Anatomy of astrophysical echoes from axion dark matter

Elisa Todarello, F. Calore, M. Regis

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Universitas Studii Taurinensis 1404

INFN Torino
Istituto Nazionale di Fisica Nucleare
Sezione di Torino

QCD axions and ALPs

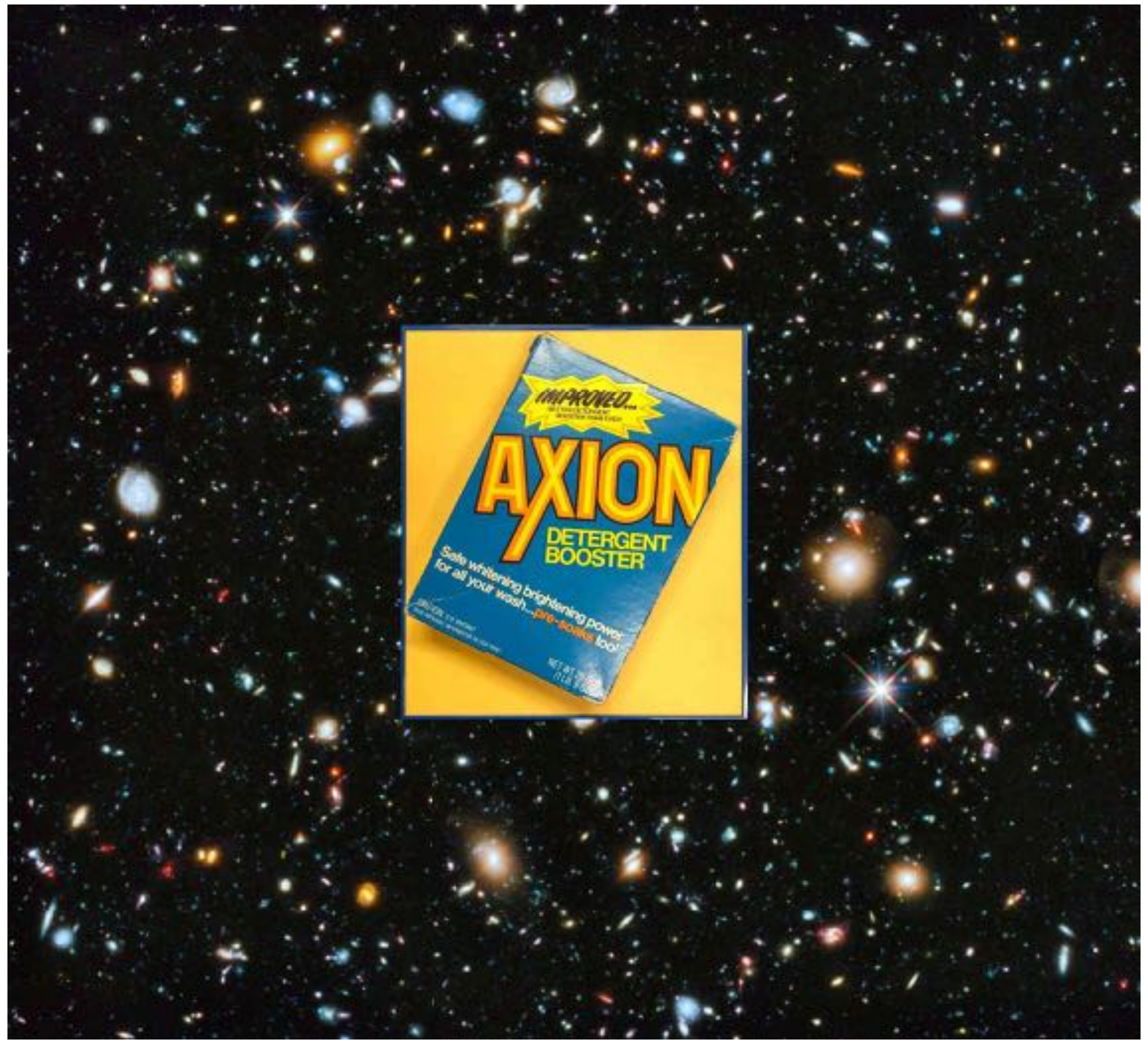
The QCD axion is a solution to the strong CP problem

It is the Goldstone boson of a global $U(1)_{PQ}$ spontaneously broken at an energy scale f

They acquire a mass during the QCD phase transition

$$mf \approx f_\pi m_\pi$$

ALPs are similar but f and m are unrelated

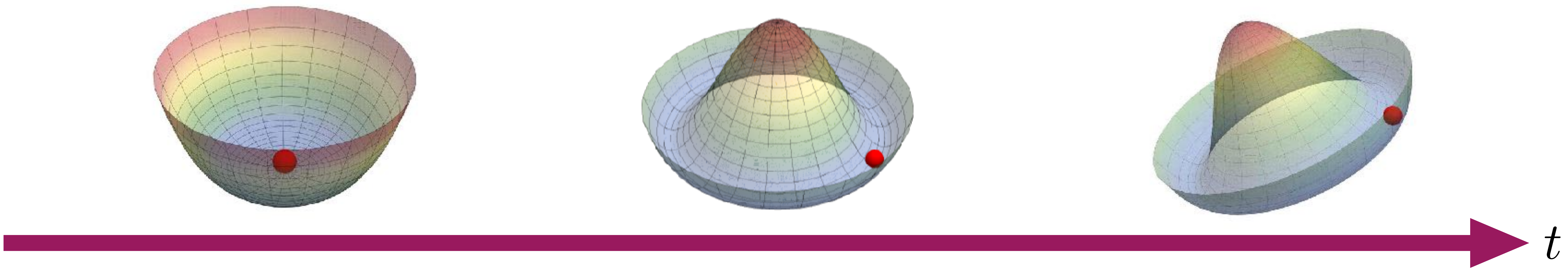


In this talk, axion = QCD axion or ALP

Axion dark matter

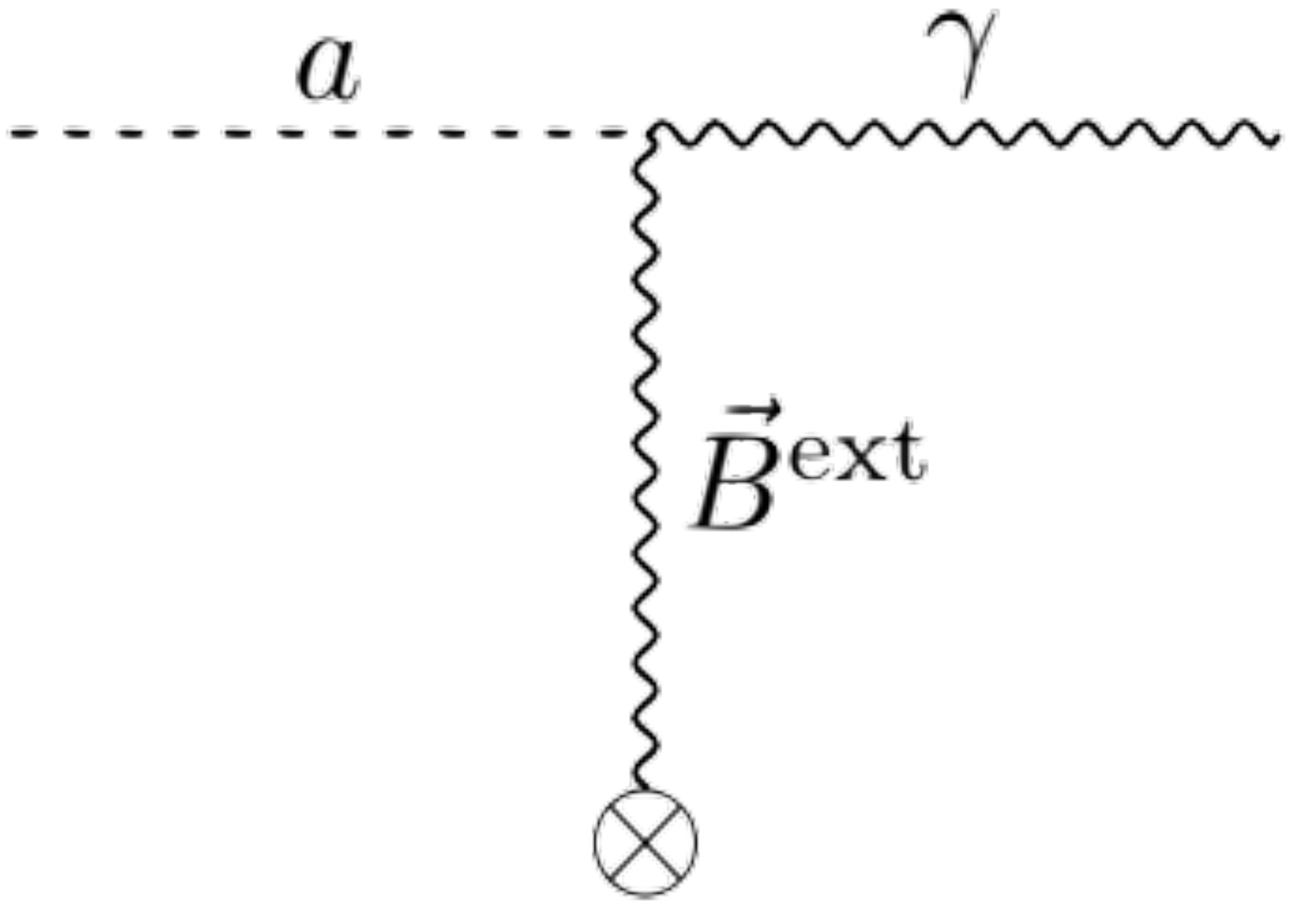
Standard production mechanism: non-thermal production by **vacuum realignment**

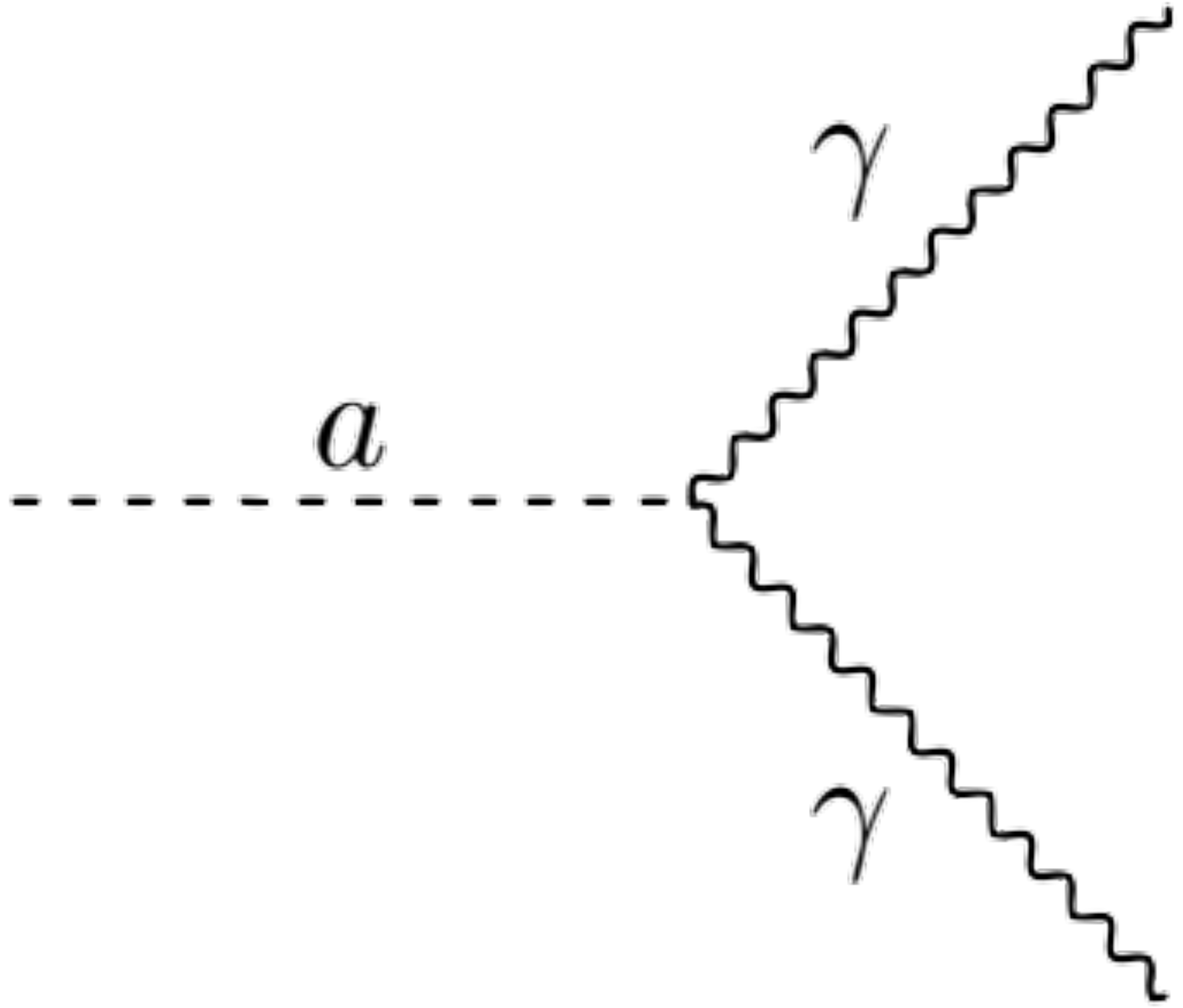
Mass becomes important when $m \approx H$



Axion-photon interaction

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



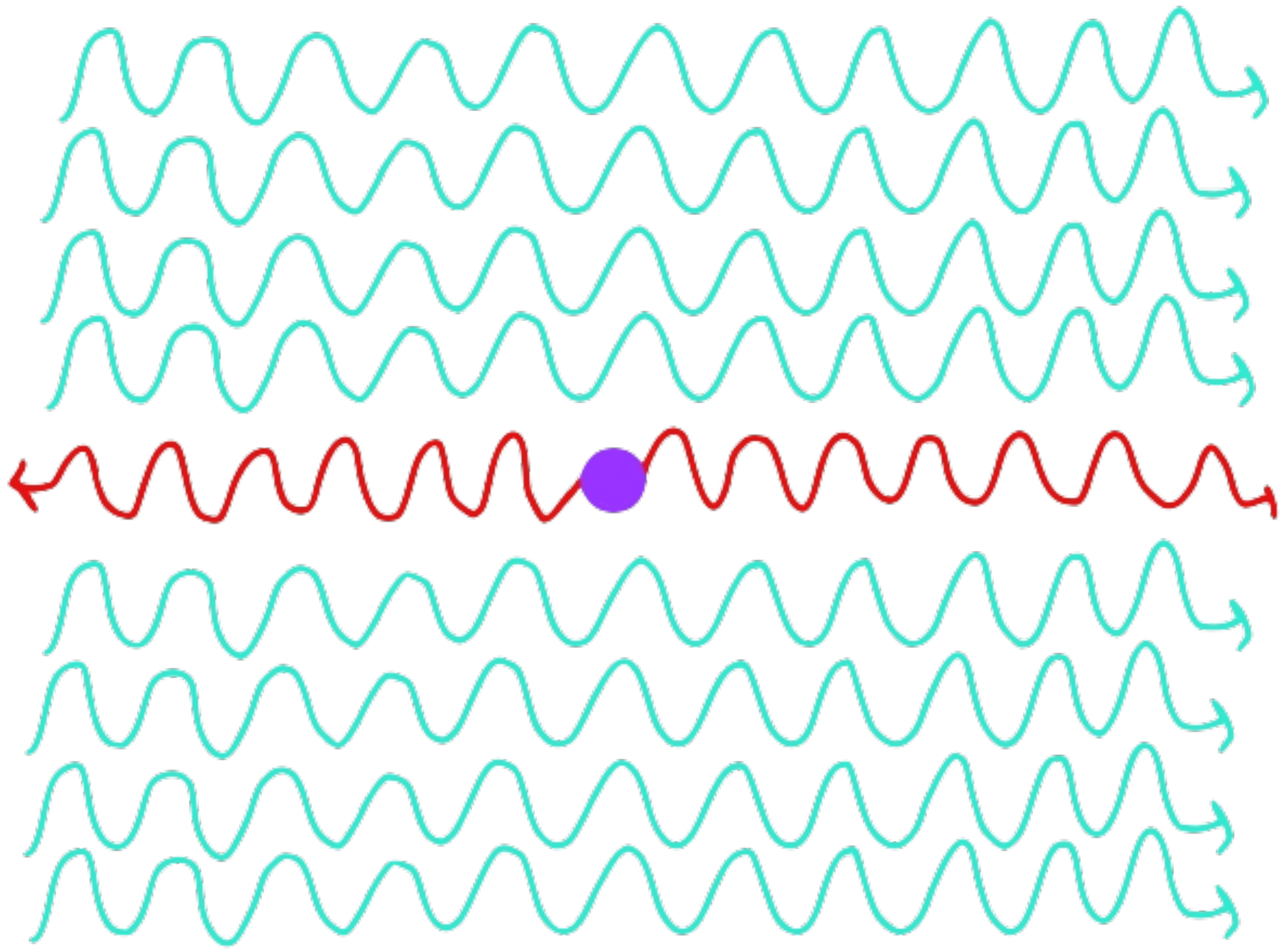


Decay rate into photons

$$\Gamma_{a\to\gamma\gamma} = 10^{-43}\ \mathrm{yr}^{-1} \left(\frac{g}{10^{-15}\ \mathrm{GeV}^{-1}}\right)^2 \left(\frac{m}{10^{-5}\ \mathrm{eV}}\right)^3$$

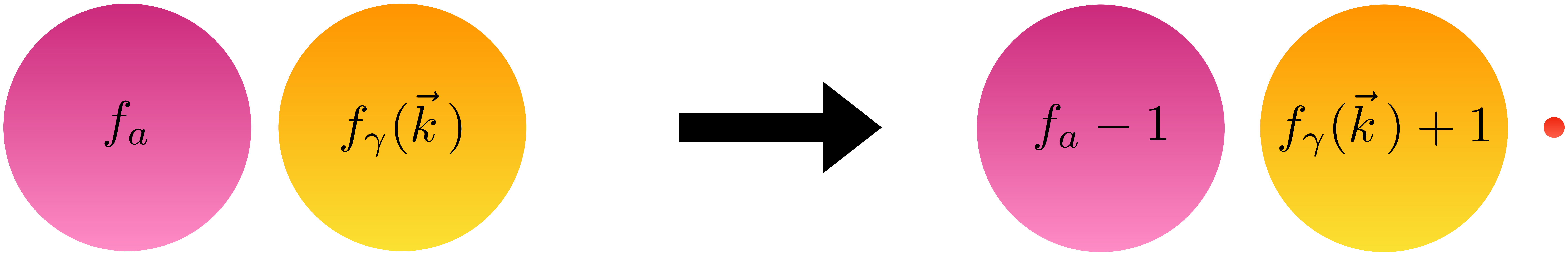
In background of photons with momentum $\vec{k}$ with $|\vec{k}| \approx m/2$ the decay rate is enhanced by the phase space density

$$f_\gamma(\vec{k}\,)$$



Bose-enhancement

$$H_{a\gamma\gamma} \sim \sum a^{\dagger}_{\gamma}(\vec{k}\,)a^{\dagger}_{\gamma}(-\vec{k}\,)a_a + h.c.$$

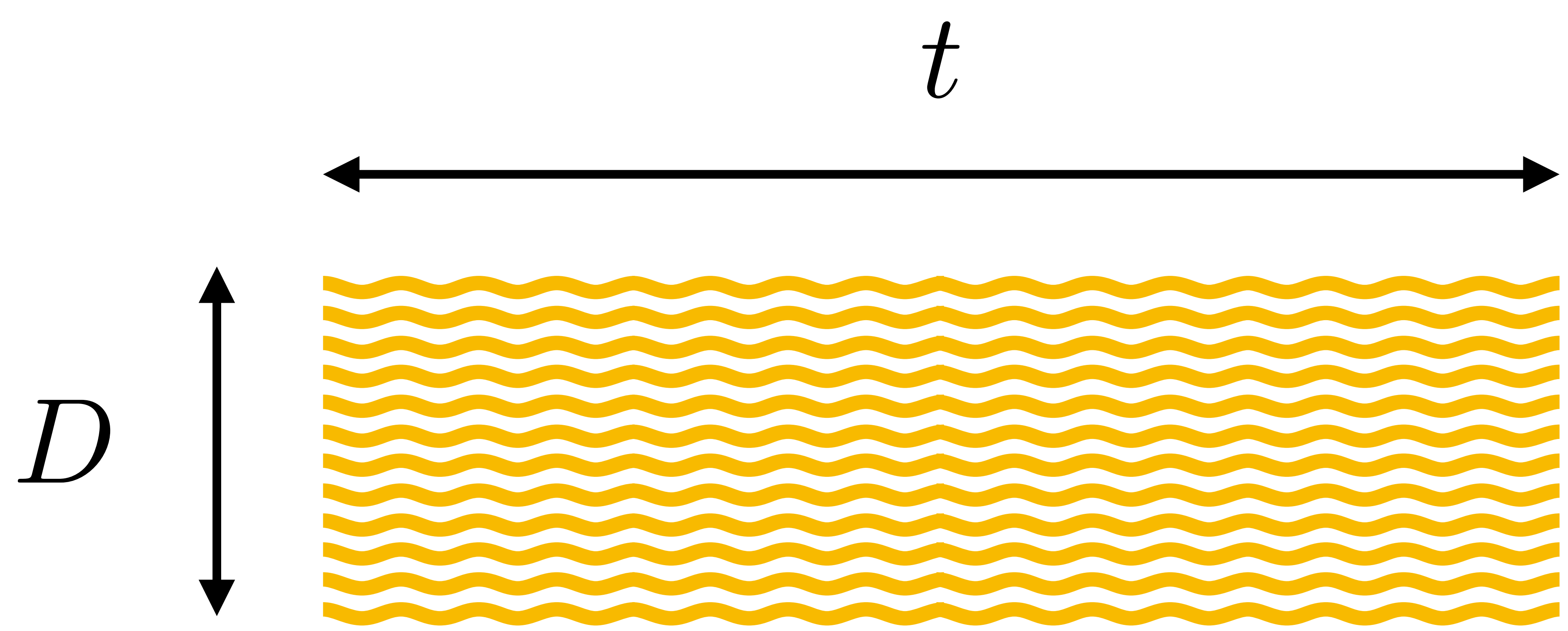


Decay rate is enhanced compared to vacuum by a factor $f_\gamma(\vec{k}\,)$

Enhancement factor

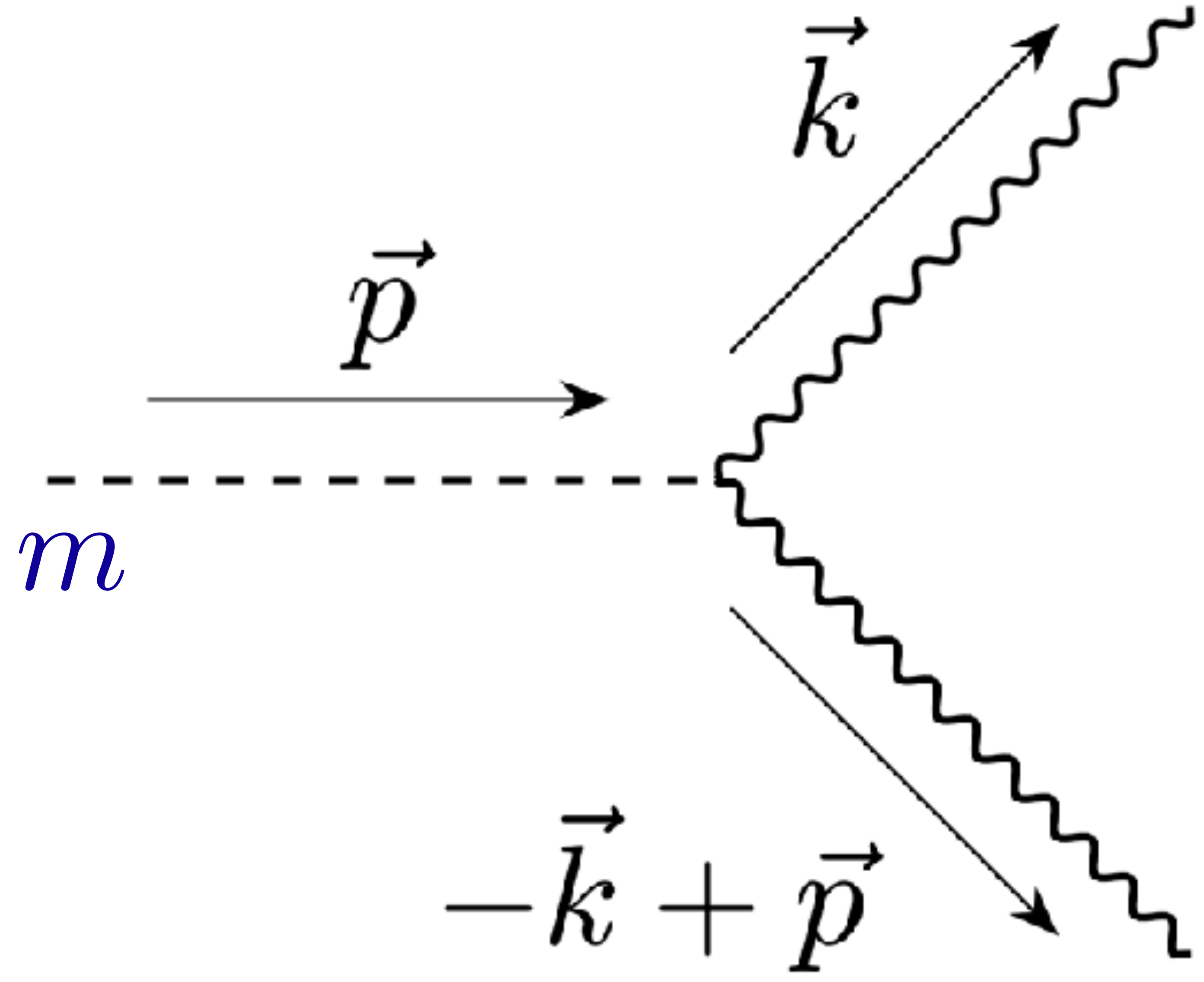
$$\rho_\gamma = \int \frac{d^3k}{(2\pi)^3}\,\omega\, f_\gamma(\vec{k}\,)$$

$$f_\gamma \sim 10^{20}\left(\frac{1}{n_{pol}}\right)\left(\frac{10^{-5}\ \mathrm{eV}}{m}\right)^3\left(\frac{1\ \mathrm{m}^2}{A}\right)\left(\frac{P}{1\ \mathrm{kW}}\right)\left(\frac{1\ \mathrm{MHz}}{\Delta\nu}\right)$$

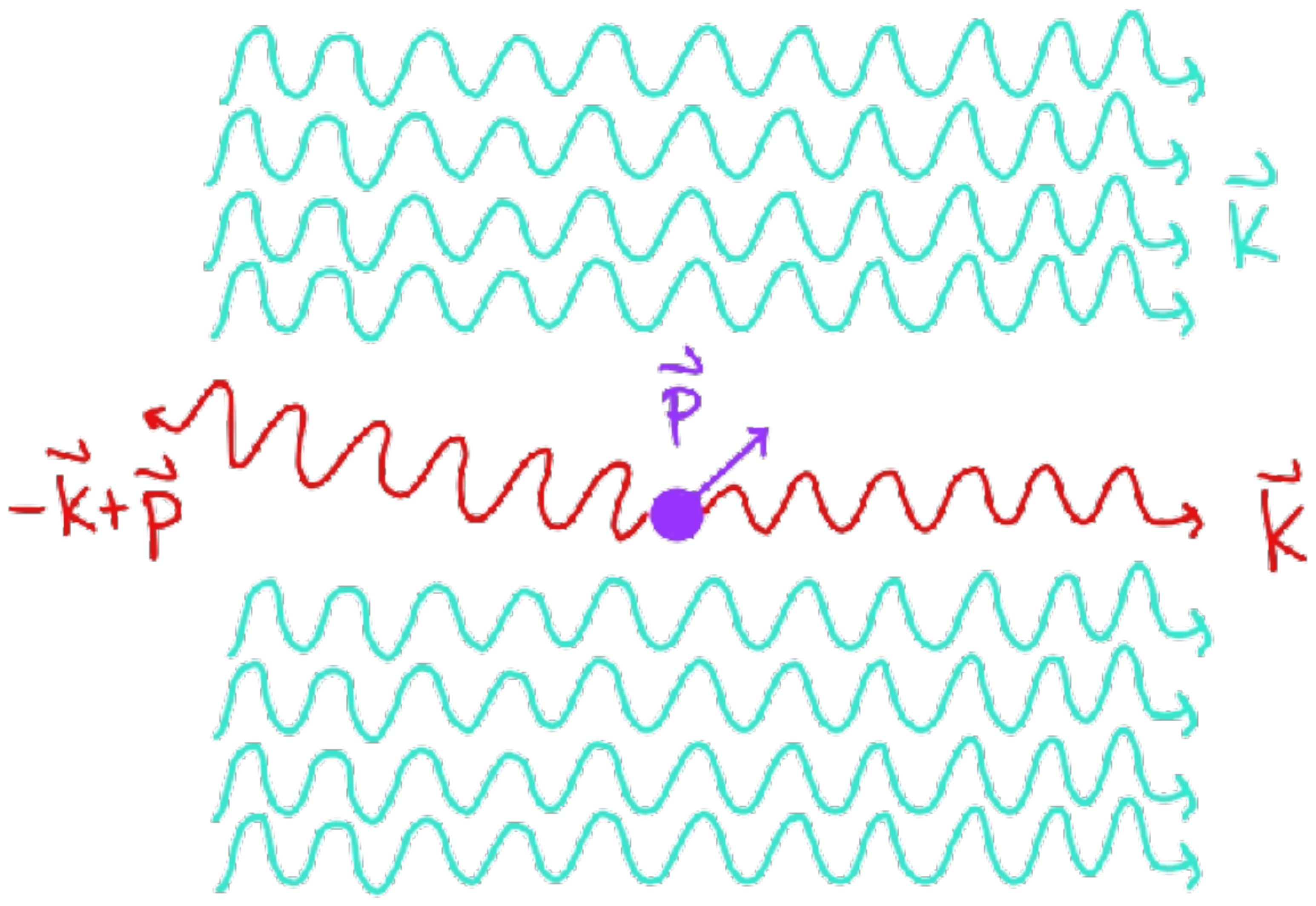


Kinematics

$$\omega_1 = \frac{m + p_{\parallel}}{2}$$



$$\omega_2 = \frac{m - p_{\parallel}}{2}$$



The echo propagates

***almost* backwards!**

The echo experiment

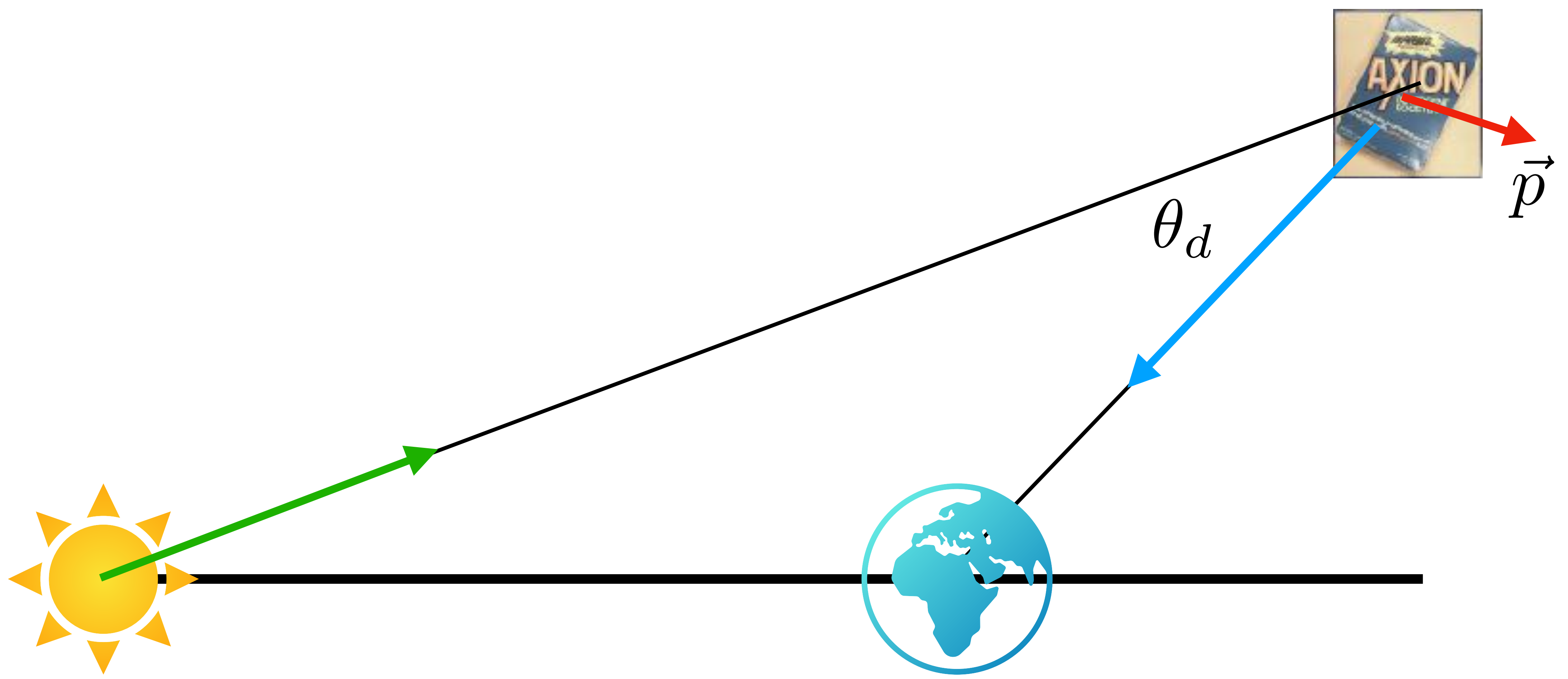
Stimulate the decay of nearby dark matter axions into photons by sending out a powerful beam to space

Detect the photons that come back

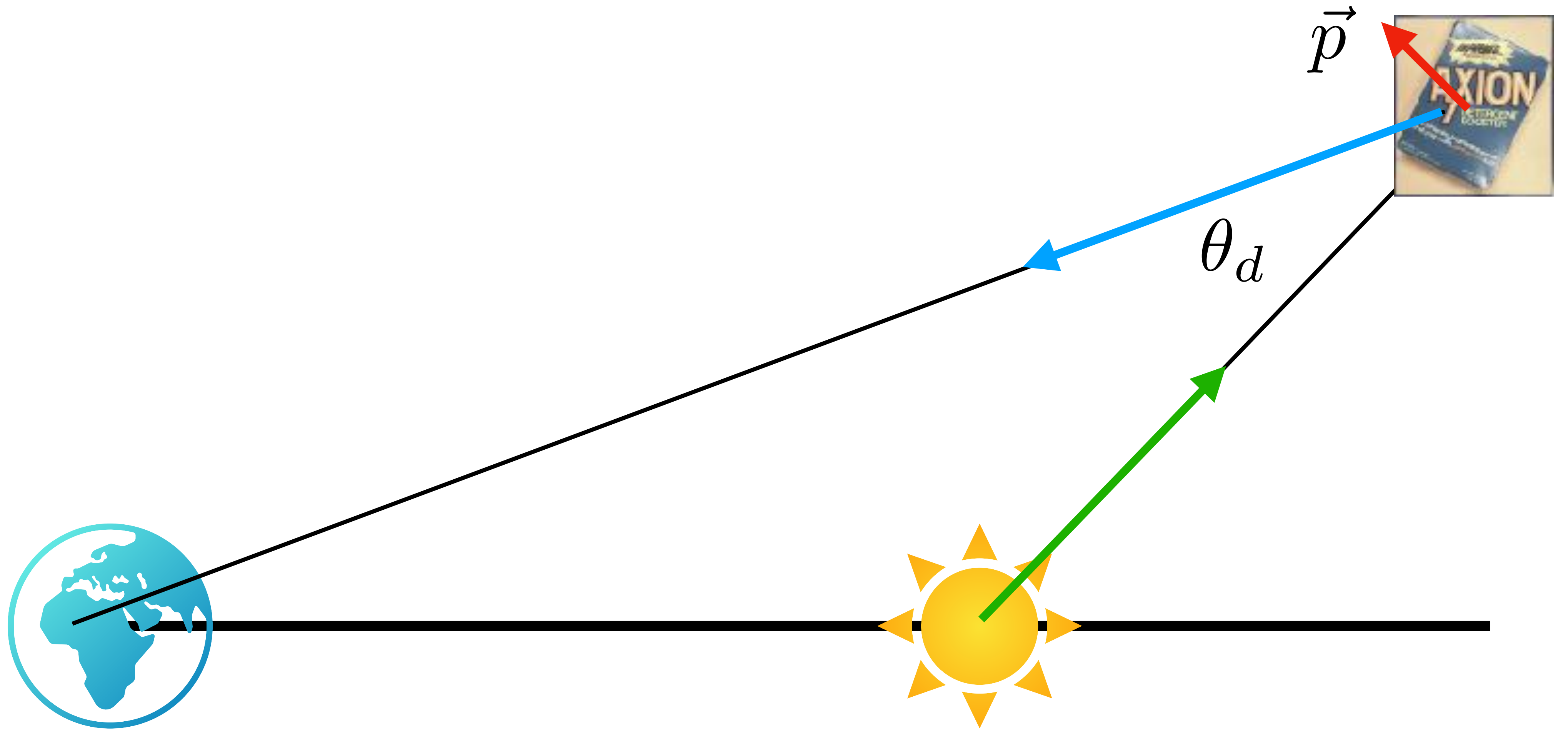
See: Arza + Sikivie, PRL (2019) 13, 131804, Arza + **E.T.**, PRD 05 (2022) 2, 023023

Echoes from natural sources

Back-light echo



Front-light echo

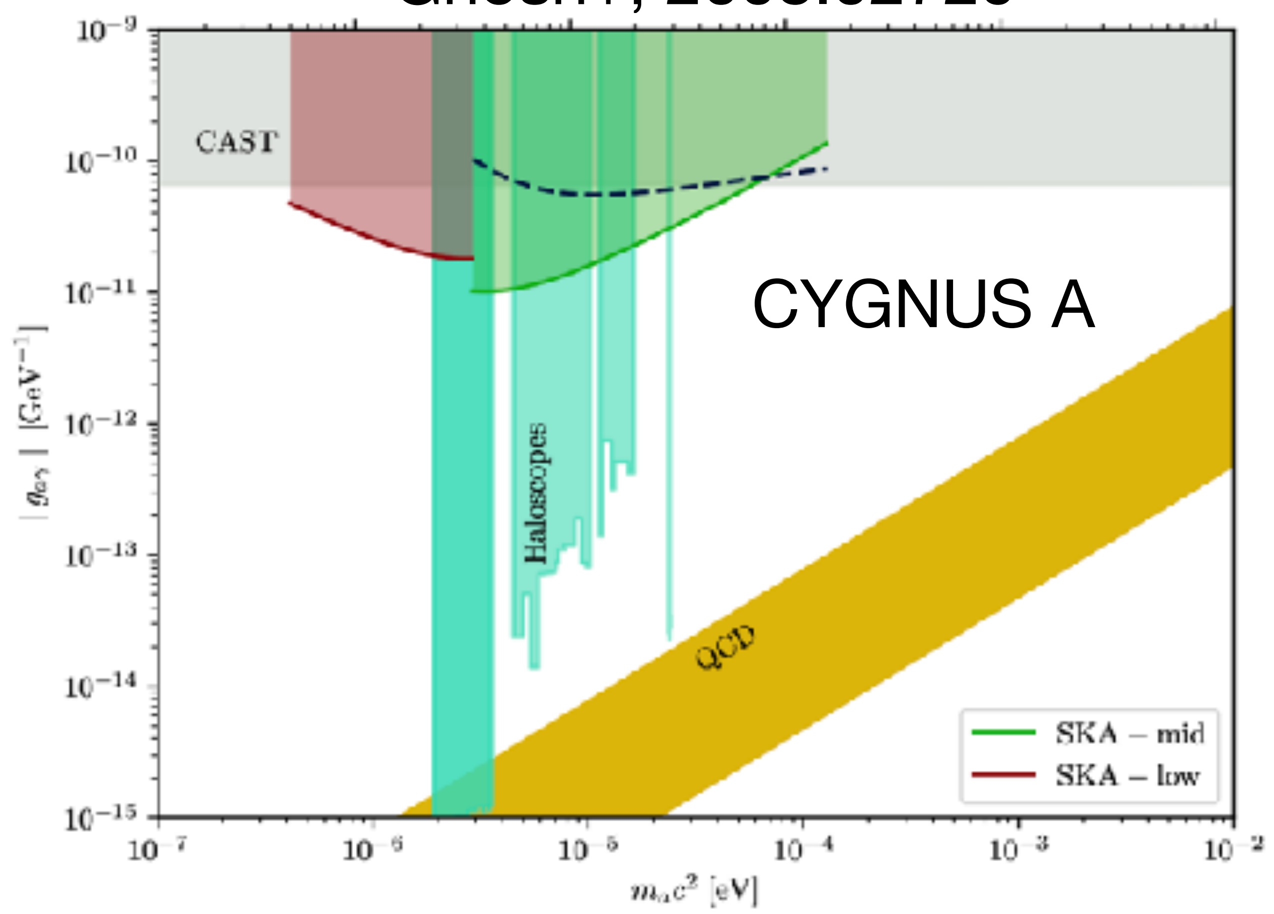


Collinear emission

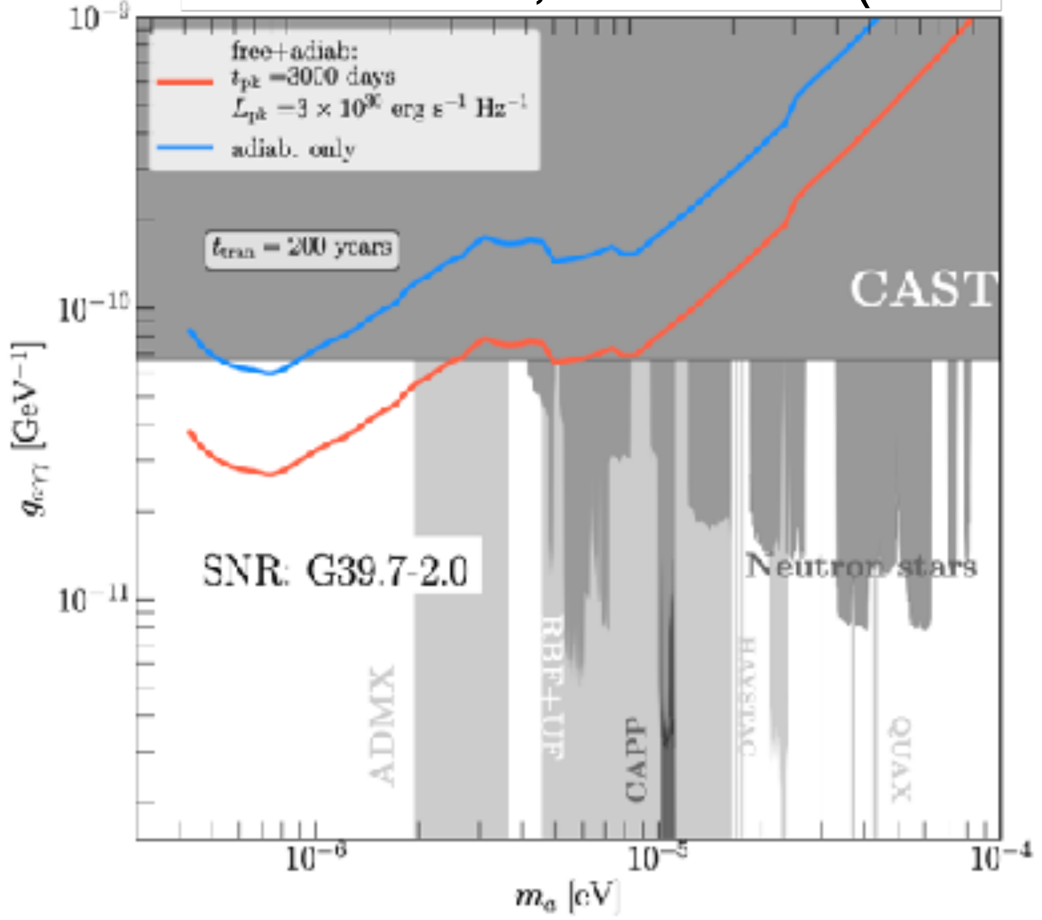
Echoes from natural sources

Back-light echo

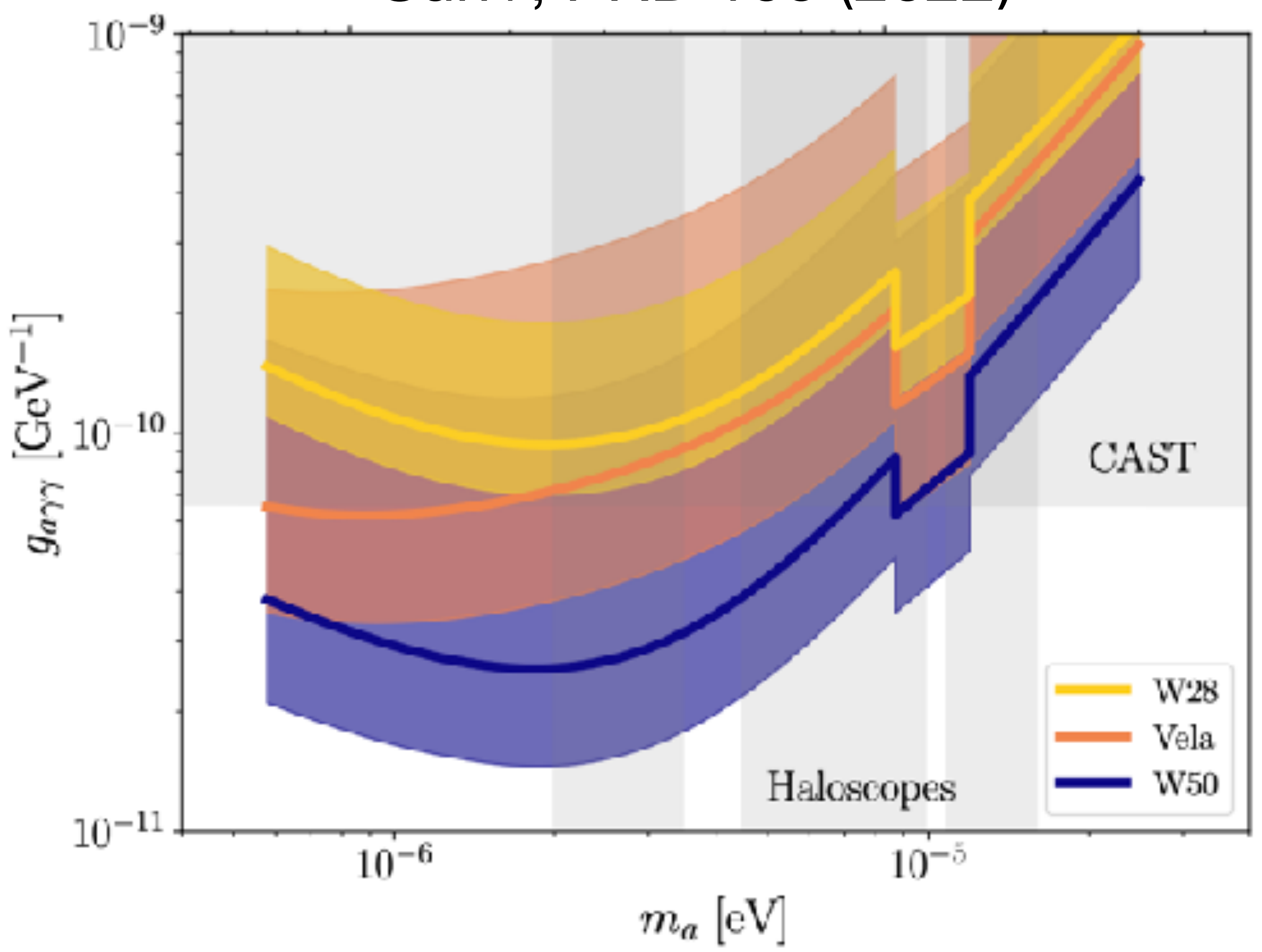
Ghosh+, 2008.02729



Buen-Abad+, PRD 105 (2022)

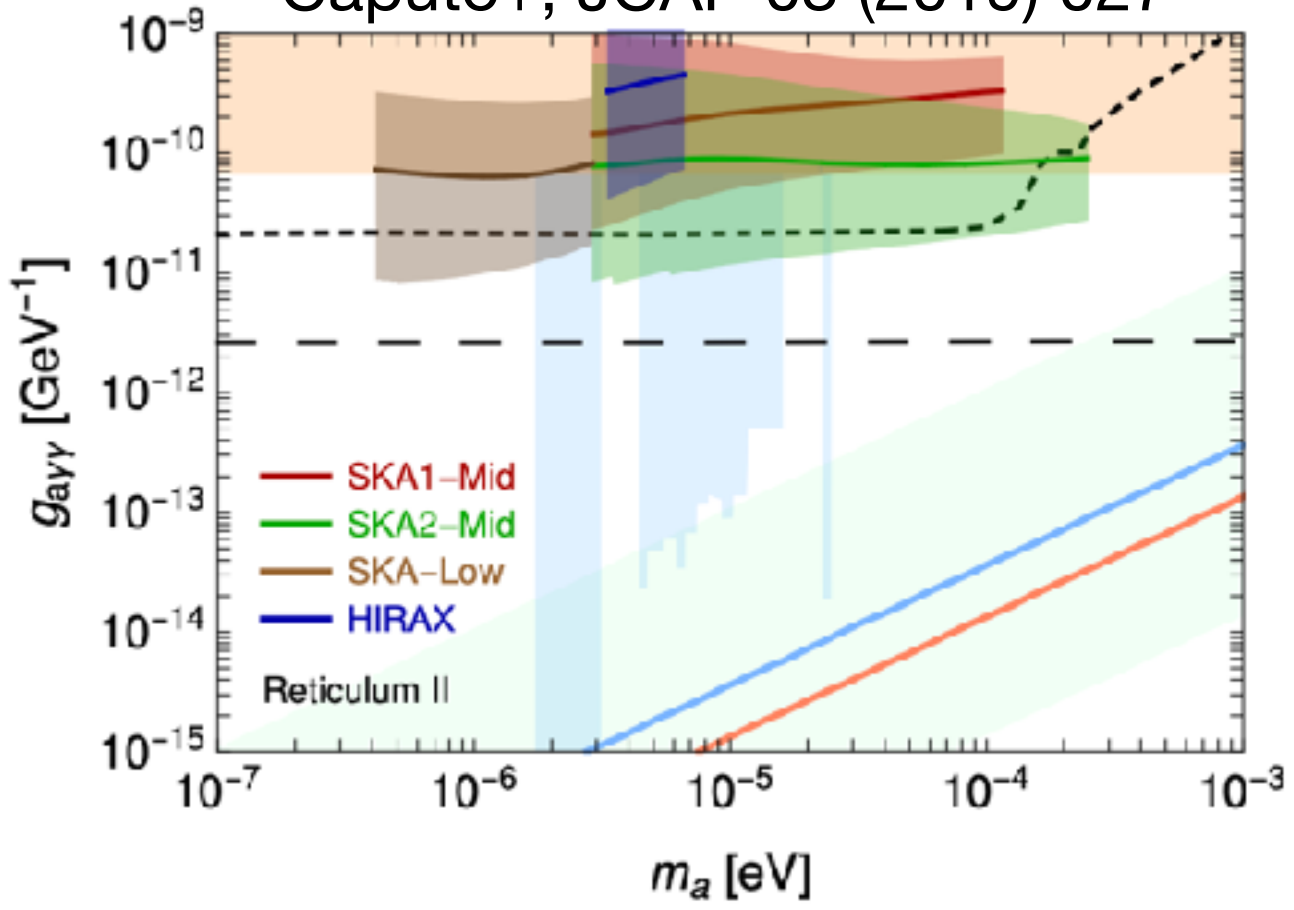


Sun+, PRD 105 (2022)



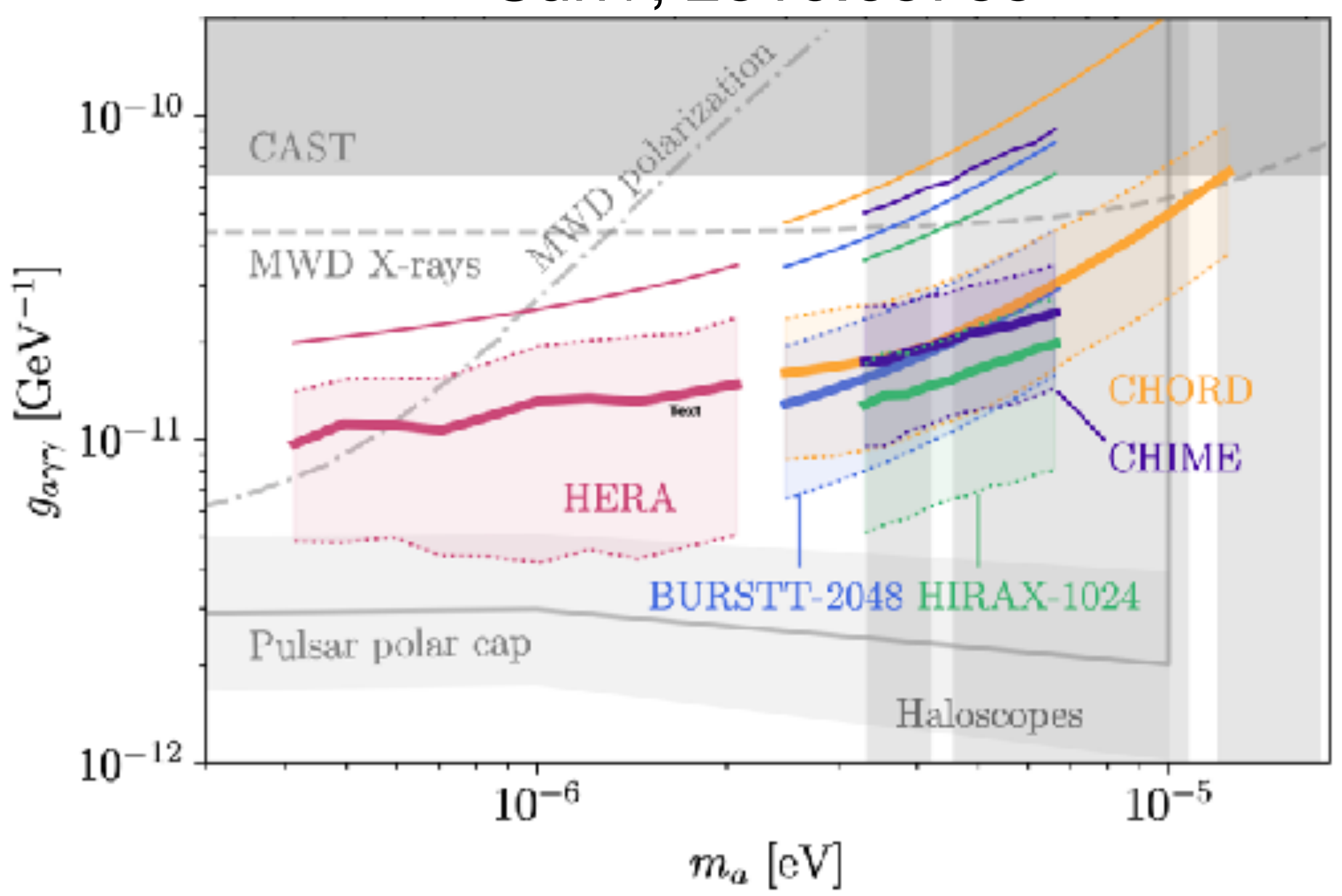
Collinear emission

Caputo+, JCAP 03 (2019) 027

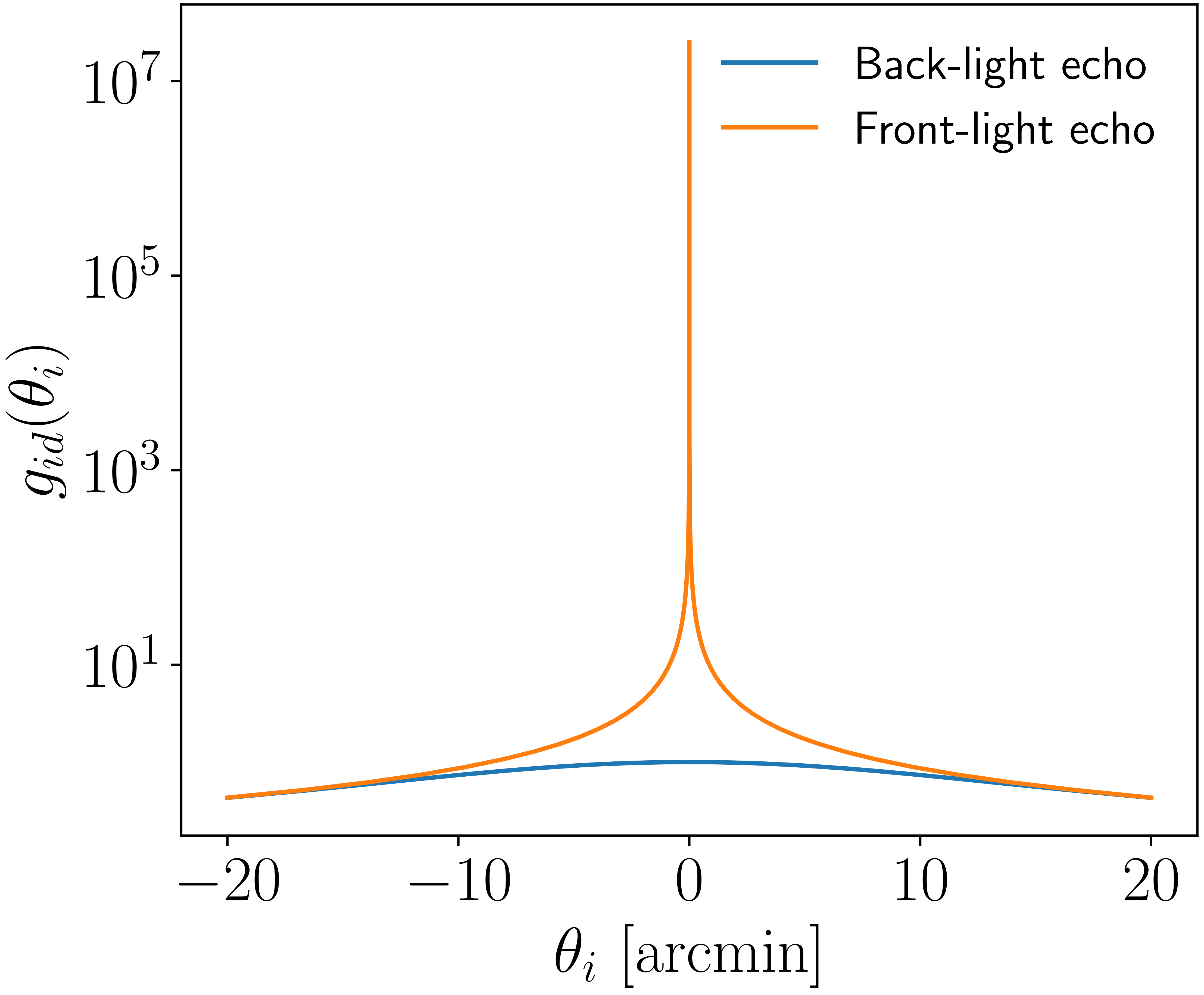


Everything

Sun+, 2310.03788

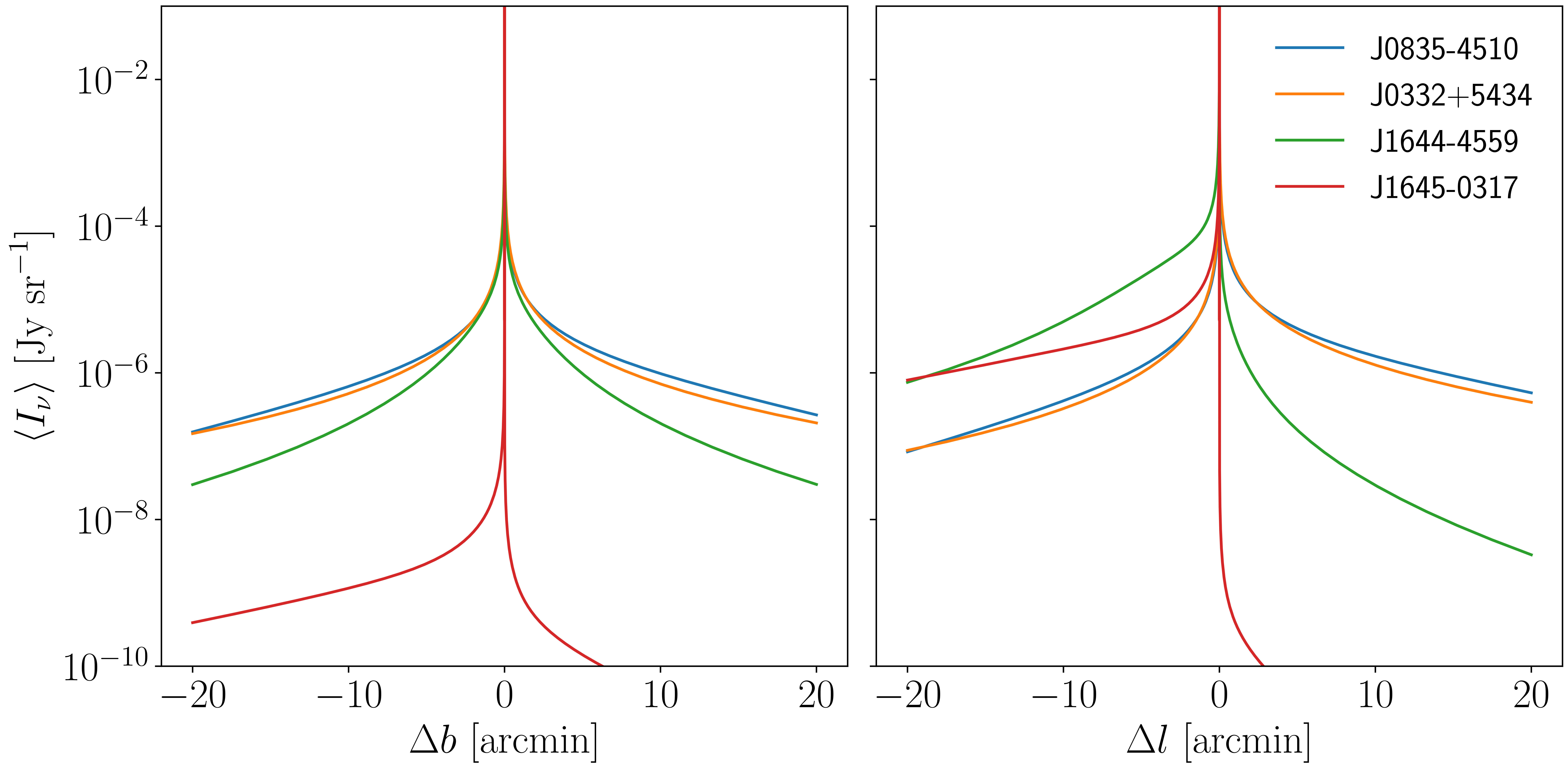


$$\theta_{i,0} \sim 2\delta v \left(\frac{x_d}{x_s} \pm 1 \right)$$

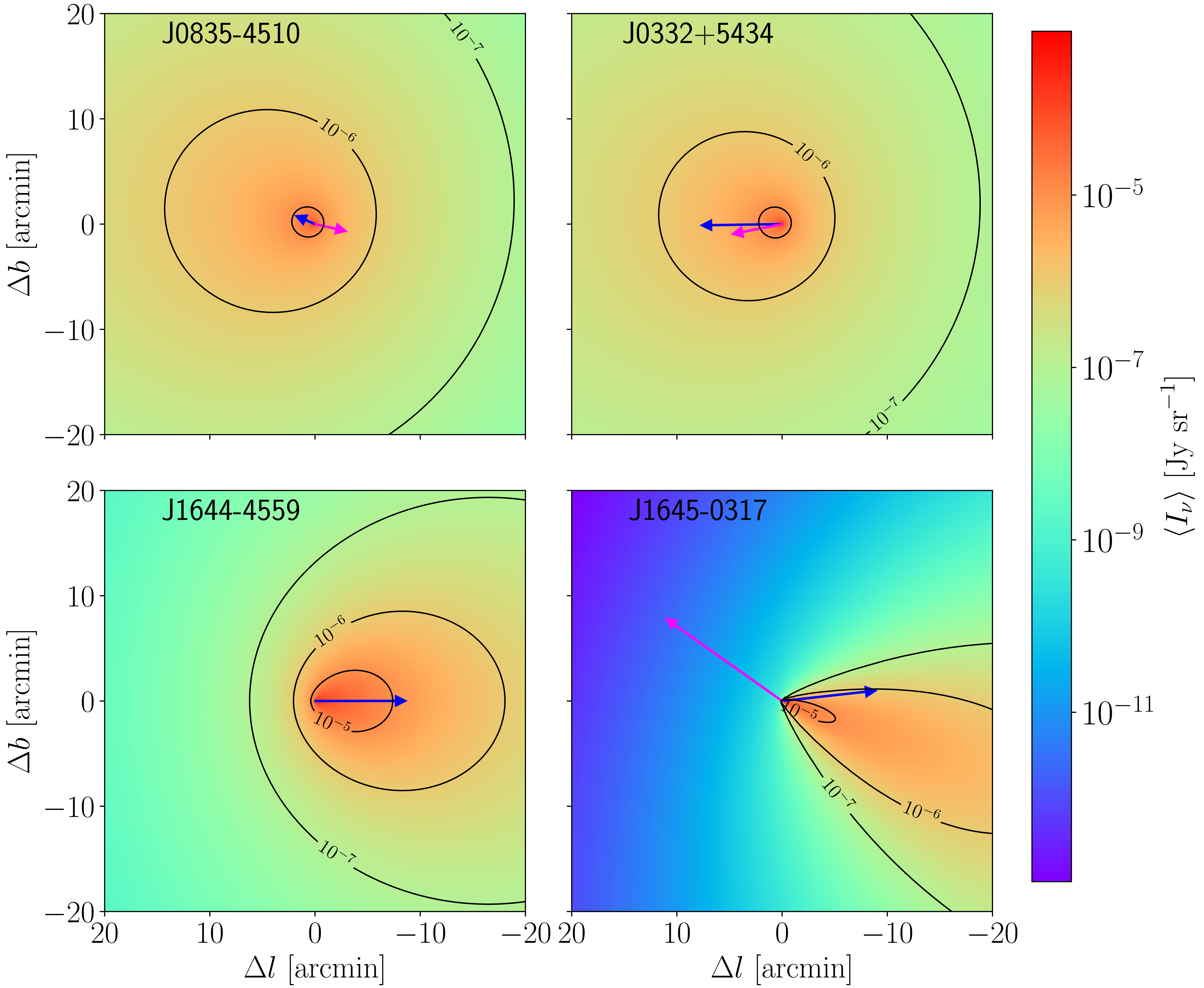


Relevant effects

- Dark matter density
- Dark matter velocity dispersion
- Dark matter average velocity
- Source's age
- Source's proper motion
- Source's distance
- Source's variability

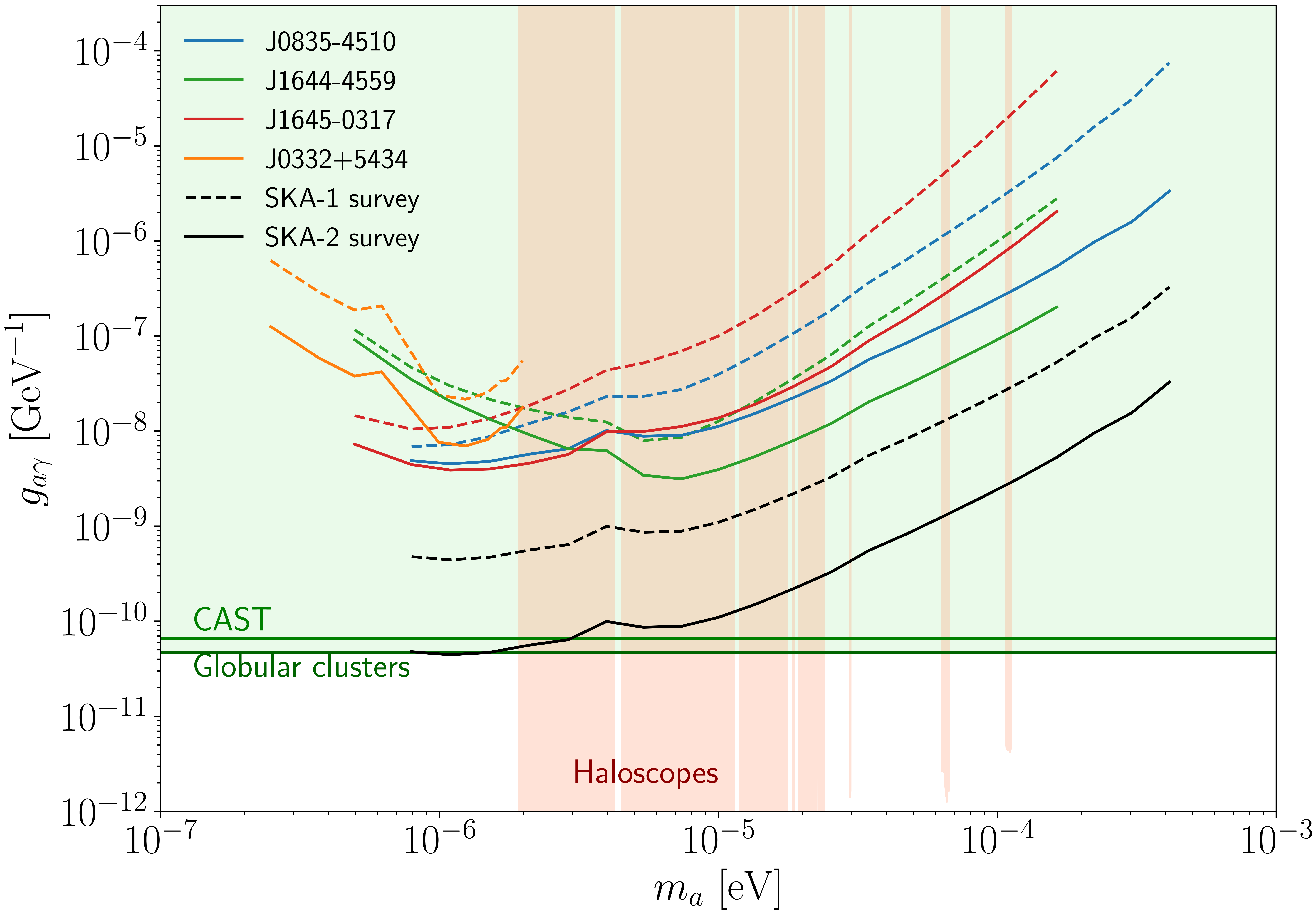


10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
$\langle I_\nu \rangle$ [Jy sr^{-1}]
-20
-10
0
10
20
Δb [arcmin]
Δl [arcmin]
J0835-4510
J0332+5434
J1644-4559
J1645-0317



J0835-4510
J0332+5434
J1644-4559
J1645-0317
10^{-7}
10^{-6}
10^{-5}
Δb [arcmin]
Δl [arcmin]
$\langle I_\nu \rangle$ [Jy sr^{-1}]
10^{-5}
10^{-7}
10^{-9}
10^{-11}

THANK YOU



J0835-4510
J1644-4559
J1645-0317
J0332+5434
SKA-1 survey
SKA-2 survey
CAST
Globular clusters
Haloscopes
$g_{a\gamma}$ [GeV^{-1}]
m_a [eV]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}

Flux Density

$$S_\nu(t) = \frac{\pi g^2}{16 m_a}\, S_\nu^{(0)}(t) \int d\Omega_i\, B(\Omega_i) \int dx_d\, \rho_a(\vec{x}_{ds})\, \frac{L_\nu(t_{em})}{L_\nu(t - \tilde{x}_s(t))} \left(\frac{\tilde{x}_s(t)}{\tilde{x}_{ds}(t_{em})}\right)^2 h(\omega, \vec{x}_{ds}, t_{em})$$

$$h(\omega_k, \vec{x}_{ds}) = \frac{1}{(2\pi)^{3/2}\delta v^3}\, e^{-\frac{\langle v_t \rangle^2}{2\delta v^2}}\, e^{-\frac{(\varepsilon - \langle v_{||} \rangle)^2}{2\delta v^2}}\, e^{-\frac{(\omega_k \theta_d / m_a - \langle v_\perp \rangle)^2}{2\delta v^2}}$$

$$\theta_d = \pm \frac{x_s}{x_{ds}} \theta_i$$