CONSTRAINING PRIMORDIAL BLACK HOLES THROUGH BIG BANG NUCLEOSYNTHESIS

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OUTLINE

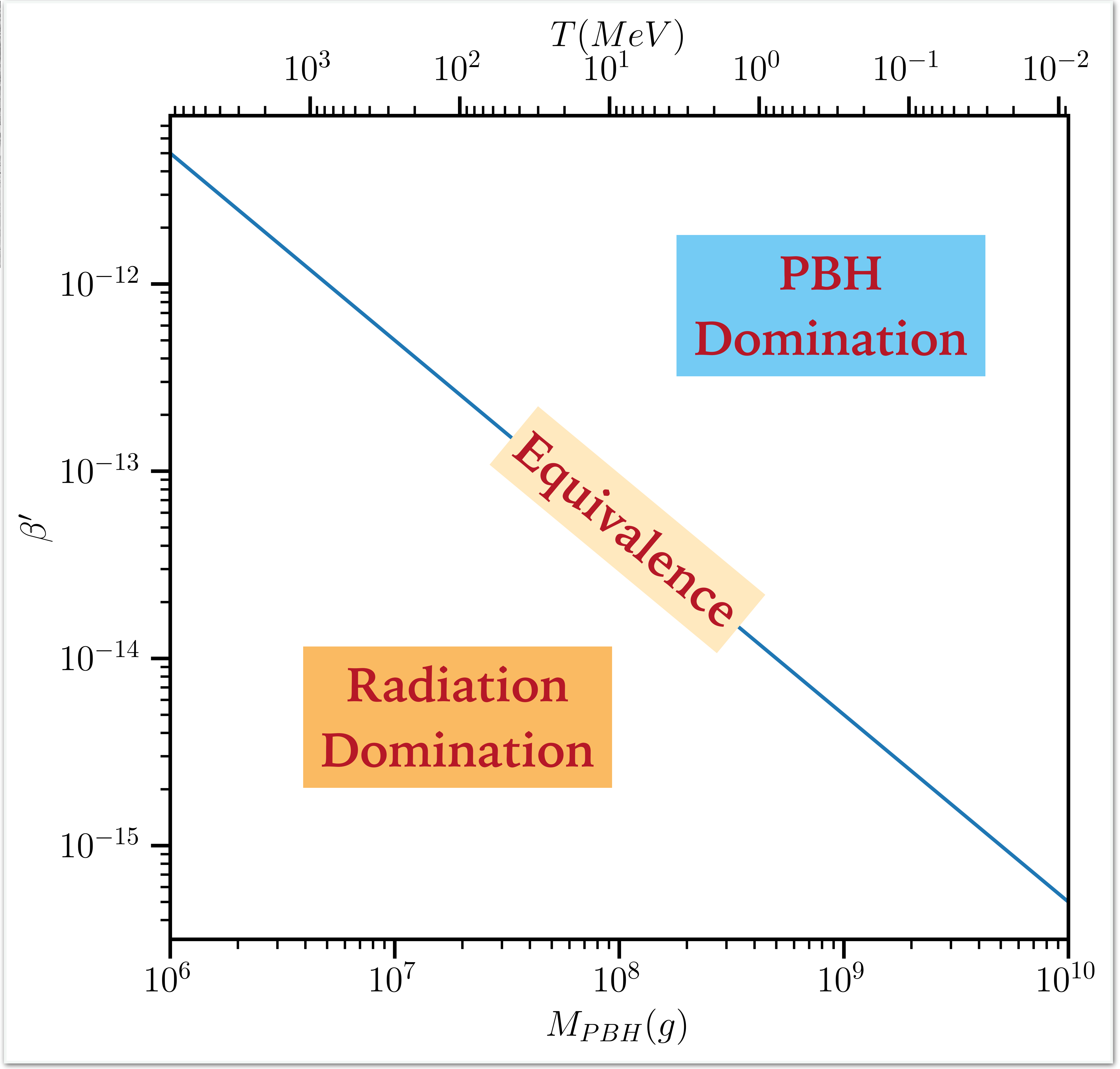
- Primordial Black Holes;
- Big Bang Nucleosynthesis;
- Effects of evaporation;
- Methods;
- Parthenope3.0;
- Results;
- Conclusions.

PRIMORDIAL BLACK HOLES

$$\beta = \frac{\rho_{PBH}(T_f)}{\rho_r(T_f)}$$

PBH density fraction at formation

$$\beta' \sim \beta \gamma^{1/2}$$



PBHs can induce an early matter-dominated epoch before evaporation if

$$\rho_{PBH}(T_{ev}) \geq \rho_r(T_{ev}) \Leftrightarrow \beta \gtrsim \frac{T_{ev}}{T_f} \sim 5 \times 10^{-10} \left(\frac{10^4 g}{M_{\text{PBH}}} \right)$$

We **never** consider beta values above this threshold.

BIG BANG NUCLEOSYNTHESIS

Starts when the reactions

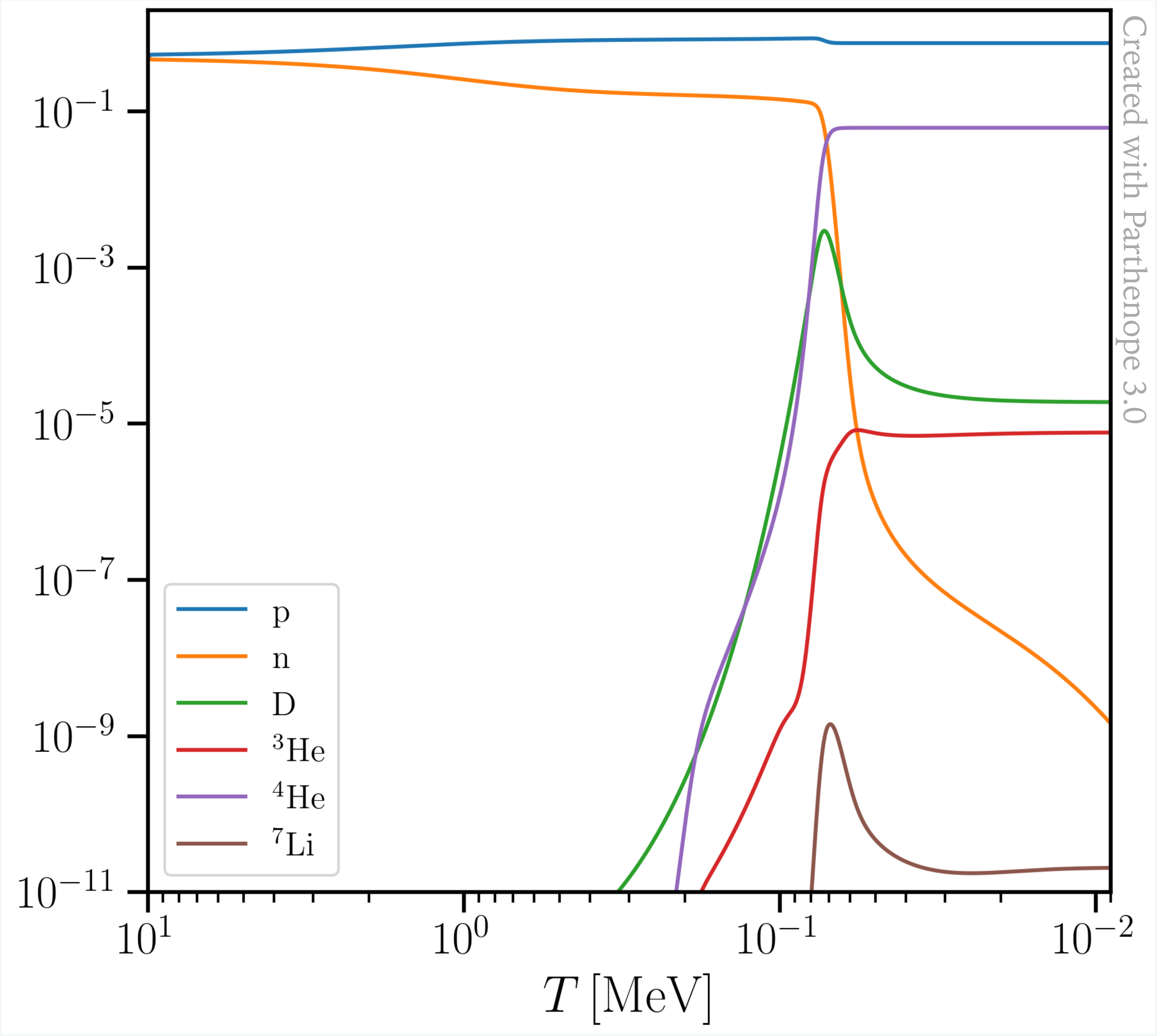
$$n + e^+ \longleftrightarrow p + \bar{\nu}_e \qquad n + \nu_e \longleftrightarrow p + e^-$$

freeze out at $T \sim 0.7\ MeV$.

A fraction of the relic neutrons decay, the remaining start the chain of reactions:

$$\mathrm{p} + \mathrm{n} \longrightarrow {}^2\mathrm{H} + \gamma$$
$$\mathrm{p} + {}^2\mathrm{H} \longrightarrow {}^3\mathrm{He} + \gamma$$
$${}^2\mathrm{H} + {}^2\mathrm{H} \longrightarrow {}^3\mathrm{He} + \mathrm{n}$$
$${}^2\mathrm{H} + {}^2\mathrm{H} \longrightarrow {}^3\mathrm{H} + \mathrm{p}$$
$${}^3\mathrm{He} + {}^2\mathrm{H} \longrightarrow {}^4\mathrm{He} + \mathrm{p}$$
$${}^3\mathrm{H} + {}^2\mathrm{H} \longrightarrow {}^4\mathrm{He} + \mathrm{n}$$

Almost all the neutrons go into Helium4!



EFFECTS OF EVAPORATION

Thermal

- **Cosmological evolution:** PBHs can play a role in the evolution of the background metric, modifying the time-temperature relation (Friedmann eq.).
- **Initial Conditions:** entropy injection by PBHs changes the evolution of the baryon-to-photon ratio.

Non-Thermal

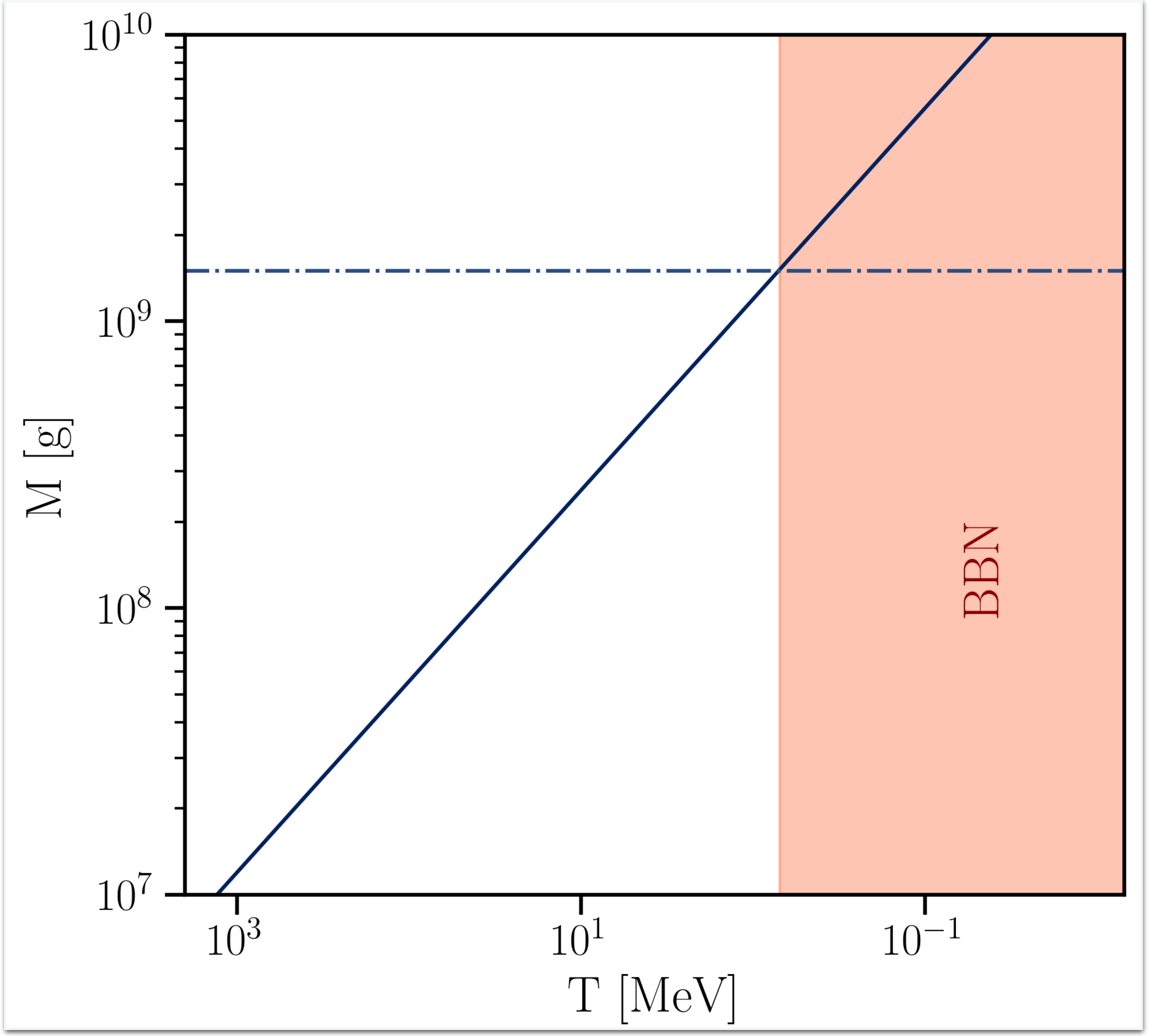
- **Reaction rates:** high energy neutrinos and baryons from evaporation can induce extra inter-conversions.
- **Dissociation:** high energy hadrons and photons can dissociate newly formed nuclei.

EFFECTS OF EVAPORATION

Evaporation: $\frac{dM}{dt} \propto -\frac{1}{M^2}$ $\tau \propto M^3$

BHs with $M_{PBH} \gtrsim 10^9 g$ evaporate during BBN.

We will consider **lighter** BHs whose products of evaporation thermalize **before** the onset of nuclear reactions.



EFFECTS OF EVAPORATION

Non-standard Hubble rate

$$H^2 = \frac{8\pi G}{3}\left(\rho_r + \rho_{PBH}\right)$$

↓

Neutron-proton equilibrium alteration

↓

Effect on Helium-4 abundance

Entropy injection

$$\frac{ds}{dt} + 3H\,s = -\frac{3}{4}\frac{dM_{PBH}/dt}{M_{PBH}}\frac{\rho_{PBH}}{\rho_r}s$$

↓

Non-standard baryon-to-photon ratio evolution

↓

Effect on Deuterium abundance

METHODS

$$H^2 = \frac{8\pi G}{3}\left(\rho_r + \rho_{PBH}\right)$$

Friedmann Equation

$$\frac{d\rho_{PBH}}{dt} + 3H\rho_{PBH} = \frac{dM_{PBH}/dt}{M_{PBH}}\rho_{PBH}$$

Boltzmann Equation (matter)

$$\frac{d\rho_r}{dt} + 4H\rho_r = -\frac{dM_{PBH}/dt}{M_{PBH}}\rho_{PBH}$$

Boltzmann Equation (radiation)

$$\frac{d\rho_{PBH}}{dT} - \frac{3H}{T}\frac{H}{H_{\text{eff}}}\rho_{PBH} = -\frac{dM_{PBH}/dt}{M_{PBH}}\frac{\rho_{PBH}}{TH_{\text{eff}}}$$

PBH energy density evolution

$$\frac{d\eta}{dt} = \frac{3}{4}\frac{dM_{PBH}/dt}{M_{PBH}}\frac{\rho_{PBH}}{\rho_r}\eta$$

Baryon-to-photon ratio

$$H_{\text{eff}} = H + \frac{dM_{PBH}/dt}{M_{PBH}}\frac{\rho_{PBH}}{4\rho_r}$$

PARTHENOPE 3.0

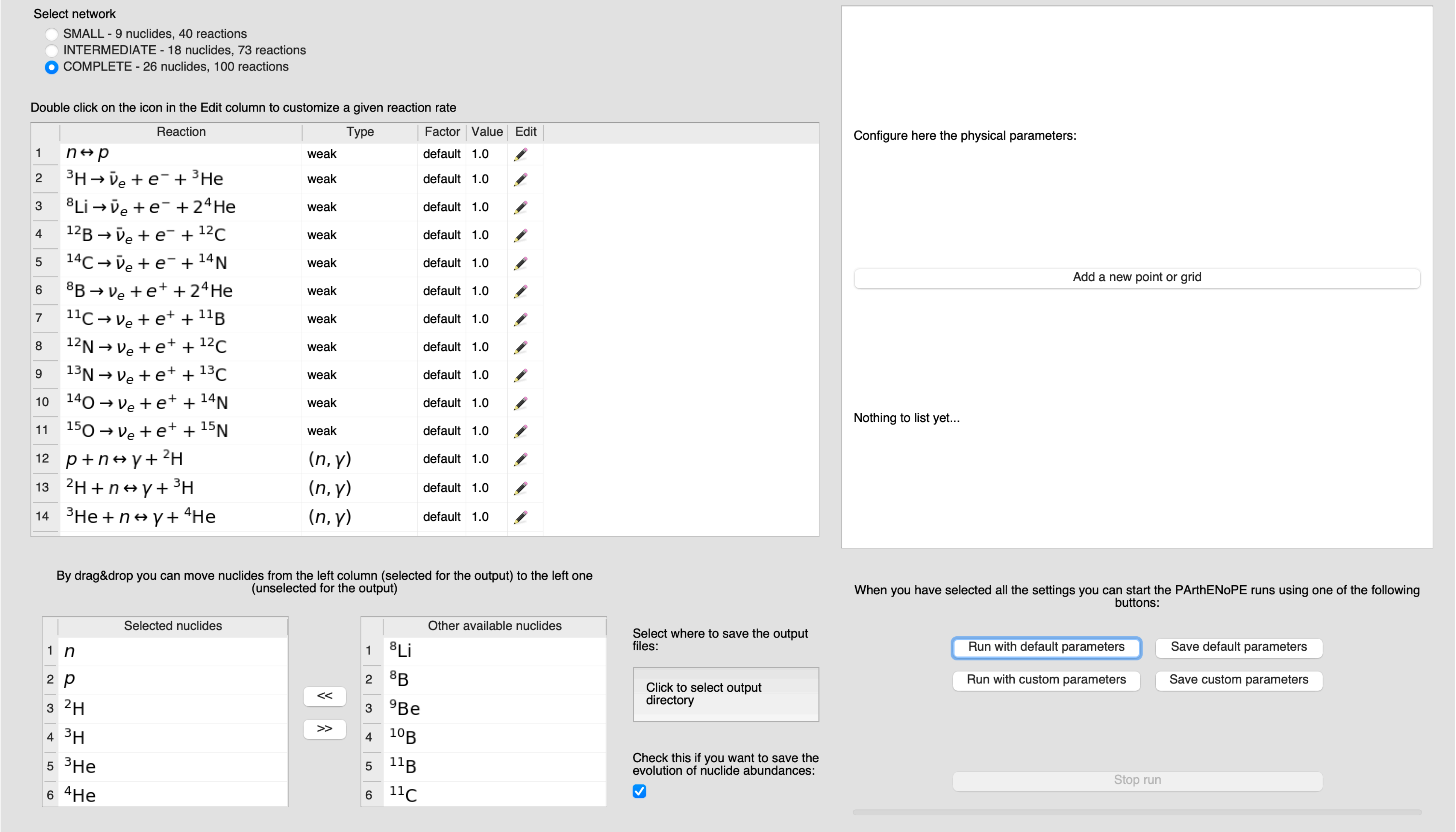
PArthENoPE

Public Algorithm Evaluating the Nucleosynthesis of Primordial Elements

PArthENoPE computes the abundances of light nuclides produced during Big Bang Nucleosynthesis.
Starting from nuclear statistic equilibrium conditions,
the program solves the set of coupled ordinary differential equations,
follows the departure from chemical equilibrium of nuclear species,
and determines their asymptotic abundances as a function of several input
cosmological parameters as the baryon density, the number of effective neutrinos,
the value of cosmological constant and the neutrino chemical potential.

For further information and help visit the web page

http://parthenope.na.infn.it



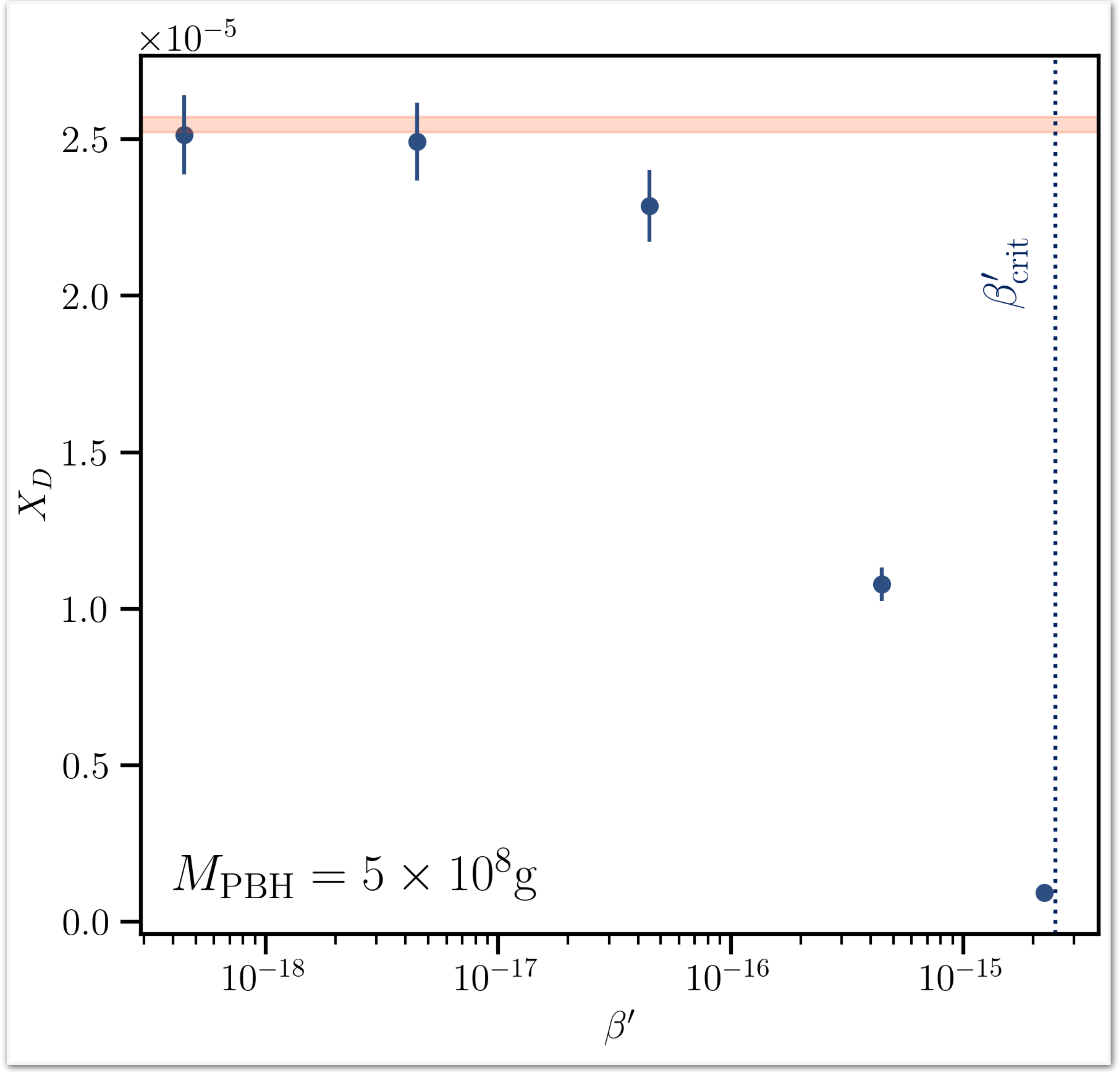
Pisanti, Ofelia, et al. "PArthENoPE: Public algorithm evaluating the nucleosynthesis of primordial elements." *Computer Physics Communications* 178.12 (2008): 956-971.

RESULTS

Here I show the results for the primordial nuclides abundances computed with Parthenope3.0, modified to include the PBHs effect on the Hubble rate and baryon-to-photon ratio.

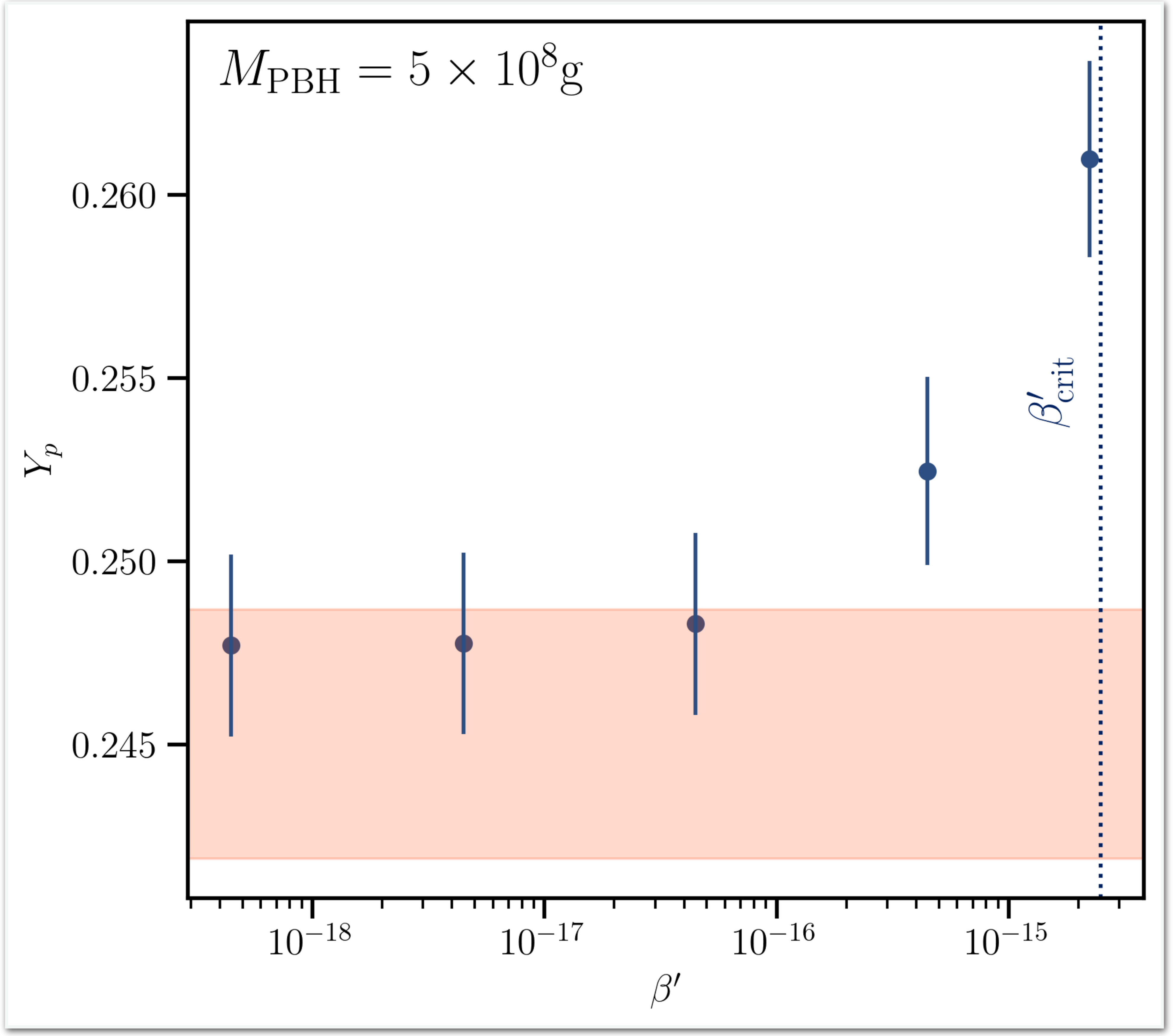
Deuterium

Mostly sensible to η

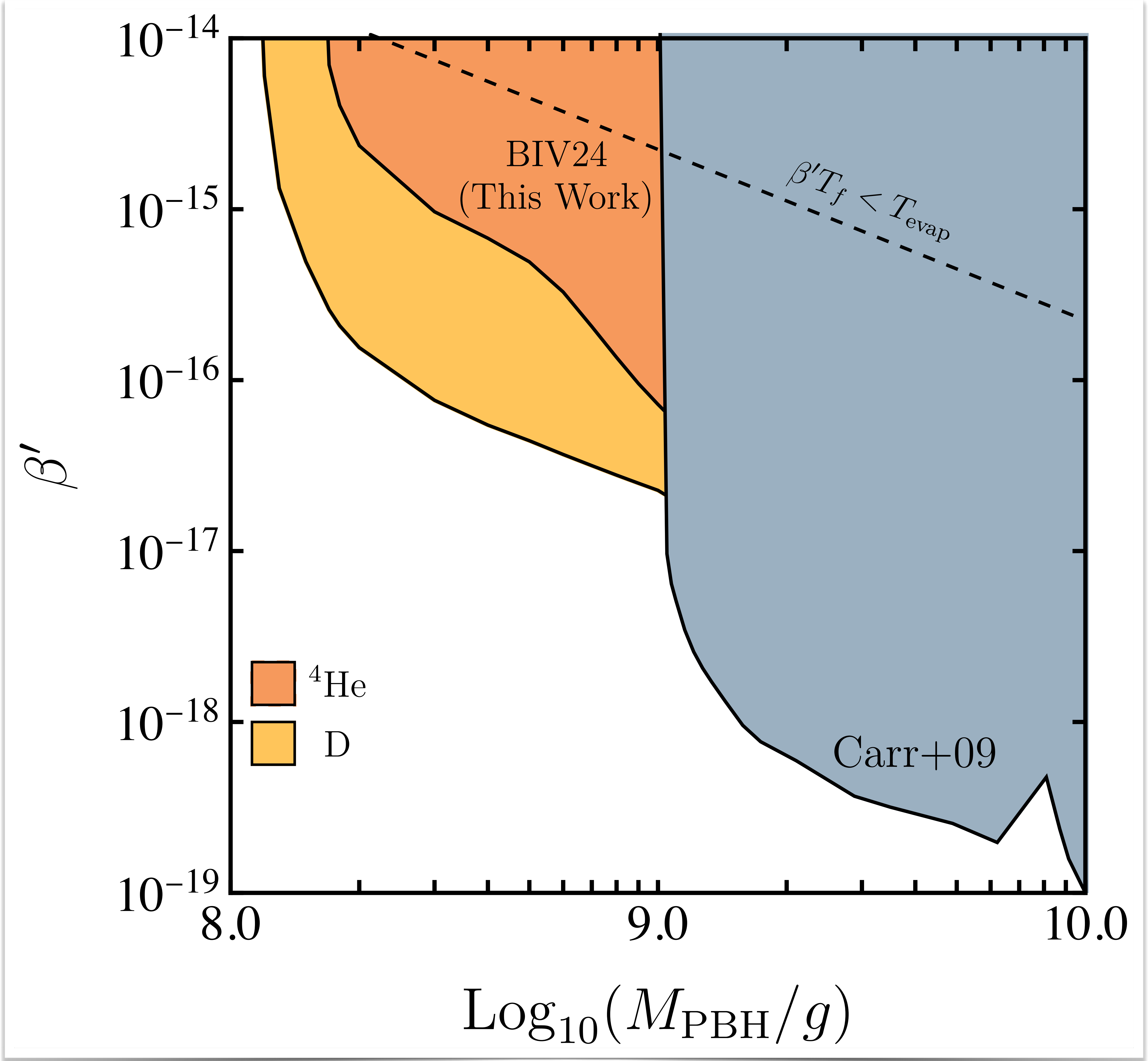


Helium4

Mostly sensible to H



RESULTS



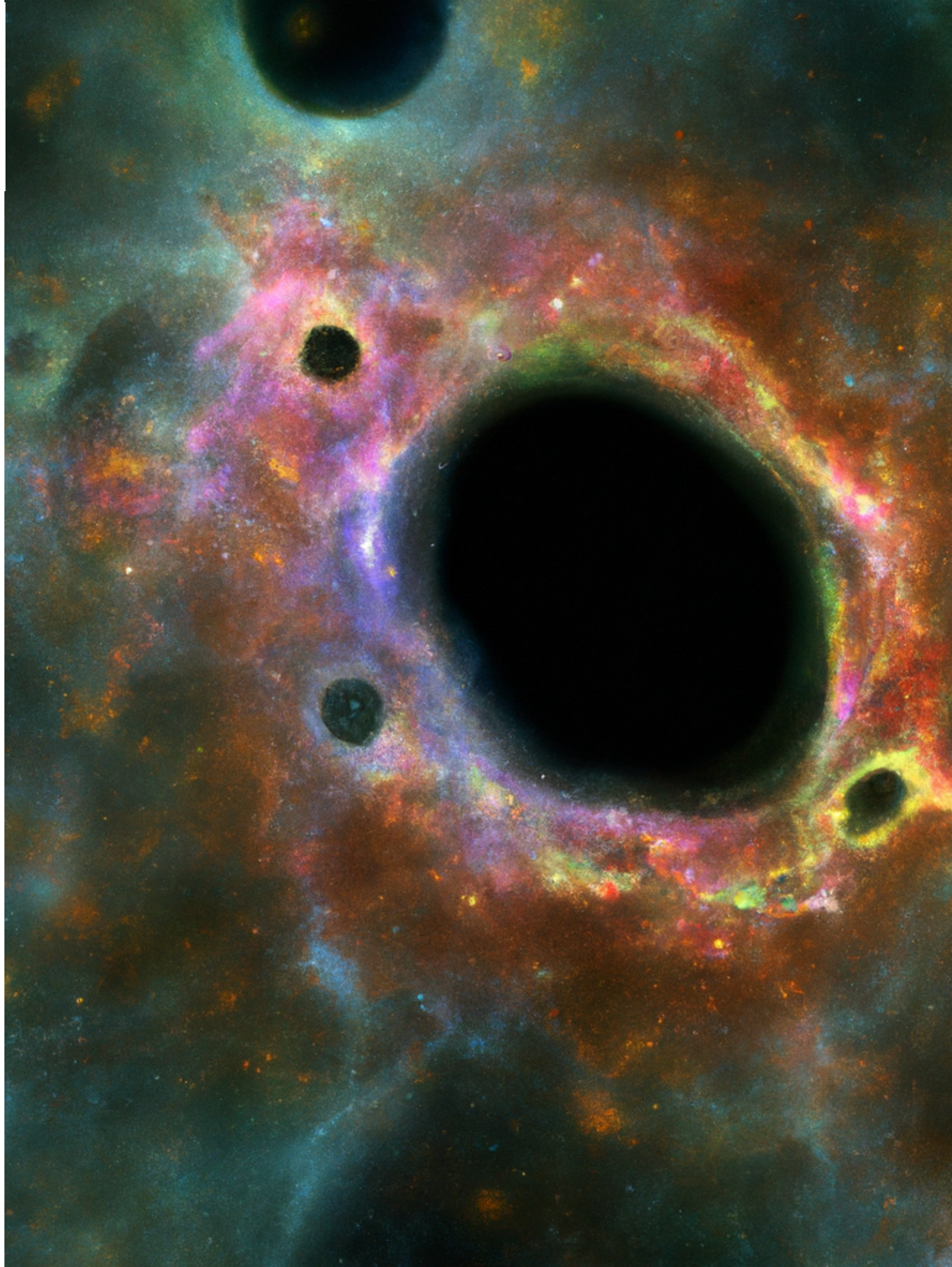
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
β'
BIV24
(This Work)
$\beta' T_f < T_{\rm evap}$
Carr+09
^{4}He
D
8.0
9.0
10.0
$\mathrm{Log}_{10}(M_{\rm PBH}/g)$

CONCLUSIONS

- We solved the equations for background cosmology and entropy in presence of PBHs;
- We included the modified Hubble rate and baryon-to-photon ratio into the Parthenope3.0 code;
- We checked the effect of different amounts of PBHs on the primordial abundance of light nuclei;
- We were able to improve the existing bounds in the considered mass range.

THANKS FOR YOUR ATTENTION!

Grazie per l'attenzione!



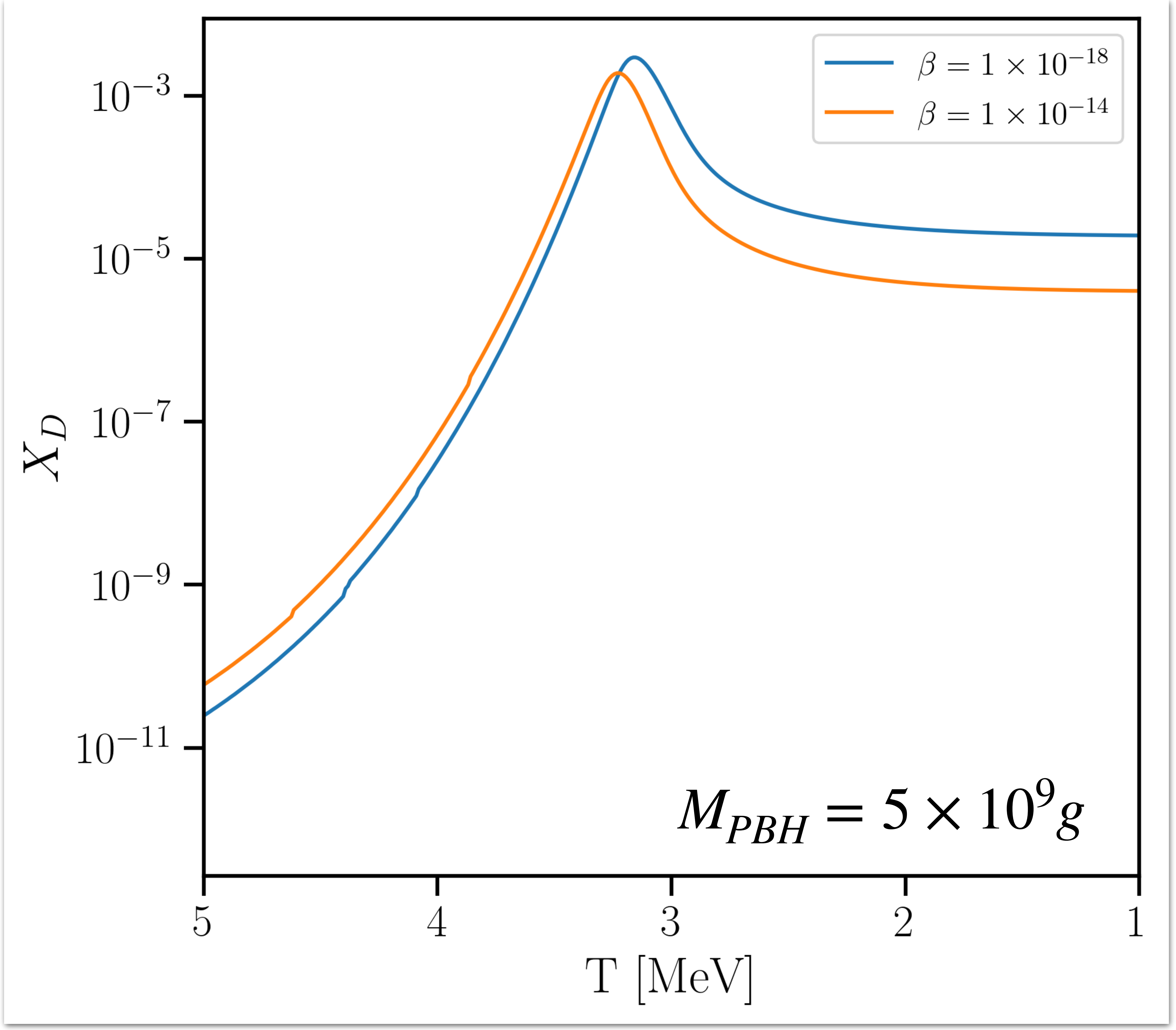
DEUTERIUM PRODUCTION

$$\Delta_D \simeq 2.2\,\mathrm{MeV}$$

Deuterium
binding energy

$$\eta^{-1} e^{-\Delta_D/T}$$

Number of photons with $E \gtrsim \Delta_D$
over baryons



ENTROPY INJECTION

$$\frac{ds}{dt} + 3H_{\text{eff}}\, s = 0$$

Entropy C.E.

$$\frac{dn_b}{dt} + 3H\, n_b = 0$$

Baryon number density conservation

$$\eta_b = \frac{n_b}{n_\gamma} \propto g_s(T)\frac{n_b}{s}$$

Baryon-to-photon ratio

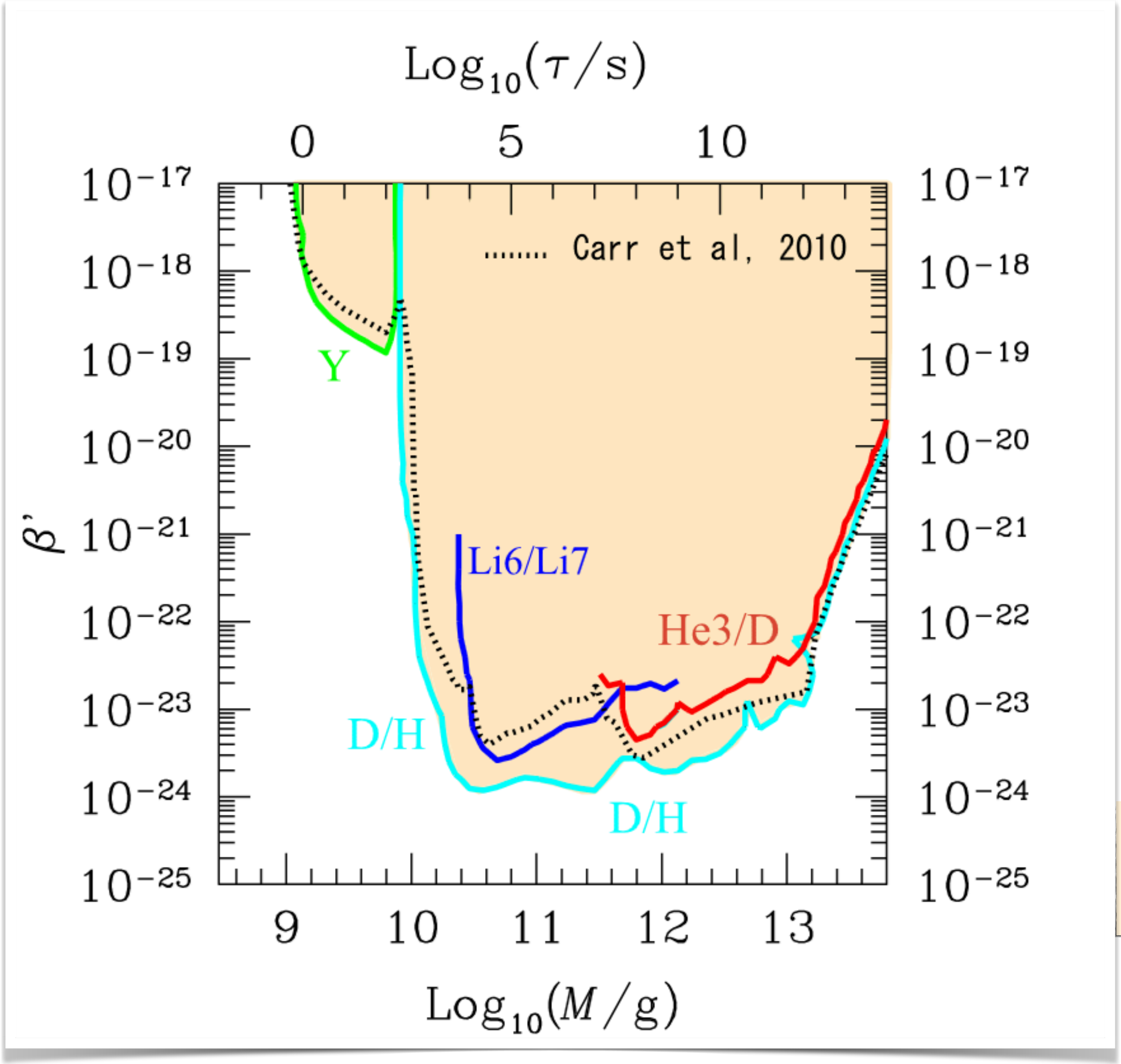
Entropy from PBH evaporation can lower the baryon-to-photon ratio:

$$\frac{d\eta}{dt} = \frac{3}{4}\frac{dM_{PBH}/dt}{M_{PBH}}\frac{\rho_{PBH}}{\rho_r}\eta$$

Its value is fixed at recombination so we account for its modification by considering an higher initial value with respect to the standard case.

EFFECTS OF EVAPORATION

$\beta' \sim \beta \gamma^{1/2}$



Non-thermal effects have been widely discussed previously.

We focus on the thermal ones which can be dominant for lower masses.

Upper bounds obtained considering non-thermal effects.

- B. Carr, K. Kohri, Y. Sendouda and J. Yokoyama, 'Constraints on primordial black holes', *Reports on Progress in Physics*, vol. 84, no. 11, p. 116 902, 2021.

EFFECTS OF EVAPORATION

Numerical solutions for the Hubble rate shown for different beta values.

$$H = \sqrt{\frac{8\pi G\bar{\rho}}{3}\left(e^x + e^y\right)}$$

The effect of PBHs is much larger at the beginning of BBN.