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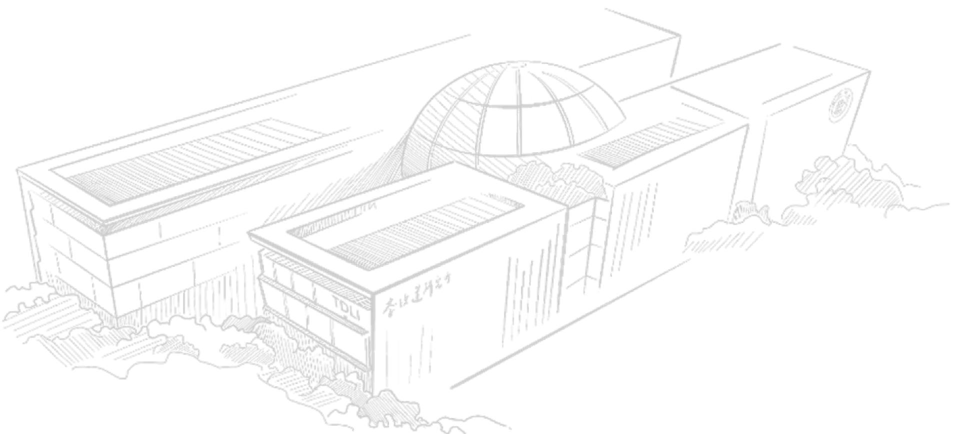


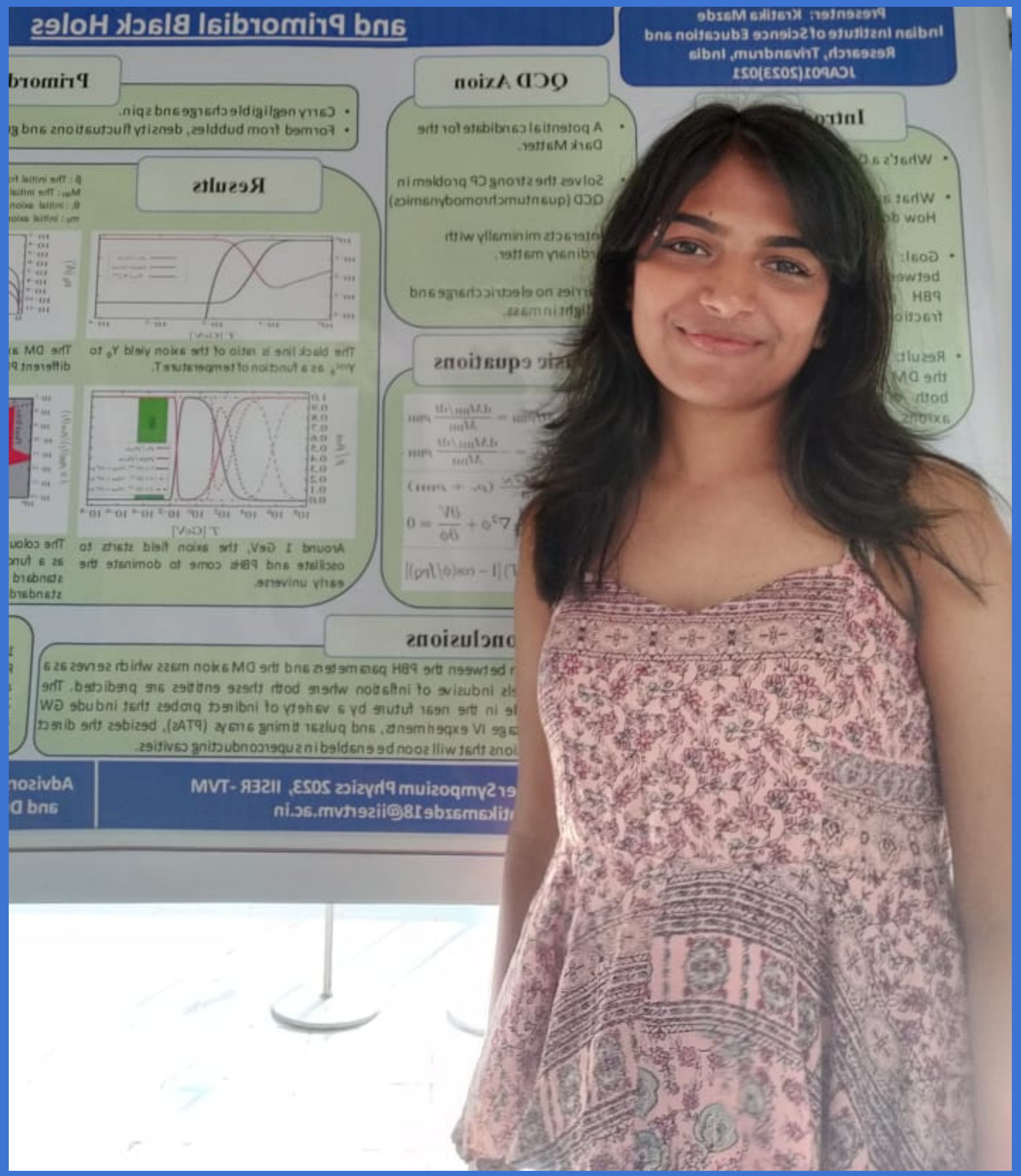
Primordial Black Holes and Particle Dark Matter are Intimately Intertwined

Luca Visinelli (TDLI & SJTU)

New Horizons in Primordial Black Hole Physics (NEHOP) 2023
June 19, 2023

Based on:
K. Mazde, **LV**, JCAP **2301**, 021 (2023) [arXiv: 2209.14307]

Work in collaboration with:



Kratika Mazde
Master student 2023

Now Ph.D. candidate at Sorbonne

K. Mazde, **Luca Visinelli**
JCAP **2301**, 021 (2023) [arXiv: 2209.14307]

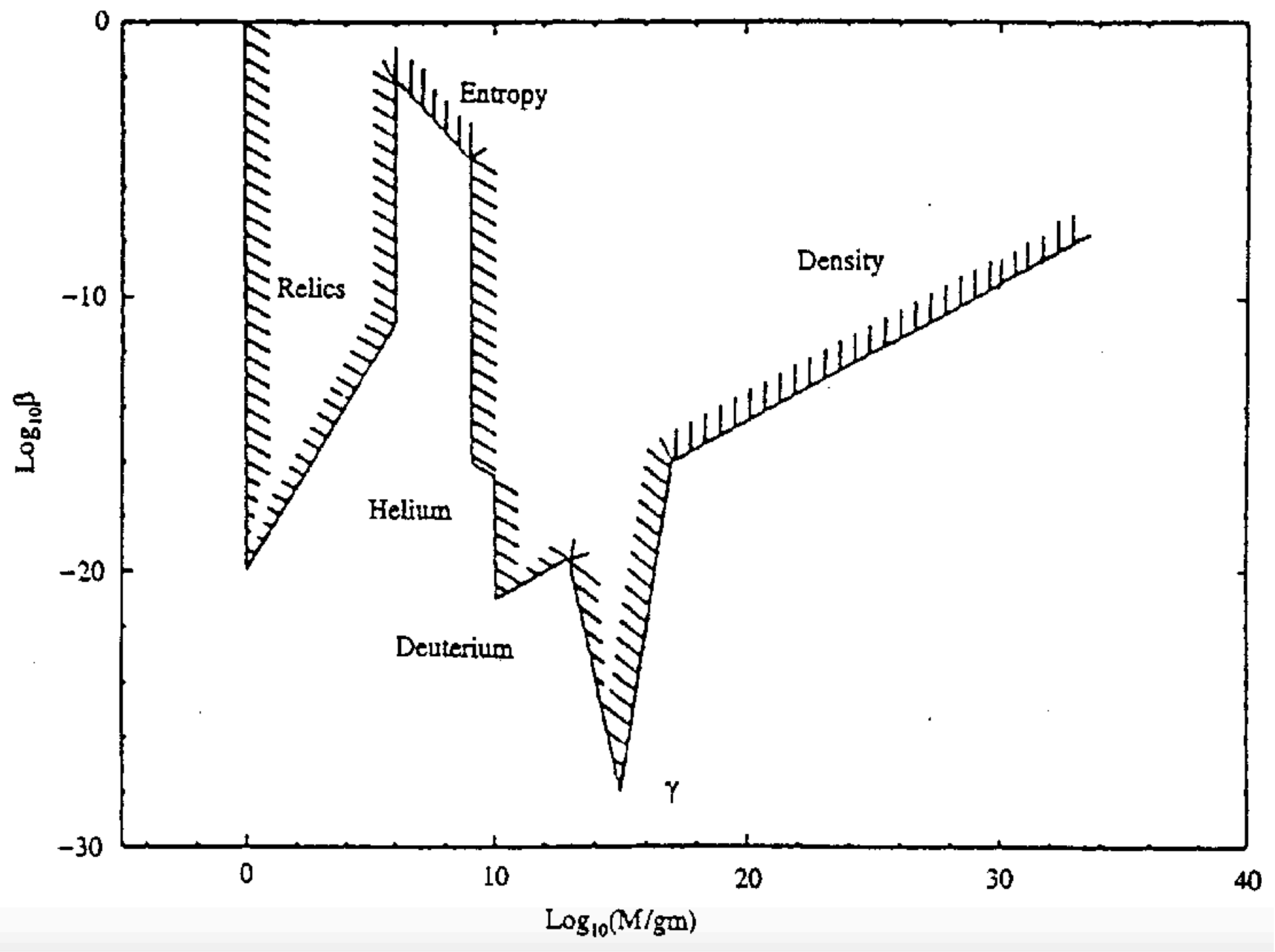
Outline of the project

- **Motivation:** Investigate the early universe from direct and indirect searches of axions and study the properties of the cosmological models.

- **Goal:** Relate the mass and abundance of PBHs with the properties of axions

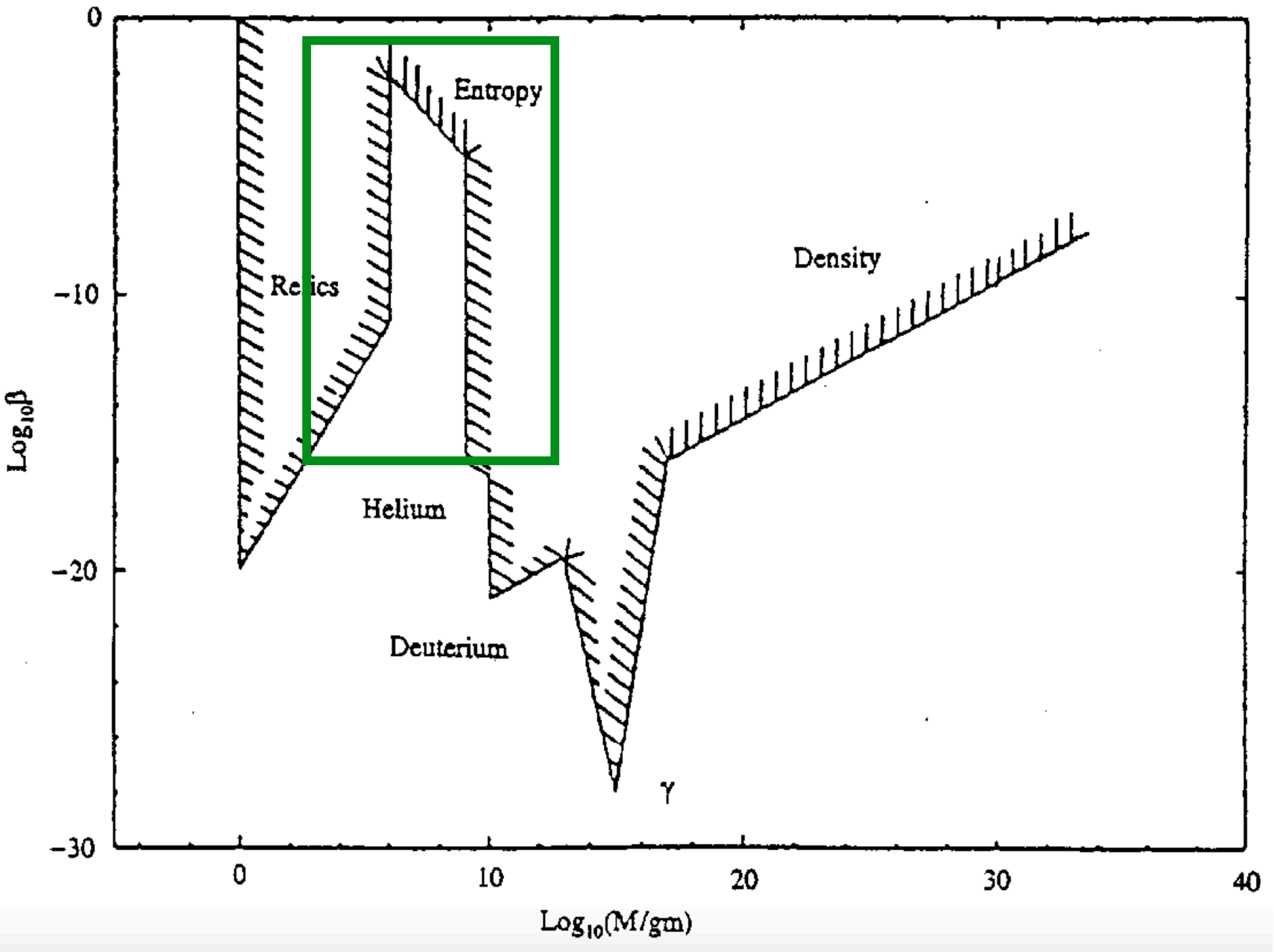
- **Interest:** A widened range of the DM axion mass motivates its search in new windows and with different techniques (e.g. **LV**, Gondolo 2010)

Outline of the project



Carr, Gilbert, Lidsey 1994

Outline of the project



Carr, Gilbert, Lidsey 1994

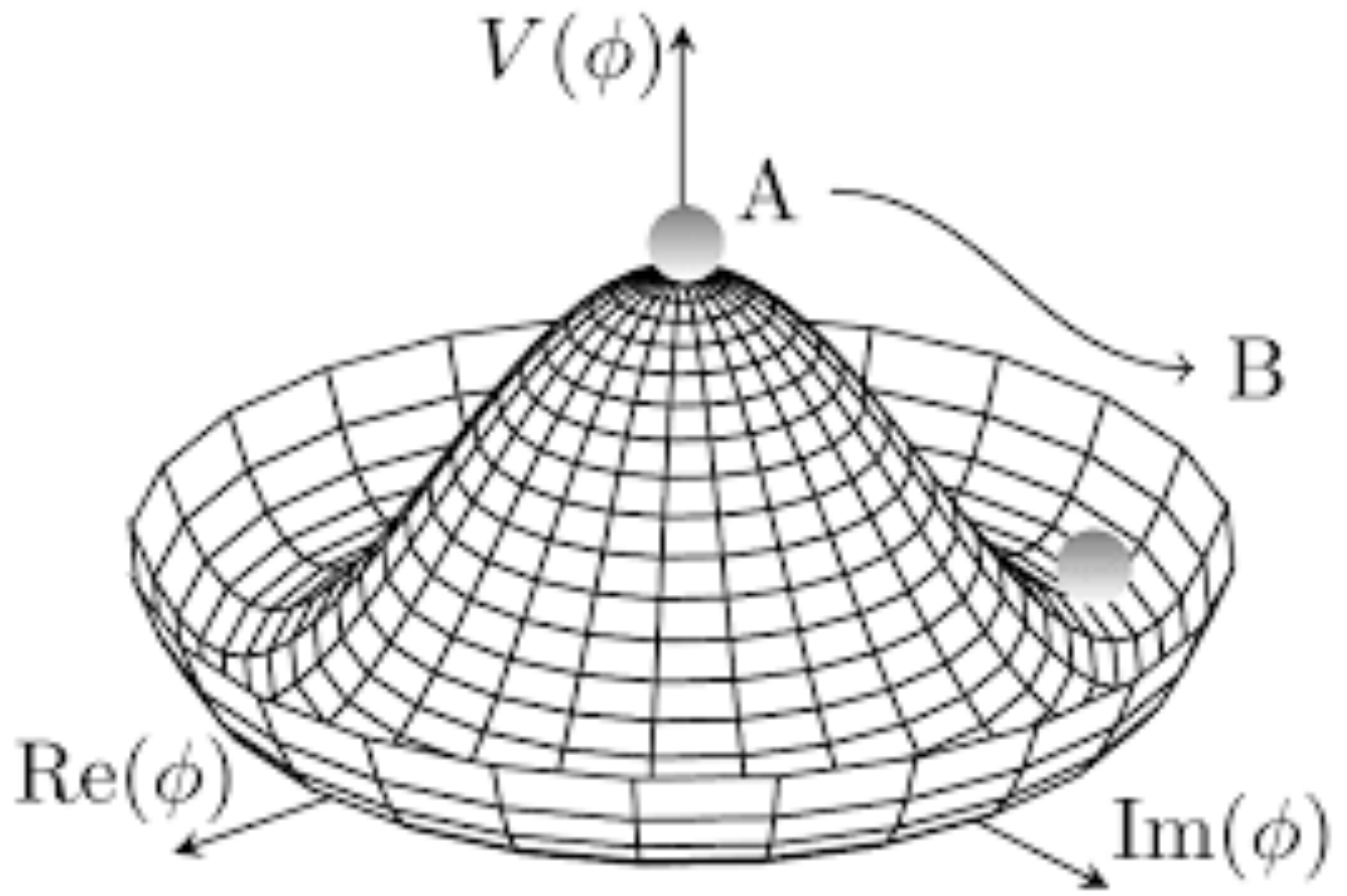
Can we account for the axion?

The axion is a pseudo-Nambu Goldstone boson (PNGB) resulting from the SSB of a global U(1) symmetry

The QCD axion arises in relation to the solution of the strong-CP problem by Peccei and Quinn

Axions are generally light and feebly coupled to the SM:

$$g_a \propto m_a \propto \frac{1}{f_a}$$



Essential literature:

[Peccei, Quinn: PRL 38 (1977) 1440–1443]

[Wilczek: PRL 40 (1978) 279–282]

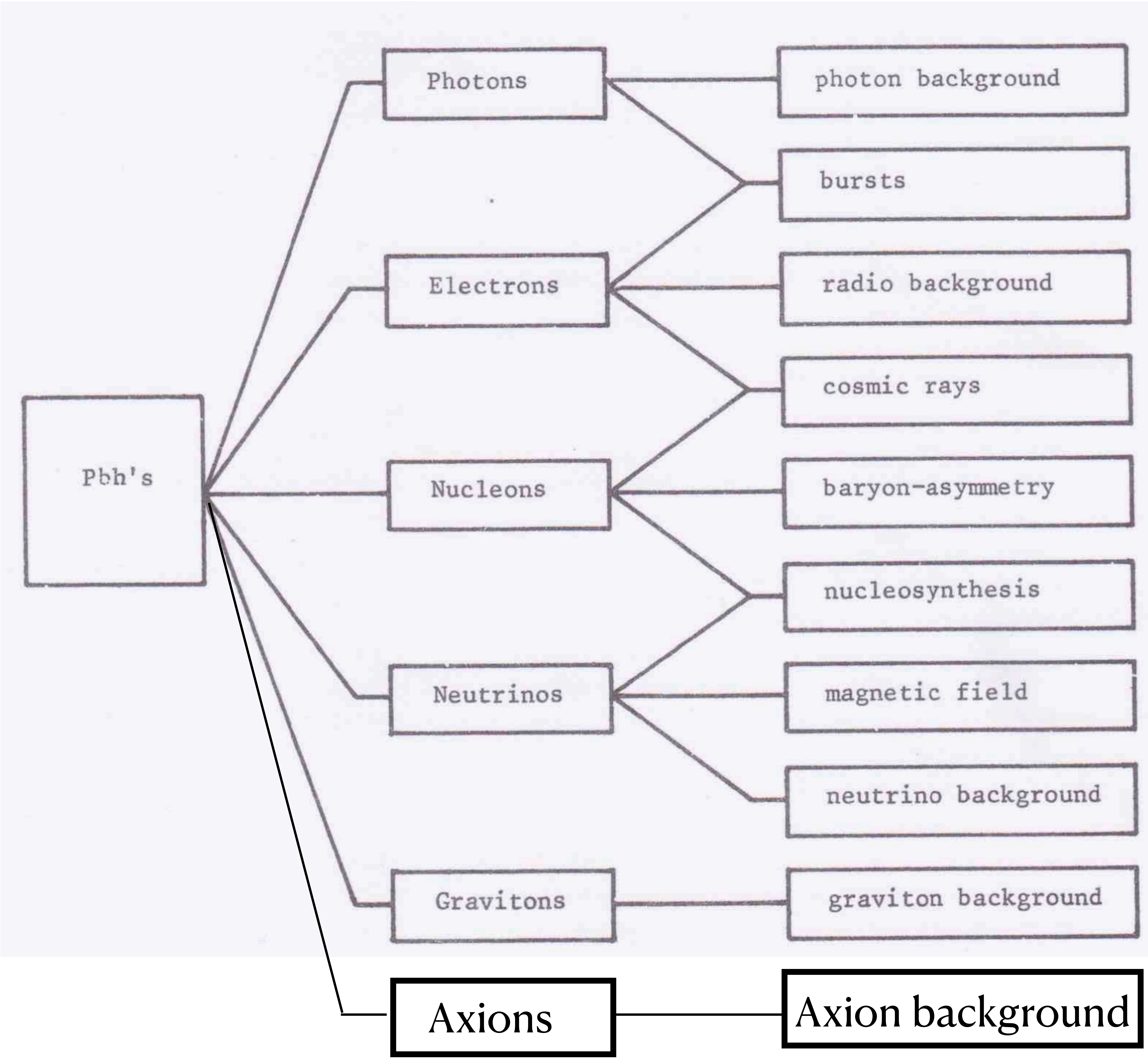
[Georgi et al.: Phys. Lett. B 169 (1986) 73–78]

[Weinberg: PRL 40 (1978) 223–226]

[Sikivie: PRL 51 (1983) 1413]

[Turner: PRL 59 (1986) 2489]

Production of cold axions



Slide from Bernard Carr

WARNING: QCD axions as dark matter come from vacuum realignment mechanism

See talks by Isabella Masina, Daniele Montanino, Nicolás Bernal for axions from evaporating PBHs

Production of cold axions

QCD axion DM produced from vacuum realignment mechanism

(Preskill+ 83; Abbott & Sikivie 83; Dine & Fischler 83; Turner 83)

The axion acquires a small mass from its interaction with gluons. Chiral perturbation theory gives

(Weinberg 78)

$$\boxed{m_a} = \frac{\chi_0^{1/2}}{f_a} \approx 6\,\mu\mathrm{eV}\left(\frac{10^{12}\,\mathrm{GeV}}{\boxed{f_a}}\right)$$

Axion mass **Energy scale**

Thermal effects (QCD instantons) lead to a temperature dependence above QCD phase transition:

(Gross+ 81)

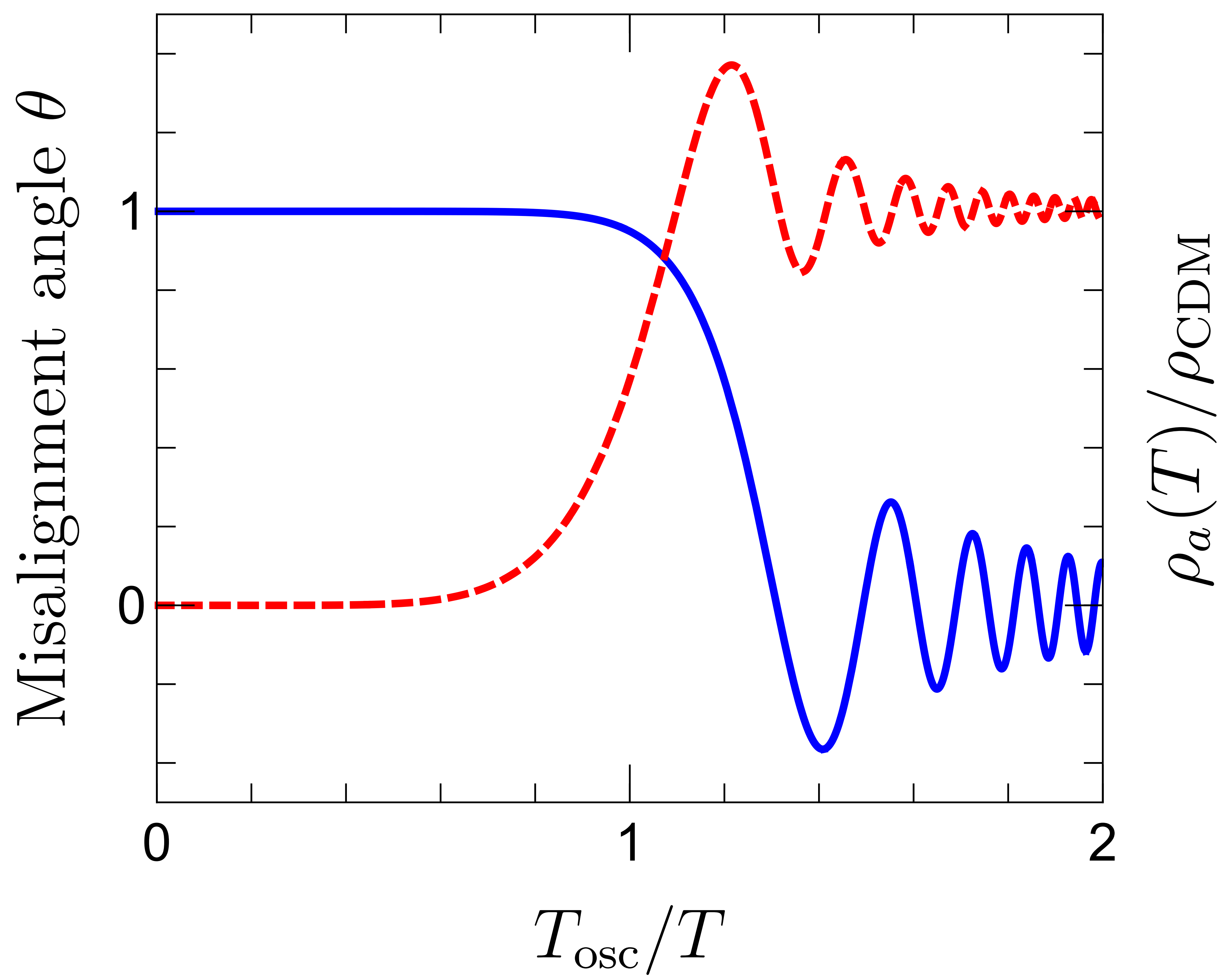
$$m_a \propto \left(\frac{\Lambda_{\rm QCD}}{T}\right)^{\gamma} \quad \text{with} \quad \gamma \approx 4 \quad \text{for} \quad T \gtrsim \Lambda_{\rm QCD}$$

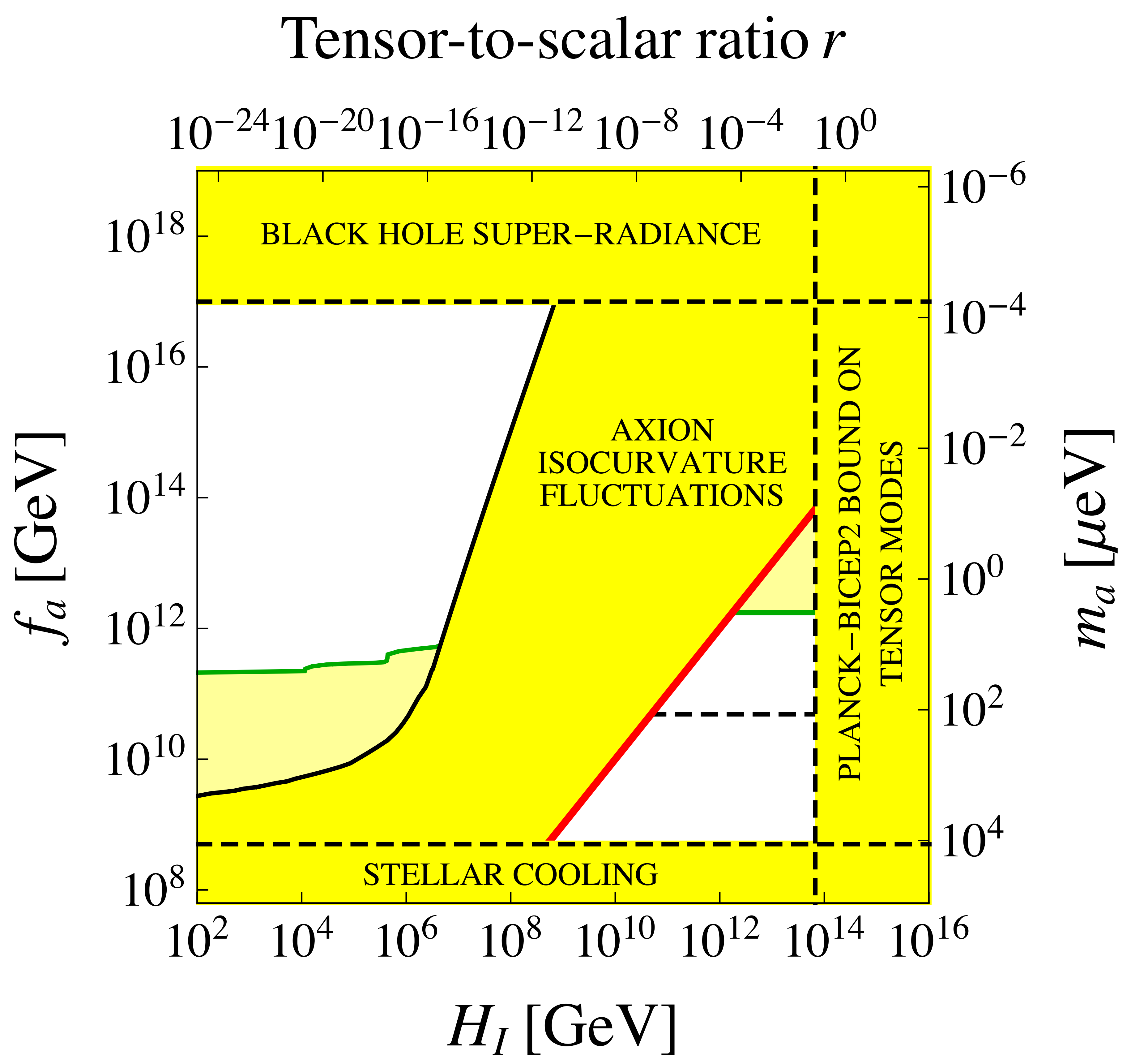
Production of cold QCD axions

$$m(T_{\rm osc}) \sim 3H(T_{\rm osc})$$

Idea: a modified Hubble rate affects the dynamics of the axion

Dine 83; Lazarides+ 87; **LV**, Gondolo 2010





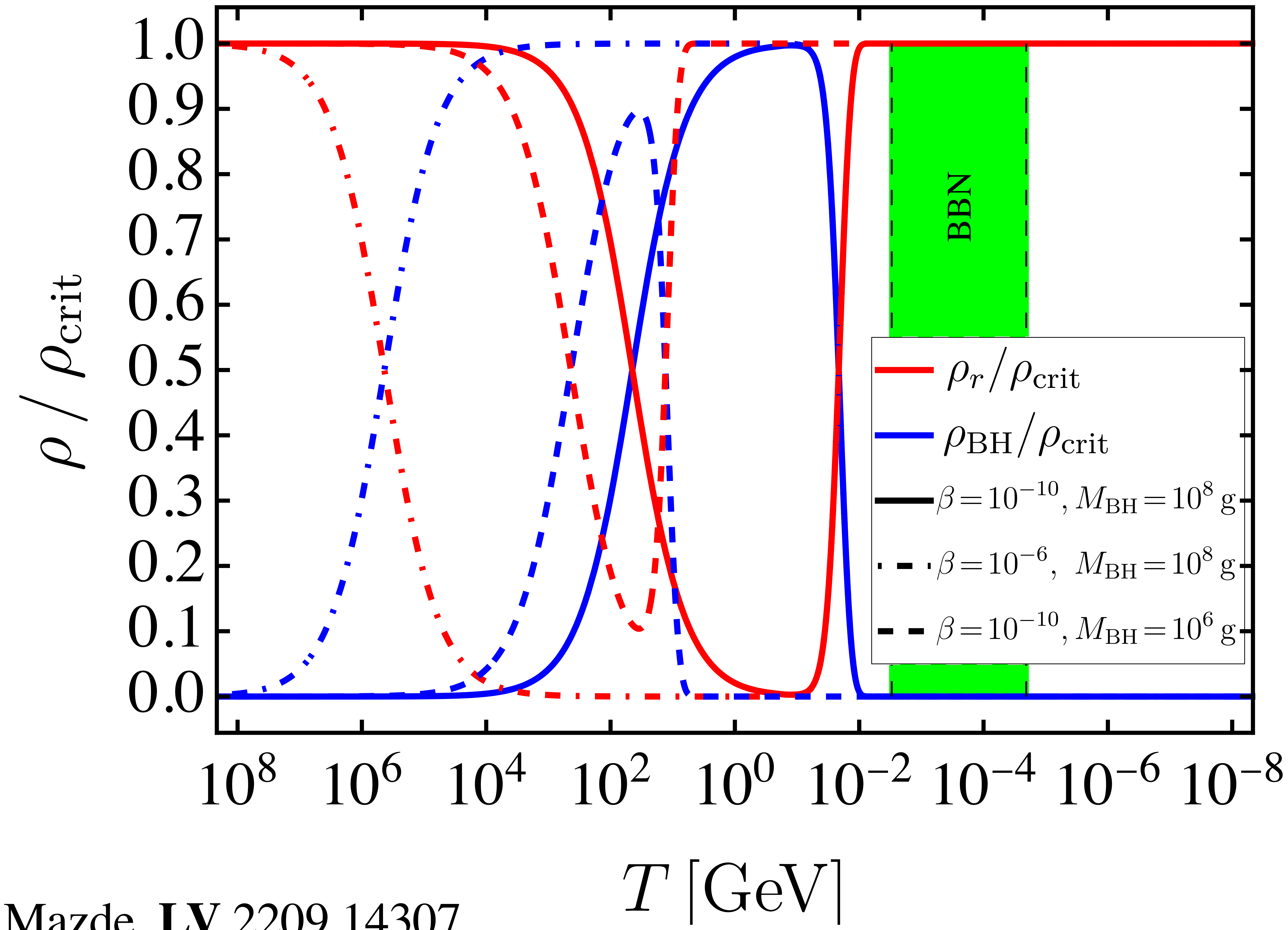
Figures from Di Luzio, Nardi, Giannotti, **LV** 2003.01100

PBHs might lead to a change in $H(T)$

Parameters:

$$\beta \equiv \frac{\rho_{\rm BH}(t_{\rm form})}{\rho_{\rm crit}(t_{\rm form})}$$

$$M_{\rm BH} \approx \frac{0.1}{G H_{\rm form}}$$



Mazde, **LV** 2209.14307

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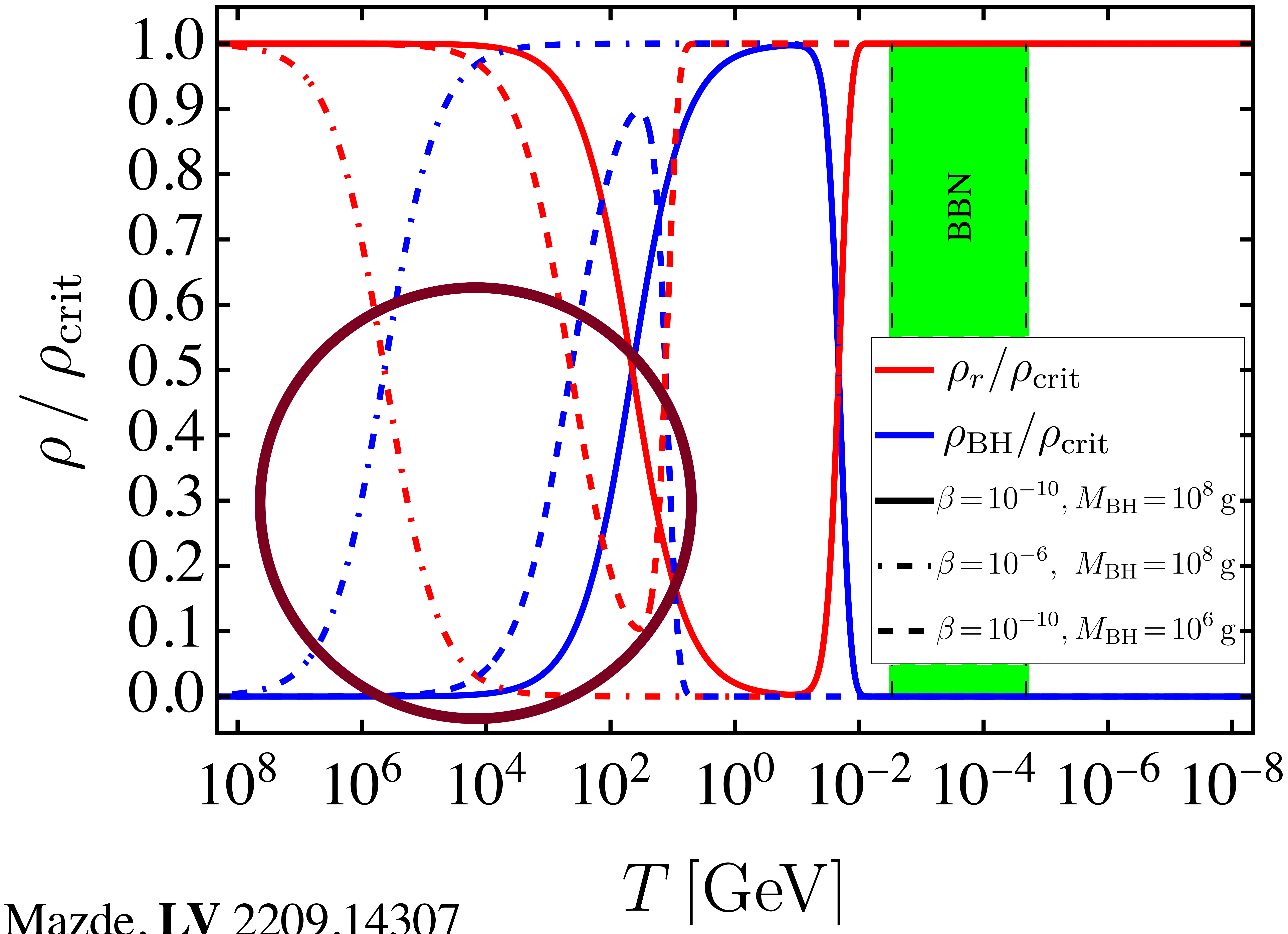
Early PBH domination

$$\frac{\rho_{\rm BH}}{\rho_r} \propto a \propto T^{-1}$$



Mazde, **LV** 2209.14307

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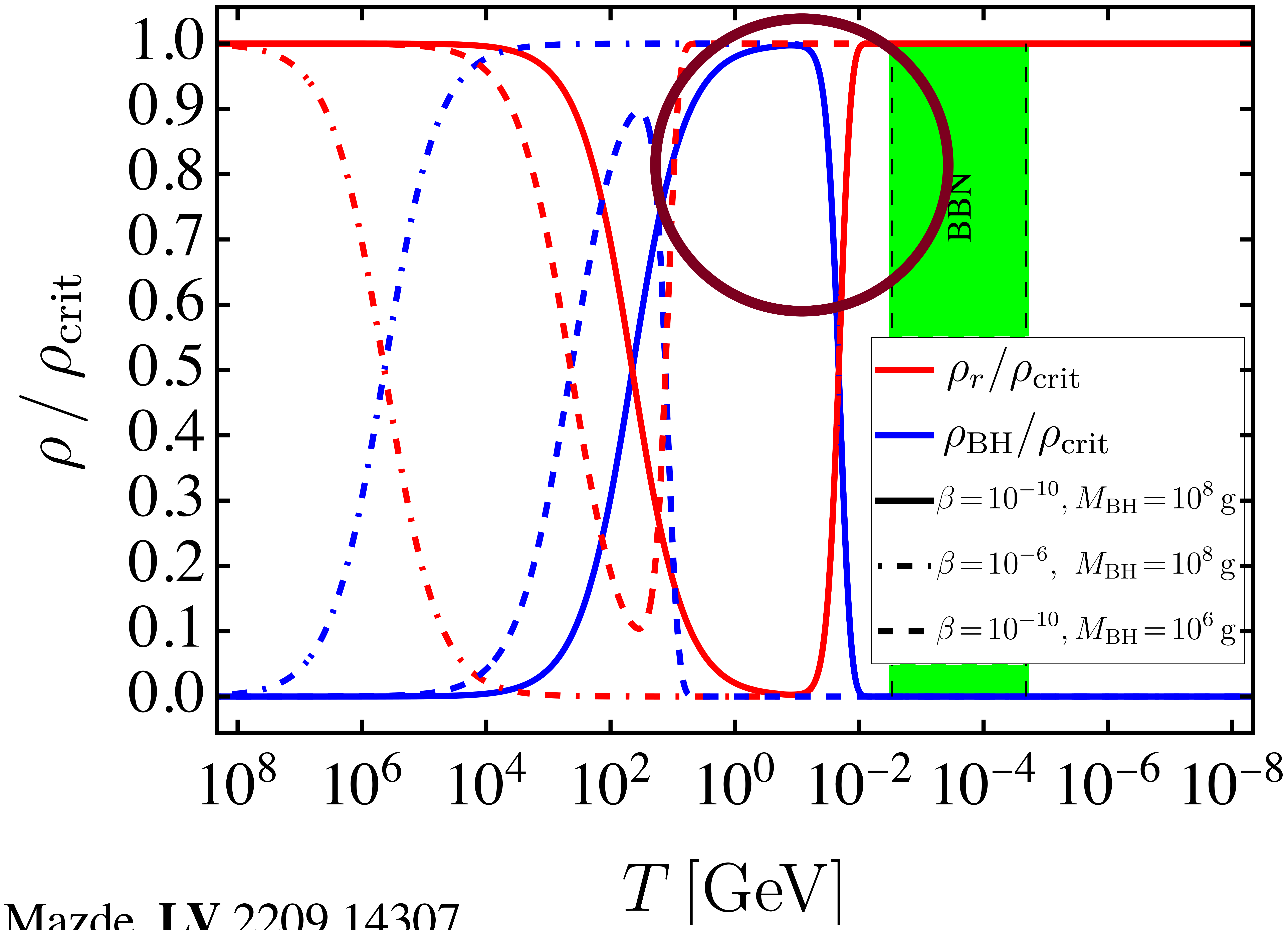
PBH evaporation of rate

$$\frac{{\rm d}\, \ln M_{\rm BH}}{{\rm d}\, t} \propto M_{\rm BH}^{-3}$$



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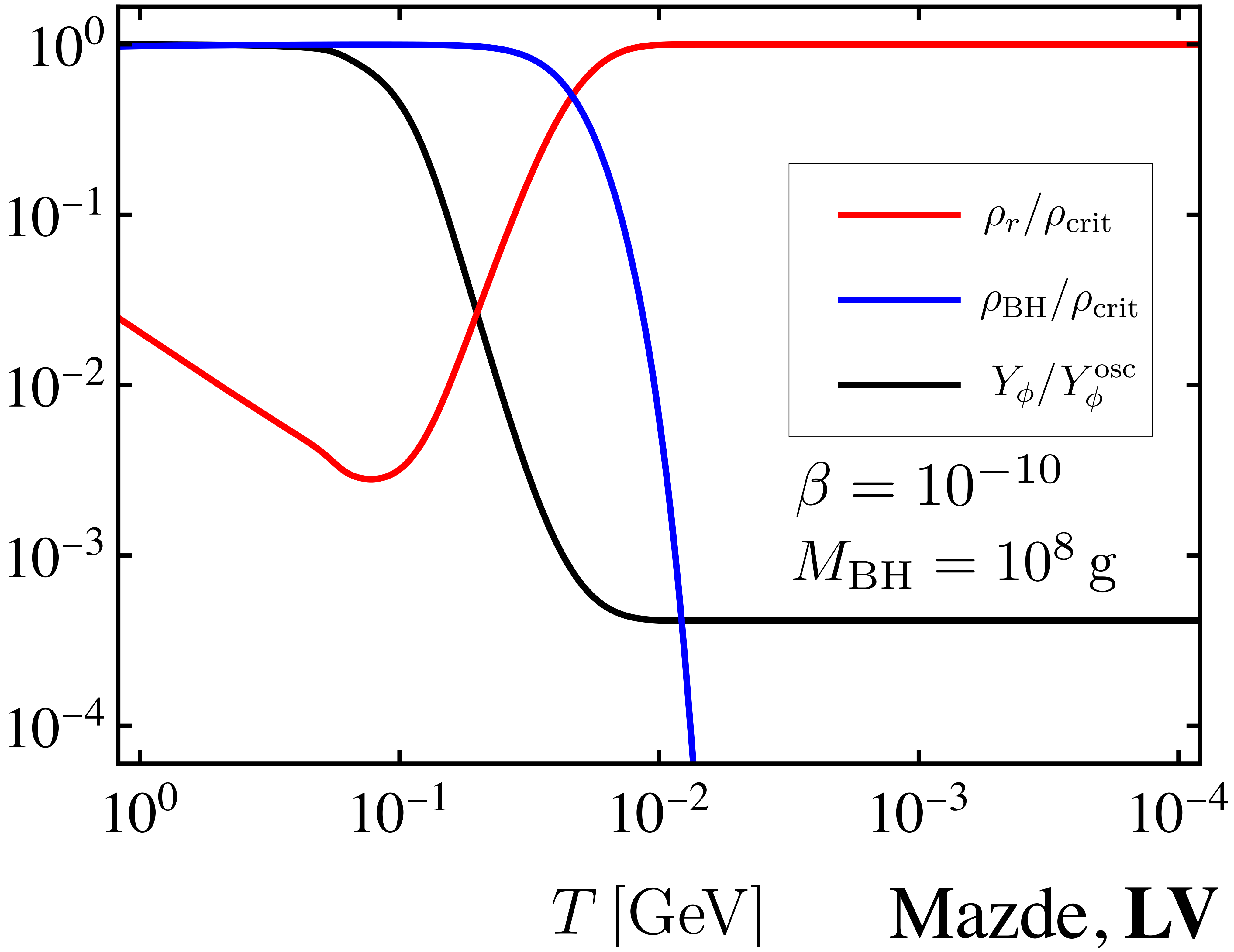
Axion dilution during PBH evaporation

We solve numerically the axion equation of motion with the background from radiation+PBH

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0$$

ϕ : axion field

V: axion potential



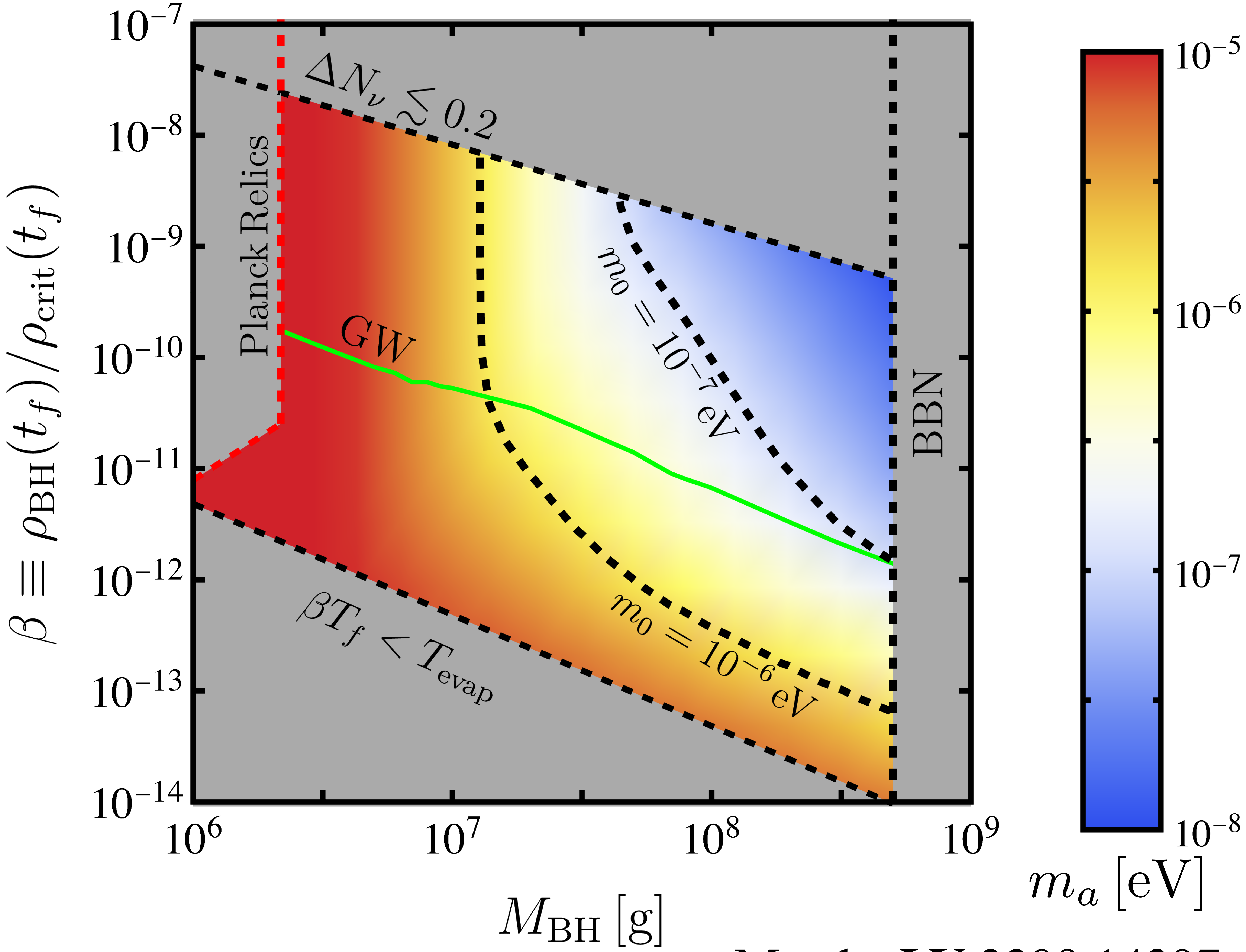
$$Y_\phi \equiv \frac{n_\phi}{s(T)}$$

Entropy dilution from PBH evaporation

https://github.com/lucavisinelli/AXIONPBH

Mazde, **LV** 2209.14307

Results



Lower bound: consistency

Upper bound: secondary GWs at CMB

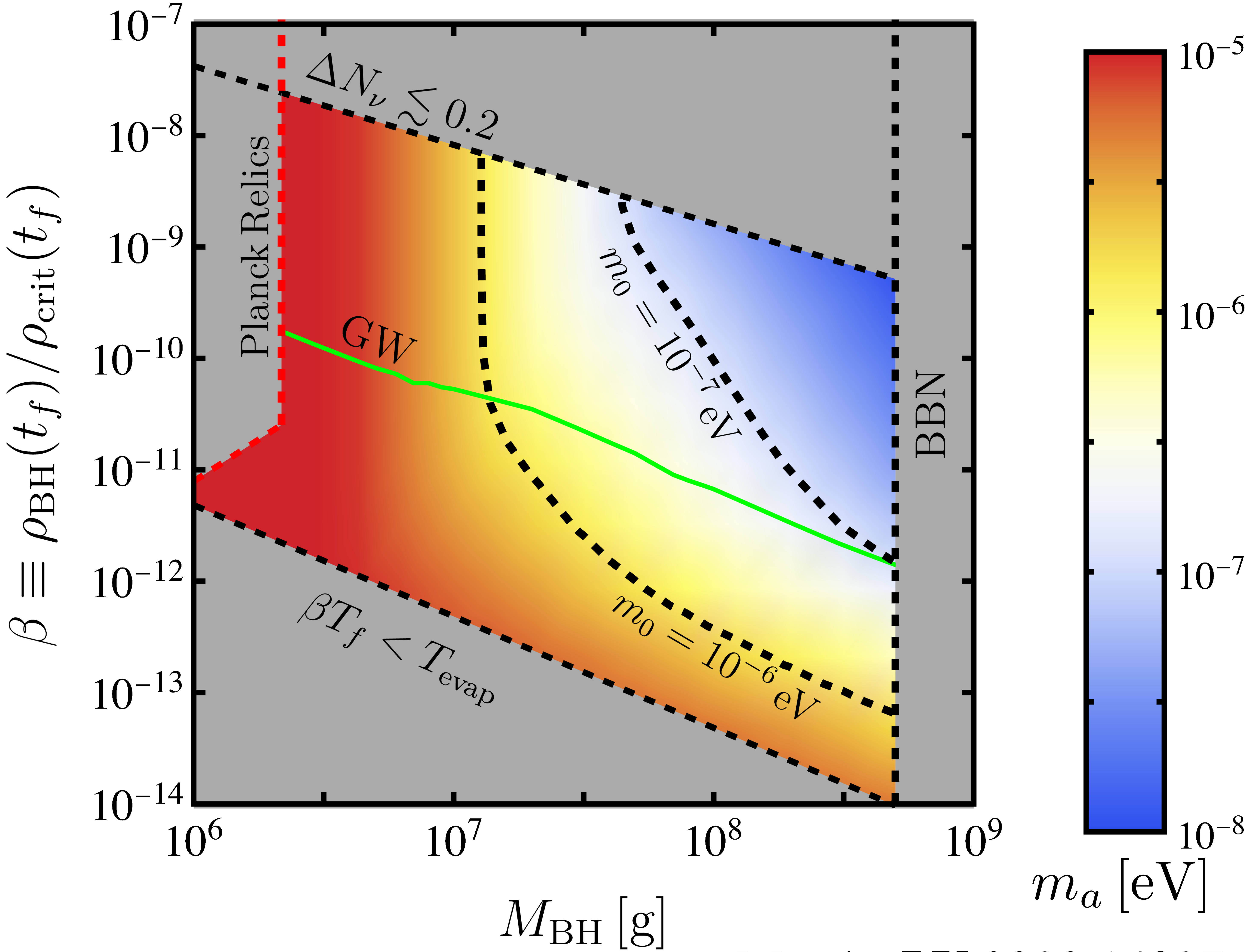
Left bound: PBH nuggets as DM

Right bound: PBH evaporation prior BBN

Green line: expected sensitivity from GW detectors

Mazde, **LV** 2209.14307

Results



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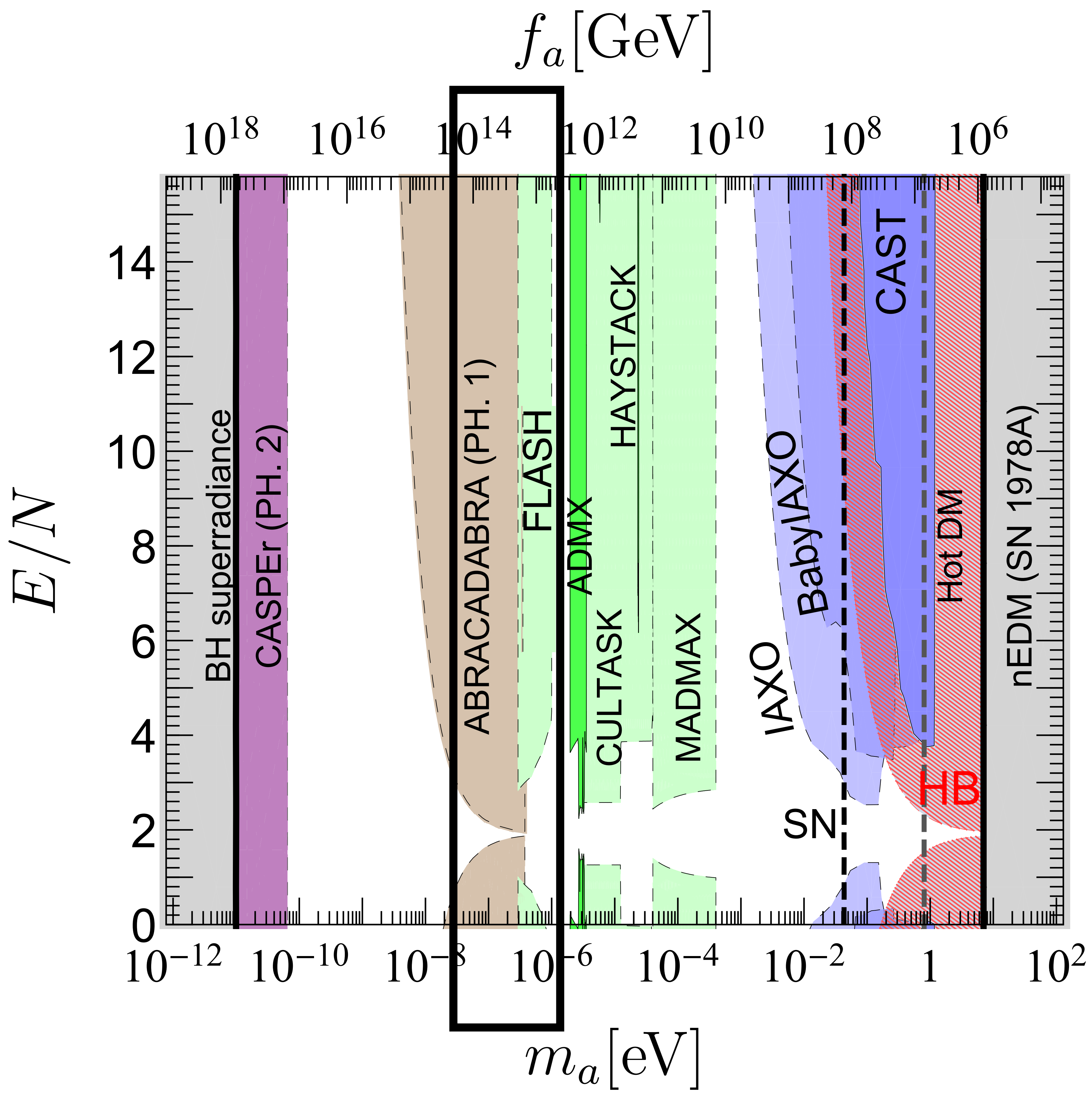
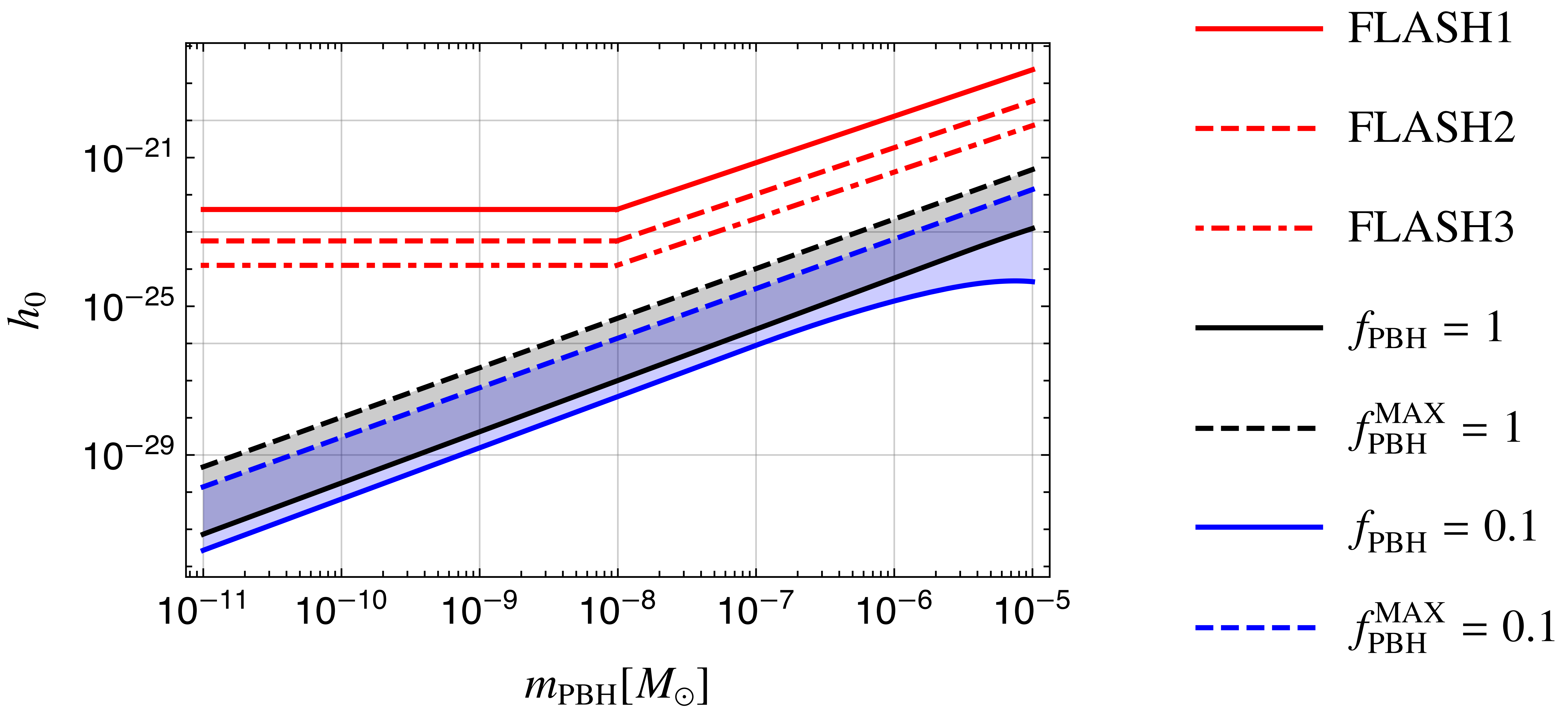


Di Luzio, Nardi, Giannotti, **LV** 2003.01100

Reach of FLASH spectroscopy

$$\mathcal{L} \supset \sqrt{-g}\left(-\frac{1}{4}g_{\mu\alpha}g_{\nu\beta}F^{\mu\nu}F^{\alpha\beta}\right)$$ Leads to a photon-graviton coupling



FLASH (C. Gatti + 2023); Work with Michael Zantedeschi

See also 1911.02427

Coding up warm inflation

Four modules for assessing:

- `Inflaton_Model`
  - Monomial potential
  - Hilltop-like potential
  - Natural Inflation potential
  - Beta-exponential potential
  - Runaway potential
- `Background`
- `Perturbations`
- `Scalar_Dissipation_function`

Gabriele Montefalcone

Vikas Aragam

Katherine Freese

Montefalcone, Aragam, Freese, **LV**
2209.14908; 2212.04482

+ GITHUB code available at:
https://github.com/GabrieleMonte/WarmSPy

Solving the set of perturbations during inflation, provides the spectra of perturbations

Conclusions

Amendment to Bernard Carr's talk:
PBHs might play an inportant role not only if their fractions is small
but even if they have already evaporated

The presence of PBHs in the Universe can be used to explore the consequences of new physics

If DM is in axions, their abundance could have been affected by "light" PBHs prior BBN.

The axion mass window might not be located where expected in the standard cosmology

The scenario will be probed heavily by improved GW sensitivity and refined $\Delta N_{\rm eff}$