Phenomenology of Axion Decay into Photons

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Axions 2024
Gainesville, 26.04.2024

Outline

- **Axion spontaneous decay**
  - **E.T.** + Regis + Reynoso-Cordova + Taoso + Vaz + Brinchman,

    "Robust bounds on ALP dark matter from dwarf spheroidal galaxies in the optical MUSE-Faint survey"

    2307.07403 (Accepted in JCAP)
- **Axion stimulated decay**
  - **E.T.** + Calore + Regis,

    "Anatomy of astrophysical echoes from axion dark matter"

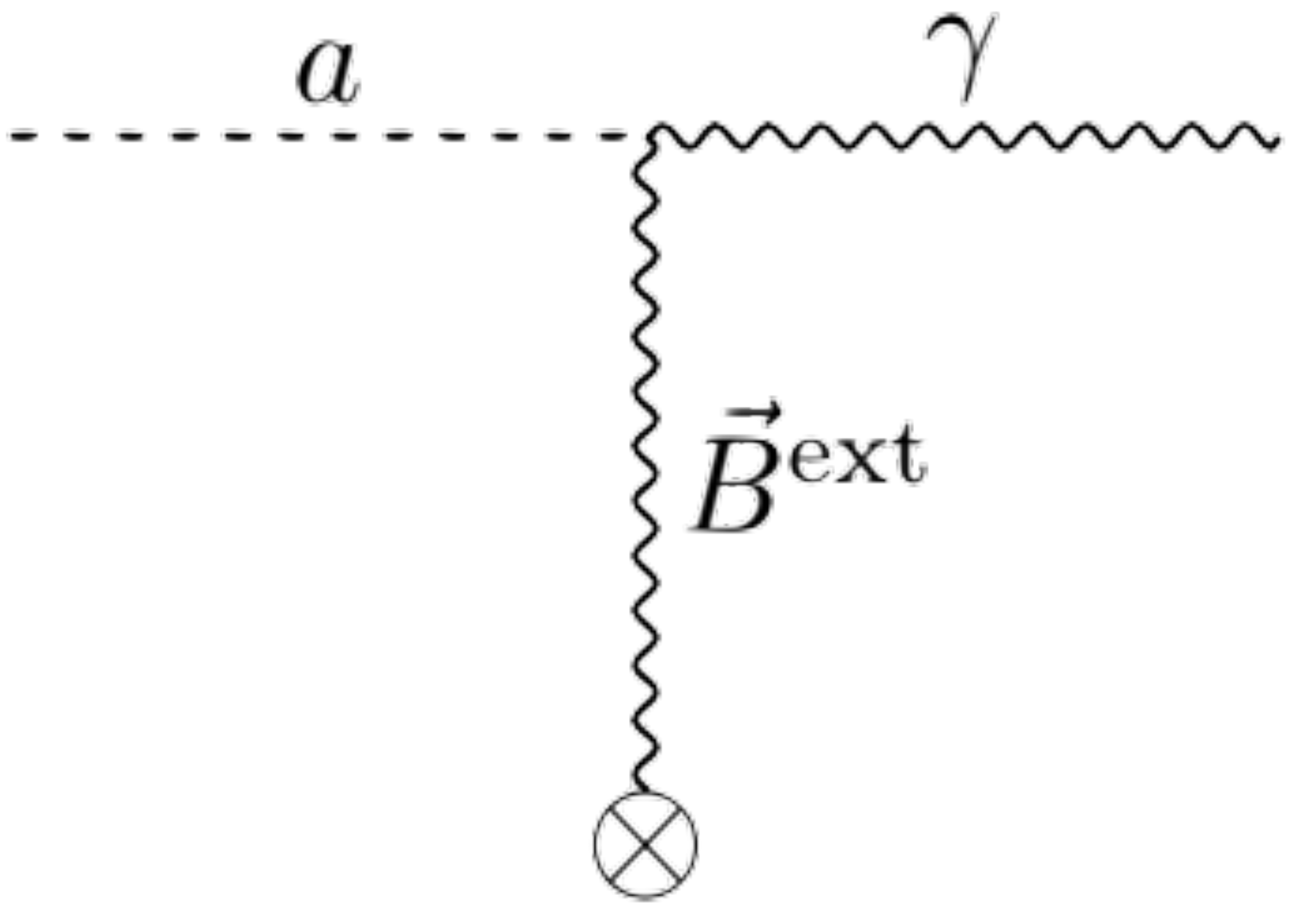
    2311.00051 (Accepted in JCAP)
  - Arza + **E.T.**,

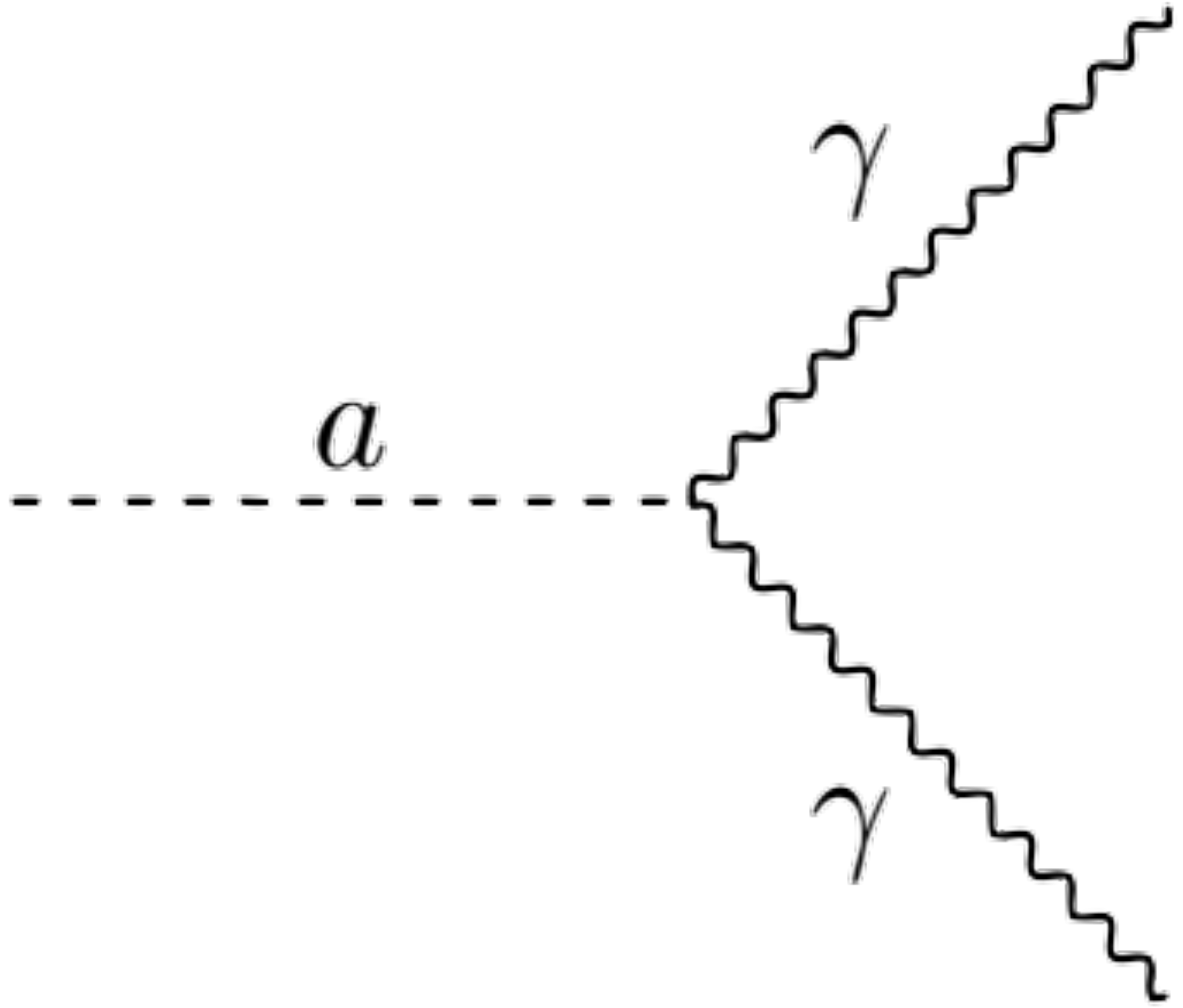
    "Axion dark matter echo: A detailed analysis"

    Phys.Rev.D 105 (2022) 2, 023023

Axion-photon interaction

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

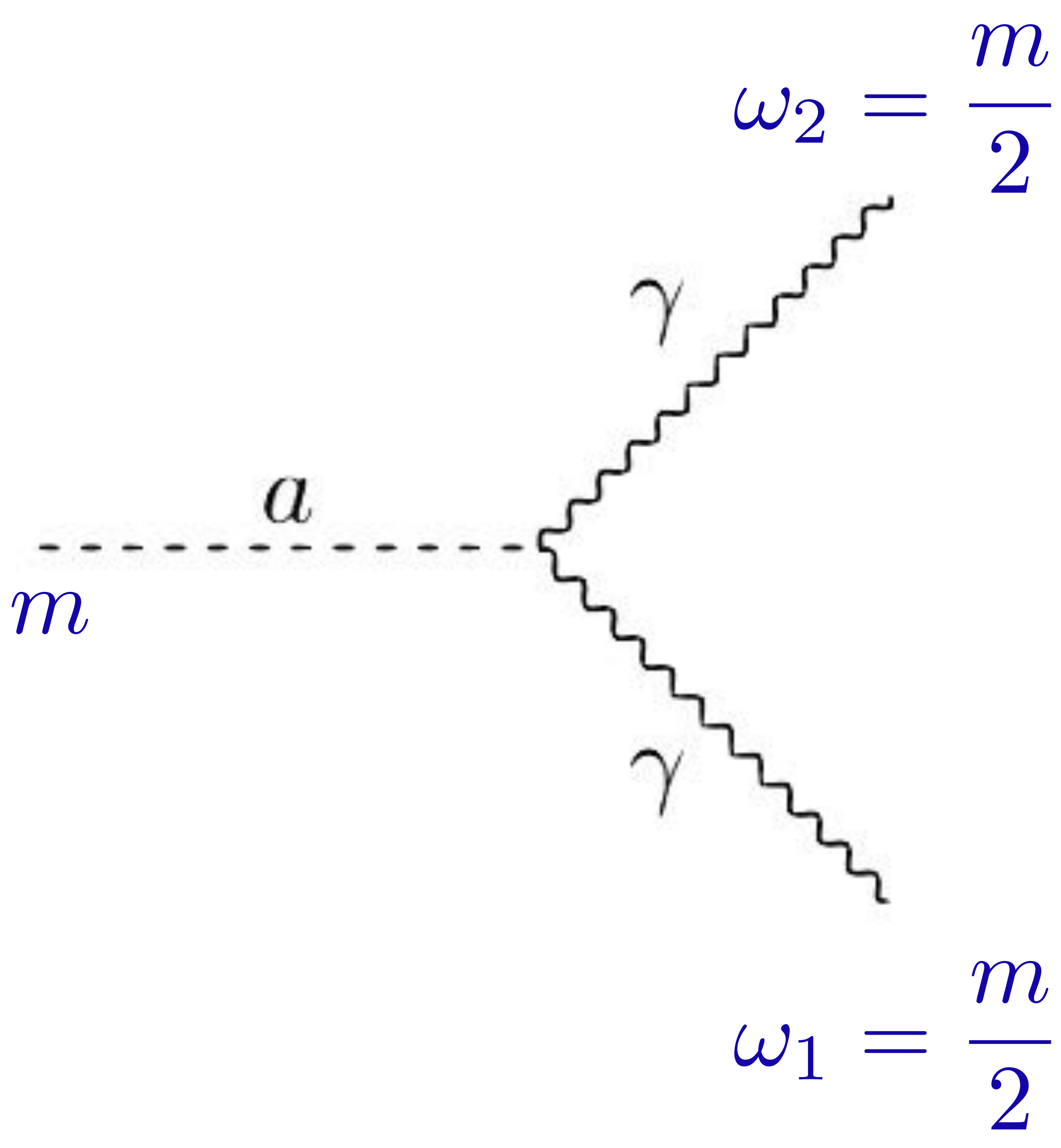


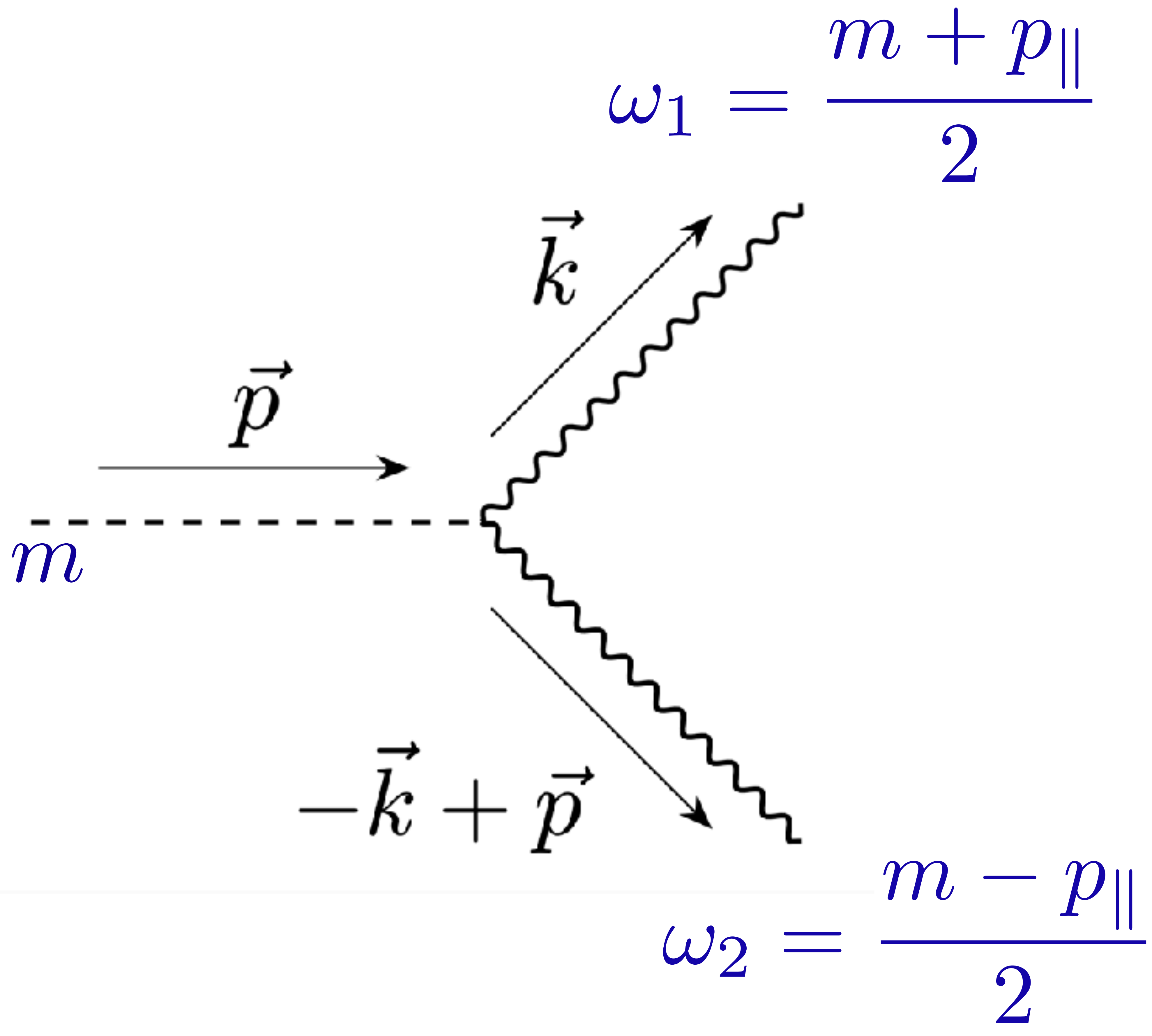


In this talk, axion = QCD axion or ALP

Axion spontaneous decay

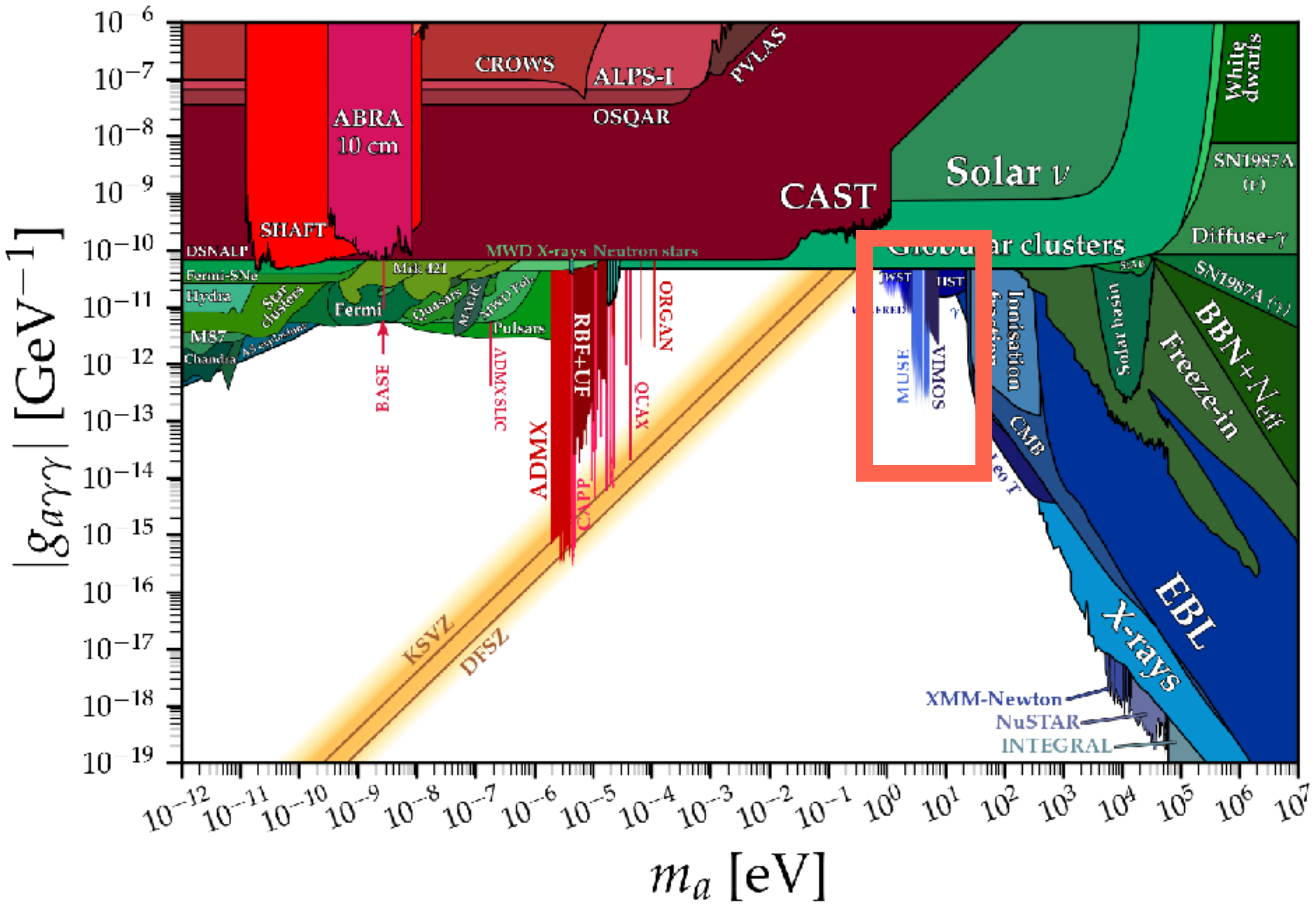
Kinematics


$\omega_2 = \frac{m}{2}$
γ
a
m
γ
$\omega_1 = \frac{m}{2}$


$\omega_1 = \frac{m + p_\parallel}{2}$
$\vec{k}$
$\vec{p}$
m
$-\vec{k} + \vec{p}$
$\omega_2 = \frac{m - p_\parallel}{2}$

Decay rate in vacuum

$$\Gamma_{a\to\gamma\gamma} \sim 10^{-22}\ \mathrm{yr}^{-1} \left(\frac{g}{10^{-13}\ \mathrm{GeV}^{-1}}\right)^2 \left(\frac{m}{4\ \mathrm{eV}}\right)^3$$



Dwarf Galaxies

- Dark matter rich
- High mass-to-light ratio
- Typical mass $10^8 - 10^9 \ M_\odot$
- Typical radius $1 \ \mathrm{kpc}$
- Energy density $\rho \sim 4 \ \mathrm{GeV \ cm^{-3}}$
- Distance $100 \ \mathrm{kpc}$

Sculptor dwarf galaxy. Photo by ESO.

The MUSE instrument

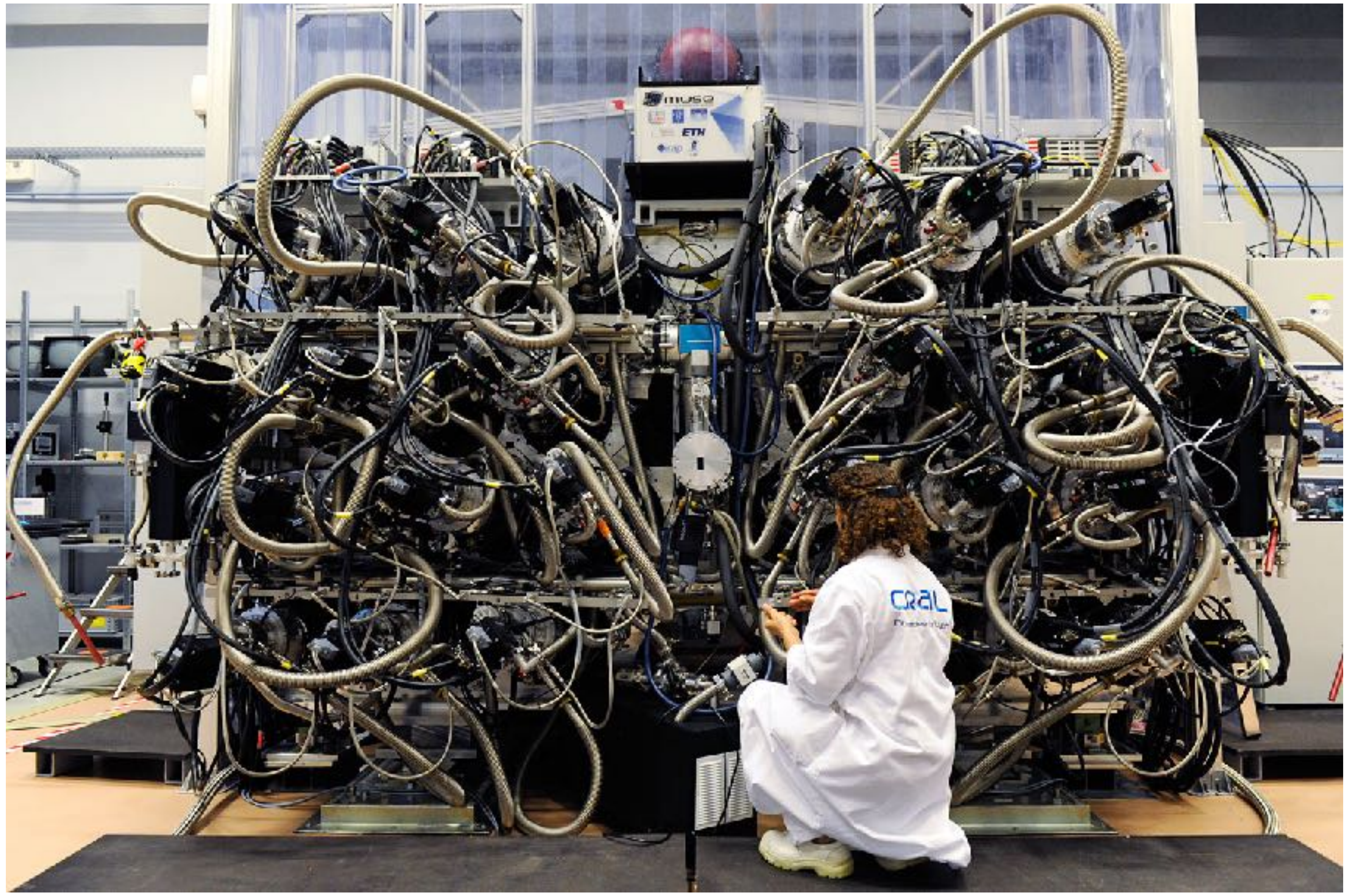
Multi Unit Spectroscopic Explorer

- Measures flux in ~3720 channels

$$4700\ \text{Å} < \lambda < 9350\ \text{Å}$$

$$2.65\ \text{eV} < m < 5.27\ \text{eV}$$

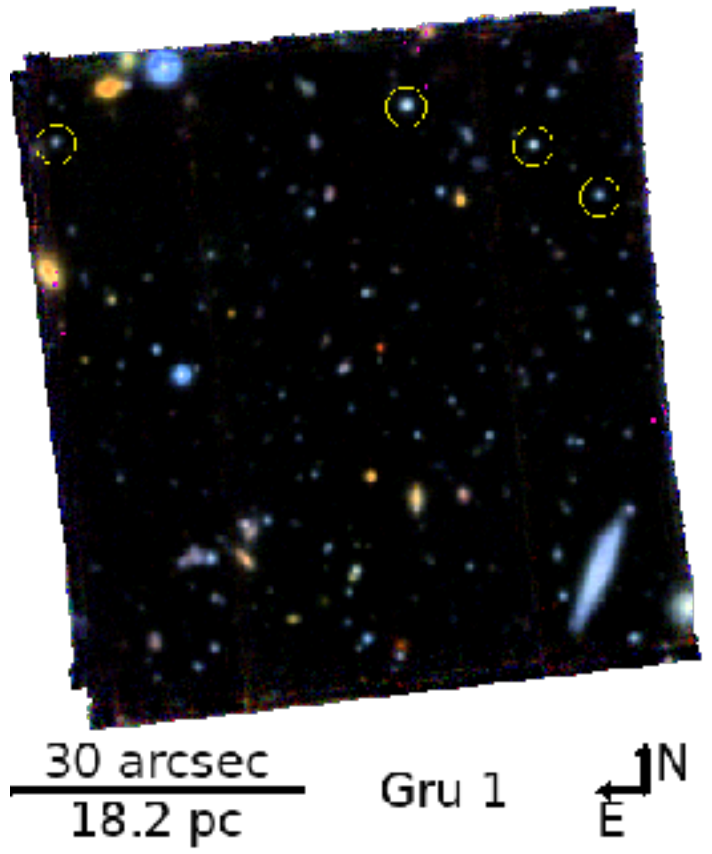
- Wavelength sampling $1.25\ \text{Å}$
- Spectral resolution $\lambda/\Delta\lambda > 10^3$
- Field of view $1' \times 1'$
- Spatial resolution $\sim 0.5''$

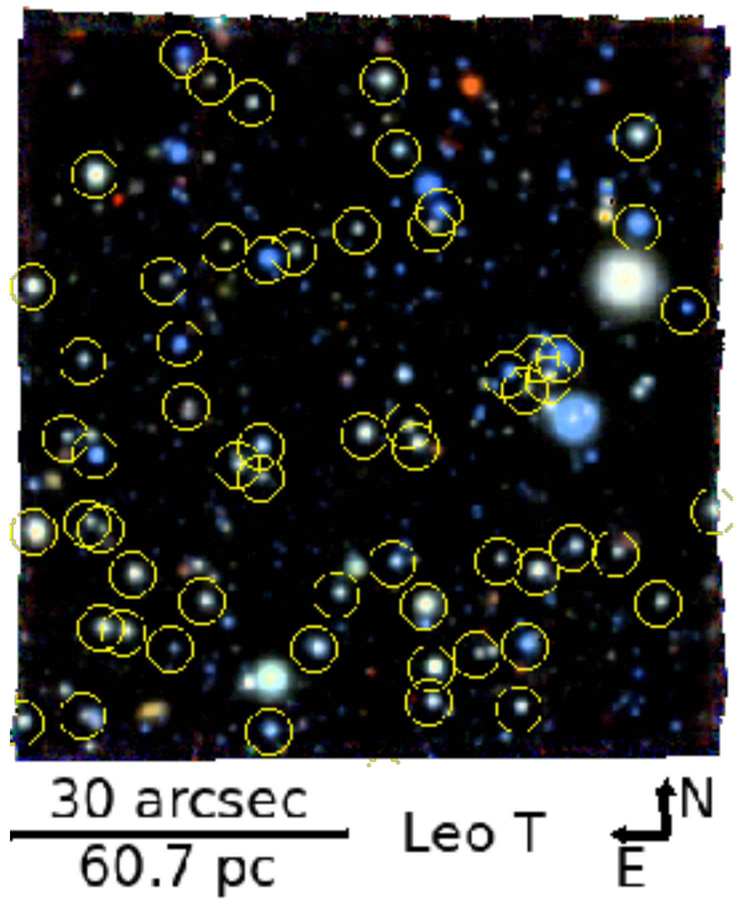


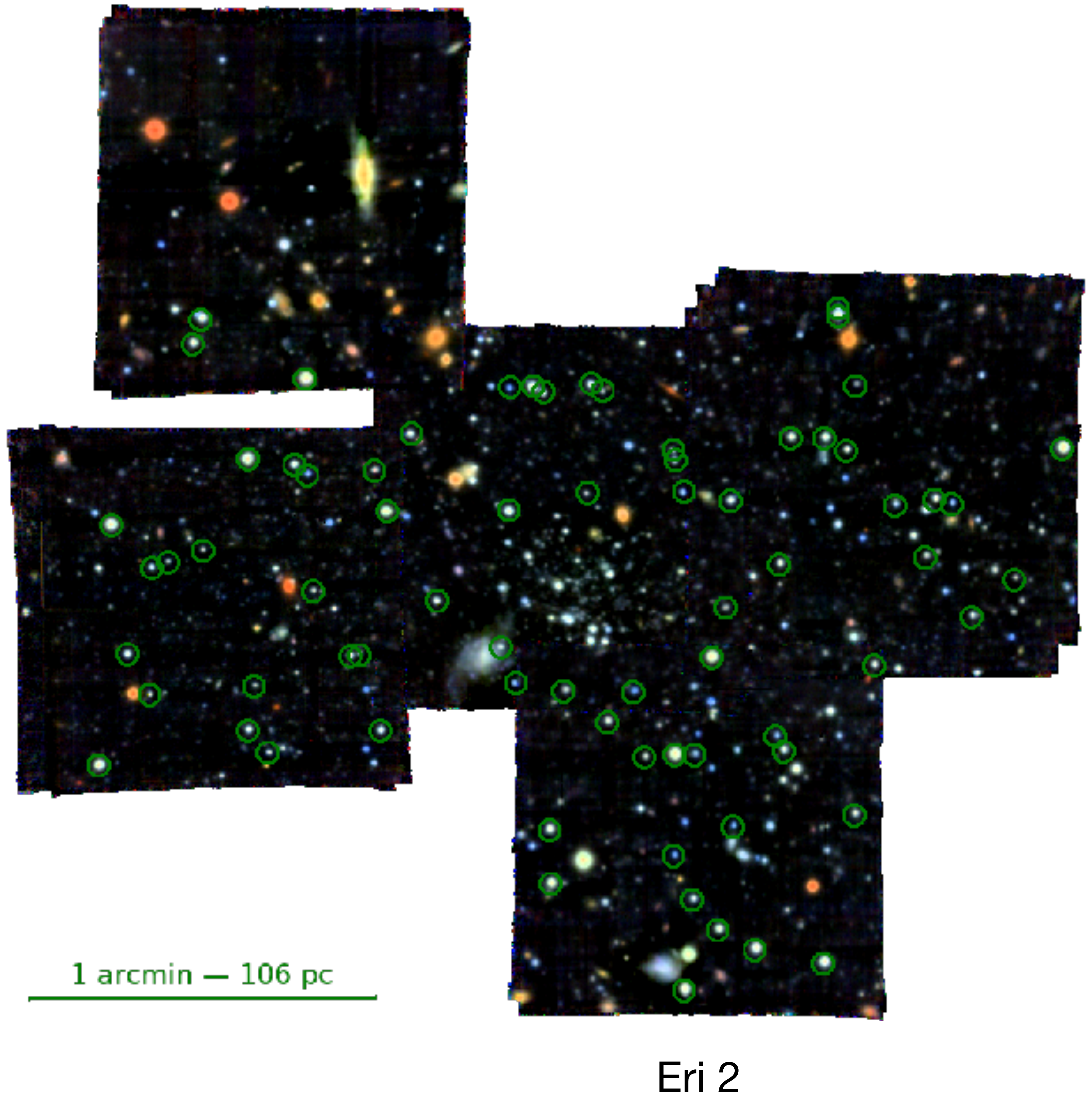
muse

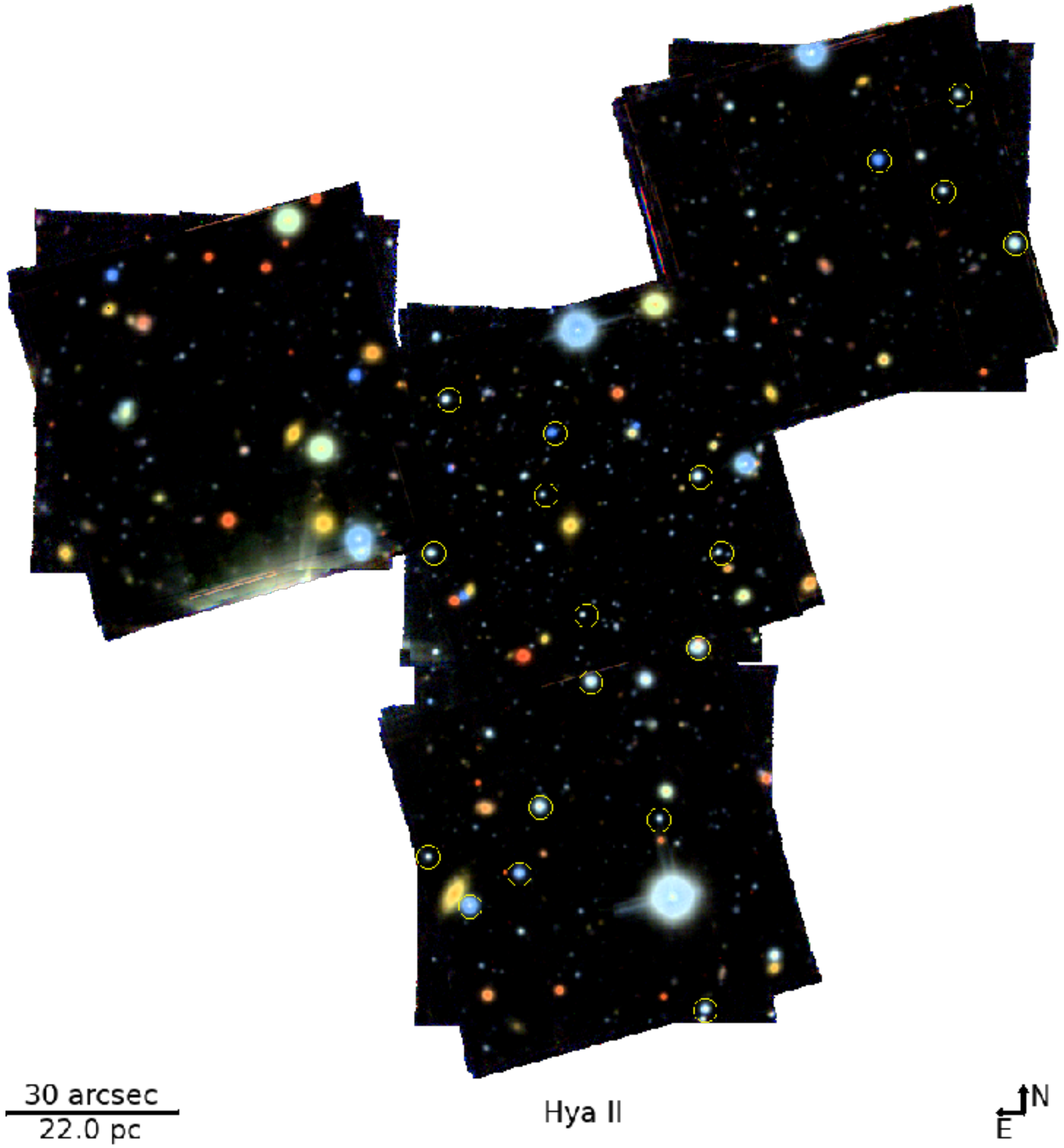
multi unit spectroscopic explorer

The MUSE-Faint Survey









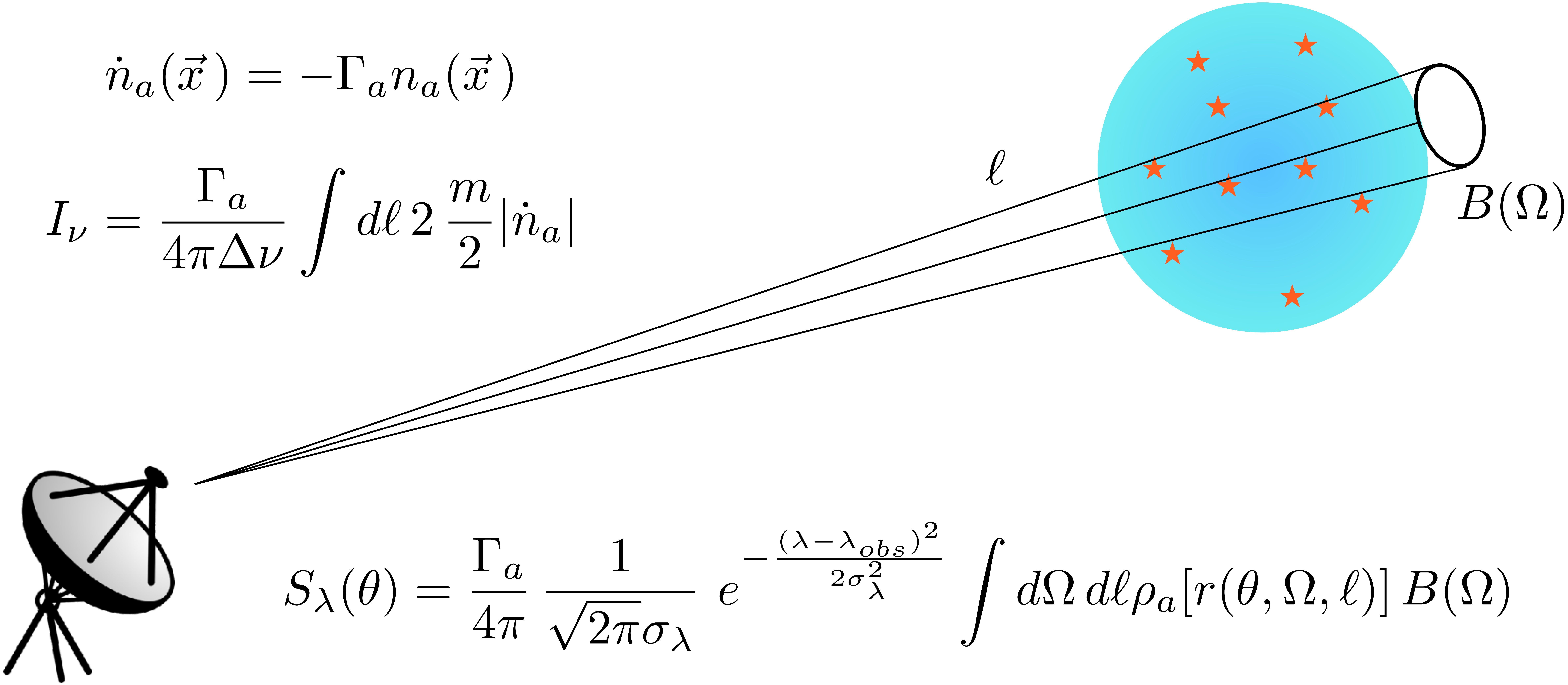
+ Sculptor

Zoutendijk+, The MUSE-Faint survey. III, 2112.09374

Flux density from ALP decay

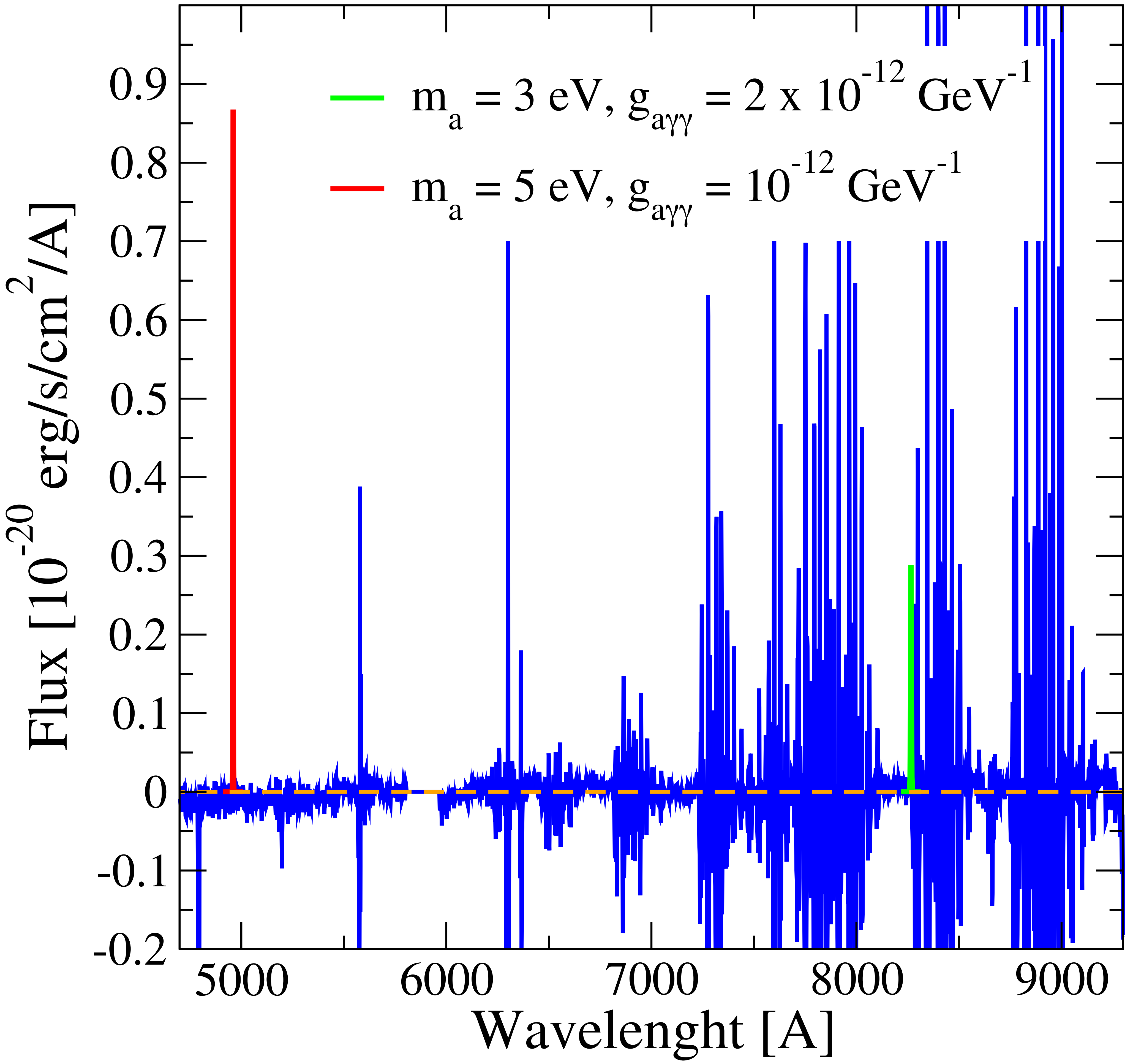
$$\dot{n}_a(\vec{x}\,) = -\Gamma_a n_a(\vec{x}\,)$$

$$I_\nu = \frac{\Gamma_a}{4\pi\Delta\nu}\int d\ell\, 2\,\frac{m}{2}|\dot{n}_a|$$



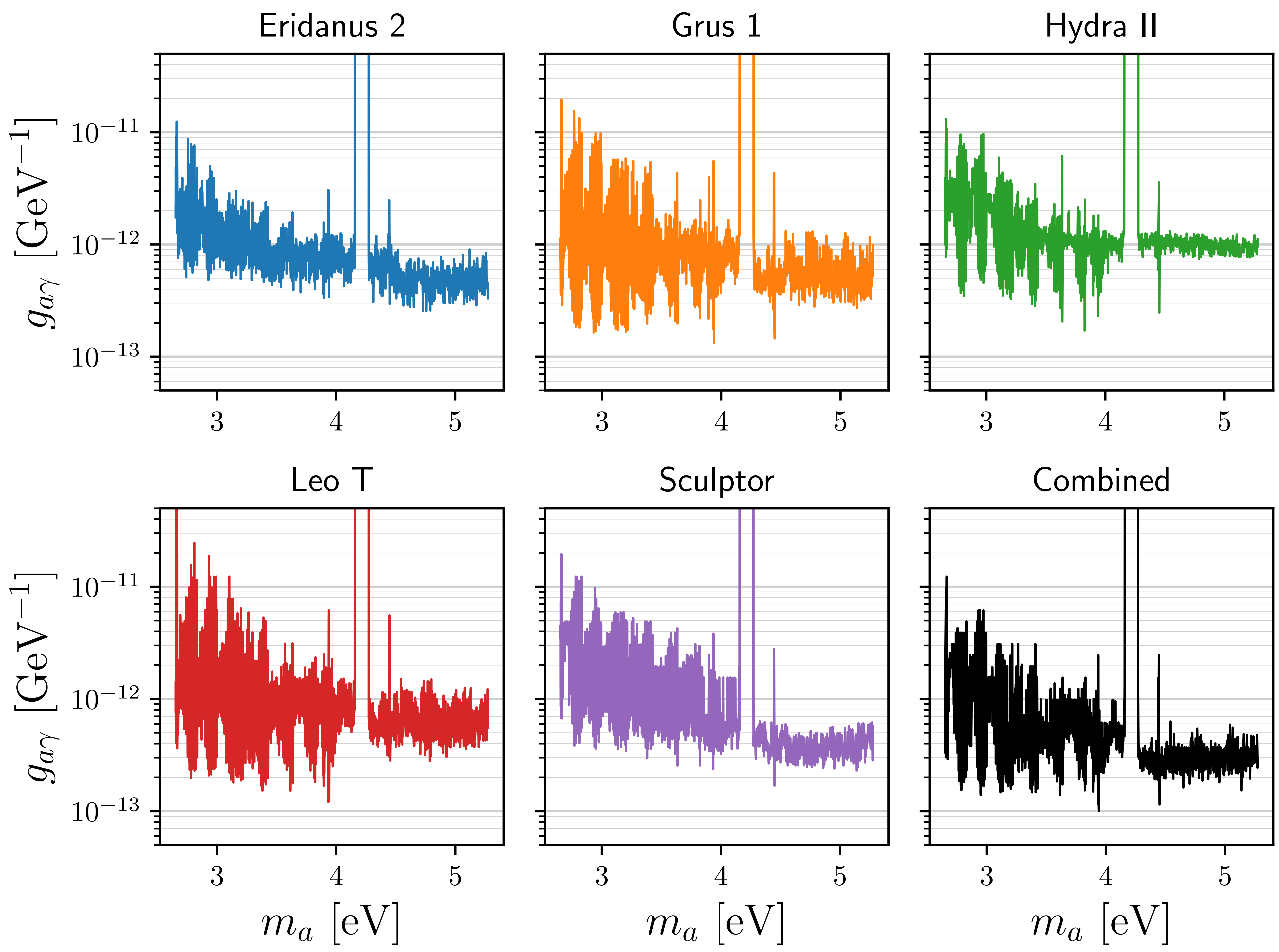
$$S_\lambda(\theta) = \frac{\Gamma_a}{4\pi}\frac{1}{\sqrt{2\pi}\sigma_\lambda}\, e^{-\frac{(\lambda-\lambda_{obs})^2}{2\sigma_\lambda^2}}\int d\Omega\, d\ell \rho_a[r(\theta,\Omega,\ell)]\, B(\Omega)$$

Signal

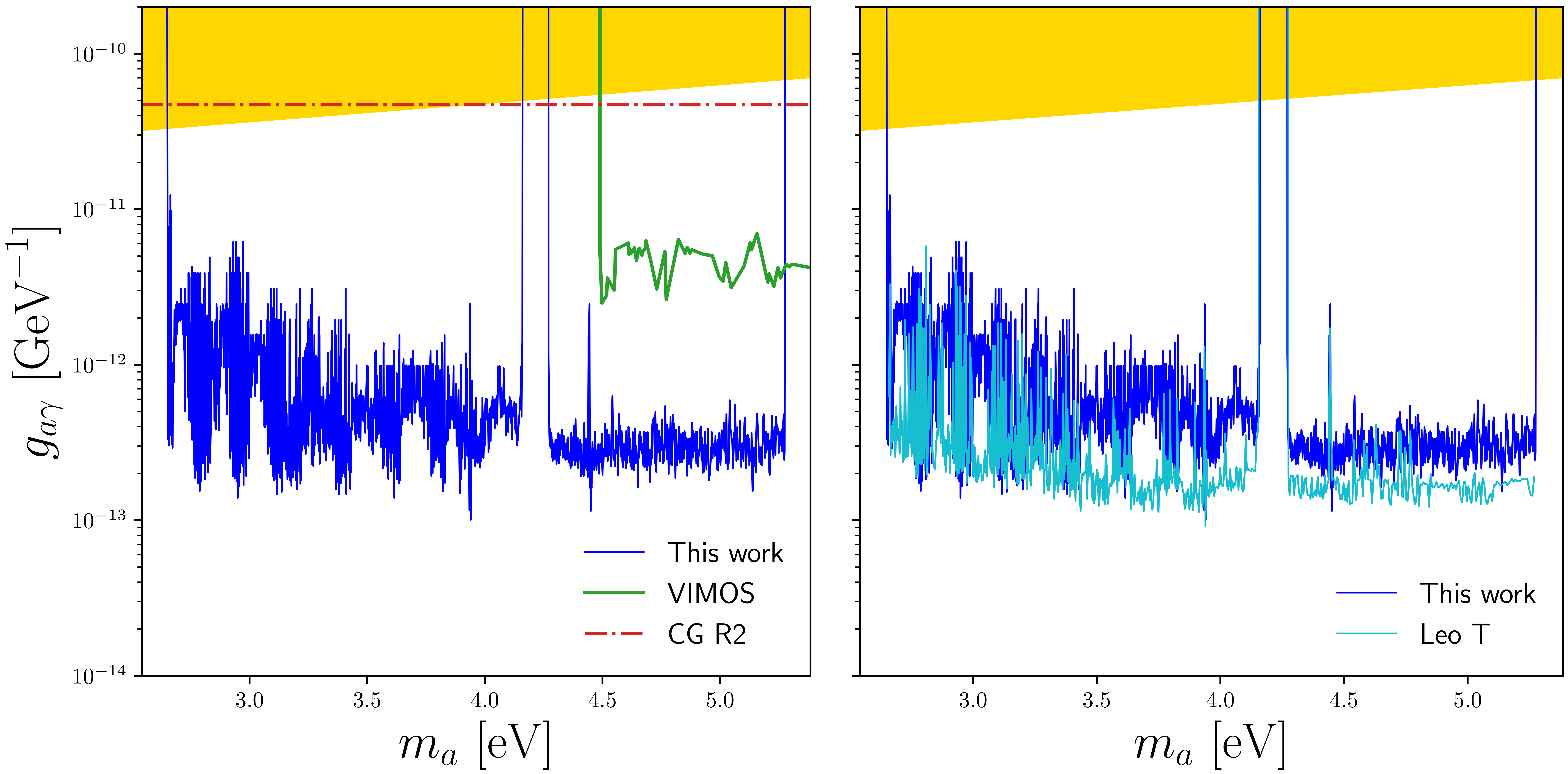


m_a = 3 eV, $g_{a\gamma\gamma}$ = 2 x 10^{-12} GeV^{-1}
m_a = 5 eV, $g_{a\gamma\gamma}$ = 10^{-12} GeV^{-1}
Flux [10^{-20} erg/s/cm^2/A]
Wavelenght [A]
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
5000
6000
7000
8000
9000

NFW profile



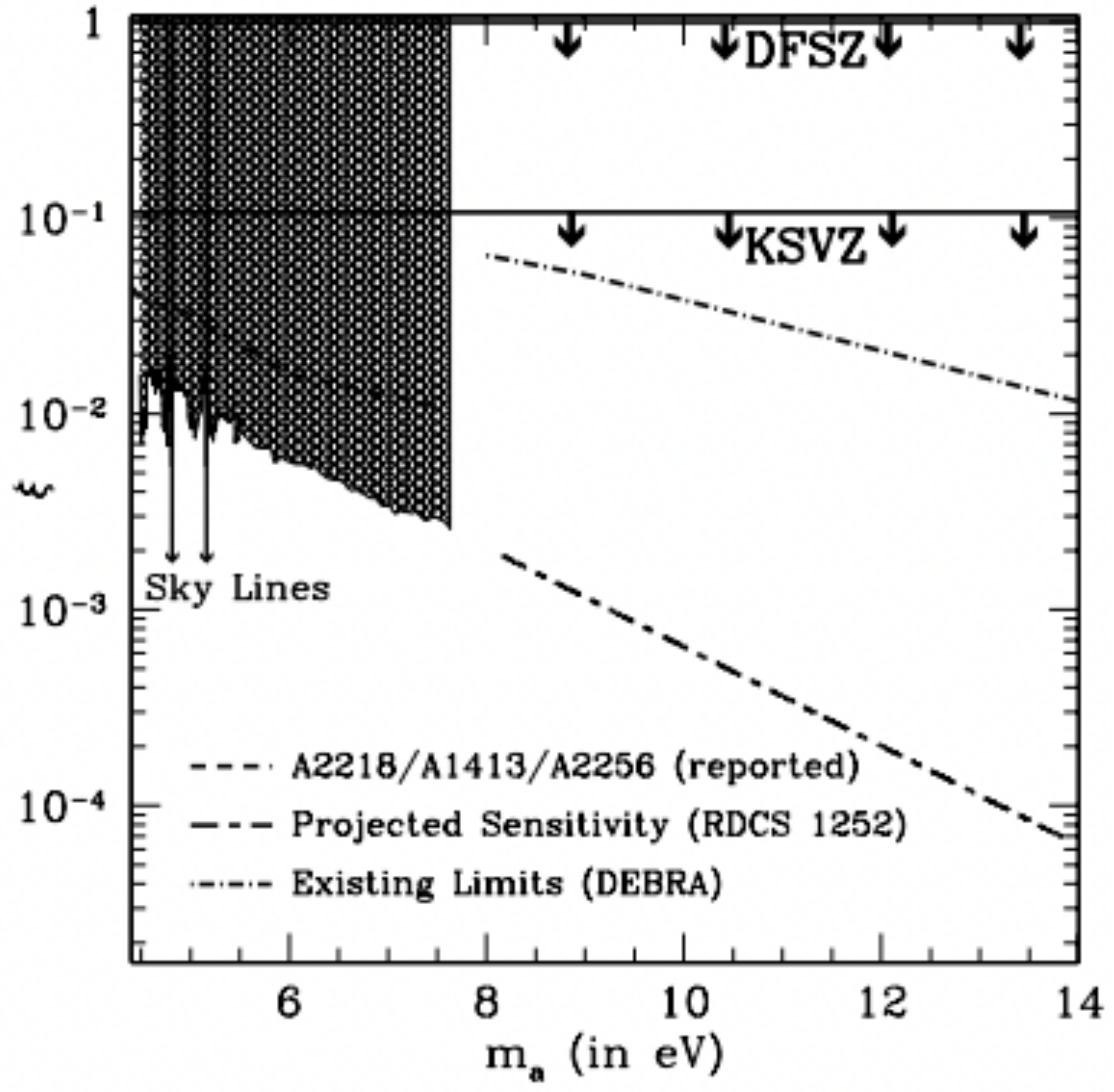
Eridanus 2
Grus 1
Hydra II
Leo T
Sculptor
Combined
$g_{a\gamma}$ [GeV^{-1}]
10^{-11}
10^{-12}
10^{-13}
3
4
5
m_a [eV]



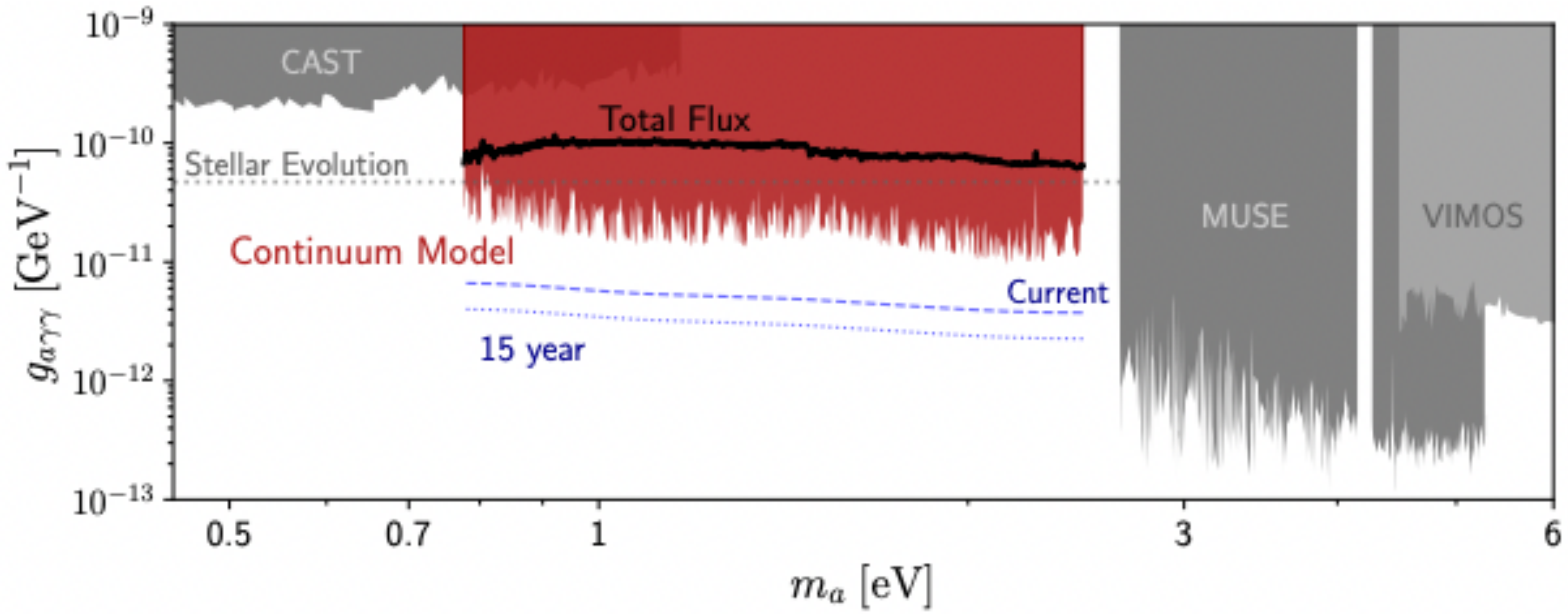
Regis+, Phys.Lett.B 814 (2021)

Similar Work

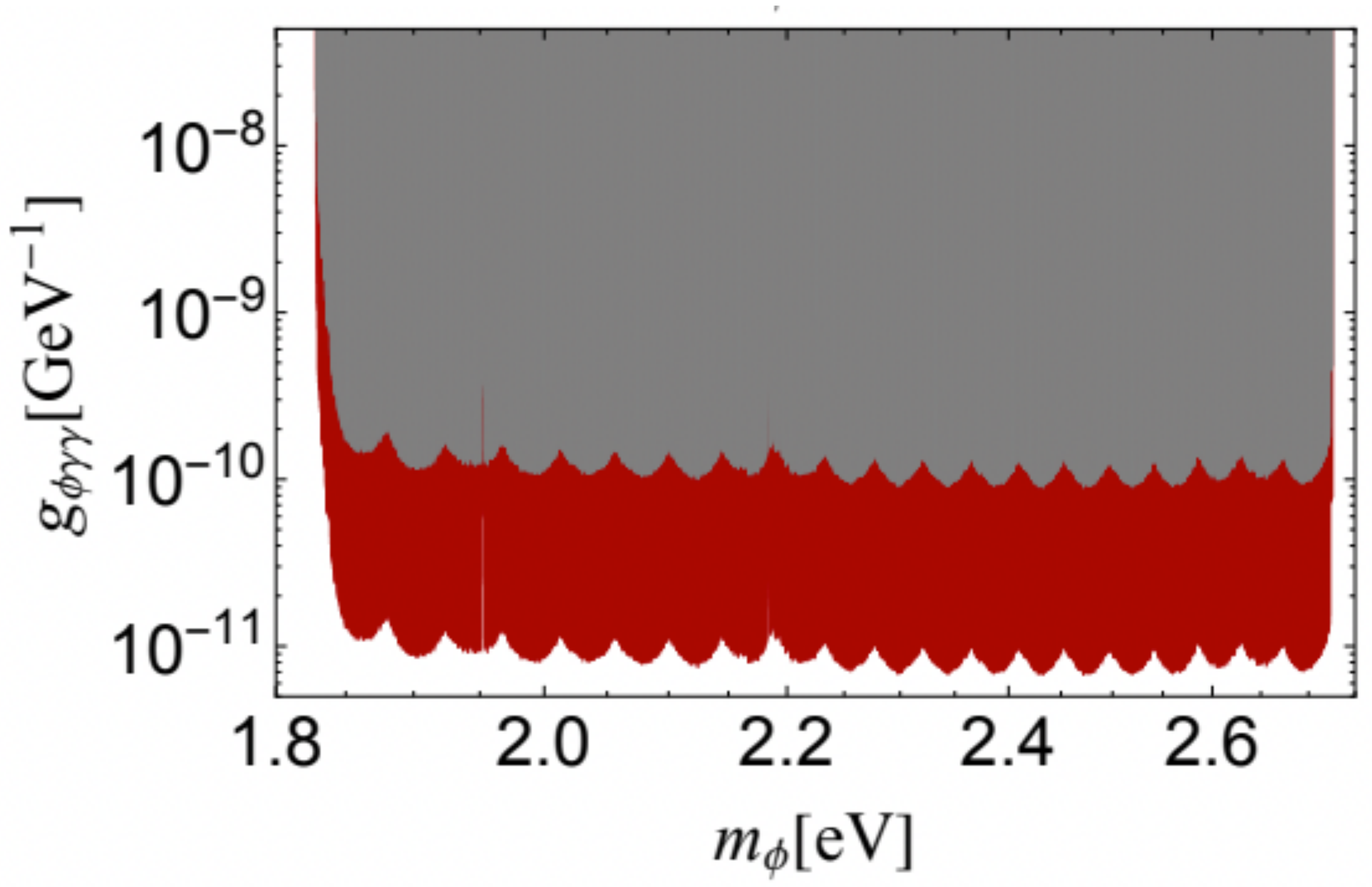
Grin+, PRD 75 (2007), VIMOS, galaxy clusters



Janish+, 2310.15395, JWST, blank sky



Yin+, 2402.07976, WINERED, dwarf galaxies



See also Roy+, 2311.04987 for forecasts with JWST

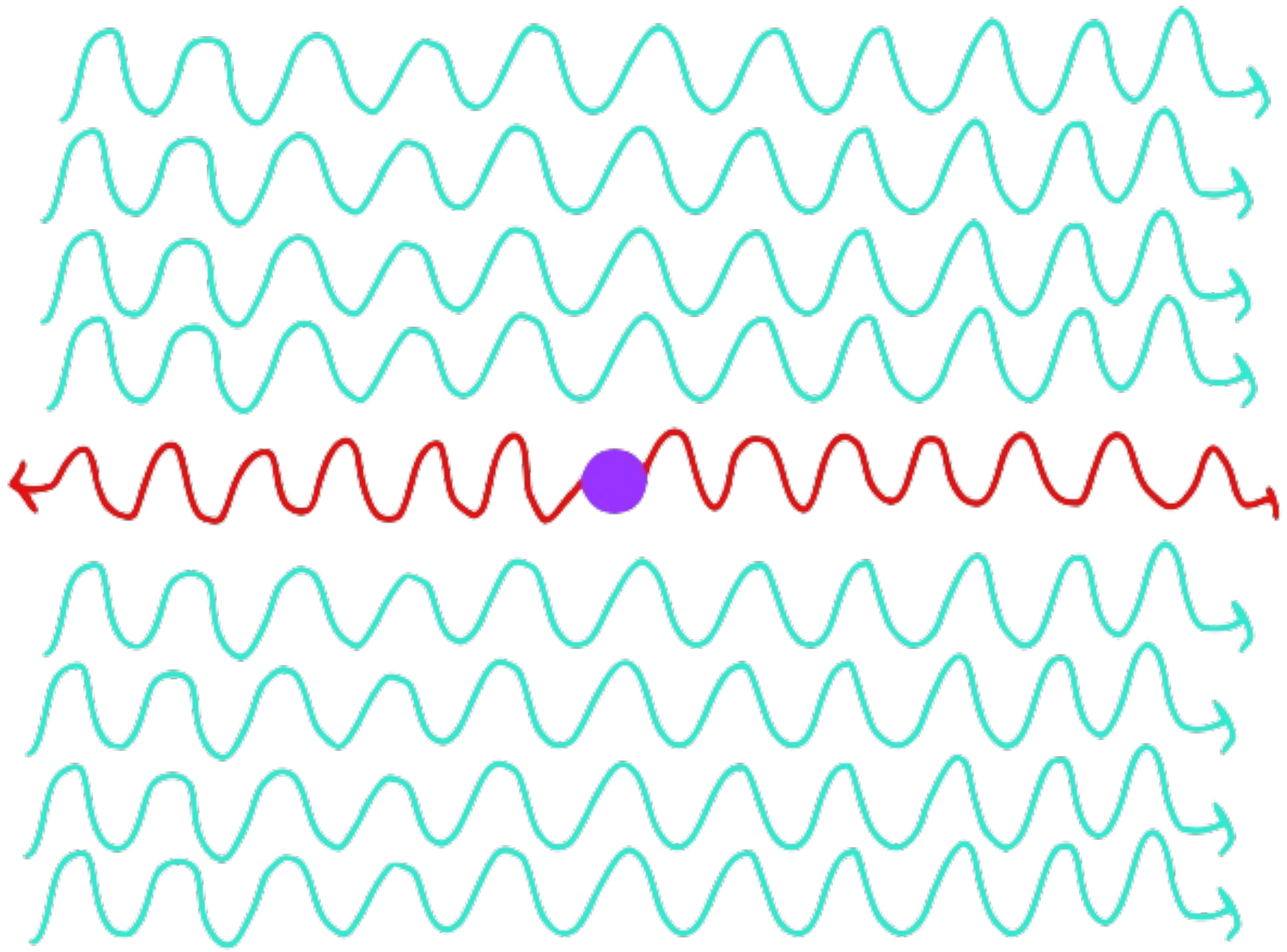
Axion stimulated decay

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 $\vec{k}$ the decay rate is enhanced by a factor

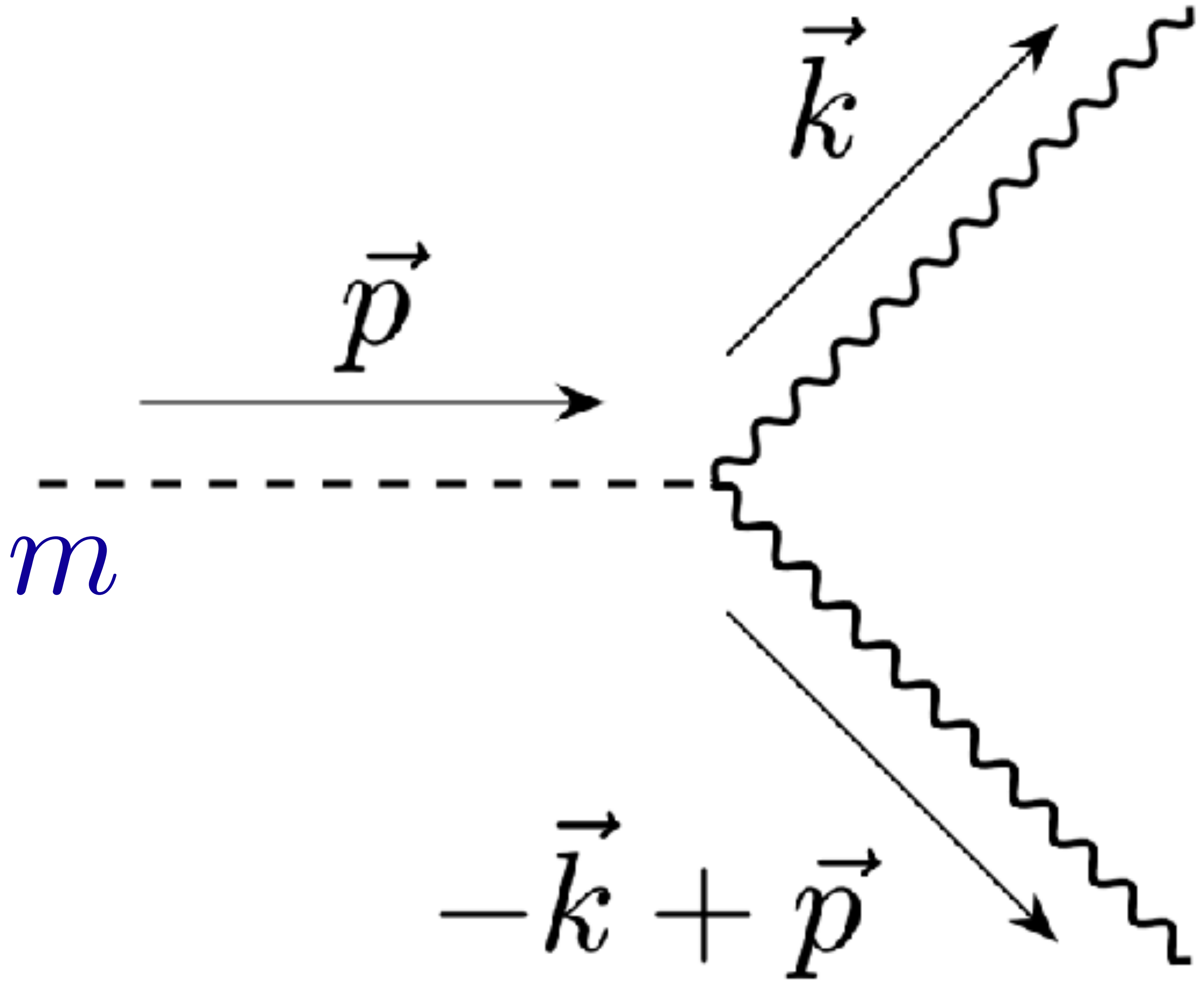
$$f_\gamma(\vec{k})$$



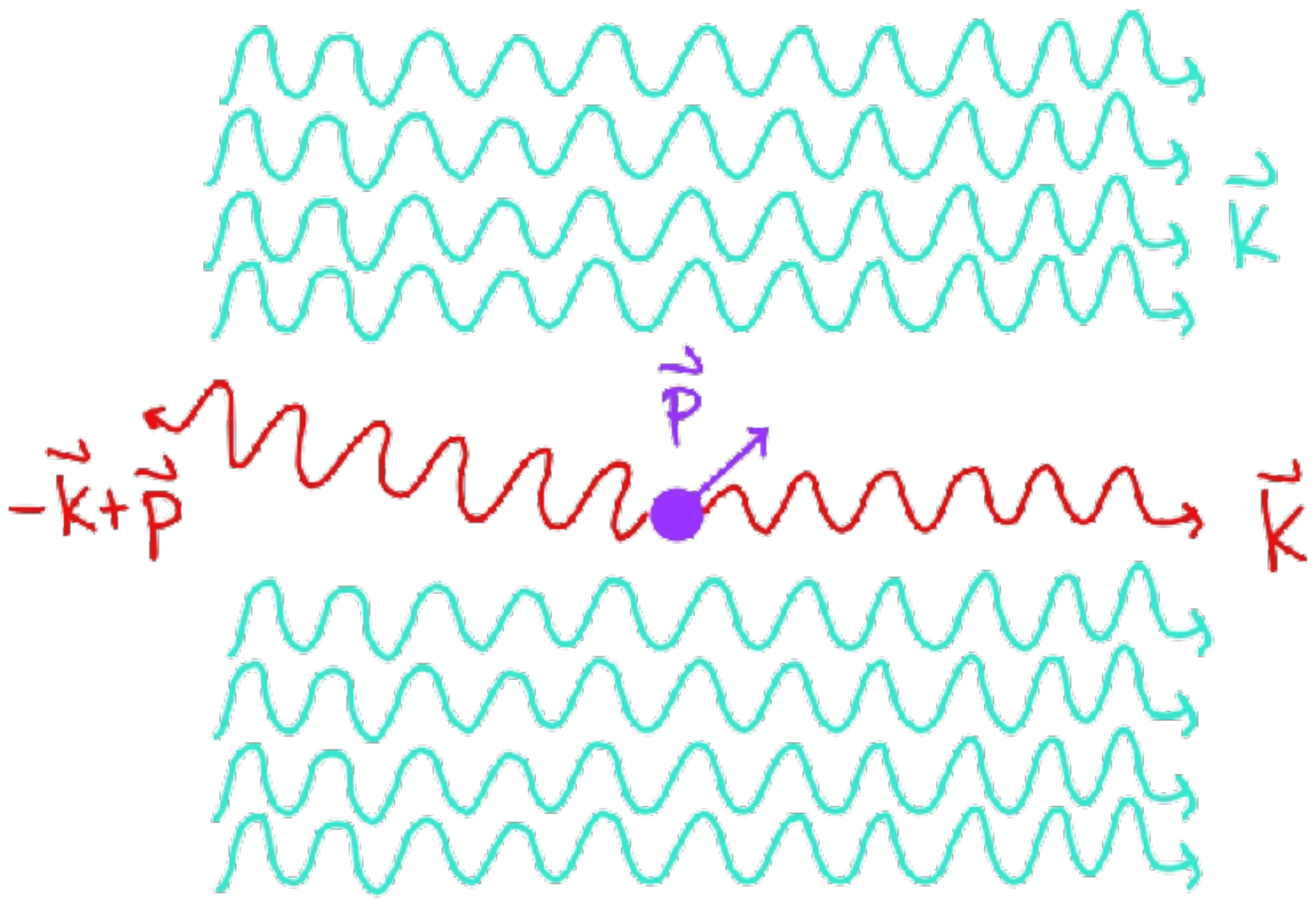
$$|\vec{k}| \sim \frac{m}{2}$$

Kinematics

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



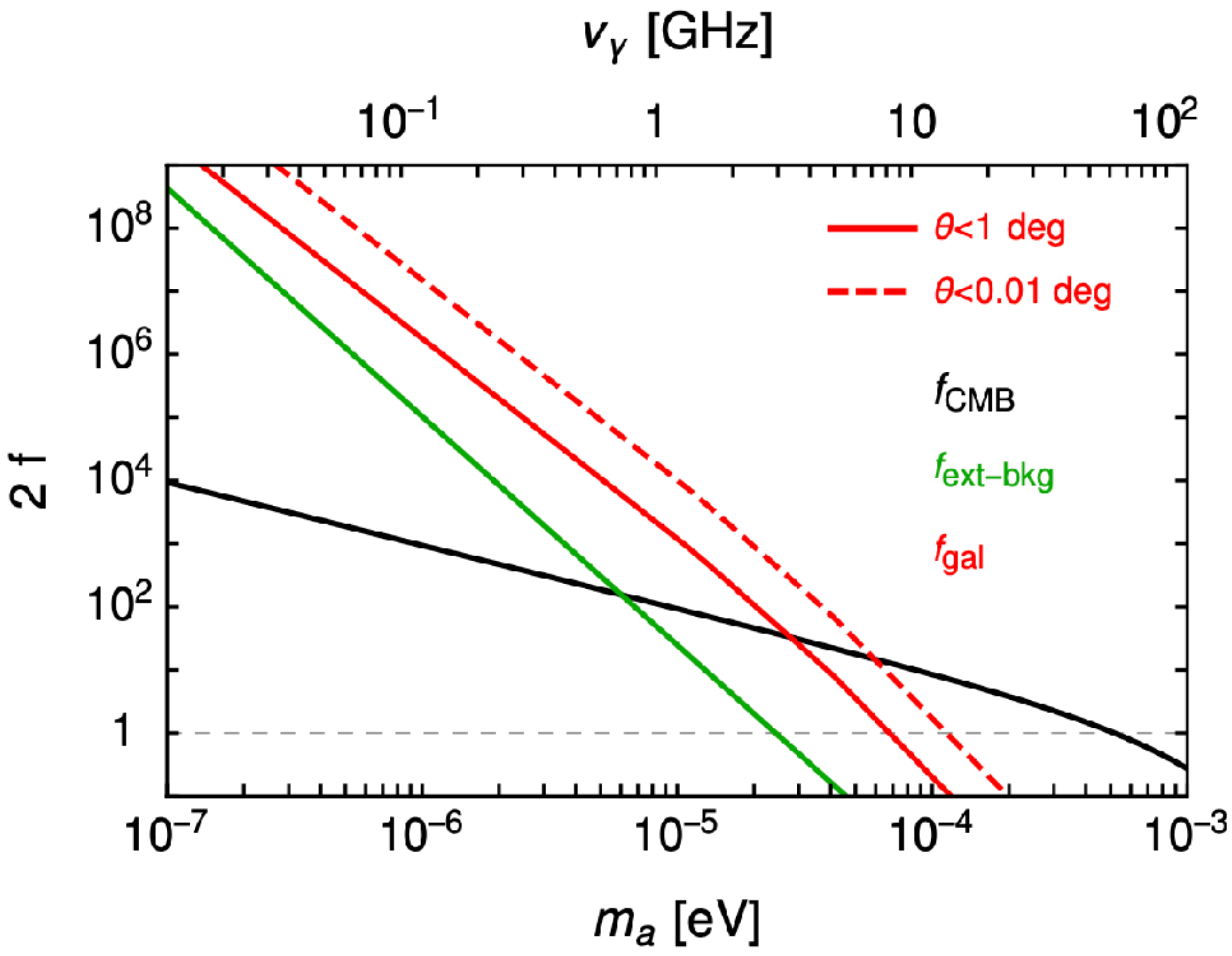
$$\omega_2 = \frac{m - p_{\parallel}}{2}$$



The echo propagates

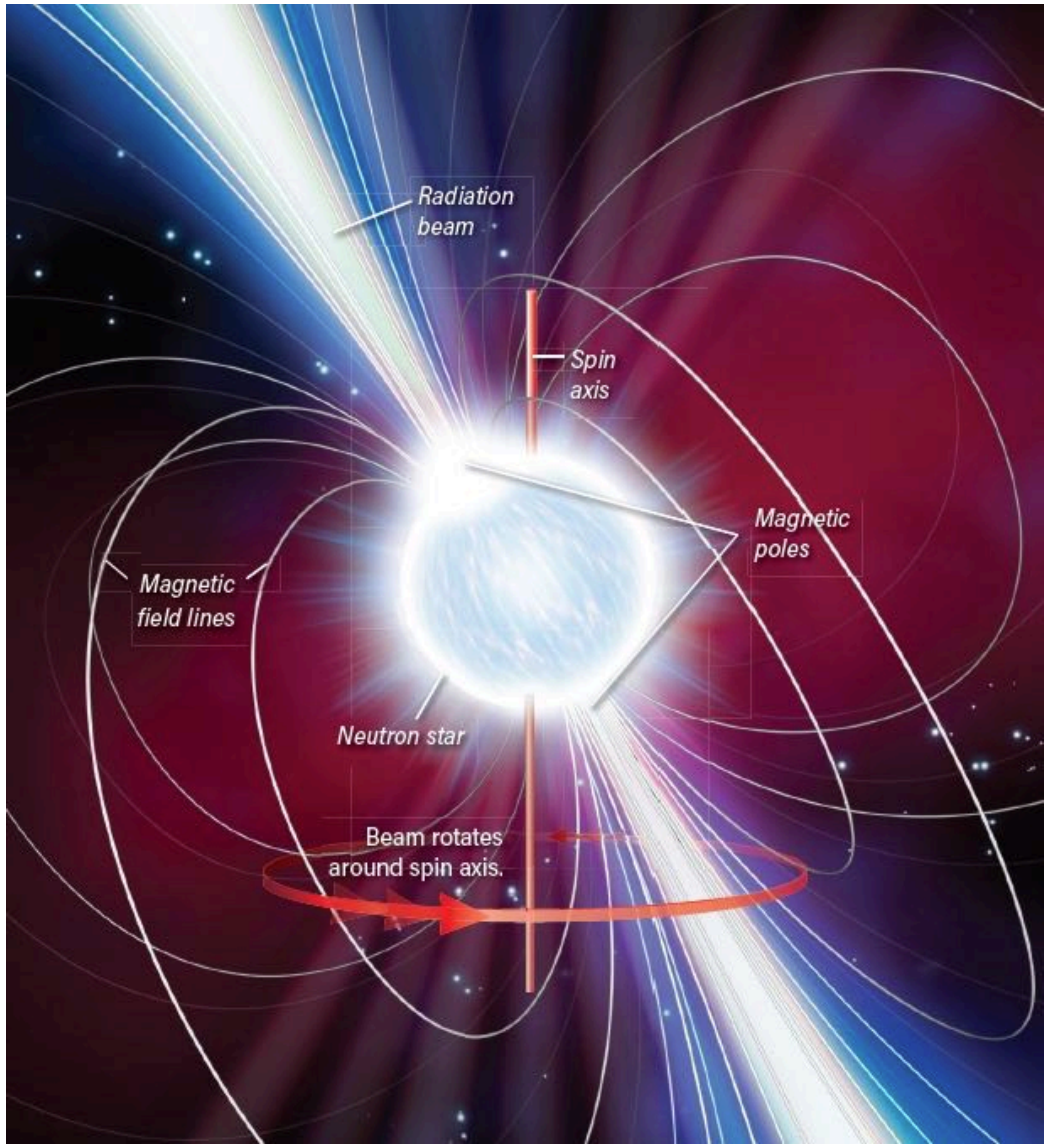
***almost* backwards!**

Enhancement factor



Caputo+, JCAP 03 (2019) 027

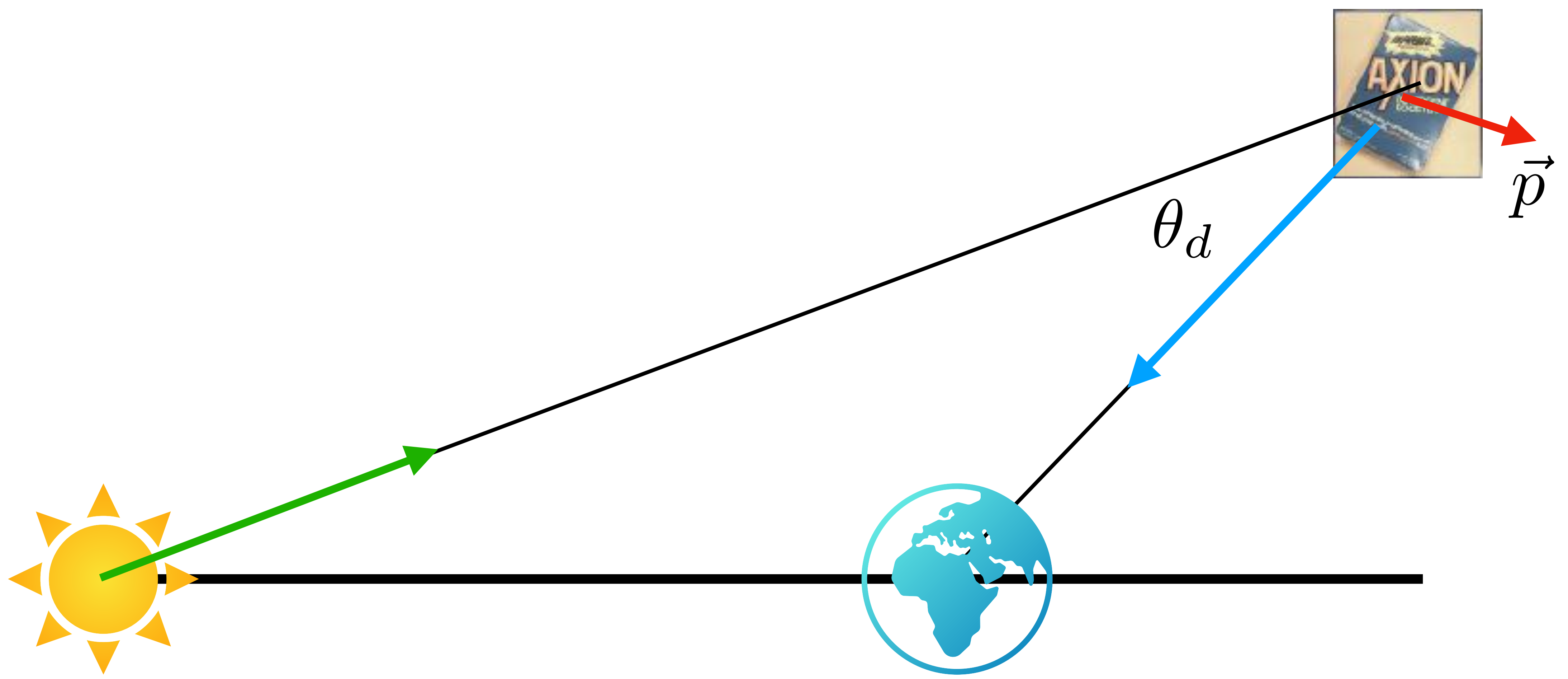
Detailed Study of the Echo from a Point Source



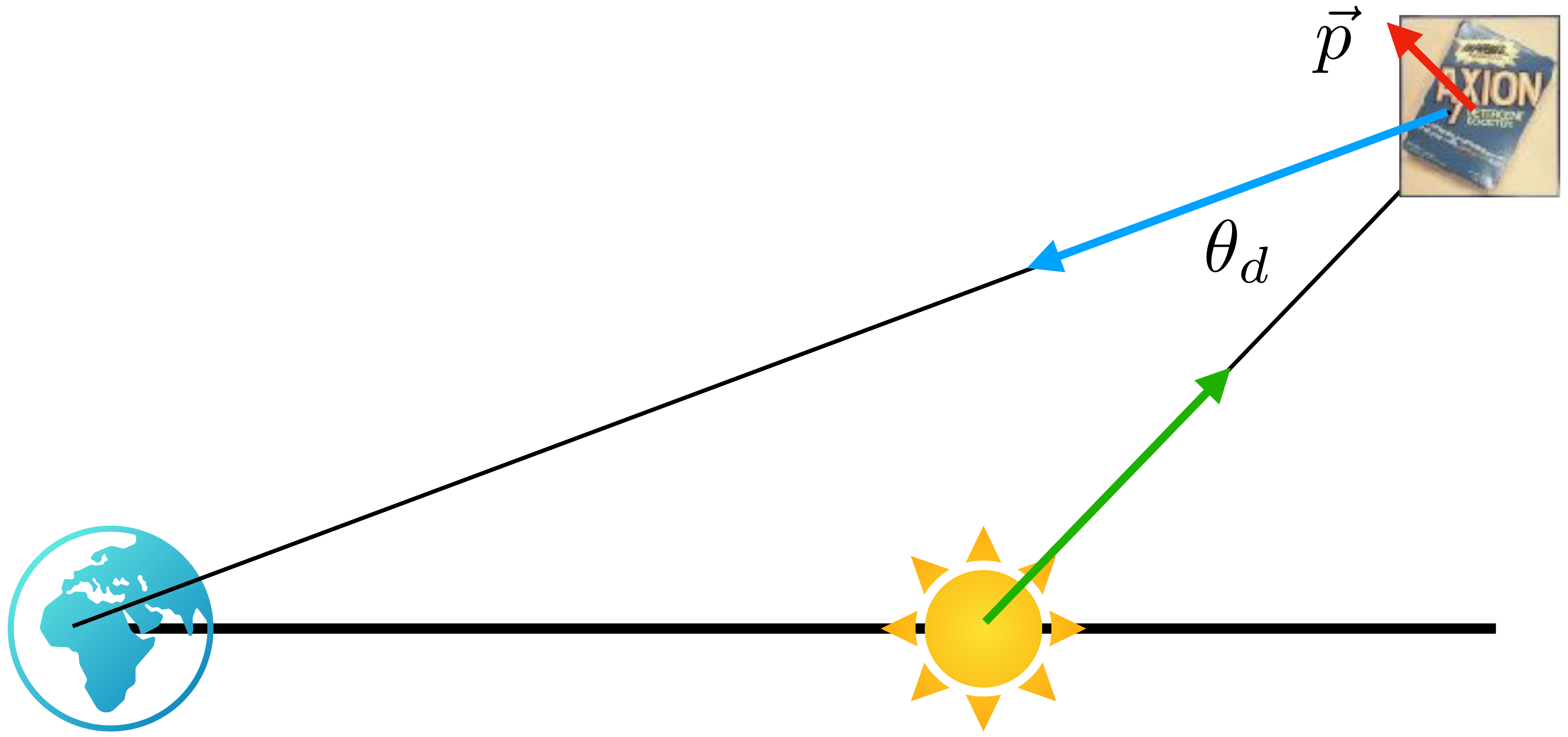
E.T., F. Calore, M. Regis, 2311.00051

Echoes from natural sources

Back-light echo



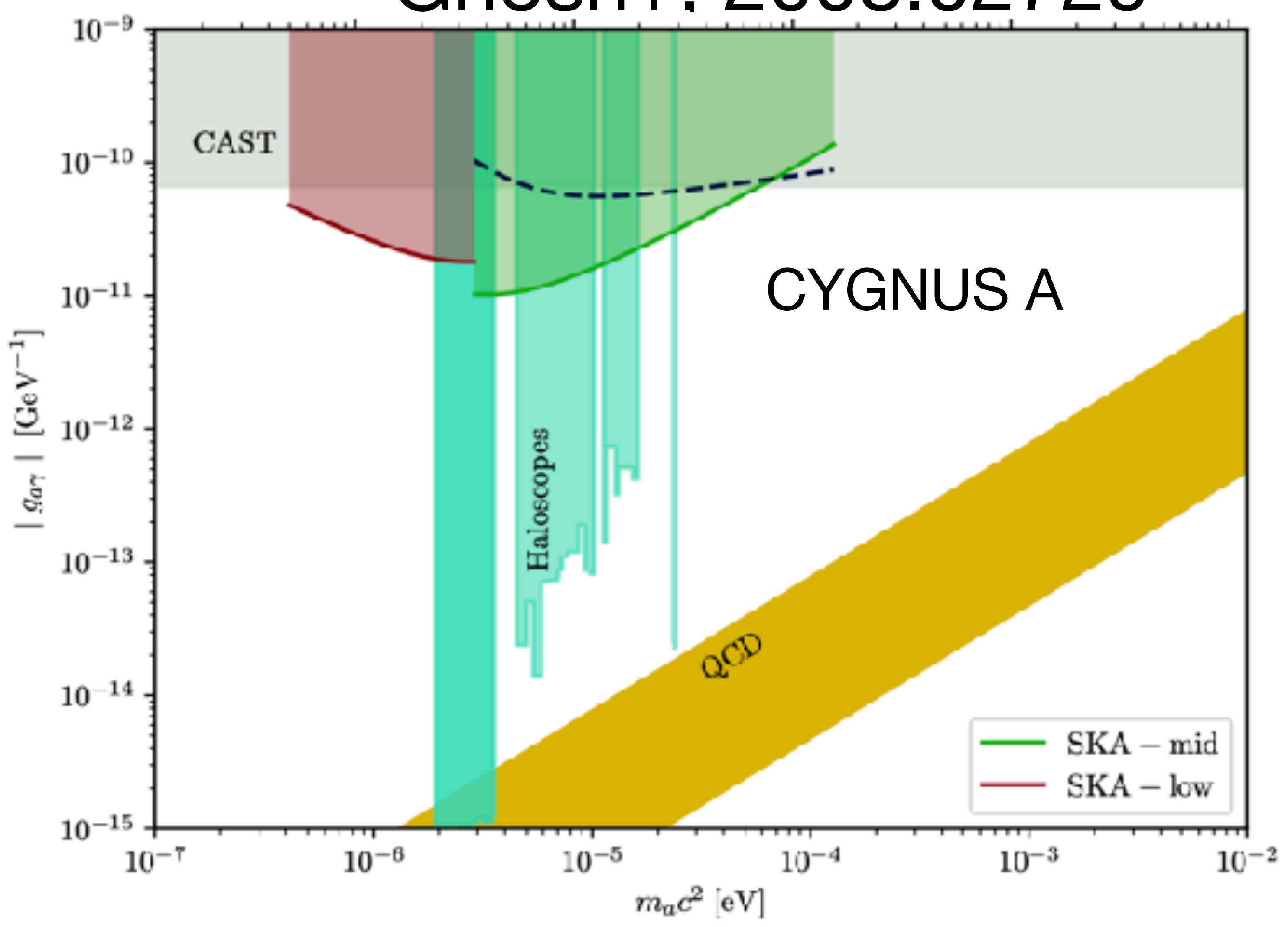
Front-light echo



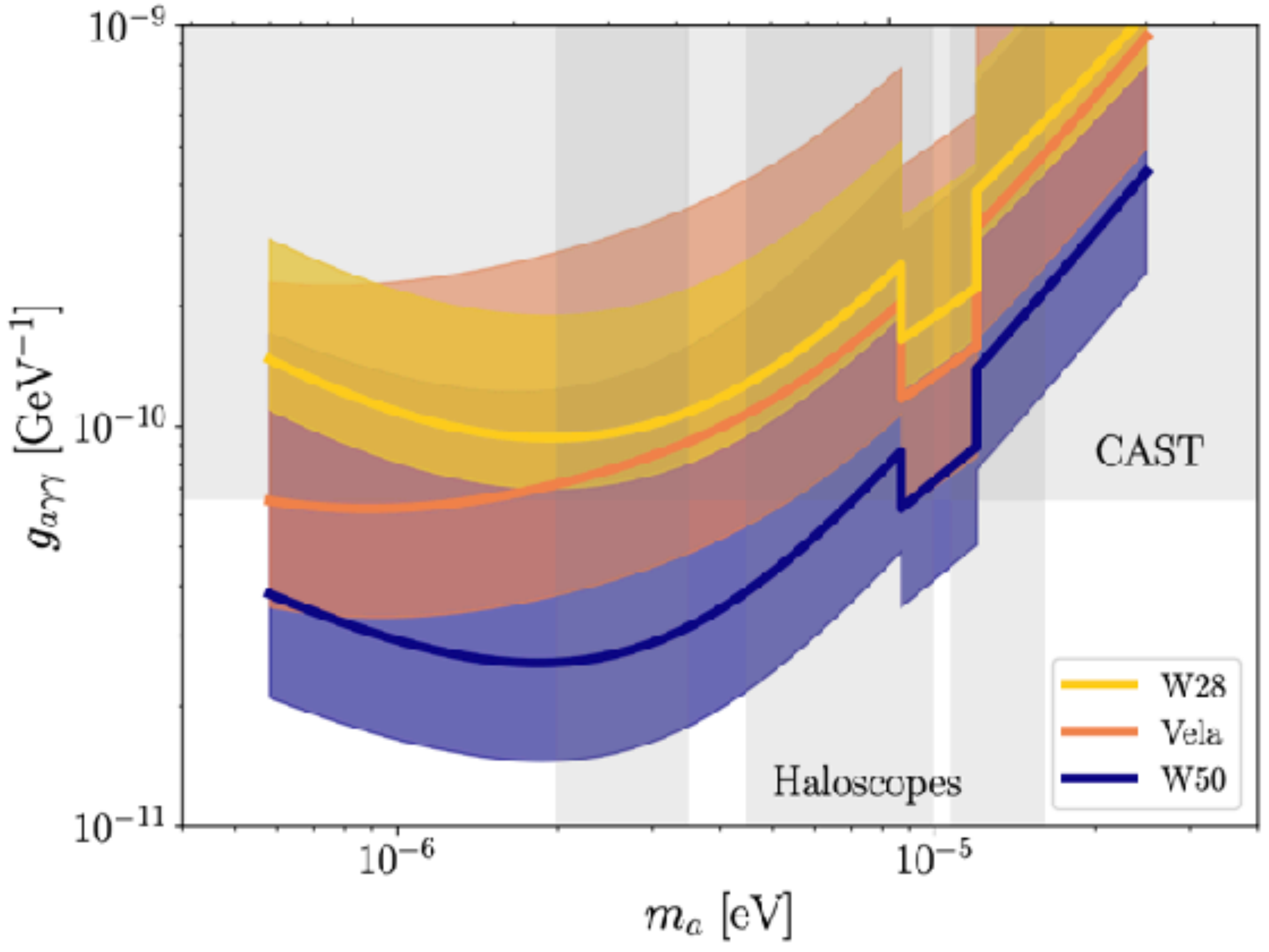
Collinear emission

Back-light echo

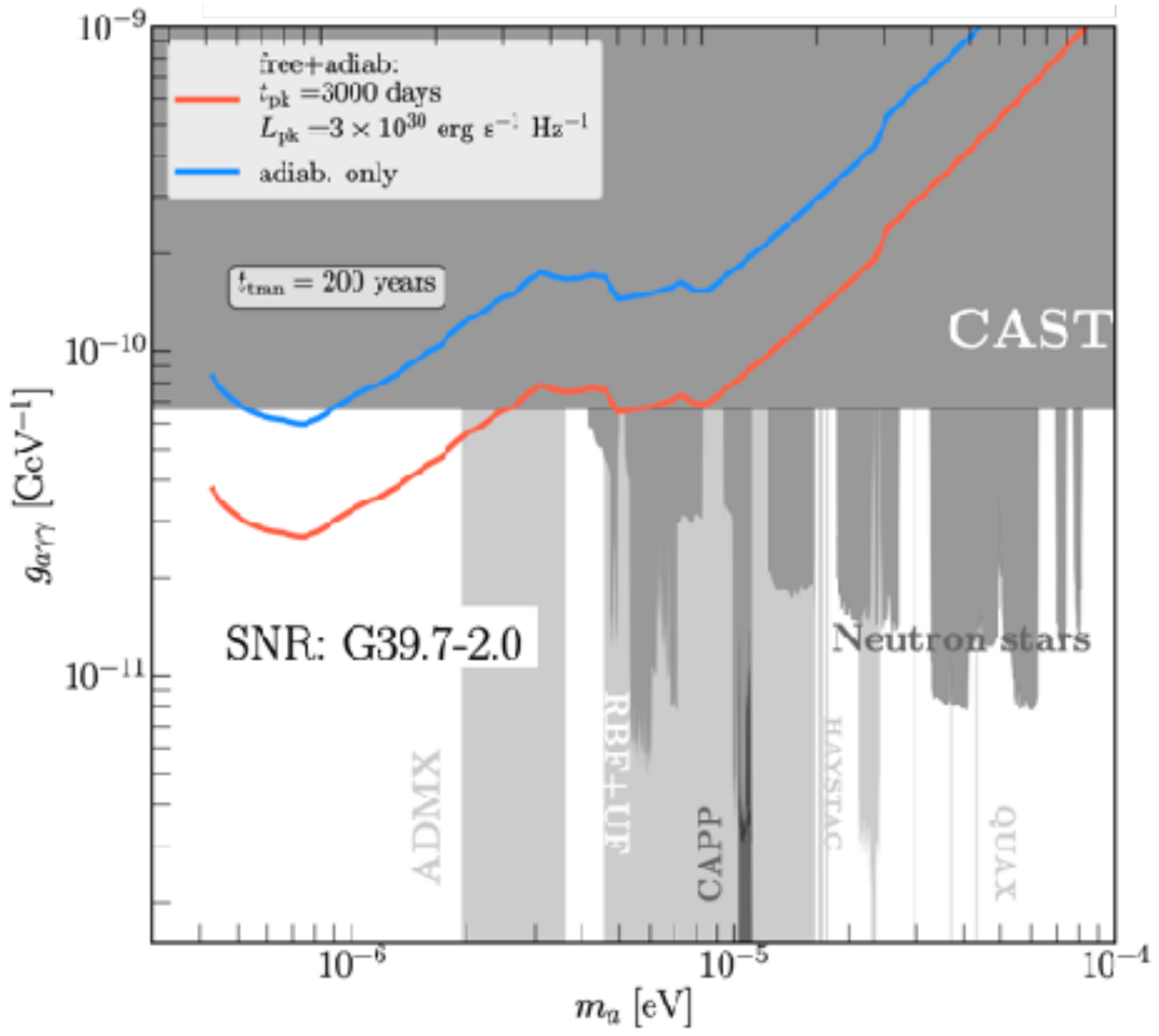
Ghosh+, 2008.02729



Sun+, PRD 105 (2022)

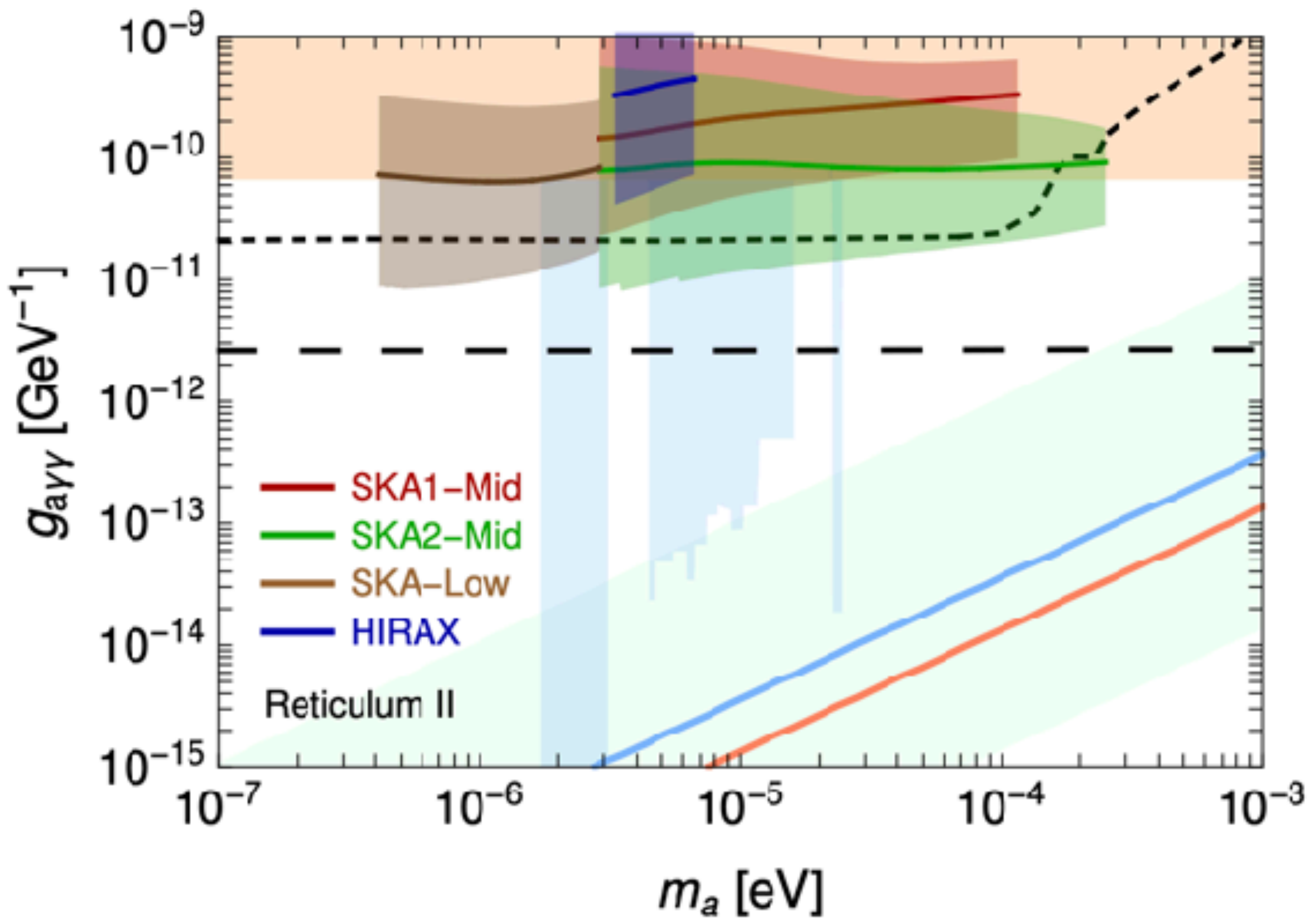


Buen-Abad+, PRD 105 (2022)



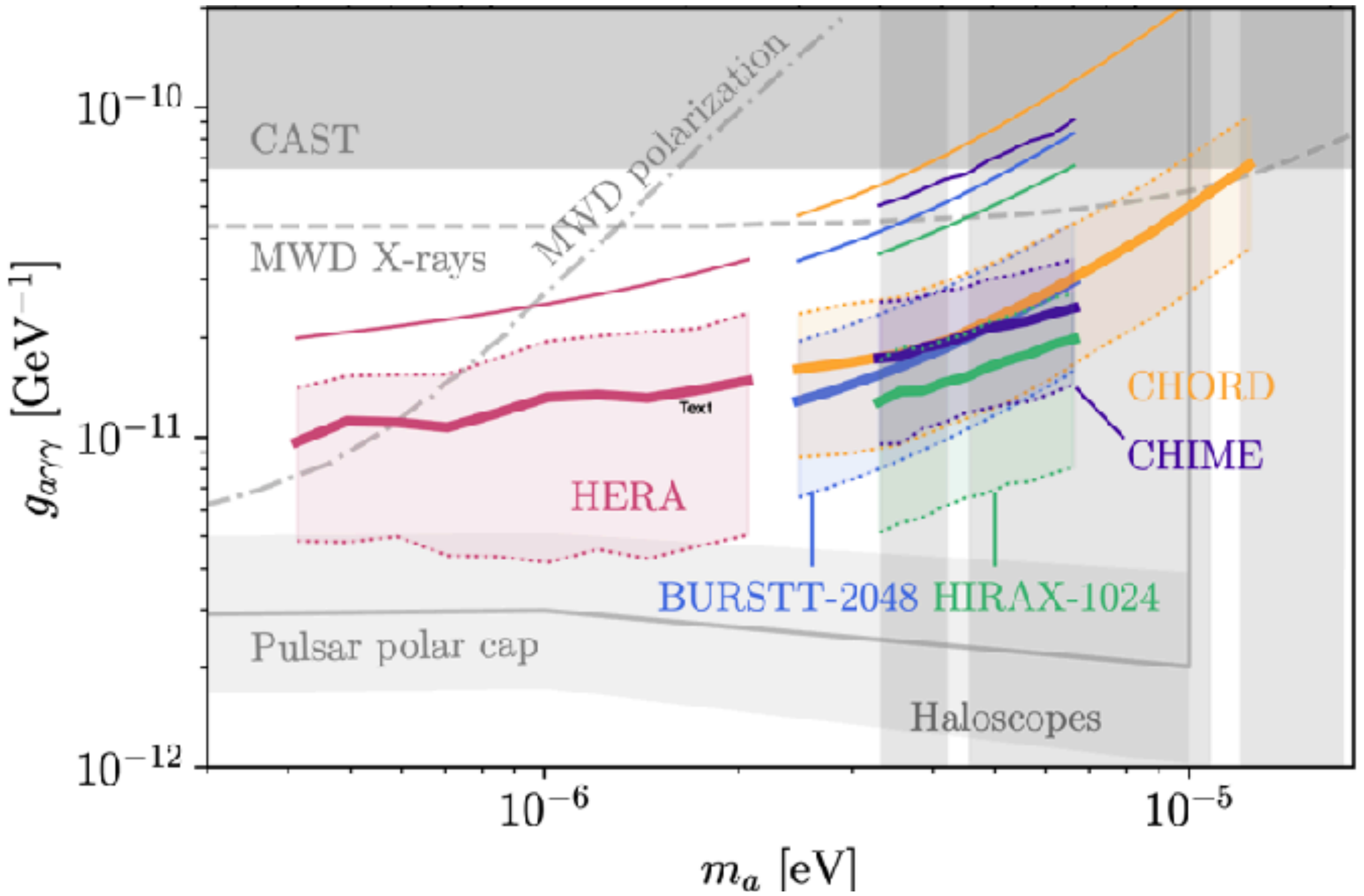
Collinear emission

Caputo+, JCAP 03 (2019) 027



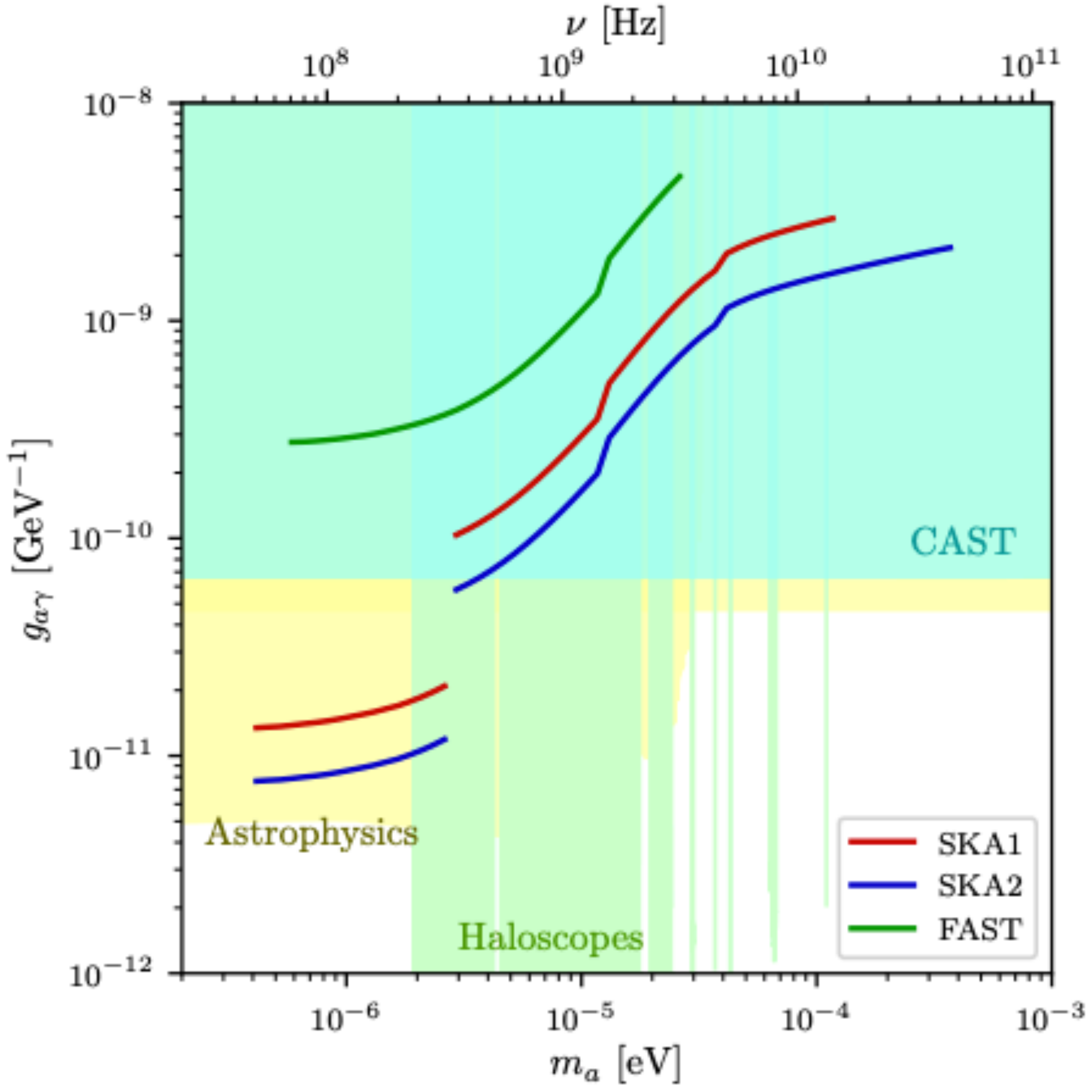
Everything

Sun+,
Phys.Rev.D 109 (2024),
all sky



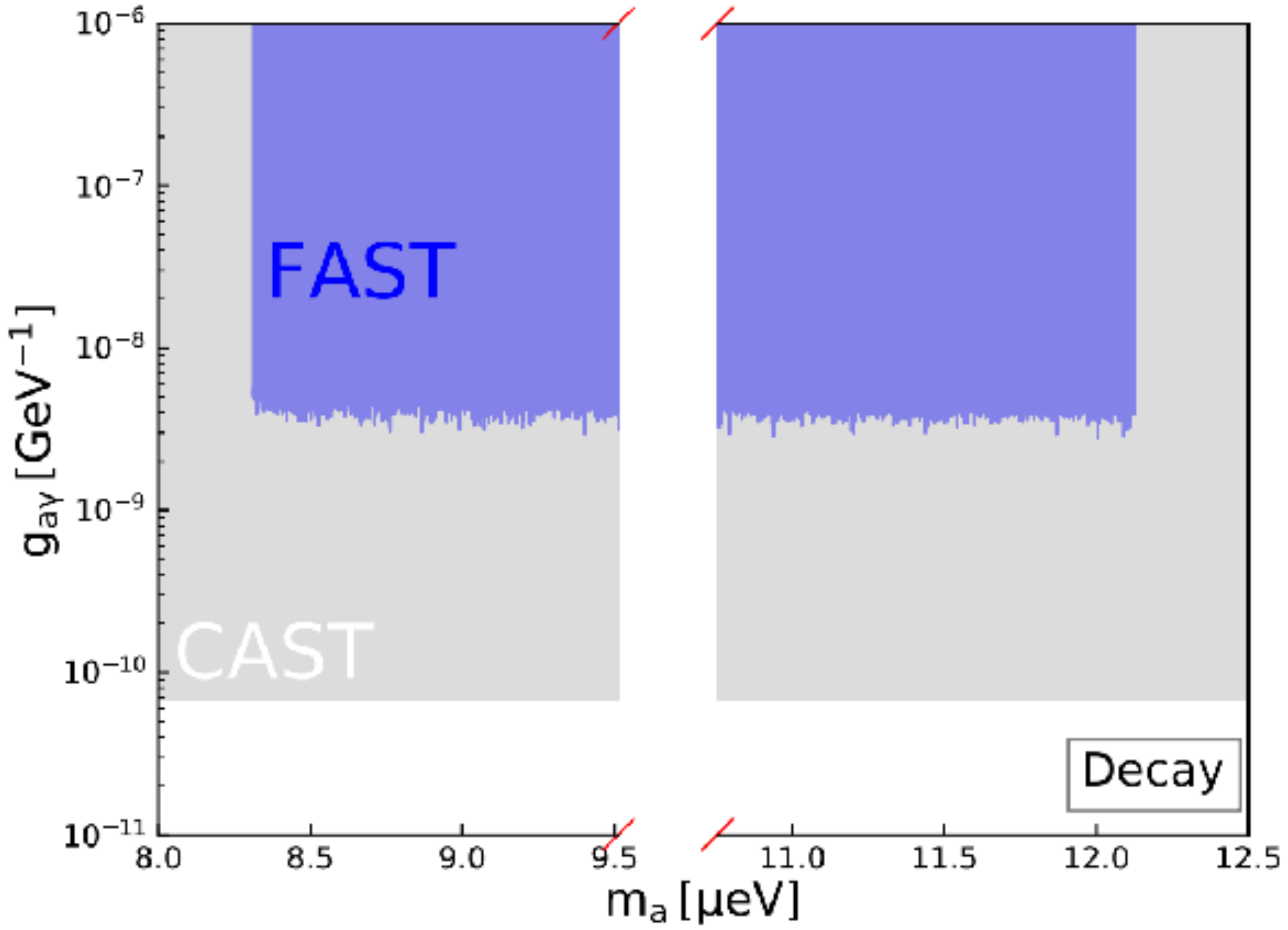
Back-light echo

Dev+,
JCAP 04 (2024) 045,
echo from galactic center



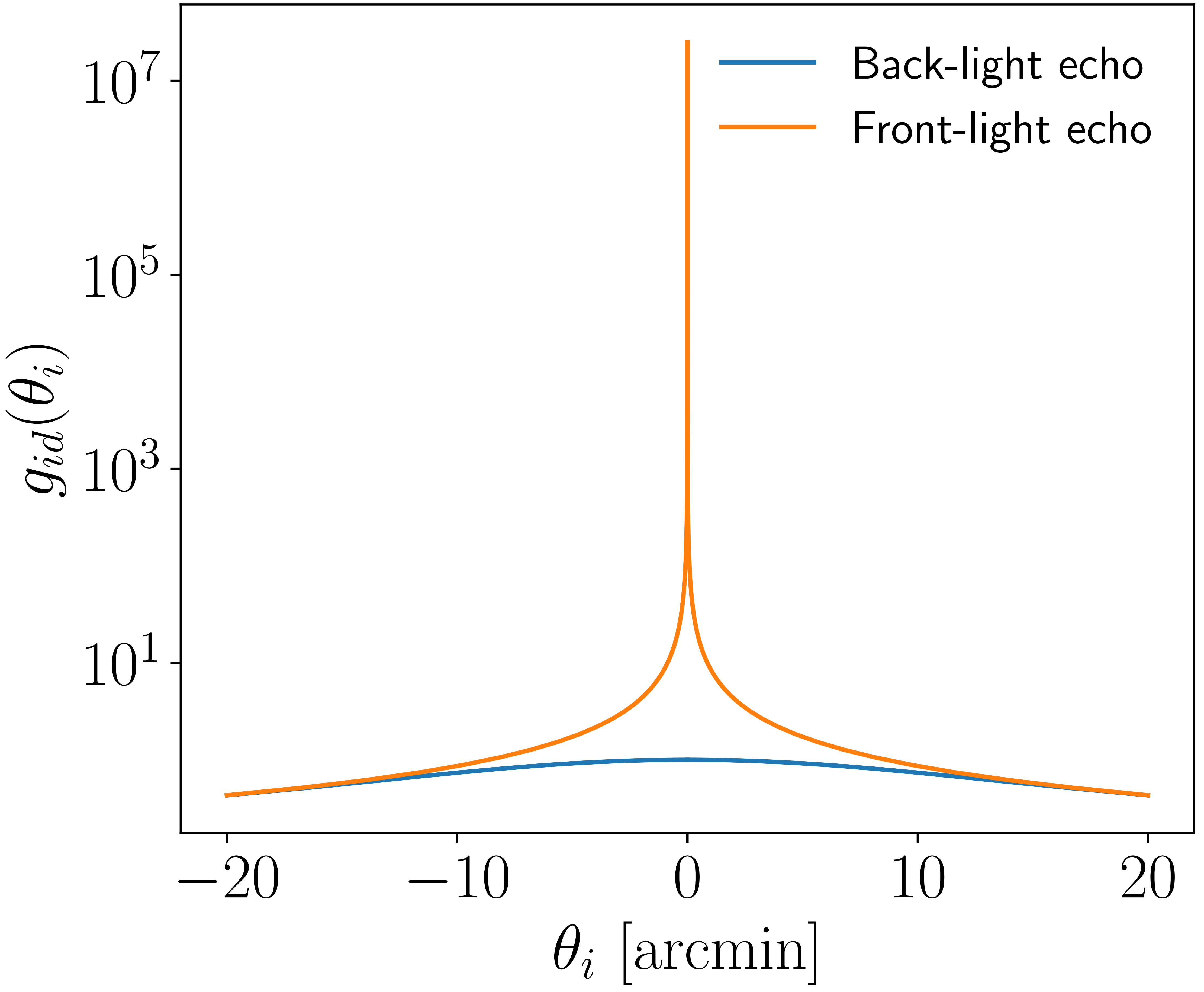
Collinear emission
Real data

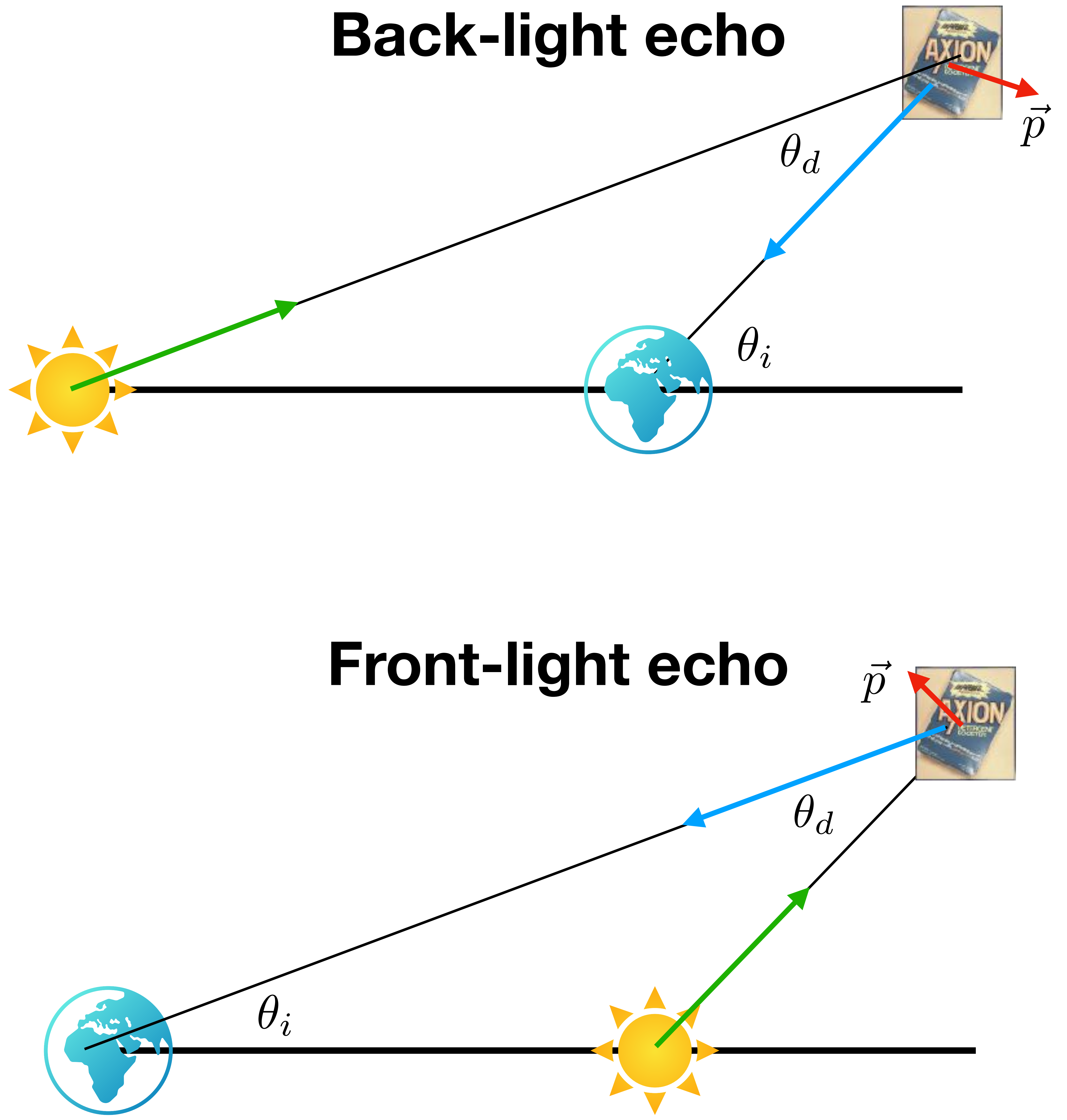
Guo+, 2404.04881



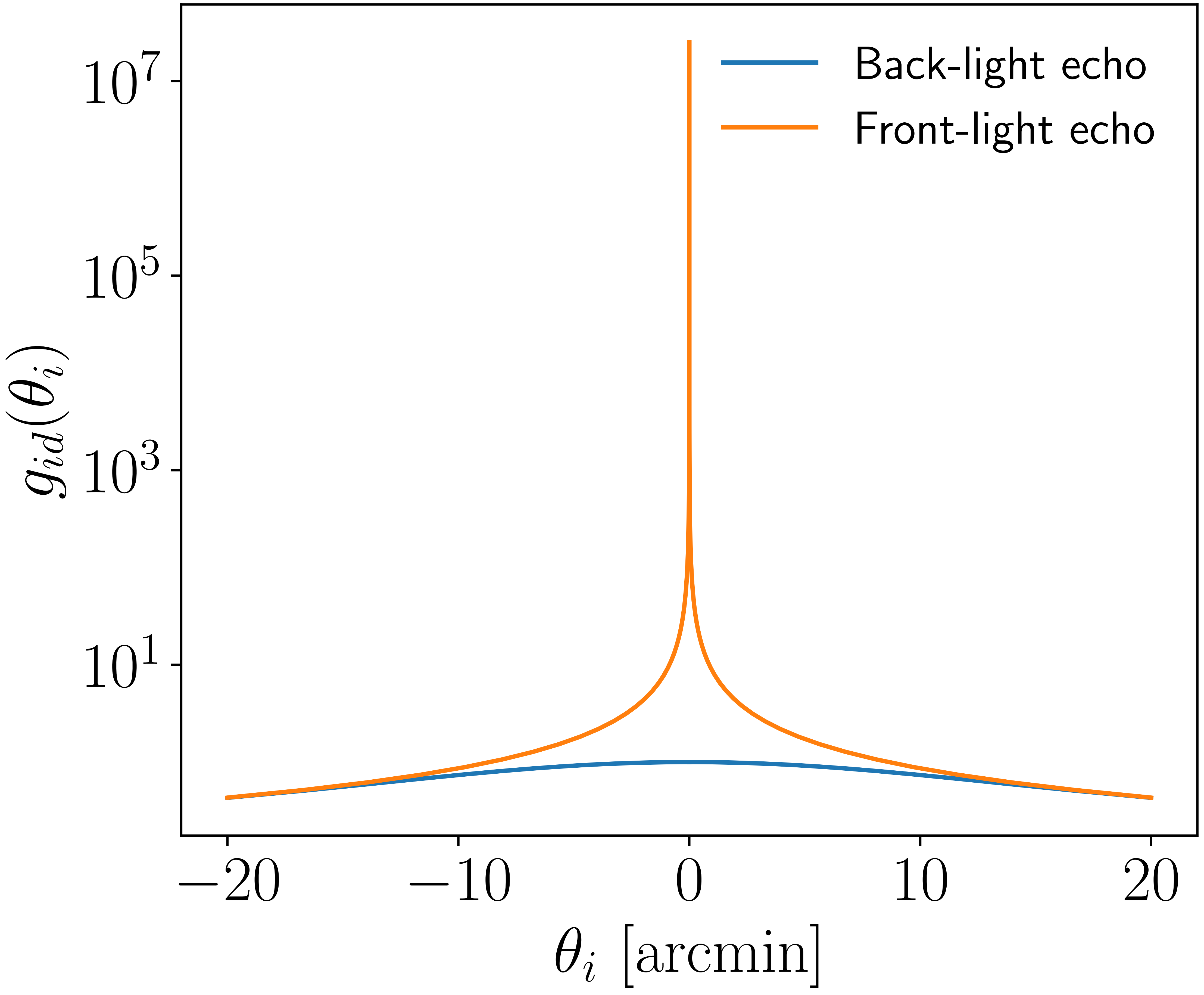
2-hour radio observation of
Coma Berenices dwarf galaxy with FAST

$$\theta_{i,0} \sim 2\delta v$$



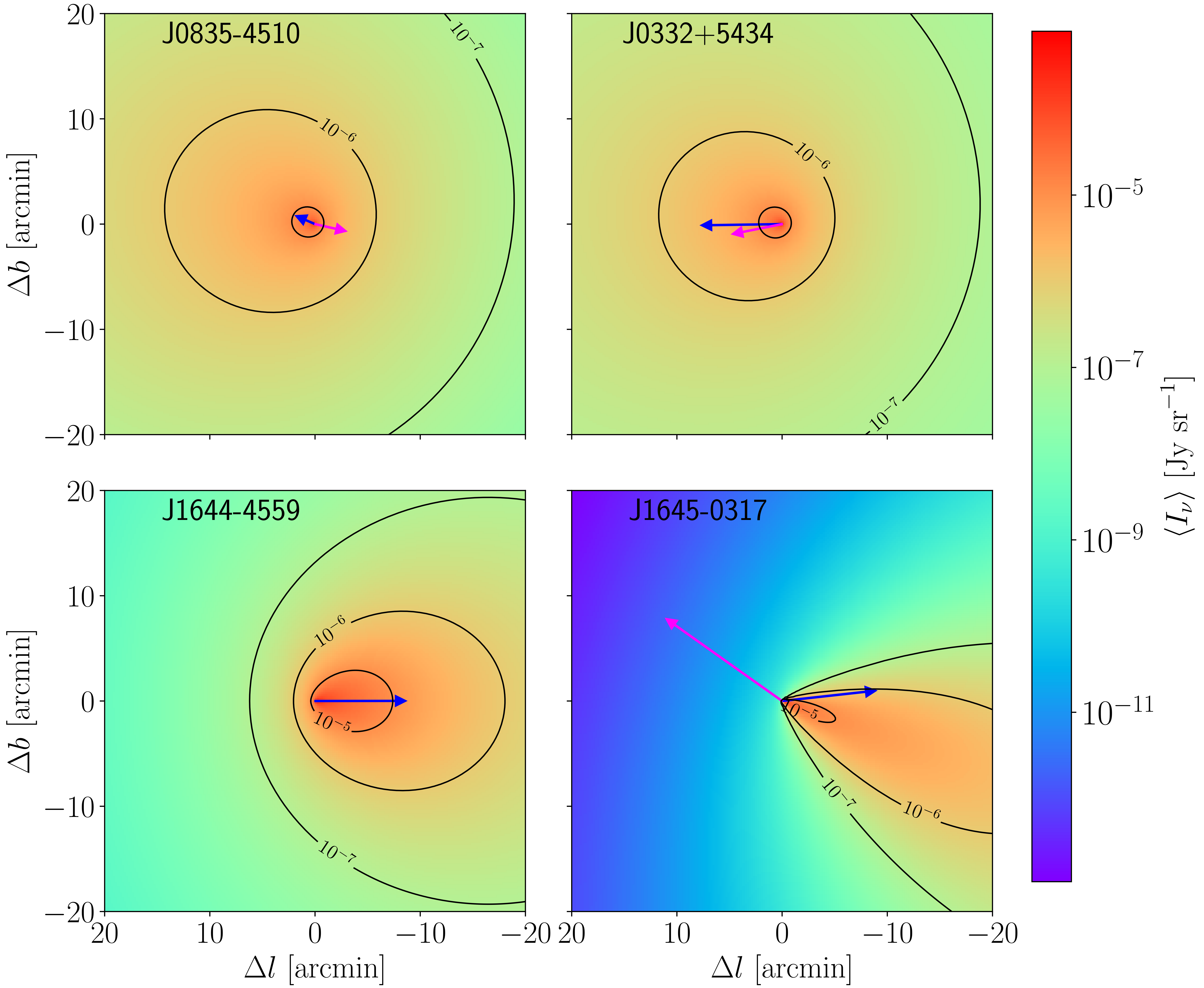


$$\theta_{i,0} \sim 2\delta v$$

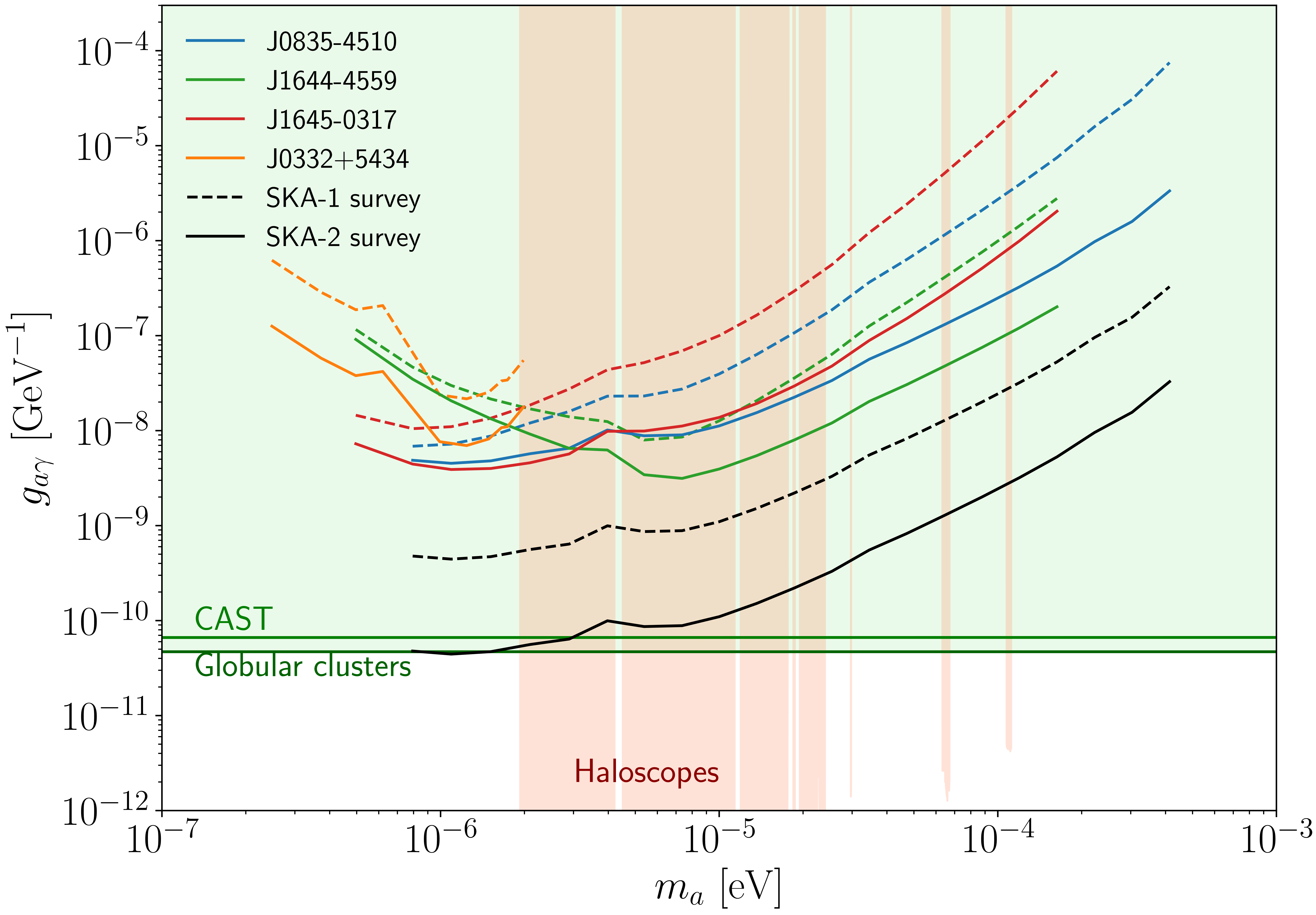


Relevant effects

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



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



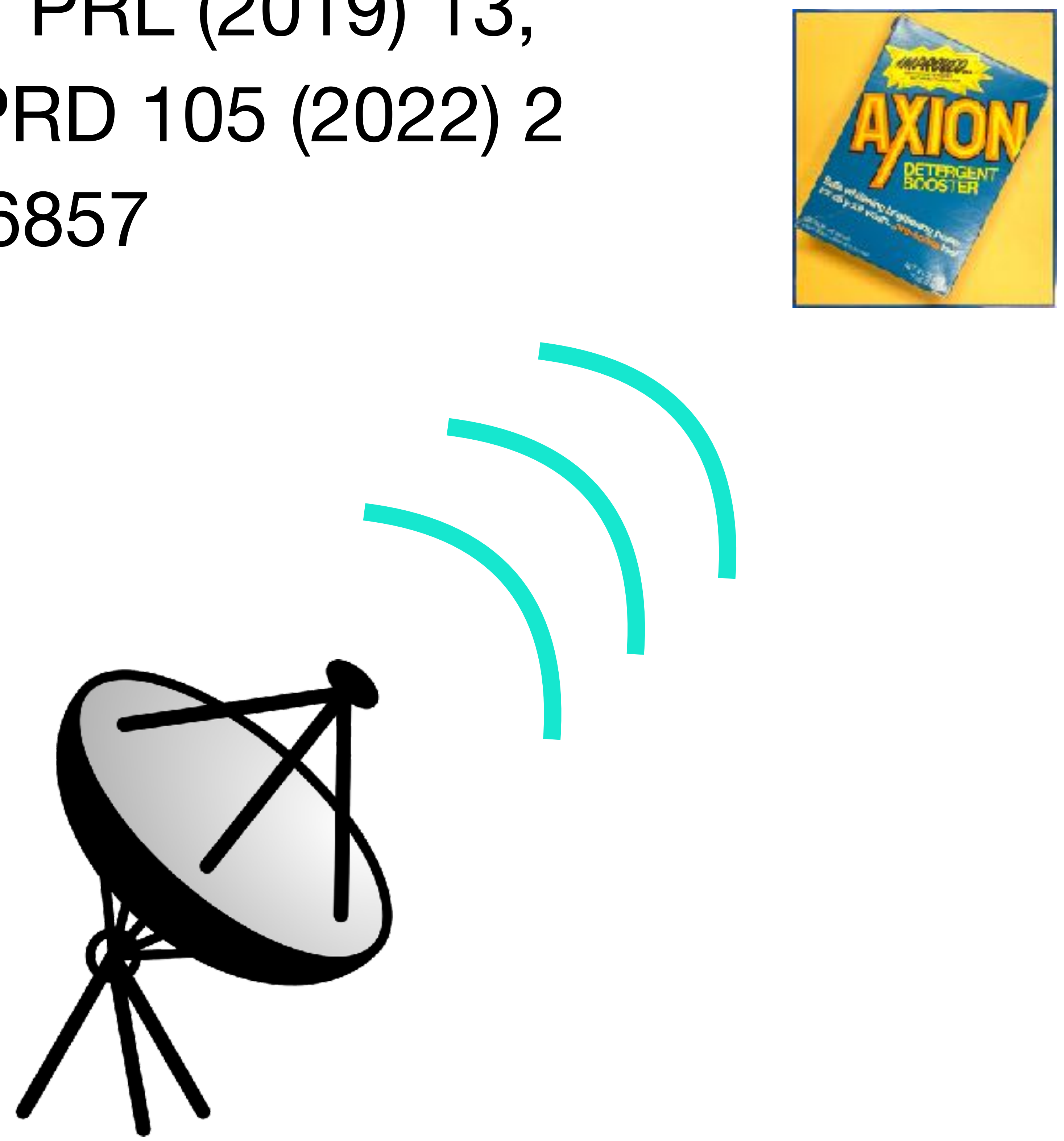
J0835-4510
J1644-4559
J1645-0317
J0332+5434
SKA-1 survey
SKA-2 survey
CAST
Globular clusters
Haloscopes
$g_{a\gamma}$ [GeV^{-1}]
m_a [eV]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}

An echo from an artificial source

Arza + Sikivie, PRL (2019) 13,

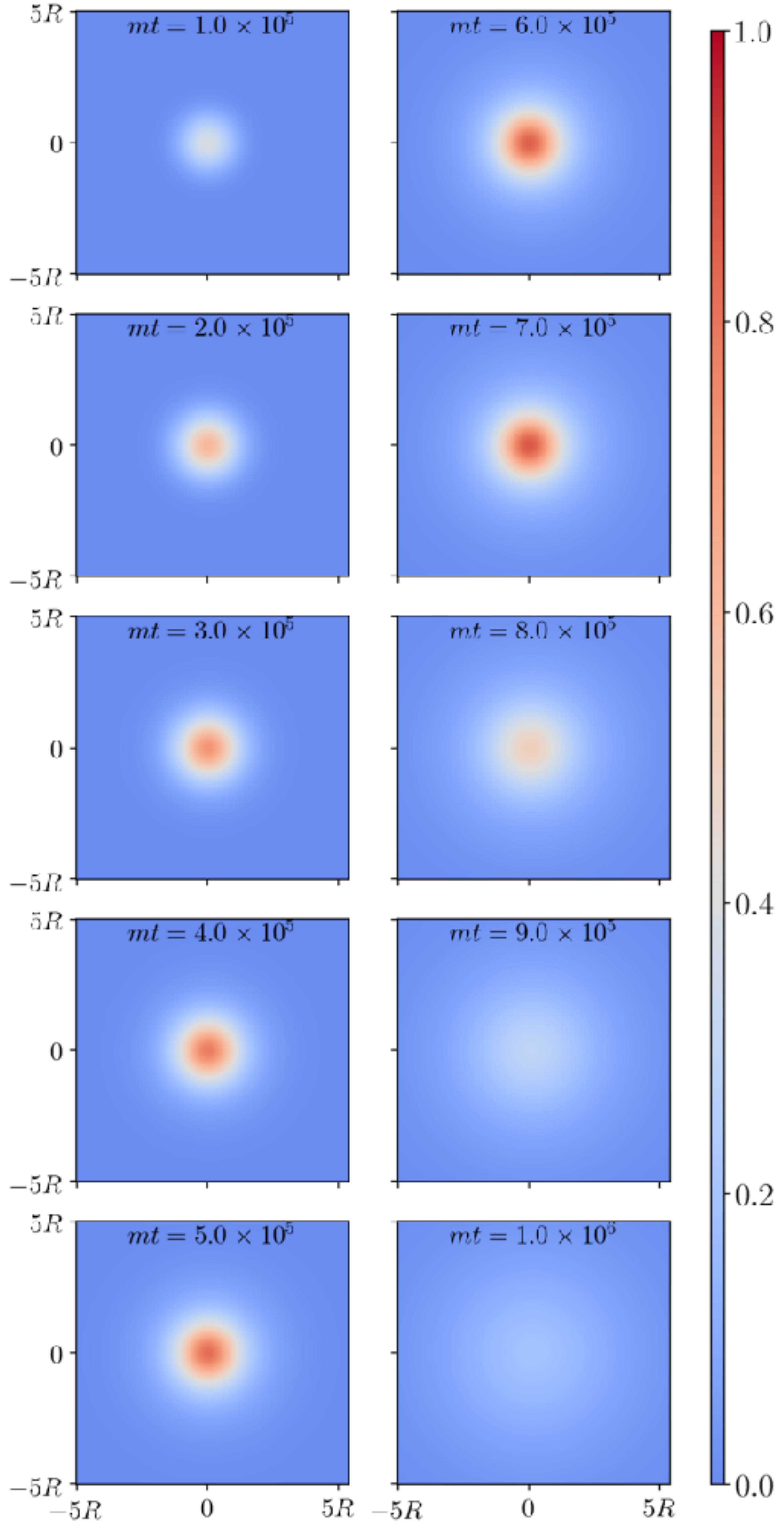
Arza + **E.T.**, PRD 105 (2022) 2

Arza+, 2309.06857

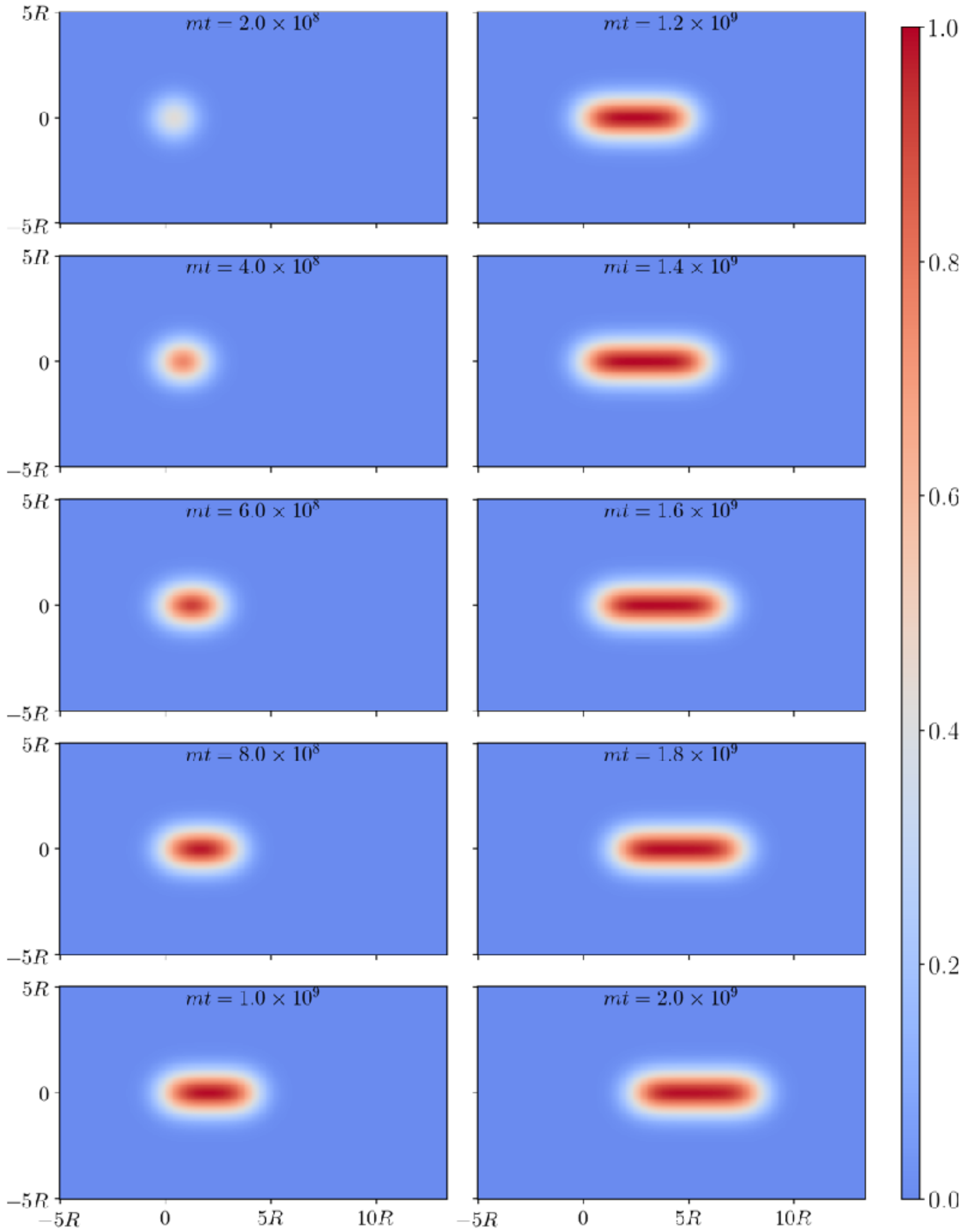


Stimulate the decay of nearby dark matter axions into photons by sending out a powerful beam to space

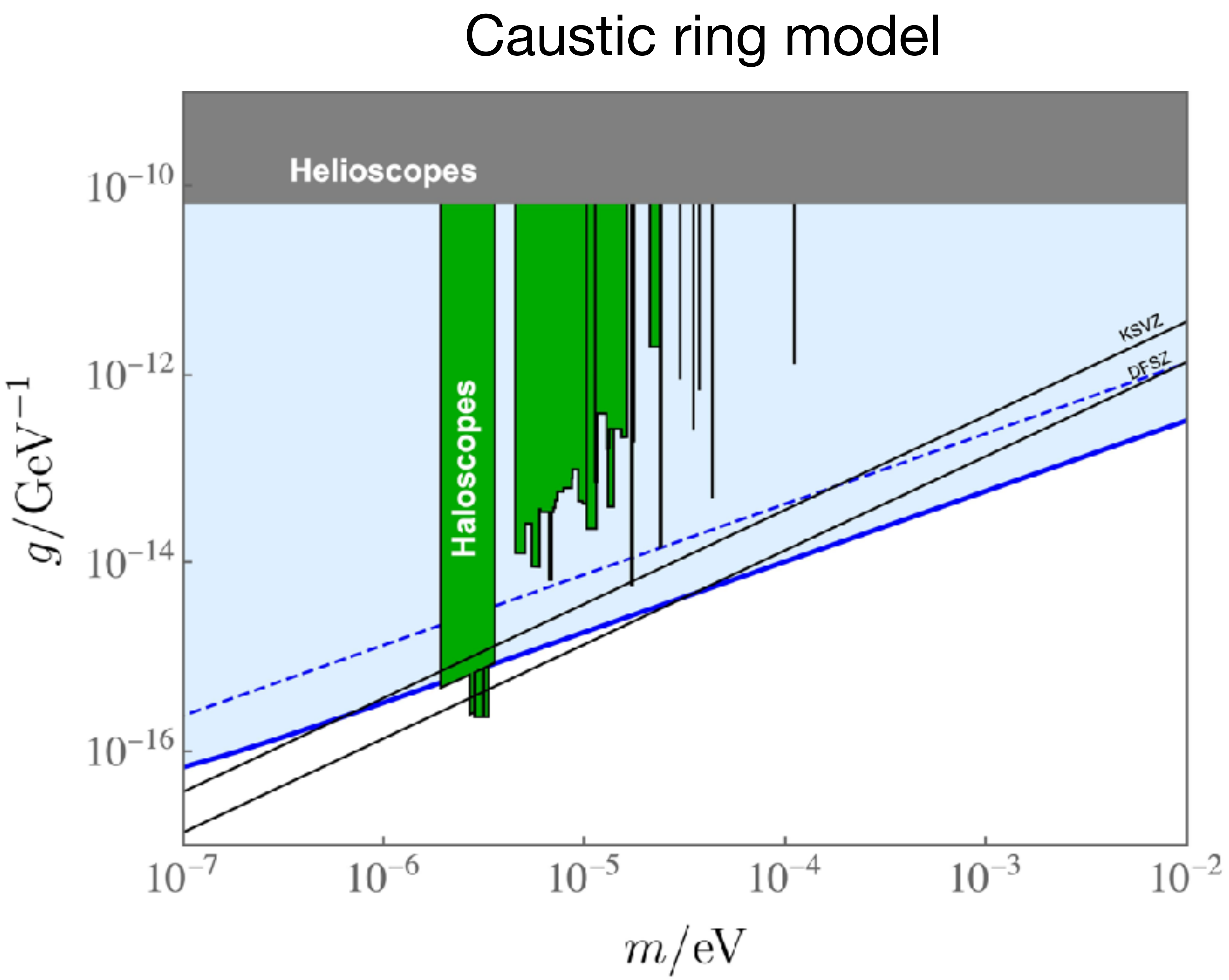
Detect the photons that come back

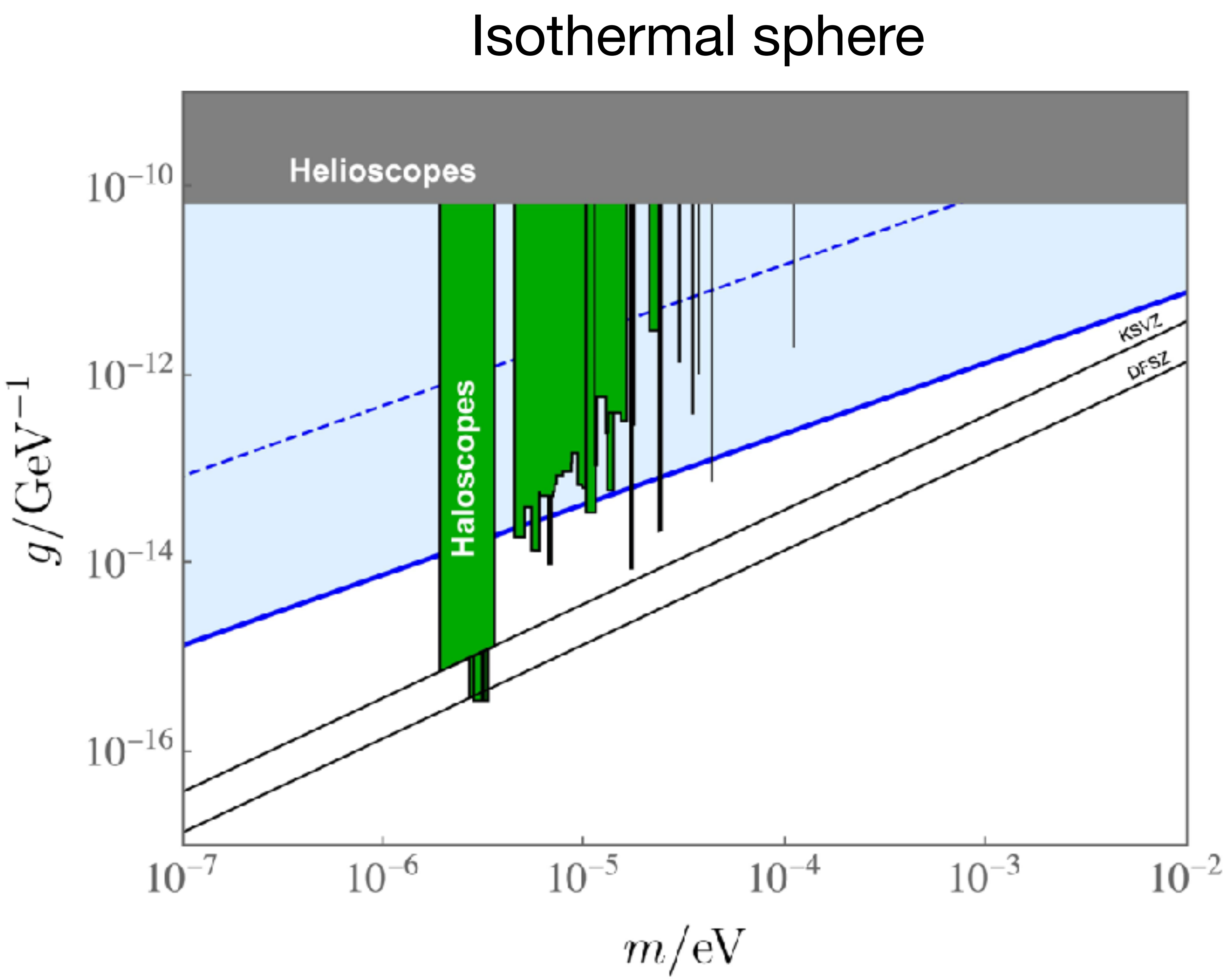


mt = 1.0 × 10^5
mt = 2.0 × 10^5
mt = 3.0 × 10^5
mt = 4.0 × 10^5
mt = 5.0 × 10^5
mt = 6.0 × 10^5
mt = 7.0 × 10^5
mt = 8.0 × 10^5
mt = 9.0 × 10^5
mt = 1.0 × 10^6
5R
0
−5R
1.0
0.8
0.6
0.4
0.2
0.0



mt = 2.0 × 10^8
mt = 4.0 × 10^8
mt = 6.0 × 10^8
mt = 8.0 × 10^8
mt = 1.0 × 10^9
mt = 1.2 × 10^9
mt = 1.4 × 10^9
mt = 1.6 × 10^9
mt = 1.8 × 10^9
mt = 2.0 × 10^9
5R
0
−5R
10R
1.0
0.8
0.6
0.4
0.2
0.0

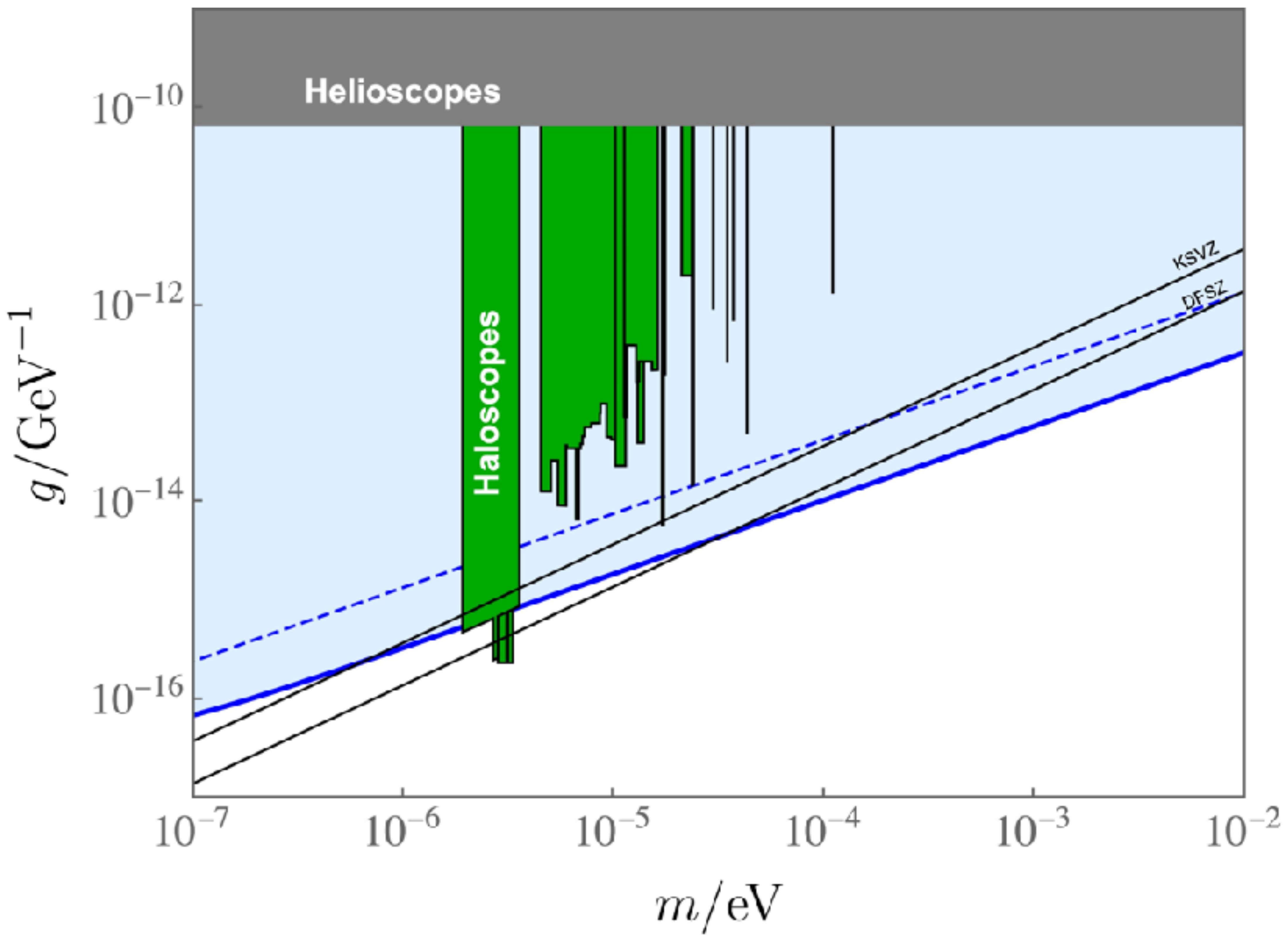




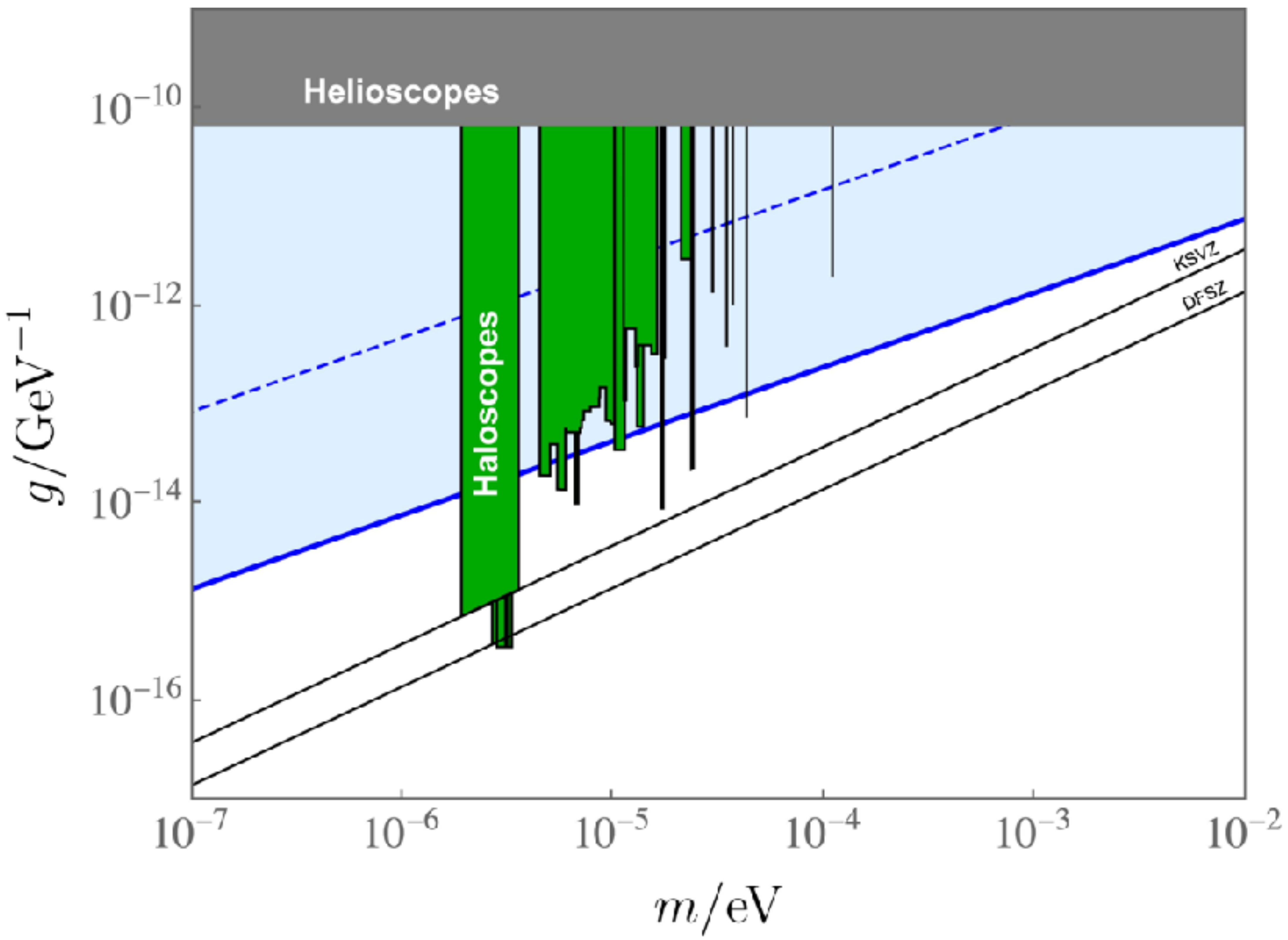
$$\begin{aligned} \rho &= 1\ \text{GeV cm}^{-3} \\ v &= 300\ \text{km/s} \\ \delta v &= 70\ \text{m/s} \\ v_\perp &= 5\ \text{km/s} \end{aligned}$$

$$\begin{aligned} \rho &= 0.45\ \text{GeV cm}^{-3} \\ v &= 230\ \text{km/s} \\ \delta v &= 270\ \text{km/s} \end{aligned}$$

Caustic ring model



Isothermal sphere



Fixed energy to cover a factor of 2 in axion mass (dashed)

$$E = 10\,\mathrm{MW\,yr} \quad s/n = 5 \quad T_n = 20\,\mathrm{K} \quad R = 50\,\mathrm{m} \quad R_c = 100\,\mathrm{m}$$

$$t_{\mathrm{off}} = \frac{1}{2\delta\omega} \qquad \delta\omega = \delta p_z/2$$

Conclusions

- Spontaneous axion decay into photons, search strategy for masses above 1 eV
- For lower masses enhanced decay rate
  - Natural sources
  - Human made source: the echo experiment