Recent Developments on Primordial Black Holes

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Holography and the Swampland

Be'er Sheva, 21st of March 2023

DISRUPTED LAYER

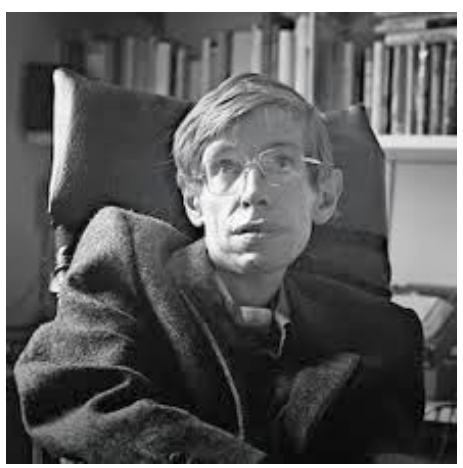
Contemporary Art by **Zohar Gotesman**
in the Archaeology Wing

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.

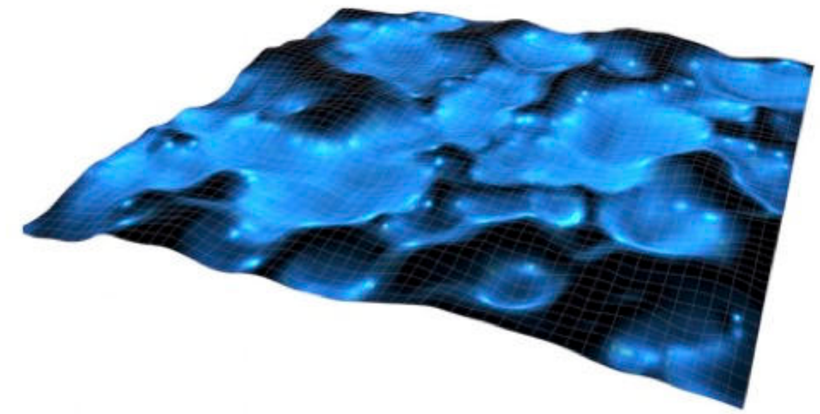
★ Conclusion disproved by Carr & Hawking (1974), reinvigorated PBH research (nearly 2000 papers to date).

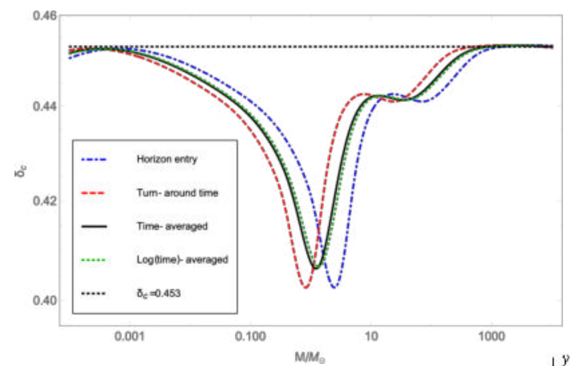


Primordial Black Hole Formation

PBH Formation Mechanisms

- ★ Large density perturbations (inflation)

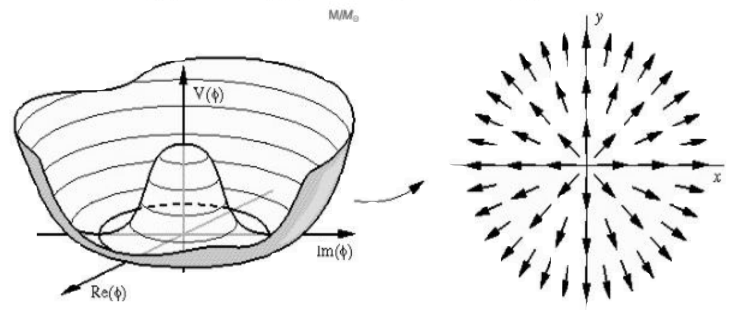


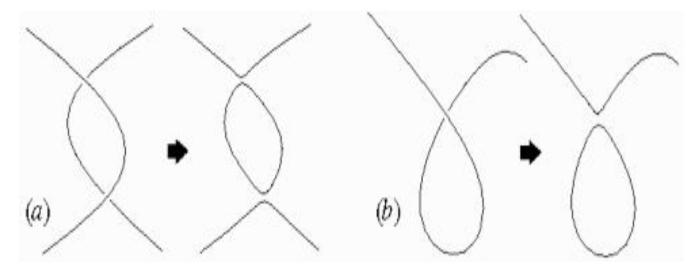


[Byrnes *et al.* 2018]

- ★ Pressure reduction

- ★ Cosmic string loops

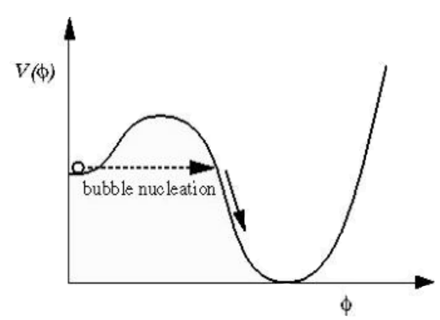


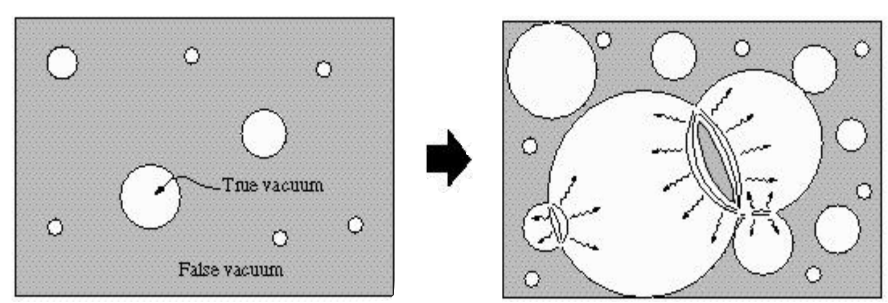


http://www.damtp.cam.ac.uk/research/gr/public/cs_phase.html

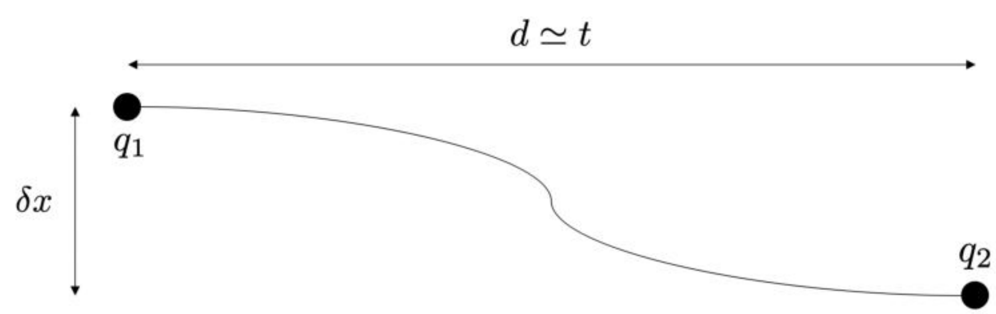
http://www.damtp.cam.ac.uk/research/gr/public/cs_top.html

- ★ Bubble collisions





- ★ Quark confinement



[Dvali, FK, Zantedesschi 2021]

- ★ ...

PBH Formation from Inflationary Overdensities

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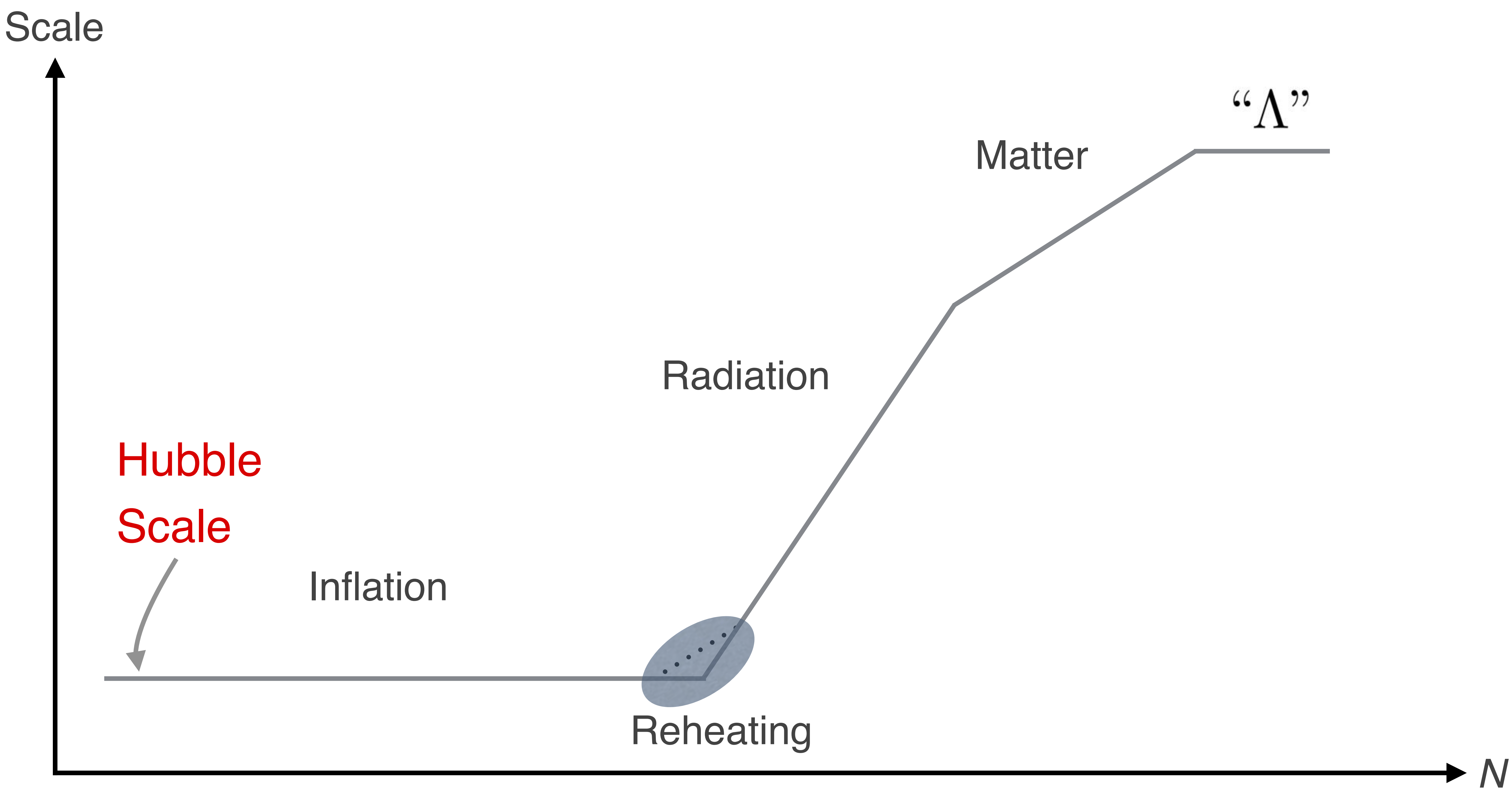
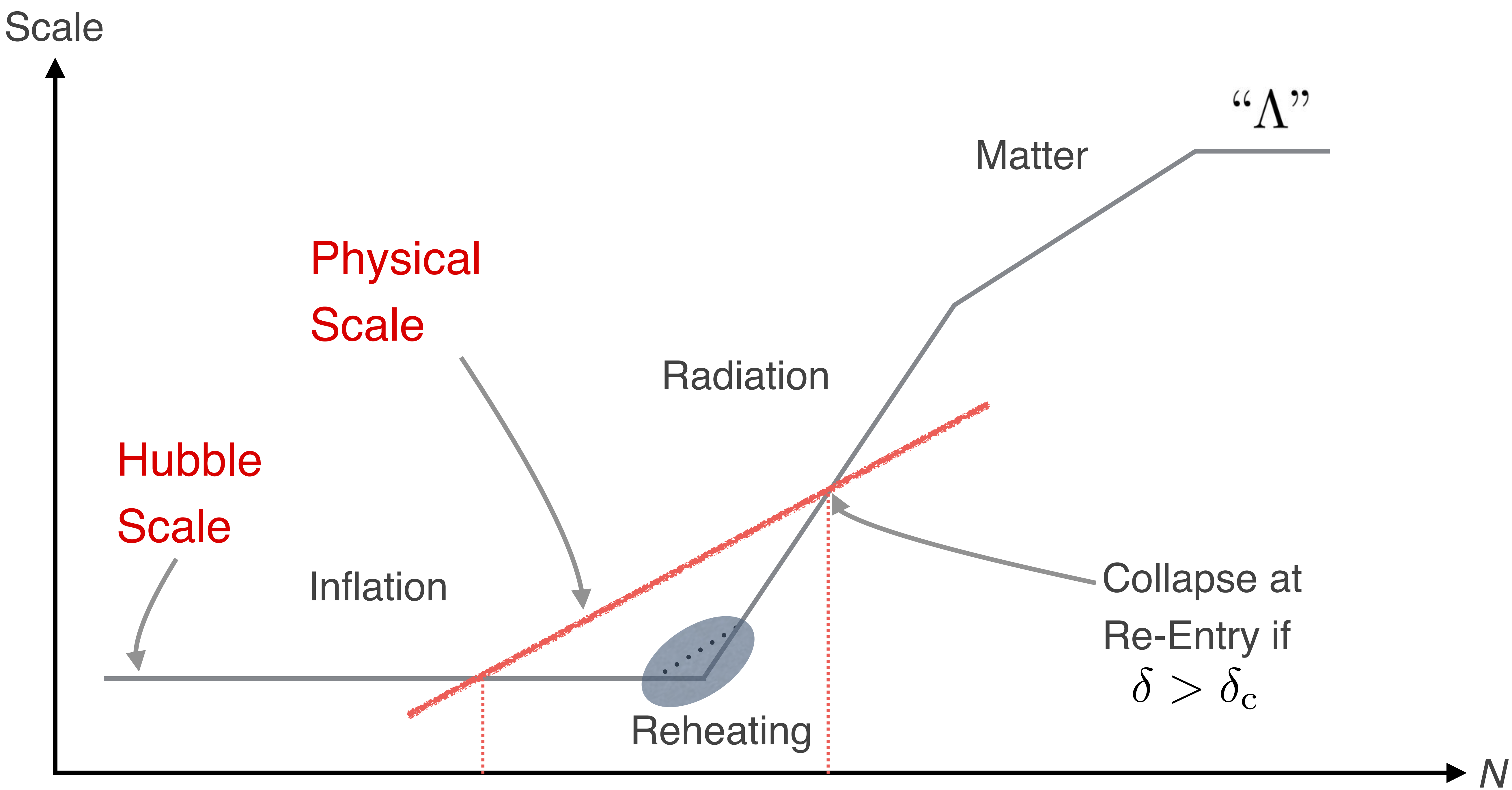
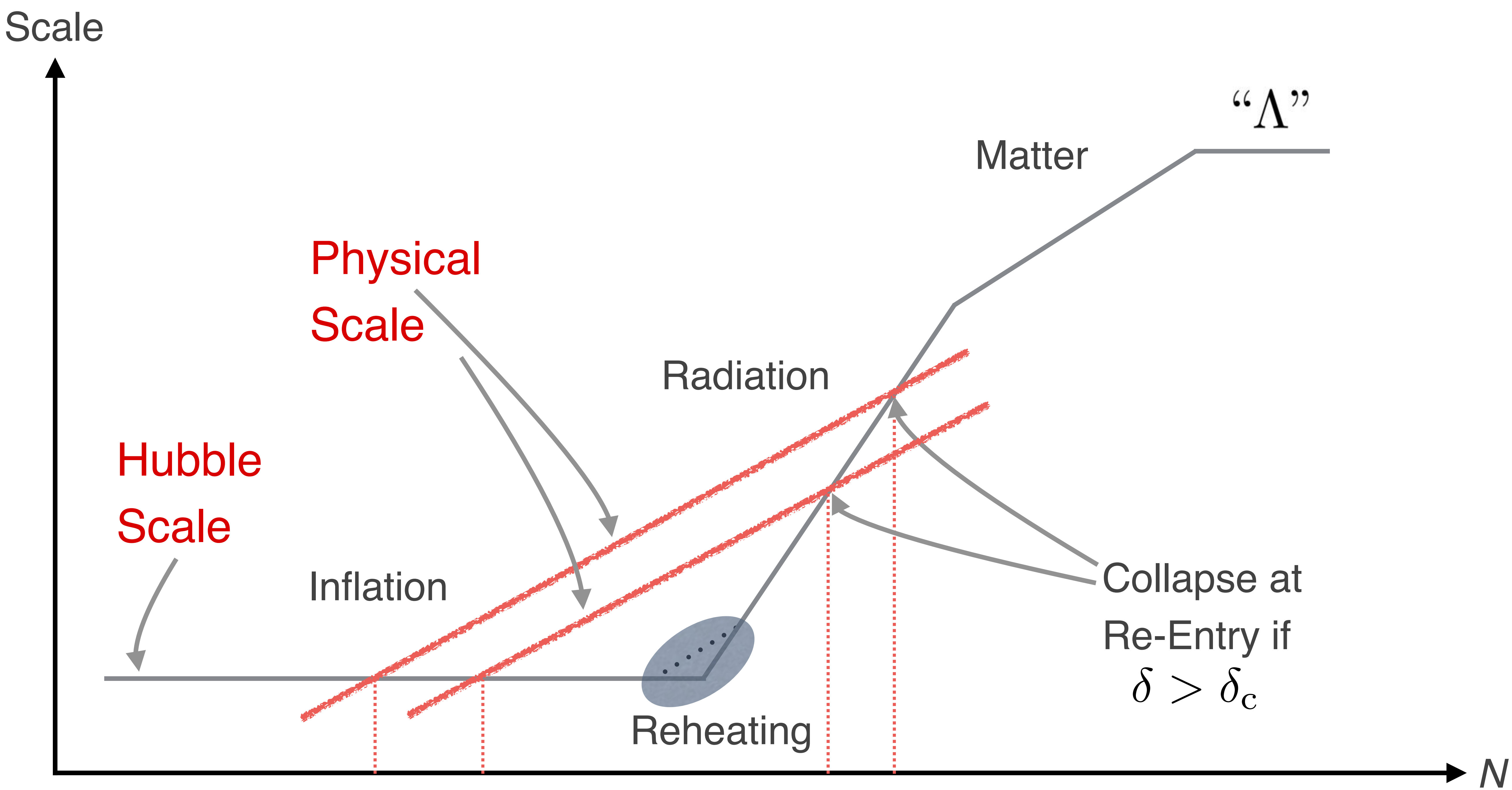


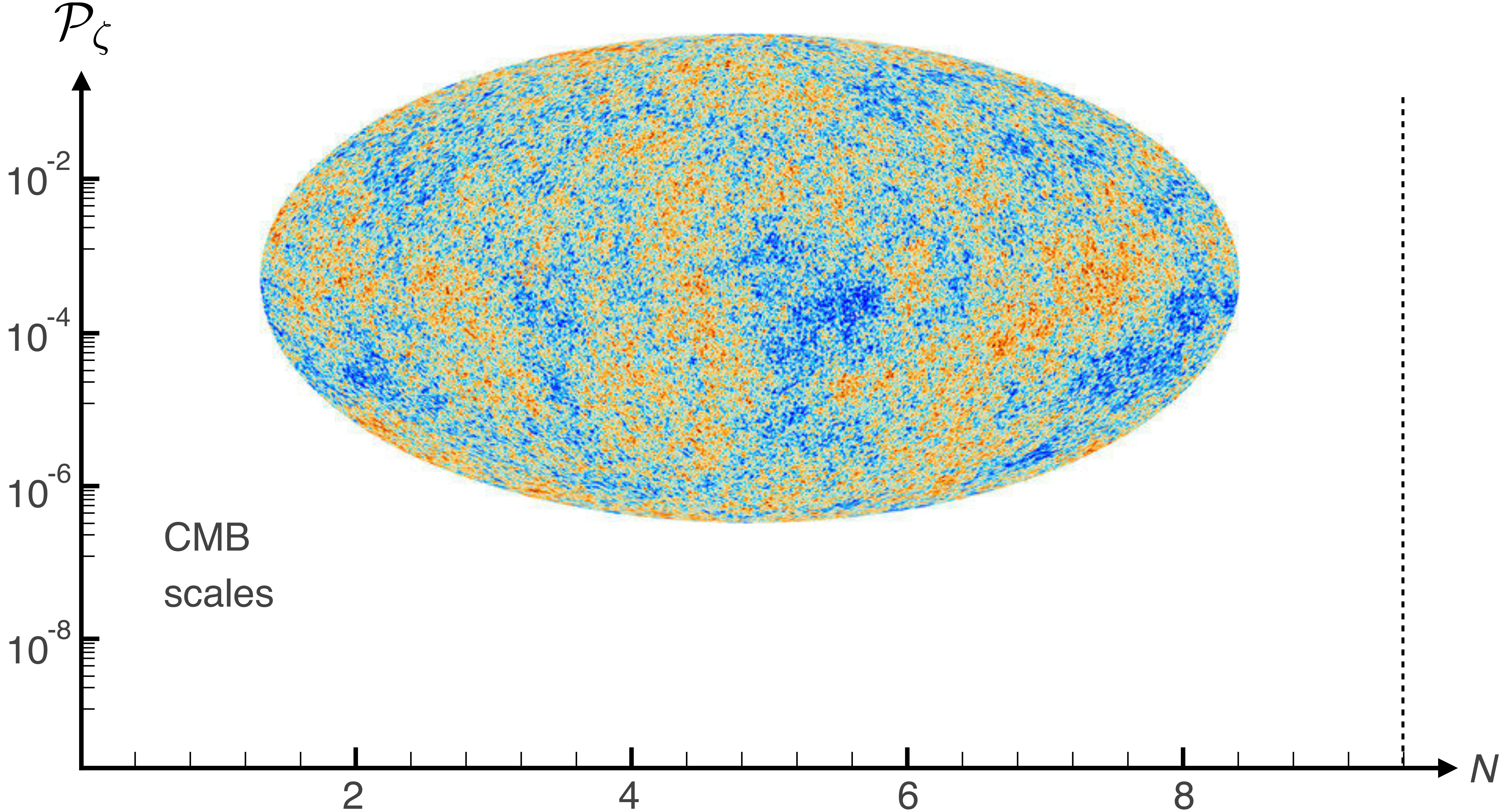
PBH Formation from Inflationary Overdensities



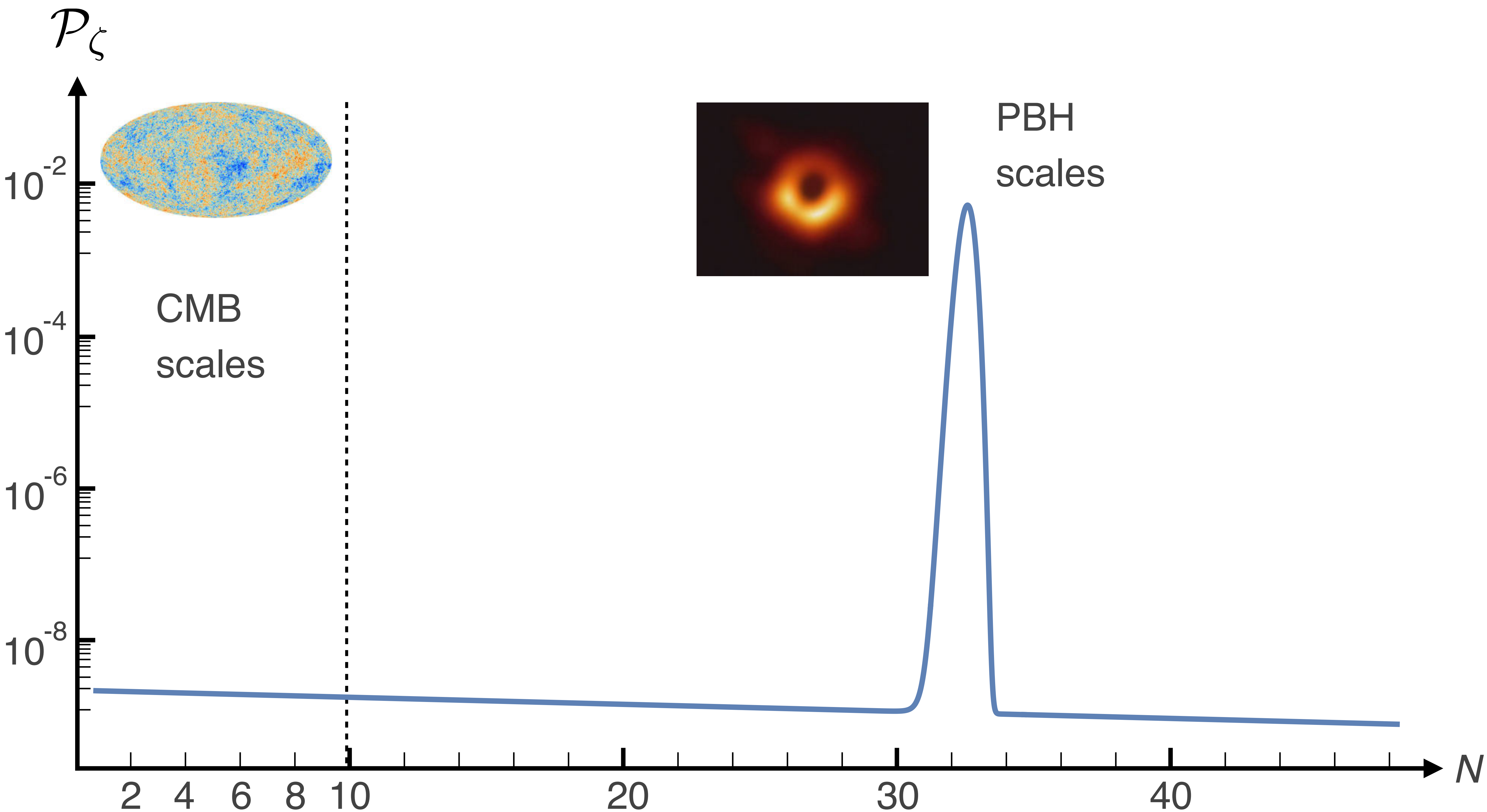
PBH Formation from Inflationary Overdensities



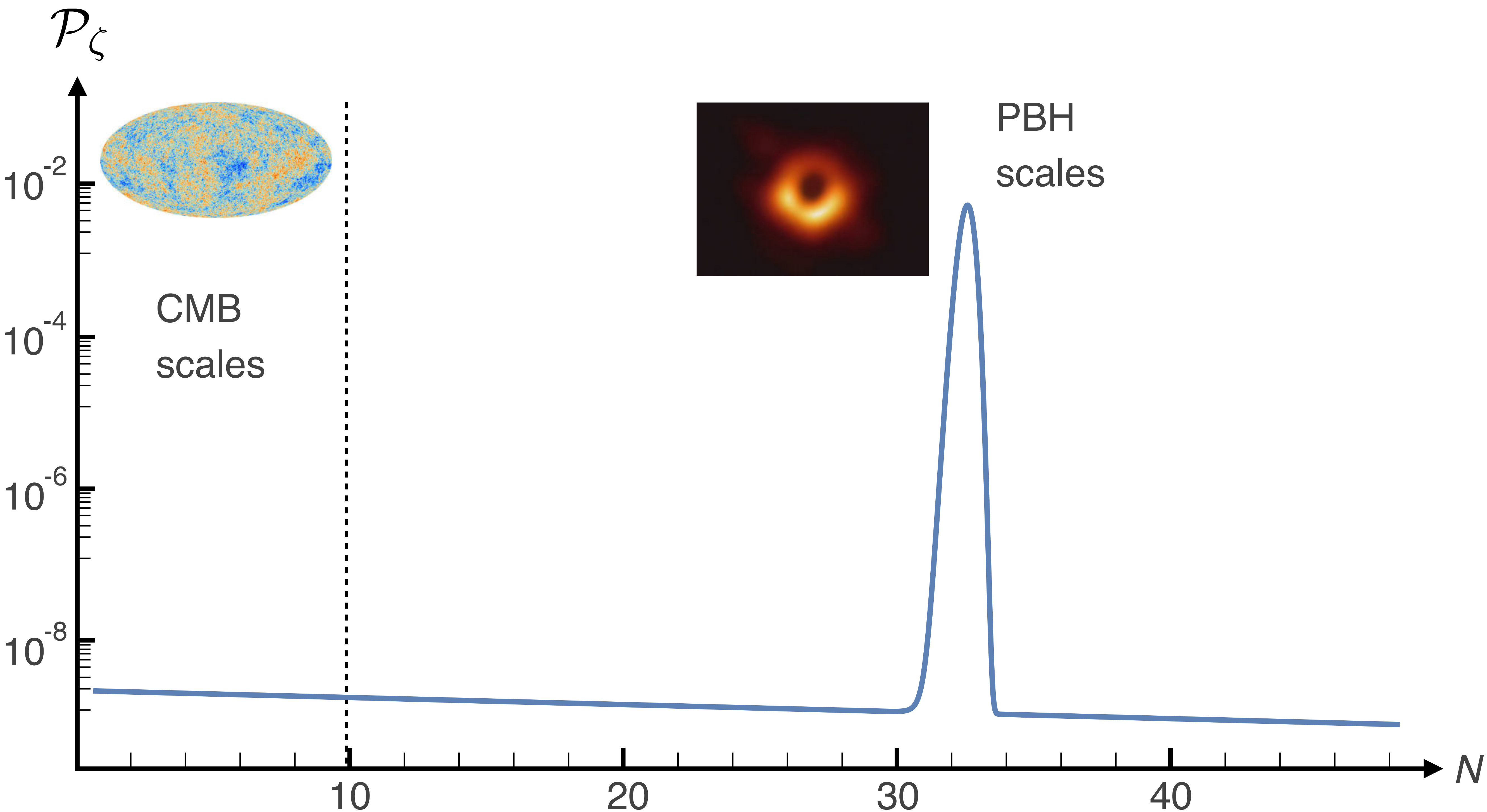
PBH Formation — Scales



PBH Formation — Scales



PBH Formation — Scales

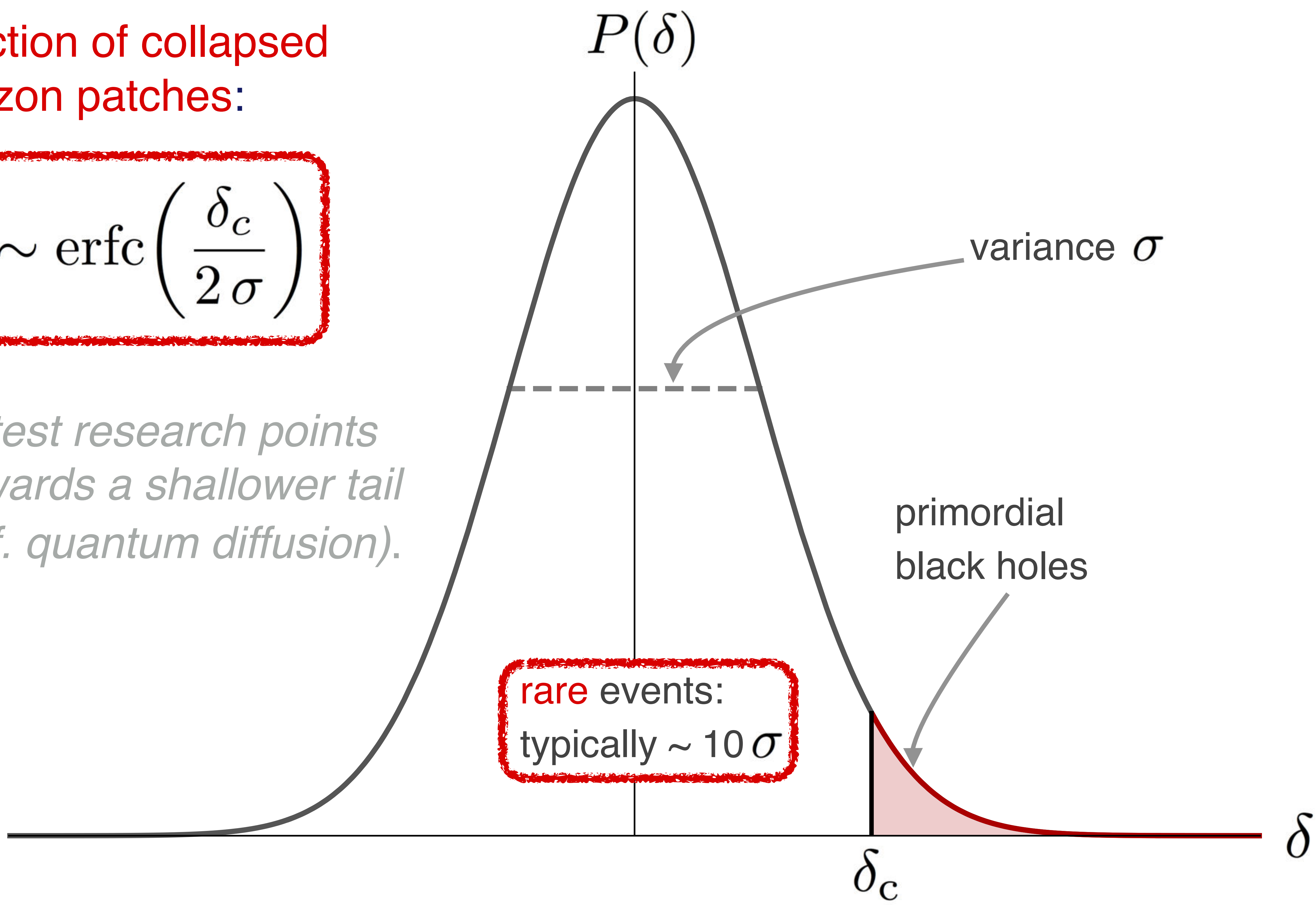


PBH Formation — Rare Events

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:

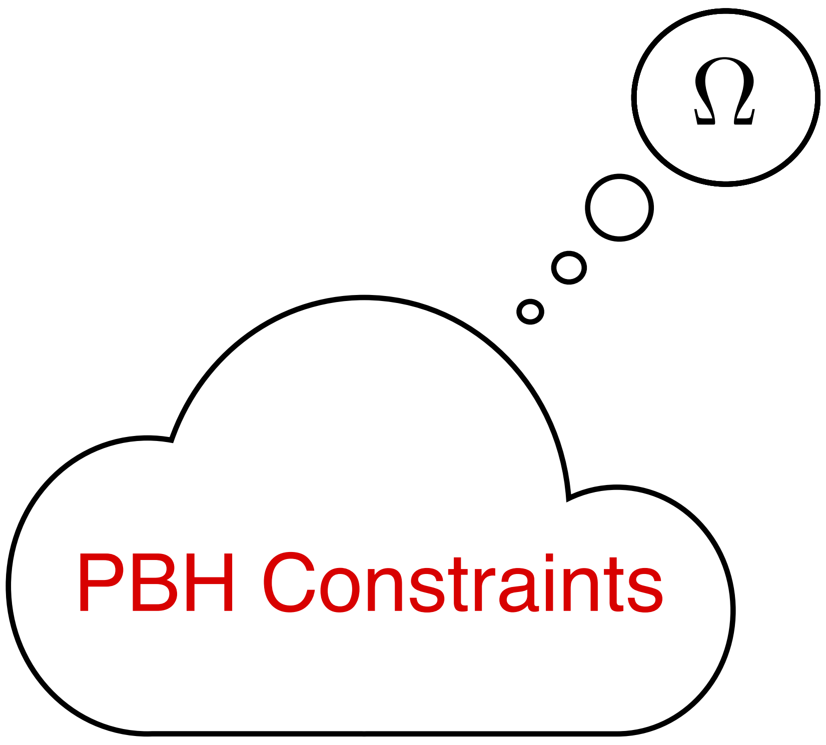
★ Assume that all PBH have mass: $10^{20}\,\mathrm{g}$

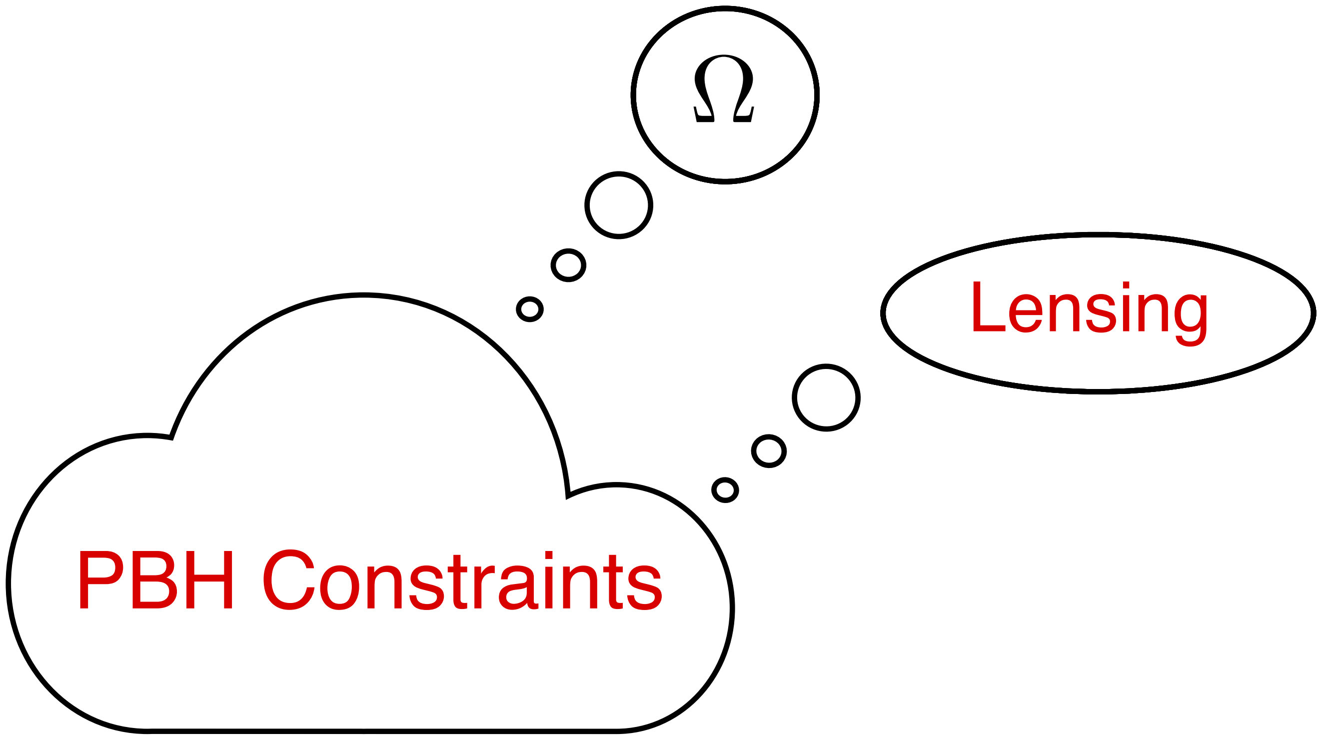
★ Size: $10^{-8}\,\mathrm{cm}$

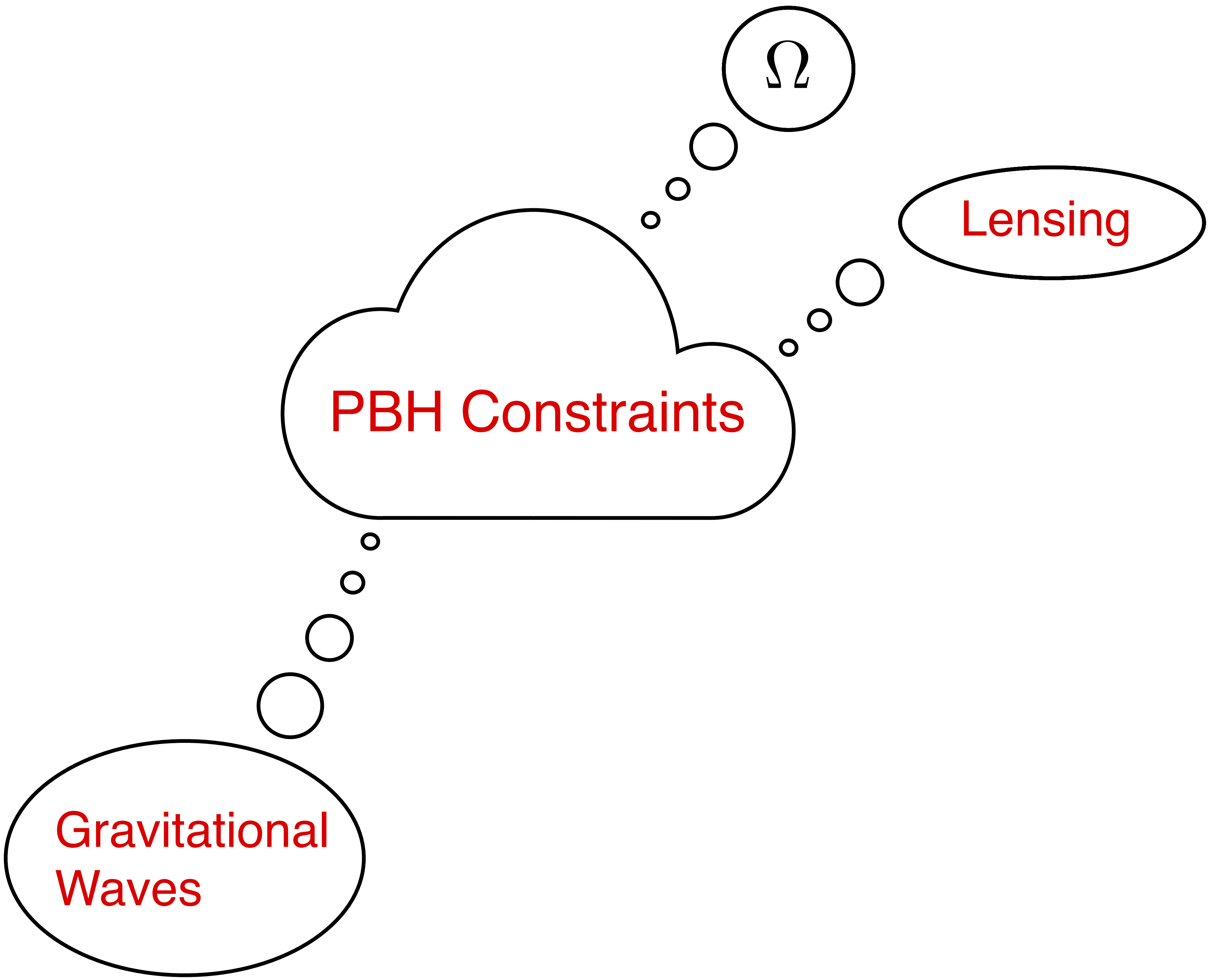
★ Number in our Galaxy: 10^{25}

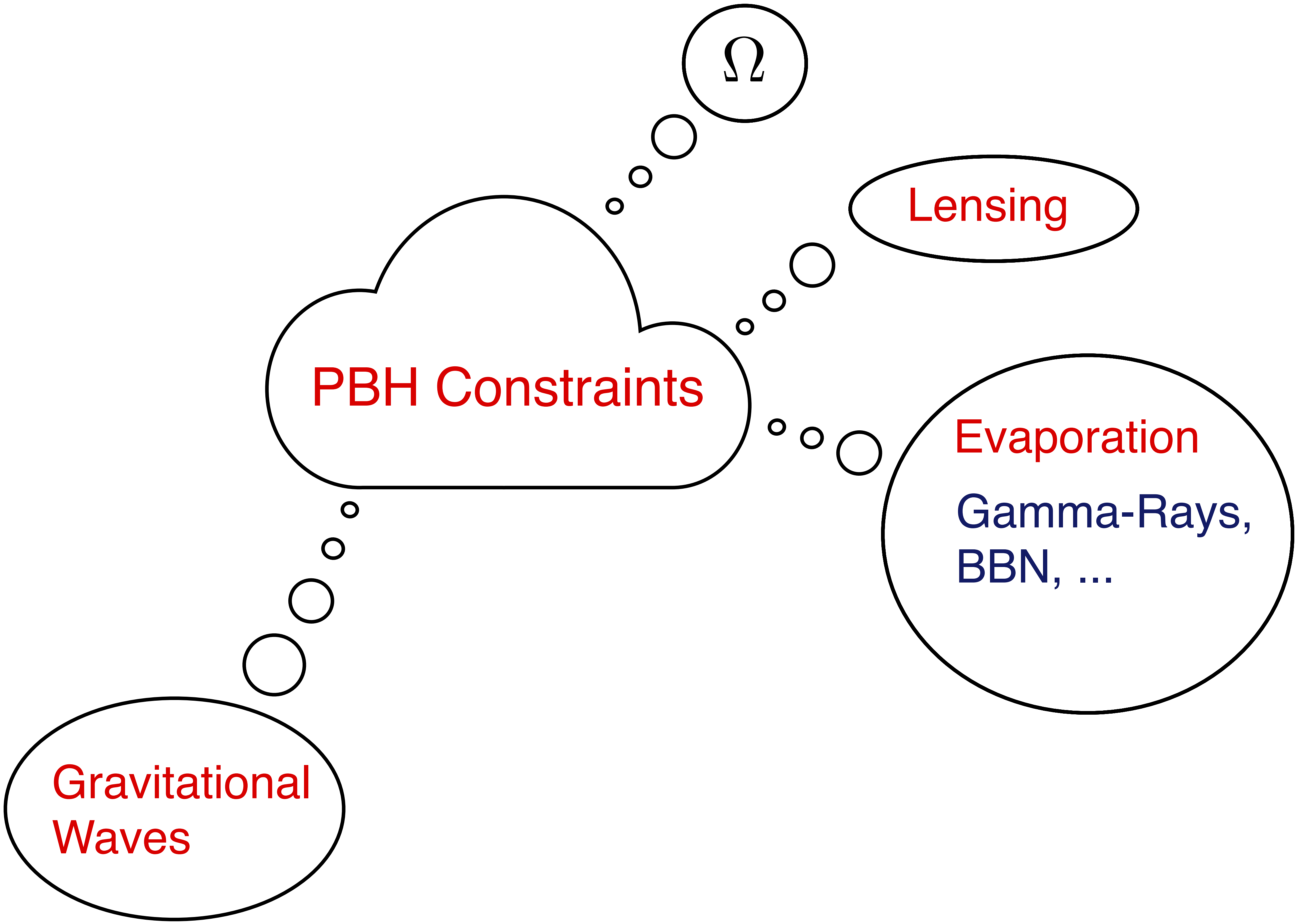
★ Distance: $10\,\mathrm{AU}$

PBH Constraints

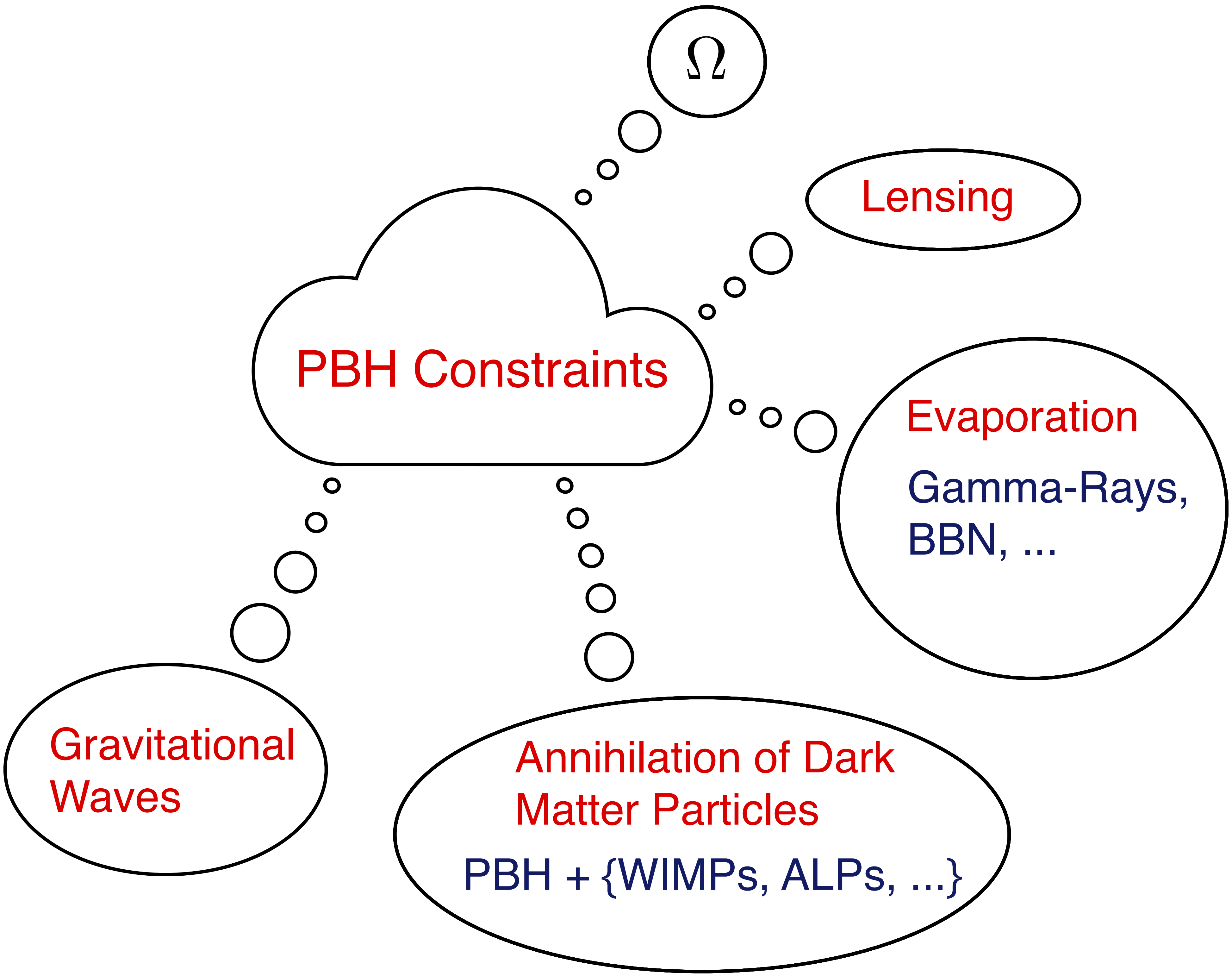

Ω
PBH Constraints


Ω
Lensing
PBH Constraints


Ω
Lensing
PBH Constraints
Gravitational Waves



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


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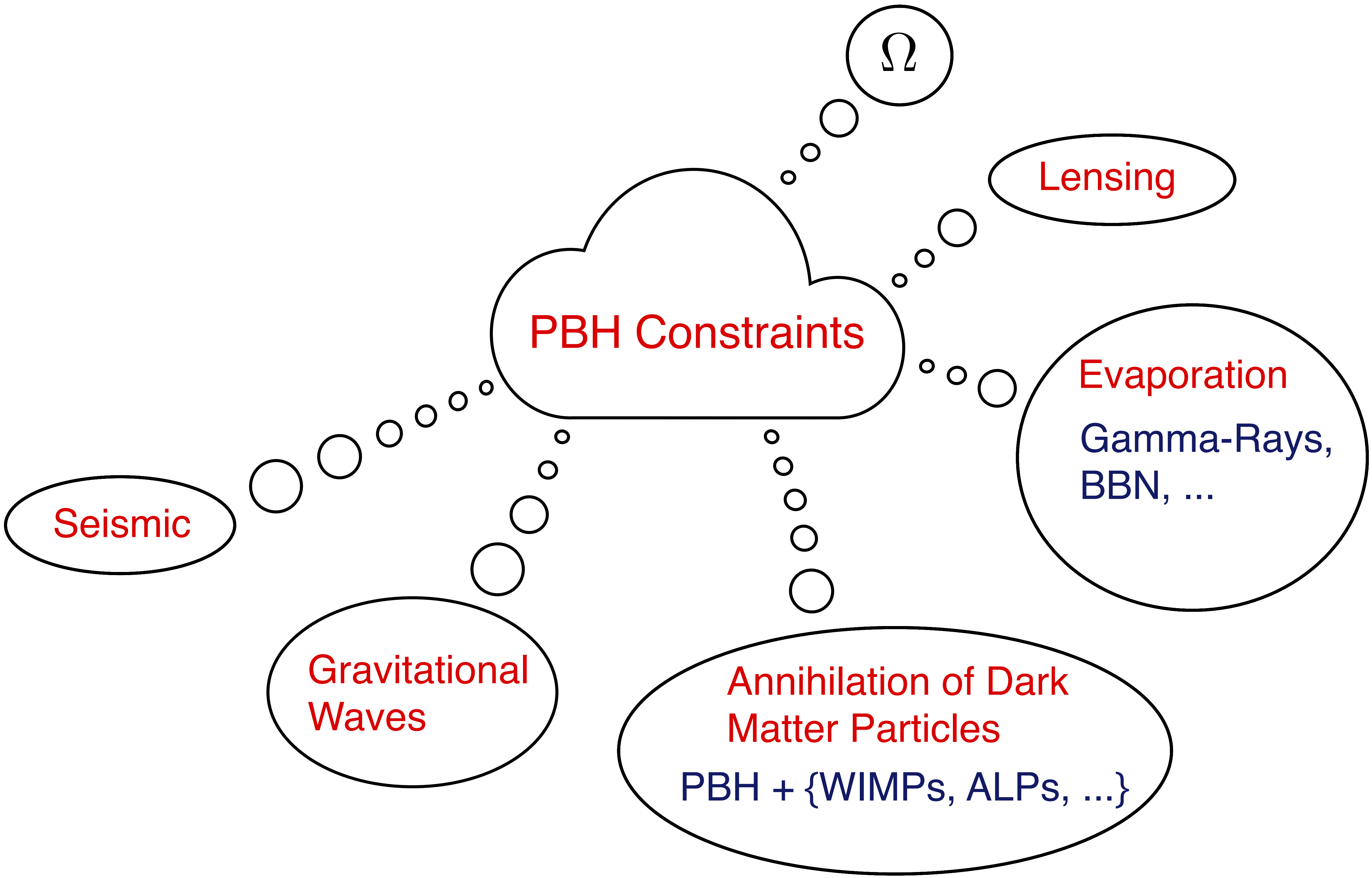
Evaporation
Gamma-Rays, BBN, ...
Gravitational Waves
Annihilation of Dark Matter Particles
PBH + {WIMPs, ALPs, ...}


Ω
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Evaporation
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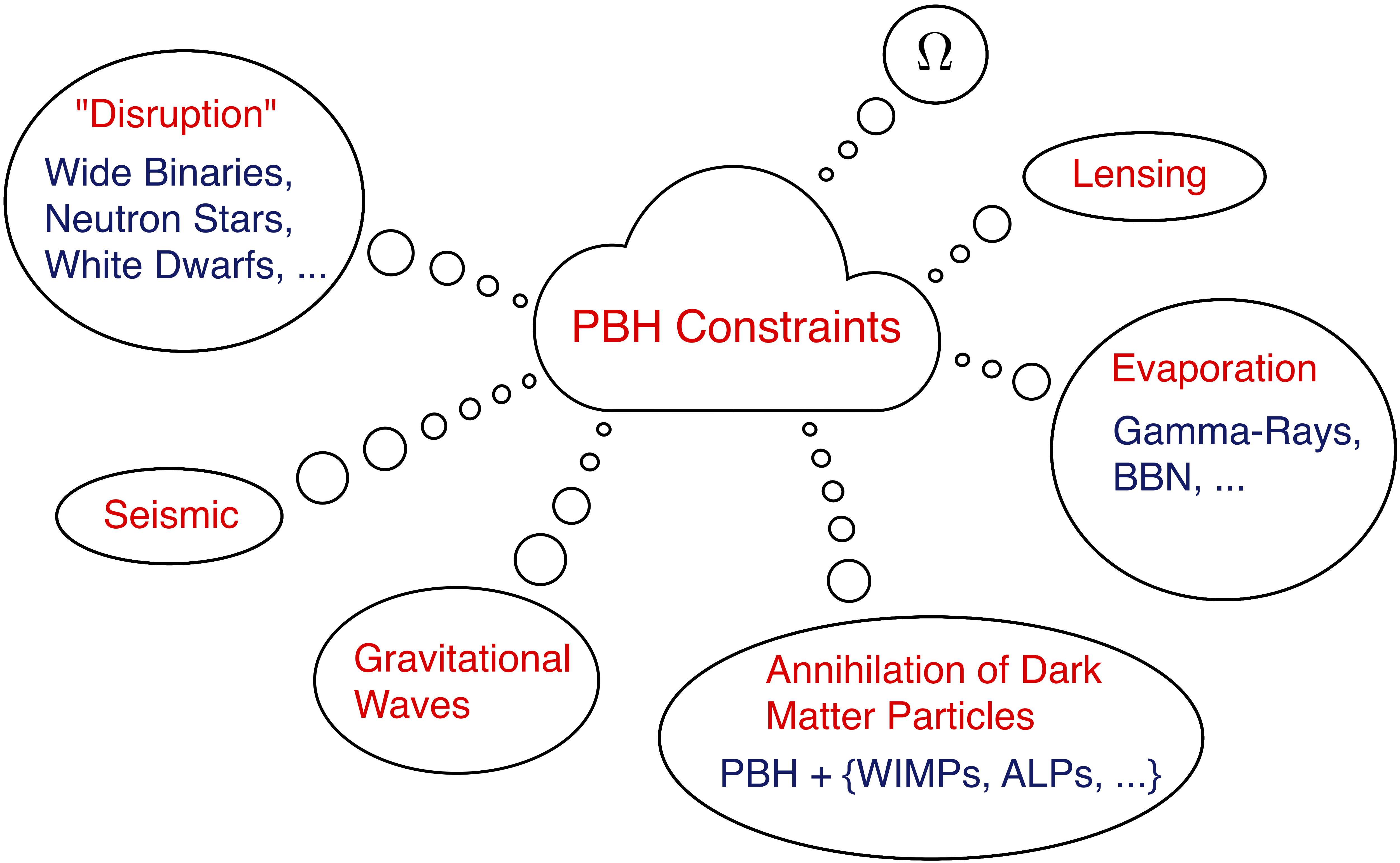
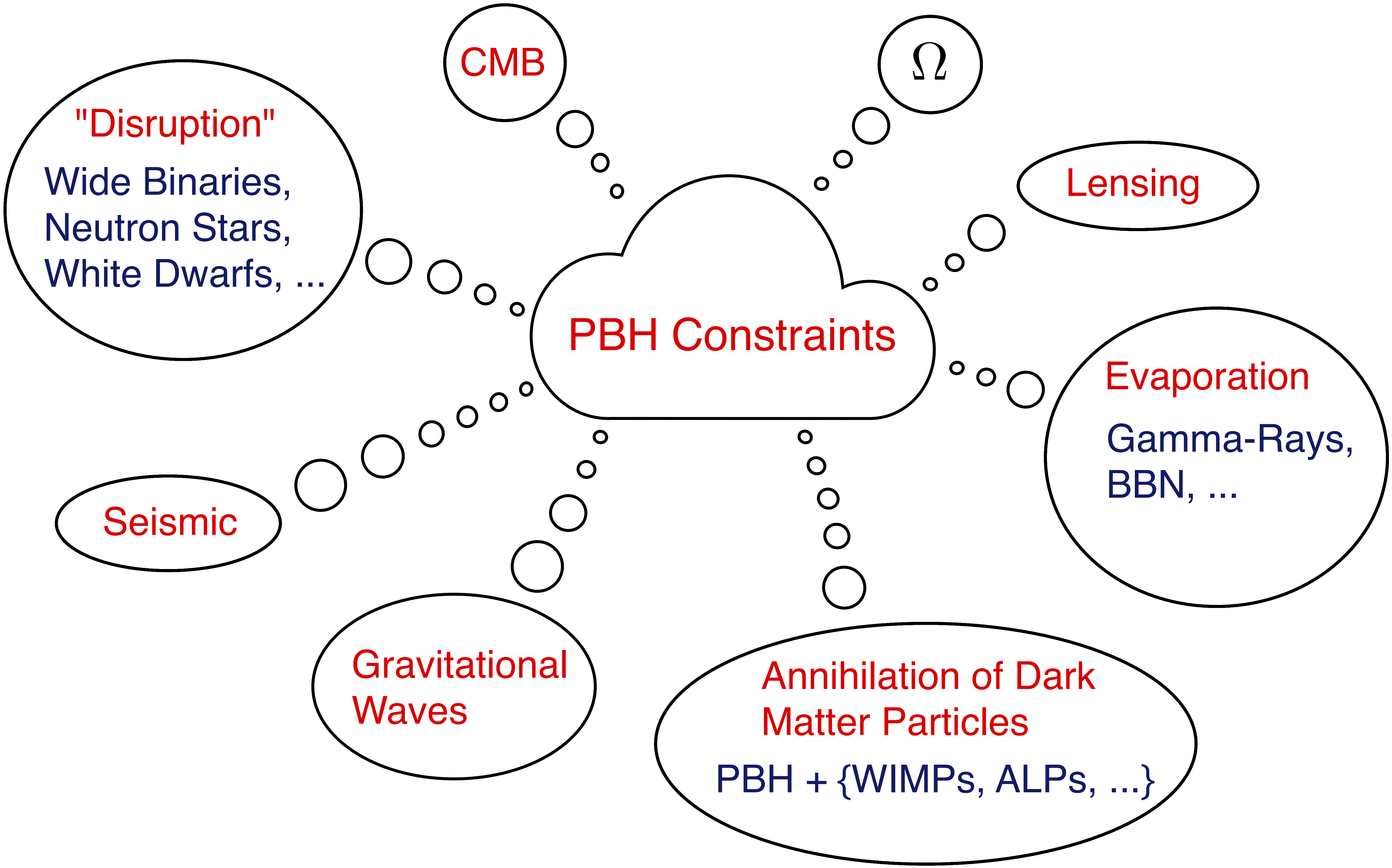


PBH Constraints
Ω
"Disruption"
Wide Binaries,
Neutron Stars,
White Dwarfs, ...
Lensing
Evaporation
Gamma-Rays,
BBN, ...
Seismic
Gravitational
Waves
Annihilation of Dark
Matter Particles
PBH + {WIMPs, ALPs, ...}



PBH Constraints
CMB
Ω
Lensing
"Disruption"
Wide Binaries,
Neutron Stars,
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BBN, ...
Seismic
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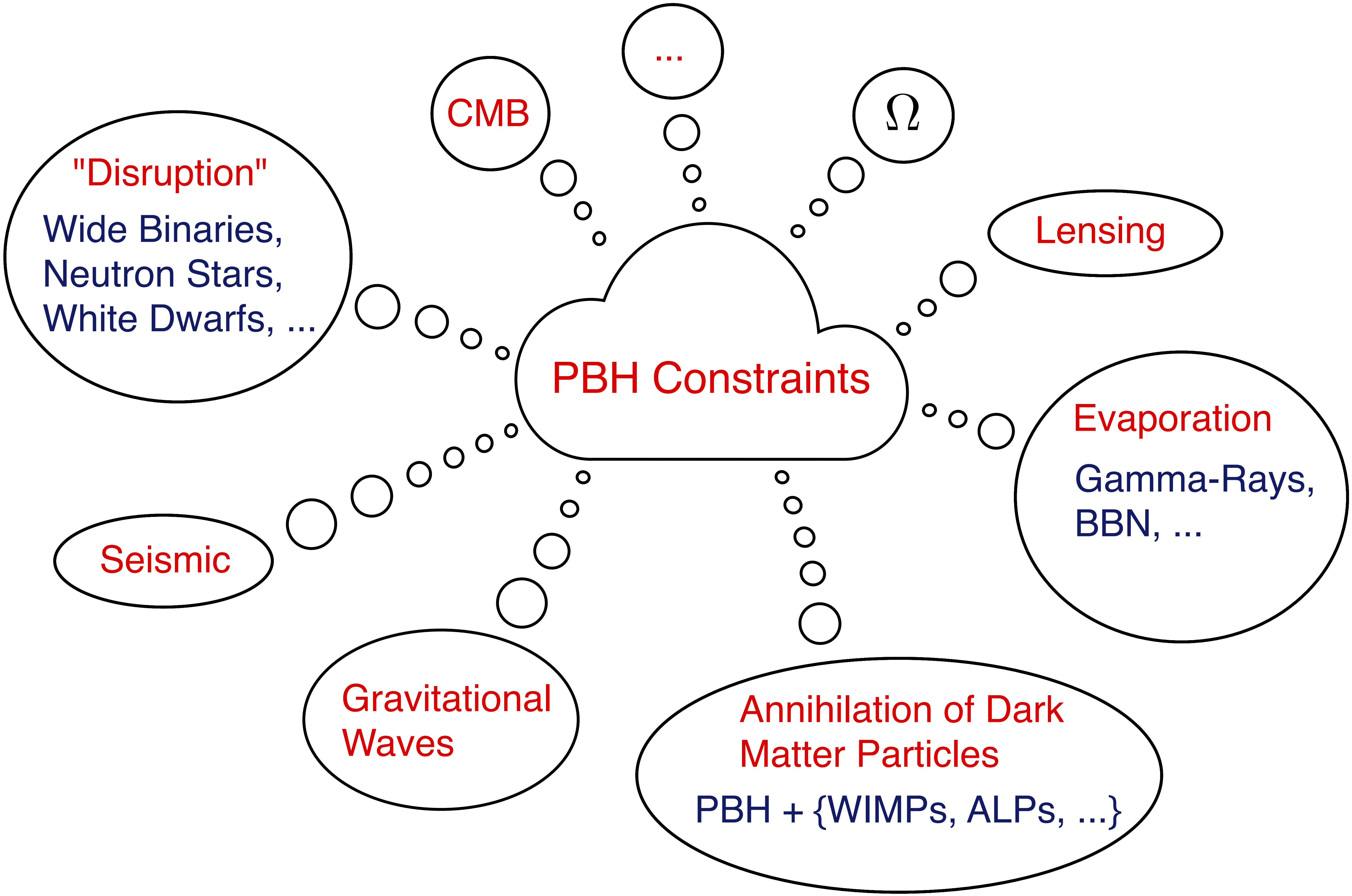

PBH Constraints
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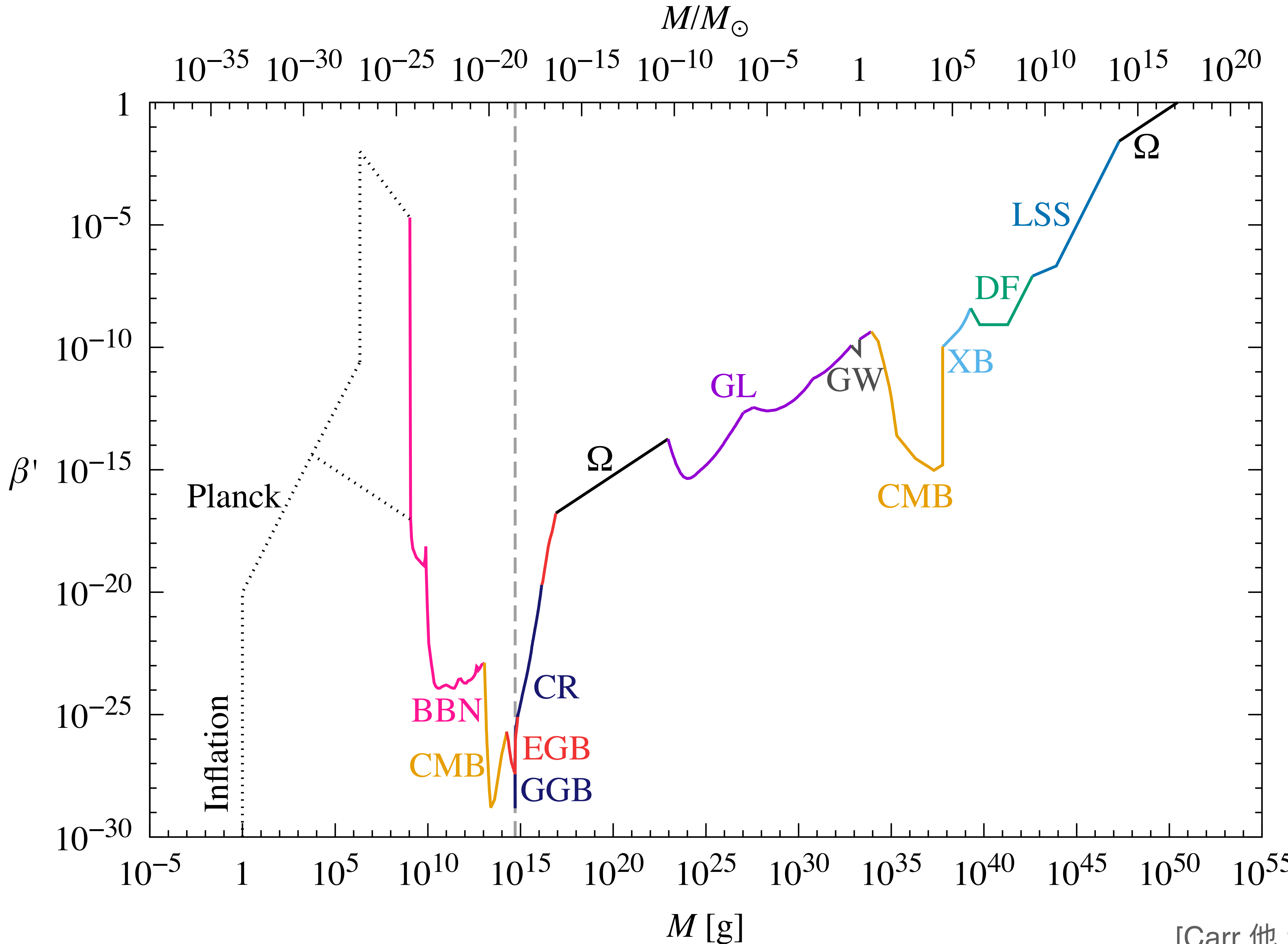
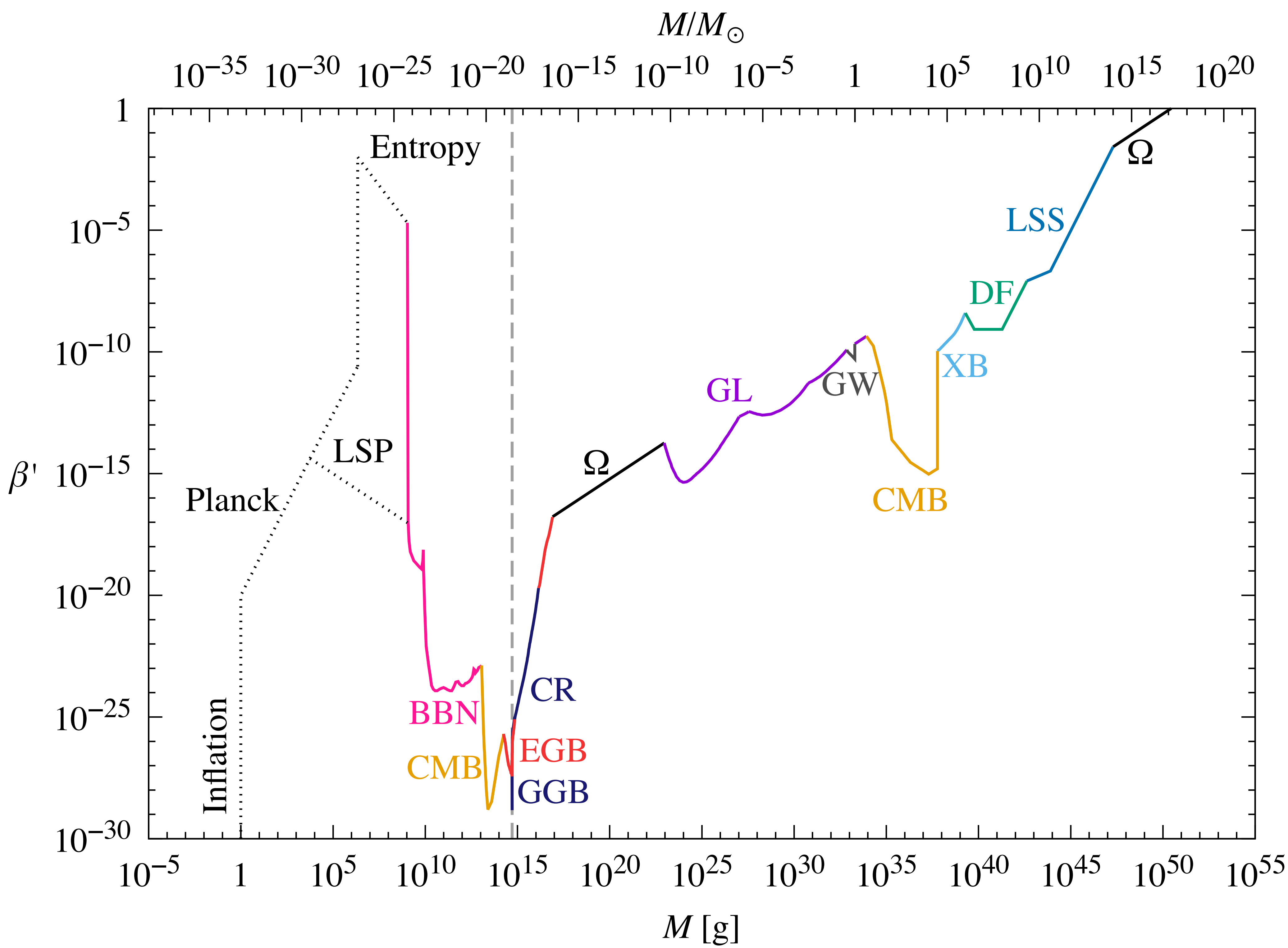
PBH Constraints at Formation



[Carr 他 2021]

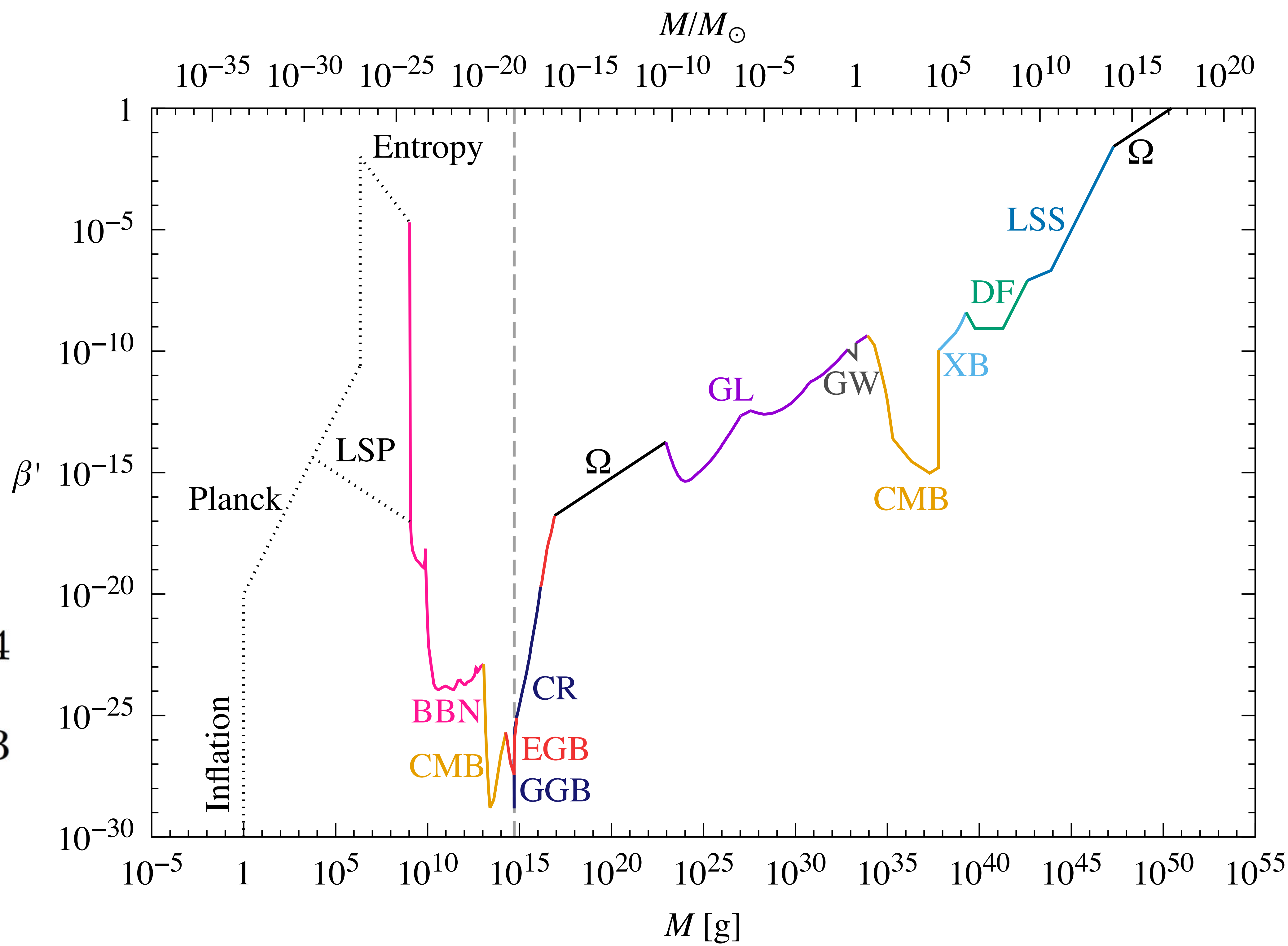
PBH Constraints at Formation



[Carr 他 2021]

PBH Constraints at Formation

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



[Carr 他 2021]

★ Note that

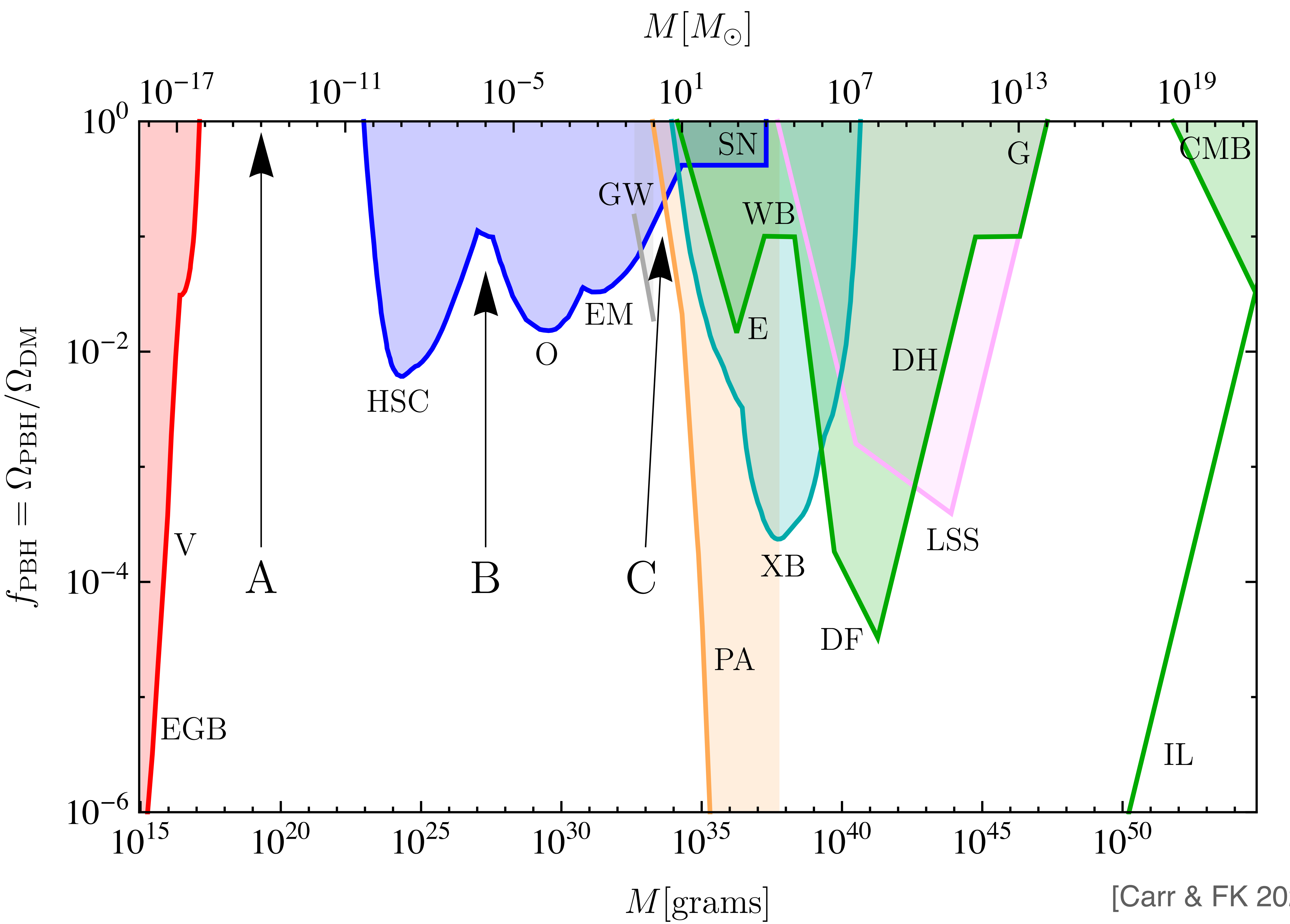
$$\rho_{\rm rad} \propto a^{-4}$$

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

and hence

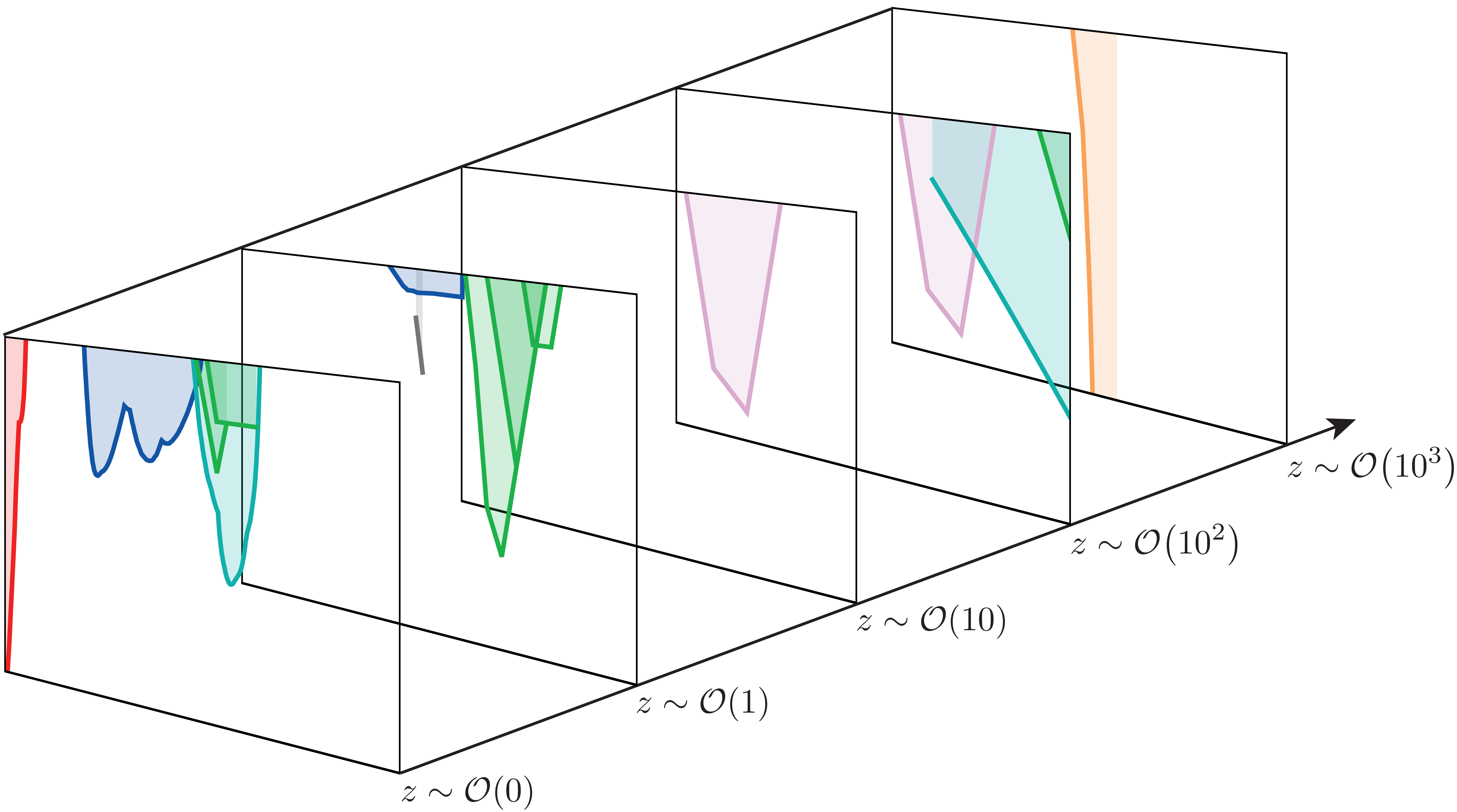
$$\Omega_{\rm PBH} \propto a$$

Current PBH Constraints



[Carr & FK 2020]

PBH Constraints — Redshift Dependence



[Carr & FK 2020]

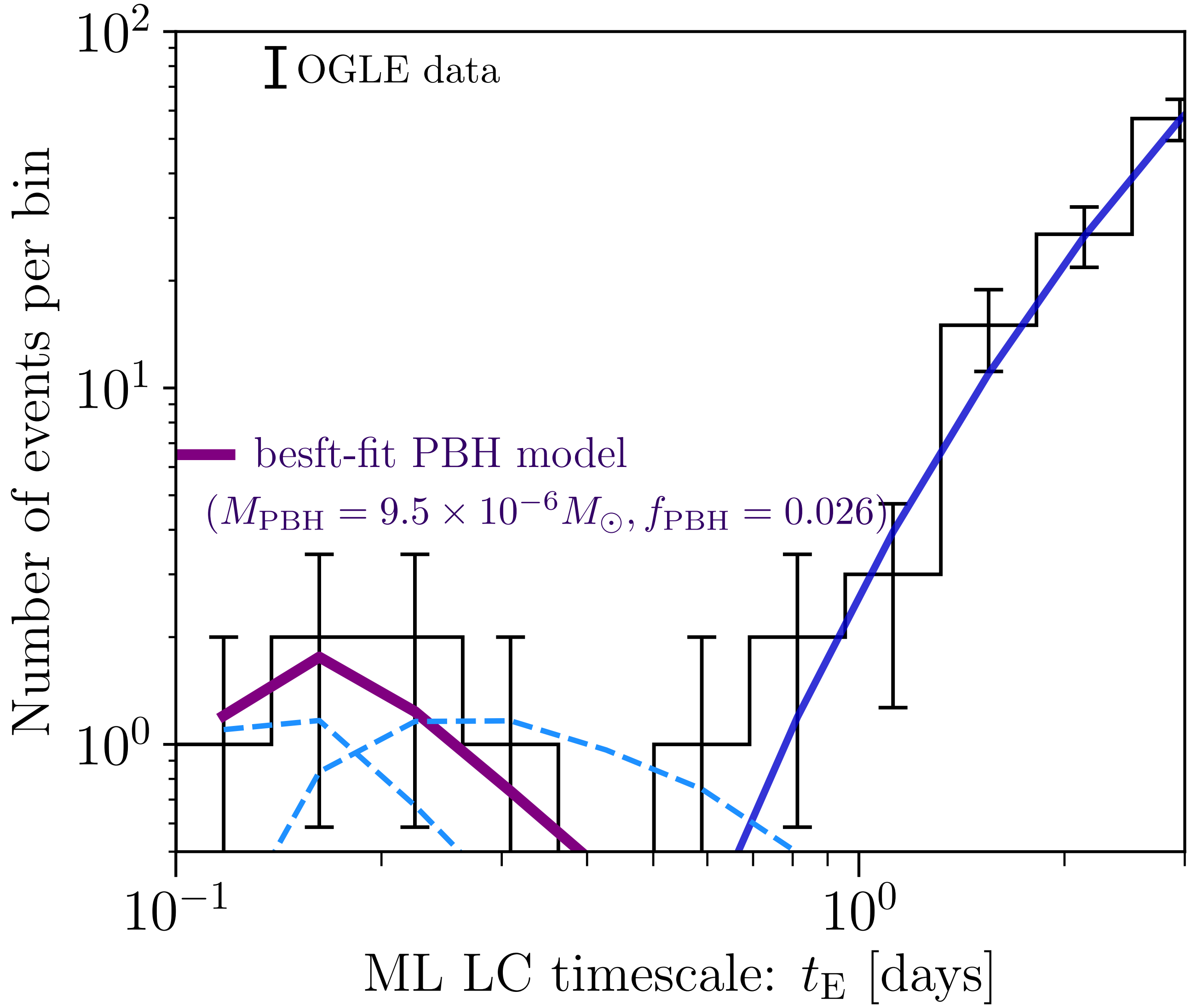
Observational Hints for Primordial Black Holes

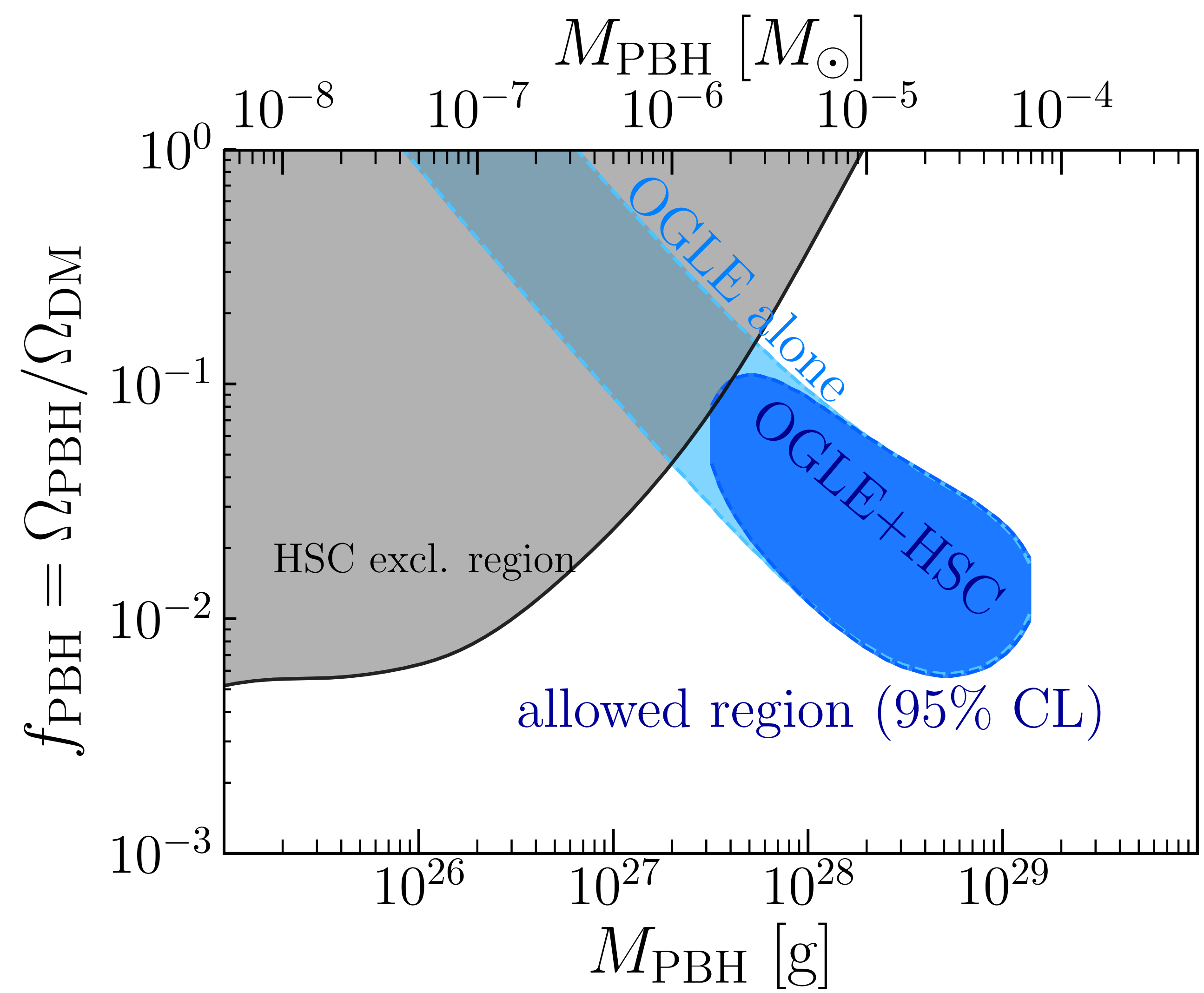
Evidence?

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!

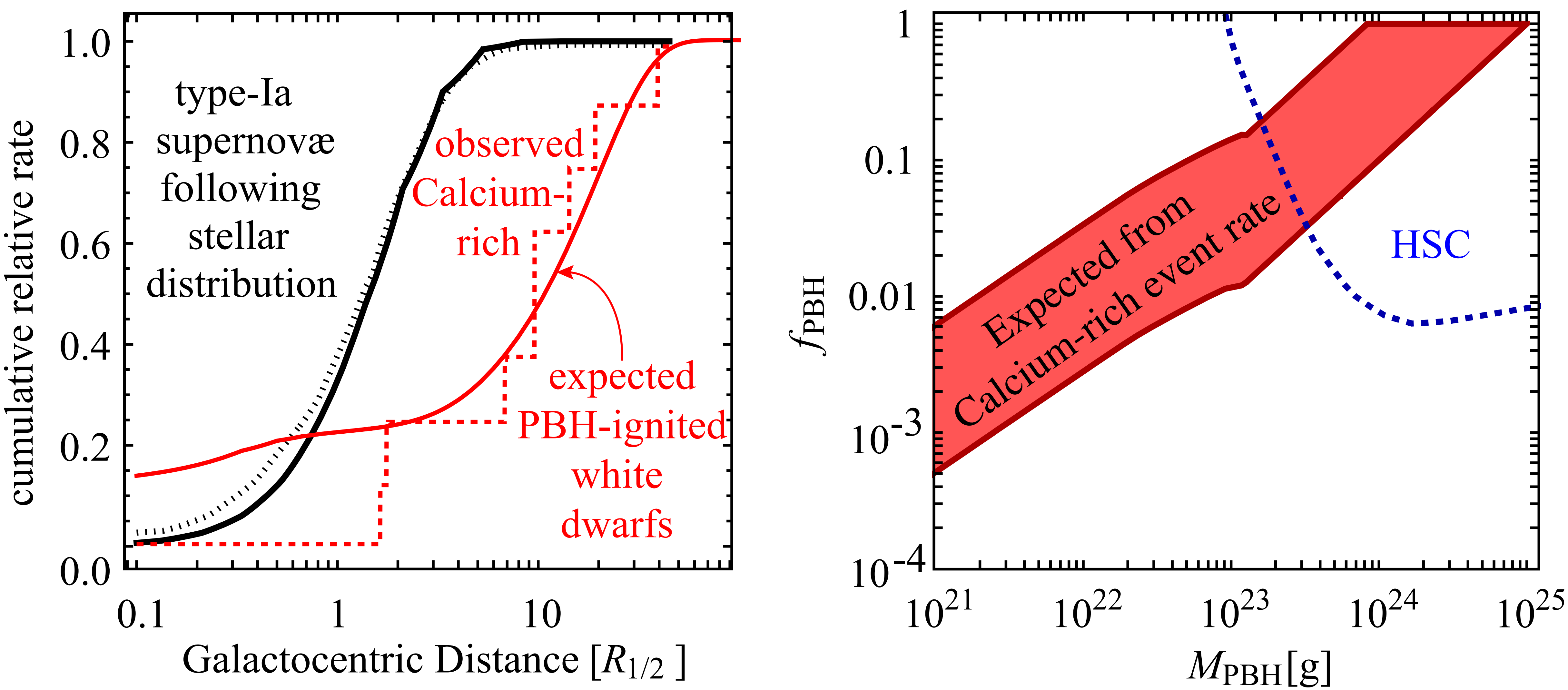




[Niikura *et al.* 2019]

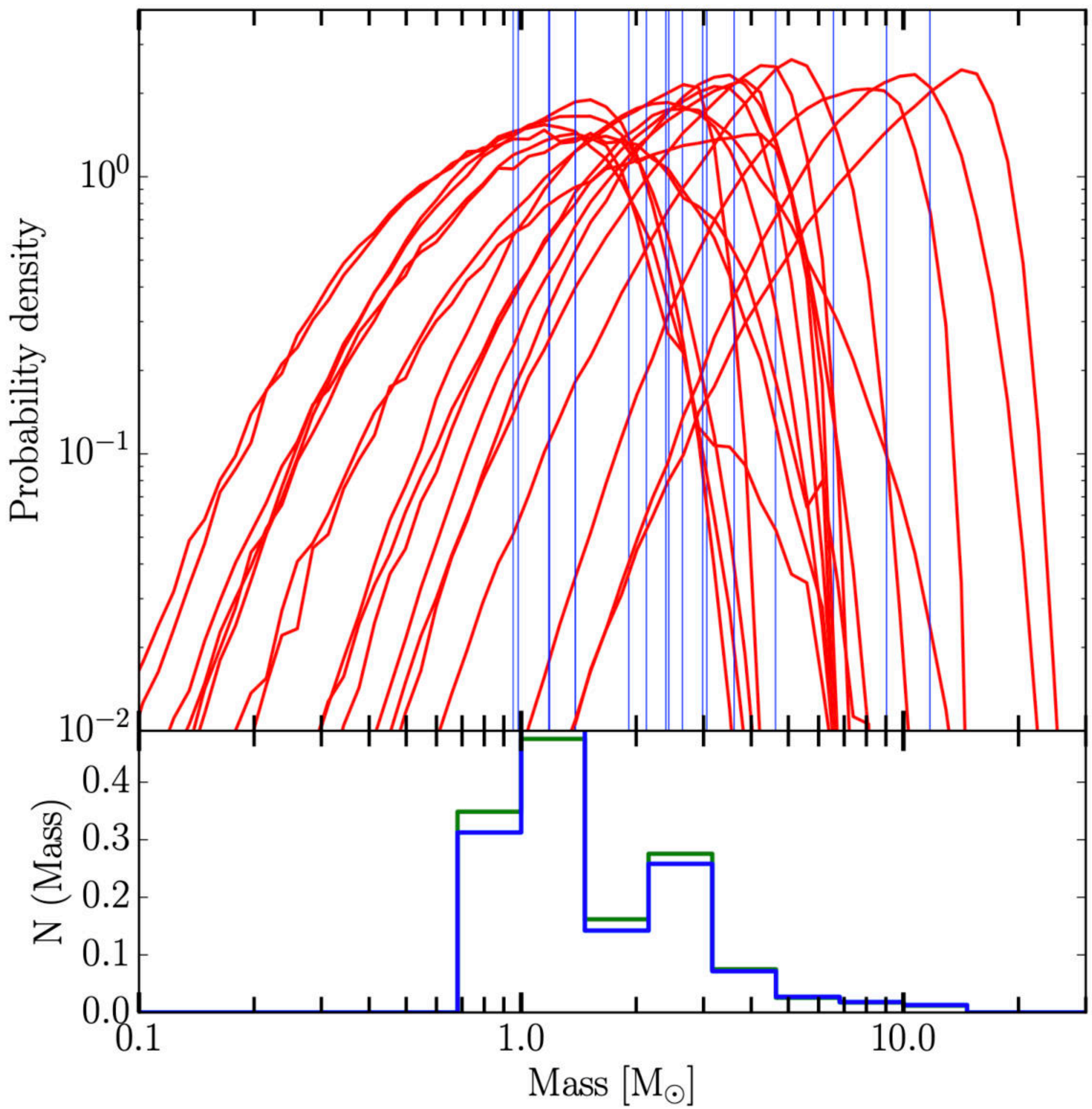
Calcium-Rich Gap Transients

★ 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]

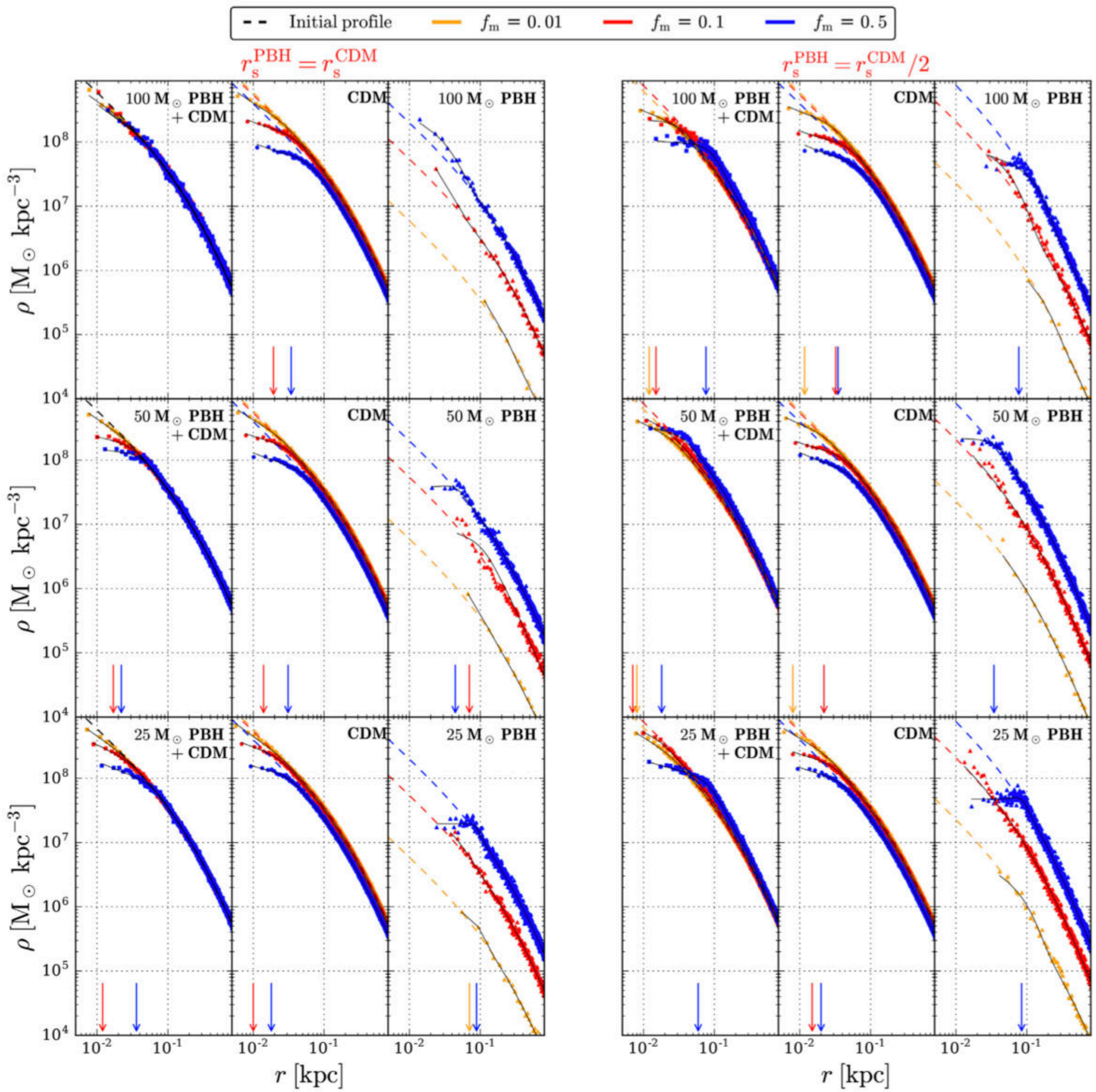
Excess of Lenses in Galactic Bulge



[Wyrzykowski & Mandel 2020]

- ★ 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.

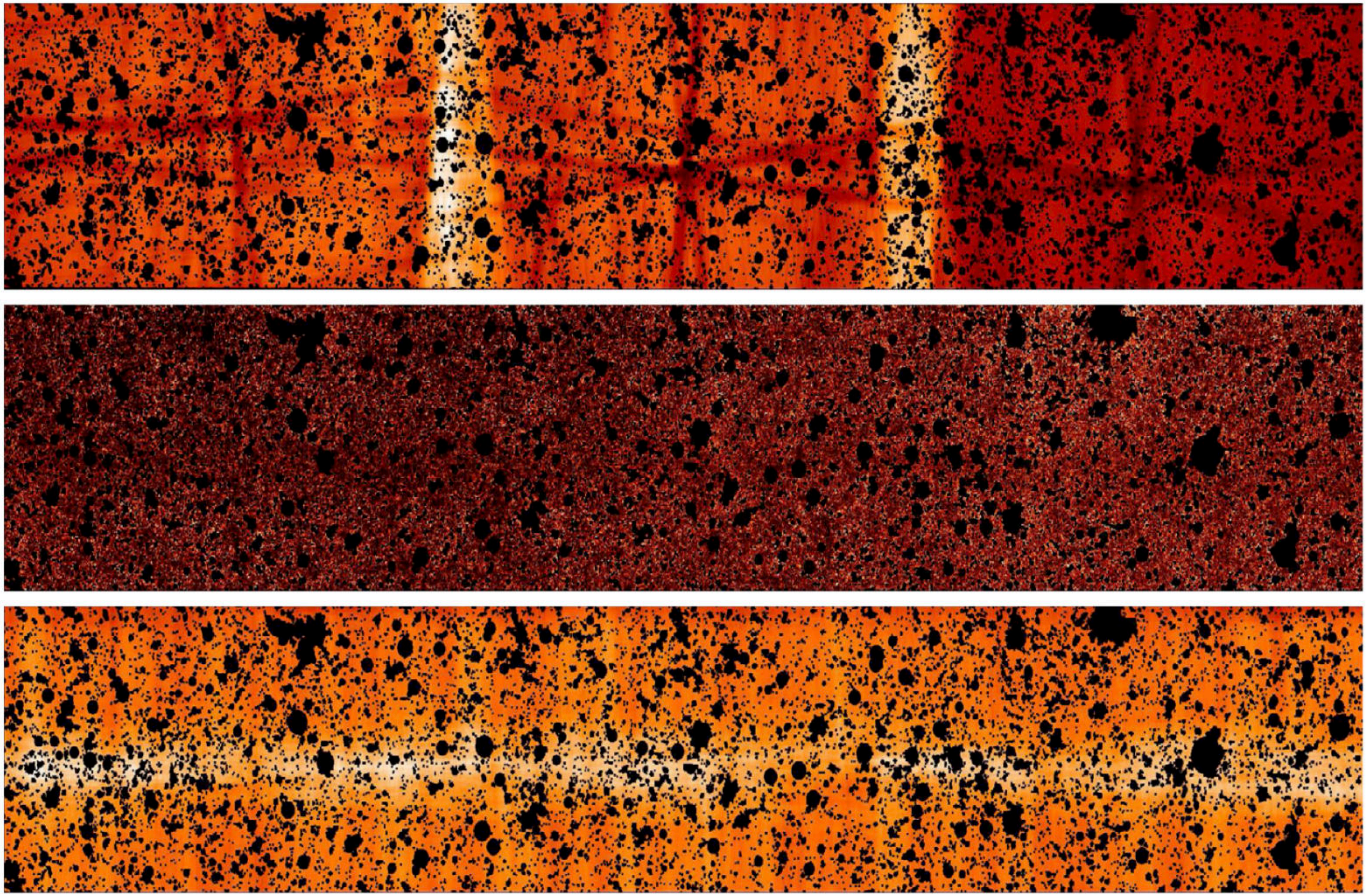
Ultra-faint Dwarf Galaxies



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

Correlations of Cosmic Infrared/X-Ray Backgrounds

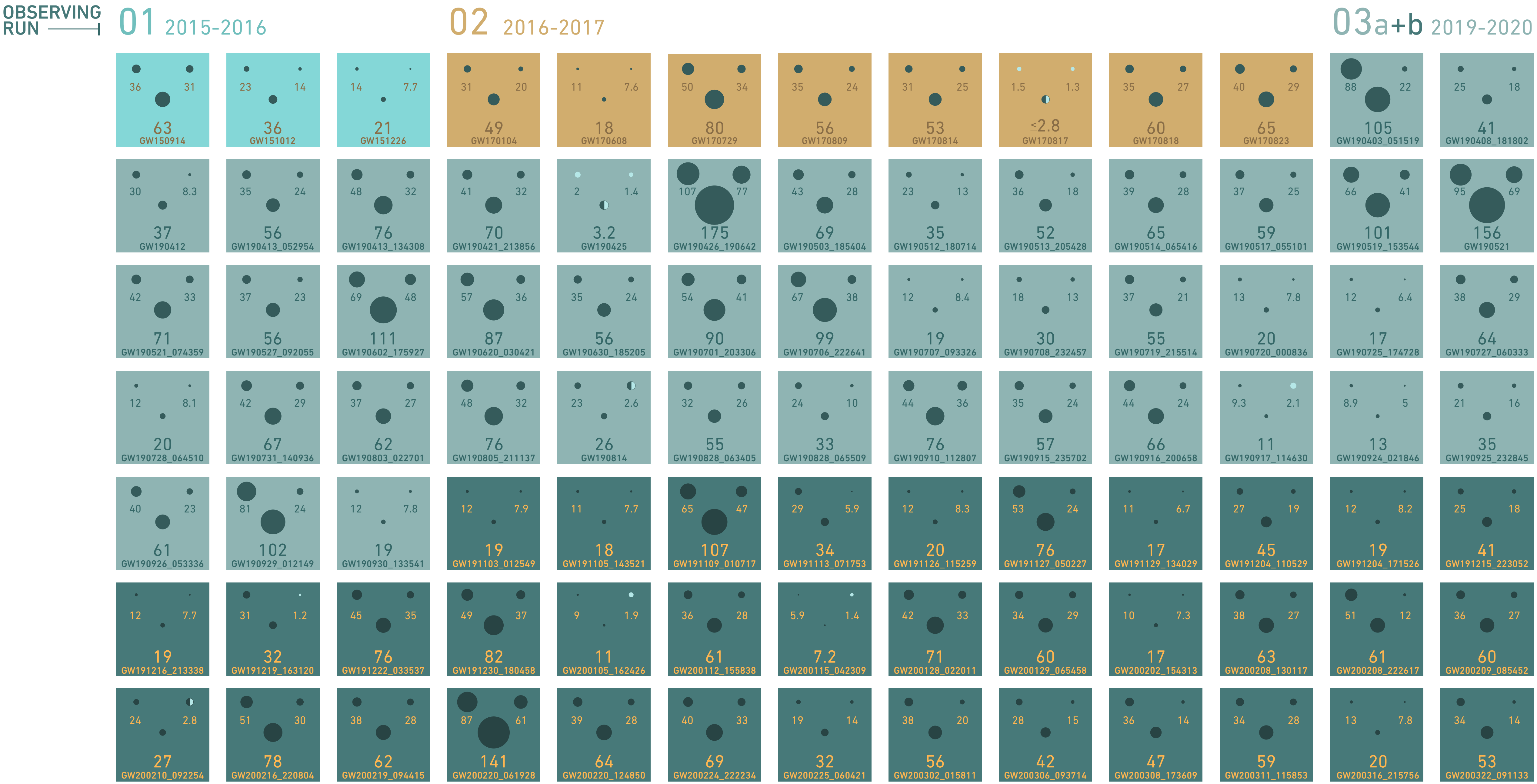


[Capelluti *et al.* 2013]

★ PBHs generate early structure and respective backgrounds

GRAVITATIONAL WAVE **MERGER** DETECTIONS

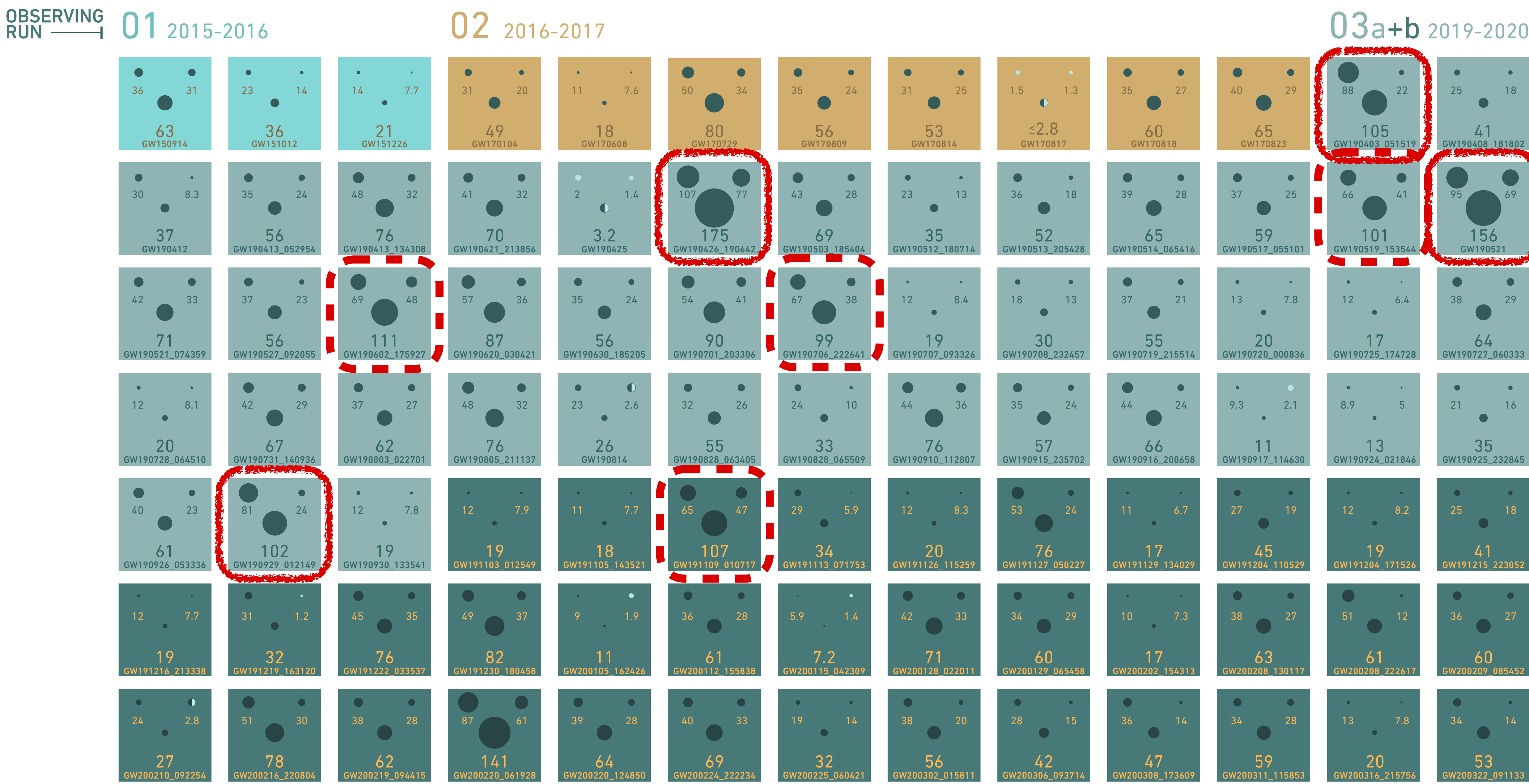
SINCE 2015



LIGO VIRGO KAGRA

GRAVITATIONAL WAVE **MERGER** DETECTIONS

→ SINCE 2015

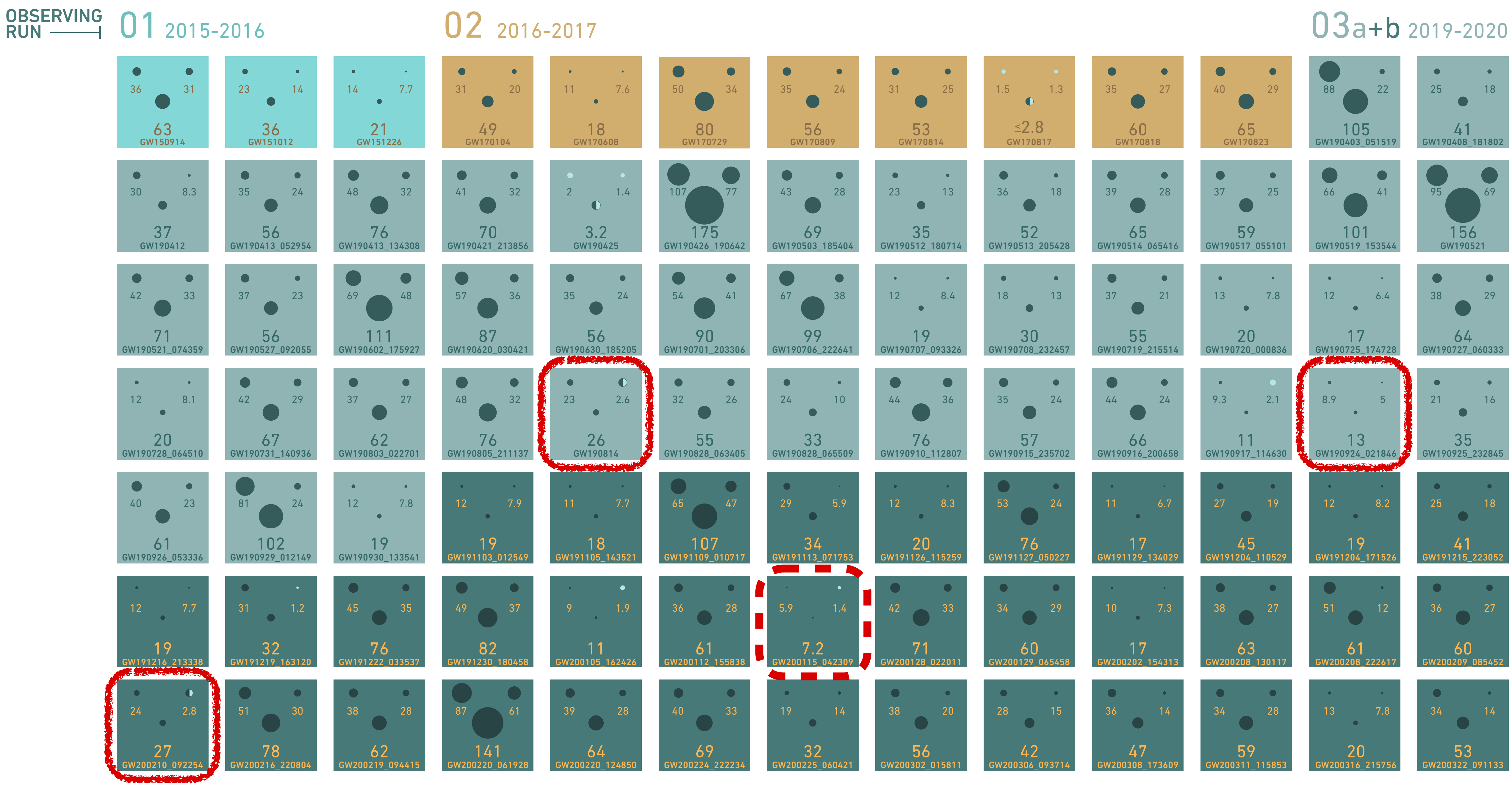


★ Black hole progenitors in the pair-instability mass gap (i.e. above ~ 60 $M_\odot$)

LIGO VIRGO KAGRA

GRAVITATIONAL WAVE **MERGER** DETECTIONS

→ SINCE 2015

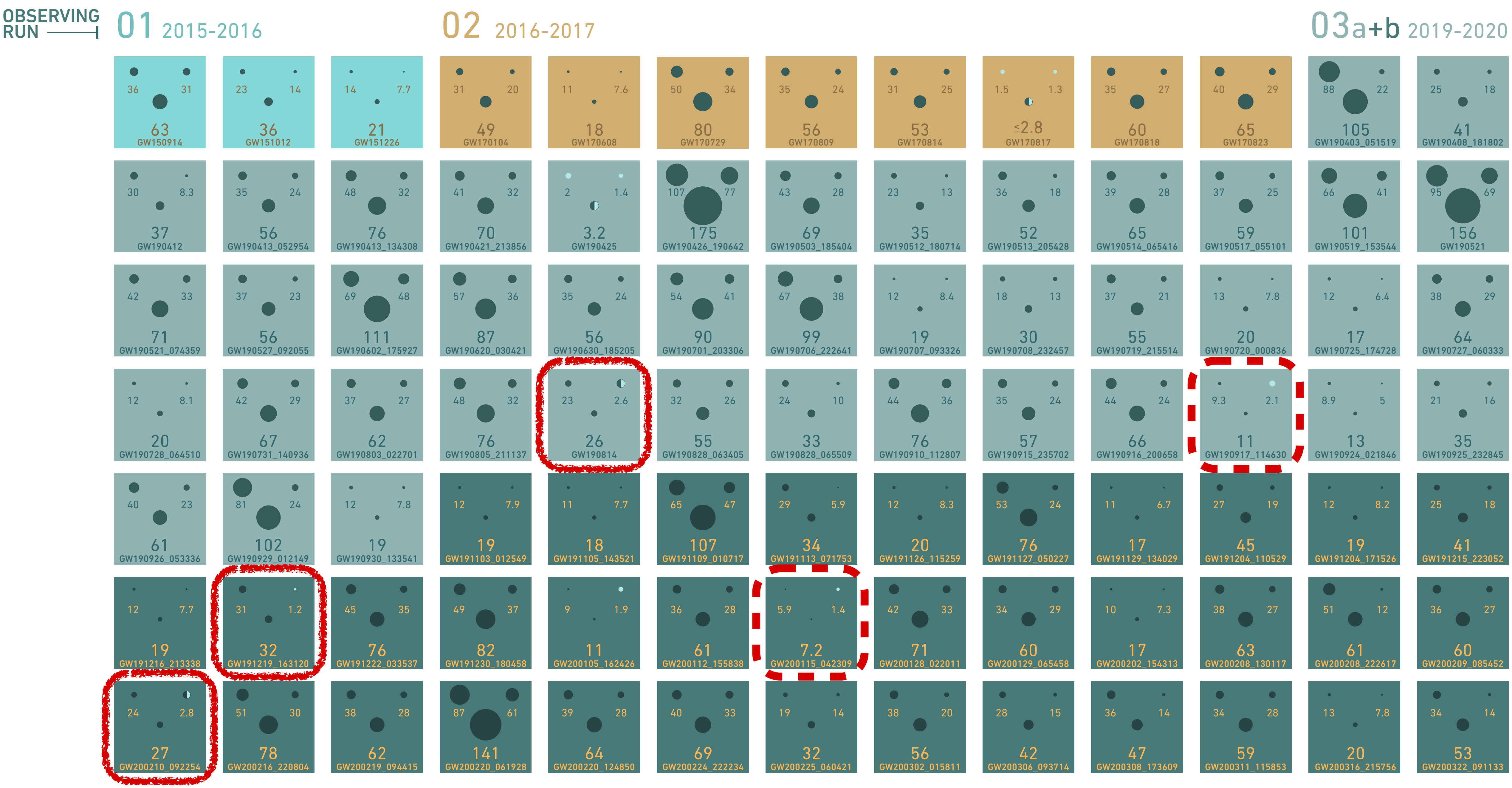


★ Black hole progenitors in the lower mass gap (i.e. between 2 and 5 $M_\odot$)

LIGO VIRGO KAGRA

GRAVITATIONAL WAVE **MERGER** DETECTIONS

SINCE 2015



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

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

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 [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

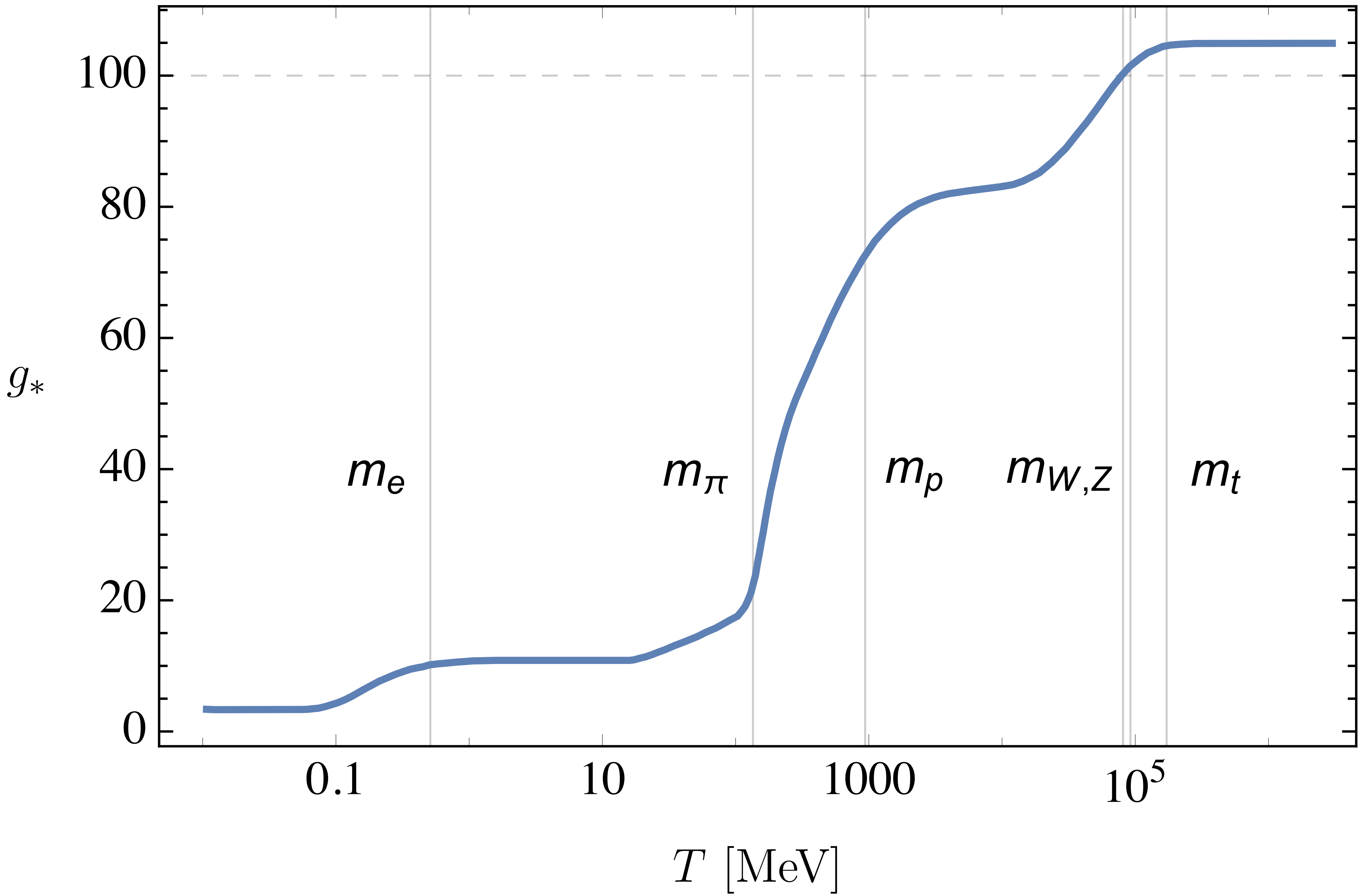
★ Four subsolar candidates with SNR > 8 and a FAR < 2 yr^{-1}

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

Thermal History

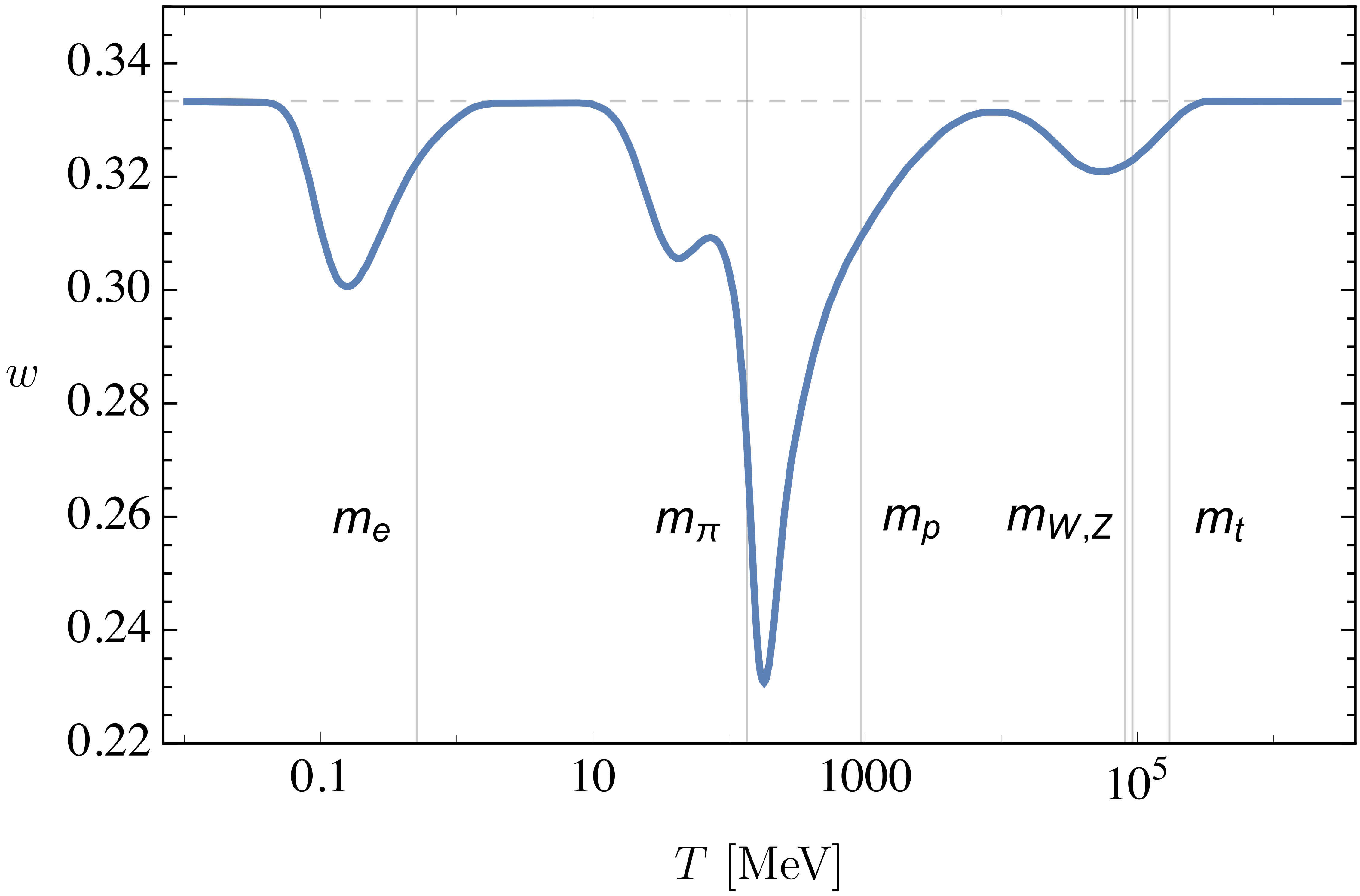
Thermal History of the Universe

★ Changes in the relativistic degrees of freedom:



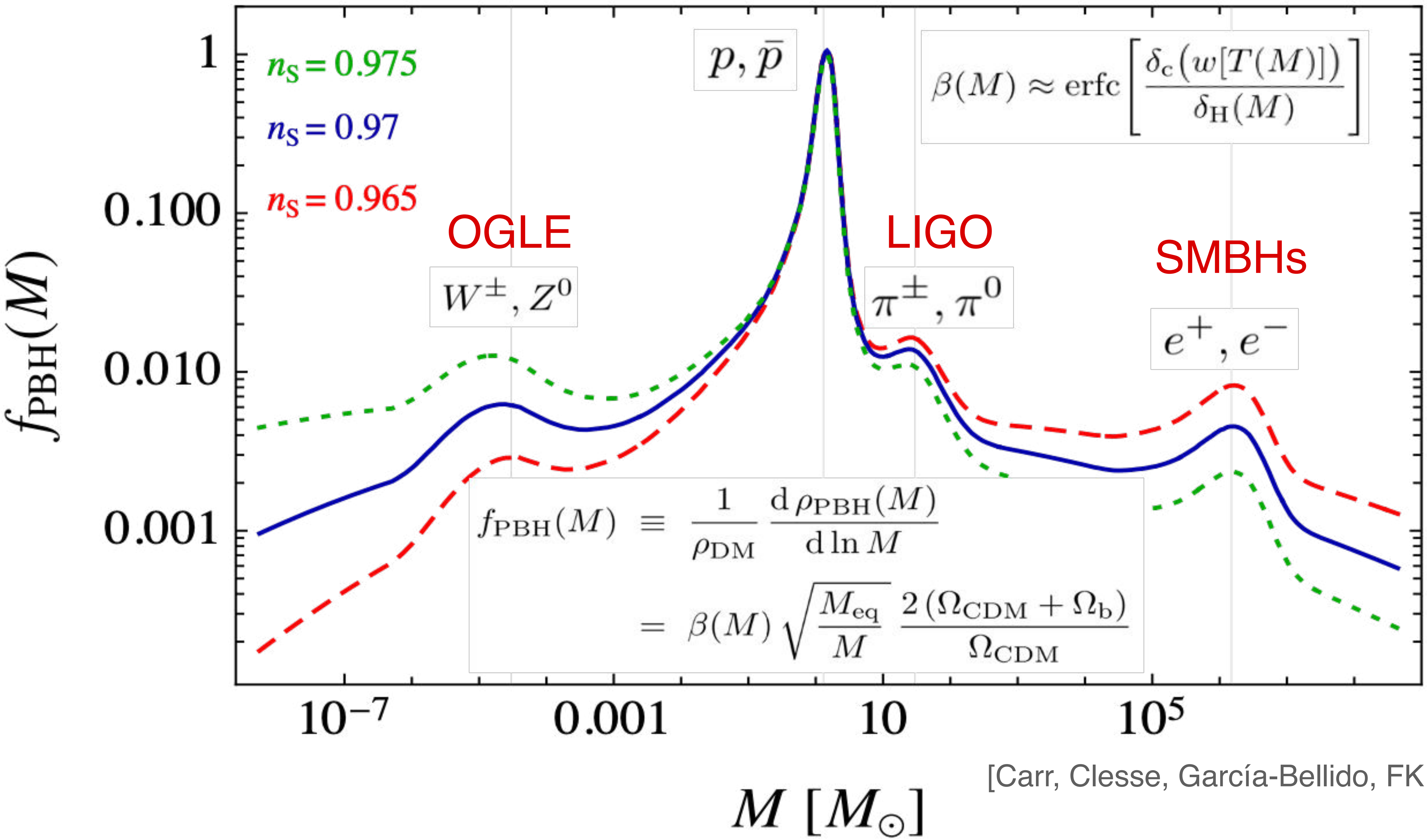
Thermal History of the Universe

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



Thermal History of the Universe

★ An essentially featureless power spectrum leads to:



[Carr, Clesse, García-Bellido, FK 2020]

Primordial Black Holes from Confinement

work with Dvali & 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.

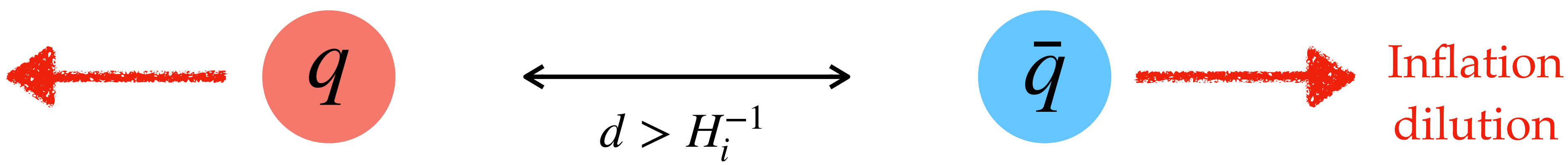
- ★ PBH formation happens in the strong-coupling regime.

A New Approach

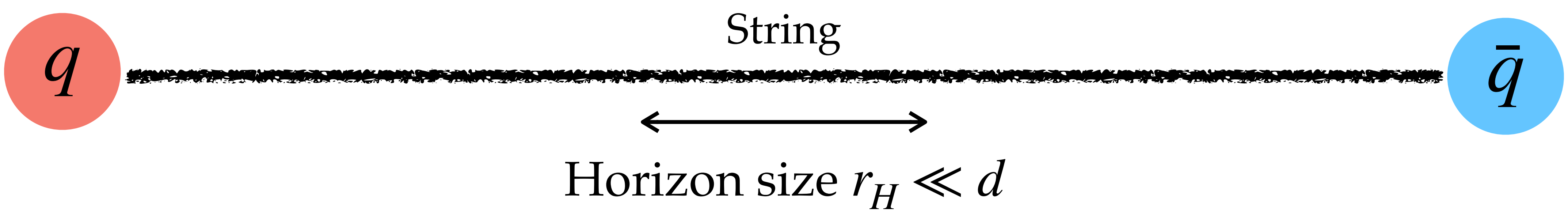
- We propose a novel PBH formation mechanism which is
  - assumption-minimal,
  - free of exponential fine-tuning,
  - avoids strong coupling,
  - works with standard QCD*,
  - compatible with observations.

Confinement Formation Mechanism

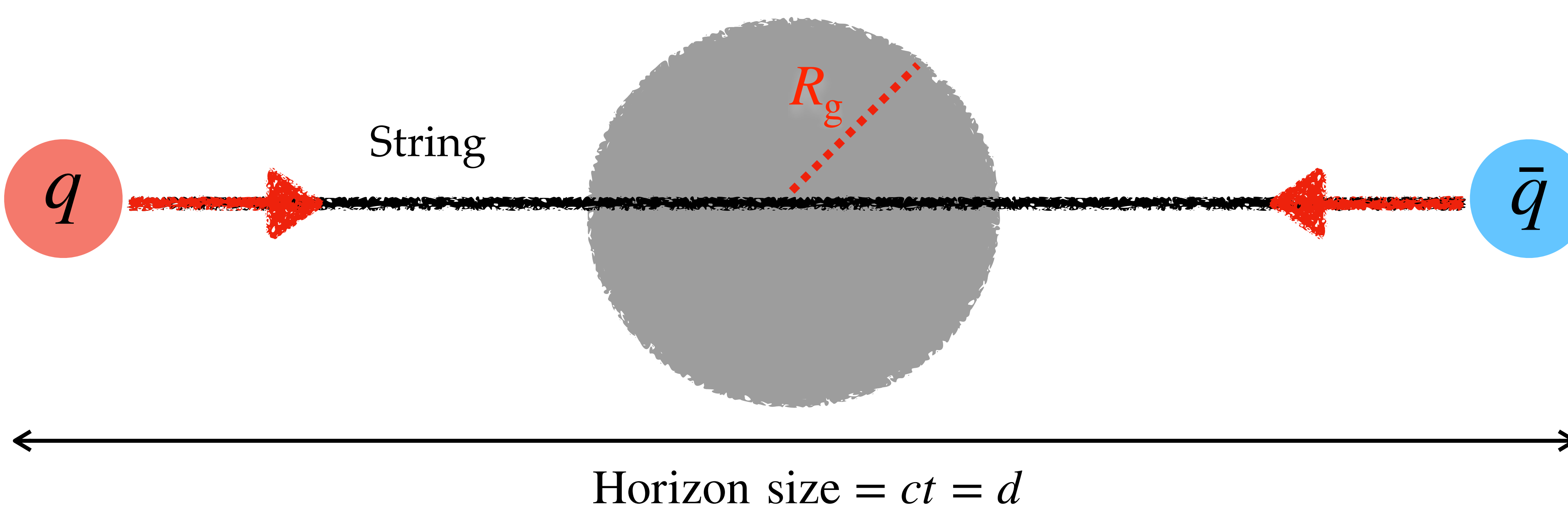
★ **1. Ingredient:** de Sitter fluctuations produce quarks during inflation.



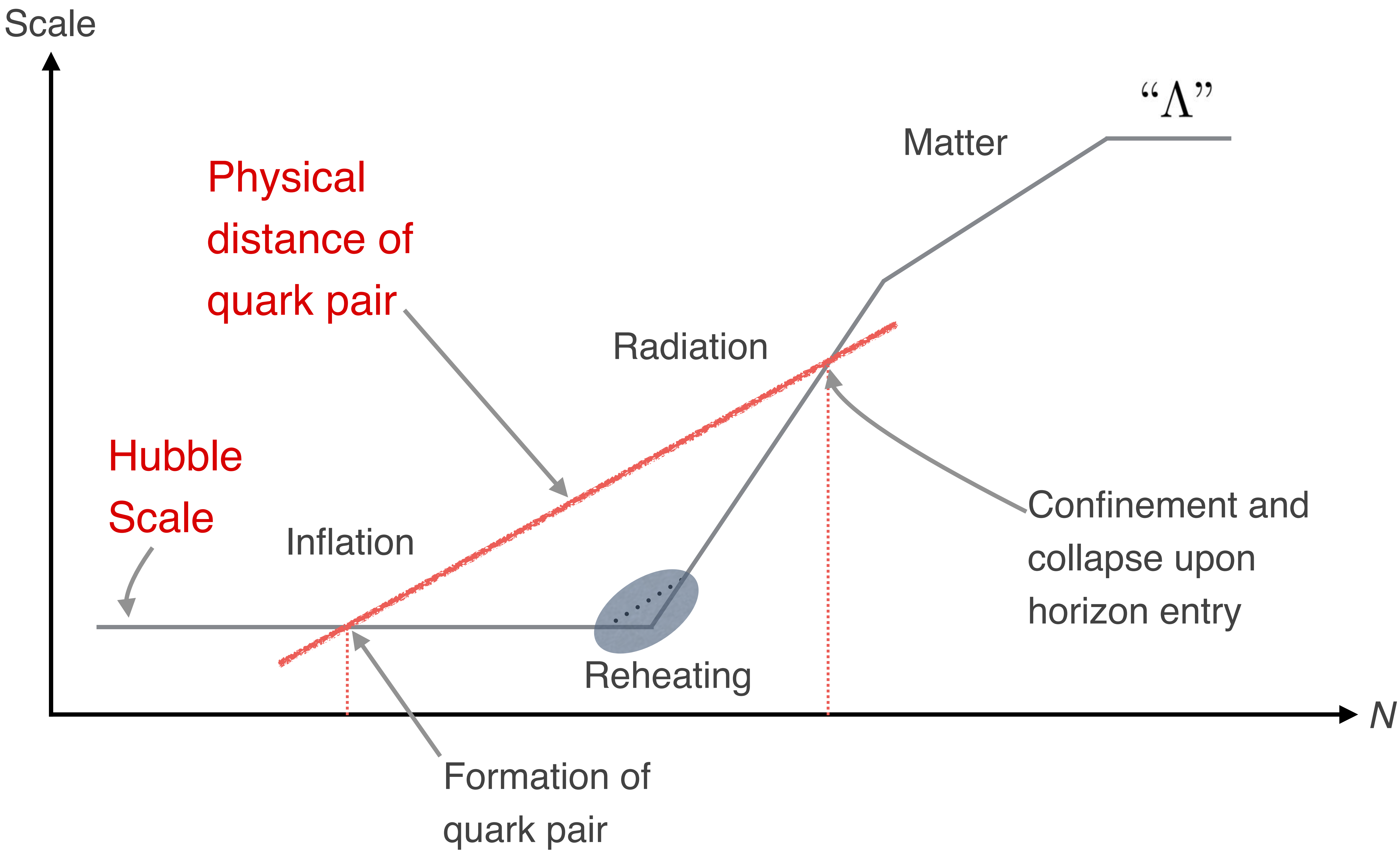
★ **2. Ingredient:** Confinement at energy scale Λ_c, $M_q/\Lambda_c \gg 1$



★ **3. Ingredient:** Black hole formation after horizon entry

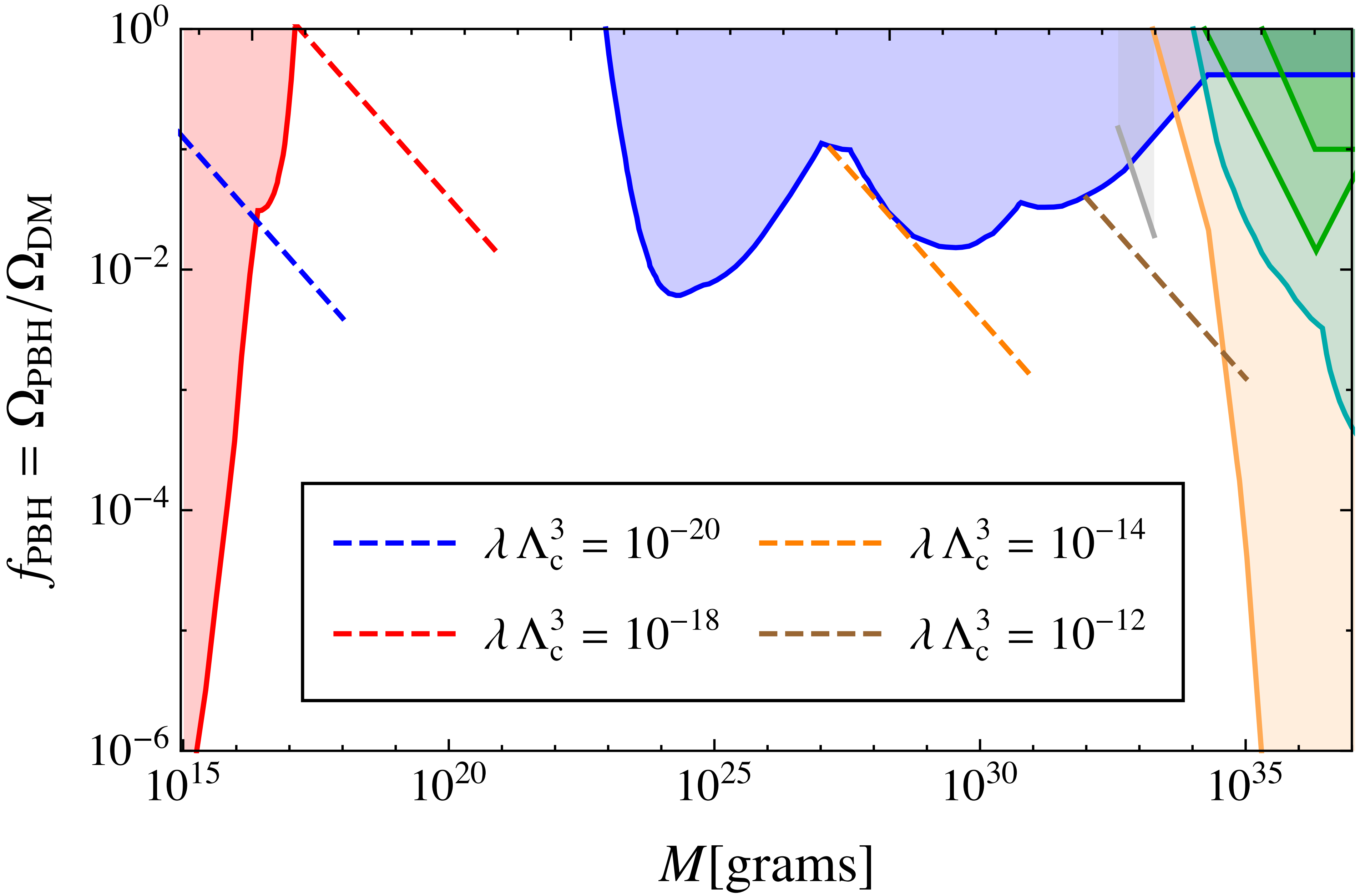


Formation Scales



Dark Matter from Confinement

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



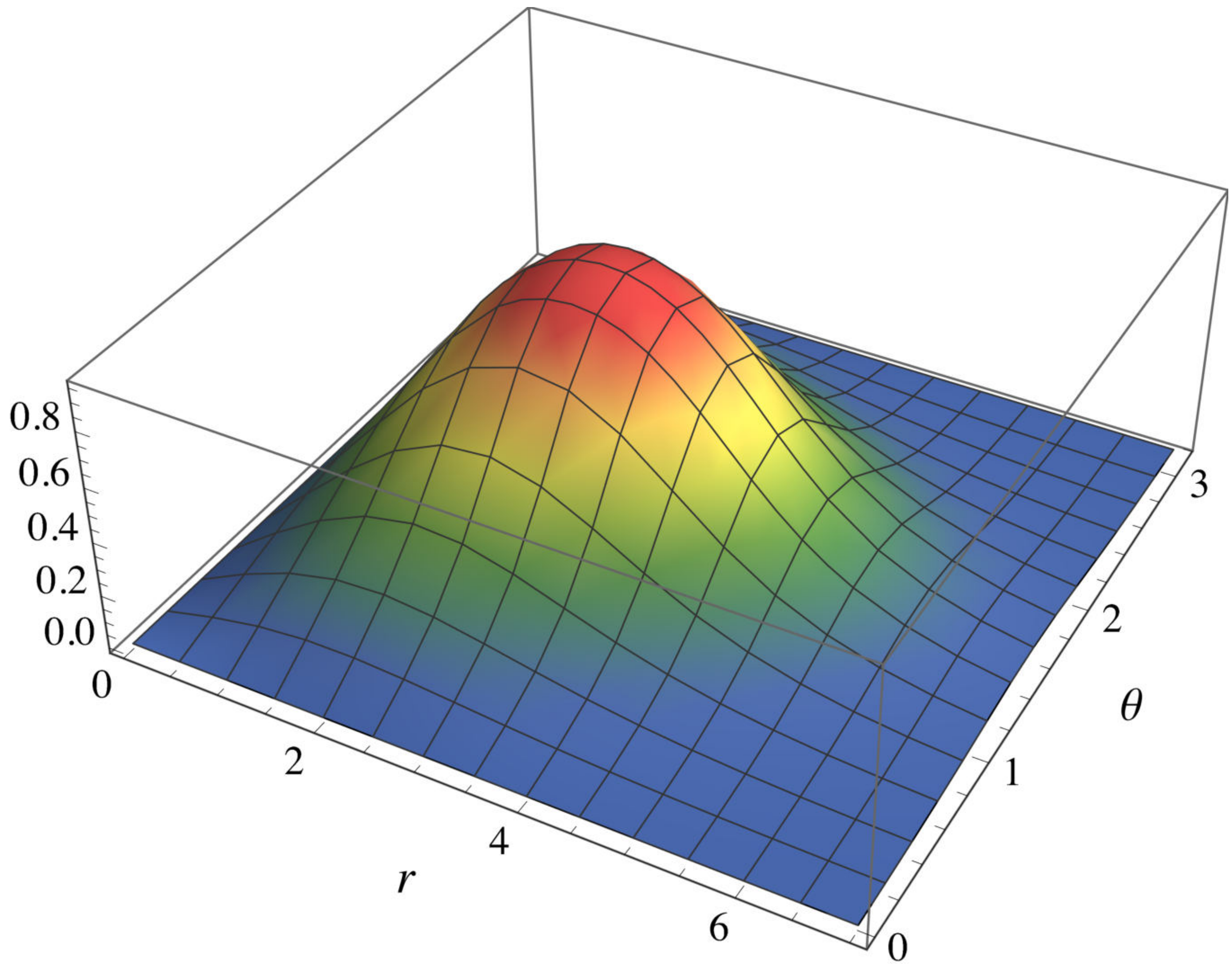
★ Find: $$f_{\rm PBH} \equiv \frac{\rho_{\rm PBH}(t)}{\rho_{\rm CDM}(t)} = \frac{32\pi}{3}\lambda\Lambda_c^3\left(\frac{M_{\rm PBH}}{M_{\rm eq}}\right)^{-1/2}$$

Black Hole

Vortices

work with Dvali & Zantedeschi

Formation of Vortices



[Dvali, FK, Zantedeschi 2022]

Formation of Vortices

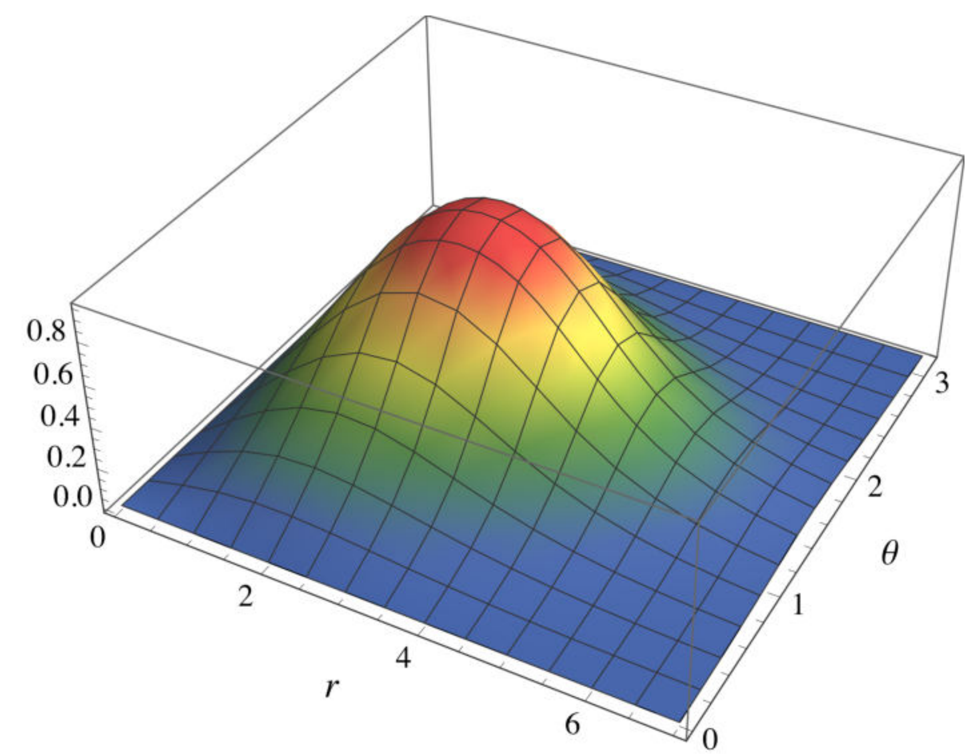
- Black Holes can be understood as saturons.

[Dvali 2021]

- We showed that these admit vortex structure, in the case of near-extremal spin.

- PBHs from confinement 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.



[Dvali, FK, Zantedeschi 2022]

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

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.

- There are many formation mechanisms for PBHs with distinct characteristics, partly offering a potential to be probed in the near future, including the quantum nature of black holes.

Black Holes as a Link between Micro and Macro Physics

(Carr)

Relics

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

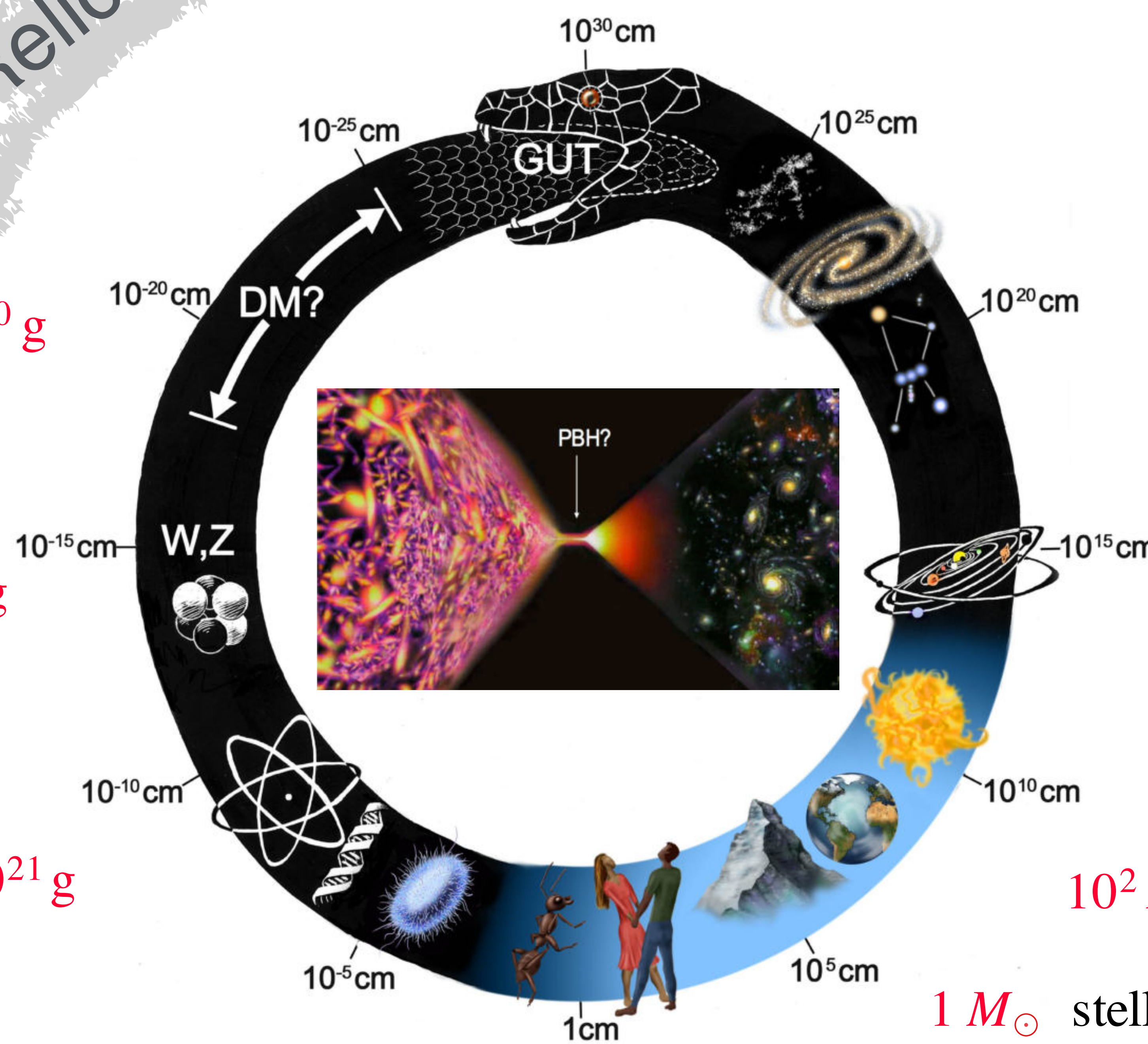
Planck 10^{-5} g

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

Albert Escrivà,[1,2,*] Florian Kühnel,[3,4,†] and Yuichiro Tada[5,2,6,‡]

[1]*Service de Physique Théorique, Université Libre de Bruxelles, Boulevard du Triomphe CP225, B-1050 Brussels, Belgium* (previous affiliation)

[2]*Department of Physics, Nagoya University, Nagoya 464-8602, Japan*

[3]*Arnold Sommerfeld Center, Ludwig-Maximilians-Universität, Theresienstraße 37, 80333 München, Germany,*

[4]*Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany*

[5]*Institute for Advanced Research, Nagoya University, Nagoya 464-8601, Japan*

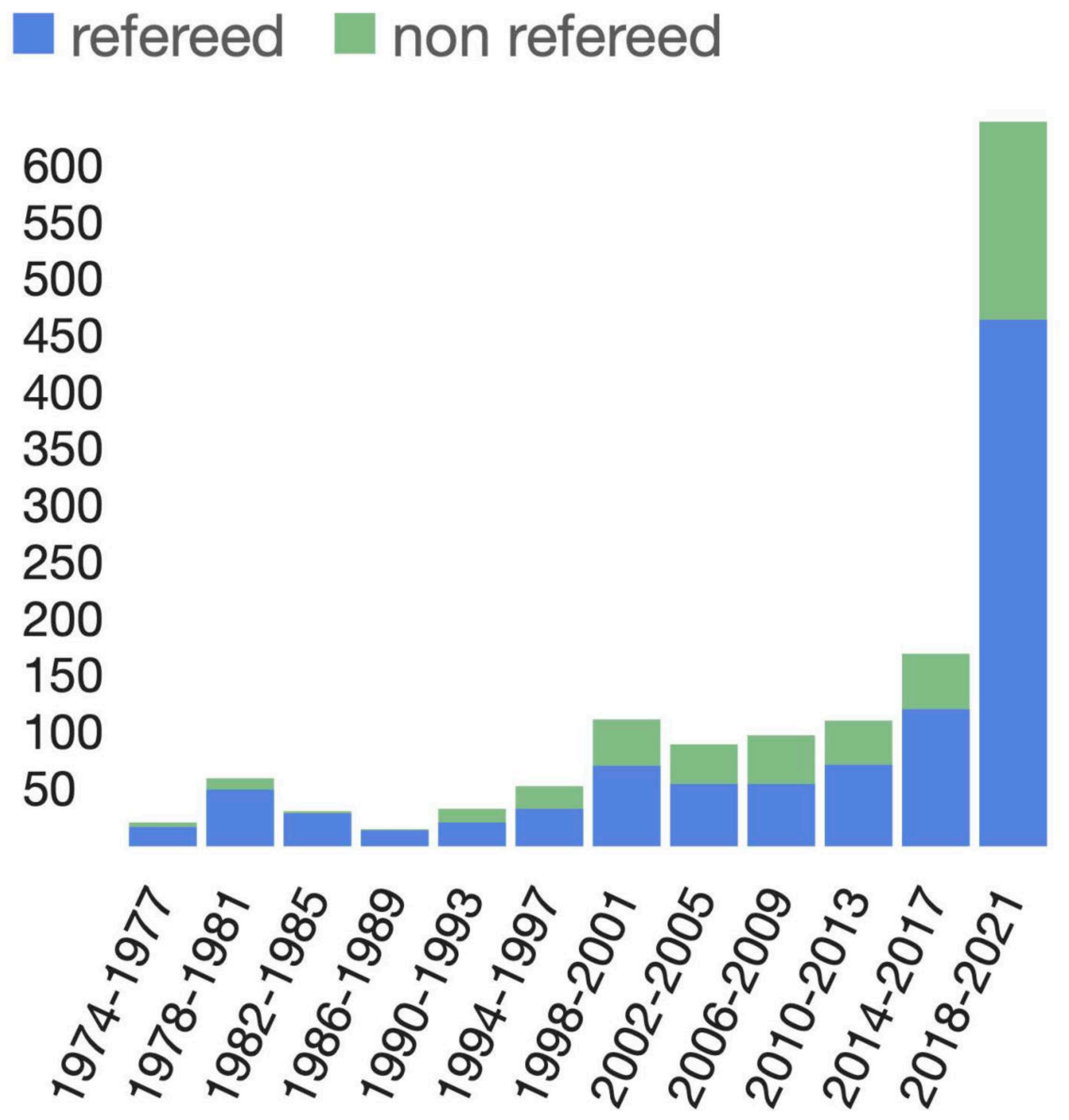
[6]*Theory Center, IPNS, KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*

(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.

Addendum

Primordial Black Holes are Popular!



[SAO/NASA Astrophysics Data System]

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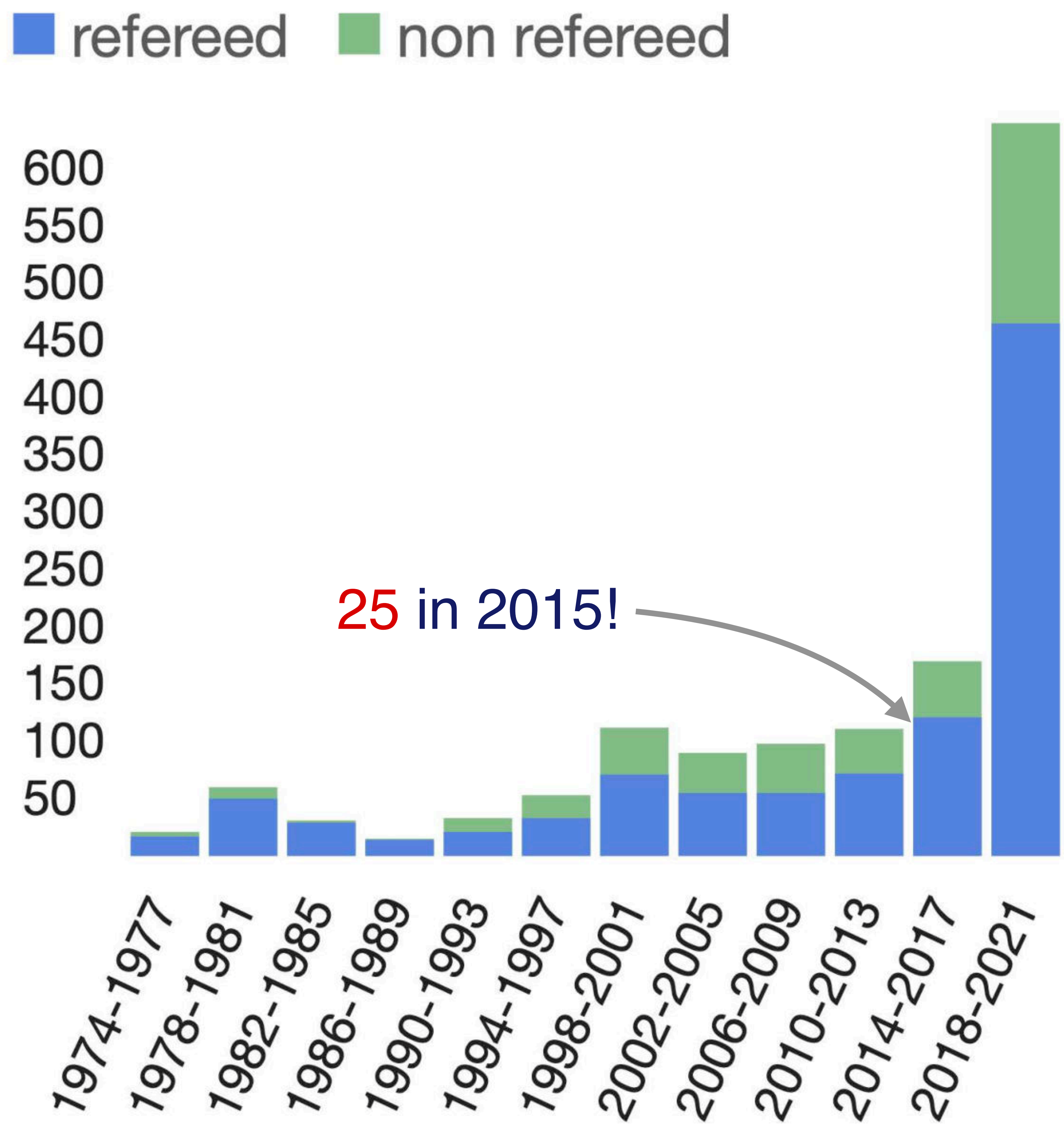

[SAO/NASA Astrophysics Data System]

Primordial Black Holes from Confinement

work with Dvali & 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,
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- ★ works with standard QCD*,
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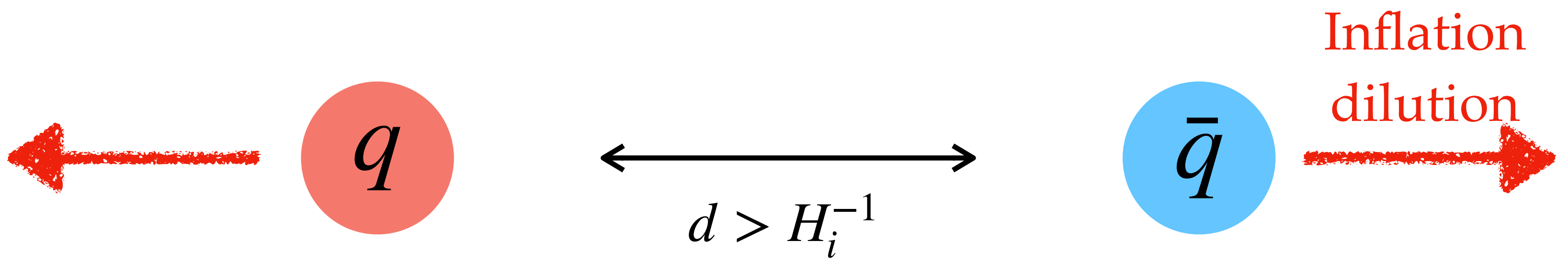
Confinement Formation Mechanism

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



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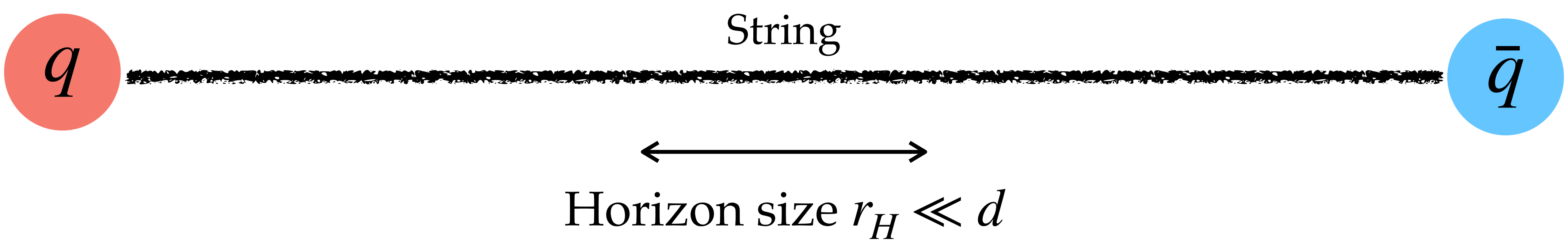

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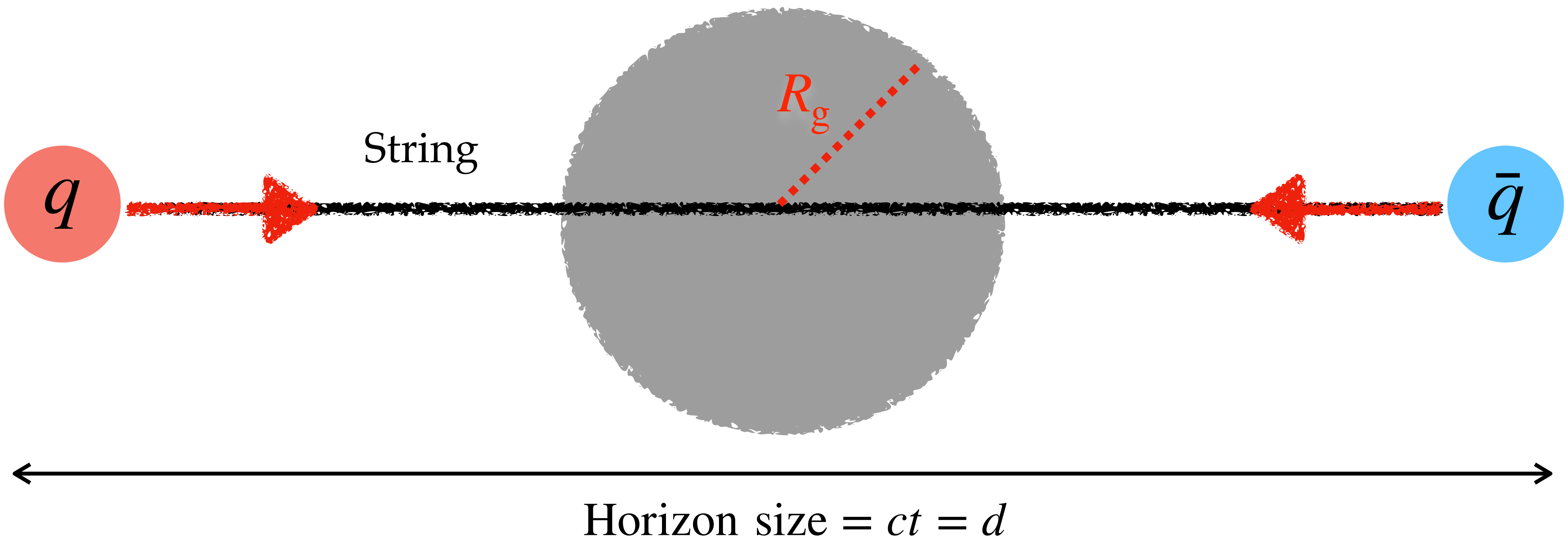
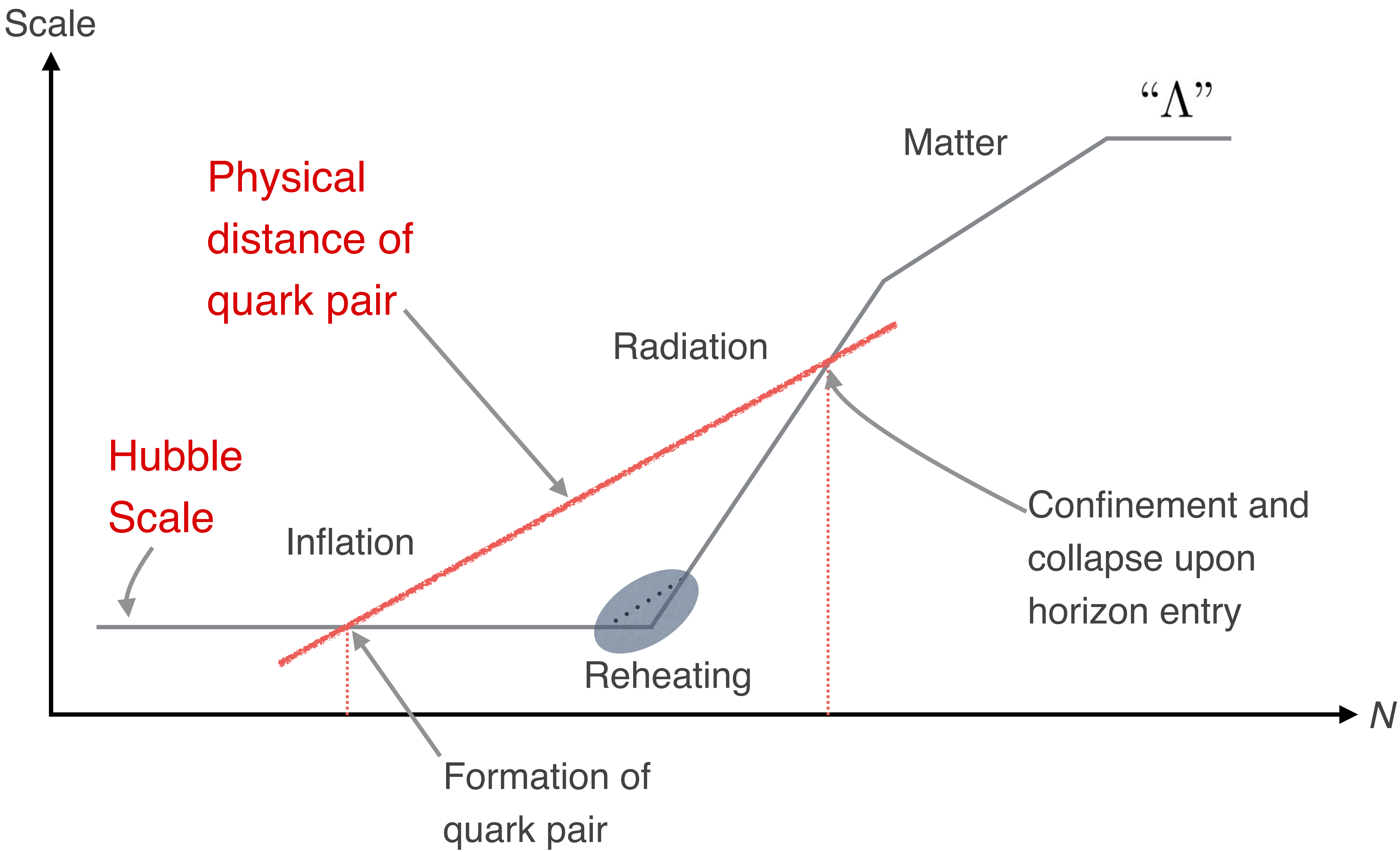


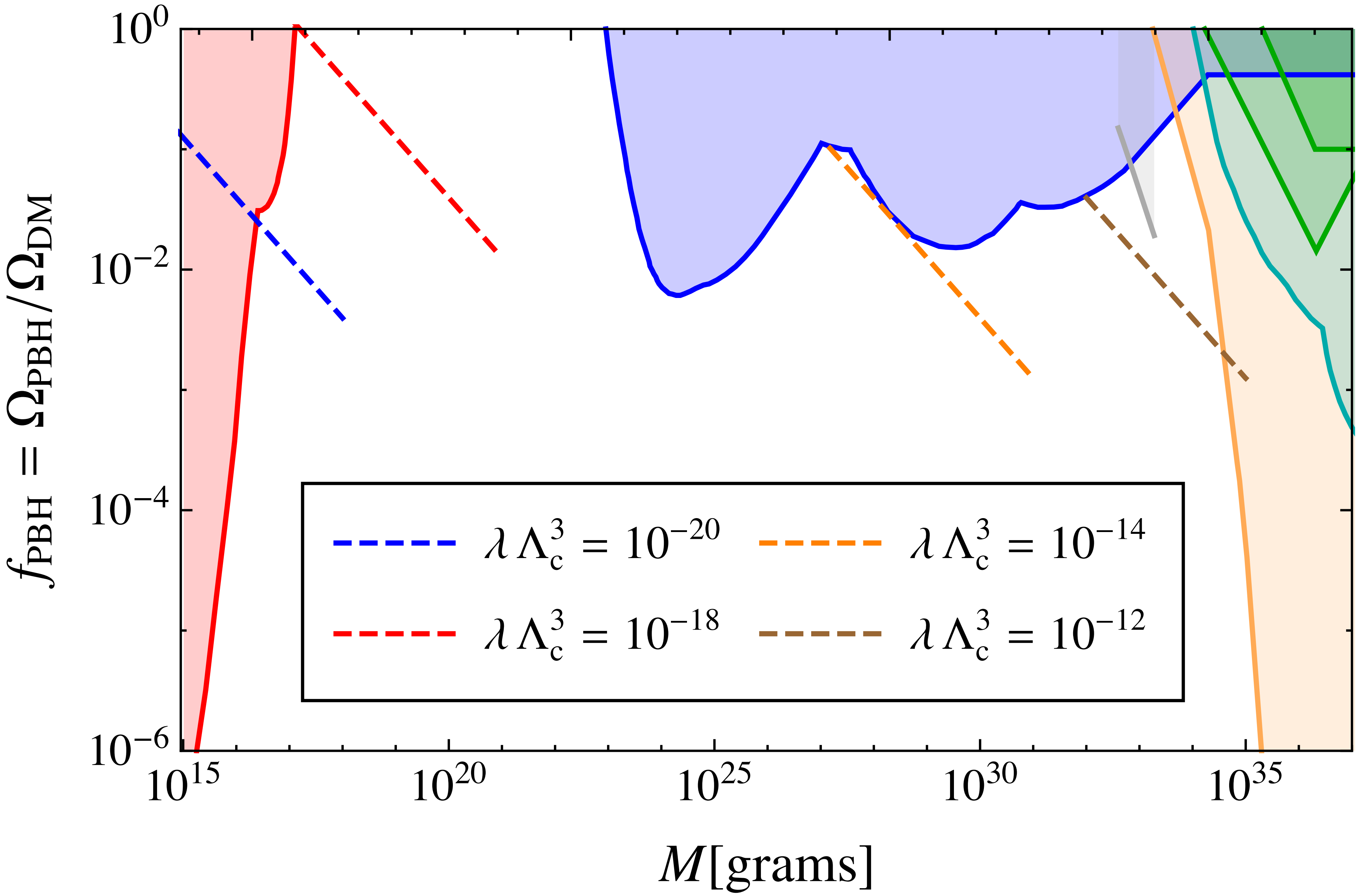
- Acceleration of the quarks $a = \Lambda_c^2 / m_q$ quickly leads to their ultra-relativistic motion.
- The energy stored in the string is $E \simeq \Lambda_c^2 \, t \simeq M_g, \quad R_g \gg \Lambda_c^{-1}$.
- PBHs from inflationary overdensities are heavier by a factor $\sim \Lambda_c^2$.

Formation Scales



Dark Matter from Confinement

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

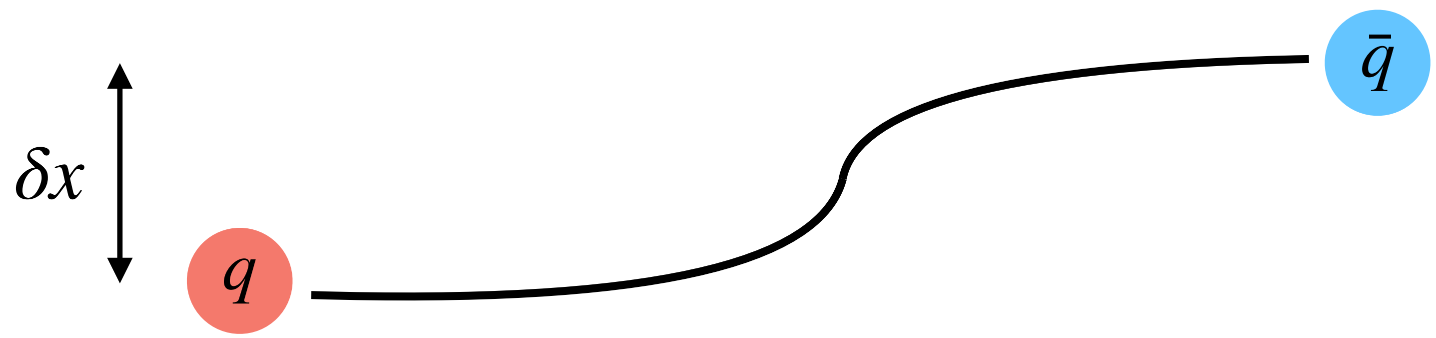


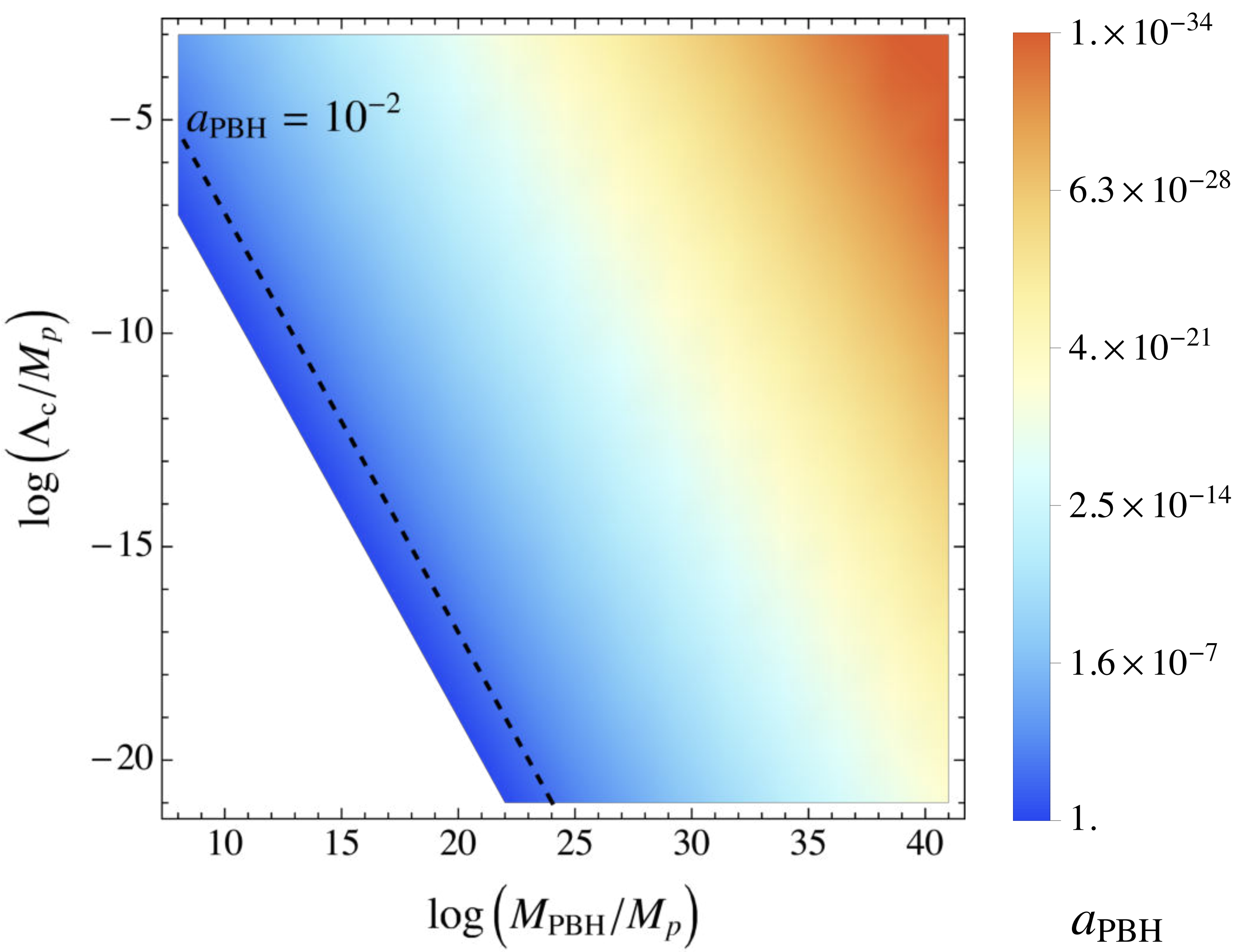
★ Find: $$f_{\rm PBH} \equiv \frac{\rho_{\rm PBH}(t)}{\rho_{\rm CDM}(t)} = \frac{32\pi}{3}\,\lambda\Lambda_c^3\left(\frac{M_{\rm PBH}}{M_{\rm eq}}\right)^{-1/2}$$

High-Spin Subsolar PBHs

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

$$\delta x \simeq \sqrt{N_e}\, H_i^{-1}$$



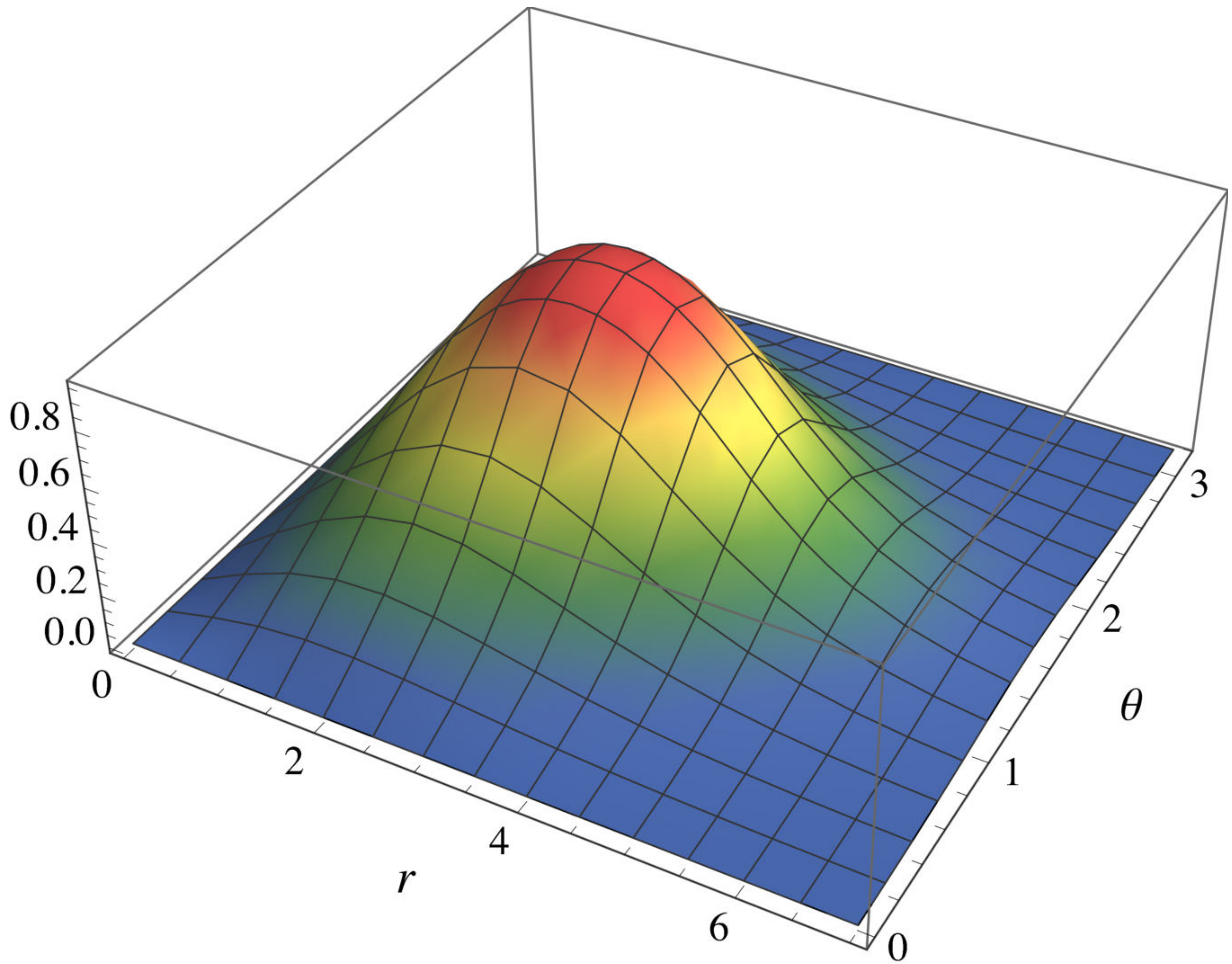


★ This leads to potentially significant spin:

$$a_{\rm PBH} \simeq \frac{\delta x}{R_g}$$

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

Formation of Vortices



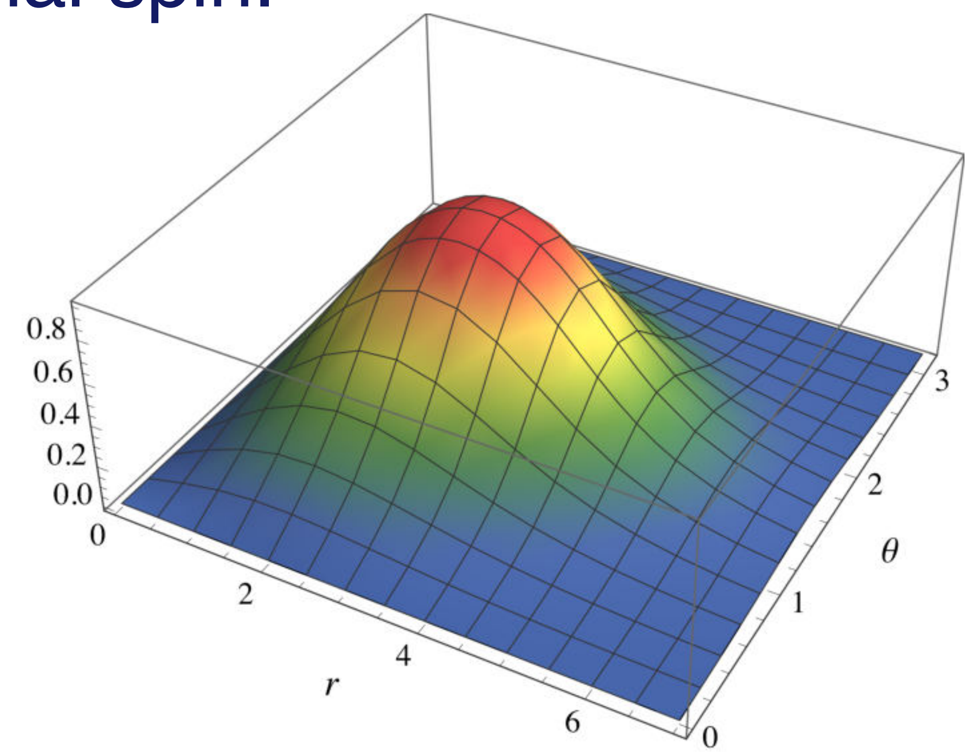
[Dvali, FK, Zantedeschi 2021]

Formation of Vortices

- Black Holes can be understood as saturons (*see talk by Dvali*)

- We showed that these admit vortex structure (*see talk by Zantedeschi*), in the case of near-extremal spin.

- PBHs from confinement could provide ideal prerequisites for vortex formation due to highly spinning light PBHs.



[Dvali, FK, Zantedeschi 2021]

- 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.

More on Constraints

Constraints — A Worthwhile Remark

★ These constraints are not just nails in a coffin!

(Carr)

★ All constraints have caveats and might change.

★ Each constraint is a potential signature.

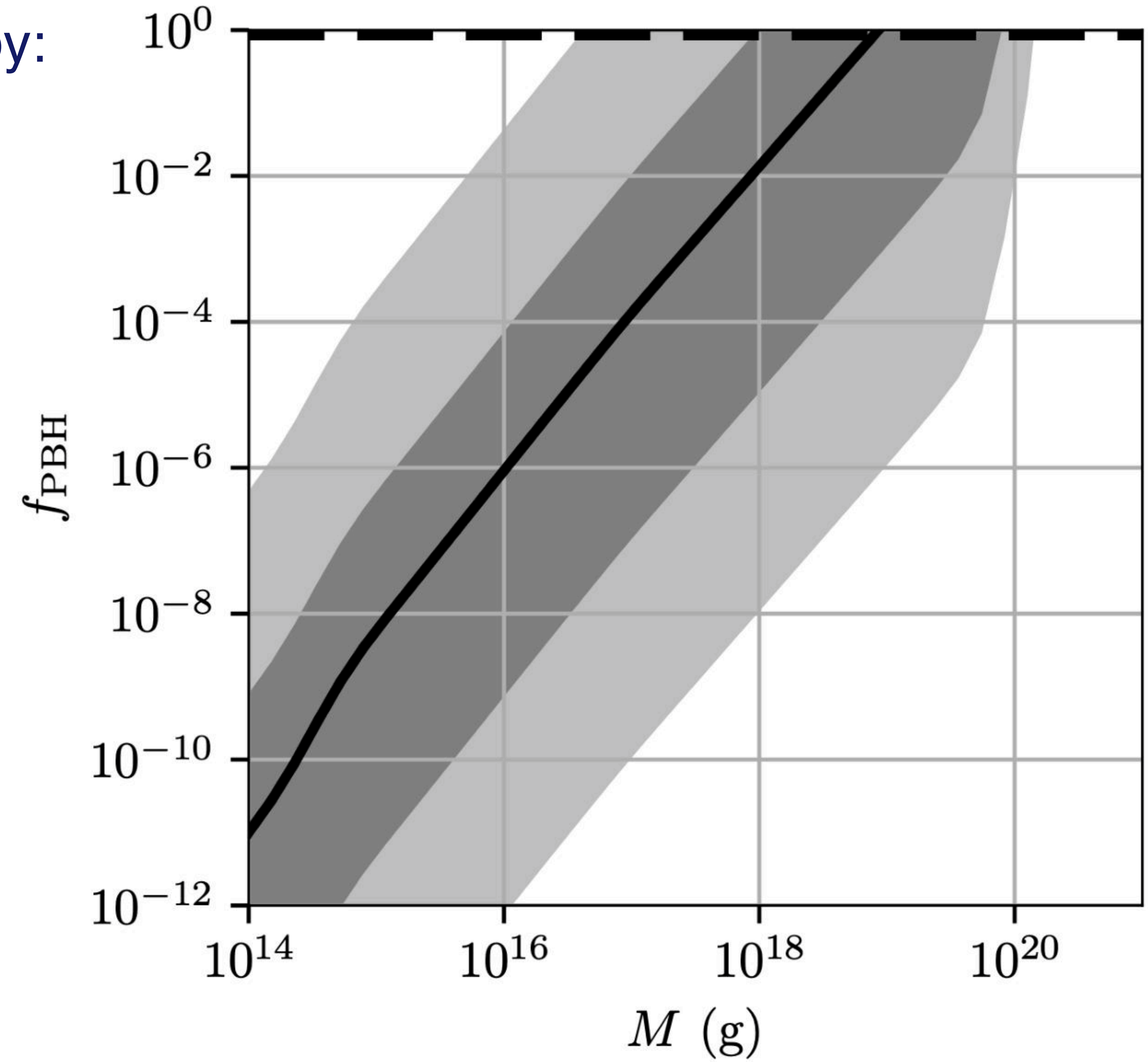
★ PBHs are important even if $f_{\rm PBH} \ll 1$.

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
    - ...

Constraints — Uncertainties on Hawking Radiation

- Uncertainties induced by:
  - instrument characteristics
  - computation of the (extra)galactic photon fluxes
  - statistical treatment
  - computation of the Hawking radiation



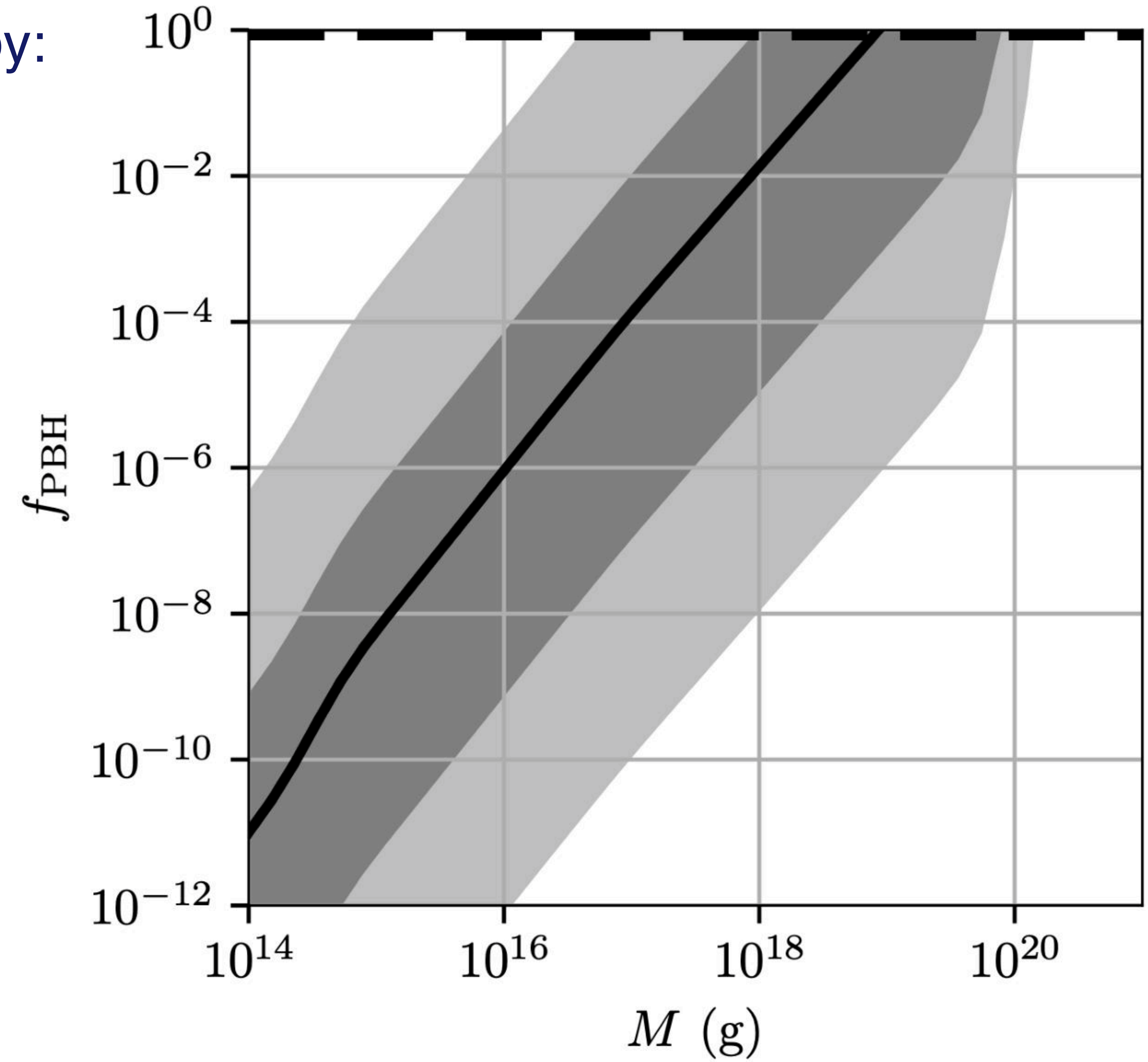
[Auffinger 2022]

Constraints — Uncertainties on Hawking Radiation

- Uncertainties induced by:
  - instrument characteristics
  - computation of the (extra)galactic photon fluxes
  - statistical treatment
  - computation of the Hawking radiation

These constraints might even *entirely disappear*, due to quantum back-reaction!

(see work by Dvali *et al.*)



[Auffinger 2022]

Micro & Macro

PBH & Particle Dark Matter

★ Always when $f_{\mathrm{PBH}} < 1$ there must be another DM component!

PBH & Particle Dark Matter

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- ★ Study a combined scenario: DM = PBHs + Particles

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  - Study WIMP annihilations in PBH halos:
    - The annihilation rate $\Gamma \propto n^2$.

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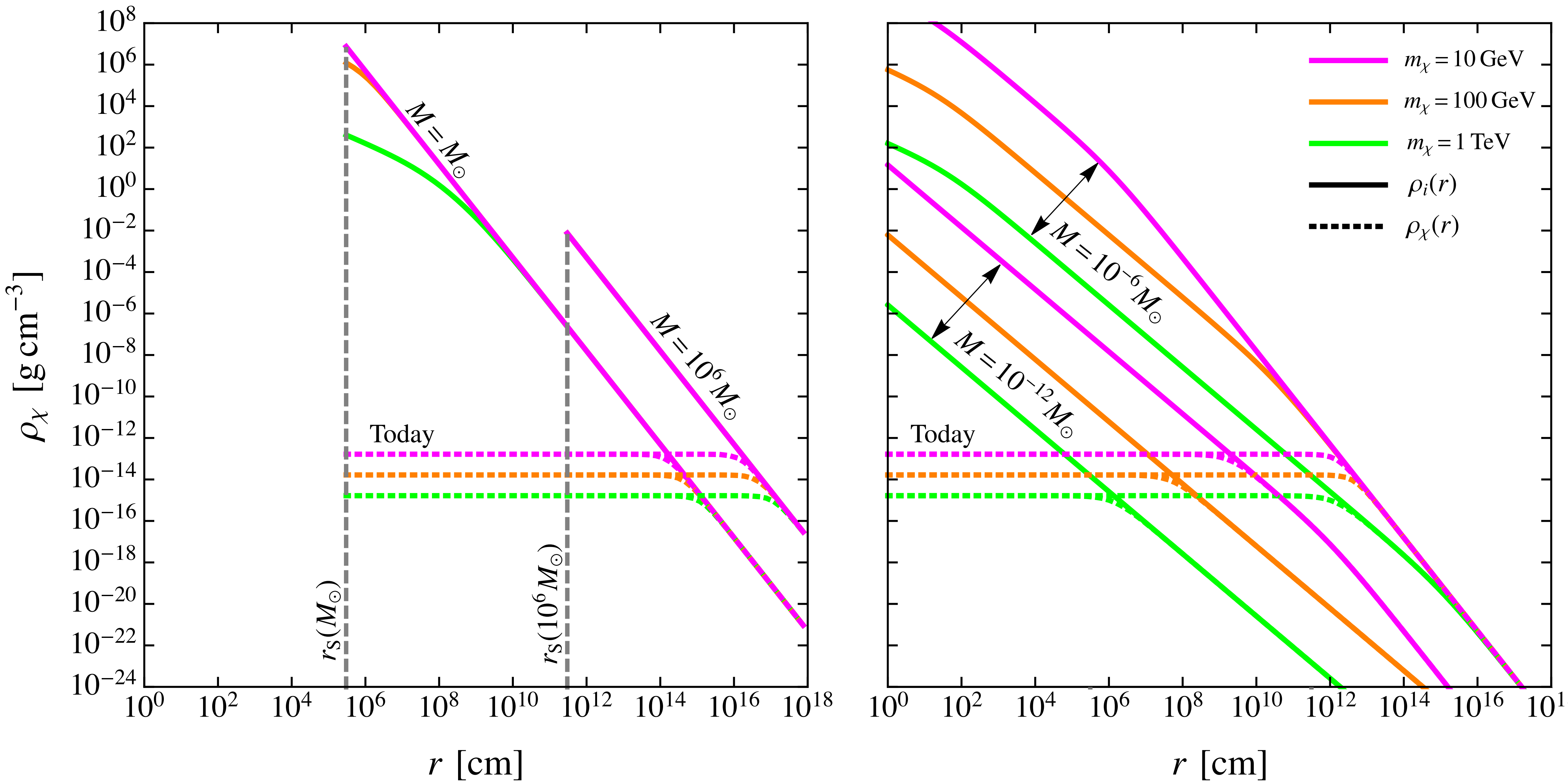
  - Study WIMP annihilations in PBH halos:
    - The annihilation rate $\Gamma \propto n^2$.
    - Halo profile does matter; enhancement of Γ in density spikes.
      1) Derive the density profile of the captured WIMPs;
      2) calculate the annihilation rate;
      3) and compare to data.

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

PBHs & WIMPs



[Carr, FK, Visinelli 2021]

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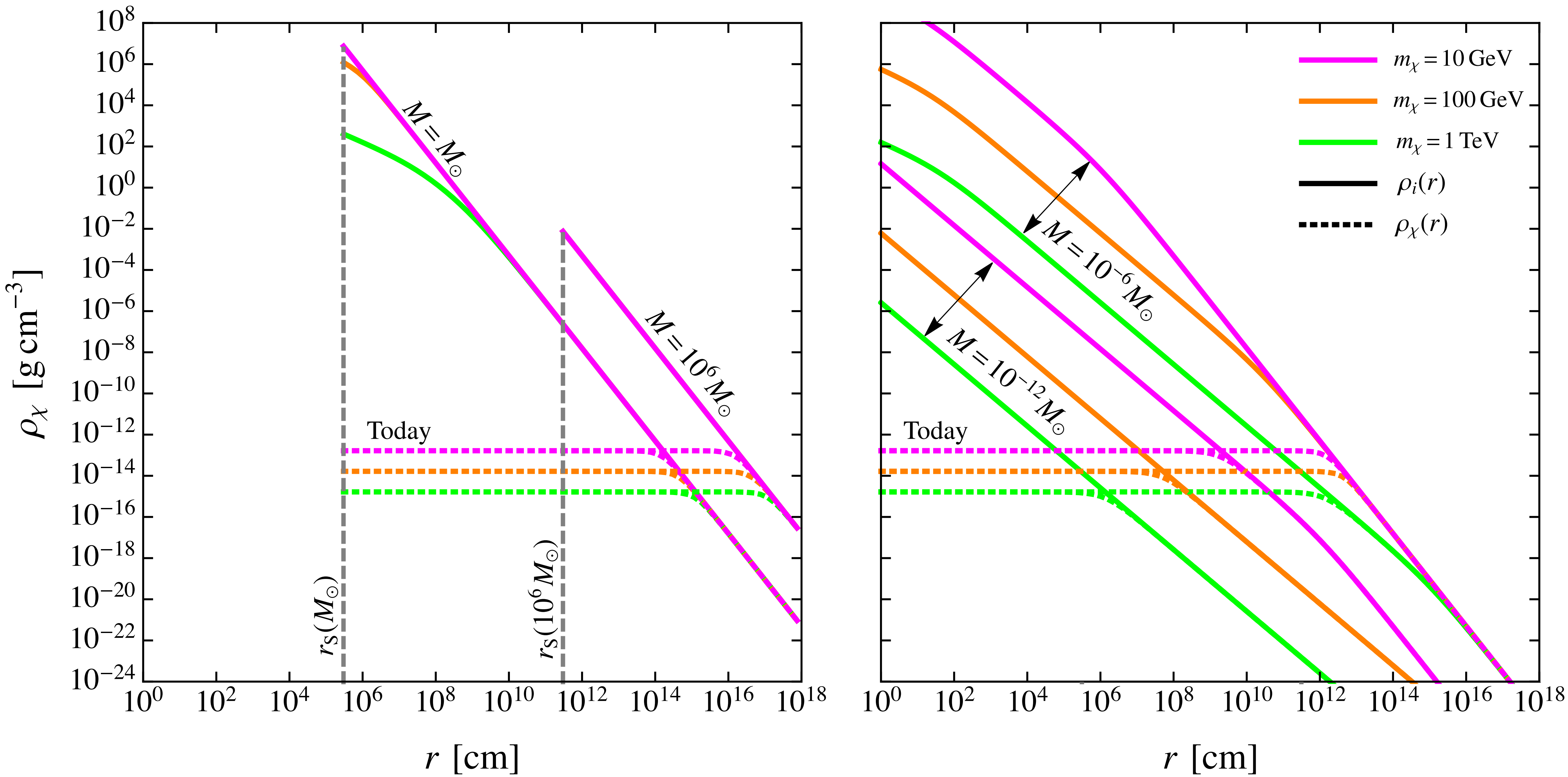
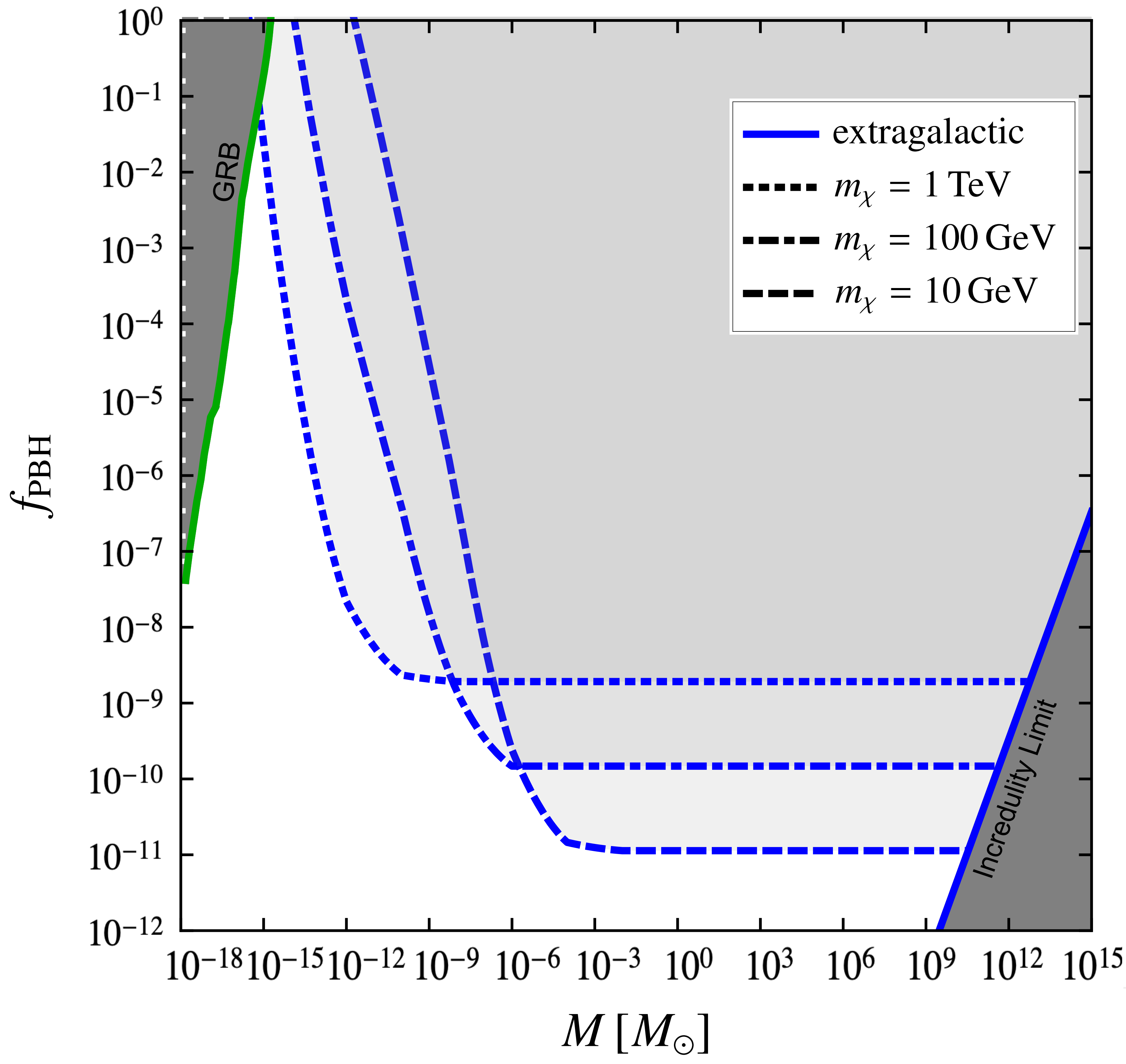


[Carr, FK, Visinelli 2021]

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

PBHs & WIMPs



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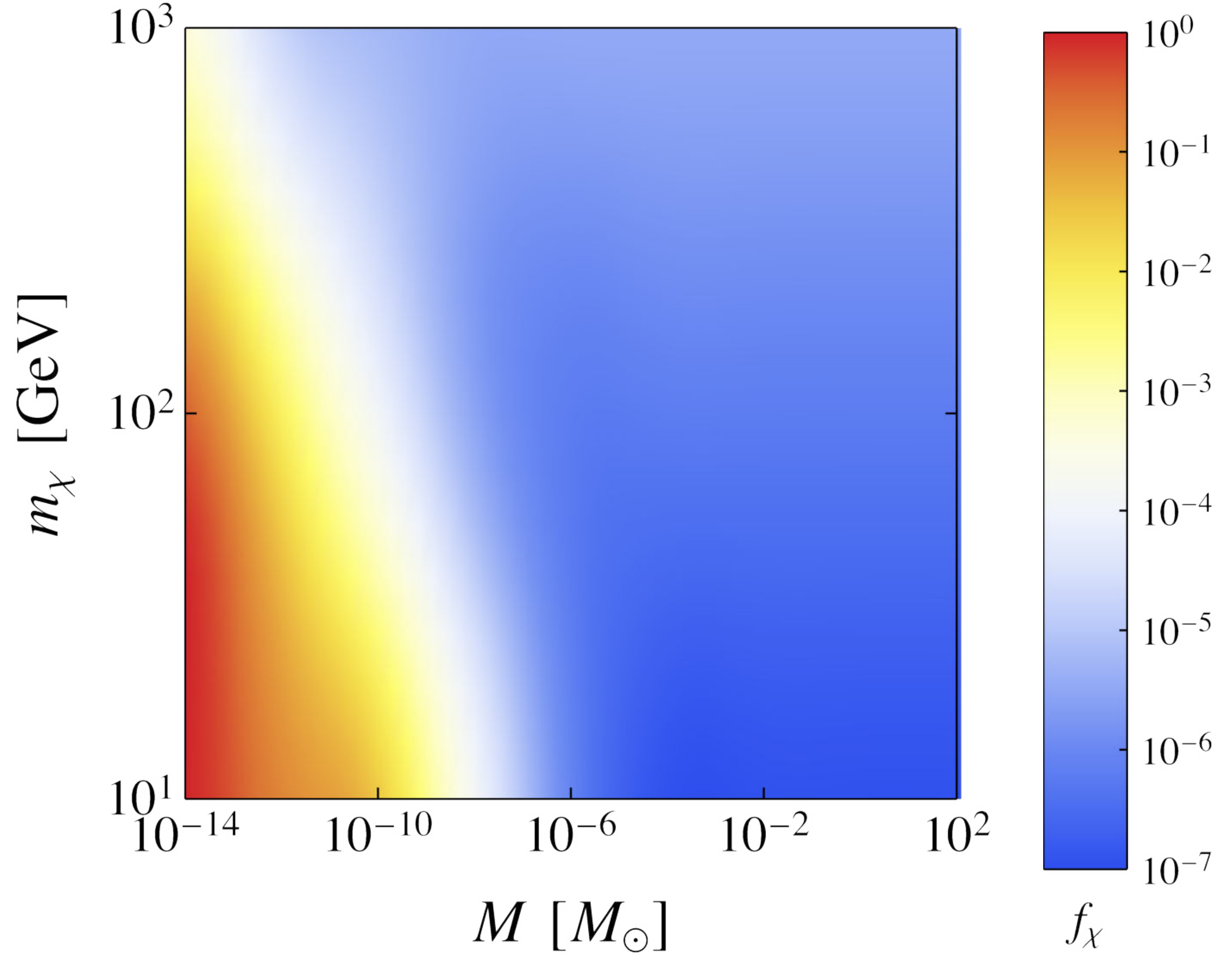

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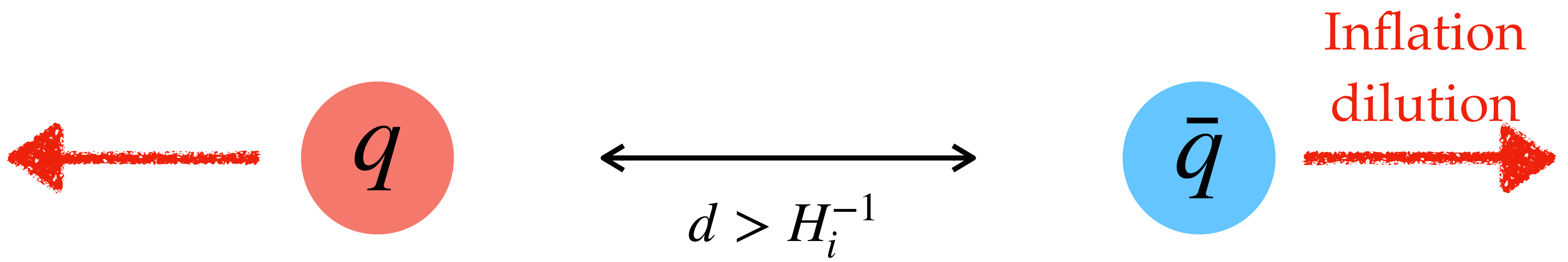

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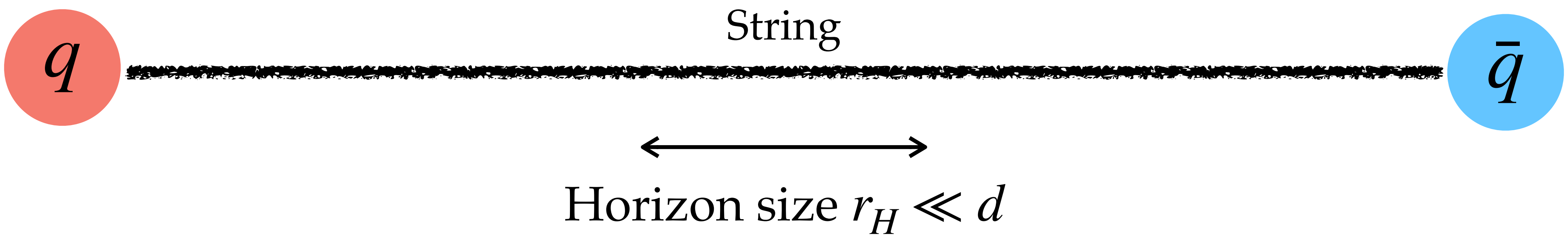

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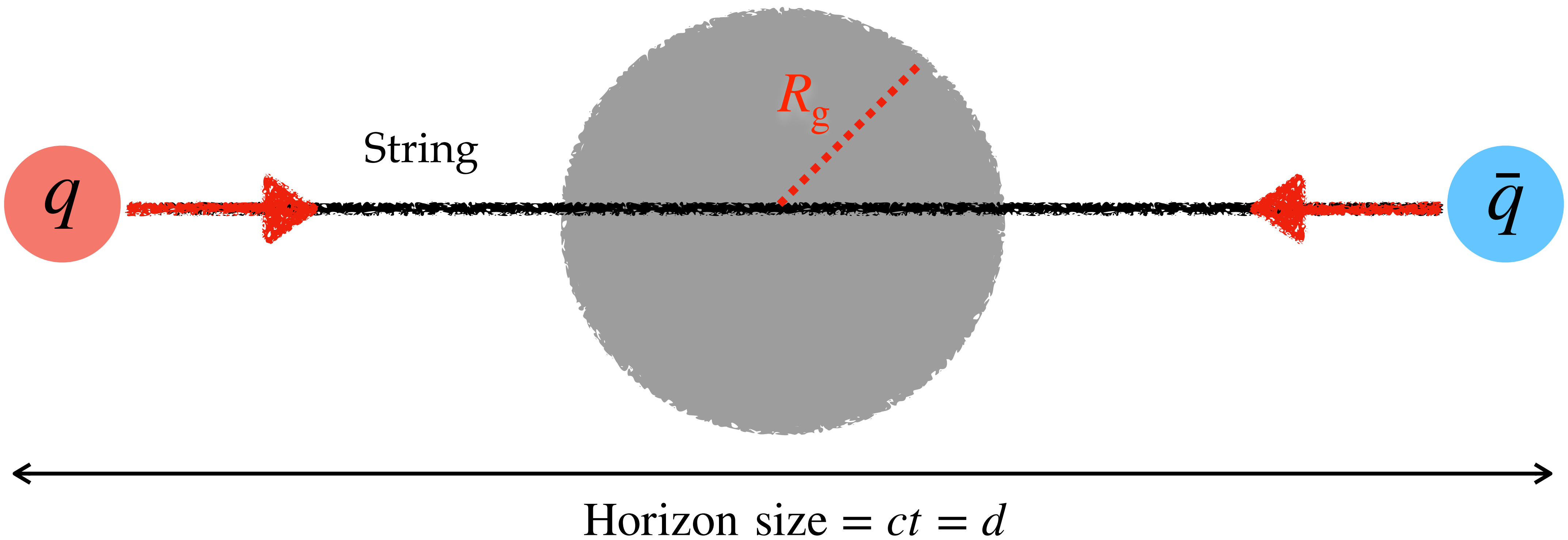

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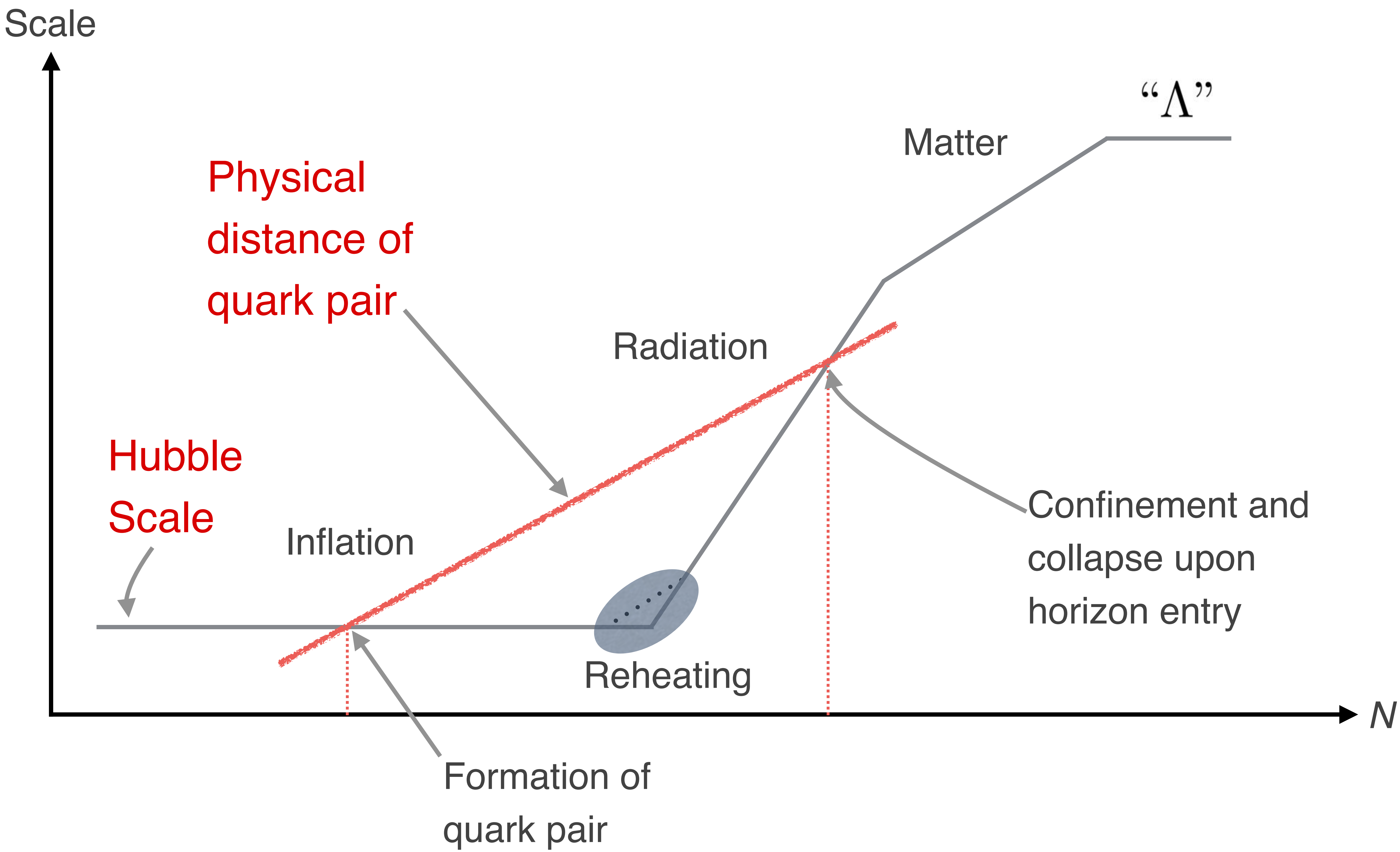

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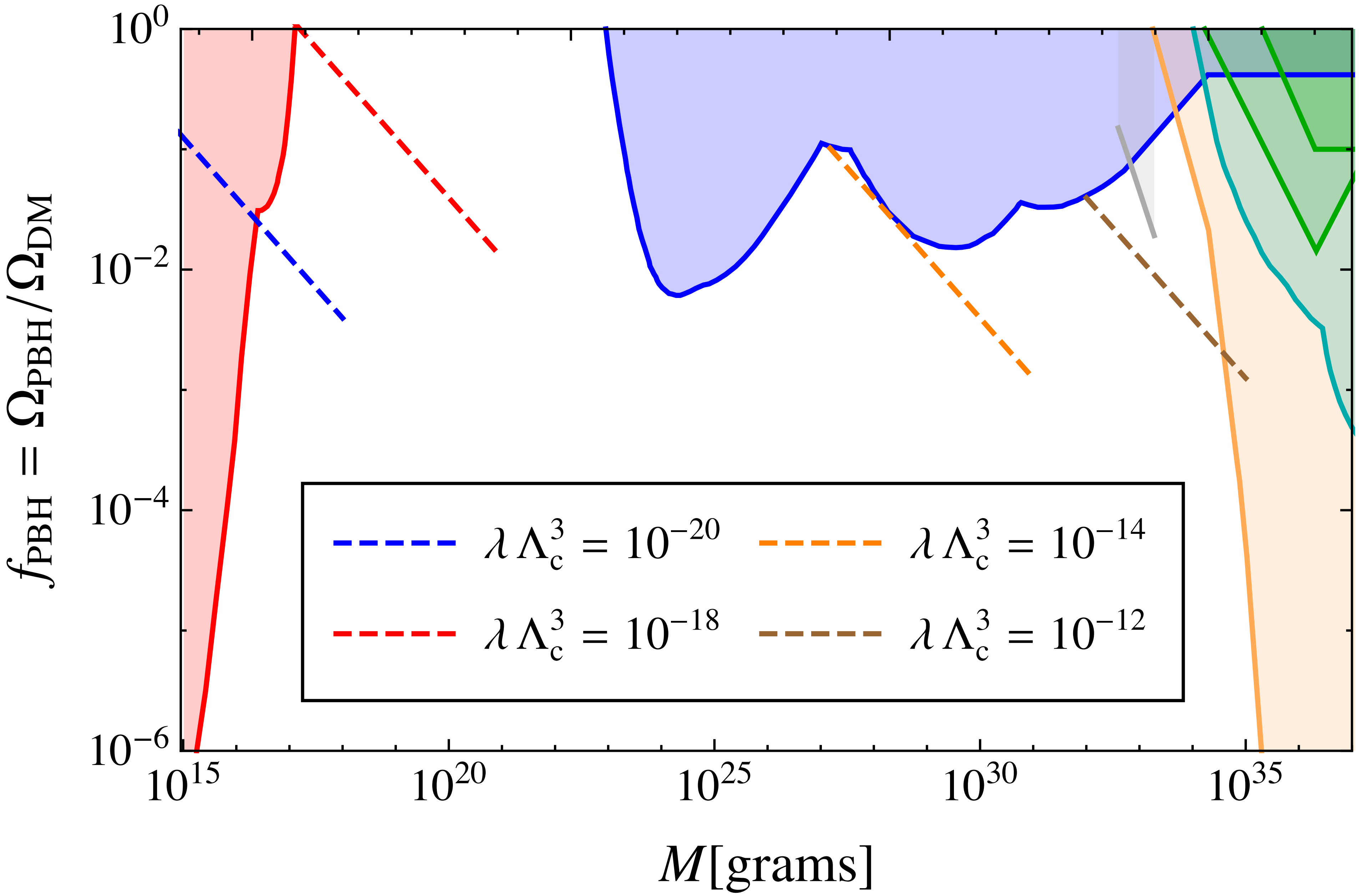
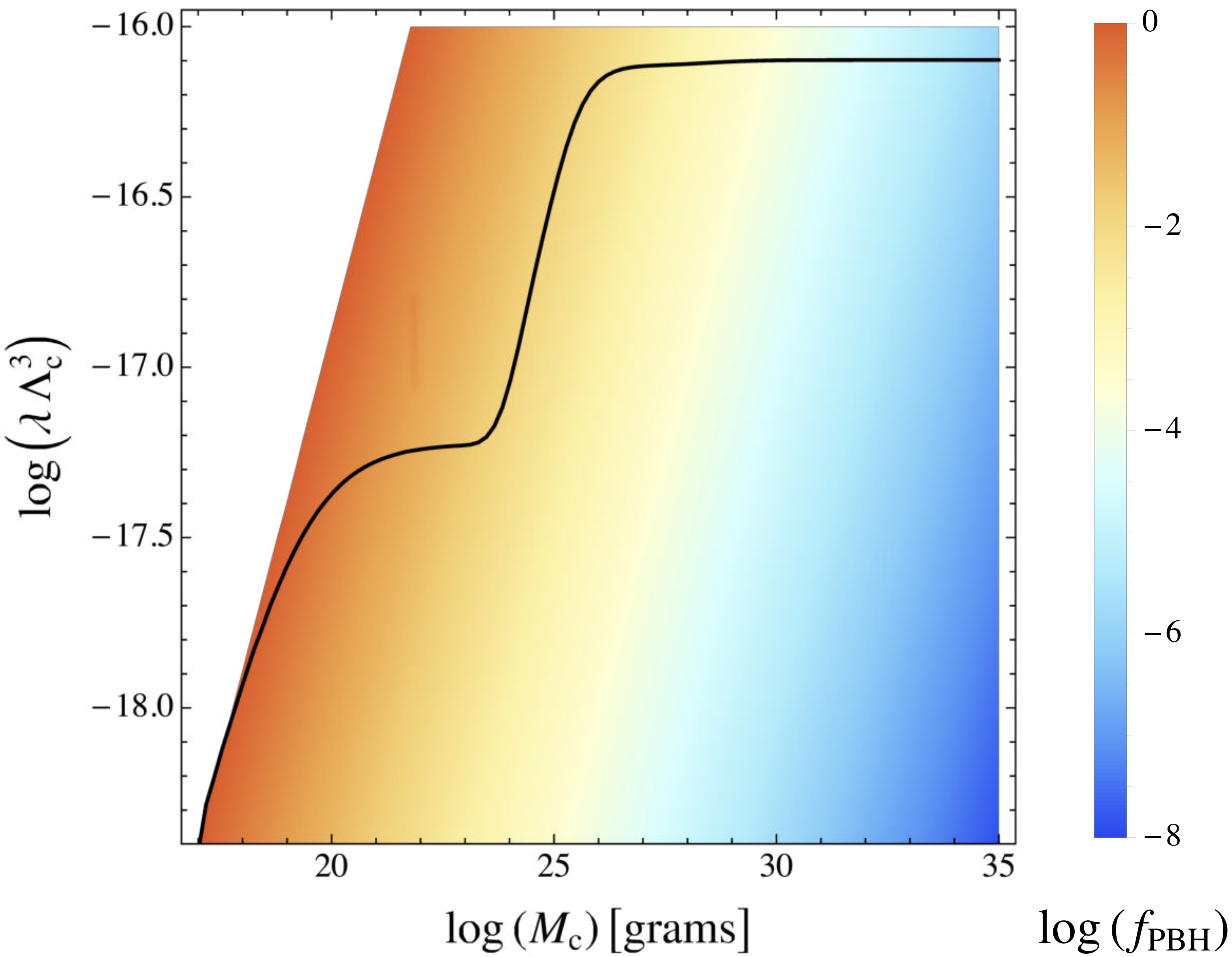


★ Find: $$f_{\rm PBH} \equiv \frac{\rho_{\rm PBH}(t)}{\rho_{\rm CDM}(t)} = \frac{32\pi}{3}\,\lambda\Lambda_c^3\left(\frac{M_{\rm PBH}}{M_{\rm eq}}\right)^{-1/2}$$

Extended-Constraint Analysis

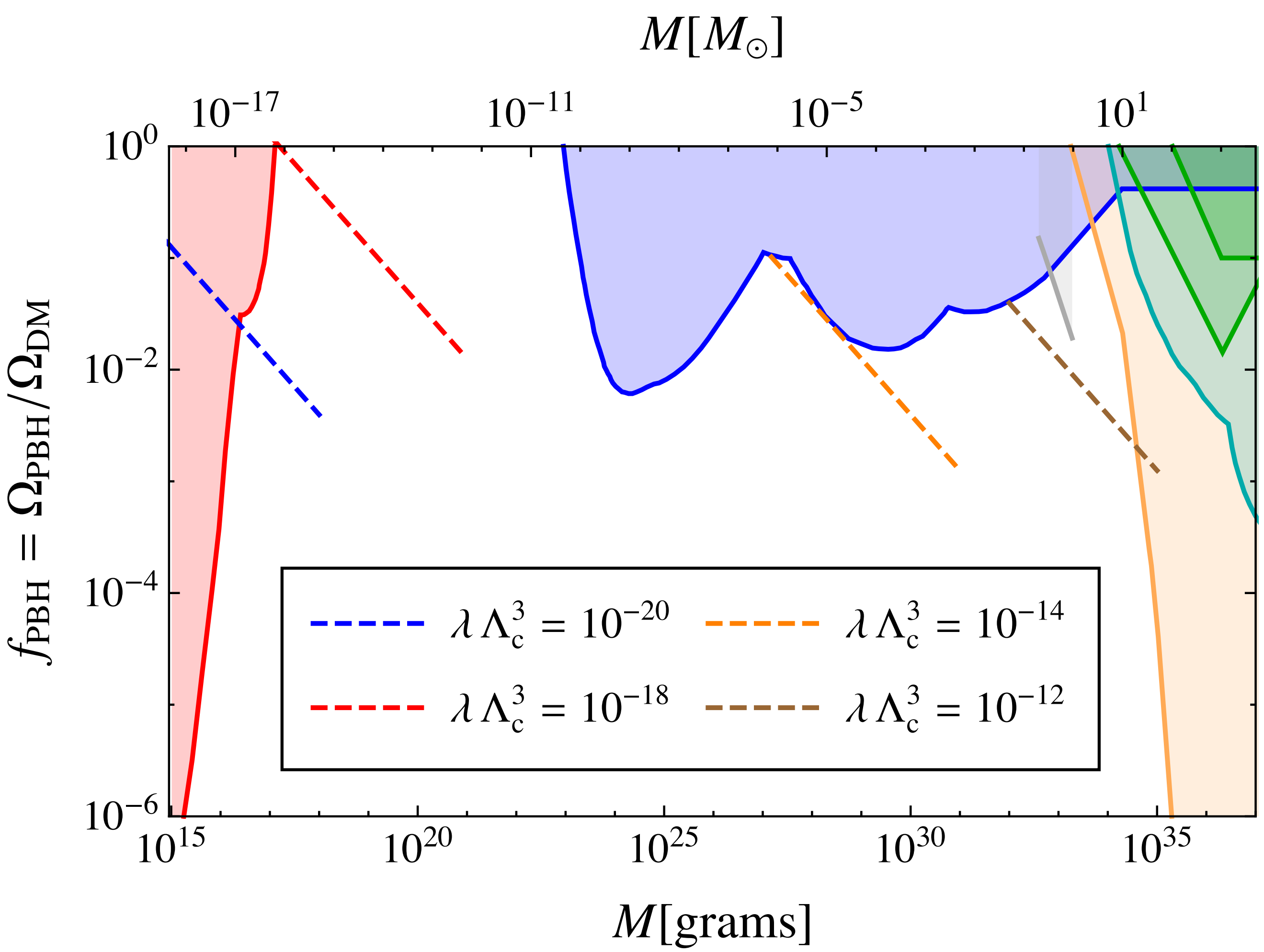
★ Require: $$\int_{M_1}^{M_2} \mathrm{d}\ln M_{\rm PBH}\, \frac{\mathrm{d} f_{\rm PBH}(M_{\rm PBH})}{\mathrm{d}\ln M_{\rm PBH}} \frac{1}{f_{\rm max}(M_{\rm PBH})} \overset{!}{\leq} 1$$

[Carr *et al.* 2017]



- ★ Full compatibility with observations below the black line, here, exemplary for $M_{\rm peak} \sim 10^{17}$ g.
- ★ Results: Possible to accommodate 100% of PBH dark matter...
- ★ ... at the same time provide seeds for supermassive black holes in galactic centres.

Dark Matter



Monochromatic spectrum

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

Extended spectrum

$$\int_{M_1}^{M_2} {\rm d}\ln M_{\rm PBH}\,\frac{{\rm d}f_{\rm PBH}(M_{\rm PBH})}{{\rm d}\ln M_{\rm PBH}}\frac{1}{f_{\rm max}(M_{\rm PBH})} \overset{!}{\leq} 1$$

100% of dark matter!

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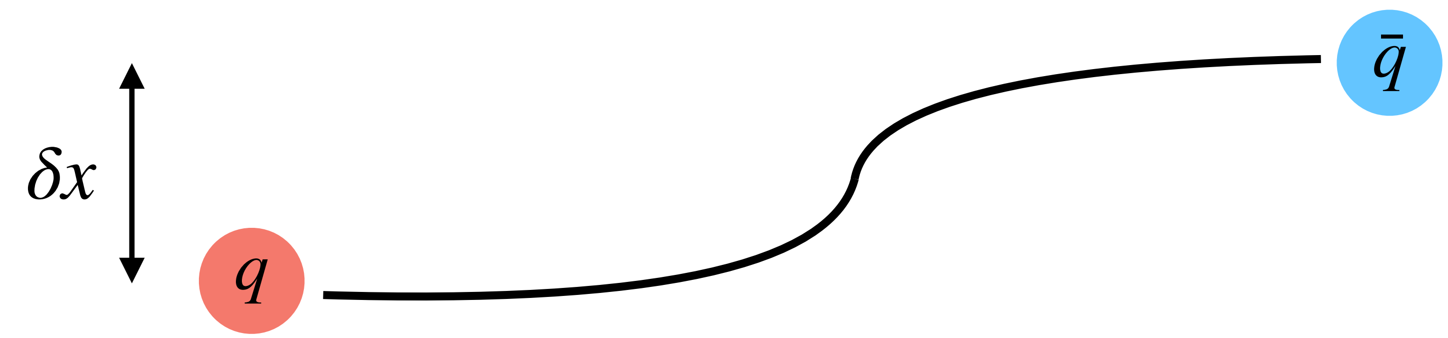
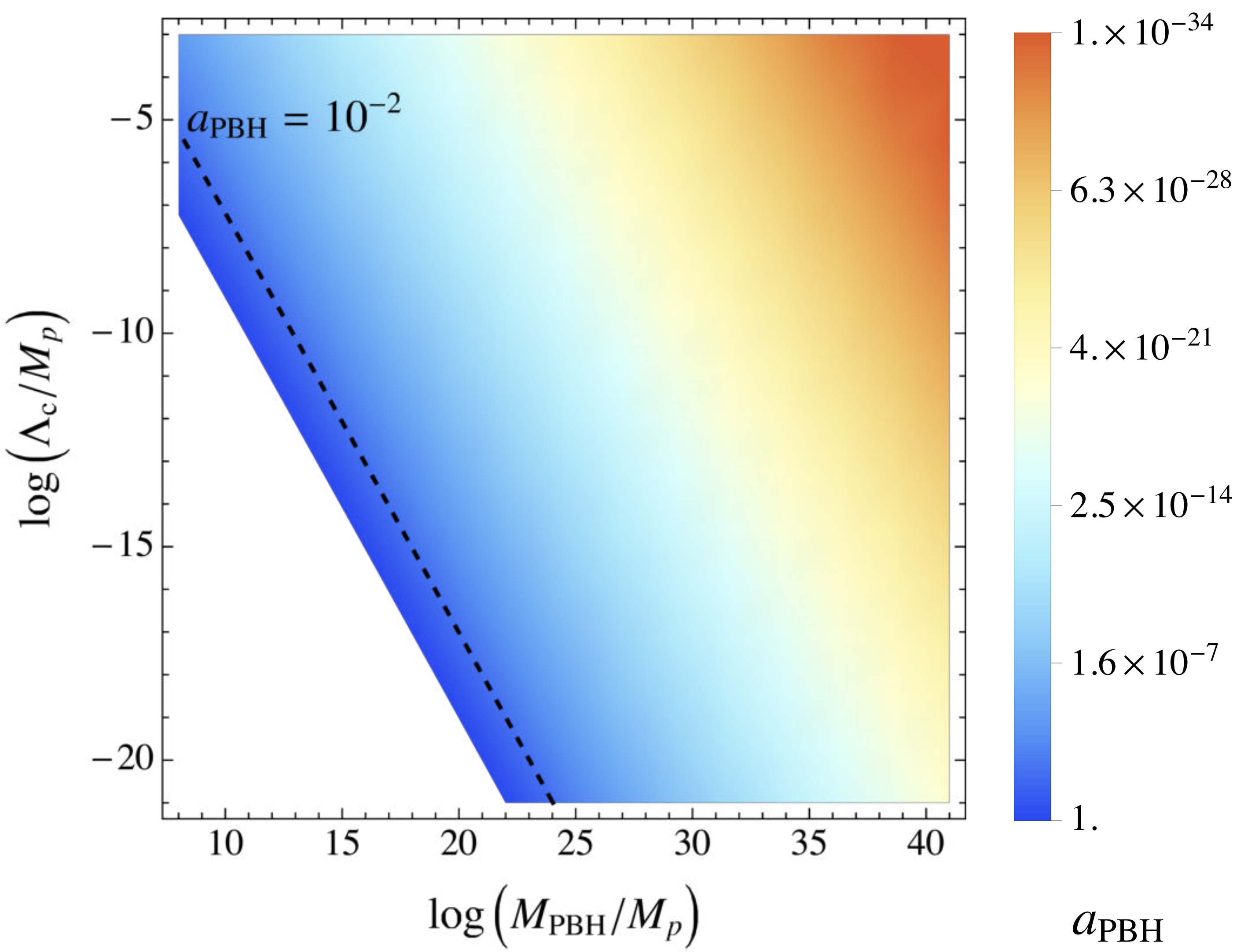




★ This leads to potentially significant spin:

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

*Embedding within Standard QCD**

★ Remember, our required assumption, for the string not to break:

$$\Lambda_c < M_q$$

★ However, standard QCD values indicate the opposite: $\Lambda_c > M_q$.

★ It looks like, our mechanism cannot work with QCD...

Embedding within Standard QCD*

★ It is natural for the confinement scale and mass to change in the early Universe!

$$g_y \bar{\psi}_L \psi_R \phi \qquad \qquad \frac{1}{4g^2} F_{\mu\nu} F^{\mu\nu}$$

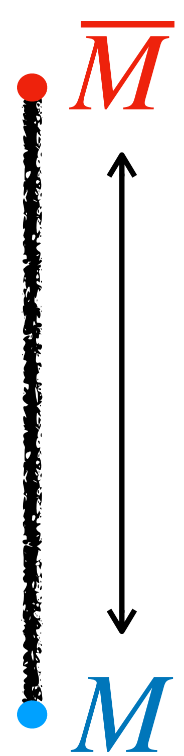
★ Couplings are expectation values of fields and can be very different in the early Universe.

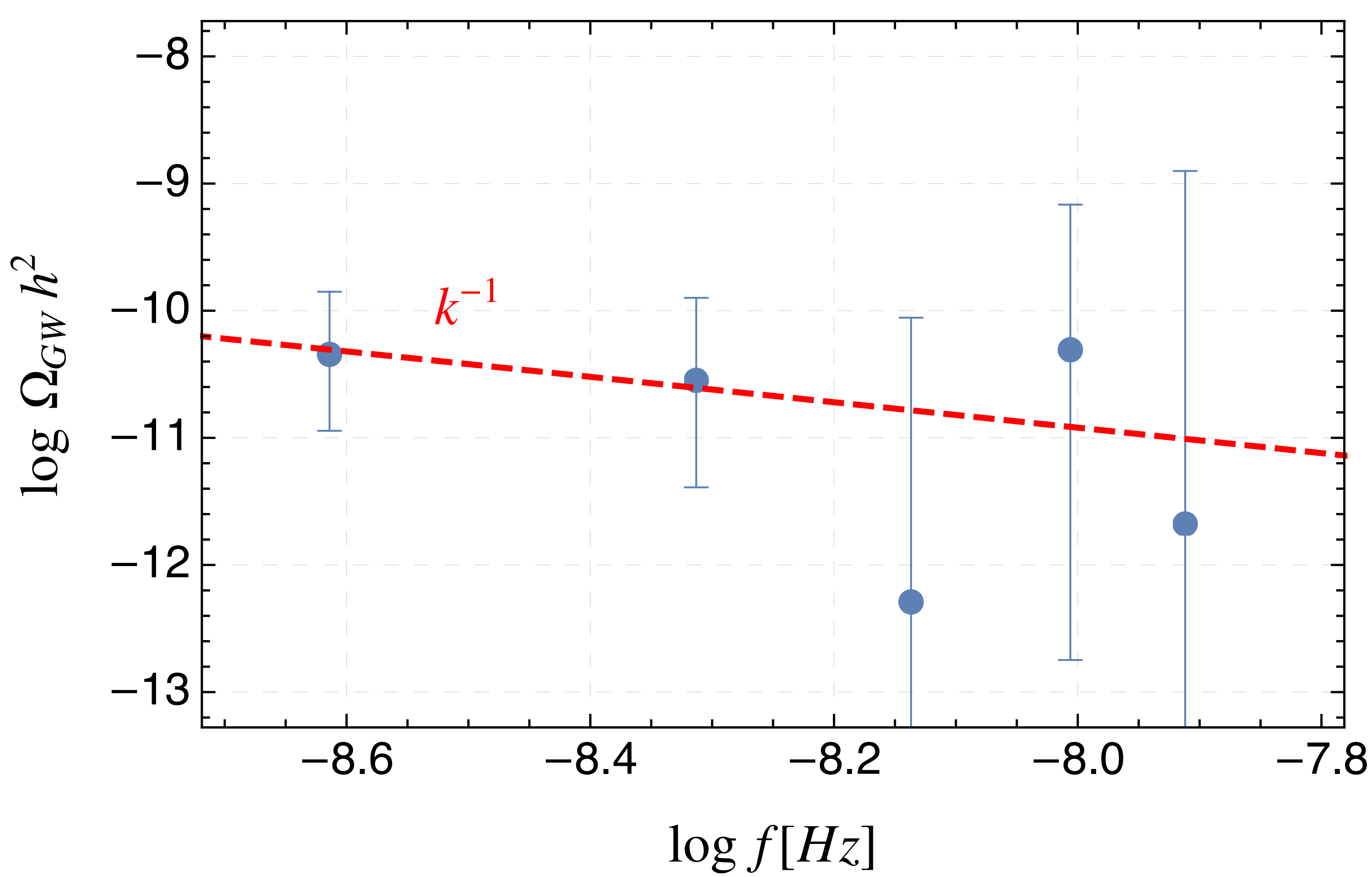
★ Requirement: Low-temperature expectation value should set the right coupling values.

This should happen before BBN, leaving large room for PBH production via the confinement mechanism.

Gravitational Waves

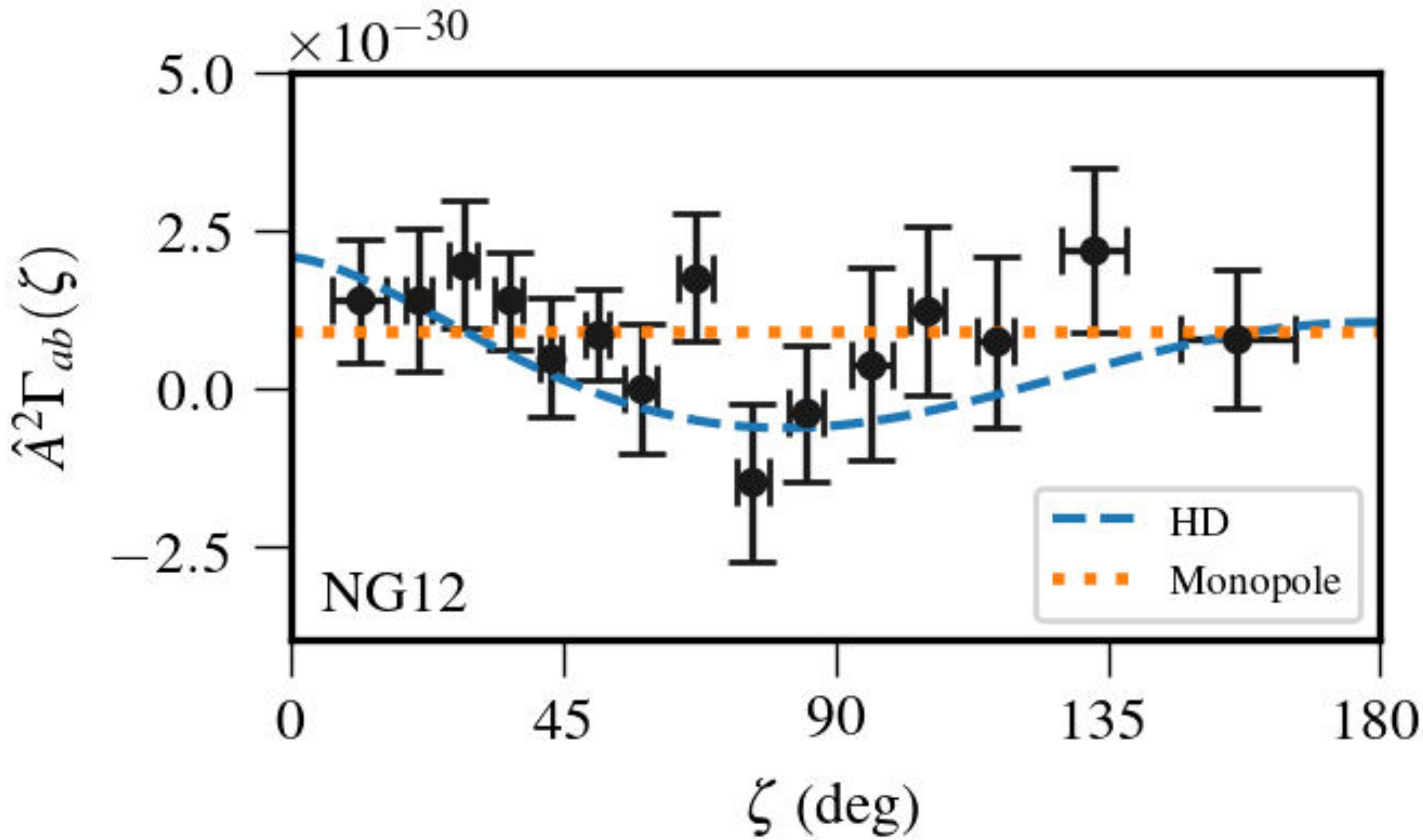
- After horizon entry, the quarks quickly move towards each other, emitting gravitational waves.
  - This is similar to dual to systems of dual monopole/anti-monopole pairs connected by a string. [cf. Martin & Vilenkin 1997; Leblond, Shlaer, Siemens 2009]
  - NANOGrav data from pulsar-timing observations indicate the presence of a stochastic gravitational-wave background.





NANOGrav

★ There might be a lack of Hellings-Downs correlation. - *still unclear*



[Arzoumanian *et al.* 2021]

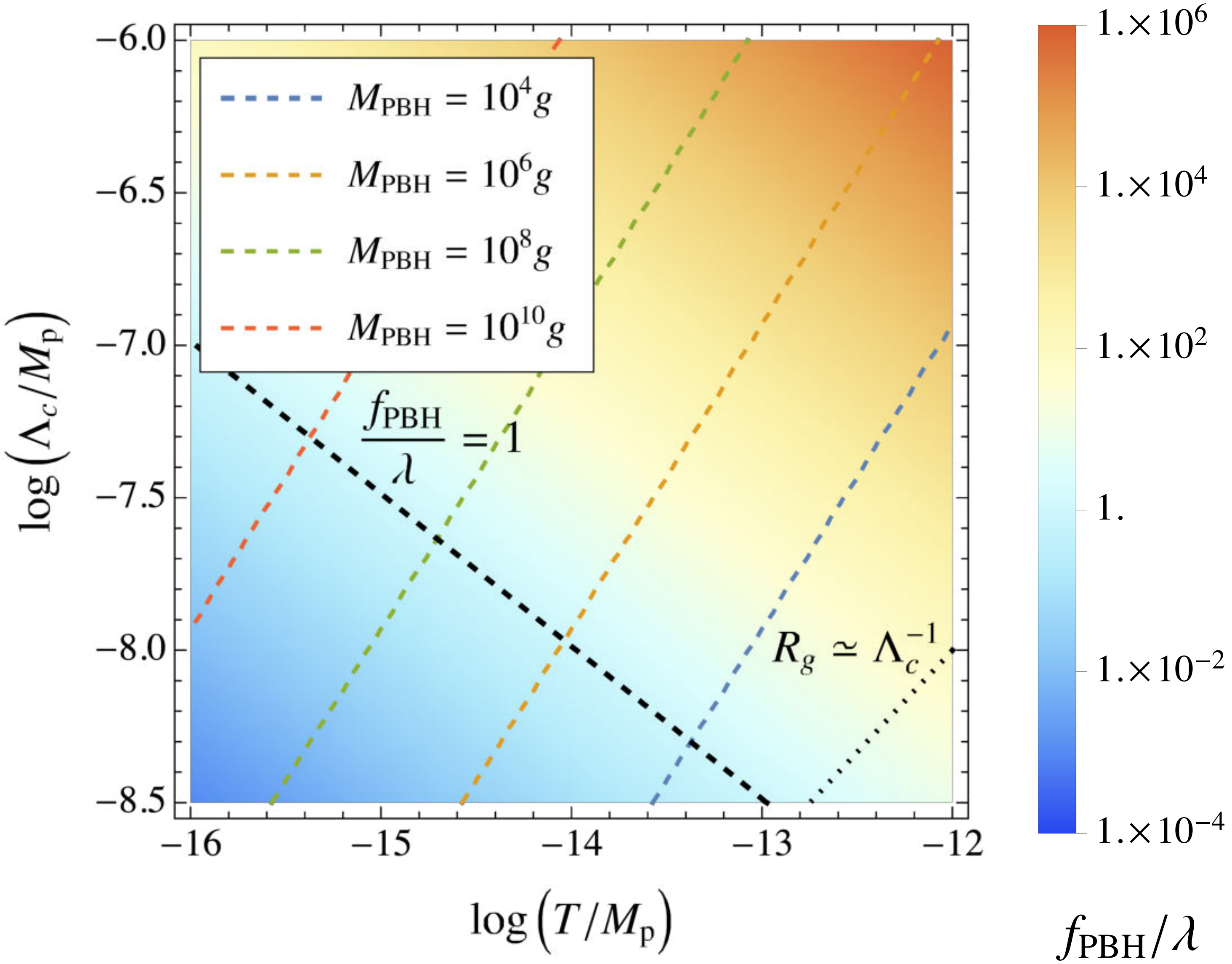
★ We can easily generate a monopolar signal upon adding e.g. $\sim \phi\,\bar{q}q$ with coupling strength relatively weaker by $\sim 10^{-3}$.

Light PBH Dark Matter?

★ The exclusion of light ($M_{\rm PBH} \lesssim 10^{15}$ g) PBHs is based on the validity of semiclassical Hawking radiation throughout most of the evaporation.

★ This is unjustified (and likely to be entirely false), as suggested by recent studies of black holes on the full quantum level.

[Dvali *et al.* 2020]



★ Results suggest that due to the holes' enormous memory capacity, their lifetime τ might be significantly prolonged.

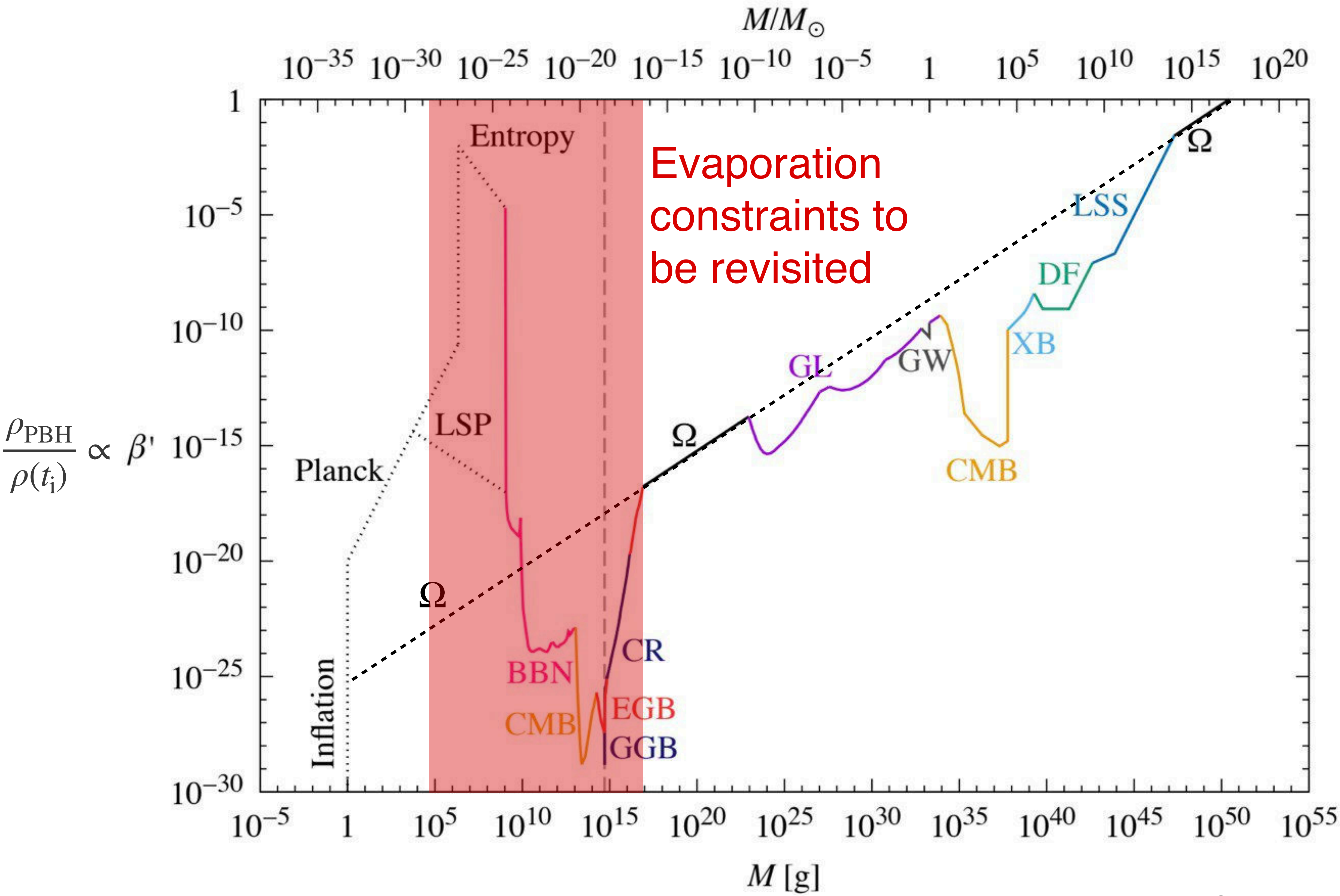
★ A conservative estimate is:

$$\tau \to \tilde{\tau} \geq \tau S^2$$

Entropy of the black hole

★ This opens up a large window for light PBH dark matter.

Light PBH Dark Matter?



[Carr *et al.* 2021]

Formation II:
Critical Collapse

Critical Collapse

★ Usually: Assume

$$M_{BH} \propto M_H$$

horizon mass

★ Critical scaling:

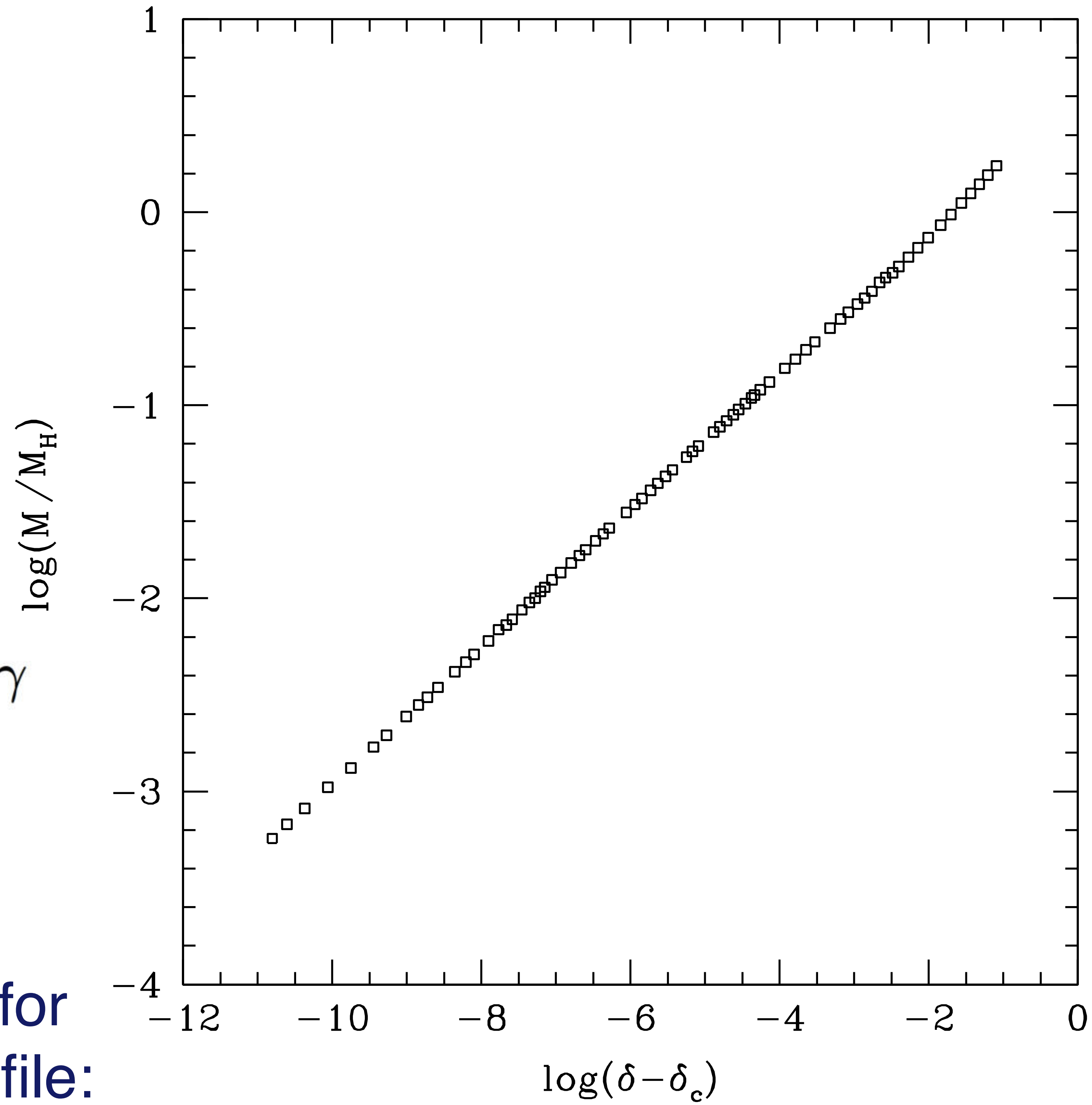
[Choptuik '93]

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

density contrast

★ Radiation domination and for spherical Mexician-hat profile:

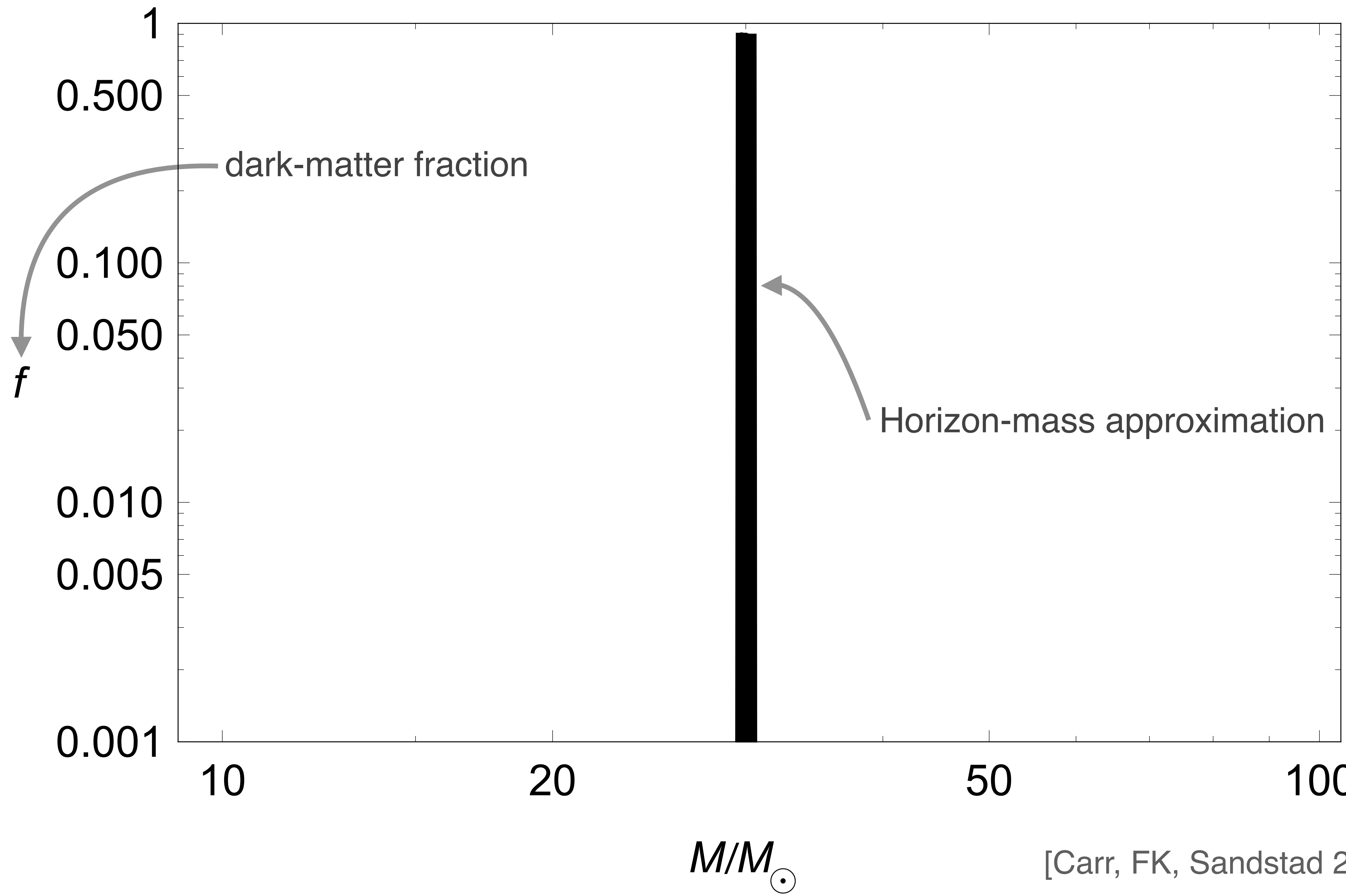
$$k \approx 3.3\,, \quad \delta_c \approx 0.45\,, \quad \gamma \approx 0.36$$



[Musco, Miller, Polnarev 2008]

Critical Collapse

★ How would this look for monochromatic mass function?



[Carr, FK, Sandstad 2016]

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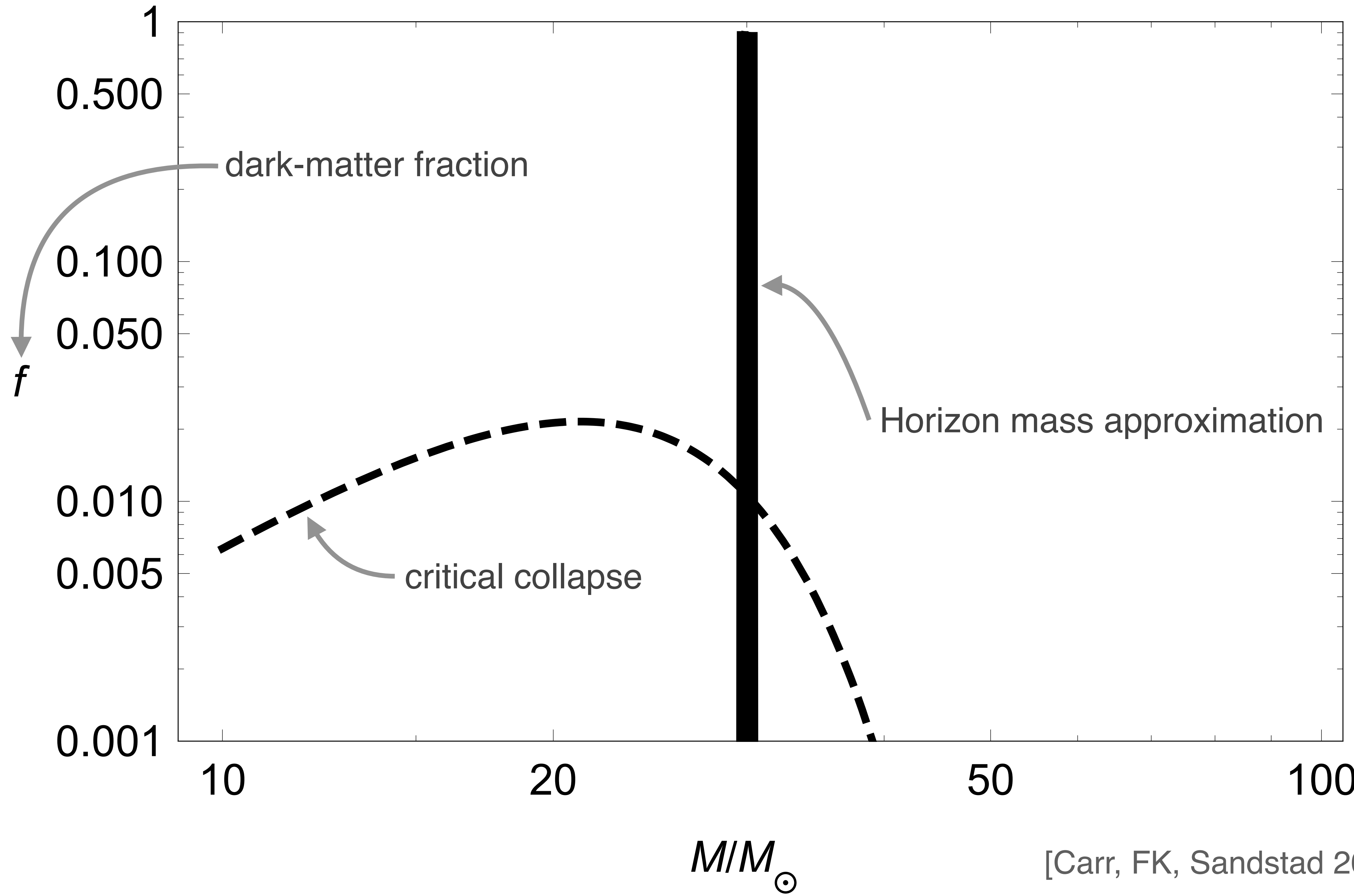

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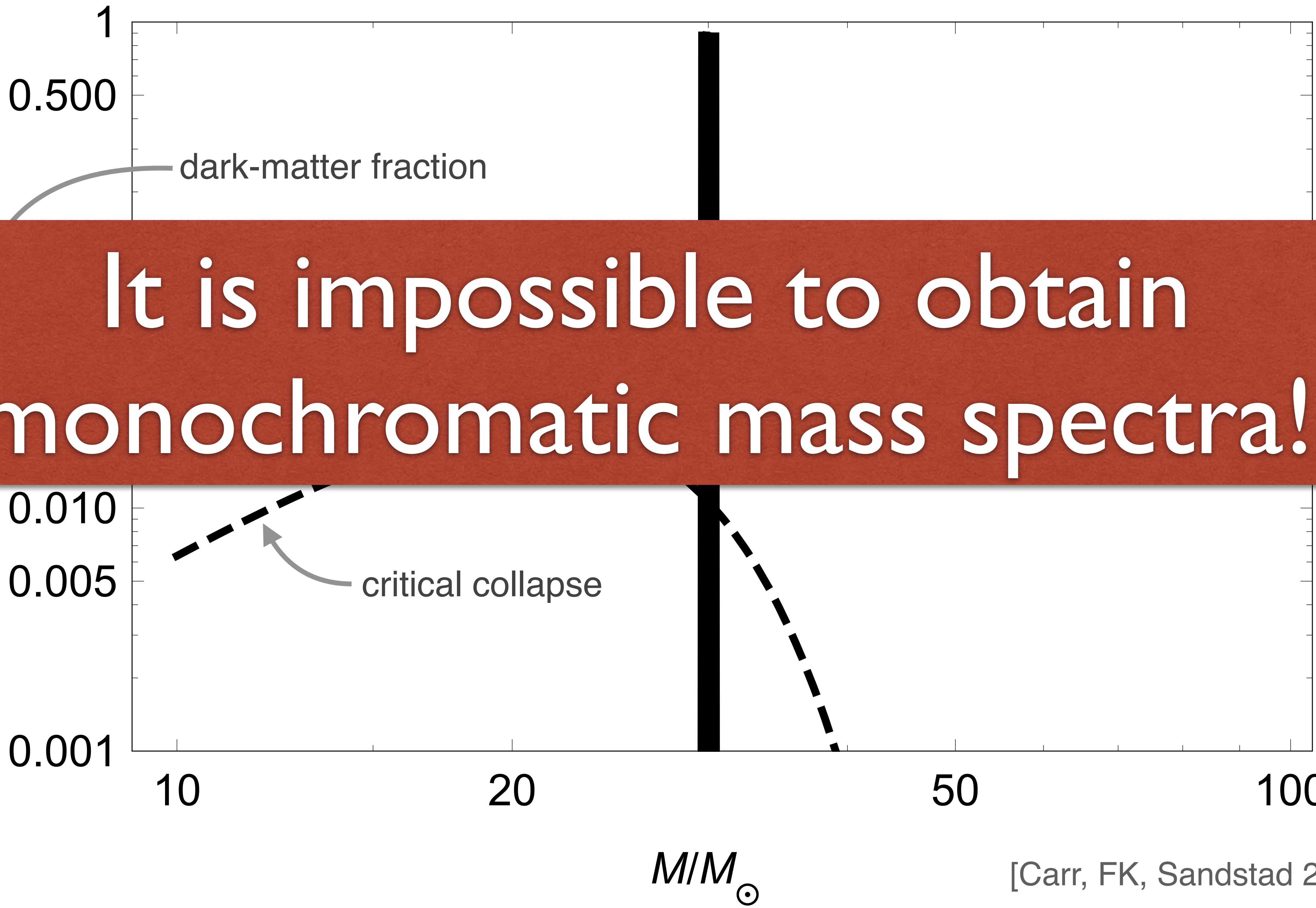
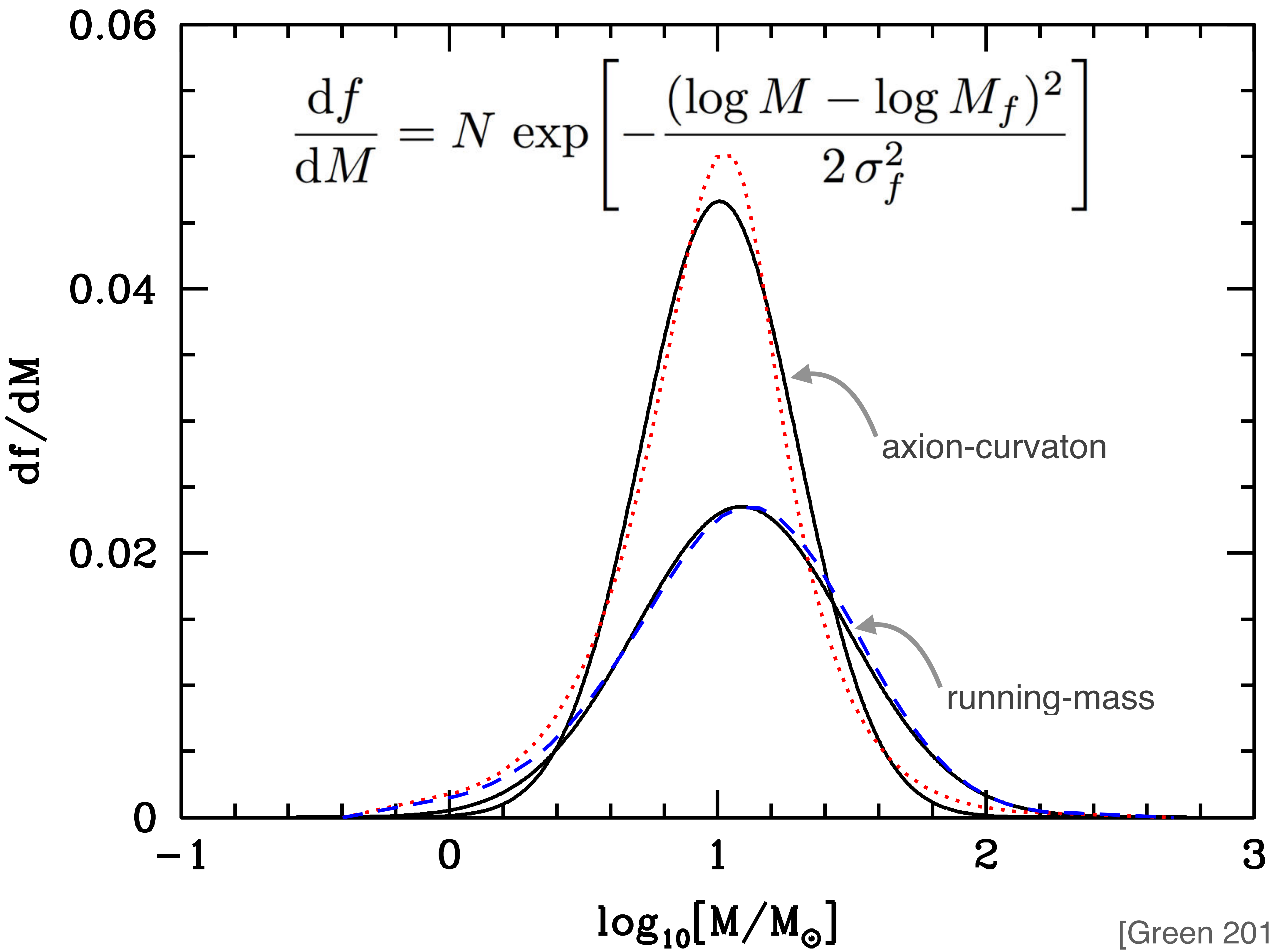


It is impossible to obtain monochromatic mass spectra!

[Carr, FK, Sandstad 2016]

More Systematic Study



[Green 2016]

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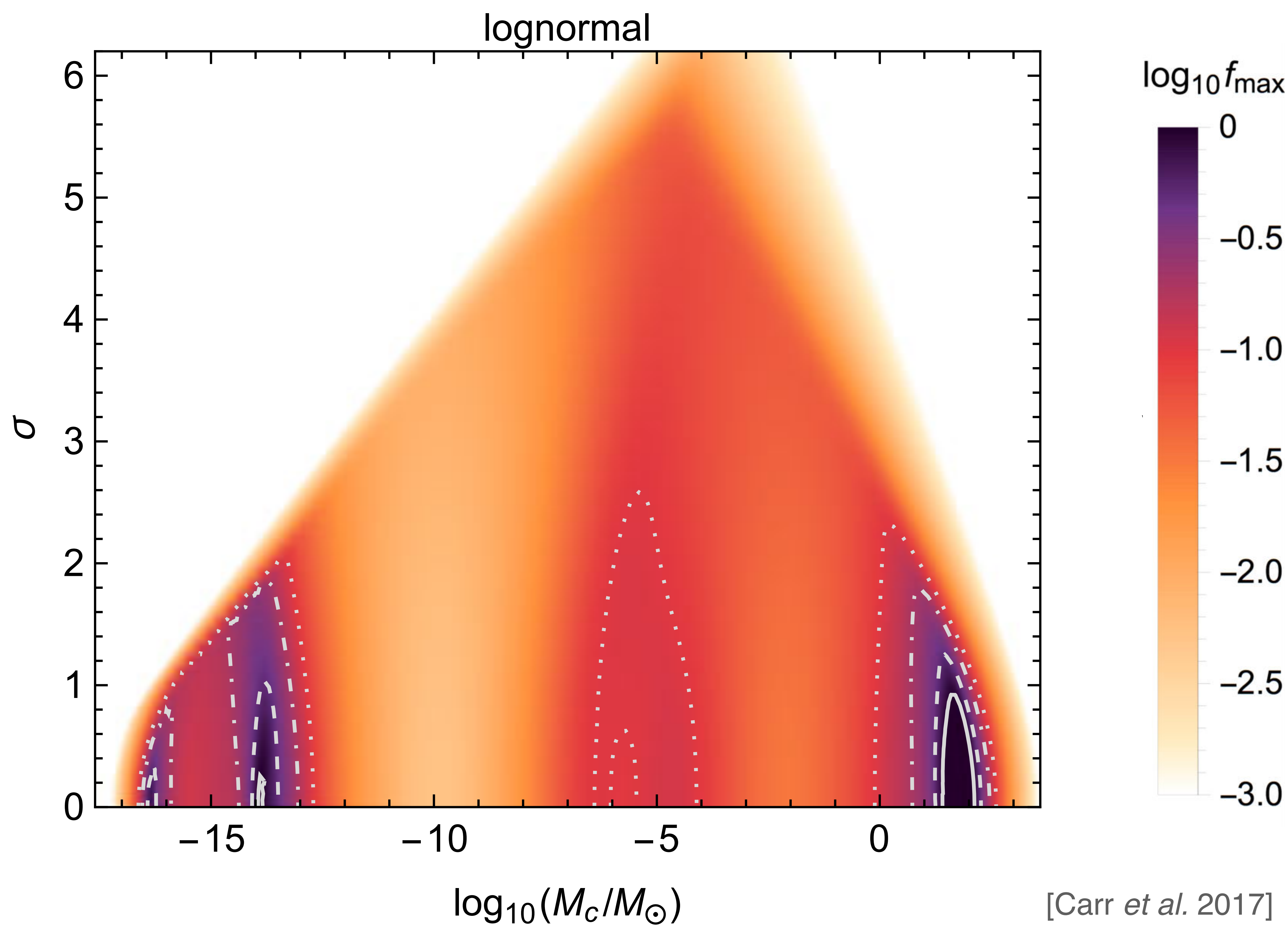


[Carr *et al.* 2017]

Lepton Flavour Asymmetry

Lepton Flavour Asymmetry

★ Lepton flavour asymmetries are defined as

$$\ell_\alpha \equiv \frac{n_\alpha - n_{\bar{\alpha}} + n_{\nu_\alpha} - n_{\bar{\nu}_\alpha}}{s}\,, \quad \alpha \in \{e,\, \mu,\, \tau\}$$

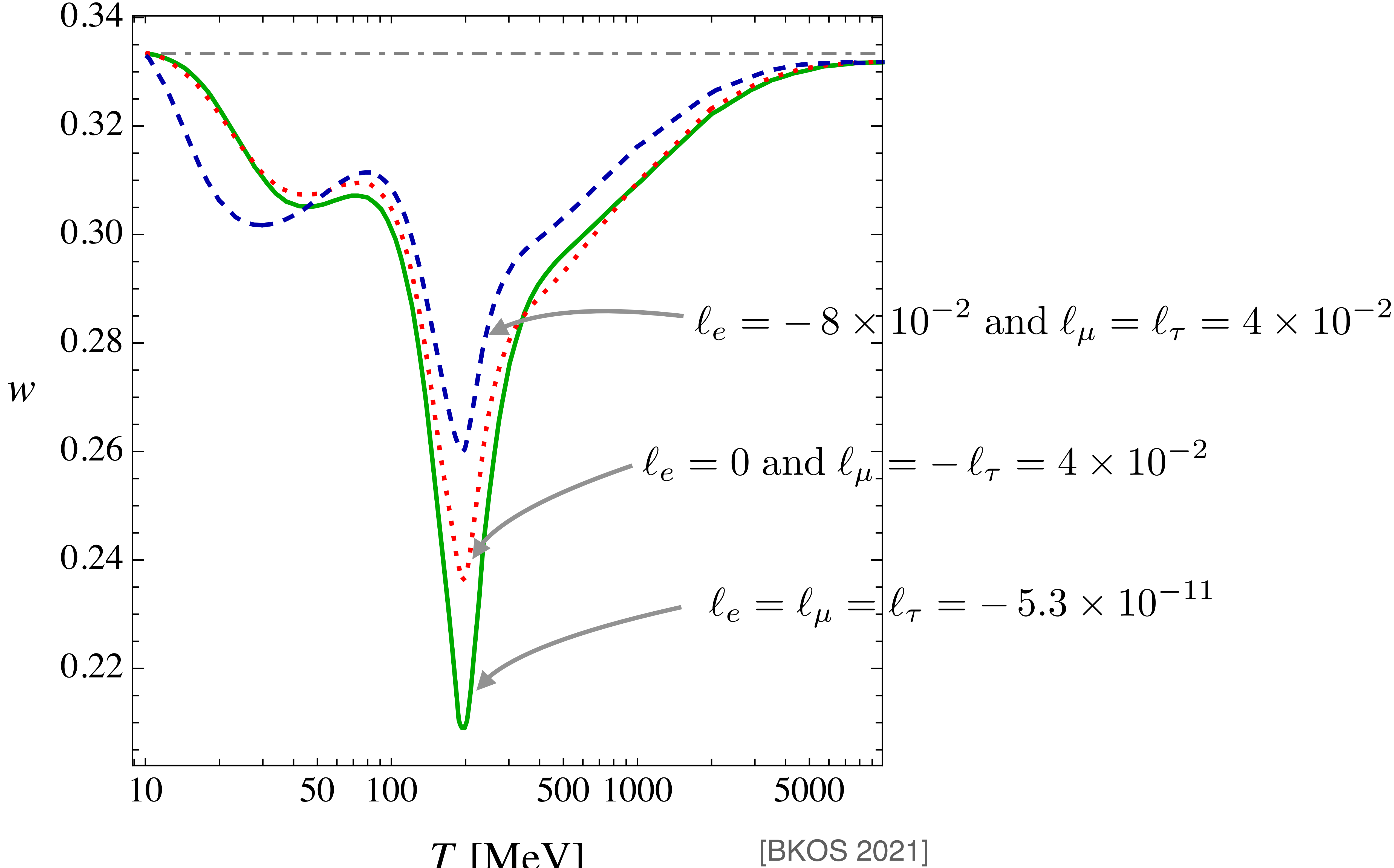
$n_\alpha, n_{\bar{\alpha}}, n_{\nu_\alpha}, n_{\bar{\nu}_\alpha}$	number densities of (anti)leptons and corresponding (anti)neutrinos
s	entropy densities

★ CMB constraints are quite weak:

$$|\ell_e + \ell_\mu + \ell_\tau| < 1.2 \times 10^{-2}$$

(unlike baryon asymmetry: $b = 8.7 \times 10^{-11}$)

Lepton Flavour Asymmetry



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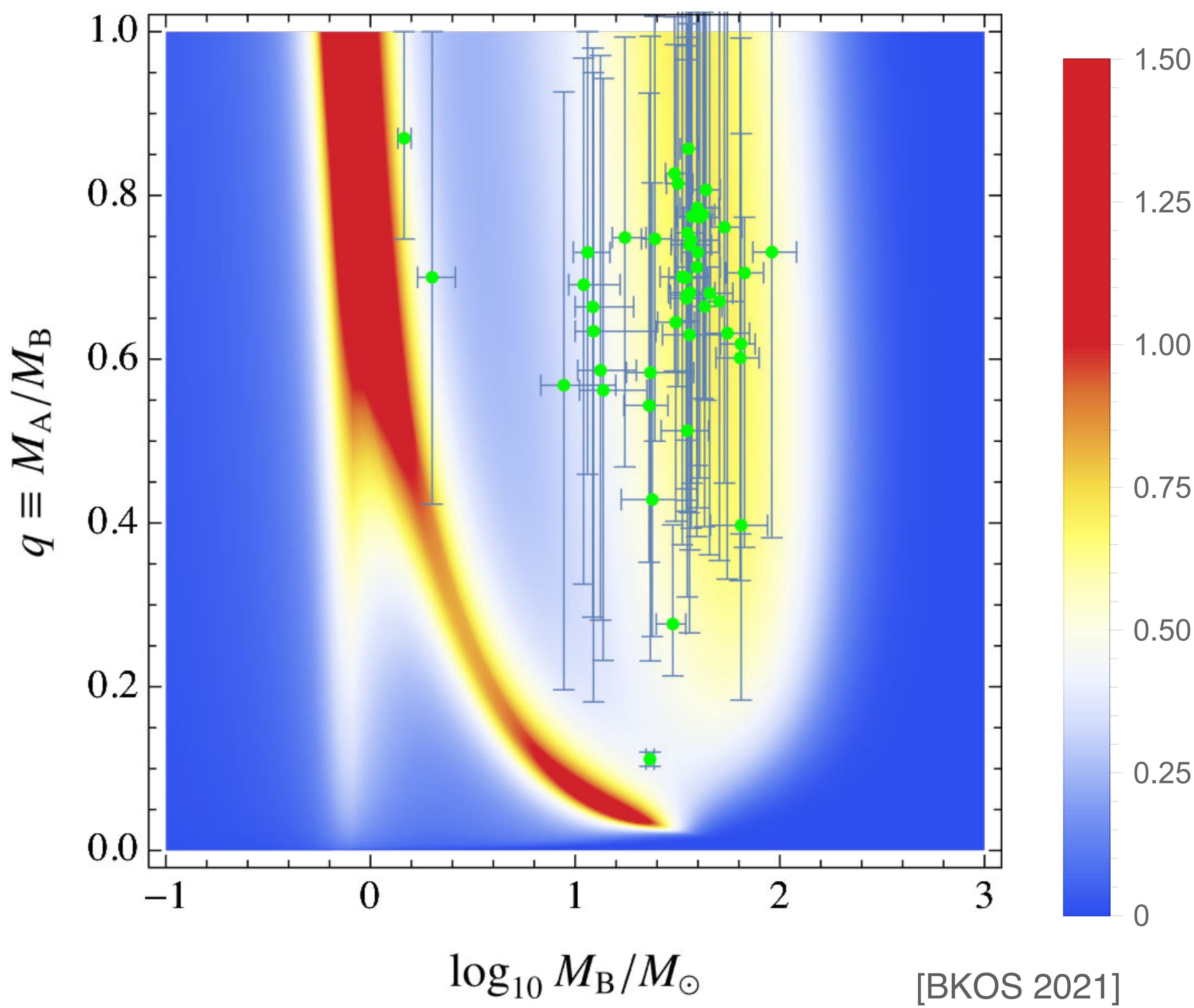
Lepton Flavour Asymmetry

$$\ell_e = \ell_\mu = \ell_\tau = -5.3 \times 10^{-11}$$



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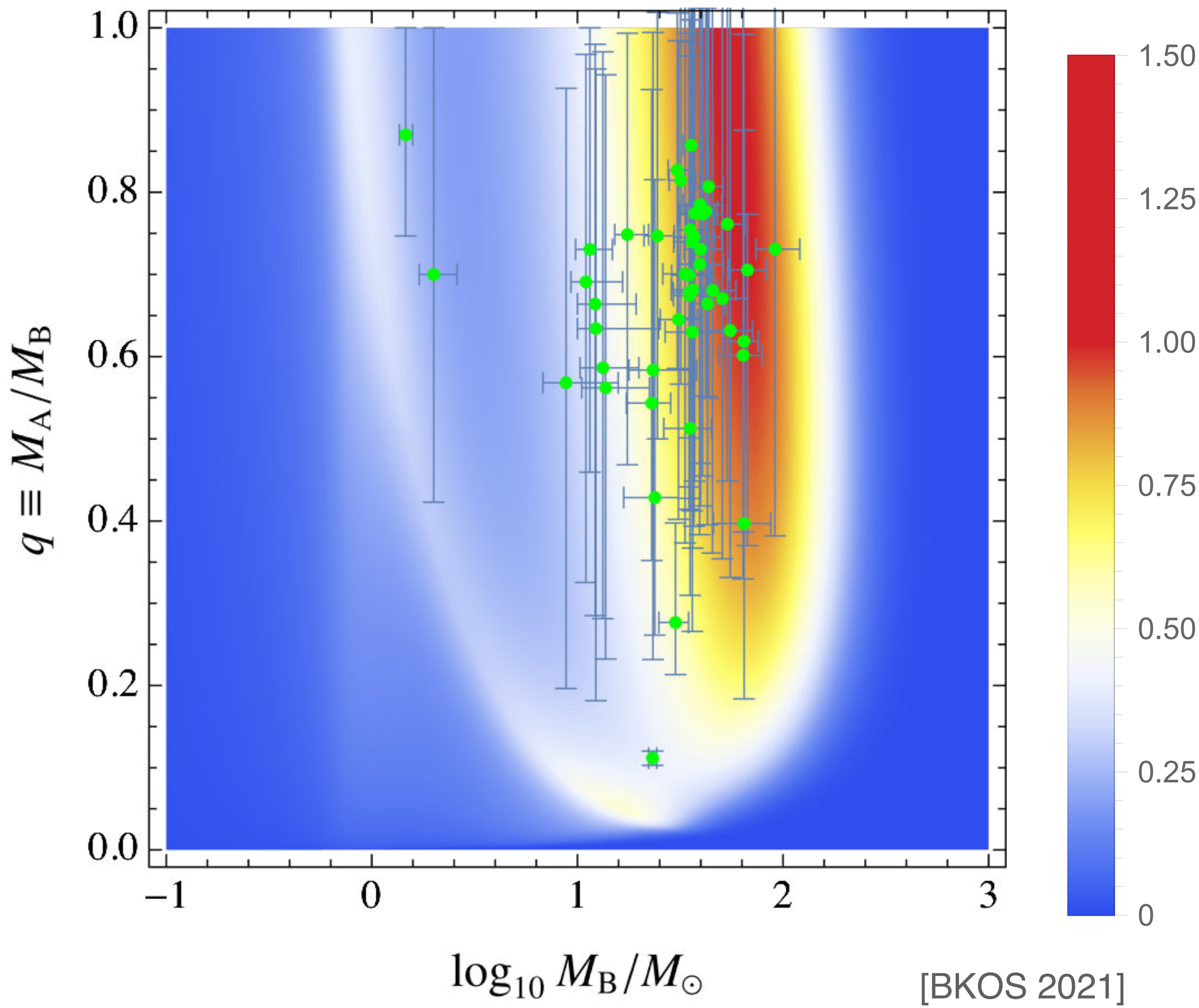
Lepton Flavour Asymmetry

$\ell_e = -8 \times 10^{-2}$ and $\ell_\mu = \ell_\tau = 4 \times 10^{-2}$



[BKOS 2021]