Primordial Black Holes as Dark Matter

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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?

How do they form?

Which support do we have for them?

What are Primordial Black Holes?

How do they form?

Which support do we have for them?

What are Primordial Black Holes?

How do they form?

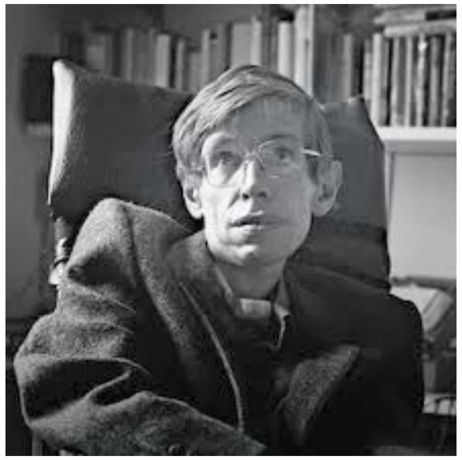
Which support do we have for them?

What are Primordial Black Holes (PBHs)?

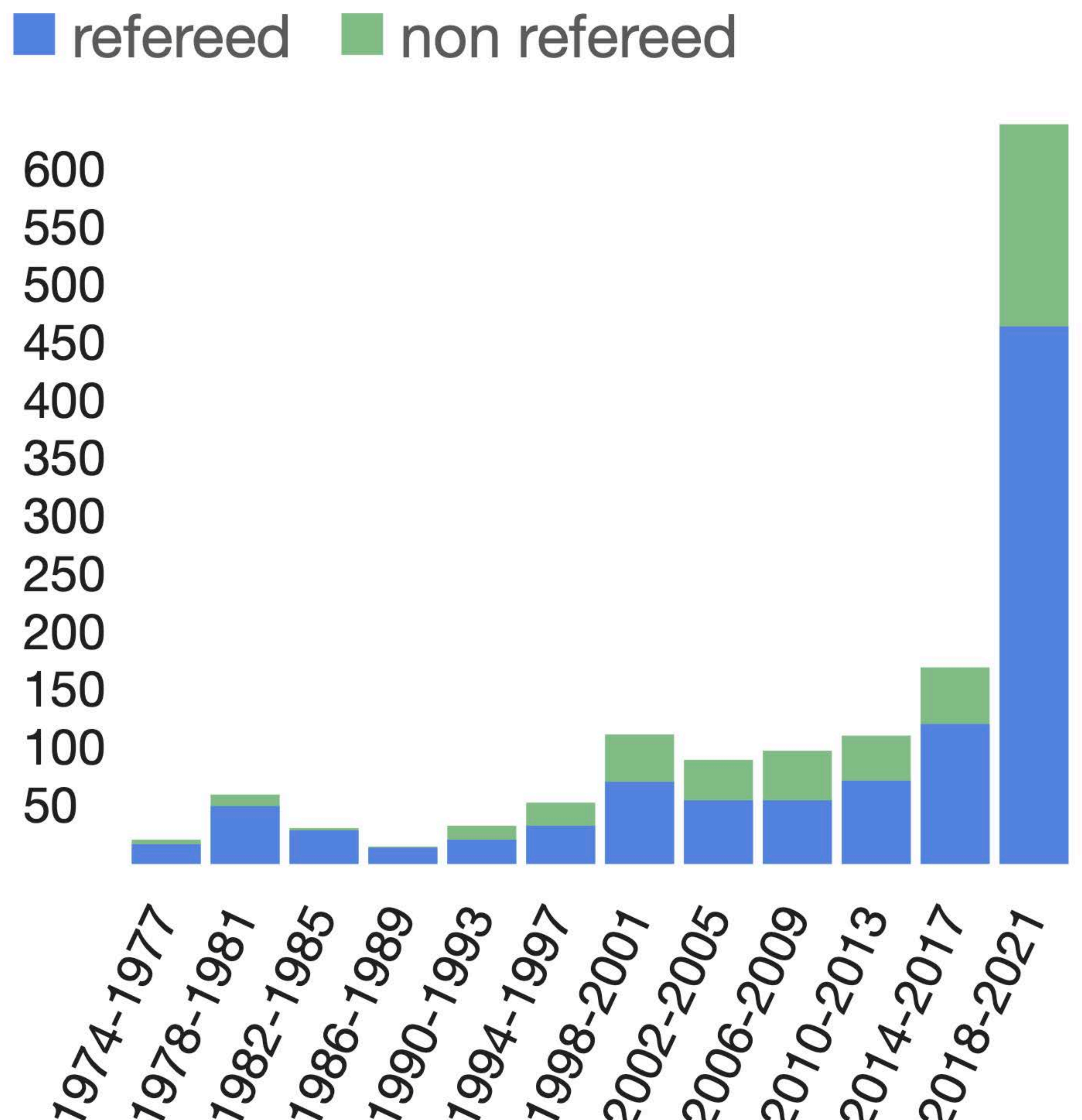
★ Black holes formed in the early Universe (in particular: *non-stellar*).

★ 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).

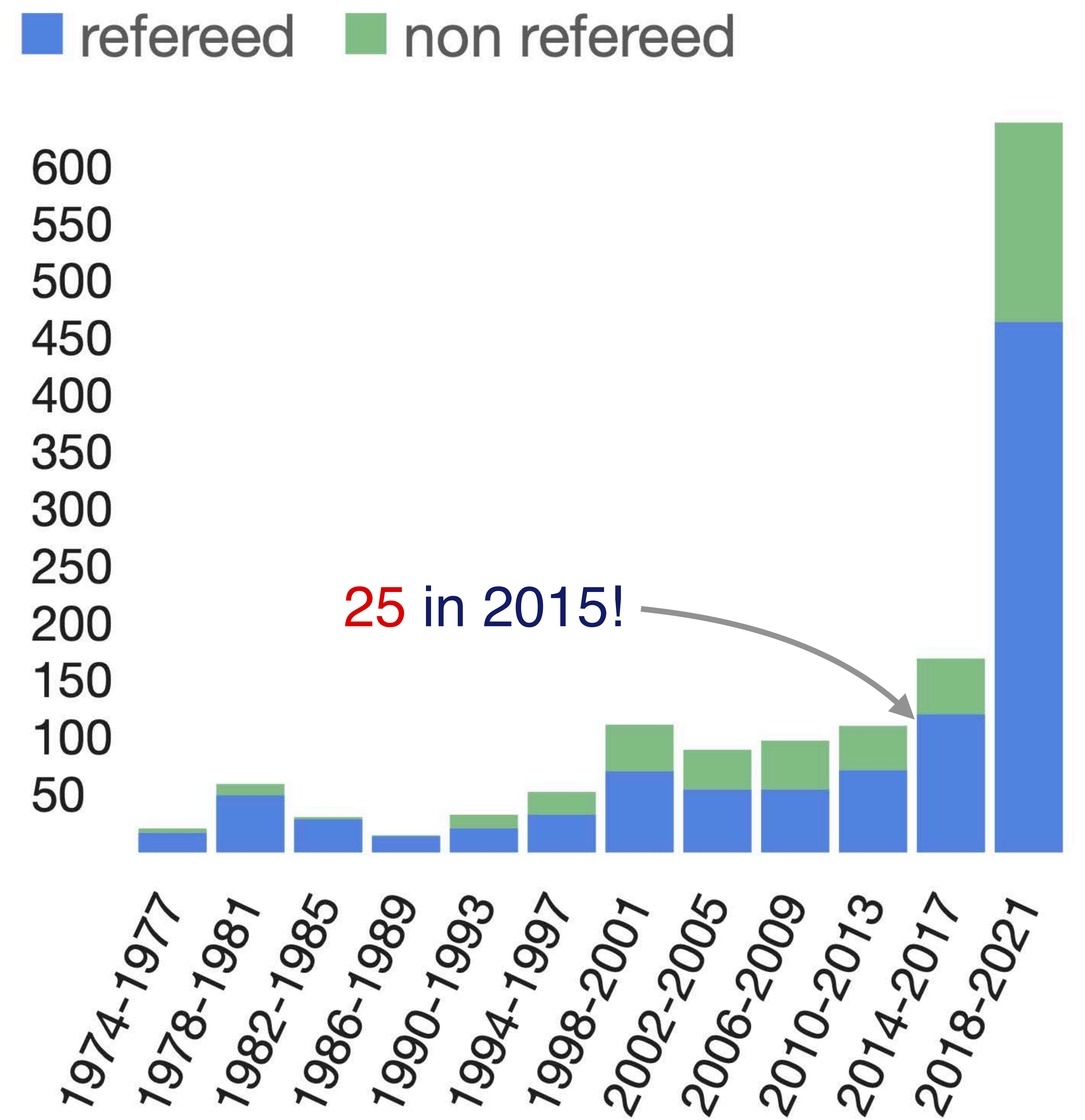


Primordial Black Holes are Popular!



[SAO/NASA Astrophysics Data System]

Primordial Black Holes are Popular!

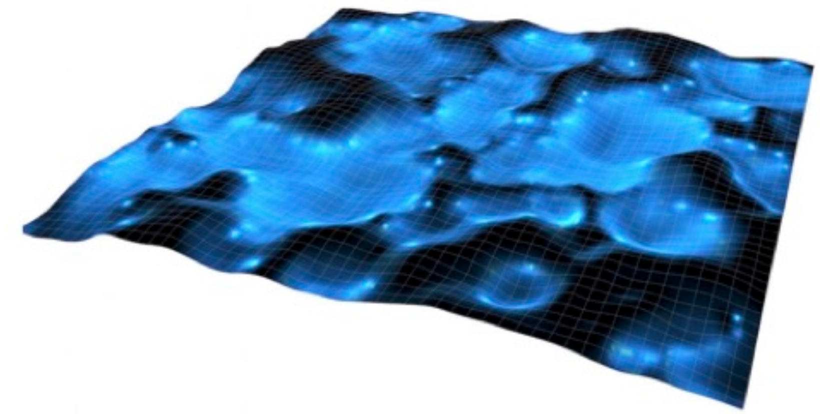


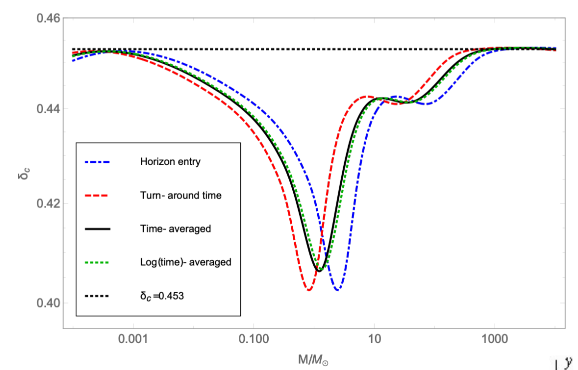
[SAO/NASA Astrophysics Data System]

Primordial Black Hole Formation

PBH Formation Mechanisms

- ★ Large density perturbations (inflation)

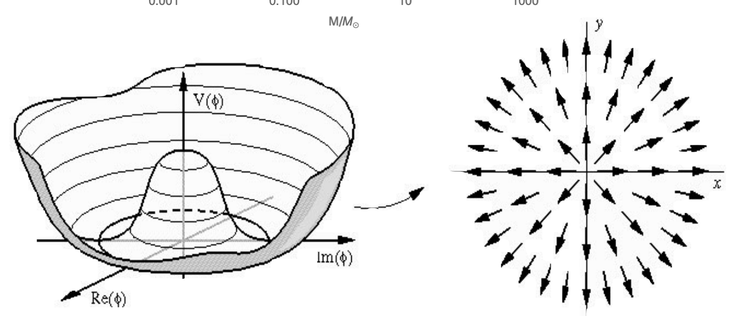




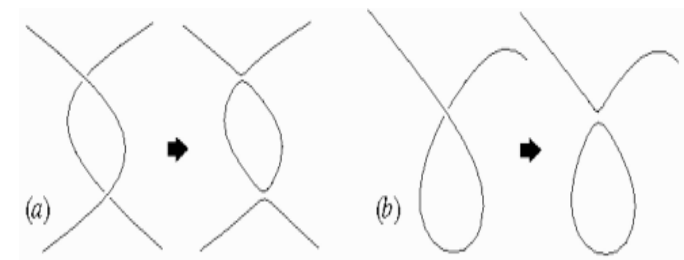
[Byrnes *et al.* 2018]

- ★ Pressure reduction

- ★ Cosmic string loops

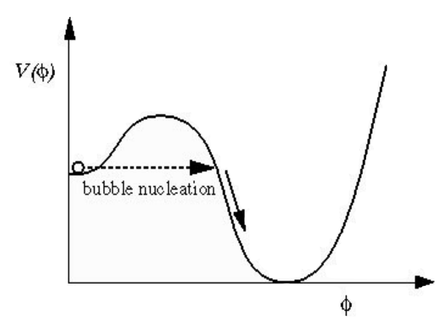


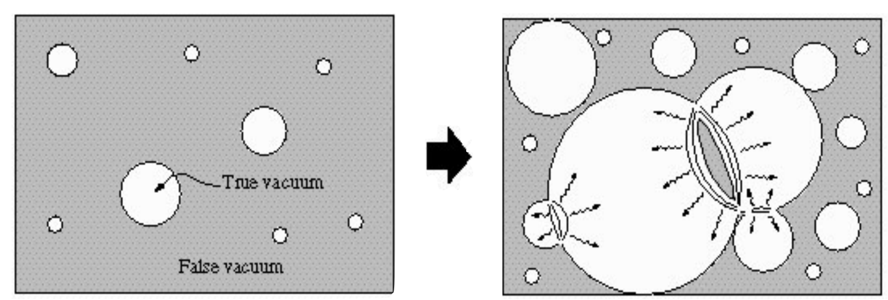
http://www.damtp.cam.ac.uk/research/gr/public/cs_phase.html



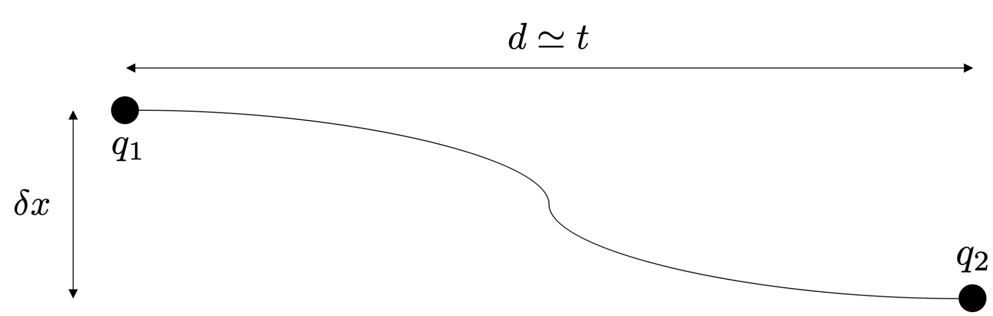
http://www.damtp.cam.ac.uk/research/gr/public/cs_top.html

- ★ Bubble collisions



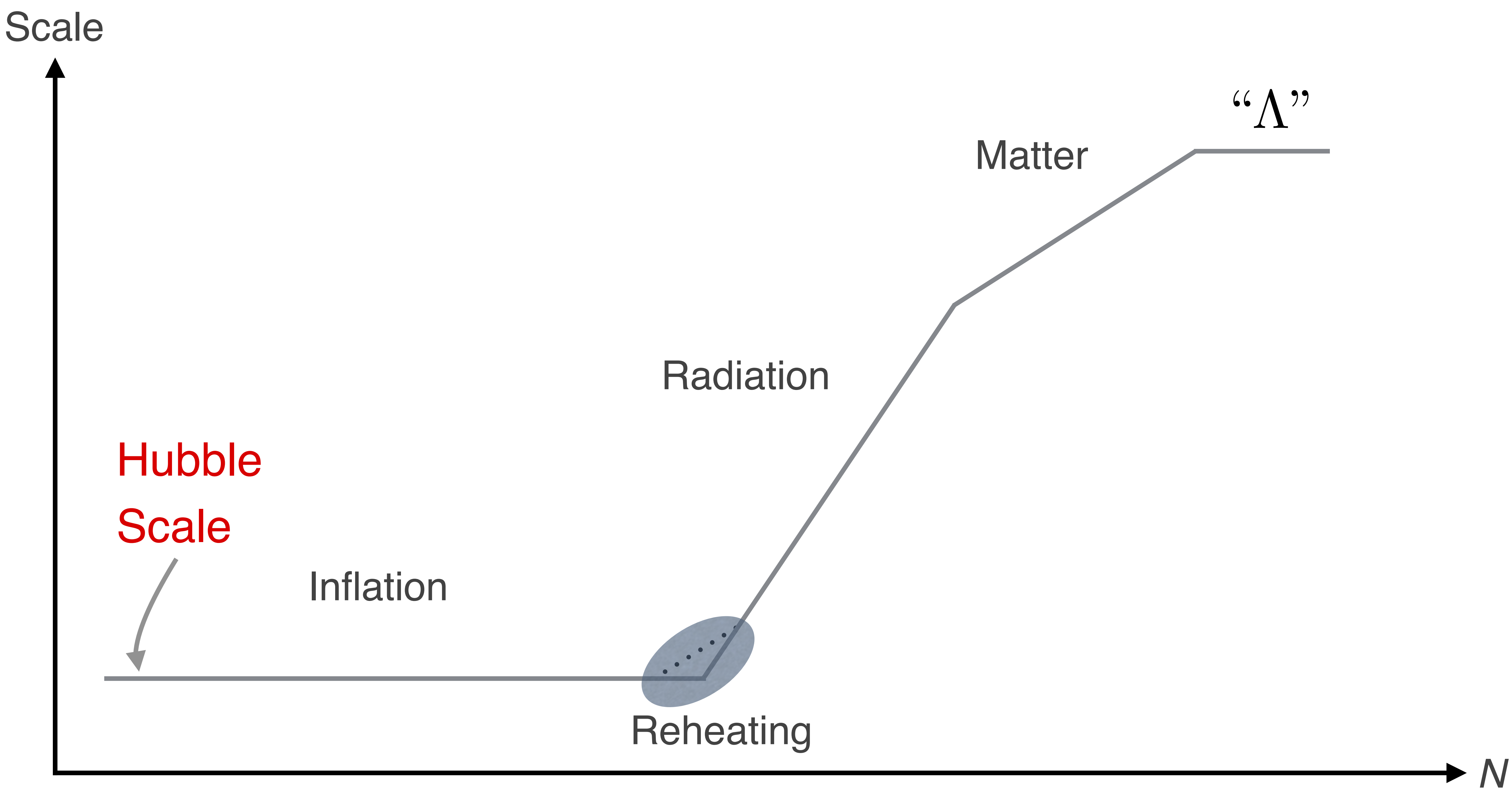


- ★ Quark confinement

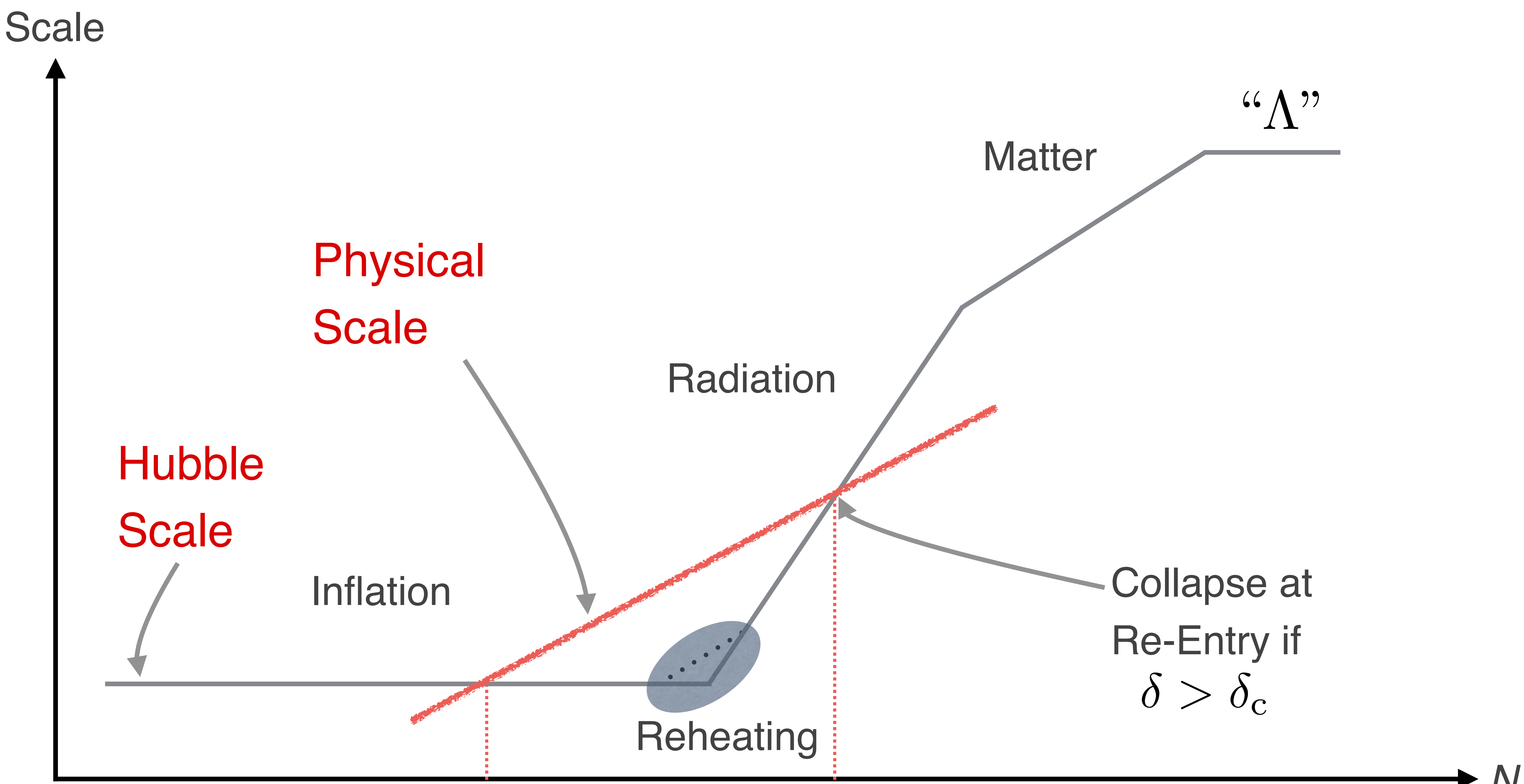


- ★ Q-balls, Multiverse...

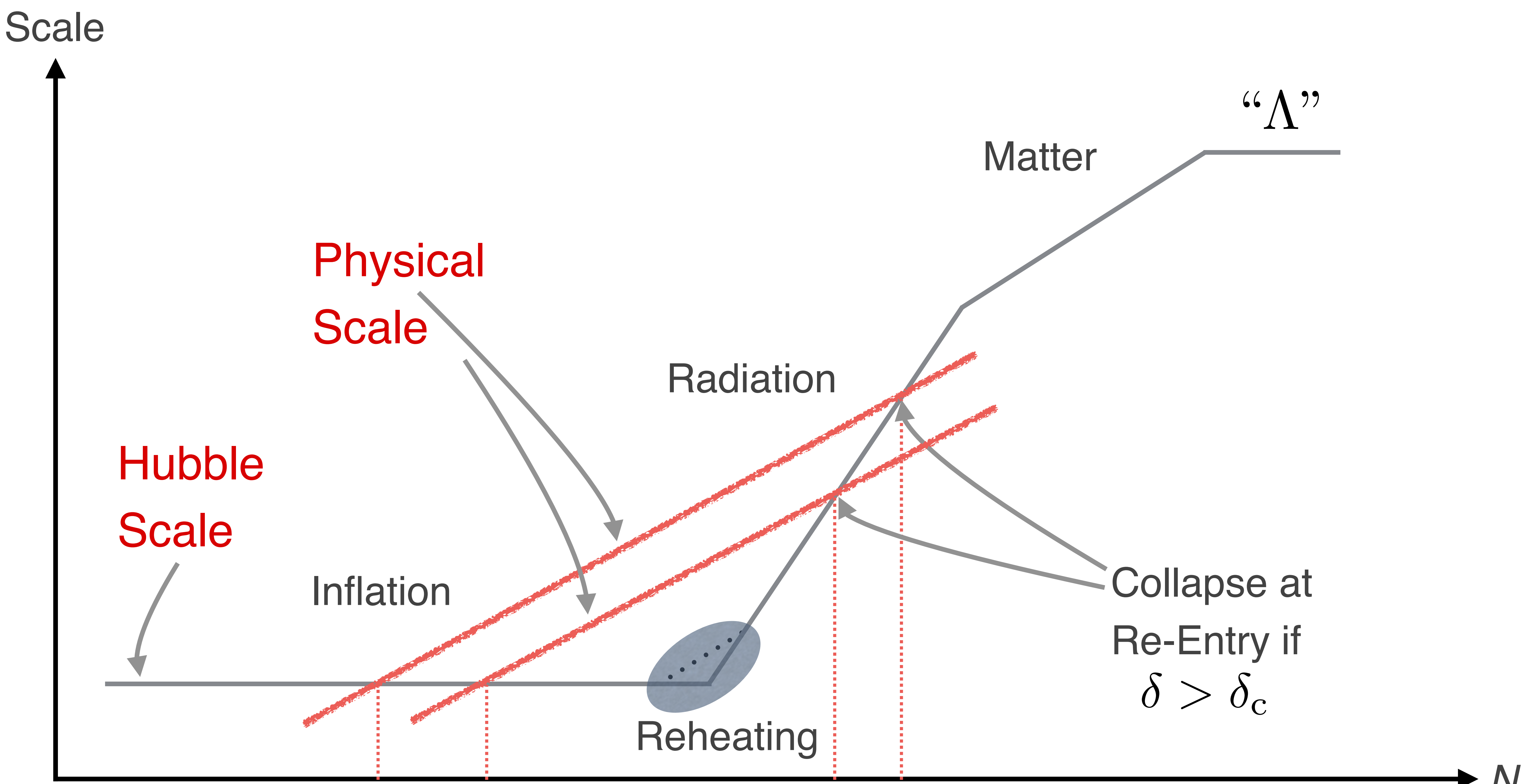
PBH Formation from Inflationary Overdensities



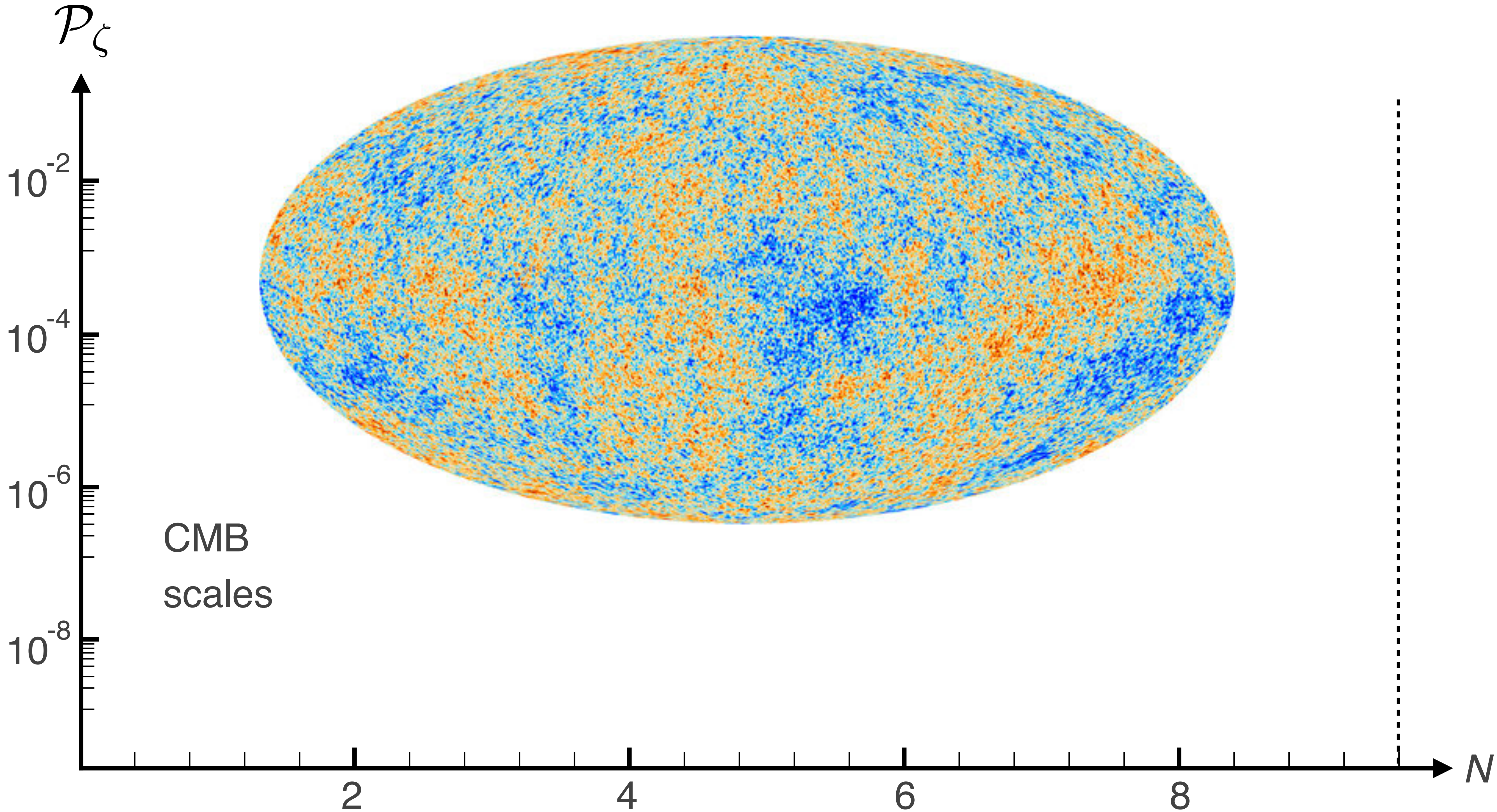
PBH Formation from Inflationary Overdensities



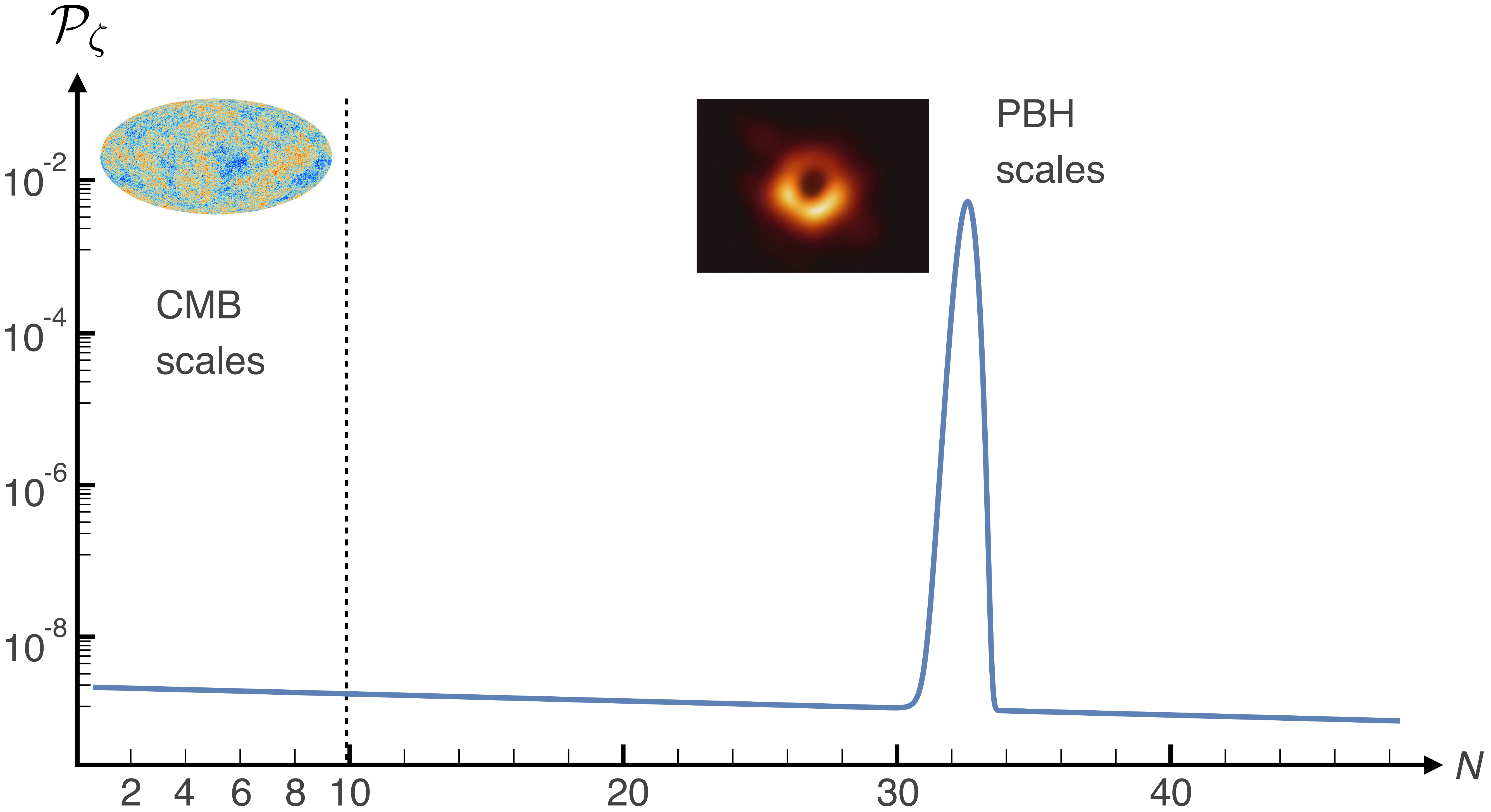
PBH Formation from Inflationary Overdensities



PBH Formation — Scales



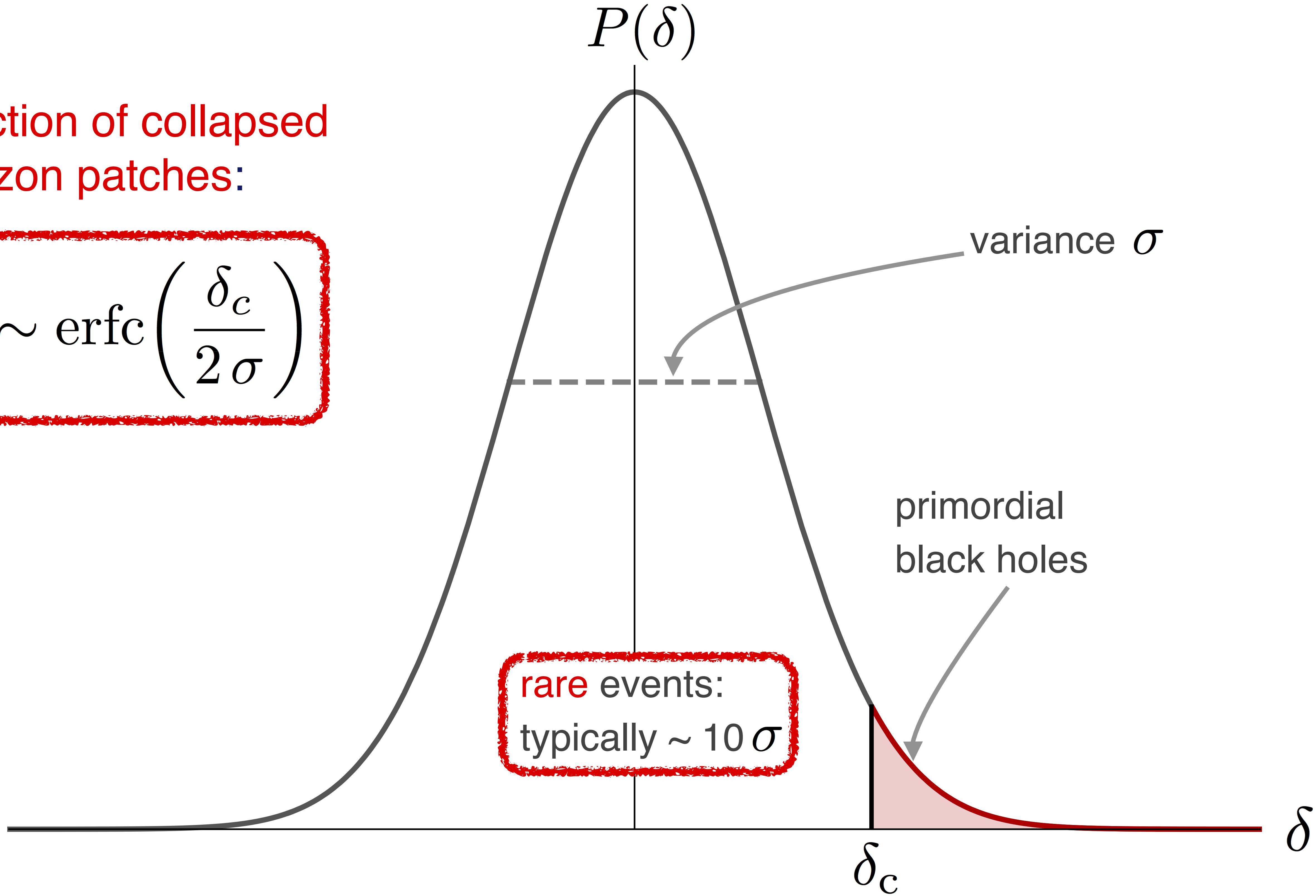
PBH Formation — Scales



PBH Formation — Rare Events

Fraction of collapsed horizon patches:

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

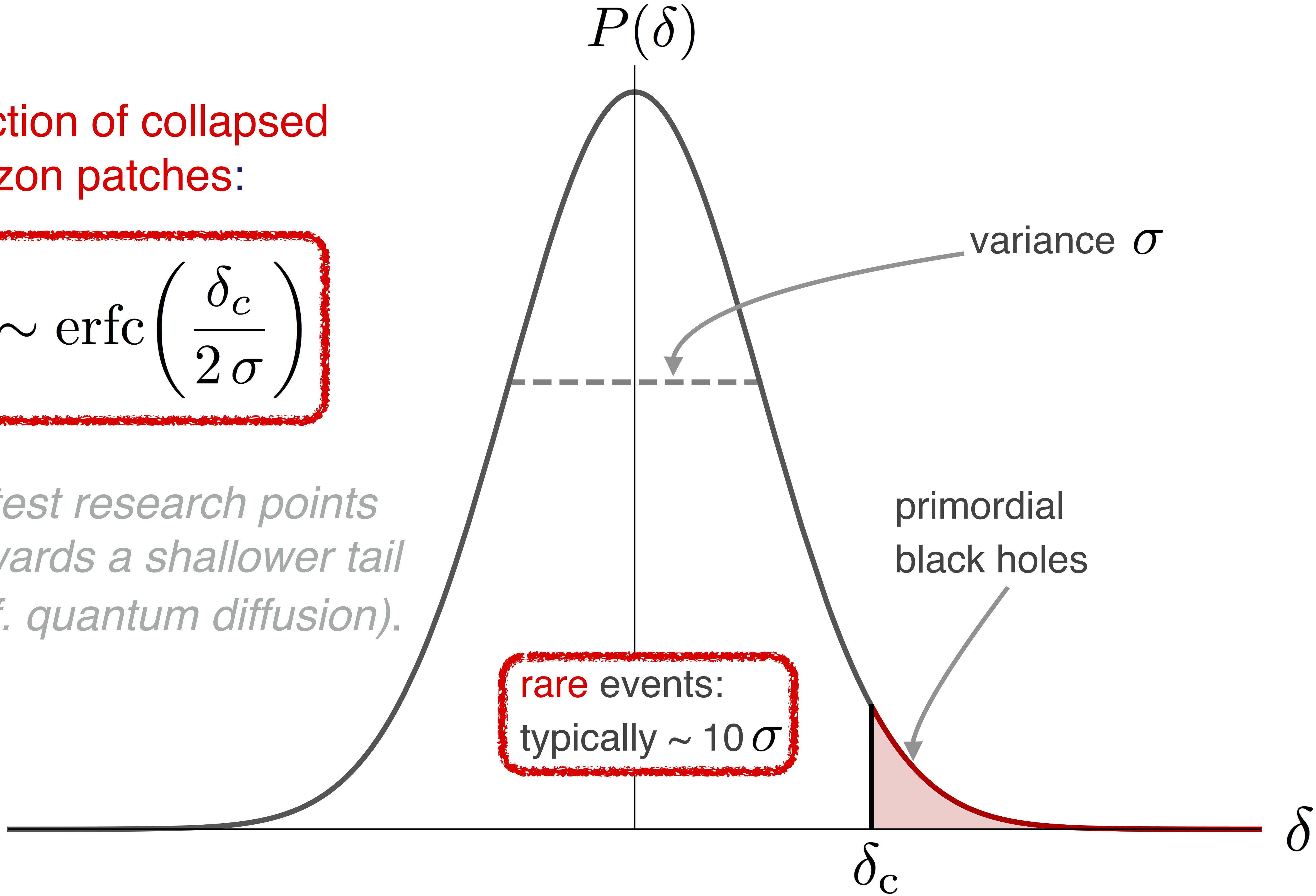


PBH Formation — Rare Events

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} g
- ★ Size: 10^{-8} cm
- ★ Number in our Galaxy: 10^{25}
- ★ Distance: 10 AU

PBH — Probes of Scales

★ PBHs probe a huge range of scales:

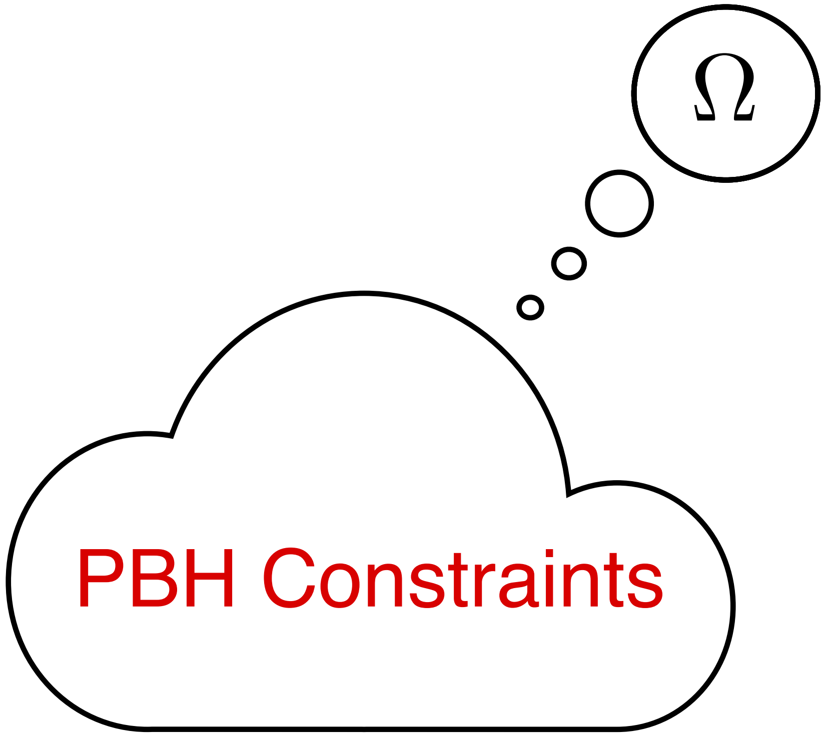
$M \sim 10^{-5}\mathrm{g}$ Quantum Gravity: Planck relics, Extra dimensions and higher-dimensional black holes, …

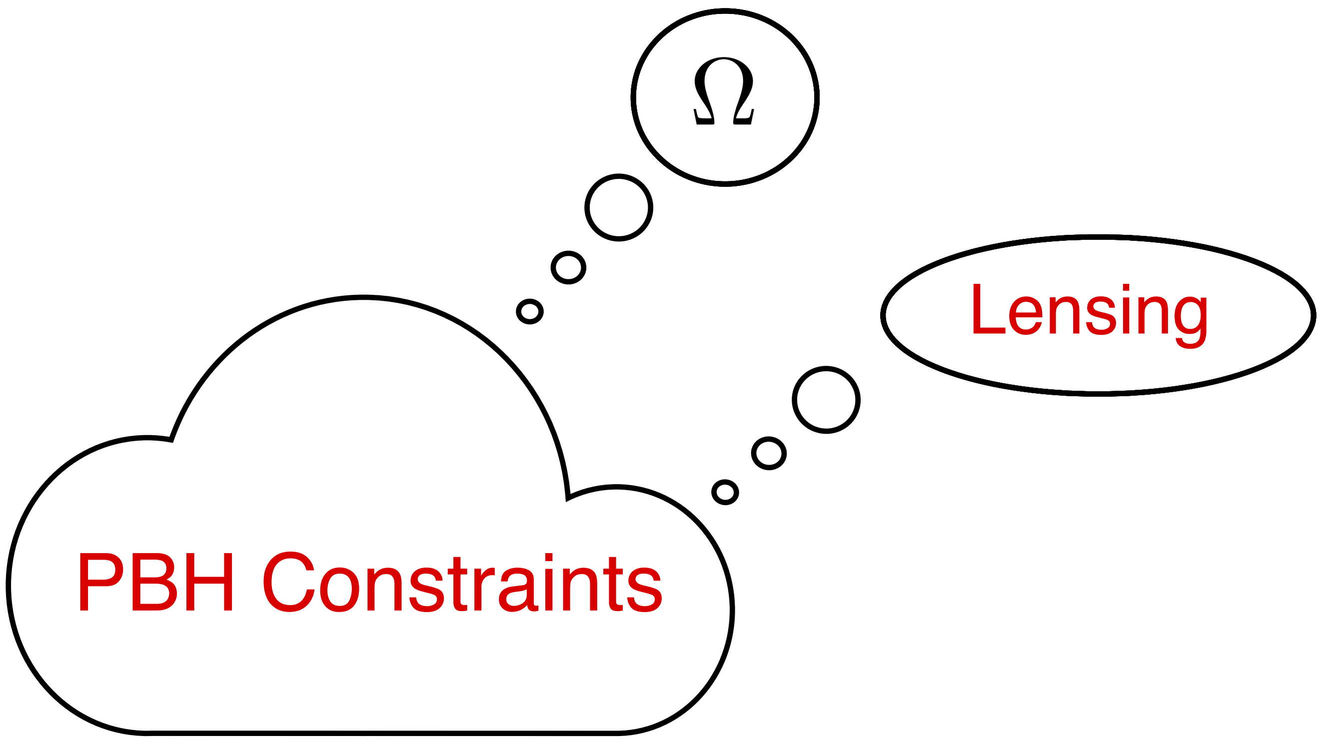
$M \lesssim 10^{15}\mathrm{g}$ Early Universe: Nucleosynthesis, Reionisation, …

$M \sim 10^{15}\mathrm{g}$ High-Energy Physics: Cosmological and galactic gamma-rays, …

$M \gtrsim 10^{15}\mathrm{g}$ Gravity: Critical phenomena,
Cold dark matter,
Dynamical effects, Lensing effects,
Gravitational waves,
Black holes in galactic nuclei, …

PBH Constraints


Ω
PBH Constraints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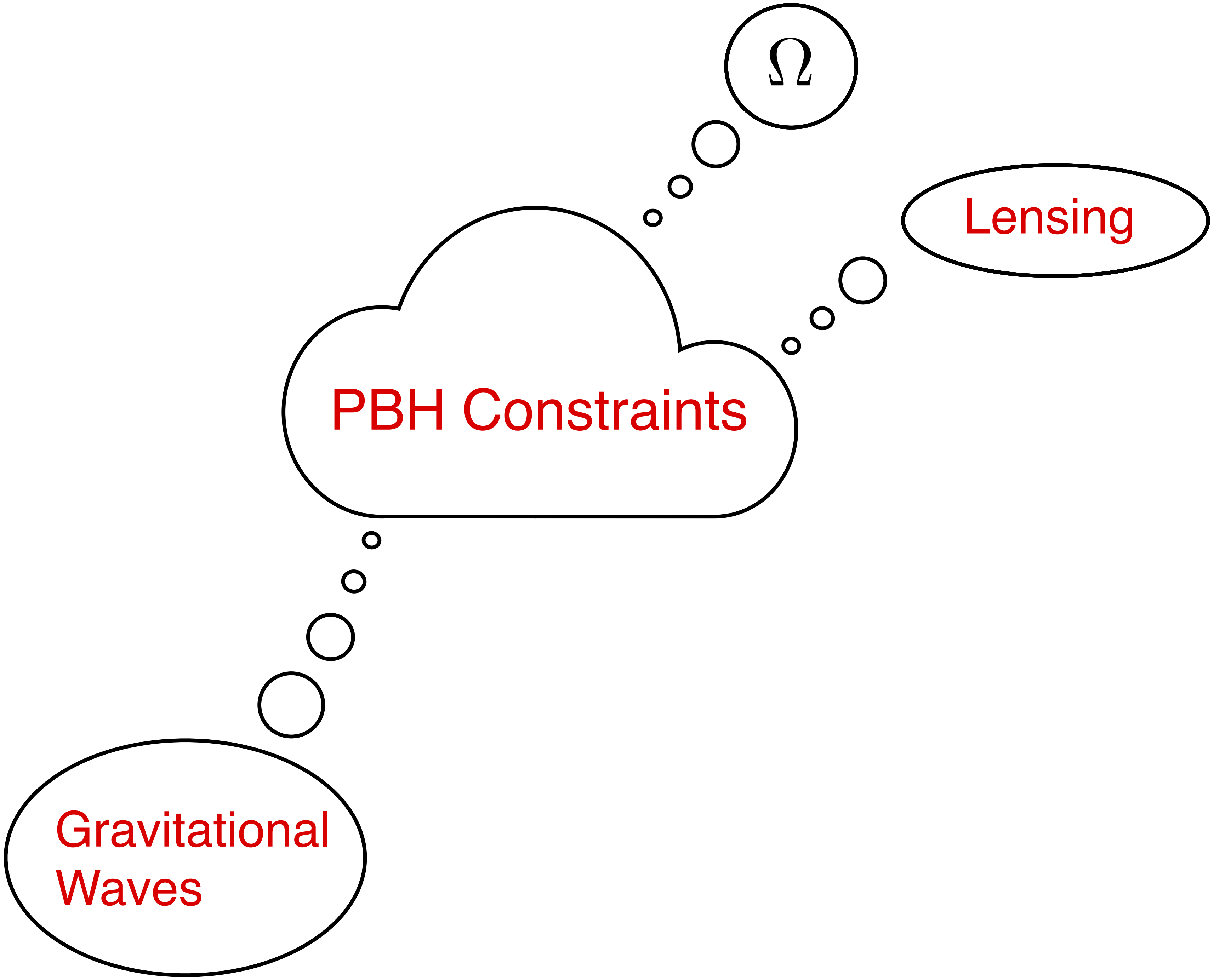
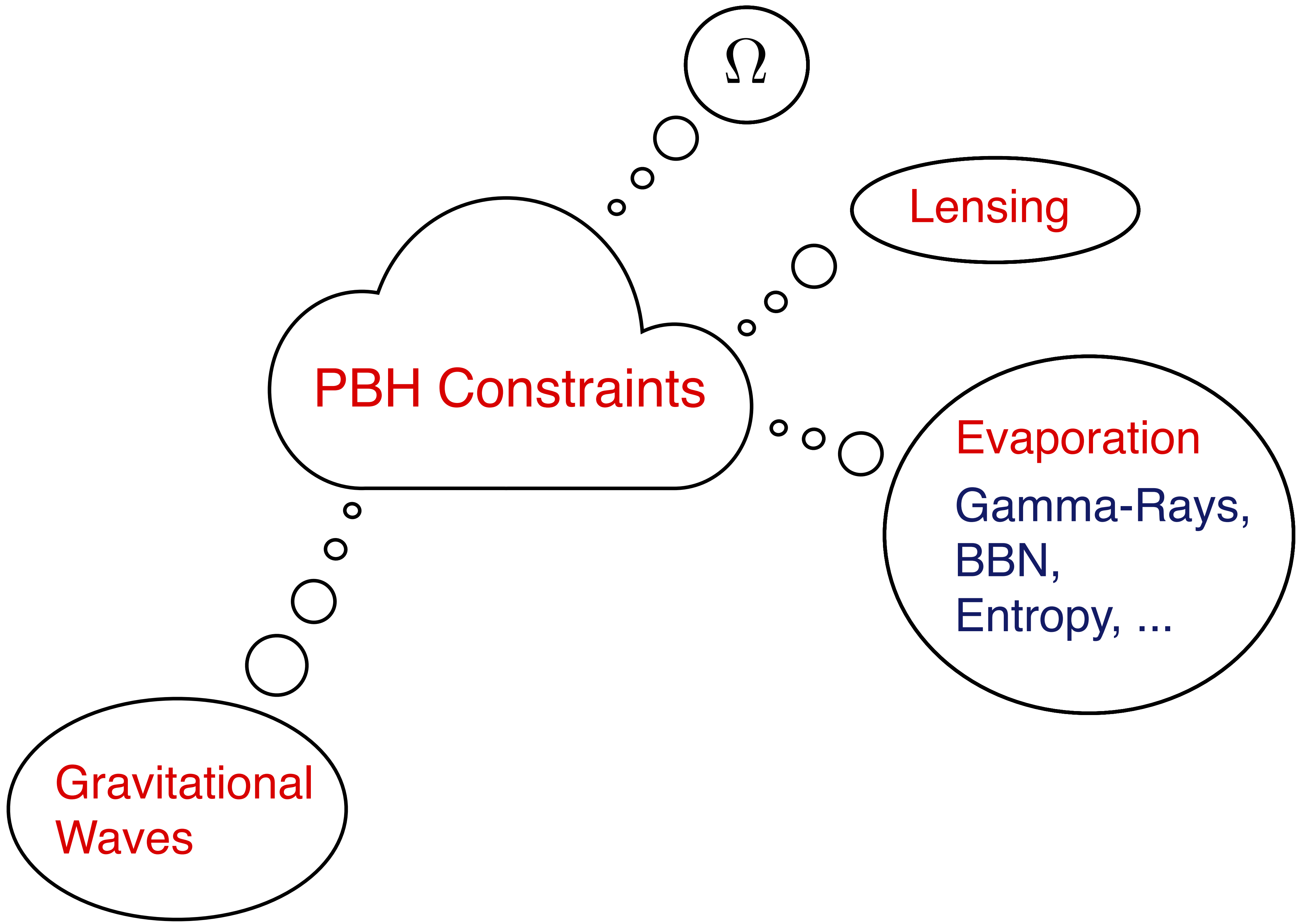
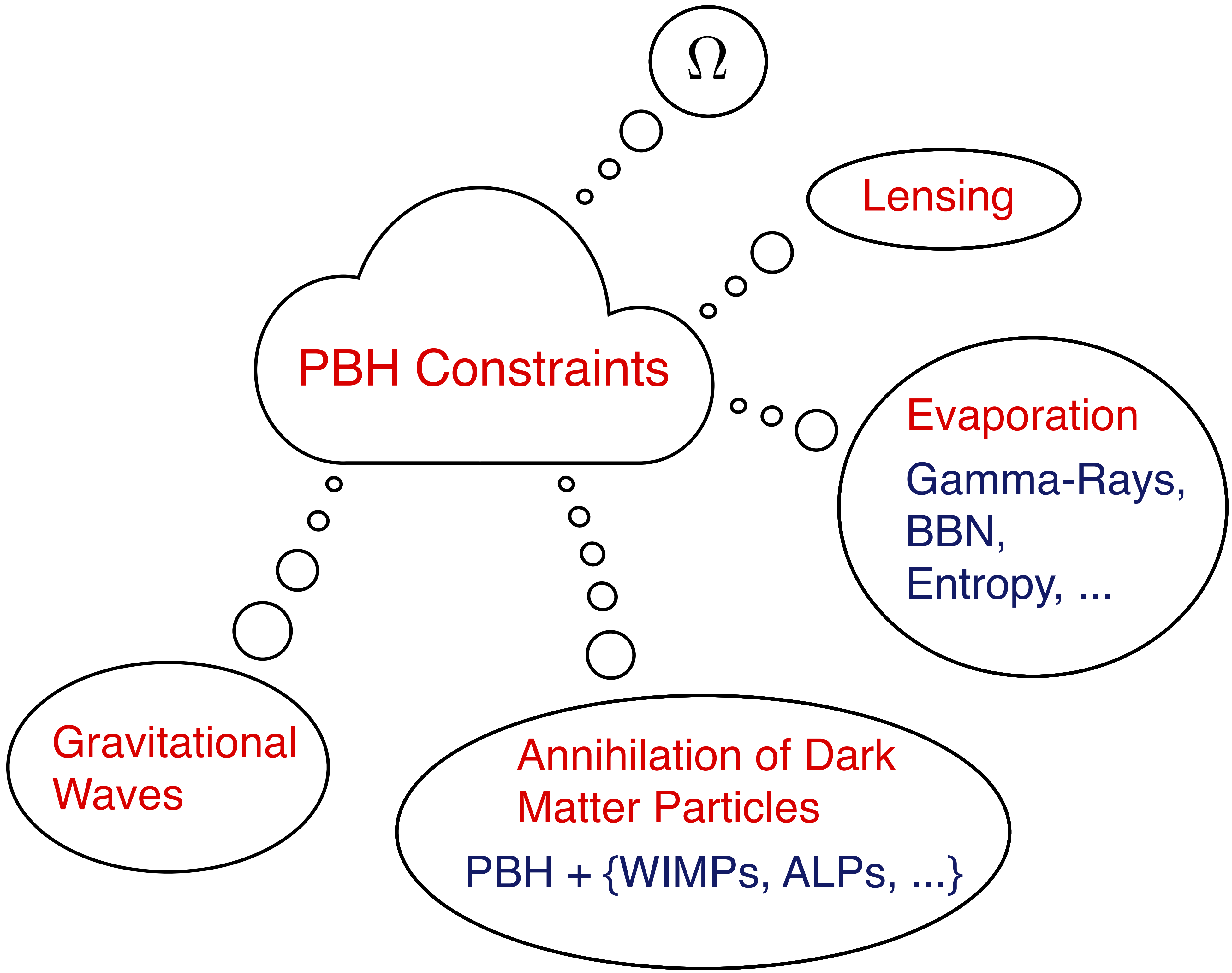
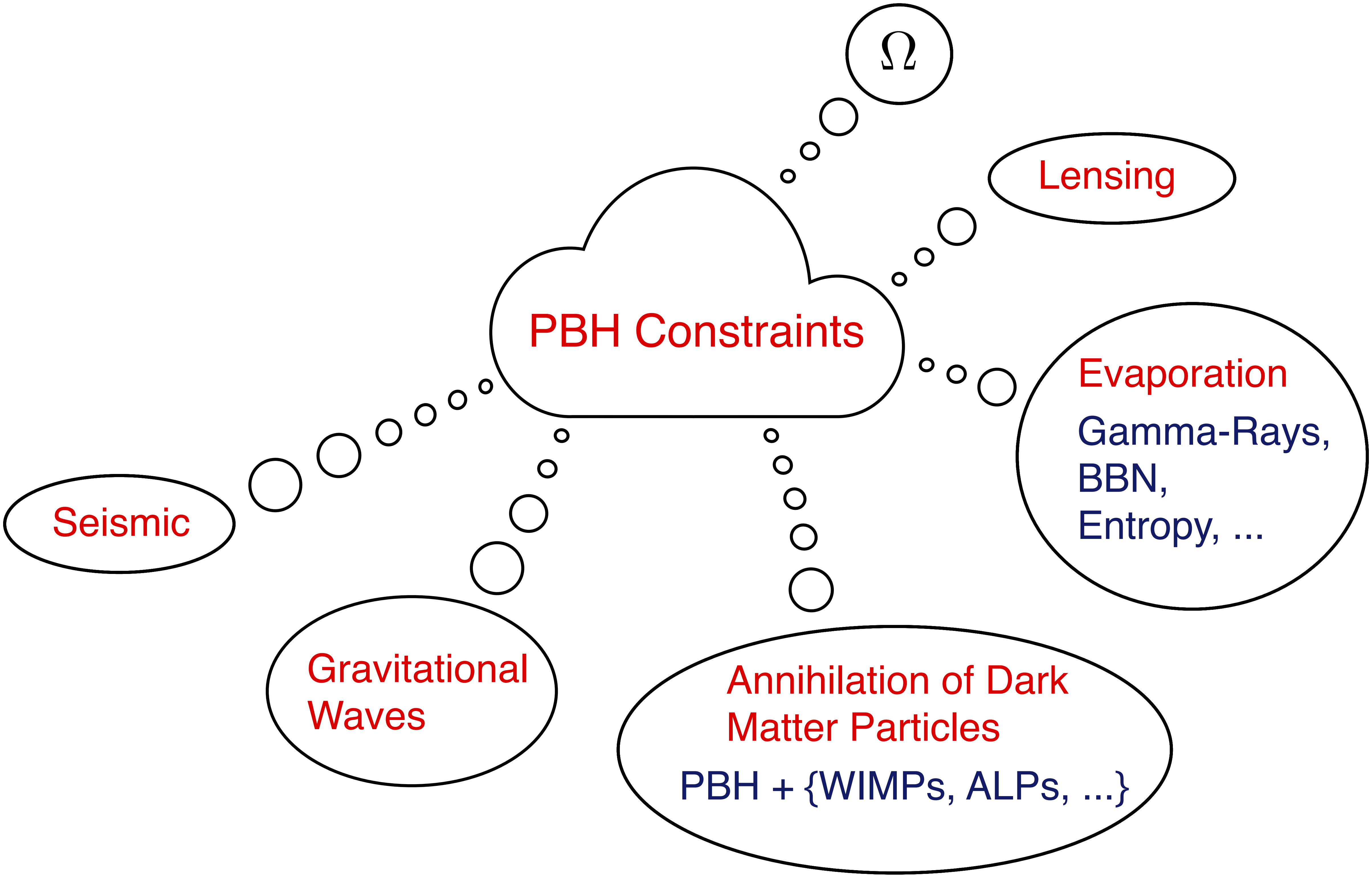
Lensing
PBH Constraints


Ω
Lensing
PBH Constraints
Gravitational
Waves


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



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


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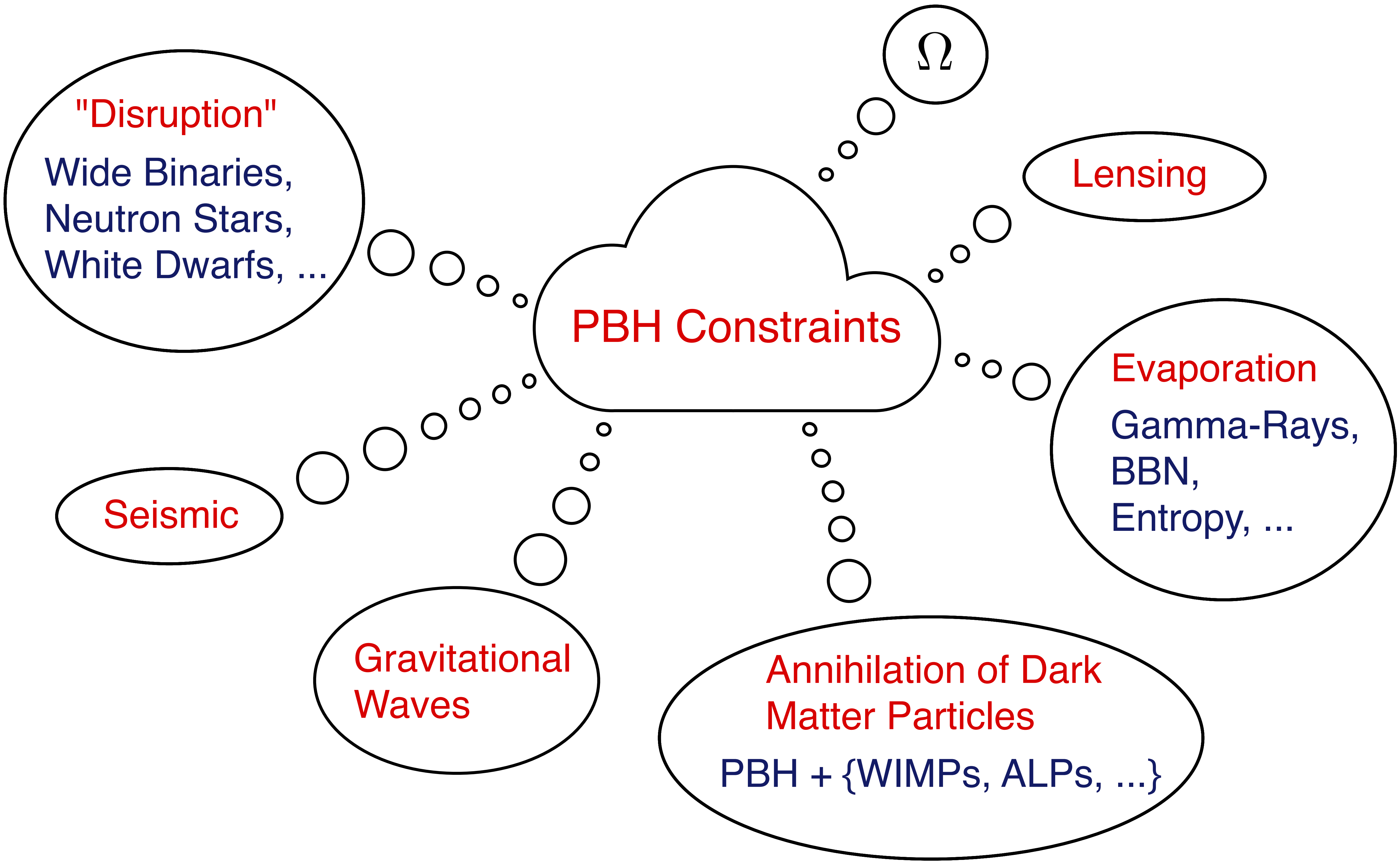
PBH Constraints
Ω
"Disruption"
Wide Binaries,
Neutron Stars,
White Dwarfs, ...
Lensing
Evaporation
Gamma-Rays,
BBN,
Entropy, ...
Seismic
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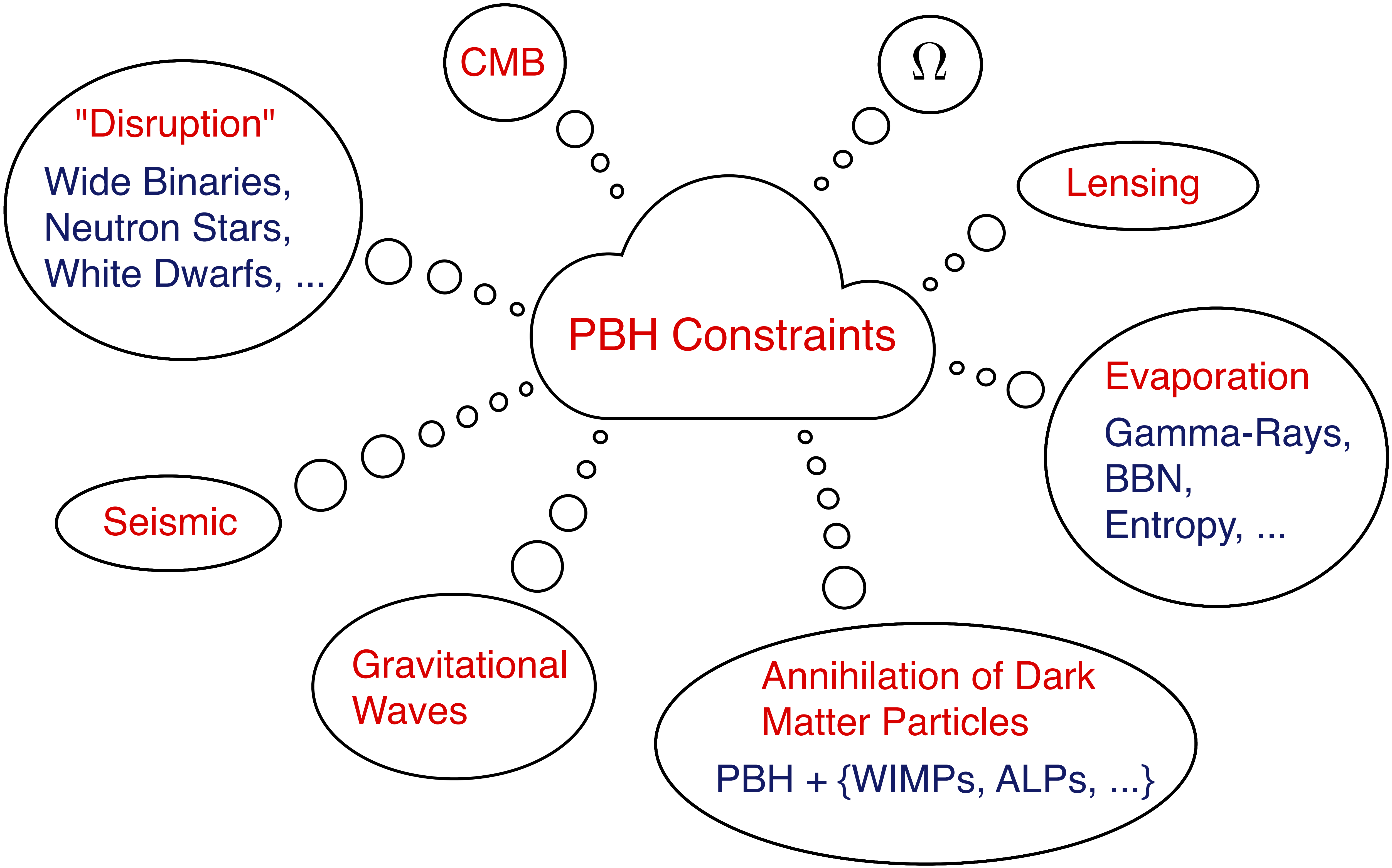
PBH Constraints
CMB
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Wide Binaries,
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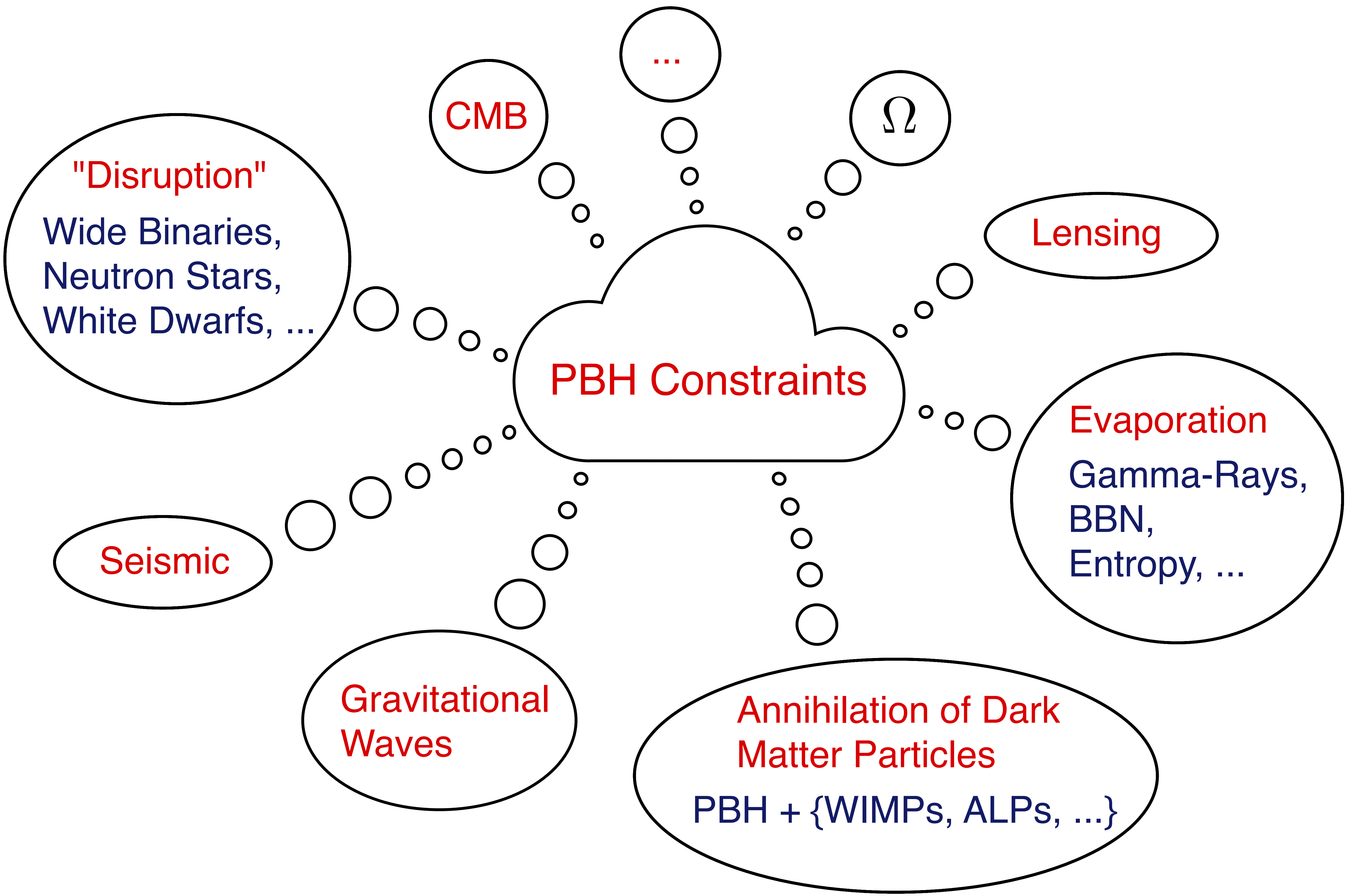
PBH Constraints
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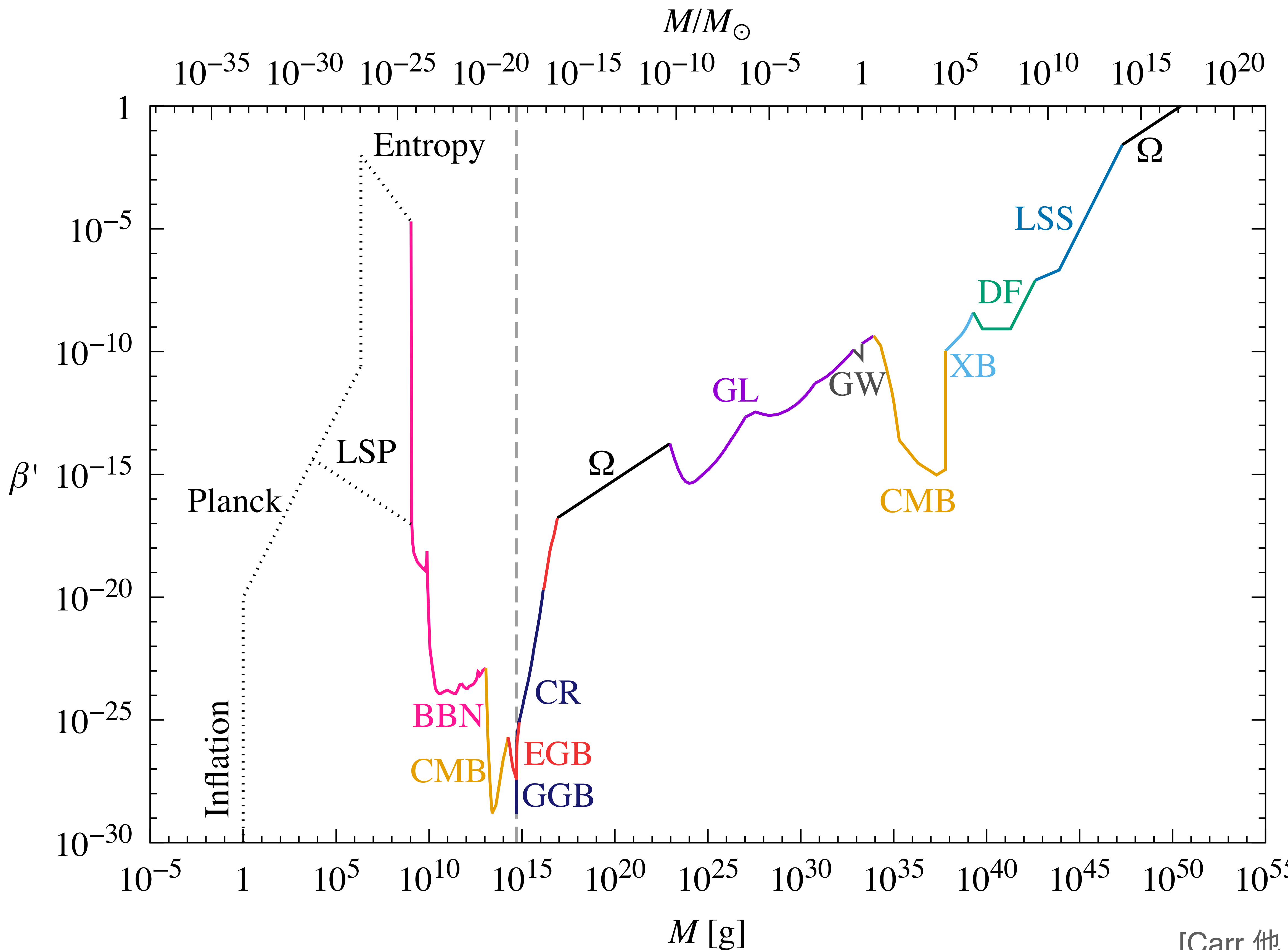
PBH + {WIMPs, ALPs, ...}

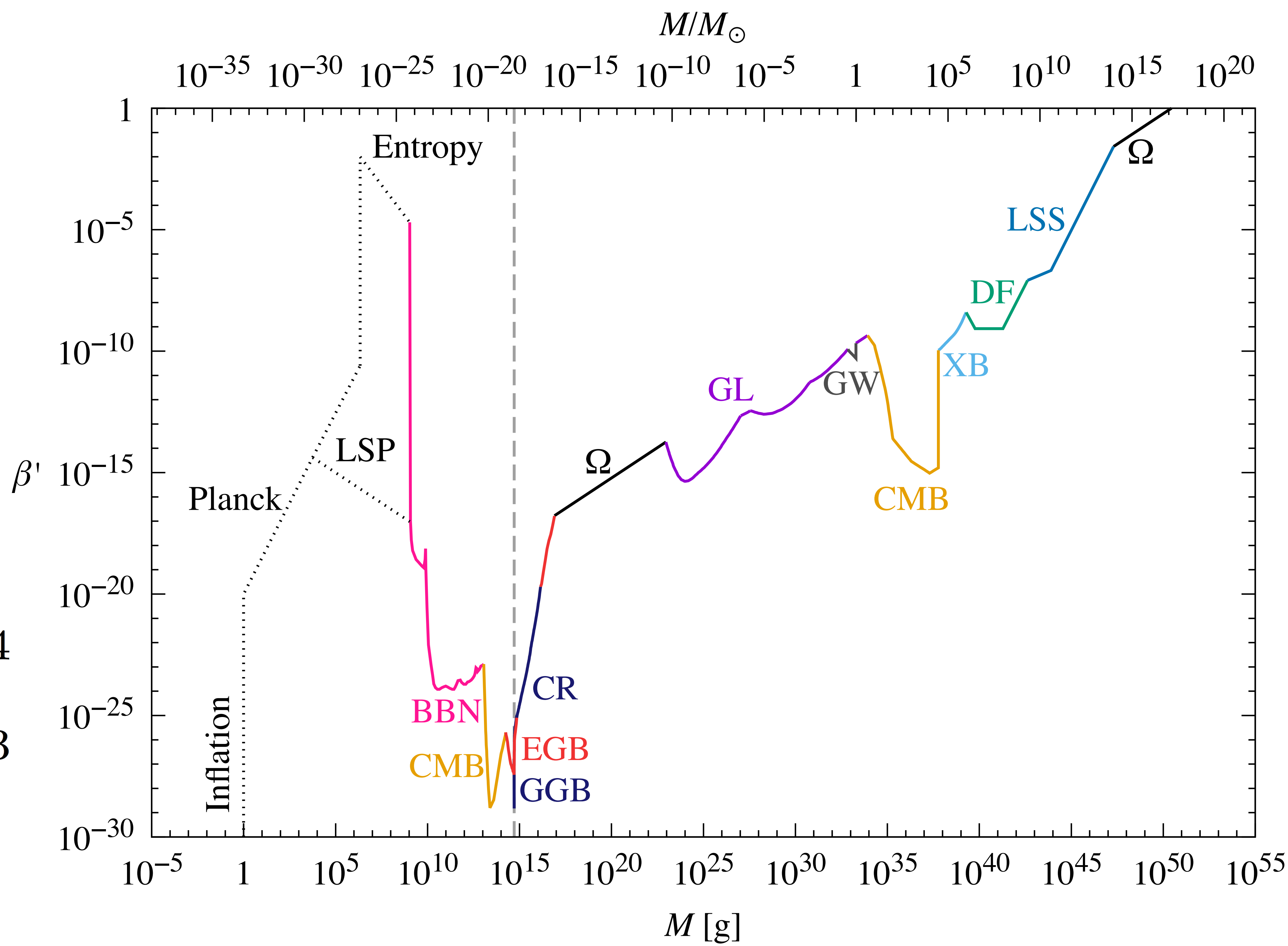
PBH Constraints at Formation



[Carr 他 2021]

PBH Constraints at Formation

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



[Carr 他 2021]

★ Note that

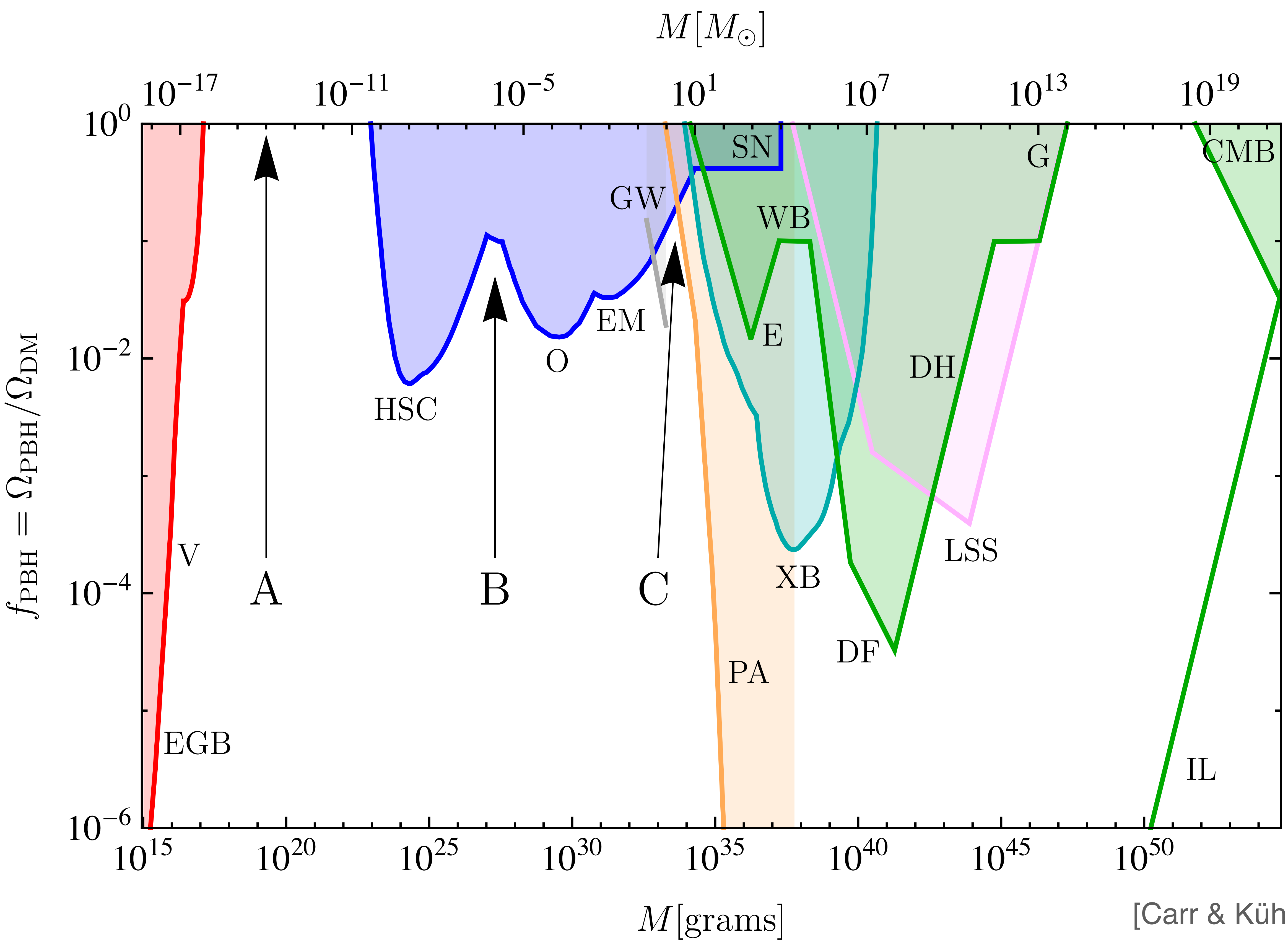
$$\rho_{\rm rad} \propto a^{-4}$$

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

and hence

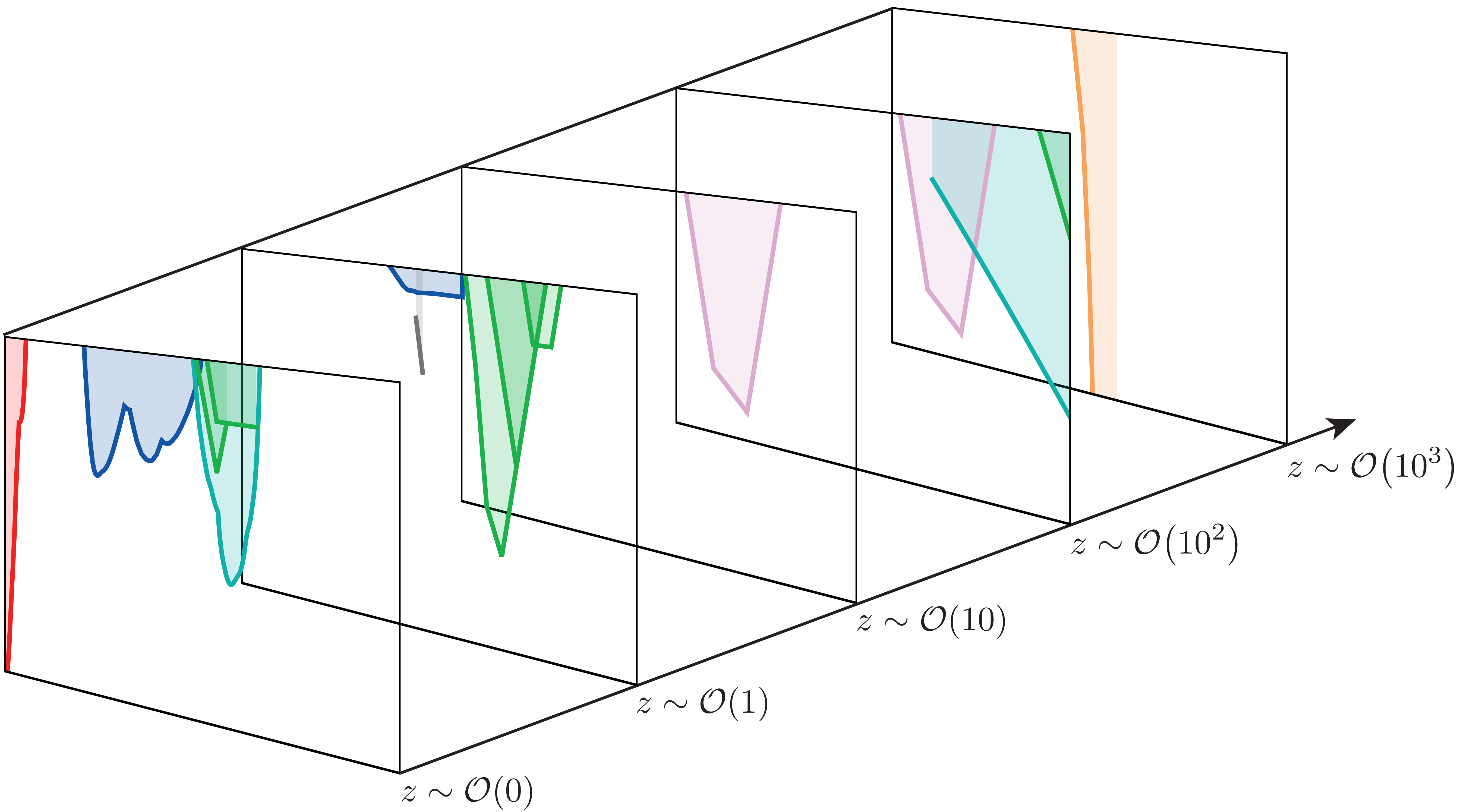
$$\Omega_{\rm PBH} \propto a$$

Current PBH Constraints



[Carr & Kühnel 2020]

PBH Constraints — Redshift Dependence



[Carr & Kühnel 2020]

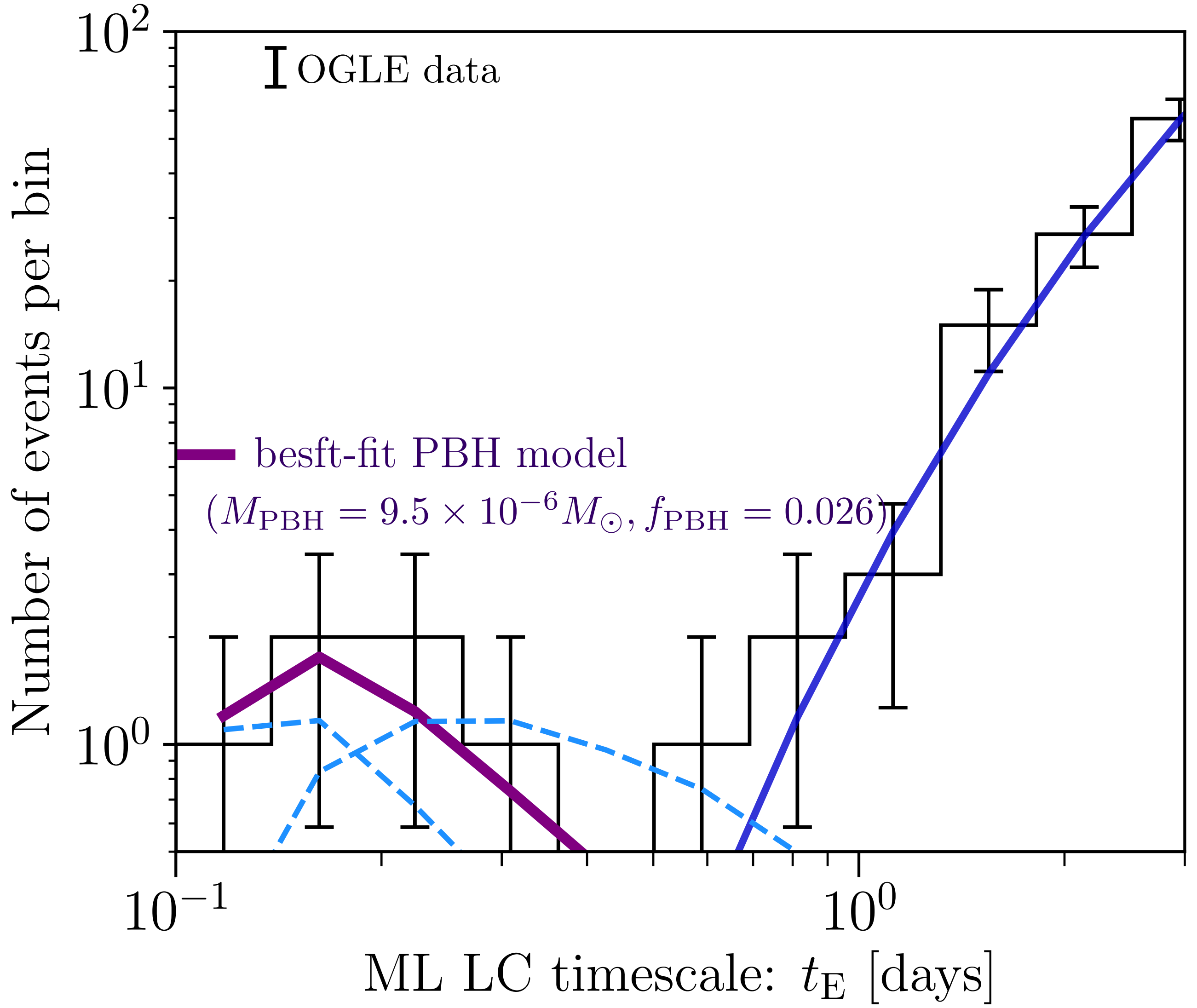
Observational Hints for Primordial Black Holes

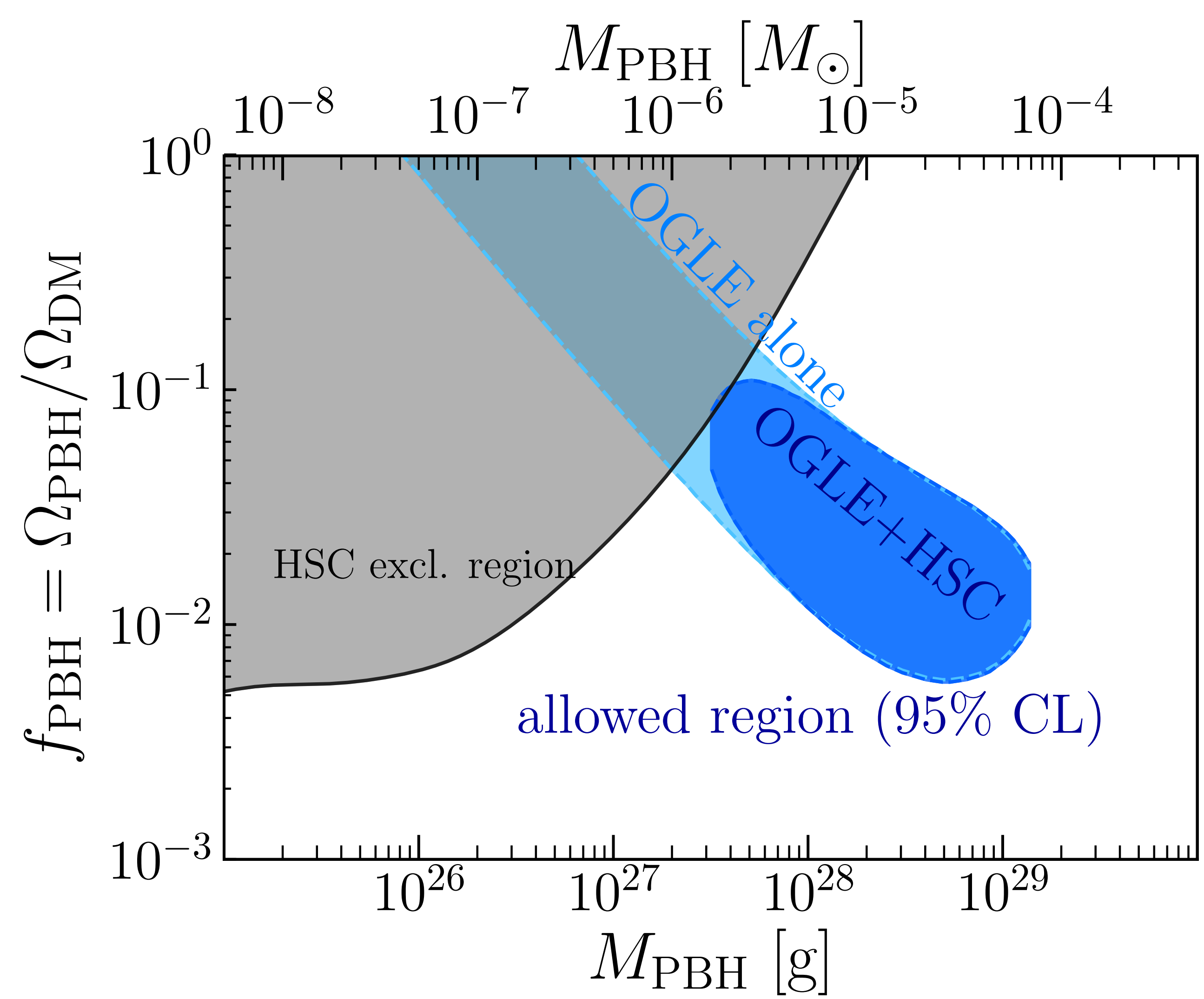
Evidence?

Observational ~~Hints~~ for Primordial Black Holes

Planetary-Mass Microlensing

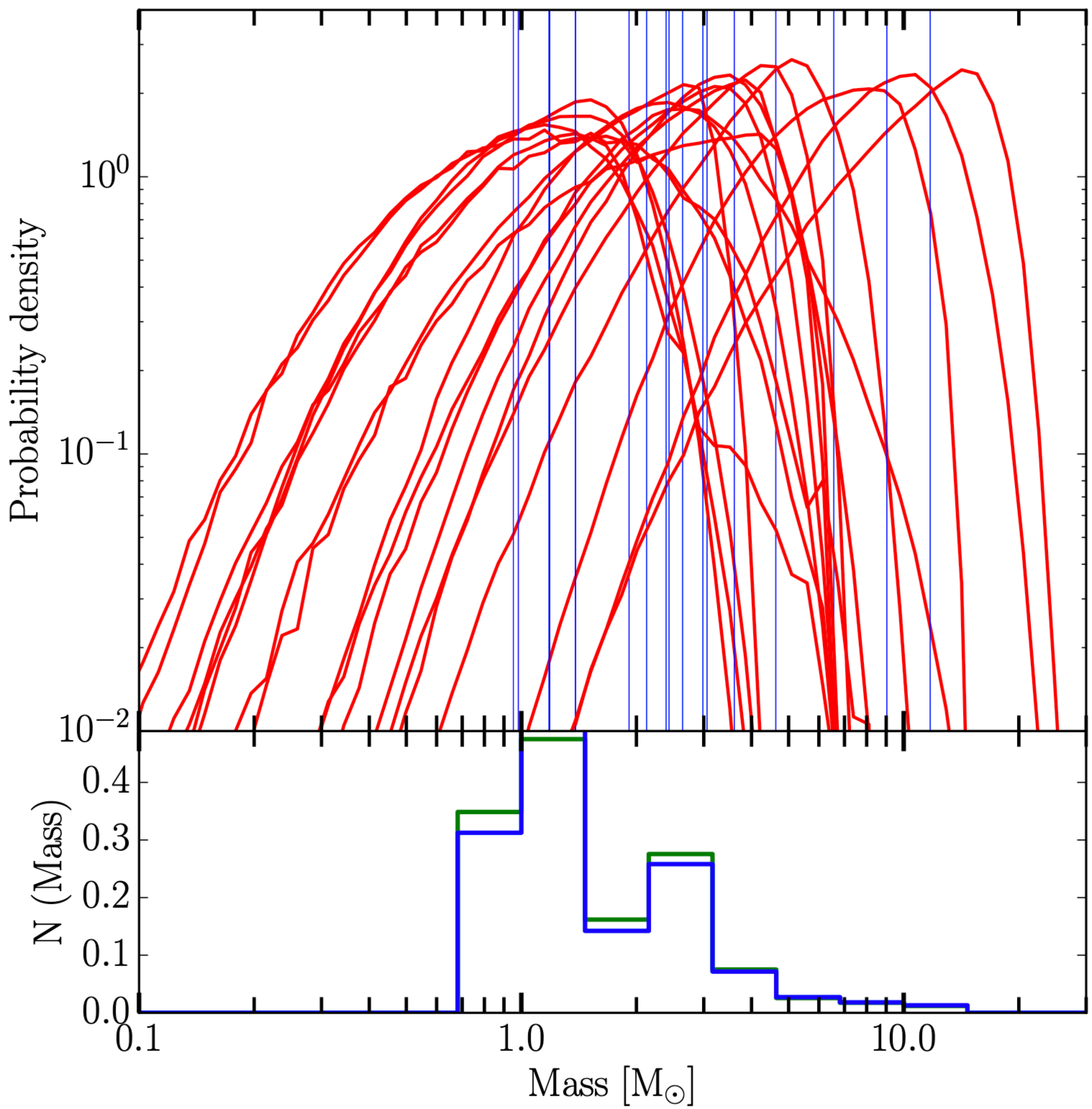
- ★ OGLE detected a particular population of microlensing events:
  - ★ 0.1 - 0.3 days light-curve timescale - origin unknown! Could be free-floating planets... or PBHs!





[Niikura *et al.* 2019]

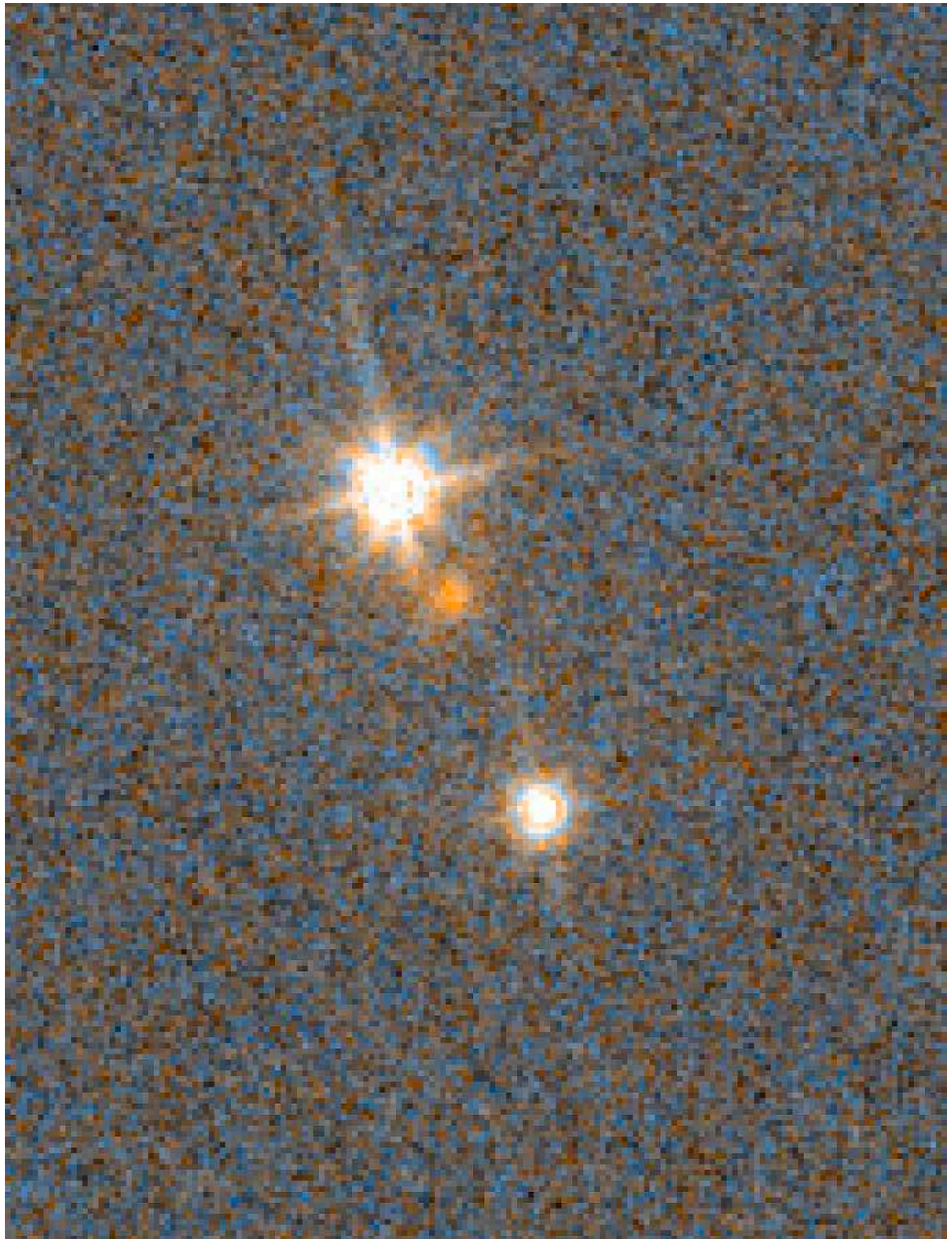
Excess of Lenses in Galactic Bulge



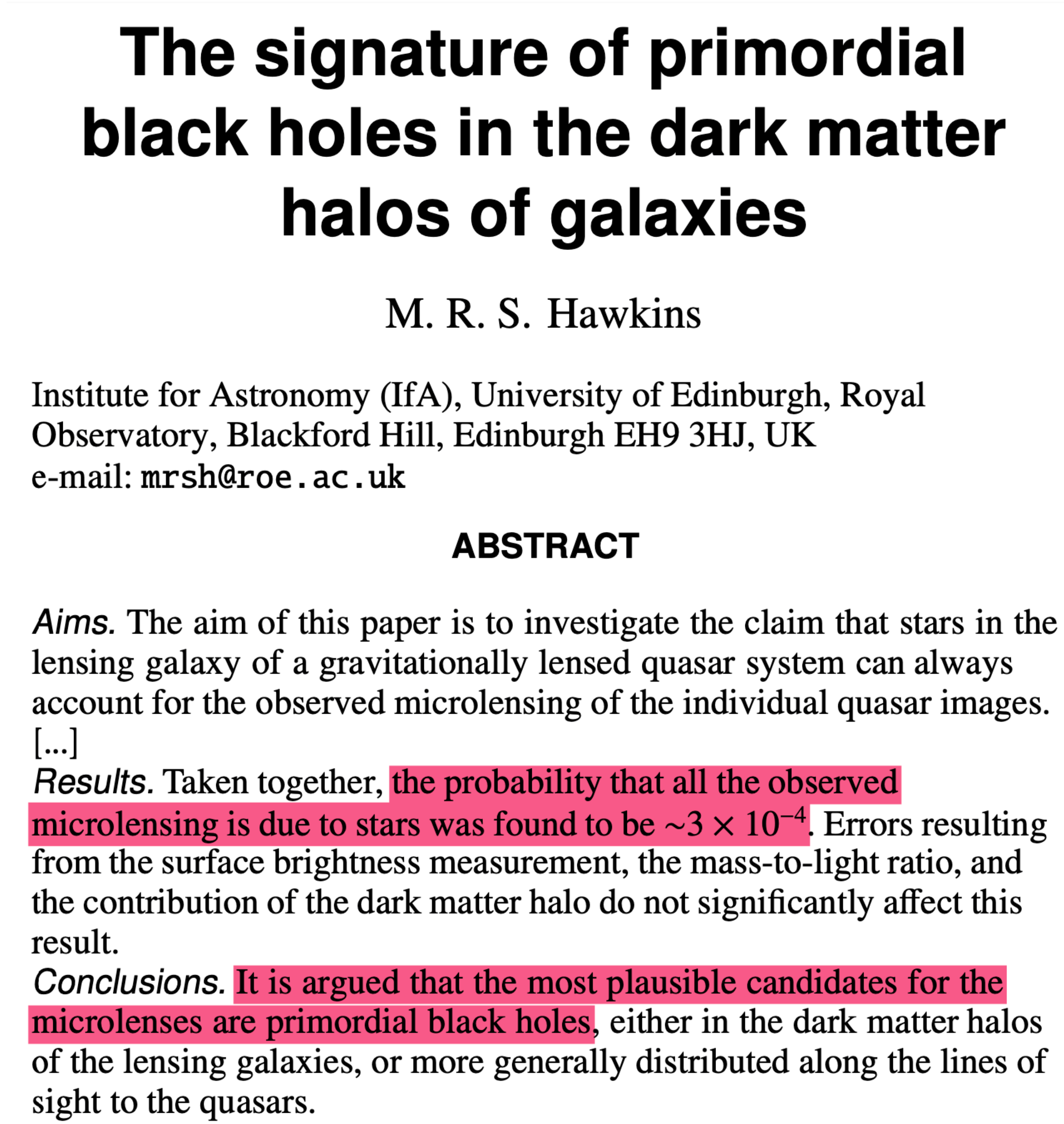
- ★ OGLE has detected 58 long-duration microlensing events in the Galactic bulge.
- ★ 18 of these cannot be main-sequence stars and are very likely black holes.
- ★ Their mass function overlaps the low mass gap from 2 to 5 $M_\odot$.
- ★ These are not expected to form as the endpoint of stellar evolution.

[Wyrzykowski & Mandel 2020]

Quasar Microlensing



HST image of lensed quasar HE1104–1805


The signature of primordial black holes in the dark matter halos of galaxies

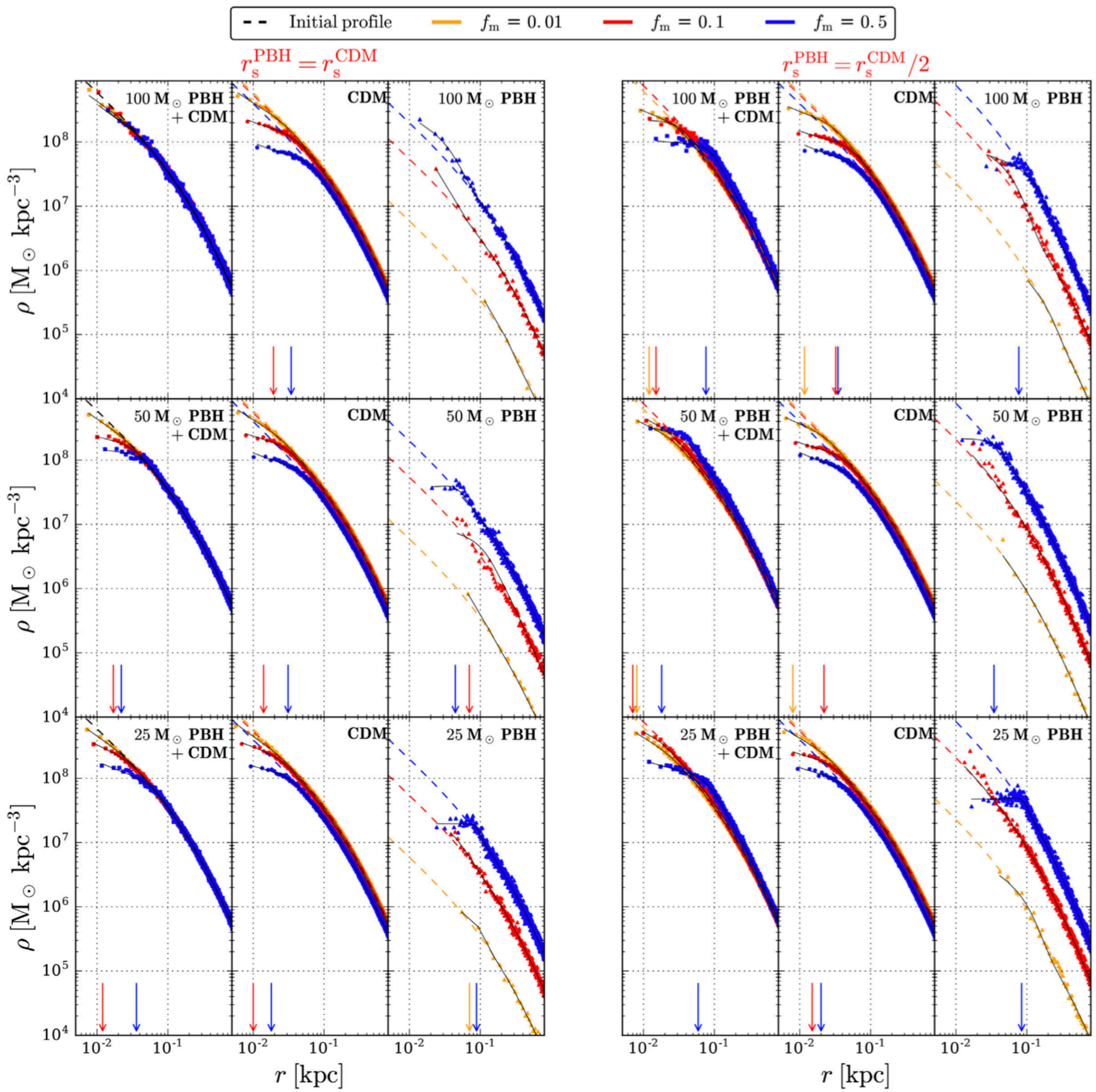
M. R. S. Hawkins

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

ABSTRACT

Aims. The aim of this paper is to investigate the claim that stars in the lensing galaxy of a gravitationally lensed quasar system can always account for the observed microlensing of the individual quasar images.
[...]
Results. Taken together, the probability that all the observed microlensing is due to stars was found to be $\sim 3 \times 10^{-4}$. Errors resulting from the surface brightness measurement, the mass-to-light ratio, and the contribution of the dark matter halo do not significantly affect this result.
Conclusions. It is argued that the most plausible candidates for the microlenses are primordial black holes, either in the dark matter halos of the lensing galaxies, or more generally distributed along the lines of sight to the quasars.

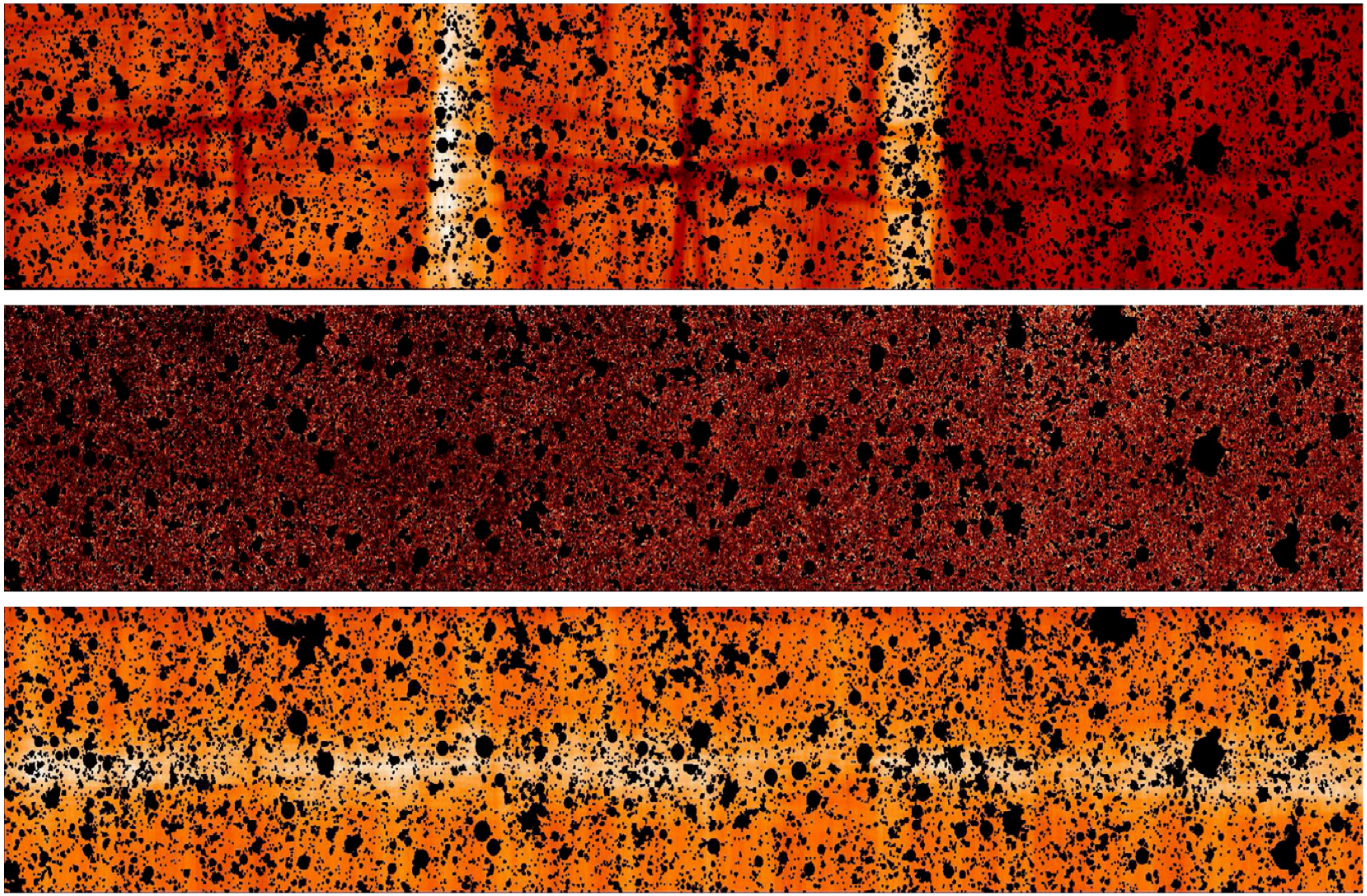
Ultra-faint Dwarf Galaxies



[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

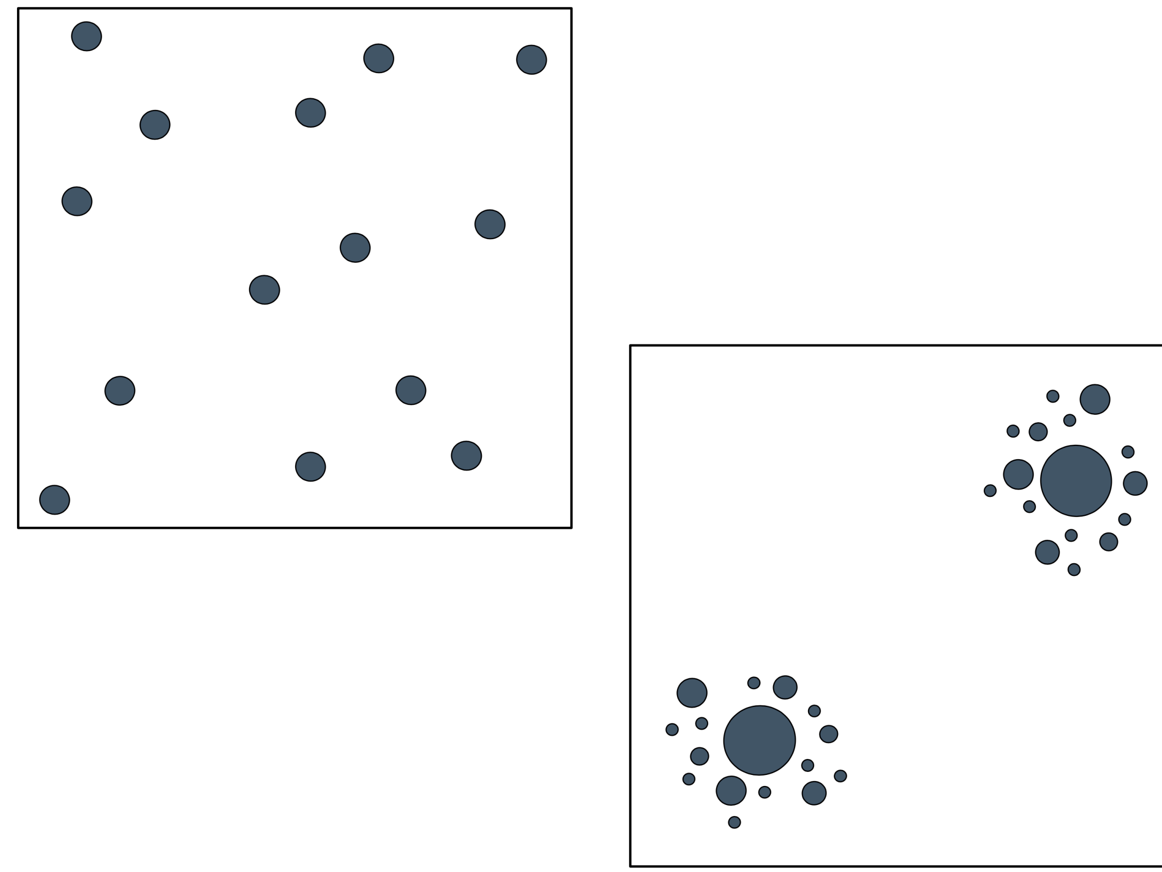


[Capelluti *et al.* 2013]

★ PBHs generate early structure and respective backgrounds

Evidence of Dark Matter Clumping with HST

[Meneghetti, Natarajan, Downer 2020]



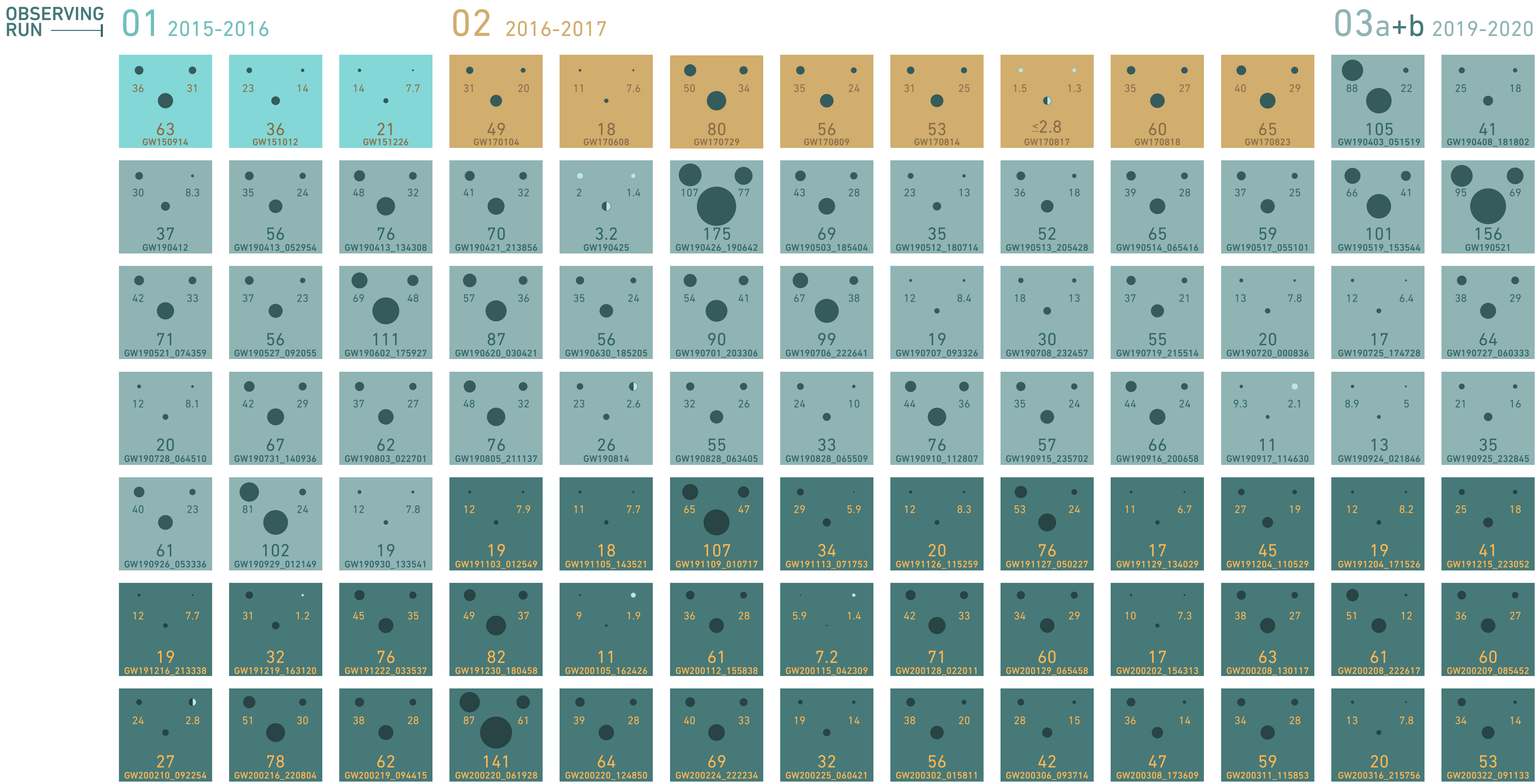
[García-Bellido 2018]

homogeneous vs clumped
dark matter distribution

★ This is the norm for PBHs!

GRAVITATIONAL WAVE **MERGER** DETECTIONS

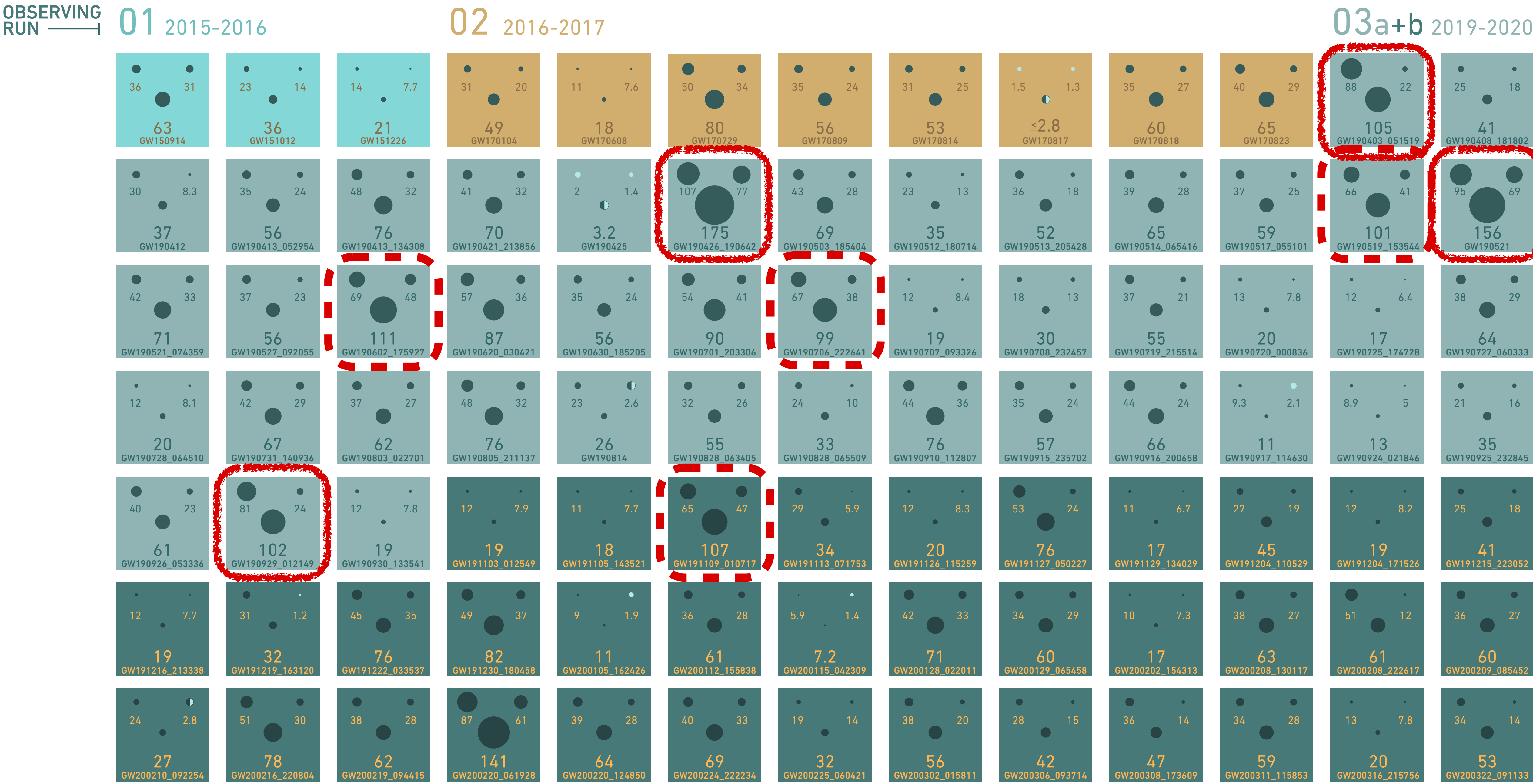
SINCE 2015



LIGO VIRGO KAGRA

GRAVITATIONAL WAVE **MERGER** DETECTIONS

→ SINCE 2015

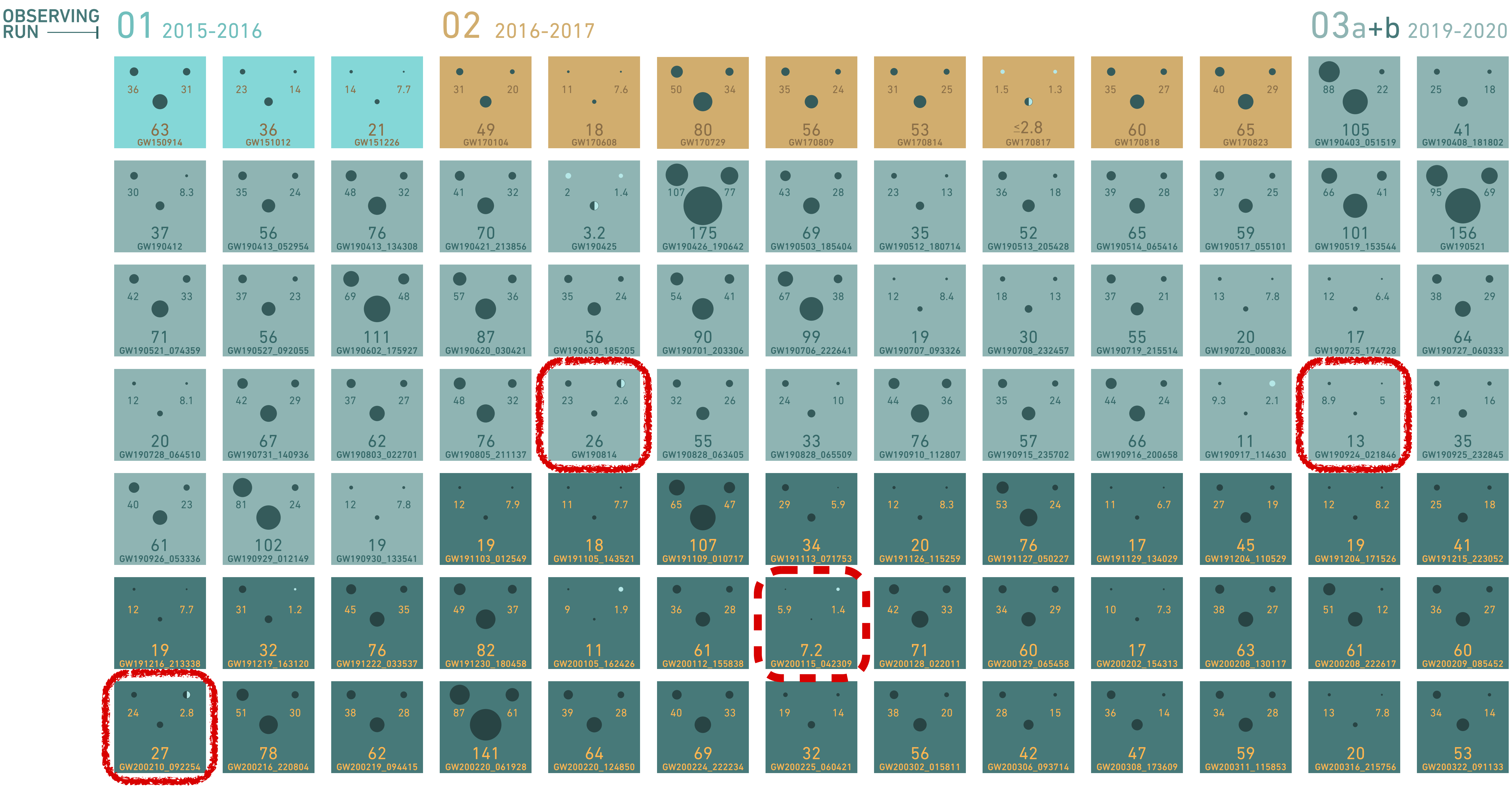


★ Black hole progenitors in the pair-instability mass gap (i.e. between ~ 60 and 140 $M_\odot$)

LIGO VIRGO KAGRA

GRAVITATIONAL WAVE **MERGER** DETECTIONS

→ SINCE 2015

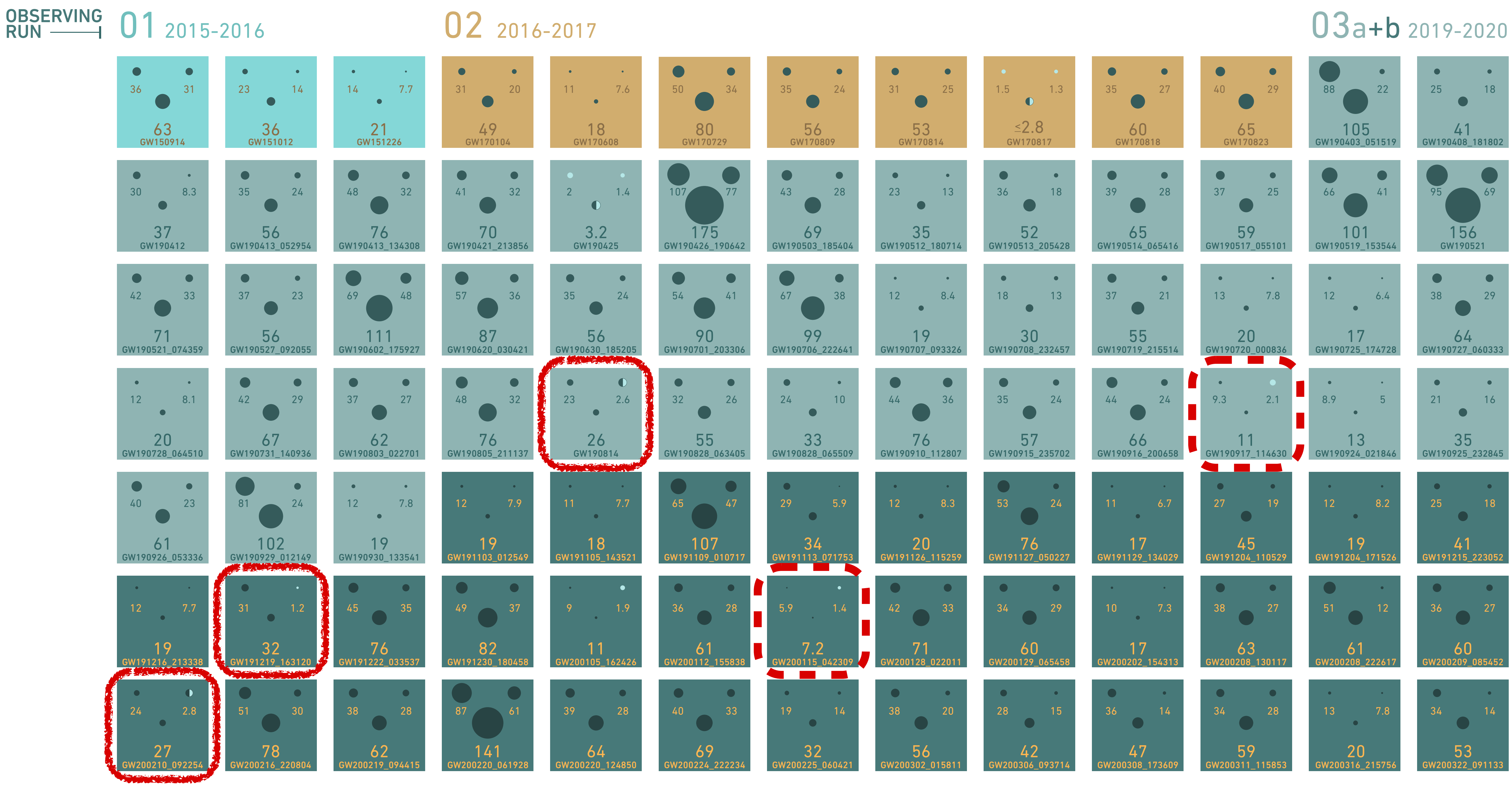


★ Black hole progenitors in the lower mass gap (i.e. between 2 and 5 $M_\odot$)

LIGO VIRGO KAGRA

GRAVITATIONAL WAVE **MERGER** DETECTIONS

SINCE 2015



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

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!

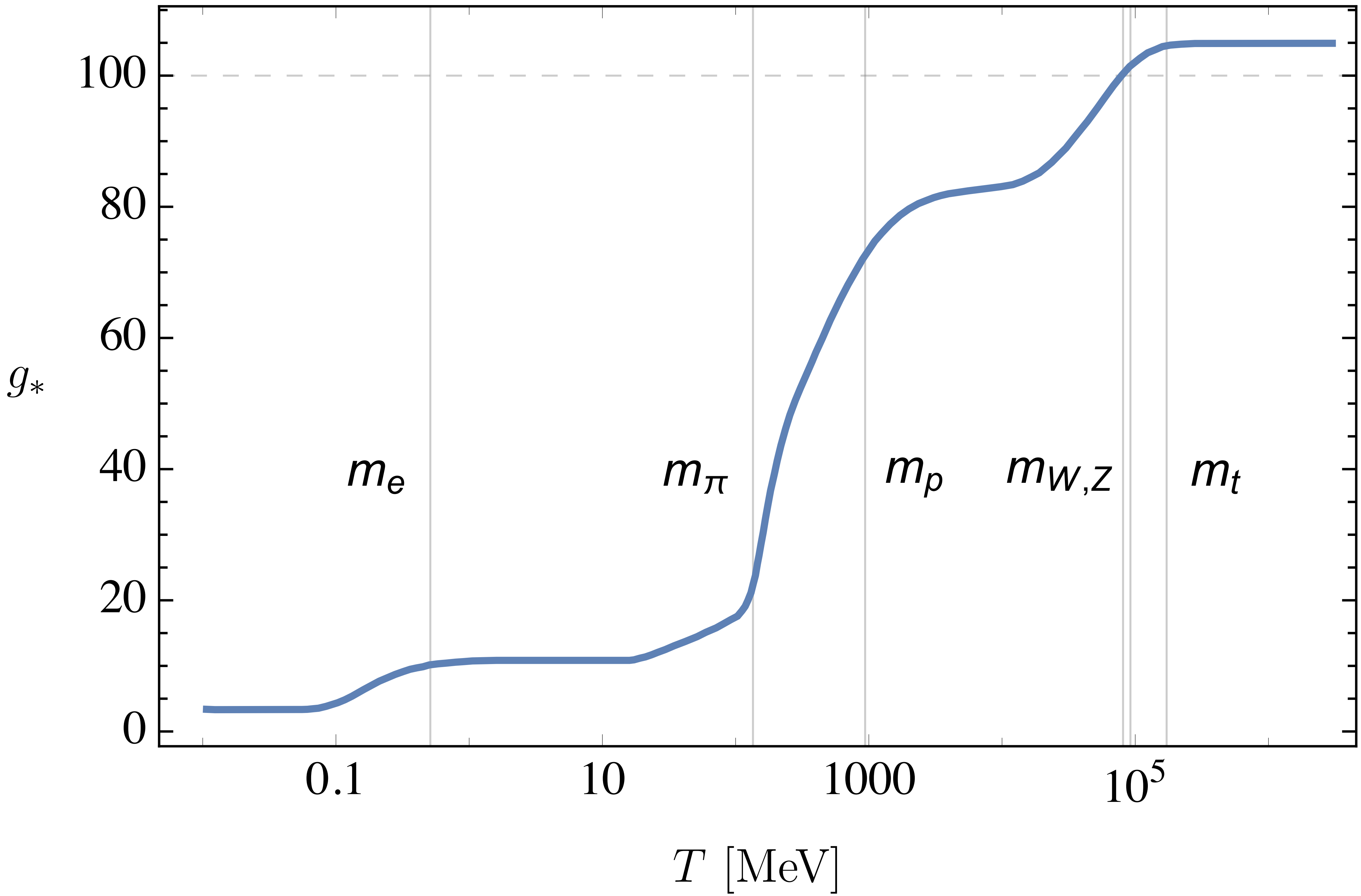
Further Support/Evidence for PBHs

- High-redshift quasars (... up to $10^8\,M_\odot$ at z = 13)
- Fast radio bursts
- Missing-pulsar problem
- Properties of low-mass-X-ray binaries
- Non-flat rotation curves at high redshift
- ...

Thermal History

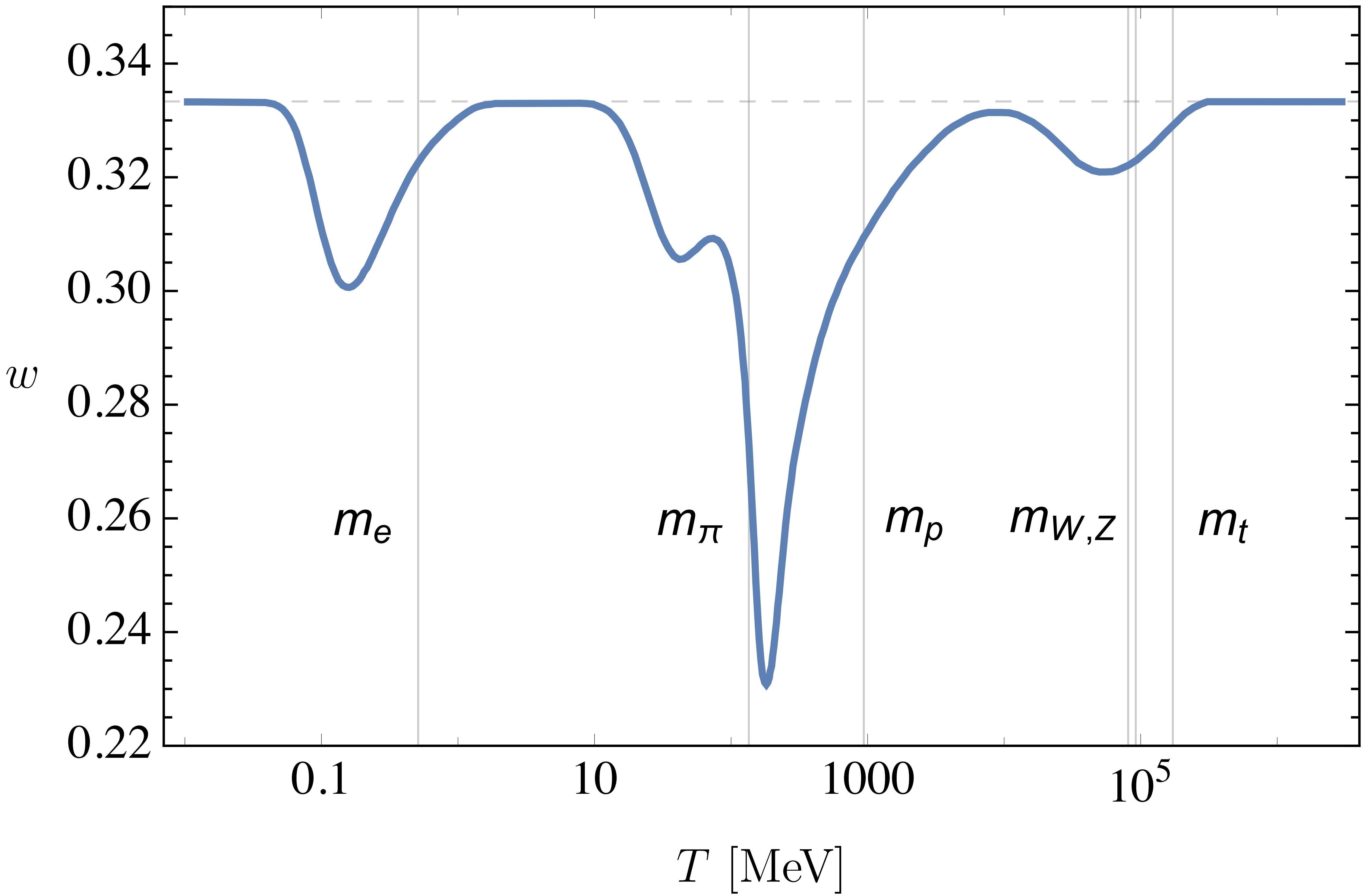
Thermal History of the Universe

★ Changes in the relativistic degrees of freedom:



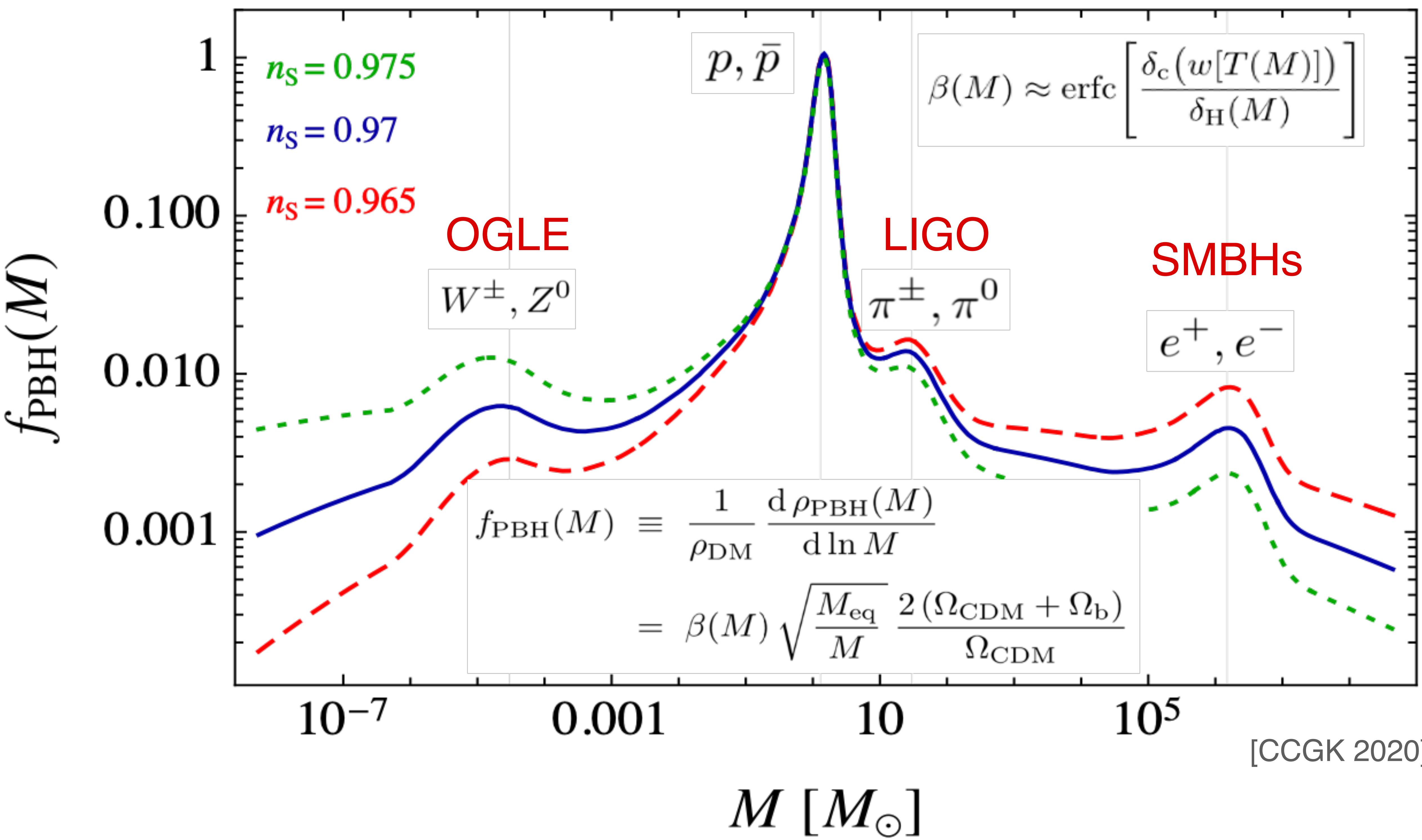
Thermal History of the Universe

★ 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)

$10^{23} M_\odot$ Universal

Planck 10^{-5} g

$10^{12} M_\odot$ SLAB

exploding* 10^{10} g
(BBN)

$10^{9} M_\odot$ QSO

evaporating* 10^{15} g

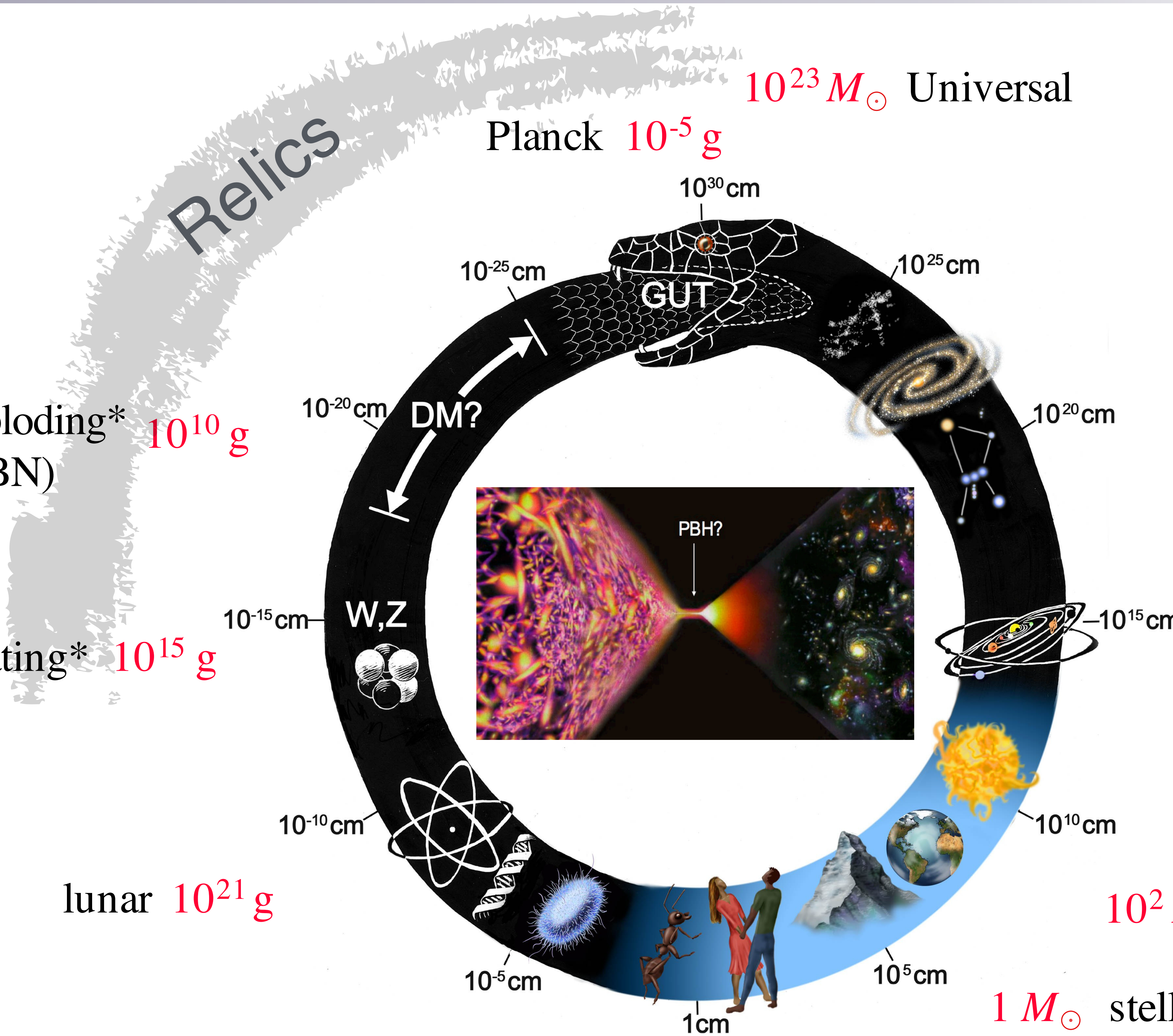
$10^{6} M_\odot$ MW

lunar 10^{21} g

$10^{2} M_\odot$ IMBH

$1\ M_\odot$ stellar

terrestrial 10^{25} g



[Figure from Abrams & Primack 2012]

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

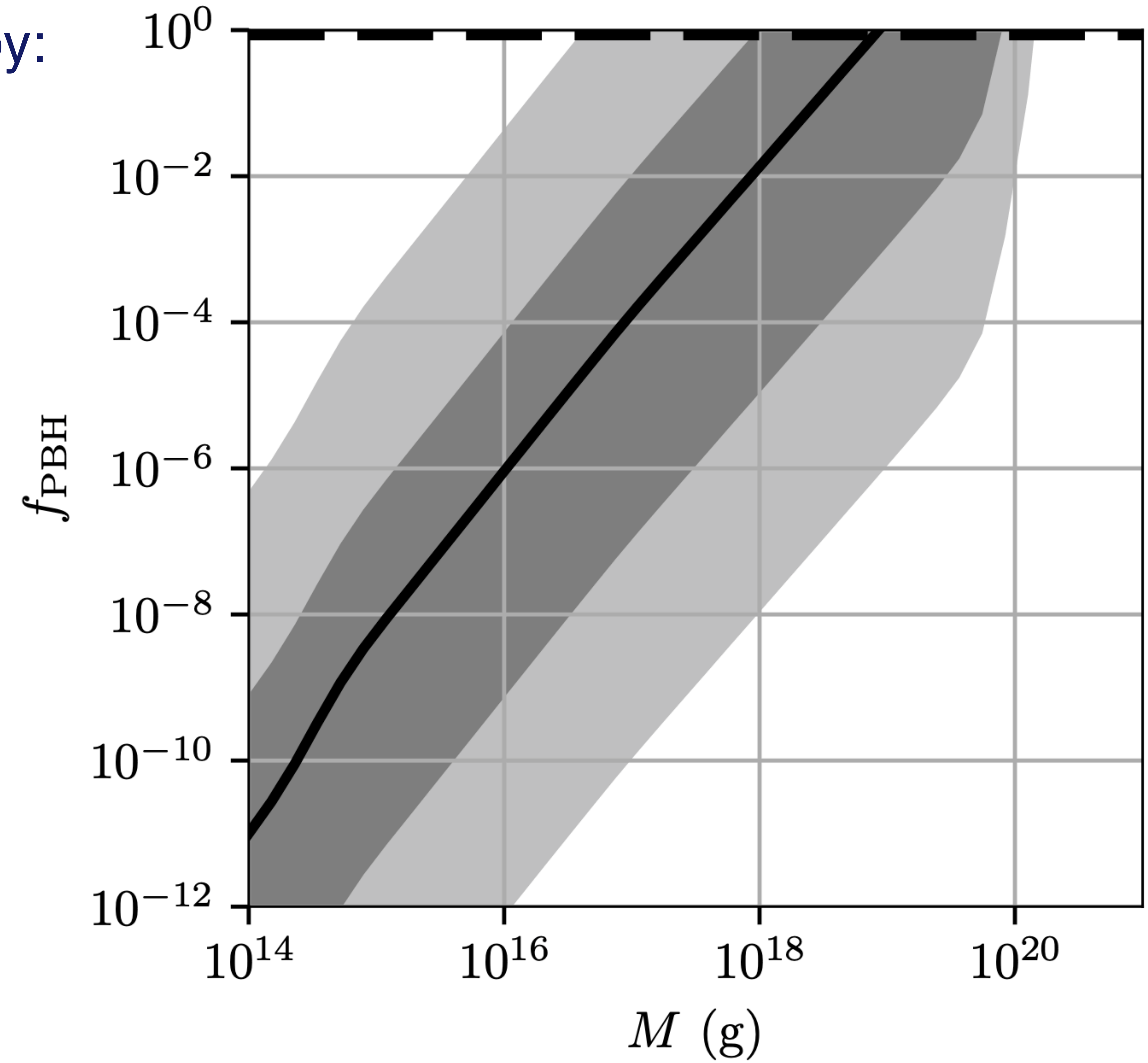
- May constraints rely on rather on uncertain, restrictive, simplistic or even incorrect assumptions!

  → 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



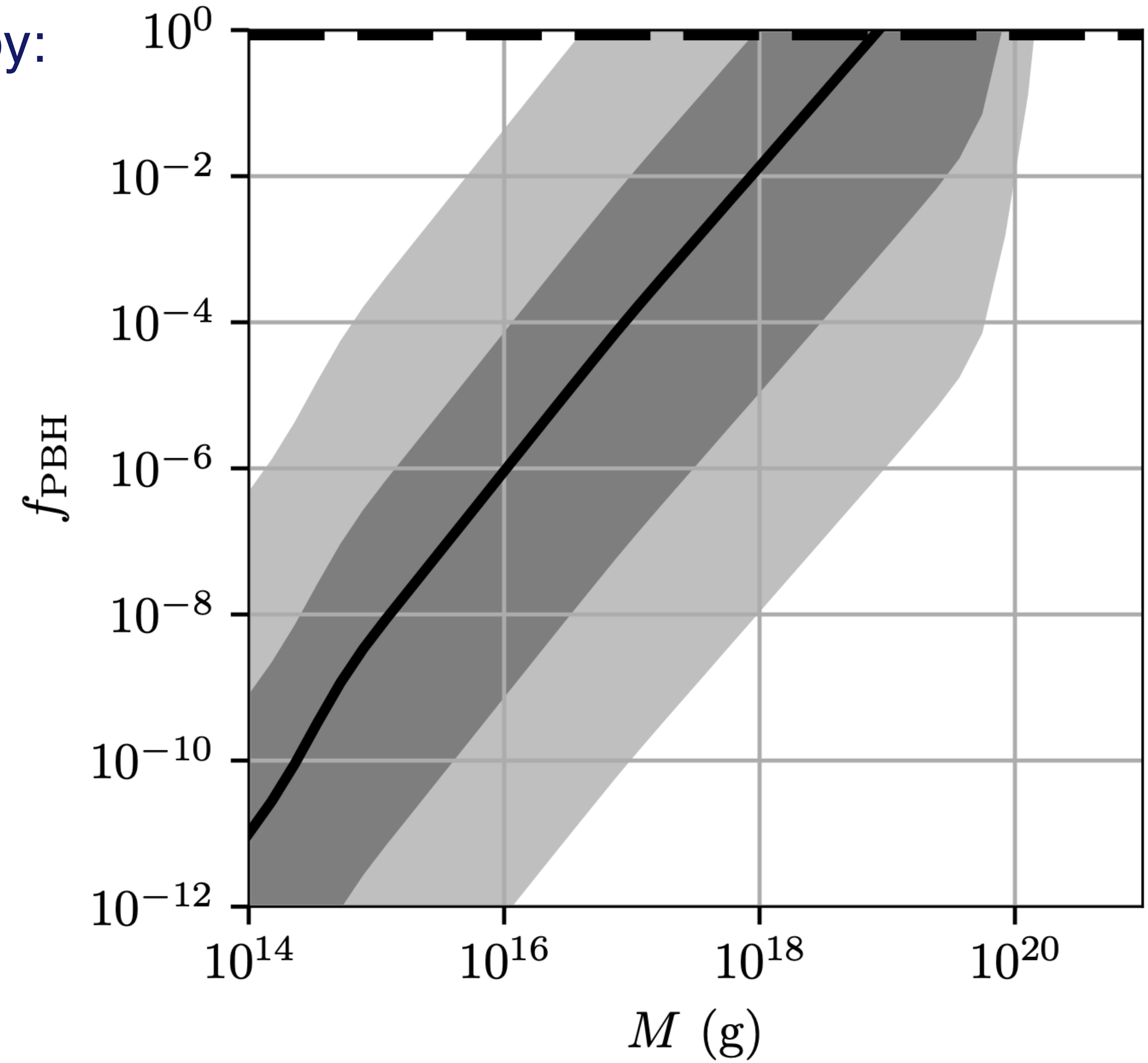
[Auffinger 2022]

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 $f_{\rm PBH} < 1$ there must be another DM component!

PBH & Particle Dark Matter

- ★ Always when $f_{\rm PBH} < 1$ there **must** be another DM component!
- ★ Study a **combined** scenario: **DM = PBHs + Particles**

PBH & Particle Dark Matter

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- Study a combined scenario: DM = PBHs + Particles
  - The latter will be accreted by the former; formation of halos.

PBH & Particle Dark Matter

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

PBH & Particle Dark Matter

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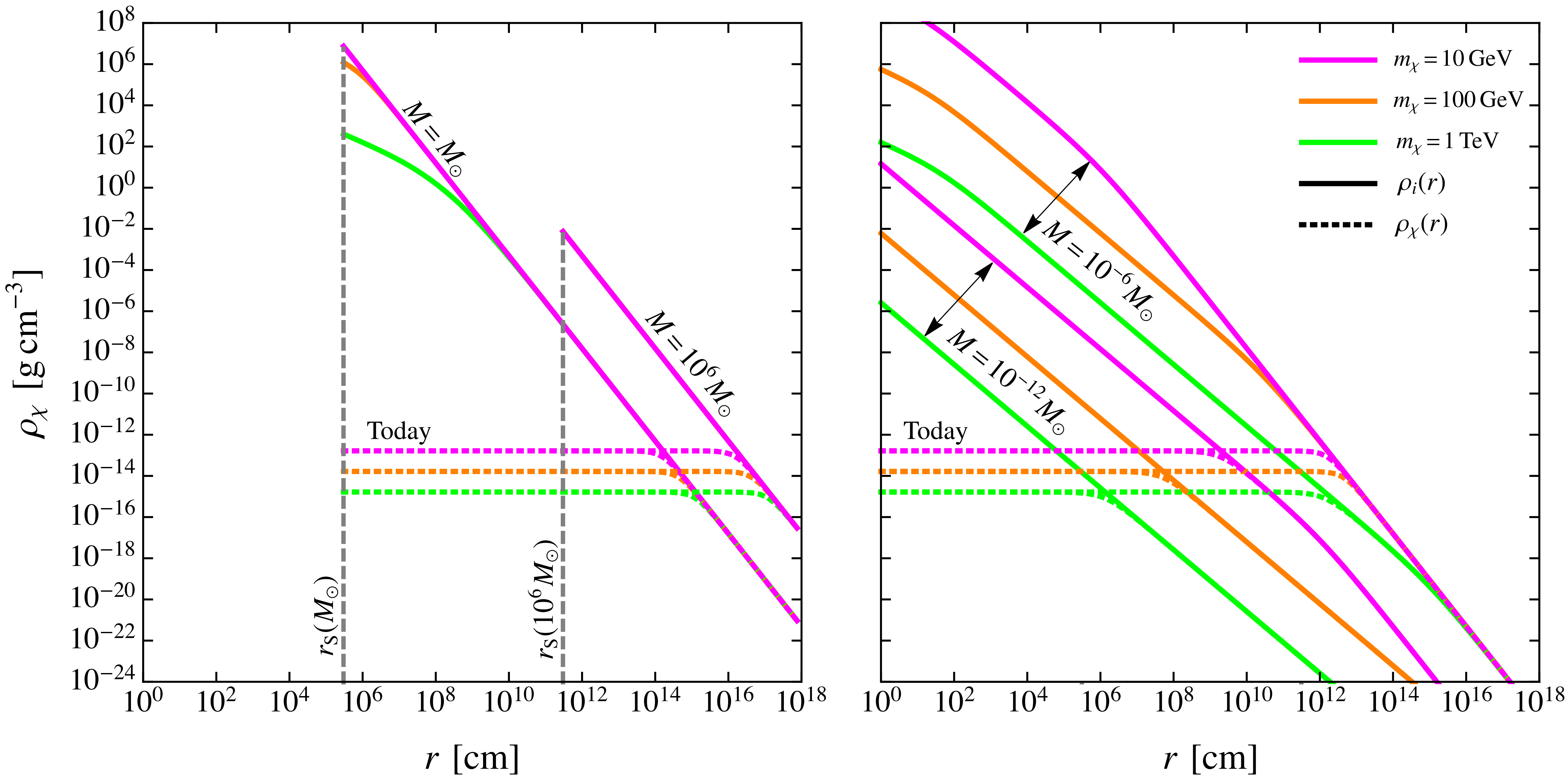
- ★ Study a combined scenario: DM = PBHs + Particles
  - ★ The latter will be accreted by the former; formation of halos.
  - ★ Study WIMP annihilations in PBH halos:
    - ★ The annihilation rate $\Gamma \propto n^2$.
    - ★ Halo profile does matter; enhancement of Γ in density spikes.
      1) Derive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

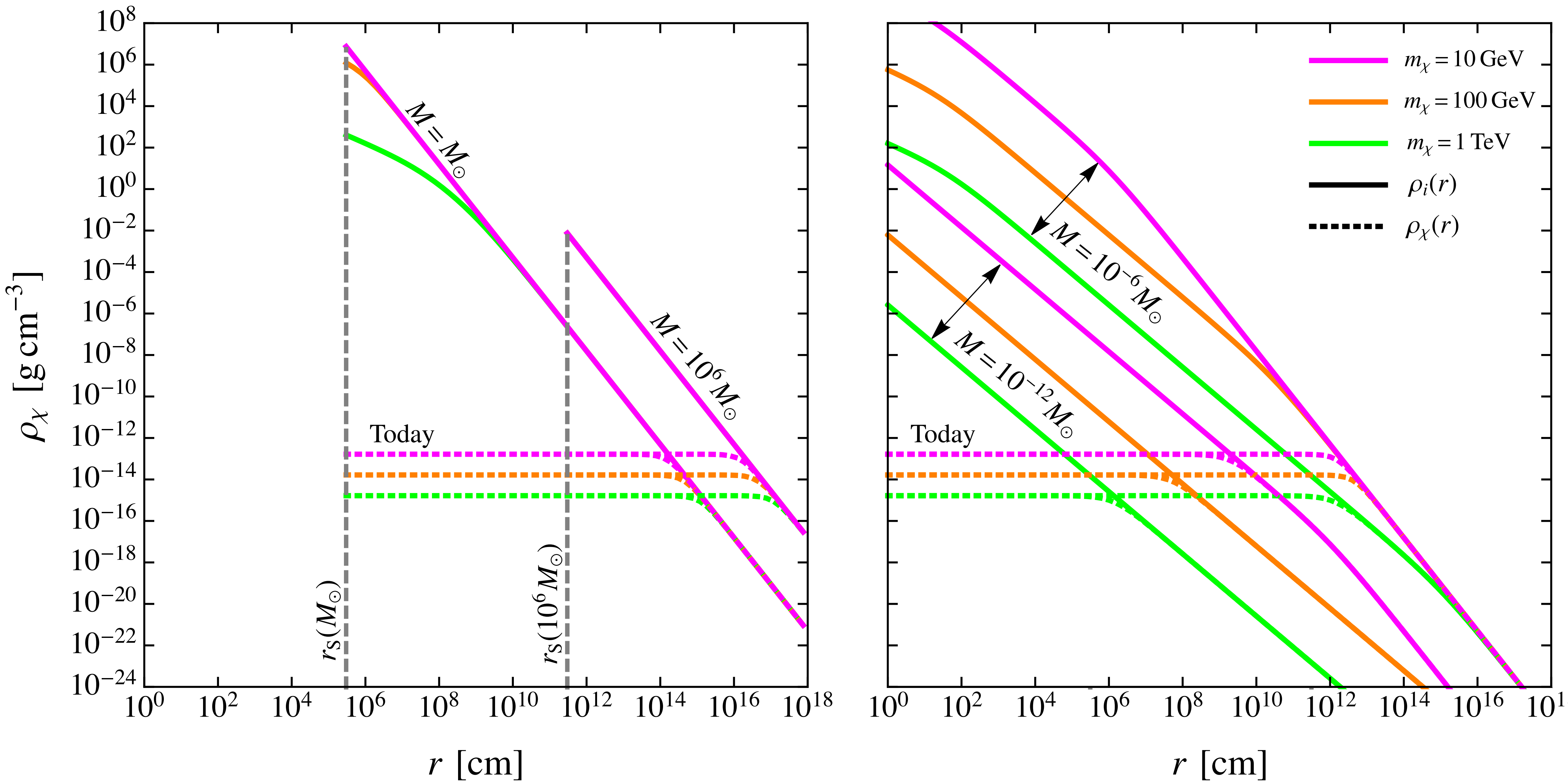
[Eroshenko 2016,
Boucenna *et al*. 2017,
Adamek *et al*. 2019,
Carr, Kühnel, Visinelli 2020 & 2021]

PBHs & WIMPs



[Carr, Kühnel, Visinelli 2021]

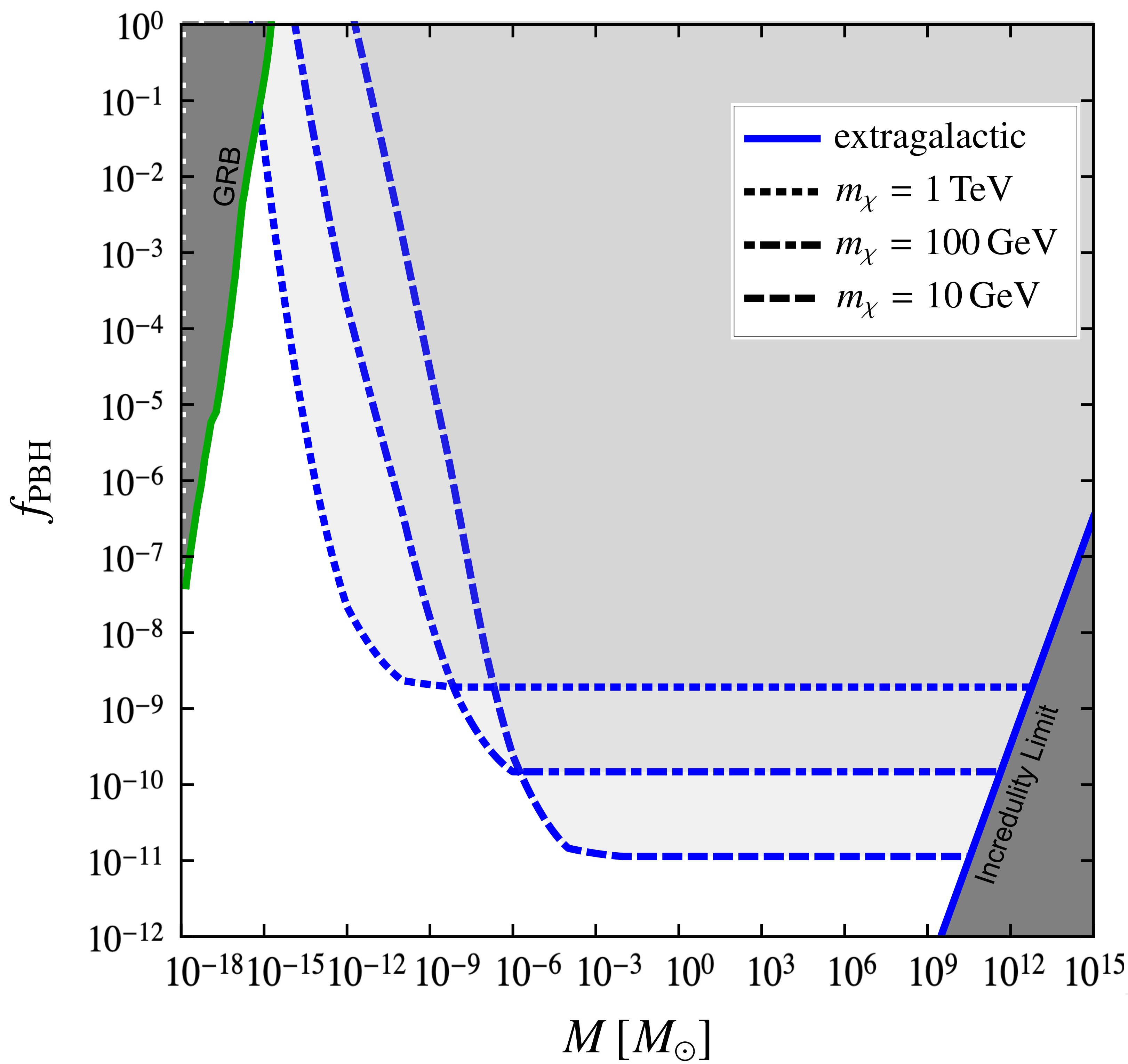
PBHs & WIMPs



[Carr, Kühnel, Visinelli 2021]

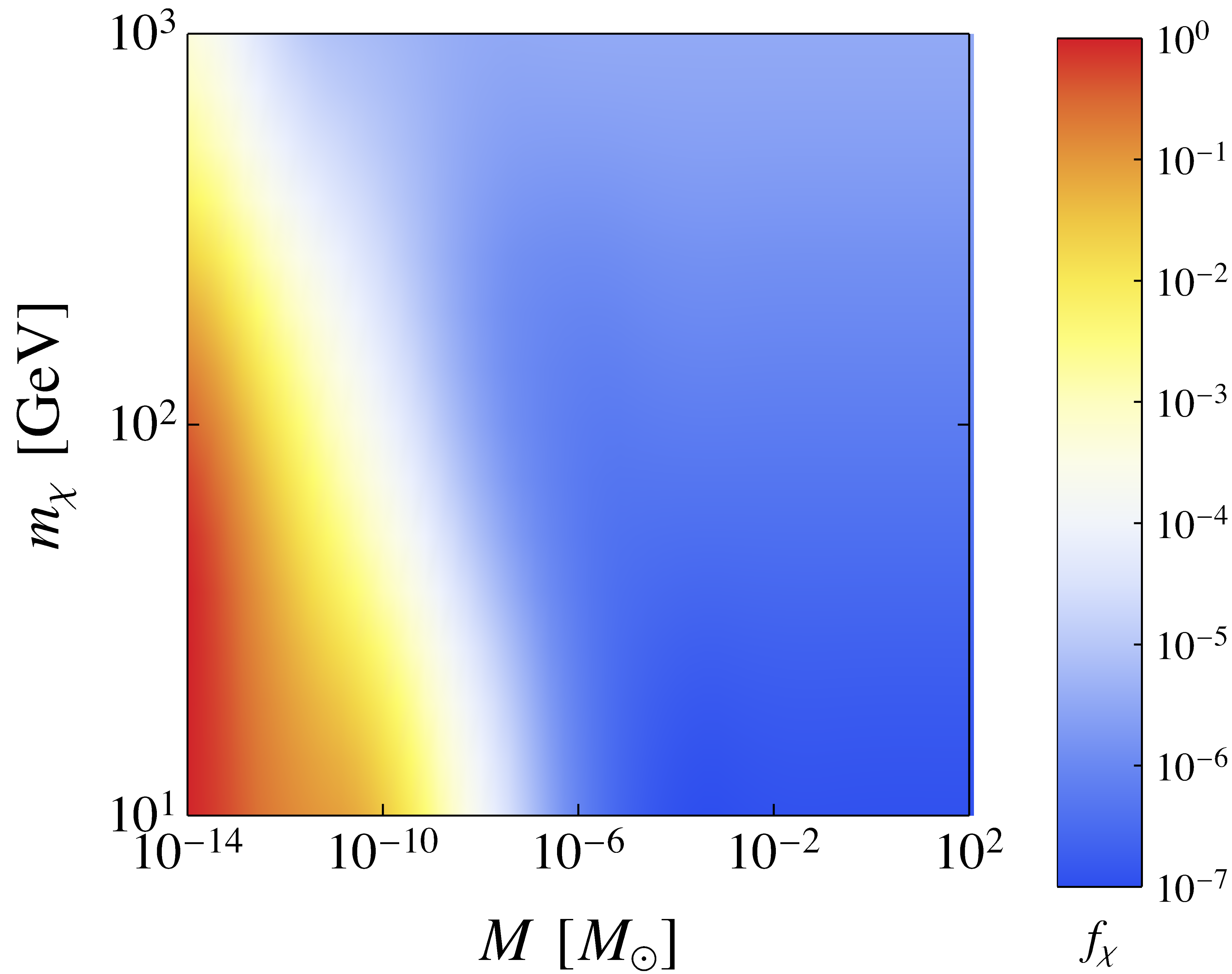
★ Annihilations lead to plateaux in the present-day halos.

PBHs & WIMPs



[Carr, Kühnel, Visinelli 2021]

PBHs & WIMPs



[Carr, Kühnel, Visinelli 2021]

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

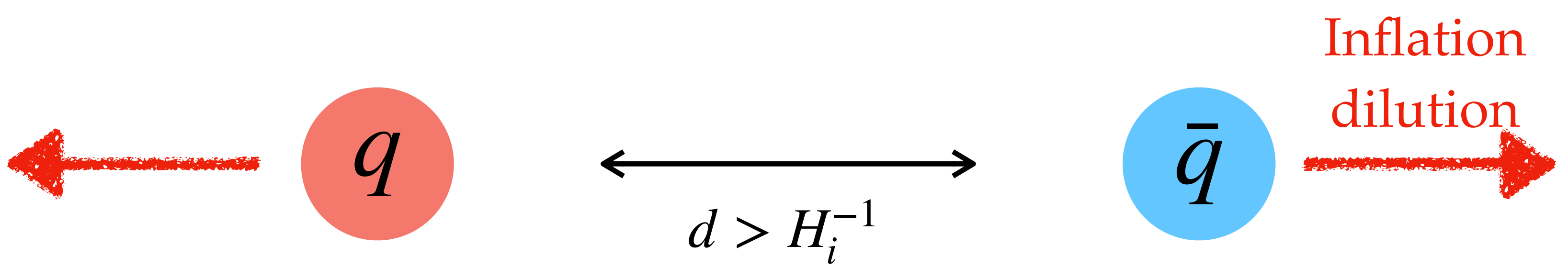
★ We propose a novel PBH formation mechanism which is

- ★ assumption-minimal,
- ★ free of exponential fine-tuning,
- ★ avoids strong coupling,
- ★ works with standard QCD*,
- ★ compatible with observations.

Primordial Black Holes from Confinement

Confinement Formation Mechanism

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



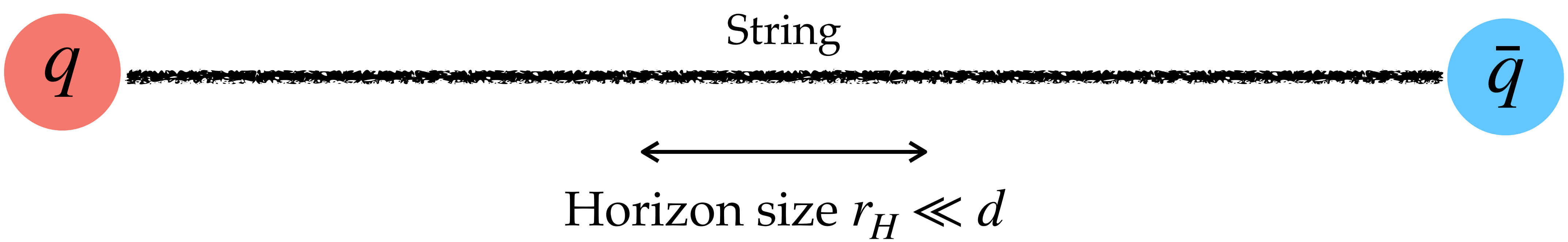
★ Focus on a simple pair case.

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

★ Quarks quickly move out of causal contact.

Confinement Formation Mechanism

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



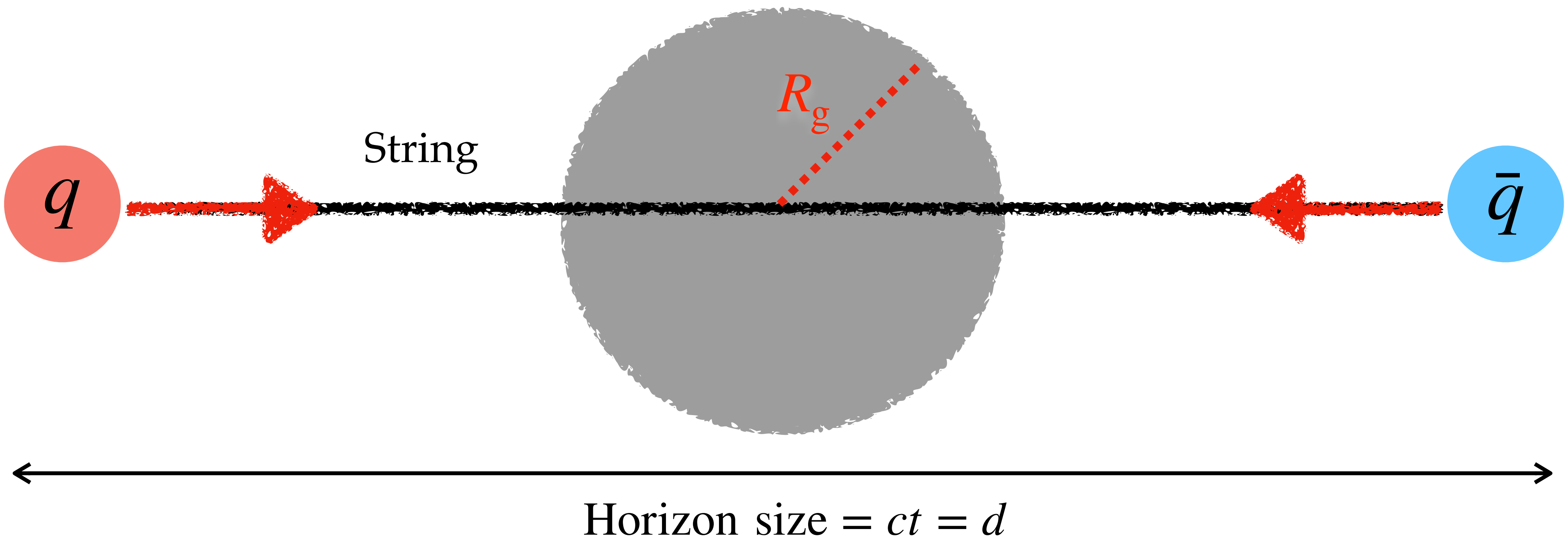
★ Flux tubes form connecting quark/anti-quark pairs.

★ 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

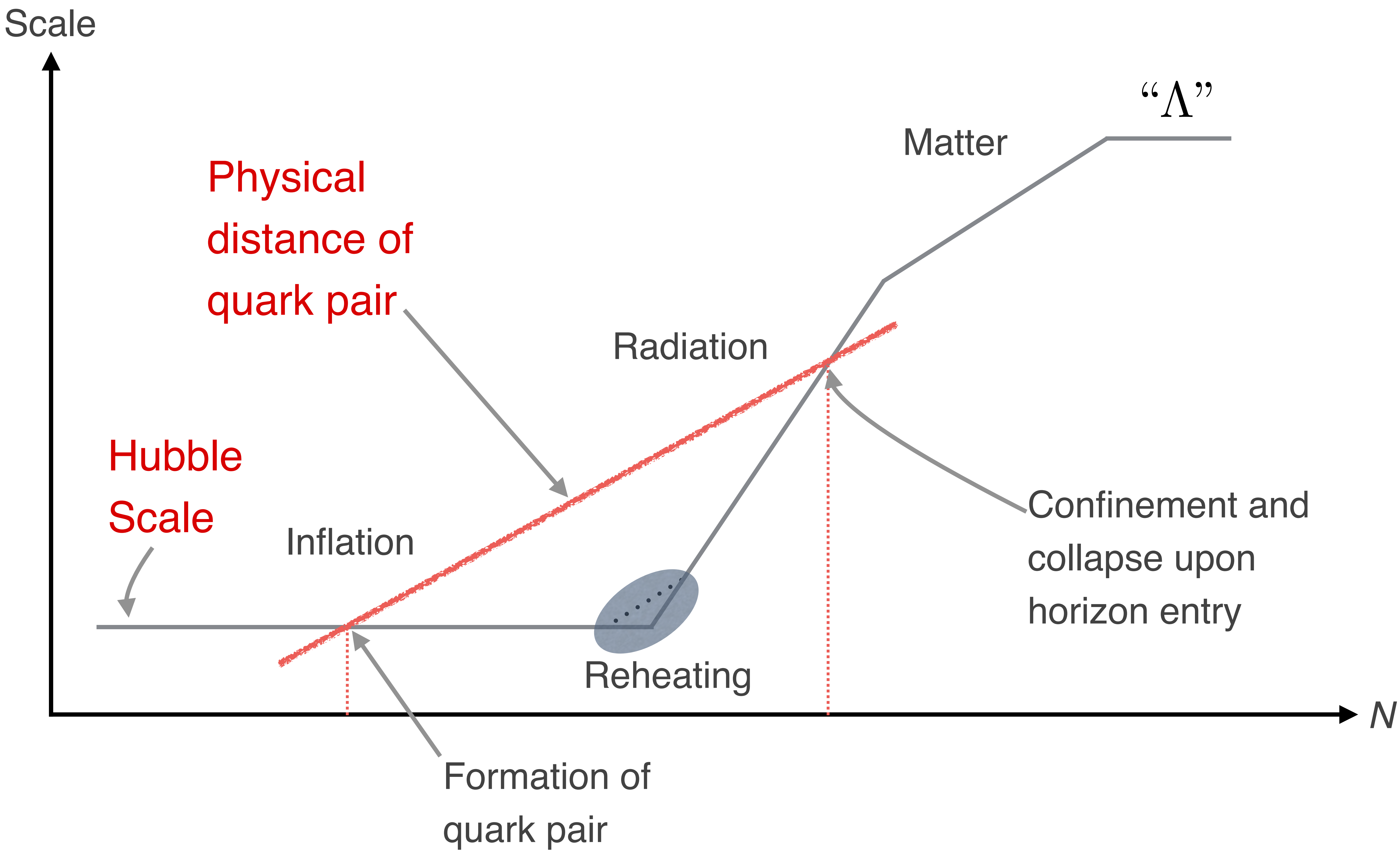


★ Acceleration of the quarks $a = \Lambda_c^2 / m_q$ quickly leads to their ultra-relativistic motion.

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

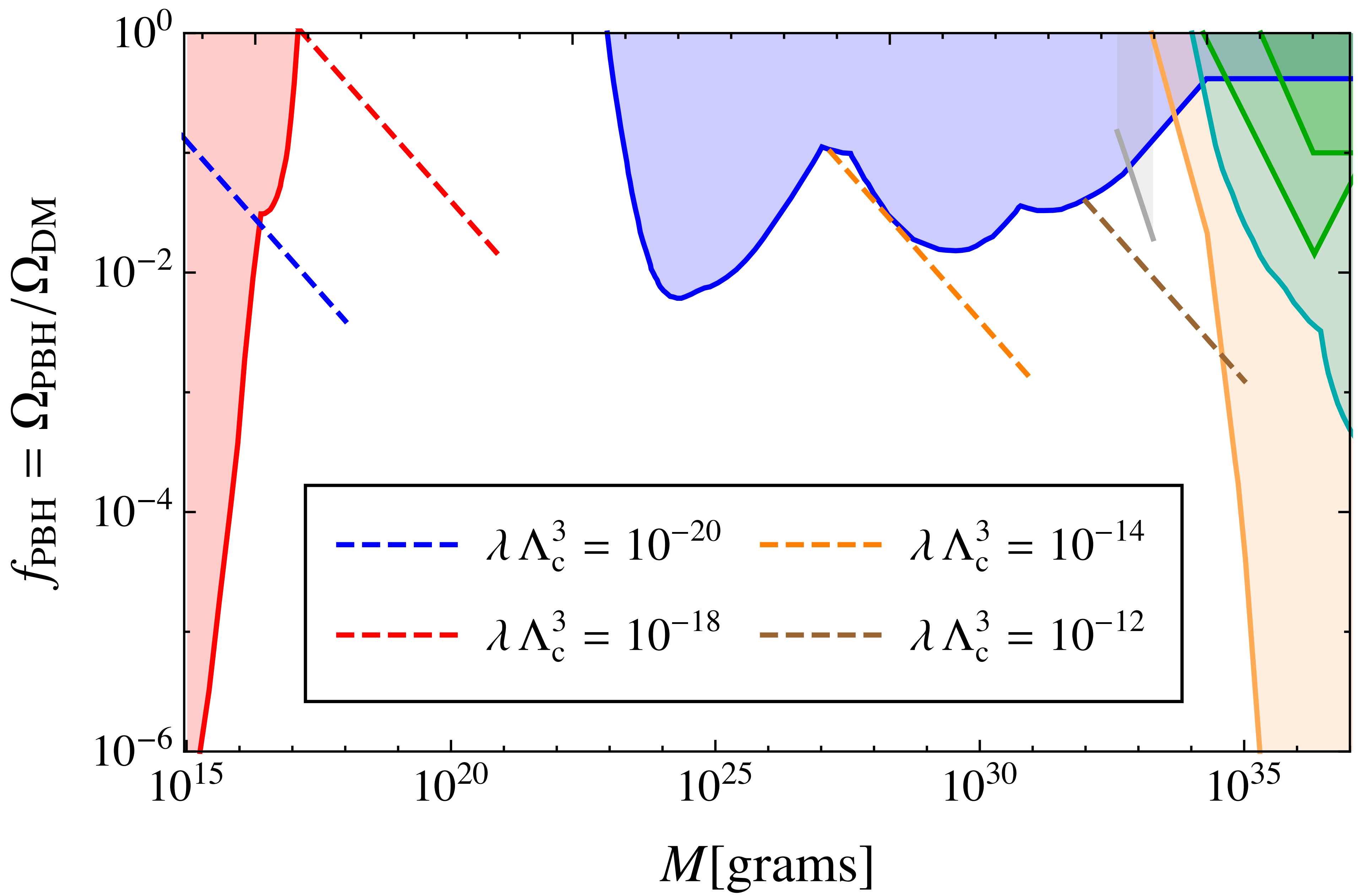
★ PBHs from inflationary overdensities are heavier by a factor $\sim \Lambda_c^2$.

Formation Scales



Dark Matter from Confinement

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

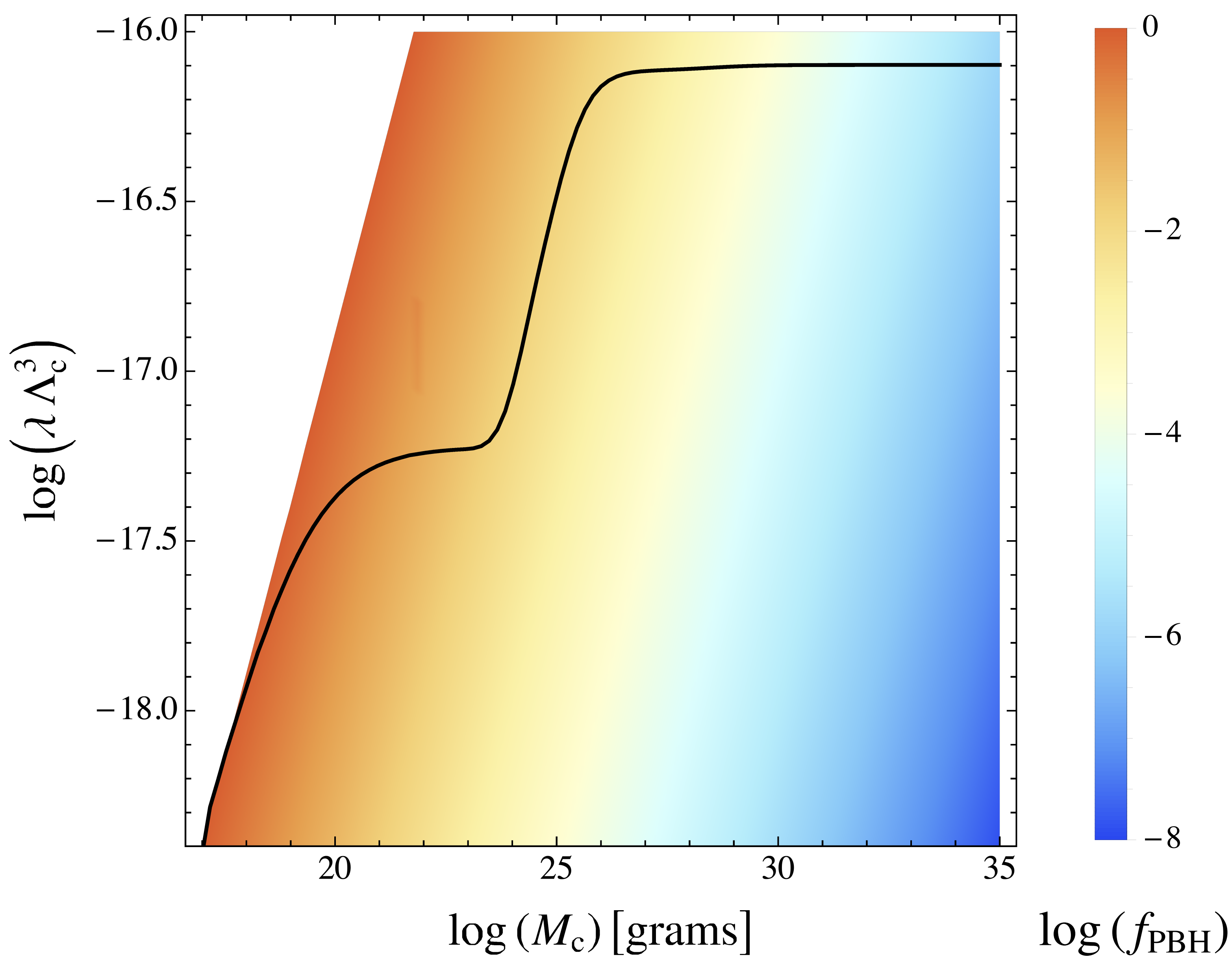


★ Find: $$f_{\rm PBH} \equiv \frac{\rho_{\rm PBH}(t)}{\rho_{\rm CDM}(t)} = \frac{32\pi}{3}\lambda\Lambda_c^3\left(\frac{M_{\rm PBH}}{M_{\rm eq}}\right)^{-1/2}$$

Extended-Constraint Analysis

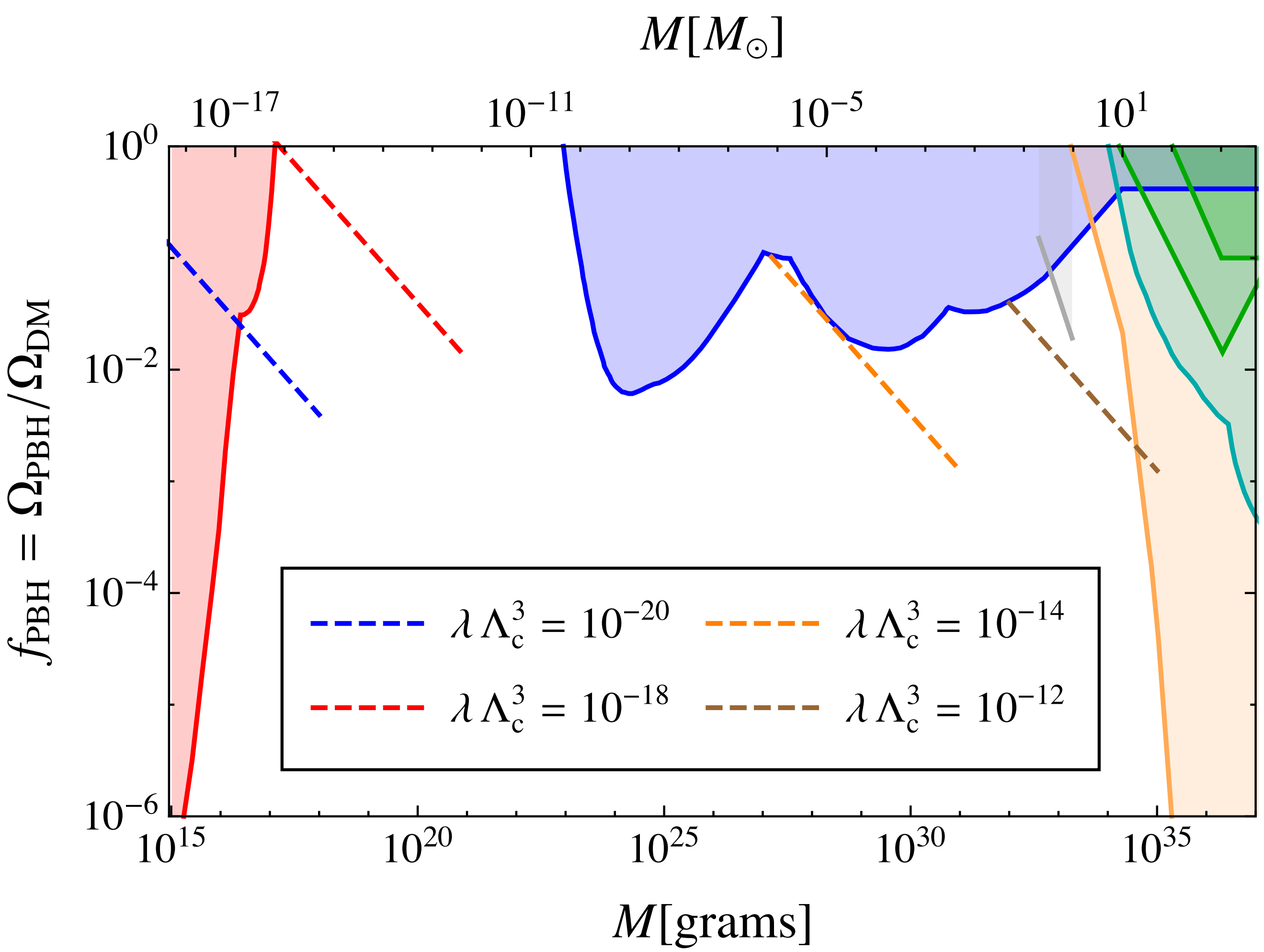
★ Require: $$\int_{M_1}^{M_2} \mathrm{d}\ln M_{\mathrm{PBH}}\, \frac{\mathrm{d}f_{\mathrm{PBH}}(M_{\mathrm{PBH}})}{\mathrm{d}\ln M_{\mathrm{PBH}}}\, \frac{1}{f_{\max}(M_{\mathrm{PBH}})} \overset{!}{\leq} 1$$

[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...
- ★ ... <u>at the same time</u> 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

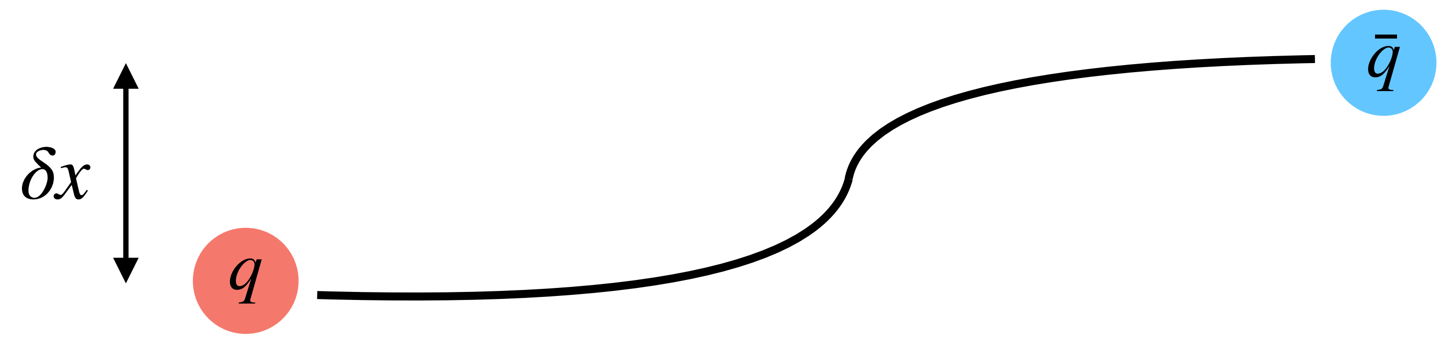
$$\int_{M_1}^{M_2} {\rm d}\ln M_{\rm PBH}\, \frac{{\rm d}f_{\rm PBH}(M_{\rm PBH})}{{\rm d}\ln M_{\rm PBH}}\, \frac{1}{f_{\rm max}(M_{\rm PBH})} \overset{!}{\leq} 1$$

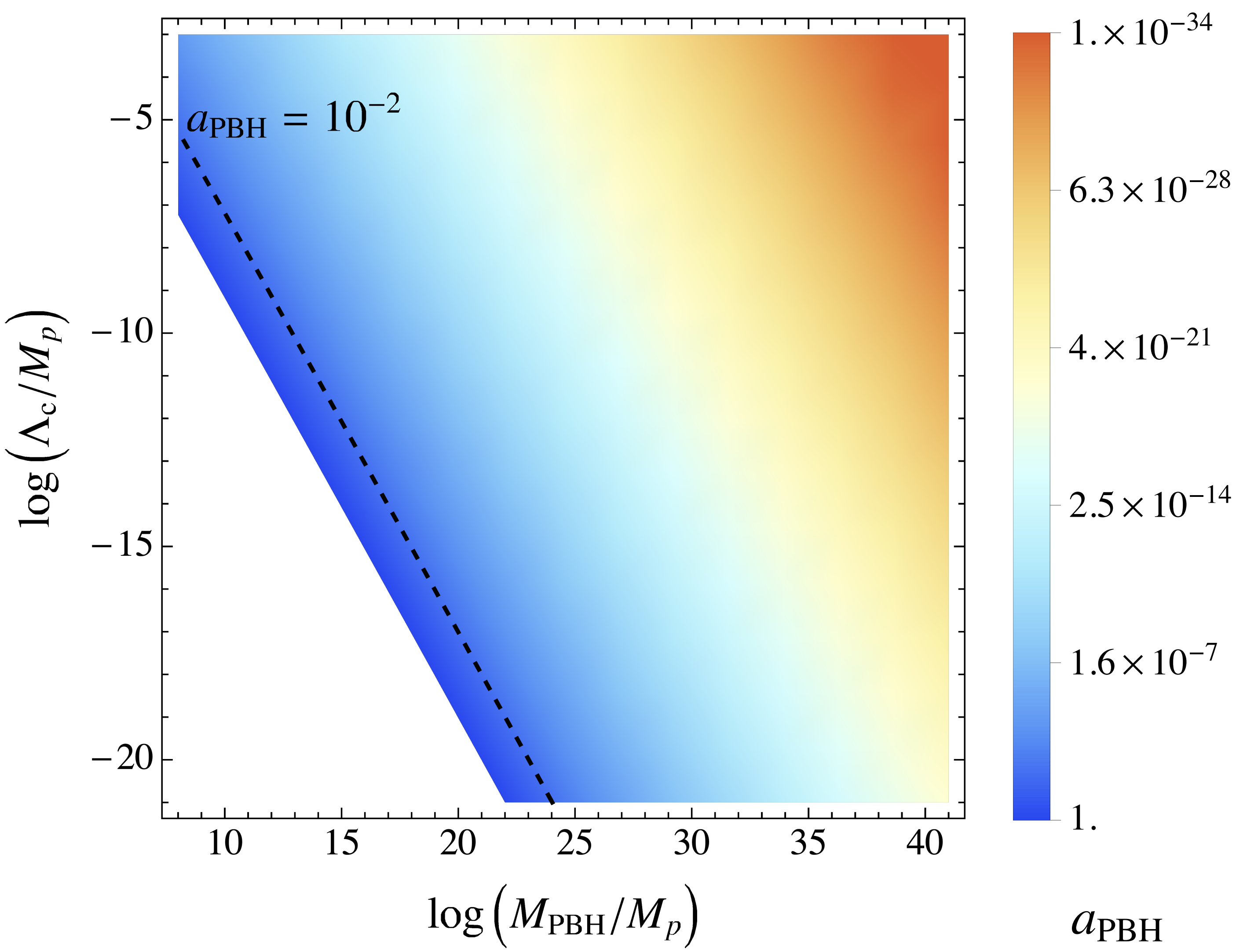
100% of dark matter!

High-Spin Subsolar PBHs

★ 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:

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

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

*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!

$$g_{\rm y}\bar{\Psi}_{\rm L}\Psi_{\rm R}\phi \qquad\qquad \frac{1}{4g^2}F_{\mu\nu}F^{\mu\nu}$$

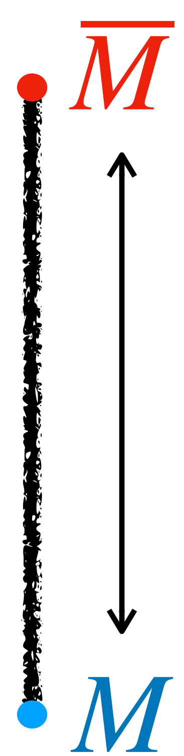
★ Couplings are expectation values of fields and can be very different in the early Universe.

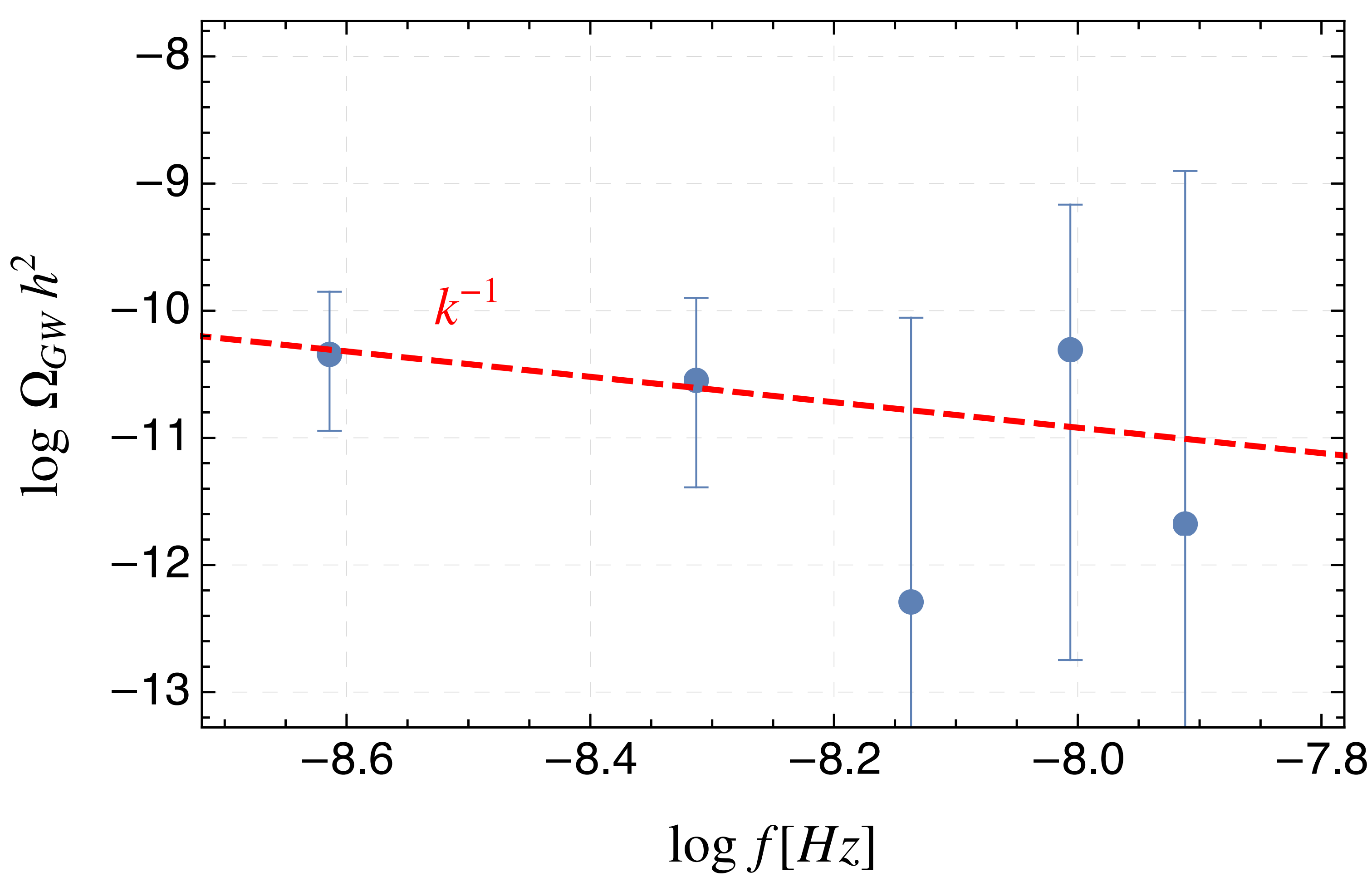
★ Requirement: Low-temperature expectation value should set the right coupling values.

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

Gravitational Waves

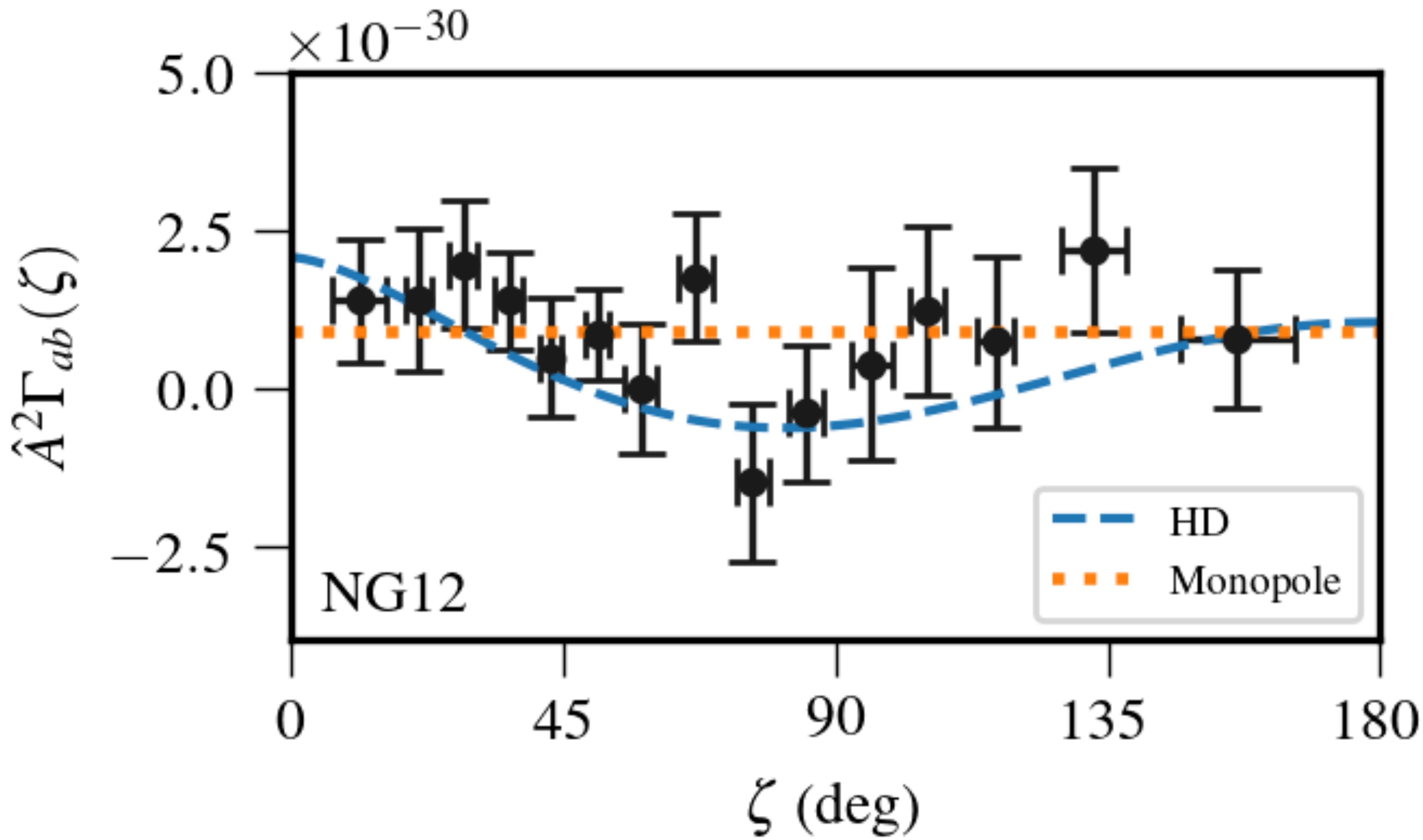
- After horizon entry, the quarks quickly move towards each other, emitting gravitational waves.
  - This is similar to dual to systems of dual monopole/anti-monopole pairs connected by a string. [cf. Martin & Vilenkin 1997; Leblond, Shlaer, Siemens 2009]
  - NANOGrav data from pulsar-timing observations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

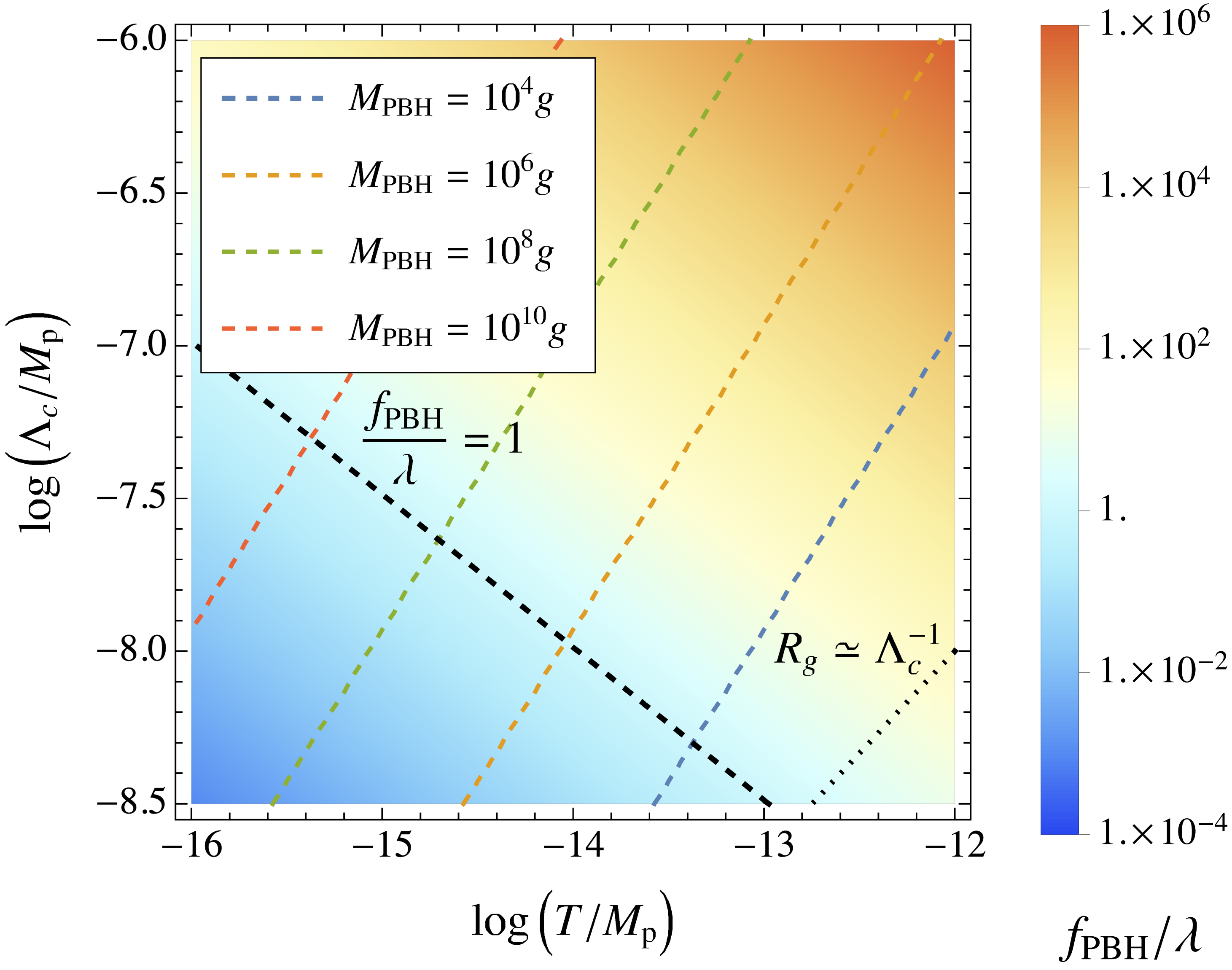
★ We can easily generate a monopolar signal upon adding e.g. $\sim \phi\, \bar{q}q$ with coupling strength relatively weaker by $\sim 10^{-3}$.

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.

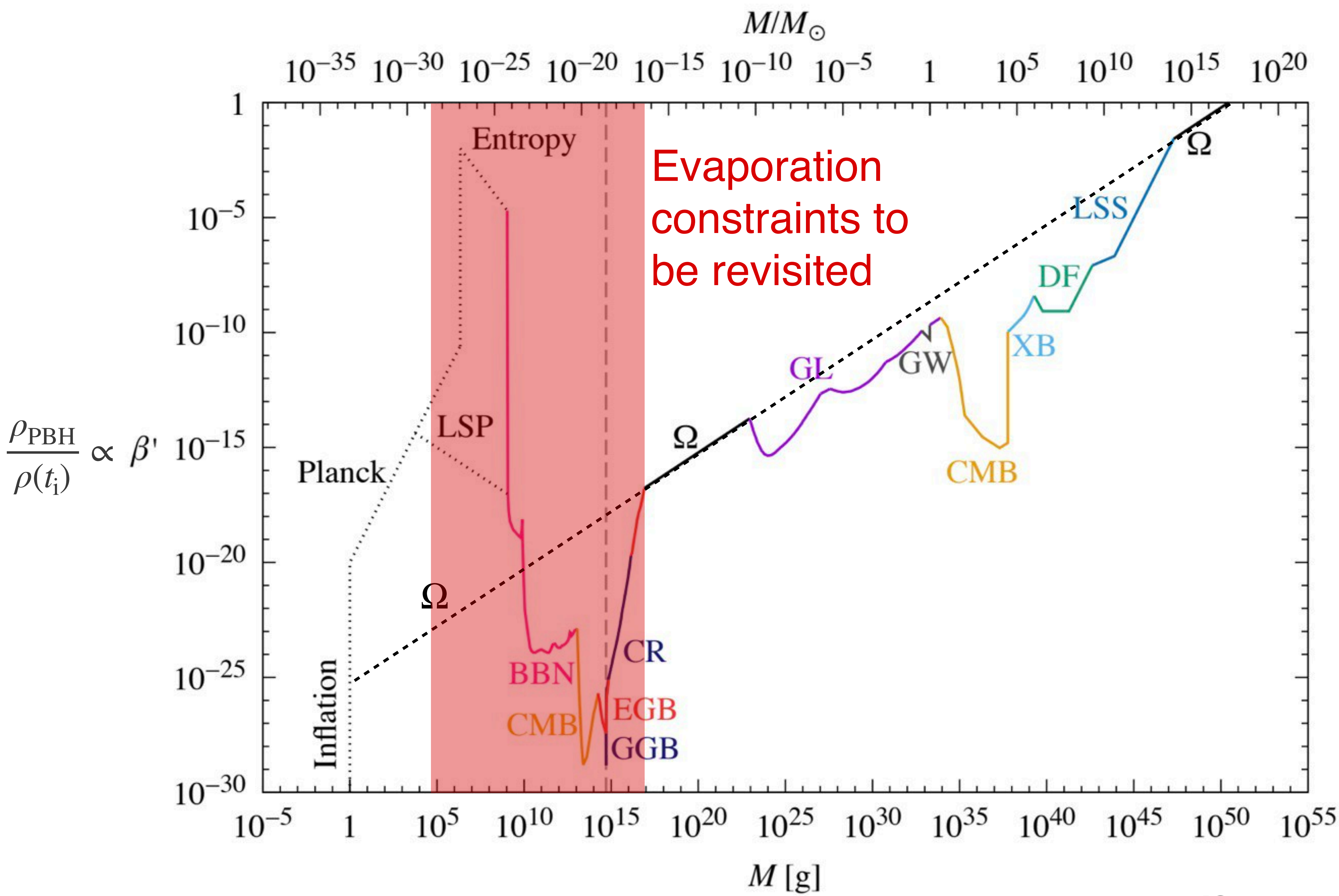
★ A conservative estimate is:

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

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:

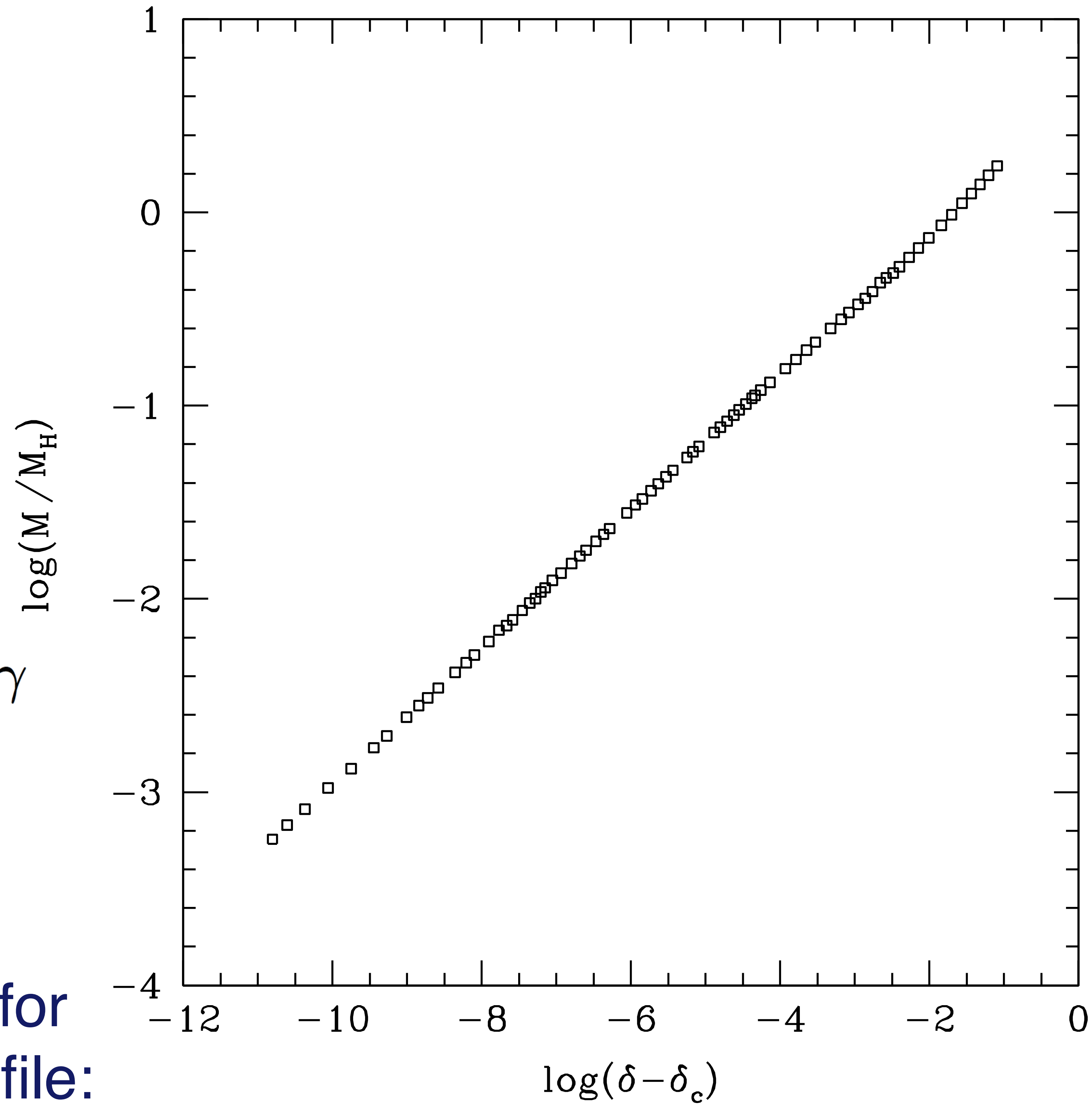
[Choptuik '93]

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

density contrast

★ Radiation domination and for spherical Mexican-hat profile:

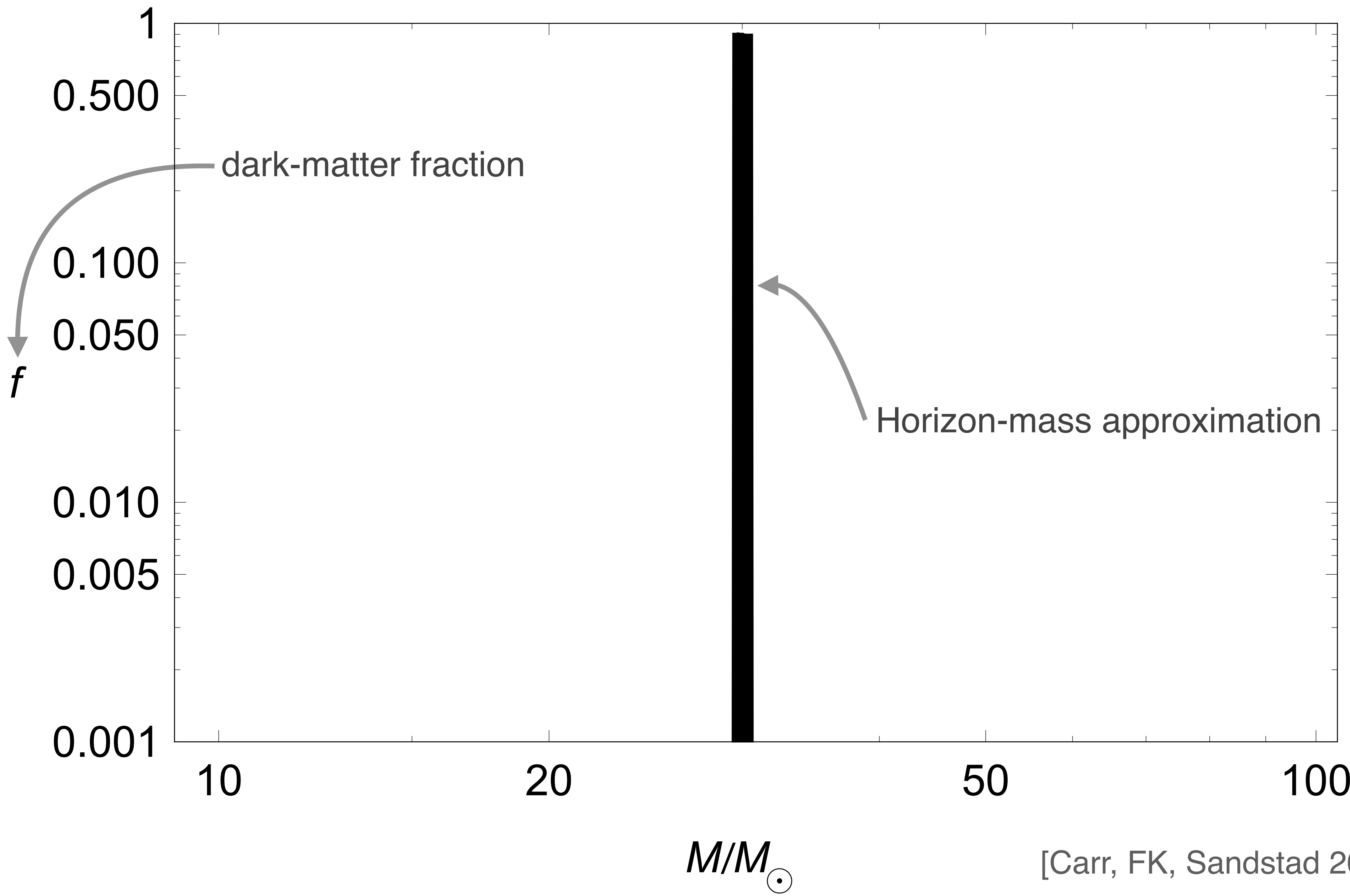
$$k \approx 3.3\ , \quad \delta_c \approx 0.45\ , \quad \gamma \approx 0.36$$



[Musco, Miller, Polnarev 2008]

Critical Collapse

★ How would this look for monochromatic mass function?



[Carr, FK, Sandstad 2016]

Critical Collapse

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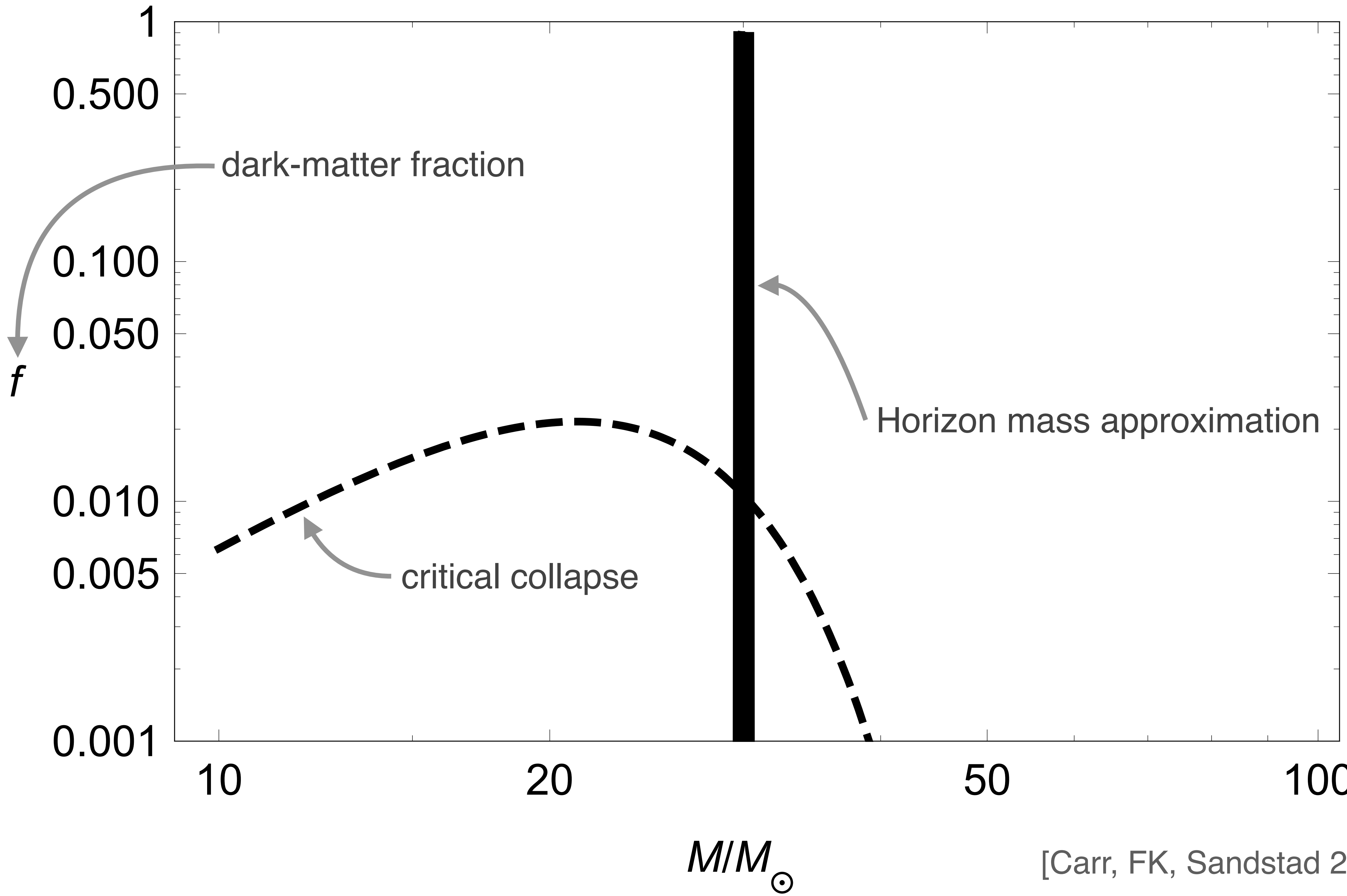

[Carr, FK, Sandstad 2016]

Critical Collapse

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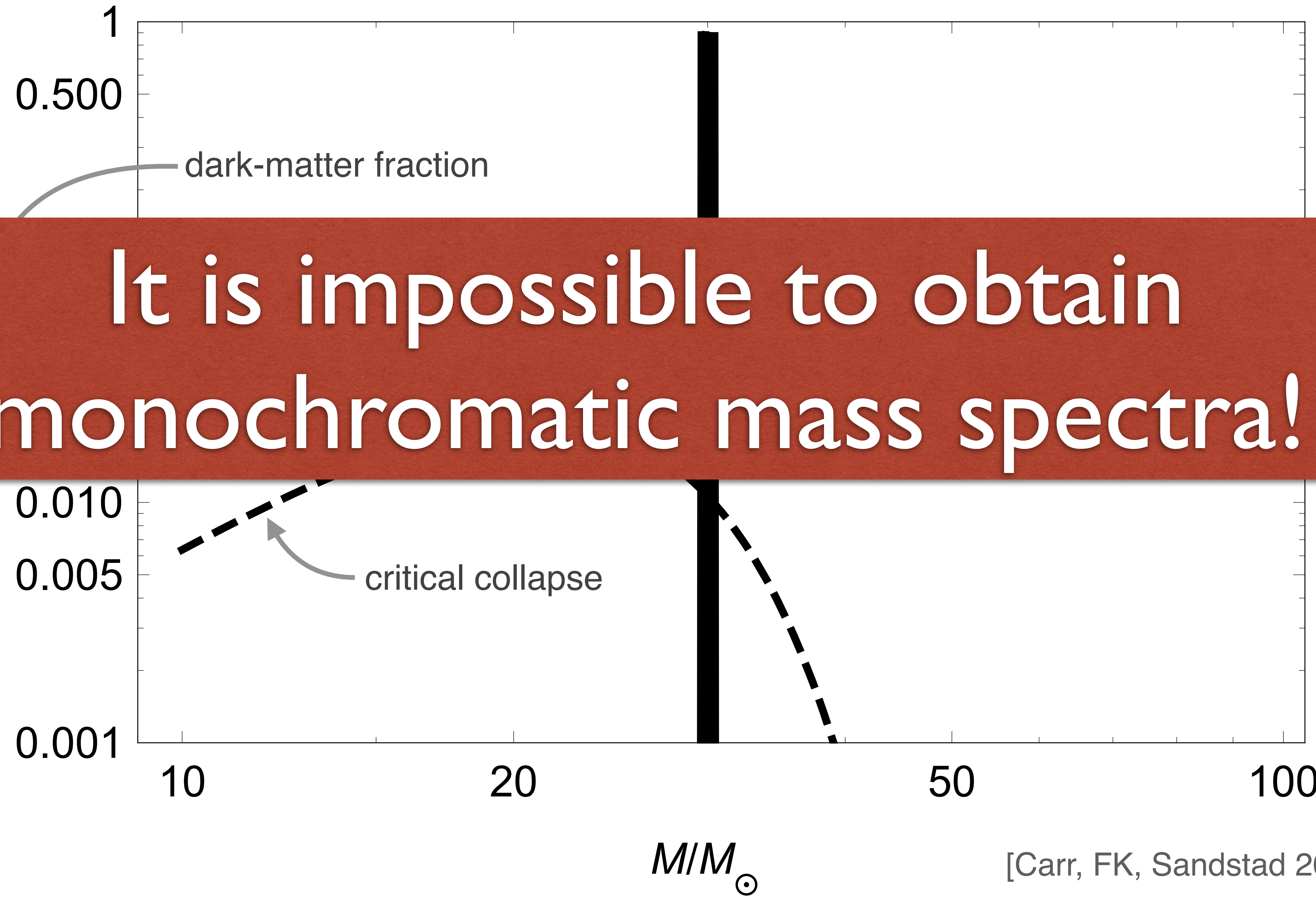
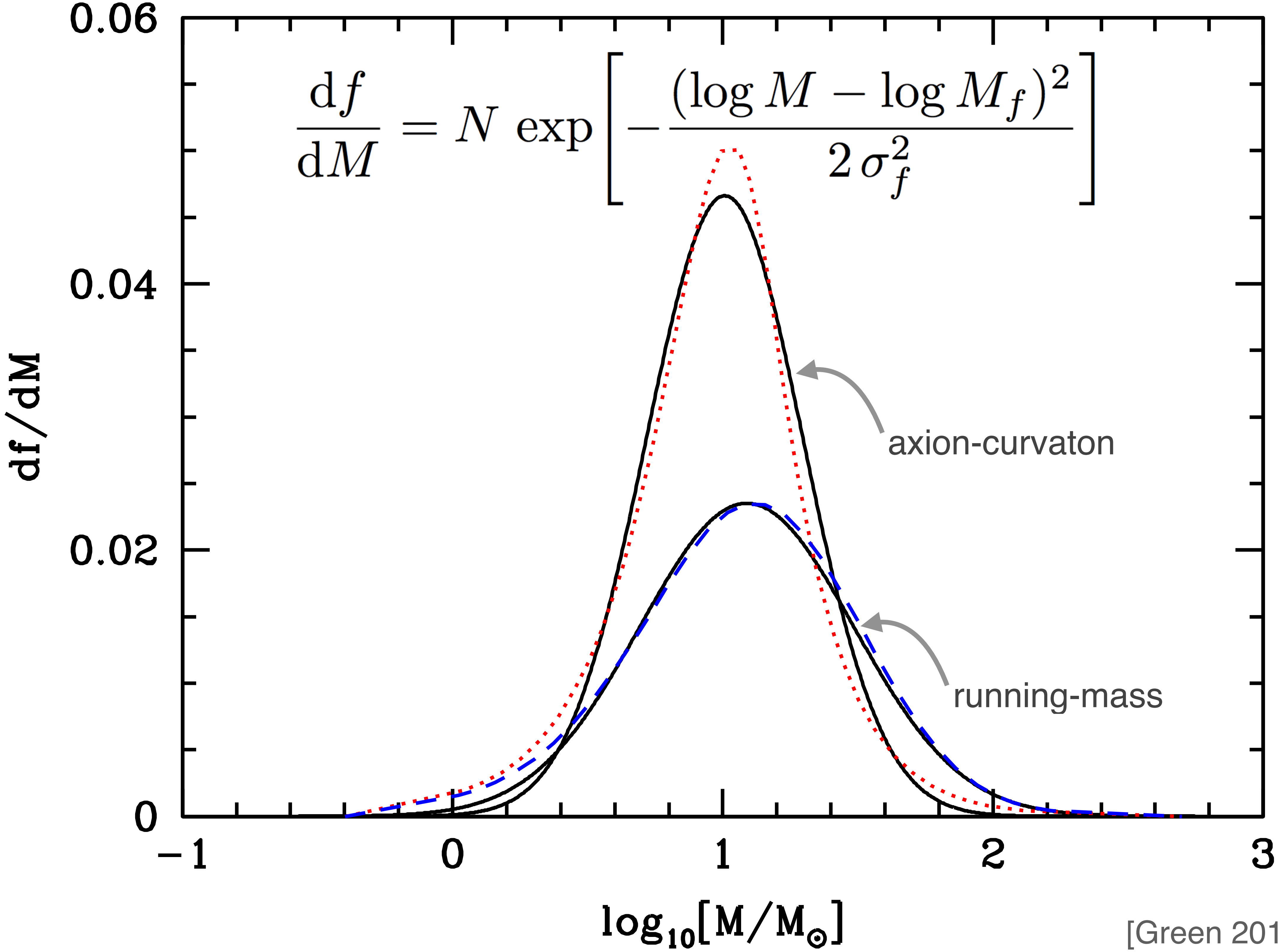


It is impossible to obtain monochromatic mass spectra!

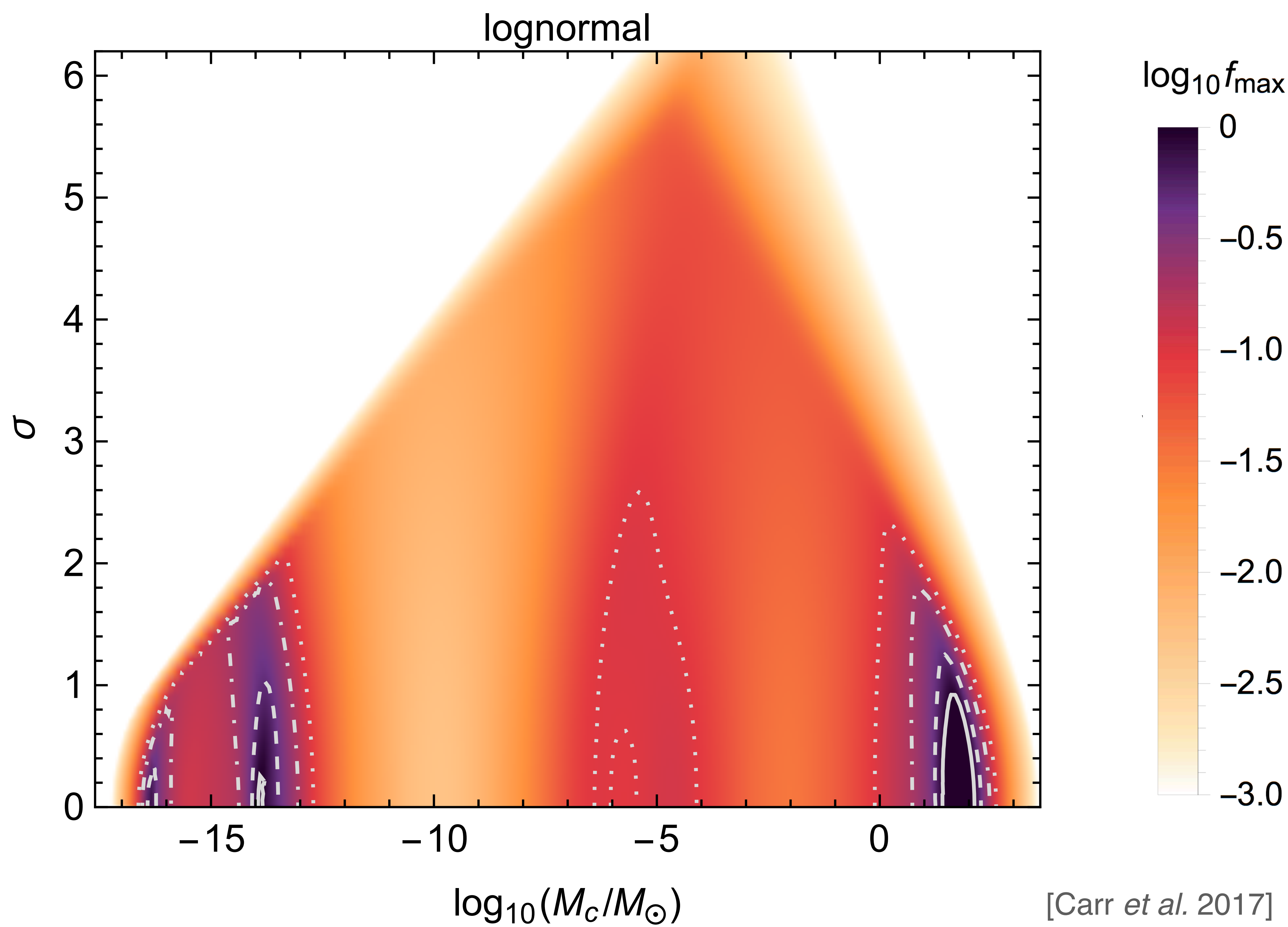
[Carr, FK, Sandstad 2016]

More Systematic Study



[Green 2016]

More Systematic Study



[Carr *et al.* 2017]

Observational Conundra

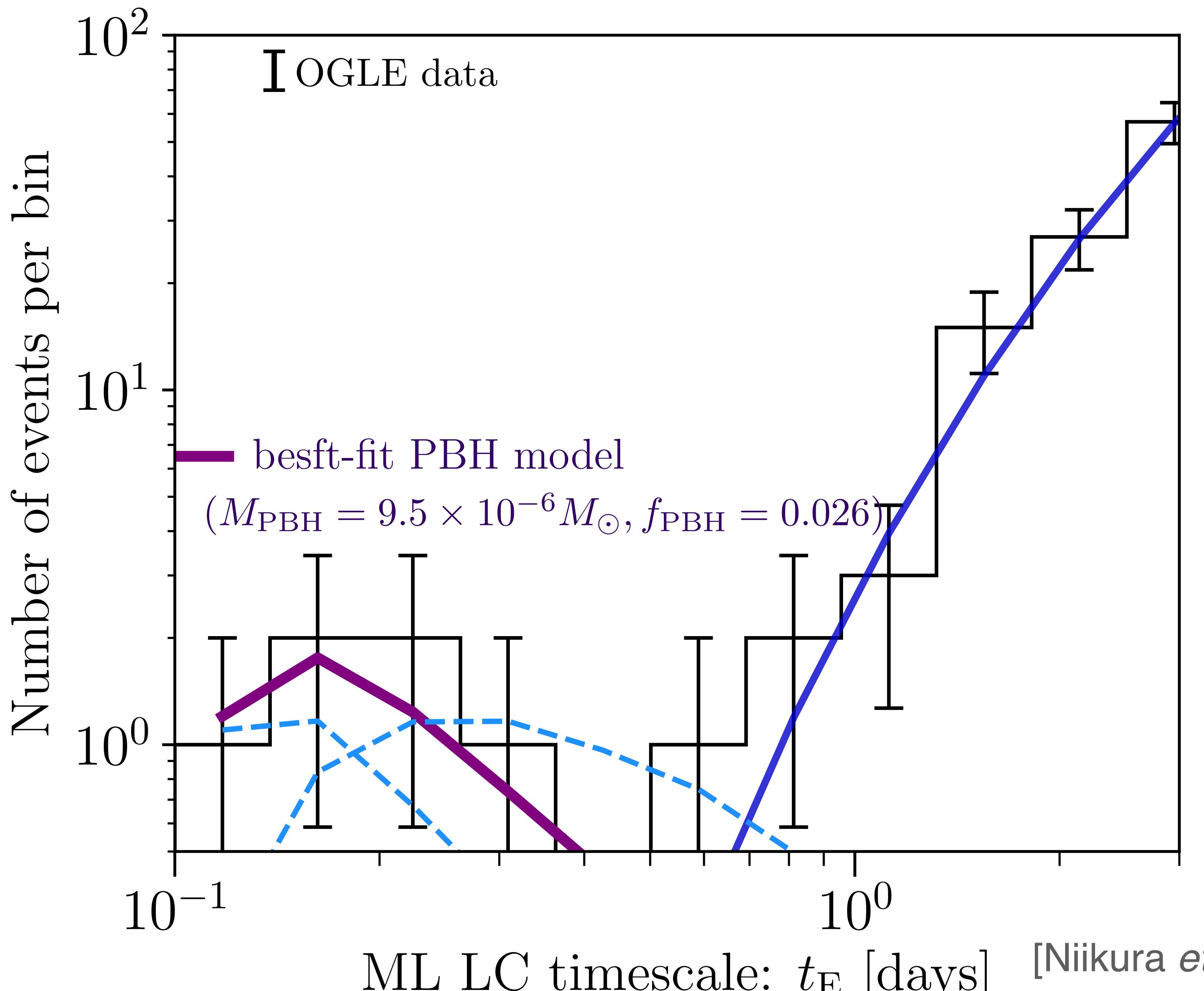
Microlensing

- OGLE detected a population of microlensing events:
  - 1 - 300 days light-curve timescale - origin known.
    Should be brown dwarfs, MS stars, white dwarfs, and neutron stars.

1.3 m Warsaw University Telescope Las Campanas Observatory, Chile

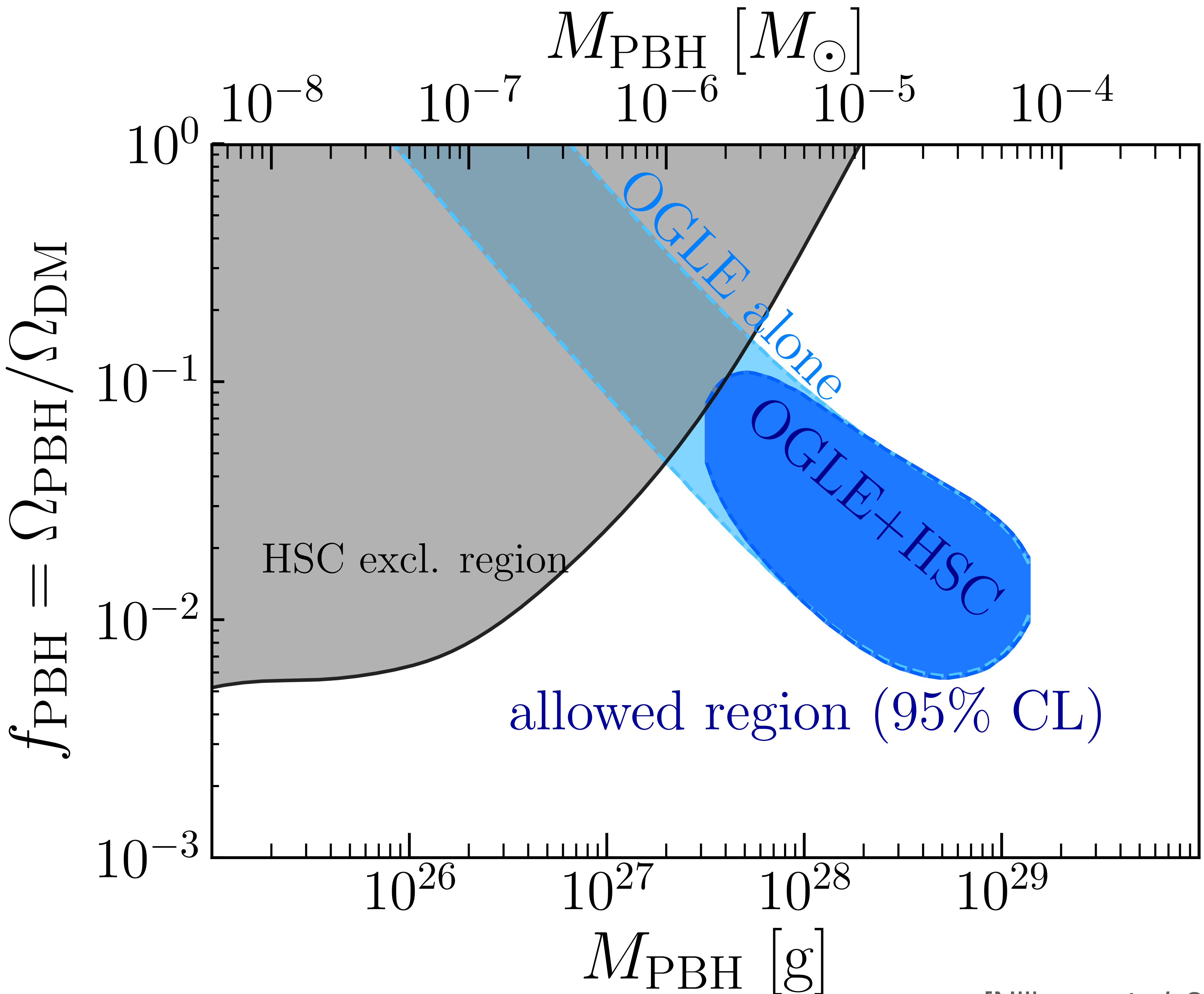
Did OGLE Detect PBHs?

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



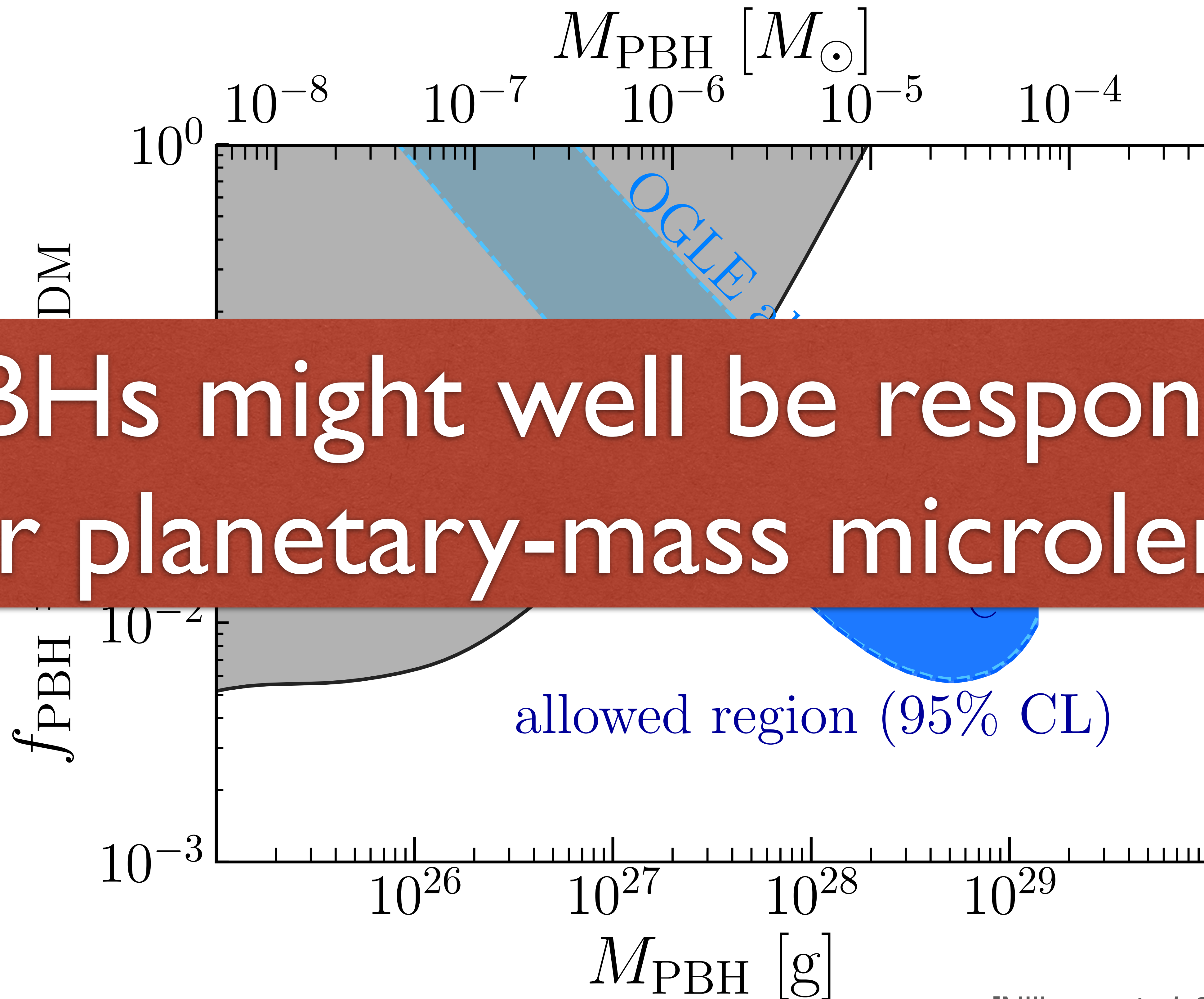
[Niikura *et al.* 2019]

Did OGLE Detect PBHs?



[Niikura *et al.* 2019]

Did OGLE Detect PBHs?



PBHs might well be responsible for planetary-mass microlenses.

[Niikura *et al.* 2019]

More Observational Evidence

- **Quasar Microlensing:** 24 microlensed quasars, some of which have a misaligned lensing galaxy, so *cannot* be stars!

[Hawkins 1993, 2020]

$$f_{\rm PBH}\Big|_{M\sim\mathcal{O}(M_\odot)} > 0.07$$

- **OGLE/GAIA Excess of Dark Lenses in the Galactic Bulge:** ~ 20 lenses in the mass gap 2 - 5 $M_\odot$, so cannot stellar black holes!

[Wyrzykowski and Mandel 2019]

- **Cosmic Infrared/X-ray Backgrounds:** Spatial coherence of the X-ray and infrared source-subtracted backgrounds (> 5 σ) require PBHs $\mathcal{O}(M_\odot)$.

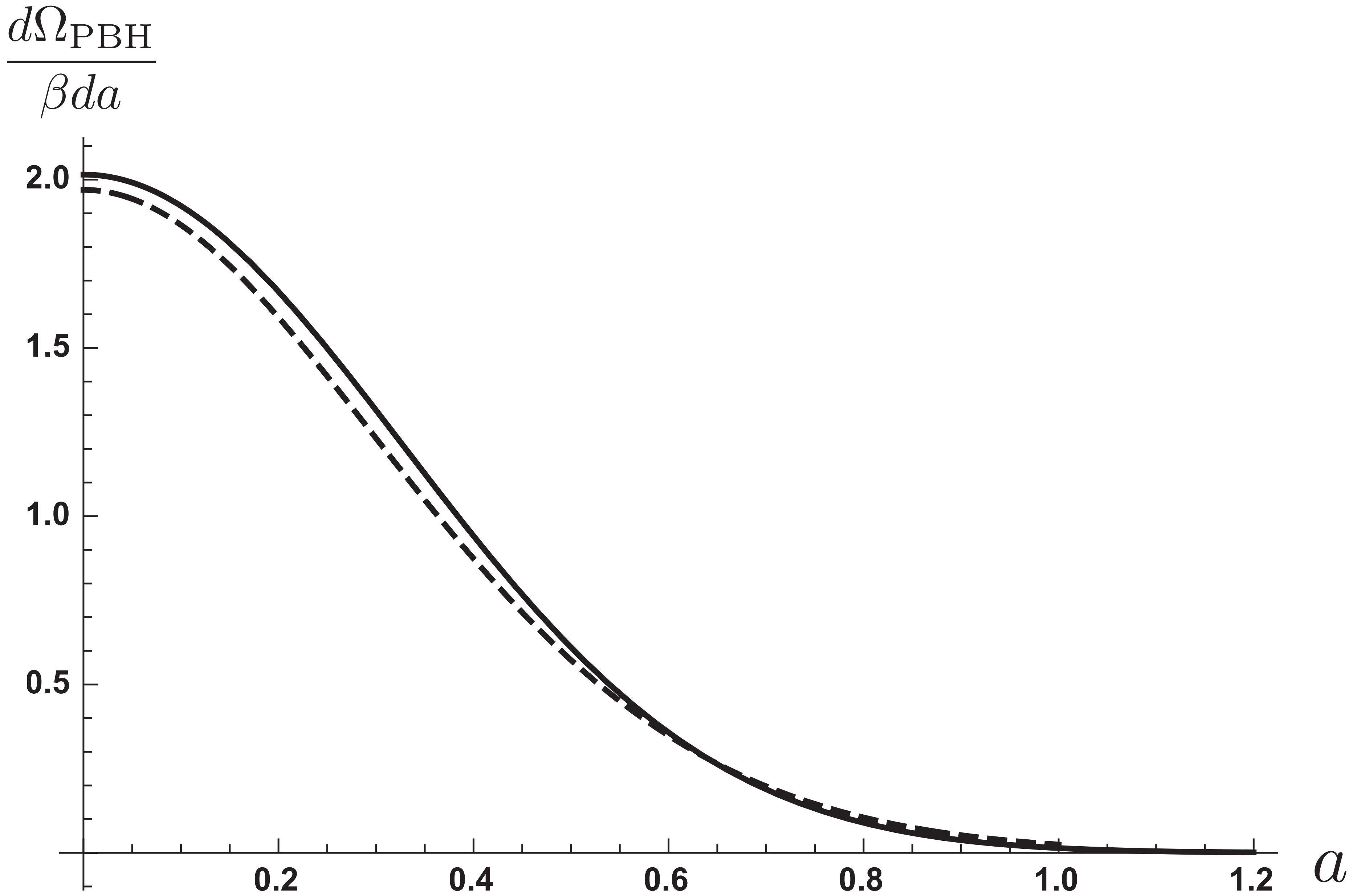
[Kashlinsky 2005, 2016]

- **Ultra-Faint Dwarf Galaxies:** Non-observation of ultra-faint dwarf galaxies below a critical radius, can be explained if they are dynamical disrupted by PBHs of mass 20 - 100 $M_\odot$.

[Clesse & García-Bellido 2018]

Gravitational Waves

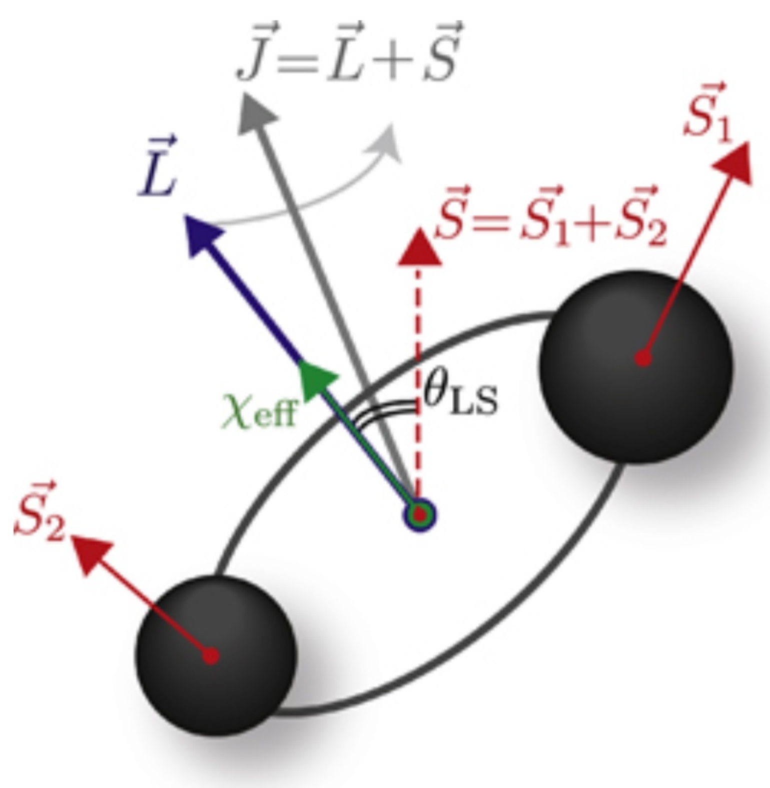
- ★ Gravitational-wave emission from black-hole binaries
  - ★ For PBH (produced in RD) we expect close to zero spin.



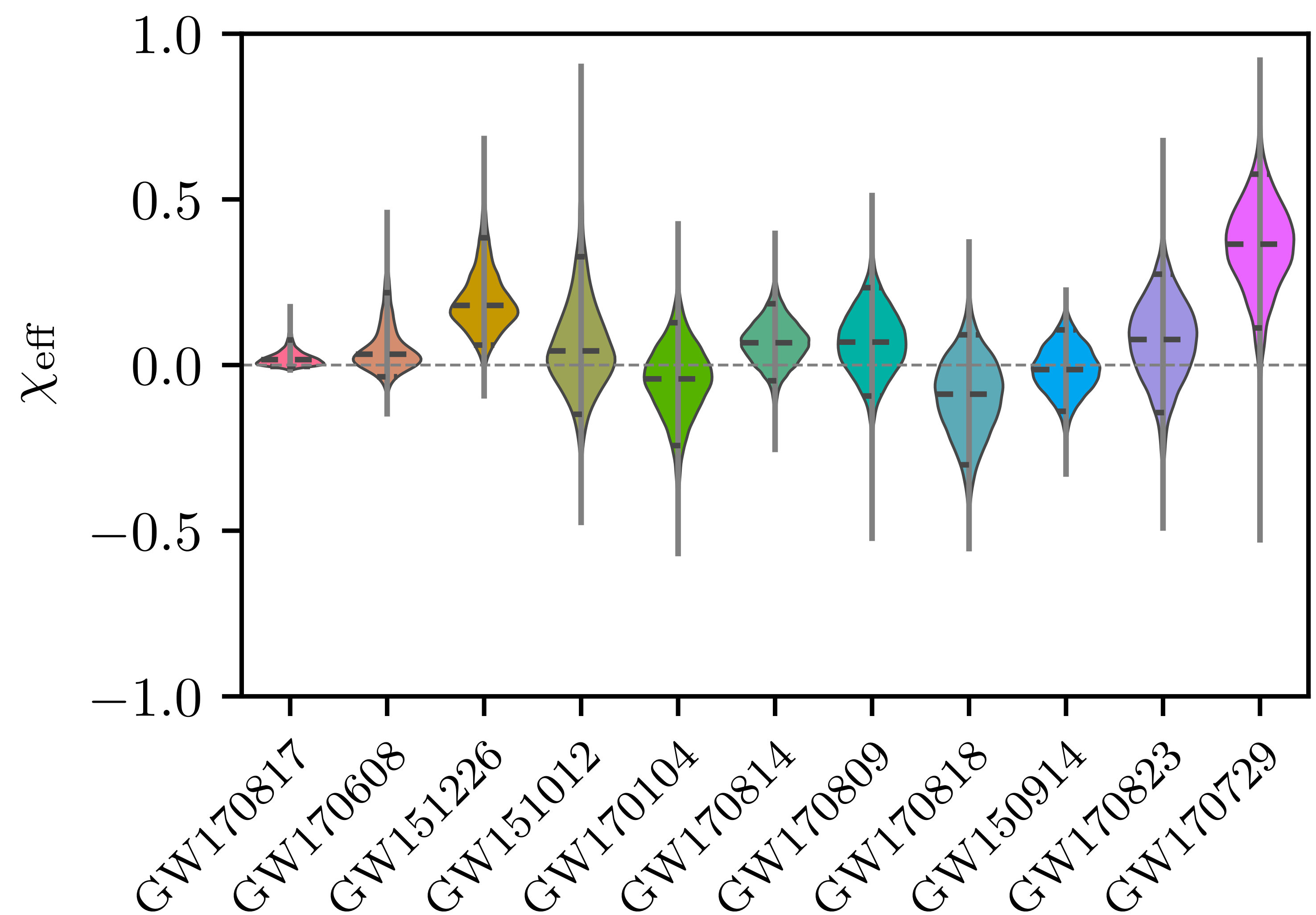
[Chiba & Yokoyama 2017]

Gravitational Waves

- Gravitational-wave emission from black-hole binaries
  - For PBH (produced in RD) we expect close to zero spin.
  - Inferred spin from observed black-hole binary mergers:

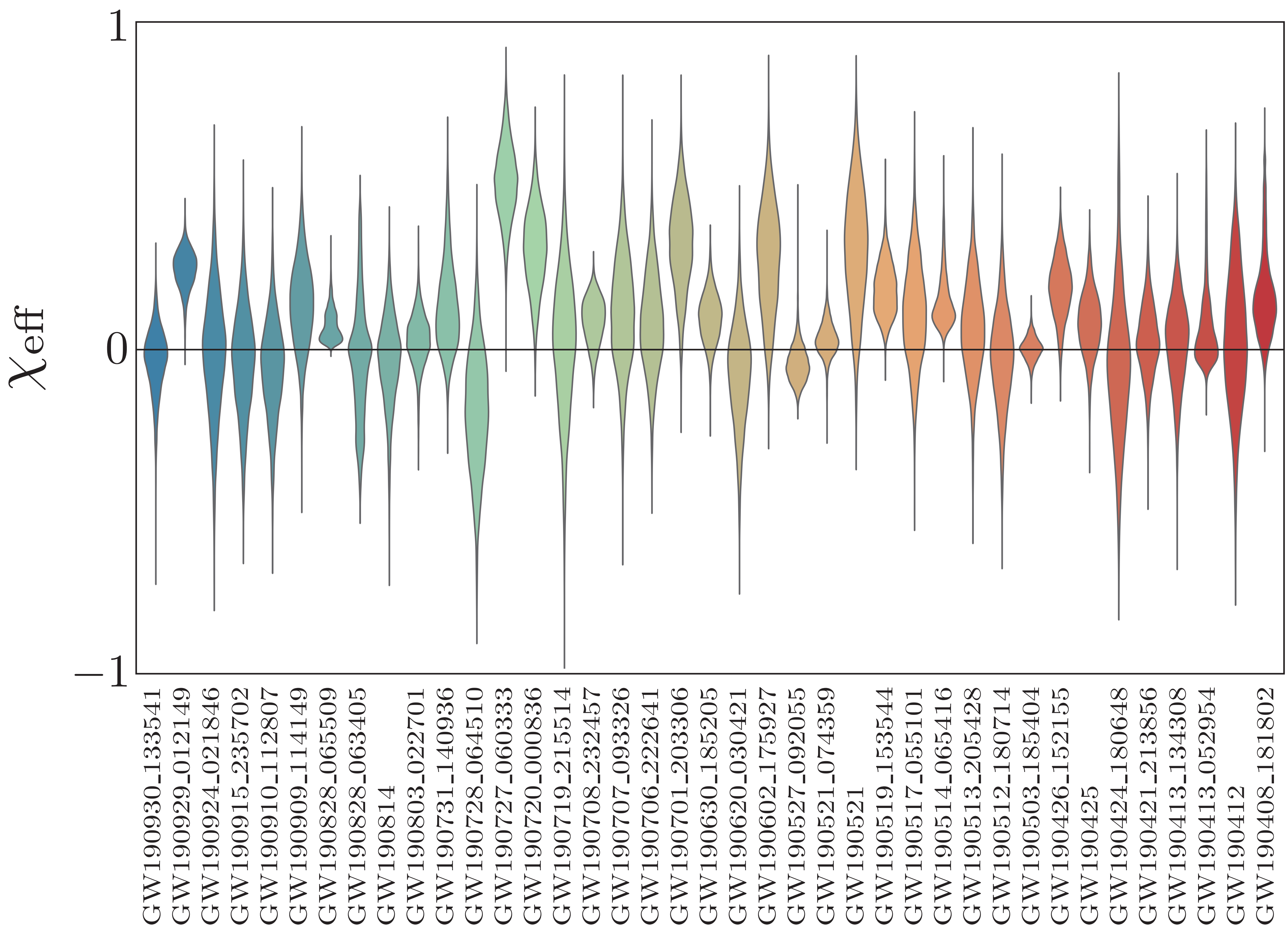


$$\chi_{\rm eff} = \frac{c}{G(m_1+m_2)}\left(\frac{\vec{S}_1}{m_1}+\frac{\vec{S}_2}{m_2}\right)\cdot\vec{L}$$



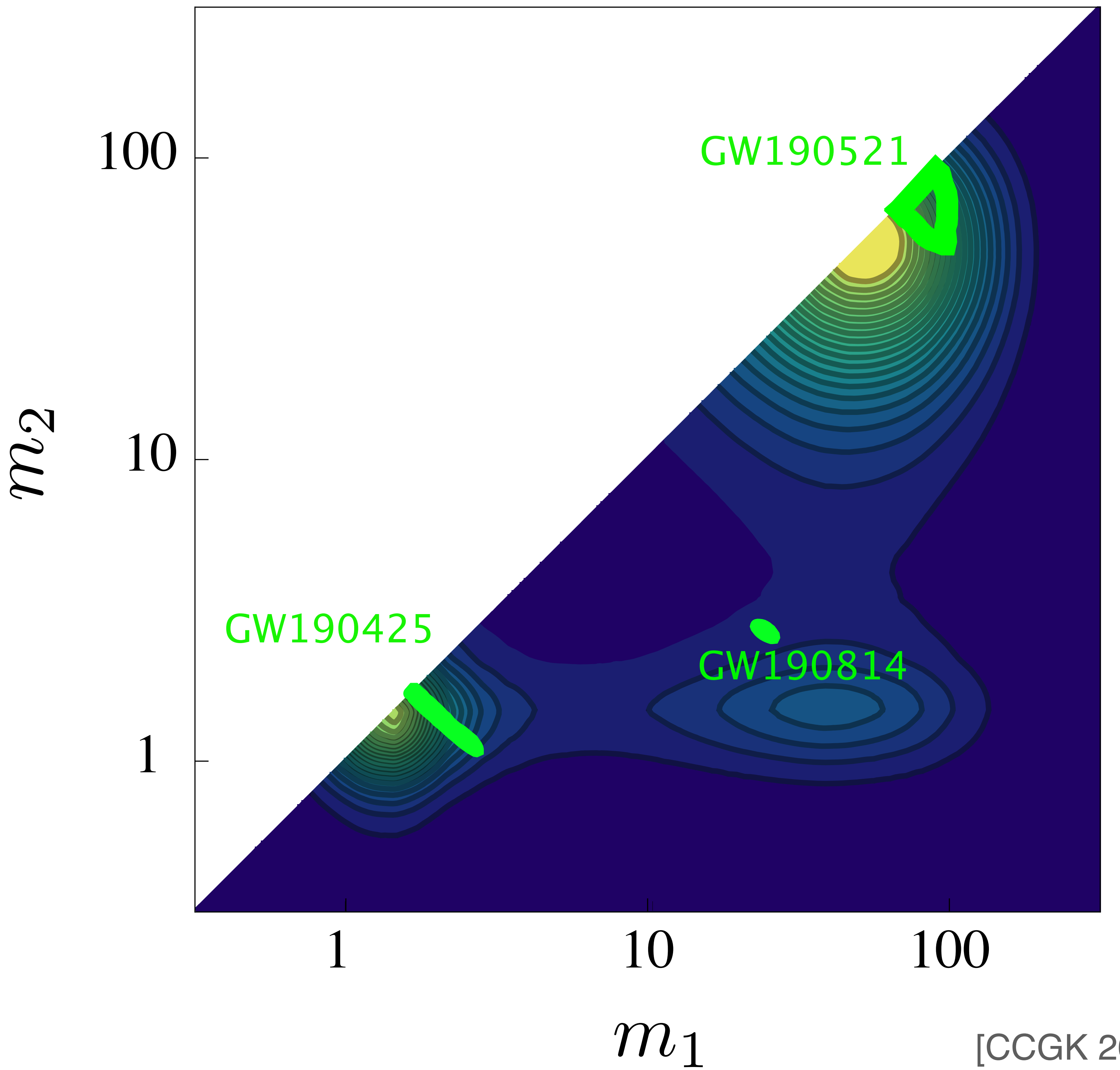
[LIGO Scientific, Virgo 2018]

Gravitational Waves



[Abbott *et al.* 2020]

LIGO/Virgo Merger-Rate Predictions

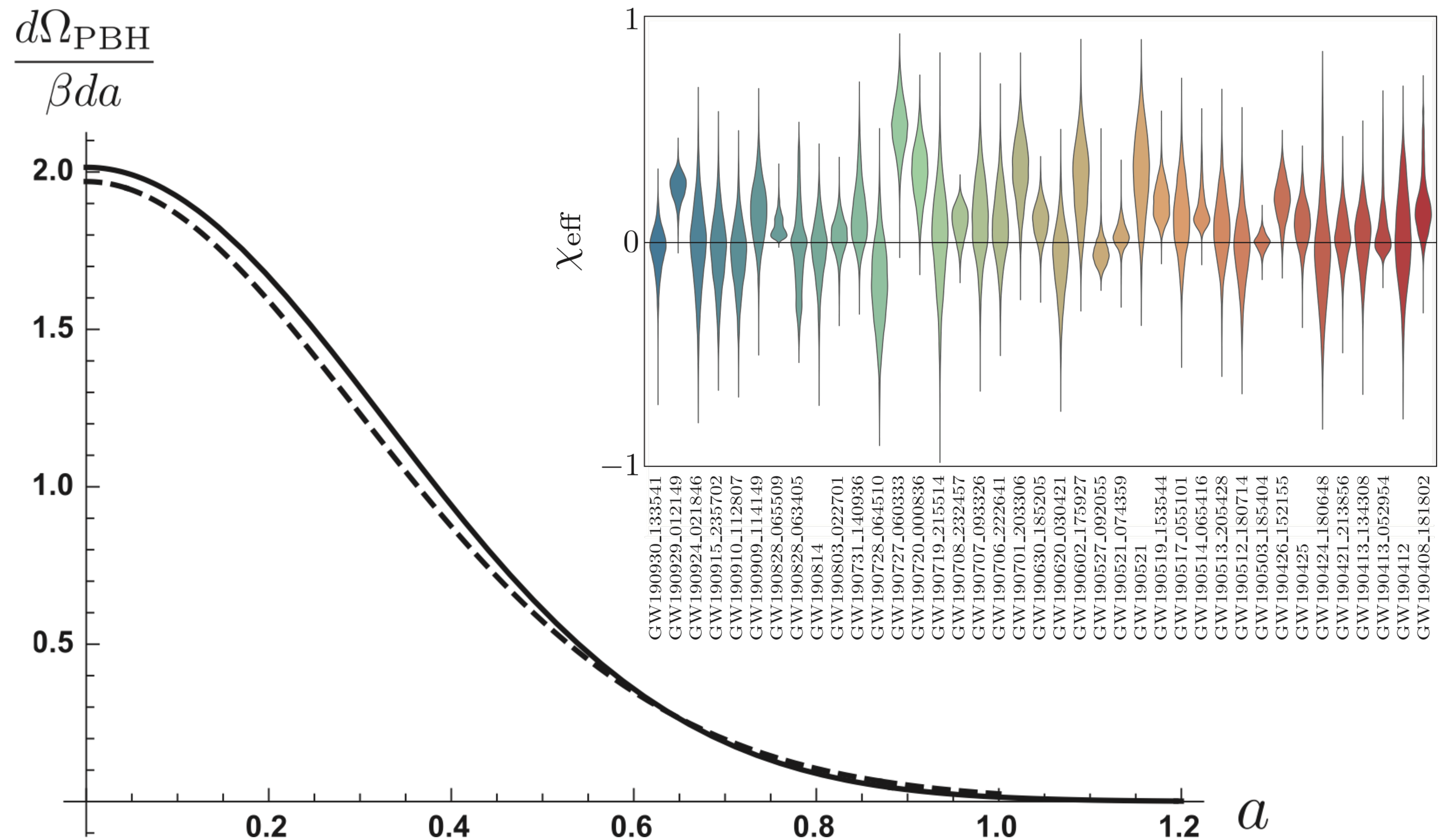


[CCGK 2020]

Spin

★ Gravitational-wave emission from black-hole binaries

★ For PBH (produced in RD) we expect close to zero spin.



[Chiba & Yokoyama 2017]

Lepton Flavour Asymmetry

★ Lepton flavour asymmetries are defined as

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

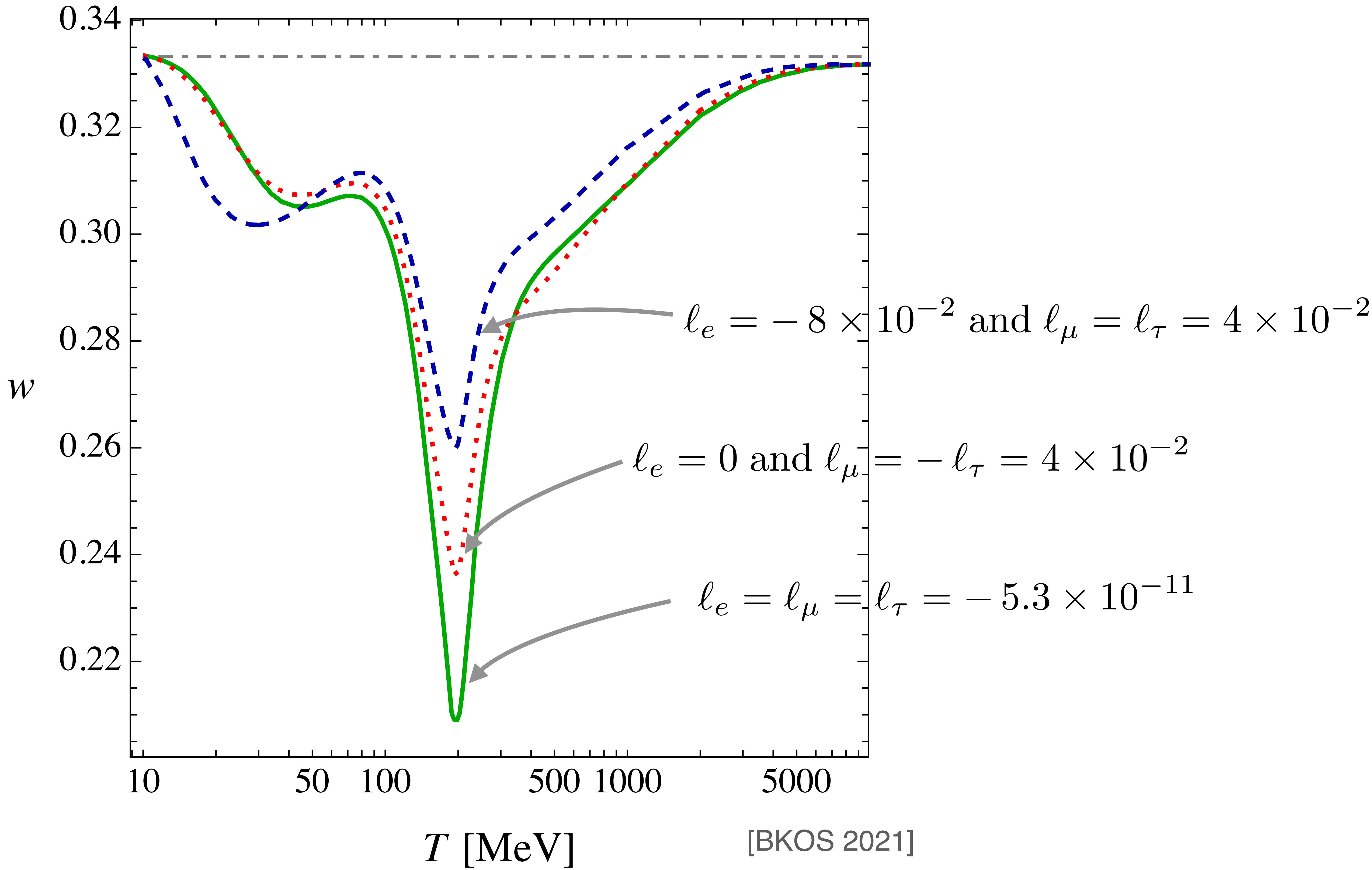
$n_\alpha, n_{\bar{\alpha}}, n_{\nu_\alpha}, n_{\bar{\nu}_\alpha}$	number densities of (anti)leptons and corresponding (anti)neutrinos
s	entropy densities

★ CMB constraints are quite weak:

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

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

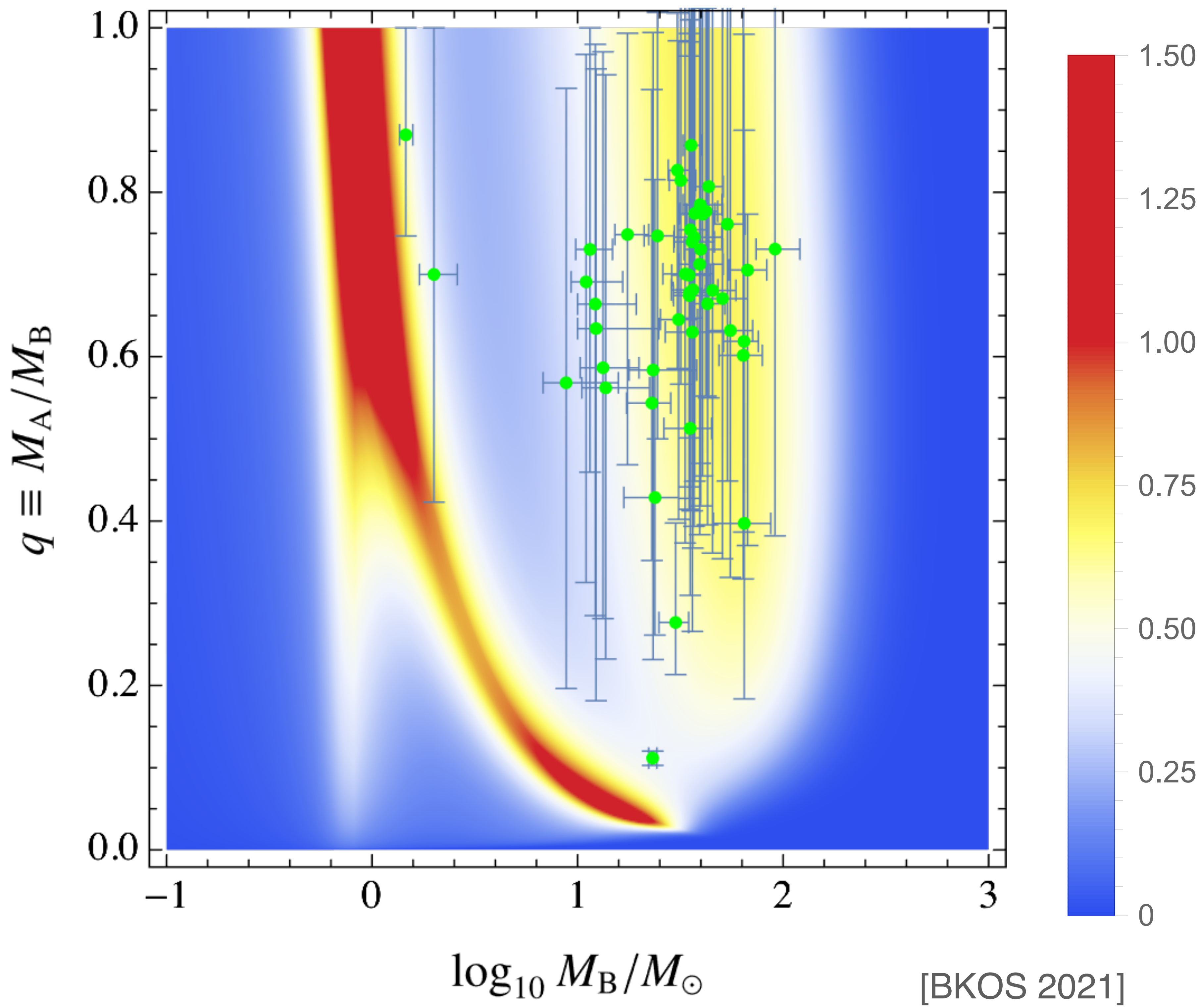
Lepton Flavour Asymmetry



[BKOS 2021]

Lepton Flavour Asymmetry

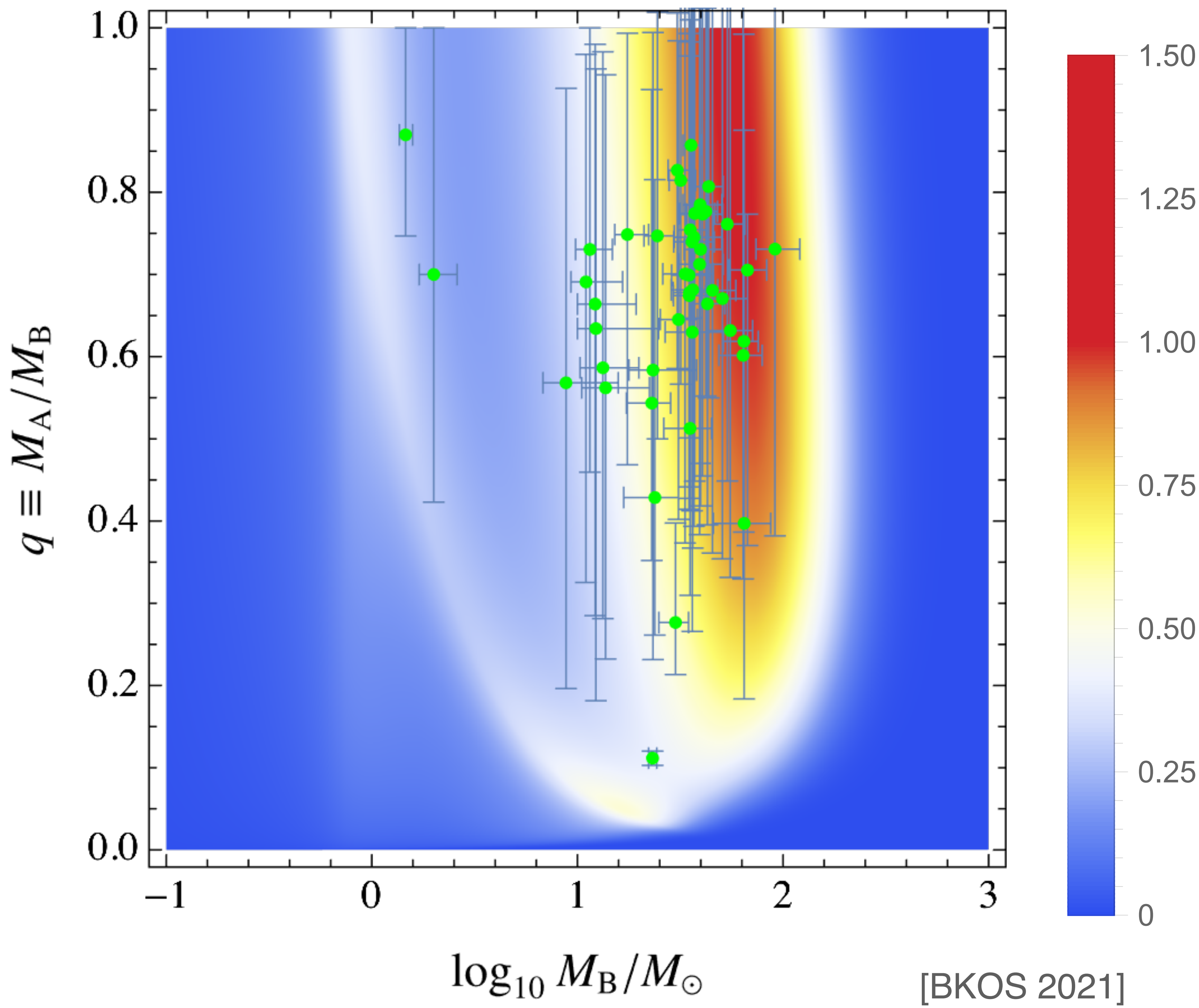
$$\ell_e = \ell_\mu = \ell_\tau = -5.3 \times 10^{-11}$$



[BKOS 2021]

Lepton Flavour Asymmetry

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



[BKOS 2021]