Thermal History and Primordial Black Holes

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Stockholm University

The Oskar Klein Centre

PASCOS 2019

The University of Manchester - 4th of July 2019

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work in particular with

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Katie Freese

Juan García-Bellido

Glenn Starkman

PBH Generalities

Oskar Klein centre

★ Astrophysical black holes: From $10^{10}\,M_\odot$ down to $1\,M_\odot$, but not lower.

★ Have a look at the density $\rho_S = 10^{18} \left(\frac{M}{M_\odot}\right)^{-2} \frac{\mathrm{g}}{\mathrm{cm}^3}$

→ To form smaller black holes we need higher density.

→ Compare to cosmological density $\rho_C = 10^{6} \left(\frac{t}{\mathrm{s}}\right)^{-2} \frac{\mathrm{g}}{\mathrm{cm}^3}$

→ Formation at early times; primordial black holes (PBHs).

★ Masses of primordial black holes:

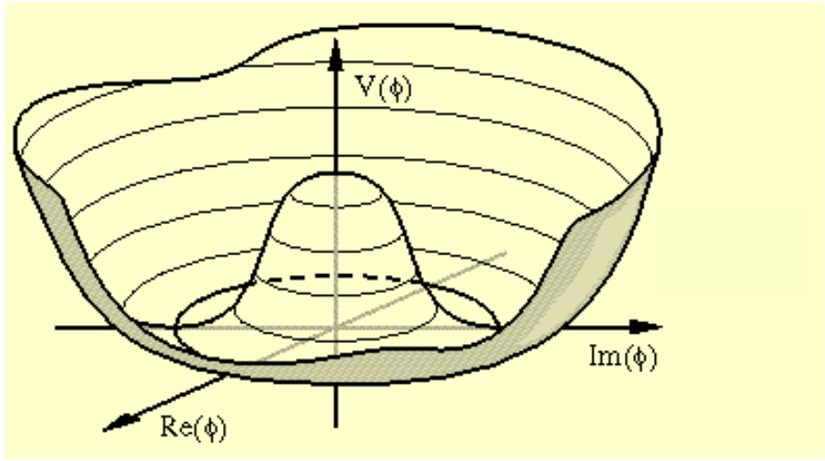
$$M\big(t = 10^{-23}\,\mathrm{s}\big) = 10^{15}\,\mathrm{g}\,, \quad M\big(t = 10^{-6}\,\mathrm{s}\big) = M_\odot$$

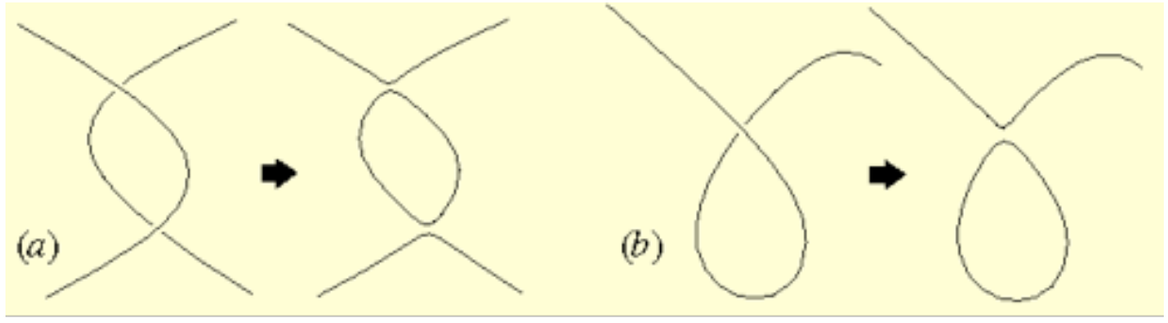
PBH Formation Mechanisms

- Formation of primordial black holes

PBH Formation Mechanisms

- Formation of primordial black holes by
  - Cosmic string loops

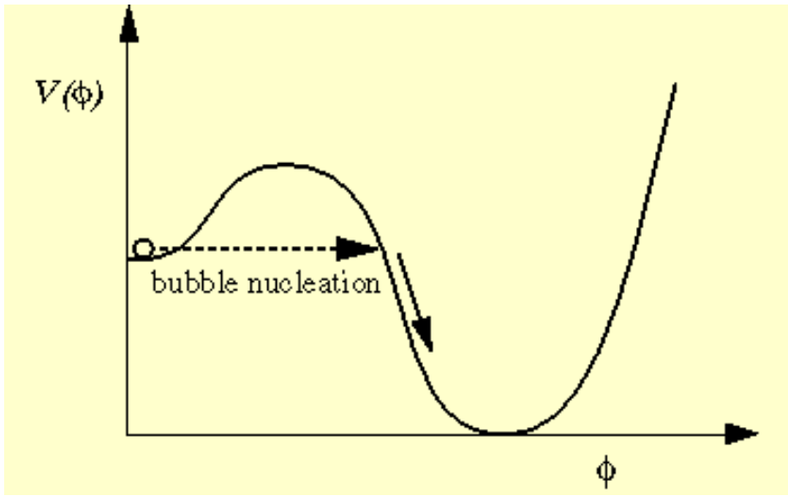


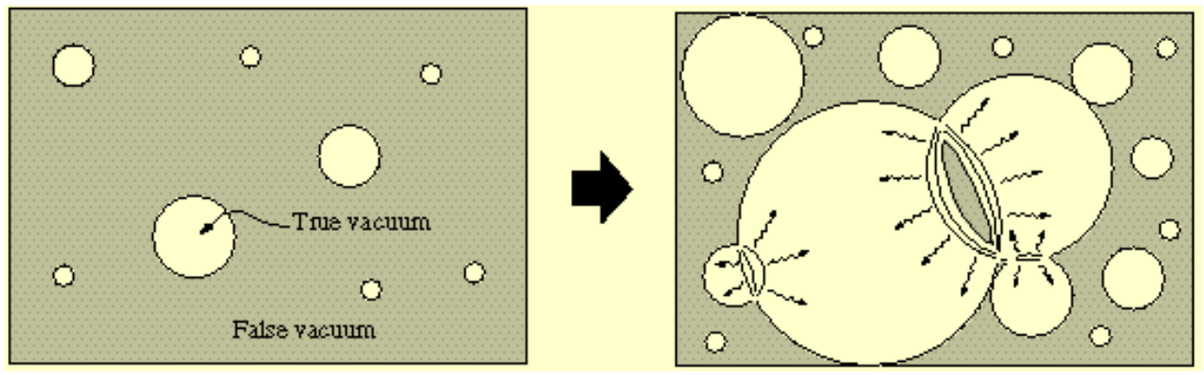


http://www.damtp.cam.ac.uk/research/gr/public/cs_top.html

PBH Formation Mechanisms

- Formation of primordial black holes by
  - Cosmic string loops
  - Bubble collisions

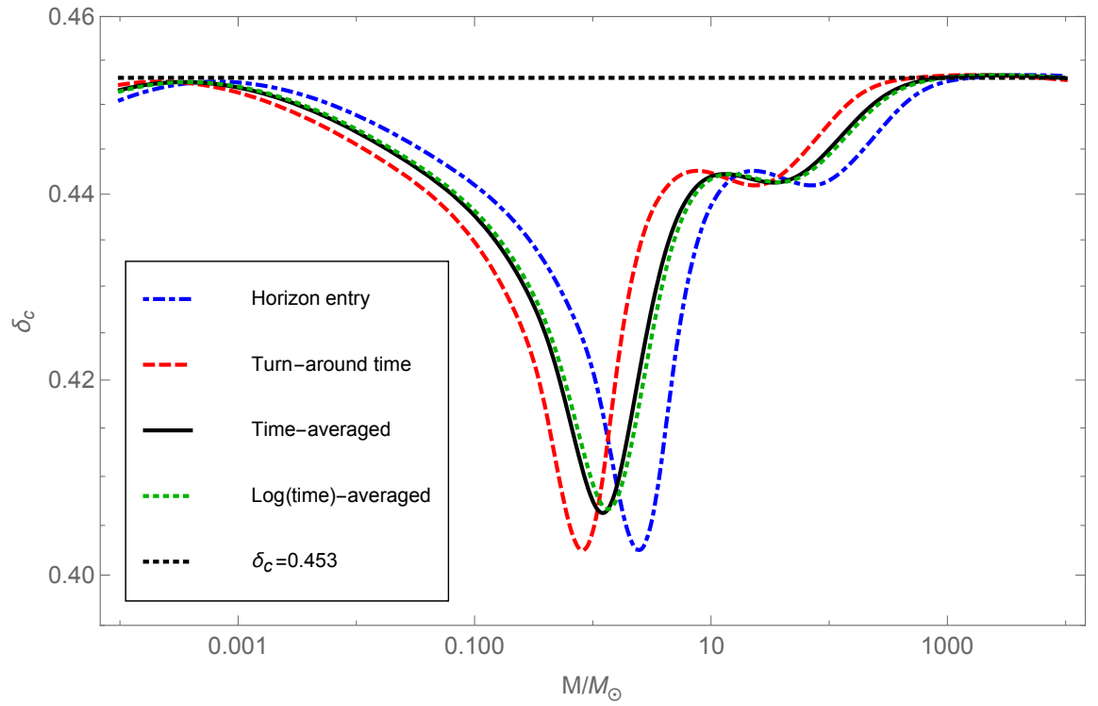




http://www.damtp.cam.ac.uk/research/gr/public/cs_phase.html

PBH Formation Mechanisms

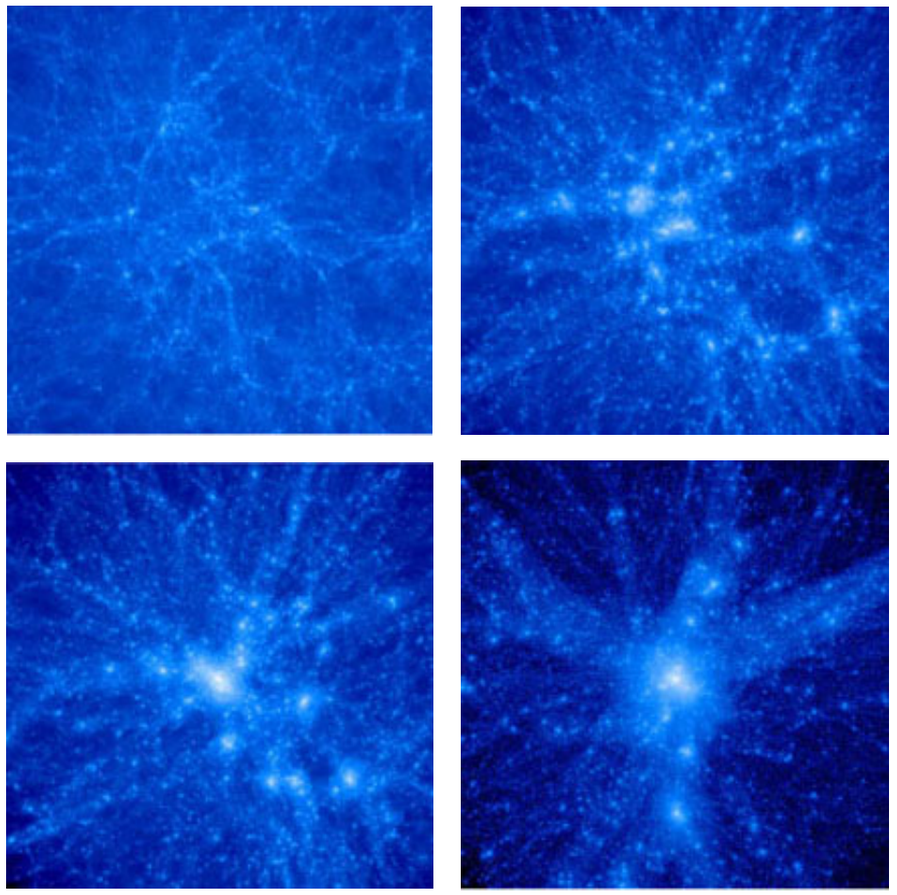
- Formation of primordial black holes by
  - Cosmic string loops
  - Bubble collisions
  - Pressure reduction



[Byrnes *et al.* 2018]

PBH Formation Mechanisms

- Formation of primordial black holes by
  - Cosmic string loops
  - Bubble collisions
  - Pressure reduction
  - Large density perturbations of inflationary origin



https://ned.ipac.caltech.edu/level5/Sept12/Kravtsov/Kravtsov3.html

→ Simple estimate:

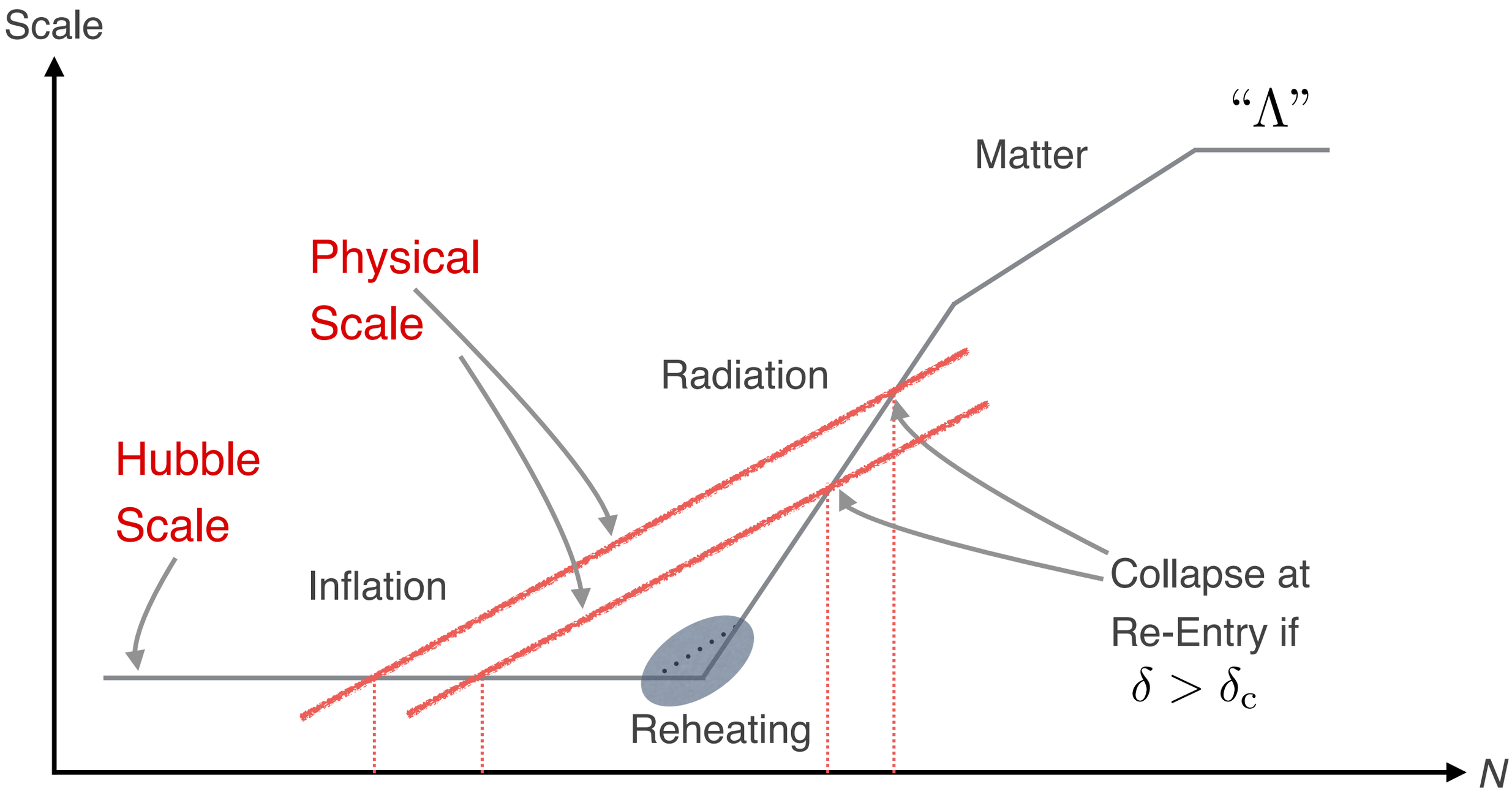
[Carr 1975]

$$R > R_J \quad \Rightarrow \quad \delta > w \quad , \quad \text{for} \quad p = w\,\rho \quad w > 0$$

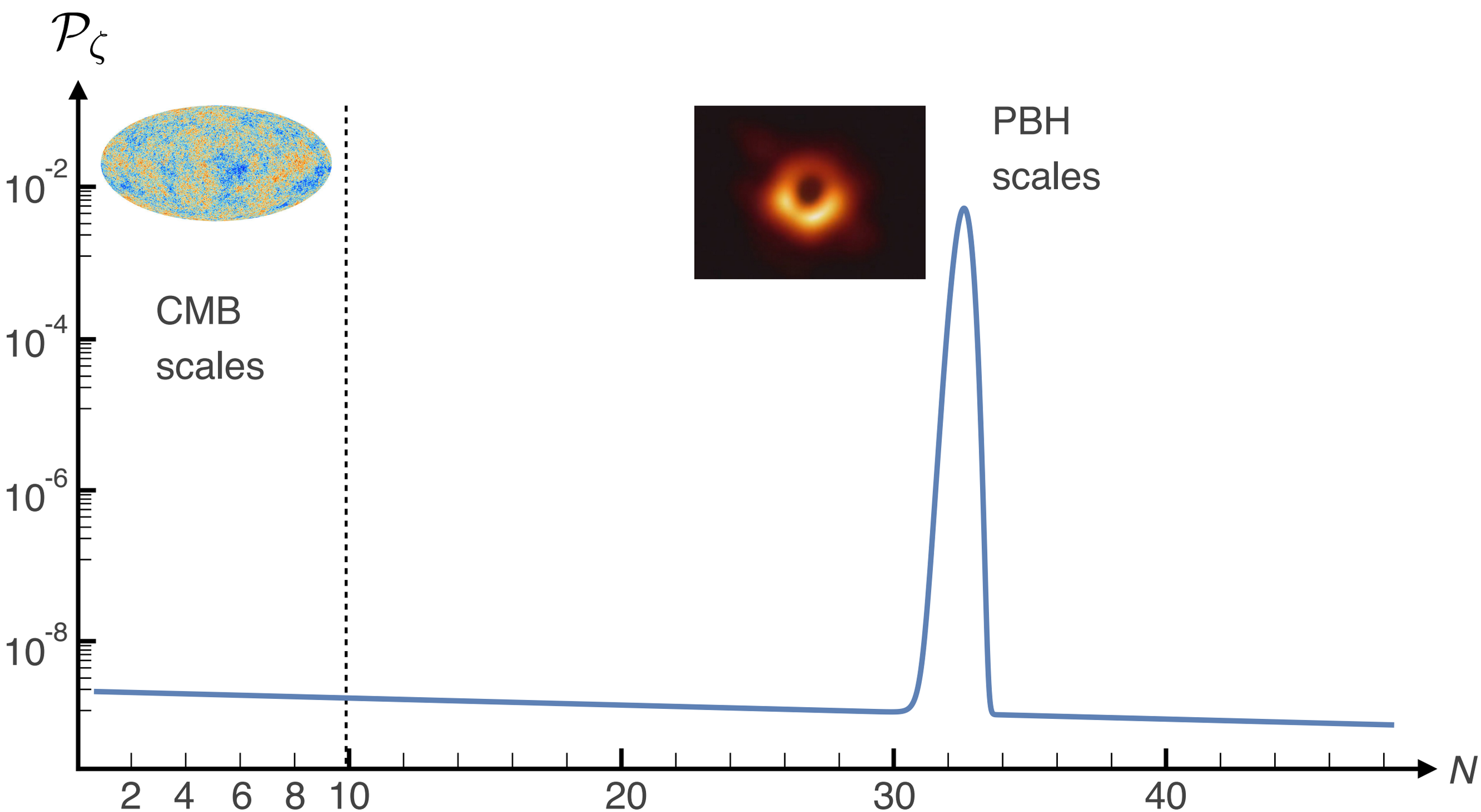
scale of the over density

Jeans length

PBH Formation - Scales



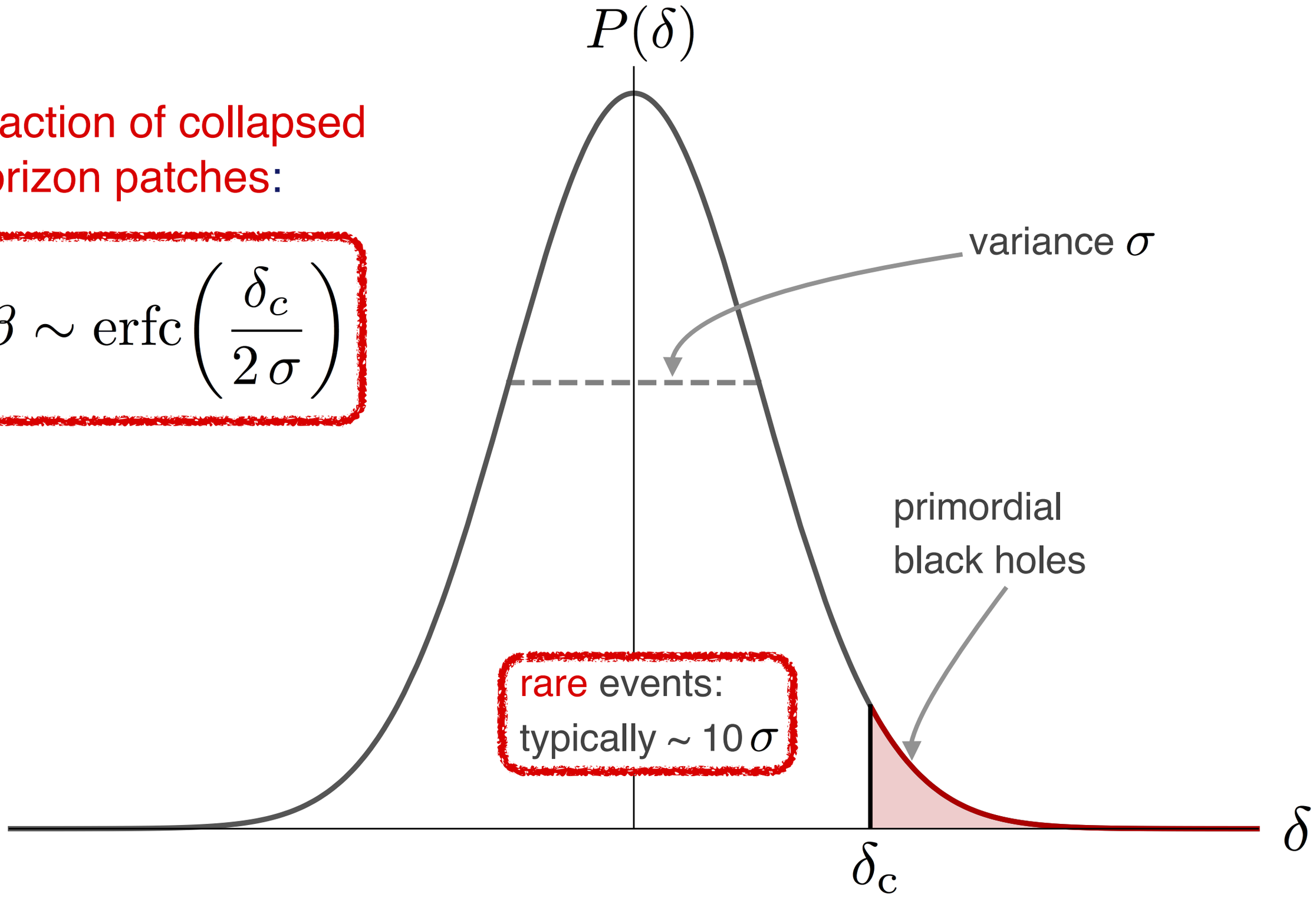
PBH Formation - Scales



PBH Formation - Rare Events

Fraction of collapsed horizon patches:

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



PBH — Probes of Scales

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★ 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 at Formation

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

β'

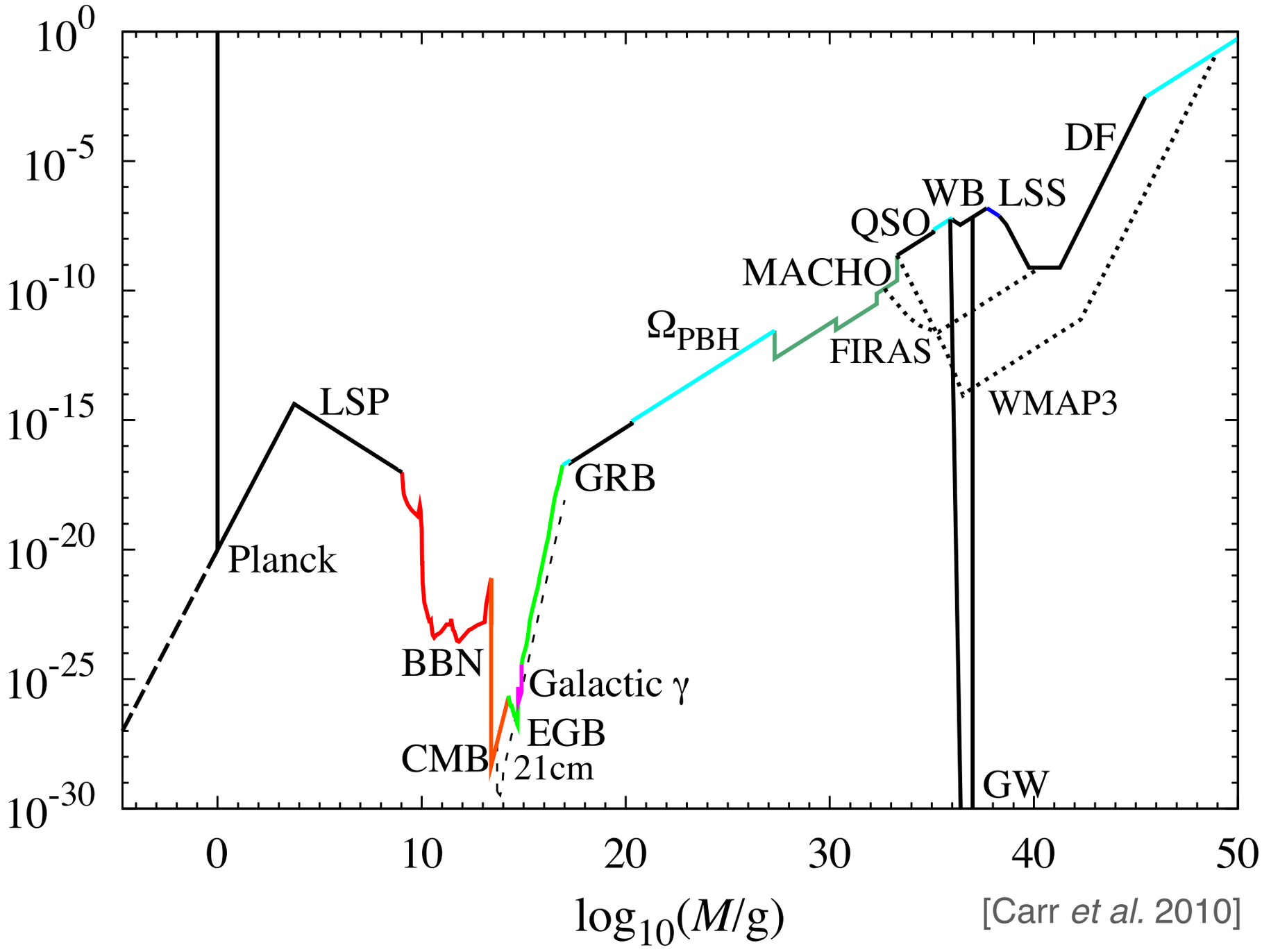
★ Note that

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

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

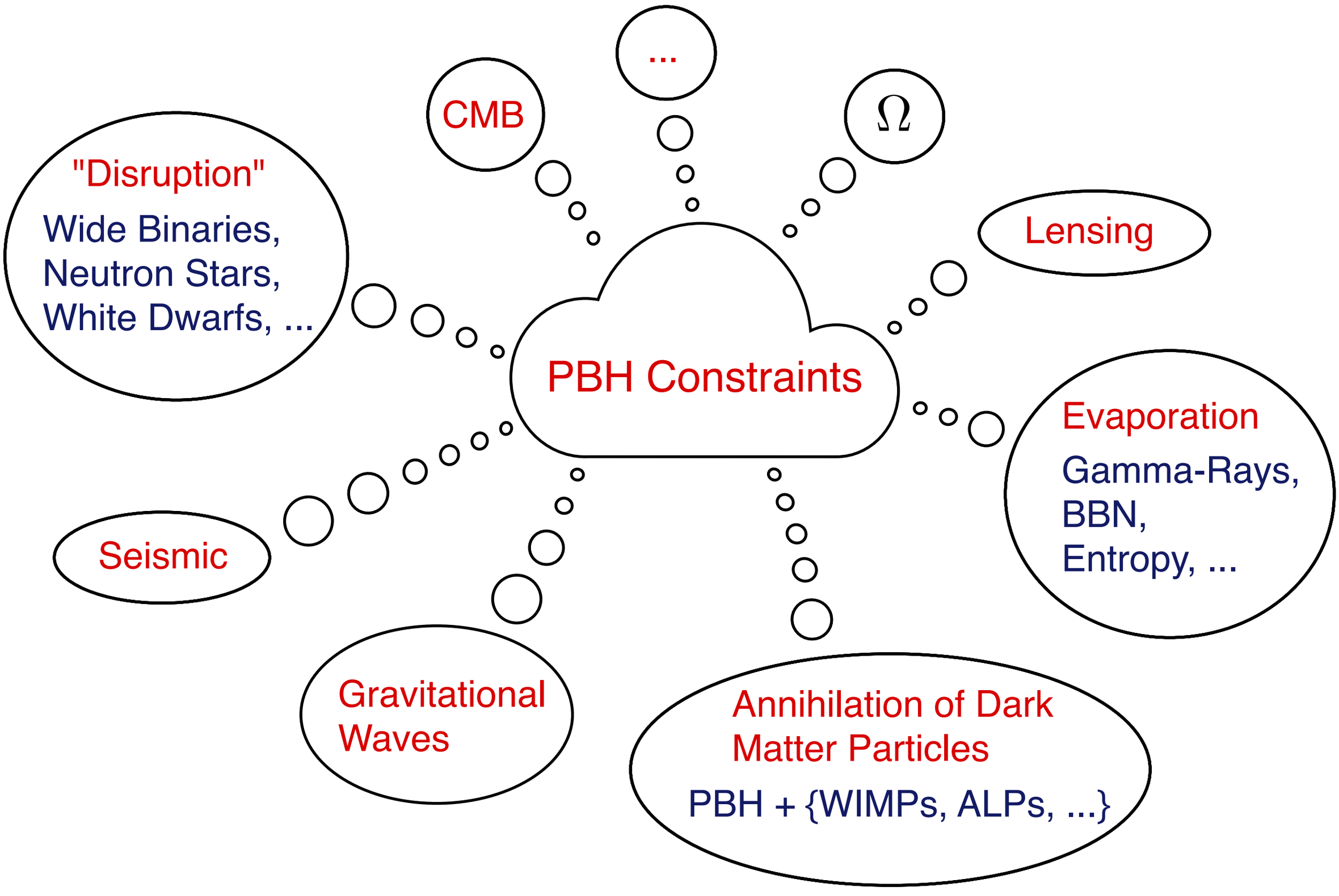
and hence

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



[Carr *et al.* 2010]

PBH Constraints



Observational Conundra

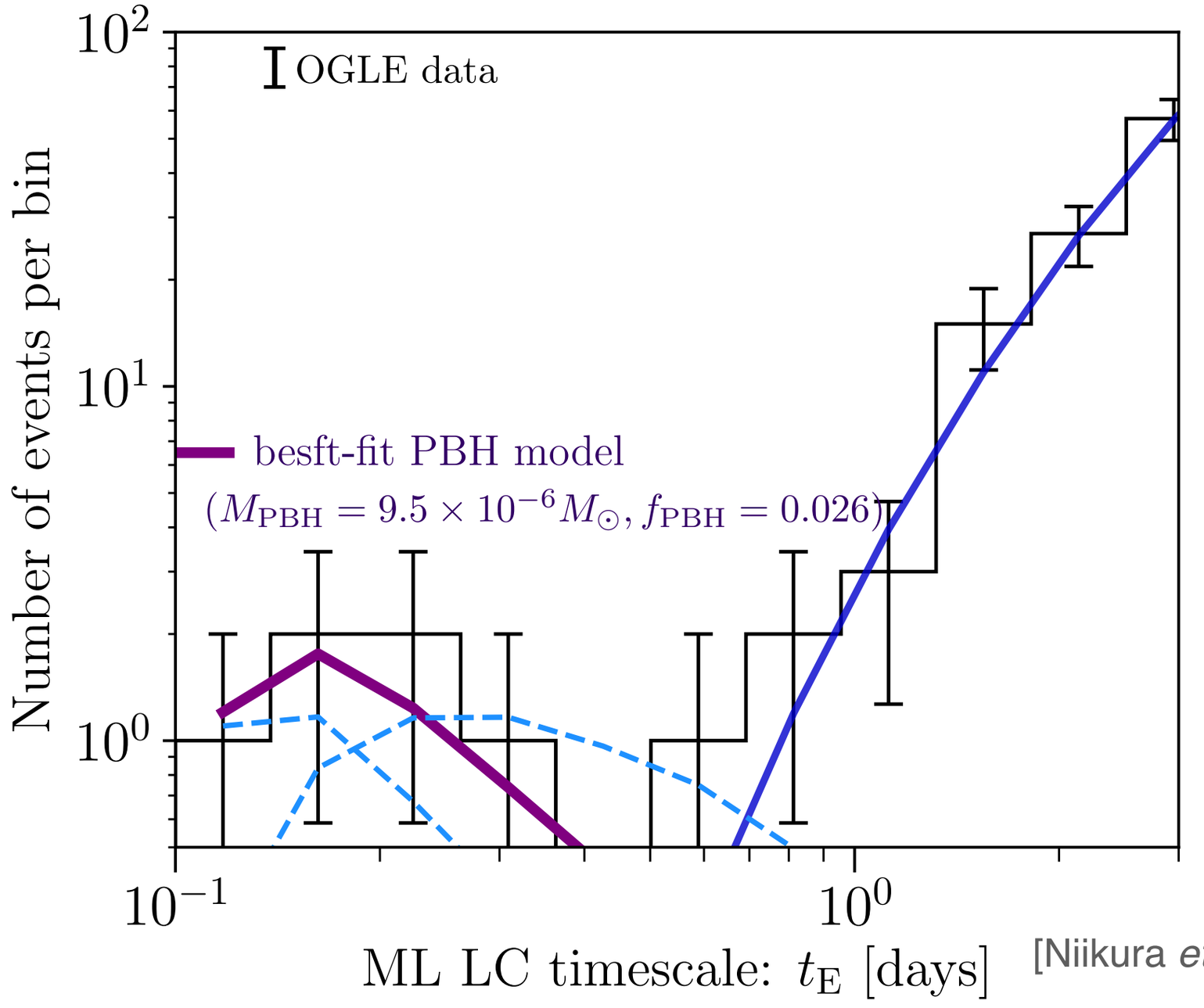
Microlensing

- 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

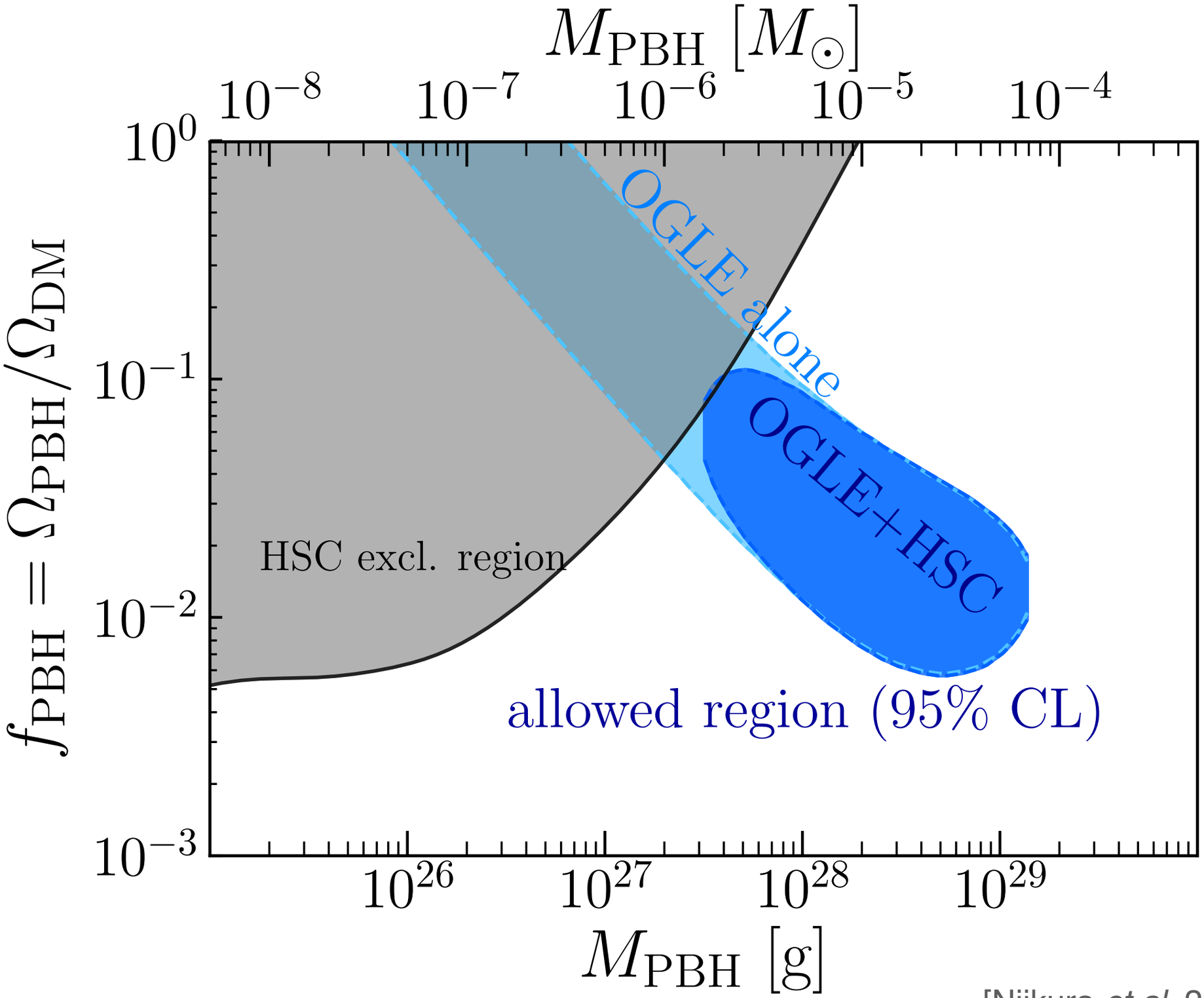
Did OGLE Detect PBHs?

- ... 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]

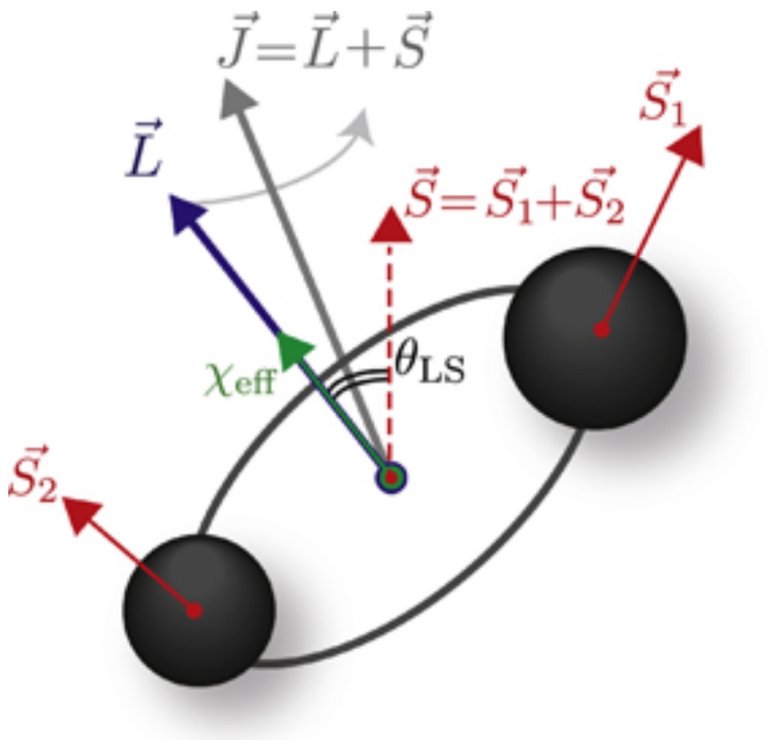
Did OGLE Detect PBHs?



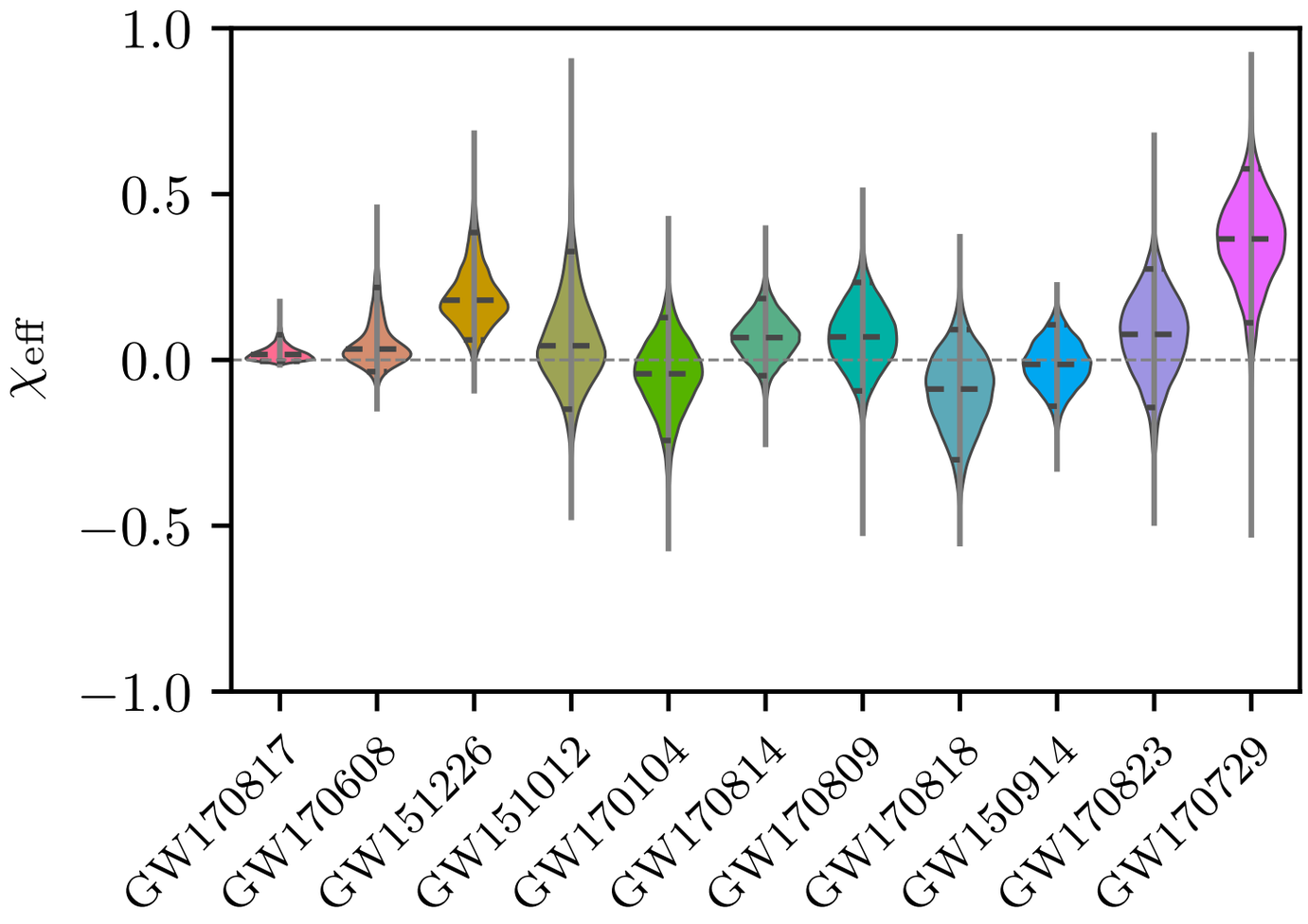
[Niikura *et al.* 2019]

- For PBH 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]

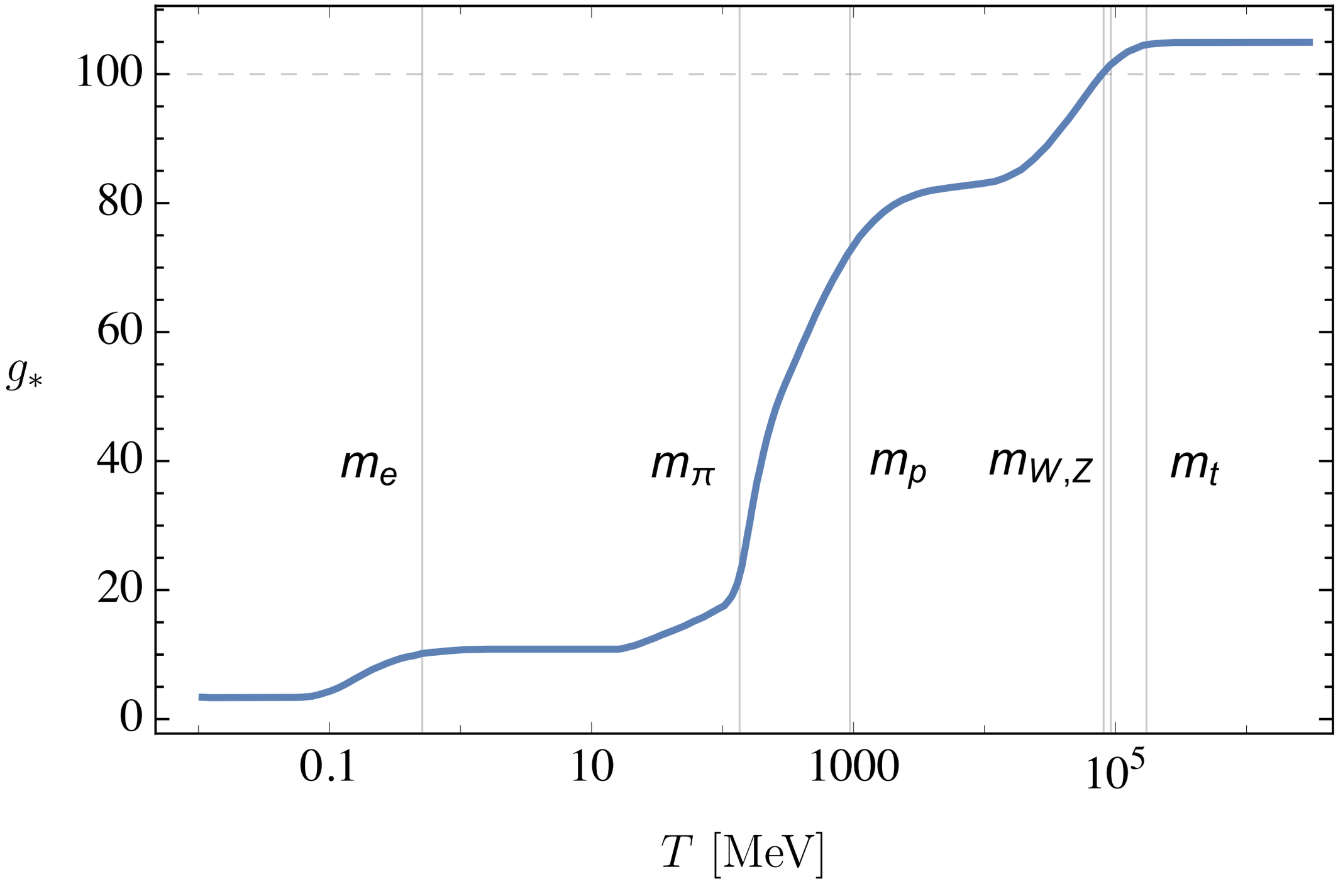
Thermal History

A

Thermal History Mystery

Thermal History of the Universe

★ Changes in the relativistic degrees of freedom:



Thermal History of the Universe

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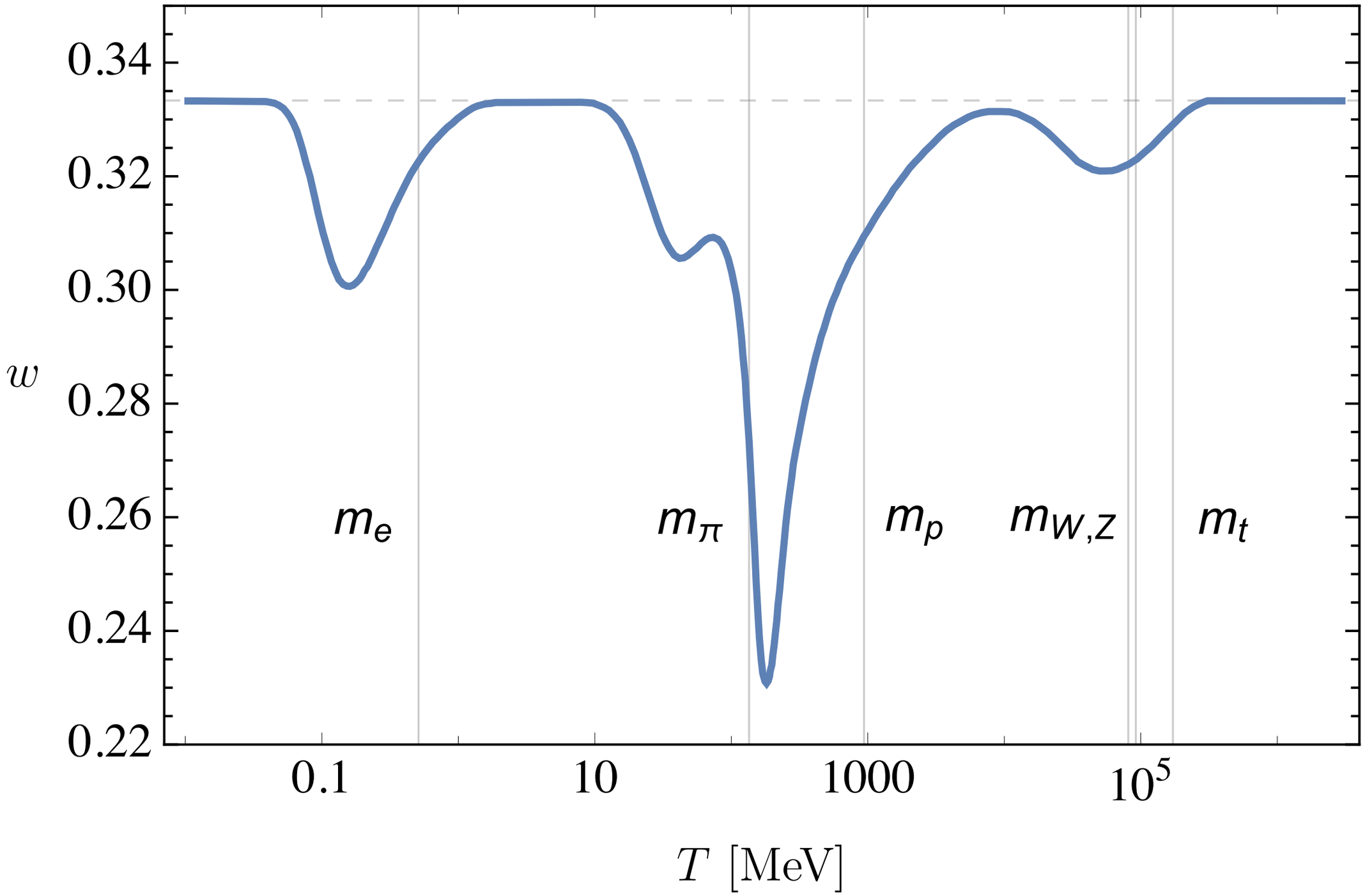
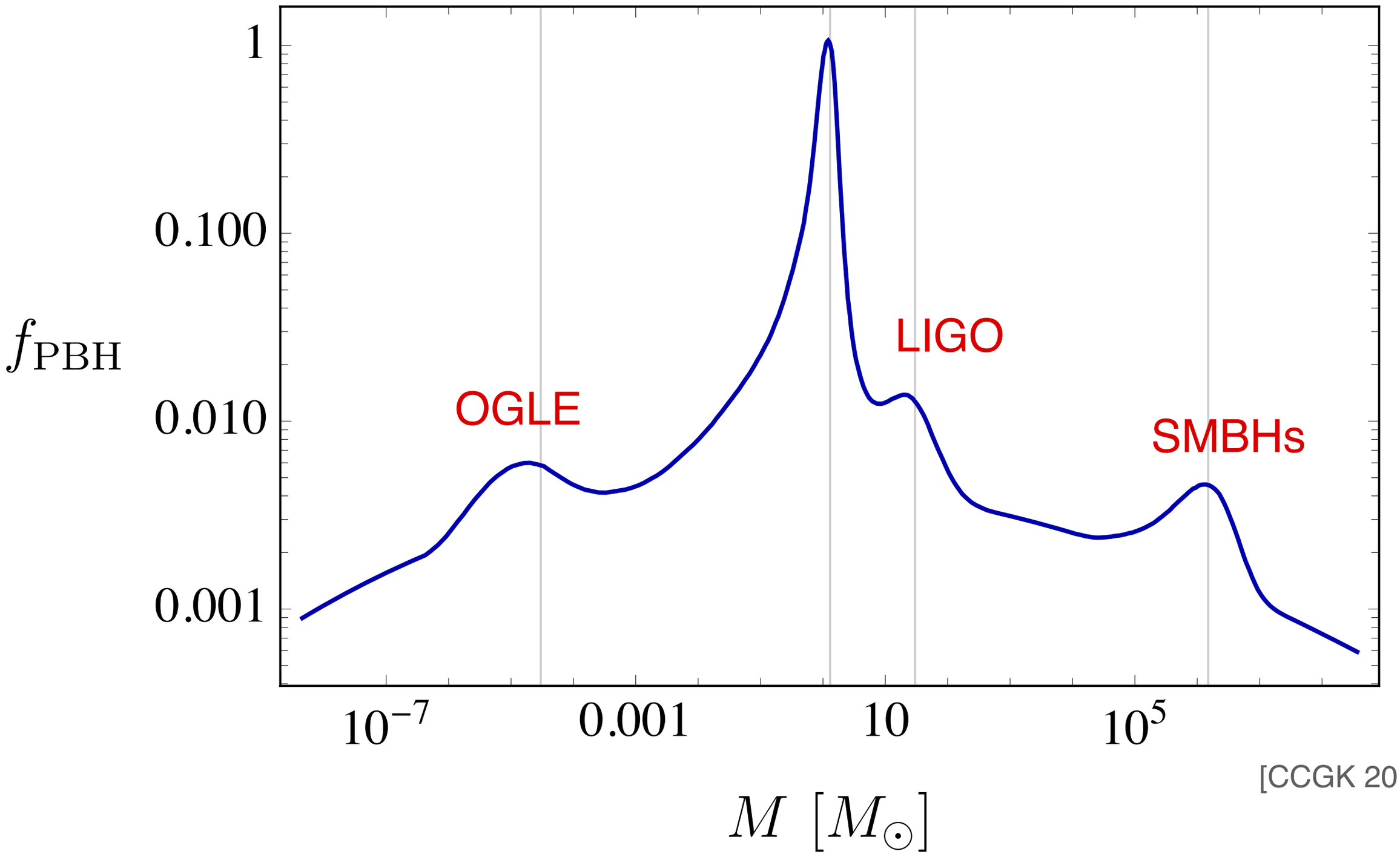
★ Changes in the equation-of-state parameter $w = p/\rho$:



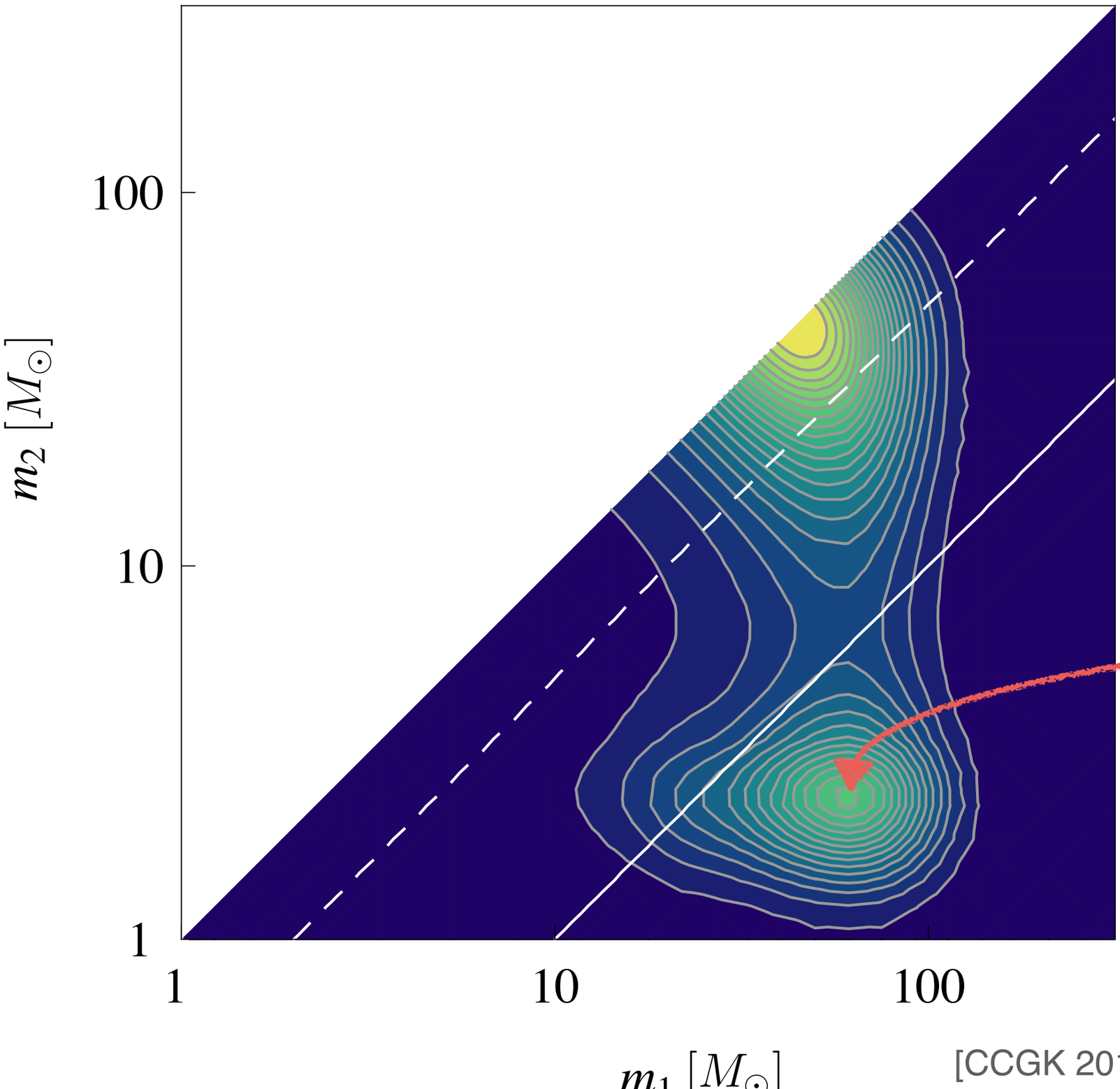
Oskar Klein centre

★ An essentially featureless PBH mass spectrum leads to:



[CCGK 2019]

LIGO/Virgo Merger Rates



Prediction of low mass-ratio merger!

[CCGK 2019]

Conclusion

Conclusion

- Primordial black holes are very interesting!
- They potentially influence physics on many different scales, and could manifest themselves via a plethora of different signatures.
- The thermal history of the Universe naturally encodes scales relevant to observational conundra.
- In turn, primordial black holes can explain at the same time ALL of:
  a) OGLE microlensing events;
  b) LIGO GW events;
  c) The SMBHs in galactic centres;
  d) All of the dark matter.
- The quantum diffusion leads to a strong enhancement of the primordial black-hole production.