Primordial Black Holes

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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*.

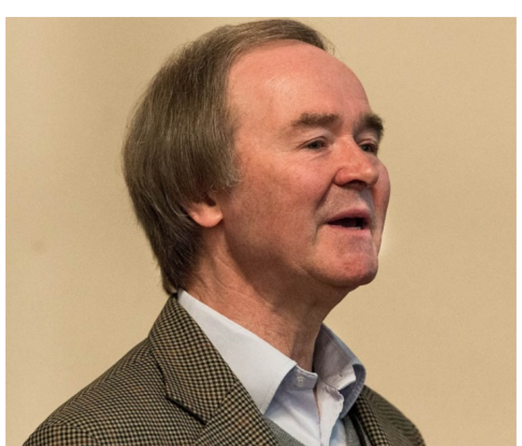
*since most conference participants work on particle dark matter

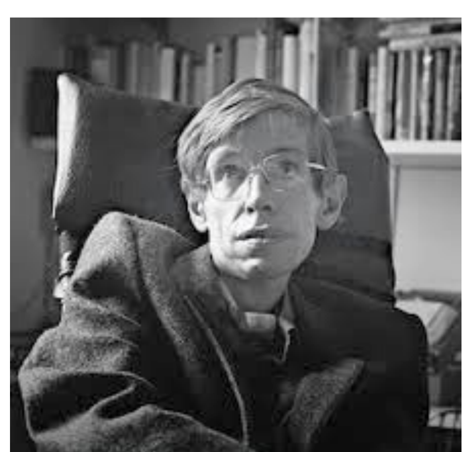
What are Primordial Black Holes (PBHs)?

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

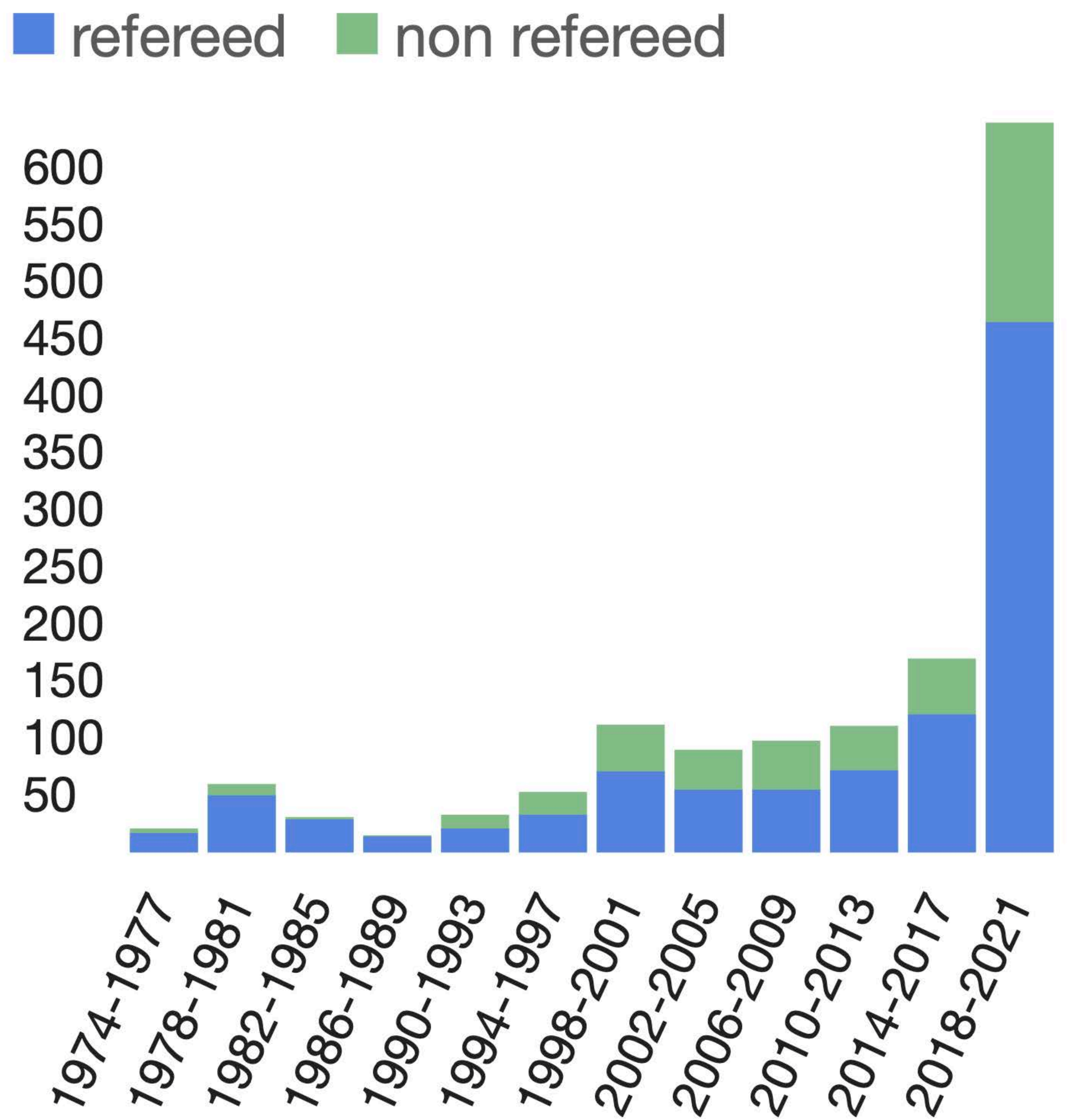
★ First proposed by Novikov and Zel'dovič in the late 1960th, but their conclusion was negative for the existence of PBHs.

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



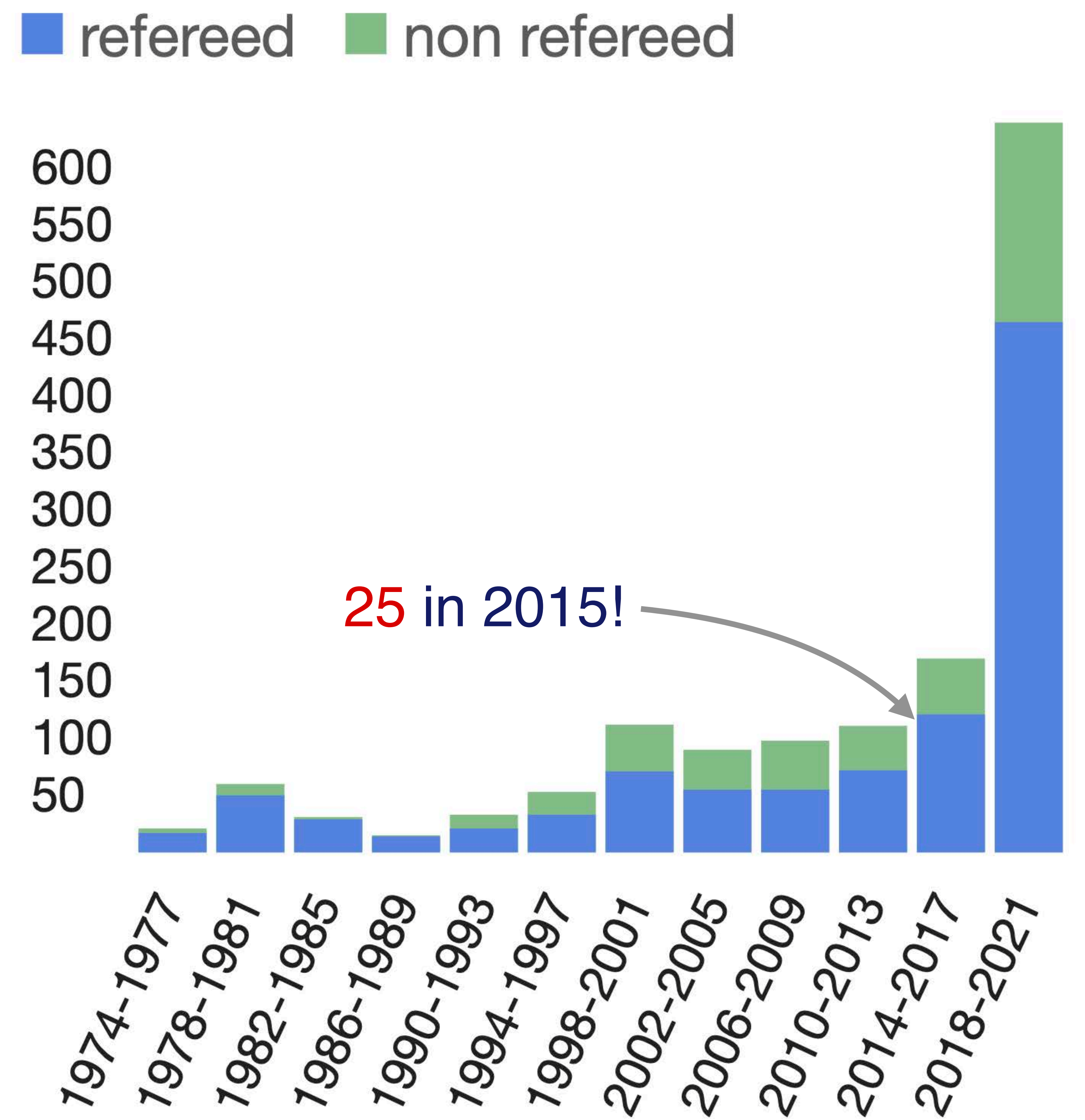


Primordial Black Holes are Popular!



[SAO/NASA Astrophysics Data System]

Primordial Black Holes are Popular!

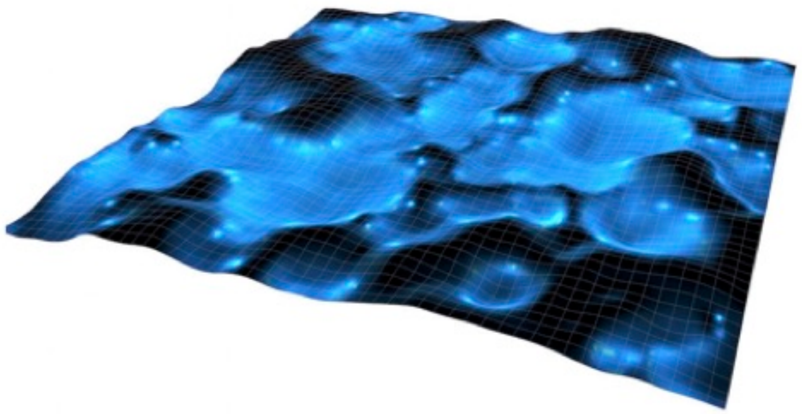


[SAO/NASA Astrophysics Data System]

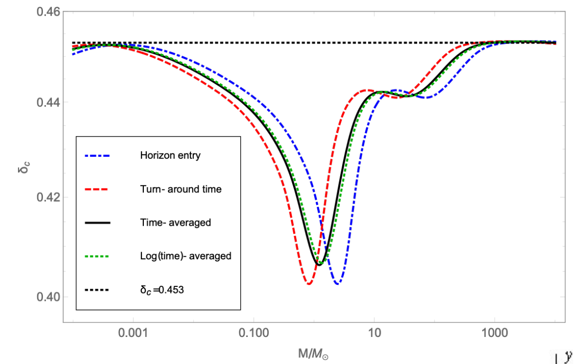
Primordial Black Hole Formation

PBH Formation Mechanisms

★ Large density perturbations (inflation)

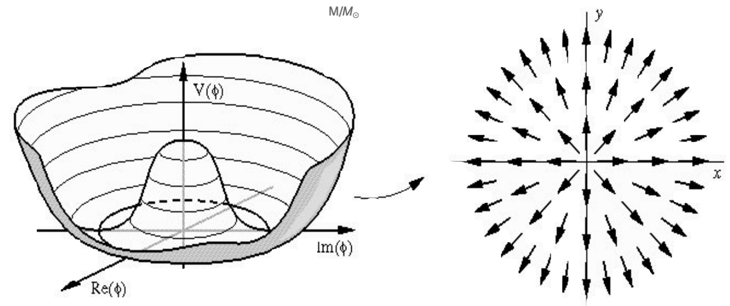


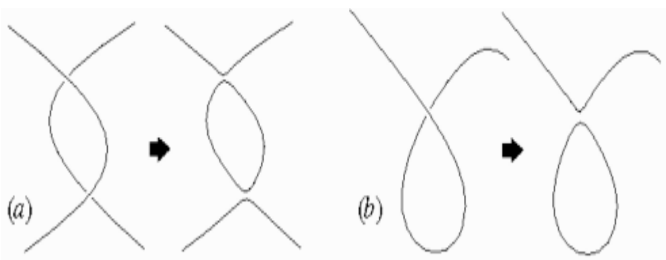
★ Pressure reduction



[Byrnes *et al.* 2018]

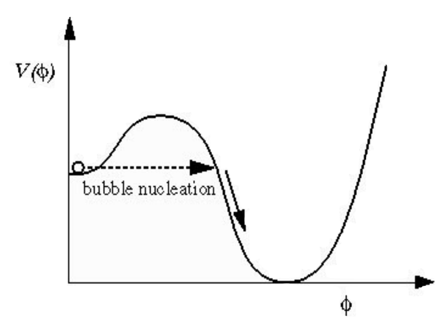
★ Cosmic string loops

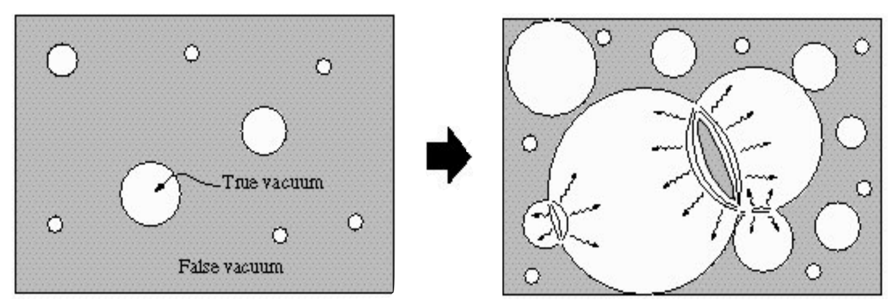




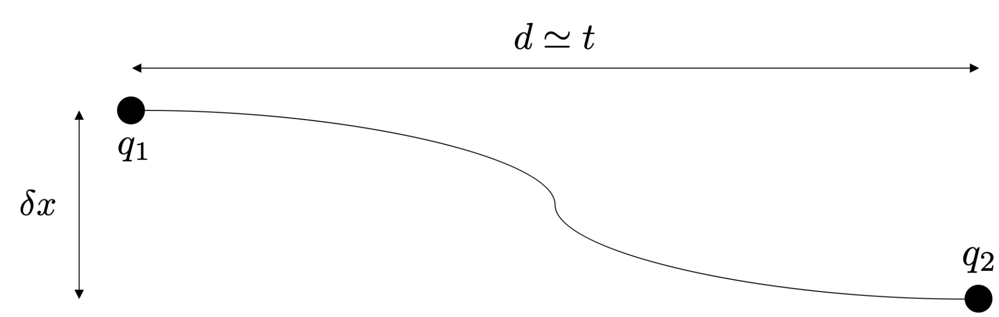
http://www.damtp.cam.ac.uk/research/gr/public/cs_phase.html http://www.damtp.cam.ac.uk/research/gr/public/cs_top.html

★ Bubble collisions



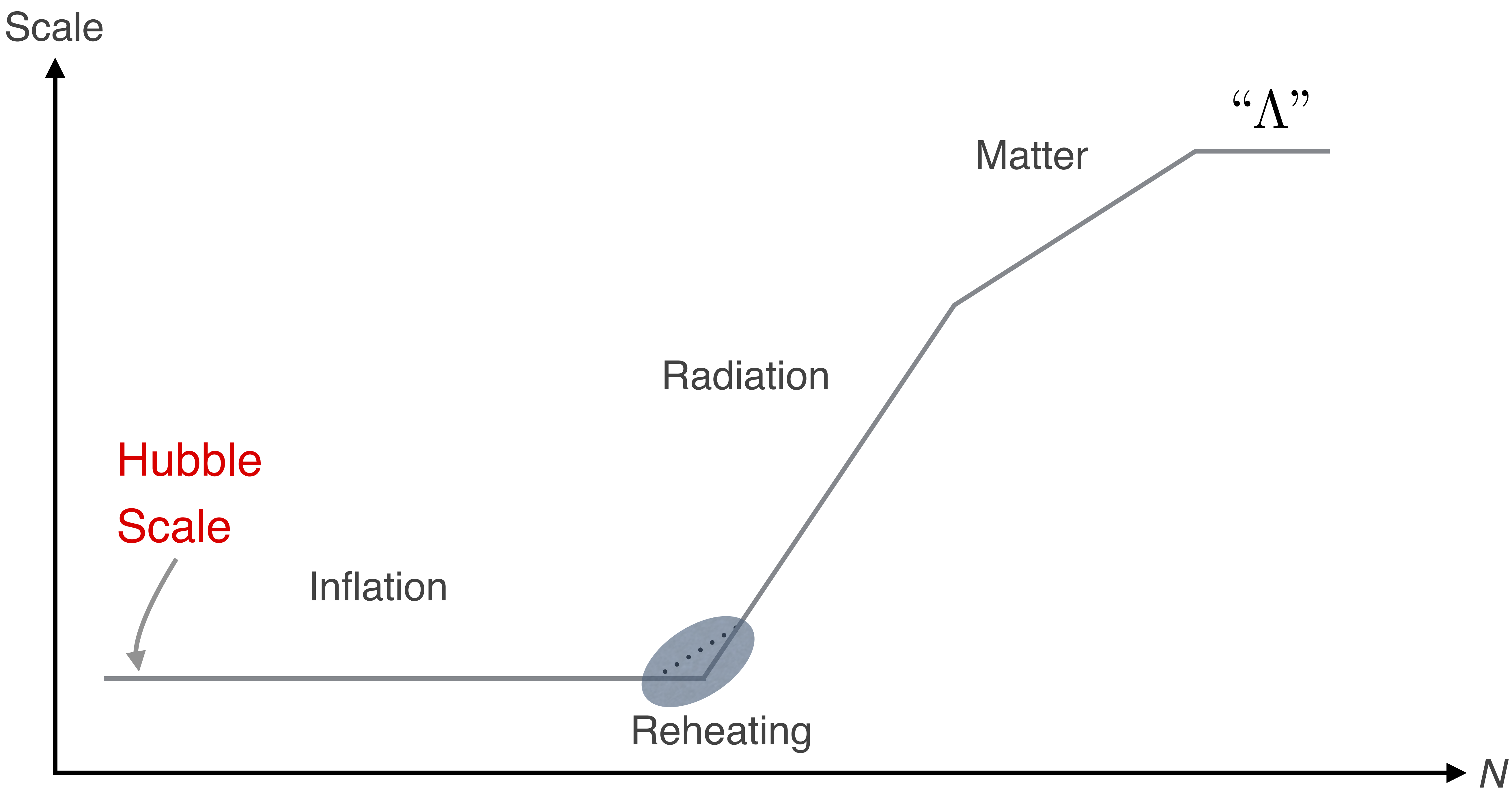


★ Quark confinement

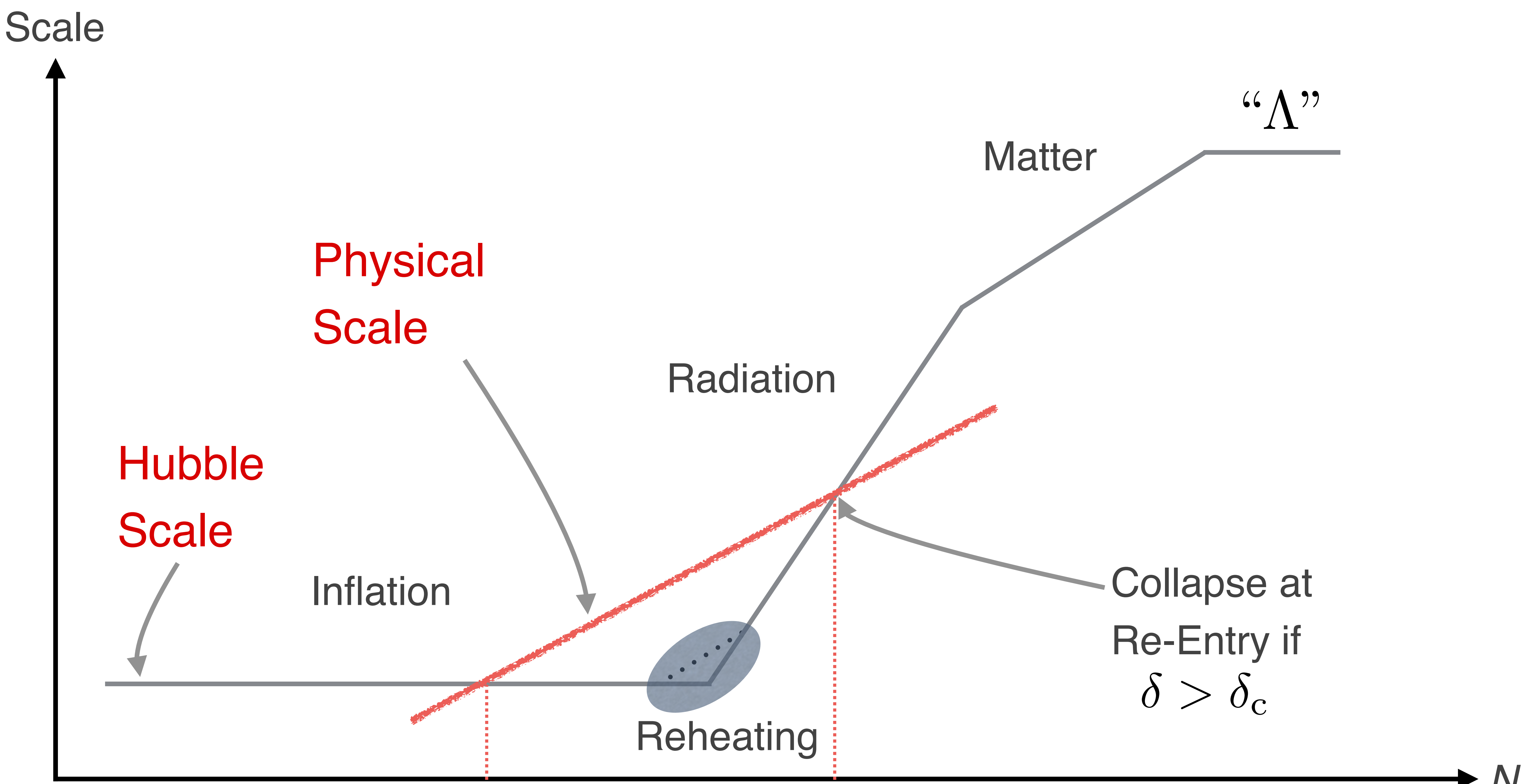


★ Q-balls, Multiverse...

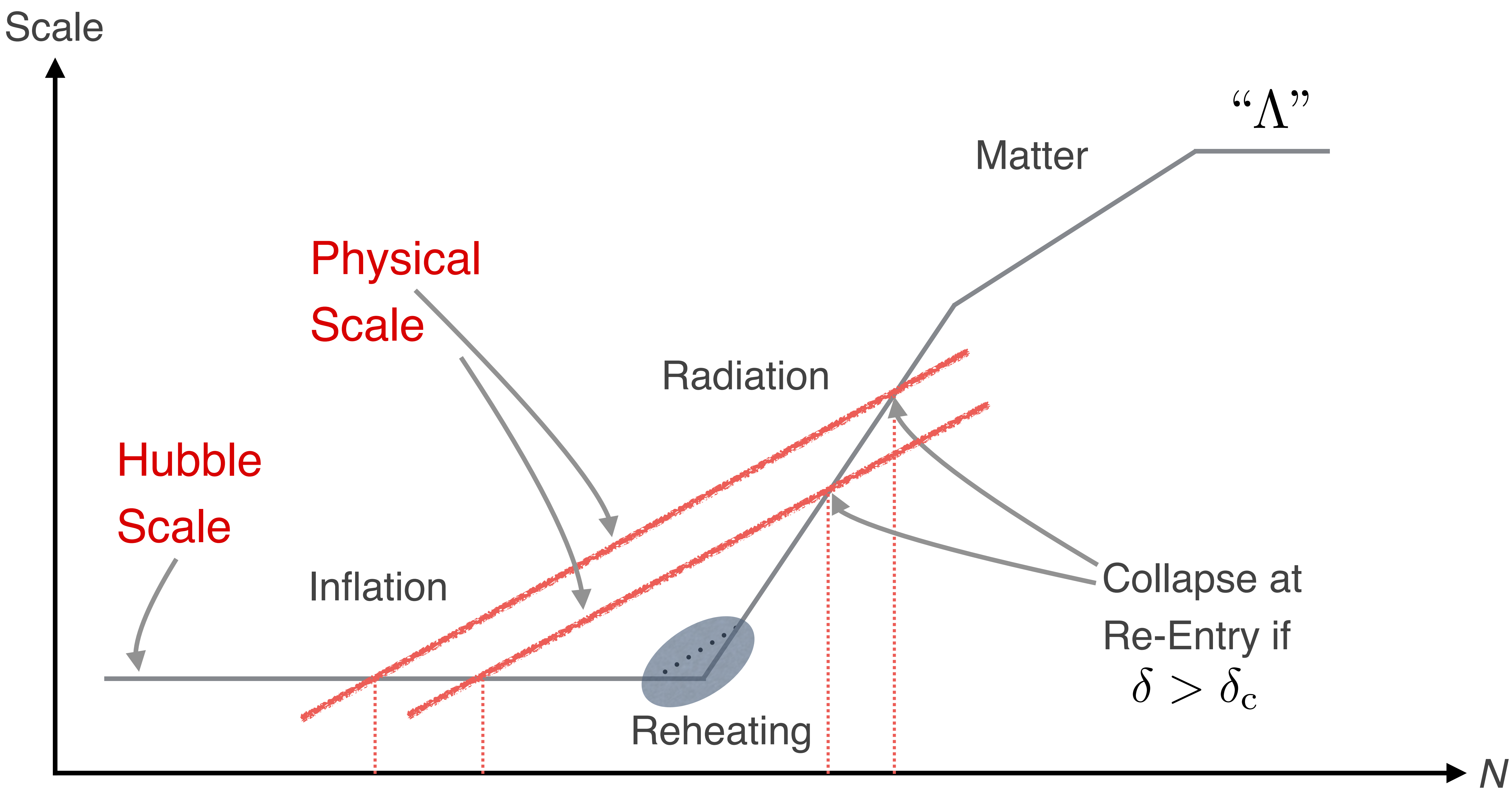
PBH Formation from Inflationary Overdensities



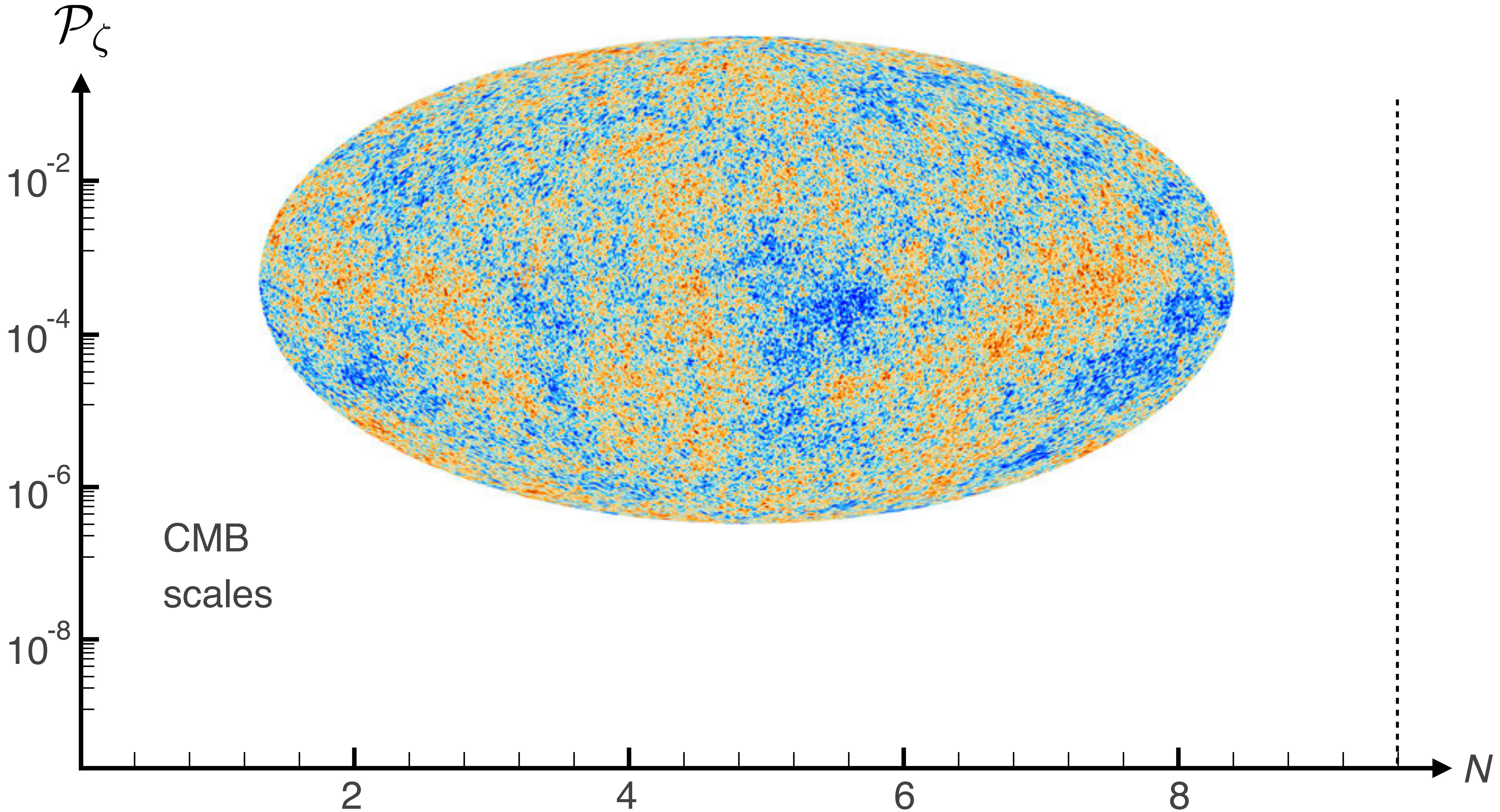
PBH Formation from Inflationary Overdensities



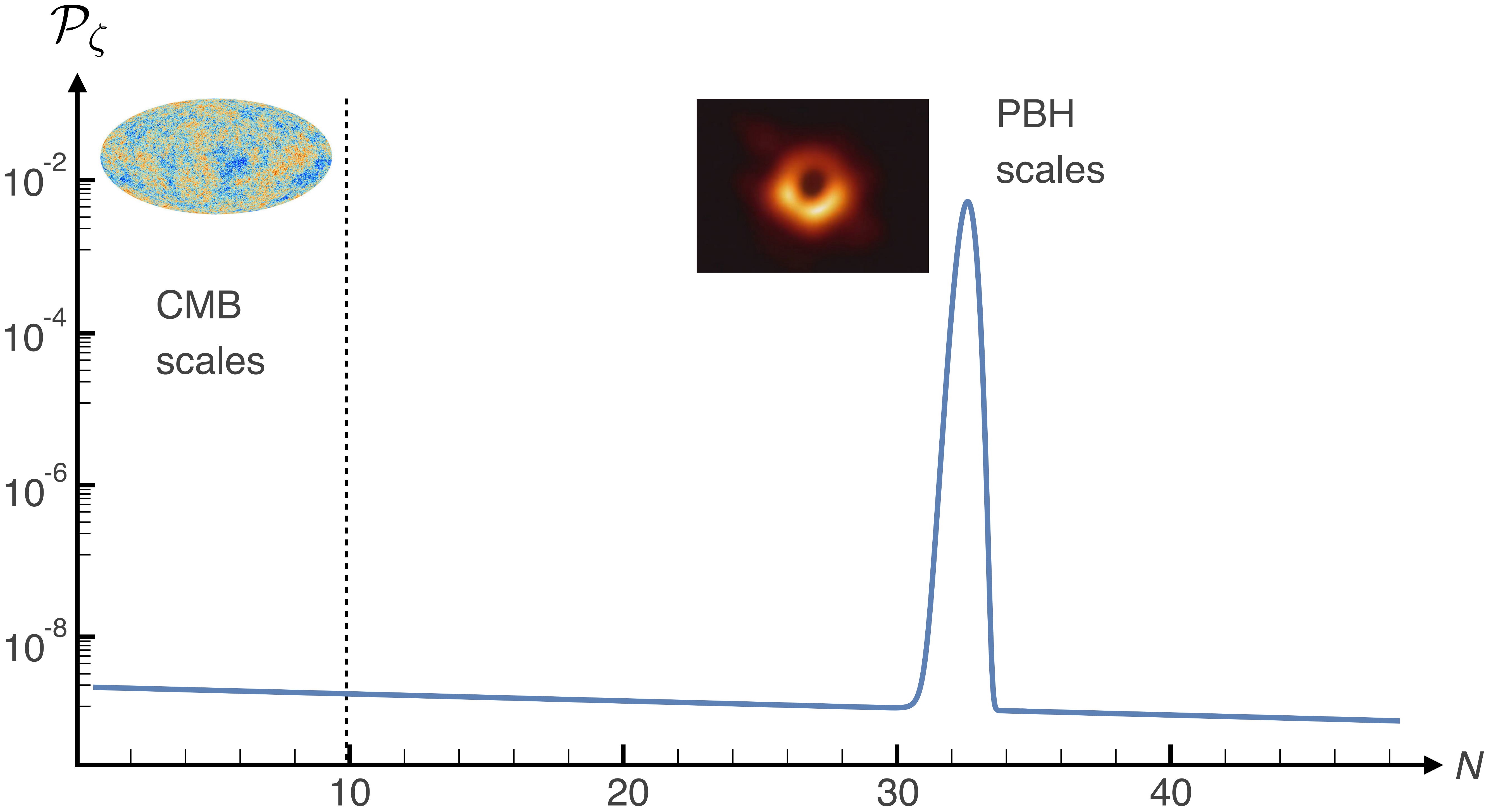
PBH Formation from Inflationary Overdensities



PBH Formation — Scales



PBH Formation — Scales

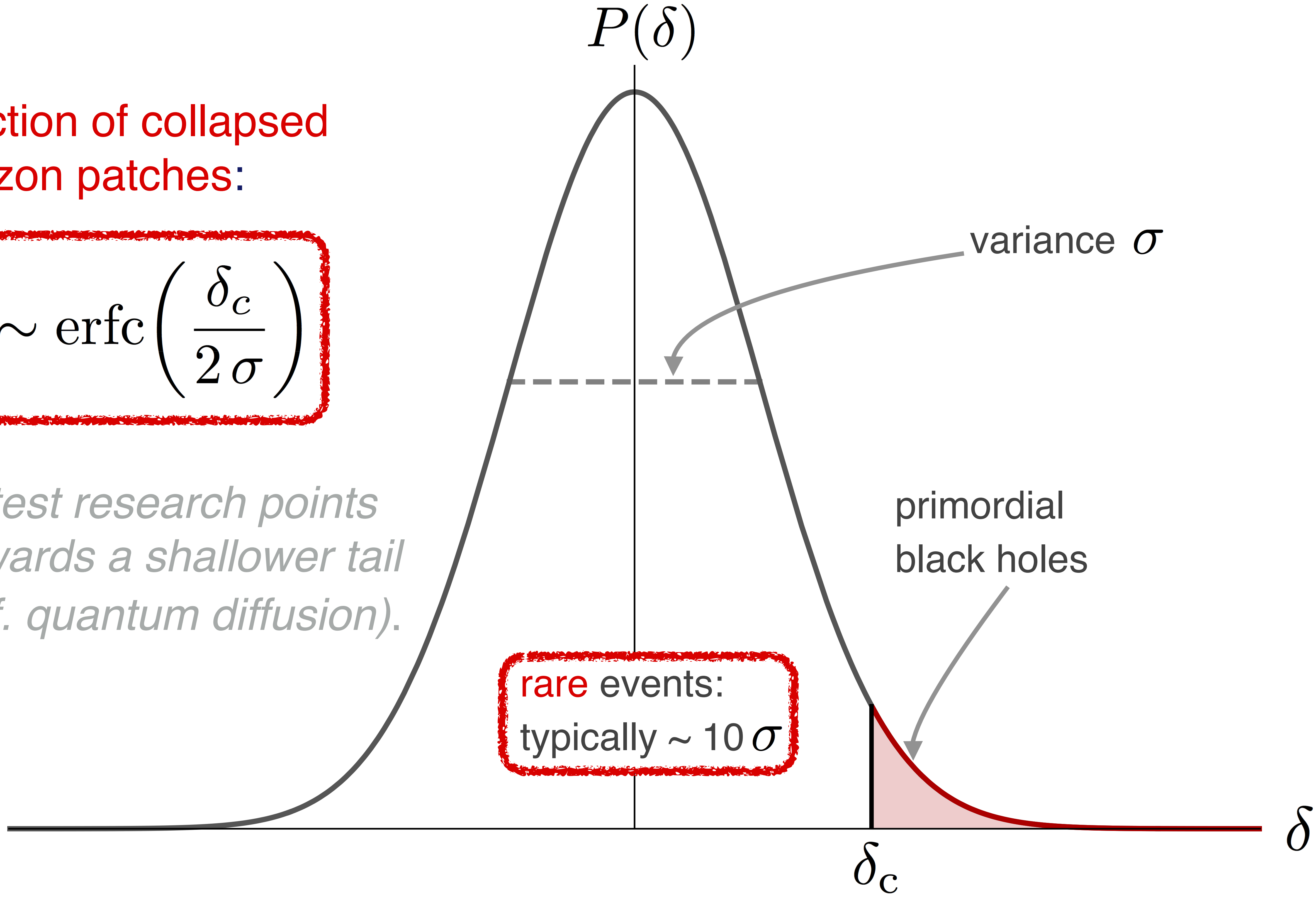


PBH Formation — Rare Events

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).

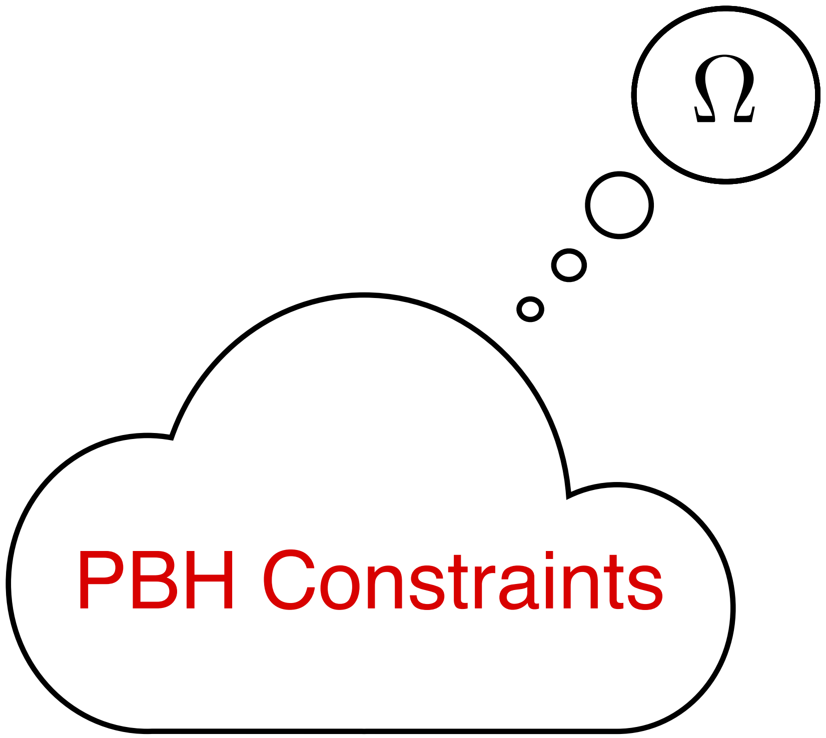


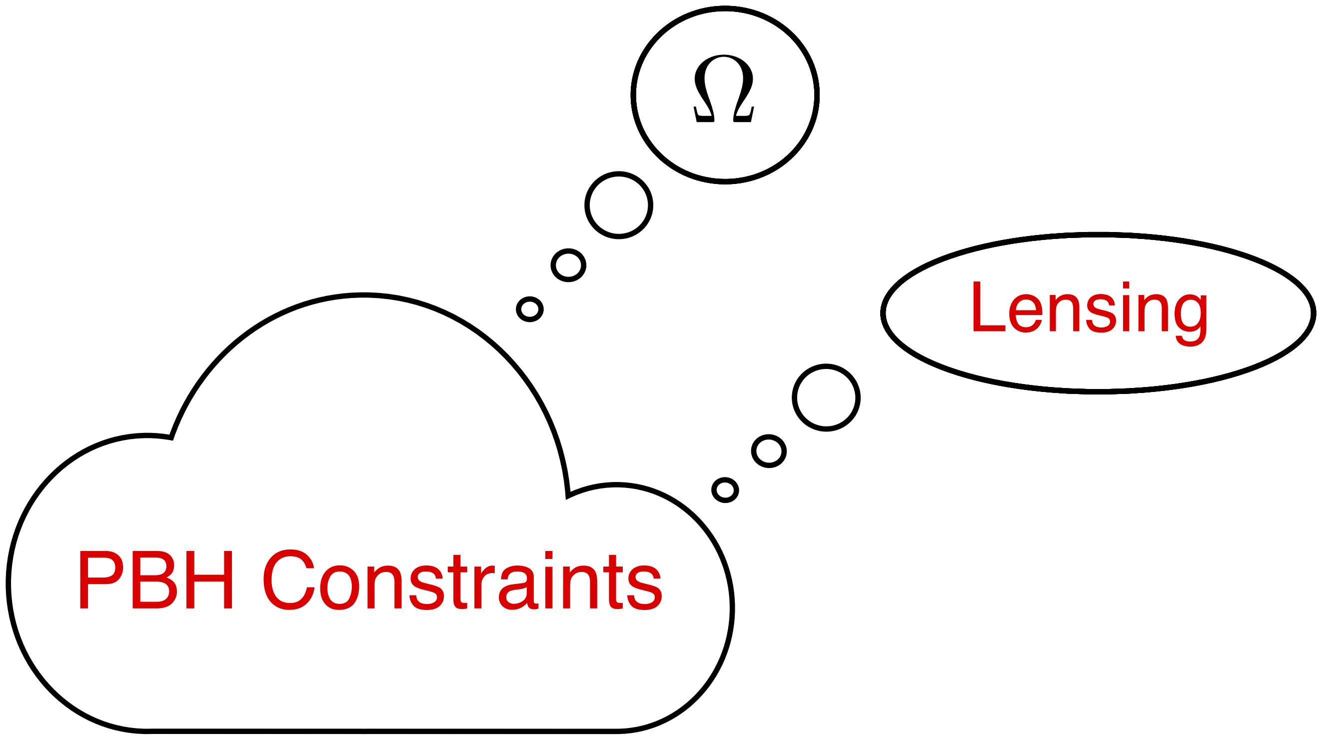
PBH — Some Numbers

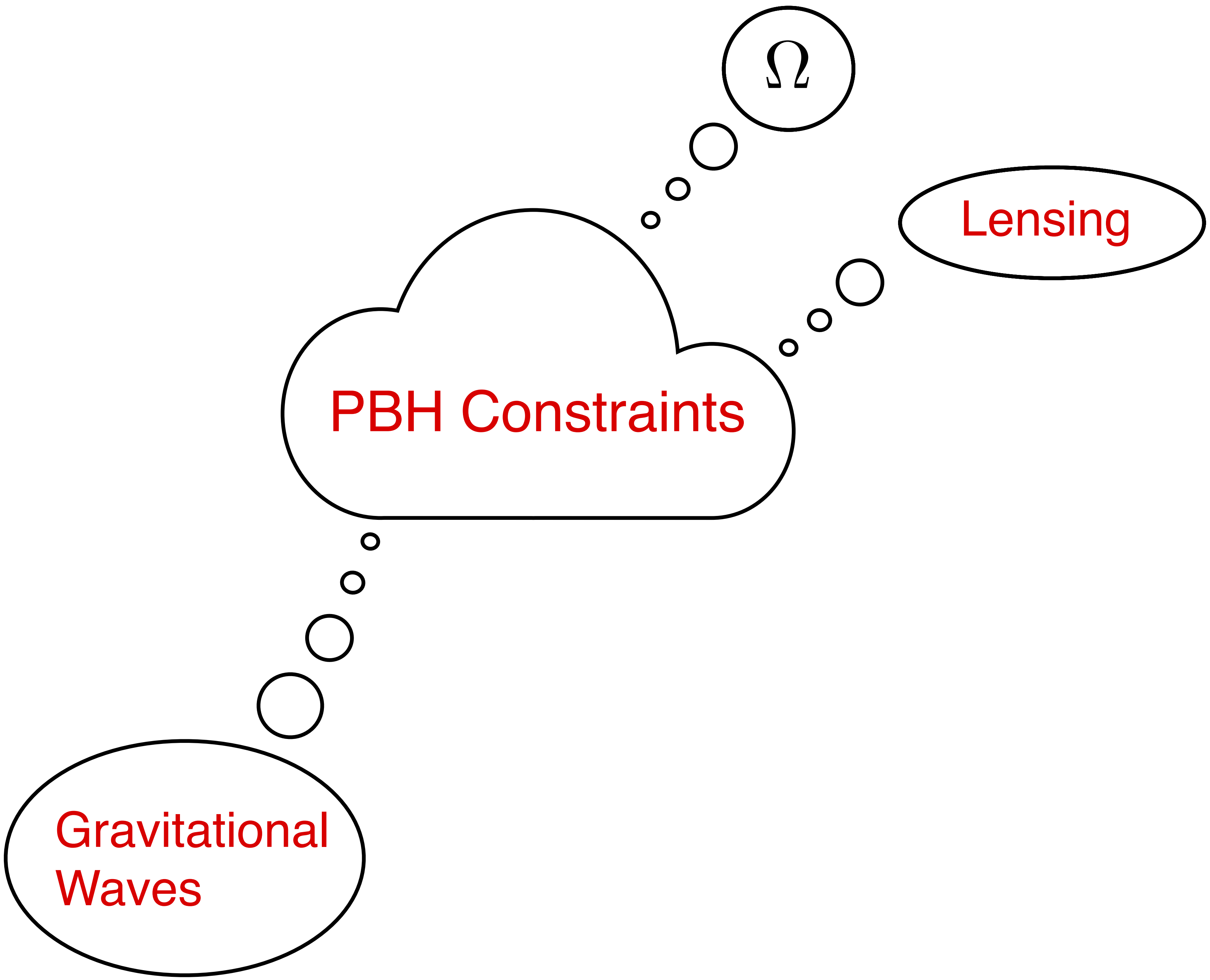
★ If primordial black holes constituted all of the dark matter:

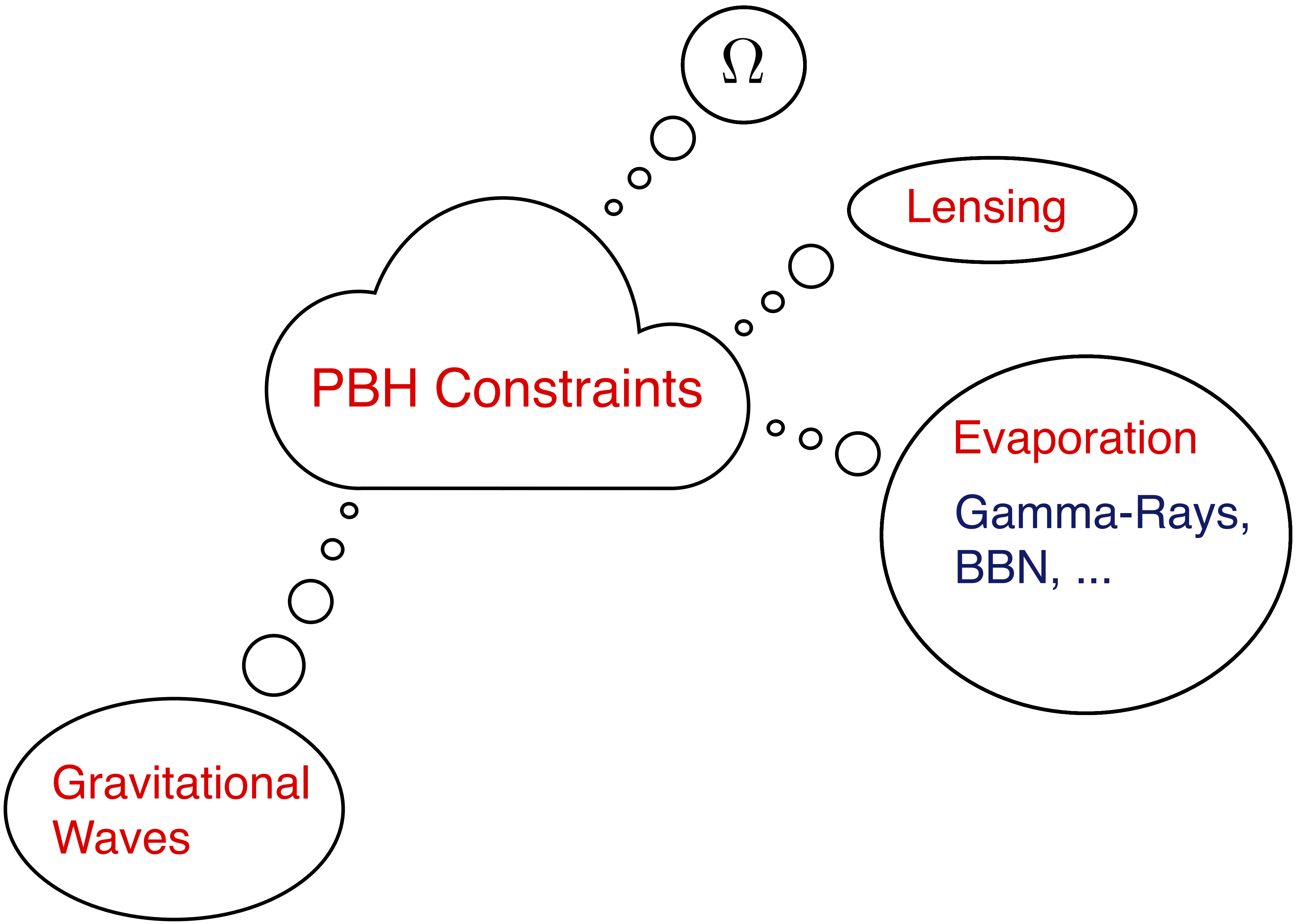
- ★ Assume that all PBH have mass: $10^{20}\,\mathrm{g}$
- ★ Size: $10^{-8}\,\mathrm{cm}$
- ★ Number in our Galaxy: 10^{25}
- ★ Distance: $10\,\mathrm{AU}$

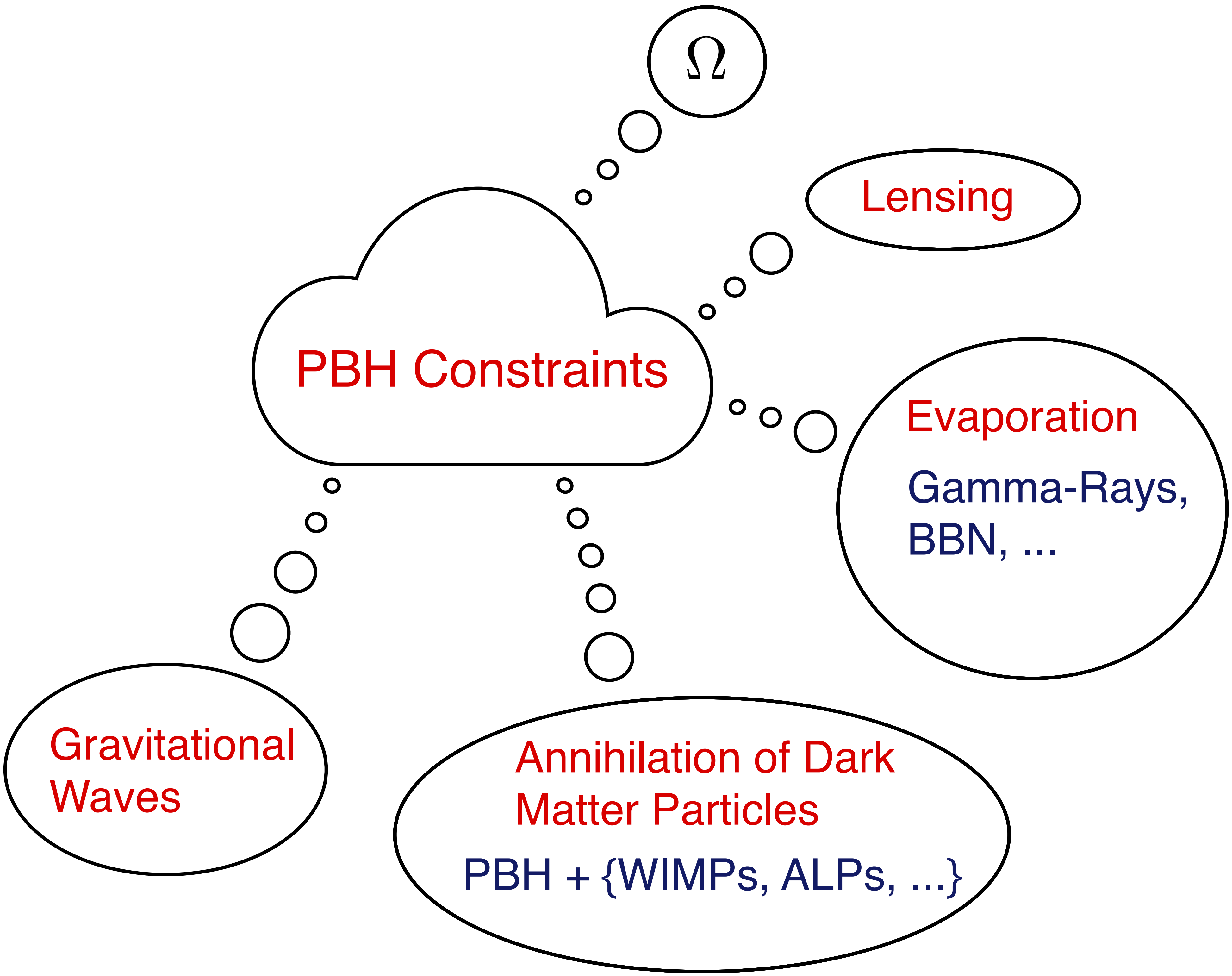
PBH Constraints


Ω
PBH Constraints

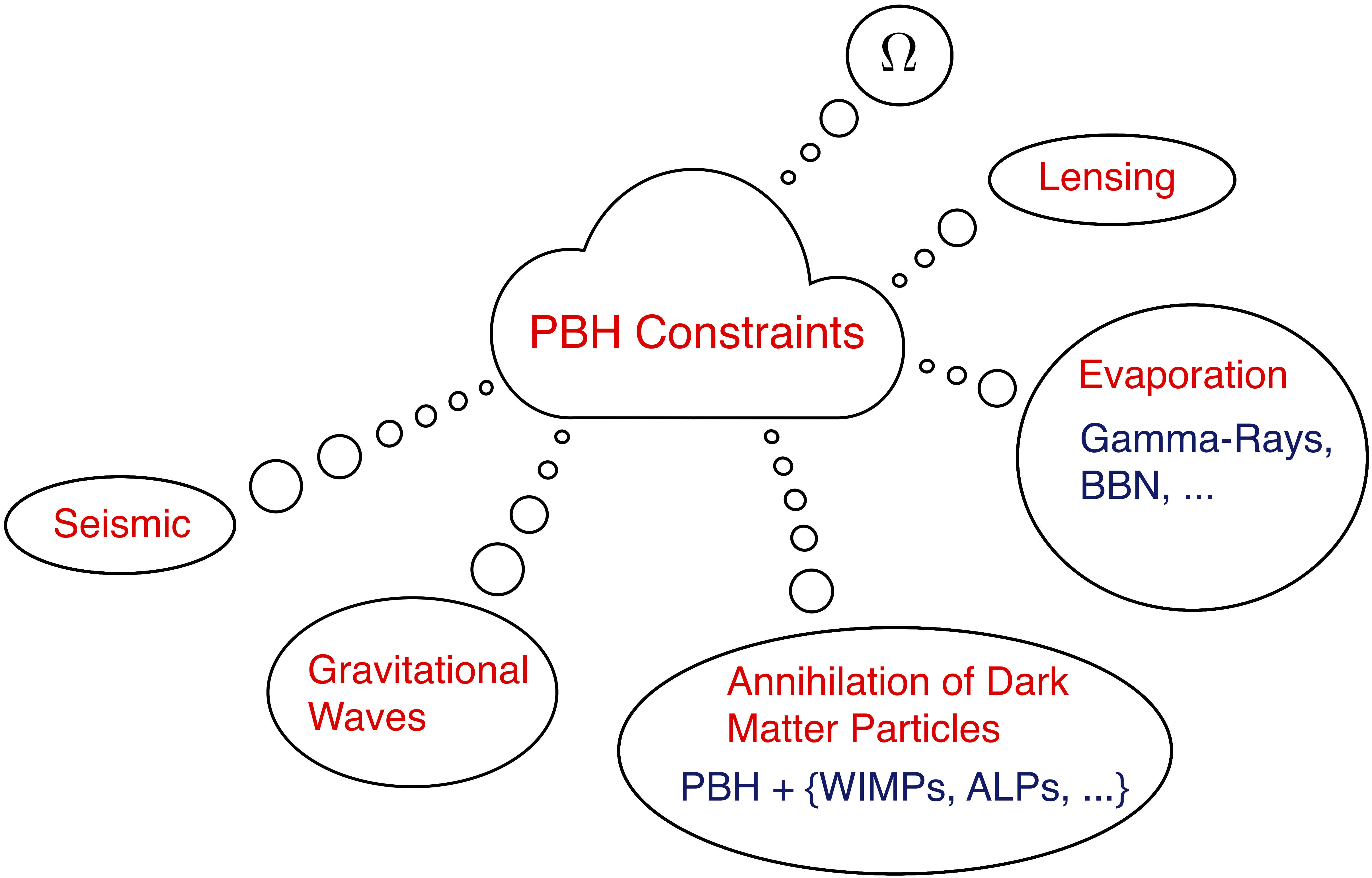

Ω
Lensing
PBH Constraints

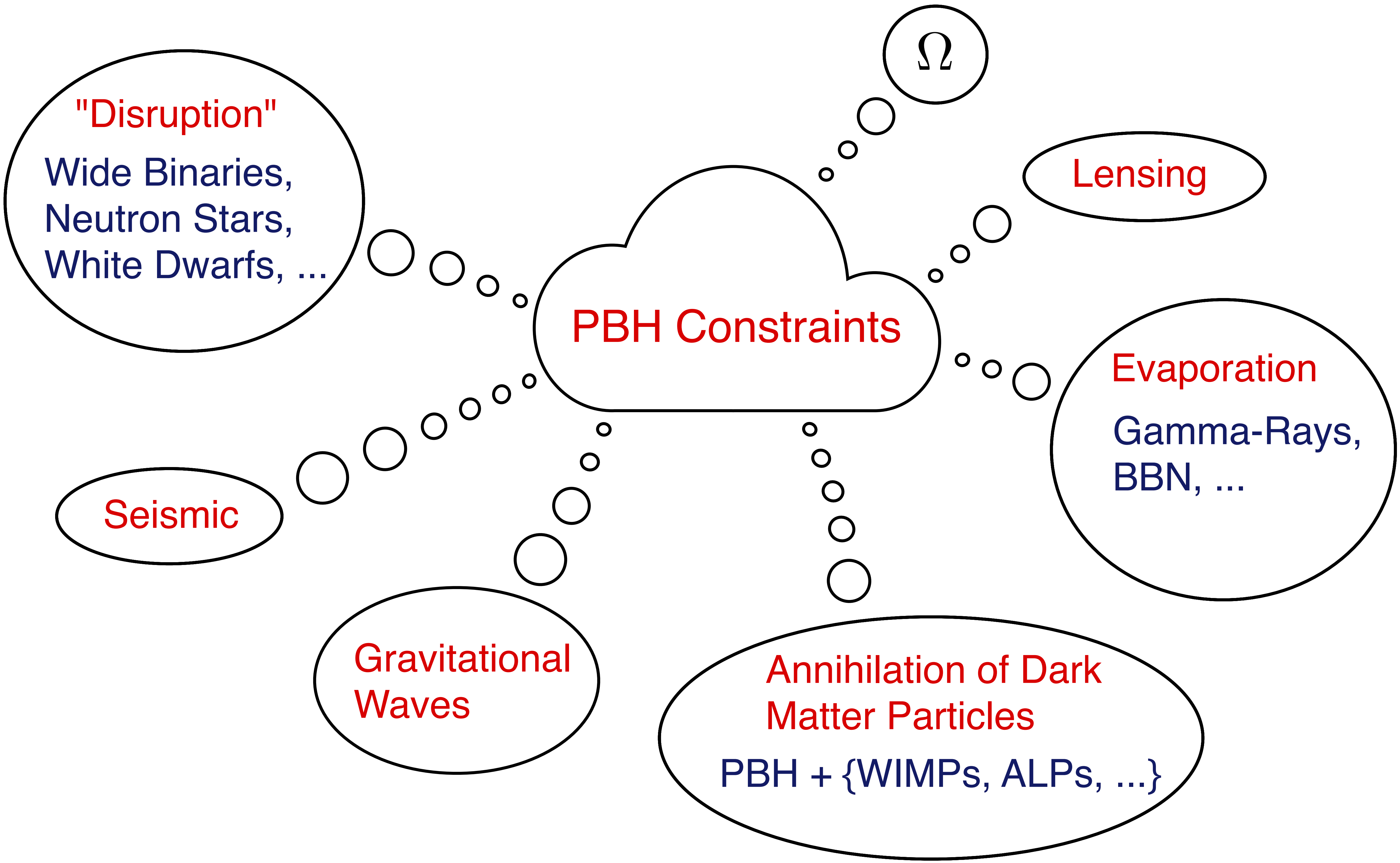

Ω
Lensing
PBH Constraints
Gravitational
Waves


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



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


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


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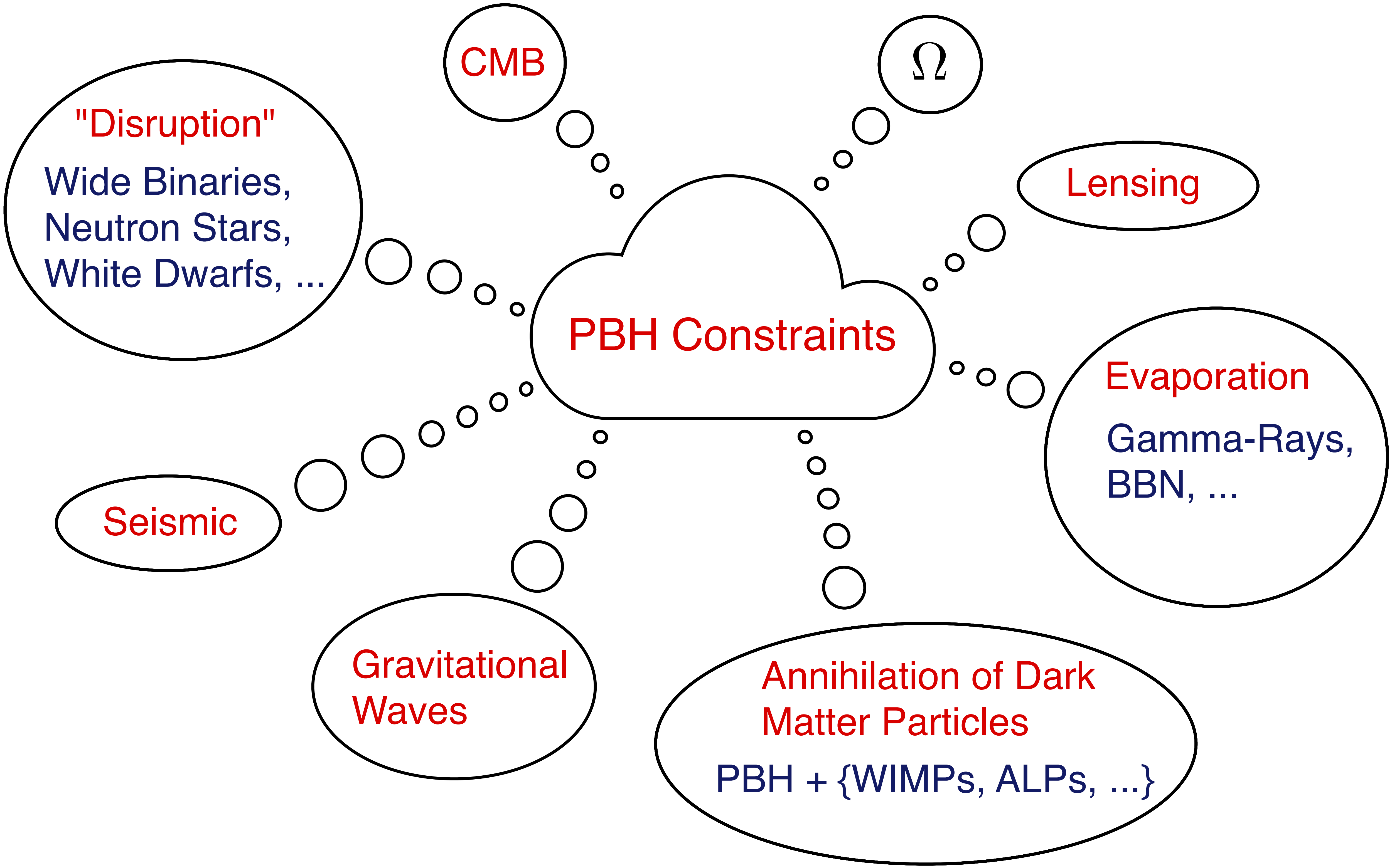
Matter Particles
PBH + {WIMPs, ALPs, ...}


PBH Constraints
CMB
Ω
Lensing
"Disruption"
Wide Binaries,
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Matter Particles
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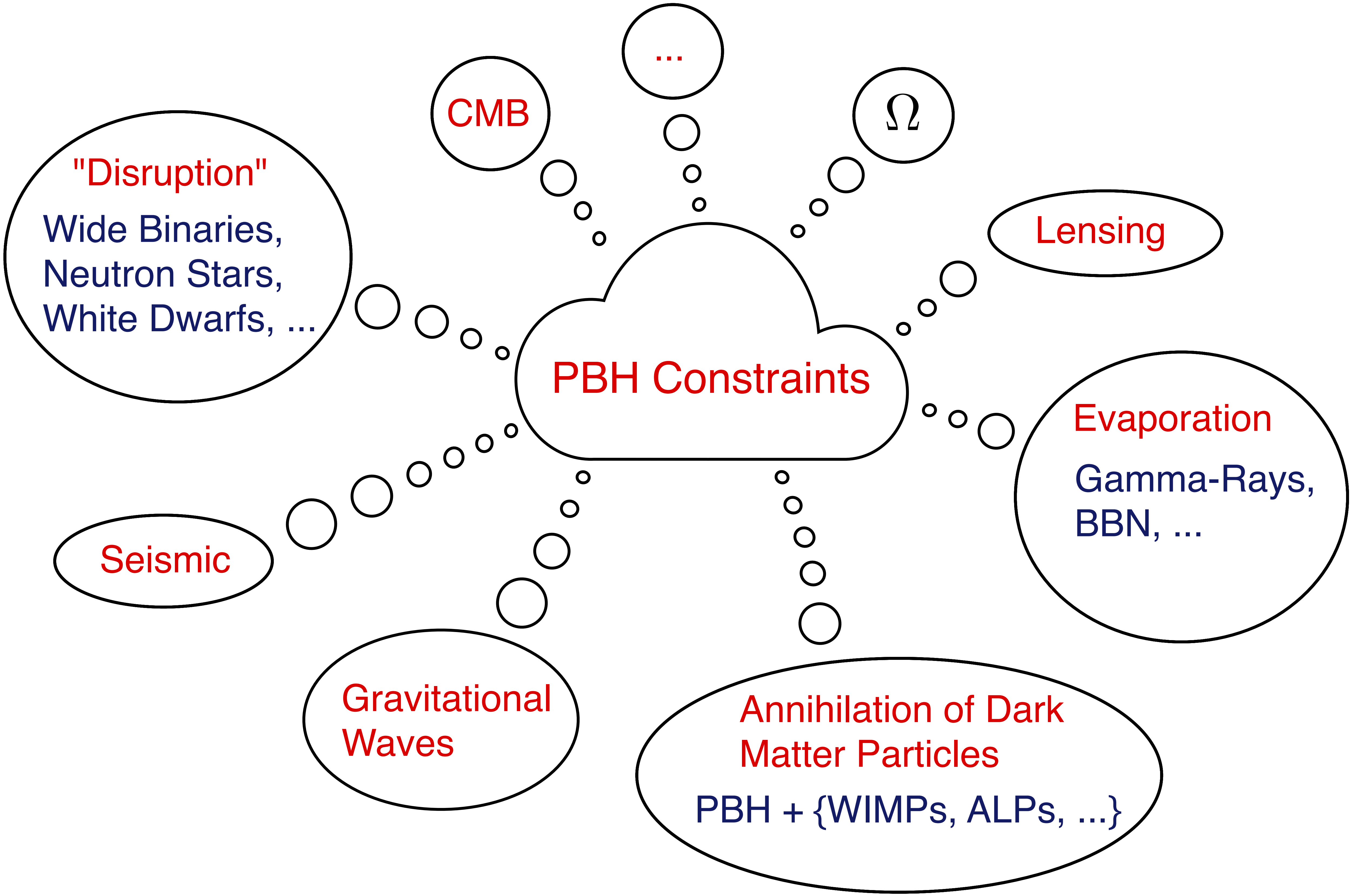

...
CMB
Ω
"Disruption"
Wide Binaries,
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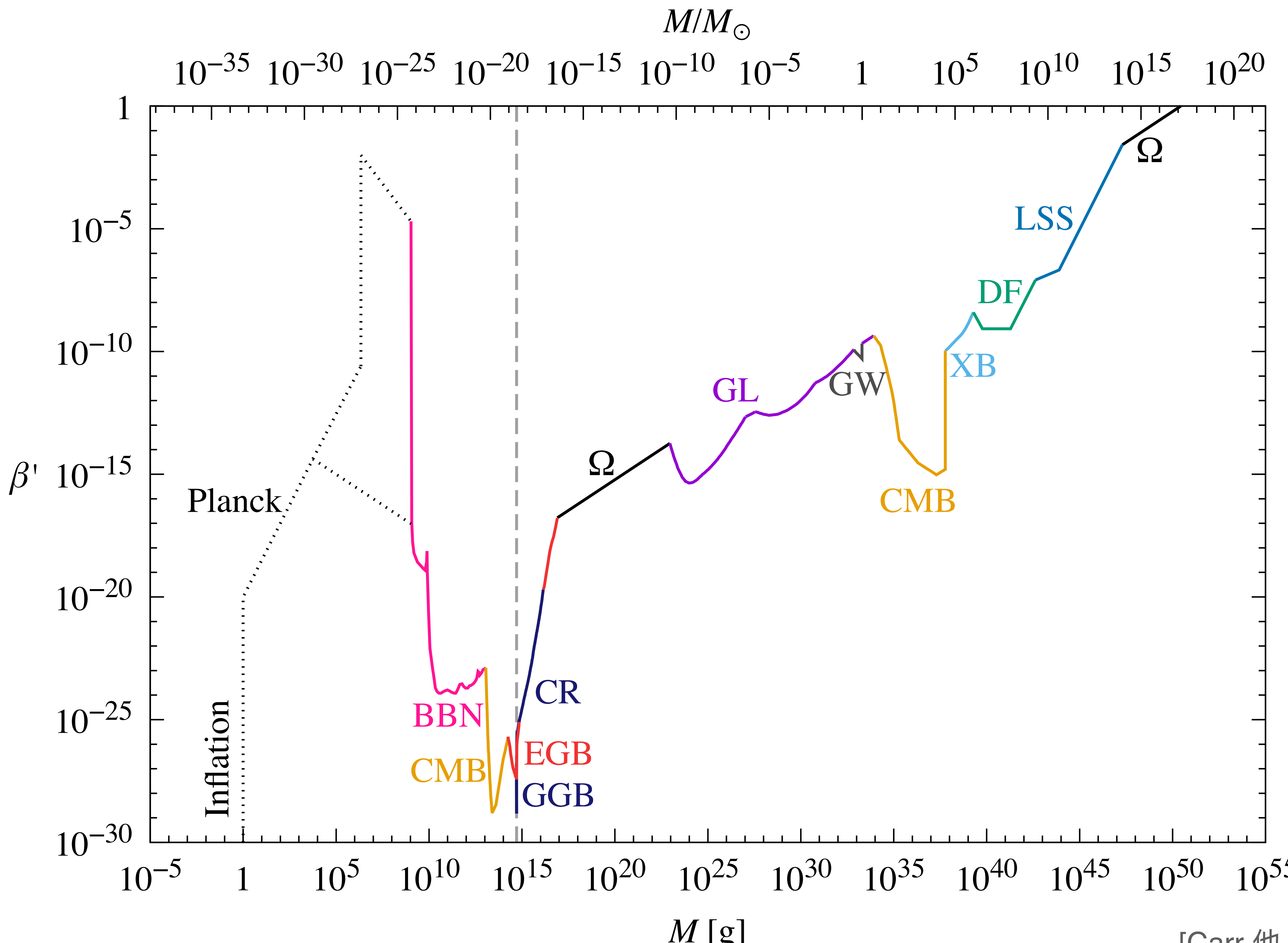
Lensing
PBH Constraints
Evaporation
Gamma-Rays,
BBN, ...
Seismic
Gravitational
Waves
Annihilation of Dark
Matter Particles
PBH + {WIMPs, ALPs, ...}

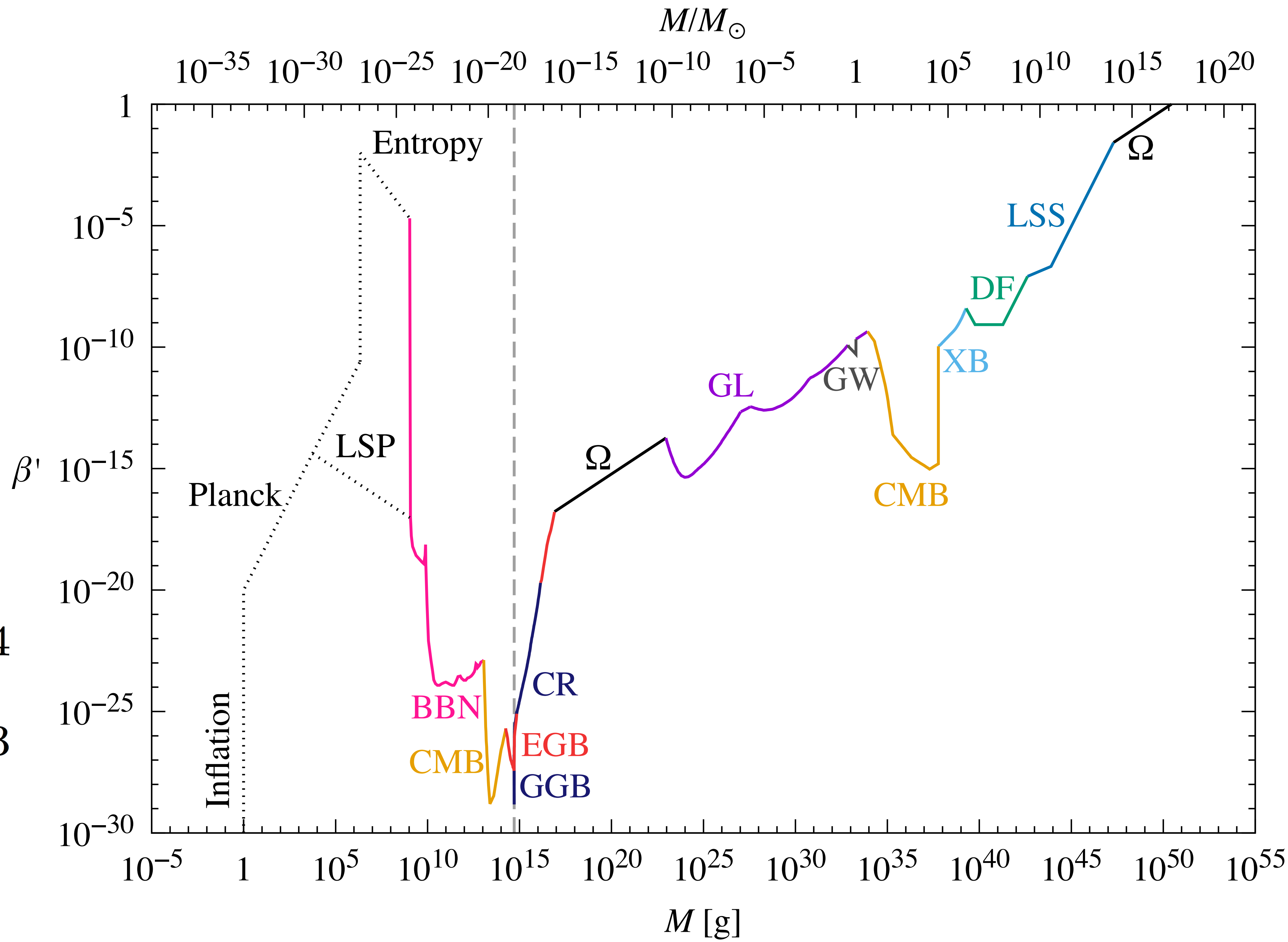
PBH Constraints at Formation



[Carr 他 2021]

PBH Constraints at Formation

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



[Carr 他 2021]

★ Note that

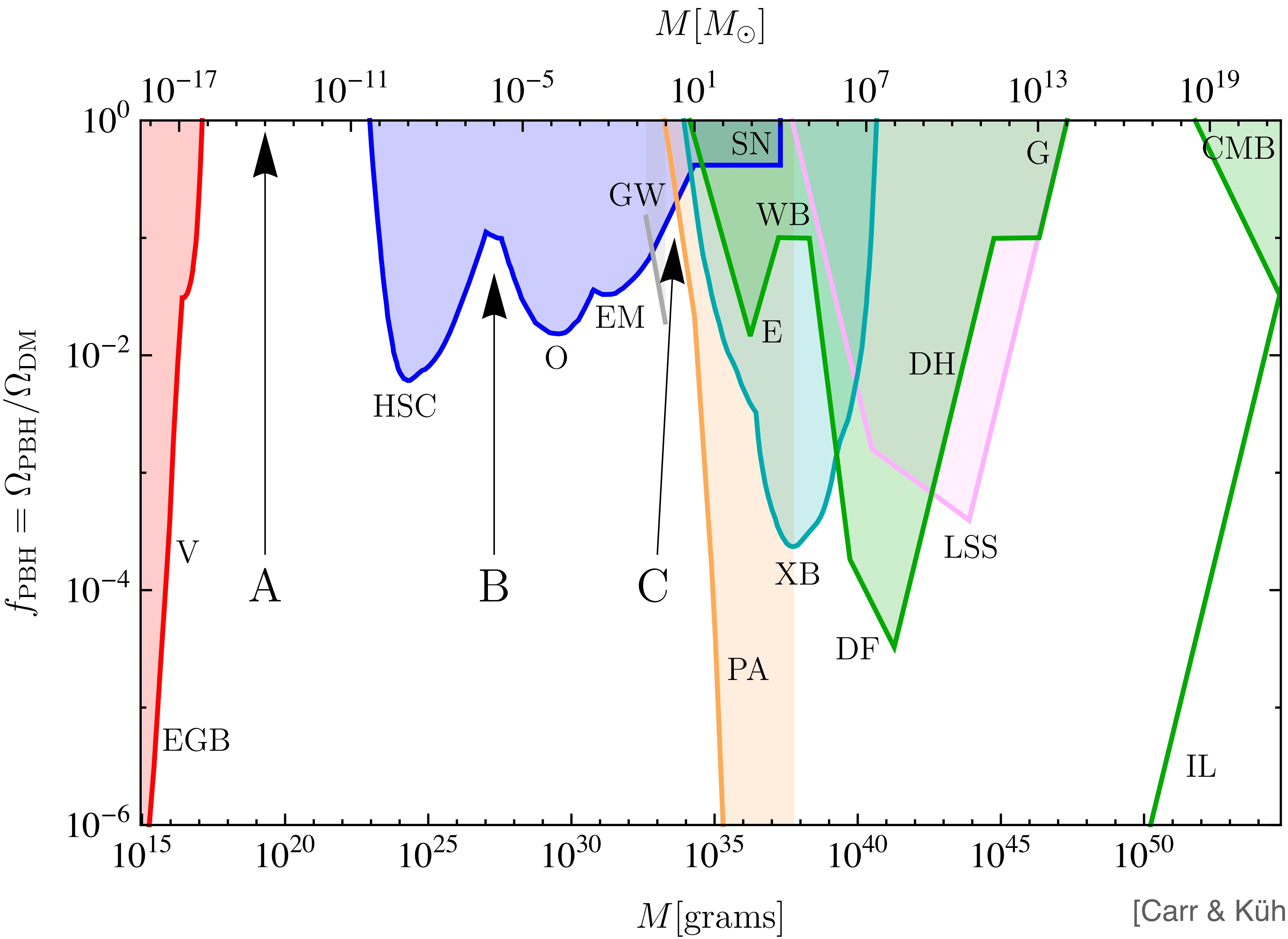
$$\rho_{\rm rad} \propto a^{-4}$$

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

and hence

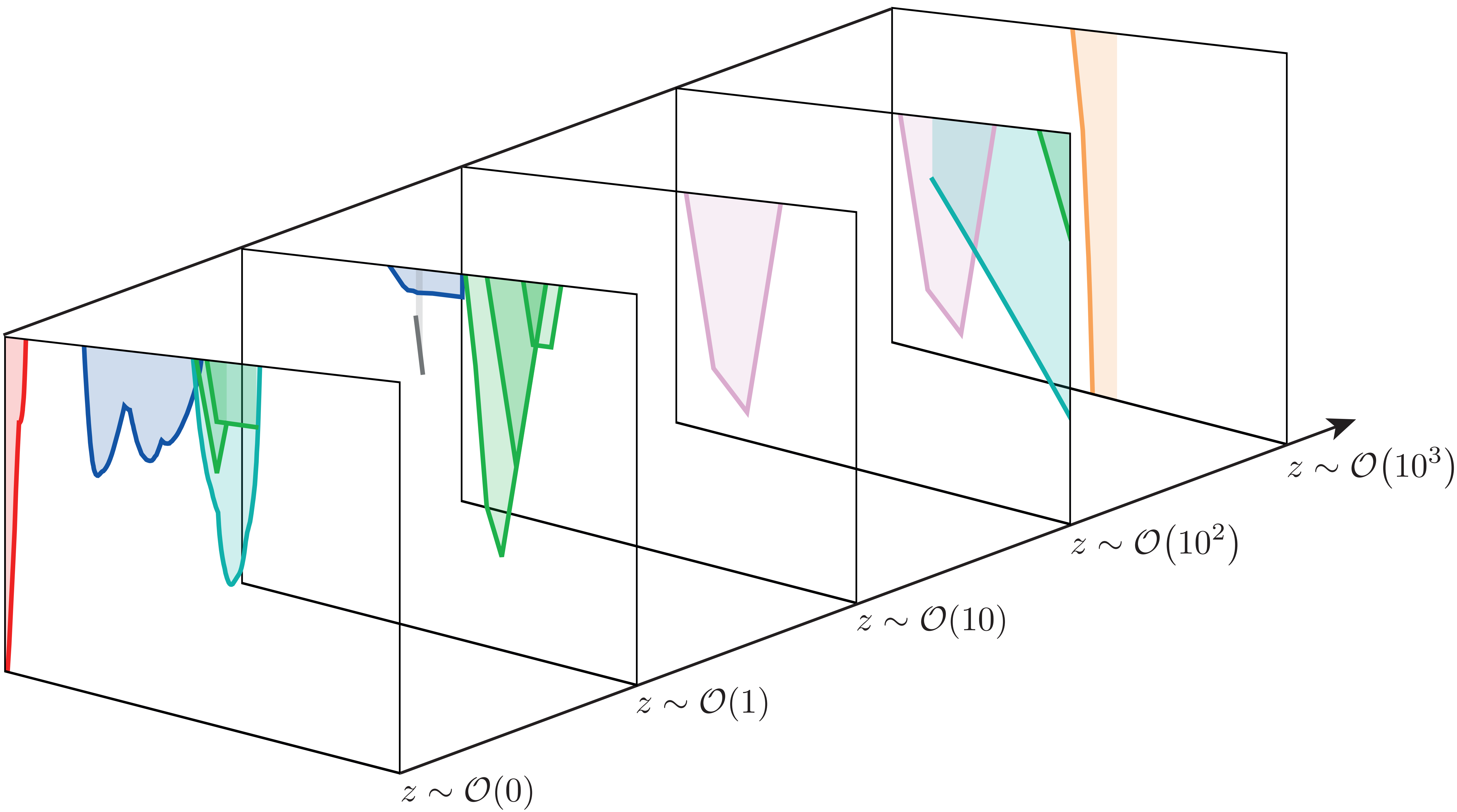
$$\Omega_{\rm PBH} \propto a$$

Current PBH Constraints



[Carr & Kühnel 2020]

PBH Constraints — Redshift Dependence



[Carr & Kühnel 2020]

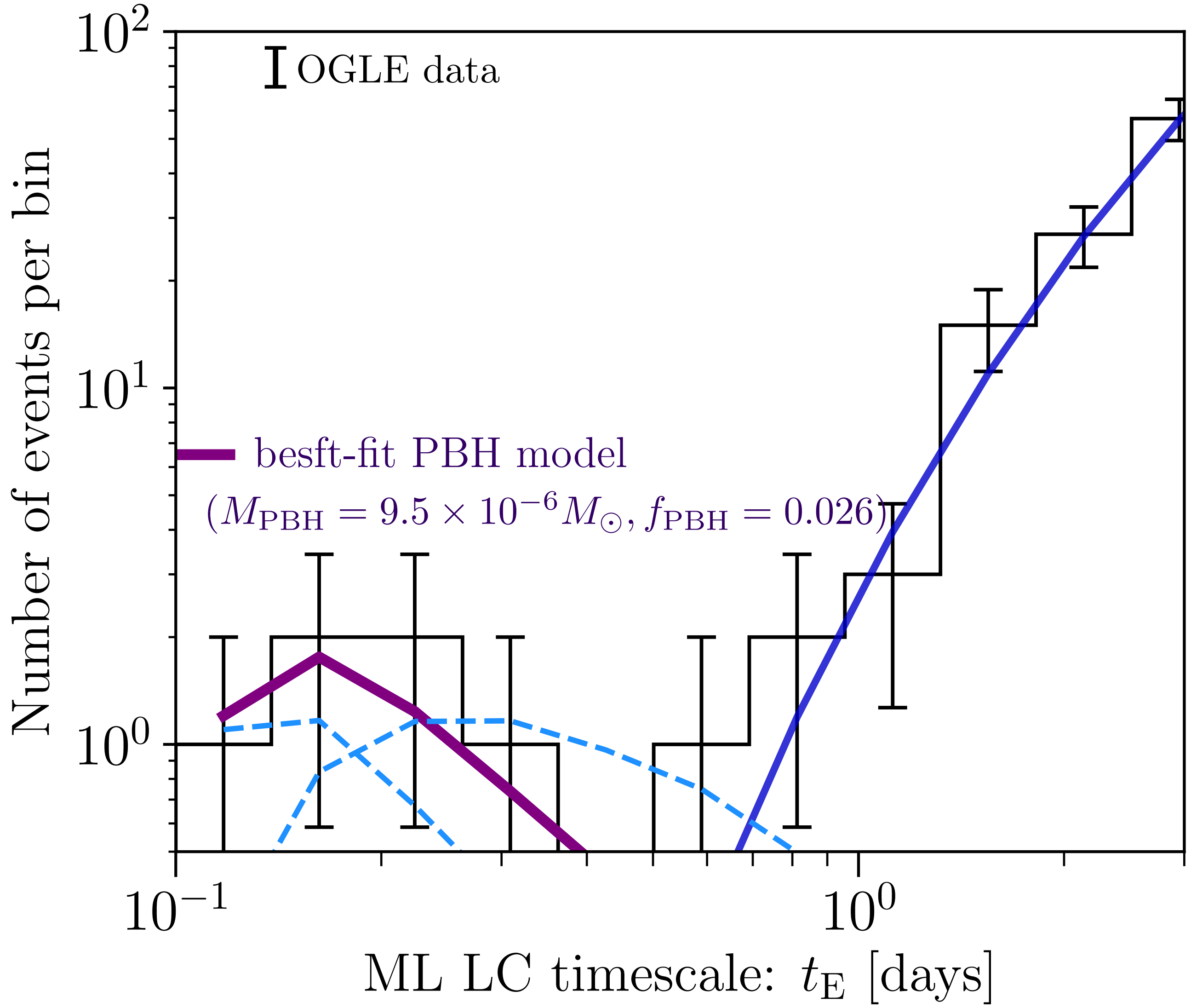
Observational Hints for Primordial Black Holes

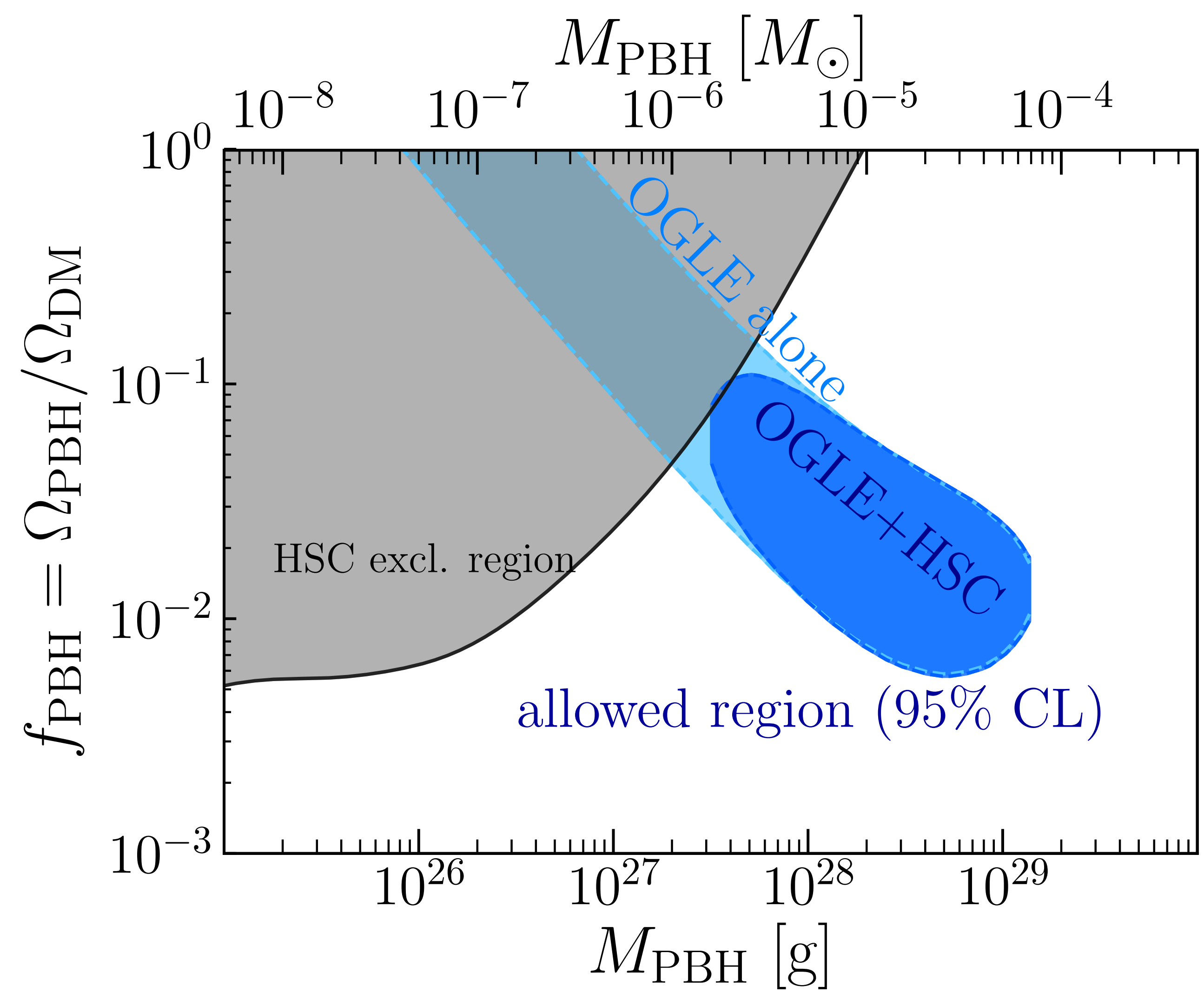
Evidence?

Observational ~~Hints~~
for Primordial Black Holes

Planetary-Mass Microlensing

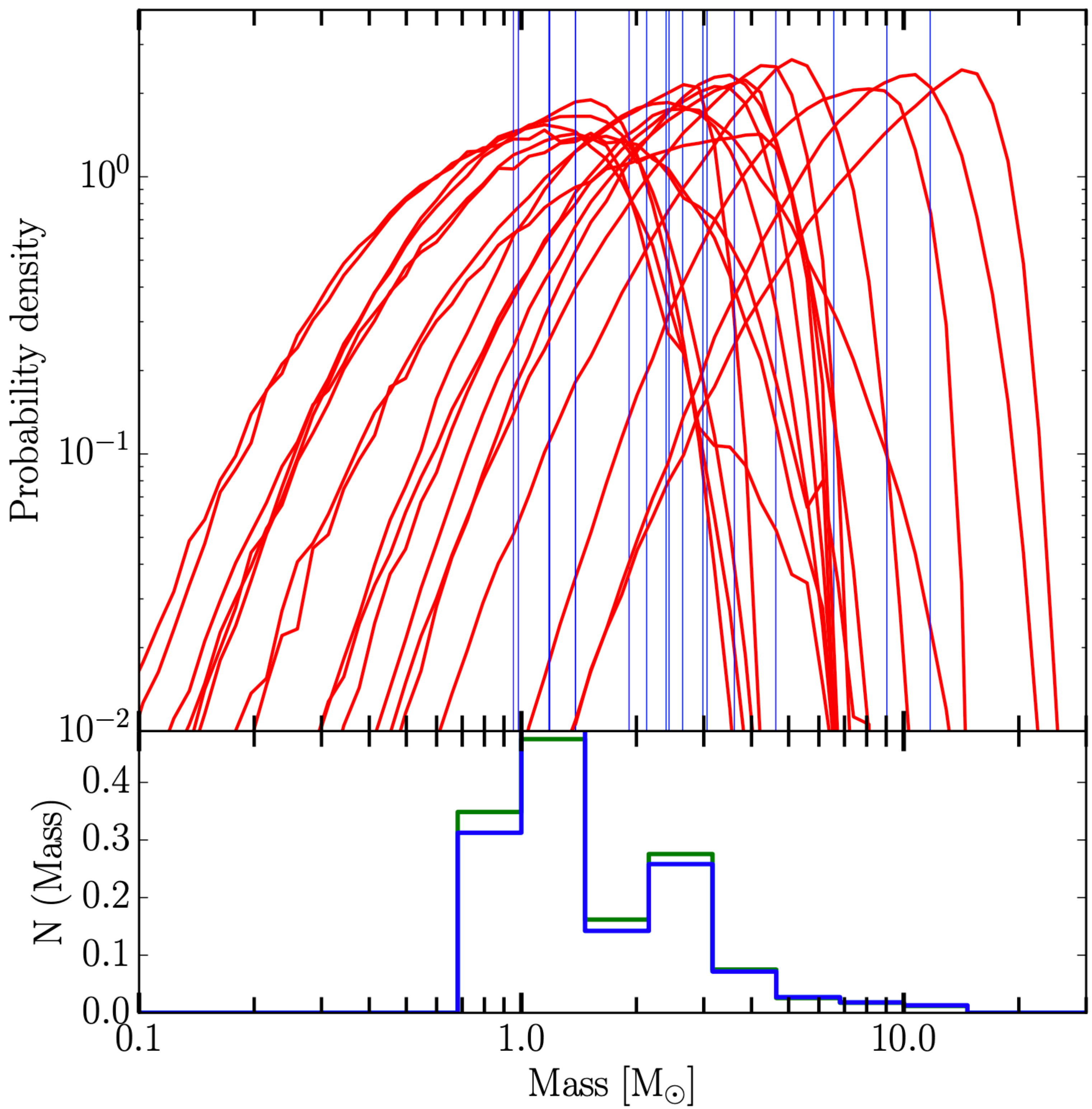
- OGLE detected a particular population of microlensing events:
  - 0.1 - 0.3 days light-curve timescale - origin unknown!
    Could be free-floating planets... or PBHs!





[Niikura *et al.* 2019]

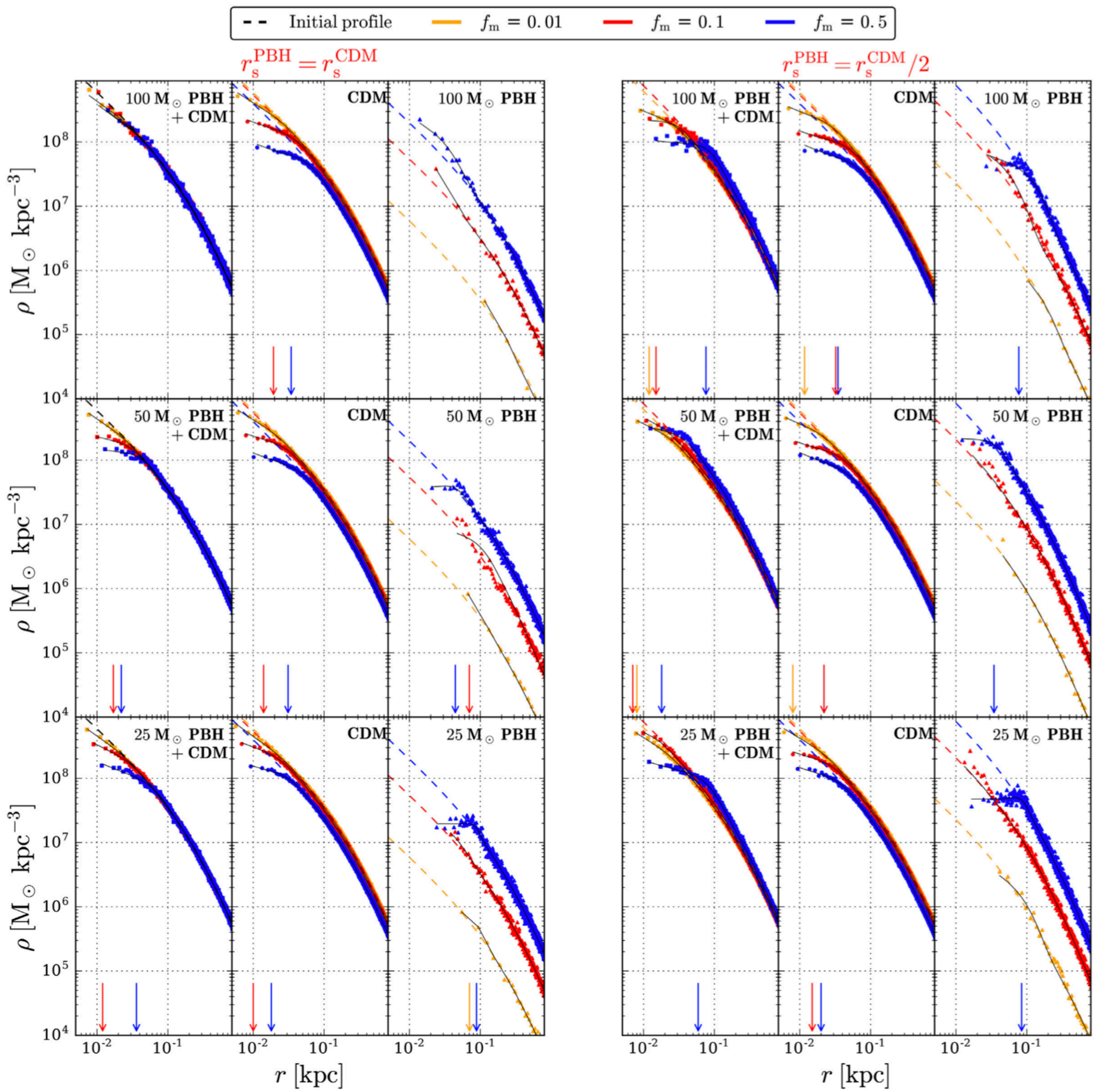
Excess of Lenses in Galactic Bulge



- 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]

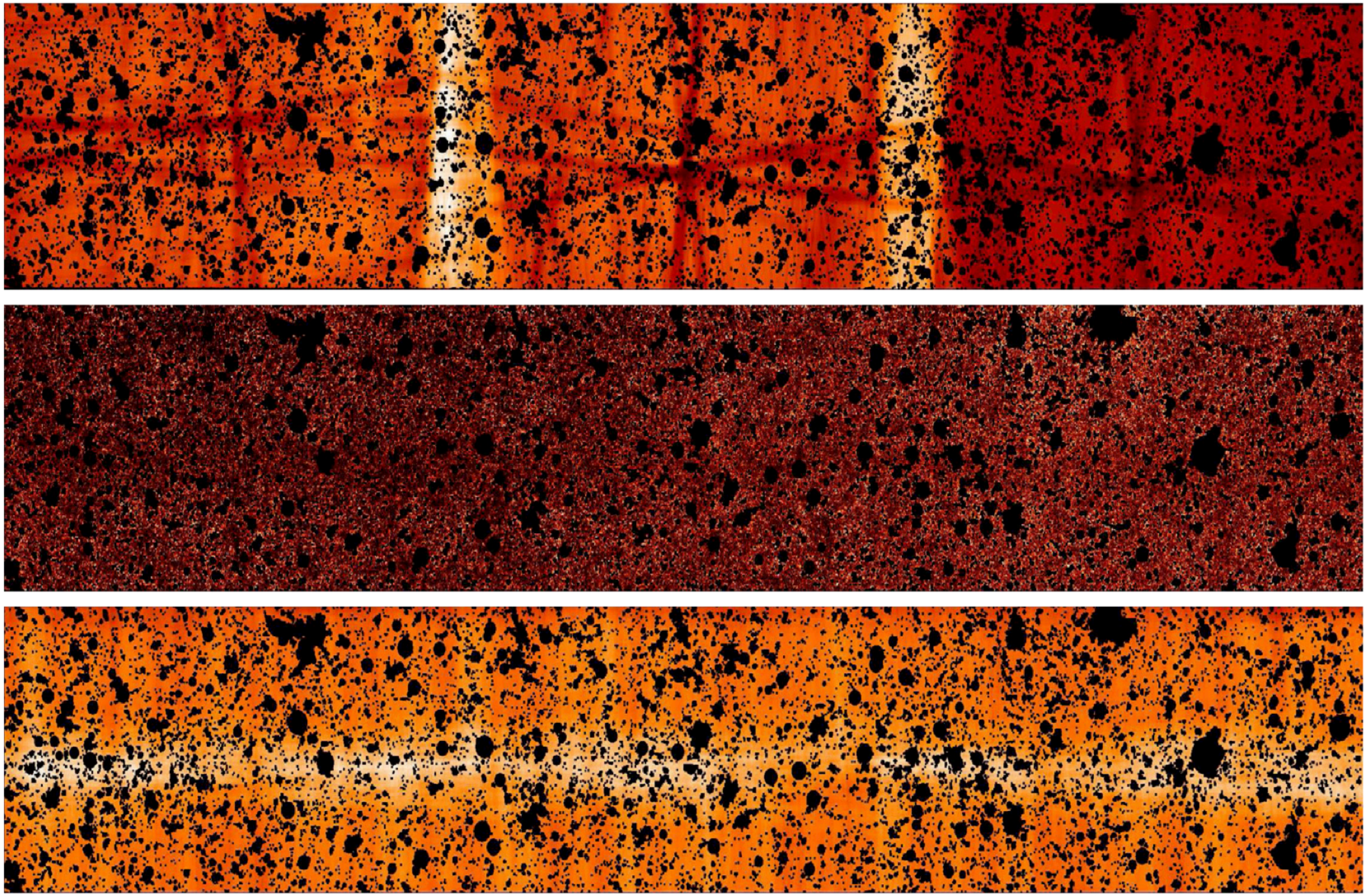
Ultra-faint Dwarf Galaxies



[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

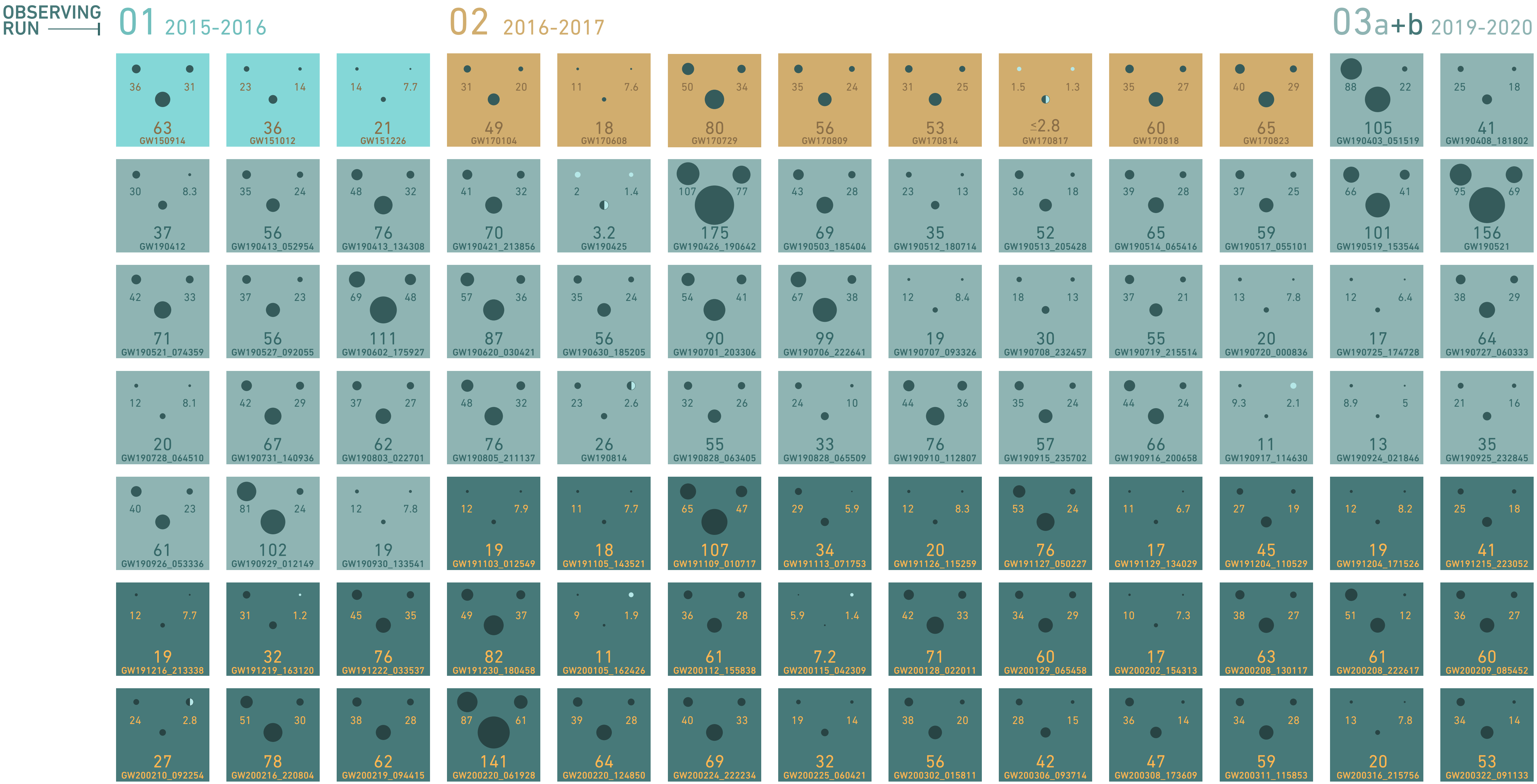


[Capelluti *et al.* 2013]

★ PBHs generate early structure and respective backgrounds

GRAVITATIONAL WAVE **MERGER** DETECTIONS

SINCE 2015



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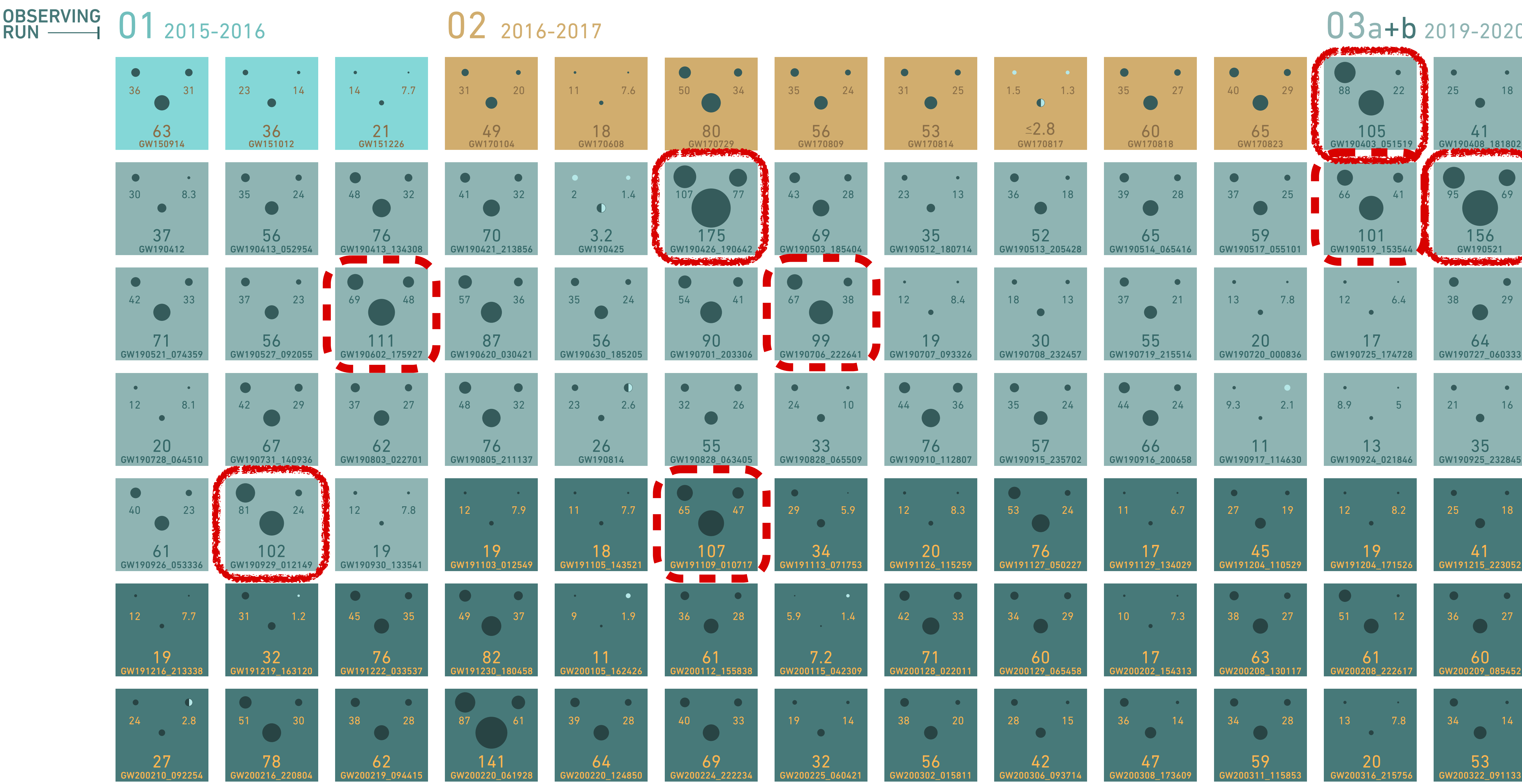
GRAVITATIONAL WAVE **MERGER** DETECTIONS

→ SINCE 2015



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

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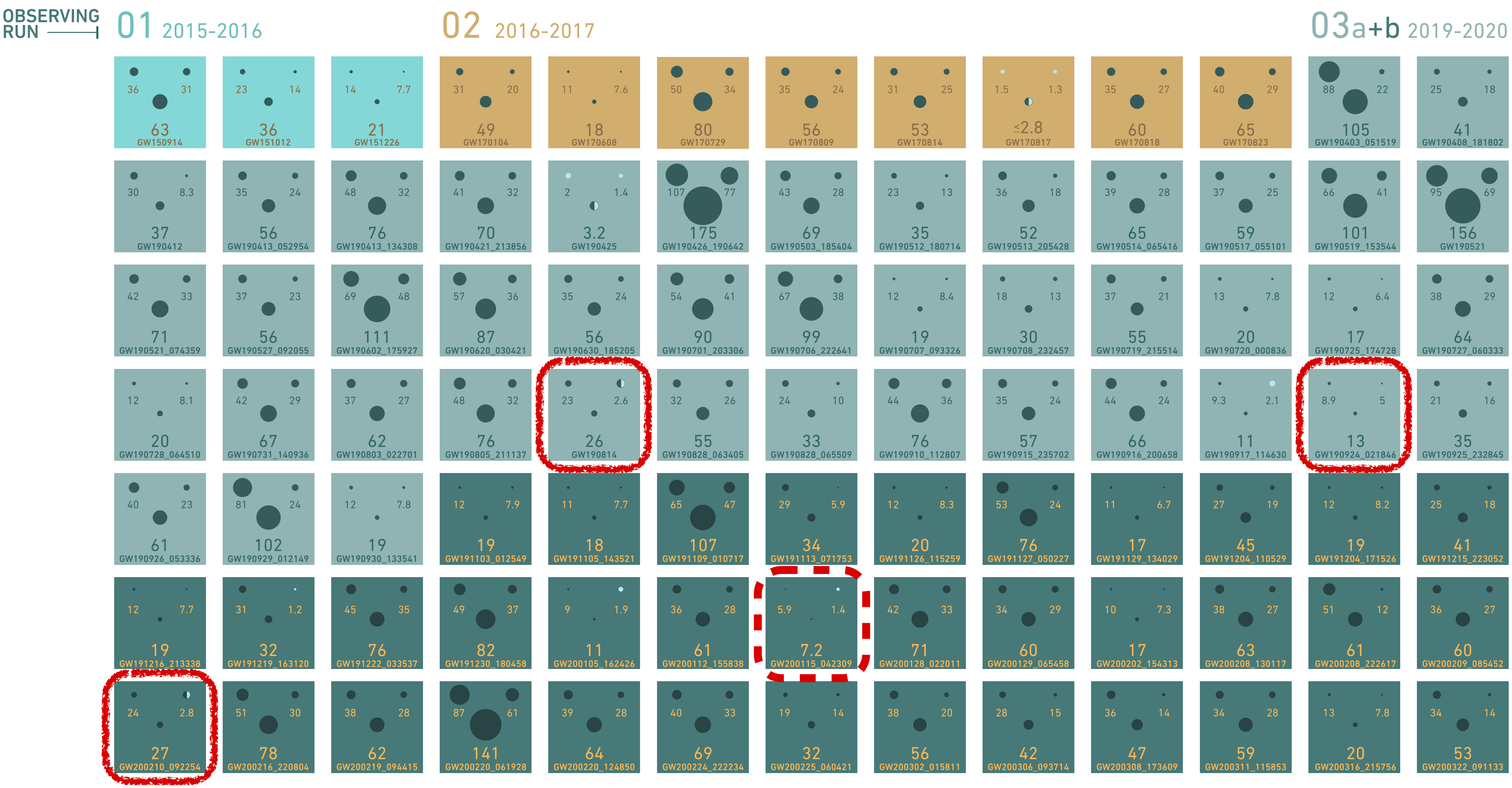
GRAVITATIONAL WAVE **MERGER** DETECTIONS

SINCE 2015

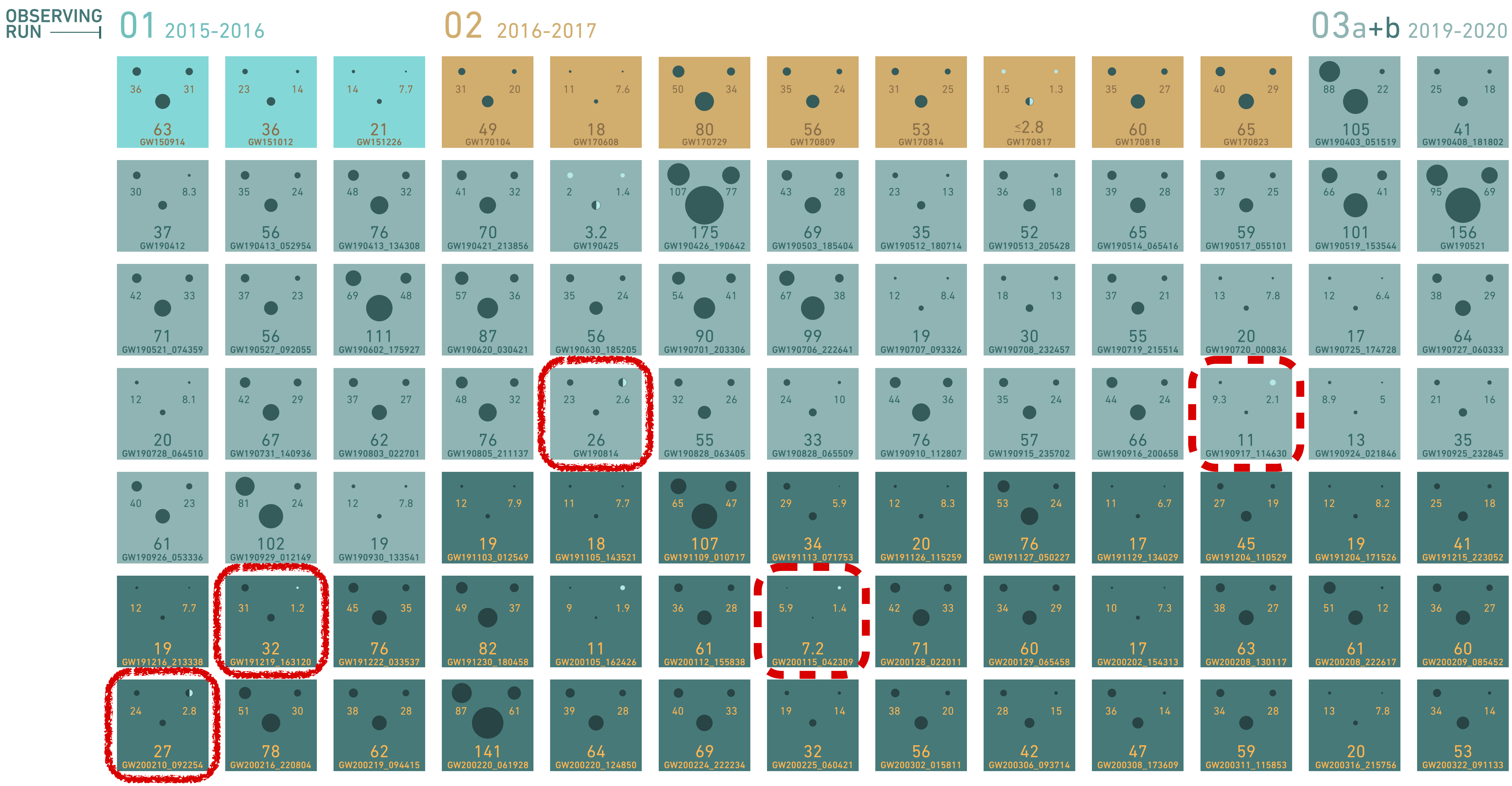


★ Black hole progenitors in the lower mass gap (i.e. between 2 and 5 $M_{\odot}$)

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

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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!

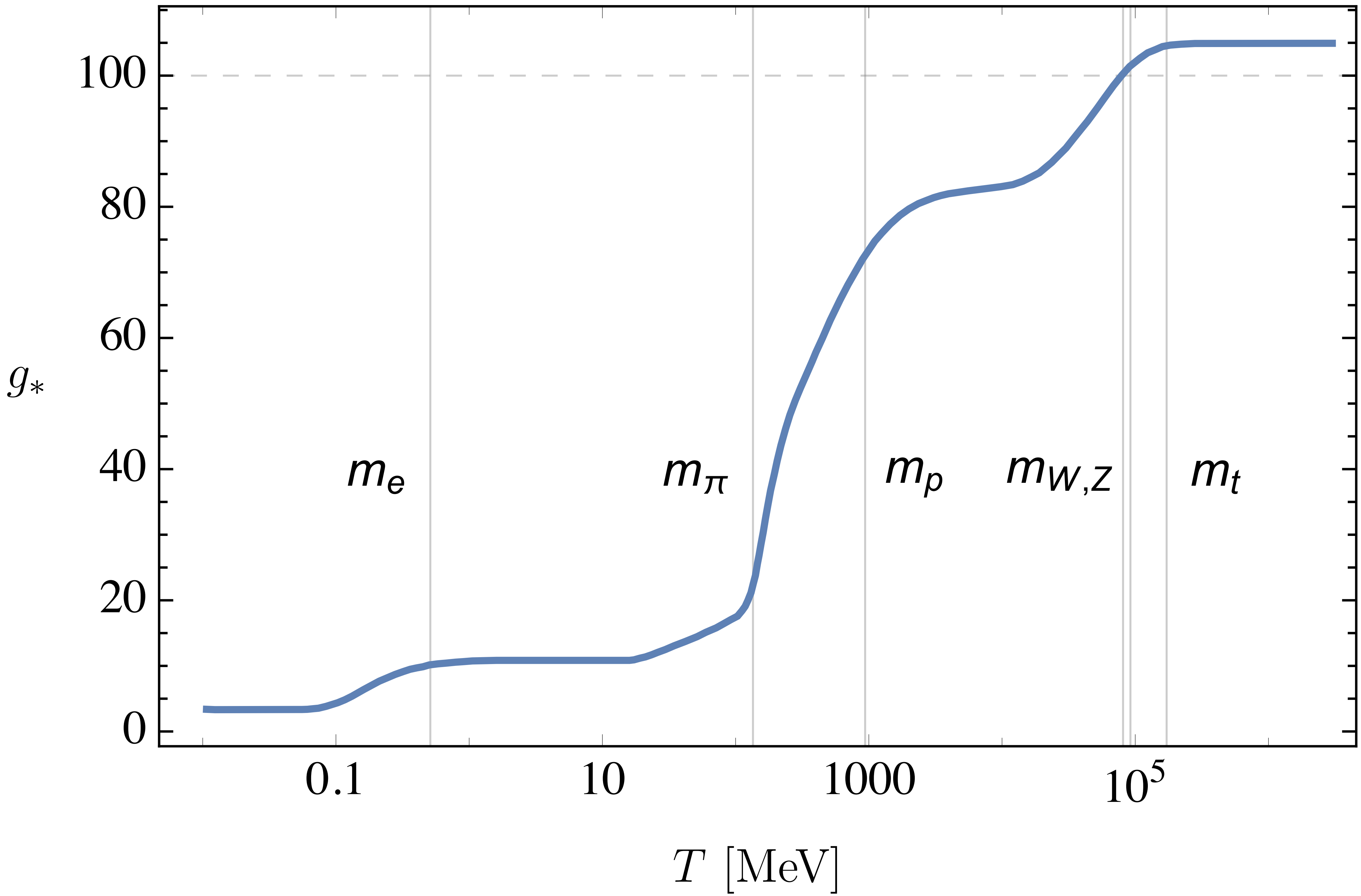
Further Support / Evidence for PBHs

- 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

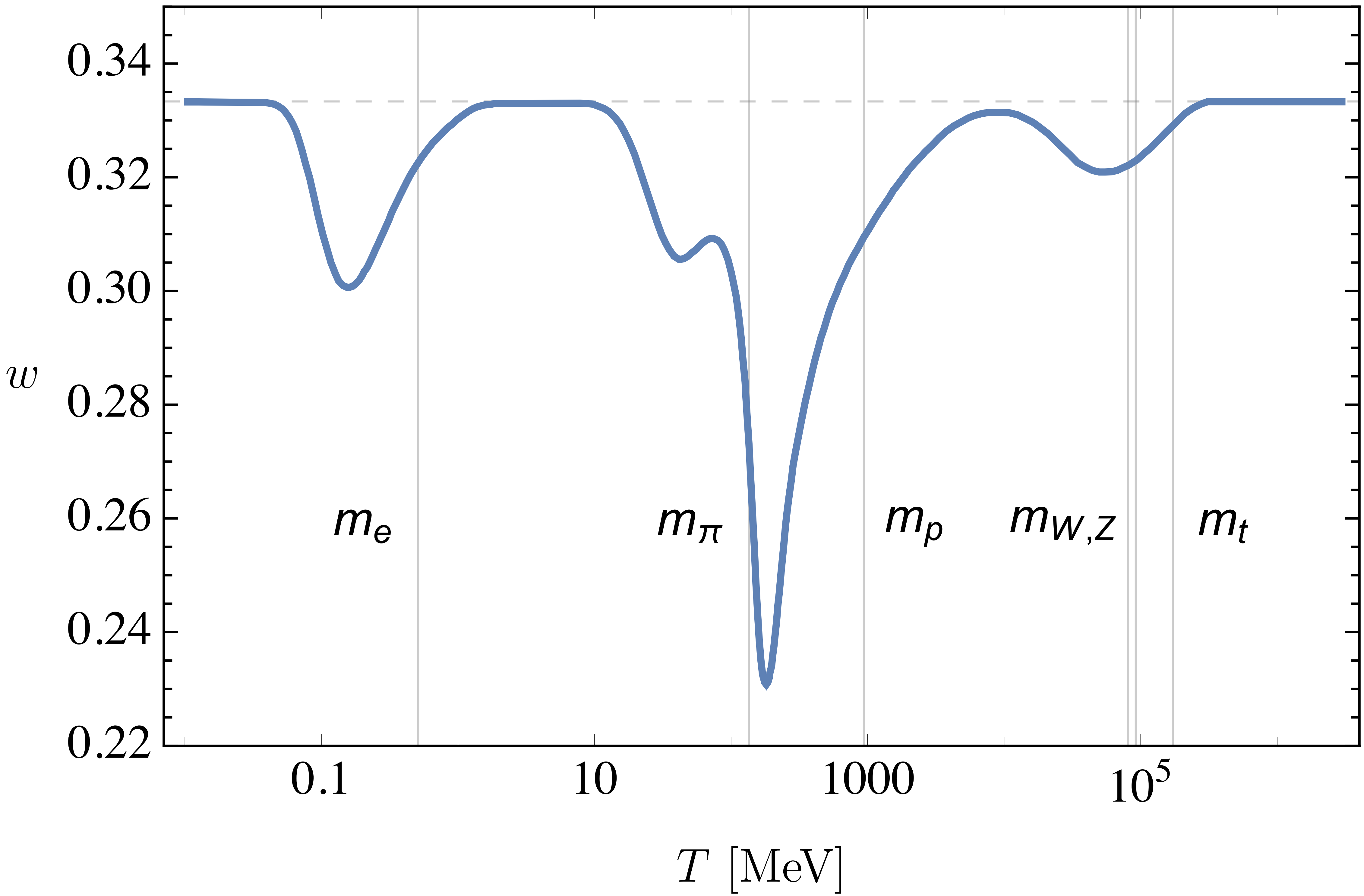
Thermal History of the Universe

★ Changes in the relativistic degrees of freedom:



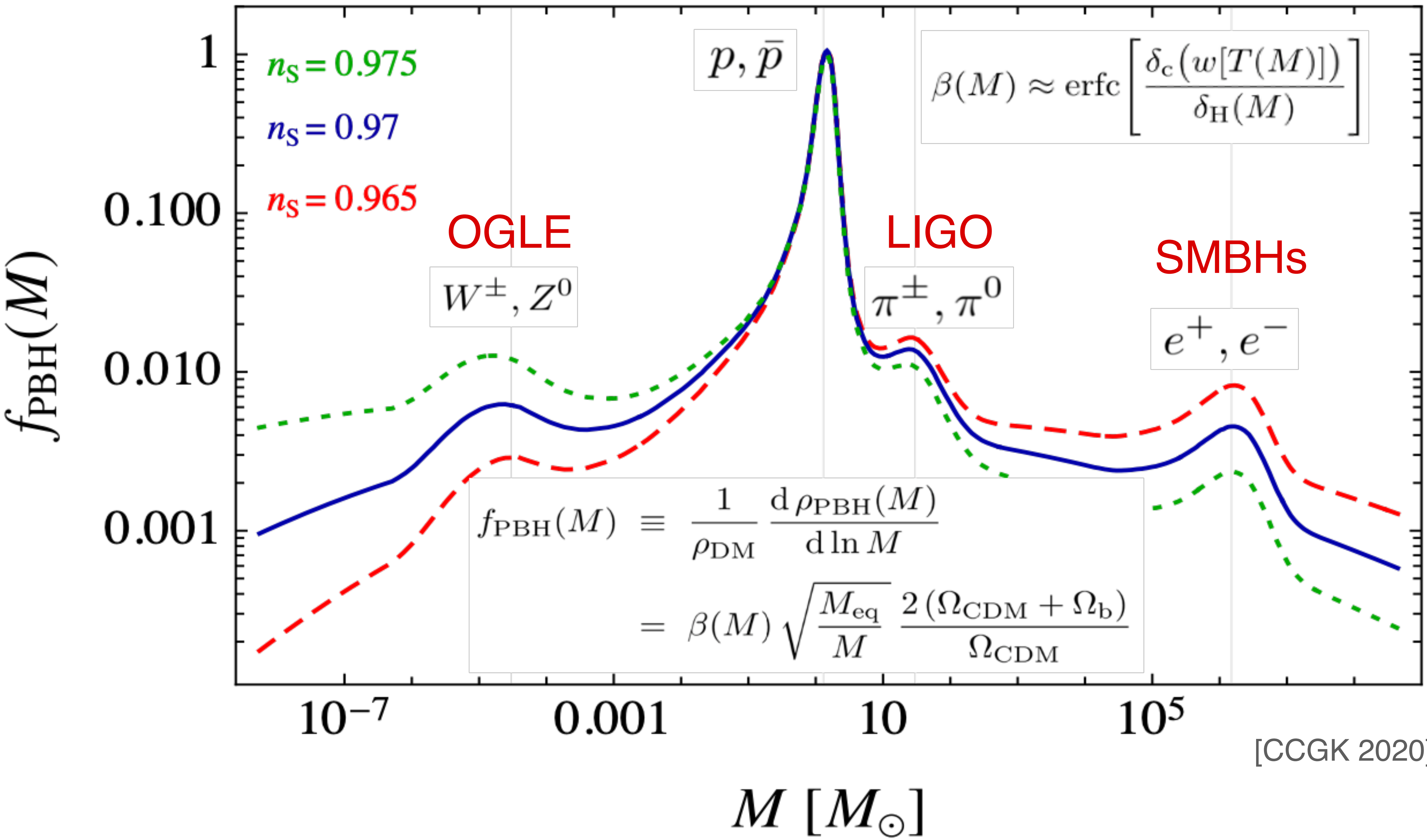
Thermal History of the Universe

★ 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

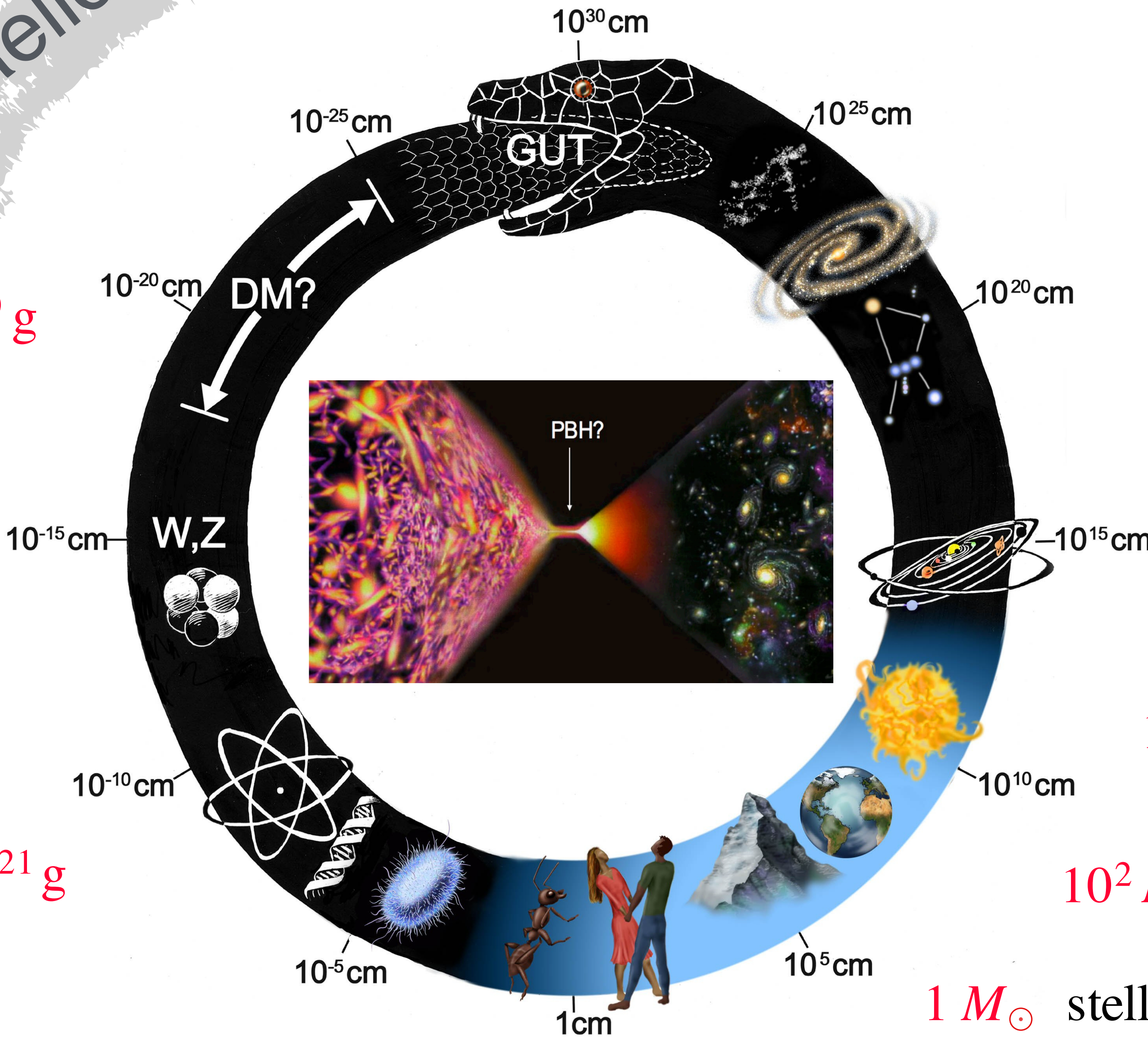
$10^{12}\,M_\odot$ SLAB

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

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

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

$1\,M_\odot$ stellar



[Figure from Abrams & Primack 2012]

Addendum

Primordial Black Holes from Confinement

work with Dvali & Zantedeschi

Important Issues

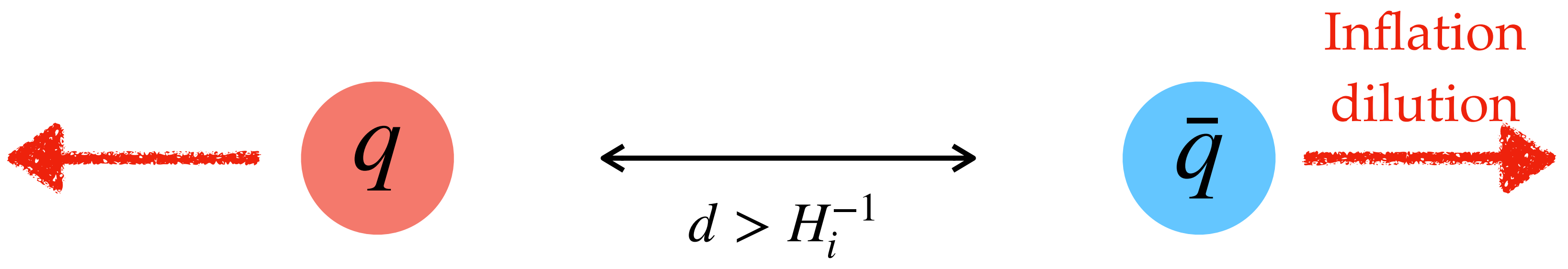
- The standard approach of PBH formation has two main issues:
  - In order to have a given percentage of PBH dark matter requires exponential fine-tuning.
  - PBH formation happens in the strong-coupling regime.

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.



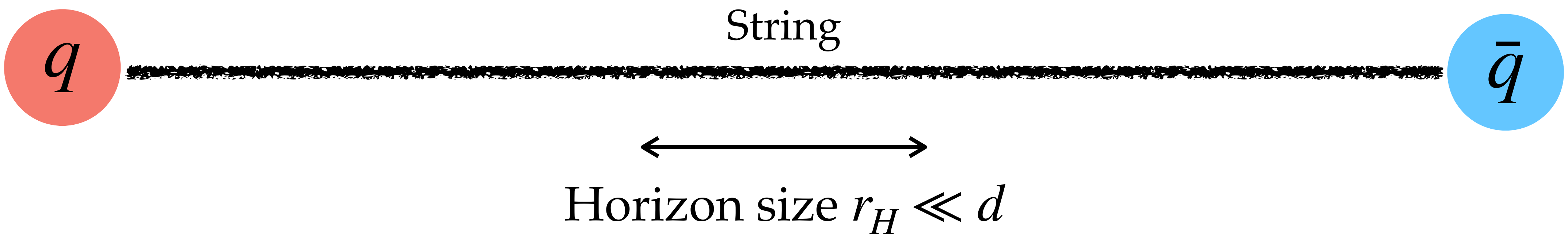
★ Focus on a simple pair case.

★ 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, $M_q/\Lambda_c \gg 1$



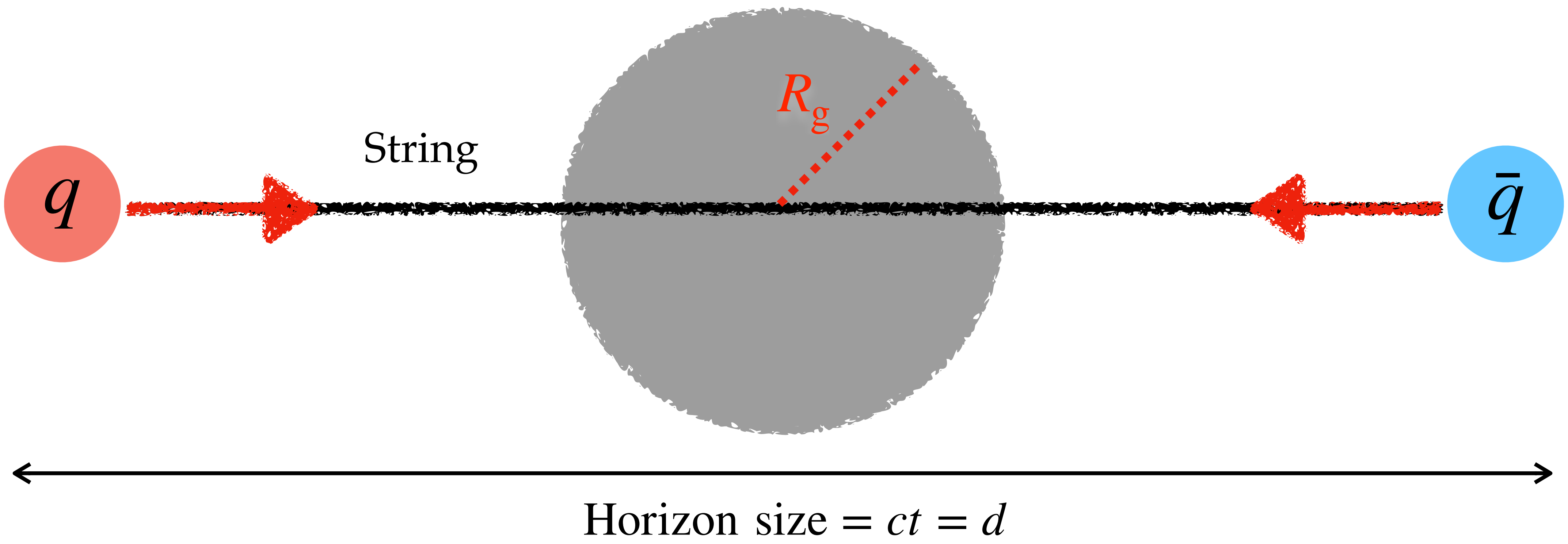
★ Flux tubes form connecting quark/anti-quark pairs.

★ 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 $M_q/\Lambda_c \gg 1$.

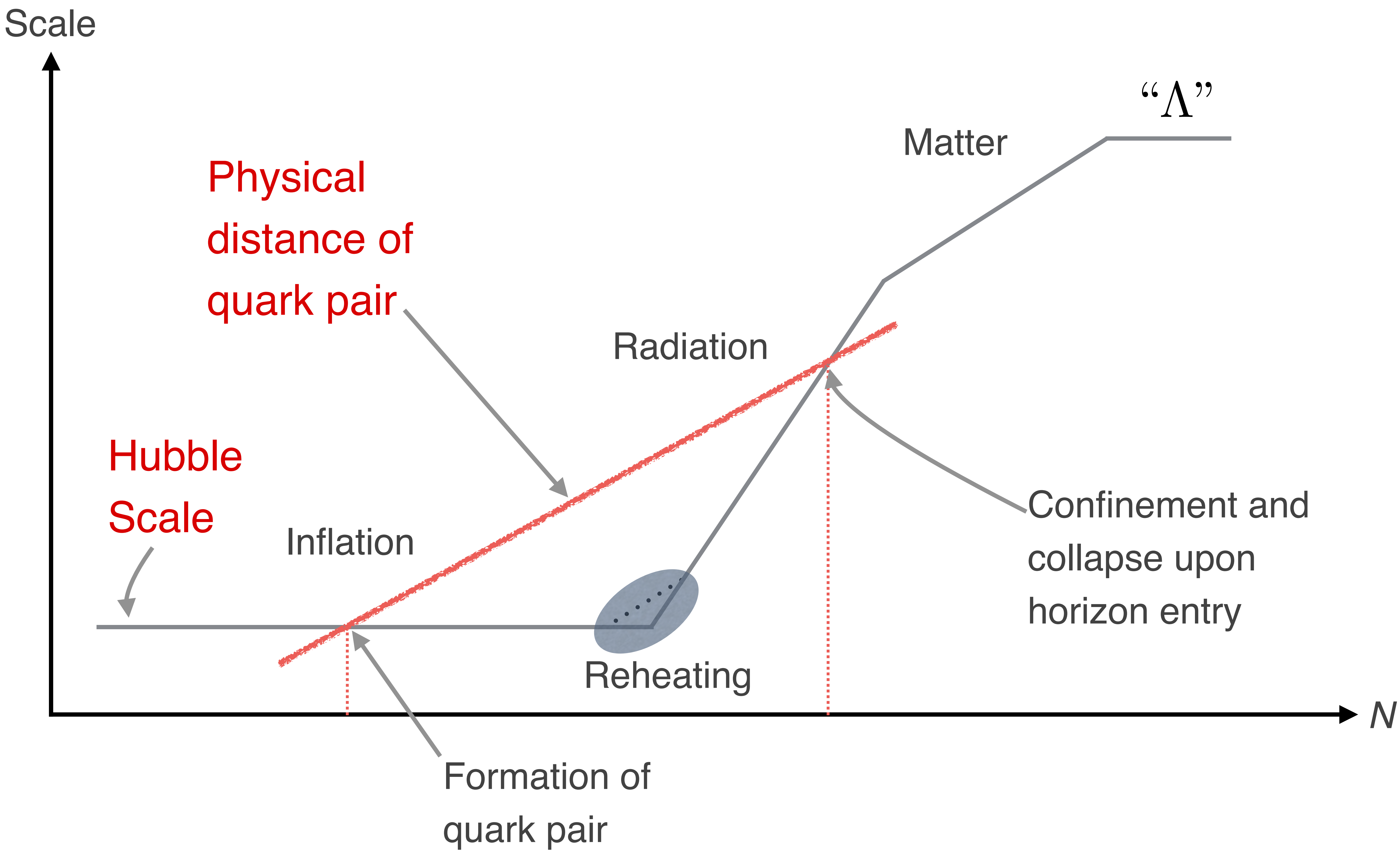
Confinement Formation Mechanism

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



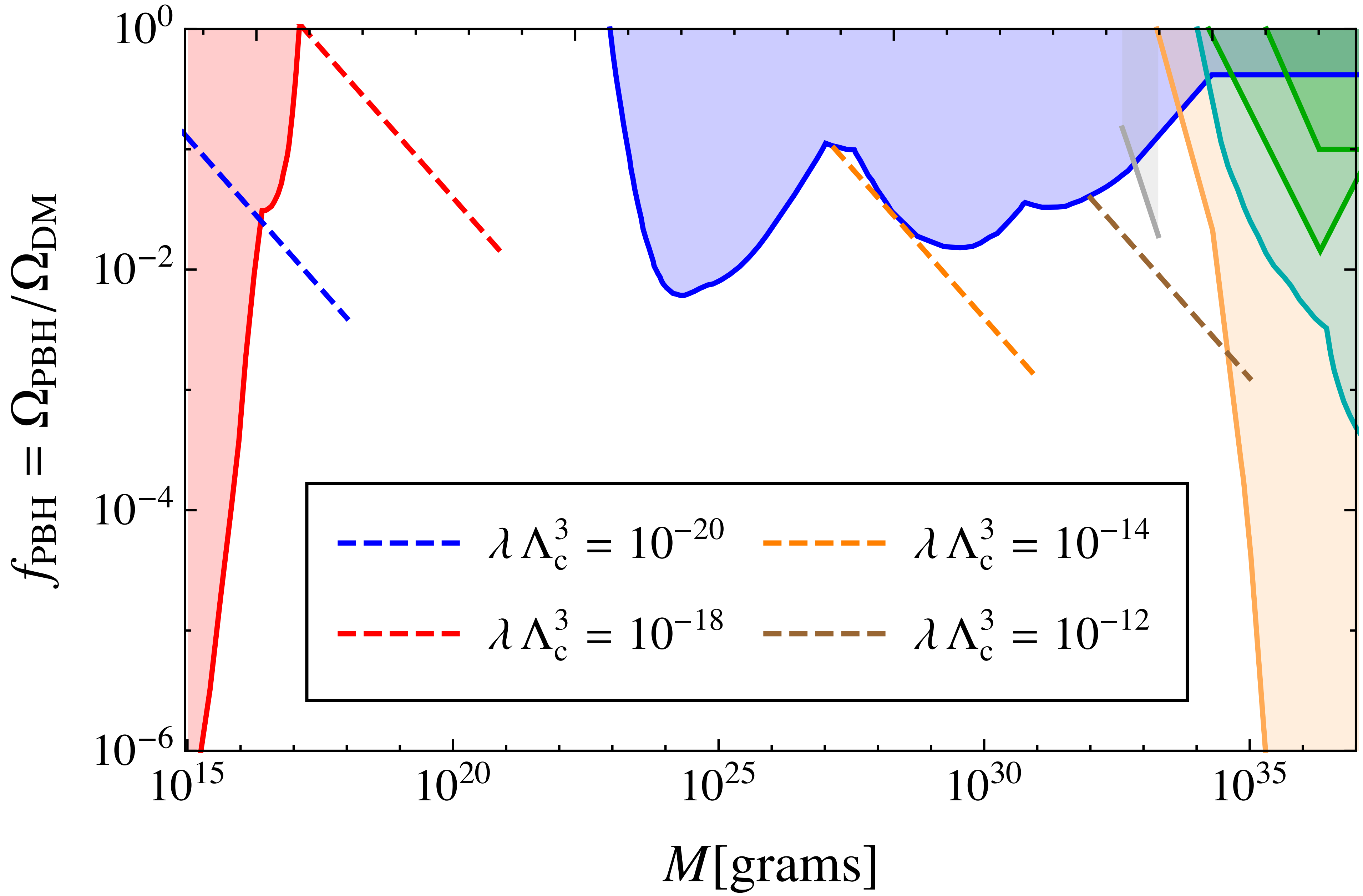
- ★ Acceleration of the quarks $a = \Lambda_c^2 / m_q$ quickly leads to their ultra-relativistic motion.
- ★ The energy stored in the string is $E \simeq \Lambda_c^2 \, t \simeq M_g, \quad R_g \gg \Lambda_c^{-1}$.
- ★ PBHs from inflationary overdensities are heavier by a factor $\sim \Lambda_c^2$.

Formation Scales



Dark Matter from Confinement

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

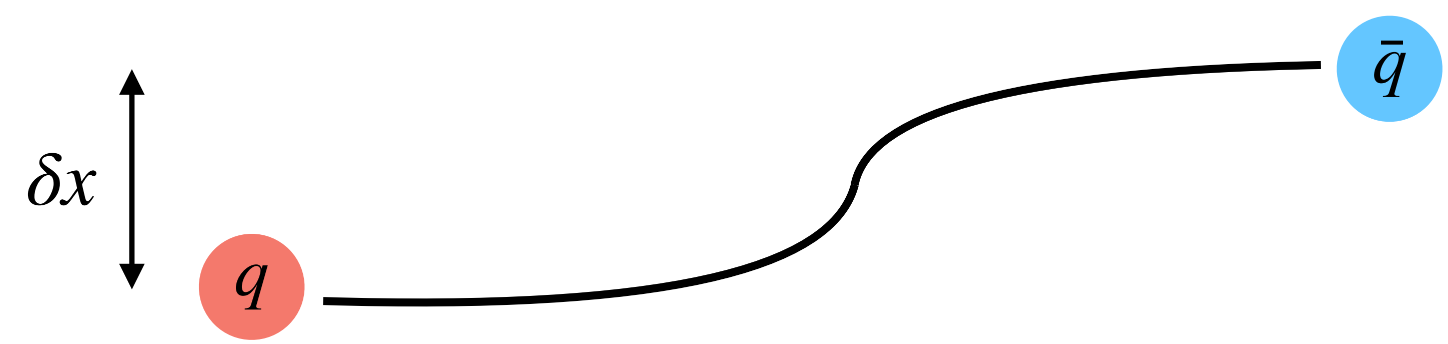


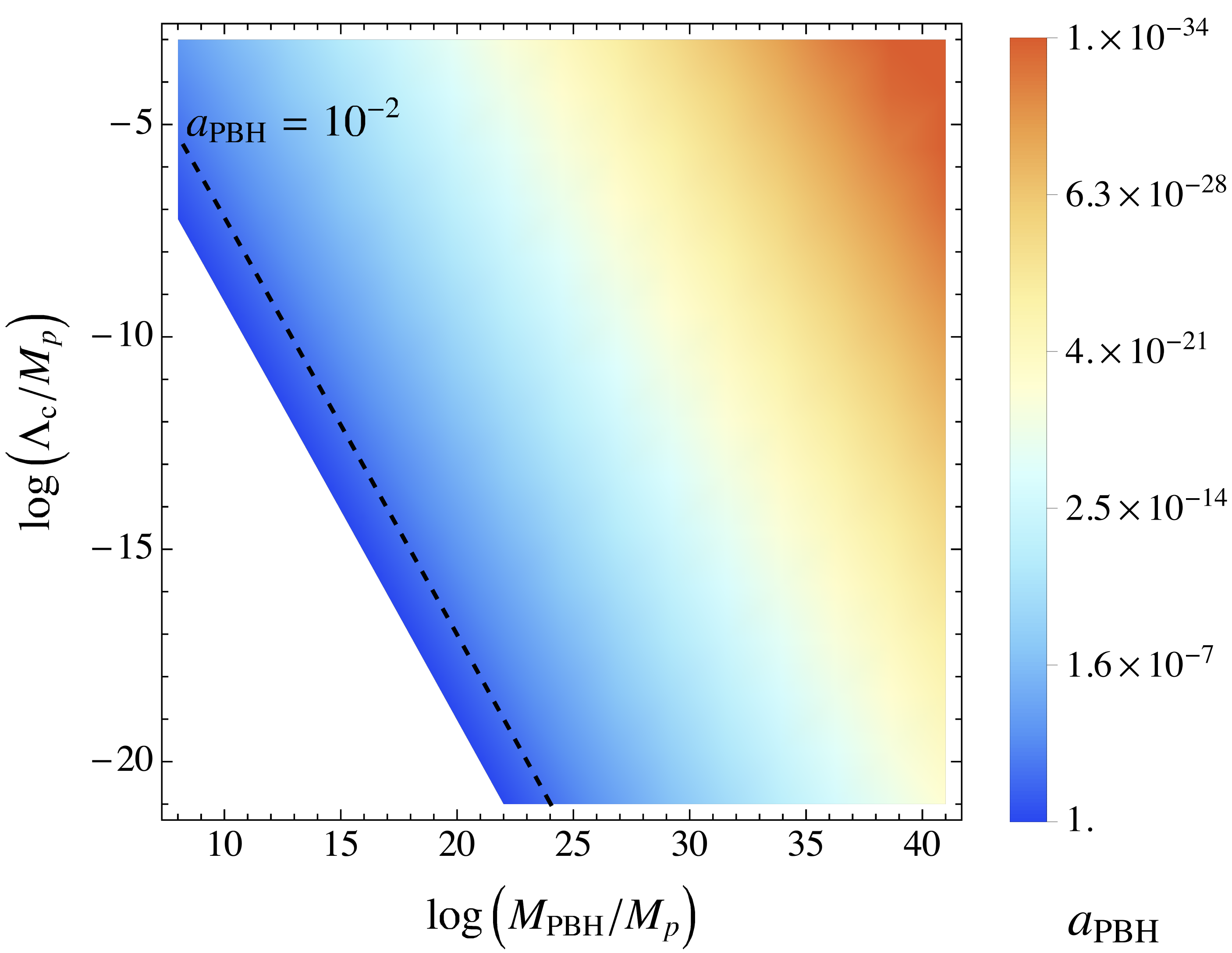
★ Find: $f_{\rm PBH} \equiv \frac{\rho_{\rm PBH}(t)}{\rho_{\rm CDM}(t)} = \frac{32\pi}{3}\lambda\Lambda_c^3\left(\frac{M_{\rm PBH}}{M_{\rm eq}}\right)^{-1/2}$

High-Spin Subsolar PBHs

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

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

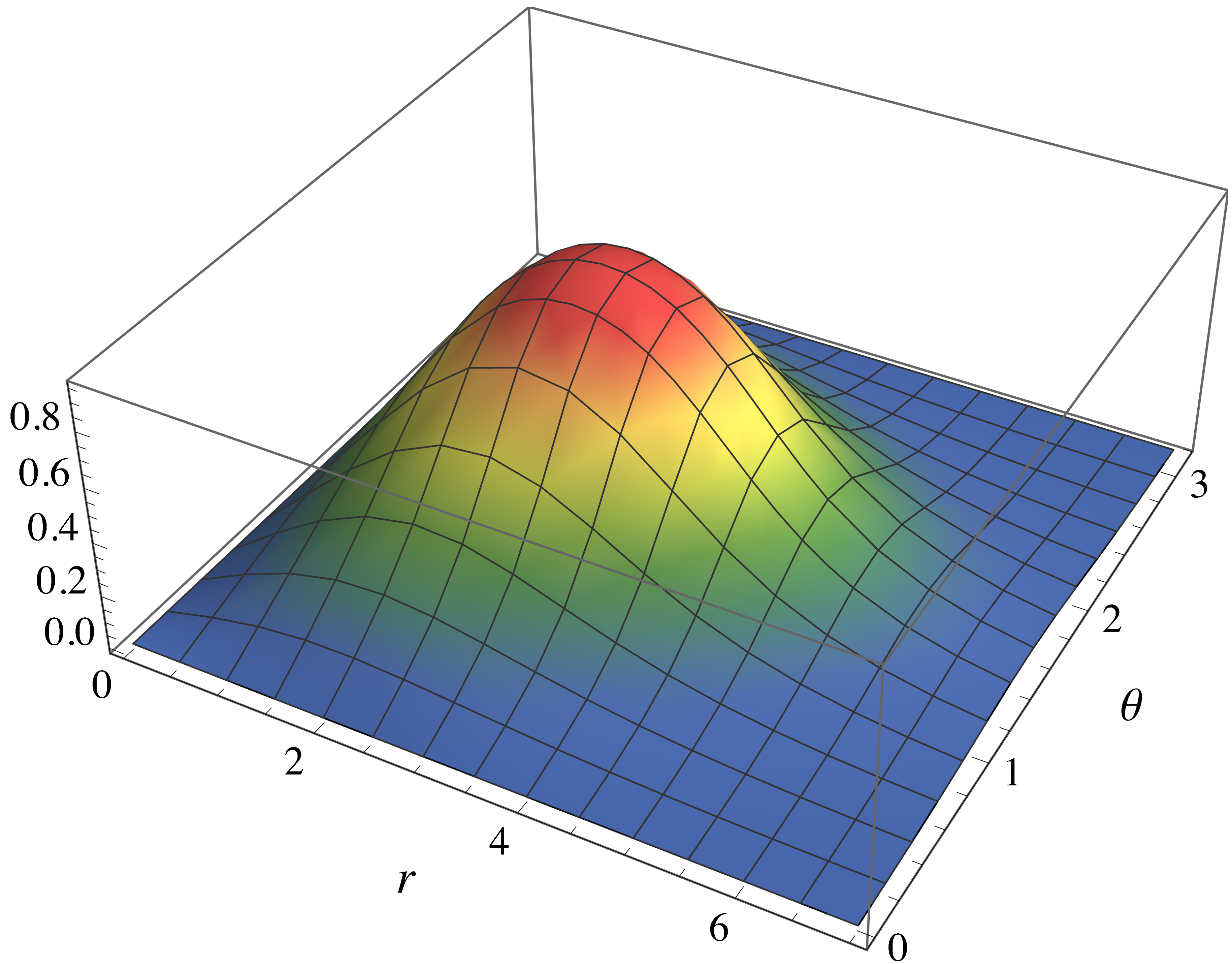




★ This leads to potentially significant spin:

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

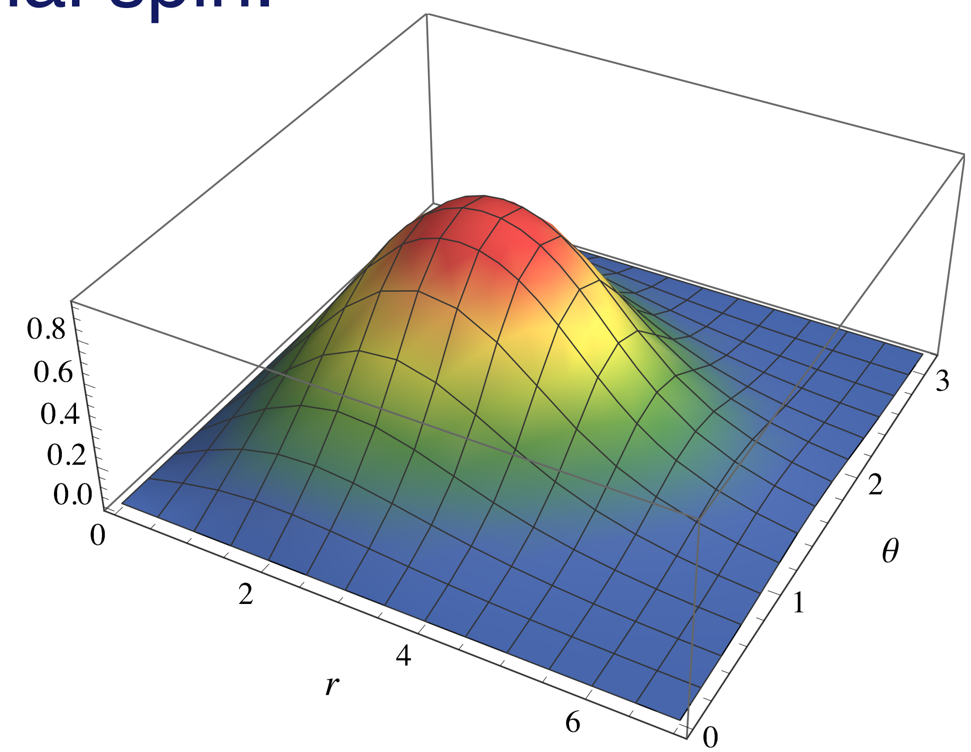
Formation of Vortices



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



[Dvali, Kühnel, Zantedeschi 2021]

- 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

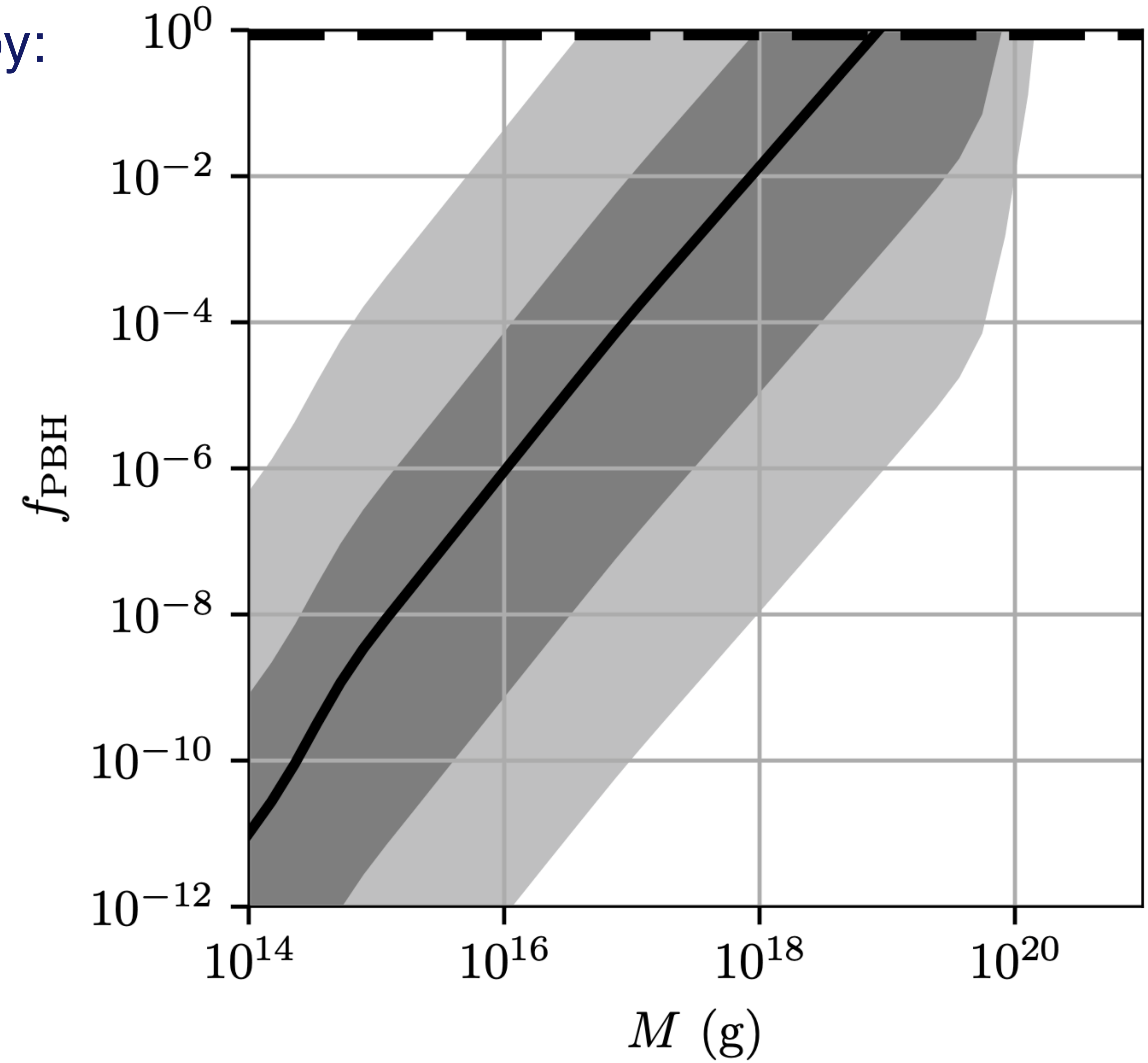
- May constraints rely on rather on uncertain, restrictive, simplistic or even incorrect assumptions!

  → 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

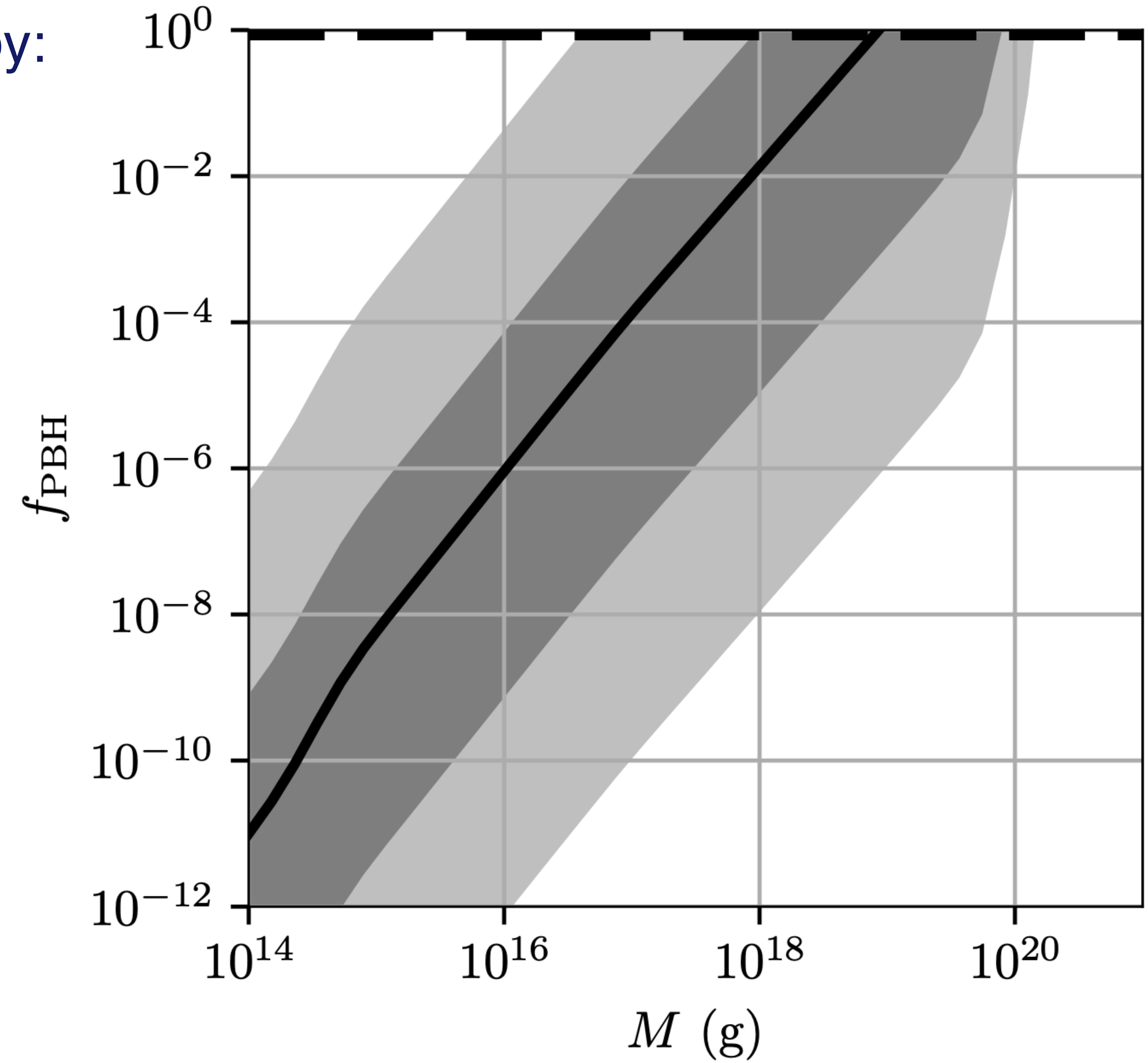


[Auffinger 2022]

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!



[Auffinger 2022]

(see work by Dvali *et al.*)

Micro & Macro

PBH & Particle Dark Matter

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

PBH & Particle Dark Matter

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

PBH & Particle Dark Matter

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PBH & Particle Dark Matter

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PBH & Particle Dark Matter

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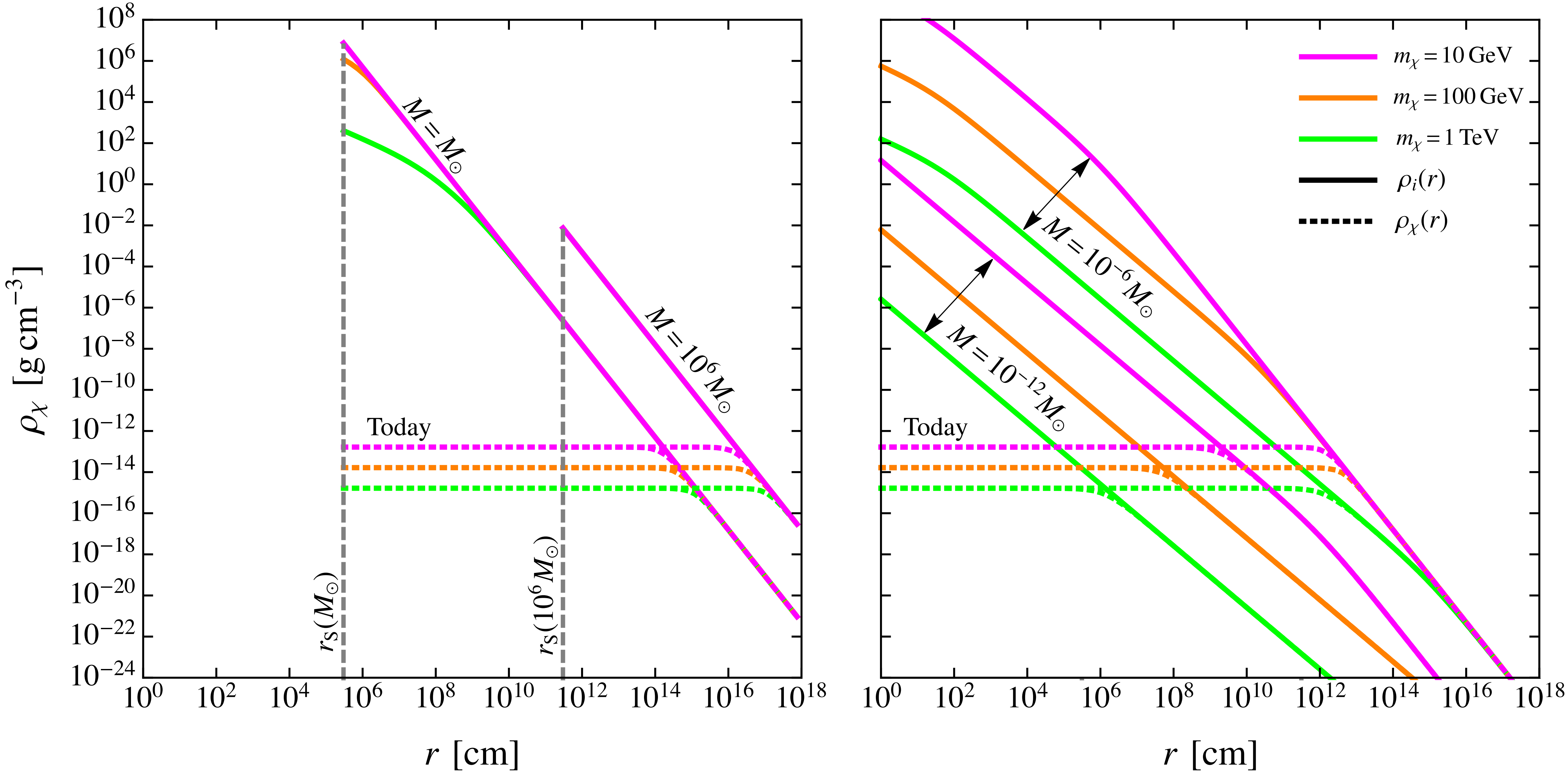
  - ★ The latter will be accreted by the former; formation of halos.
  - ★ Study WIMP annihilations in PBH halos:
    - ★ The annihilation rate $\Gamma \propto n^2$.
    - ★ Halo profile does matter; enhancement of Γ in density spikes.
      1) Derive the density profile of the captured WIMPs;
      2)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

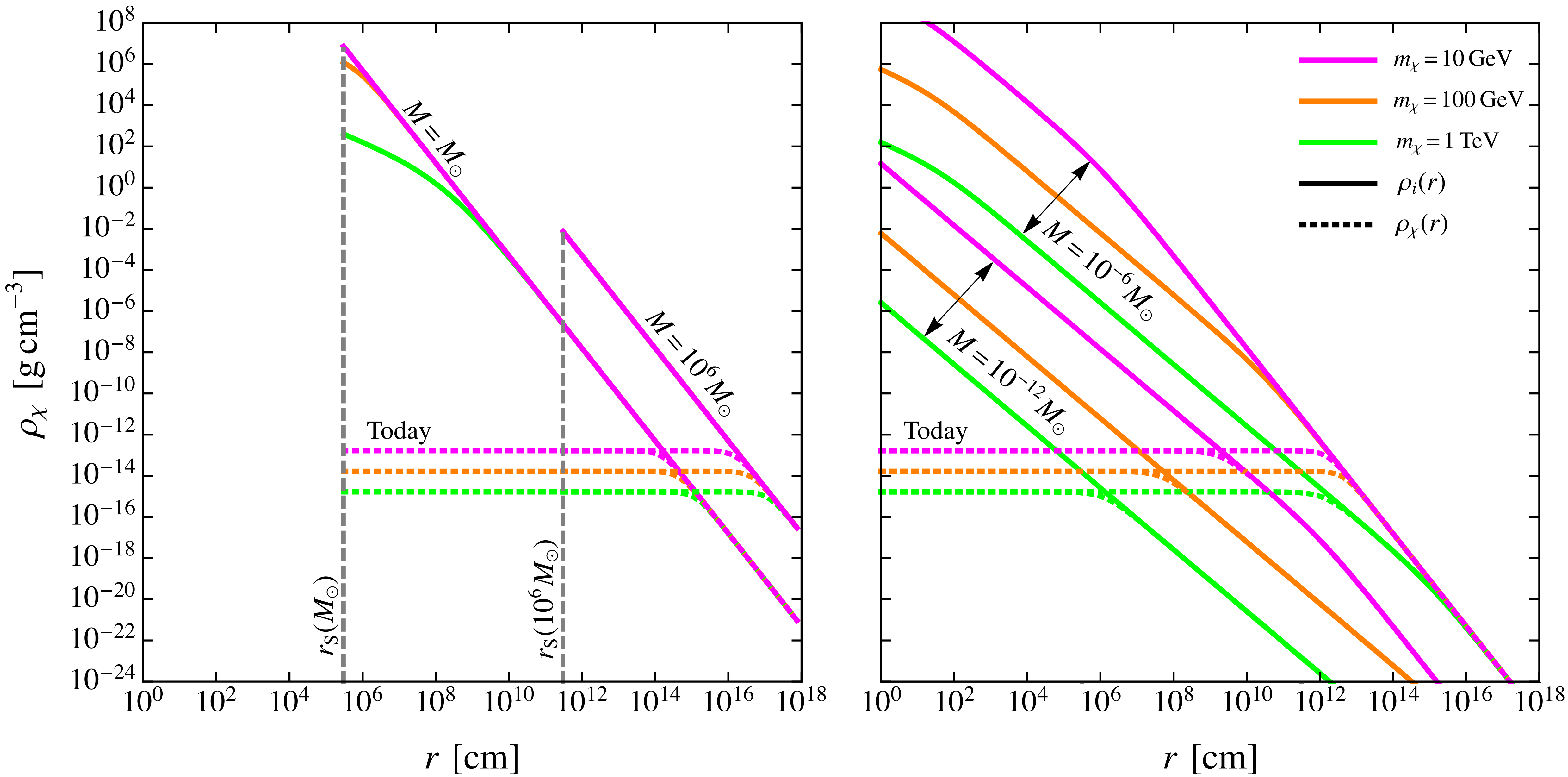
[Eroshenko 2016,
Boucenna *et al*. 2017,
Adamek *et al*. 2019,
Carr, Kühnel, Visinelli 2020 & 2021]

PBHs & WIMPs



[Carr, Kühnel, Visinelli 2021]

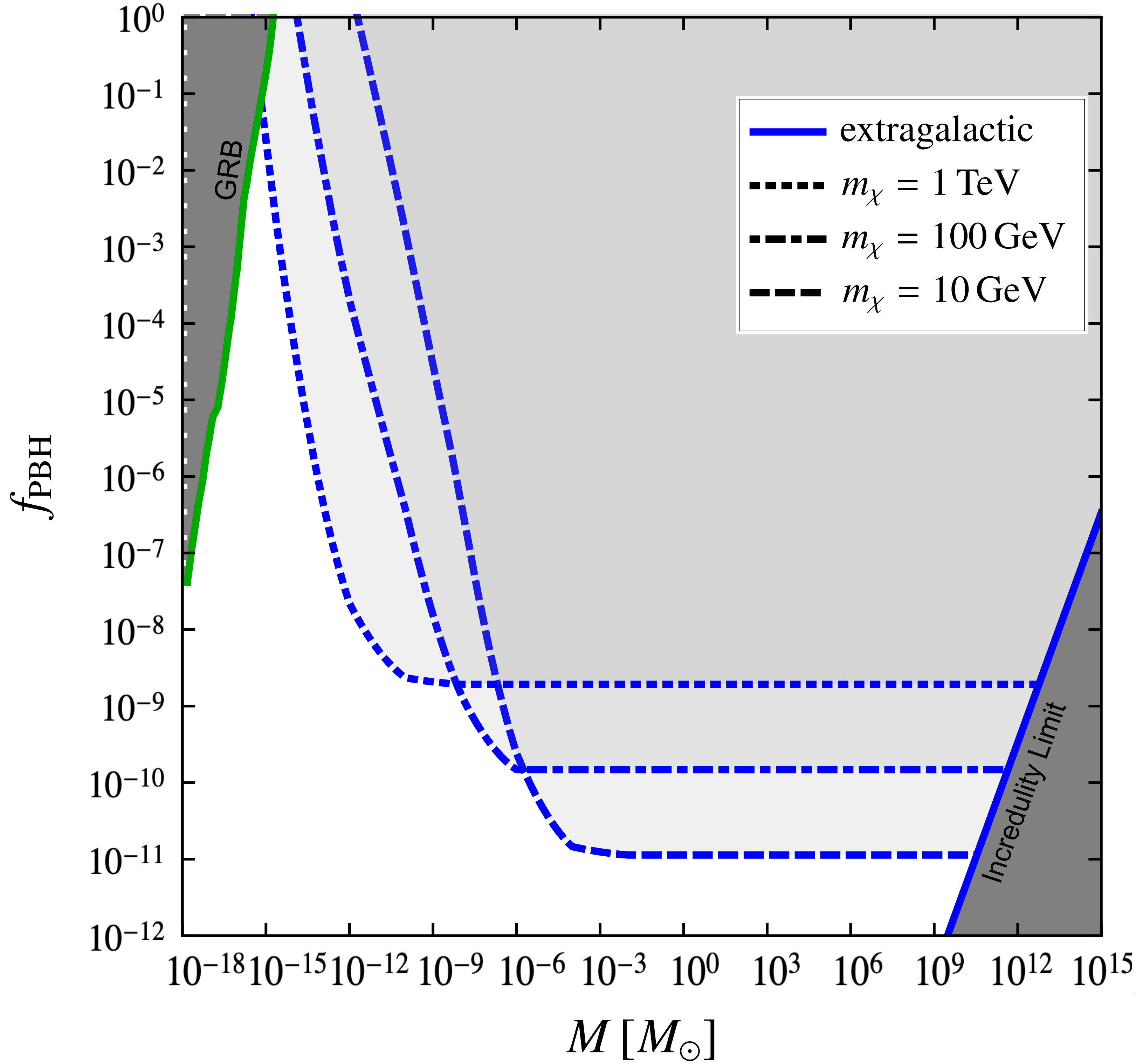
PBHs & WIMPs



[Carr, Kühnel, Visinelli 2021]

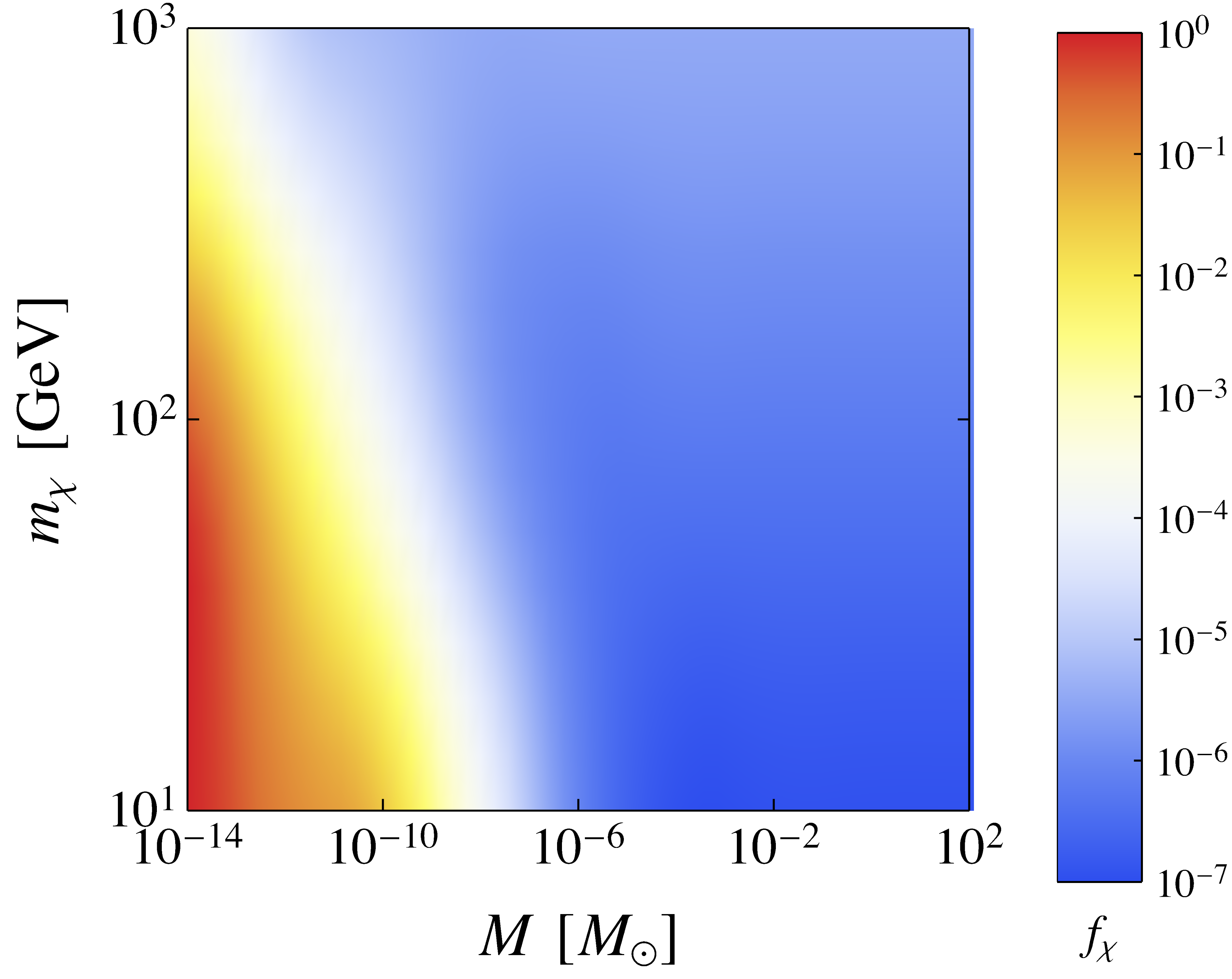
★ Annihilations lead to plateaux in the present-day halos.

PBHs & WIMPs



[Carr, Kühnel, Visinelli 2021]

PBHs & WIMPs



[Carr, Kühnel, Visinelli 2021]

Primordial Black Holes from Confinement

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.

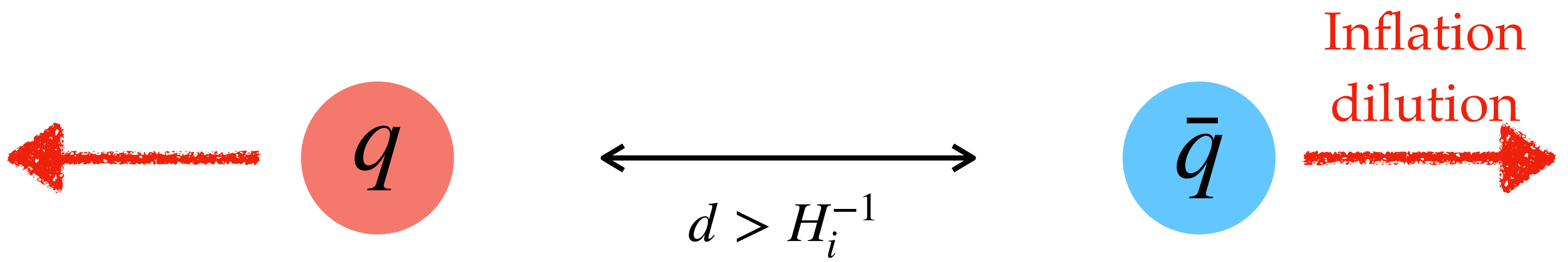
  - PBH formation happens in the strong-coupling regime.

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.



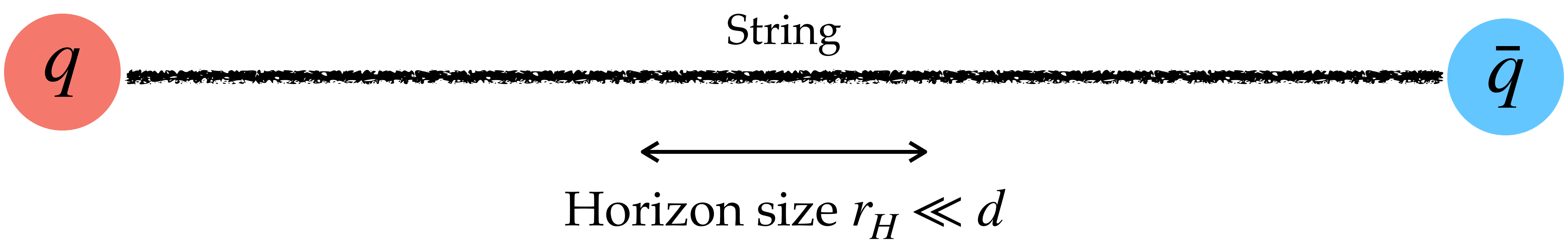
★ Focus on a simple pair case.

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

★ Quarks quickly move out of causal contact.

Confinement Formation Mechanism

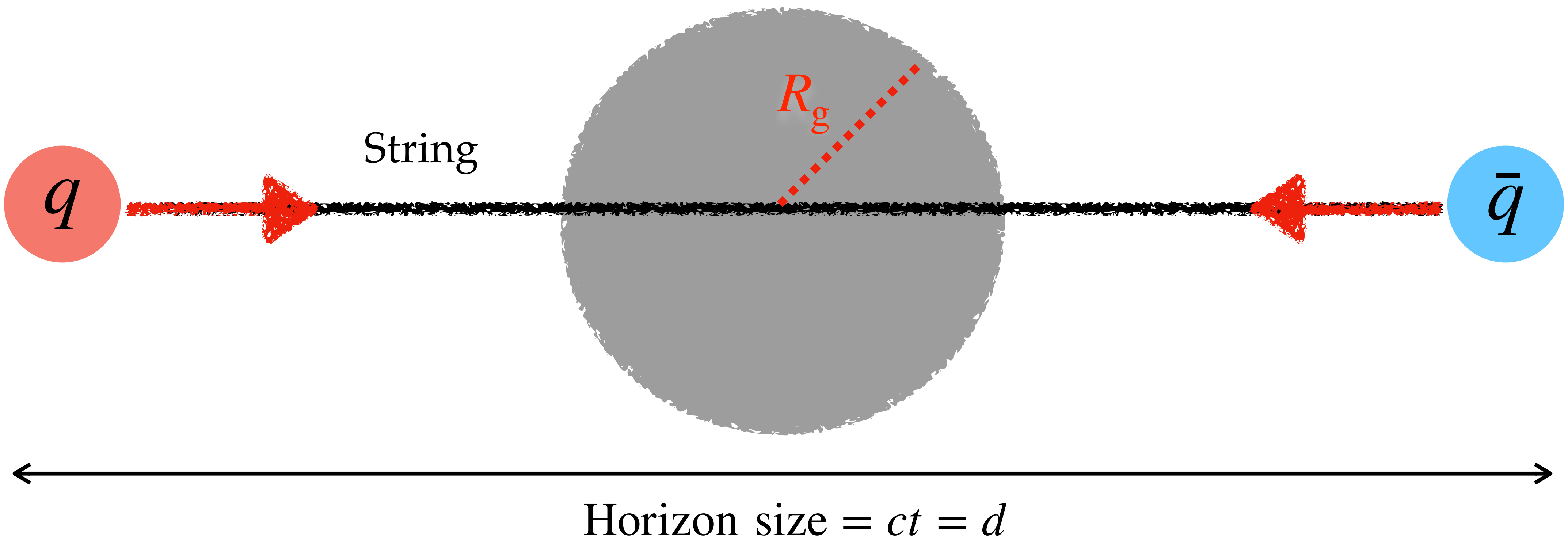
★ **2. Ingredient:** Confinement at energy scale Λ_c, $M_q/\Lambda_c \gg 1$



- ★ 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 $M_q/\Lambda_c \gg 1$.

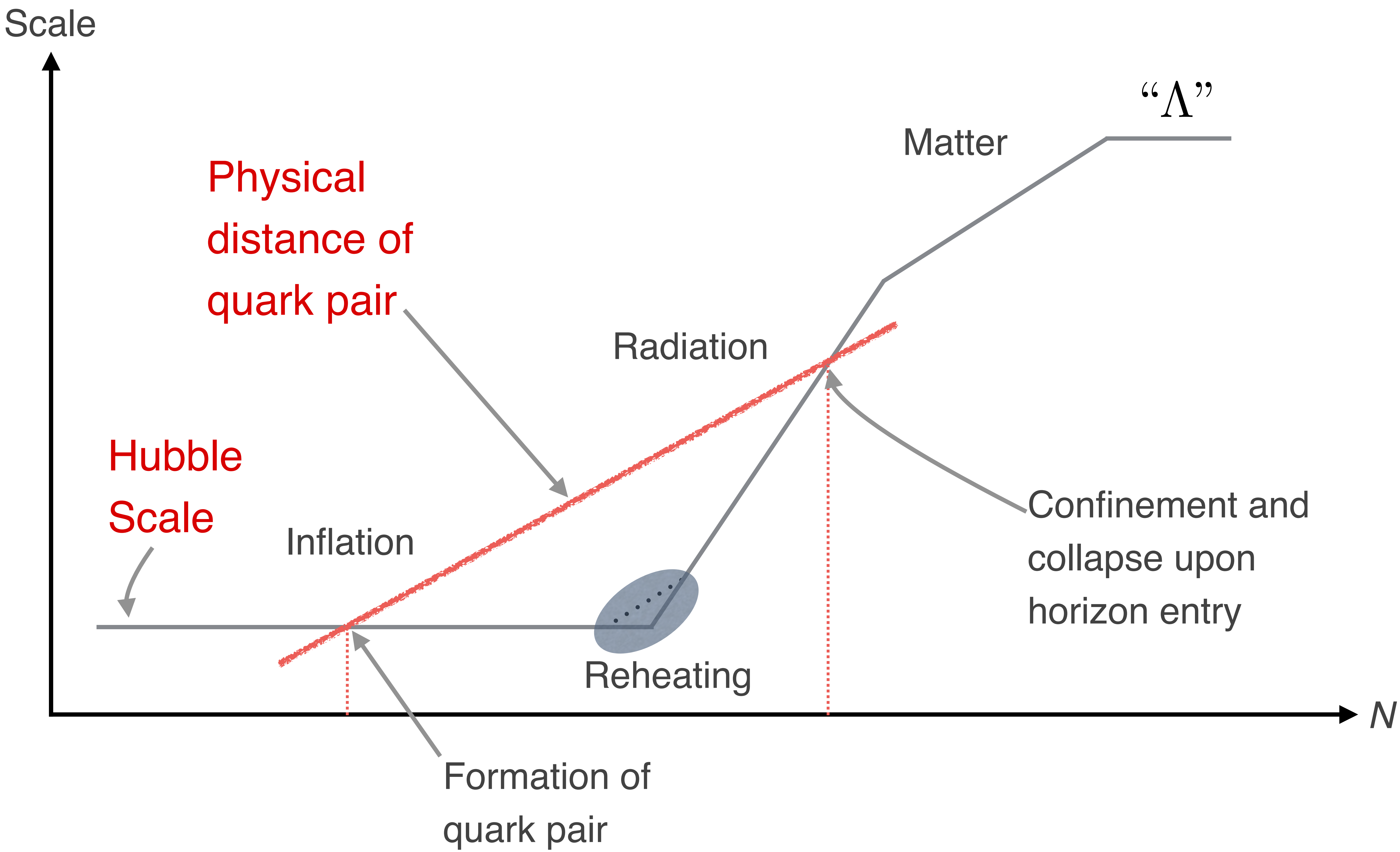
Confinement Formation Mechanism

★ **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



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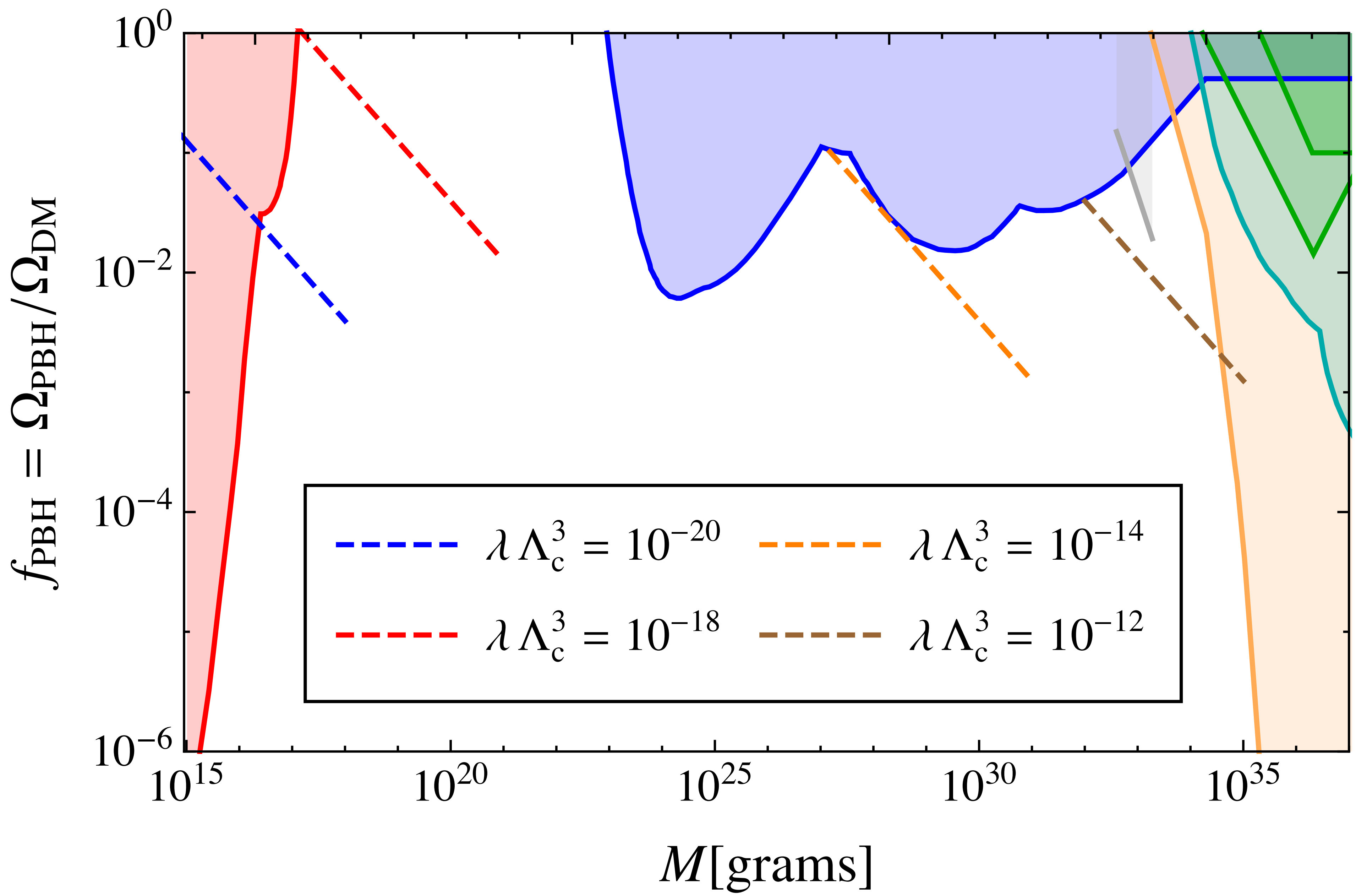
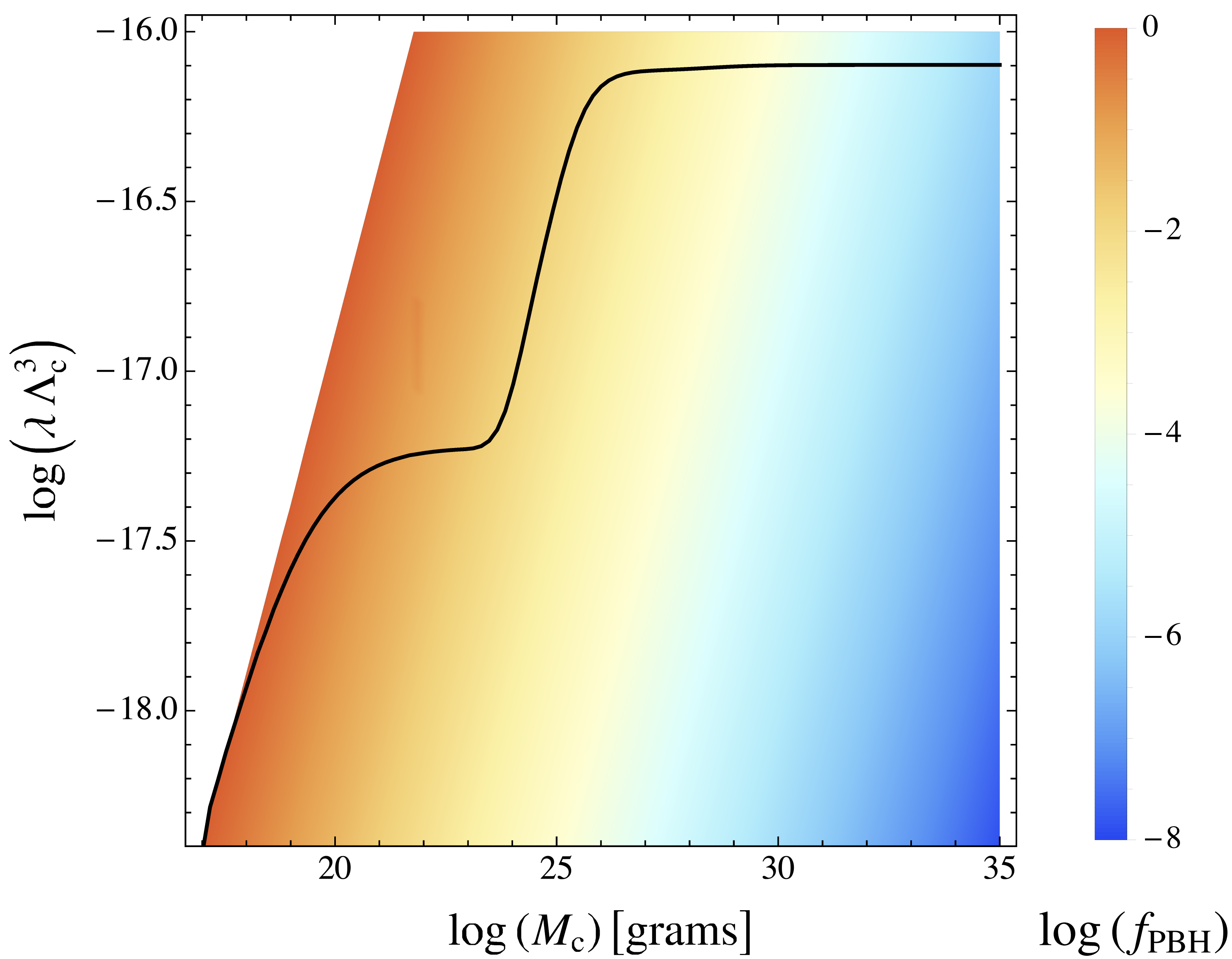


★ Find: $$f_{\rm PBH} \equiv \frac{\rho_{\rm PBH}(t)}{\rho_{\rm CDM}(t)} = \frac{32\pi}{3}\,\lambda\Lambda_c^3\left(\frac{M_{\rm PBH}}{M_{\rm eq}}\right)^{-1/2}$$

Extended-Constraint Analysis

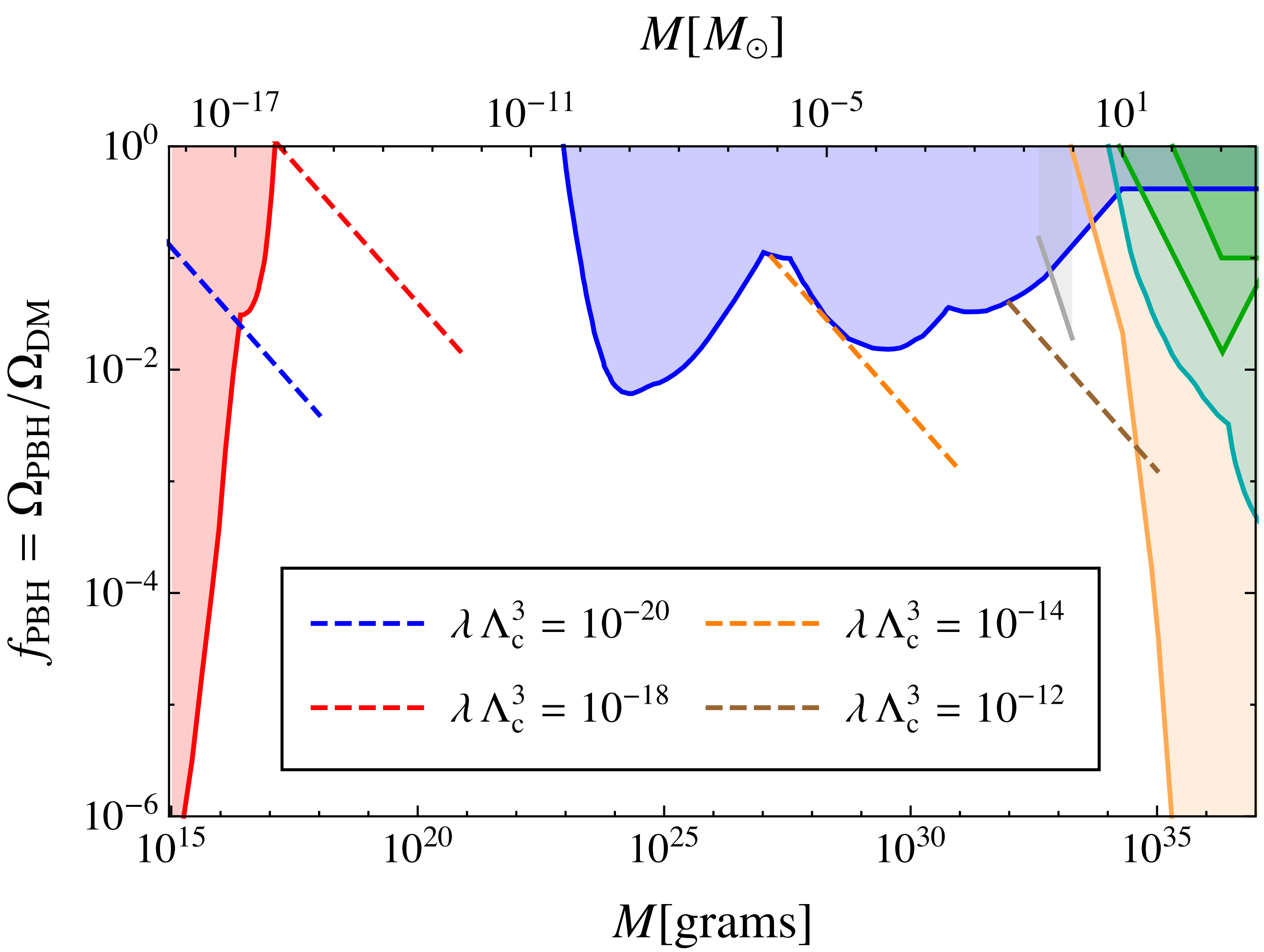
★ Require: $$\int_{M_1}^{M_2} \mathrm{d}\ln M_{\mathrm{PBH}} \, \frac{\mathrm{d} f_{\mathrm{PBH}}(M_{\mathrm{PBH}})}{\mathrm{d}\ln M_{\mathrm{PBH}}} \frac{1}{f_{\max}(M_{\mathrm{PBH}})} \overset{!}{\leq} 1$$

[Carr *et al.* 2017]



- Full compatibility with observations below the black line, here, exemplary for $M_{\mathrm{peak}} \sim 10^{17}$ 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

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

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!

High-Spin Subsolar PBHs

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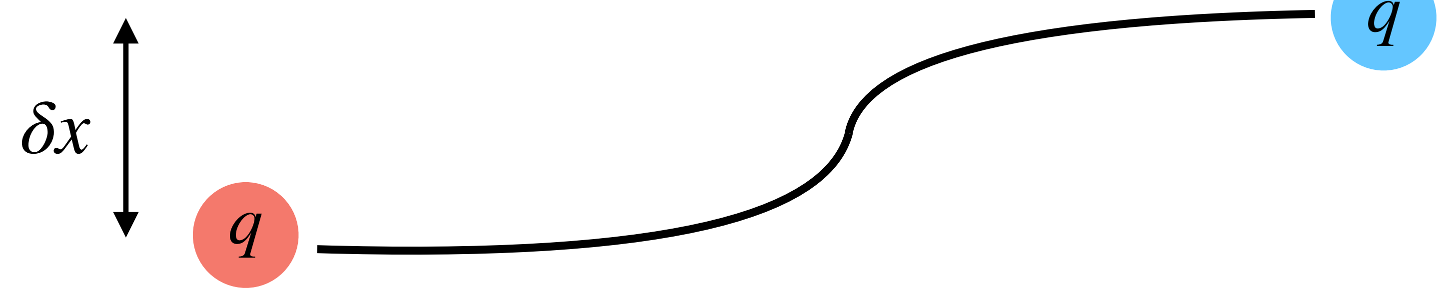
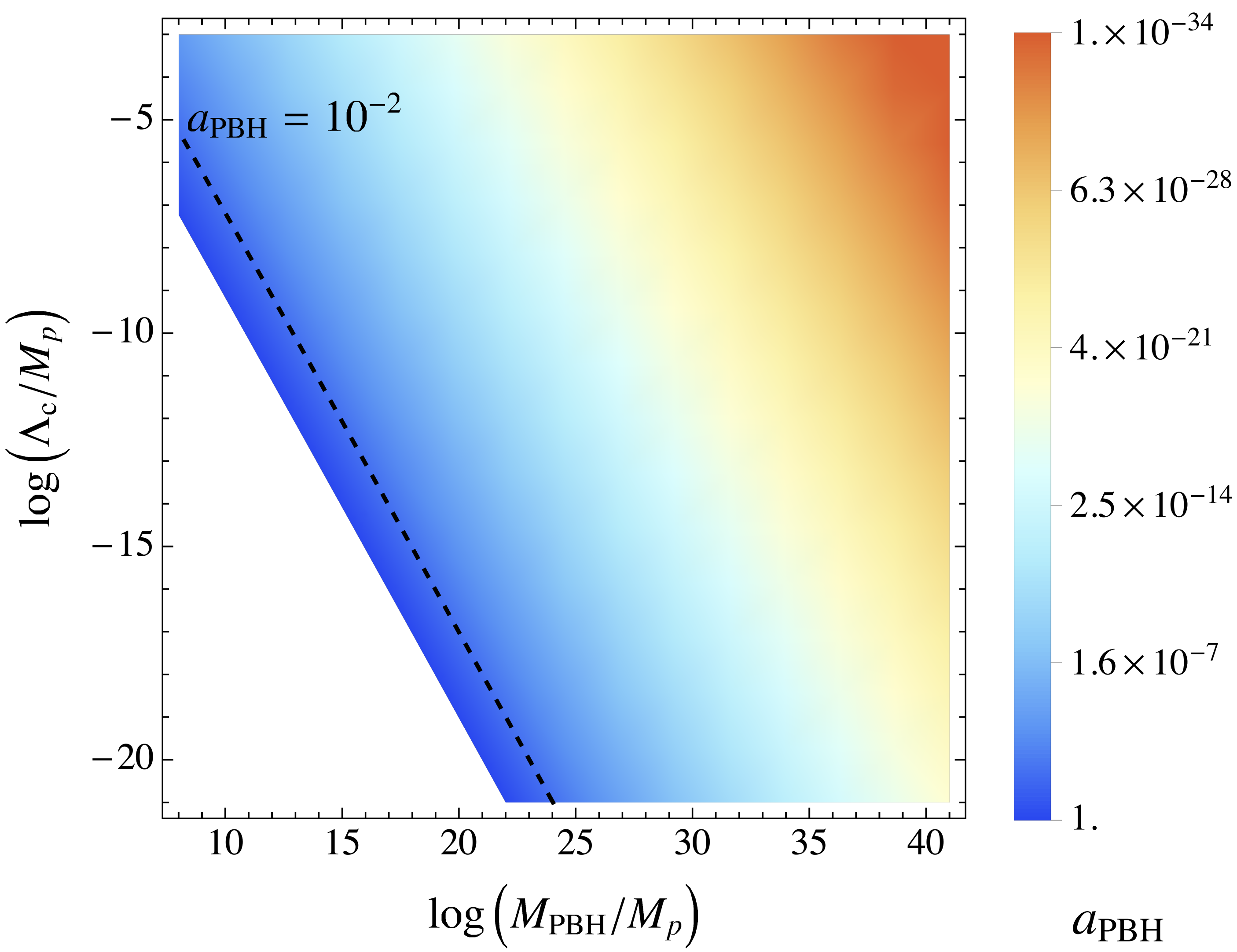
$$\delta x \simeq \sqrt{N_{\rm e}}\, H_{\rm i}^{-1}$$





★ This leads to potentially significant spin:

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

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

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!

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

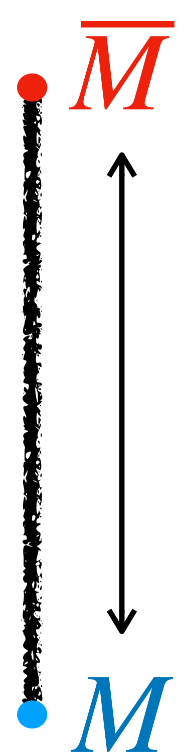
- Couplings are expectation values of fields and can be very different in the early Universe.

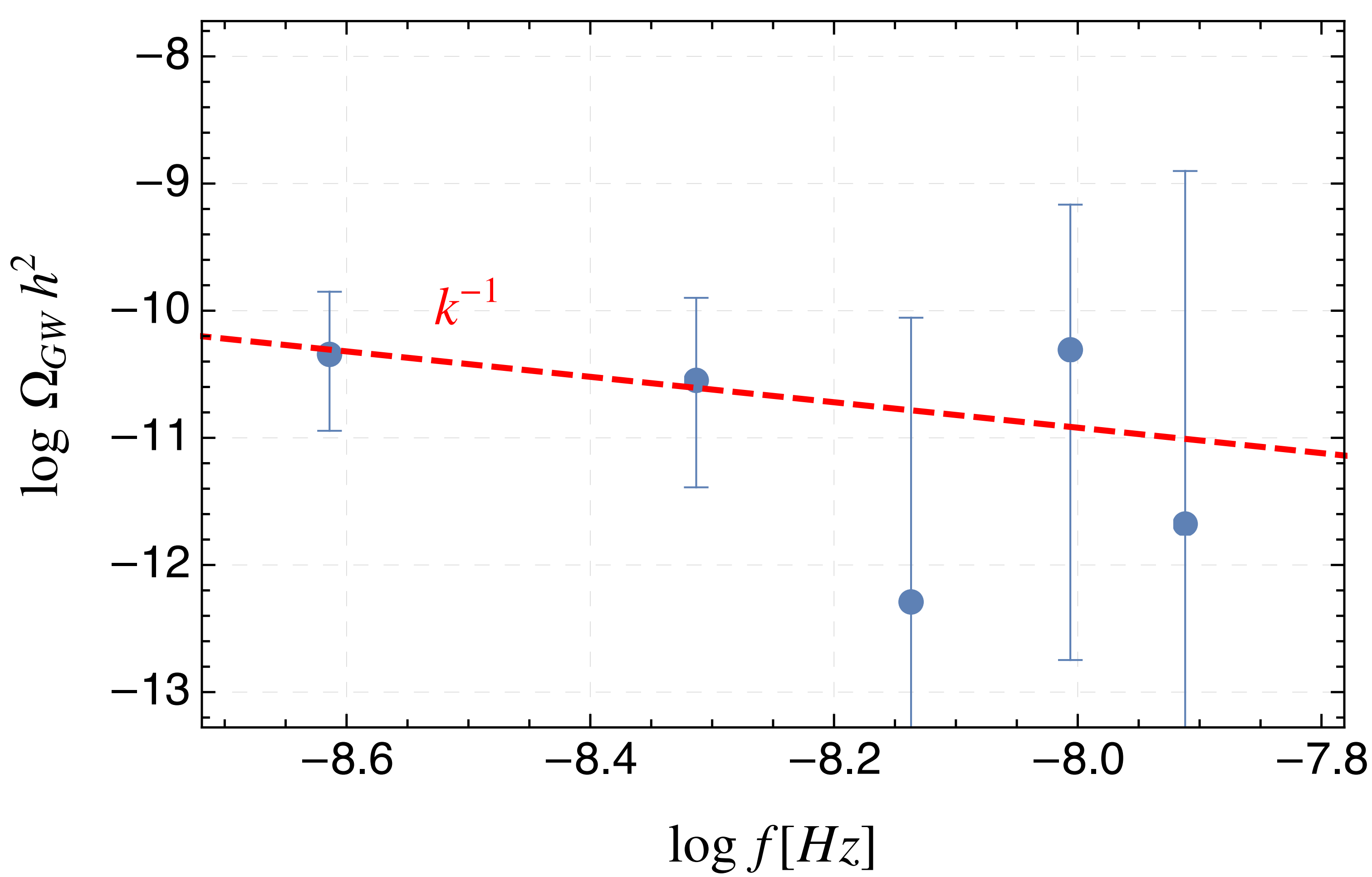
  - Requirement: Low-temperature expectation value should set the right coupling values.

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

Gravitational Waves

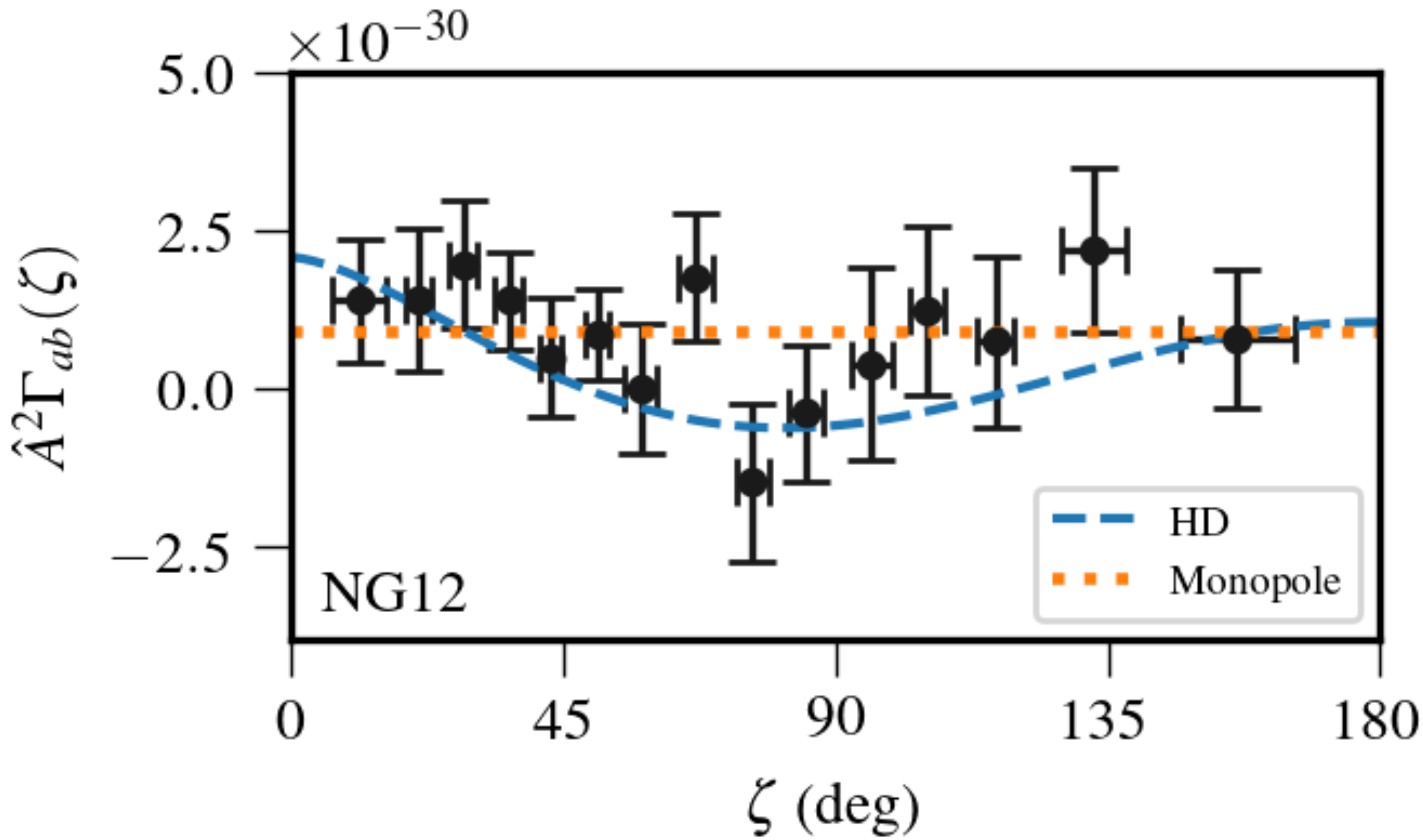
- ★ After horizon entry, the quarks quickly move towards each other, emitting gravitational waves.
  - ★ This is similar to dual to systems of dual monopole/anti-monopole pairs connected by a string. [cf. Martin & Vilenkin 1997; Leblond, Shlaer, Siemens 2009]
  - ★ NANOGrav data from pulsar-timing observations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

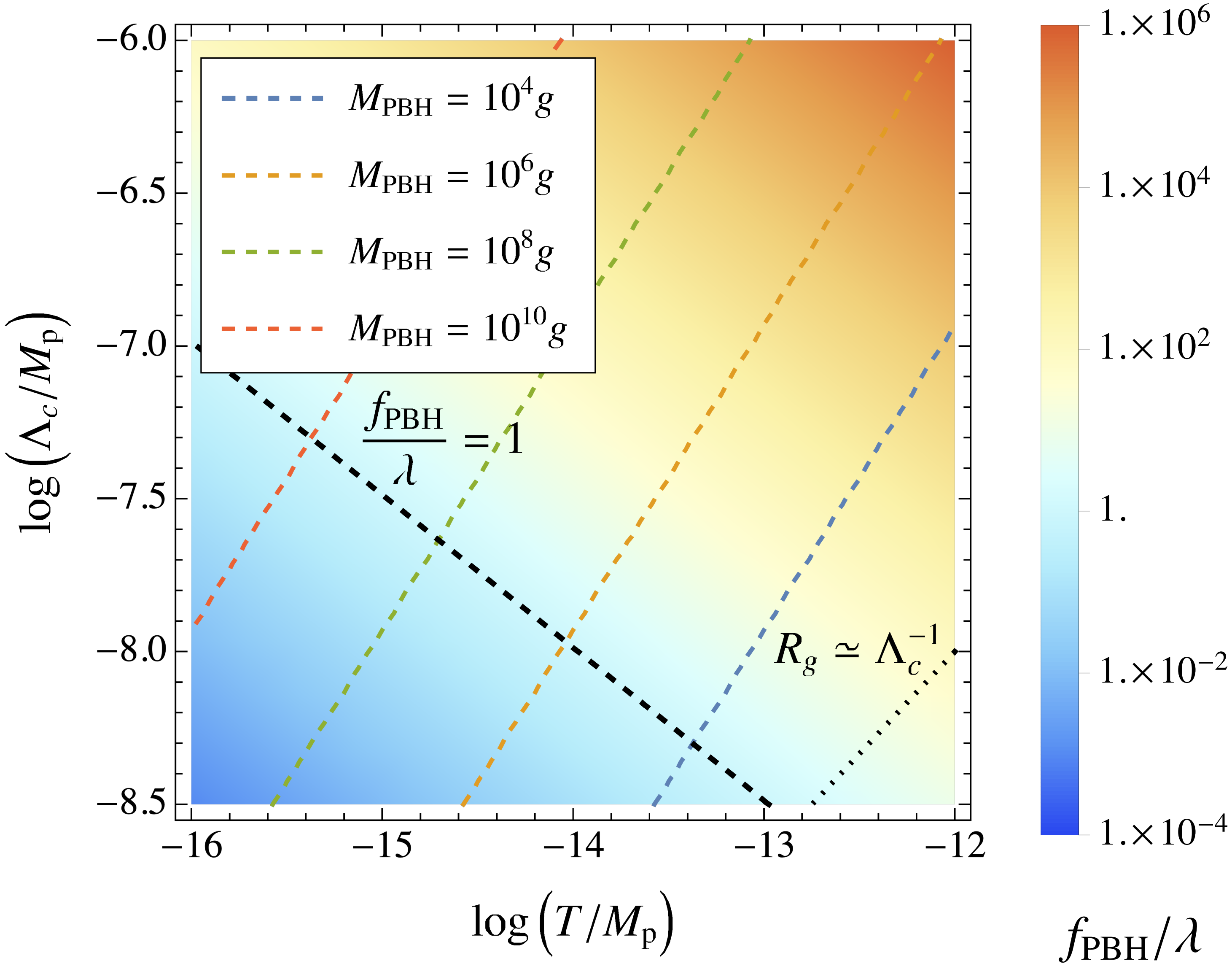
★ We can easily generate a monopolar signal upon adding e.g. $\sim \phi\, \bar{q} q$ with coupling strength relatively weaker by $\sim 10^{-3}$.

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.

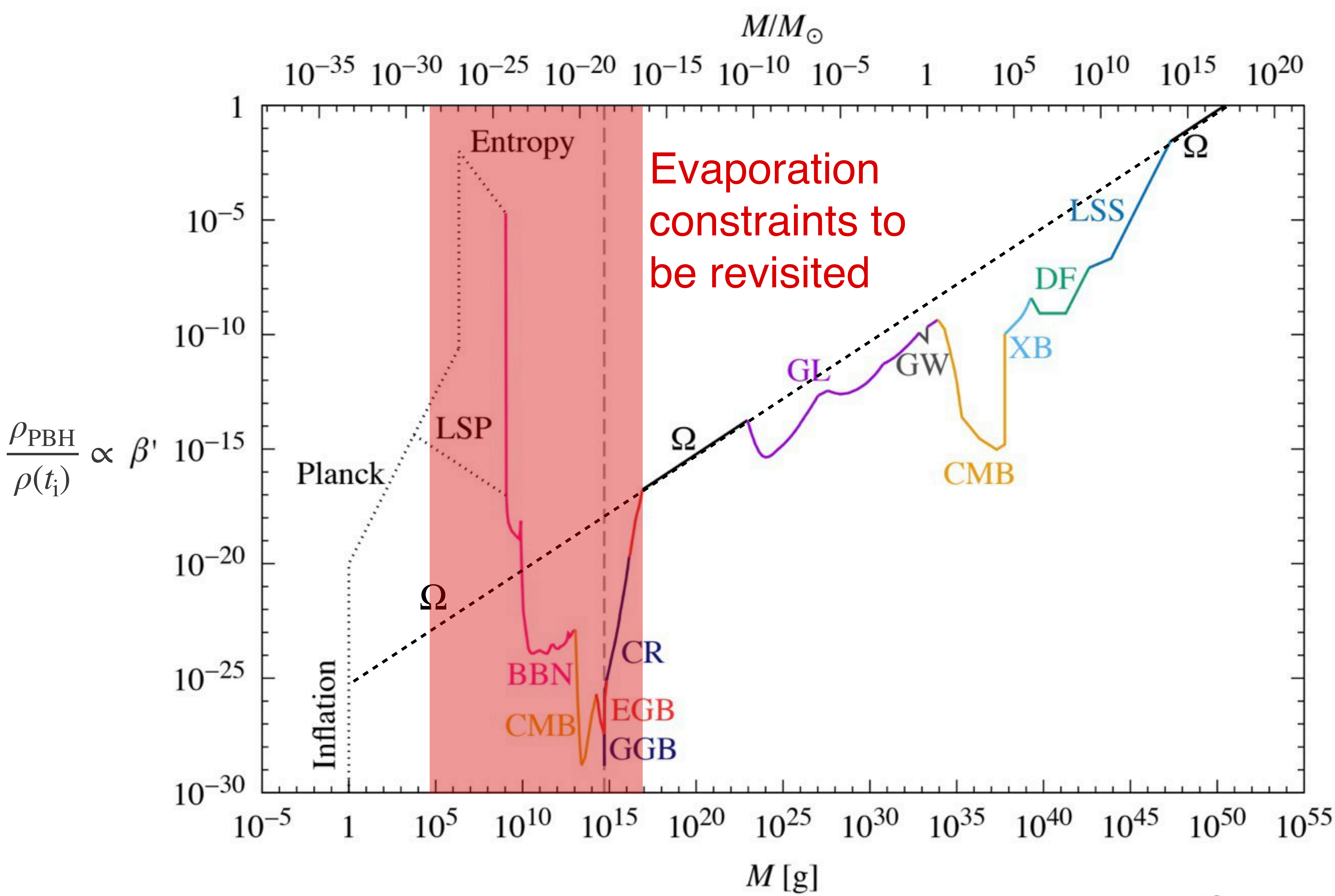
★ A conservative estimate is:

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

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:

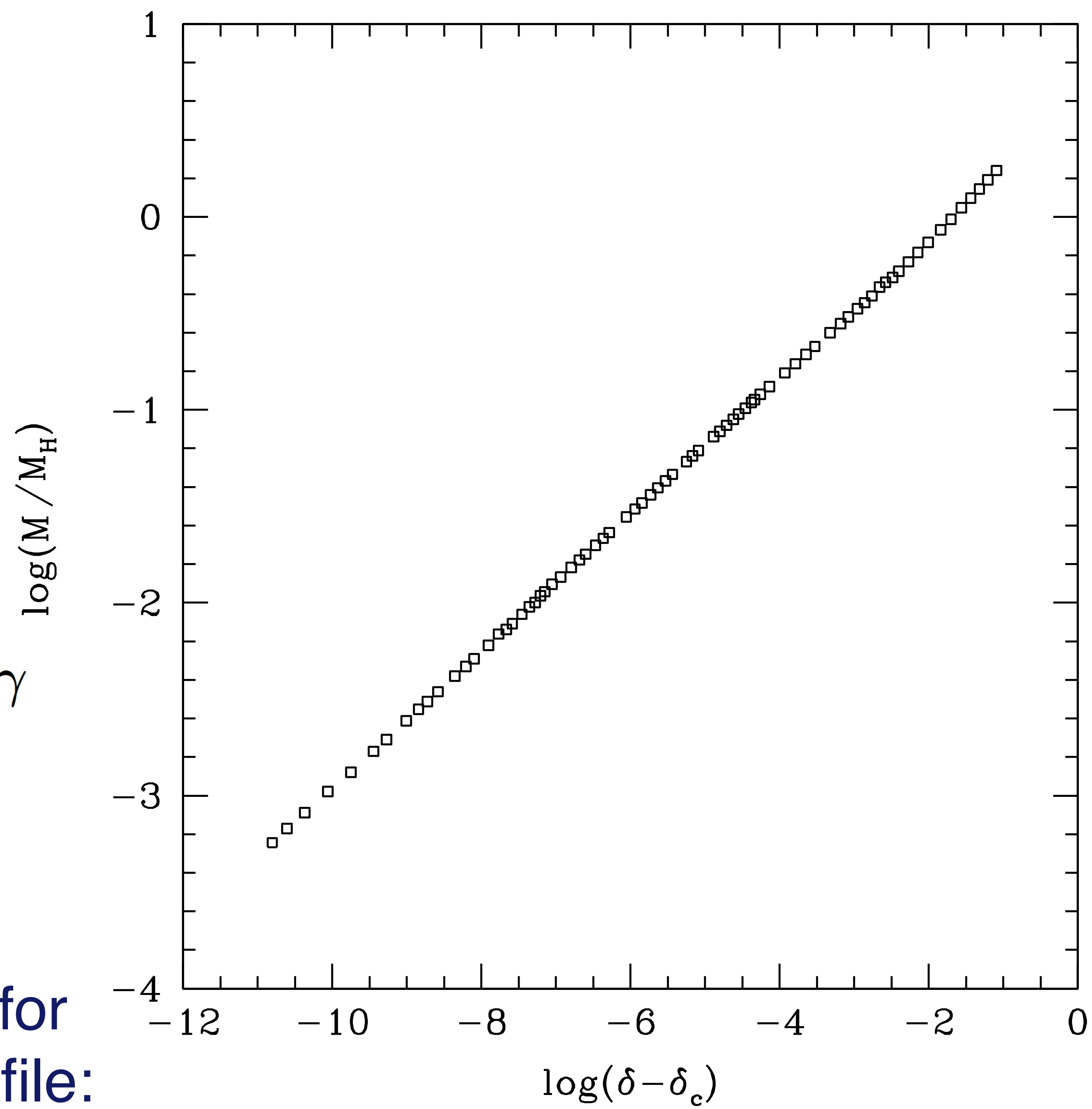
[Choptuik '93]

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

density contrast

★ Radiation domination and for spherical Mexican-hat profile:

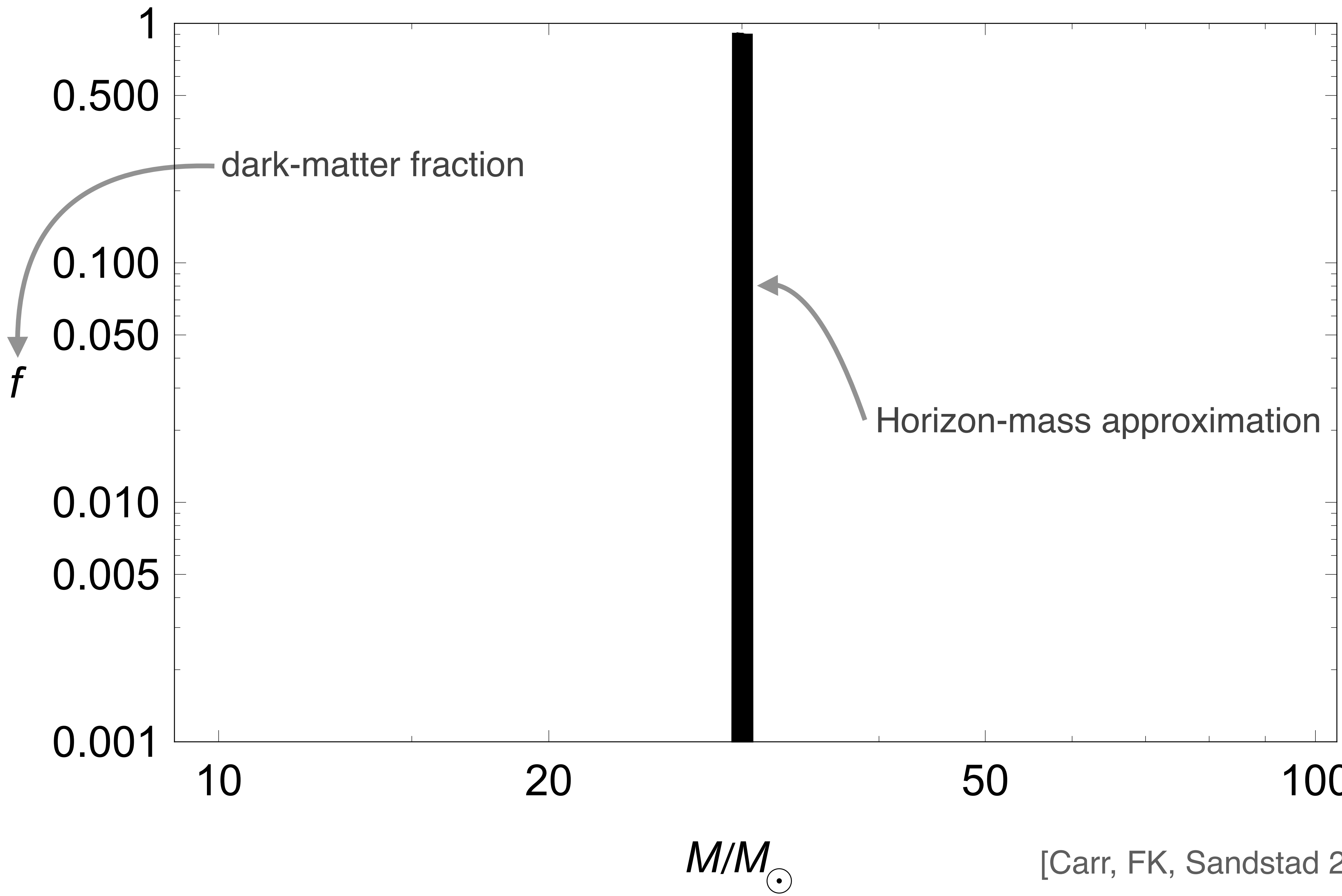
$$k \approx 3.3\ , \quad \delta_c \approx 0.45\ , \quad \gamma \approx 0.36$$



[Musco, Miller, Polnarev 2008]

Critical Collapse

★ How would this look for monochromatic mass function?



[Carr, FK, Sandstad 2016]

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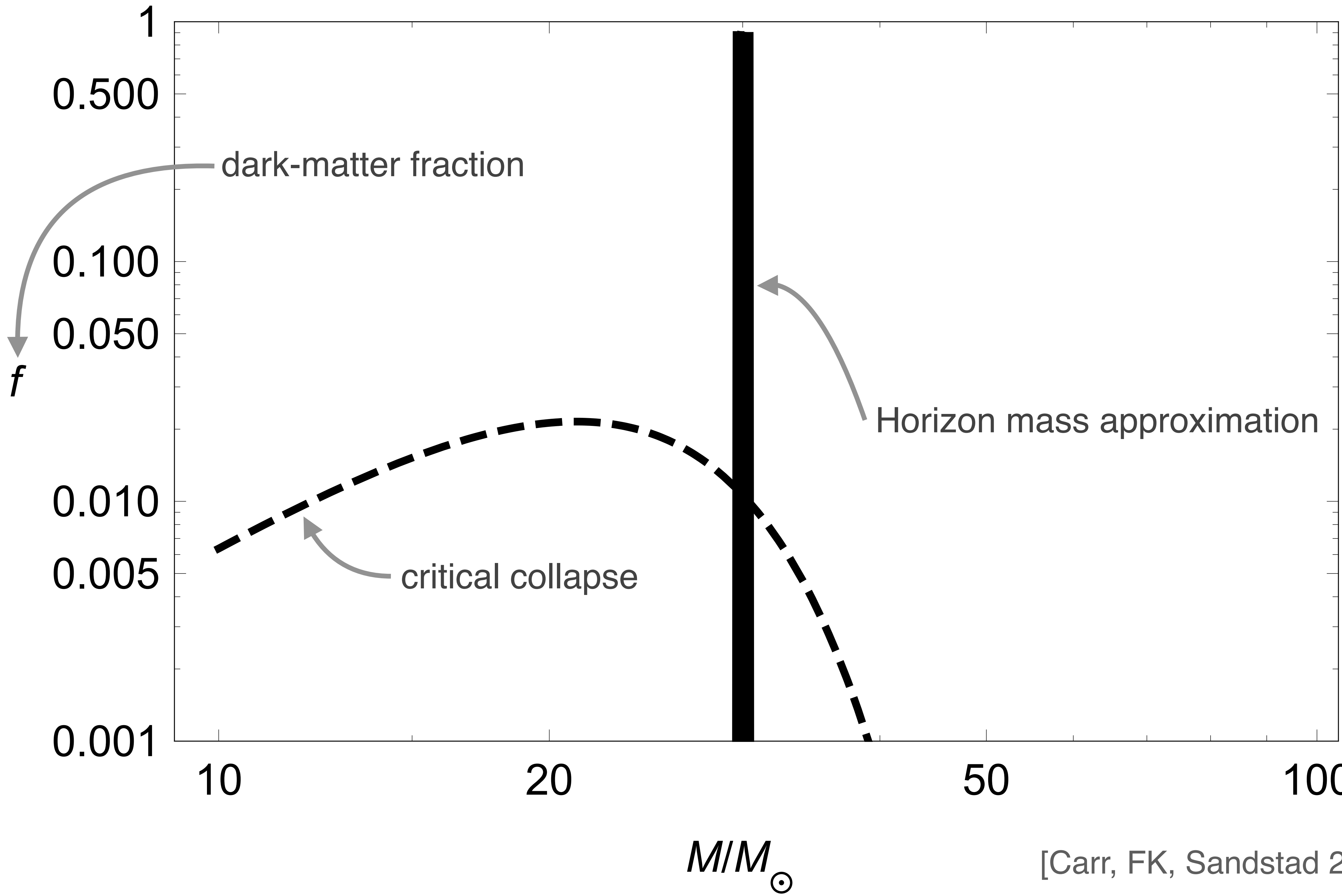

[Carr, FK, Sandstad 2016]

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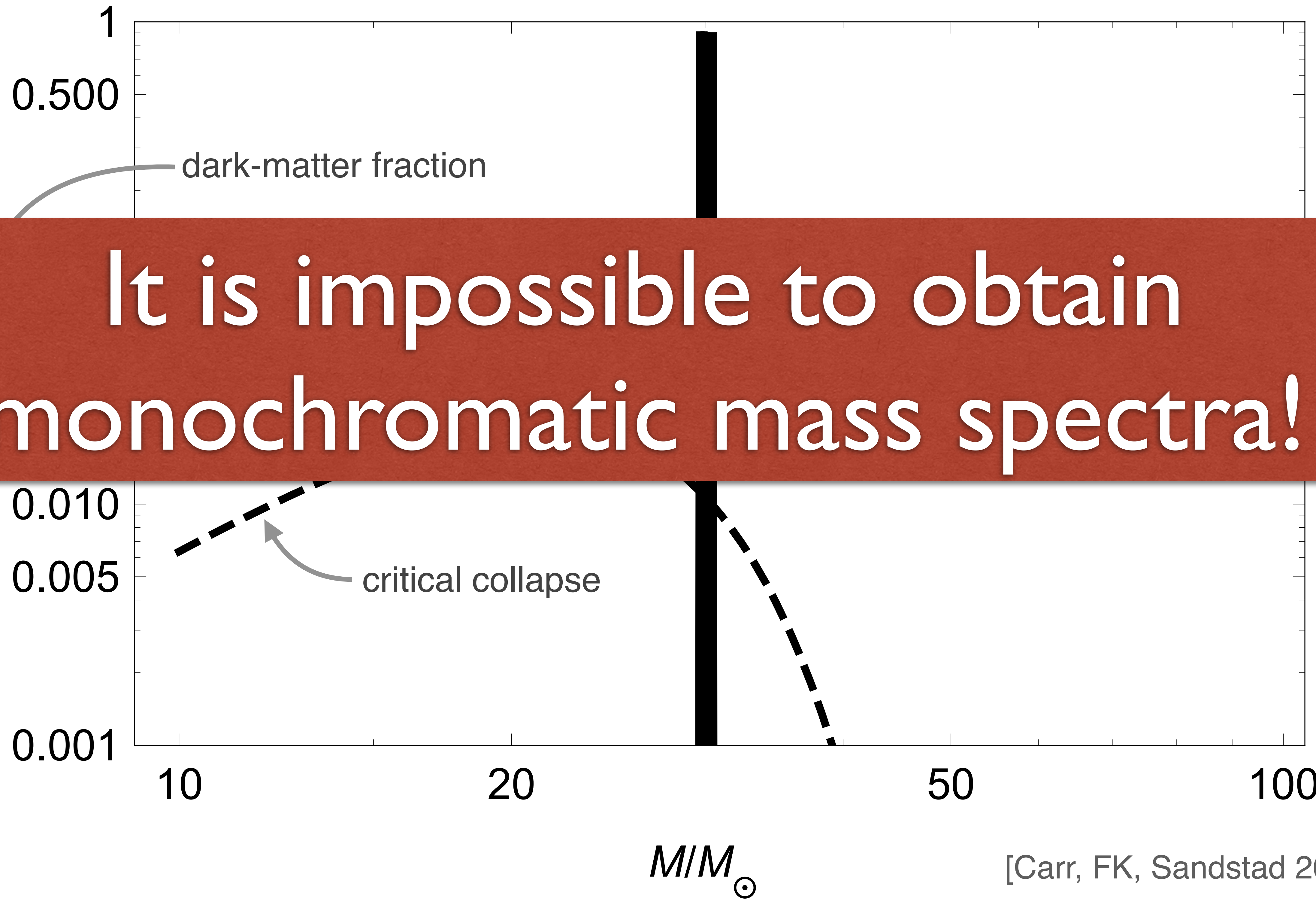
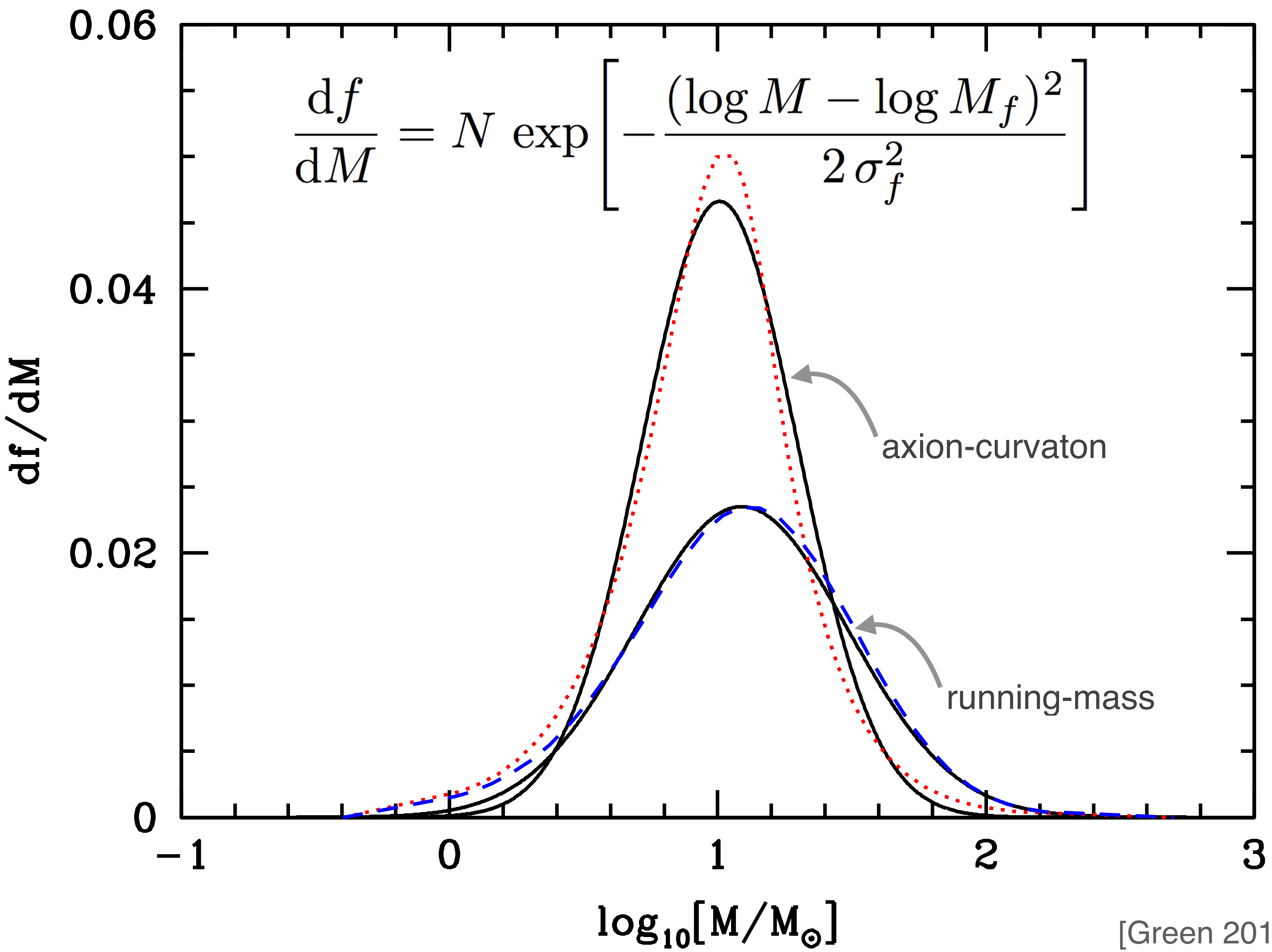


[Carr, FK, Sandstad 2016]

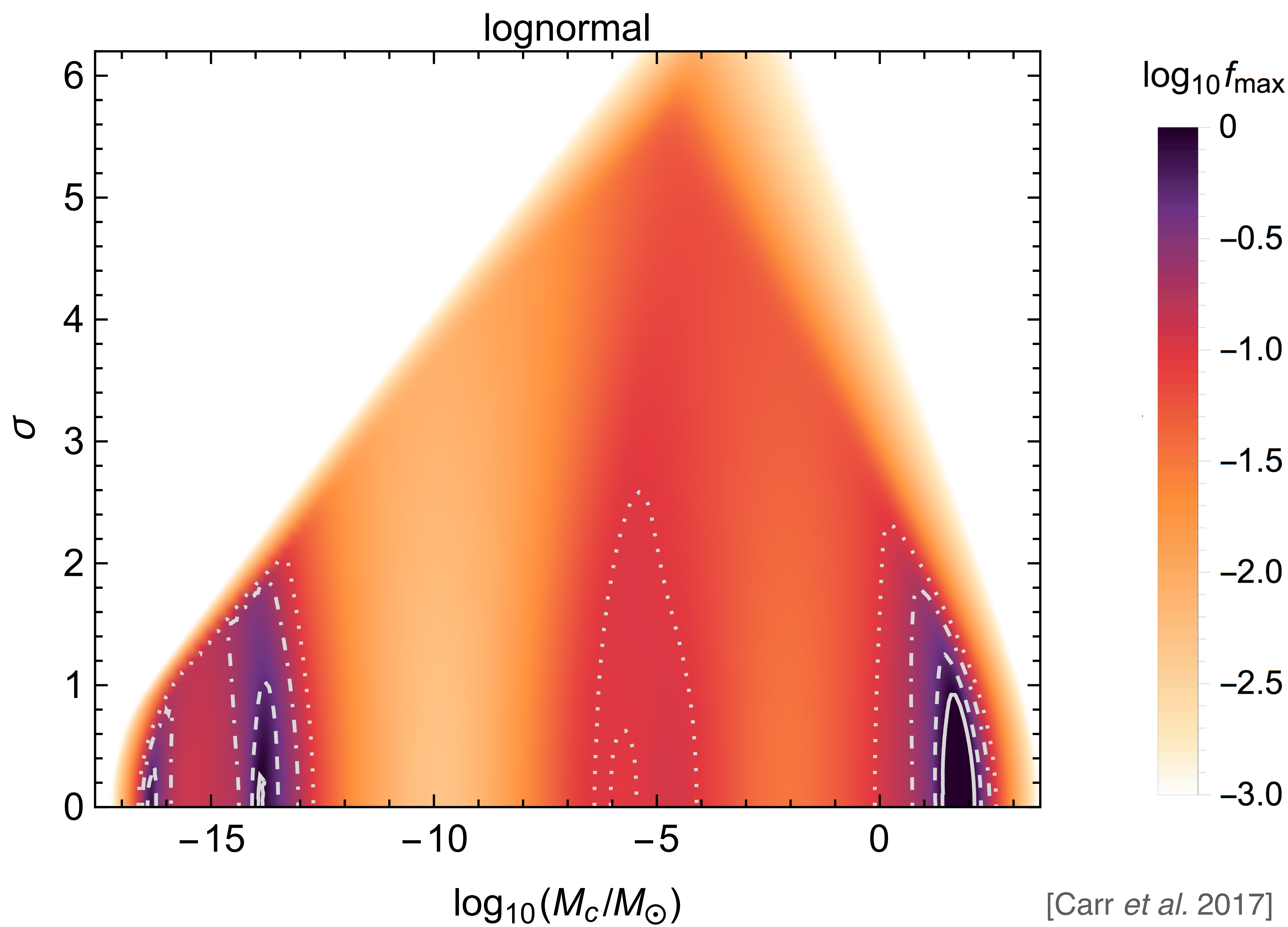
It is impossible to obtain monochromatic mass spectra!

More Systematic Study



[Green 2016]

More Systematic Study



[Carr *et al.* 2017]

Lepton Flavour Asymmetry

Lepton Flavour Asymmetry

★ Lepton flavour asymmetries are defined as

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

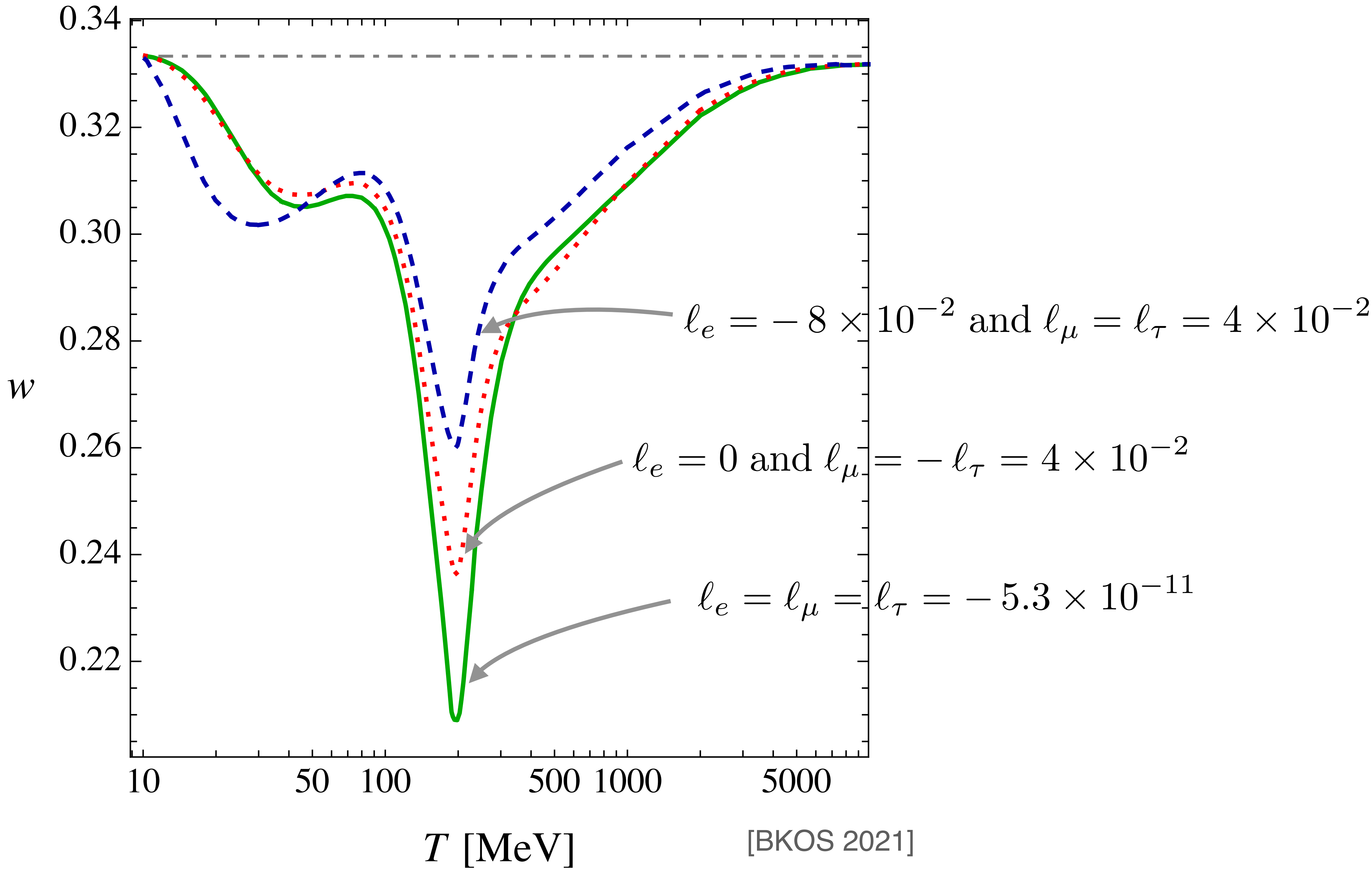
$n_\alpha, n_{\bar{\alpha}}, n_{\nu_\alpha}, n_{\bar{\nu}_\alpha}$	number densities of (anti)leptons and corresponding (anti)neutrinos
s	entropy densities

★ CMB constraints are quite weak:

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

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

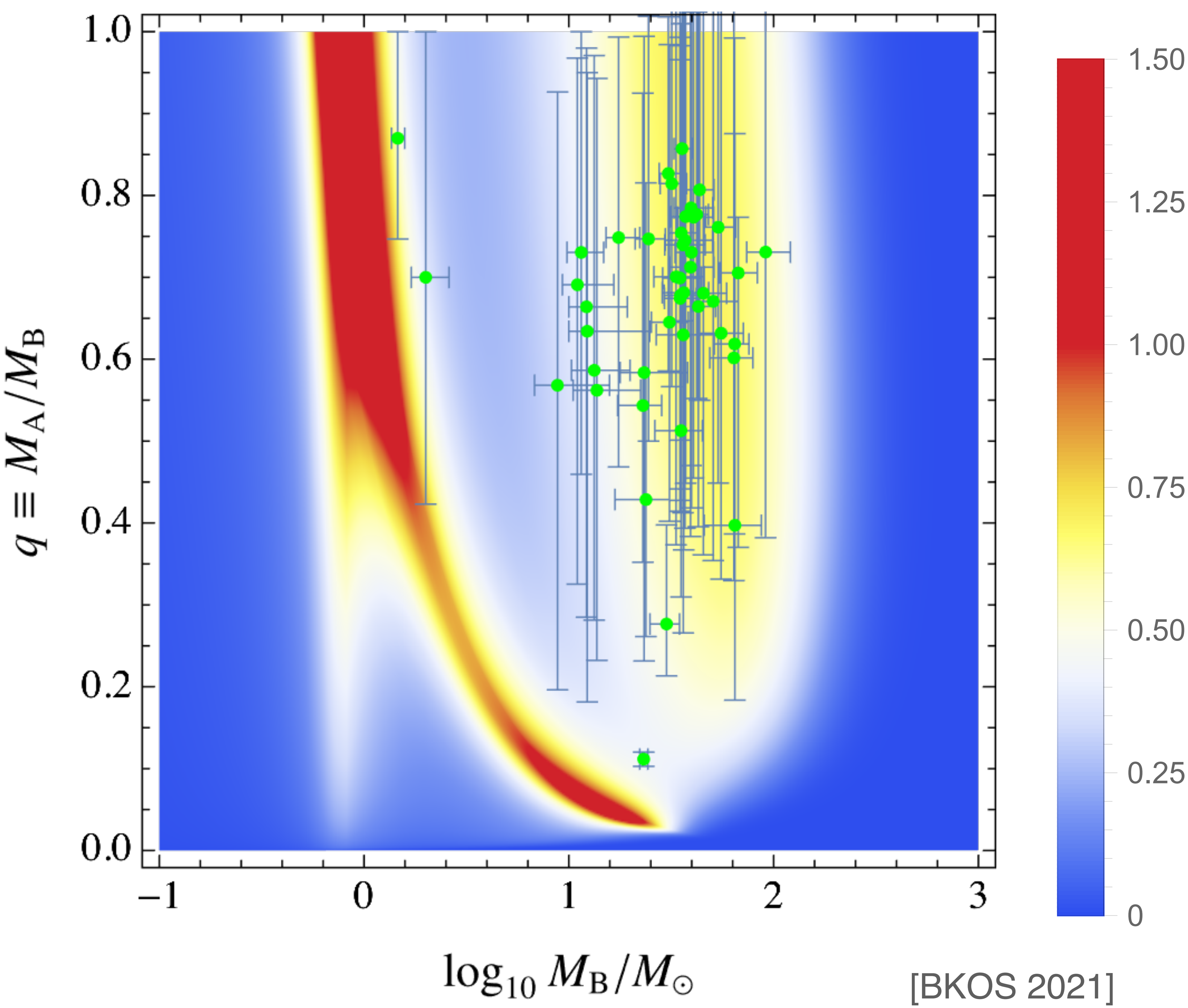
Lepton Flavour Asymmetry



[BKOS 2021]

Lepton Flavour Asymmetry

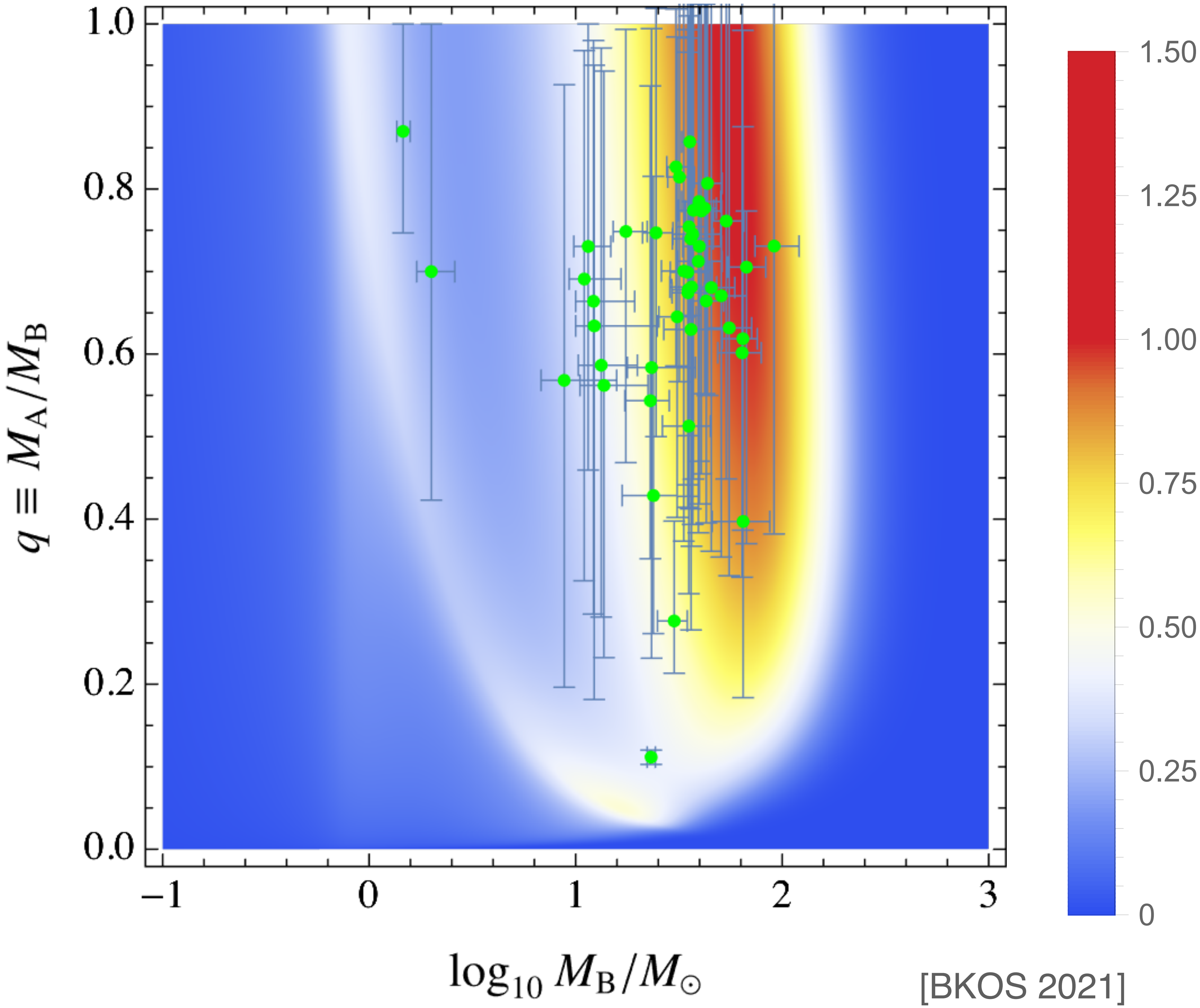
$\ell_e = \ell_\mu = \ell_\tau = -5.3 \times 10^{-11}$



[BKOS 2021]

Lepton Flavour Asymmetry

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



[BKOS 2021]