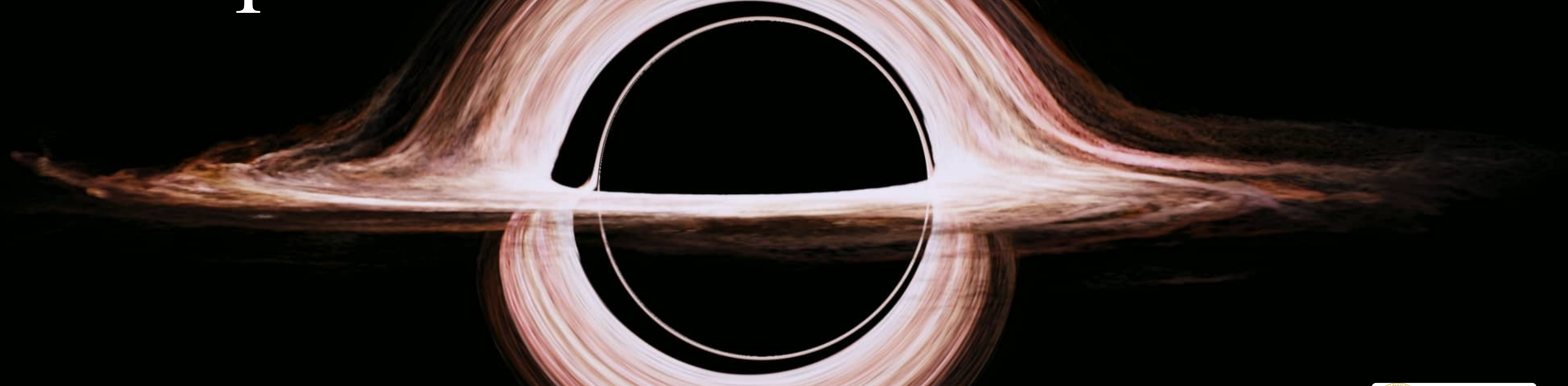
Axion-like particles from light primordial black holes



Daniele Montanino

Università del Salento

INFN Istituto Nazionale di Fisica Nucleare

Based on F. Schiavone, D. M. A. Mirizzi, F. Capozzi, JCAP 08 (2021) 063

NEHOP

NEW HORIZONS IN PRIMORDIAL BLACK HOLE PHYSICS

Naples, Italy

June 19th to June 21st 2023

Framework

- Ultra Light (M<10^9g) BHs evaporate before BBN leaving very small imprint on actual Universe.

- In the standard scenario, the product of evaporation (except gravitational waves) enter in thermal equilibrium and thus are undetectable. The only way to prove the existence of ULPBHs is through relic GWs emitted by PBH scattering or merging (low frequencies) or evaporation itself (high frequencies).

- In the non-standard scenario, evaporation is an unavoidable source of new light or heavy particles that can live till now, like axions, dark photons, sterile neutrinos, WIMPS etc. These particles can be dark matter or dark radiation.

- We consider a scenario where ULPBH evaporate in standard particles + 1 light axion like particles (ALPs). For simplicity we consider a population of single mass nonrotating PBHs

- The instantaneous spectrum of a particle with spin s and energy ω from a nonrotating, uncharged PBH of mass M is given by

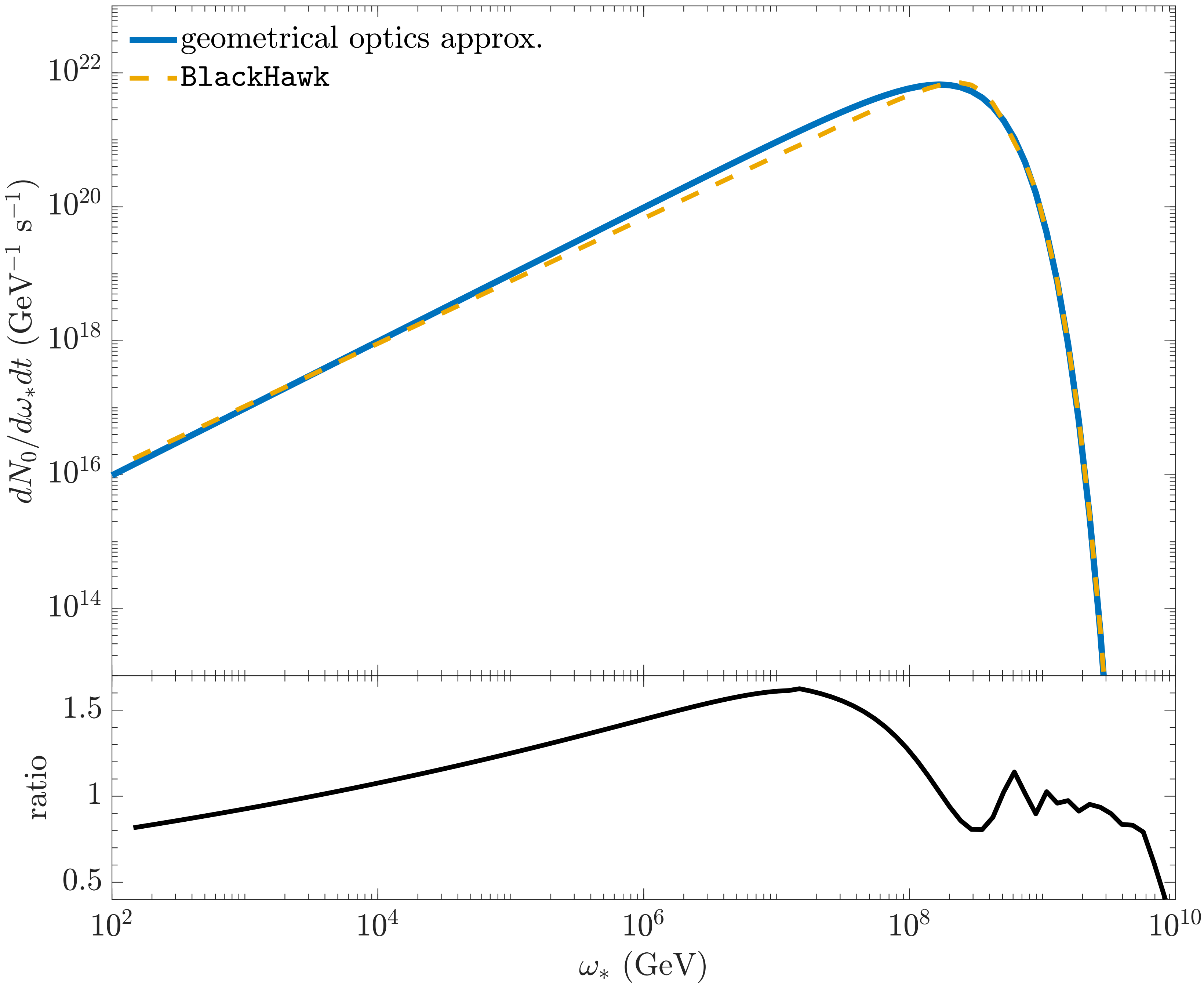
$$\frac{dN_s}{d\omega dt} \equiv \phi_s(\omega, M) = \frac{1}{2\pi} \frac{\Gamma_s(\omega, M)}{e^{\omega/T_{\rm BH}} - (-1)^{2s}} ,$$

where $\Gamma_s(\omega,M)$ is the *graybody factor* (probability that emitted particles are reabsorbed into the hole)

- For light spin-0 particles the GB factor can be approximated by (*geometric optic approximation*)

$$\Gamma_0(\omega, M) \simeq \frac{\kappa_a M^2 \omega^2}{m_P^4} = \frac{\kappa_a}{(8\pi)^2} \left(\frac{\omega}{T_{\rm BH}}\right)^2$$

where the factor κ_a=27.6 is chosen in such a way that the total flux calculated with this approximation coincides to those calculated with `BlackHawk`



geometrical optics approx.
BlackHawk
$dN_0/d\omega_* dt$ (GeV^{-1} s^{-1})
10^{22}
10^{20}
10^{18}
10^{16}
10^{14}
ratio
1.5
1
0.5
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
ω_* (GeV)

- The PBH mass loss rate is given by

$$\frac{dM}{dt} = -\sum_s \int d\omega\, \omega \frac{dN_s}{d\omega dt} \equiv -\frac{f(M)}{M^2}$$

where $f(M)$ is a function obtaining summing over all particle states with mass $m < T_{\rm BH}$

- For light BHs ($M < 10^9$g) $T_{\rm BH} \gg 100$GeV and thus all SM particles (+ 1 scalar) are involved in the BH evaporation. We neglect further massive non standard states

- With these assumptions $f(M) \simeq m_{\rm P}^4 f_{\rm ev}$ with $f_{\rm ev} = 4.26 \times 10^{-3}$. Using this approximation

$$M(t) = M \left(1 - \frac{3 f_{\rm ev} m_P^4 t}{M^3}\right)^{1/3} \equiv M \left(1 - \frac{t}{\tau_{\rm BH}}\right)^{1/3}$$

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

- For $M < 10^9$g BHs evaporate before BBN leaving very small imprint on actual Universe

- Universe evolution is described by FRW and Boltzmann equations

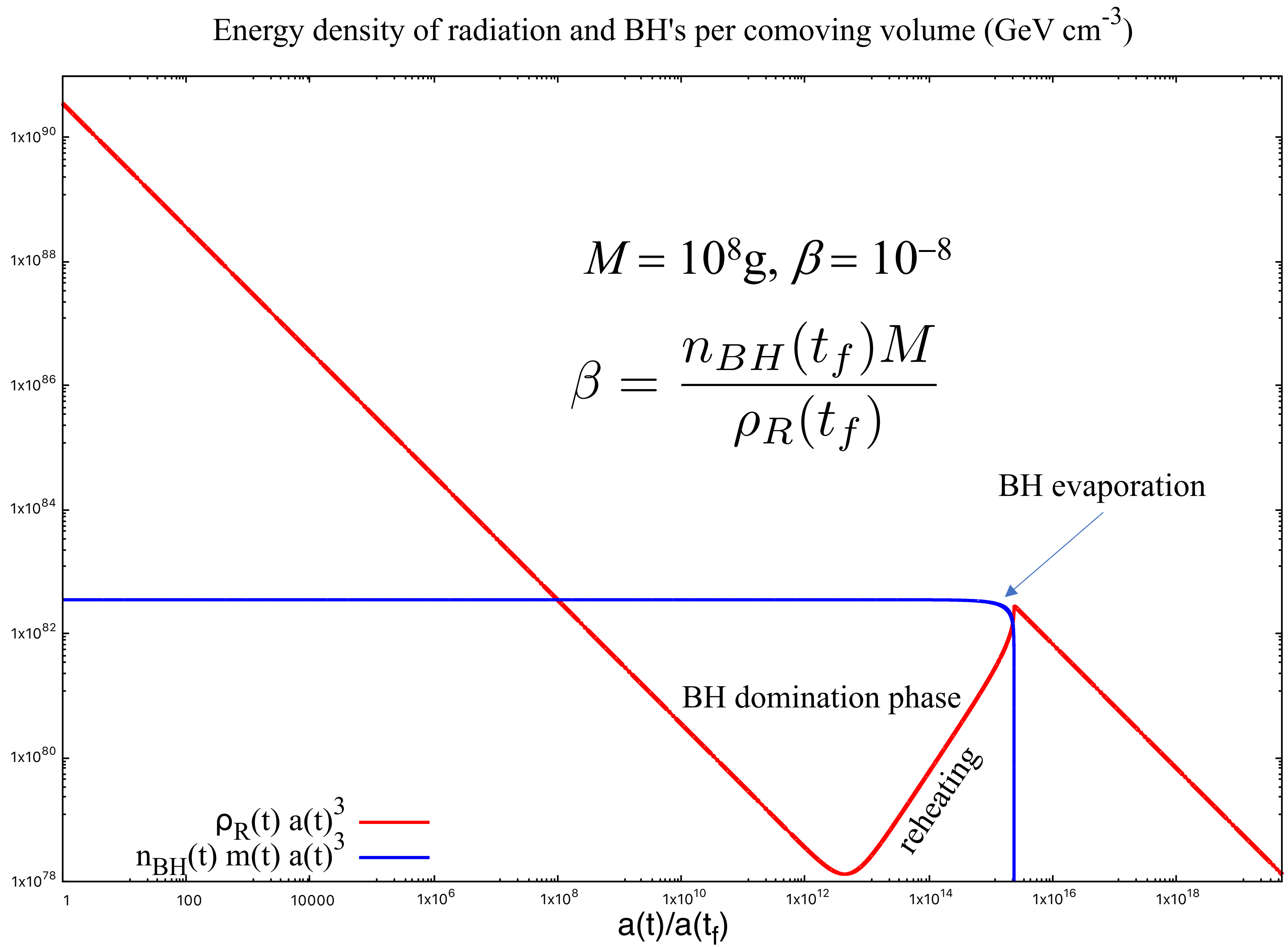
$$\begin{cases} H^2(t) = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3m_{\rm P}^2}\left[\rho_r(t) + M(t)n_{\rm BH}(t)\right] \\ \\ \dot{\rho}_r(t) + 4H(t)\rho_r(t) = -n_{\rm BH}(t)\dot{M}(t) \end{cases}$$

where $n_{\rm BH}(t)=n_{\rm BH}(t_f)/a^3(t)$ scales like matter, with $n_{\rm BH}(t_f)$ BH number density @ formation time [$a(t_f)=1$ by definition]

- If the ratio between BH energy density and radiation density at the time t_f respects the condition

$$\beta = \frac{n_{BH}(t_f)M}{\rho_R(t_f)} \gg \beta_c = (3f_{ev})^{1/2}\frac{m_P}{M} = 2.43 \times 10^{-14}\left(\frac{10^8\,{\rm g}}{M}\right)$$

we have that the Universe is BH (matter-like) dominated during most of the evolution until all the BHs evaporate. In this case the results are almost independent to the initial conditions



Energy density of radiation and BH's per comoving volume (GeV cm^{-3})
$M = 10^8$g, $\beta = 10^{-8}$
$\beta = \frac{n_{BH}(t_f) M}{\rho_R(t_f)}$
BH evaporation
BH domination phase
reheating
$\rho_R(t)\, a(t)^3$
$n_{BH}(t)\, m(t)\, a(t)^3$
1x10^{90}
1x10^{88}
1x10^{86}
1x10^{84}
1x10^{82}
1x10^{80}
1x10^{78}
1
100
10000
1x10^{6}
1x10^{8}
1x10^{10}
1x10^{12}
1x10^{14}
1x10^{16}
1x10^{18}
$a(t)/a(t_f)$

- The ALP number density at the end of BH evaporation is given by

$$\frac{dn_a}{dk}(k_*, \tau_{\rm BH}) = n_{BH}^* \int_{t_f}^{\tau_{\rm BH}} \phi_0 \left[k_* \frac{a_*}{a(t)}, M(t) \right] \frac{a_*}{a(t)} dt$$

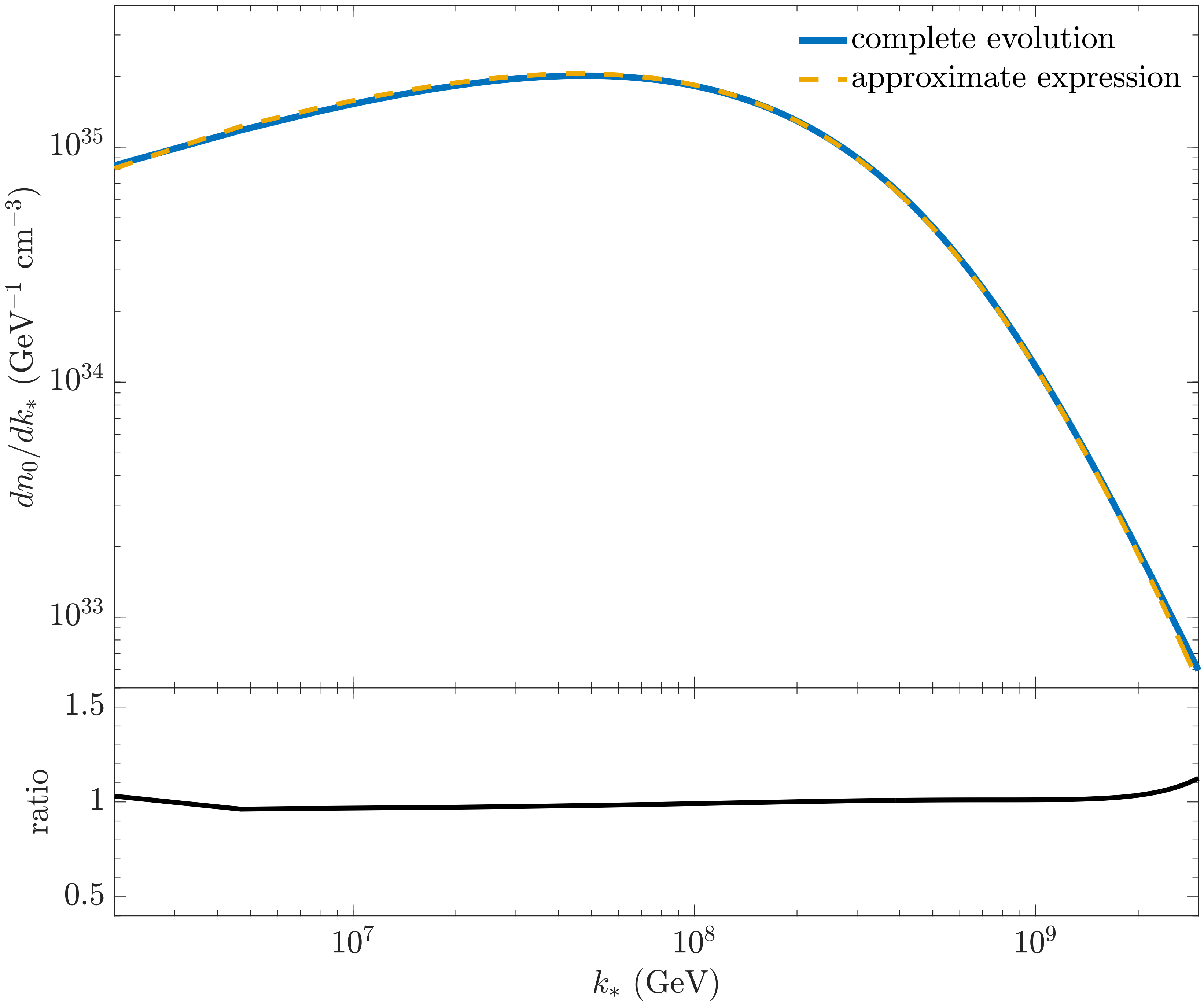
where k=|**k**|=ω is the ALP energy and starred quantities refer to evaporation time

- In the hypothesis of BH dominance and a monochromatic mass spectrum the ALP number density is given by

$$\frac{dn_a}{dk}(k_*, \tau_{\rm BH}) \simeq \frac{f_{\rm ev}\kappa_a}{4\pi^2} \left(\frac{m_P}{M}\right)^2 T_{\rm BH}^2 \mathcal{I}\left(\frac{k_*}{T_{\rm BH}}\right)$$

with

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



complete evolution
approximate expression
dn_0/dk_* (GeV^{-1} cm^{-3})
10^{35}
10^{34}
10^{33}
ratio
1.5
1
0.5
10^7
10^8
10^9
k_* (GeV)

- The ALP number density must be scaled to the present epoch

$$\frac{dn_a}{dk}(k,t_0) \simeq 3.27 \times 10^{-3} \left(\frac{m_P}{M}\right)^2 T_{\rm BH,0}^2 \mathcal{I}\left(\frac{k}{T_{\rm BH,0}}\right)$$

$$\simeq 2.02 \times 10^{-5} \left(\frac{10^5 {\rm g}}{M}\right)^2 \left(\frac{T_{\rm BH,0}}{1{\rm eV}}\right)^2 \mathcal{I}\left(\frac{k}{T_{\rm BH,0}}\right) \,{\rm cm}^{-3}\,{\rm keV}^{-1}$$

where

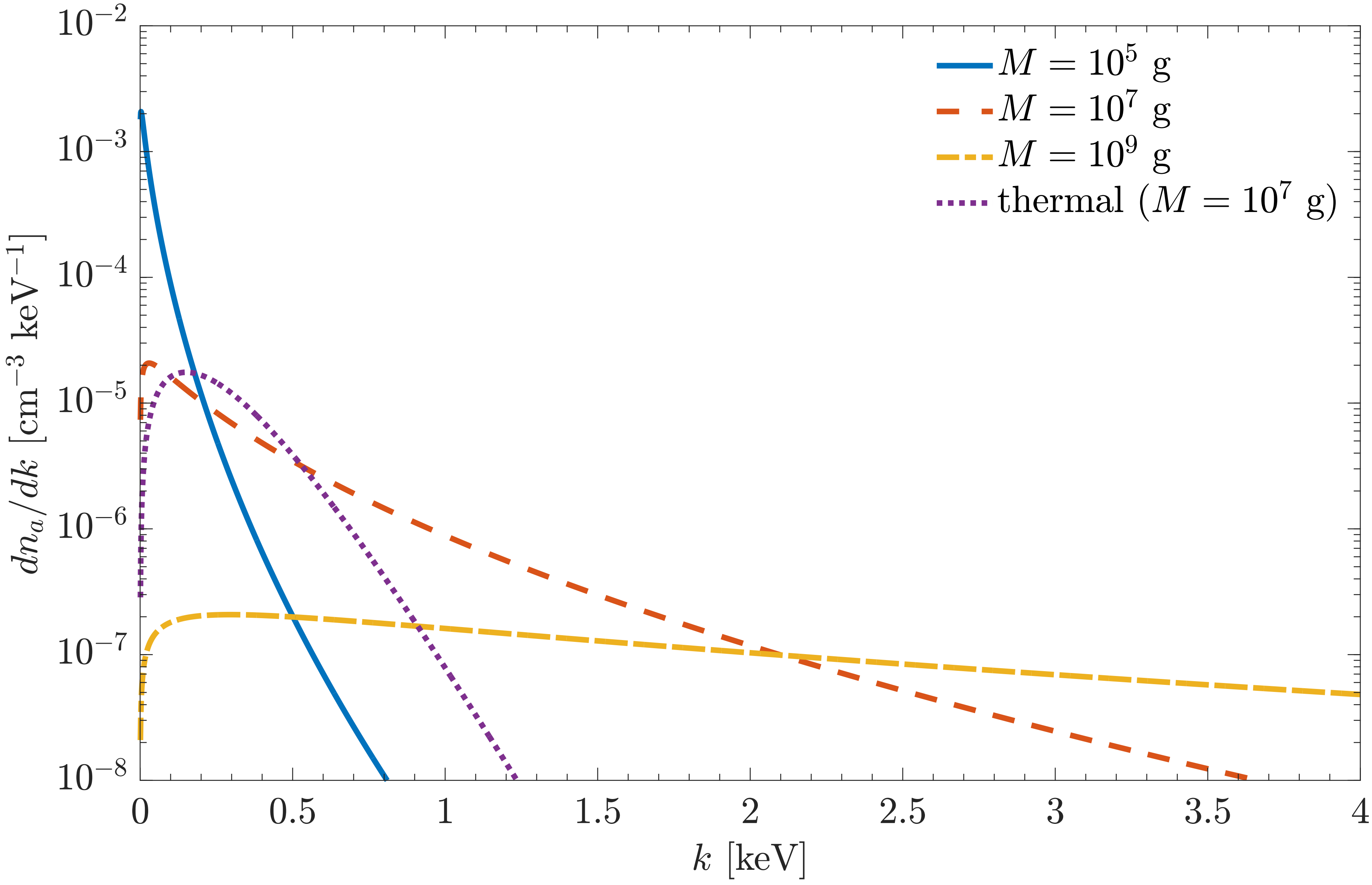
$$T_{\rm BH,0} = \frac{T_{\rm BH}}{1+z_*} \simeq 9.47 \left(\frac{100}{g_S(T_*)}\right)^{1/12} \left(\frac{M}{10^5\,{\rm g}}\right)^{1/2} \,{\rm eV}$$

with z^* redshift at BH evaporation

- The total ALP number density is

$$n_a = \int_0^\infty \frac{dn_a}{dk}(k,t_0)dk = 1.18 \times 10^{-2} \left(\frac{m_P}{M}\right)^2 T_{\rm BH,0}^3$$

$$= 6.18 \times 10^{-5} \left(\frac{100}{g_S(T_*)}\right)^{1/4} \left(\frac{10^5\,{\rm g}}{M}\right)^{1/2} \,{\rm cm}^{-3}$$



$M = 10^5$ g
$M = 10^7$ g
$M = 10^9$ g
thermal ($M = 10^7$ g)
dn_a/dk [cm^{-3} keV^{-1}]
k [keV]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0
0.5
1
1.5
2
2.5
3
3.5
4

- The ALP total energy density is given by

$$\rho_a = \int_0^\infty d\omega\omega \frac{dn_a}{dk}(\omega, t_0) = 5.14 \times 10^{-2} \left(\frac{m_P}{M}\right)^2 T_{\mathrm{BH},0}^4$$

$$= 2.49 \times 10^{-3} \left(\frac{100}{g_S(T_*)}\right)^{1/3} \mathrm{eV\,cm}^{-3}$$

- This ALP background might behave as dark radiation for $m_a \ll 10$ MeV if they are stable on cosmological time scales contributing to an extra-component of the effective number of neutrinos

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

- This value is in the reach of next generation experiments. Notice that this value does not depend on ALP coupling with photons or electrons/nuclei

- ALPs interact with photons through the Lagrangian

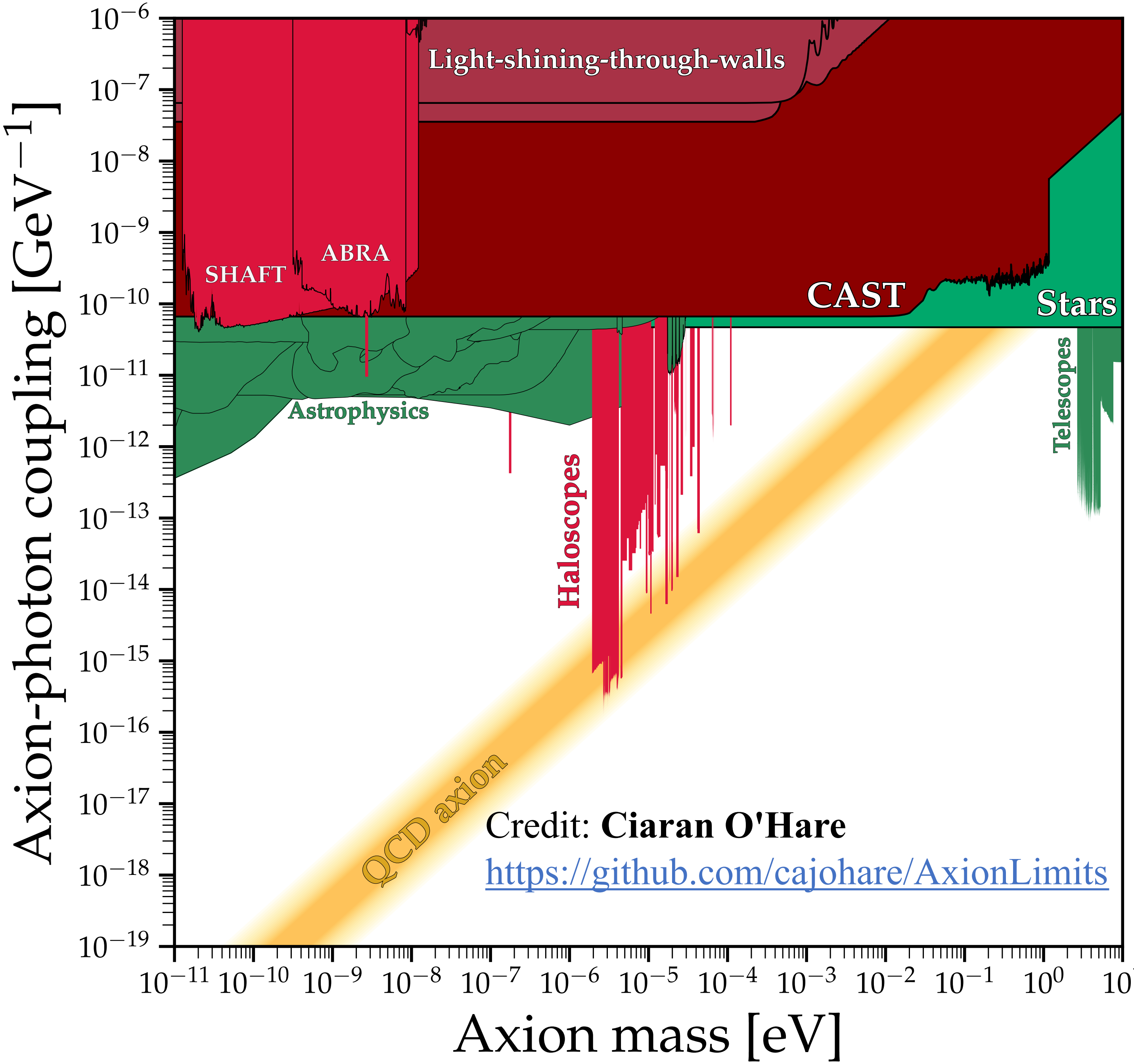
$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma}\, \mathbf{E} \cdot \mathbf{B}\, a$$

- Light ($m_a \ll \omega$) ALPs can oscillate into photons in an external magnetic field. For a beam propagating in x_3 direction in an external magnetic field **B** the evolution equation is

$$i\frac{\partial}{\partial x_3}\begin{pmatrix} A_\perp \\ A_\parallel \\ a \end{pmatrix} = \begin{bmatrix} -\frac{\omega_{\rm pl}^2}{2\omega} + \Delta_{\rm CMB} - i\frac{\Gamma}{2} & 0 & 0 \\ 0 & -\frac{\omega_{\rm pl}^2}{2\omega} + \Delta_{\rm CMB} - i\frac{\Gamma}{2} & \frac{g_{a\gamma} B_T}{2} \\ 0 & \frac{g_{a\gamma} B_T}{2} & -\frac{m_a^2}{2\omega} \end{bmatrix} \begin{pmatrix} A_\perp \\ A_\parallel \\ a \end{pmatrix}$$

  - ✓ $A_\perp$ ($A_\parallel$) is the perpendicular (parallel) component to the transverse magnetic field $\mathbf{B}_{\rm T}=\mathbf{B}-B_3\mathbf{e}_3$
  - ✓ $\omega_{\rm pl}^2=4\pi\alpha n_{\rm e}/m_{\rm e}$ is the plasma frequency of the medium
  - ✓ $\Delta_{\rm CMB} \propto \rho_{\rm CMB}$ is the contribution to the photon polarization by the CMB radiation
  - ✓ Γ accounts for photon non-coherent scattering and absorption
  - ✓ we neglect the effect of vacuum birefringence

- For beams propagating across cosmological distances all the quantities must be appropriately scaled



Light-shining-through-walls
SHAFT
ABRA
CAST
Stars
Astrophysics
Haloscopes
Telescopes
QCD axion
Credit: **Ciaran O'Hare**
https://github.com/cajohare/AxionLimits
Axion-photon coupling [GeV^{-1}]
Axion mass [eV]

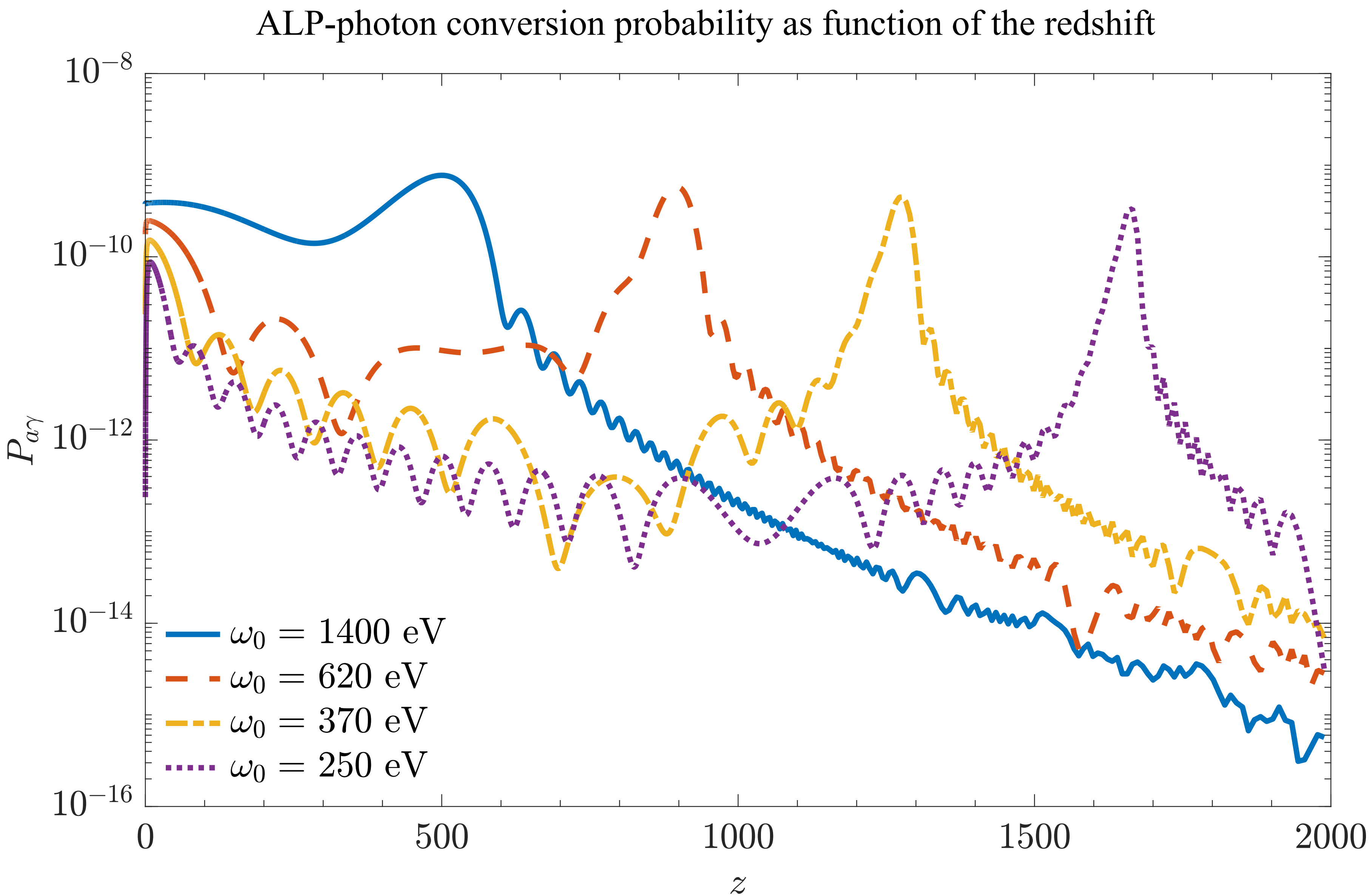
- Planck data constrain primordial magnetic field strength to <1nG on a coherent scale of l~1Mpc. Very little is known on intergalactic magnetic fields.

- We model the primordial *B*-field as a network of cells with size set by its coherence length. The strength of **B** is assumed to be the same in every domain, but its direction changes in a random way from one cell to another. This choice is not critical since we have proven that with a realistic (Kolmogorov-like) spectrum the results are almost the same.

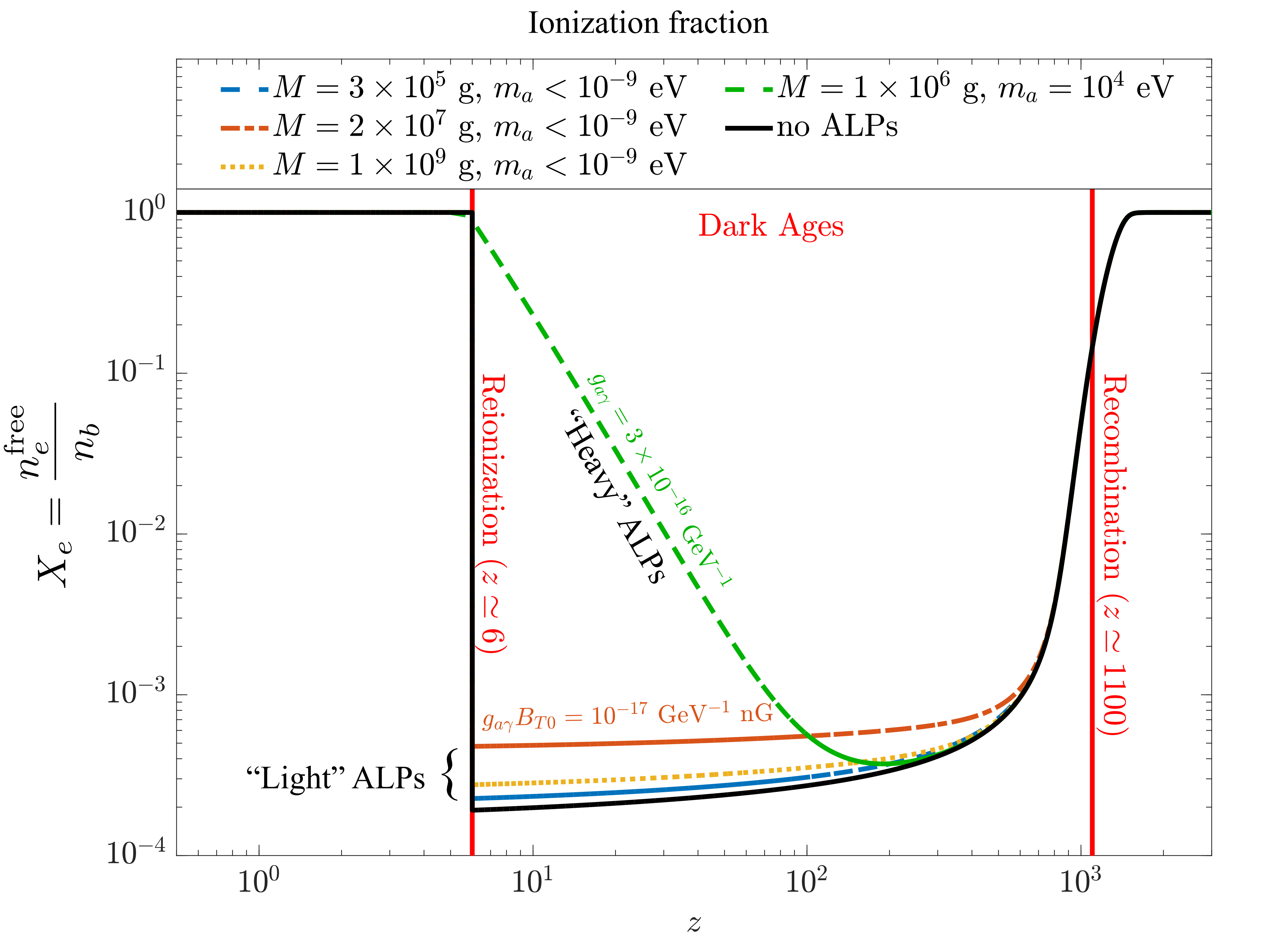
- For simplicity we do not consider B-field evolution in early universe. Strength of the magnetic field simply scales as $(1+z)^2$, while the coherence length as $(1+z)^{-1}$.

- In the period $6 \lesssim z \lesssim 1100$ we have the so called “dark ages”, during which virtually all H and He atoms were neutral (except for a very low fraction of ionized hydrogen).

- ~keV energy primordial ALPs coming from PBH evaporation (or any other mechanism) can convert into photons and scatter on neutral atoms (through photoelectric and Compton scattering) triggering an electromagnetic shower resulting in the reionization of the medium.



ALP-photon conversion probability as function of the redshift
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
$P_{a\gamma}$
0
500
1000
1500
2000
z
$\omega_0 = 1400$ eV
$\omega_0 = 620$ eV
$\omega_0 = 370$ eV
$\omega_0 = 250$ eV



Ionization fraction
$M = 3 \times 10^5$ g, $m_a < 10^{-9}$ eV
$M = 2 \times 10^7$ g, $m_a < 10^{-9}$ eV
$M = 1 \times 10^9$ g, $m_a < 10^{-9}$ eV
$M = 1 \times 10^6$ g, $m_a = 10^4$ eV
no ALPs
Dark Ages
Reionization ($z \simeq 6$)
Recombination ($z \simeq 1100$)
"Heavy" ALPs
$g_{a\gamma} = 3 \times 10^{-16}$ GeV^{-1}
$g_{a\gamma} B_{T0} = 10^{-17}$ GeV^{-1} nG
"Light" ALPs
$X_e = \frac{n_e^{\rm free}}{n_b}$
z
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^0
10^1
10^2
10^3

- The value of the Thomson optical depth of the Universe is given by

$$\tau = \int_0^\infty dz \left| \frac{dt}{dz} \right| \sigma_T n_e^{\rm free}(z)$$

with $\sigma_T = 6.65\times10^{-25}$ cm^{-1} is the Thomson cross section and $n_e^{\rm free}(z)$ is the number of free electrons. This number must be compared to experimental determination by the Planck 2018 measurement

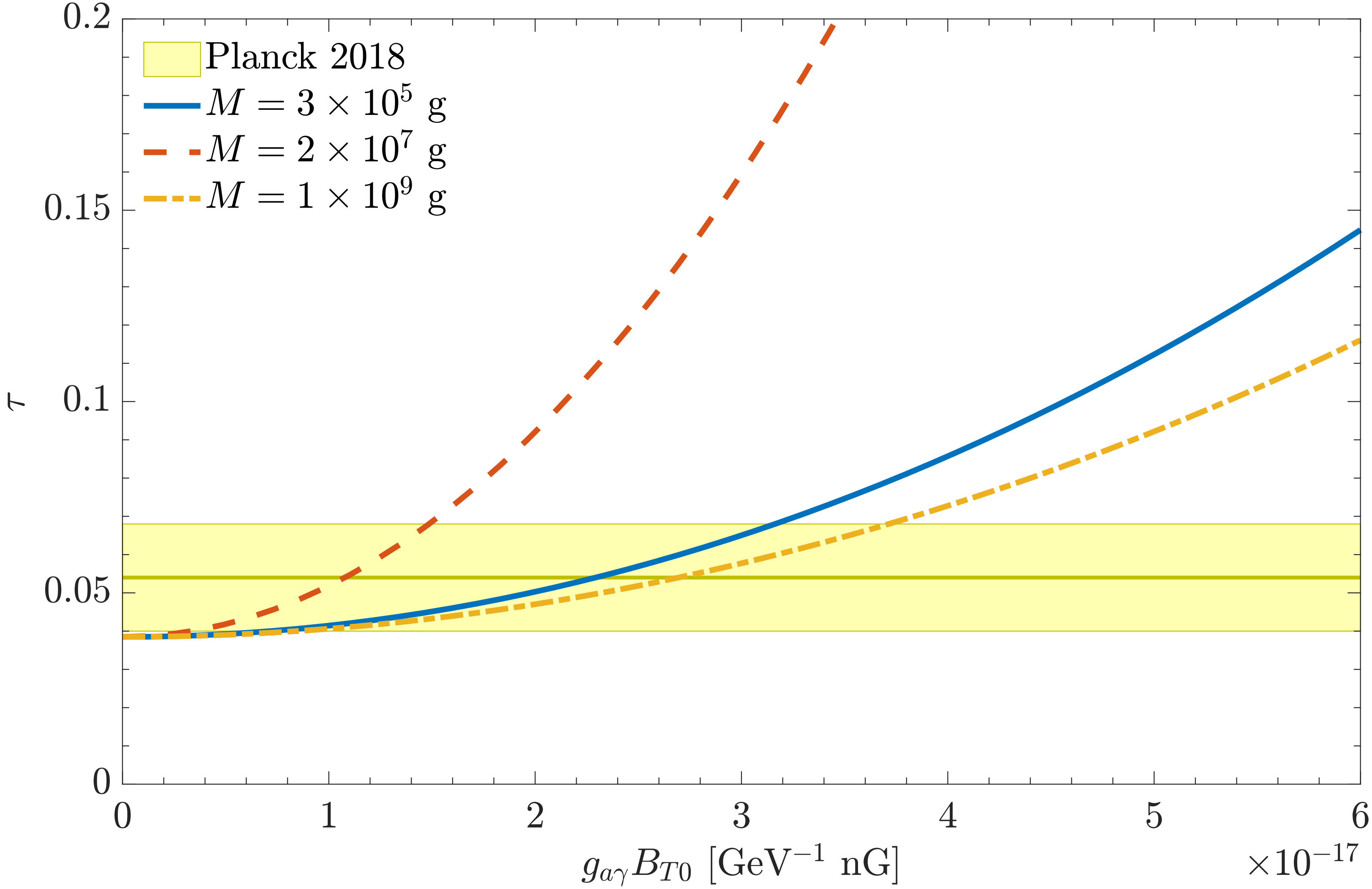
$$\tau_{\rm exp} = 0.054 \pm 0.007$$

For $z<6$ the intergalactic medium is completely ionized. The contribution to optical depth for $z<6$ is $\tau_{z<6}=0.038$. Imposing that

$$\tau_{\rm ALP} < \tau_{\rm exp}^{2\sigma} - \tau_{z<6} \simeq 0.030$$

we obtain upper bounds on the product $g_{a\gamma}B_{T0}$ (where "0" refers to the today value)

$$g_{a\gamma} B_{T0} \lesssim \mathcal{O}(10^{-15}\text{–}10^{-17})\,{\rm GeV}^{-1}\,{\rm nG}$$

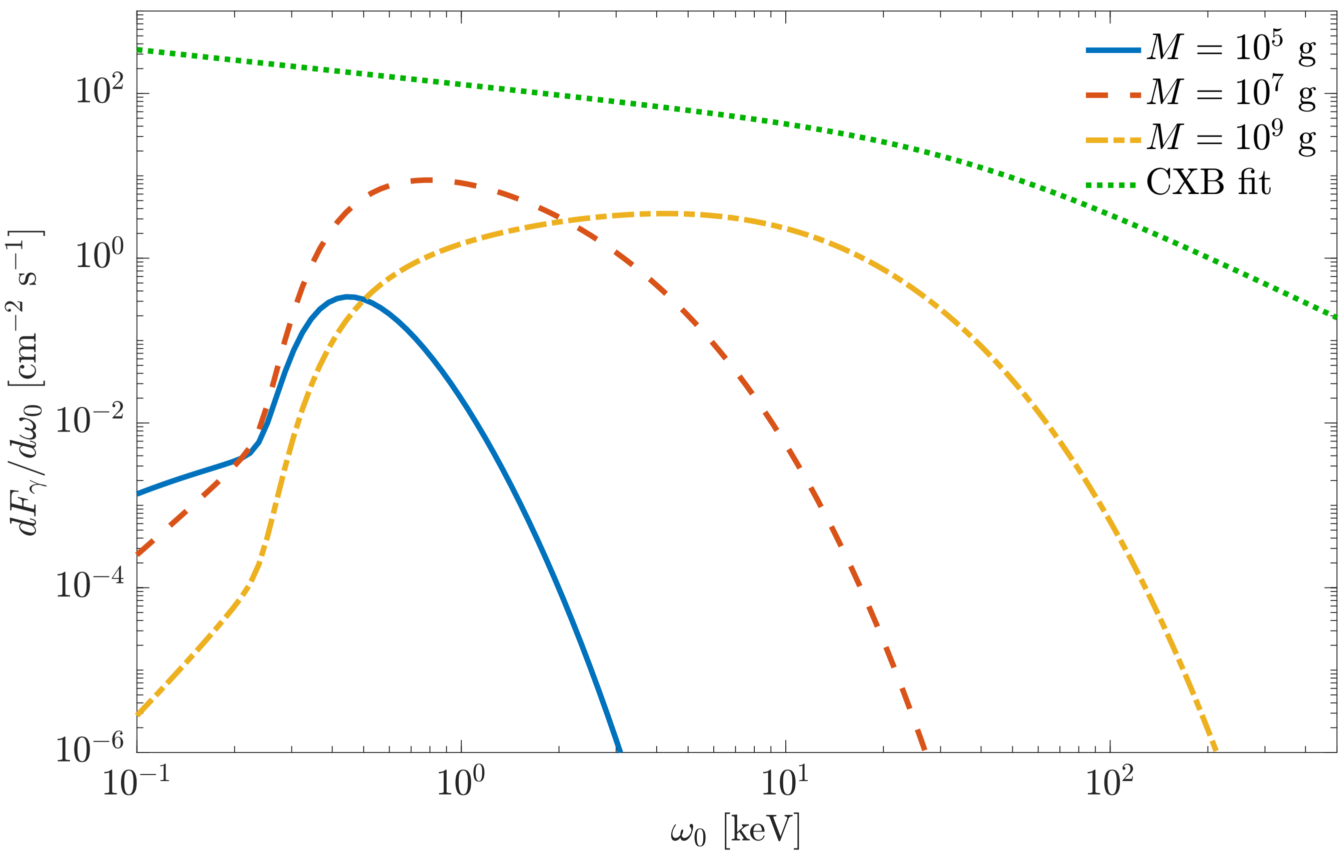


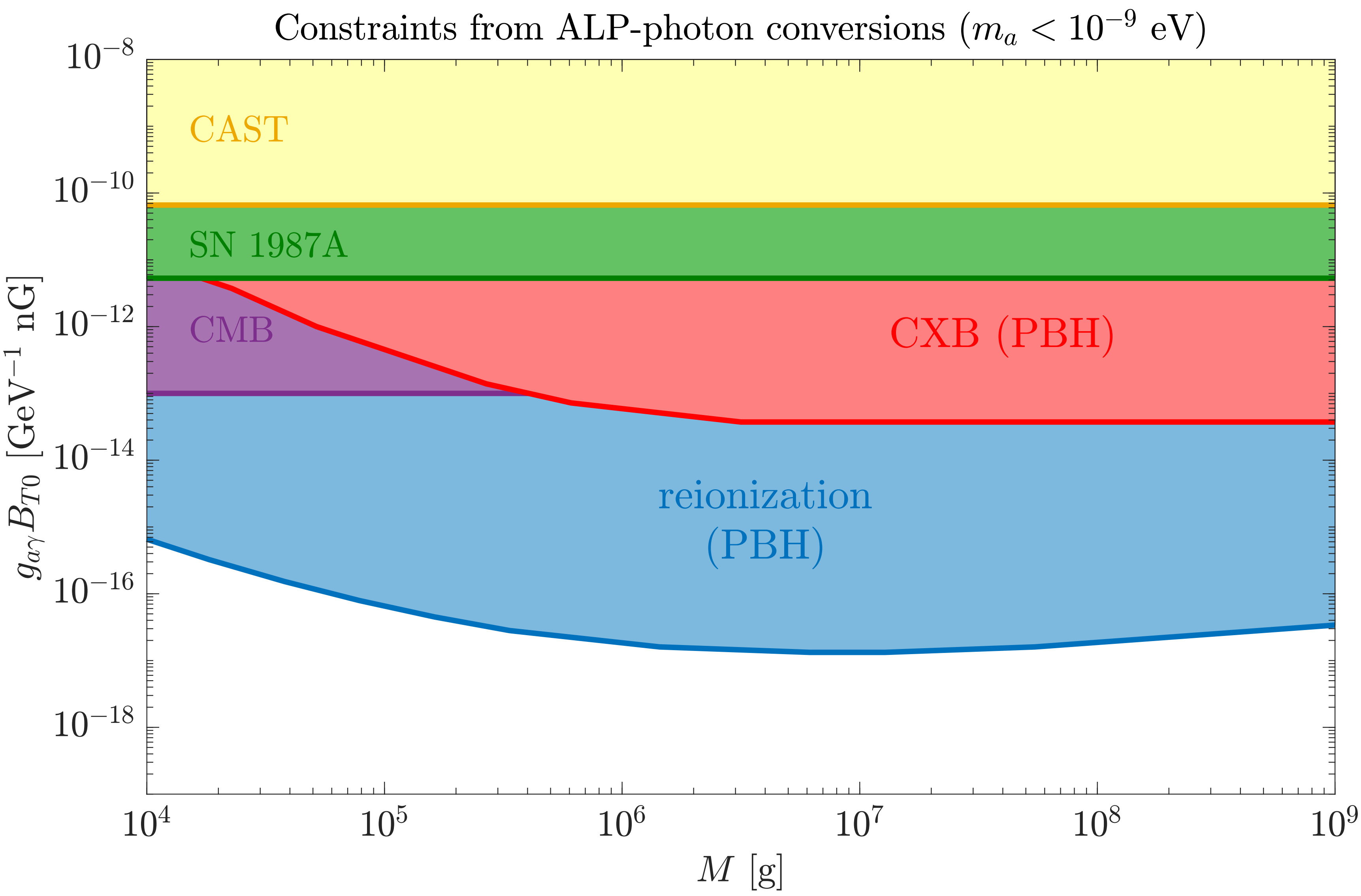
Planck 2018
$M = 3 \times 10^5$ g
$M = 2 \times 10^7$ g
$M = 1 \times 10^9$ g
0.2
0.15
0.1
0.05
0
τ
0
1
2
3
4
5
6
$g_{a\gamma} B_{T0}$ [GeV^{-1} nG]
$\times 10^{-17}$

- Imposing that the photon fluxes from ALP conversions do not exceed Cosmic X-ray Background (CXB) fit in literature we obtain a bound on the product $g_{a\gamma}B_{T0}$ (where "0" refers to the today value)

- Although this bound in not competitive respect to those coming from reionization, we must remark that the latter depends upon the ambient magnetic fields during ALP conversion.

$$g_{a\gamma}B_{T0} = 10^{-14}\,\mathrm{GeV}^{-1}\,\mathrm{nG}$$





Constraints from ALP-photon conversions ($m_a < 10^{-9}$ eV)
CAST
SN 1987A
CMB
CXB (PBH)
reionization
(PBH)
$g_{a\gamma} B_{T0}$ [GeV^{-1} nG]
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^4
10^5
10^6
10^7
10^8
10^9
M [g]

- The EUVE and ROSAT space telescopes discovered an excess in the X-ray spectrum of the Virgo and the Coma Cluster

- It was suggested that a this excess can be can be due by the conversion of a background of ~keV ALPs into photons in the intercluster (B~1μG) magnetic field.

- The estimated photon luminosity from ALP-photon conversion in the cluster is

$$\mathcal{L} = 1.24 \times 10^{41} \left(\frac{100}{g_S(T_*)}\right)^{1/3} \left(\frac{g_{a\gamma}}{10^{-13}\,\mathrm{GeV}^{-1}}\right)^2 \left(\frac{B}{2\,\mu\mathrm{G}}\right)^2 \left(\frac{L}{1\,\mathrm{kpc}}\right) \mathrm{erg\,s}^{-1}$$

which is just one order of magnitude of the excess rate measured:

$$\mathcal{L} \simeq 1.6 \times 10^{42}\,\mathrm{erg\,s}^{-1}$$

- A value of $g_{a\gamma} > 10^{-13}$ GeV^{-1} can thus in principle explain the Cluster excess.

- ALPs can also radiatively decay into photons in absence of B-field. The decay rate is given by

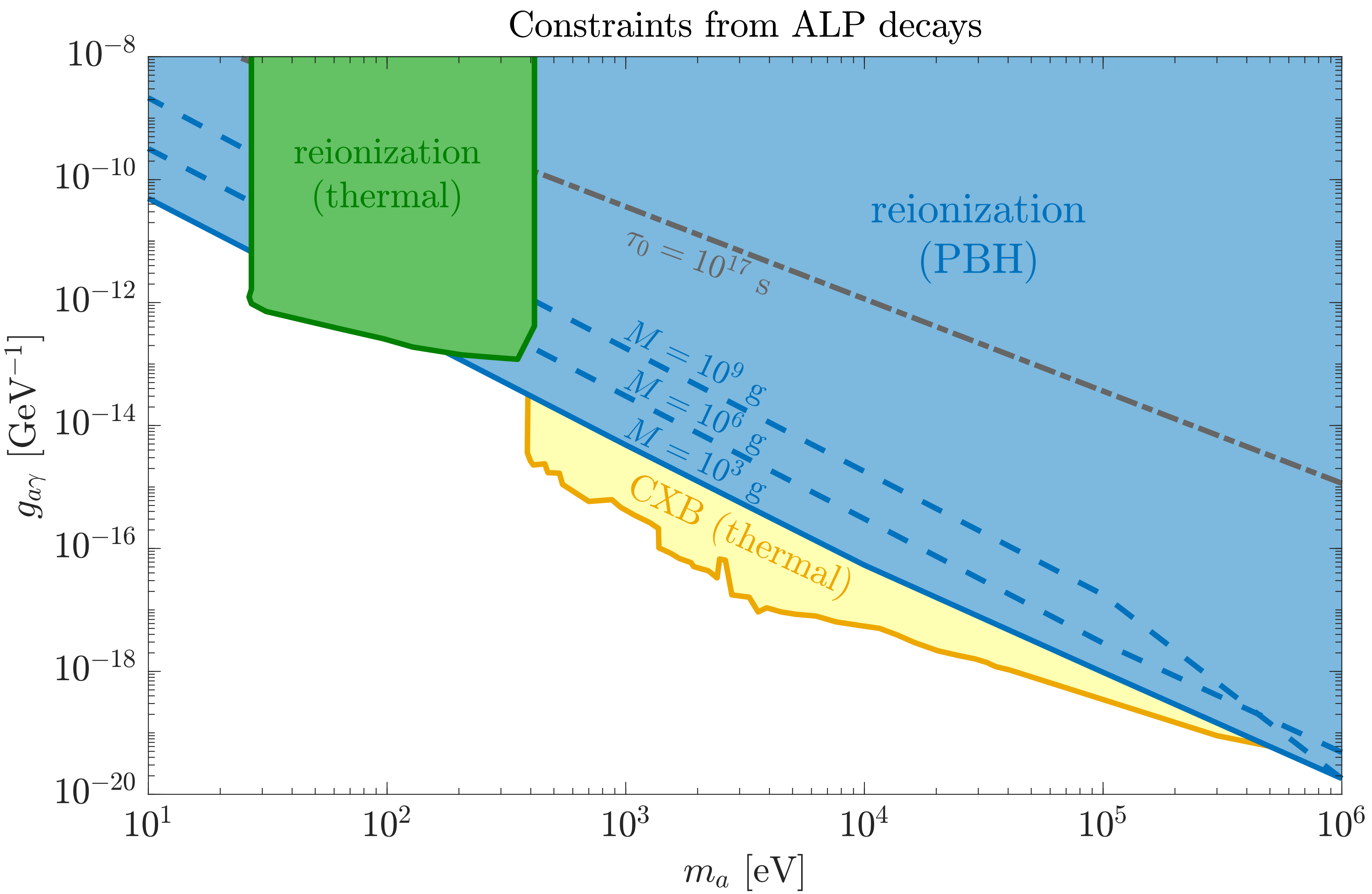
$$\Gamma_{a\gamma} = \frac{m_a^3 g_{a\gamma}^2}{64\pi} \simeq 7.55 \times 10^{-40} \left(\frac{m_a}{1\,\mathrm{eV}}\right)^3 \left(\frac{g_{a\gamma}}{10^{-17}\,\mathrm{GeV}^{-1}}\right)^2 \mathrm{s}^{-1}$$

- Valuable effects on reionization can be obtained for ALP mass greater than ~10eV.

- Photons produced in the decay can reionize the intergalactic medium like in the case of conversion in magnetic field.

- Very massive ALPs are mostly non relativistic at the time of reionization thus producing photons of energy $\omega \gtrsim m_a/2$. More massive ALPs produce more energetic photons and thus a slower decay rate (and thus, lower values of $g_{a\gamma}$) is required to produce an efficient reionization.

- For lighter ALP masses, photons are mostly relativistic. Although the decay time is enhanced by the boost factor, ALPs can decay into photons with energies $\omega > m_a/2$.



Constraints from ALP decays
reionization
(thermal)
reionization
(PBH)
$\tau_0 = 10^{17}$ s
$M = 10^9$ g
$M = 10^6$ g
$M = 10^3$ g
CXB (thermal)
$g_{a\gamma}$ [GeV^{-1}]
m_a [eV]
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^1
10^2
10^3
10^4
10^5
10^6

Conclusions

- PBH with mass M<10^9g evaporate before BBN leaving very small imprints on cosmological observables.
- However they can evaporate also in non-standard particles (DM particles, Axions or Axion-like particles, Dark Photons, sterile neutrinos…). The evaporation rate into these particles is determined only by gravitational coupling and not by the coupling with Standard Model Particle, due to the equivalence principle.
- We have considered non rotating BH evaporation in light (m_a<MeV) and ultralight ($m_a \ll$eV) Axion Like Particles. ALPs can leave an imprint on present universe through conversion in into photons via oscillations in cosmological magnetic fields or through decay.
- Bounds on ALP mass and coupling with photons can be obtained by reionization during Dark Ages and Cosmic X-ray Background data.
- ALPs production enhancement can be obtained through a mechanism called *Superradiance* in rotating BHs. This mechanism is under scrutiny.