Primordial Black Holes

Florian Kühnel

Max Planck Institute for Physics

École Normale Supérieure Summer Institue
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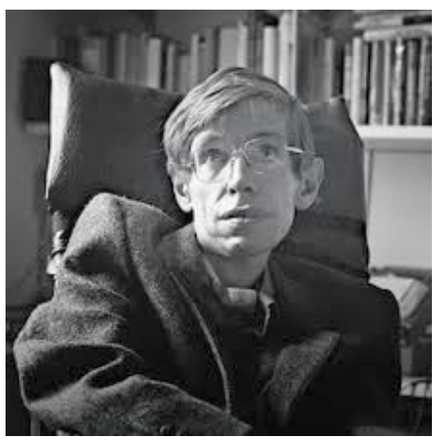
Historical Remarks

What are Primordial Black Holes (PBHs)?

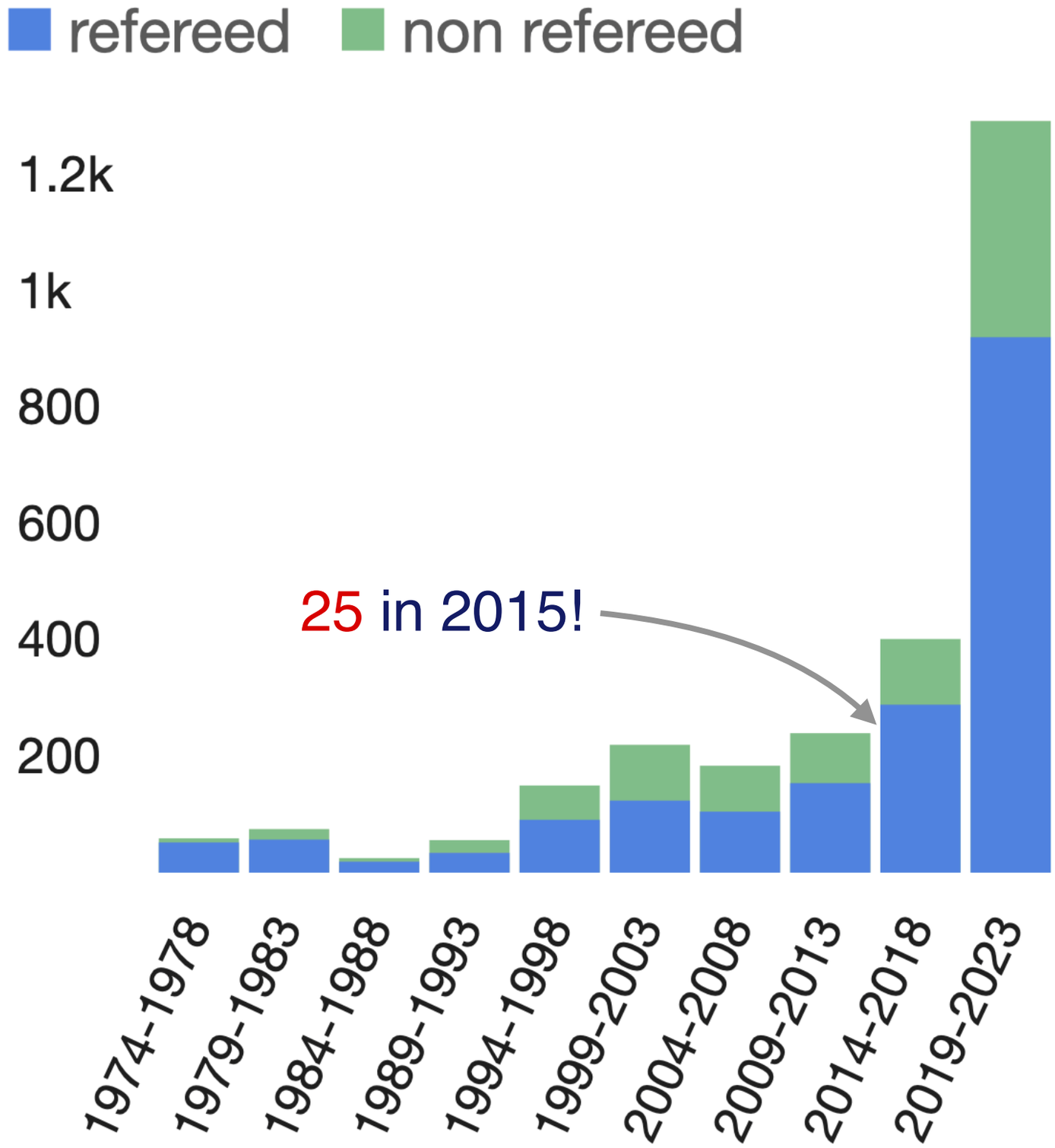
- ★ Black holes formed in the early* Universe (in particular: *non-stellar*).

- ★ 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).



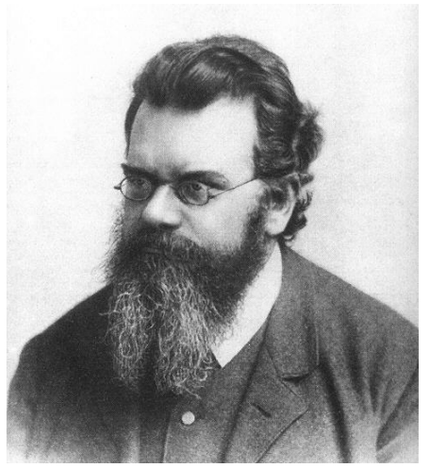
Primordial Black Holes are Popular!



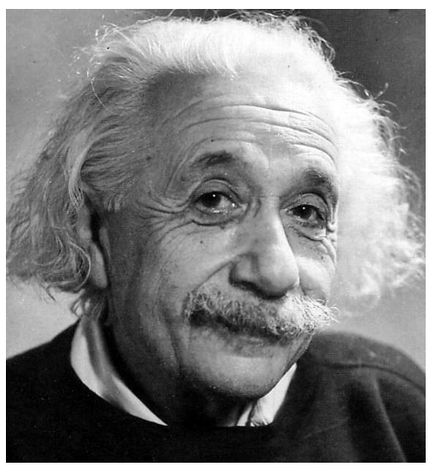
[SAO/NASA Astrophysics Data System]

Black Hole Evaporation

Quantum Mechanics



Thermodynamics



General Relativity

★ Black hole radiation

[Hawking 1974]

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

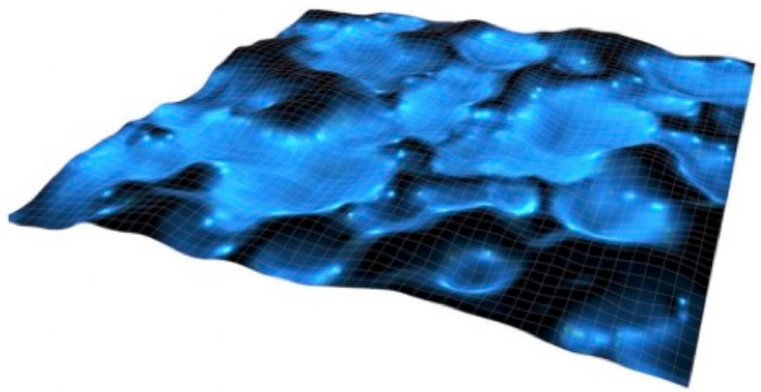
★ PBHs are important even if never observed!

Primordial Black Hole

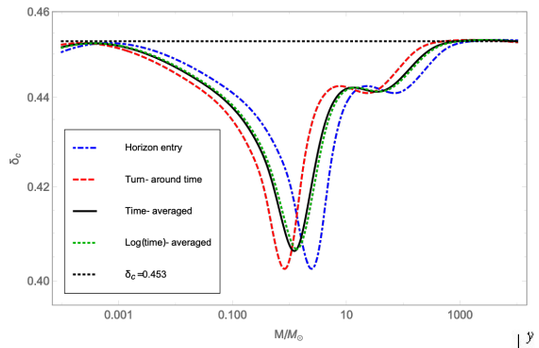
Formation Primer

PBH Formation Mechanisms

★ Large density perturbations (inflation)

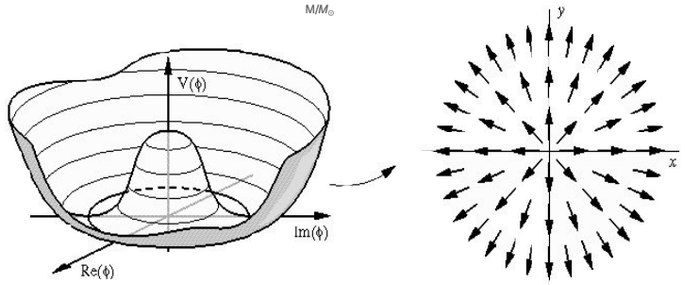


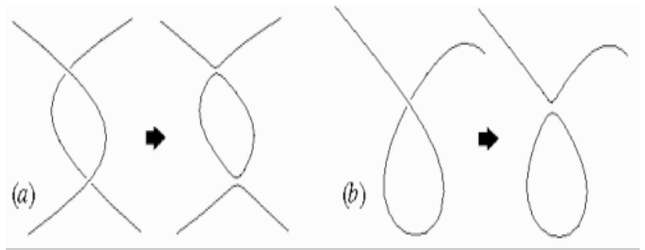
★ Pressure reduction



[Byrnes *et al.* 2018]

★ Cosmic string loops

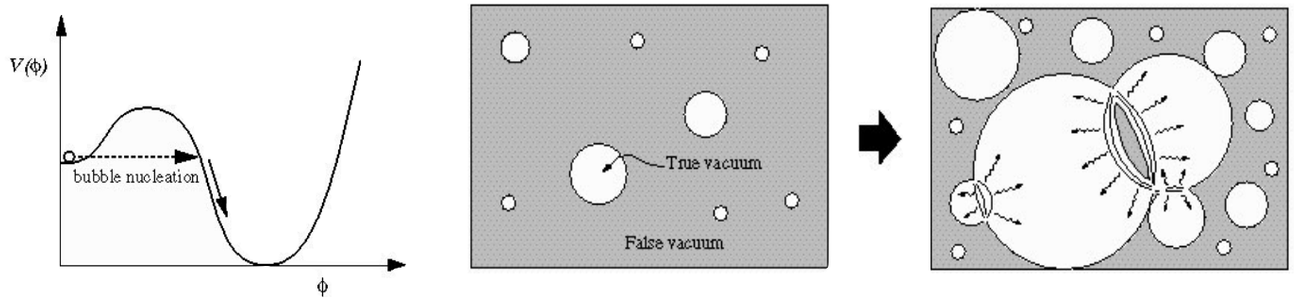




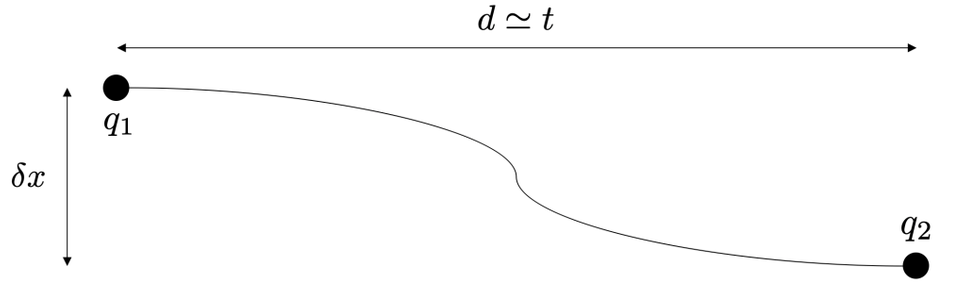
http://www.damtp.cam.ac.uk/research/gr/public/cs_phase.html

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

★ Bubble collisions



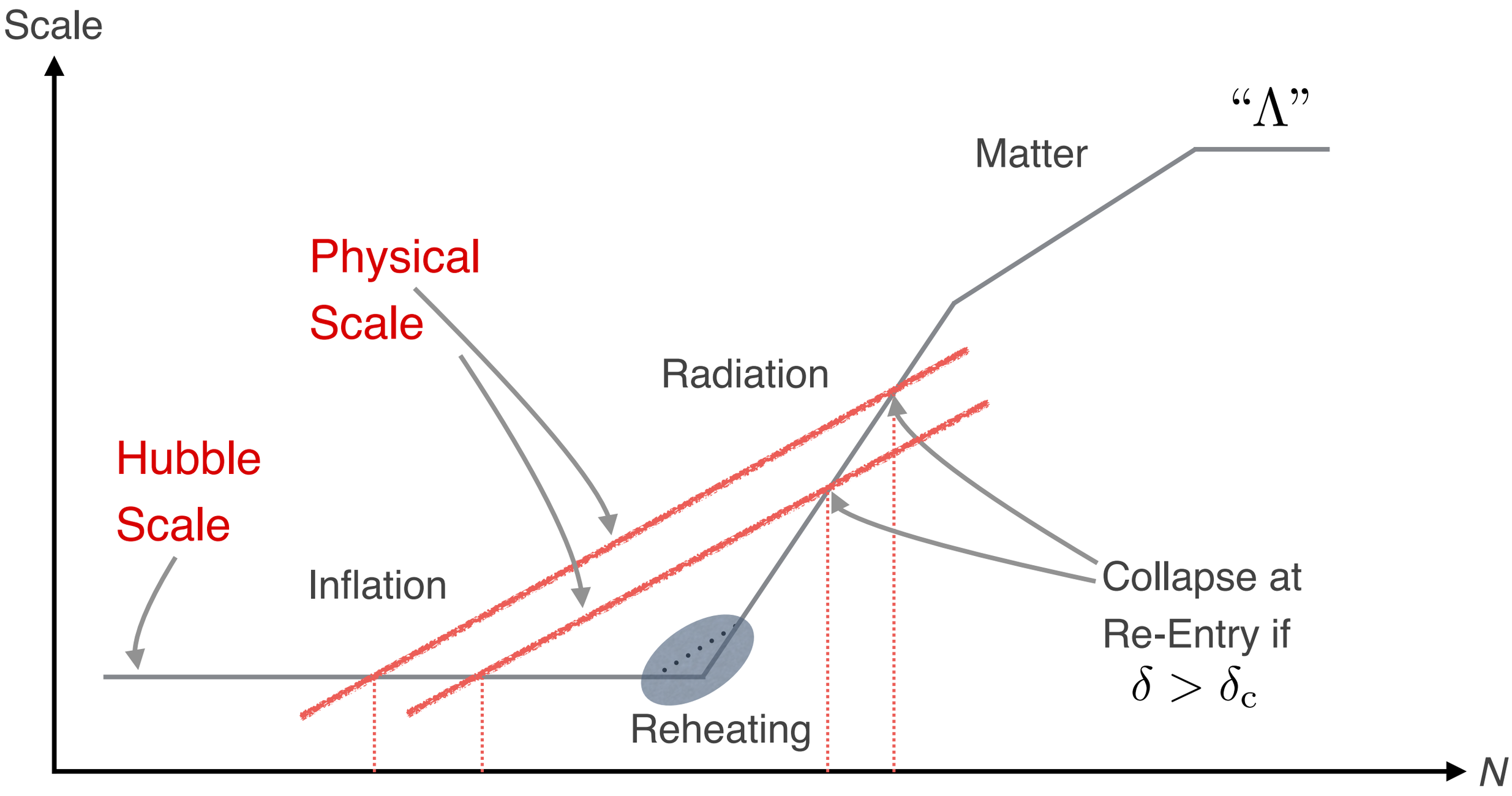
★ Quark confinement



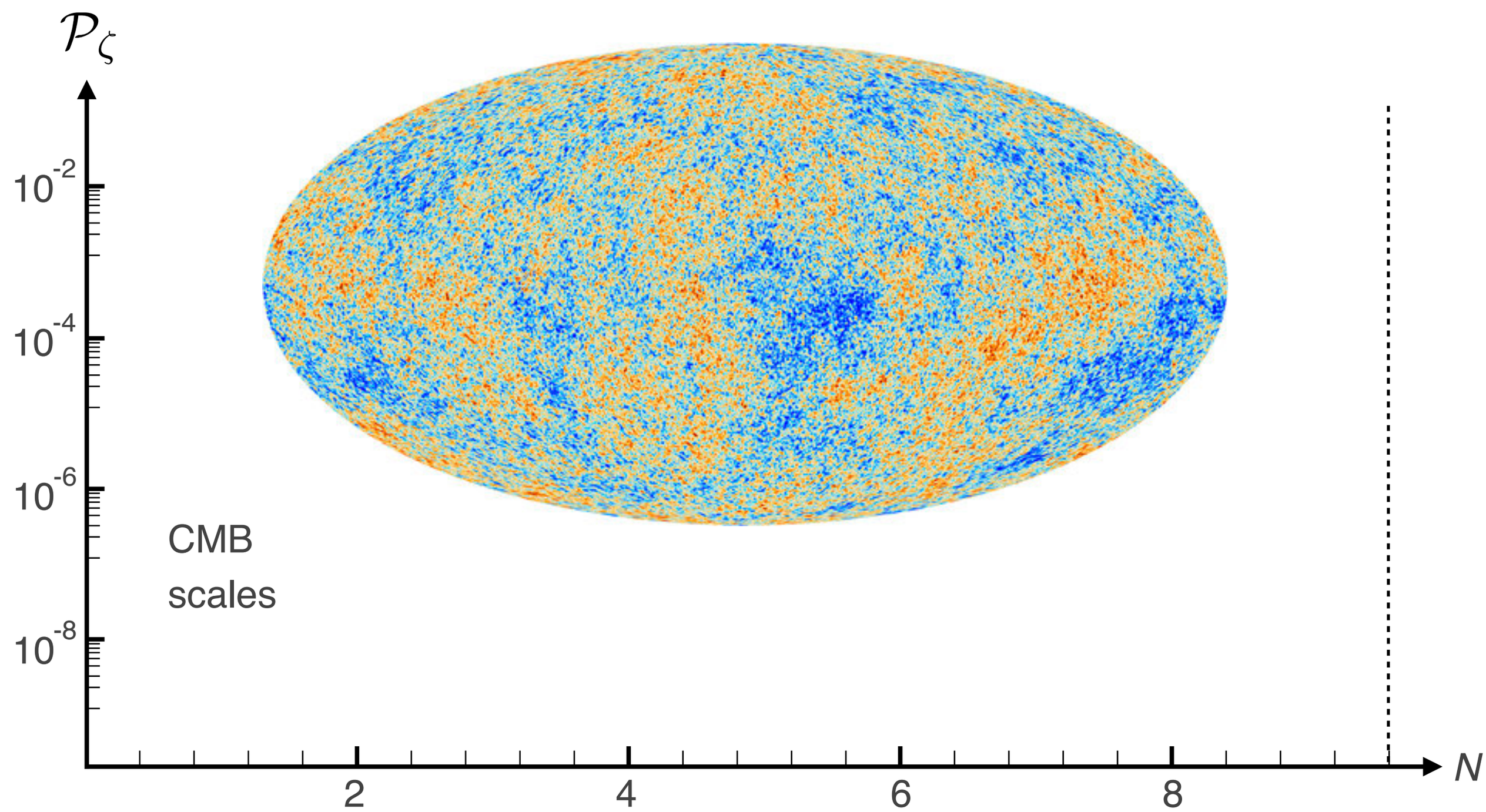
[Dvali, FK, Zantedesschi 2021]

★ Scalar-field fragmentation (see Kusenko's talk), ...

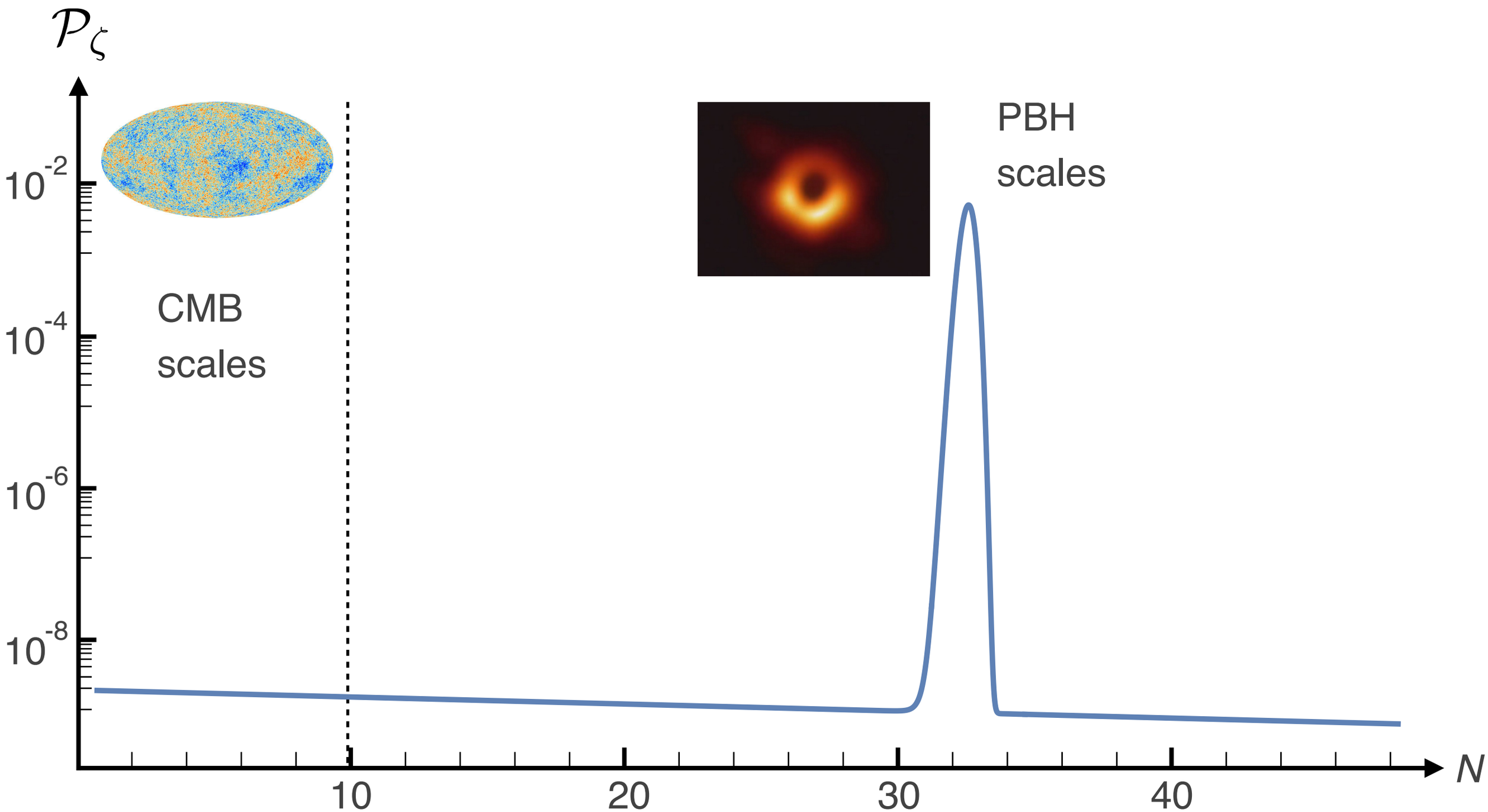
PBH Formation from Inflationary Overdensities



PBH Formation — Scales



PBH Formation — Scales

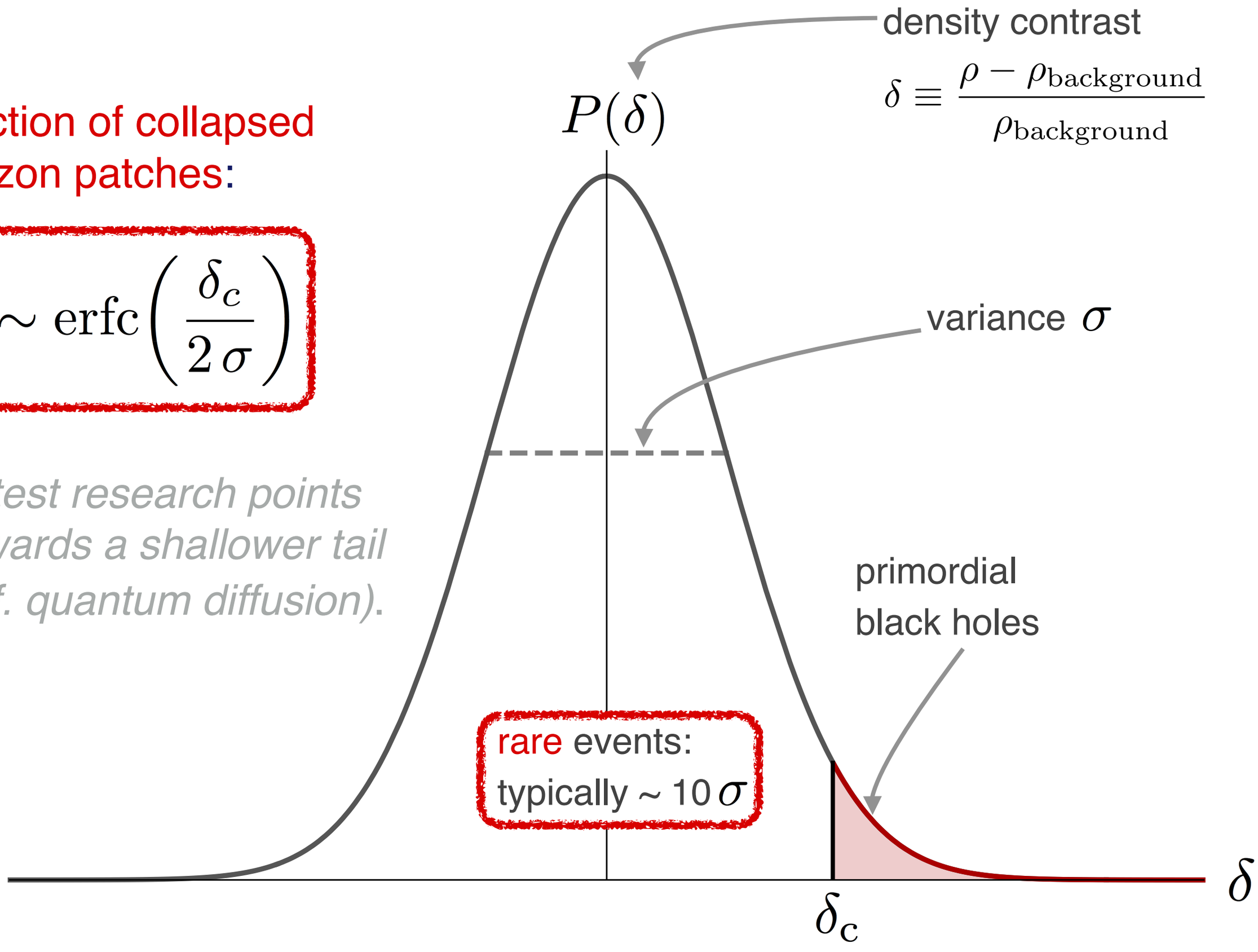


PBH Formation — Rare Events

Fraction of collapsed horizon patches:

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

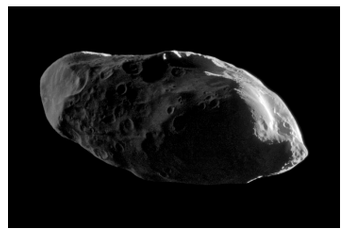
Latest research points towards a shallower tail (c.f. quantum diffusion).



PBHs — Some Numbers

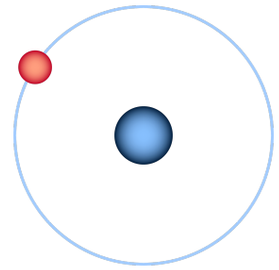
★ If primordial black holes constituted all of the dark matter:

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



Saturn satellite *Prometheus*

★ Size: $10^{-8}\,\mathrm{cm}$

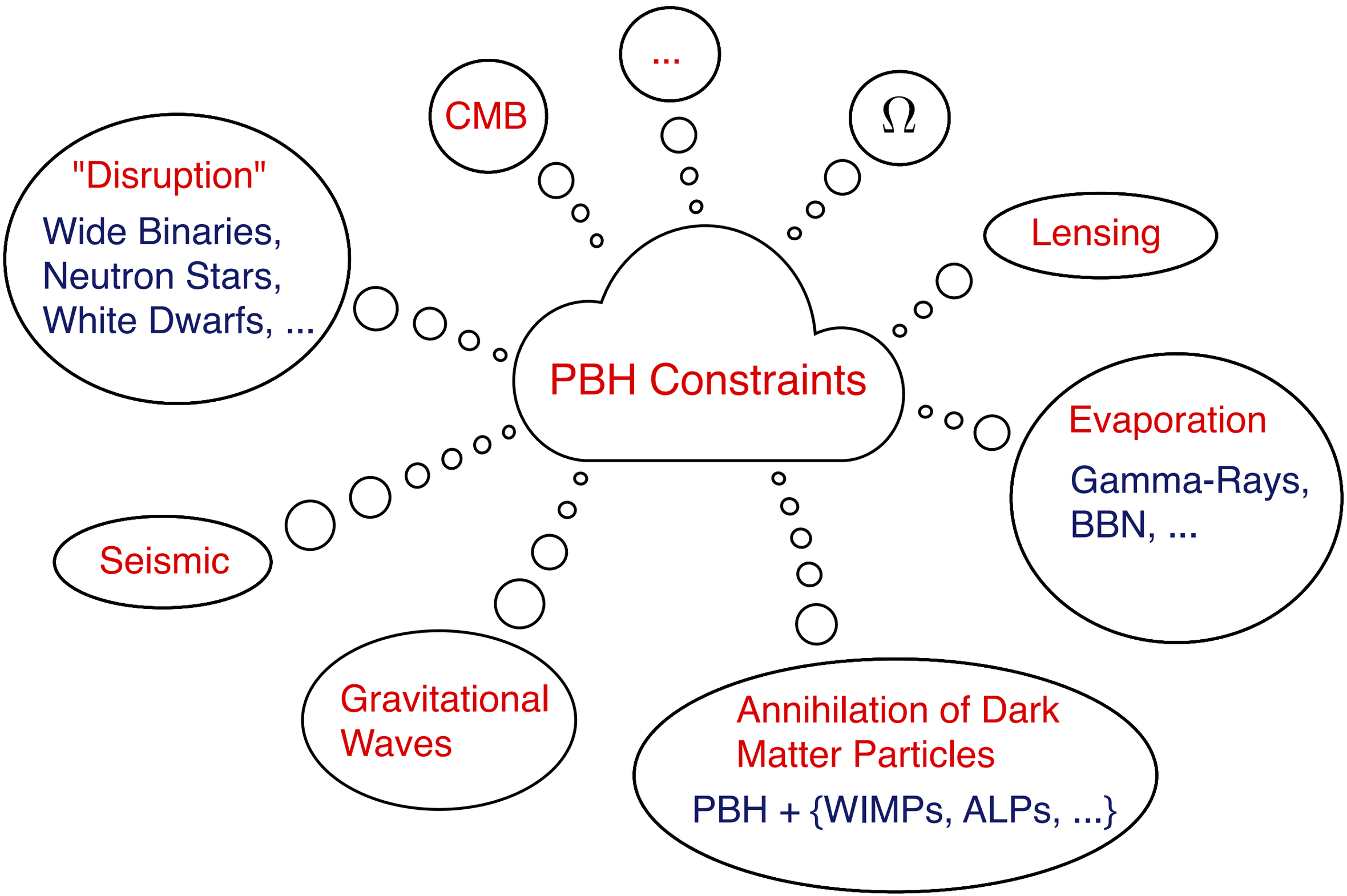


Hydrogen Atom

★ Number in our Galaxy: 10^{25}

★ Distance: $10\,\mathrm{AU}$

Primordial Black Hole Constraints


...
CMB
Ω
"Disruption"
Wide Binaries,
Neutron Stars,
White Dwarfs, ...
Lensing
PBH Constraints
Evaporation
Gamma-Rays,
BBN, ...
Seismic
Gravitational
Waves
Annihilation of Dark
Matter Particles
PBH + {WIMPs, ALPs, ...}

PBH Constraints at Formation

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

β'

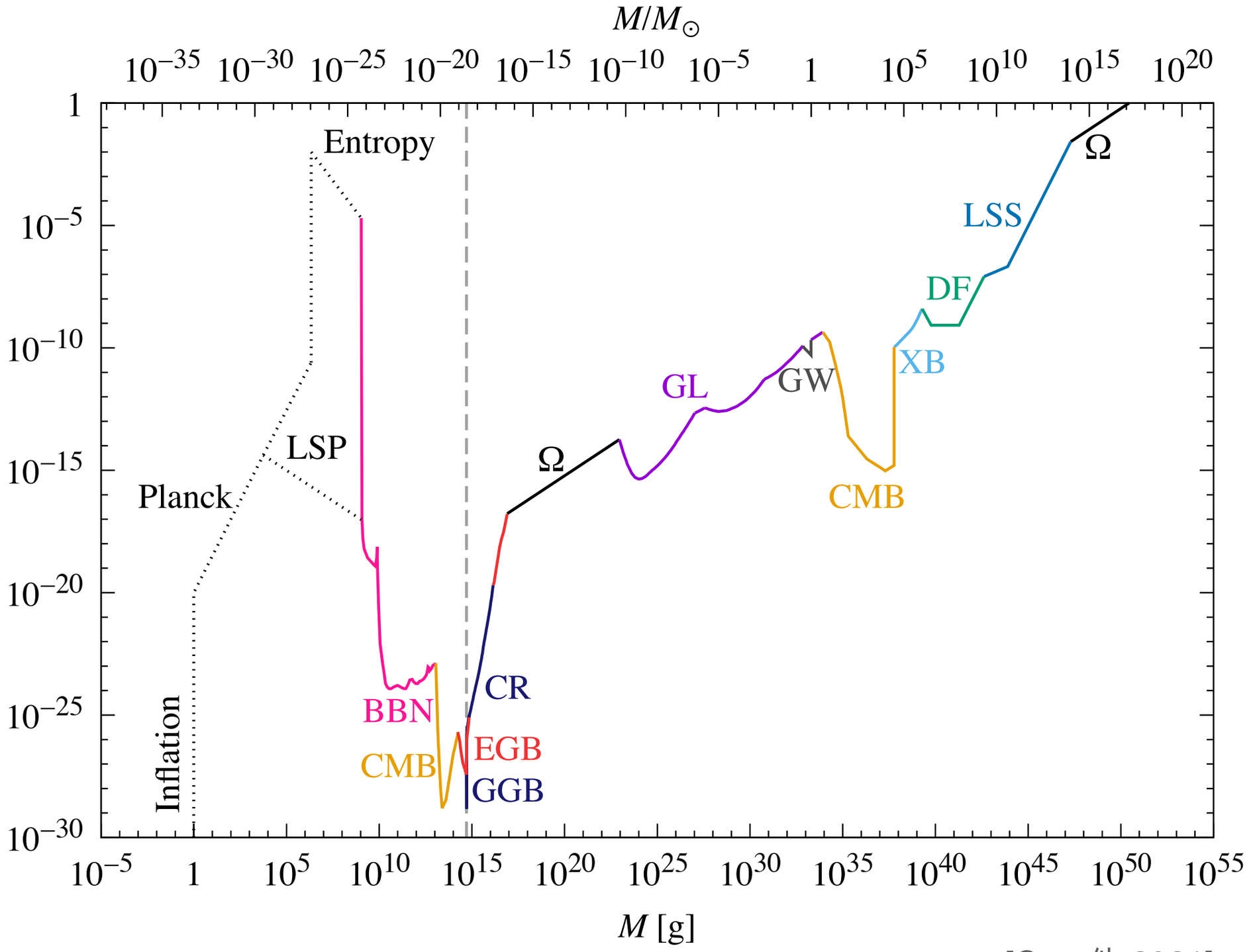
★ Note that

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

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

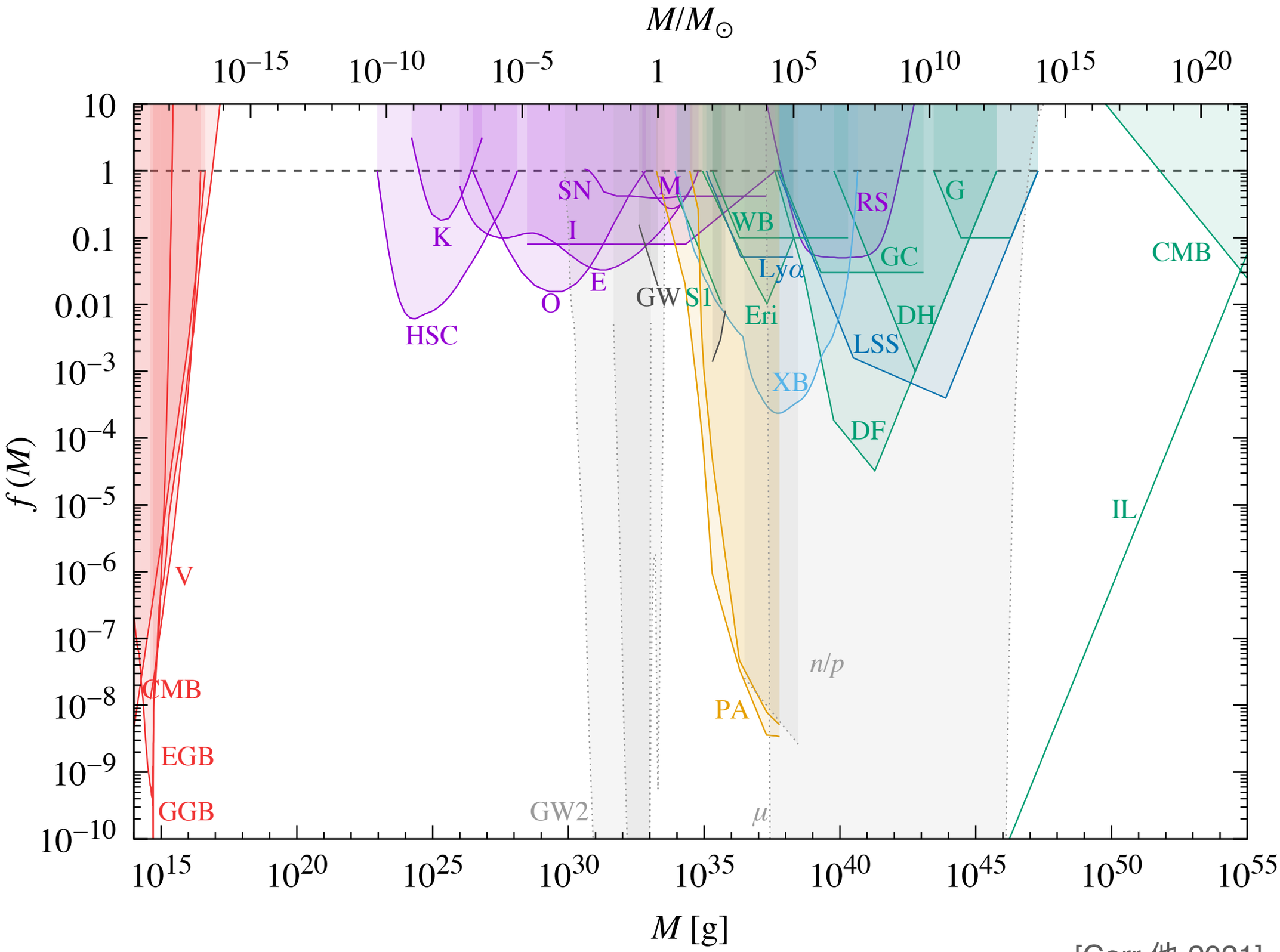
and hence

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



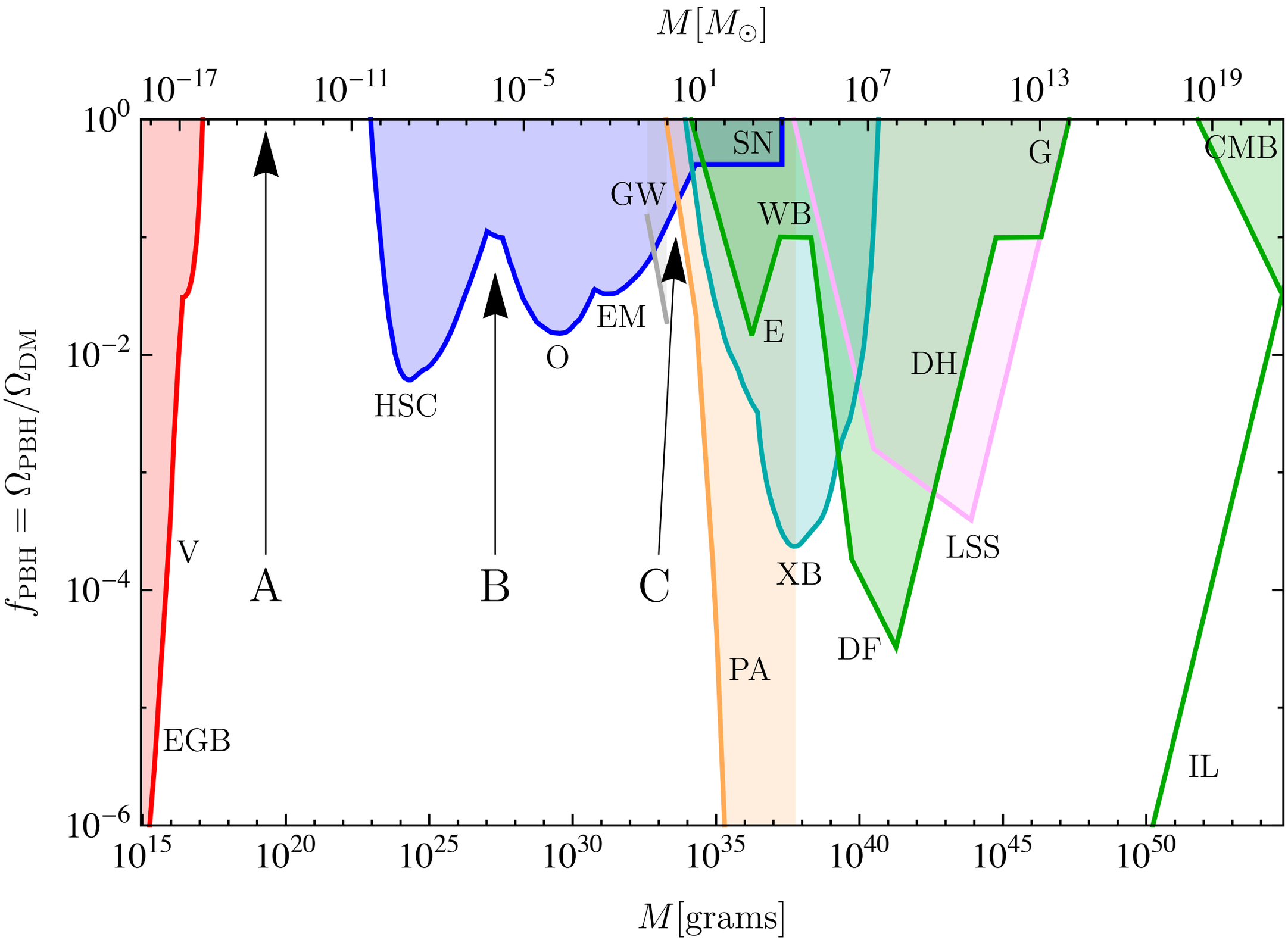
[Carr 他 2021]

Current PBH Constraints



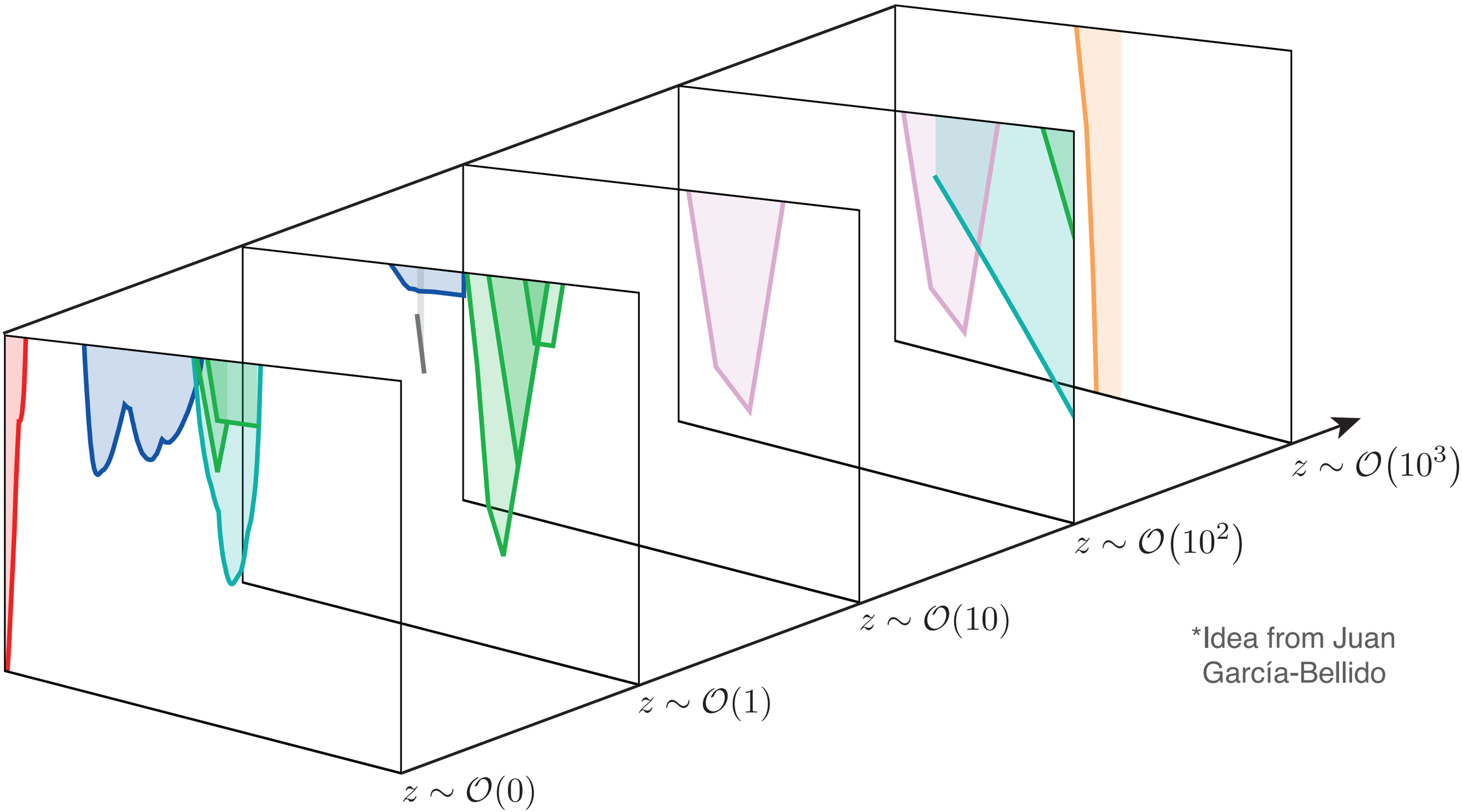
[Carr 他 2021]

Current PBH Constraints



[Carr & FK 2020]

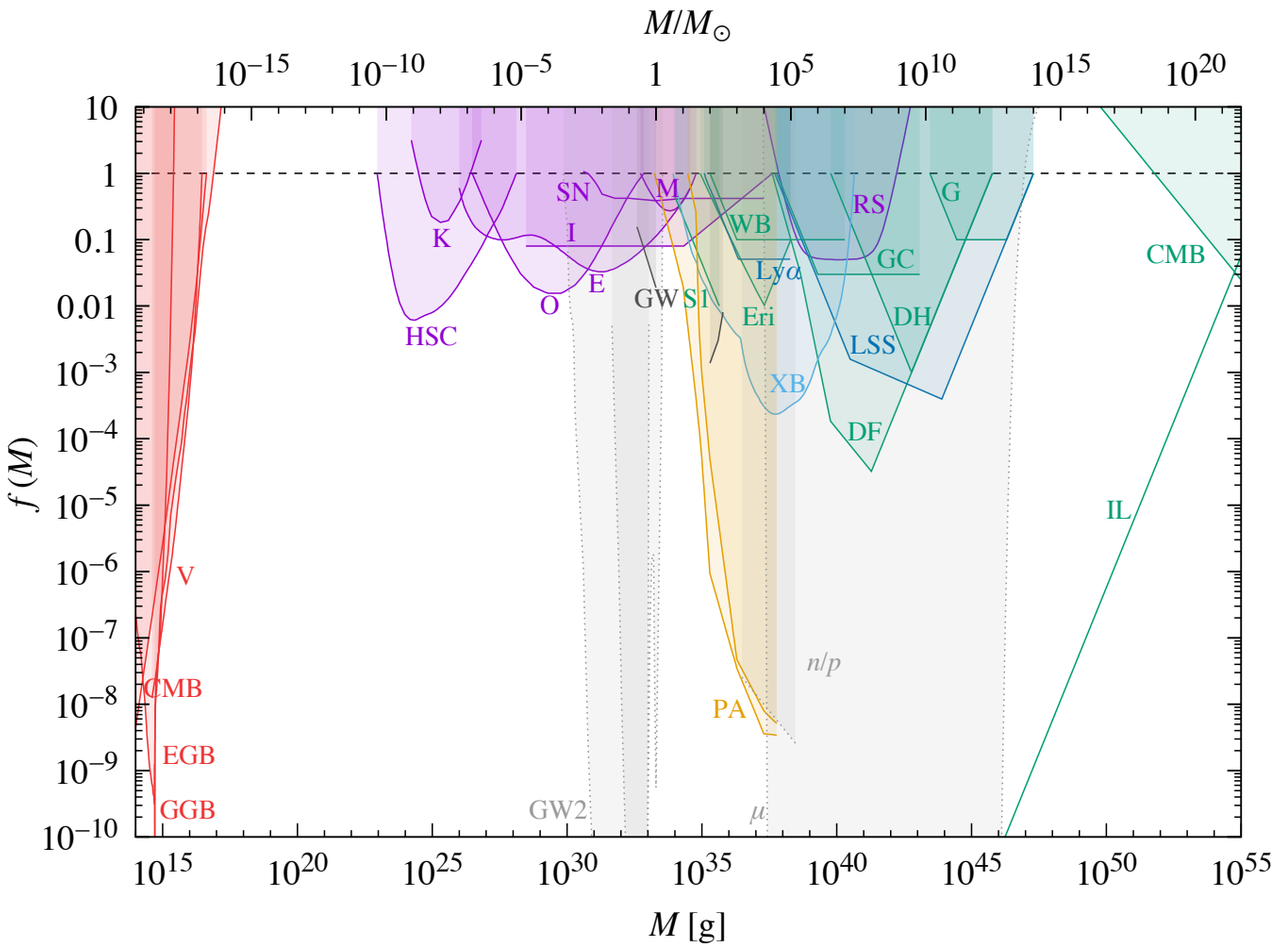
PBH Constraints — Redshift Dependence



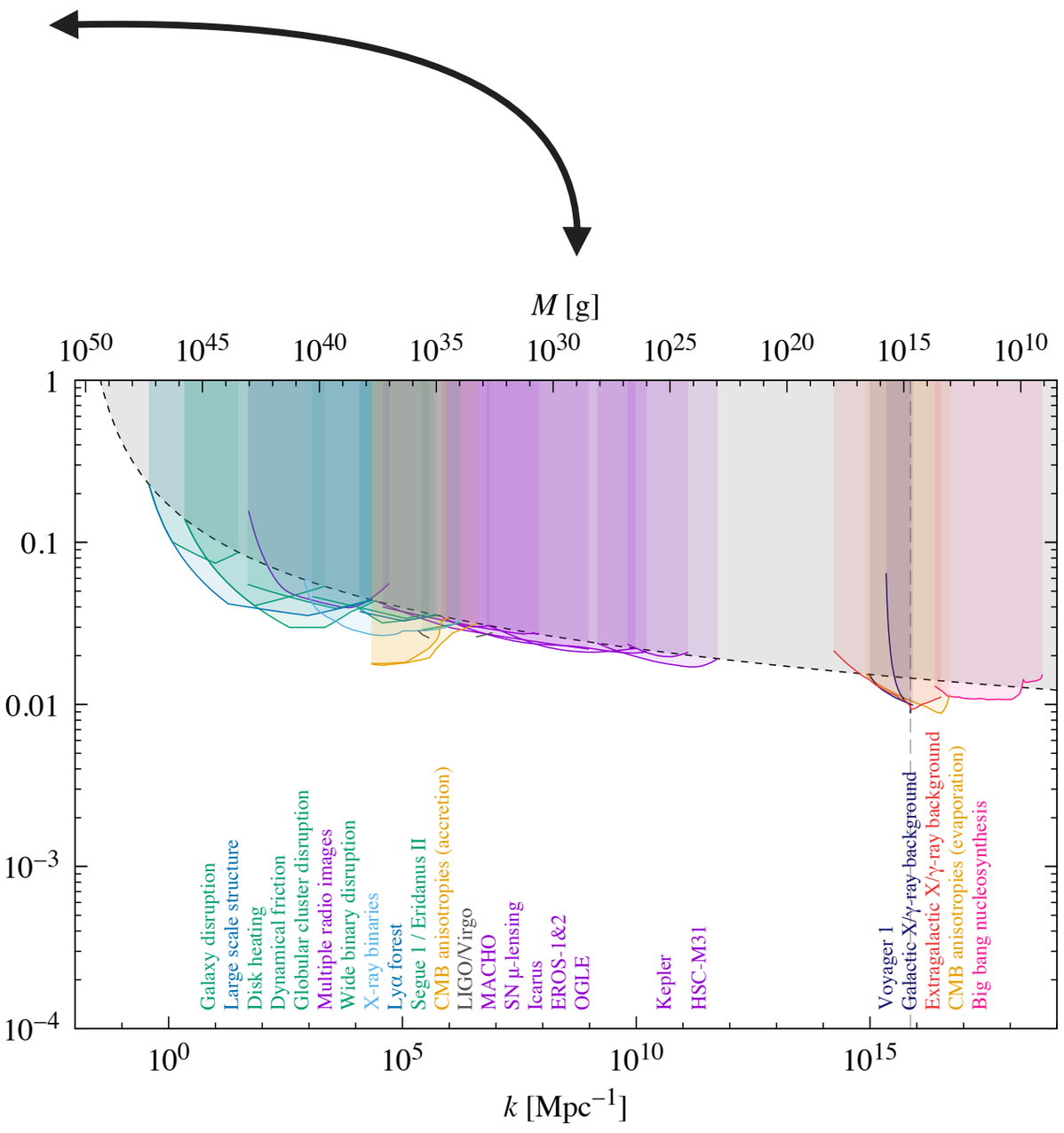
*Idea from Juan García-Bellido

[Carr & FK 2020*]

PBH Constraints — Primordial Power Spectrum

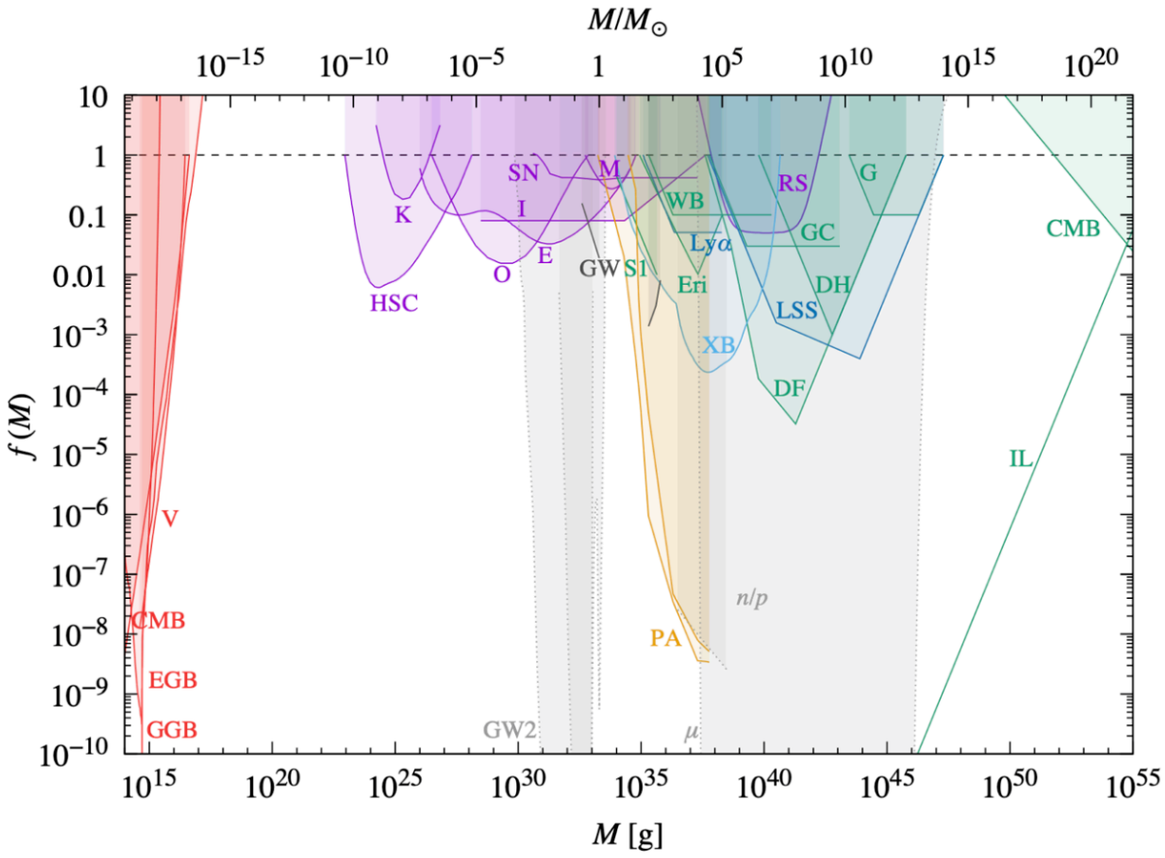


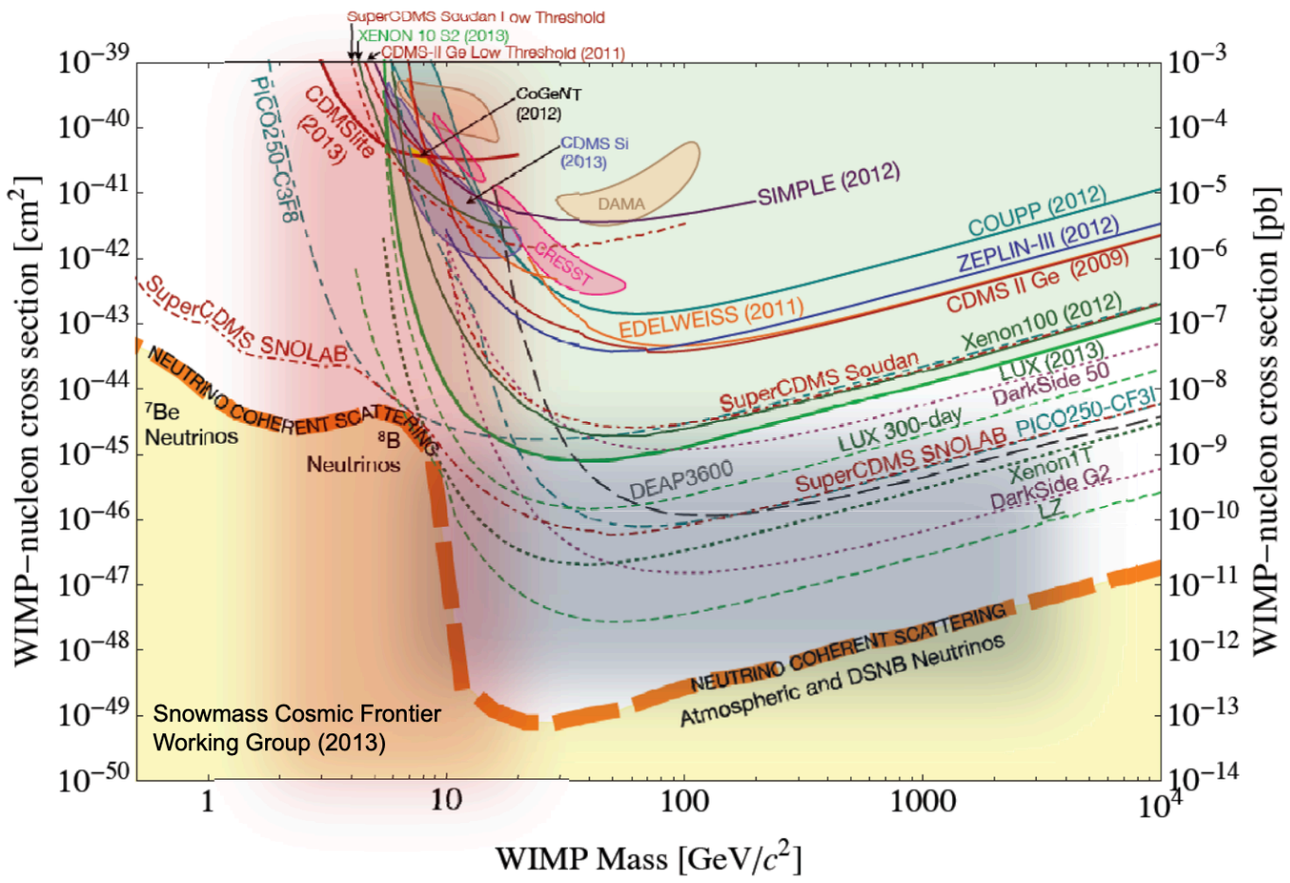
$$f_{\rm PBH} \hookrightarrow \beta \sim \mathrm{erfc}\left(\frac{\delta_c}{2\,\sigma}\right) \hookrightarrow \mathcal{P}$$



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

Constraints — Uncertainties

- 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
  - ...

Primordial Black Holes

and

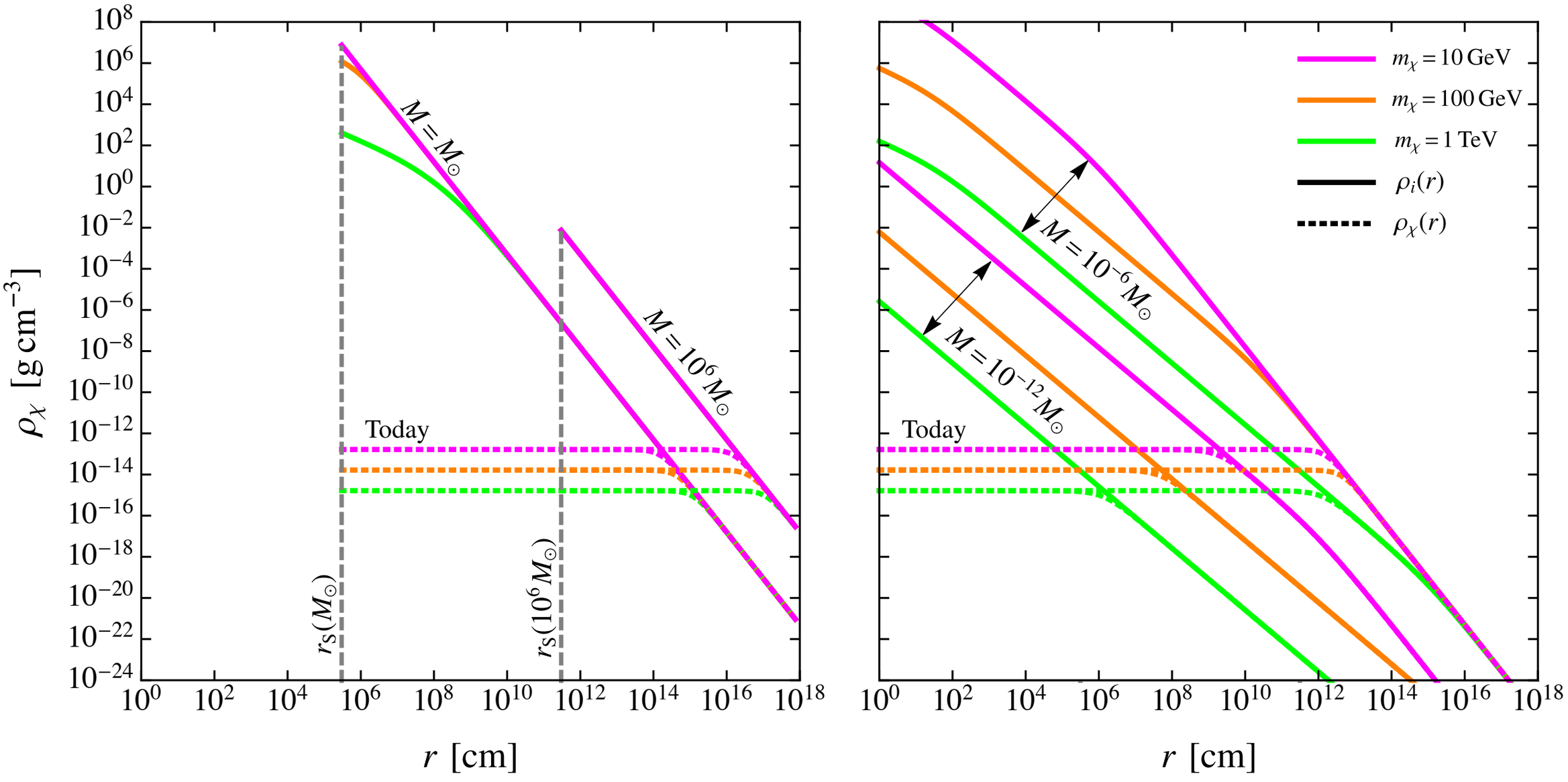
Particle Dark Matter

PBH & Particle Dark Matter

- ★ Always when $f_{\rm PBH} < 1$ 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 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, Witte *et al.* 2022]

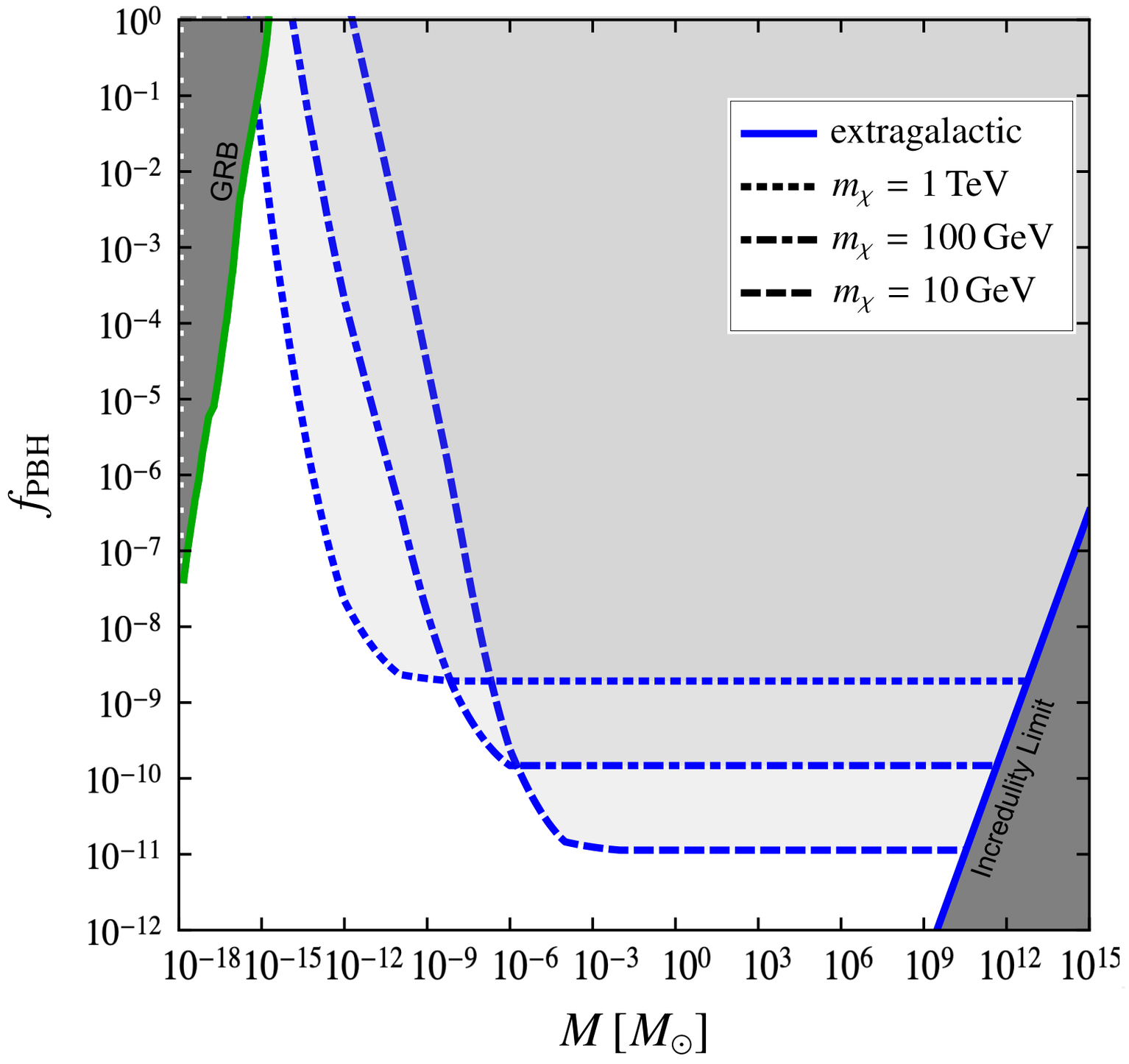
PBHs & WIMPs



[Carr, FK, Visinelli 2021]

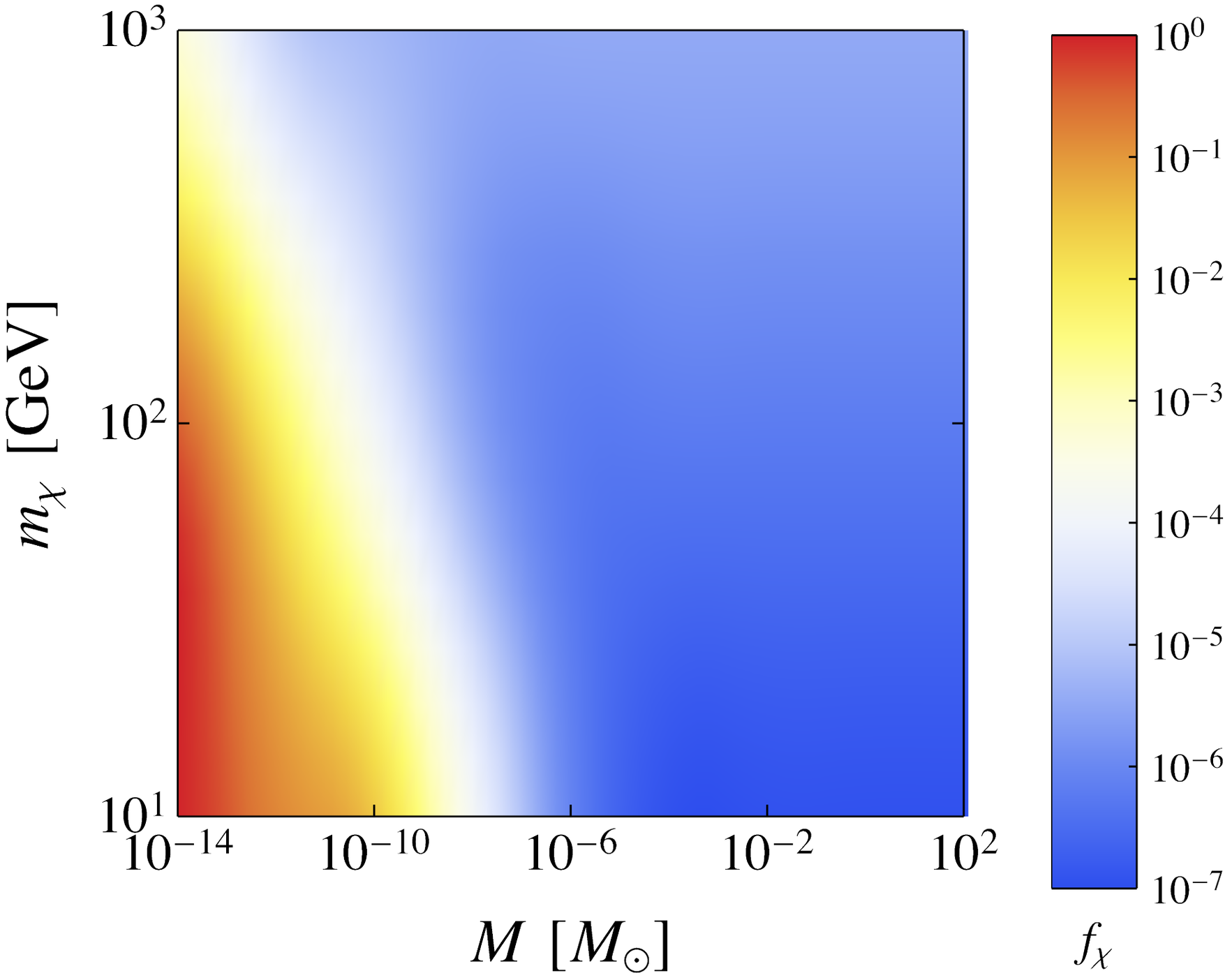
★ Annihilations lead to plateaux in the present-day halos.

PBHs & WIMPs



[Carr, FK, Visinelli 2021]

PBHs & WIMPs



[Carr, FK, Visinelli 2021]

Monochromatic

versus

Extended Mass Spectra

Critical Collapse

★ Usually: Assume

$$M_{BH} \propto M_H$$

horizon mass

★ Critical scaling:

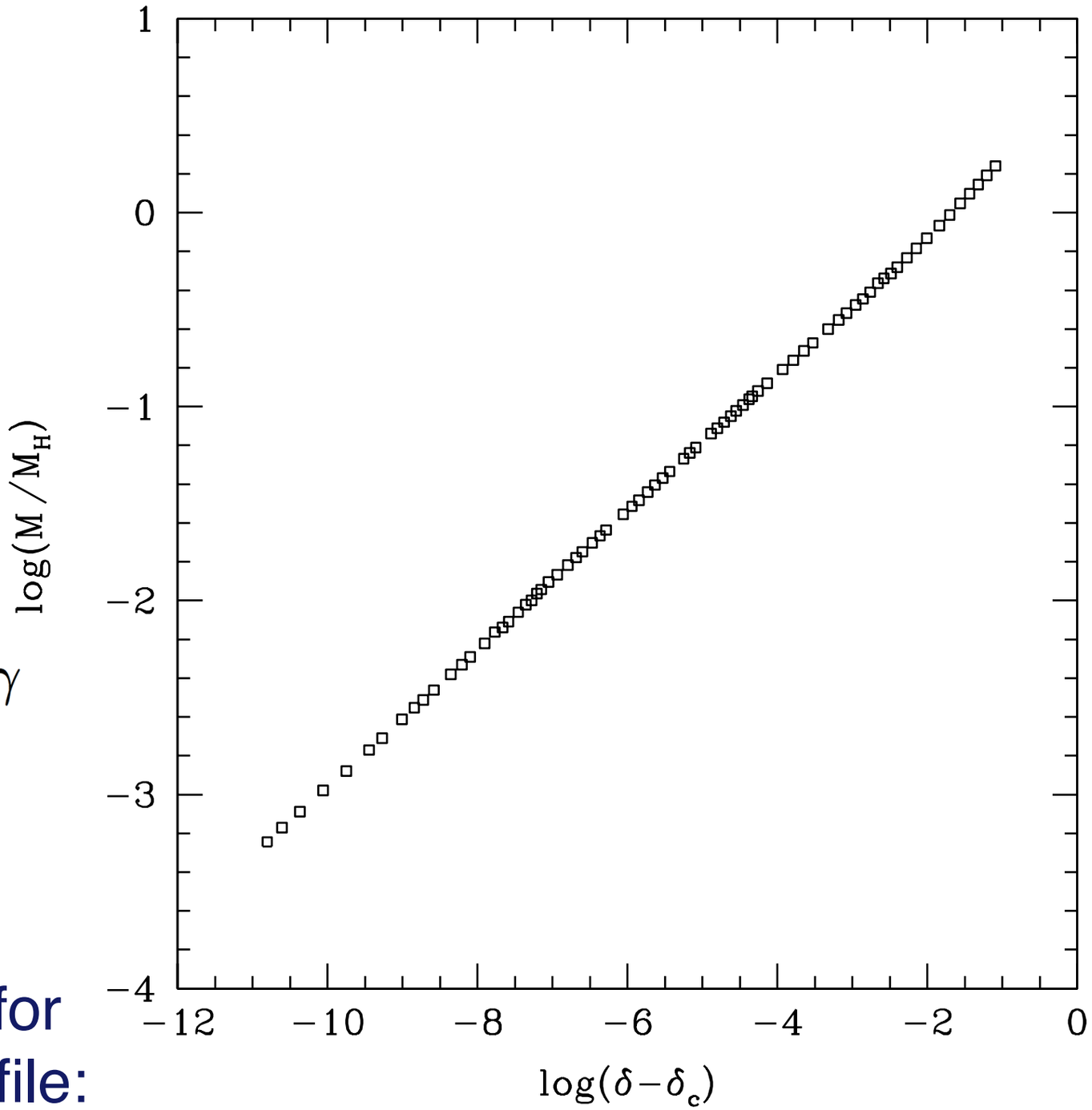
[Choptuik '93]

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

density contrast

★ Radiation domination and for spherical Mexician-hat profile:

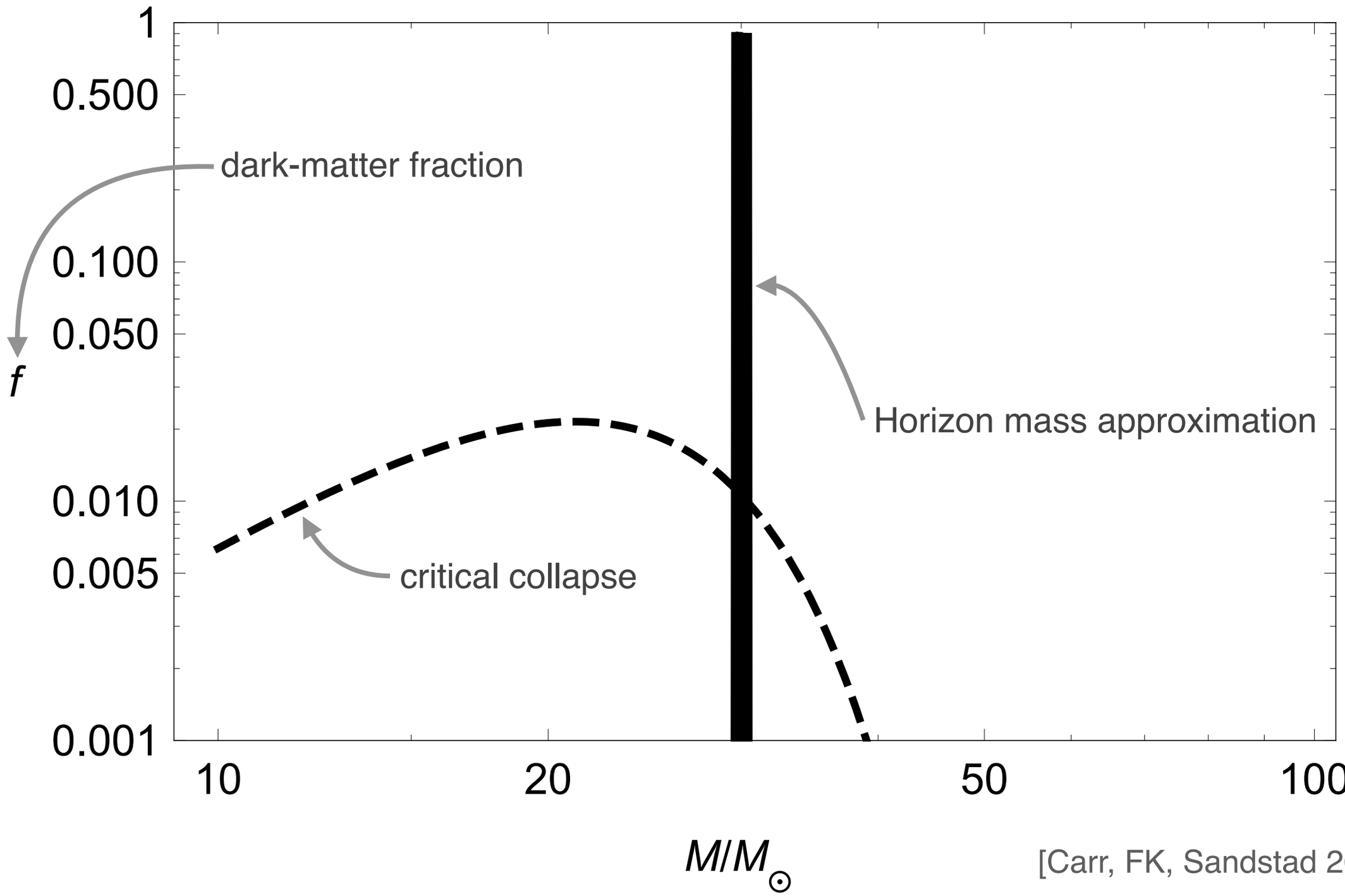
$$k \approx 3.3\,, \quad \delta_c \approx 0.45\,, \quad \gamma \approx 0.36$$



[Musco, Miller, Polnarev 2008]

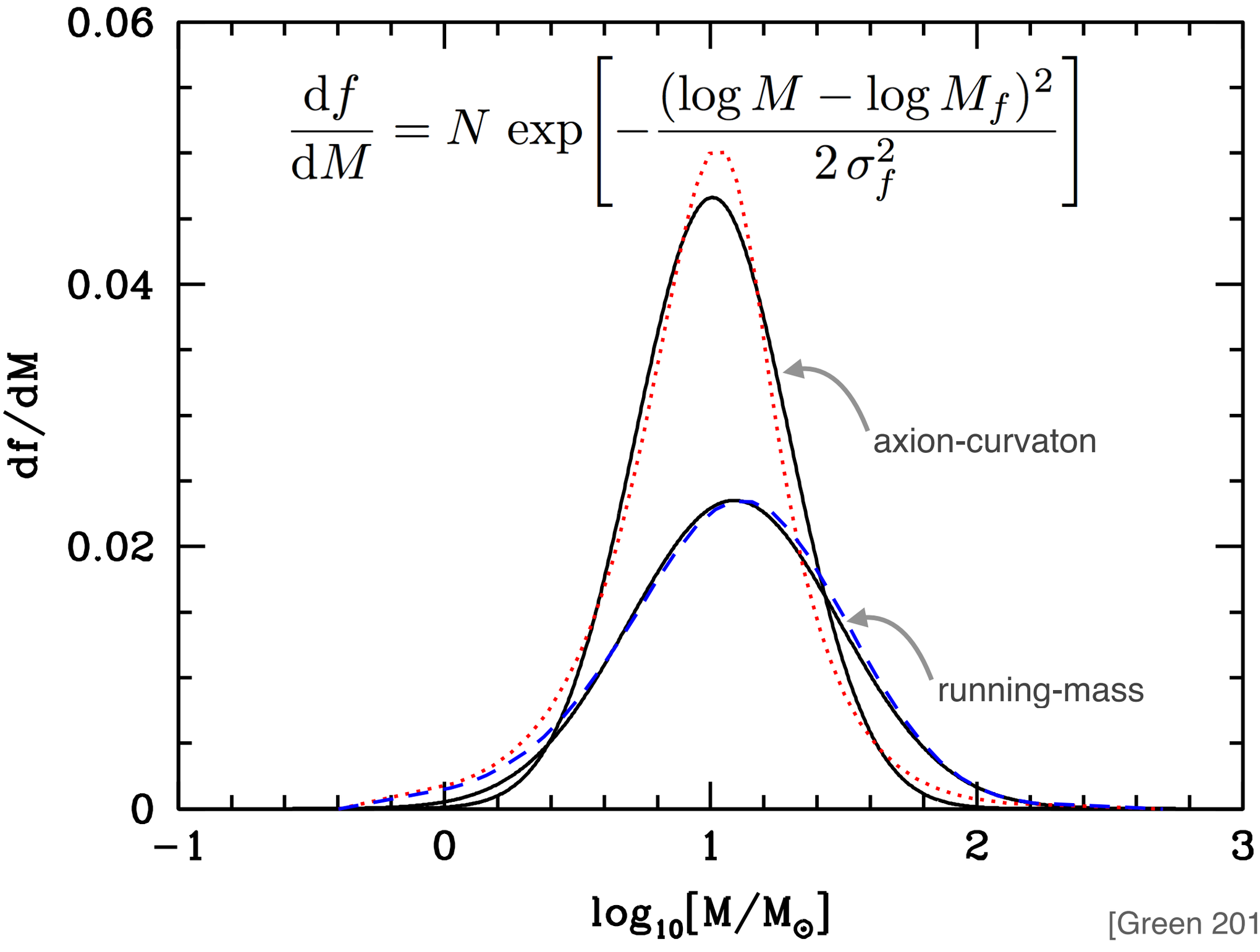
Critical Collapse

★ How would this look for monochromatic mass function?



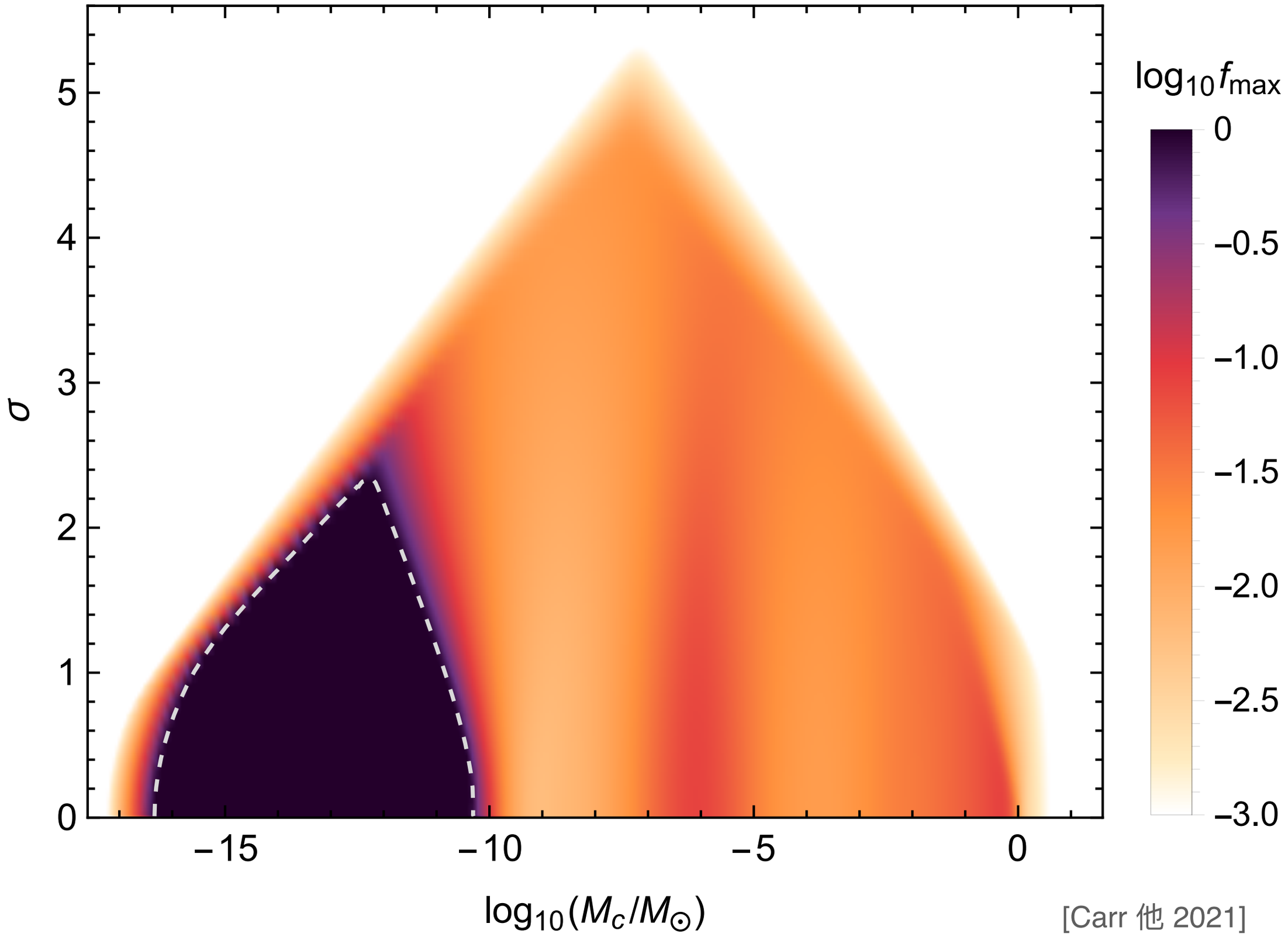
[Carr, FK, Sandstad 2016]

More Systematic Study



[Green 2016]

More Systematic Study



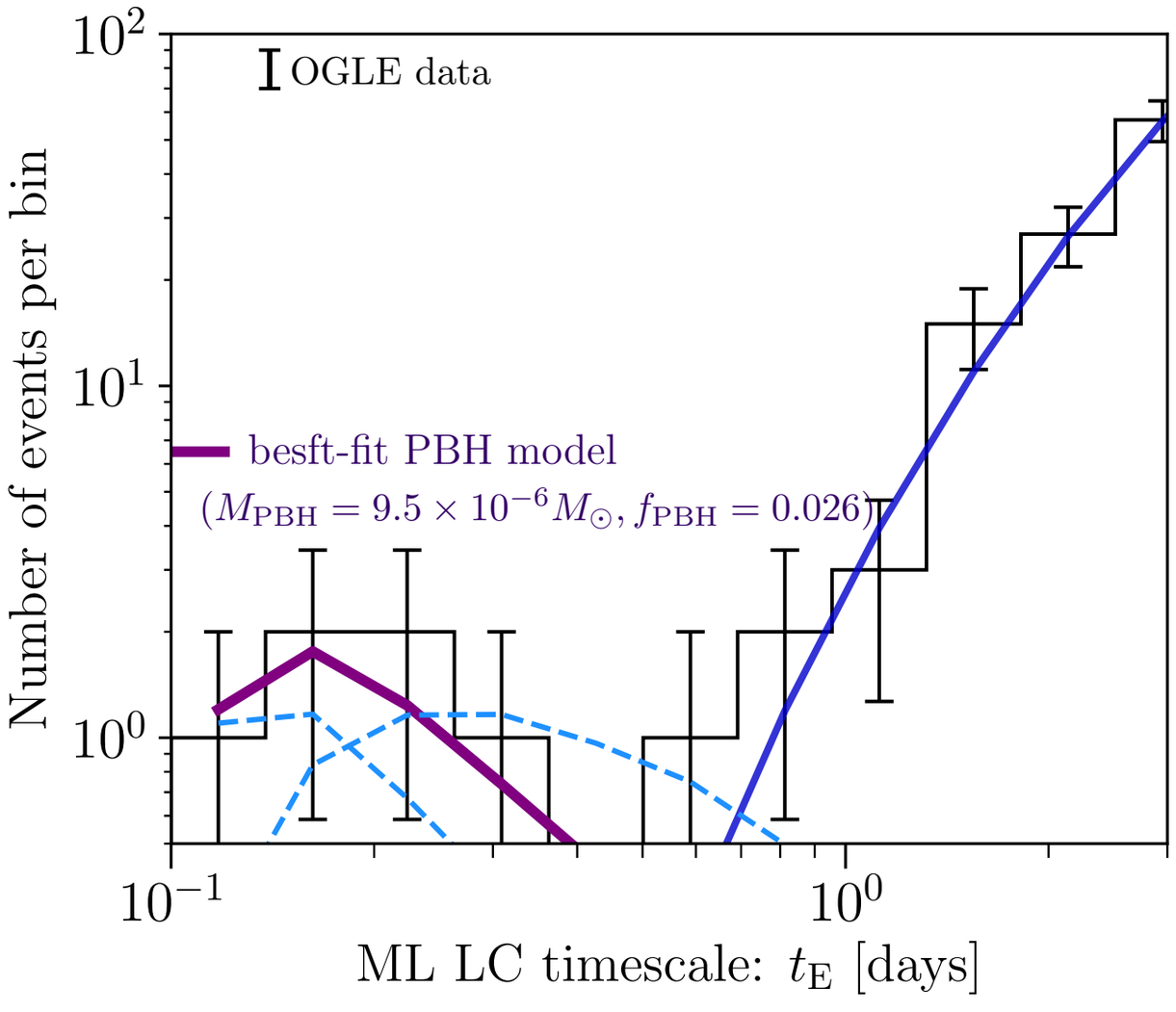
[Carr 他 2021]

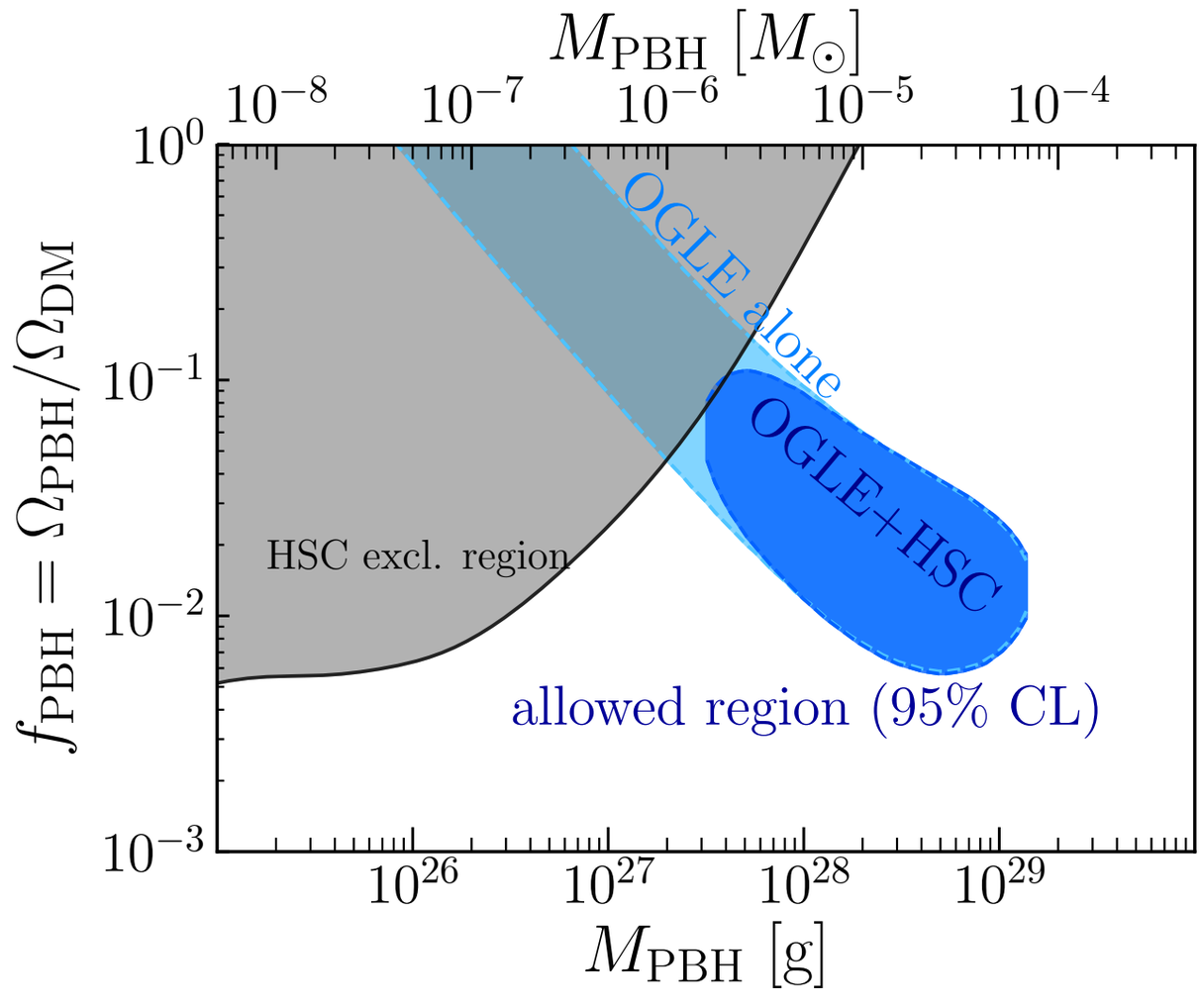
Observational Hints for Primordial Black Holes

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

Planetary-Mass Microlensing

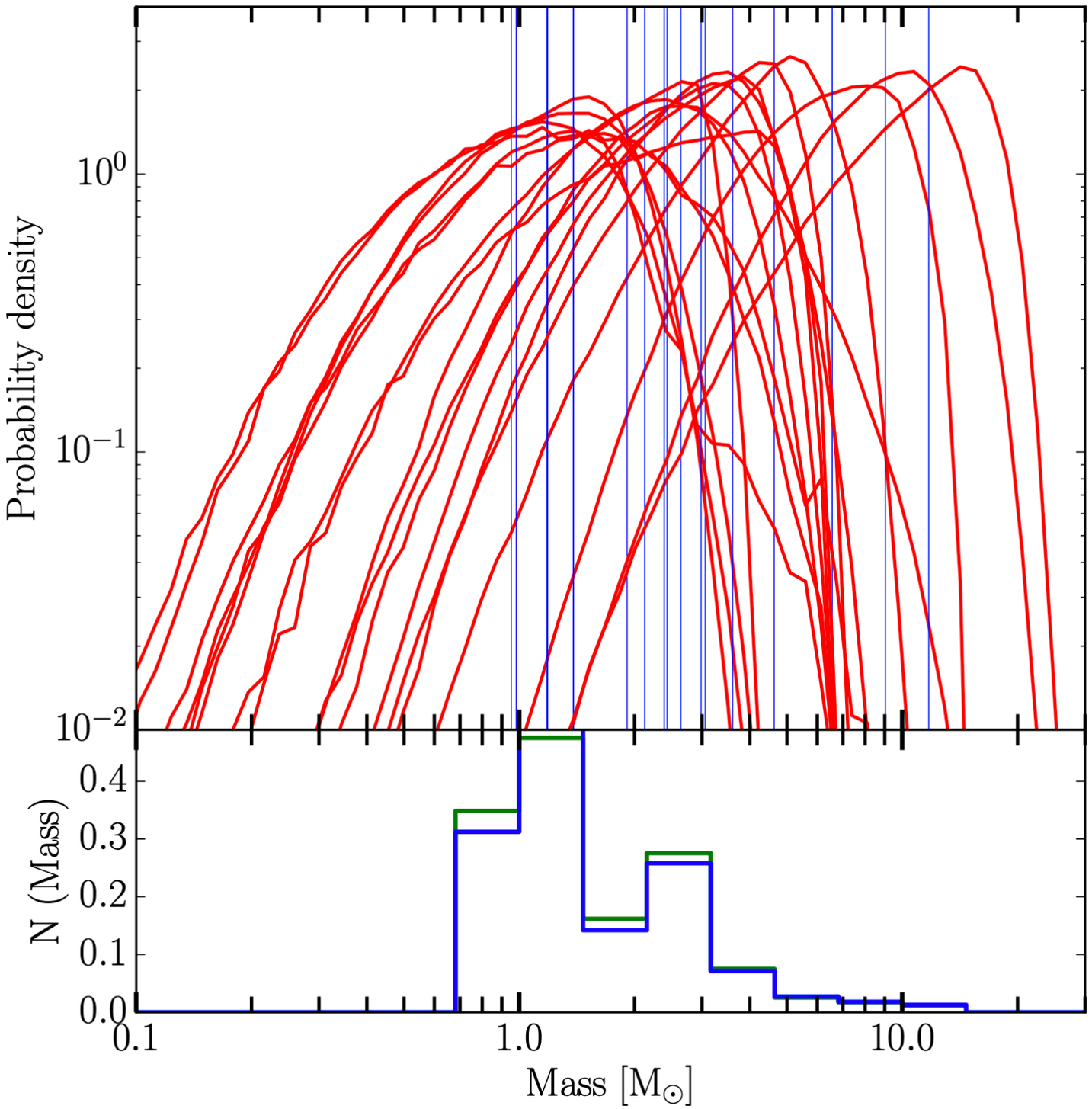
- OGLE detected a particular population of microlensing events:
  - 0.1 - 0.3 days light-curve timescale - origin unknown!
    Could be free-floating planets... or PBHs!





[Niikura *et al.* 2019]

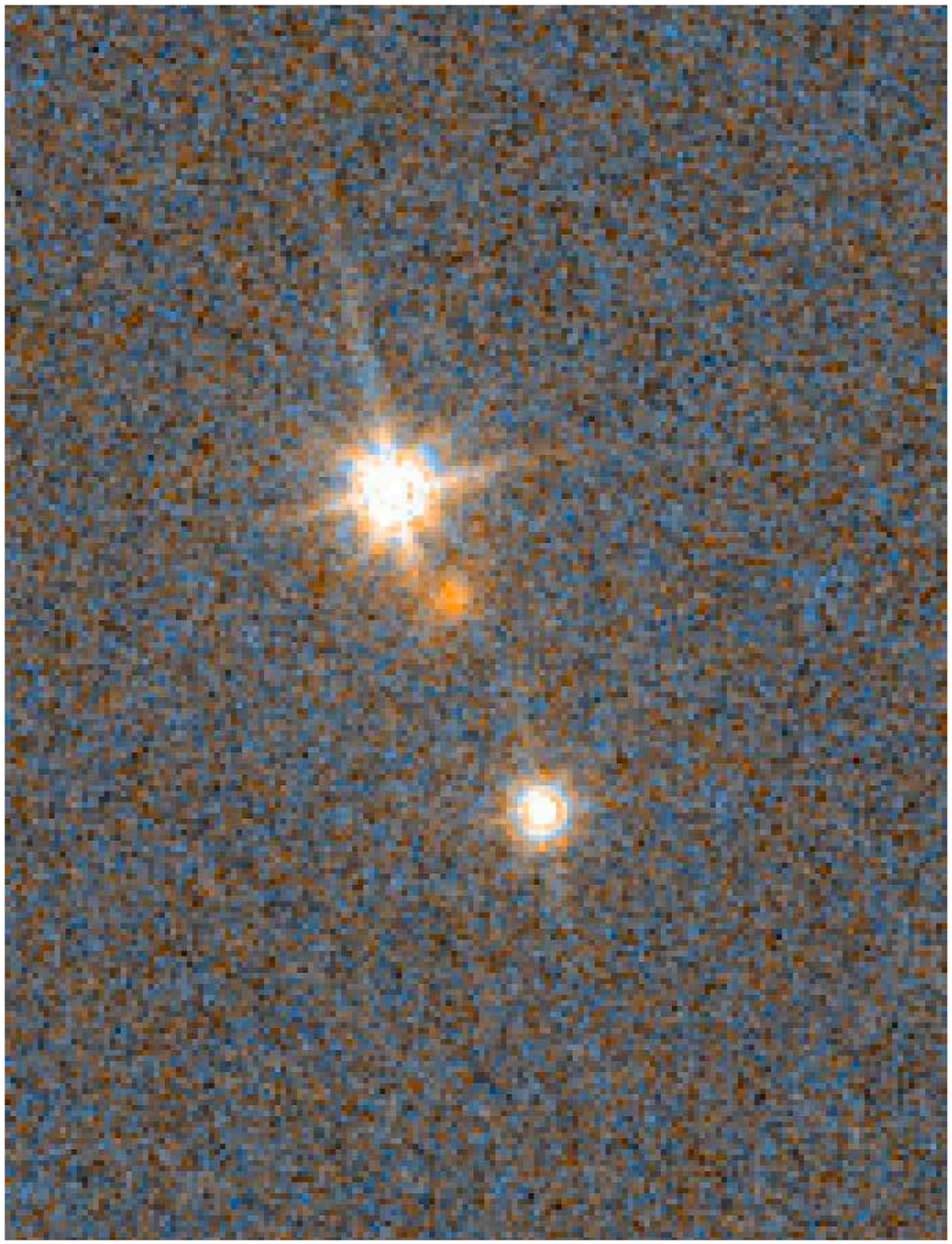
Excess of Lenses in Galactic Bulge



- 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.

[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

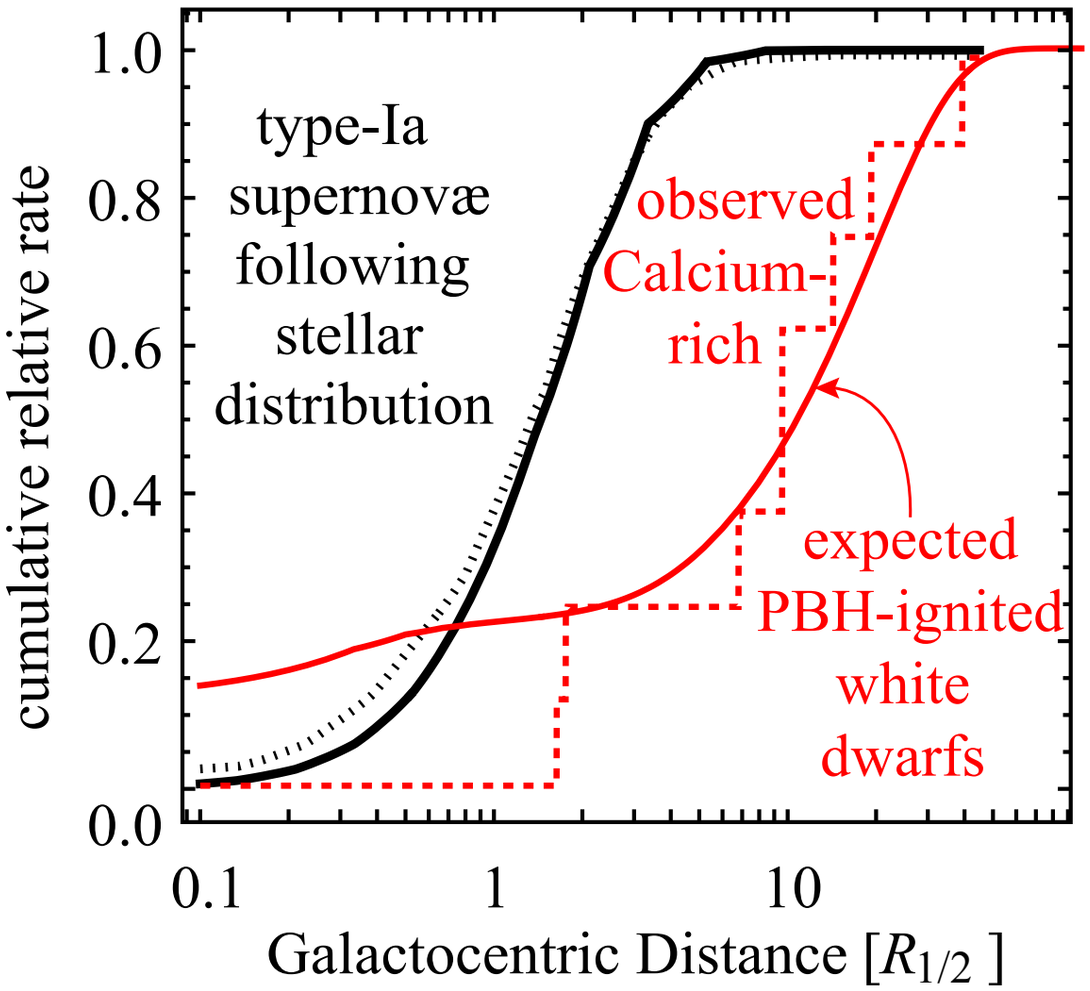
Institute for Astronomy (IfA), University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK
e-mail: mrsh@roe.ac.uk

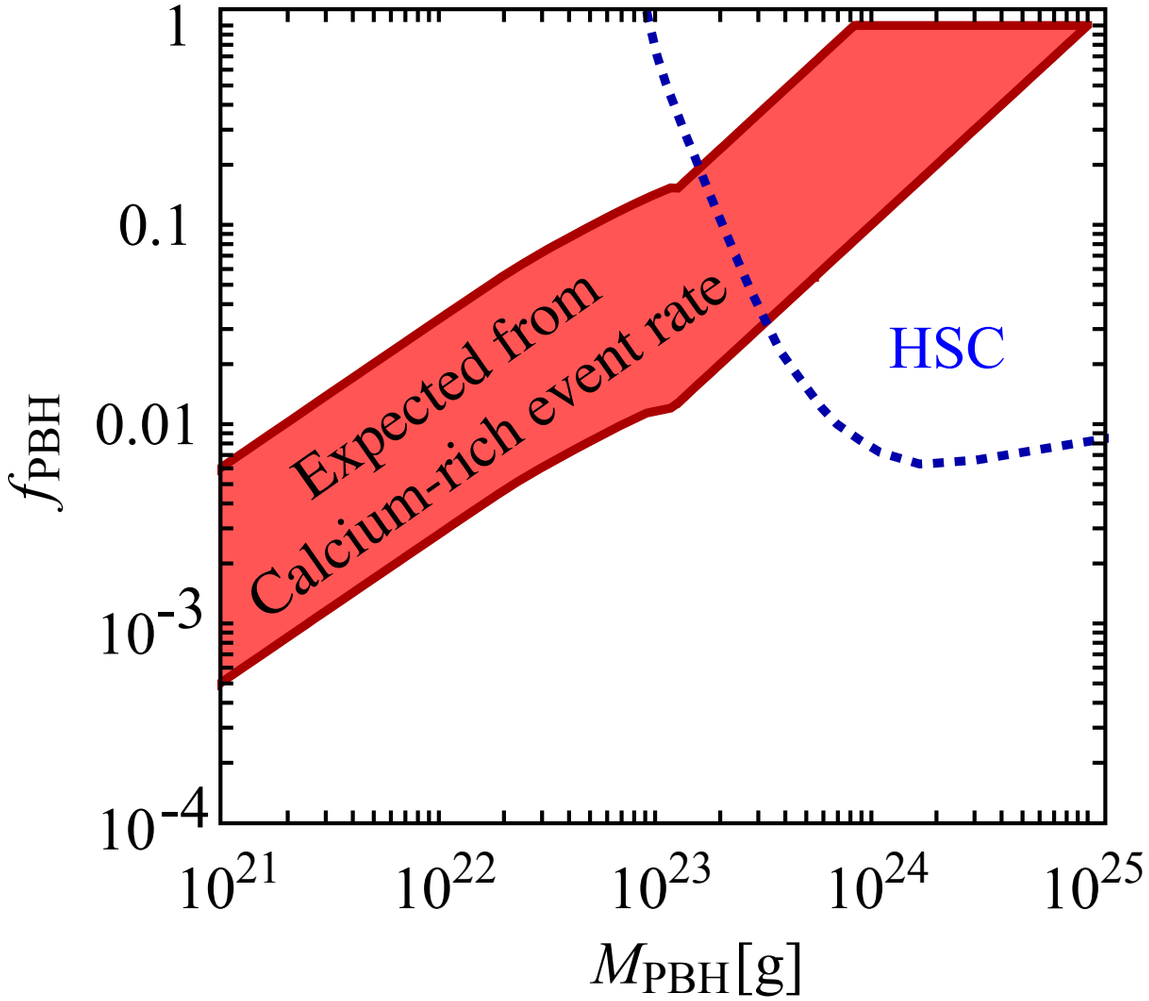
ABSTRACT

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

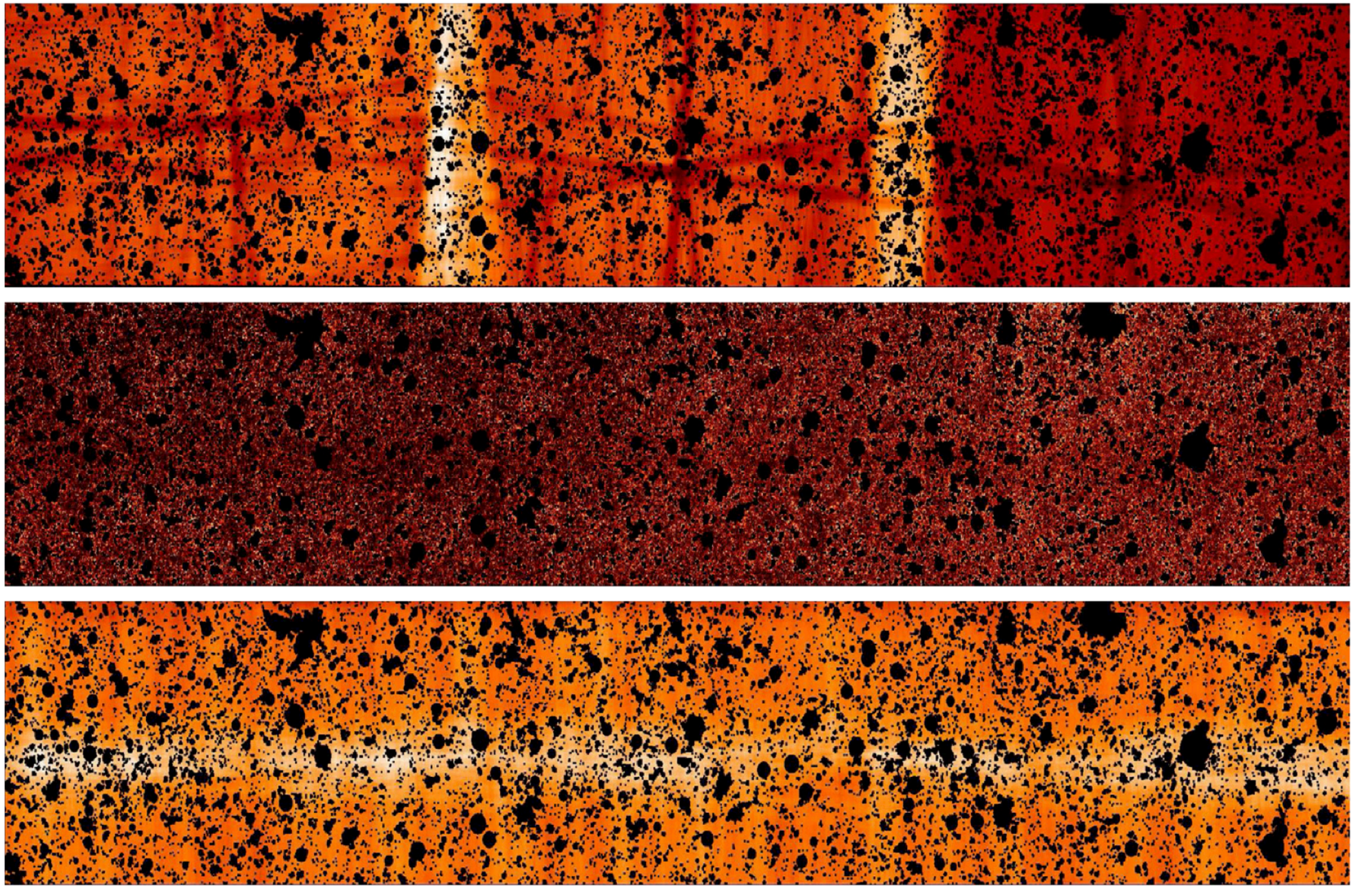
★ A supernova population of so-called calcium-rich gap transients has been shown to clearly not to follow the stellar distribution but rather a would-be compact dark matter one.





[Smirnov *et al.* 2023]

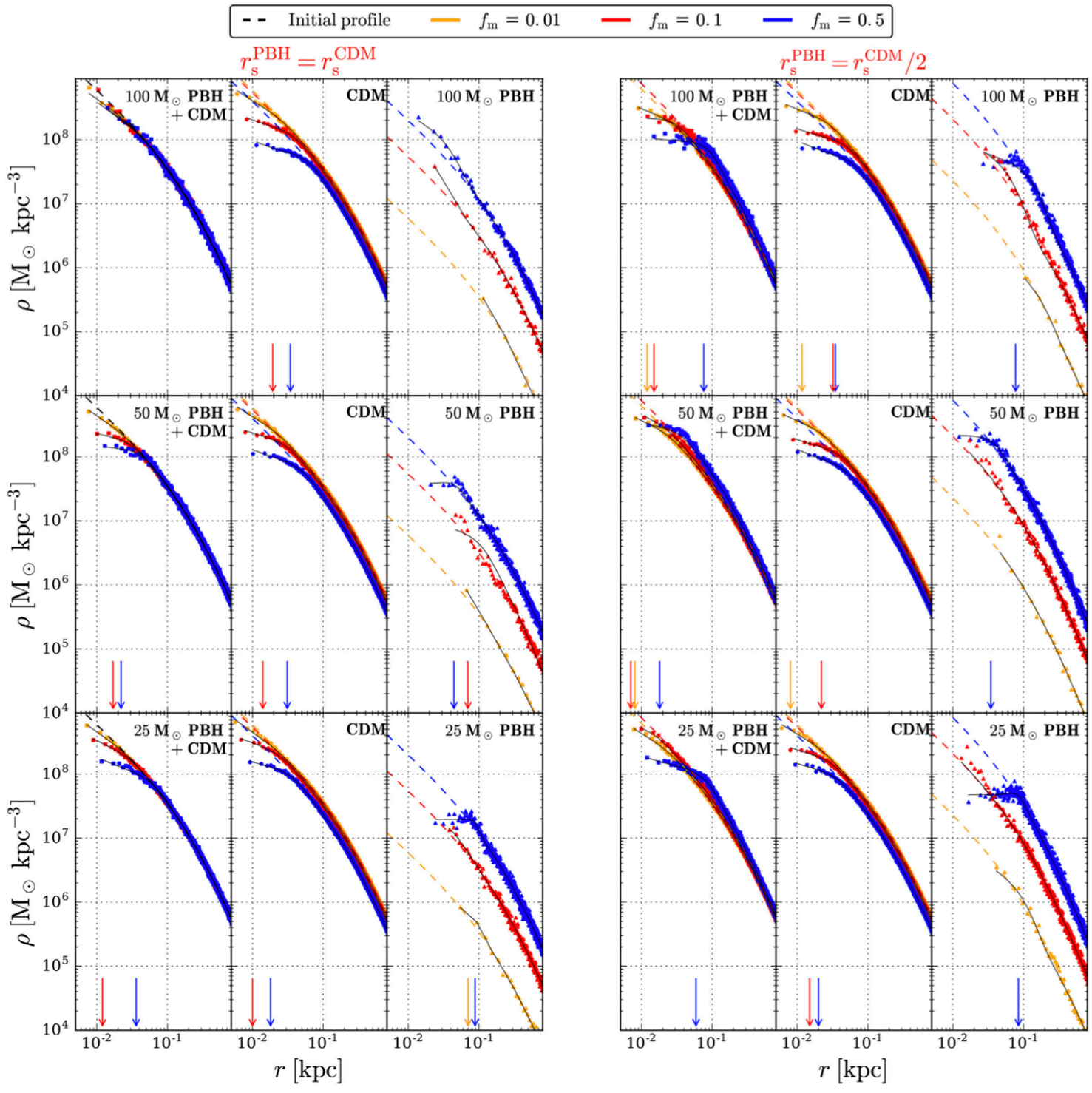
Correlations of Cosmic Infrared/X-Ray Backgrounds



[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 $M_\odot$.

GRAVITATIONAL WAVE **MERGER** DETECTIONS

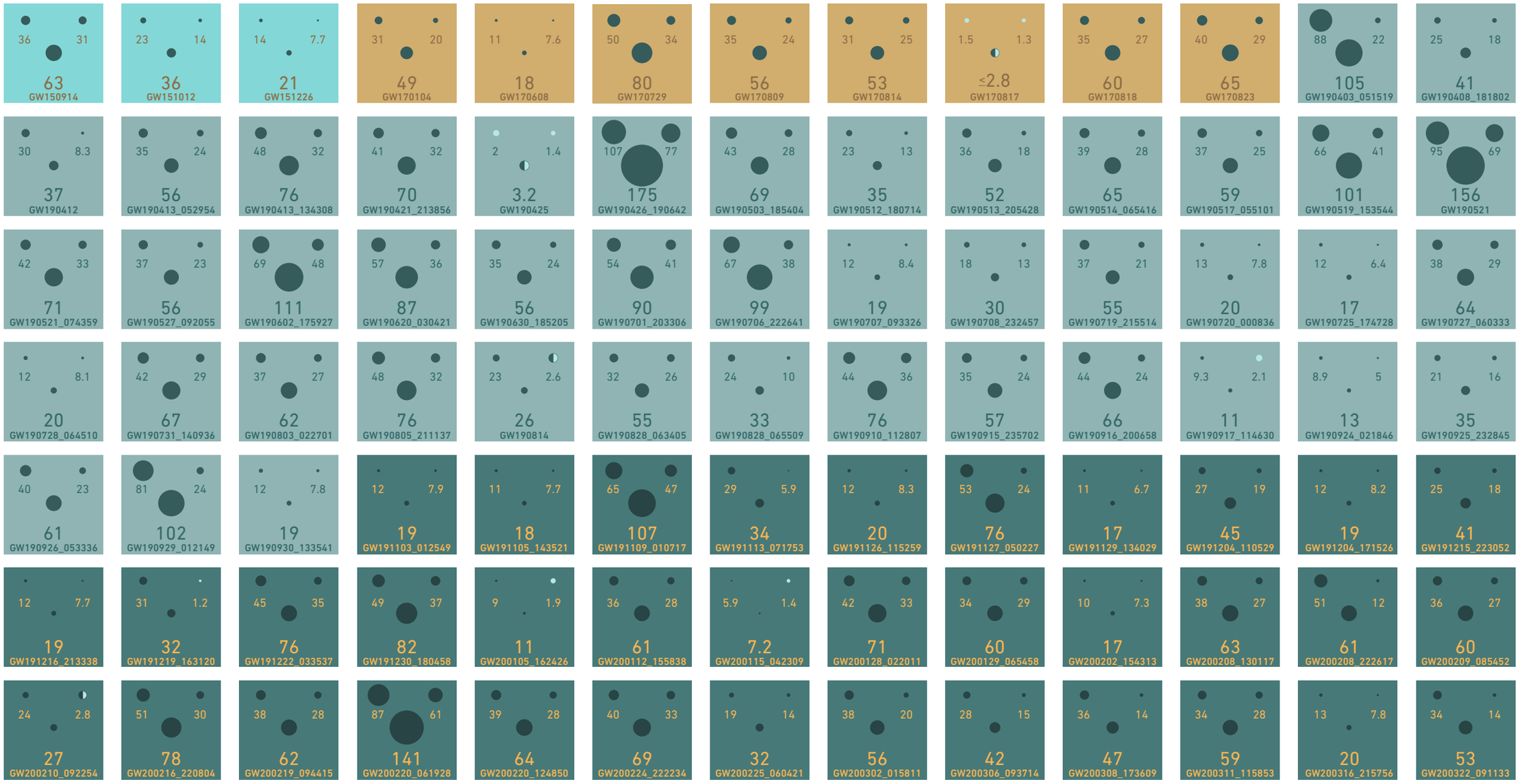
SINCE 2015

OBSERVING RUN

01 2015-2016

02 2016-2017

03a+b 2019-2020



GRAVITATIONAL WAVE **MERGER** DETECTIONS

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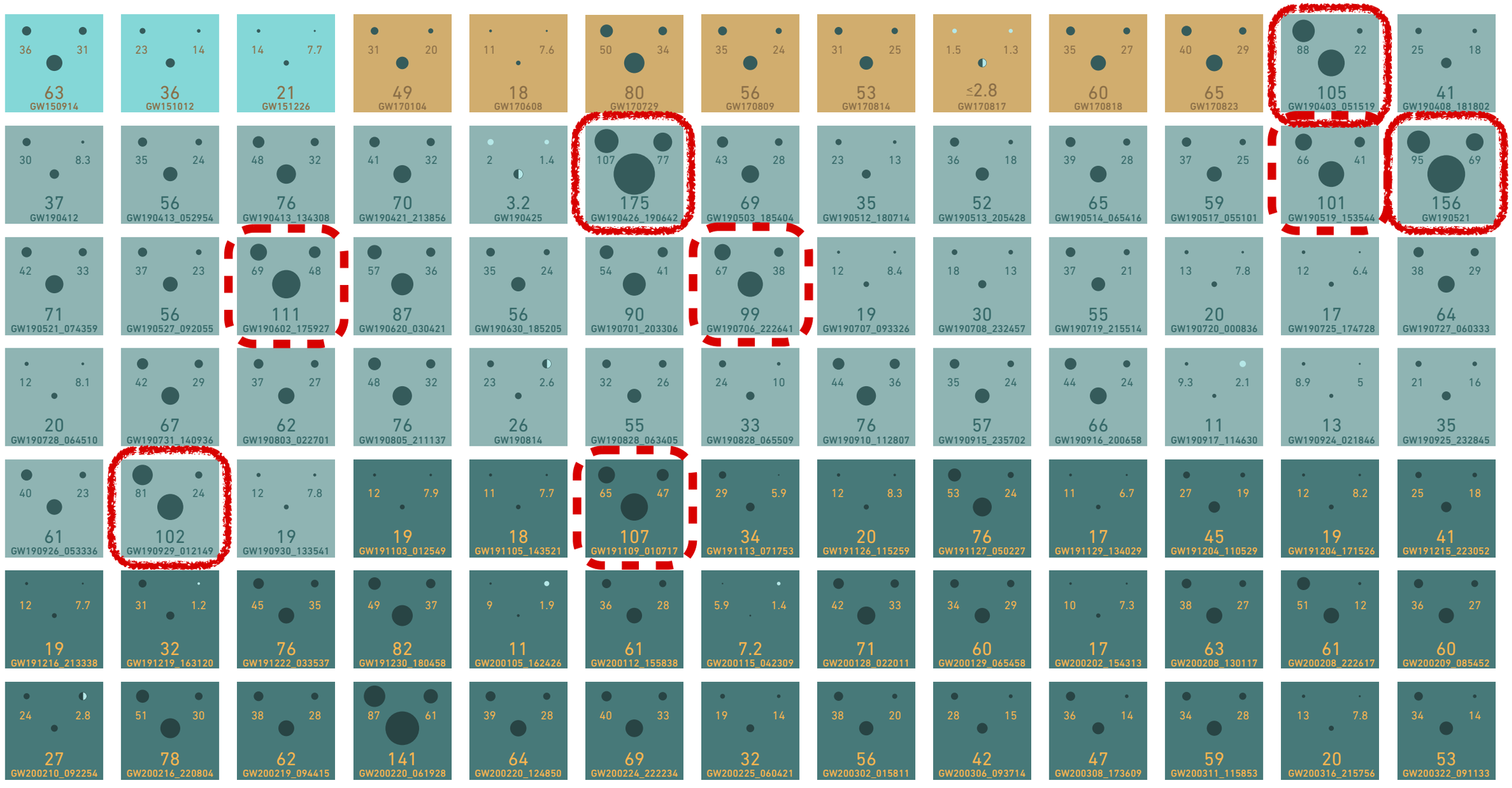


★ Black hole progenitors in the pair-instability mass gap (i.e. above ~ 60 $M_\odot$)

LIGO VIRGO KAGRA

GRAVITATIONAL WAVE **MERGER** DETECTIONS

→ SINCE 2015

OBSERVING RUN

01 2015-2016 | 02 2016-2017 | 03a+b 2019-2020

36 31 63 GW150914	23 14 36 GW151012	14 7.7 21 GW151226	31 20 49 GW170104	11 7.6 18 GW170608	50 34 80 GW170729	35 24 56 GW170809	31 25 53 GW170814	1.5 1.3 ≤2.8 GW170817	35 27 60 GW170818	40 29 65 GW170823	88 22 105 GW190403_051519	25 18 41 GW190408_181802
30 8.3 37 GW190412	35 24 56 GW190413_052954	48 32 76 GW190413_134308	41 32 70 GW190421_213856	2 1.4 3.2 GW190425	107 77 175 GW190426_190642	43 28 69 GW190503_185404	23 13 35 GW190512_180714	36 18 52 GW190513_205428	39 28 65 GW190514_065416	37 25 59 GW190517_055101	66 41 101 GW190519_153544	95 69 156 GW190521
42 33 71 GW190521_074359	37 23 56 GW190527_092055	69 48 111 GW190602_175927	57 36 87 GW190620_030421	35 24 56 GW190630_185205	54 41 90 GW190701_203306	67 38 99 GW190706_222641	12 8.4 19 GW190707_093326	18 13 30 GW190708_232457	37 21 55 GW190719_215514	13 7.8 20 GW190720_000836	12 6.4 17 GW190725_174728	38 29 64 GW190727_060333
12 8.1 20 GW190728_064510	42 29 67 GW190731_140936	37 27 62 GW190803_022701	48 32 76 GW190805_211137	23 2.6 26 GW190814	32 26 55 GW190828_063405	24 10 33 GW190828_065509	44 36 76 GW190910_112807	35 24 57 GW190915_235702	44 24 66 GW190916_200658	9.3 2.1 11 GW190917_114630	8.9 5 13 GW190924_021846	21 16 35 GW190925_232845
40 23 61 GW190926_053336	81 24 102 GW190929_012149	12 7.8 19 GW190930_133541	12 7.9 19 GW191103_012549	11 7.7 18 GW191105_143521	65 47 107 GW191109_010717	29 5.9 34 GW191113_071753	12 8.3 20 GW191126_115259	53 24 76 GW191127_050227	11 6.7 17 GW191129_134029	27 19 45 GW191204_110529	12 8.2 19 GW191204_171526	25 18 41 GW191215_223052
12 7.7 19 GW191216_213338	31 1.2 32 GW191219_163120	45 35 76 GW191222_033537	49 37 82 GW191230_180458	9 1.9 11 GW200105_162426	36 28 61 GW200112_155838	5.9 1.4 7.2 GW200115_042309	42 33 71 GW200128_022011	34 29 60 GW200129_065458	10 7.3 17 GW200202_154313	38 27 63 GW200208_130117	51 12 61 GW200208_222617	36 27 60 GW200209_085452
24 2.8 27 GW200210_092254	51 30 78 GW200216_220804	38 28 62 GW200219_094415	87 61 141 GW200220_061928	39 28 64 GW200220_124850	40 33 69 GW200224_222234	19 14 32 GW200225_060421	38 20 56 GW200302_015811	28 15 42 GW200306_093714	36 14 47 GW200308_173609	34 28 59 GW200311_115853	13 7.8 20 GW200316_215756	34 14 53 GW200322_091133

★ 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

OBSERVING RUN

01 2015-2016 | 02 2016-2017 | 03a+b 2019-2020

36 31 63 GW150914	23 14 36 GW151012	14 7.7 21 GW151226	31 20 49 GW170104	11 7.6 18 GW170608	50 34 80 GW170729	35 24 56 GW170809	31 25 53 GW170814	1.5 1.3 ≤2.8 GW170817	35 27 60 GW170818	40 29 65 GW170823	88 22 105 GW190403_051519	25 18 41 GW190408_181802
30 8.3 37 GW190412	35 24 56 GW190413_052954	48 32 76 GW190413_134308	41 32 70 GW190421_213856	2 1.4 3.2 GW190425	107 77 175 GW190426_190642	43 28 69 GW190503_185404	23 13 35 GW190512_180714	36 18 52 GW190513_205428	39 28 65 GW190514_065416	37 25 59 GW190517_055101	66 41 101 GW190519_153544	95 69 156 GW190521
42 33 71 GW190521_074359	37 23 56 GW190527_092055	69 48 111 GW190602_175927	57 36 87 GW190620_030421	35 24 56 GW190630_185205	54 41 90 GW190701_203306	67 38 99 GW190706_222641	12 8.4 19 GW190707_093326	18 13 30 GW190708_232457	37 21 55 GW190719_215514	13 7.8 20 GW190720_000836	12 6.4 17 GW190725_174728	38 29 64 GW190727_060333
12 8.1 20 GW190728_064510	42 29 67 GW190731_140936	37 27 62 GW190803_022701	48 32 76 GW190805_211137	23 2.6 26 GW190814	32 26 55 GW190828_063405	24 10 33 GW190828_065509	44 36 76 GW190910_112807	35 24 57 GW190915_235702	44 24 66 GW190916_200658	9.3 2.1 11 GW190917_114630	8.9 5 13 GW190924_021846	21 16 35 GW190925_232845
40 23 61 GW190926_053336	81 24 102 GW190929_012149	12 7.8 19 GW190930_133541	12 7.9 19 GW191103_012549	11 7.7 18 GW191105_143521	65 47 107 GW191109_010717	29 5.9 34 GW191113_071753	12 8.3 20 GW191126_115259	53 24 76 GW191127_050227	11 6.7 17 GW191129_134029	27 19 45 GW191204_110529	12 8.2 19 GW191204_171526	25 18 41 GW191215_223052
12 7.7 19 GW191216_213338	31 1.2 32 GW191219_163120	45 35 76 GW191222_033537	49 37 82 GW191230_180458	9 1.9 11 GW200105_162426	36 28 61 GW200112_155838	5.9 1.4 7.2 GW200115_042309	42 33 71 GW200128_022011	34 29 60 GW200129_065458	10 7.3 17 GW200202_154313	38 27 63 GW200208_130117	51 12 61 GW200208_222617	36 27 60 GW200209_085452
24 2.8 27 GW200210_092254	51 30 78 GW200216_220804	38 28 62 GW200219_094415	87 61 141 GW200220_061928	39 28 64 GW200220_124850	40 33 69 GW200224_222234	19 14 32 GW200225_060421	38 20 56 GW200302_015811	28 15 42 GW200306_093714	36 14 47 GW200308_173609	34 28 59 GW200311_115853	13 7.8 20 GW200316_215756	34 14 53 GW200322_091133

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

LIGO VIRGO KAGRA

GRAVITATIONAL WAVE **MERGER** DETECTIONS

→ SINCE 2015

The Astrophysical Journal Letters, 896:L44 (20pp), 2020 June 20 https://doi.org/10.3847/2041-8213/ab960f

OPEN ACCESS

CrossMark

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

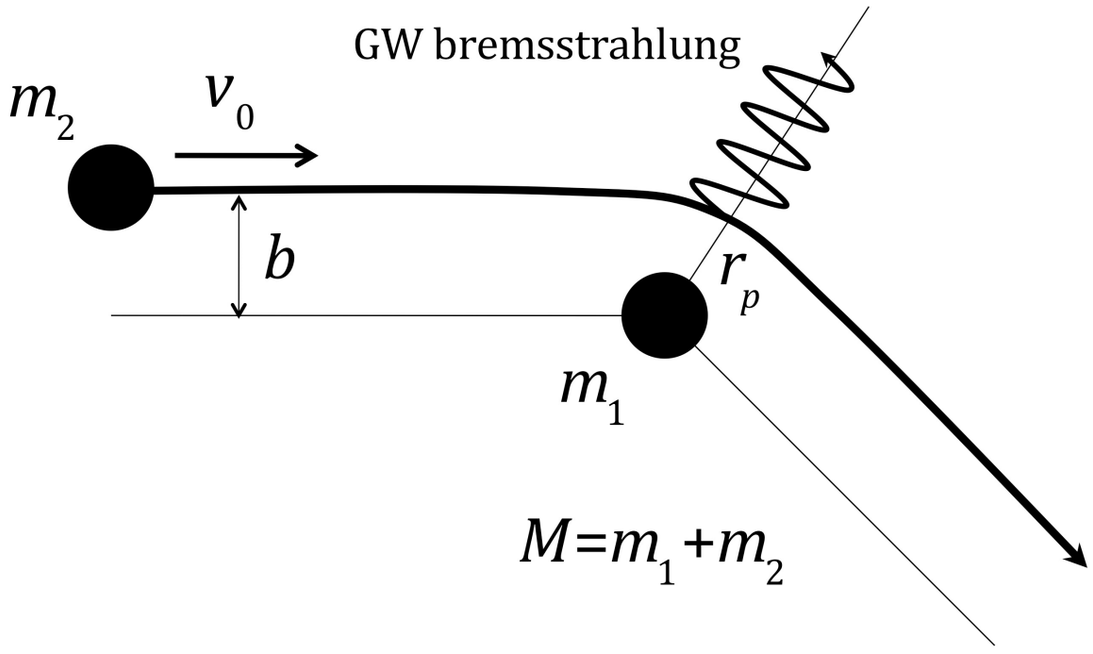
★ Five strong subsolar candidates with SNR > 8 and a FAR < 2 yr^{-1}

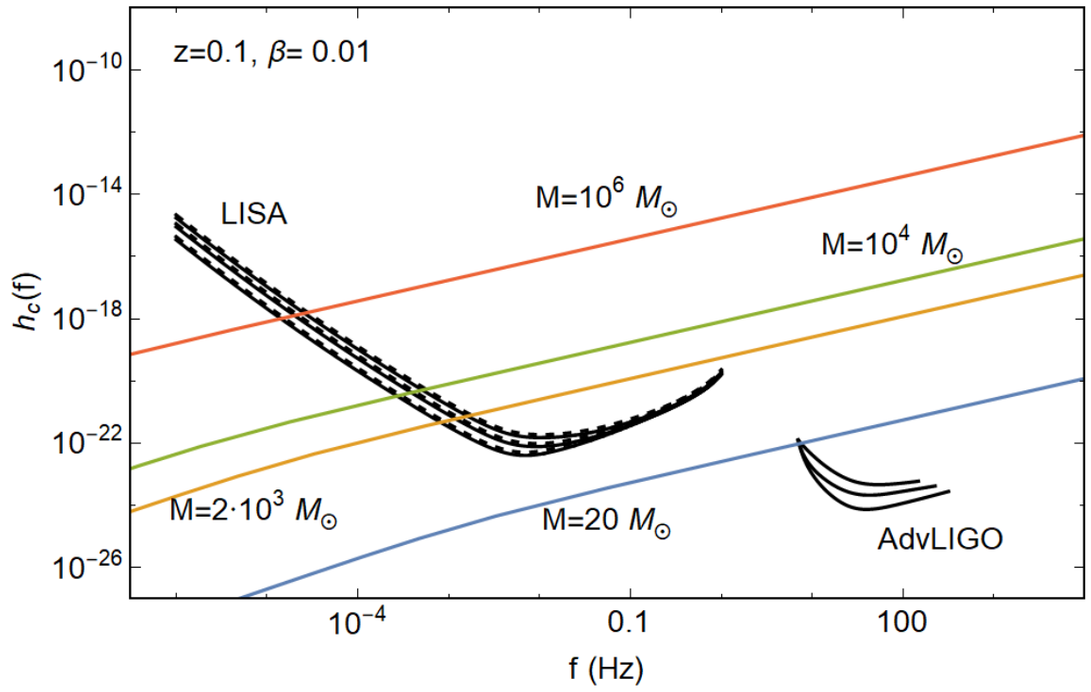
★ Possibly the first confirmed detection of a subsolar mass PBH with the next 24 months!

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

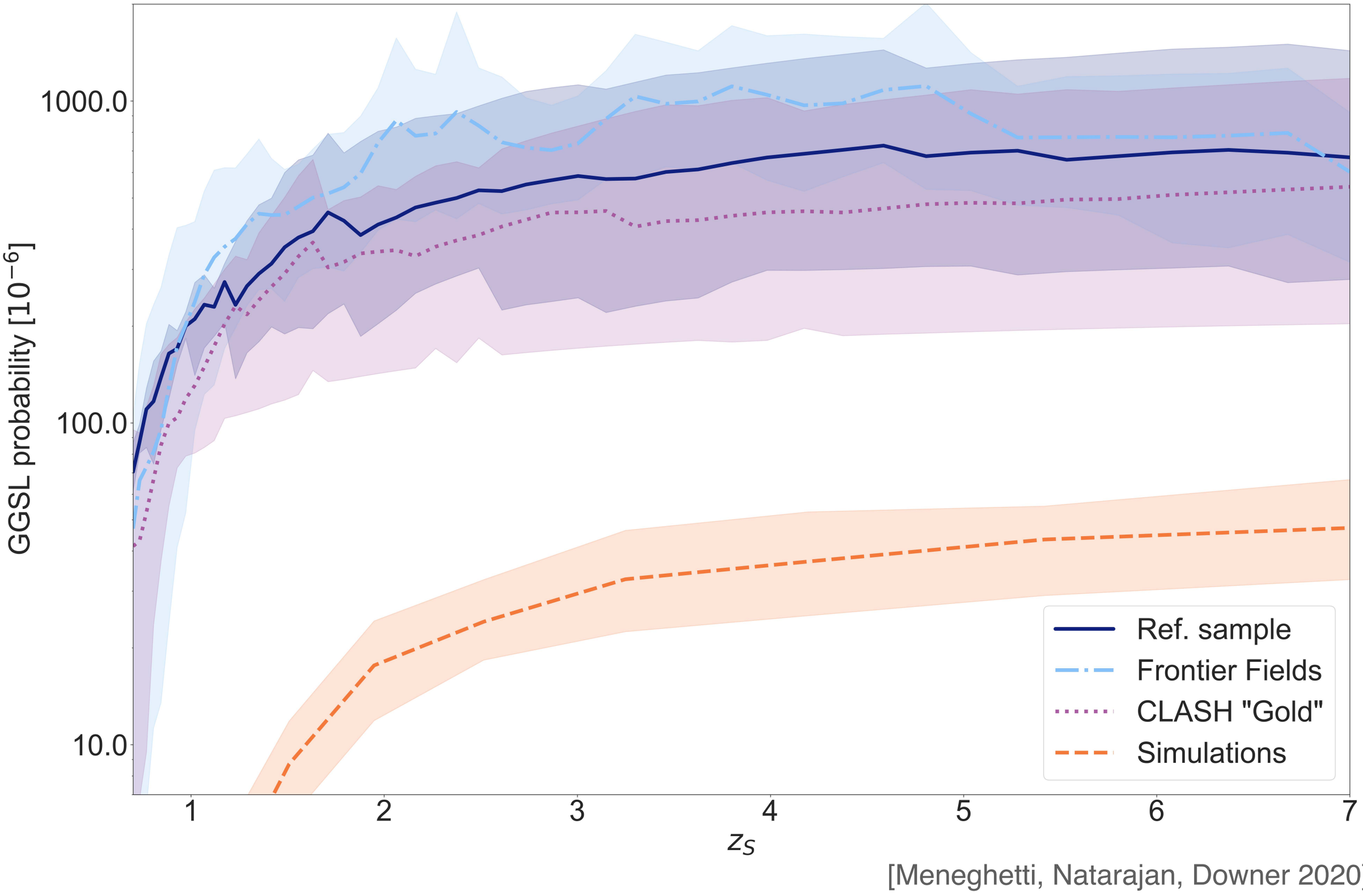
- Gravitational-wave emission from hyperbolic PBH encounters.





[Garcia-Bellido & Nesseris 2017]

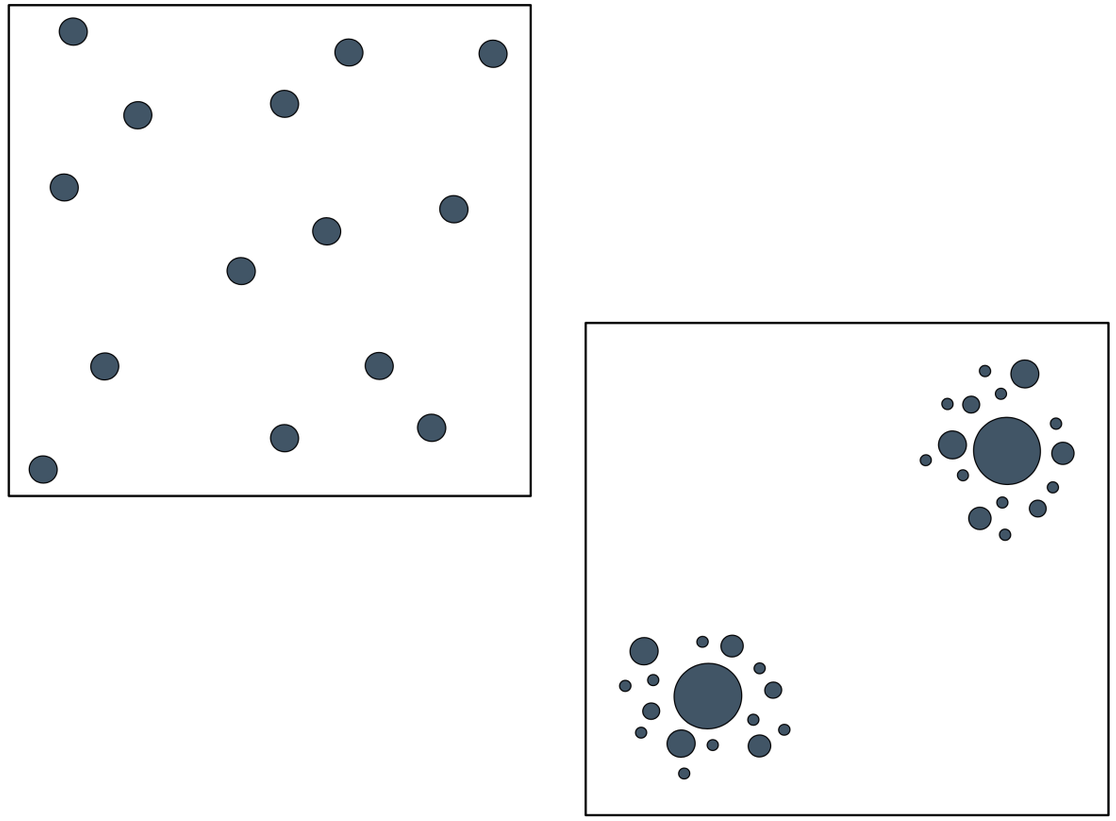
Evidence of Dark Matter Clumping with HST



[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!

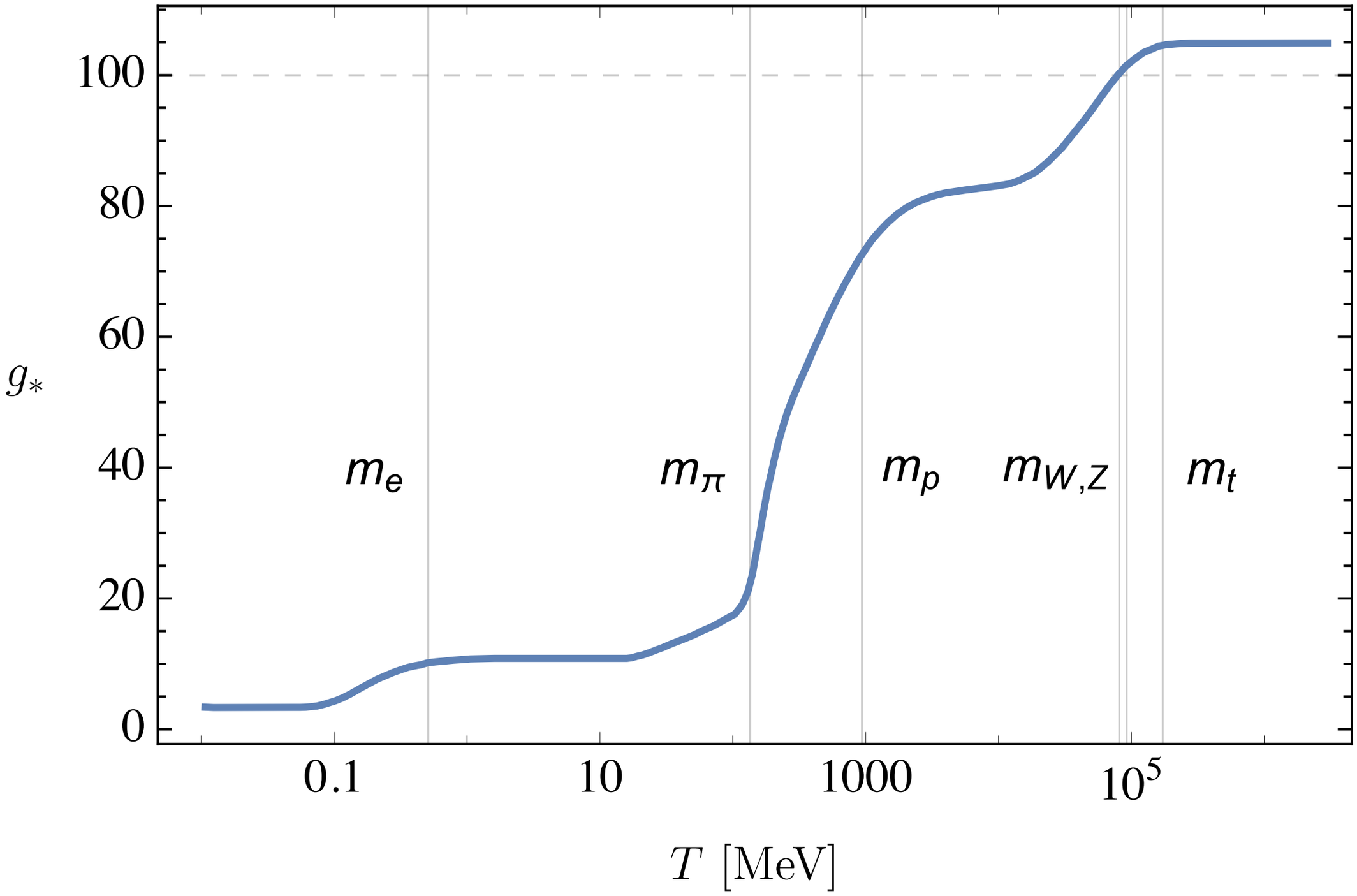
Further Reasons for PBHs

- Primordial black holes could furthermore explain
  - high-redshift galaxy candidates (up to $z = 16$!)
  - MACHO microlensing results
  - Seeds for supermassive black holes
  - fast radio bursts
  - missing pulsars
  - ...

A Unified Scenario

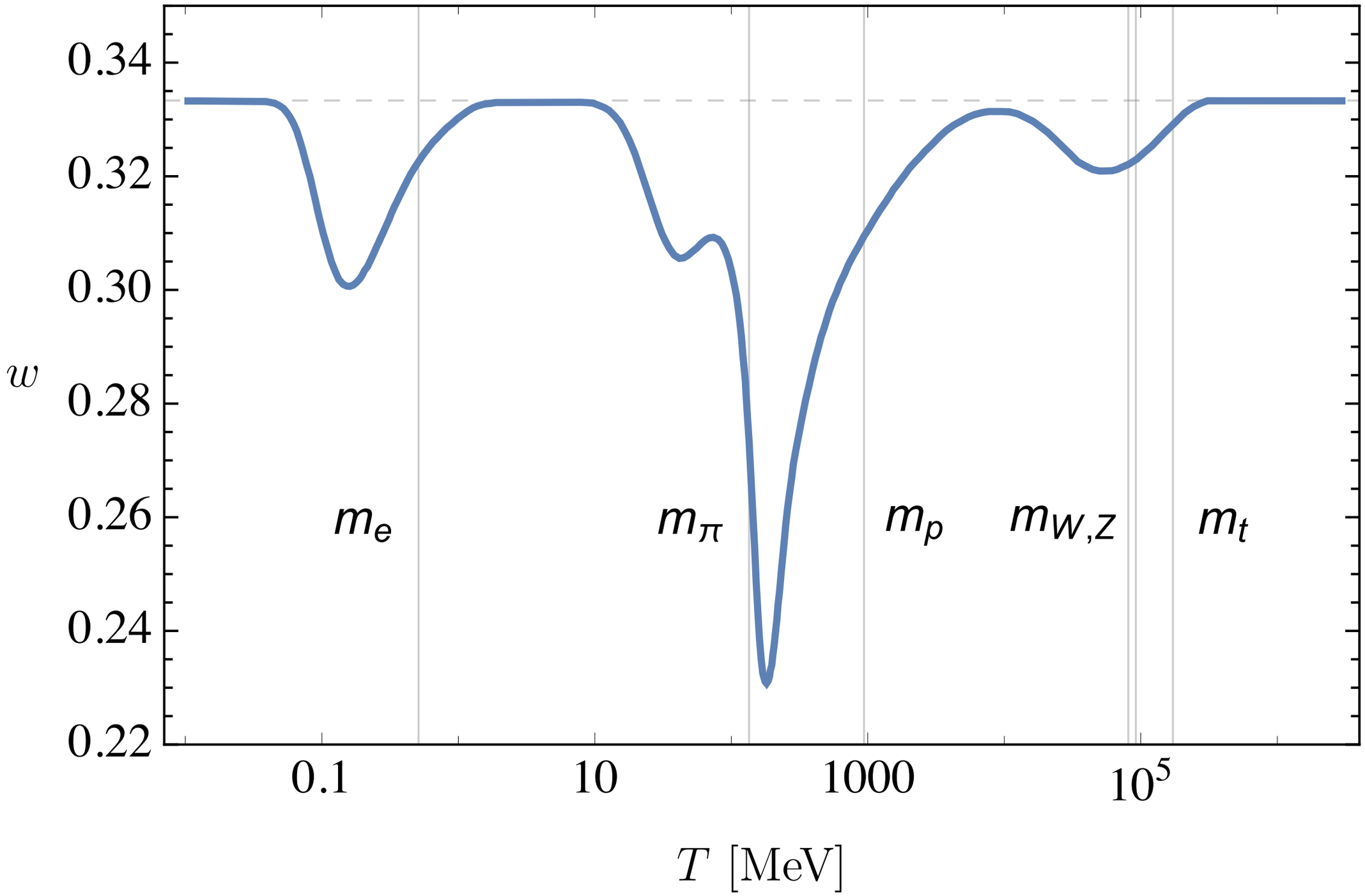
Thermal History of the Universe— Degrees of Freedom

★ 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:

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

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]

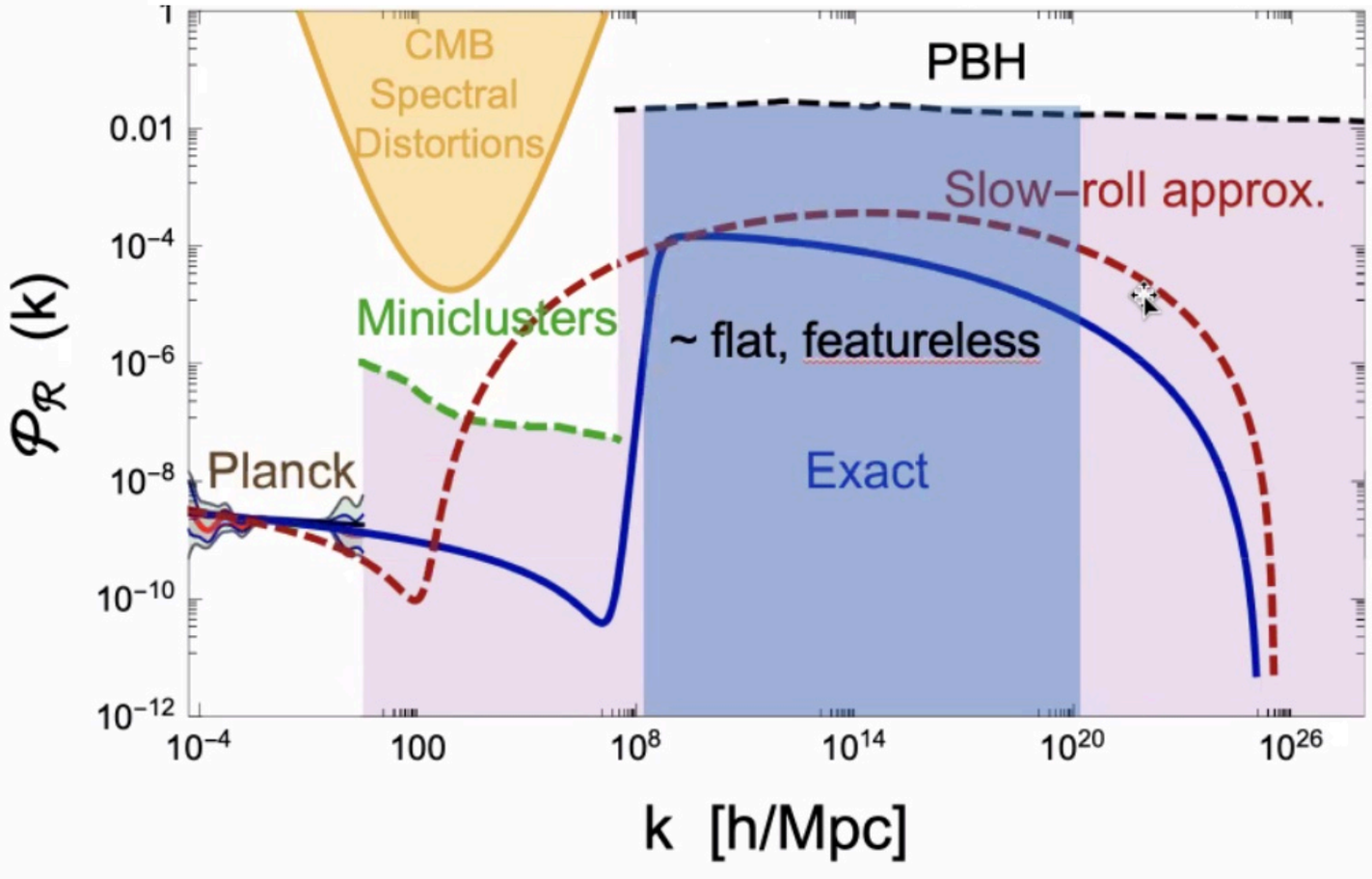
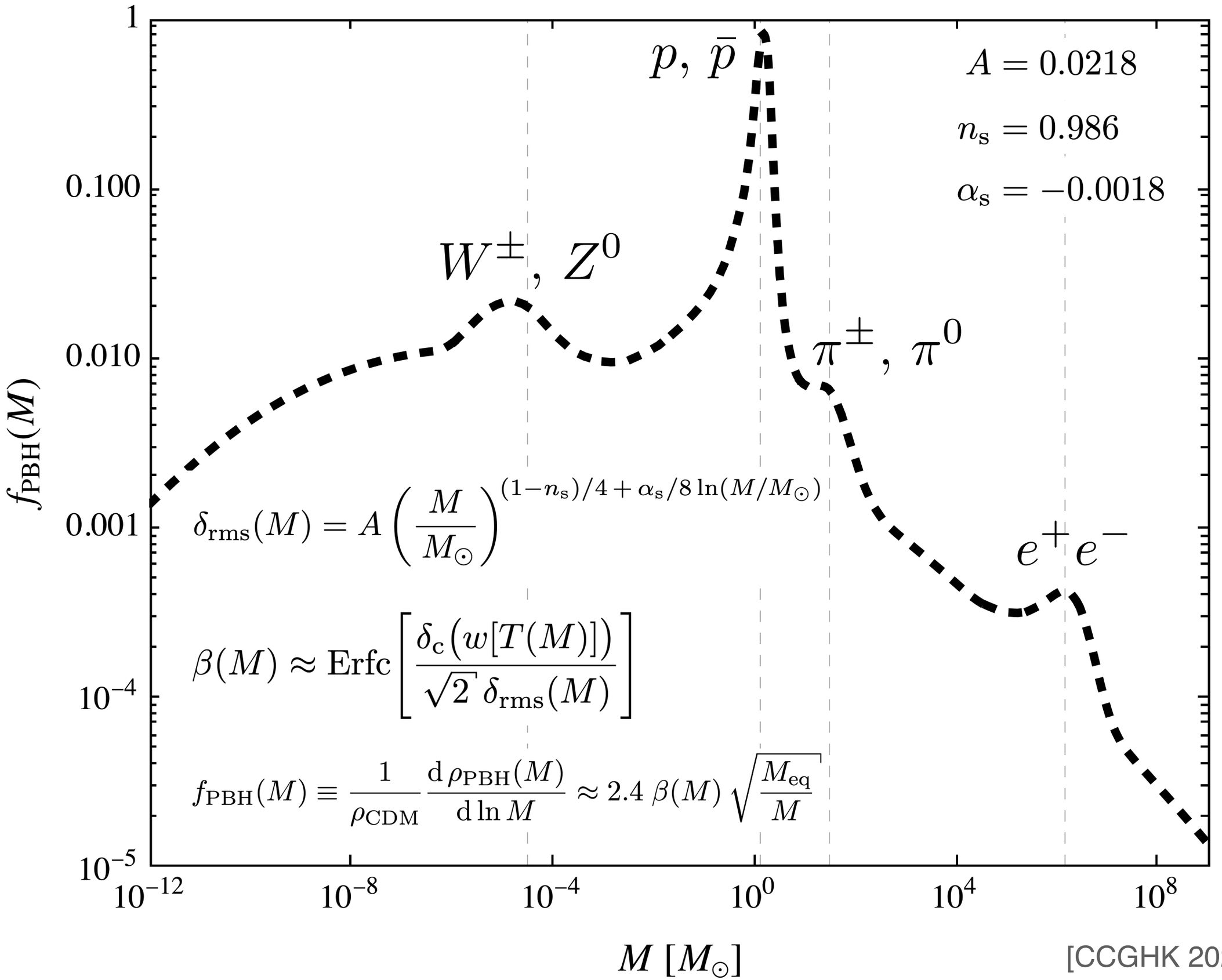


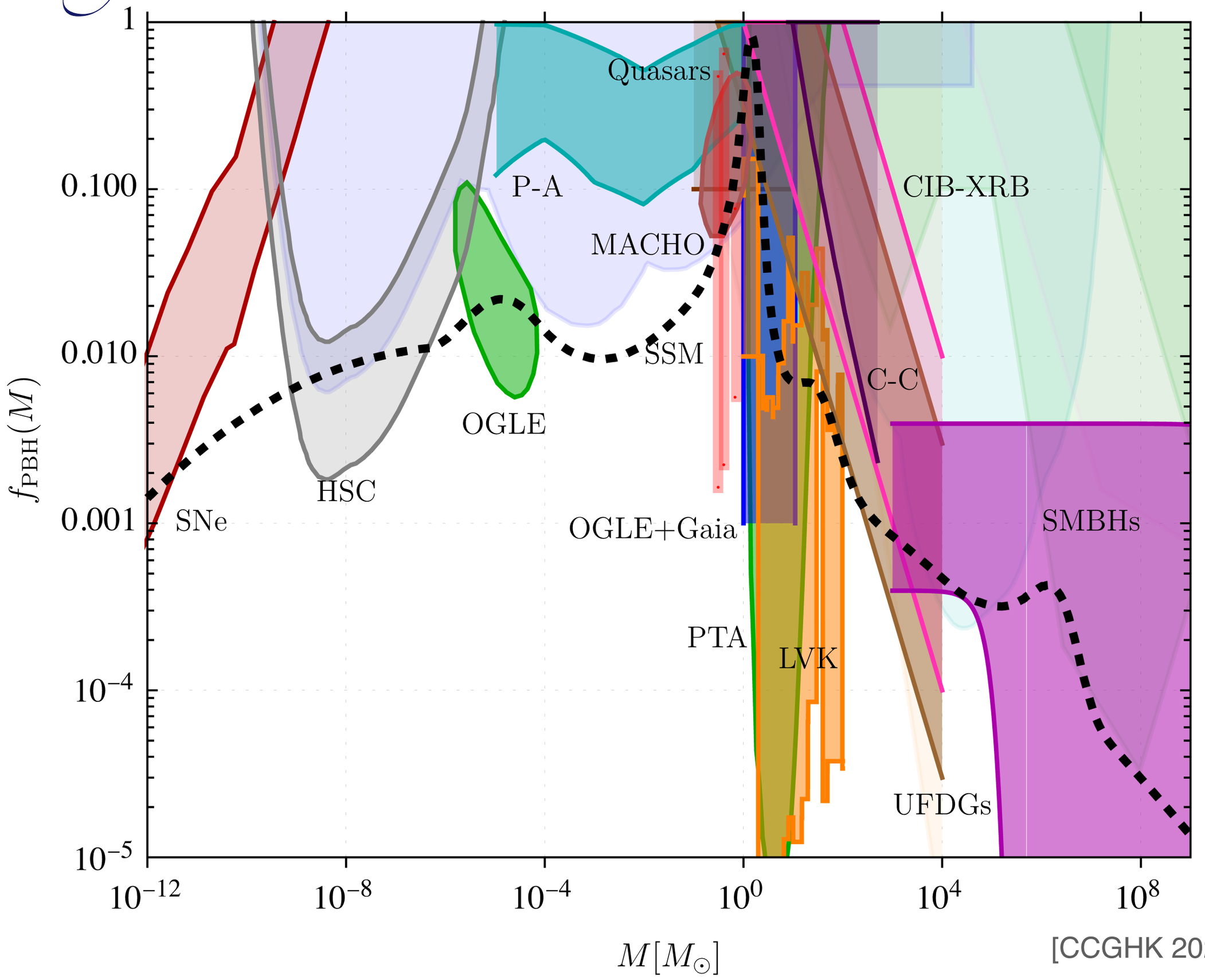
Figure from García-Bellido

PBH Mass Function



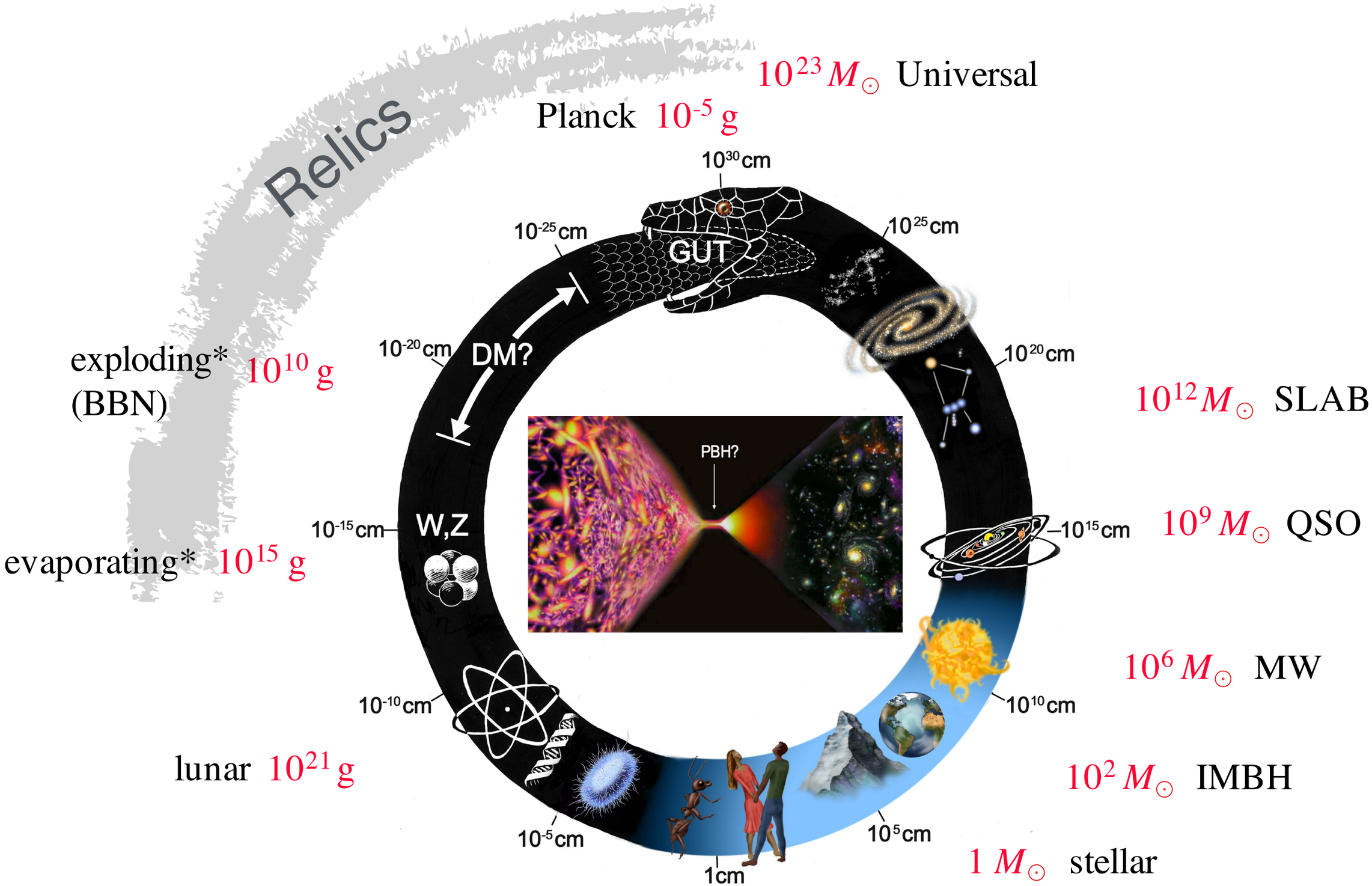
[CCGHK 2023]

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