

*Primordial  
Black Holes*

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Florian Kühnel

*Max Planck Institute for Physics*

— Cosmology in Miramare 2023 —



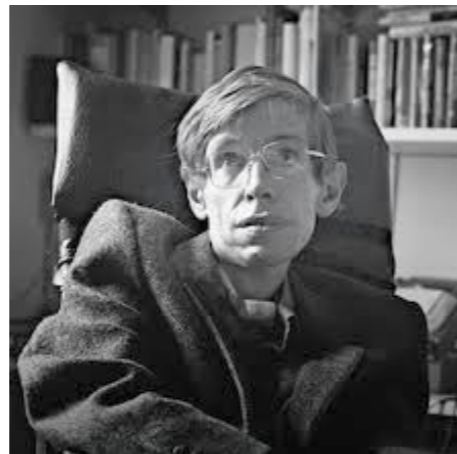
*Historical Remarks*

# What are Primordial Black Holes (PBHs)?

- ★ Black holes formed in the early\* Universe (in particular: *non-stellar*).
- ★ First proposed by Novikov and Zel'dovič in the late 1960th, but their conclusion was negative for the existence of PBHs.

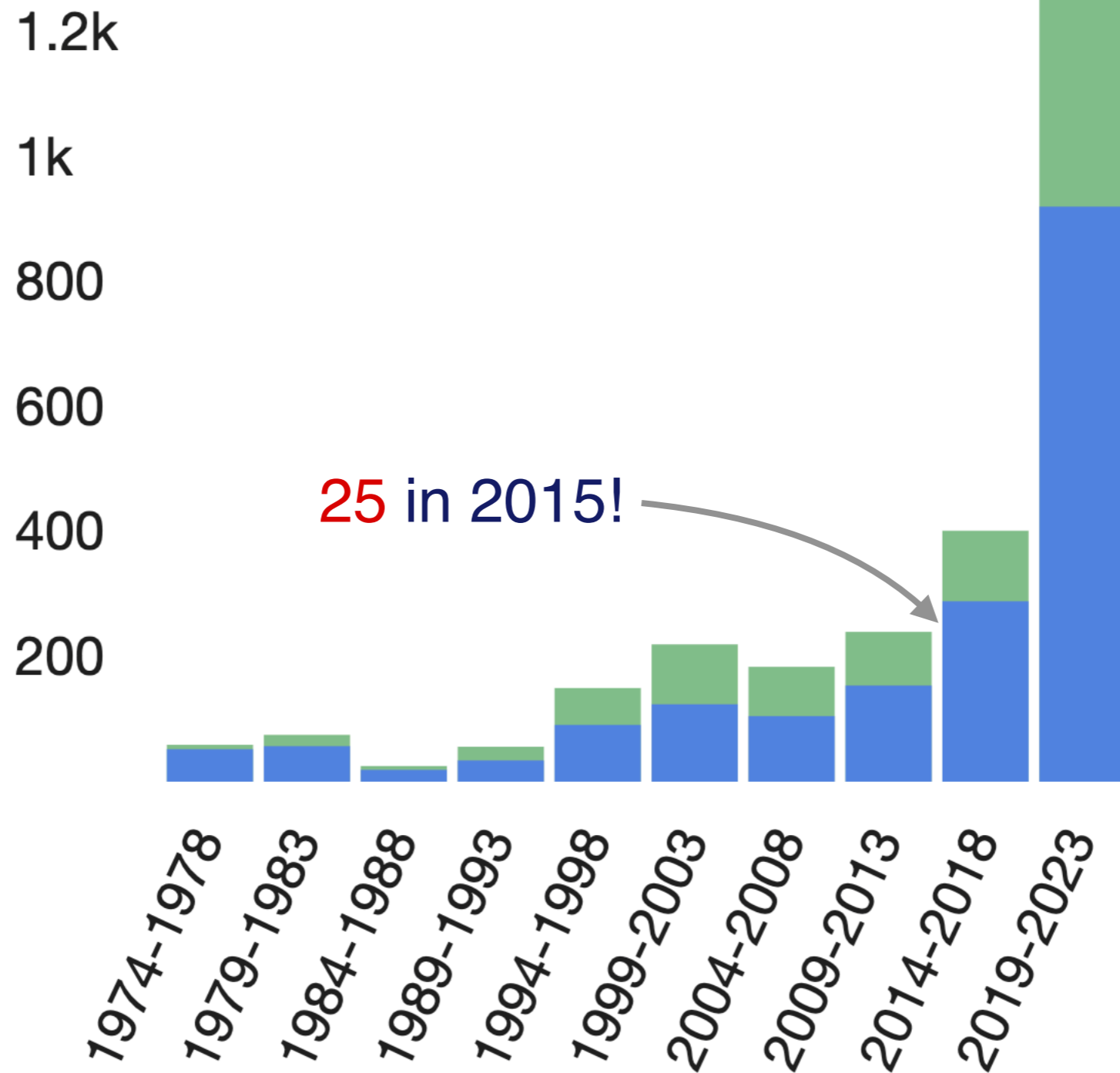


- ★ Conclusion disproved by Carr & Hawking (1974), reinvigorated PBH research (around 3000 papers to date).



# *Primordial Black Holes are Popular!*

■ refereed ■ non refereed



[SAO/NASA  
Astrophysics  
Data System]

# Black Hole Evaporation



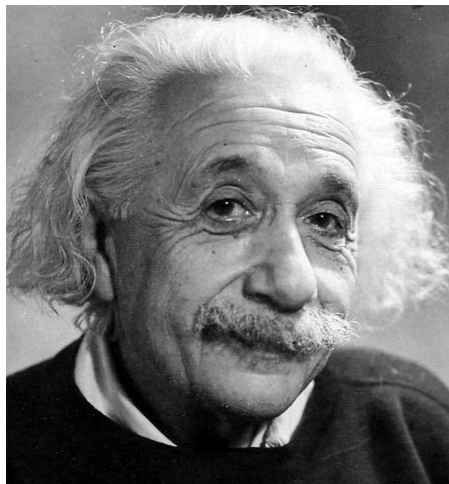
Thermodynamics

★ Black hole radiation

[Hawking 1974]

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

Quantum Mechanics



General Relativity



★ PBHs are important even if never observed!

A decorative frame with scrollwork at the corners and wavy lines at the top and bottom, enclosing the text.

*Primordial Black Hole*

*Formation Primer*

# PBH Formation Mechanisms

★ Large density perturbations (inflation)

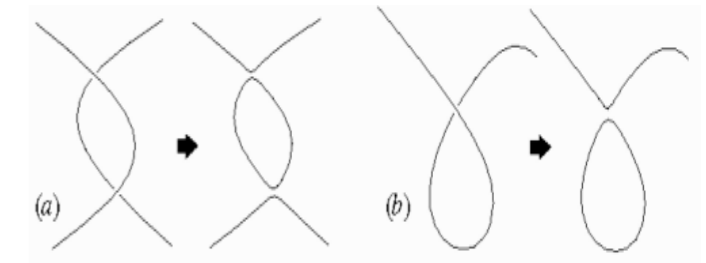
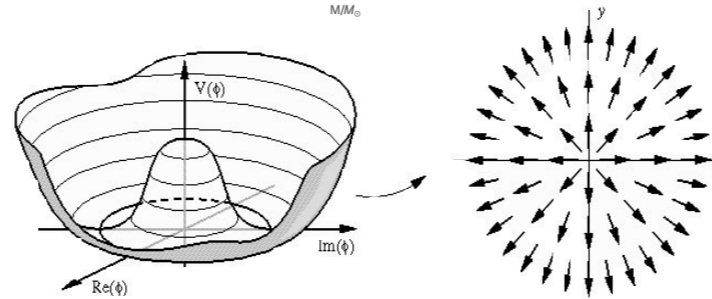
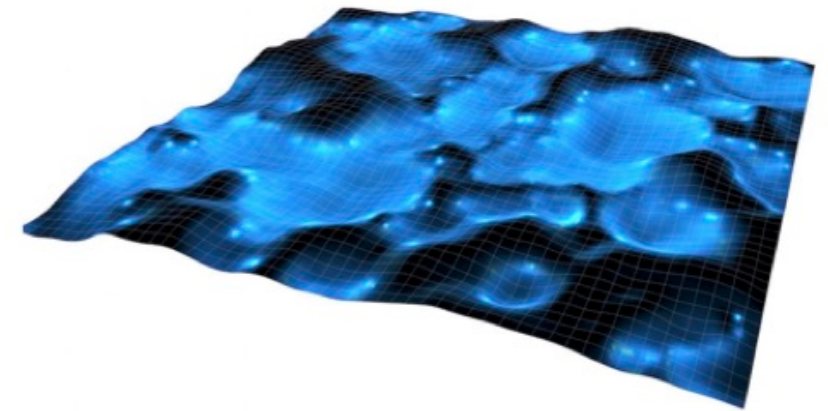
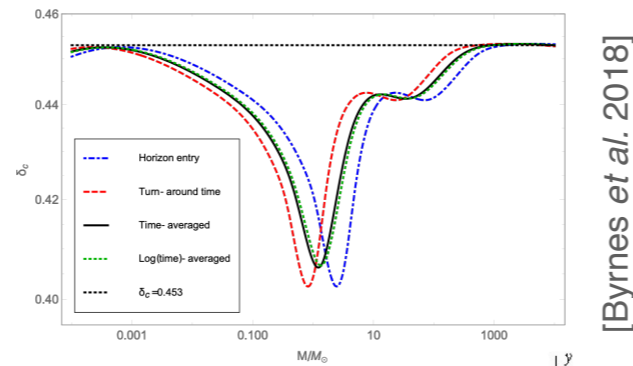
★ Pressure reduction

★ Cosmic string loops

★ Bubble collisions

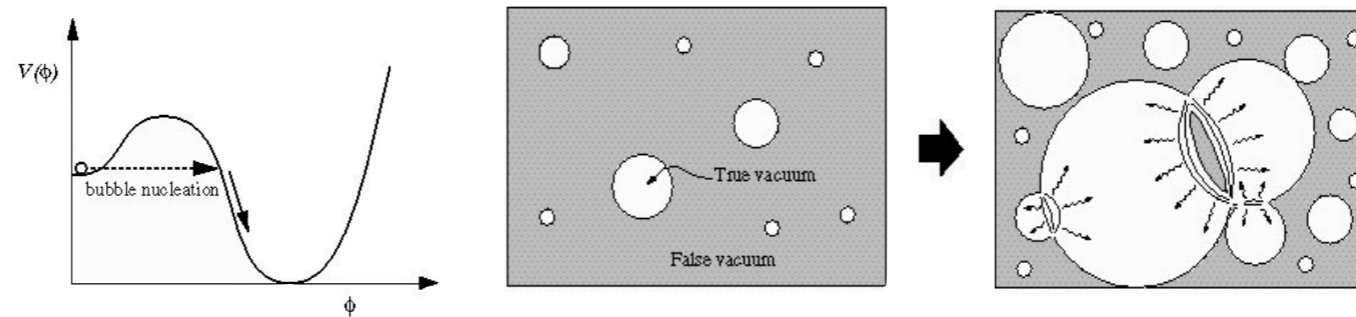
★ Quark confinement

★ Scalar-field fragmentation, ...

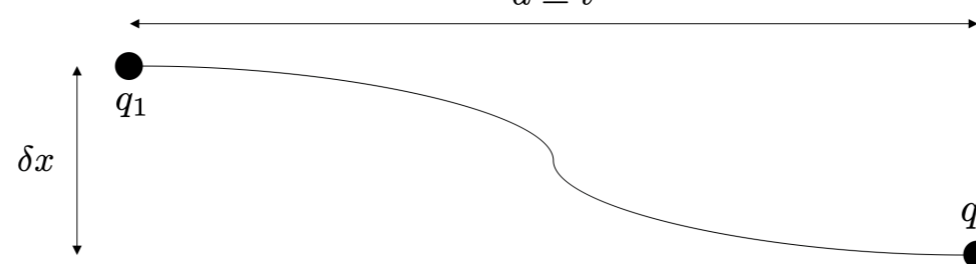


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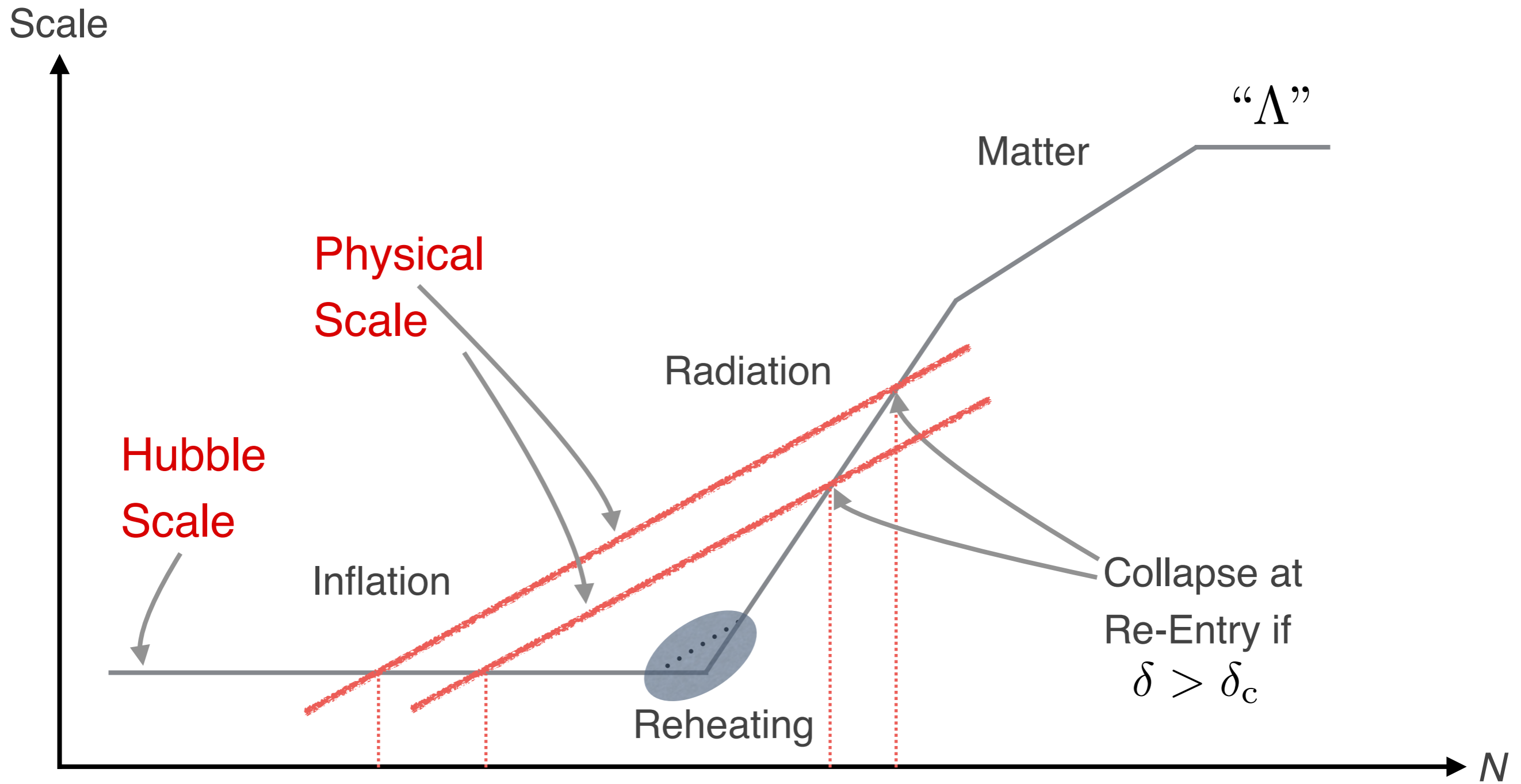


$d \simeq t$



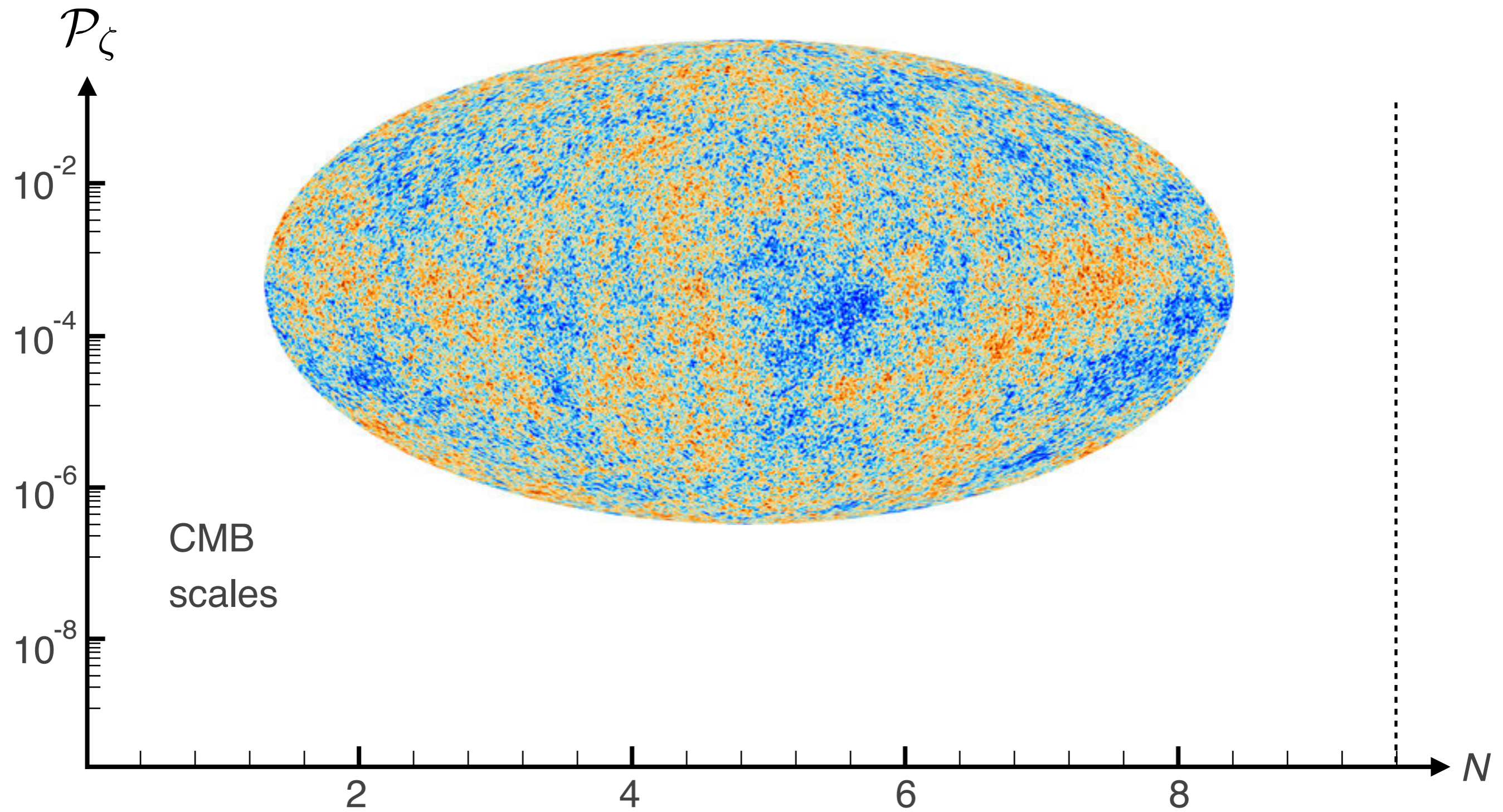
[Dvali, FK, Zantedeschi 2021]

# *PBH Formation from Inflationary Overdensities*

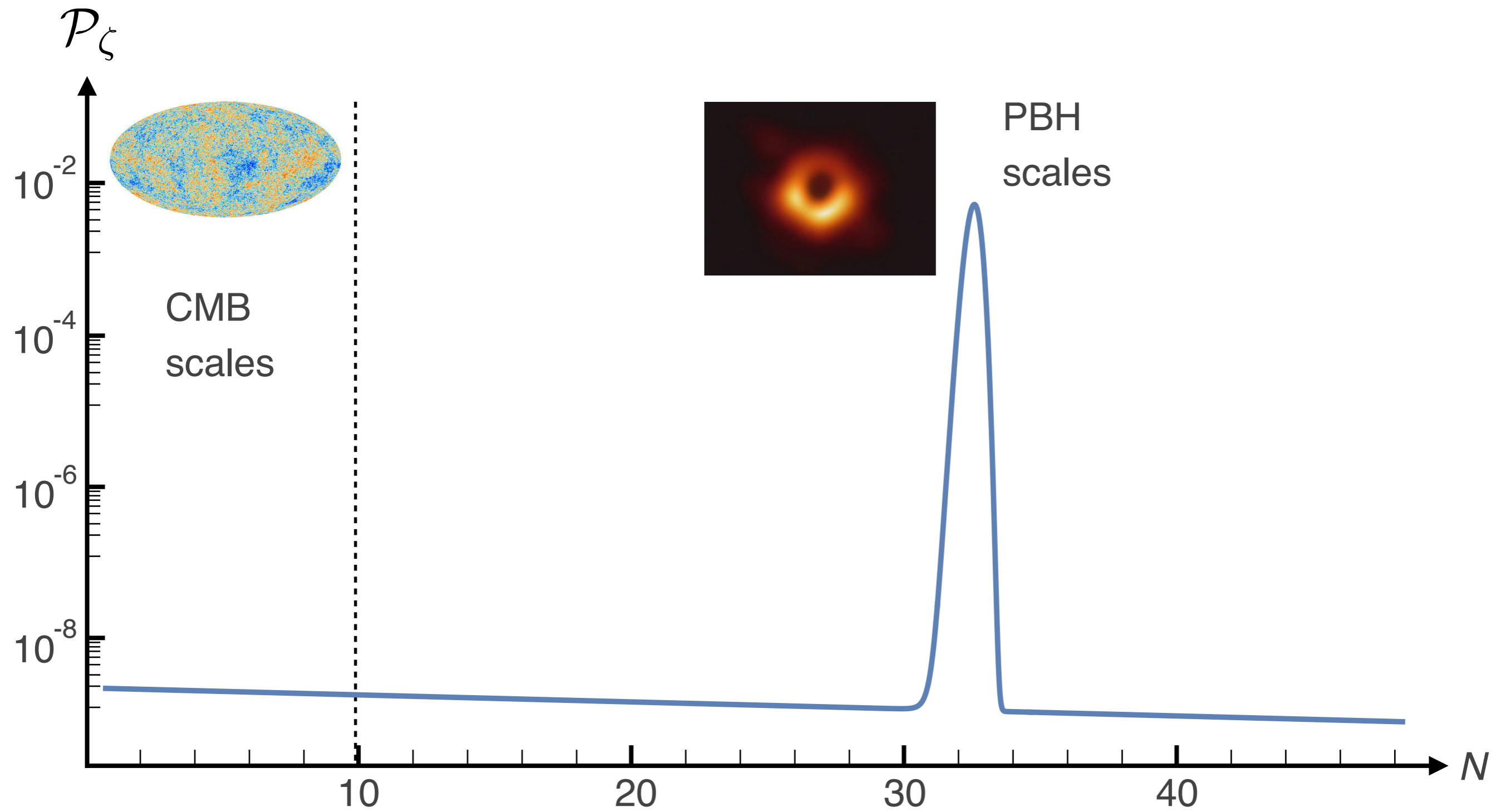




# *PBH Formation — Scales*



# *PBH Formation — Scales*



# PBH Formation — Rare Events

Fraction of collapsed horizon patches:

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

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

rare events:  
typically  $\sim 10\sigma$

density contrast

$$\delta \equiv \frac{\rho - \rho_{\text{background}}}{\rho_{\text{background}}}$$

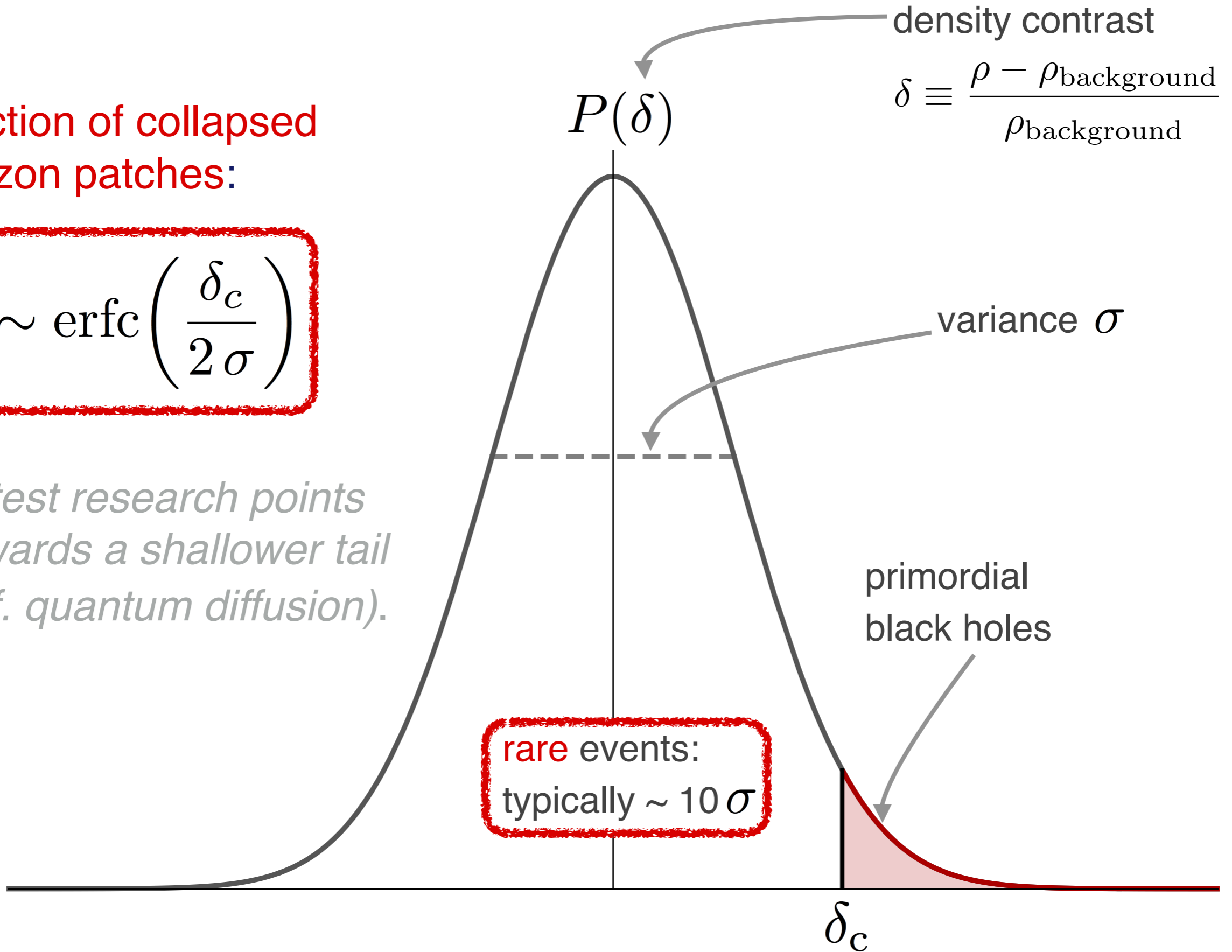
$P(\delta)$

variance  $\sigma$

primordial black holes

$\delta_c$

$\delta$



# *PBHs — Some Numbers*

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

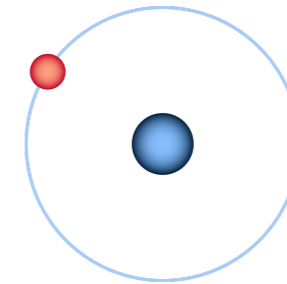
★ Assume that all PBH have mass:  $10^{20}$  g



Saturn satellite  
*Prometheus*

★ Size:

$10^{-8}$  cm



Hydrogen  
Atom

★ Number in our Galaxy:

$10^{25}$

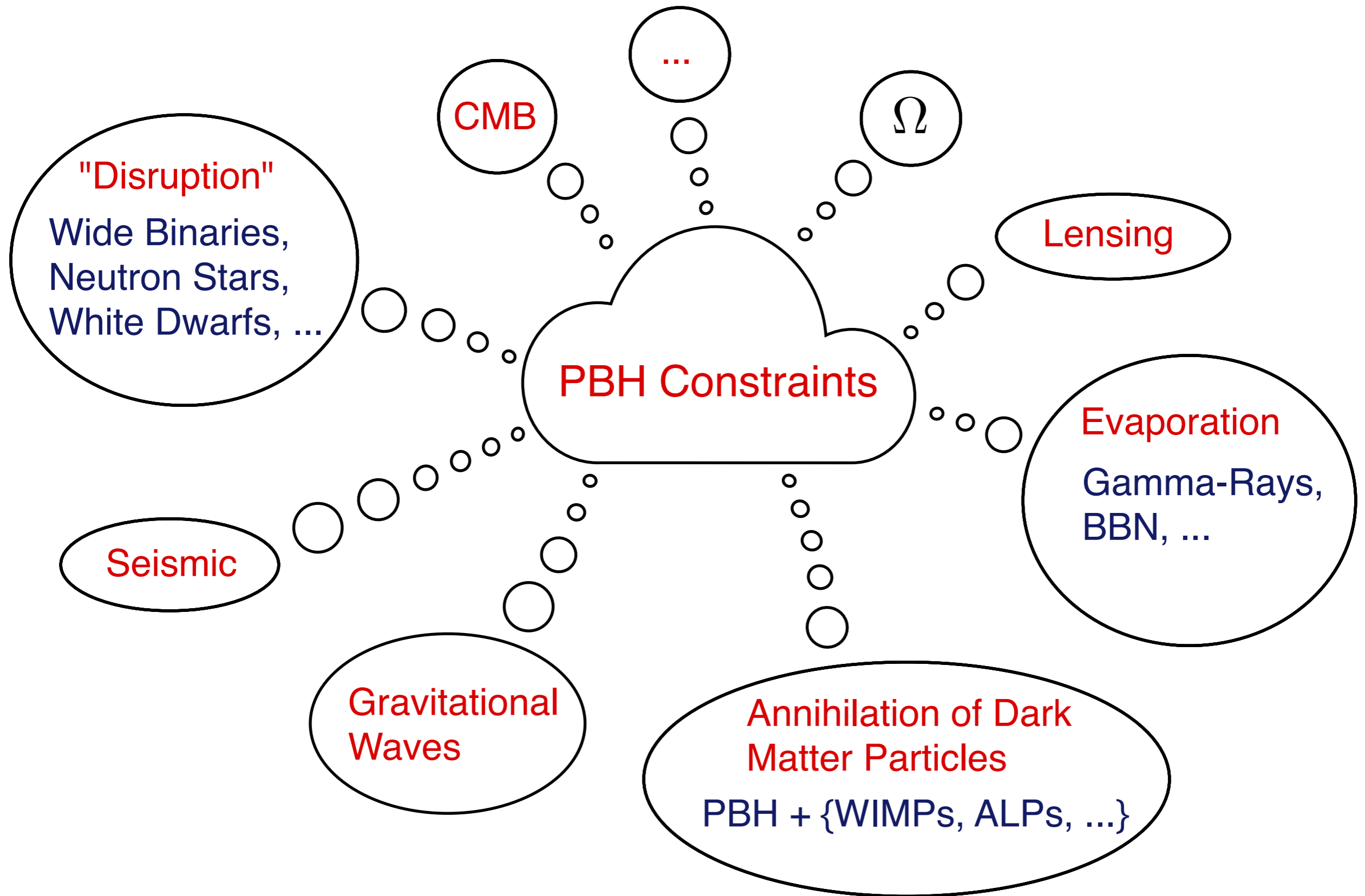
★ Distance:

10 AU

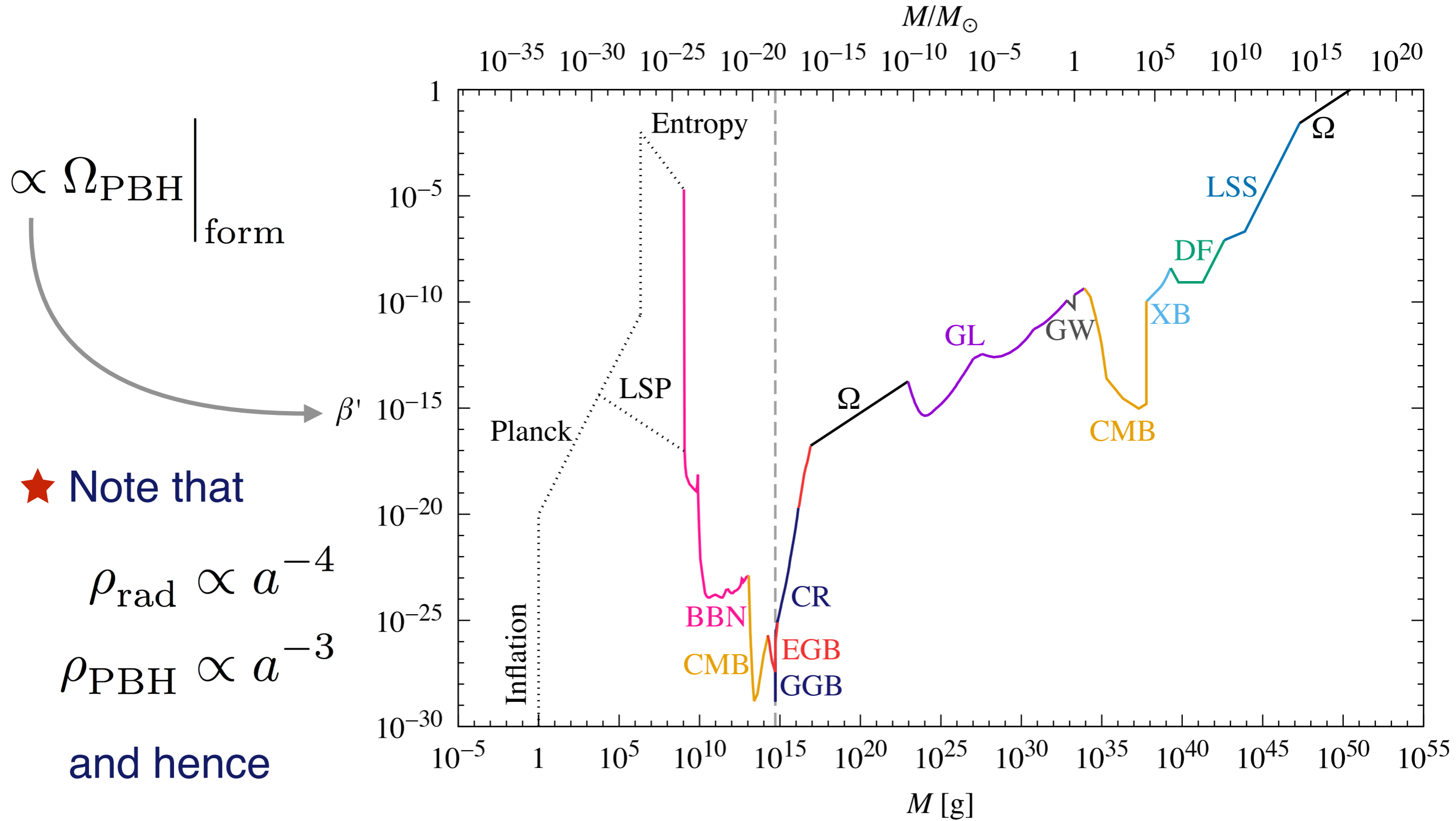
A decorative frame with scrollwork at the corners and a wavy border. The text is centered within the frame.

*Primordial Black Hole*

*Constraints*

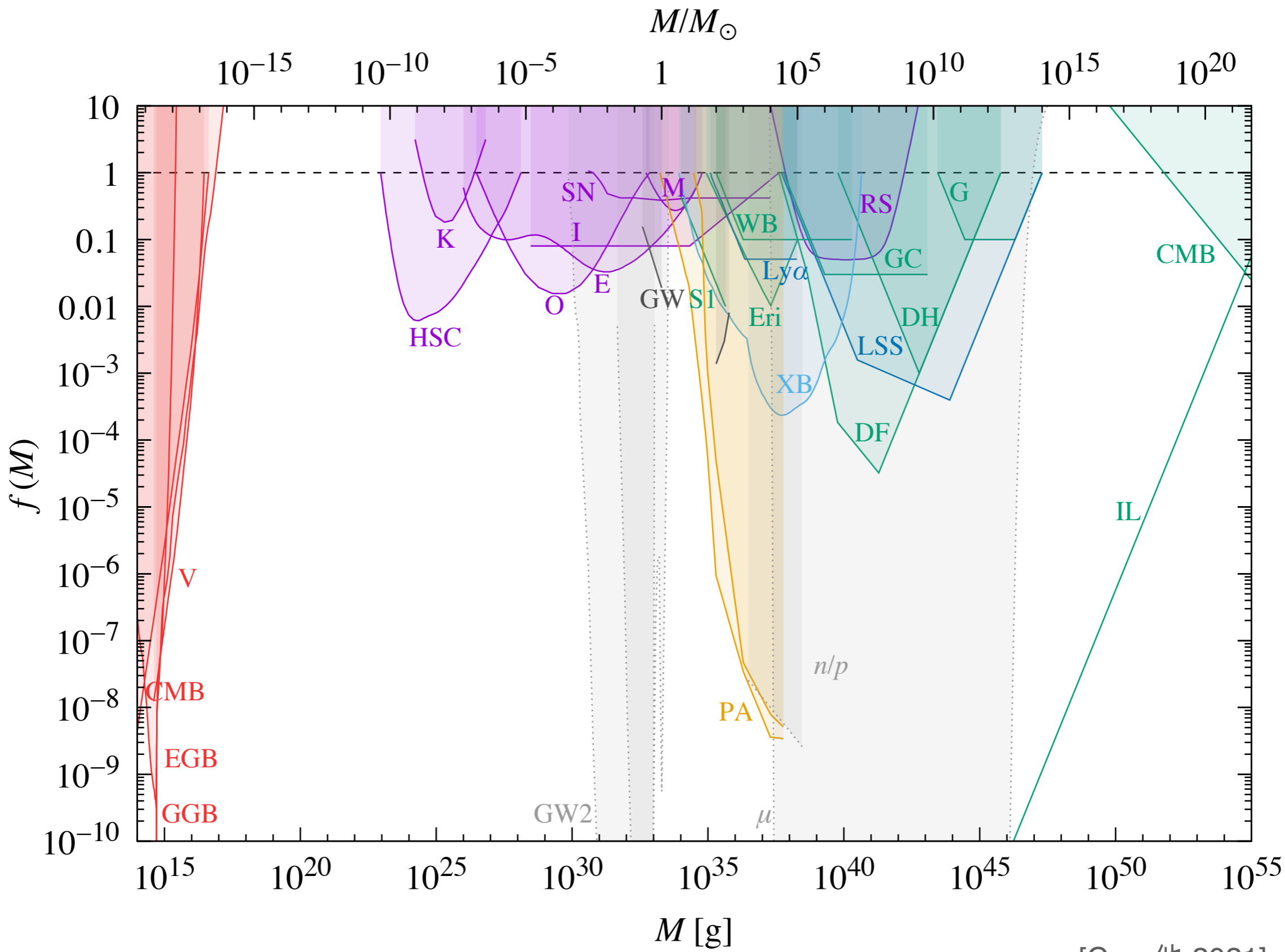


# PBH Constraints at Formation



[Carr 他 2021]

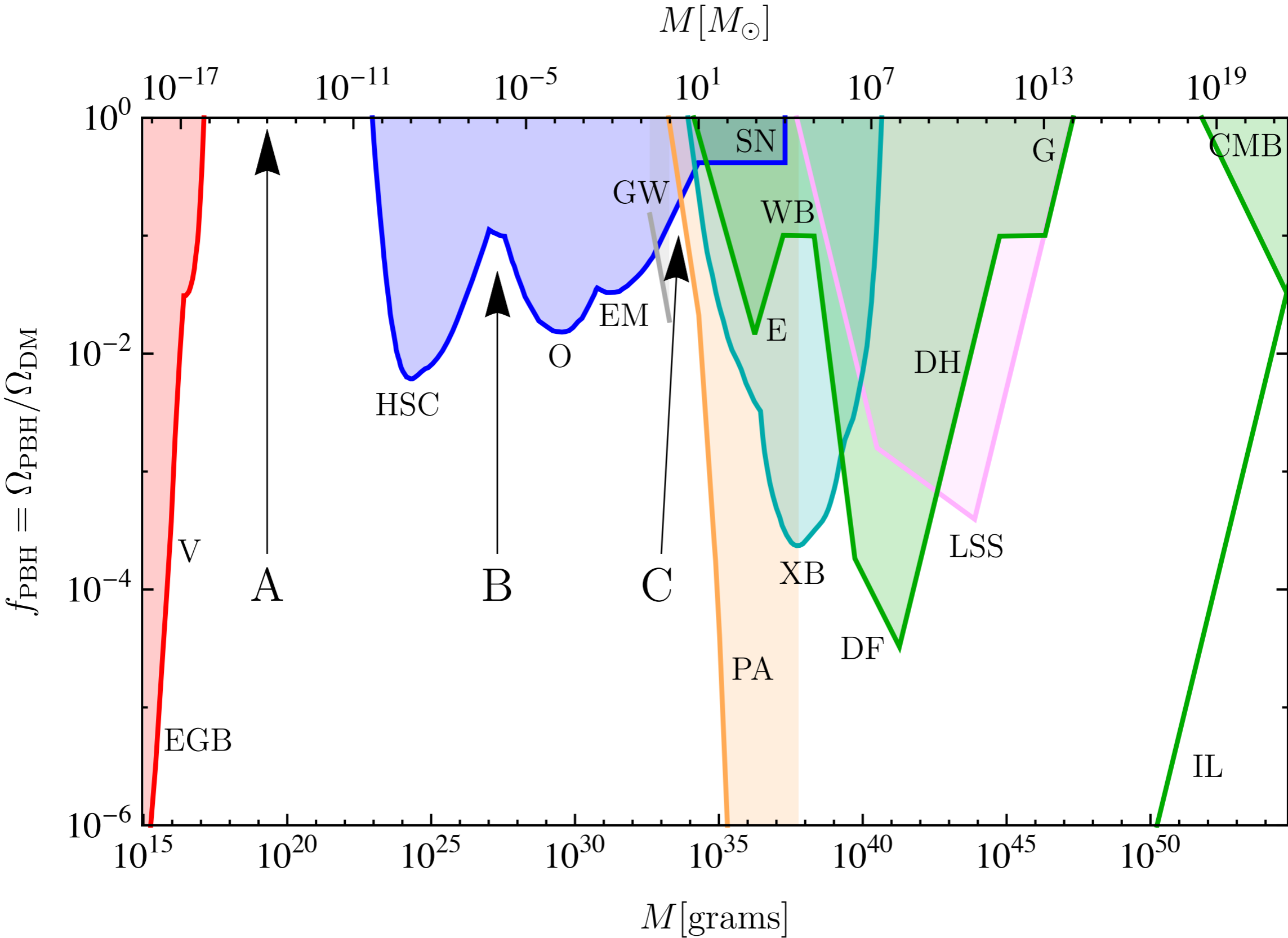
# Current PBH Constraints



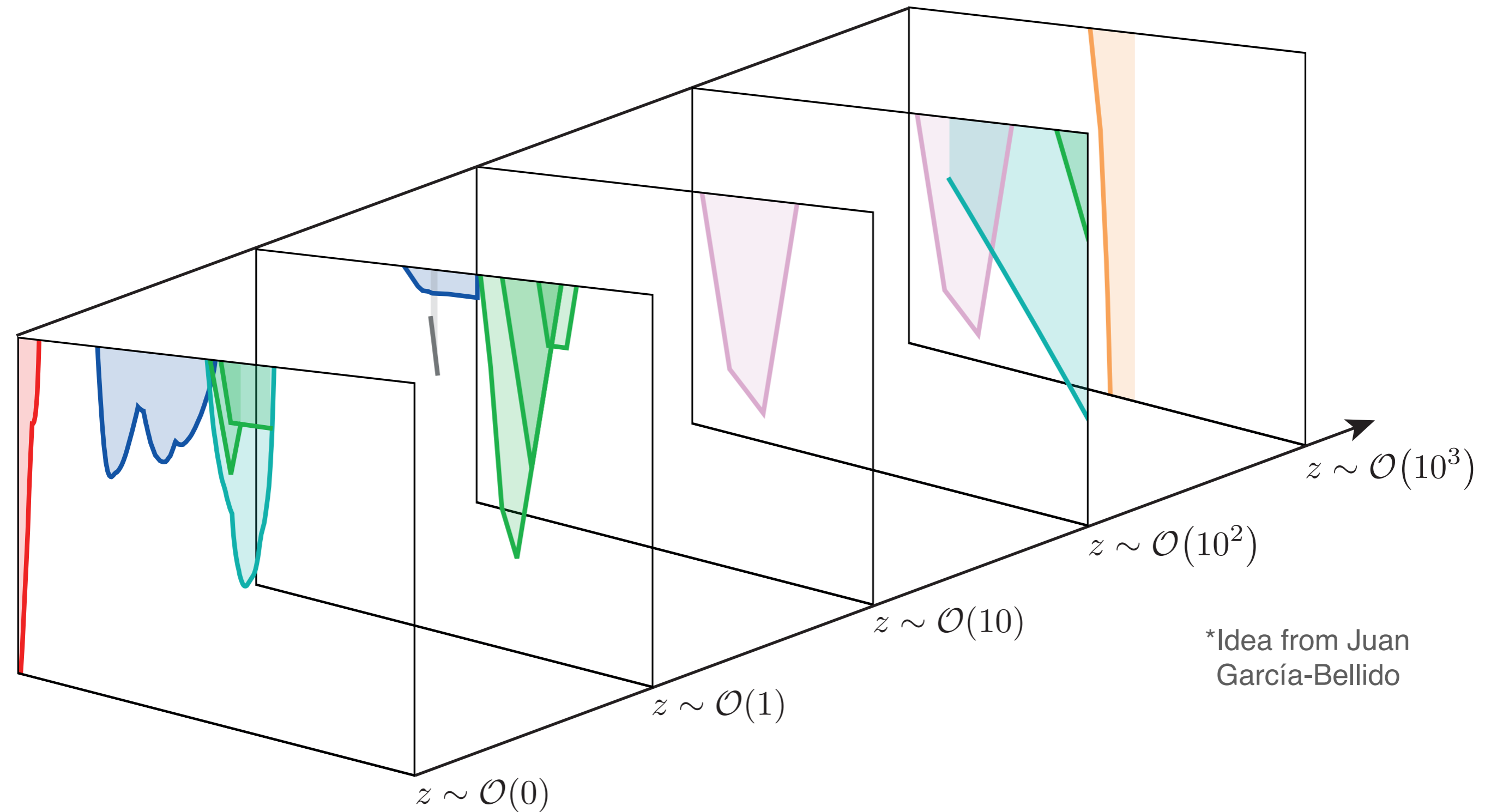
[Carr 他 2021]



# Current PBH Constraints



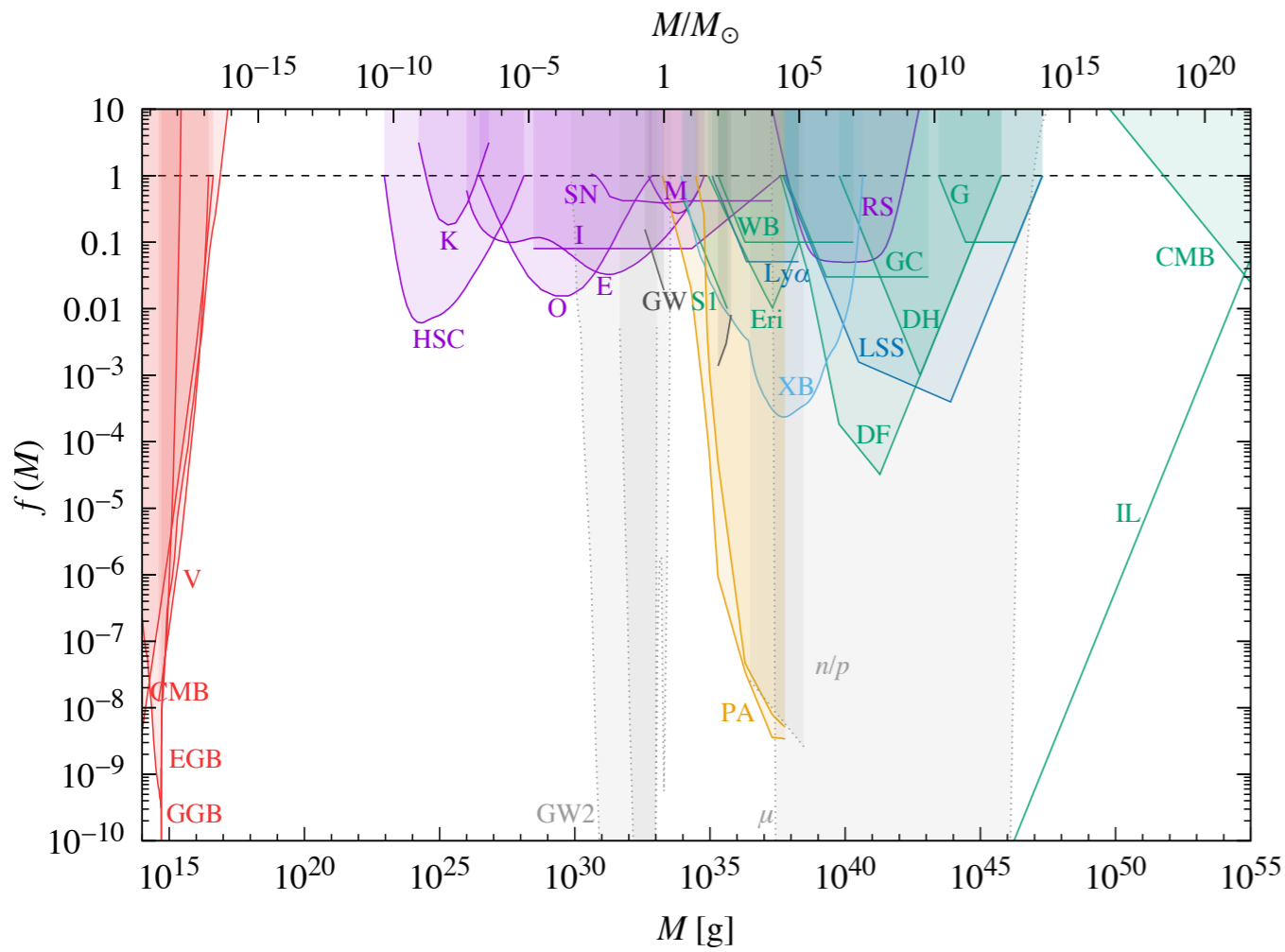
# *PBH Constraints — Redshift Dependence*



\*Idea from Juan García-Bellido

[Carr & FK 2020\*]

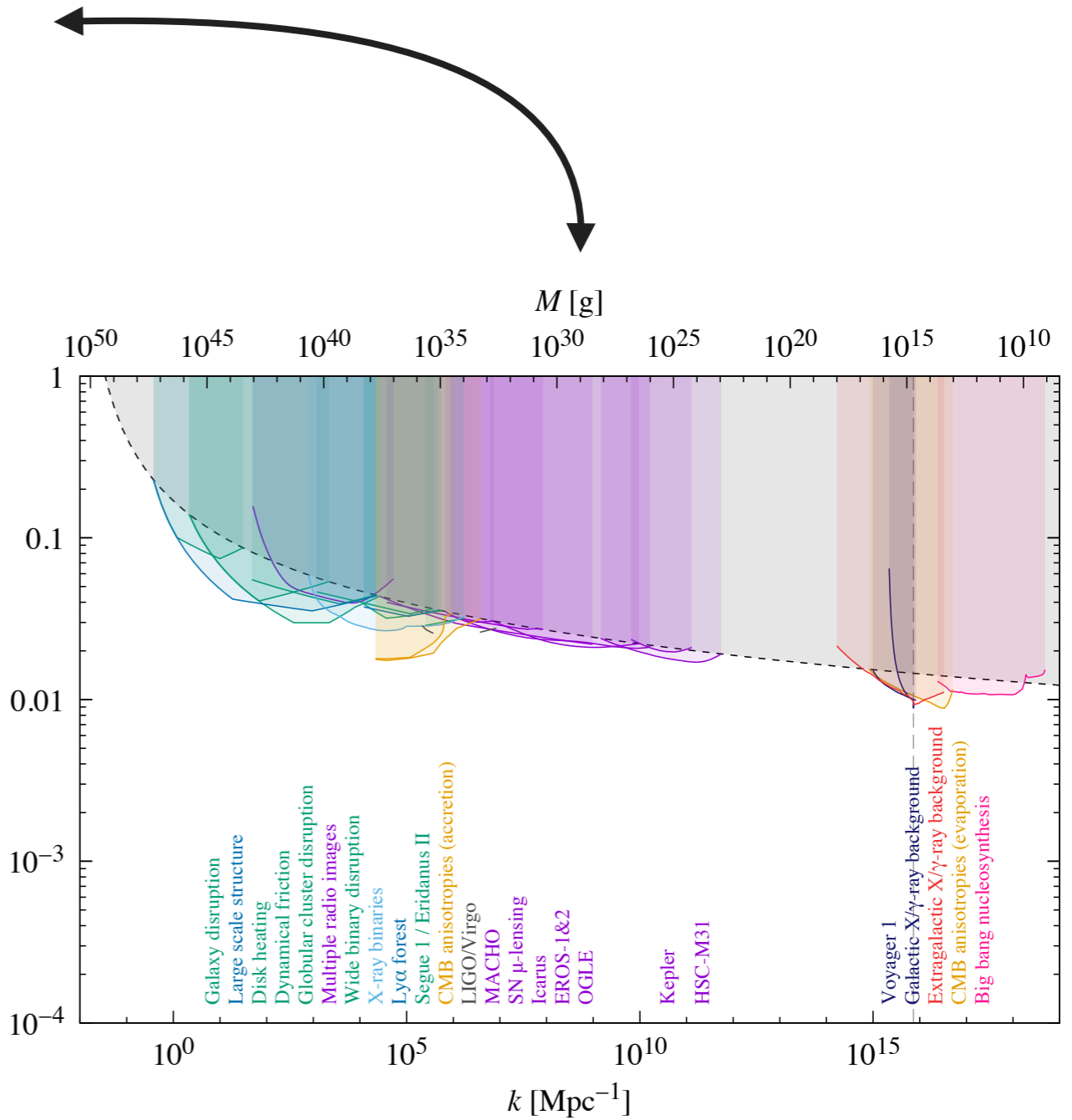
# PBH Constraints — Primordial Power Spectrum



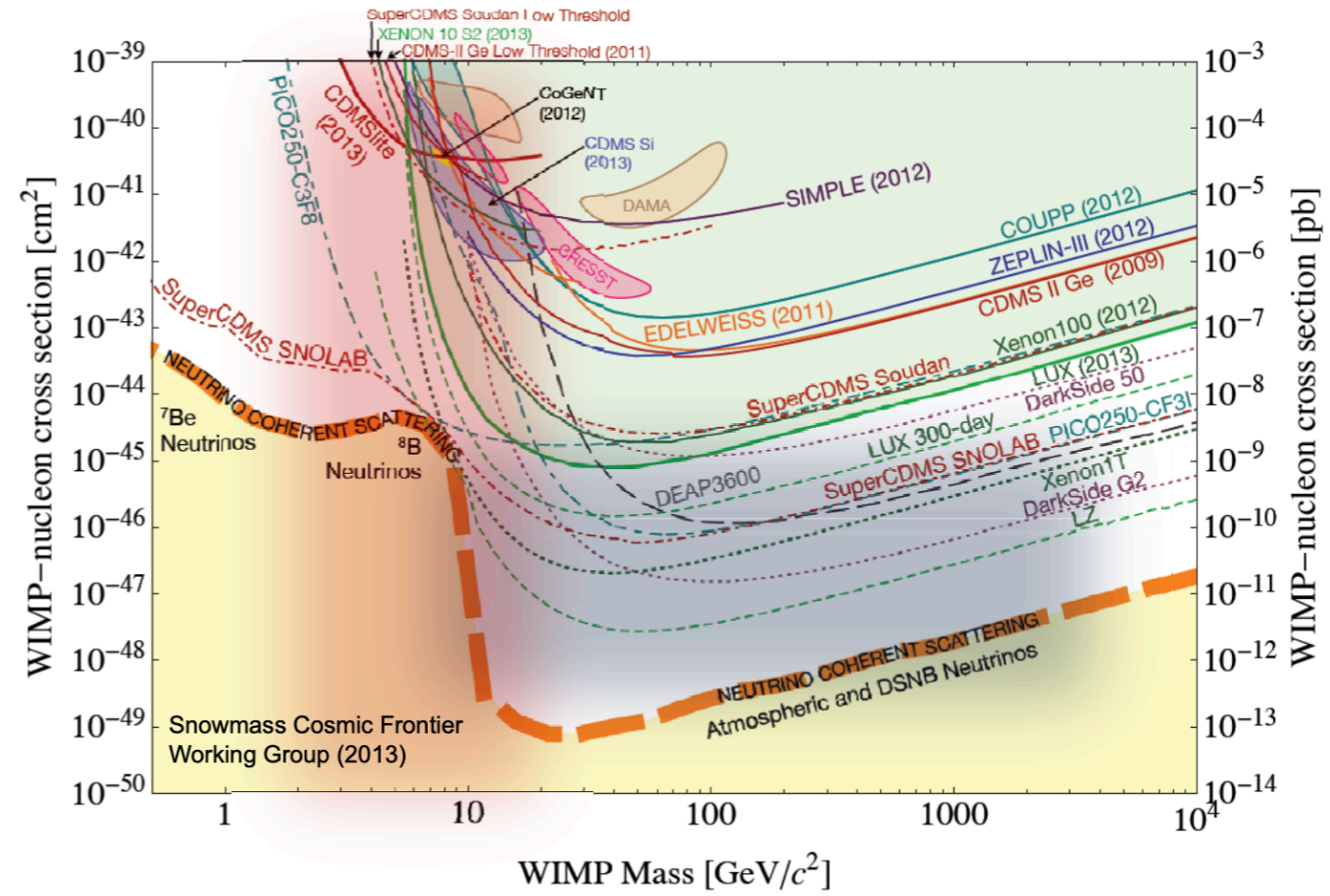
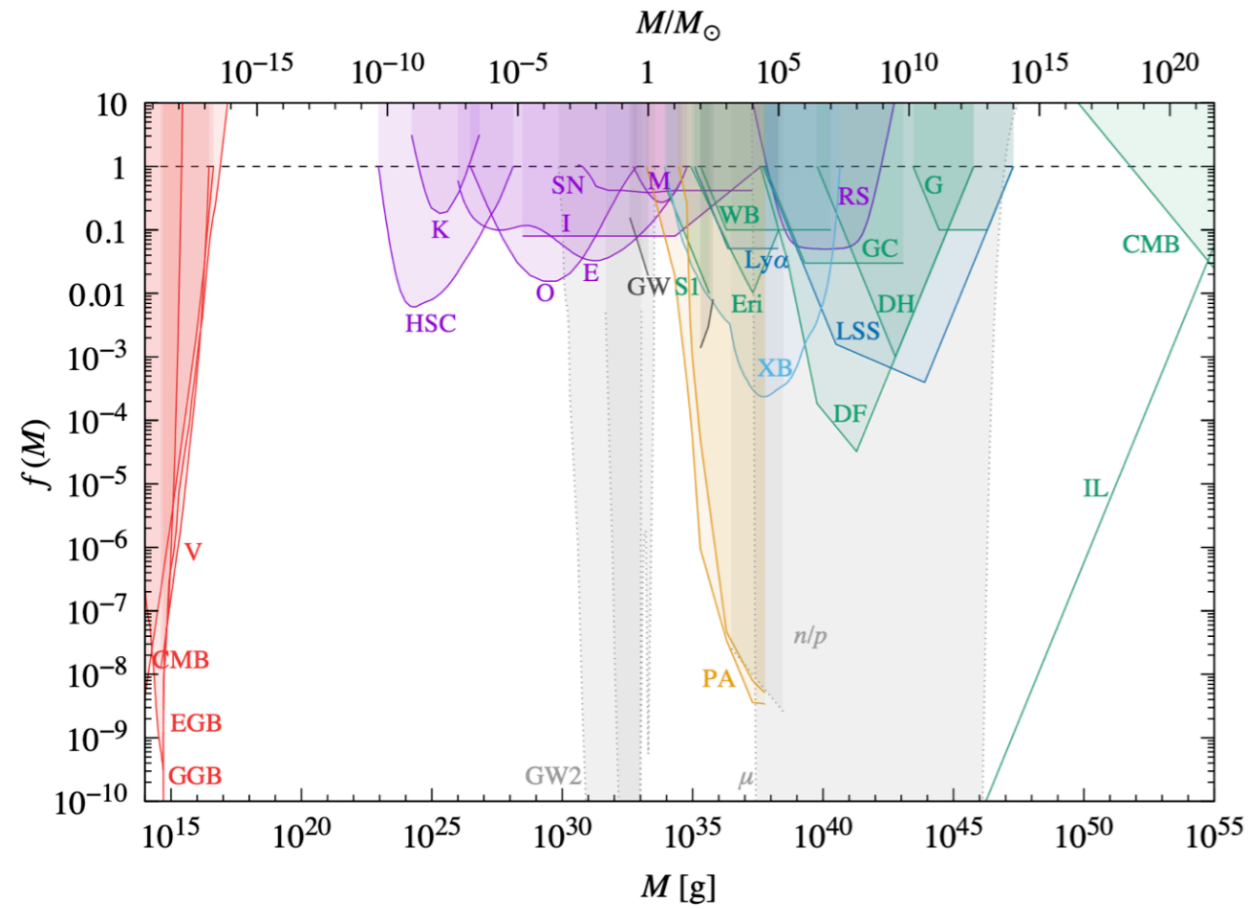
$f_{\text{PBH}}$

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

$\mathcal{P}$



# 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  $f_{\text{PBH}} \ll 1$ .

A decorative frame with scrollwork at the corners and top/bottom curves, enclosing the text.

*Primordial Black Holes*

*and*

*Particle Dark Matter*

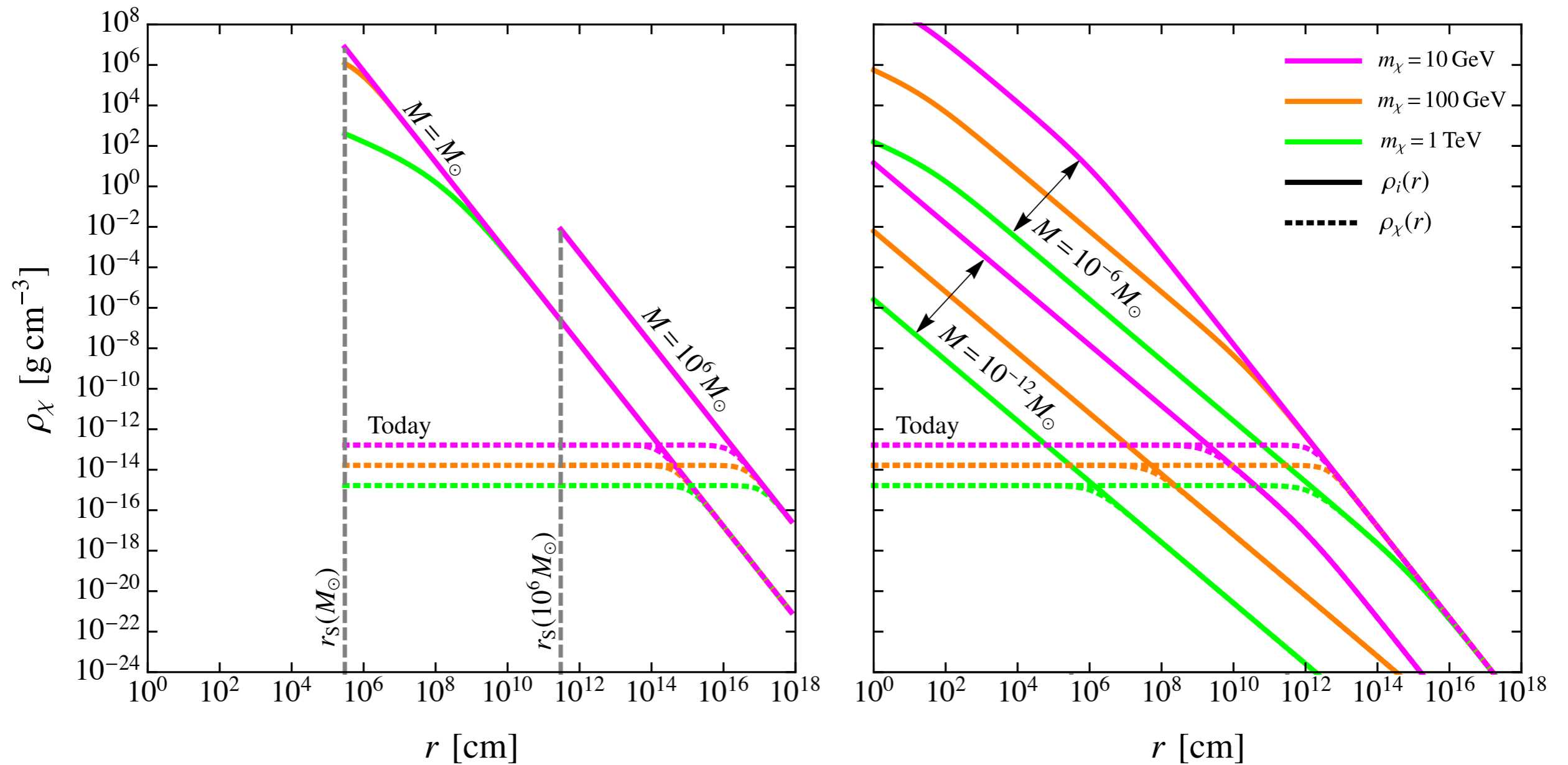
# PBH @ Particle Dark Matter

- ★ Always when  $f_{\text{PBH}} < 1$  there **must** be another dark matter component!
- ★ Study a **combined** scenario: **Dark Matter = PBHs + Particles**
  - ★ The latter will be **accreted** by the former; **formation of halos**.
  - ★ Study **WIMP annihilations** in PBH halos:
    - ★ The annihilation rate  $\Gamma \propto n^2$ .
    - ★ Halo profile does matter; **enhancement** of  $\Gamma$  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, Witte *et al.* 2022]



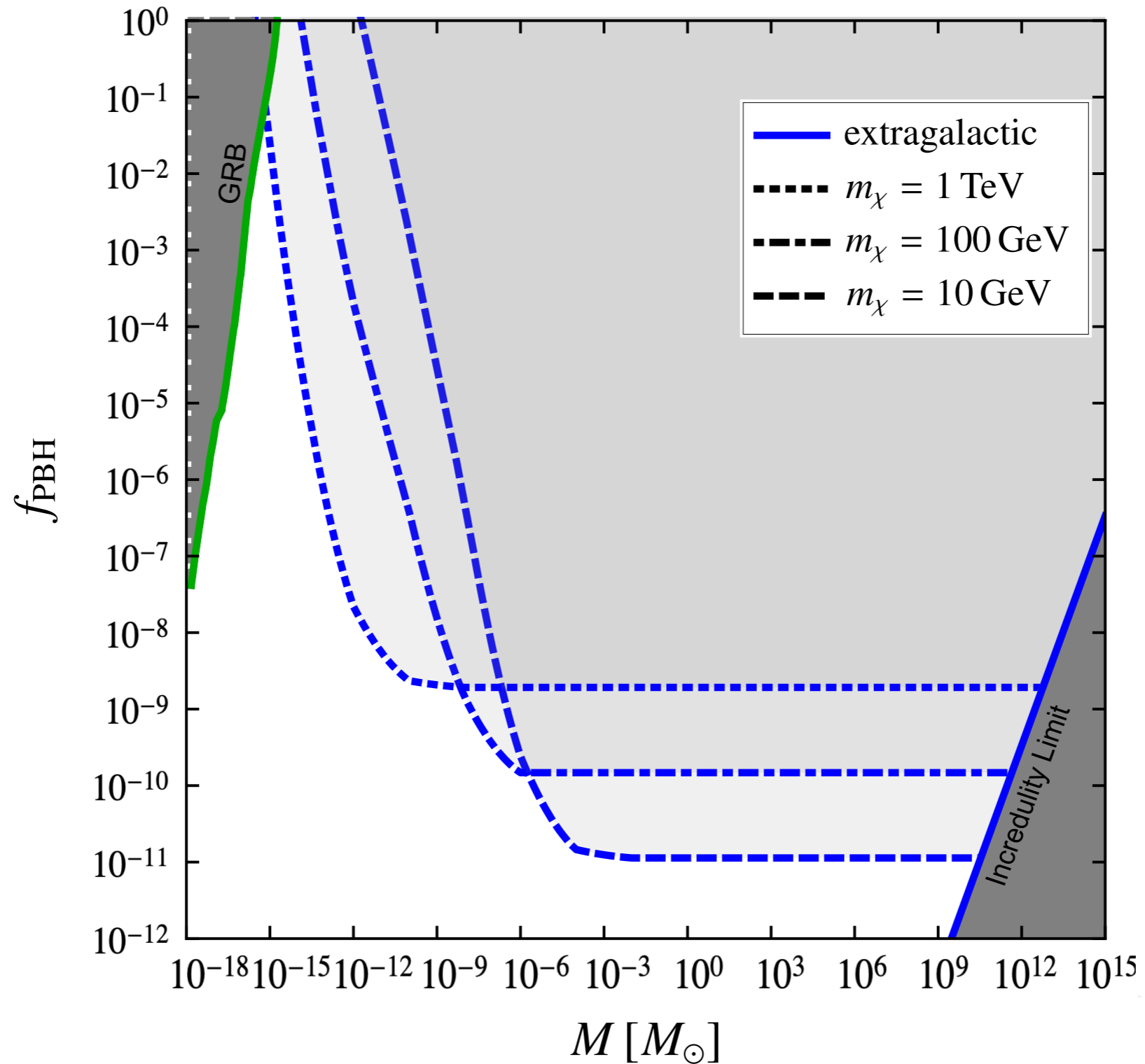
# PBHs @ WIMPs



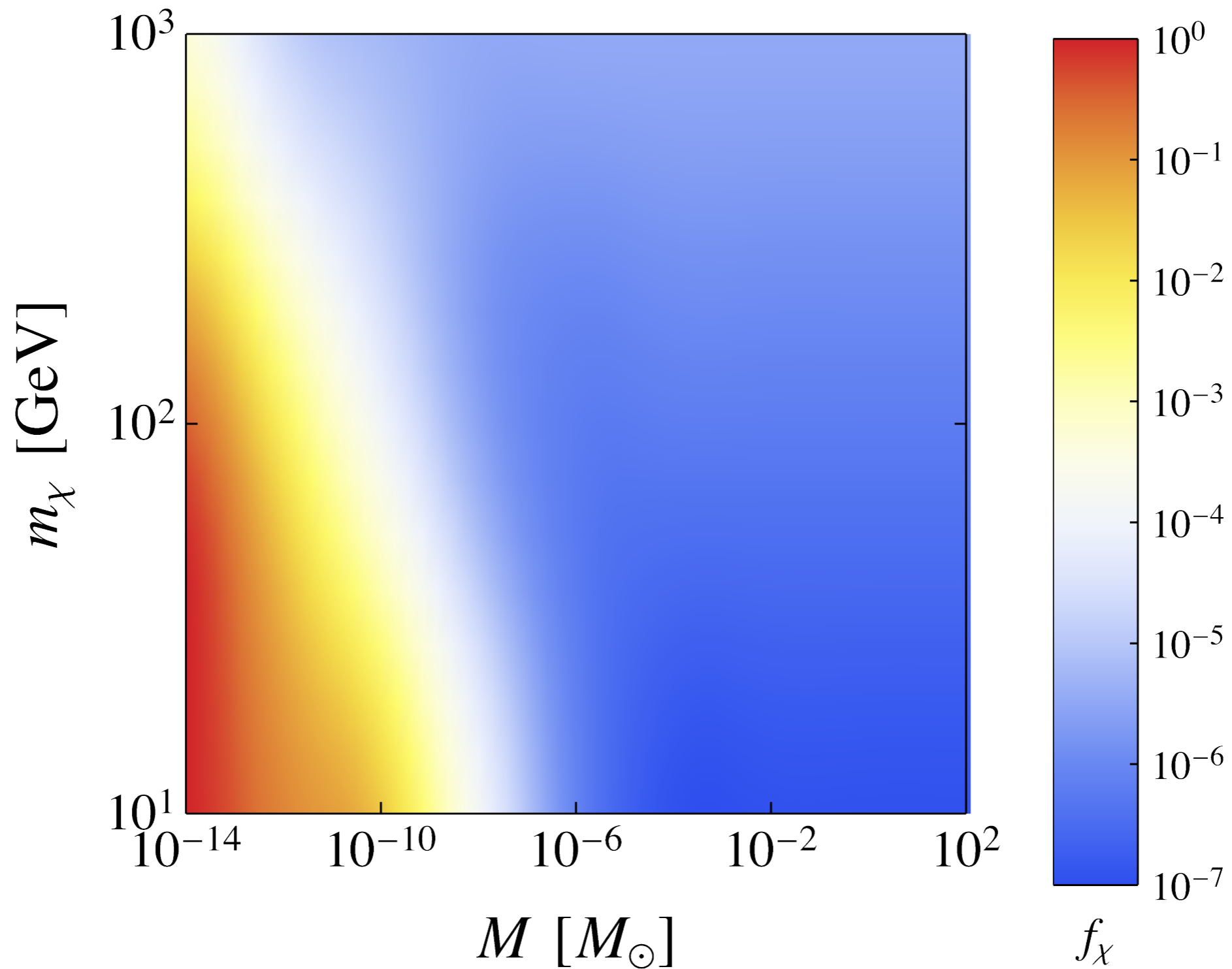
[Carr, FK, Visinelli 2021]

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

# PBHs @ WIMPs



# *PBHs @ WIMPs*





*Monochromatic*

*versus*

*Extended Mass Spectra*

# Critical Collapse

★ Usually: Assume

$$M_{BH} \propto M_H$$

↑  
horizon mass

★ Critical scaling:

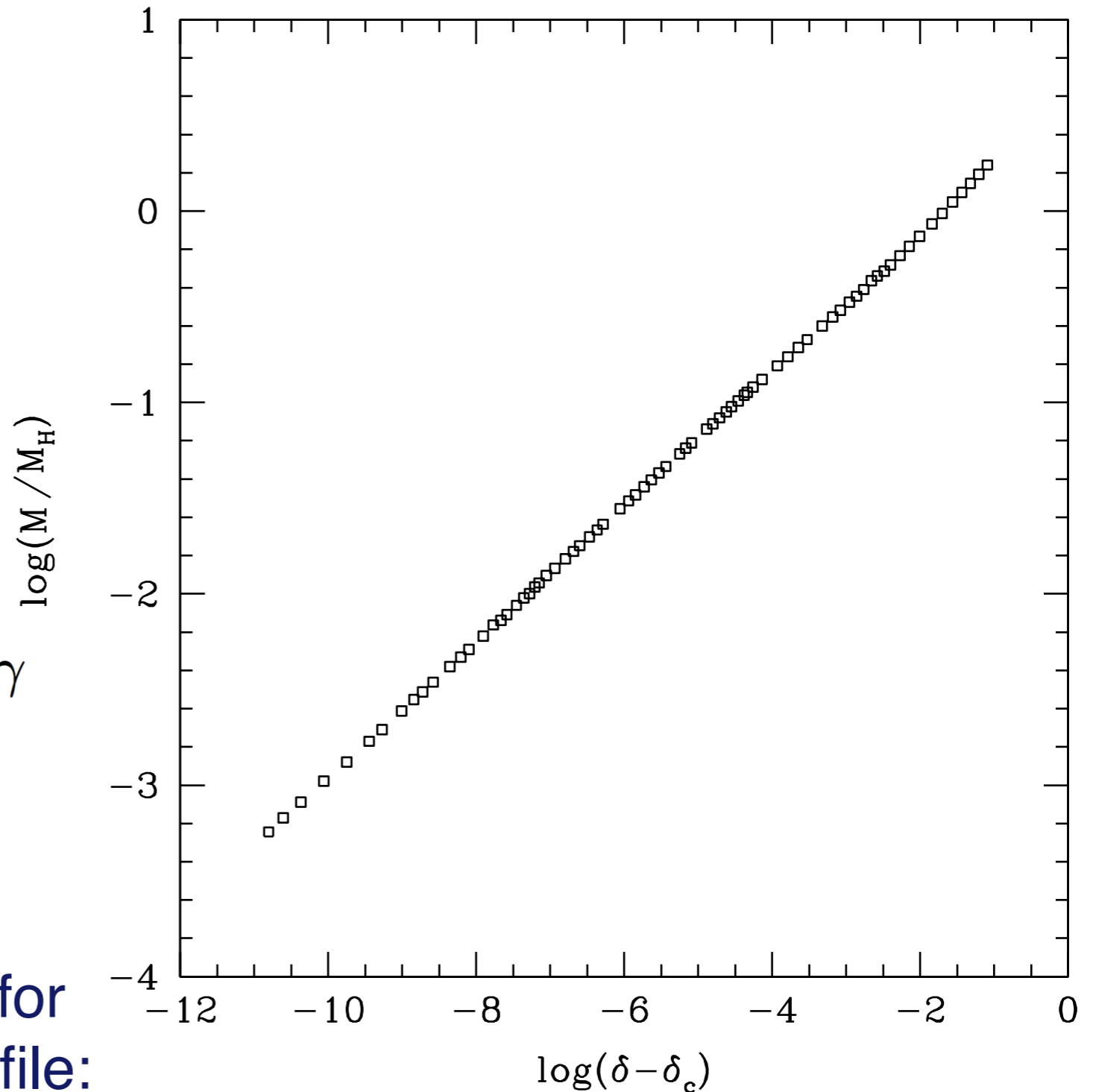
[Choptuik '93]

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

↑  
density contrast

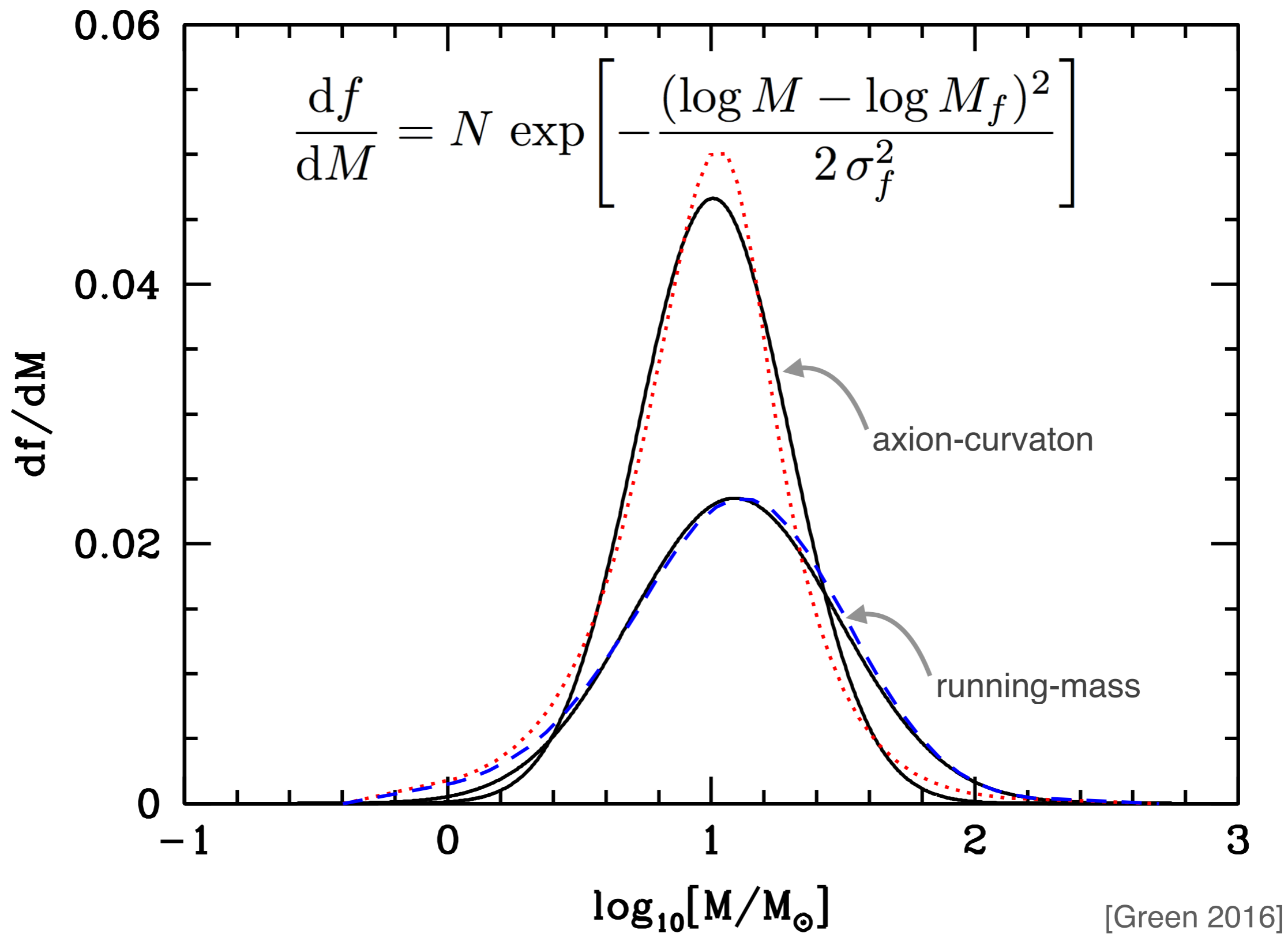
★ Radiation domination and for spherical Mexican-hat profile:

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

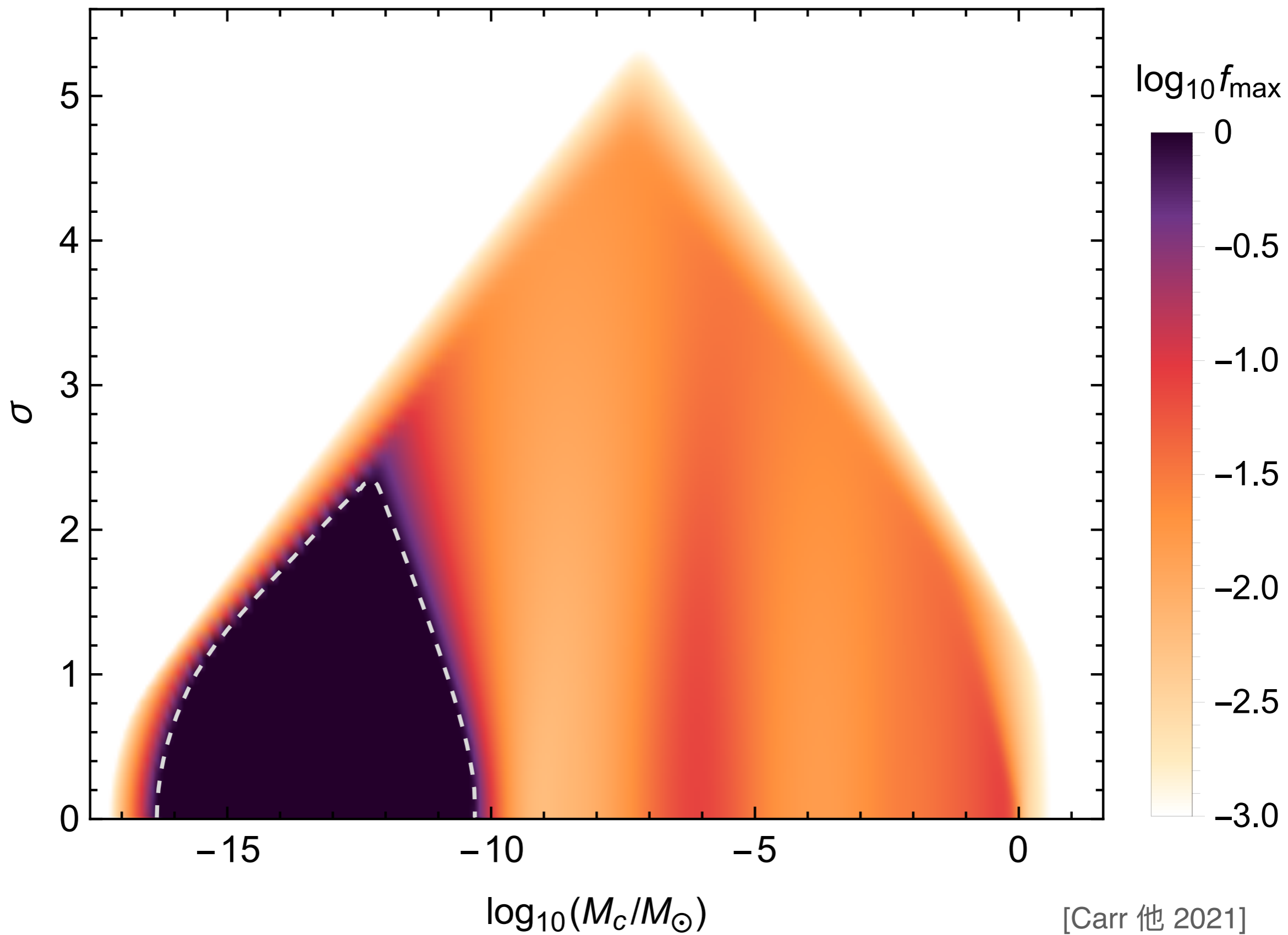


[Musco, Miller, Polnarev 2008]

# More Systematic Study



*More Systematic Study*



*Evidence?*

*Observational ~~Hints~~ for*

*Primordial Black Holes*

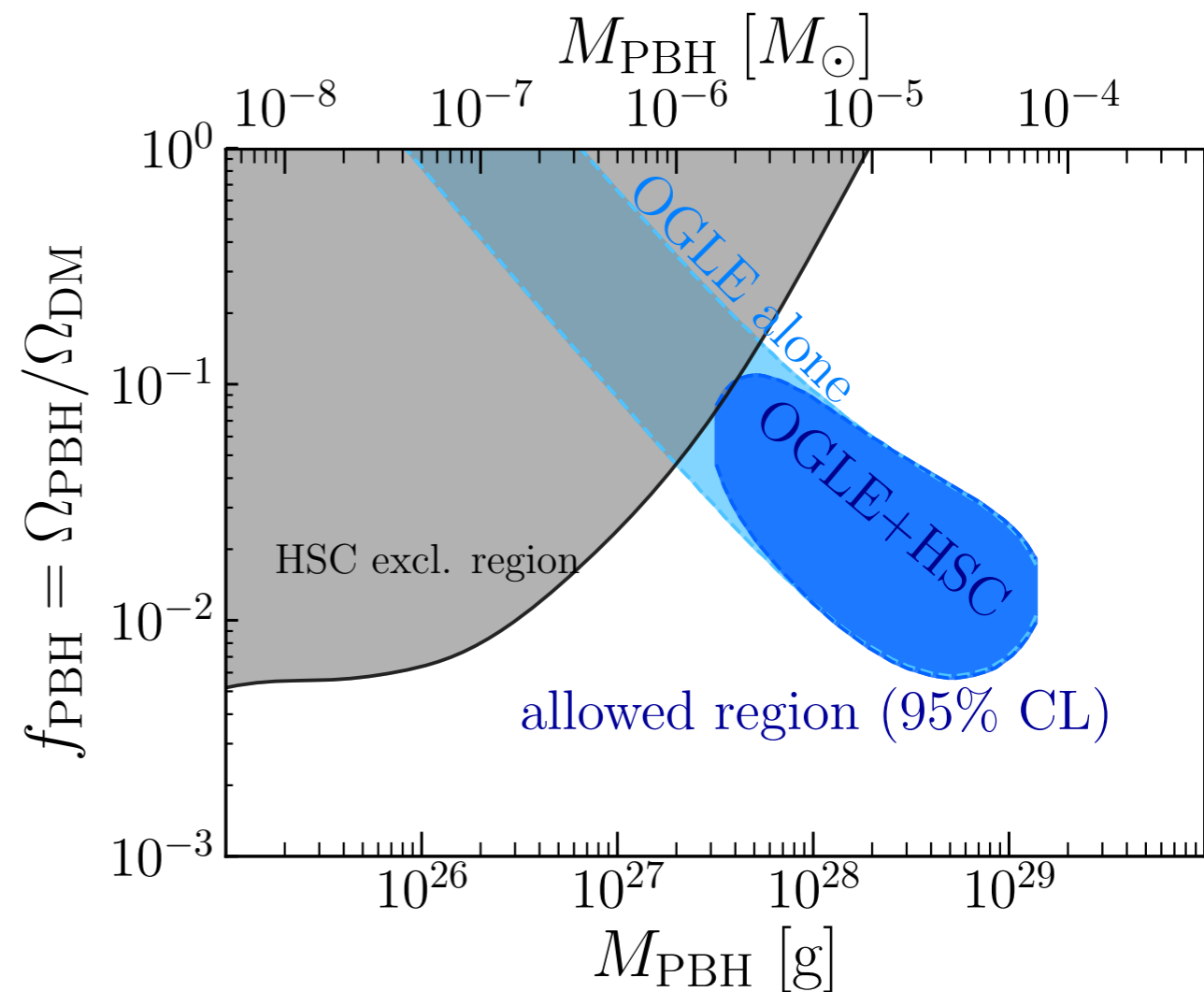
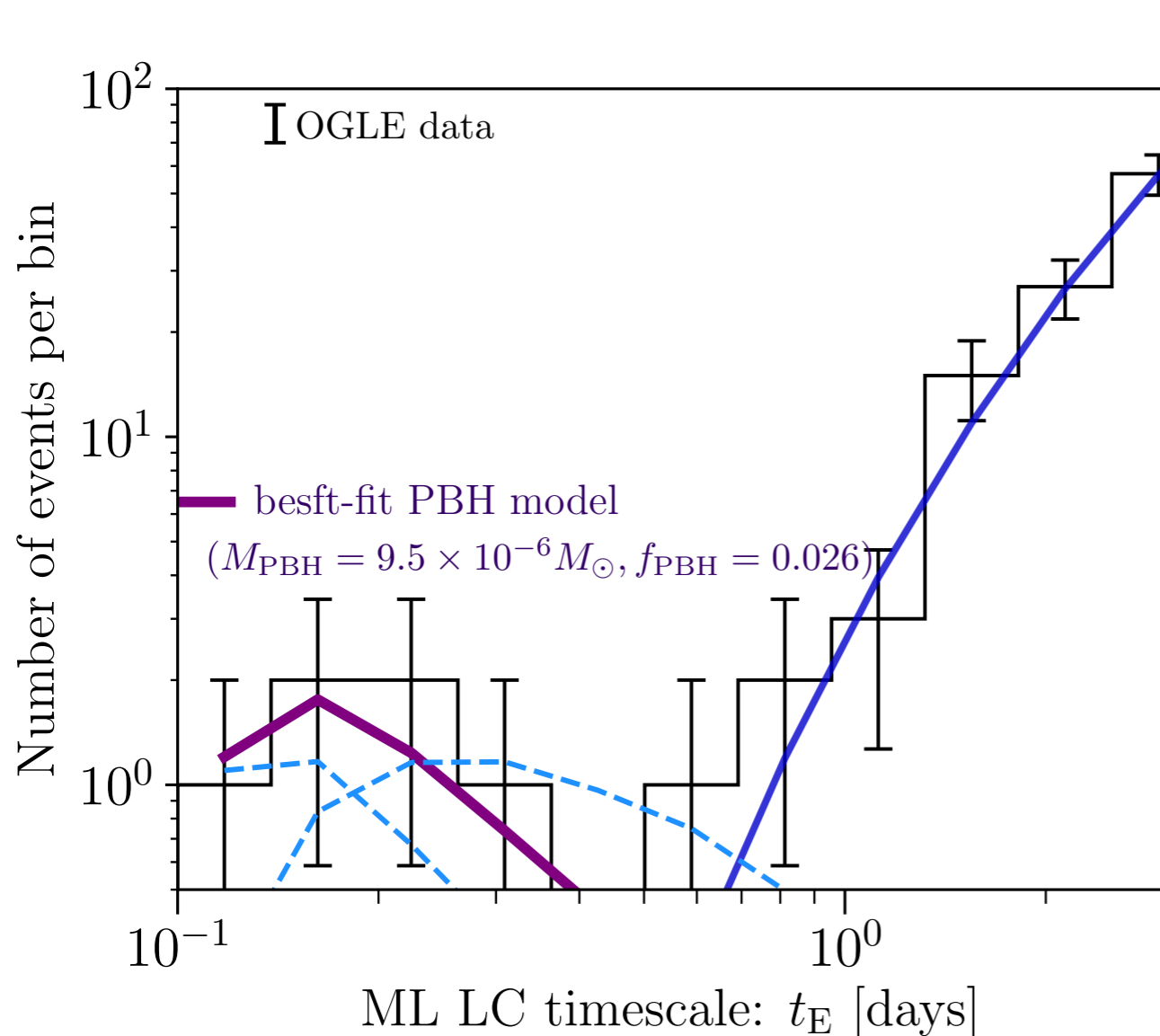


# Planetary-Mass Microlensing

★ OGLE detected a particular **population** of microlensing events:

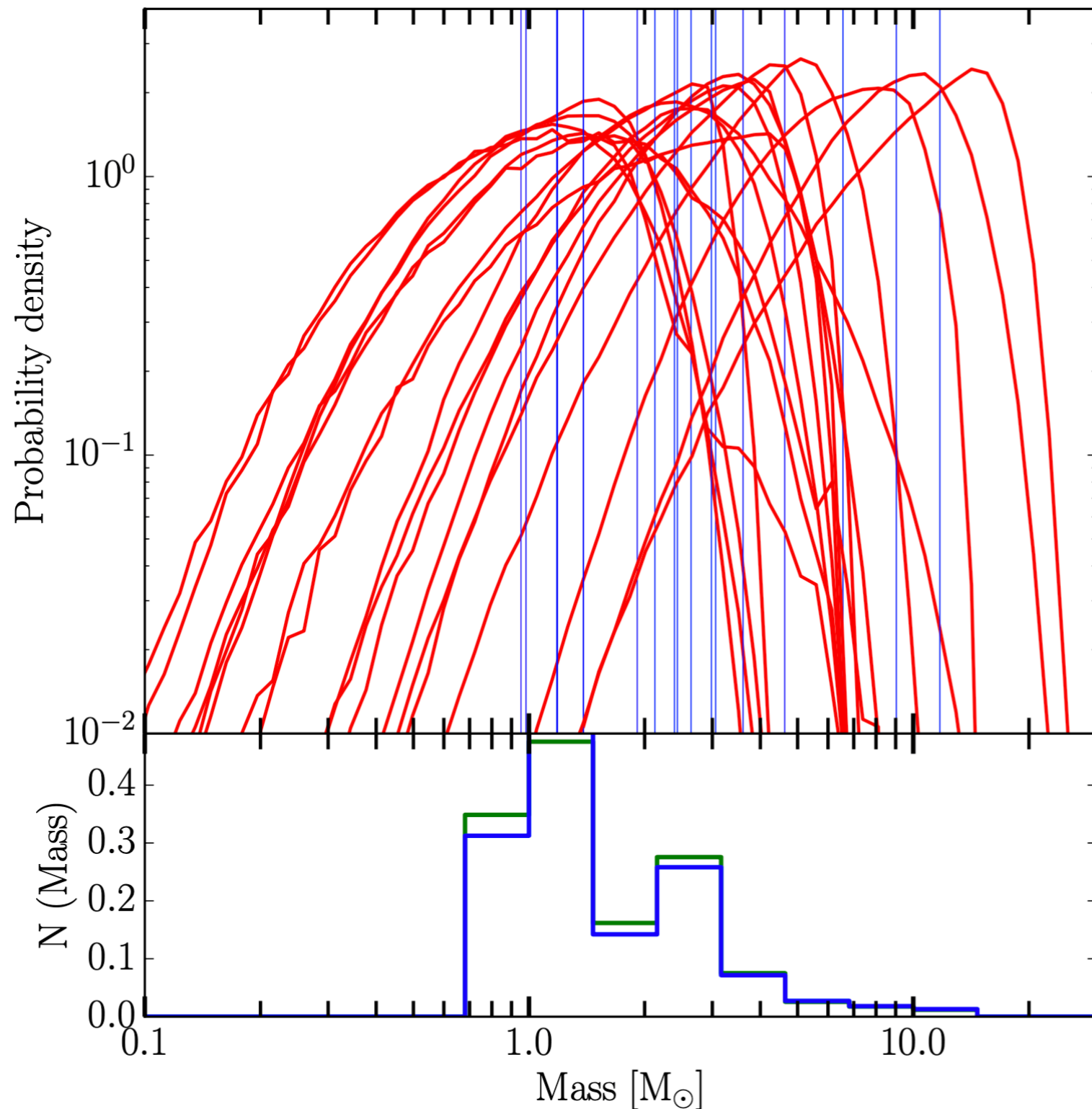
★ **0.1 - 0.3 days** light-curve timescale - origin **unknown!**

Could be free-floating planets... or **PBHs!**



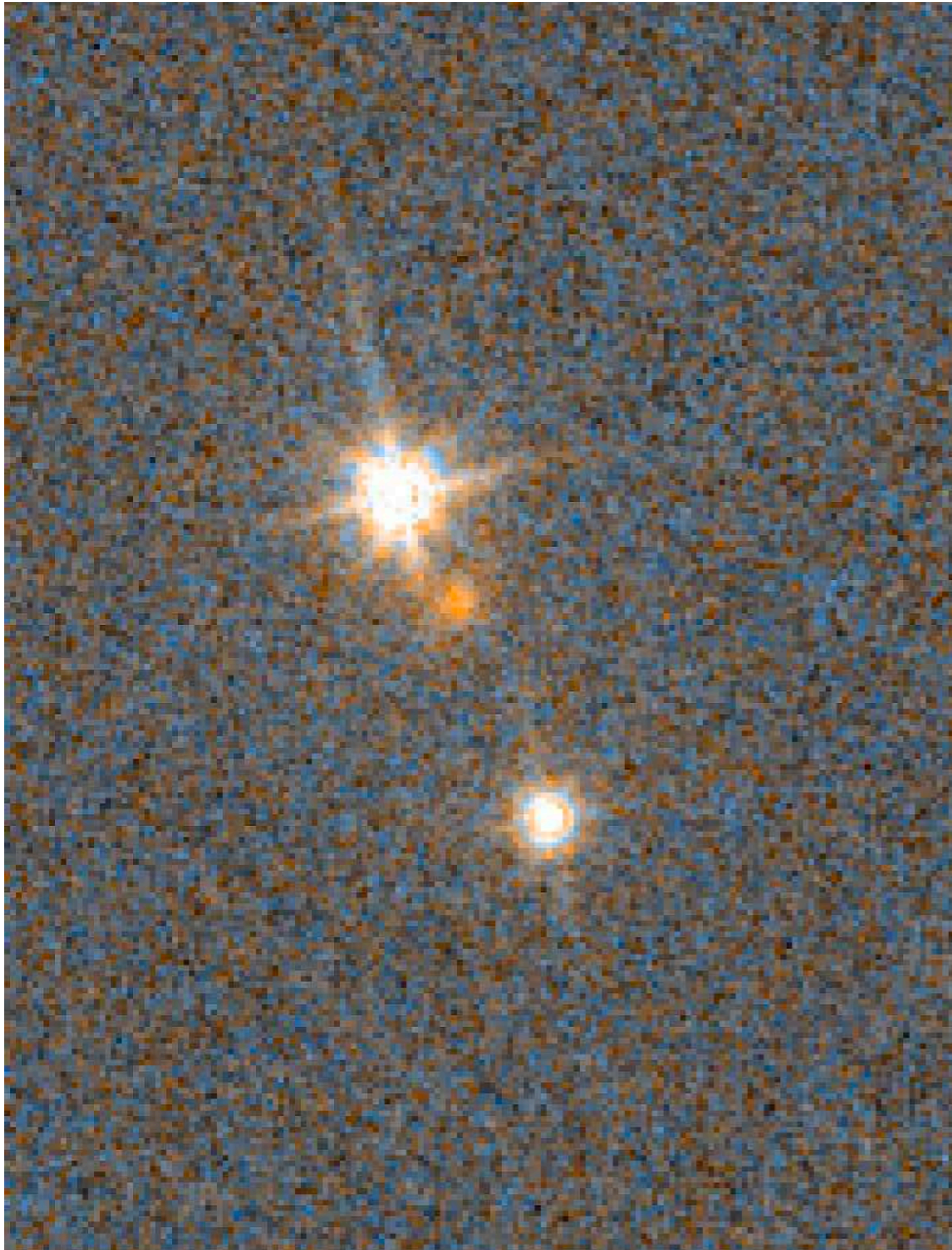
[Niikura *et al.* 2019]

# 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.

# 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

Institute for Astronomy (IfA), University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK  
e-mail: mrsh@roe.ac.uk

### ABSTRACT

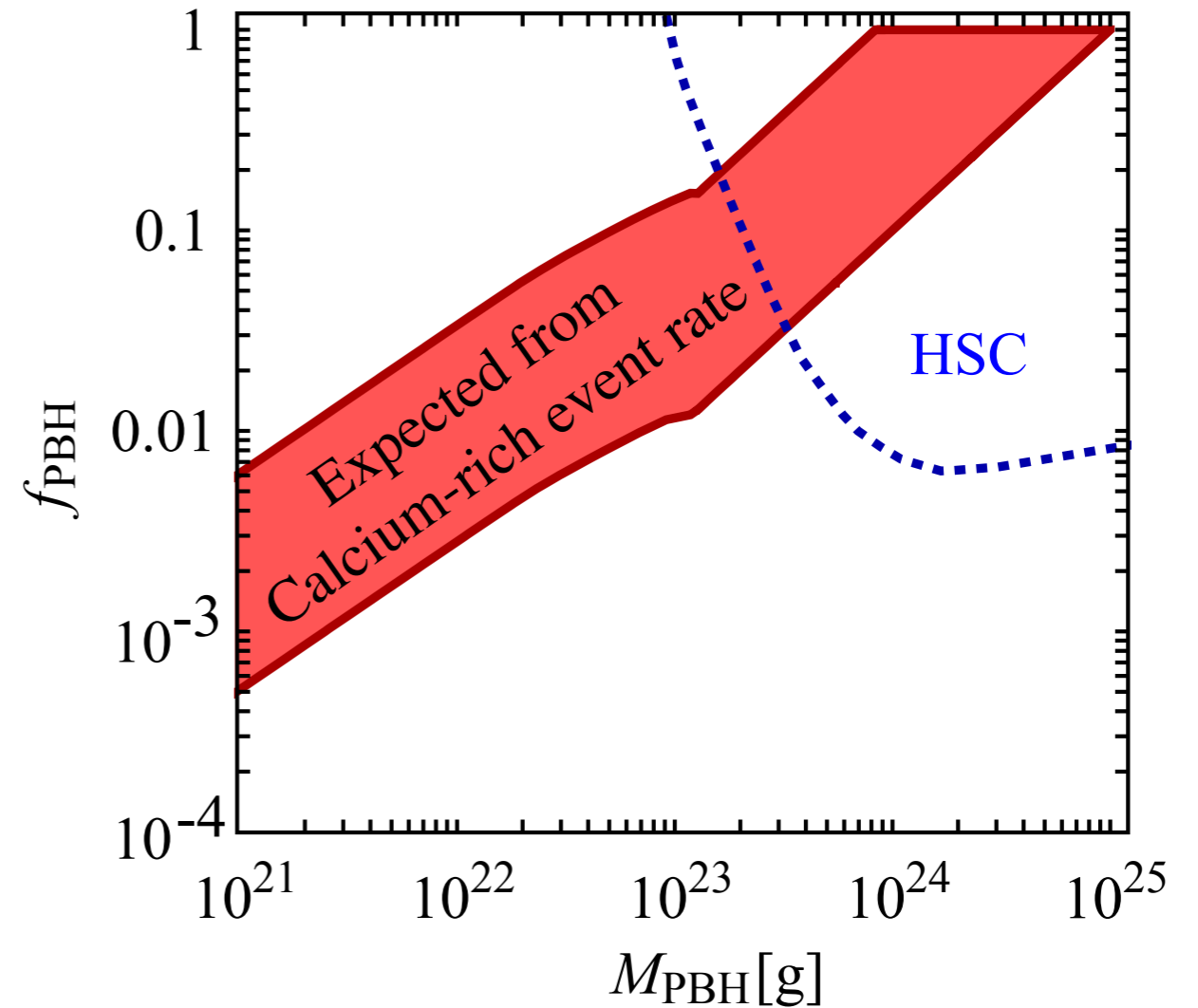
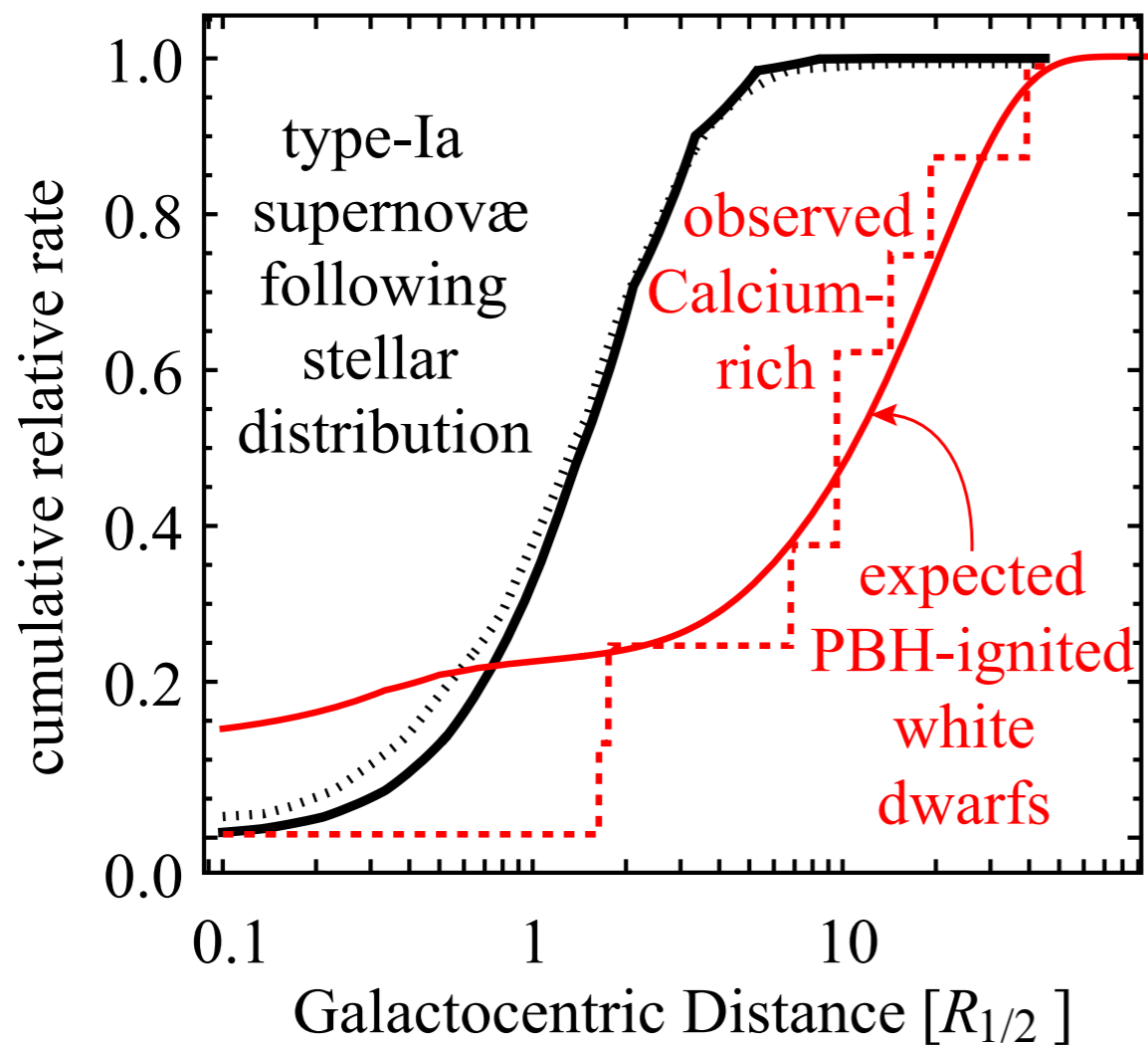
*Aims.* The aim of this paper is to investigate the claim that stars in the lensing galaxy of a gravitationally lensed quasar system can always account for the observed microlensing of the individual quasar images. [...]

*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.

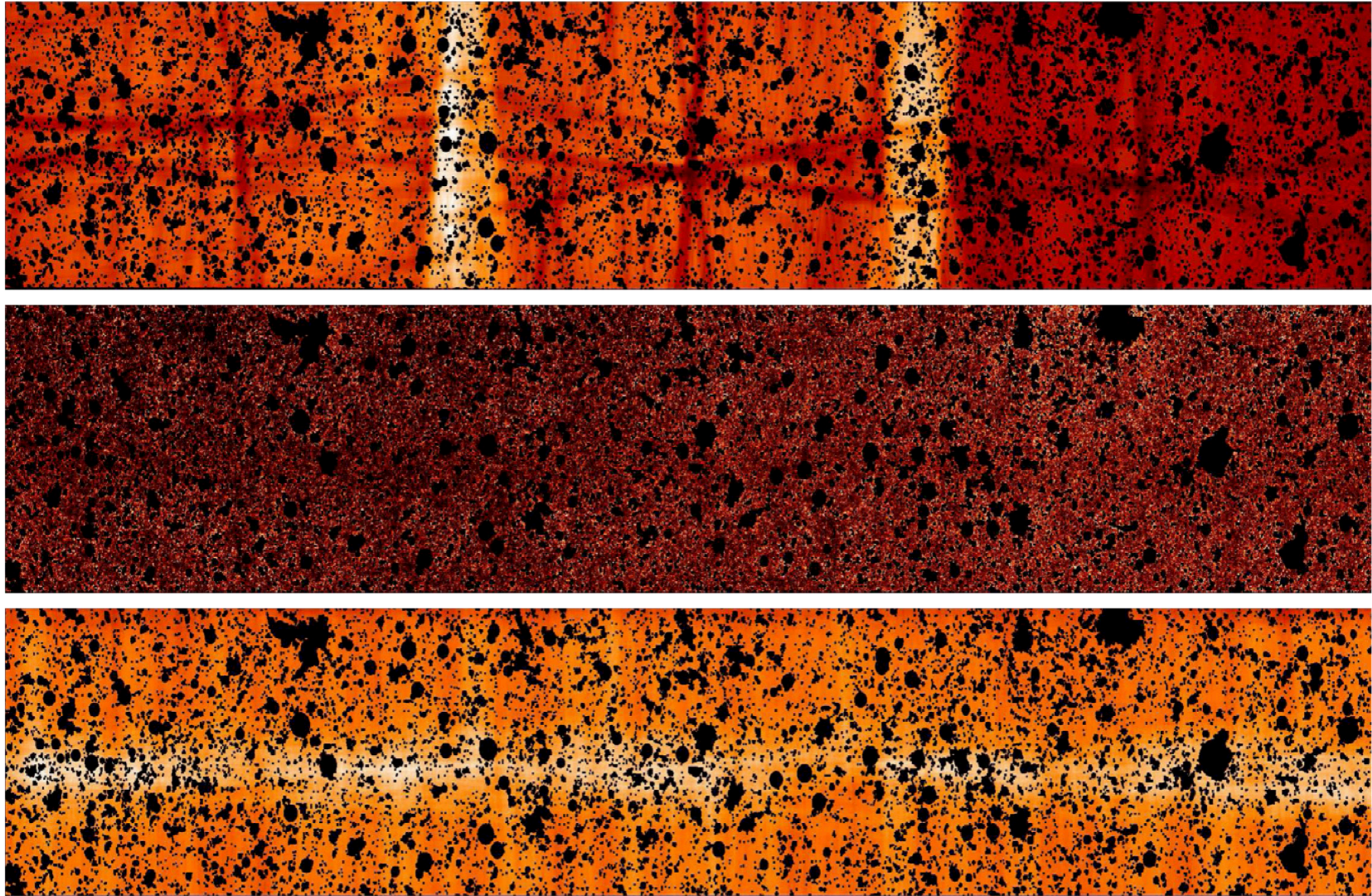
*Conclusions.* It is argued that the most plausible candidates for the microlenses are primordial black holes, either in the dark matter halos of the lensing galaxies, or more generally distributed along the lines of sight to the quasars.

# 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.**



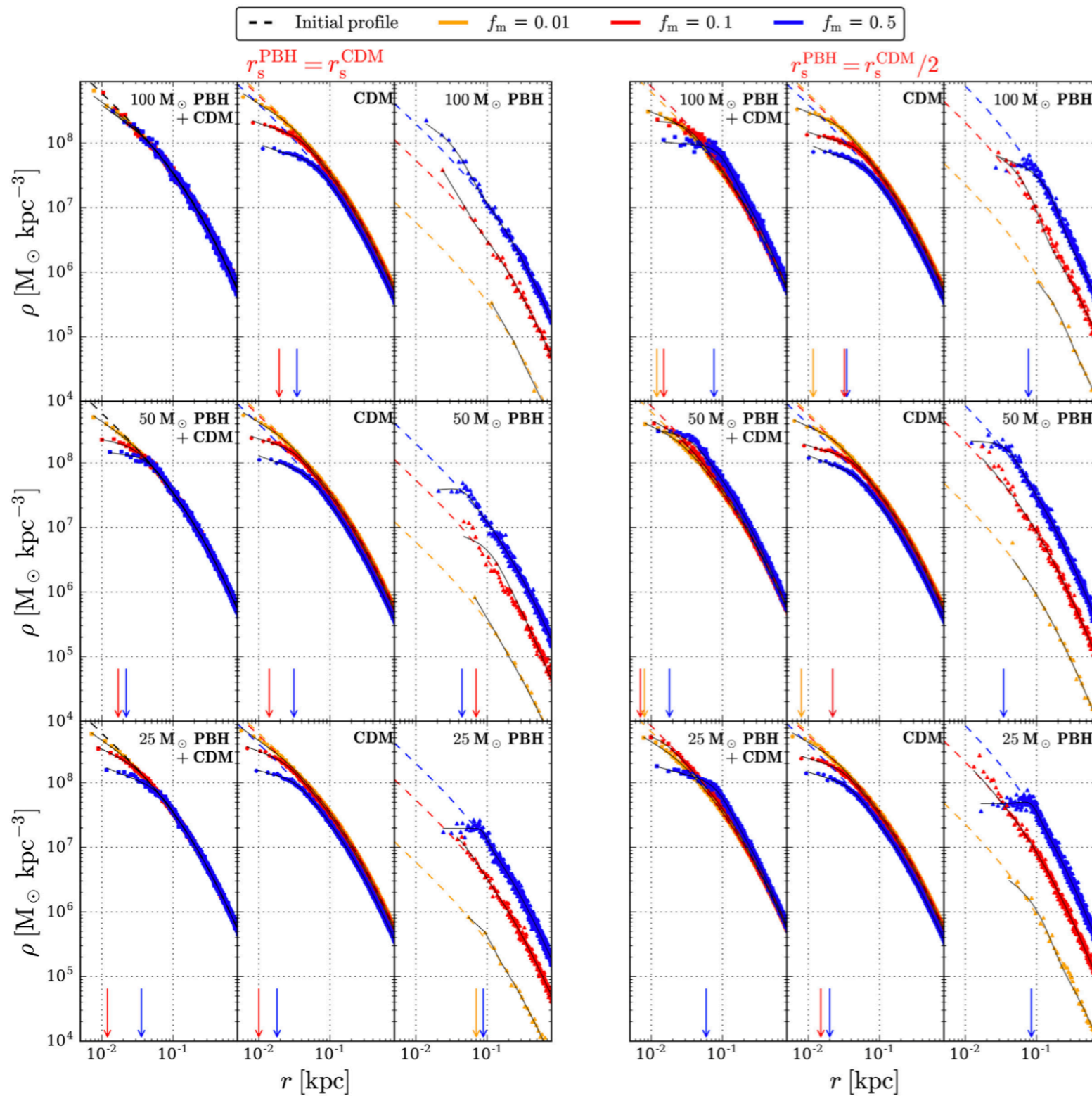
# Correlations of Cosmic Infrared/X-Ray Backgrounds



[Cappelluti *et al.* 2013]

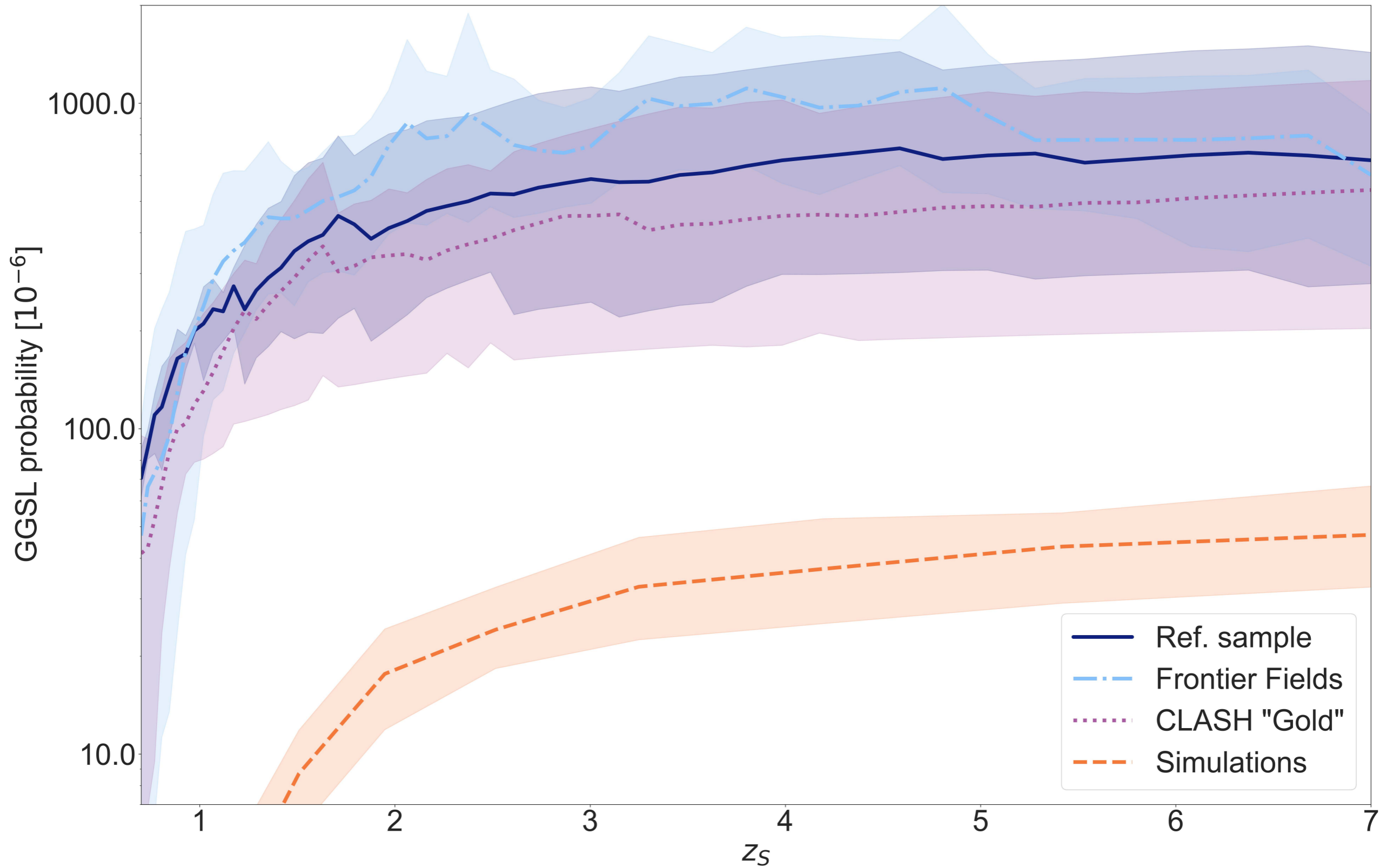
★ PBHs generate early structure and respective backgrounds

# Ultra-faint Dwarf Galaxies



- ★ **Non-detection** of dwarf galaxies smaller than  $\sim 10 - 20$  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*

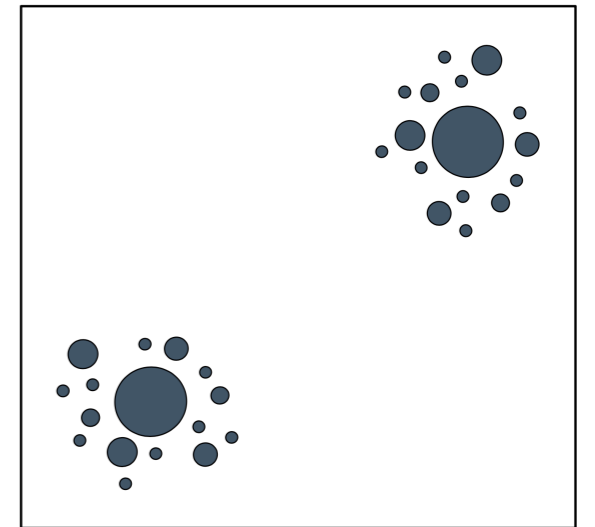
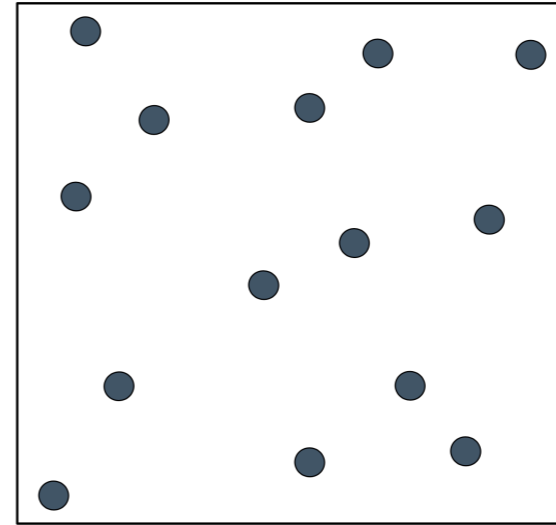


[Meneghetti, Natarajan, Downer 2020]

# *Evidence of Dark Matter Clumping with HST*



[Meneghetti, Natarajan, Downer 2020]



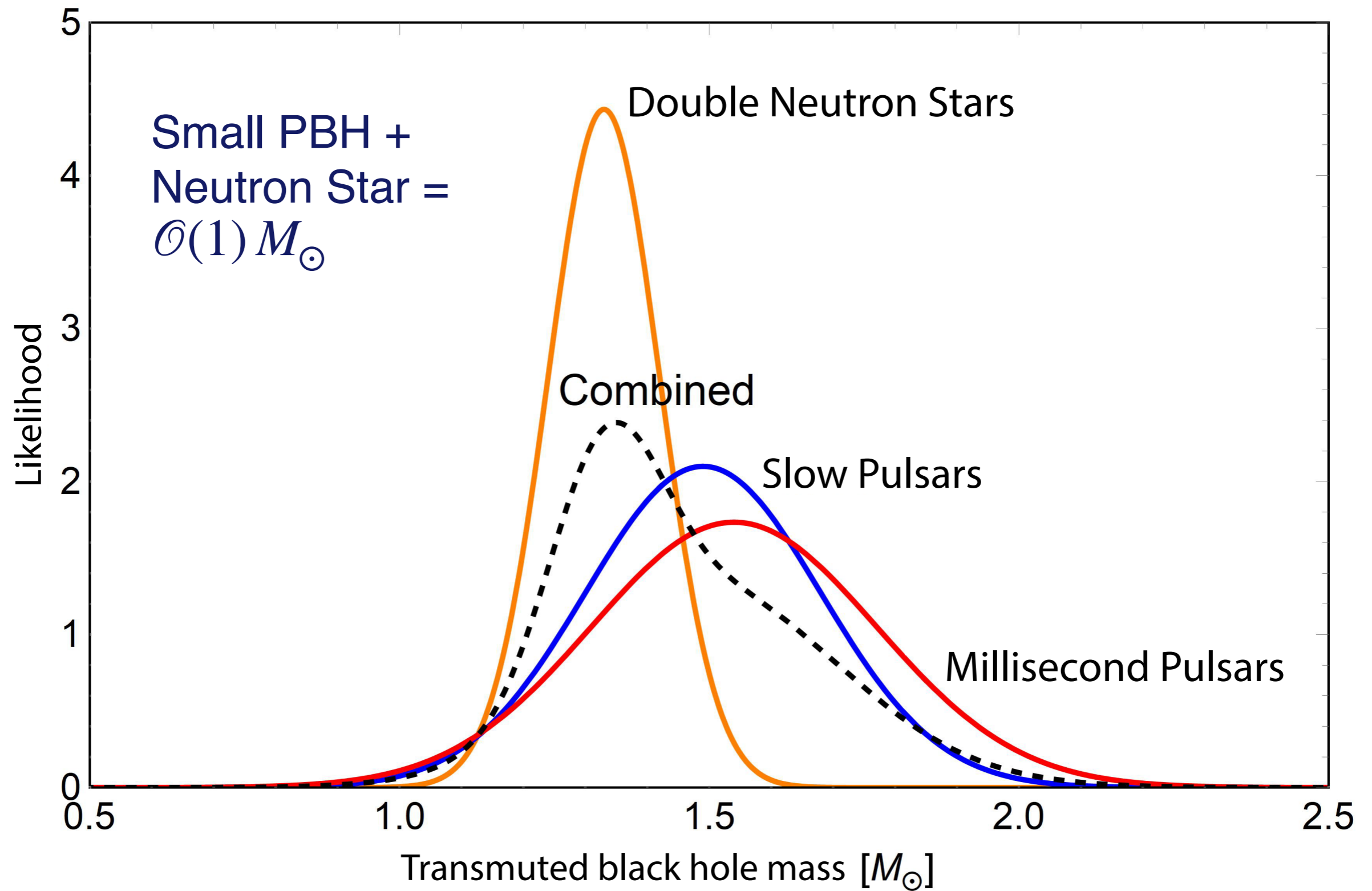
[García-Bellido 2018]

homogeneous versus clumped  
dark matter distribution

★ This is the **norm** for **PBHs!**

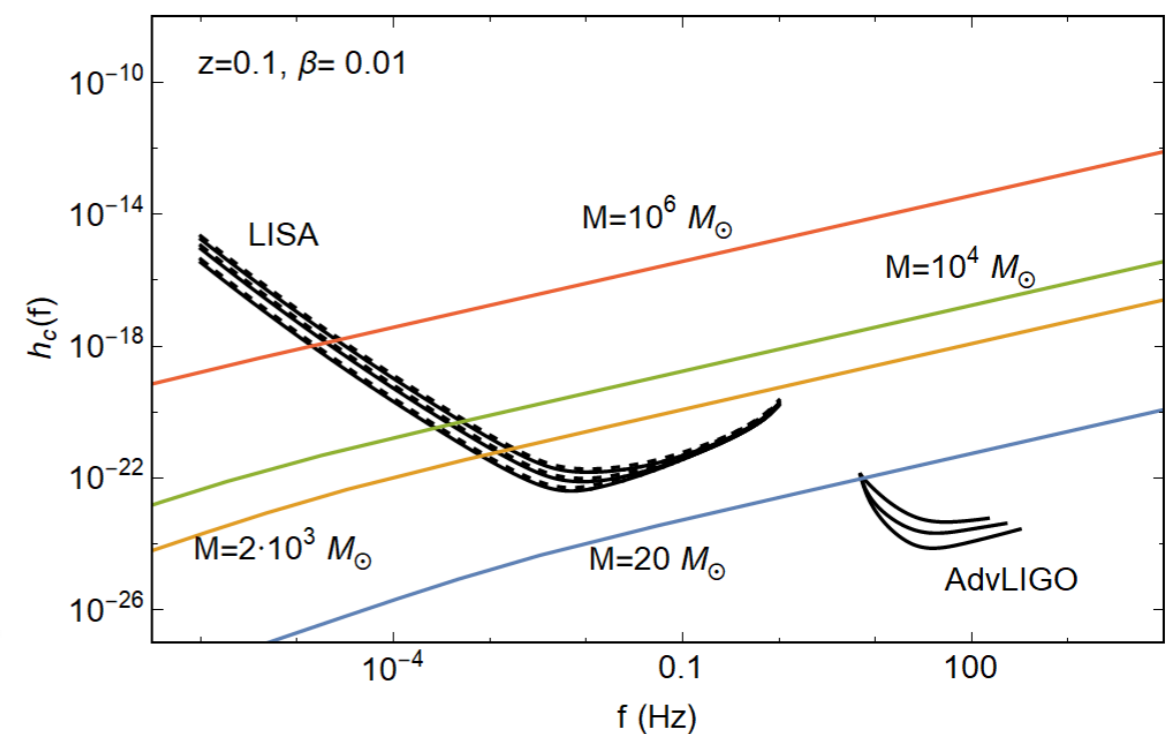
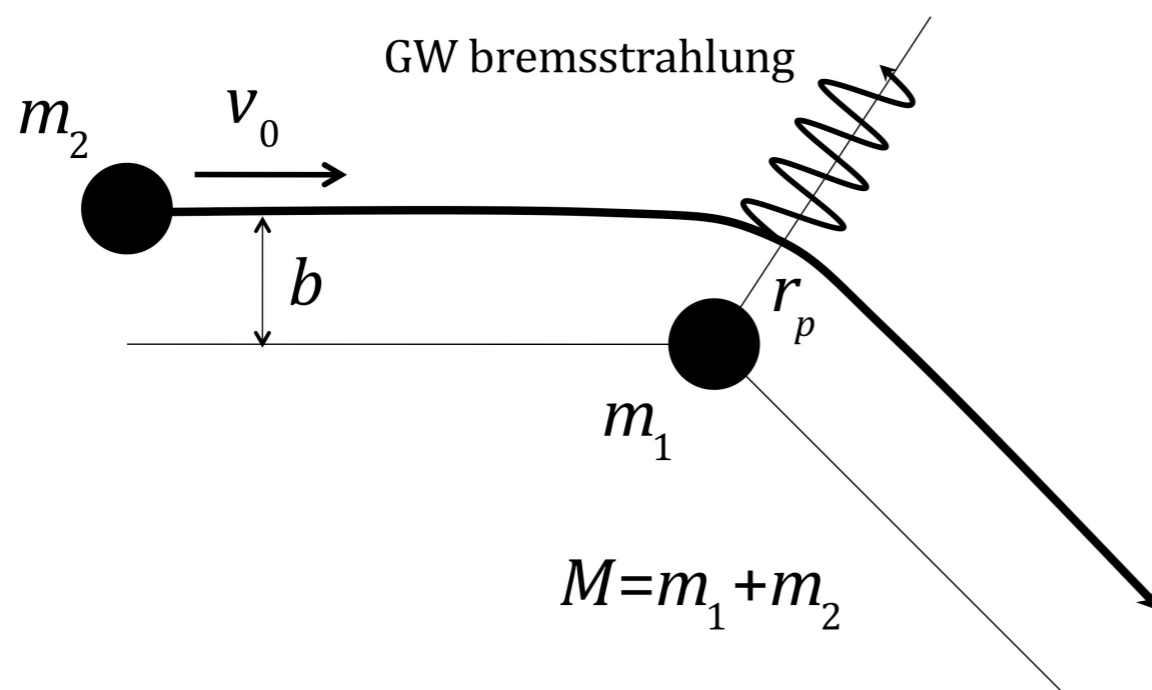


# *Transmuted Solar-Mass Black Holes*



# Gravitational Waves from 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**.





# GRAVITATIONAL WAVE MERGER DETECTIONS

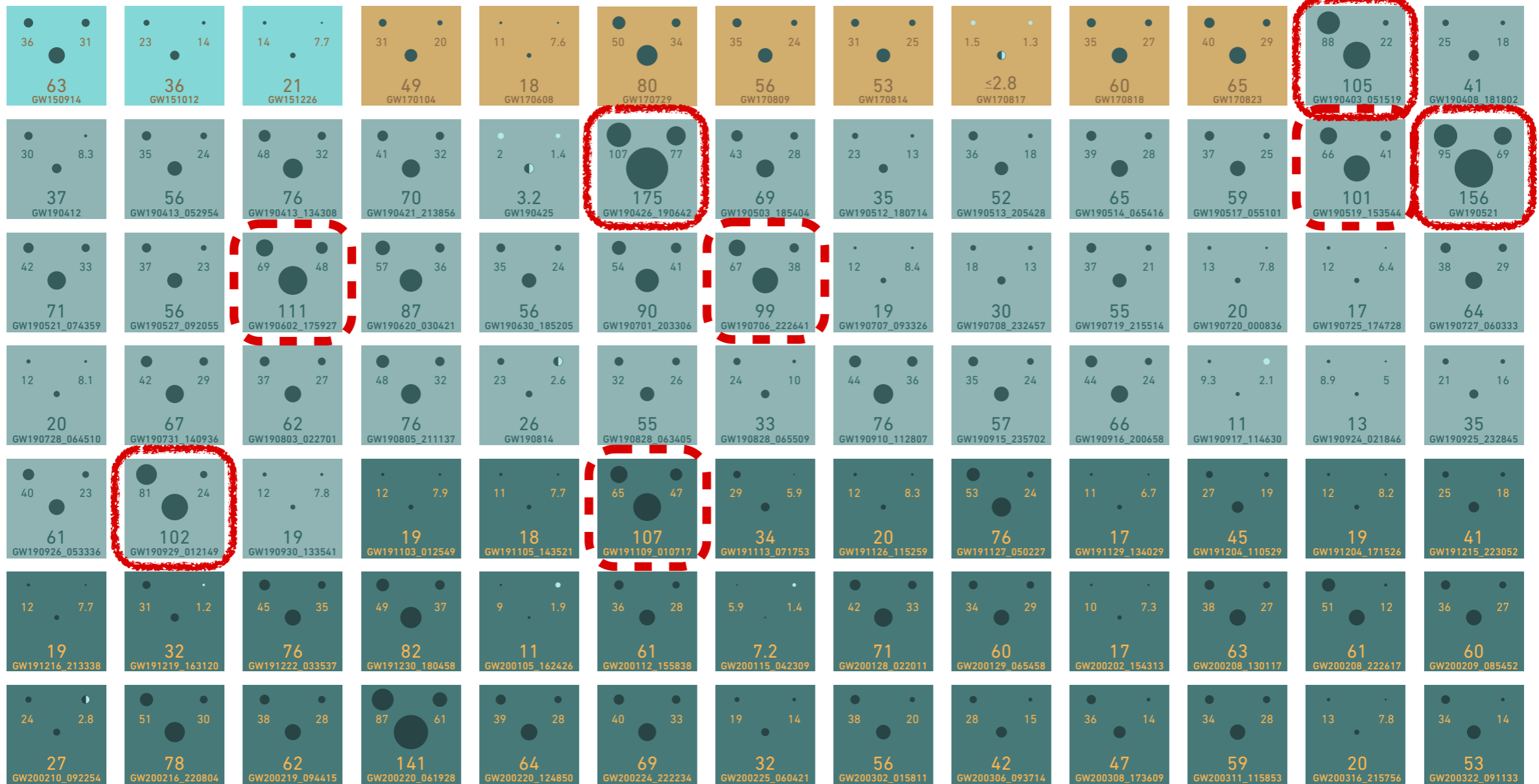
→ SINCE 2015

OBSERVING RUN

01 2015-2016

02 2016-2017

03a+b 2019-2020



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



# GRAVITATIONAL WAVE MERGER DETECTIONS

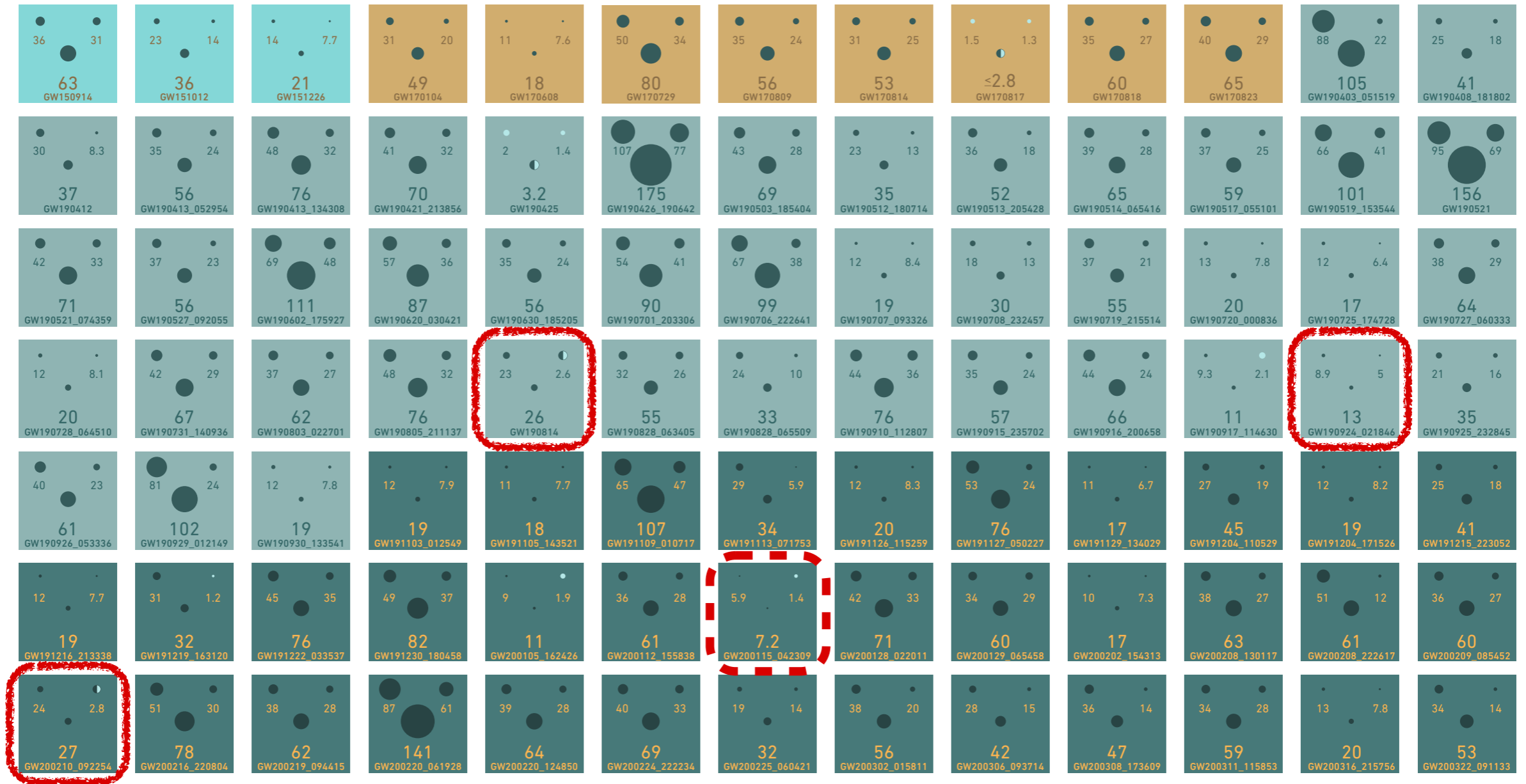
→ SINCE 2015

OBSERVING RUN

01 2015-2016

02 2016-2017

03a+b 2019-2020



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



# GRAVITATIONAL WAVE MERGER DETECTIONS

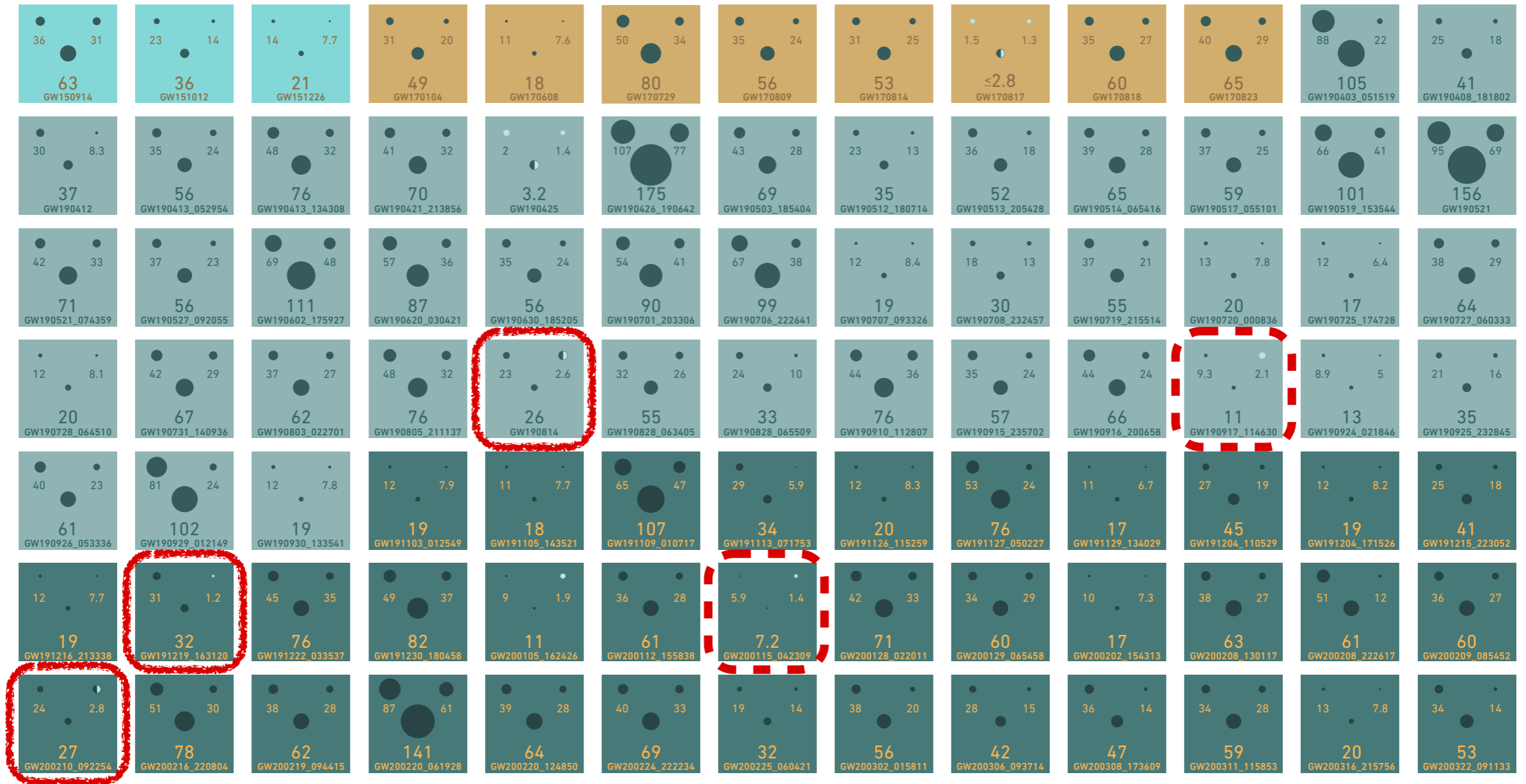
→ SINCE 2015

OBSERVING RUN

01 2015-2016

02 2016-2017

03a+b 2019-2020



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





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

R. Abbott<sup>1</sup>, [...]

### **Abstract**

We report the observation of a compact binary coalescence involving a  $22.2\text{--}24.3 M_{\odot}$  black hole and a compact object with a mass of  $2.50\text{--}2.67 M_{\odot}$  [...] **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  $q < 0.25$ )



# Subsolar Black Holes - The Smoking Gun!

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

Date	FAR [yr <sup>-1</sup> ]	$m_1[M_\odot]$	$m_2[M_\odot]$	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<sup>-1</sup>
- ★ Possibly the first confirmed detection of a subsolar mass PBH with the next 24 months!



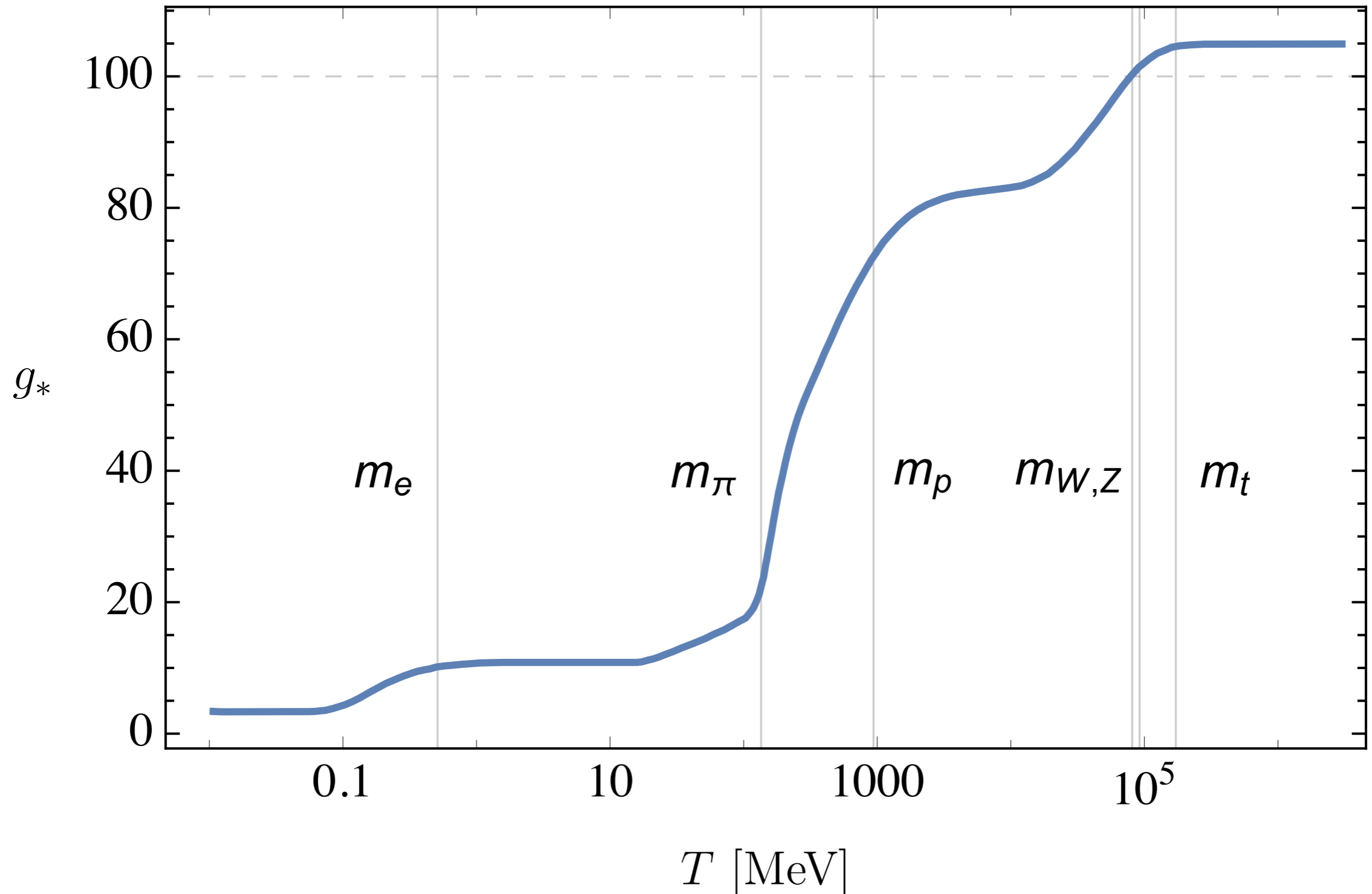


*A Unified Scenario*

\*work with Carr, Clesse,  
García-Bellido, Hawking

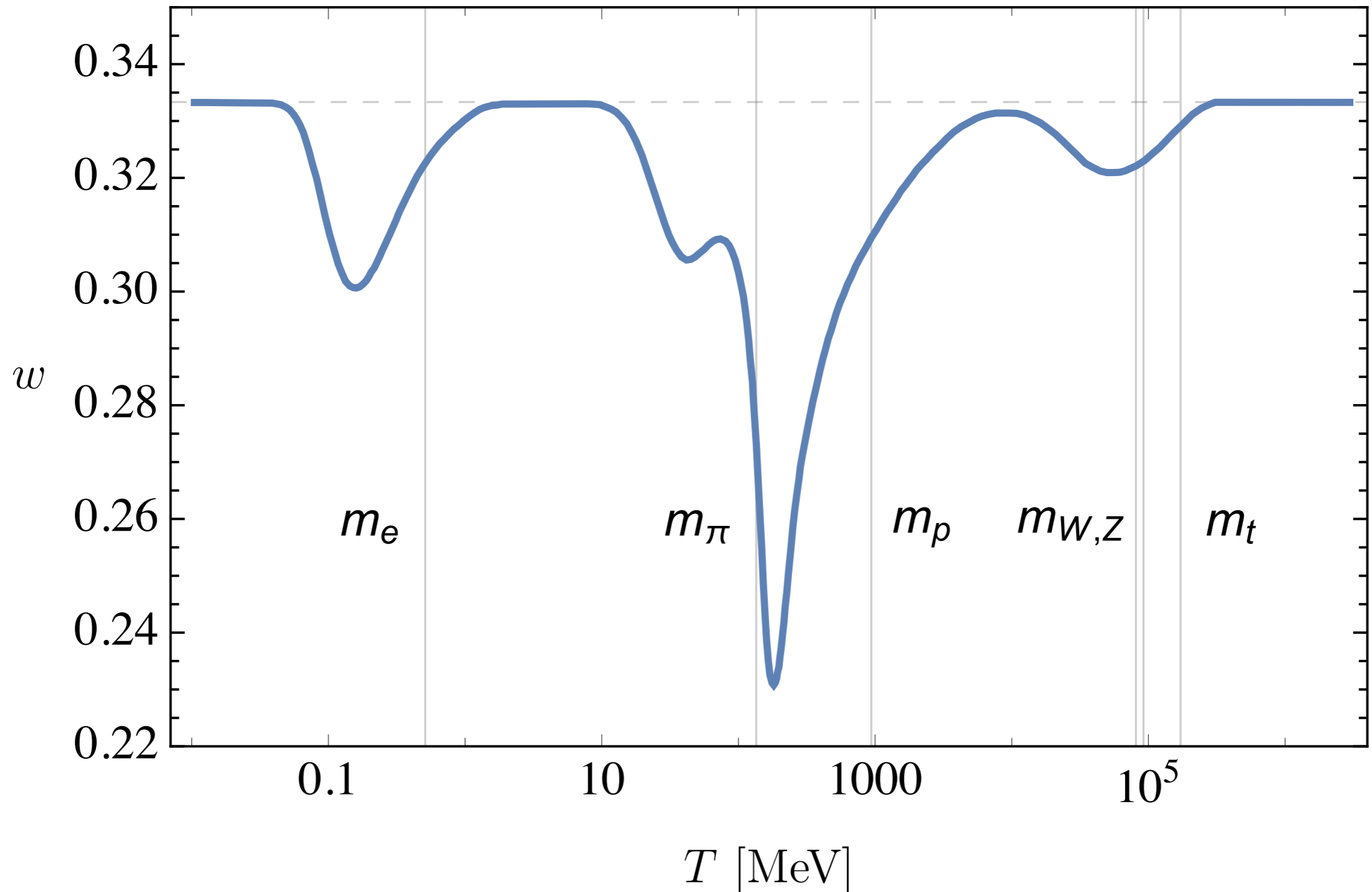
# *Thermal History of the Universe — Degrees of Freedom*

★ 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]

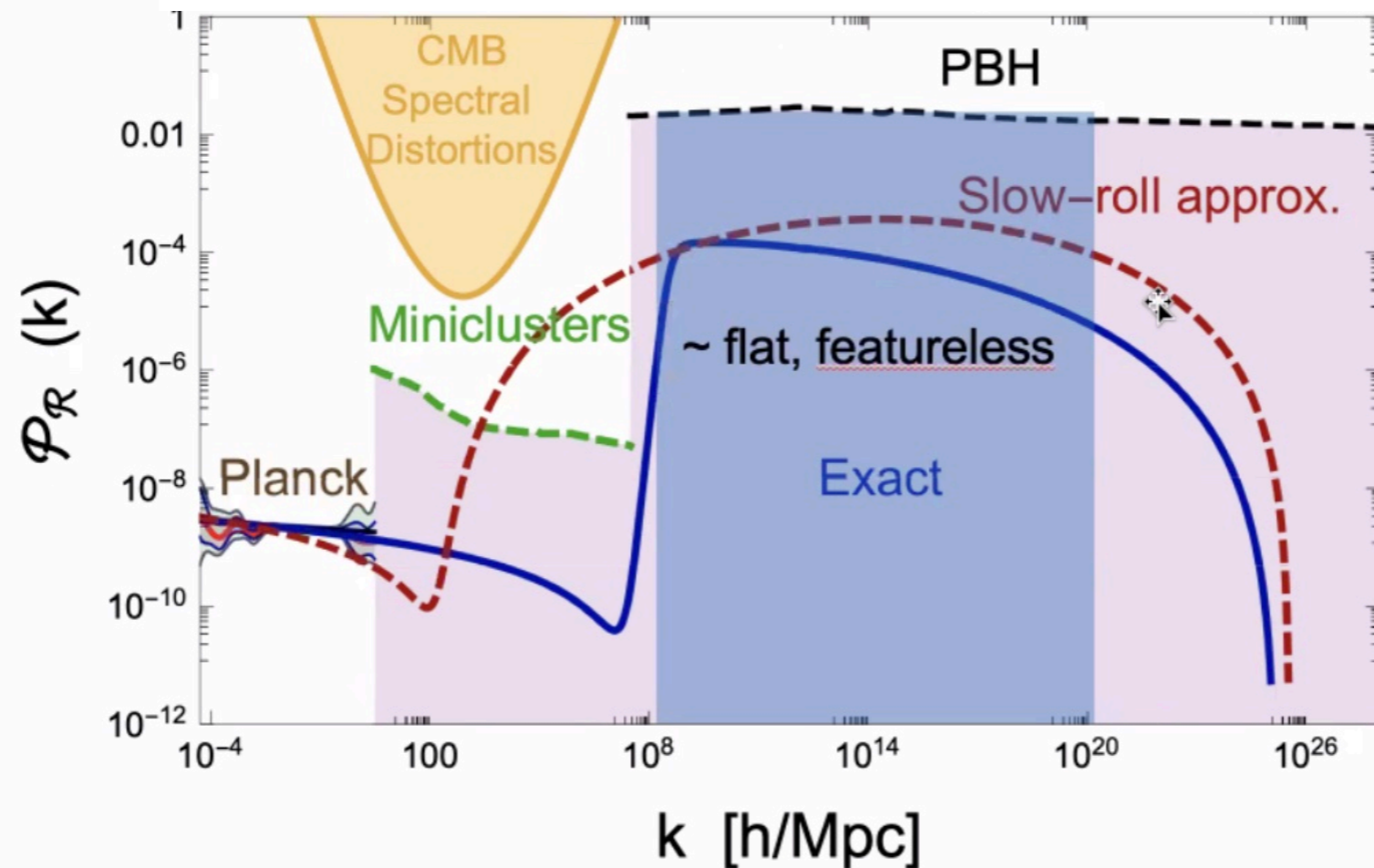
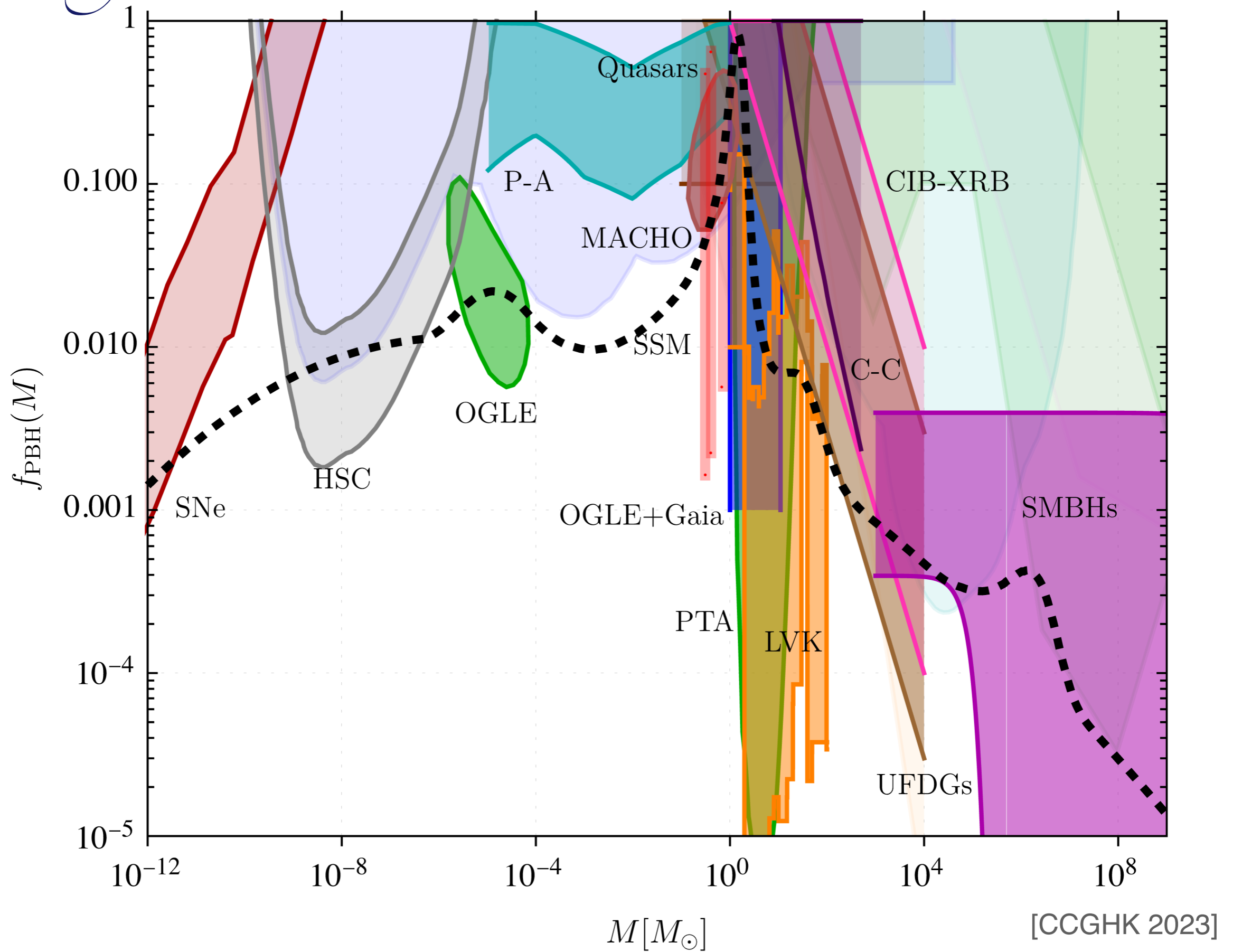
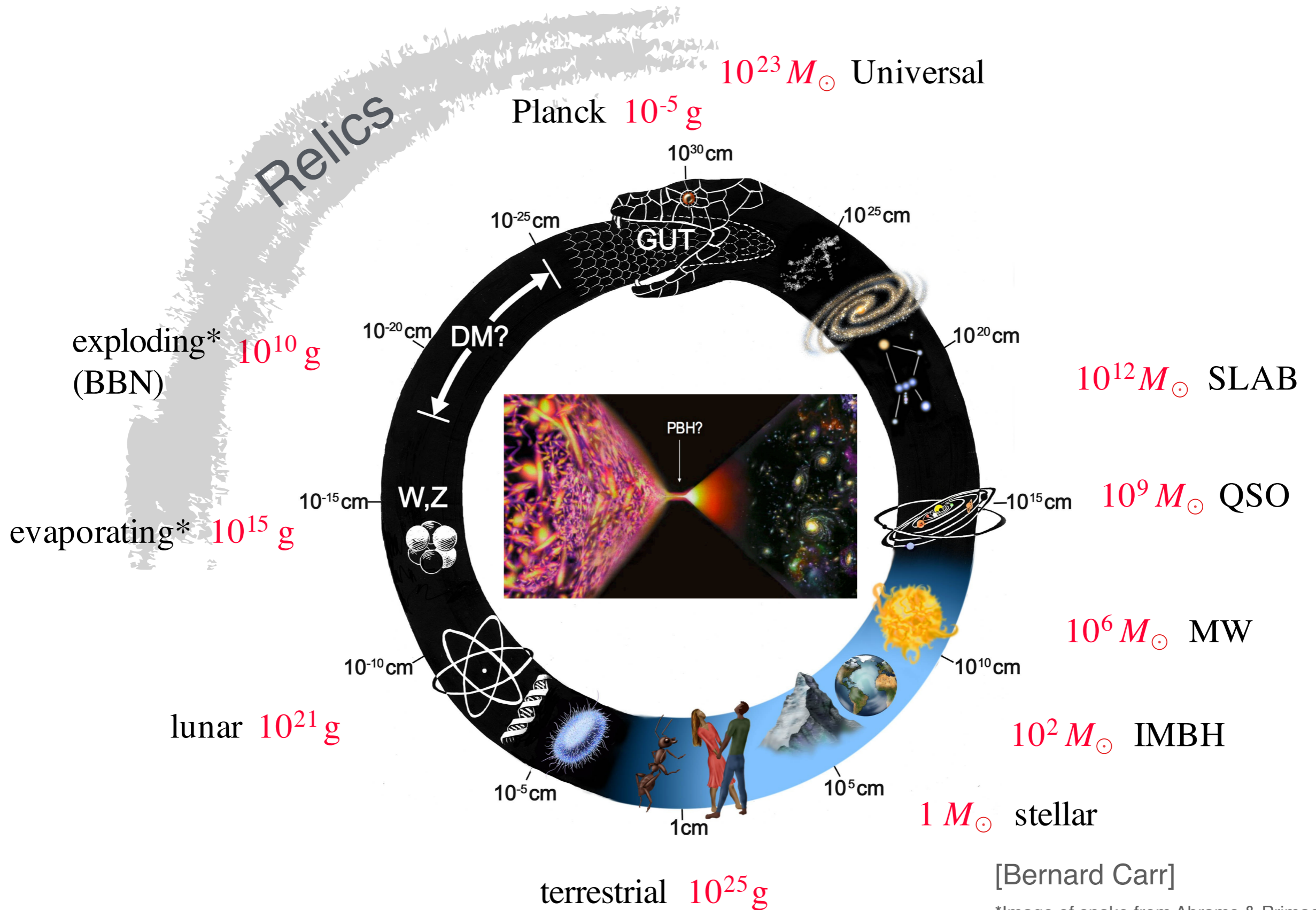


Figure from García-Bellido

# Connecting all Positive Evidences!



# 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,<sup>1,\*</sup> S. Clesse,<sup>2,†</sup> J. García-Bellido,<sup>3,‡</sup> M. R. S. Hawkins,<sup>4,§</sup> and F. Kühnel<sup>5,¶</sup>

<sup>1</sup>*School of Physics and Astronomy, Queen Mary University of London*

<sup>2</sup>*Service de Physique Théorique, University of Brussels (ULB)*

<sup>3</sup>*Instituto de Física Teórica, Universidad Autónoma de Madrid*

<sup>4</sup>*Royal Observatory Edinburgh*

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(Dated: Wednesday 7<sup>th</sup> 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.