IBS-ICTP Workshop on Axion-Like Particles

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Axion-like particles from primordial black holes shining through the Universe

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Based on arXiv:2107.03420 with D. Montanino, A. Mirizzi and F. Capozzi

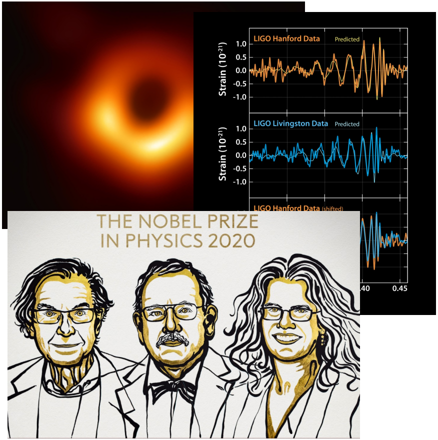
Axion-like particles

- Axions first proposed as a solution to the strong-CP problem via the Peccei-Quinn mechanism[1]
- Axion-like (neutral pseudoscalar) particles postulated in several BSM theories
- Various thermal and non-thermal production mechanisms for a cosmic axion background[2]

[1] Peccei and Quinn 1977
[2] Dror et al. 2021 [2101.09287]

Primordial black holes

- Density fluctuations in the Early Universe collapsed below their Schwarzschild radius[3]
- "Hot topic" in modern cosmology
- Invoked to explain SMBHs, LIGO/VIRGO data, dark matter...



[3] Zel'dovich and Novikov 1967; Hawking 1971; Carr and Hawking 1974

PBH formation and evolution

PBH mass at formation

$$M \sim m_P^2 \, t_f \sim 10^{15} \left(\frac{t_f}{10^{-23}\,\mathrm{s}} \right) \mathrm{g}$$

- PBHs behave as matter: $\rho_{\rm BH}/\rho_r \sim a$
- Early matter domination is possible
- Broad mass range: between inflation and BBN[4] $10\,\mathrm{g} \lesssim M \lesssim 10^9\,\mathrm{g}$

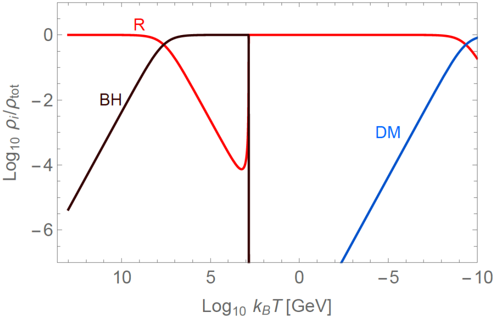


Figure from Masina 2020 [2004.04740]

[4] Papanikolaou et al. 2020 [2010.11573]

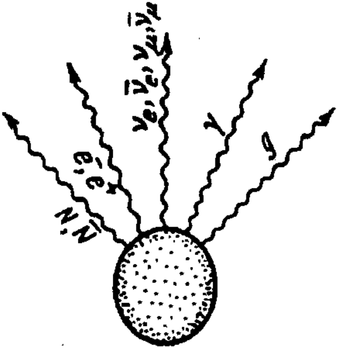
Hawking radiation

Hawking emission rate ($Q = J = 0$)

$$\frac{\mathrm{d}N_s}{\mathrm{d}\omega\,\mathrm{d}t} = \frac{1}{2\pi}\frac{\Gamma_s(\omega, M)}{e^{\omega/T_{\mathrm{BH}}} - (-1)^{2s}}$$ [Hawking 1975]

Black-hole temperature

$$T_{\mathrm{BH}} = \frac{m_{\mathrm{P}}^2}{8\pi M} \simeq 10^7 \left(\frac{10^6\,\mathrm{g}}{M}\right) \mathrm{GeV}$$



- "Democratic" emission for $m < T_{\mathrm{BH}}$: all SM states plus one ALP
- Non-thermal ALP production mechanism

Graybody factors

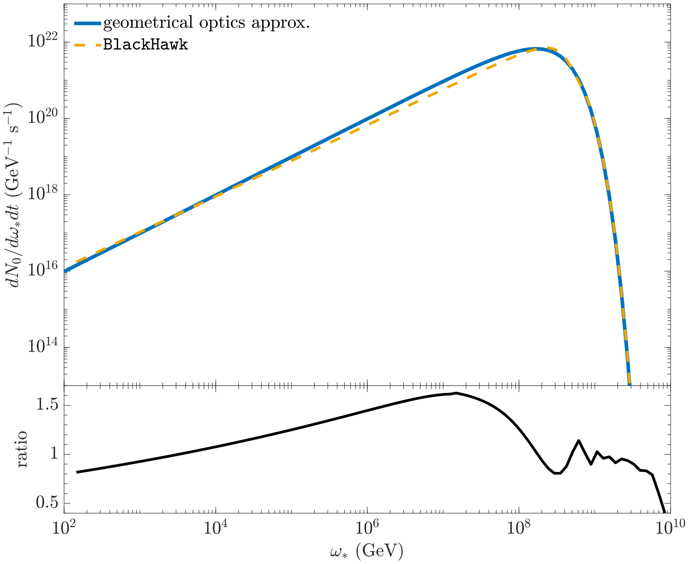
- Graybody factors $\Gamma_s(\omega, M)$: complicated functions, depending on the spin s of radiated particles
- Usually computed numerically (e.g. via `BlackHawk`[5])
- However, for high $T_{\rm BH}$ (i.e. high ω) "geometrical optics" holds

Geometrical optics approximation

$$\Gamma_s(\omega, M) \simeq \frac{27 M^2 \omega^2}{m_P^4}$$

[5] Arbey and Auffinger 2021 [1905.04268]

Geometrical optics approximation



Mass loss rate and lifetime

Mass loss rate

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\sum_s \int \mathrm{d}\omega\, \omega \frac{\mathrm{d}N_s}{\mathrm{d}\omega \mathrm{d}t} \equiv -\frac{m_P^4 f_{\mathrm{ev}}}{M^2}$$

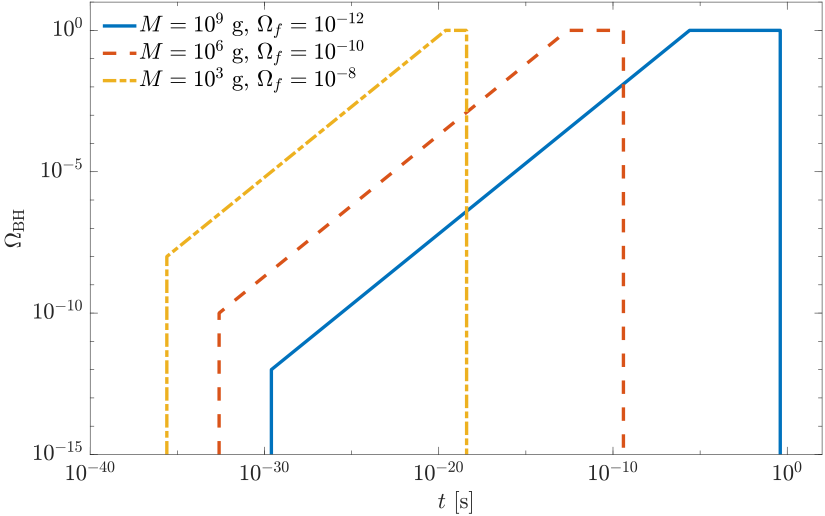
Evolution of PBH mass

$$M(t) = M\left(1 - \frac{t}{\tau_{\mathrm{BH}}}\right)^{1/3}$$

PBH lifetime

$$\tau_{\mathrm{BH}} = \frac{1}{3 f_{\mathrm{ev}}} \frac{M^3}{m_P^4} \simeq 4.16 \times 10^{-1} \left(\frac{M}{10^9\,\mathrm{g}}\right)^3 \,\mathrm{s}$$

Evolution of PBH density



Hawking ALP spectra

- ALP spectra obtained by integrating Hawking emission rate over PBH lifetime in an expanding matter-dominated Universe

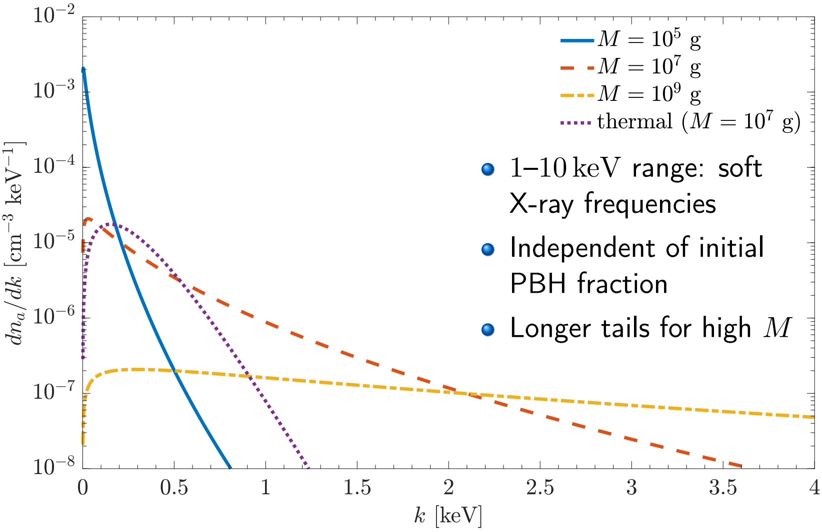
Spectral shape factor

$$\mathcal{I}(x) = x^2 \int_0^1 \frac{\theta^{-2}(1-\theta)^{2/3}}{\exp\left[x\theta^{-2/3}(1-\theta)^{1/3}\right]-1}\,\mathrm{d}\theta$$

- Mass spectrum of PBHs simply assumed monochromatic[6]
- Spectra calculated at PBH evaporation, then redshifted to the present epoch

[6] Other PBH mass spectra reviewed in Carr et al. 2020 [2002.12778]

Hawking ALP spectra



- 1–10 keV range: soft X-ray frequencies
- Independent of initial PBH fraction
- Longer tails for high M

ALP extra radiation

- Ultrarelativistic ALPs contribute to extra or dark radiation
- Contribution measured as a deviation from the standard effective number of neutrinos $N_{\rm eff} = 3.046$

ALP contribution to extra radiation

$$\Delta N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_a(T_0)}{\rho_{\rm CMB}(T_0)} \simeq 0.042\left(\frac{100}{g_S(T_*)}\right)^{1/3}$$

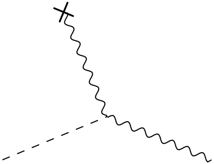
- Present experimental value[7]: $N_{\rm eff} = 2.99 \pm 0.17$

[7] Aghanim et al. 2020 [1807.06209]

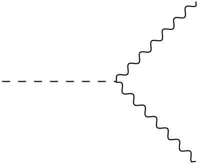
ALP-photon coupling

Signatures of this model from the ALP-photon coupling $g_{a\gamma}$:

- Ultralight ALPs ($m_a \lesssim 10^{-9}\,\mathrm{eV}$): $a \to \gamma$ conversions (cosmological magnetic fields required, $B_0 \sim 1\,\mathrm{nG}$)



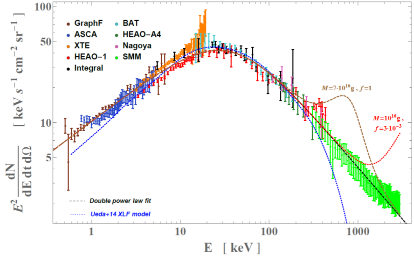
- "Heavy" ALPs ($m_a \gtrsim 10\,\mathrm{eV}$): $a \to \gamma\gamma$ decays

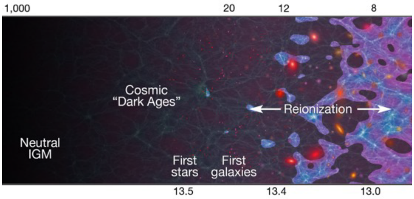


Astrophysical and cosmological signatures

These two processes inject high-energy photons in the Universe contributing to:

- The present-day cosmic X-ray background (CXB), directly measured by experiments
- The history of reionization, measured by the Thomson optical depth τ





Bounds on ALP-photon coupling

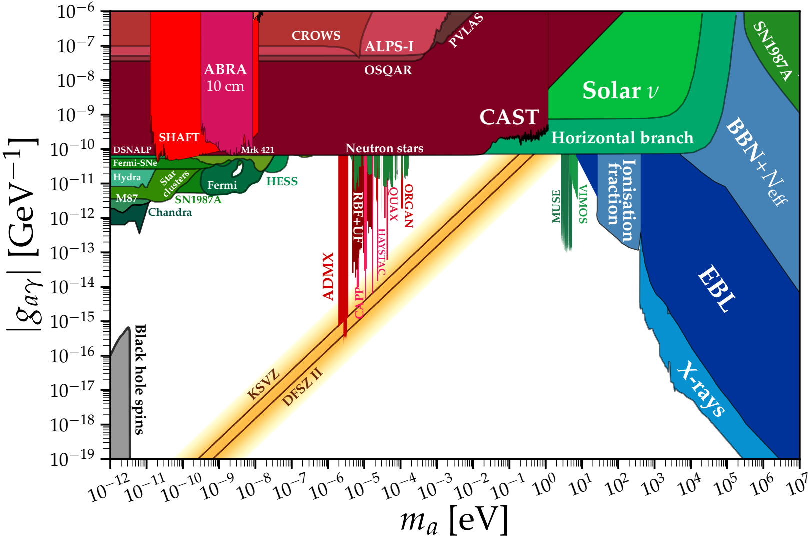


Figure from https://github.com/cajohare/AxionLimits

ALP-photon mixing in flat spacetime

ALP-photon Lagrangian

$$\mathcal{L} = \underbrace{\frac{1}{2}(\partial_\mu a \partial^\mu a + m_a^2 a^2)}_{\text{ALP kinetic term}} \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{e.m. term}} \underbrace{-\frac{g_{a\gamma}}{4}F_{\mu\nu}\tilde{F}^{\mu\nu}a}_{a\gamma \text{ interaction term}} + \begin{pmatrix}\text{higher}\\ \text{orders}\end{pmatrix}$$

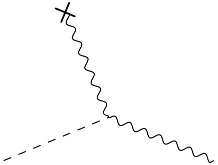
E-L equations in a constant magnetic field[8]

$$\left[i\partial_x + \begin{pmatrix} \Delta_\perp & 0 & 0 \\ 0 & \Delta_\parallel & \Delta_{a\gamma} \\ 0 & \Delta_{a\gamma} & \Delta_a \end{pmatrix} \right] \begin{pmatrix} A_\perp \\ A_\parallel \\ a \end{pmatrix} = 0$$

$\Delta_{\text{QED},\lambda} + \Delta_{\text{pl}} + \Delta_{\text{CMB}}$

$g_{a\gamma} B_T / 2$

$-m_a^2/2\omega$



- 2×2 mixing problem

[8] Raffelt and Stodolsky 1988

Mixing parameters

$$\Delta_{a\gamma} \simeq 1.52 \times 10^{-3} \left(\frac{g_{a\gamma}}{10^{-12}\,\mathrm{GeV}^{-1}} \right) \left(\frac{B_T}{10^{-9}\,\mathrm{G}} \right) \mathrm{Mpc}^{-1}$$

$$\Delta_{a} \simeq -7.8 \times 10^{5} \left(\frac{m_a}{10^{-10}\,\mathrm{eV}} \right)^2 \left(\frac{\omega}{1\,\mathrm{keV}} \right)^{-1} \mathrm{Mpc}^{-1}$$

$$\Delta_{\mathrm{pl}} \simeq -1.1 \times 10^{-2} \left(\frac{\omega}{1\,\mathrm{keV}} \right)^{-1} \left(\frac{n_e}{10^{-7}\,\mathrm{cm}^{-3}} \right) \mathrm{Mpc}^{-1}$$

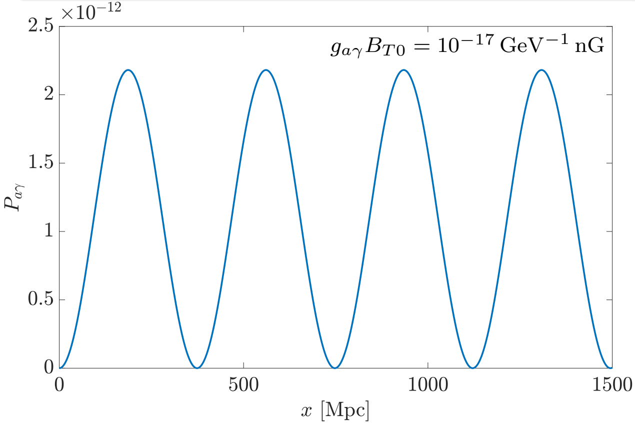
$$\Delta_{\mathrm{QED}} \simeq 4.1 \times 10^{-18} \left(\frac{\omega}{1\,\mathrm{keV}} \right) \left(\frac{B_T}{10^{-9}\,\mathrm{G}} \right)^2 \mathrm{Mpc}^{-1}$$

$$\Delta_{\mathrm{CMB}} \simeq 2.62 \times 10^{4} \left(\frac{T}{1\,\mathrm{eV}} \right)^4 \left(\frac{\omega}{1\,\mathrm{keV}} \right) \mathrm{Mpc}^{-1}$$

Mixing in a constant field

Oscillation probability

$$P(x) = \sin^2(2\theta)\sin^2\left(\frac{\Delta_{\rm osc}x}{2}\right)$$

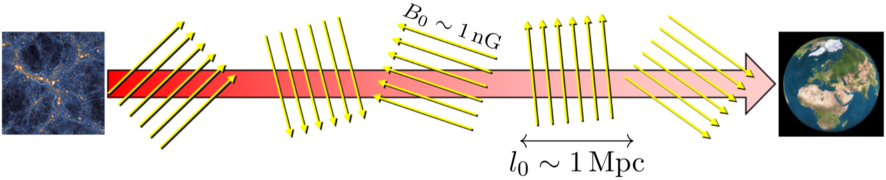


$$\tan 2\theta = \frac{2\Delta_{a\gamma}}{\Delta_\lambda}$$

$$\Delta_{\rm osc} = \sqrt{\Delta_\lambda^2 + 4\Delta_{a\gamma}^2}$$

$$\ell_{\rm osc} = \frac{2\pi}{\Delta_{\rm osc}}$$

ALP-photon conversions in primordial magnetic fields



- Expansion of the Universe
- Full 3-dimensional problem
- Photon absorption by the intergalactic medium

Photon absorption rate[9]

$$\Gamma(\omega) = \sigma_{\mathrm{H}}^{\mathrm{PE}}(\omega) n_{\mathrm{H}} + \sigma_{\mathrm{He}}^{\mathrm{PE}}(\omega) n_{\mathrm{He}} + \sigma_{\mathrm{KN}}(\omega) n_e$$

electron density

H/He density

Photoelectric effect on H/He

Compton scattering

[9] Evoli et al. 2016 [1602.08433]

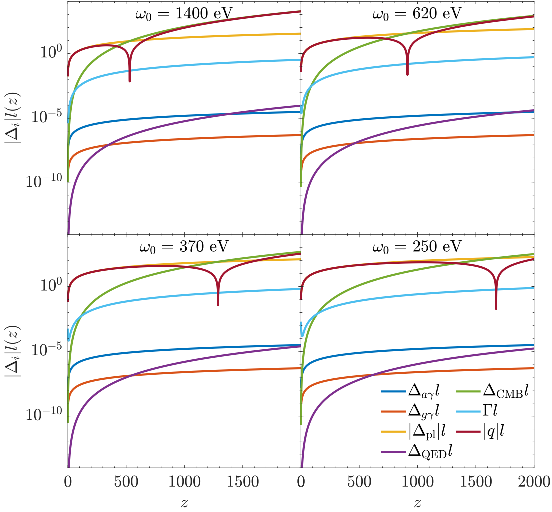
Redshift of parameters

- A sequence of redshift parameters is built as $z_{n+1} = z_n + \Delta z_n$
- Δz_n: how much time relativistic ALPs take to cross a domain of size $l_n = l_0/(1+z_n)$

Time-redshift relation

$$\frac{\mathrm{d}z}{\mathrm{d}t} = -(1+z)H_0\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}$$

Redshift of parameters



$g_{a\gamma} B_{T0} = 10^{-17}\,\mathrm{GeV}^{-1}\,\mathrm{nG}$

$$\Delta_a^{(n)} = \Delta_a^{(0)} (1 + z_n)^{-1}$$

$$\Delta_{a\gamma}^{(n)} = \Delta_{a\gamma}^{(0)} (1 + z_n)^2$$

$$\Delta_{\rm QED}^{(n)} = \Delta_{\rm QED}^{(0)} (1 + z_n)^5$$

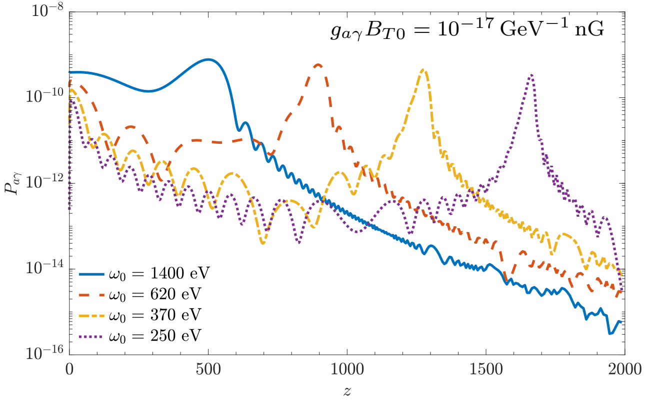
$$\Delta_{\rm pl}^{(n)} = \Delta_{\rm pl}^{(0)} (1 + z_n)^2$$

$$\Delta_{\rm CMB}^{(n)} = \Delta_{\rm CMB}^{(0)} (1 + z_n)^5$$

Conversion probability

Recursive probability formula [Evoli et al. 2016]

$$P_{a\gamma}^{(n+1)} = \left[P_{a\gamma}^{(n)} + (\Delta_{a\gamma}^{(n)} l_n)^2 \mathrm{sinc}^2 \left(\frac{q_n l_n}{2} \right) \right] e^{-\Gamma_n l_n}$$

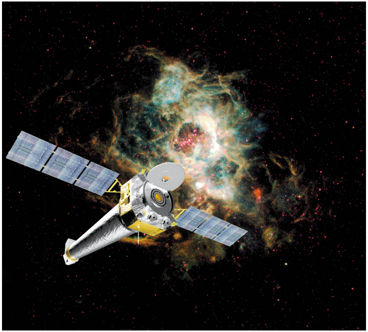


Accounts for:

- Expansion
- Conversions
- Absorption

The cosmic X-ray background

- Since the 1960s, several space experiments have detected a diffuse electromagnetic background radiation
- Referred to as the cosmic X-ray background (CXB) in the $0.1–100\,\mathrm{keV}$ energy band
- Most sources in the low-energy part resolved (e.g. active galactic nuclei)
- Less complete picture at high energies



The Chandra X-Ray Observatory

The cosmic X-ray background

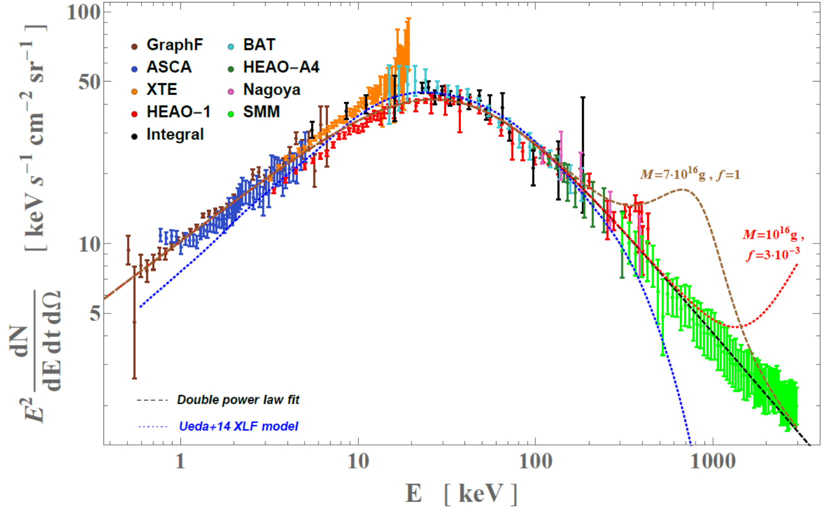


Figure from Ballesteros et al. 2020 [1906.10113]

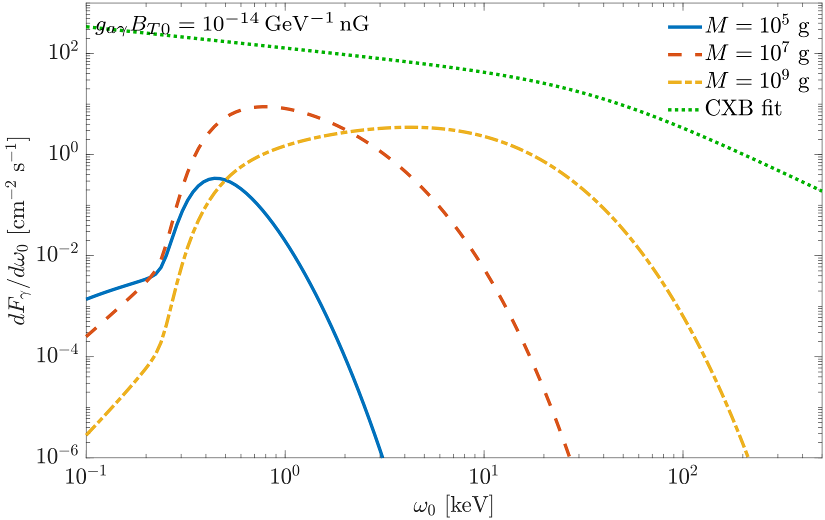
X-ray fluxes from ALP conversions

Present X-ray flux from conversions

$$\frac{\mathrm{d}F_\gamma}{\mathrm{d}\omega_0}(\omega_0, t_0) = \frac{\mathrm{d}F_a}{\mathrm{d}\omega_0}(\omega_0, t_0) P_{a\gamma}(\omega_0, t_0)$$

- Conversion probability evolved until present-day using the recursive formula
- Mixing parameter $g_{a\gamma} B_{T0}$ constrained by imposing that the obtained flux does not exceed the measured one

X-ray fluxes from ALP conversions



Soft X-ray excess from galaxy clusters

- Several galaxy clusters exhibit excess luminosity in the soft X-ray spectrum
- Possibly explained by a "cosmic axion background"[10] converting into photons inside the cluster magnetic fields ($\sim \mu\mathrm{G}$)
- Similar results can be reproduced with PBHs

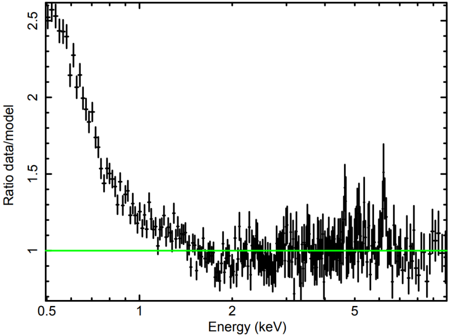
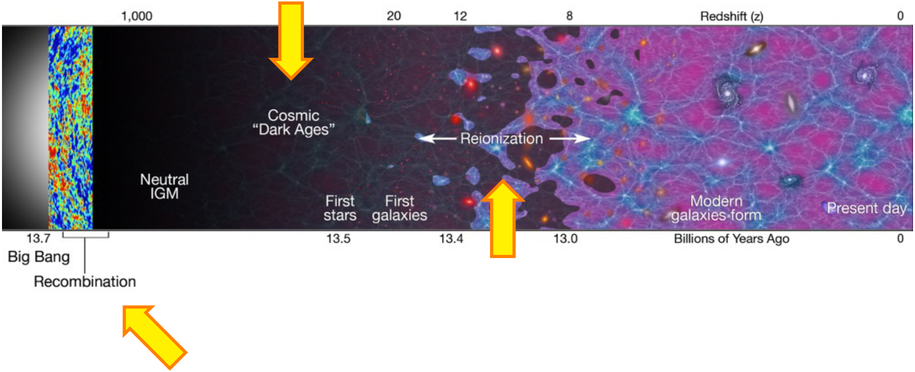


Figure from Petrucci et al. 2007 [0706.0134]

[10] Conlon and Marsh 2013 [1305.3603], Angus et al. 2014 [1312.3947]

Ionization history of the Universe



Reionization from ALP conversions

- ALPs convert into high-energy photons which may ionize neutral atoms after recombination

Photon spectrum

Ionized H atoms by a single photon

Free electrons produced in n-th domain

$$\Delta n_e^{\text{free}}(z_n) = \int_0^\infty \mathrm{d}\omega_n \, \frac{\mathrm{d}n_\gamma}{\mathrm{d}\omega_n} f_S(z_n) f_I(z_n) \frac{\omega_n}{13.6\,\mathrm{eV}}$$

Fraction of free photons

Fraction of ionizing photons

The ionization fraction

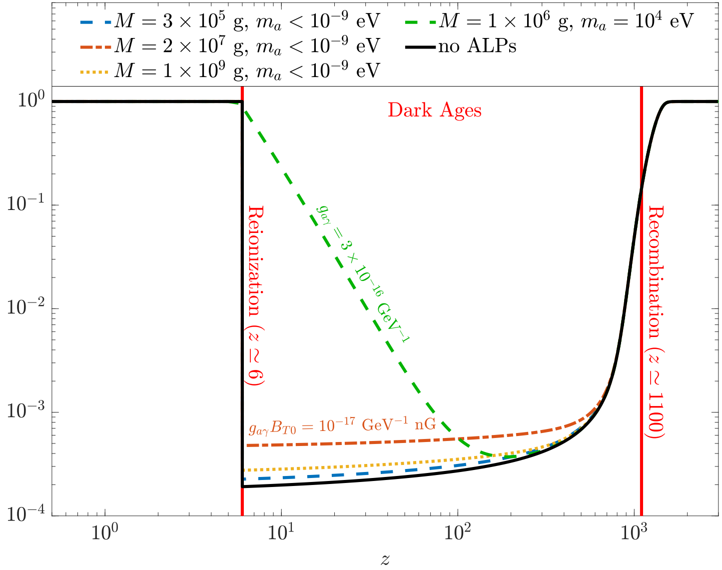
Ionization fraction

$$X_e(z_n) = \frac{n_e^{\rm free}(z_n)}{n_H(z_n)} = X_e^0(z_n) + \sum_{i=1}^{n} \frac{\Delta n_e^{\rm free}(z_i)}{n_{\rm H}(z_i)}$$

- The standard evolution of the ionization fraction of the Universe $X_e^0(z)$ can be computed numerically[11]
- It is modified by the injection of extra free electrons

[11] https://www.cfa.harvard.edu/~sasselov/rec/

The ionization fraction



Optical depth

- The increased ionization contributes to the optical depth of the Universe

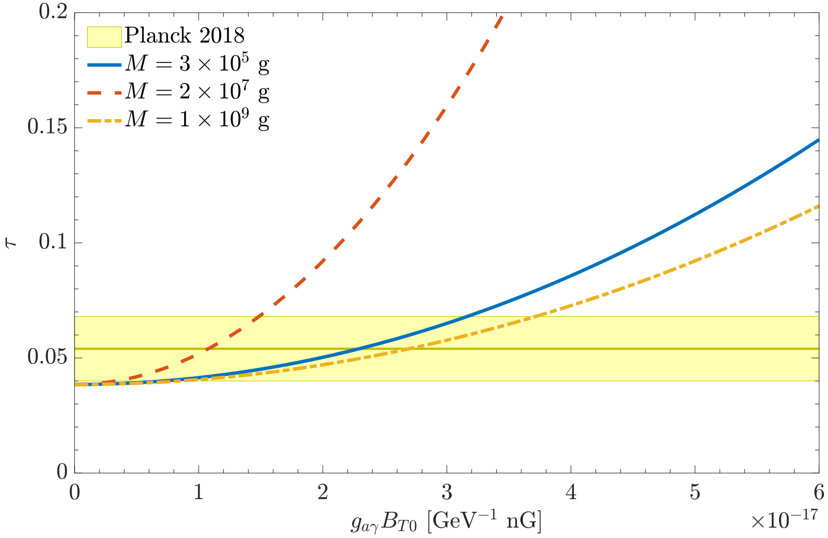
Thomson optical depth

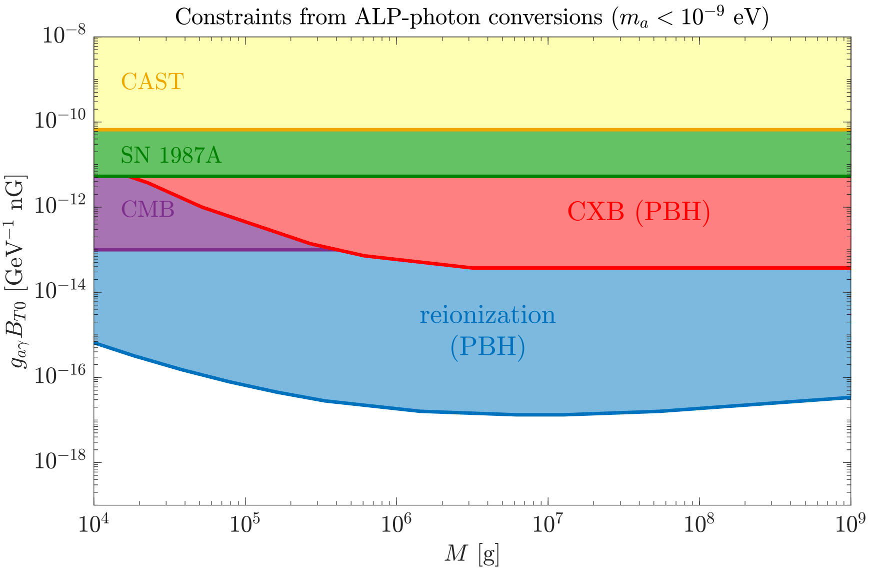
$$\tau = \int_0^\infty \mathrm{d}z \left|\frac{\mathrm{d}t}{\mathrm{d}z}\right| \sigma_T n_e^{\mathrm{free}}(z)$$

- Impose that the obtained value of τ does not exceed the measured one[12] to constrain $g_{a\gamma} B_{T0}$

[12] Aghanim et al. 2020 [1807.06209]

Optical depth





Bounds from CAST [1705.02290], SN 1987A [1410.3747] and CMB distortions [0905.4865]

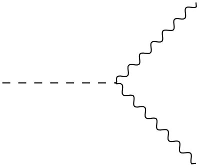
reported assuming $B_0 = 1\,\mathrm{nG}$

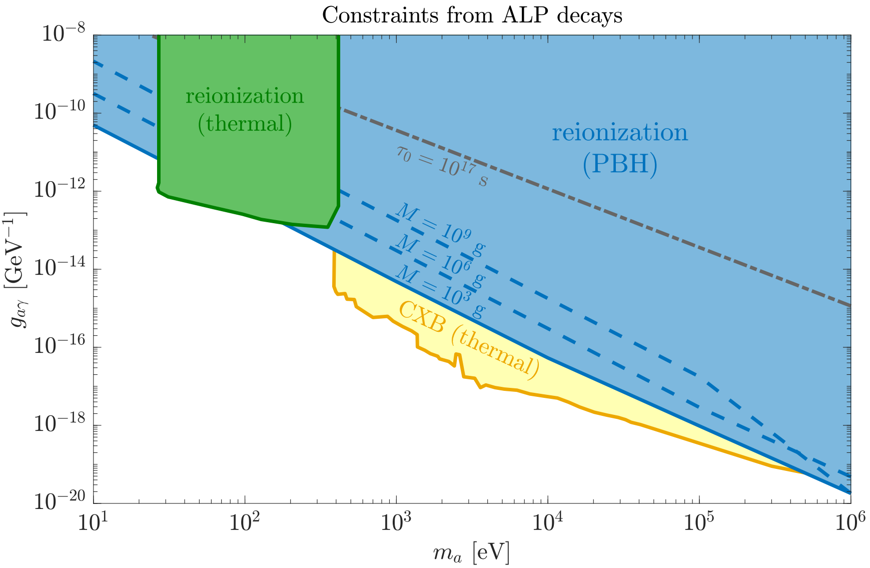
Decay of massive ALPs

$a \to \gamma\gamma$ decay rate

$$\Gamma_{a\gamma} = \frac{m_a^3 g_{a\gamma}^2}{64\pi} \simeq 7.55 \times 10^{-40} \left(\frac{m_a}{1\,\mathrm{eV}}\right)^3 \left(\frac{g_{a\gamma}}{10^{-17}\,\mathrm{GeV}^{-1}}\right)^2 \mathrm{s}^{-1}$$

- Decay is relevant for $\Gamma_{a\gamma}^{-1} <$ age of the Universe (including Lorentz boosts)
- Focus on “heavy” ALPs
- Photon spectrum obtained by solving a Boltzmann equation including absorption and production terms





Bounds for thermal production from Cadamuro and Redondo 2012 [1110.2895]

Conclusions

- PBH domination is a possible occurrence in the Early Universe
- Several observable signatures if PBHs emit axion-like particles
- Stringent constraints on ALP-photon mixing in this scenario
- Further developments: include gravitons (e.g. from spinning PBHs) and graviton-photon conversions in the picture

Selected references

More recent papers about PBHs and Hawking radiation:

- Carr et al. 2020 [2002.12778]
- Hooper et al. 2019 [1905.01301], Hooper et al. 2020 [2004.00618]
- Masina 2020 [2004.04740], Auffinger et al. 2021 [2012.09867], Masina 2021 [2103.13825]
- Arbey et al. 2021 [2104.04051]

About axion-like particles from PBHs:

- Bernal et al. 2021 [2107.13575], [2110.04312]

Thank you for your attention!