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Back to Phase Space: cosmology of the axion-fermion coupling

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Based on

F. D'Eramo, F. Hajkarim, **AL** JCAP 03 (2024) 009 (2311.04974)

F. D'Eramo, **AL** PRD 110 (2024) 11, 116028 (2410.21253)

A. Dekker, F. D'Eramo, **AL** (in preparation)

COST

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האוניברסיטה העברית בירושלים

THE HEBREW UNIVERSITY OF JERUSALEM

The framework

Axion production from thermal bath

Gauge bosons

$$\mathscr{L}_V = \frac{a}{8\pi f_a}\left(\alpha_s \widetilde{G}^{\mu\nu} G_{\mu\nu} + c_\gamma \alpha_{\text{em}} \widetilde{F}^{\mu\nu} F_{\mu\nu}\right)$$

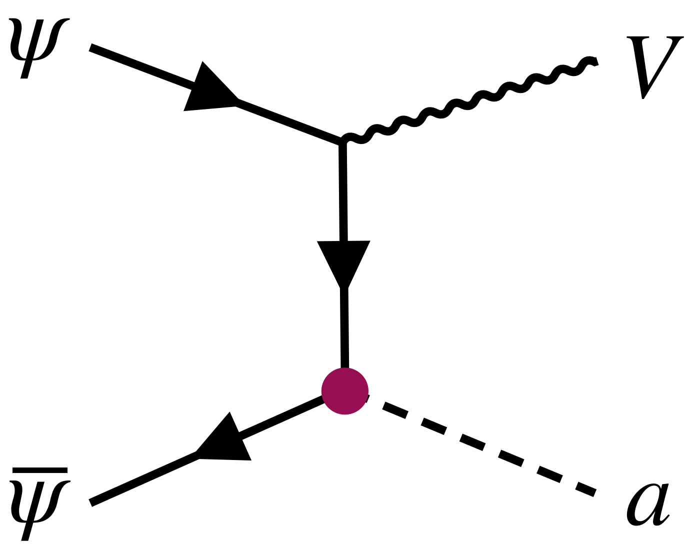
$$\Gamma_V \propto \frac{\alpha_V^2 T^3}{f_a^2}$$ **UV**

The framework

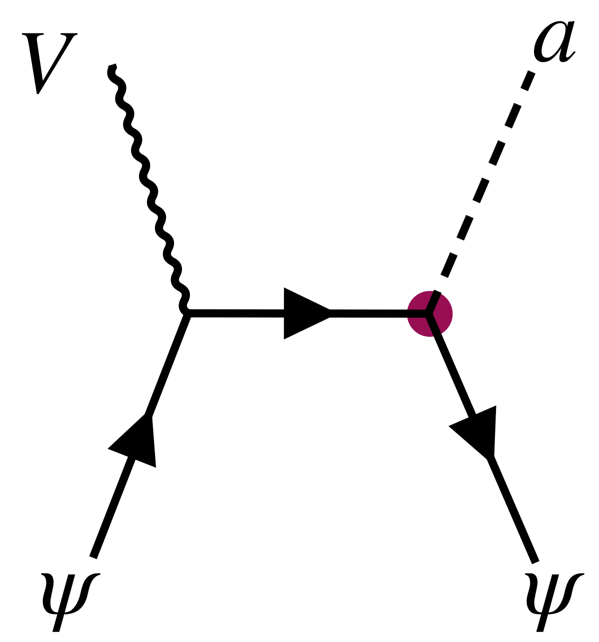
Axion production from thermal bath

Fermions, flavor conserving (this talk)

$$\mathscr{L}_\psi = -\frac{\partial_\mu a}{2f_a}\sum_\psi c_\psi \overline{\psi}\gamma^\mu\gamma^5\psi$$

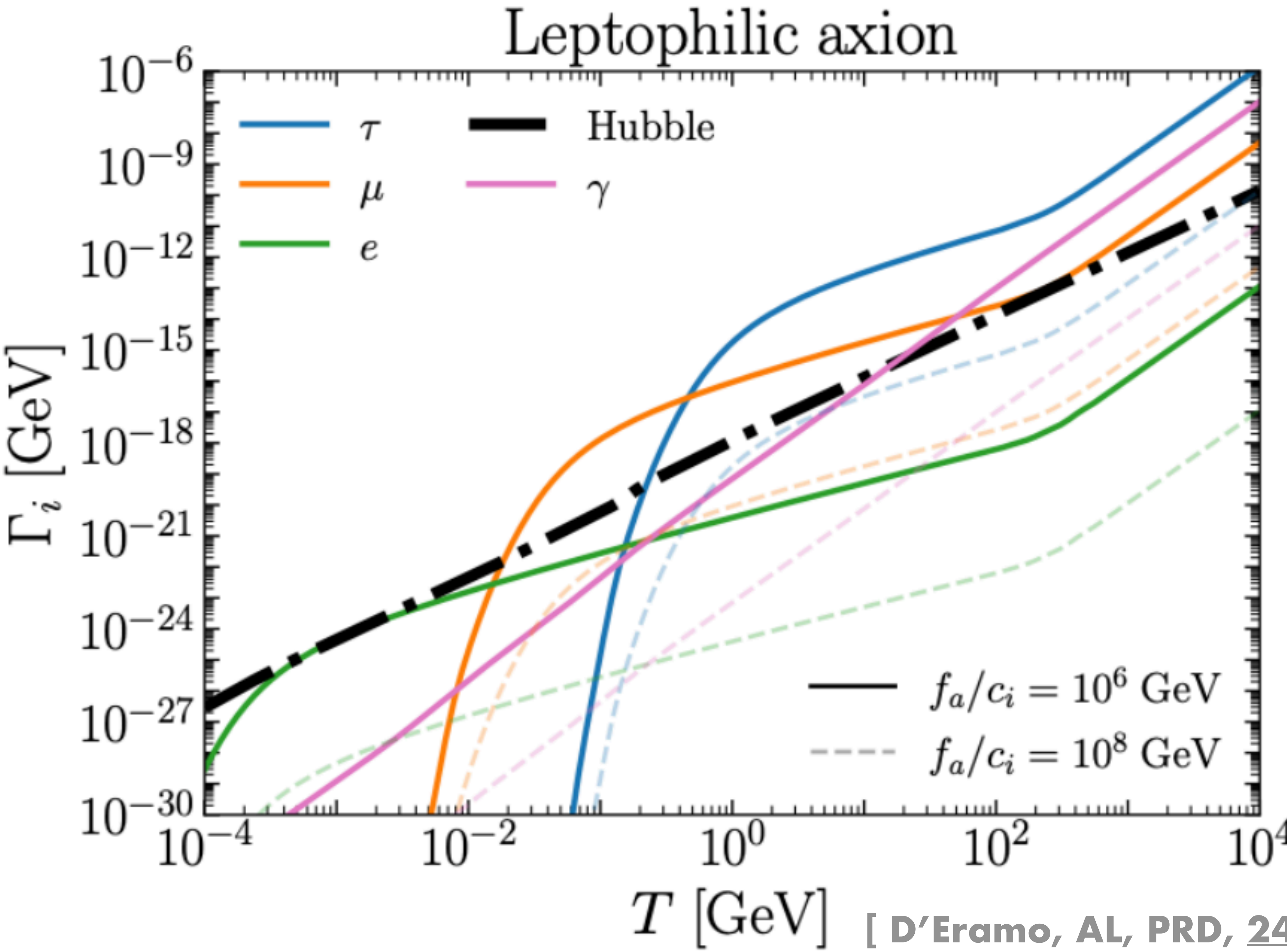


$$\Gamma_\psi \propto \frac{\alpha_V c_\psi^2 m_\psi^2}{f_a^2} T \qquad \textbf{IR}$$



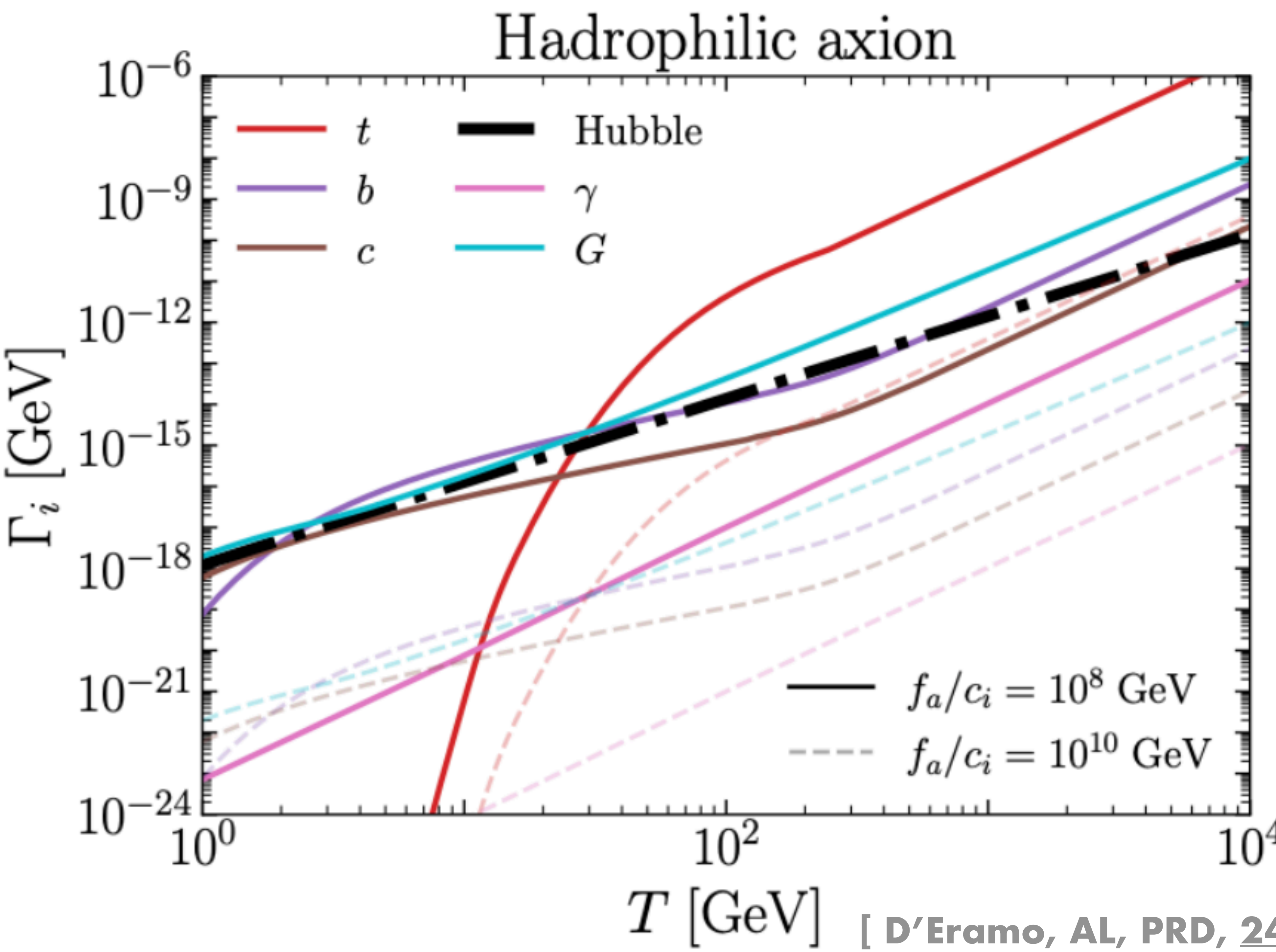
We work in the limit $m_a \ll m_\psi$ **and** $T < v_{\rm EW}$

Axion production from SM fermions



[D'Eramo, AL, PRD, 2410.21253]

Axion production from SM fermions



[D'Eramo, AL, PRD, 2410.21253]

Cosmological observables

- **Quasi-thermal Dark Radiation** $m_a < \mathrm{eV}$

Relativistic relic around CMB

Dark radiation production → **Phase space distribution** → Precise $\Delta N_{\rm eff}$

- **Quasi-thermal Dark Matter** $m_a \gtrsim \mathrm{keV}$

Bound coming from small scale observables

DM production → **Phase space distribution** → DM power spectrum and observables

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Cosmological observables

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$m_a \gtrsim \mathrm{keV}$

What is dark radiation?

Additional relativistic particles with relevant abundance @ CMB

$$\rho(T_{\rm CMB}) = \rho_\gamma + \rho_\nu + \rho_a \qquad N_{\rm eff} = N_{\rm eff}^{\rm SM} + \Delta N_{\rm eff}$$

New physics?

SM theory: $N_{\rm eff}^{\rm SM} = 3.0440 \pm 0.0002$ Drewes+ [2402.18481] or 3.043? Cielo+ [PRD108(2023)]

Measurements: $N_{\rm eff}^{\rm CMB} = 2.99 \pm 0.17$ [PLANCK 2018]

Upcoming:

$\sigma(N_{\rm eff}) \simeq 0.05$ Simons Observatory [JCAP02(2019)056]

$\sigma(N_{\rm eff}) \simeq 0.03$ CMB - S4 [Snowmass 2021 - 2203.08024]

Precise and accurate calculation of $\Delta N_{\rm eff}$ is required!

Boltzmann equation formalism

Model-dependent collision term

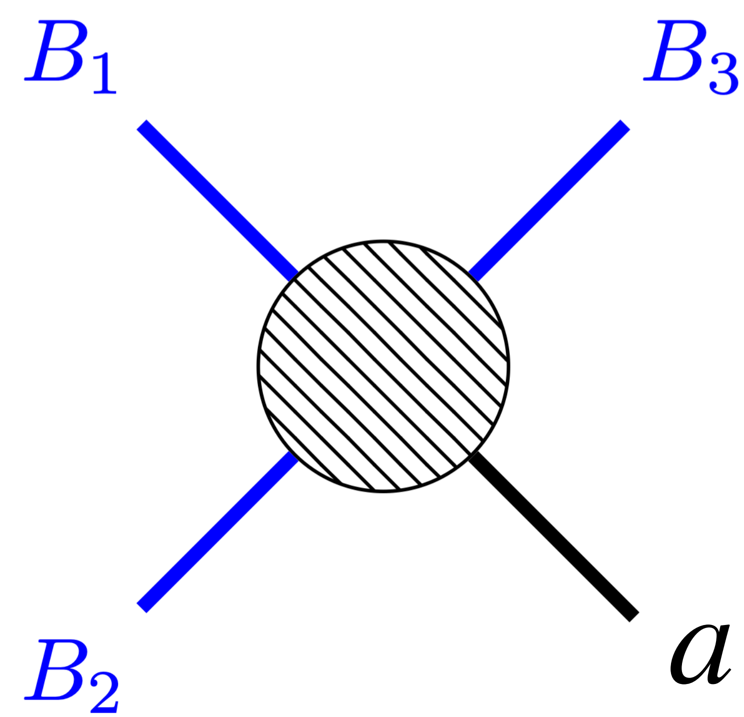
Backreaction

Feedback on the bath

$$\frac{d\mathscr{F}_a}{dt} = \mathscr{C}(p,t)\left(1 - \frac{\mathscr{F}_a}{\mathscr{F}_a^{\rm eq}}\right)$$

$$\frac{d\rho_B}{dt} = -3H(1+w)\rho_B - \int \frac{d^3p}{(2\pi)^3}\frac{d\mathscr{F}_a(p,t)}{dt}$$

$$H = \frac{\sqrt{\rho_B + \rho_a}}{\sqrt{3}M_{\rm Pl}}$$



Phase space effects on Dark Radiation

From instantaneous decoupling $\Delta N_{\rm eff} \approx 0.027 \left(\frac{106.75}{g_{*s}(T_{\rm D})} \right)^{4/3}$

Approximated methods cannot treat <u>precisely</u>

1) Non-thermalized relics detectable (1-10)%

2) Non-instantaneous decoupling detectable (1-10)%

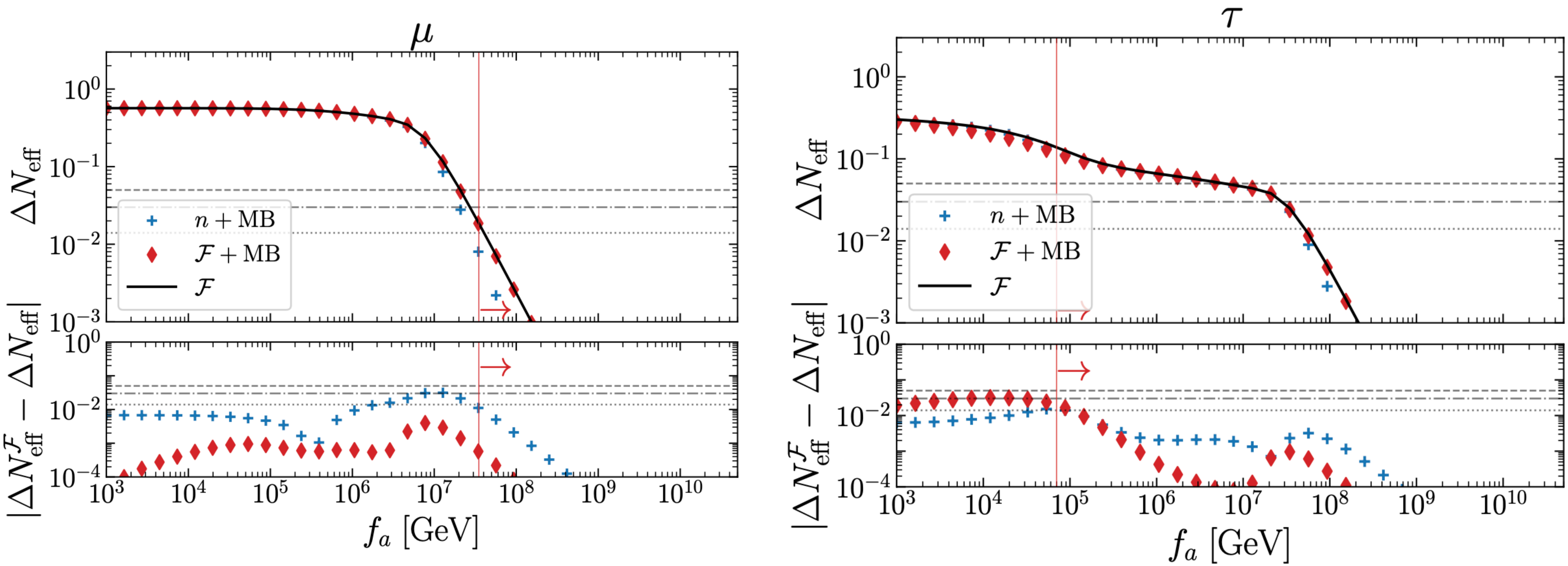
3) Quantum statistics effects sometimes detectable

4) Energy exchange with thermal bath undetectable

For more see: [D'Eramo, Hajkarim, AL, 2311.04974]

$$\text{Boltzmann eq.} \longrightarrow \mathscr{F}_a(p,t) \longrightarrow \quad \rho_a = \int \frac{d^3k}{(2\pi)^3} E_a \mathscr{F}_a \longrightarrow \Delta N_{\rm eff}$$

Leptophilic axion

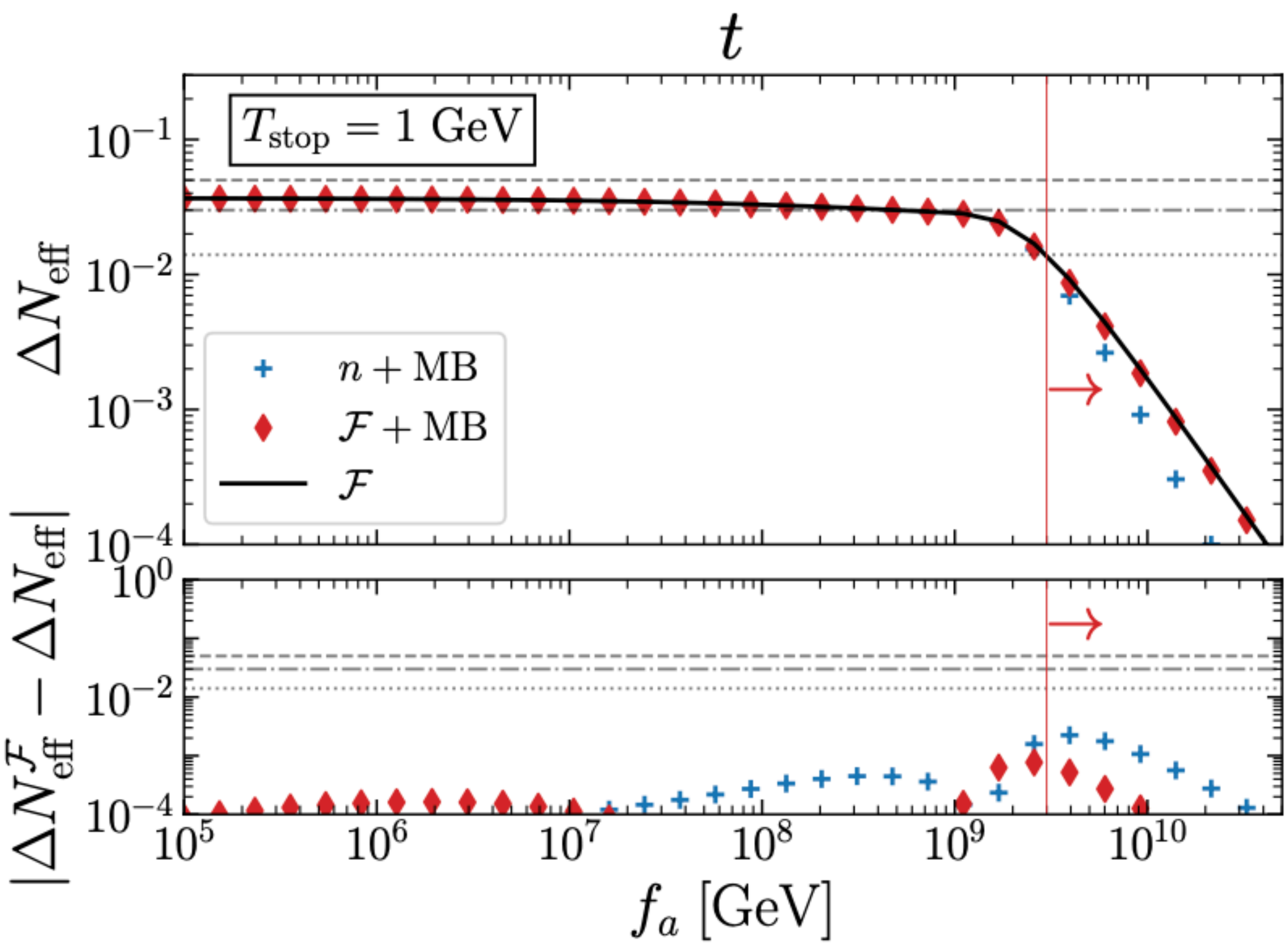


spectral distortions and non-thermalized relics

+ g_* effects around GeV

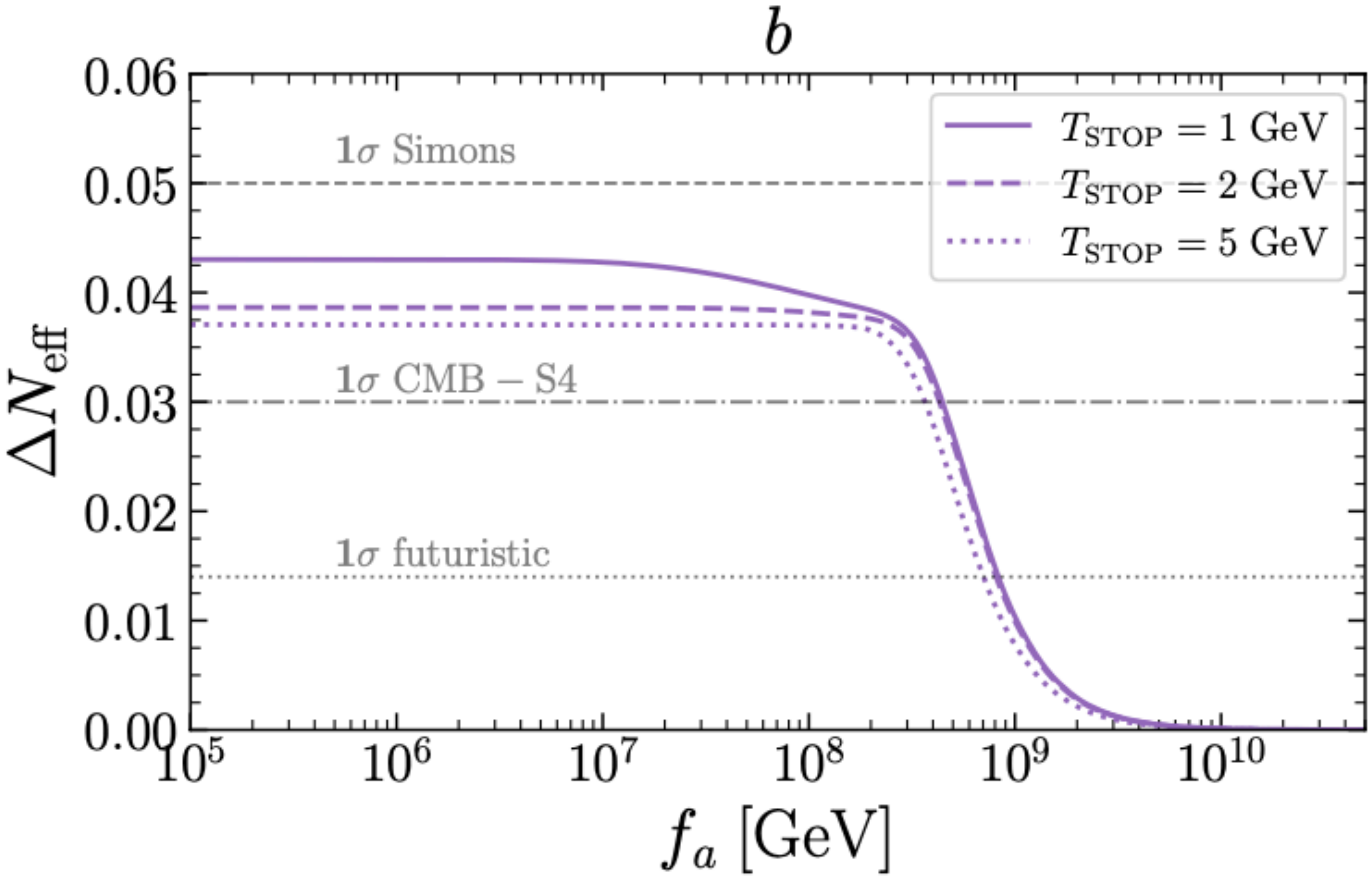
[D'Eramo, **AL**, PRD, 2410.21253]

Hadrophilic axion: top



[D'Eramo, **AL**, PRD, 2410.21253]

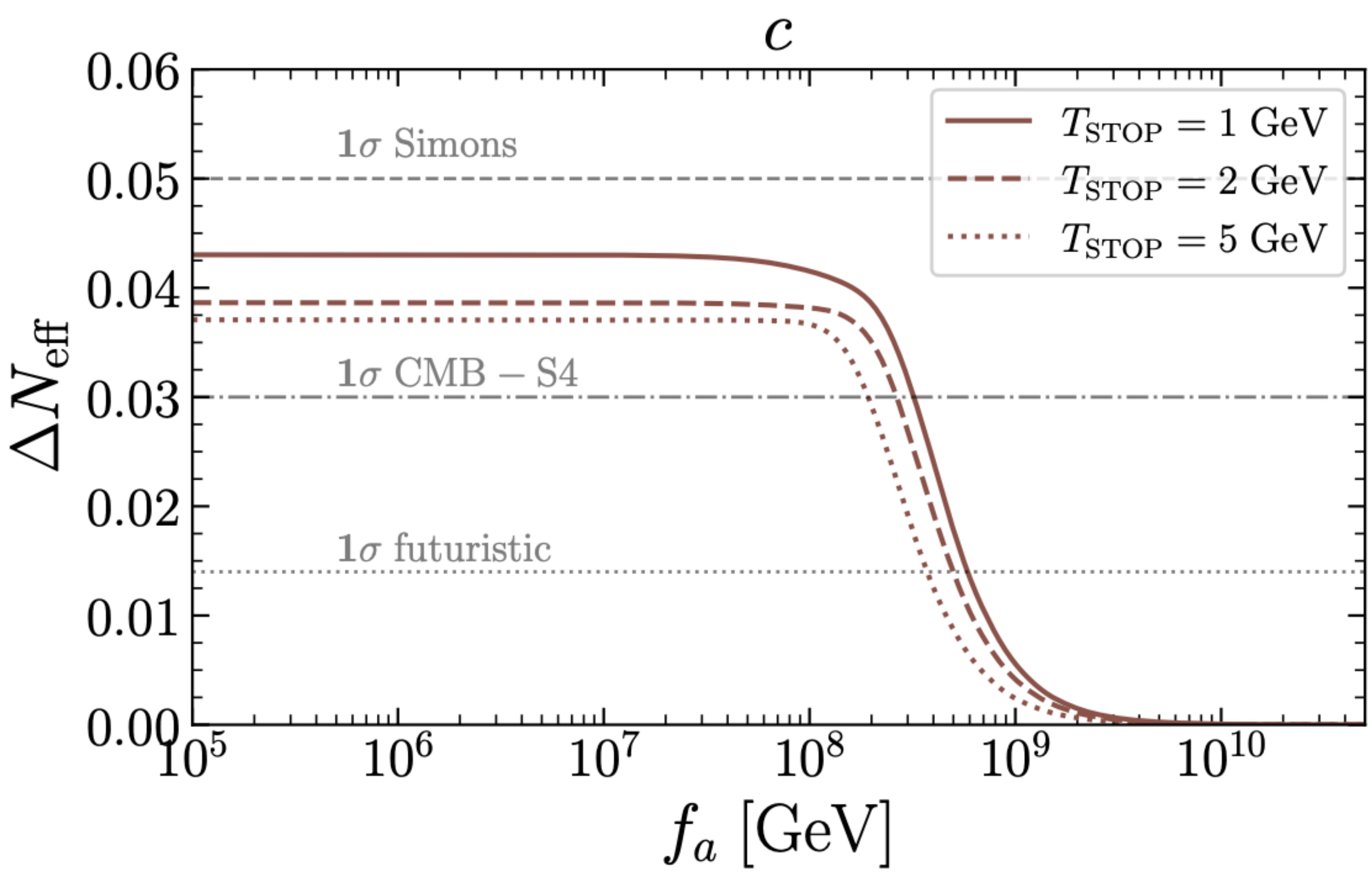
Hadrophilic axion: bottom



[D'Eramo, **AL**, PRD, 2410.21253]

Dependence on TSTOP for values of f_a that allow for thermality to be reached

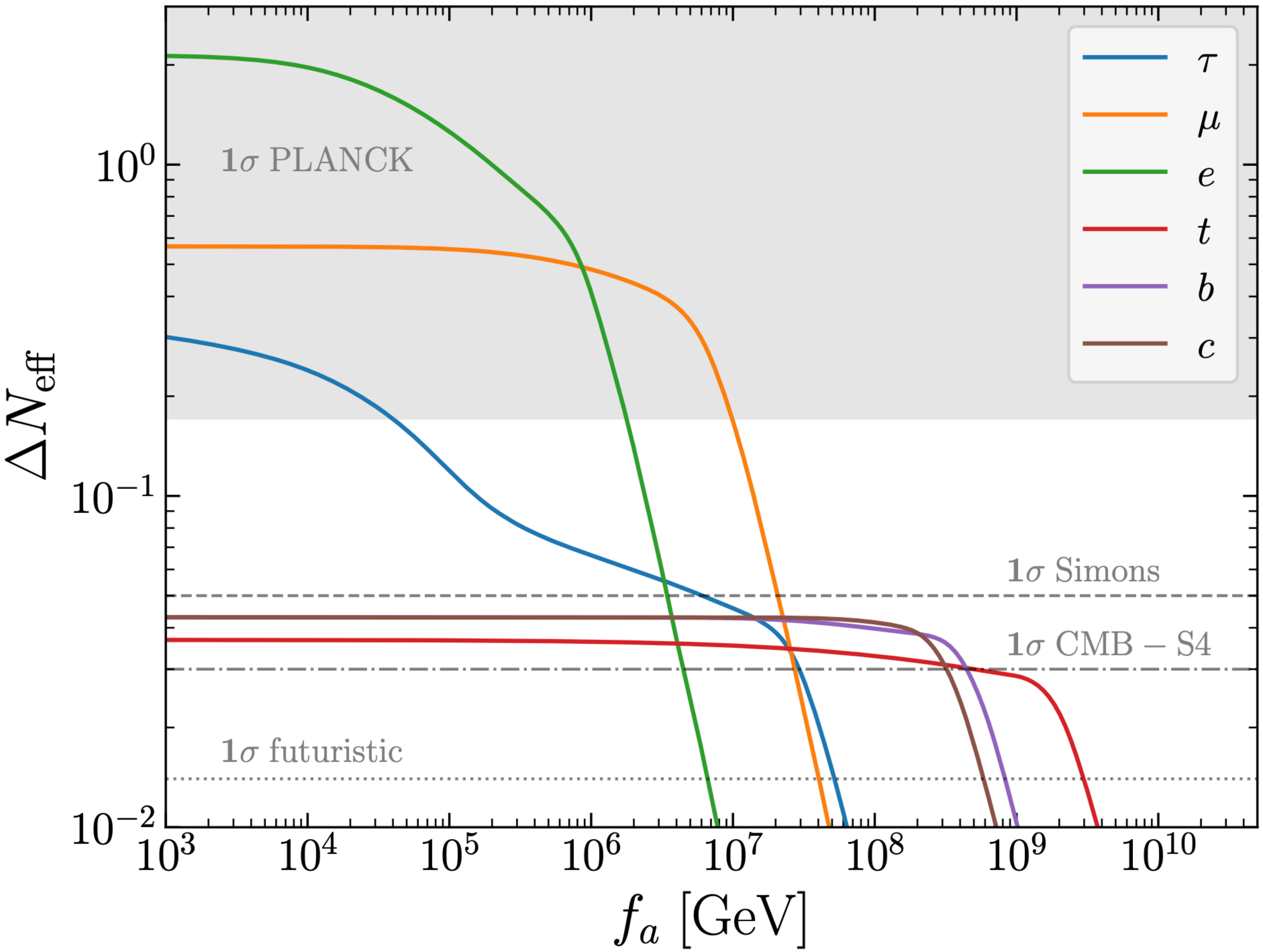
Hadrophilic axion: charm



[D'Eramo, **AL**, PRD, 2410.21253]

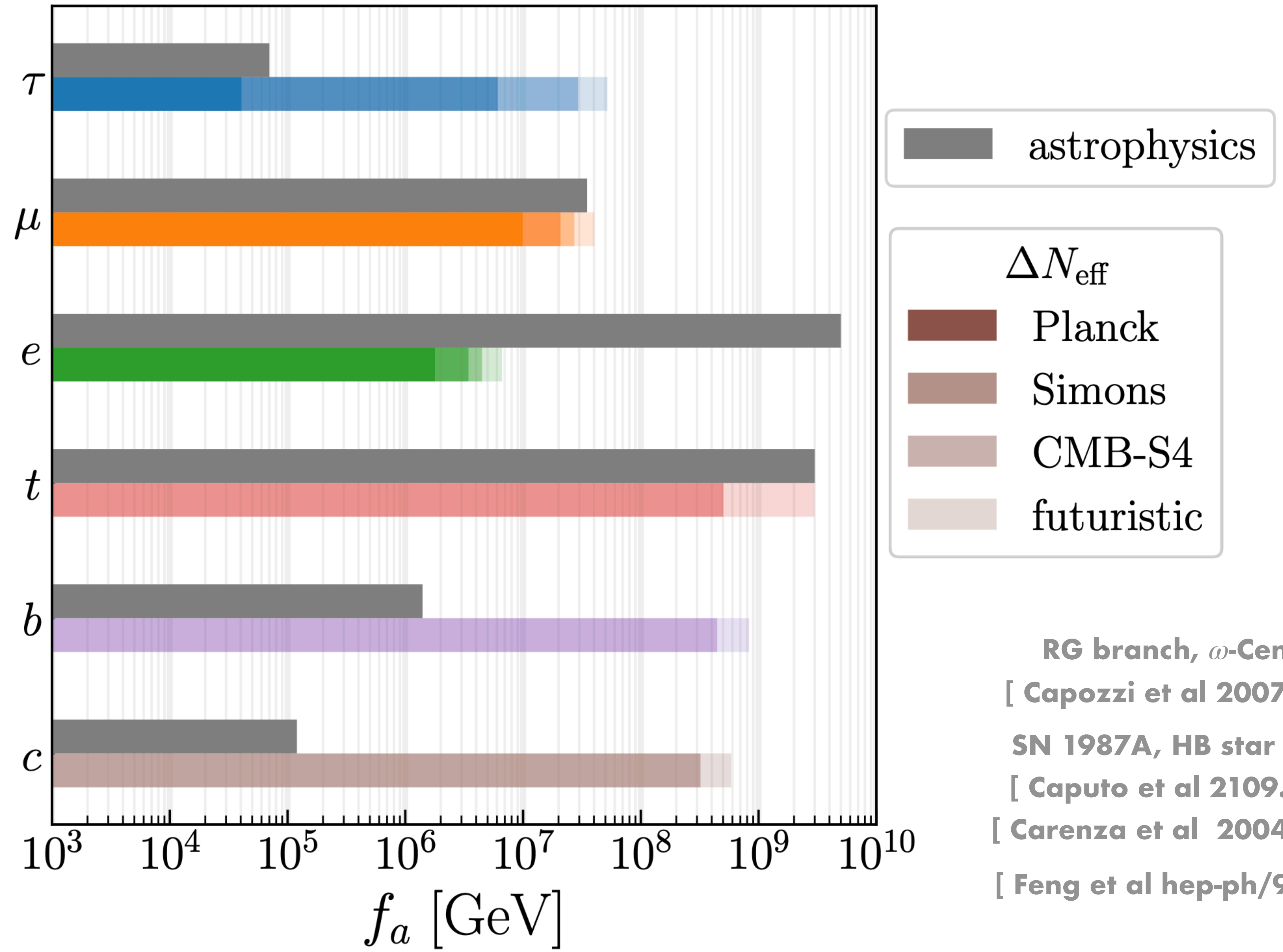
Dependence on TSTOP for all values of f_a

Axion dark radiation summary



[D'Eramo, **AL**, PRD, 2410.21253]

Axion dark radiation bounds



RG branch, ω-Centauri
[Capozzi et al 2007.03694]

SN 1987A, HB star cooling
[Caputo et al 2109.03244]
[Carenza et al 2004.08399]

[Feng et al hep-ph/9709411]

[D'Eramo, **AL**, PRD, 2410.21253]

Cosmological observables

$m_a < \mathrm{eV}$

- **Quasi-thermal Dark Matter** $m_a \gtrsim \mathrm{keV}$

Bound coming from small scale observables

DM production → **Phase space distribution** → **DM power spectrum and observables**

Bounds on thermal axion DM

Quasi-thermal axions can be too warm, we impose

$$\sqrt{\langle v^2 \rangle_{\mathscr{F}_a}} < \sqrt{\langle v^2 \rangle_{\mathrm{WDM}}}$$

$$m_a > 19\ \mathrm{keV} \left(\frac{m_{\mathrm{WDM}}}{5.3\ \mathrm{keV}} \right)^{4/3} \left(\frac{\sigma_q}{3.6} \right) \left(\frac{106.75}{g_{*s}(T_{\mathrm{prod}})} \right)^{1/3}$$

Reference WDM constraints from small-scale observables (e.g. Lyman — α)

$$\sigma_q^2 = \frac{\int dq\ q^4 \mathscr{F}_a}{\int dq\ q^2 \mathscr{F}_a}$$

Reference production temperature (fermion mass)

Results for freeze-in keV axions

ψ	$m_a^{\rm min}$(keV)	$f_a^{\rm relic}$(GeV)	$-\Delta g_{a\gamma\gamma}$ (GeV^{-1})	$\tau_{a\to\gamma\gamma}$(sec)	Allowed?
electron	42	5.2×10^{7}	2.5×10^{-14}	2.8×10^{18}	✗
muon	36	3.2×10^{8}	7.1×10^{-20}	5.6×10^{29}	✓
tau	20	4.4×10^{8}	5.6×10^{-22}	5.3×10^{34}	✓
charm	20	4.1×10^{9}	1.5×10^{-23}	7.0×10^{37}	✓
bottom	21	6.6×10^{9}	5.1×10^{-24}	5.4×10^{38}	✓
top	18	2.7×10^{10}	1.0×10^{-28}	1.3×10^{48}	✓

[Dekker, D'Eramo, AL, in prep.]

Summary

$$\mathscr{L}_\psi = -\frac{\partial_\mu a}{2f_a} \sum_\psi c_\psi \bar{\psi} \gamma^\mu \gamma^5 \psi$$

$m_a < \mathrm{eV}$

Axion Dark Radiation

$m_a \gtrsim \mathrm{keV}$

Axion Dark Matter

For different reasons both require a solution for the momentum distribution!

...and outlook

Much to do, different cosmologies, different models, all in phase space!

Thank you!

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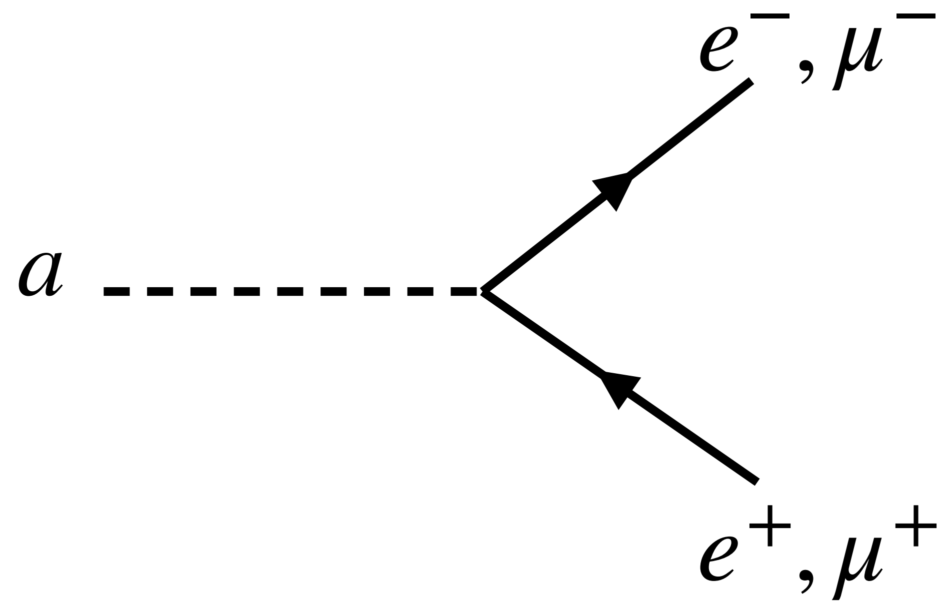
Bounds on axion-fermion coupling



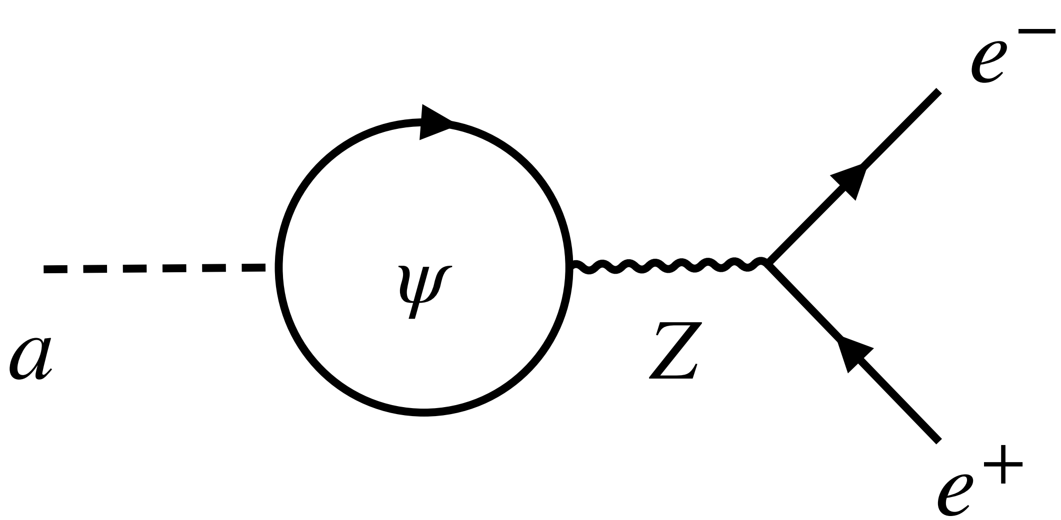
$$\frac{f_a}{c_e} > 5 \times 10^9 \text{ GeV}$$

RG branch, ω-Centauri
[Capozzi et al 2007.03694]

$$\frac{f_a}{c_\mu} > 3.5 \times 10^7 \text{ GeV}$$

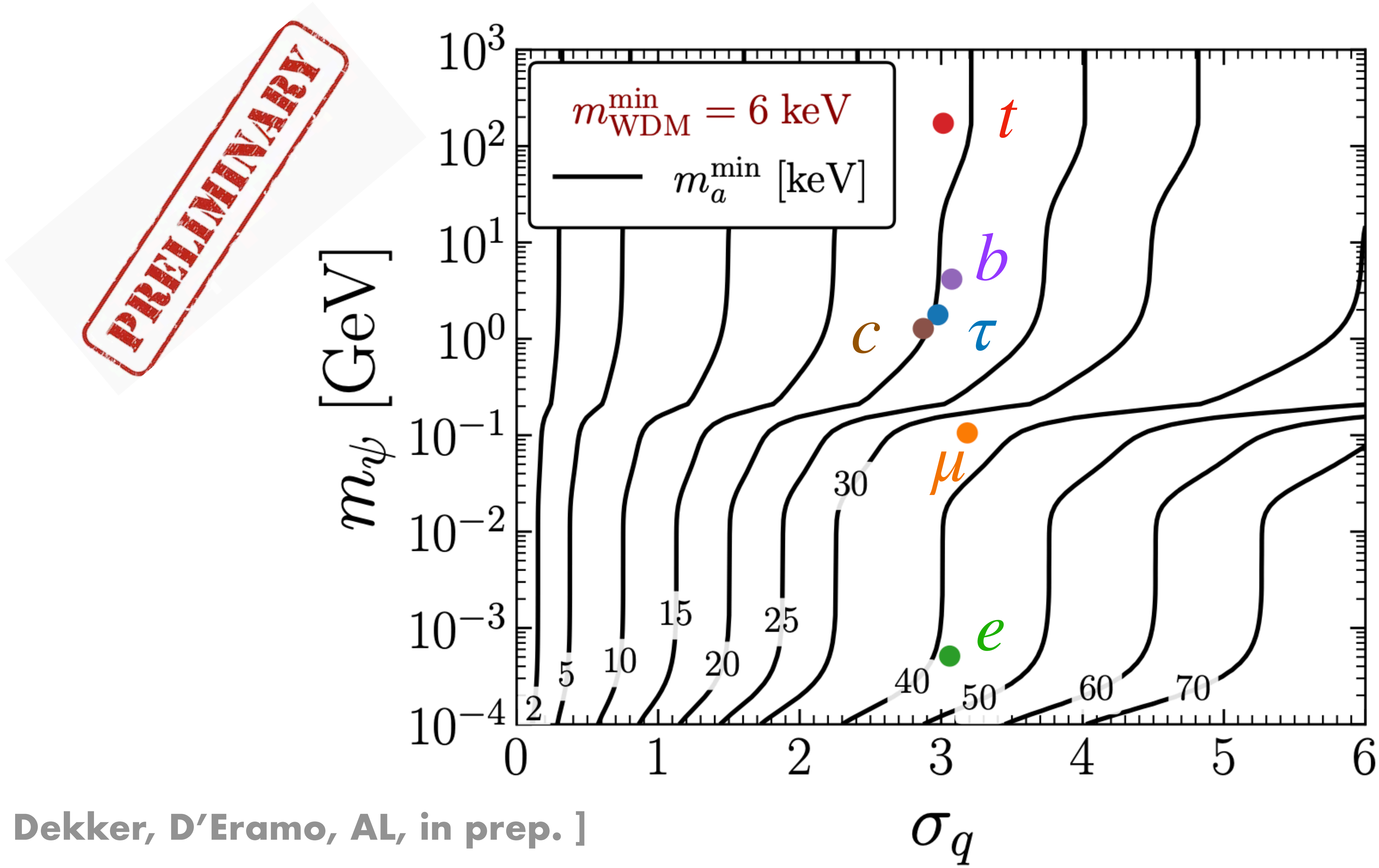
SN 1987A, HB star cooling
[Caputo et al 2109.03244]
[Carenza et al 2004.08399]

Other fermions are constrained at one loop [Feng et al hep-ph/9709411]



$$\frac{f_a}{c_\psi} > \text{GeV} \times \begin{cases} 3.1 \times 10^9 & \psi = t \\ 1.4 \times 10^6 & \psi = b \\ 1.2 \times 10^5 & \psi = c \\ 7.0 \times 10^4 & \psi = \tau \end{cases}$$

Warmness bounds, visually



[Dekker, D'Eramo, AL, in prep.]

$$m_a > 19\ \mathrm{keV} \left(\frac{m_{\rm WDM}}{5.3}\right)^{4/3} \left(\frac{\sigma_q}{3.6}\right) \left(\frac{106.75}{g_{*s}(T_{\rm prod})}\right)^{1/3}$$

Boltzmann equation, IR freeze-in

$$\frac{d\mathcal{F}_a}{dt} = \mathcal{C}(p,t)$$

$$\mathcal{F}_a(q,T) = \int d\log T \left(1 + \frac{1}{3}\frac{d\log g_{*s}}{d\log T}\right)\frac{\mathcal{C}(q,T)}{H}$$

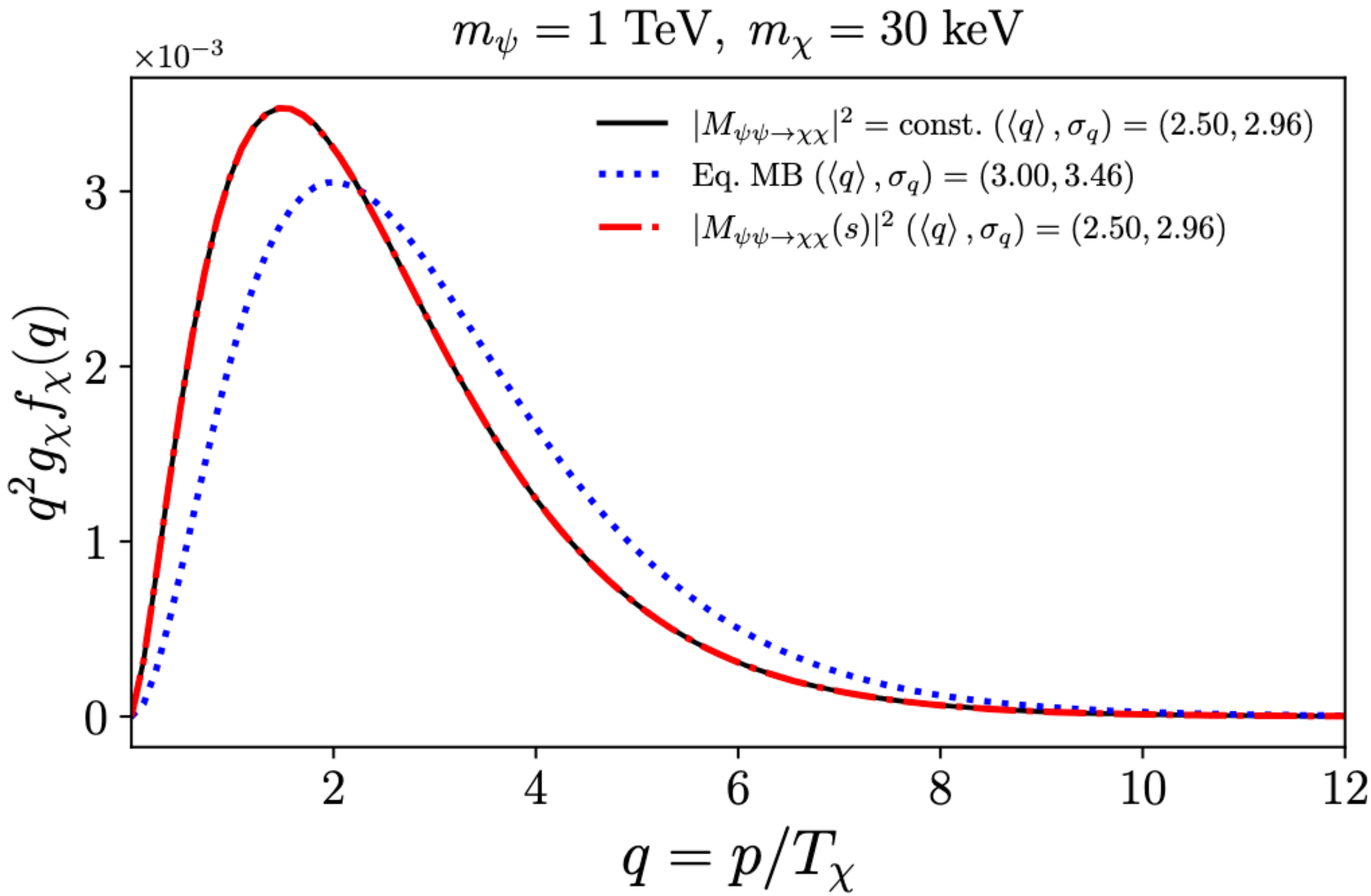
Radiation domination

$$H = \frac{\sqrt{\rho_B}}{\sqrt{3}M_{\rm Pl}}$$

Comoving momentum, entropy conservation

$$q \propto pa = \frac{p}{T}\left(\frac{g_{*s}(T)}{g_{*s}(T_{\rm prod})}\right)^{1/3}$$

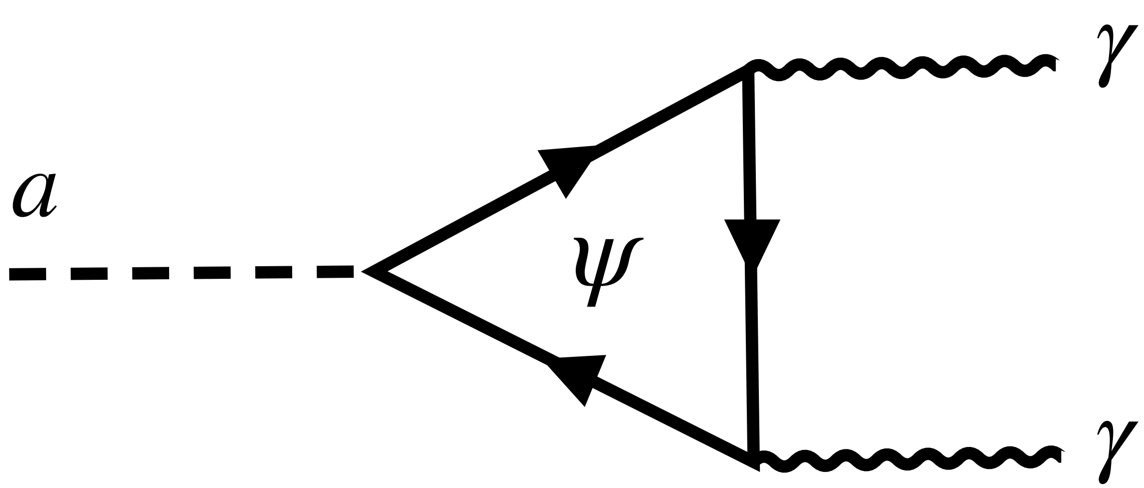
Phase space distribution, example



Constraints on keV axions

A coupling to photons is induced via a fermion loop

[Bauer et al 1708.00443]
[Bauer et al 2012.12272]



$$\Delta g_{a\gamma\gamma} \approx -\frac{\alpha_{\rm em} N^c_\psi Q^2_\psi}{12\pi f_a}\left(\frac{m_a}{m_\psi}\right)^2$$

[Calore et al 2209.06299]
[eg. Roach et al 2207.04572]

X-ray, NuStar, INTEGRAL, constrain

$$g_{a\gamma\gamma} < 10^{-19}\ {\rm GeV}^{-1}$$

for axions in the 10 keV - 100 keV range.
We check for $(m_a^{\rm min}, f_a^{\rm relic})$ if the bound is respected or not