

*Primordial Black Holes*



*as*

*Dark Matter*

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**Florian Kühnel**

work in particular with

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Marit Sandstad

Glenn Starkman

Talk at

‘Advances in Theoretical Cosmology in light of Data’

Stockholm, the 25th of July, 2017

★ Black-hole (BH) formation for  $R < R_S$

★ Astrophysical: From  $10^9 M_\odot$  down to  $M_\odot$  but **not lower**.

★ Have a look at the density  $\rho_S = 10^{18} \left( \frac{M}{M_\odot} \right)^{-2} \frac{\text{g}}{\text{cm}^3}$

→ To form smaller black holes we need higher density

→ Compare to **cosmological density**  $\rho_C = 10^6 \left( \frac{t}{\text{s}} \right)^{-2} \frac{\text{g}}{\text{cm}^3}$

→ Formation at early times; **primordial black holes (PBHs)**

★ Masses of primordial black holes:  $M(t = 10^{-45} \text{ s}) = M_{\text{Planck}}$ ,

$$M(t = 10^{-23} \text{ s}) = 10^{15} \text{ g}, \quad M(t = 10^{-6} \text{ s}) = M_\odot$$

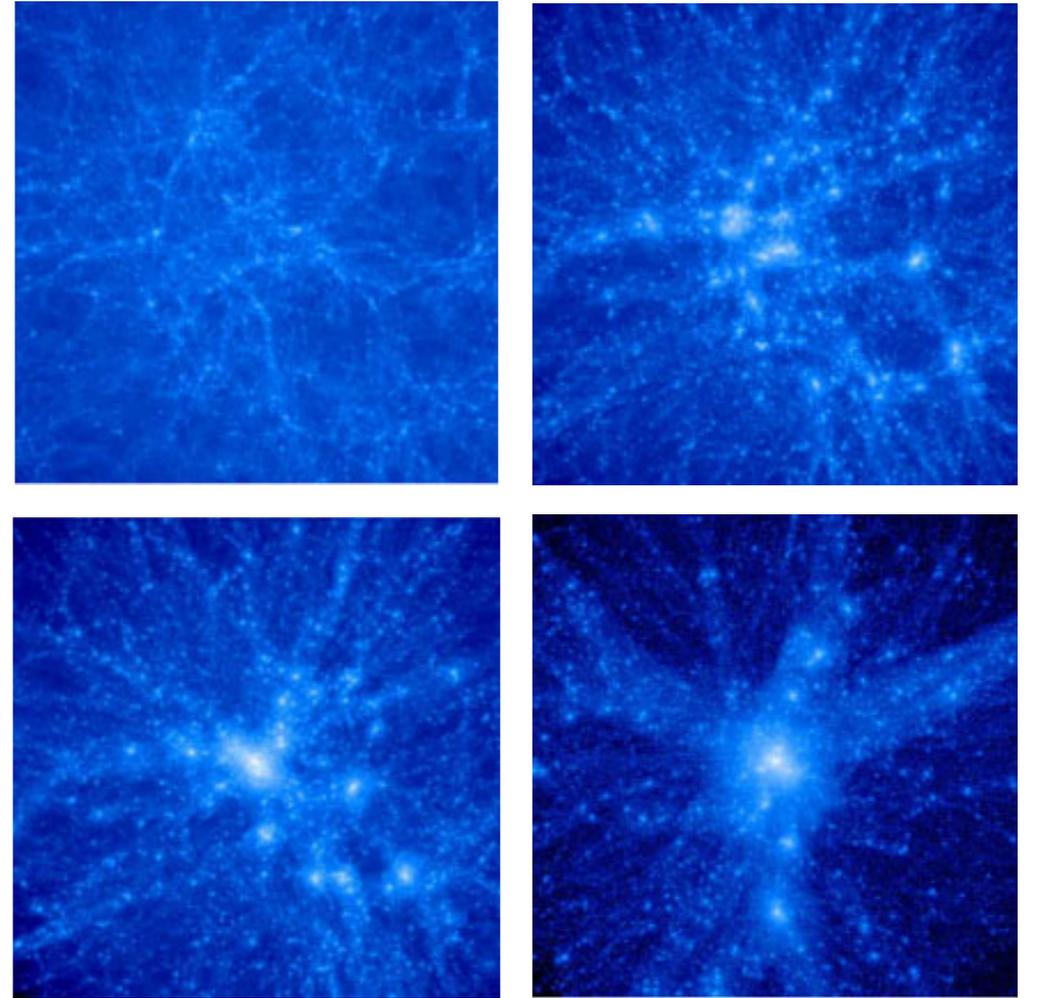
# Primordial Black Holes — Formation

★ **Formation** of primordial black holes by

- ★ Cosmic string loops
- ★ Bubble collisions
- ★ Large density perturbations of inflationary origin

➔ Simple estimate:

[Carr 1975]



$$R > R_J$$

$\Rightarrow$

$$\delta_H > w$$

, for  $p = w \rho$

↑  
scale of the over density

↙  
Jeans length

# Primordial Black Holes — Probes of Scales



★ Probe a **huge range of scales:**

$M \sim 10^{-5} \text{g}$  **Quantum Gravity:**

Planck relics, Extra dimensions and higher-dimensional black holes, ...

$M \lesssim 10^{15} \text{g}$  **Early Universe:**

Baryogenesis, Nucleosynthesis, Reionisation, ...

$M \sim 10^{15} \text{g}$  **High-Energy Physics:**

Cosmological and galactic gamma-rays, ...

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$M \gtrsim 10^{15} \text{g}$  **Gravity:**

Critical phenomena,  
Cold dark matter,  
Lensing effects,  
Gravitational waves,  
Black holes in galactic nuclei, ...

★ Usually: Assume

$$M_{BH} \propto M_H$$

horizon mass

★ Critical scaling:

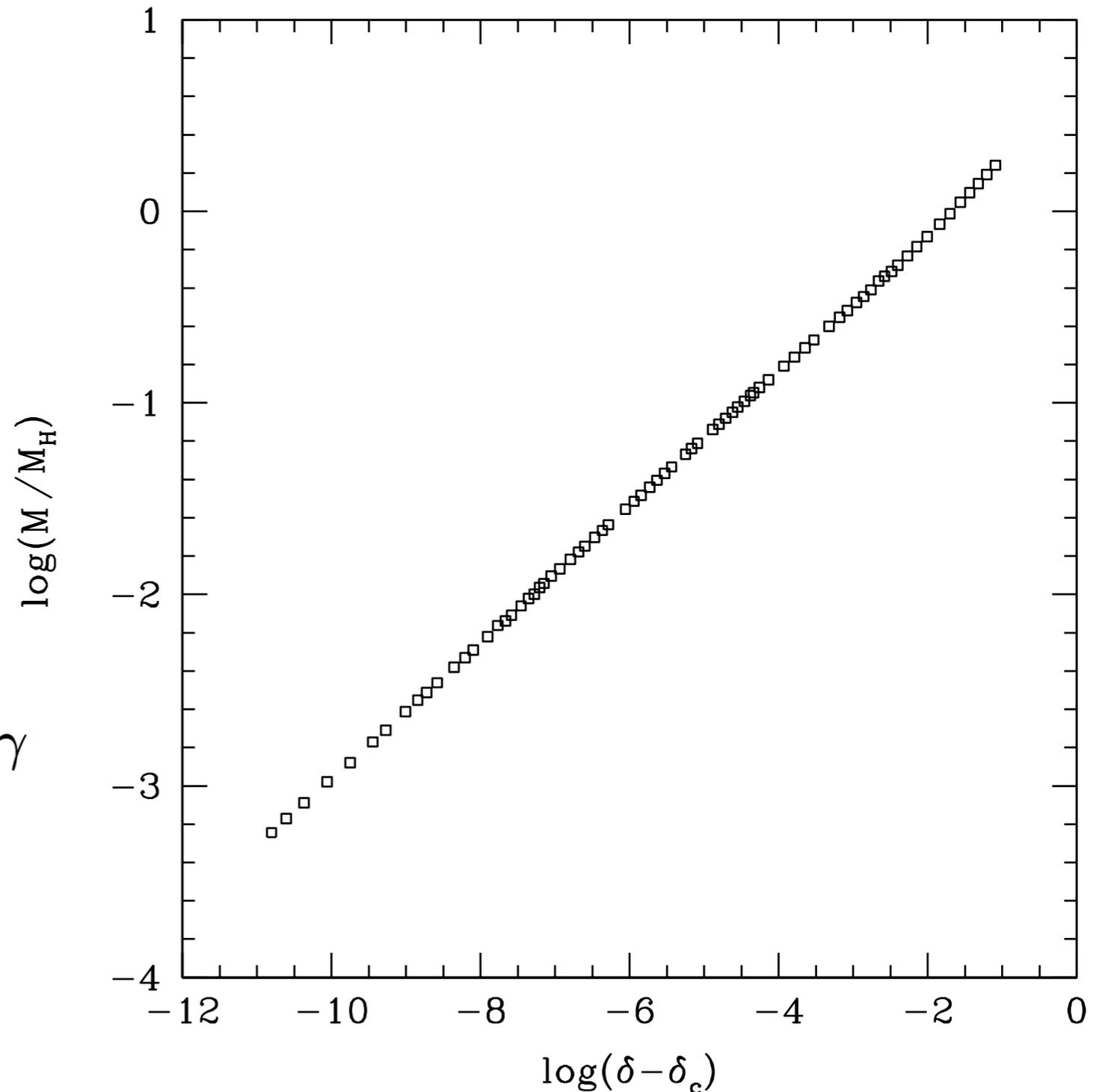
[Choptuik '93]

$$M_{BH} = k M_H (\delta - \delta_c)^\gamma$$

density contrast

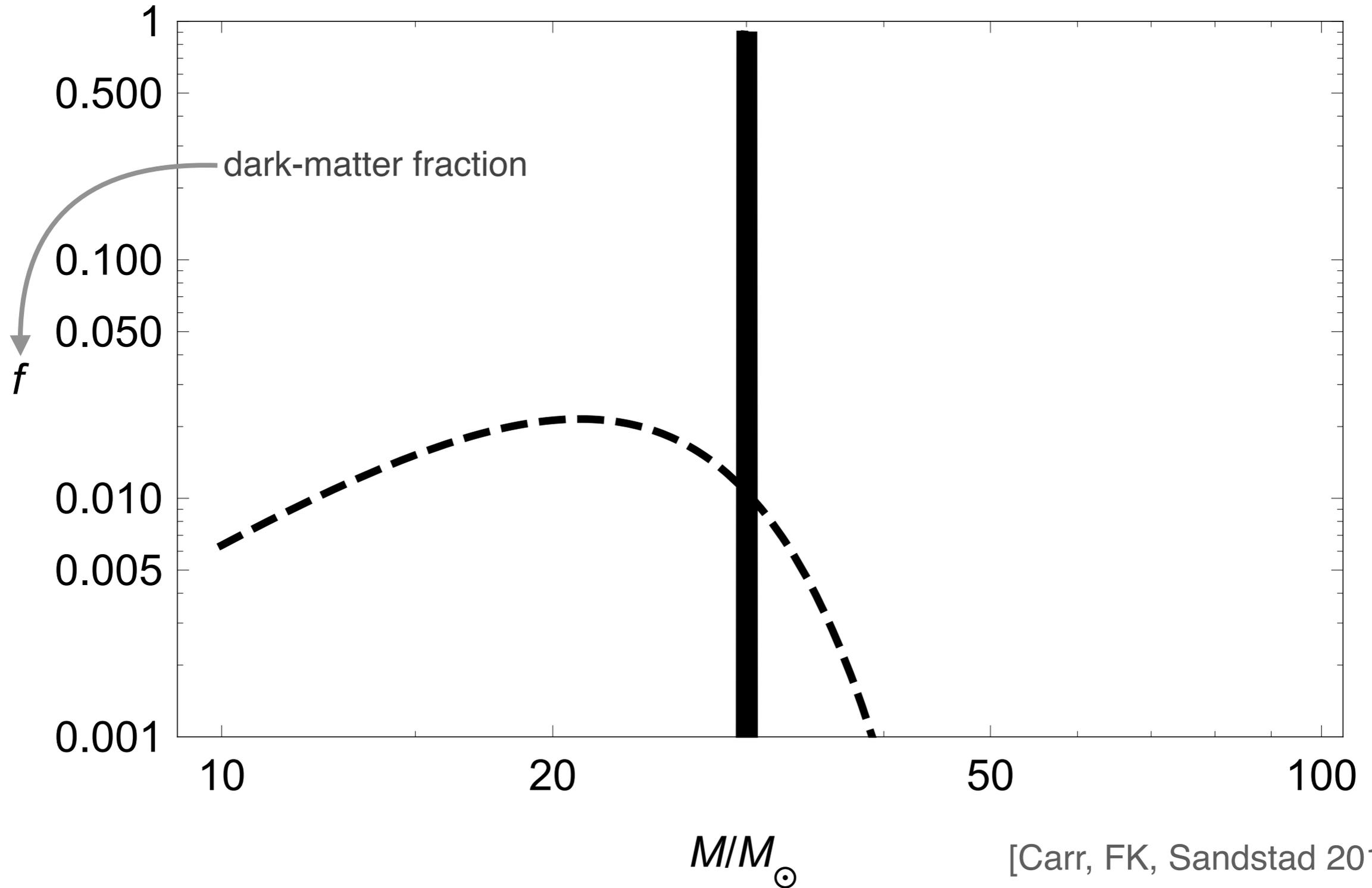
★ Radiation domination:

$$k \approx 3.3, \quad \delta_c \approx 0.45, \quad \gamma \approx 0.36$$

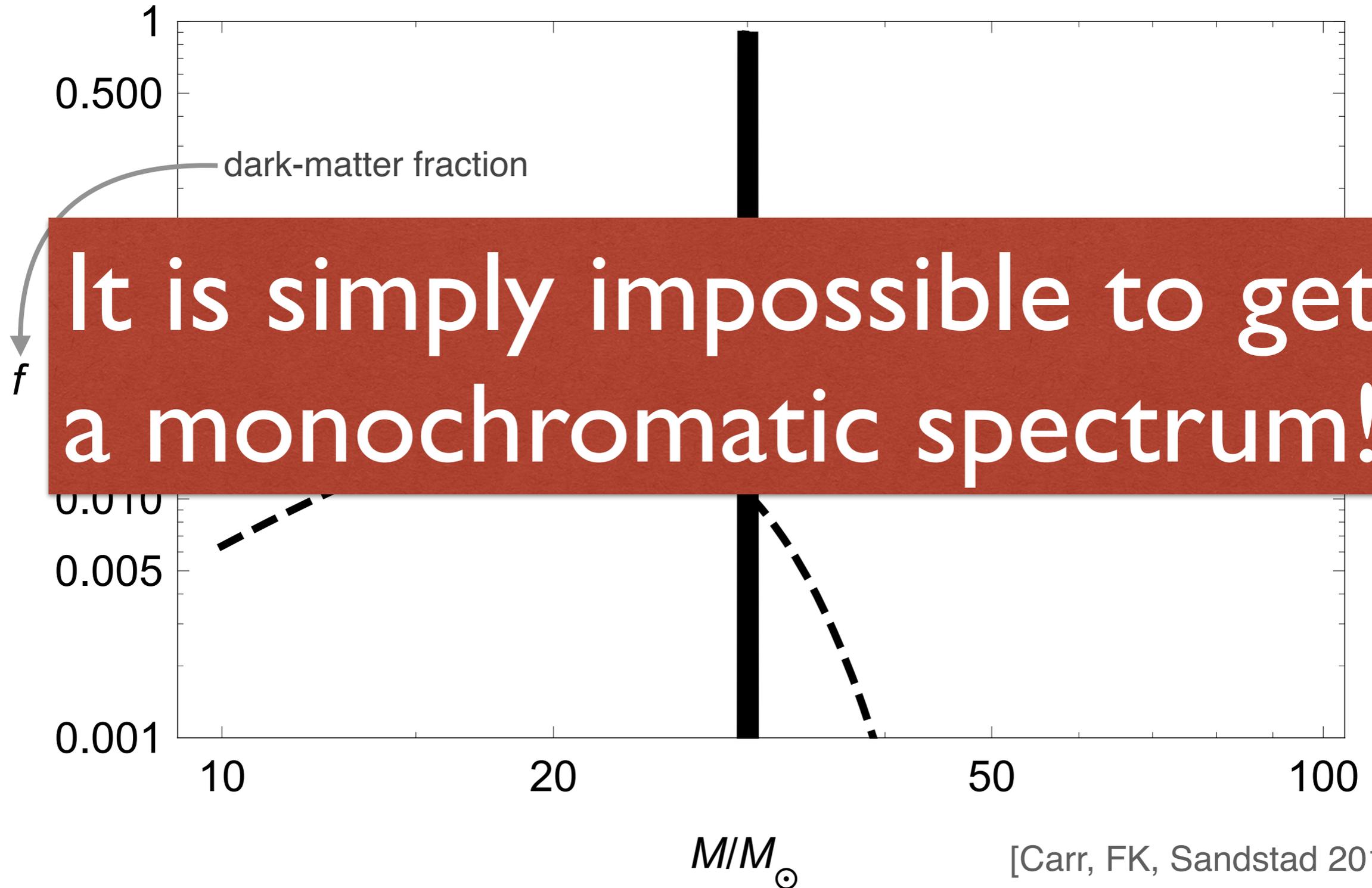


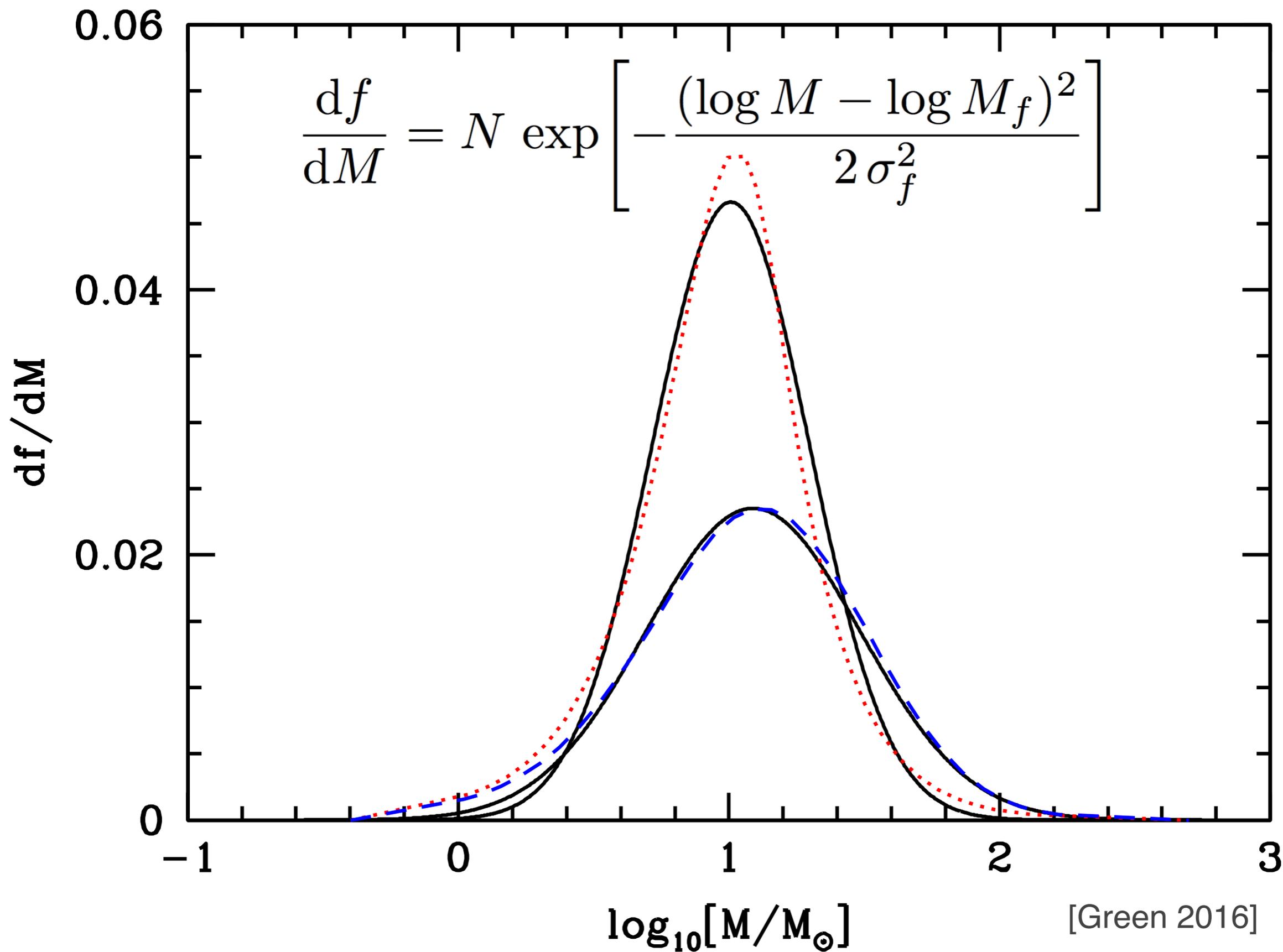
[Miller et al. 2004]

★ How would this look for monochromatic mass function?

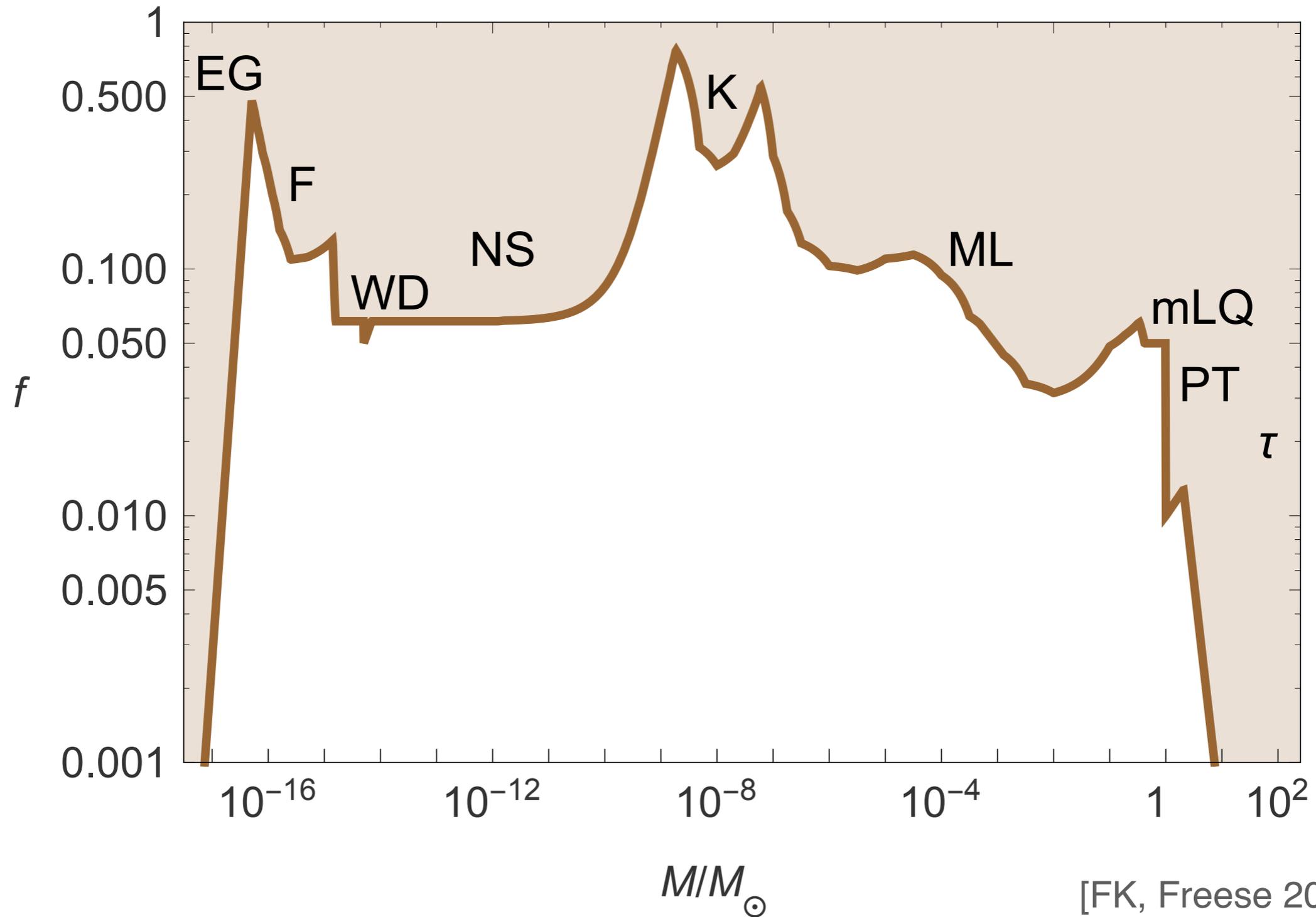


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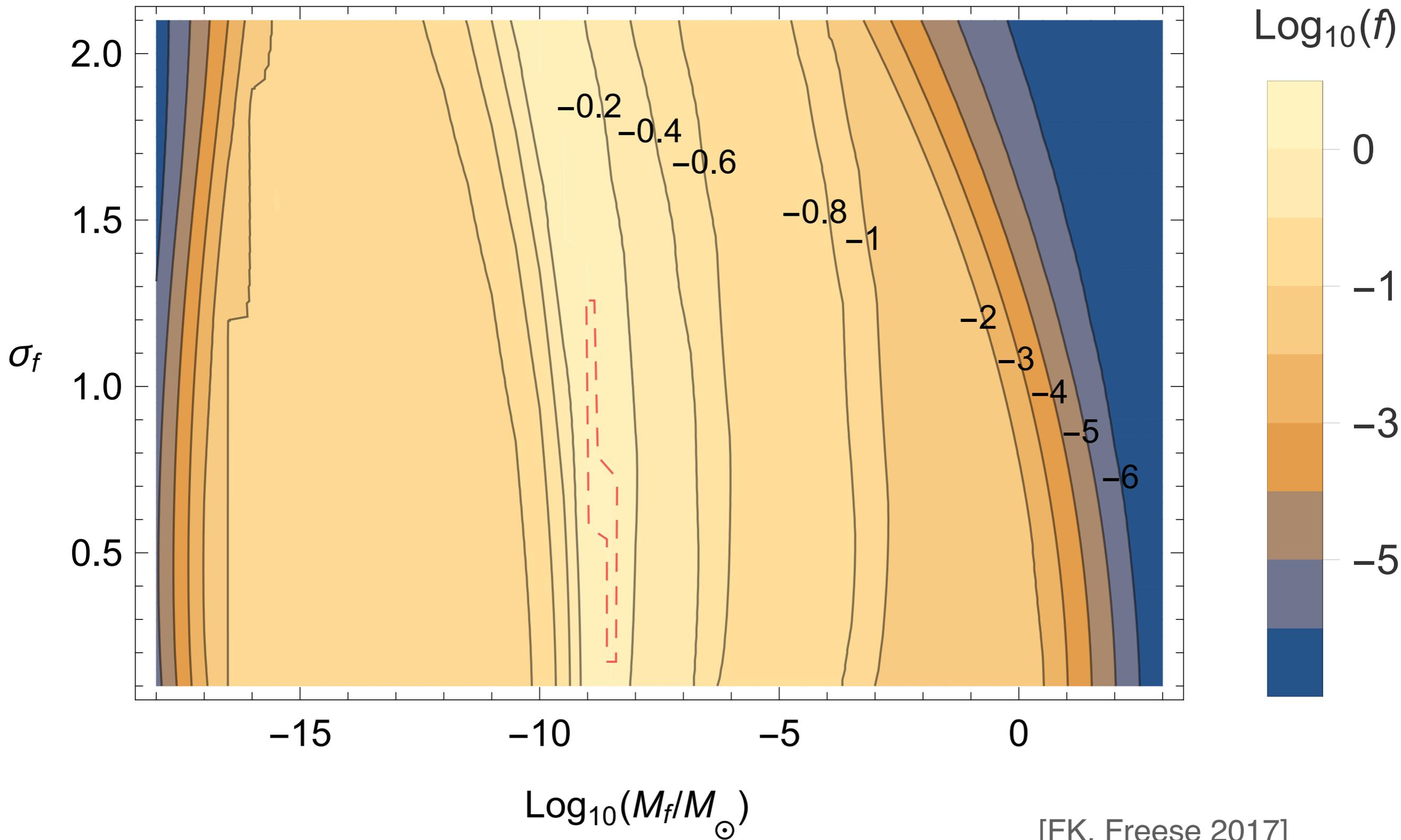


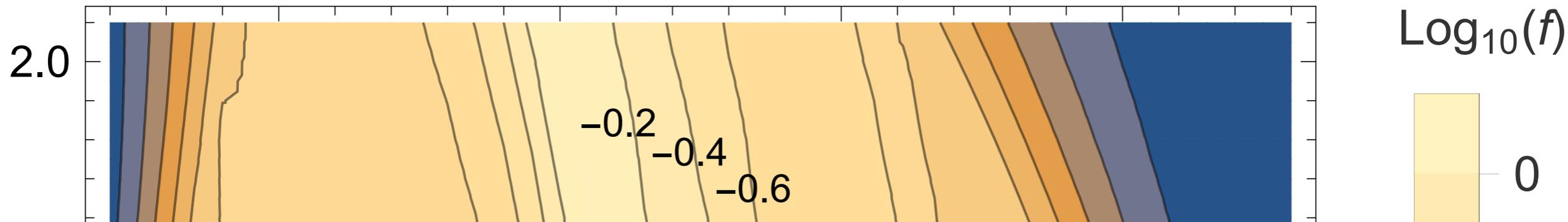


★ We applied this to **this constrain “curtain”**:

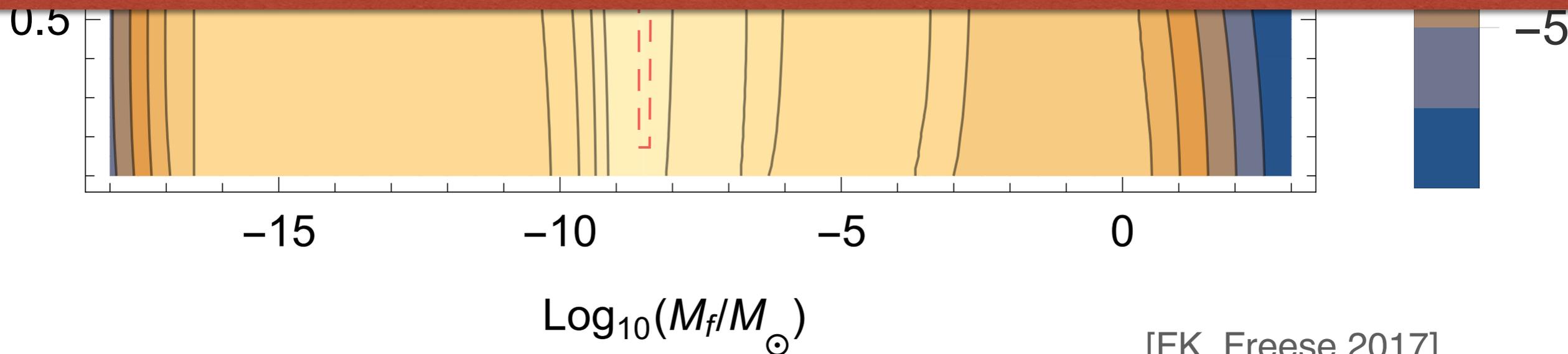


# More Systematic Study — Results

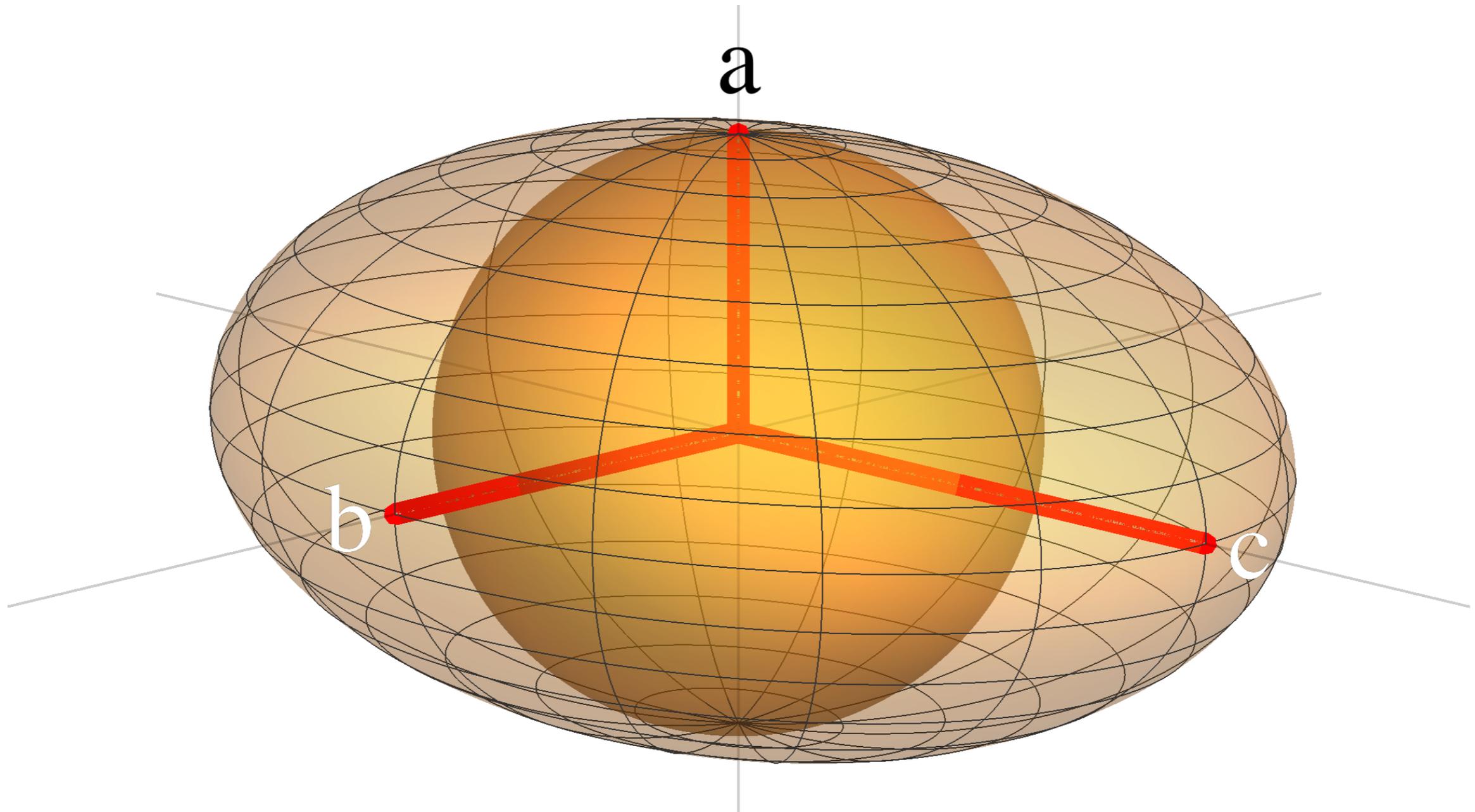




It is crucial to re-derive the constraints for (the realistic(!) case) of extended mass functions!



- ★ Consider the simplest non-sphericity: **An Ellipsoid**



## ★ Non-Sphericity

[FK, Sandstad 2016]

$$\frac{\delta_{ec}}{\delta_c} \simeq 1 + \kappa \left( \frac{\sigma^2}{\delta_c^2} \right)^\gamma$$

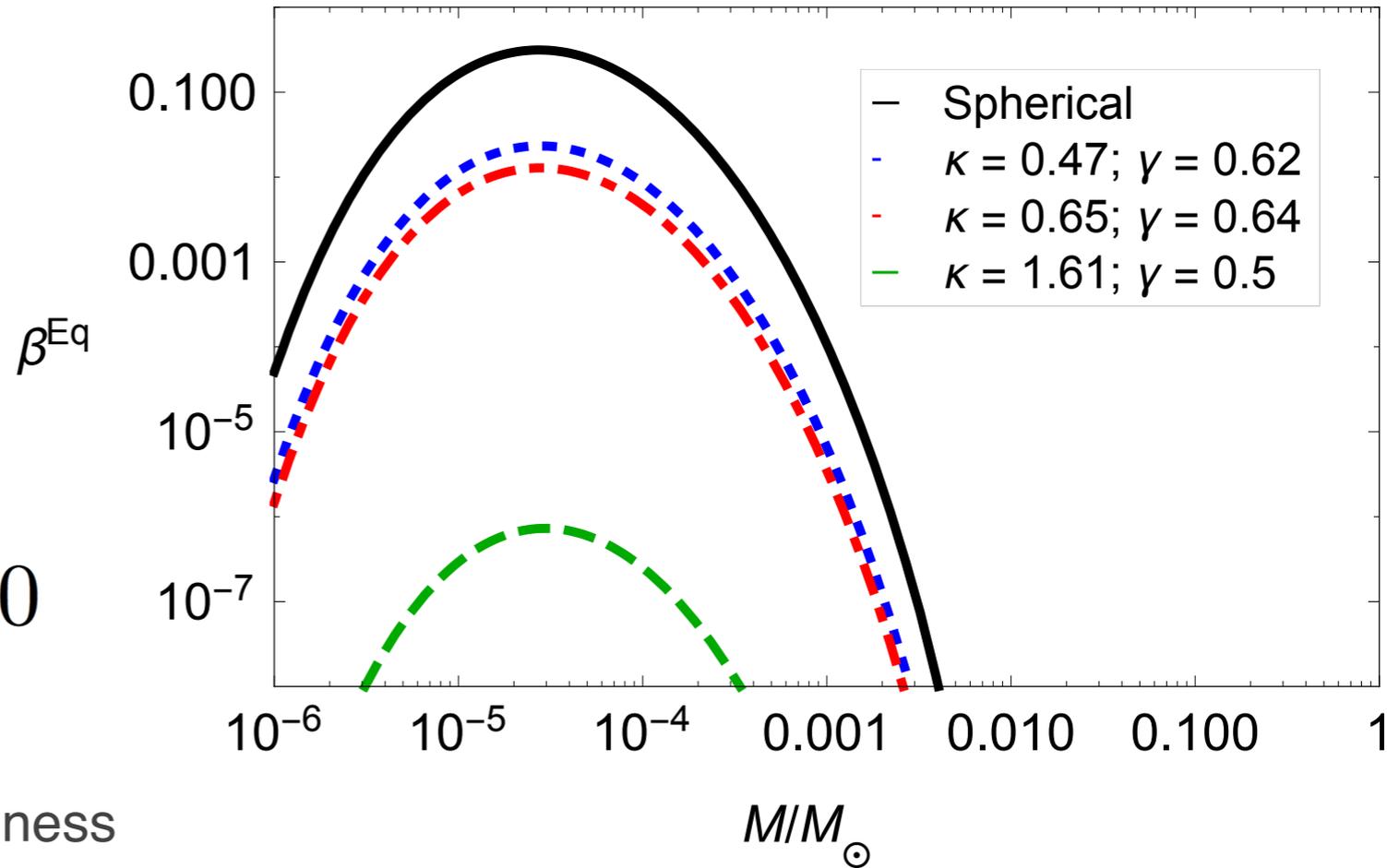
ellipsoidal threshold

spherical threshold

$$\langle e \rangle = \frac{3\sigma}{\sqrt{10\pi}\delta}, \quad \langle p \rangle = 0$$

ellipticity

prolateness



- ★ Simple estimate: As the collapse starts along shortest axis first,  
 → consider collapse of largest enclosed sphere (green curve):

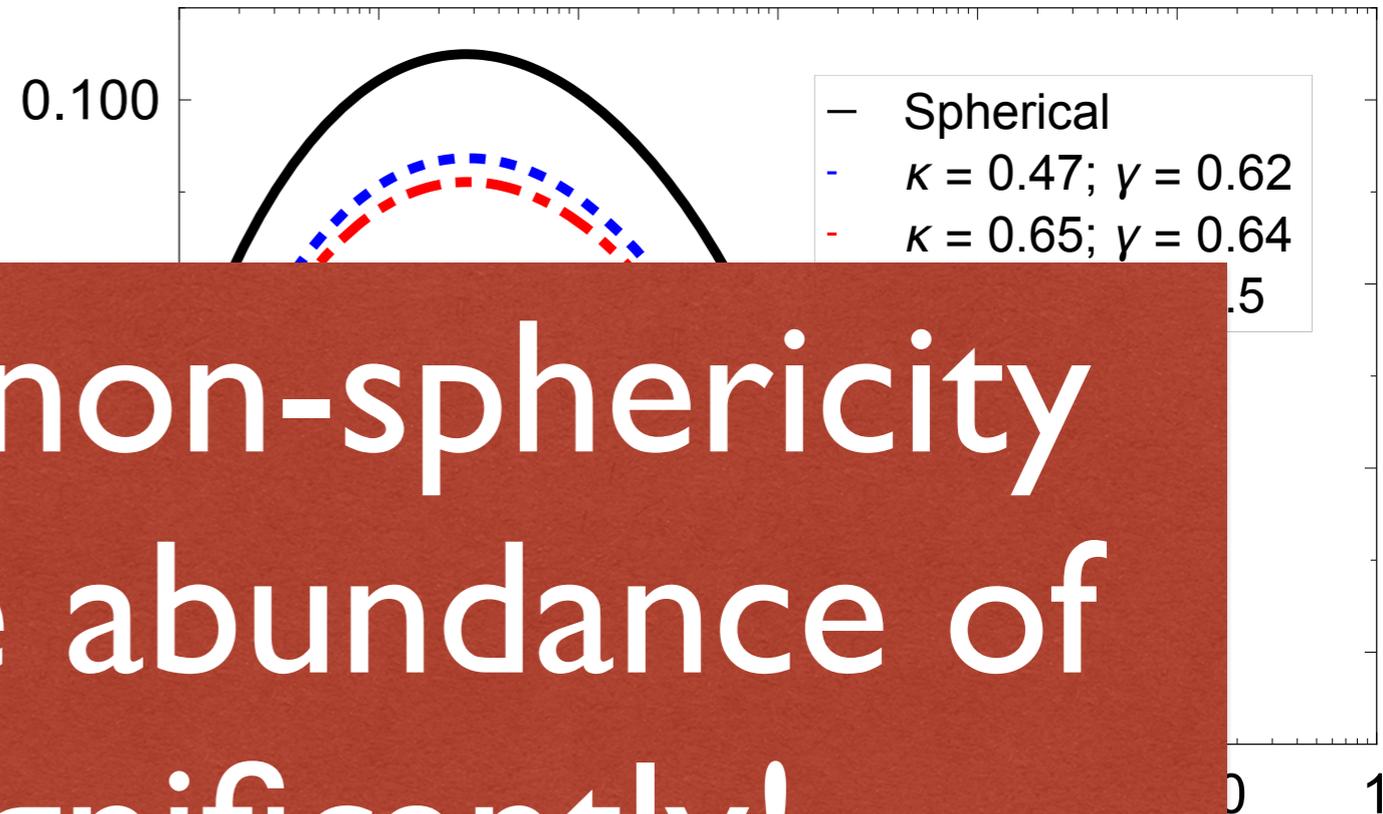
$$\frac{\delta_{ec}}{\delta_c} \simeq (1 + 3e) = 1 + \frac{9}{\sqrt{10\pi}} \left( \frac{\sigma^2}{\delta_c^2} \right)^{1/2}$$

## ★ Non-Sphericity

[FK, Sandstad 2016]

ellipsoidal threshold

$$\frac{\delta_{ec}}{\delta_c} \sim 1 + \kappa \left( \frac{\sigma^2}{\delta_c^2} \right)^\gamma$$



Even slight non-sphericity  
reduces the abundance of  
PBHs significantly!

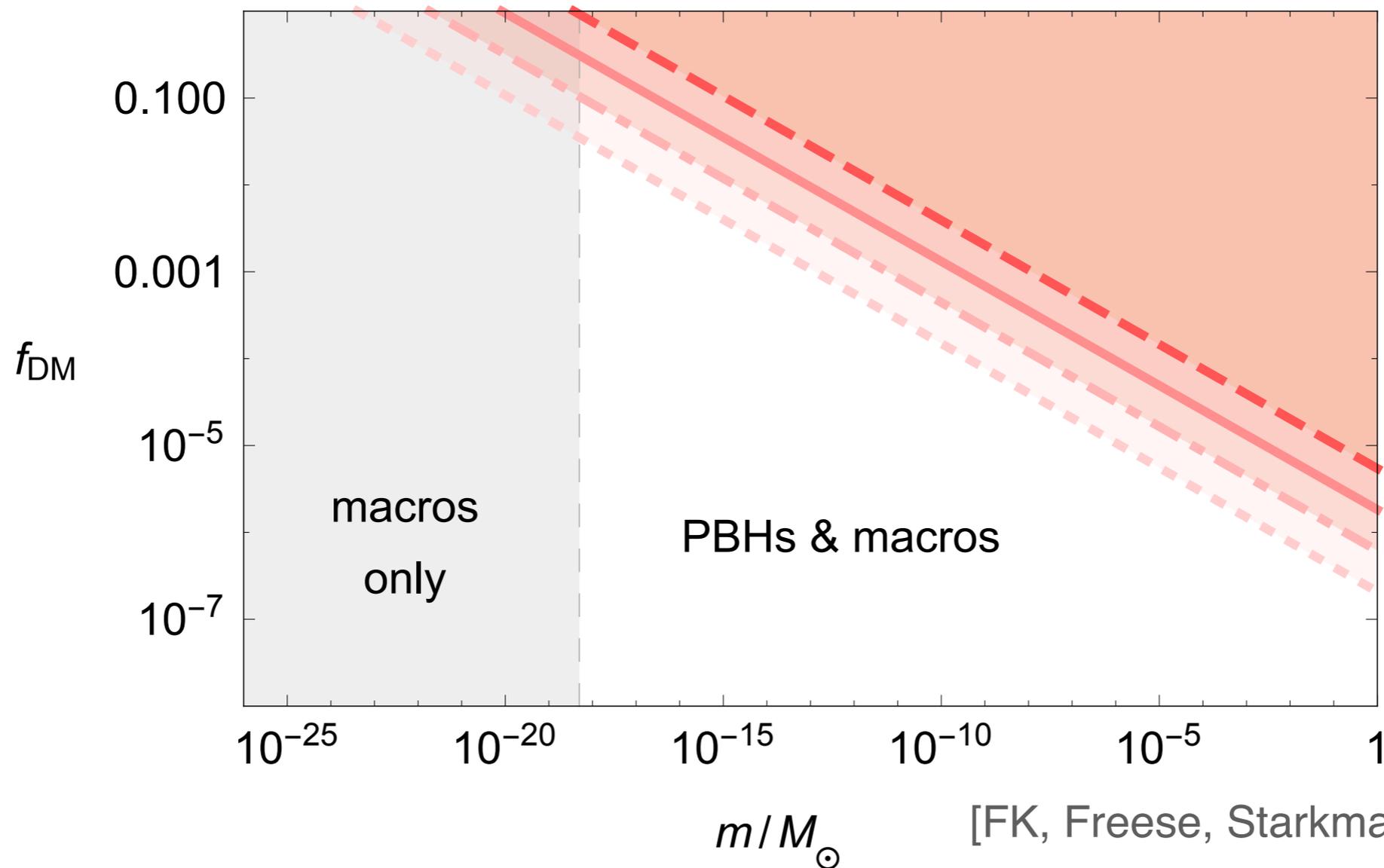
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# Gravitational Waves from PBHs

- ★ If PBHs constitute a significant fraction of the dark matter, at the center of our Galaxy one would have a very large number of **PBH inspiralling into SgrA\***.

➔ Stochastic enhancement; Detection forecasts for **LISA**:

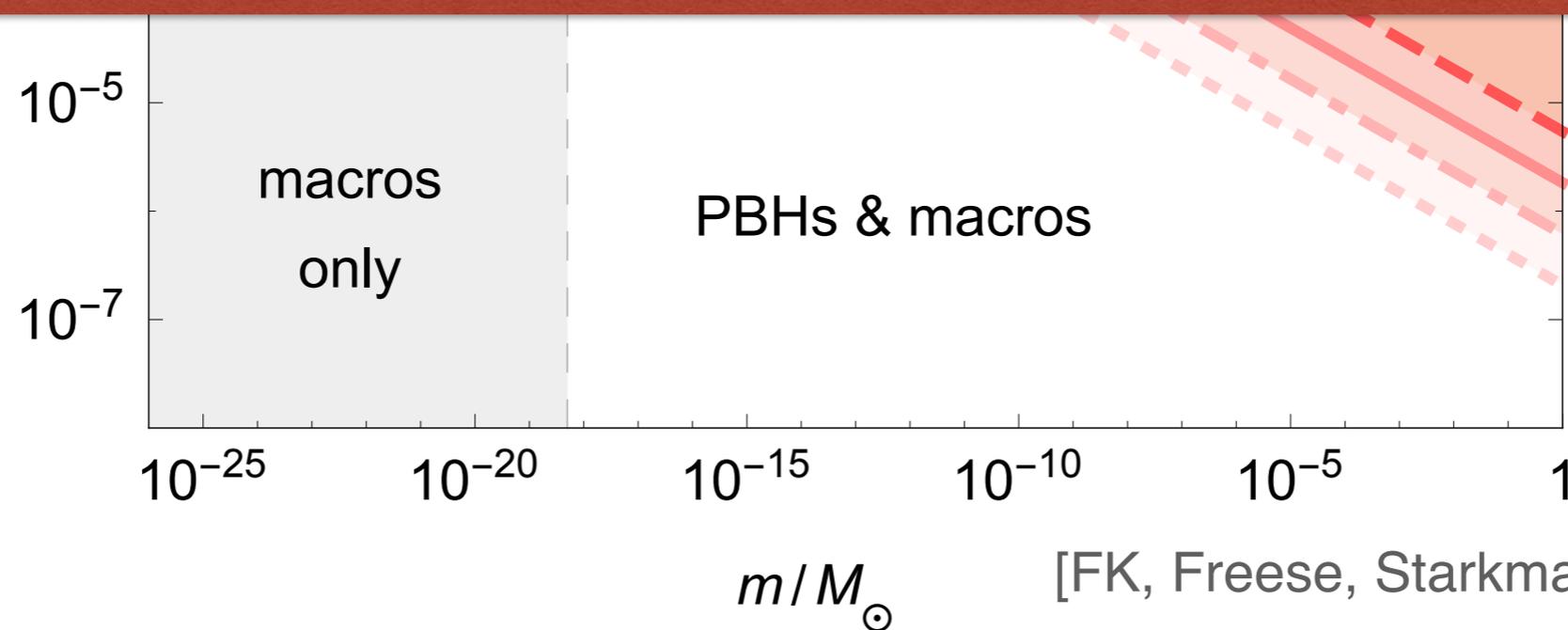


[FK, Freese, Starkman, Matas 2017]

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LISA will be a splendid PBH dark-matter detection machine!\*



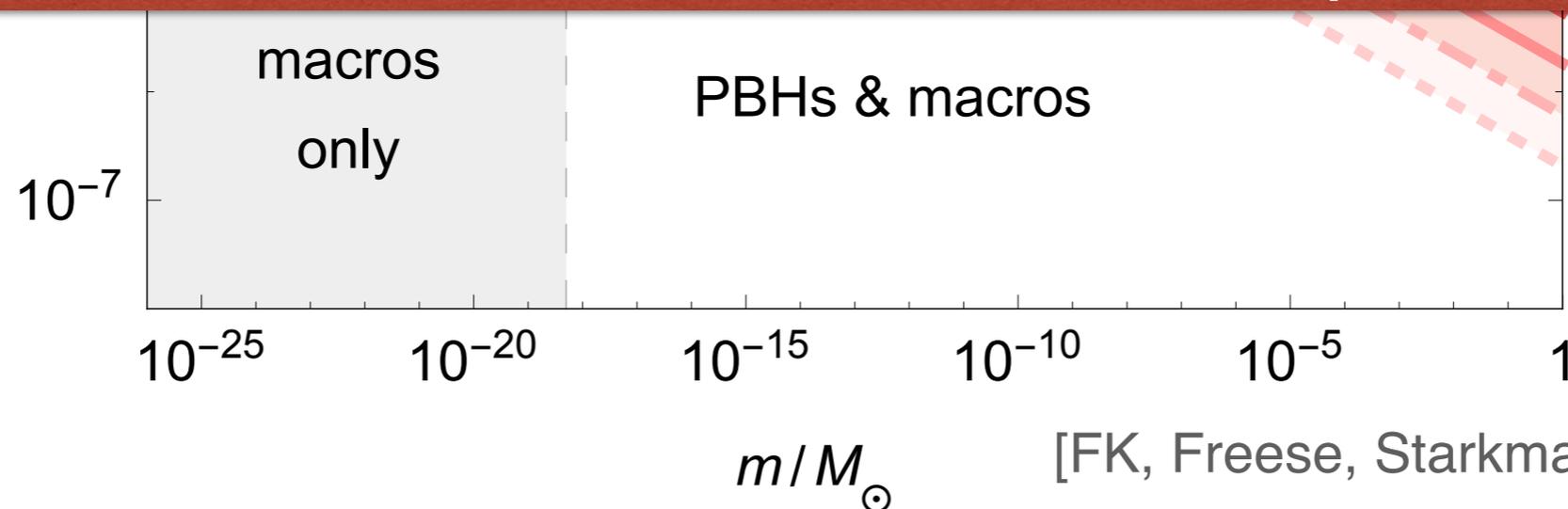
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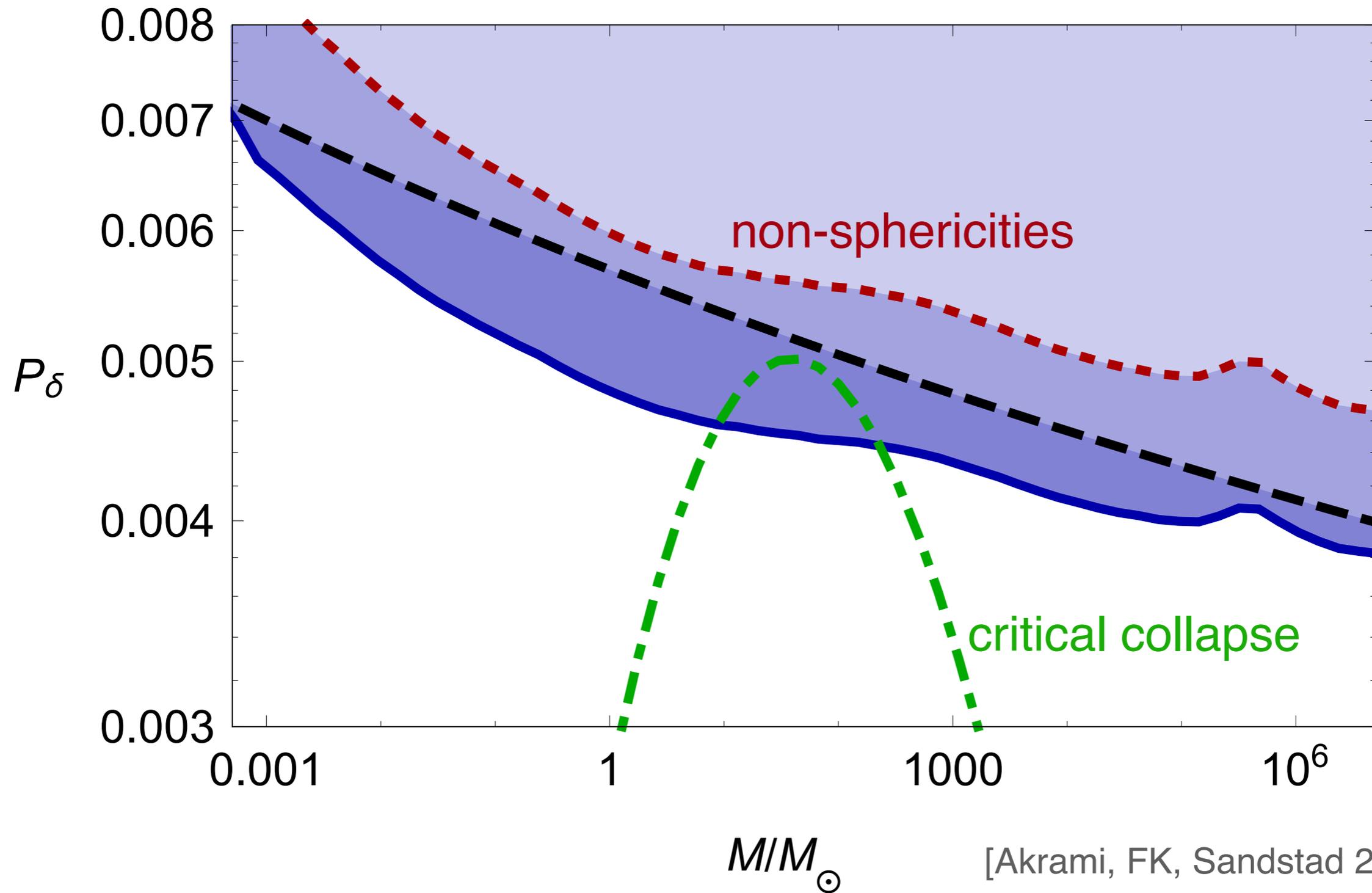
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\*If there is a substantial fraction of macroscopic dark matter.



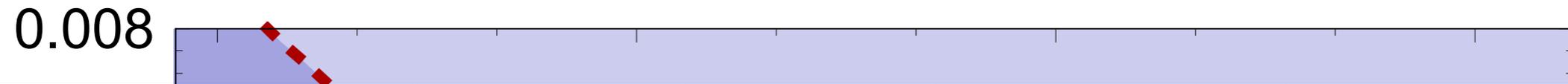
# Constraints on the Primordial Power Spectrum?

★ **Uncertainty due to non-sphericities and critical collapse:**

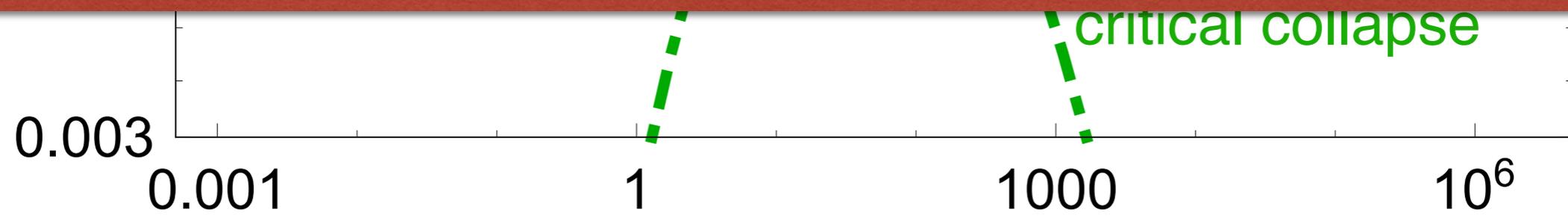


# Constraints on the Primordial Power Spectrum?

- ★ Uncertainty due to non-sphericities and critical collapse:



The primordial power spectrum is essentially not constrained from current constraints on the PBH abundance!



$M/M_{\odot}$

[Akrami, FK, Sandstad 2017]

- ★ Primordial black holes are very **interesting!**
  - ★ They are **unique probes** of their formation scenarios.
  - ★ They could **provide the entire dark matter**.
  - ★ A detailed understanding their **formation** is crucial.
  - ★ **Extended** mass spectra require special care when **comparing to constraints**.
  - ★ **LISA** might detect them!
  - ★ Also, **combined dark-matter scenarios** (PBHs + WIMPs or sterile neutrinos) might be well constraint in the near future.