Leptogenesis via absorption by primordial black holes

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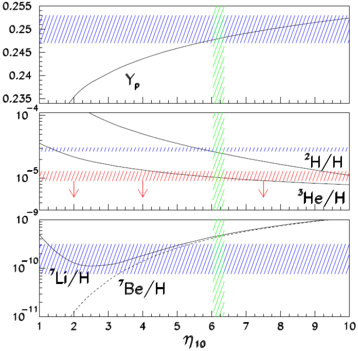
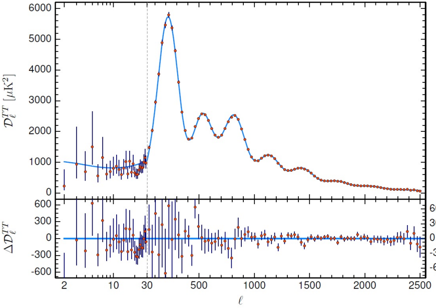
Outline

- **Introduction**
- Primordial black holes & baryogenesis
- Asymmetric capture
- Asymmetry evolution

Baryon asymmetry of the Universe (BAU)

$$\eta_b \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.14 \pm 0.19) \times 10^{-10}. \text{ [PDG]} \qquad (1)$$





[Planck 2018]

[Iocco, Mangano, Miele, Pisanti, Serpico, Phys. Rept. 472 (2009) 1]

Sakharov conditions

A non-zero baryon asymmetry can be obtained via particle interactions if [Sakharov, JETP Lett. 5 (1967) 24]

- B-**number is not conserved**
- C and CP symmetries are violated (CPV)
- Processes are not in thermal equilibrium

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BAU cannot be explained only within Standard Model (SM).

B (and L) numbers are not exactly conserved in SM. At $T > T_{EW} \simeq 160\,\text{GeV}$ $(B+L)_L$-violating processes proceed in thermal equilibrium.

$B/3 - L_\alpha$ numbers are still conserved, $\alpha = e, \mu, \tau$

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Black holes in the early Universe (PBH)

Region collapses into PBH with $M \simeq m_{Pl}^2 t$ if

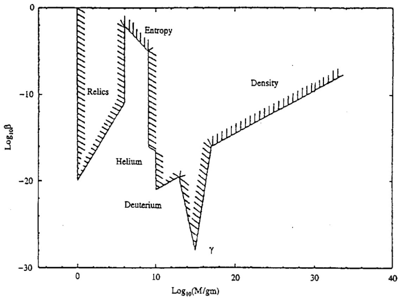
$$\frac{\delta\rho}{\rho} \geqslant \delta_c \sim 1/3$$

Mass spectra: monochromatic, log-normal, power law

Evaporated ($M < 10^{15}$ g) PBH dilute entropy density by [Chaudhuri, Dolgov, JETP **133** 5, (2021) 552]

$$S = \epsilon\, 10^5\, M/\text{grams} \qquad (2)$$

James Webb galaxies discovery at $z \sim 5$ reinforces PBH seeding galaxy formation models



[Carr, Gilbert, Lidsey, PRD **50** (1994) 4853]

B-genesis via primordial black holes

PBH emits particles via **Hawking radiation** [Hawking, ApJ **206**, (1976) 1] as a black-body with

$$T = \frac{\hbar c^3}{8\pi GMk} \approx 10^{-7} \frac{M_\odot}{M}\,\mathrm{K} \tag{3}$$

Mechanism incorporating Hawking radiation [Dolgov, PRD **24** (1981) 4]

- Light PBH emits mesons A with different partial decay widths $A \to H\bar{L}$, $A \to \bar{H}L$, $m_H \gg m_L$
- B-number flux from PBH appears due to different gravitational barrier for H and L

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Asymmetric capture mechanism

was proposed in [Dolgov, NAP, arXiv:2009.04361]

- Similarly to GUT decay mechanism

$$\varepsilon' \equiv \frac{\sigma(X + a \to X + c) - \sigma(\bar{X} + a \to \bar{X} + c)}{\sigma(X + a \to X + c) + \sigma(\bar{X} + a \to \bar{X} + c)} \tag{4}$$

  comes from interference with triangular-loop diagram. Order of magnitude $\varepsilon' \sim f^2$

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- CP violation

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- B-number can be conserved since black hole has no baryonic charge
- Asymmetry generation can proceed in thermal equilibrium

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Flow velocity difference $v_- \equiv v_X - v_{\bar{X}} \simeq \varepsilon' v_{av}$ leads to baryon number $N_B = 4\pi r^2 v_- t_H n_x$ production per PBH. For evaporated PBH with monochromatic mass-spectrum

$$\eta_b \approx 5 \cdot 10^{-24} \frac{\epsilon}{f^2} \frac{m_X}{\mathrm{GeV}} \tag{5}$$

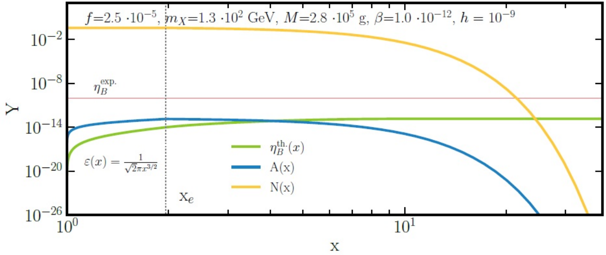
Appropriate model

Minimal model was first suggested in

[Ambrosone, Calabrese, Fiorillo, Miele, Morisi, PRD **105** 4 (2022) 045001]

$$\mathcal{L}_{int} = -g_{\bar{a}X}\bar{\phi}\bar{a}X - g_{\bar{c}X}\bar{\phi}\bar{c}X - g_{\bar{b}Y}\bar{\phi}\bar{b}Y \\ - g_{\bar{Y}X}\psi\bar{Y}X - g_{\bar{b}a}\psi\bar{b}a - g_{\bar{b}c}\psi\bar{b}c + \mathrm{h.c.} \quad (6)$$

with heavy fermions X, Y, b and scalar fields ϕ, ψ and SM particles a, c



$N = \frac{n_X + n_{\bar{X}}}{2s}$

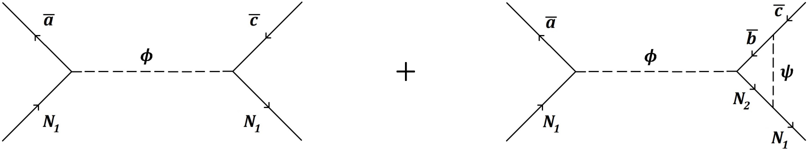
$A = \frac{n_X - n_{\bar{X}}}{s}$

$x = m_X/T$

x_e – evaporation time

CPV in Yukawa interactions

arises from tree diagram interference with triangular diagram



resulting in [ACFMM, PRD **105** 4 (2022) 045001]

$$\varepsilon' \equiv \frac{\mathrm{Im}\{g_{c1} g^*_{12} g^*_{b2} g_{bc}\}}{|g_{a1}|^2} \mathrm{Im}\{\mathcal{I}\} \simeq \frac{f^2}{\sqrt{2\pi} x^{3/2}}, \tag{7}$$

kinematic factor $\mathcal{I}$ includes integration over loop.

Note, another possibility is to consider $\phi \bar{a} \to \phi \bar{c}$

Motion equation

In [Dolgov, NAP, PRD **104** 8 (2021) 083524] equation [Nandra, Lasenby, Hobson, MNRAS 422 (2012) 2931] is considered

$$\ddot{r} + \gamma\dot{r} + qH^2 r + \frac{r_g}{2r^2} = 0,^{(i)} \qquad r_g \ll r \ll r_H \equiv 1/H, \tag{8}$$

without $\gamma\dot{r}$ is solved under $H \sim \mathrm{Const}$ approximation

$$r = r_{max} \cos^{2/3}\left(\frac{3Ht}{2}\right), \quad r_{max}^3 = r_H^2 r_g \tag{9}$$

perturbative account for $\gamma\dot{r}$ leads to

$$r_{max} \to r'_{max} = r_{max}(1+\gamma t)$$

Captured particles and antiparticles difference $\delta N = 4\pi r_{max}^3 \varepsilon' \gamma t_H n_X$ and generated asymmetry $\eta_b \sim 0.03\epsilon f^6 \frac{T_{form} m_{Pl}}{m_X^2}$

(i) $q \equiv -\ddot{a}\dot{a}/a^2 = 1$ for radiation-dominated Universe

Solution is accurate if $t_{cap} \ll t_H$ i.e. for particles near PBH.

Consider $x \equiv m_1/T$ thus Hubble parameter $H = m_*/x^2$, $m_* \equiv m_1^2/m_{Pl}^*$.[(ii)] Also $r(t) \to \rho(x) \equiv r/r_g$:

$$x^2\rho'' + \left(\frac{\gamma}{m_*}x^3 - 2x\right)\rho' + \rho + \left(\frac{x}{x_a}\right)^4 \frac{1}{2\rho^2} = 0. \tag{10}$$

with $x = \xi^\alpha$,[(iii)] $\rho = \xi^{(3\alpha+1)/2} w$ one obtains,

$$w'' = A\frac{\xi^{-\frac{1}{2}(1+\alpha)}}{w^2}, \tag{11}$$

an Emden-Fowler equation, $A \equiv -(10\xi_a^{4\alpha})^{-1}$

(ii) Reduced Planck mass $m_{Pl}^* \approx 7 \times 10^{17}$ GeV

(iii) $\alpha = 1/\sqrt{5}$

Absorption rate

Number of particles captured from distances $r_0 \div r_0 + \delta r$ is

$$\delta N = 4\pi r_0^2 \delta r \, n_1 = 4\pi r_g^3 n_1(T) \rho_0^2 \frac{\delta \rho}{\delta x} \delta x$$

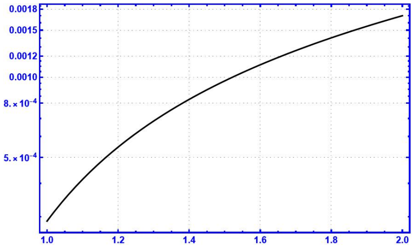
At x they are captured from $\rho_0 = 1/f(x)$ if $\rho = \rho_0 f(x)$. Absorption rate per PBH

$$\Gamma_{abs1}(x) \equiv \frac{N'}{n_1(x)} = 4\pi r_g^3 \rho_0^2 v(x, \rho_0) = 4\pi r_g^3 \frac{f'(x)}{f^3(x)} \tag{12}$$

Total absorption rate

$$\Gamma_{abs} = \Gamma_{abs1} n_{PBH}$$
$$= 3.33\epsilon \left(\frac{x_a}{x}\right)^3 \frac{f'(x)}{f^3(x)}$$

$\epsilon = \rho_{PBH}/\rho_{rel} \ll 1$ at appearance time x_a



$\Gamma_{abs}(x)$ for $x_a = 0.1$, $\epsilon \sim 10^{-4}$

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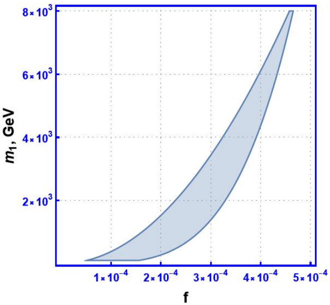

- Annihilation processes freeze-out $\Gamma_{ann} \ll H$

$$g_1 \frac{3 \cdot 10^{13}\,\mathrm{GeV}}{m_1} \left(\frac{f}{0.04}\right)^4 < x_f \sim 1 \quad (13)$$

- To connect asymmetry to SM sector

$$g_* \frac{3 \cdot 10^{13}\,\mathrm{GeV}}{m_1} \left(\frac{f}{0.13}\right)^4 > x_{EW} \equiv \frac{m_1}{T_{EW}} \quad (14)$$

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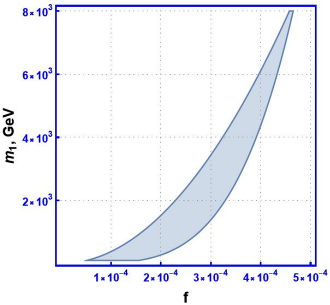

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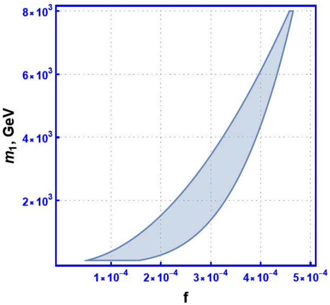

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- Single-PBH accretion applicability

$$x \lesssim \left(\frac{\pi^4}{90\zeta(3)\epsilon}\right)^{1/3} x_a \qquad (15)$$

Boltzmann equations

for particle and antiparticle number densities

$$\partial_t n_1 + 3Hn_1 = -\tilde{\Gamma}_{abs} n_1 - \tilde{\Gamma}_{ann}(n_1^2 - n_{eq}^2)$$
$$\partial_t n_{\bar{1}} + 3Hn_{\bar{1}} = -\tilde{\Gamma}_{abs} n_{\bar{1}} - \tilde{\Gamma}_{ann}(n_{\bar{1}}^2 - n_{eq}^2)$$

Consider BAU normalized by entropy density $s = \frac{2\pi^2}{45} g_* T^3$

$$\Delta_{Y_B} = (8.75 \pm 0.23) \times 10^{-11} \tag{16}$$

and number density $Y \equiv n_1/s$, $\bar{Y} \equiv n_{\bar{1}}/s$

$$\partial_x Y = -\Gamma_{abs} Y - \Gamma_{ann}(Y^2 - Y_{eq}^2)$$
$$\partial_x \bar{Y} = -\Gamma_{abs} \bar{Y} - \Gamma_{ann}(\bar{Y}^2 - Y_{eq}^2)$$

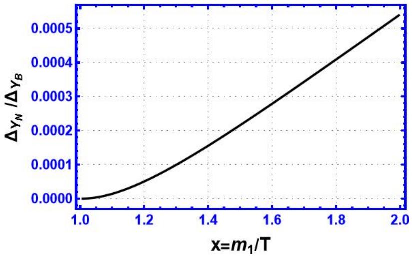
with $\Gamma_{ann} = \tilde{\Gamma}_{ann} s/Hx$

Asymmetry evolution

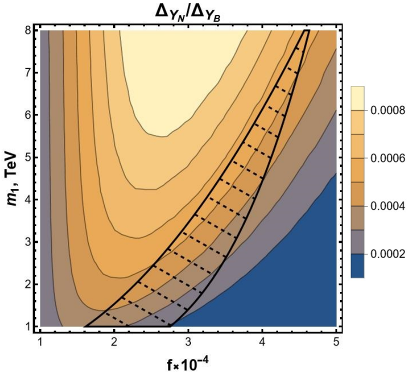
Consider $\Delta_{Y_N} \equiv Y - \bar{Y}$, $2Y_{av} \equiv Y + \bar{Y}$ then

$$\frac{dY_{av}}{dx} = -\Gamma_{abs} Y_{av} - \Gamma_{ann}(Y_{av}^2 - Y_{eq}^2),$$
$$\frac{d\Delta_{Y_N}}{dx} = \delta\Gamma_{abs} Y_{av} - \Gamma_{abs}\Delta_{Y_N} - 2\Gamma_{ann}\Delta_{Y_N} Y_{av}.$$

$\delta\Gamma_{abs} \sim \varepsilon'\Gamma_{abs}$



with $x_a = 0.1$, $\epsilon \sim 10^{-4}$



Intermediate conclusion

- Motion equation can be solved only approximately
- Light fermions capture by PBHs cannot provide significant Δ_{Y_B} fraction
- Other possibilities to realize this scenario, parameter ranges, etc. should be investigated

Supplementary materials

Primordial nucleosynthesis

Saha equation for $p + n \leftrightarrows {}^2\mathrm{H} + \gamma$

$$Y_D = \sqrt{\frac{8}{\pi}}\zeta(3)\left(\frac{m_D T}{m_p^2}\right)^{3/2}\eta_b e^{-\Delta/T}$$

$\Delta \equiv m_D - m_p - m_n$

Recombination

Equation on temperature fluctuation (see for instance [Davidson, 2008]) $\Theta \equiv \Delta T/T$

$$\ddot{\Theta} + c_s^2 k^2 \Theta = F, \quad c_s = [3(1 + 3\Omega_B/\Omega_\gamma)]^{-1/2}$$

enhances spectrum odd peaks

Primordial black holes spectra

Monochromatic spectrum (suitable if $\Delta M \sim M$)

$$\frac{dn_{PBH}}{dM} = \delta(M - M_0) \tag{17}$$

Log-normal spectrum (smooth symmetric peak from for example SR inflation)

$$\frac{dn}{dM} = \mu^2 e^{-\gamma \ln(M/M_0)} \tag{18}$$

Power spectrum (from scale-invatiant fluctuations)

$$\frac{dn}{dM} \propto M^{-\alpha}, \quad \alpha = \frac{2(1+2w)}{1+w} \tag{19}$$

Scattering & CPT-theorem

Optical theorem:

$$\Gamma_{p_1,\sigma_1,n_1;p_2,\sigma_2,n_2\dots} = \Gamma_{p_1,-\sigma_1,n_1^c;p_2,-\sigma_2,n_2^c\dots}$$

where $\Gamma_{\dots}$ – is transition probability from a given initial state into complete set of final states.
To make difference in

$$\sum_{a,c} \sigma(X + a \to X + c) \neq \sum_{a,c} \sigma(\bar{X} + a \to \bar{X} + c)$$

apart from $X + a \to X + c$ should be channels without X particle in final state, like $X + a \to Y + b$