Leptogenesis via absorption by primordial black holes

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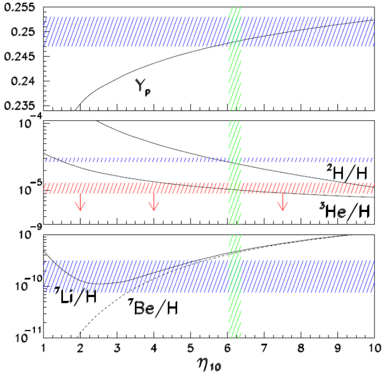
Outline

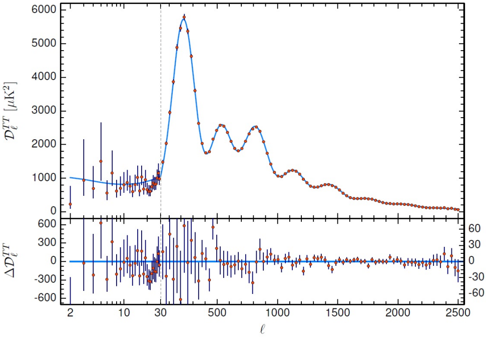
- **Introduction**
- Asymmetry through absorption
- Particle model
- On parameters

Baryon asymmetry of the Universe (BAU)

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



[F. Iocco et al, Phys. Rept. 472 (2009) 1]



[Planck 2018]

Sakharov conditions

BAU appearance via elementary particles interactions requires
[A. Sakharov, JETP Lett. 5 (1967) 24]

- If $B_{in} = B_{fin}$: no asymmetry is generated $\Rightarrow$ B**-number non-conservation**
- If $\Gamma(I \to F_j) = \Gamma(\bar{I} \to \bar{F}_j)$: cancellation $\Rightarrow$ C **&** CP **symmetries violation (CPV)**
- $F_i \to F_j$ wash out *non-conserved* B-number $\Rightarrow$ **Deviation from thermal equilibrium**

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Standard Model

- Conserves **B** $-$ **L** number instead of **B** and **L** separatively (plus $L_\mu - L_e$, $L_\tau - L_\mu$)
- Violates C & CP symmetries: $J \sim 0.02 \sin\delta$ (for ν-sector)
- Has electroweak phase transition of II kind (*in thermal equilibrium*)

Still, the SM allows to transfer part of L-number to B-number

Baryogenesis models

- Leptogenesis: heavy Majorana neutrino N_i decay [S. Davidson,E. Nardi Y. Nir Phys. Rept. 466 (2008) 105-177] or oscillations [E. Akhmedov, V. Rubakov, A. Smirnov Phys. Rev. Lett. 81 (1998) 1359-1362]
- Electroweak baryogenesis: new scalar fields to make EW phase transition of I kind [J. McDonald Phys. Lett. B 323 (1994) 339-346]
- GUT-baryogenesis
  - $SO(10)$, etc.
  - $SU(5)$ and PBH [D. Hooper, G. Krnjaic PRD 103 (2021) 4, 043504]
- Hawking emission [A. D. Dolgov, PRD **24** (1981) 4]

Black holes in the early Universe (PBH). Why?

James Webb discoveries of galaxies with $z \gtrsim 5$ strengthen models with PBH seeding galaxies formation.

Region collapses into PBH of $M \simeq m_{Pl}^2 t$ if
[A. Escrivá, C. Germani, R. Sheth, PRD 101 (2020) 4, 044022]

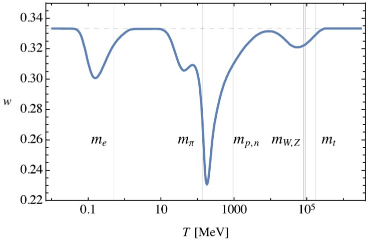
$$\frac{\delta\rho}{\rho} \geqslant \delta_c \sim 1/3 \ \ (0.4)$$

Some mechanisms:

- Inflationary
- Bubbles collision
- Domain walls collapse
- Equation of state $\mathcal{P} = w\rho$ softening

Spectra:

- Monochromatic
- Log-normal
- Power law



for further reading [B. Carr, F. Kühnel, SciPost Phys.Lect.Notes 48 (2022) 1]

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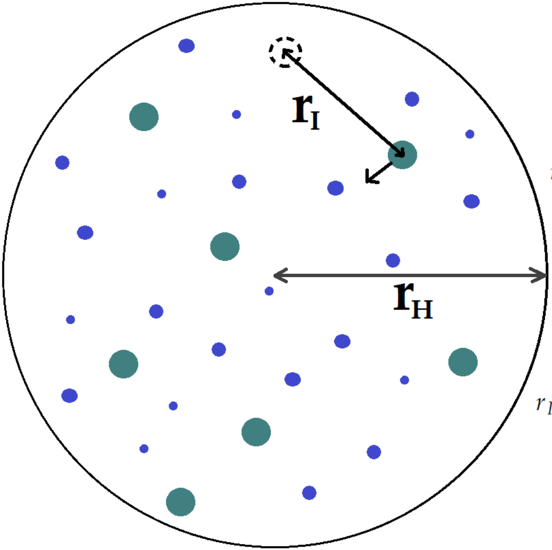
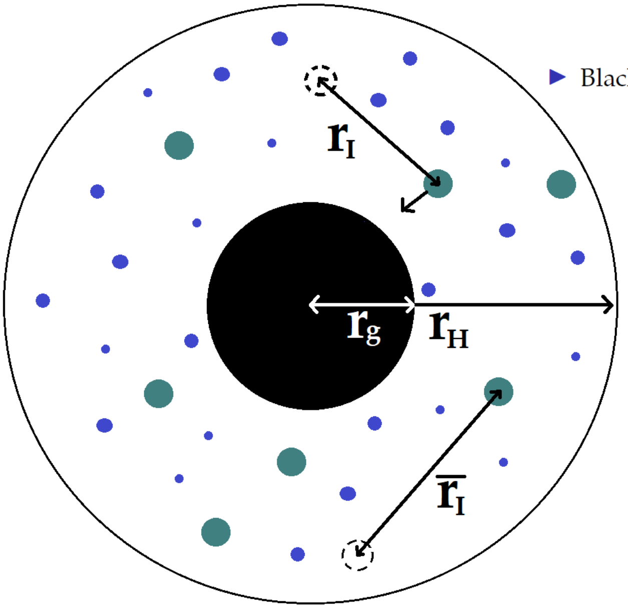
Idea



$r_H = 1/H \sim m_{Pl}/T^2$

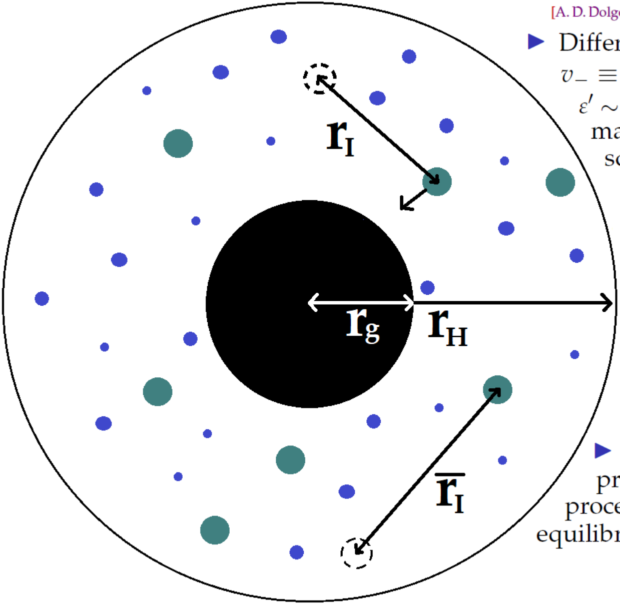
$r_I = (\langle \sigma v \rangle \, n)^{-1} \propto m^2/T^3$

Idea



- Black hole only has M, Q, J

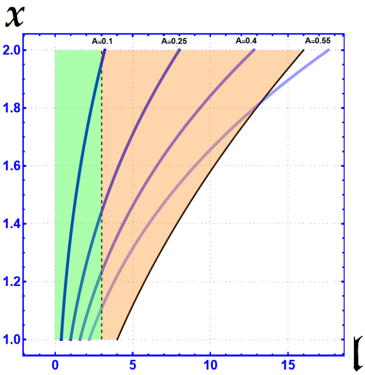
Idea



[A. D. Dolgov, NAP, arXiv:2009.04361]

- Different flow velocity
  $v_- \equiv v_X - v_{\bar{X}} \simeq \varepsilon' v_{av}$
  $\varepsilon' \sim f^2$– CPV magnitude in scatterings
  - v_- leads to different numbers of captured particles and antiparticles
- Asymmetry production *can* proceed in thermal equilibrium

Motion in the early Universe



Dimensionless variables

$t = \frac{x^2}{2m_*}, \quad r = \mathfrak{l}\, r_g(x = 1)$

$x \equiv m_1/T, \quad m_* \equiv \frac{m_1^2}{m_{Pl}^*}.$(i)

$$r_H = \frac{1}{H} \to \mathfrak{l}_H \sim (x/x_a)^2$$

$$r_I = \frac{1}{\langle \sigma v \rangle\, n_{rel}} \to \mathfrak{l}_I \sim \mathcal{A} x^3 / x_a^2$$

$x_a < 1$ – PBH appearance time,

$$\mathcal{A} \equiv 10^{-15} \left(\frac{0.1}{f} \right)^4 \frac{m_1}{\text{GeV}}$$

- $r_I < r_{acc} \simeq 2GM/c_{s,\infty}^2$ – Bondi accretion (green)
- $r_{acc} < r_I < r_H$ – free fall (orange)

(i) $m_{Pl}^* = m_{Pl} \sqrt{90/8\pi^3 g_*(T)} \approx 7 \times 10^{17}$ GeV

Expansion influence [A. D. Dolgov, NAP, PRD **104** 8 (2021) 083524]

Universe expansion adds [R. Nandra, A. Lasenby, M. Hobson, MNRAS 422 (2012) 2931]

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

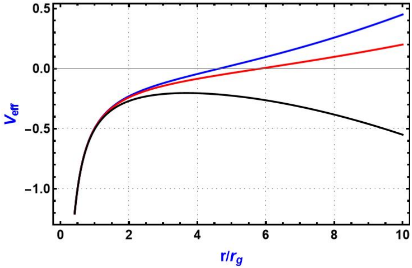
$$\gamma \equiv \langle\sigma v\rangle\, n_{rel} = 1/r_I$$

under $H \sim$ Const assumption

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

take into account $\gamma\dot{r}$: $r_e \to r_e' = r_e(1+\gamma t)$

Generated number per PBH
$N_B = 4\pi r_e^3 \epsilon' \gamma t_H n_X$ and asymmetry
$\eta_b \sim 0.03\epsilon f^6 T_a m_{Pl}/m_X^2$



Potential for (2) with $r_g/r_H = 0.1$

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

Solution applicability: $\delta H/H \approx H t_{cap} \ll 1 \rightarrow (r/r_e)^{3/2} \ll 1.$

Dimensionless equation

$$x^2 \mathfrak{l}'' + \left(\frac{1}{\mathcal{A}} - 2x\right)\mathfrak{l}' + \mathfrak{l} + \left(\frac{x}{x_a}\right)^4 \frac{\mathfrak{l}_{BH}}{2\mathfrak{l}^2} = 0.$$

by $x = \xi^{\alpha}$,[iii] $\mathfrak{l} = \xi^{(3\alpha+1)/2} w$
can be simplified to

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

Emden-Fowler
$C \equiv -(10\xi_a^{4\alpha})^{-1}$

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

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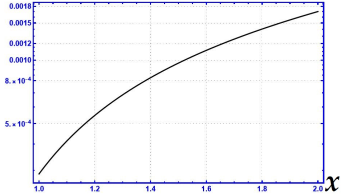
Consider $\delta N = 4\pi r_0^2 \delta r\, n_1 = 4\pi r_g^3 n_1(T)\mathfrak{l}_0^2 \frac{\delta \mathfrak{l}}{\delta x}\delta x$.
At x time particles captured from $\mathfrak{l}_0 = 1/f(x)$ if $\mathfrak{l} = \mathfrak{l}_0 f(x)$. Rates are

$$\Gamma_{abs1}(x) \equiv \frac{N'}{n_1(x)} = 4\pi r_g^3 \mathfrak{l}_0^2 v(x, \mathfrak{l}_0) = 4\pi r_g^3 \frac{f'(x)}{f^3(x)}$$



For monochromatic population

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

[iii] $\alpha = 1/\sqrt{5}$

Particles accretion

Hydrodynamic equations

$$\frac{\partial n}{\partial t} + \mathrm{div}\{n\mathbf{v}\} = -\Gamma_{ann}(n\bar{n} - n_{eq}^2),$$

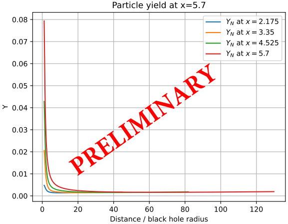
$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}, \nabla)\mathbf{v} = -\nabla p - F_{grav} - F_{cosm} - \gamma v$$

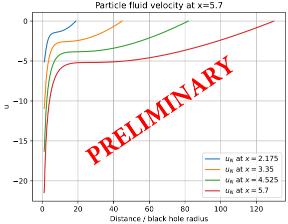
for $\Upsilon \equiv n/s^{(\mathrm{iv})}$, $u \equiv \partial\mathfrak{l}/\partial x$:

$$\Upsilon'_x + (u\Upsilon)'_{\mathfrak{l}} = \frac{3\Upsilon}{x} - \frac{2u\Upsilon}{\mathfrak{l}} - \frac{sx\Gamma_{ann}}{m_*}\left(\Upsilon\bar{\Upsilon} - \Upsilon_{eq}^2\right),$$

$$u'_x + uu'_{\mathfrak{l}} + \frac{\tilde{c}_s^2}{\Upsilon}\Upsilon'_{\mathfrak{l}} = \frac{u}{x} - \frac{\gamma x}{m_*}u - \frac{\mathfrak{l}}{x^2} - \frac{x^2}{x_a^4}\frac{\mathfrak{l}_{BH}}{2\mathfrak{l}^2}.$$

Newtonian limit holds for $x \lesssim 2\pi x_a^{2/3}$





(iv) Entropy density $s \equiv (\rho + \mathcal{P})/T = \frac{2\pi^2}{45} g^* T^3$

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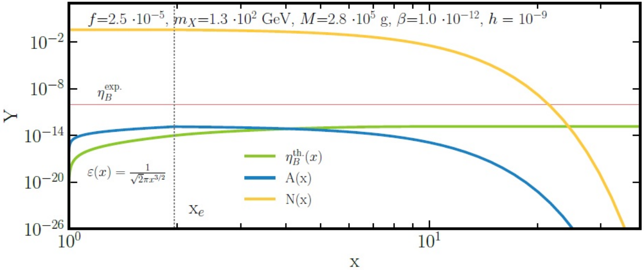
Appropriate model [A. Ambrosone et al, PRD **105** 4 (2022) 045001]

$$\mathcal{L}_{int} = - g_{\bar{a}X}\phi^\dagger \bar{a} X - g_{\bar{c}X}\phi^\dagger \bar{c} X - g_{\bar{b}Y}\phi^\dagger \bar{b} Y$$
$$- g_{\bar{Y}X}\psi \bar{Y} X - g_{\bar{b}a}\psi \bar{b} a - g_{\bar{b}c}\psi \bar{b} c + \text{h.c.} \quad (3)$$

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



x_e – PBH evaporation time,

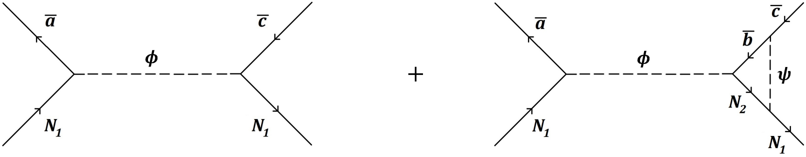
$$N \equiv \frac{n_X + n_{\bar{X}}}{2s}$$

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

Sterile neutrinos $N_{1,2}$ are more convenient choice

CPV in Yukawa model

arises from interference



leading to [ACFMM, PRD **105** 4 (2022) 045001]

$$\varepsilon' \equiv \frac{\mathrm{Im}\{g_{c1}g_{12}^{*}g_{b2}^{*}g_{bc}\}}{|g_{a1}|^2}\mathrm{Im}\{\mathcal{I}\} \simeq \frac{f^2}{\sqrt{2\pi}x^{3/2}}, \qquad (4)$$

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

There are other possibilities such as $\phi\bar{a} \to \phi\bar{c}$

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Parameter space

- Relatively stable particles are considered

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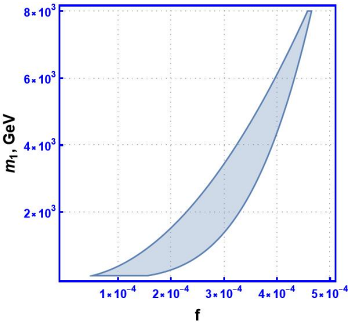

- Annihilation processes freeze-out when $\Gamma_{ann} \ll H$:

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

- To connect asymmetry to SM sector

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

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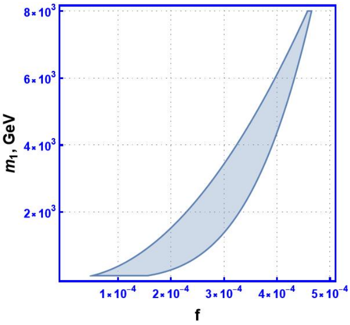

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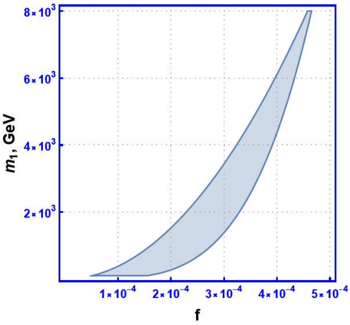

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- Effective capture $r_g > \lambda_p$: PBH appearance time, $x_a > \sqrt{2m_1/m^*_{Pl}}$

- Single PBH accretion

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

Estimation

$$\partial_t f_1 - Hp\partial_p f_1 = \mathcal{I}_{coll},$$
$$\partial_t f_{\bar{1}} - Hp\partial_p f_{\bar{1}} = \mathcal{I}'_{coll}.$$

Normalize BAU on entropy density, $s = \frac{2\pi^2}{45} g_* T^3$,

$$\Delta_{Y_B} = (8.75 \pm 0.23) \times 10^{-11}, \qquad (5)$$

and also number density, $Y \equiv n_1/s$, $\bar{Y} \equiv n_{\bar{1}}/s$. In $(t,p) \to (x, y \equiv p/T)$ integrated equations are

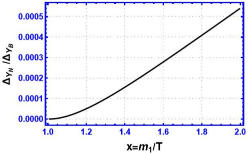
$$\partial_x Y = -\Gamma_{abs} Y - \Gamma_{ann}(Y^2 - Y_{eq}^2),$$
$$\partial_x \bar{Y} = -\Gamma_{abs} \bar{Y} - \Gamma_{ann}(\bar{Y}^2 - Y_{eq}^2),$$

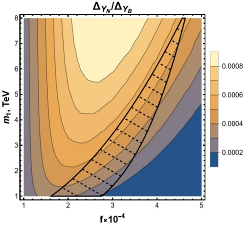
with $\Gamma_{ann} = s\, x f^4/m_* m_1^2 \propto 1/x^2$

Asymmetry evolution $\Delta_{Y_N} \equiv Y - \bar{Y}$

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

with $\delta\Gamma_{abs} \sim \varepsilon' \Gamma_{abs}$ and $Y_{av} \equiv (Y + \bar{Y})/2$





for $x_a = 0.1$, $\epsilon = \rho_{PBH}/\rho_{rel} \sim 10^{-4}$

Intermediate conclusions

- Asymmetry production in absorption by PBH does not require $B/L/B-L$ number non-conservation at the level of elementary particles interactions
- Accretion in the early Universe is magnified by decelerated expansion. Seemingly, equation of motion cannot be exactly solved
- Fluid velocity difference of fermions in Yukawa couplings is proportional to $f^2/x^{3/2}$

Supplementary materials

BAU & BBN

Saha equation for $Y_D \equiv n_D/n_b$ (for $p + n \leftrightarrows {}^2\mathrm{H} + \gamma$)

$\Delta_D \equiv m_p + m_n - m_D = 2.22\,\mathrm{MeV}$.
$\Delta \equiv m_n - m_p = 1.3\,\mathrm{MeV}$.

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

$Y_D/Y_n(T_D) = 1$ for $\eta_b \sim 10^{-9} \Rightarrow$
$T_D \simeq 65\,\mathrm{KeV}$ ($T_N \simeq 75\,\mathrm{KeV}$).

Neutron-proton relation at freeze-out, $T_f \simeq 0.8\,\mathrm{MeV}$,
$\kappa_{np}(T_f) \equiv n_n(T_f)/n_p(T_f) = e^{-\Delta/T_f} = 0.18$.
Due to n-decay with $\tau \sim 880\,\mathrm{s}$:

$$\kappa_{np}(T_N) = \frac{\kappa_{np}(T_f)e^{-t/\tau_n}}{1 + \kappa_{np}(1 - e^{-t_N/\tau_n})} \sim 0.14$$

and

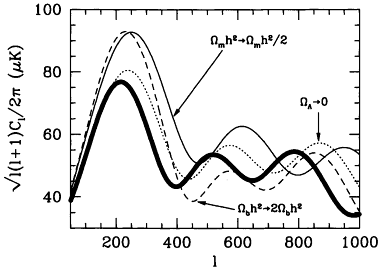
$$Y_{^4\mathrm{He}} = \frac{2}{\kappa_{np}^{-1}(T_N) + 1} \simeq 0.25$$

BAU & CMB

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

$$\ddot{\Theta} + c_s^2 k^2 \Theta = F, \quad c_s = \left[3(1+3\Omega_B/4\Omega_\gamma)\right]^{-1/2}$$

enhances spectrum odd peaks



[S. Dodelson, Modern Cosmology (2003)]

PBHs spectra

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

$$\frac{dn_{PBH}}{dM} = \delta(M - M_0) \tag{6}$$

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

$$\frac{dn}{dM} = \mu^2 e^{-\gamma \ln(M/M_0)} \tag{7}$$

Power spectrum (from scale-invatiant fluctuations)

$$\frac{dn}{dM} \propto M^{-\alpha}, \quad \alpha = \frac{2(1 + 2w)}{1 + w} \tag{8}$$

Scattering & CPT-theorem

CPT + Optical theorem $\Rightarrow \Gamma_{p_1,\sigma_1,n_1;p_2,\sigma_2,n_2\ldots} = \Gamma_{p_1,-\sigma_1,n_1^c;p_2,-\sigma_2,n_2^c\ldots}$ where $\Gamma_{\ldots}$ – is transition probability from a given initial state into complete set of final states:

- $\sigma(X+a \to all) = \sigma(\overline{X}+\bar{a} \to all)$. If there are states like $Y+b$ in «all» then, in general, $\sigma(X+a \to X+all) \neq \sigma(\bar{X}+\bar{a} \to \bar{X}+all)$.

Thus to make difference in

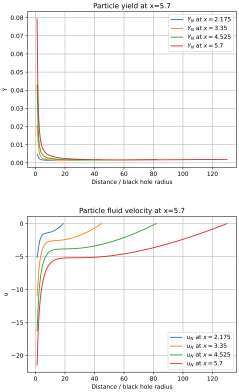
$$\sum_{a,c} \sigma(X+a \to X+c) \neq \sum_{a,c} \sigma(\bar{X}+a \to \bar{X}+c)$$

one needs:

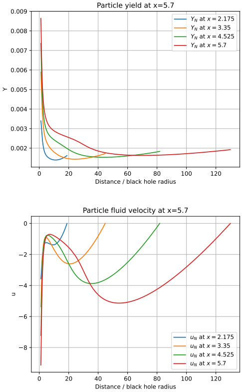
1. Final states without X particle
2. At least two different scattering channels for X

Some details on numerical solution

Solution



Solution (without free-fall)



Bondi solution