Primordial Black Holes as Dark Matter Candidates

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Max Planck Institute for Physics

— News from the Dark, Episode Eight —
Université Libre de Bruxelles
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Historical Remarks

What are Primordial Black Holes (PBHs)?

- ★ Black holes formed in the early* Universe (in particular: *non-stellar*).

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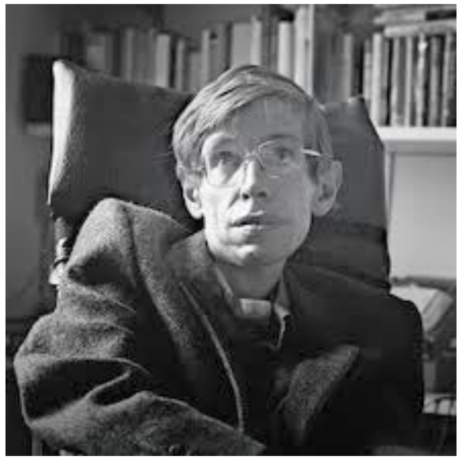
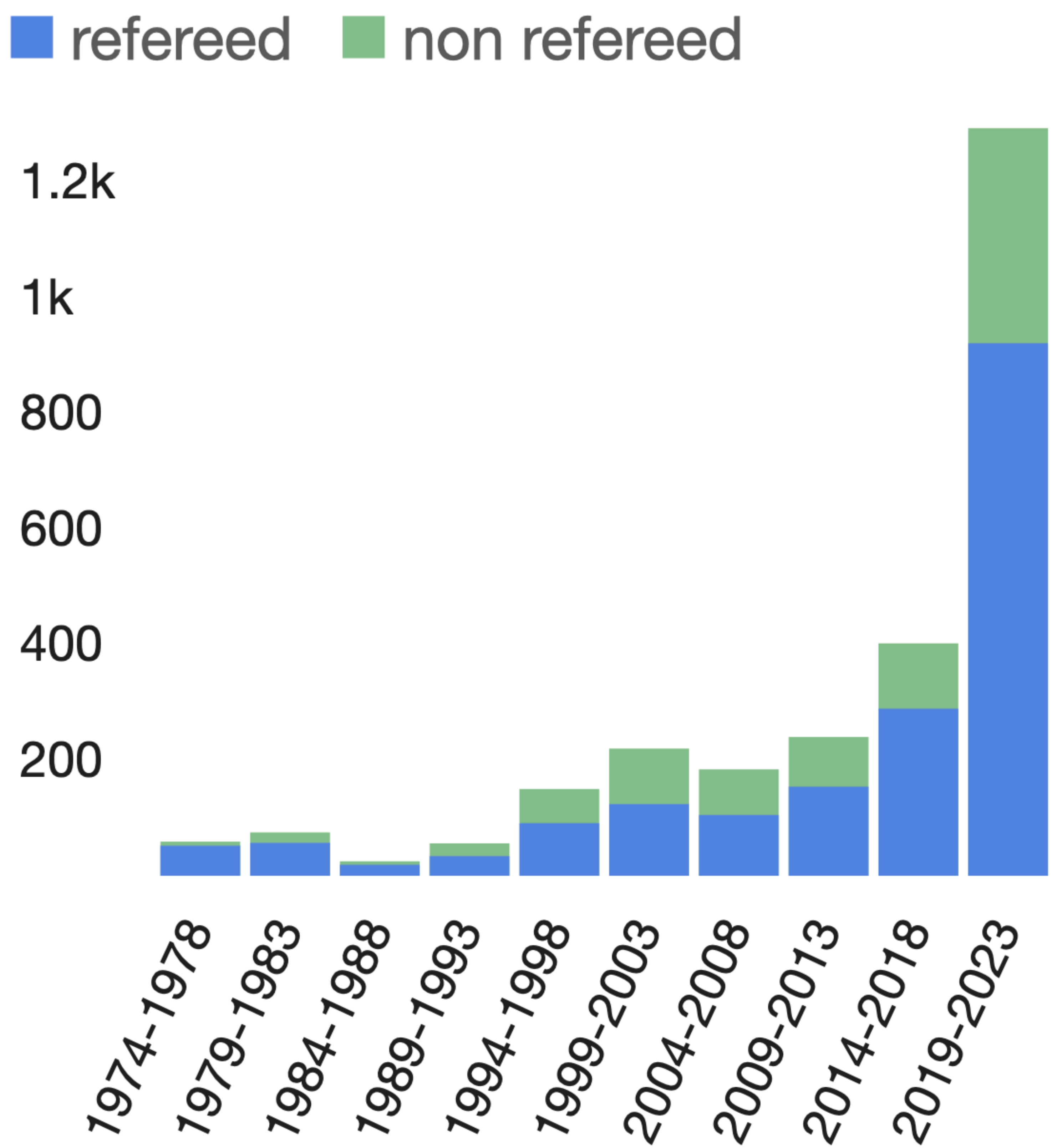
★ First proposed by Novikov and Zel'dovič in the late 1960th, but their conclusion was negative for the existence of PBHs.

★ Conclusion disproved by Carr & Hawking (1974), reinvigorated PBH research (around 3000 papers to date).



Primordial Black Holes are Popular!



[SAO/NASA Astrophysics Data System]

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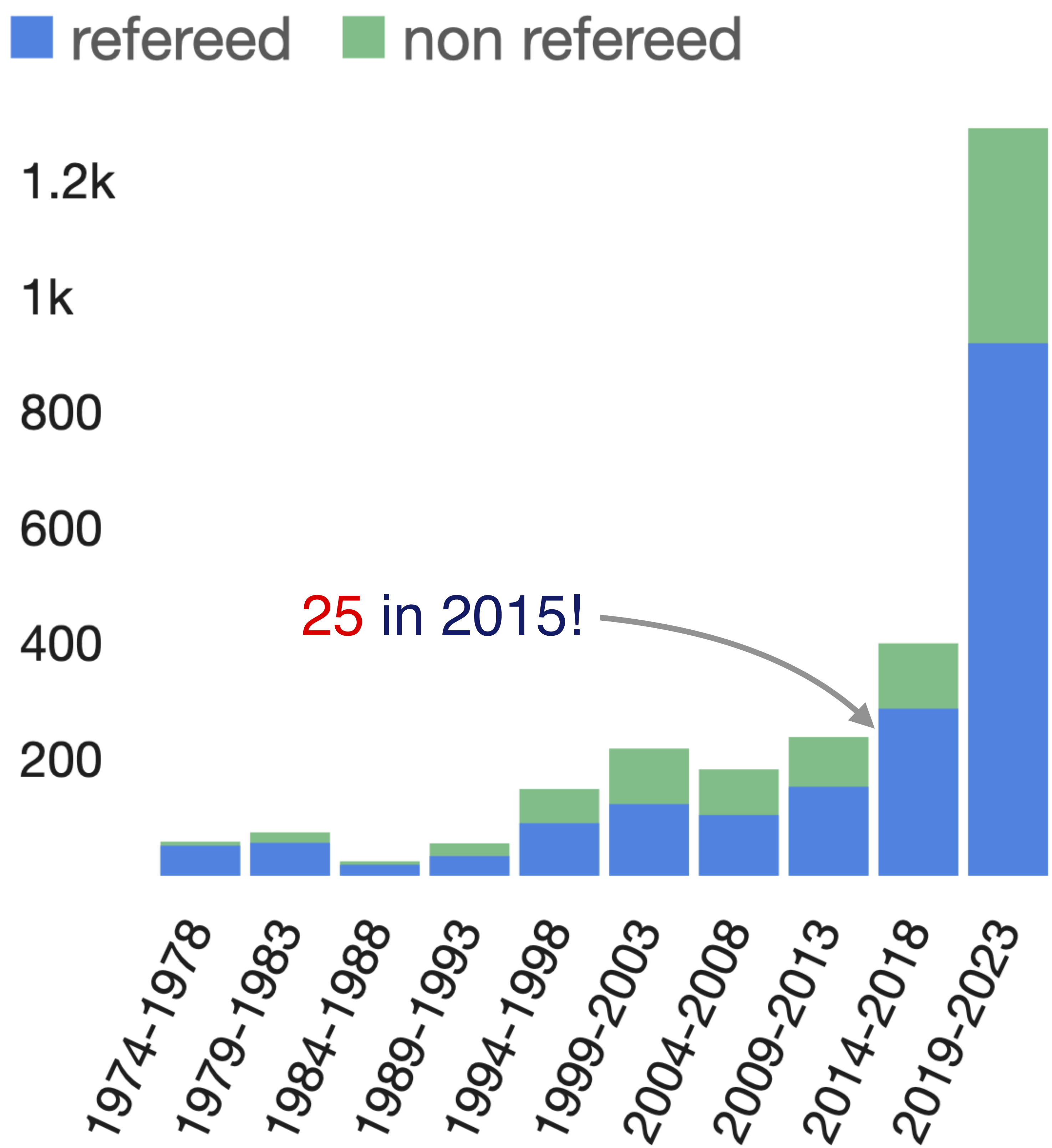
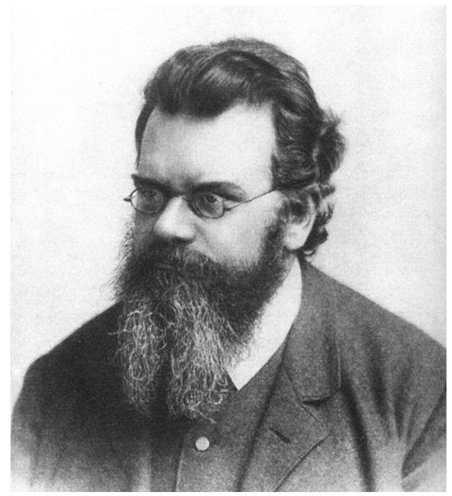


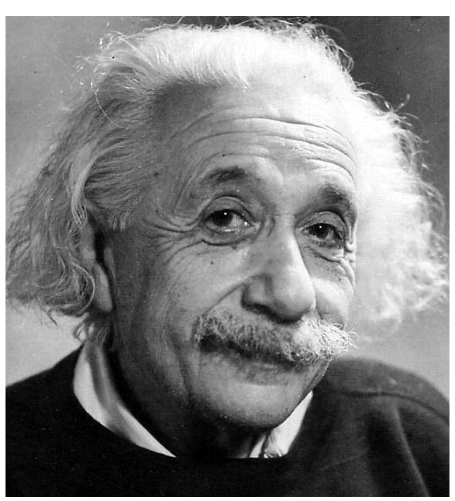
[SAO/NASA Astrophysics Data System]

Black Hole Evaporation



Thermodynamics

Quantum Mechanics



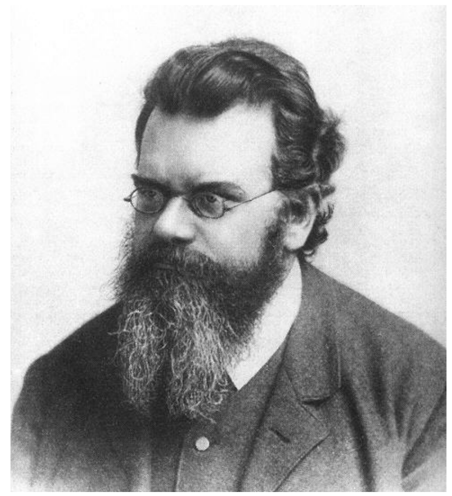
General Relativity

★ Black hole radiation

[Hawking 1974]

$$T_{BH}[\mathrm{K}] = 10^{-7}\,\frac{M_\odot}{M}$$

Black Hole Evaporation



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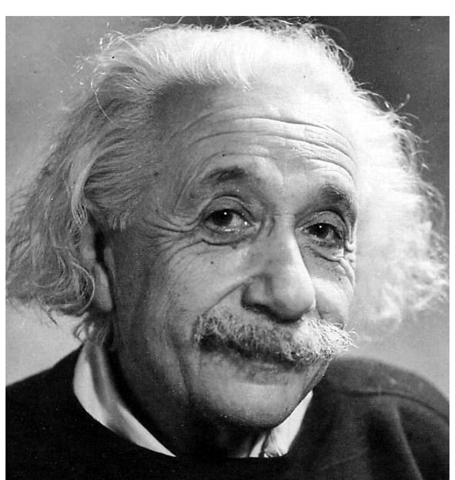

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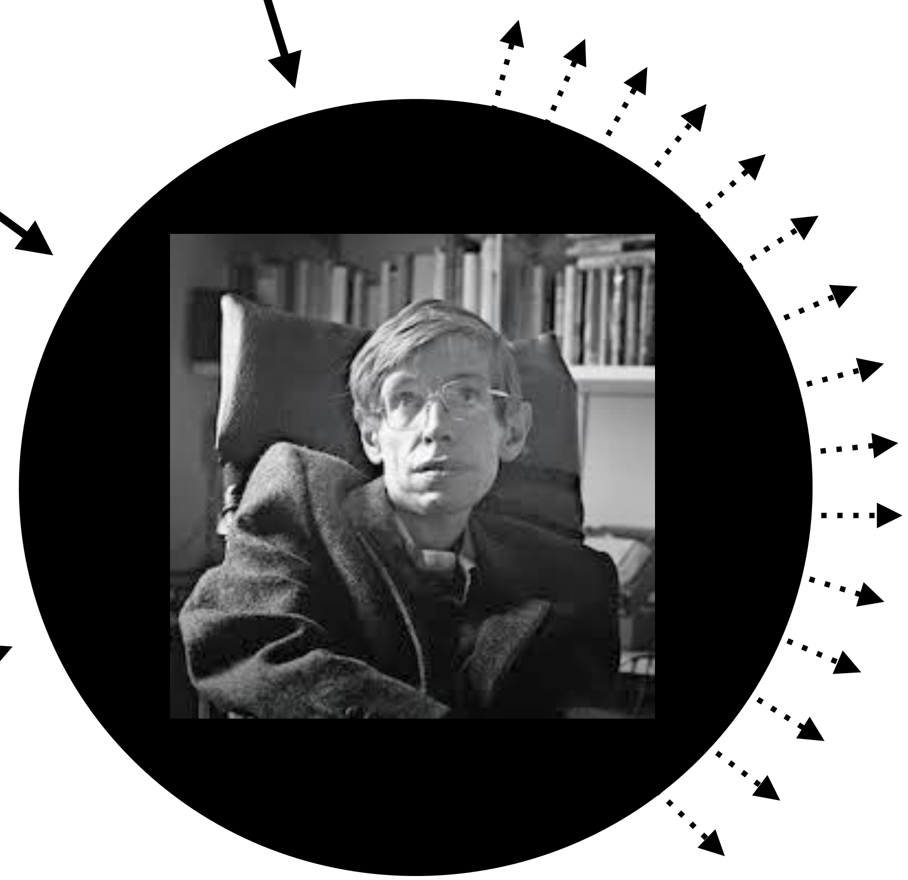


★ Black hole radiation

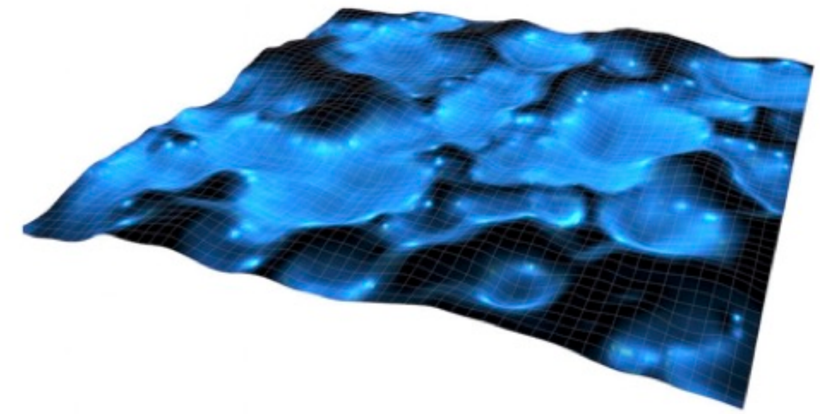
[Hawking 1974]

$$T_{BH}[\mathrm{K}] = 10^{-7}\,\frac{M_\odot}{M}$$

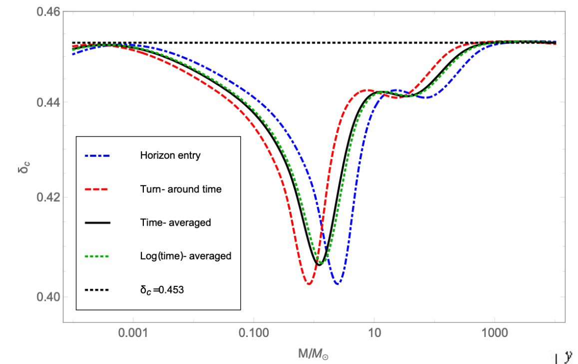
★ PBHs are important even if never observed!

Primordial Black Hole Formation Primer

PBH Formation Mechanisms

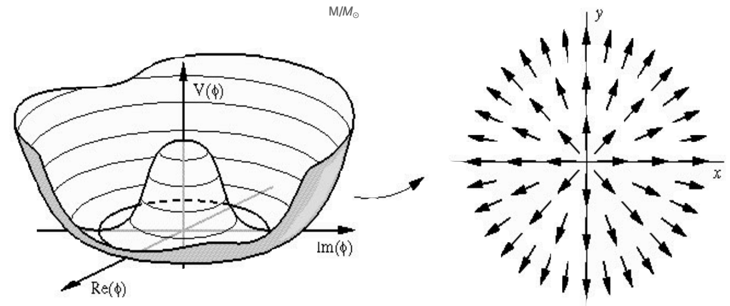


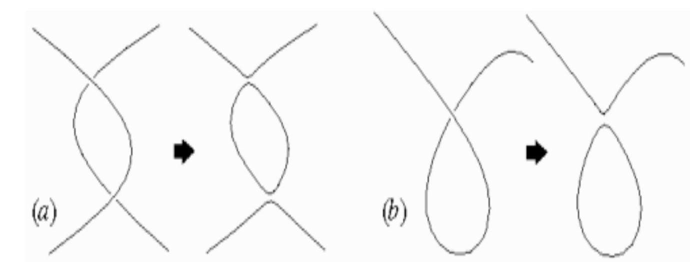
★ Large density perturbations (inflation)



[Byrnes *et al.* 2018]

★ Pressure reduction

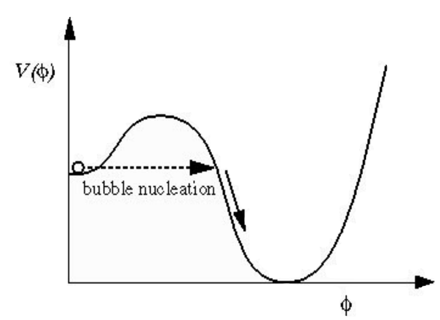


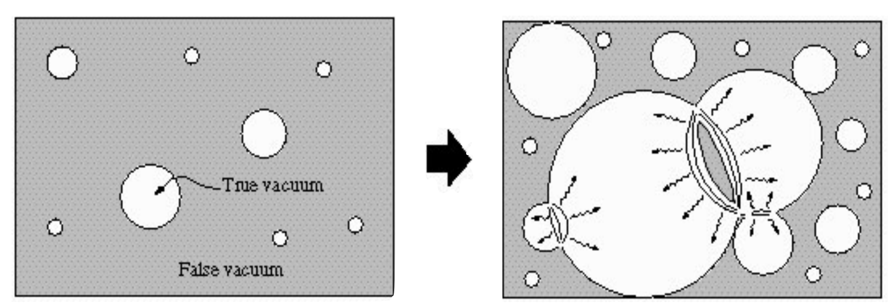


★ Cosmic string loops

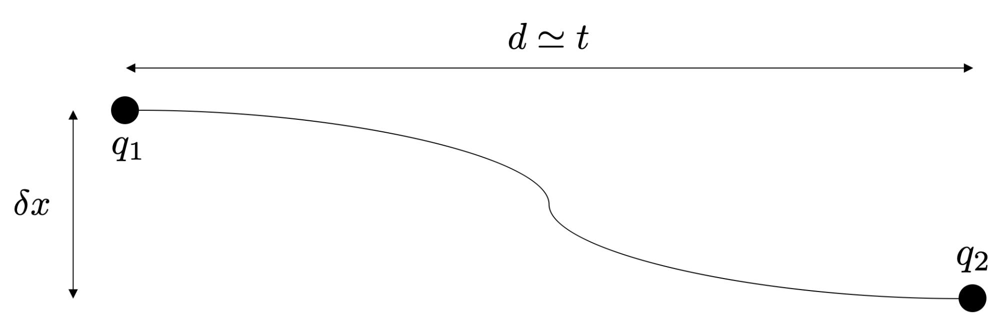
http://www.damtp.cam.ac.uk/research/gr/public/cs_phase.html

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





★ Bubble collisions



★ Quark confinement

[Dvali, FK, Zantedesschi 2021]

★ Scalar-field fragmentation, ...

PBH Formation from Inflationary Overdensities

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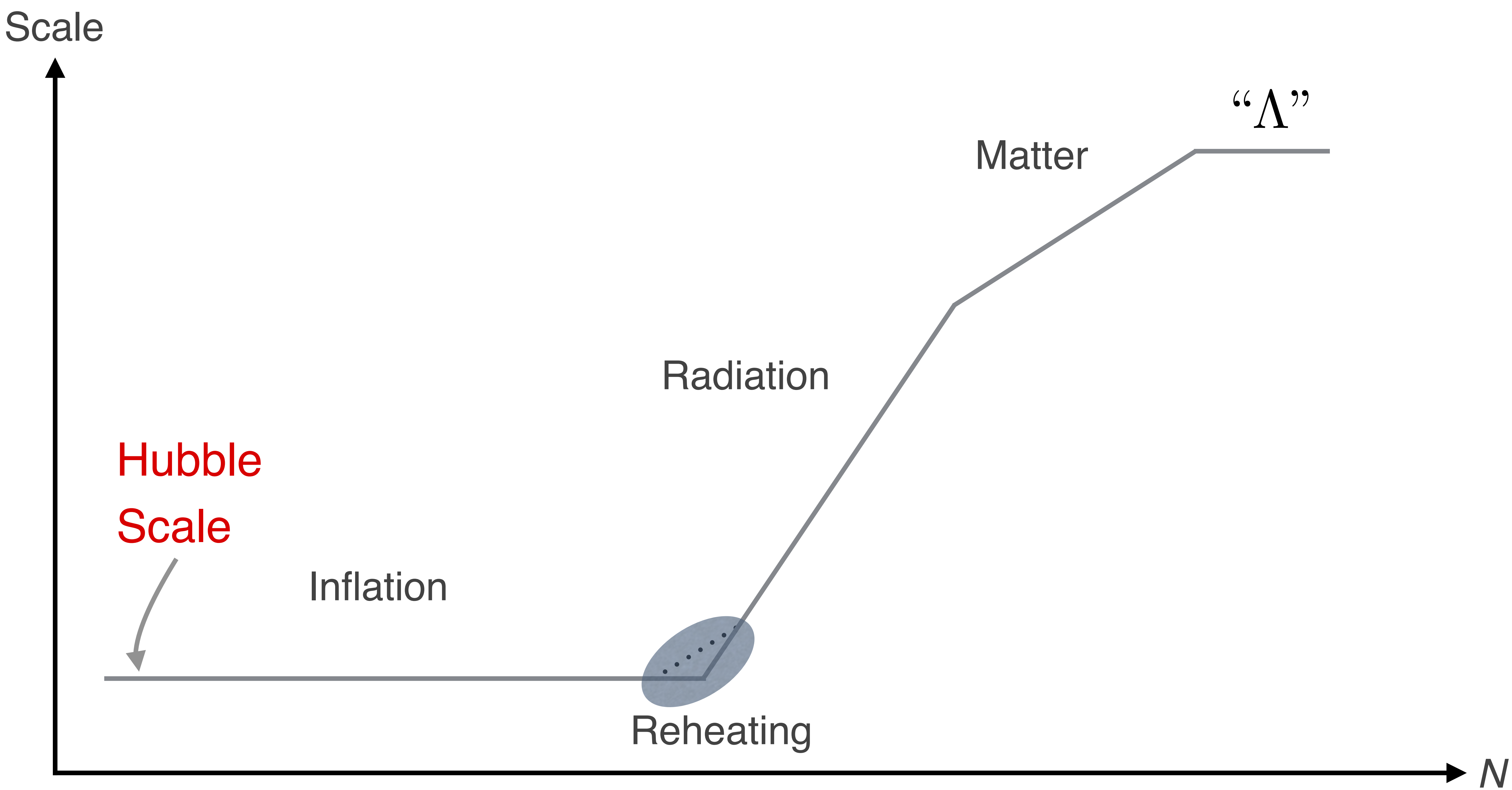
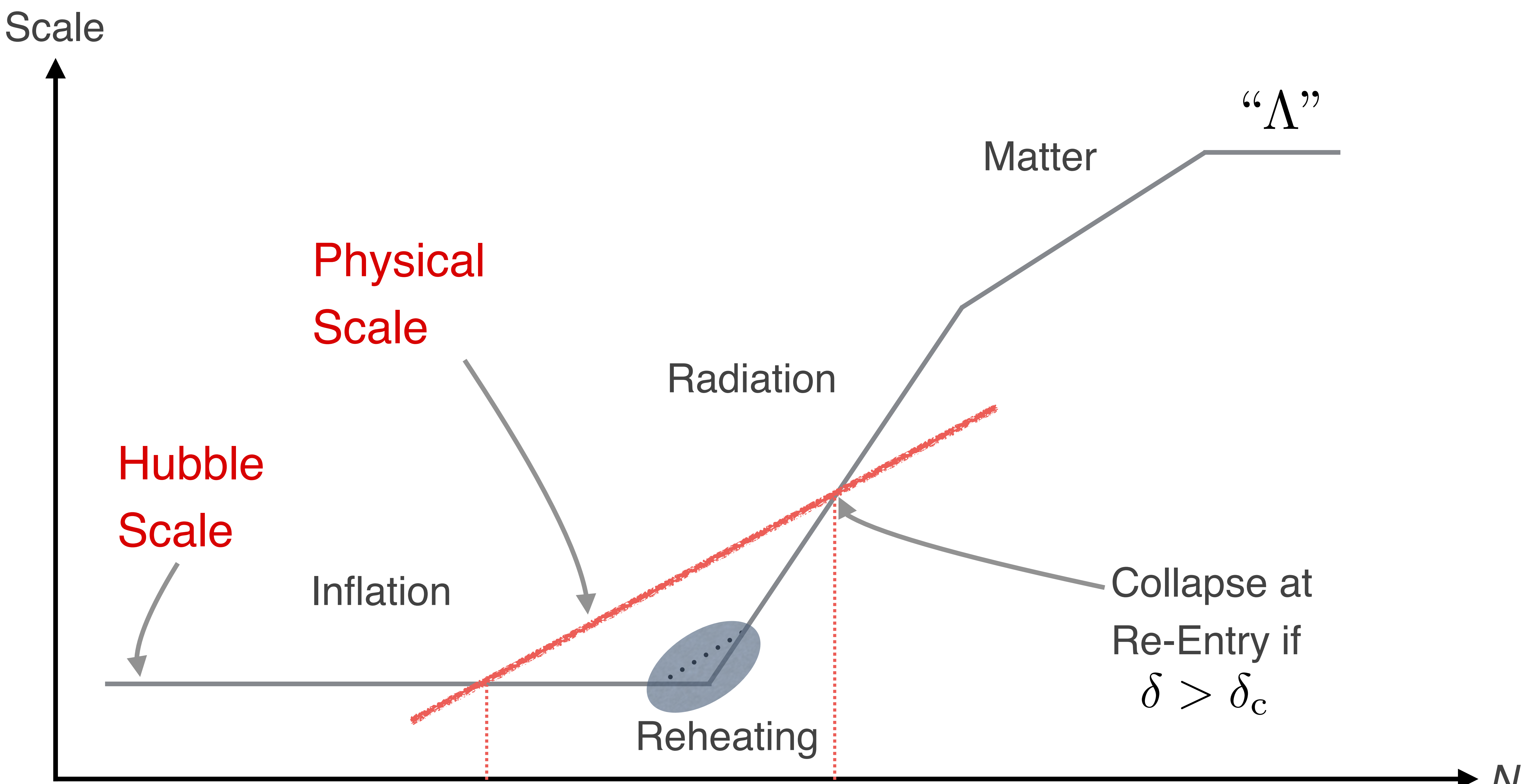


PBH Formation from Inflationary Overdensities



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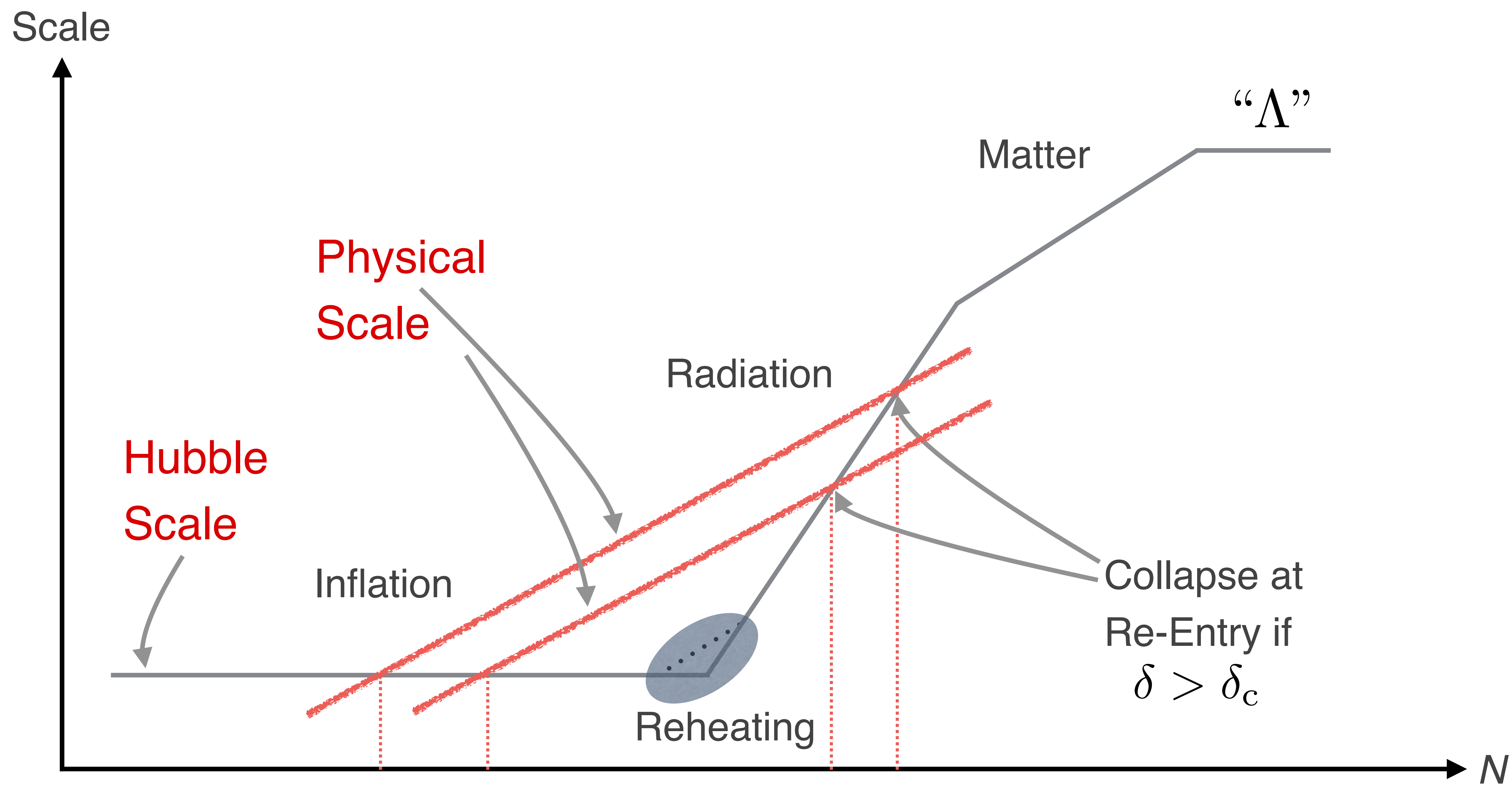
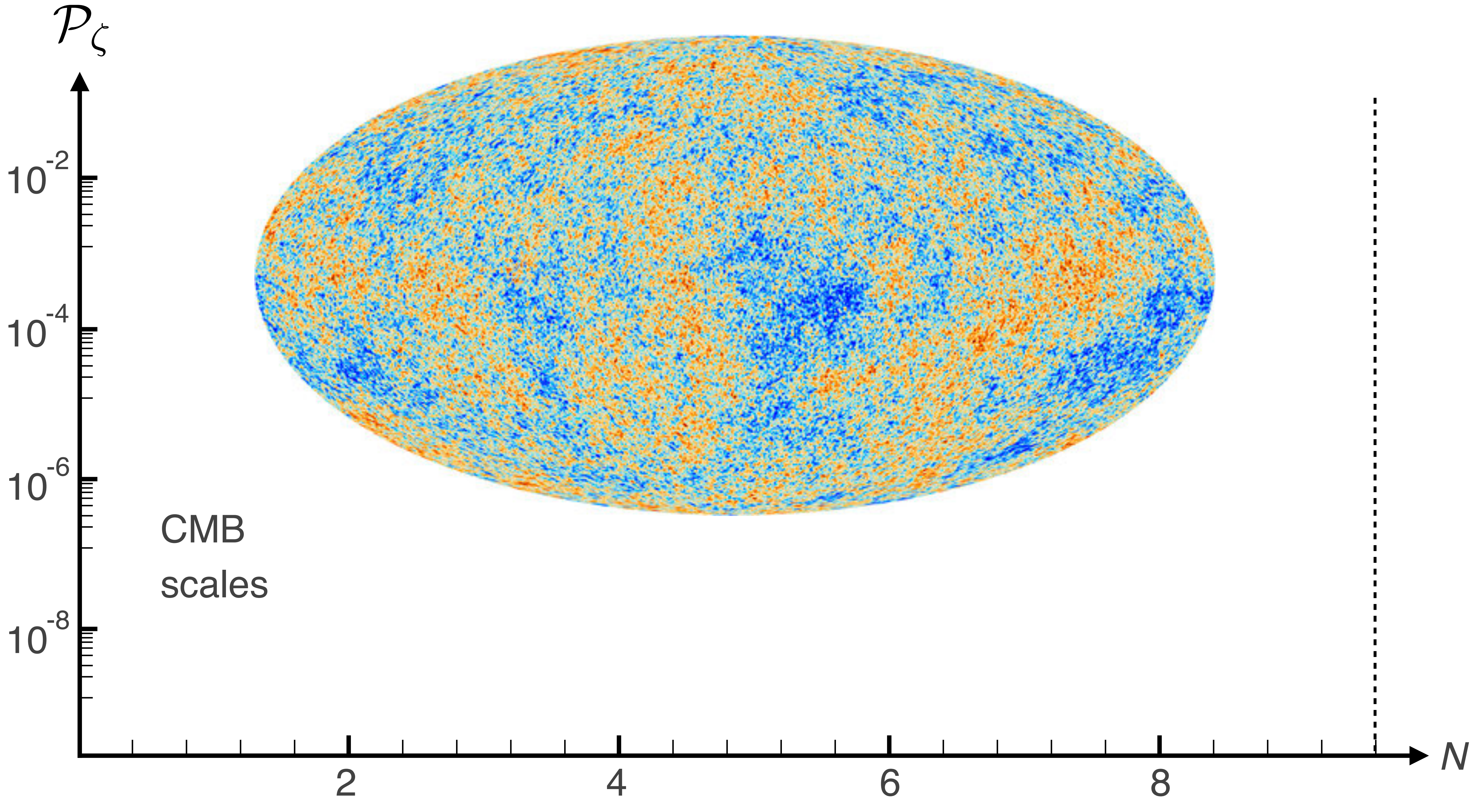


PBH Formation — Scales



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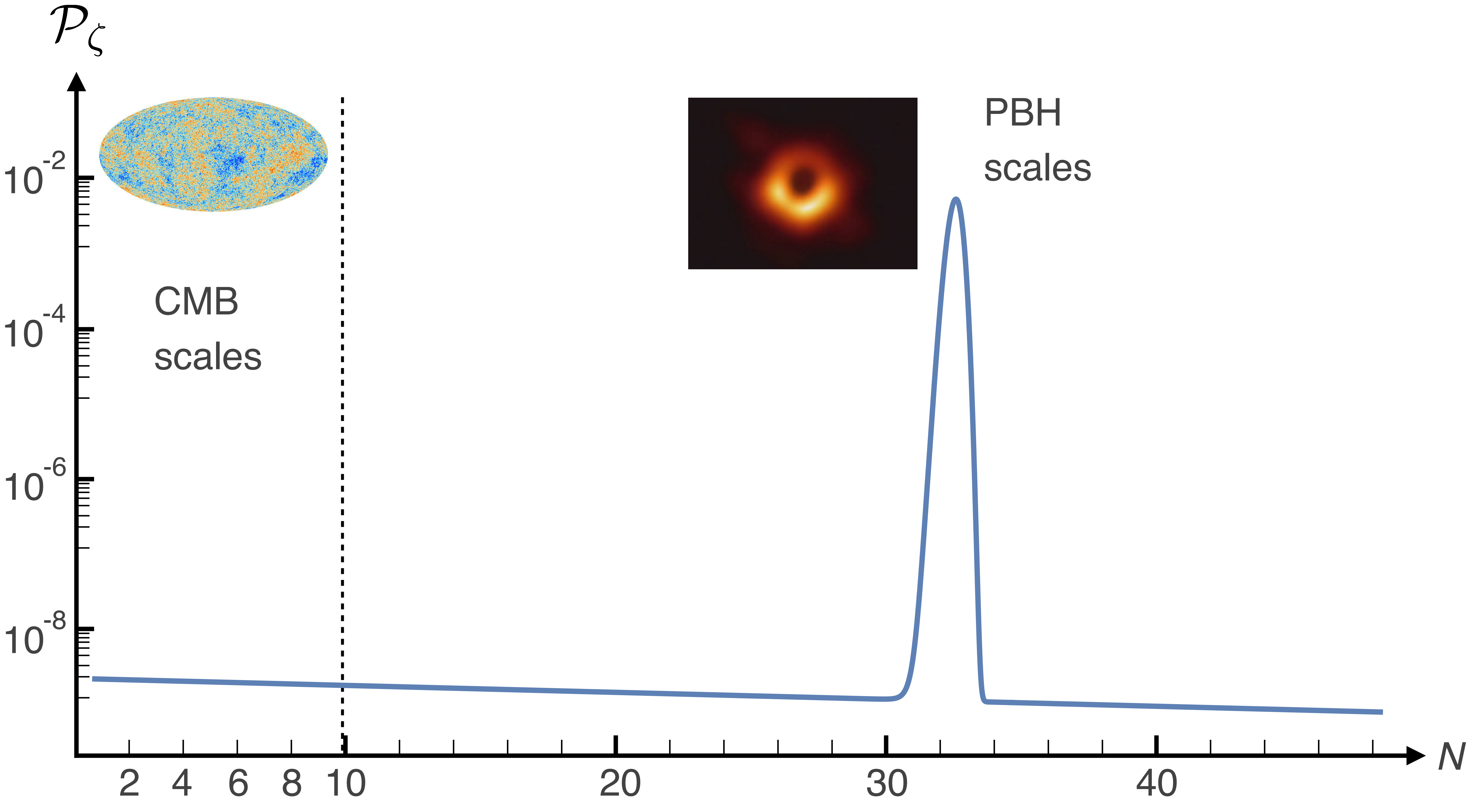

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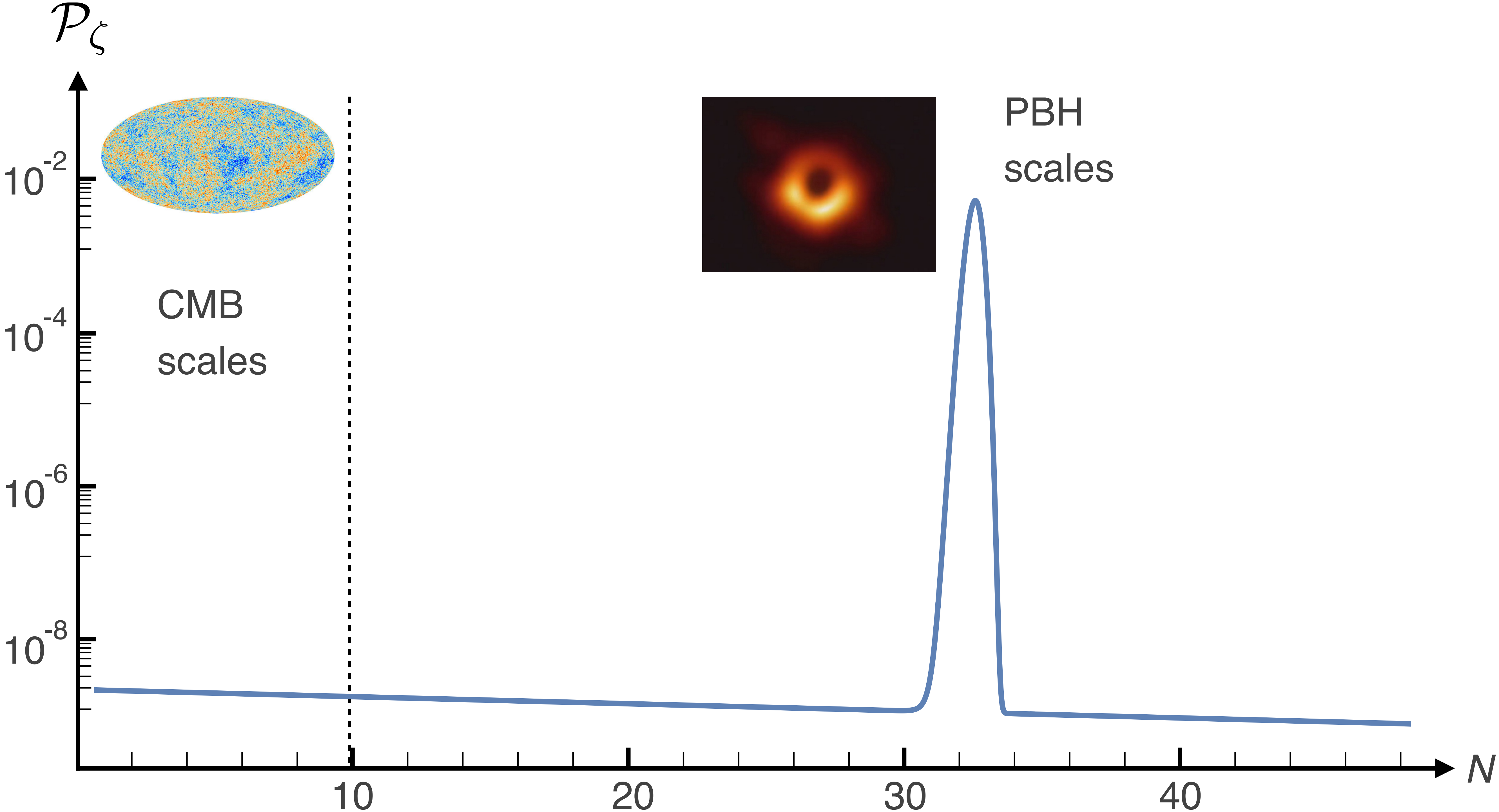
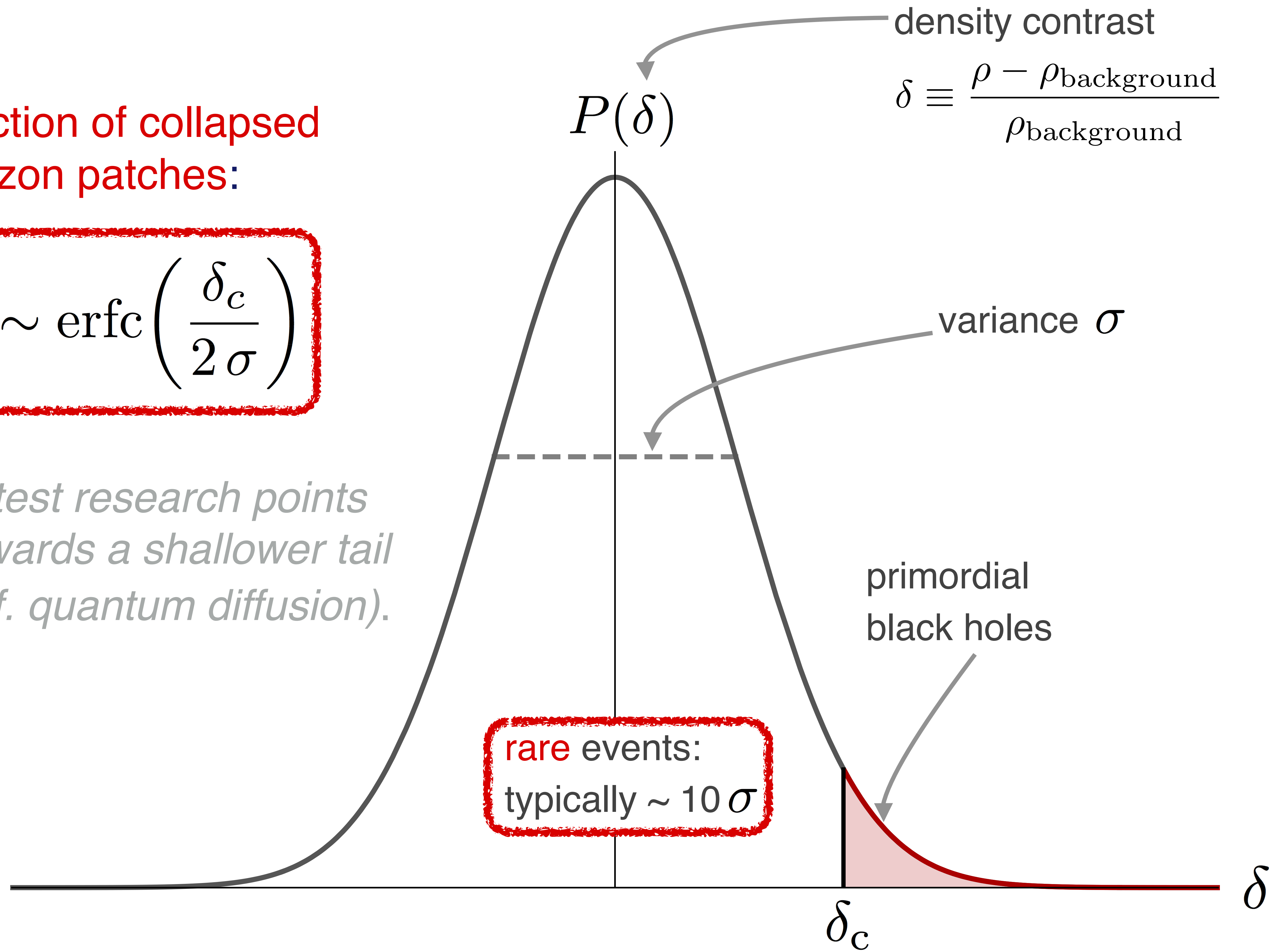


PBH Formation — Rare Events

Fraction of collapsed horizon patches:

$$\beta \sim \mathrm{erfc}\left(\frac{\delta_c}{2\,\sigma}\right)$$

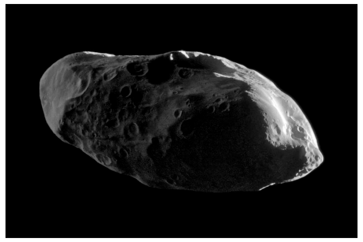
Latest research points towards a shallower tail (c.f. quantum diffusion).



PBHs — Some Numbers

★ If primordial black holes constituted all of the dark matter:

- ★ Assume that all PBH have mass: 10^{20} g



Saturn satellite *Prometheus*

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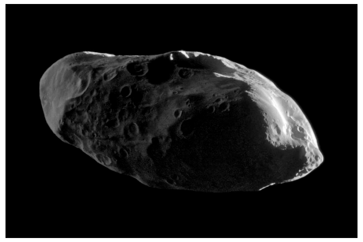
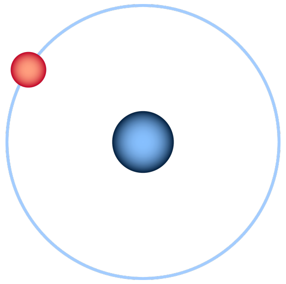


Saturn satellite *Prometheus*

- ★ Size: $10^{-8}\,\mathrm{cm}$



Hydrogen Atom

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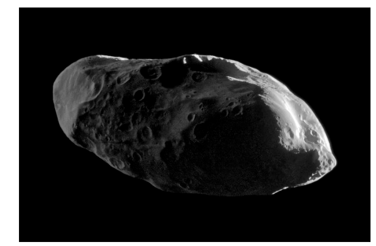

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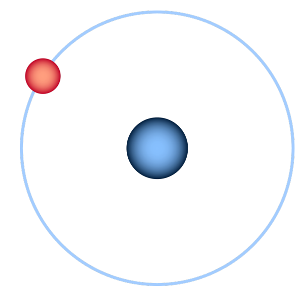

Hydrogen Atom

★ Number in our Galaxy: 10^{25}

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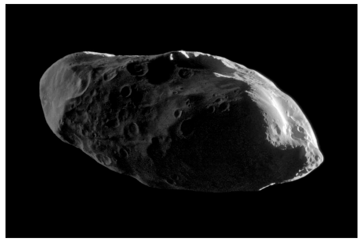

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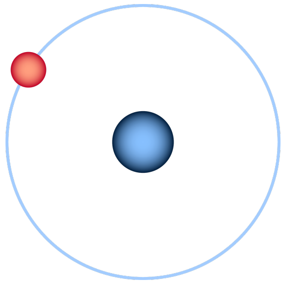


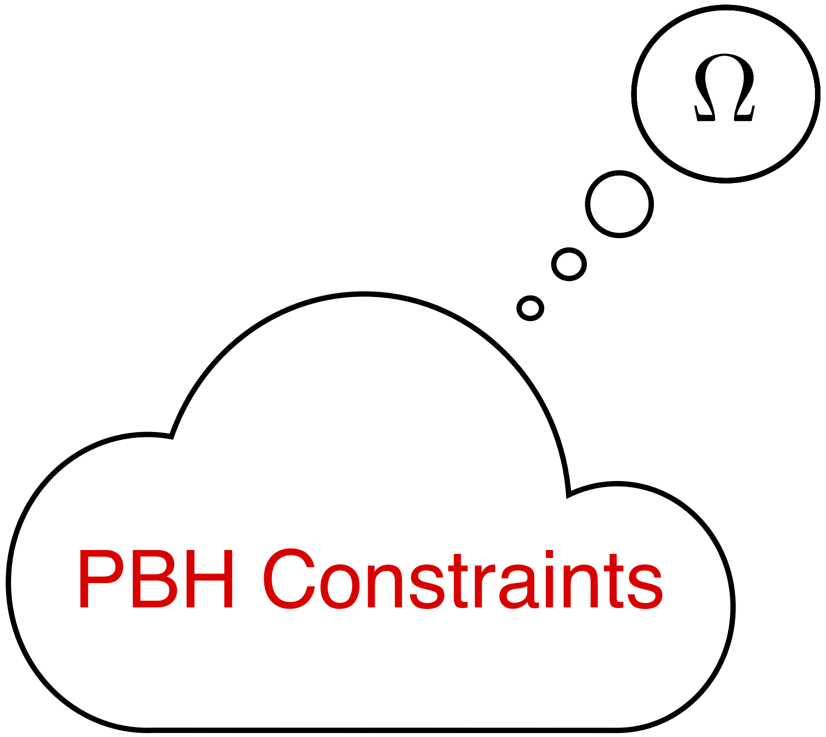
Hydrogen Atom

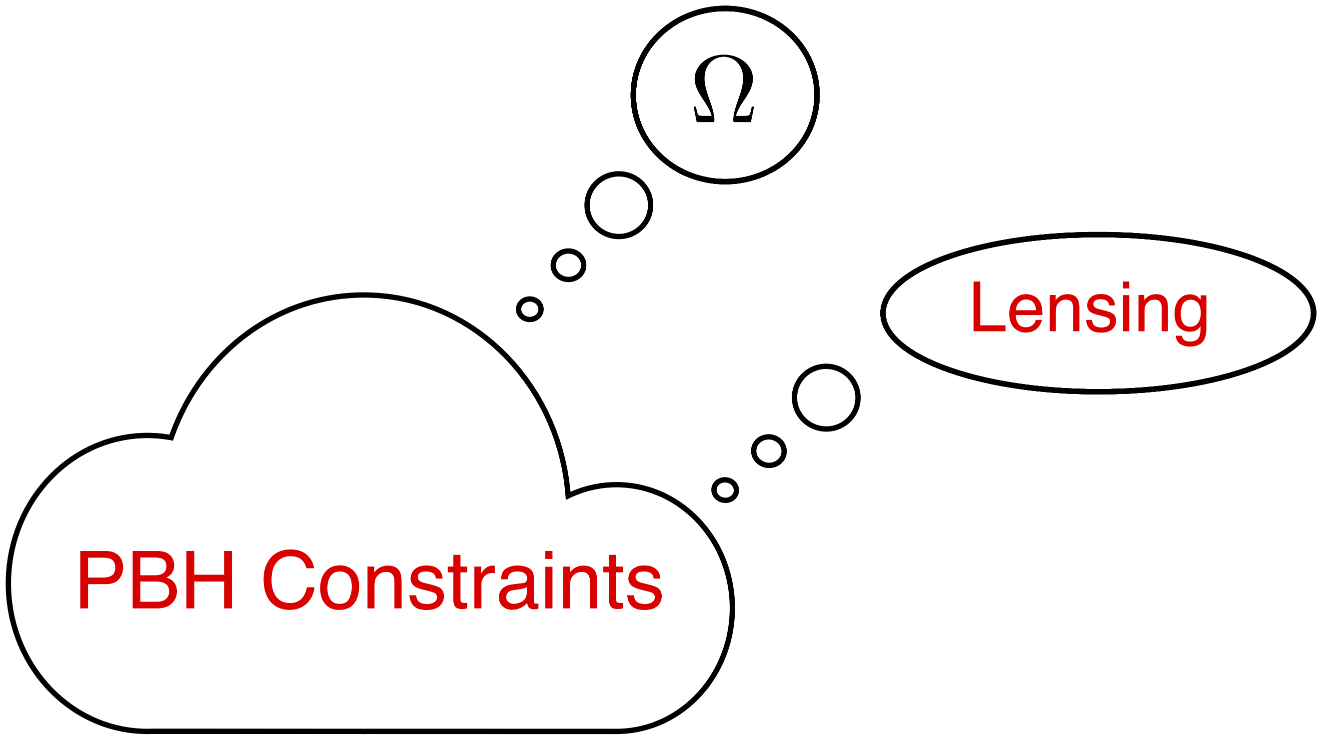
★ Number in our Galaxy: 10^{25}

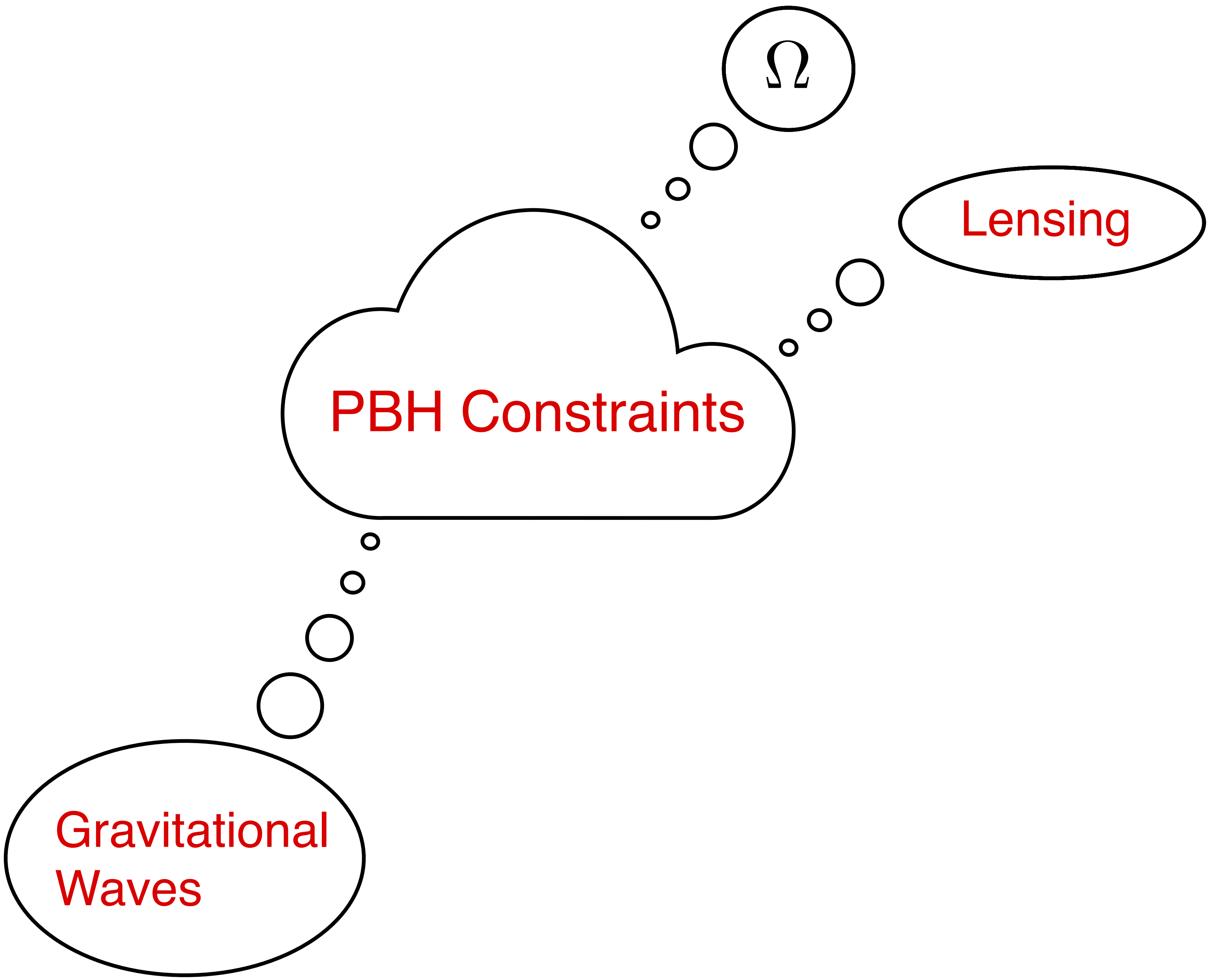
★ Distance: 10 AU

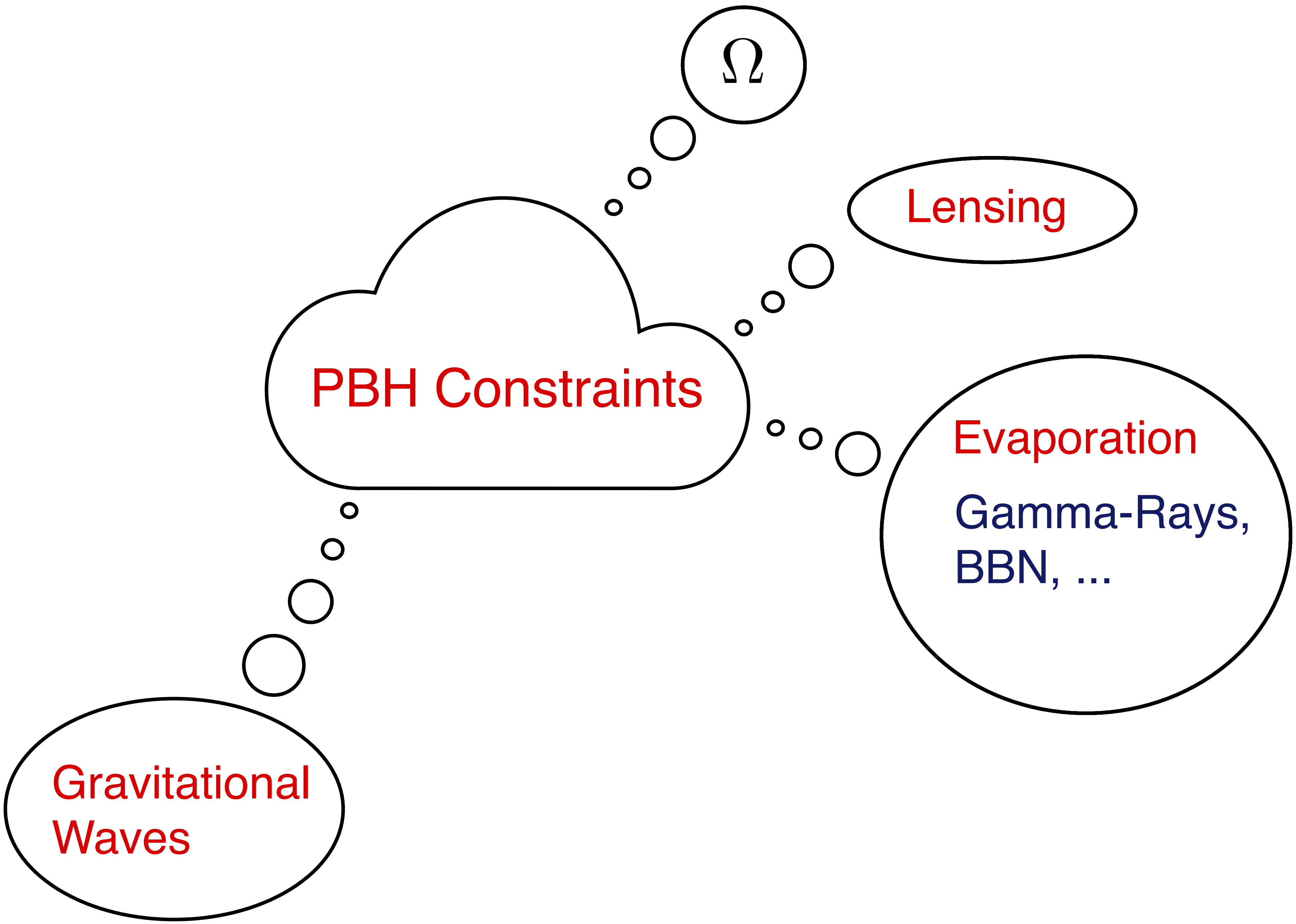
Primordial Black Hole Constraints

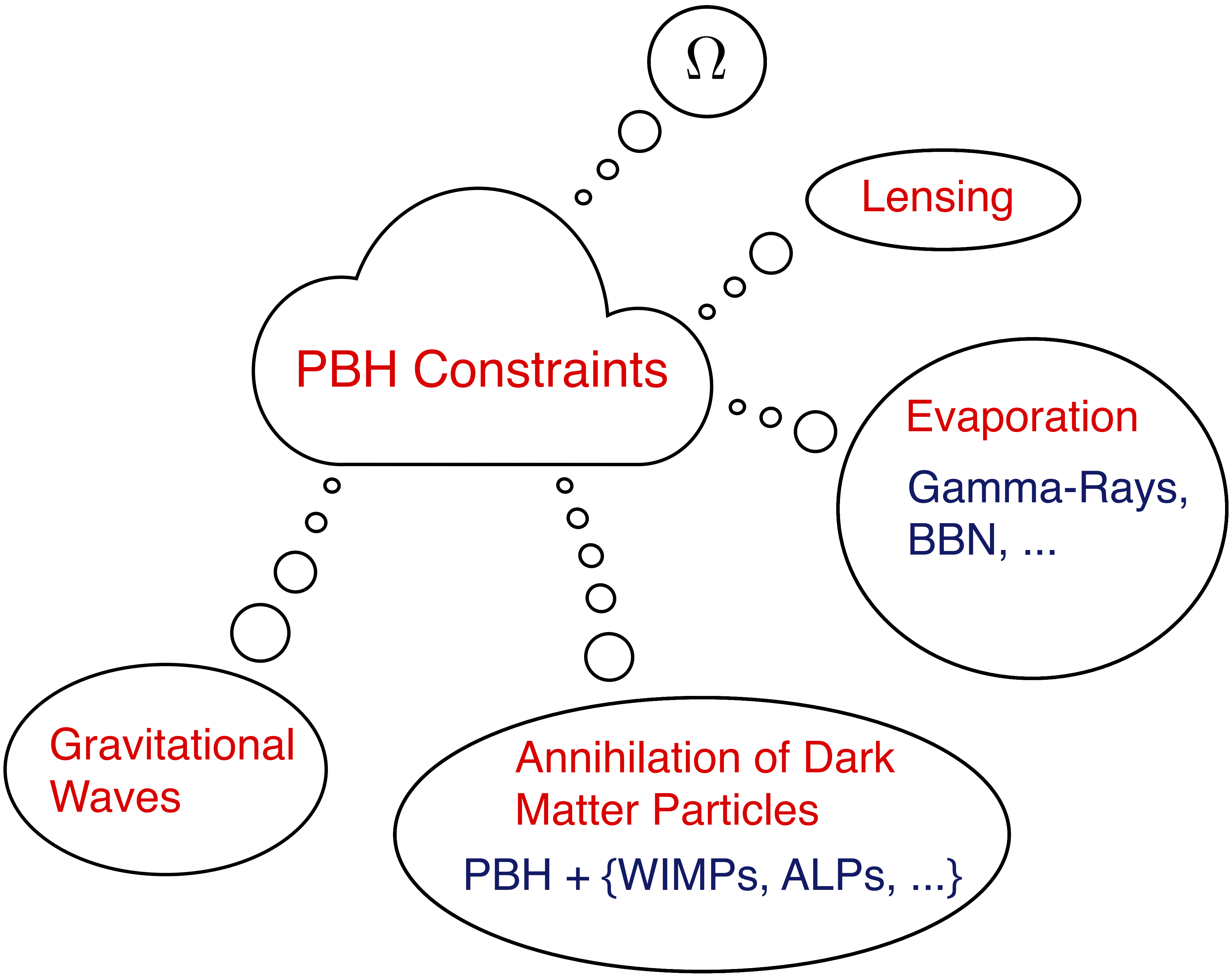
PBH Constraints

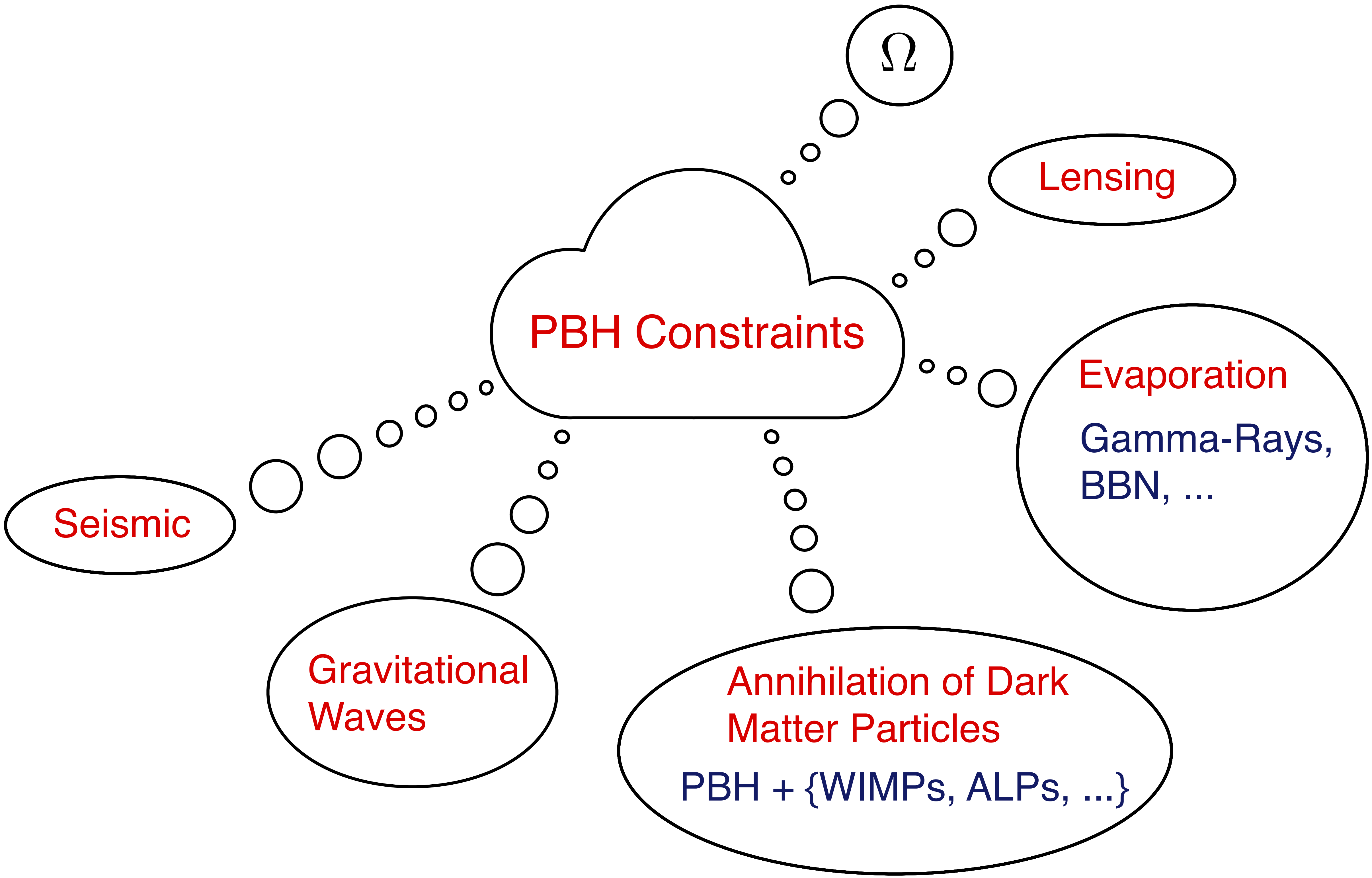

PBH Constraints
Ω


Ω
Lensing
PBH Constraints


Ω
Lensing
PBH Constraints
Gravitational
Waves


Ω
Lensing
PBH Constraints
Evaporation
Gamma-Rays,
BBN, ...
Gravitational
Waves


Ω
Lensing
PBH Constraints
Evaporation
Gamma-Rays,
BBN, ...
Gravitational
Waves
Annihilation of Dark
Matter Particles
PBH + {WIMPs, ALPs, ...}


Ω
Lensing
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Evaporation
Gamma-Rays,
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Seismic
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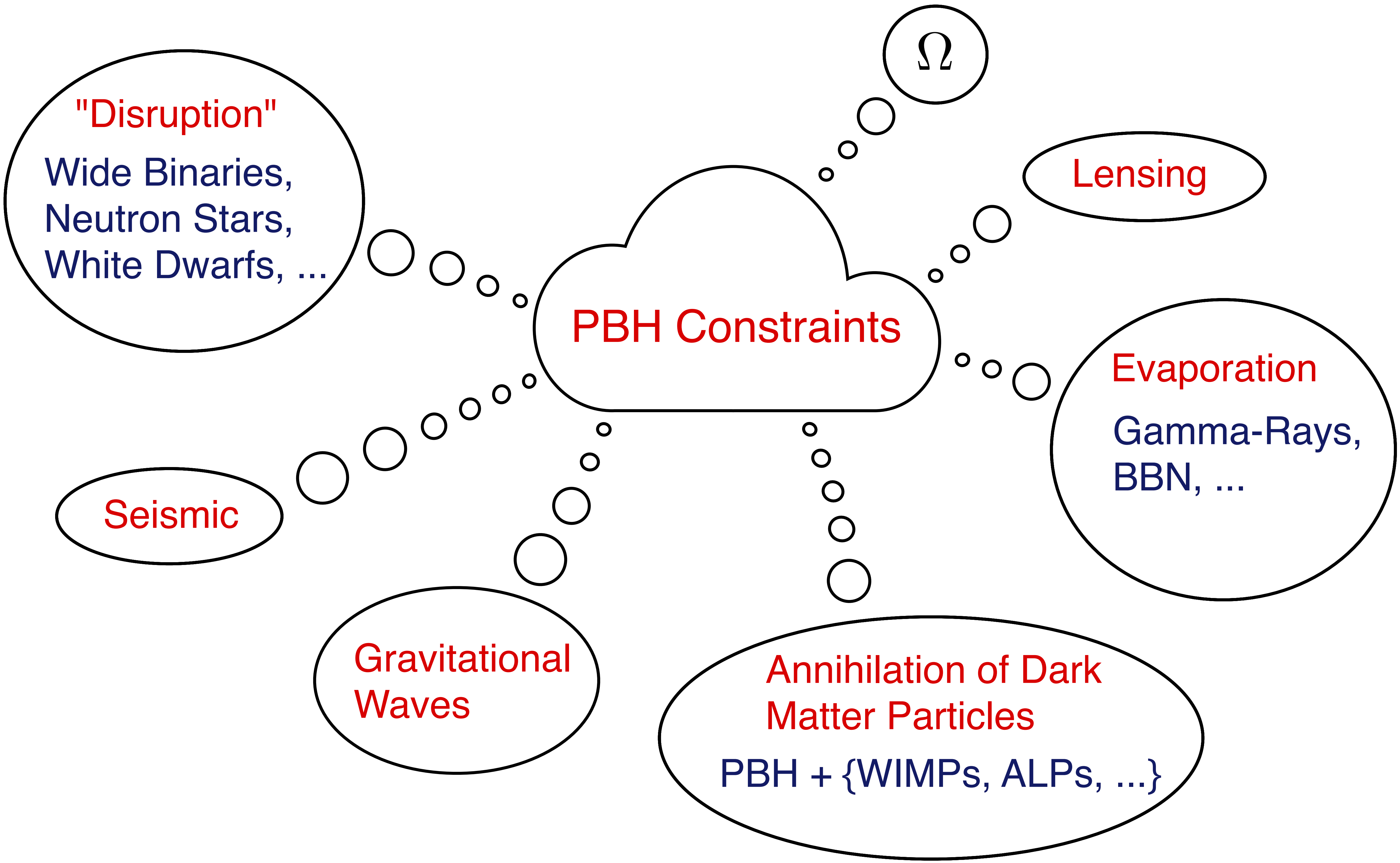
Ω
"Disruption"
Wide Binaries,
Neutron Stars,
White Dwarfs, ...
Lensing
PBH Constraints
Evaporation
Gamma-Rays,
BBN, ...
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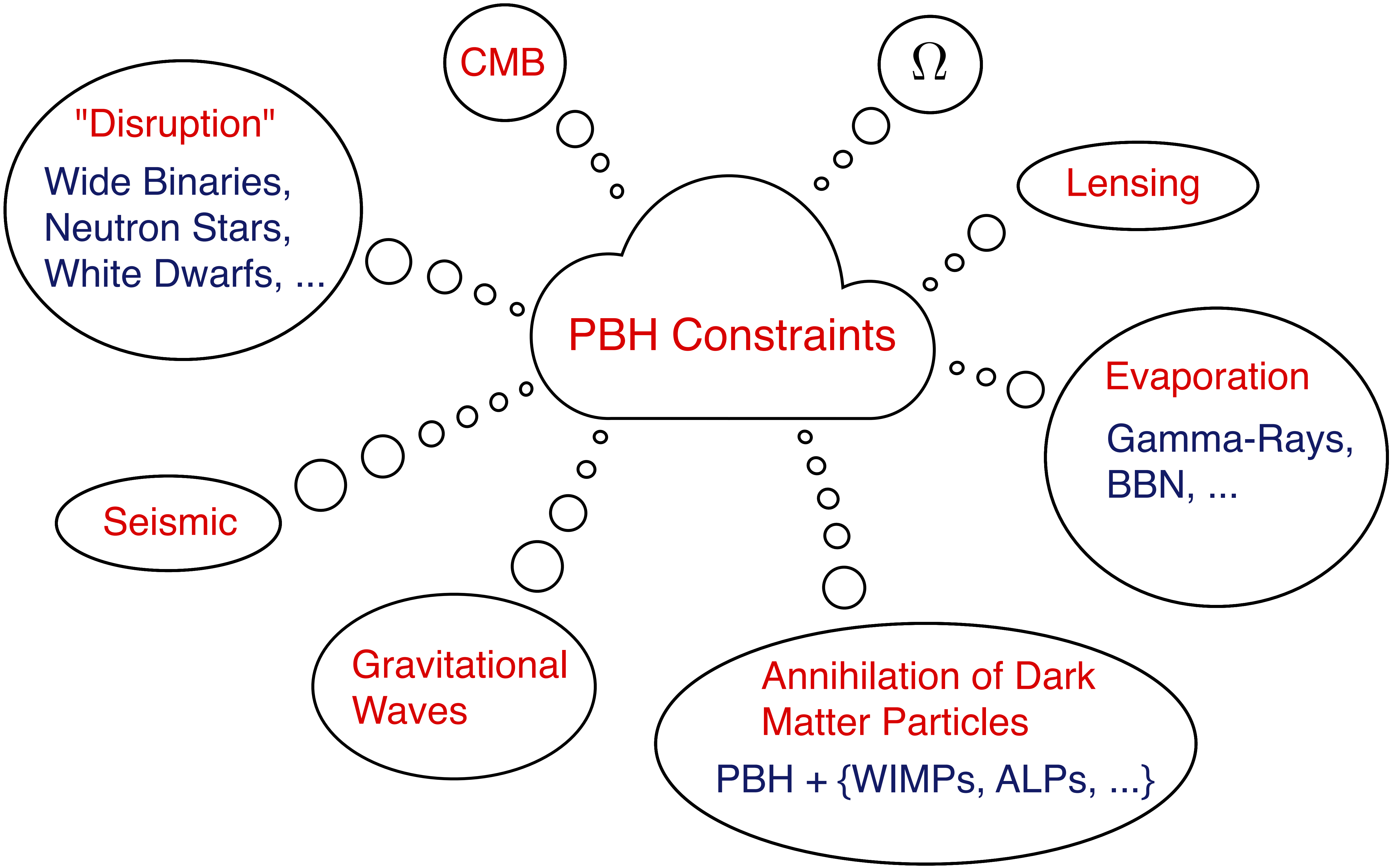

PBH Constraints
CMB
Ω
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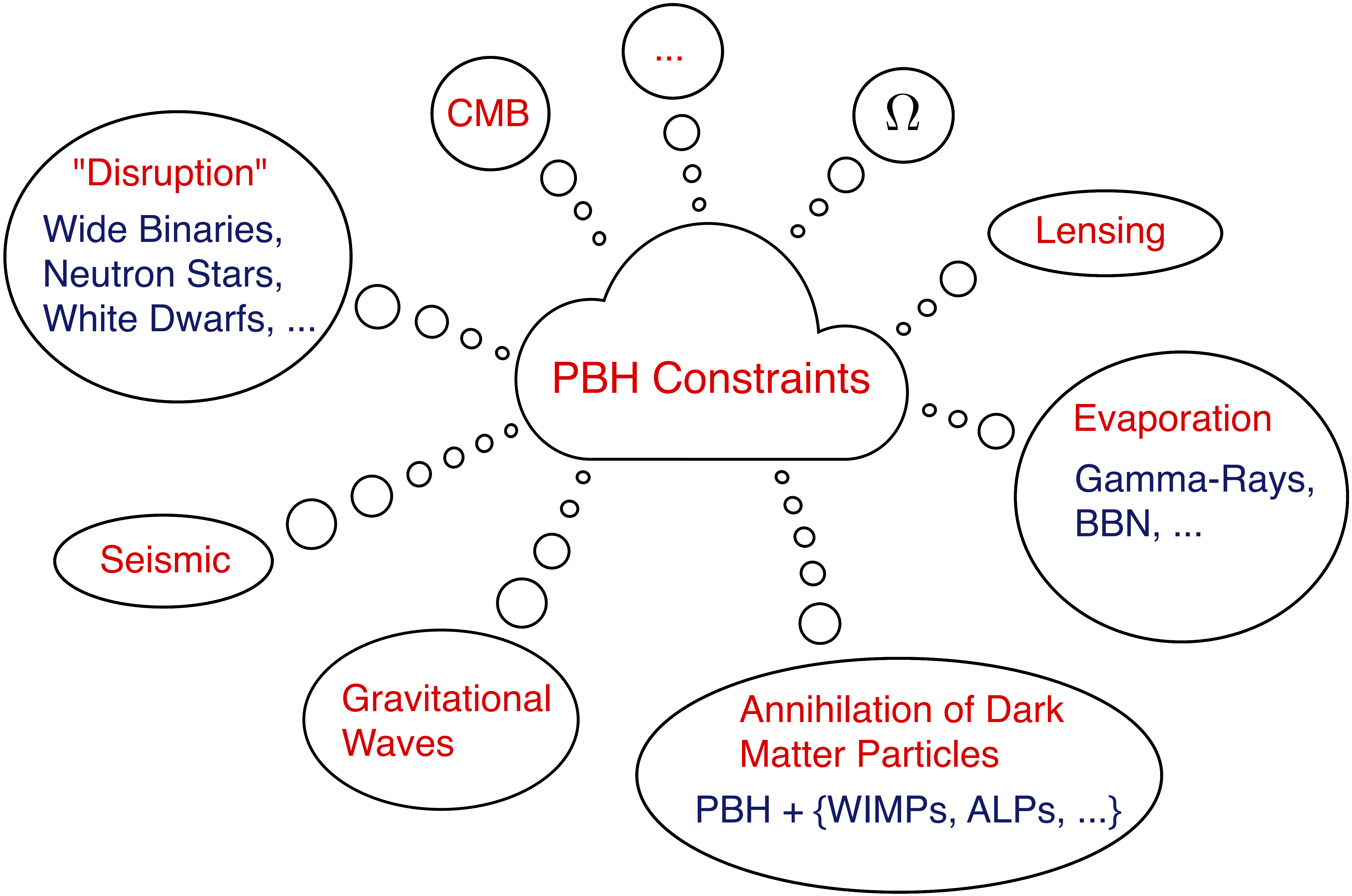
PBH Constraints
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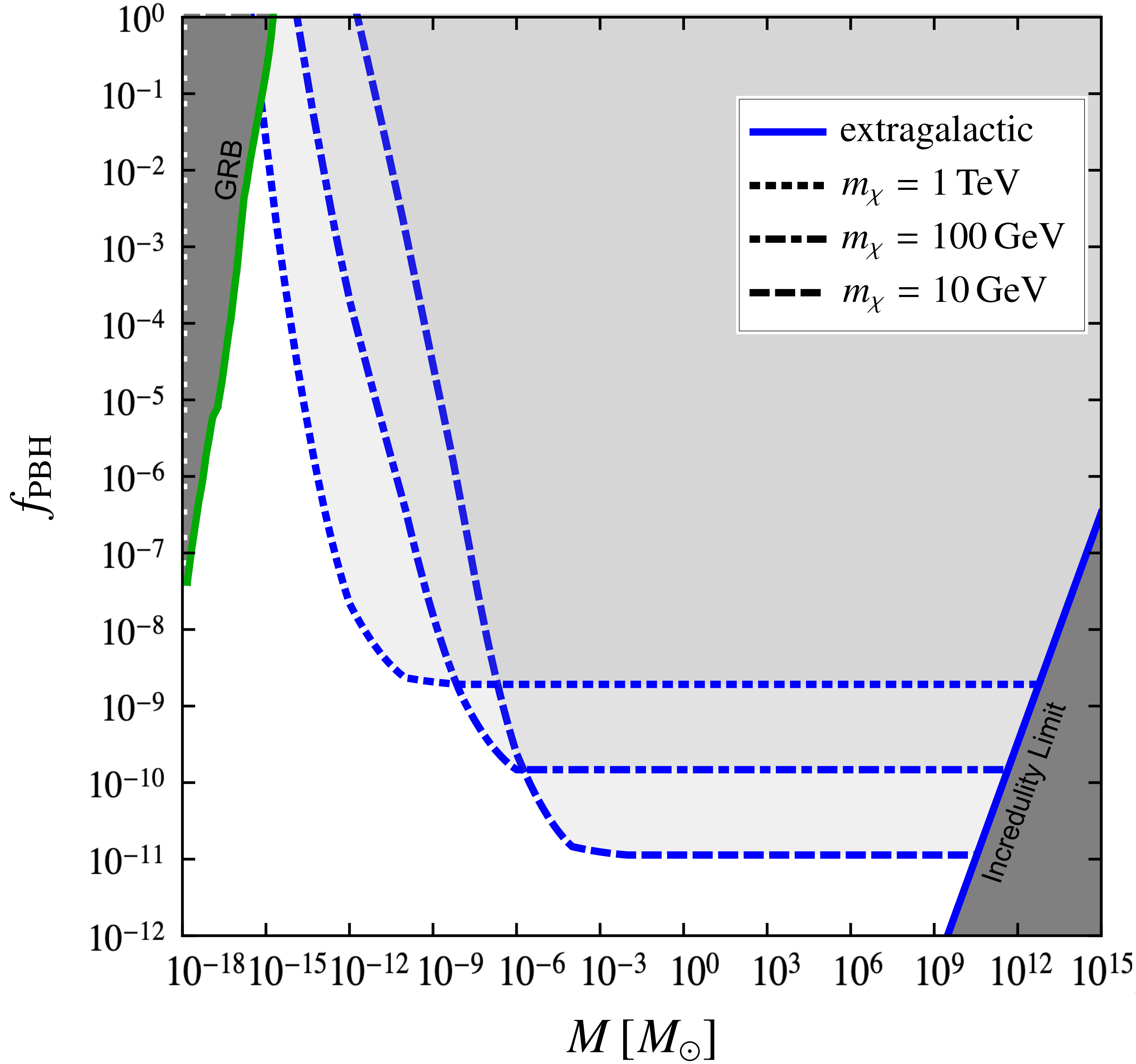
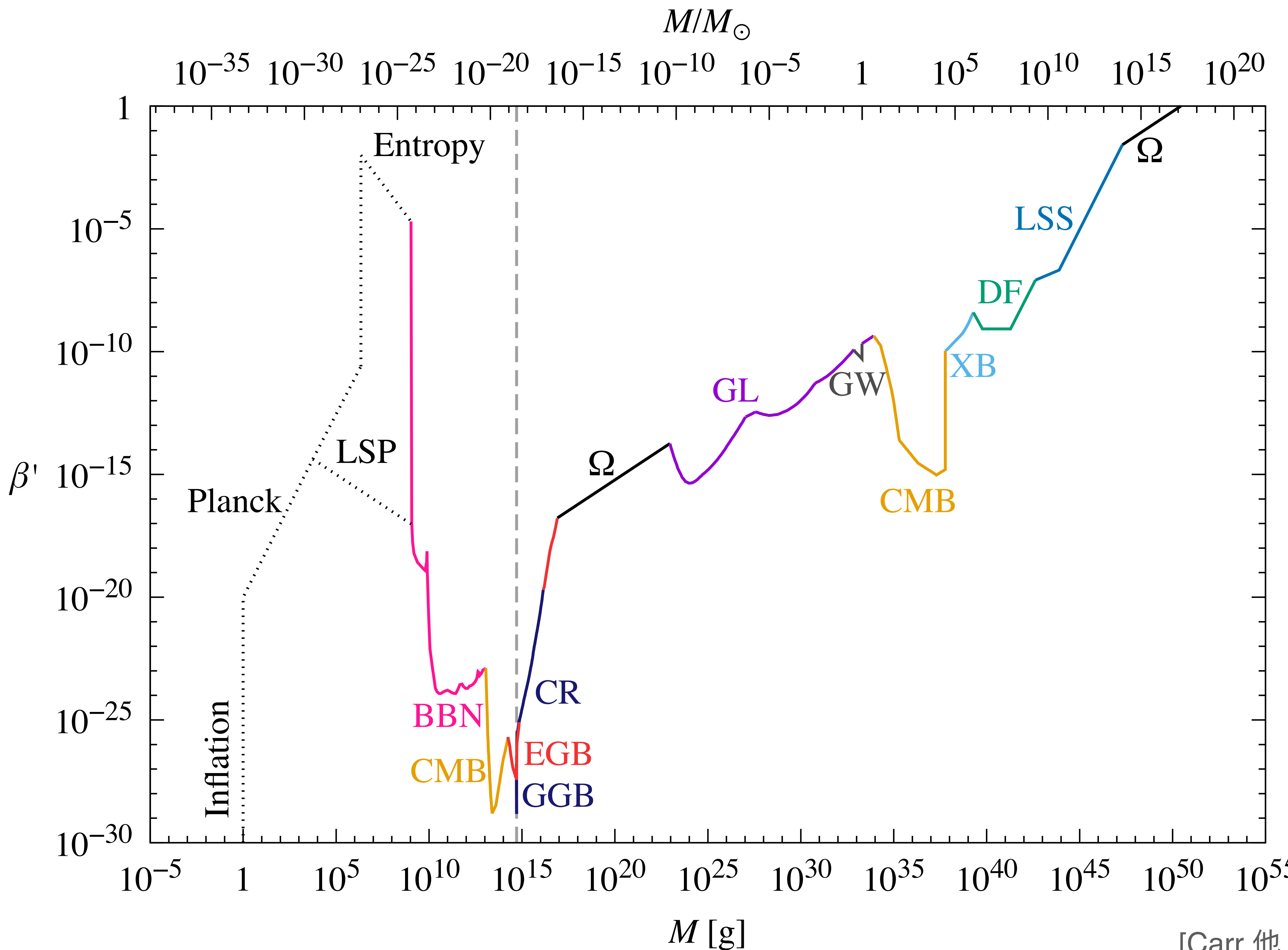
PBHs & WIMPs



[Carr, FK, Visinelli 2021]

PBH Constraints at Formation



[Carr 他 2021]

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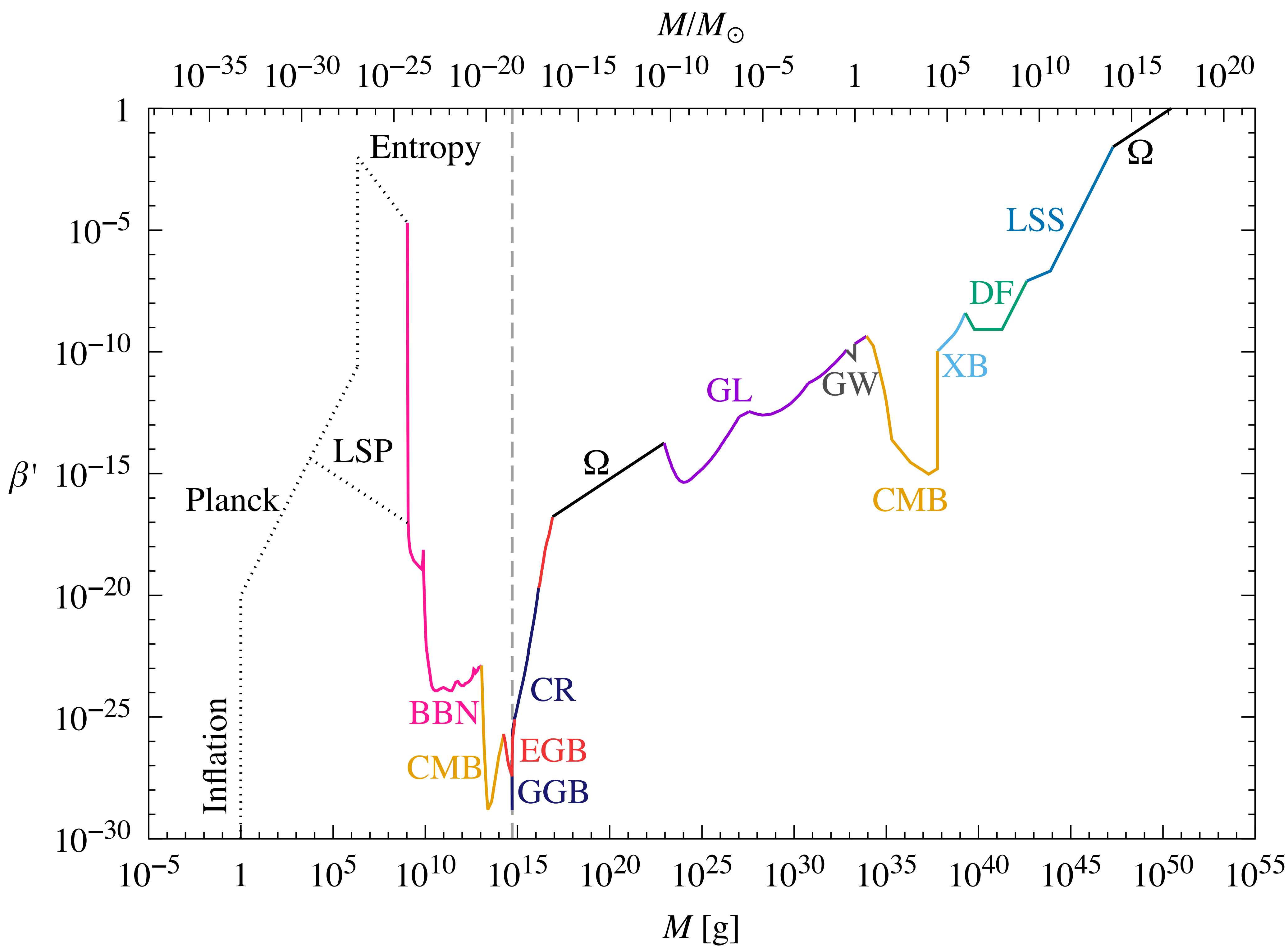
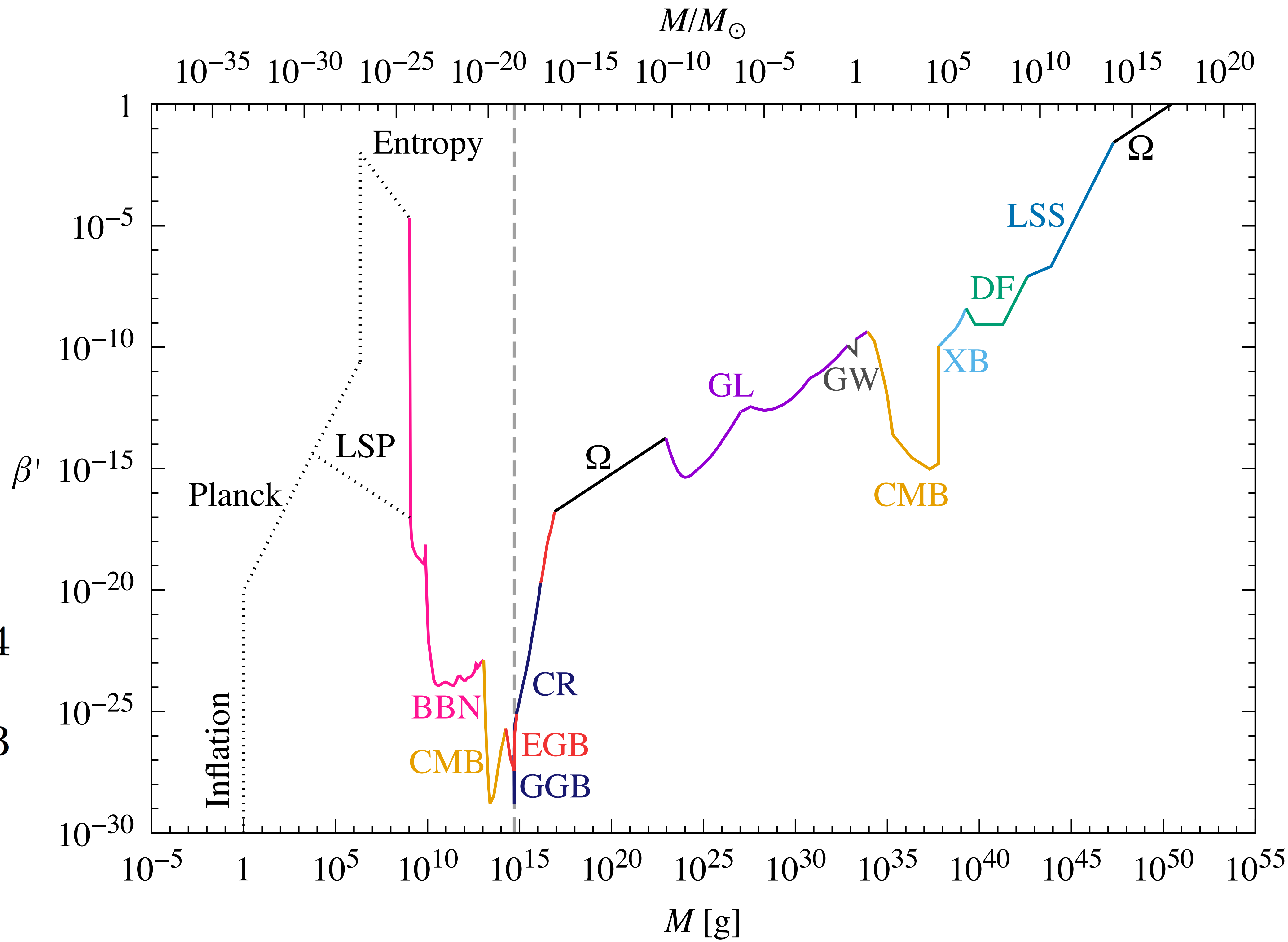


[Carr 他 2021]

PBH Constraints at Formation

$$\propto \Omega_{\rm PBH}\Big|_{\rm form}$$



[Carr 他 2021]

★ Note that

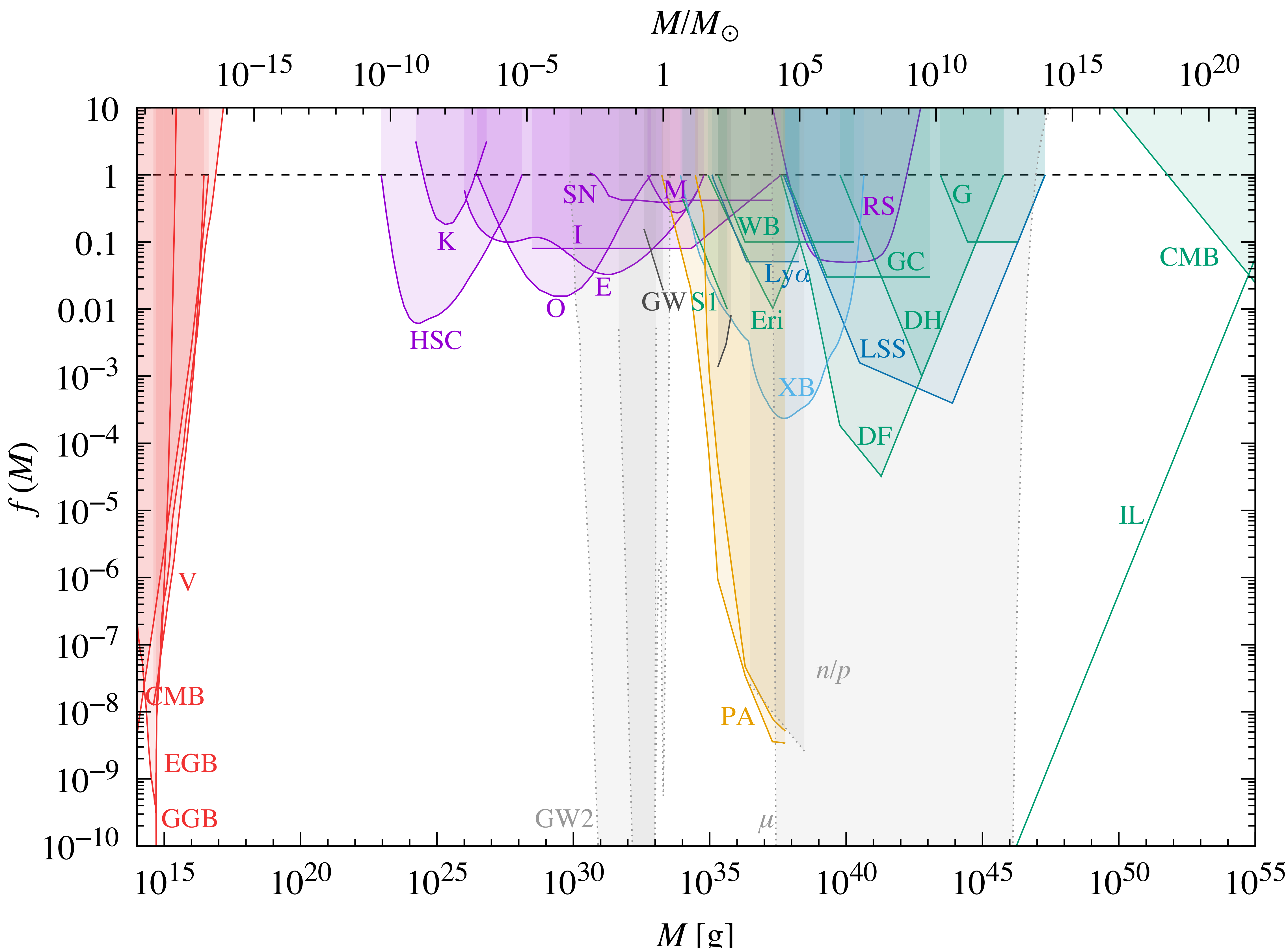
$$\rho_{\rm rad} \propto a^{-4}$$

$$\rho_{\rm PBH} \propto a^{-3}$$

and hence

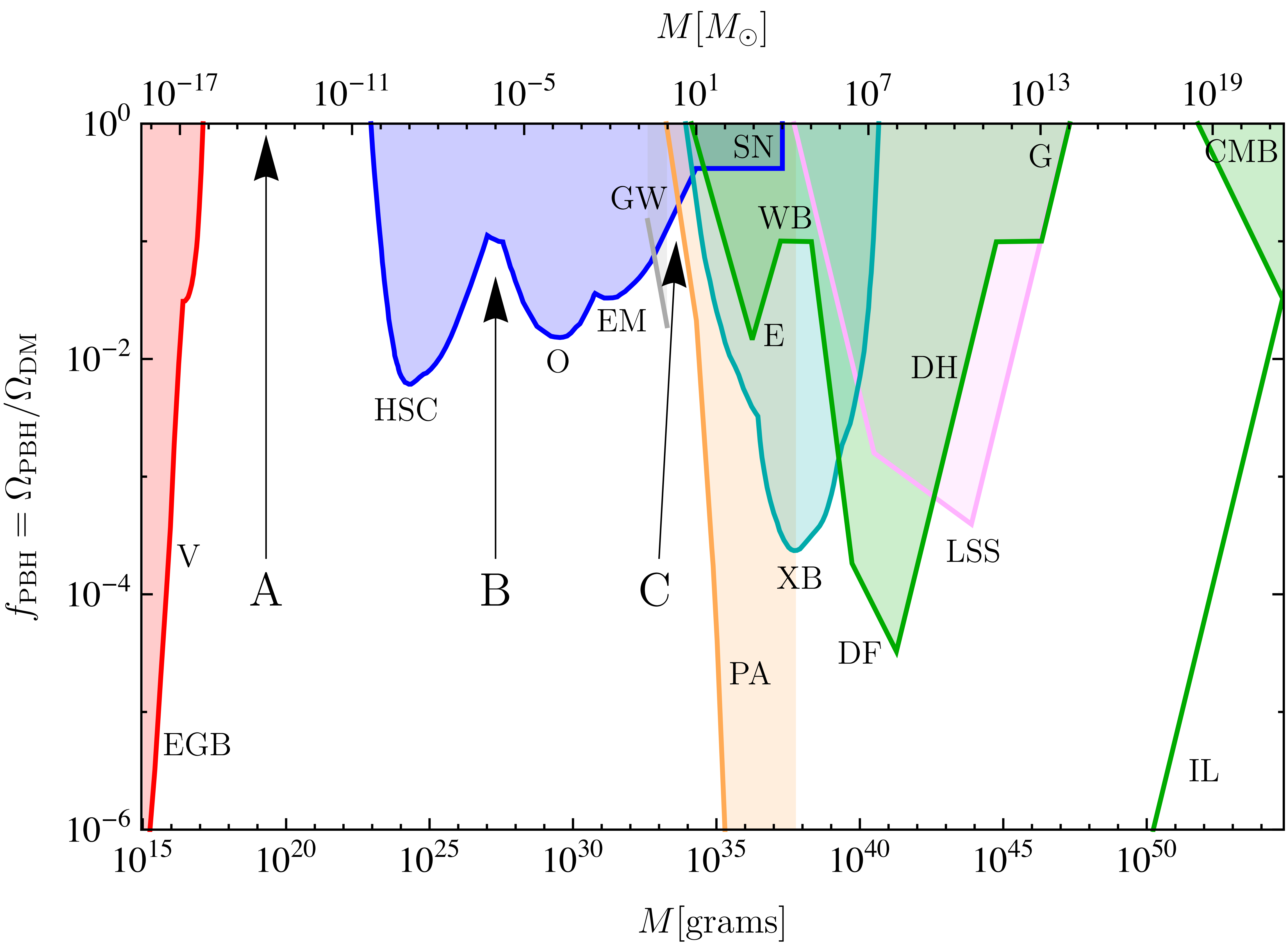
$$\Omega_{\rm PBH} \propto a$$

Current PBH Constraints



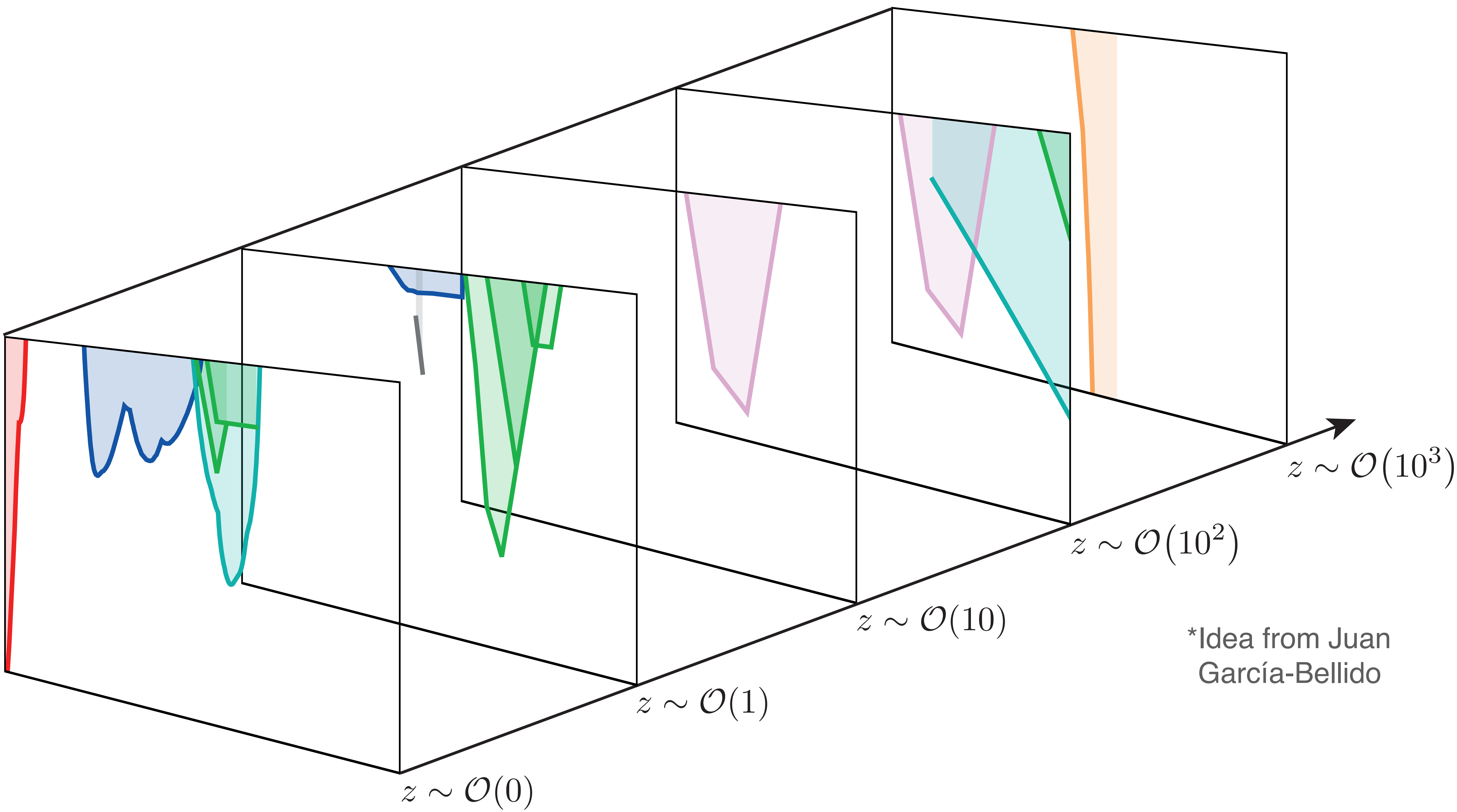
[Carr 他 2021]

Current PBH Constraints



[Carr & FK 2020]

PBH Constraints — Redshift Dependence



*Idea from Juan García-Bellido

[Carr & FK 2020*]

Observational Hints for Primordial Black Holes

Evidence?

Observational ~~Hints~~ for Primordial Black Holes

Work based on collaboration with phenomenal physicists:

Bernard Carr

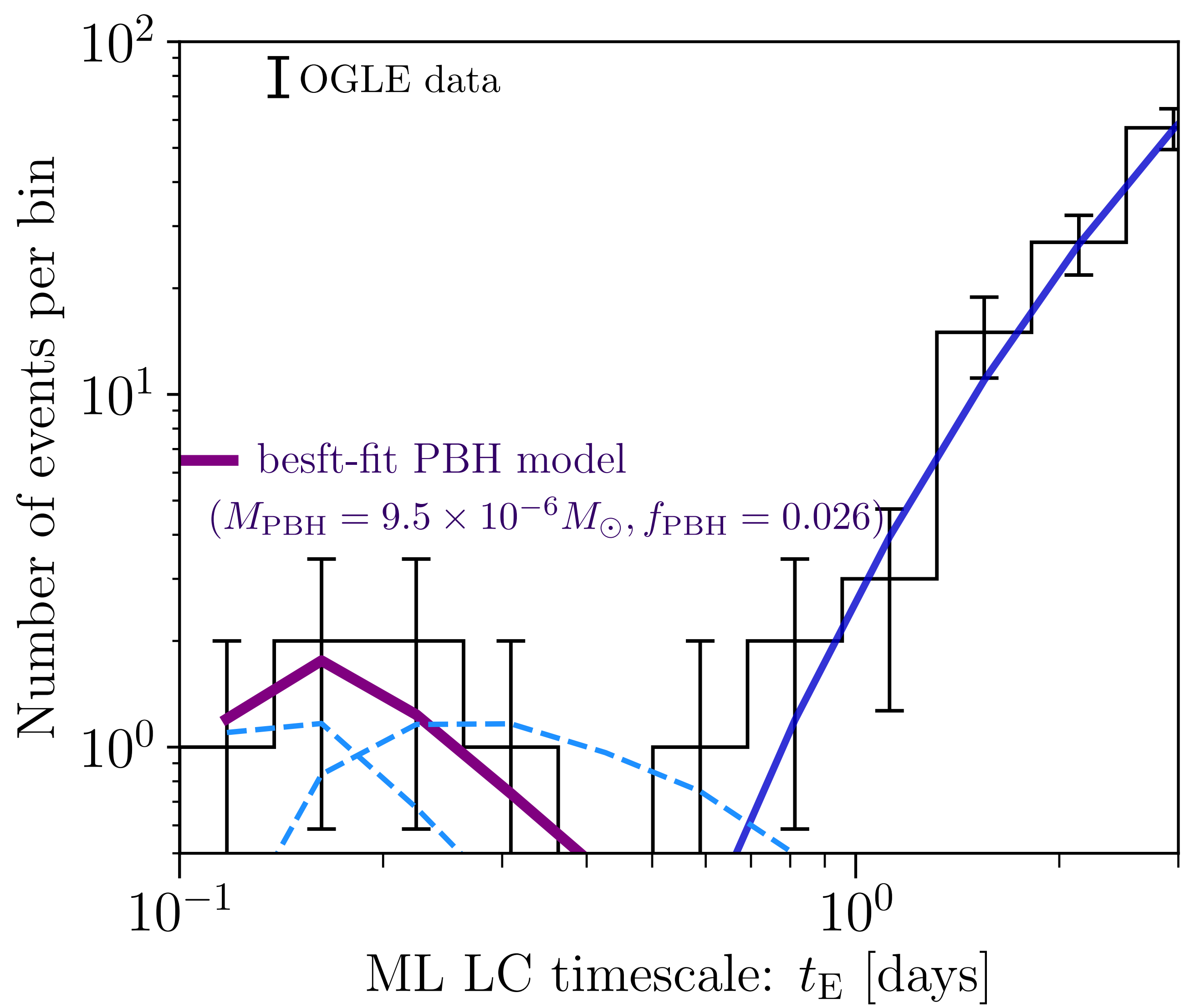
Sébastien Clesse

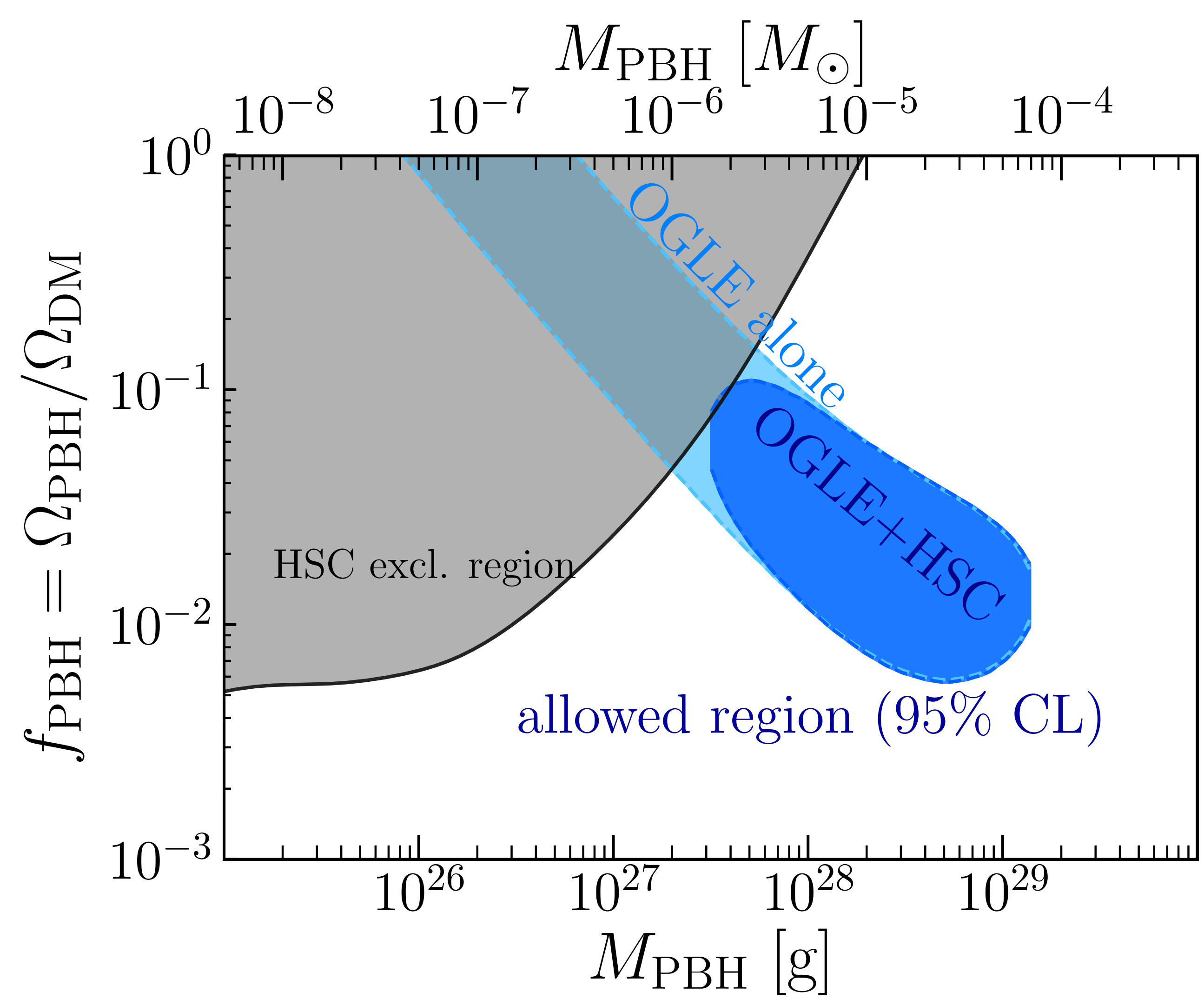
Juan García-Bellido

Michael Hawkins

Planetary-Mass Microlensing

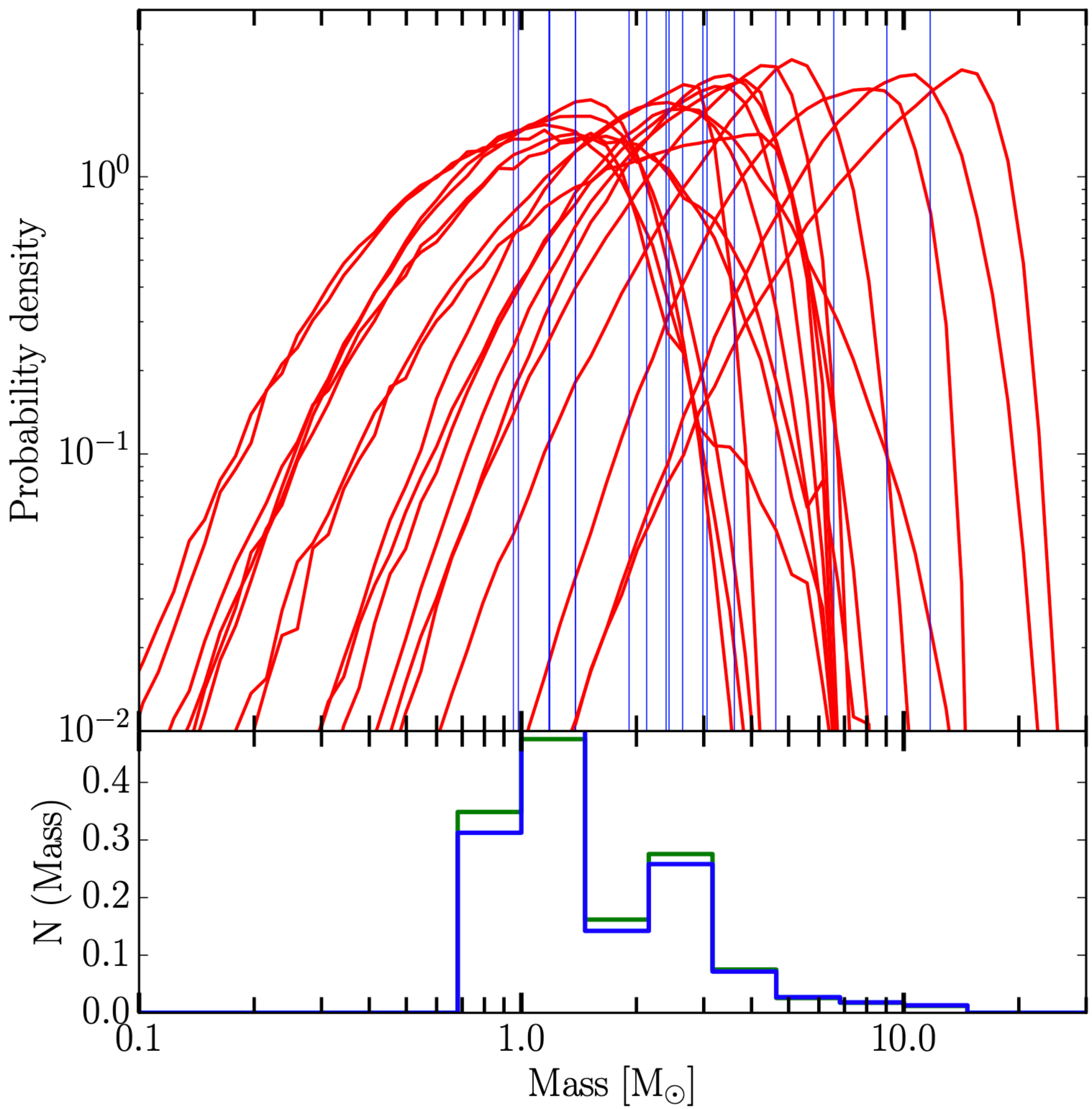
- ★ OGLE detected a particular population of microlensing events:
  - ★ 0.1 - 0.3 days light-curve timescale - origin unknown! Could be free-floating planets... or PBHs!





[Niikura *et al.* 2019]

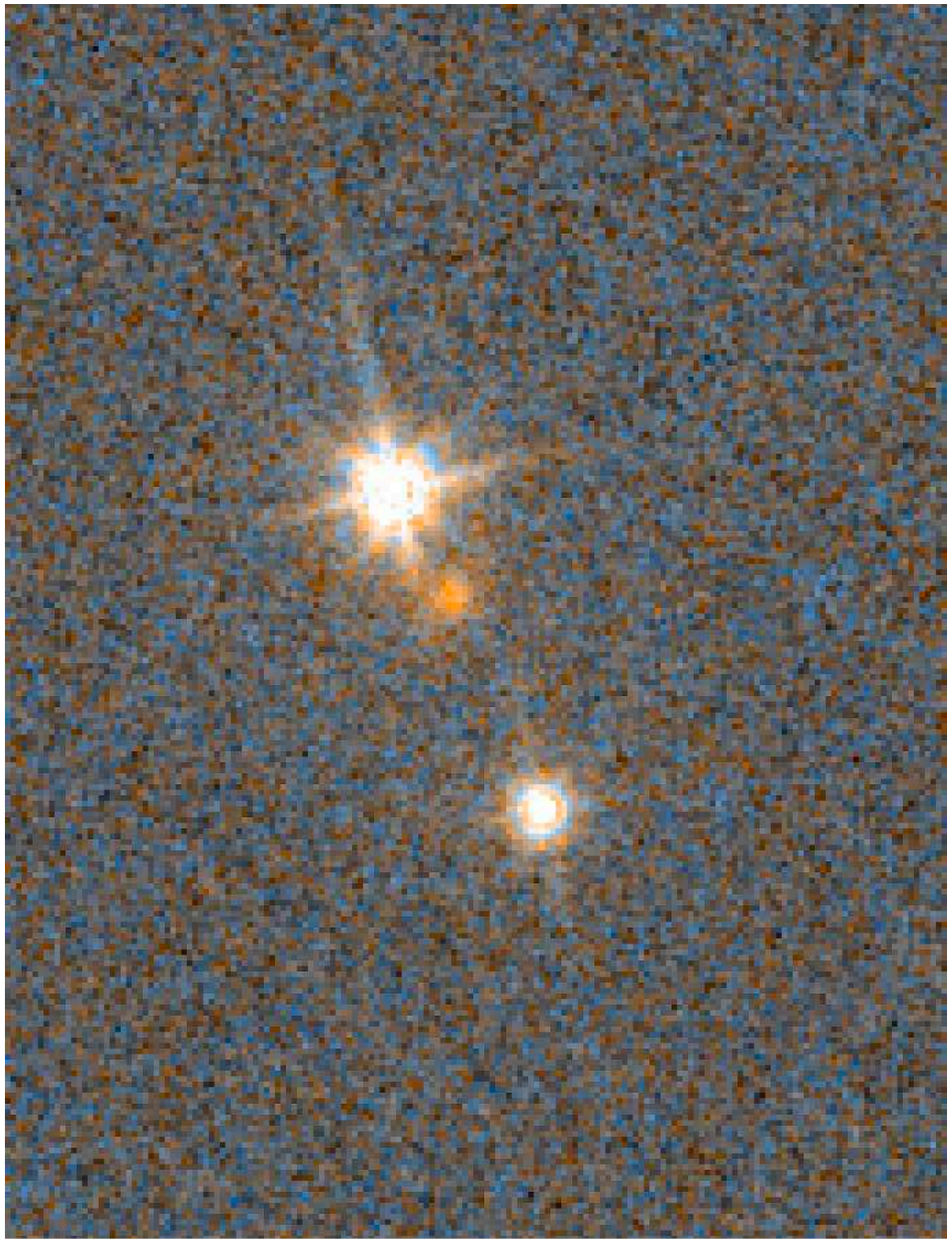
Excess of Lenses in Galactic Bulge



- OGLE has detected 58 long-duration microlensing events in the Galactic bulge.
- 18 of these cannot be main-sequence stars and are very likely black holes.
- Their mass function overlaps the low mass gap from 2 to 5 $M_\odot$.
- These are not expected to form as the endpoint of stellar evolution.

[Wyrzykowski & Mandel 2020]

Quasar Microlensing



HST image of lensed quasar HE1104–1805

The signature of primordial black holes in the dark matter halos of galaxies

M. R. S. Hawkins

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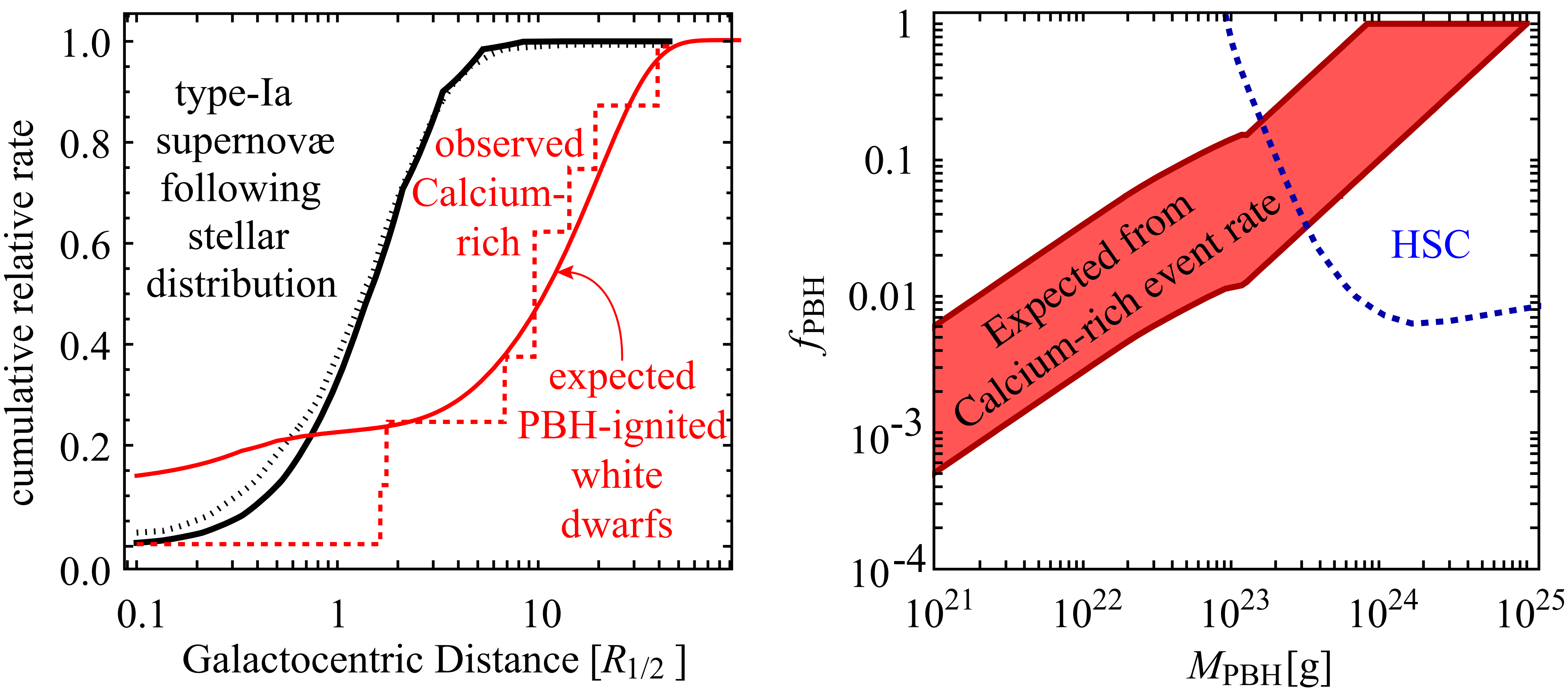
e-mail: `mrsh@roe.ac.uk`

ABSTRACT

Aims. The aim of this paper is to investigate the claim that stars in the lensing galaxy of a gravitationally lensed quasar system can always account for the observed microlensing of the individual quasar images.
[...]
Results. Taken together, the probability that all the observed microlensing is due to stars was found to be $\sim 3 \times 10^{-4}$. Errors resulting from the surface brightness measurement, the mass-to-light ratio, and the contribution of the dark matter halo do not significantly affect this result.
Conclusions. It is argued that the most plausible candidates for the microlenses are primordial black holes, either in the dark matter halos of the lensing galaxies, or more generally distributed along the lines of sight to the quasars.

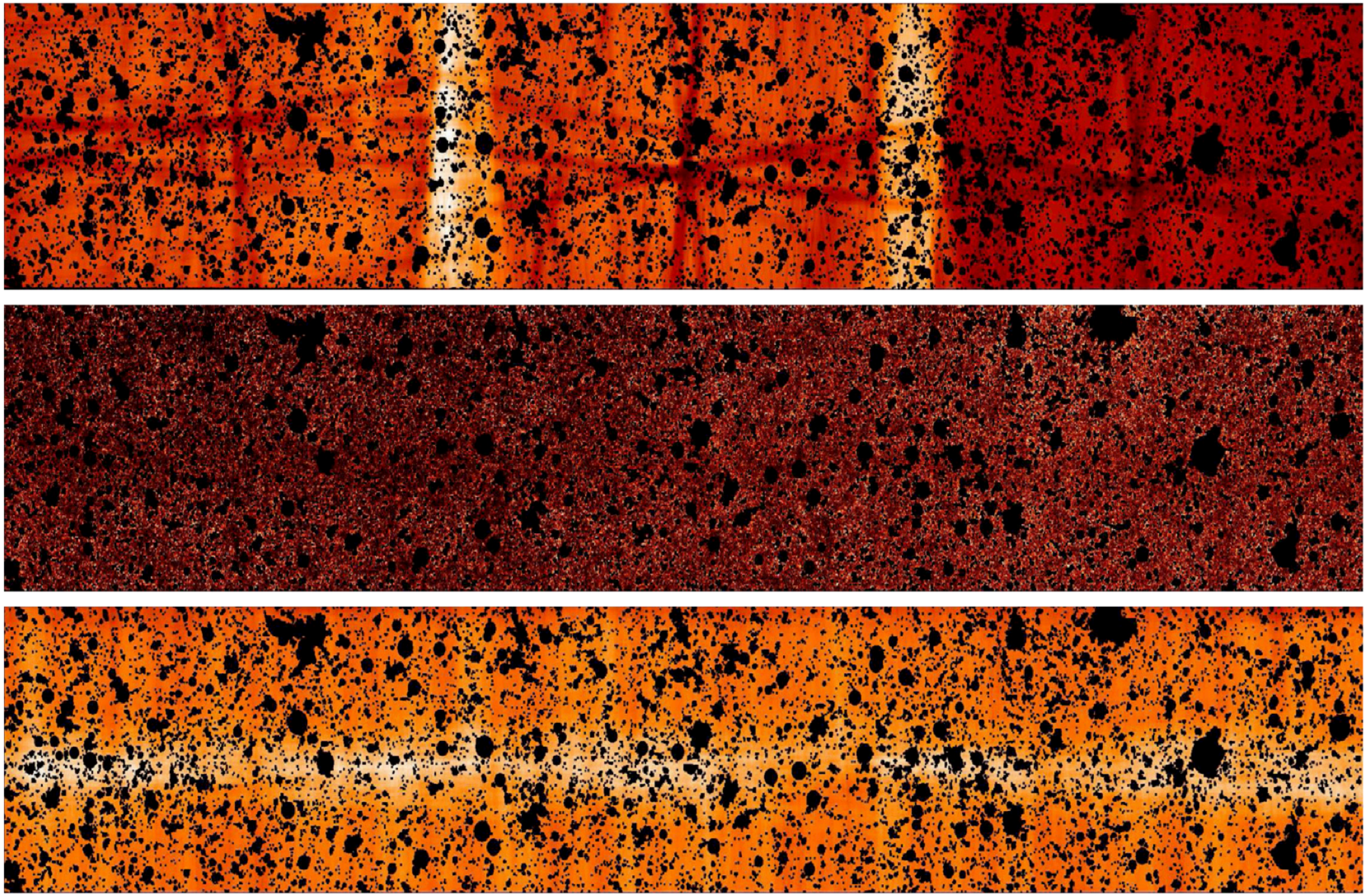
Calcium-Rich Gap Transients

★ A supernova population of so-called calcium-rich gap transients has been shown to clearly not to follow the stellar distribution but rather a would-be compact dark matter one.



[Smirnov *et al.* 2023]

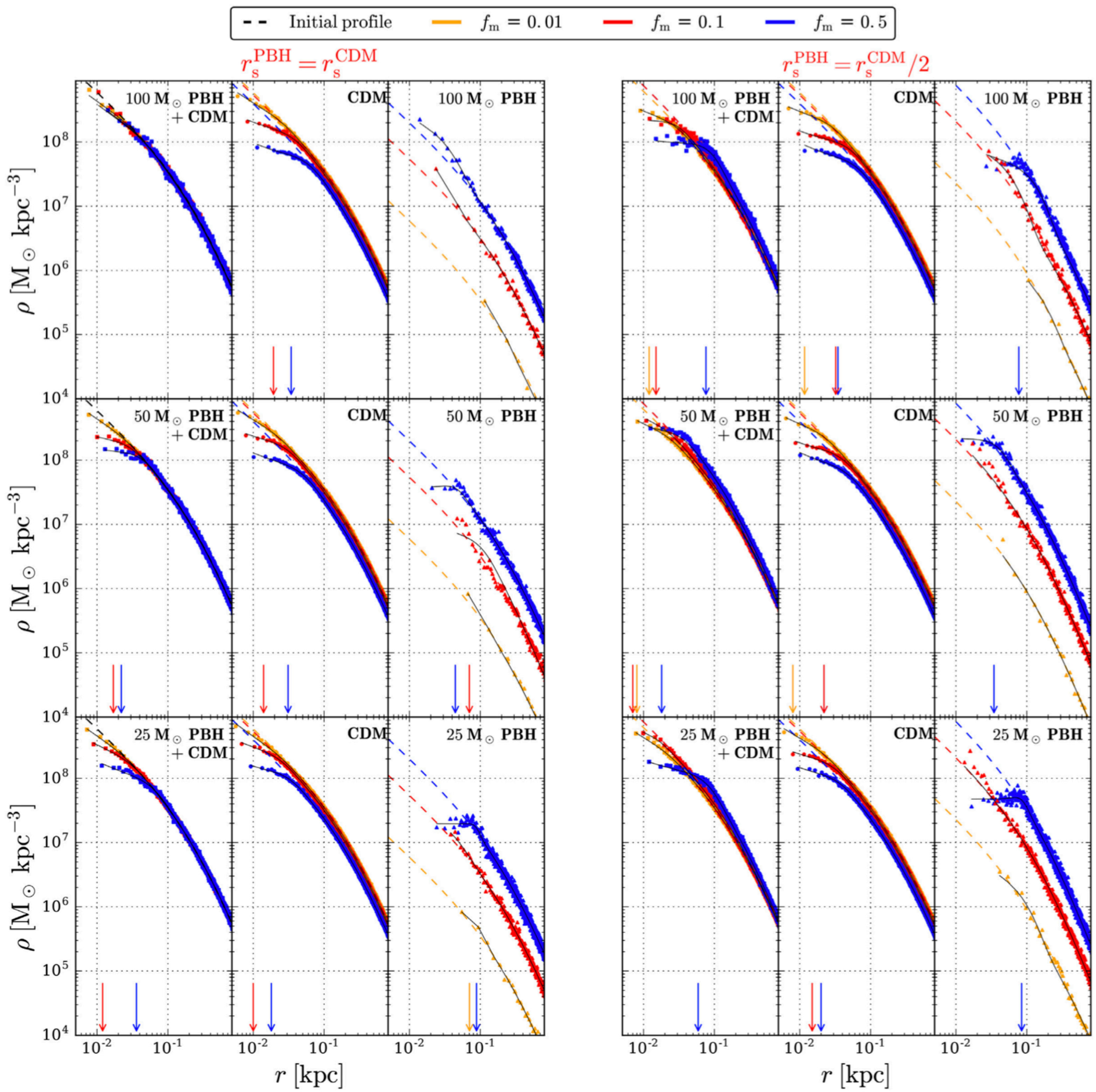
Correlations of Cosmic Infrared/X-Ray Backgrounds



[Cappelluti *et al.* 2013]

★ PBHs generate early structure and respective backgrounds

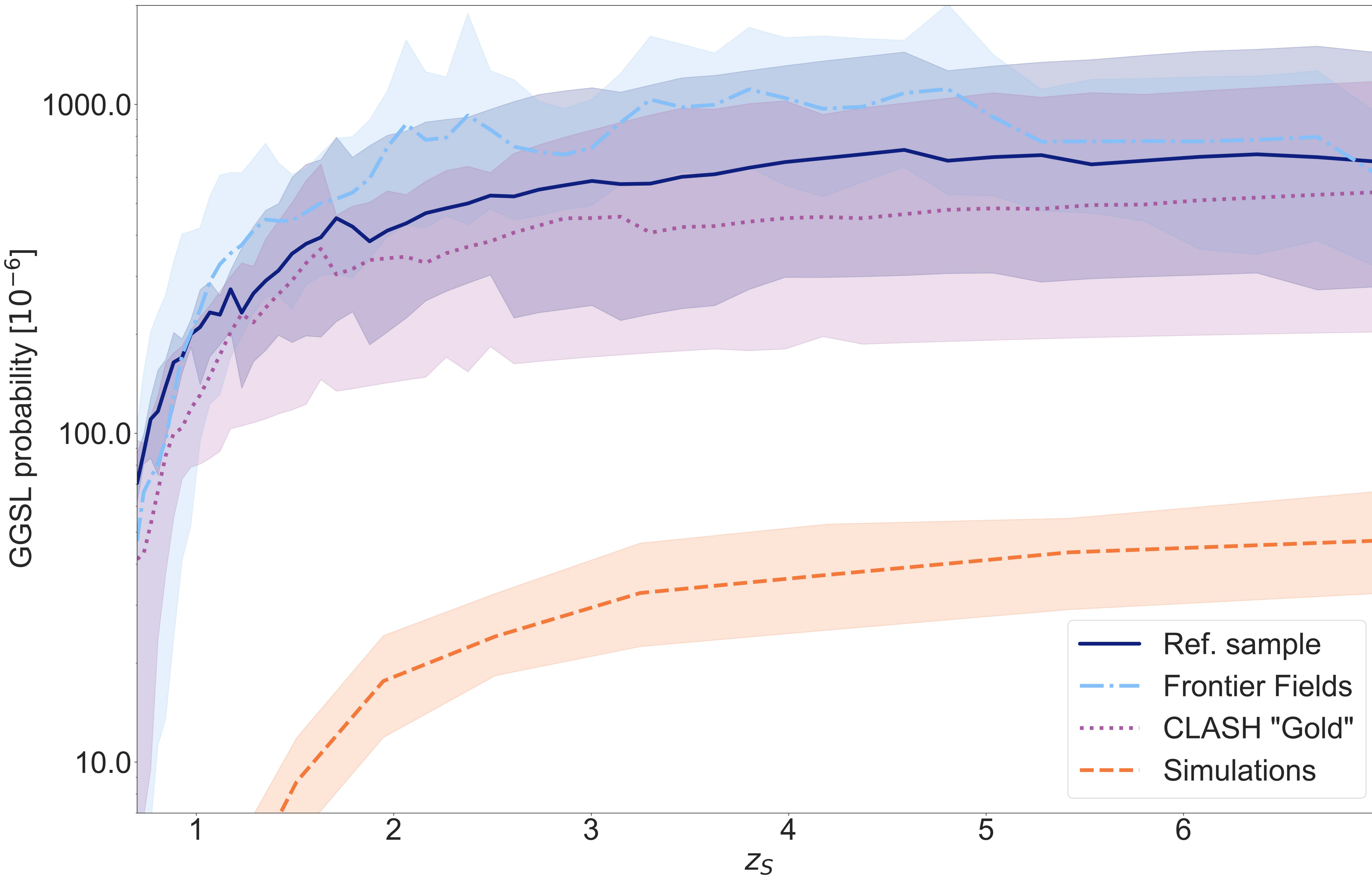
Ultra-faint Dwarf Galaxies



[Boldrini *et al.* 2020]

- ★ Non-detection of dwarf galaxies smaller than ~ 10 – 20 pc
- ★ Ultra-faint dwarf galaxies are dynamically unstable below some critical radius in the presence of PBH dark matter!
- ★ This works with a few percent of PBH dark matter of 25 – 100 $M_\odot$.

Evidence of Dark Matter Clumping with HST



[Meneghetti, Natarajan, Downer 2020]

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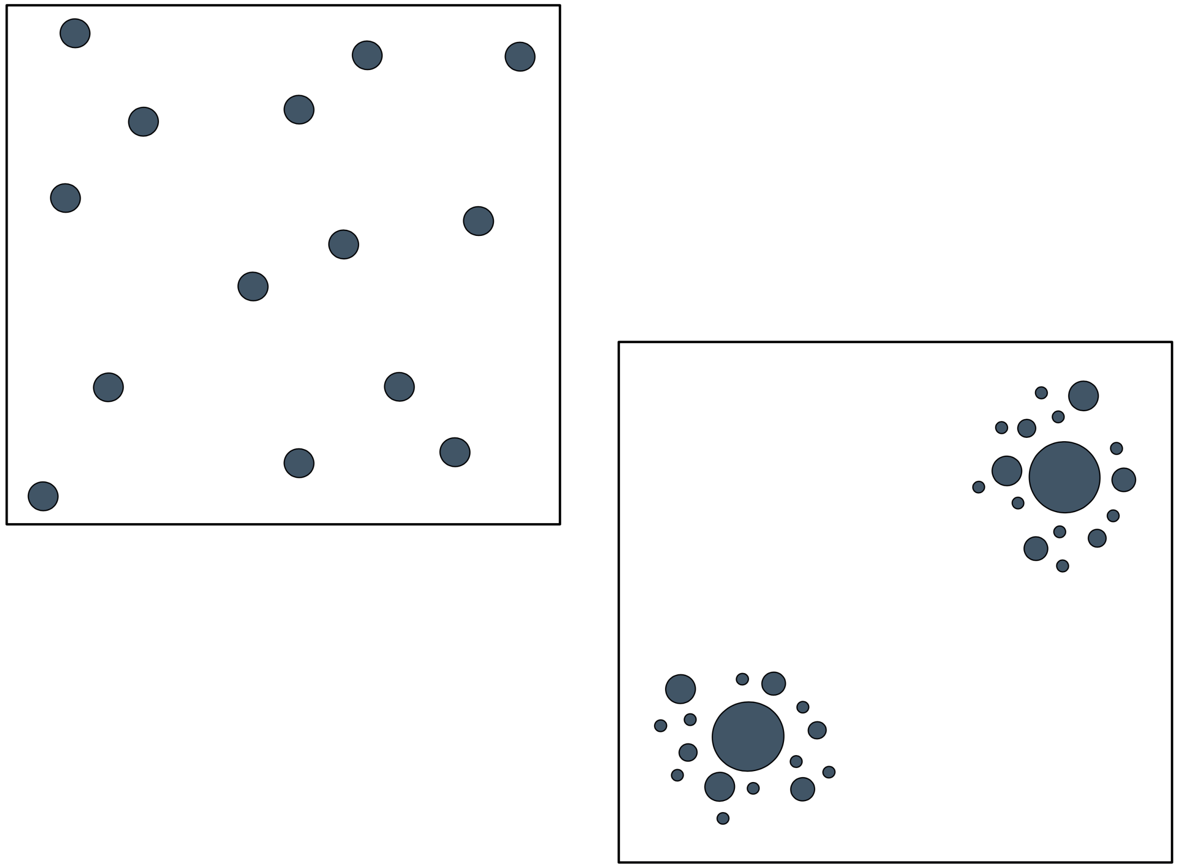
[Meneghetti, Natarajan, Downer 2020]

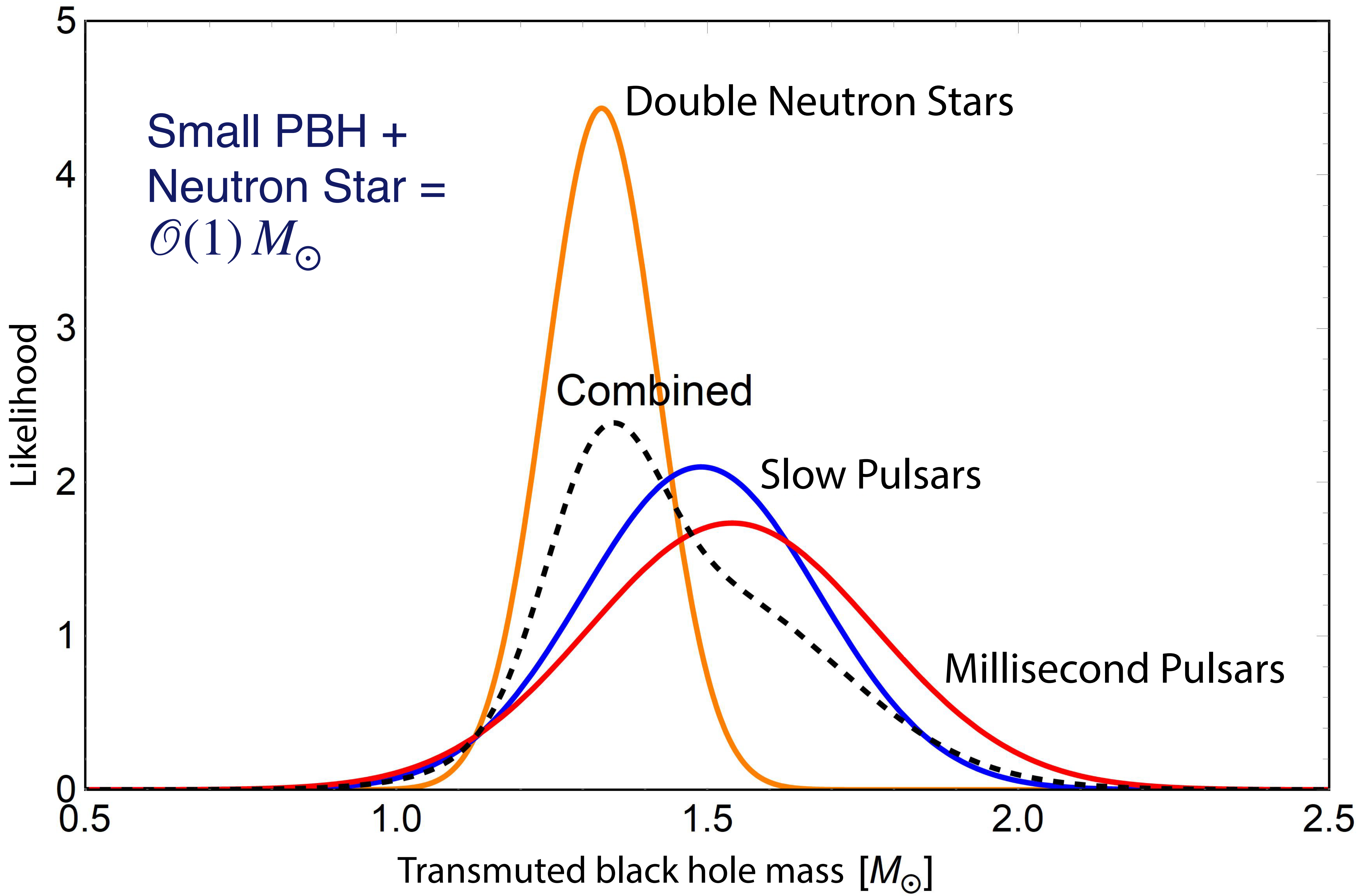


[García-Bellido 2018]

homogeneous versus clumped dark matter distribution

★ This is the norm for PBHs!

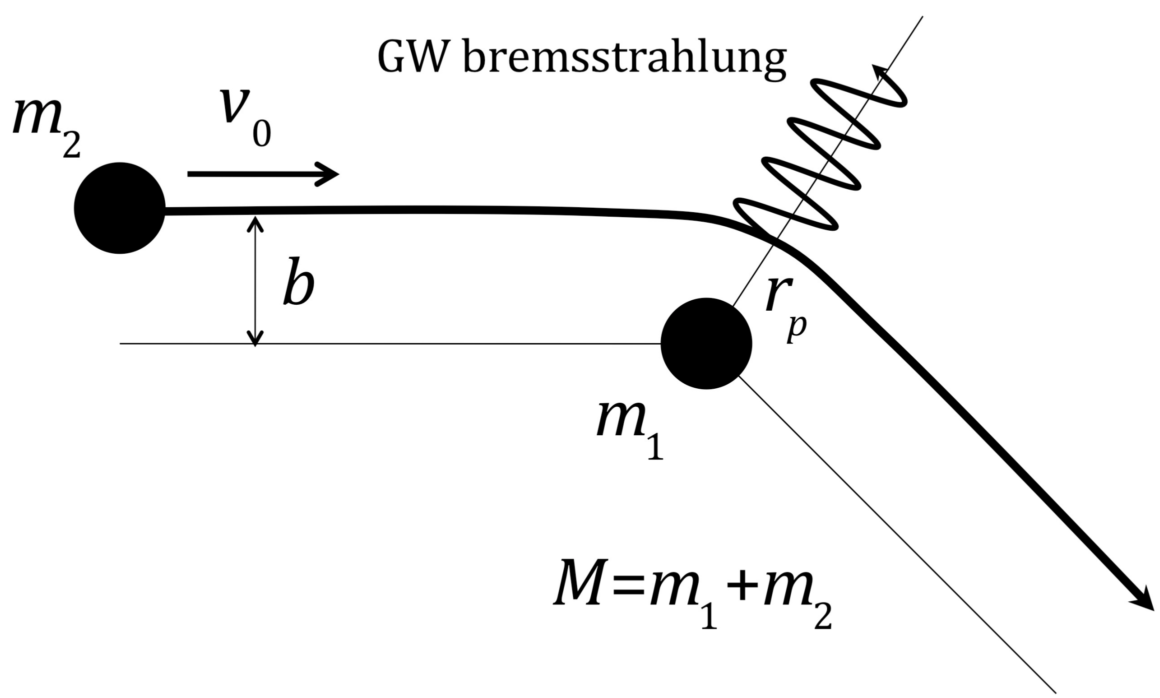
Transmuted Solar-Mass Black Holes

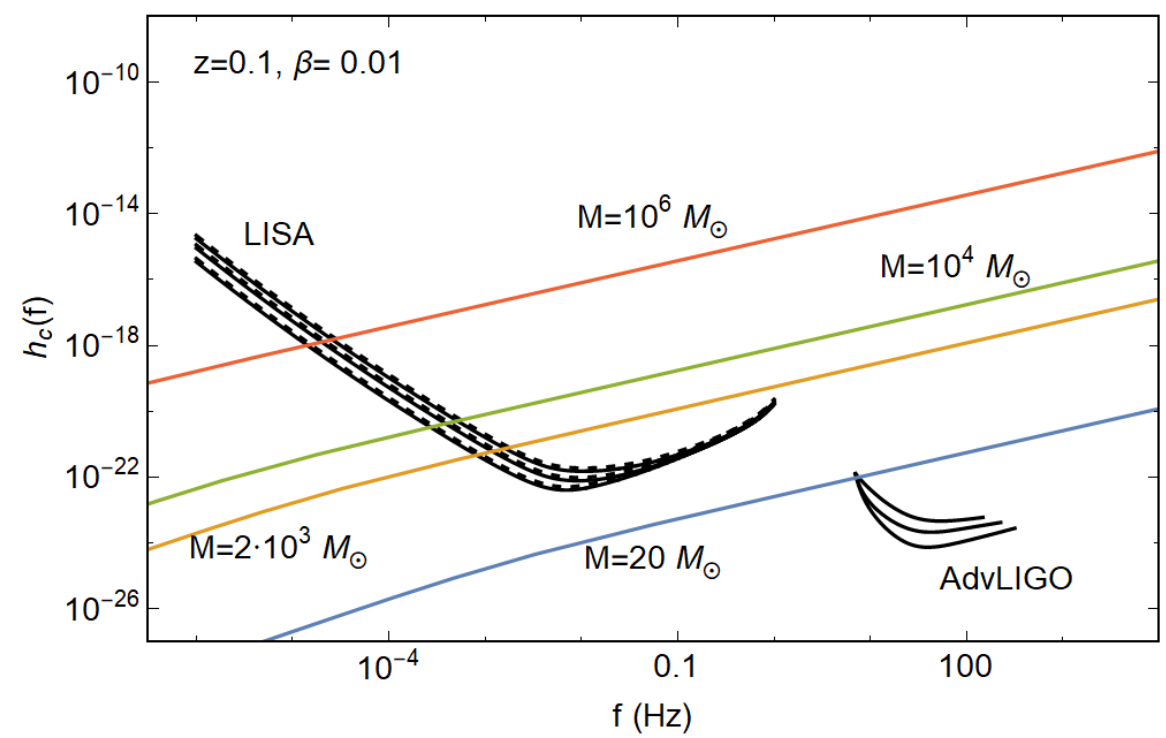


[Takhistov, Fuller, Kusenko 2017]

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
    2) Individual mergers
  - Gravitational-wave emission from hyperbolic PBH encounters.

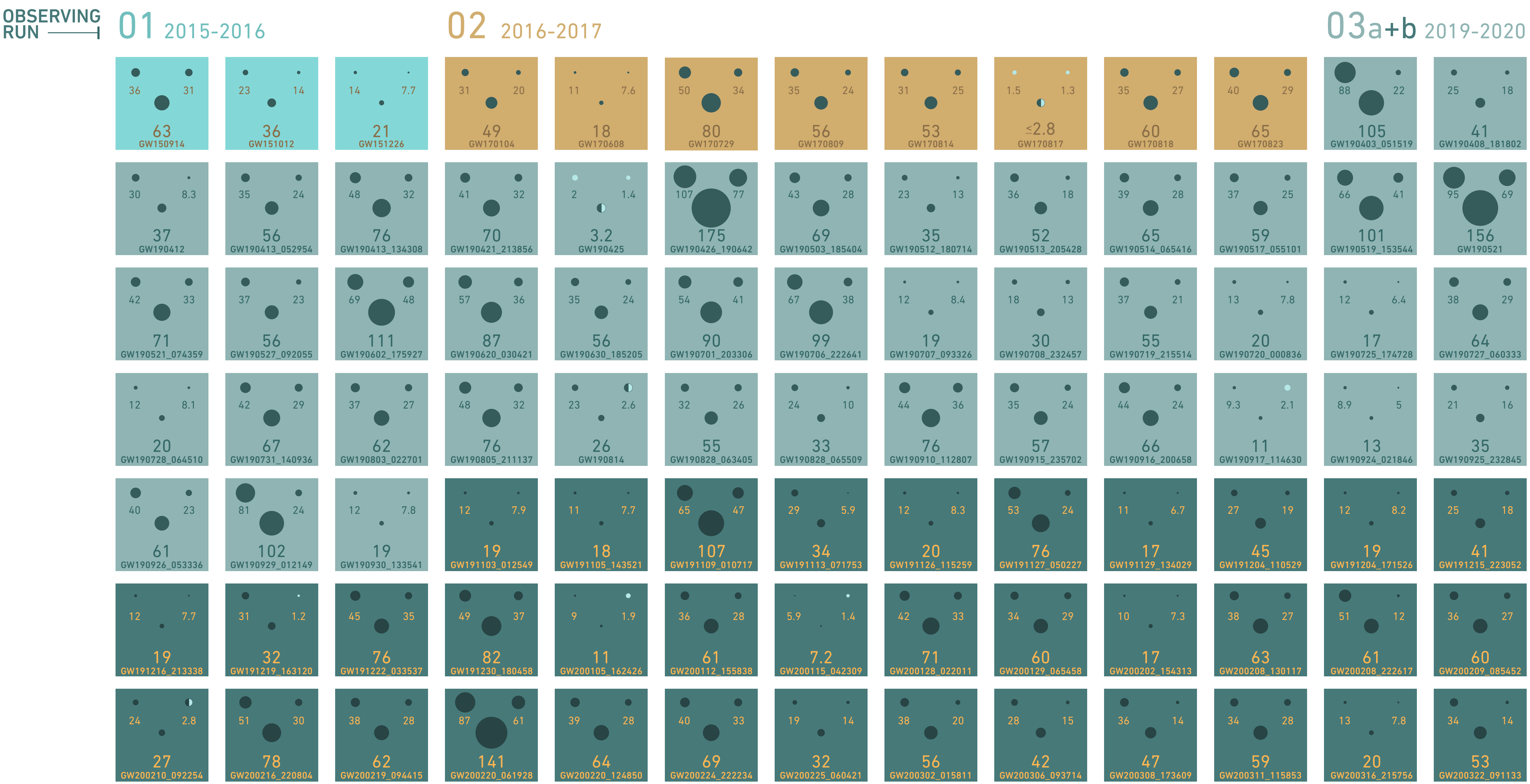




[Garcia-Bellido & Nesseris 2017]

GRAVITATIONAL WAVE **MERGER** DETECTIONS

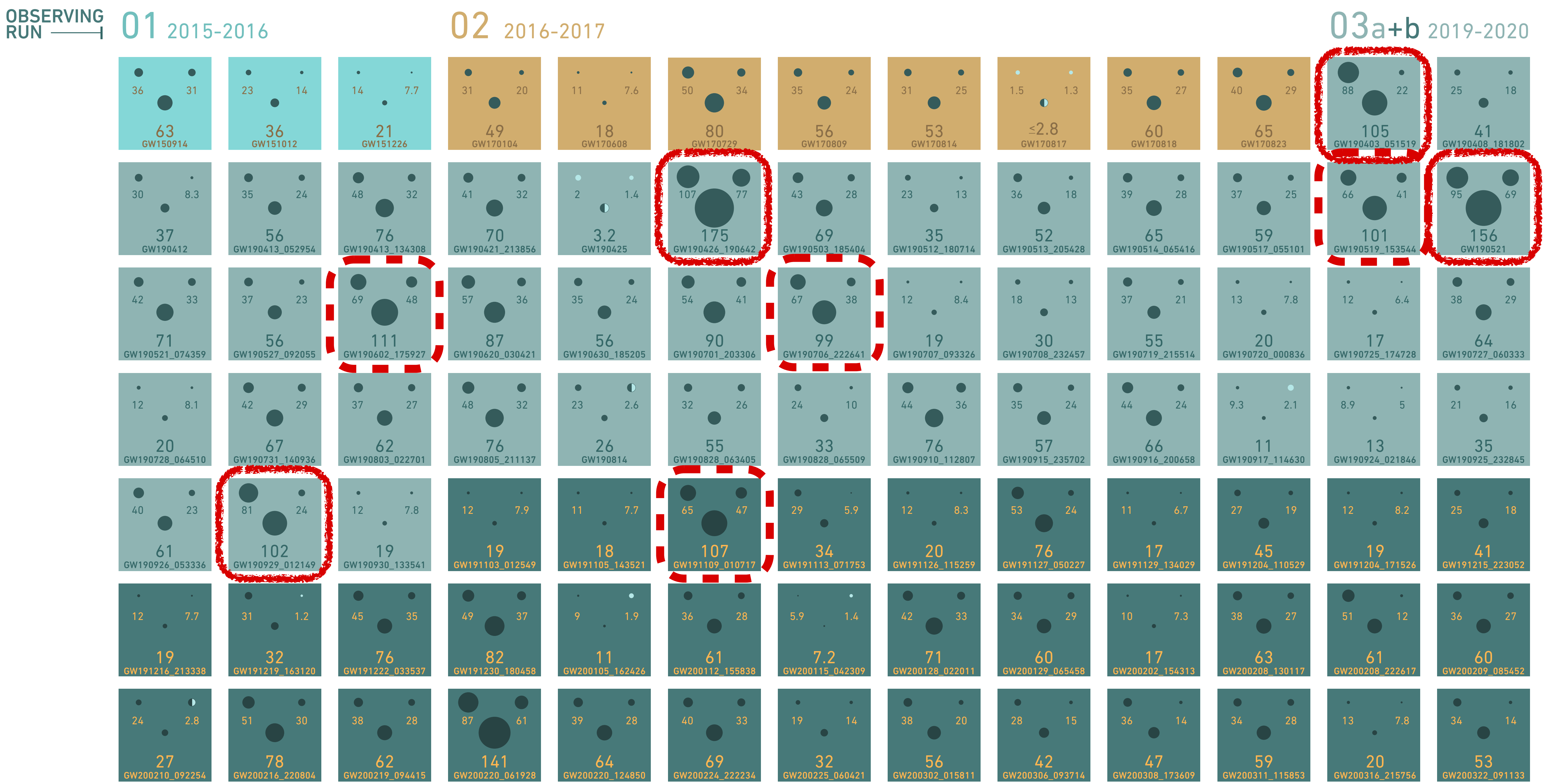
→ SINCE 2015



LIGO VIRGO KAGRA

GRAVITATIONAL WAVE **MERGER** DETECTIONS

→ SINCE 2015

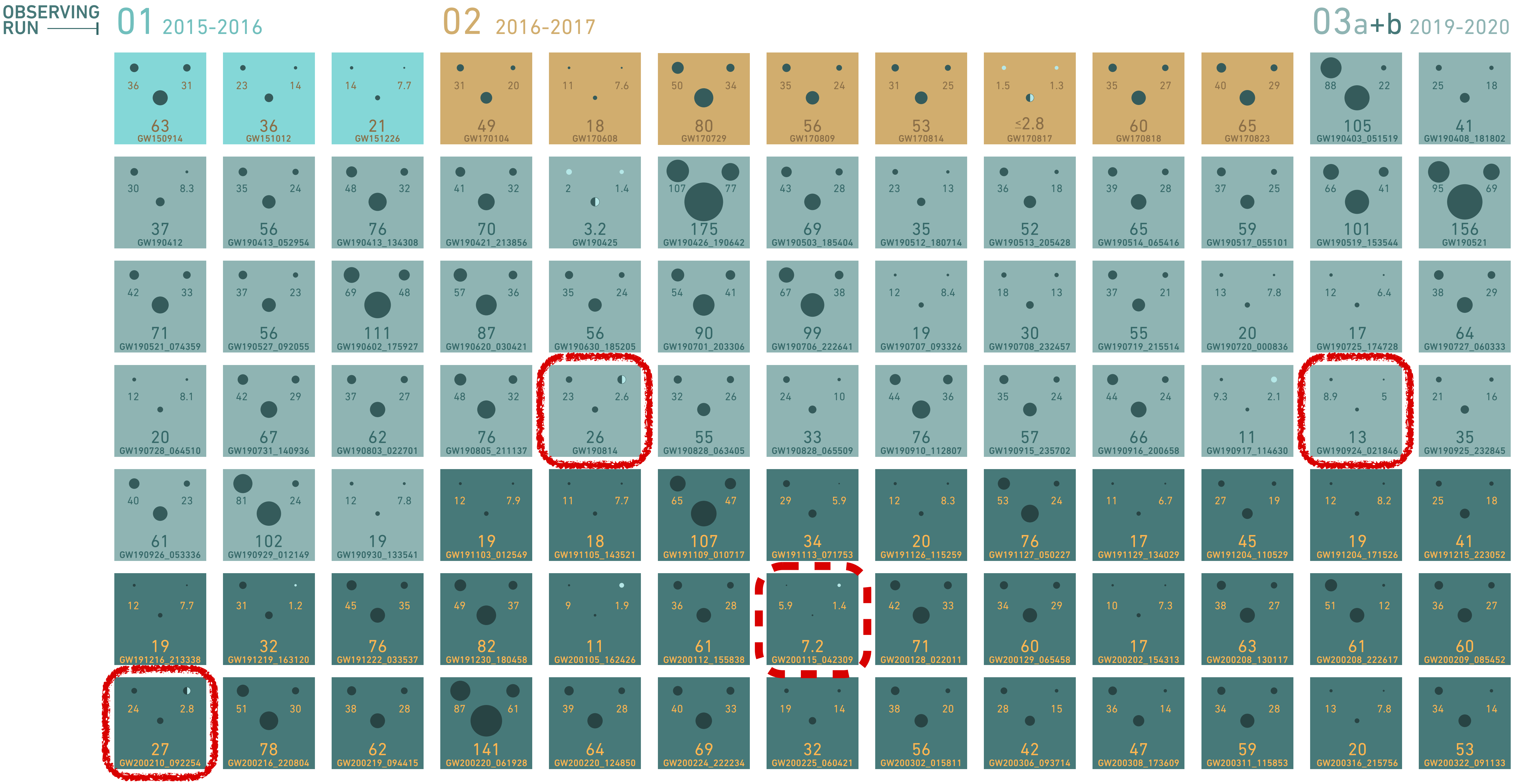


★ Black hole progenitors in the pair-instability mass gap (i.e. above ~ 60 $M_\odot$)

LIGO VIRGO KAGRA

GRAVITATIONAL WAVE **MERGER** DETECTIONS

SINCE 2015

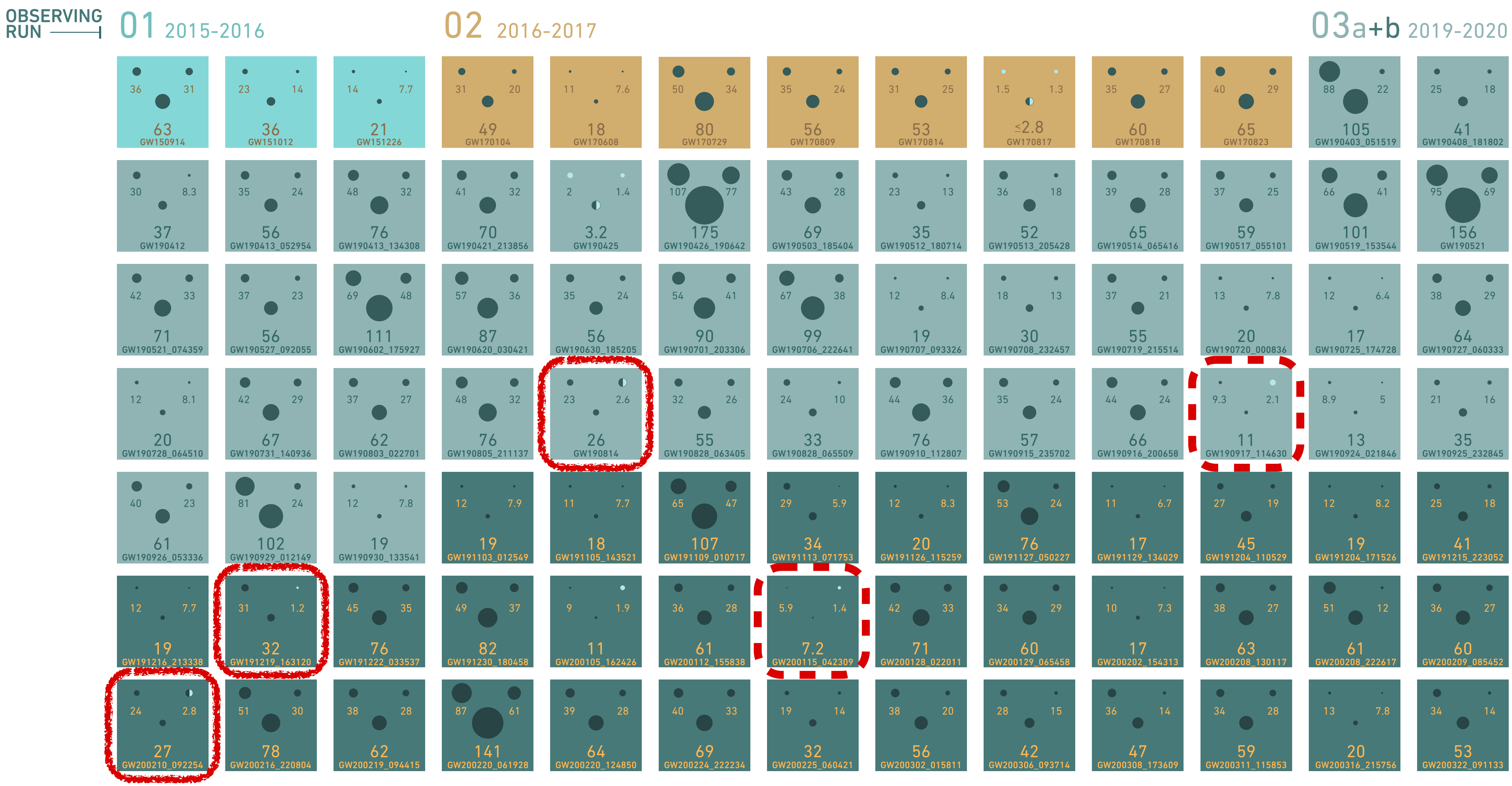


★ Black hole progenitors in the lower mass gap (i.e. between 2 and 5 $M_\odot$)

LIGO VIRGO KAGRA

GRAVITATIONAL WAVE **MERGER** DETECTIONS

→ SINCE 2015



★ Asymmetric black hole progenitors (mass ratio $q < 0.25$)

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GRAVITATIONAL WAVE **MERGER** DETECTIONS

→ SINCE 2015

THE ASTROPHYSICAL JOURNAL LETTERS, 896:L44 (20pp), 2020 June 20 https://doi.org/10.3847/2041-8213/ab960f

GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object

R. Abbott[1], [...]

Abstract

We report the observation of a compact binary coalescence involving a 22.2–24.3 $M_\odot$ black hole and a compact object with a mass of 2.50–2.67 $M_\odot$ [...] the combination of mass ratio, component masses, and the inferred merger rate for this event challenges all current models of the formation and mass distribution of compact-object binaries.

★ Asymmetric black hole progenitors (mass ratio $q < 0.25$)

LIGO VIRGO KAGRA

Subsolar Black Holes - The Smoking Gun!

★ Recent reanalysis of LIGO data updated merger rates and low mass ratios:

Date	FAR [yr^{-1}]	$m_1[M_\odot]$	$m_2[M_\odot]$	spin-1-z	spin-2-z	H SNR	L SNR	V SNR	Network SNR
2017-04-01	0.41	4.90	0.78	−0.05	−0.05	6.32	5.94	–	8.67
2017-03-08	1.21	2.26	0.70	−0.04	−0.04	6.32	5.74	–	8.54
2020-03-08	0.20	0.78	0.23	0.57	0.02	6.31	6.28	-	8.90
2019-11-30	1.37	0.40	0.24	0.10	−0.05	6.57	5.31	5.81	10.25
2020-02-03	1.56	1.52	0.37	0.49	0.10	6.74	6.10	-	9.10

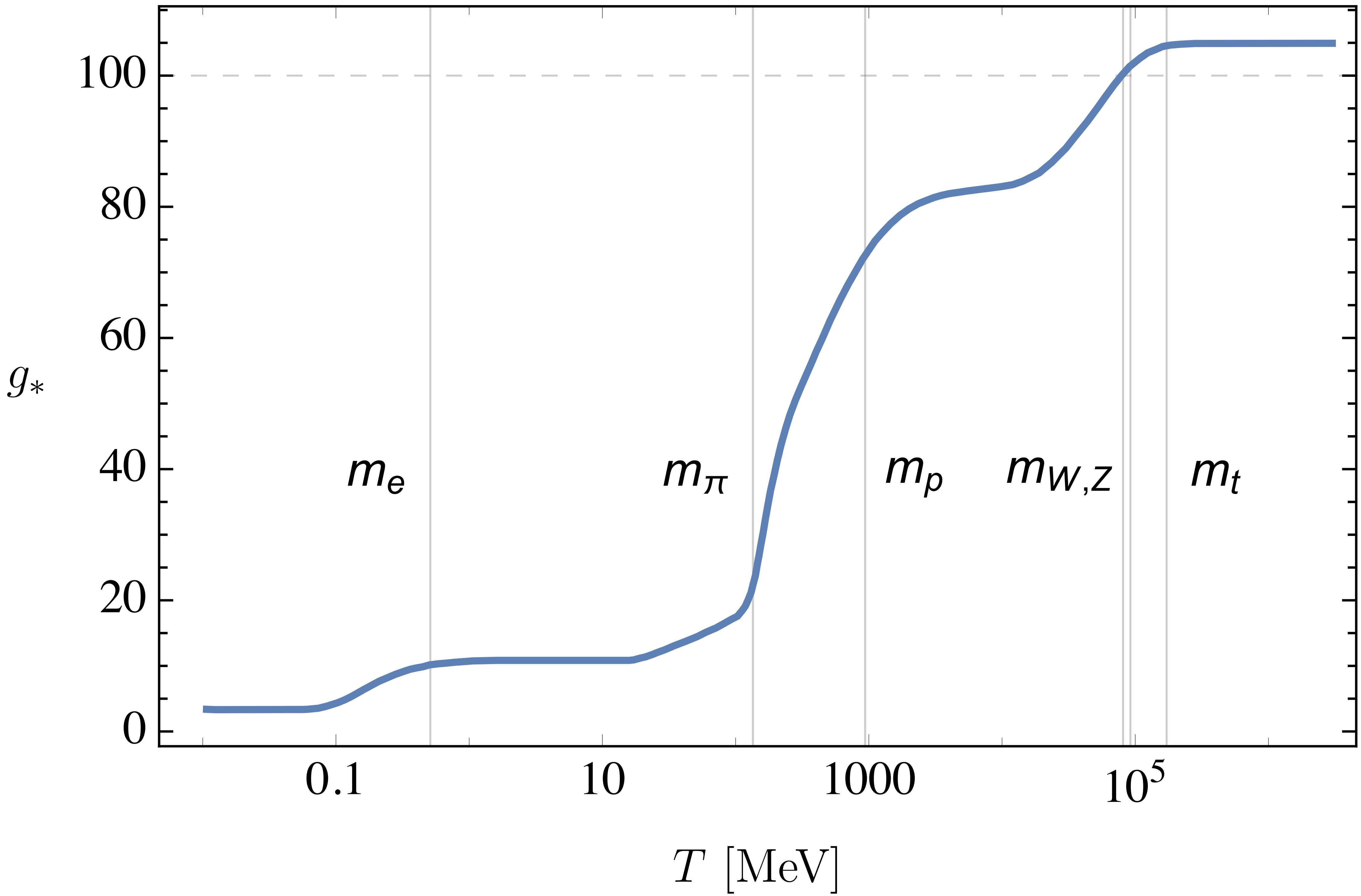
★ Five strong subsolar candidates with SNR > 8 and a FAR < 2 yr^{-1}

★ Possibly the first confirmed detection of a subsolar mass PBH with the next 24 months!

A Unified Scenario

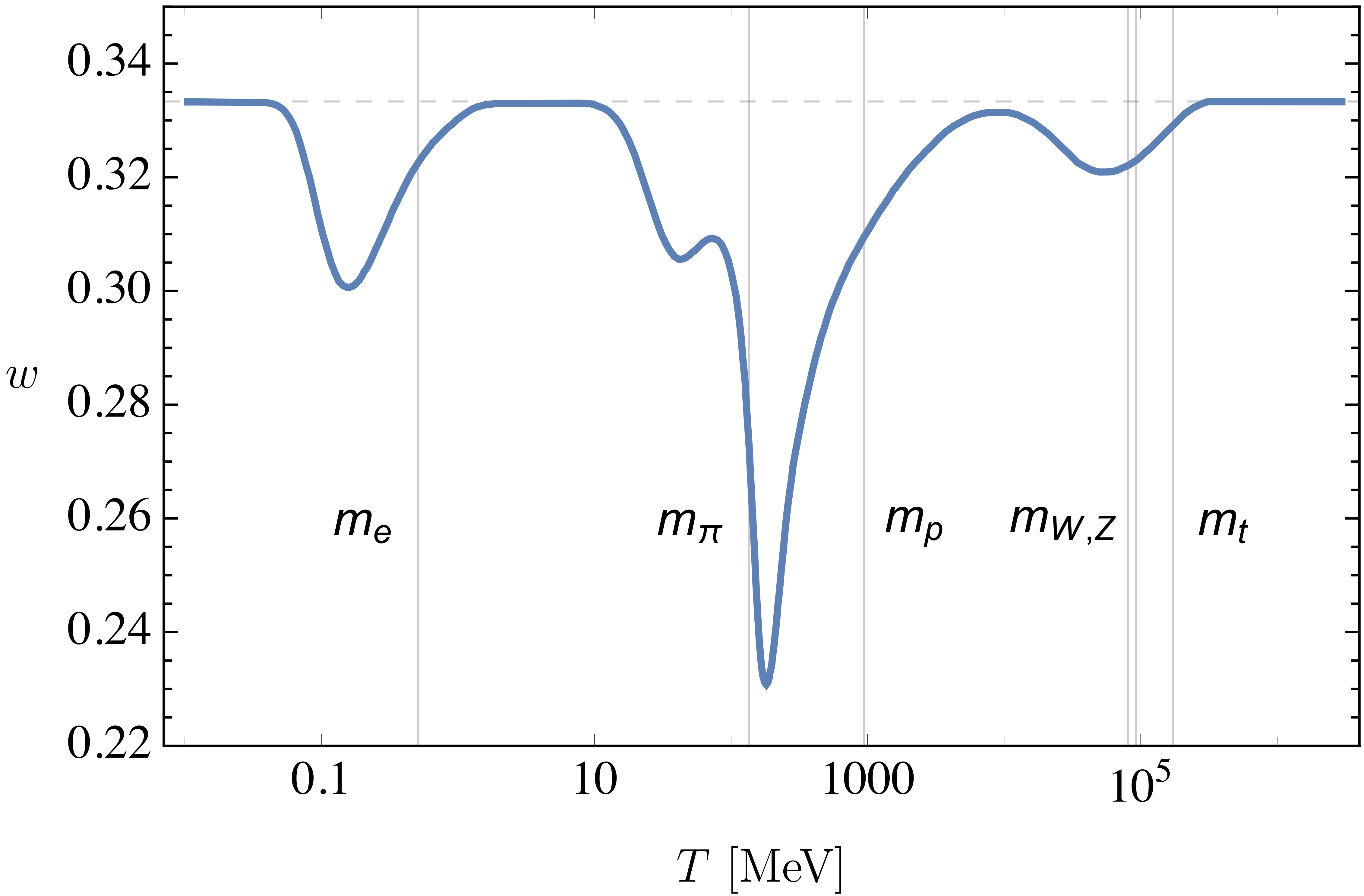
Thermal History of the Universe — Degrees of Freedom

★ Changes in the relativistic degrees of freedom:



Thermal History of the Universe — Equation of State

★ Changes in the equation-of-state parameter $w = p/\rho$:



Primordial Power Spectrum — Planck to PBH

- Consider an essentially featureless power spectrum:

$$\mathcal{P}(k) \sim k^{n_s - 1 + \frac{1}{2}\alpha_s \ln(k/k_*)}$$

as suggested by Planck, albeit on *large non-PBH scales*...

- Connection to *small PBH scales* for instance by critical Higgs inflation.

[García-Bellido, Ruiz-Morales 2017]

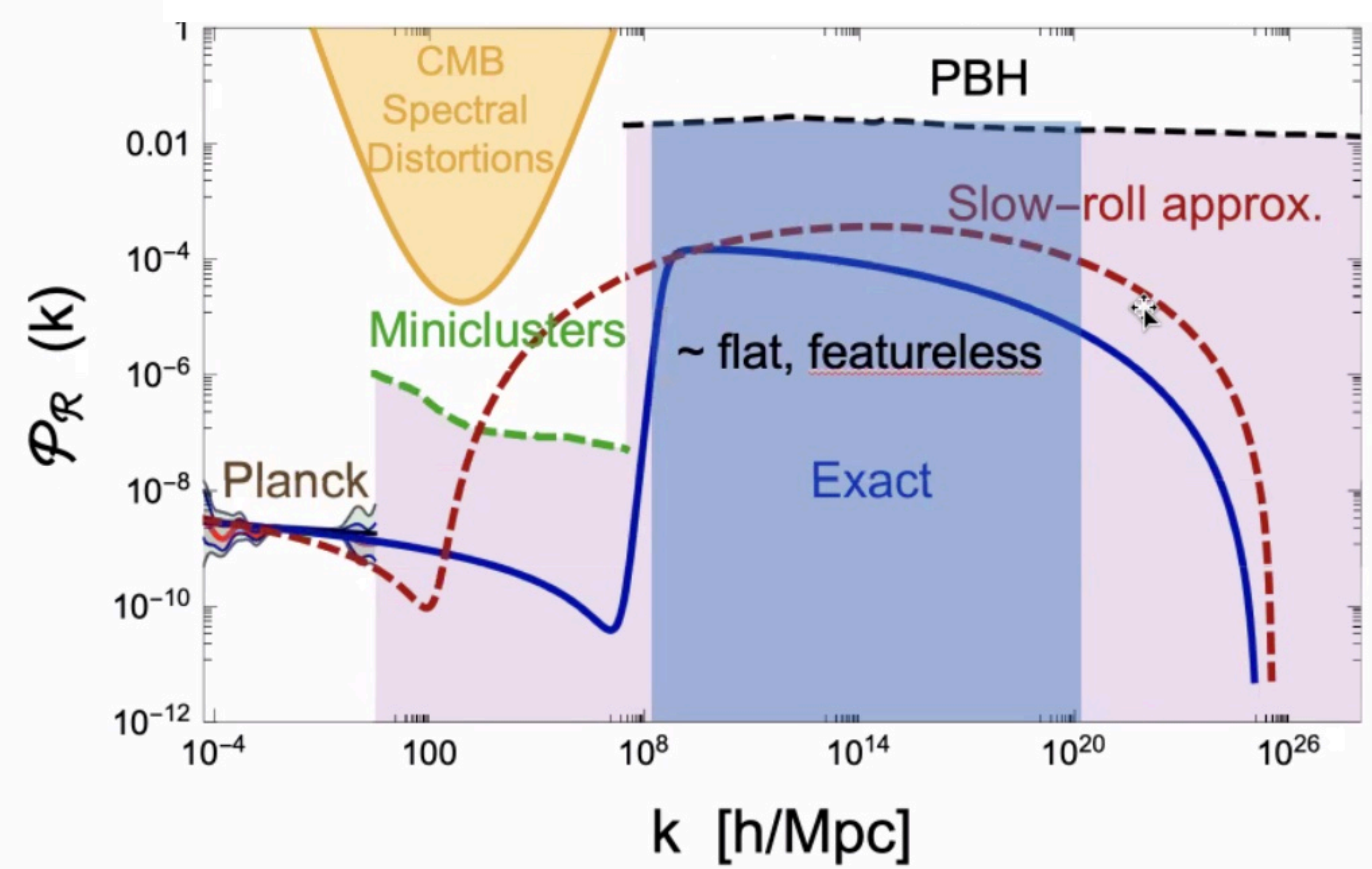
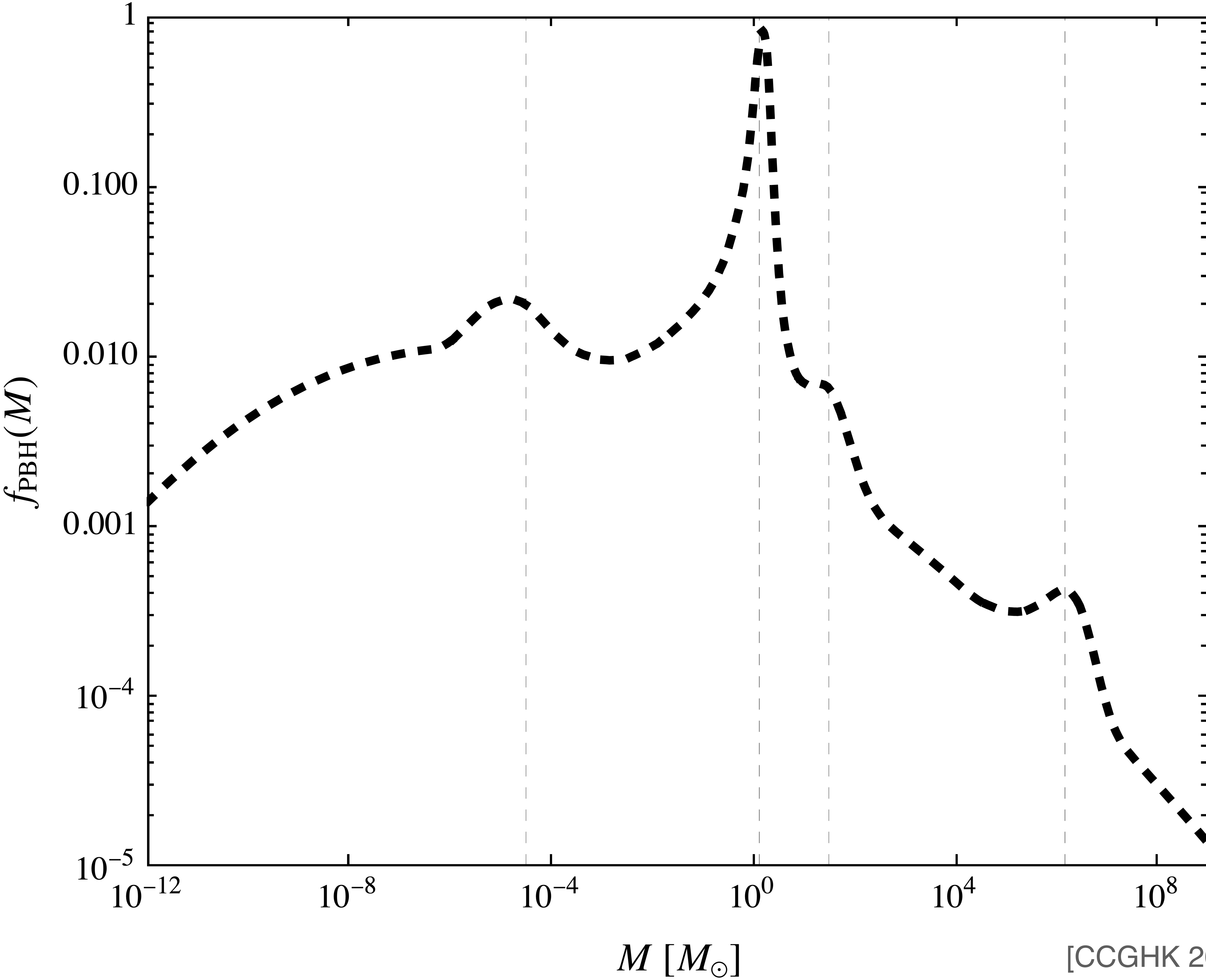


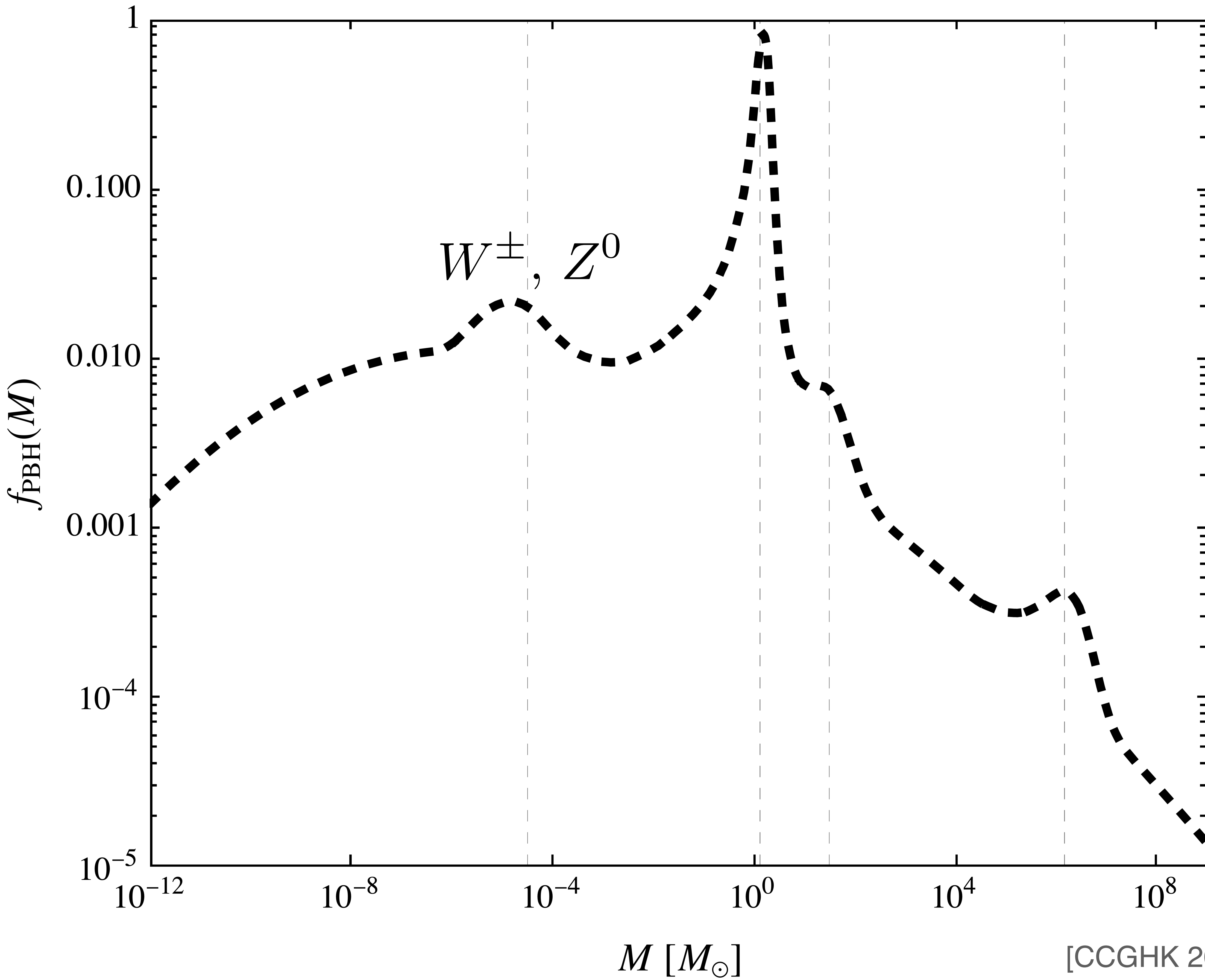
Figure from García-Bellido

PBH Mass Function



[CCGHK 2023]

PBH Mass Function



[CCGHK 2023]

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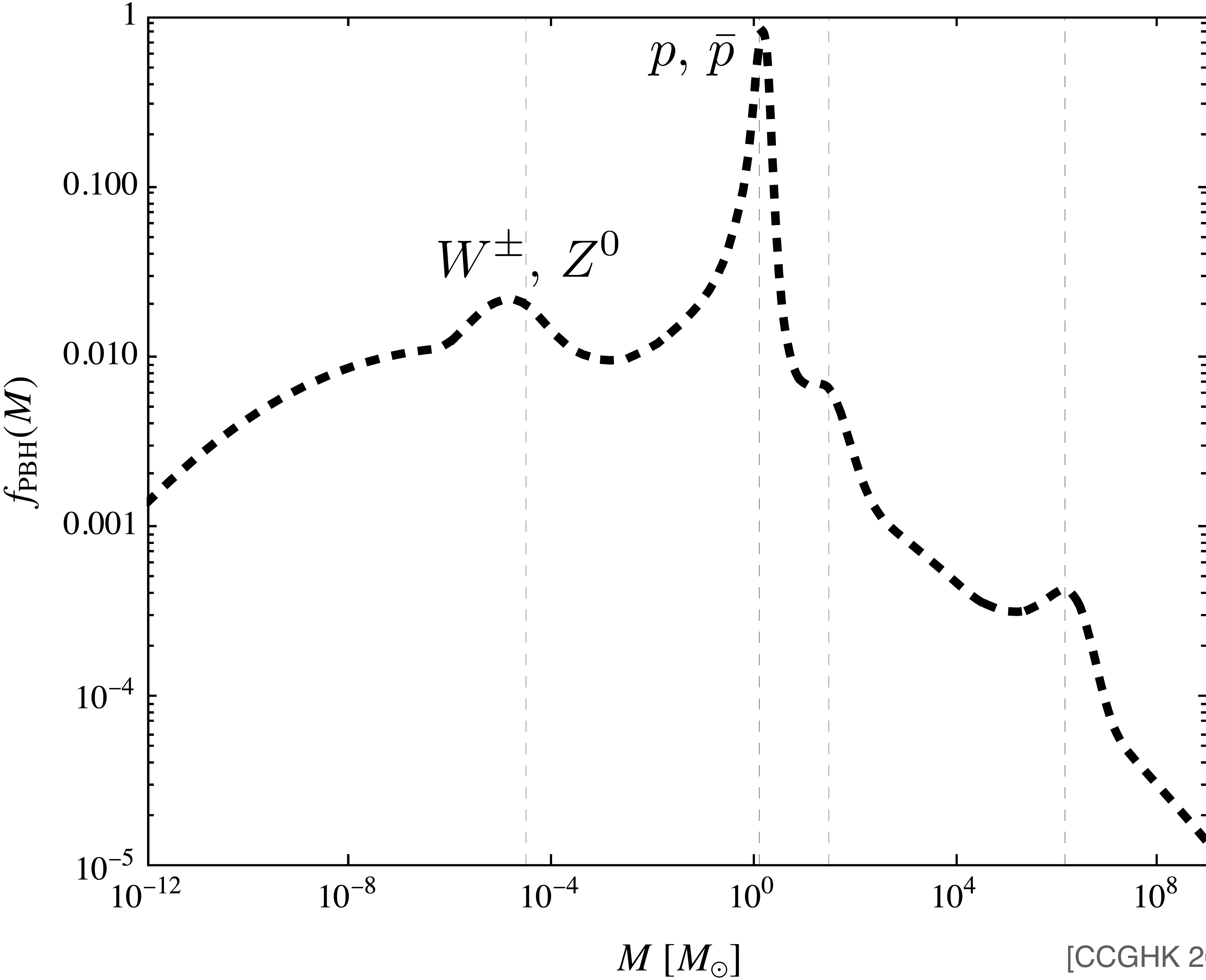
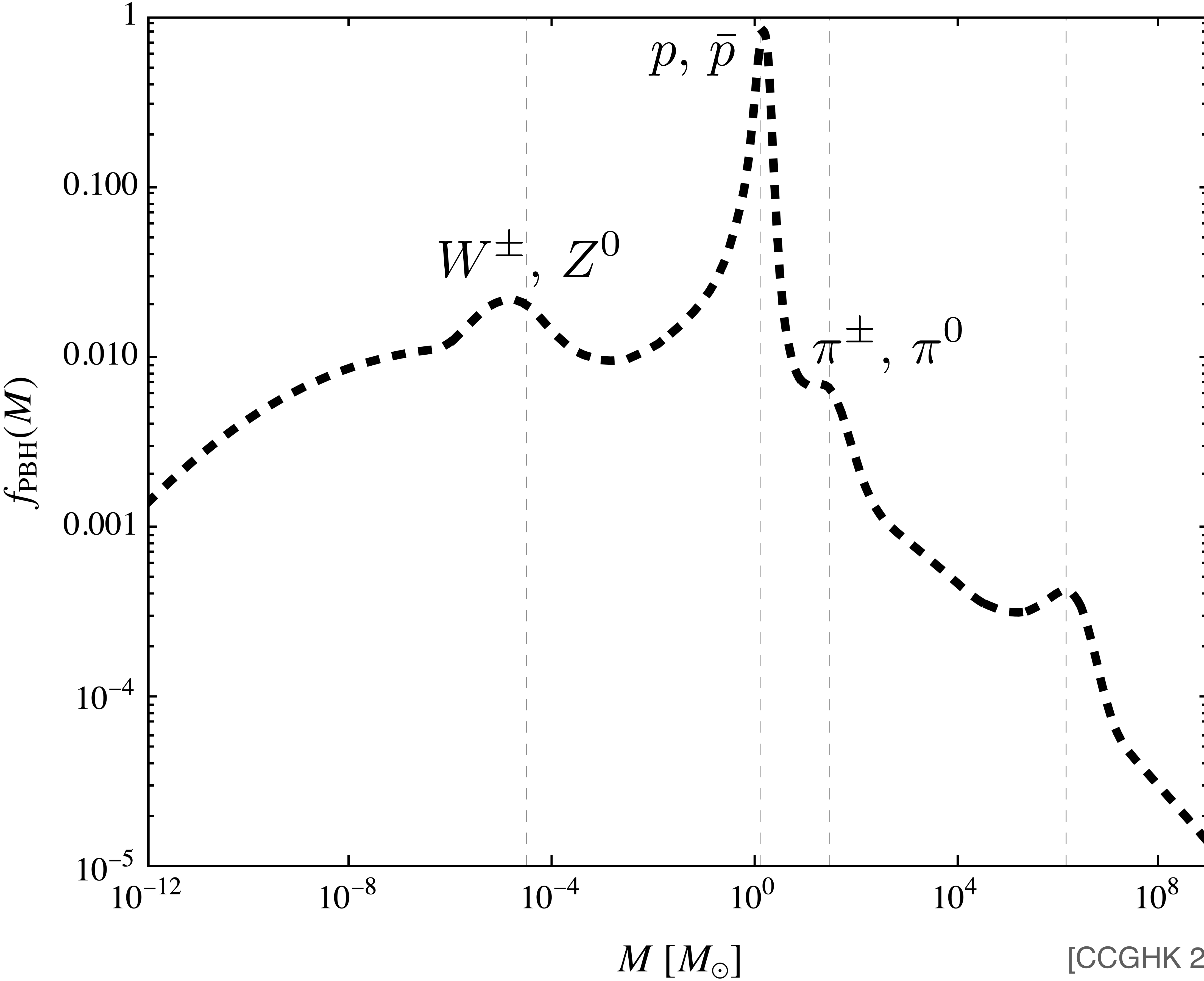


[CCGHK 2023]

PBH Mass Function



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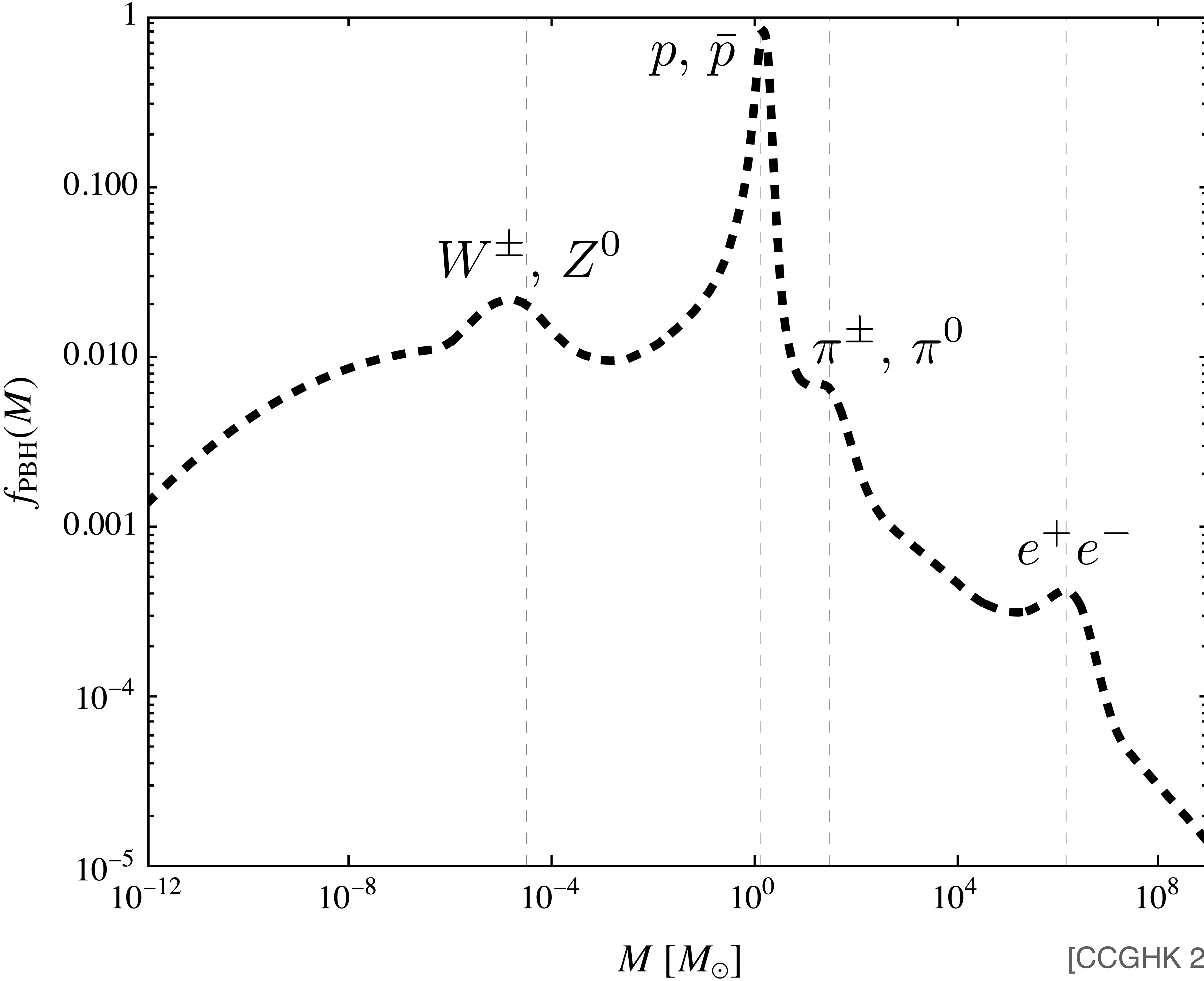
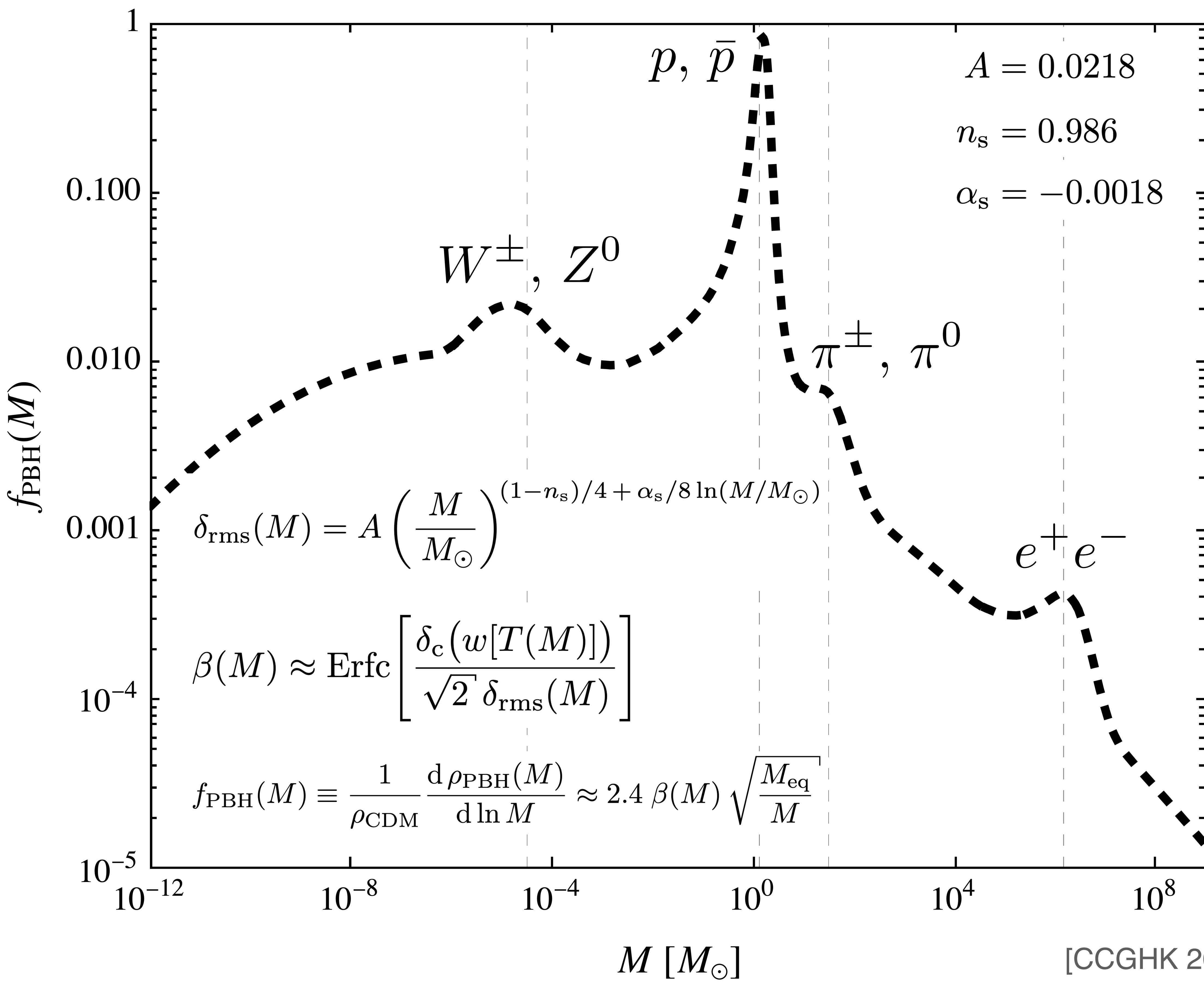
PBH Mass Function



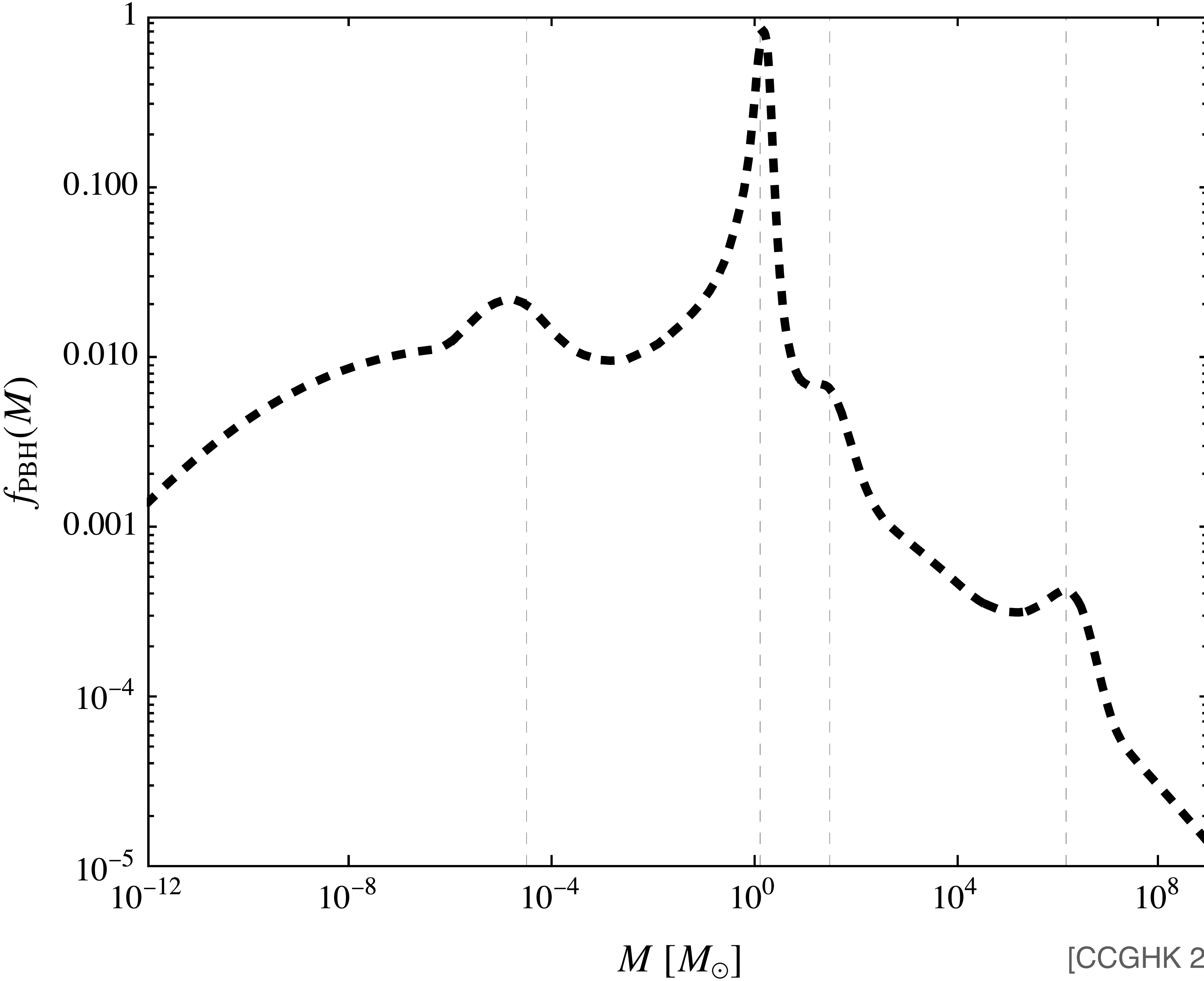
[CCGHK 2023]

PBH Mass Function



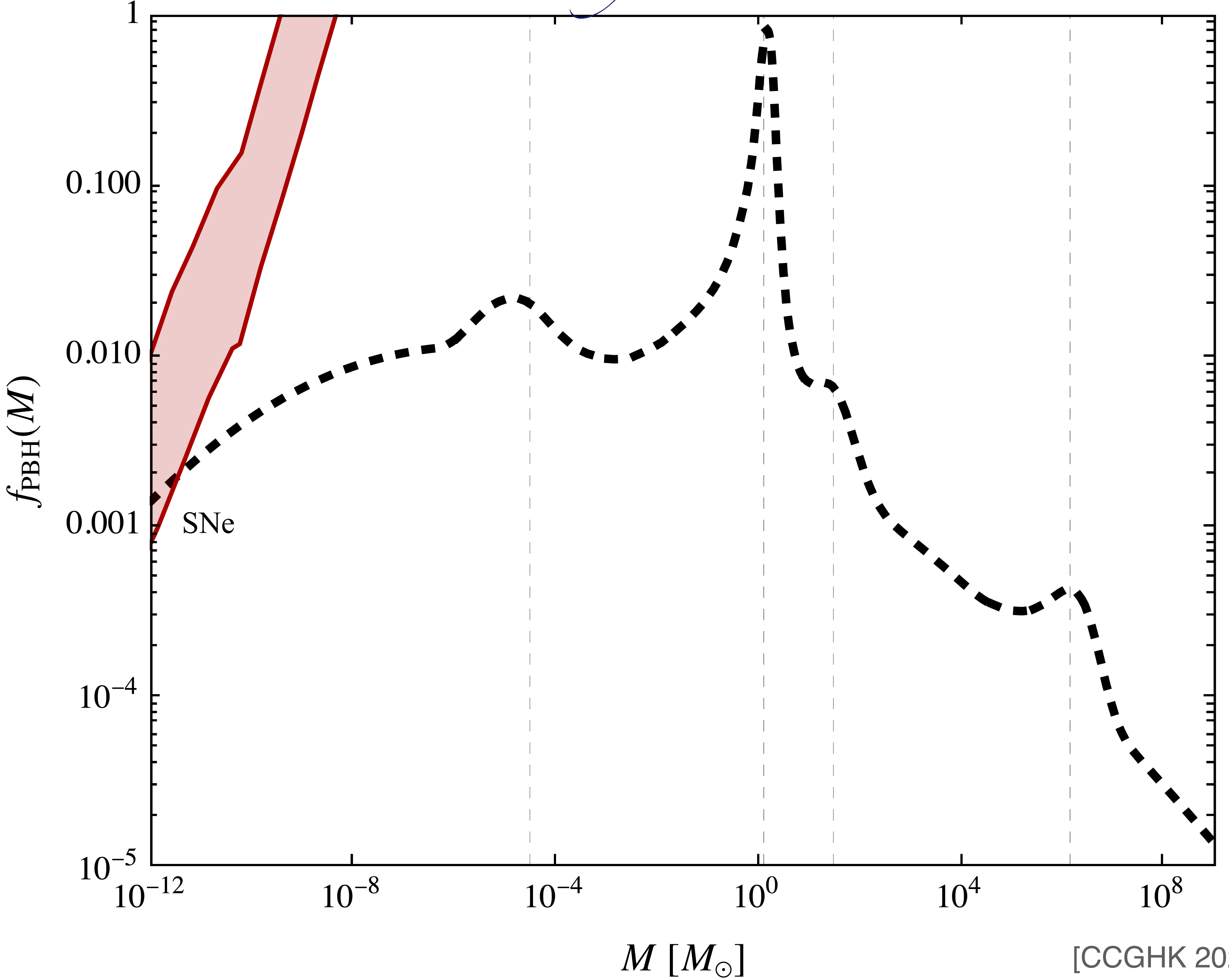
[CCGHK 2023]

PBH Mass Function



[CCGHK 2023]

PBH Mass Function — Confronted with Observations



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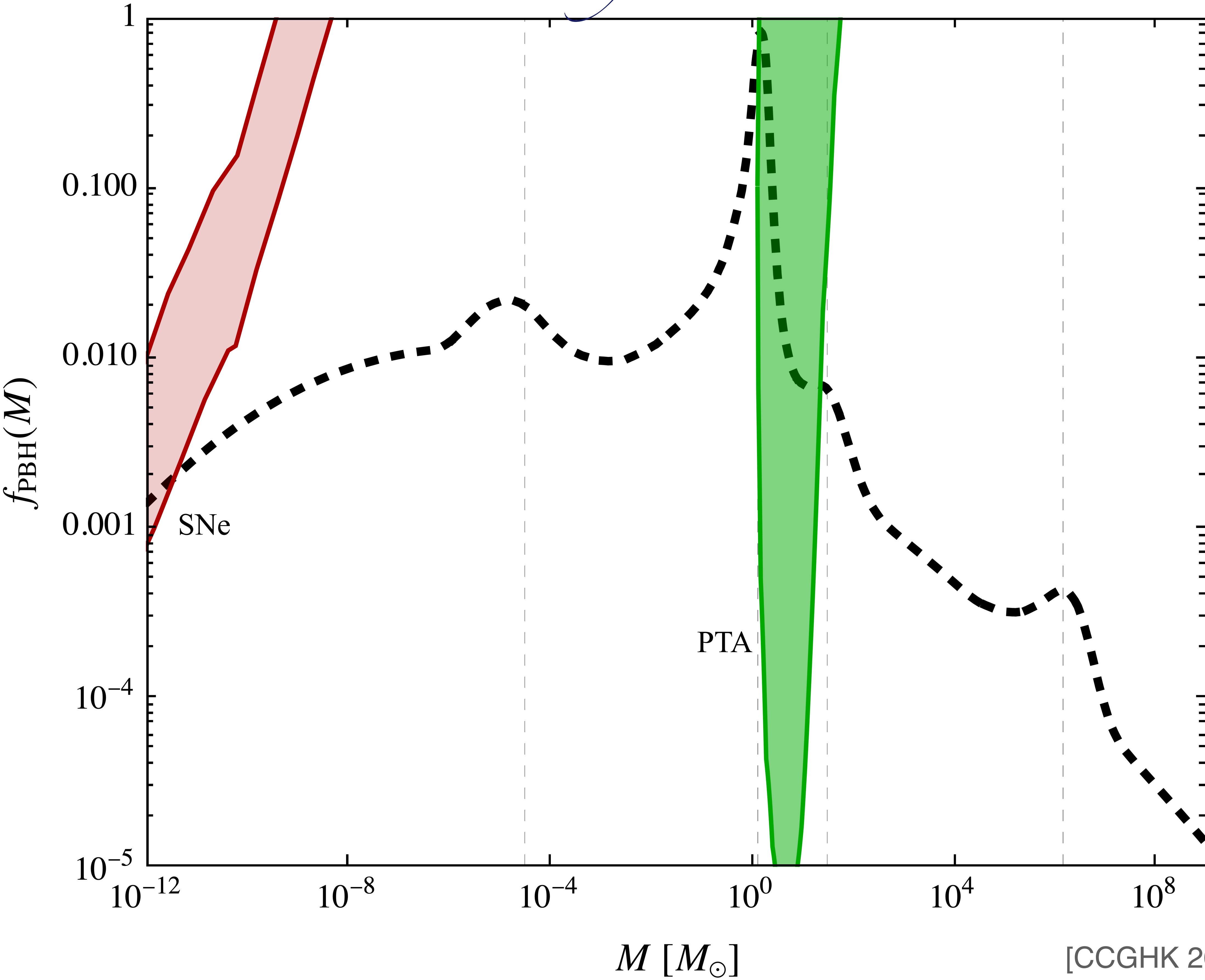

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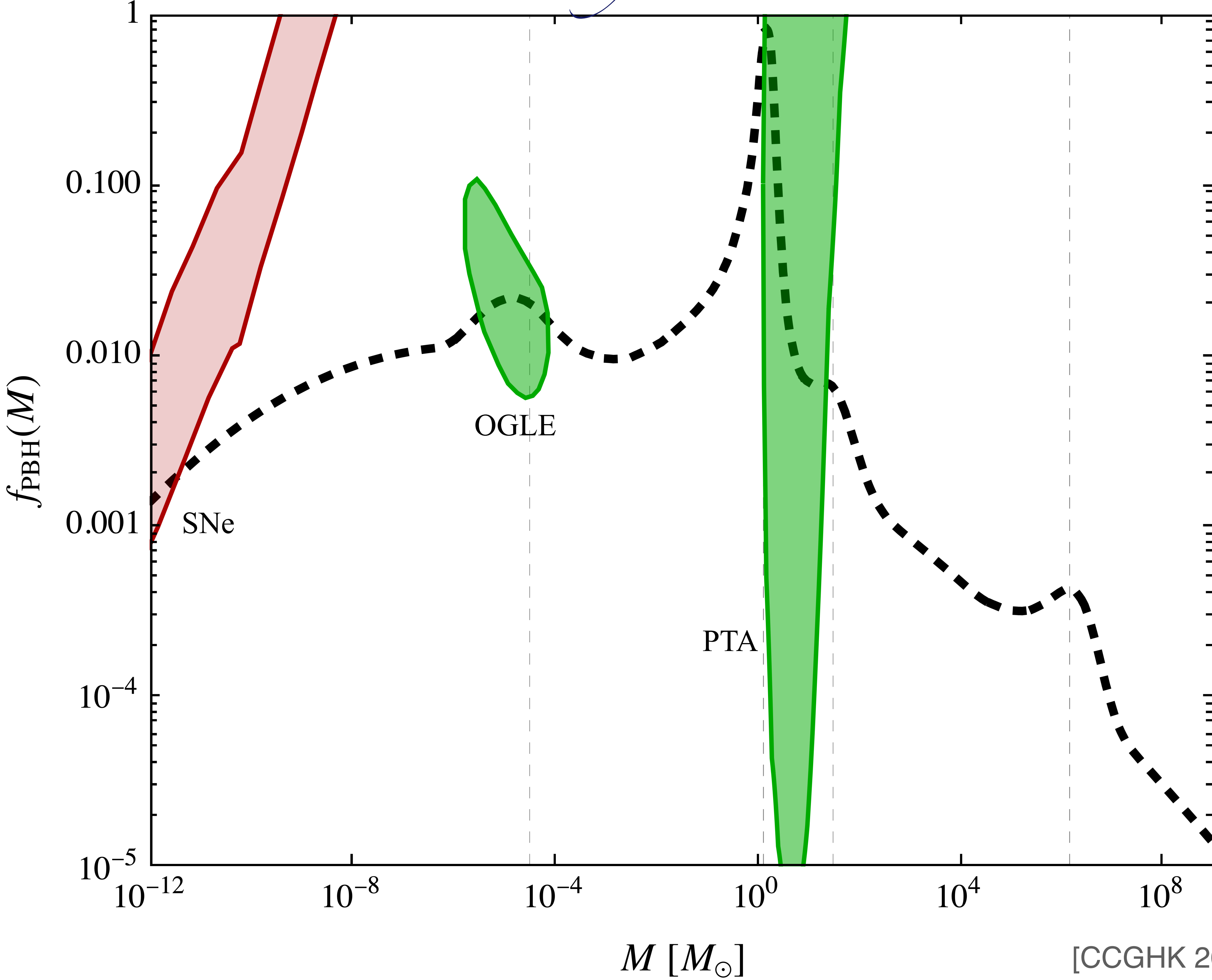

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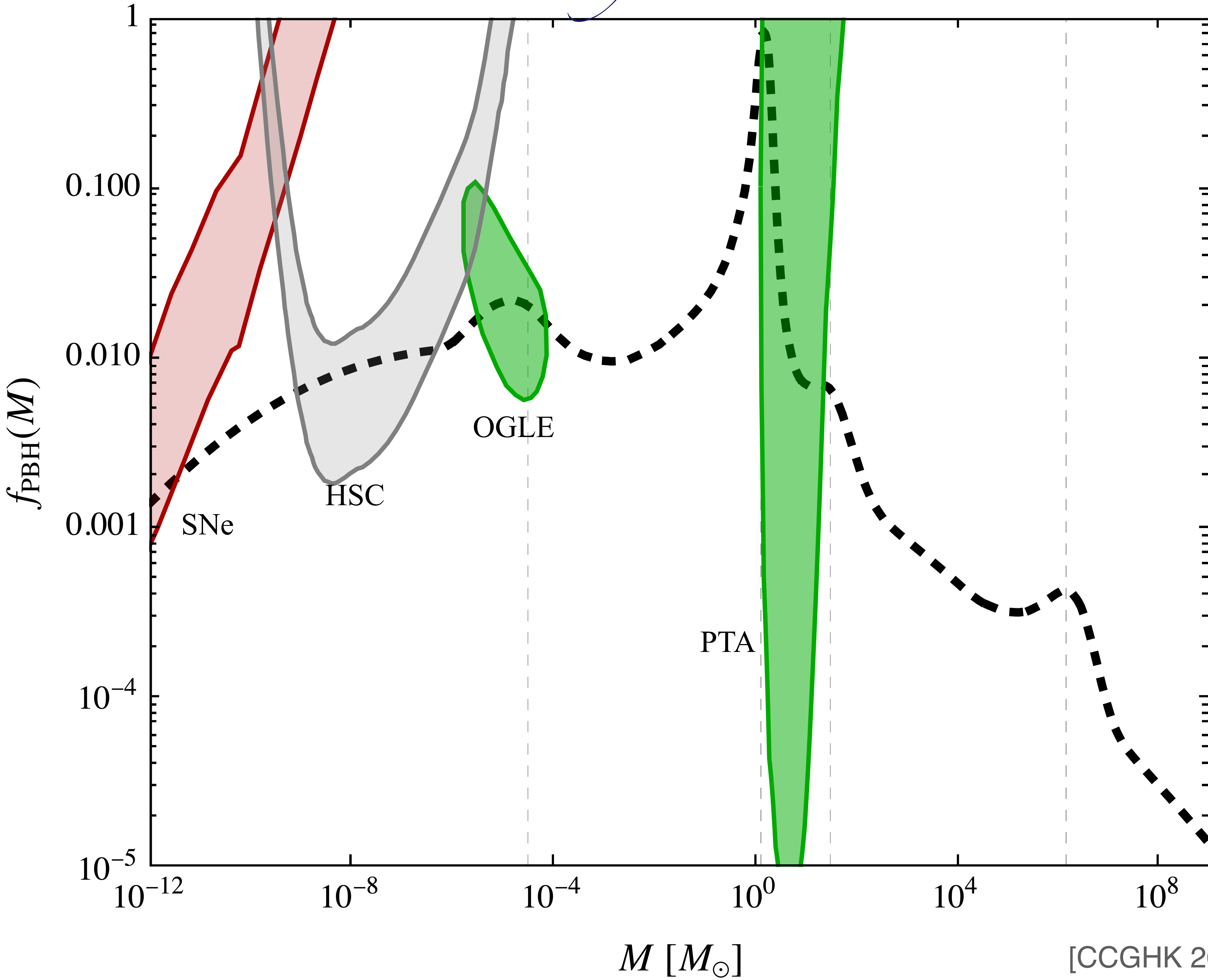

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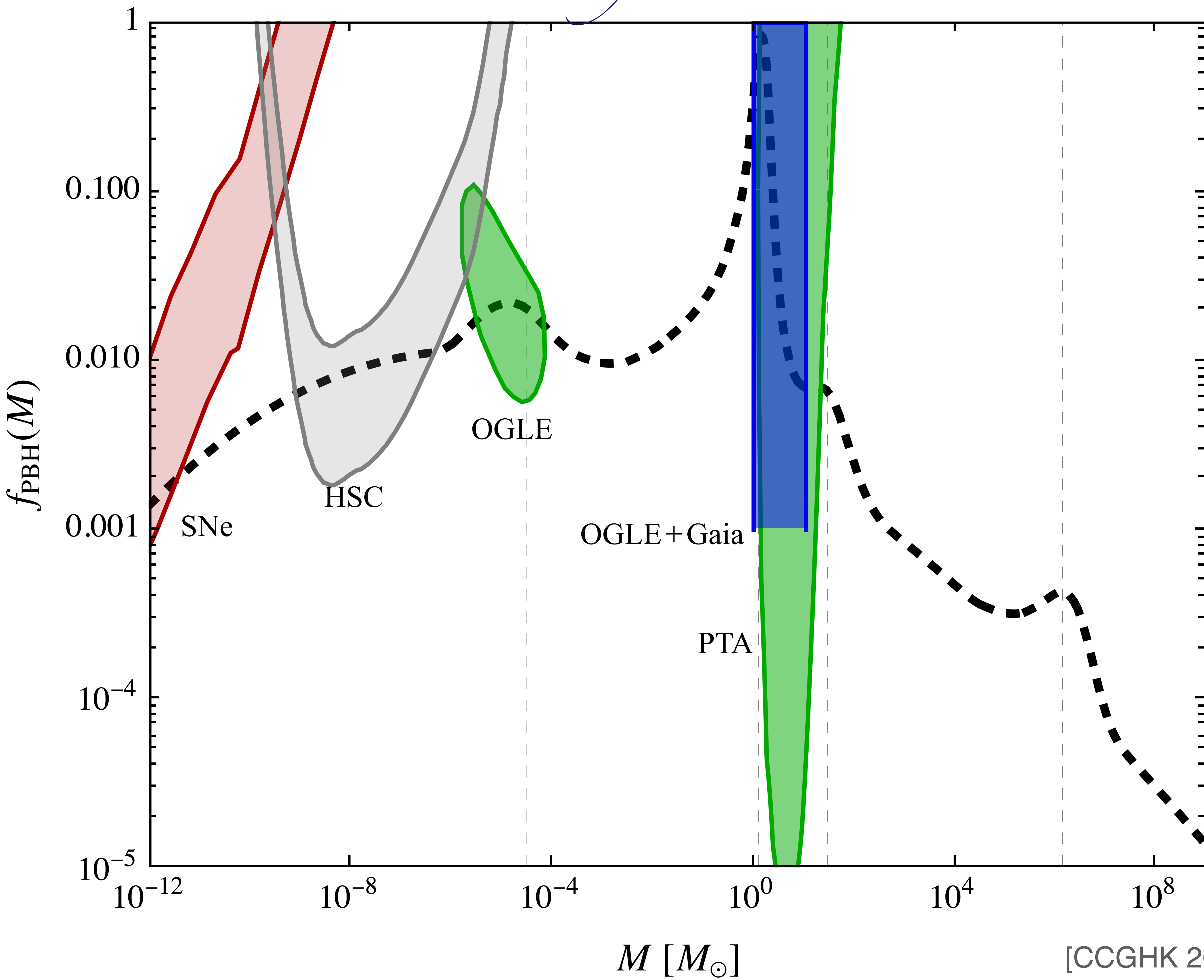

[CCGHK 2023]

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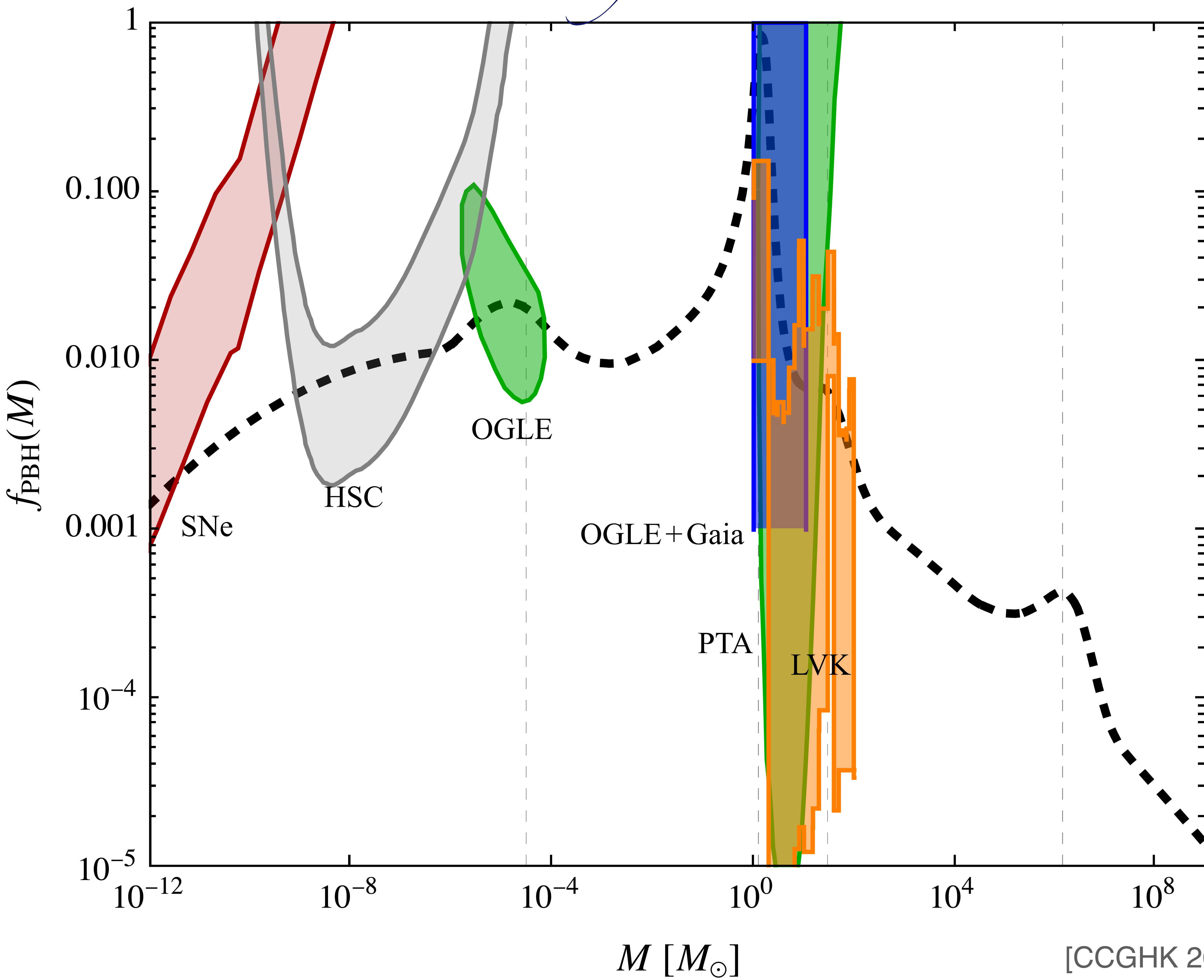

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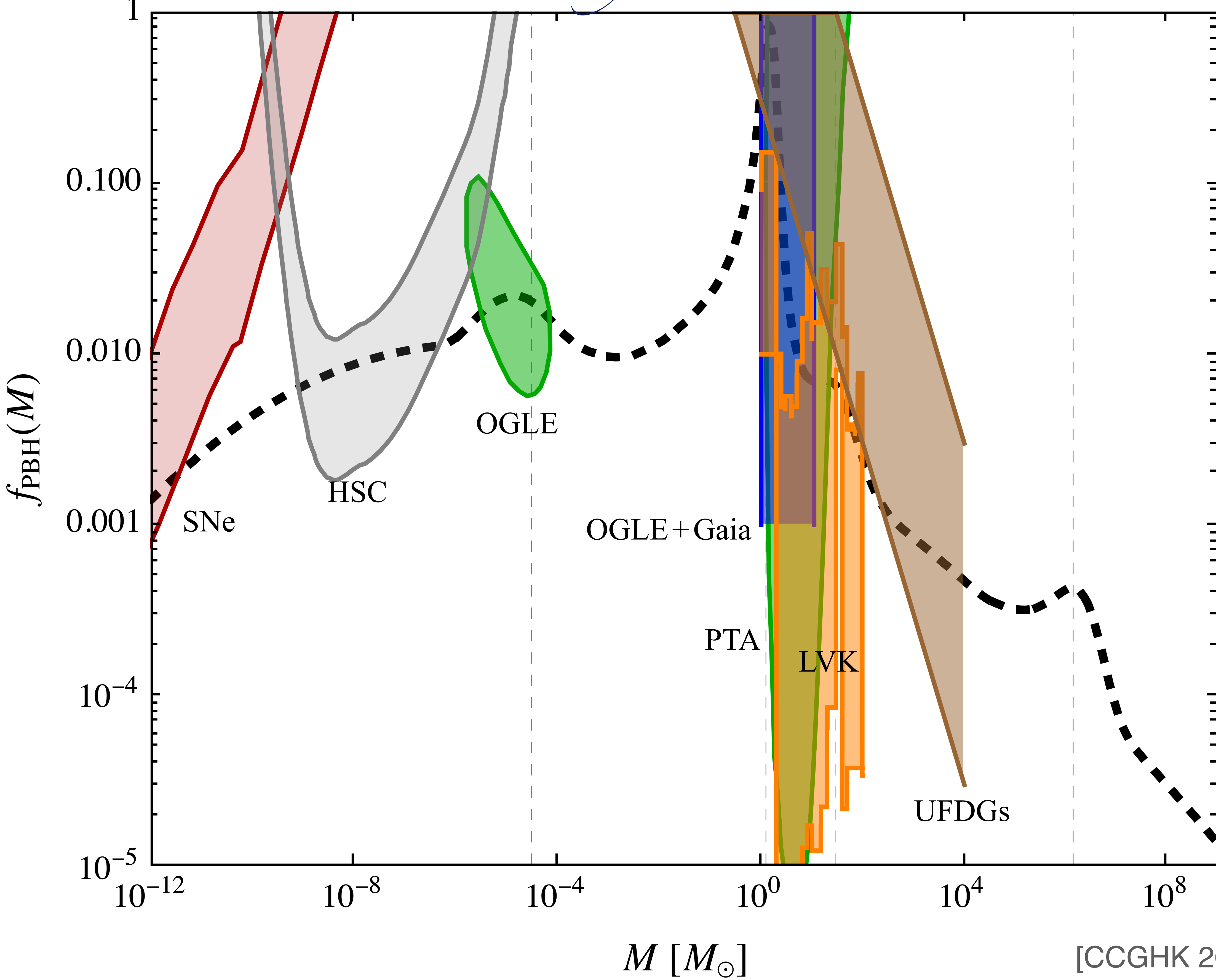

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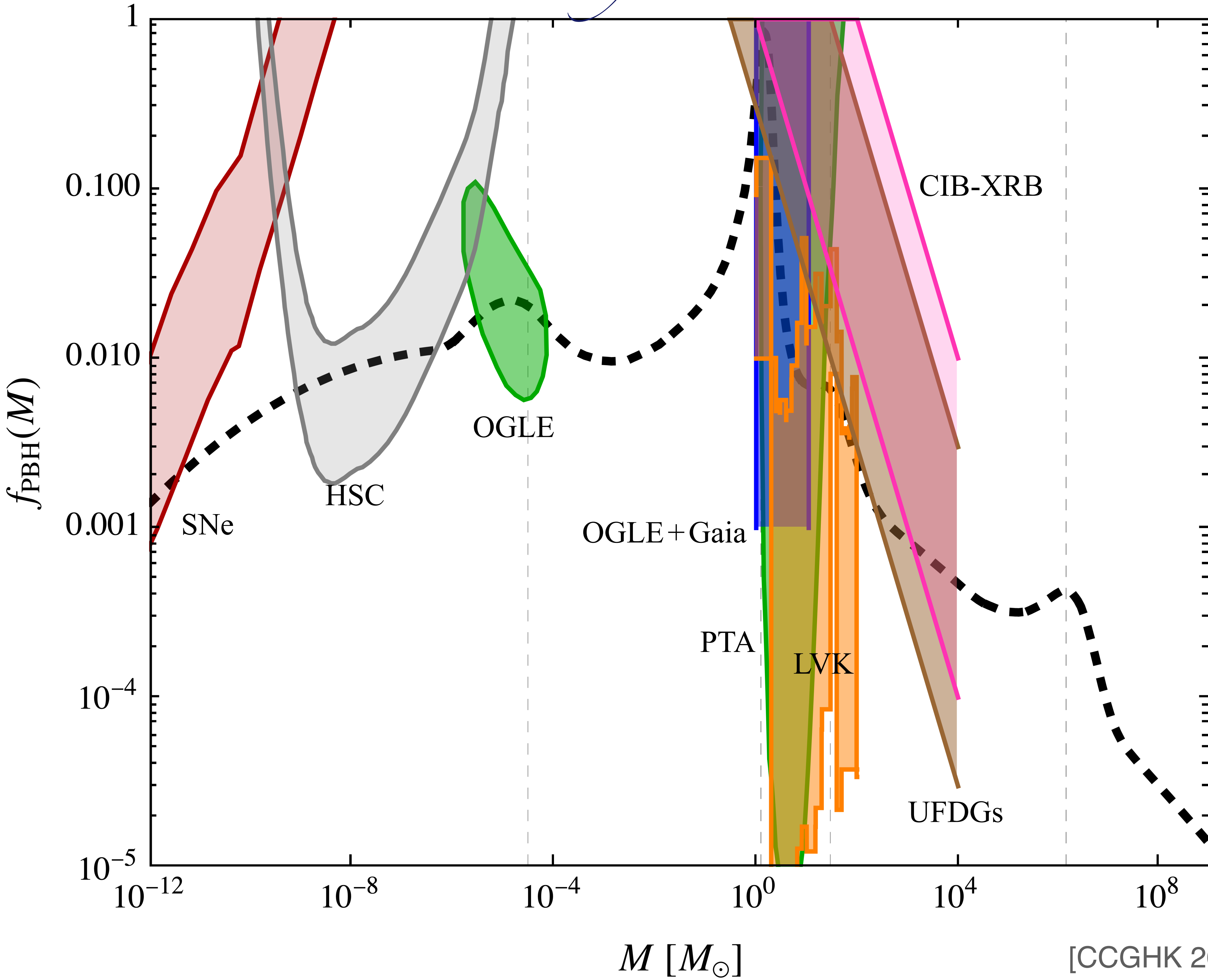

[CCGHK 2023]

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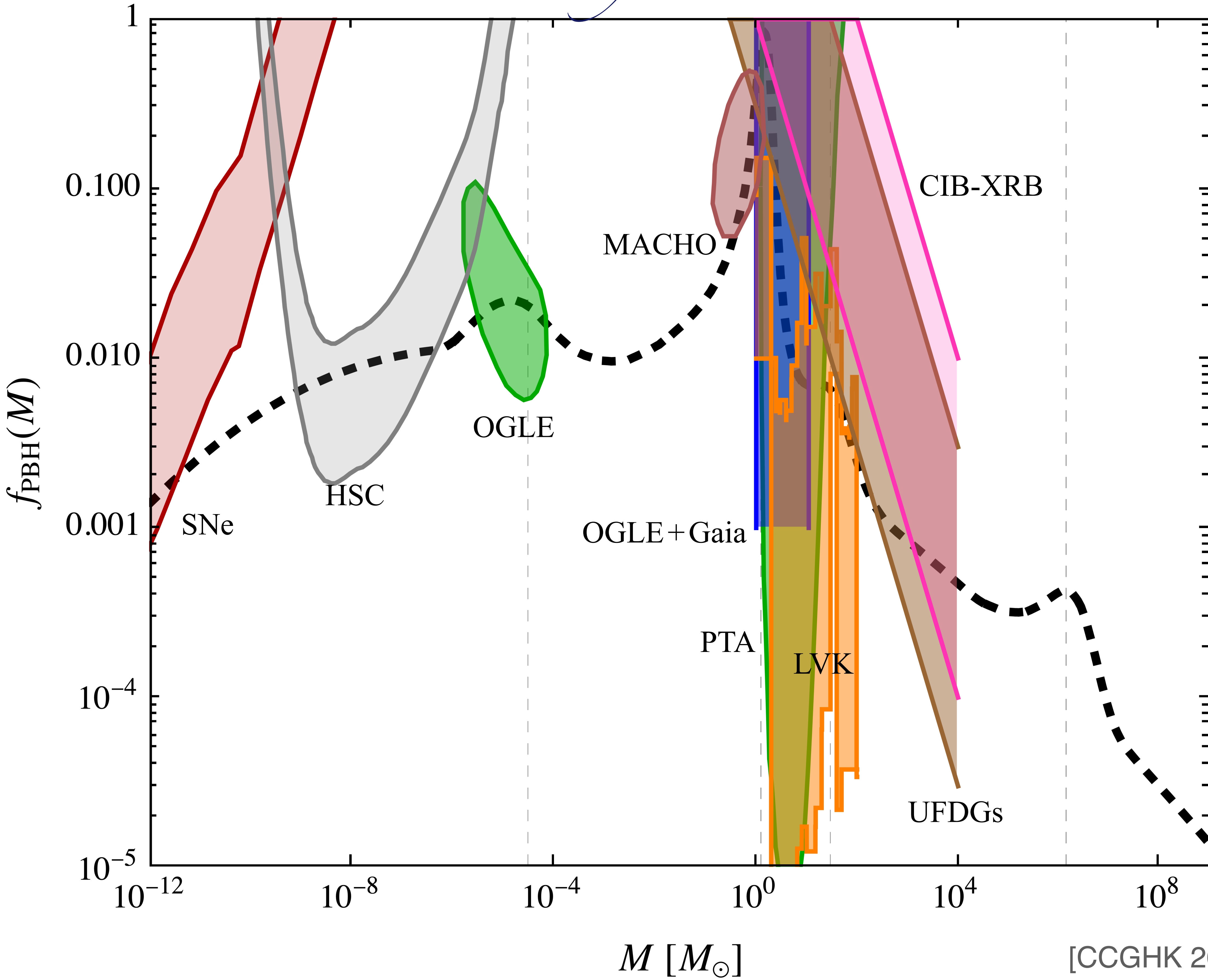

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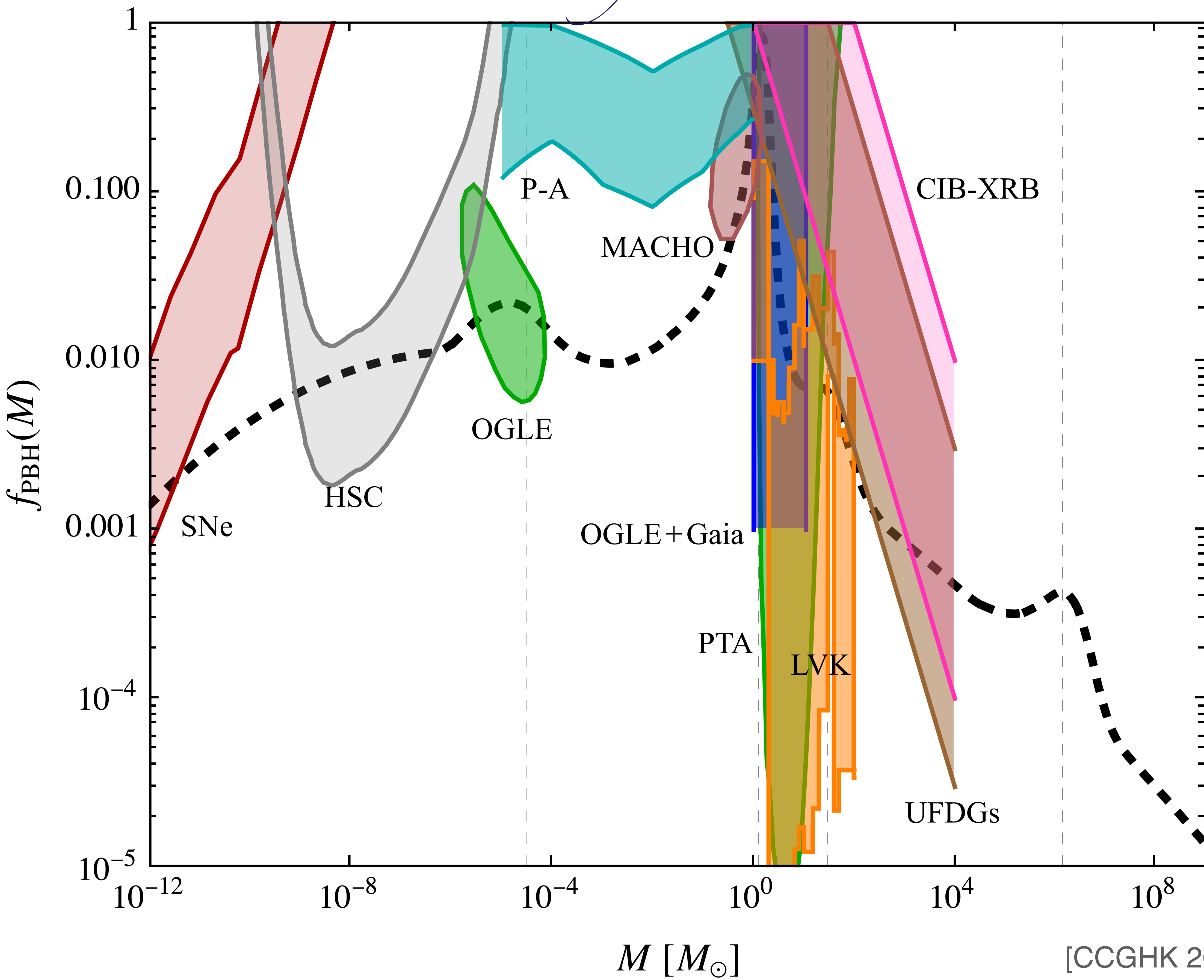

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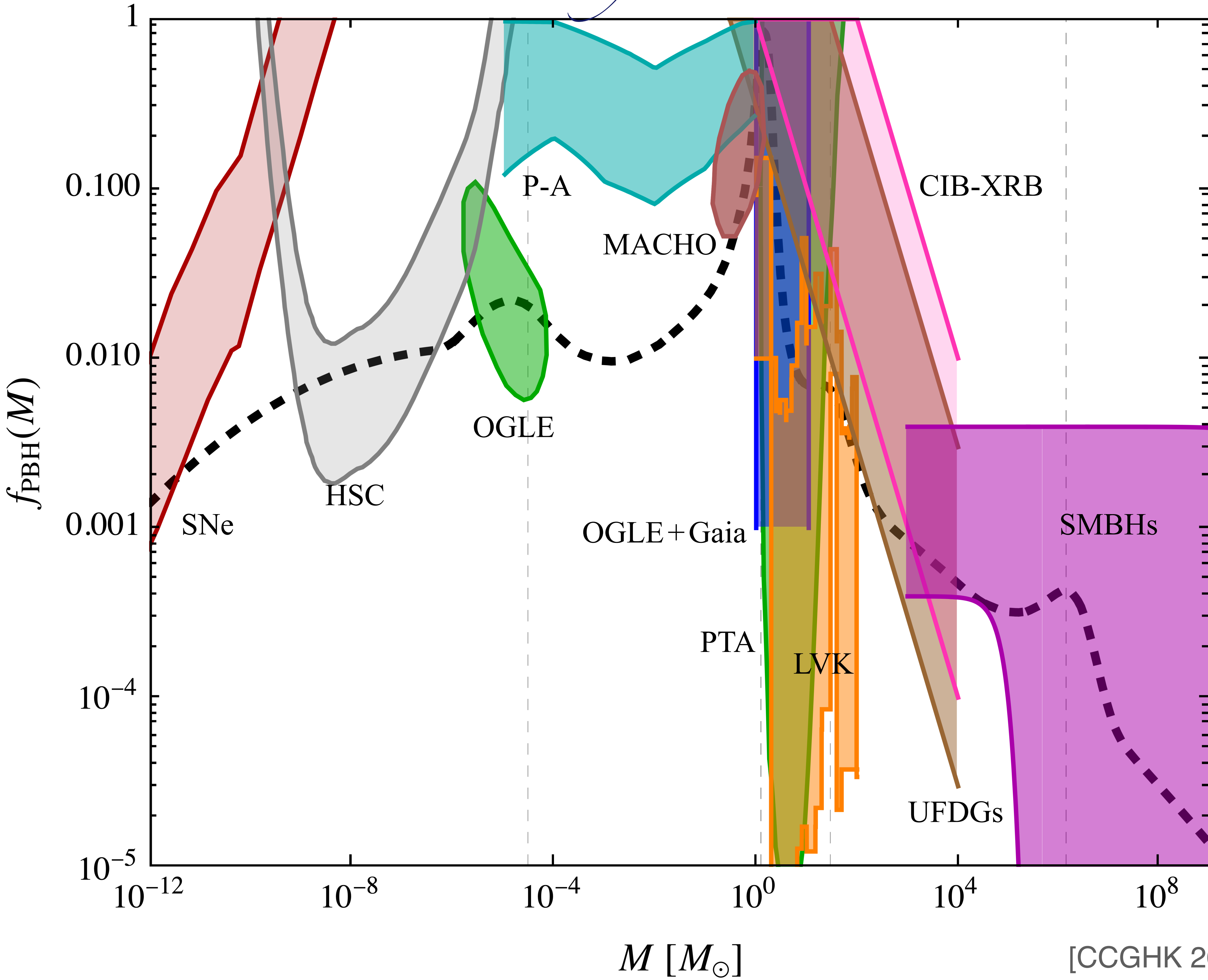
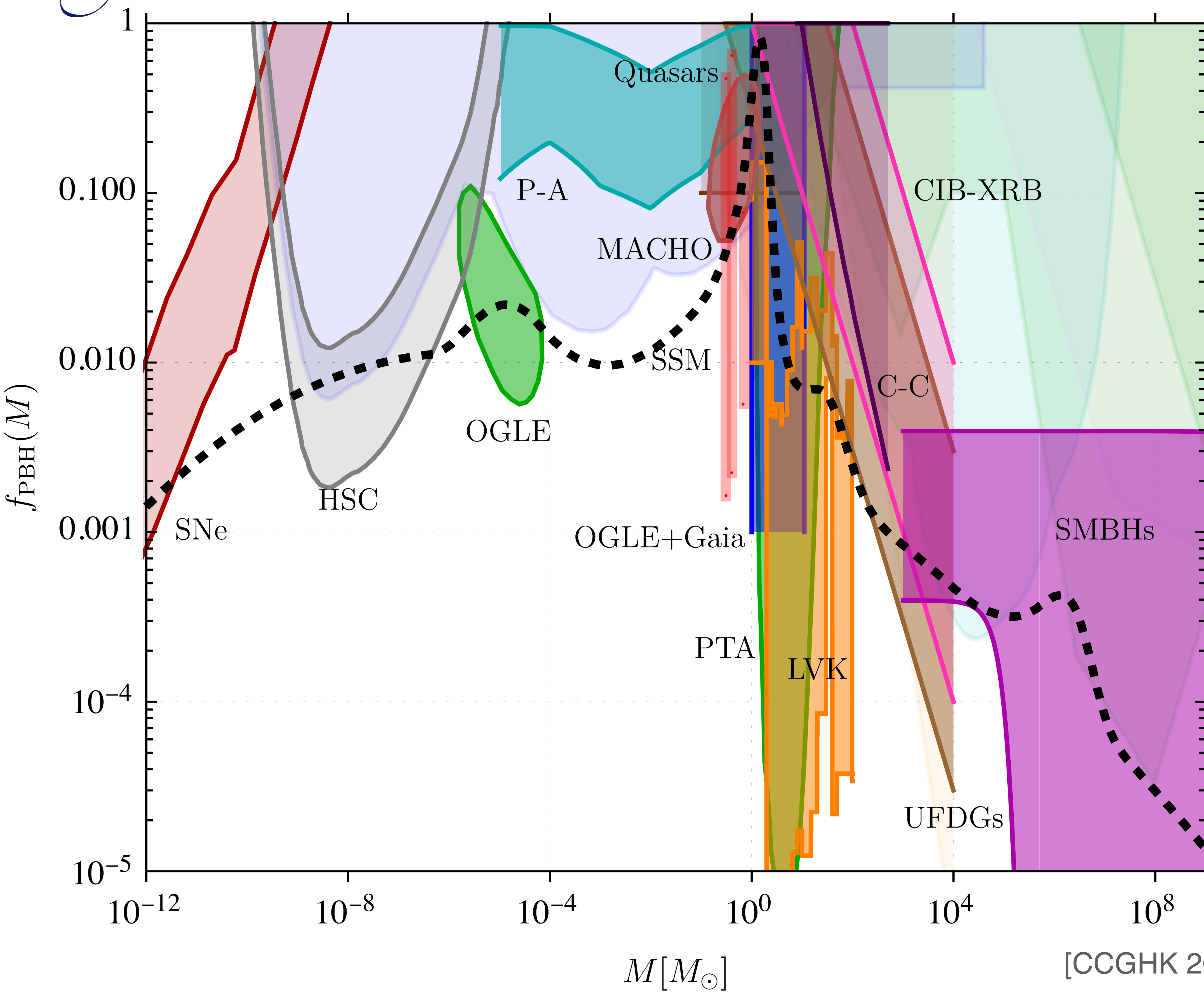


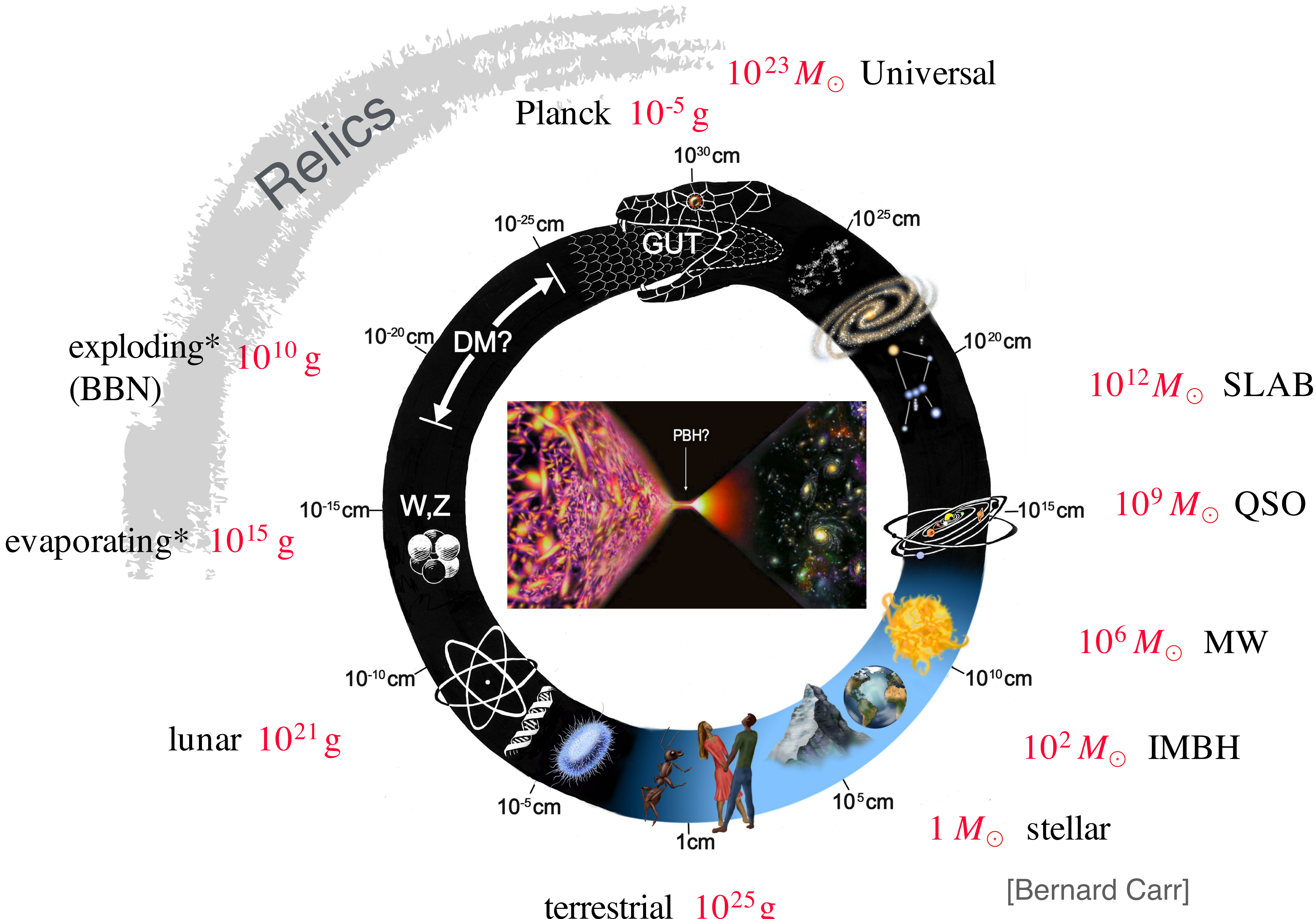
[CCGHK 2023]

Connecting all Positive Evidences!



[CCGHK 2023]

Black Holes as a Link between Micro and Macro Physics



[Bernard Carr]

*Image of snake from Abrams & Primack 2012

Shall Ye Become Positivists!

Observational Evidence for Primordial Black Holes: A Positivist Perspective

B. J. Carr,[1,*] S. Clesse,[2,†] J. García-Bellido,[3,‡] M. R. S. Hawkins,[4,§] and F. Kühnel[5,¶]

[1] *School of Physics and Astronomy, Queen Mary University of London*

[2] *Service de Physique Théorique, University of Brussels (ULB)*

[3] *Instituto de Física Teórica, Universidad Autonóma de Madrid*

[4] *Royal Observatory Edinburgh*

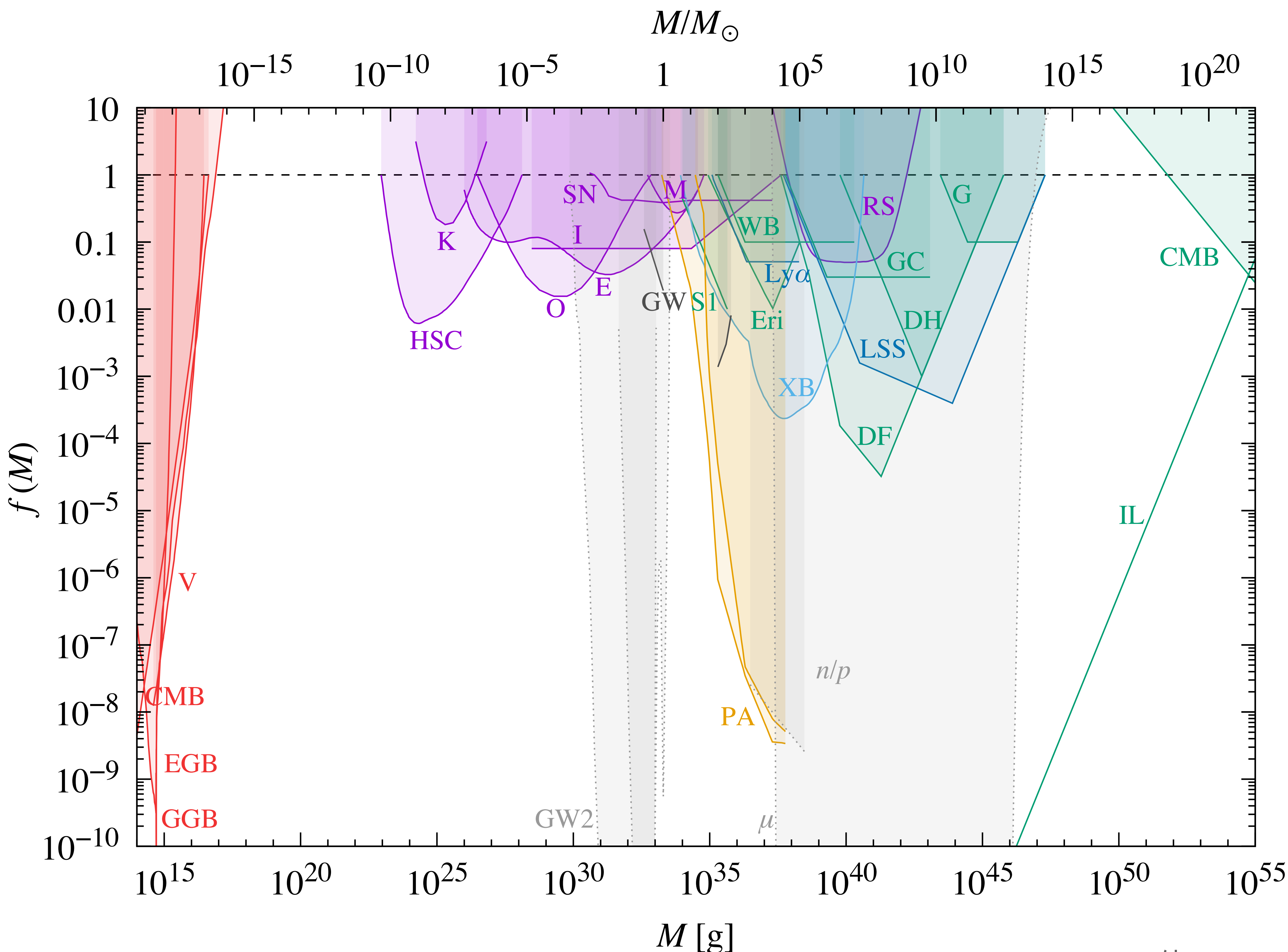
[5] *Max Planck Institute for Physics,*

(Dated: Wednesday 7th June, 2023, 12:34am)

We review numerous arguments for primordial black holes (PBHs) based on observational evidence from a variety of lensing, dynamical, accretion and gravitational-wave effects. This represents a shift from the usual emphasis on PBH constraints and provides what we term a positivist perspective. Microlensing observations of stars and quasars suggest that PBHs of around $1\,M_\odot$ could provide much of the dark matter in galactic halos, this being allowed by the Large Magellanic Cloud observations if the PBHs have an extended mass function. More generally, providing the mass and dark matter fraction of the PBHs is large enough, the associated Poisson fluctuations could generate the first bound objects at a much earlier epoch than in the standard cosmological scenario. This simultaneously explains the recent detection of high-redshift dwarf galaxies, puzzling correlations of the source-subtracted infrared and X-ray cosmic backgrounds, the size and the mass-to-light ratios of ultra-faint-dwarf galaxies, the dynamical heating of the Galactic disk, and the binary coalescences observed by LIGO/Virgo/KAGRA in a mass range not usually associated with stellar remnants. Even if PBHs provide only a small fraction of the dark matter, they could explain various other observational conundra, and sufficiently large ones could seed the supermassive black holes in galactic nuclei or even early galaxies themselves. We argue that PBHs would naturally have formed around the electroweak, quantum chromodynamics and electron-positron annihilation epochs, when the sound-speed inevitably dips. This leads to an extended PBH mass function with a number of distinct bumps, the most prominent one being at around $1\,M_\odot$, and this would allow PBHs to explain much of the evidence in a unified way.

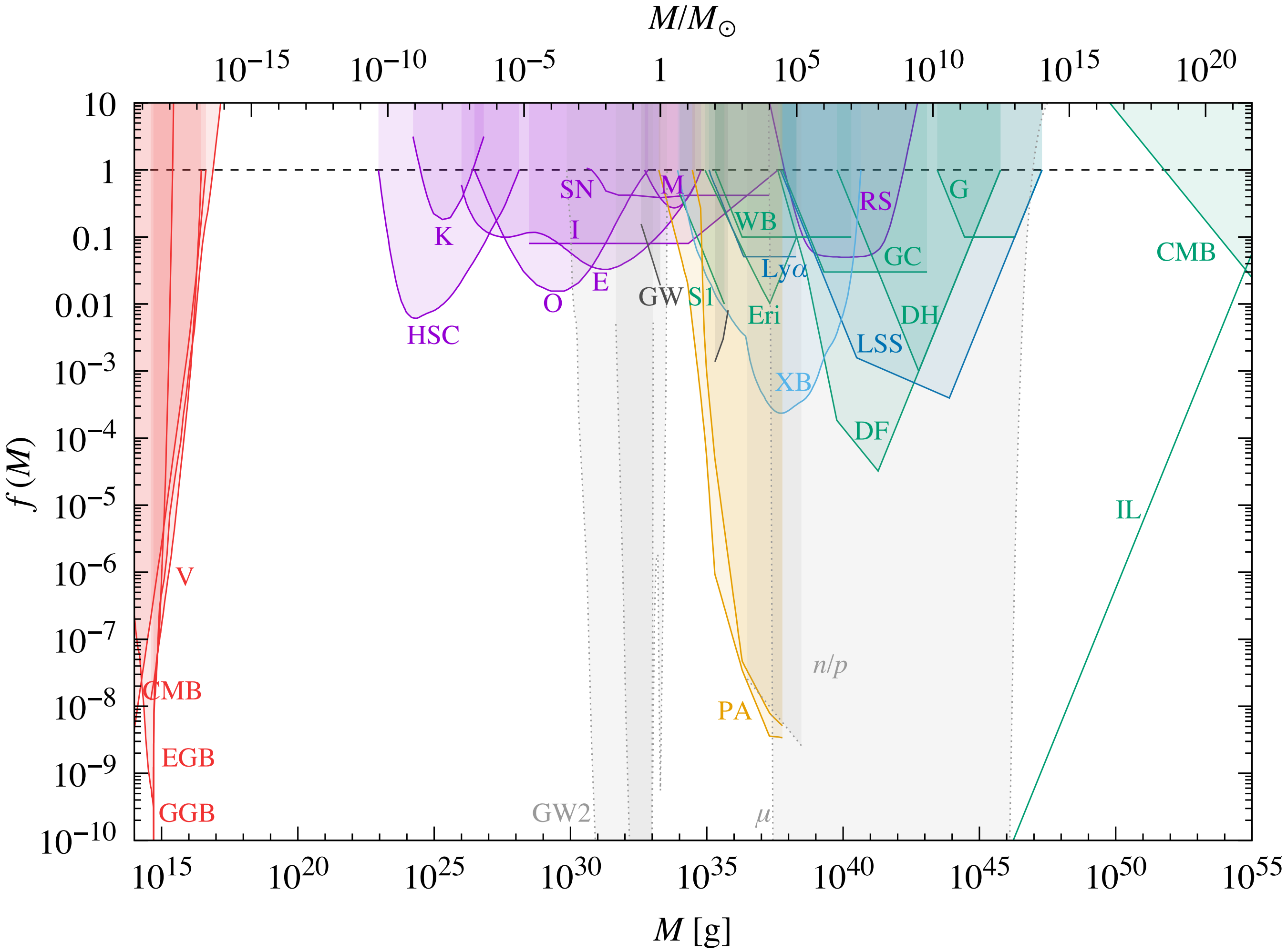
Addendum

Current PBH Constraints



[Carr 他 2021]

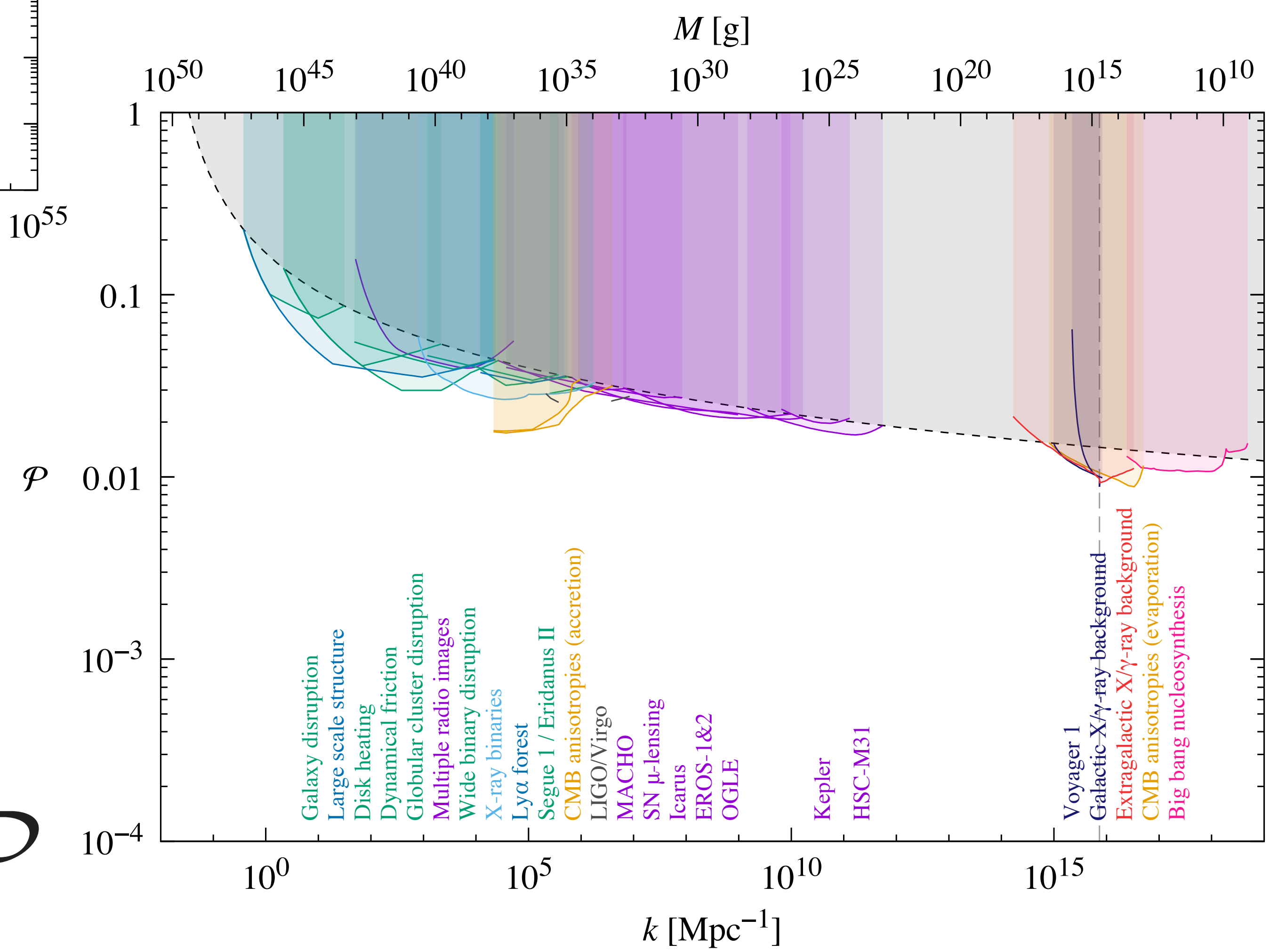
PBH Constraints — Primordial Power Spectrum



f_{PBH}

$$\beta \sim \mathrm{erfc}\left(\frac{\delta_c}{2\,\sigma}\right)$$

$\mathcal{P}$



[Carr 他 2021]

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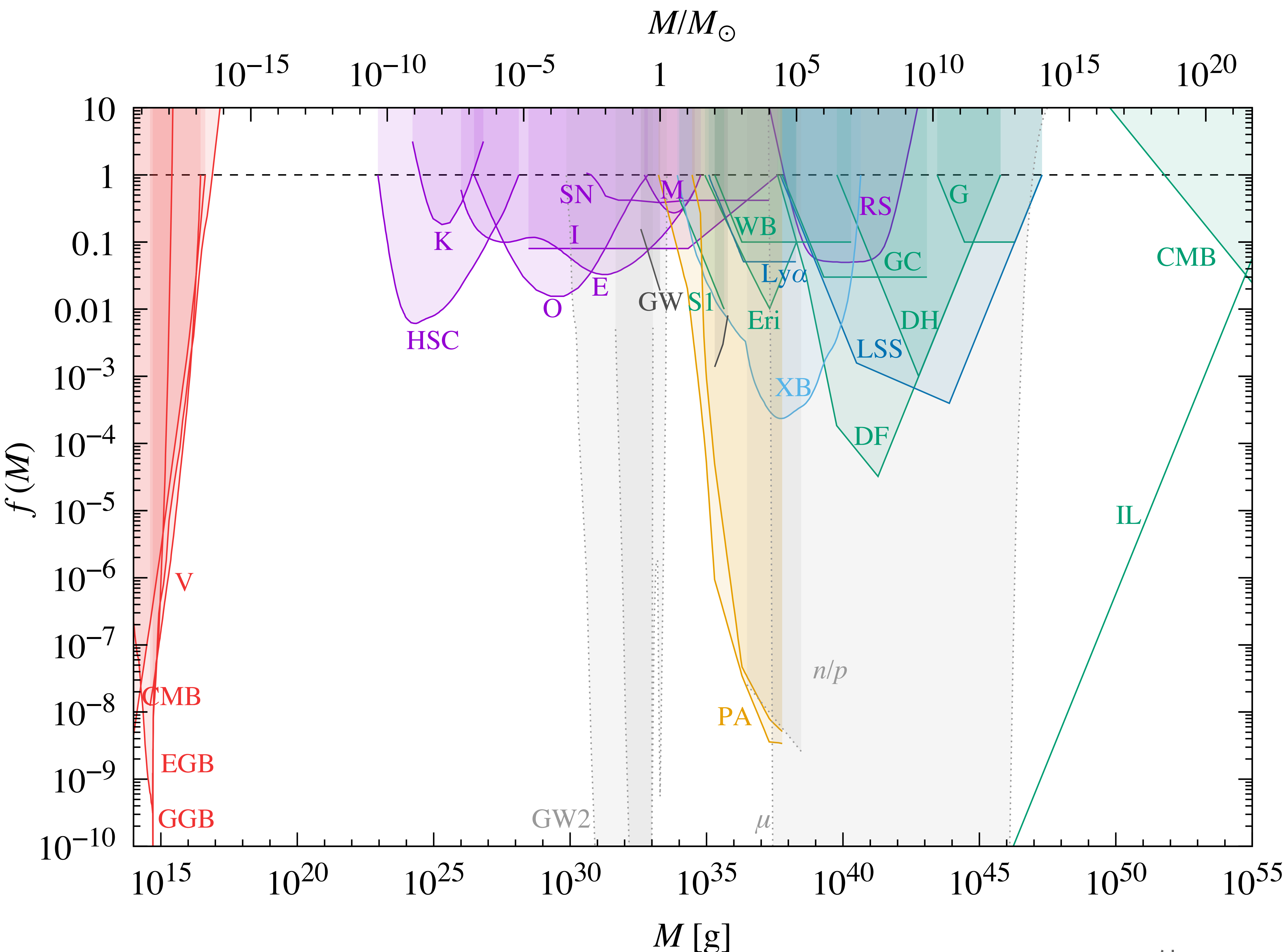
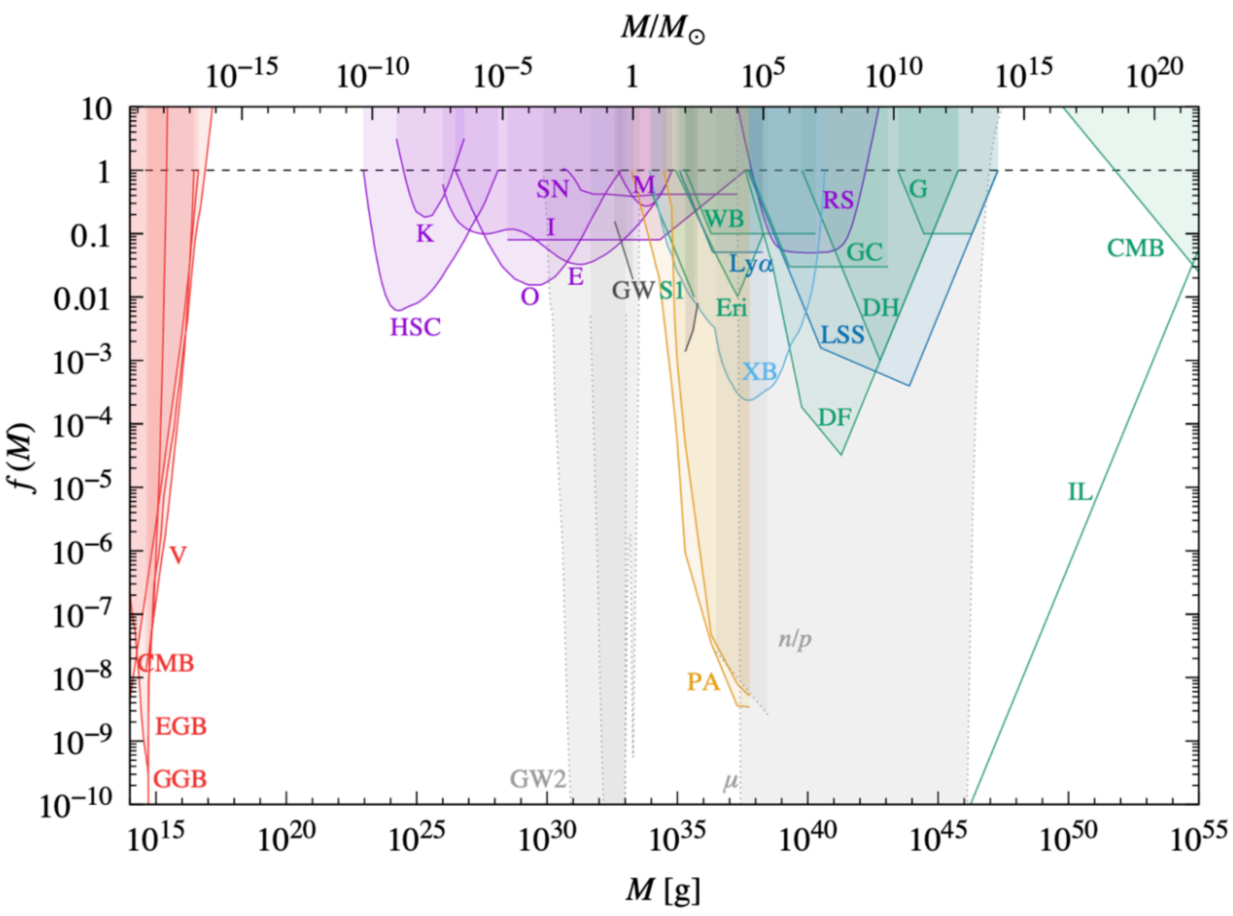
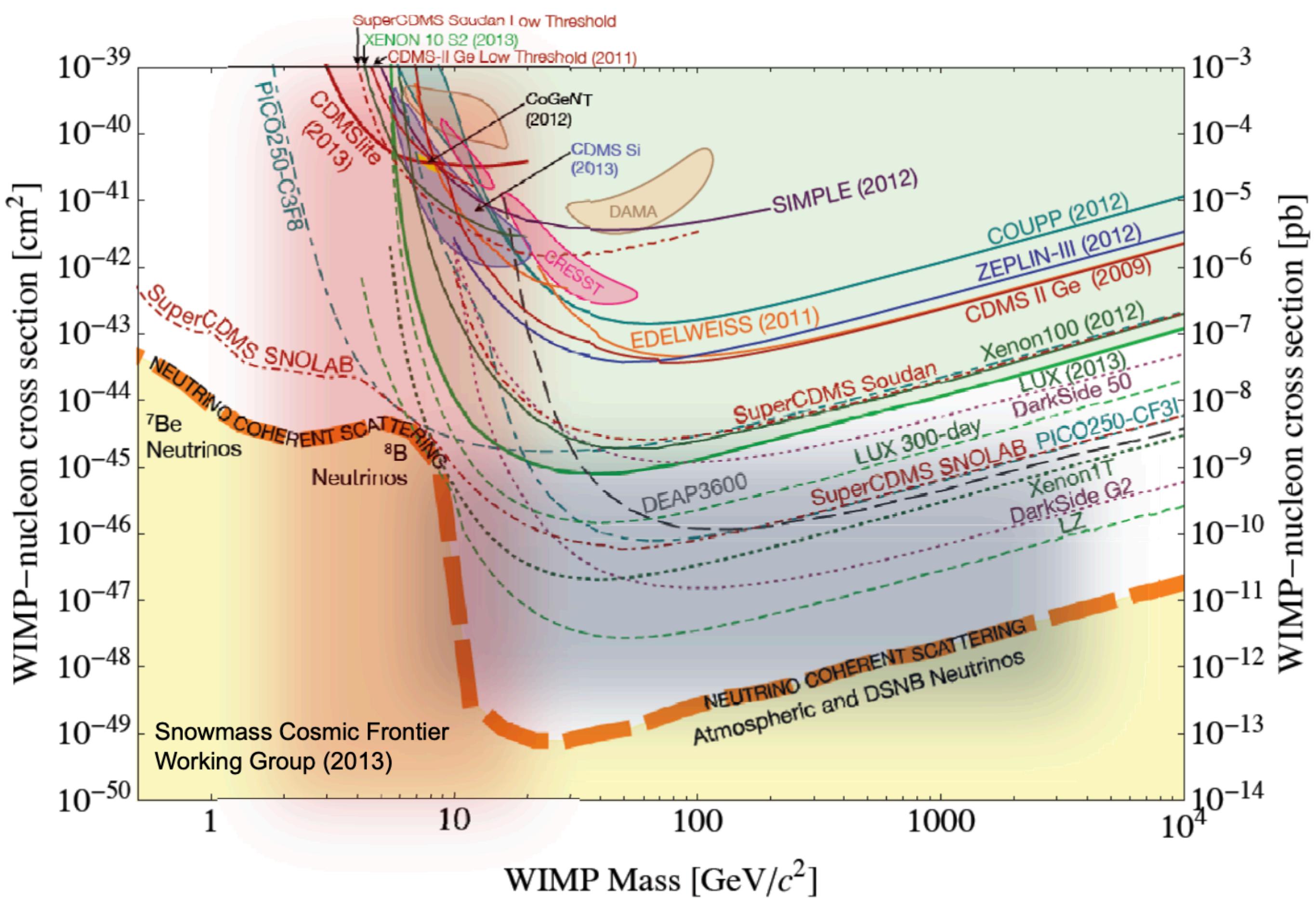


[Carr 他 2021]

PBH versus WIMP Constraints





Caveats

and

Uncertainties

Constraints — A Worthwhile Remark

- These constraints are not just nails in a coffin!

(Carr)

- All constraints have caveats and might change.

- Each constraint is a potential signature.

- PBHs are important even if $f_{\rm PBH} \ll 1$.

Monochromatic

versus

Extended Mass Spectra

Critical Collapse

★ Usually: Assume

$$M_{BH} \propto M_H$$

horizon mass

★ Critical scaling:

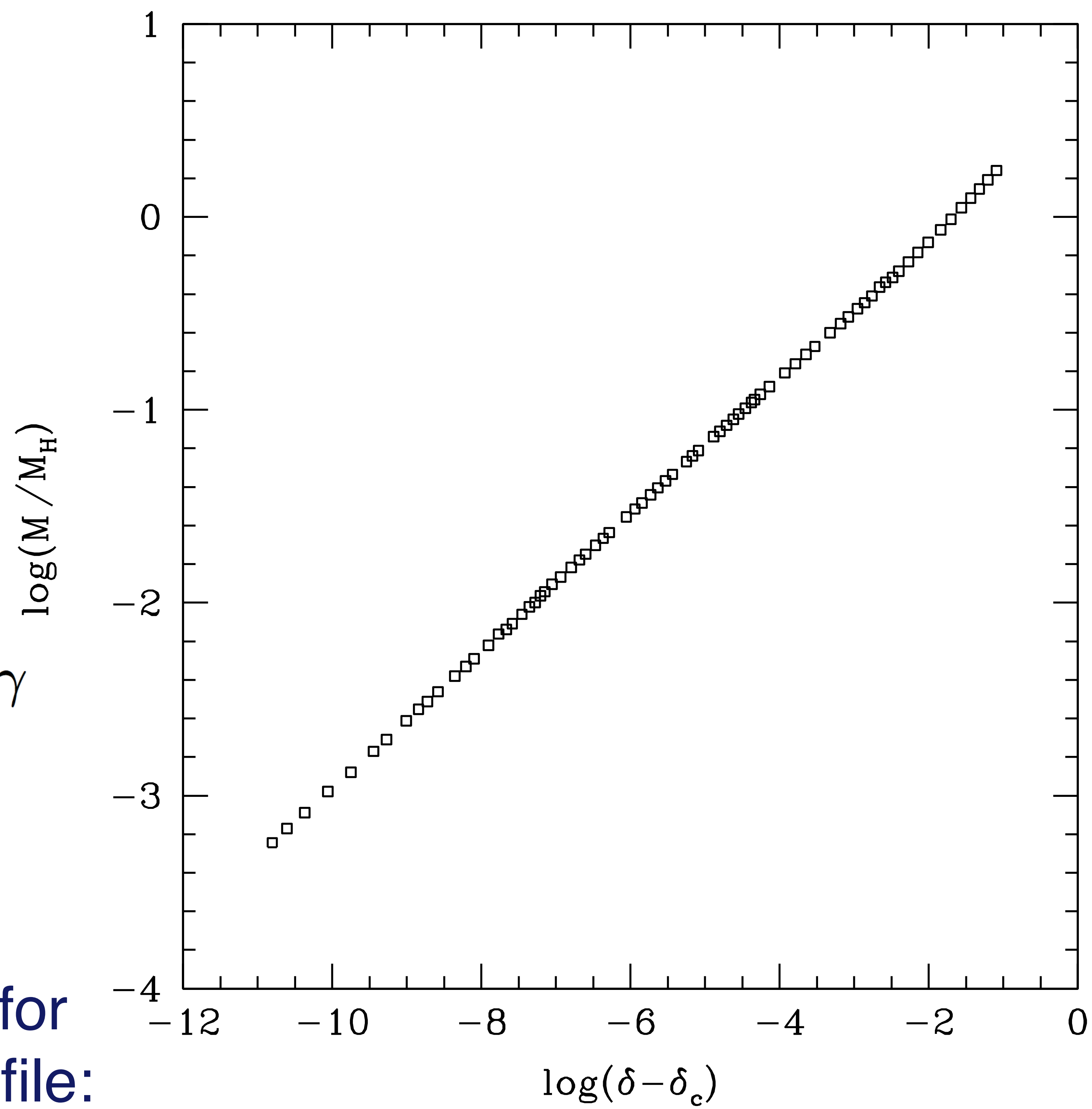
[Choptuik ’93]

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

density contrast

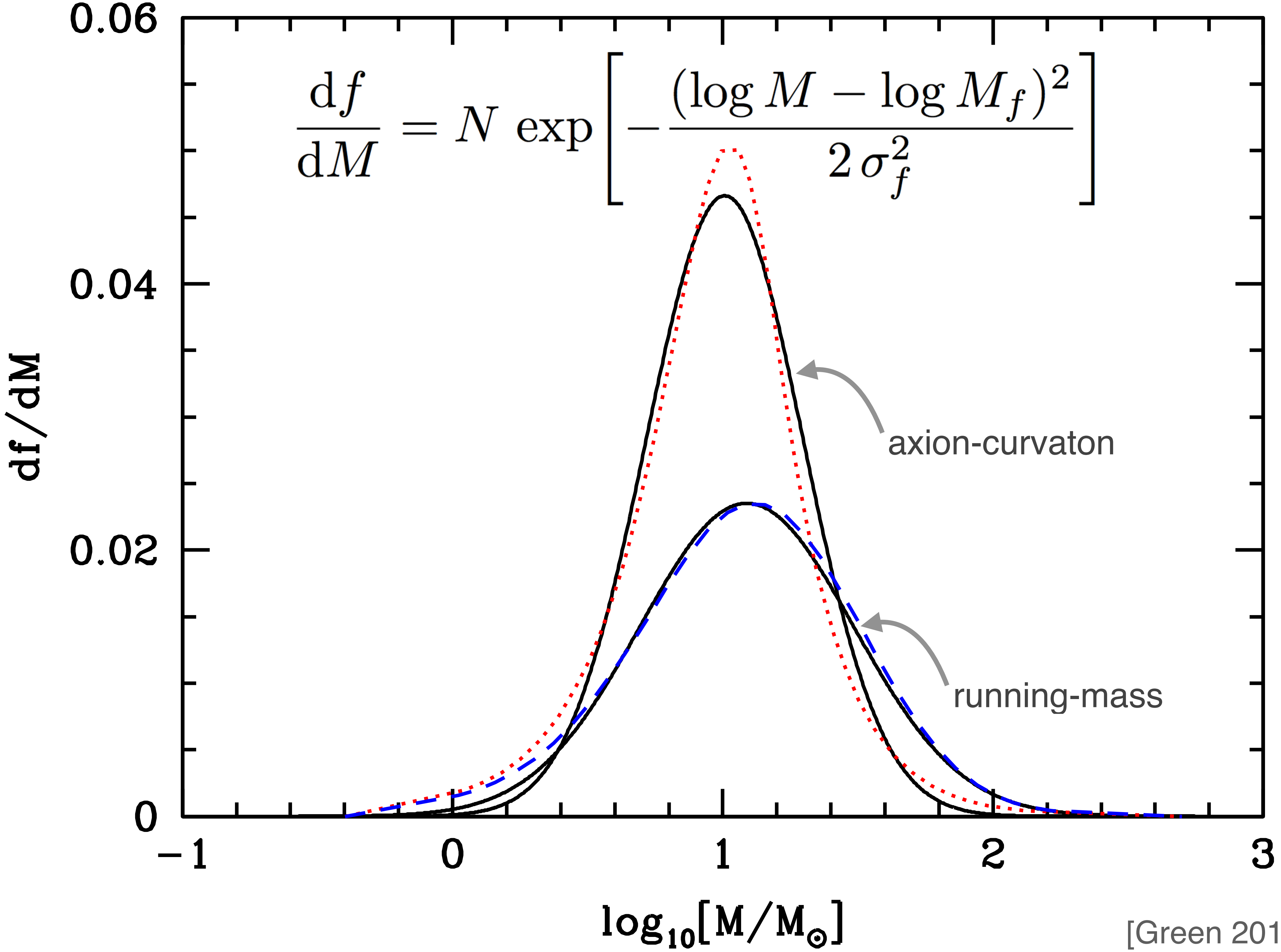
★ Radiation domination and for spherical Mexician-hat profile:

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



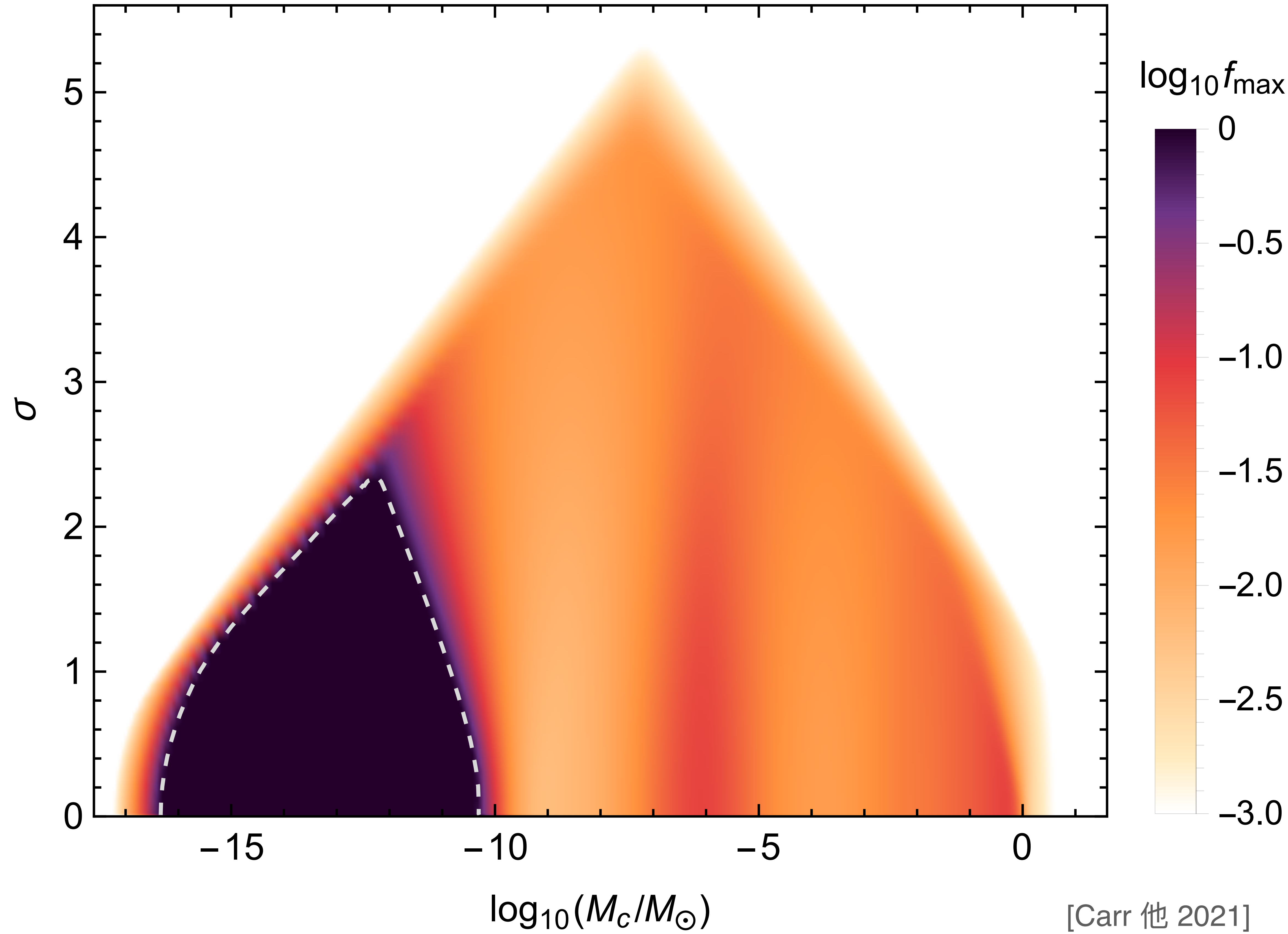
[Musco, Miller, Polnarev 2008]

More Systematic Study



[Green 2016]

More Systematic Study



[Carr 他 2021]

Primordial Black Holes

and

Particle Dark Matter

PBH & Particle Dark Matter

- ★ Always when $f_{\rm PBH} < 1$ there **must** be another dark matter component!

PBH & Particle Dark Matter

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

PBH & Particle Dark Matter

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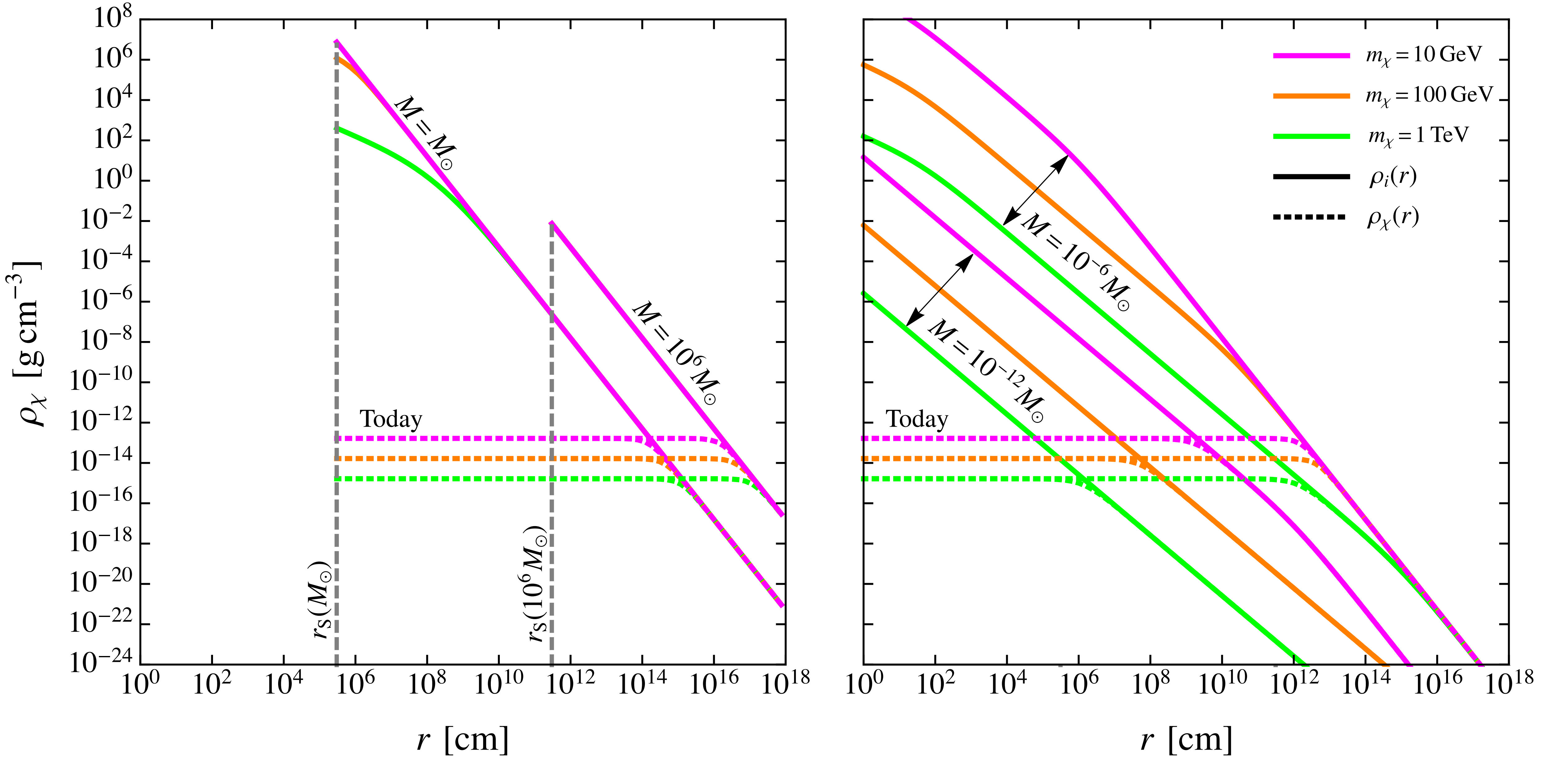
  - ★ Study WIMP annihilations in PBH halos:
    - ★ The annihilation rate $\Gamma \propto n^2$.
    - ★ Halo profile does matter; enhancement of Γ in density spikes.
      1) Derive the density profile of the captured WIMPs;
      2) calculate the annihilation rate;
      3) and compare to data.

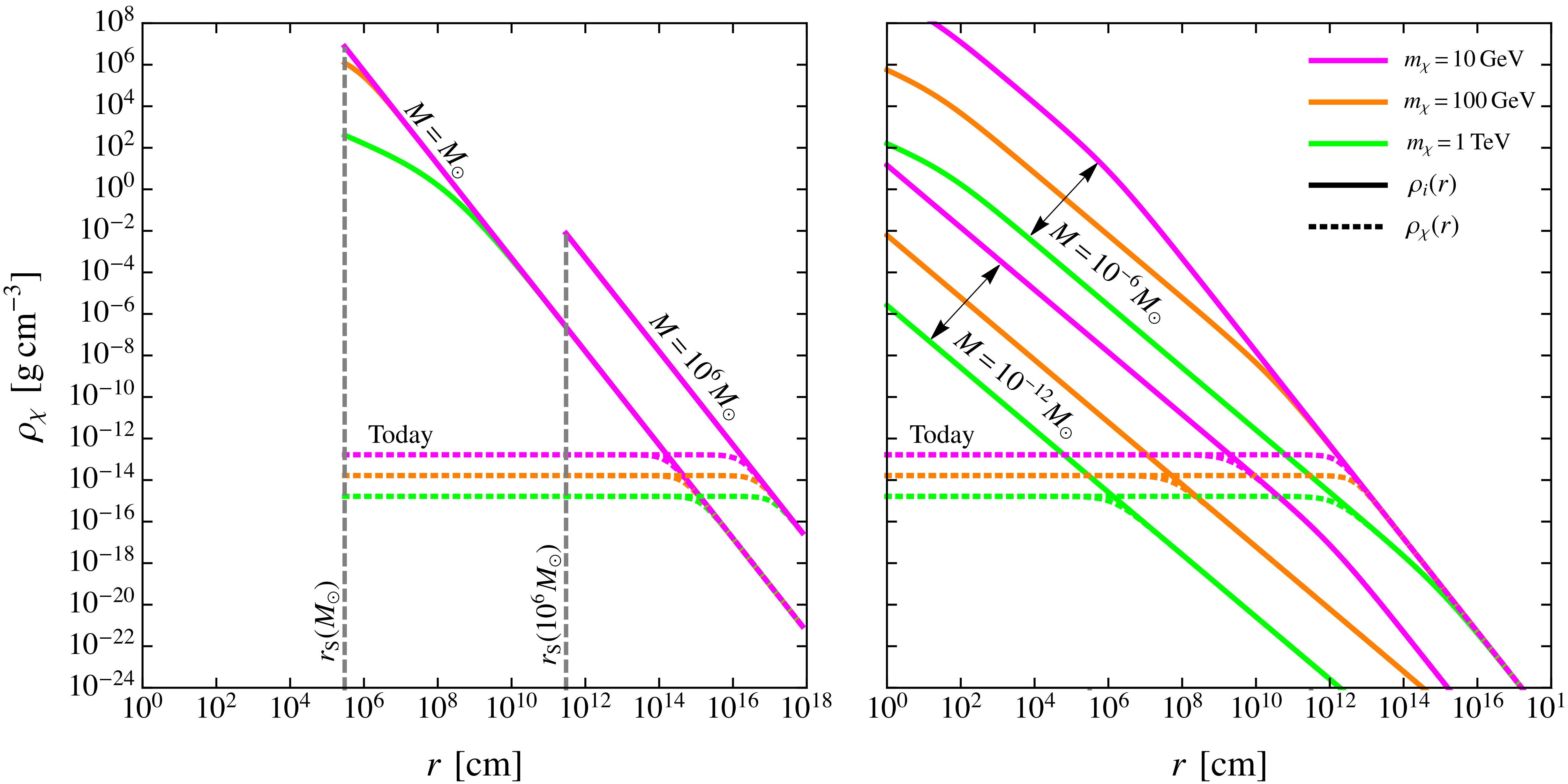
[Eroshenko 2016, Boucenna *et al*. 2017, Adamek *et al*. 2019, Carr, FK, Visinelli 2020 & 2021, Boudaud *et al.* 2021, Witte *et al.* 2022]

PBHs & WIMPs



[Carr, FK, Visinelli 2021]

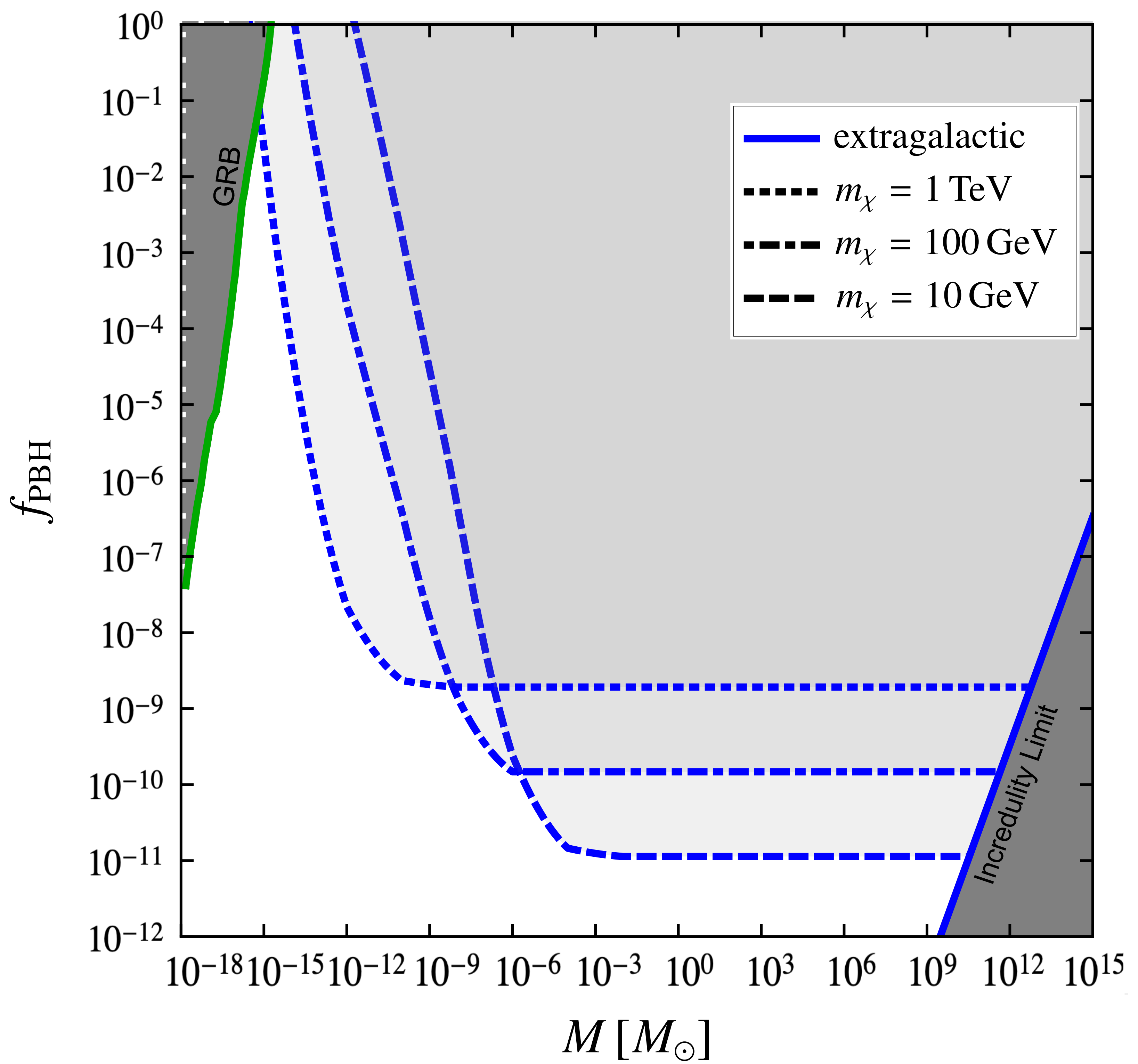
PBHs & WIMPs



[Carr, FK, Visinelli 2021]

★ Annihilations lead to plateaux in the present-day halos.

PBHs & WIMPs



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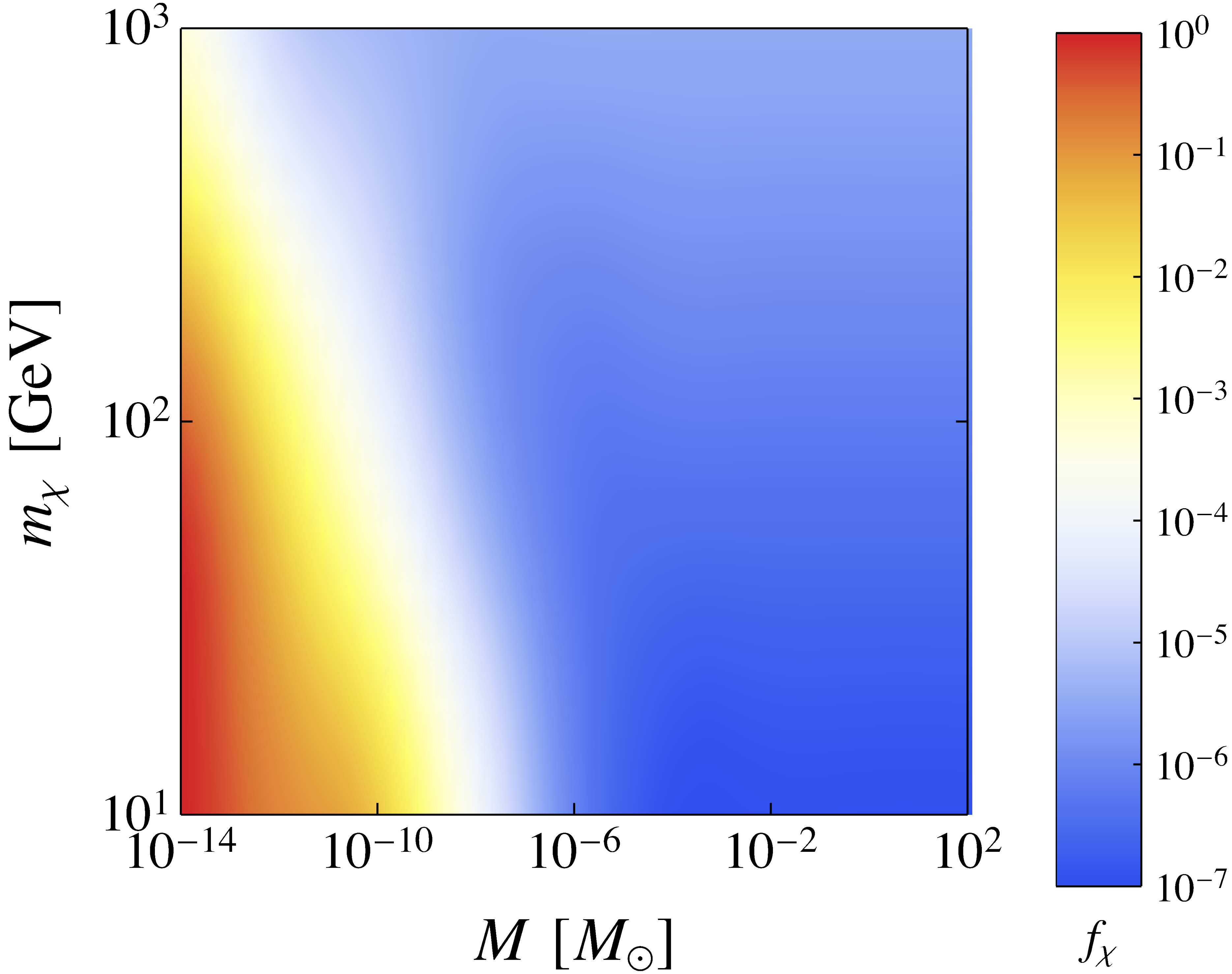
PBHs & WIMPs



[Carr, FK, Visinelli 2021]