Primordial Black Holes:
Positivist Perspective and Quantum Quiddity

Florian Kühnel

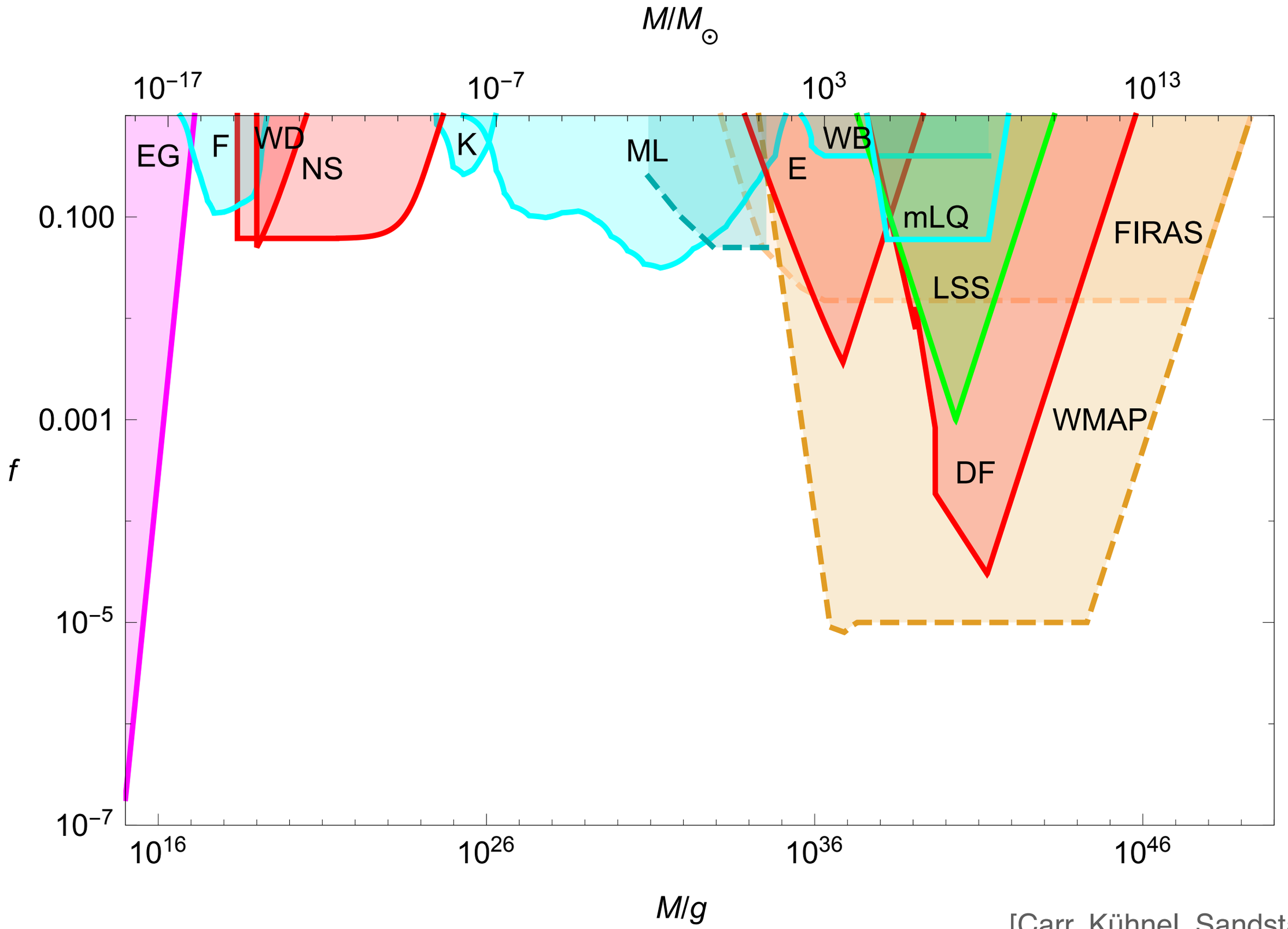
Max Planck Institute for Physics,
Garching (near Munich), Germany

— New Horizons in Primordial Black Hole Physics '24 —
Edinburgh, Monday, the 16th of June 2024

In 2016…

2016 — Bielefeld, Germany

PBH Constraints back in the Days (2016)



[Carr, Kühnel, Sandstad 2016]

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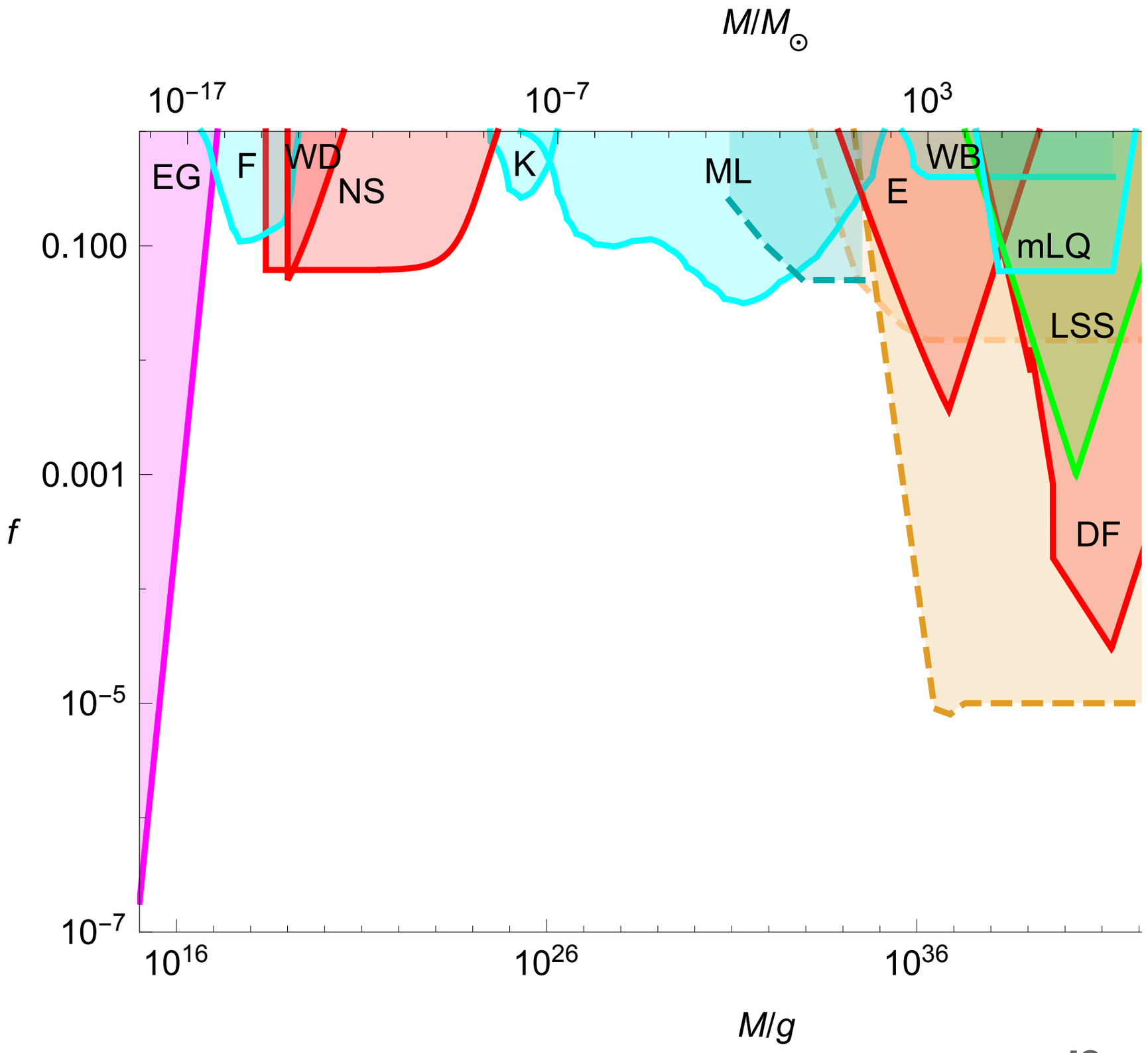

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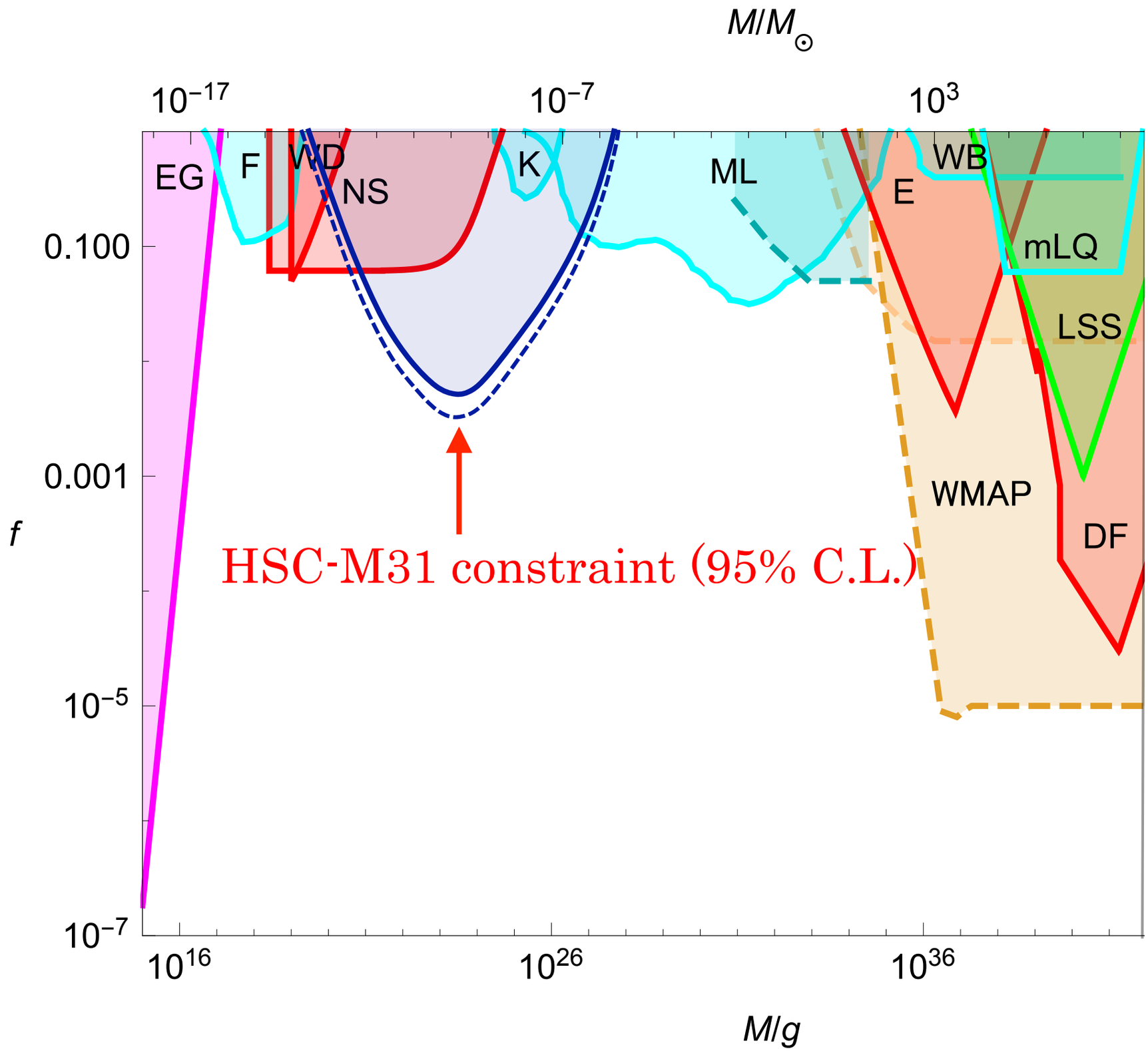

[Niikura 他 2017 - v1]

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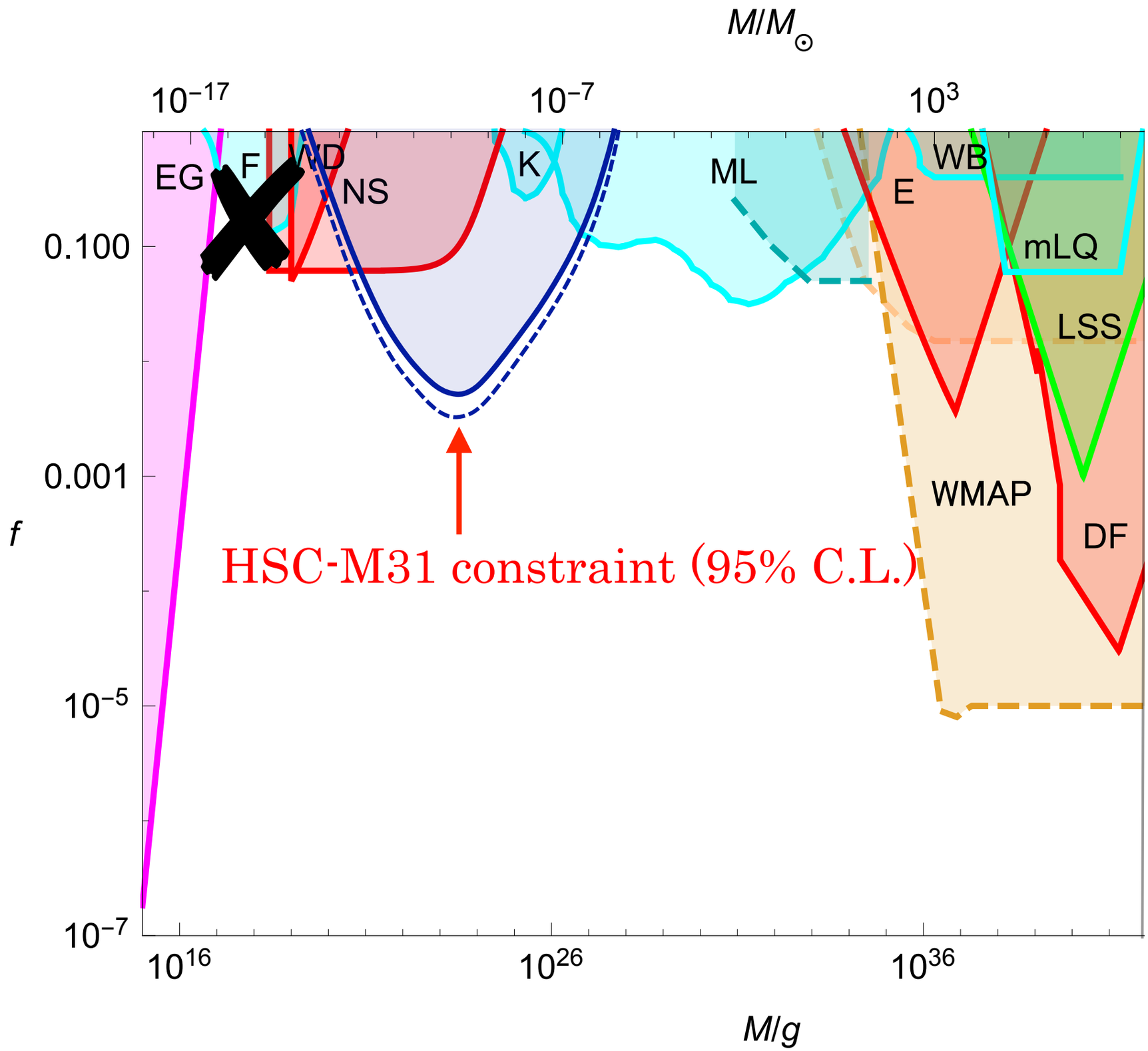

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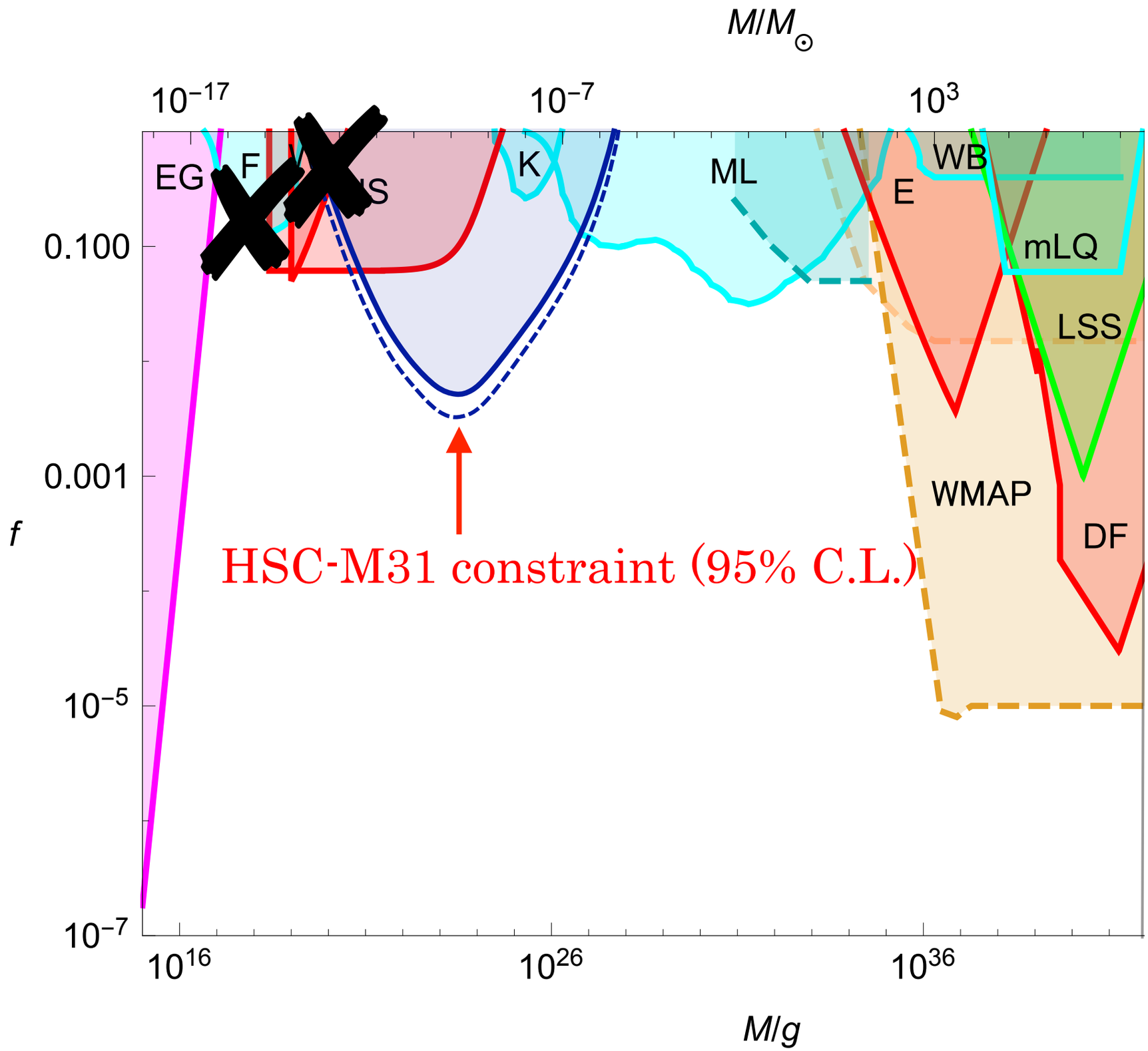

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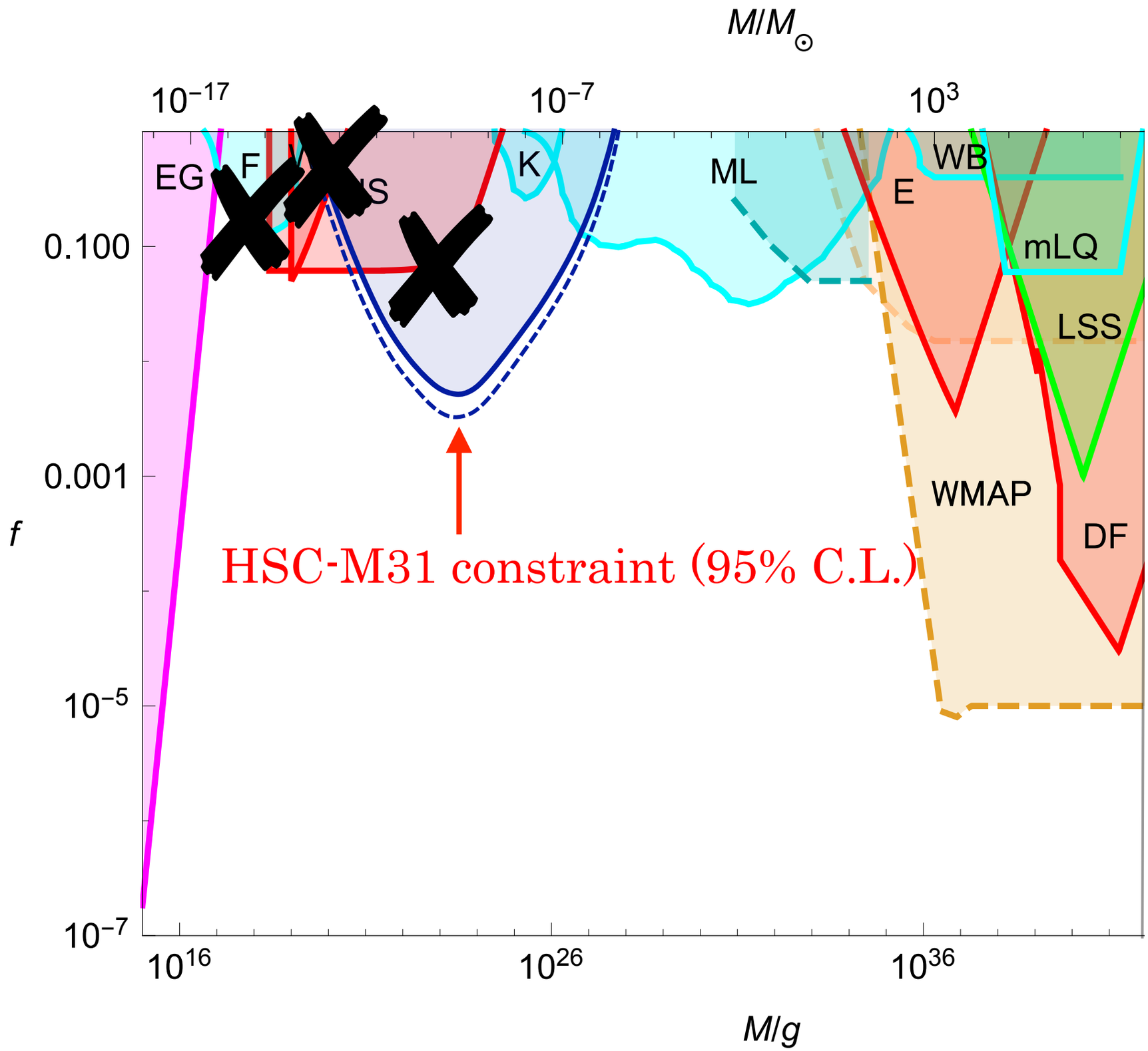

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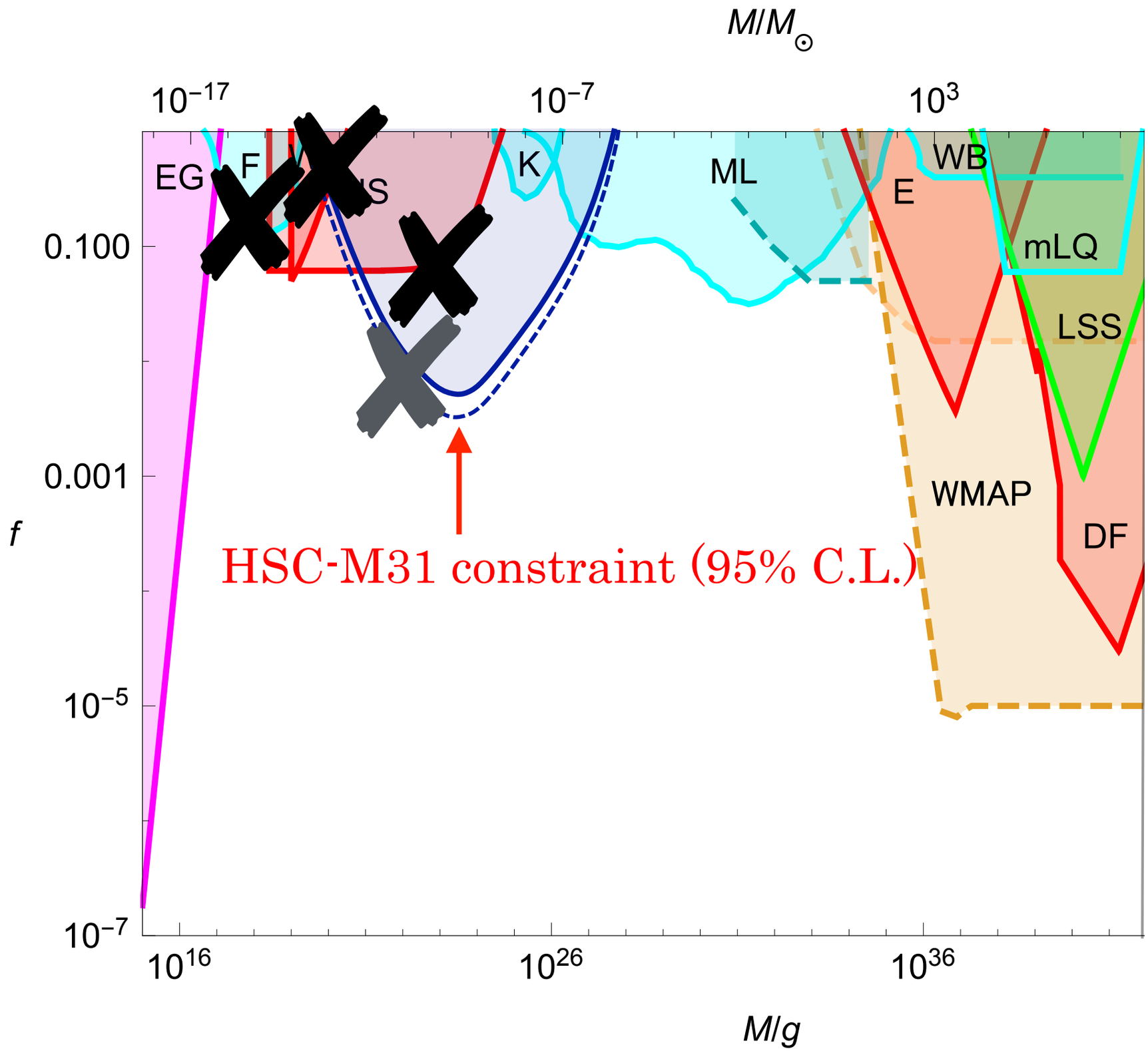
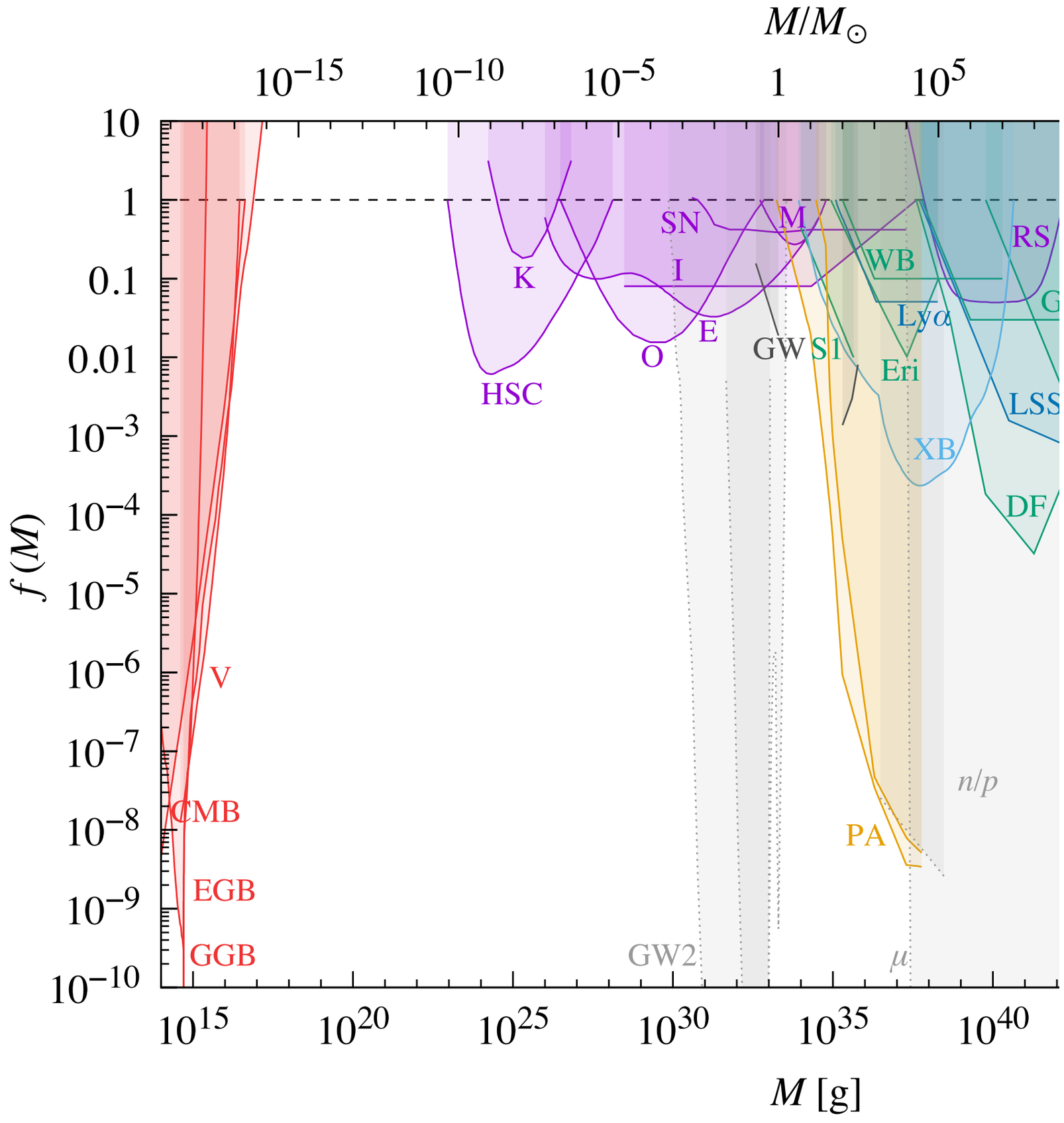


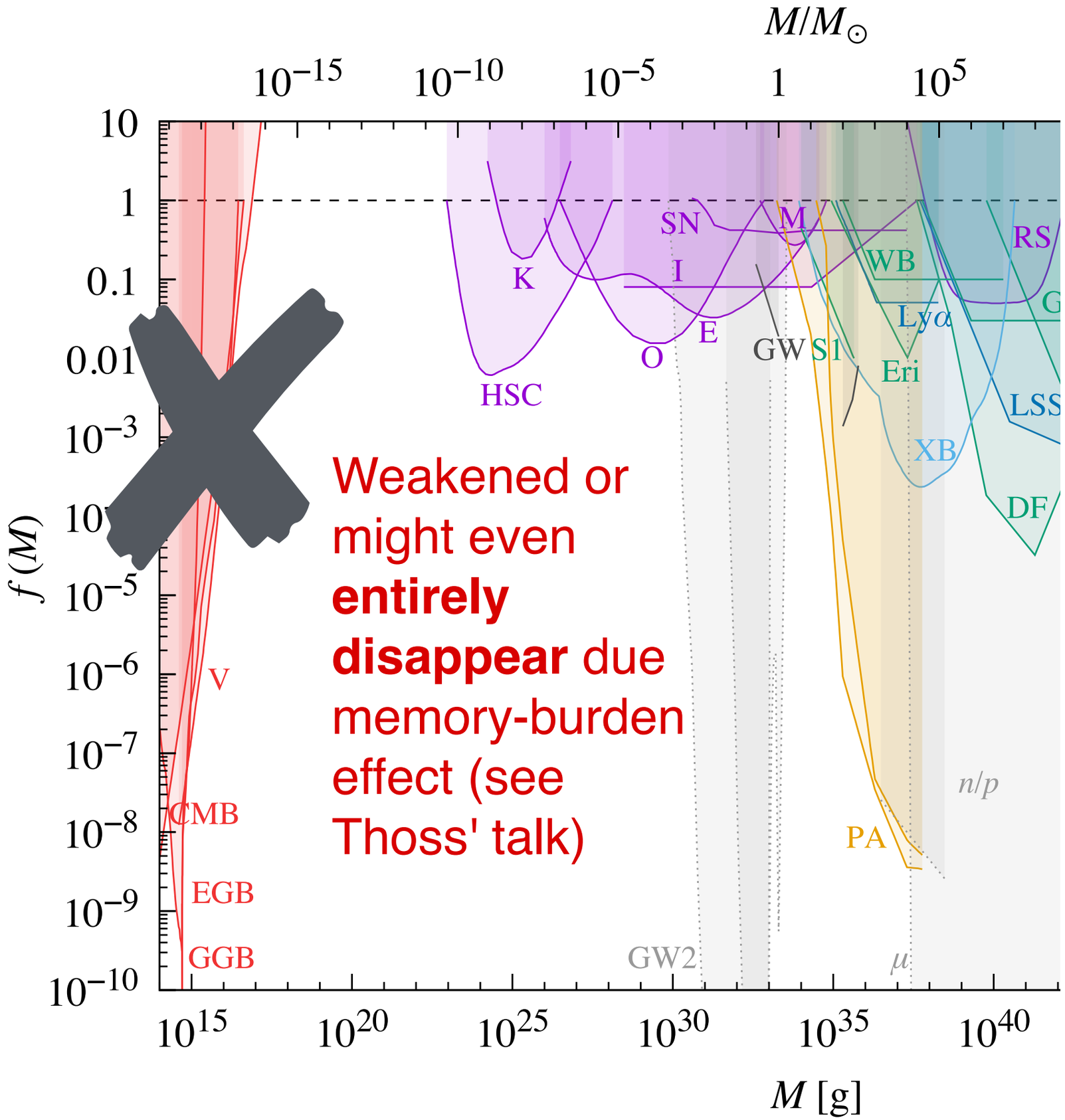
[Niikura 他 2017 - v1]

Current PBH Constraints



[Carr 他 2021]

Current PBH Constraints



[Carr 他 2021]

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 $f_{\mathrm{PBH}} \ll 1$.

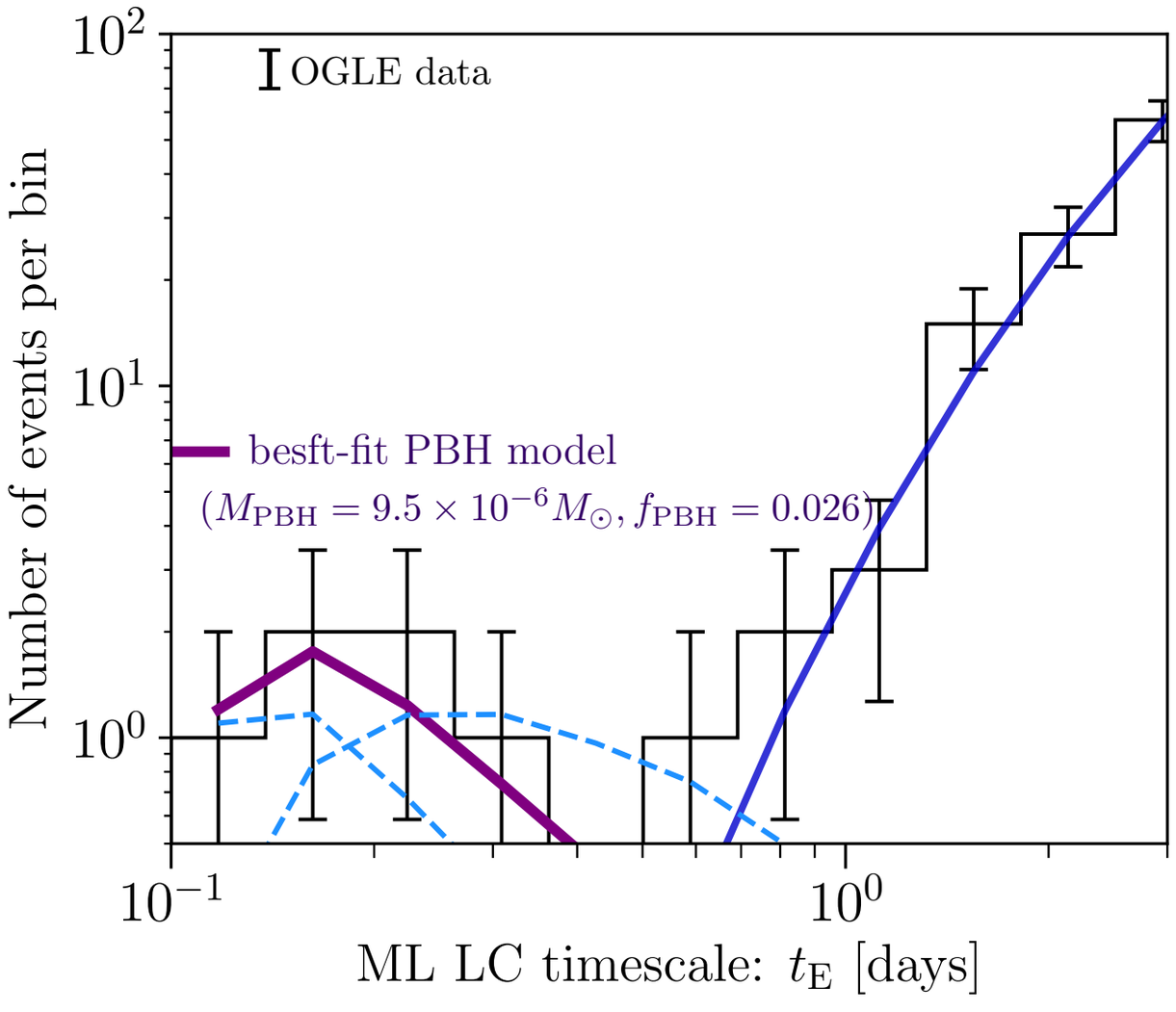
Observational Hints for Primordial Black Holes

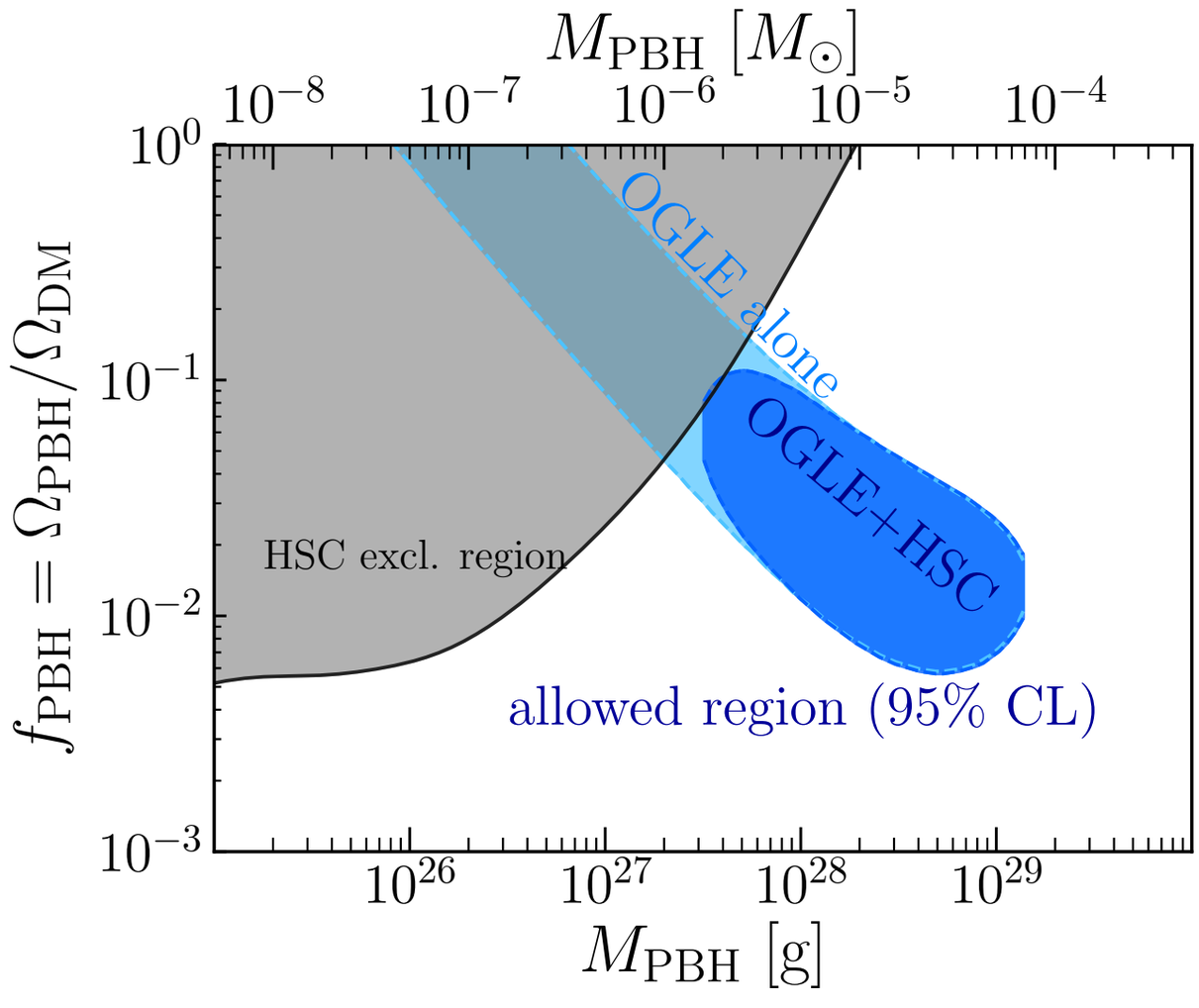
Evidence?
Observational ~~Hints~~ for
Primordial Black Holes

*work with Carr, Clesse,
García-Bellido, Hawkins

Planetary-Mass Microlensing

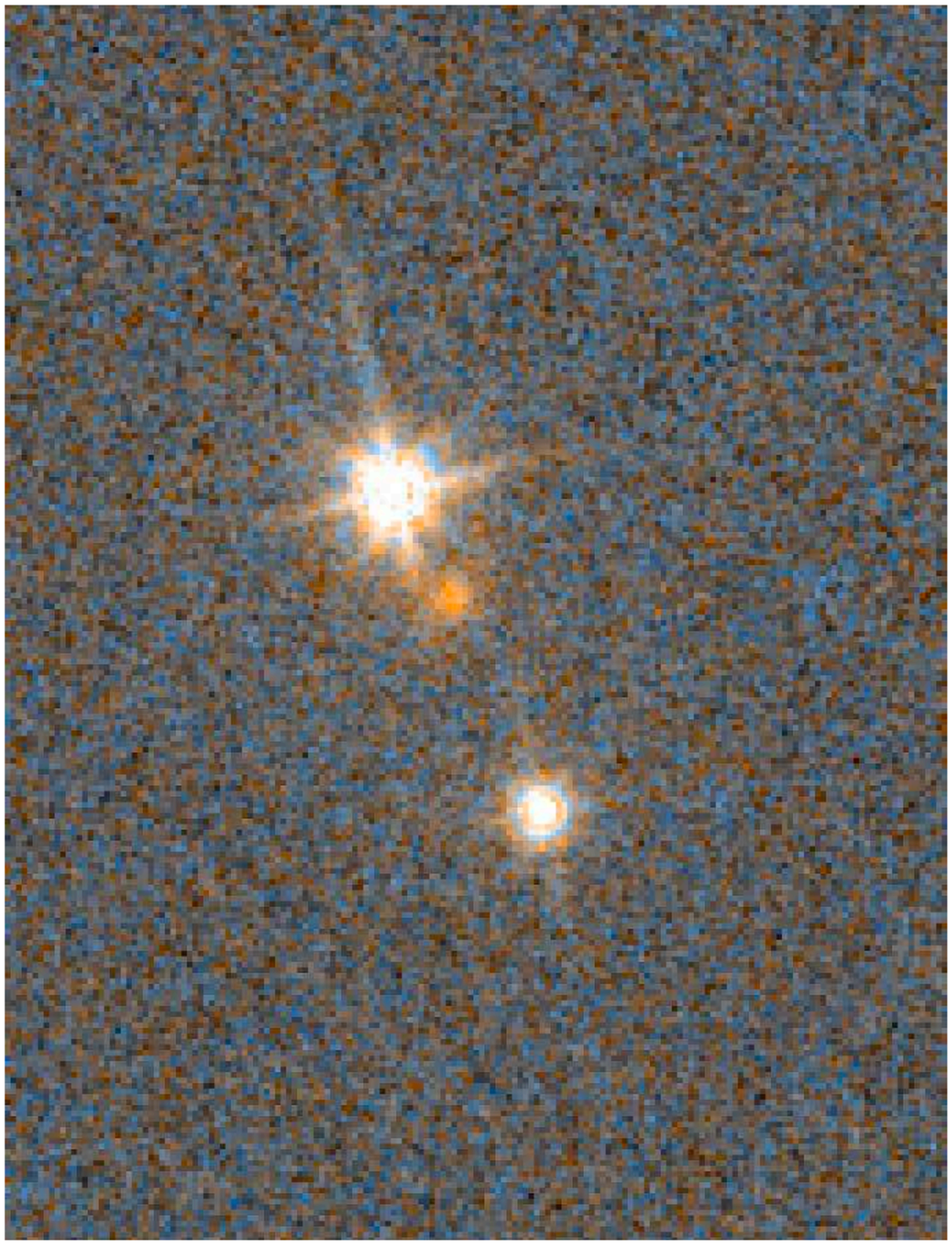
- OGLE detected a particular population of microlensing events:
  - 0.1 - 0.3 days light-curve timescale - origin unknown!
    Could be free-floating planets... or PBHs!





[Niikura, *Takada, Yokoyama, Sumi, Masaki* 2019]

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

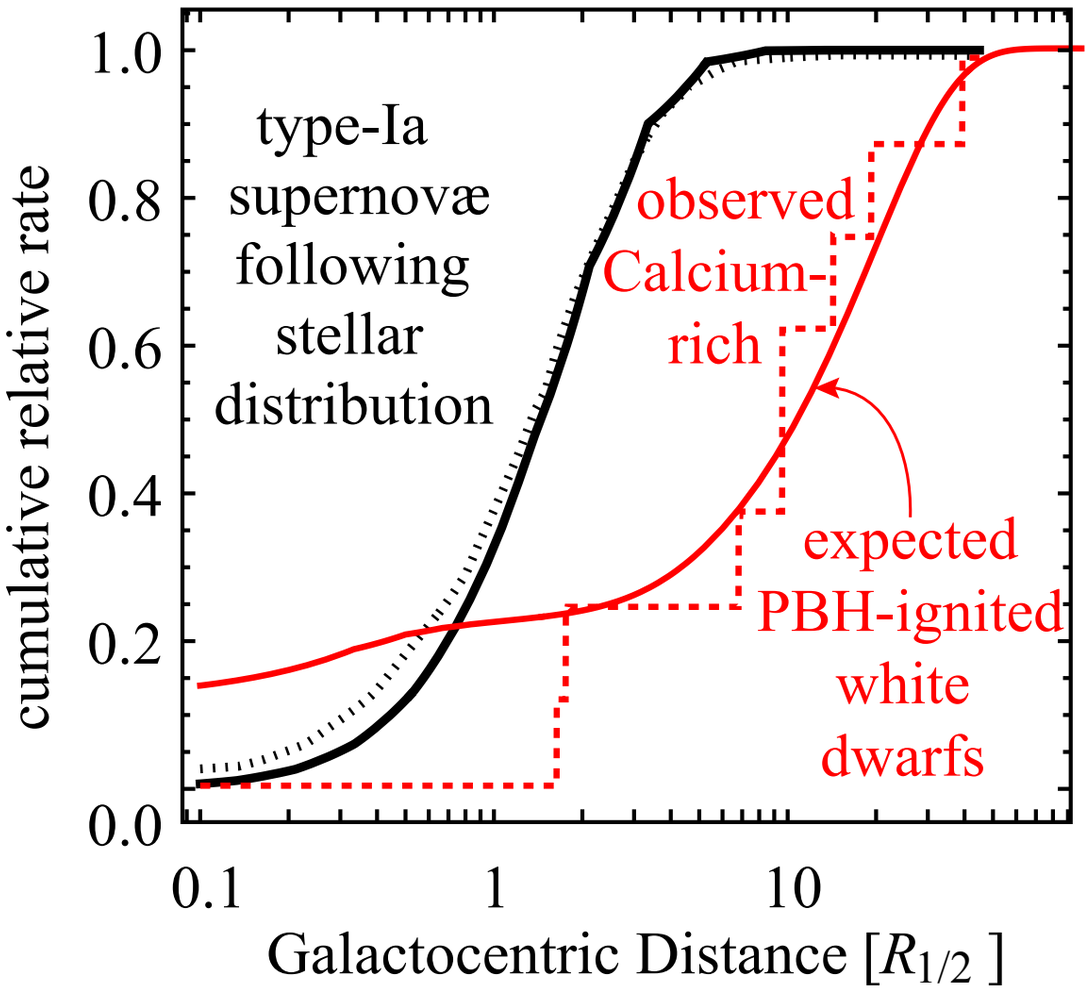
Institute for Astronomy (IfA), University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK
e-mail: mrsh@roe.ac.uk

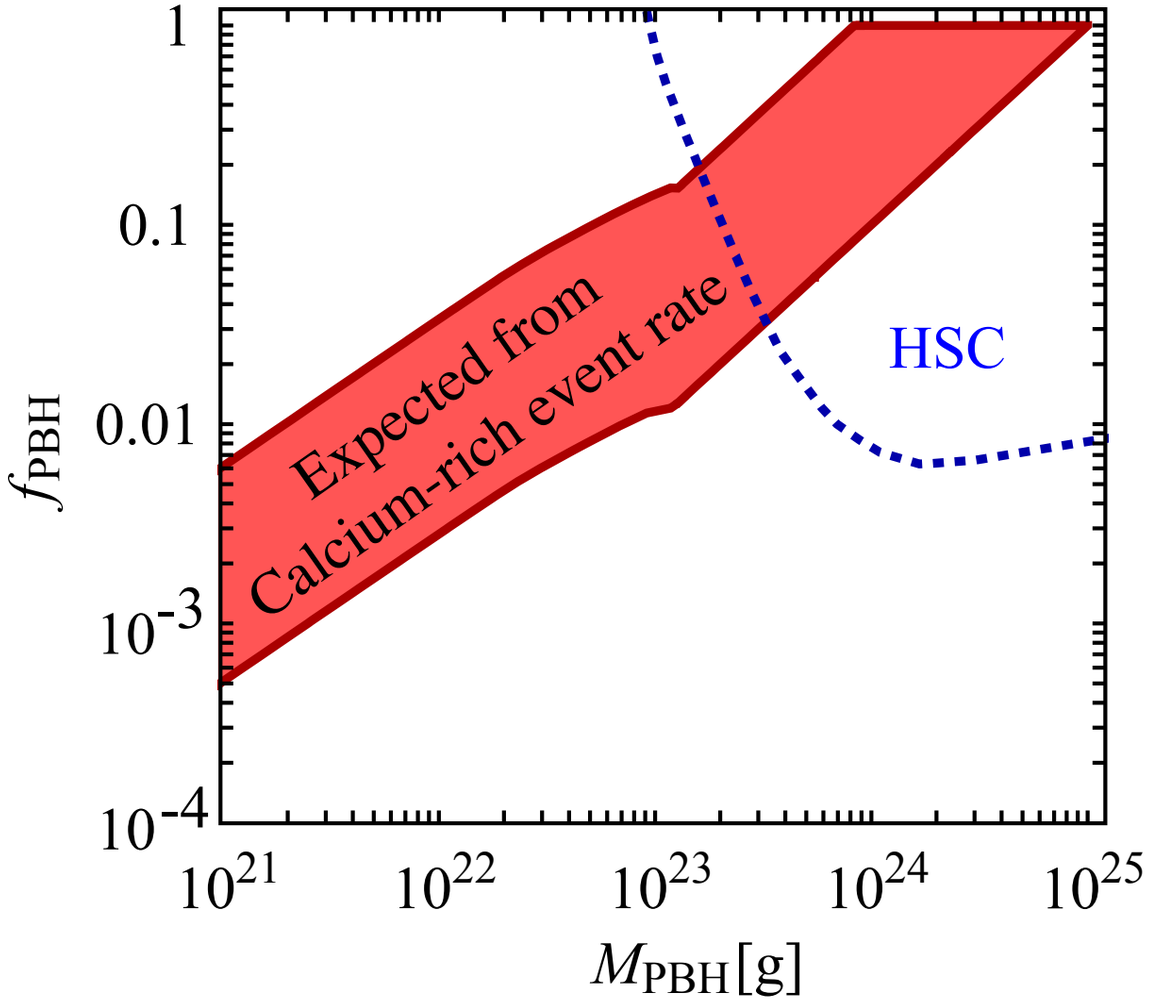
ABSTRACT

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.





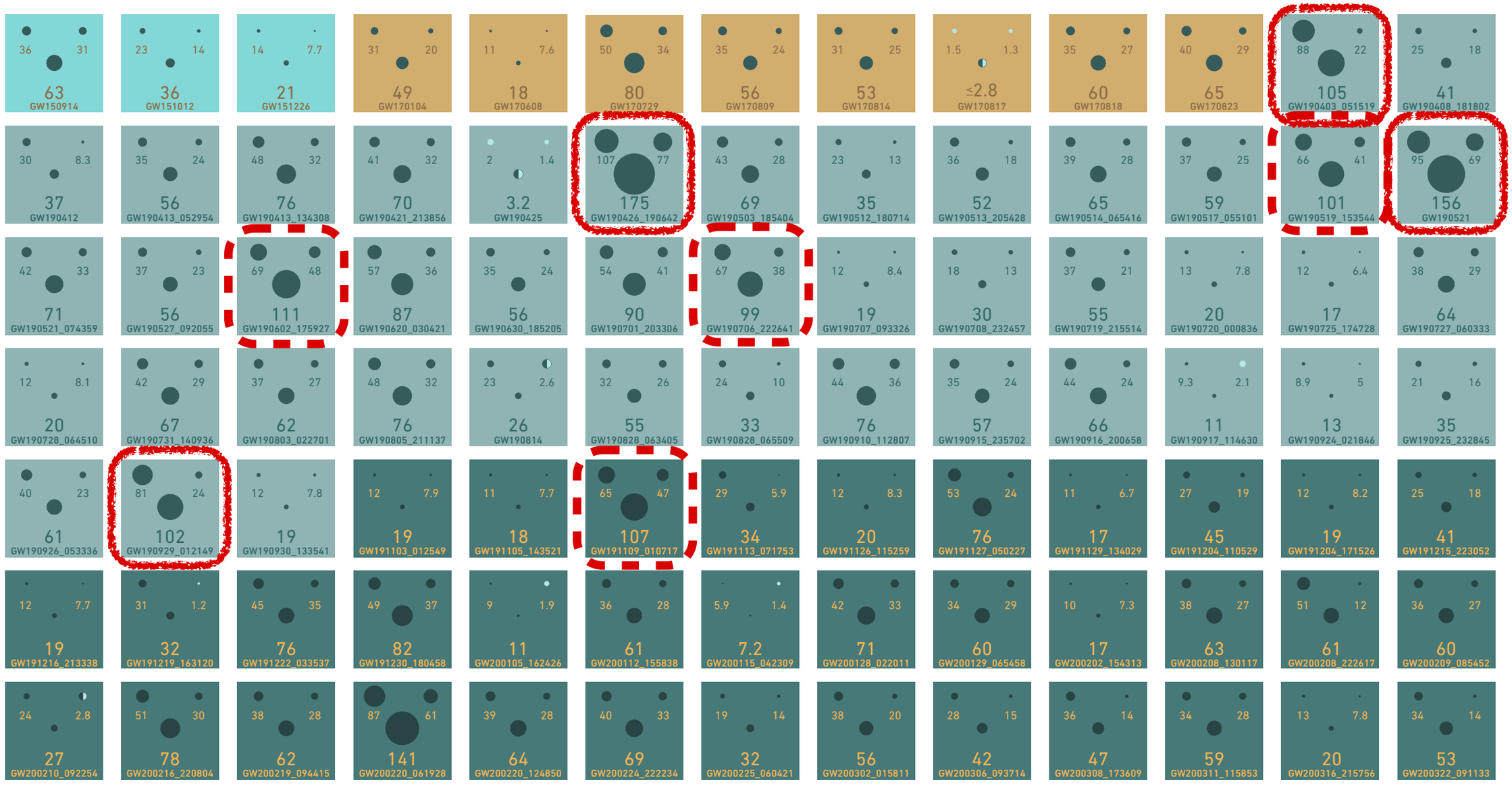
[Smirnov *et al.* 2023]

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 ~ 60 $M_\odot$)

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

[Phukon *et al.* 2021, Abbott *et al.* 2022]

★ 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!

Subsolar PBHs Discovered in the next 24 Months?

[Chris van den Broeck]

contra

pro

[me]

Subsolar PBHs Discovered in the next 24 Months?

[Chris van den Broeck]

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the wager

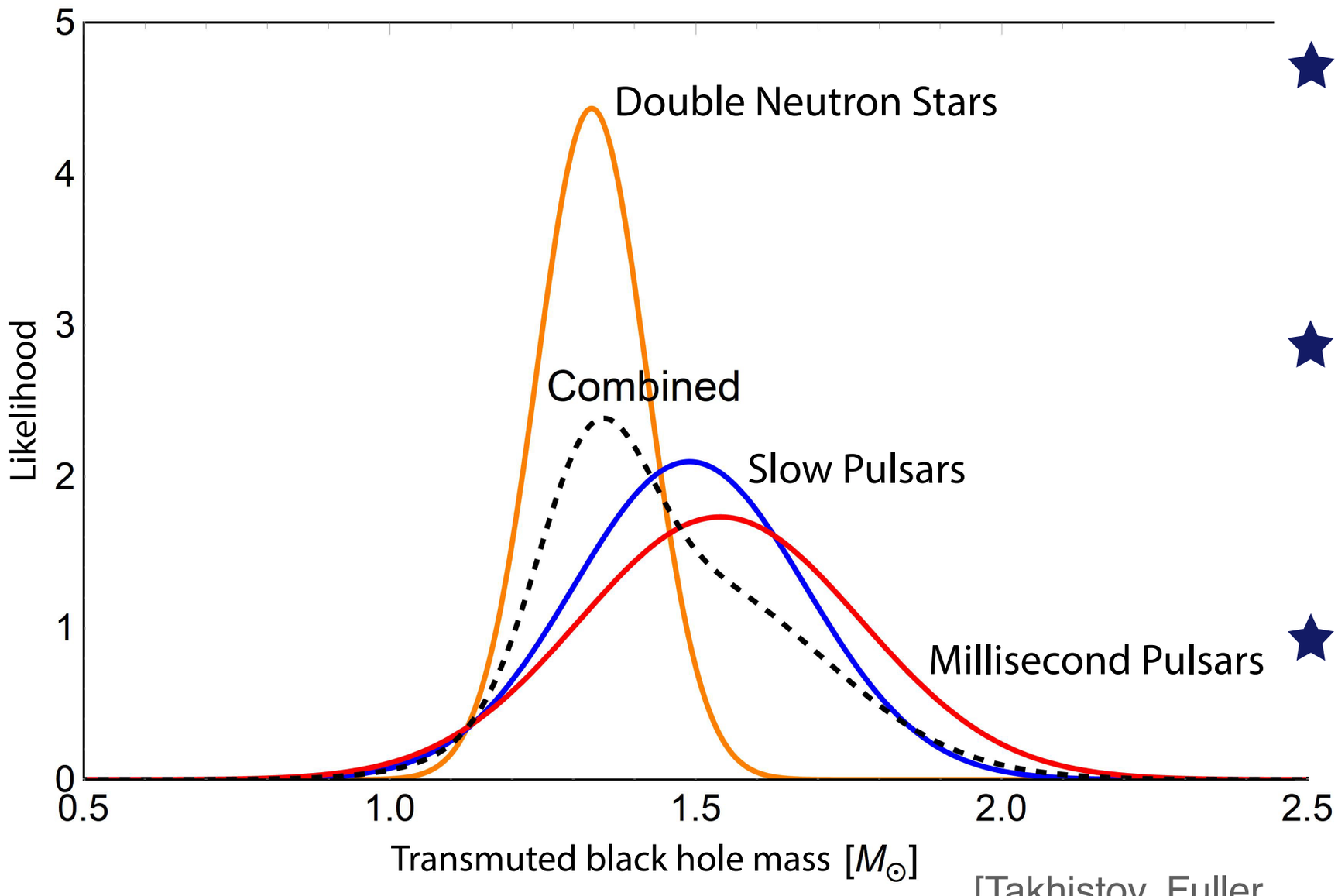
pro

[me]

More PBH Hints / Pieces of Evidence

- Correlations in CIR/CXR source-subtracted backgrounds
- High-redshift galaxies (up to $z \sim 13$)
- OGLE/Gaia microlensing events in the lower mass gap (also LVK)
- LVK asymmetric mergers
- HSC/Subaru pixel-lensing event in asteroidal mass range
- Minimum size of ultrafaint dwarf galaxies
- ...

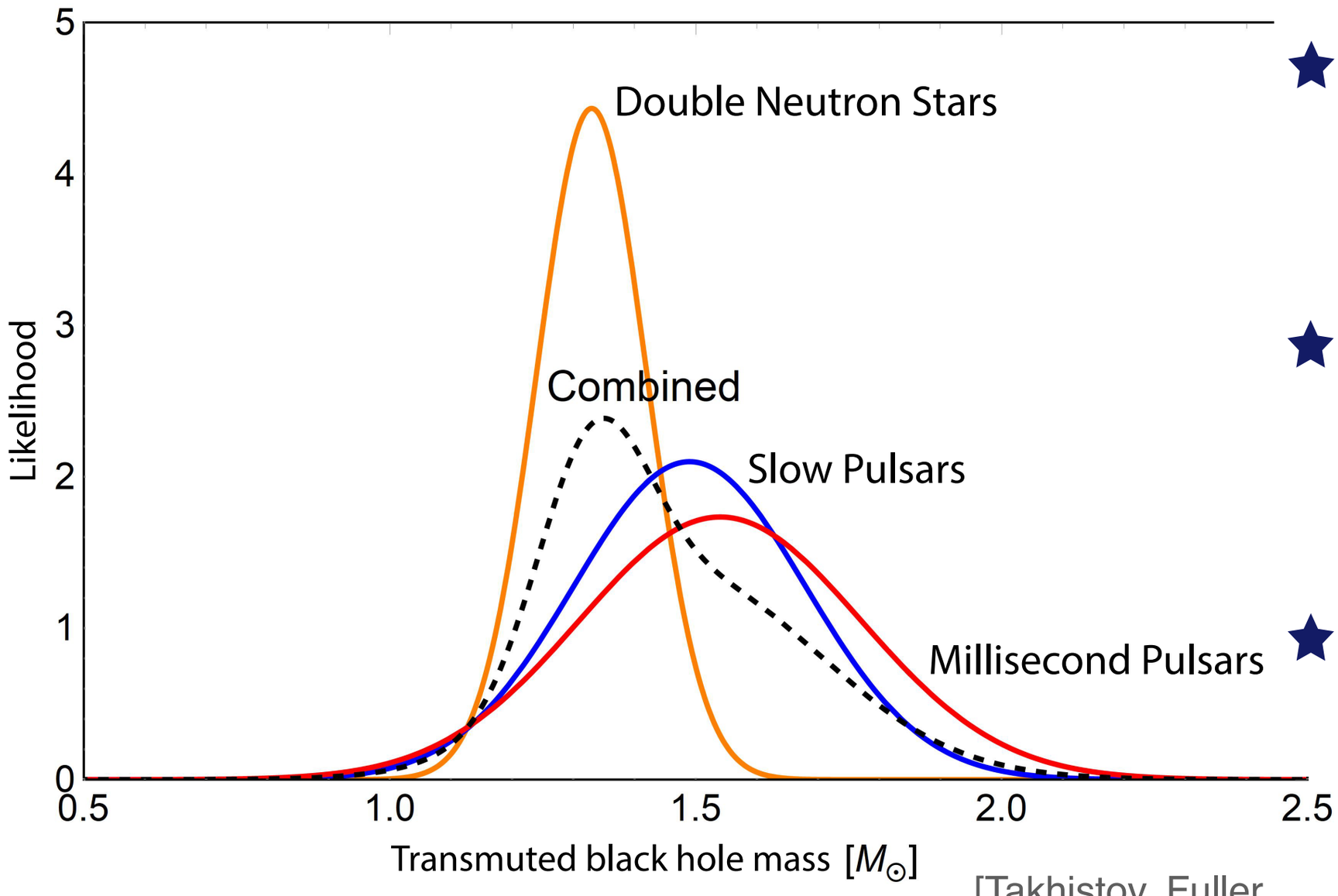
Transmuted Solar-Mass Black Holes



[Takhistov, Fuller, Kusenko 2017]

- Small PBH + Neutron Star = $\mathcal{O}(1)\,M_\odot$ black hole.
- Yields a characteristic mass distribution of black holes.
- This can explain all r-process elements in the Universe, including gold.

Transmuted Solar-Mass Black Holes



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★ Yields a characteristic mass distribution of black holes.

★ This can explain all r-process elements in the Universe, including gold.

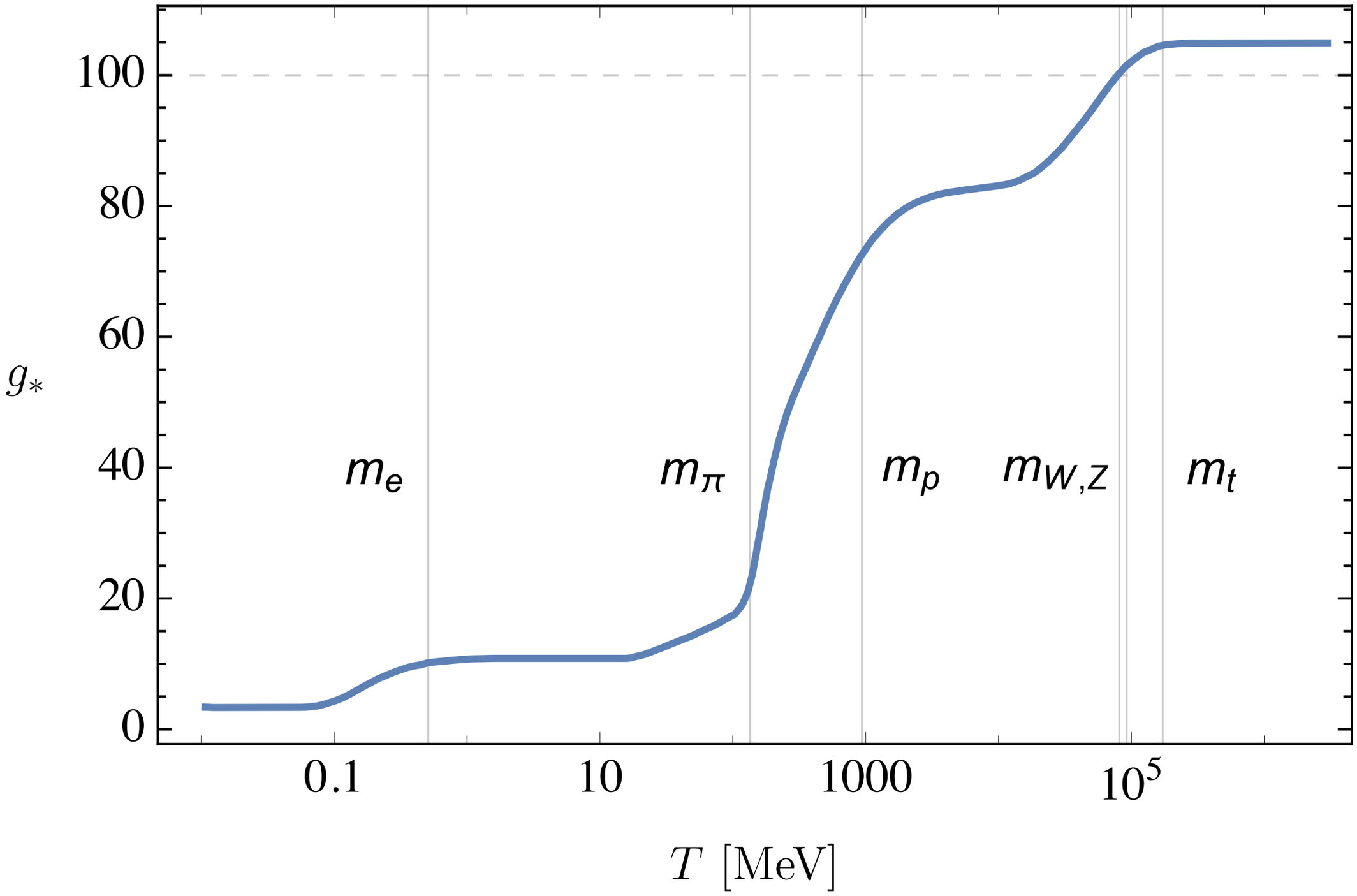
(... of which a single neutron star could generate up to 10 Earth masses $\sim 10^{30}$ GBP*).*

A Unified Scenario

*work with Carr, Clesse, García-Bellido

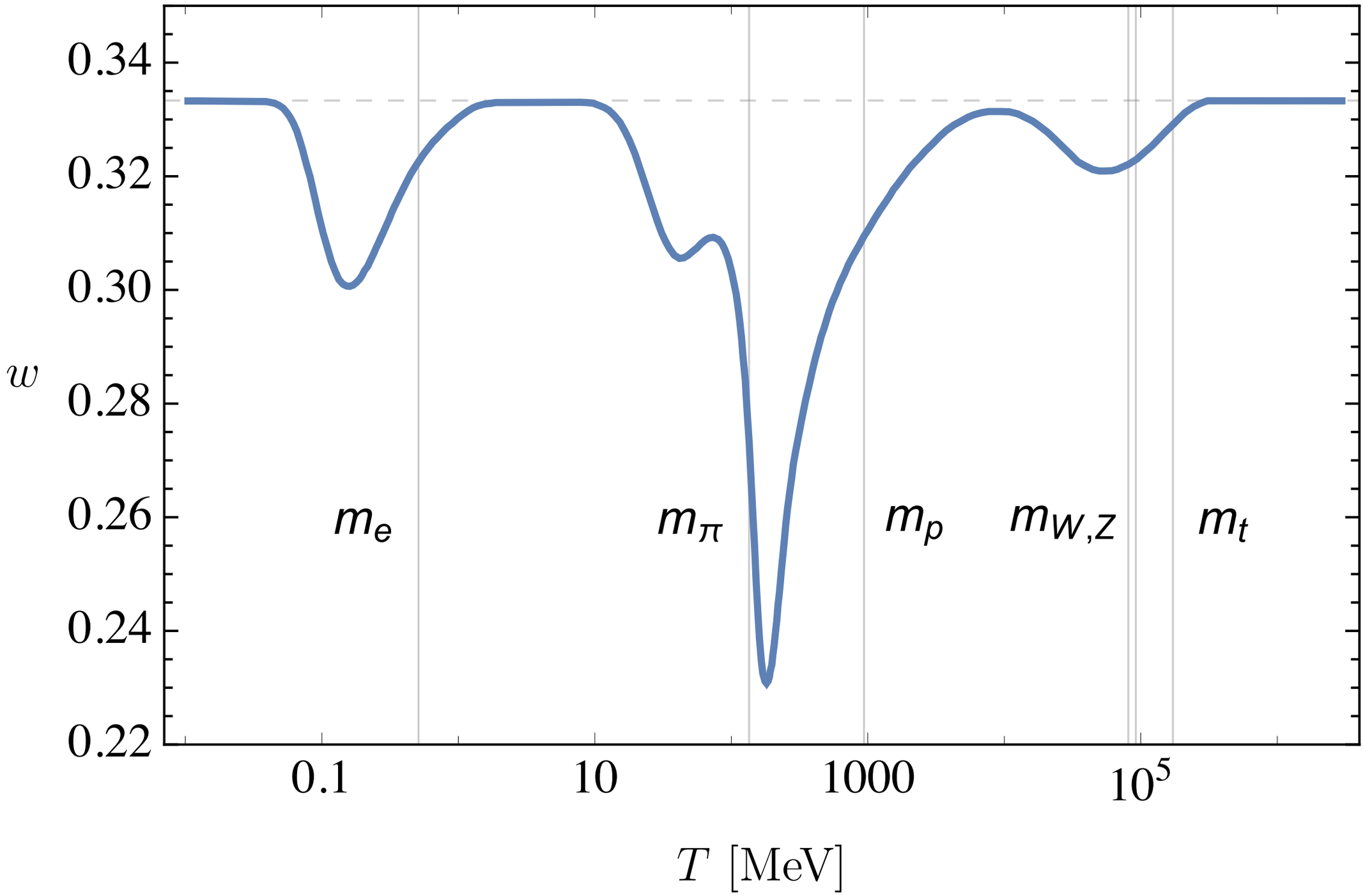
Thermal History of the Universe— Degrees of Freedom

★ 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:

$$\mathcal{P}(k) \sim k^{n_\mathrm{s}-1+\frac{1}{2}\alpha_\mathrm{s}\ln(k/k_*)}$$

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]

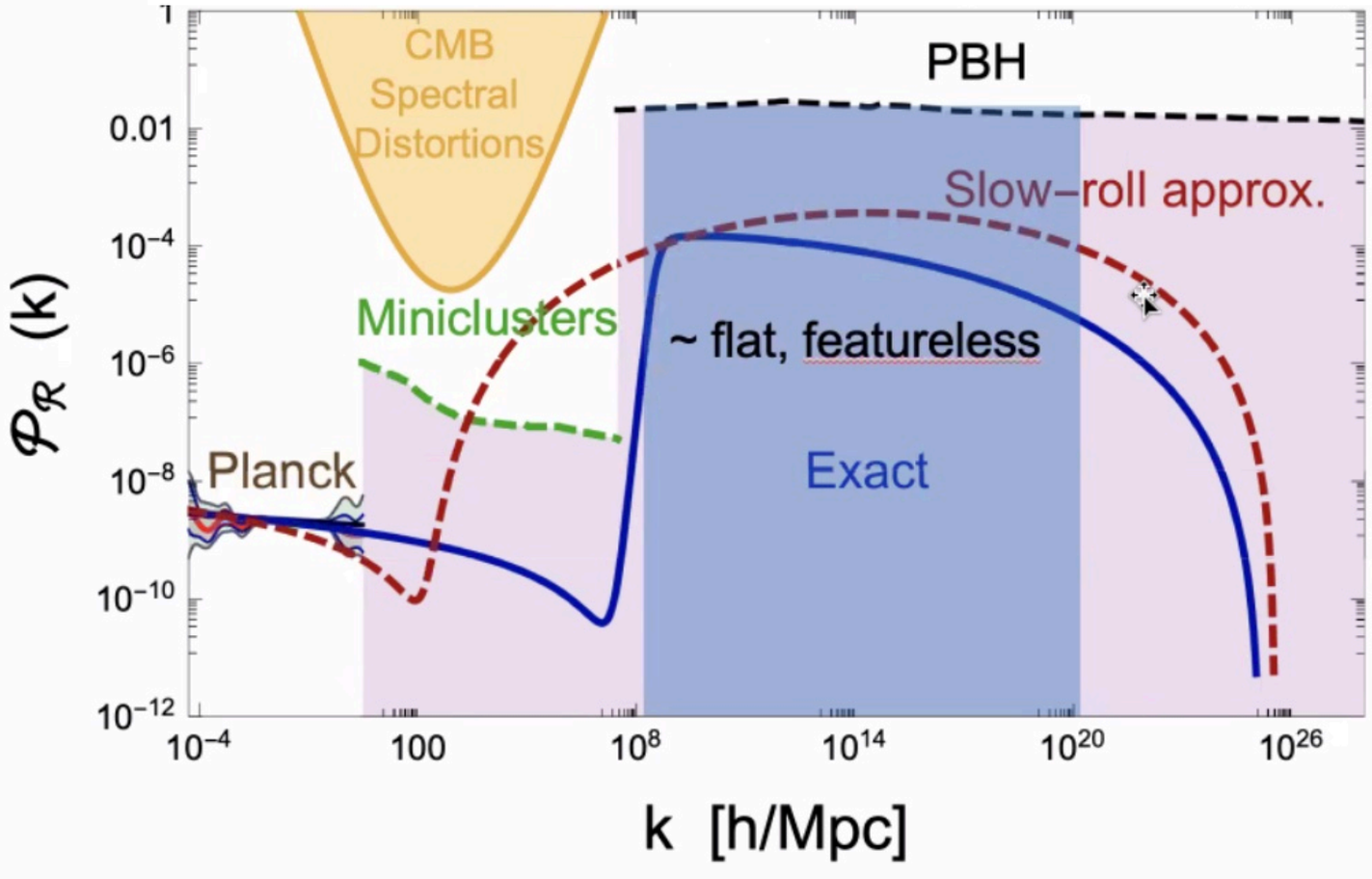
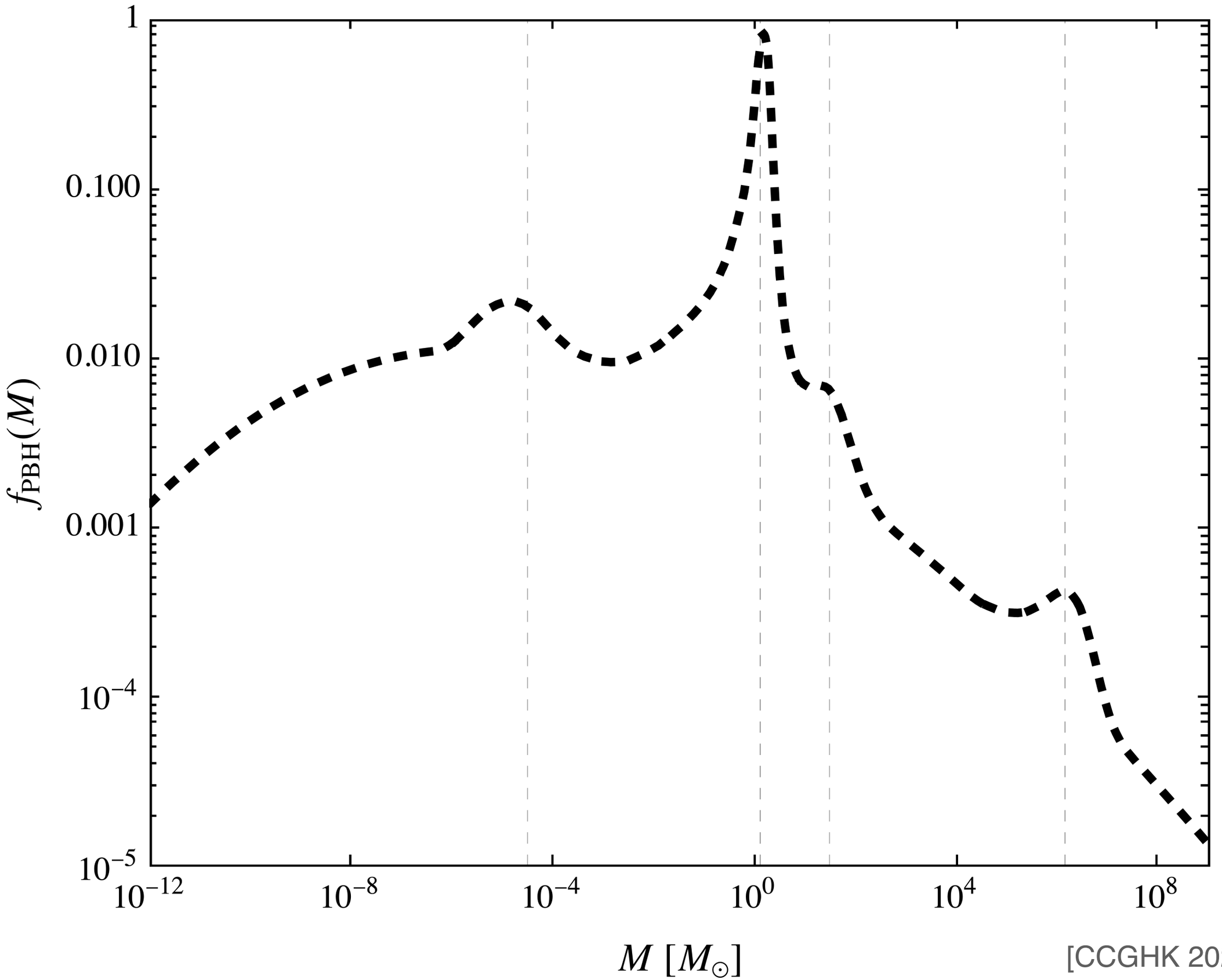


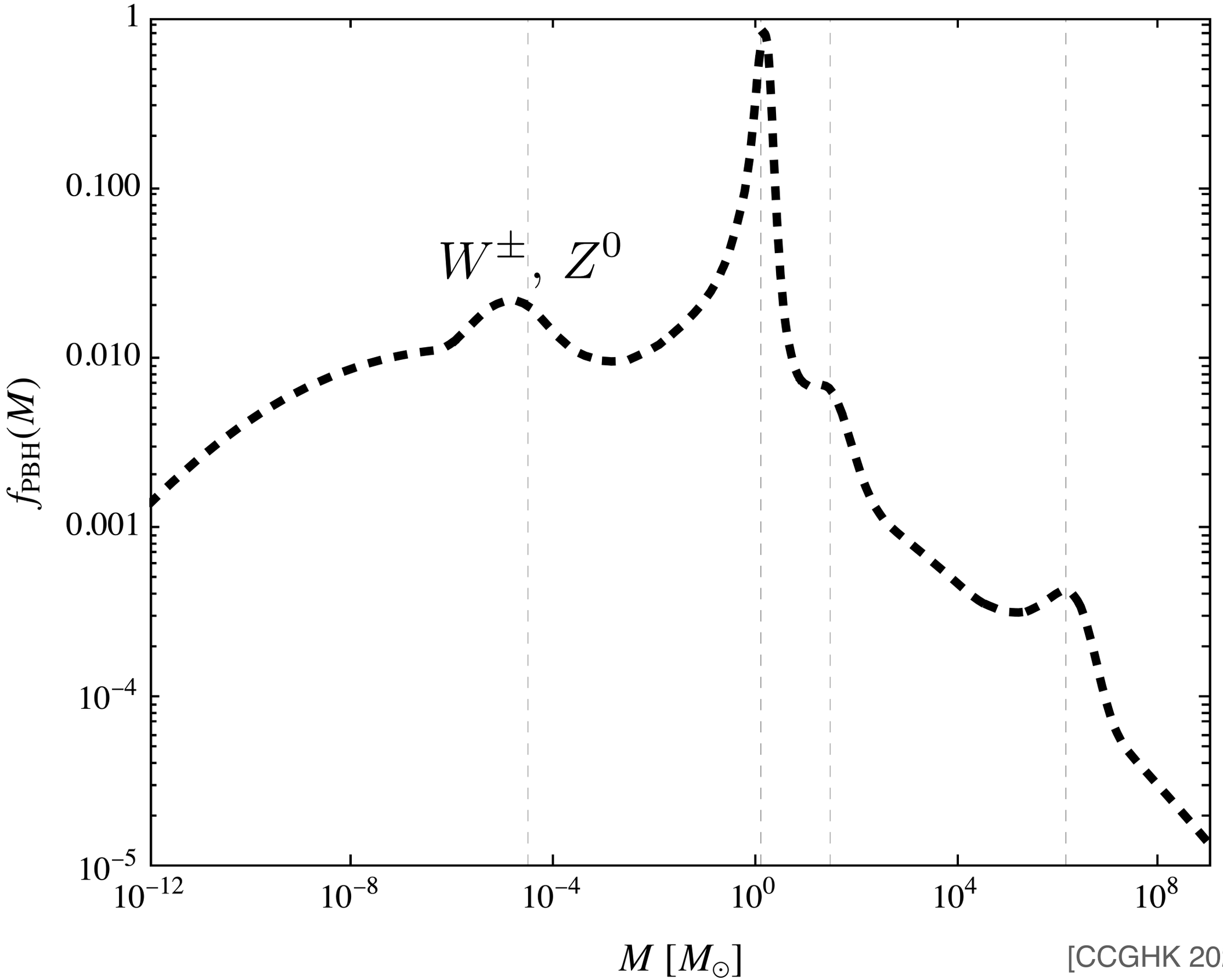
Figure from García-Bellido

PBH Mass Function



[CCGHK 2023]

PBH Mass Function



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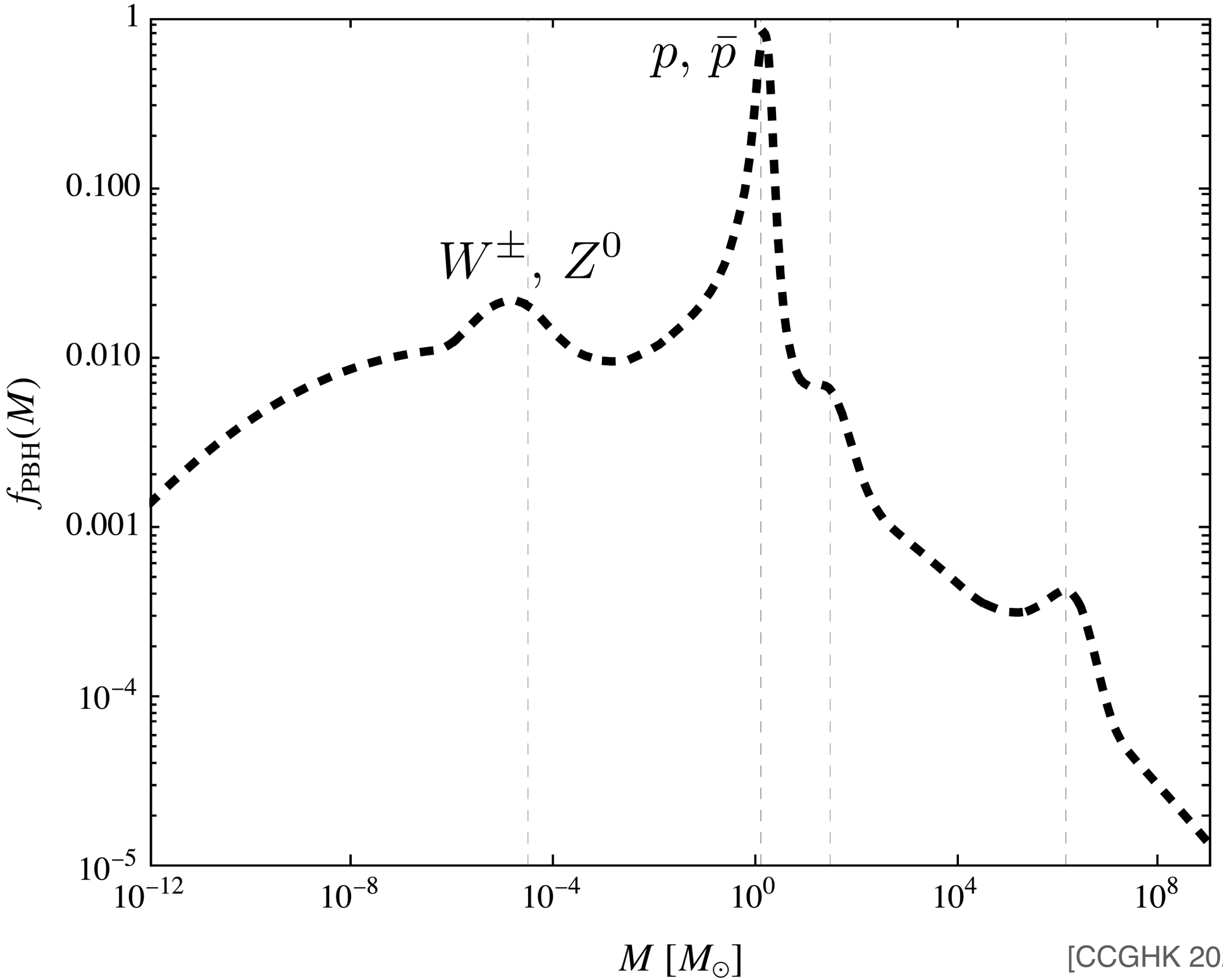

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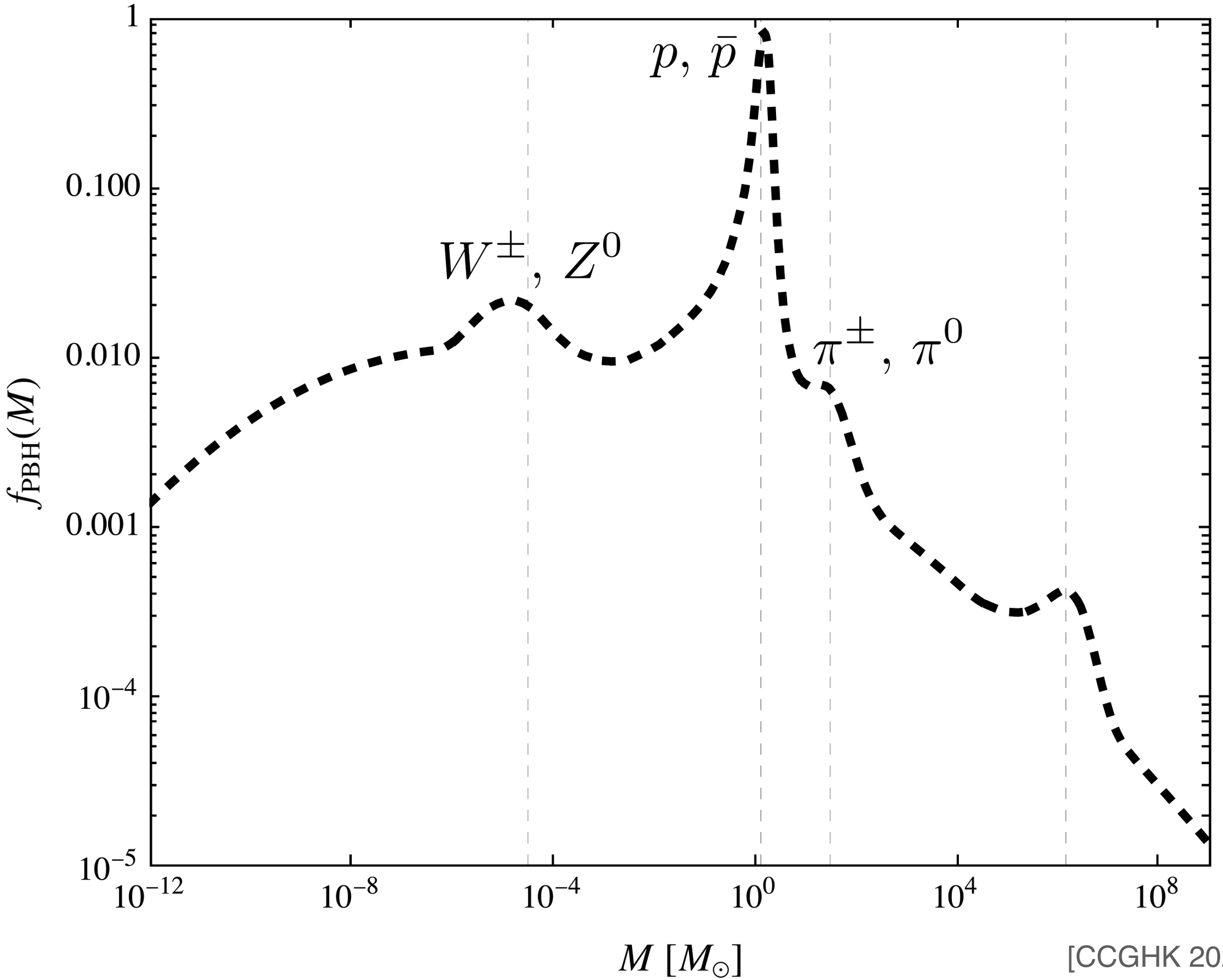

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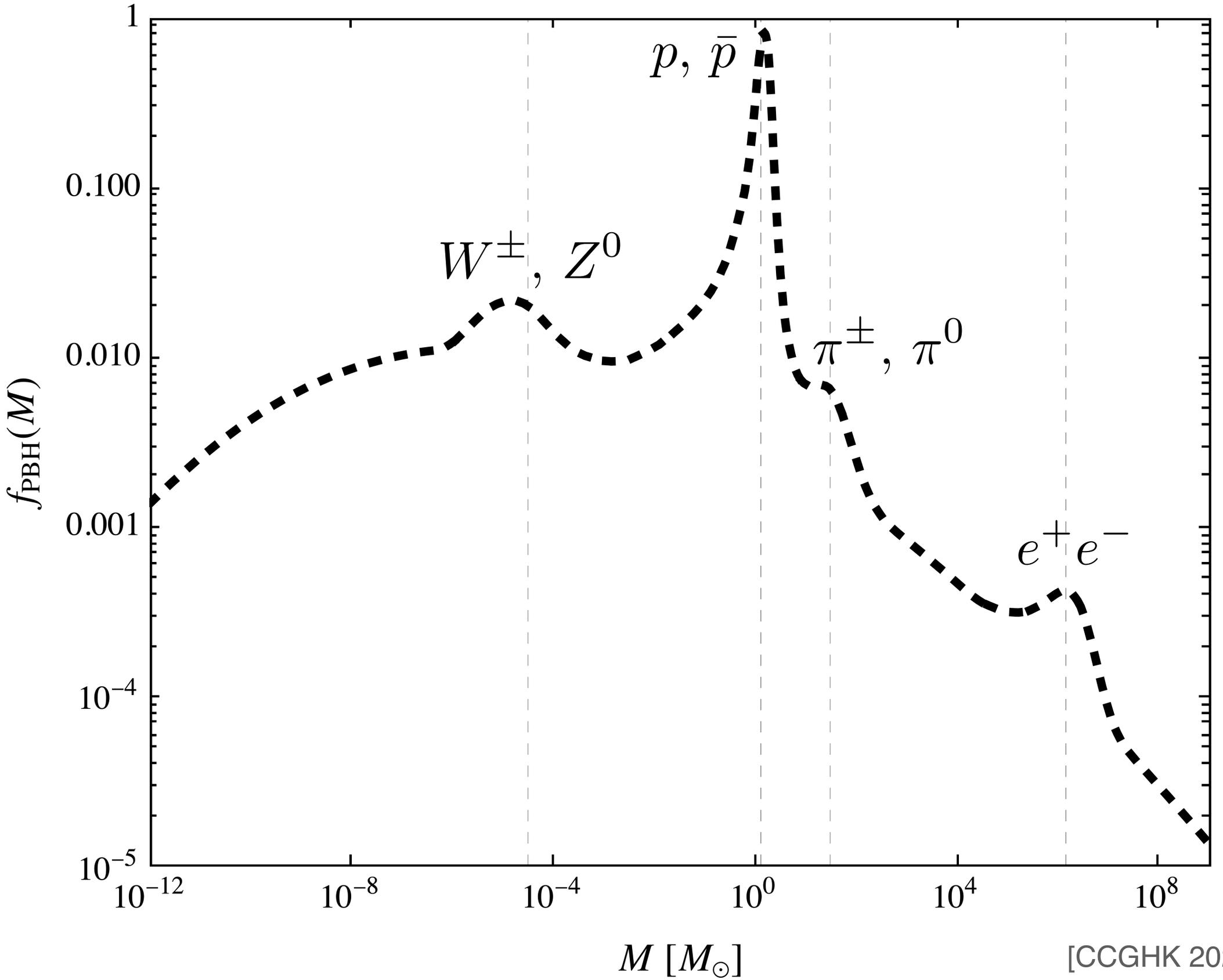

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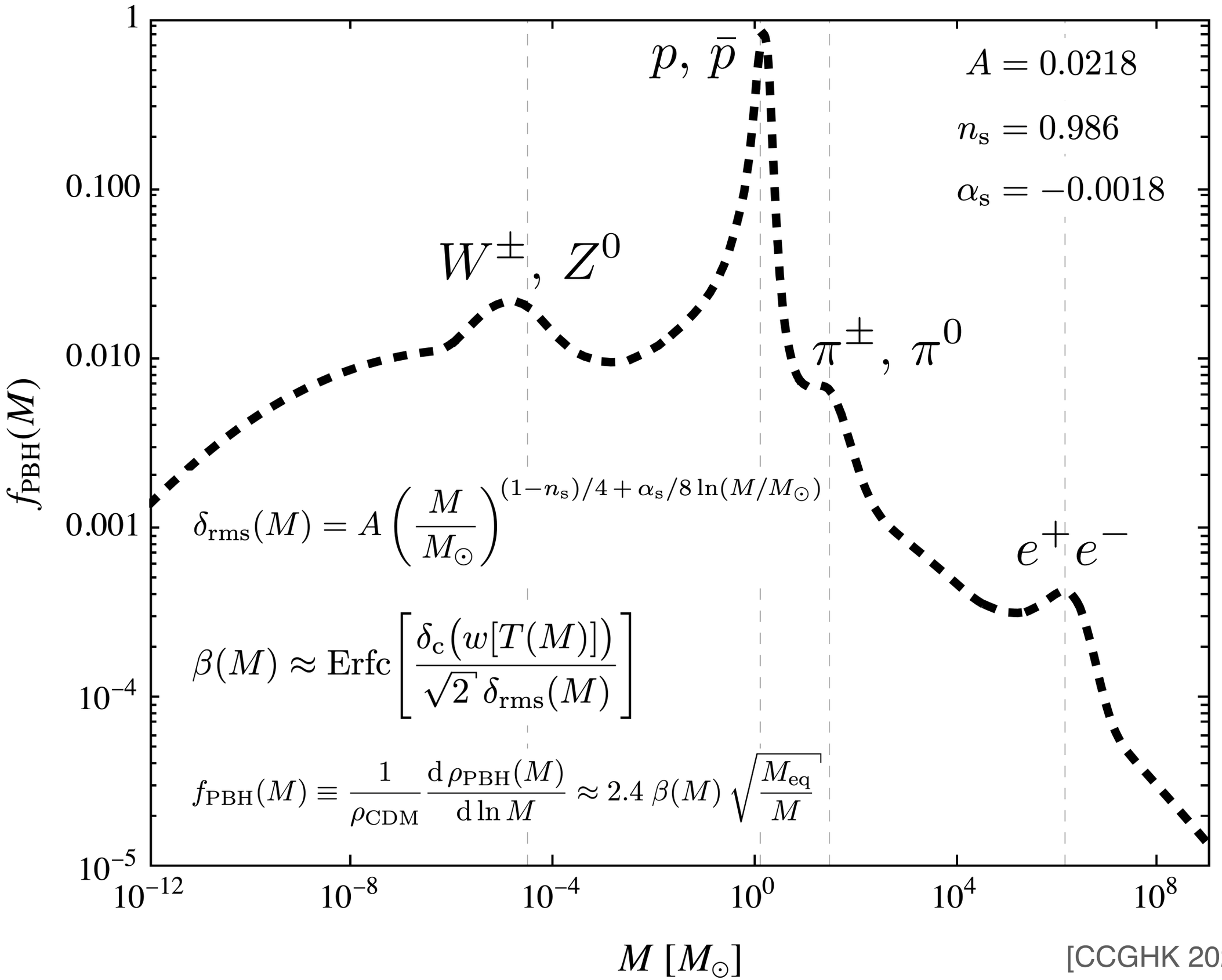
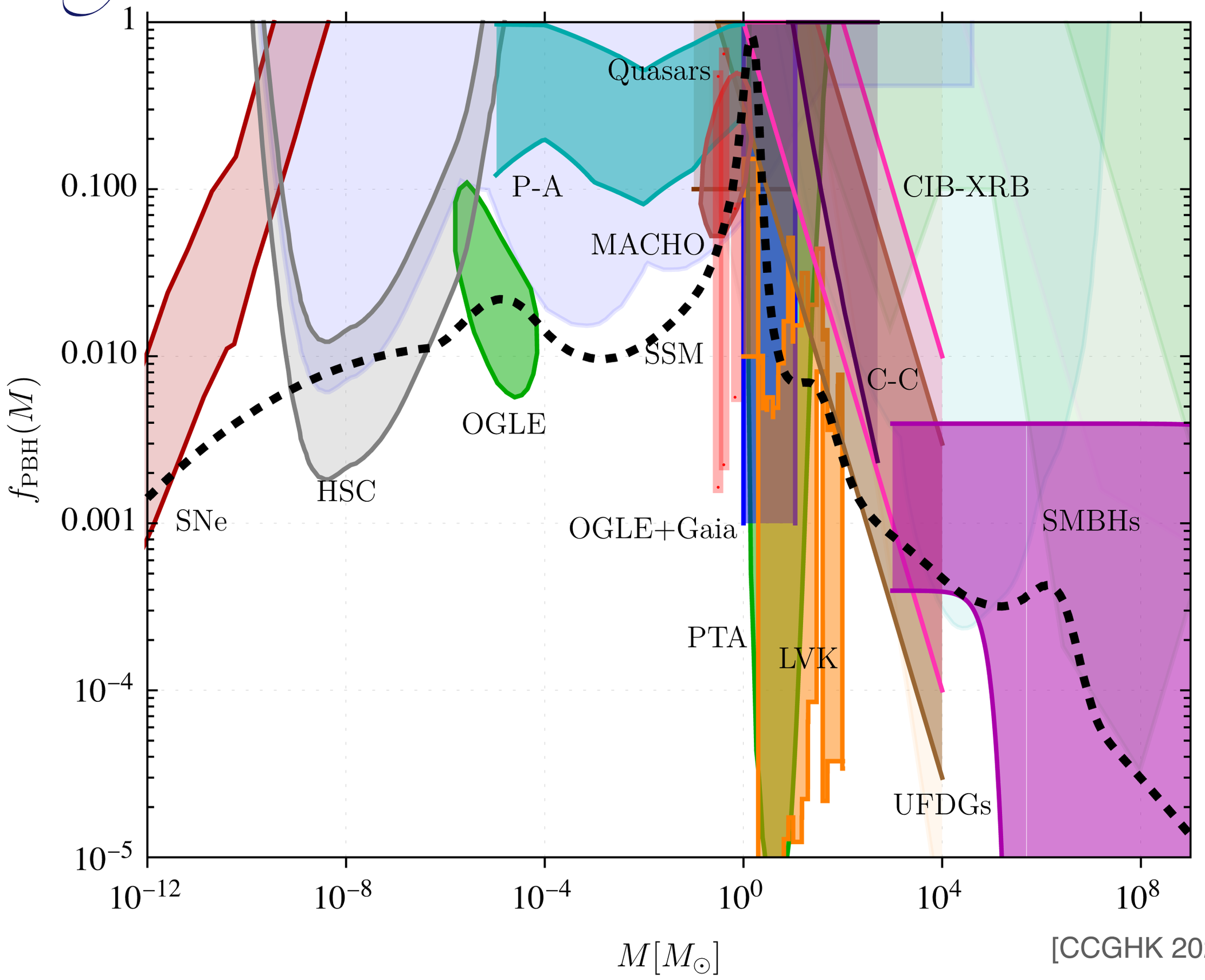


[CCGHK 2023]

Connecting all Positive Evidences!



[CCGHK 2023]

Shall Ye Become Positivists!

Physics Reports 1054 (2024) 1–68

Contents lists available at ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

Observational evidence for primordial black holes: A positivist perspective

B.J. Carr [a], S. Clesse [b], J. García-Bellido [c], M.R.S. Hawkins [d], F. Kühnel [e,*]

[a] School of Physics and Astronomy, Queen Mary University of London, United Kingdom
[b] Service de Physique Théorique, University of Brussels (ULB), Belgium
[c] Instituto de Física Teórica UAM/CSIC, Universidad Autonoma de Madrid, Spain
[d] Department of Physics and Astronomy, University of Edinburgh, United Kingdom
[e] Max Planck Institute for Physics, Germany

Quantum Quiddity

*see talks by Thoss and Zantedeschi

Quantum Aspects

- ★ Black Holes can be understood as *saturons*, ie. configuration of maximum entropy *compatible with unitarity* (cf. work by *Dvali*).

- ★ Black holes evaporation *leaves the semi-classical regime* at latest at half-mass, possibly much earlier (see *Thoss'* talk).

- ★ This results in inevitable *deviations from thermality* and *entropy-suppressed evaporation rate*, opening up a large mass range for *ultra-light PBHs* as (quasi) remnants! (see *Thoss'* talk).

Quantum Aspects

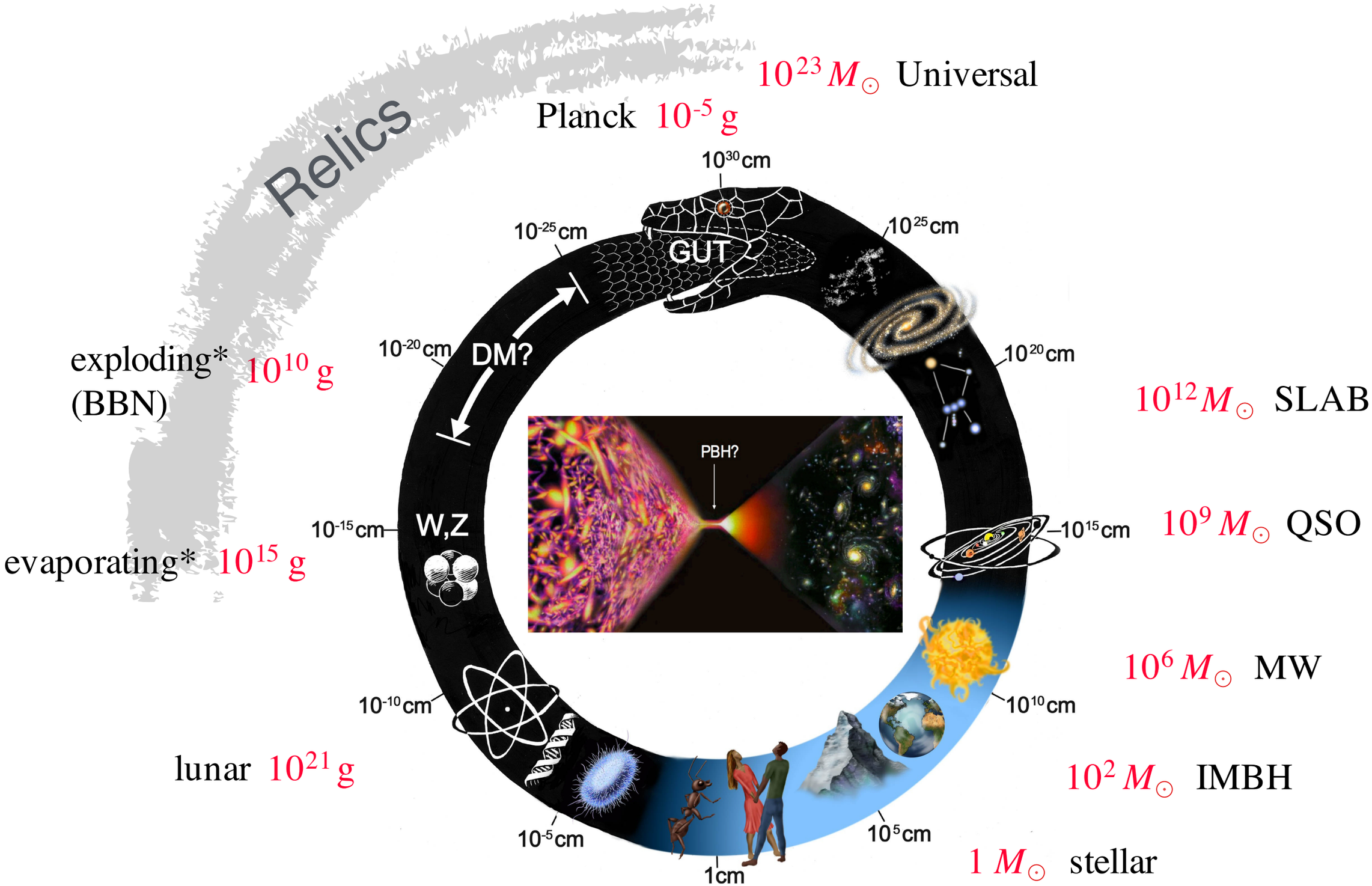
- ★ Furthermore, we showed that (near-)extremally-spinning black holes admit vortex structure (*Dvali, Kühnel, Zantedeschi*) (*see talk by Zantedeschi*).

- ★ *PBHs from confinement* (*Dvali, Kühnel, Zantedeschi*) could provide ideal prerequisites for vortex formation due to highly spinning light PBHs.

- ★ If these PBHs provide the dark matter, their vorticity might explain primordial magnetic fields.

- ★ Besides, vorticity provides a topological meaning to the stability of extremal black holes.

Black Holes as a Link between Micro and Macro Physics



[Bernard Carr]

*Image of snake from Abrams & Primack 2012

Black Holes & Cosmology 2024

International Conference

11th to 15th of March 2024

University of The Bahamas, Nassau

Opening Talk by Nobel Laureate

Professor Reinhard Genzel

Public Lecture by

Professor Matt Caplan

Professor Matt Caplan

Confirmed Invited Speakers include:

Andreas Albrecht
Earl Bellinger
Gianfranco Bertone
Alessandra Buonanno
Andreas Burkert
Nico Cappelluti
Bernard Carr
Gia Dvali
Glennys Farrar
Juan García-Bellido
Reinhard Genzel
David Kaiser
Will Kinney
Sasha Kashlinsky
Michela Mapelli
Emil Mogola
Samaya Nissanke
Remo Ruffini
Ravi Sheth
Subir Sakar
Lárus Thorlacius

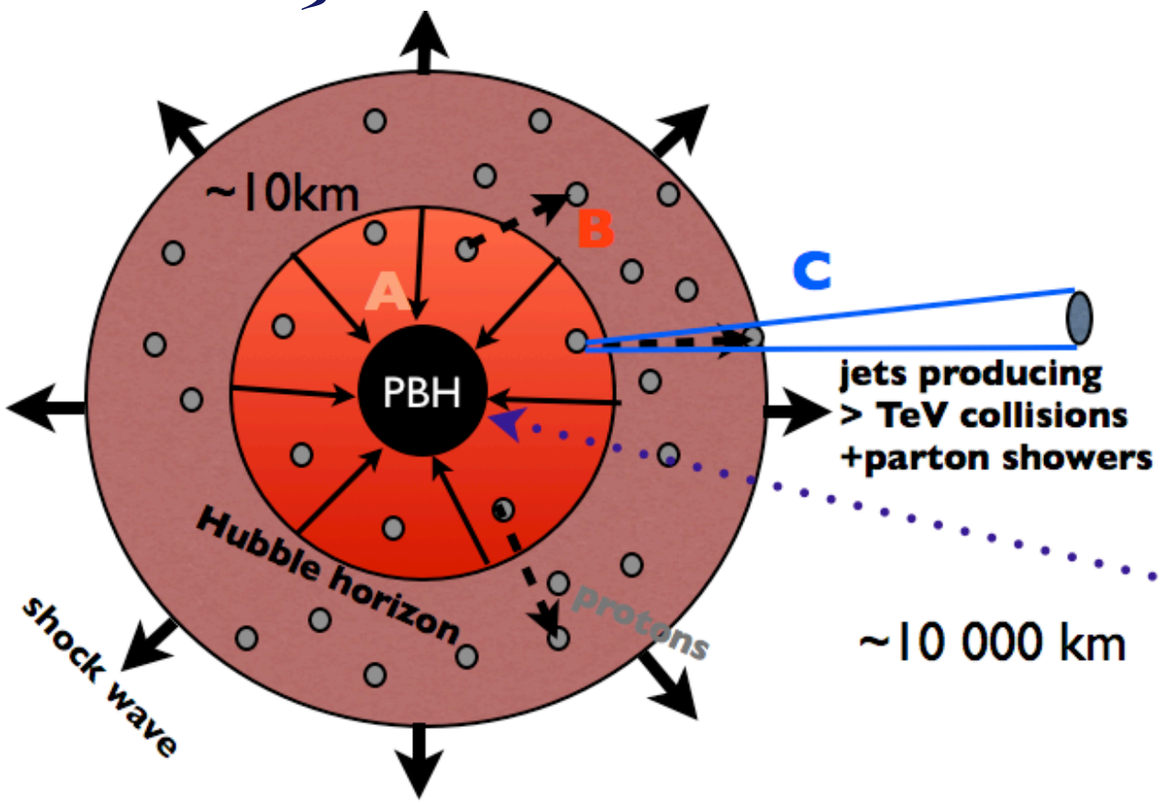
Organisational Committee:

Florian Kühnel (Chair), Jaco de Swart, Katherine Freese, Pandora Johnson, Eduardo Guendelman, Claude McNamarah, Remo Ruffini, Carlton Watson

See you at BHCos '26!

Appendices

Primordial Supernovae

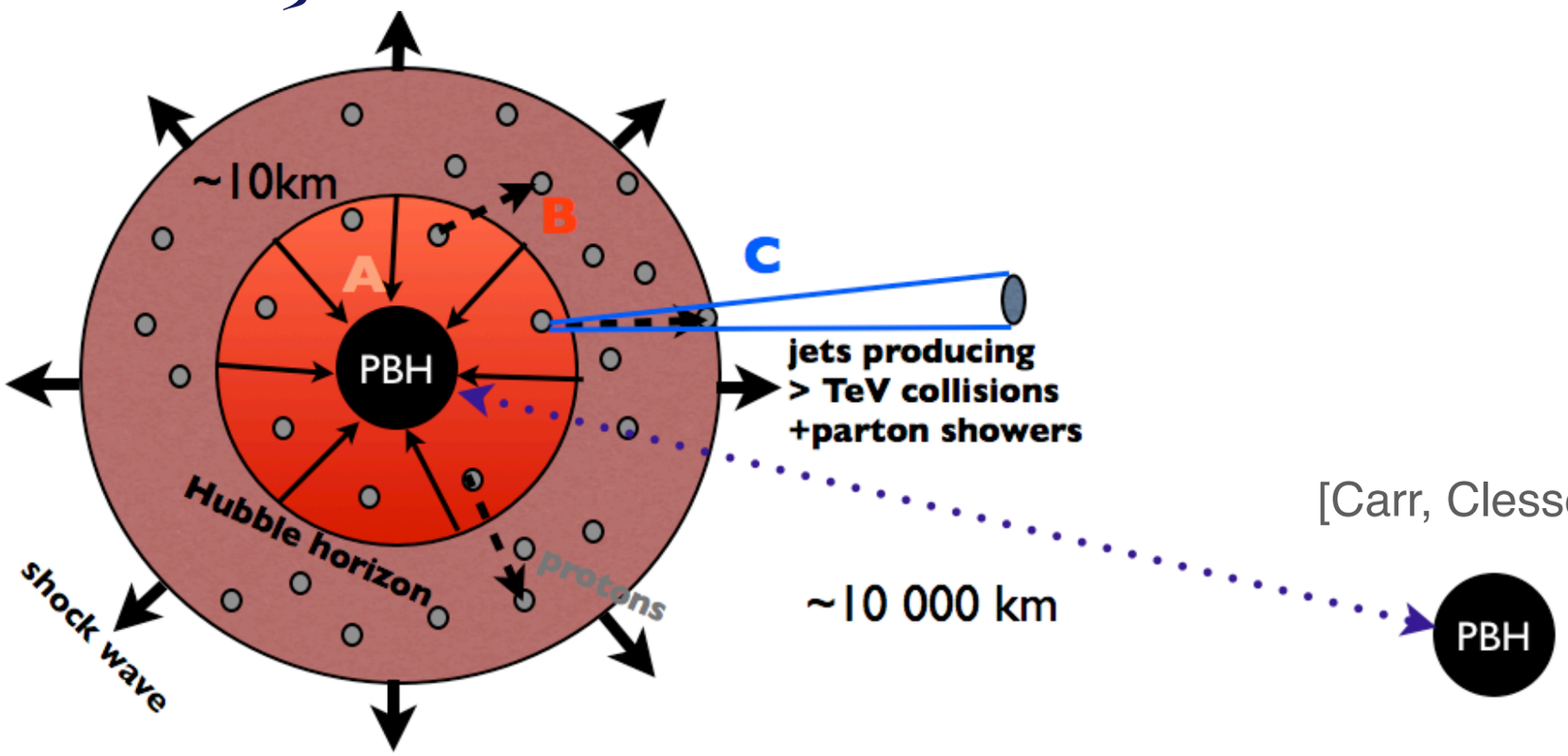


[Carr, Clesse, García-Bellido 2020]

~10 000 km

PBH

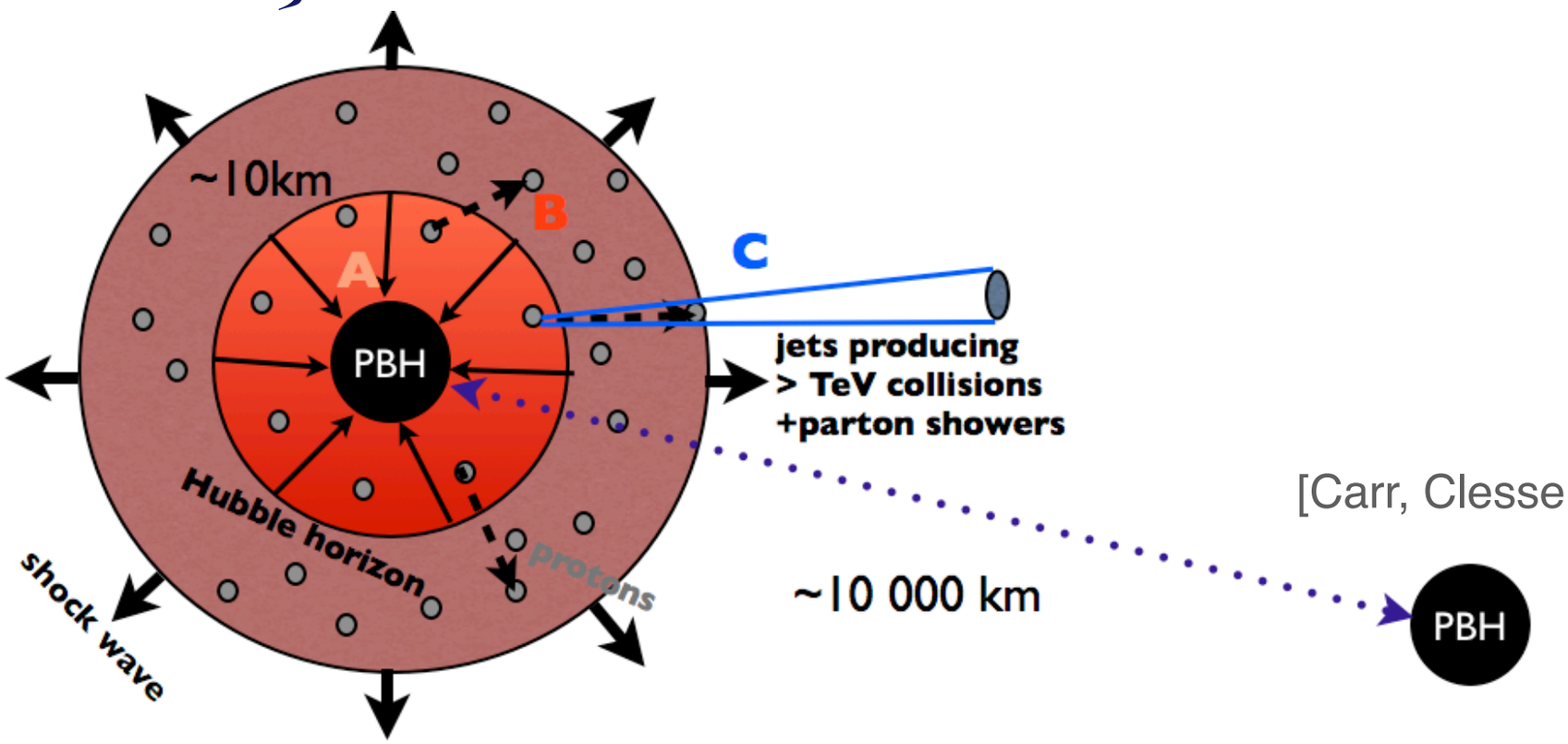
Primordial Supernovae



[Carr, Clesse, García-Bellido 2020]

★ PBH collapse during the QCD transition accelerates particles over several orders of magnitude above their rest mass.

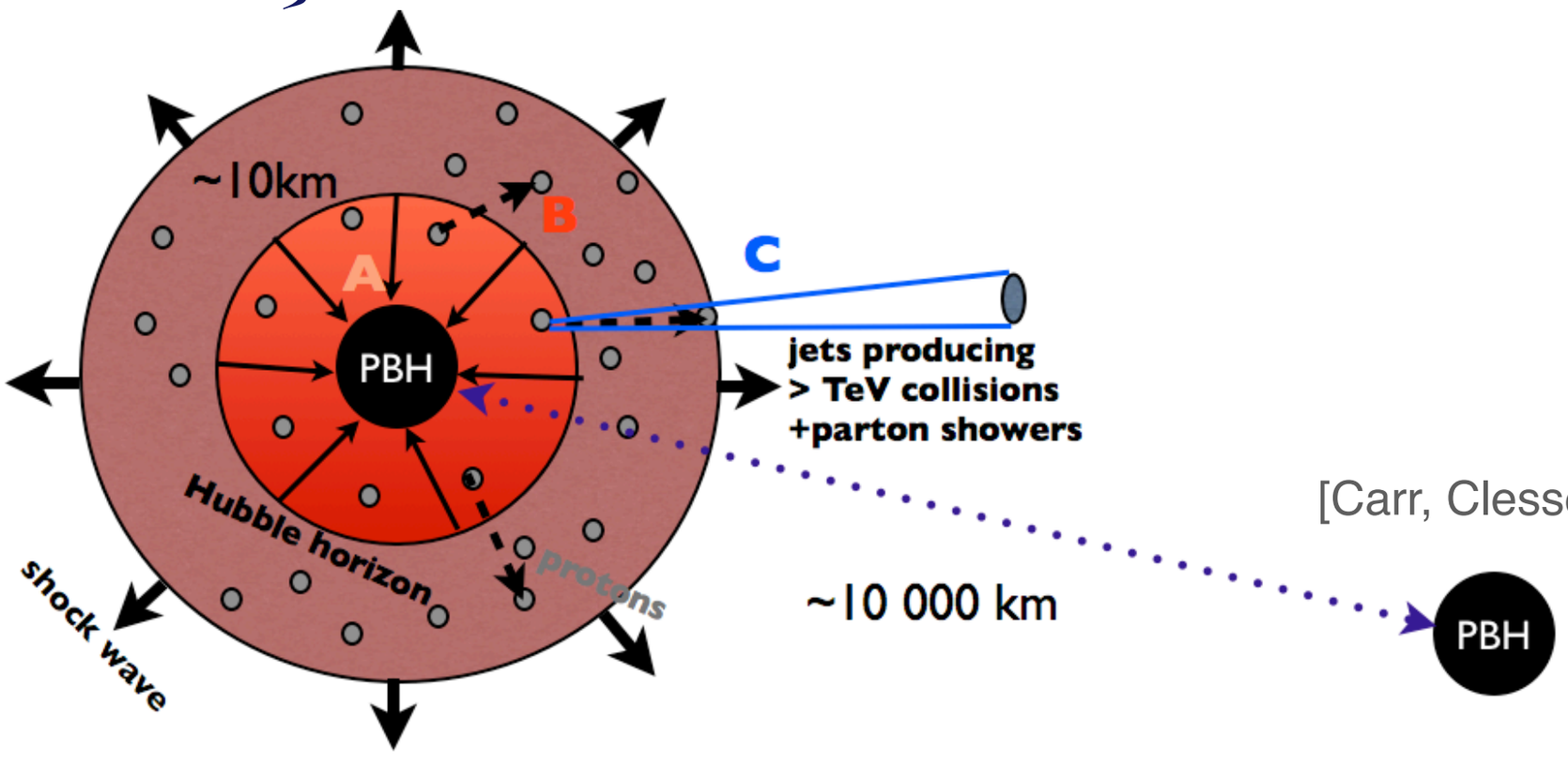
Primordial Supernovae



[Carr, Clesse, García-Bellido 2020]

- PBH collapse during the QCD transition accelerates particles over several orders of magnitude above their rest mass.
- Interactions in the surrounding high-density plasma lead to electro-weak sphaleron processes.

Primordial Supernovae



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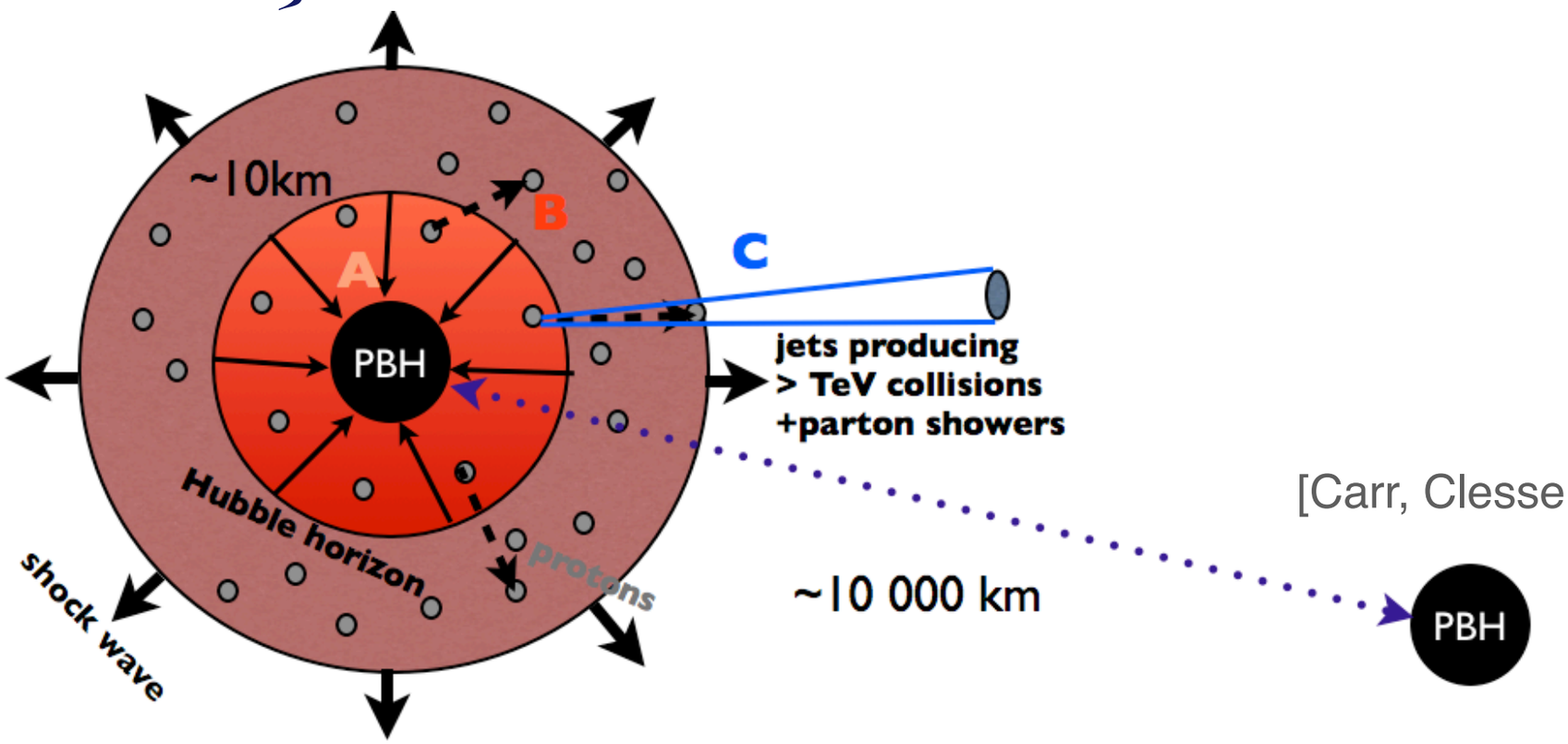
- This *locally* yields an $\mathcal{O}(1)$ baryon asymmetry.

Primordial Supernovae



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- ★ Interactions in the surrounding high-density plasma lead to electro-weak sphaleron processes.
- ★ This *locally* yields an $\mathcal{O}(1)$ baryon asymmetry.
- ★ The fraction of PBHs 10^{-9} in turn explains the observed baryon asymmetry of the Universe!

Primordial Black Holes from Confinement

*work with Dvali and Zantedeschi

Important Issues

★ The standard approach of PBH formation has two main issues:

★ In order to have a given percentage of PBH dark matter requires exponential fine-tuning.

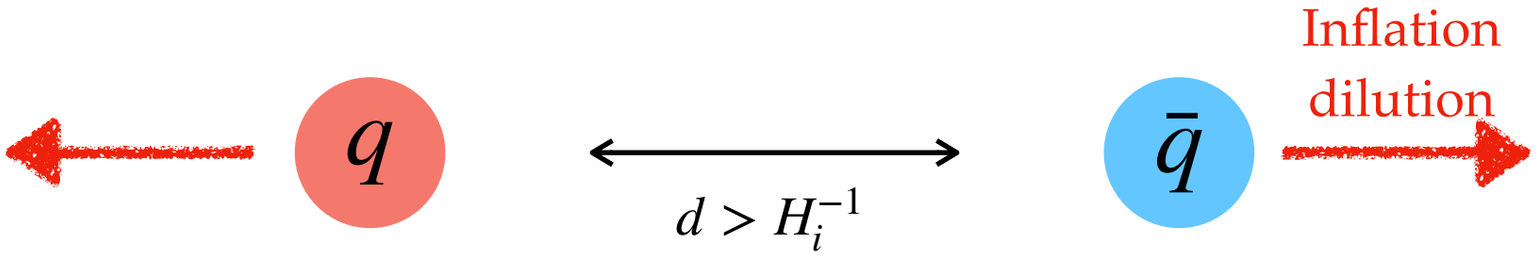
★ PBH formation happens in the strong-coupling regime.

A New Approach

- We propose a novel PBH formation mechanism which is
  - assumption-minimal,
  - free of exponential fine-tuning,
  - avoids strong coupling,
  - works with standard QCD*,
  - compatible with observations.

Confinement Formation Mechanism

★ **1. Ingredient:** de Sitter fluctuations produce quarks during inflation.



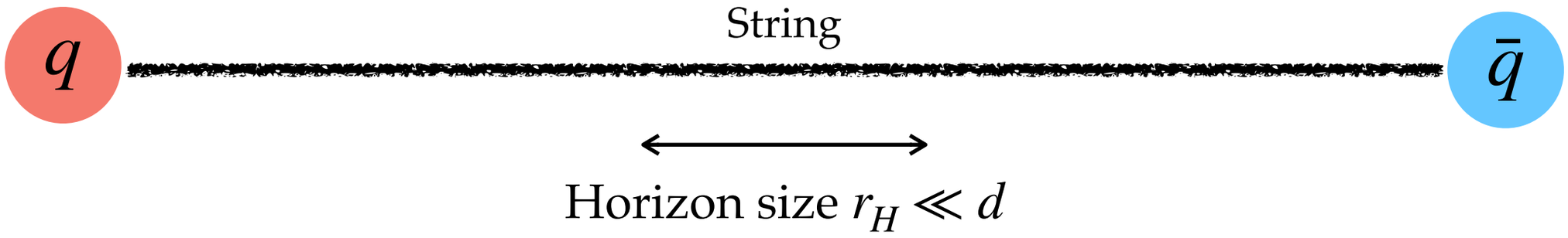
★ Focus on a simple pair case.

★ Distance grows as $d \propto e^{N_e}$.

★ Quarks quickly move out of causal contact.

Confinement Formation Mechanism

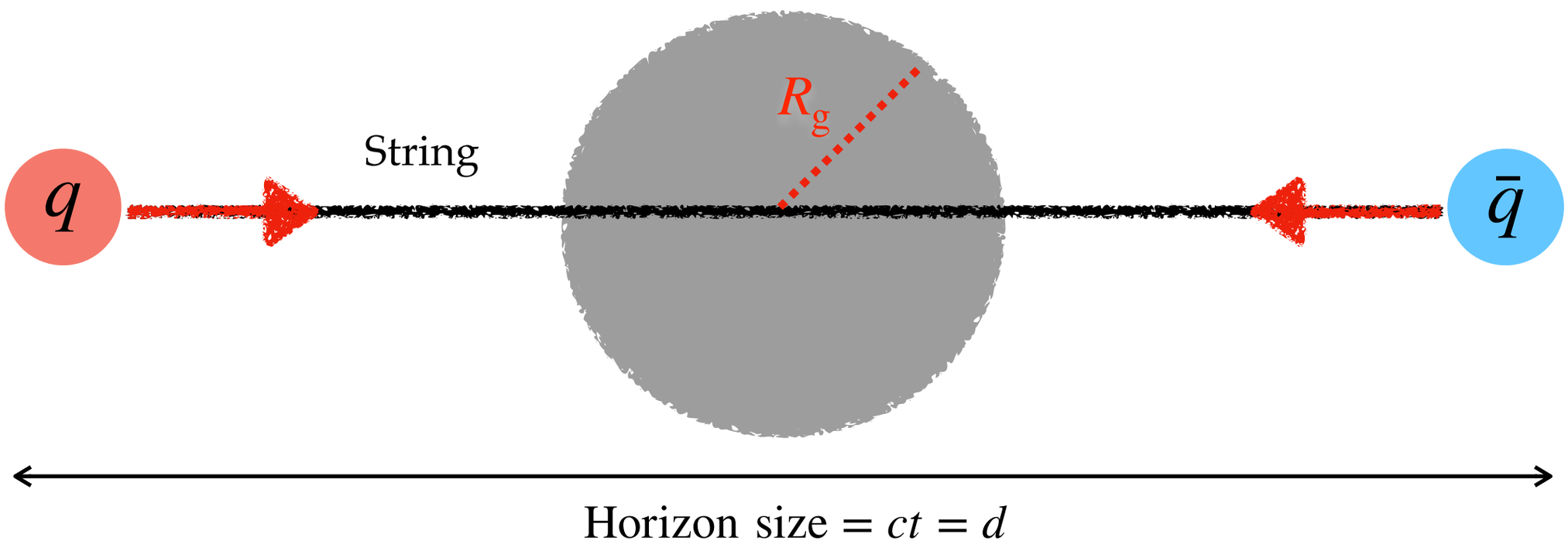
★ 2. Ingredient: Confinement at energy scale Λ_c, $M_q/\Lambda_c \gg 1$



- ★ Flux tubes form connecting quark/anti-quark pairs.
- ★ The system cannot collapse as long as $d > r_H$.
- ★ String breaking into quarks pair, $P_{\text{tunnel}} \propto e^{-\pi \left(M_q/\Lambda_c\right)^2}$, suppressed as long as $M_q/\Lambda_c \gg 1$.

Confinement Formation Mechanism

★ 3. Ingredient: Black hole formation upon horizon entry

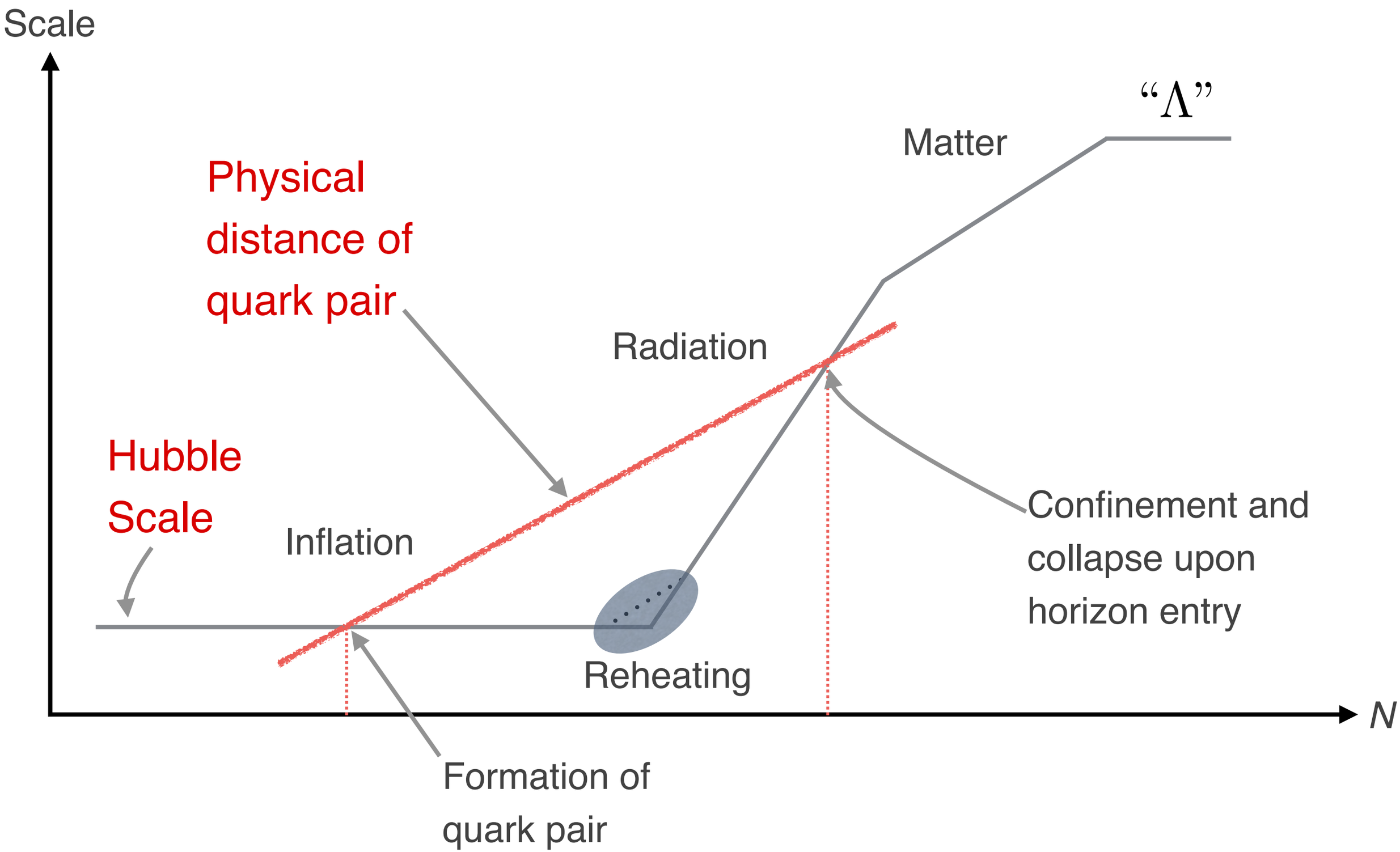


★ Acceleration of the quarks $a = \Lambda_c^2/m_q$ quickly leads to their ultra-relativistic motion.

★ The energy stored in the string is $E \simeq \Lambda_c^2\, t \simeq M_g, \quad R_g \gg \Lambda_c^{-1}$.

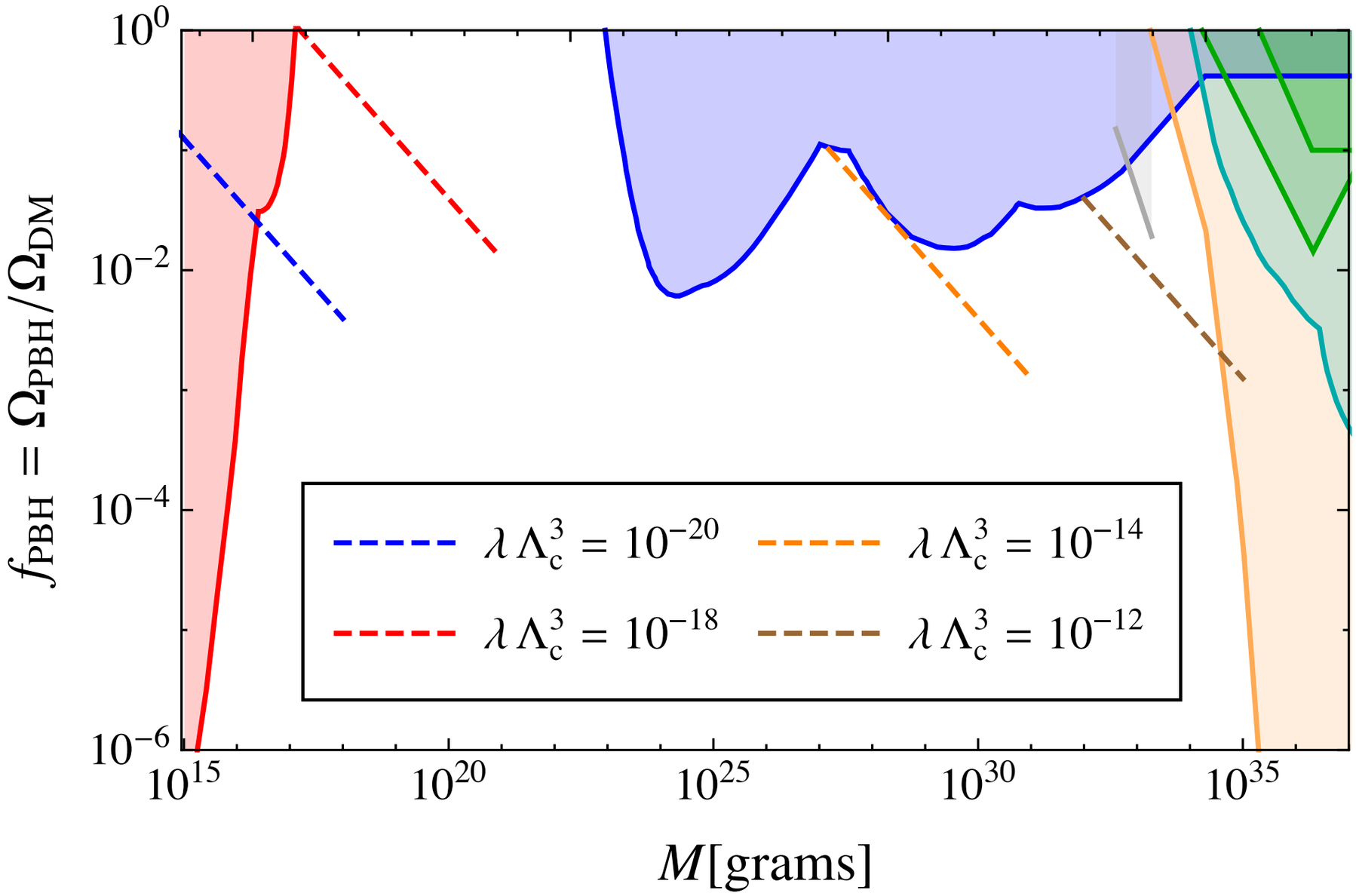
★ PBHs from inflationary overdensities are heavier by a factor $\sim \Lambda_c^2$.

Formation Scales



Dark Matter from Confinement

★ Present-day dark matter distribution vs *monochromatic* constraints:

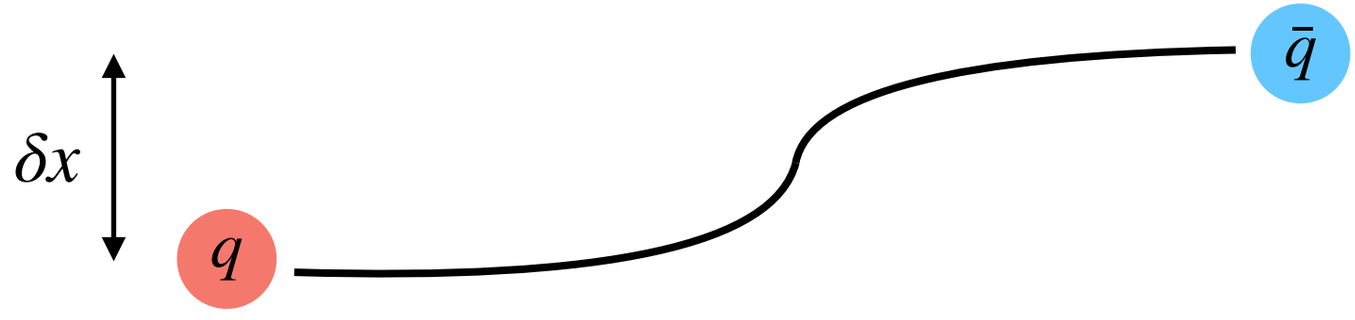


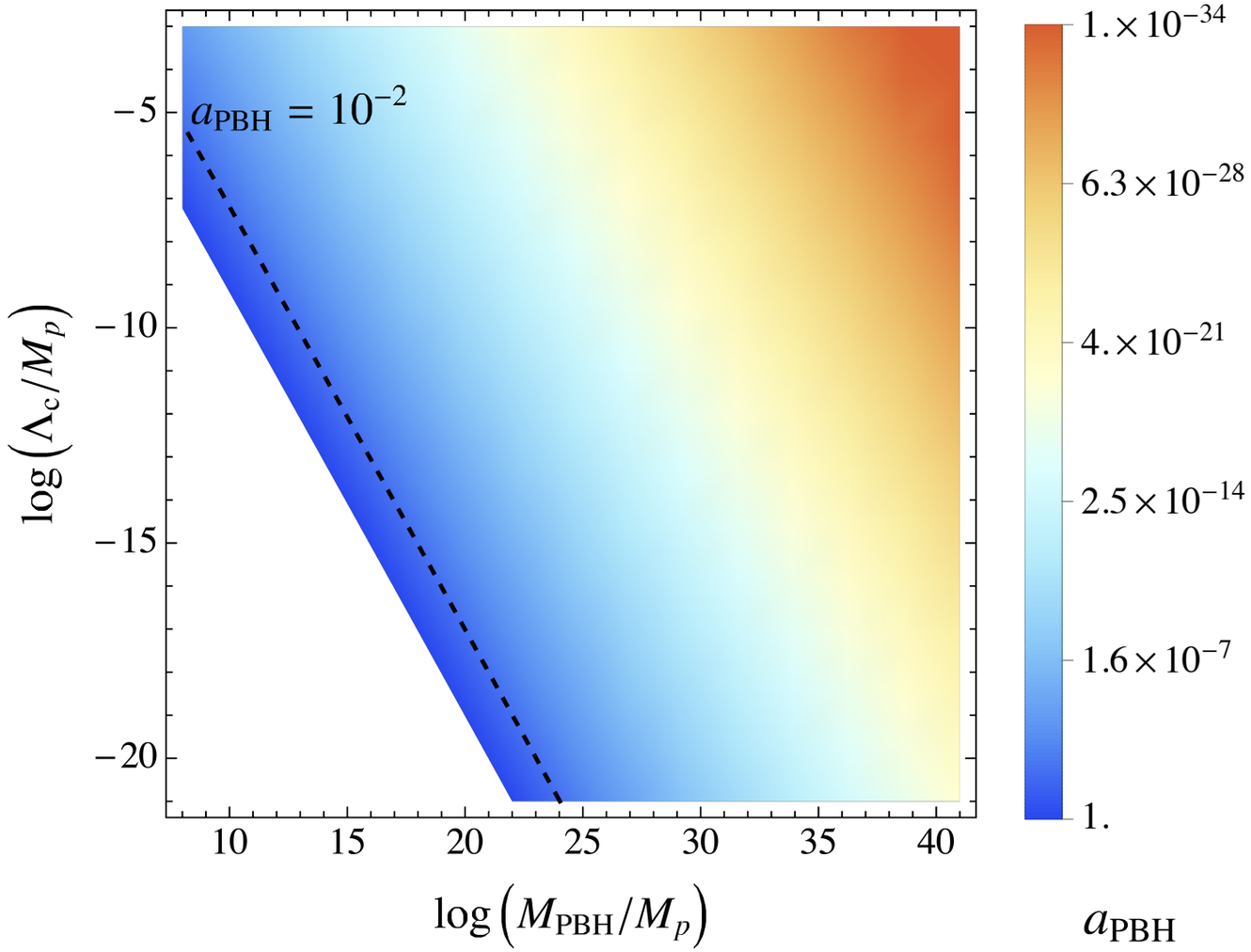
★ Find: $$f_{\rm PBH} \equiv \frac{\rho_{\rm PBH}(t)}{\rho_{\rm CDM}(t)} = \frac{32\pi}{3}\,\lambda\Lambda_{\rm c}^3\left(\frac{M_{\rm PBH}}{M_{\rm eq}}\right)^{-1/2}$$

High-Spin Subsolar PBHs

★ During inflation, the string undergoes a Brownian motion, induced by de Sitter quantum fluctuations, leading to deviation from straightness:

$$\delta x \simeq \sqrt{N_{\rm e}}\, H_{\rm i}^{-1}$$





★ This leads to potentially significant spin:

$$a_{\rm PBH} \simeq \frac{\delta x}{R_{\rm g}}$$

$$\simeq \frac{1}{H\, M_{\rm PBH}} \log\left(\frac{H\, M_{\rm PBH}}{\Lambda_{\rm c}^2}\right)^{1/2}$$