Primordial Black Holes as Dark Matter

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The Dark Side of the Universe

Sydney, 5th of December 2022

A Diplomatic Remark:*

There is a distinction of primordial black holes being *the* dark matter (ie. all of it) or a part of it; the latter could well be both *microscopic* and *macroscopic*.

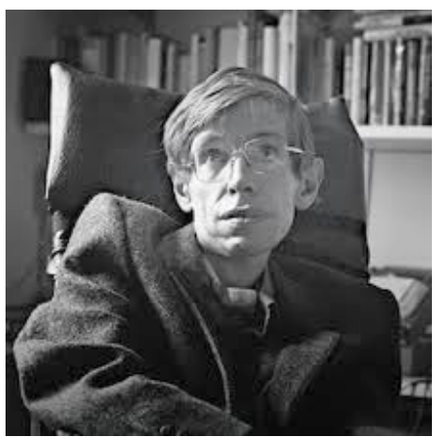
*since most conference participants work on particle dark matter

What are Primordial Black Holes (PBHs)?

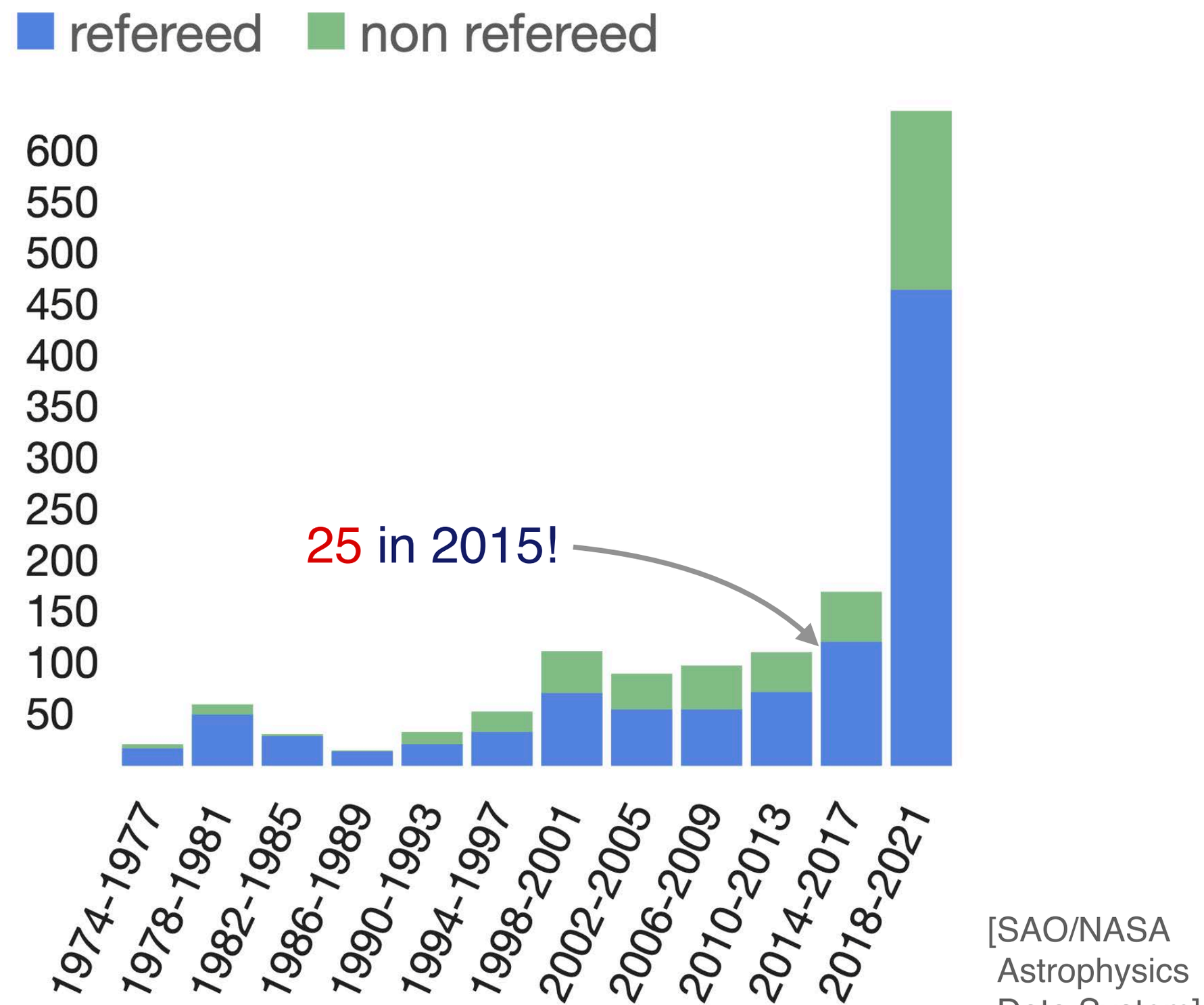
- ★ Black holes formed in the early Universe (in particular: *non-stellar*).

- ★ 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 (nearly 2000 papers to date).



Primordial Black Holes are Popular!

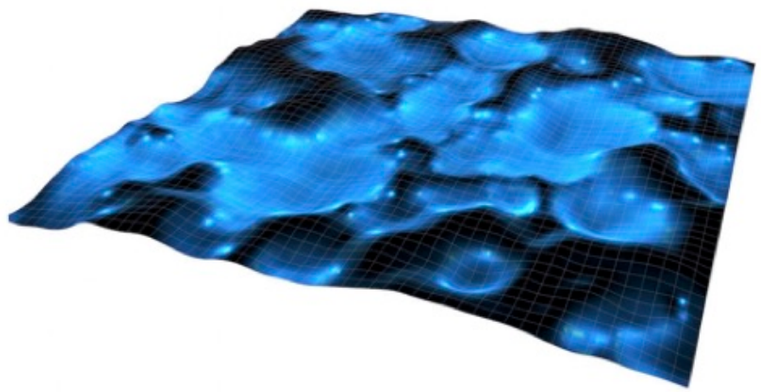


[SAO/NASA Astrophysics Data System]

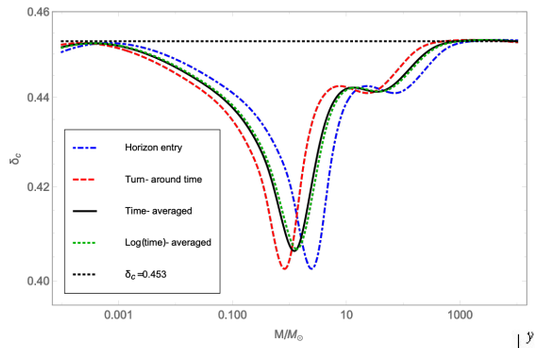
Primordial Black Hole Formation

PBH Formation Mechanisms

★ Large density perturbations (inflation)

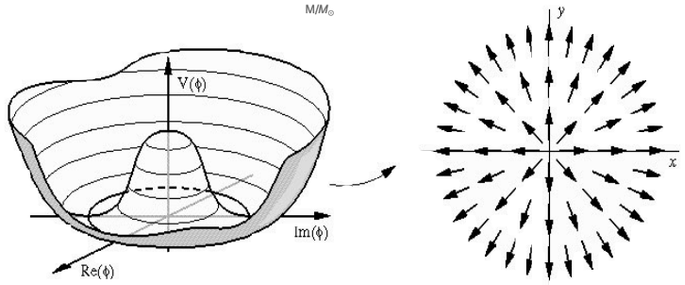


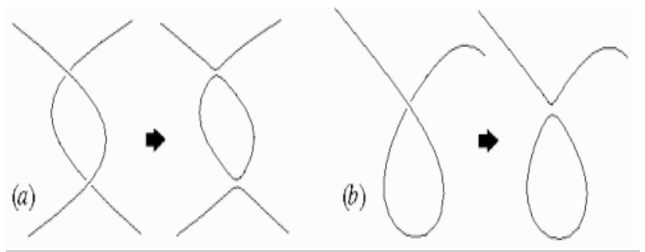
★ Pressure reduction



[Byrnes *et al.* 2018]

★ Cosmic string loops

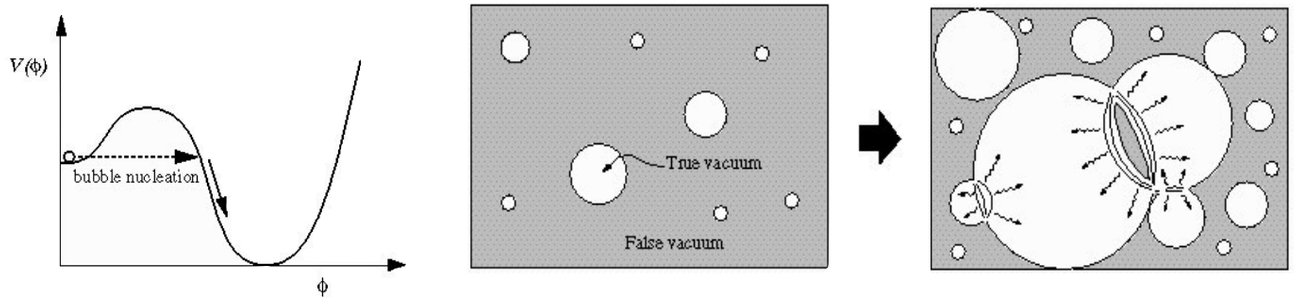




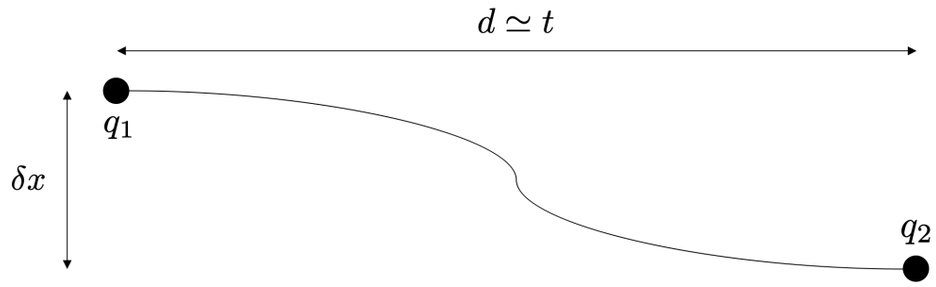
http://www.damtp.cam.ac.uk/research/gr/public/cs_phase.html

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

★ Bubble collisions

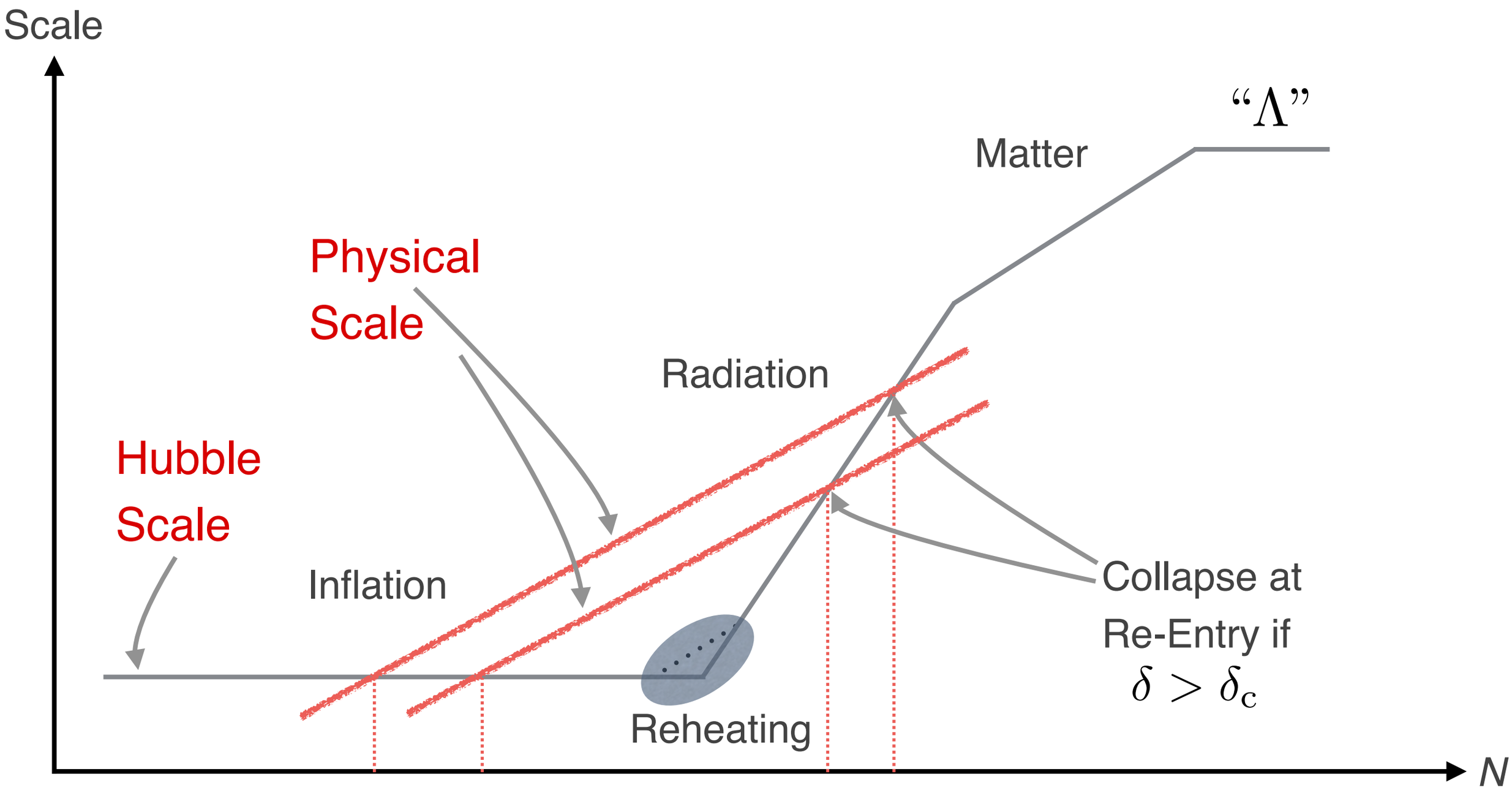


★ Quark confinement

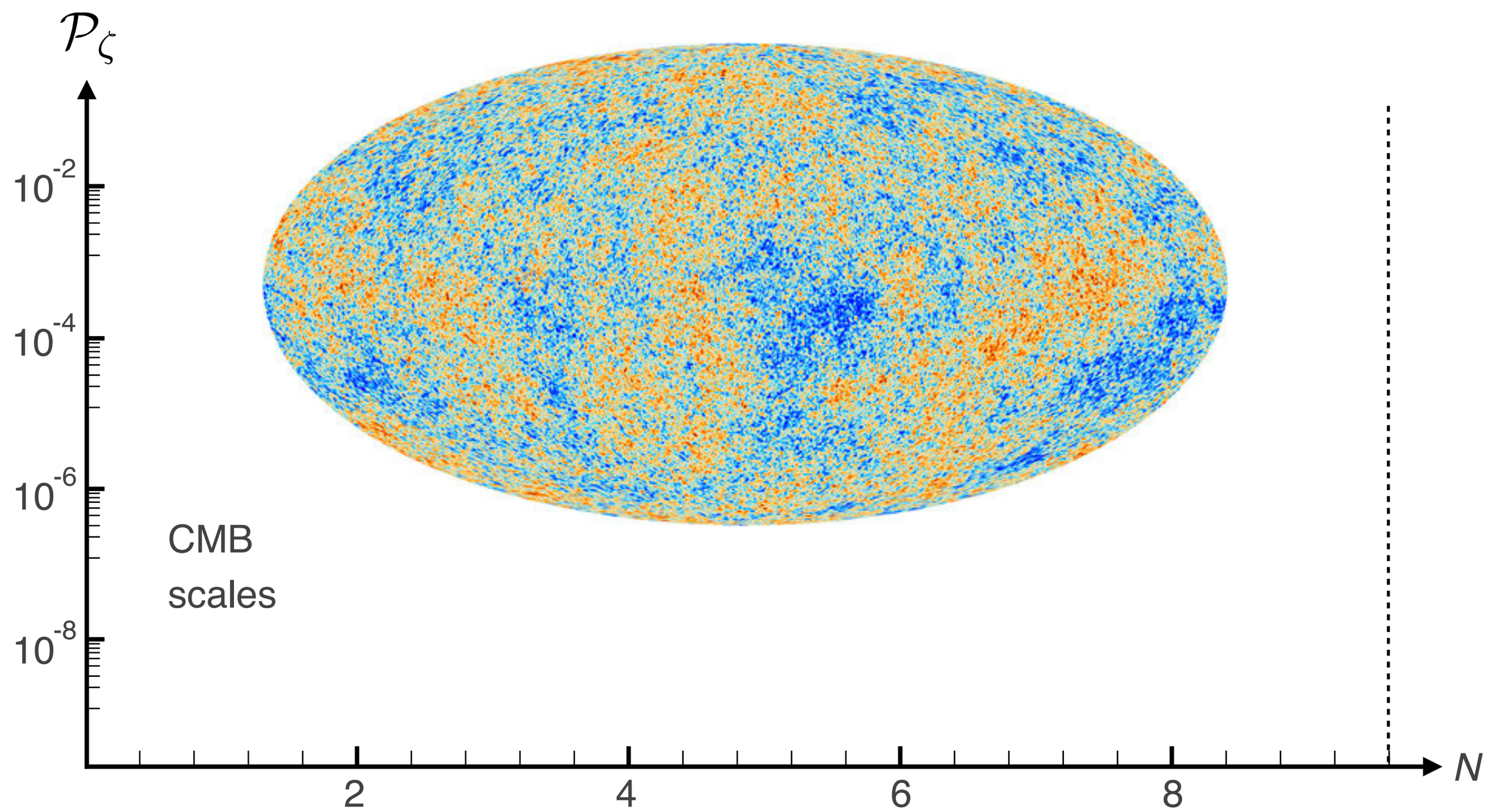


★ Q-balls, Multiverse...

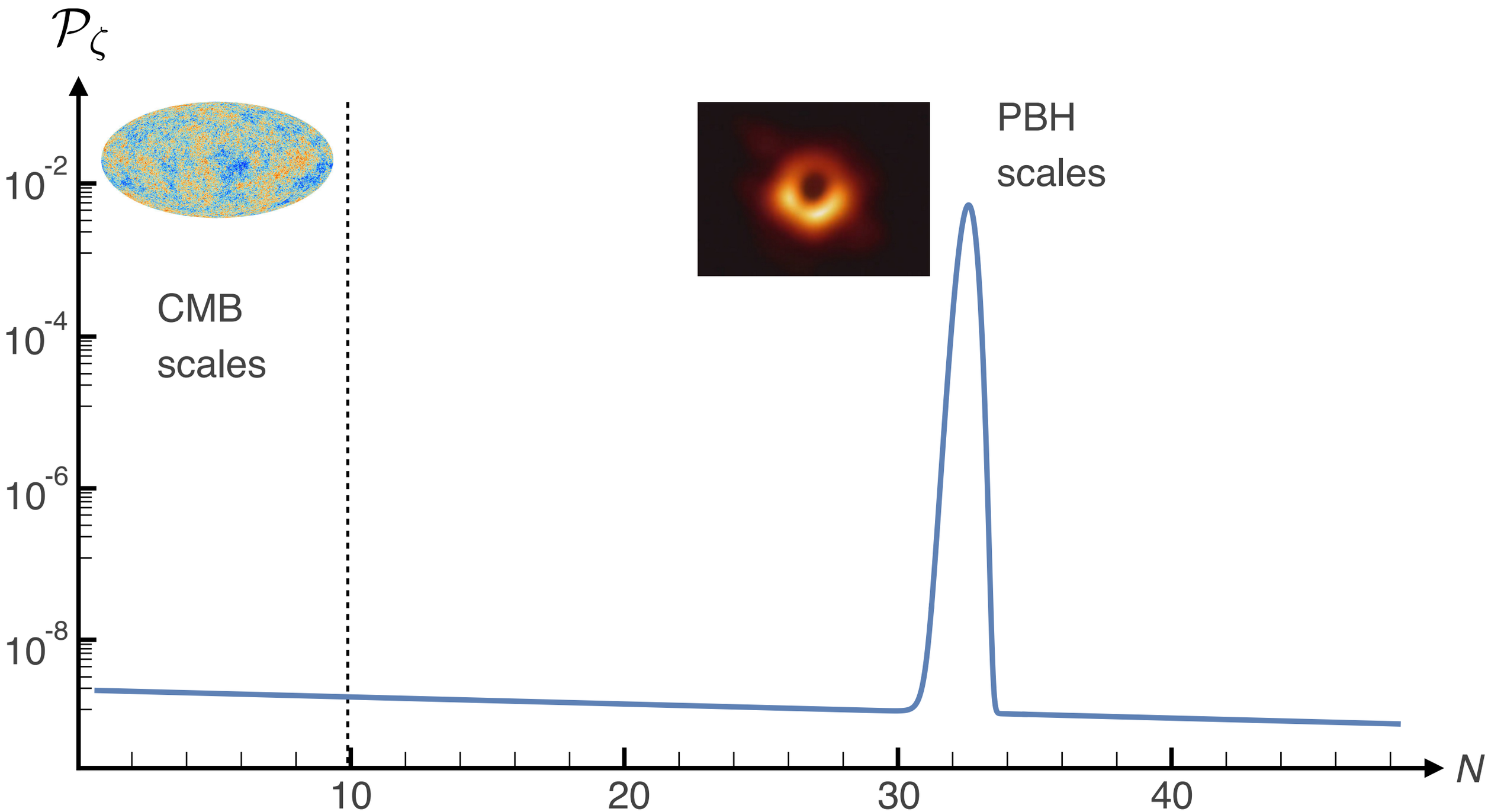
PBH Formation from Inflationary Overdensities



PBH Formation — Scales



PBH Formation — Scales

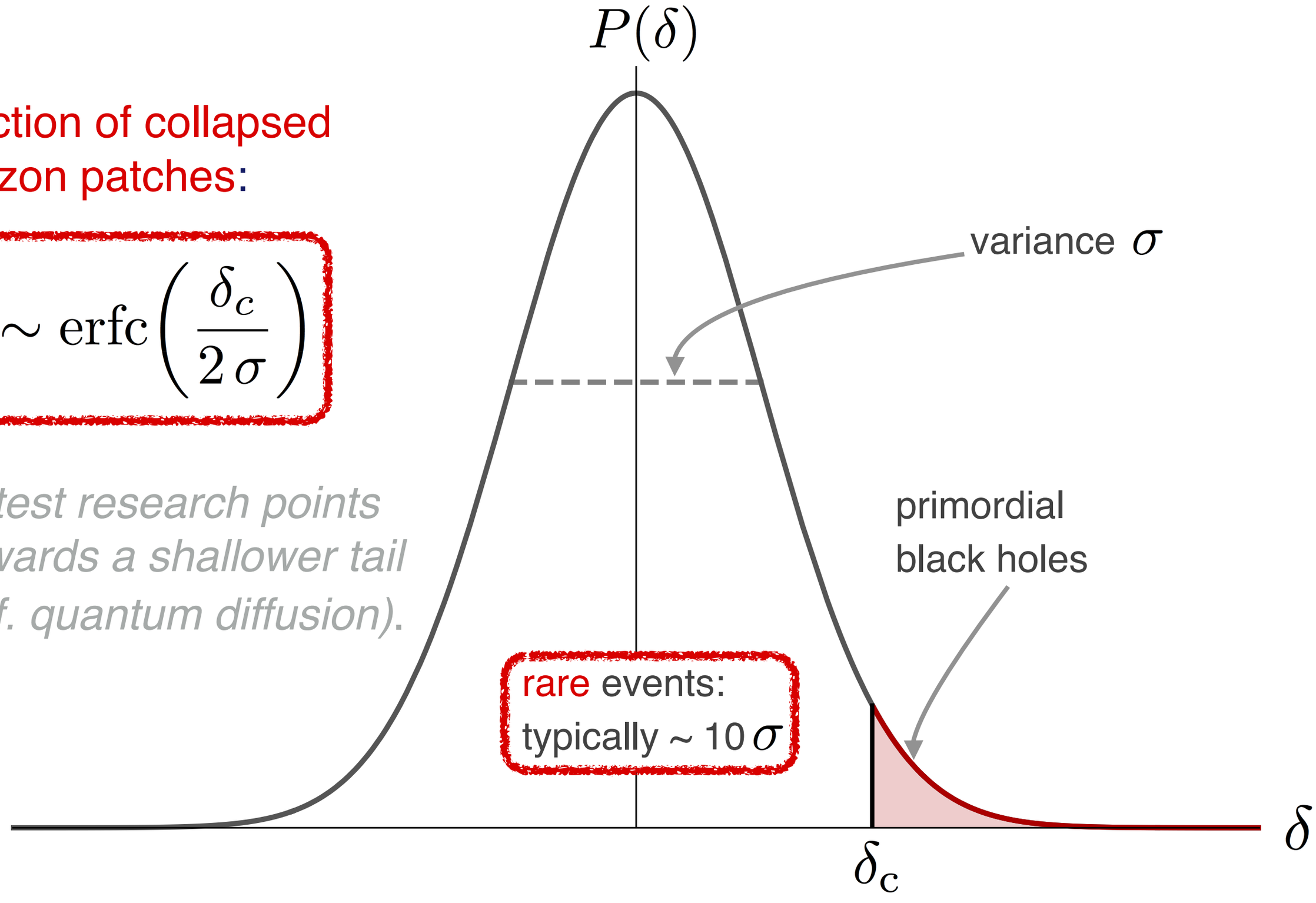


PBH Formation — Rare Events

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).



PBH — Some Numbers

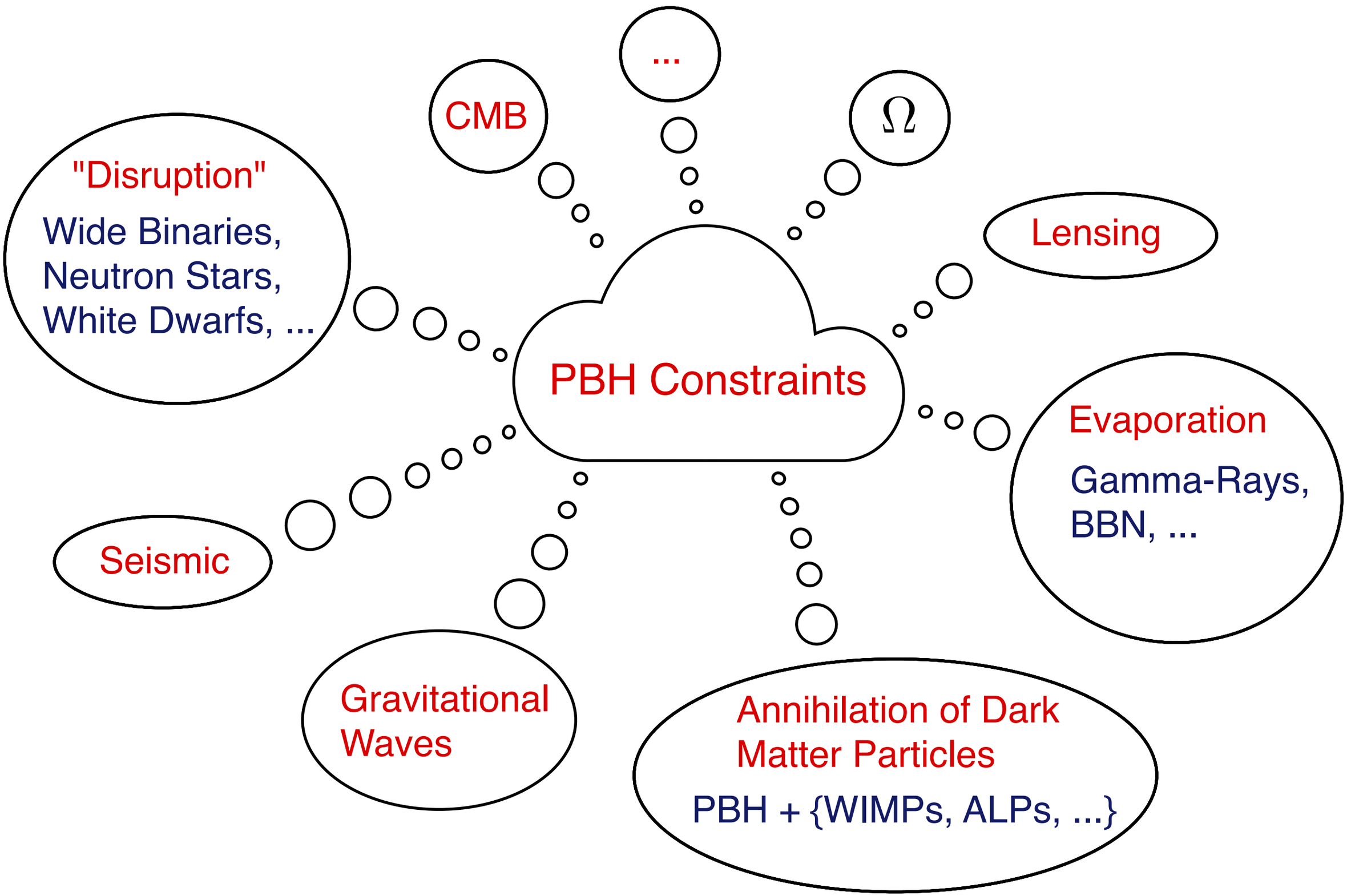
★ If primordial black holes constituted all of the dark matter:

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

★ Size: $10^{-8}\,\mathrm{cm}$

★ Number in our Galaxy: 10^{25}

★ Distance: $10\,\mathrm{AU}$


...
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'

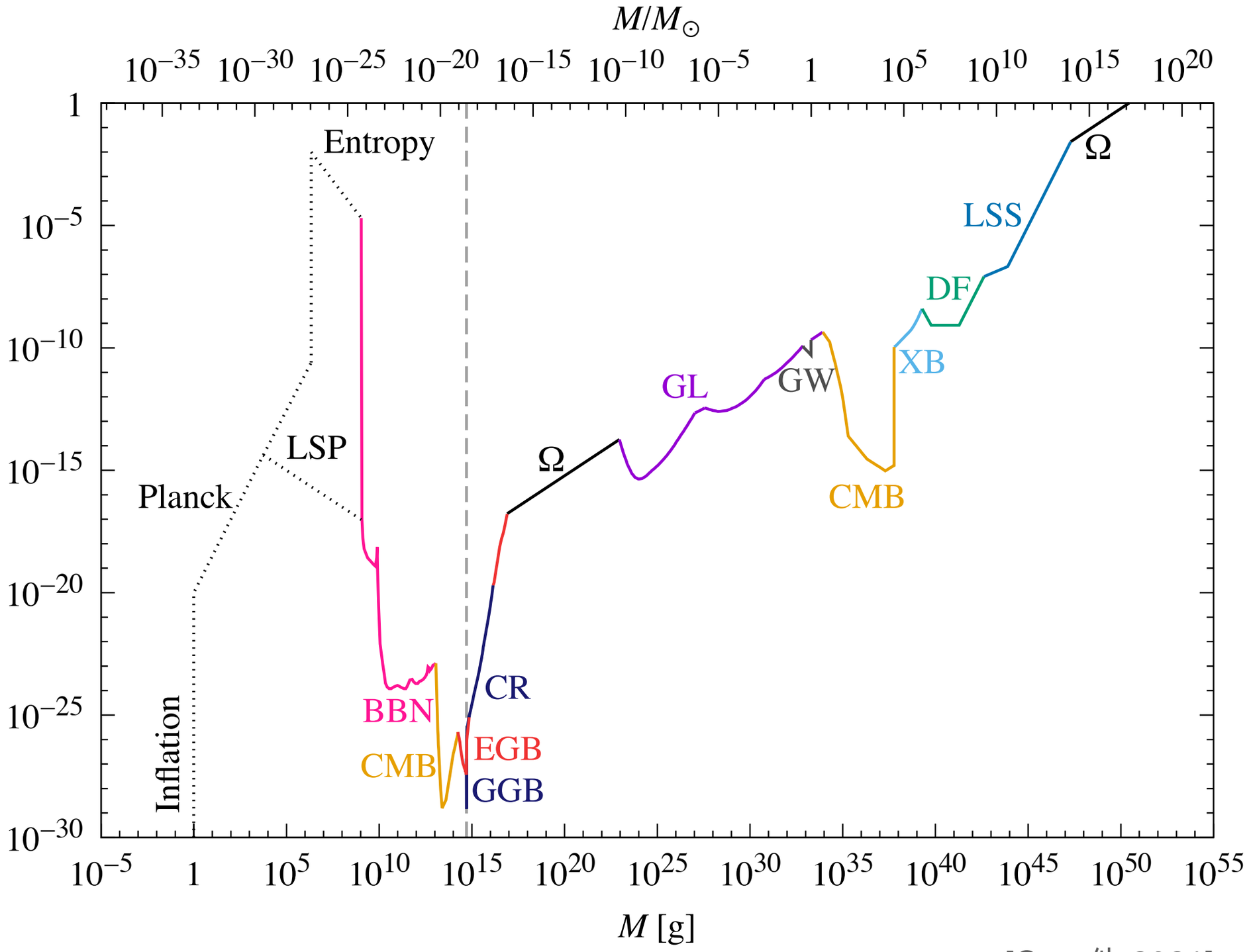
★ Note that

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

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

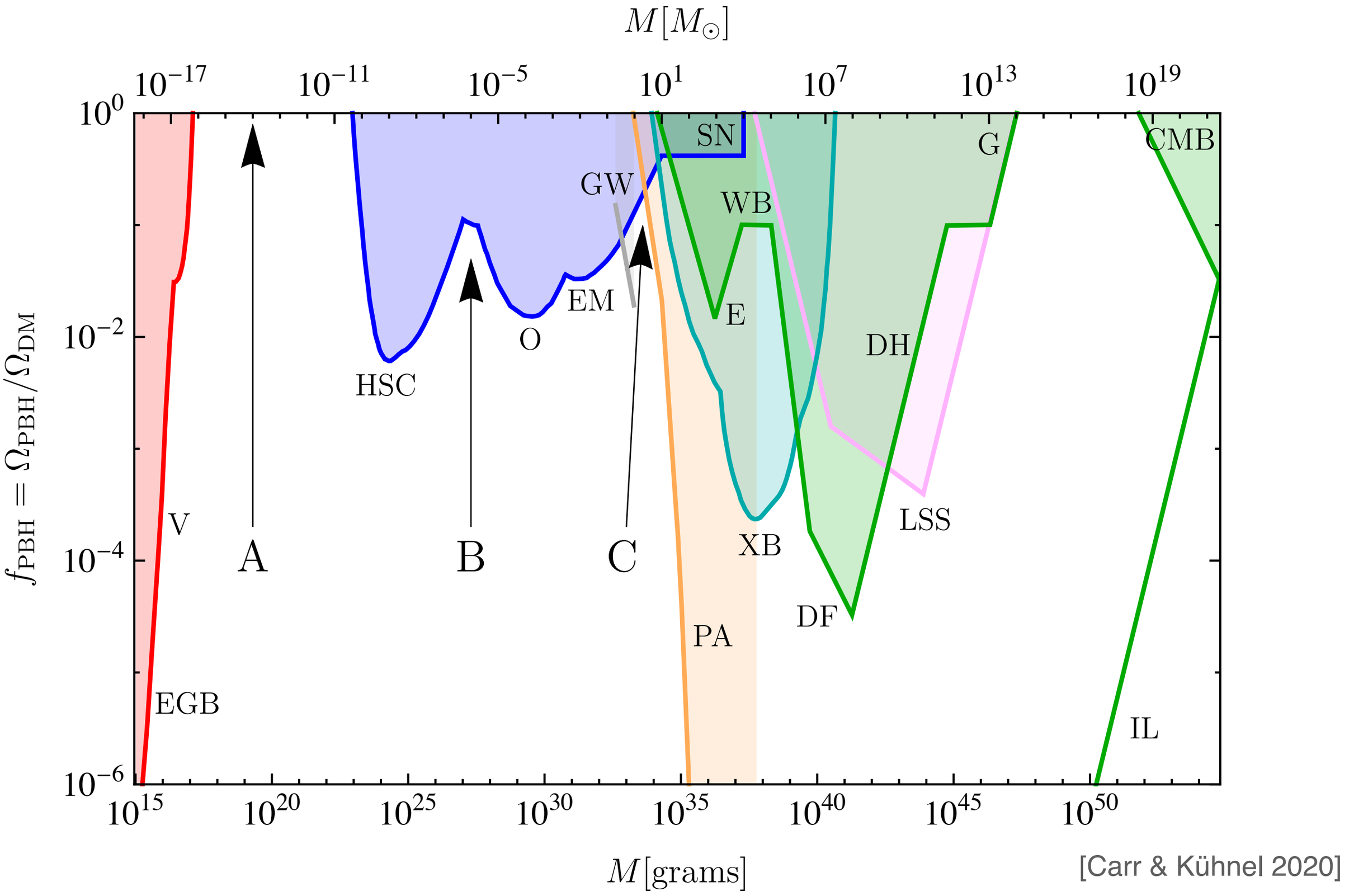
and hence

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



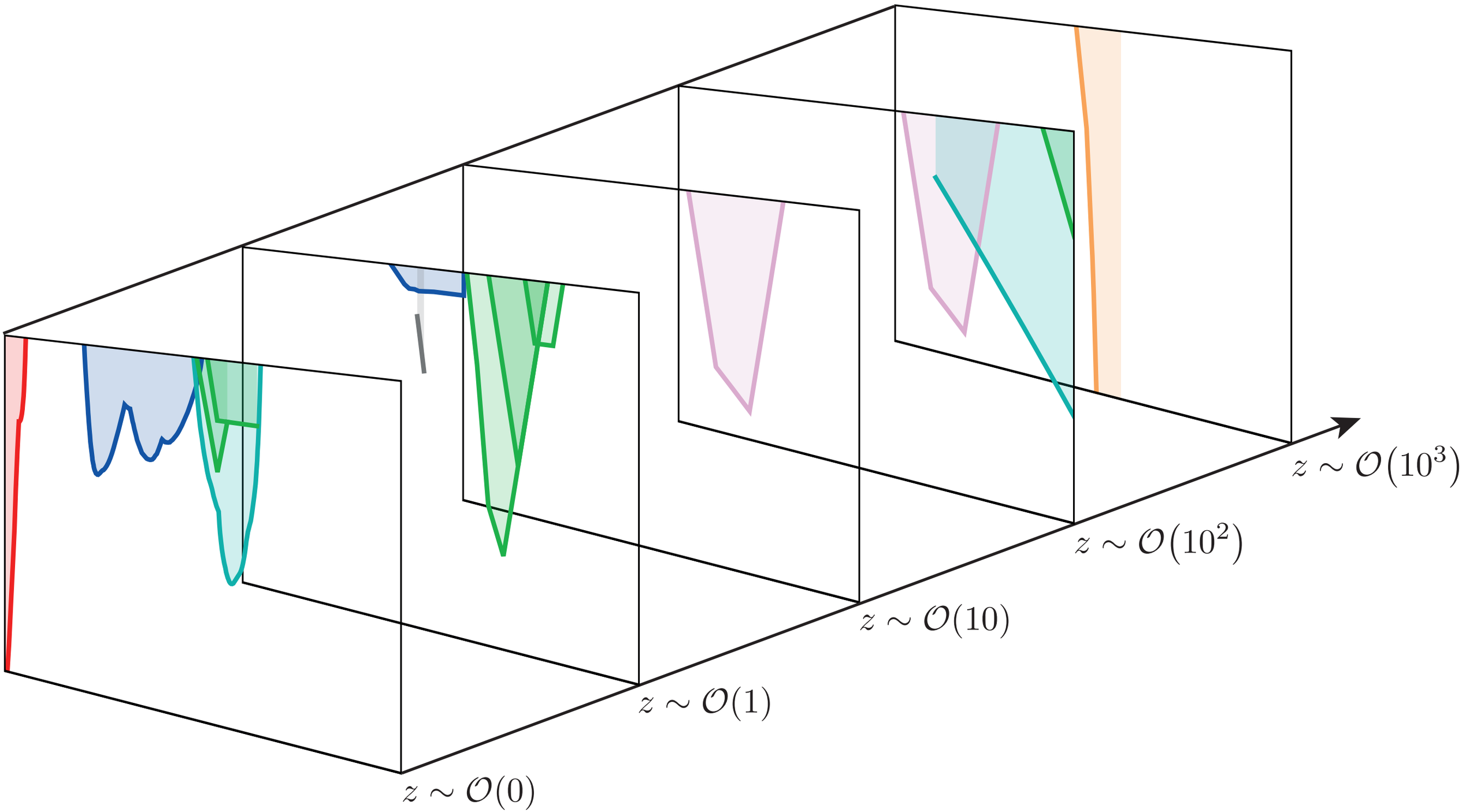
[Carr 他 2021]

Current PBH Constraints



[Carr & Kühnel 2020]

PBH Constraints — Redshift Dependence



[Carr & Kühnel 2020]

Observational Hints for Primordial Black Holes

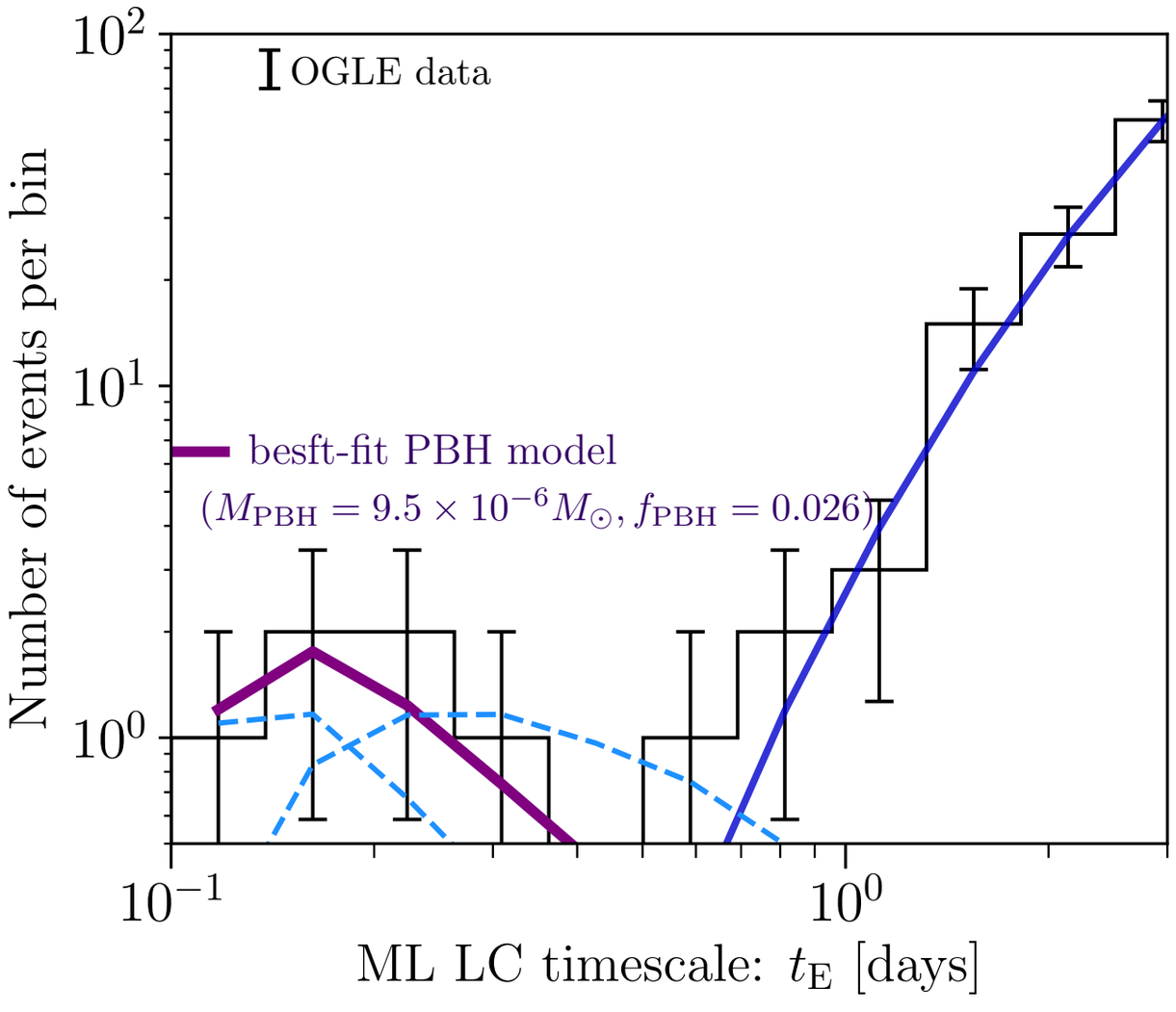
Evidence?

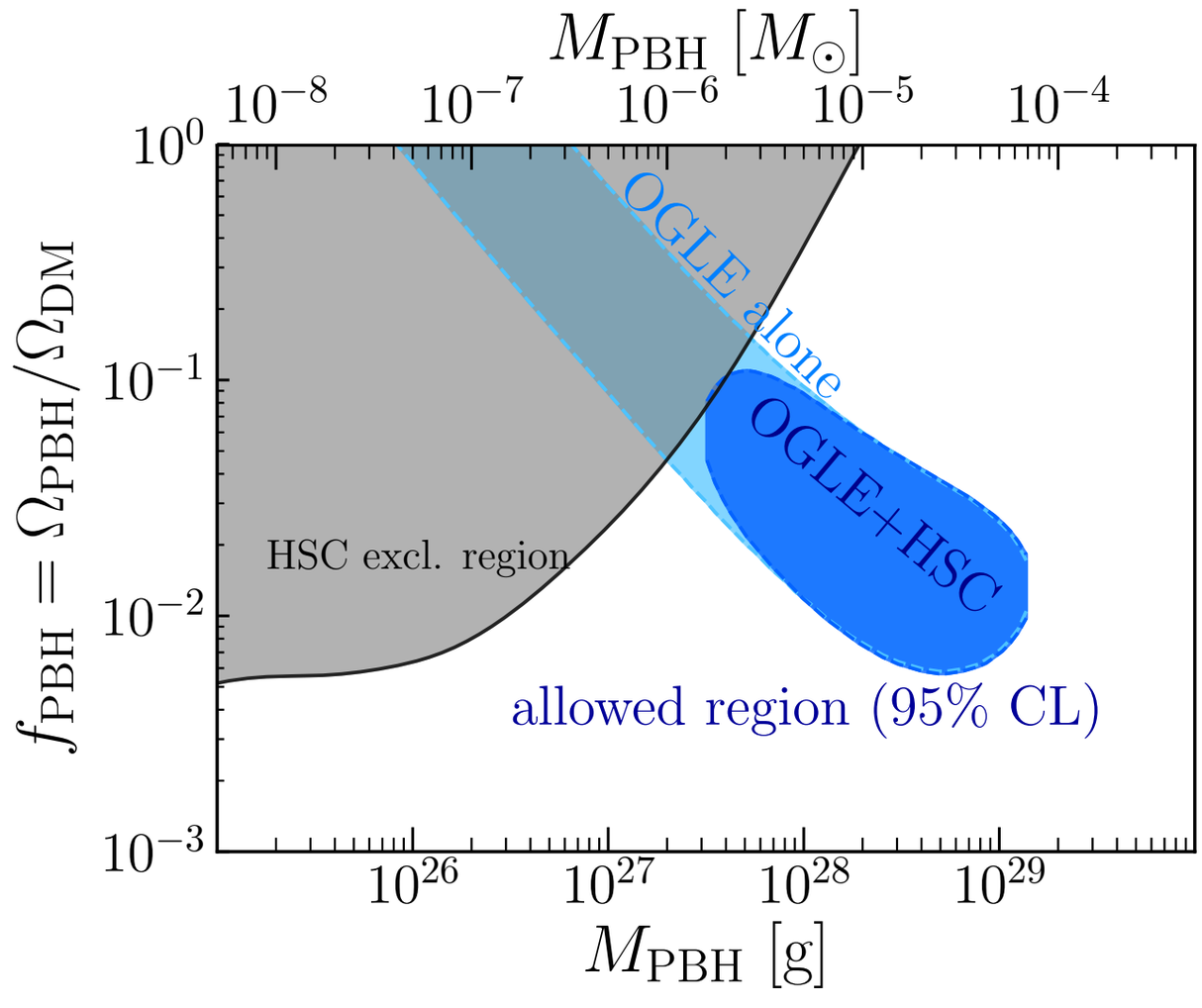
Observational ~~Hints~~

for Primordial Black Holes

Planetary-Mass Microlensing

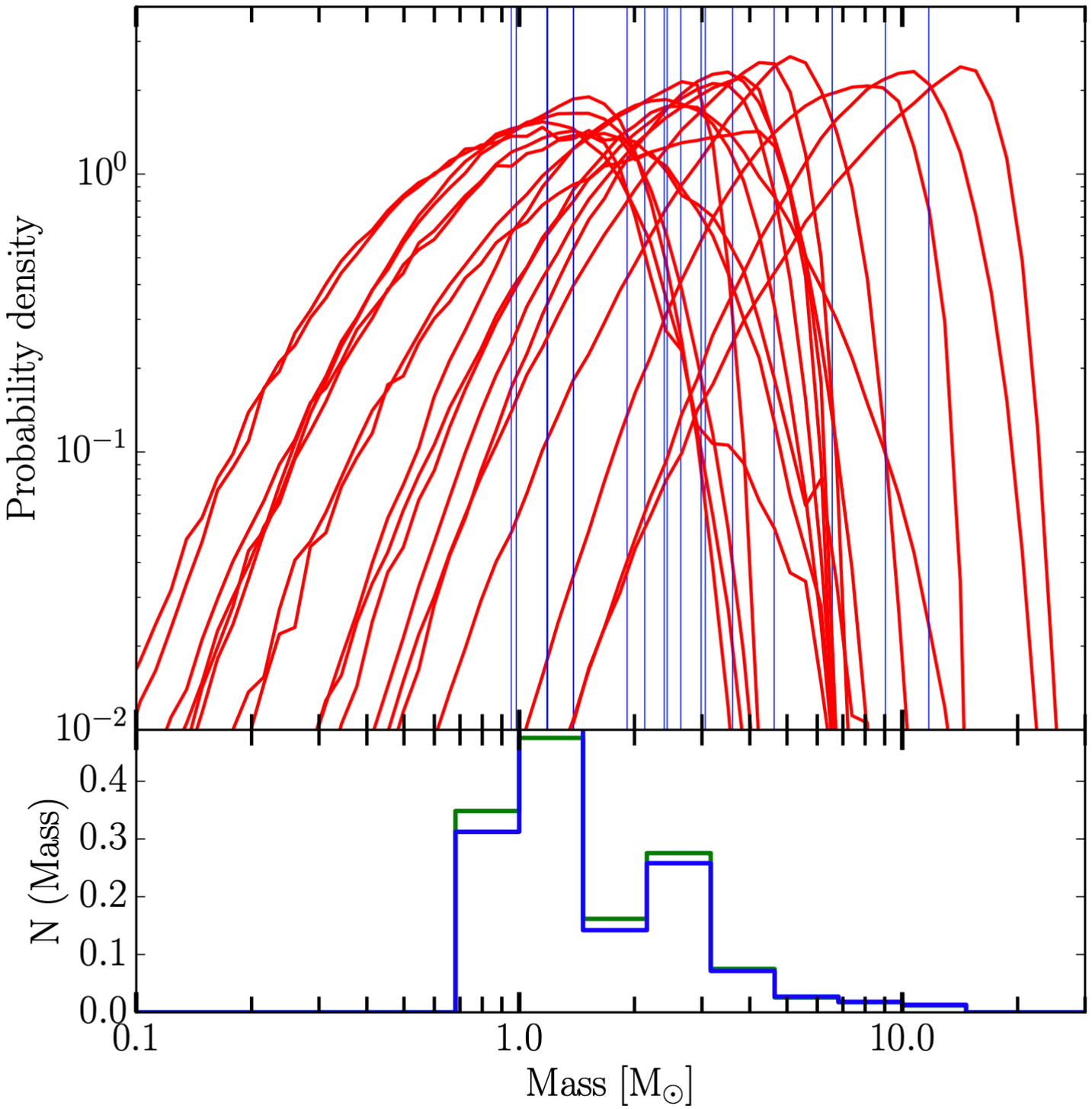
- OGLE detected a particular population of microlensing events:
  - 0.1 - 0.3 days light-curve timescale - origin unknown!
    Could be free-floating planets... or PBHs!





[Niikura *et al.* 2019]

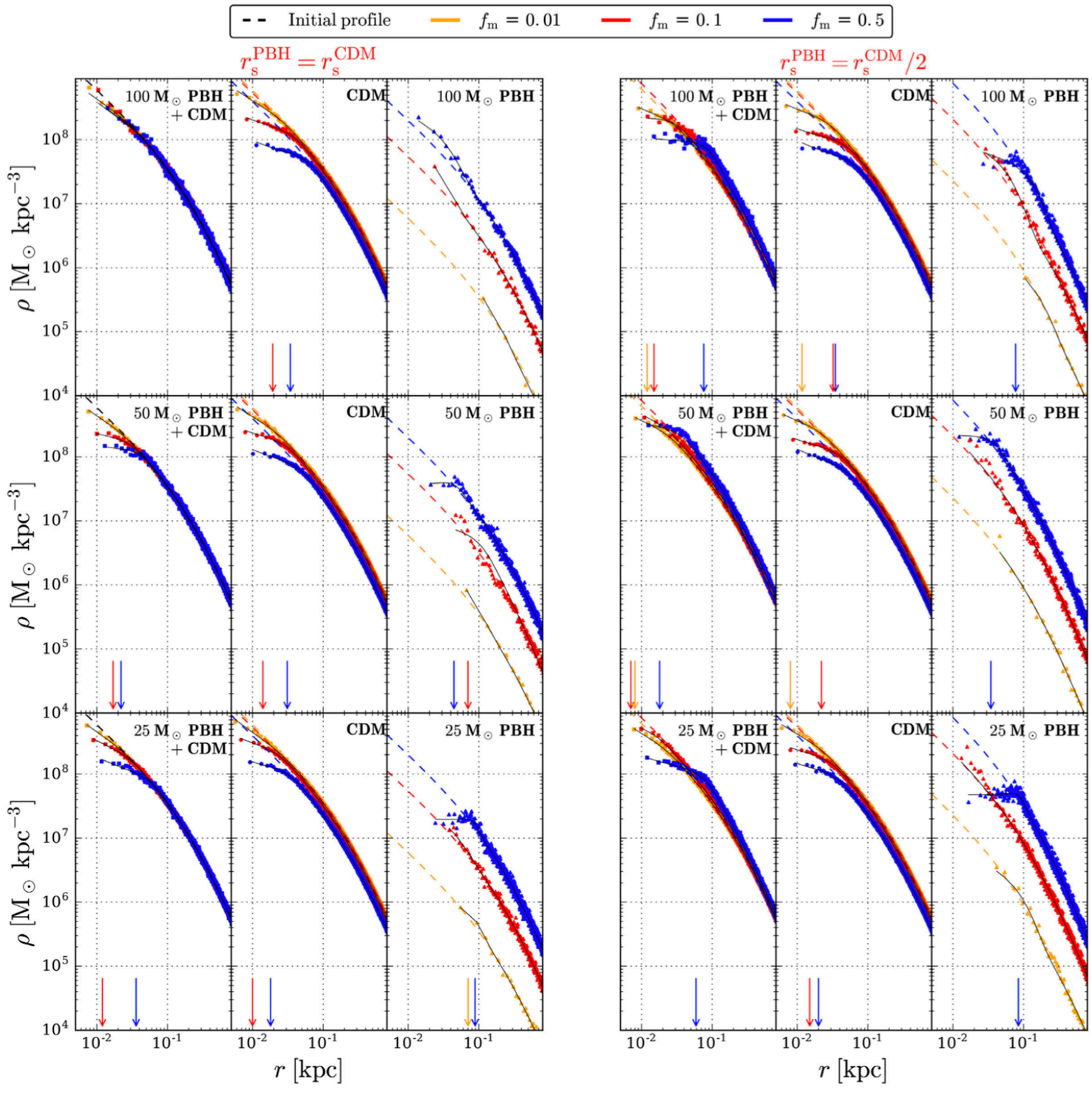
Excess of Lenses in Galactic Bulge



- 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]

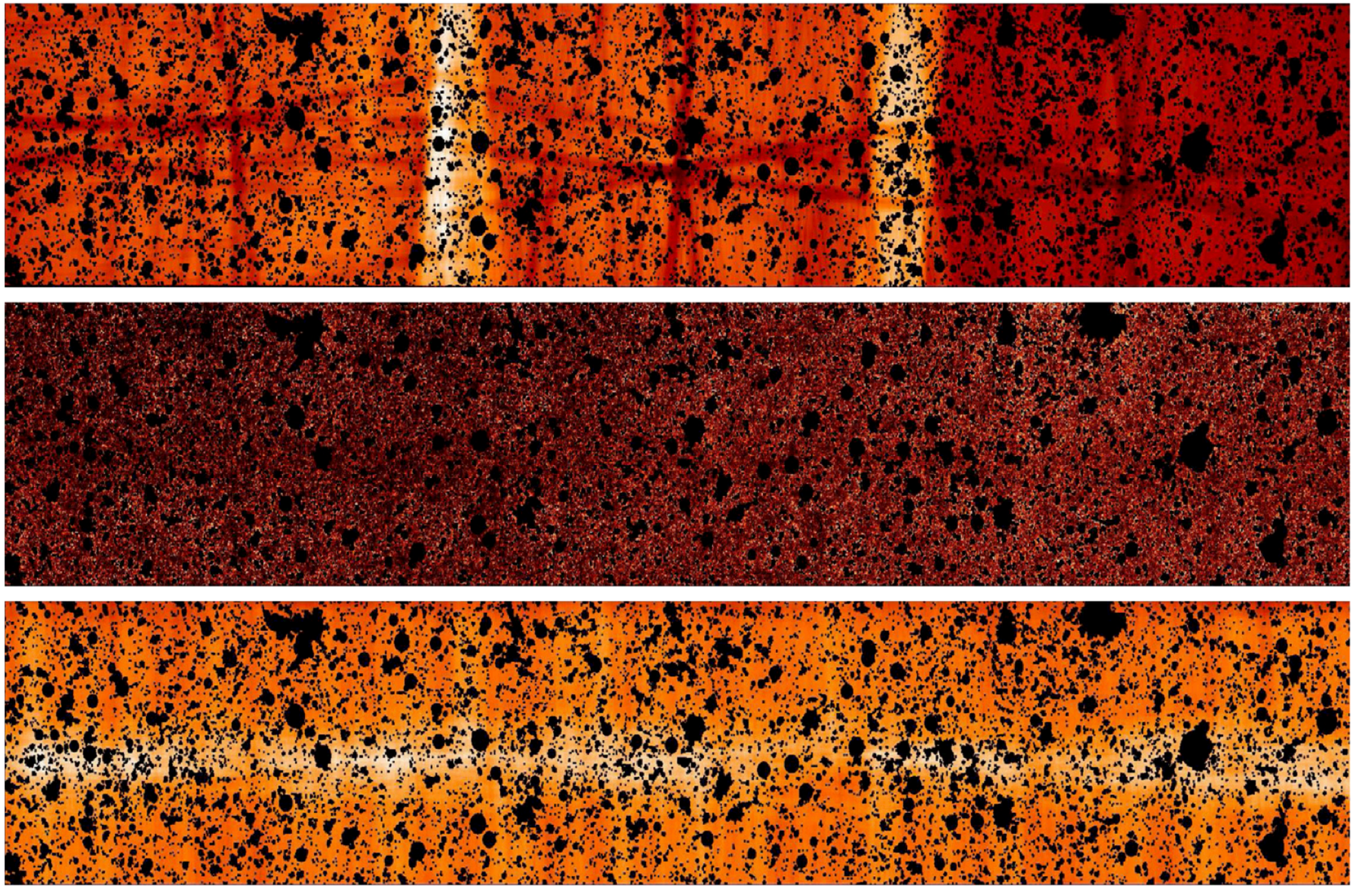
Ultra-faint Dwarf Galaxies



- ★ 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 CDM!
- ★ This works with a few percent of PBH DM of 25 – 100 $M_\odot$.

[Boldrini *et al.* 2020]

Correlations of Cosmic Infrared/X-Ray Backgrounds



[Capelluti *et al.* 2013]

★ PBHs generate early structure and respective backgrounds

GRAVITATIONAL WAVE **MERGER** DETECTIONS

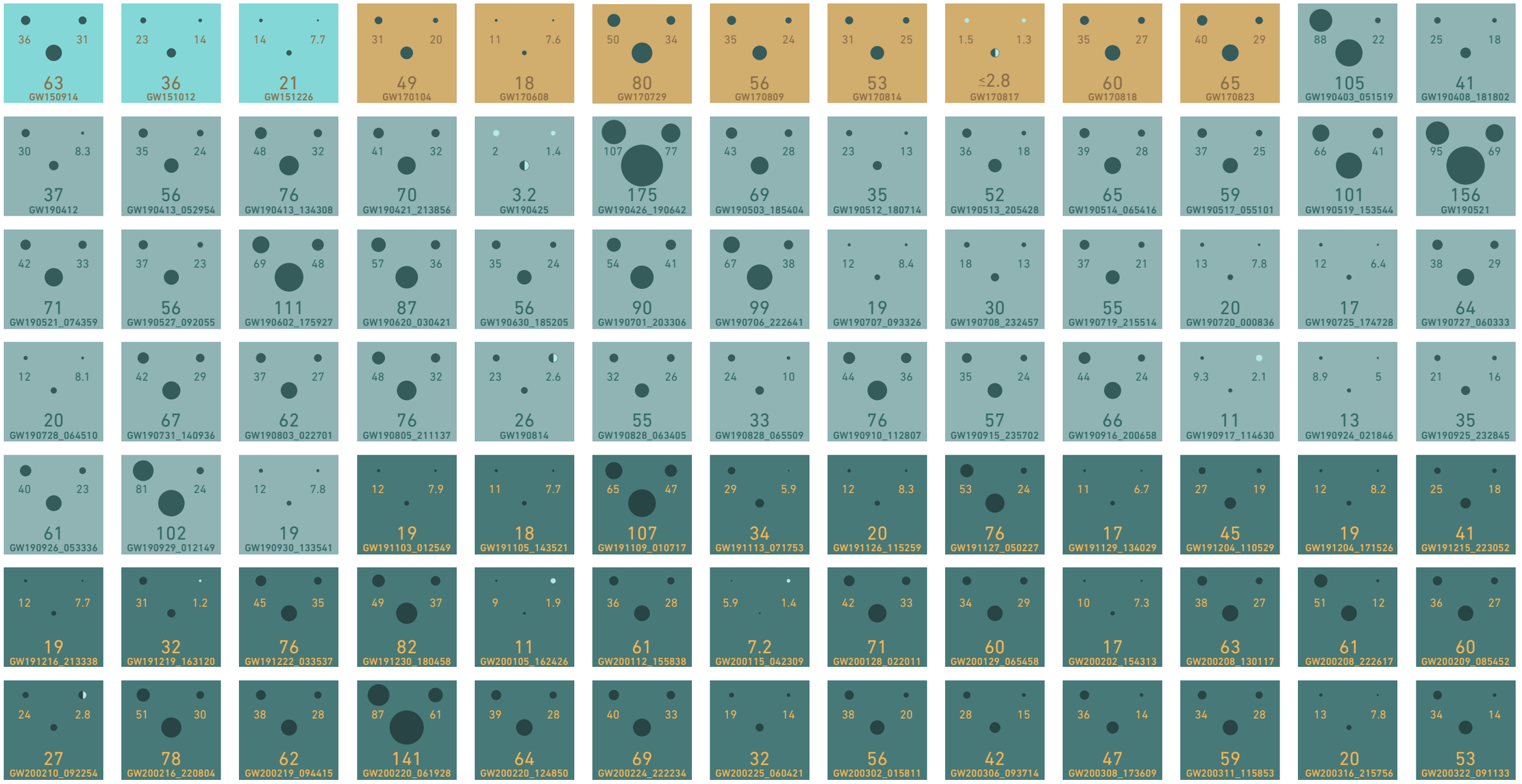
SINCE 2015

OBSERVING RUN

01 2015-2016

02 2016-2017

03a+b 2019-2020



GRAVITATIONAL WAVE **MERGER** DETECTIONS

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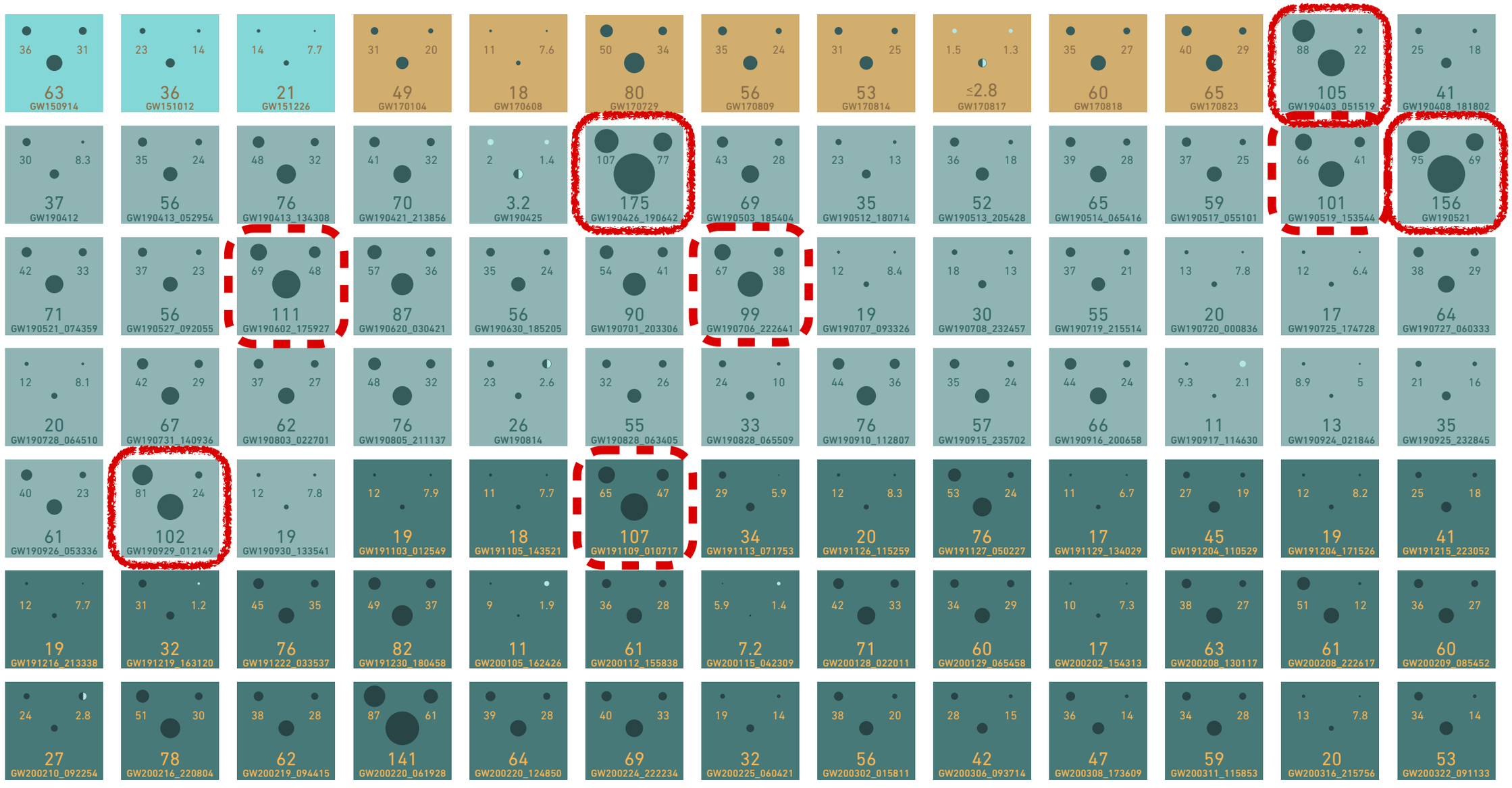

★ Black hole progenitors in the pair-instability mass gap (i.e. above ~ 60 $M_\odot$)

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 $M_\odot$)

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GRAVITATIONAL WAVE **MERGER** DETECTIONS

→ SINCE 2015

OBSERVING RUN

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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 $q < 0.25$)

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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

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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 by *Phukon et al.* '21 with updated merger rates and low mass ratios:

FAR $[\mathrm{yr}^{-1}]$	$\ln \mathcal{L}$	UTC time	mass 1 $[M_\odot]$	mass 2 $[M_\odot]$
0.1674	8.457	2017-03-15 15:51:30	3.062	0.9281
0.2193	8.2	2017-07-10 17:52:43	2.106	0.2759
0.4134	7.585	2017-04-01 01:43:34	4.897	0.7795
1.2148	6.589	2017-03-08 07:07:18	2.257	0.6997

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

★ Note that an order-one dark matter fraction of subsolar PBHs is still possible!

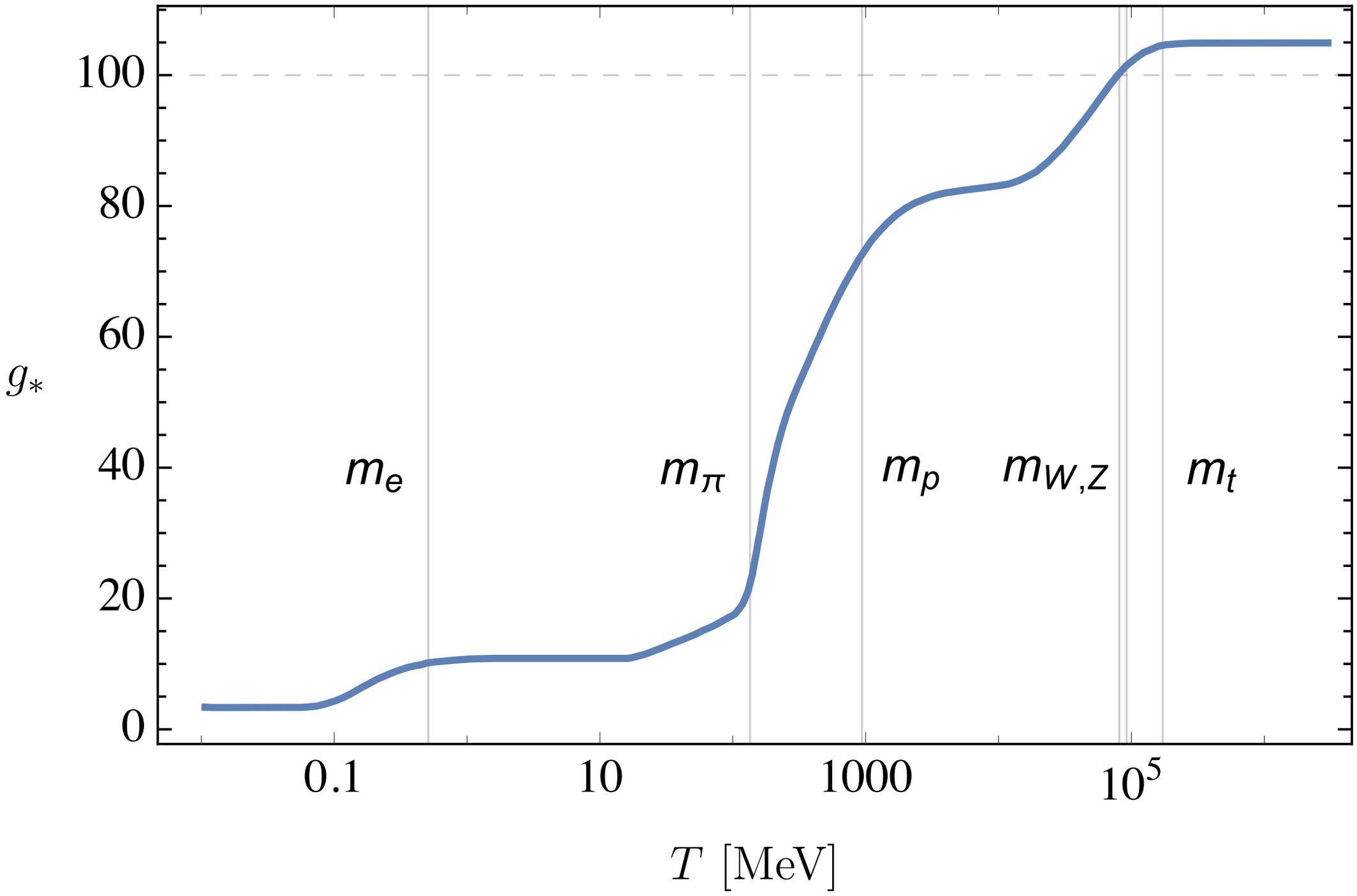
Further Support / Evidence for PBHs

- ★ High-redshift quasars (up to $10^8\,M_\odot$ at $z = 13$)
- ★ Fast radio bursts
- ★ Missing-pulsar problem
- ★ Excess of lenses in Galactic bulge
- ★ Clumping of dark matter
- ★ ...

Thermal History

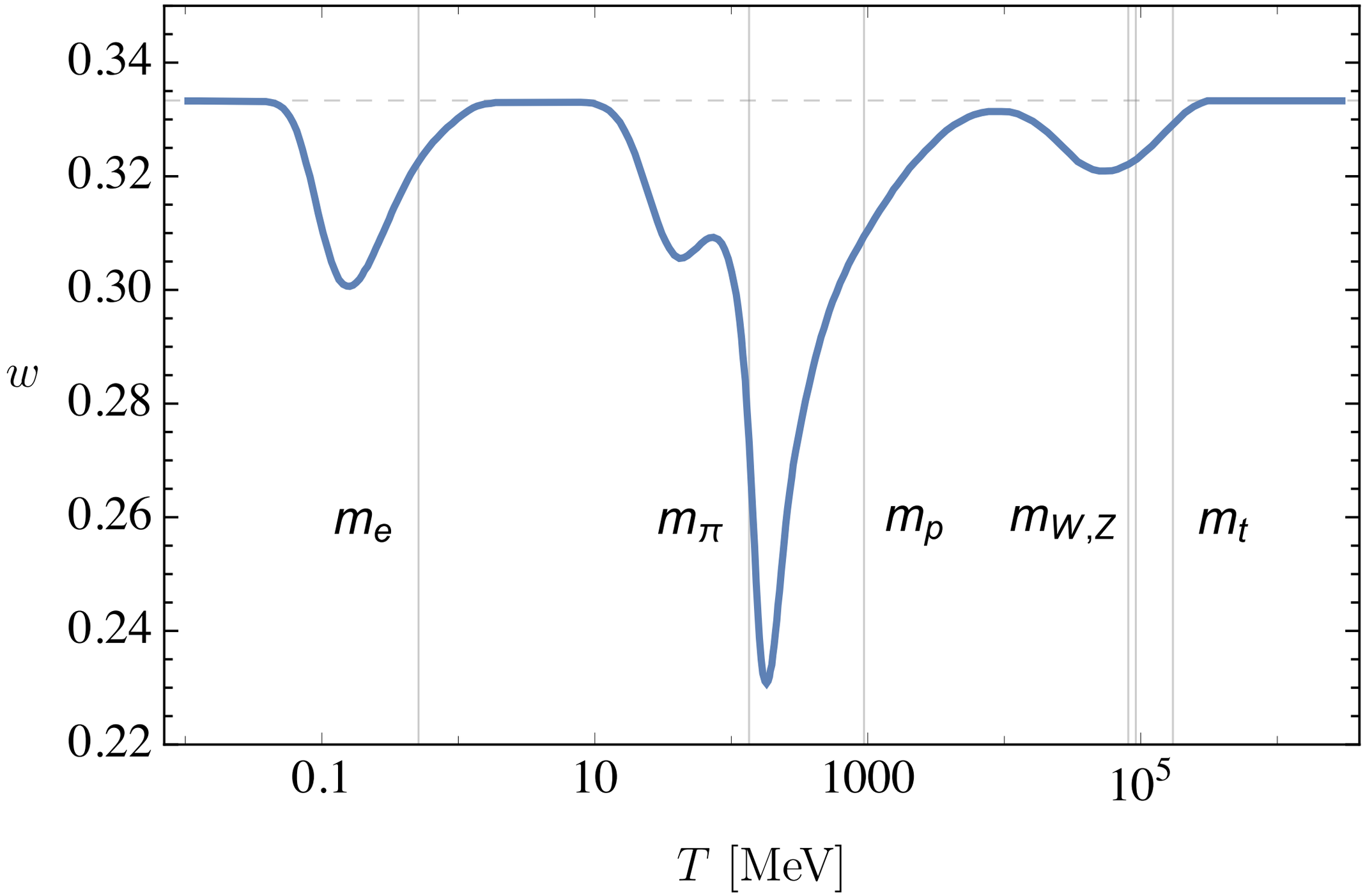
Thermal History of the Universe

★ Changes in the relativistic degrees of freedom:



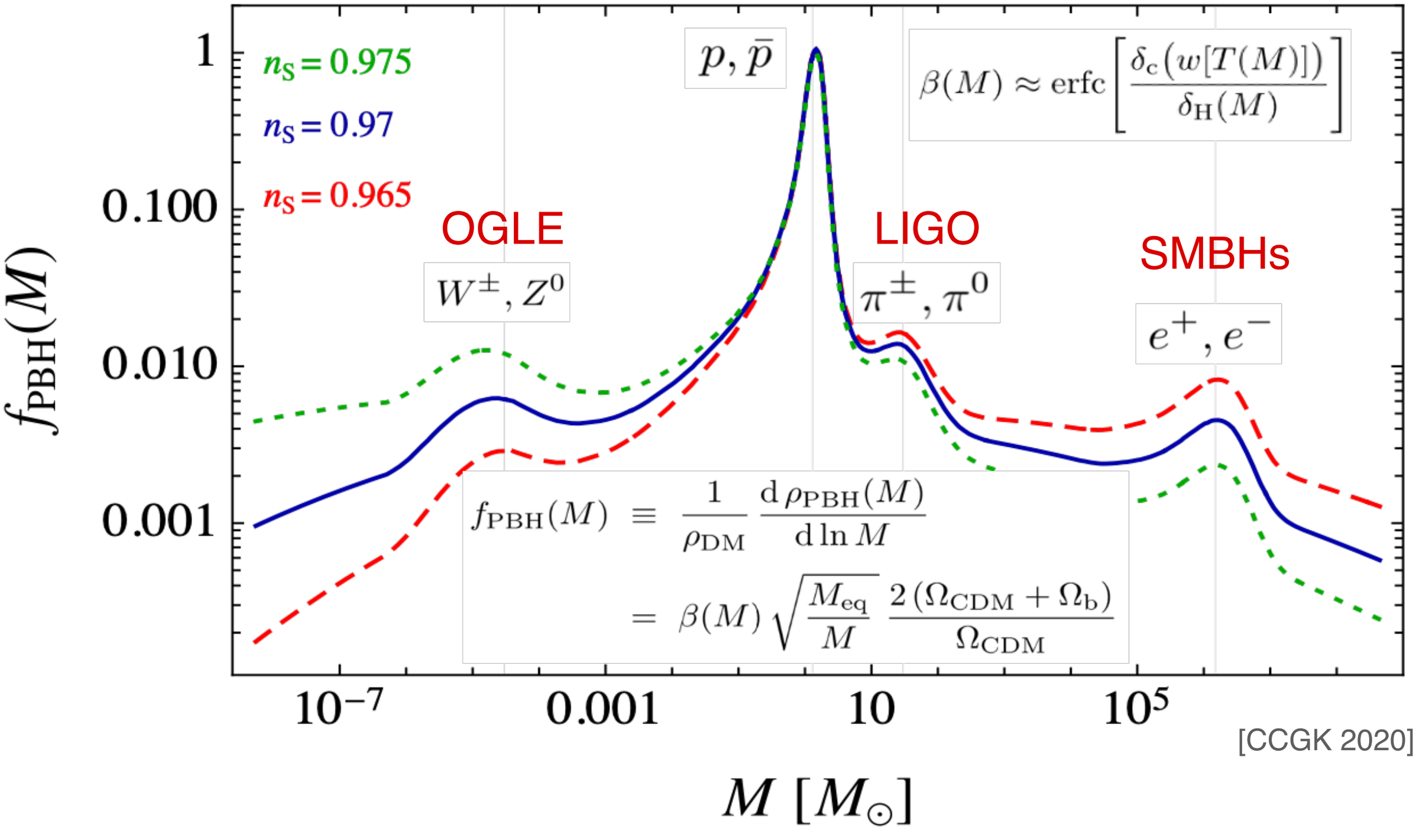
Thermal History of the Universe

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



Thermal History of the Universe

★ An essentially featureless power spectrum leads to:



[CCGK 2020]

Conclusion

Conclusion

- Primordial black holes influence physics on many different scales, and manifest themselves via a plethora of different signatures.

- At present, they are *not* tightly constraint in general and can easily constitute 100% of the dark matter, even in several mass ranges.

- There are many hints for their existence from OGLE and other microlensing surveys, LIGO/Virgo gravitational-wave events etc.

- The thermal history of the Universe naturally provides peaks in the PBH mass function at several relevant scales.

Black Holes as a Link between Micro and Macro Physics

(Carr)

Relics

$10^{23}\,M_\odot$ Universal

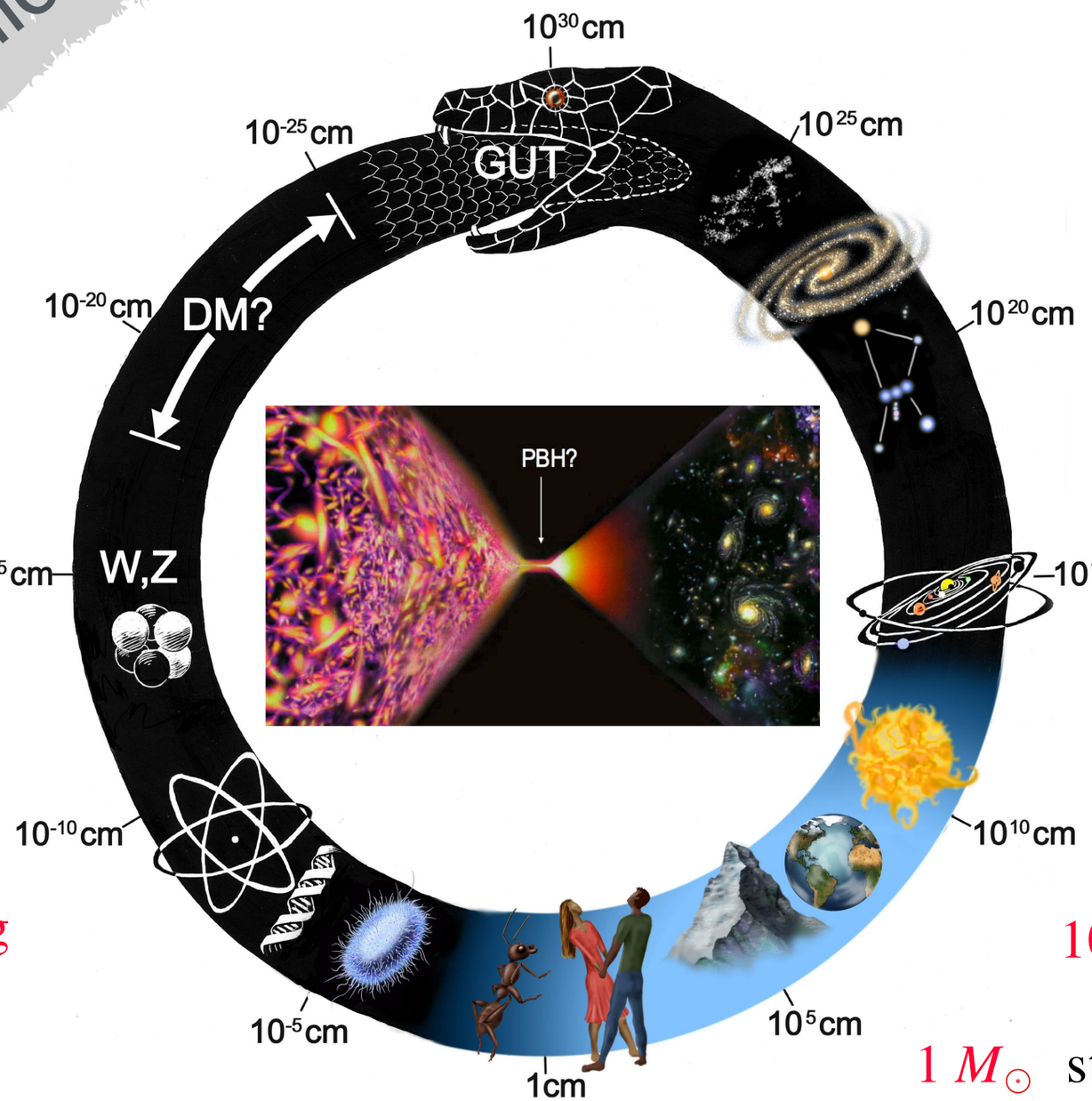
Planck 10^{-5} g

exploding* 10^{10} g
(BBN)

evaporating* 10^{15} g

lunar 10^{21} g

terrestrial 10^{25} g



$10^{12}\,M_\odot$ SLAB

$10^{9}\,M_\odot$ QSO

$10^{6}\,M_\odot$ MW

$10^{2}\,M_\odot$ IMBH

$1\,M_\odot$ stellar

[Figure from Abrams & Primack 2012]

A Brand-New Review! ~120 pages, > 500 References

Primordial Black Holes

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(Dated: Friday 11th November, 2022, 1:26am)

We review aspect of primordial black holes, i.e., black holes which have been formed in the early Universe. Special emphasis is put on their formation, their rôle as dark matter candidates and their manifold signatures, particularly through gravitational waves.