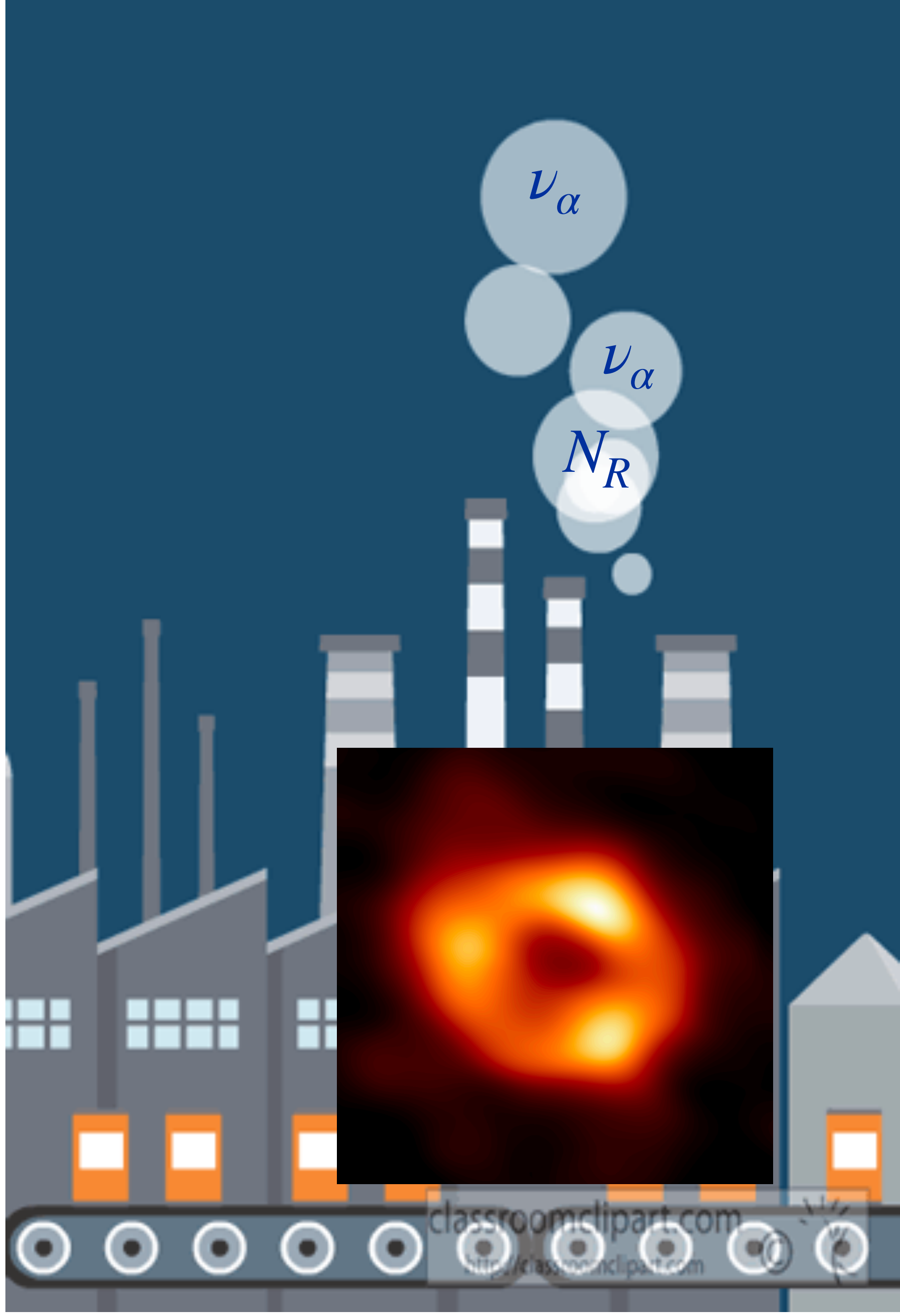
Primordial Black Holes and Leptogenesis: An Unexpected Interplay



EHT Collaboration

Yuber F. Perez-Gonzalez

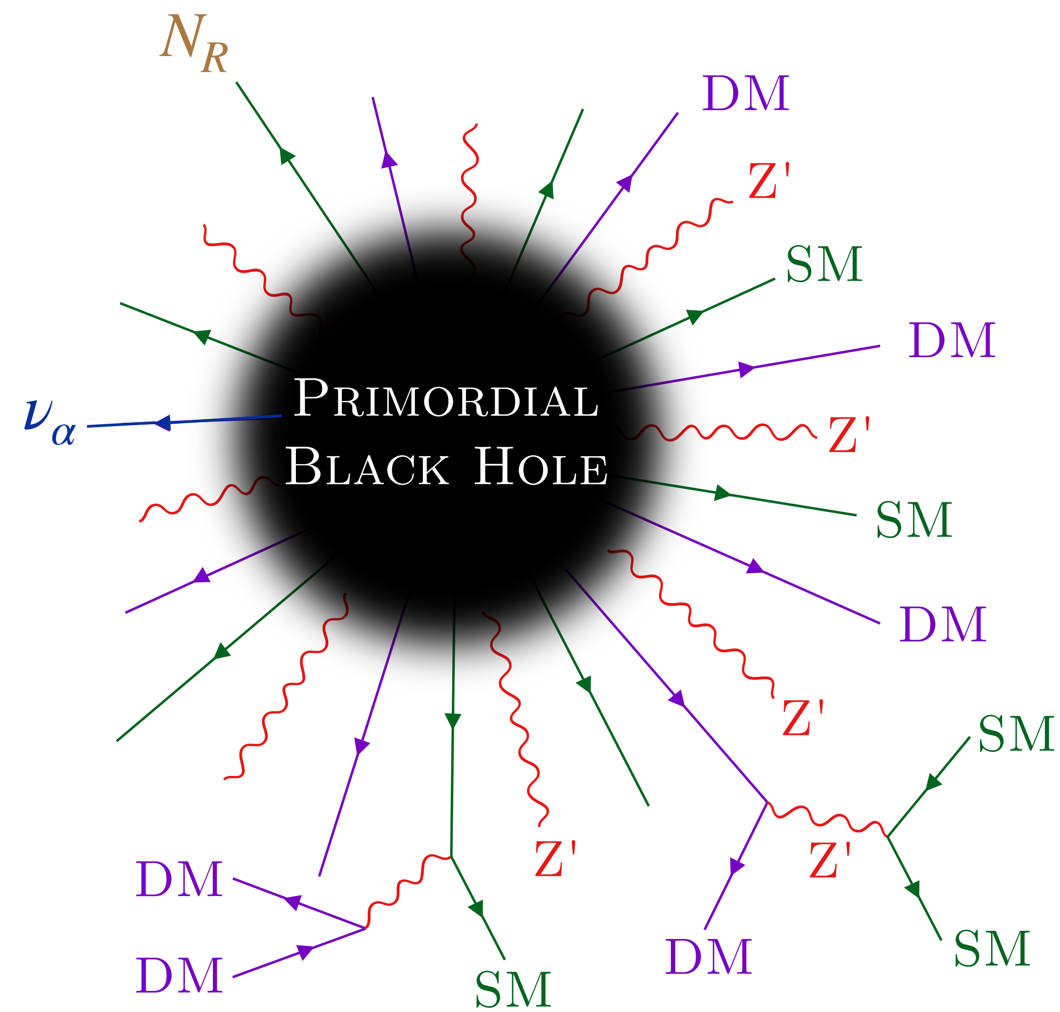
IFT Seminar/NuTs Workshop
May 23rd, 2022

Durham University

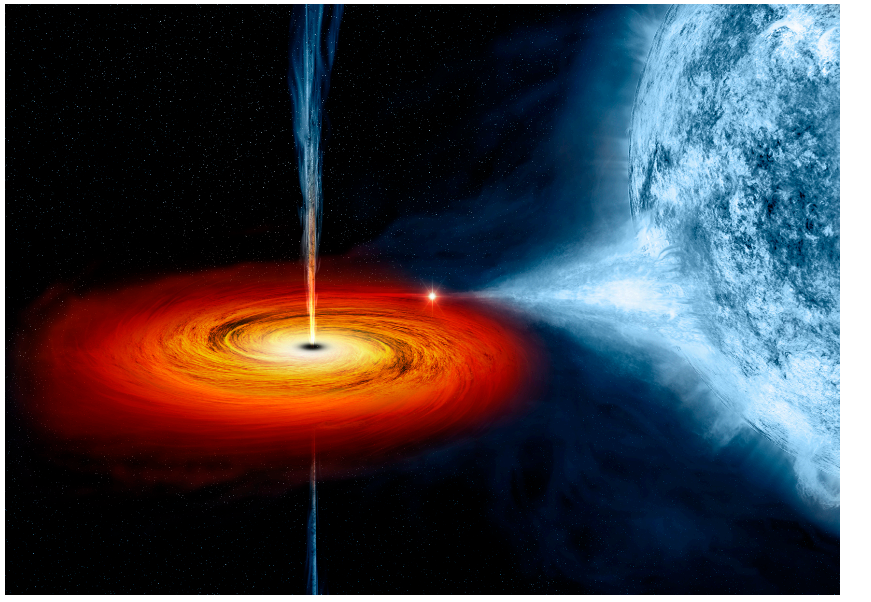
IPPP

What's the impact of having evaporating Primordial Black Holes for Leptogenesis models?

- *Introduction:*
  - PBHs — Formation/Evaporation
  - Thermal Leptogenesis
- Interplay between PBHs ↔ Leptogenesis
- Testing these scenarios?
- In progress



Primordial Black Holes (PBH)



Astrophysical Black Holes

$M \gtrsim 3M_\odot$

Formation

Lighter Black Holes → Large densities

$r_S = 2GM$

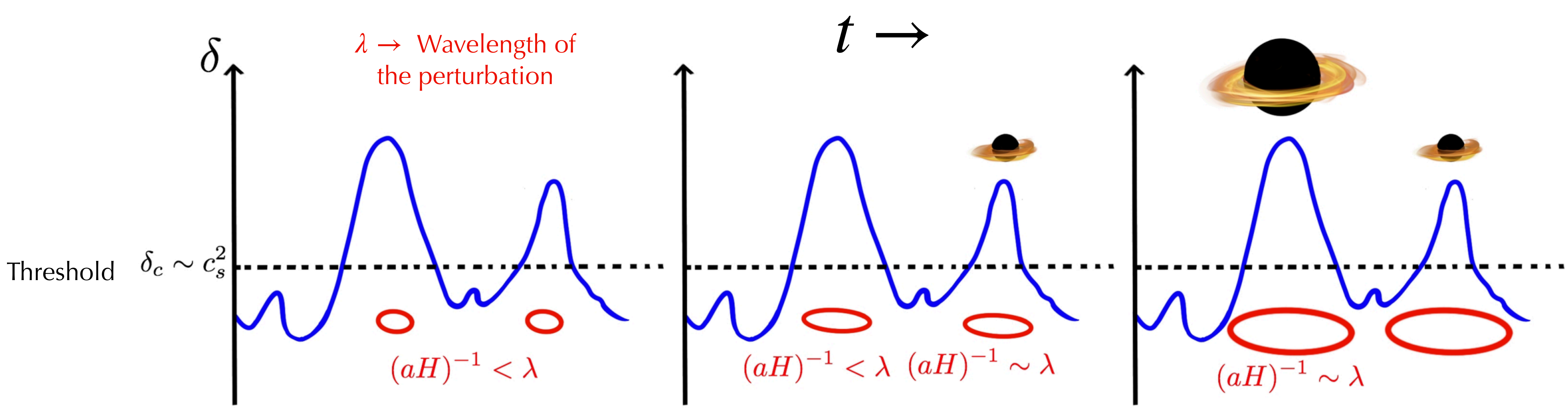
$$M_i \sim \frac{t}{G} \sim 10^{15} \left(\frac{t}{10^{-23}\ \mathrm{s}} \right)\ \mathrm{g}$$

Formation

$$\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}}$$

- Bubble collisions
- Pressure reduction
- Collapse of density fluctuations

$$M_{\mathrm{BH,i}} \propto \underbrace{\frac{4\pi}{3}\rho\frac{1}{H^3}}_{\text{Mass contained in the horizon}}$$



Taken from Villanueva-Domingo, Mena, Palomares-Ruiz 2103.12087

PBH form when the density perturbation enters the Hubble horizon

Fraction of the total energy in PBH

$$\beta = \frac{\rho_{\mathrm{PBH}}}{\rho_{\mathrm{tot}}}$$

Assume a monochromatic mass distribution

All PBHs with the same mass

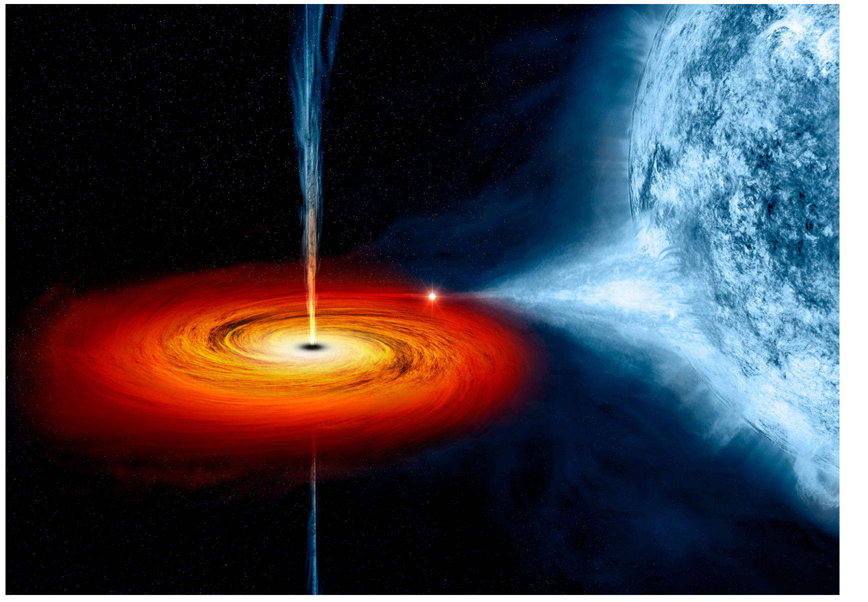
$M_{\mathrm{BH},i}\,,\ \beta$

Carr et al. 2002.12778

PBHs don't grow as fast as the Horizon

Hawking, Carr & Hawking, '74

Primordial Black Holes (PBH)



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Assume a monochromatic mass distribution

$M_{\mathrm{BH},i}\,,\ \beta$

Evaporation

Quantum effects are important

$r_S \sim \lambda_C$

$r_S \sim 0.015\ \mathrm{fm} \left(\frac{M}{10^{13}\ \mathrm{g}} \right)$

Black Holes evaporate by thermal emission

Hawking, 1975

All degrees of freedom!

Evaporation

Schwarzschild BH

Hawking Instantaneous Spectrum

$$\frac{d^2N_i}{dp\,dt} = \frac{g_i}{2\pi^2}\frac{\sigma_{s_i}(M,p,\mu_i)}{\exp[E_a(p)/T] - (-1)^{2s_i}}\frac{p^3}{E_a(p)}$$

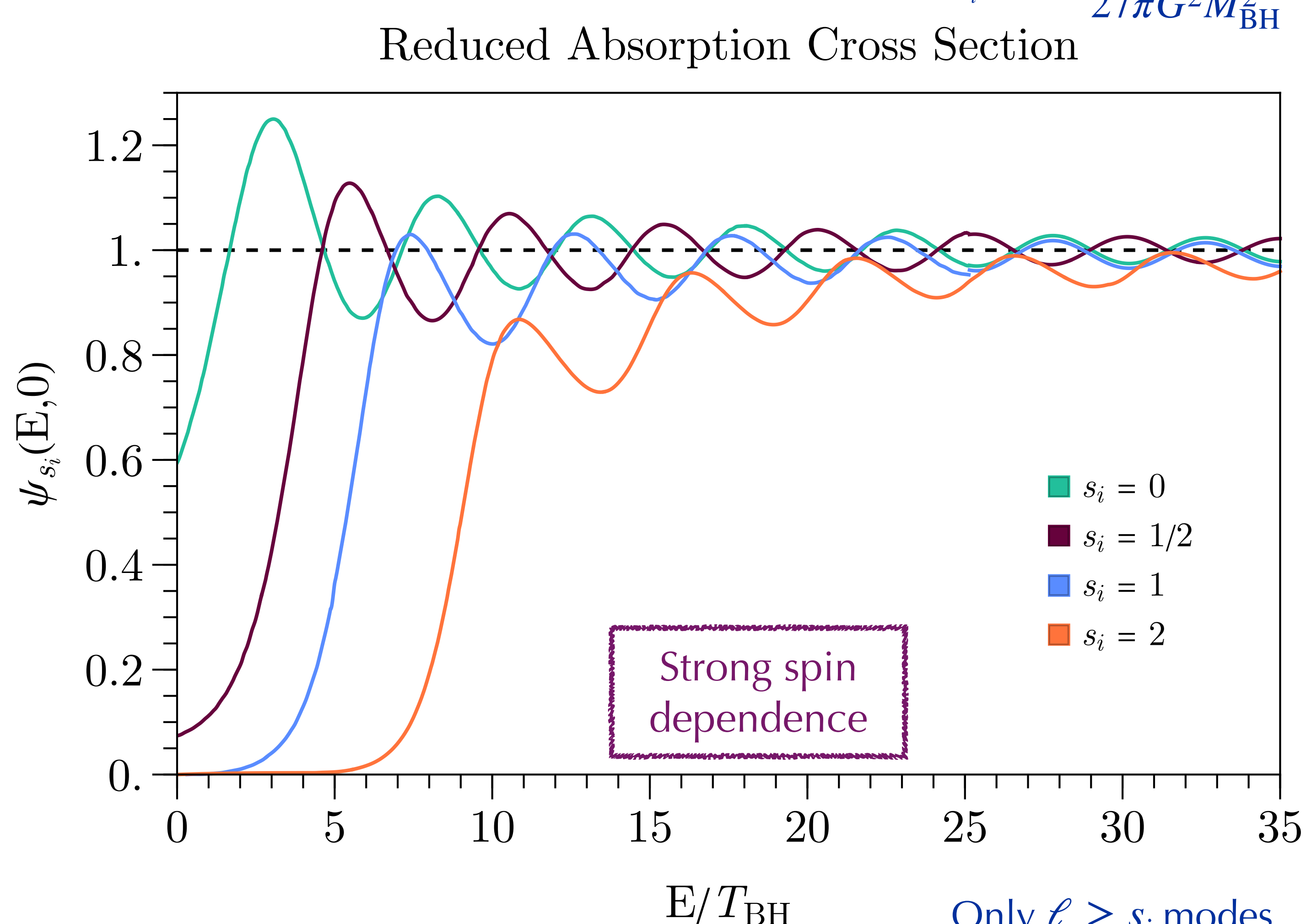
Absorption cross section

BH Temperature $T = \frac{\hbar c^3}{8\pi G M k}$

$$\approx 1.06\ \text{GeV}\left(\frac{10^{13}\ \text{g}}{M}\right)$$

*Hic depositum est, quod mortale fuit Isaaci Newtoni

$$\psi_{s_i}(E) \equiv \frac{\sigma_{s_i}(E)}{27\pi G^2 M_{BH}^2}$$



Only $\ell \geq s_i$ modes

Evaporation

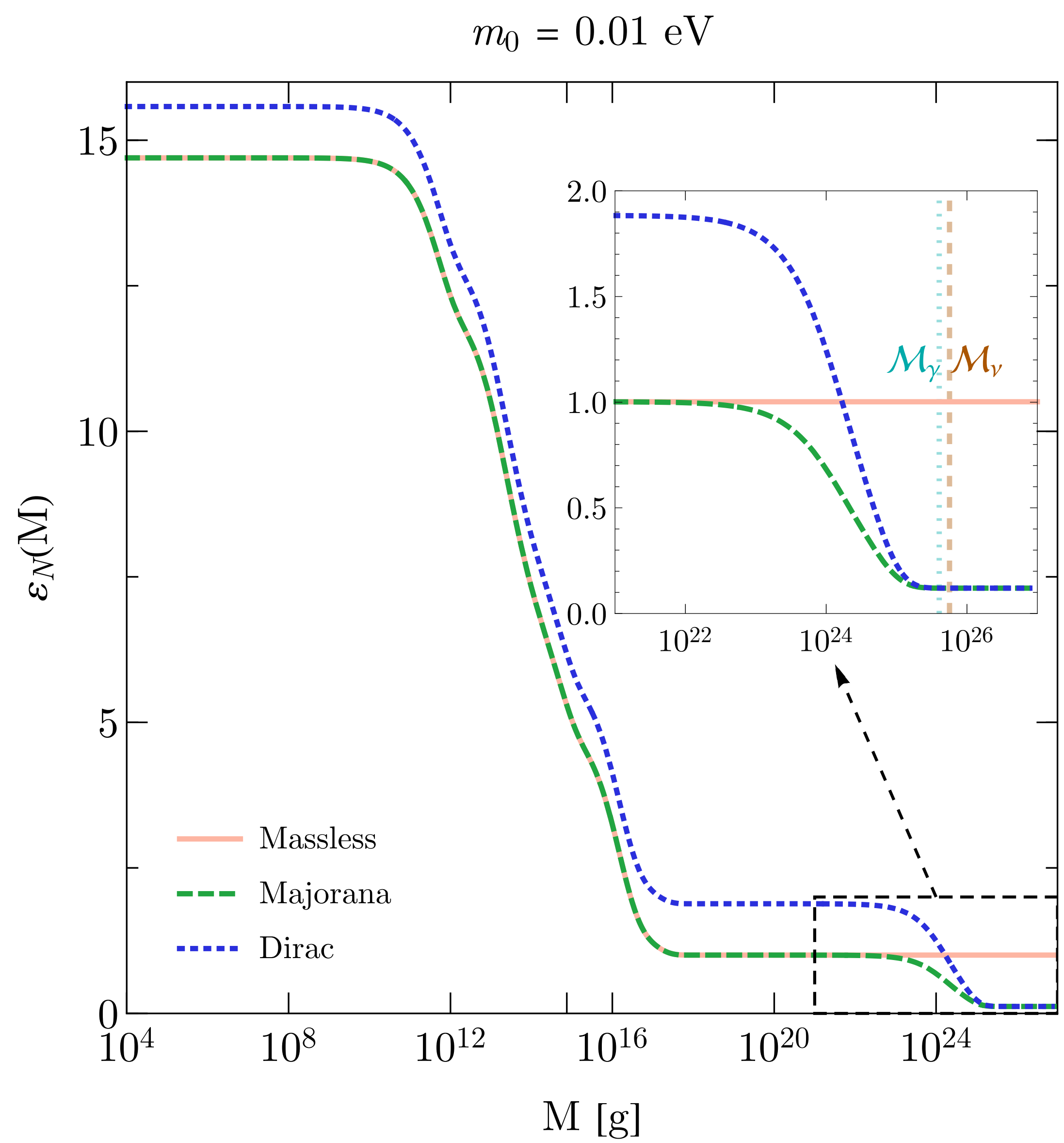
BHs lose mass over time

$$\frac{dM_{\rm BH}}{dt} = -\sum_i \int_0^\infty E_i \frac{d^2\mathcal{N}_i}{dpdt} dp$$

$$= -\underbrace{\varepsilon(M_{\rm BH})}_{\text{Evaporation function}} \frac{M_P^4}{M_{\rm BH}^2}$$

Depends on the set of possible particles to be emitted

J. MacGibbon, 1991



BH lifetime

$$\tau = \frac{1}{M_{\rm P}^4} \int_{M_{\rm P}}^{M_{\rm i}} \frac{M^2 dM}{\varepsilon(M)}$$

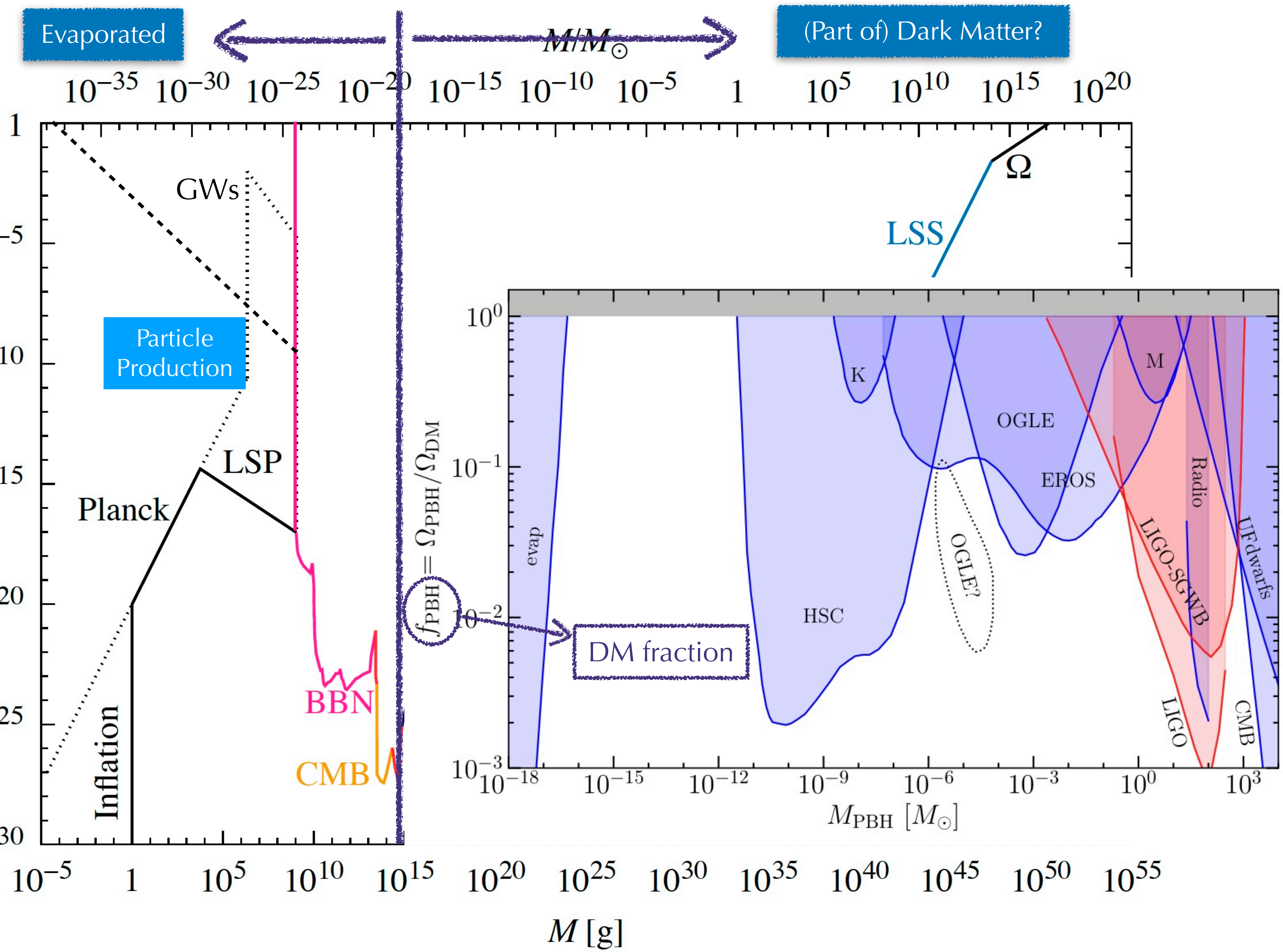
Planck mass

BH with $M_{\rm i} = M_\odot$:

$$\tau \approx 2 \times 10^{67} \text{ years}$$

$$\approx 10^{57} * \text{age of the Universe}$$

Reduced β



$$\beta' = \beta\, \gamma^{1/2} \left(\frac{g_{*f}}{106.75}\right)^{1/4}$$

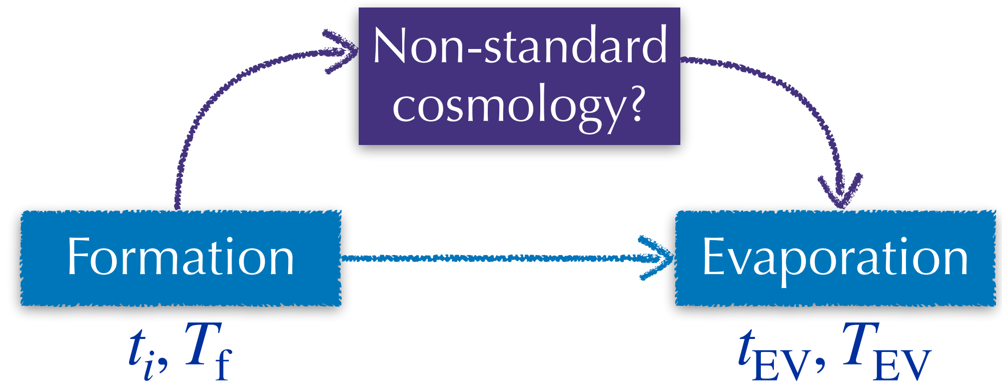
Gravitational collapse factor

We focus on the region $M_{\rm BH,i} \leq 10^9$ g

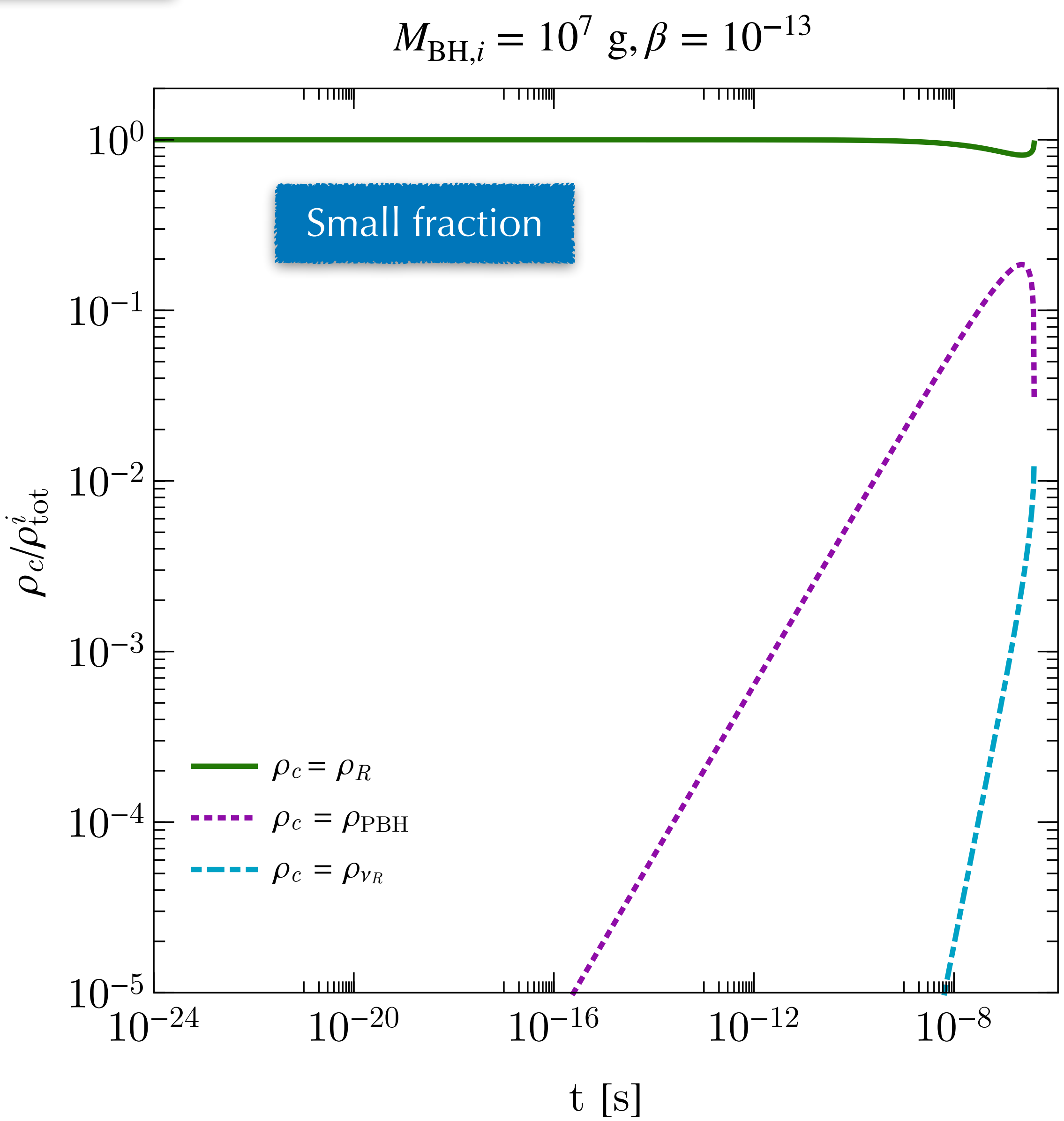
Carr et al. 2002.12778
Domènech et al. 2012.08151

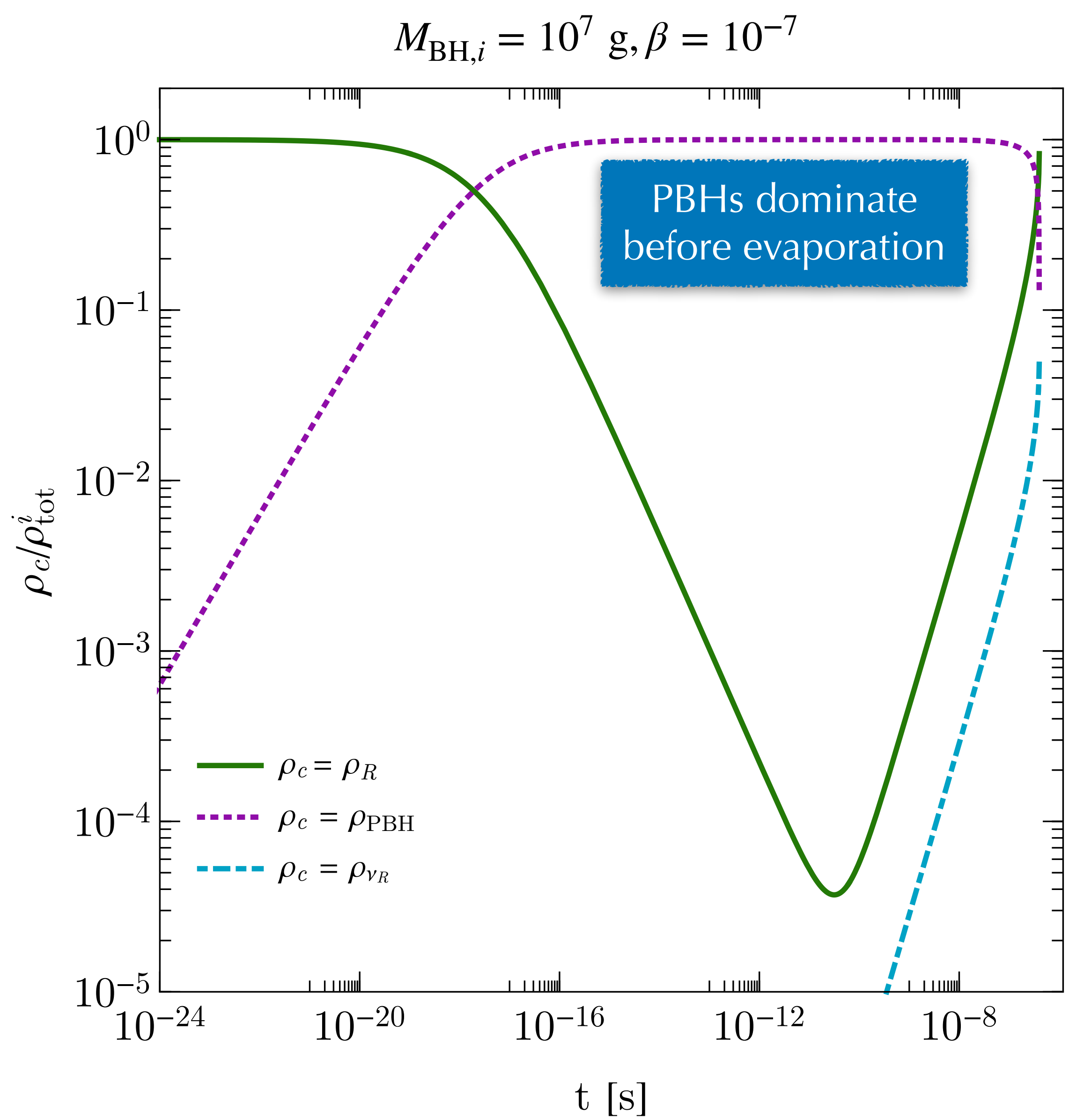
B. Kavanagh
10.5281/zenodo.3538999

PBHs: Rise and Fall



PBHs behave (almost) as matter





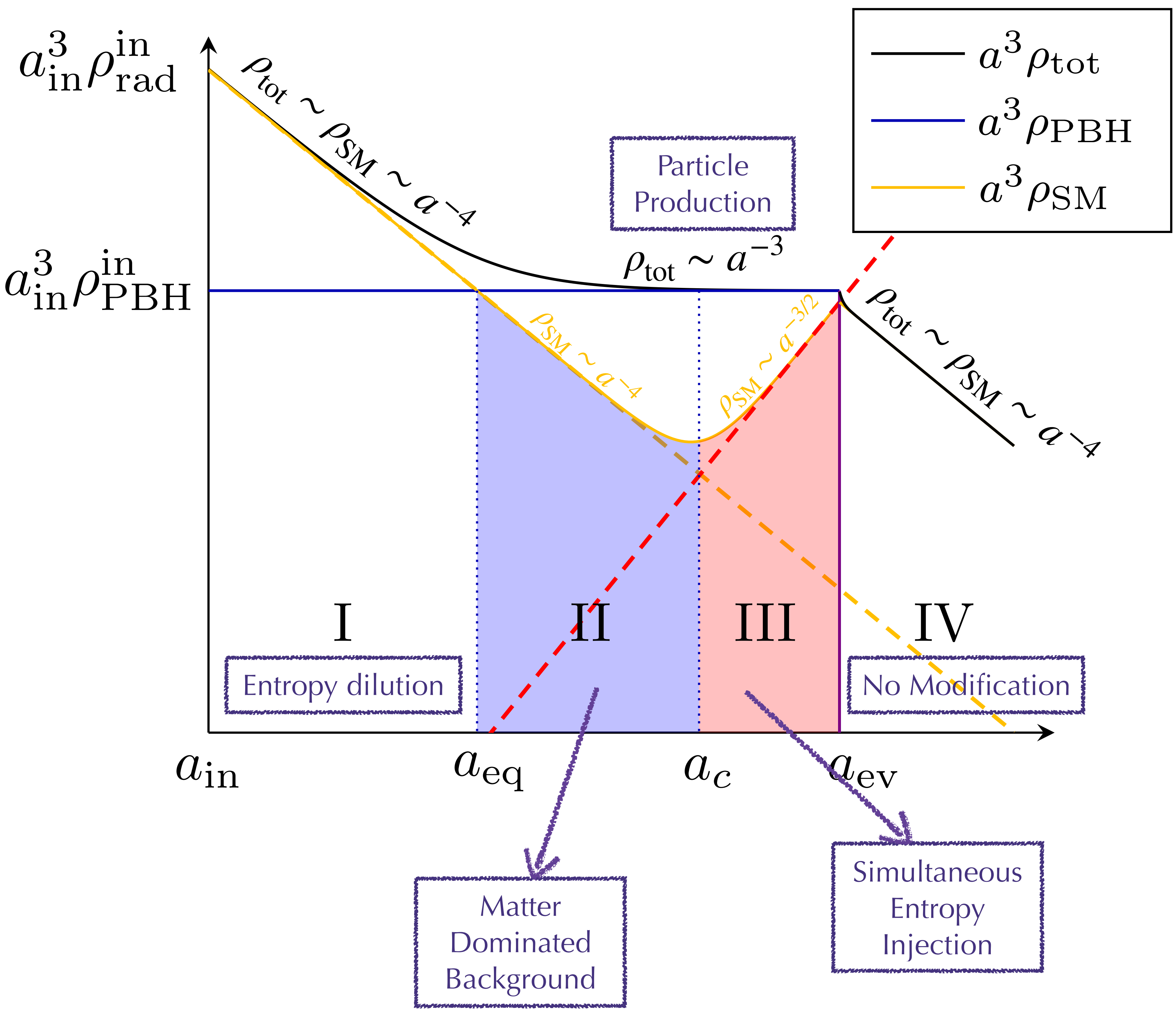
Initial fraction

$$\beta \gtrsim 2.5 \times 10^{-14} \left(\frac{g_*(T_f)}{106.75}\right)^{-\frac{1}{4}} \left(\frac{M_i}{10^8\ \mathrm{g}}\right)^{-1} \left(\frac{\varepsilon_D(M_i)}{15.35}\right)^{\frac{1}{2}}$$

Hooper et al, 1905.01301

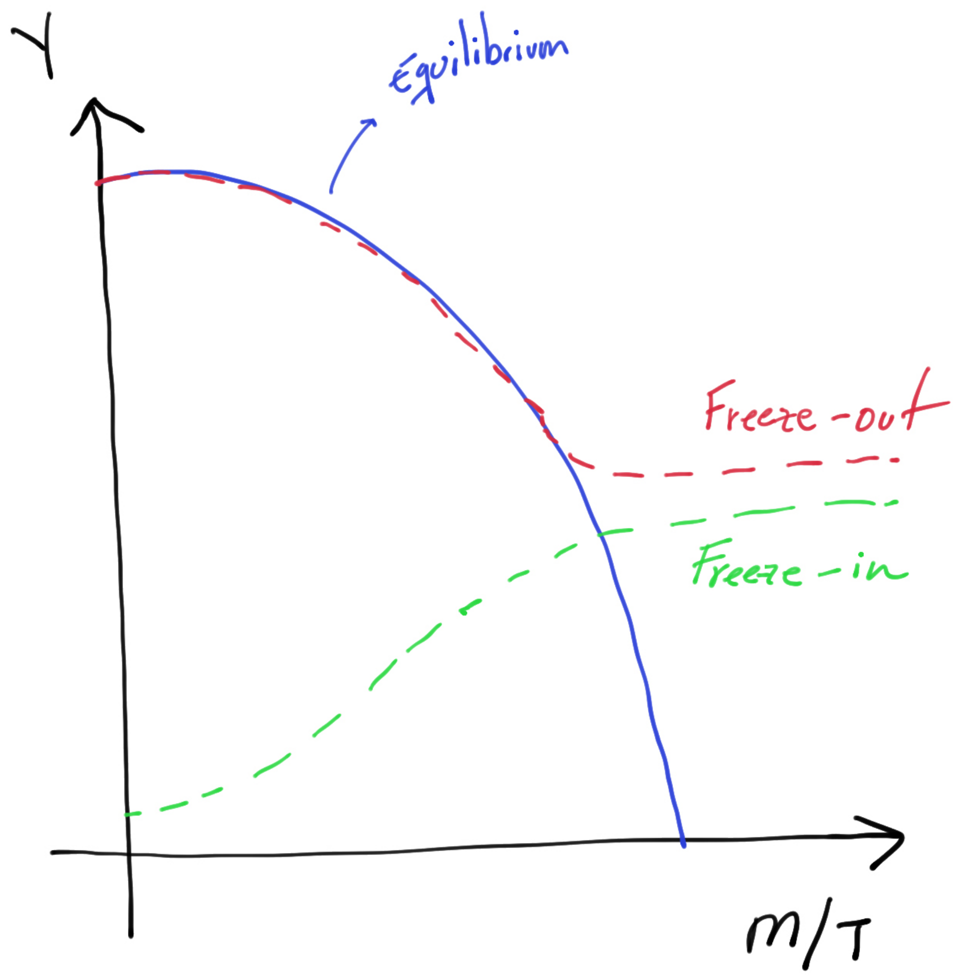
PBHs: Rise and Fall

In a PBH dominated Early Universe



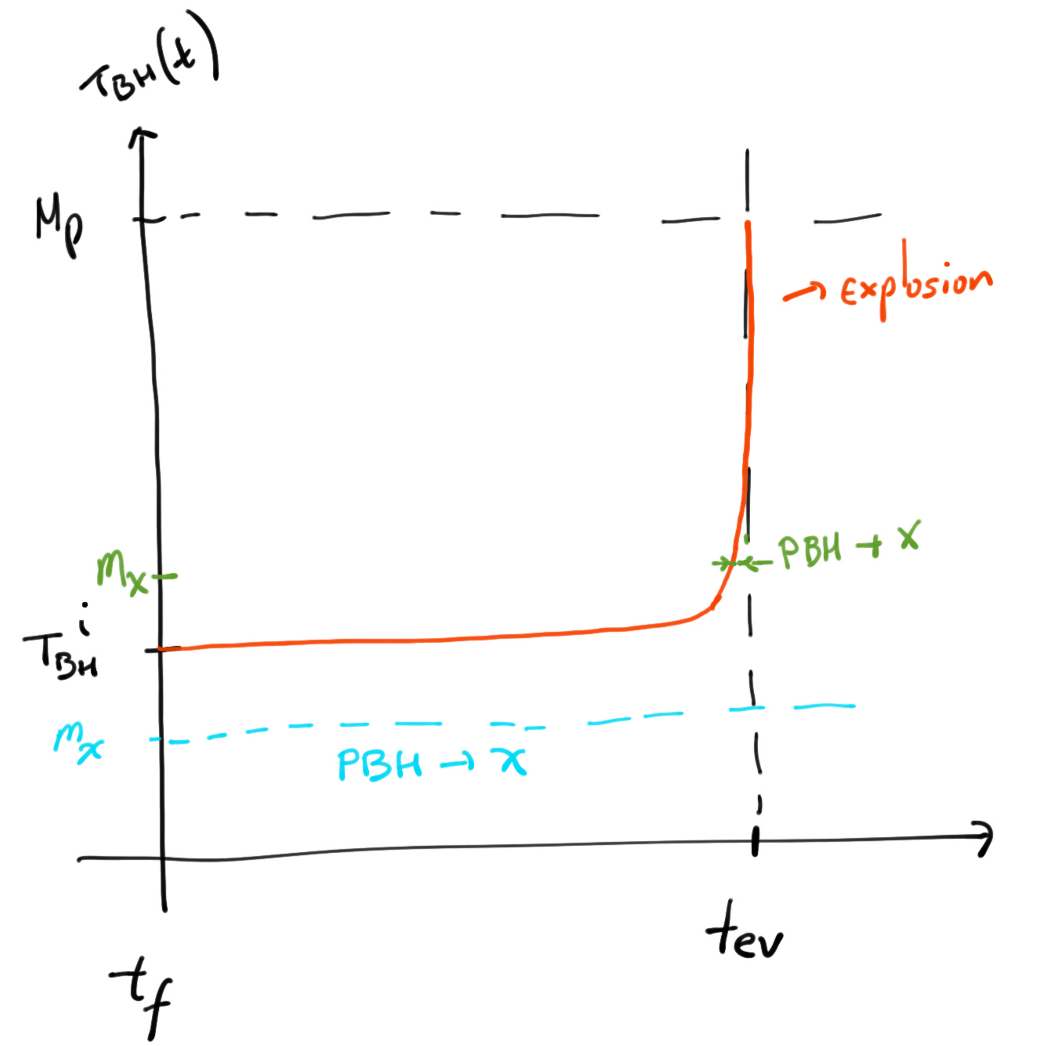
Why is interesting the particle production via evaporation?

(Thermal) Particle decoupling



Abundances depend on masses and interactions

Hawking Evaporation



Abundances depend on masses and PBH parameters

Interplay??

- ❖ Modified Cosmology
- ❖ Particle production
- ❖ Entropy dilution

Why is interesting the particle production via evaporation?

DM production
(Besides PBH-DM)

- Purely Gravitationally interacting DM
- Modify Freeze-In/Freeze-out mechanisms

Fujita et al, 1401.1909
Morrison et al,1812.10606
Baldes et al, 2004.14773
Masina, 2004.04740, 2103.13825
Cheek, Heurtier, YFPG, Turner
2107.00013, 2107.00016
.
.
.

Baryon Asymmetry

- Modifying Baryogenesis scenarios
- Leptogenesis scenarios
- Producing a local asymmetry at PBH formation
- Connections with PBH-DM

Baumann, Steinhadt, Turok, 0703250
Yamada and Iso, 1610.02586
Fujita et al, 1401.1909
Morrison et al,1812.10606
García-Bellido, Carr, Clesse,
1904.11482
Hooper and Krnjaic, 2010.01134
.
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.

Dark Radiation

- Production of hot gravitons
- Testable from future measurements on $\Delta N_{\rm eff}$

Hooper, Krnjaic, McDermott, 1905.01301
Lunardini, YFPG, 1910.07864
Masina, 2004.04740, 2103.13825
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Thermal Leptogenesis in a nutshell

Baryon asymmetry

$$\eta_{\rm CMB} = (6.23 \pm 0.17) \times 10^{-10}$$

$$\eta_{\rm BBN} = (6.08 \pm 0.06) \times 10^{-10}$$

Sakharov Conditions

- Baryon and Lepton number violation
- CP violation
- Departure from thermal equilibrium

Type I seesaw:

$$-\mathscr{L} \supset \frac{1}{2} M_{N_i} \overline{N_i^c} N_i + \overline{\ell}_\alpha H^* Y_{\alpha i} N_i + \text{H.c.}$$

$$m_\nu \sim \frac{Y_\nu^2 v^2}{M_N} \sim \mathcal{O}(0.1 \text{ eV})$$

$$Y_\nu = \frac{1}{v} U_{\rm PMNS} \sqrt{m_\nu} R^T M_N^T$$

Casas, Ibarra, 2001

Boltzmann Equations

$$\frac{dn_{N_i}}{dz} = D_i (n_{N_i} - n_{N_i}^{\rm eq})$$

$$\frac{dn_{\rm B-L}}{dz} = \sum_i \epsilon_i D_i (n_{N_i} - n_{N_i}^{\rm eq}) - \mathscr{W}_i n_{\rm B-L}$$

Washout

$$LH \leftrightarrow \overline{L}\overline{H}$$

$$\Delta L = 2$$

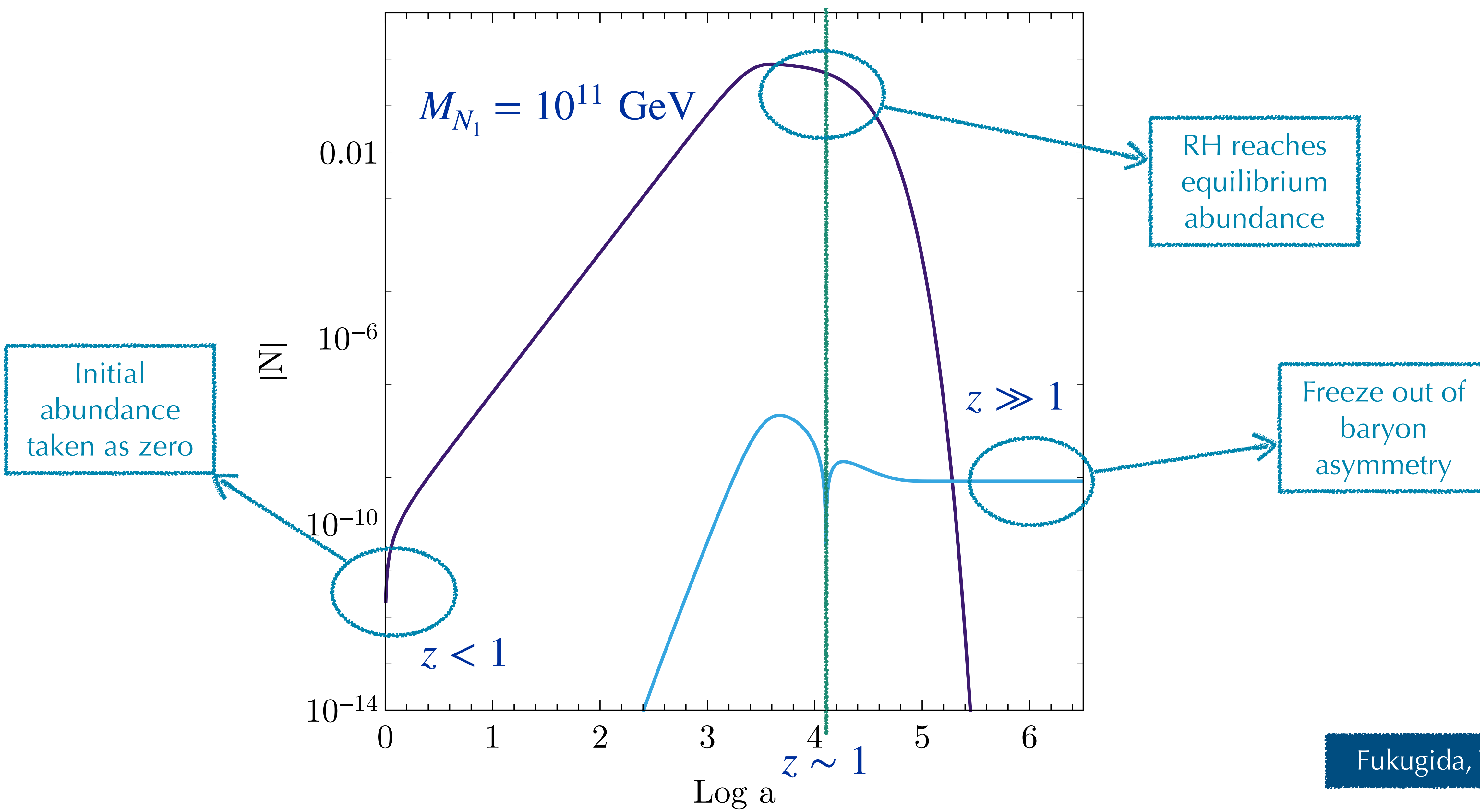
Fukugida, Yanagida, '86

Thermal Leptogenesis in a nutshell

$z \equiv \frac{M_{N_1}}{T}$

At $T \sim M_N$ RH neutrinos are created → ($N \to LH$, $N \to \bar{L}H$) → Lepton asymmetry is created → (Sphaleron processes) → Baryon asymmetry

$LH \to N$



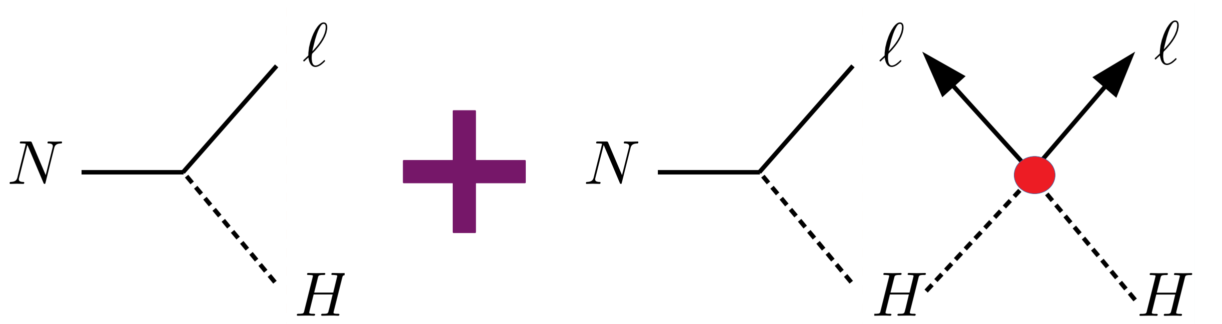
Fukugida, Yanagida, '86

High Scale Leptogenesis

$M_N \gtrsim 10^{12}$ GeV

$M_{N_1} < M_{N_2} < M_{N_3}$

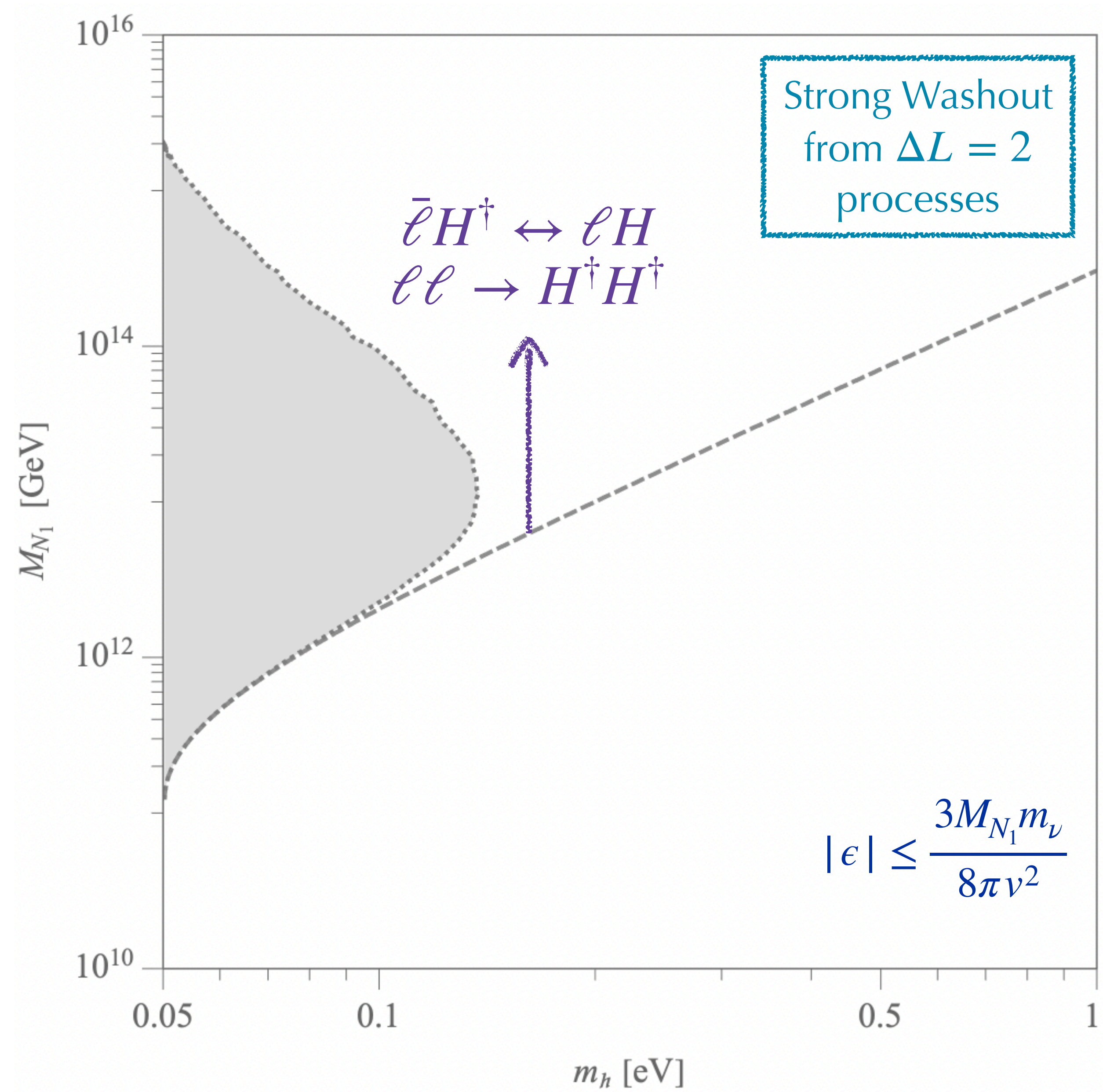
CP violation from interference



$$\frac{\epsilon}{M_N} \propto \frac{m_\nu}{v^2} \propto \sqrt{\sigma_{\Delta L=2}}$$

$\Delta L = 2$ interactions would be in equilibrium if

$$M_{N_1} \gtrsim 4 \left(\frac{0.1 \text{ eV}}{m_\nu} \right) 10^{12} \text{ GeV}$$



m_h = Heaviest neutrino mass

Maximizing over Yukawa parameters

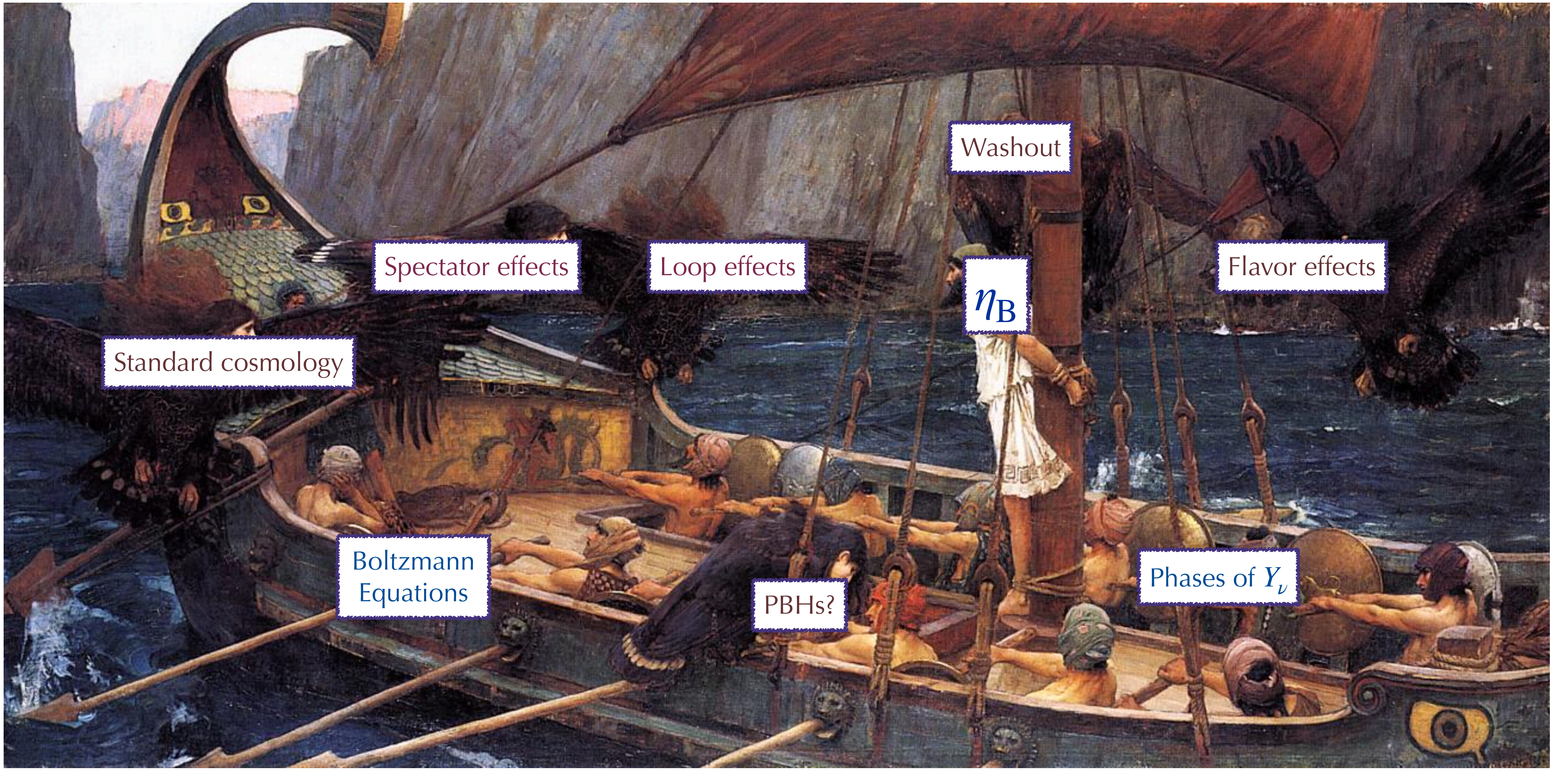
How to save HSL? → Produce RHNs after washout process have frozen out?

PBHs!

Giudice *et al.*, 2004
Buchmuller *et al.*, 2005

Intermezzo.

Universal LeptogeneSiS Equation Solver (ULYSSES)



A Granelli, K Moffat, YFPG, H Schulz and J Turner, arXiv: 2007.09150

- Leptogenesis via decays and resonant leptogenesis
- Easy parallelization
- Rapid evaluation
- Multidimensional scan of the parameter space

Interplay between PBH Evaporation and Leptogenesis

Based on:
YFPG and Turner: 2010.03565
Bernal, Fong, YFPG, Turner 2203.08823

Baryogenesis from PBHs only

Assume and additional X particle producing a $B-L$ asymmetry

$$N_X = \int_0^\tau dt \int_{M_X}^\infty dE \, \frac{d^2 N_X}{dt\, dE}$$

Total number of X particles produced

Yield of $B-L$

$$Y_X \equiv \frac{3\beta\, T_0\, N_X}{4 M_{\rm BH0}} \frac{s(T_{\rm ev})}{s(\tilde{T})}$$

Entropy dilution

$$Y_X \simeq \frac{135\zeta(3)}{\pi^3 g_\star}\, \beta \frac{T_0}{M_{\rm BH0}} \left(1+\beta\frac{T_0}{T_{\rm ev}}\right)^{-\frac{3}{4}} \times \begin{cases} \left(\frac{M_{\rm BH0}}{M_P}\right)^2 & M_X \leq r_f\, T_{\rm BH0}\,, \\ \frac{15\zeta(5)}{64\pi^2\zeta(3)} \left(\frac{M_P}{M_X}\right)^2 & M_X \geq r_f\, T_{\rm BH0}\,. \end{cases}$$

CP violation

$$Y_B^{\rm max} = \frac{30}{97}\, \epsilon\, Y_X$$

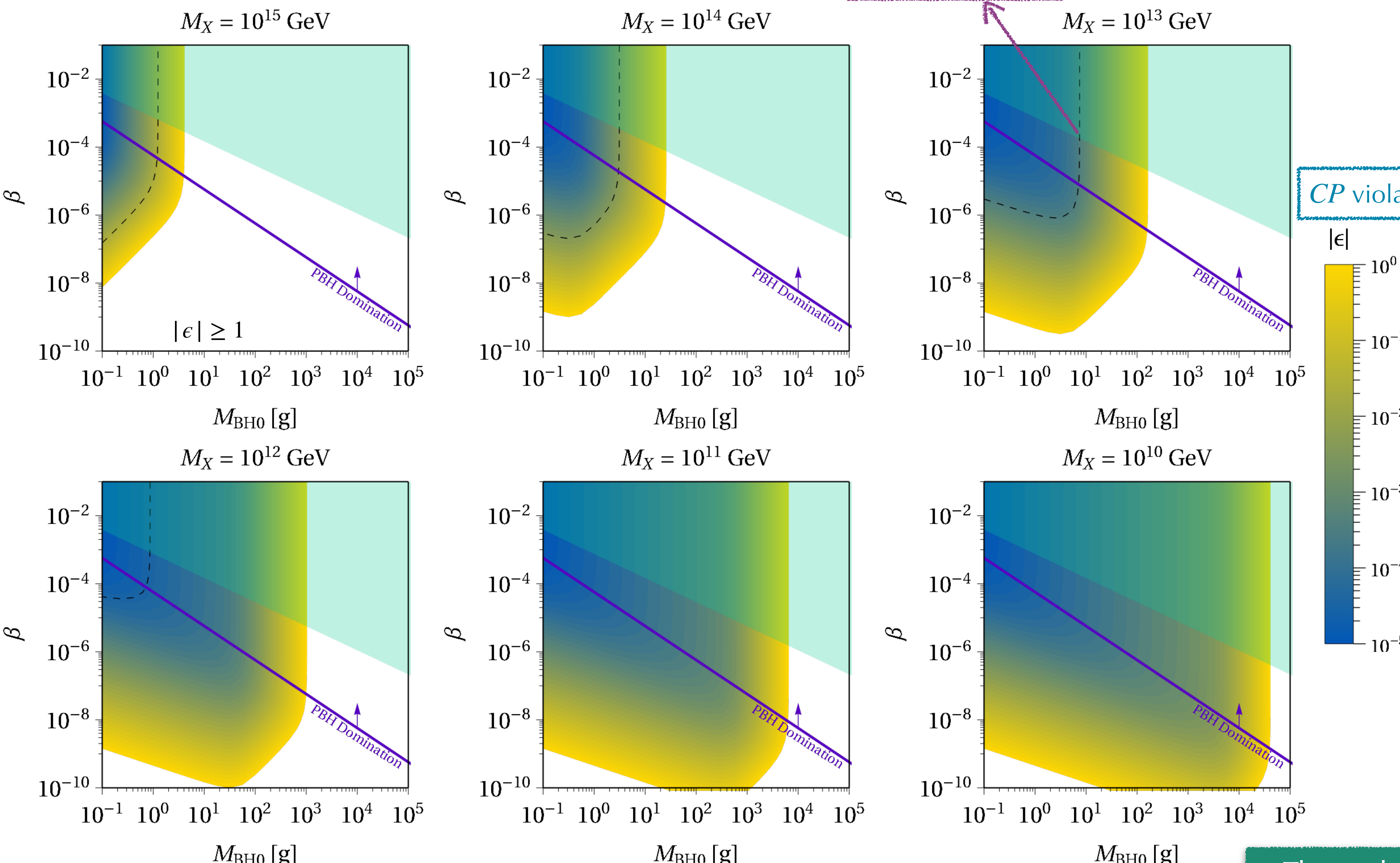
$r_f \equiv \sqrt{15\,\zeta(5)/\zeta(3)}$

Toussiant et al, '75
Barrow et al, Phys. Rev. D **43**, 984
Baumann, Steinhardt, Turok 0703250
Fujita et al, 1401.1909
Morrison et al, 1812.10606
…

Baryogenesis from PBHs only

$$Y_B^{\rm max} = \frac{30}{97}\,\epsilon\, Y_X$$

Davidson/Ibarra bound



CP violation

$m_h^2 = |\Delta m^2_{\rm atm}|$

Tuning required for $M \lesssim 10^{12}$ GeV

Thermal processes?

PBH + Leptogenesis

At $T \sim M_N$ RH neutrinos are created → ($N \to LH$, $N \to \bar{L}H$) → Lepton asymmetry is created → (Sphaleron processes) → Baryon asymmetry

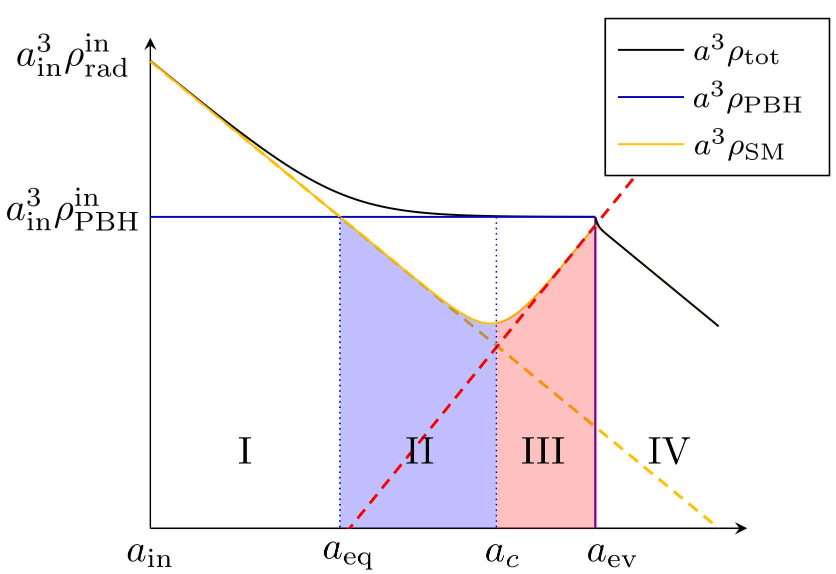
$LH \to N$

Formation → Non-standard cosmology? → Evaporation

Formation → Evaporation

Entropy dilution

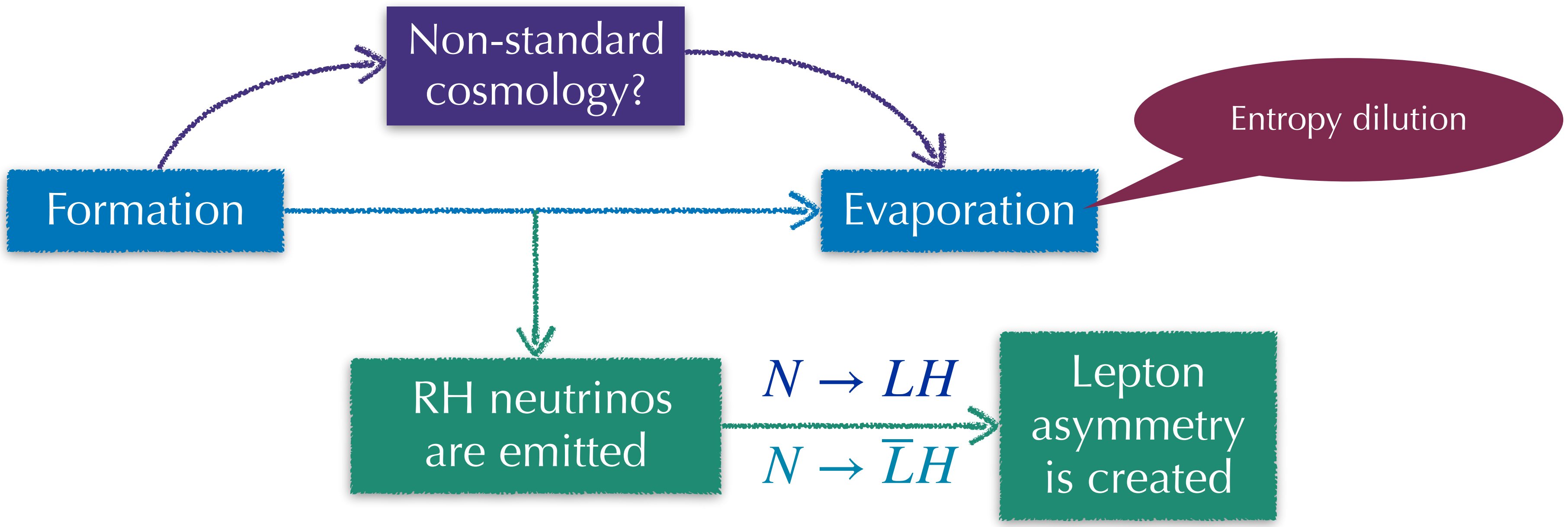
RH neutrinos are emitted → ($N \to LH$, $N \to \bar{L}H$) → Lepton asymmetry is created

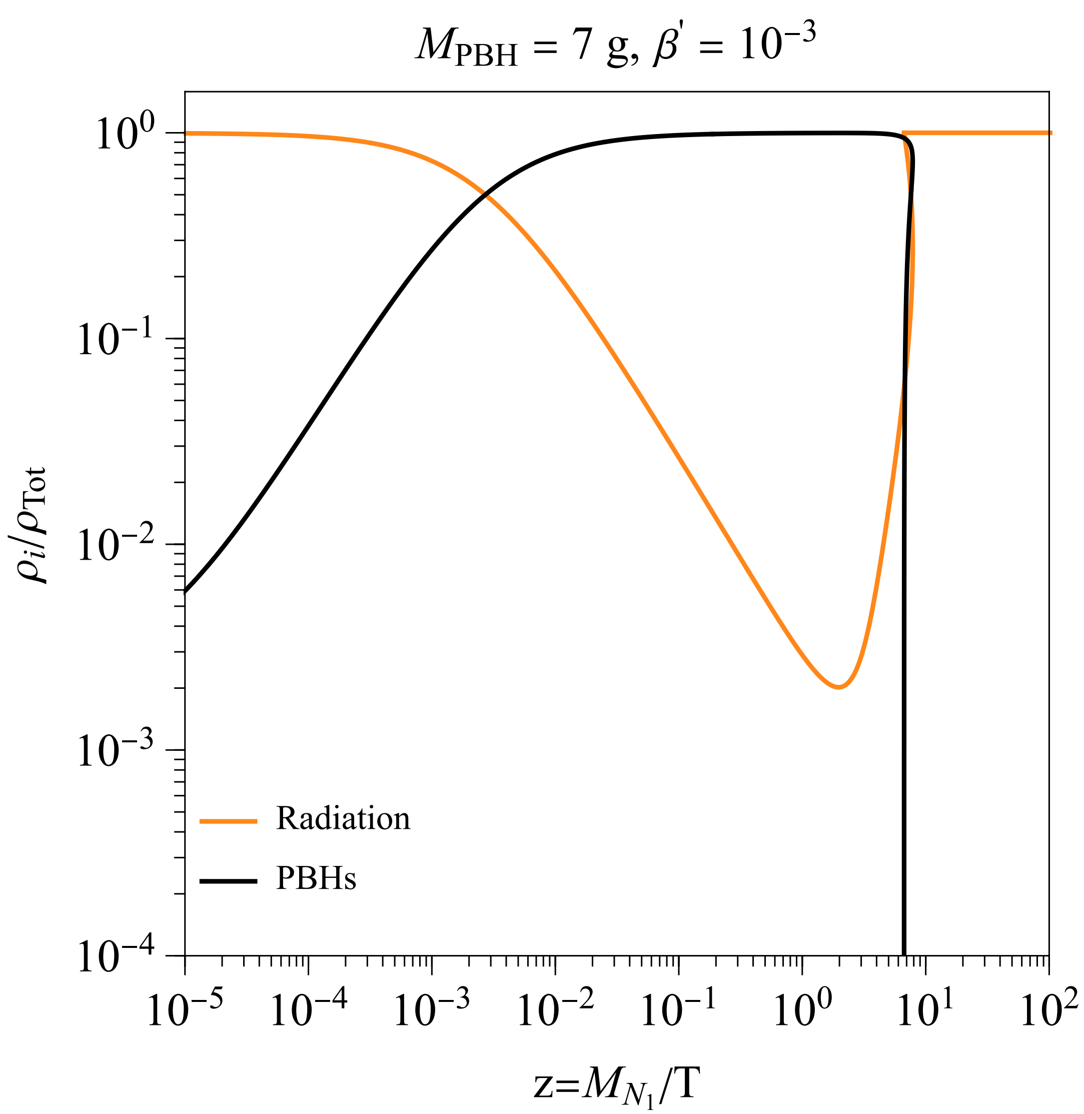


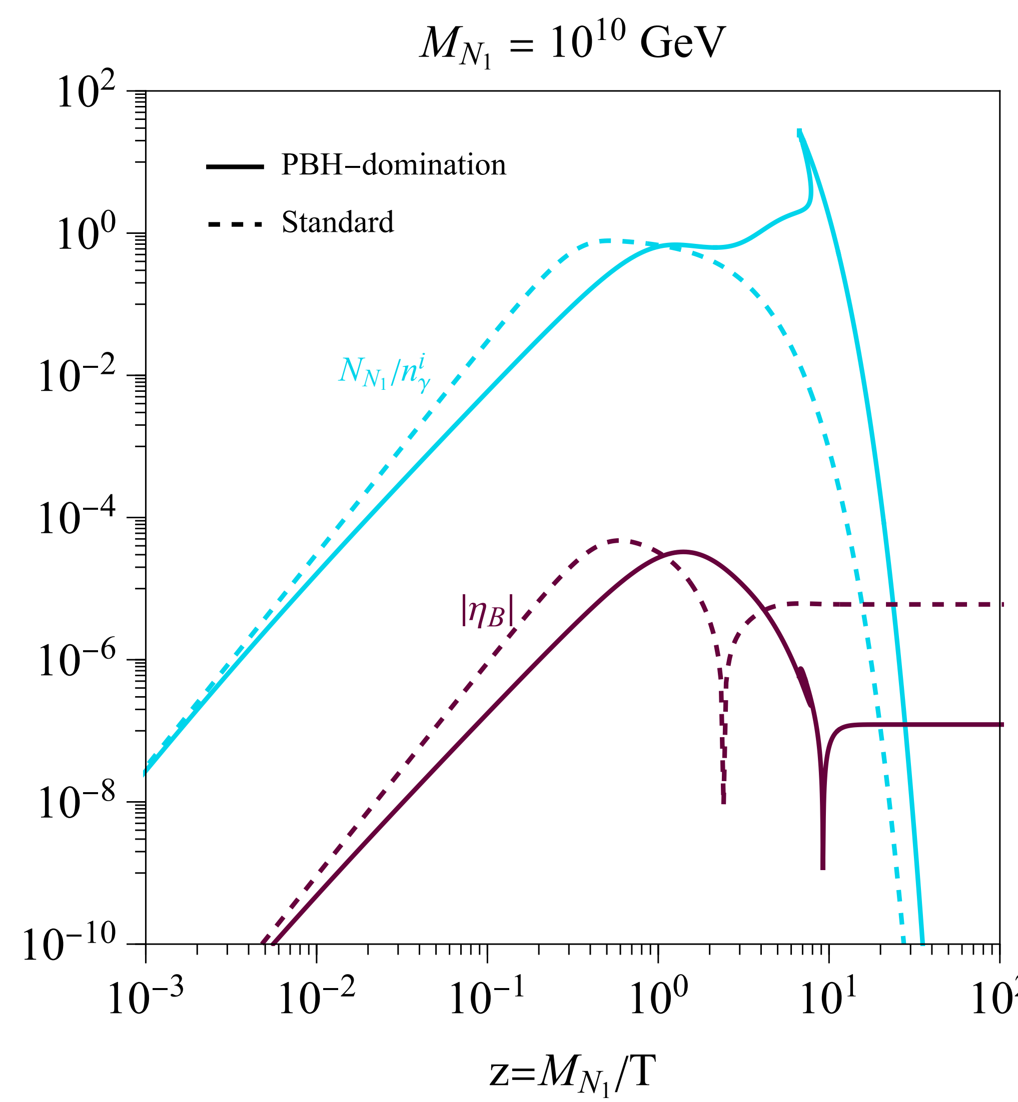
$$z_{\rm BH} \equiv \frac{M_{N_1}}{T_{\rm BH}}$$

PBH + Leptogenesis

$$z_{\rm BH} \equiv \frac{M_{N_1}}{T_{\rm BH}}$$

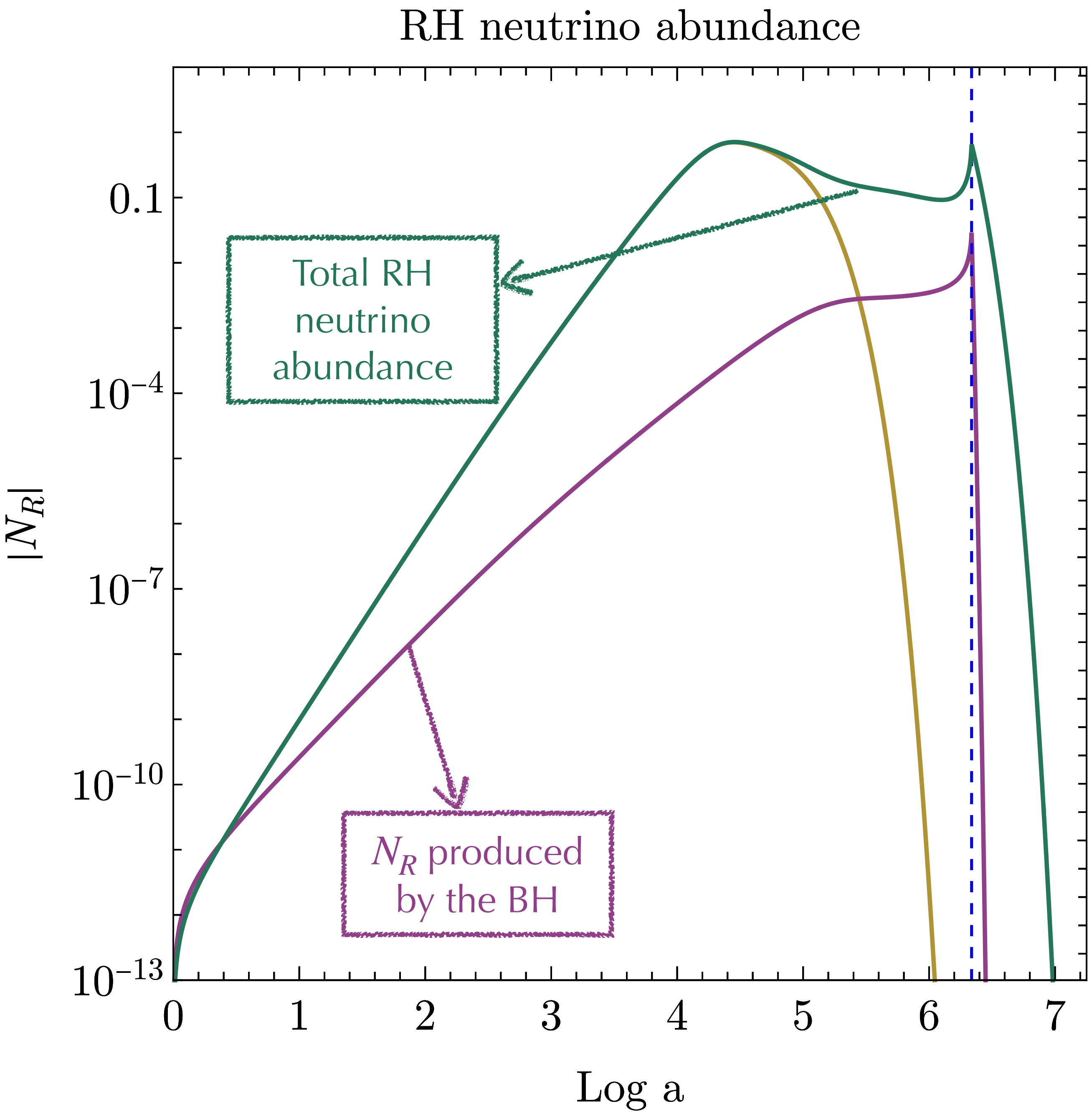


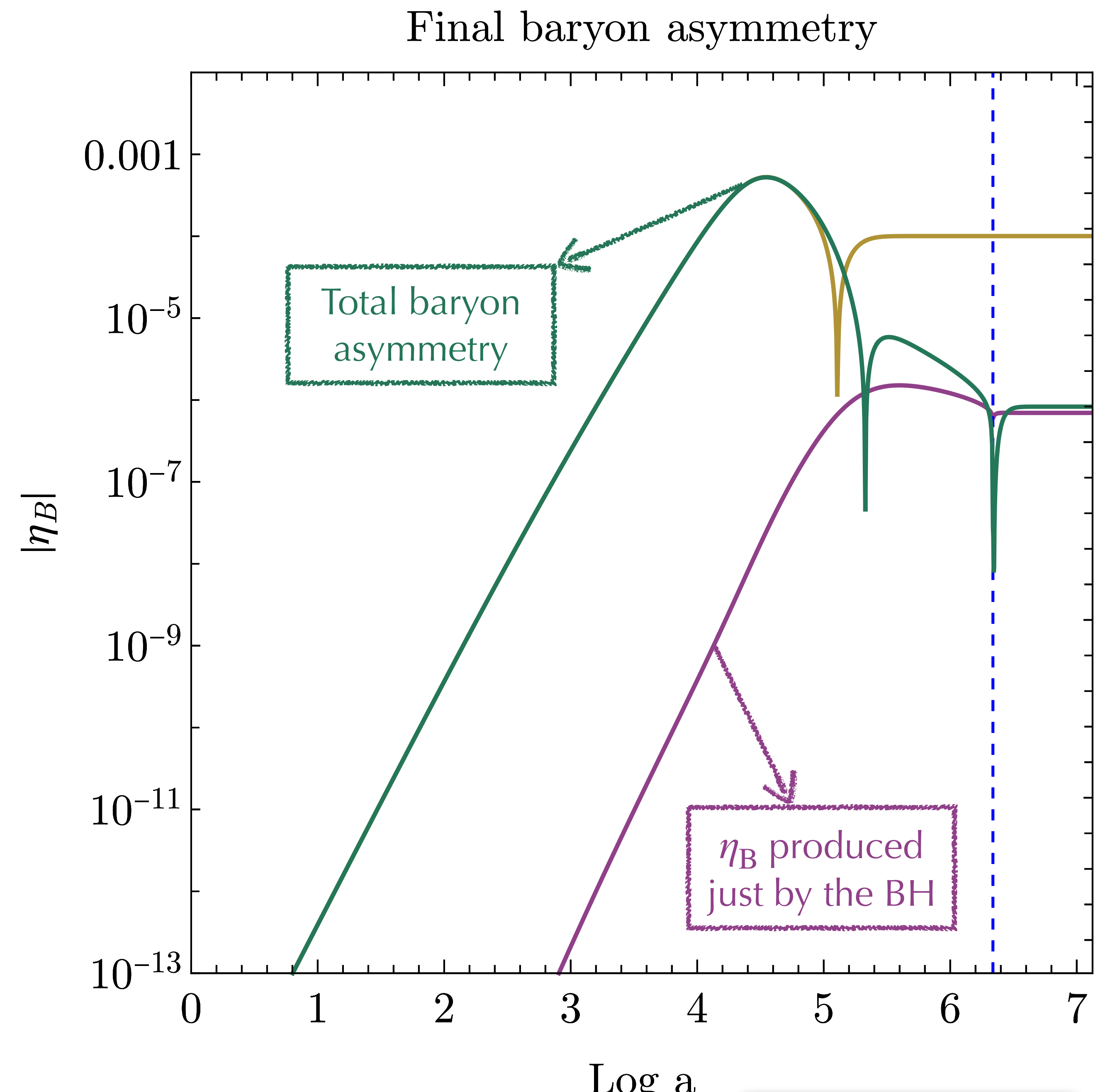




Three scenarios

A. PBH evaporate before RHs are thermally produced (IV)
B. Evaporation happens during thermal leptogenesis (II-III)
C. PBH create a RH density after the thermal case (II-III)





BH evaporation can diminish the asymmetry!

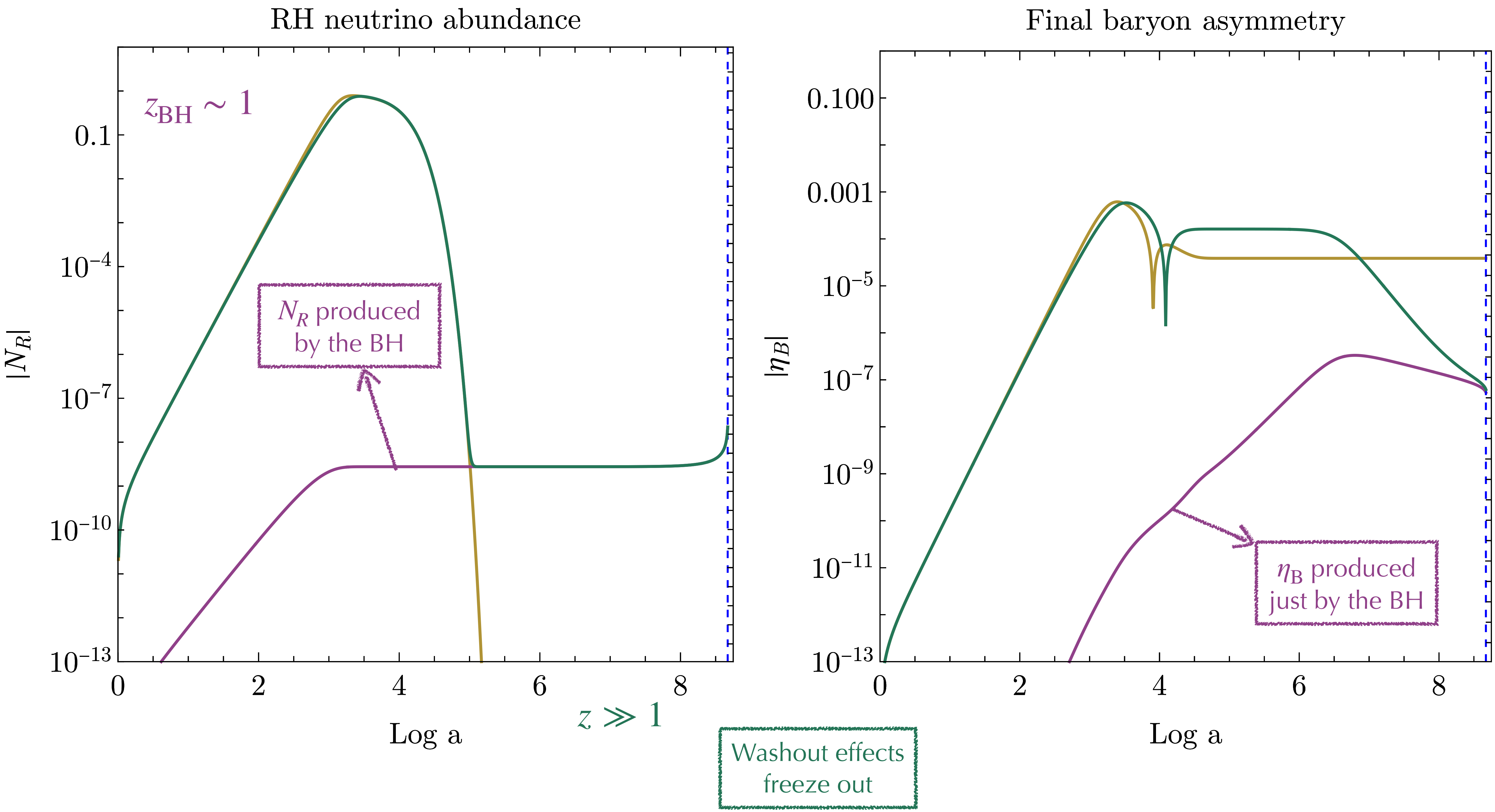
$M_i = 1.7$ g
$\beta_i' = 10^{-3}$

$M_{N_1} = 10^{11}$ GeV

C. PBH create a RH density after the thermal case

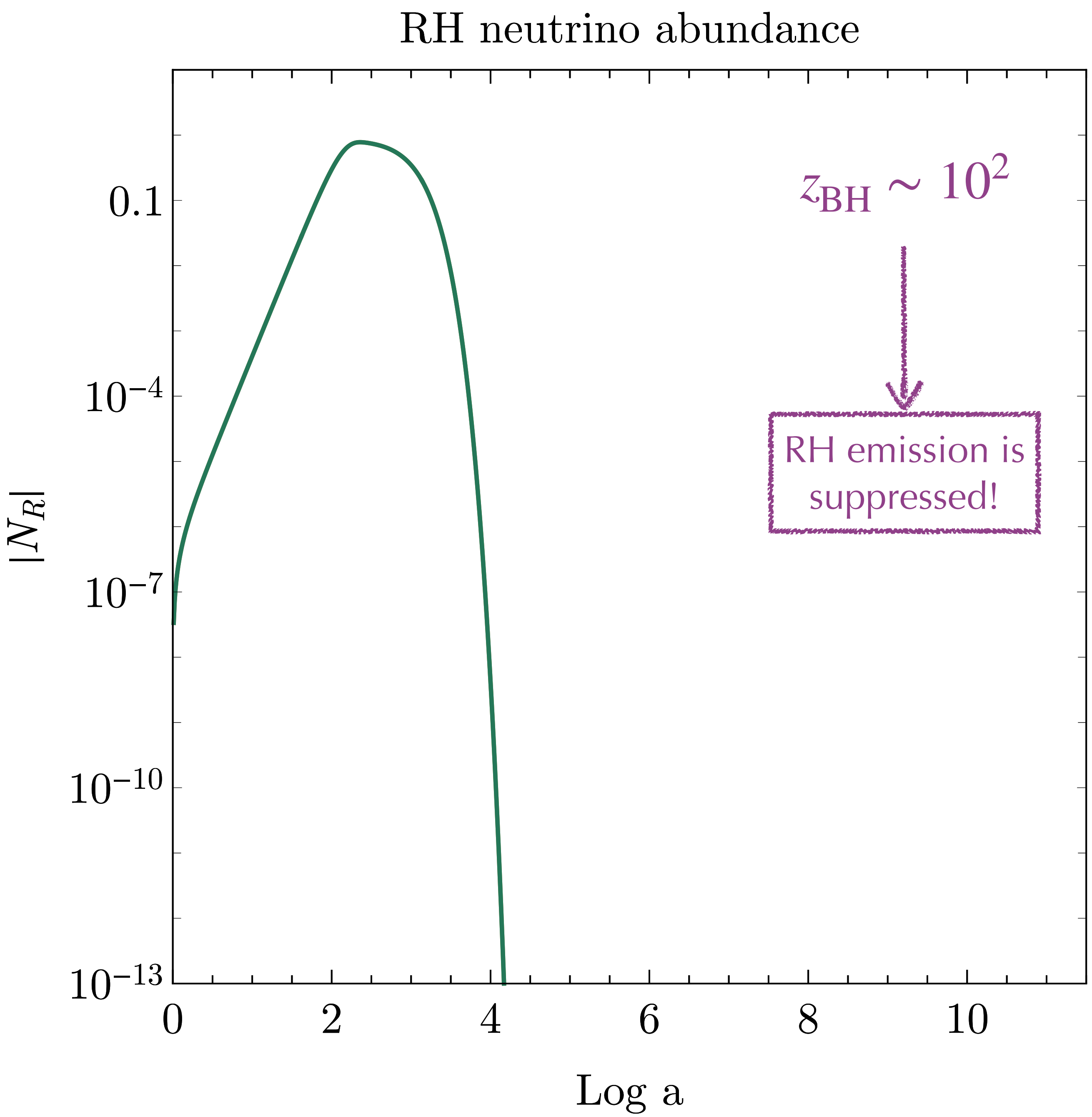
How after is "after"?

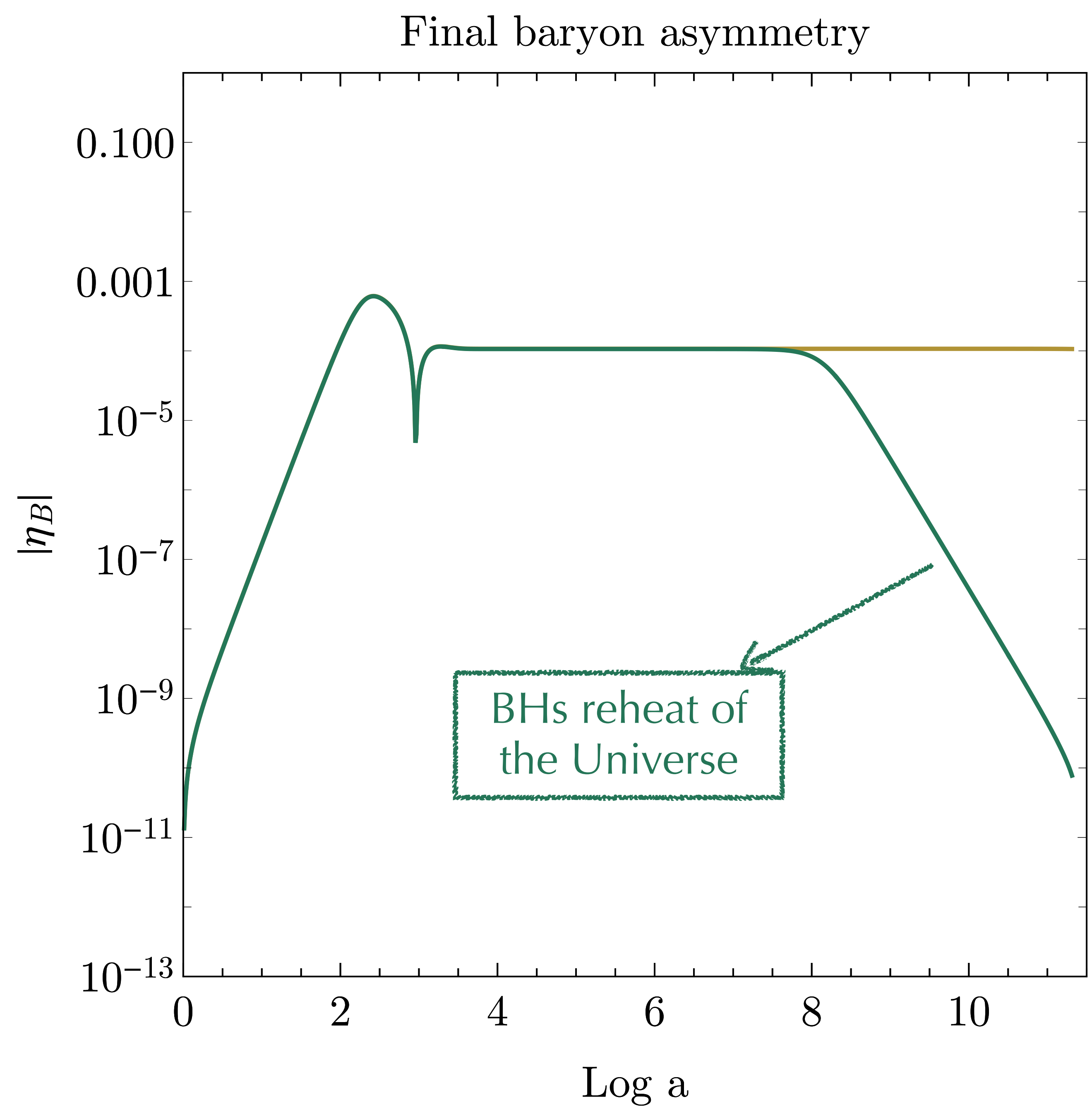
$M_i = 10^2$ g
$\beta_i' = 10^{-3}$



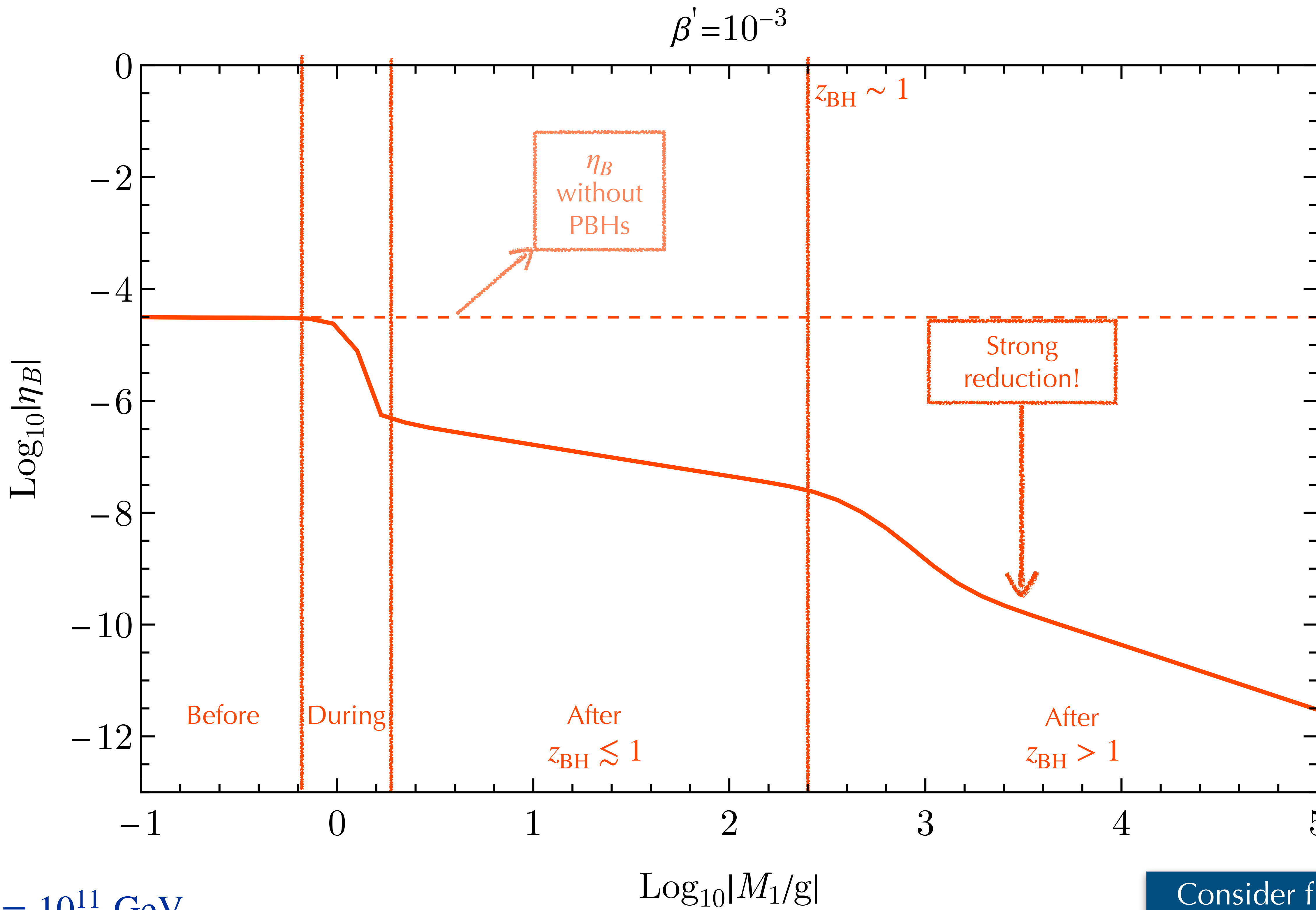
C. PBH create a RH density after the thermal case

$M_i = 10^4$ g
$\beta'_i = 10^{-3}$





$$Y_\nu = \frac{1}{v} U_{\rm PMNS} \sqrt{m_\nu} R^T M_N^T$$



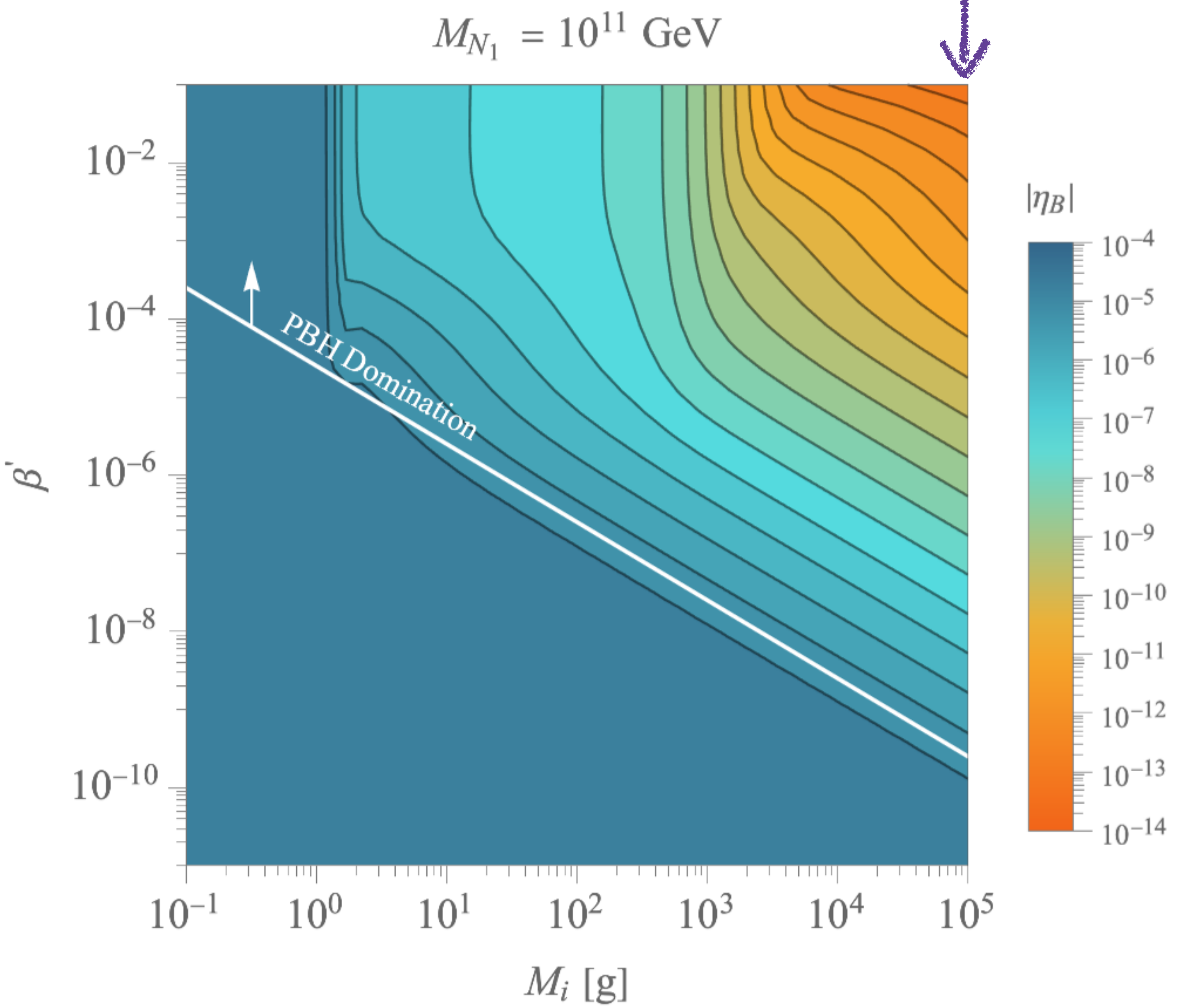
$M_{N_1} = 10^{11}$ GeV

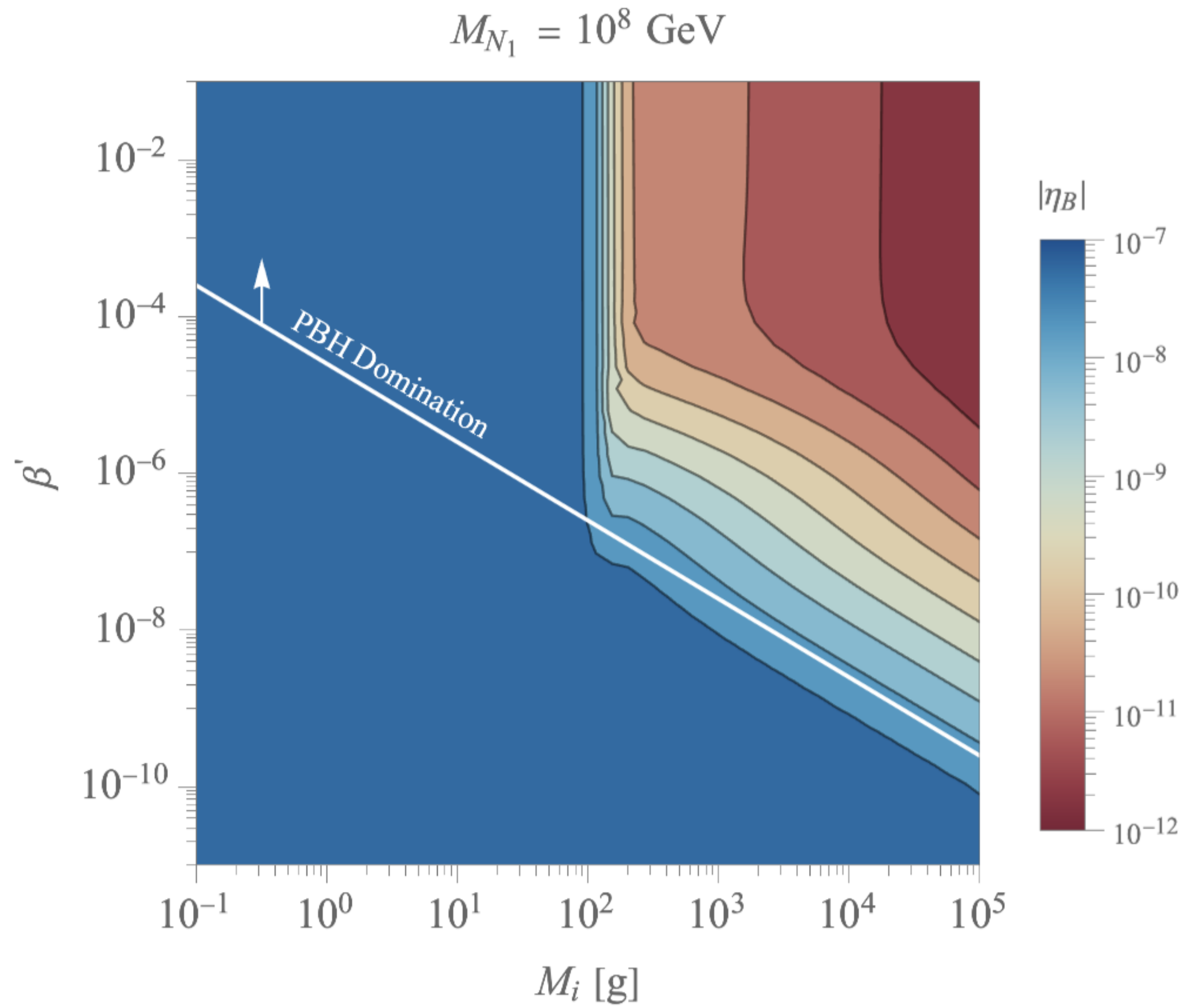
Consider fine-tuned Yukawas

Dependence on β'

How the depletion depends on the initial fraction?

$T_{ev} \gtrsim 150$ GeV*





Entropy dilution is a generic and important feature to be taken into account

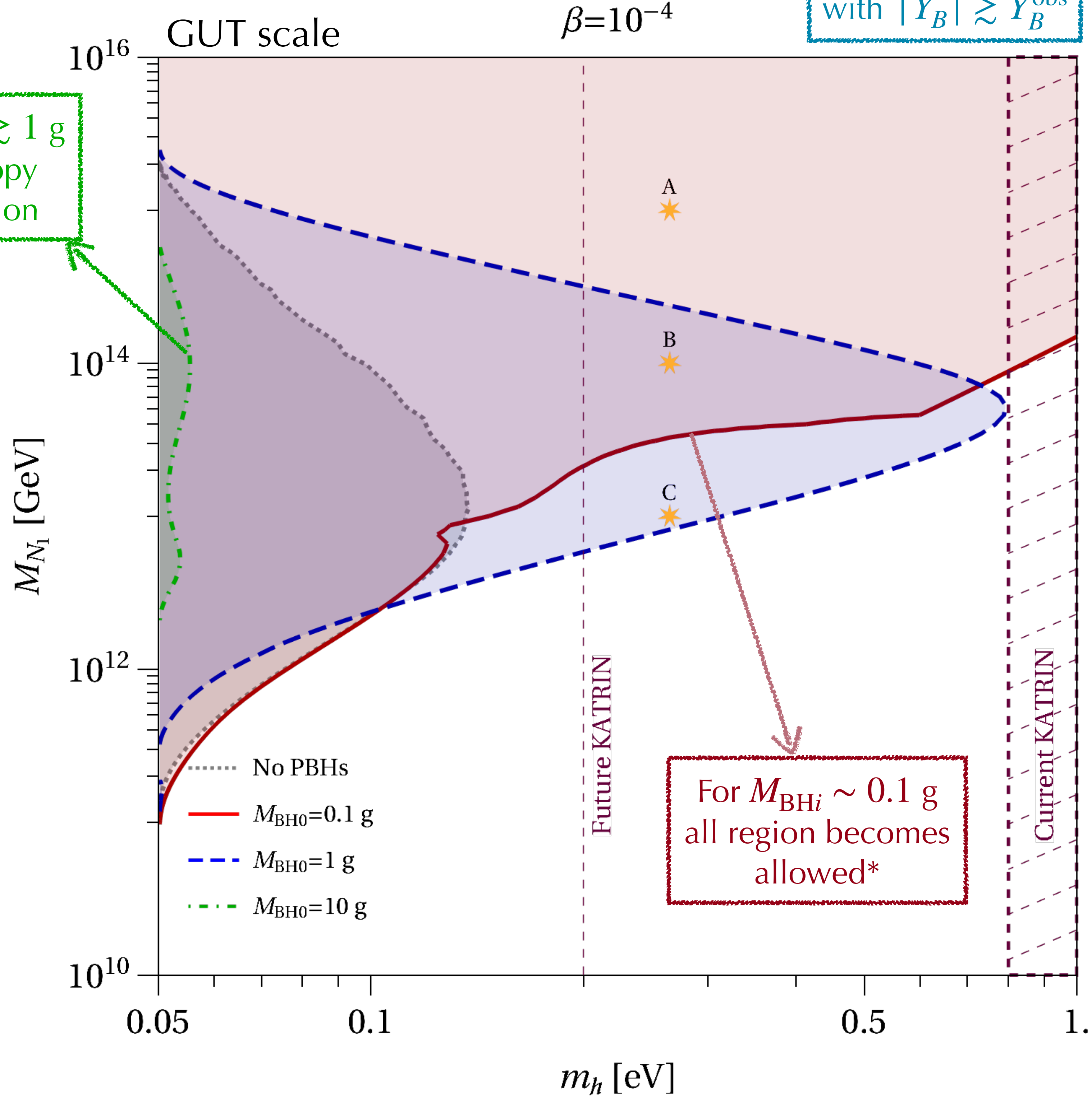
*Sphalerons in the SM plasma

Sphalerons active around PBHs
García-Bellido et al, 1904.11482
De Luca et.al., 2102.07408

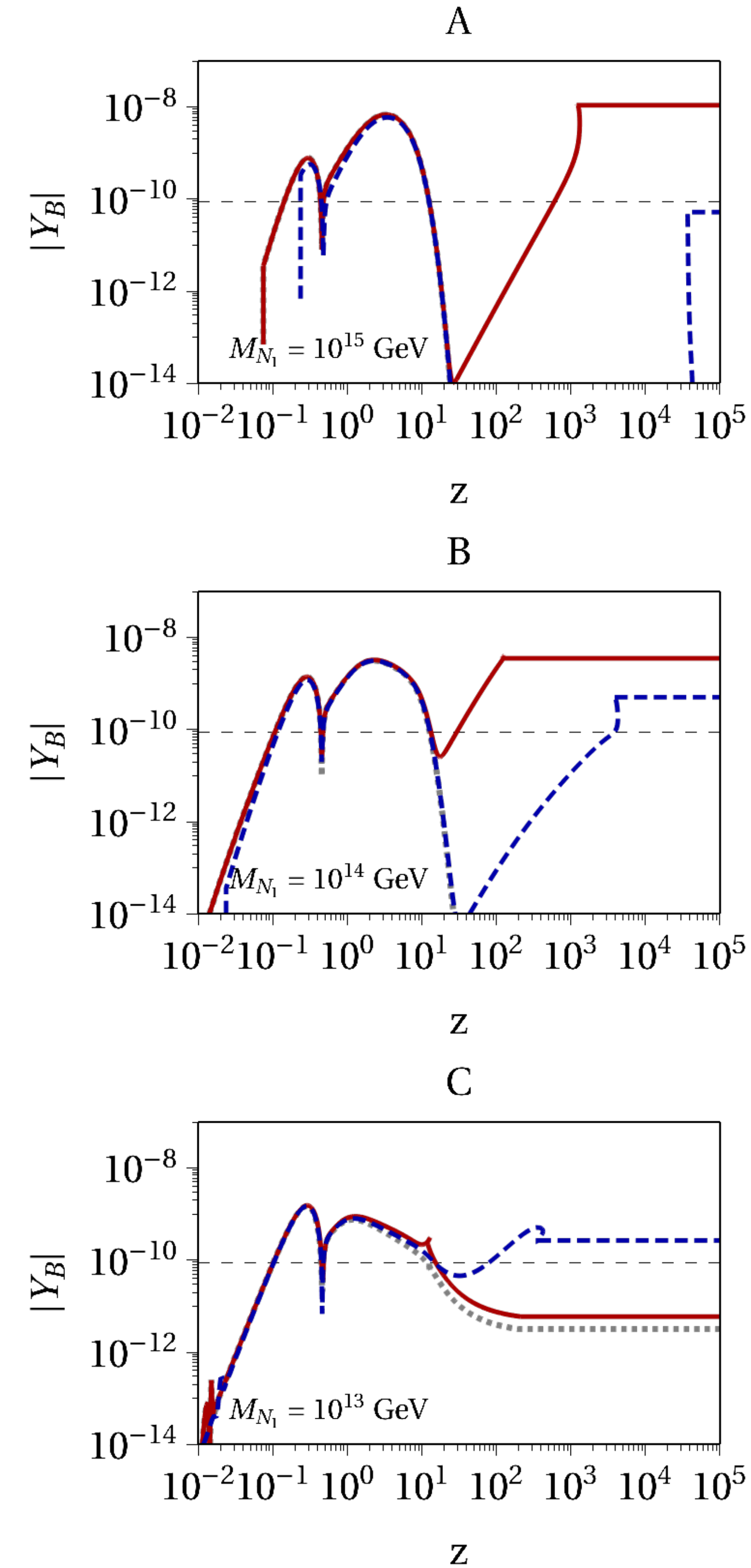
Rescuing HSL

Colored Regions with $|Y_B| \gtrsim Y_B^{\rm obs}$

$M_{{\rm BH}i} \gtrsim 1$ g
Entropy dilution



For $M_{{\rm BH}i} \sim 0.1$ g all region becomes allowed*

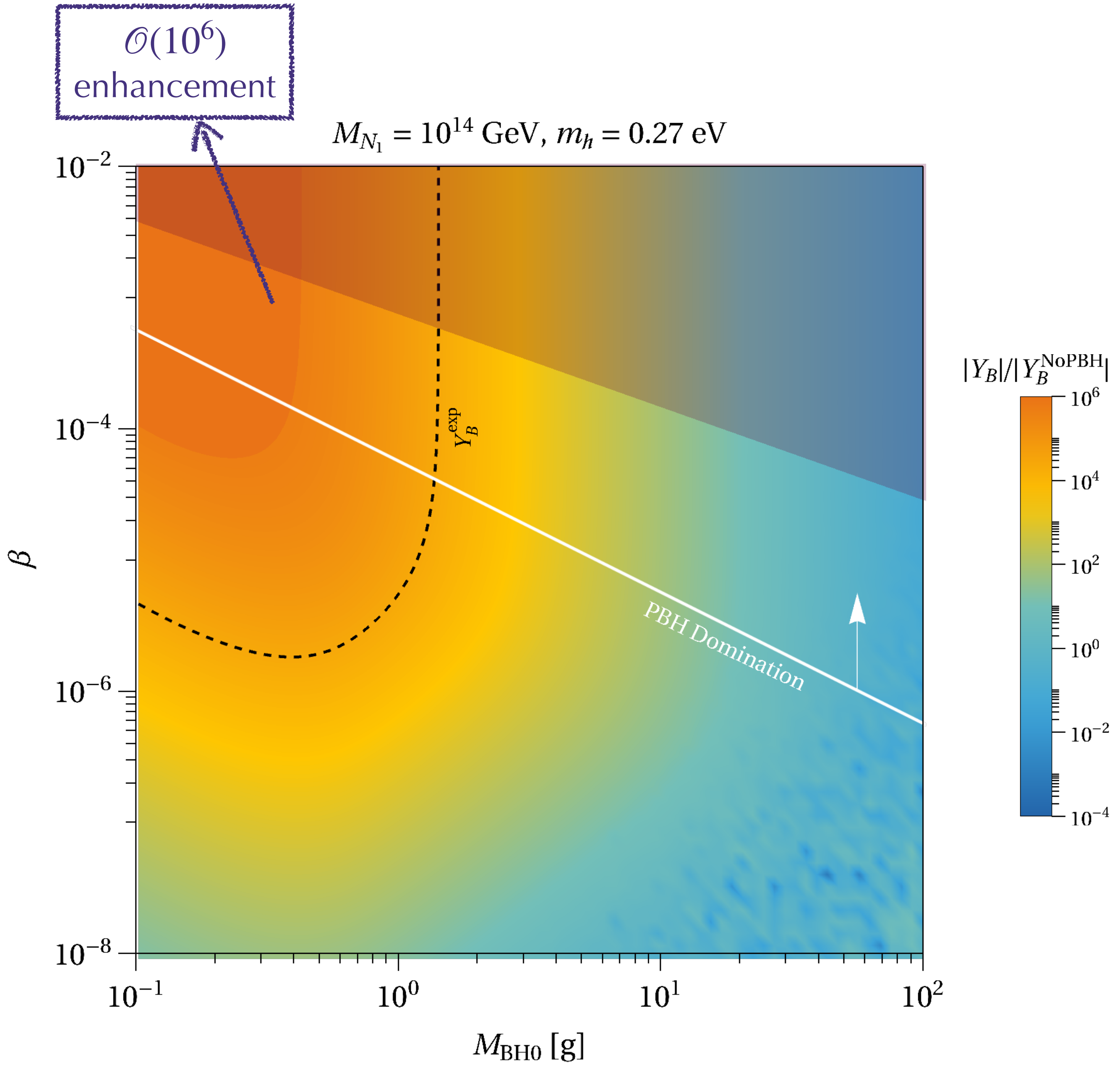


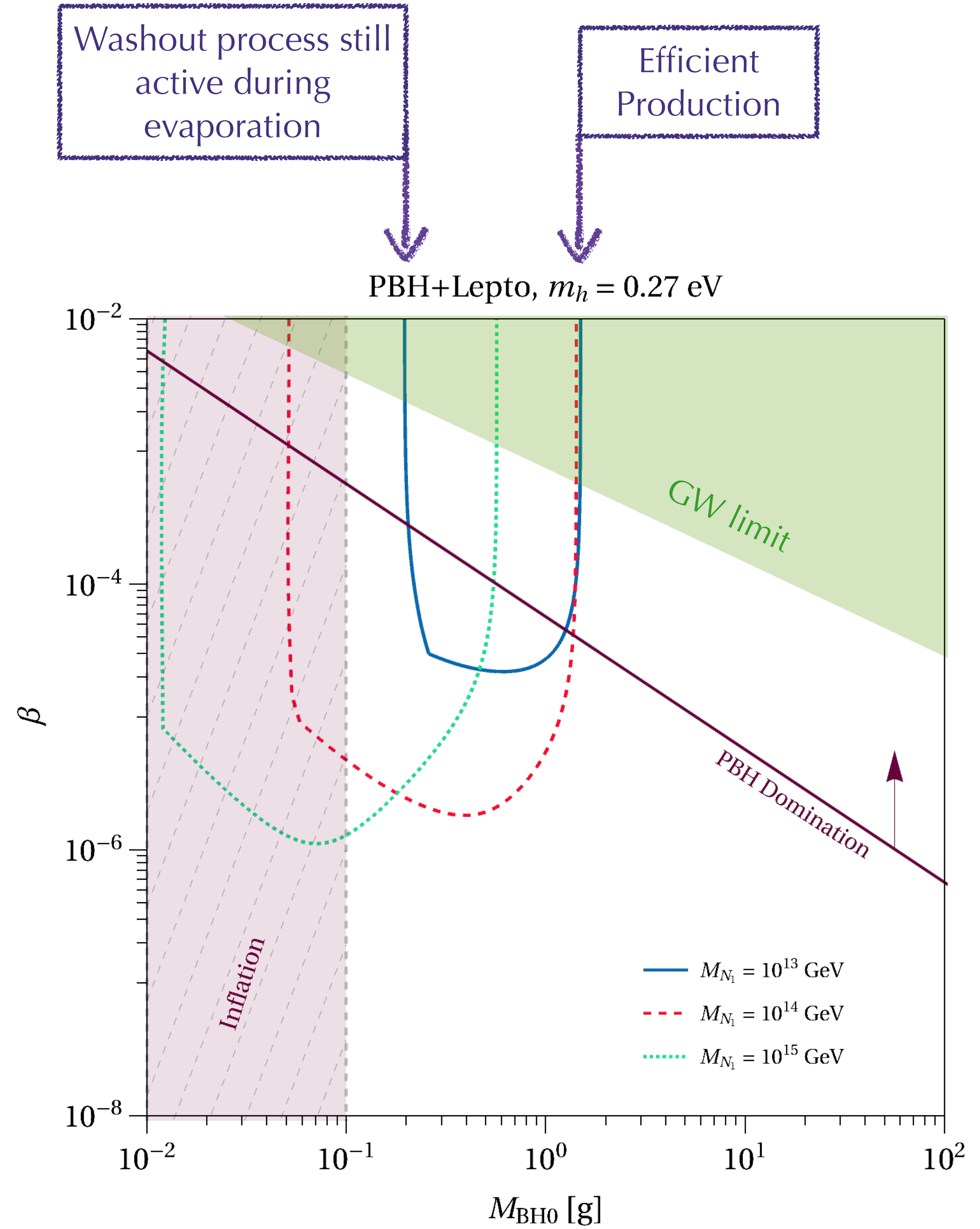
m_h = Heaviest neutrino mass

Maximizing over Yukawa parameters

*Up to perturbativity

Rescuing HSL



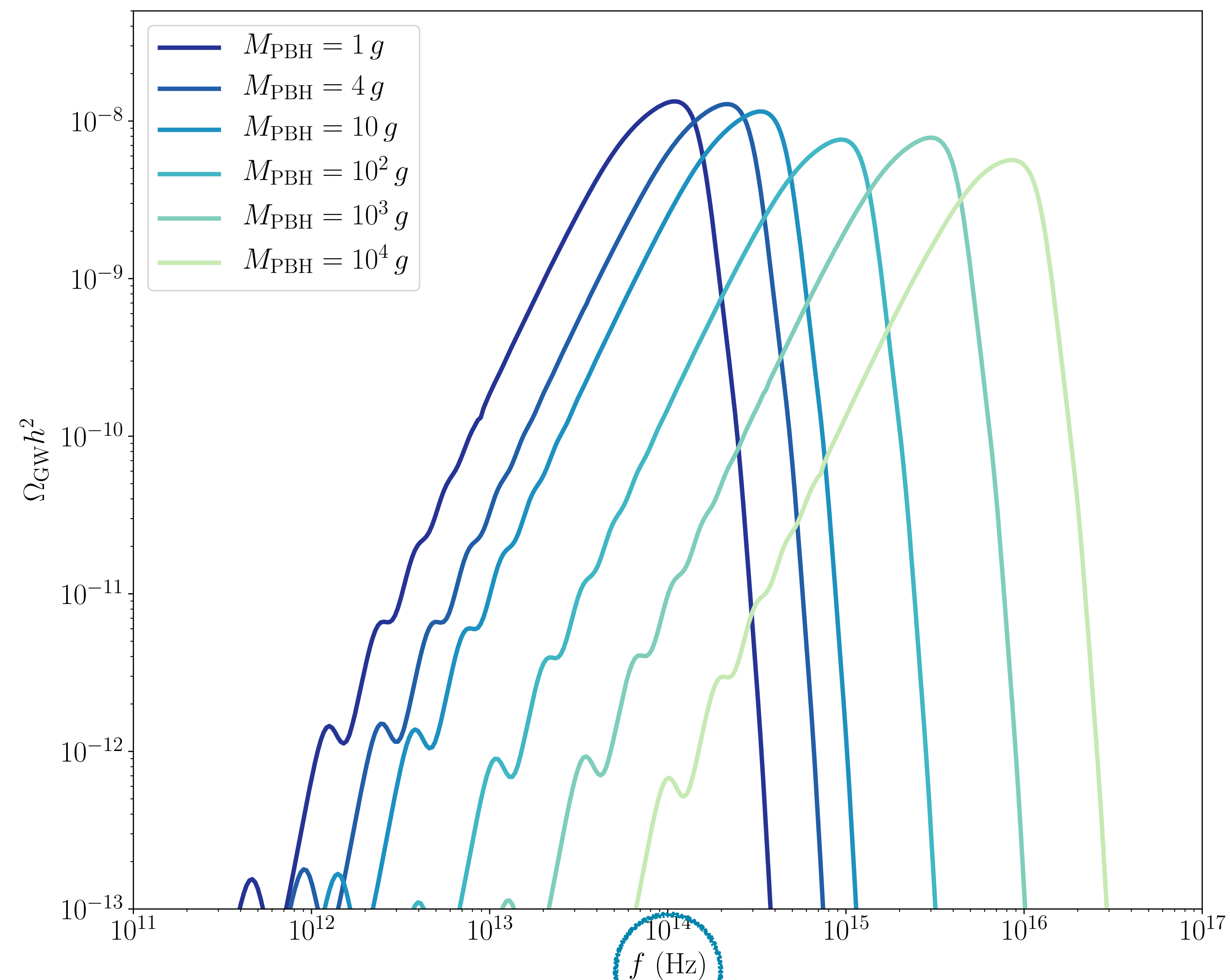


Testing these scenarios?

Gravitational Waves?

How to prove that the early Universe had a PBH-dominated era?

Example: GW produced by the evaporation



Huge frequency!

Arvanitaki, Geraci, 2013

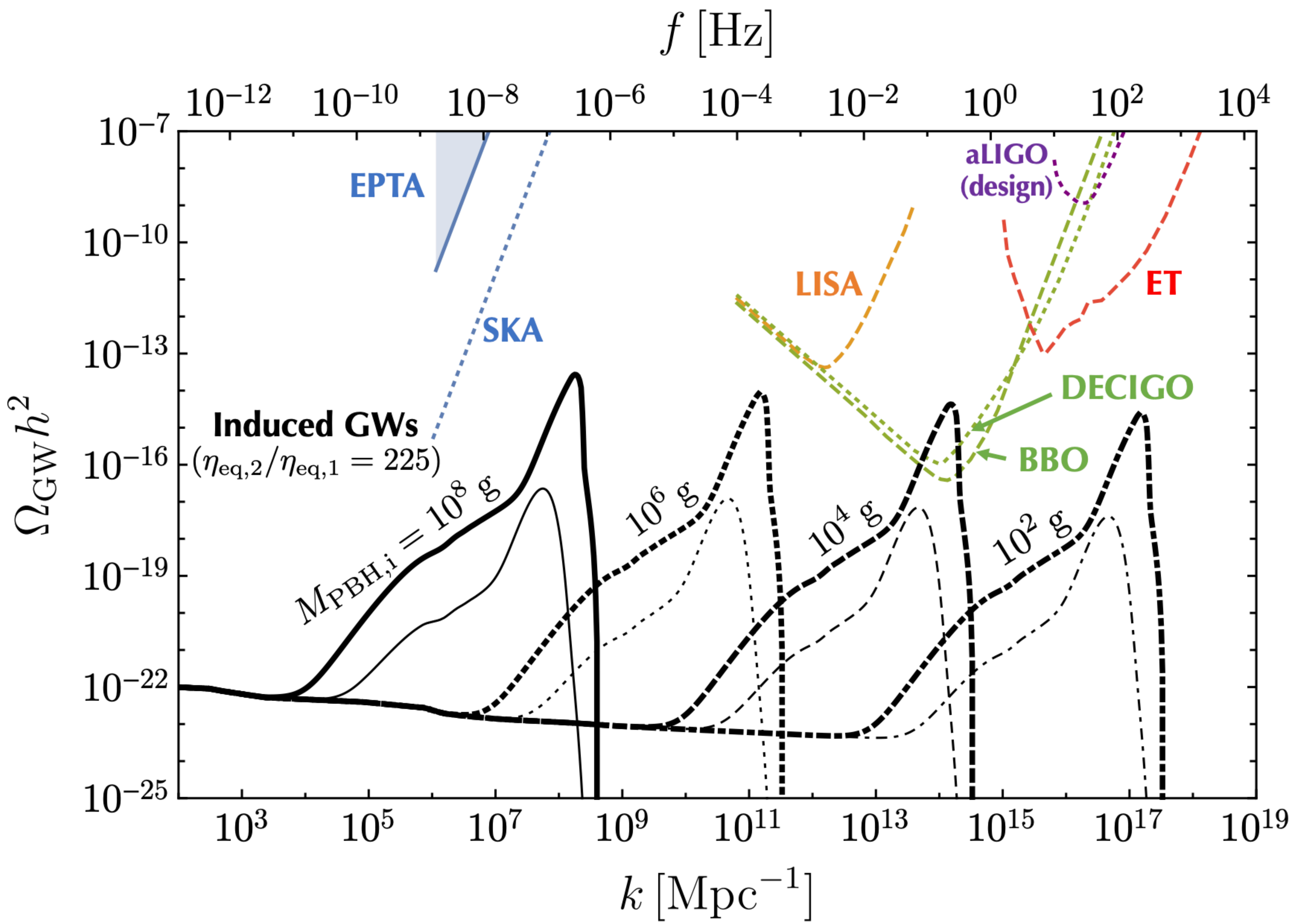
Ito et al, 2020

Chen et al, 2020

Gravitational Waves?

How to prove that the early Universe had a PBH-dominated era?

Poltergeist Mechanism



Sudden transition from a matter to radiation dominated U enhances the GWs

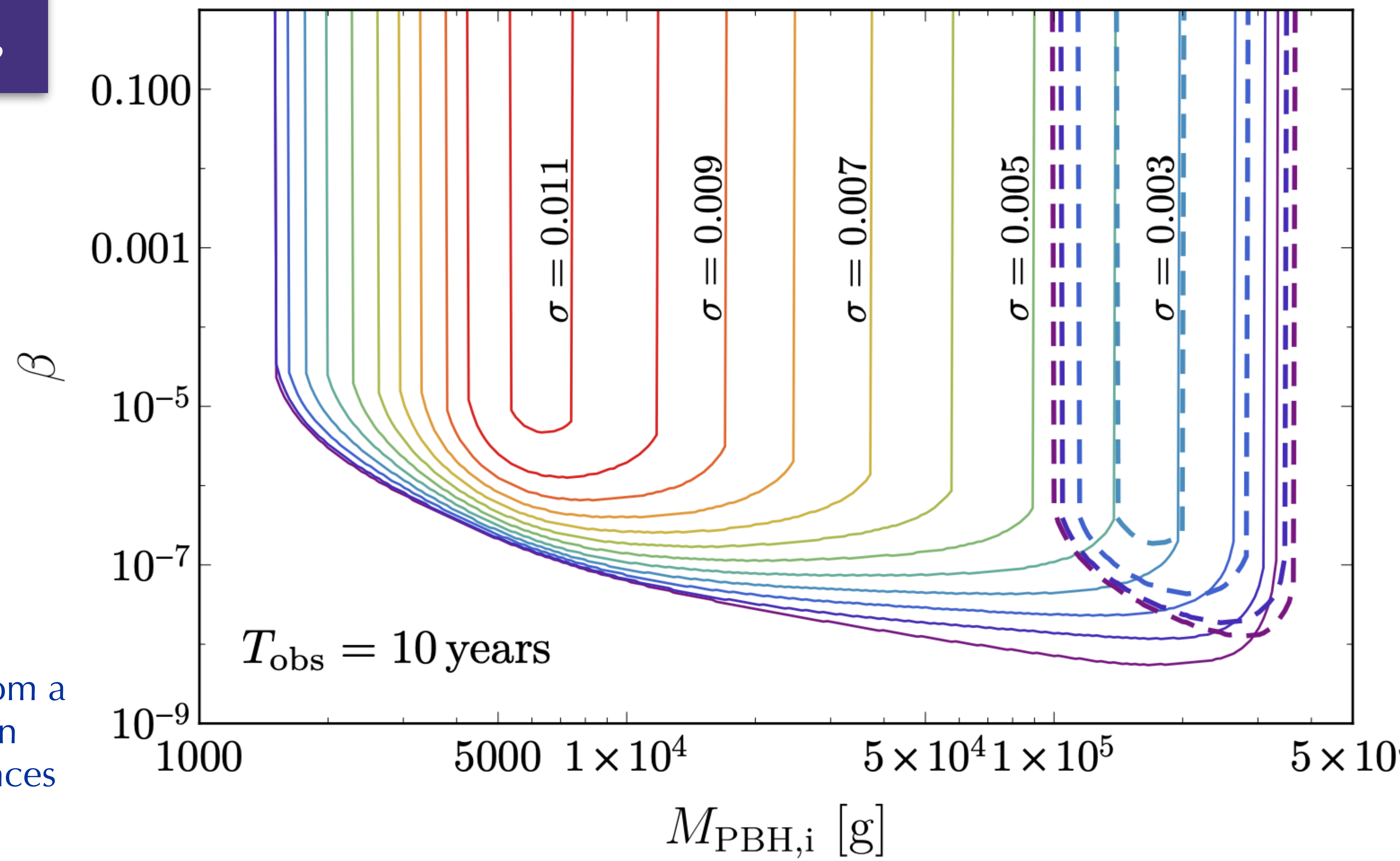
Inomata et al, 2003.10455

See also: 2205.06260

Gravitational Waves?

How to prove that the early Universe had a PBH-dominated era?

Poltergeist Mechanism



Sudden transition from a matter to radiation dominated U enhances the GWs

Inomata et al, 2003.10455

See also: 2205.06260

Falsifying Intermediate scale Leptogenesis?

DECILIGO = Full
LISA = Dashed

In progress

Based on:
Cheek, Heurtier, YFPG, Turner. To appear

Mass Distributions

Monochromatic approximation *too* approximated?

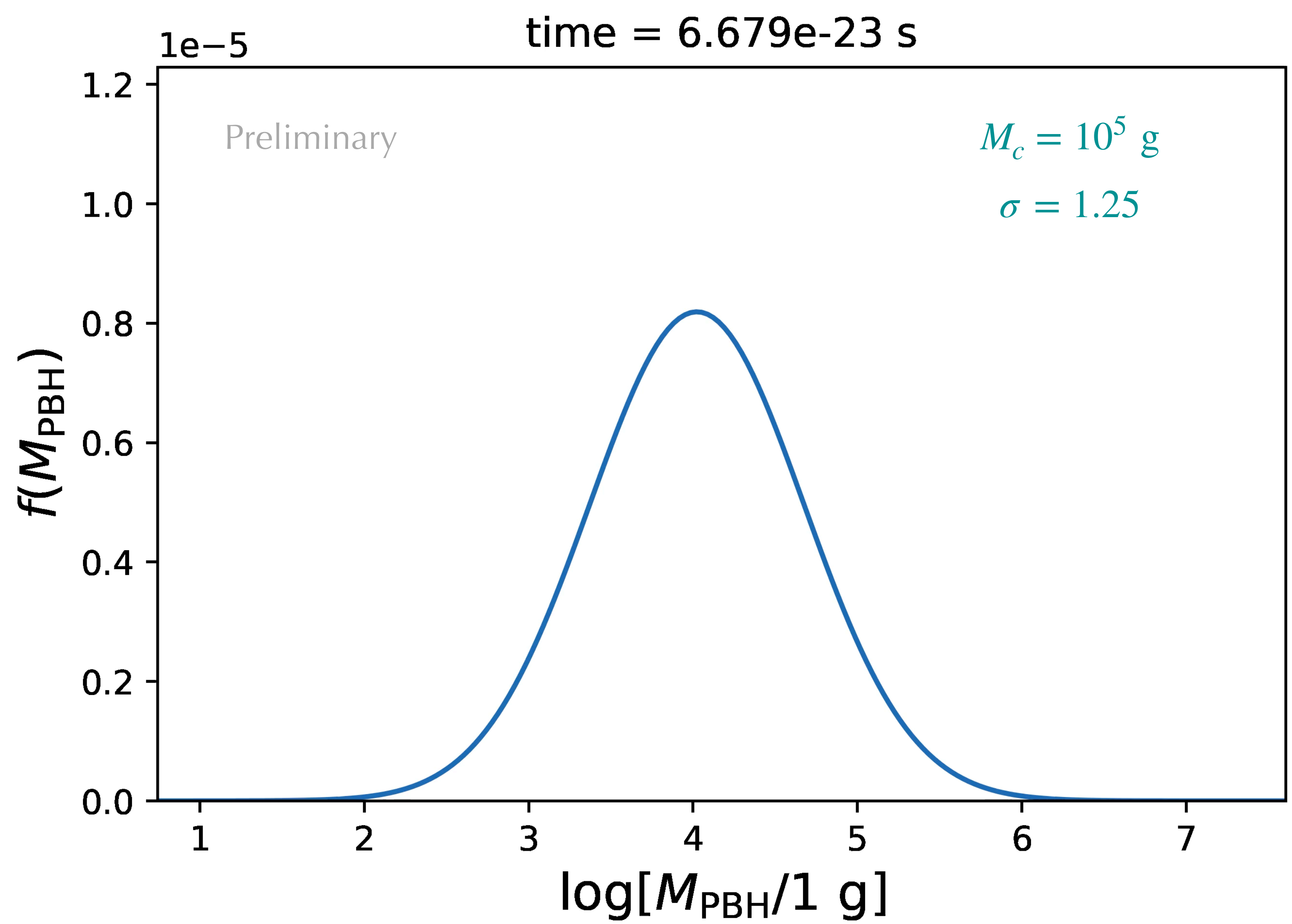
$$n_{\rm PBH} = \int dM\, f(M) \qquad f(M) = \frac{n_{\rm BH}}{\sqrt{2\pi}\sigma M} \exp\left(-\frac{\log^2(M/M_c)}{2\sigma^2}\right)$$

Log-normal distribution

Dolgov, 93
Green, 2016
Kannike, 2017

Connection with different formation mechanisms?

Having PBHs with different masses could have a distinct impact on the previous results



We aim to make our code public!

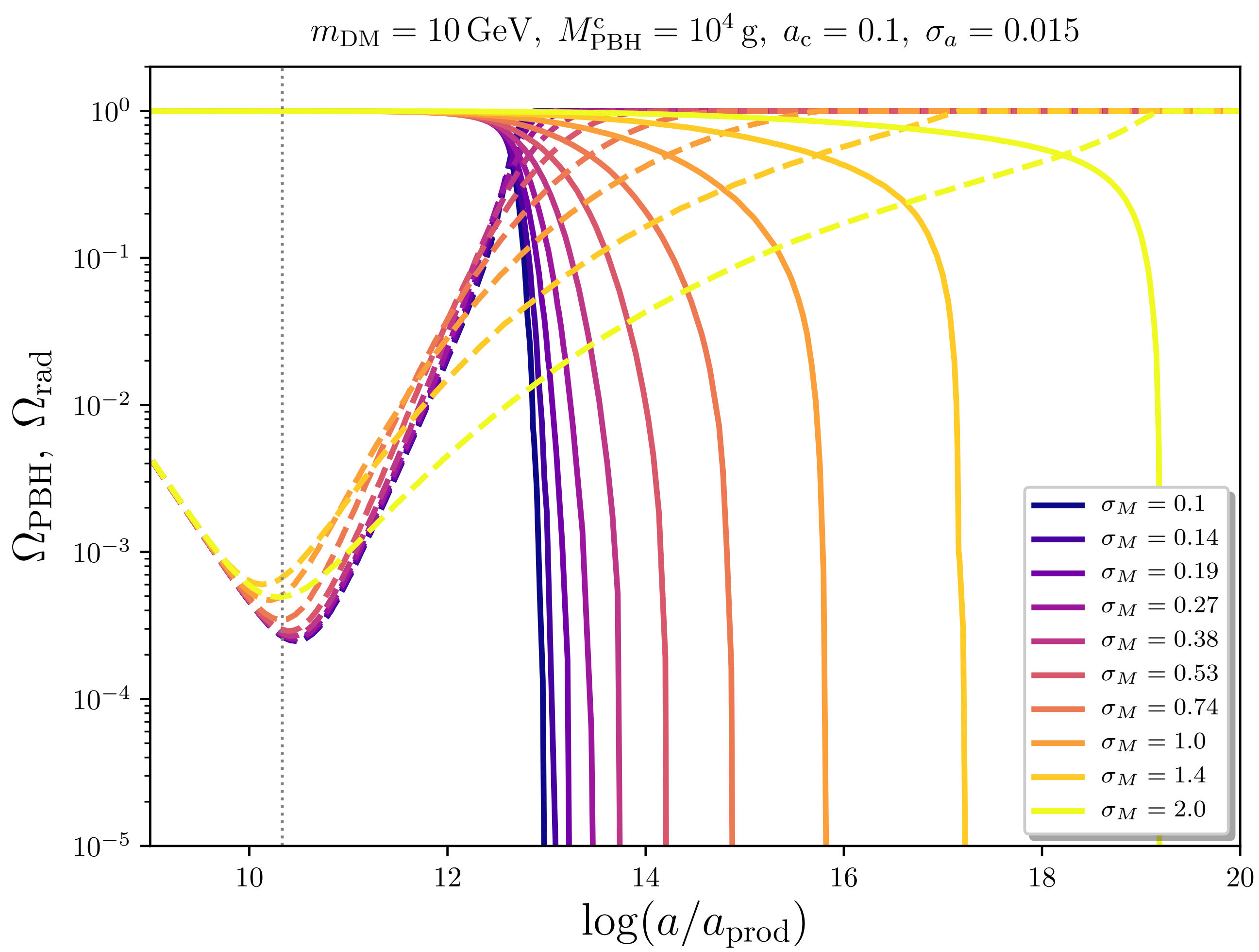
Mass Distributions

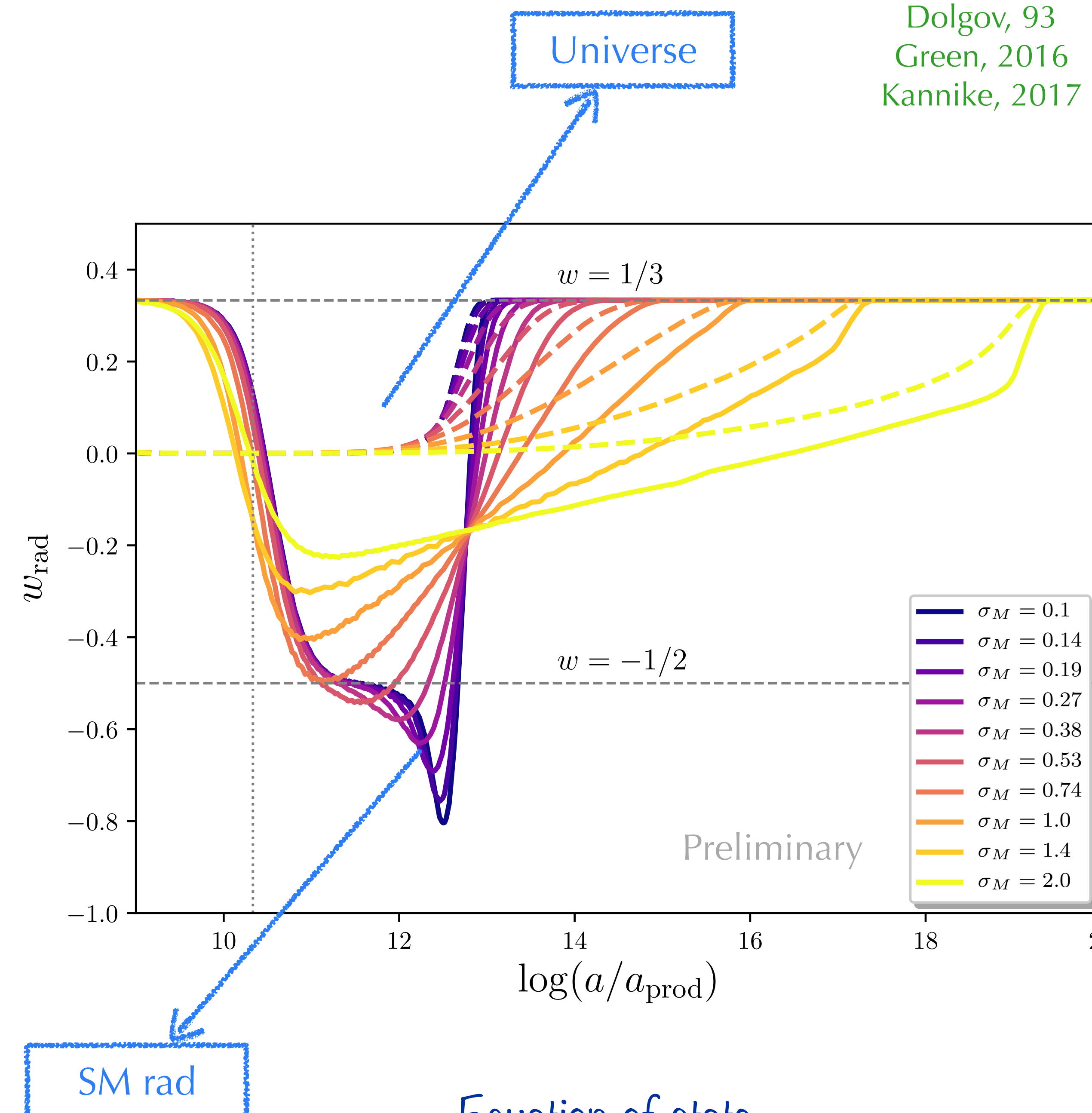
Connection with different formation mechanisms?

$$n_{\rm PBH} = \int dM\, f(M) \qquad f(M) = \frac{n_{\rm BH}}{\sqrt{2\pi}\sigma M}\exp\left(-\frac{\log^2(M/M_c)}{2\sigma^2}\right)$$

Log-normal distribution

Dolgov, 93
Green, 2016
Kannike, 2017





$$p = \omega\rho$$

$$\rho \propto a^{-3(1+\omega)}$$

Equation of state changes significantly

Mass Distributions

Monochromatic approximation *too* approximated?

Connection with different formation mechanisms?

$$n_{\rm PBH} = \int dM\, f(M) \qquad f(M) = \frac{n_{\rm BH}}{\sqrt{2\pi}\sigma M}\exp\left(-\frac{\log^2(M/M_c)}{2\sigma^2}\right)$$

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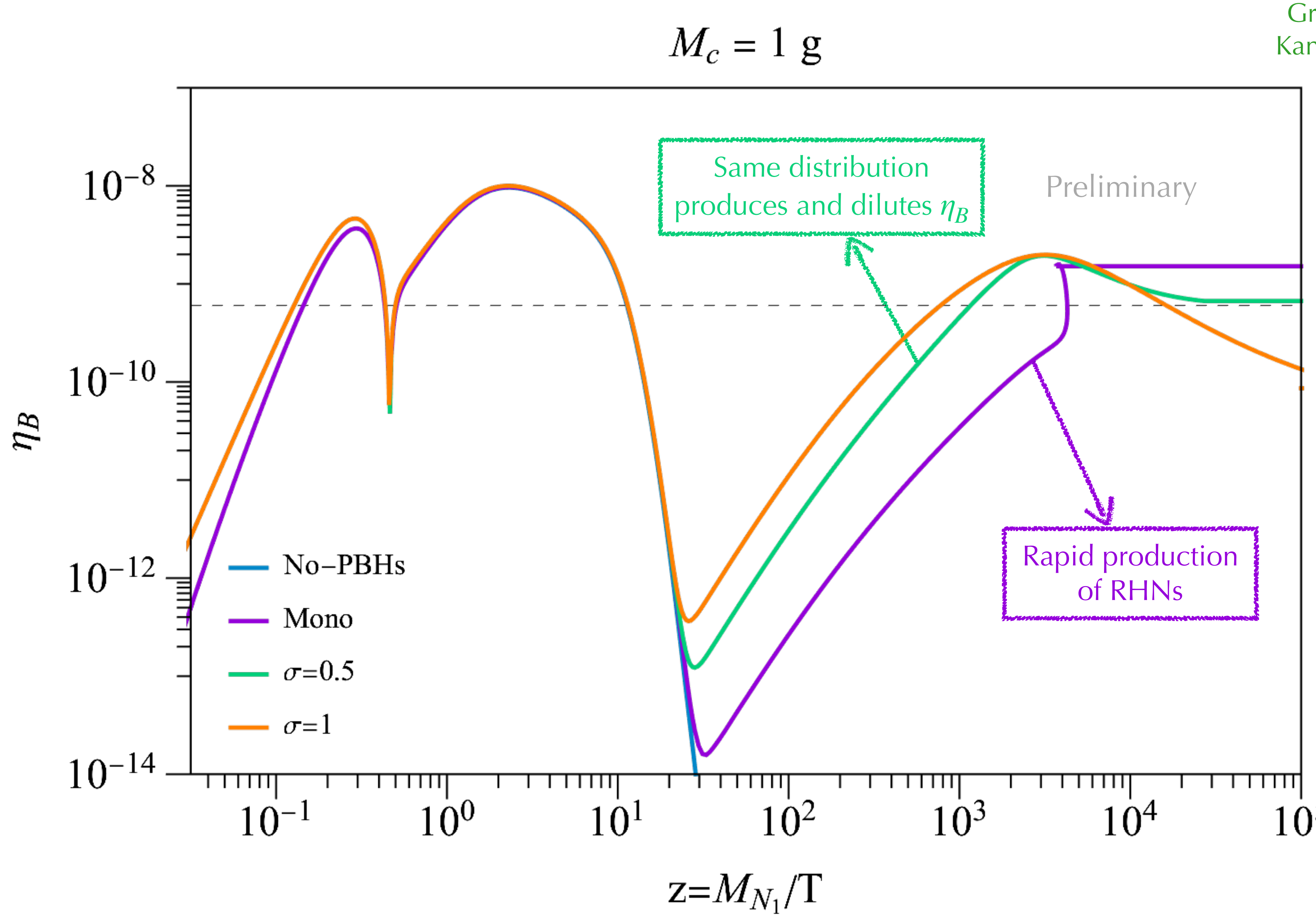


Having PBHs with different masses could have a distinct impact on the previous results

We aim to make our code public!

Conclusions

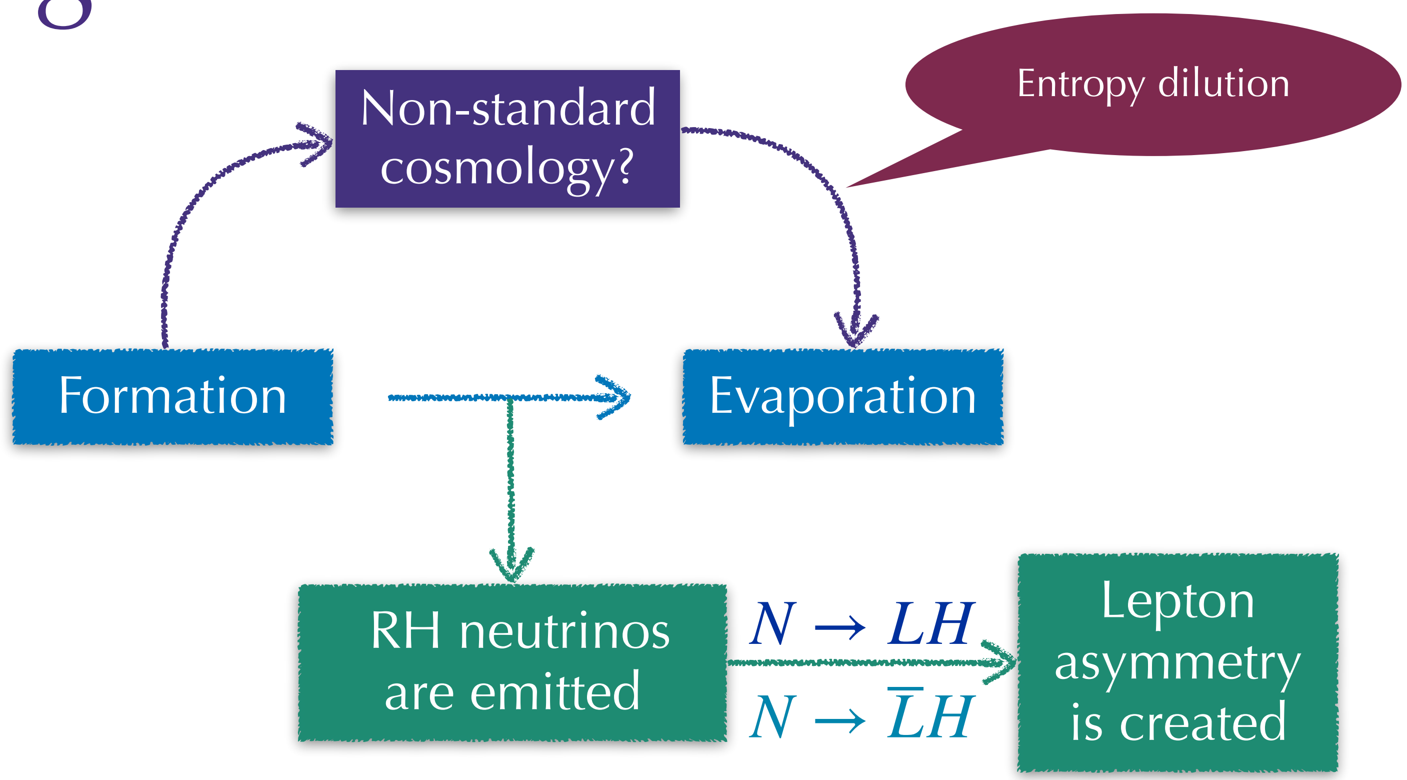
- ✤ PBH evaporation offers a unique mechanism to produce particles in the Early Universe
- ✤ The effects are threefold:
    - Universal particle emission
    - Modifying the Cosmological Background
    - Entropy dilution
- ✤ We explored the effects on leptogenesis assuming the existence of a PBH population
- ✤ Future directions:
    - Relating to "more realistic" PBH formation mechanisms (connected to PBH-DM?)
    - Low scale leptogenesis? Sphalerons around PBHs after EWPT?
    - Kerr PBH $\longrightarrow$ Additional interesting properties!

Thank you for your attention!

Backup

PBH + Leptogenesis

$$z_{\rm BH} \equiv \frac{M_{N_1}}{T_{\rm BH}}$$



Boltzmann Equations

$$aH\frac{dn_{N_1}^{\rm TH}}{da} = -\,(n_{N_1}^{\rm TH} - n_{N_1}^{\rm eq})\Gamma_{N_1}^{T}$$

Thermal contribution

$$aH\frac{dn_{N_1}^{\rm BH}}{da} = -\,n_{N_1}^{\rm BH}\Gamma_{N_1}^{\rm BH} + n_{\rm BH}\Gamma_{\rm BH\to N_1}$$

From the evaporation

Thermally averaged RH neutrino decay

$$aH\frac{dn_{\alpha\beta}^{\rm B-L}}{da} = \epsilon_{\alpha\beta}^{(1)}\left[(n_{N_1} - n_{N_1}^{\rm eq})\Gamma_{N_1}^{T} + n_{N_1}^{\rm BH}\Gamma_{N_1}^{\rm BH}\right] + \mathscr{W}_{\alpha\beta}$$

α, β → Flavor indexes

Evaporation function

$$\varepsilon_N(M) = 2f_1 + 4f_{1/2}^1 \left\{ \sum_{\ell=e,\mu,\tau} \exp\left[-\frac{M}{\beta_{1/2}M_\ell}\right] + 3\sum_q \exp\left[-\frac{M}{\beta_{1/2}M_q}\right] \right\}$$

$$+2\,\eta_\nu^N f_{1/2}^0 \sum_{a=1,2,3} \exp\left[-\frac{M}{\beta_{1/2}M_a}\right]$$

$$+16f_1 \exp\left[-\frac{M}{\beta_1 M_g}\right]$$

$$+3f_1 \left\{ 2\exp\left[-\frac{M}{\beta_1 M_W}\right] + \exp\left[-\frac{M}{\beta_1 M_Z}\right] \right\} + f_0 \exp\left[-\frac{M}{\beta_0 M_H}\right]$$

$$\beta_s = \begin{cases} 2.66 & \text{for } s = 0 \\ 4.53 & \text{for } s = \frac{1}{2} \\ 6.04 & \text{for } s = 1 \end{cases} \qquad f_s = \begin{cases} 0.267 & \text{for } s = 0 \\ 0.060 & \text{for } s = 1 \\ 0.007 & \text{for } s = 2 \end{cases} \qquad f_{1/2}^q = \begin{cases} 0.147 & \text{for } q = 0 \text{ (neutral)} \\ 0.142 & \text{for } q = 1 \text{ (charged)} \end{cases}$$

Dirac vs Majorana

Dirac neutrinos

$$\sigma^{\nu}_{\rm abs}(+1/2) = \sigma^{\nu}_{\rm abs}(-1/2)$$

Unruh, 1976

No helicity suppression

Production of light RH neutrinos!

Cecilia Lunardini, YFPG
JCAP08(2020)014

Majorana neutrinos

Heavy RH neutrinos

↓

PBH-induced Leptogenesis

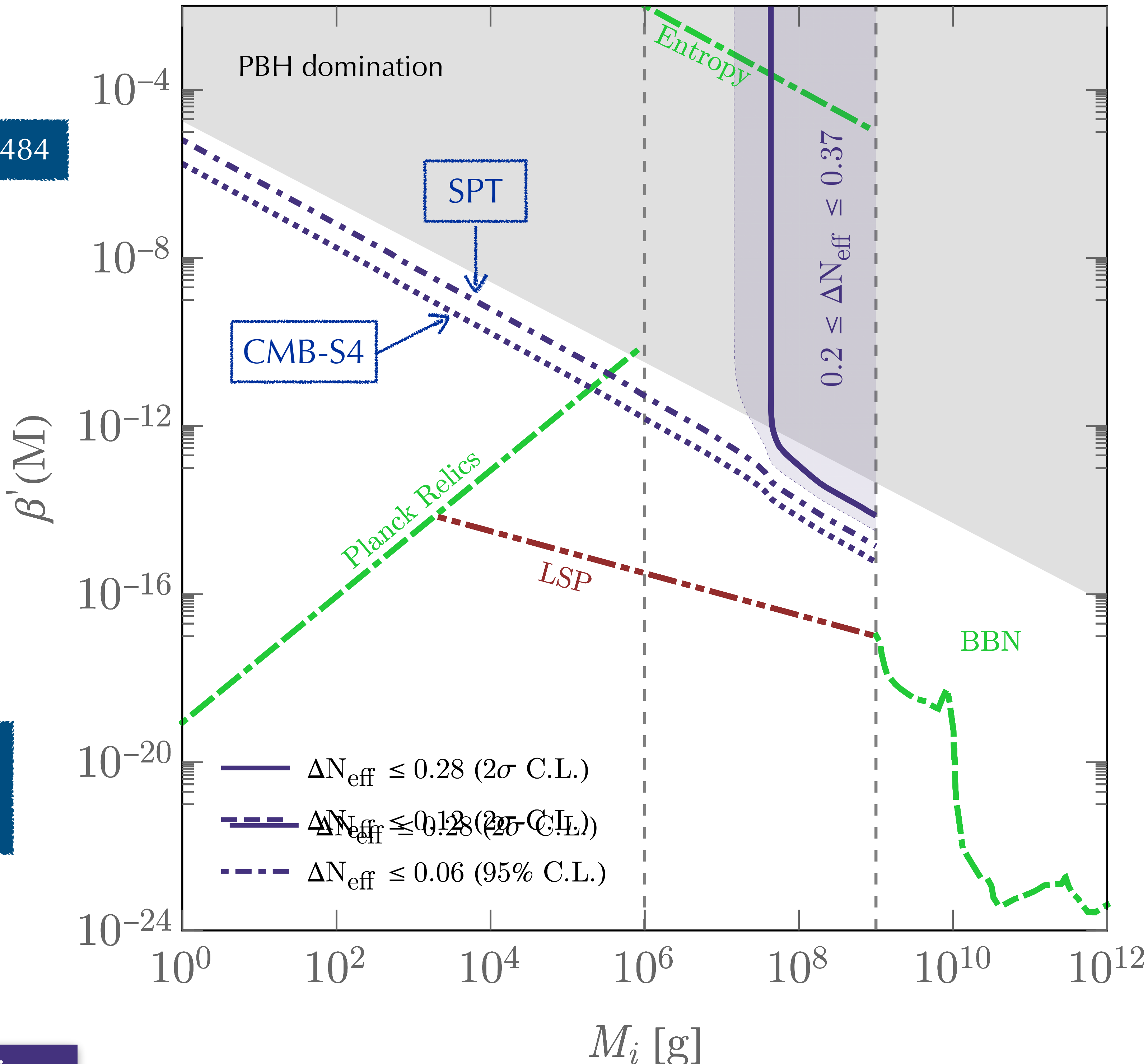
Yamada and Iso, 1610.02586
Morrison et al,1812.10606
Baldes et al, 2004.14773
Hooper and Krnjaic, 2010.01134

YFPG and Jessica Turner,
PRD 104(2021) 103021
Bernal, Fong, YFPG, Turner
2203.08823

Dirac Neutrinos

Green and Liddle, 9903484

MacGibbon, 1987
Barrow et al, 1992
Carr et al, 1994



Zel'dovich et al, 1977

Carr et al, 0912.5297

Alleviate the H_0 tension

What happens when $M \to M_{Pl}$?

Boltzmann Equations

Thermal contribution

$$aH\frac{dn_{N_1}^{\rm TH}}{da} = -\,(n_{N_1}^{\rm TH} - n_{N_1}^{\rm eq})\Gamma_{N_1}^{T}$$

$$aH\frac{dn_{N_1}^{\rm BH}}{da} = -\,n_{N_1}^{\rm BH}\Gamma_{N_1}^{\rm BH} + n_{\rm BH}\Gamma_{\rm BH\to N_1}$$

RH neutrinos emitted from the evaporation

$$z_{\rm BH} \equiv \frac{M_{N_1}}{T_{\rm BH}}$$

Thermally averaged RH neutrino decay

$$aH\frac{dn_{\alpha\beta}^{\rm B-L}}{da} = \epsilon_{\alpha\beta}^{(1)}\left[(n_{N_1} - n_{N_1}^{\rm eq})\Gamma_{N_1}^{T} + n_{N_1}^{\rm BH}\Gamma_{N_1}^{\rm BH}\right] + \mathscr{W}_{\alpha\beta}$$

α, β → Flavor indexes

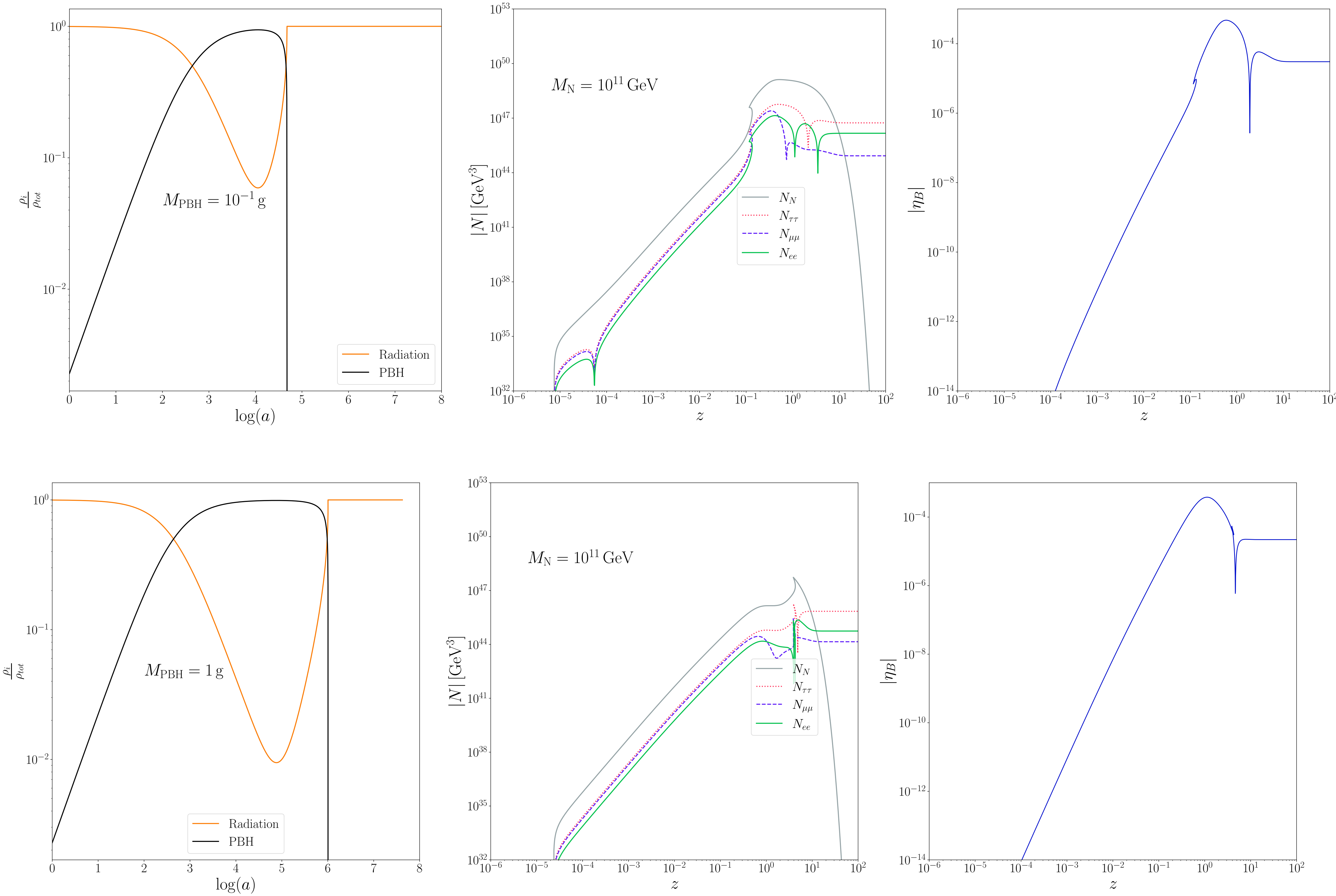
$$\Gamma_{\rm BH\to N_1} \equiv \int_0^\infty \frac{d^2\mathcal{N}_{N_1}}{dp\,dt}dp$$

$$\approx \frac{27T_{\rm BH}}{32\pi^2}\left(-z_{\rm BH}{\rm Li}_2(-e^{-z_{\rm BH}}) - {\rm Li}_3(-e^{-z_{\rm BH}})\right)$$

$$\Gamma_{N_1}^{\rm BH} \equiv \left\langle \frac{M_{N_1}}{E_{N_1}} \right\rangle_{\rm BH} \Gamma_{N_1}^0 \approx \frac{\mathscr{K}_1(z_{\rm BH})}{\mathscr{K}_2(z_{\rm BH})}\Gamma_{N_1}^0$$

Boltzmann Equations

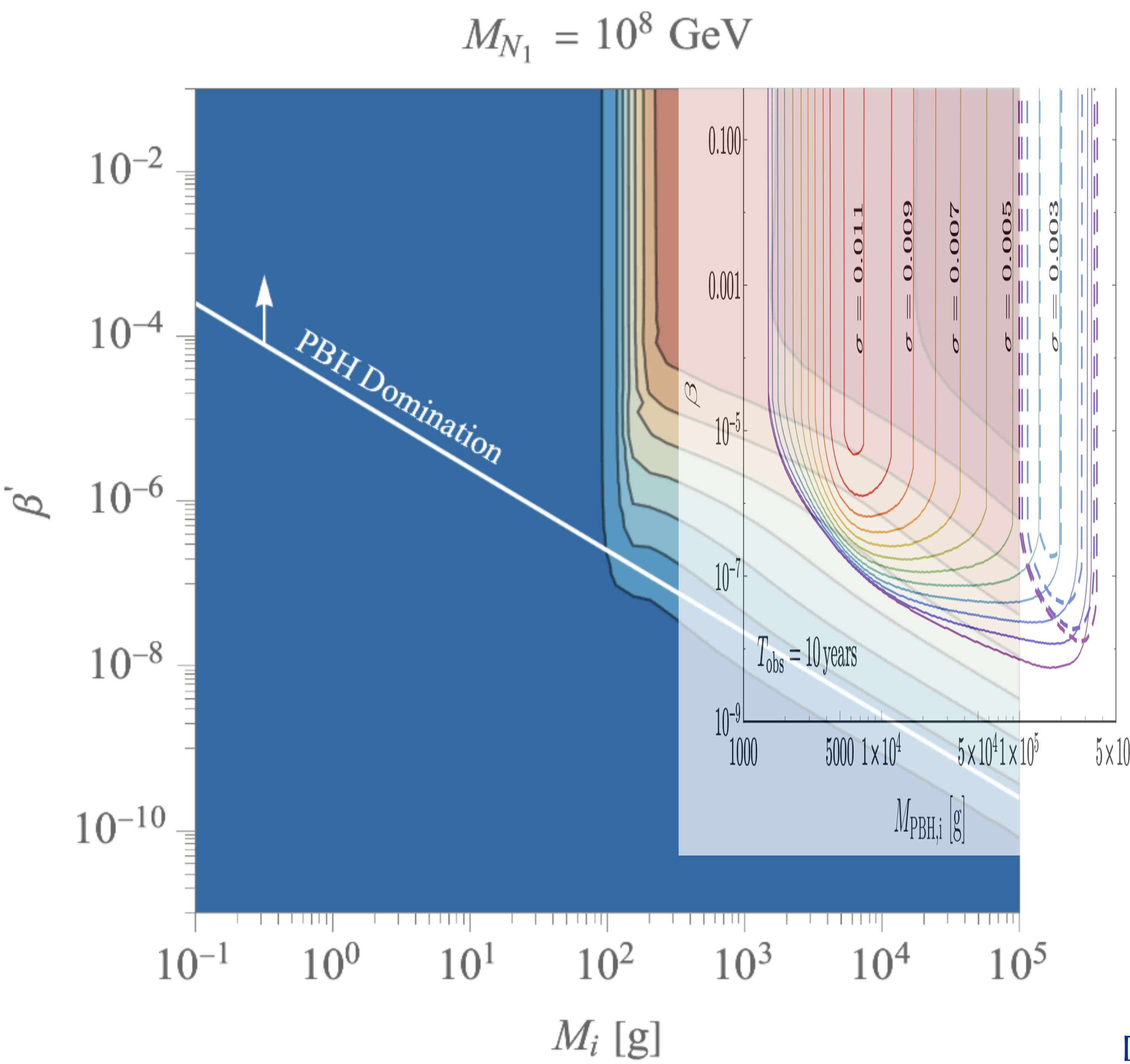
$$z_{\rm BH} \equiv \frac{M_{N_1}}{T_{\rm BH}}$$



Gravitational Waves?

How to prove that the early Universe had a PBH-dominated era?

Poltergeist Mechanism



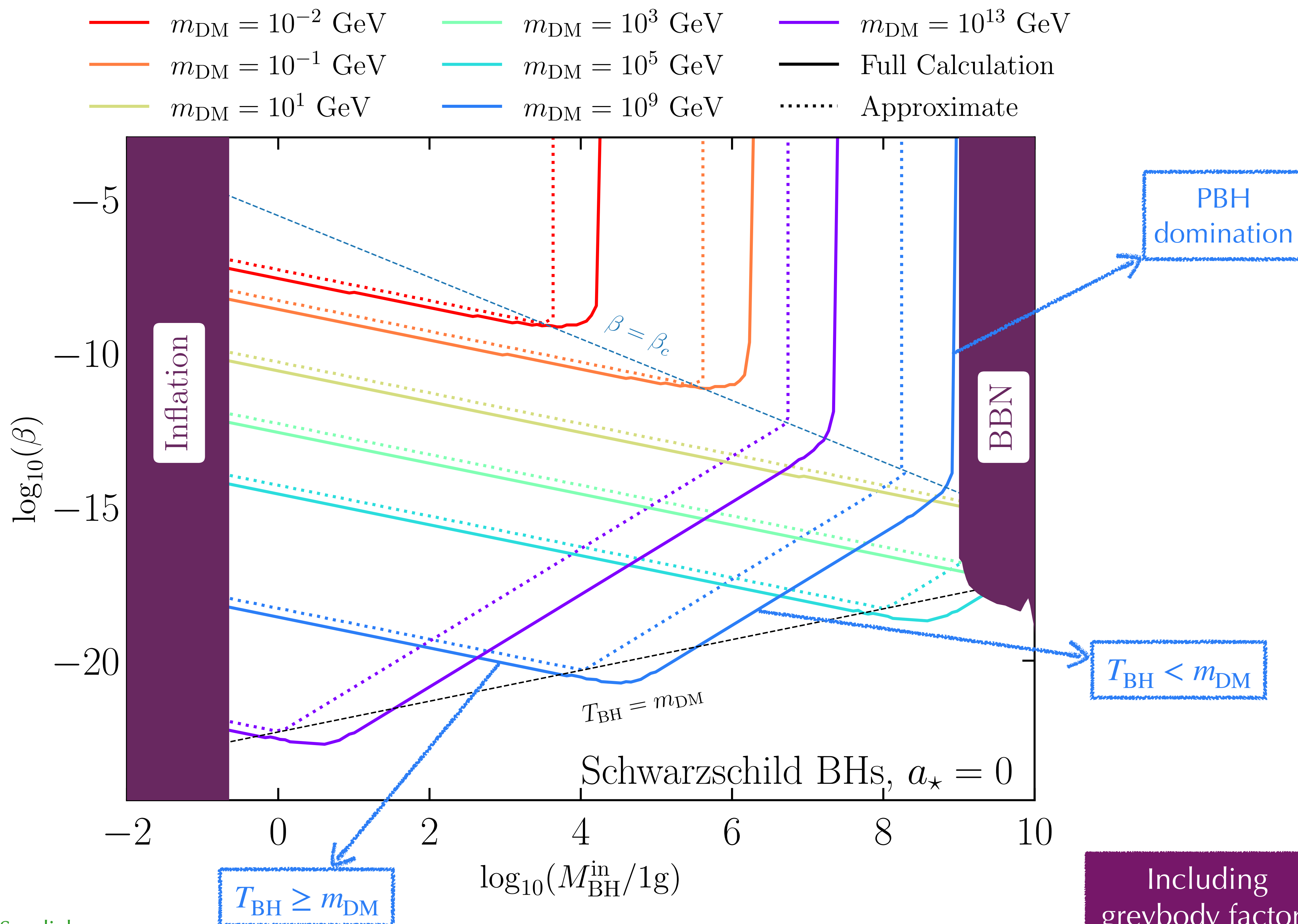
Sudden transition from a matter to radiation dominated U enhances the GWs

Inomata et al, 2003.10455

See also: 2205.06260

DECILIGO = Full
LISA = Dashed

Only Gravitational Interacting DM



Including greybody factors

Dashed from Gondolo, Sandick, Shams Es Haghi 2009.02424

Freeze-Out

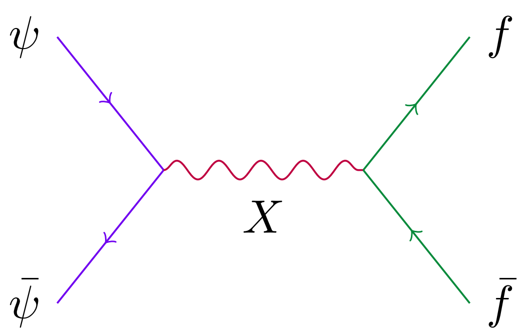
What would be the interplay with other DM production mechanisms?

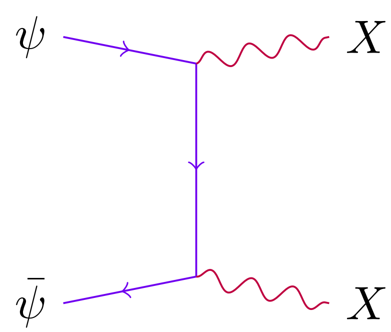
Assume a dark $U(1)_X$

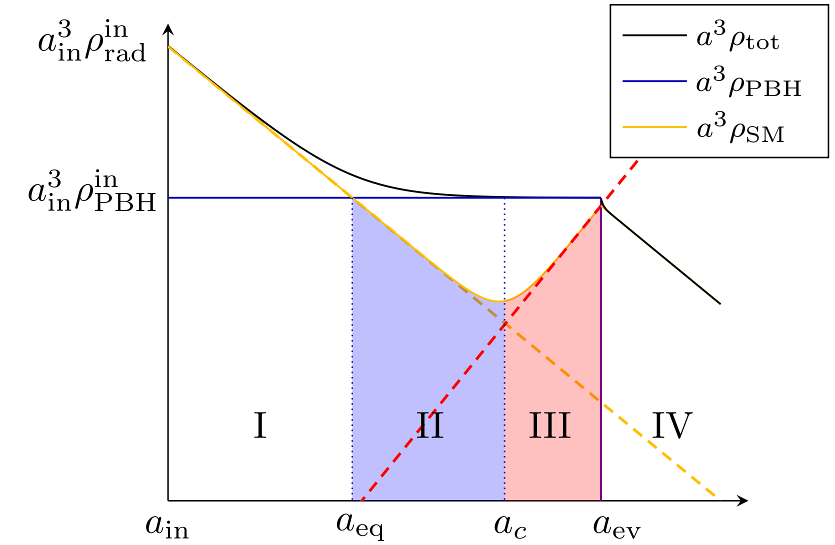
$\psi \longrightarrow$ DM

$X \longrightarrow$ Mediator

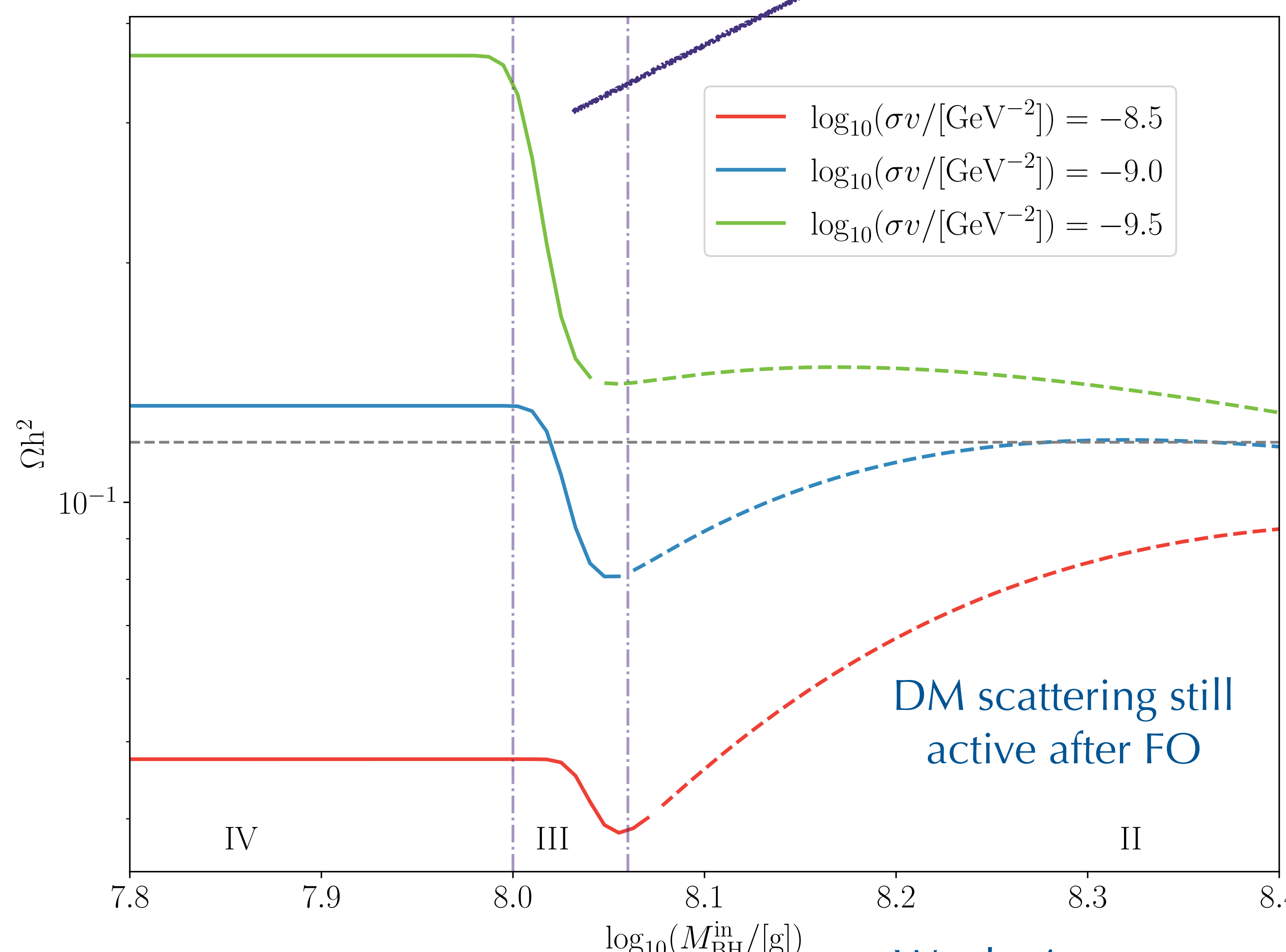
$f \longrightarrow$ SM fermions







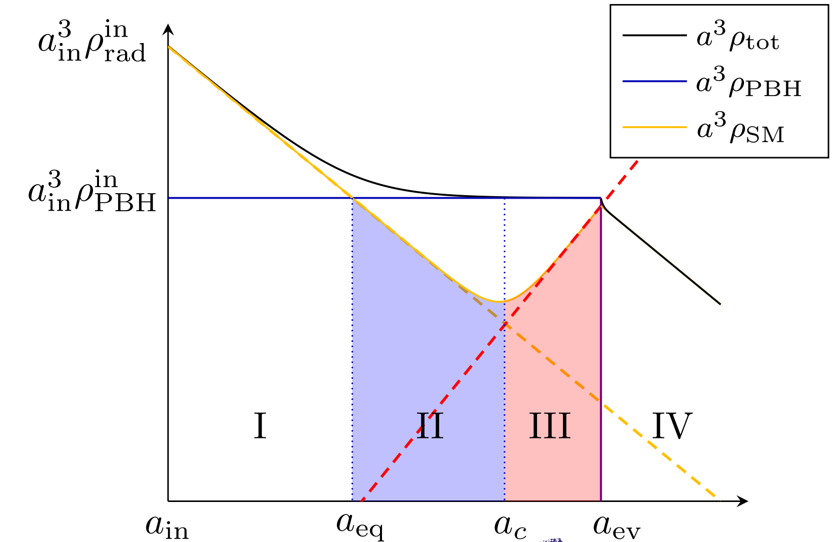
Entropy dilution

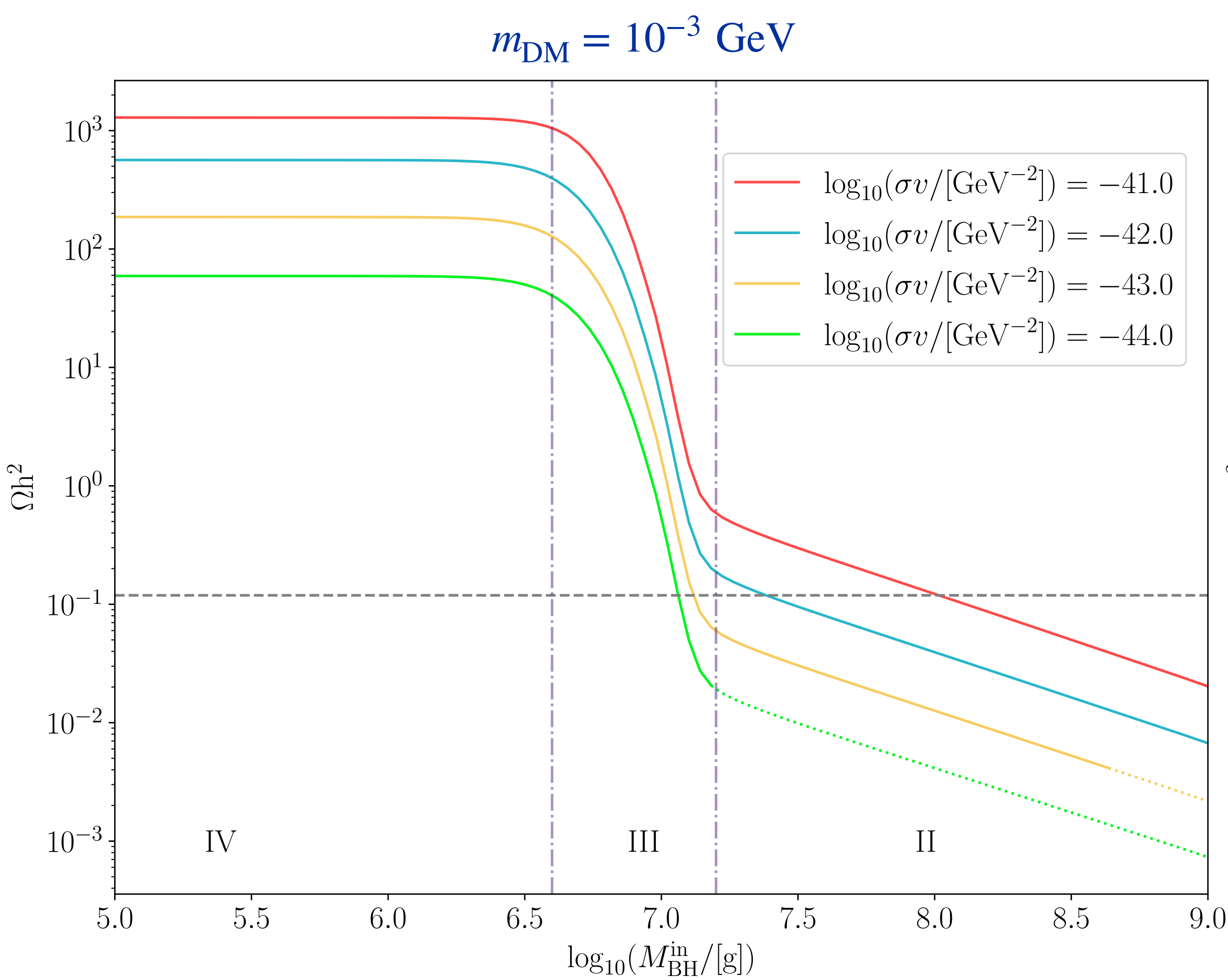


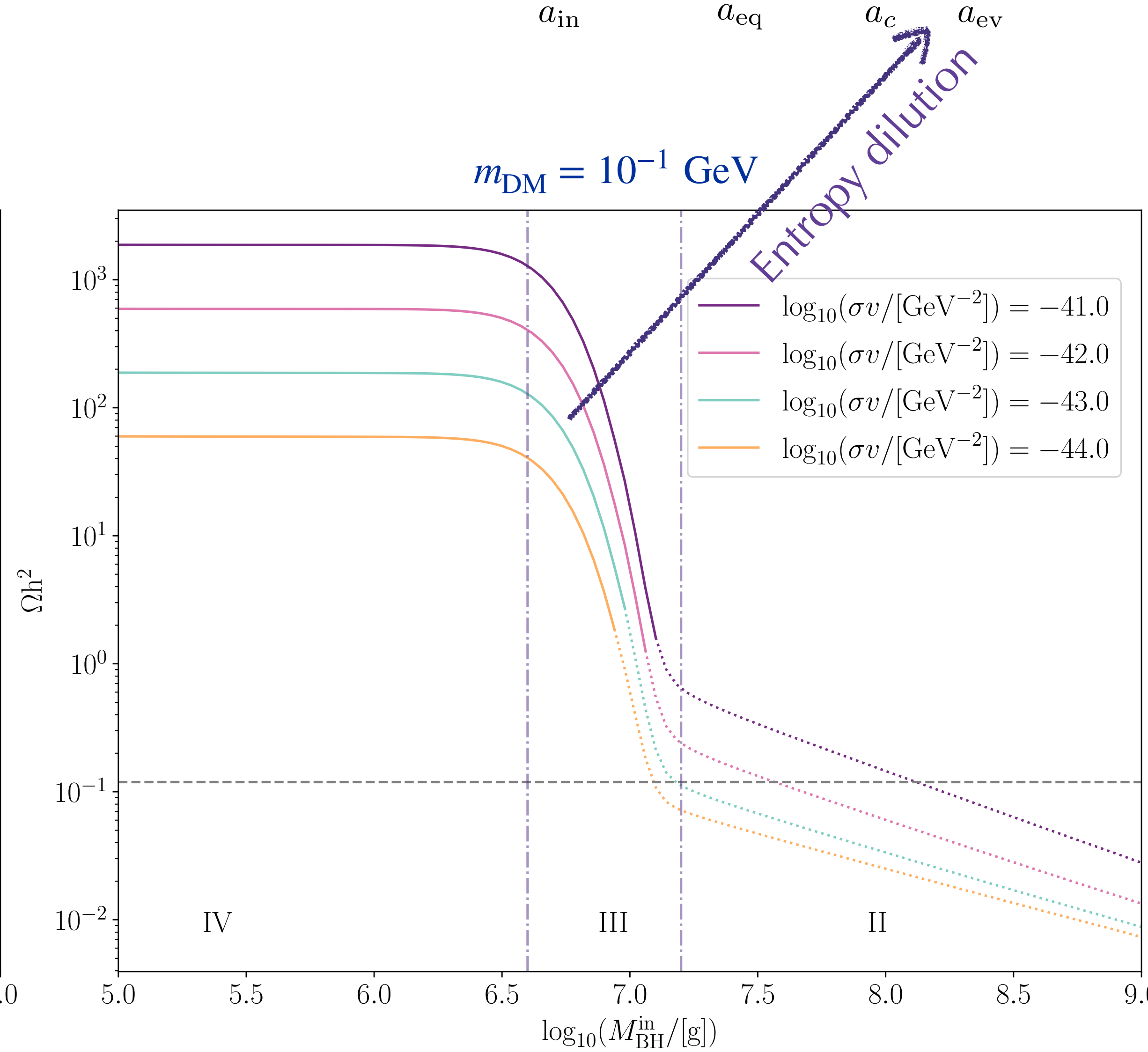
We don't trust our code in this region…

Freeze-In

Overproduction is "cured" with the dilution







$m_X = 10$ GeV

Dotted lines: Warm DM constraints