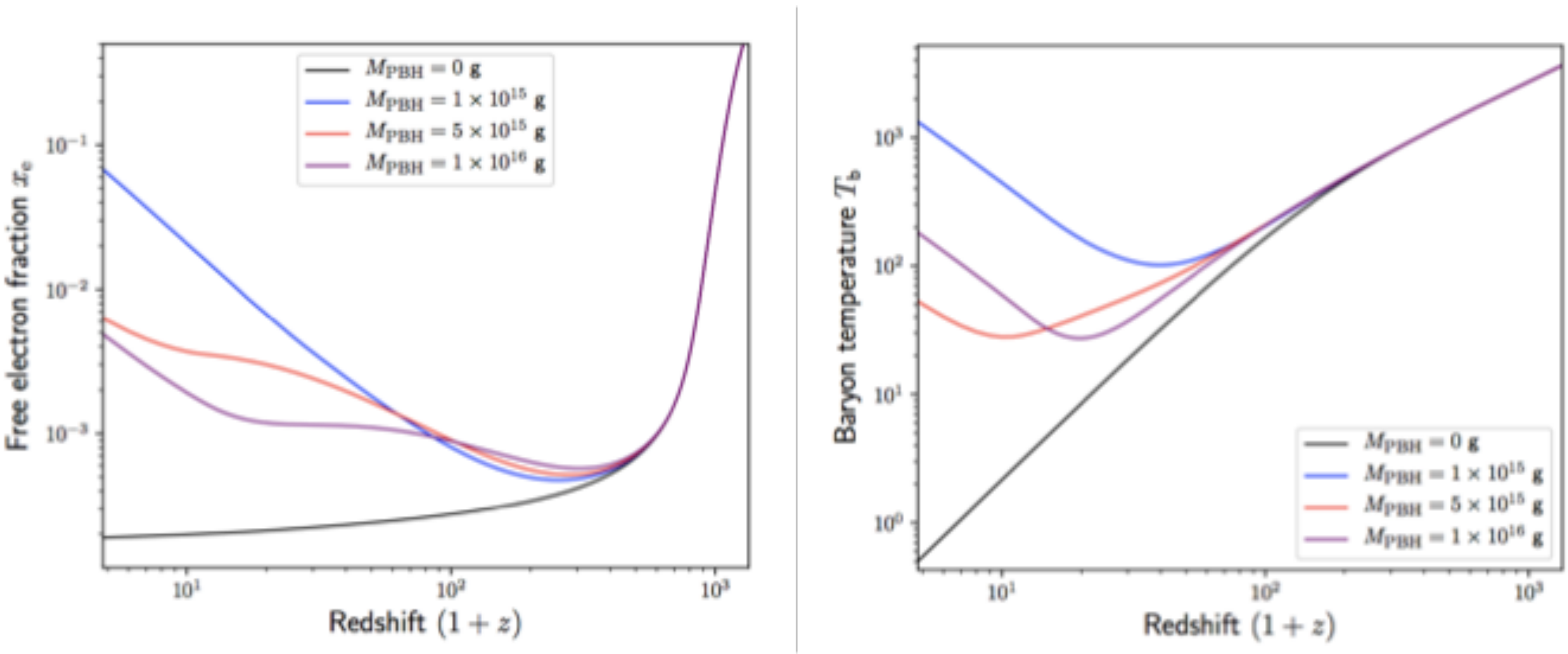
baryon heating



continuum
photons
+
Helium inionisation

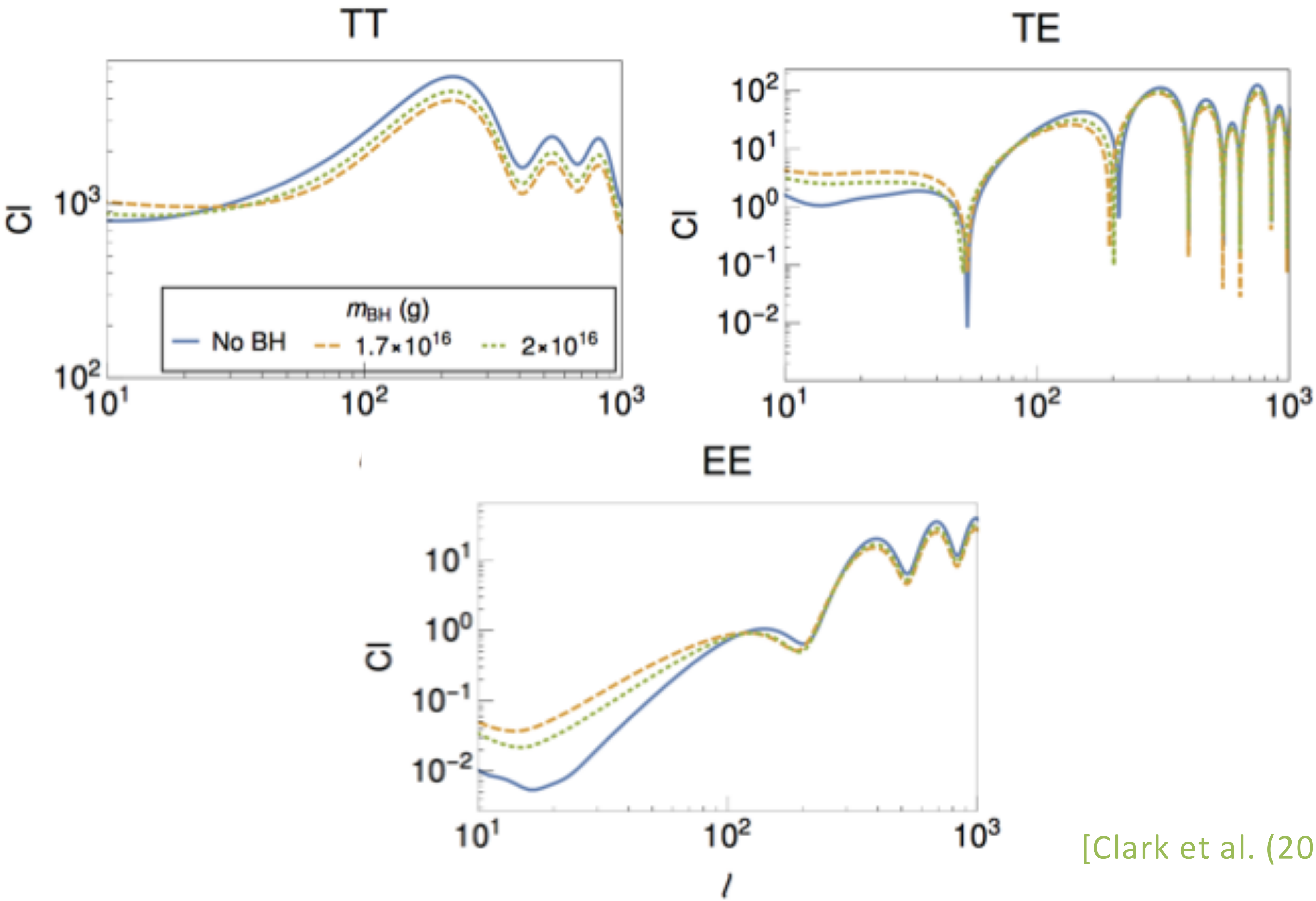
[Slatyer (2015); JH, Poulter, White, Williams (in prep.)]

Ionisation history and baryon temperature after recombination



[JH, Poulter, White, Williams (in prep.)]

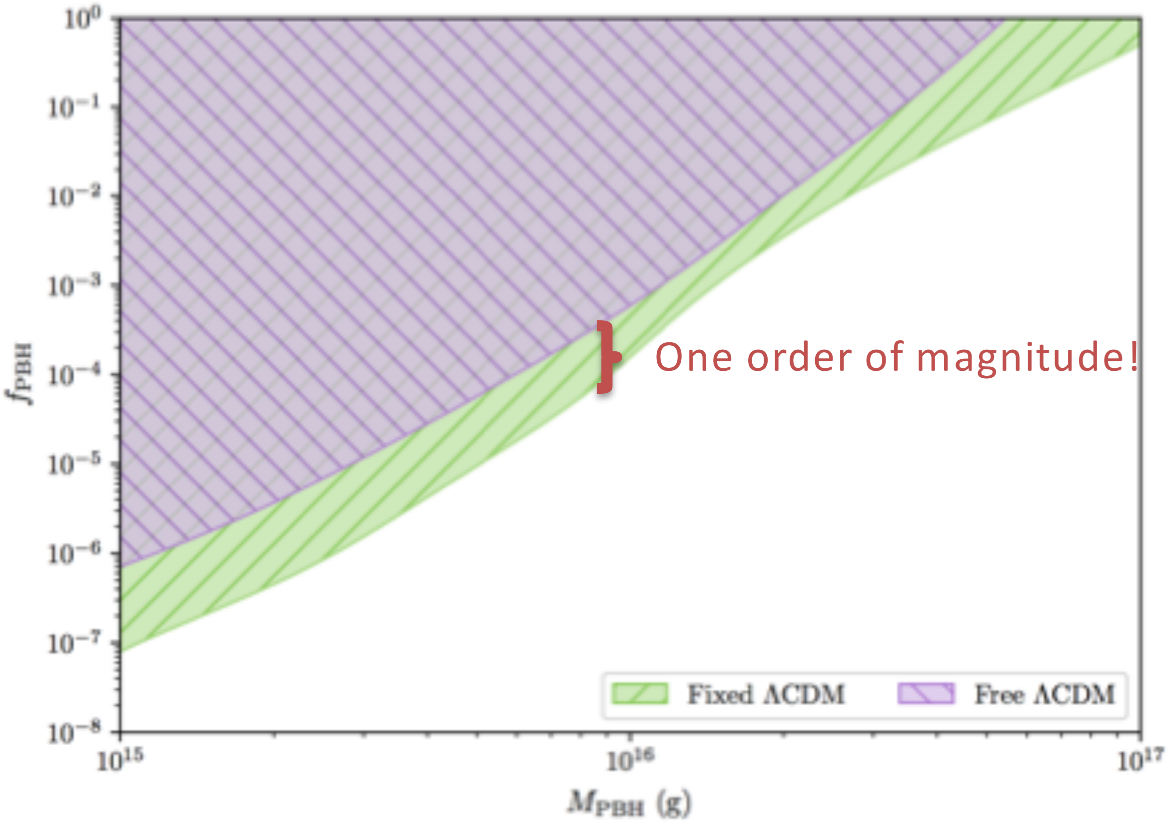
Signature of PBHs in CMB angular power spectra



[Clark et al. (2016)]

Constraints on PBH mass/fraction

PBH fraction of the DM



PBH mass
(monochromatic mass function)

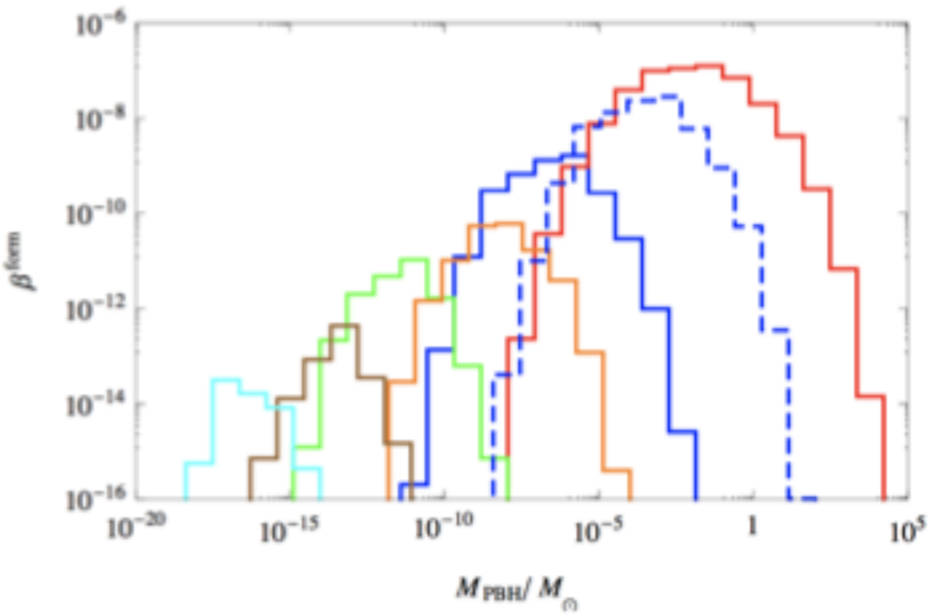
[JH, Poulter, White, Williams (in prep.)]

Extended PBH mass distributions

- Assume lognormal mass distribution

$$\frac{\mathrm{d}n}{\mathrm{d}M} \propto \exp\left[-\frac{(\log M/M_{\rm PBH})^2}{2\sigma_{10}^2}\right]$$

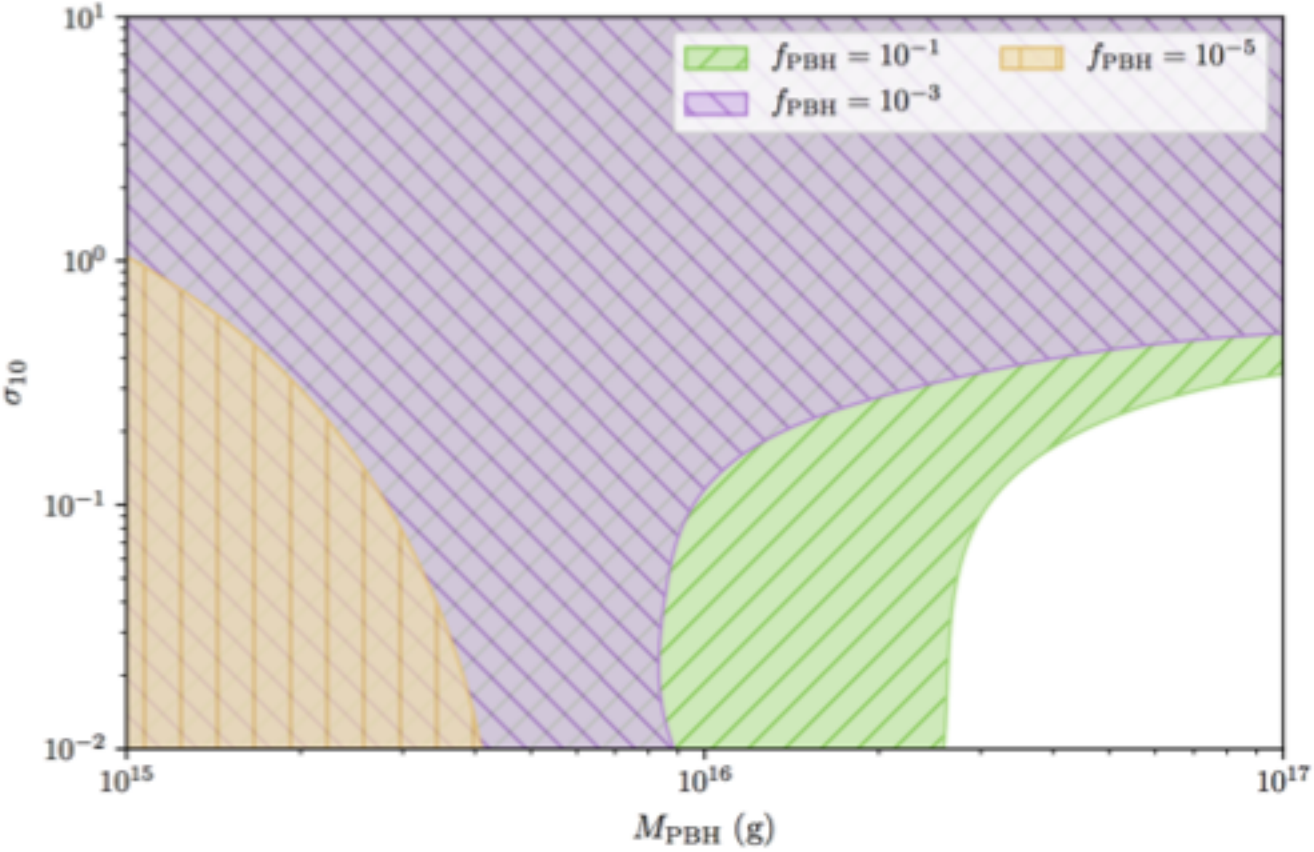
(logarithmic) width



[Clesse, Garcia-Bellido (2015)]

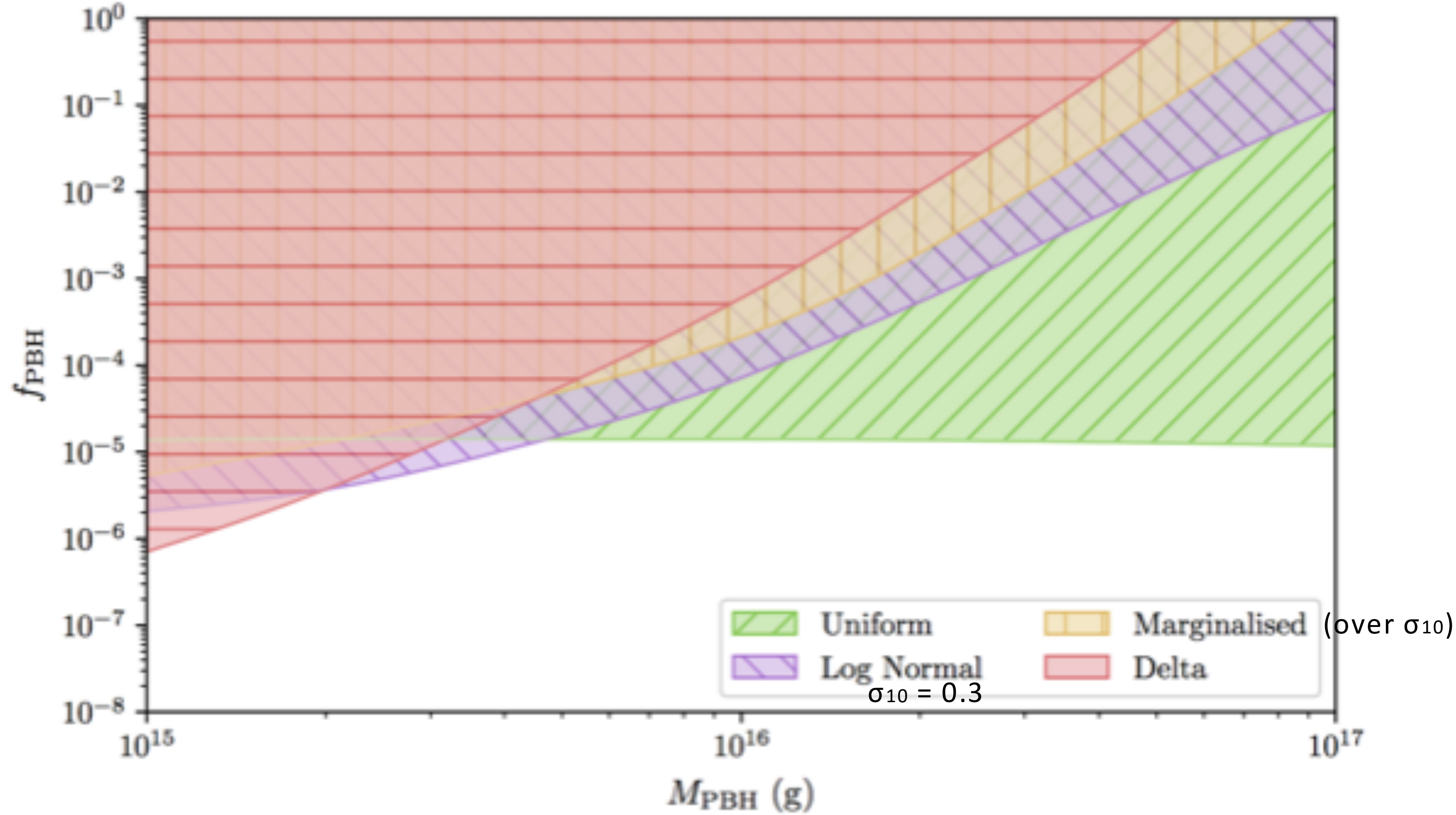
Constraints on width of lognormal mass distribution (for fixed $f_{\rm PBH}$)

(logarithmic) width



[JH, Poulter, White, Williams (in prep.)]

Constraints on PBH fraction (for fixed mass distributions)



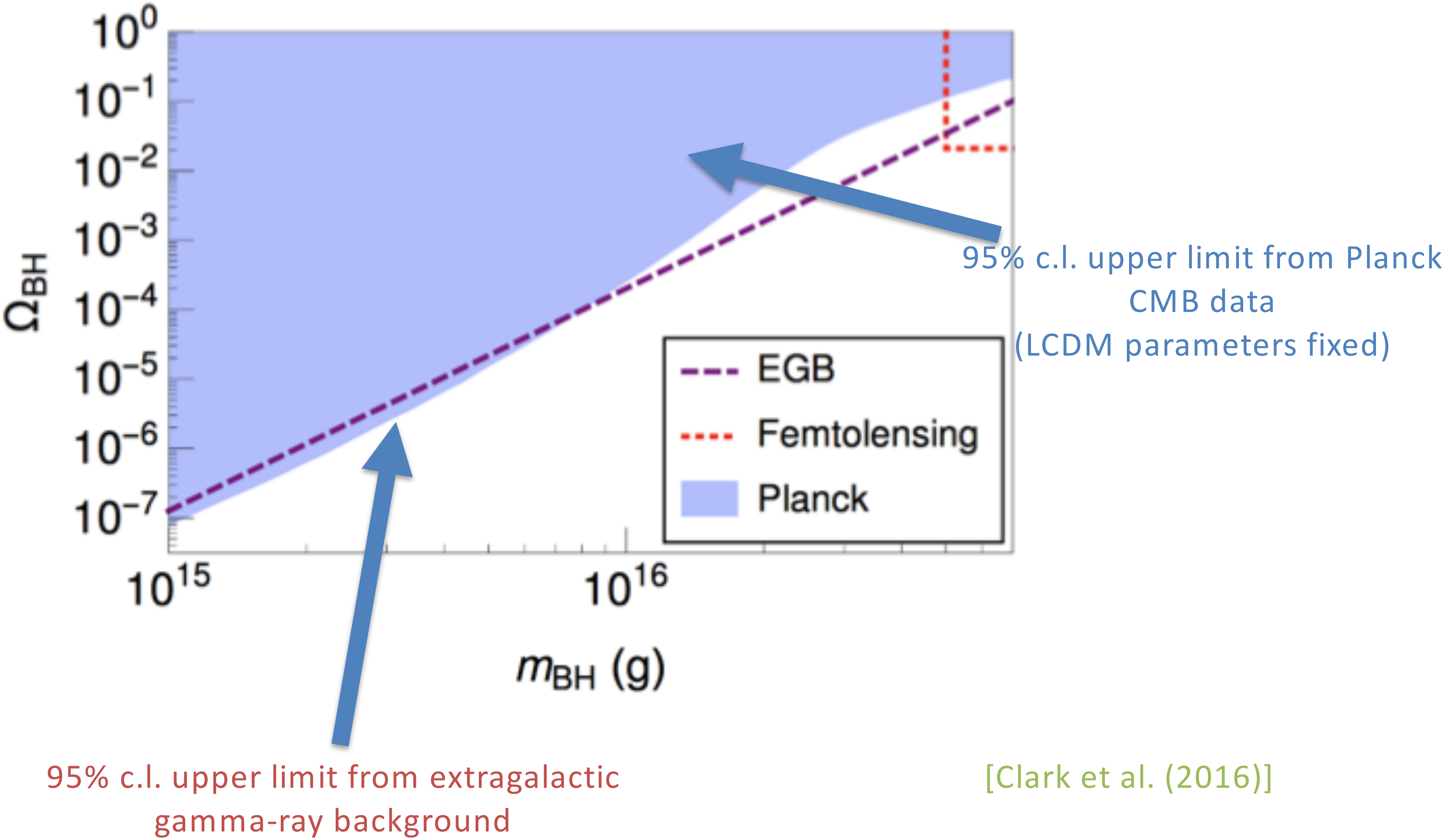
Peak of PBH mass function

[JH, Poulter, White, Williams (in prep.)]

Conclusions

- CMB anisotropies can constrain light PBHs
  - Caveat: ignoring other LCDM parameters severely biases constraints
- CMB data allow $f_{PBH} = 1$ in a small window $M_{PBH} \geq 6 \times 10^{16}$g
  - requires quasi-monochromatic mass distribution
  - may already be ruled out by γ-ray observations…
- Extended mass distributions don't help (in fact, they make things worse)

Constraints on light PBHs



[Clark et al. (2016)]