Decay signatures of axion dark matter

Elisa Todarello (University of Turin and INFN Turin)

BAM: Axions in the sky!
Barolo, 13.06.2024

Outline

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

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

    JCAP 05 (2024) 043
- **Axion stimulated decay**
  - **E.T.** + Calore + Regis,

    "Anatomy of astrophysical echoes from axion dark matter"

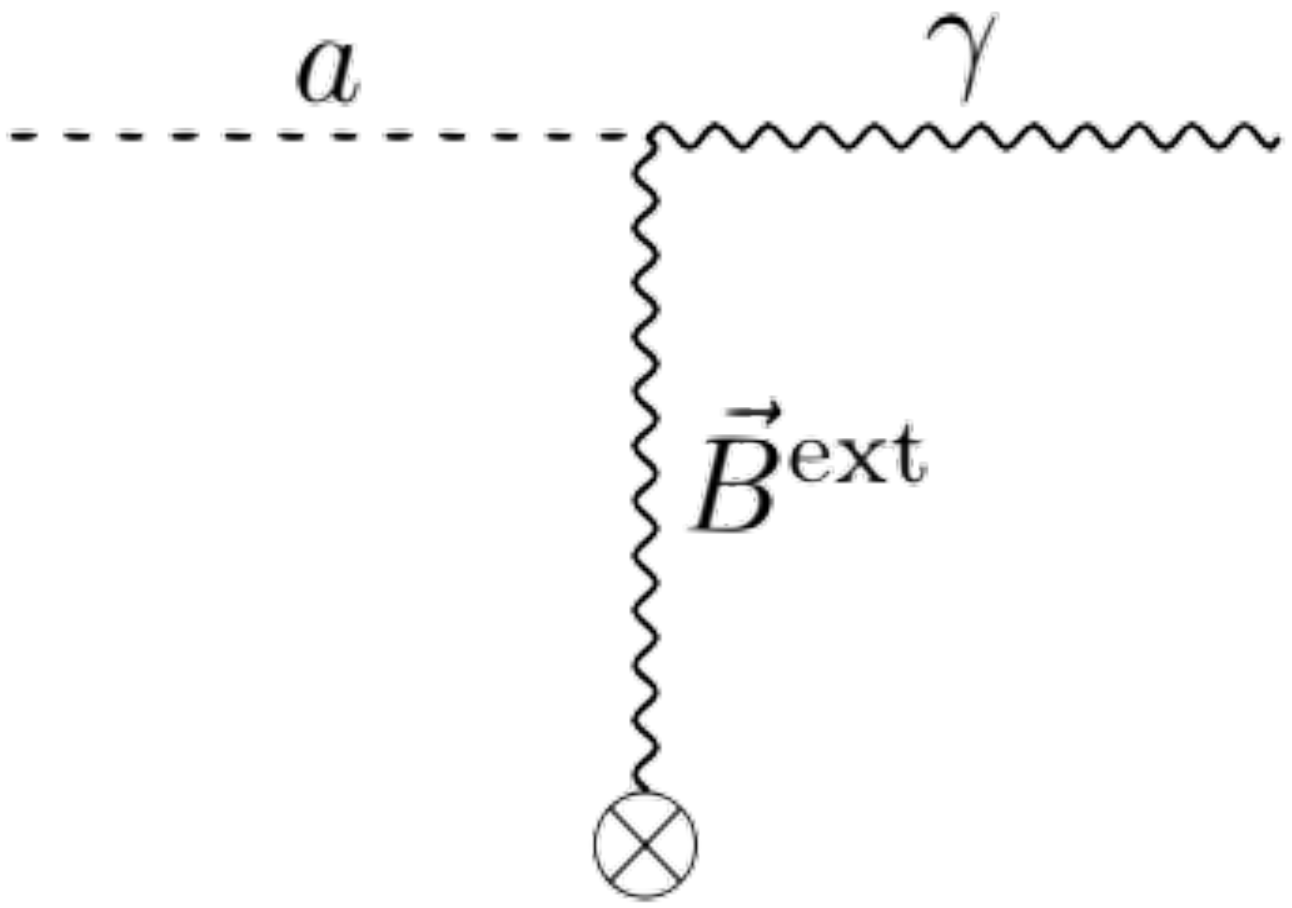
    JCAP 05 (2024) 040
  - Arza + **E.T.**,

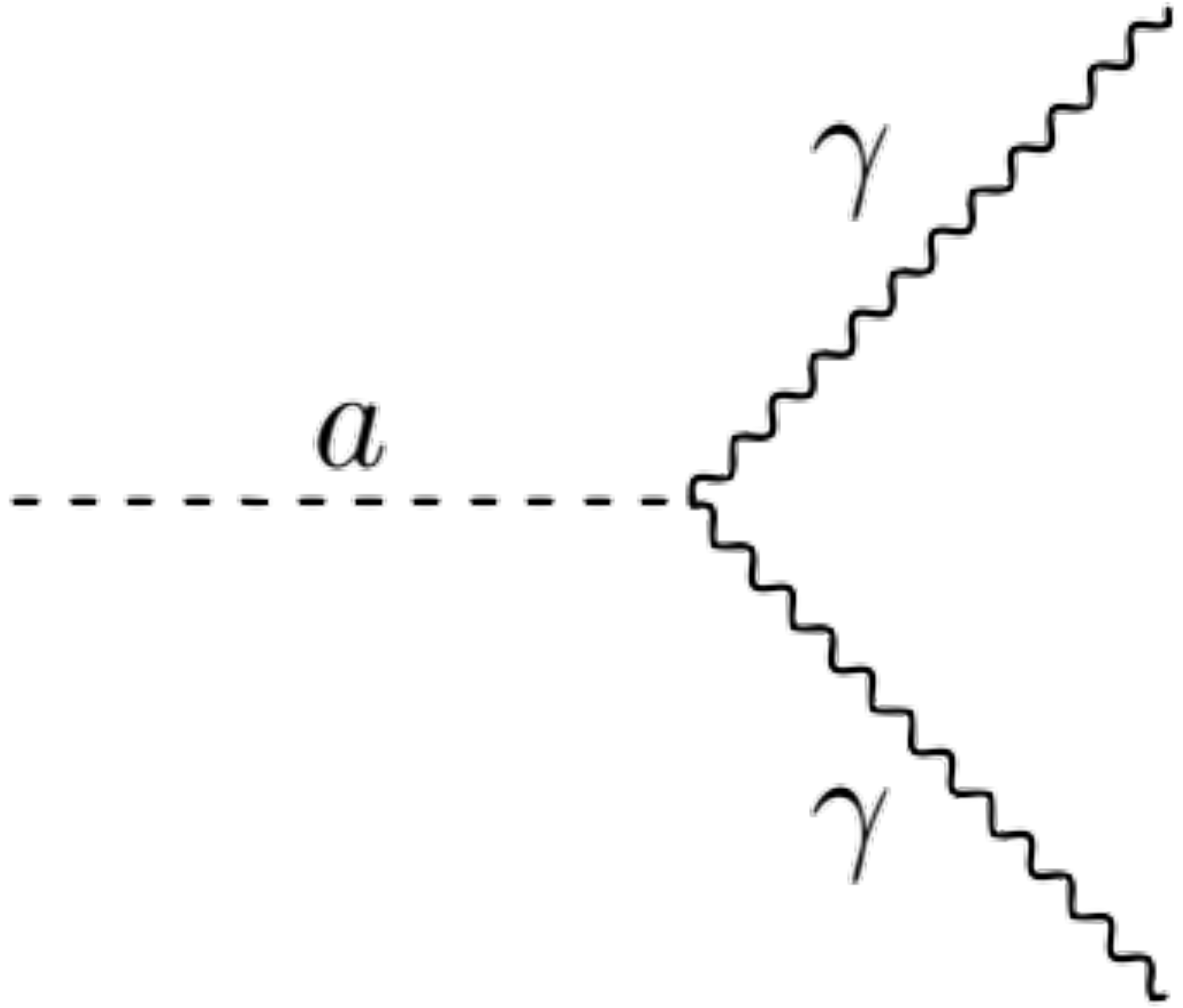
    "Axion dark matter echo: A detailed analysis"

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

Axion-photon interaction

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

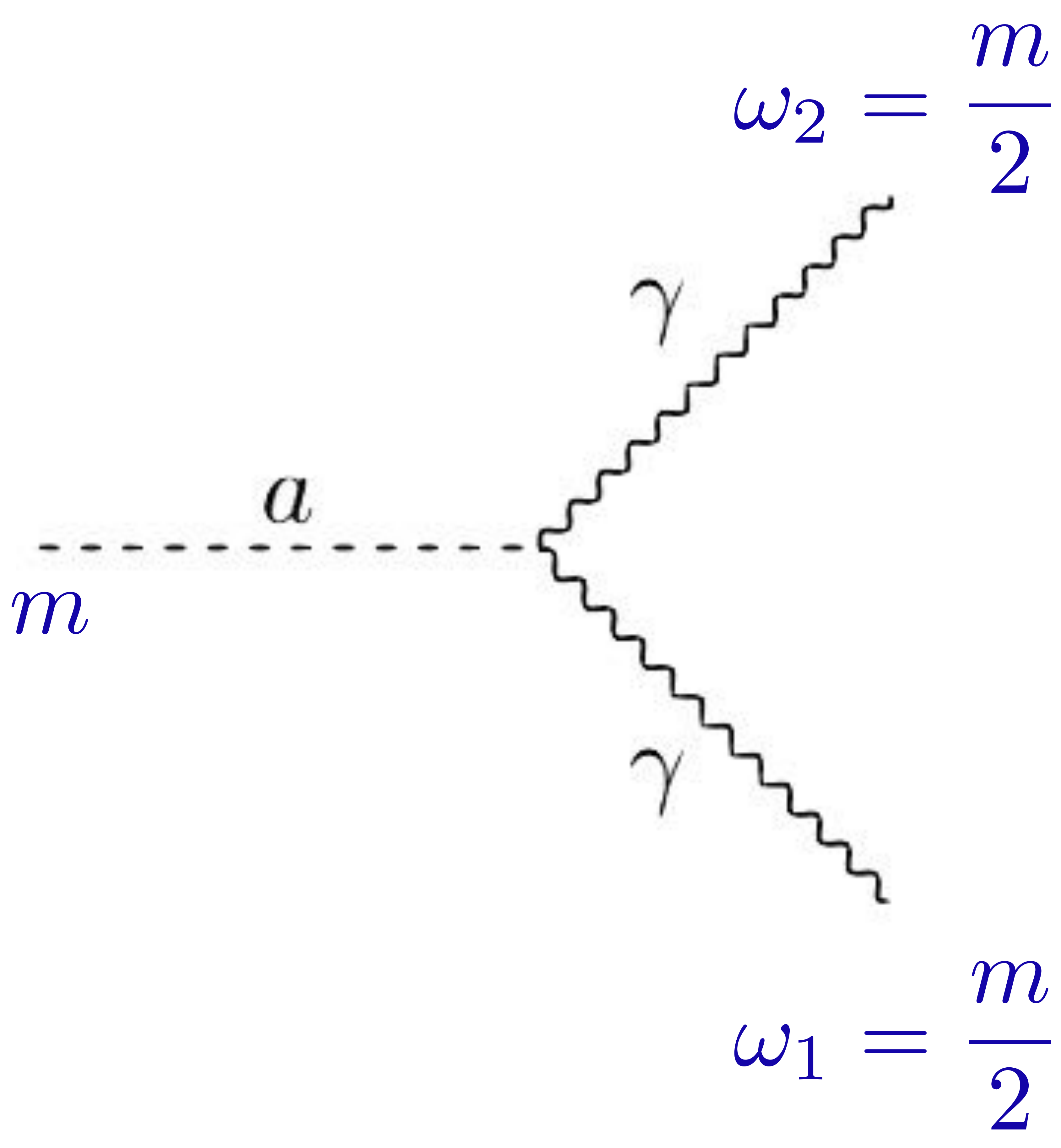




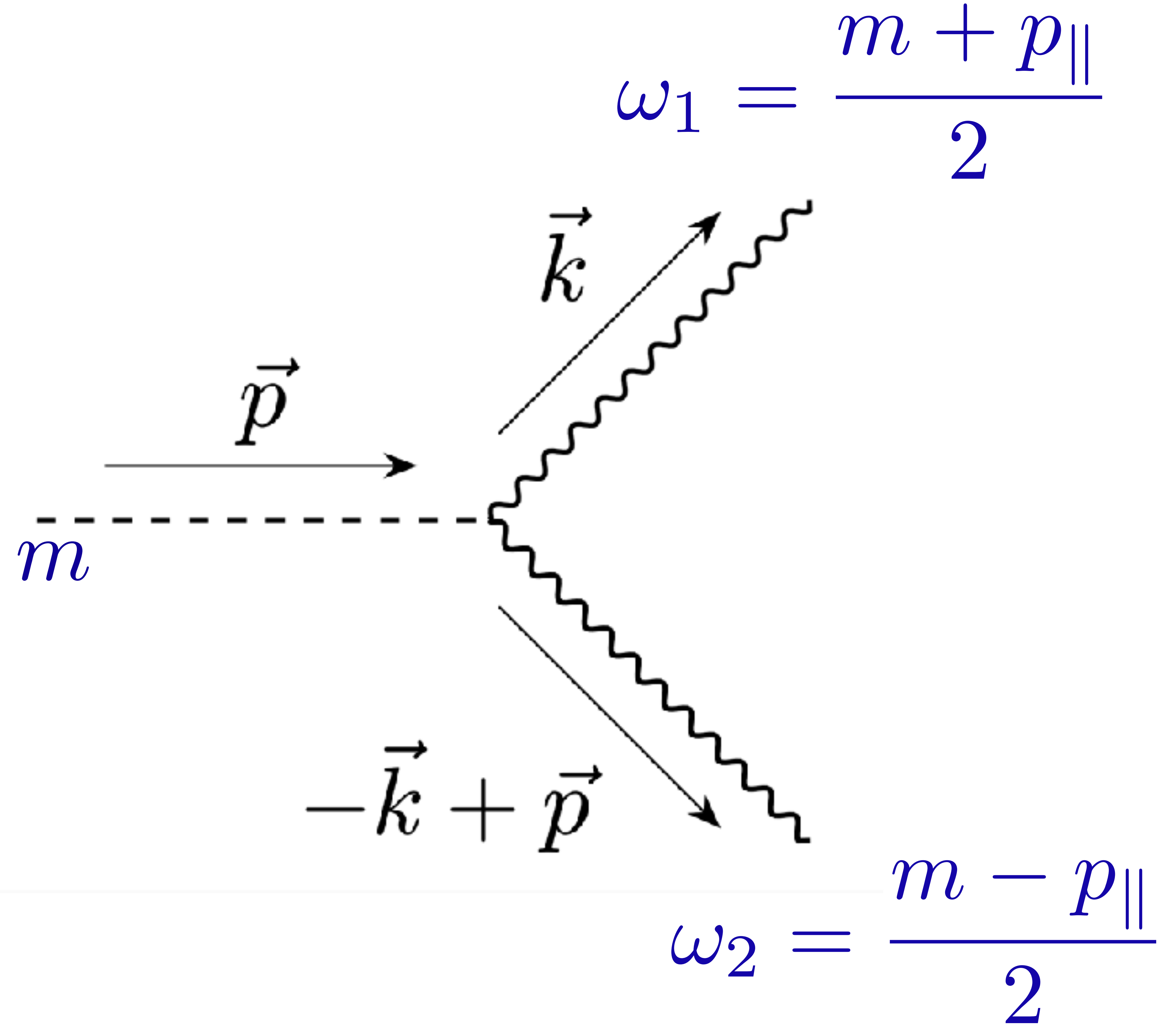
In this talk, axion = QCD axion or ALP

Axion spontaneous decay

Kinematics



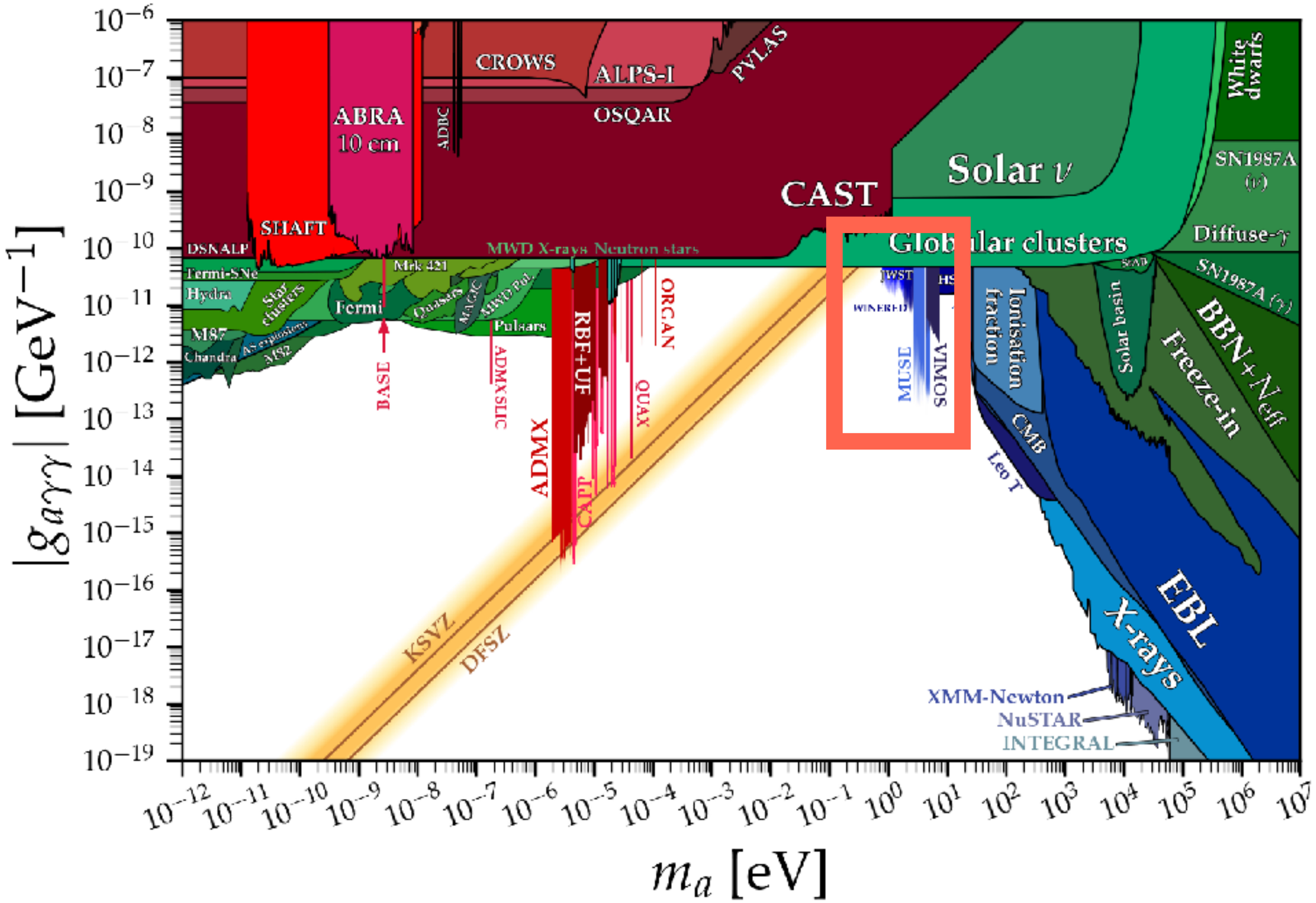
$\omega_2 = \frac{m}{2}$
γ
a
m
γ
$\omega_1 = \frac{m}{2}$



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

Decay rate in vacuum

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



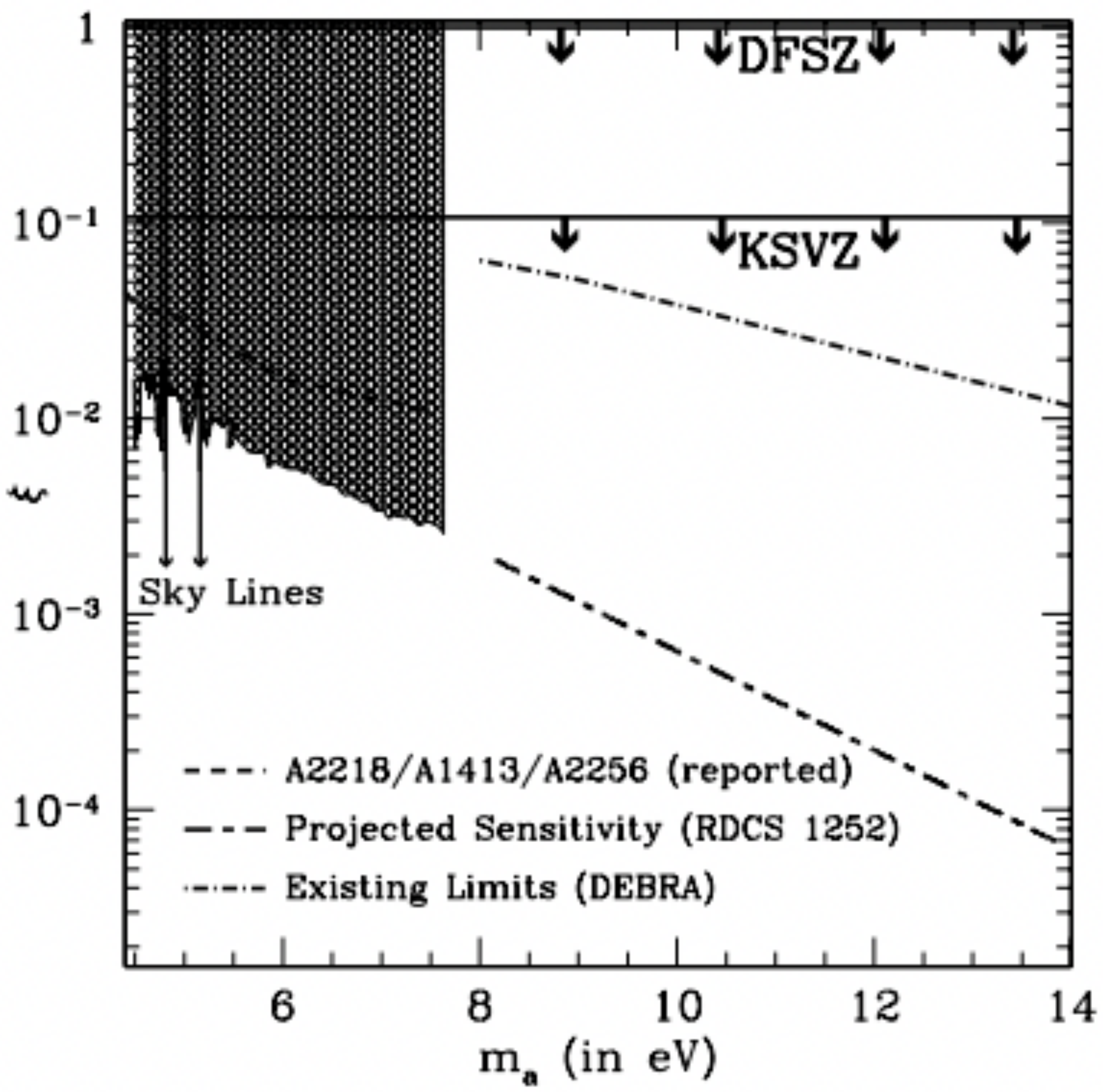
Decay in the optical band

Grin, Covone, Kneib, Kamionkowski, Blain, Jullo

PRD 75 (2007) 105018

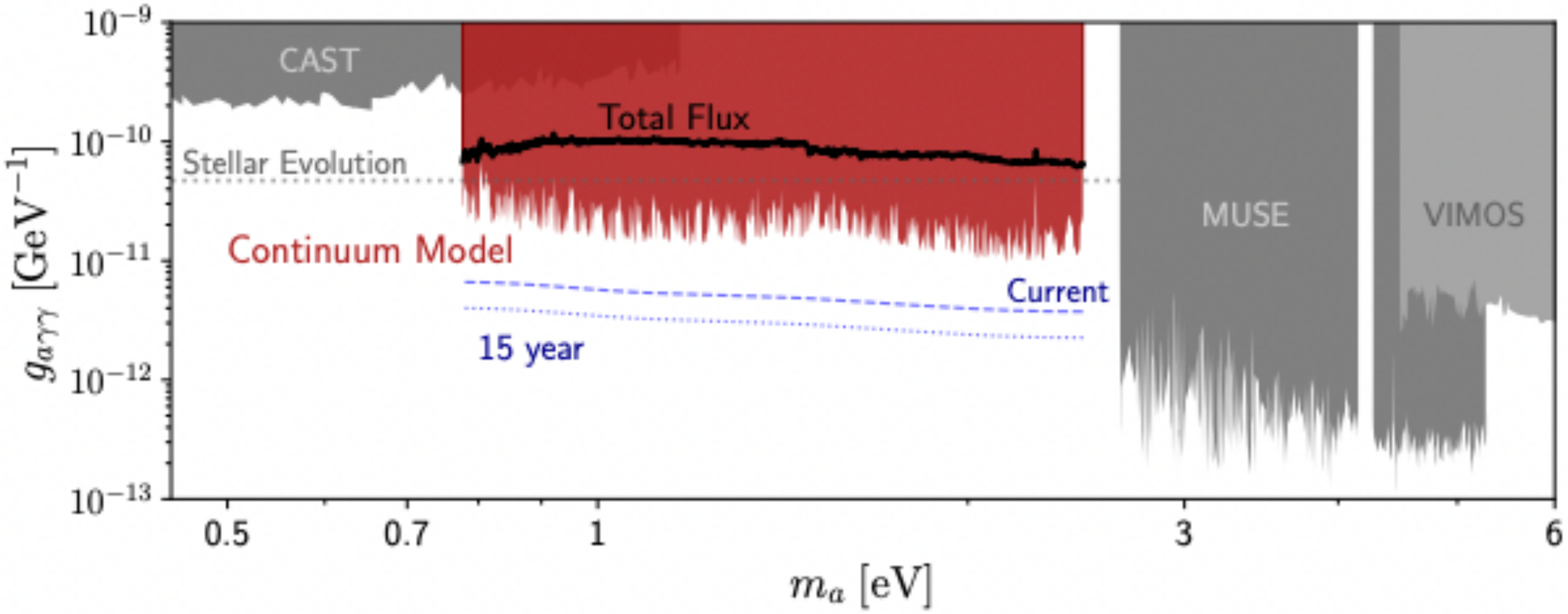
VIMOS at the Very Large Telescope

Galaxy clusters Abell 2667 and 2390

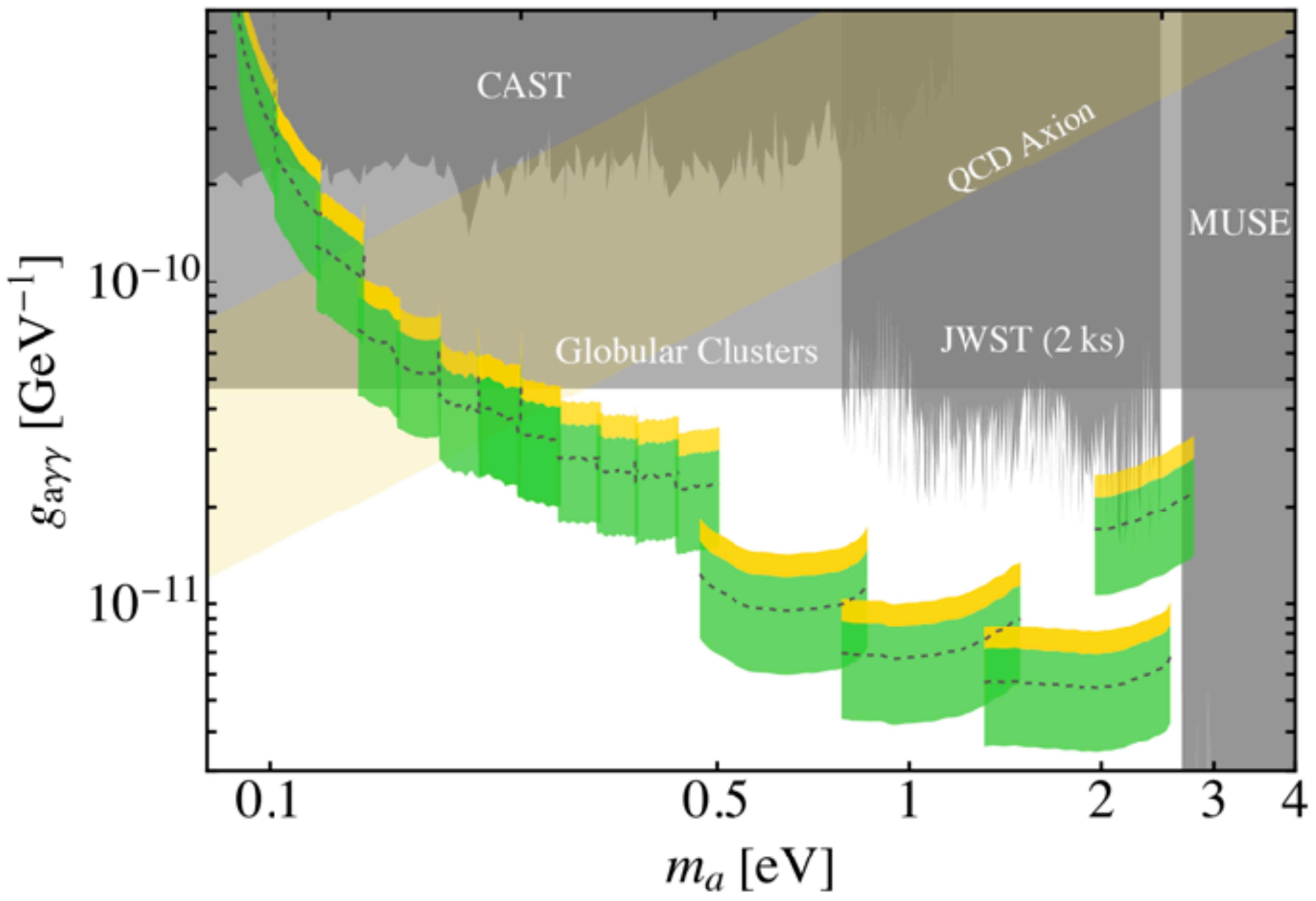


Decay in the IR band

Janish, Pinetti
2310.15395
JWST
Blank sky



Roy, Blanco, Dessert, Prabhu, Temim
2311.04987
JWST
Blank sky FORECAST at end of mission



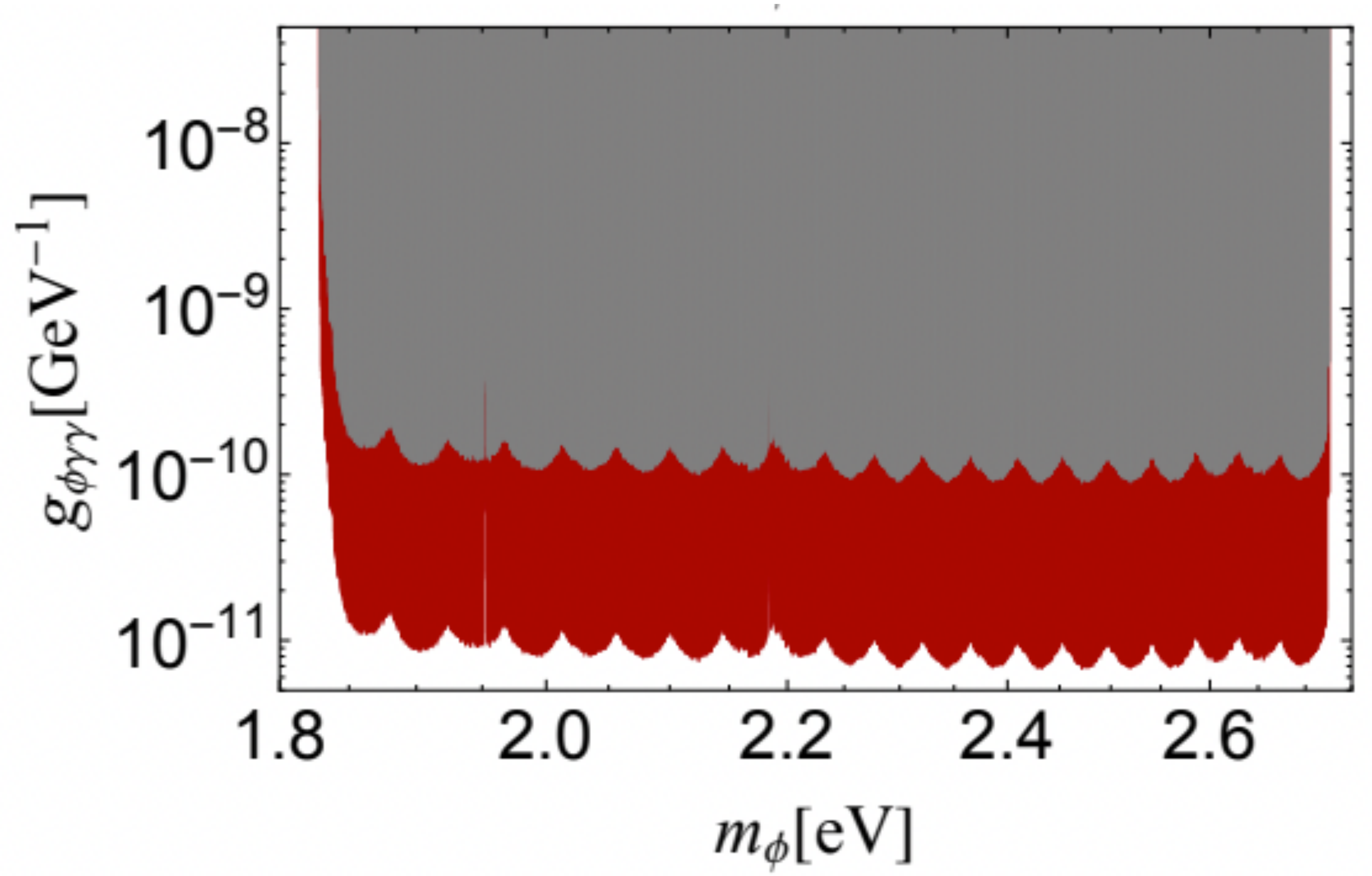
Decay in the IR band

Yin, Bessho, Ikeda, Kobayashi, Taniguchi, Sameshima, Matsunaga, Otsubo, Sarugaku, Takeuchi, Kato, Hamano, Kawakita

2402.07976

WINERED at the 6.5m Magellan Clay telescope

Dwarf galaxies Leo V and Tucana II



The MUSE instrument

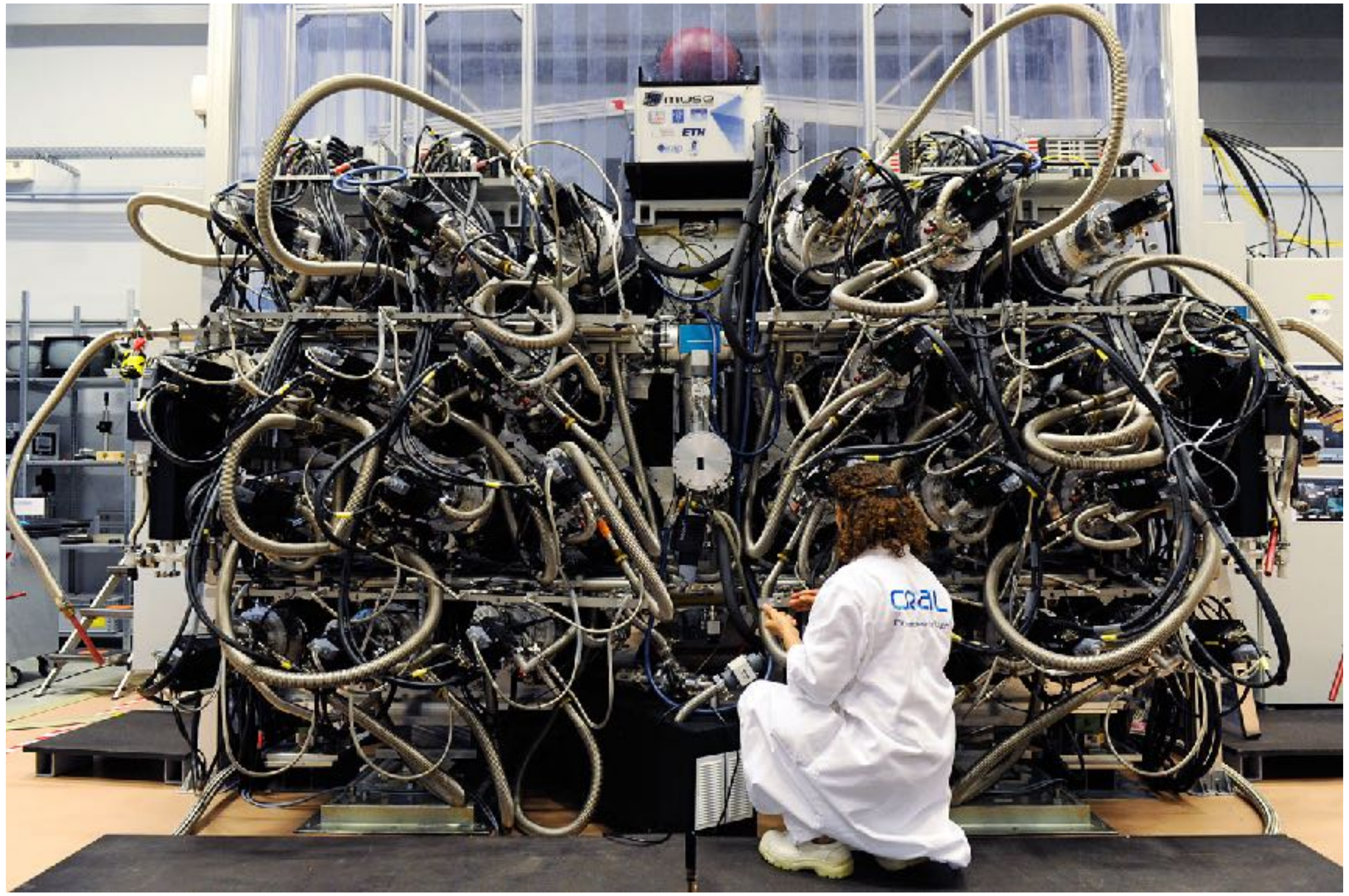
Multi Unit Spectroscopic Explorer

- 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

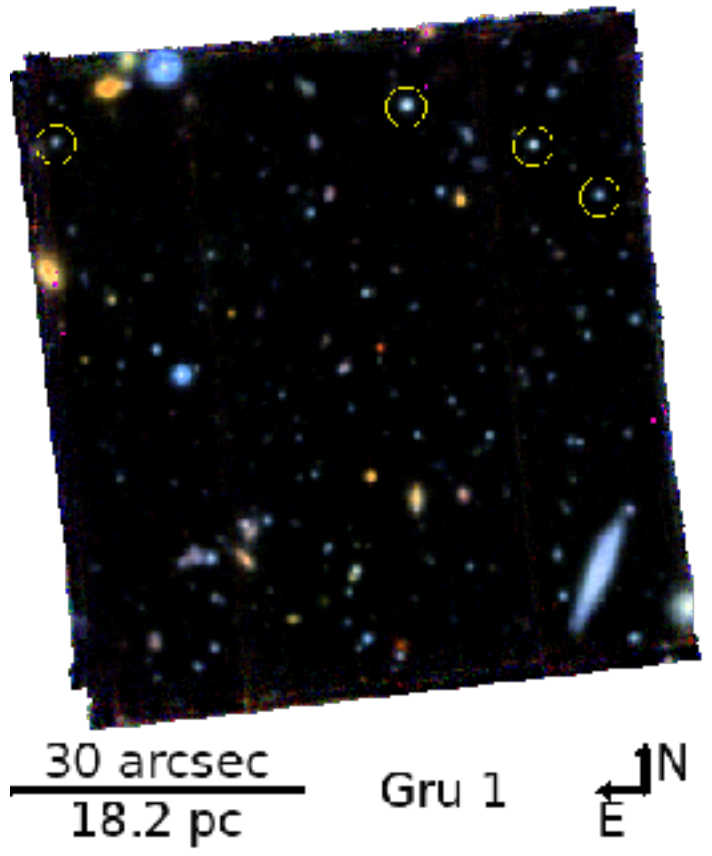
multi unit spectroscopic explorer

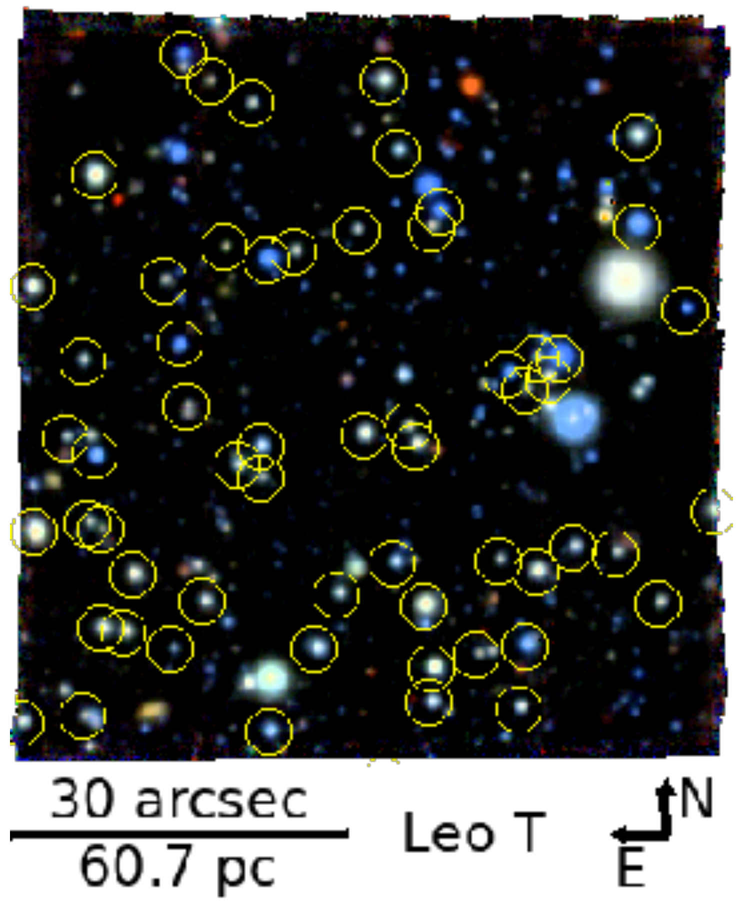
Dwarf Galaxies

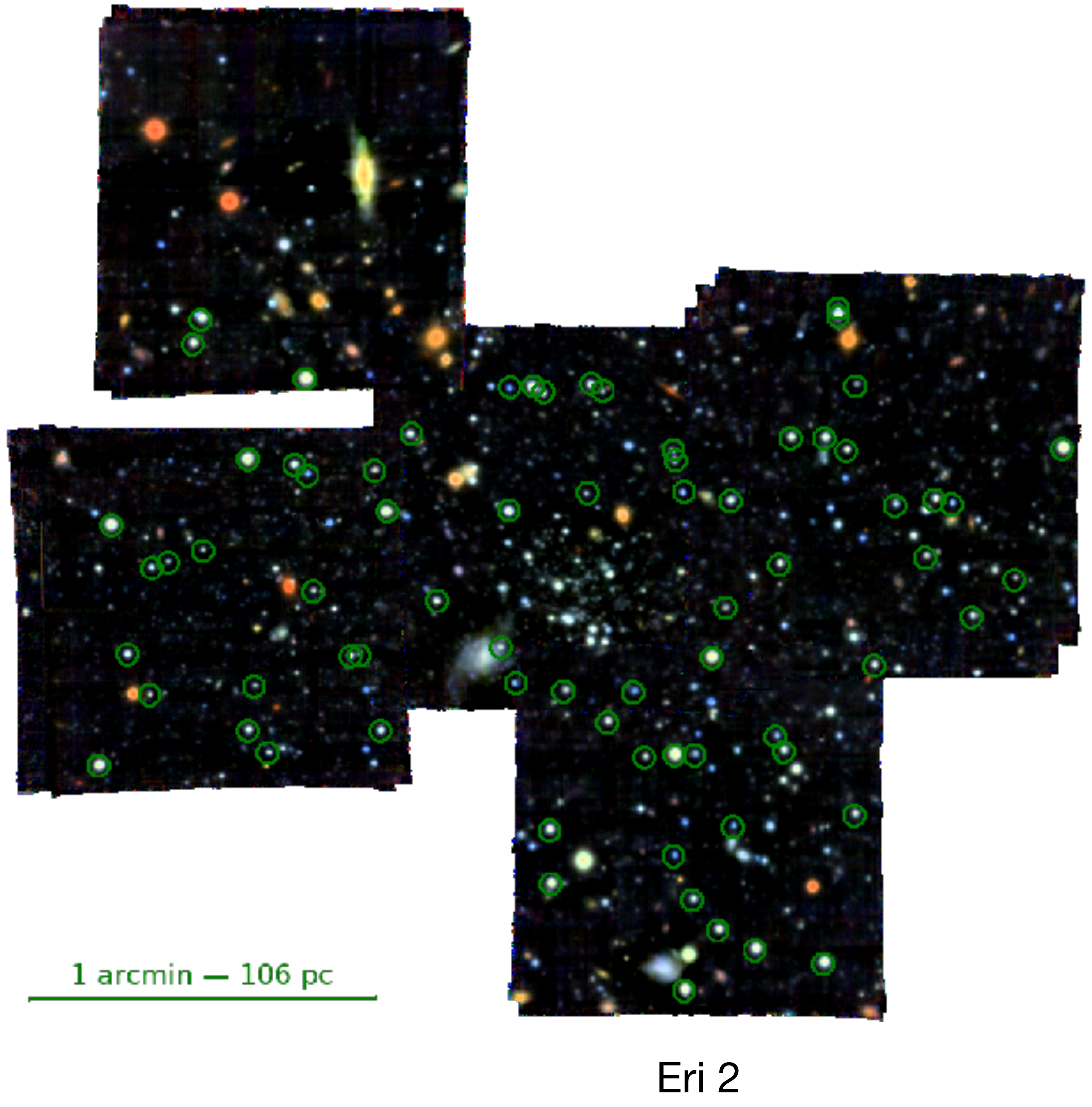
- Dark matter rich
- High mass-to-light ratio
- Typical mass $10^8 - 10^9 \ M_\odot$
- Typical radius 1 kpc
- Energy density $\rho \sim 4 \text{ GeV cm}^{-3}$
- Distance 100 kpc

Sculptor dwarf galaxy. Photo by ESO.

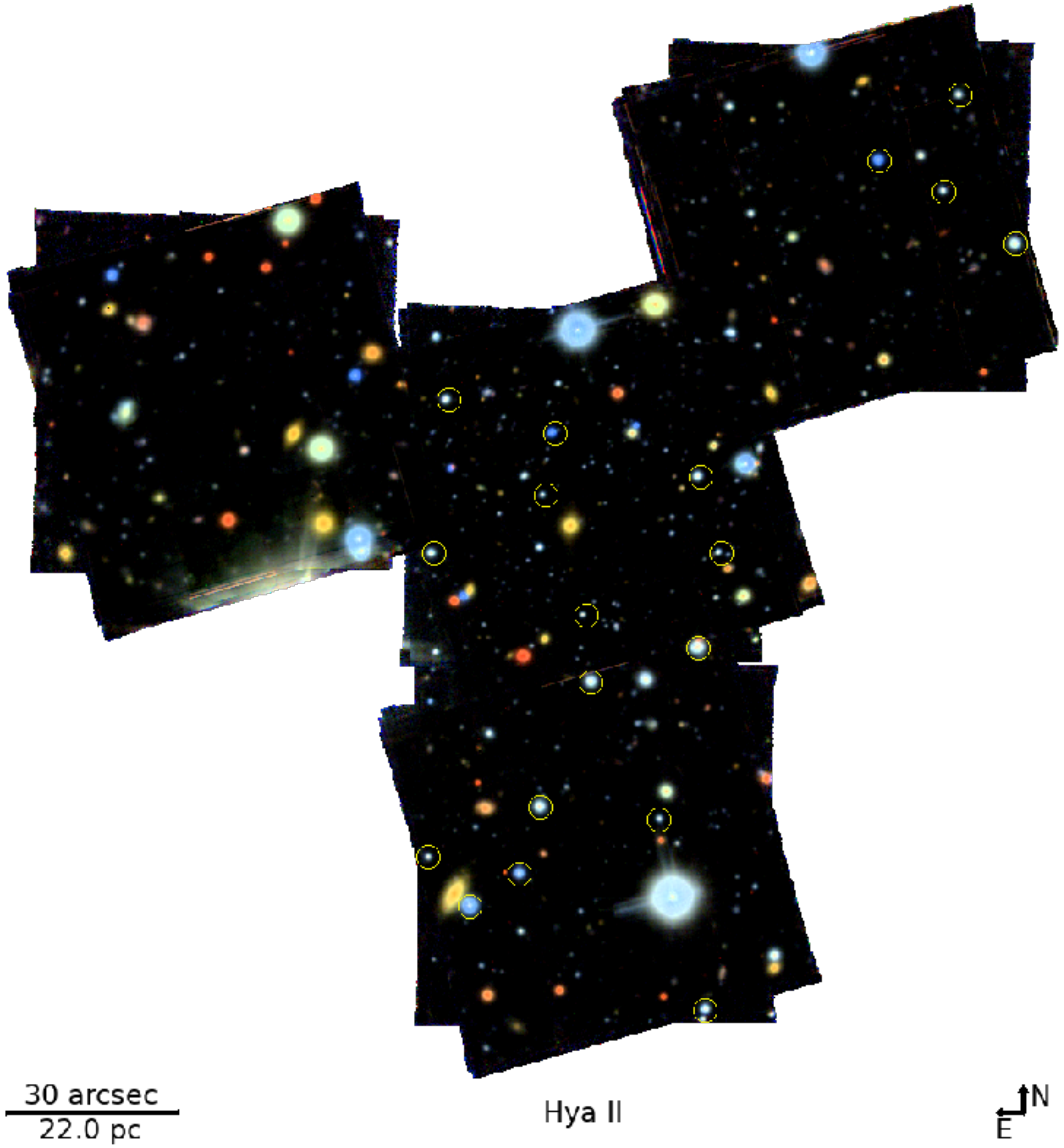
The MUSE-Faint Survey





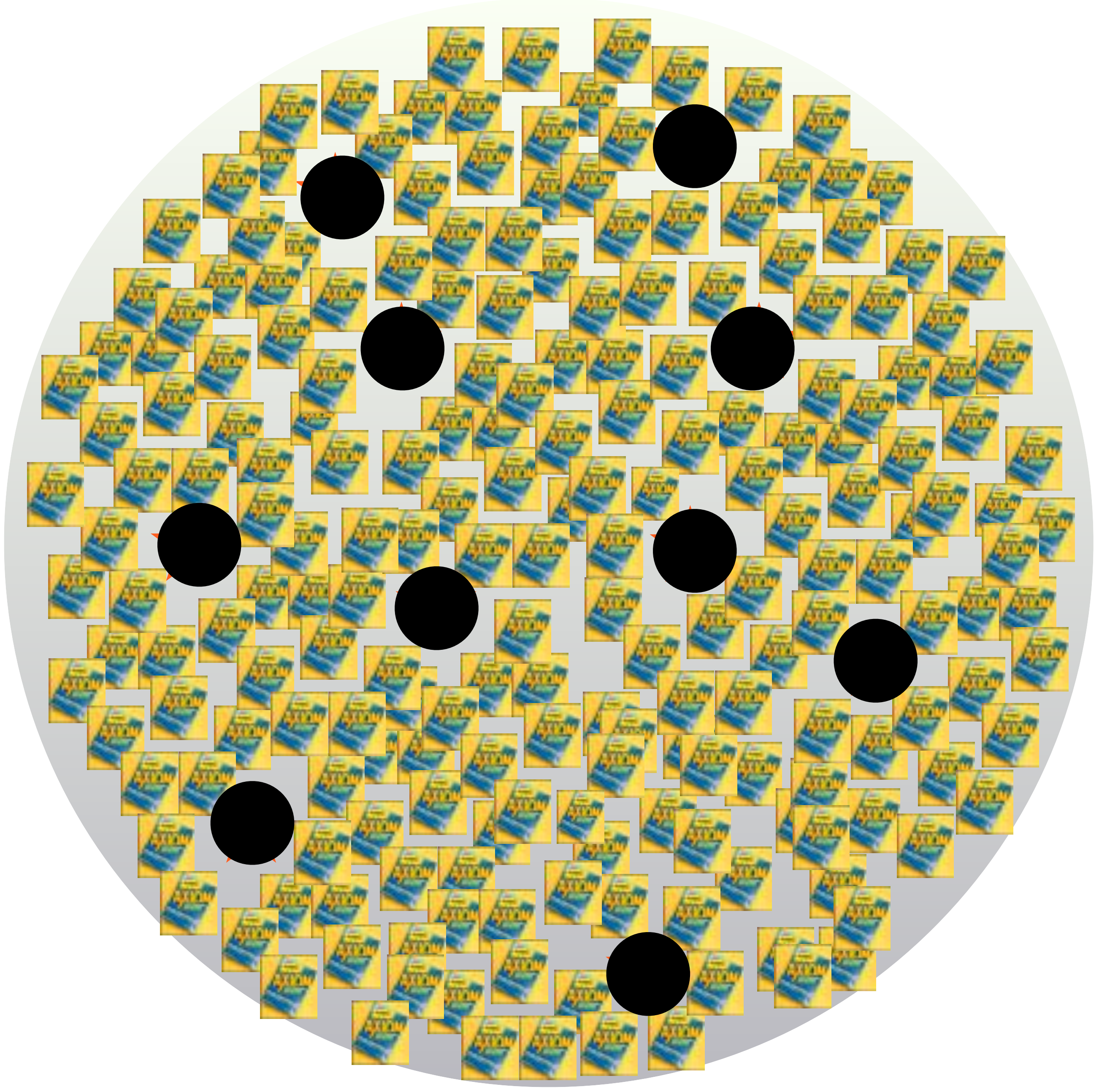


+ Sculptor



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

Look for radiation from ALP decay



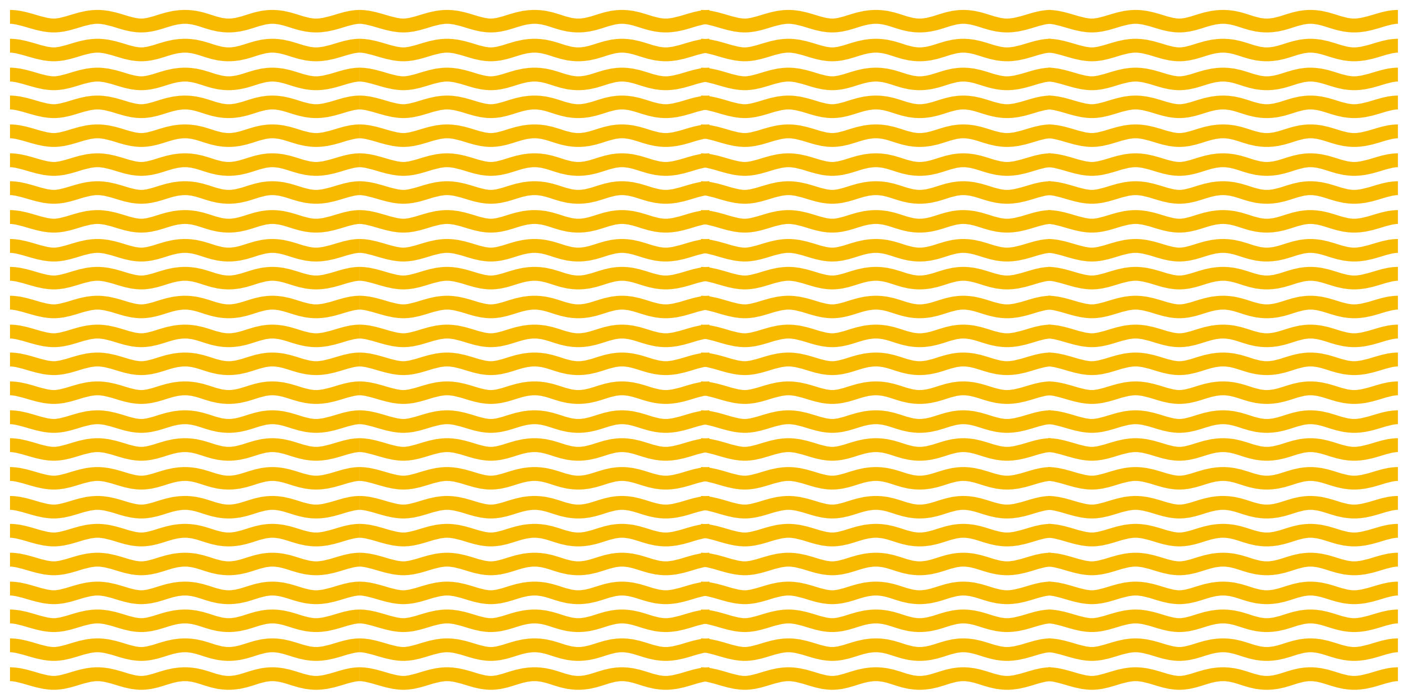
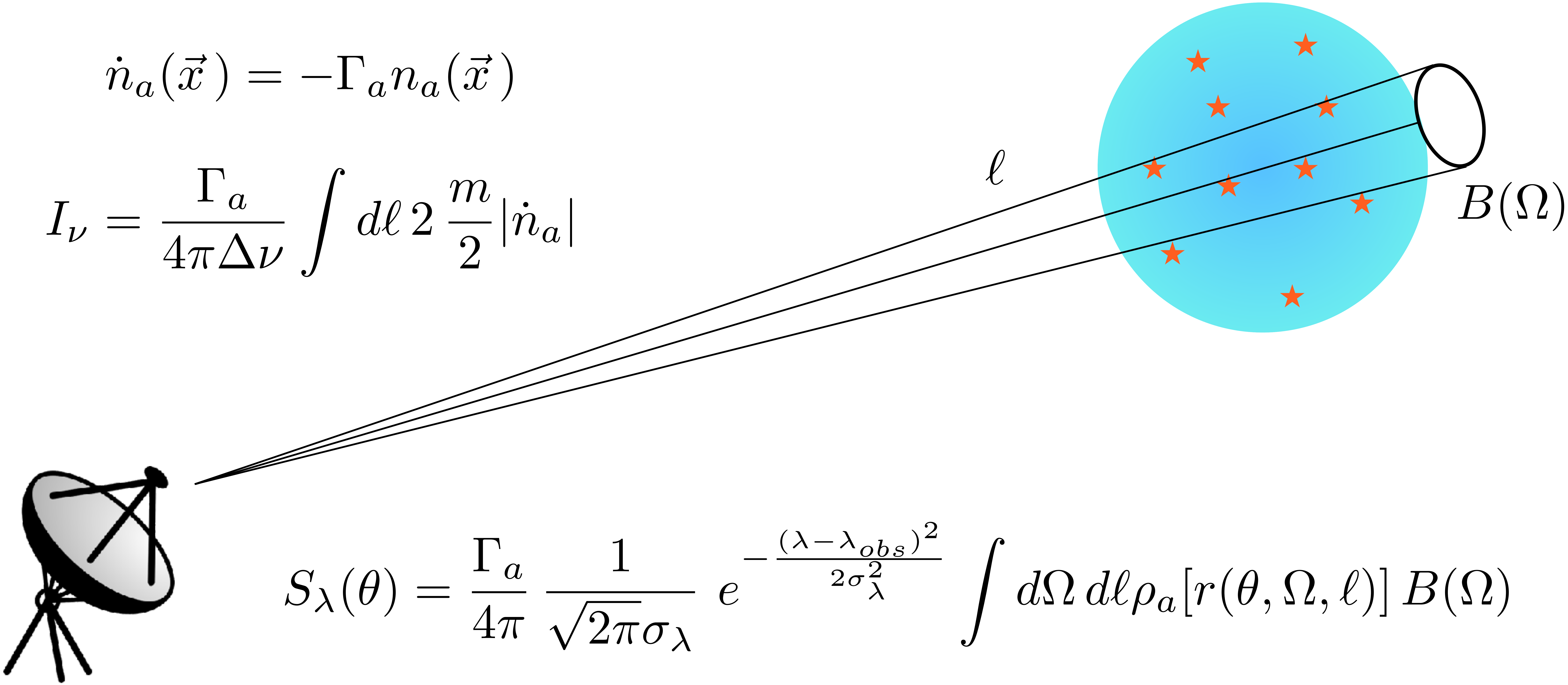


Photo by ESO/G. Hüdepohl (atacamaphoto.com)

Flux density from ALP decay

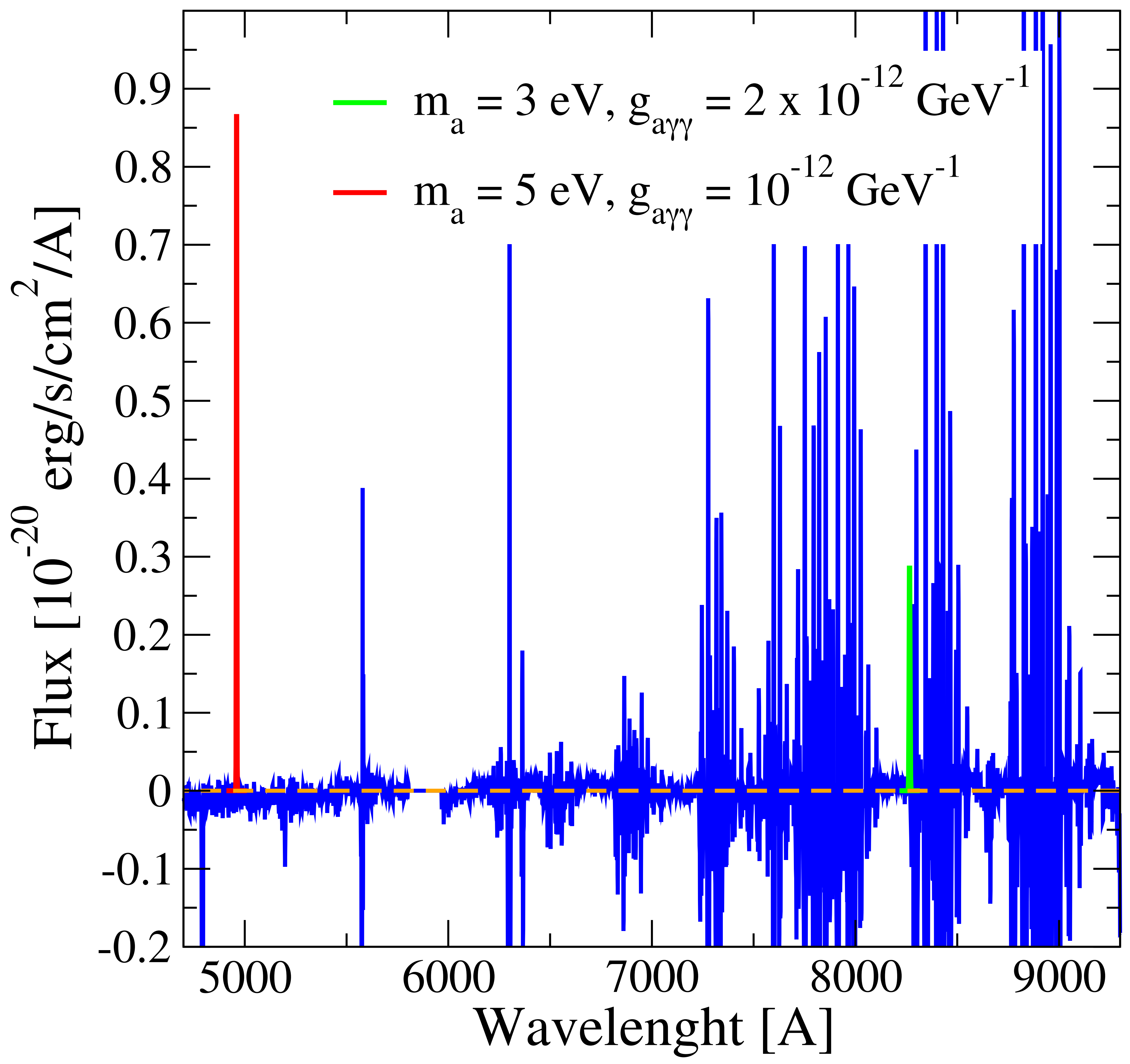
$$\dot{n}_a(\vec{x}\,) = -\Gamma_a n_a(\vec{x}\,)$$

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



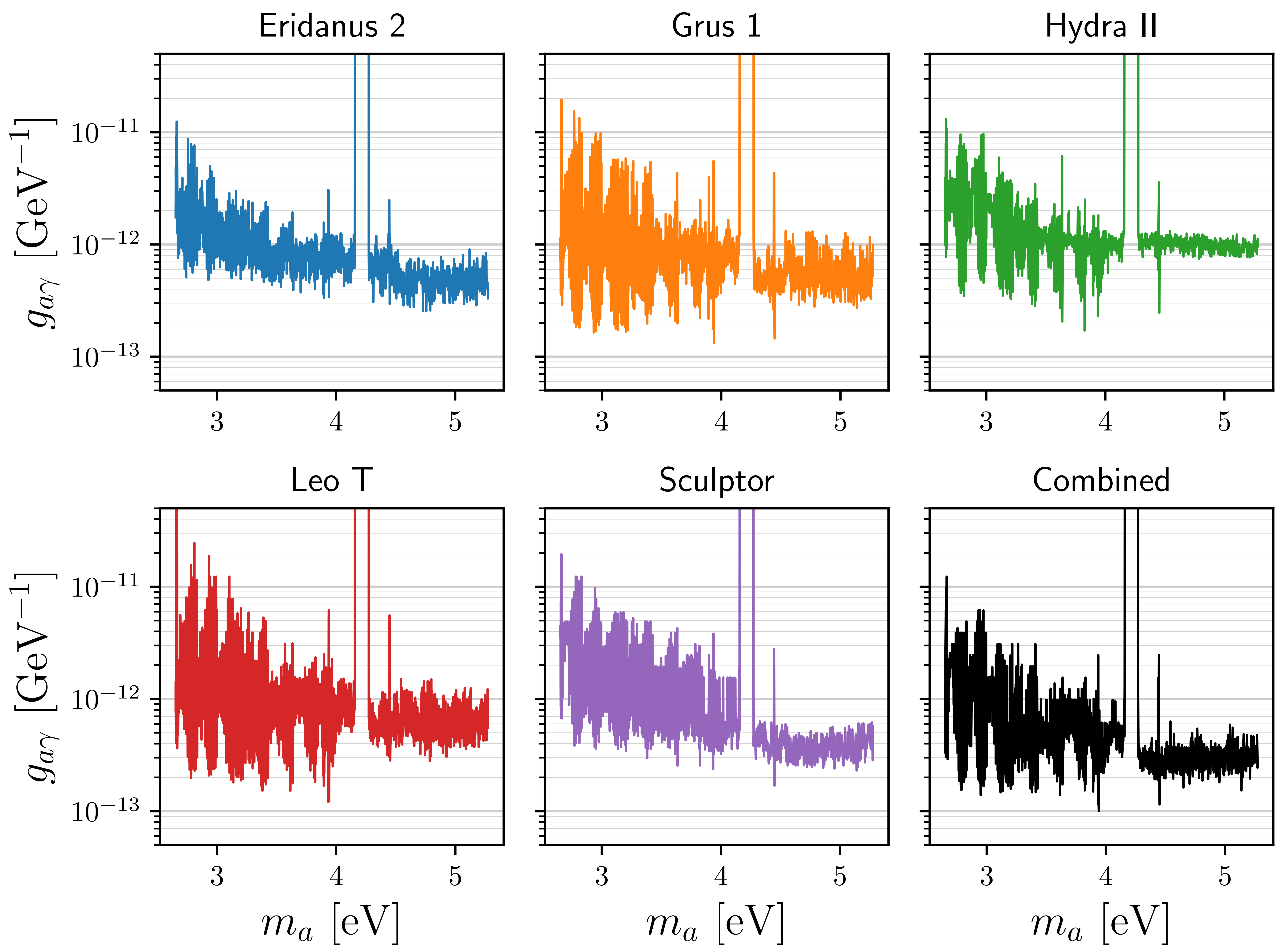
$$S_\lambda(\theta) = \frac{\Gamma_a}{4\pi}\frac{1}{\sqrt{2\pi}\sigma_\lambda}\, e^{-\frac{(\lambda-\lambda_{obs})^2}{2\sigma_\lambda^2}}\int d\Omega\, d\ell \rho_a[r(\theta,\Omega,\ell)]\, B(\Omega)$$

Signal

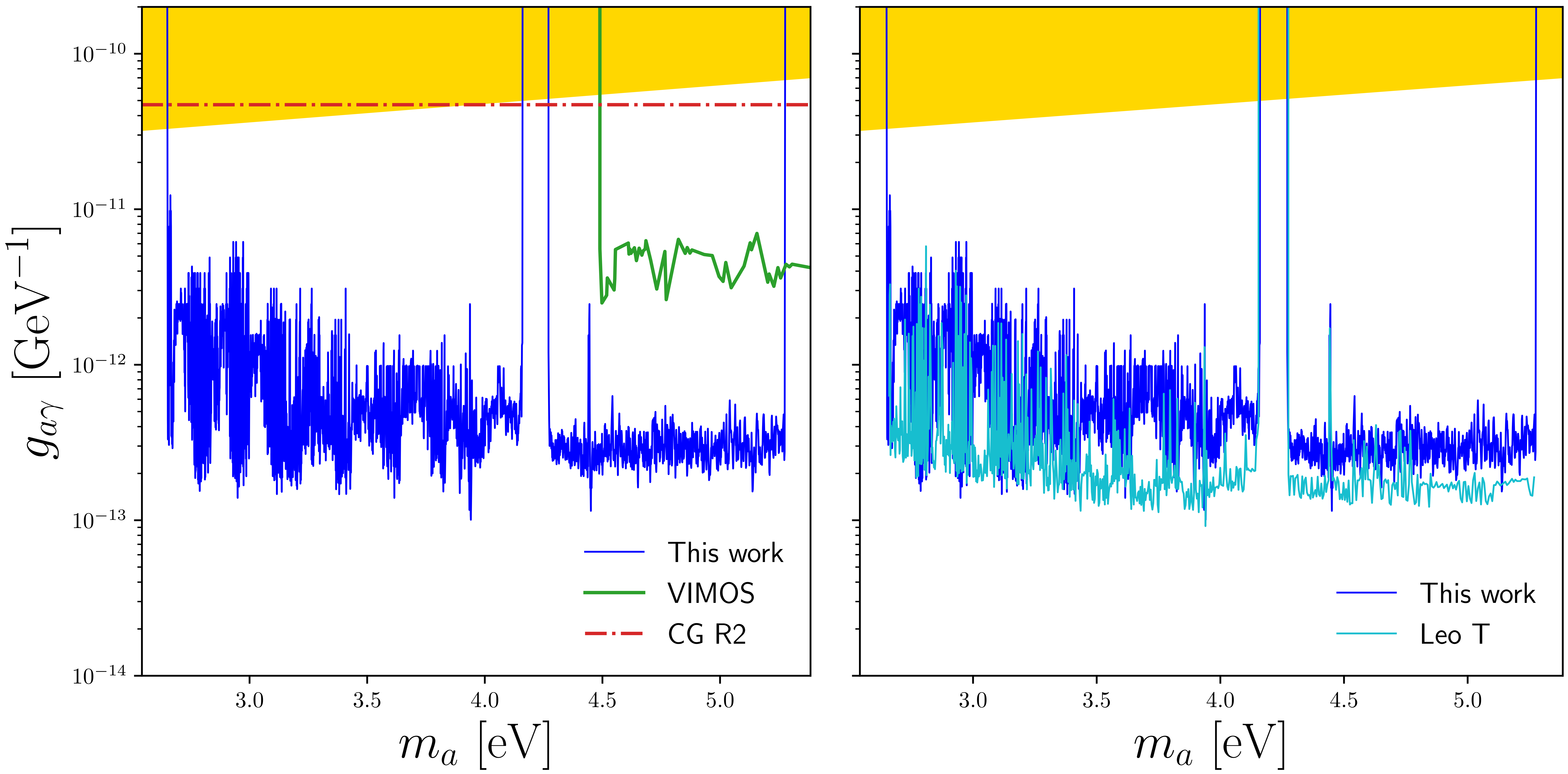


Marco Regis, Taoso, Vaz, Brinchmann, Zoutendijk, Bouché, Steinmetz
PLB 814 (2021) 136075

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]



10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
$g_{a\gamma}$ [GeV^{-1}]
3.0
3.5
4.0
4.5
5.0
m_a [eV]
This work
VIMOS
CG R2
Leo T

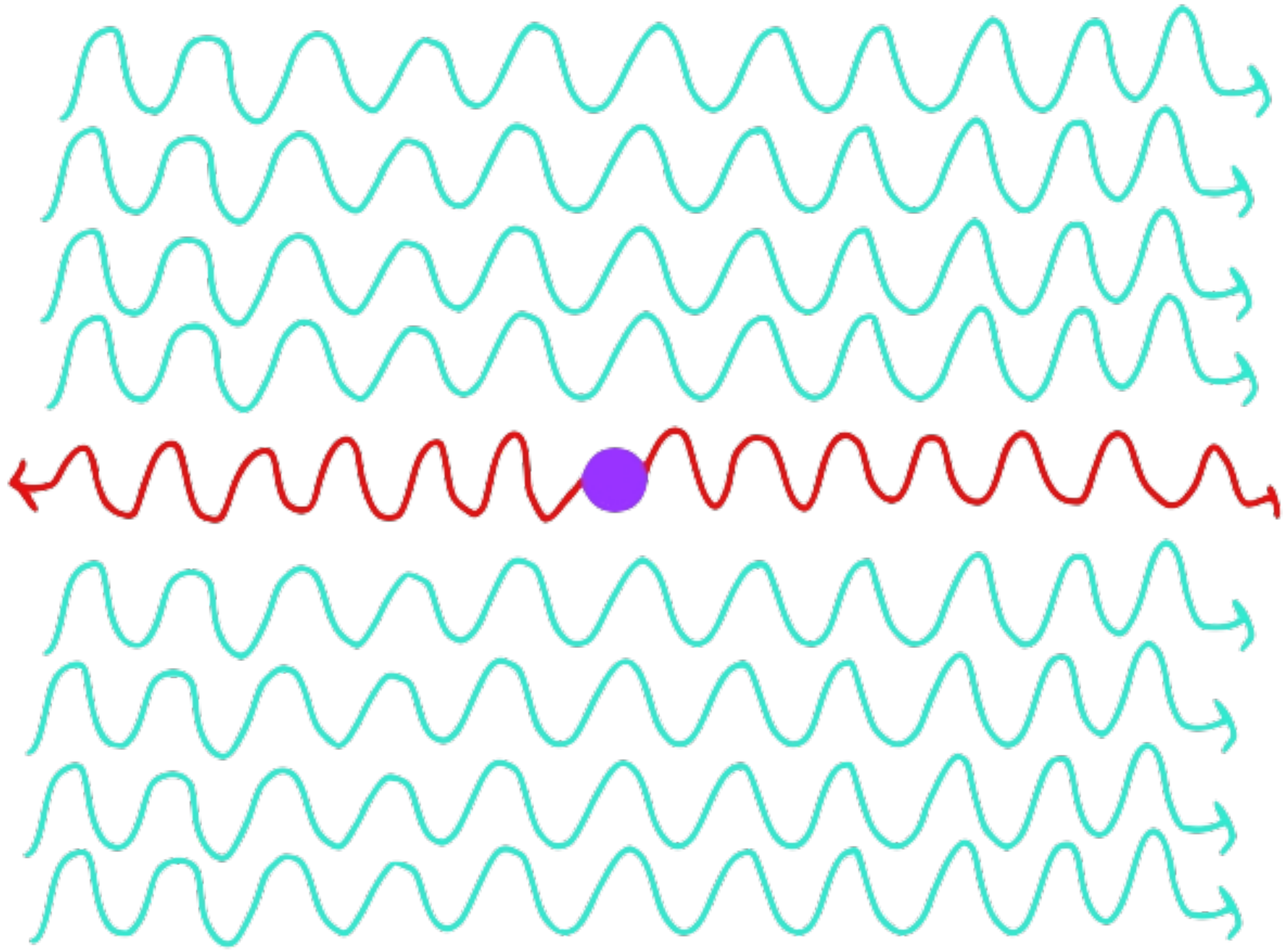
Axion stimulated decay

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

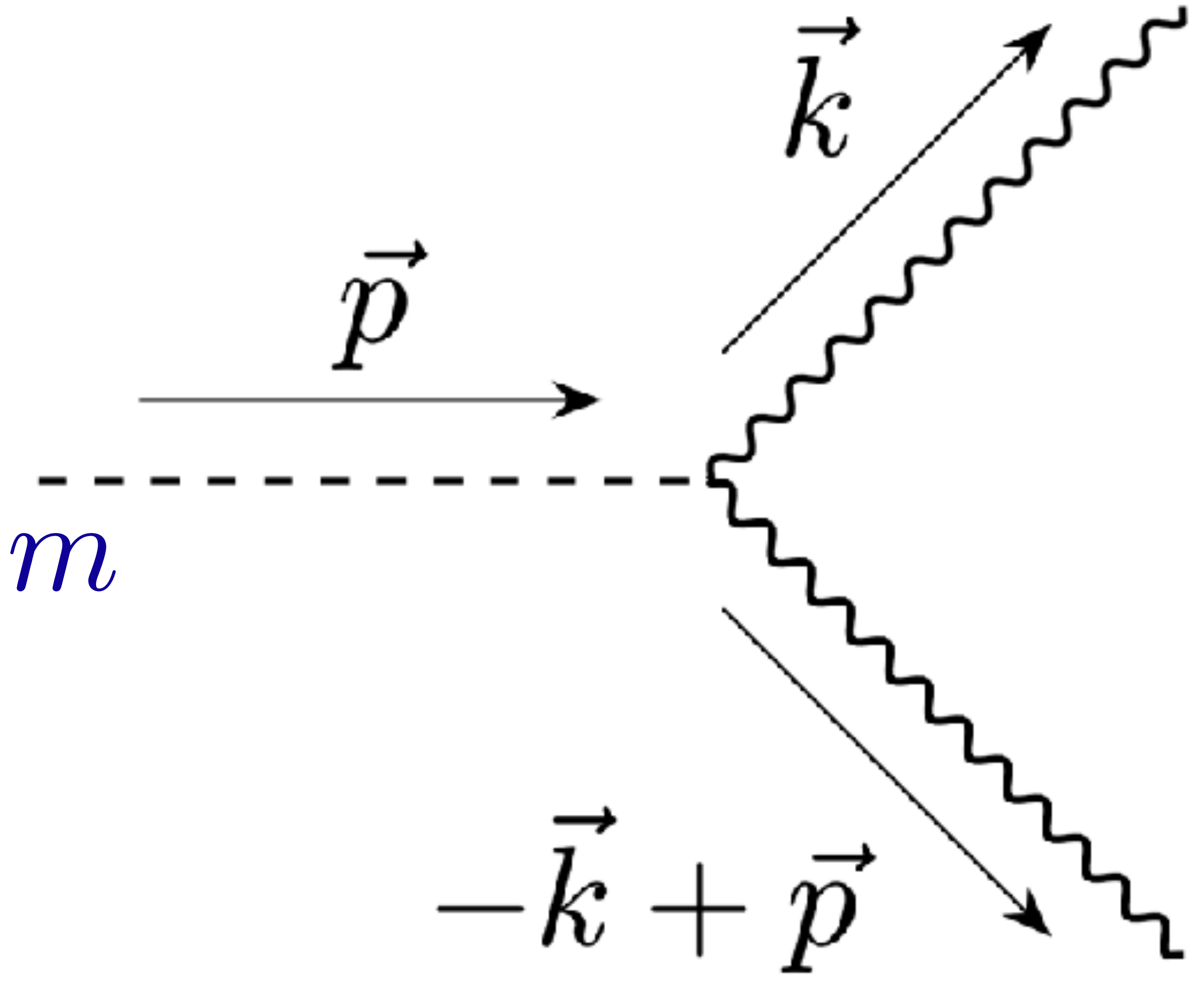
$$f_\gamma(\vec{k}\,)$$



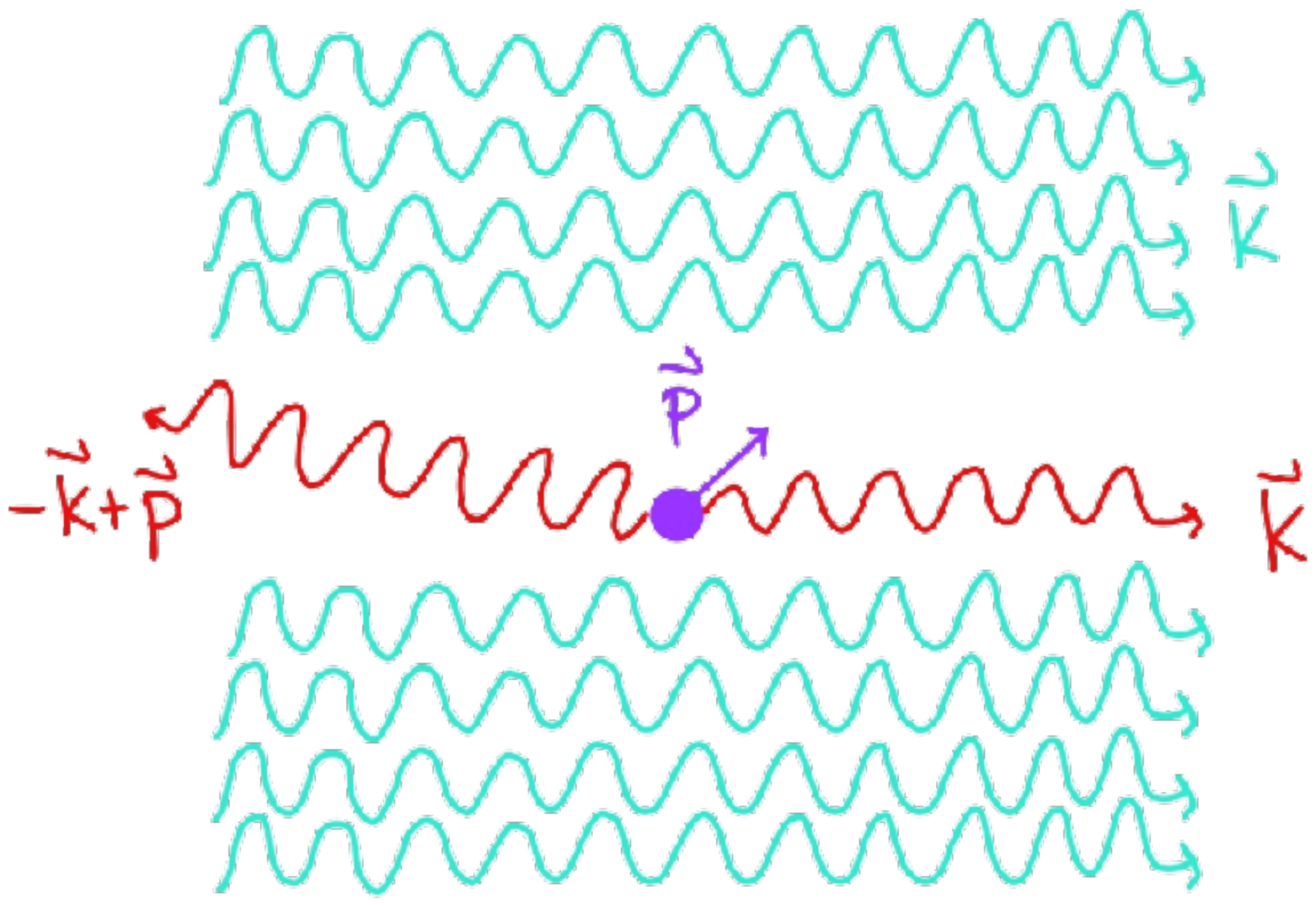
$$|\vec{k}\,| \sim \frac{m}{2}$$

Kinematics

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



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

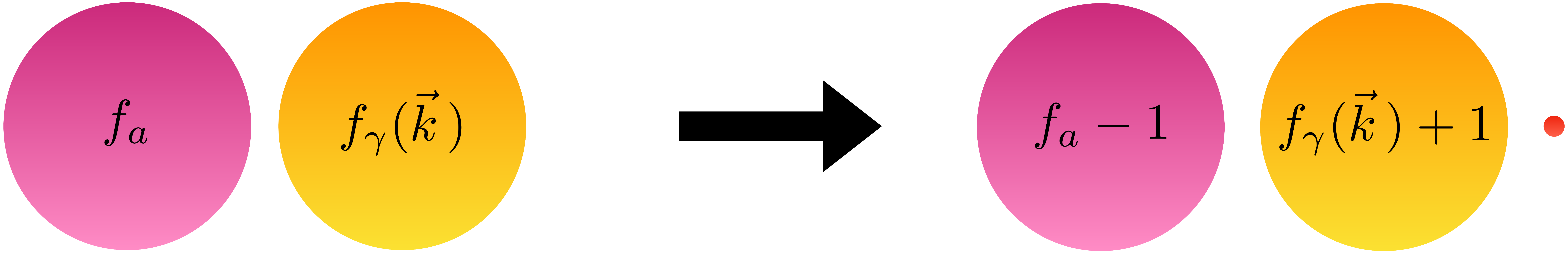


The echo propagates

***almost* backwards!**

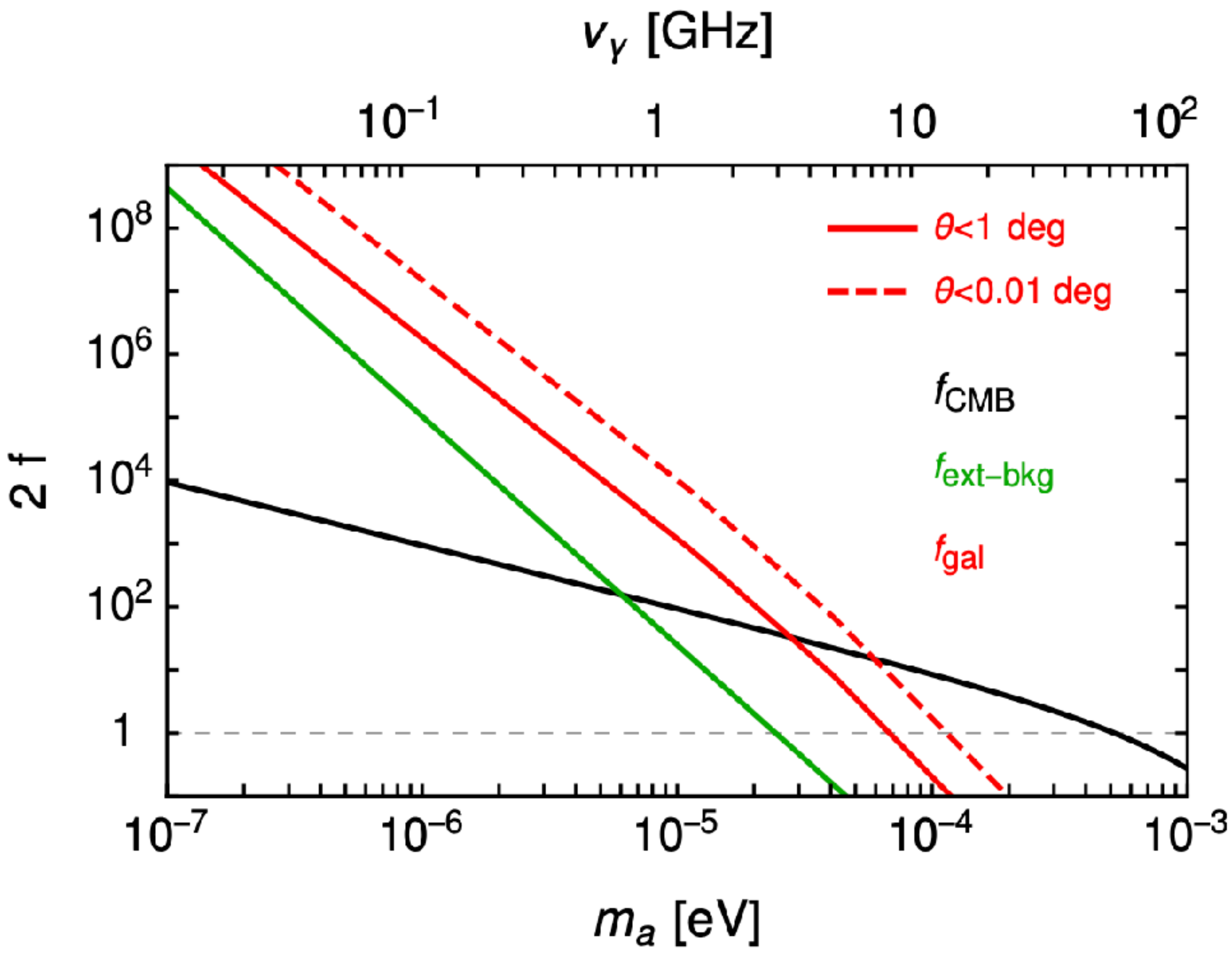
Bose-enhancement

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



- A photon of momentum $-\vec{k}$ is created
- Decay rate is enhanced compared to vacuum by a factor $f_\gamma(\vec{k})$

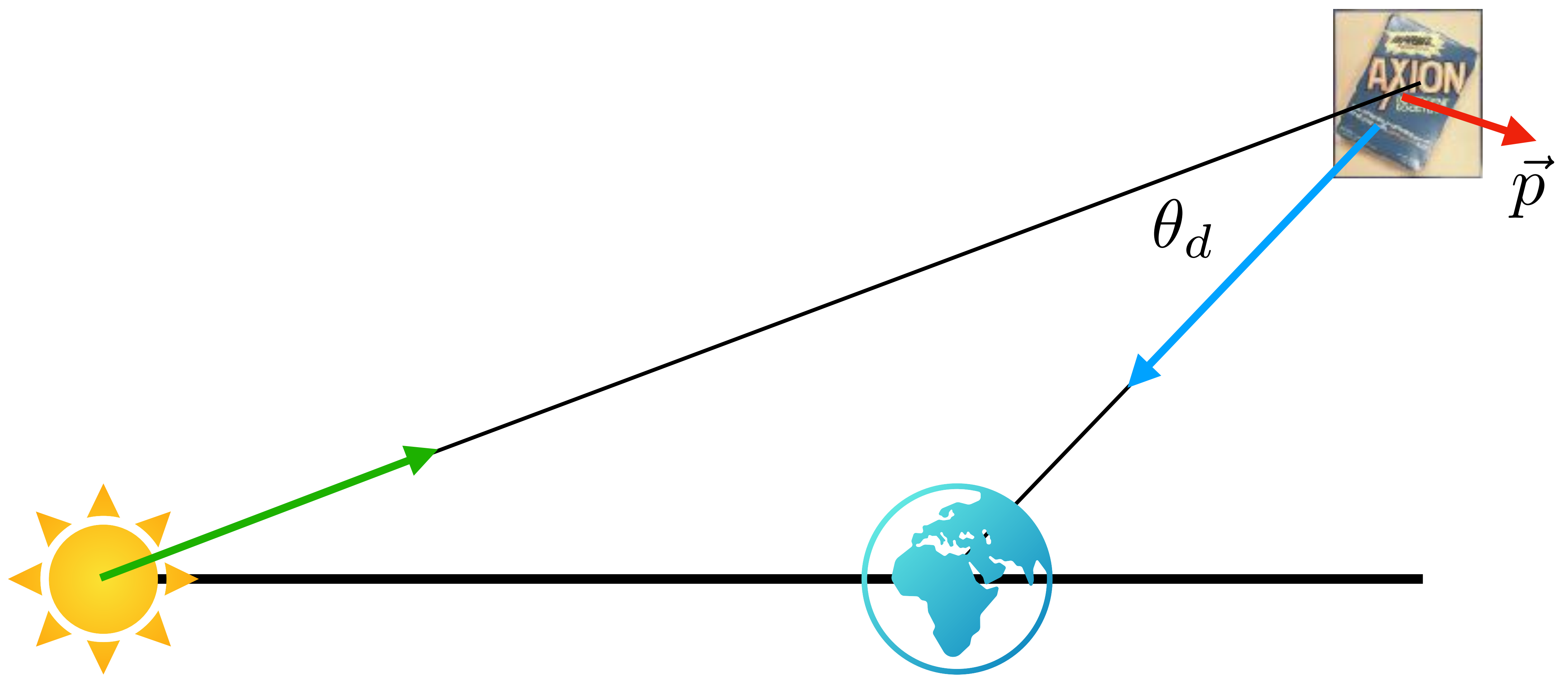
Enhancement factor



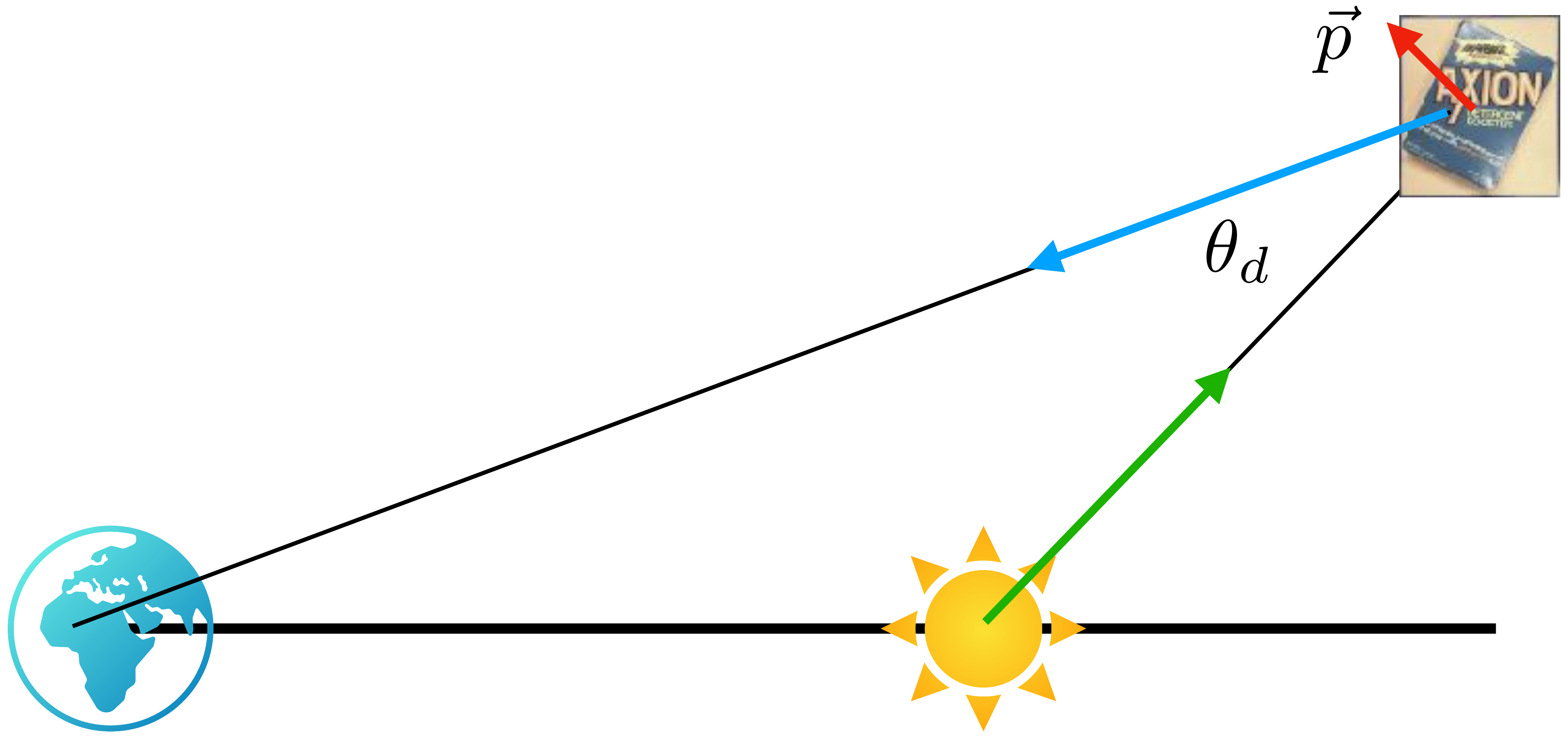
Caputo, Regis, Taoso, Witte, JCAP 03 (2019) 027

Echoes from natural sources

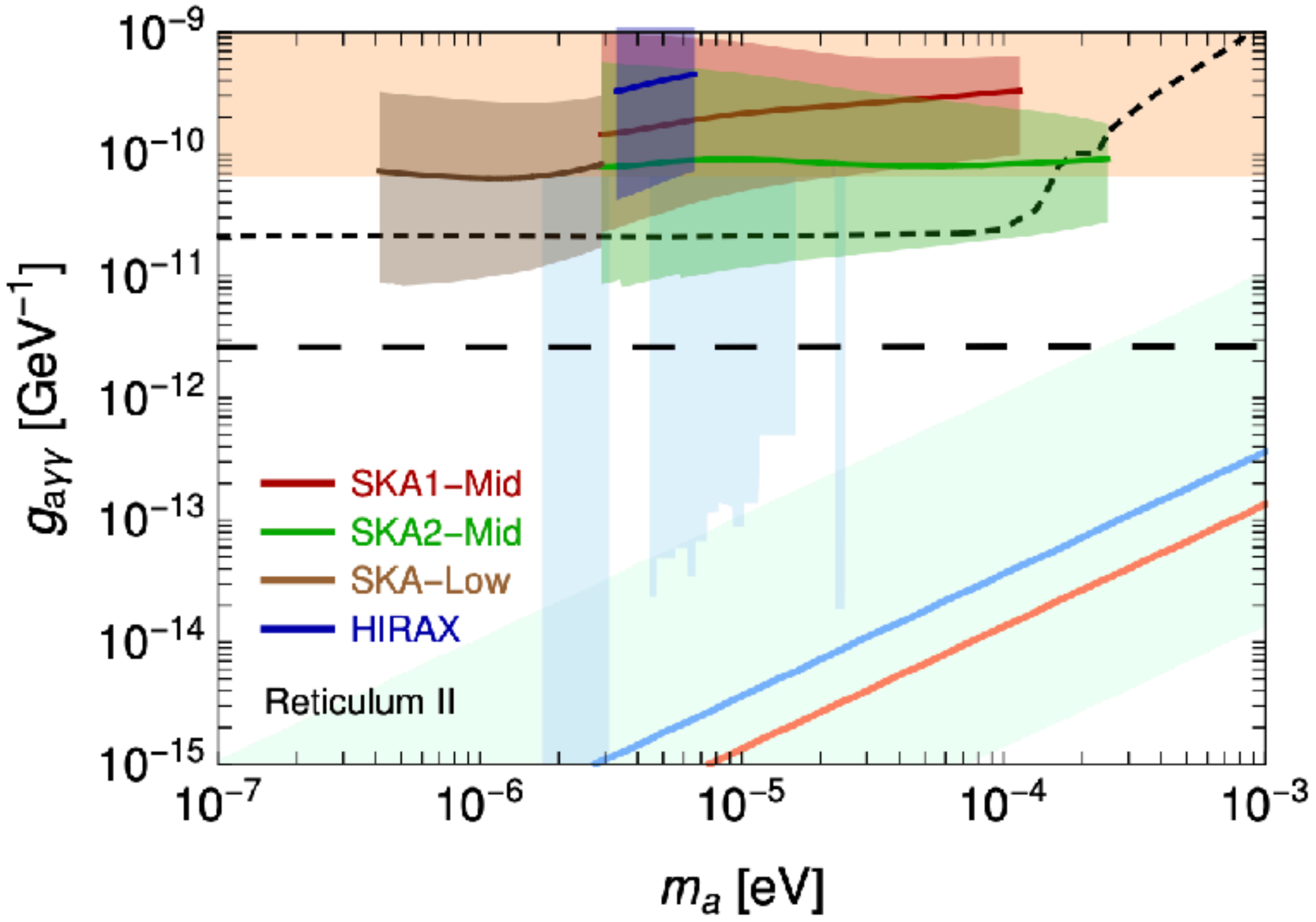
Back-light echo



Front-light echo



Collinear emission



Caputo, Regis, Taoso, Witte

JCAP 03 (2019) 027

Collinear emission

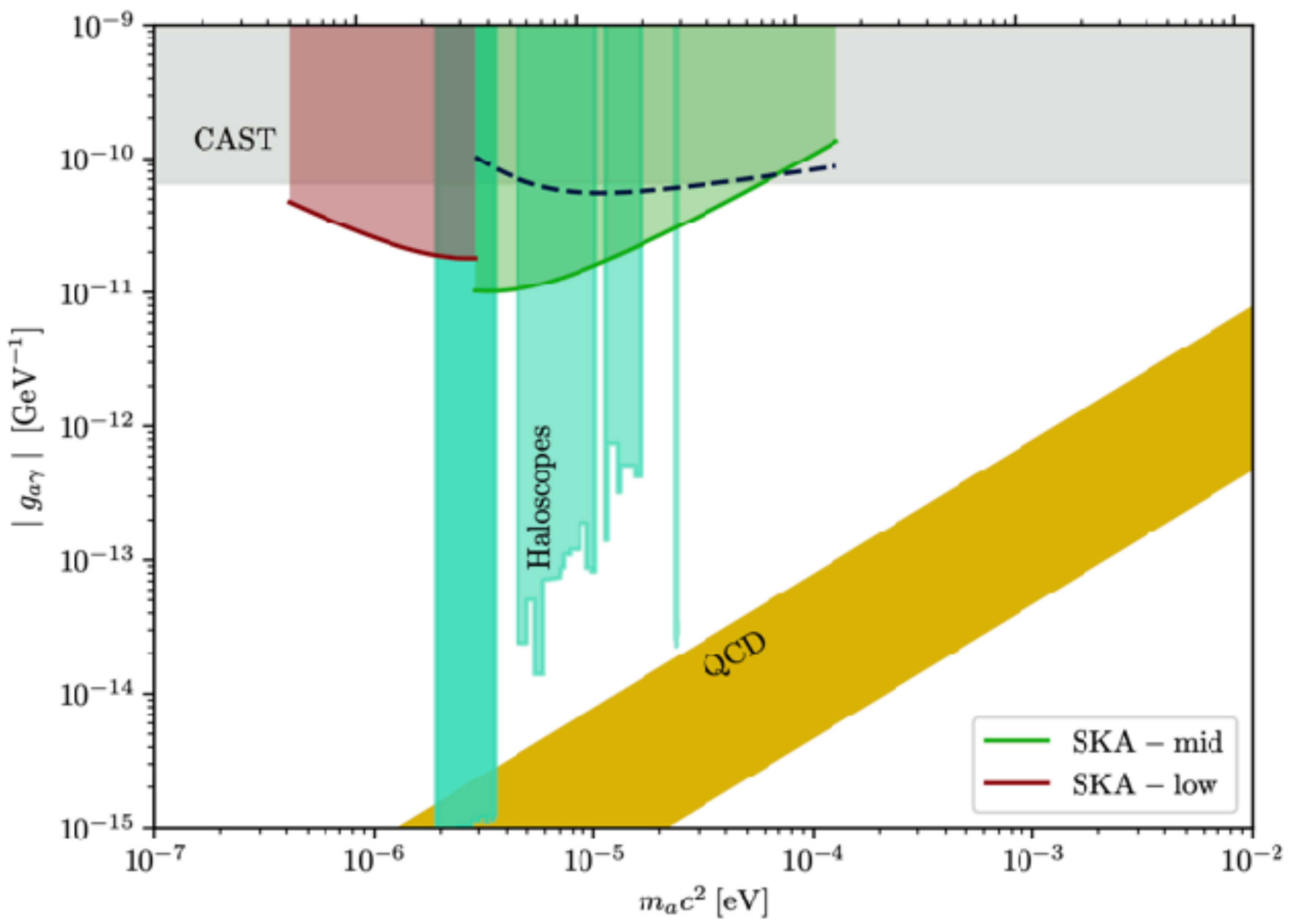
CMB, extragalactic radio bkg

Ghosh, Salvado, Miralda-Escudé

2008.02729

Backlight echo

Cygnus A

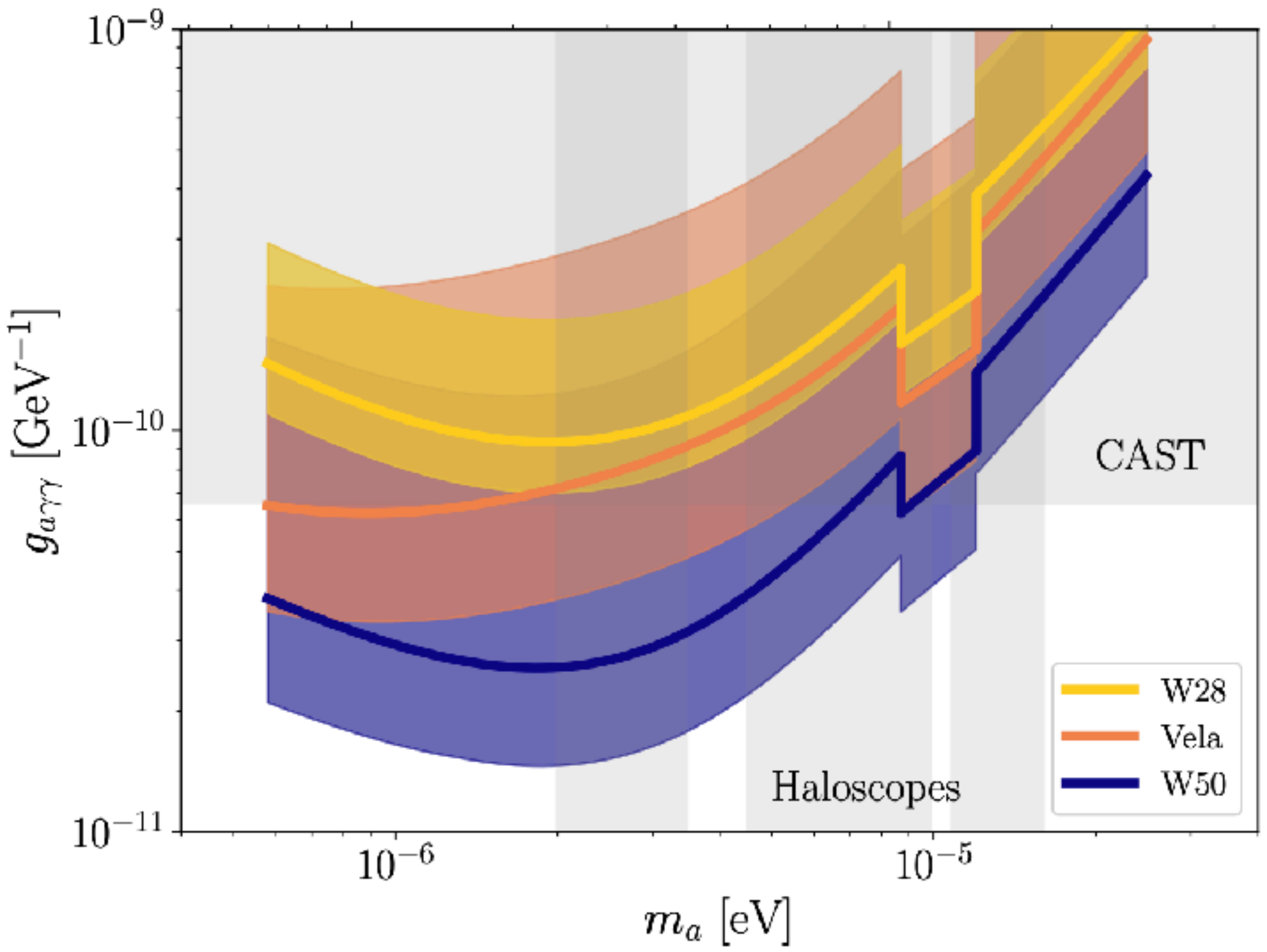


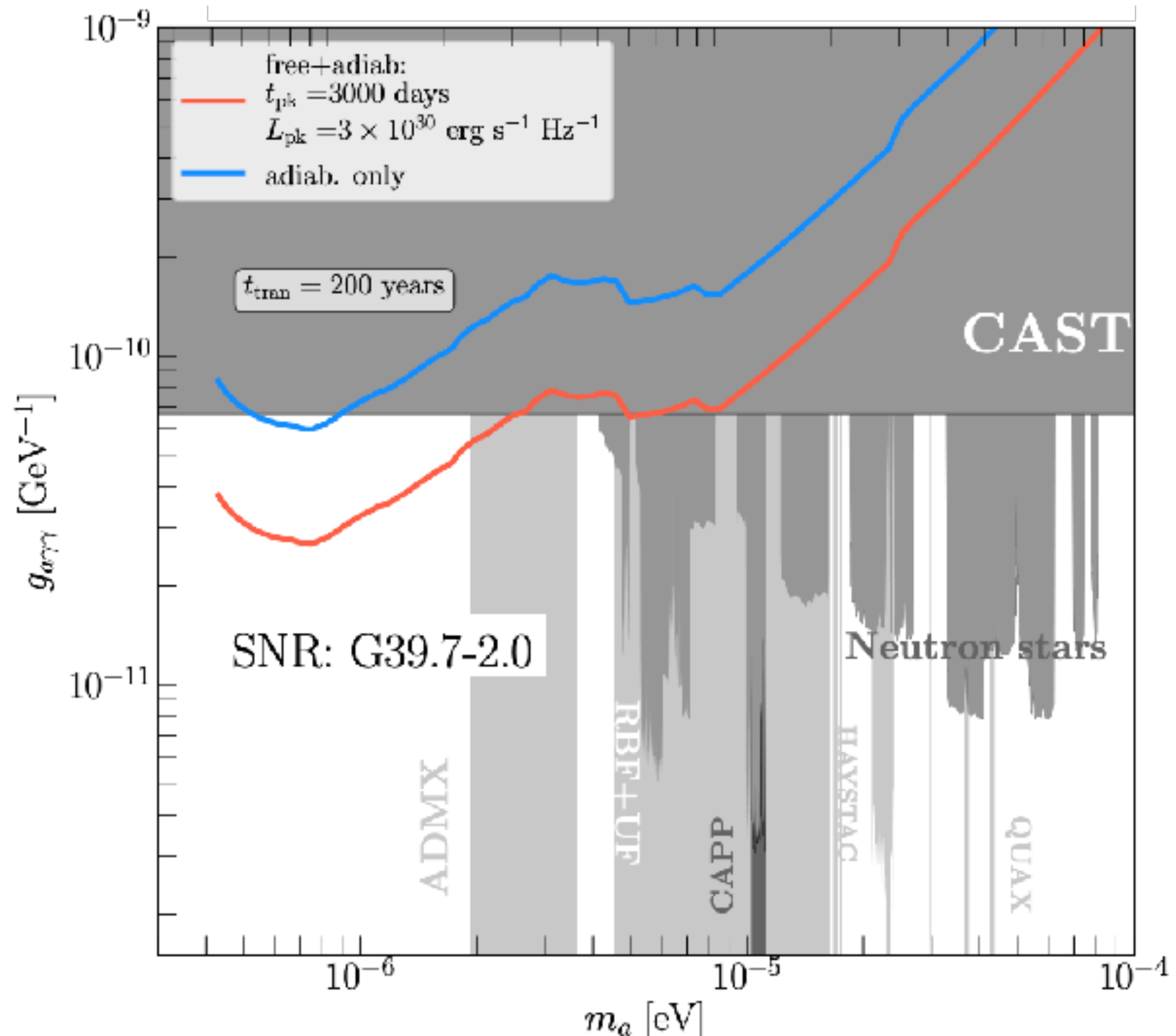
Sun, Schutz, Nambrath, Leung, Masui

PRD 105 (2022)

Backlight echo

Supernova remnant





Buen-Abad, Fan, Sun

PRD 105 (2022)

Backlight echo

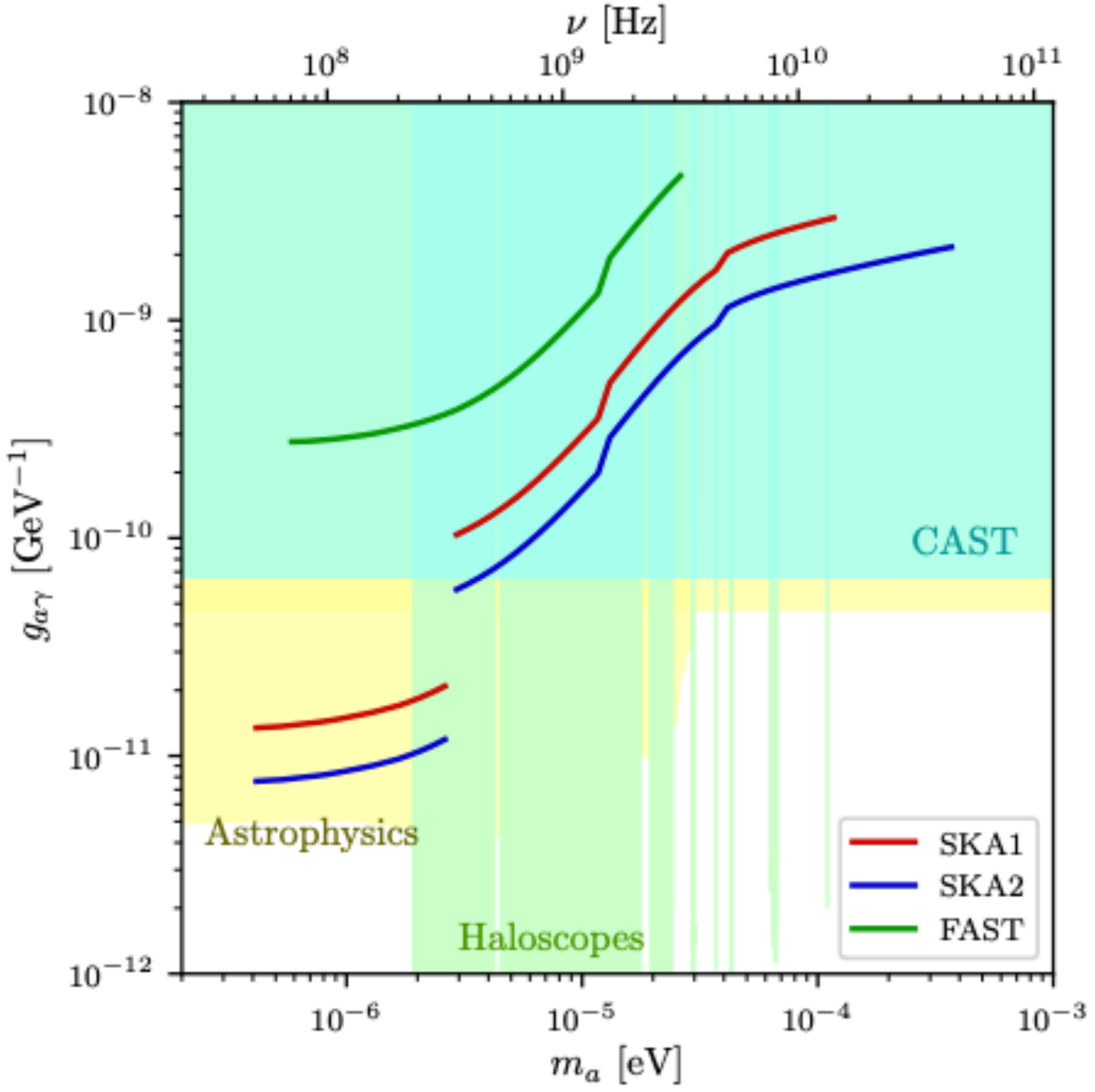
Supernova remnant

Dev, Ferrer, Okawa

JCAP 04 (2024) 045

Backlight echo

Galactic center

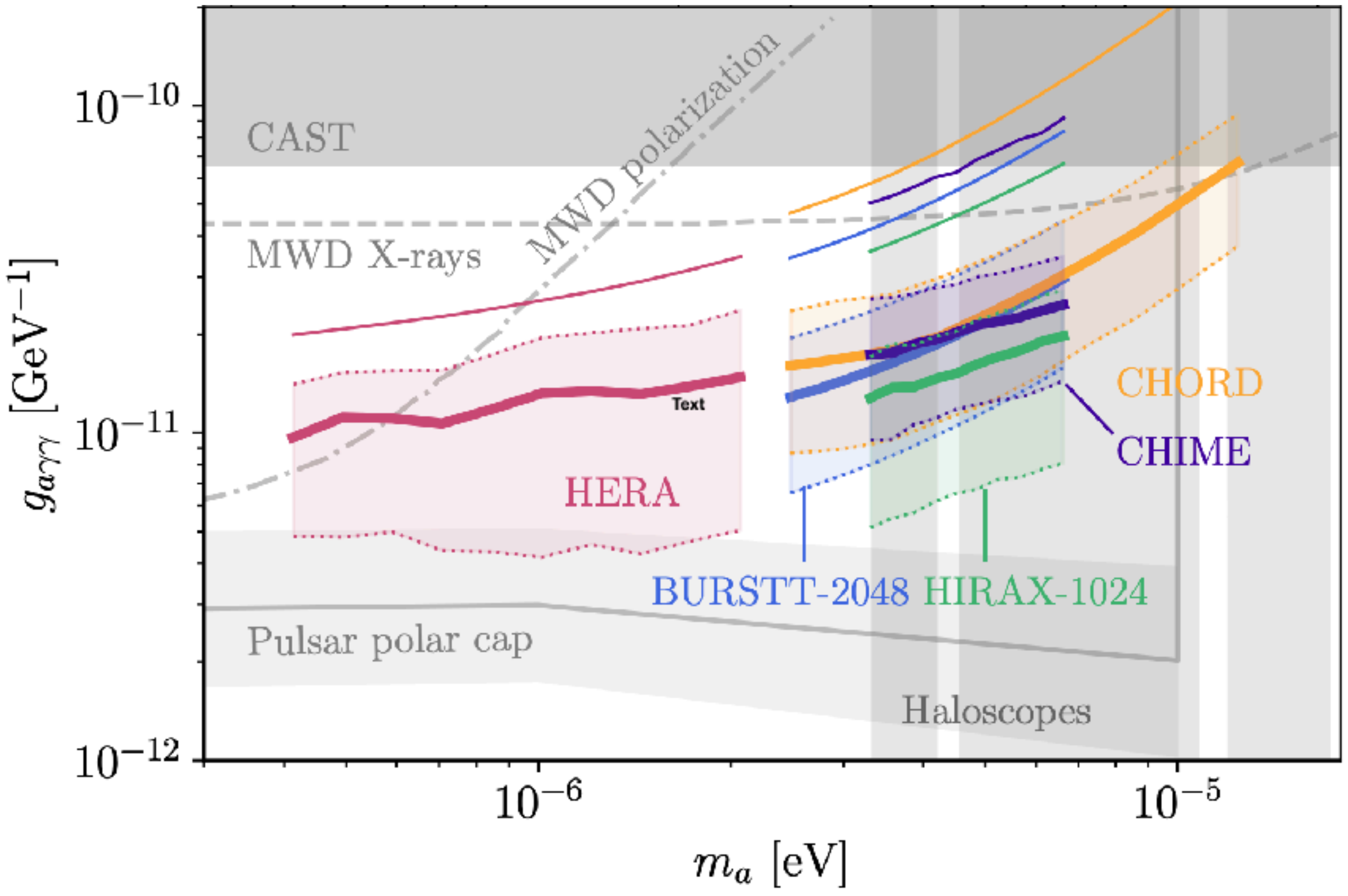


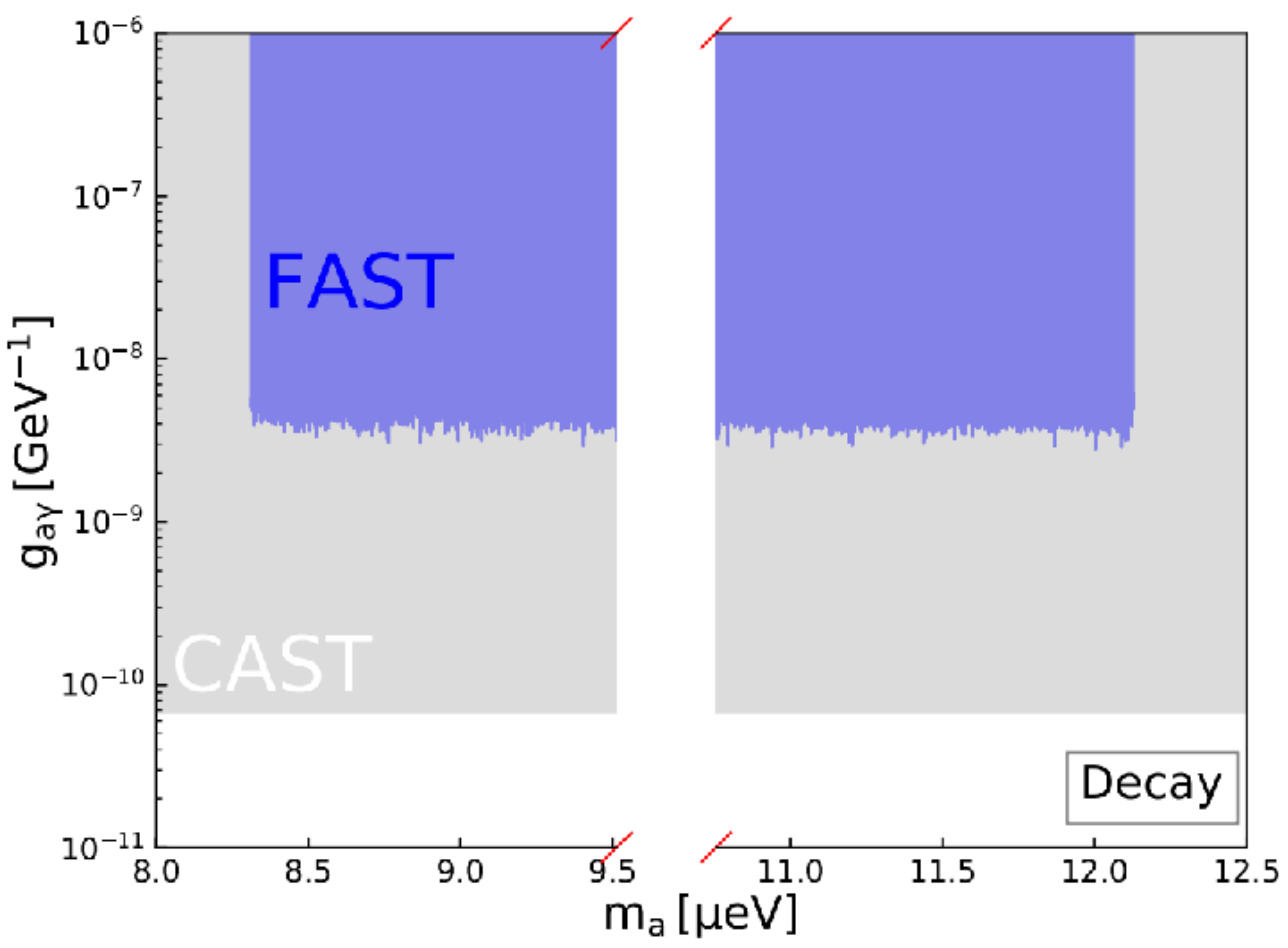
Sun, Schutz, Sewalls, Leung, Wesley Masui

PRD 109 (2024)

Everything

Extragalactic radio point sources, SNRs, Galactic synchrotron radiation





Guo, Xia, Huang

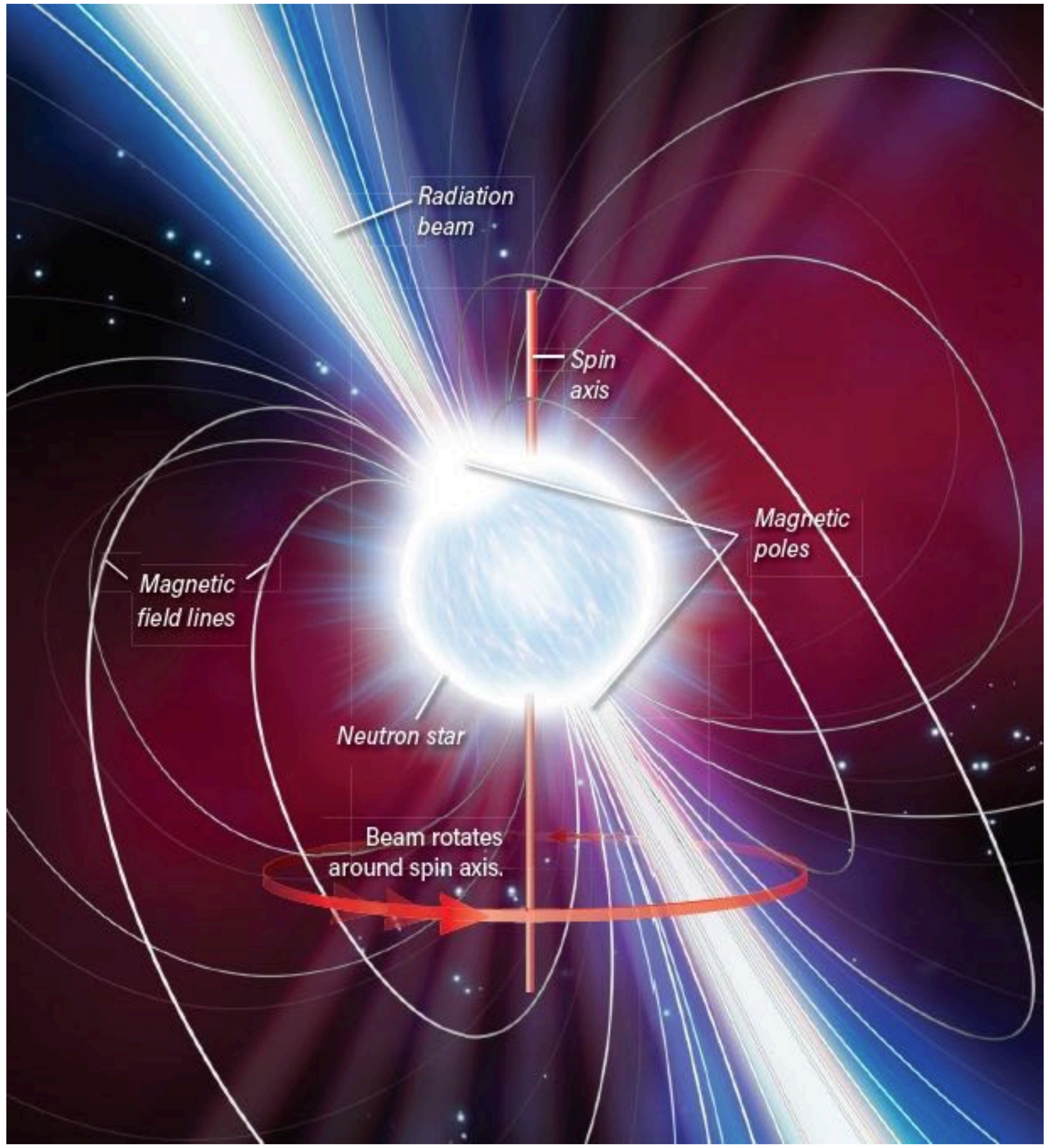
PLB 852 (2024) 138631

Collinear emission

CMB, extragalactic radio bkg

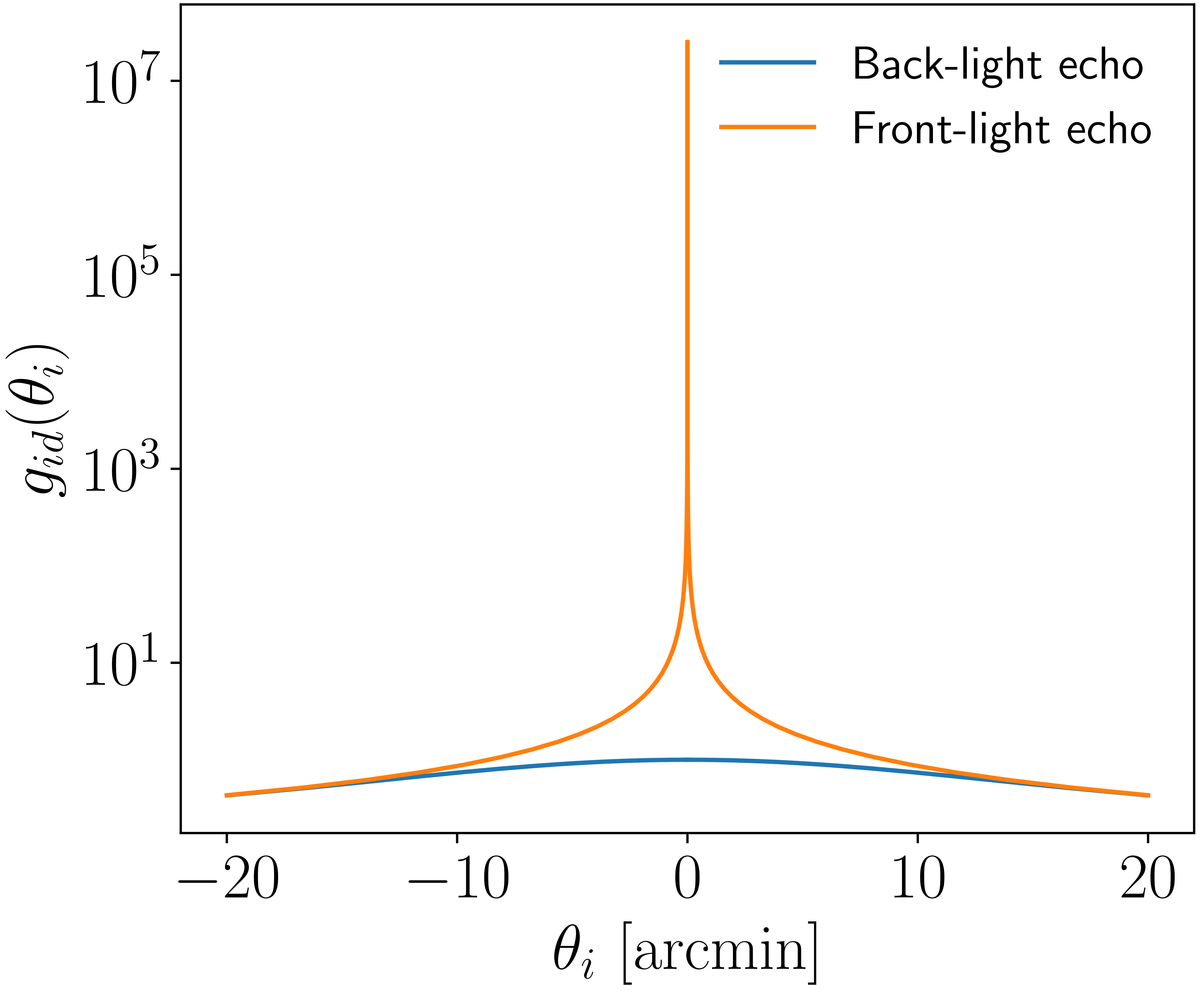
REAL DATA 2-hour observation of Coma Berenices

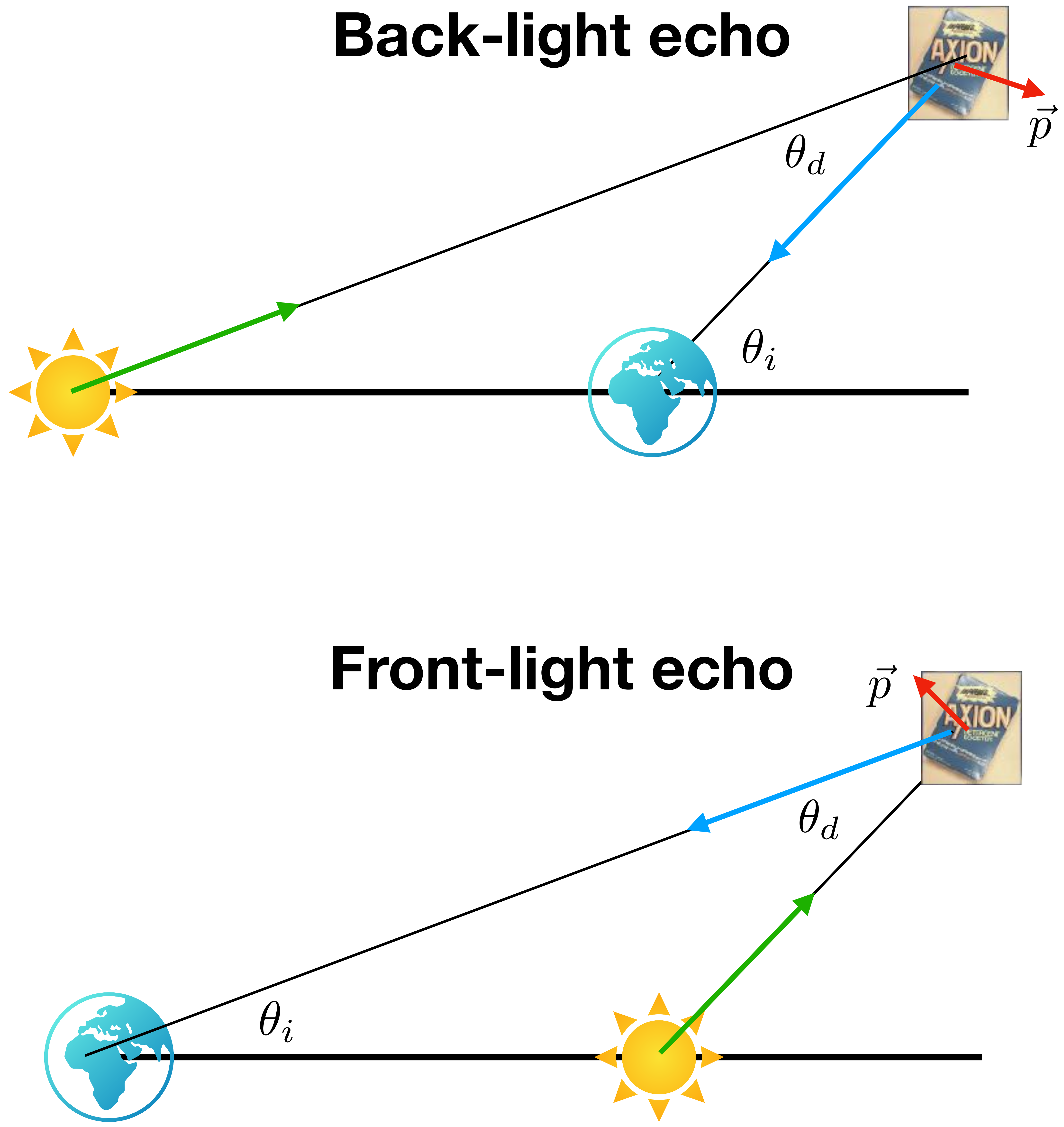
Detailed Study of the Echo from a Point Source



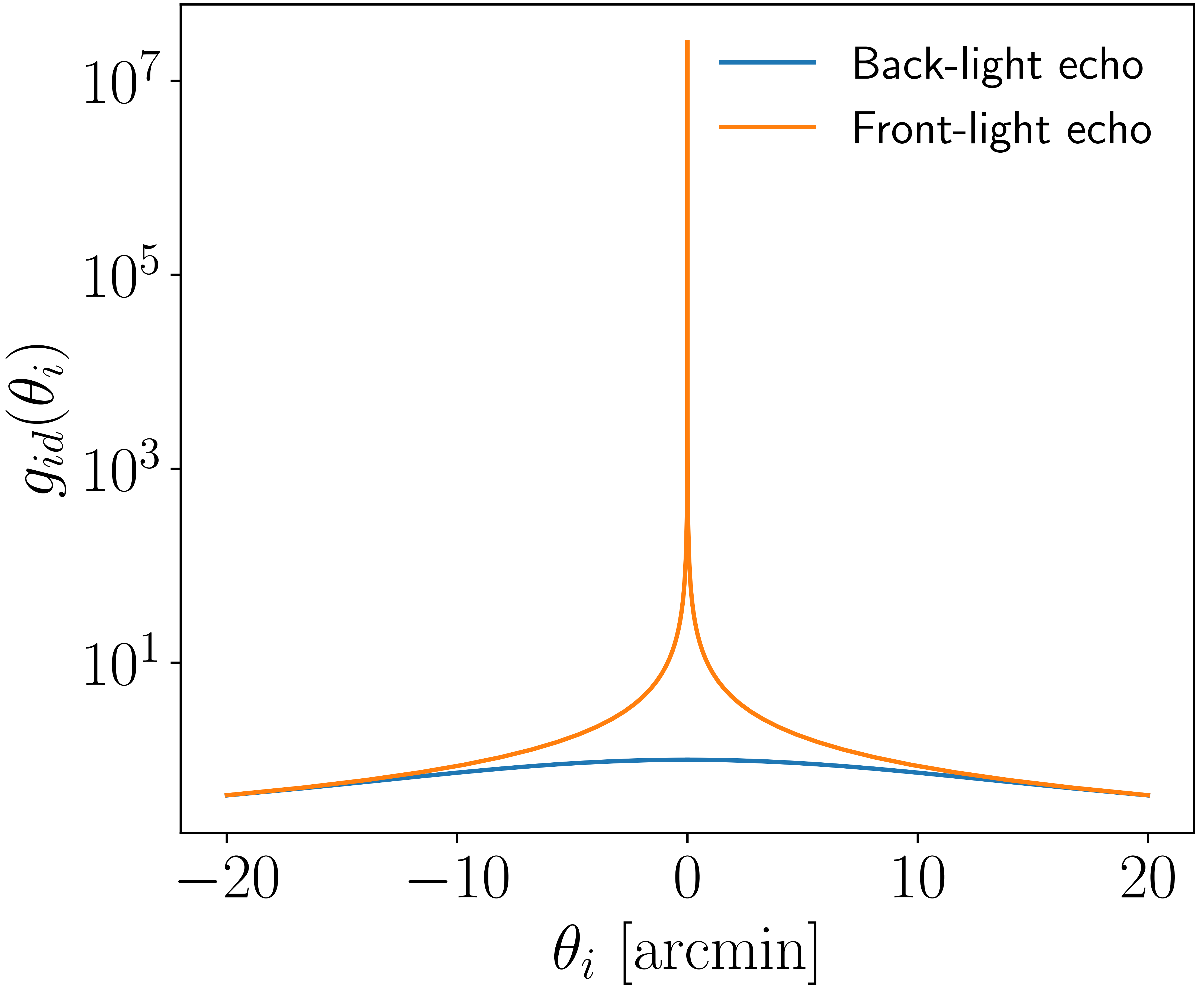
E.T., F. Calore, M. Regis, JCAP 05 (2024) 040

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



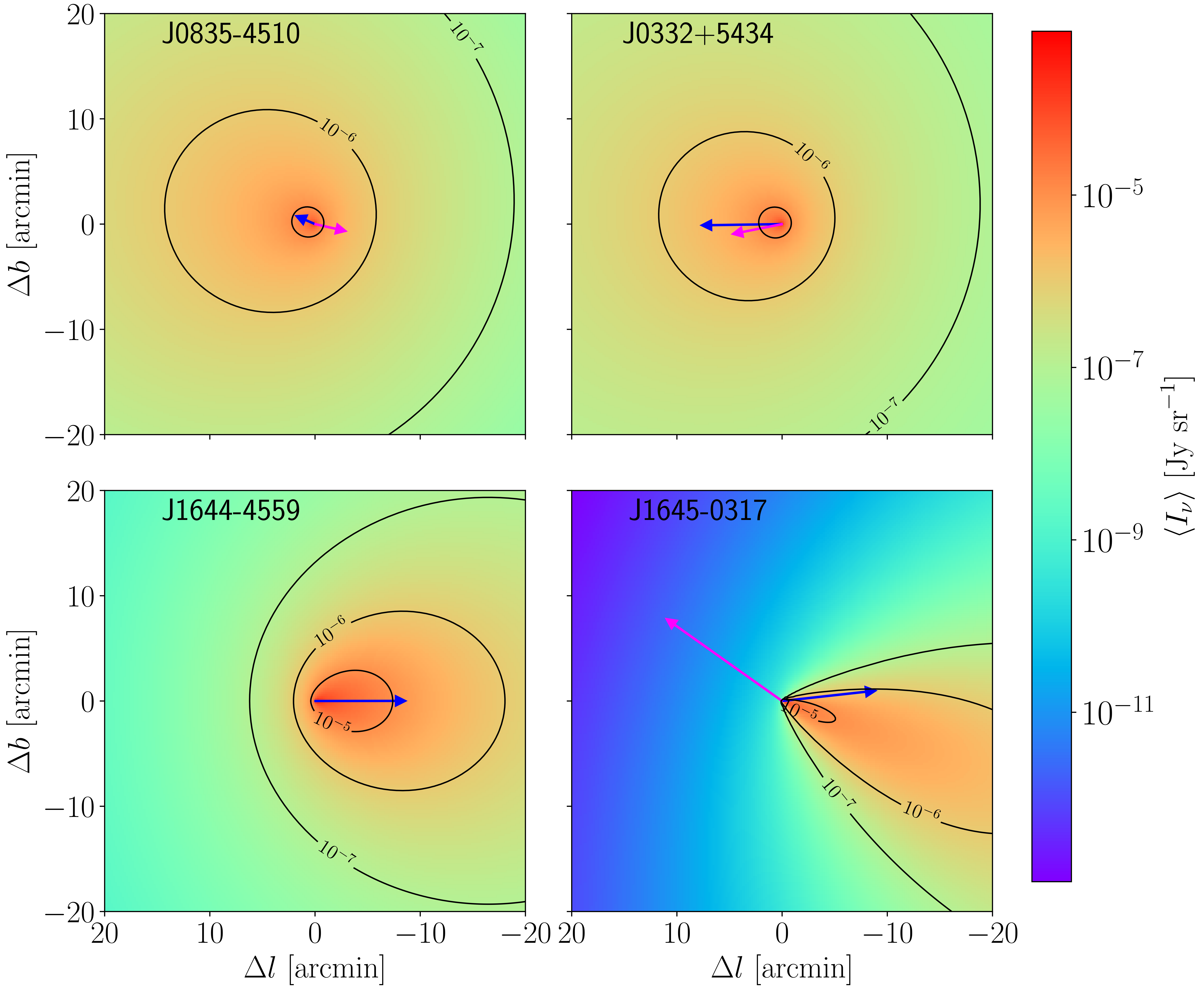


$$\theta_{i,0} \sim 2\delta v$$

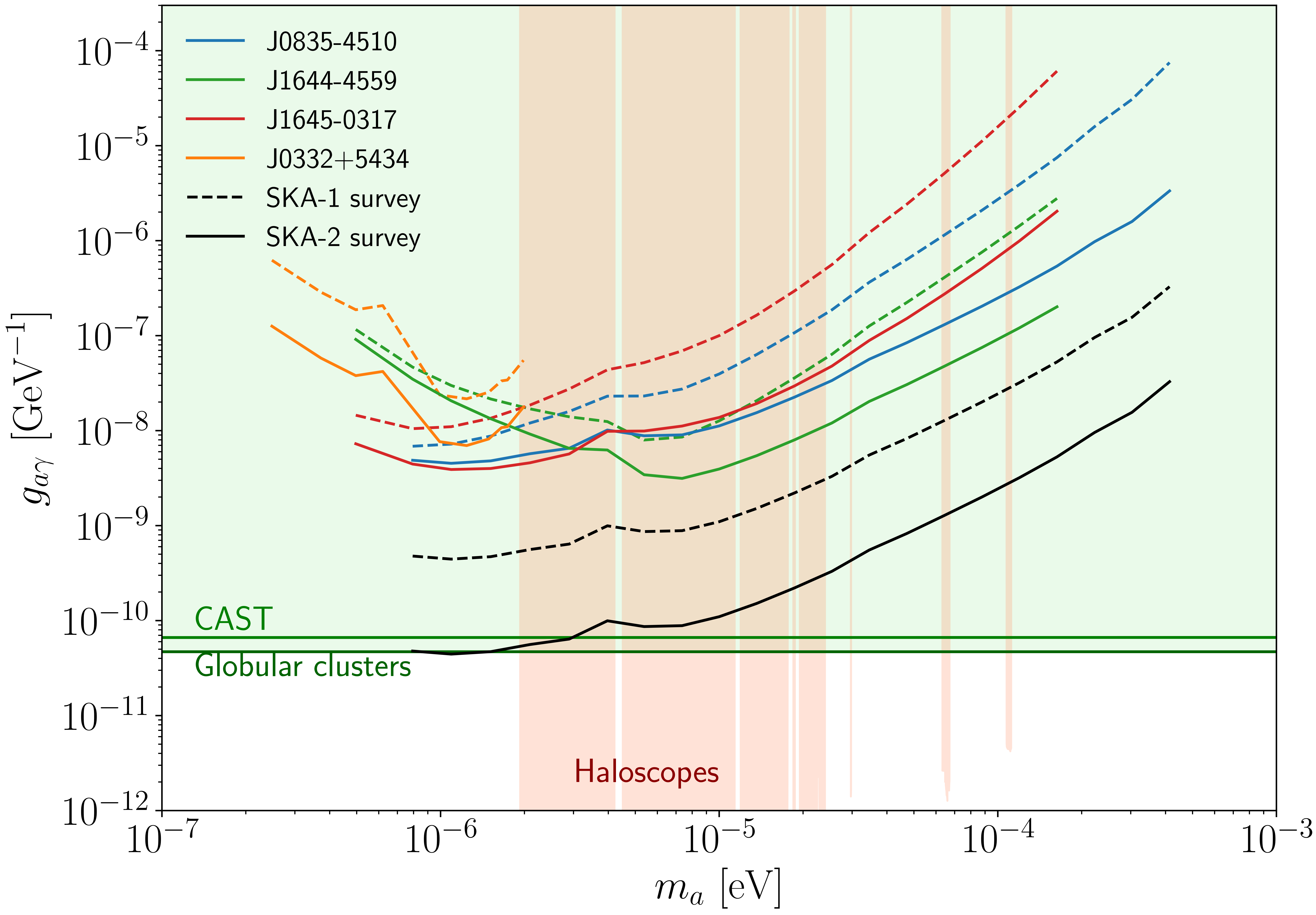


Relevant effects

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



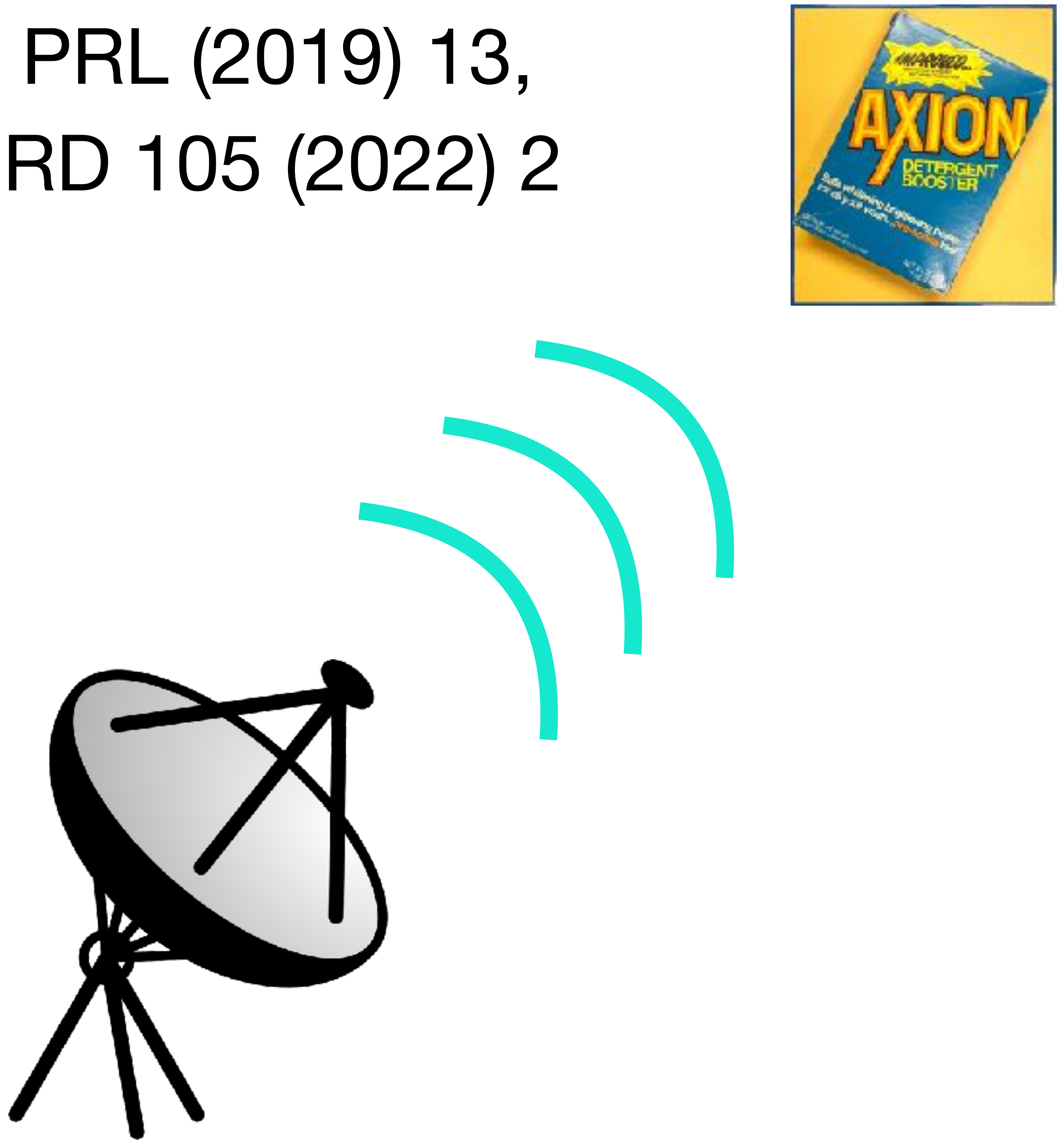
J0835-4510
J0332+5434
J1644-4559
J1645-0317
10^{-7}
10^{-6}
10^{-5}
Δb [arcmin]
Δl [arcmin]
$\langle I_\nu \rangle$ [Jy sr^{-1}]
10^{-5}
10^{-7}
10^{-9}
10^{-11}
20
10
0
−10
−20



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



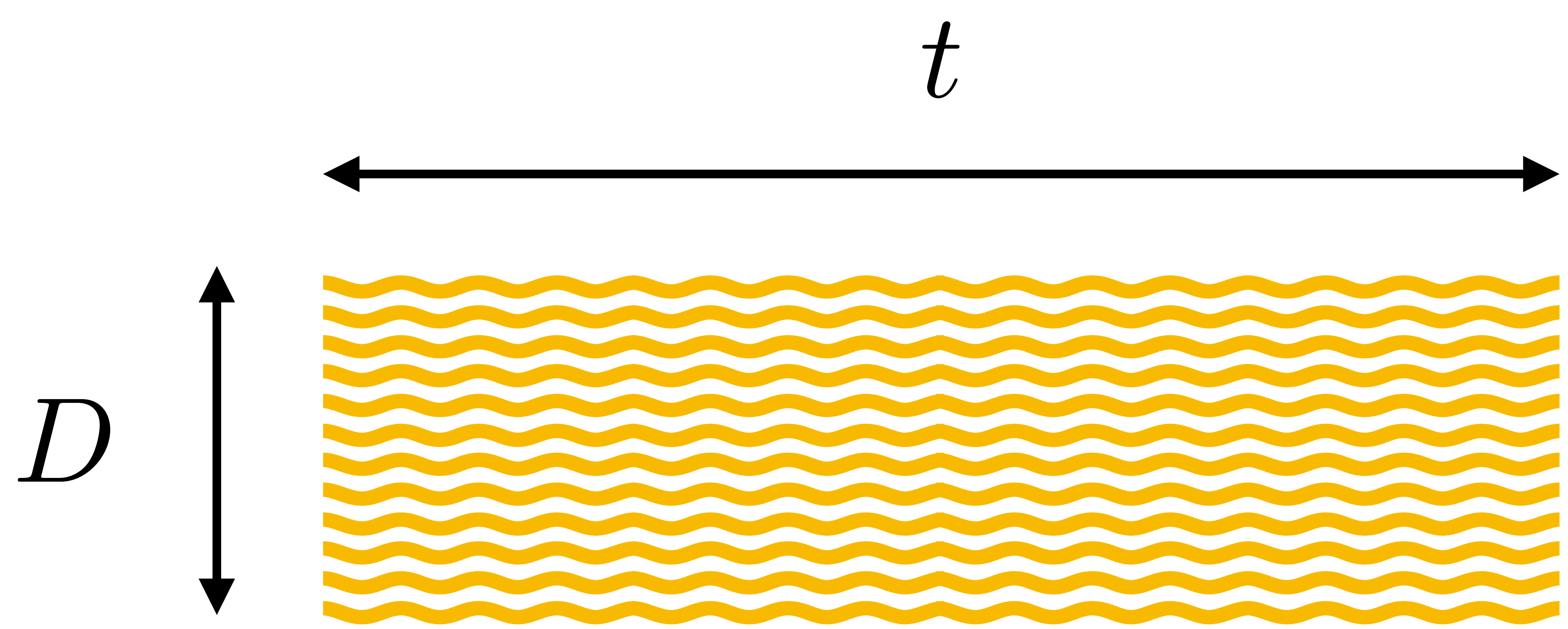
Stimulate the decay of nearby dark matter axions into photons by sending out a powerful beam to space

Detect the photons that come back

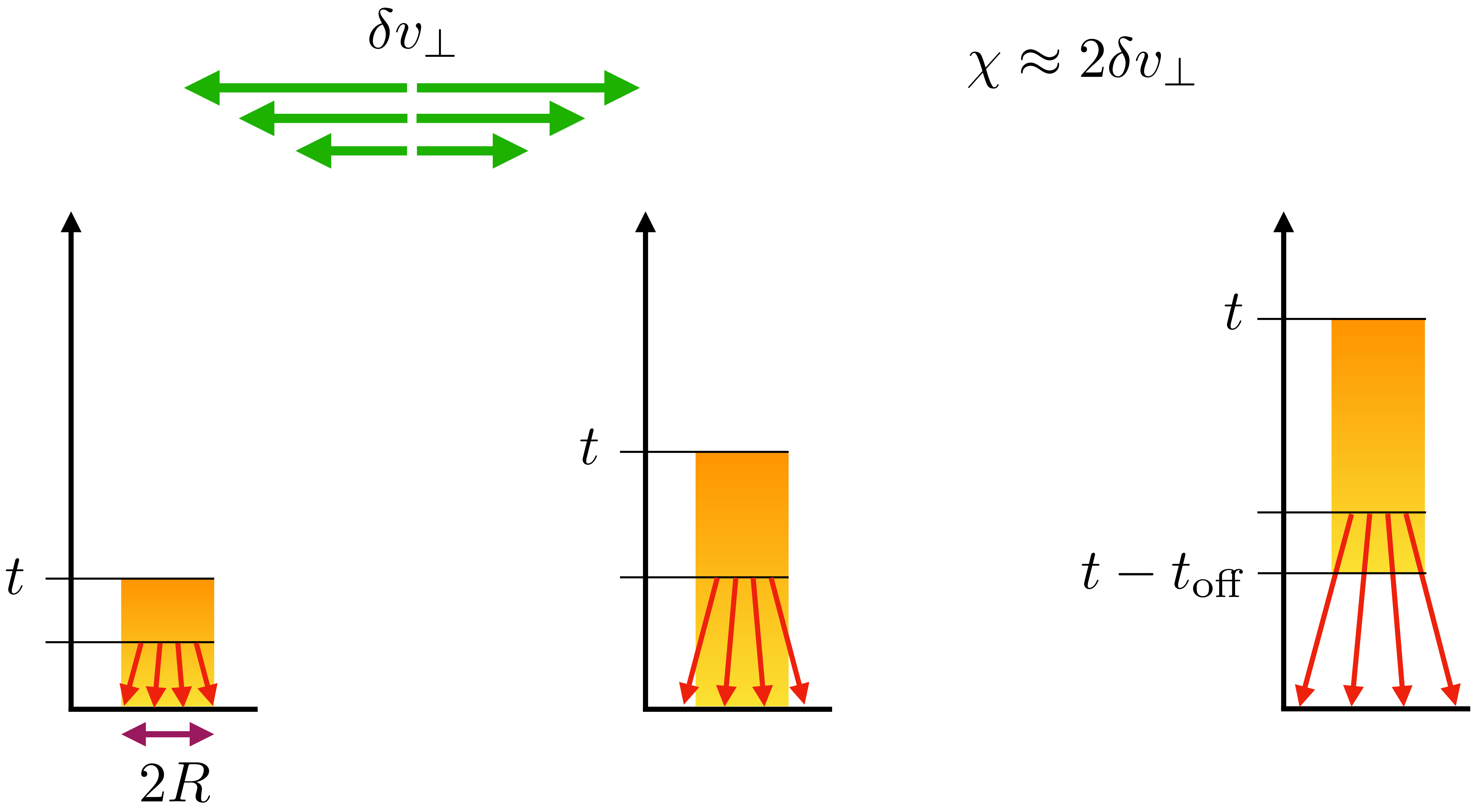
Enhancement factor

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

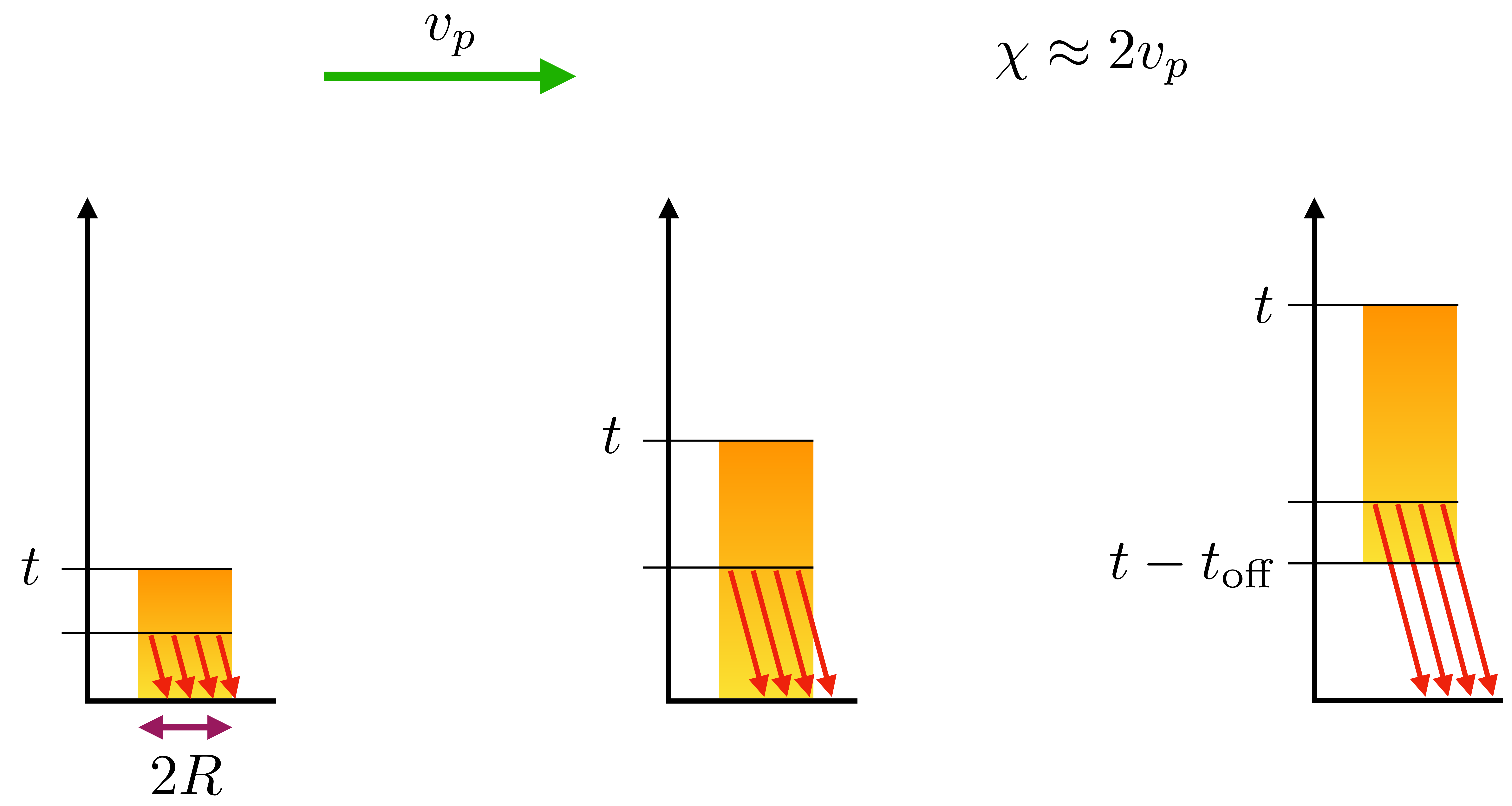
$$f_\gamma \sim 10^{20} \left(\frac{1}{n_{pol}}\right) \left(\frac{10^{-5}\ \mathrm{eV}}{m}\right)^3 \left(\frac{1\ \mathrm{m}^2}{A}\right) \left(\frac{P}{1\ \mathrm{kW}}\right) \left(\frac{1\ \mathrm{MHz}}{\Delta\nu}\right)$$

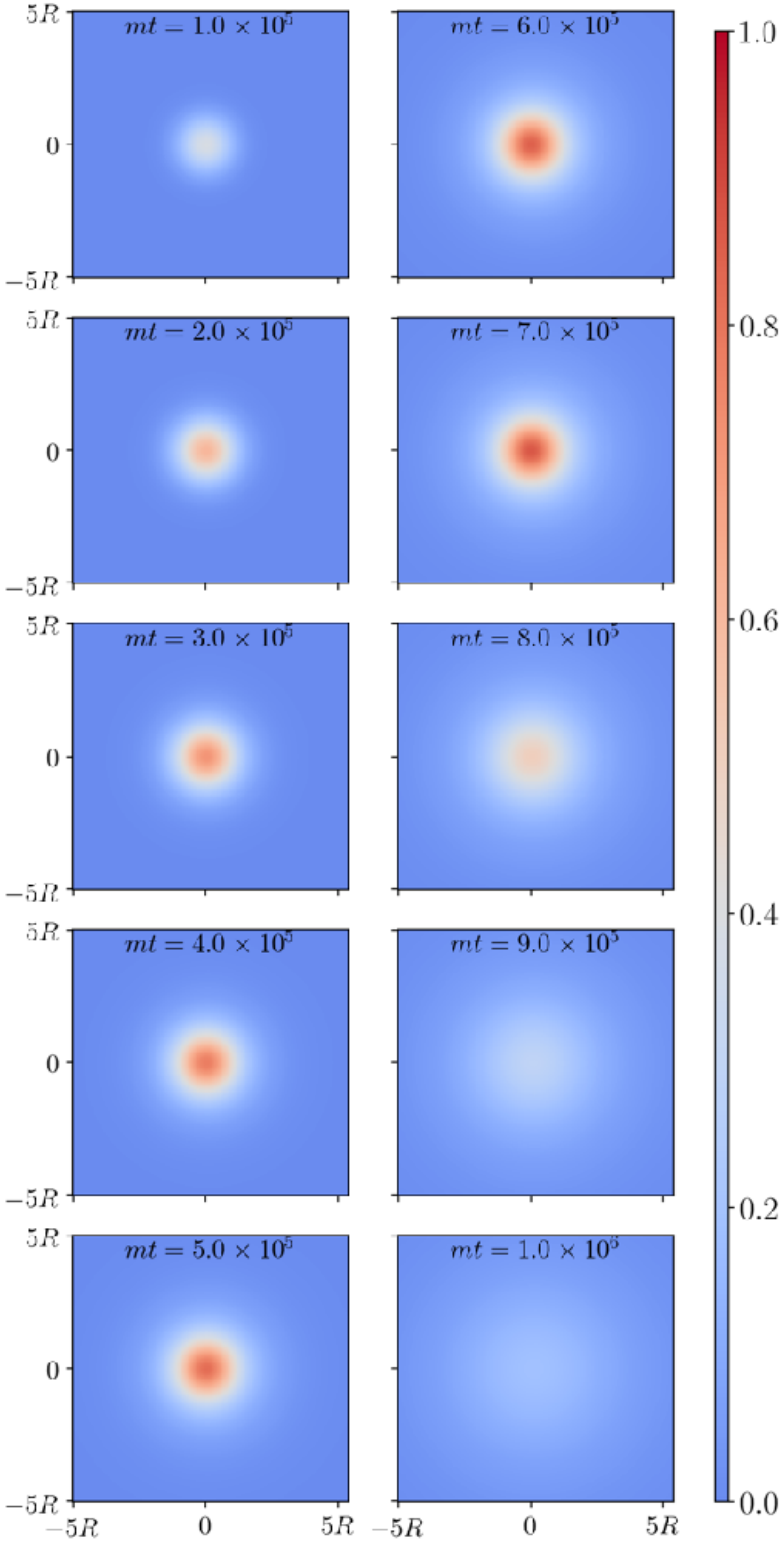


Velocity dispersion

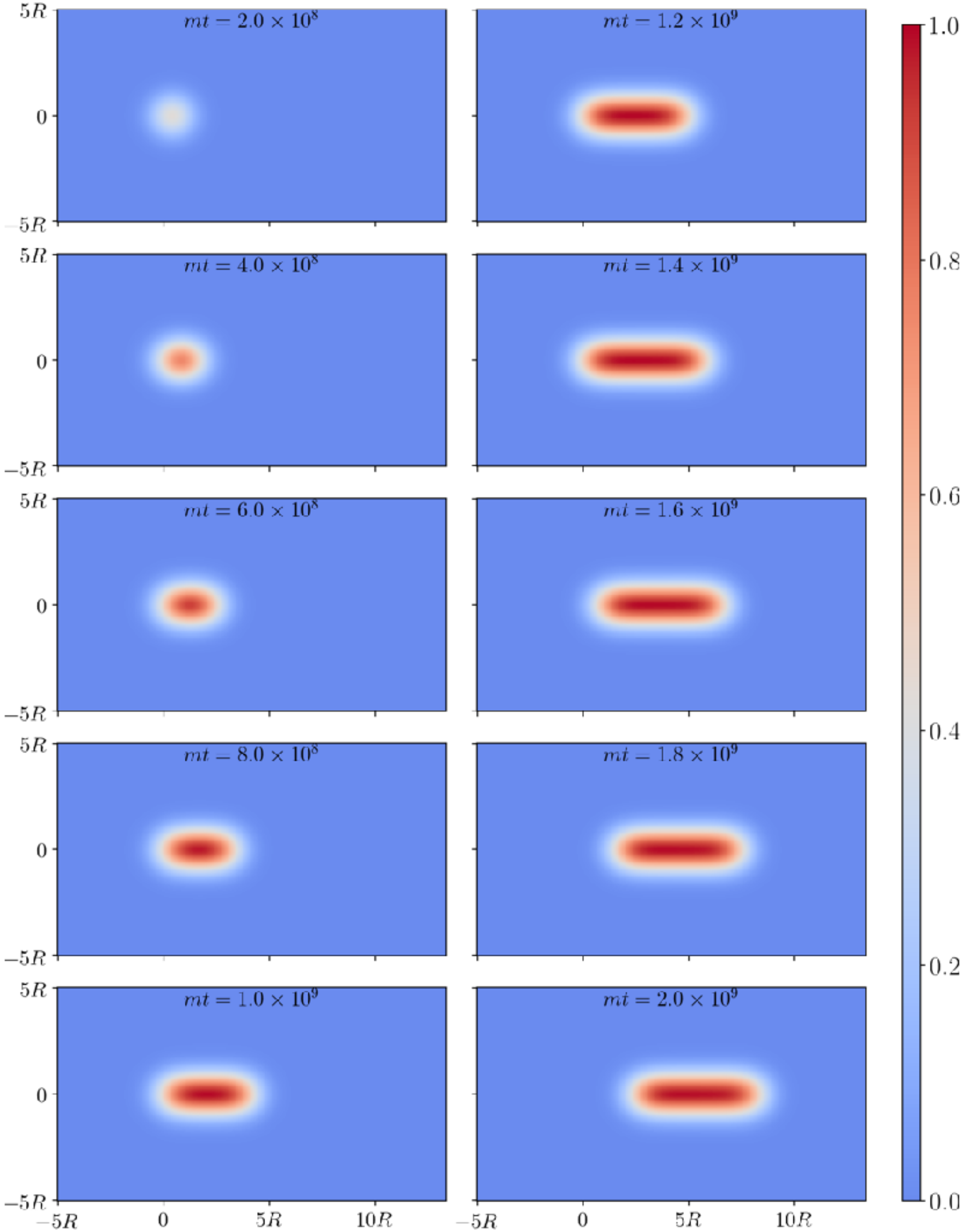


Small velocity dispersion



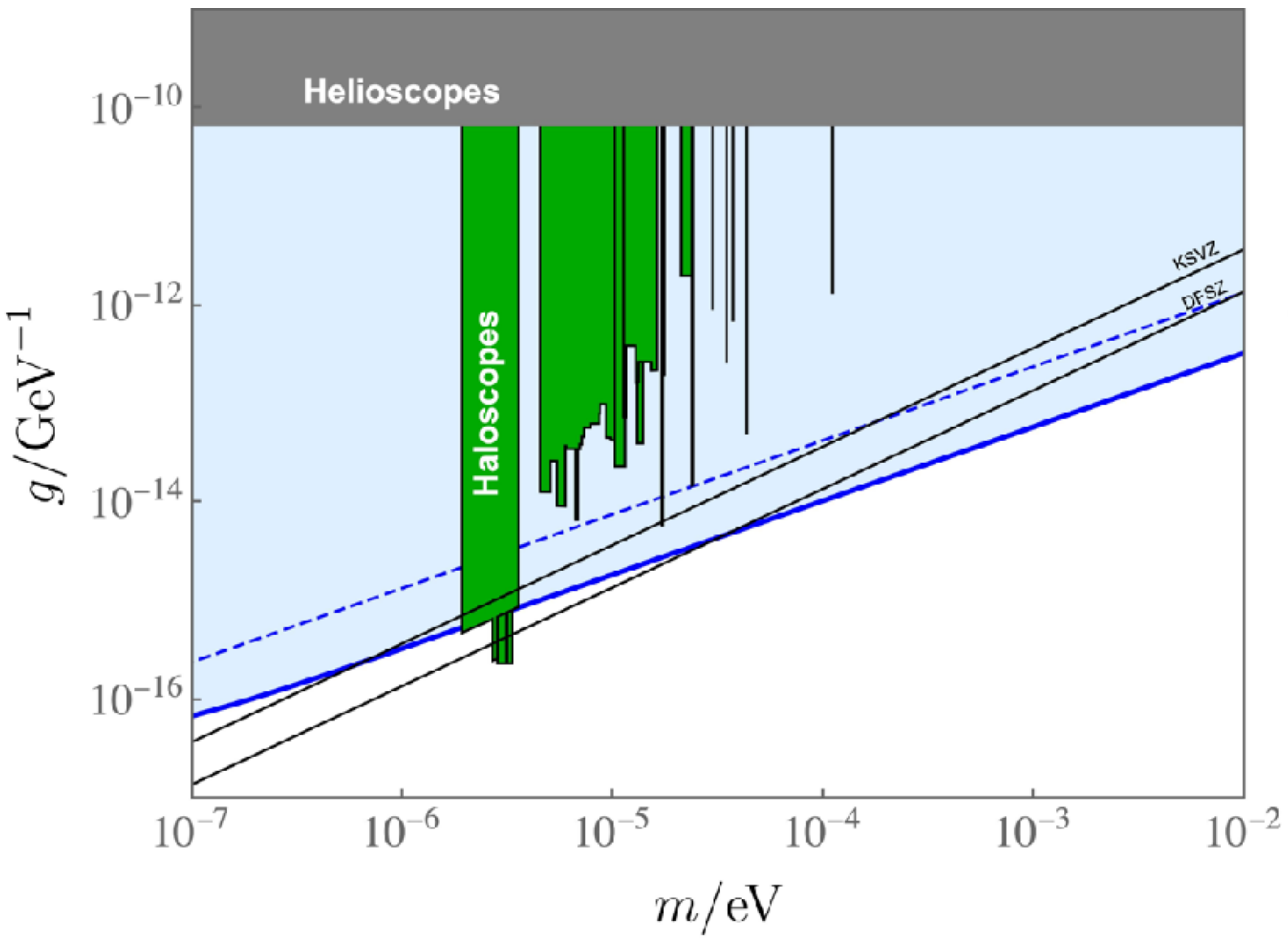


mt = 1.0 × 10^5
mt = 6.0 × 10^5
mt = 2.0 × 10^5
mt = 7.0 × 10^5
mt = 3.0 × 10^5
mt = 8.0 × 10^5
mt = 4.0 × 10^5
mt = 9.0 × 10^5
mt = 5.0 × 10^5
mt = 1.0 × 10^6
5R
0
−5R
1.0
0.8
0.6
0.4
0.2
0.0



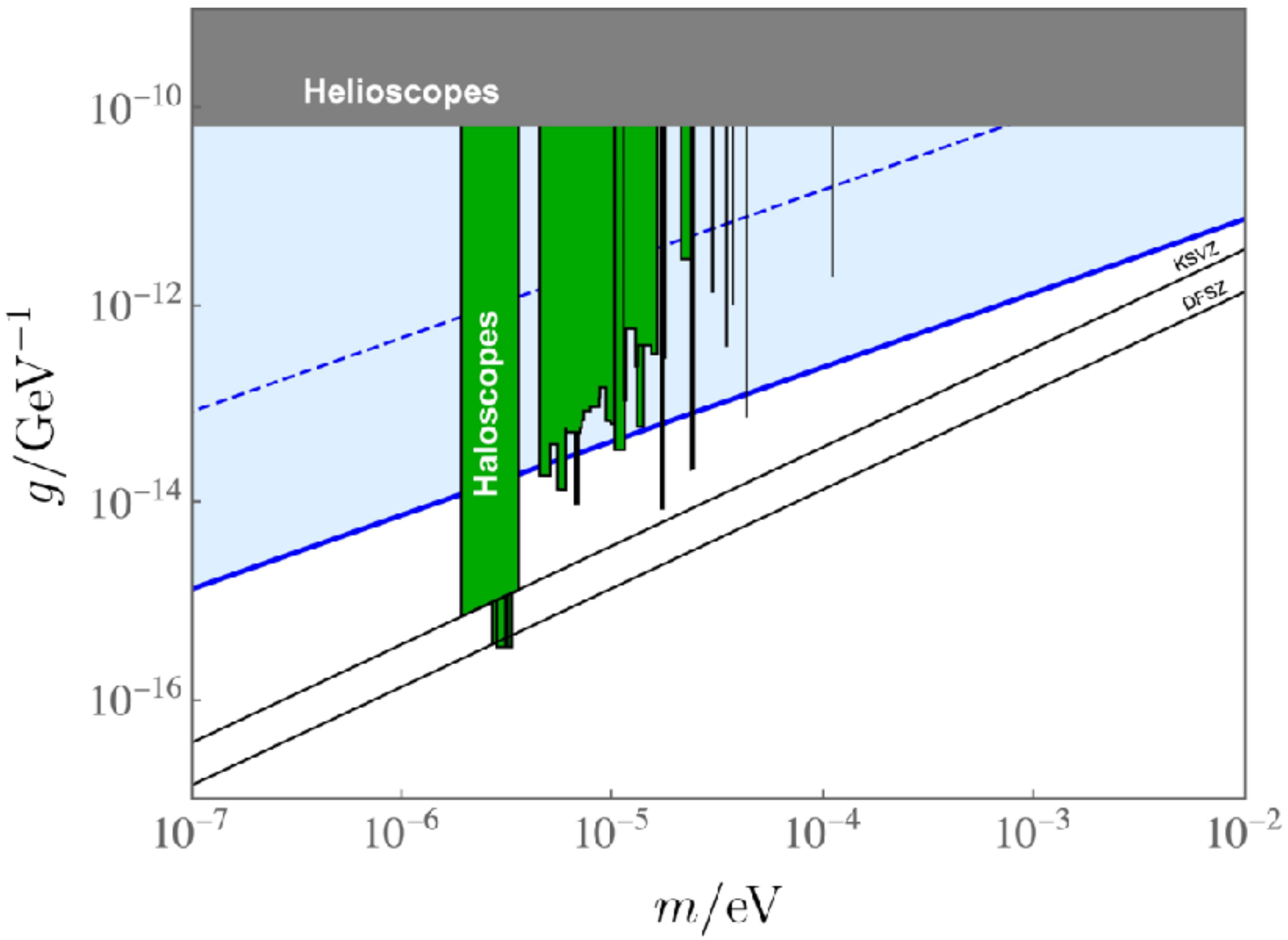
mt = 2.0 × 10^8
mt = 1.2 × 10^9
mt = 4.0 × 10^8
mt = 1.4 × 10^9
mt = 6.0 × 10^8
mt = 1.6 × 10^9
mt = 8.0 × 10^8
mt = 1.8 × 10^9
mt = 1.0 × 10^9
mt = 2.0 × 10^9
5R
0
−5R
10R
1.0
0.8
0.6
0.4
0.2
0.0

Caustic ring model



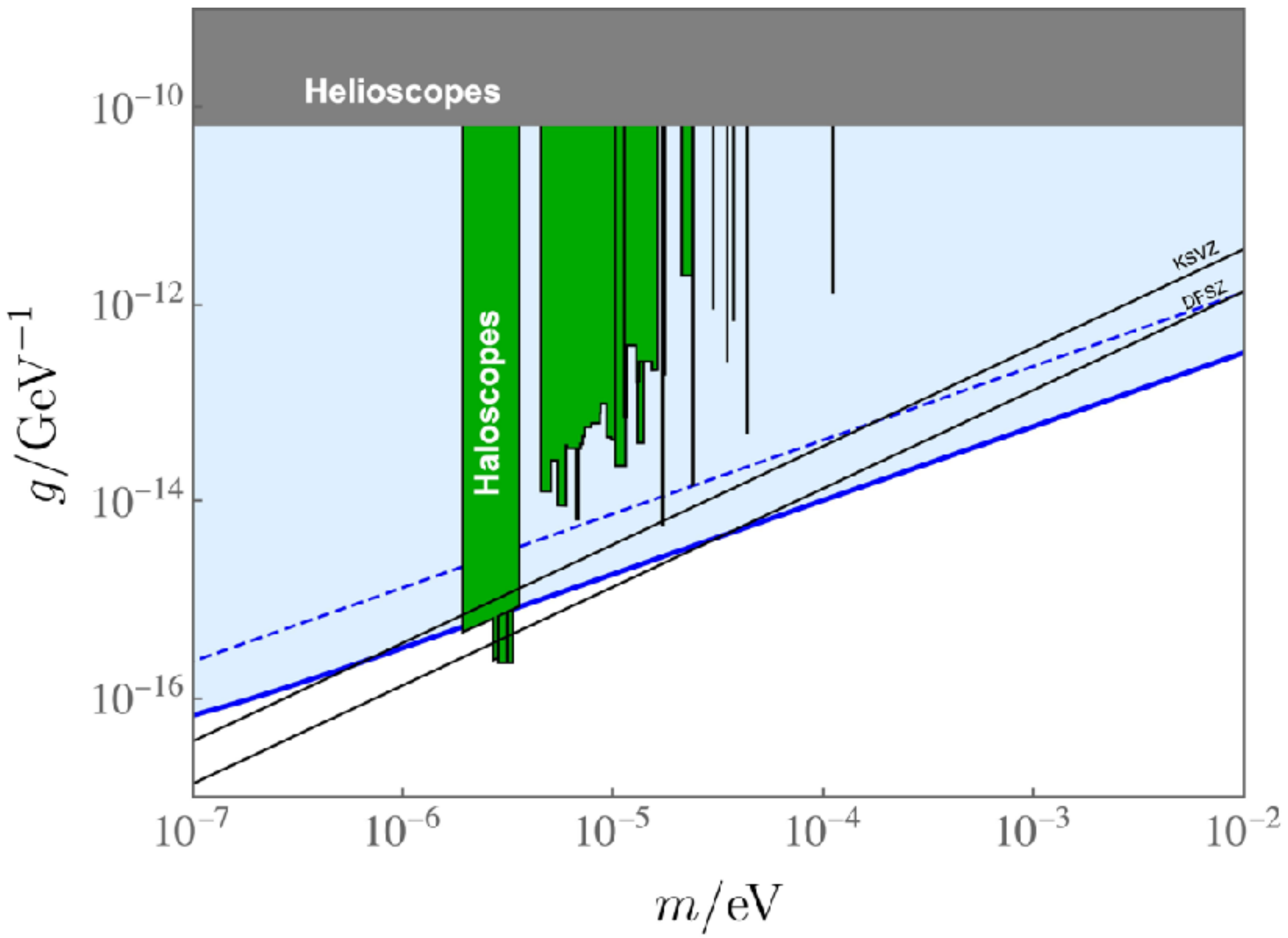
$$\rho = 1\ \mathrm{GeV\ cm}^{-3}$$
$$v = 300\ \mathrm{km/s}$$
$$\delta v = 70\ \mathrm{m/s}$$
$$v_\perp = 5\ \mathrm{km/s}$$

Isothermal sphere

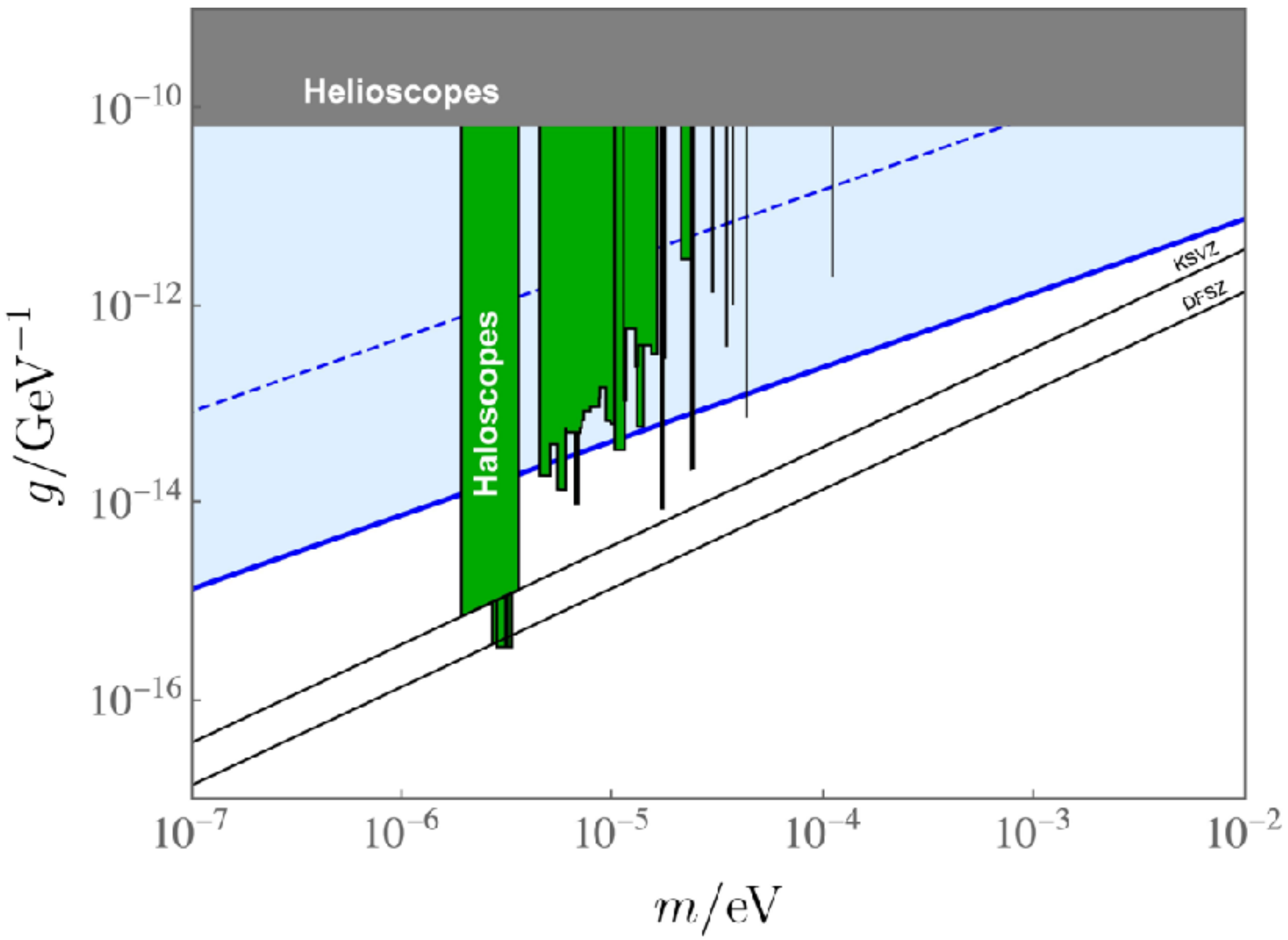


$$\rho = 0.45\ \mathrm{GeV\ cm}^{-3}$$
$$v = 230\ \mathrm{km/s}$$
$$\delta v = 270\ \mathrm{km/s}$$

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