Primordial Black Holes as Dark Matter

Florian Kühnel

New from the Dark - Episode 3

Montpellier, 25th of May 2018

work in particular with

Bernard Carr

Katherine Freese

Jens Jasche

Pavel Naselsky

Tommy Ohlsson

Glenn Starkman

Overview

- Formation of primordial black holes

- Primordial black holes and particle dark matter

- Aspects of primordial black holes and gravitational waves

- Uncertainties of primordial black-hole constraints

PBH Generalities

- 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 $$\rho_S = 10^{18} \left(\frac{M}{M_\odot}\right)^{-2} \frac{\mathrm{g}}{\mathrm{cm}^3}$$
    - → To form smaller black holes we need higher density.
    - → Compare to cosmological density $$\rho_C = 10^6 \left(\frac{t}{\mathrm{s}}\right)^{-2} \frac{\mathrm{g}}{\mathrm{cm}^3}$$
    - → Formation at early times; primordial black holes (PBHs).
- Masses of primordial black holes:

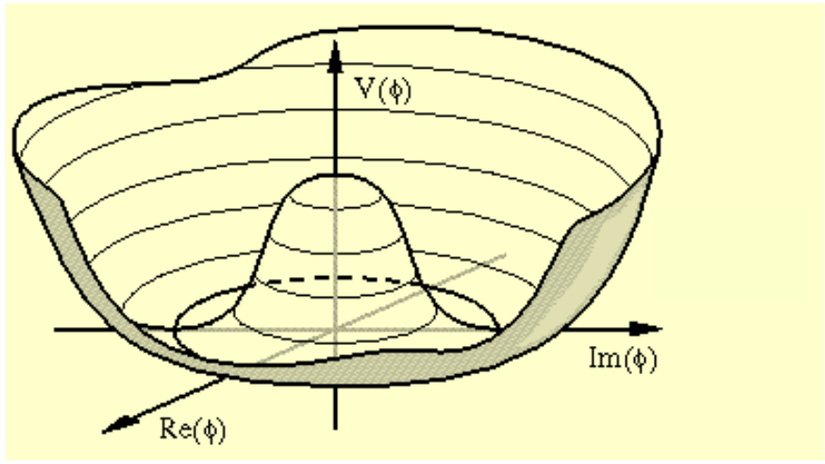
$$M\left(t = 10^{-23}\,\mathrm{s}\right) = 10^{15}\,\mathrm{g}, \qquad M\left(t = 10^{-6}\,\mathrm{s}\right) = M_\odot$$

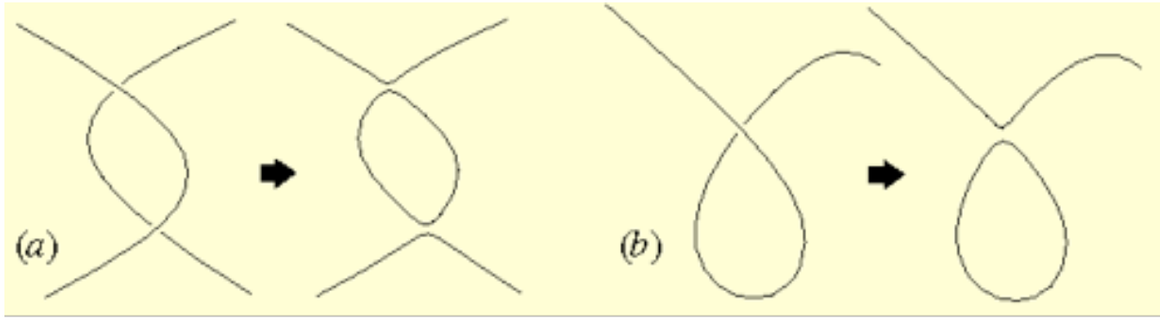
PBH Formation Mechanisms

- Formation of primordial black holes

PBH Formation Mechanisms

- Formation of primordial black holes by
  - Cosmic string loops





http://www.damtp.cam.ac.uk/research/gr/public/cs_top.html

PBH Formation Mechanisms

- Formation of primordial black holes by
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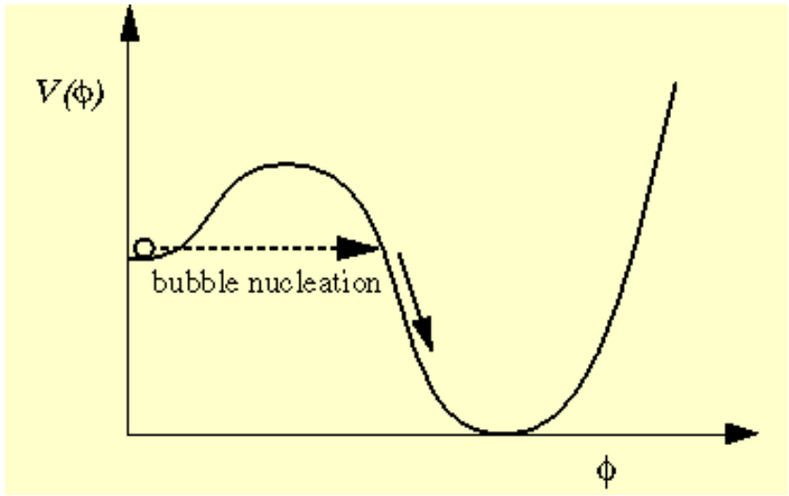

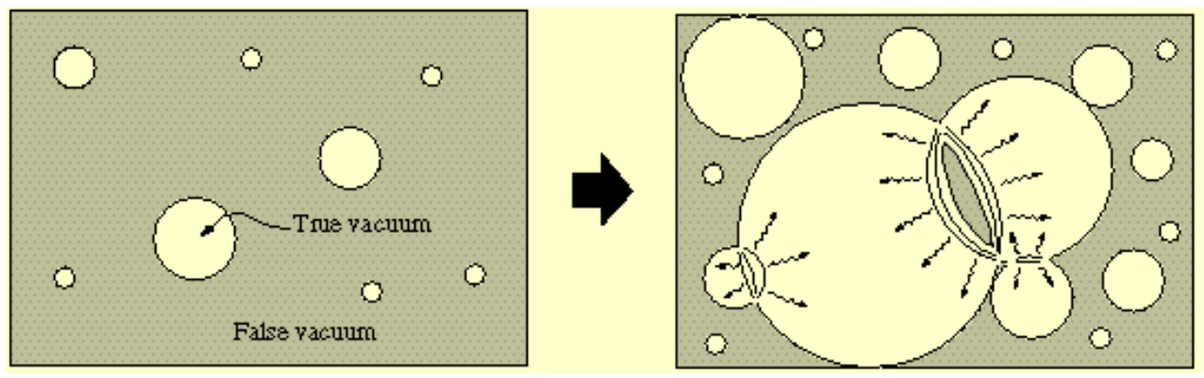

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PBH Formation Mechanisms

- Formation of primordial black holes by
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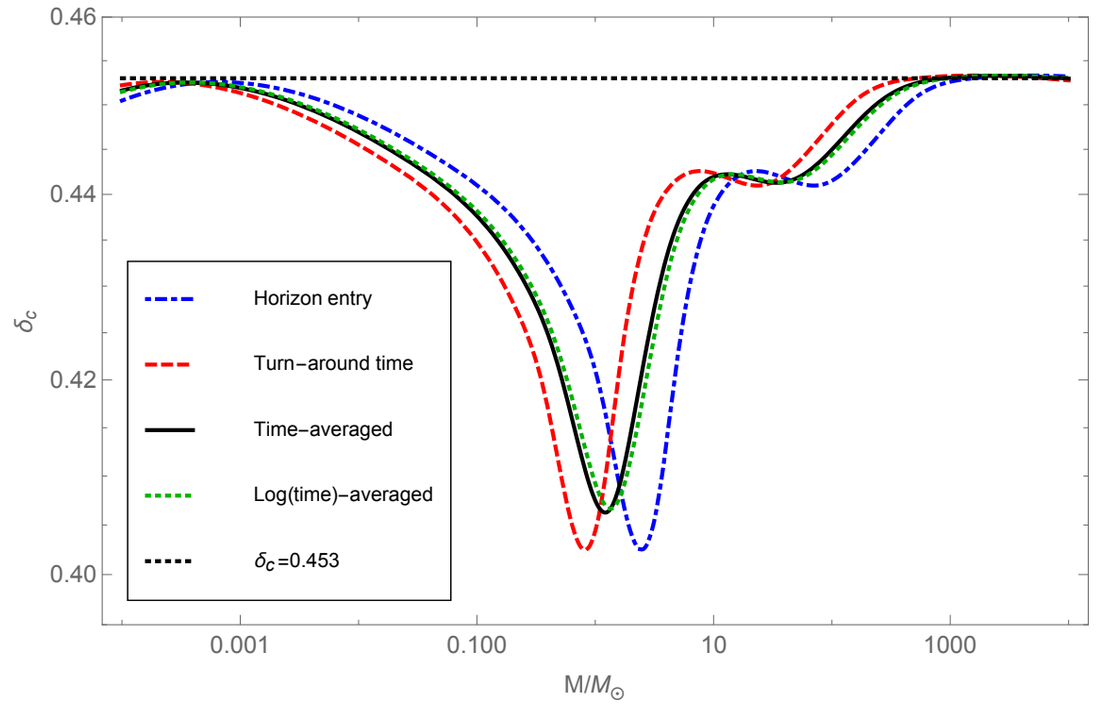
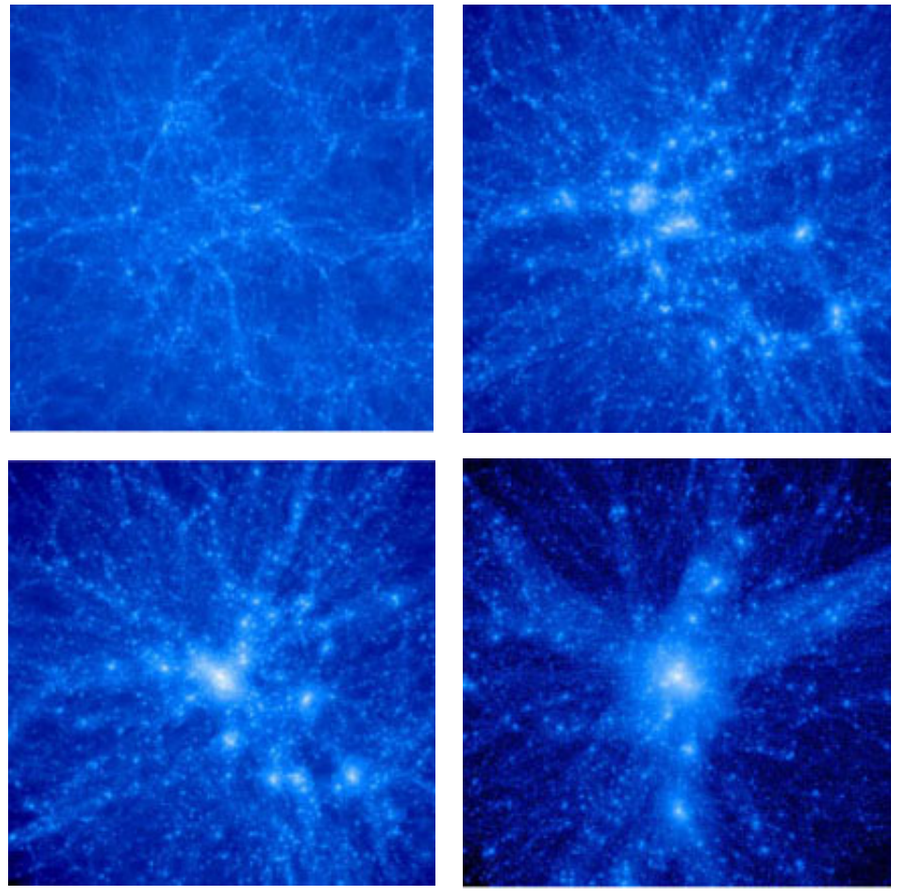
  - Pressure reduction



[Byrnes *et al.* 2018]

PBH Formation Mechanisms

- Formation of primordial black holes by
  - Cosmic string loops
  - Bubble collisions
  - Pressure reduction
  - Large density perturbations of inflationary origin



https://ned.ipac.caltech.edu/level5/Sept12/Kravtsov/Kravtsov3.html

→ Simple estimate:

[Carr 1975]

$$R > R_J \quad \Rightarrow \quad \delta_H > w \quad , \quad \text{for} \quad p = w\,\rho \qquad w > 0$$

scale of the over density

Jeans length

PBH — Probes of Scales

Oskar Klein centre

★ Probe a huge range of scales:

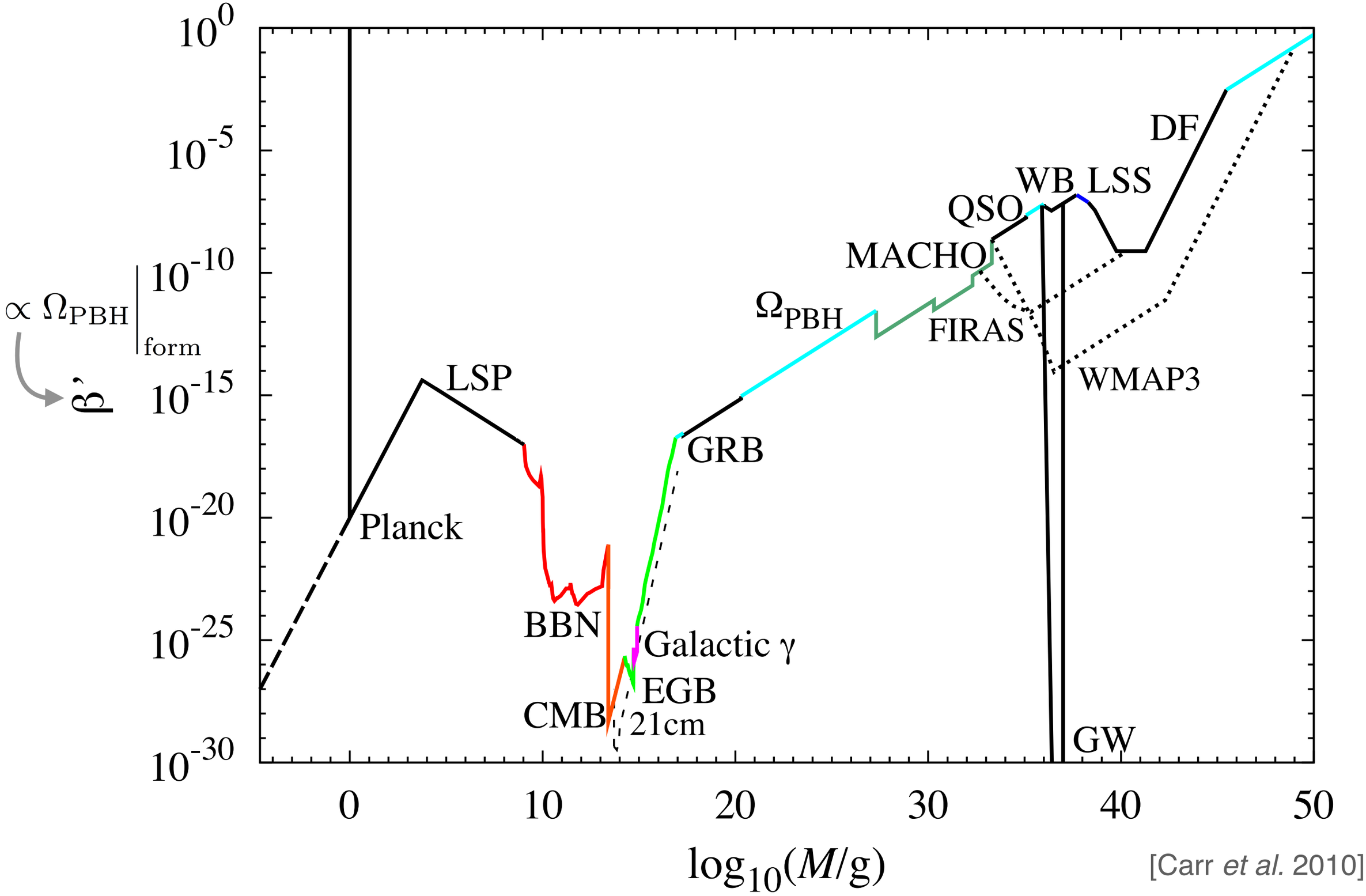
$M \sim 10^{-5}\mathrm{g}$ Quantum Gravity: Planck relics, Extra dimensions and higher-dimensional black holes, …

$M \lesssim 10^{15}\mathrm{g}$ Early Universe: Baryogenesis, Nucleosynthesis, Reionisation, …

$M \sim 10^{15}\mathrm{g}$ High-Energy Physics: Cosmological and galactic gamma-rays, …

$M \gtrsim 10^{15}\mathrm{g}$ Gravity: Critical phenomena, Cold dark matter, Dynamical effects, Lensing effects, Gravitational waves, Black holes in galactic nuclei, …

PBH Constraints at Formation



[Carr *et al.* 2010]

Critical Collapse

Oskar Klein centre

★ Usually: Assume

$$M_{BH} \propto M_H$$

horizon mass

★ Critical scaling:

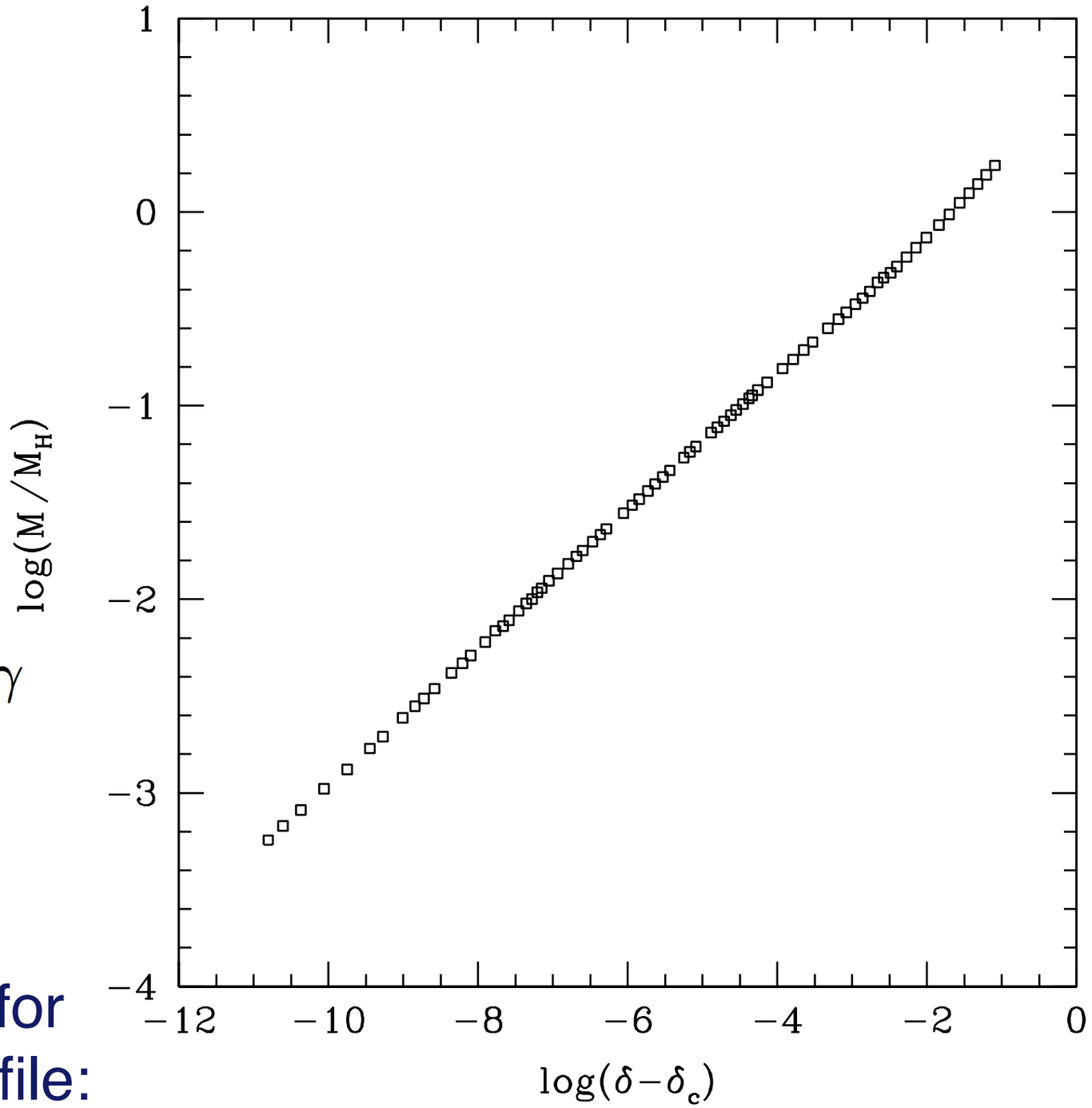
[Choptuik '93]

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

density contrast

★ Radiation domination and for spherical Mexician-hat profile:

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



[Musco, Miller, Polnarev 2008]

Critical Collapse

Oskar Klein centre

- Critical collapse for non-spherical systems?

Critical Collapse

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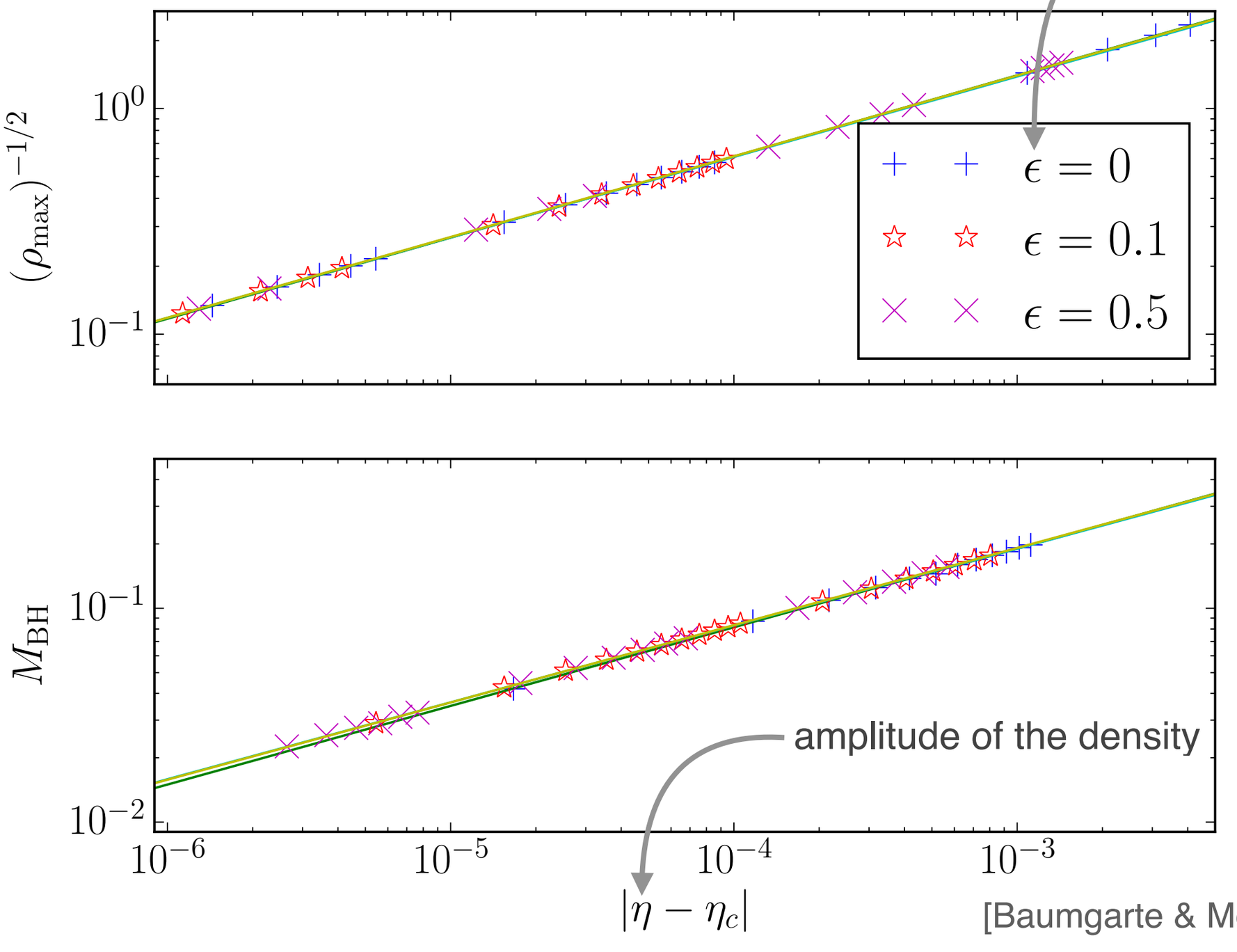
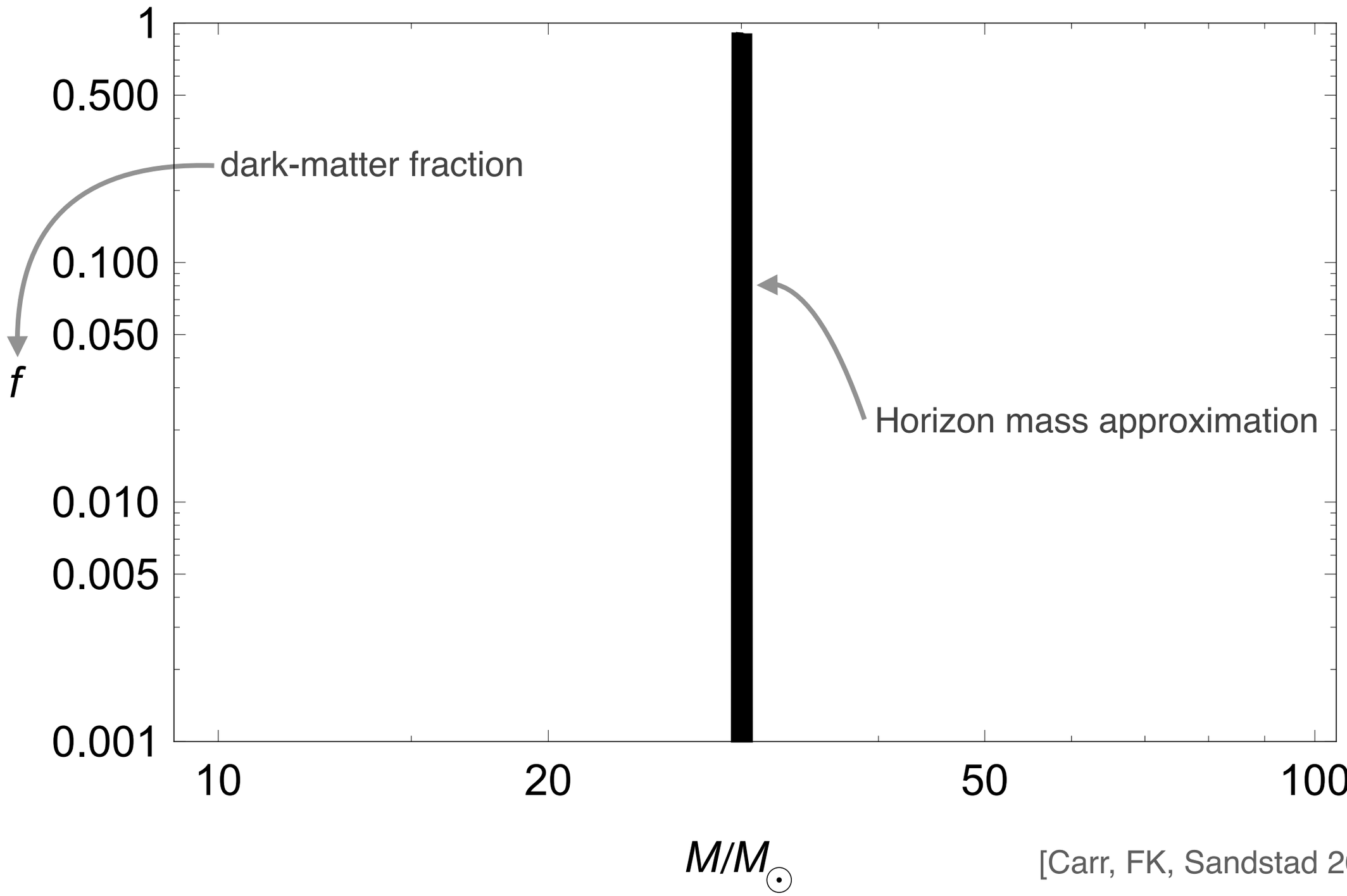
  - Axial symmetry $\rho(r,\theta) \sim \eta\, f_1(r)\big(1+\epsilon\, f_2(r,\theta)\big)$:



[Baumgarte & Montero 2015]

Oskar Klein centre

★ How would this look for monochromatic mass function?



[Carr, FK, Sandstad 2016]

Oskar Klein centre

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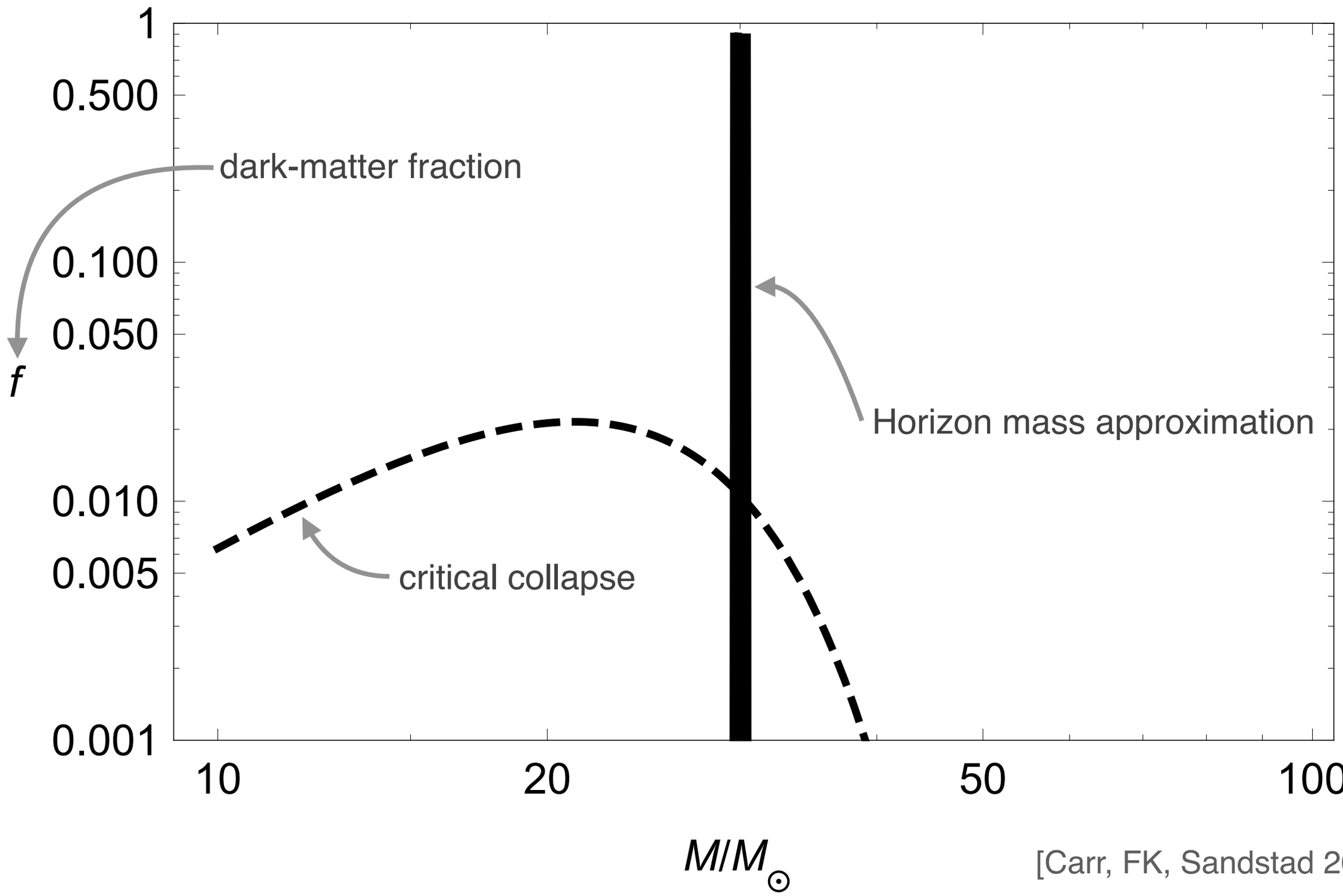
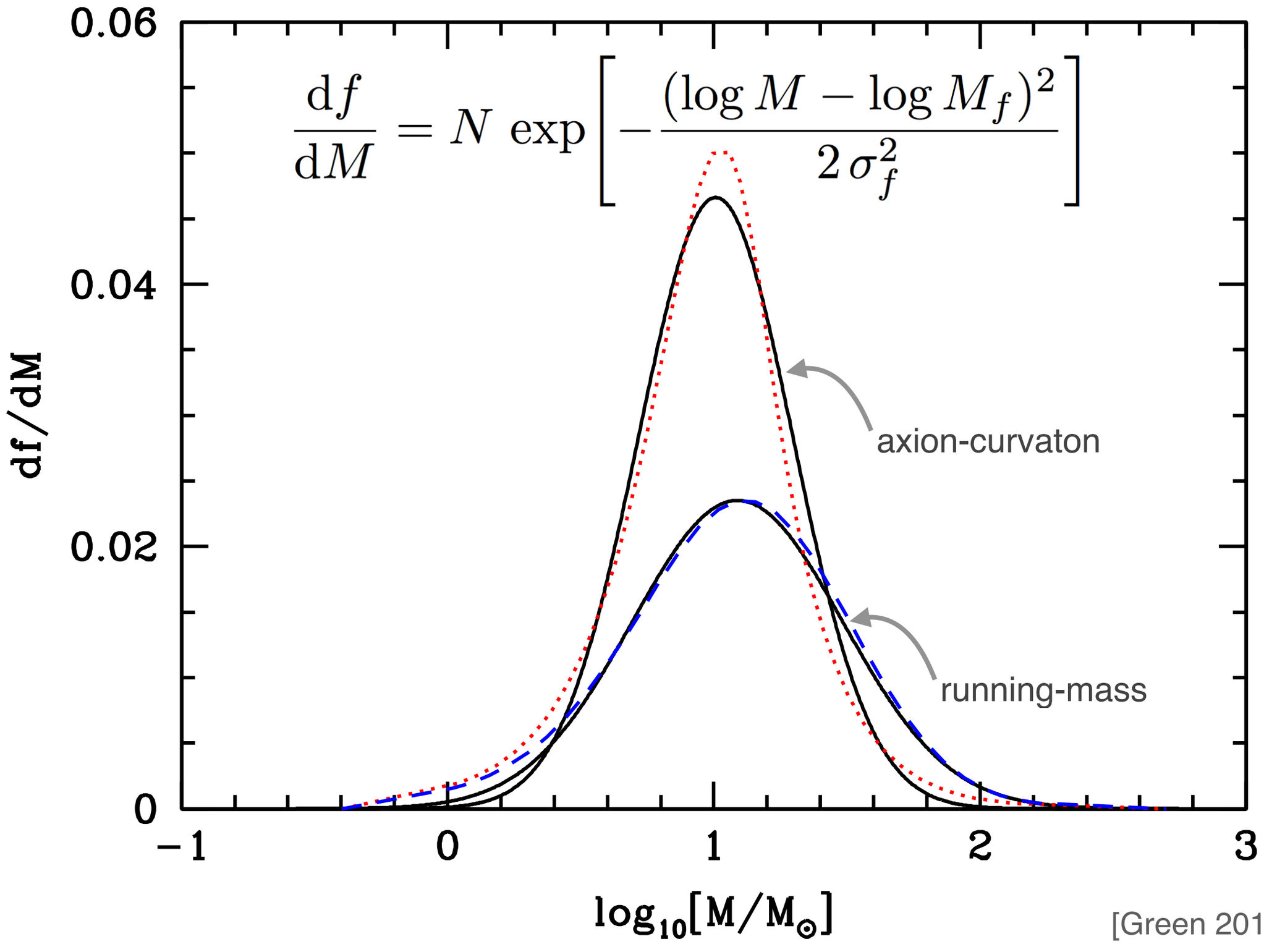


[Carr, FK, Sandstad 2016]

More Systematic Study



[Green 2016]

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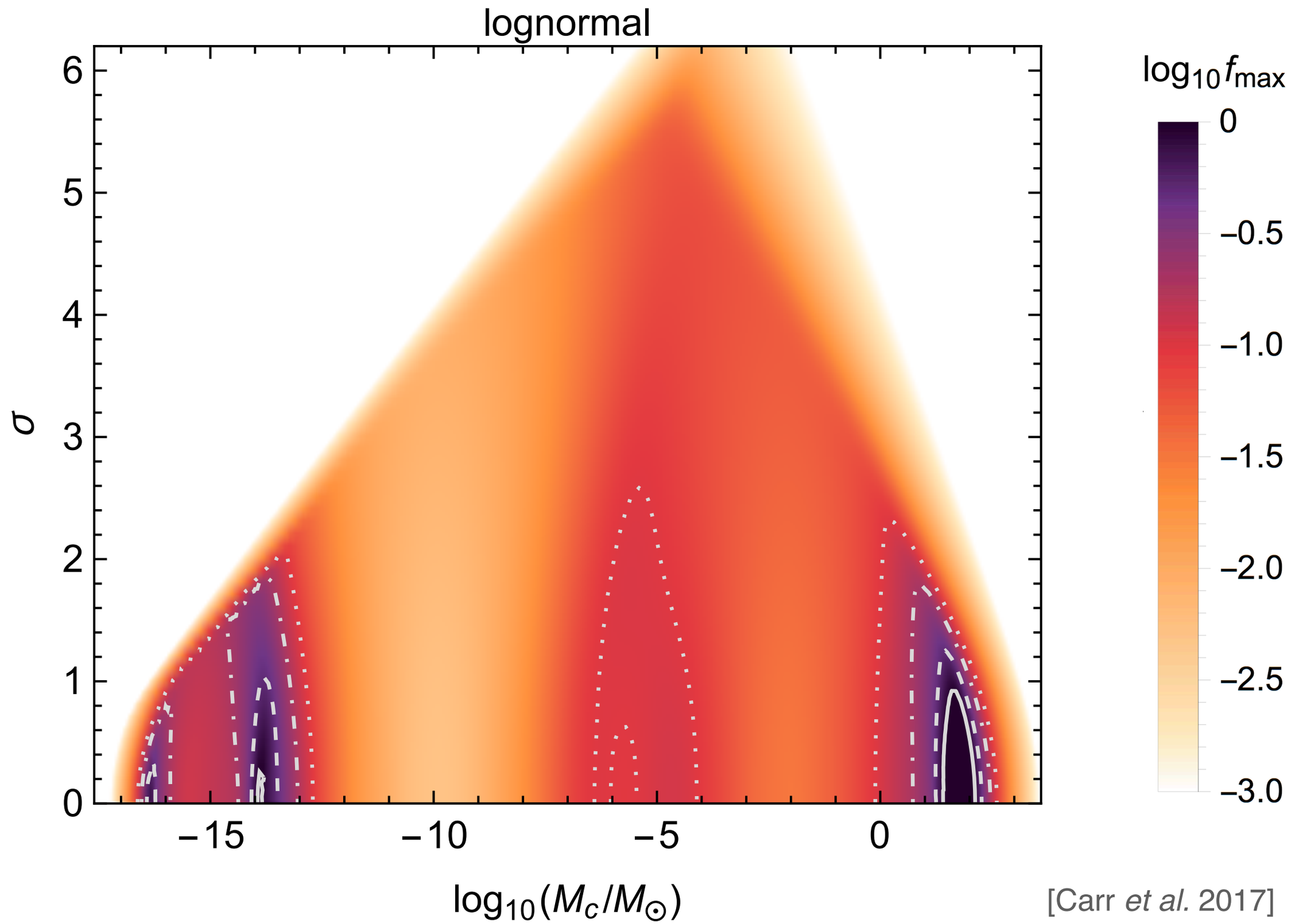

[Carr *et al.* 2017]

PBH & Particle Dark Matter

- If PBHs do not constitute the entirety of the dark matter, the latter must necessarily contain something else.

- One possibility: a combined scenario, e.g. DM = PBHs + Particles

- Let us now study WIMP annihilations in PBH halos:

  - The annihilation rate $\Gamma \propto n^2$.

    → Halo profile does matter; enhancement of Γ in density spikes.

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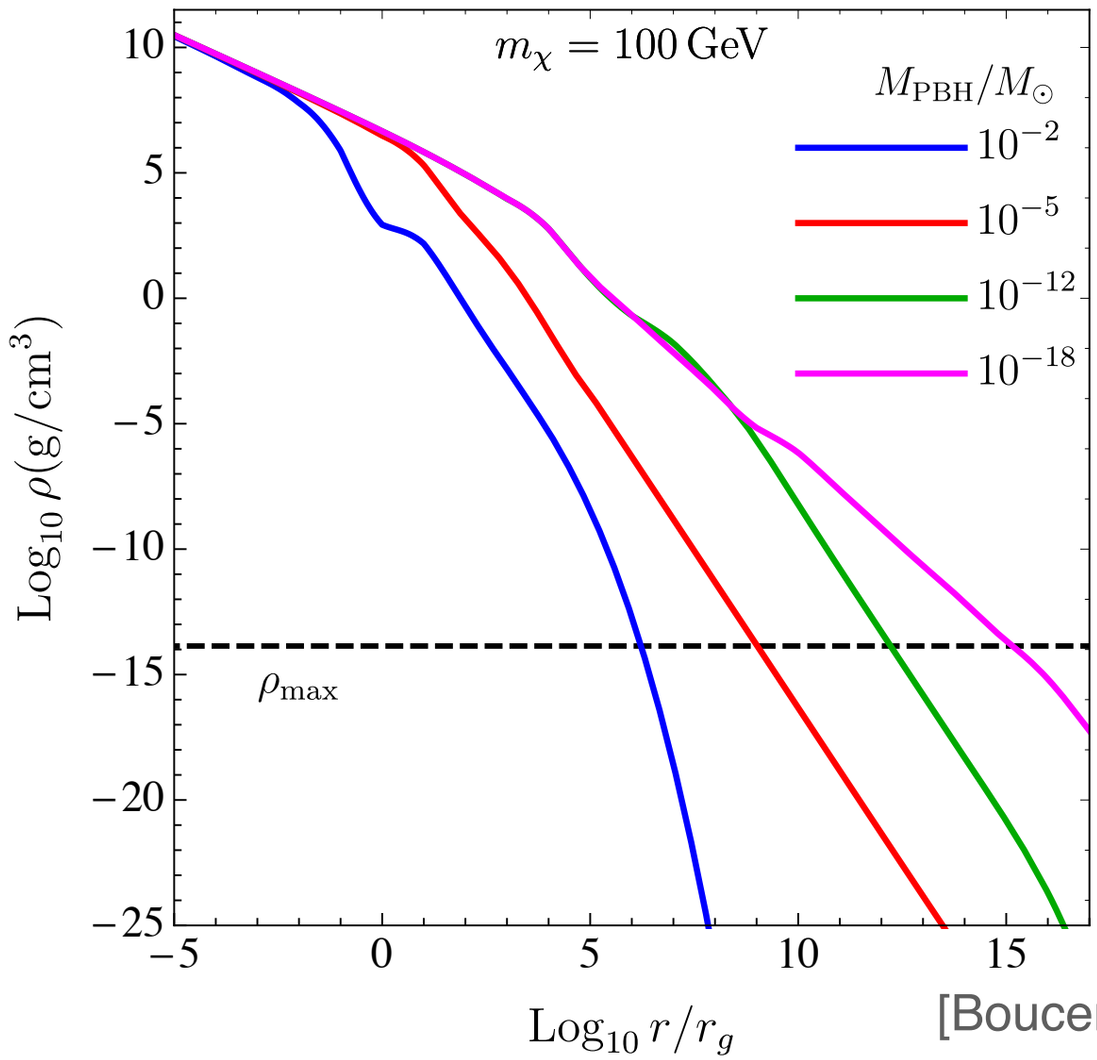

[Boucenna, FK, Ohlsson, Visinelli 2018]

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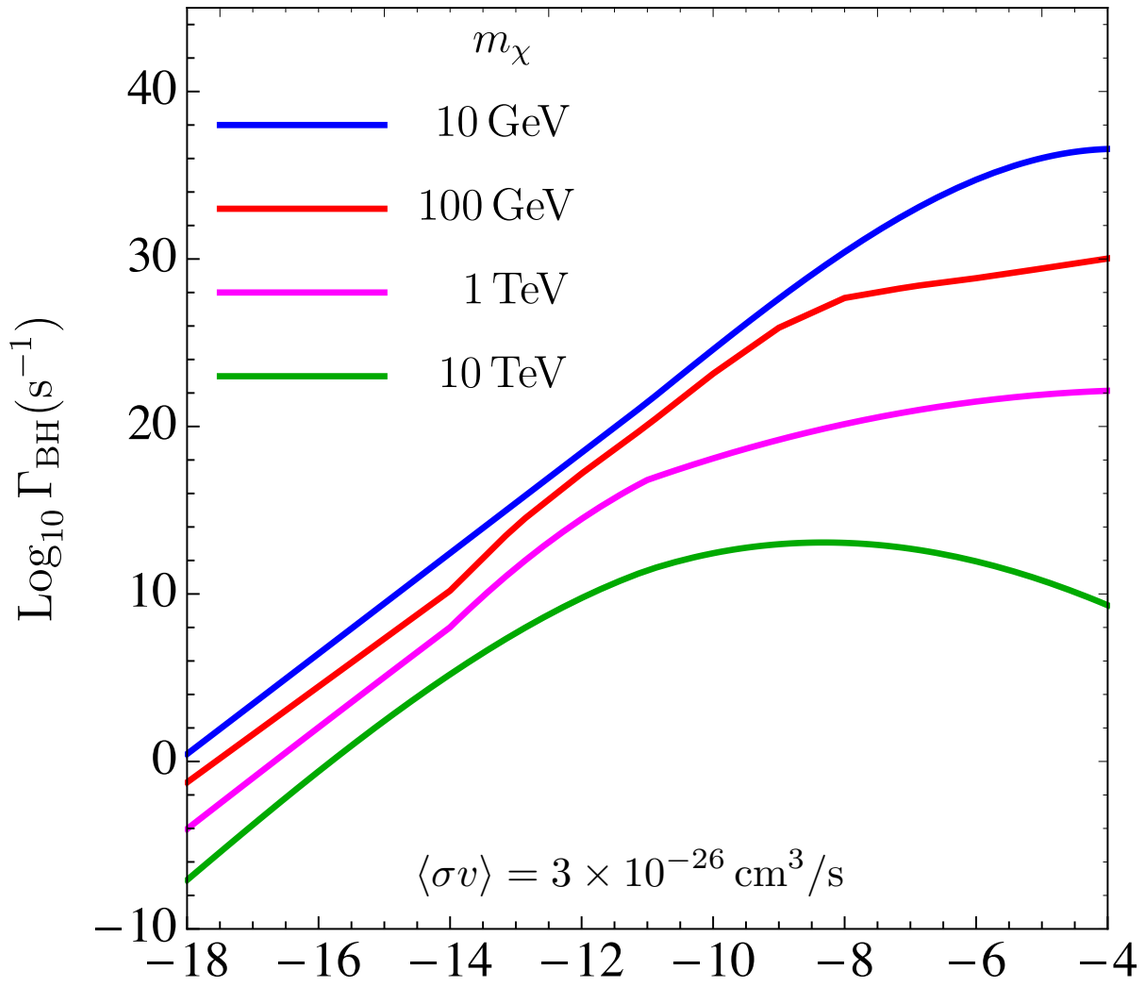

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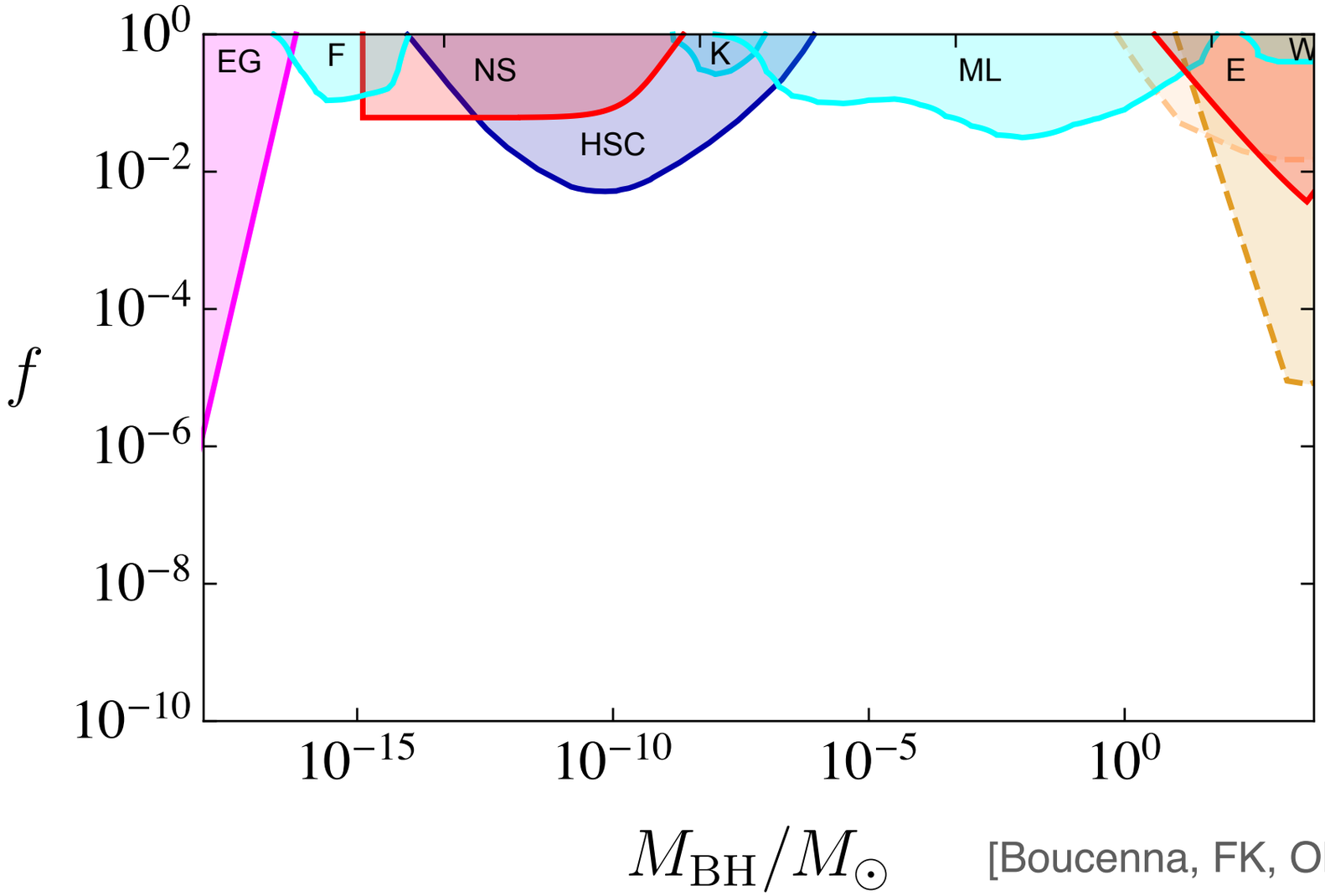

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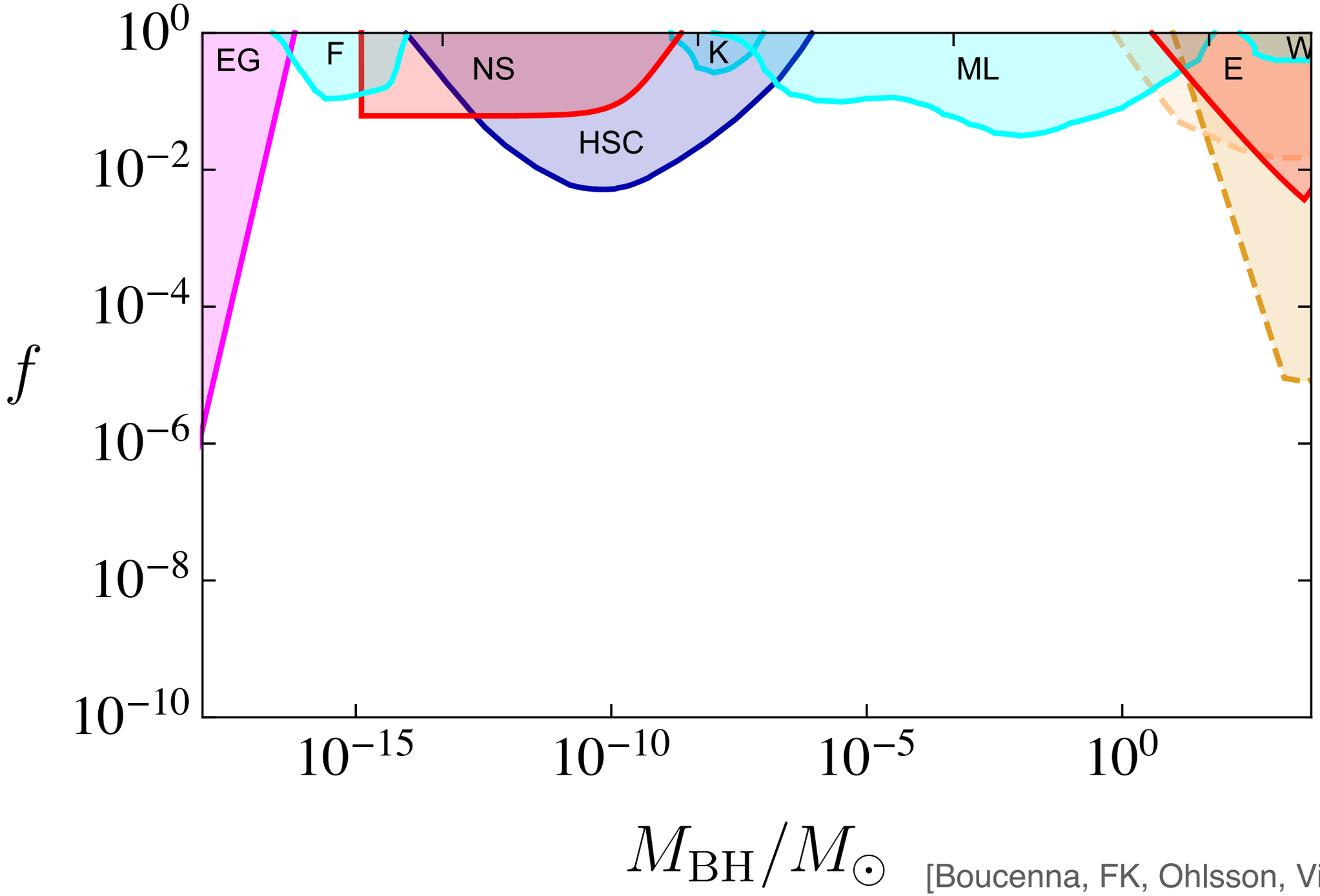

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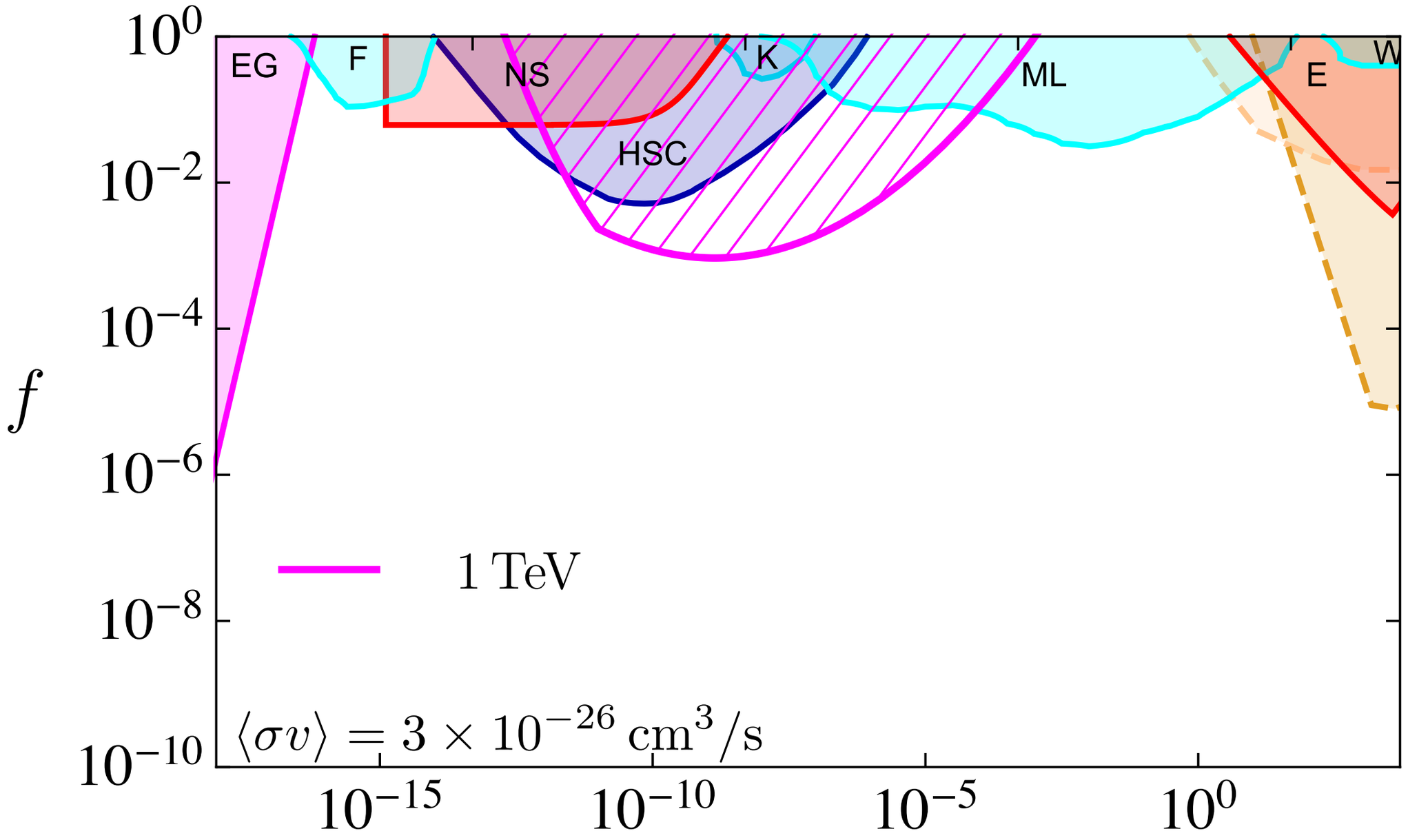

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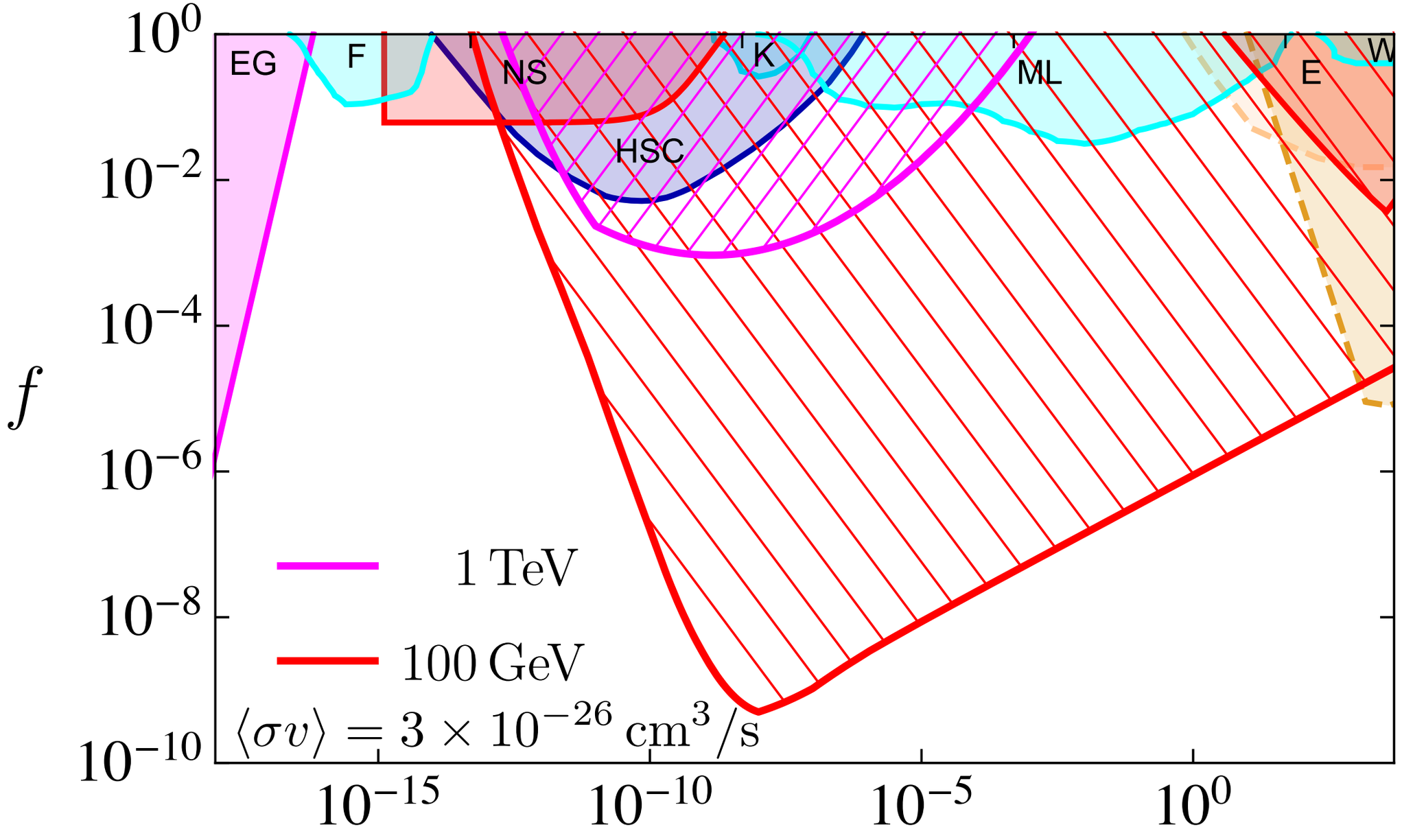

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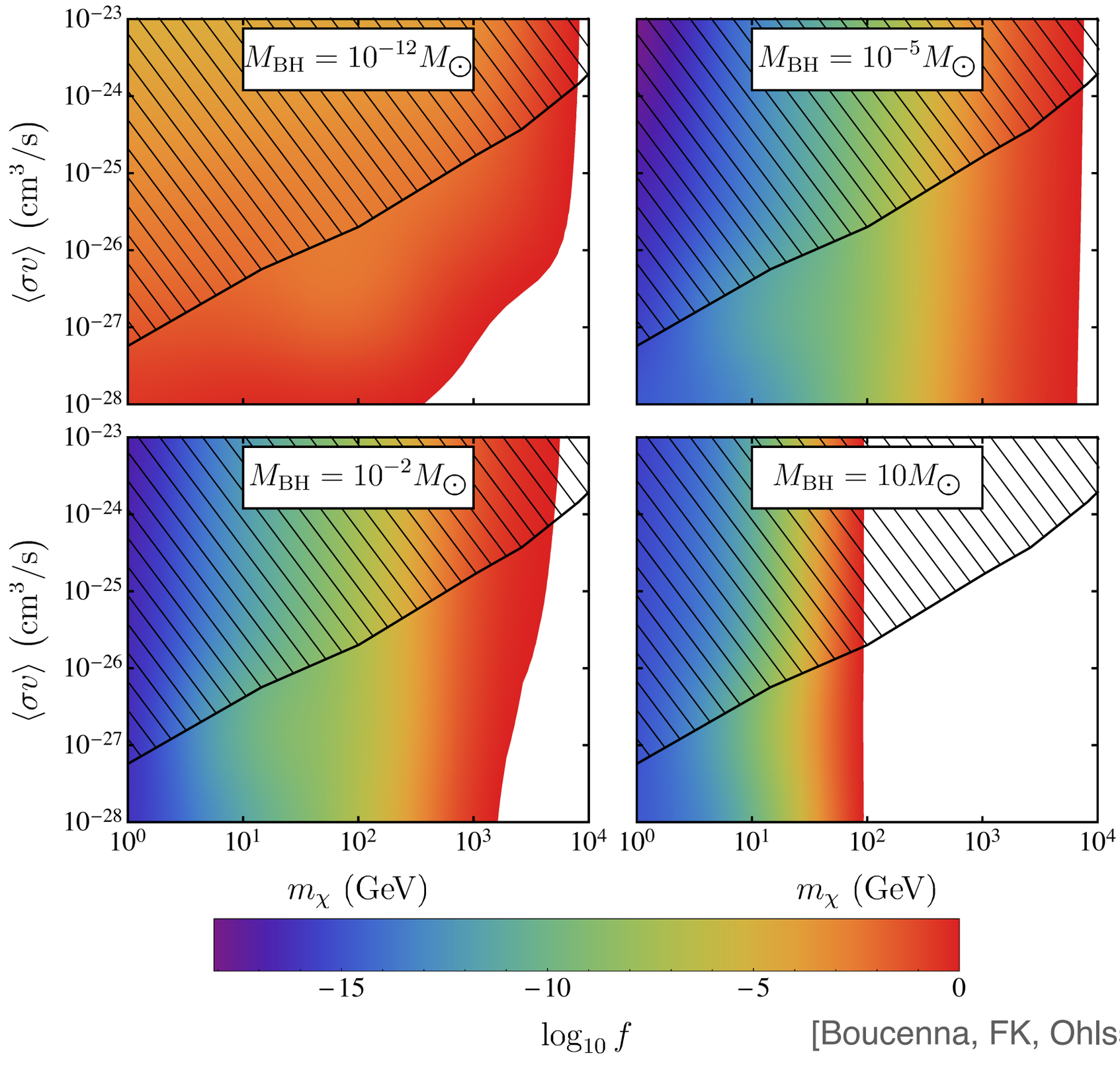

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Gravitational Waves form PBHs

Oskar Klein centre

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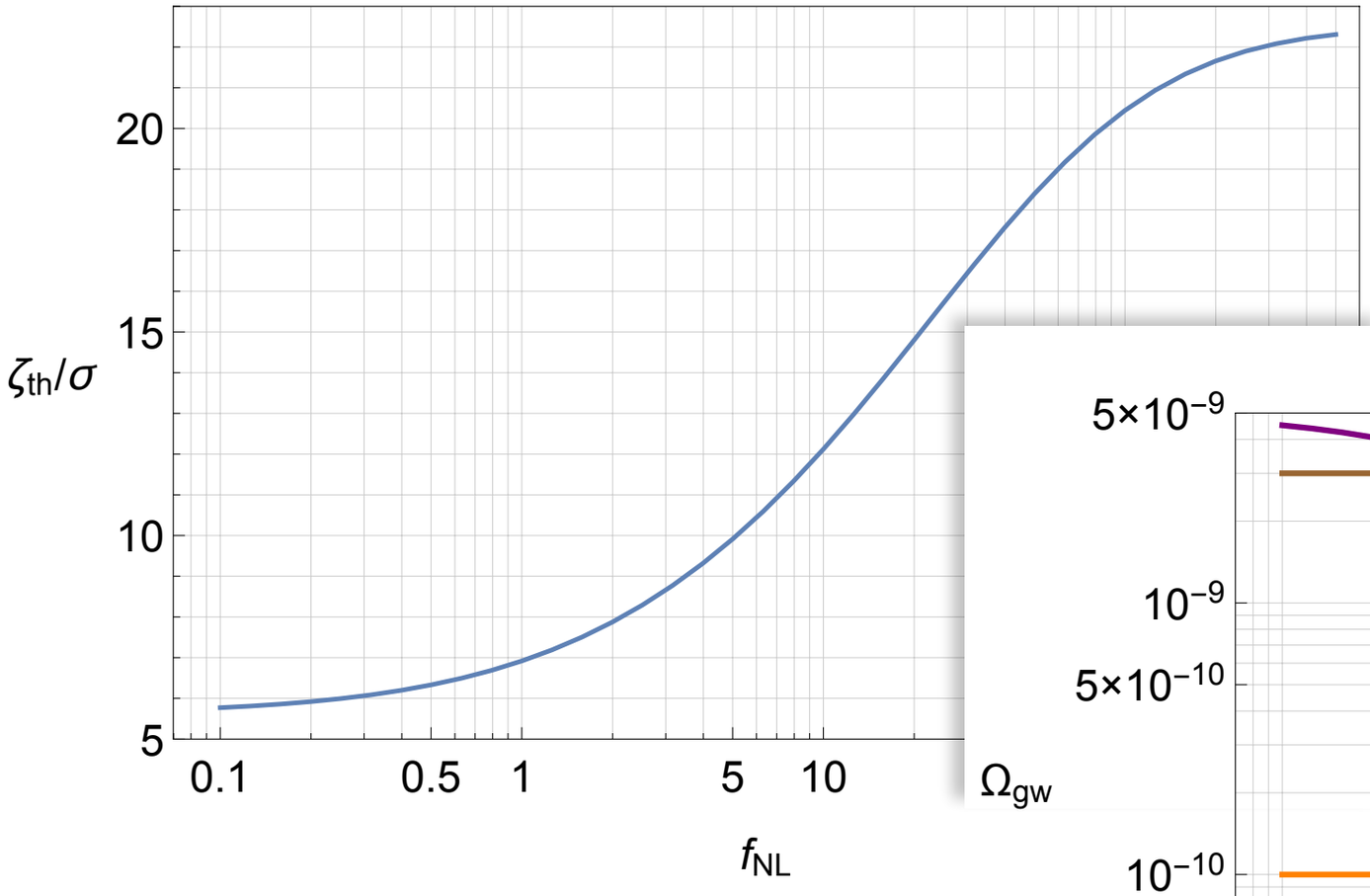
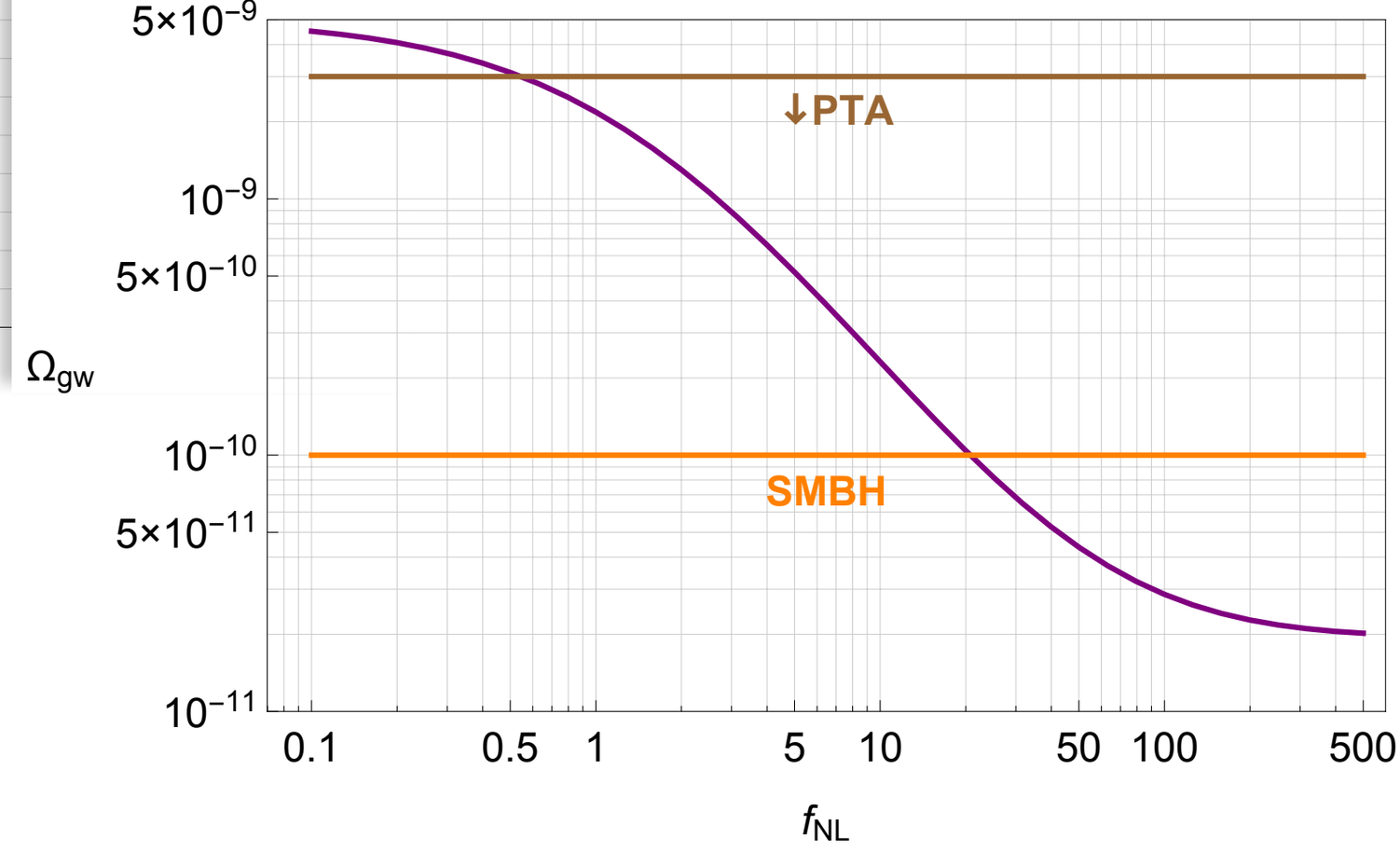


[Nakama, Silk, Kamionkowski 2017]



Gravitational Waves form PBHs

- PHBs can emit gravitational waves in various instances and times.
  - Gravitational waves from PBH formation.
  - Gravitational-wave emission from PBH binaries:
    1) Stochastic GW background

number of events

gravitational-wave energy per event

$$\Omega_{\rm gw} \approx \frac{1}{\rho_{\rm c}\, c^2} \int {\rm d}z\, \frac{N(z)}{1+z} \left(\nu_{\rm r} \frac{E_{\rm gw}}{{\rm d}\nu_{\rm r}} \right) \Bigg|_{\nu_{\rm r}=\nu(1+z)}$$

critical density

[Phinney 2001]

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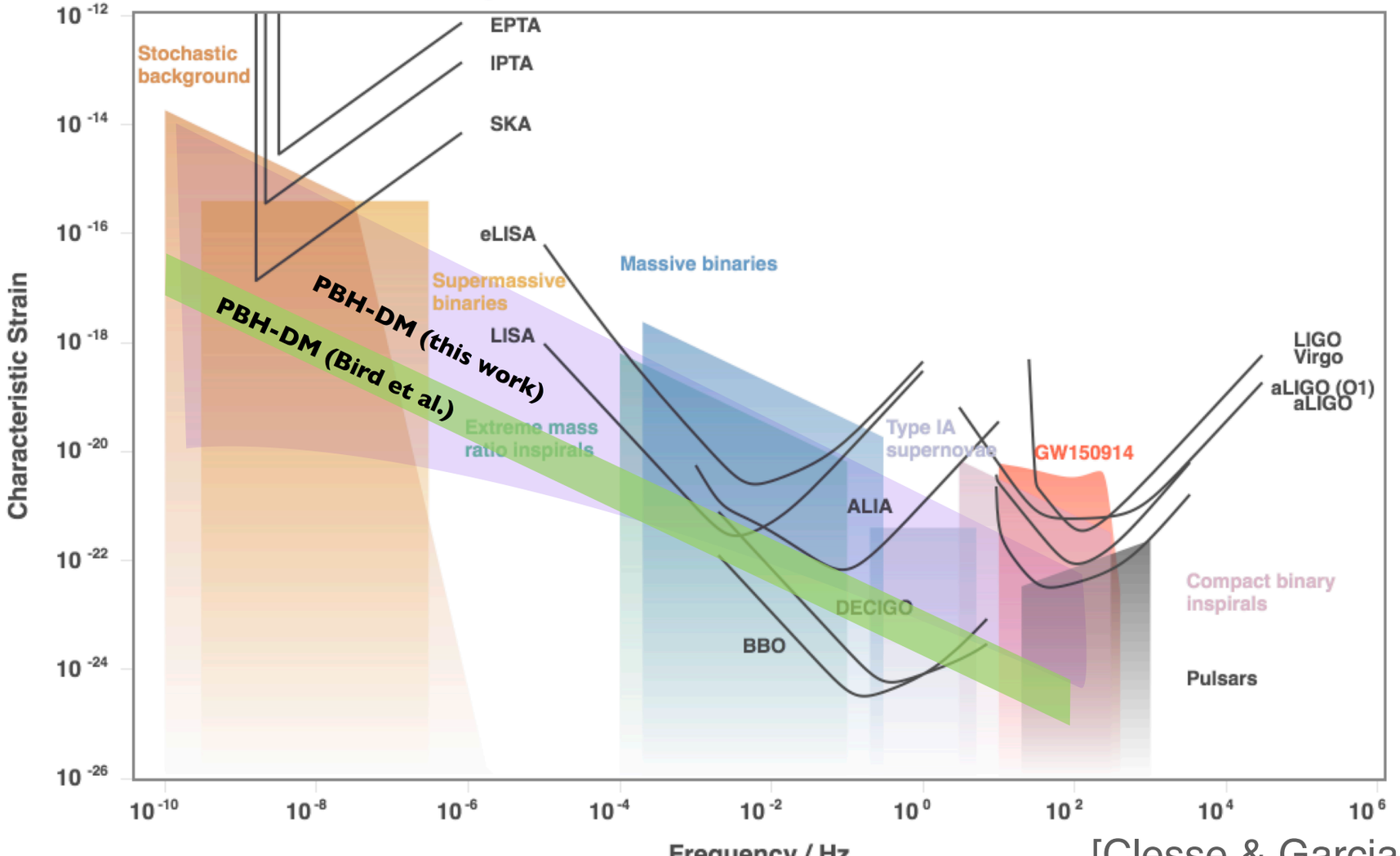

[Clesse & Garcia-Bellido 2017]

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Did LIGO detect dark matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess[1]

[1] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA*

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Primordial black holes as dark matter

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[2]*The Oskar Klein Centre for Cosmoparticle Physics, Department of Physics, Stockholm University, AlbaNova, SE–10691 Stockholm, Sweden*

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(Received 8 August 2016; published 4 October 2016)

Gravitational Waves form PBHs

Oskar Klein centre

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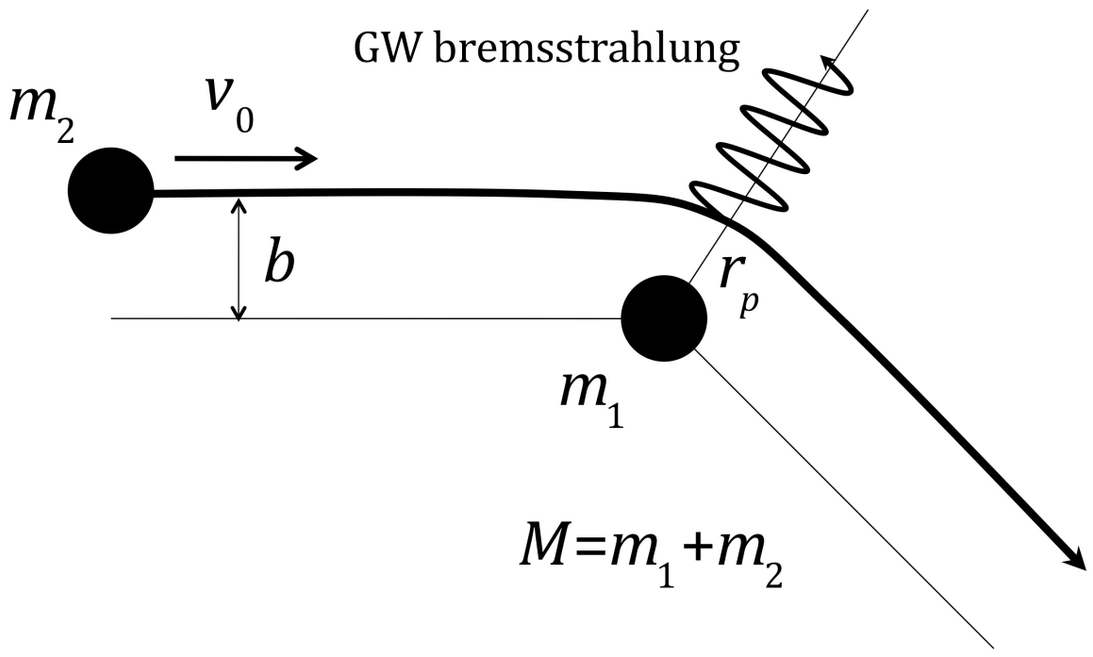
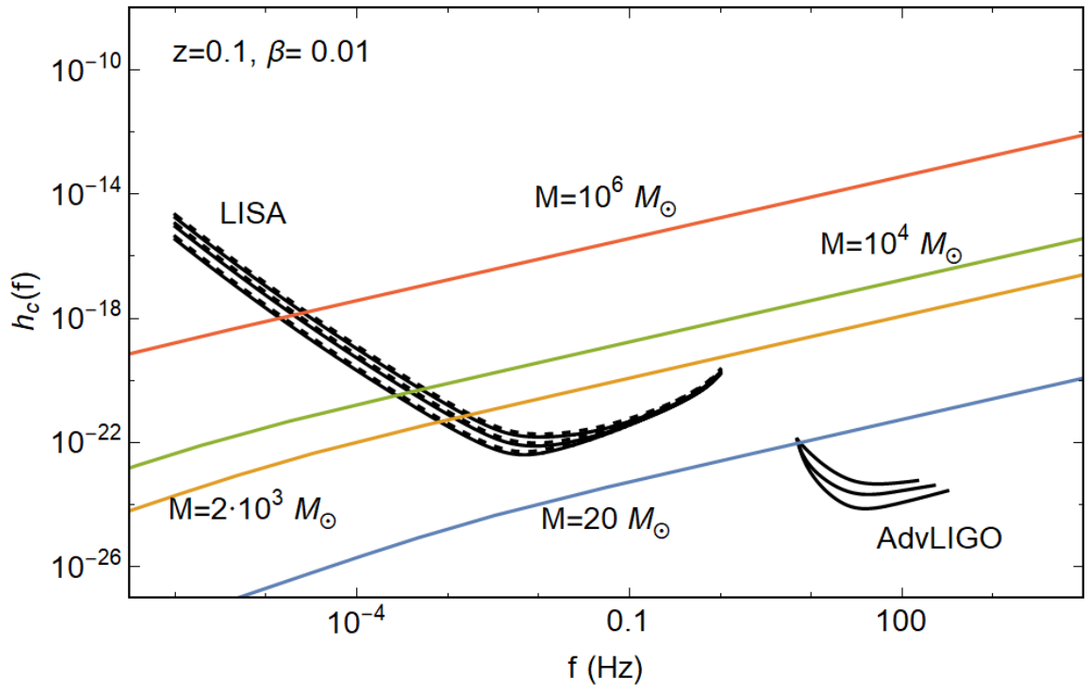
- Gravitational-wave emission from hyperbolic PBH encounters.

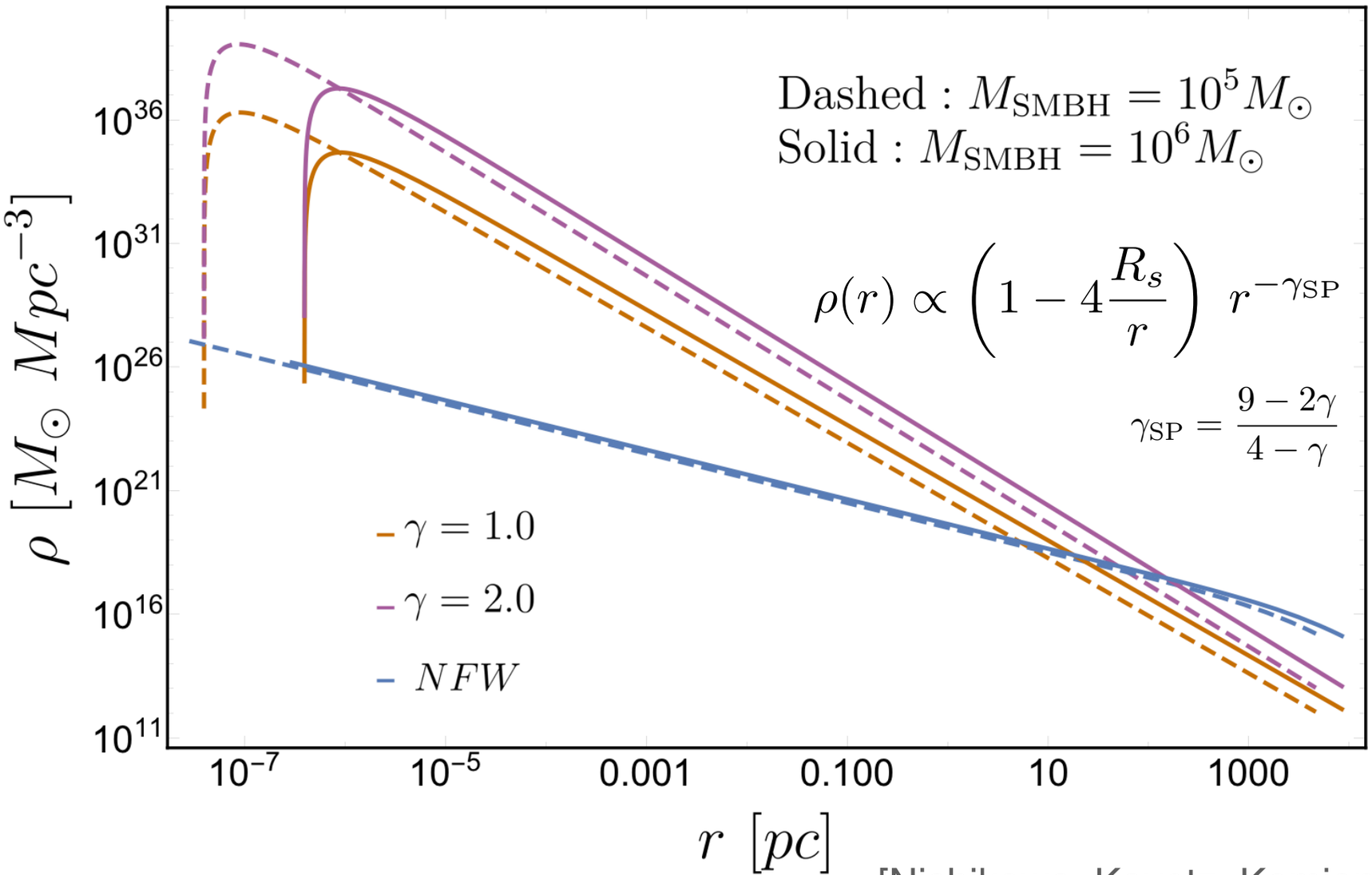




[Garcia-Bellido & Nesseris 2017]

Gravitational Waves form PBHs

- ★ Look at regions of high concentration of dark matter.
  - → Mergers of PBHs in Galactic centres.
    - ★ Adiabatic growth of SMBHs leads to formation of DM spikes.

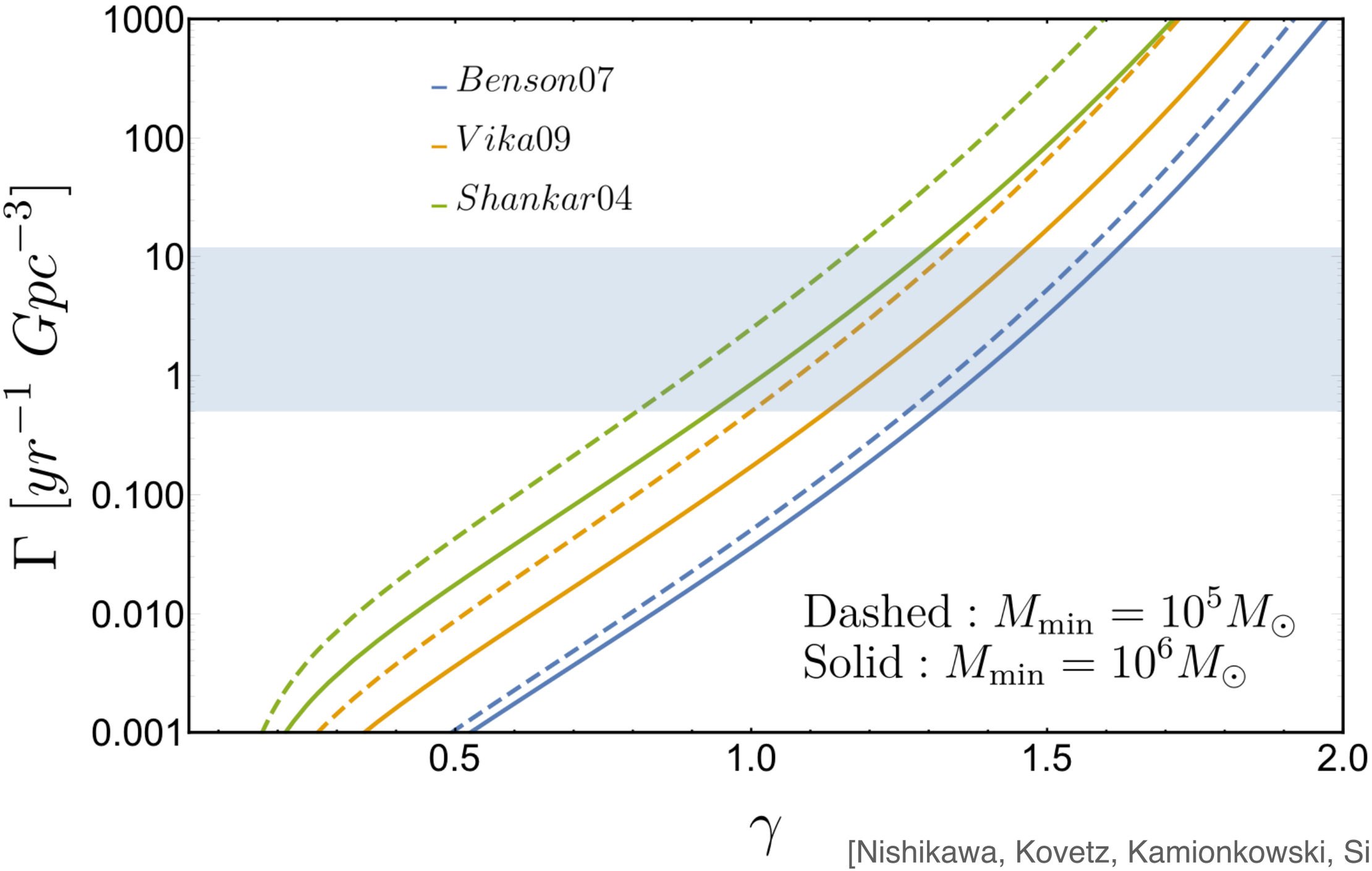


[Nishikawa, Kovetz, Kamionkowski, Silk 2017]

Gravitational Waves form PBHs

Oskar Klein centre

★ Overall merger rate:



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$$\tau = \frac{f}{\dot{f}} = \frac{1}{q}\frac{5}{96\pi^{8/3}}\frac{c^5}{(GM)^{5/3}} f^{-8/3}$$

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$$M = 4 \times 10^6 M_\odot \ , \ f = 1\mathrm{mHz}$$

→ $\tau = 6 \times 10^{19}\ \mathrm{s} = 140 \times t_{\mathrm{Hubble}}$!

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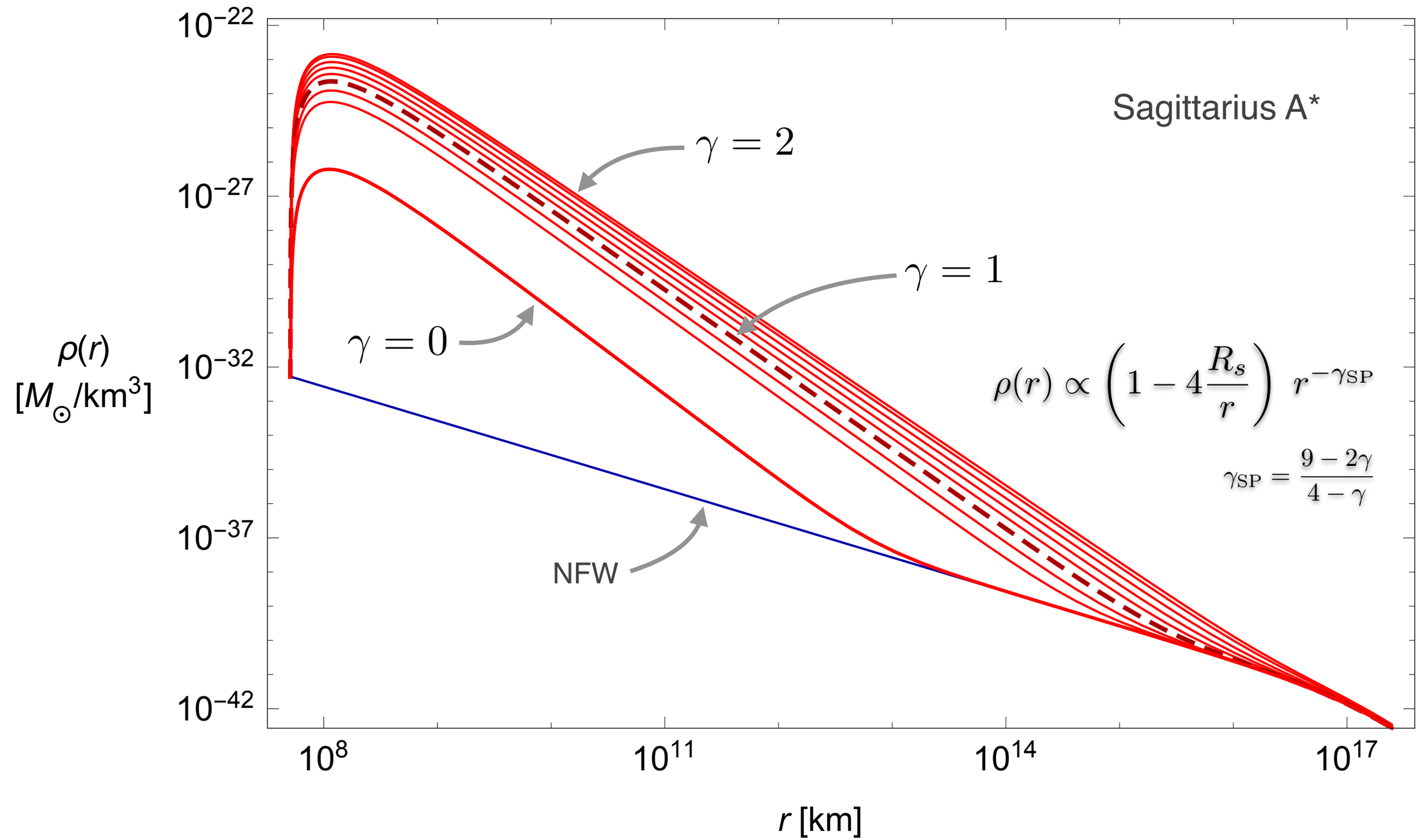
- Continuous emission

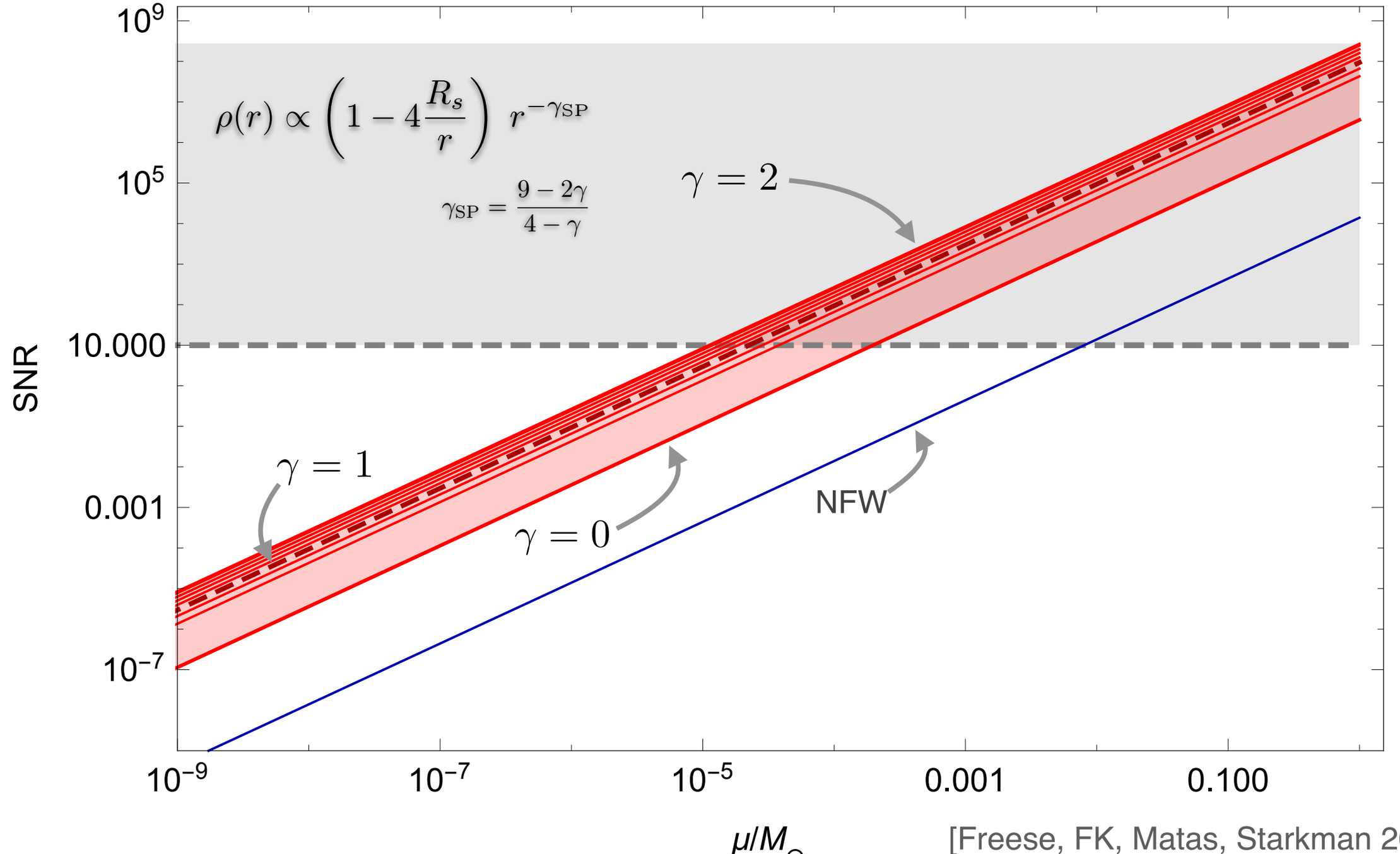
Gravitational Waves form PBHs



Gravitational Waves form PBHs

Oskar Klein centre

★ Make a conservative estimate for the detection prospects with LISA: Compute the signal-to-noise ratio (SNR), assuming *circular* orbits.



[Freese, FK, Matas, Starkman 2018]

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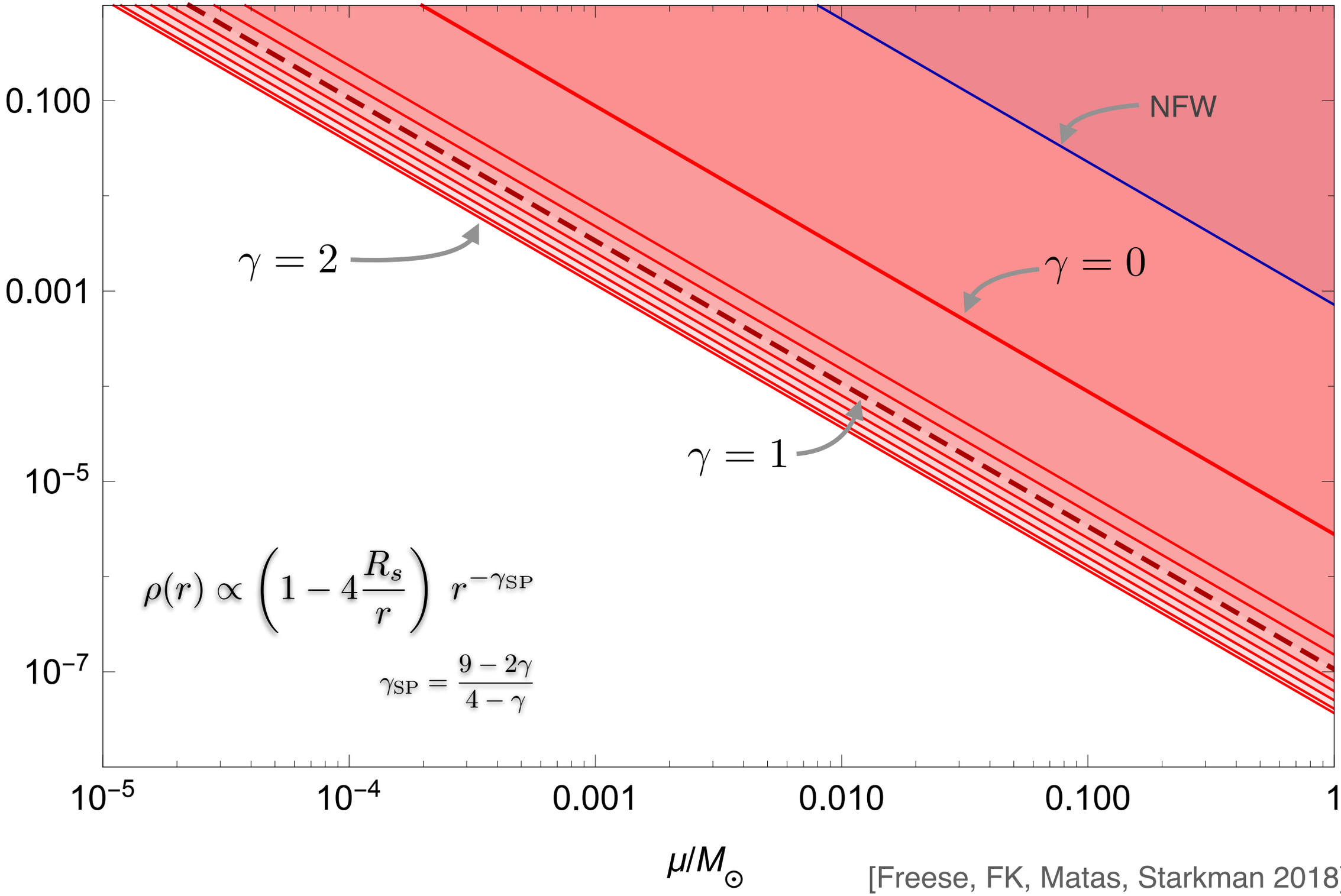

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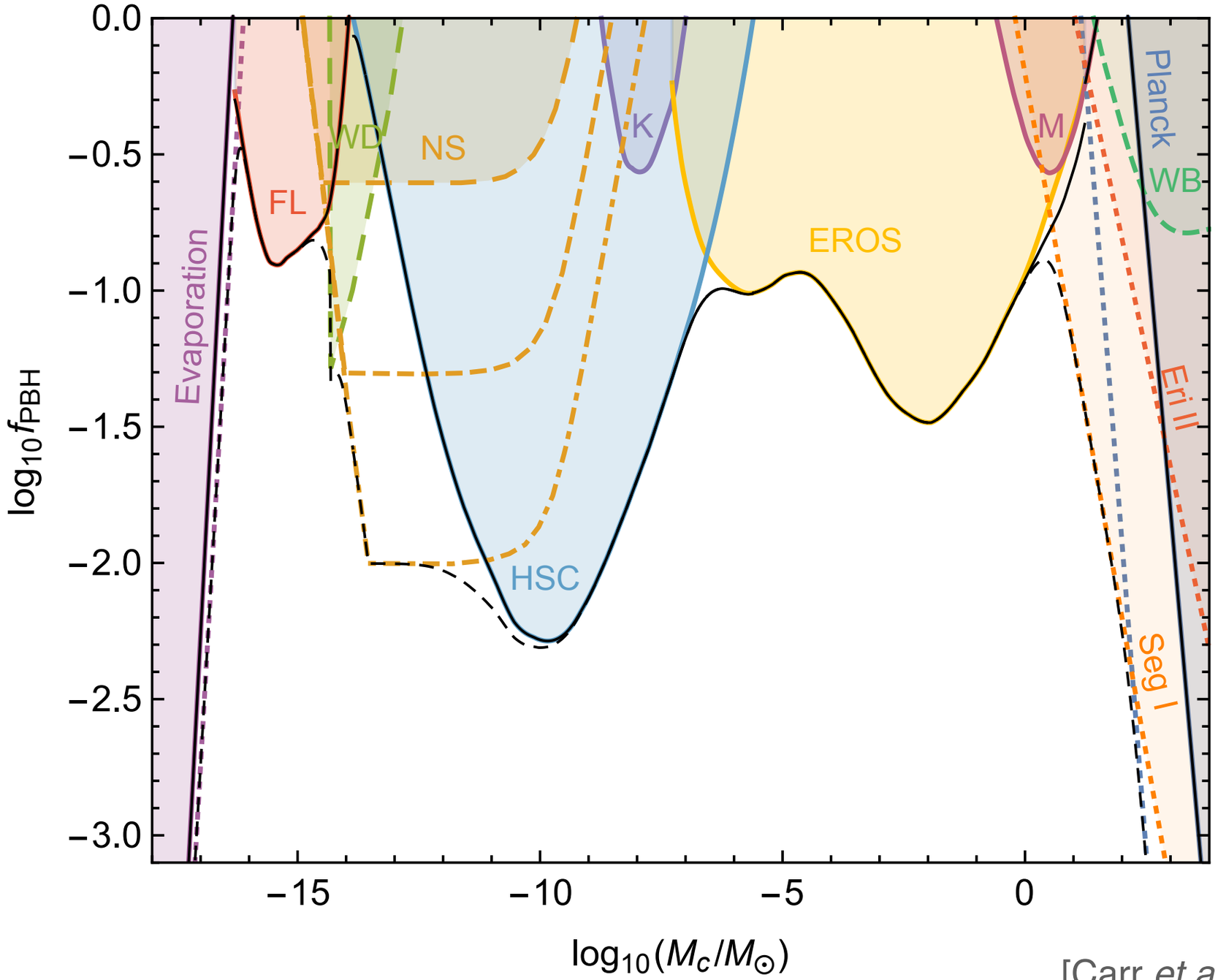
Constraints — Words of Caution

★ May constraints rely on rather on uncertain, restrictive, simplistic or even incorrect assumptions!



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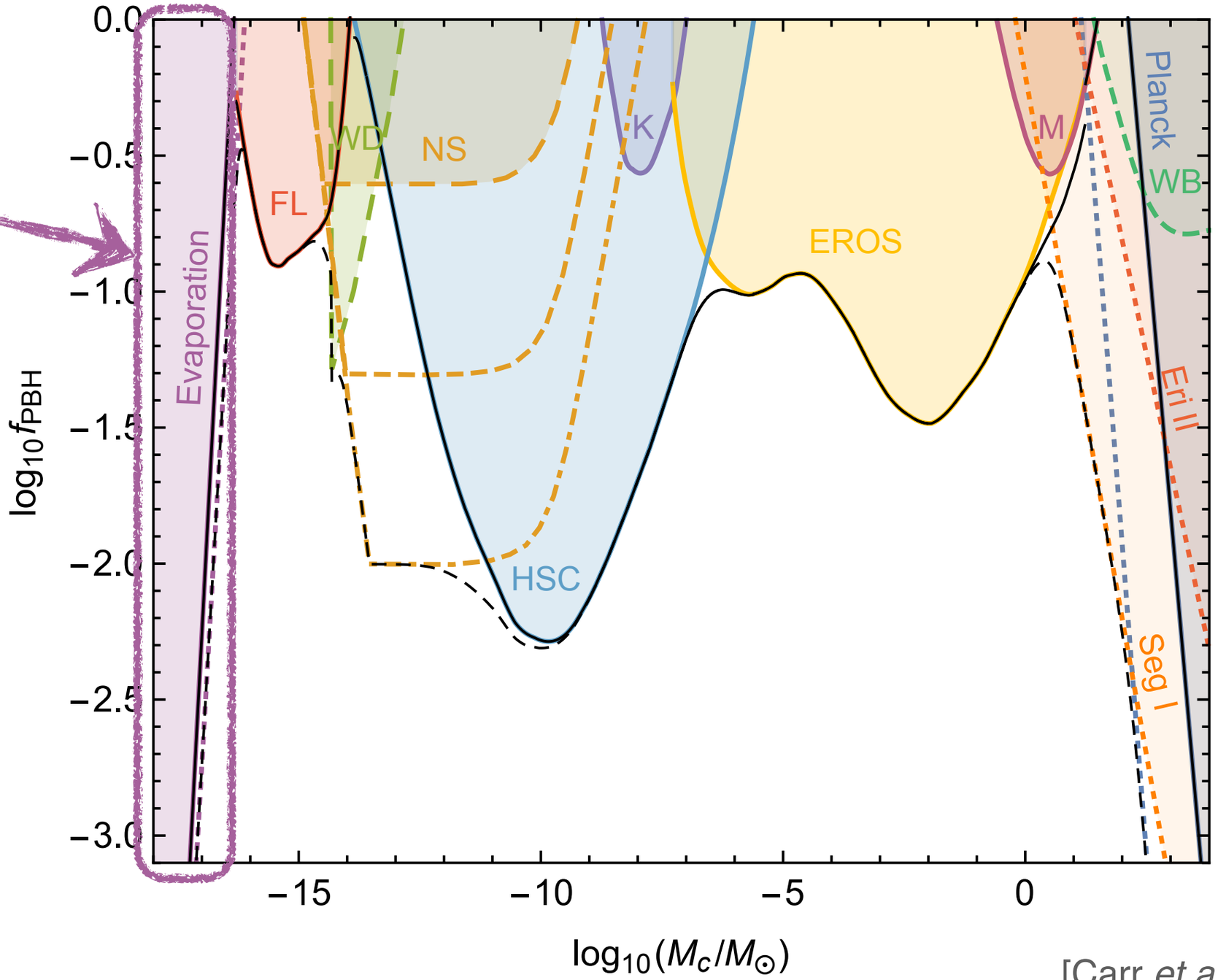

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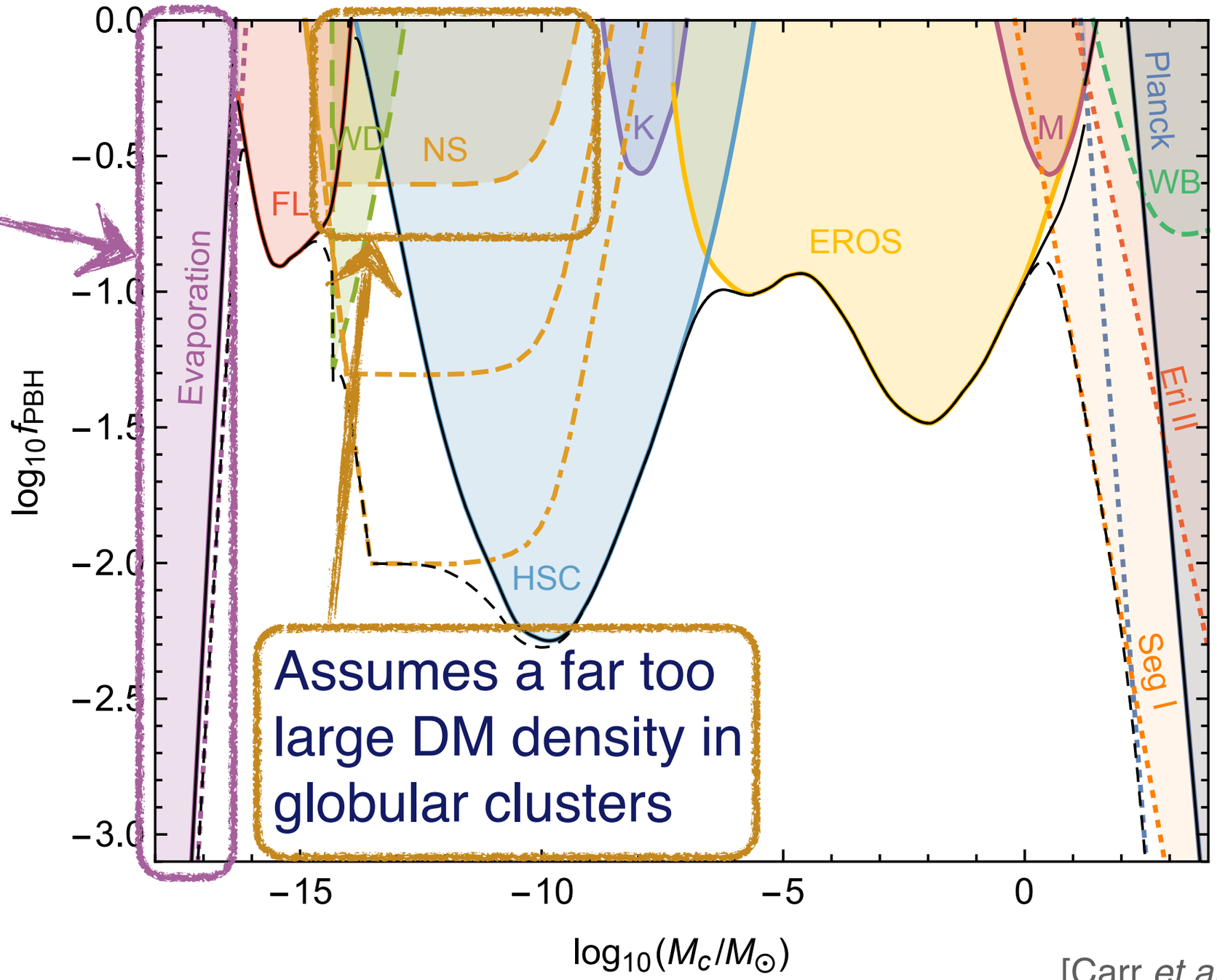
Validity of Hawking radiation



Assumes a far too large DM density in globular clusters

[Carr *et al.* 2017]

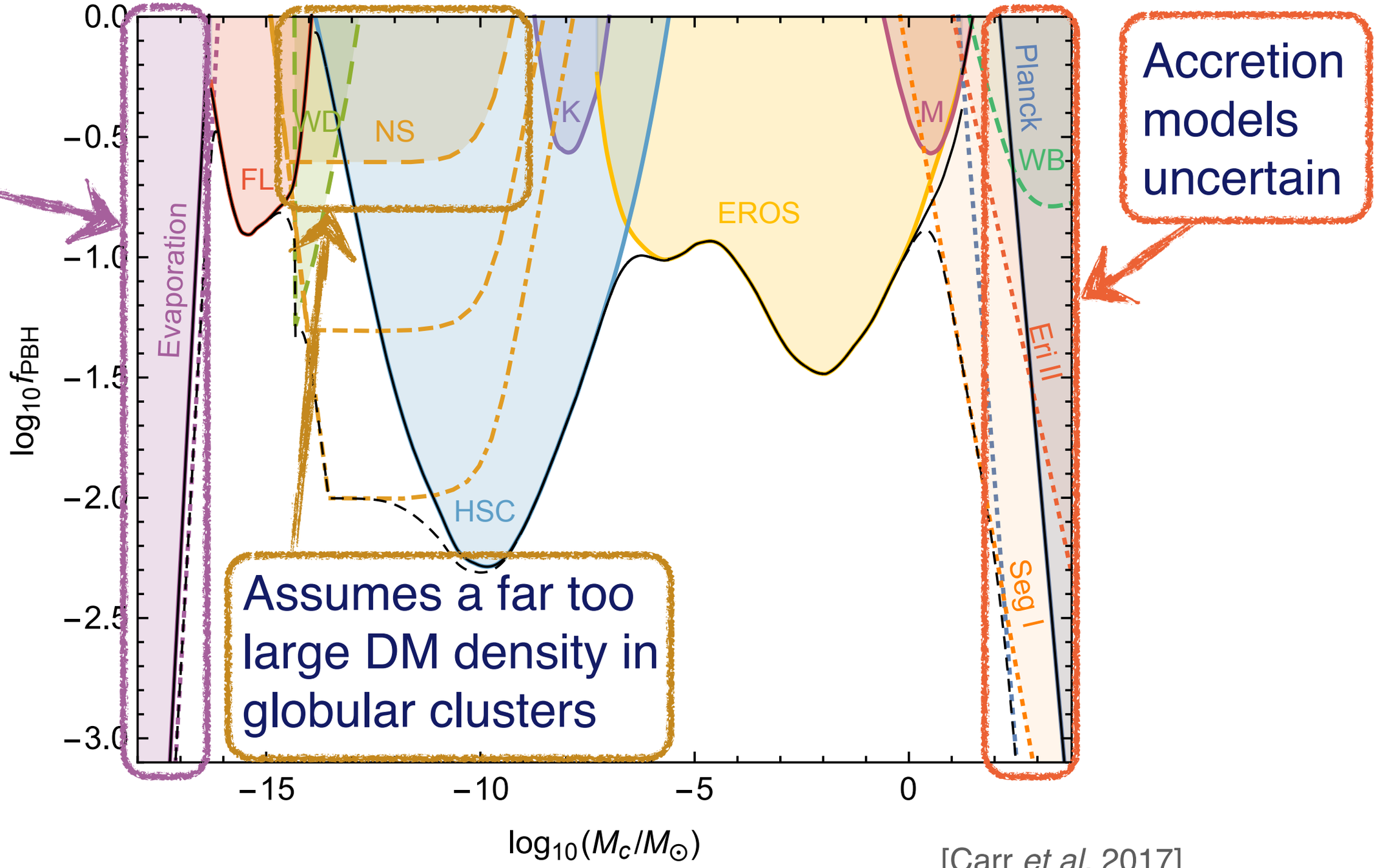
Constraints — Words of Caution

Oskar Klein centre

★ May constraints rely on rather on uncertain, restrictive, simplistic or even incorrect assumptions!

Validity of Hawking radiation

Accretion models uncertain



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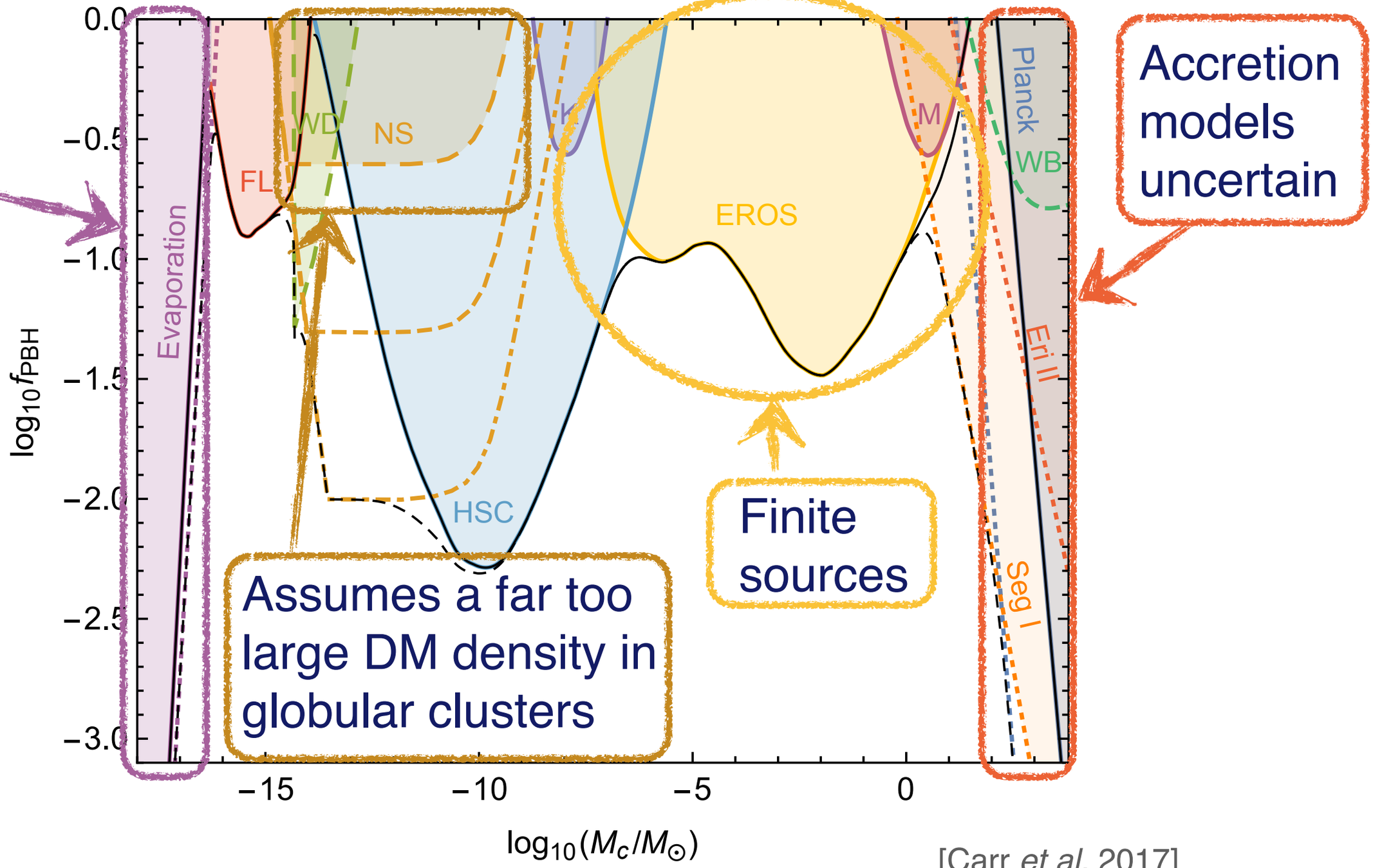

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Constraints — Words of Caution

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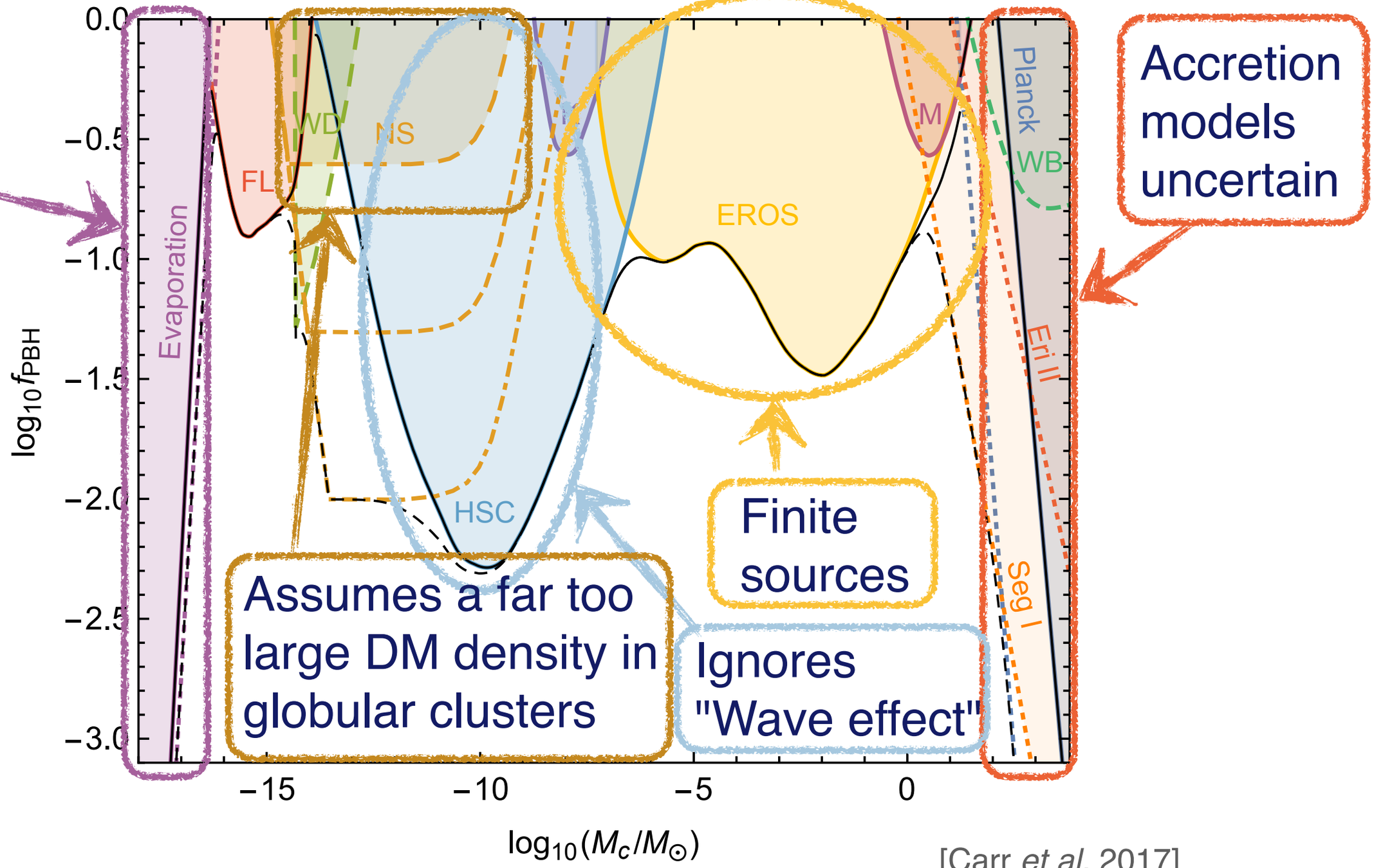


[Carr *et al.* 2017]

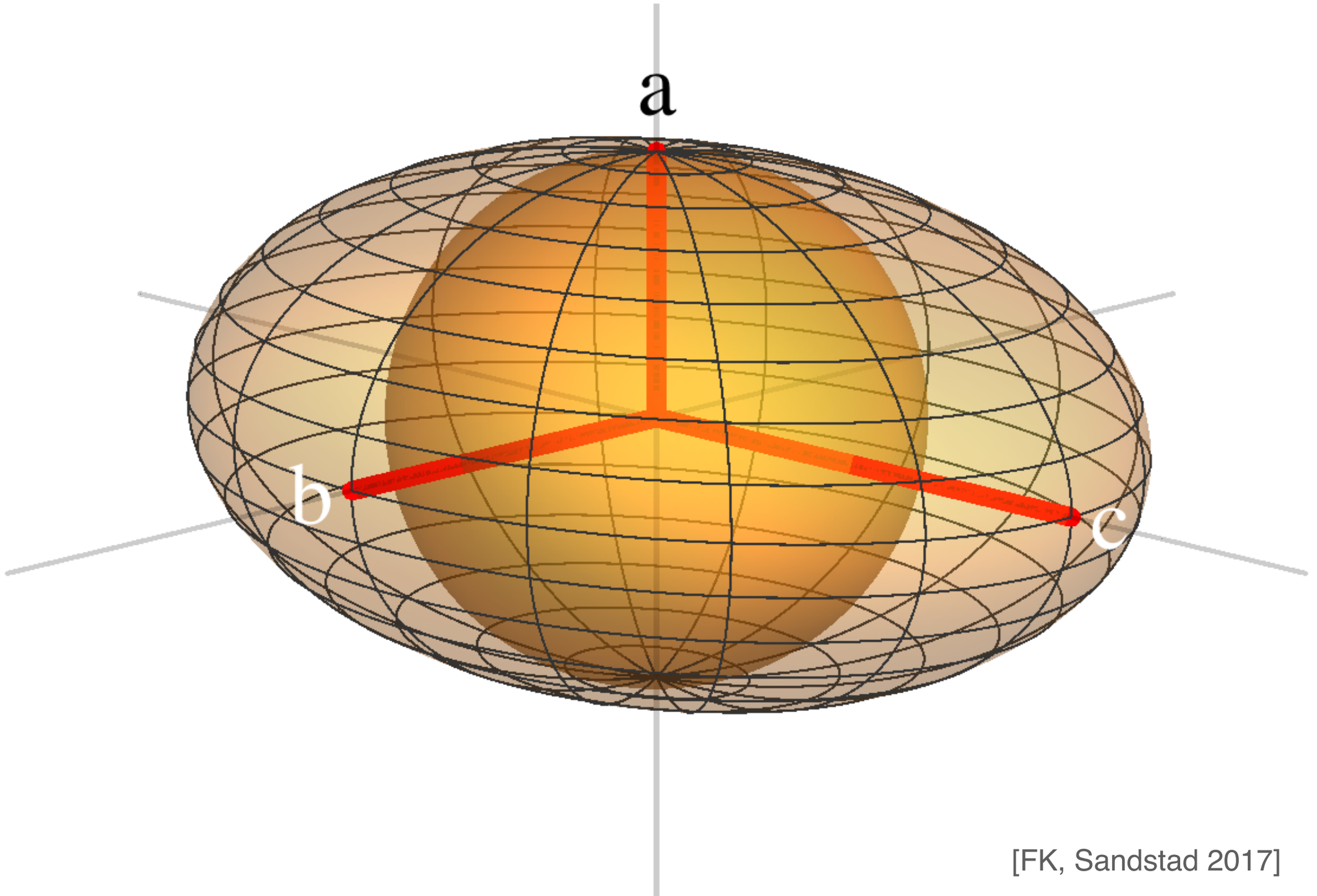
Constraints — Words of Caution

- May constraints rely on rather on uncertain, restrictive, simplistic or even incorrect assumptions!

  → We have to understand better:

  - Galactic dark-matter profile
  - Clustering
  - Accretion
  - Characteristics of the lensed sources (size, variability, ...)
  - Composition of "probes" in general
  - Velocity distribution
  - (Hawking radiation)
  - ...

Non-Spherical Effects



[FK, Sandstad 2017]

Non-Spherical Effects

★ Non-Sphericity

[FK, Sandstad 2016]

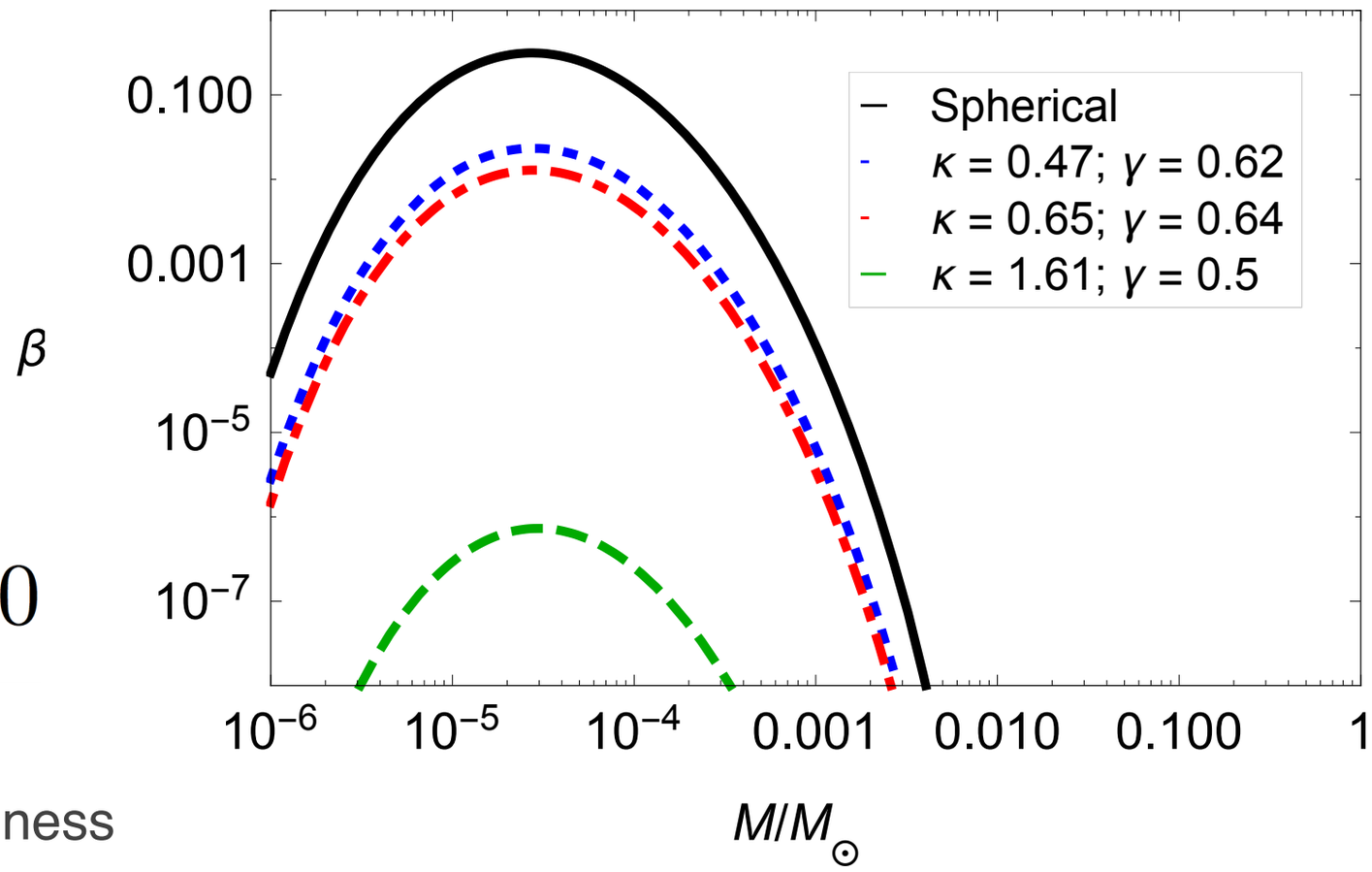
ellipsoidal threshold

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

spherical threshold

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

ellipticity — prolateness



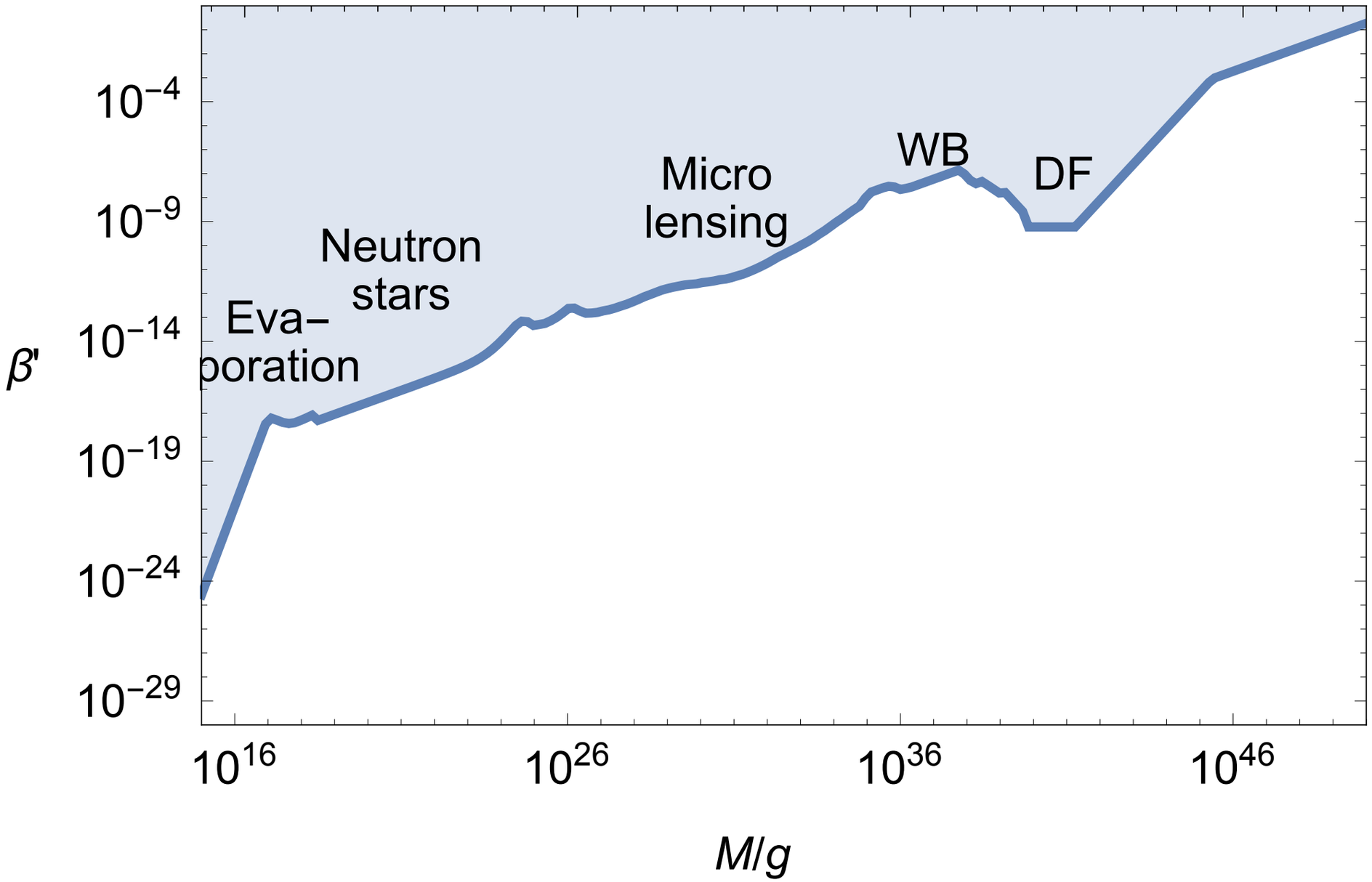
★ Simple estimate: As the collapse starts along shortest axis first,

→ consider collapse of largest enclosed sphere (green curve):

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

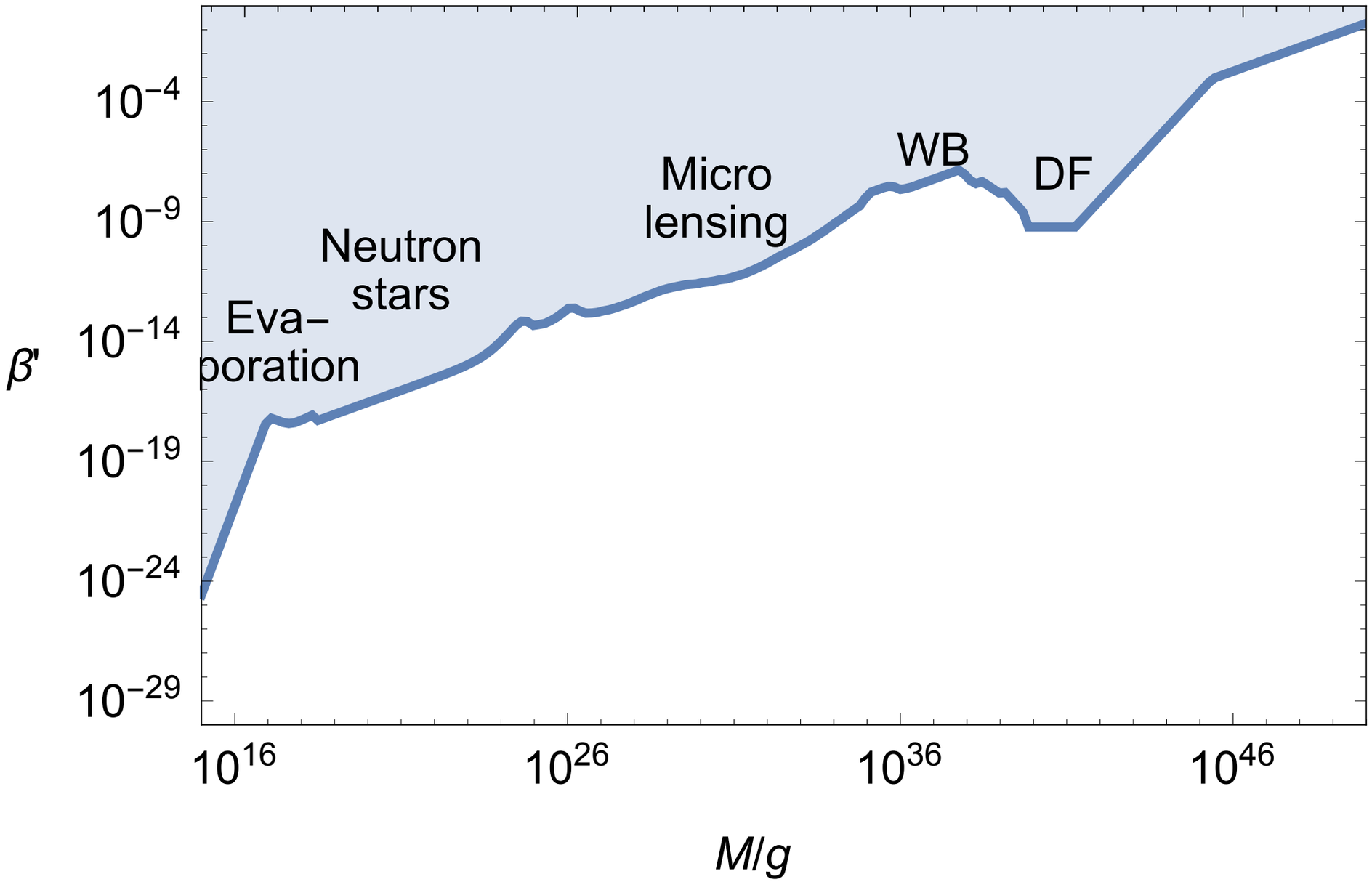
More Words of Caution

★ One may wonder how the constraints on the PBH dark-matter fraction constrain the primordial power spectrum.



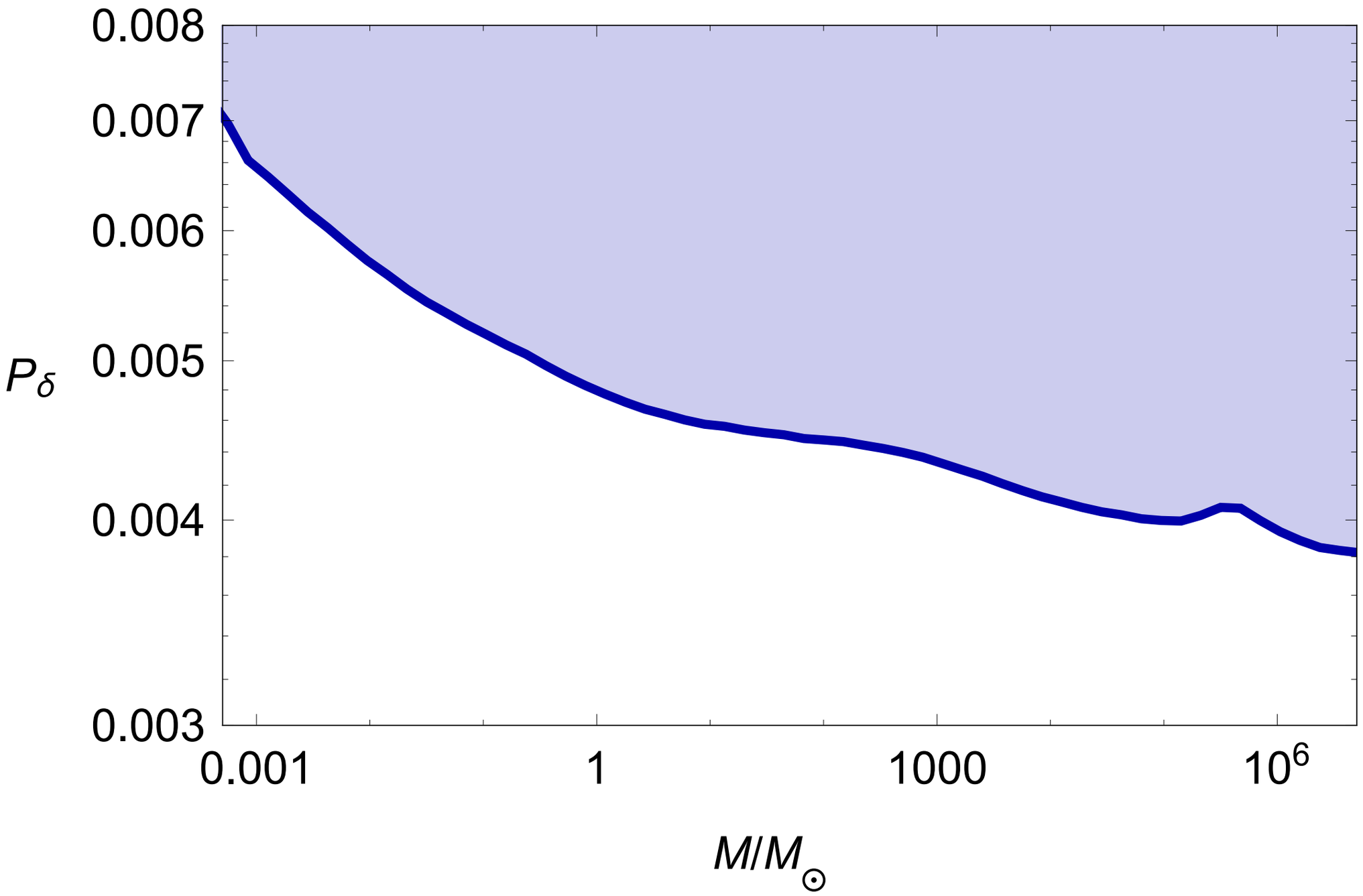
More Words of Caution

- One may wonder how the constraints on the PBH dark-matter fraction constrain the primordial power spectrum.
  - Go back to the constraints at the time of formation:



More Words of Caution

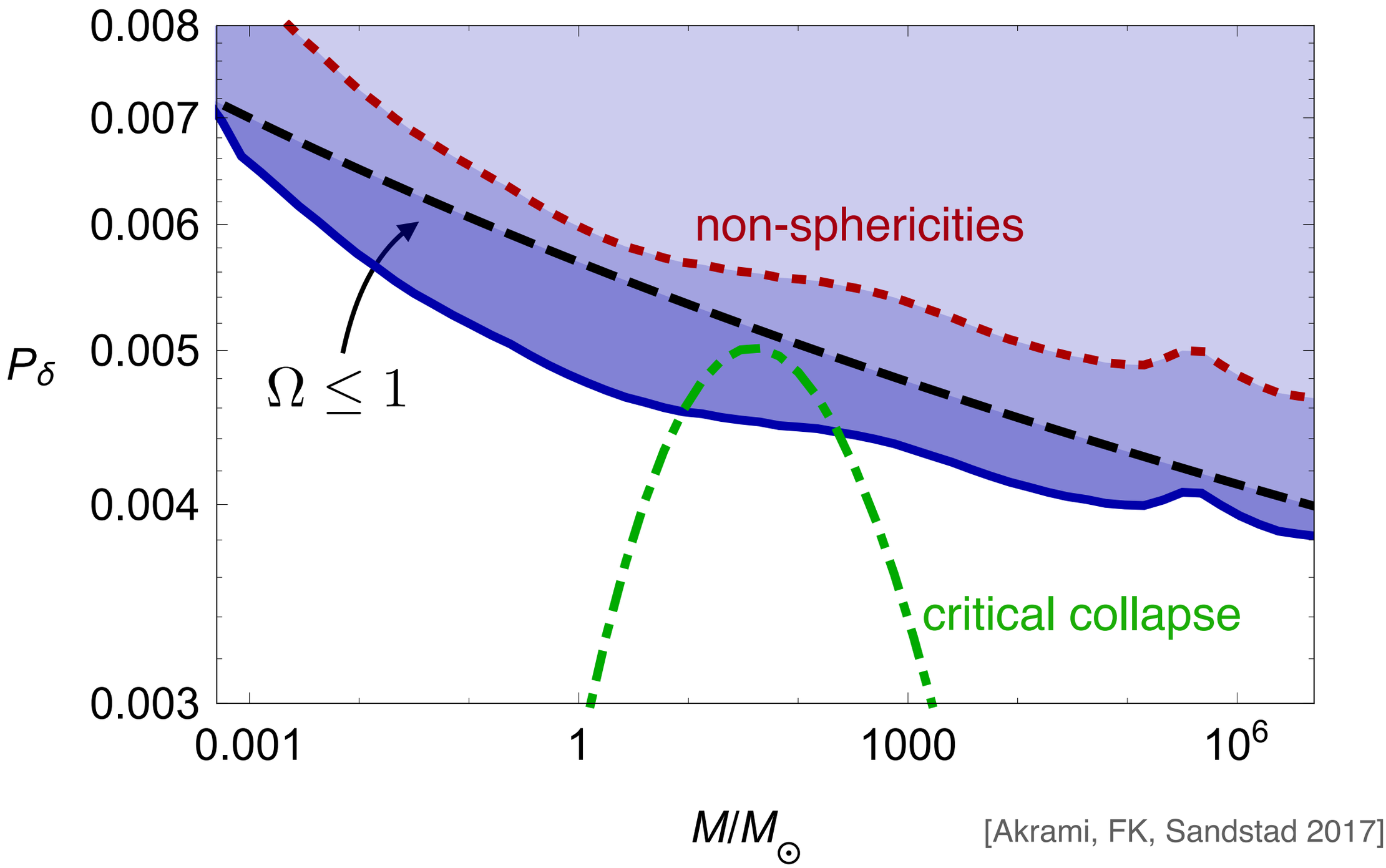
★ These constraints naïvely translate to:



Constraints on the Primordial Power Spectrum?

Oskar Klein centre

★ Take the uncertainty due to non-sphericities into account:



[Akrami, FK, Sandstad 2017]

Conclusion

- Primordial black holes are very interesting!

- A detailed understanding of their formation is crucial.

- Gravitational-wave signals from the Galactic centre may soon confirm the hypothesis that the Dark Matter is indeed comprised of primordial black holes.

- Combined dark-matter scenarios (e.g. PBHs + WIMPs) can offer bright detection prospect.

- Most of the primordial black holes constraints rely on assumptions whose validity is hard to quantify.