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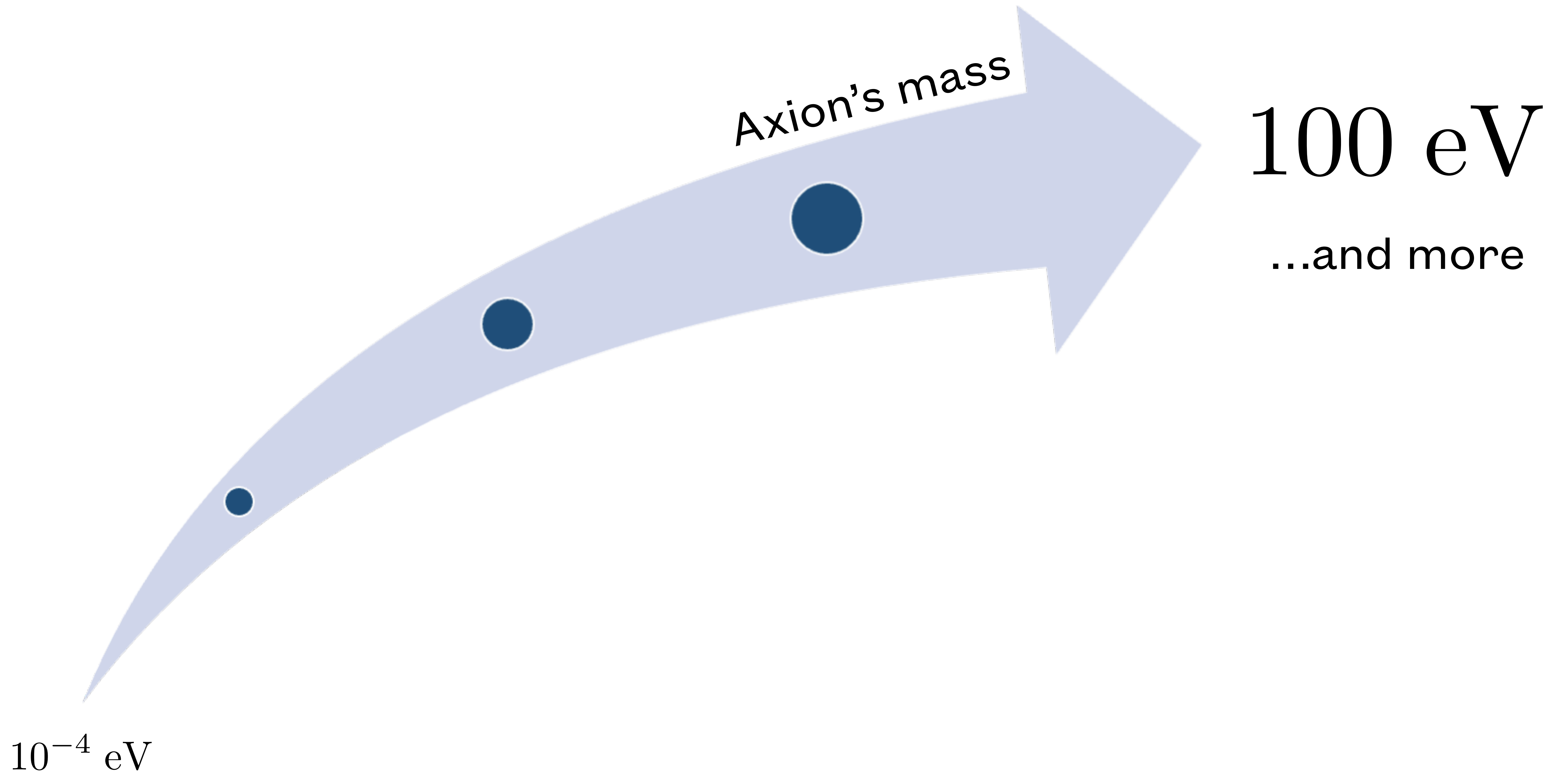
In collaboration with L. Caloni,
M. Gerbino, M. Lattanzi and L. Visinelli

Updated cosmological constraints on thermally-produced axion-like particles

NICOLA BARBIERI (INFN) – 30/06/2025

Cosmo-phenomenology of thermal axions

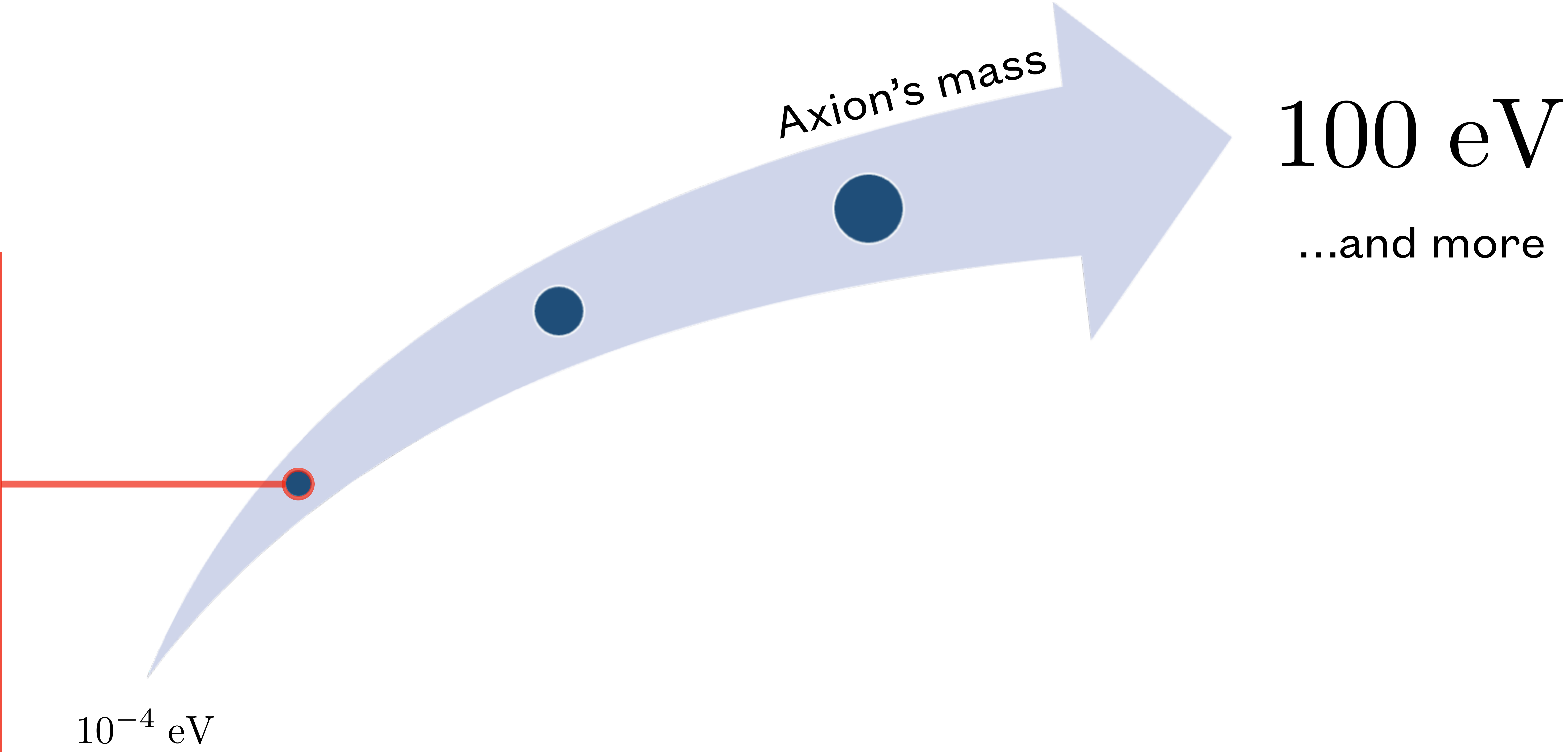


Cosmo-phenomenology of thermal axions

$$\Delta N_{\rm eff} \equiv \frac{\rho_a\left(m_a=0\right)}{\rho_{\nu,\rm mless}} \propto \left(\frac{g_a}{g_\gamma}\right)\left(\frac{T_a}{T_\gamma}\right)^4$$

$$\simeq 0.027\left(\frac{g_{*s}\left(T_d\right)}{106.75}\right)^{-4/3}$$

Light axions contribute to the energy density of **radiation**



Cosmo-phenomenology of thermal axions

Axions behaving as
Warm Dark Matter (WDM)

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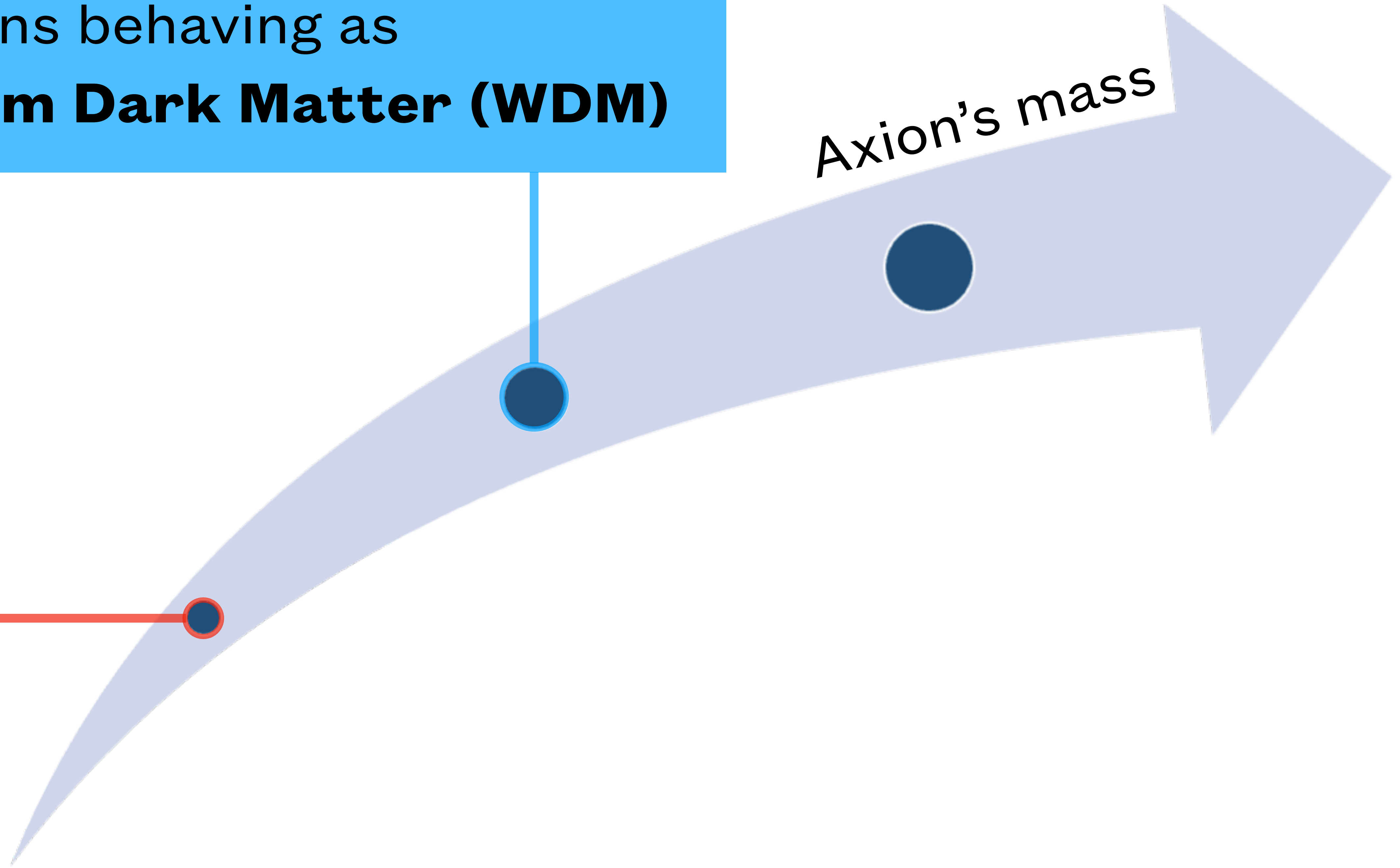


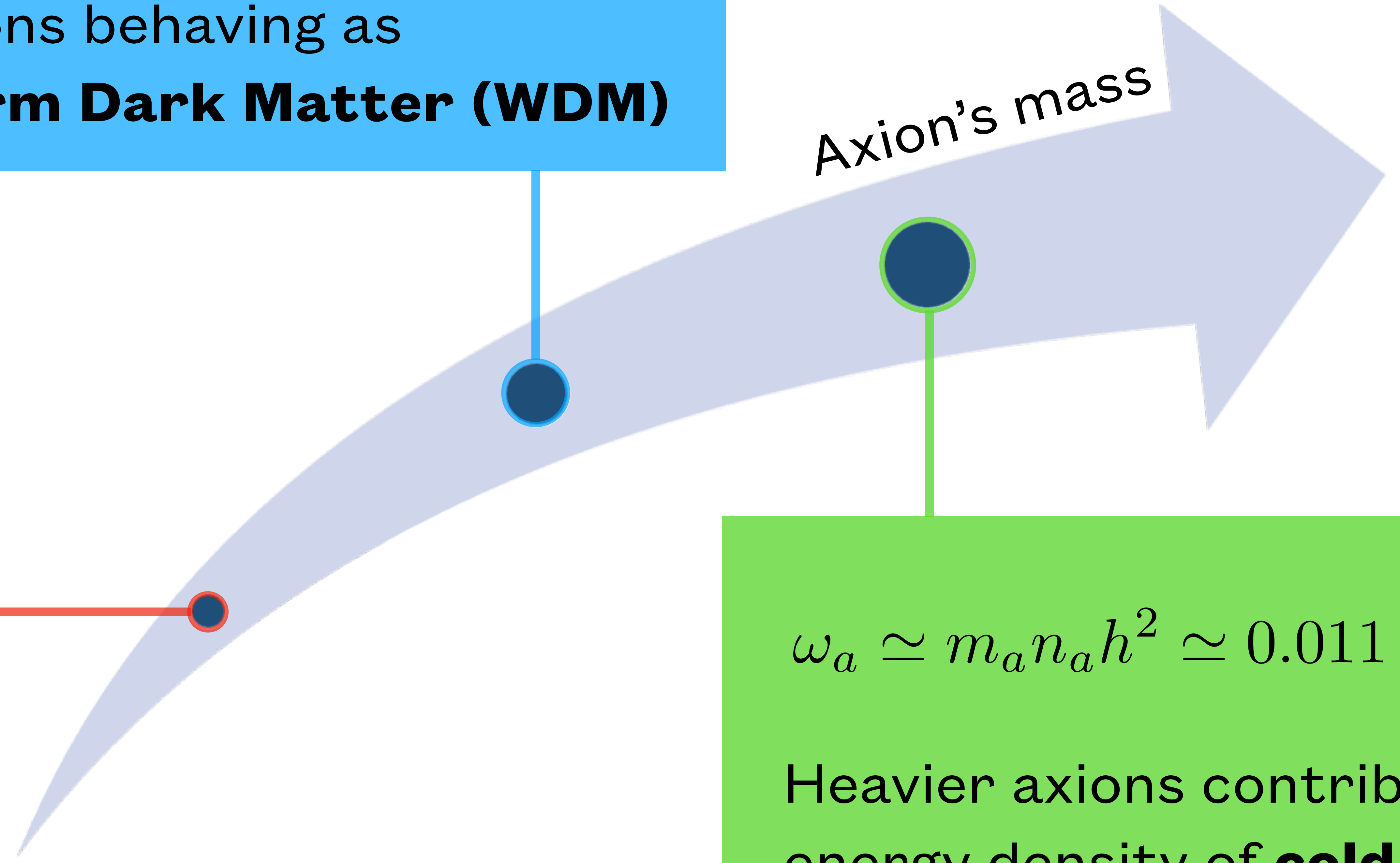
100 eV

...and more

10^{-4} eV

Cosmo-phenomenology of thermal axions

Axions behaving as
Warm Dark Matter (WDM)



$$100\ \mathrm{eV}$$

...and more

$$\Delta N_{\rm eff} \equiv \frac{\rho_a\left(m_a=0\right)}{\rho_{\nu,\rm mless}} \propto \left(\frac{g_a}{g_\gamma}\right)\left(\frac{T_a}{T_\gamma}\right)^4 \simeq 0.027\left(\frac{g_{*s}\left(T_d\right)}{106.75}\right)^{-4/3}$$

Light axions contribute to the energy density of **radiation**

$$10^{-4}\ \mathrm{eV}$$

$$\omega_a \simeq m_a n_a h^2 \simeq 0.011\left(\frac{m_a}{\mathrm{eV}}\right)\Delta N_{\rm eff}^{3/4}$$

Heavier axions contribute to the energy density of **cold dark matter (CDM)**

Pipeline

Pipeline

1

Effective modelling of ALPs interactions:

$$\mathcal{L}_a \supset \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{1}{2}m_a^2 a^2 + c_\ell \frac{\partial_\mu a}{2f_a}\,\bar{\ell}\gamma^\mu\gamma^5\ell + \frac{1}{4}g_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Pipeline

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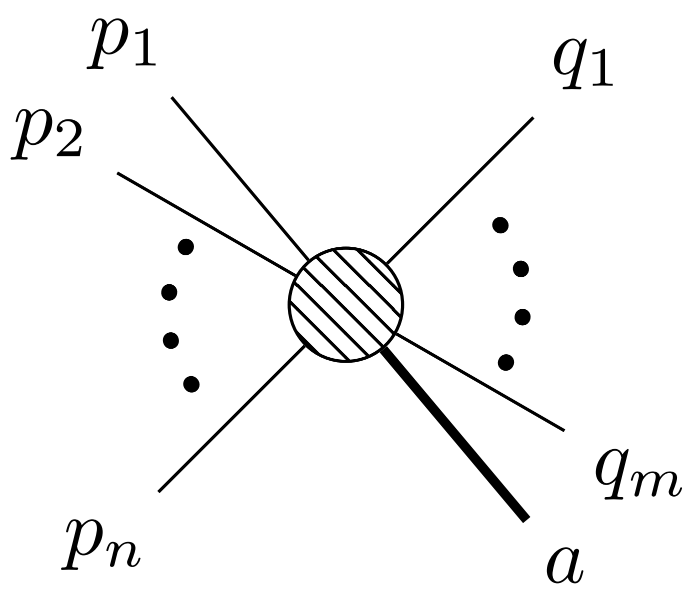
2

Computation of collision term for production processes



Pipeline

Effective modelling of ALPs interactions:

$$\mathcal{L}_a \supset \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{1}{2}m_a^2 a^2 + c_\ell \frac{\partial_\mu a}{2 f_a}\,\bar{\ell}\gamma^\mu\gamma^5\ell + \frac{1}{4} g_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

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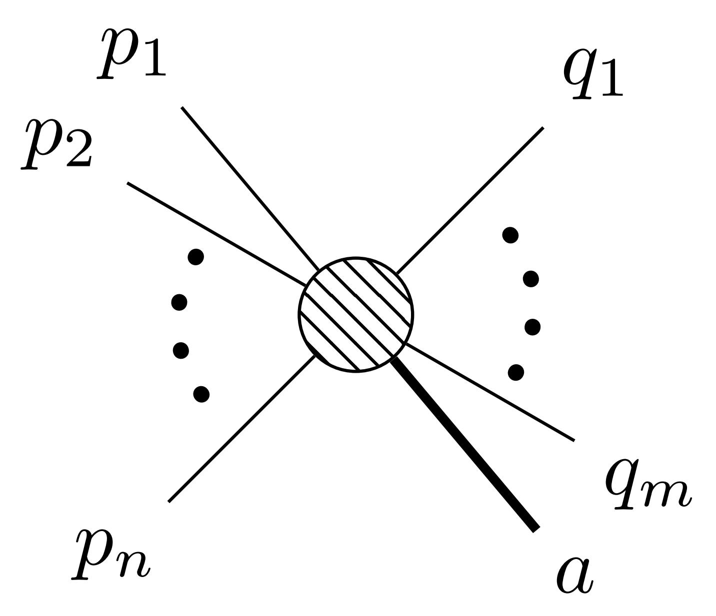


Numerical solution to the full Boltzmann equation

$$\frac{d\mathcal{F}_a(q,x)}{d\log x} = \frac{\mathcal{C}_a(q,x)}{H(x)}\left(1 - \frac{1}{3}\frac{d\log g_{*s}}{d\log x}\right)\left[1 - \frac{\mathcal{F}_a(q,x)}{\mathcal{F}_a^{\rm eq}(q,x)}\right]$$

Pipeline

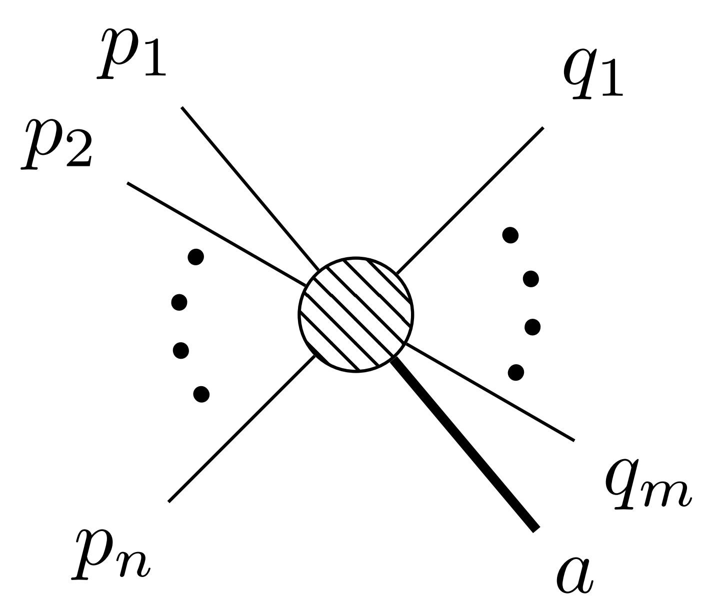
1

Effective modelling of ALPs interactions:

$$\mathcal{L}_a \supset \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{1}{2} m_a^2 a^2 + c_\ell \frac{\partial_\mu a}{2 f_a} \bar{\ell}\gamma^\mu \gamma^5 \ell + \frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

2

Computation of collision term for production processes



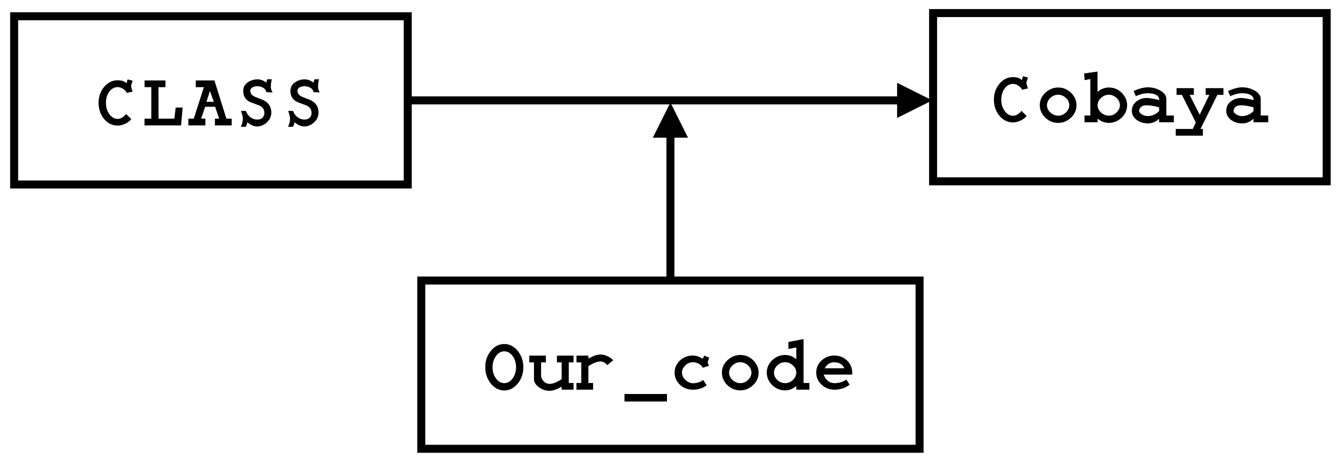
3

Numerical solution to the full Boltzmann equation

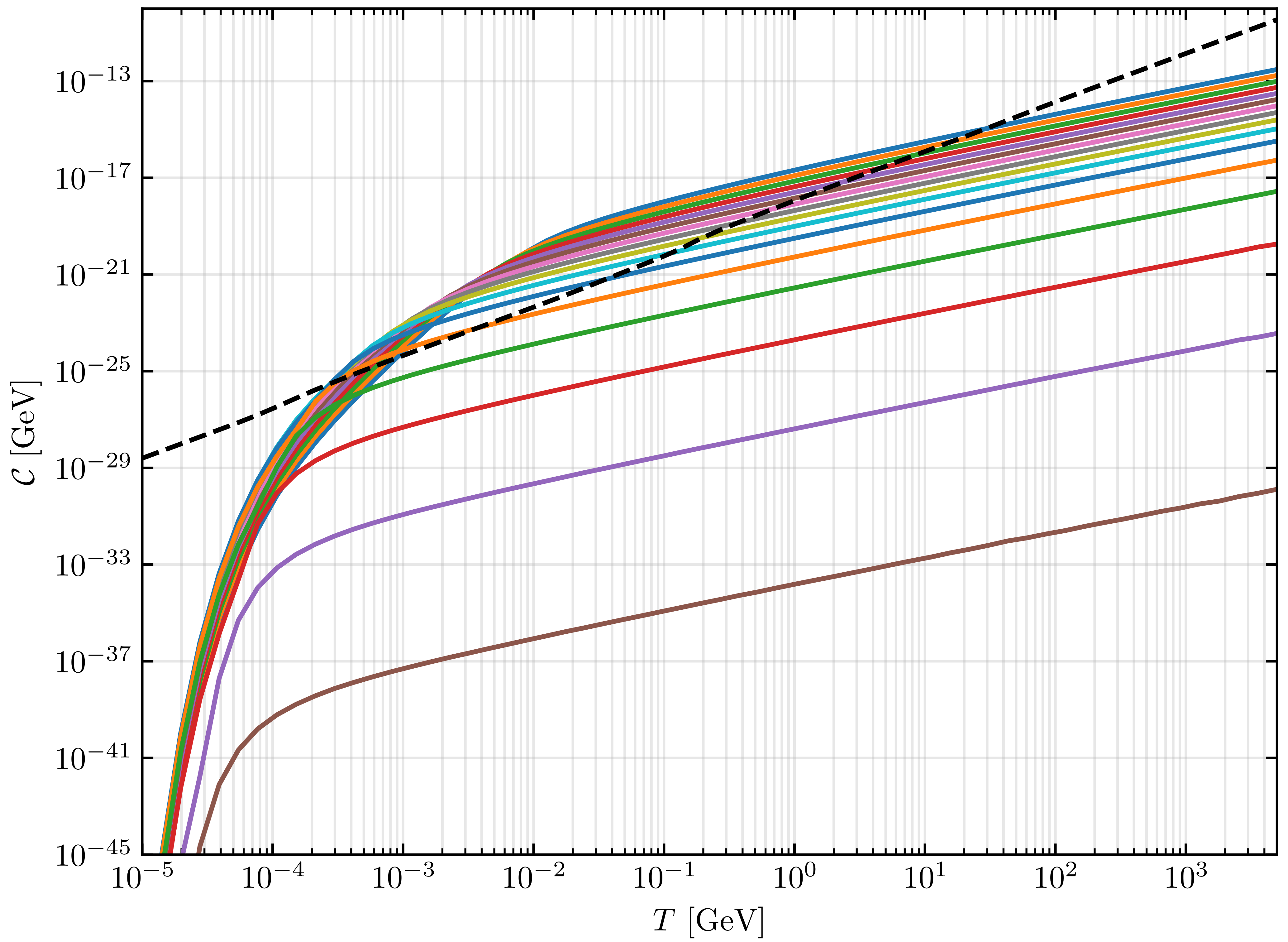
$$\frac{d\mathcal{F}_a(q,x)}{d\log x} = \frac{\mathcal{C}_a(q,x)}{H(x)} \left(1 - \frac{1}{3}\frac{d\log g_{*s}}{d\log x}\right) \left[1 - \frac{\mathcal{F}_a(q,x)}{\mathcal{F}_a^{\mathrm{eq}}(q,x)}\right]$$

4

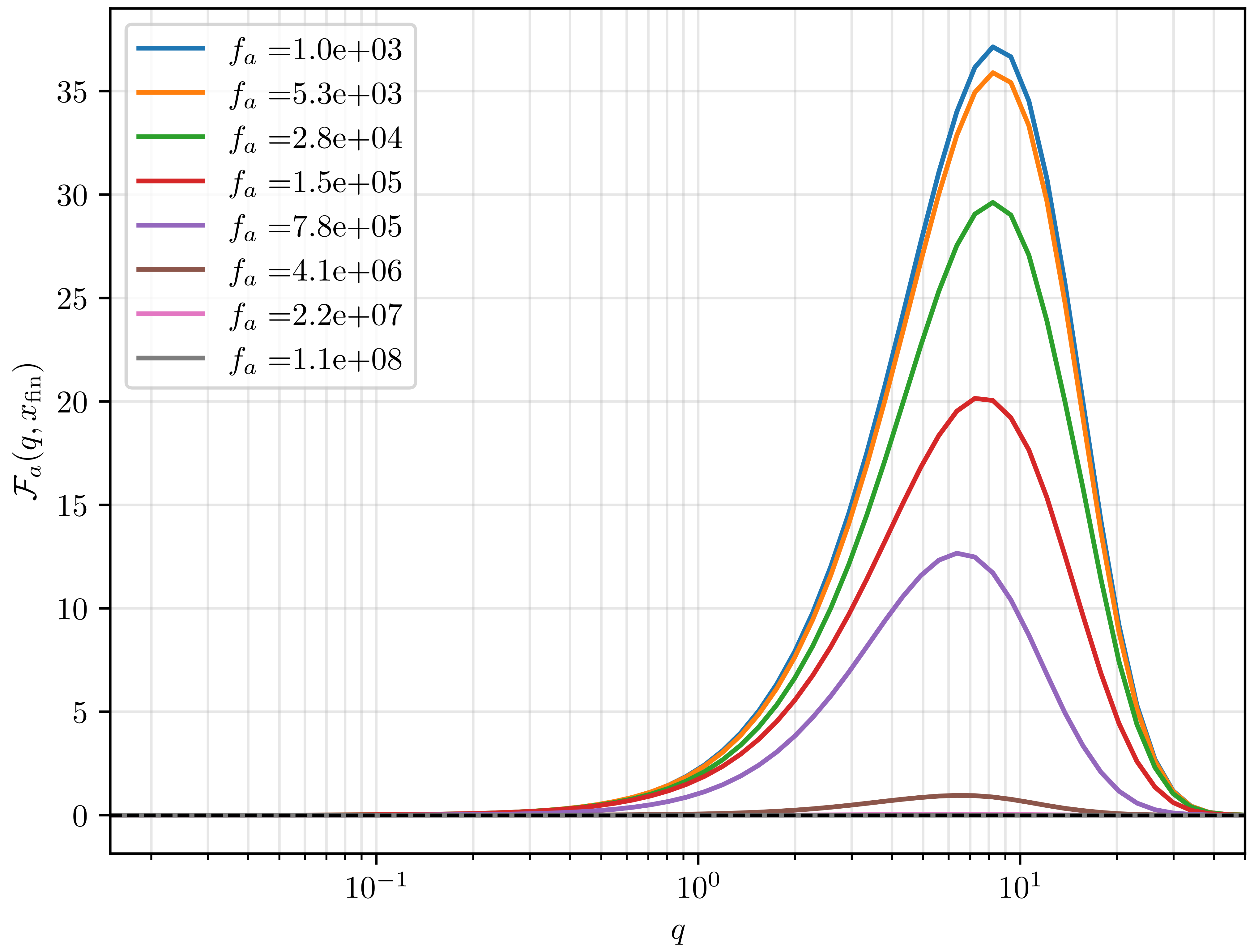
Implementation in a Boltzmann solver and subsequent MCMC analysis



Full phase-space solution - pt. 1

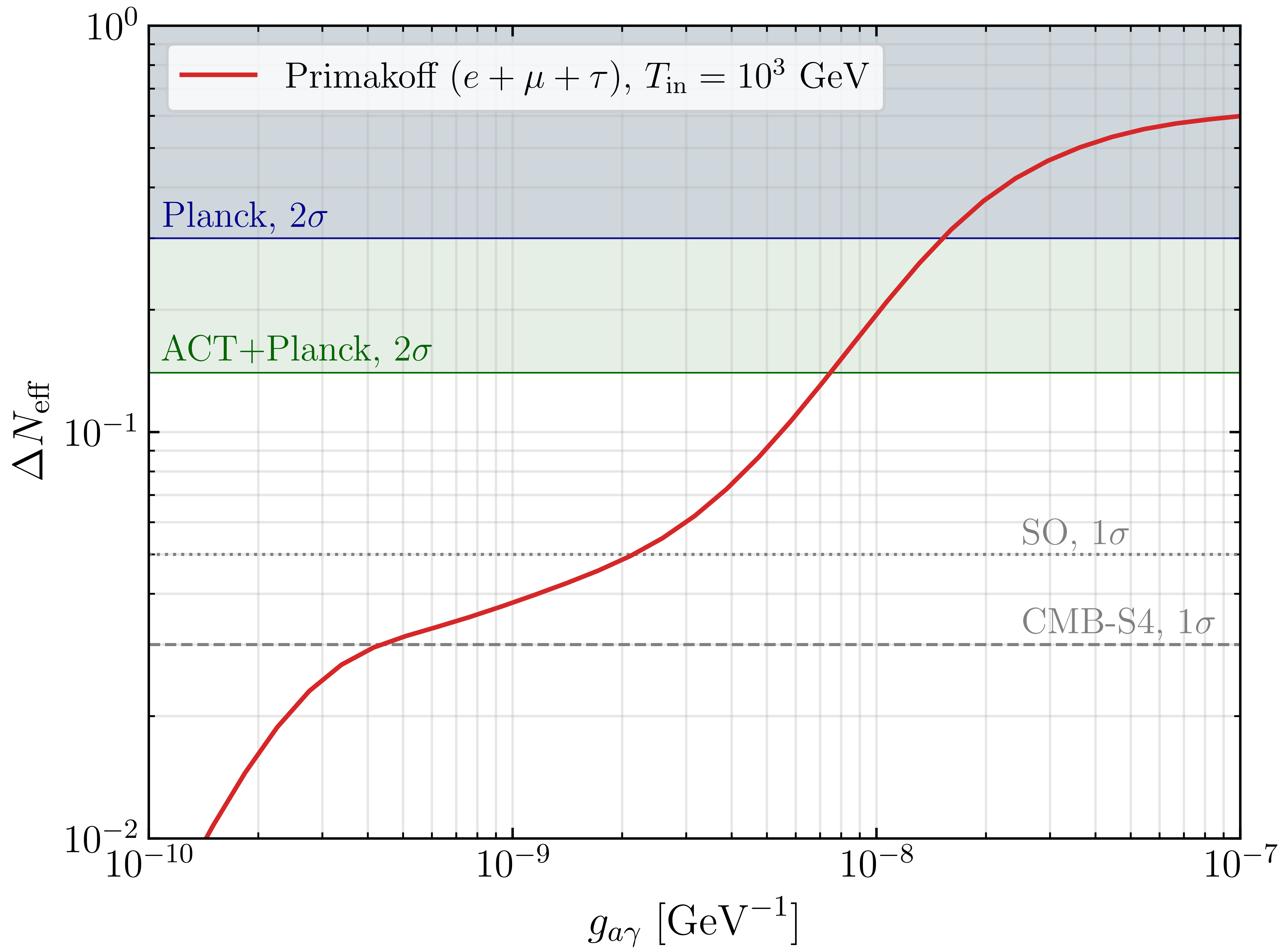


Example of collision integral numerical calculation for the electron channel lepton production, for different values of momenta and $f_a = 10^5$ GeV

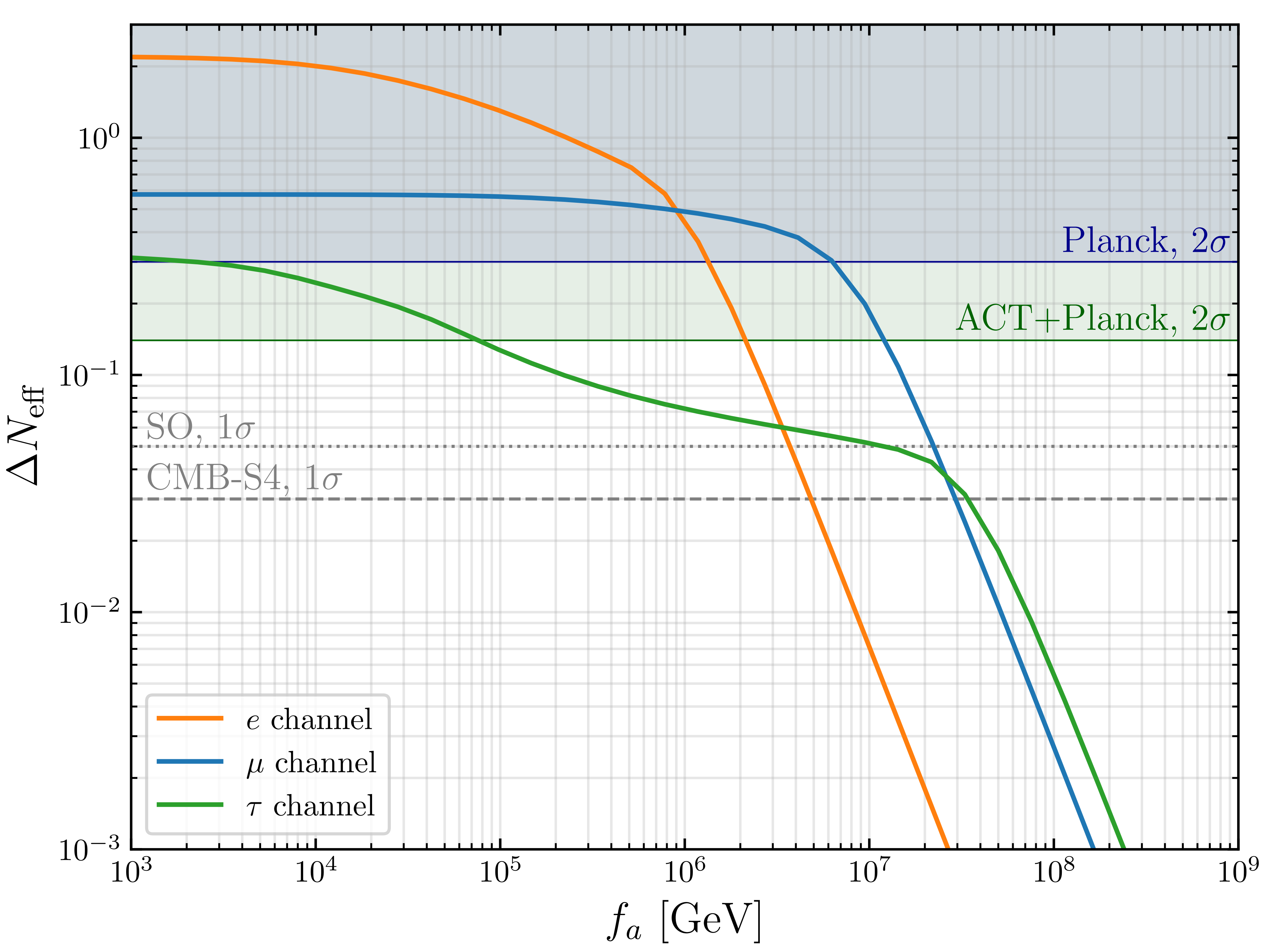


Axion's phase-space distribution function (same production channel of the previous plot), for different values of f_a

Full phase-space solution - pt. 2



Contribution to $N_{\rm eff}$ from Primakoff production (considering electrons, muons and taus as charged particles in the plasma)



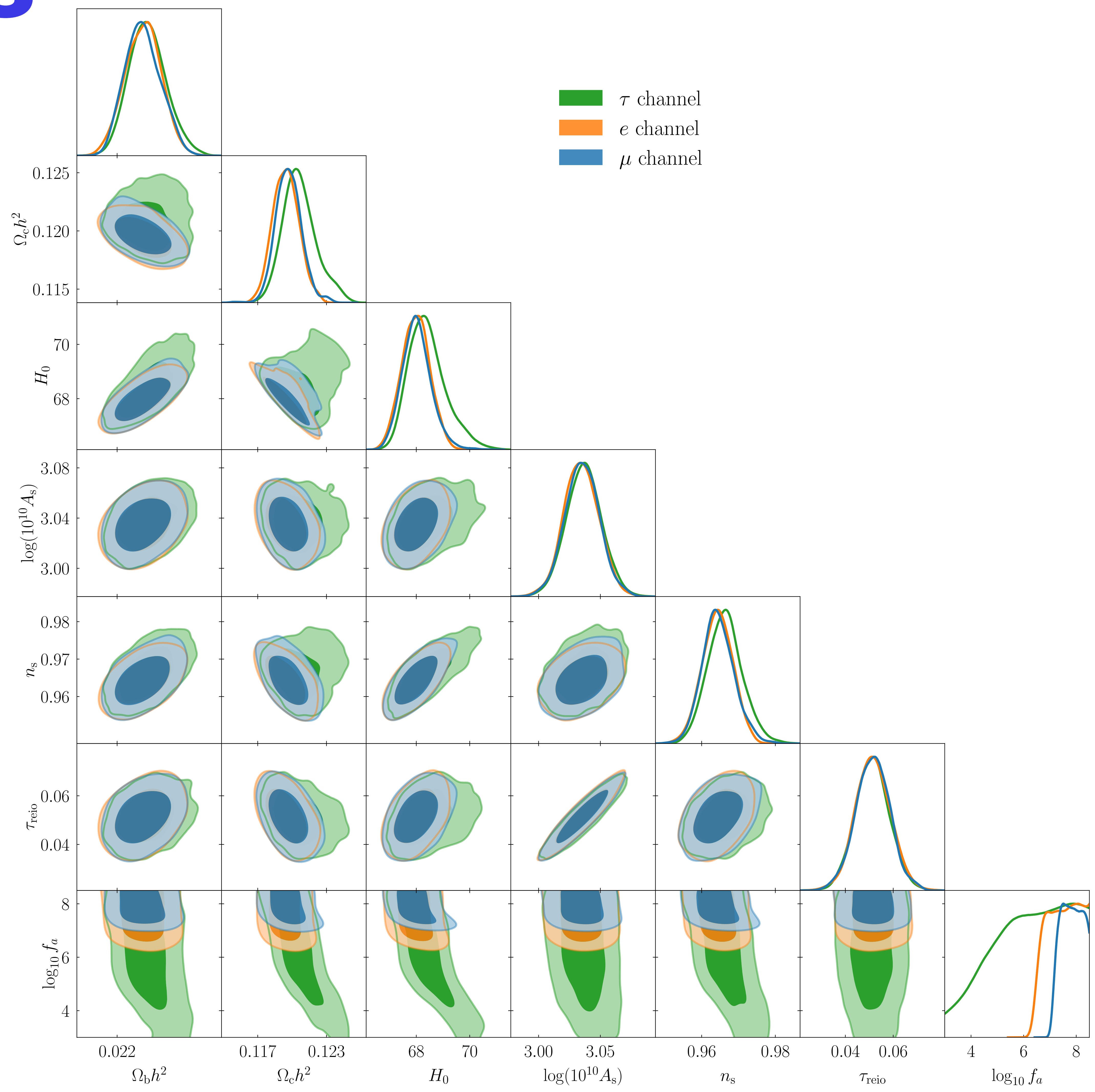
Contribution to $N_{\rm eff}$ from pair annihilation and Compton-like scattering on charged leptons

Cosmological constraints

- Analysis settings:

```
likelihood:
   planck_2018_lowl.TT: null
   planck_2018_lowl.EE: null
   planck_NPIPE_highl_CamSpec.TTTEEE: null
   Planckpr4lensing:null
```

	ΛCDM	e channel	μ channel	τ channel
Parameter	95% limits	95% limits	95% limits	95% limits
$\Omega_b h^2$	$0.02219^{+0.00028}_{-0.00027}$	$0.02220^{+0.00027}_{-0.00028}$	$0.02220^{+0.00028}_{-0.00025}$	$0.02224^{+0.00031}_{-0.00027}$
$\Omega_c h^2$	0.1194 ± 0.0021	$0.1195^{+0.0024}_{-0.0022}$	0.1197 ± 0.0022	$0.1207^{+0.0034}_{-0.0027}$
$\log(10^{10} A_s)$	$3.033^{+0.029}_{-0.028}$	3.035 ± 0.028	$3.035^{+0.029}_{-0.028}$	3.037 ± 0.028
n_s	$0.9636^{+0.0080}_{-0.0082}$	$0.9643^{+0.0081}_{-0.0084}$	$0.9645^{+0.0093}_{-0.0082}$	$0.966^{+0.010}_{-0.0090}$
τ_{reio}	0.051 ± 0.015	$0.052^{+0.015}_{-0.014}$	$0.051^{+0.015}_{-0.014}$	0.051 ± 0.014
H_0	$67.88^{+0.99}_{-0.95}$	68.0 ± 1.0	68.0 ± 1.1	$68.4^{+1.5}_{-1.3}$
$\log_{10} f_a$		> 6.55	> 7.19	—



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Thank you!

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