

*Primordial Black Holes*

*as*

*Dark Matter*

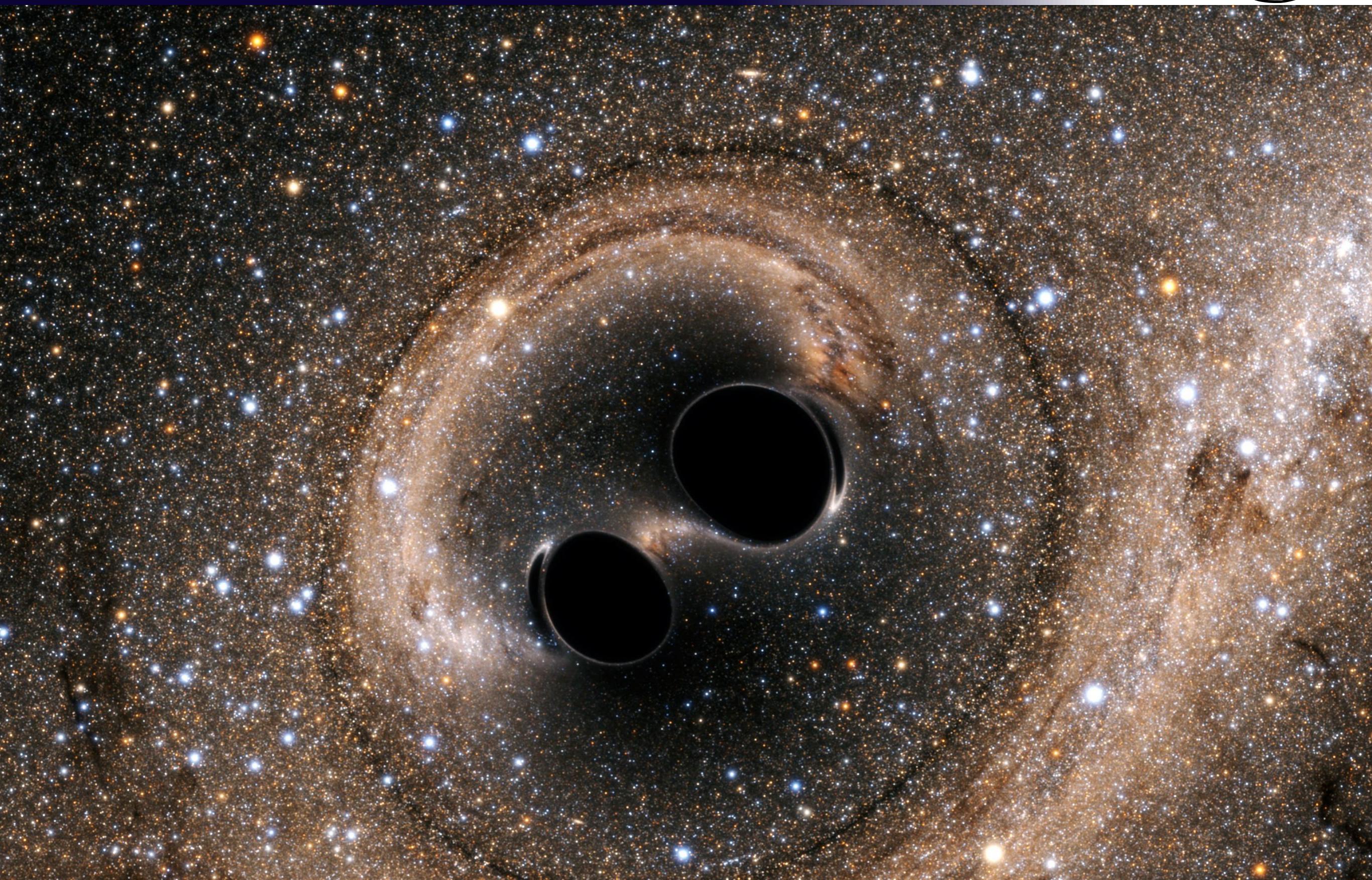
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Florian Kühnel

*LMU Munich*

*Talk at Virtual Autumn Workshop  
"Aspects of Gravity" - 6th of October 2020*

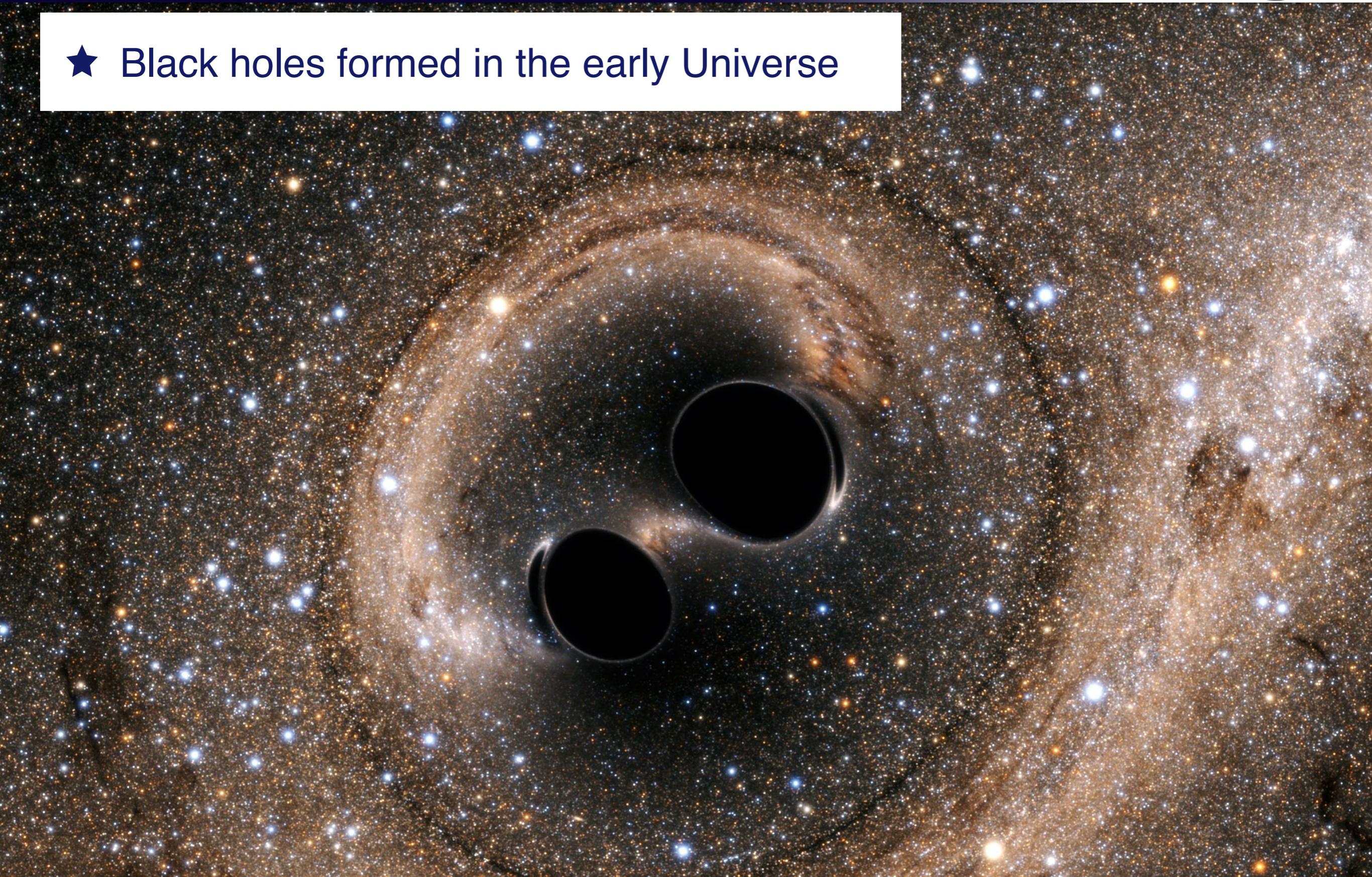
# *Primordial Black Holes*



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- ★ Black holes formed in the early Universe

- ★ First proposed by Novikov and Zel'dovič in the late 1960th



# Primordial Black Holes

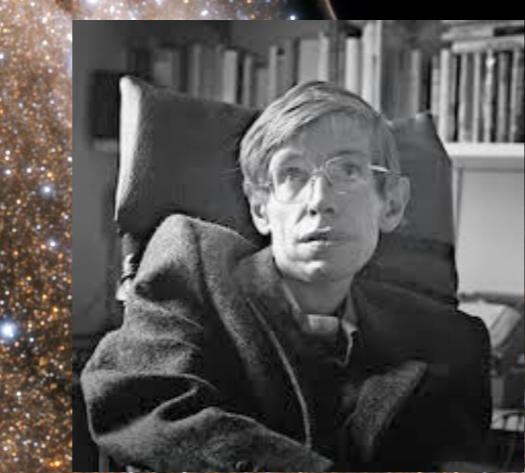
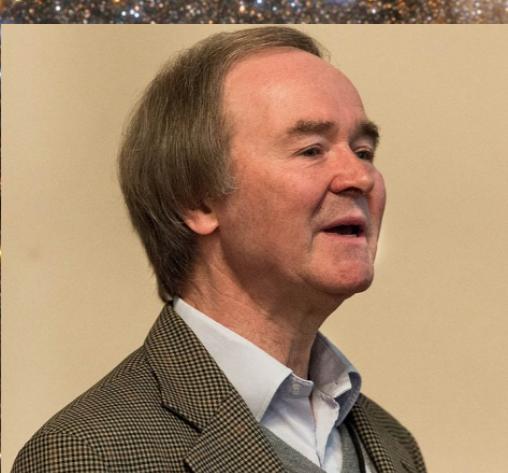


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- ★ Most prominent work by Carr, and Carr & Hawking from the 1970th



# Evaporation

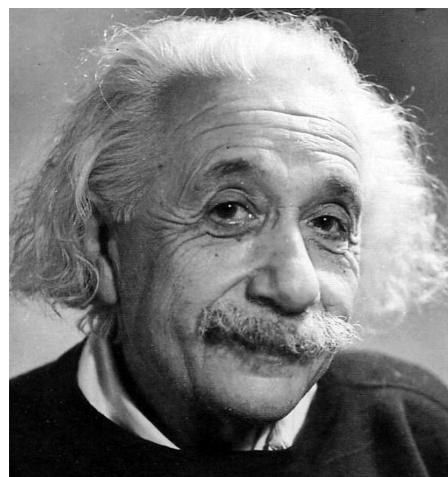


## ★ Black-hole radiation

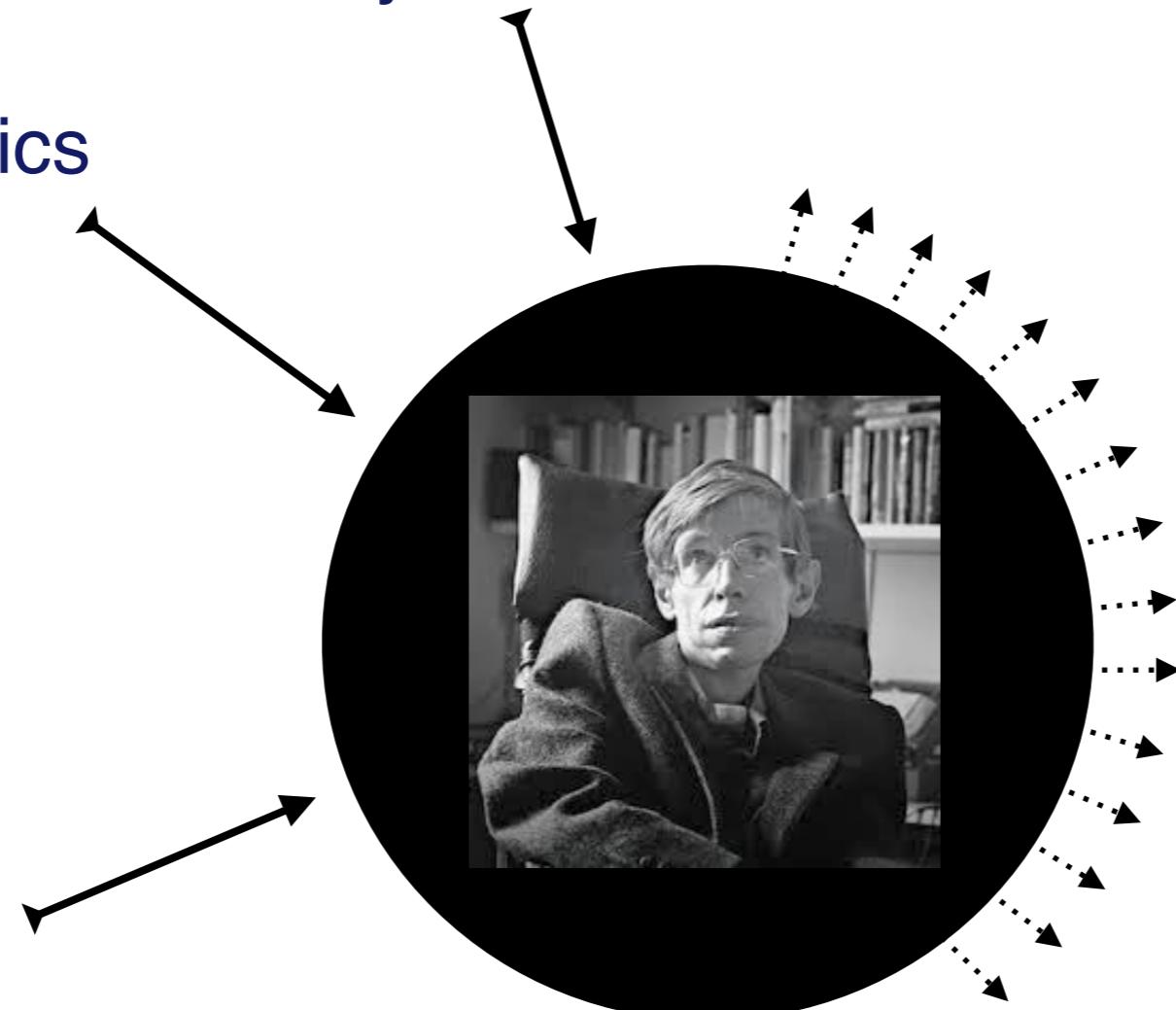
[Hawking 1974]

$$t_{\text{evaporation}}[\text{s}] = 10^{71} \left( \frac{M}{M_\odot} \right)^3$$

## Quantum Mechanics



## Thermodynamics

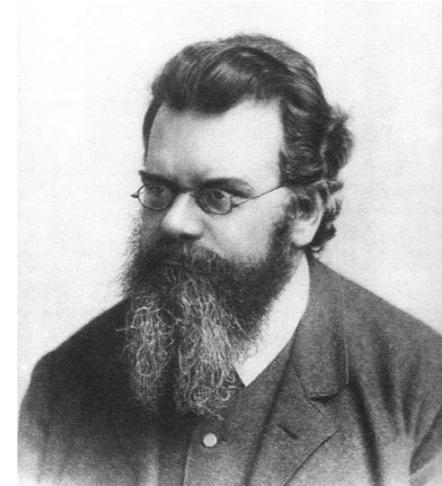


$$T_{BH}[\text{K}] = 10^{-7} \frac{M_\odot}{M}$$

$$\frac{dM}{dt} \sim -M^{-2}$$

## General Relativity

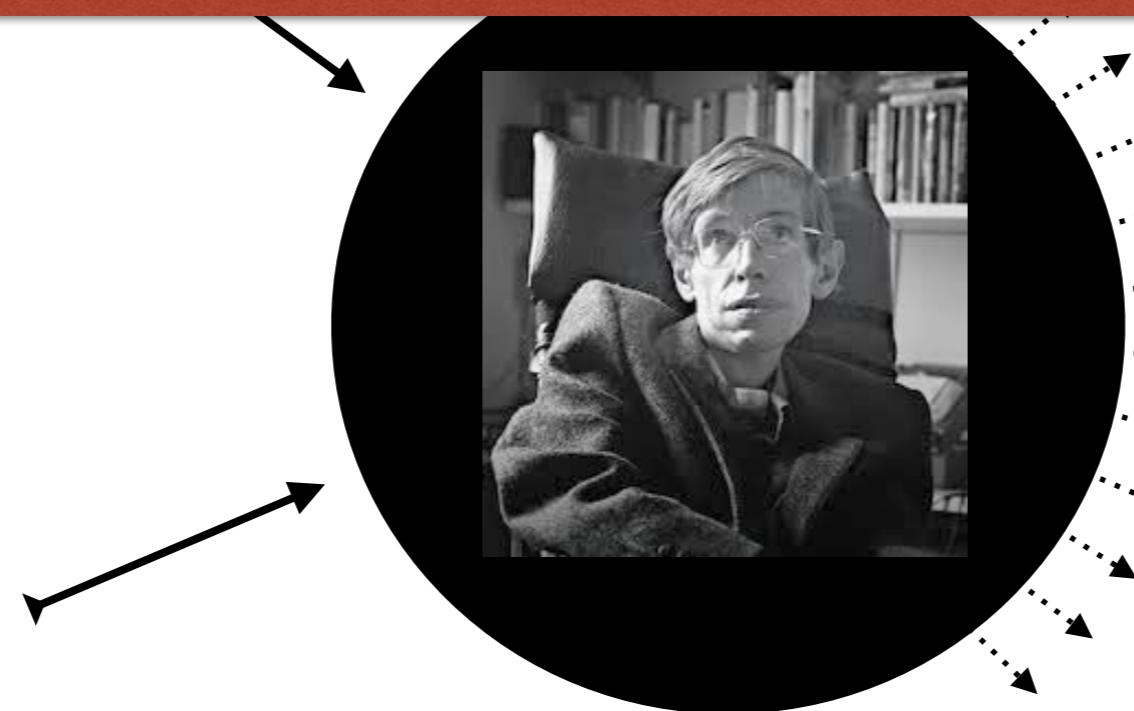
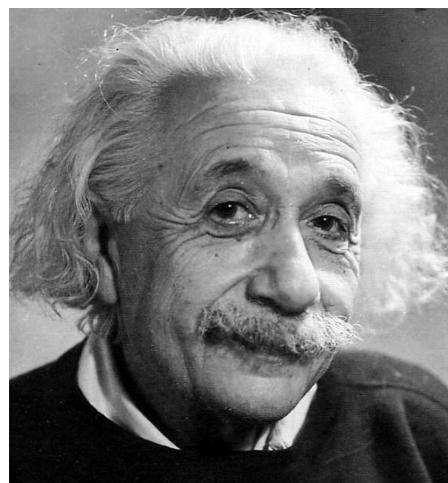
# Evaporation



★ Black-hole **radiation**

[Hawking 1974]

PBHs are important  
even if never observed!



$$\frac{dM}{dt} \sim -\frac{M_\odot}{M^2}$$

Quantum

General Relativity

# *PBH Generalities*



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



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

★ Masses of primordial black holes:

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

*Formation*

# *PBH Formation Mechanisms*

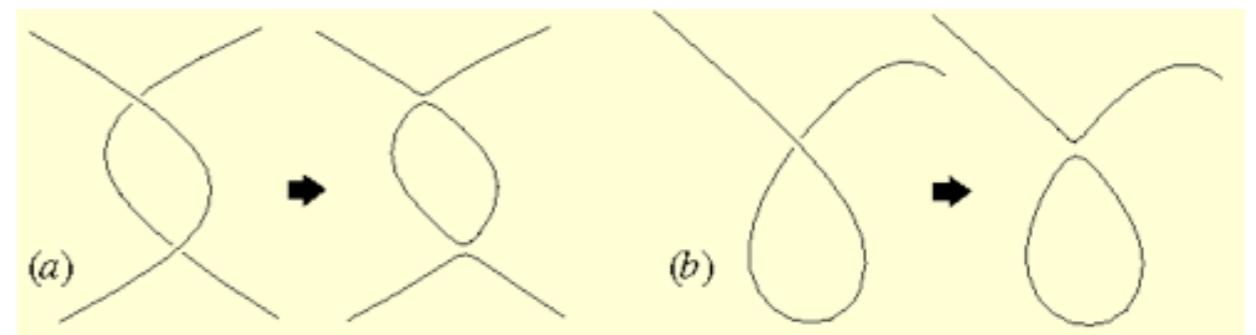
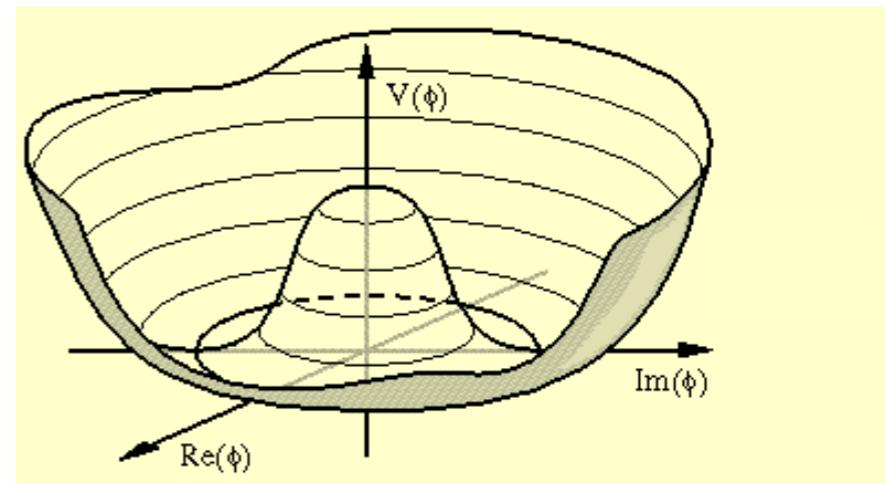


## ★ **Formation of primordial black holes**

# PBH Formation Mechanisms



- ★ Formation of primordial black holes by
- ★ Cosmic string loops

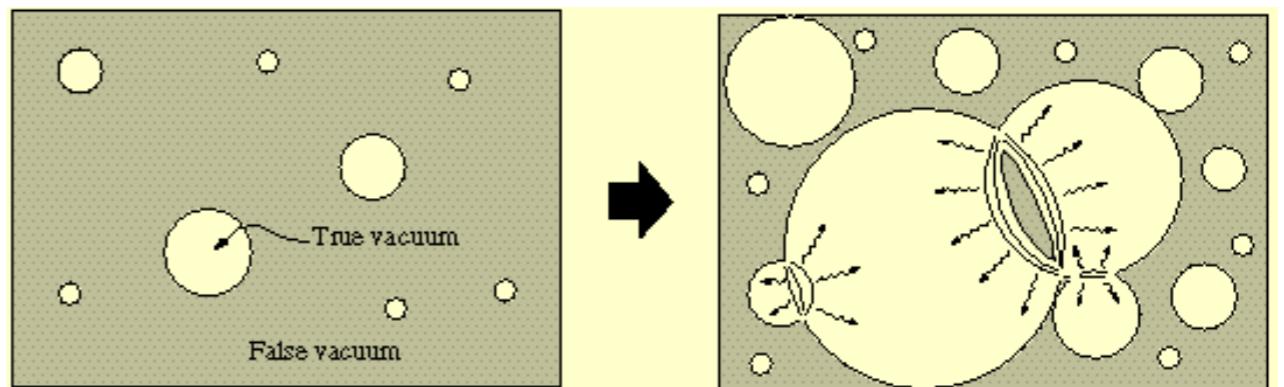
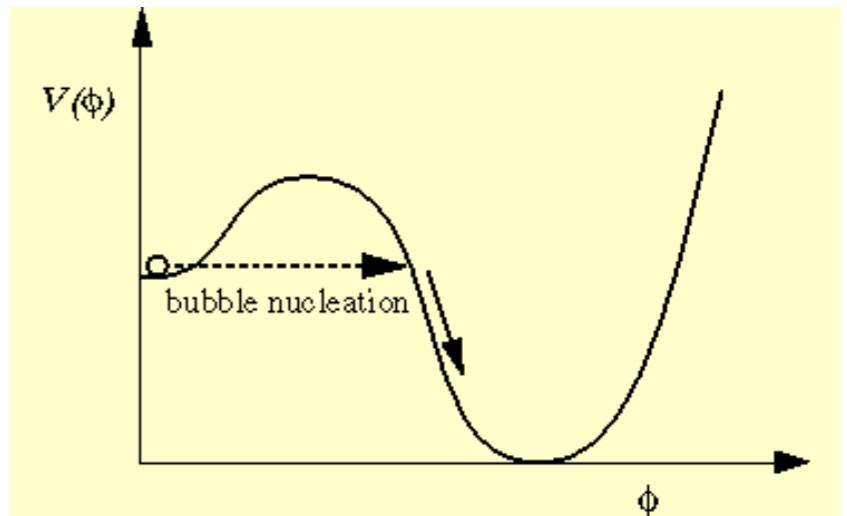


[http://www.damtp.cam.ac.uk/research/gr/public/cs\\_top.html](http://www.damtp.cam.ac.uk/research/gr/public/cs_top.html)

# PBH Formation Mechanisms



- ★ Formation of primordial black holes by
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  - ★ Bubble collisions

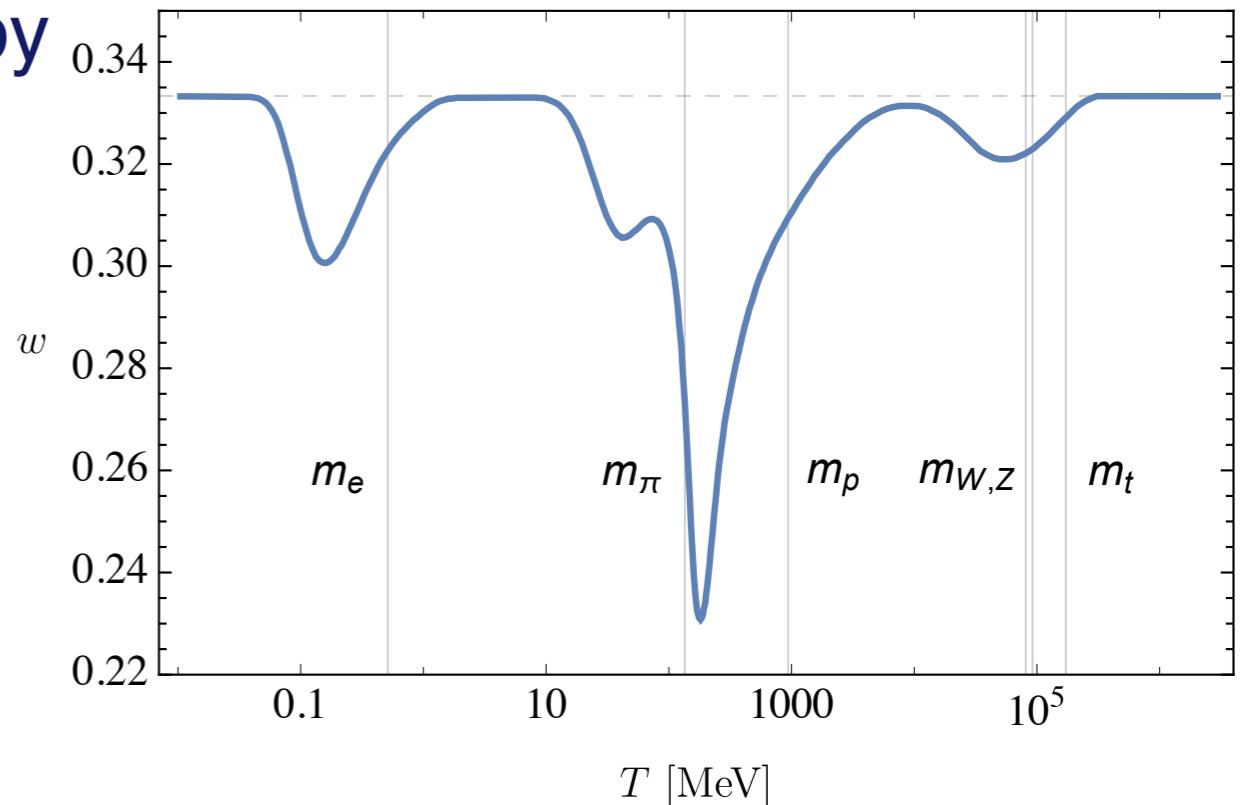


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# PBH Formation Mechanisms



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# PBH Formation Mechanisms



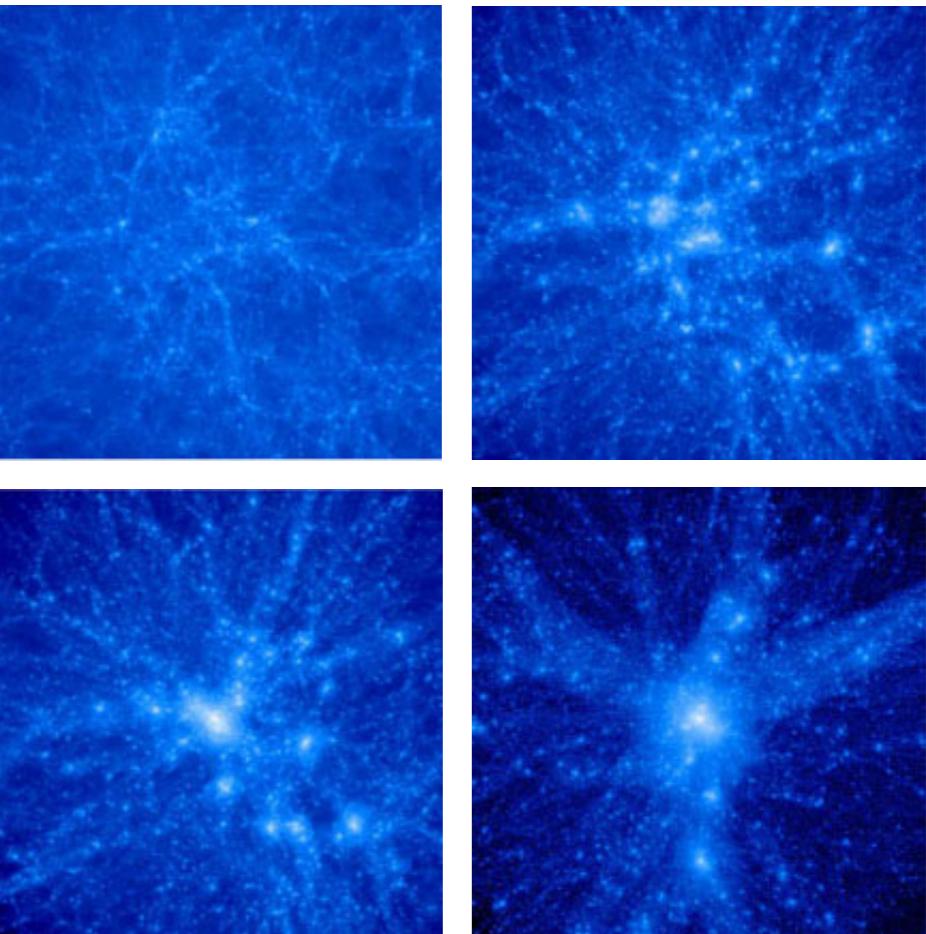
- ★ Formation of primordial black holes by
  - ★ Cosmic string loops
  - ★ Bubble collisions
  - ★ Pressure reduction
  - ★ Large density perturbations of inflationary origin

→ Simple estimate:

[Carr 1975]

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

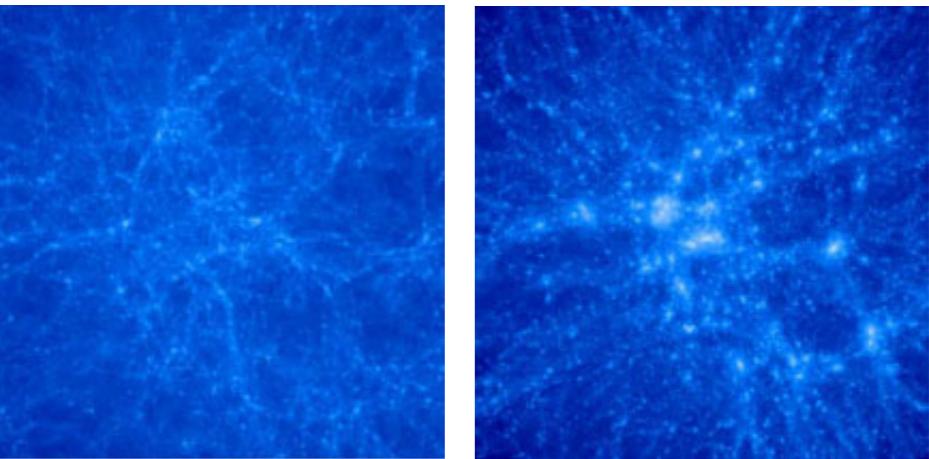
scale of the over density      Jeans length



# PBH Formation Mechanisms



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



PBH formation threshold strongly depends on the equation of state!

→ Simple estimate:

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scale of the over density

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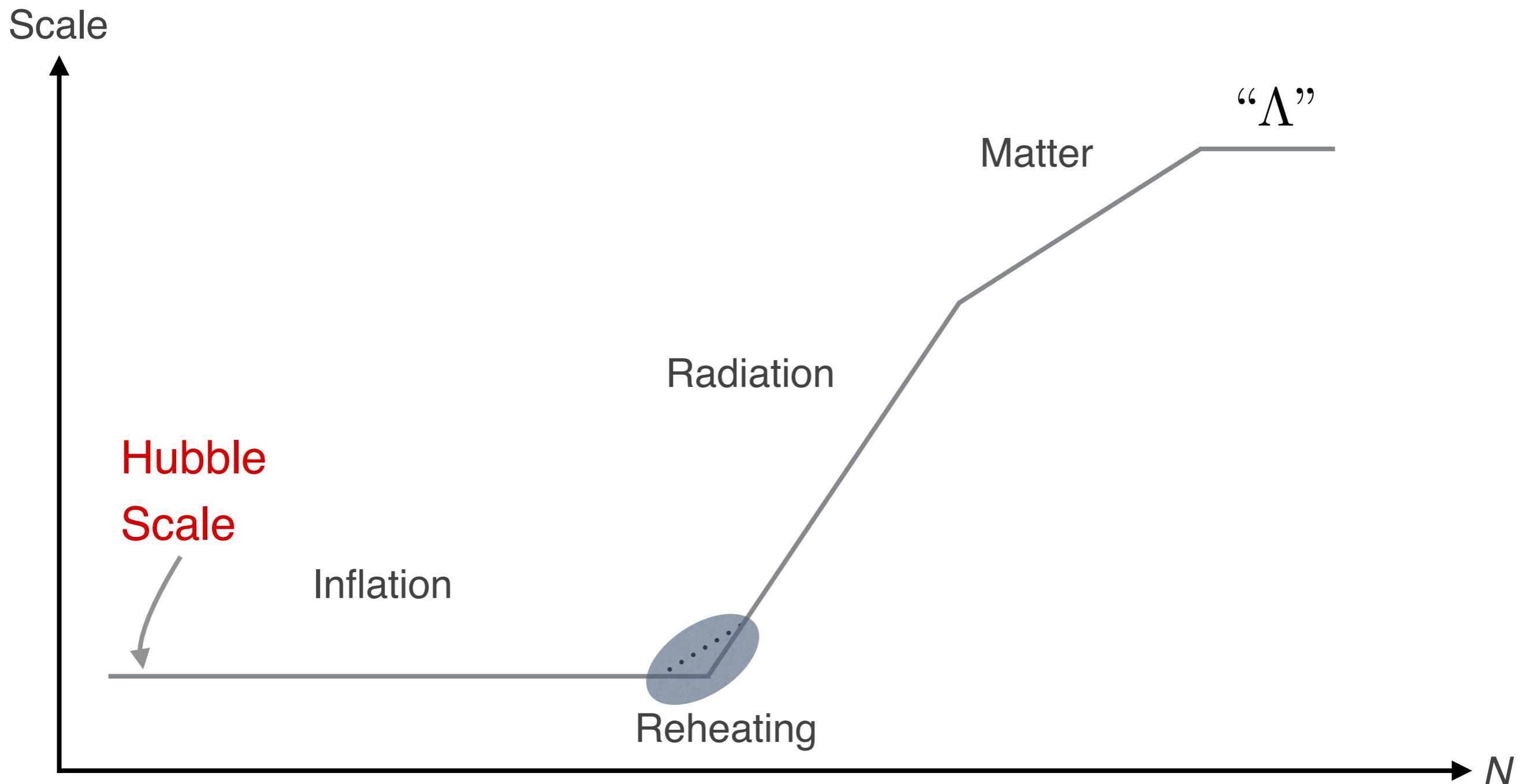
# PBH Formation - Scales



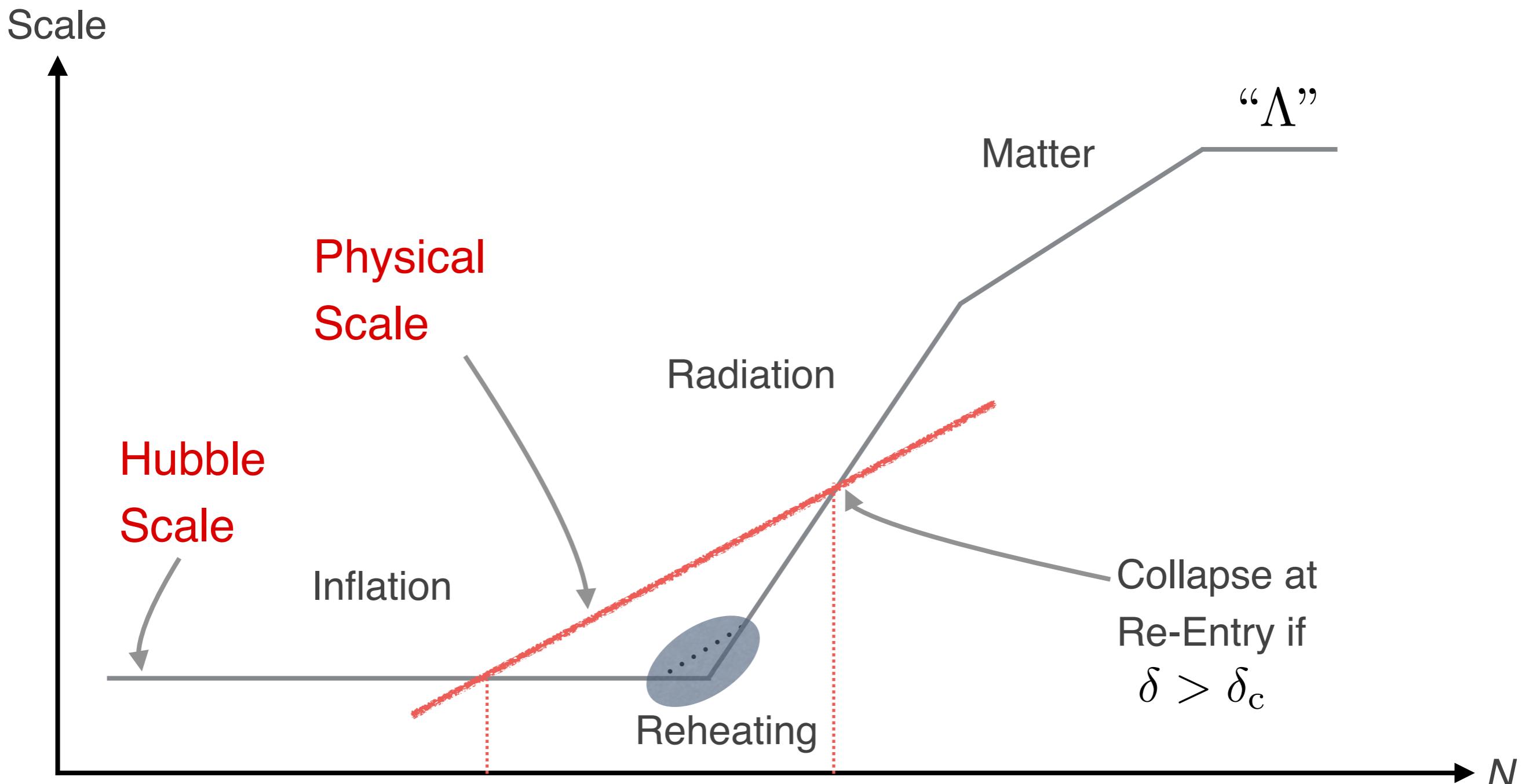
Scale



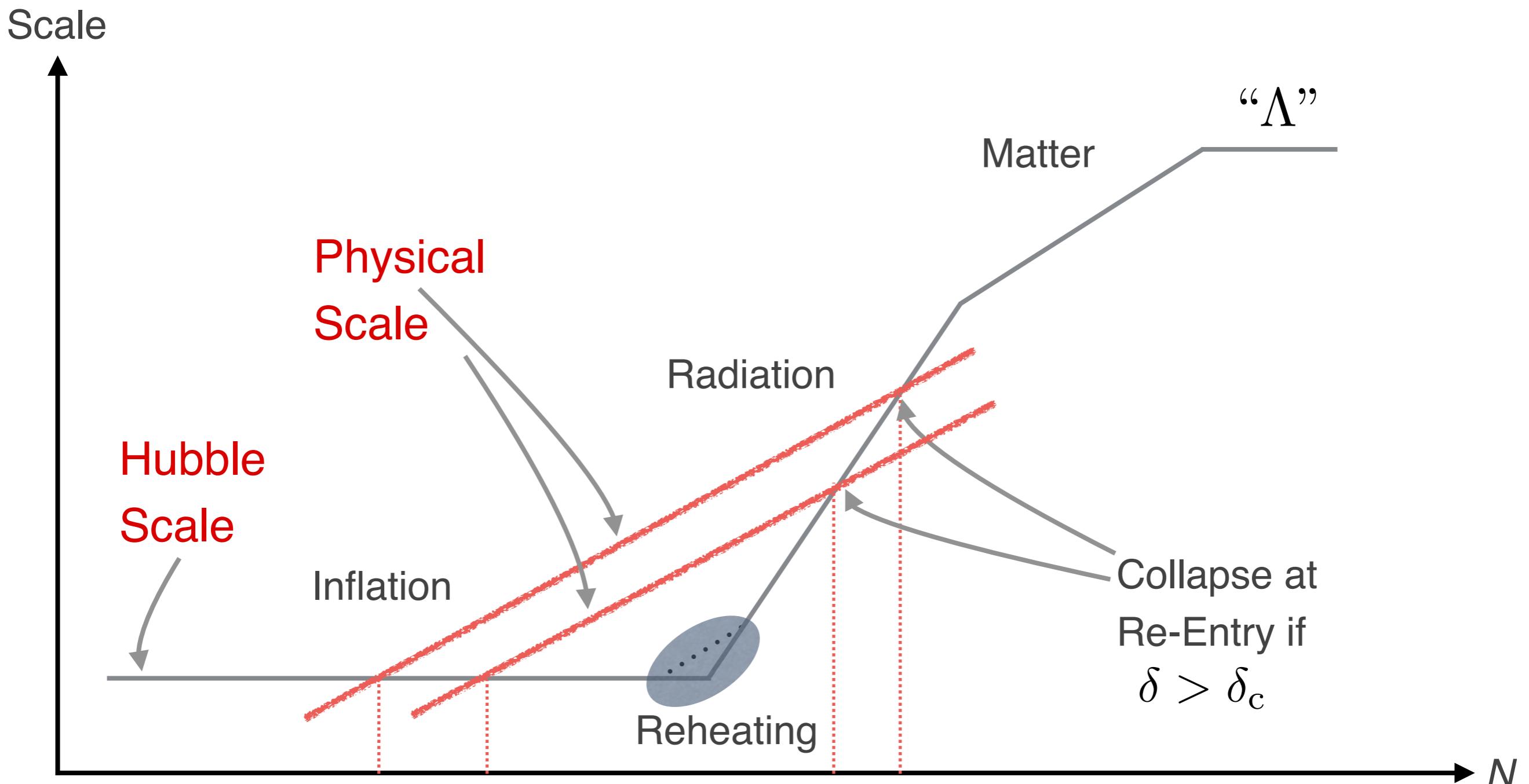
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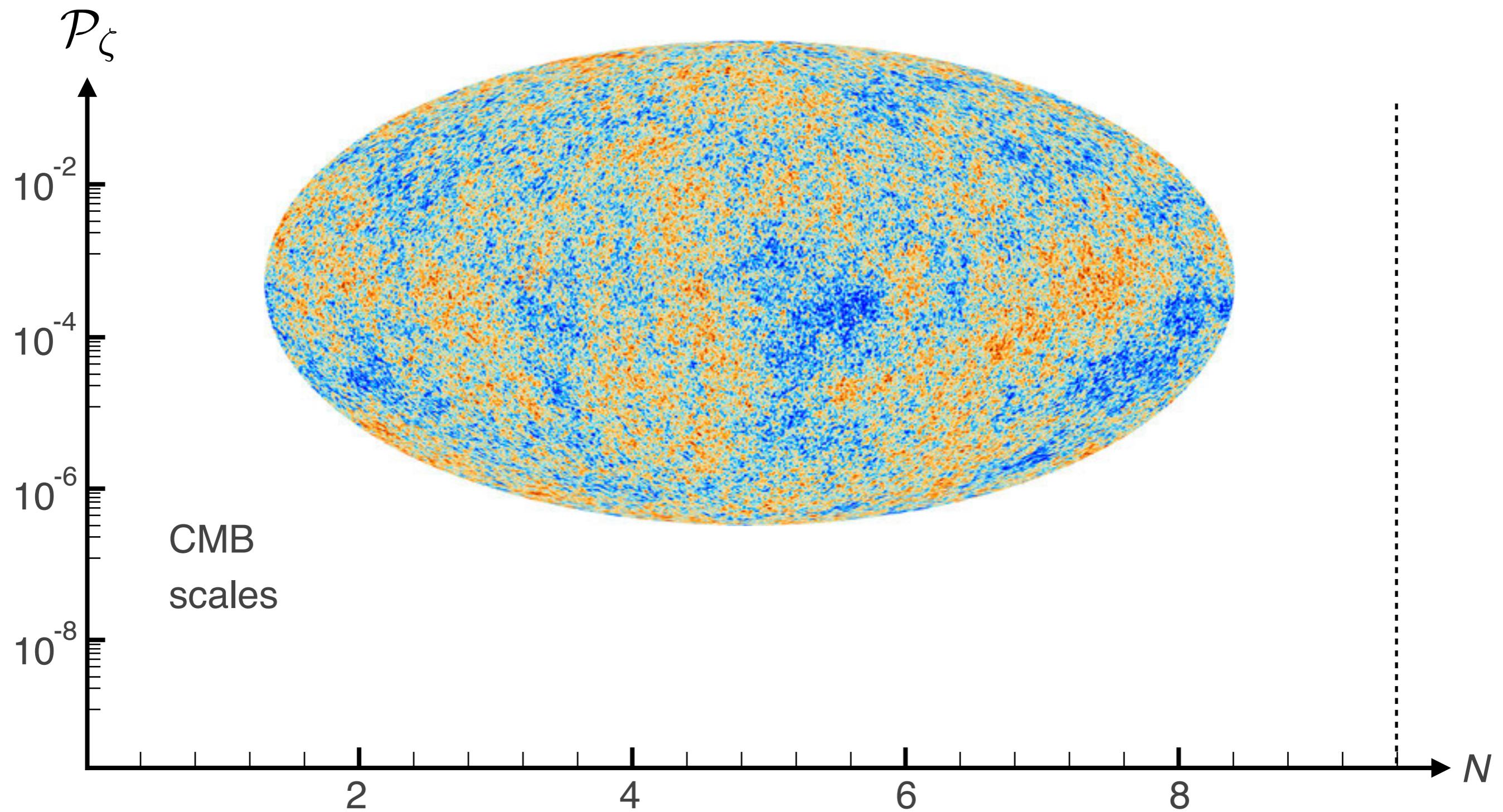
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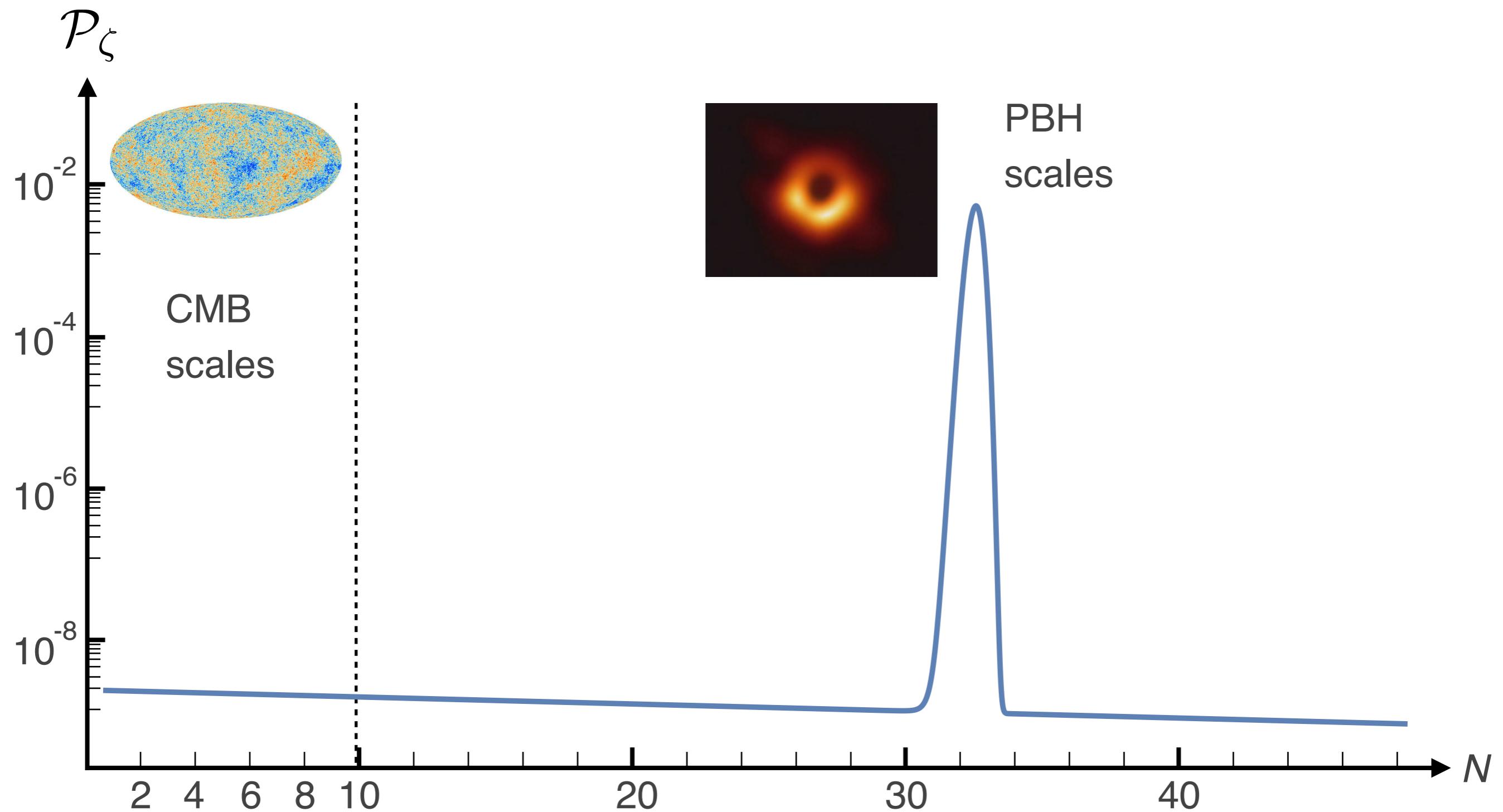
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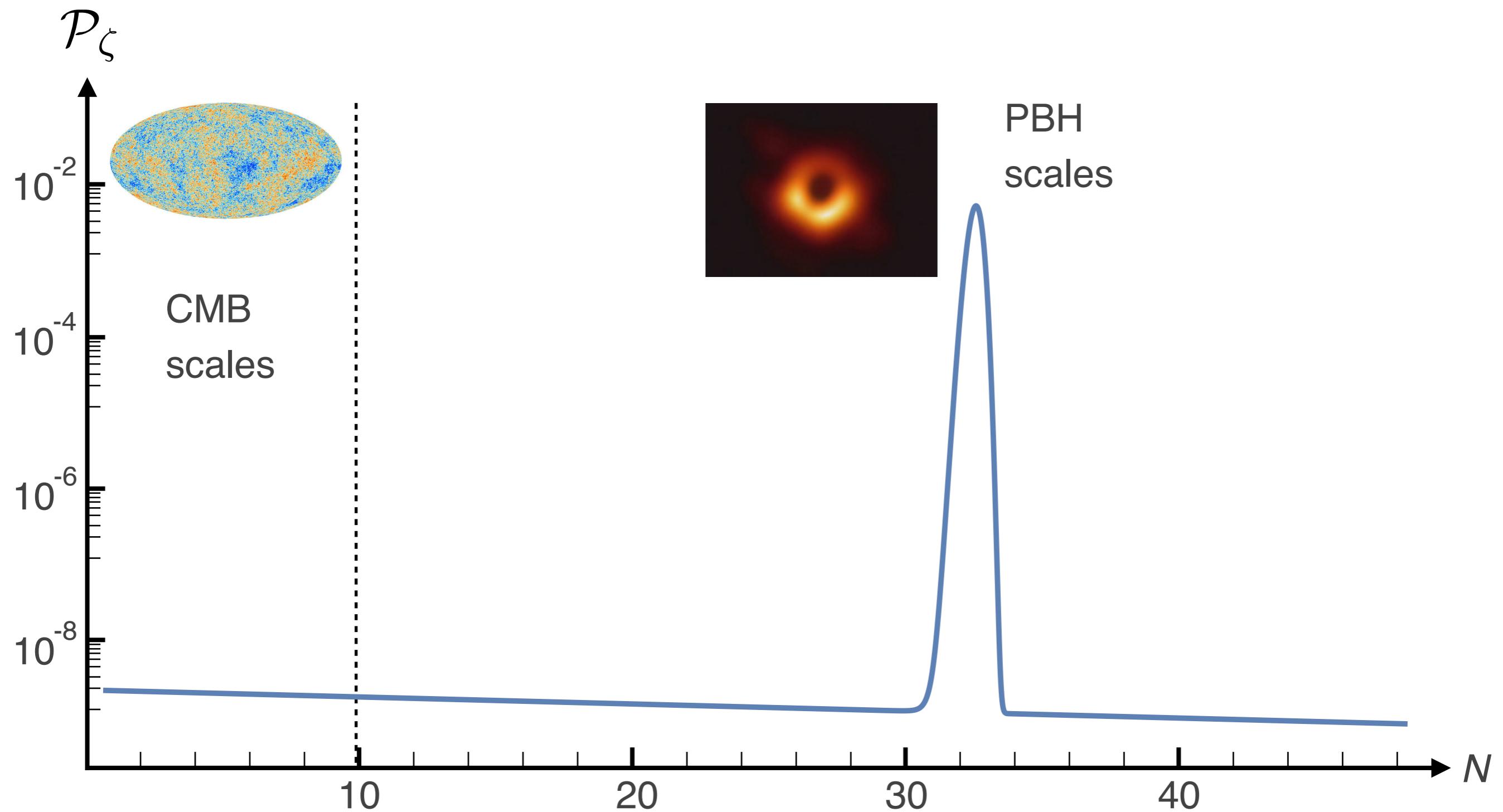
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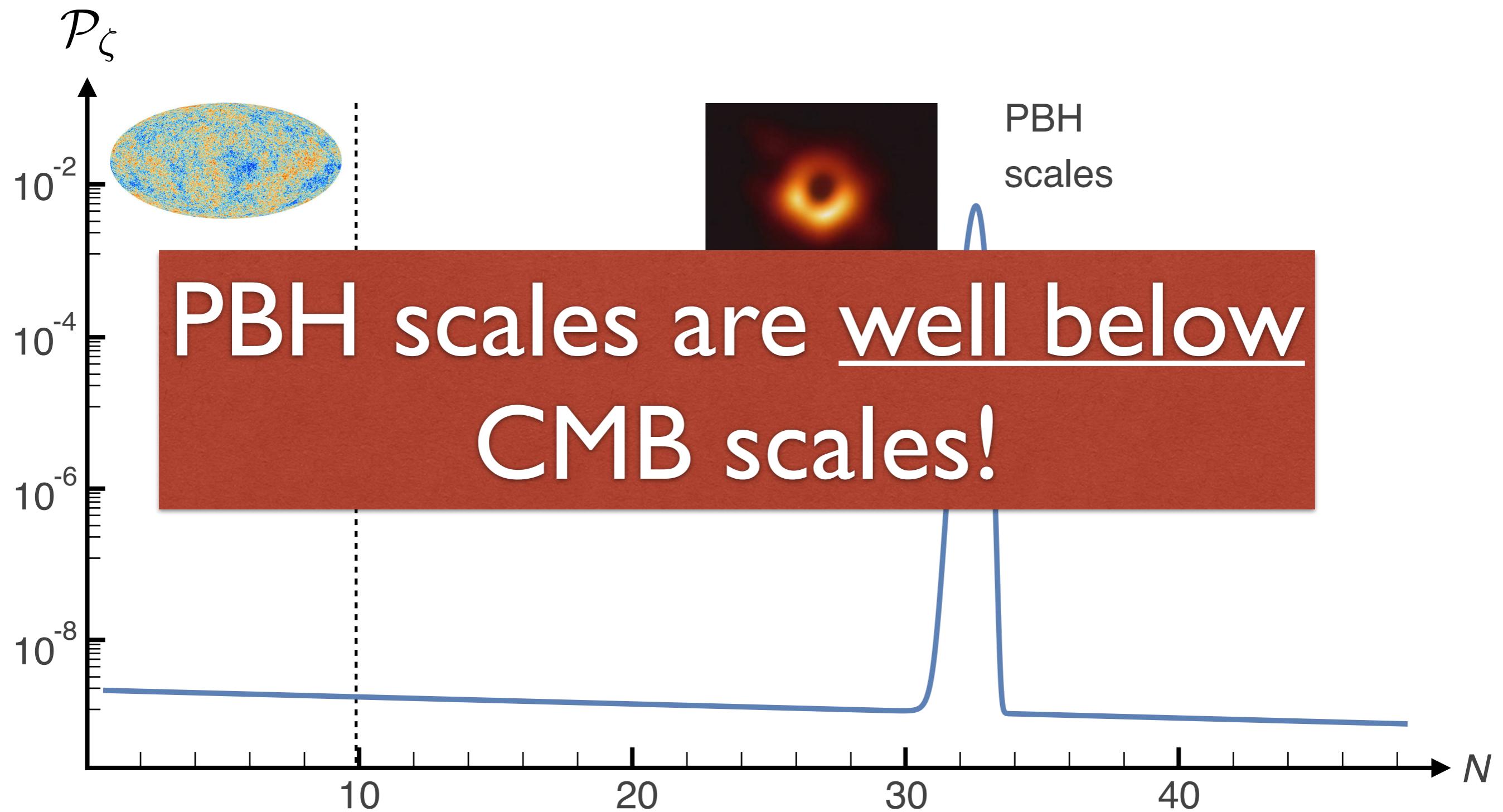
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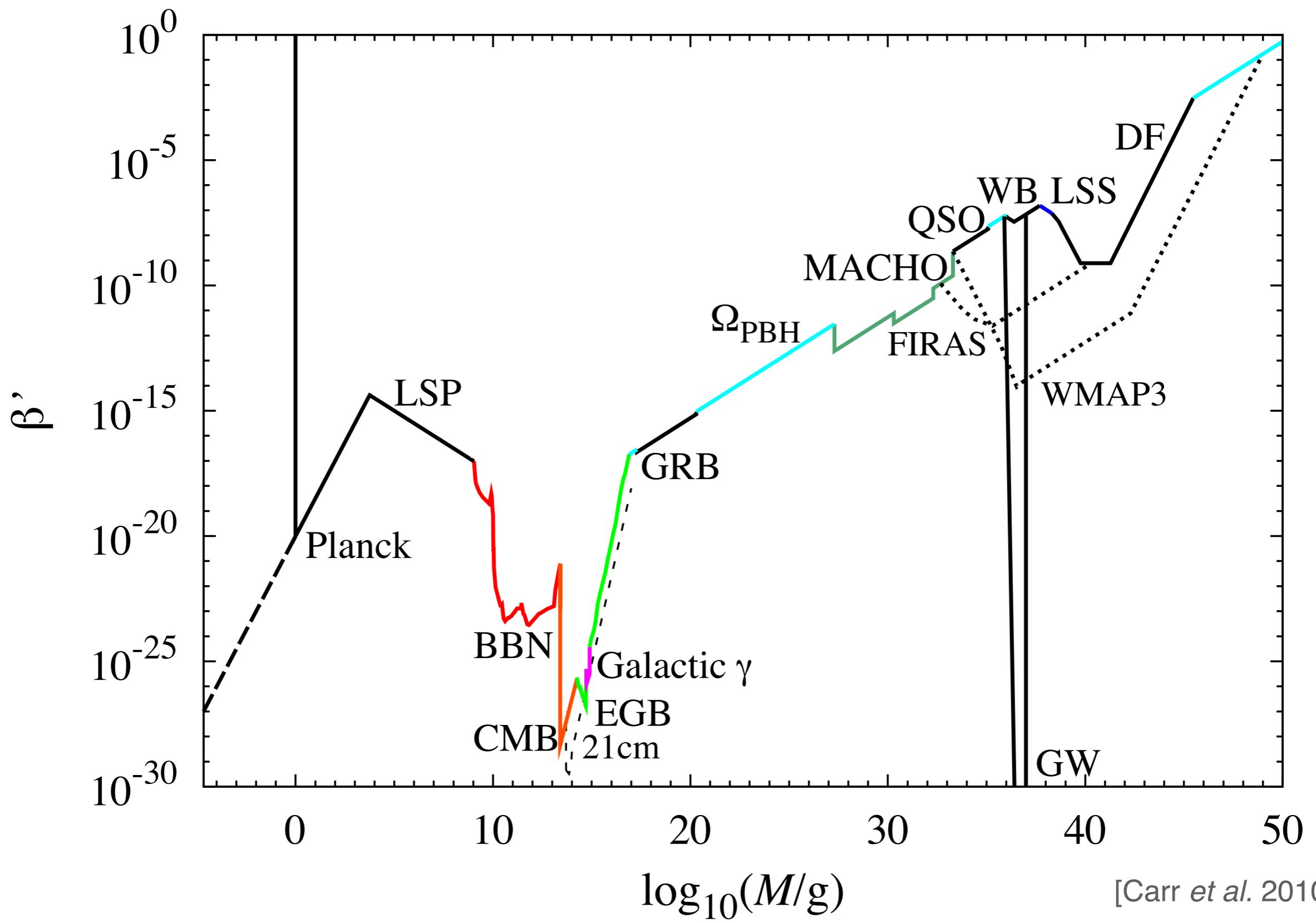
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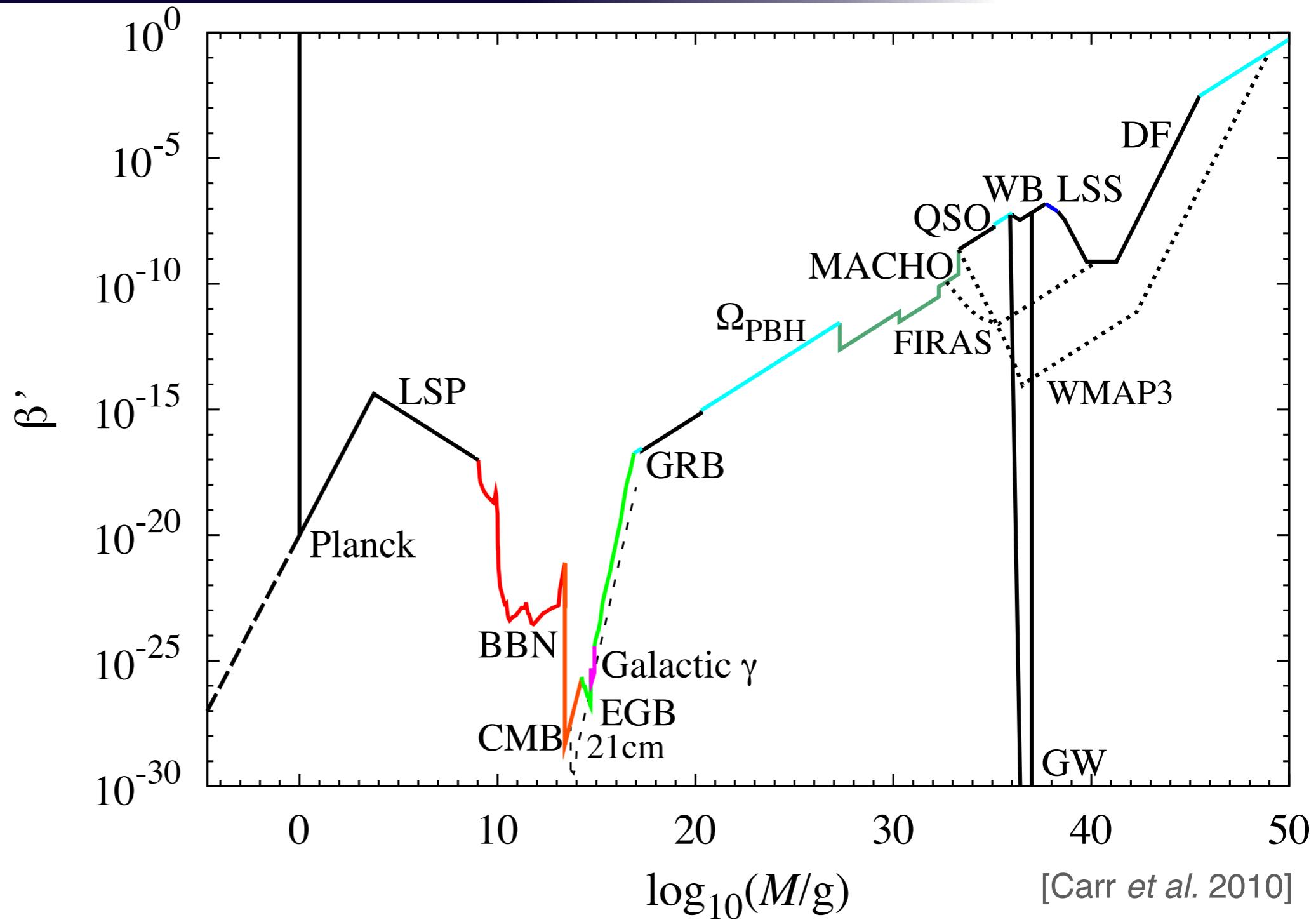
# PBH Formation - Scales



# PBH Constraints at Formation



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# PBH Constraints at Formation



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

$\dot{\beta}$

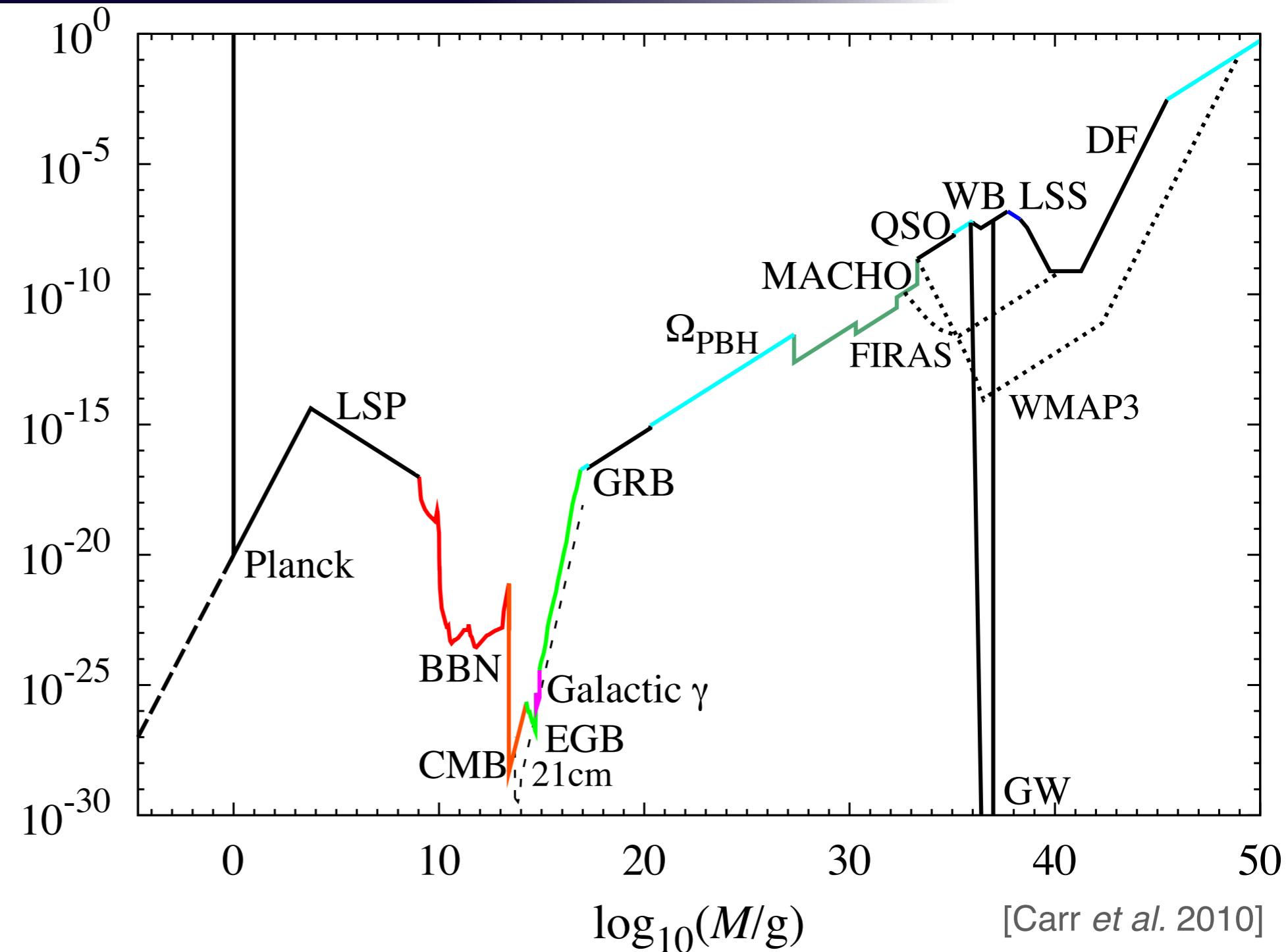
★ Note that

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

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

and hence

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



# PBH Constraints at Formation



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

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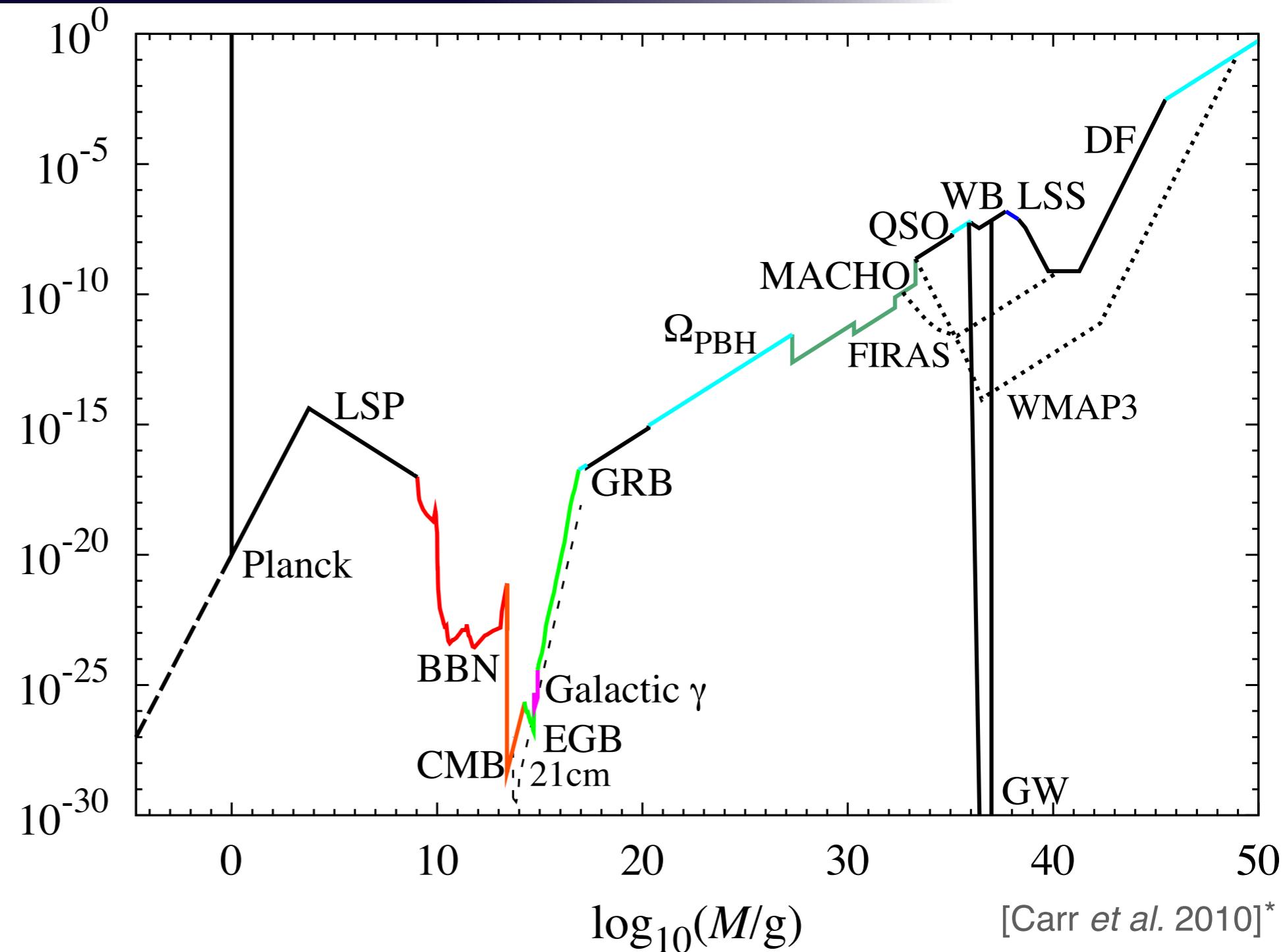
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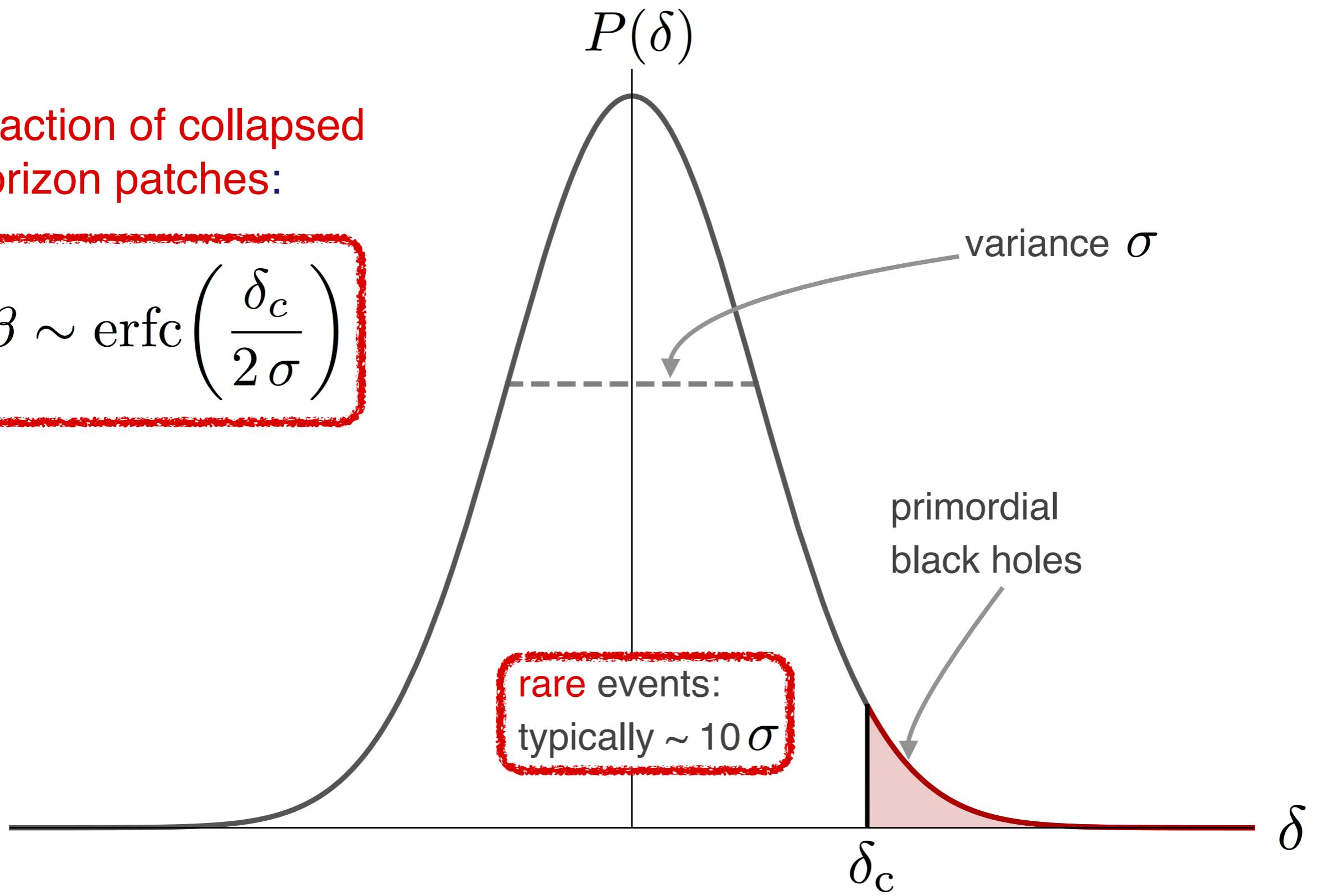
\*(more recent) constraints  
for the presently allowed  
dark-matter fraction later...

# PBH Formation - Rare Events



Fraction of collapsed horizon patches:

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



*Probes of Scales*

# PBH — Probes of Scales



- ★ PBHs probe a **huge range of scales**:

$M \sim 10^{-5}$ g **Quantum Gravity:**

Planck relics, Extra dimensions and higher-dimensional black holes, ...

$M \lesssim 10^{15}$ g **Early Universe:**

Nucleosynthesis, Reionisation, ...

$M \sim 10^{15}$ g **High-Energy Physics:**

Cosmological and galactic gamma-rays, ...

$M \gtrsim 10^{15}$ g **Gravity:**

Critical phenomena,  
Cold dark matter,  
Dynamical effects, Lensing effects,  
Gravitational waves,  
Black holes in galactic nuclei, ...

# PBH — Some Numbers



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

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

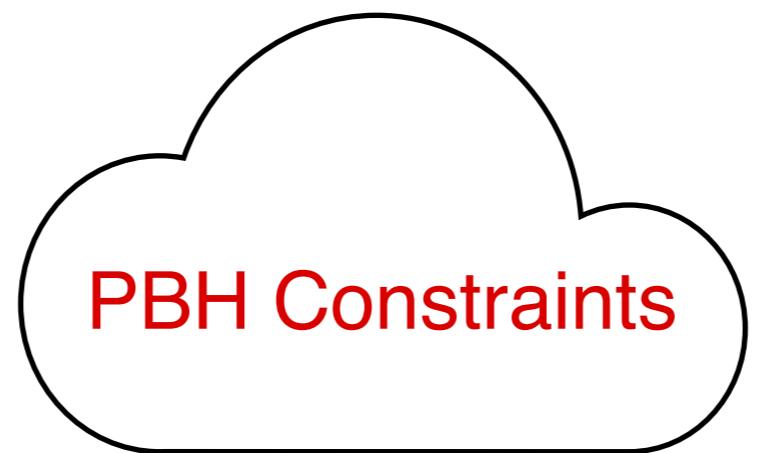
★ Size:  $10^{-8}$  cm

★ Number in our Galaxy:  $10^{25}$

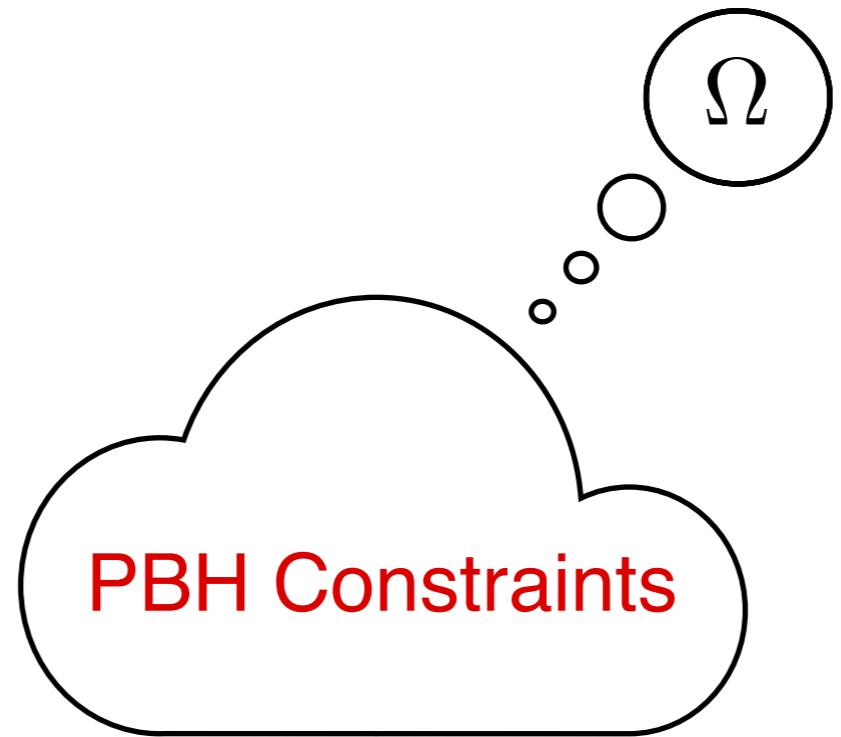
★ Distance: 10 AU

*Constraints*

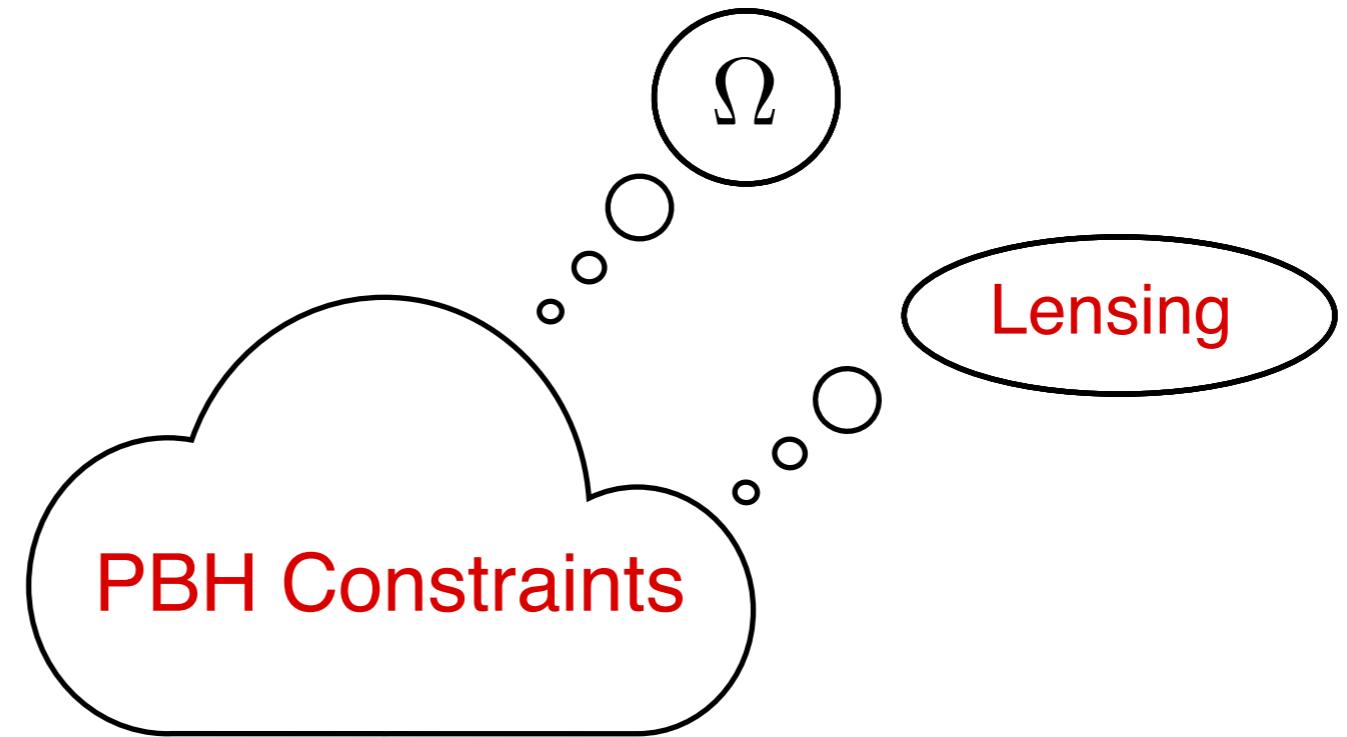
# PBH Constraints



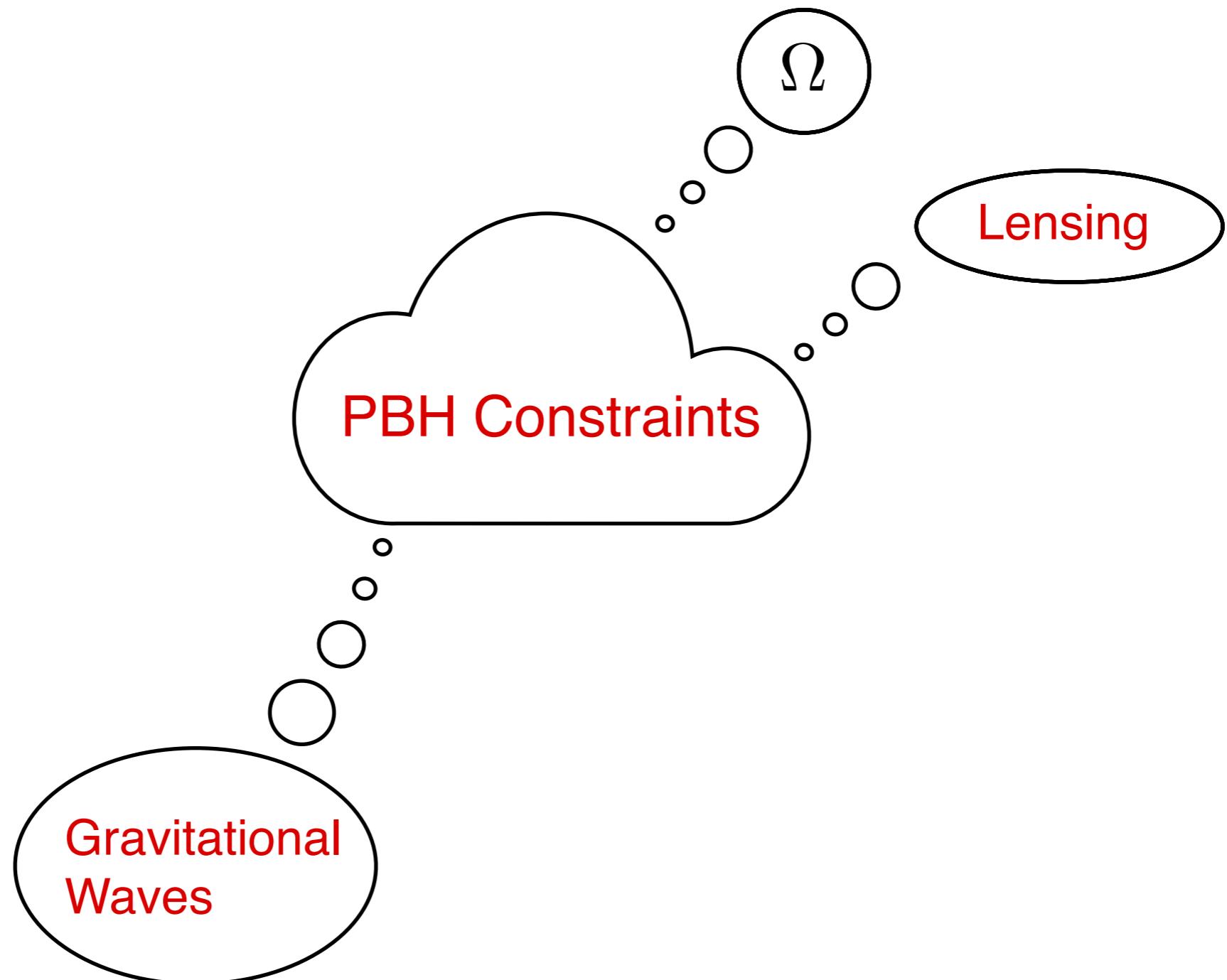
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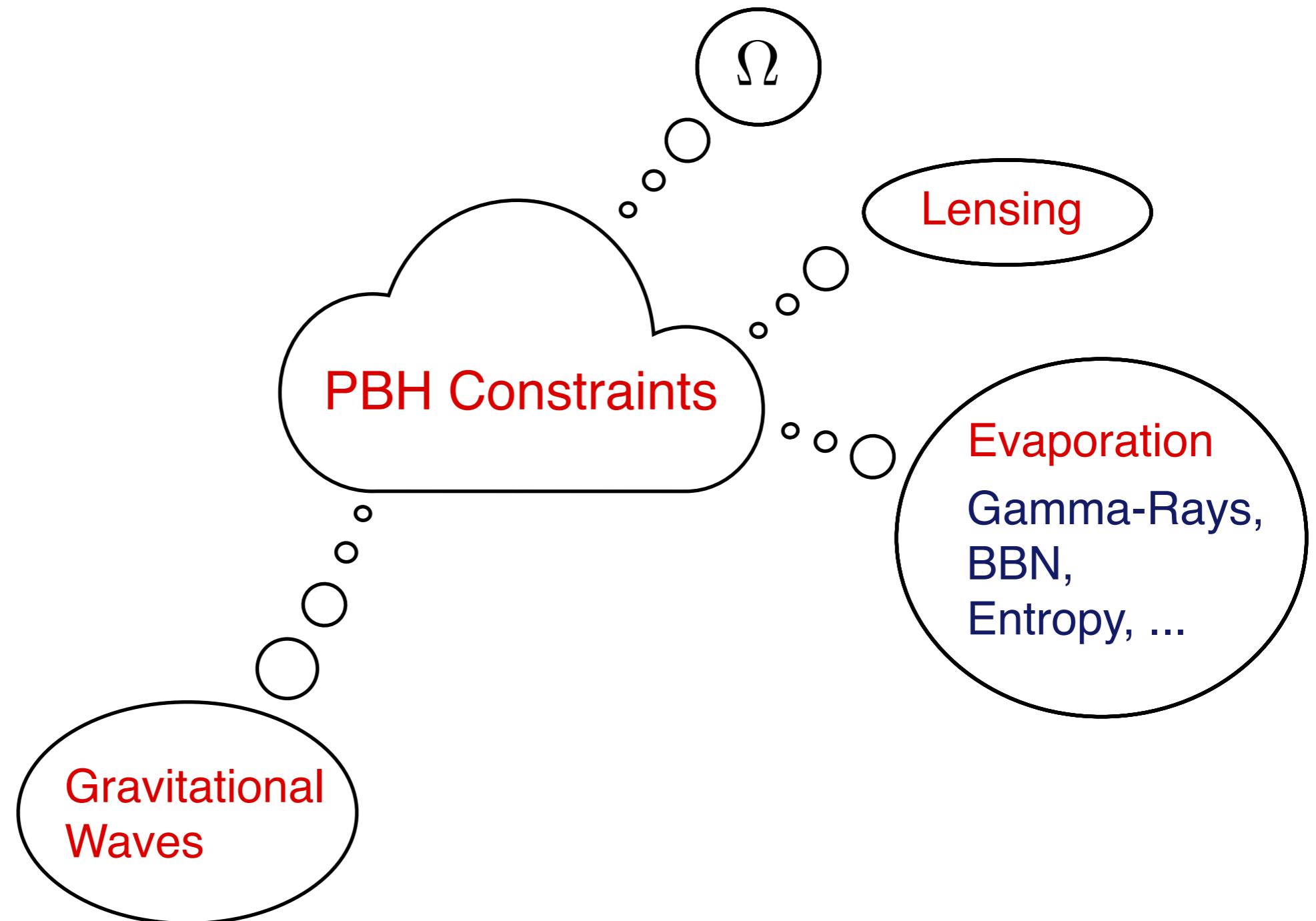
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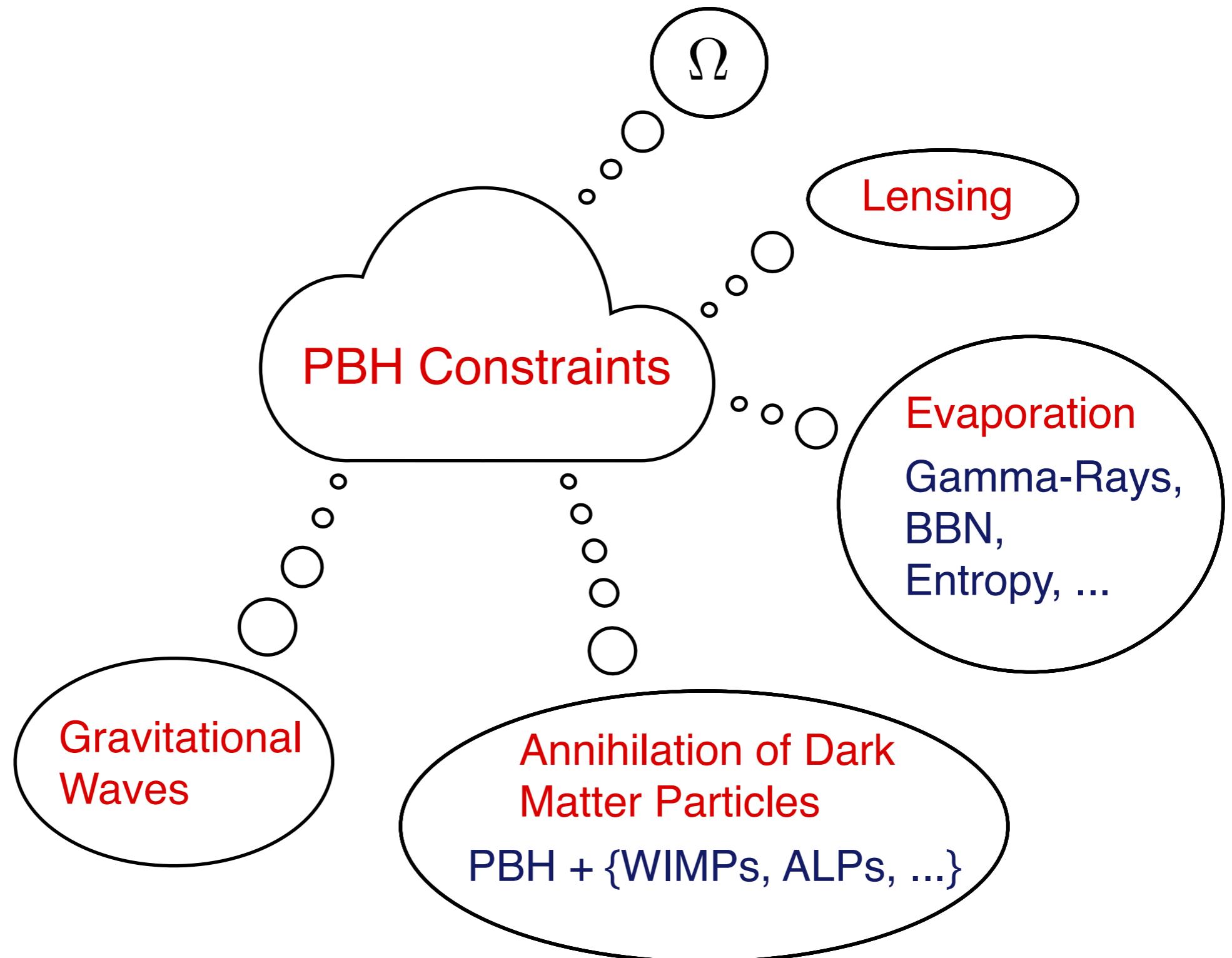
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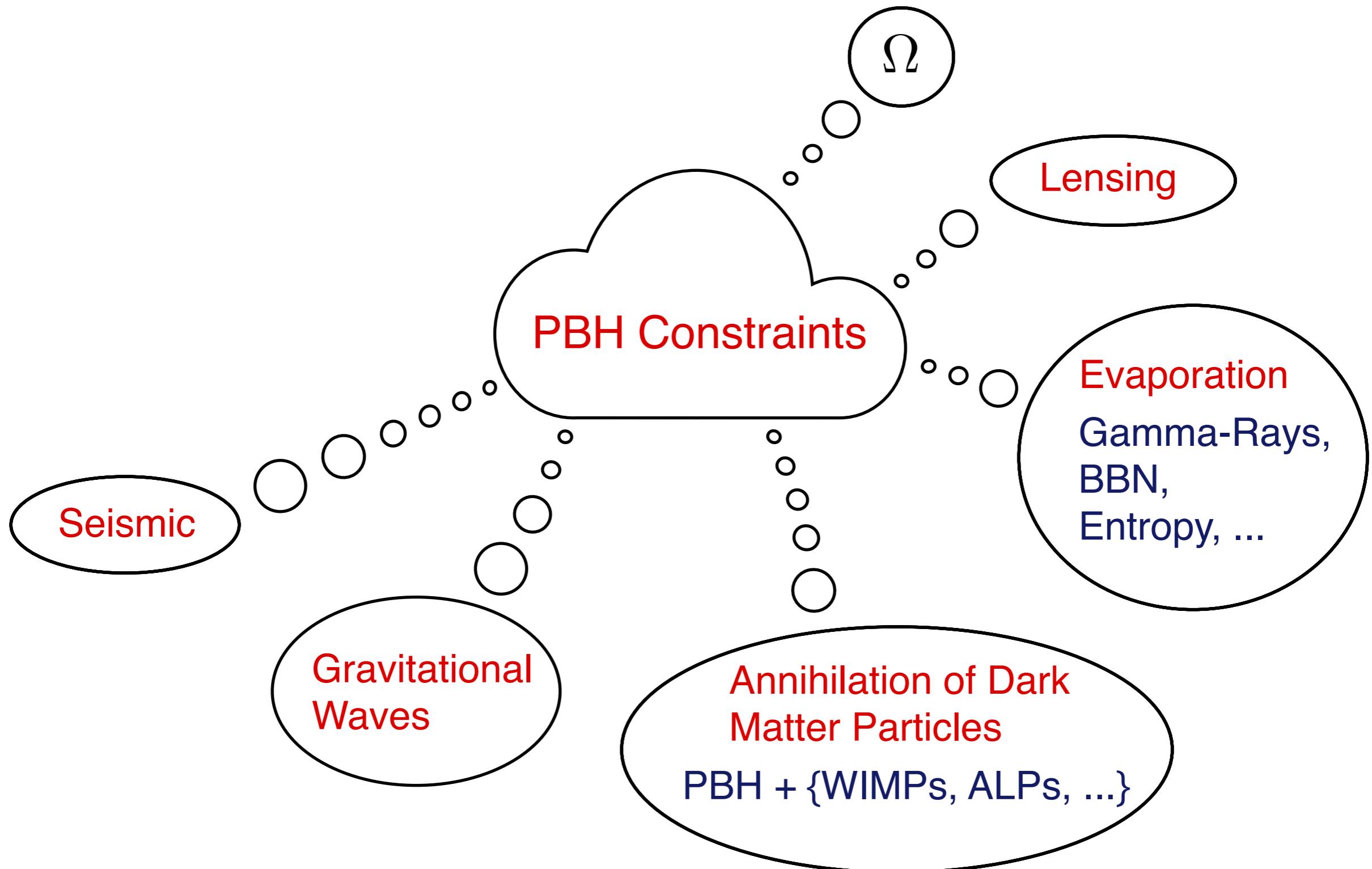
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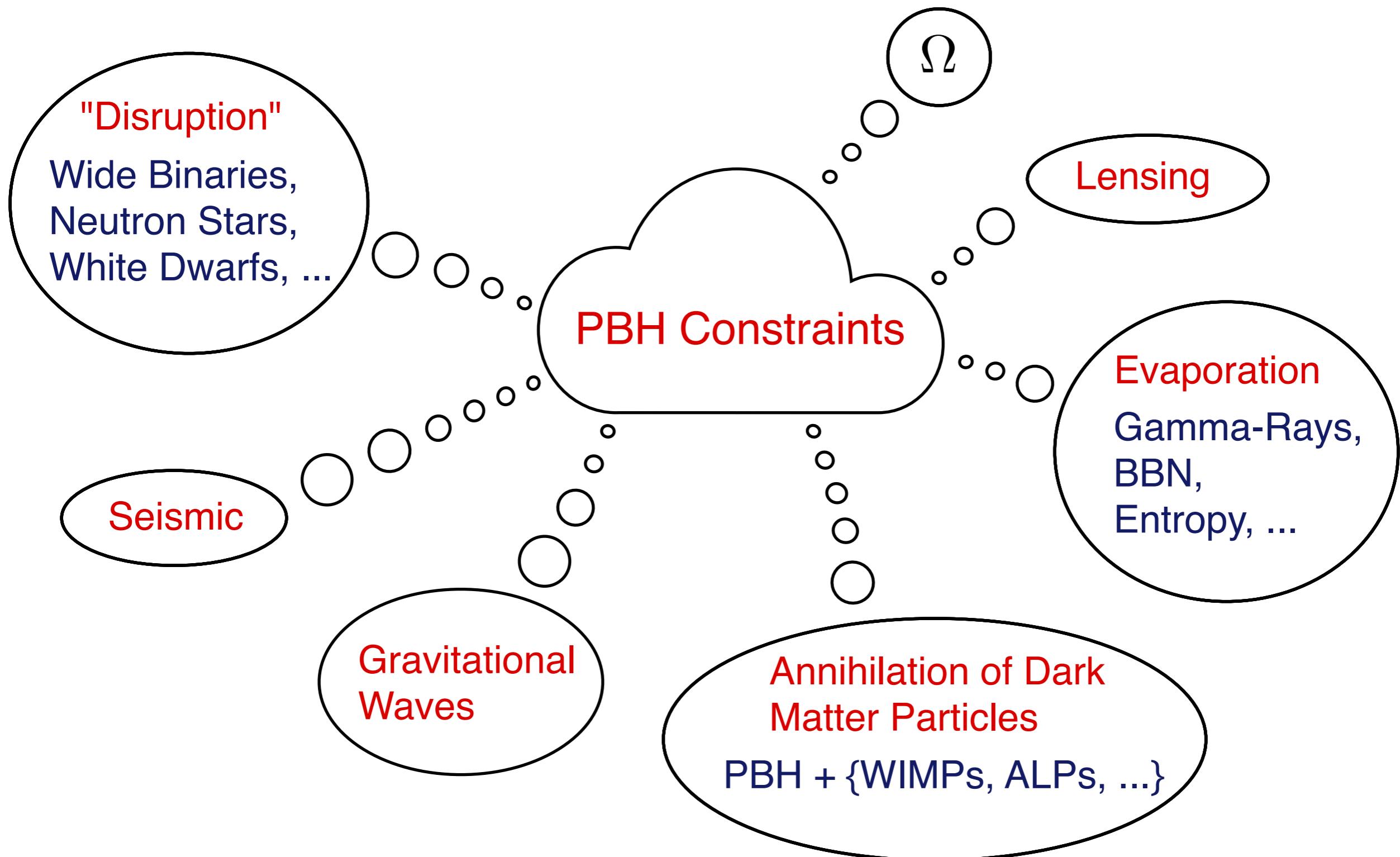
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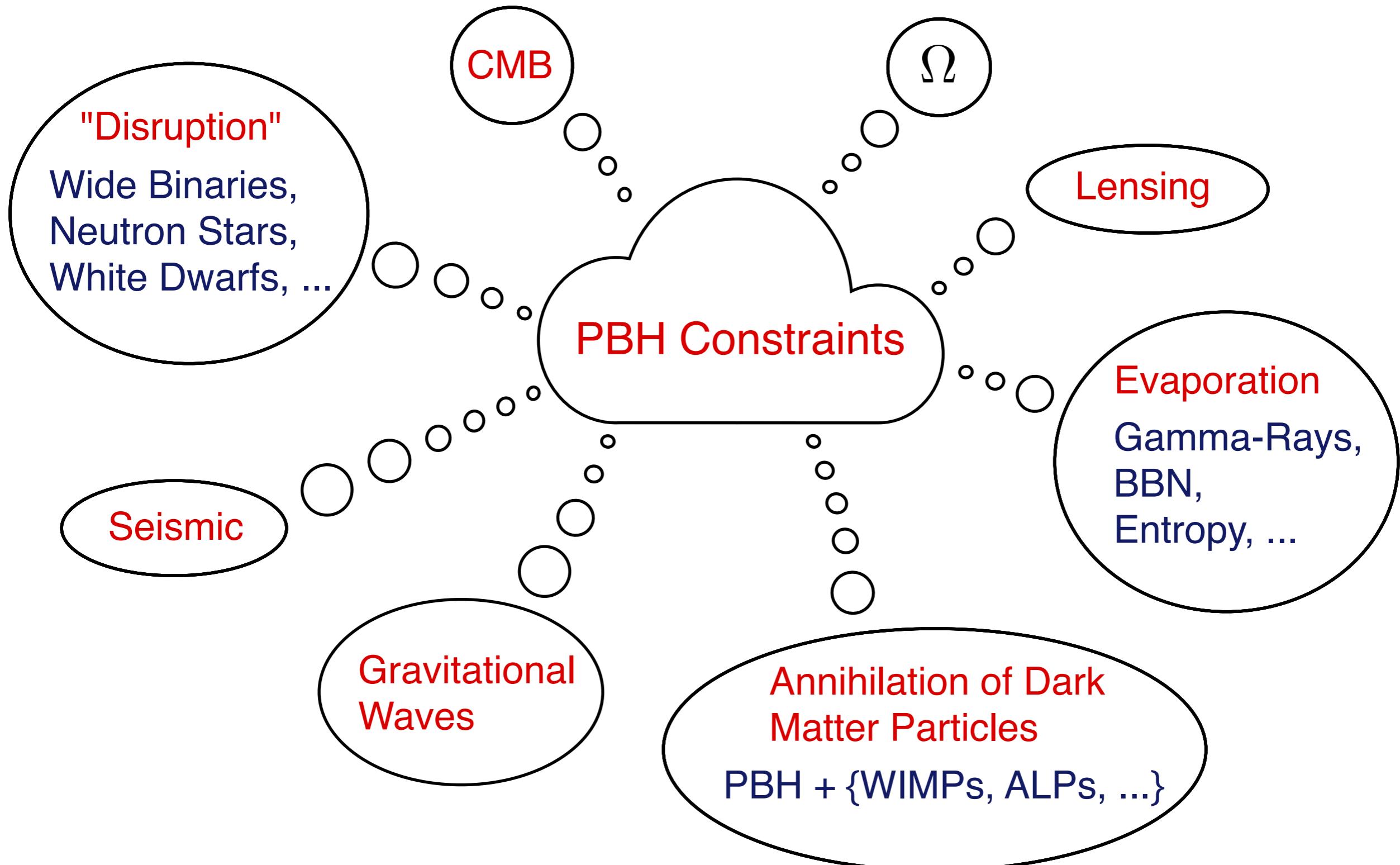
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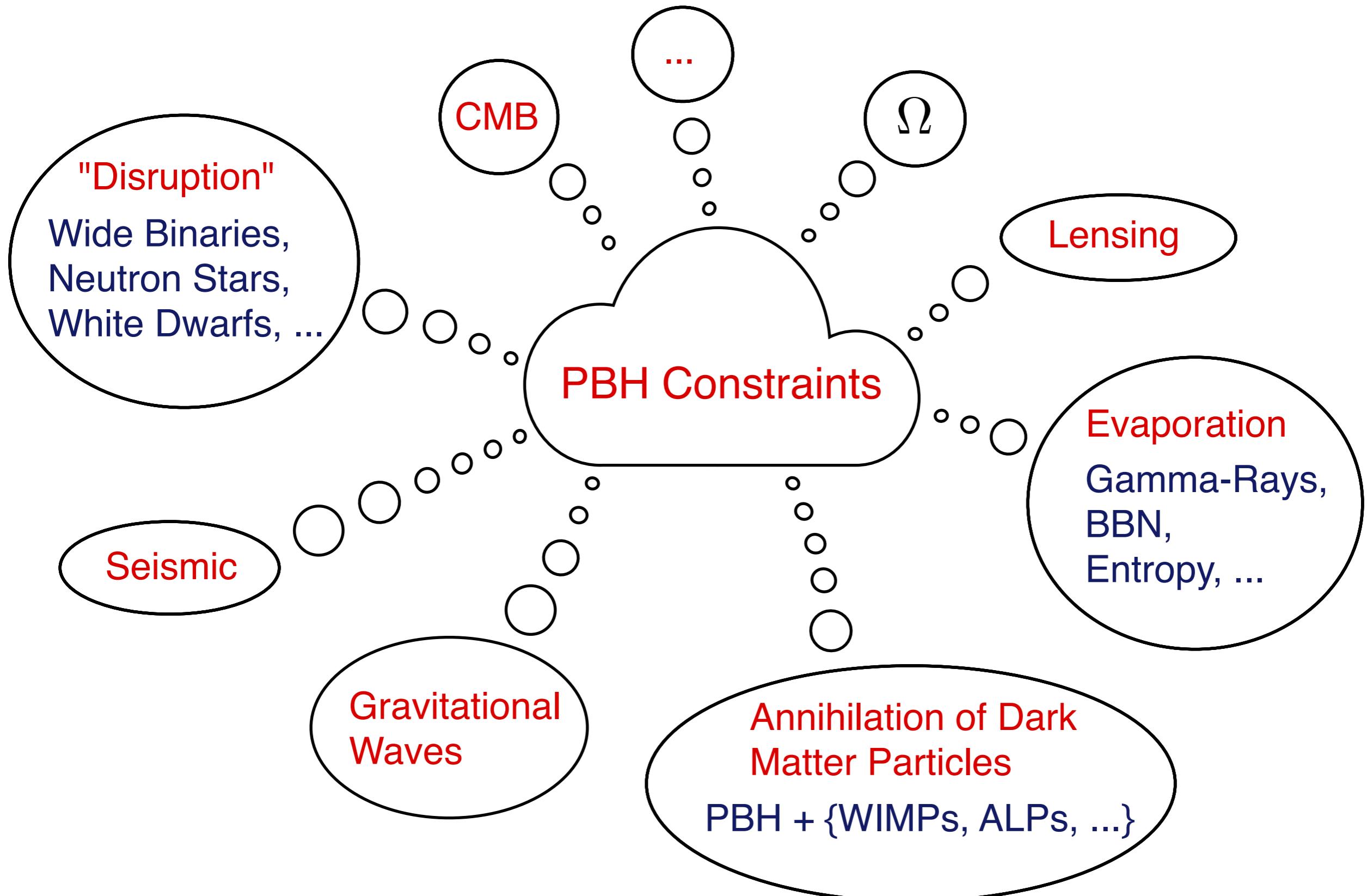
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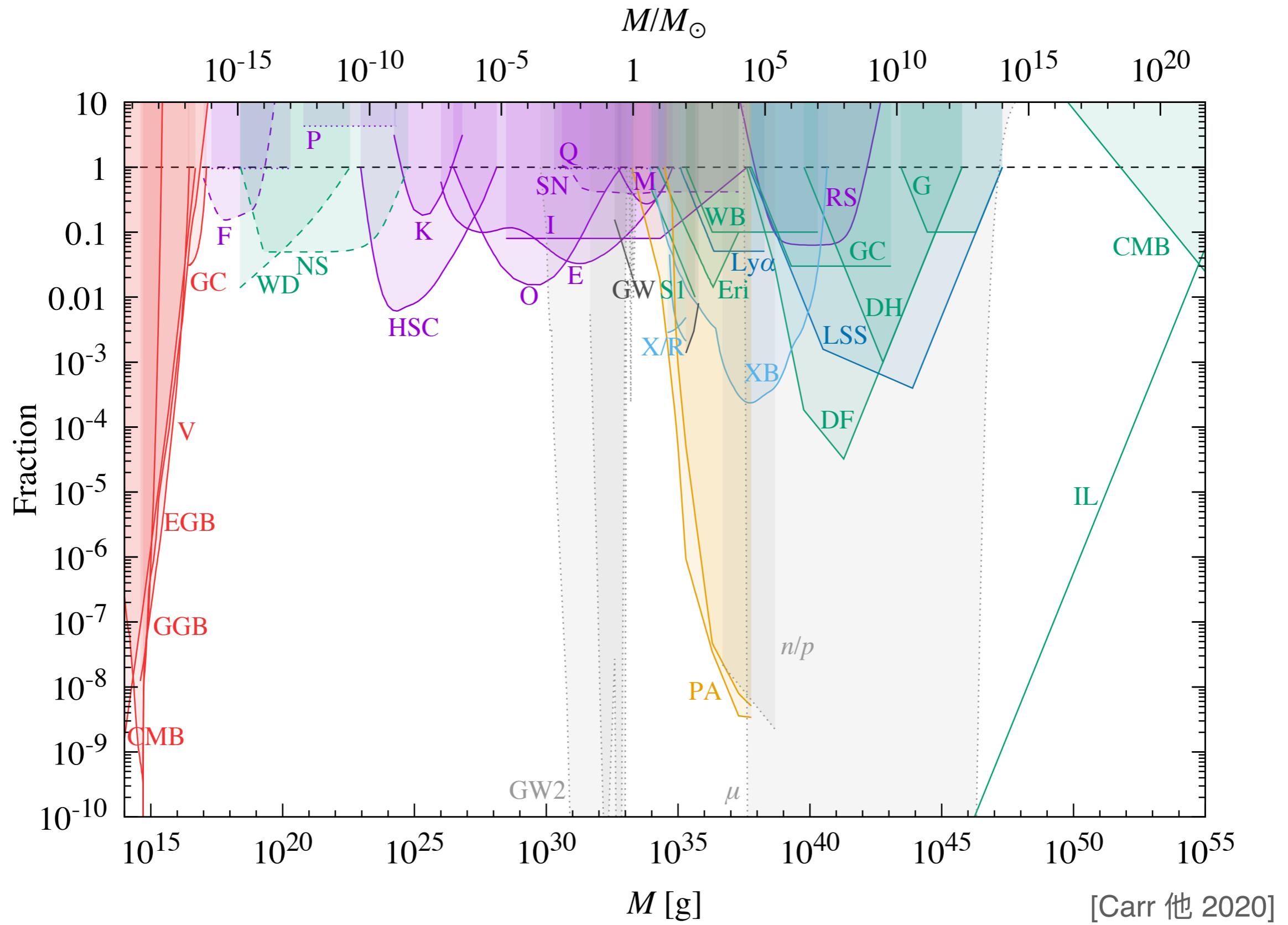
# PBH Constraints



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# PBH Constraints



# *Constraints — A Worthwhile Remark*



These constraints are not just nails in a coffin!

(Carr)

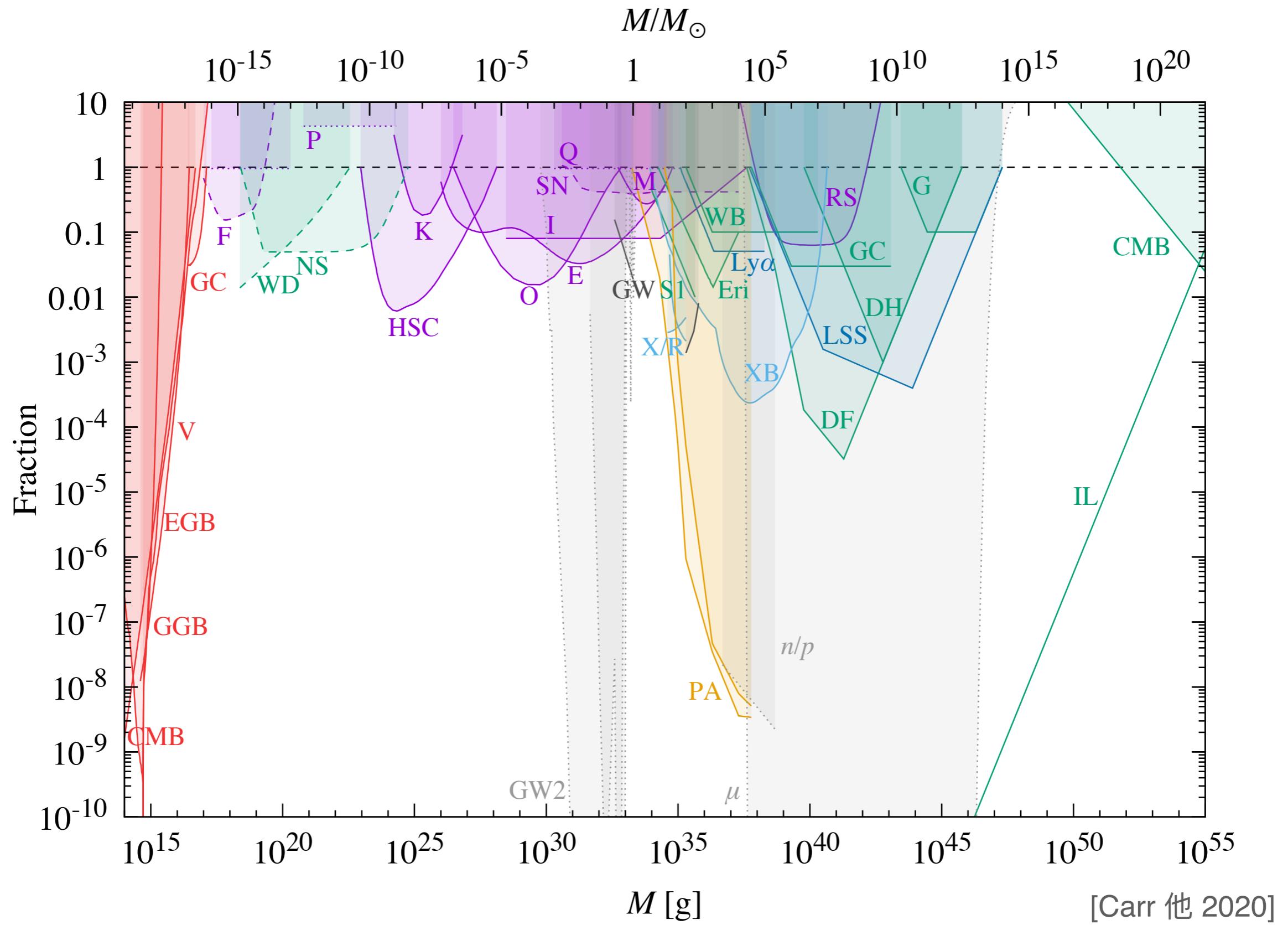


All constraints have caveats and may change

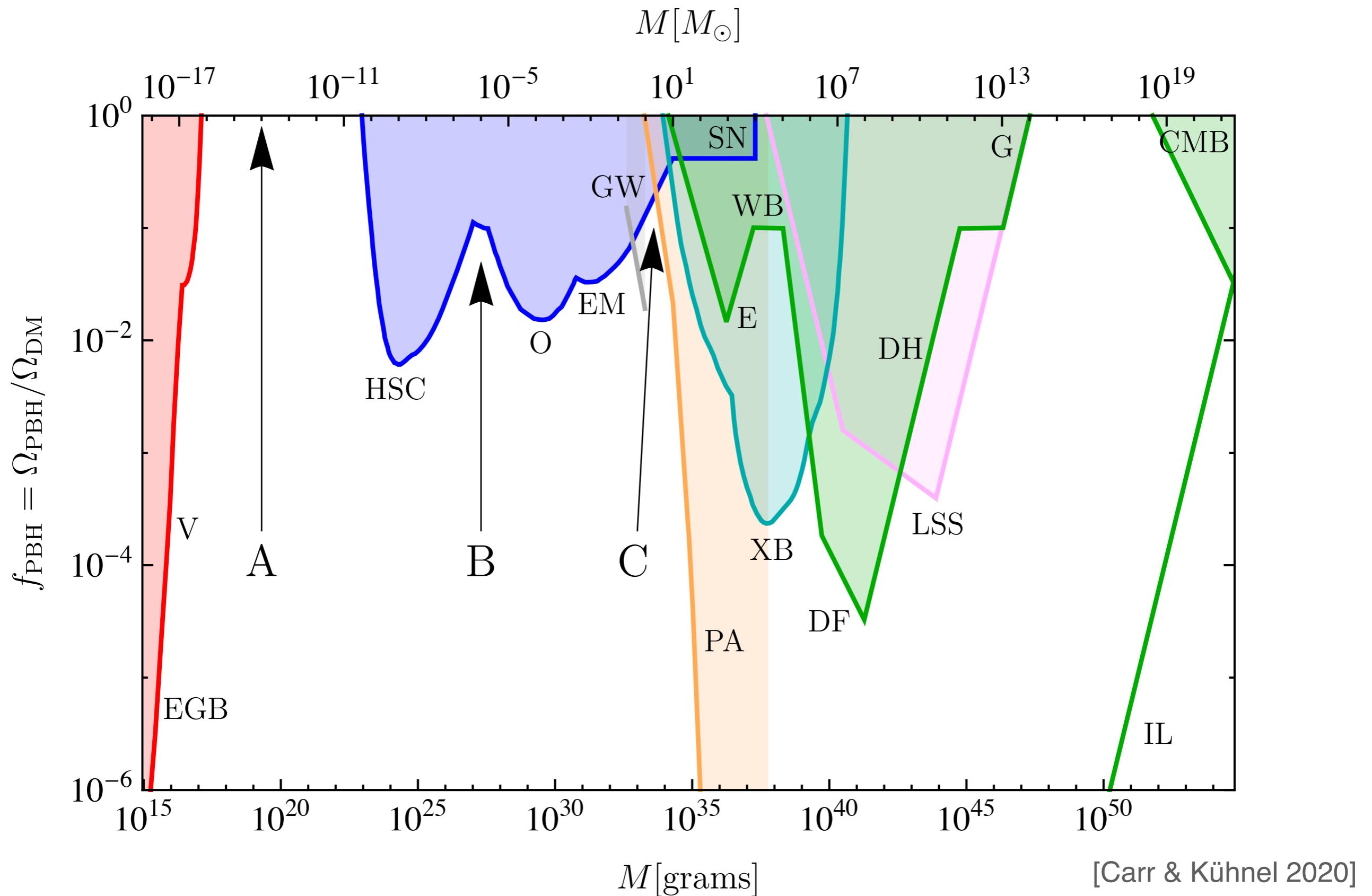
Each constraint is a potential signature

PBHs are interesting even if  $f \ll 1$

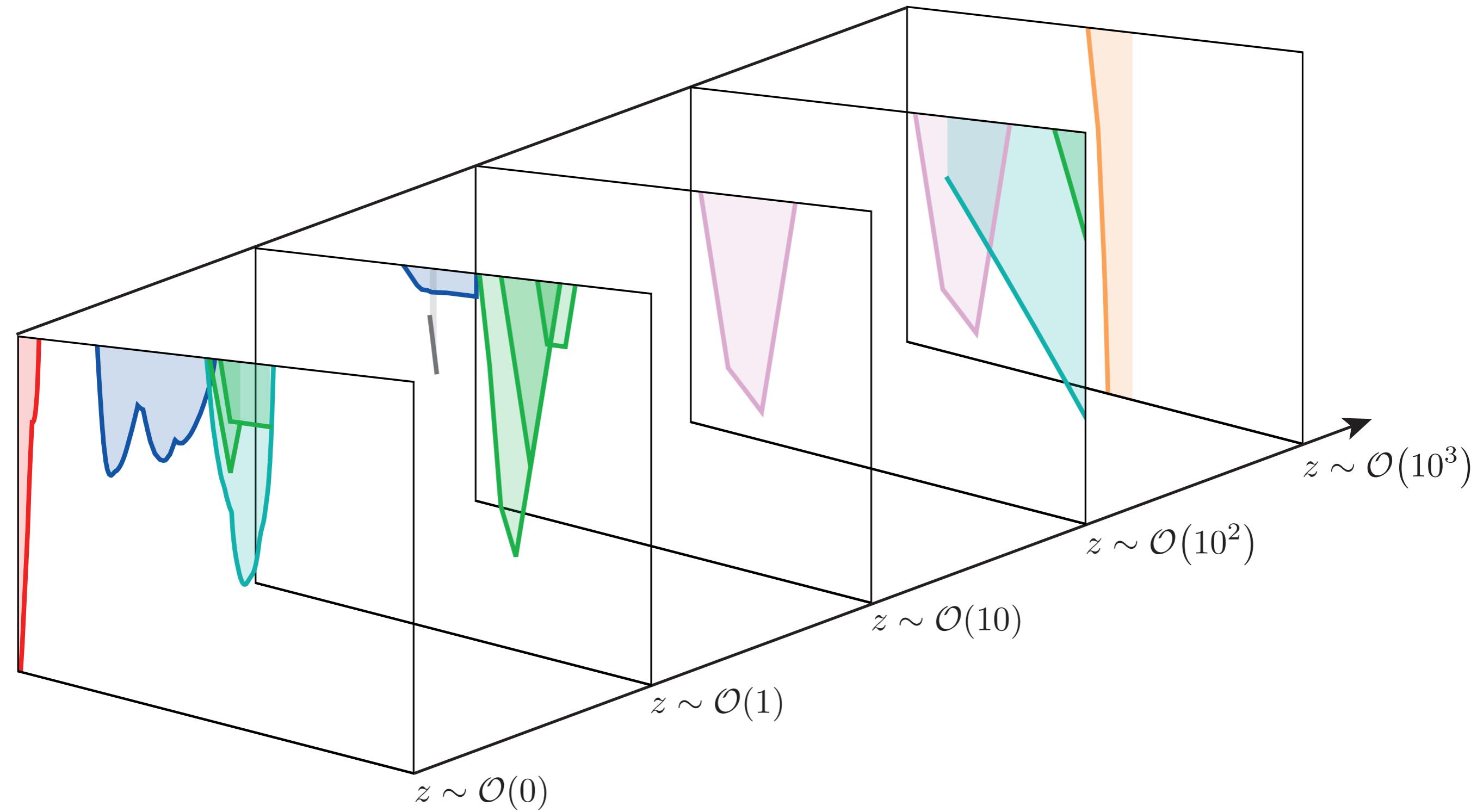
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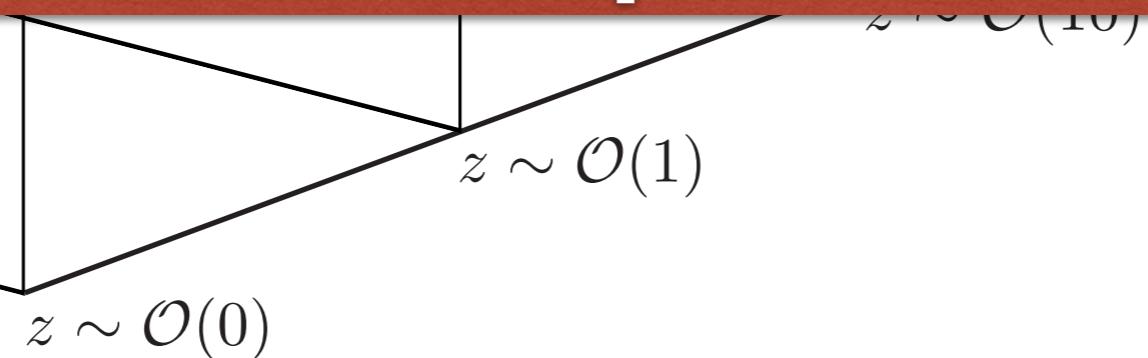
# PBH Constraints - Redshift Dependence



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There are many PBH constraints  
but these are dependent on  
redshift and are subject to many  
assumptions.



*Formation II:*  
*Critical Collapse*

# Critical Collapse



★ Usually: Assume

$$M_{BH} \propto M_H$$

↑  
horizon mass

★ Critical scaling:

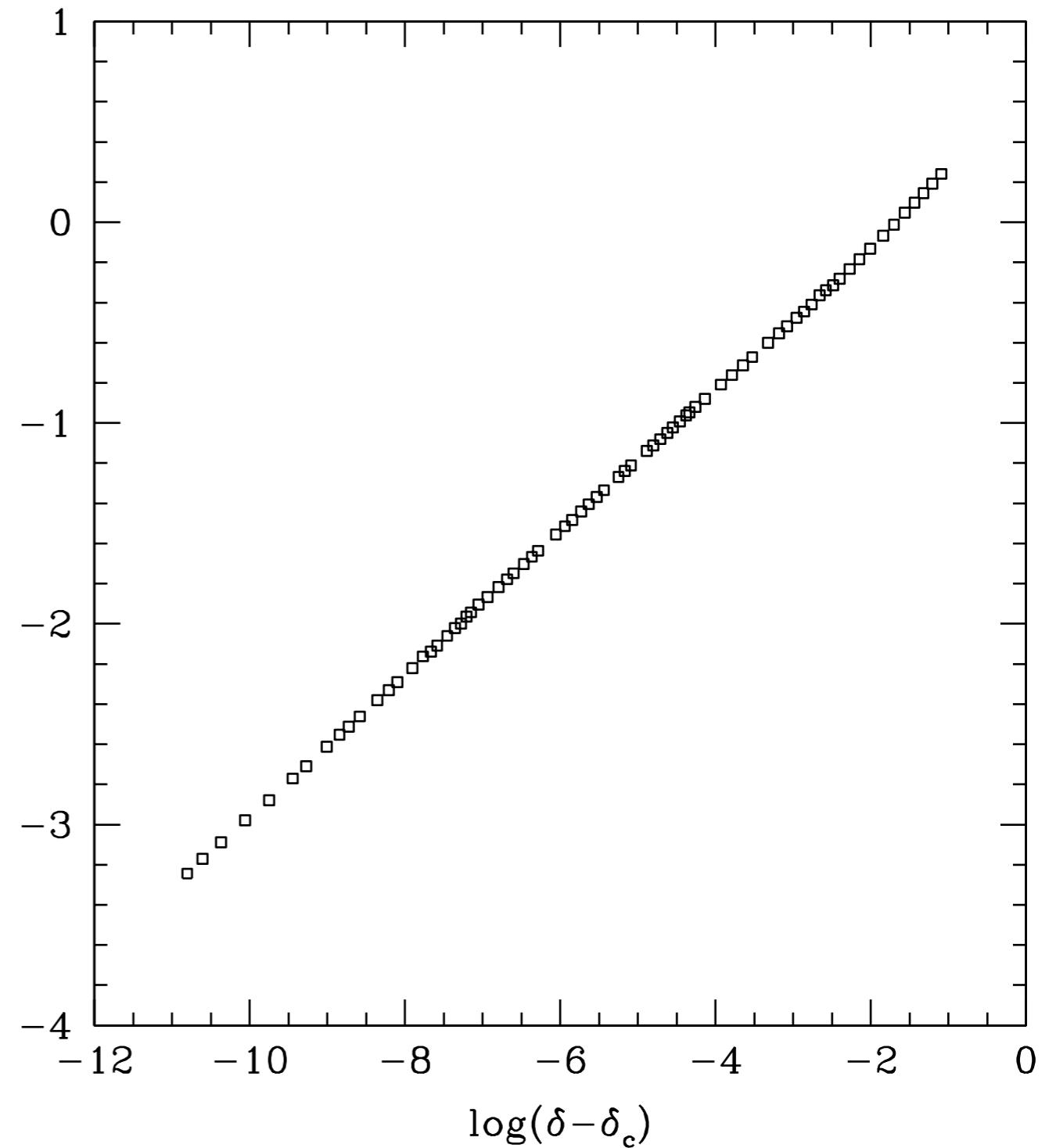
[Choptuik '93]

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

density contrast

★ Radiation domination and for spherical Mexican-hat profile:

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

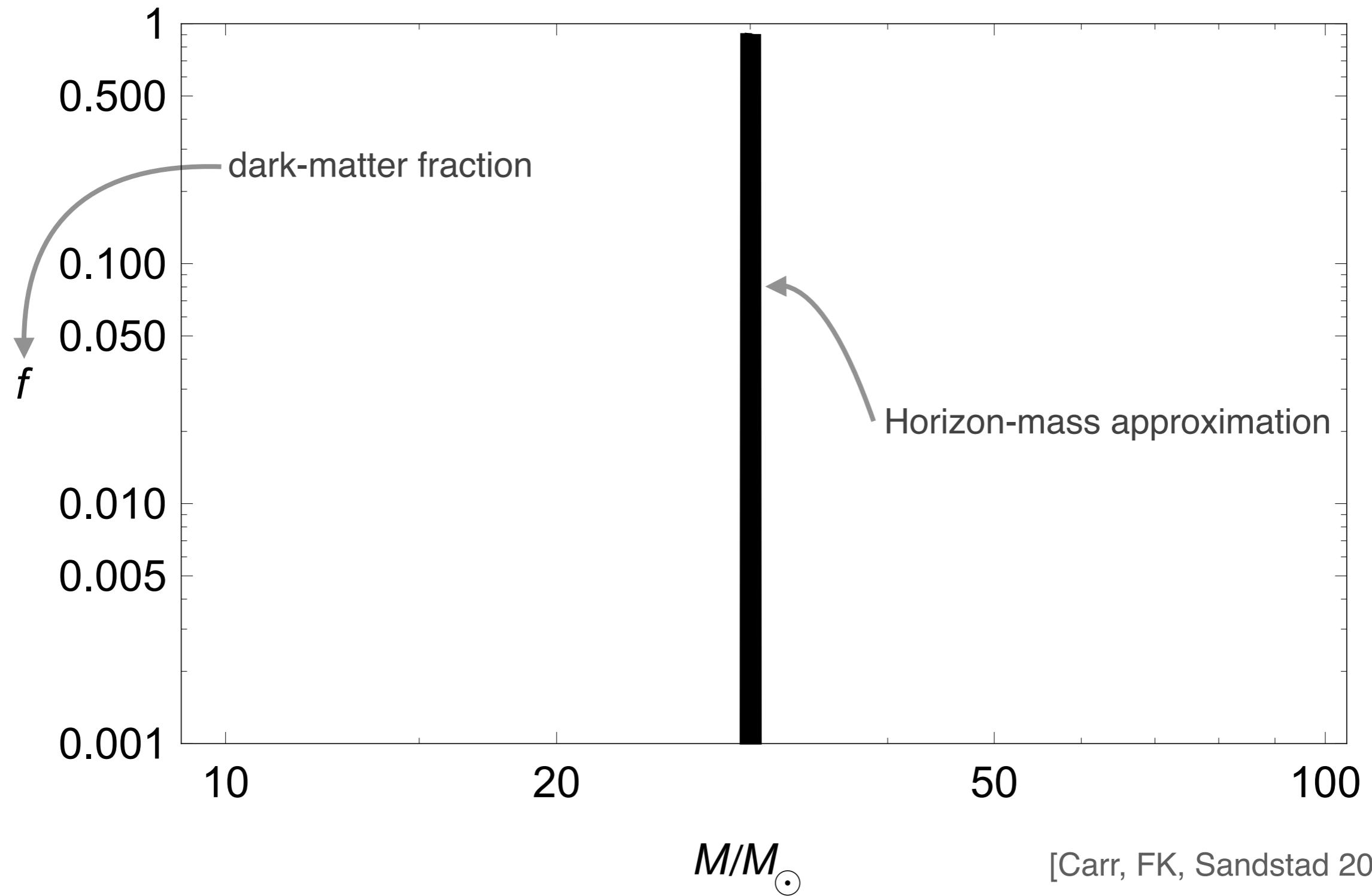


[Musco, Miller, Polnarev 2008]

# Critical Collapse



★ How would this look for **monochromatic** mass function?

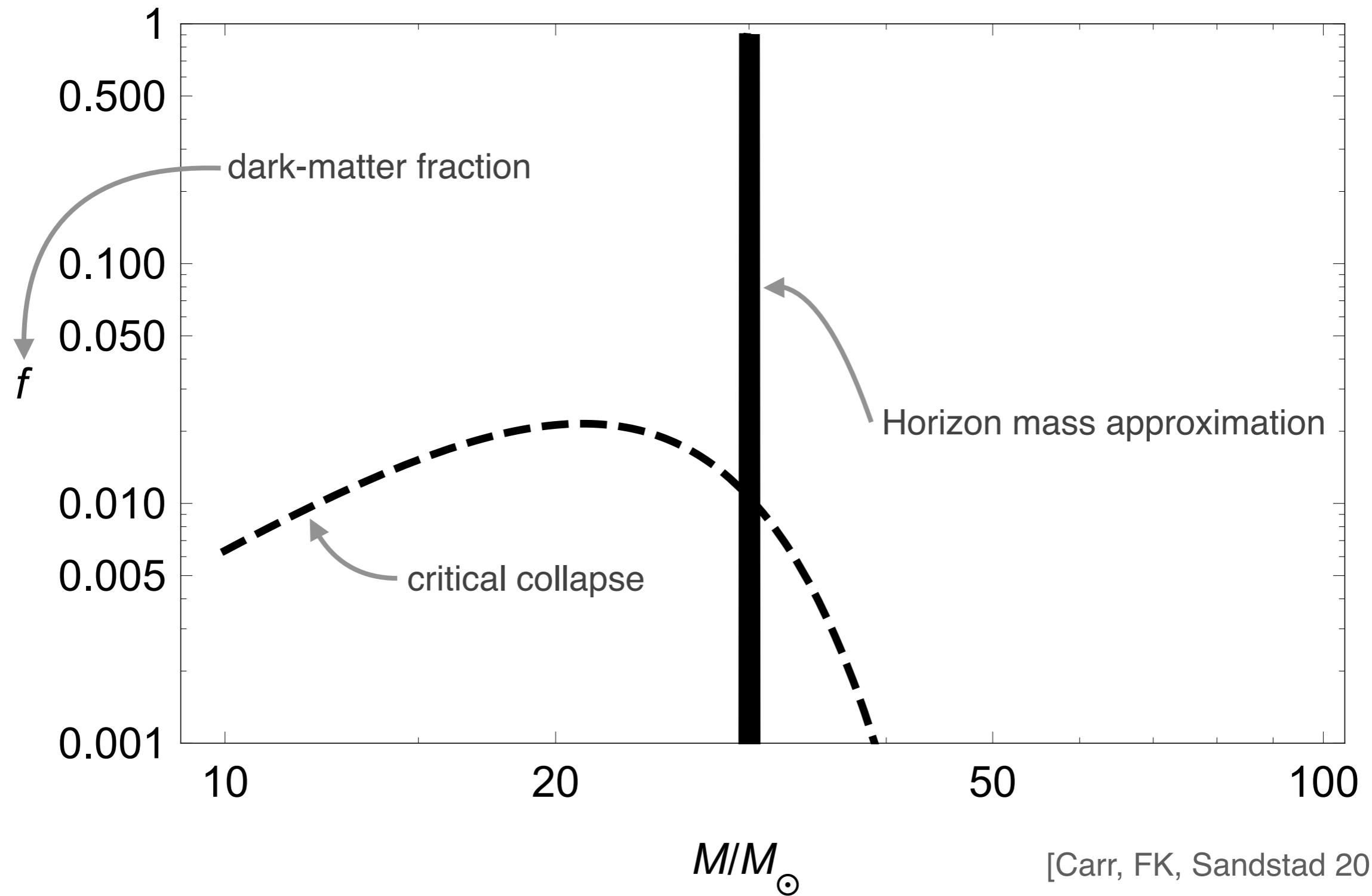


[Carr, FK, Sandstad 2016]

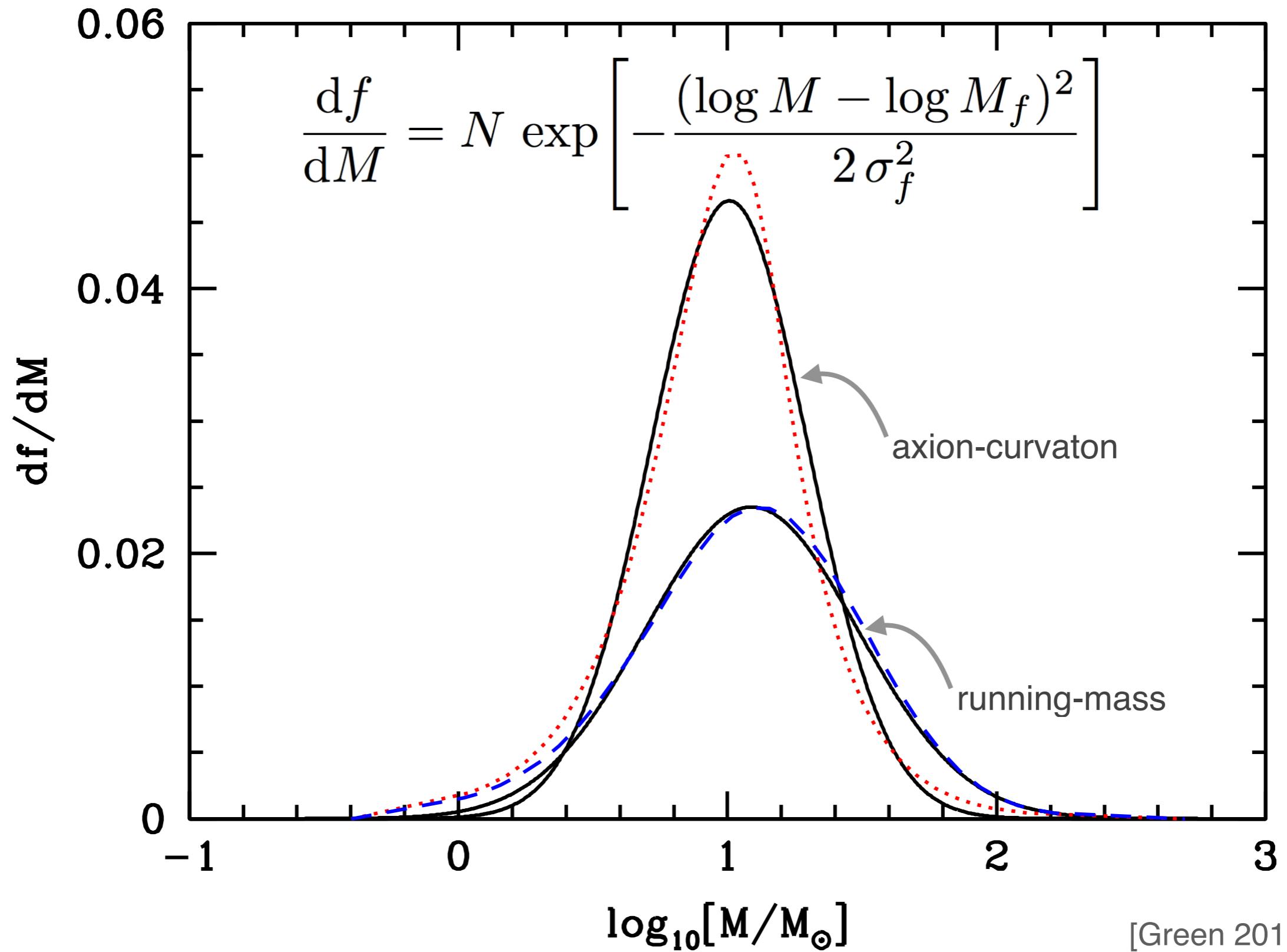
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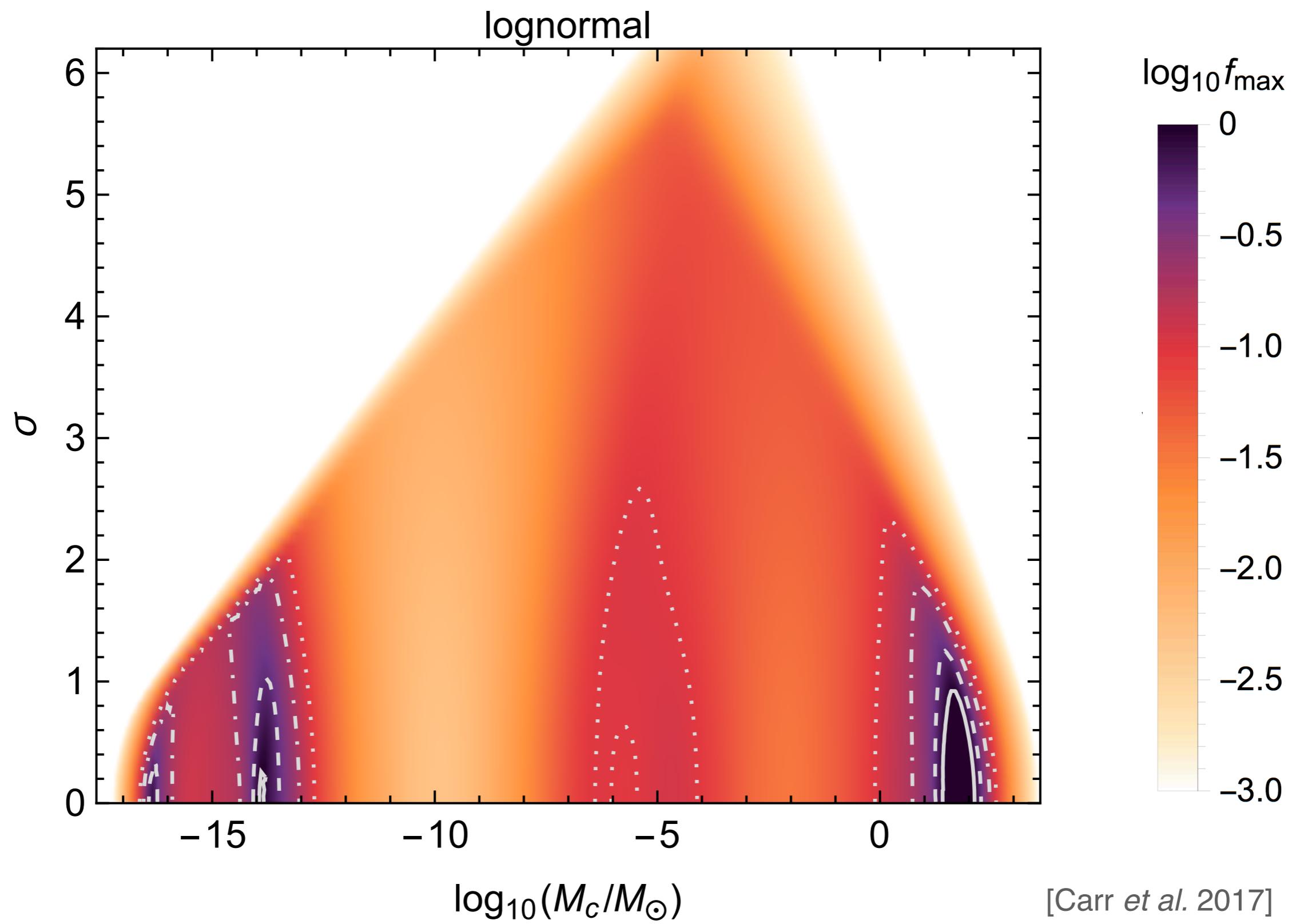
★ How would this look for **monochromatic** mass function?



# More Systematic Study



# More Systematic Study



*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.

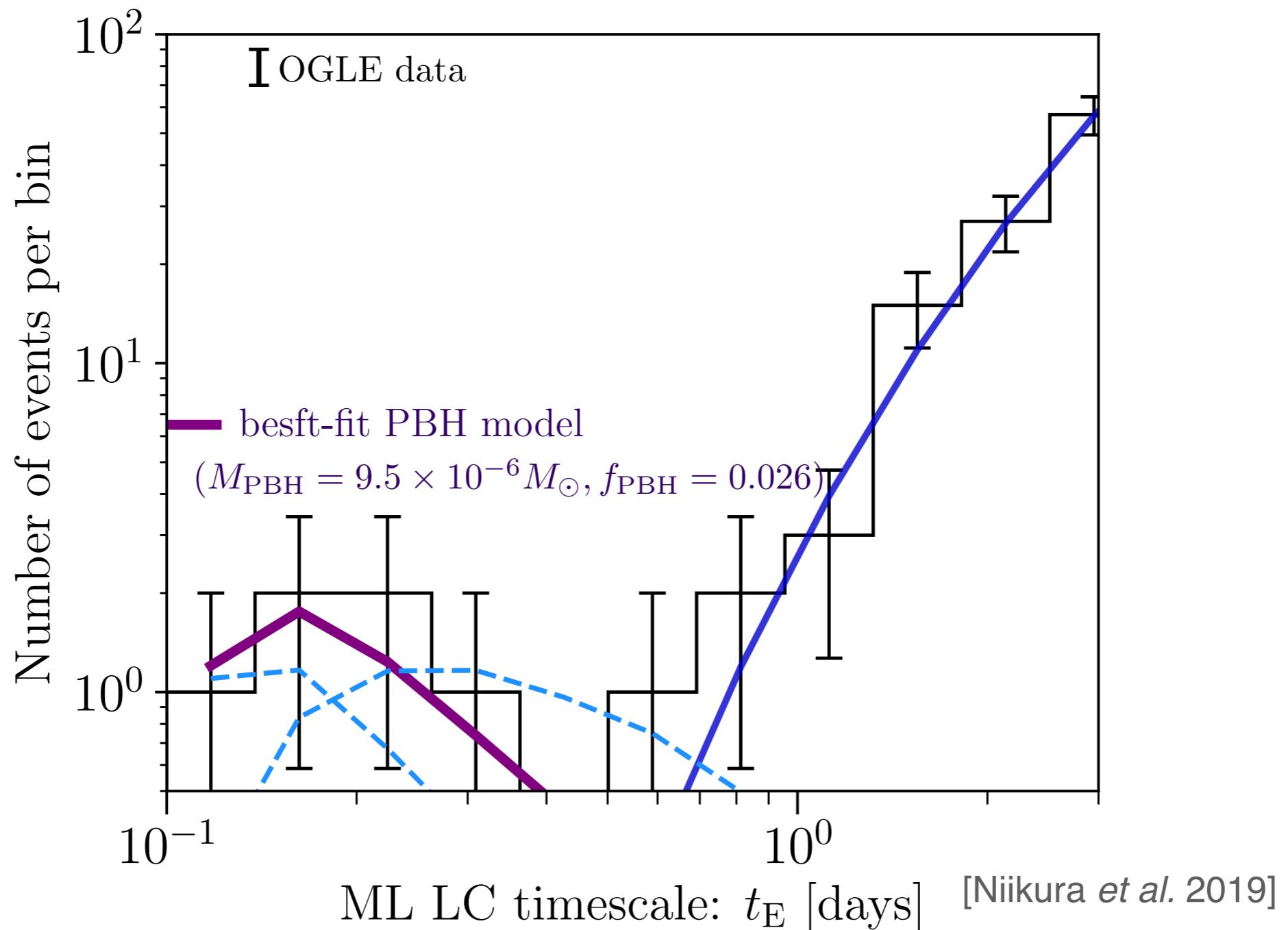


1.3 m Warsaw University Telescope Las Campanas Observatory, Chile

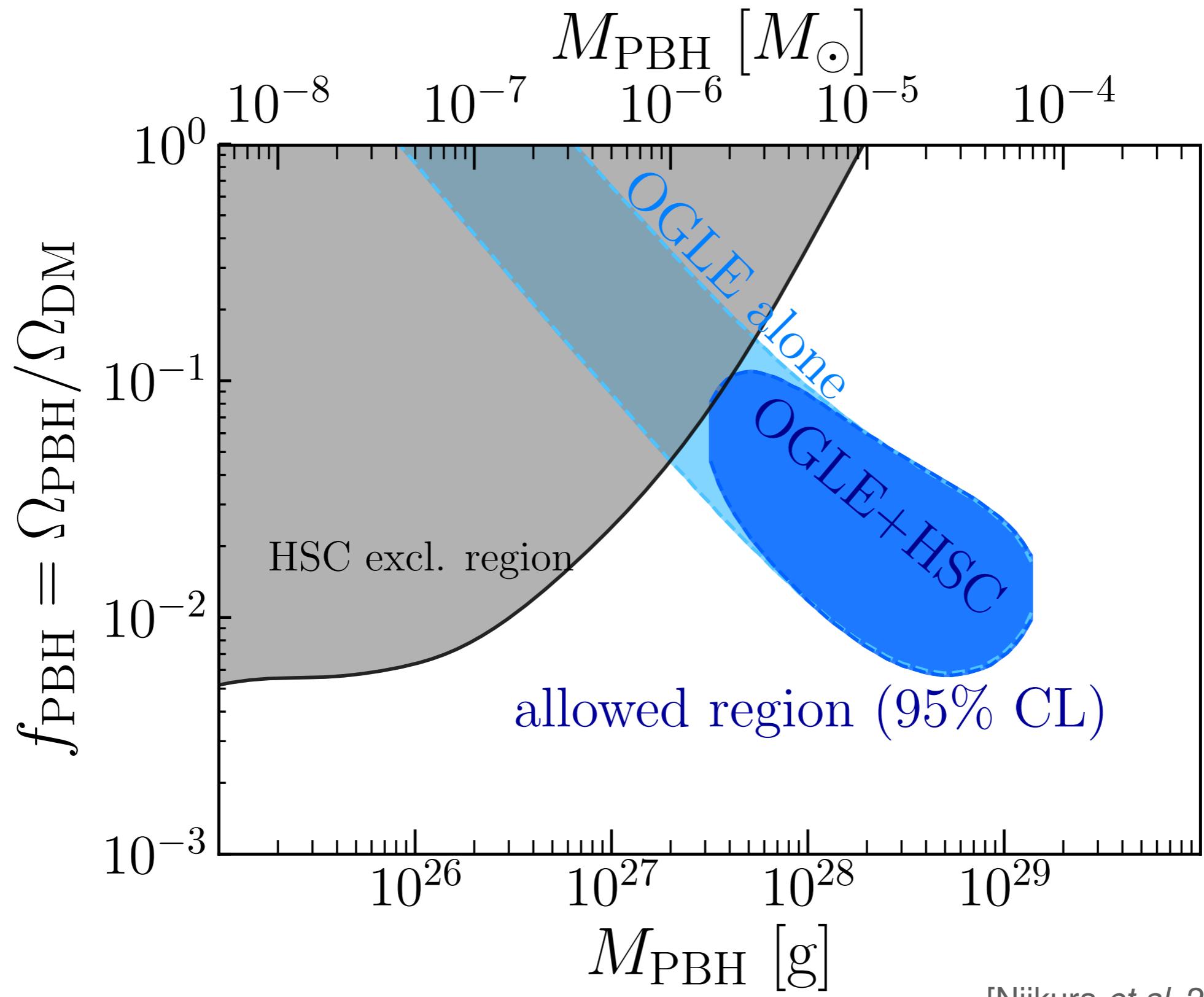
# Did OGLE Detect PBHs?



- ★ ... 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!**



# Did OGLE Detect PBHs?

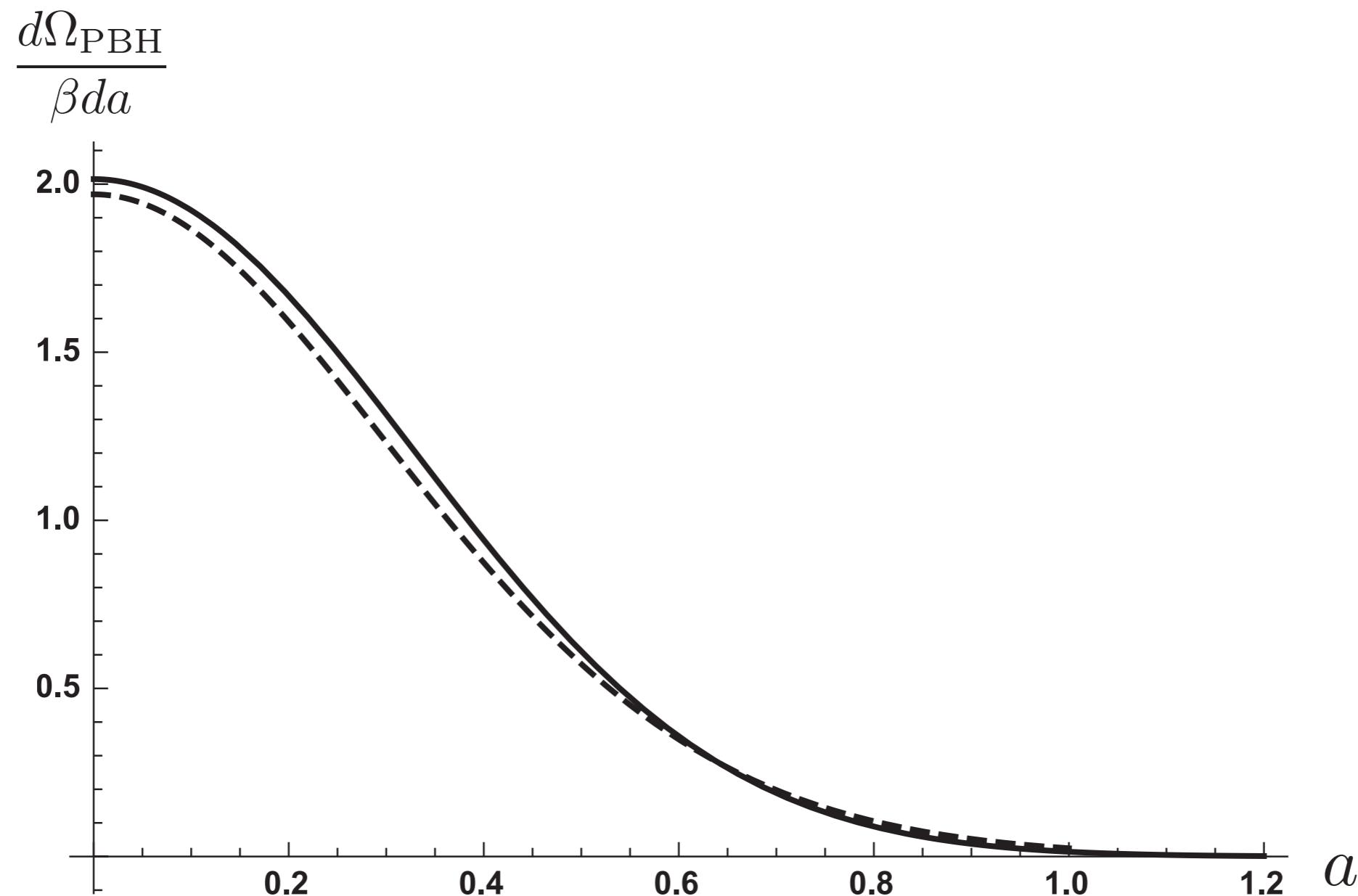


[Niikura *et al.* 2019]

# Gravitational Waves



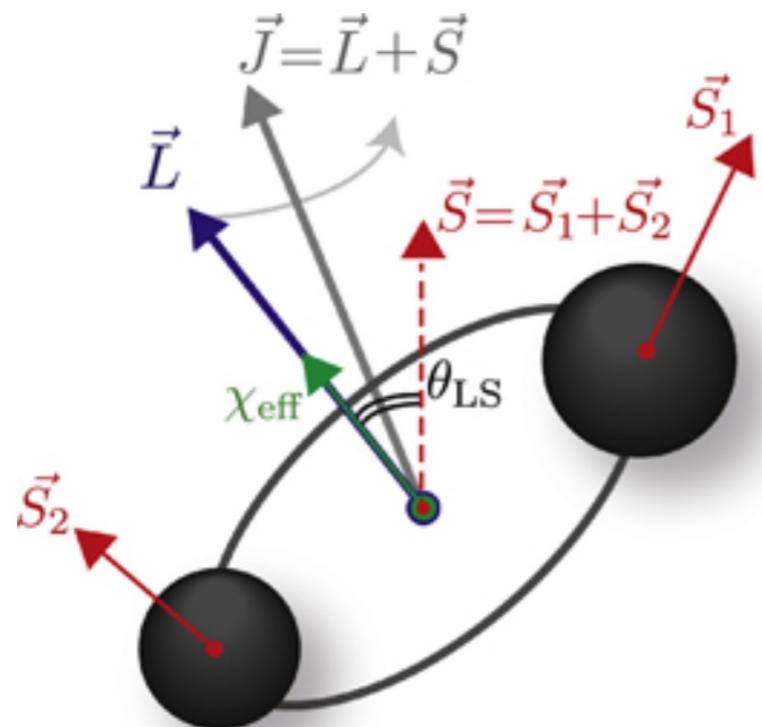
- ★ Gravitational-wave emission from black-hole binaries
- ★ For PBH (produced in RD) we expect close to zero spin.



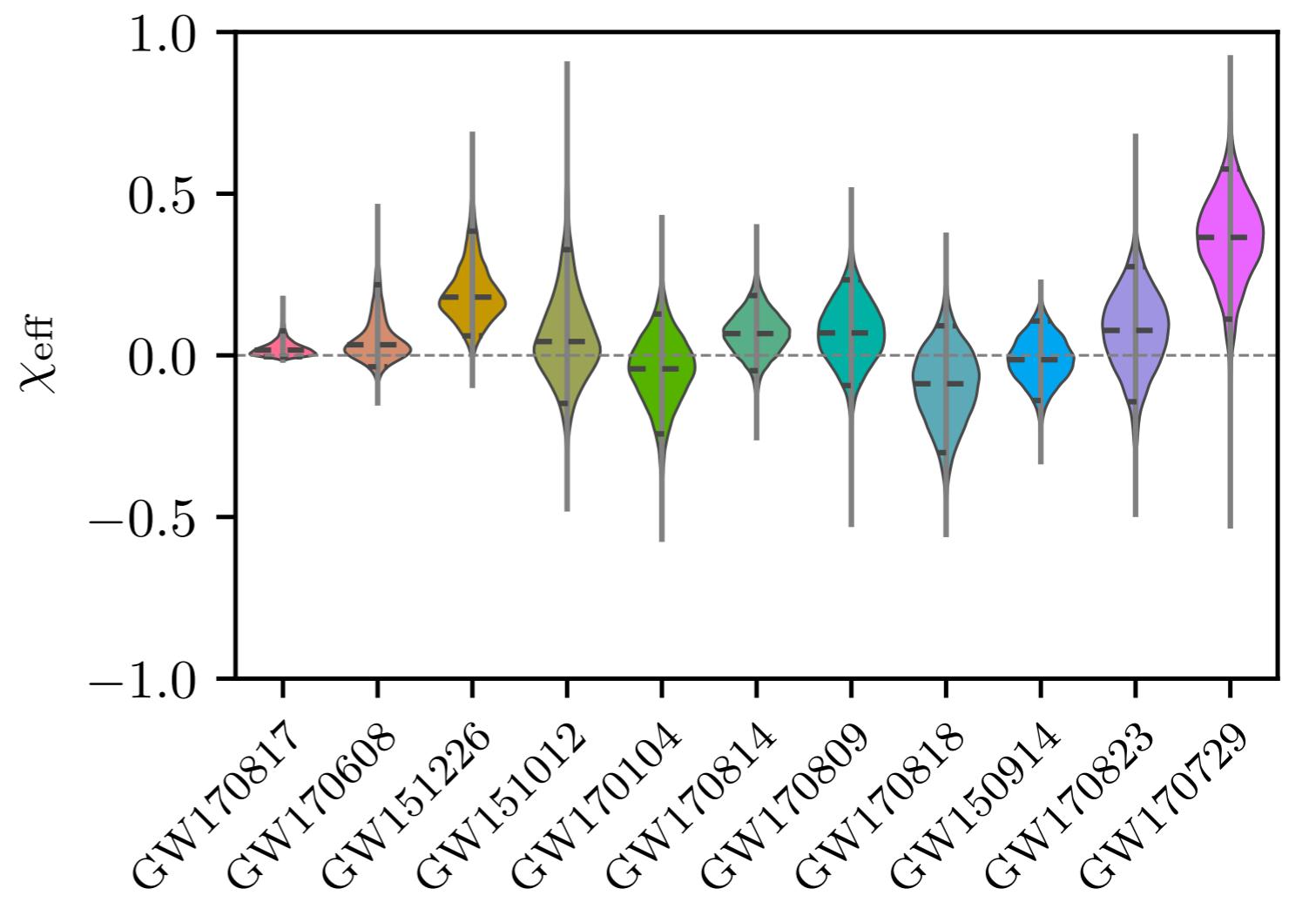
# Gravitational Waves



- ★ 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:



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



[LIGO Scientific, Virgo 2018]

# *Thermal History*

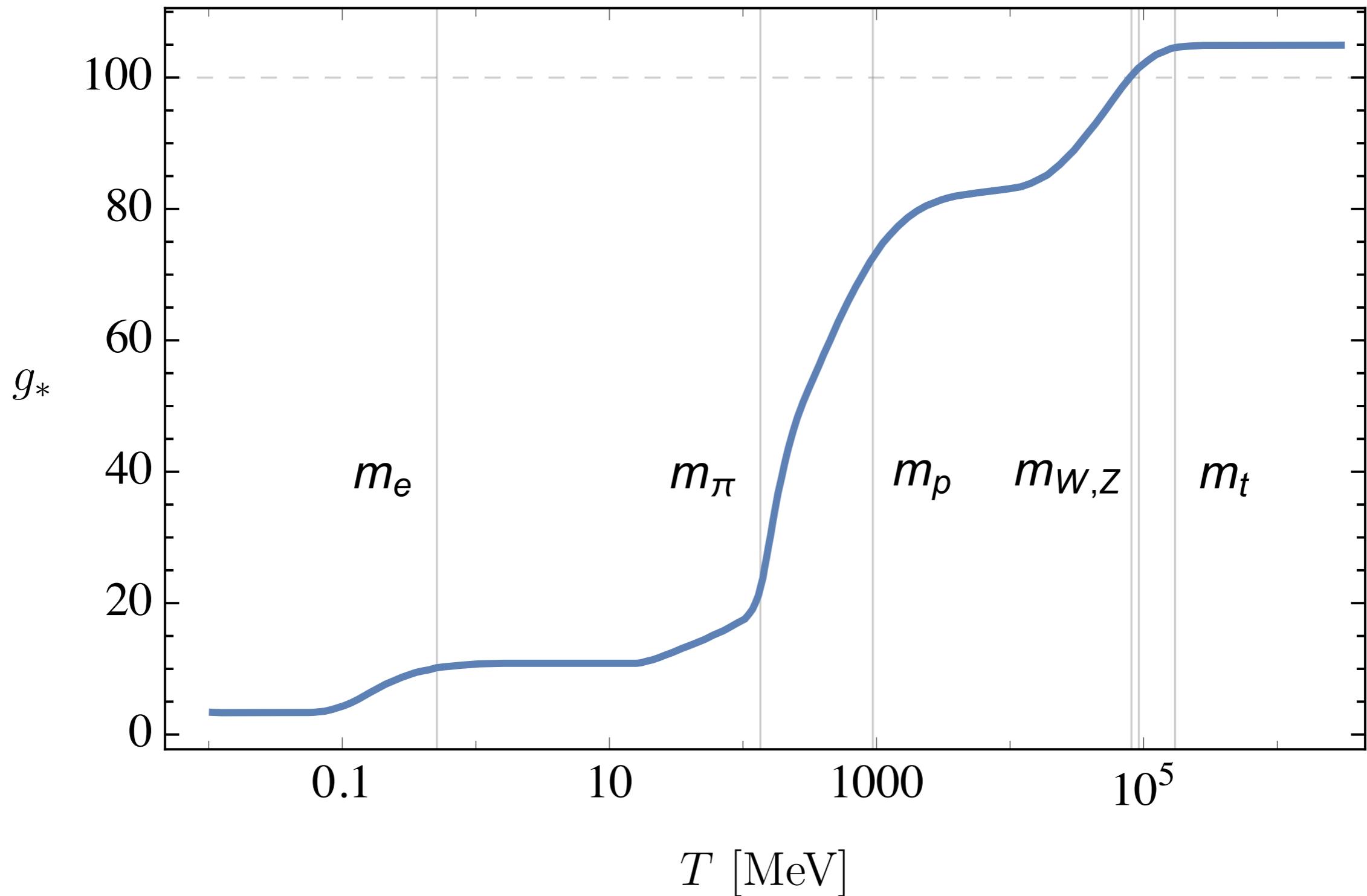
*A*

*Thermal History Mystery*



# Thermal History of the Universe

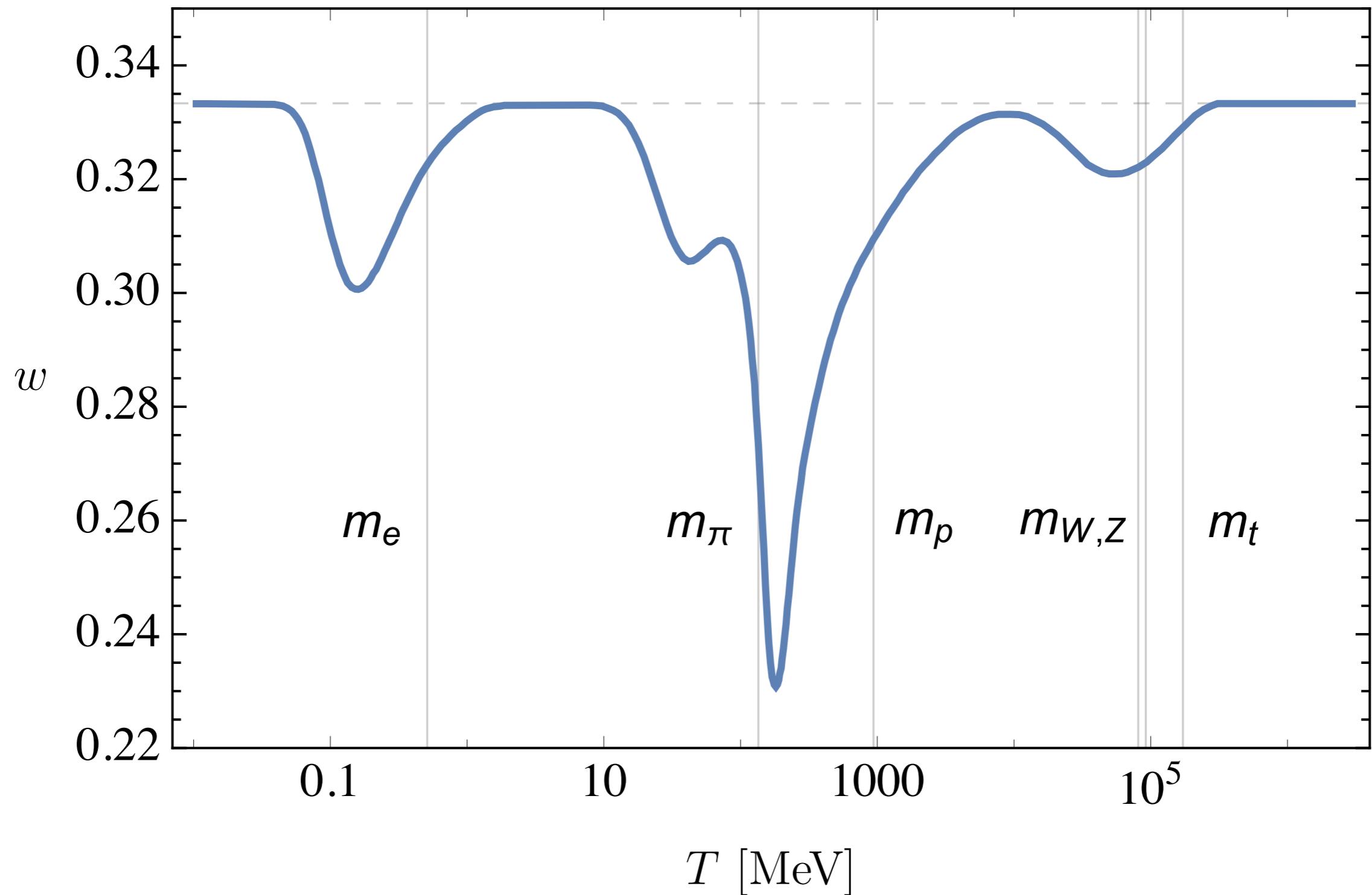
★ Changes in the **relativistic degrees of freedom**:





# Thermal History of the Universe

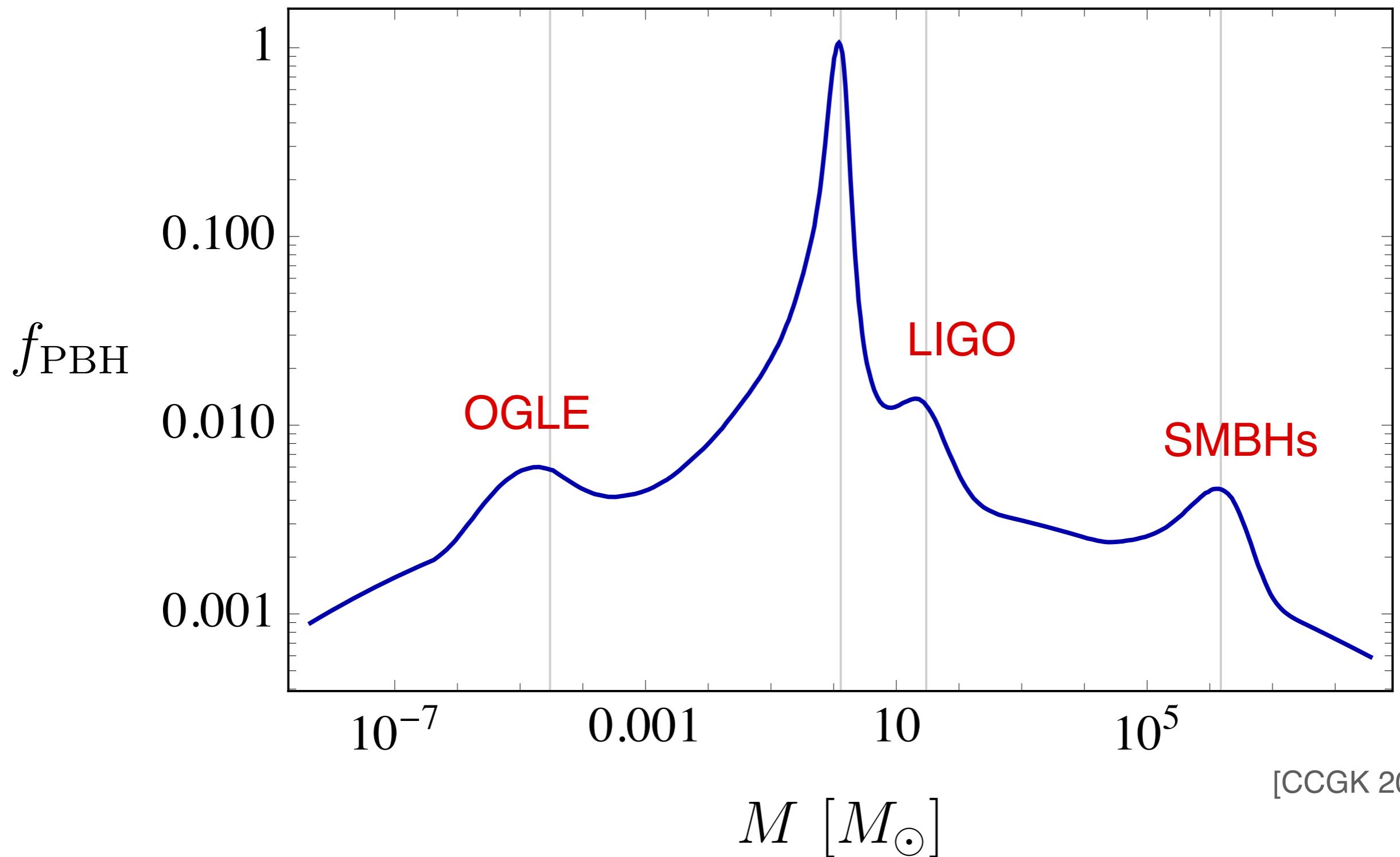
★ Changes in the equation-of-state parameter  $w = p/\rho$ :





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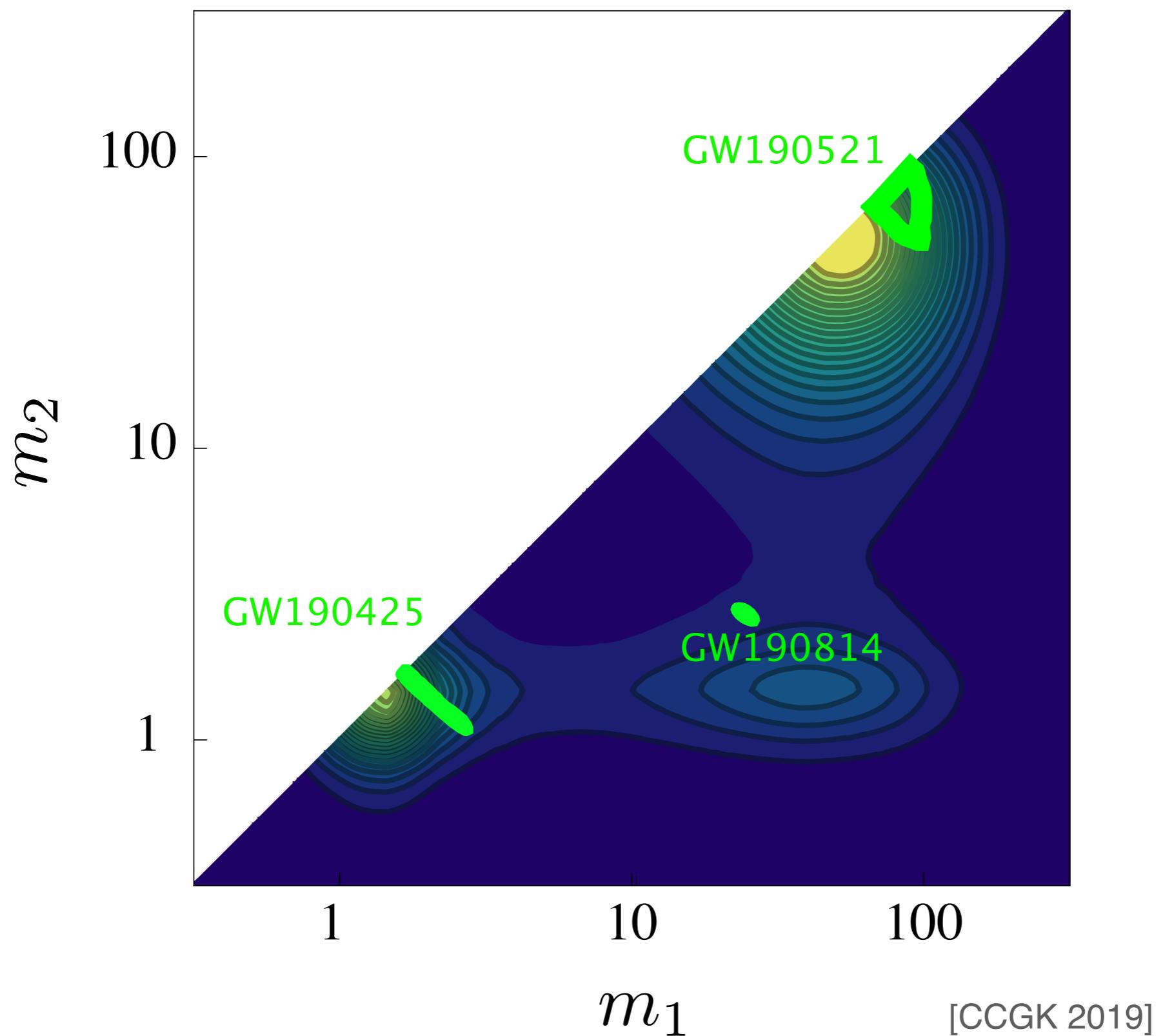
- ★ An essentially **featureless** PBH mass spectrum leads to:



[CCGK 2019]



# LIGO/Virgo Merger Rates



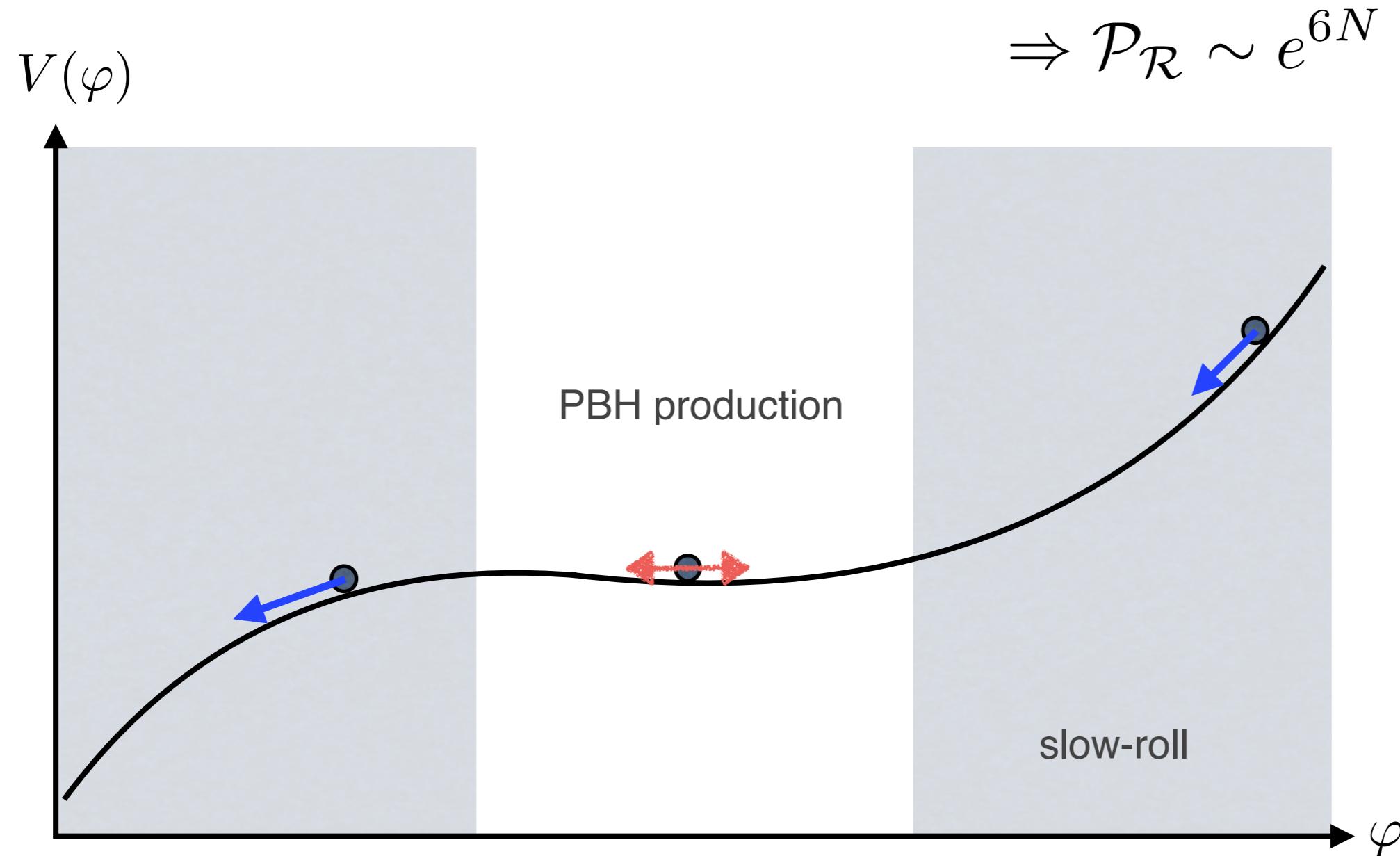
*Enhancement*

# Quantum Diffusion



- ★ Consider the possibility of a **plateau** in the inflaton potential:

$$\mathcal{P}_{\mathcal{R}} = \left( \frac{H}{2\pi\varphi'} \right)^2, \quad \varphi' \equiv \frac{d\varphi}{dN}, \quad \varphi'' + 3\varphi' + \frac{V_{,\varphi}}{H^2} \simeq \varphi'' + 3\varphi' = 0$$



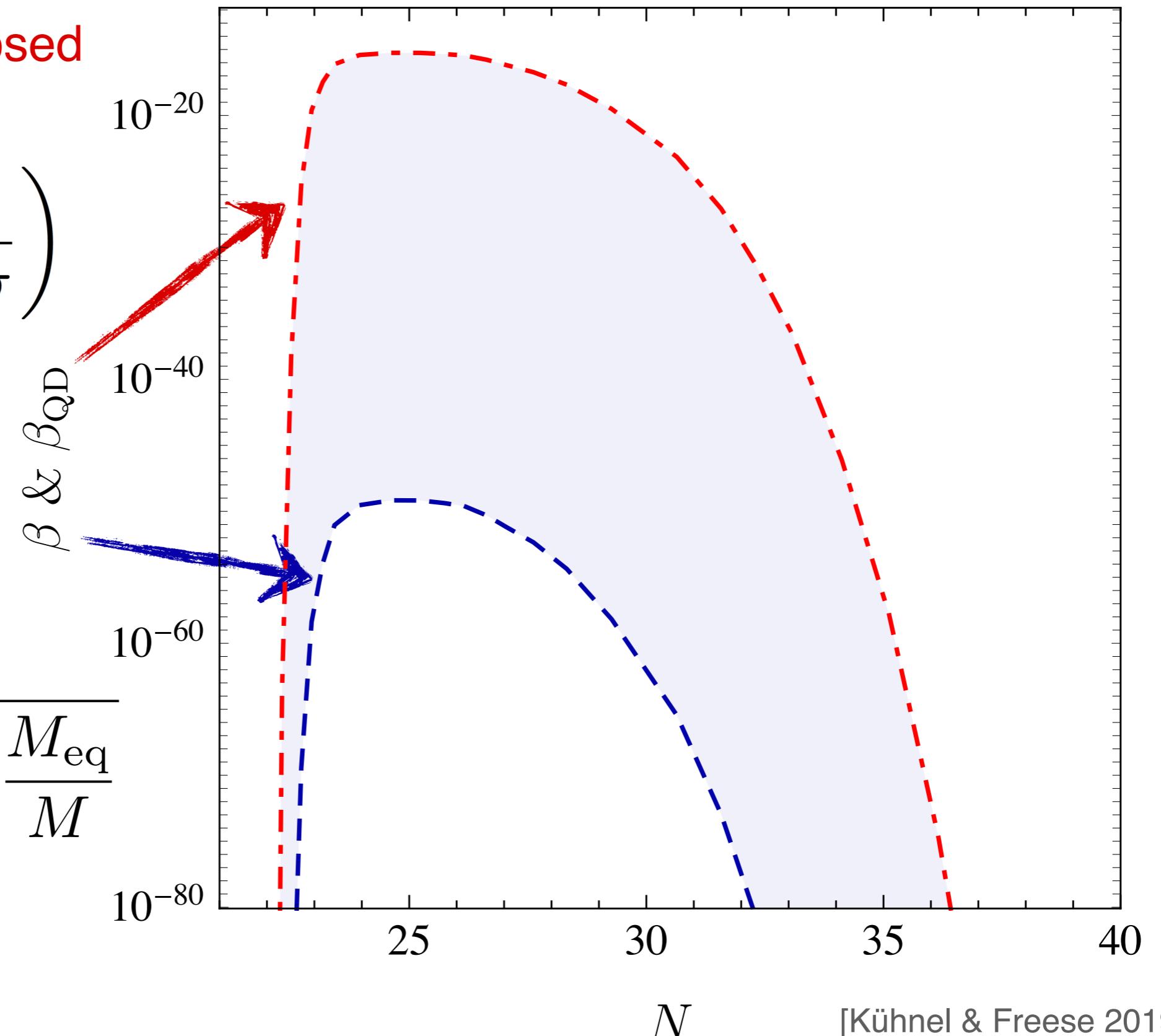
# Quantum Diffusion



Fraction of collapsed  
horizon patches:

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

$$f_{\text{PBH}} \approx 2.4 \beta \sqrt{\frac{M_{\text{eq}}}{M}}$$



$N$

[Kühnel & Freese 2019]

*Micro & Macro*

# *PBH & Particle Dark Matter*



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    - ★ Halo profile does matter; **enhancement** of  $\Gamma$  in density spikes.
      - 1) Derive the **density profile** of the captured WIMPs;
      - 2) calculate the **annihilation rate**;
      - 3) and **compare to data**.

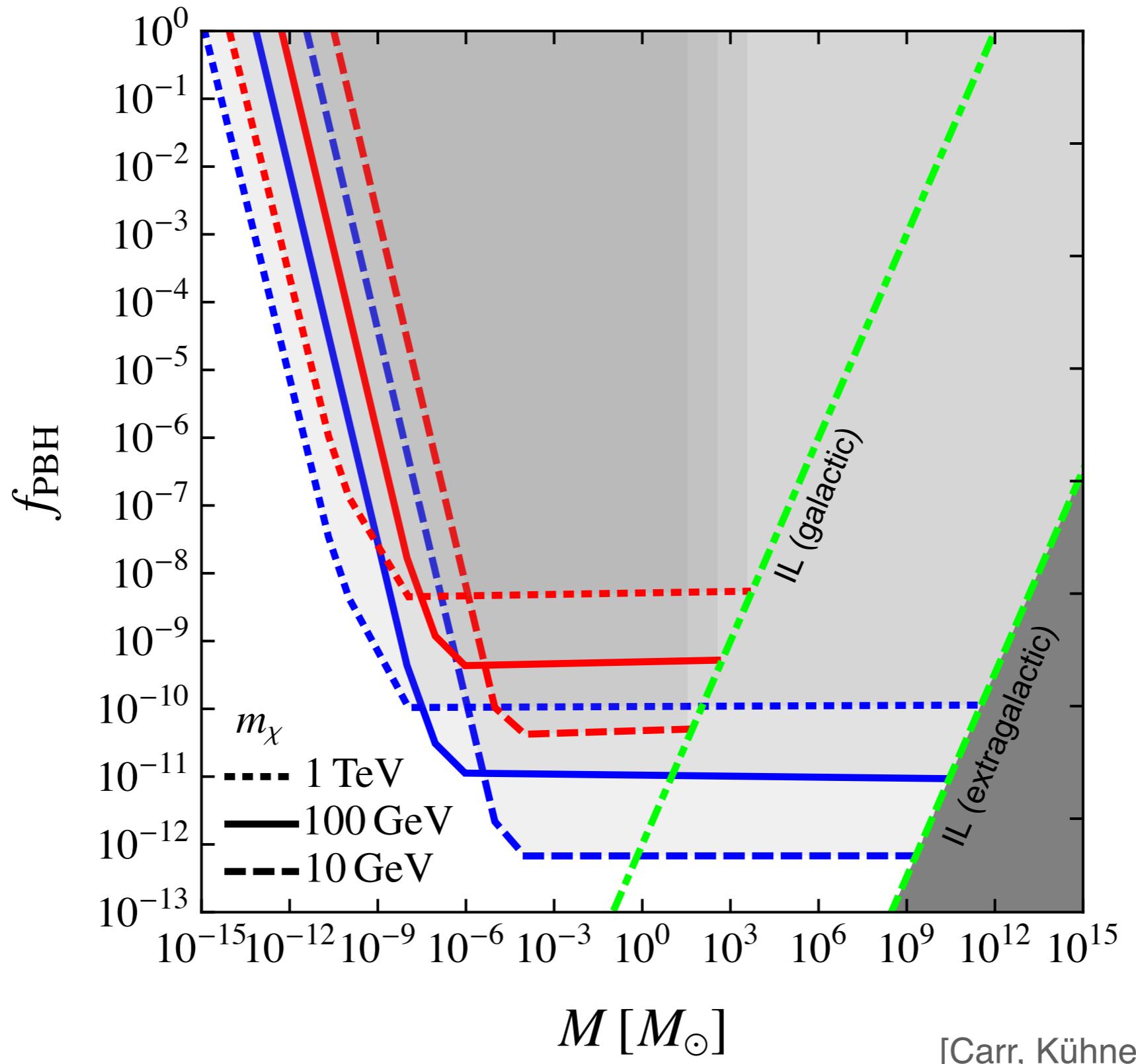
[Eroshenko 2016,

Boucenna *et al.* 2017,

Adamek *et al.* (including Byrnes) 2019,

Carr, Kühnel, Visinelli 2020\*]

# PBHs & WIMPs



[Carr, Kühnel, Visinelli 2020\*]

*Conclusion*

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- ★ Primordial black holes **influence** physics on many different scales, and manifest themselves via a **plethora** of different signatures.
- ★ The **thermal history** of the Universe **naturally encodes** scales relevant to observational conundra.
- ★ In turn, PBHs could **explain at the same time all** of:
  - a) **OGLE** microlensing events;
  - b) **LIGO** GW events;
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  - d) all of the **dark matter**.
- ★ Quantum diffusion leads to a strongly **enhanced** PBH production.
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