Searching for axion dark matter decaying into photons: from radio to X-rays

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SLAC, April 22nd, 2026

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COSMIC WISPERS CA21106

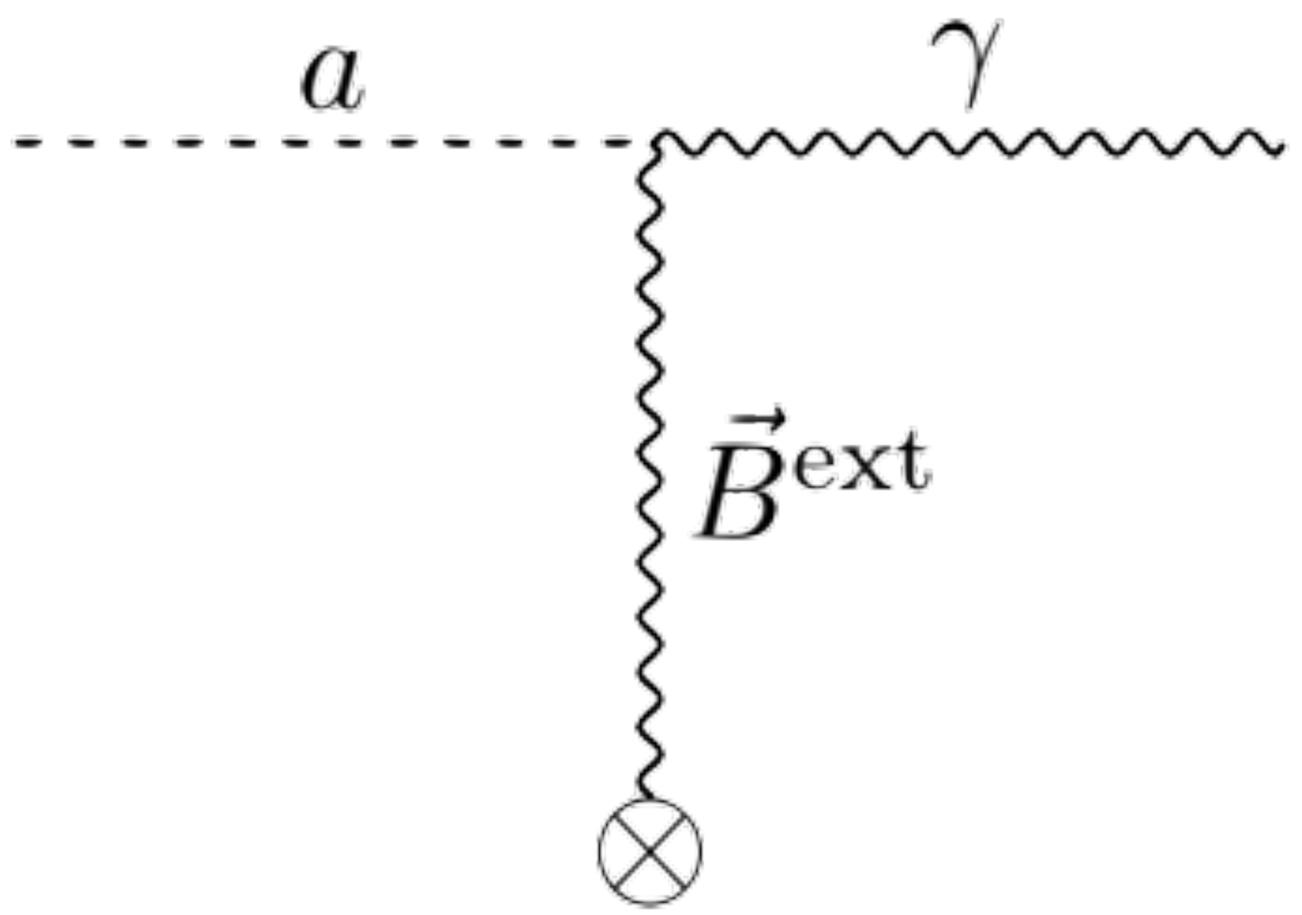
Topics

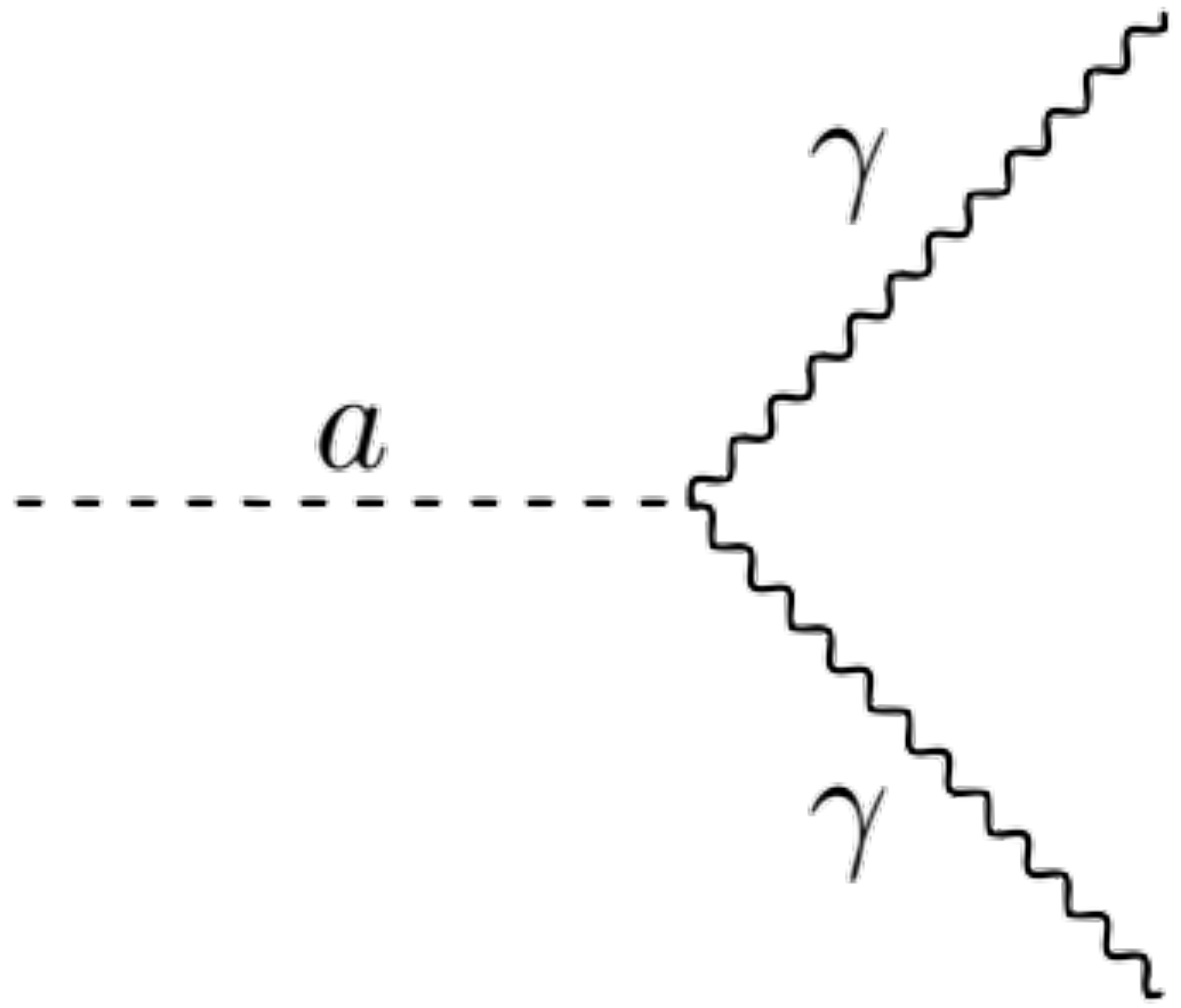
Spontaneous decay (IR and higher)

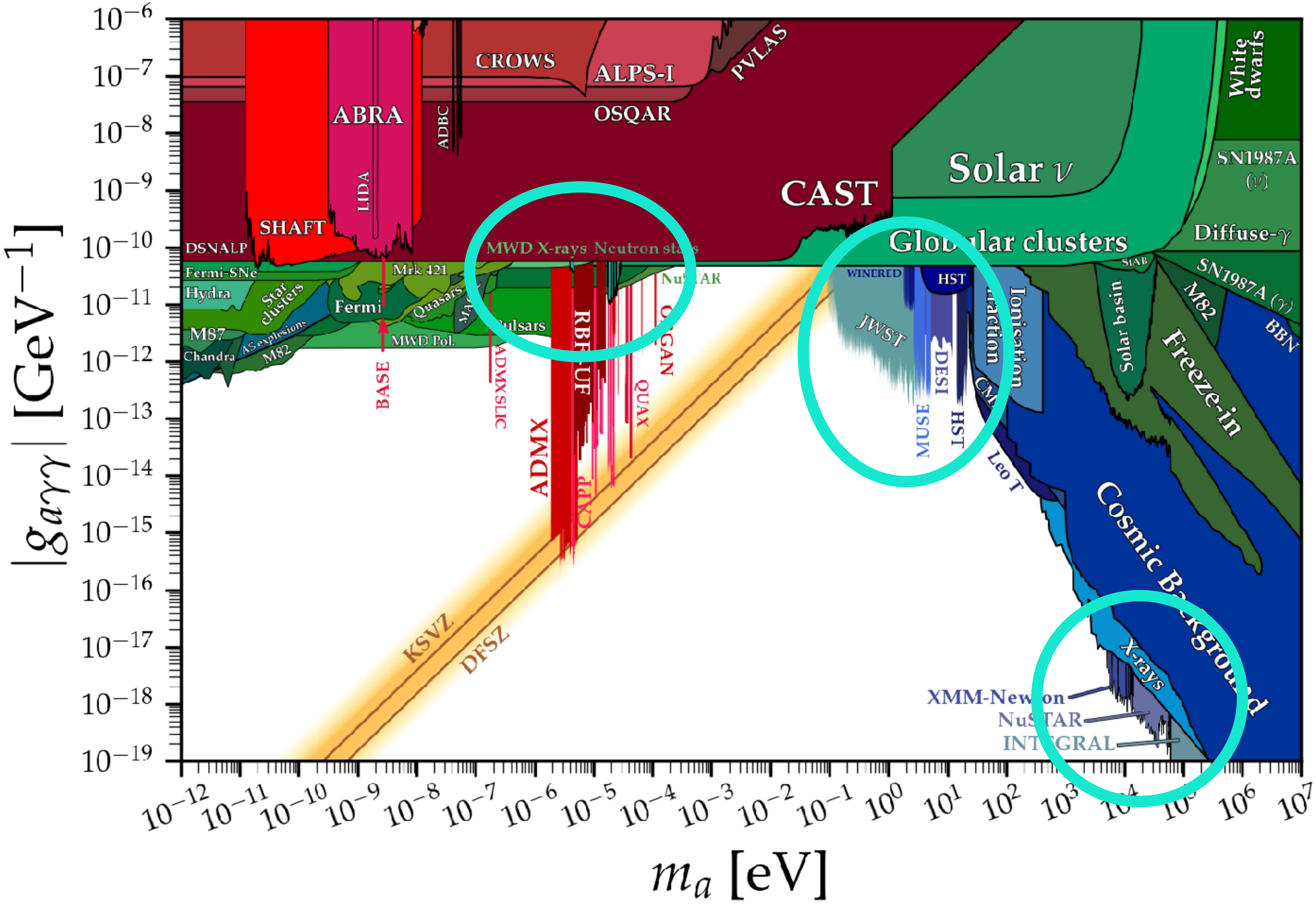
Stimulated decay (radio)

Axion-photon interaction

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

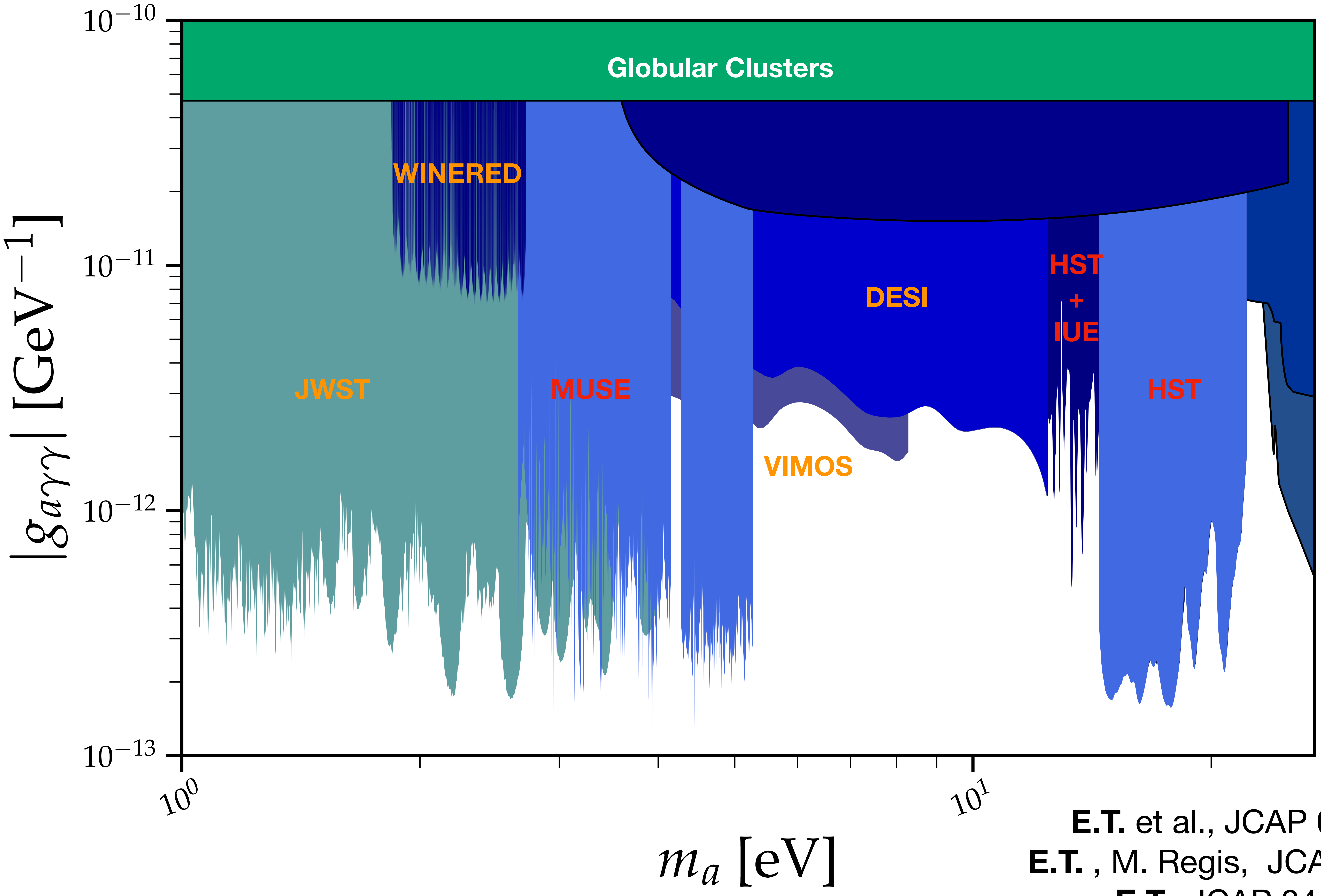






cajohare/axionlimits: Axionlimits

Spontaneous decay



E.T. et al., JCAP 05 (2024) 043
E.T. , M. Regis, JCAP 05 (2025) 070
E.T., JCAP 04 (2026) 063

Decay rate in vacuum

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

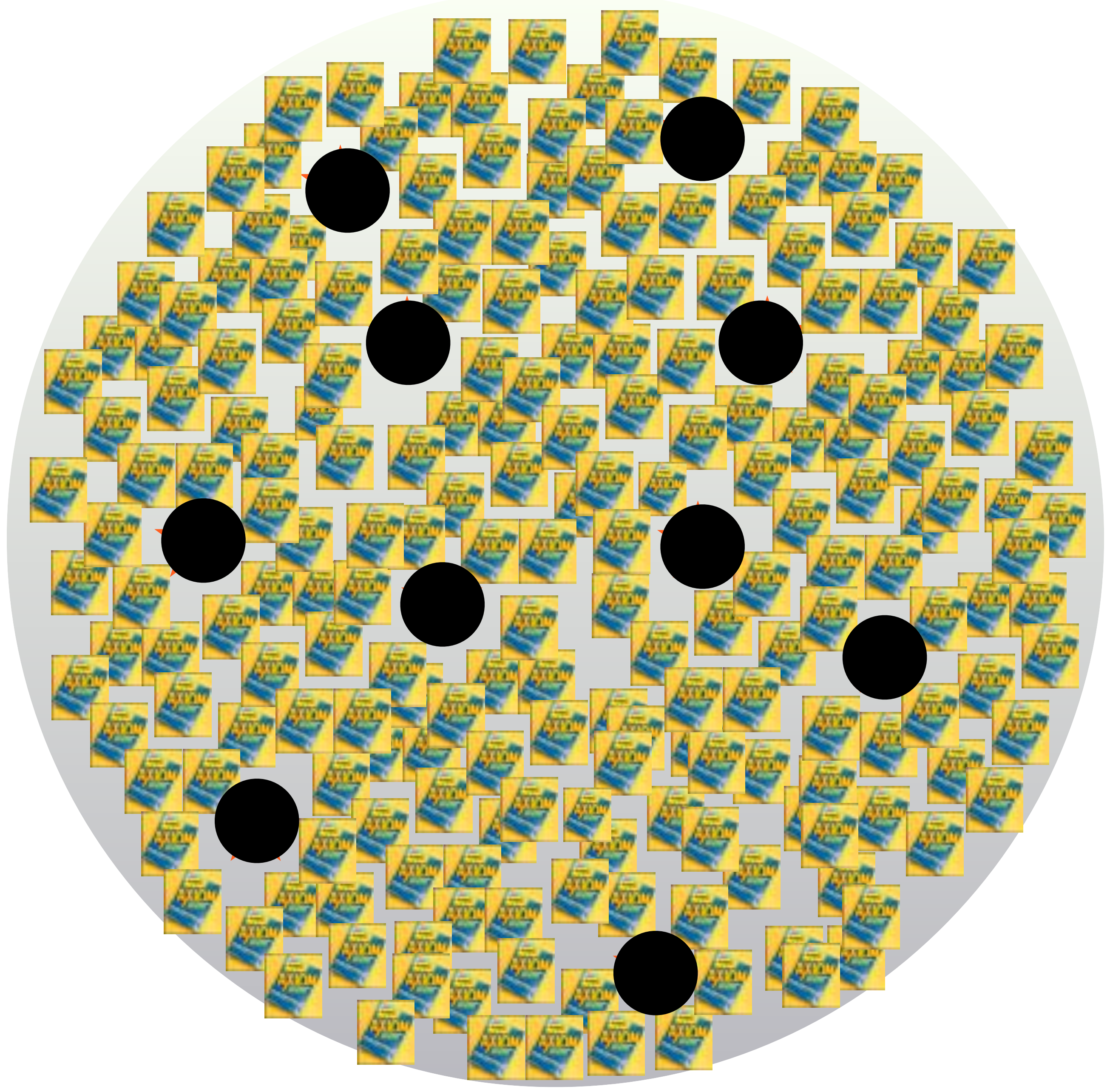
Dwarf spheroidal galaxies

Look at dark matter rich targets

Clusters of galaxies

Milky Way

Look for radiation from ALP decay



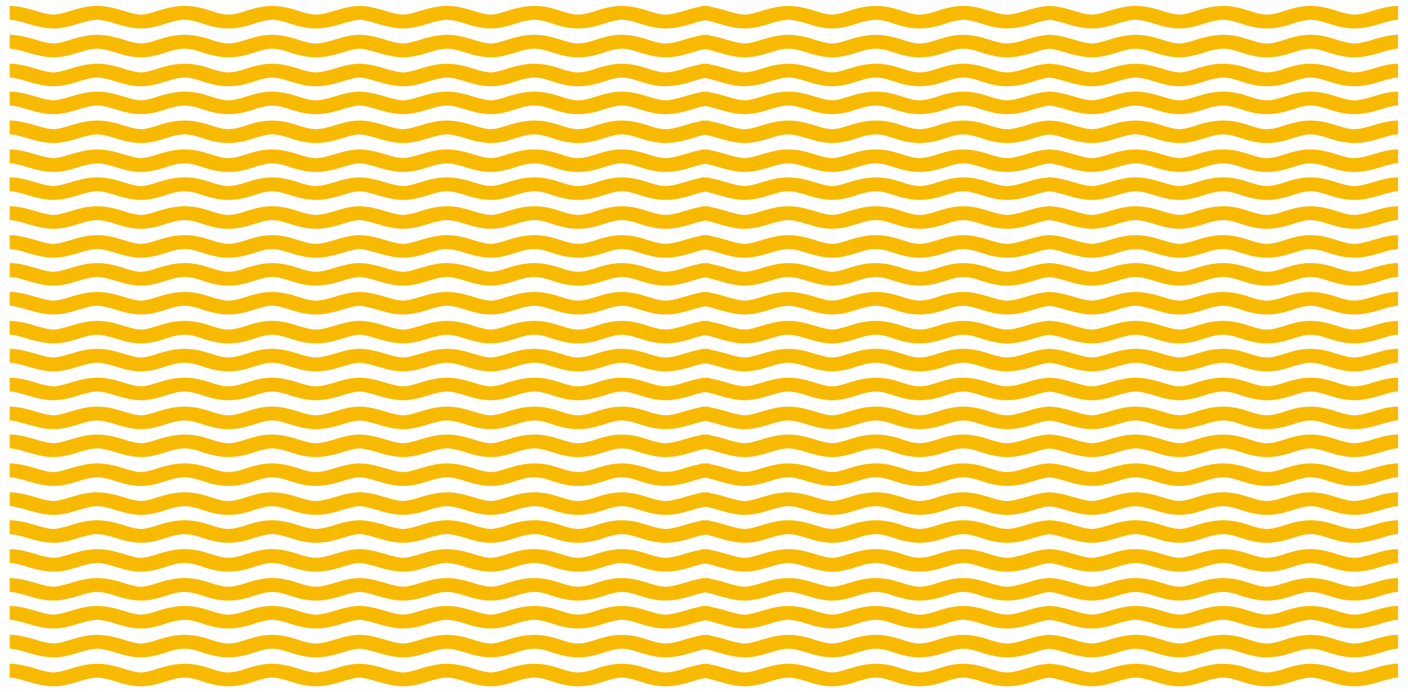


Photo by ESO/G. Hüdepohl (atacamaphoto.com)

Example: Sculptor

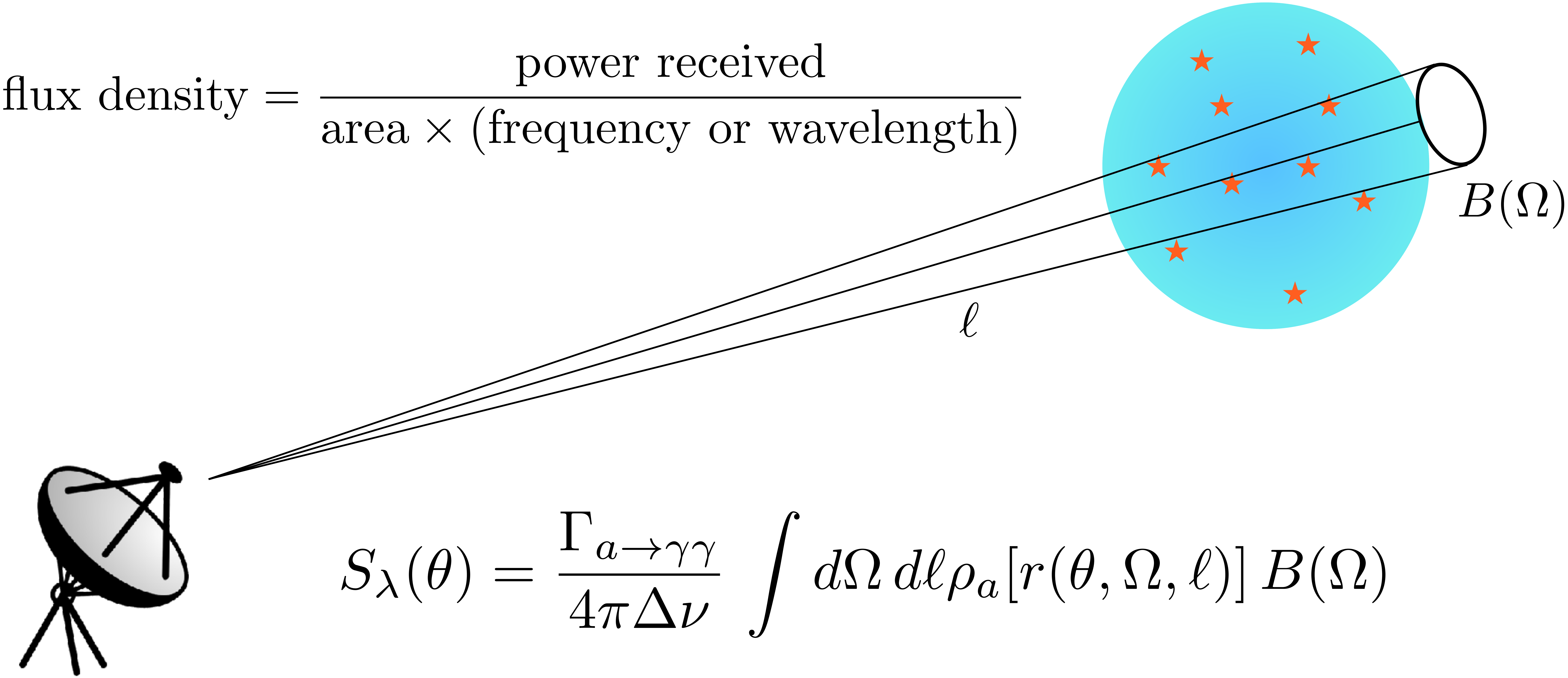
$$
\begin{aligned}
\rho_s &= 2 \times 10^7 \ M_\odot \ \mathrm{kpc}^{-3} \\
r_s &= 1.5 \ \mathrm{kpc} \\
d &= 86 \ \mathrm{kpc} \\
\\
r_{1'} &= 0.16 \, r_s \\
M_{1'} &\sim 10^5 \ M_\odot \sim 10^{71} \ \mathrm{eV}
\end{aligned}
$$

$$\Longrightarrow 10^{41} \mathrm{decays/s}$$

Sculptor dwarf galaxy. Photo by ESO.

Flux density from ALP decay

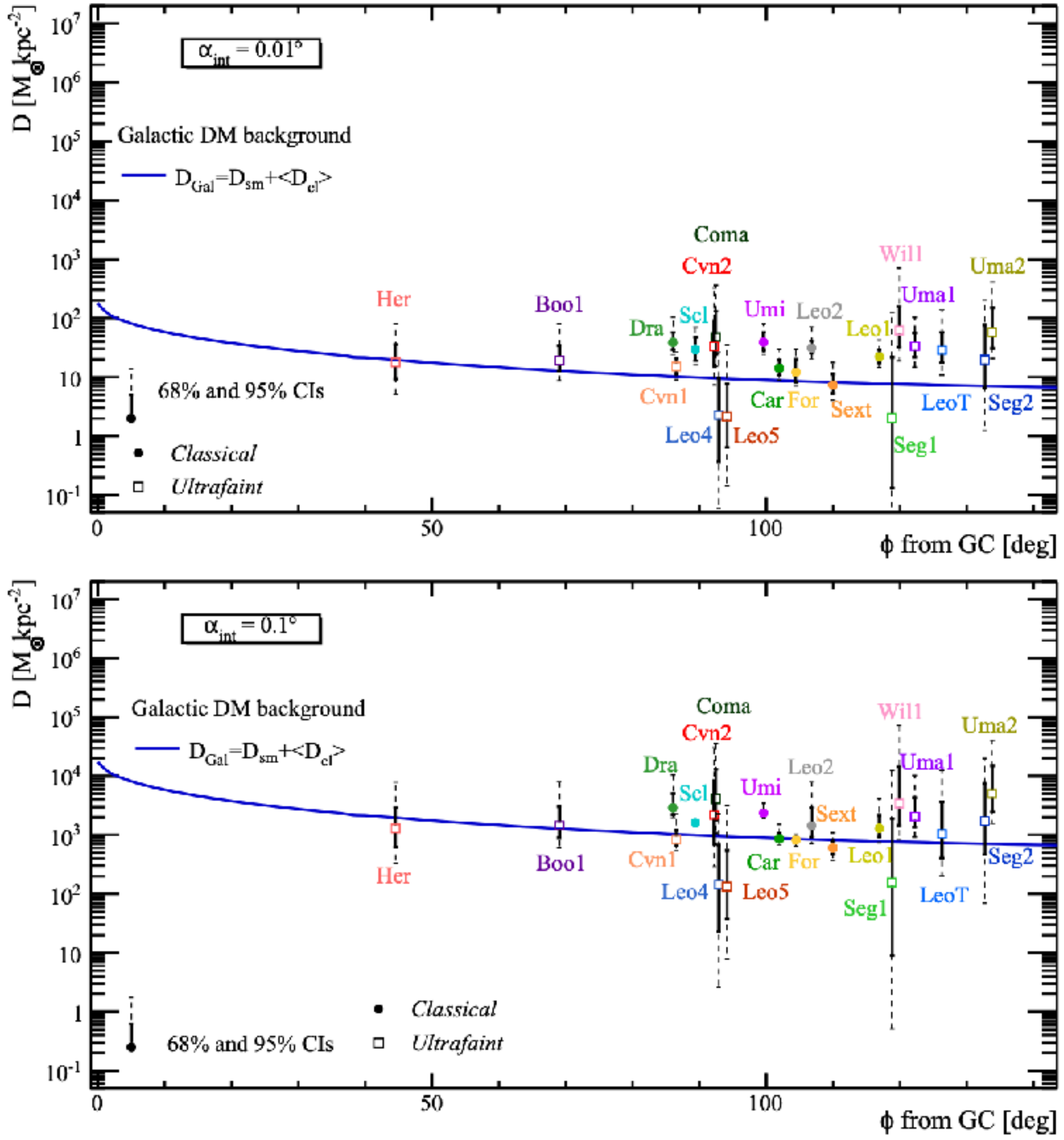
$$\text{flux density} = \frac{\text{power received}}{\text{area} \times (\text{frequency or wavelength})}$$



$$S_\lambda(\theta) = \frac{\Gamma_{a\to\gamma\gamma}}{4\pi\Delta\nu} \int d\Omega\, d\ell \rho_a[r(\theta,\Omega,\ell)]\, B(\Omega)$$

Dwarf Spheroidals

Galaxy Clusters



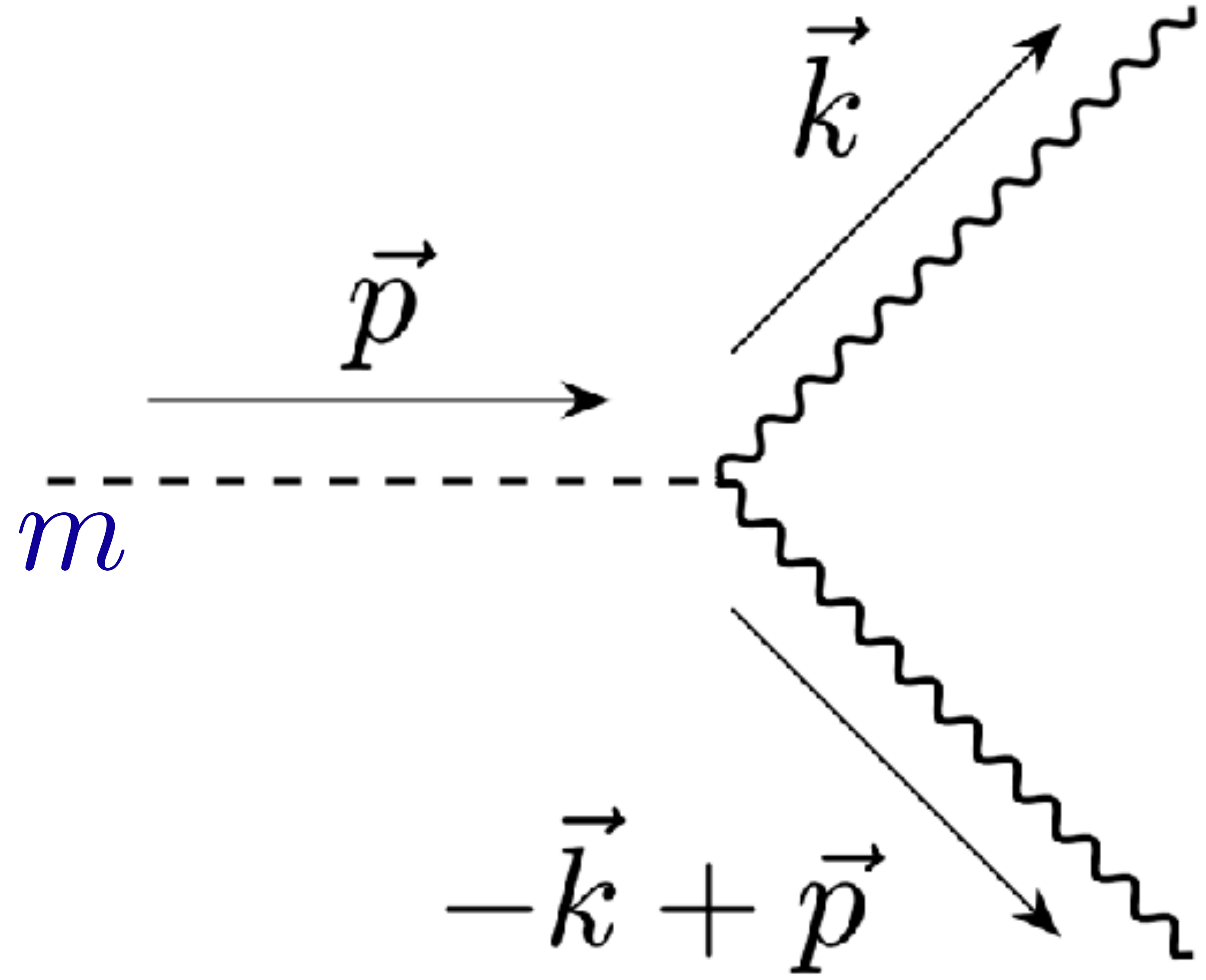
Bonnivard+, 1504.02048

Name	Index (MCXC)	l (deg)	b (deg)	d (Mpc)	α_s (deg)	$D(0.1°)$ ($M_\odot$ kpc^{-2})
A426	258	150.6	-13.3	75.0	0.44	$1.0 \cdot 10^4$
Virgo	884	283.8	74.4	15.4	1.09	$1.0 \cdot 10^4$
Coma	943	57.2	88.0	96.2	0.29	$7.3 \cdot 10^3$
Ophiuchus	1304	0.6	9.3	116.	0.27	$7.3 \cdot 10^3$
A3526	915	302.4	21.6	48.1	0.39	$6.8 \cdot 10^3$
A3627	1231	325.3	-7.1	66.0	0.32	$6.5 \cdot 10^3$
AWM7	224	146.3	-15.6	72.1	0.28	$5.7 \cdot 10^3$
A1367	792	235.1	73.0	89.3	0.24	$5.4 \cdot 10^3$
A3571	1048	316.3	28.6	160.	0.18	$5.4 \cdot 10^3$
A2199	1249	62.9	43.7	124.	0.20	$5.1 \cdot 10^3$

Combet+, 1203.1164

Kinematics of the decay

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



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

Dark matter is non relativistic

The signal is a narrow spectral line

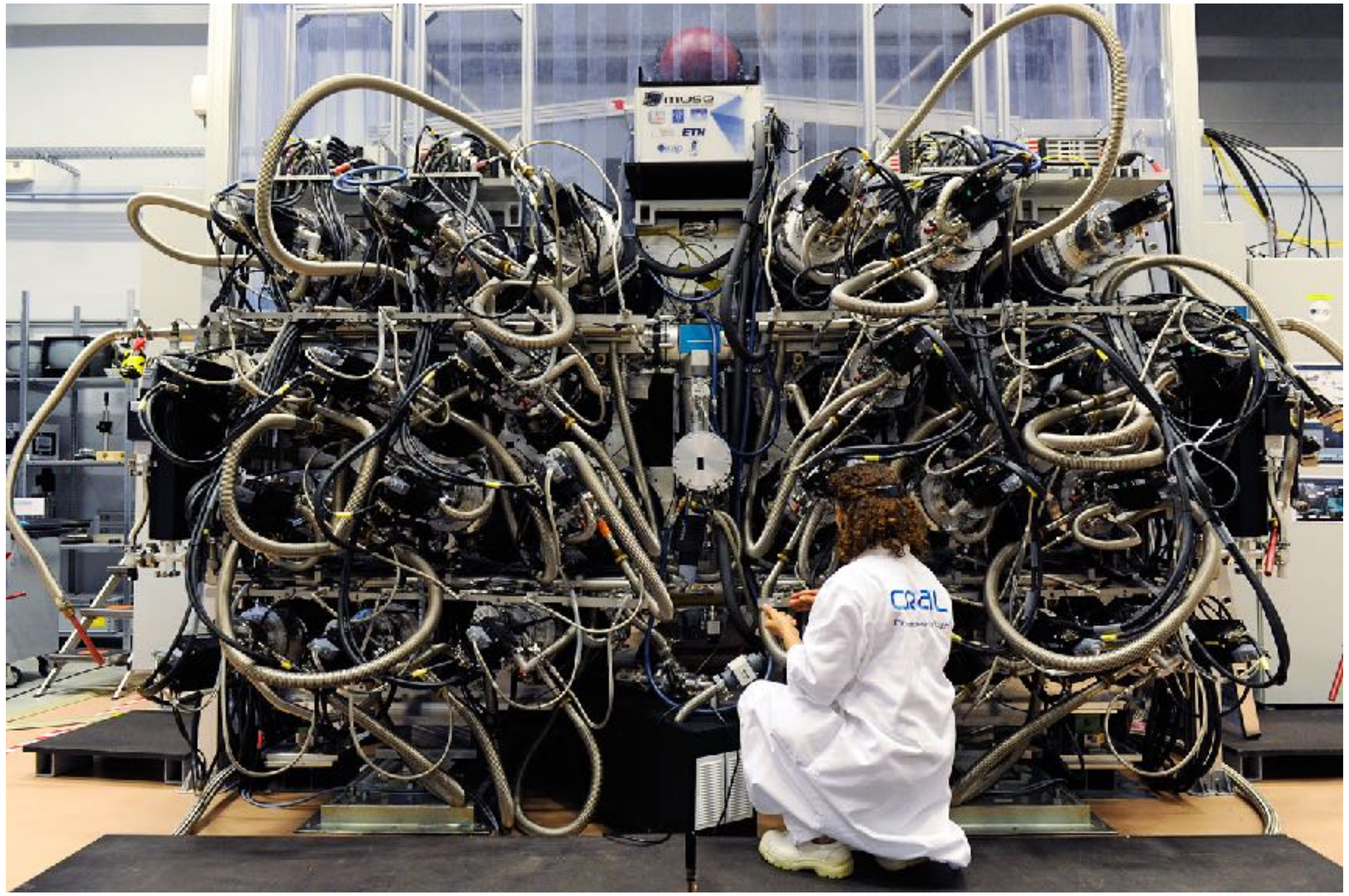
The MUSE instrument

Multi Unit Spectroscopic Explorer

- Measures flux in ~3720 channels

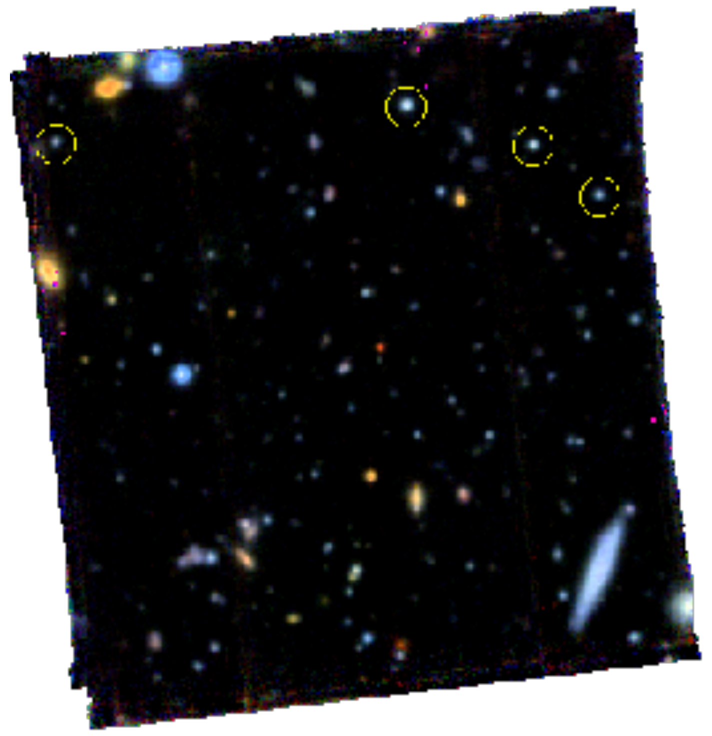
$$4700\ \text{Å} < \lambda < 9350\ \text{Å}$$
$$2.65\ \text{eV} < m < 5.27\ \text{eV}$$

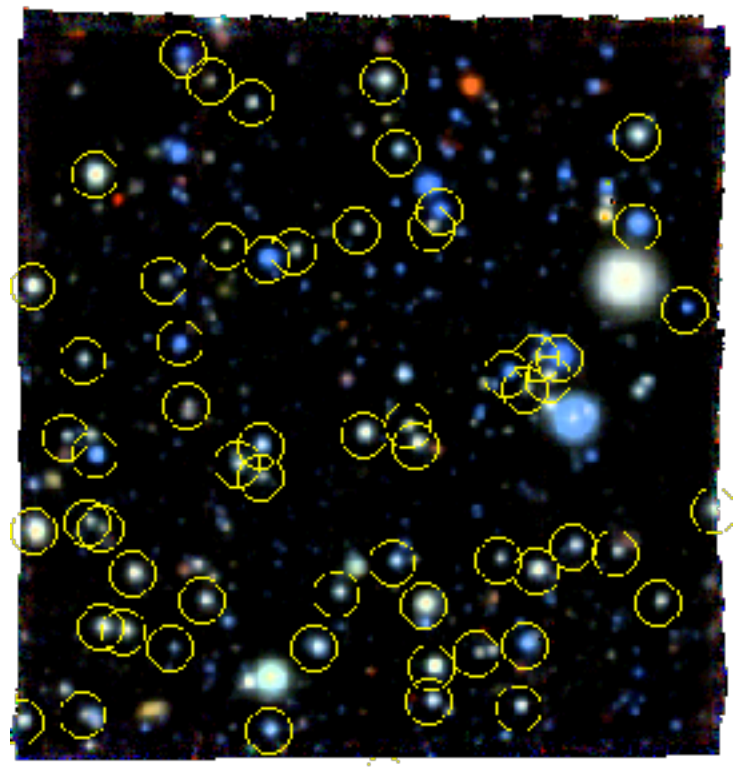
- Spectral resolution $\lambda/\Delta\lambda > 10^3$
- Field of view $1' \times 1'$
- Spatial resolution $\sim 0.5''$

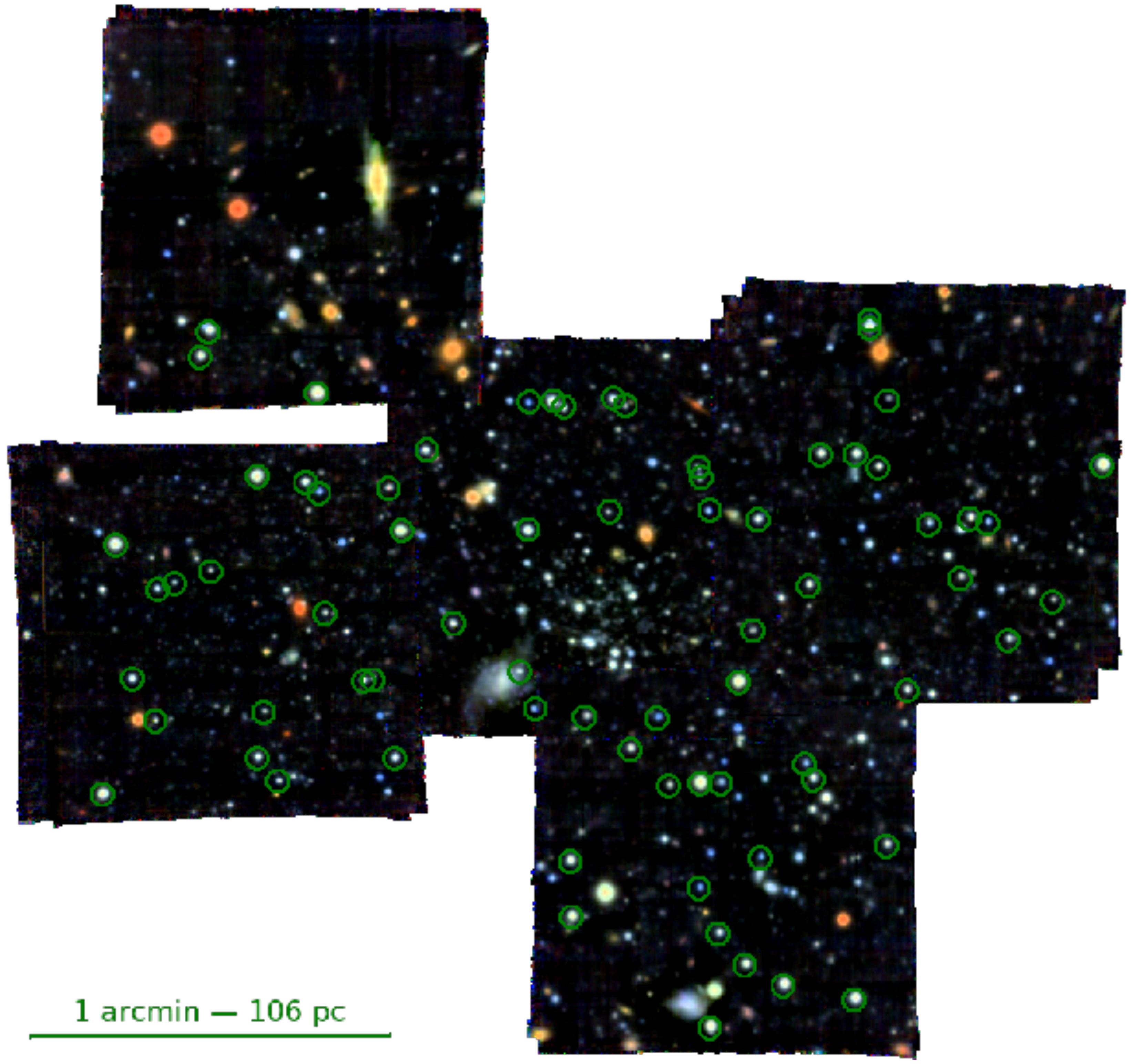


muse
multi unit spectroscopic explorer

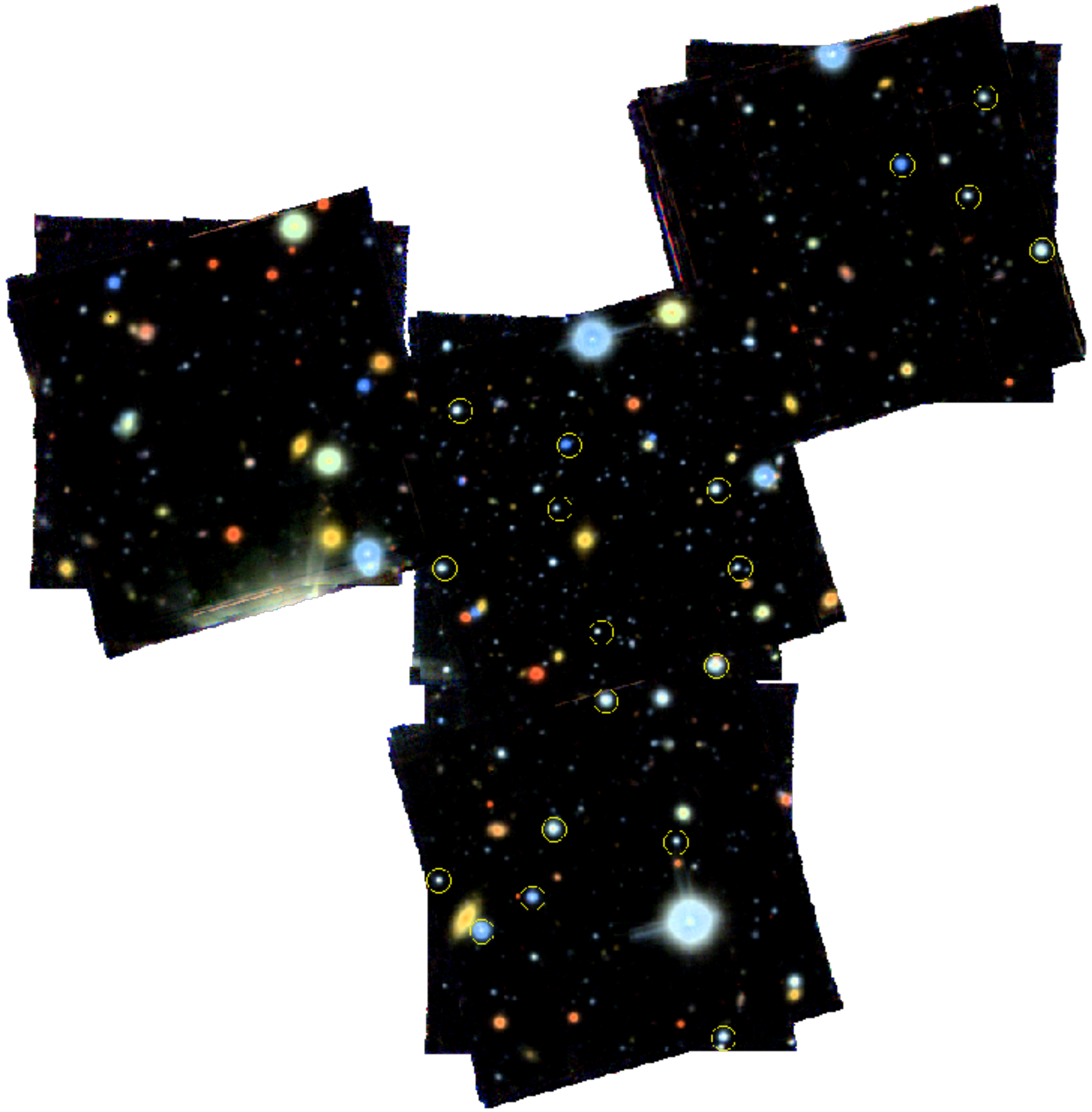
The MUSE-Faint Survey







+ Sculptor



Zoutendijk et al., The MUSE-Faint survey. III, 2112.09374

The data

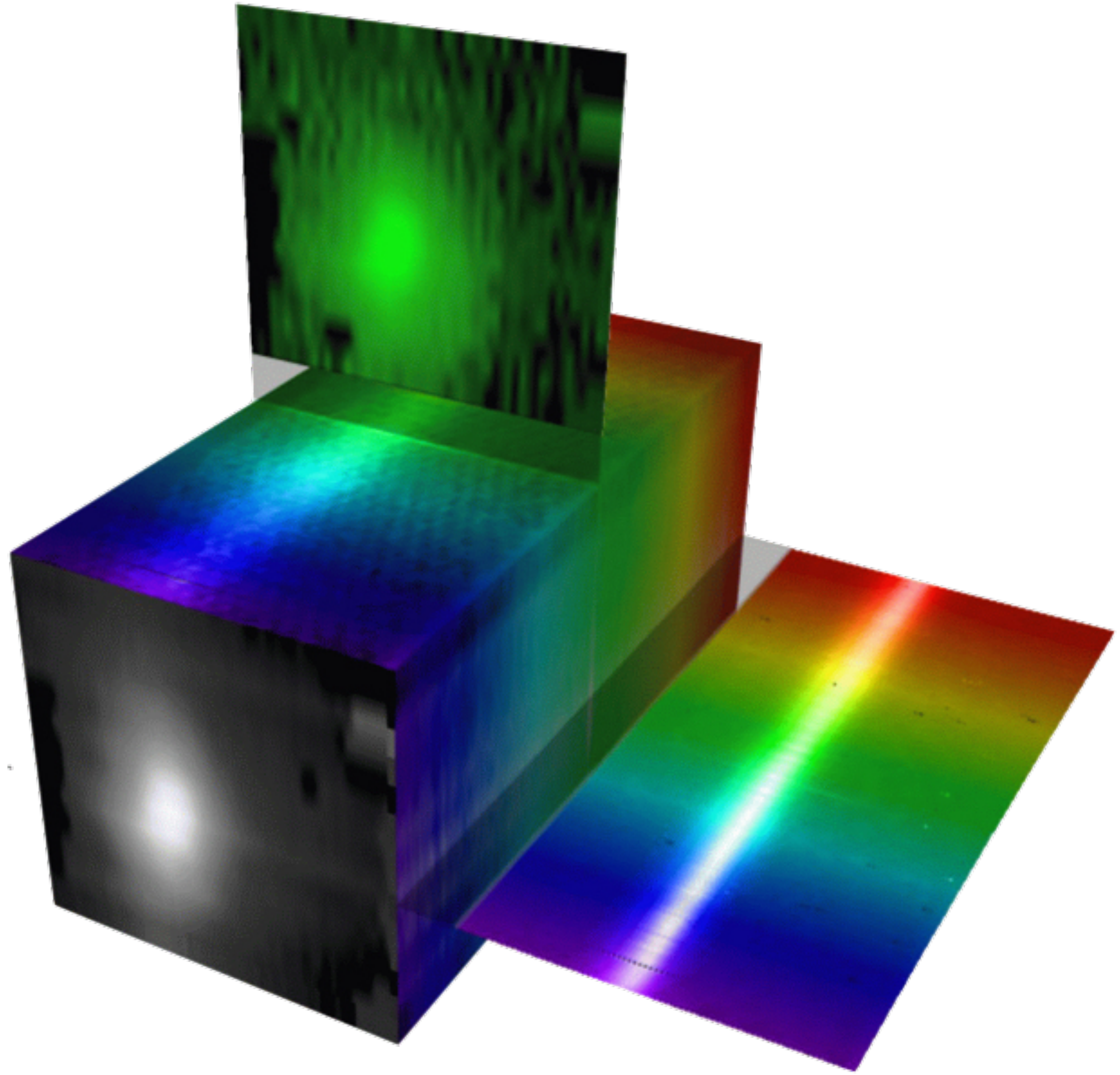
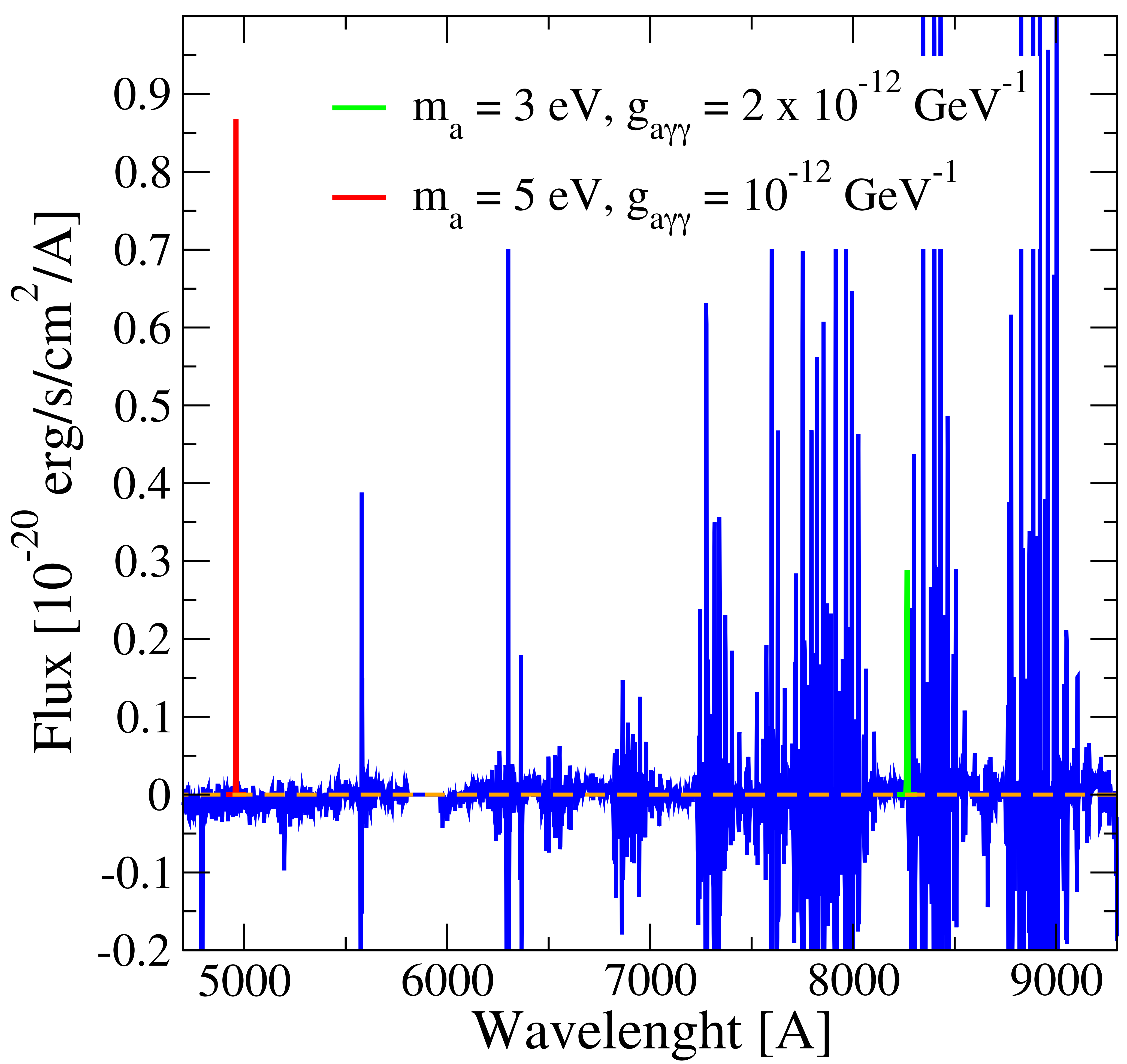
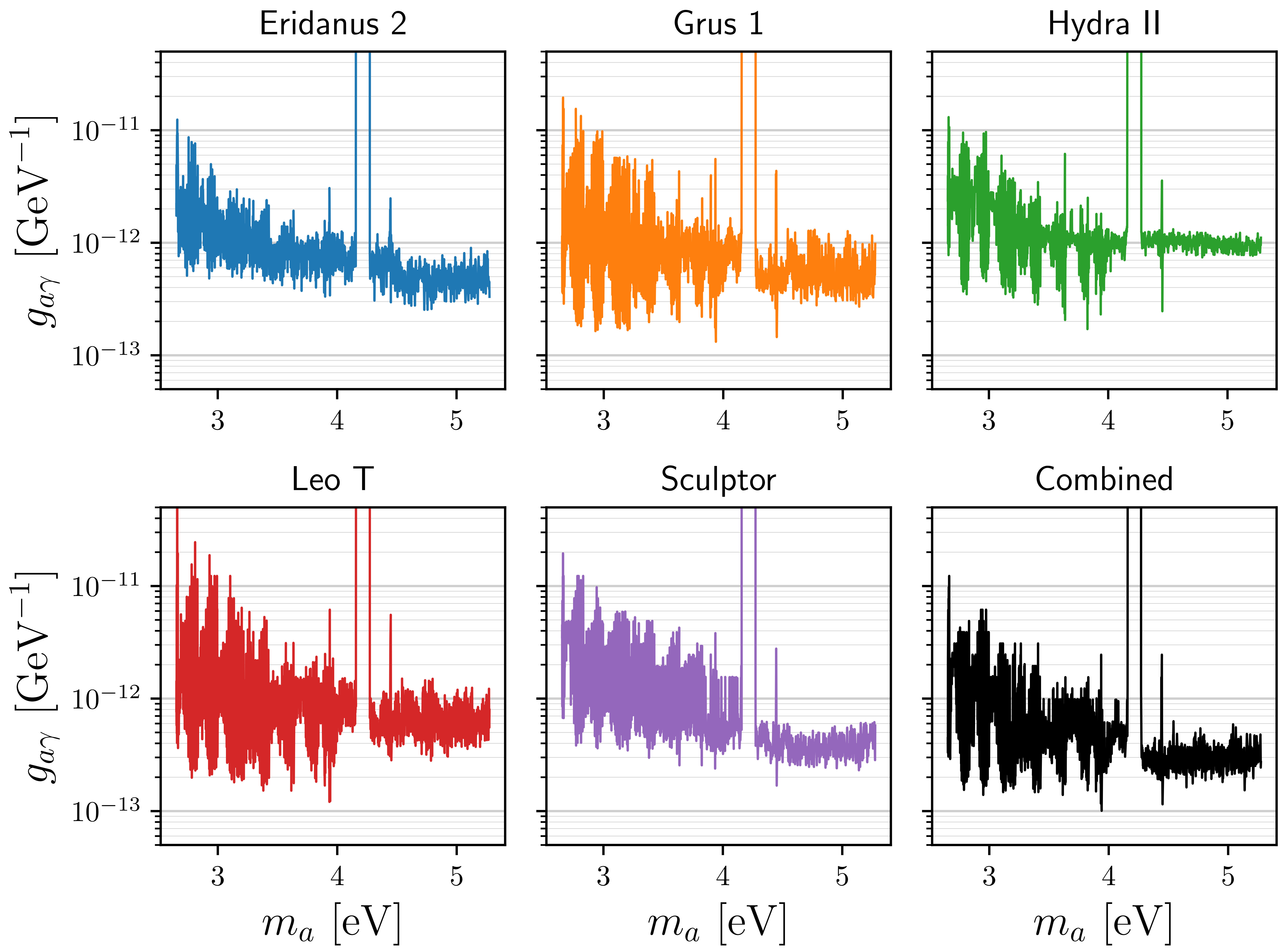


Image credit: Stephen Todd (ROE) and Douglas Pierce-Price (JAC)

The signal

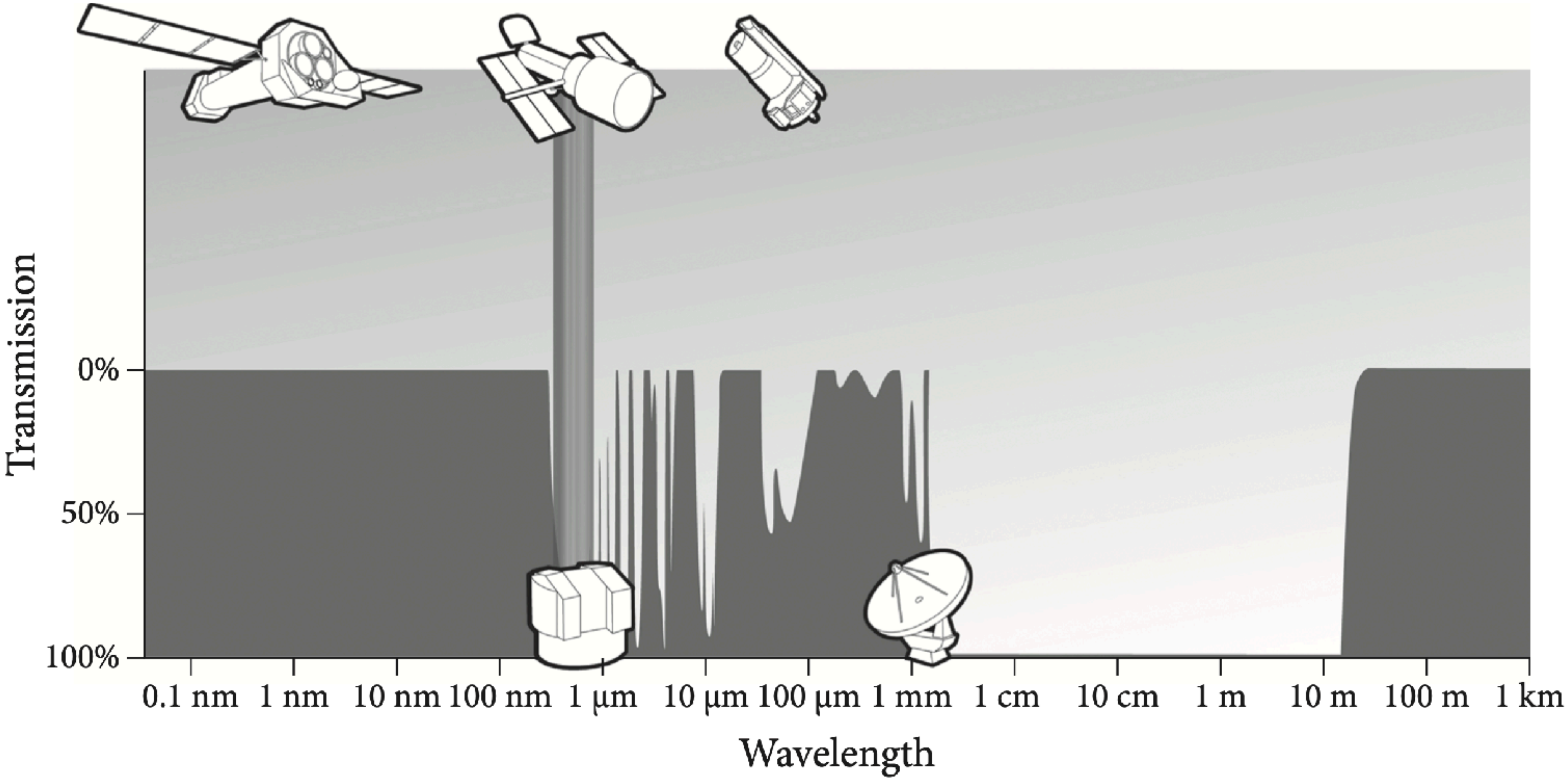


m_a = 3 eV, g_aγγ = 2 x 10^-12 GeV^-1
m_a = 5 eV, g_aγγ = 10^-12 GeV^-1
Flux [10^-20 erg/s/cm^2/A]
Wavelenght [A]
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
5000
6000
7000
8000
9000



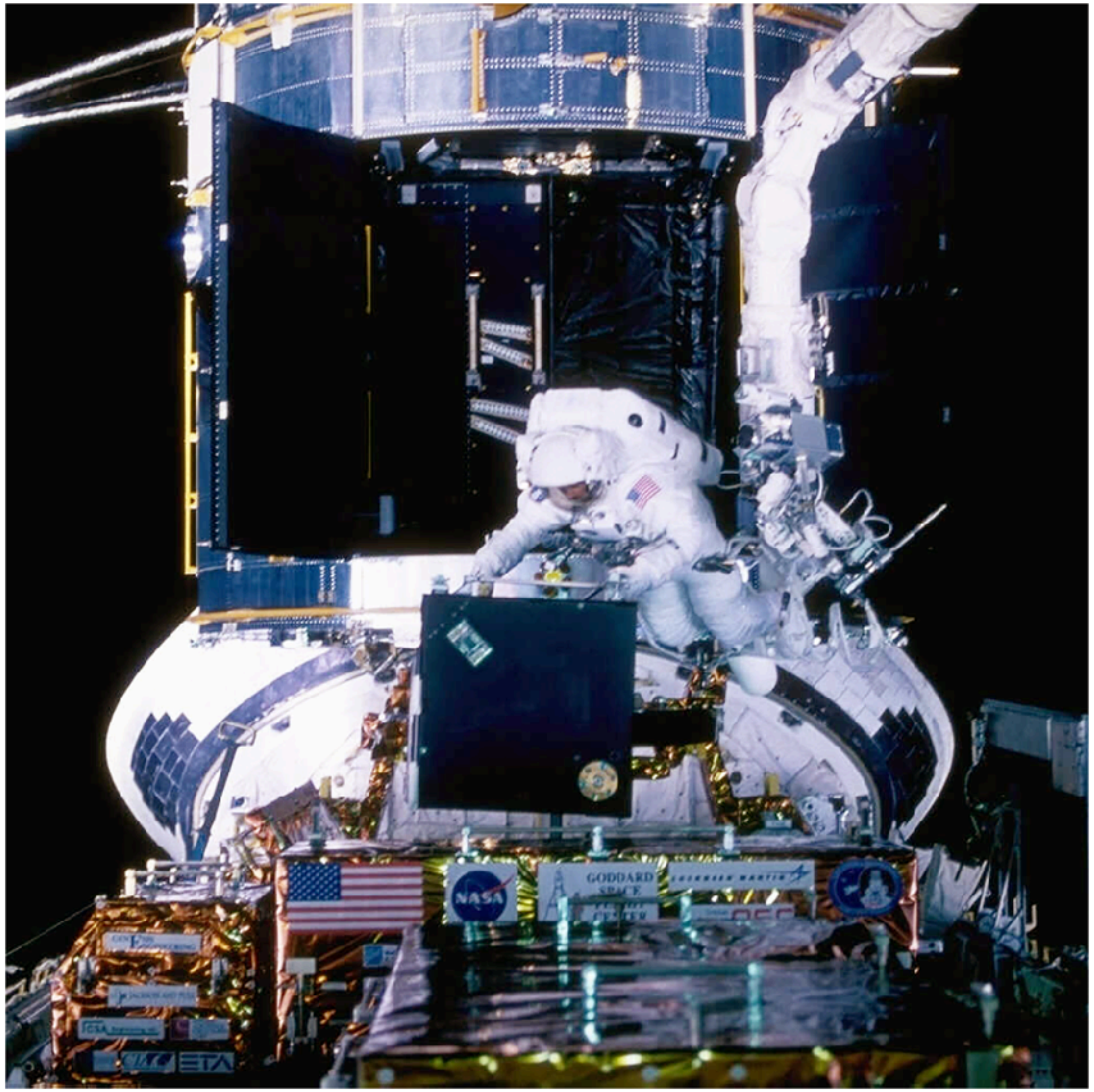
E.T. et al., JCAP 05 (2024) 043

Going to higher frequencies

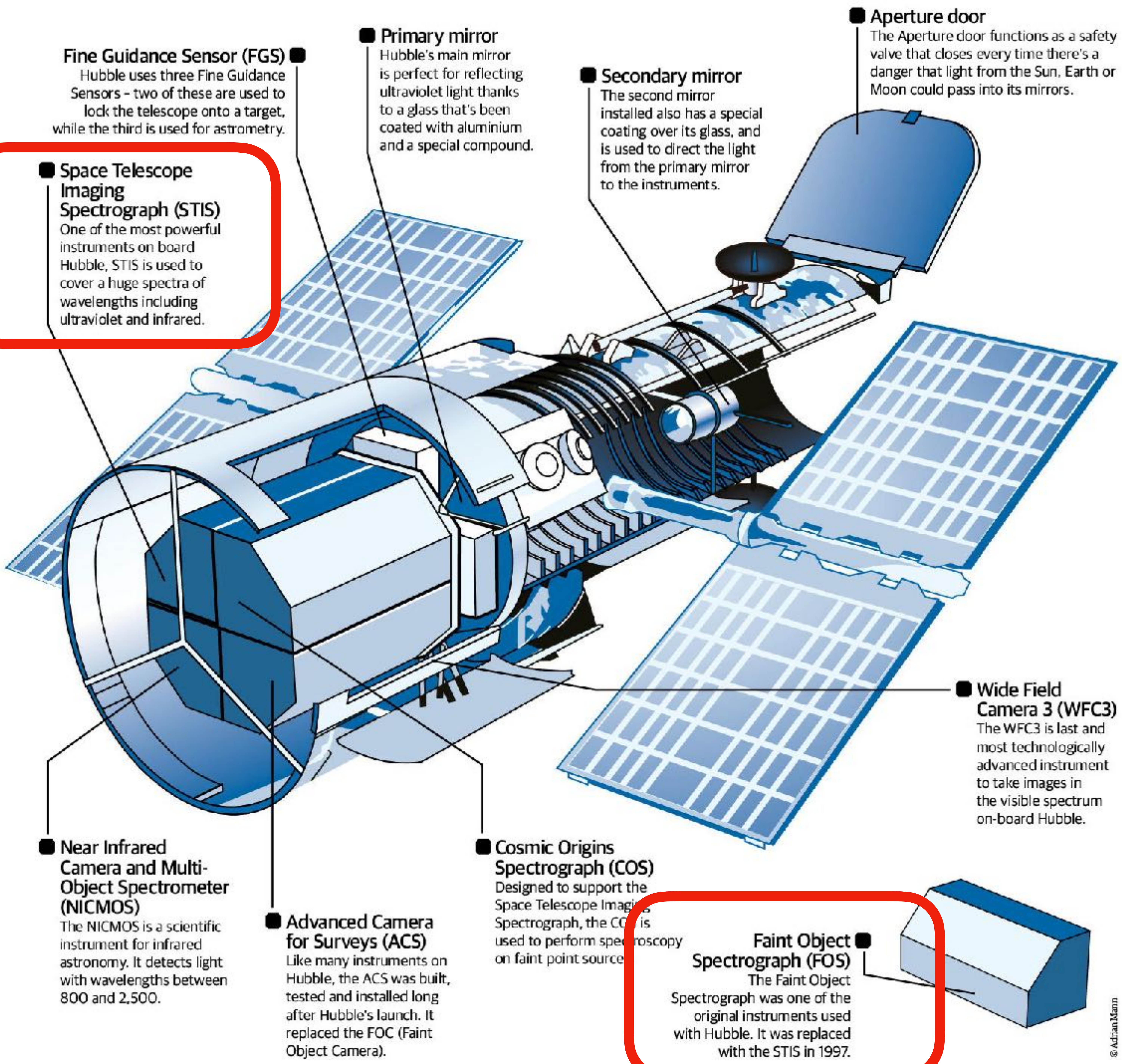


Condon, Ransom - Essential Radio Astronomy

Hubble Space Telescope



Astronaut Steve Smith carefully removes STIS from the protective enclosure that carried it into orbit aboard the Space Shuttle Discovery.



Fine Guidance Sensor (FGS)
Hubble uses three Fine Guidance Sensors - two of these are used to lock the telescope onto a target, while the third is used for astrometry.
Primary mirror
Hubble's main mirror is perfect for reflecting ultraviolet light thanks to a glass that's been coated with aluminium and a special compound.
Secondary mirror
The second mirror installed also has a special coating over its glass, and is used to direct the light from the primary mirror to the instruments.
Aperture door
The Aperture door functions as a safety valve that closes every time there's a danger that light from the Sun, Earth or Moon could pass into its mirrors.
Space Telescope Imaging Spectrograph (STIS)
One of the most powerful instruments on board Hubble, STIS is used to cover a huge spectra of wavelengths including ultraviolet and infrared.
Wide Field Camera 3 (WFC3)
The WFC3 is last and most technologically advanced instrument to take images in the visible spectrum on-board Hubble.
Near Infrared Camera and Multi-Object Spectrometer (NICMOS)
The NICMOS is a scientific instrument for infrared astronomy. It detects light with wavelengths between 800 and 2,500.
Advanced Camera for Surveys (ACS)
Like many instruments on Hubble, the ACS was built, tested and installed long after Hubble's launch. It replaced the FOC (Faint Object Camera).
Cosmic Origins Spectrograph (COS)
Designed to support the Space Telescope Imagi
Spectrograph, the CO is
used to perform spe roscopy
on faint point source
Faint Object Spectrograph (FOS)
The Faint Object Spectrograph was one of the original instruments used with Hubble. It was replaced with the STIS in 1997.

Hubble Space Telescope

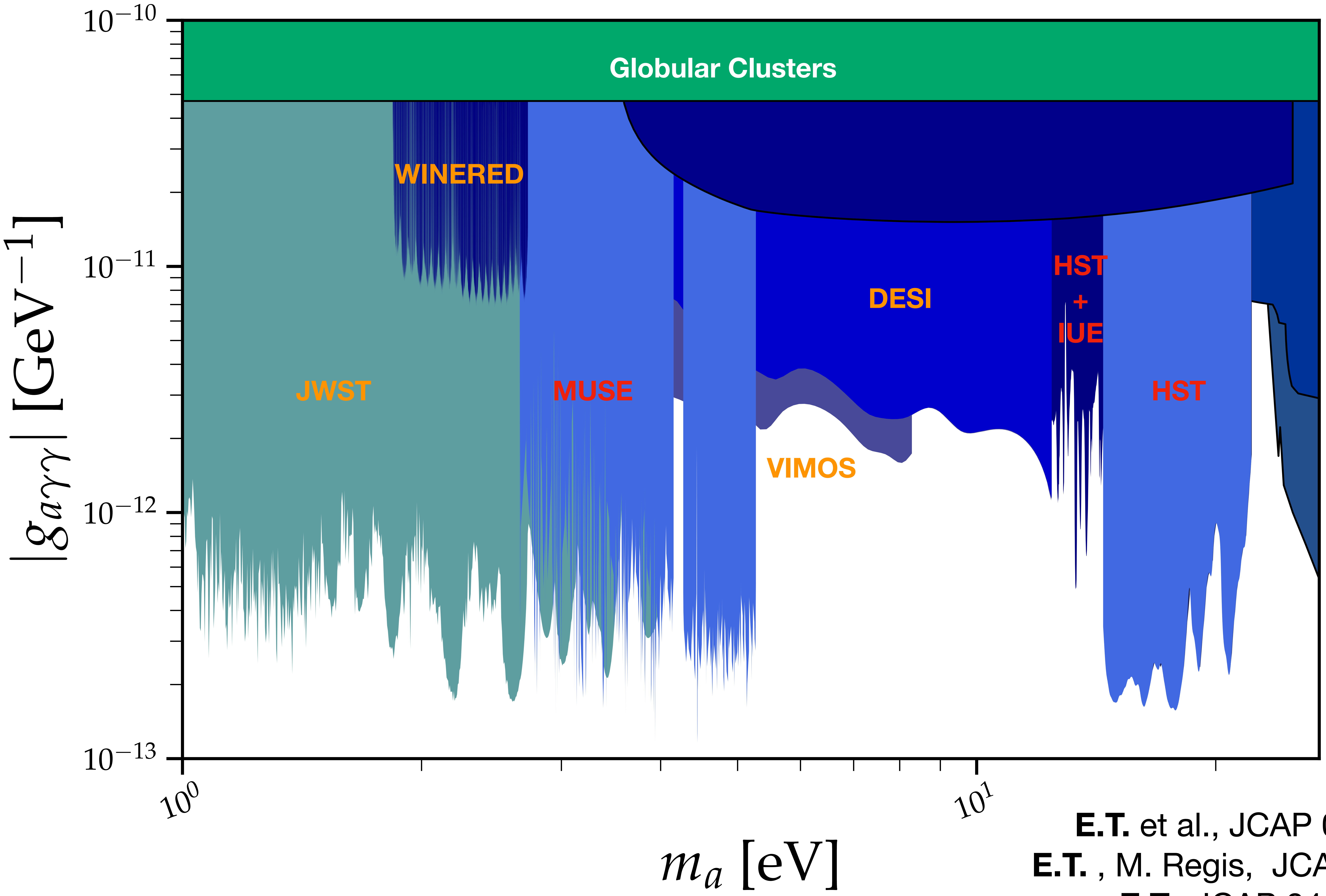
- **Cosmology** — contributed to (confirmed) the discovery of accelerating expansion of the Universe
- **Galaxies** — supermassive black holes in every galaxy, first flat accretion-disk image,
- **Star Evolution** — young stellar clusters
- **Exoplanets** — first visible-light image
- **Solar System** — Pluto surface and moons

Observations are not done with a dark matter indirect search in mind!

Can we still use the data to search for axion dark matter?

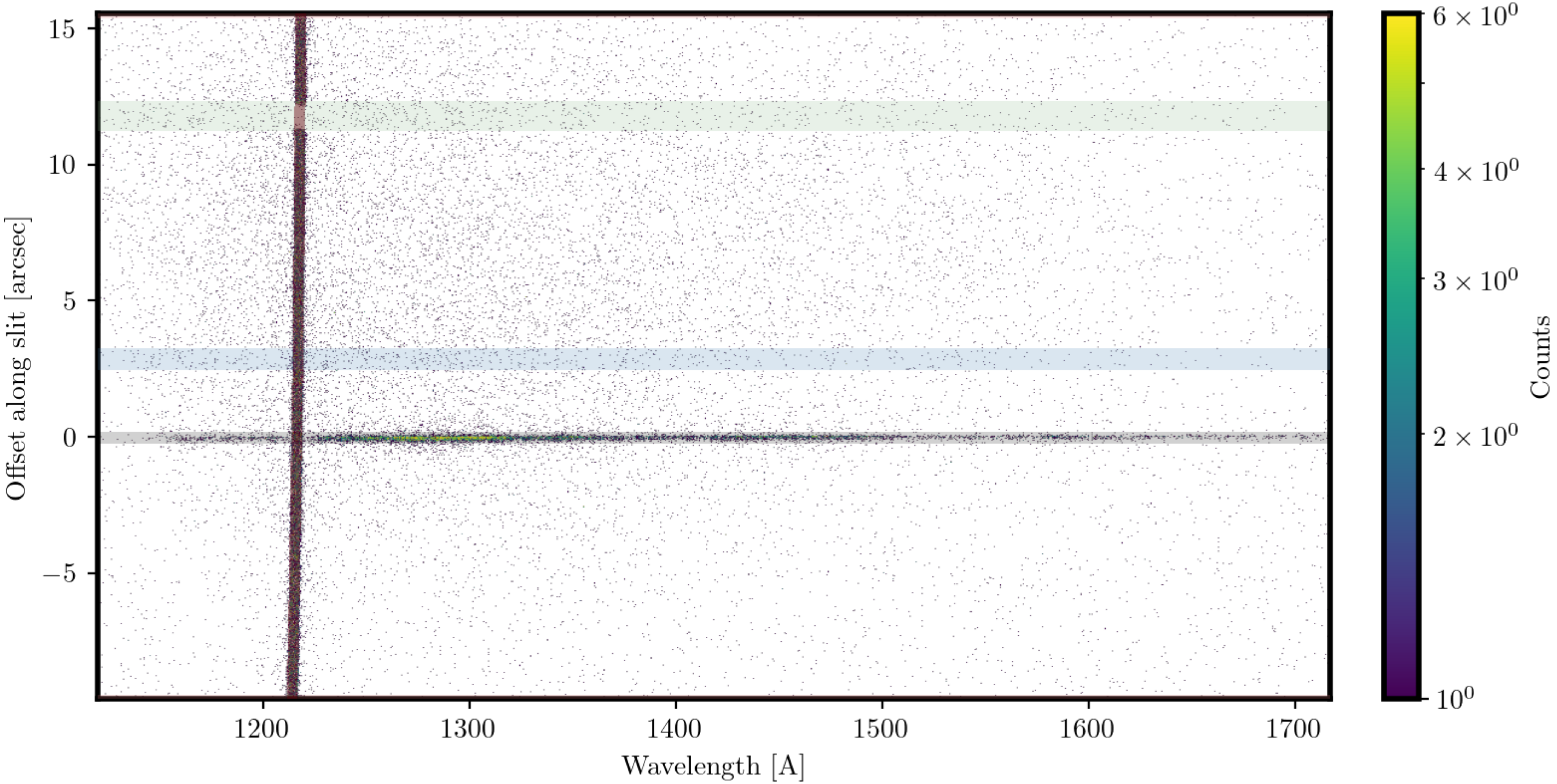
- 1-dimensional detectors
- Cannot mask bright sources
- Blank sky observations taken during science verification phase

- 2-dimensional detectors
- Blank sky search possible by masking point sourcesphase
- Few observations of dwarfs and galaxy clusters



E.T. et al., JCAP 05 (2024) 043
E.T. , M. Regis, JCAP 05 (2025) 070
E.T., JCAP 04 (2026) 063

oe7d04040_v1



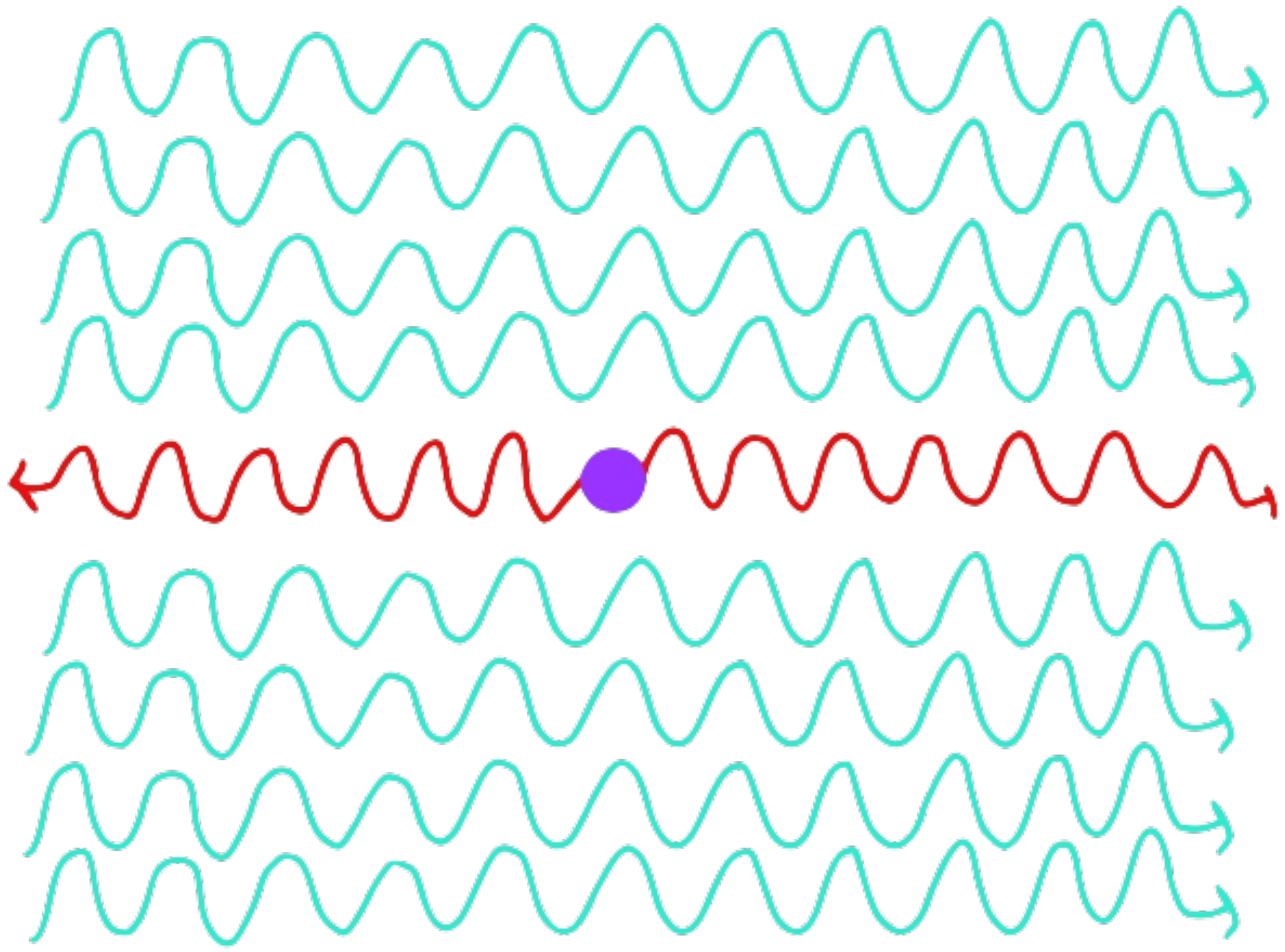
Axion stimulated decay

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

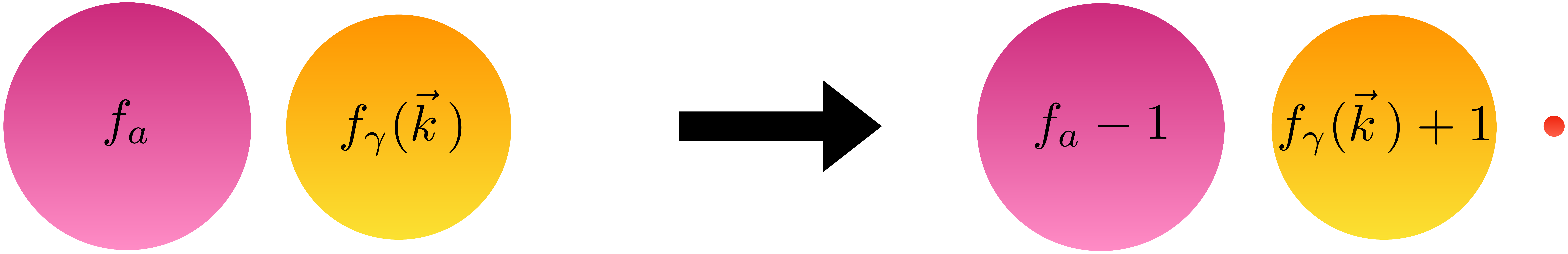
$$f_\gamma(\vec{k})$$



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

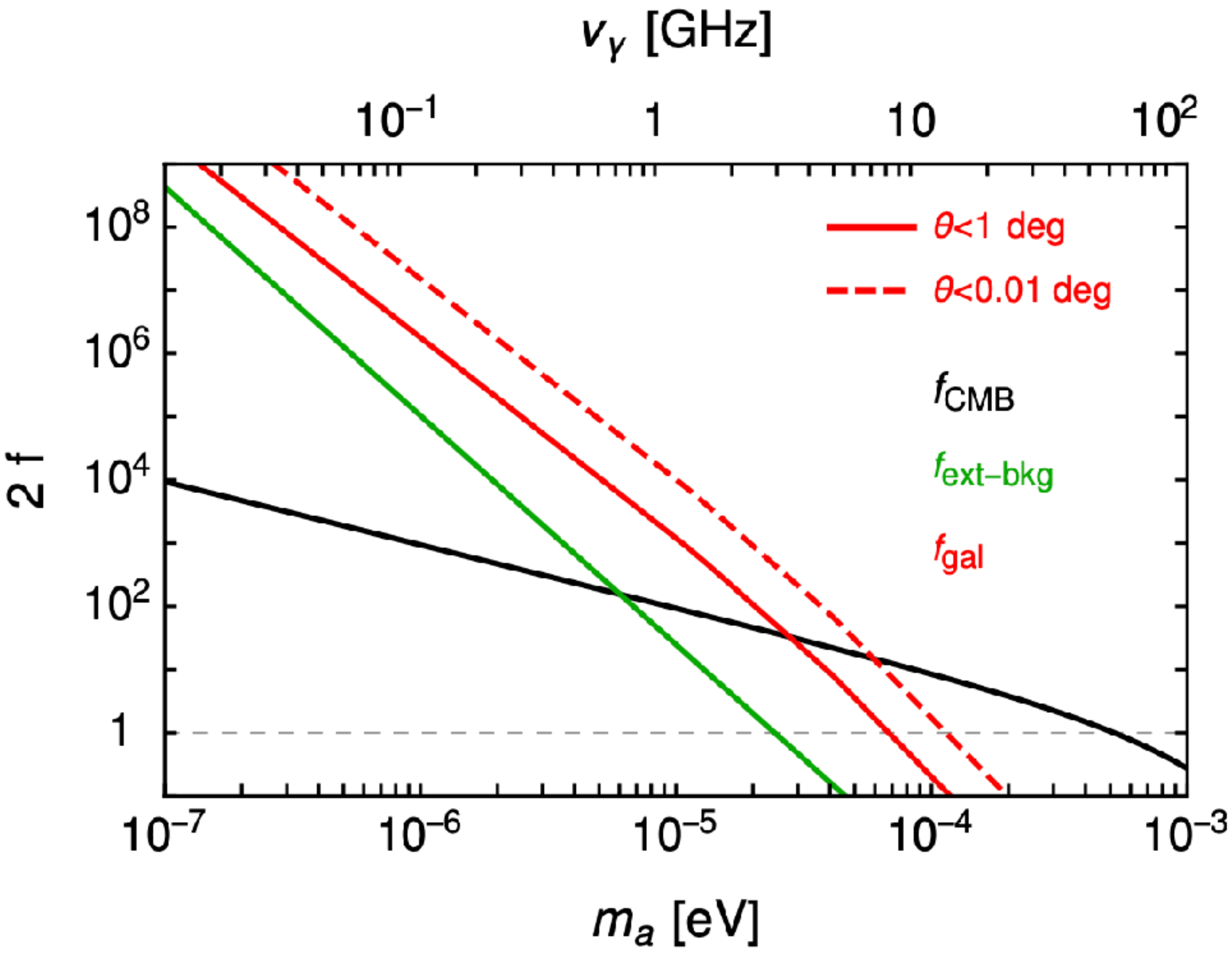
Bose-enhancement

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



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

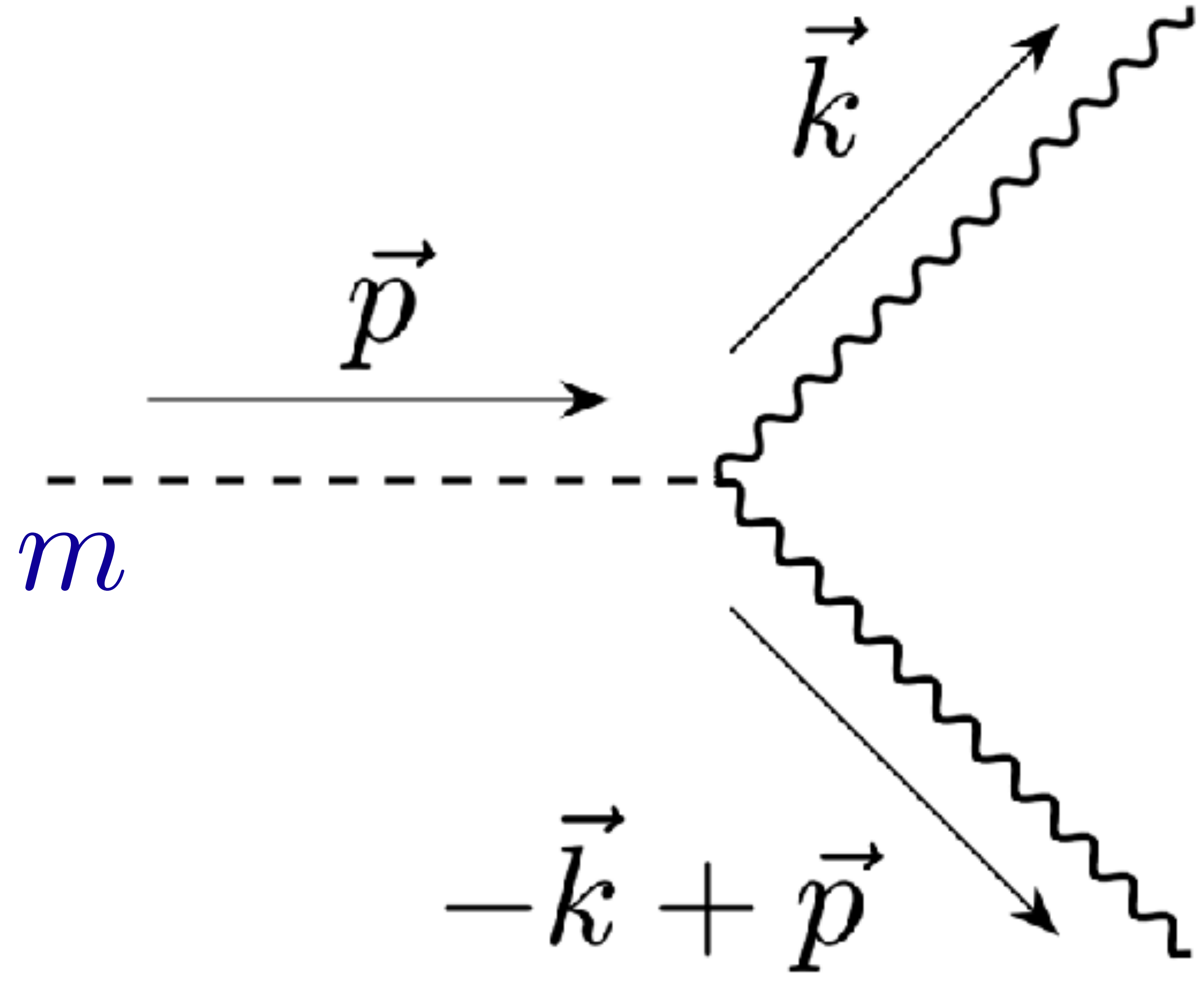
Enhancement factor



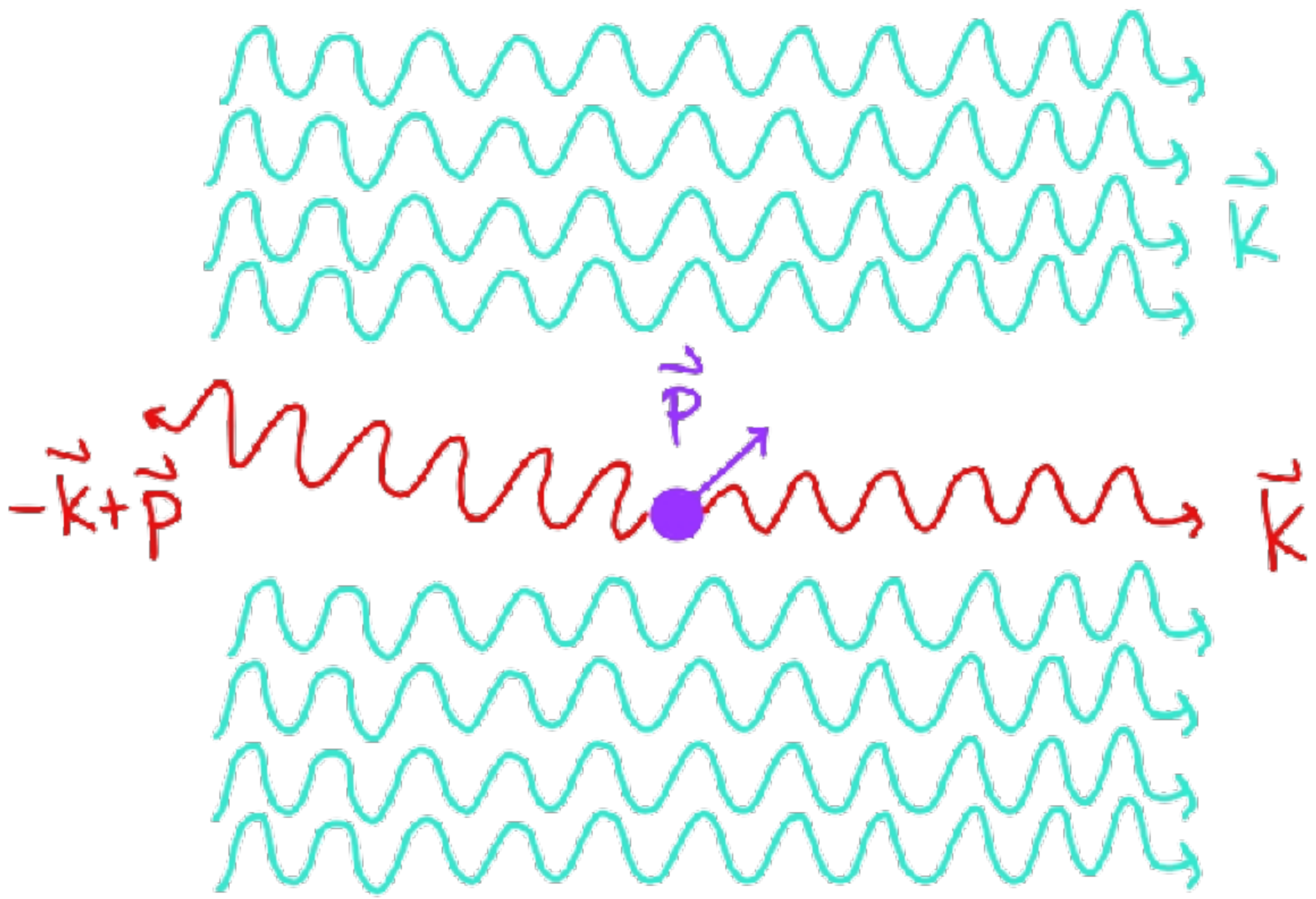
Caputo, Regis, Taoso, Witte, JCAP 03 (2019) 027

Kinematics

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



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

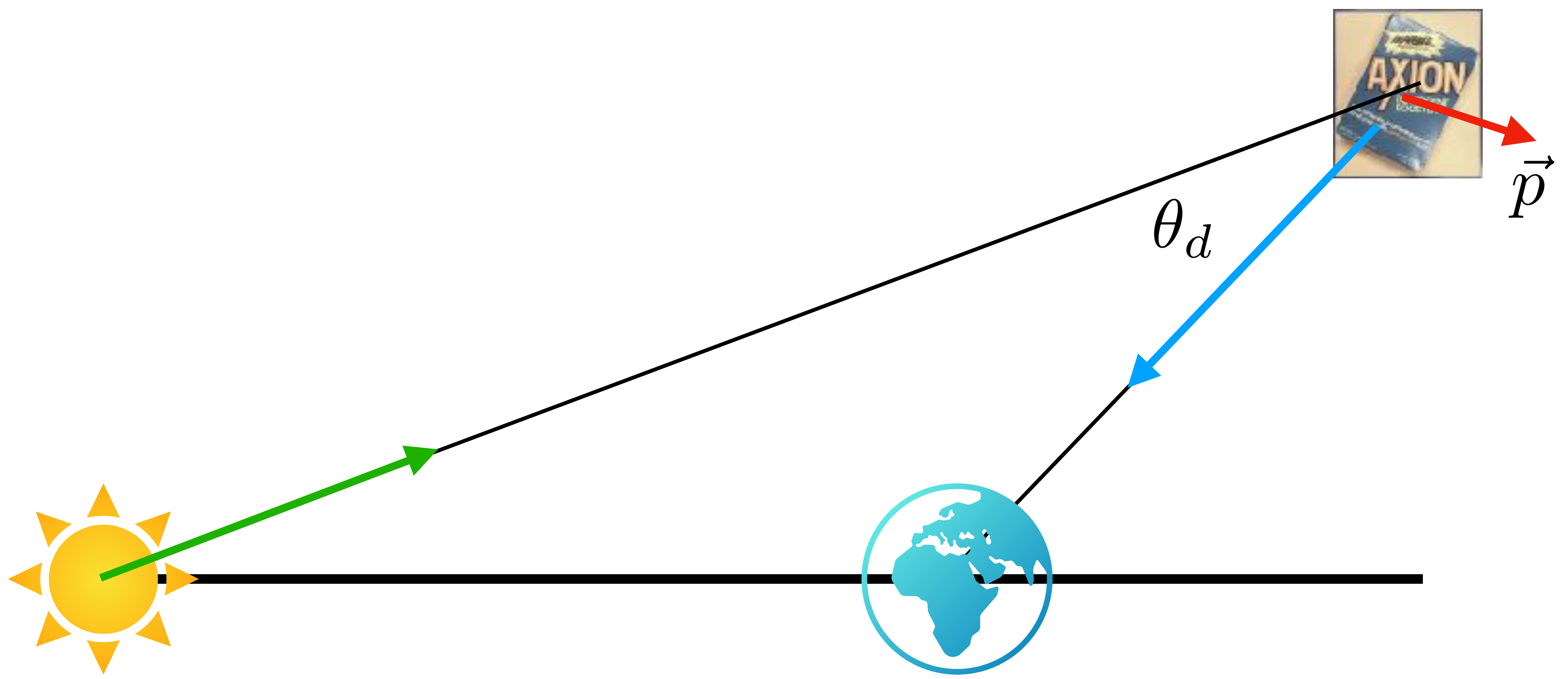


The echo propagates

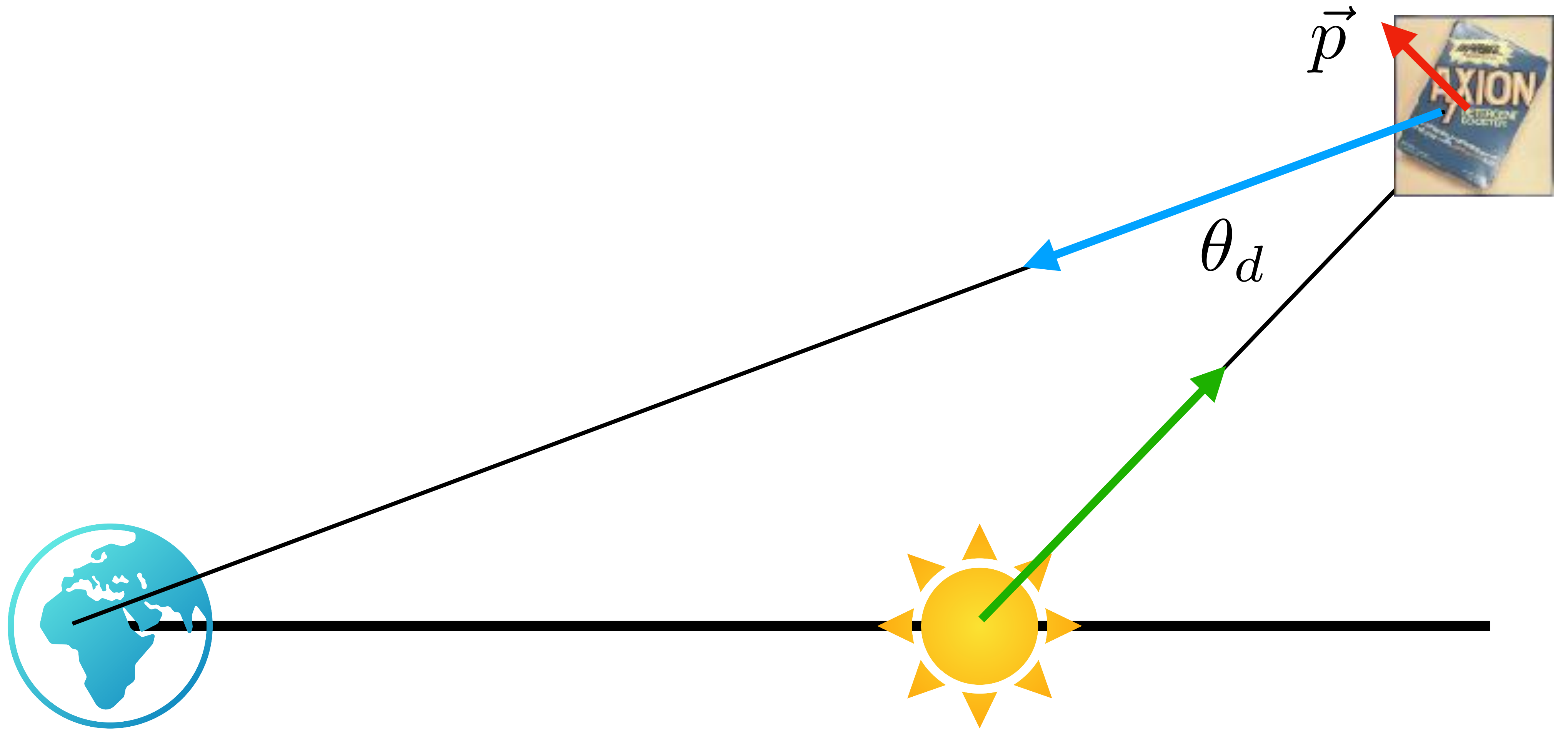
***almost* backwards!**

Echoes from natural sources

Back-light echo

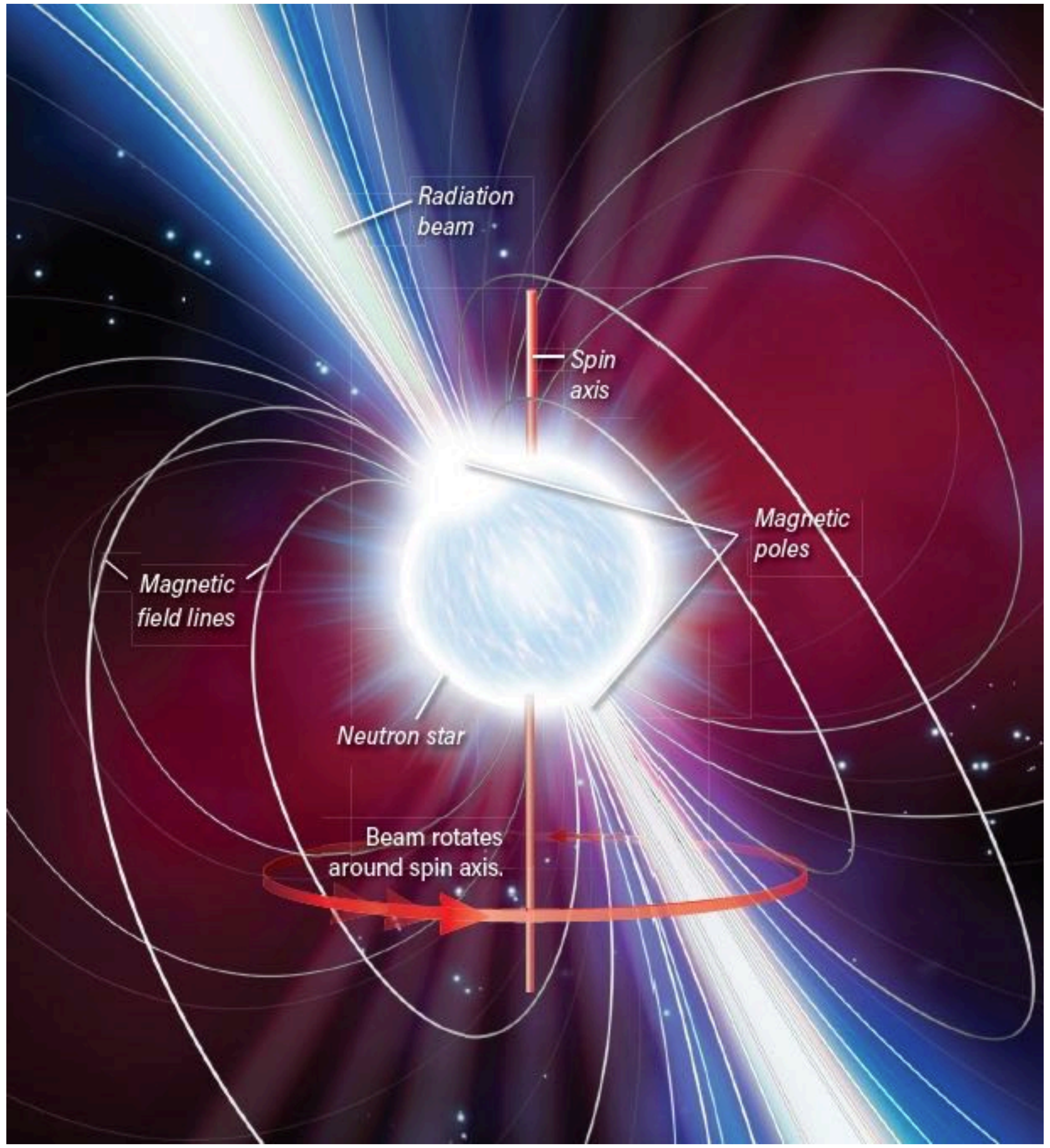


Front-light echo



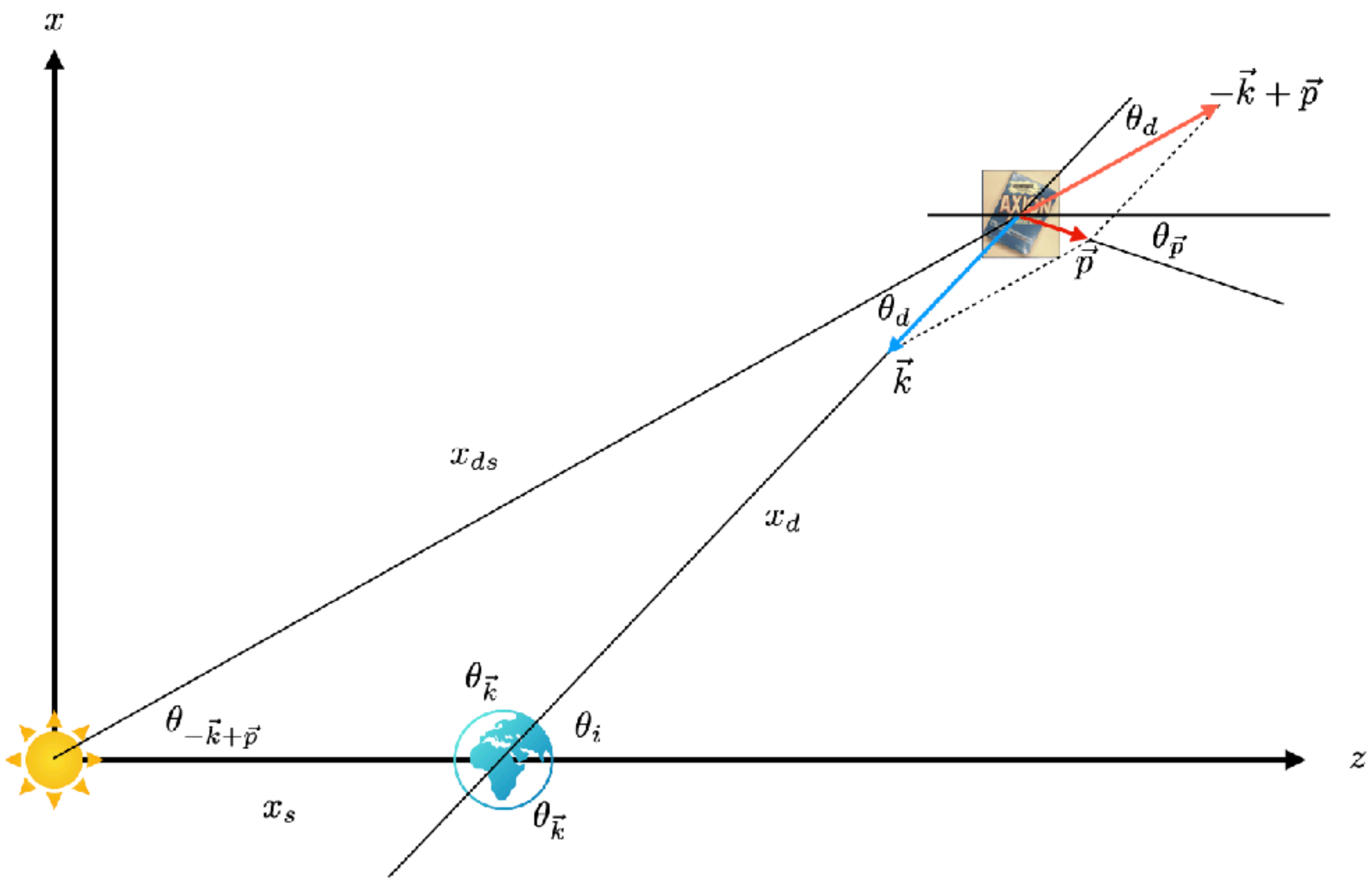
Collinear emission

Detailed Study of the Echo from a Point Source



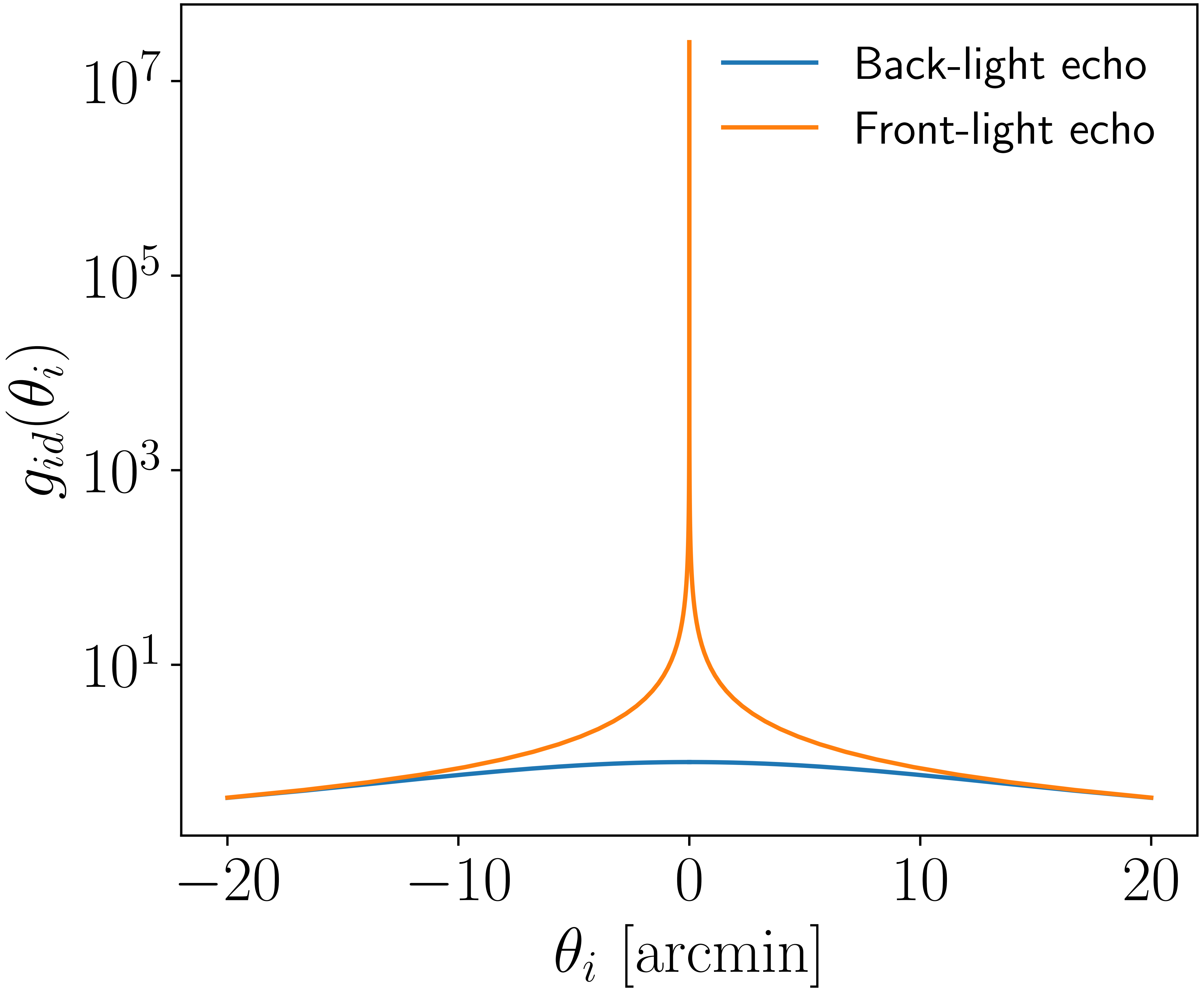
E.T., F. Calore, M. Regis,
JCAP 05 (2024) 040

Smearing of the signal



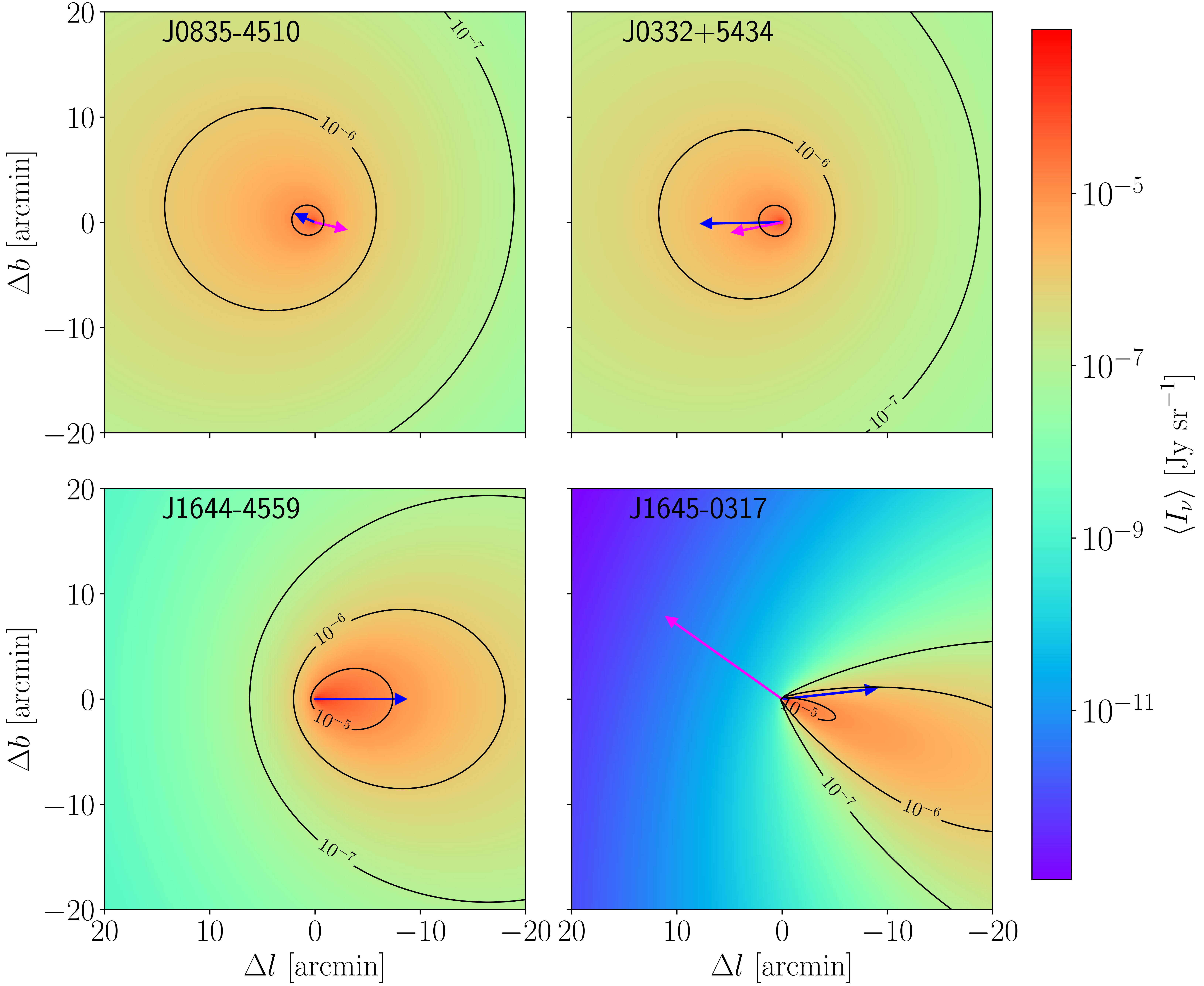
$$\theta_d = \frac{x_s}{x_{ds}}\theta_i$$

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

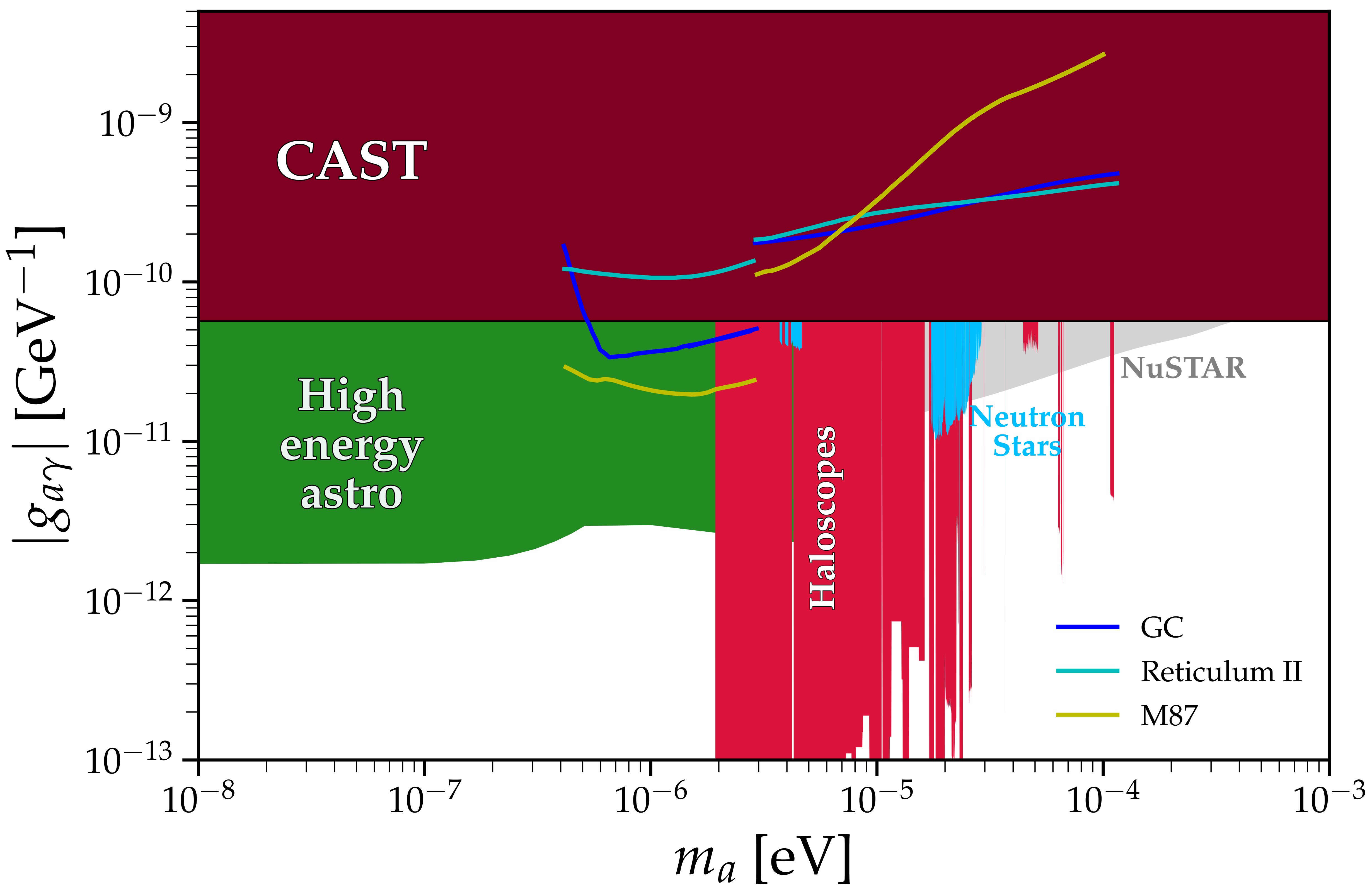


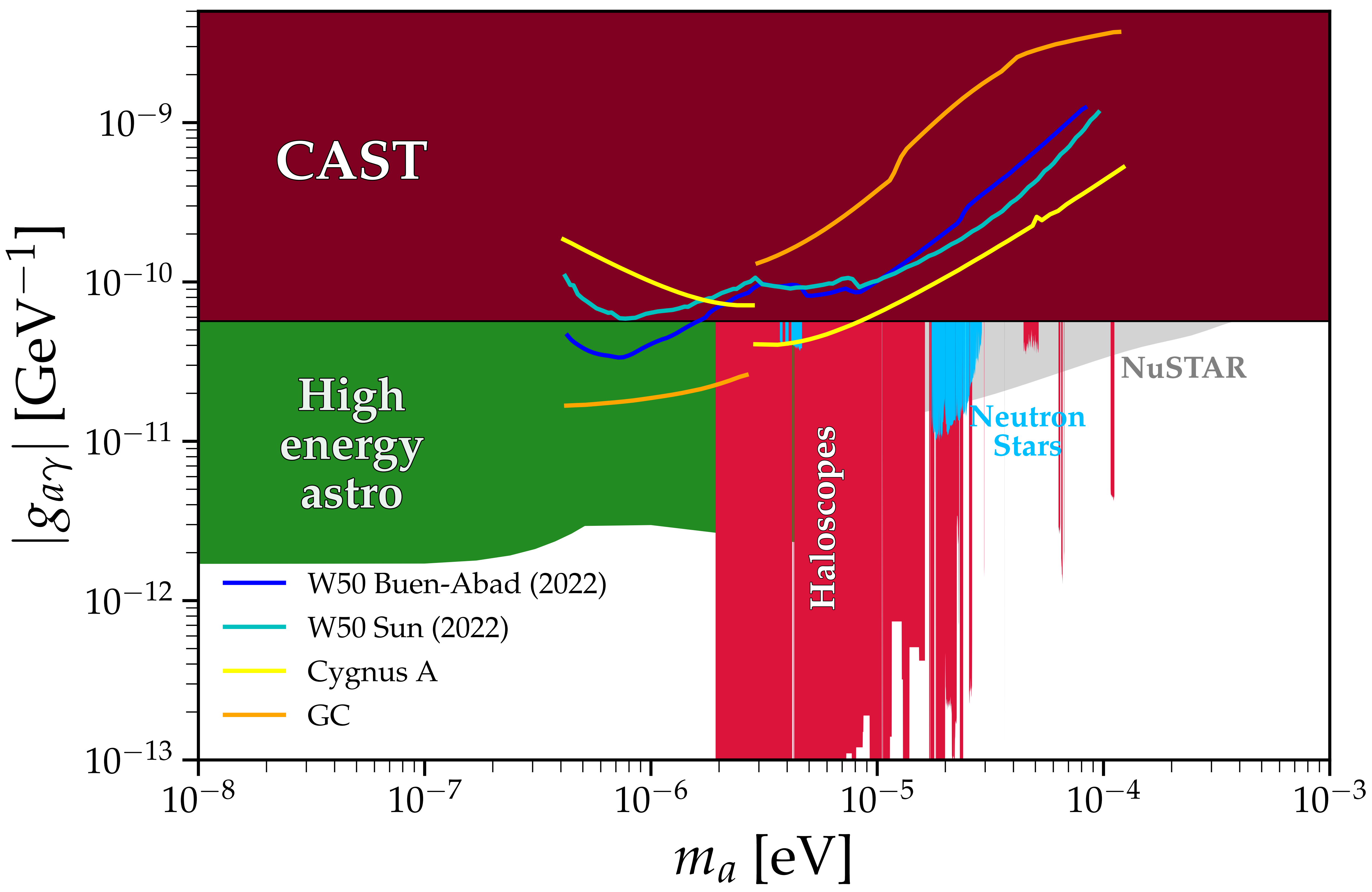
Relevant effects

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

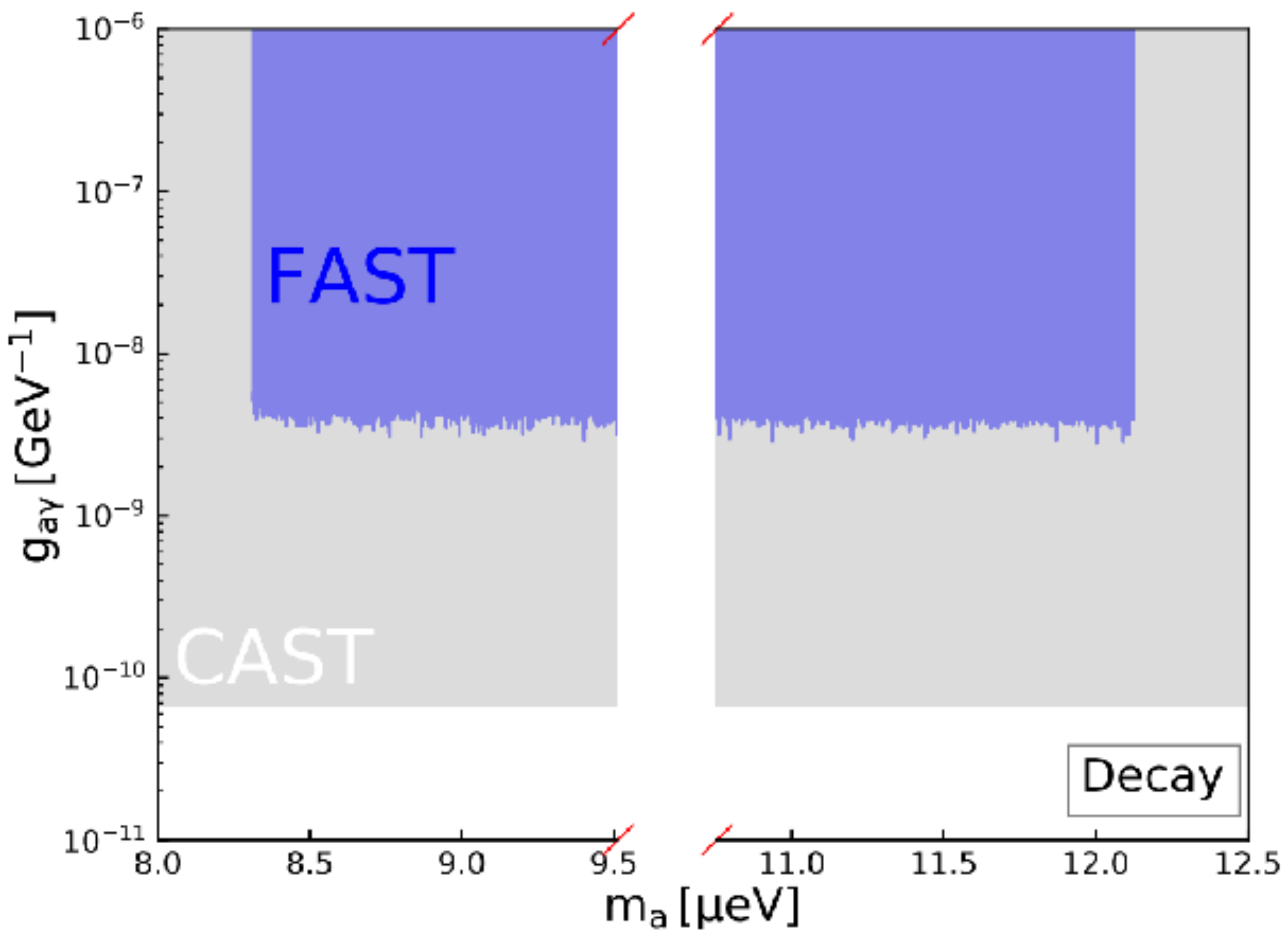

J0835-4510
J0332+5434
J1644-4559
J1645-0317
10^{-7}
10^{-6}
10^{-5}
Δb [arcmin]
Δl [arcmin]
$\langle I_\nu \rangle$ [Jy sr^{-1}]
10^{-5}
10^{-7}
10^{-9}
10^{-11}
20
10
0
-10
-20

SKA-O AA4 Forecasts





M. Regis, **E.T.** et al., SKA book, in preparation



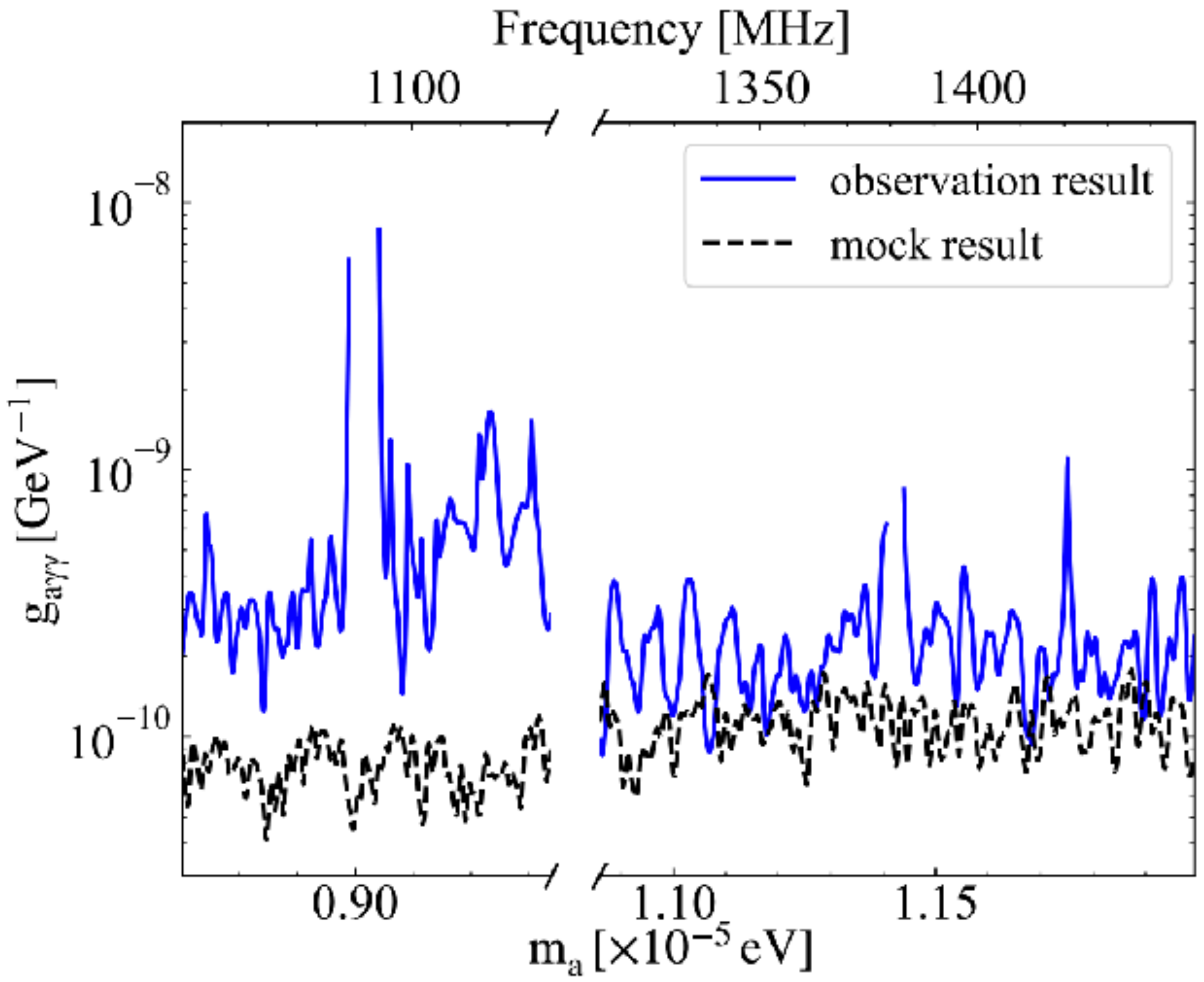
Guo, Xia, Huang

PLB 852 (2024) 138631

Collinear emission

CMB, extragalactic radio bkg

2-hour observation of Coma Berenices



Yang, Sun, Wang, Schutz, Li, Leung, Hu, Shu, Masui, Chen

2502.08913

Backlight echo

Vela supernova remnant

~30-hour observation

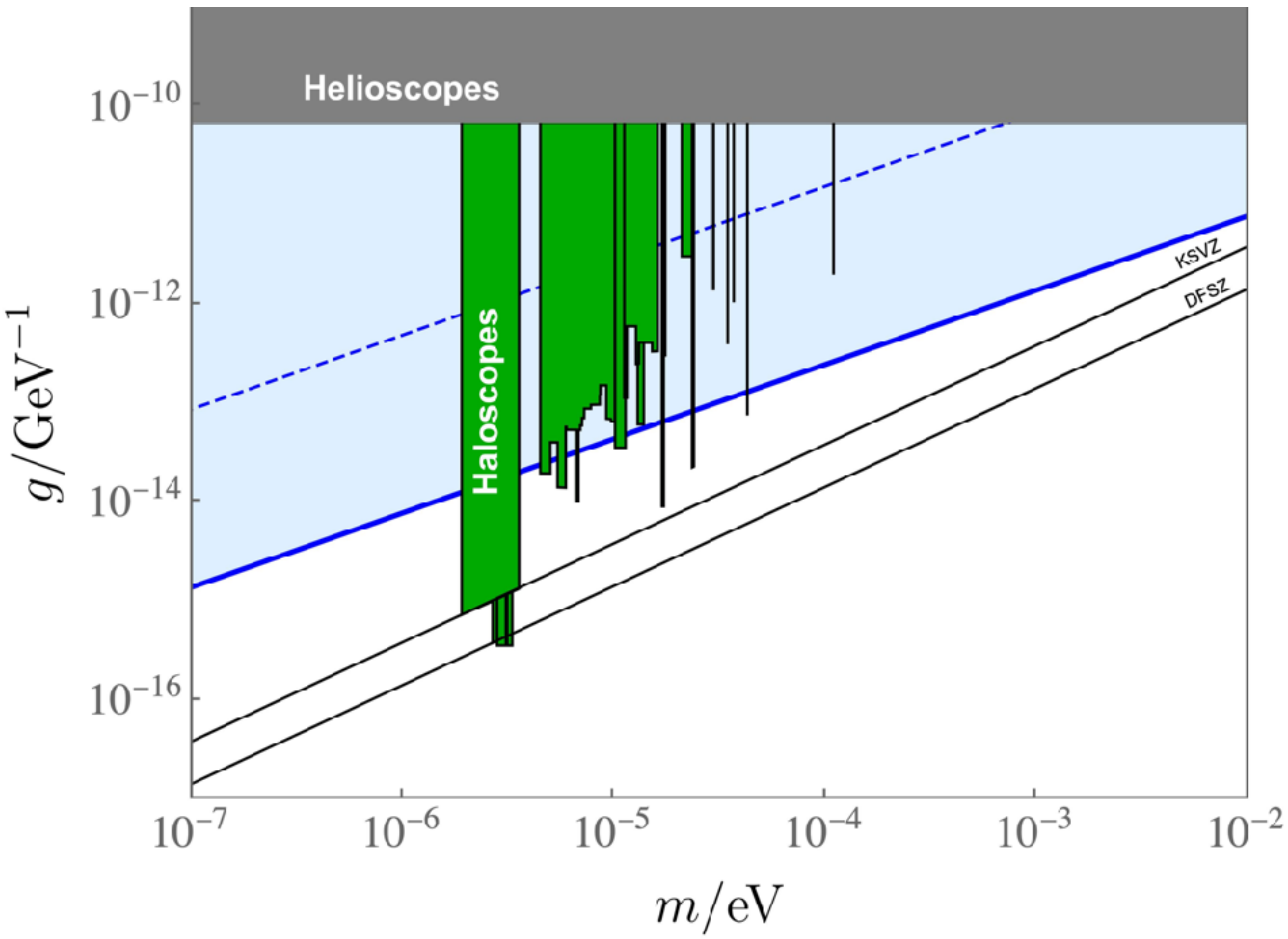
An echo from an artificial source

A. Arza, P. Sikivie, PRL (2019) 13

A. 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



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

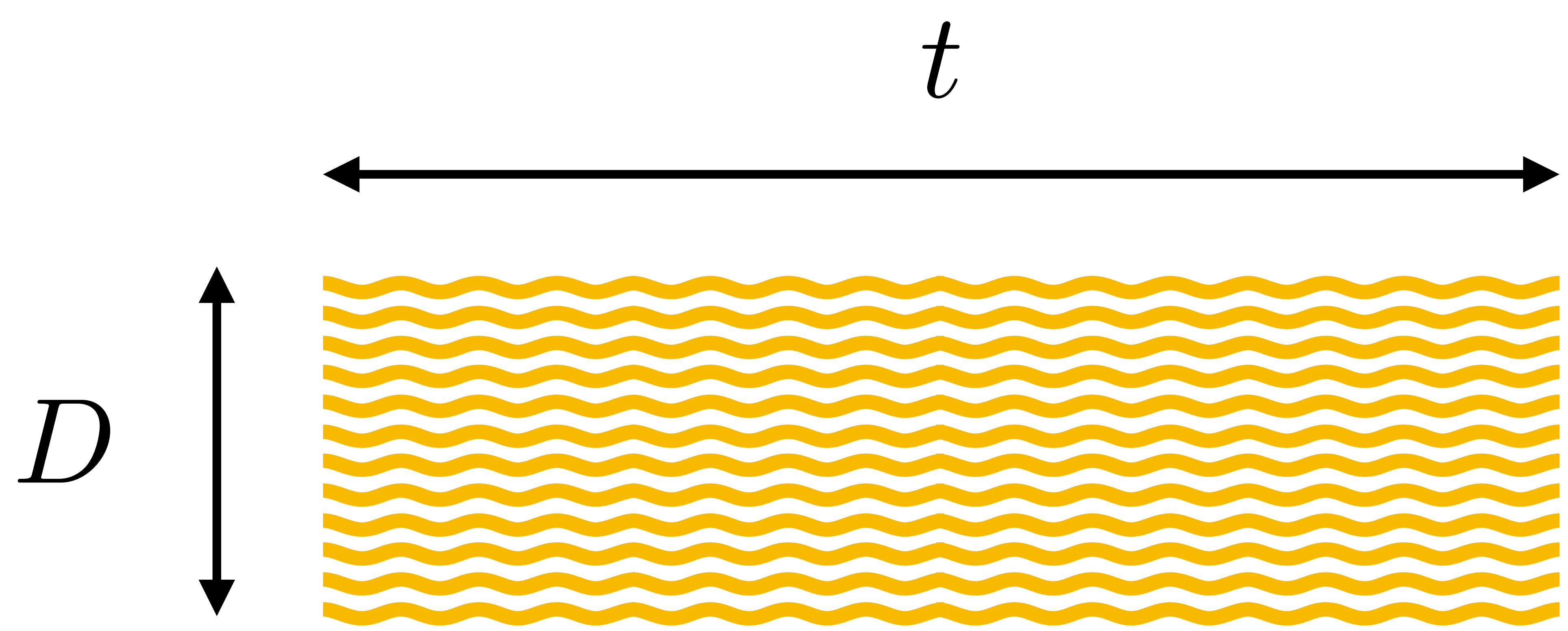
Fixed energy to cover a factor of 2 in axion mass (solid blue)

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

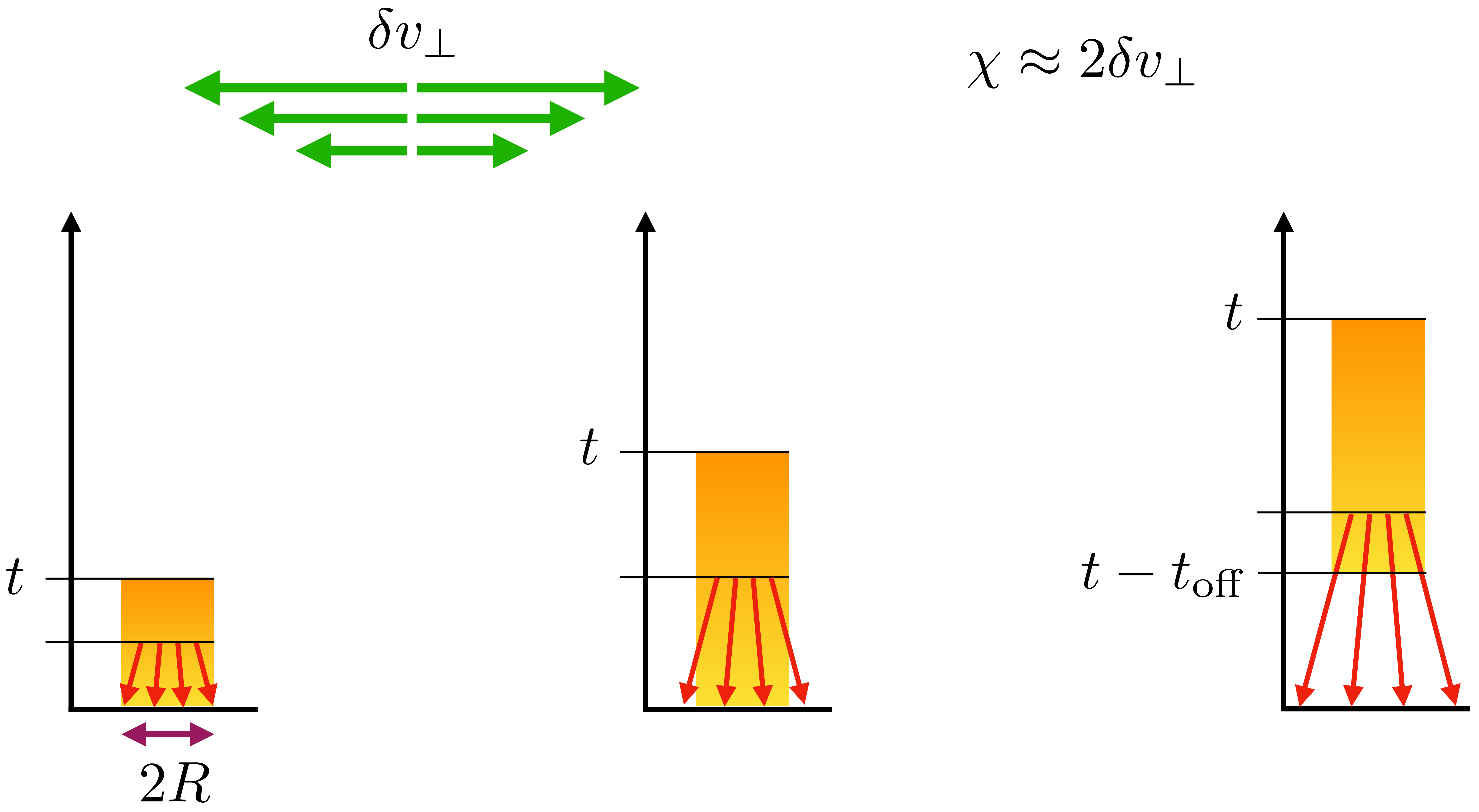
Enhancement factor

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

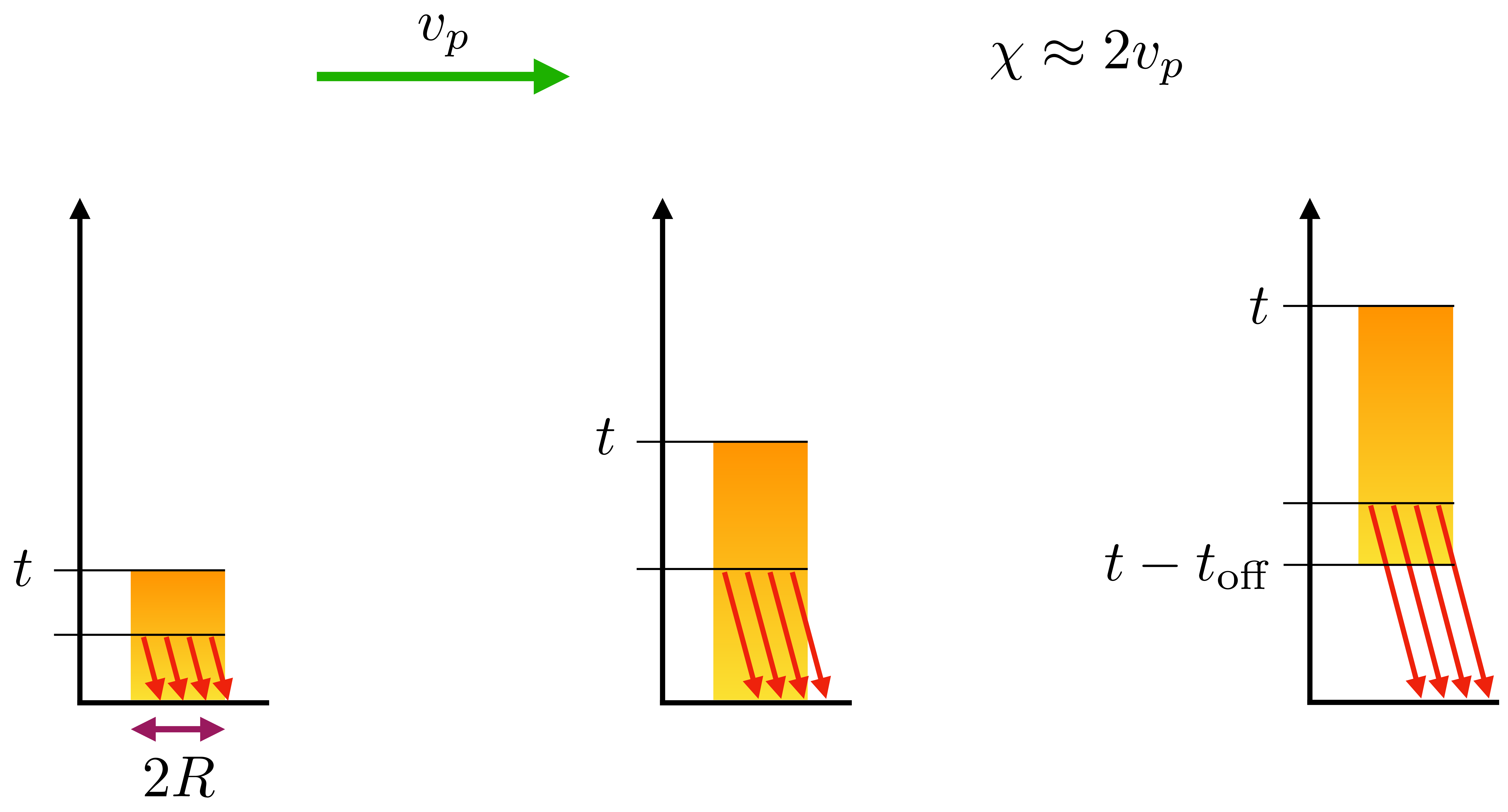
$$f_\gamma \sim 10^{20} \left(\frac{1}{n_{pol}}\right) \left(\frac{10^{-5}\ \mathrm{eV}}{m}\right)^3 \left(\frac{1\ \mathrm{m}^2}{A}\right) \left(\frac{P}{1\ \mathrm{kW}}\right) \left(\frac{1\ \mathrm{MHz}}{\Delta\nu}\right)$$

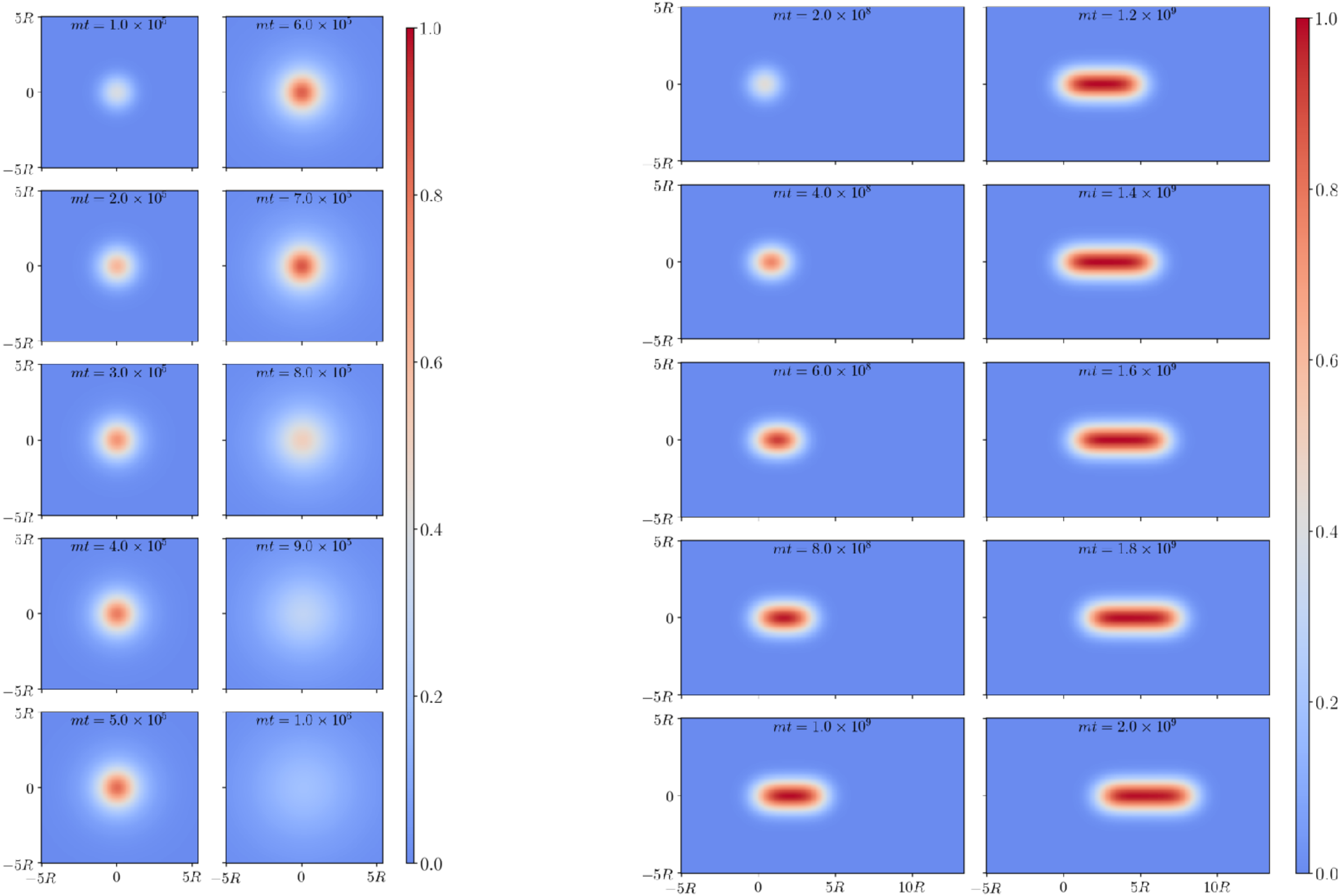


Velocity dispersion



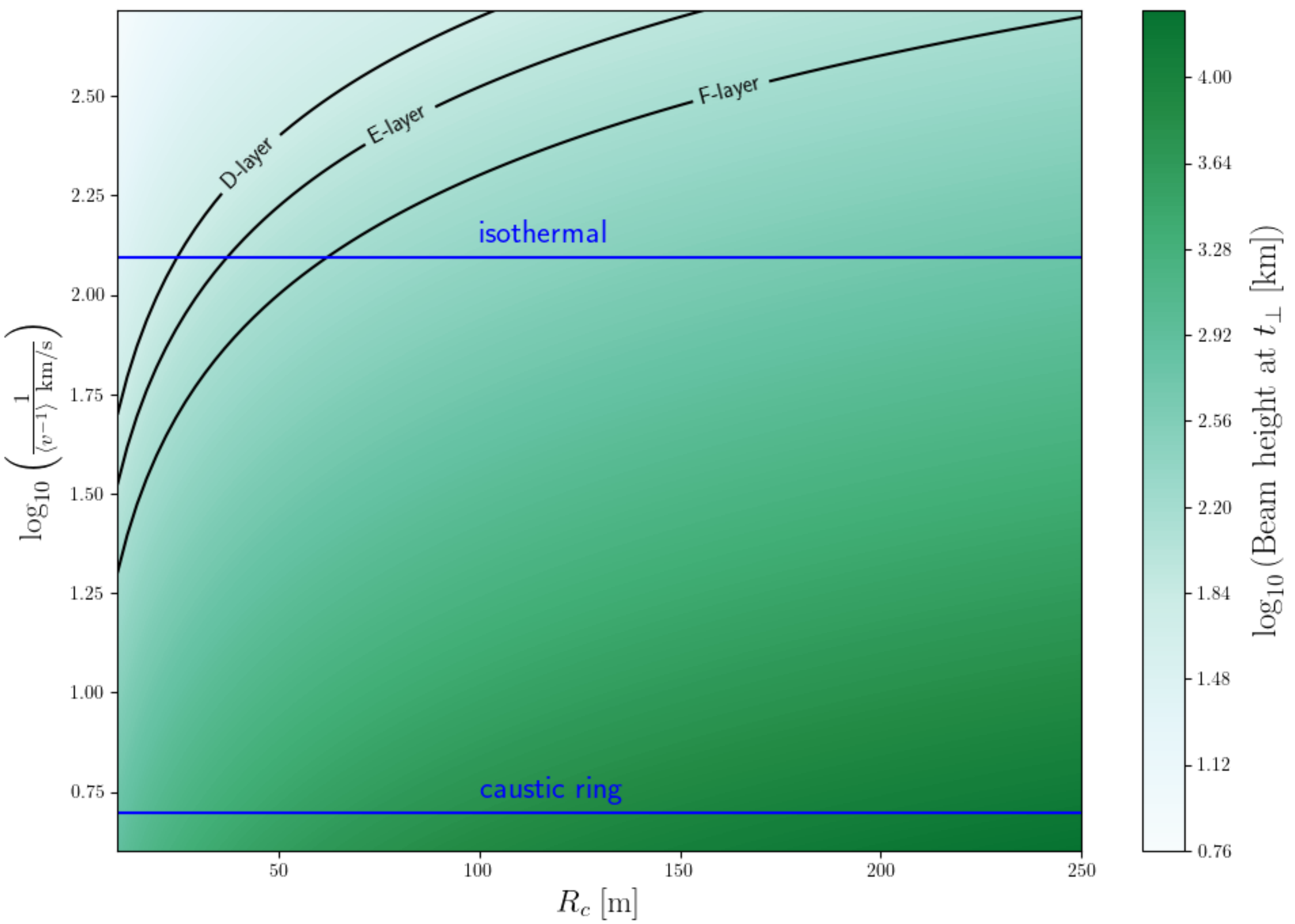
Small velocity dispersion



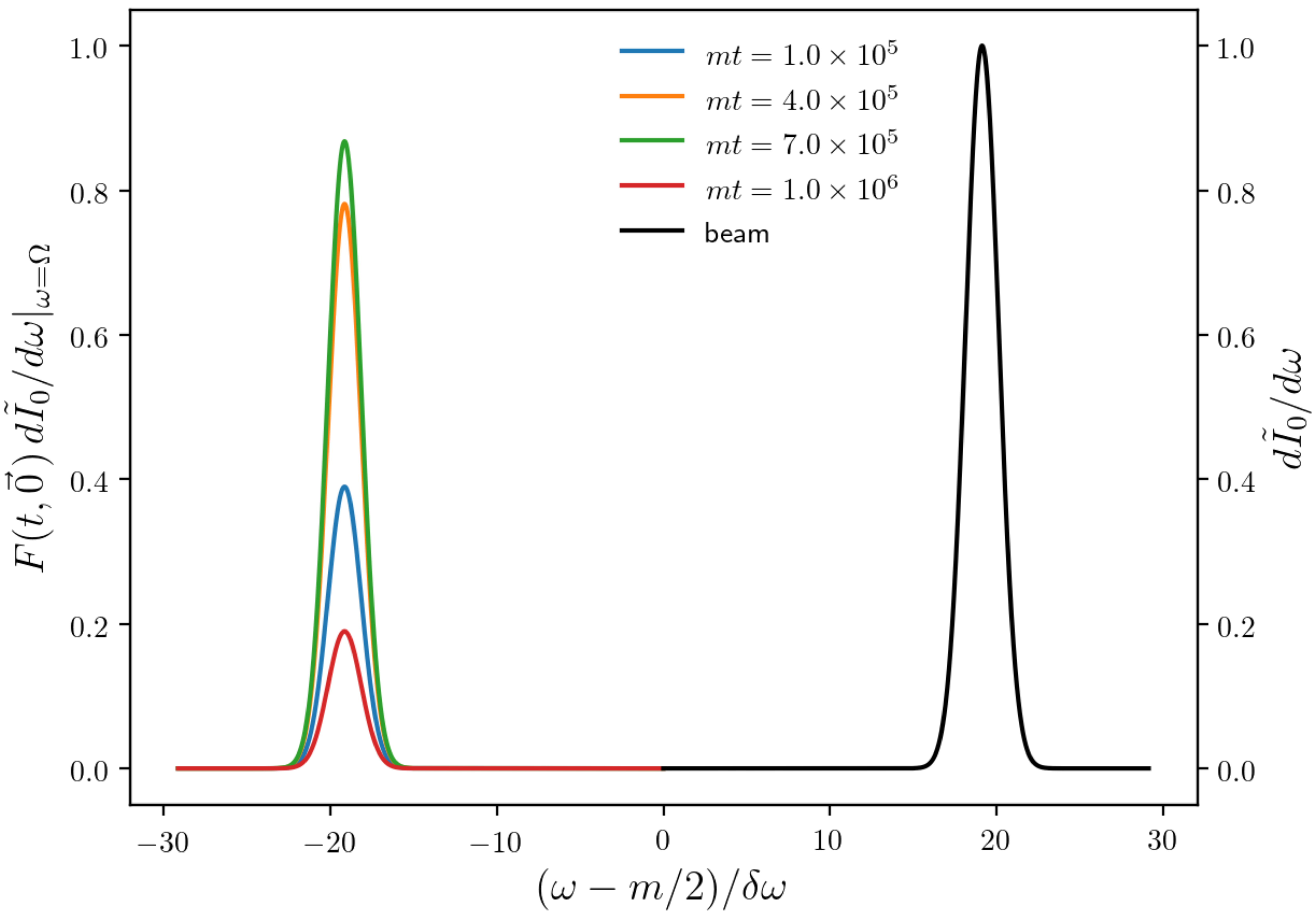


$mt = 1.0 \times 10^5$
$mt = 2.0 \times 10^5$
$mt = 3.0 \times 10^5$
$mt = 4.0 \times 10^5$
$mt = 5.0 \times 10^5$
$mt = 6.0 \times 10^5$
$mt = 7.0 \times 10^5$
$mt = 8.0 \times 10^5$
$mt = 9.0 \times 10^5$
$mt = 1.0 \times 10^6$
$mt = 2.0 \times 10^8$
$mt = 4.0 \times 10^8$
$mt = 6.0 \times 10^8$
$mt = 8.0 \times 10^8$
$mt = 1.0 \times 10^9$
$mt = 1.2 \times 10^9$
$mt = 1.4 \times 10^9$
$mt = 1.6 \times 10^9$
$mt = 1.8 \times 10^9$
$mt = 2.0 \times 10^9$
$5R$
0
$-5R$
$10R$
0.0
0.2
0.4
0.6
0.8
1.0

Beam height



D-layer
E-layer
F-layer
isothermal
caustic ring
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.75
50
100
150
200
250
R_c [m]
$\log_{10}\left(\frac{1}{\langle v^{-1}\rangle\ \mathrm{km/s}}\right)$
4.00
3.64
3.28
2.92
2.56
2.20
1.84
1.48
1.12
0.76
$\log_{10}(\text{Beam height at } t_\perp\ [\mathrm{km}])$



$mt = 1.0 \times 10^5$
$mt = 4.0 \times 10^5$
$mt = 7.0 \times 10^5$
$mt = 1.0 \times 10^6$
beam
$F(t,\vec{0})\, d\tilde{I}_0/d\omega|_{\omega=\Omega}$
$d\tilde{I}_0/d\omega$
$(\omega - m/2)/\delta\omega$
-30
-20
-10
0
10
20
30
0.0
0.2
0.4
0.6
0.8
1.0

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