An overview of searches for axion decay into photons: from radio to X-rays

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Axions in Stockholm
Stockholm, 10.07.2025

University of Nottingham
UK | CHINA | MALAYSIA

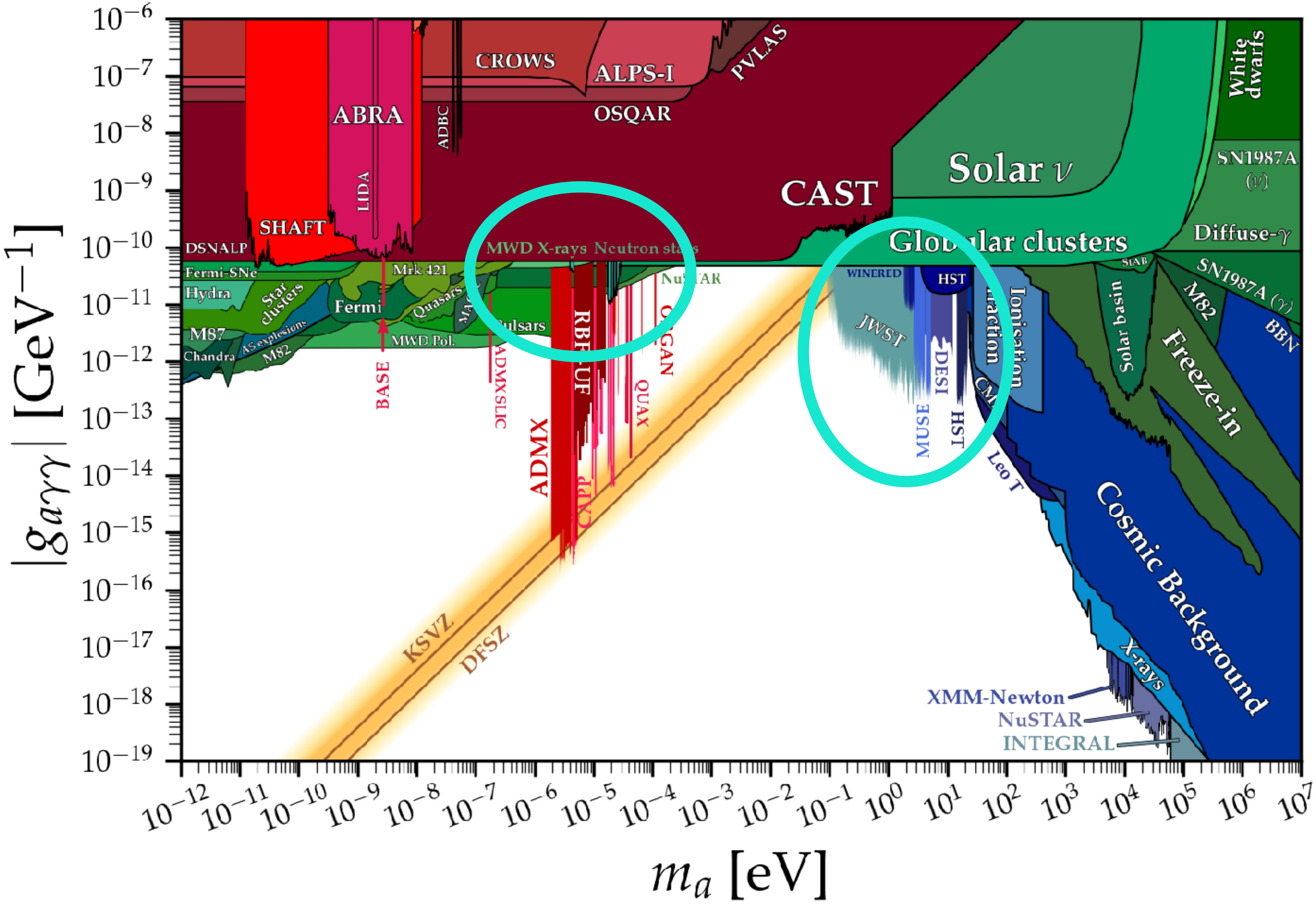
COSMIC WISPERS
CA21106

Topics

Spontaneous decay (IR and higher)

Stimulated decay (radio)

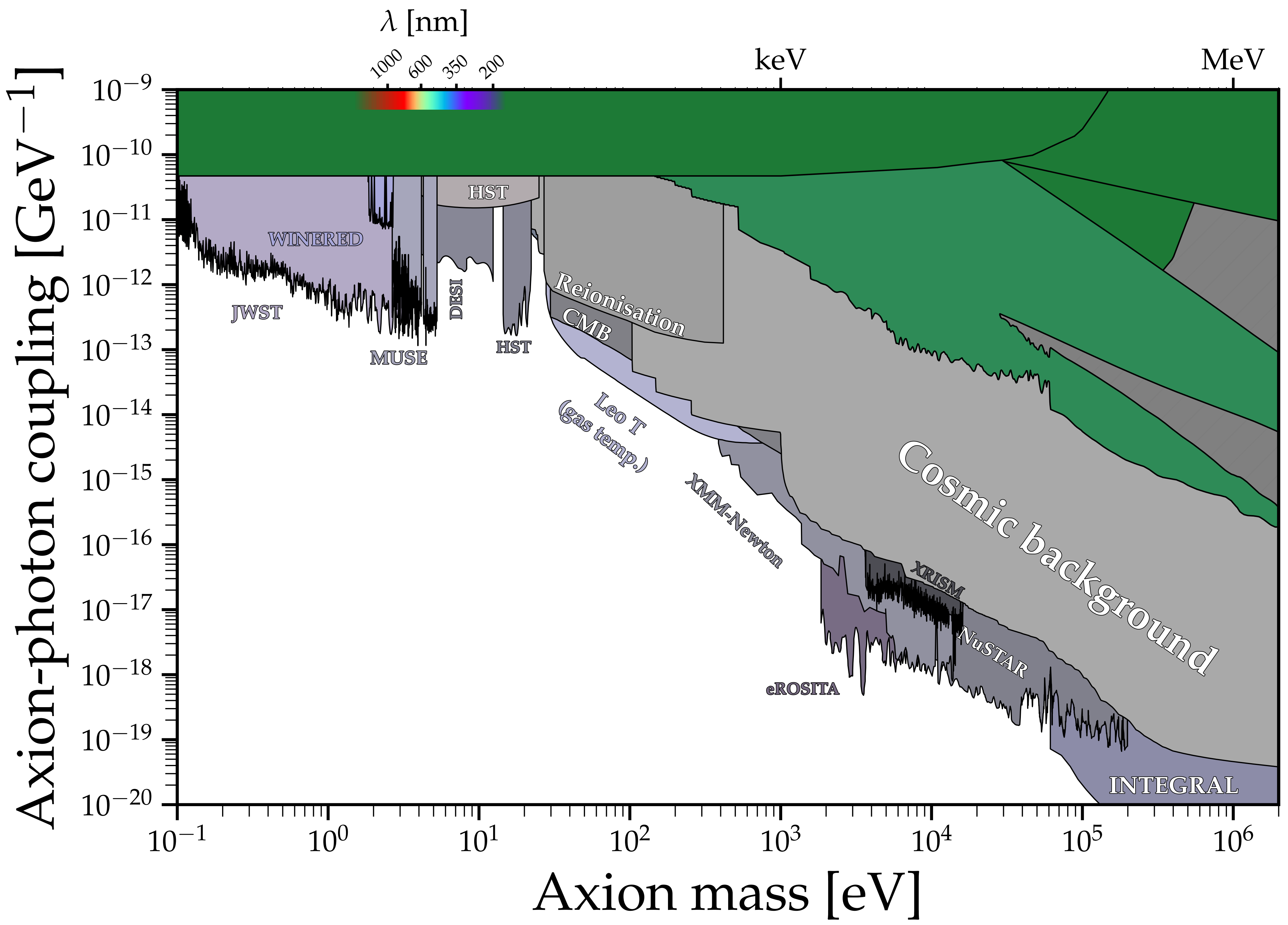
Parametric resonance (radio)



cajohare/axionlimits: Axionlimits

Spontaneous decay

References

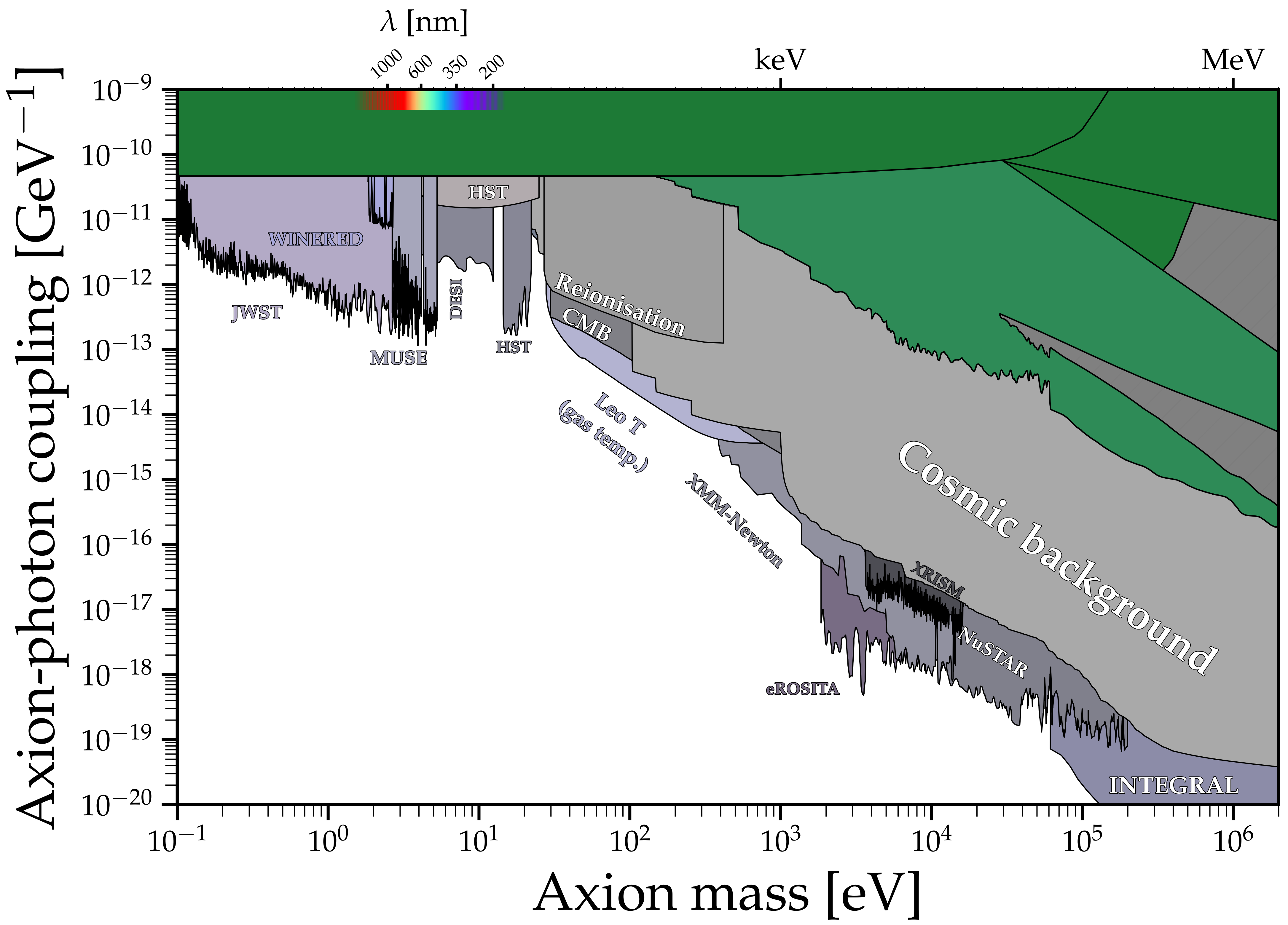


"2011 Compilation" (a subset thereof)

Cadamuro et al. "*Cosmological bounds on pseudo Nambu-Goldstone bosons*", JCAP 02 (2012) 032

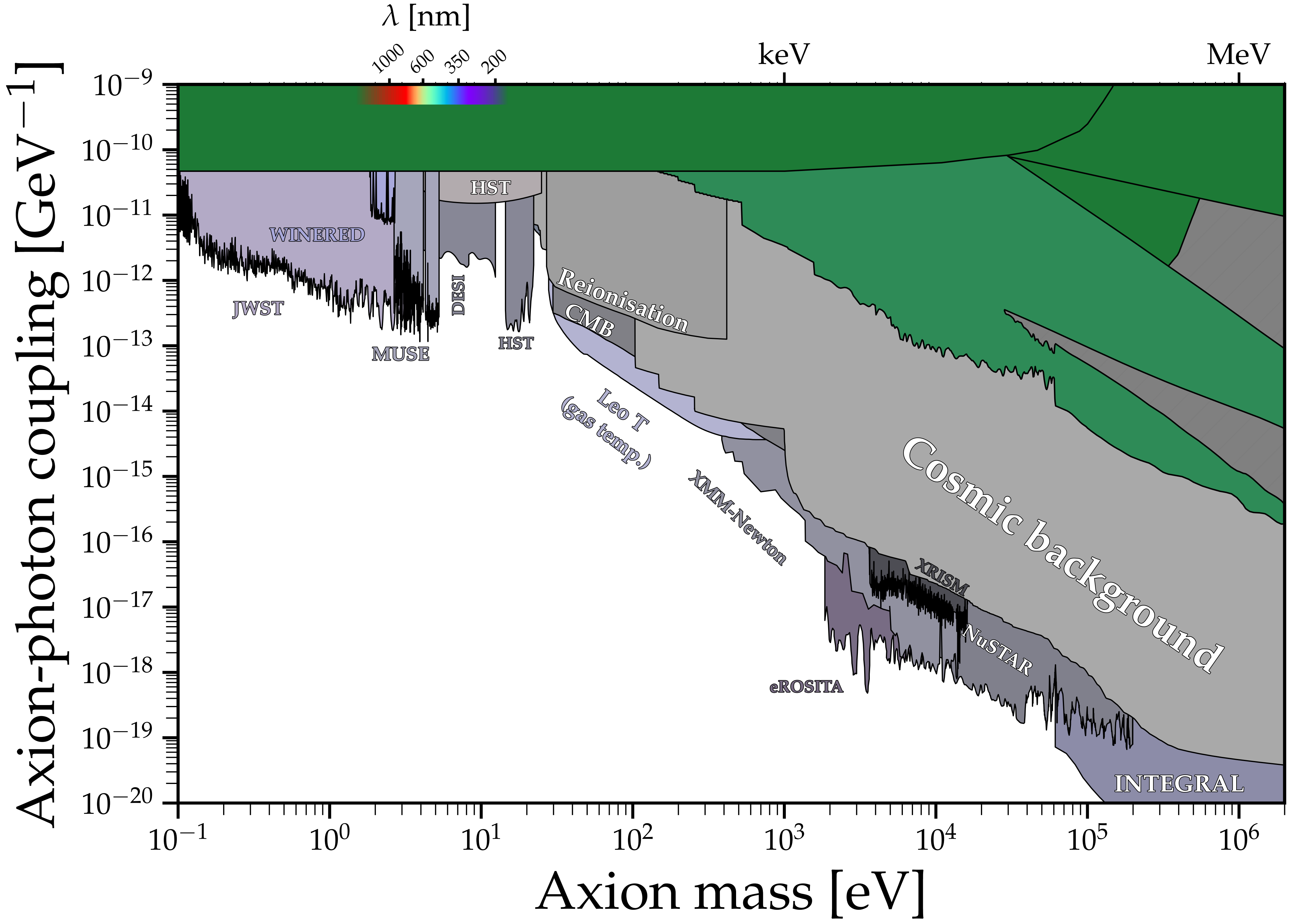
1. photons produced in ALP decays inside galaxies would show up as a peak in galactic spectra that must not exceed the known backgrounds
2. photons produced in ALP decays when the universe is transparent must not exceed the extragalactic background light
3. the ionization of primordial hydrogen caused by the decay photons must not contribute significantly to the optical depth after recombination

References

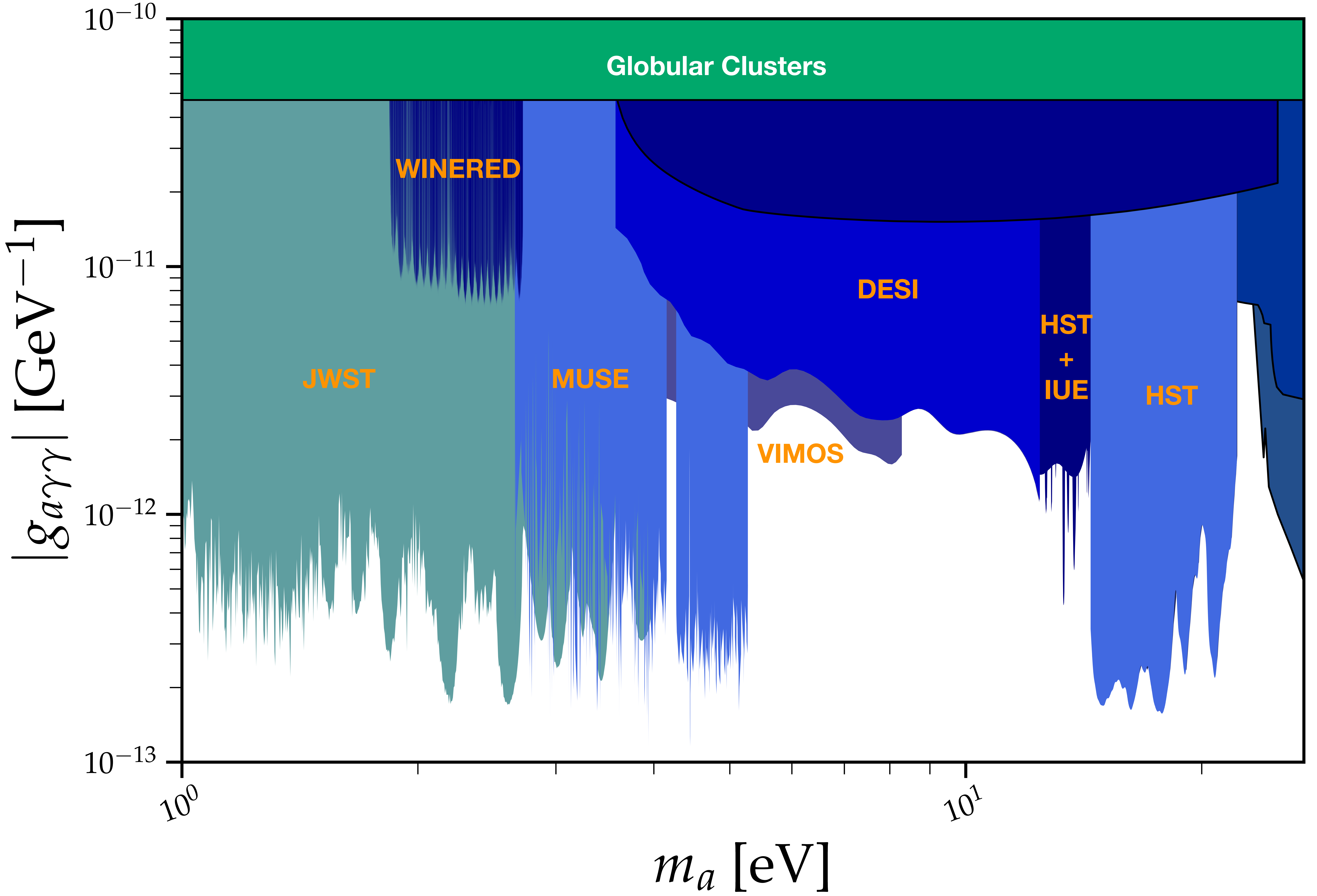


- **Cosmic Background (UV, X-ray)**
  - Porras-Bedmar et al., *"Novel bounds on decaying axionlike particle dark matter from the cosmic background"*, Phys.Rev.D 110 103501
- **CMB spectral distortions**
  - Liu et al., *"Exotic energy injection in the early universe II: CMB spectral distortions and constraints on light dark matter"*, Phys.Rev.D 108 (2023) 4, 043531
  - Capozzi et al., *"CMB and Lyman-α constraints on dark matter decays to photons"*, JCAP 06 (2023) 060

References



- **Gas heating**
  - Wadekar et al., "*Strong constraints on decay and annihilation of dark matter from heating of gas-rich dwarf galaxies*", Phys.Rev.D 106 (2022) 7, 075007
- **Cosmic optical background anisotropies**
  - Nakayama et al., *"Anisotropic cosmic optical background bound for decaying dark matter in light of the LORRI anomaly"*, Phys.Rev.D 106 (2022) 10, 103505
  - Carenza et al., "*Probing the blue axion with cosmic optical background anisotropies*", Phys.Rev.D 107 (2023) 8, 083032


Globular Clusters
WINERED
JWST
MUSE
DESI
VIMOS
HST
+
IUE
HST
10^{-10}
10^{-11}
10^{-12}
10^{-13}
$|g_{a\gamma\gamma}|$ [GeV−1]
10^{0}
10^{1}
m_a [eV]

References: IR to UV

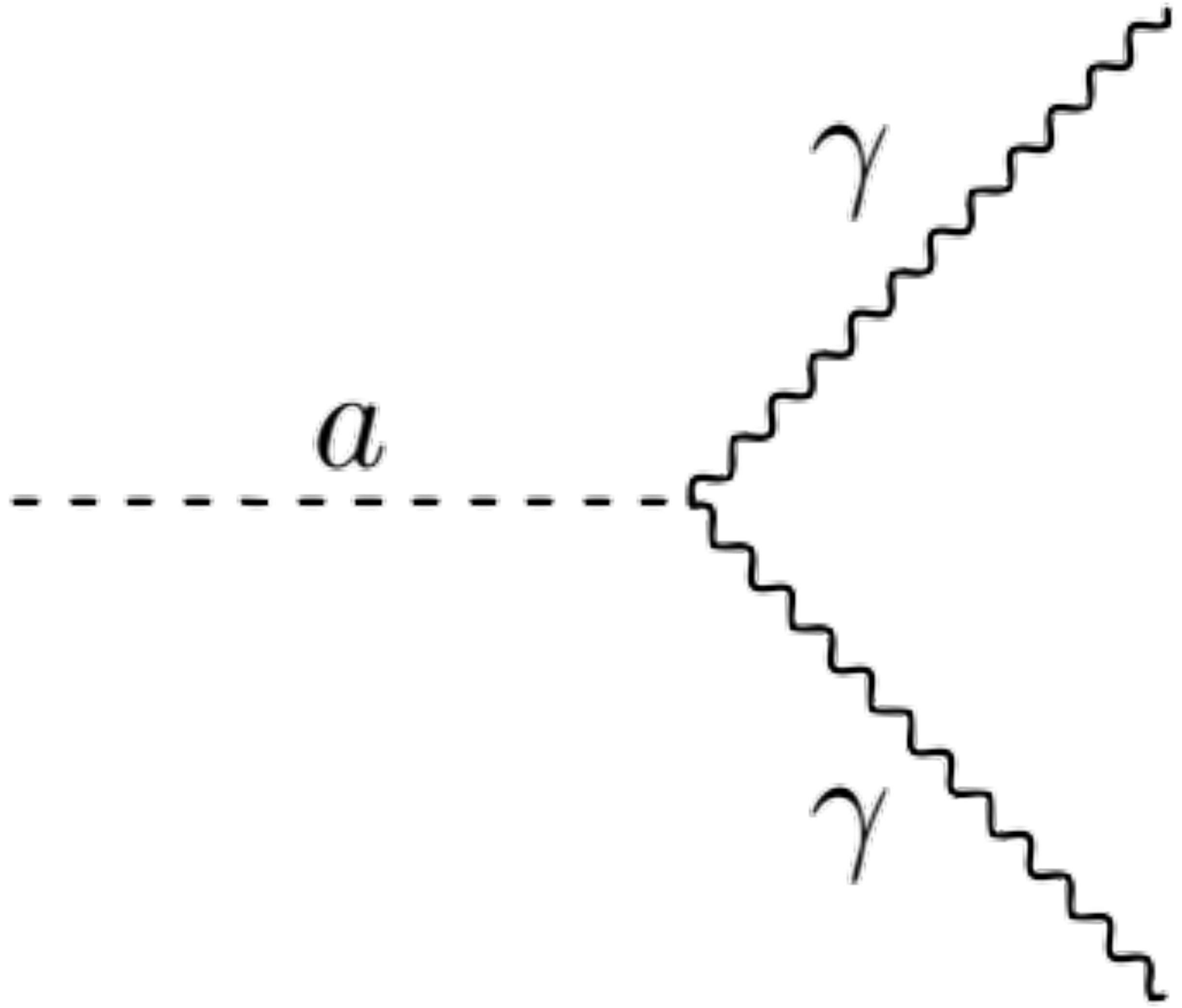
- Grin et al., *"A Telescope Search for Decaying Relic Axions"*, Phys.Rev.D 75 (2007) 105018
- Todarello et al., *"Robust bounds on ALP dark matter from dwarf spheroidal galaxies in the optical MUSE-Faint survey"*, JCAP 05 (2024) 043
- Janish et al., *"Hunting Dark Matter Lines in the Infrared Background with the James Webb Space Telescope"*, Phys.Rev.Lett. 134 (2025) 7, 071002
- Yin et al., *"First Result for Dark Matter Search by WINERED"*, Phys.Rev.Lett. 134 (2025) 5, 5
- Wang et al., *"A Spectroscopic Search for Optical Emission Lines from Dark Matter Decay"*, Phys.Rev.D 110 (2024) 10, 103007
- Todarello et al., *"Bounds on axion-like particles shining in the ultra-violet"*, JCAP 05 (2025) 070
- Saha et al., *"Shedding Infrared Light on QCD Axion and ALP Dark Matter with JWST"*, 2503.14582
- Pinetti, *"First constraints on QCD axion dark matter using James Webb Space Telescope observations"*, 2503.11753
- Todarello, *"New bounds on Axion-Like Particles in the Ultraviolet from Legacy Data"*, 2506.19962

References: X-rays

- **Blank sky**
  - Foster et al., "*Deep Search for Decaying Dark Matter with XMM-Newton Blank-Sky Observations*", Phys.Rev.Lett. 127 (2021) 5, 051101
  - Roach et al., "*Long-exposure NuSTAR constraints on decaying dark matter in the Galactic halo*", Phys.Rev.D 107 (2023) 2, 023009
  - Calore et al., "*Constraints on light decaying dark matter candidates from 16 years of INTEGRAL/SPI observations*", MNRAS 520 (2023) 3, 4167-4172
  - Dessert at al., "*Limits from the grave: resurrecting Hitomi for decaying dark matter and forecasting leading sensitivity for XRISM*", Phys.Rev.Lett. 132 (2024) 21, 211002
  - Fong et al., *"Searching for Particle Dark Matter with eROSITA Early Data"*, 2401.16747
- **Double-peak (Centaurus galaxy cluster)**
  - Yin et al., "*Double Narrow-Line Signatures of Dark Matter Decay and New Constraints from XRISM Observations*", 2503.04726

Decay rate in vacuum

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



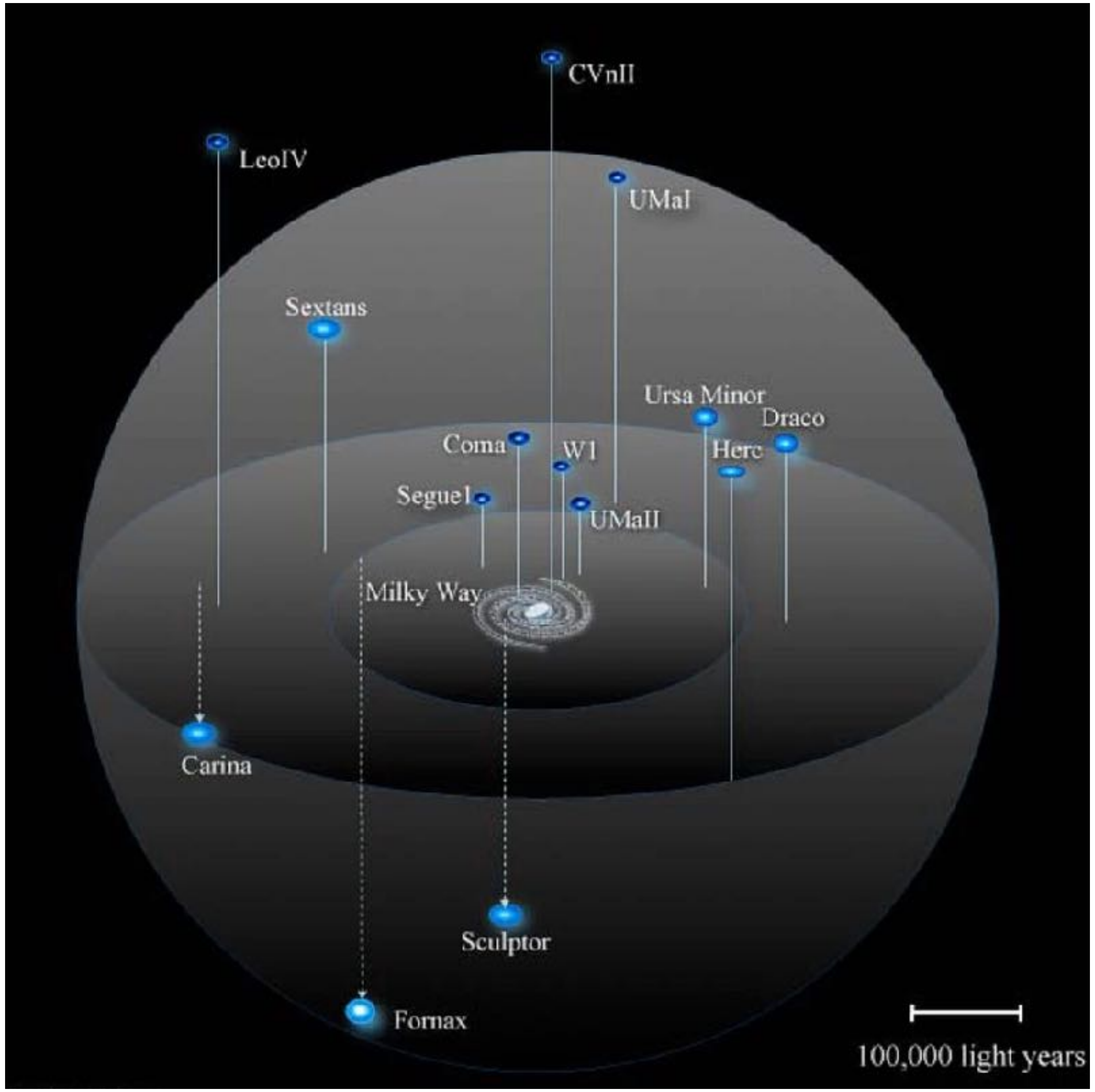
We need a lot of axions!

Dwarf spheroidal galaxies

Clusters of galaxies

Milky Way

Dwarf Spheroidals



Galaxy Clusters

Image credit: ChetGPT

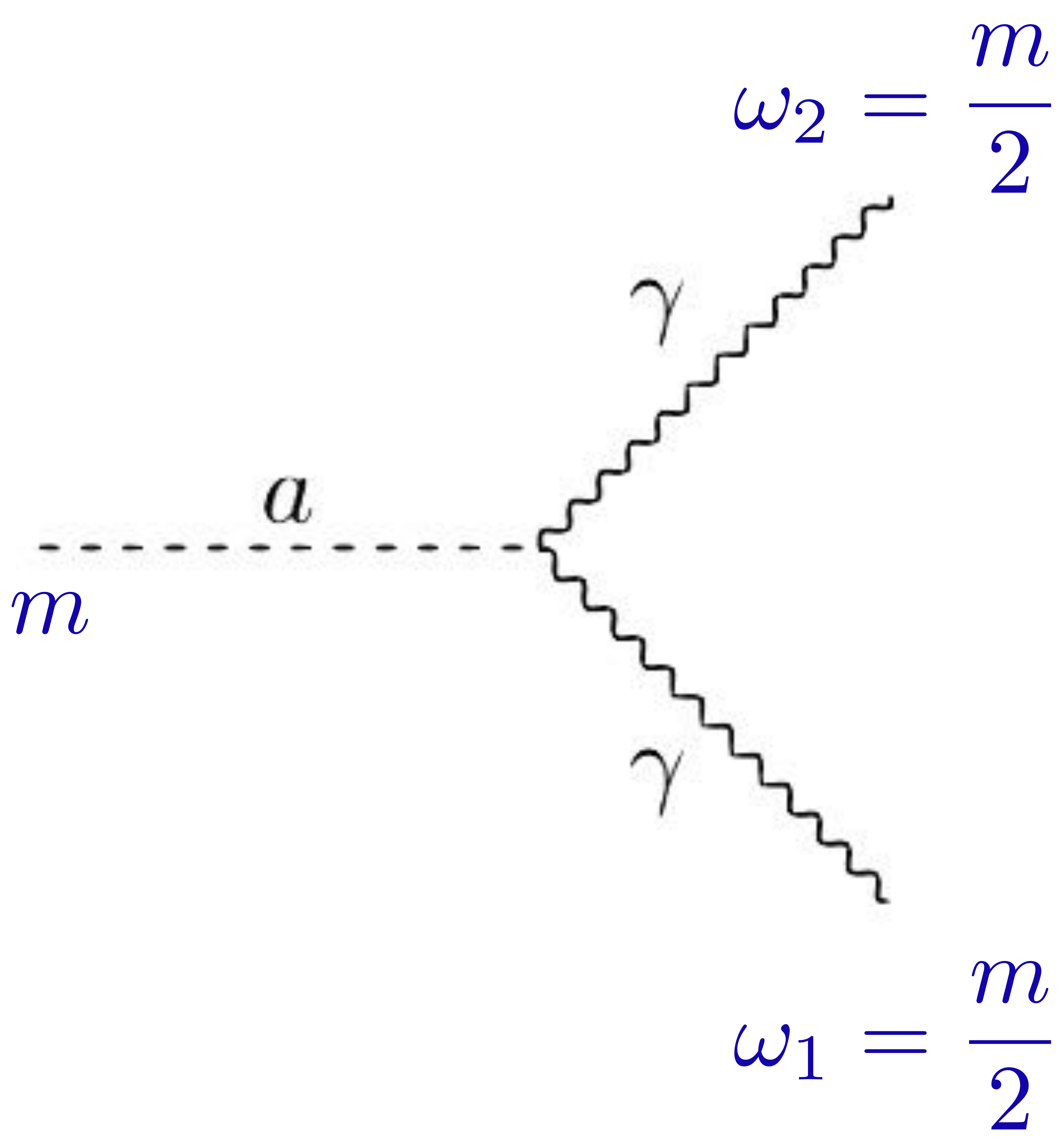
Dwarf Spheroidals

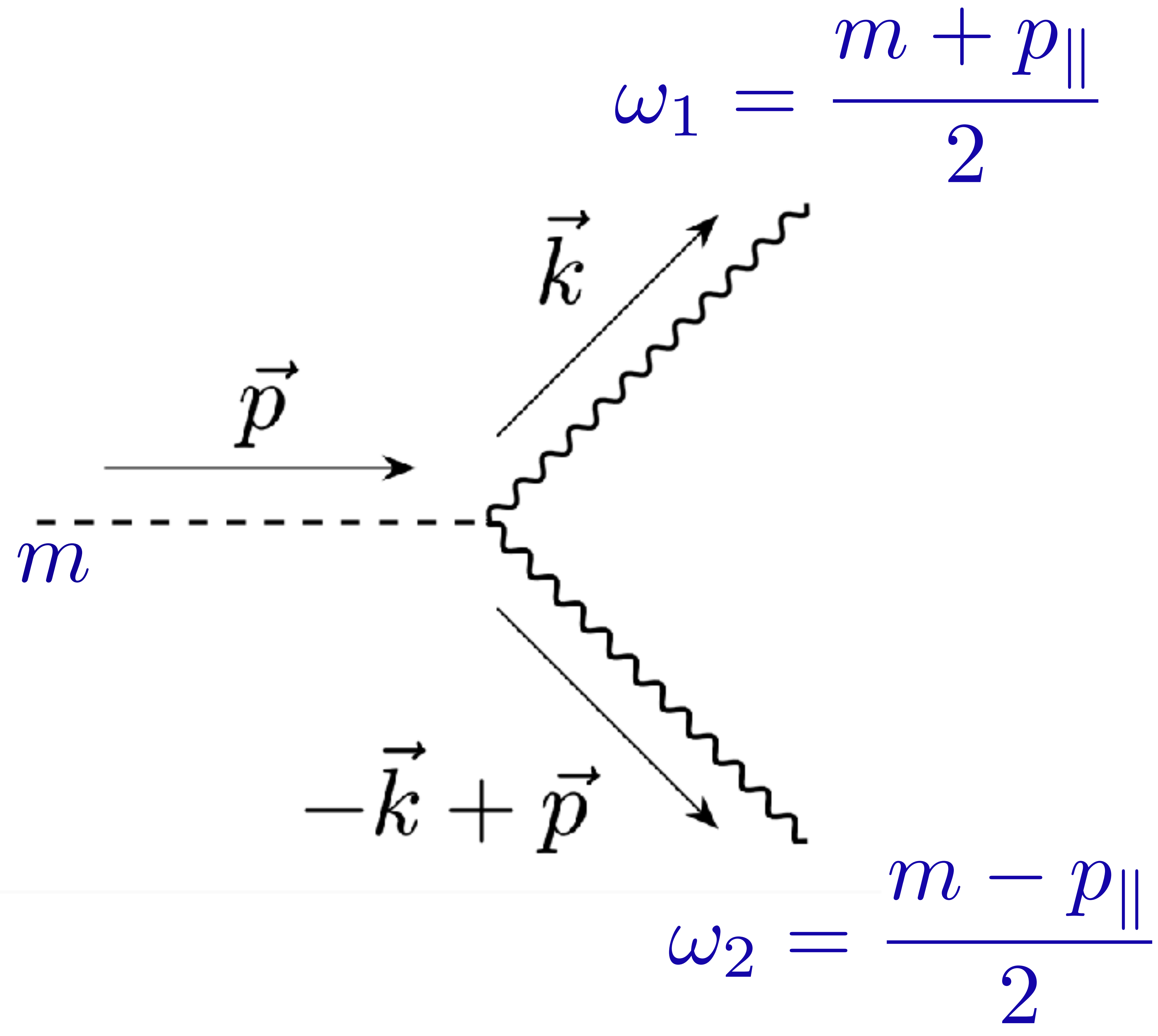
- High mass-to-light ratio
- Typical mass $10^8 - 10^9 \ M_\odot$
- Typical radius $1 \ \mathrm{kpc}$
- Typical distance $100 \ \mathrm{kpc}$

Galaxy Clusters

- High mass-to-light ratio
- Typical mass $10^{14} - 10^{15} \ M_\odot$
- Typical radius $1 \ \mathrm{Mpc}$
- Typical distance $> 10 \ \mathrm{Mpc}$

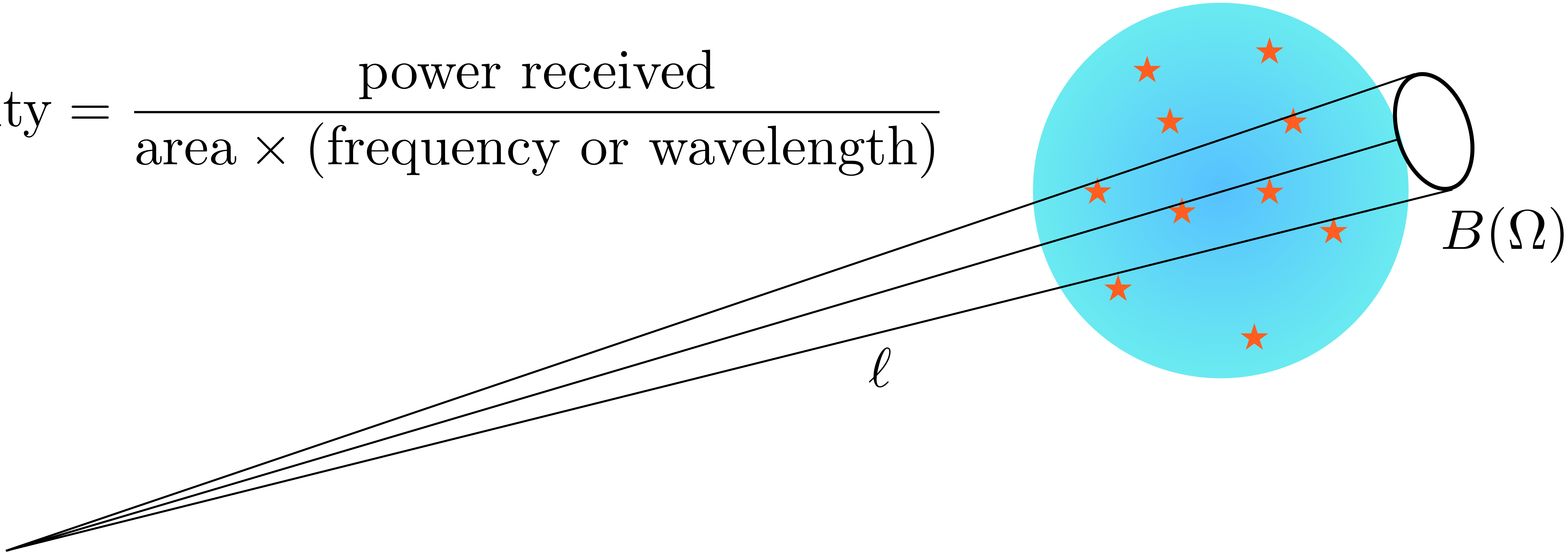
Kinematics of the decay

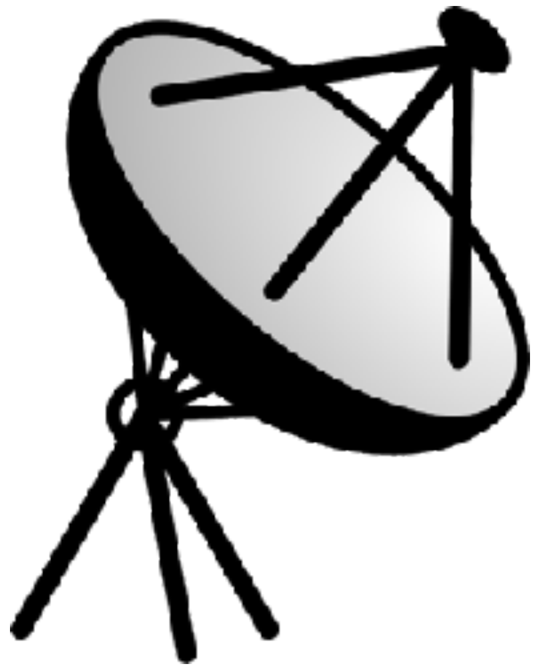




Flux density from ALP decay

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





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

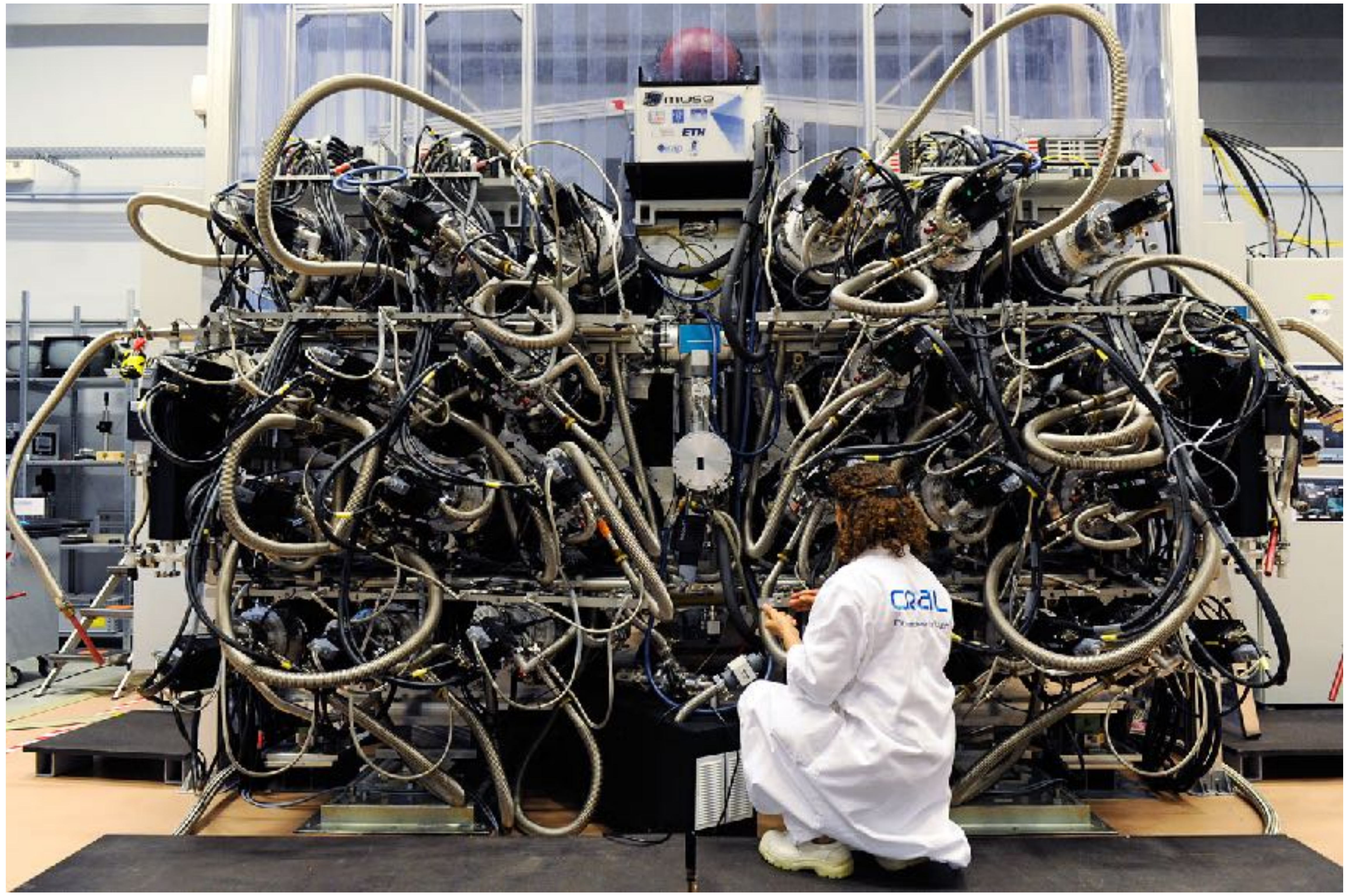
The MUSE instrument

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 data

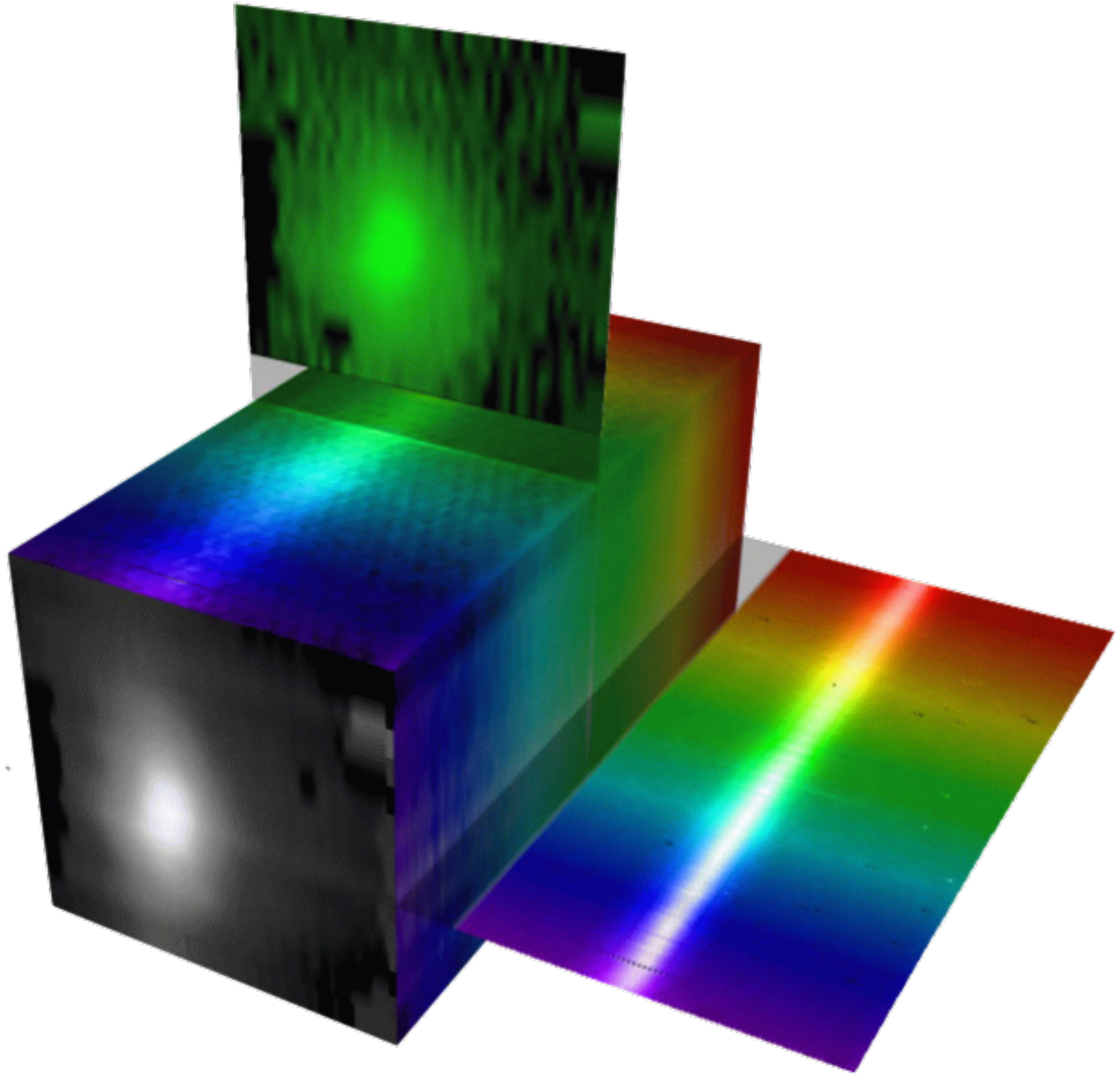
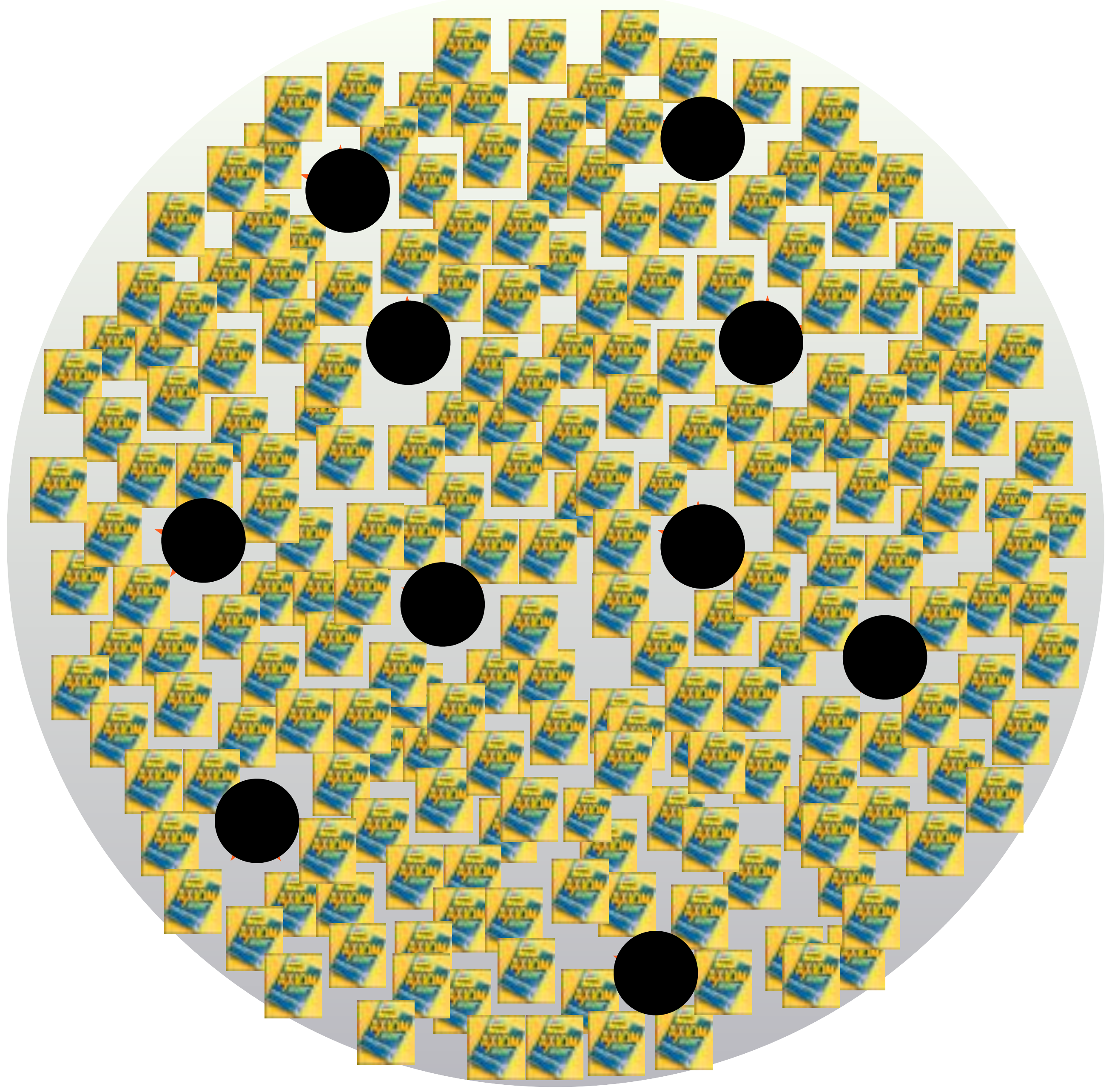


Image credit: Stephen Todd (ROE) and Douglas Pierce-Price (JAC)

Look for radiation from ALP decay



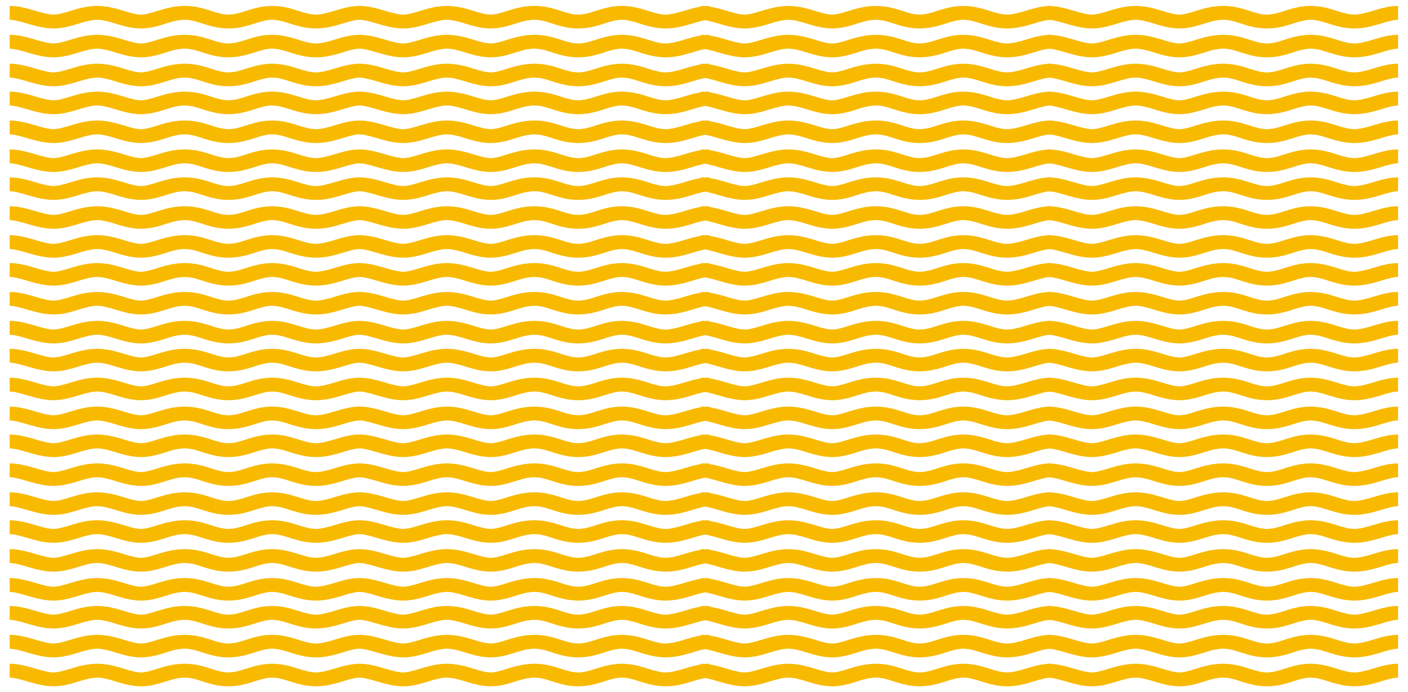
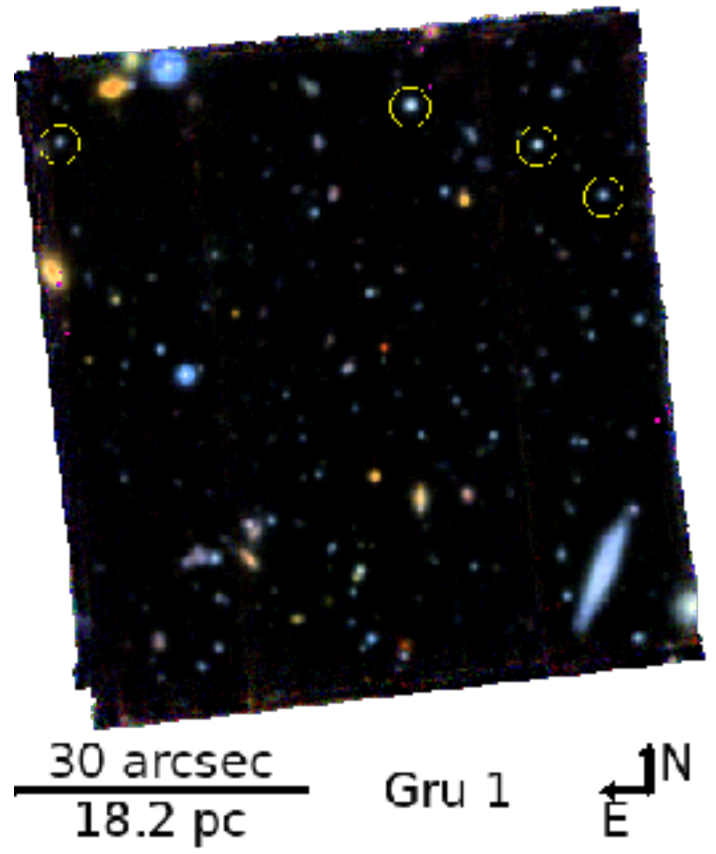
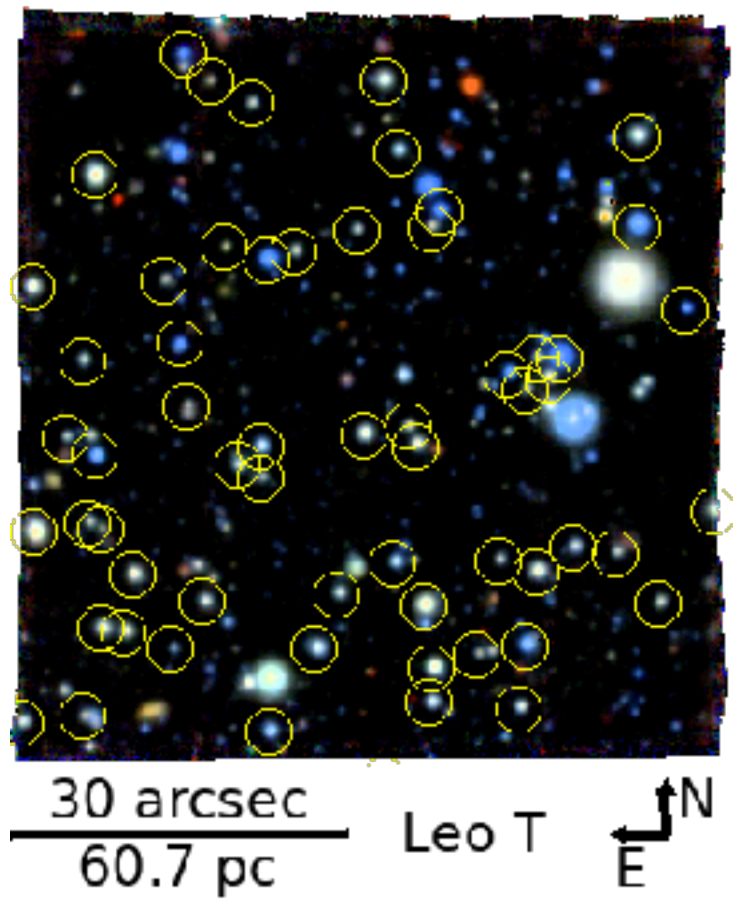
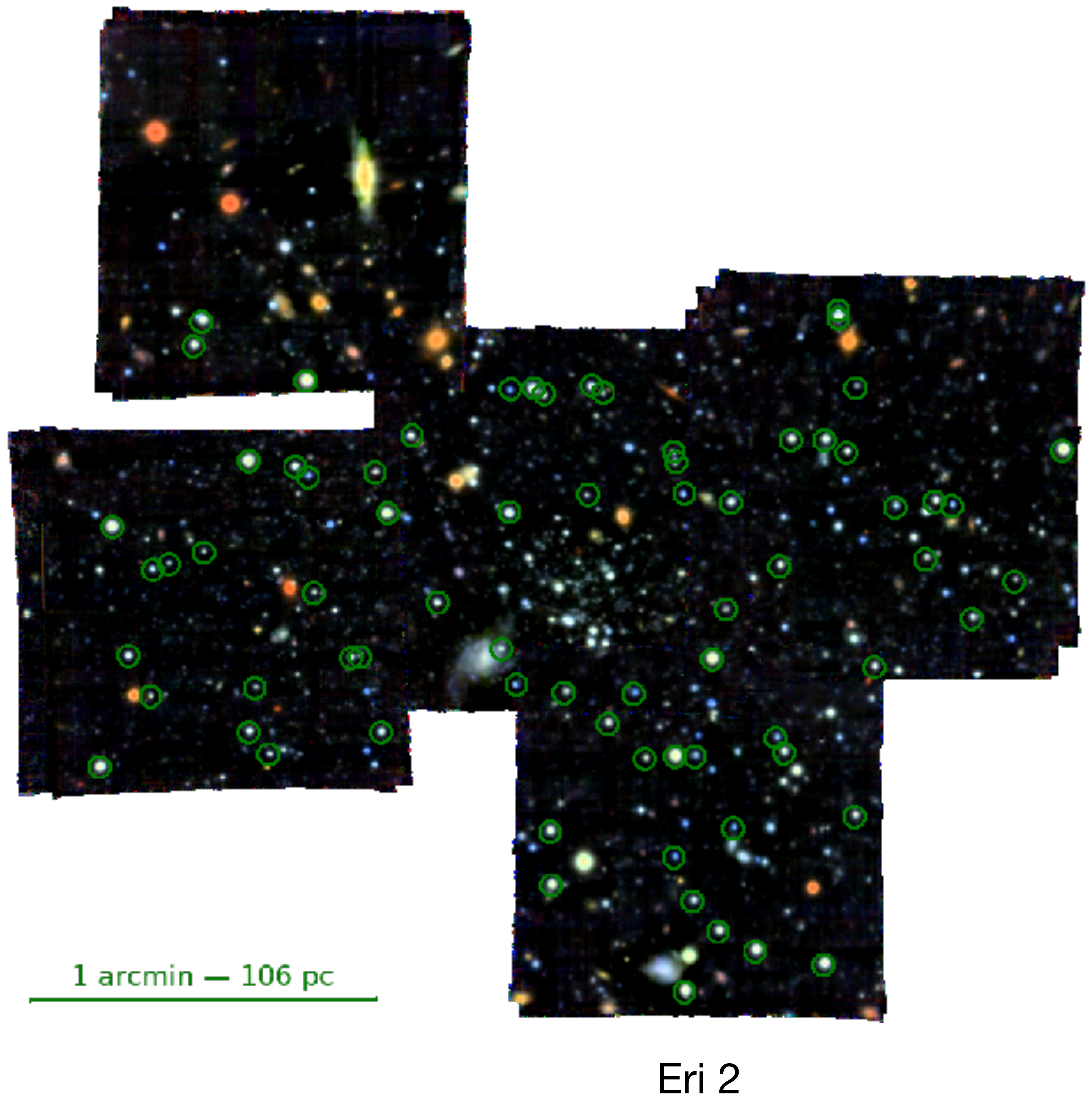


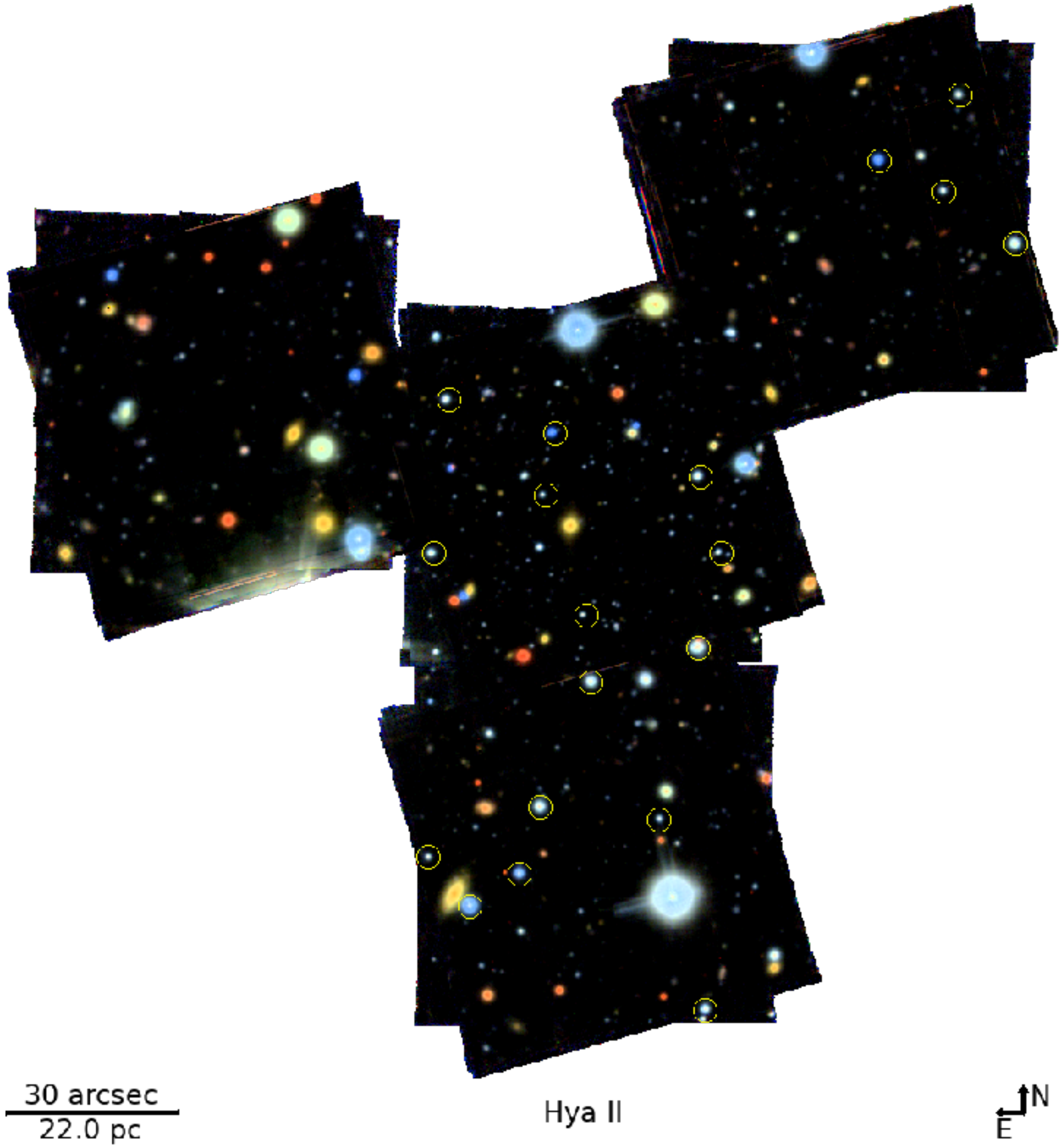
Photo by ESO/G. Hüdepohl (atacamaphoto.com)

The MUSE-Faint Survey





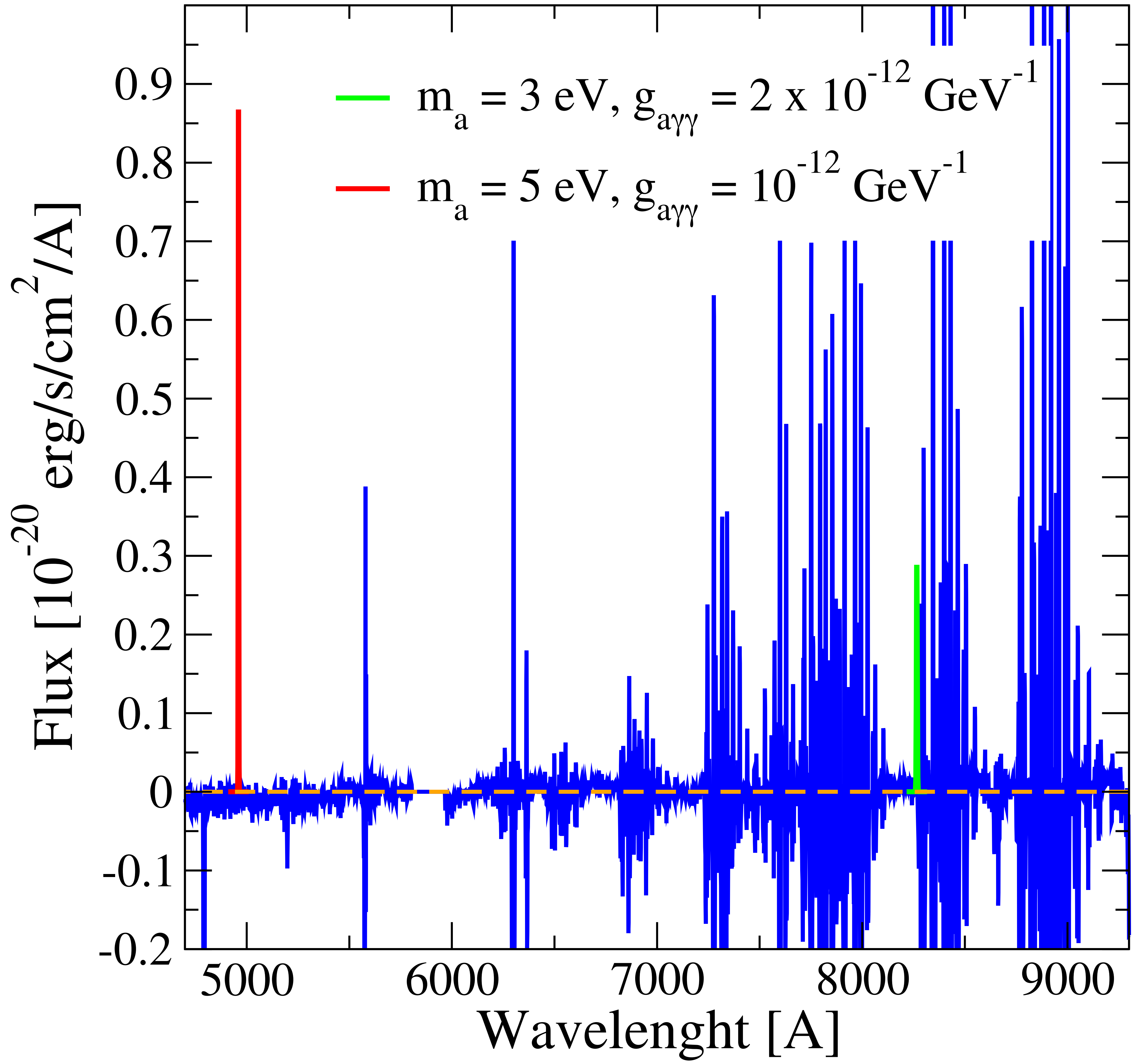




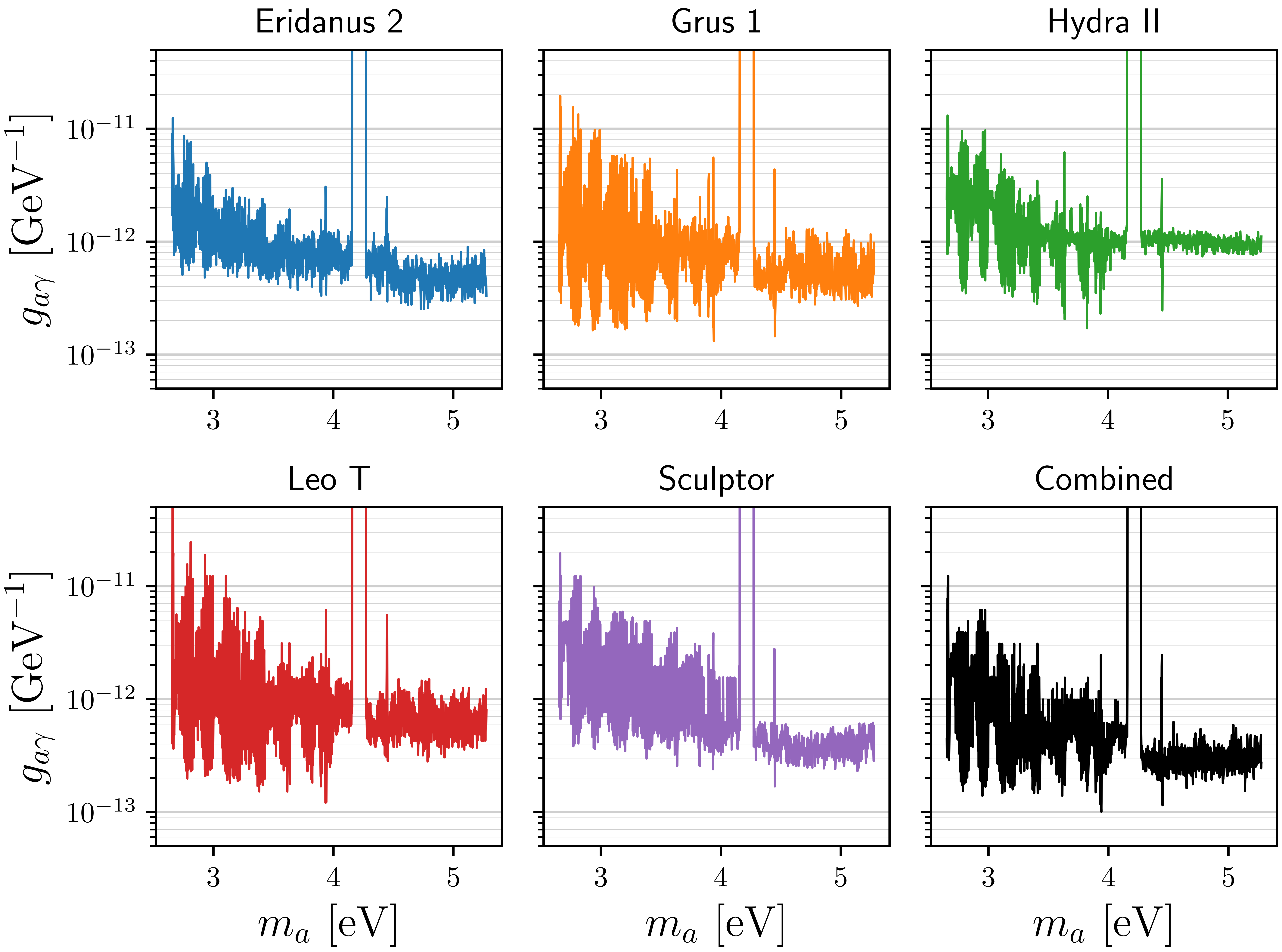
+ Sculptor

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

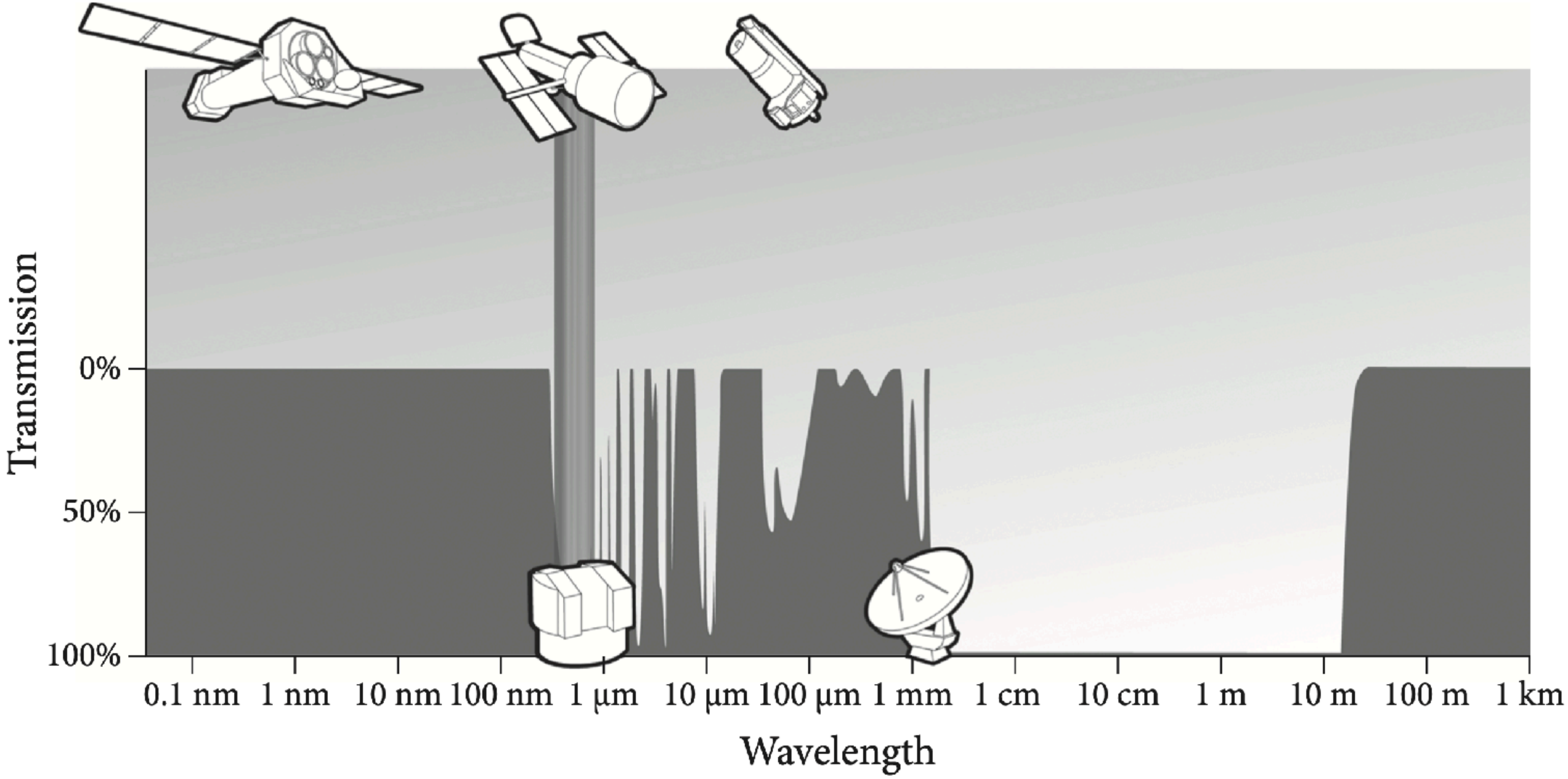
The signal



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

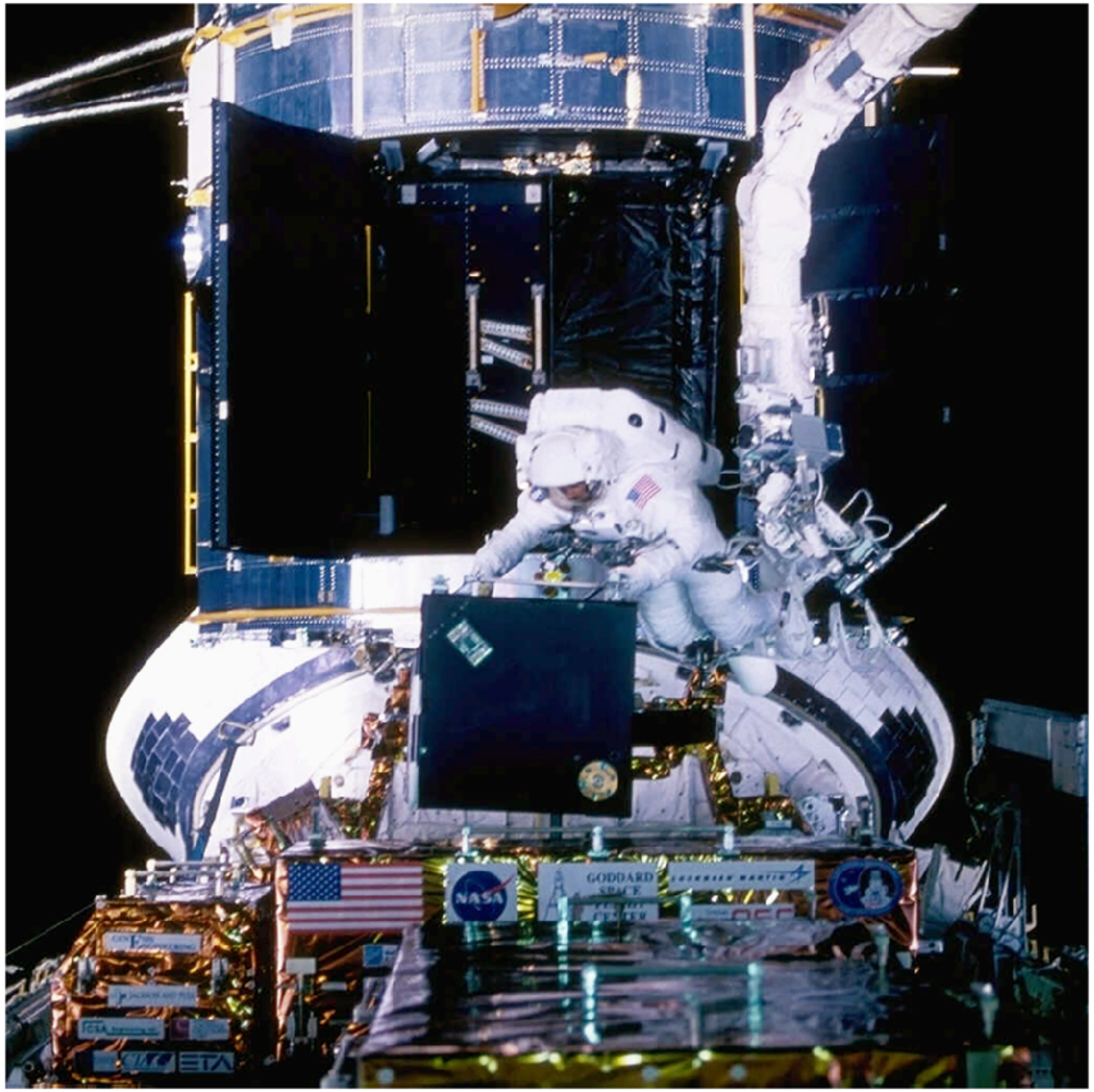

Eridanus 2
Grus 1
Hydra II
Leo T
Sculptor
Combined
$g_{a\gamma}$ [GeV^{-1}]
10^{-11}
10^{-12}
10^{-13}
3
4
5
m_a [eV]

Going to higher frequencies



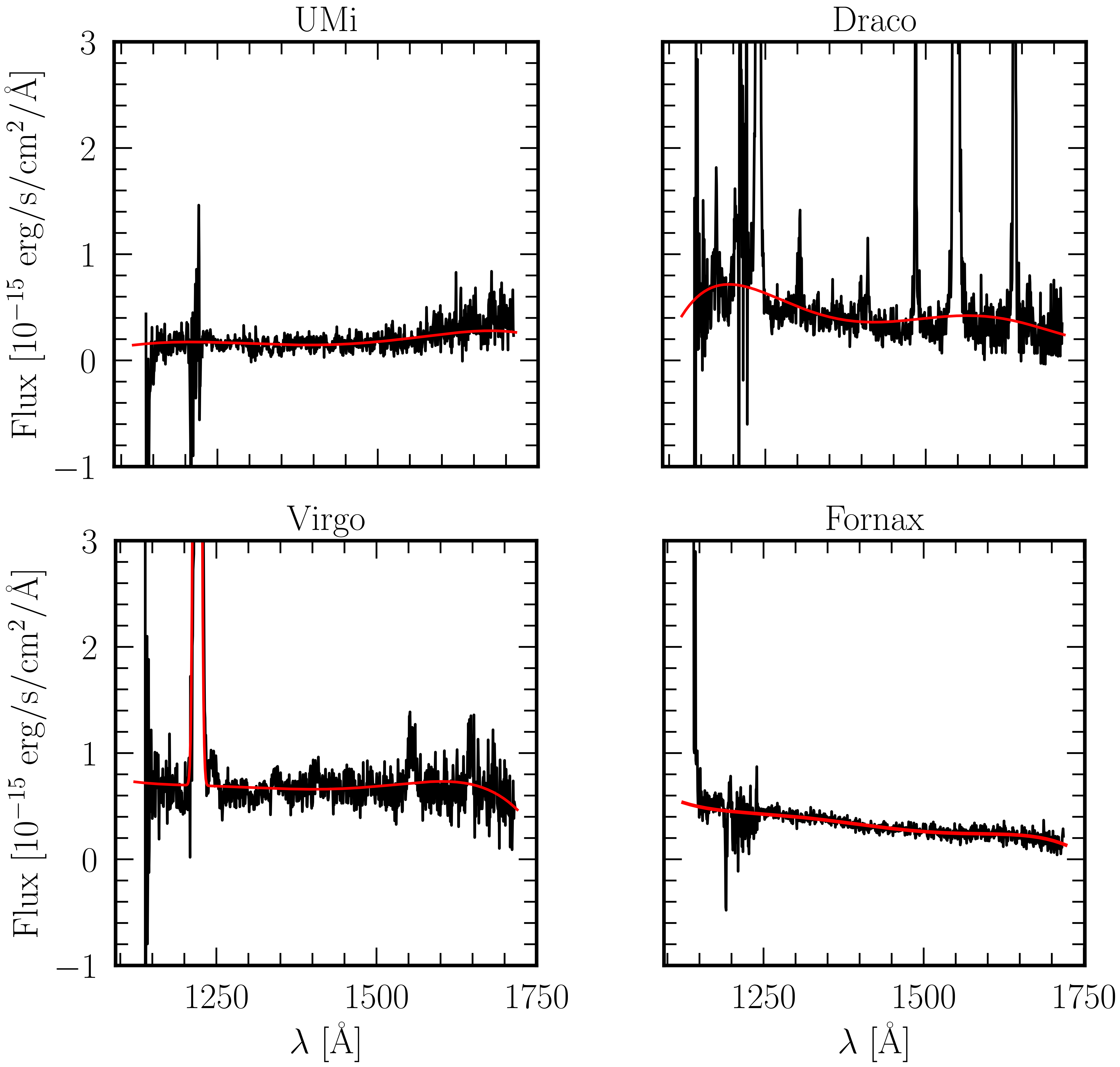
Condon, Ransom - Essential Radio Astronomy

Hubble Space Telescope



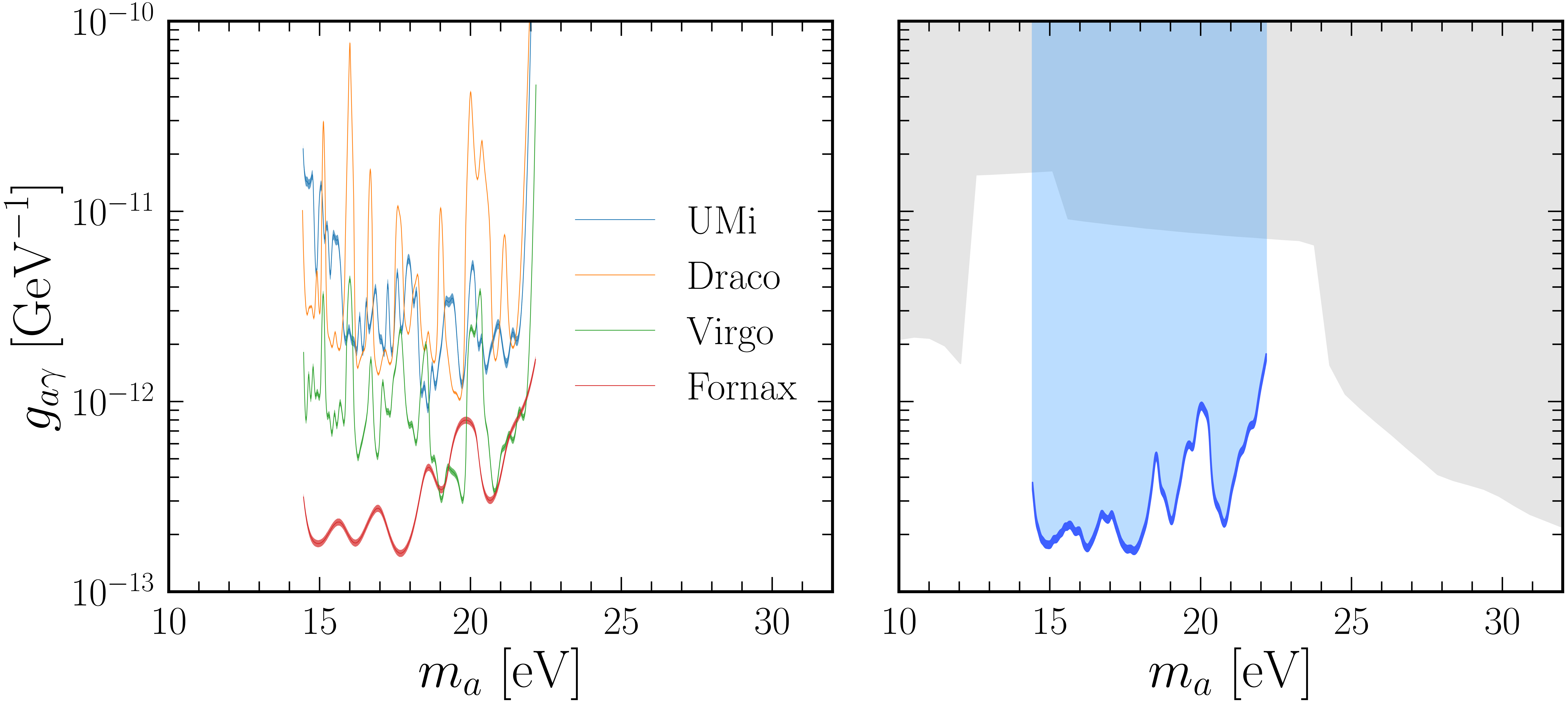
Astronaut Steve Smith carefully removes STIS from the protective enclosure that carried it into orbit aboard the Space Shuttle Discovery.

STIS Data



UMi
Draco
Virgo
Fornax
Flux [10^{-15} erg/s/cm^2/Å]
3
2
1
0
−1
1250
1500
1750
λ [Å]

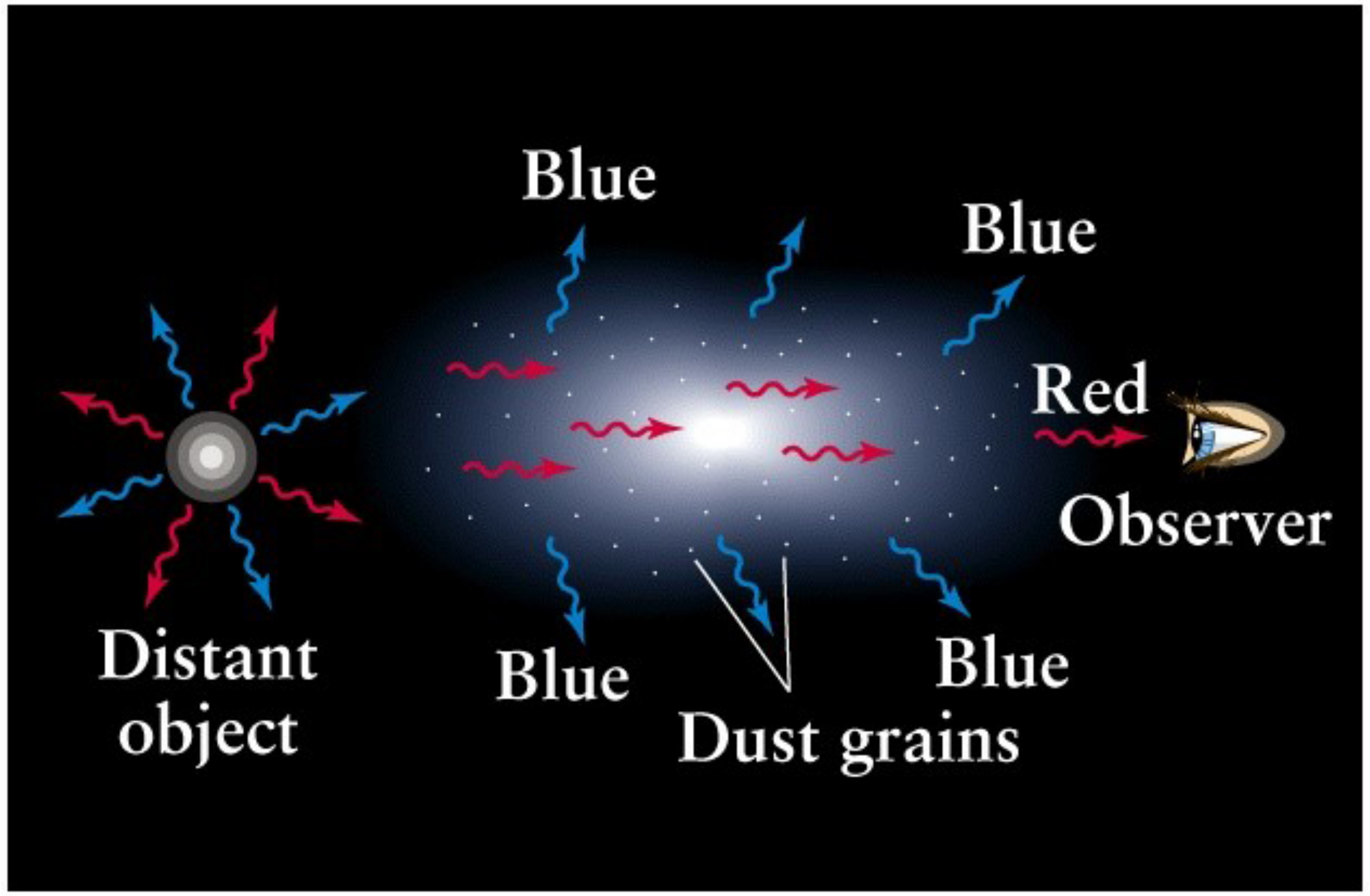
Bounds

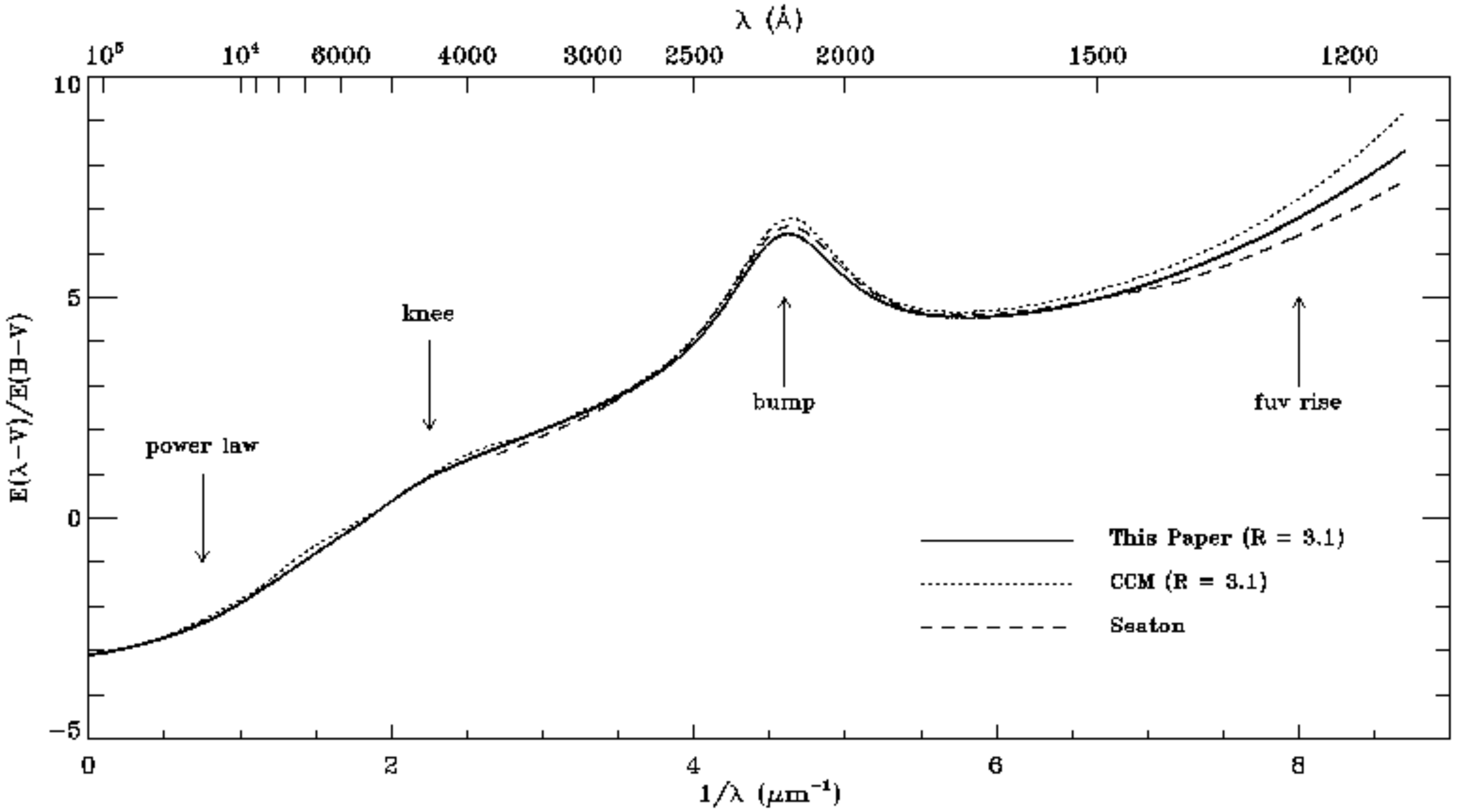


10^{-10}
10^{-11}
10^{-12}
10^{-13}
$g_{a\gamma}$ [GeV^{-1}]
10
15
20
25
30
m_a [eV]
UMi
Draco
Virgo
Fornax
10
15
20
25
30
m_a [eV]

Dust Extinction

In the UV, large optical depth due to scattering and absorption due to dust particles





Fitzpatrick, Publ.Astron.Soc.Pac. 111 (1999) 63-75

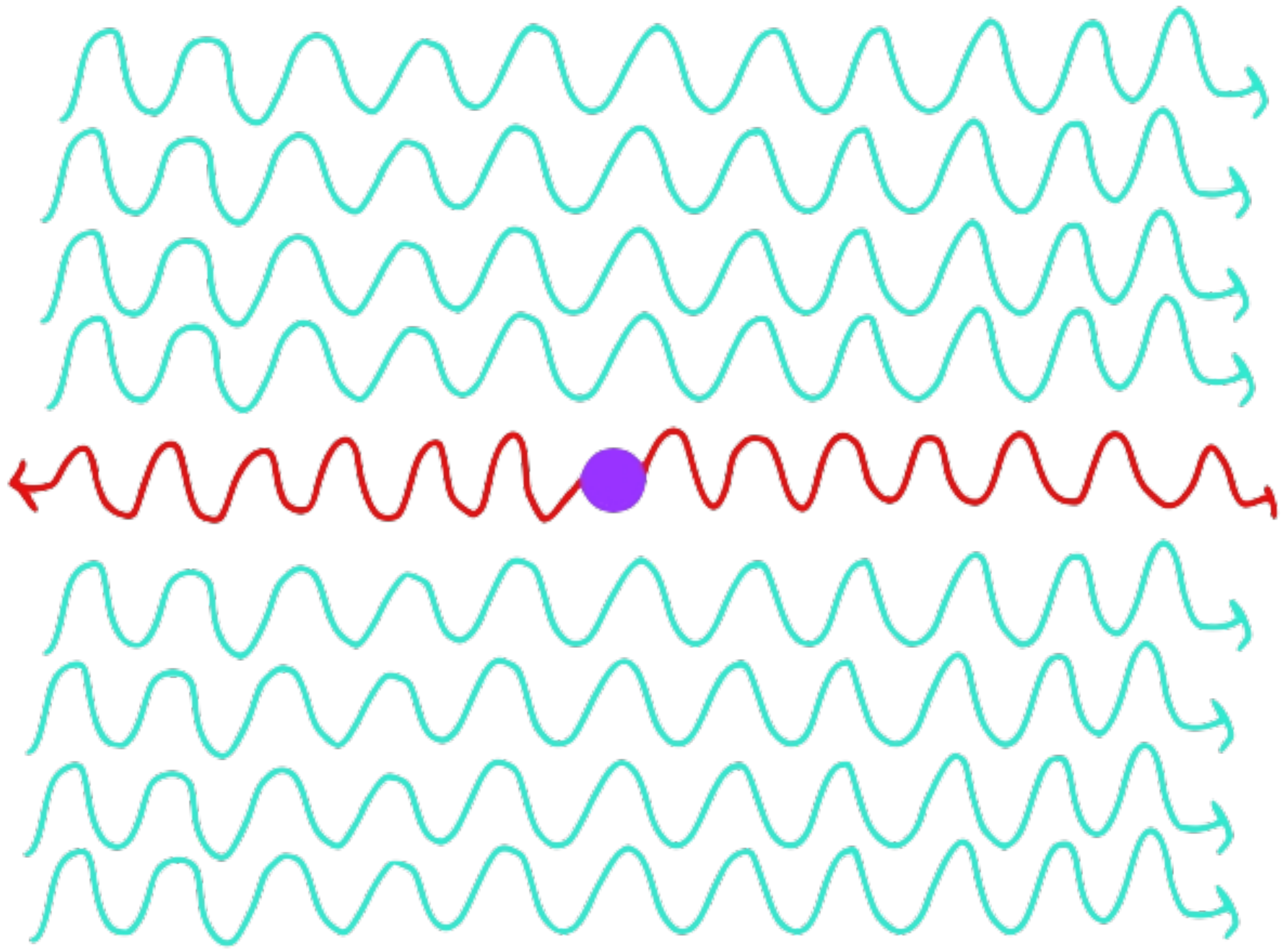
Axion stimulated decay

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

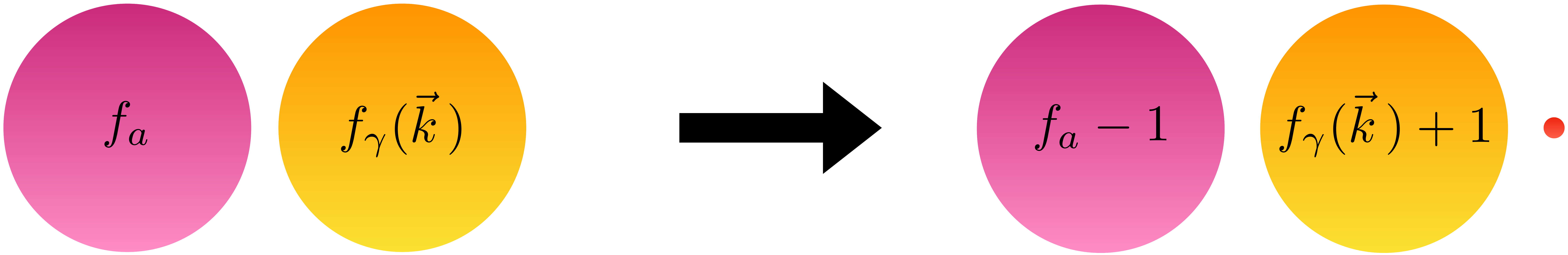
$$f_\gamma(\vec{k})$$



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

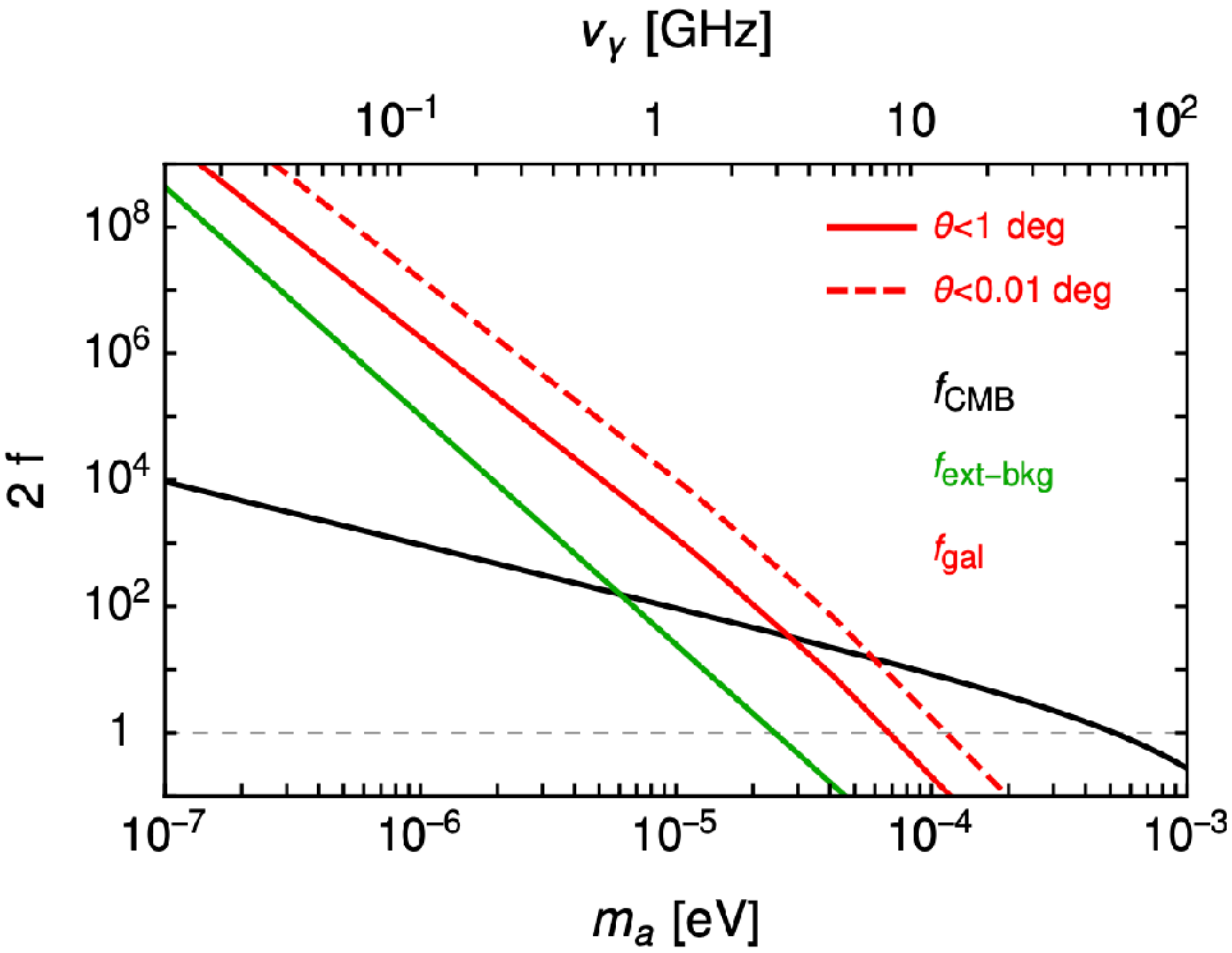
Bose-enhancement

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



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

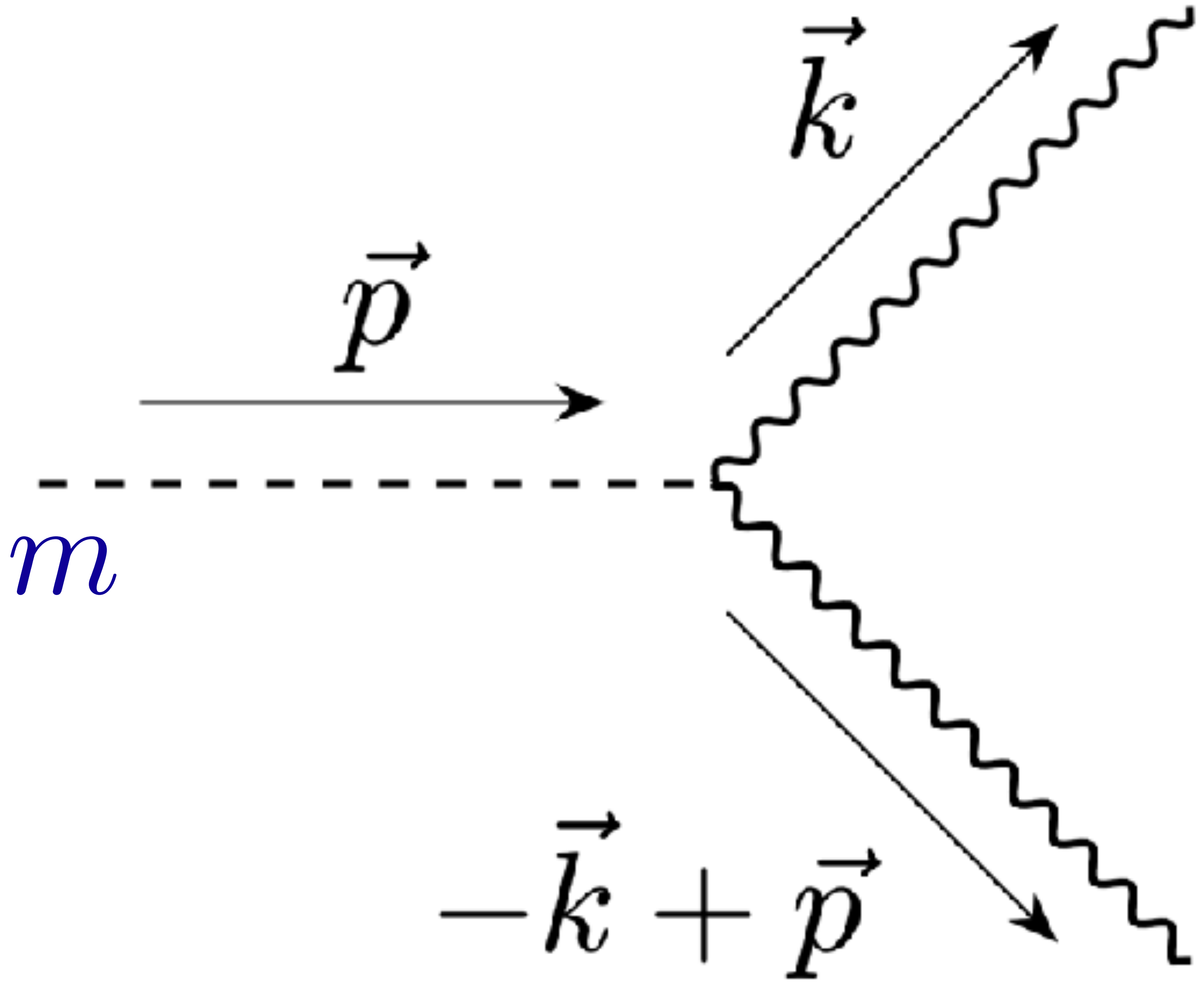
Enhancement factor



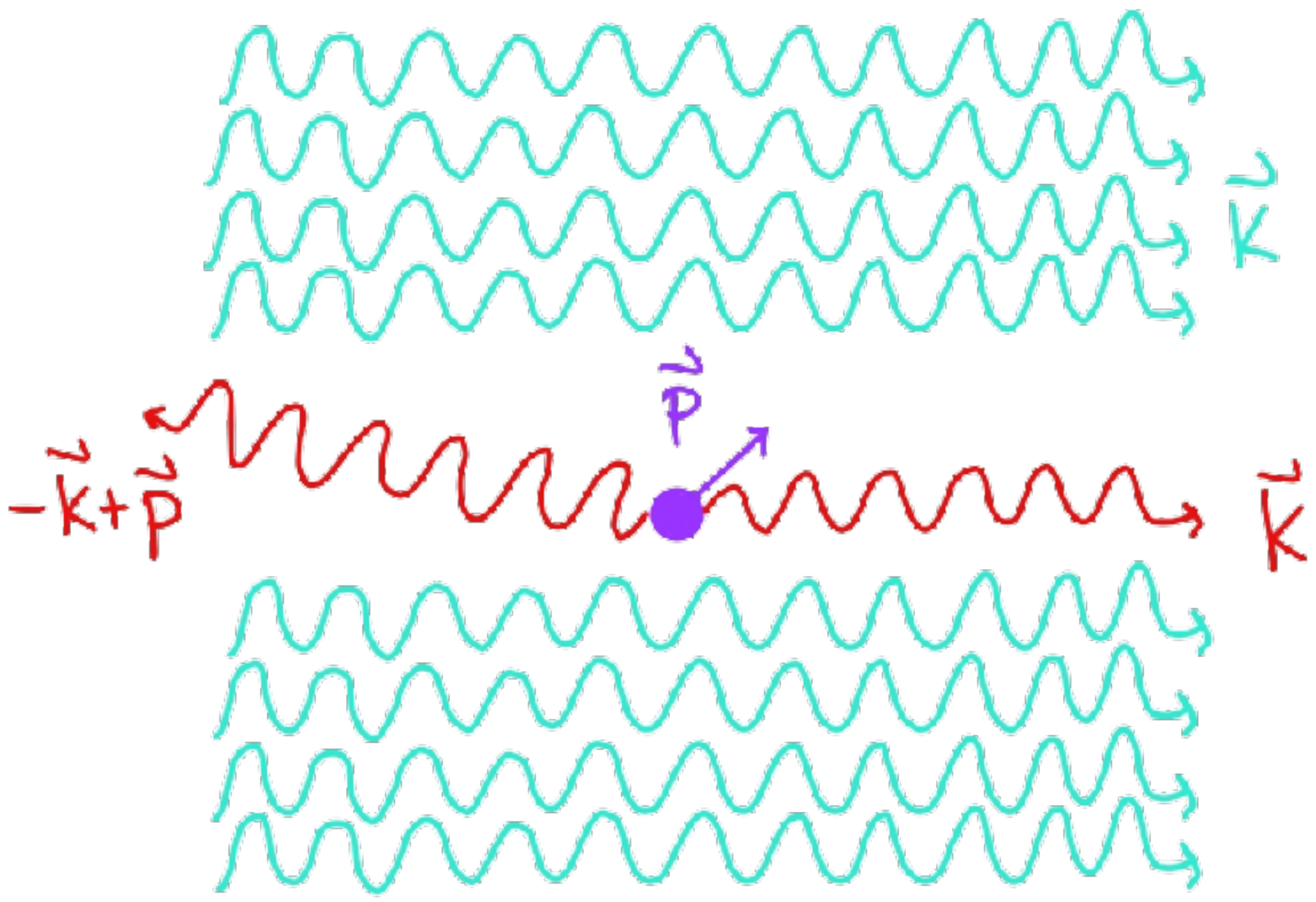
Caputo, Regis, Taoso, Witte, JCAP 03 (2019) 027

Kinematics

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



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

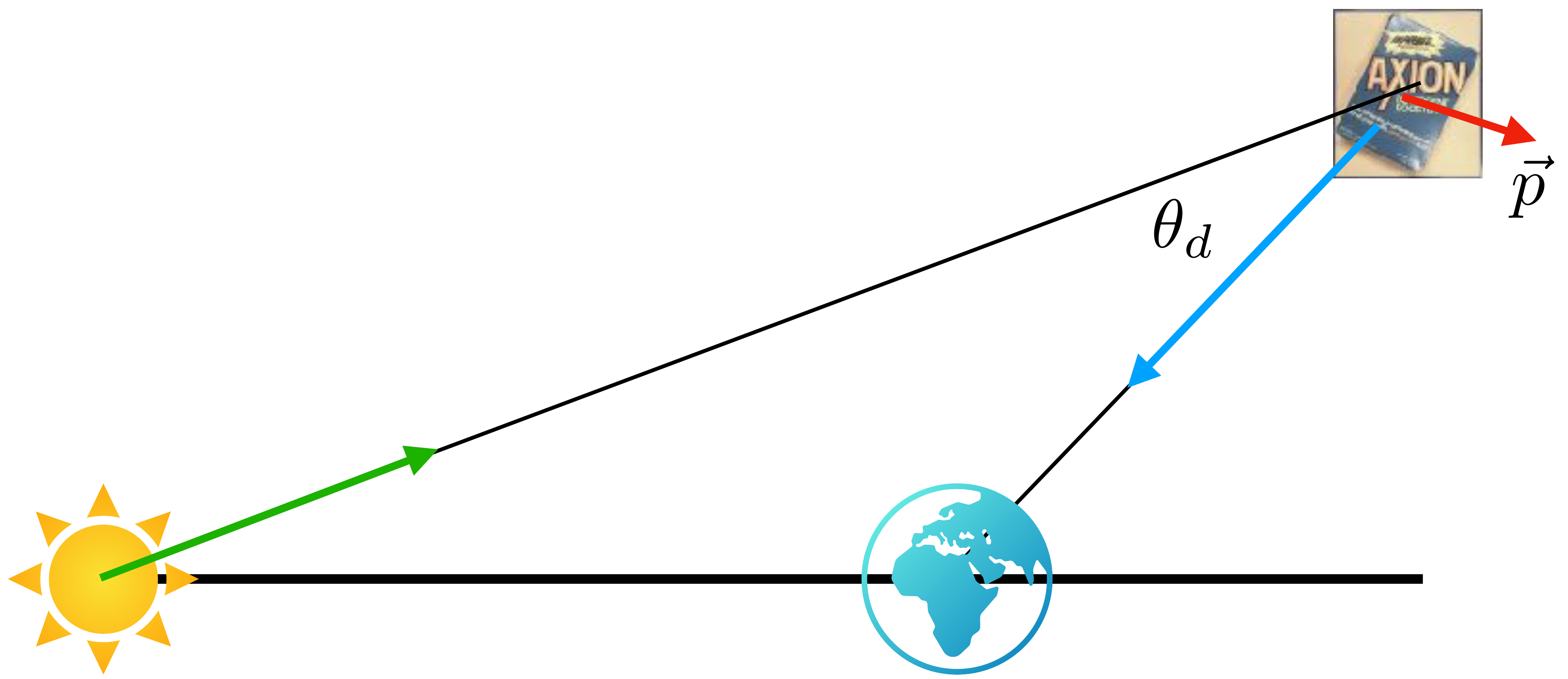


The echo propagates

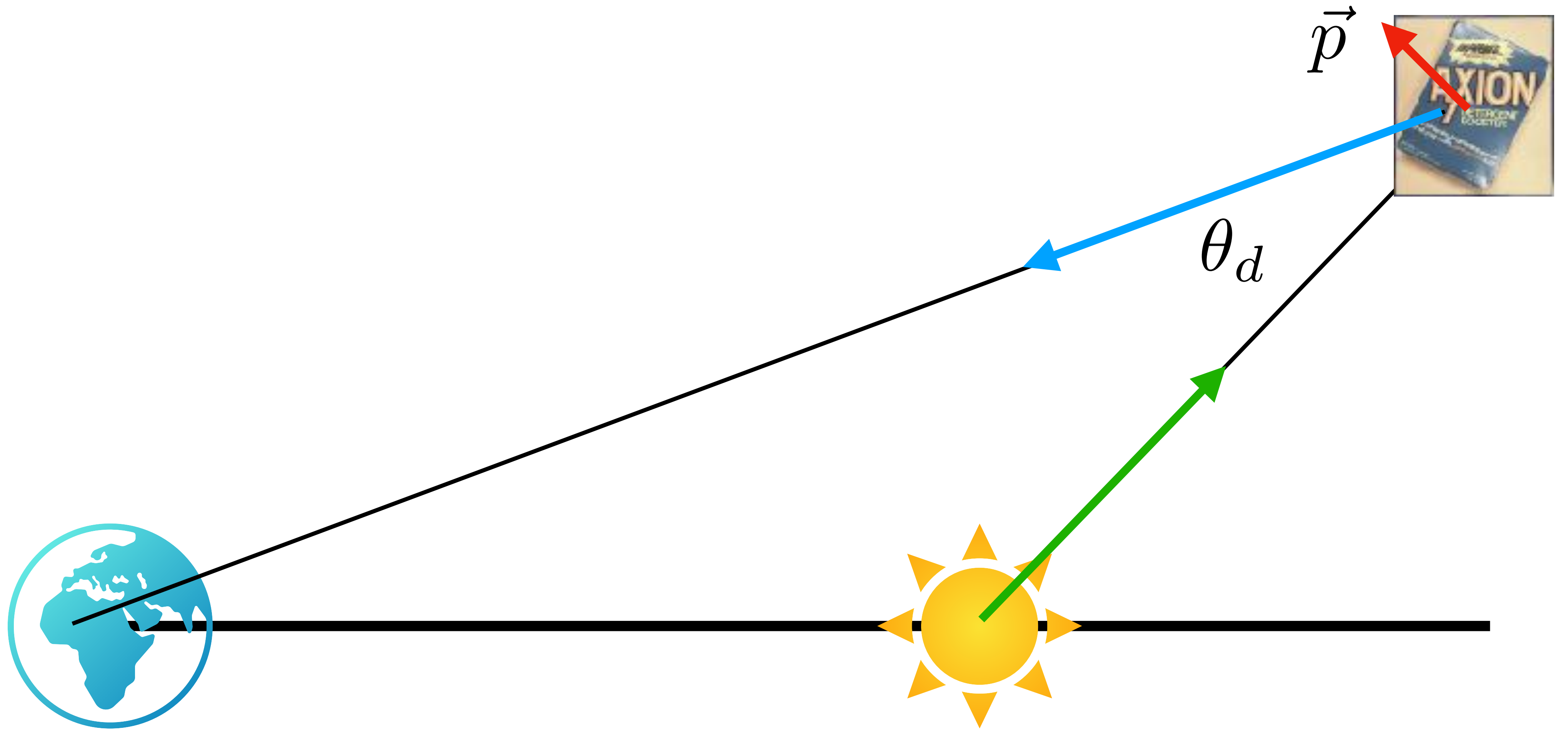
***almost* backwards!**

Echoes from natural sources

Back-light echo

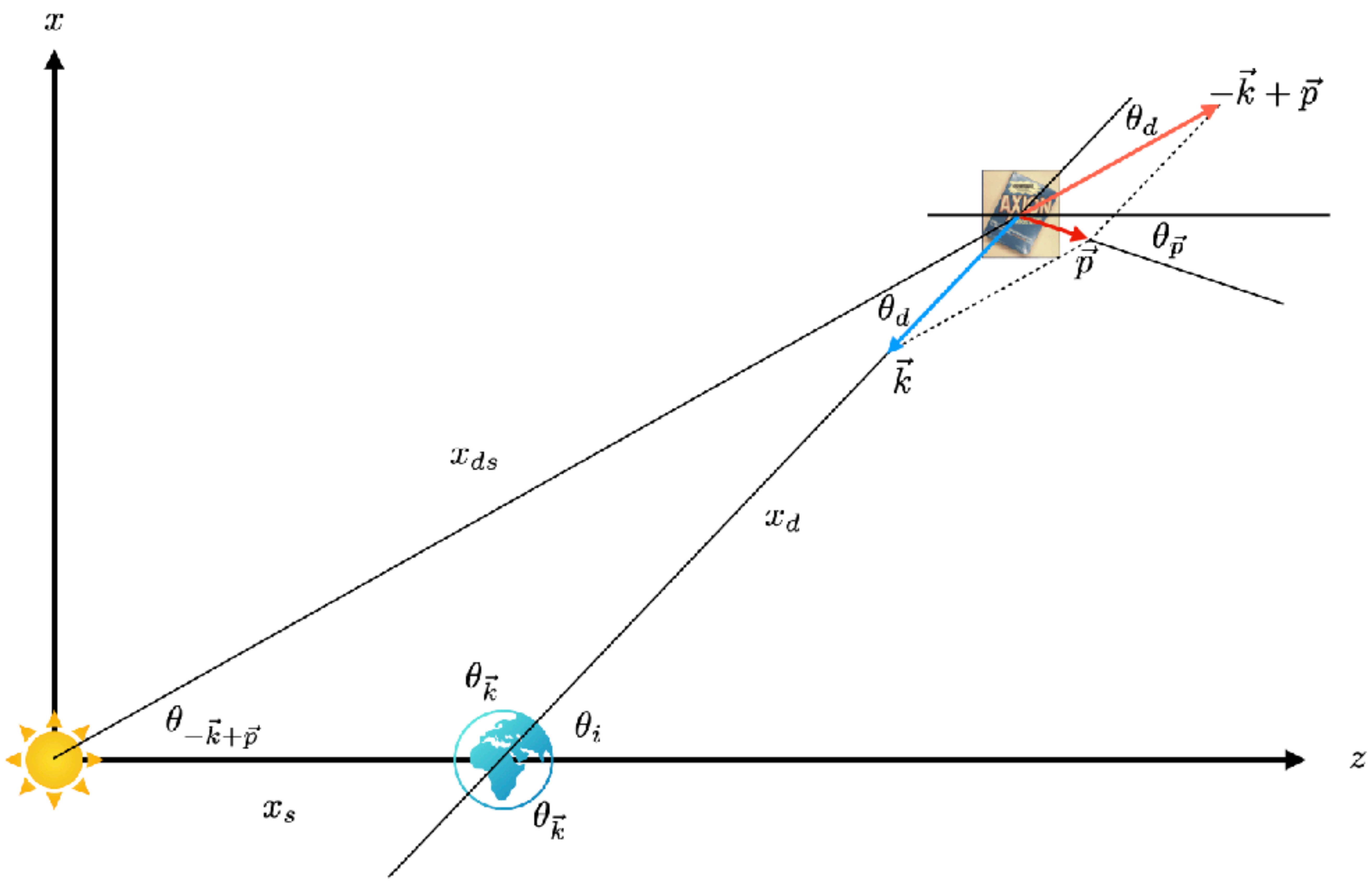


Front-light echo

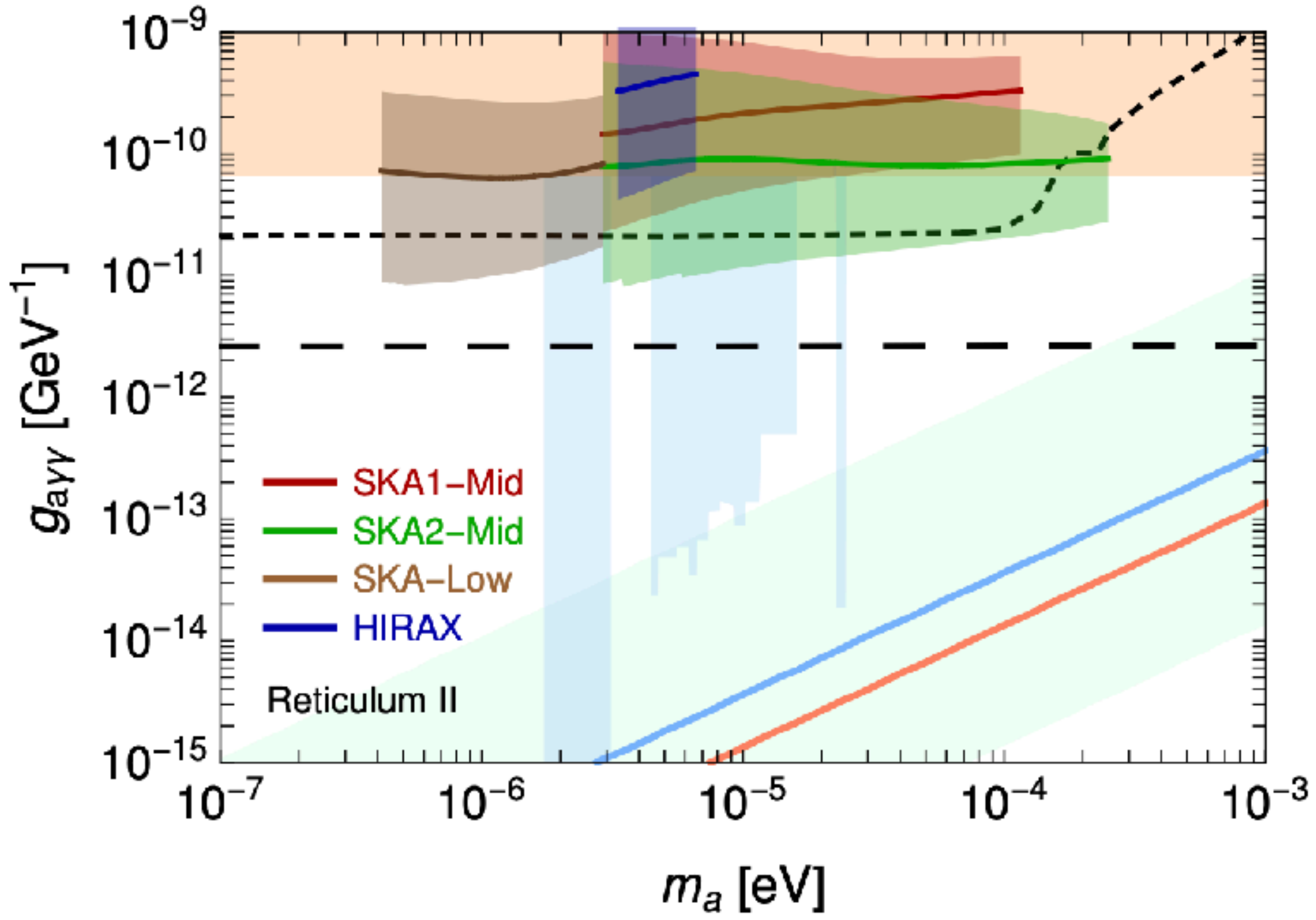


Collinear emission

Smearing of the signal



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



Caputo, Regis, Taoso, Witte

JCAP 03 (2019) 027

Collinear emission

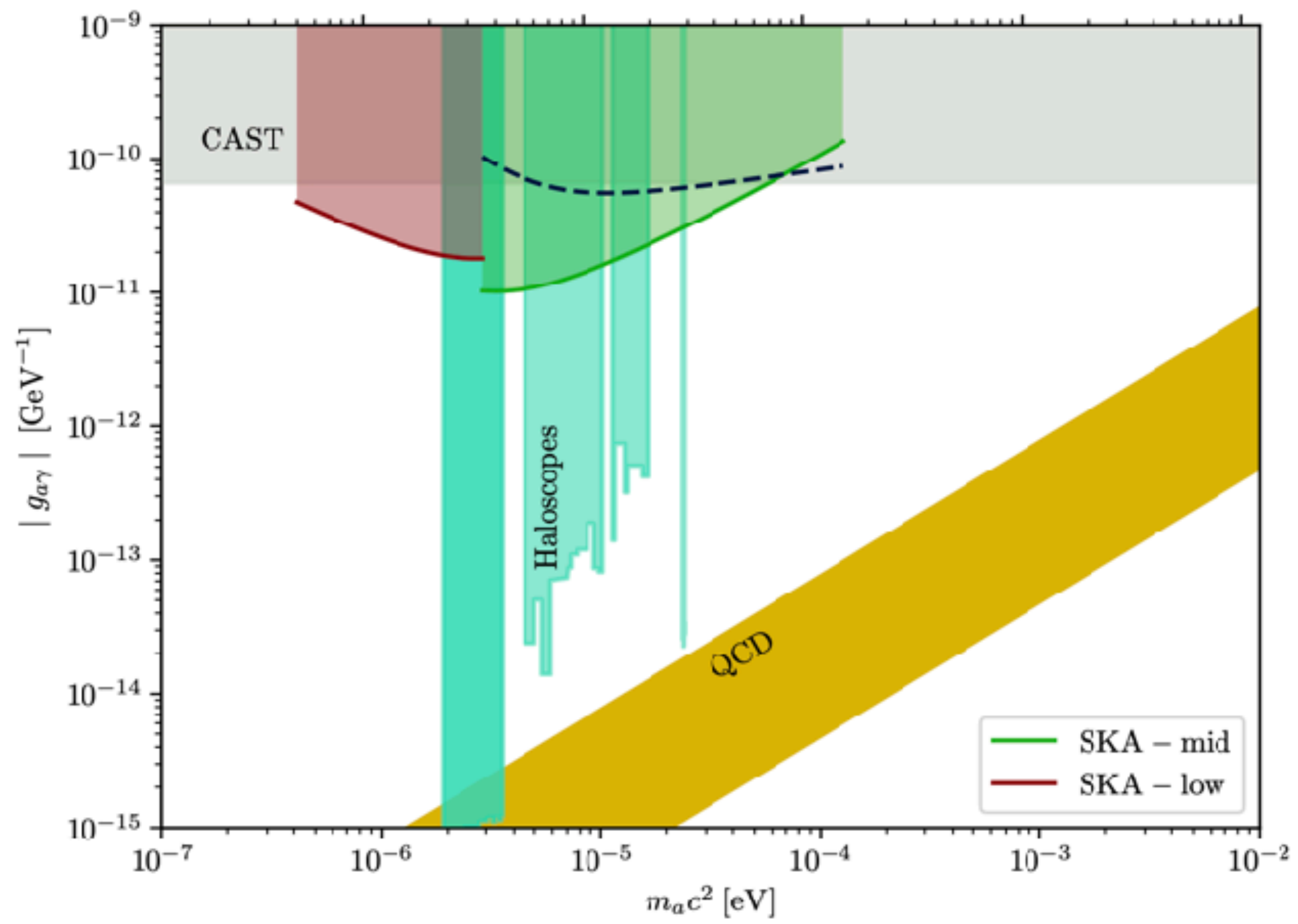
CMB, extragalactic radio bkg

Ghosh, Salvado, Miralda-Escudé

2008.02729

Backlight echo

Cygnus A

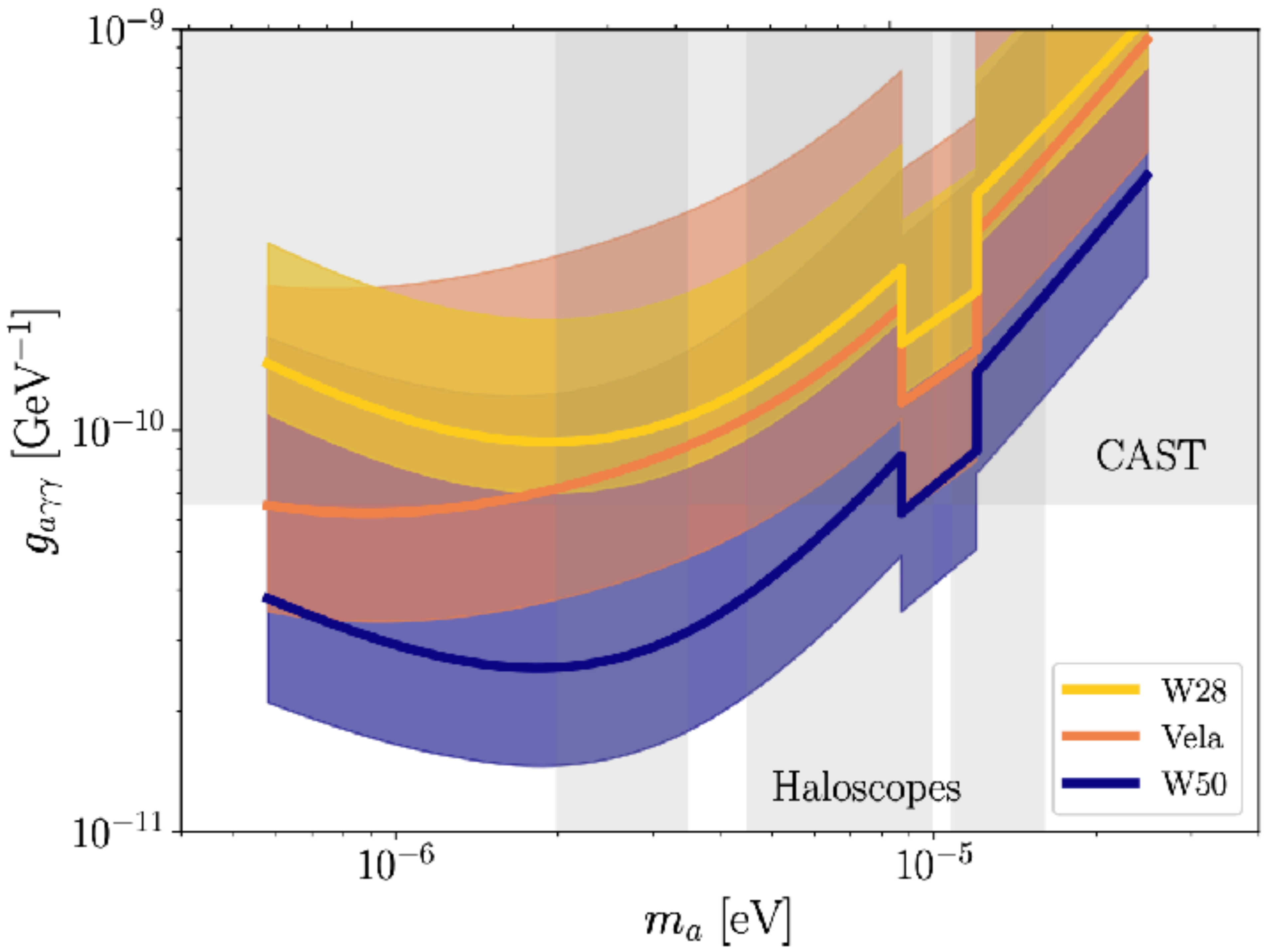


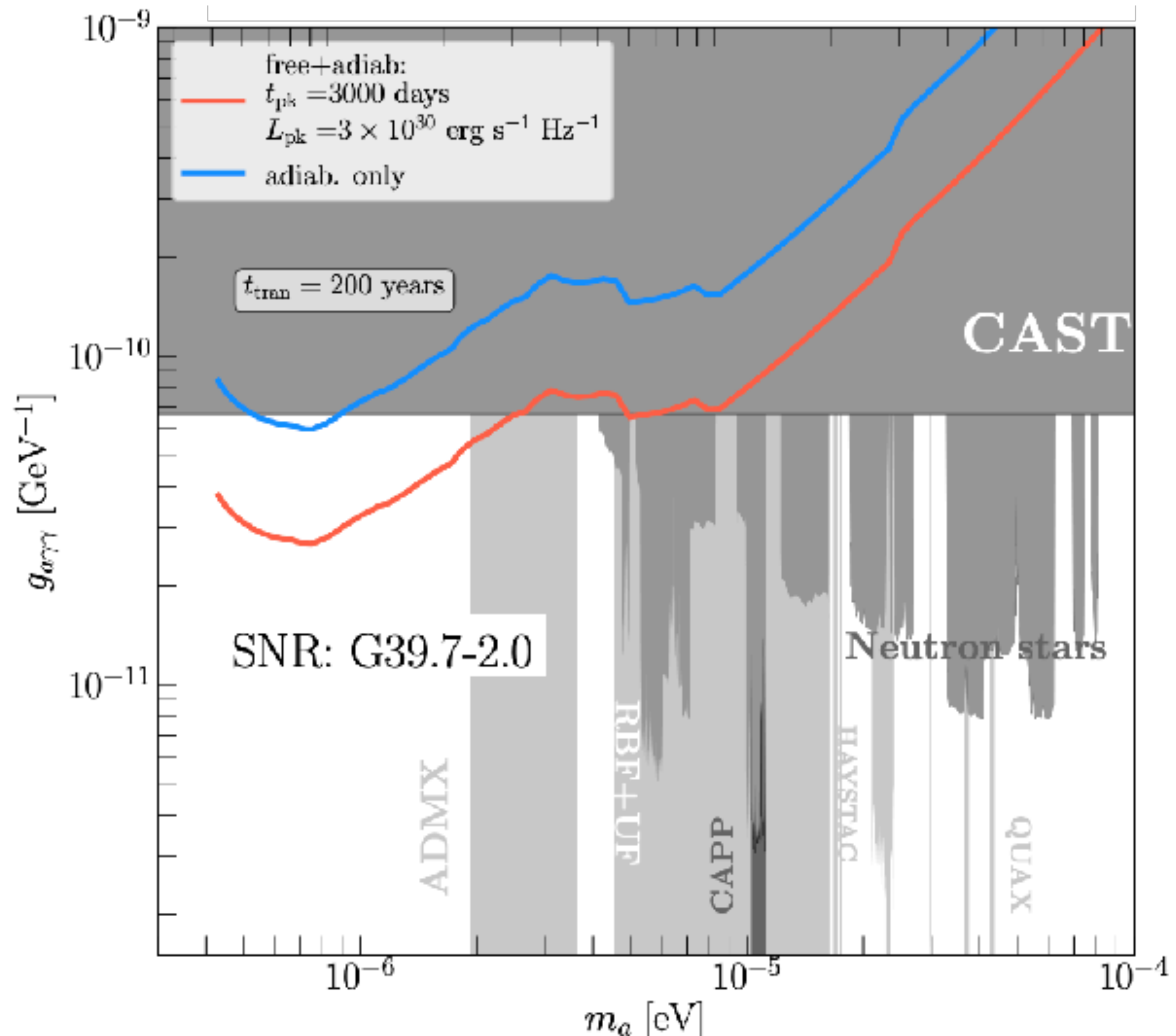
Sun, Schutz, Nambrath, Leung, Masui

PRD 105 (2022)

Backlight echo

Supernova remnant





Buen-Abad, Fan, Sun

PRD 105 (2022)

Backlight echo

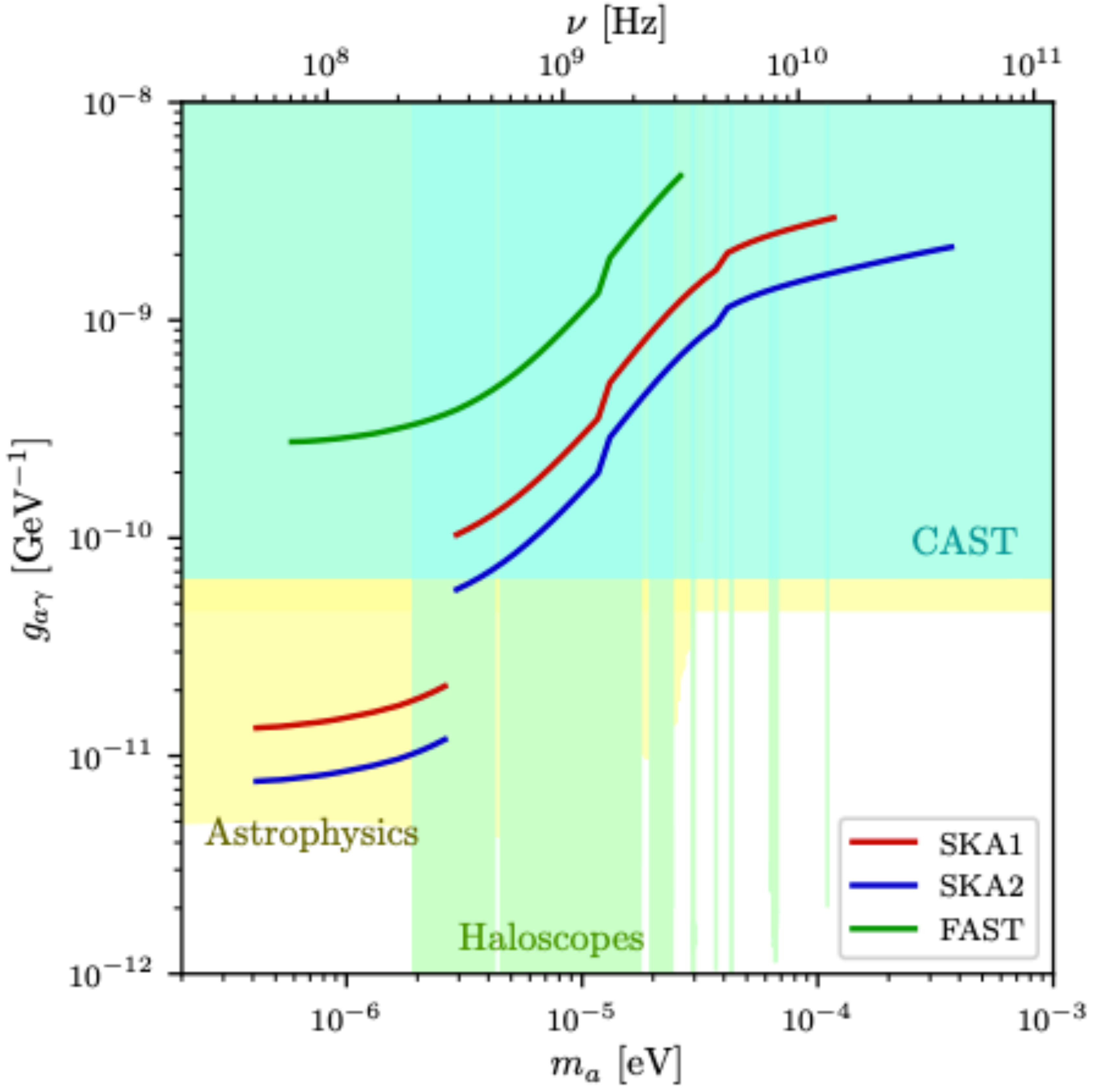
Supernova remnant

Dev, Ferrer, Okawa

JCAP 04 (2024) 045

Backlight echo

Galactic center

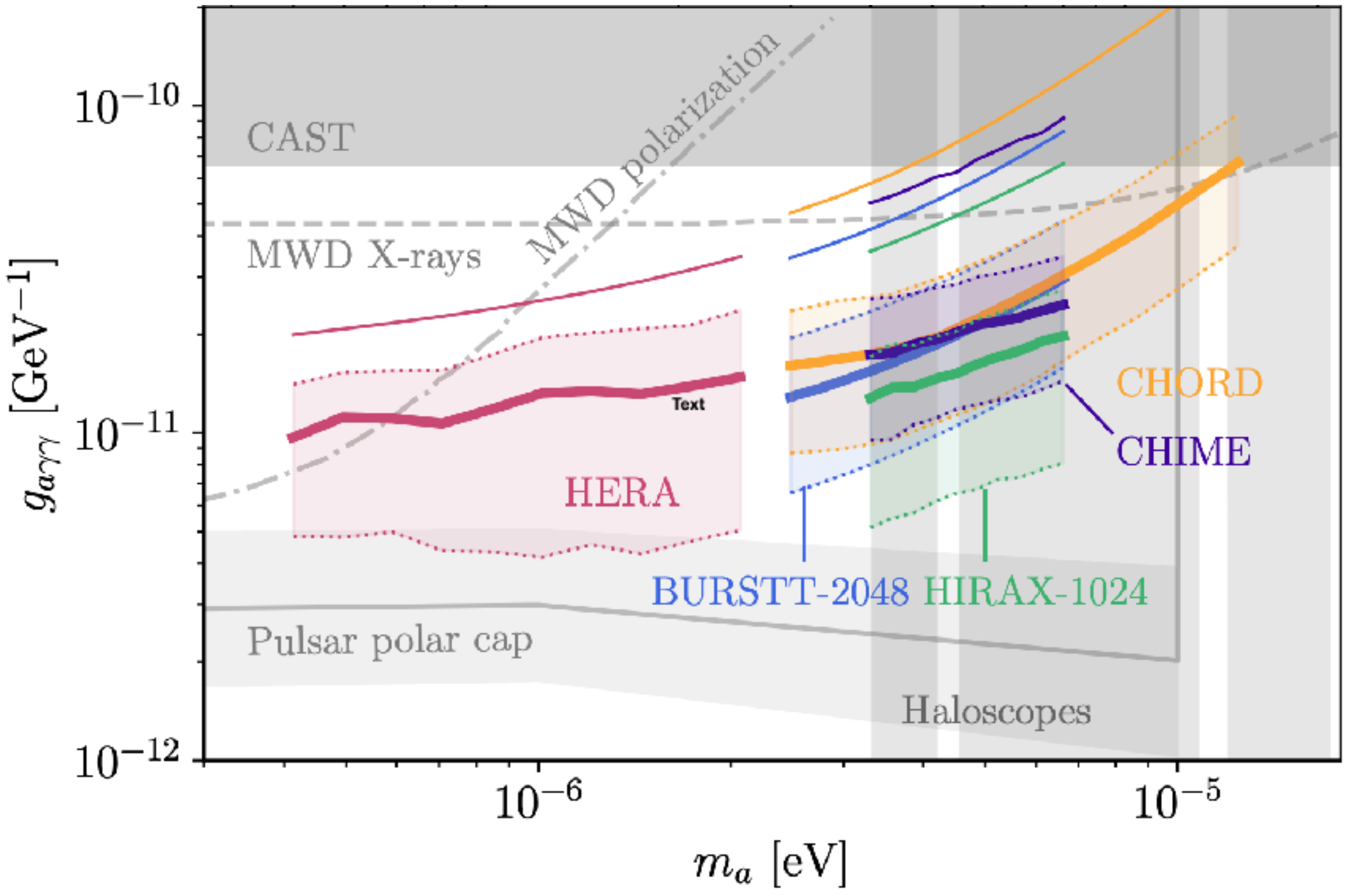


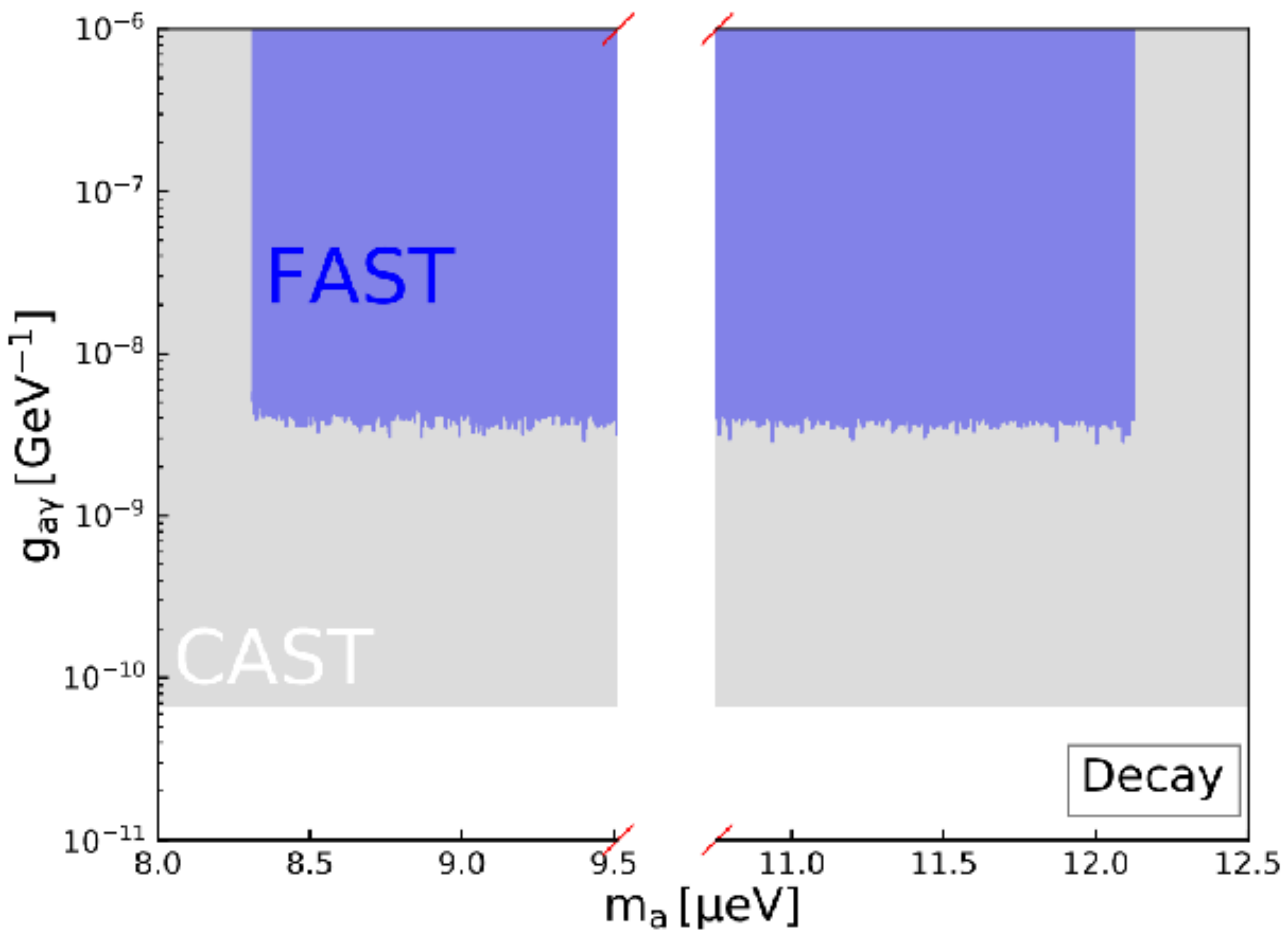
Sun, Schutz, Sewalls, Leung, Wesley Masui

PRD 109 (2024)

Everything

Extragalactic radio point sources, SNRs, Galactic synchrotron radiation





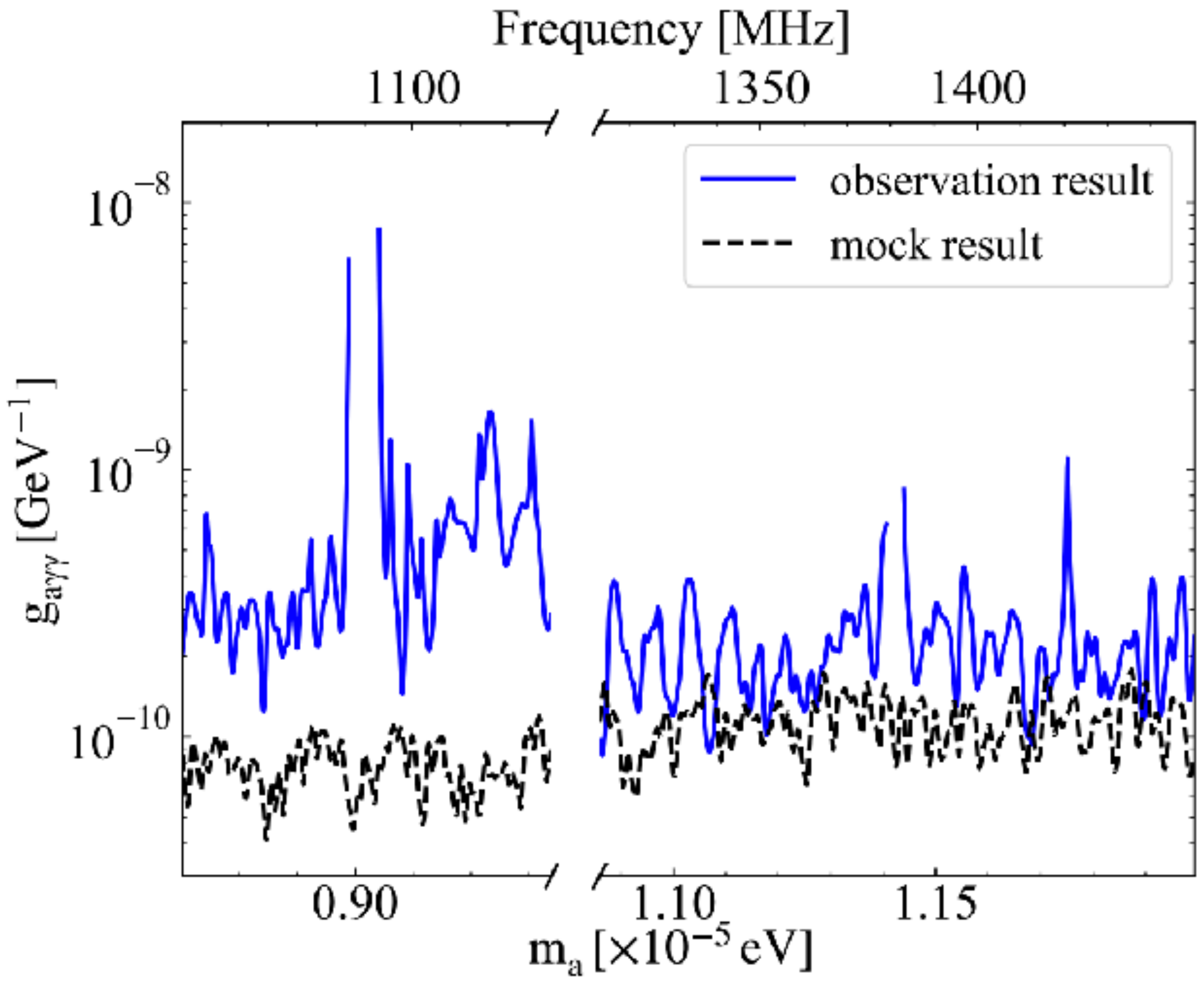
Guo, Xia, Huang

PLB 852 (2024) 138631

Collinear emission

CMB, extragalactic radio bkg

2-hour observation of Coma Berenices



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

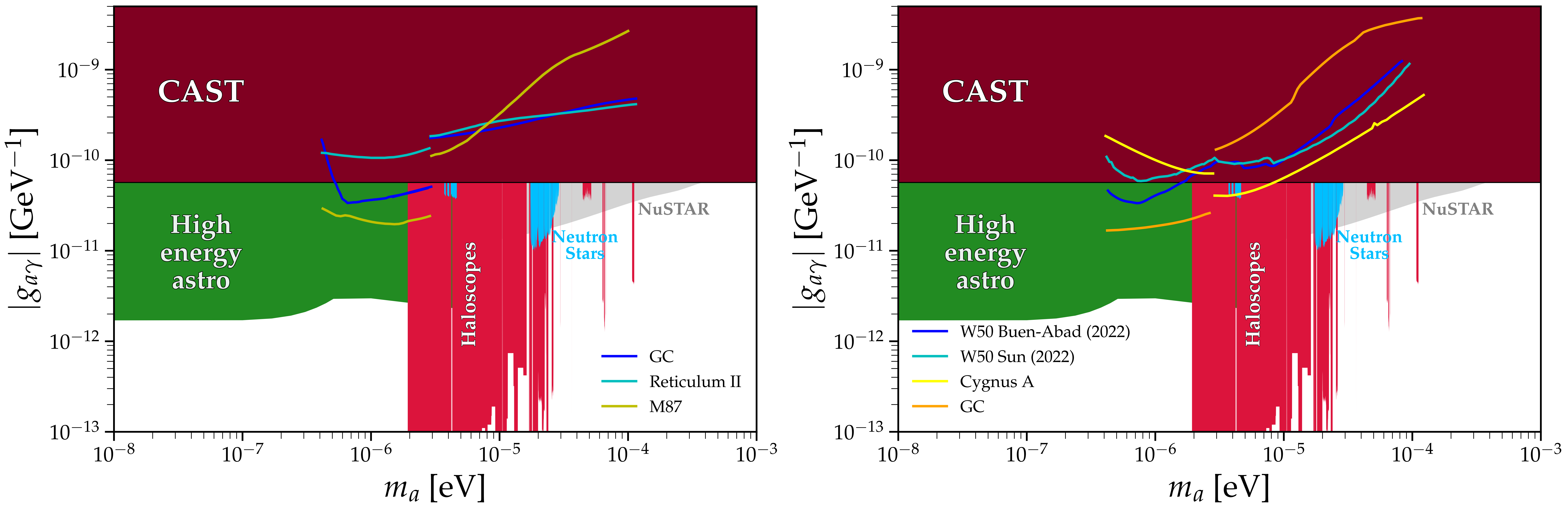
2502.08913

Backlight echo

Vela supernova remnant

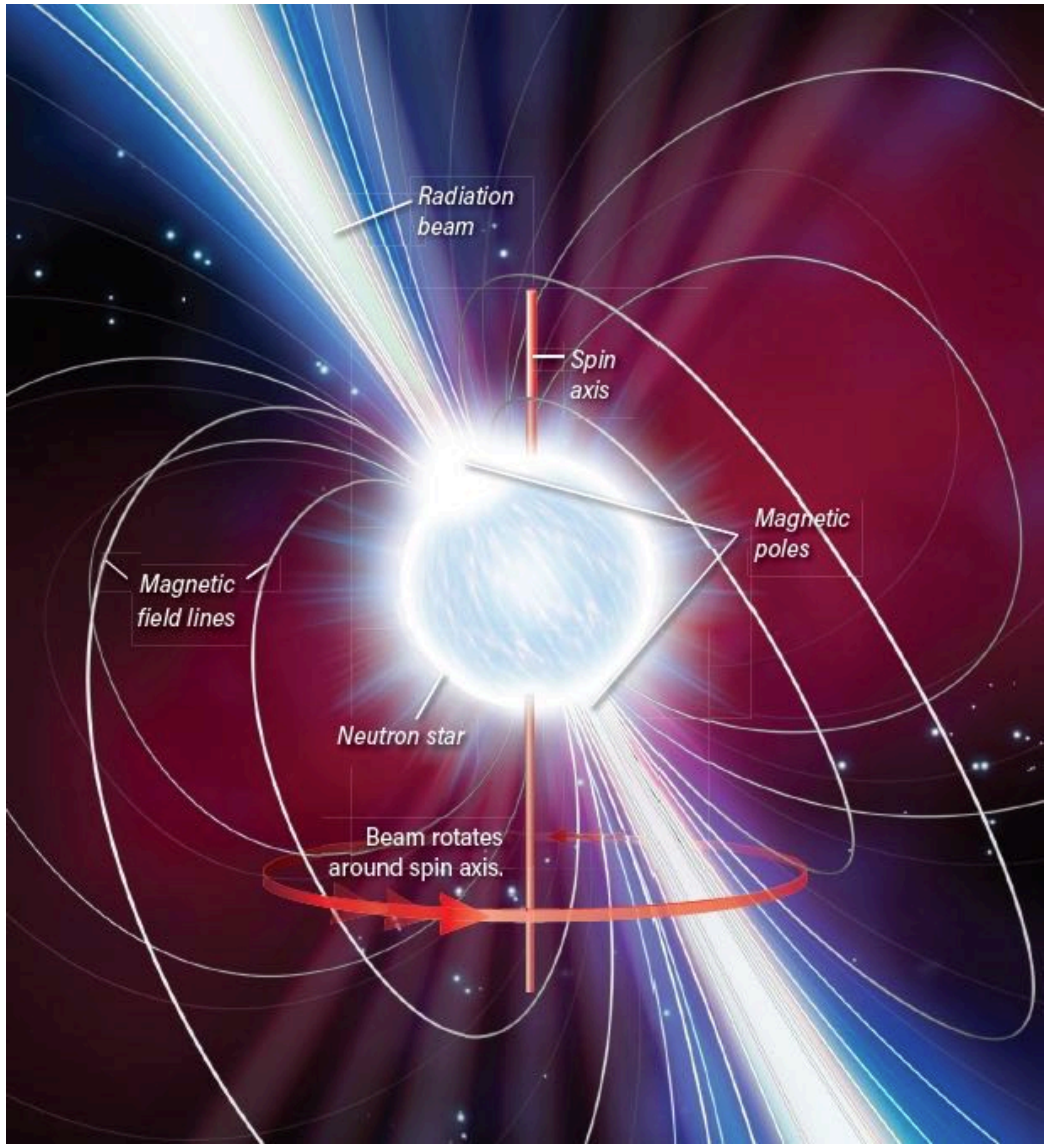
~30-hour observation

SKA-O AA4 Forecasts



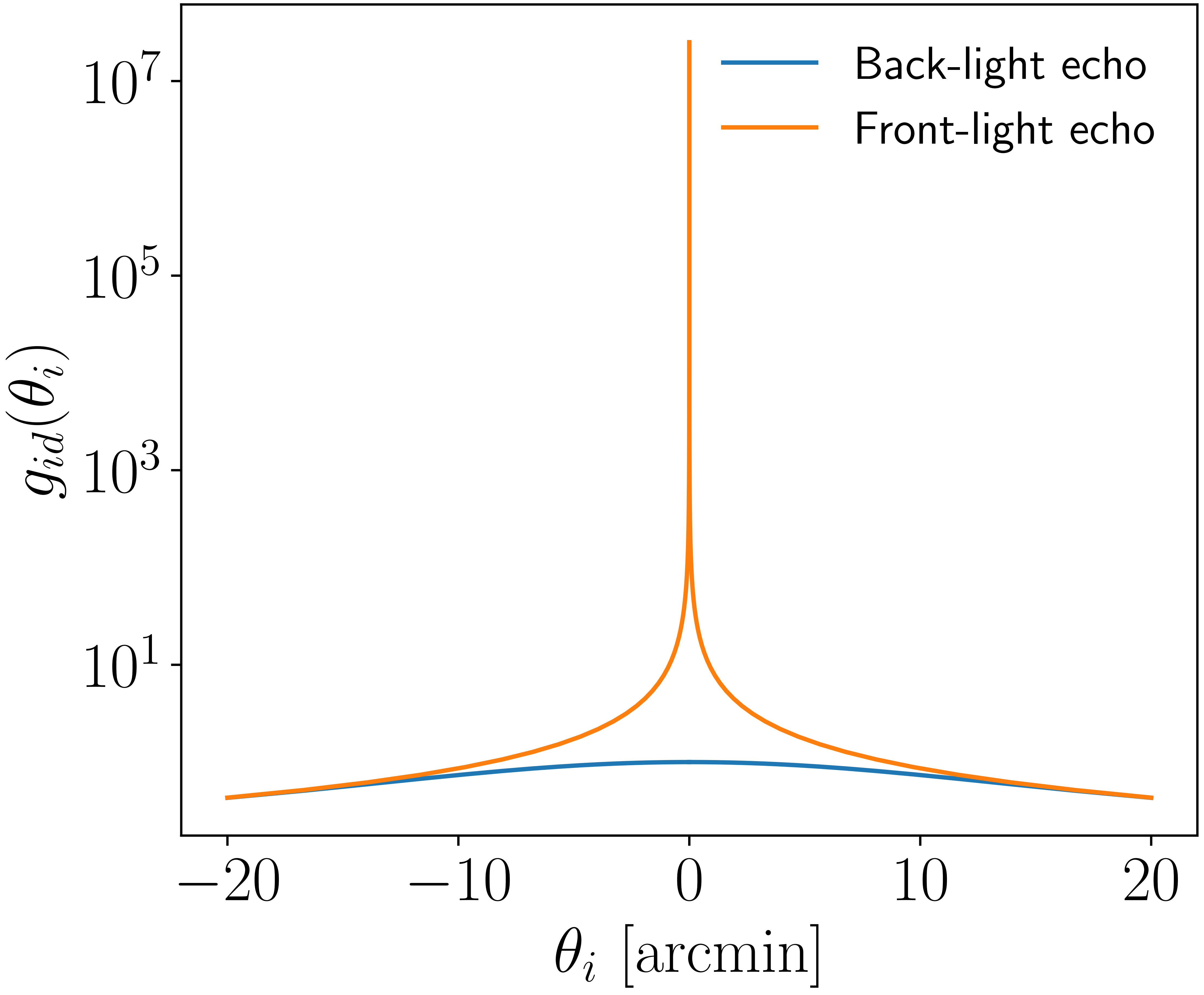
Regis, Todarello et al., SKA book, in preparation

Detailed Study of the Echo from a Point Source



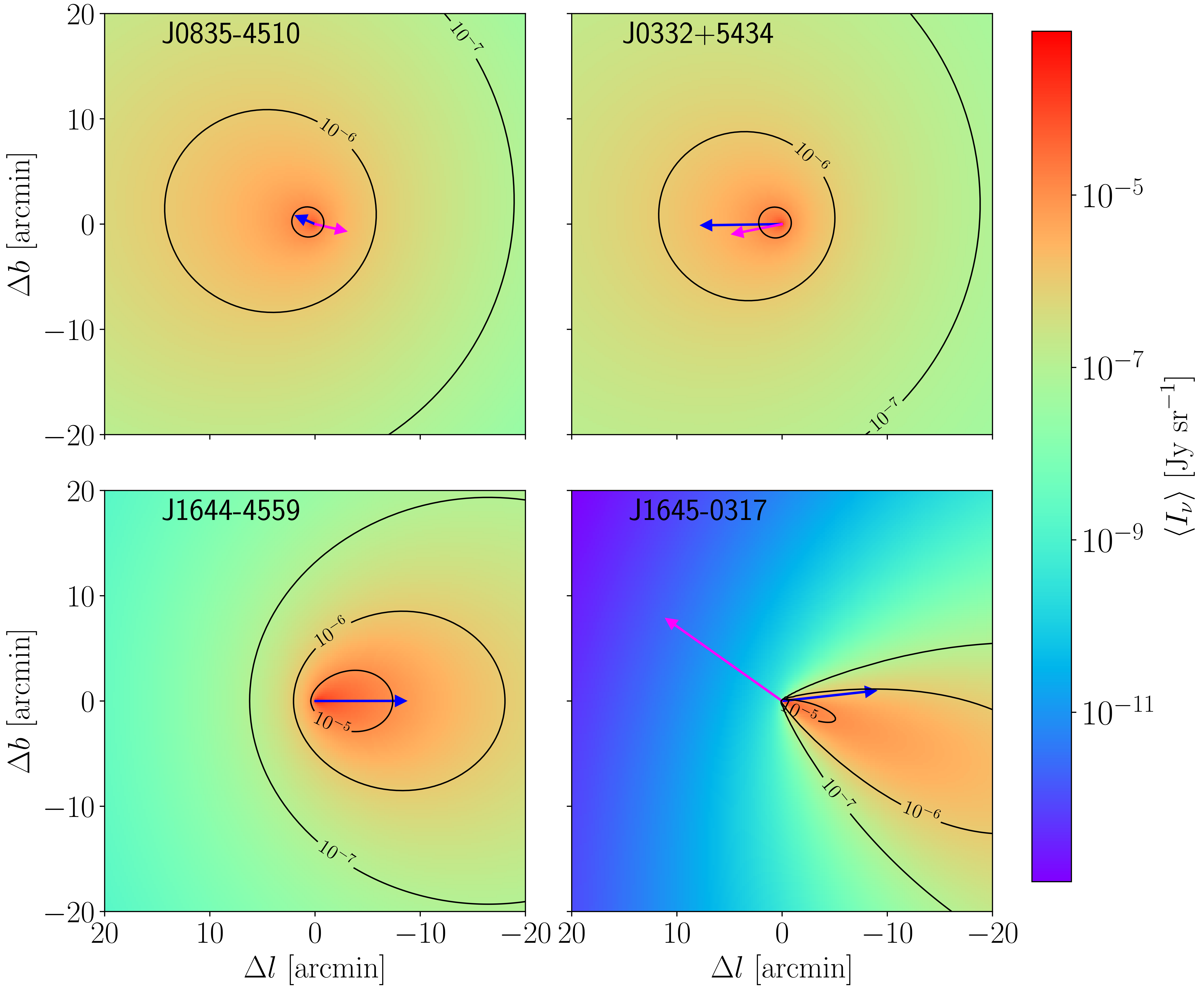
E.T., F. Calore, M. Regis, JCAP 05 (2024) 040

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



Relevant effects

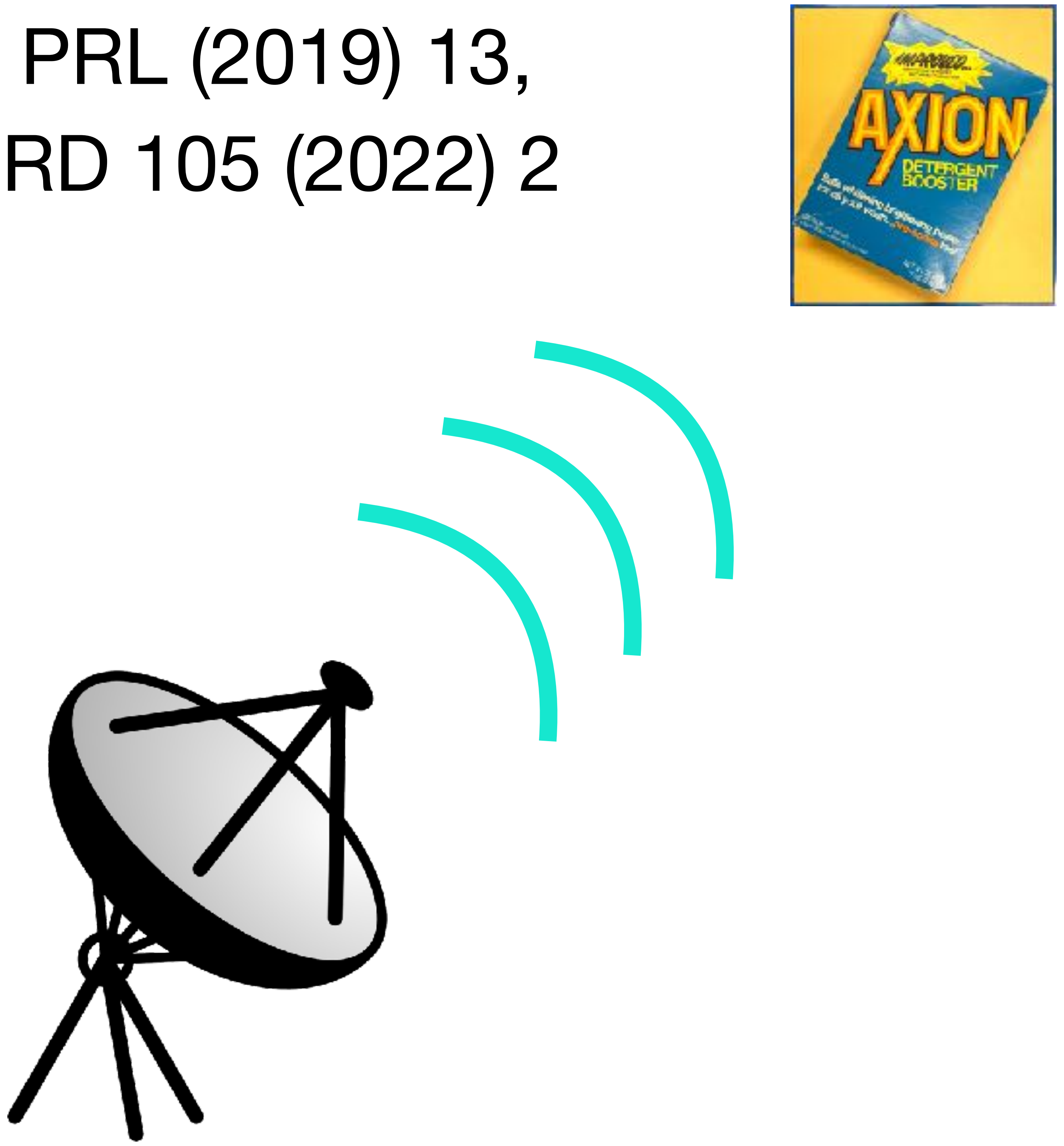
- Dark matter density
- Dark matter velocity dispersion
- Dark matter average velocity
- Source's age
- Source's proper motion
- Source's distance
- Source's variability



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

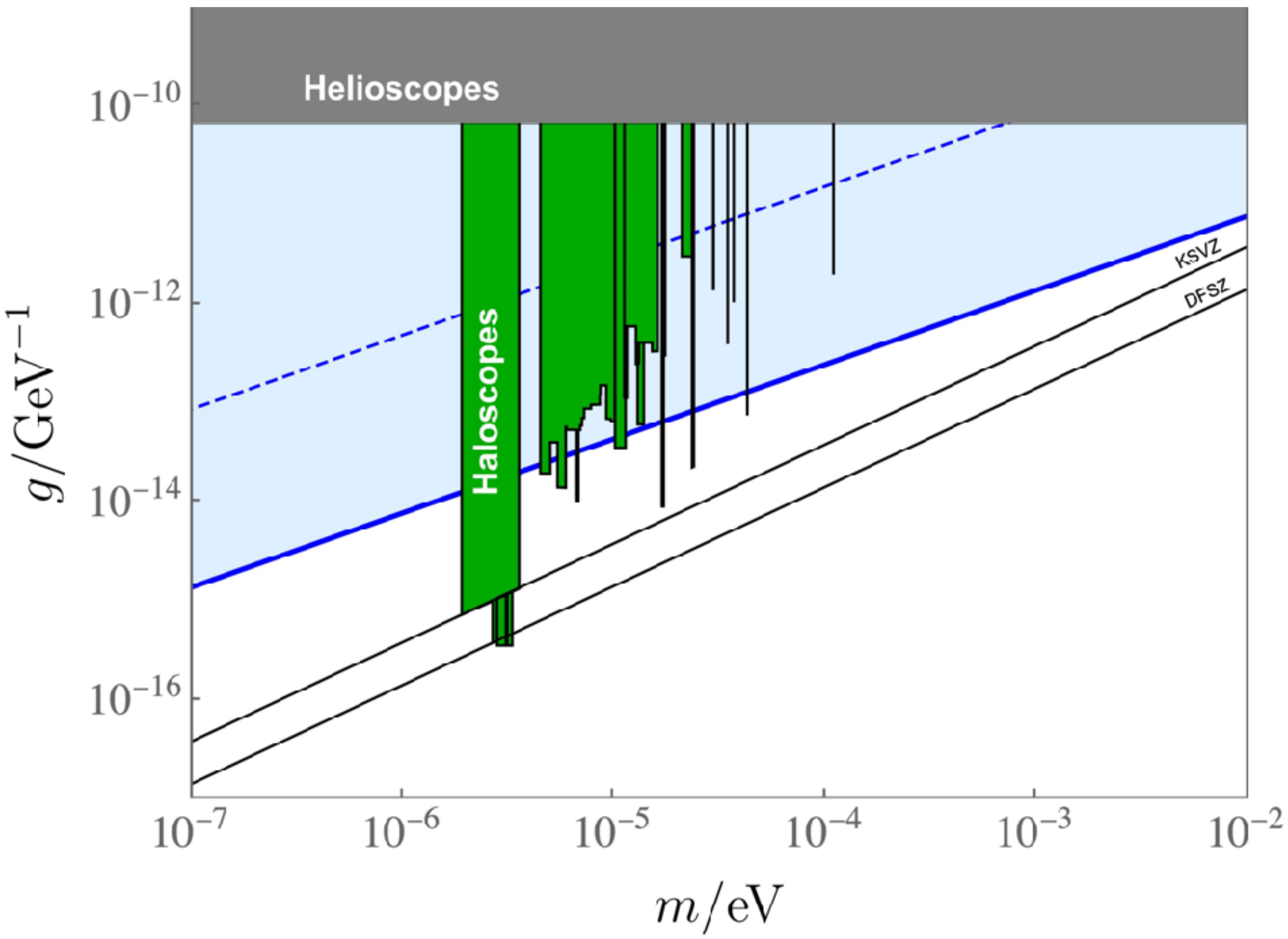
An echo from an artificial source

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

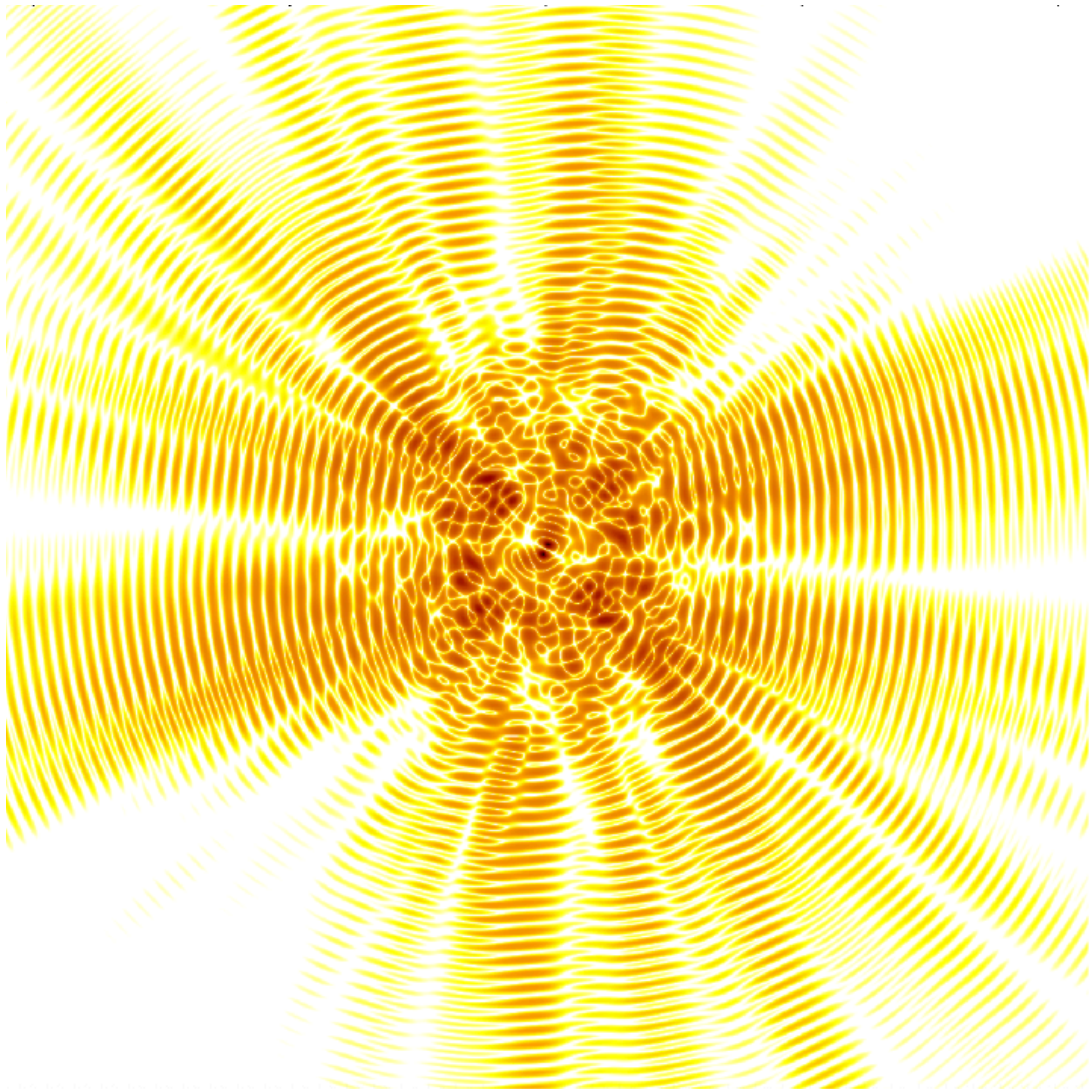


$$\begin{aligned} \rho &= 0.45\ \mathrm{GeV\ cm}^{-3} \\ v &= 230\ \mathrm{km/s} \\ \delta v &= 270\ \mathrm{km/s} \end{aligned}$$

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

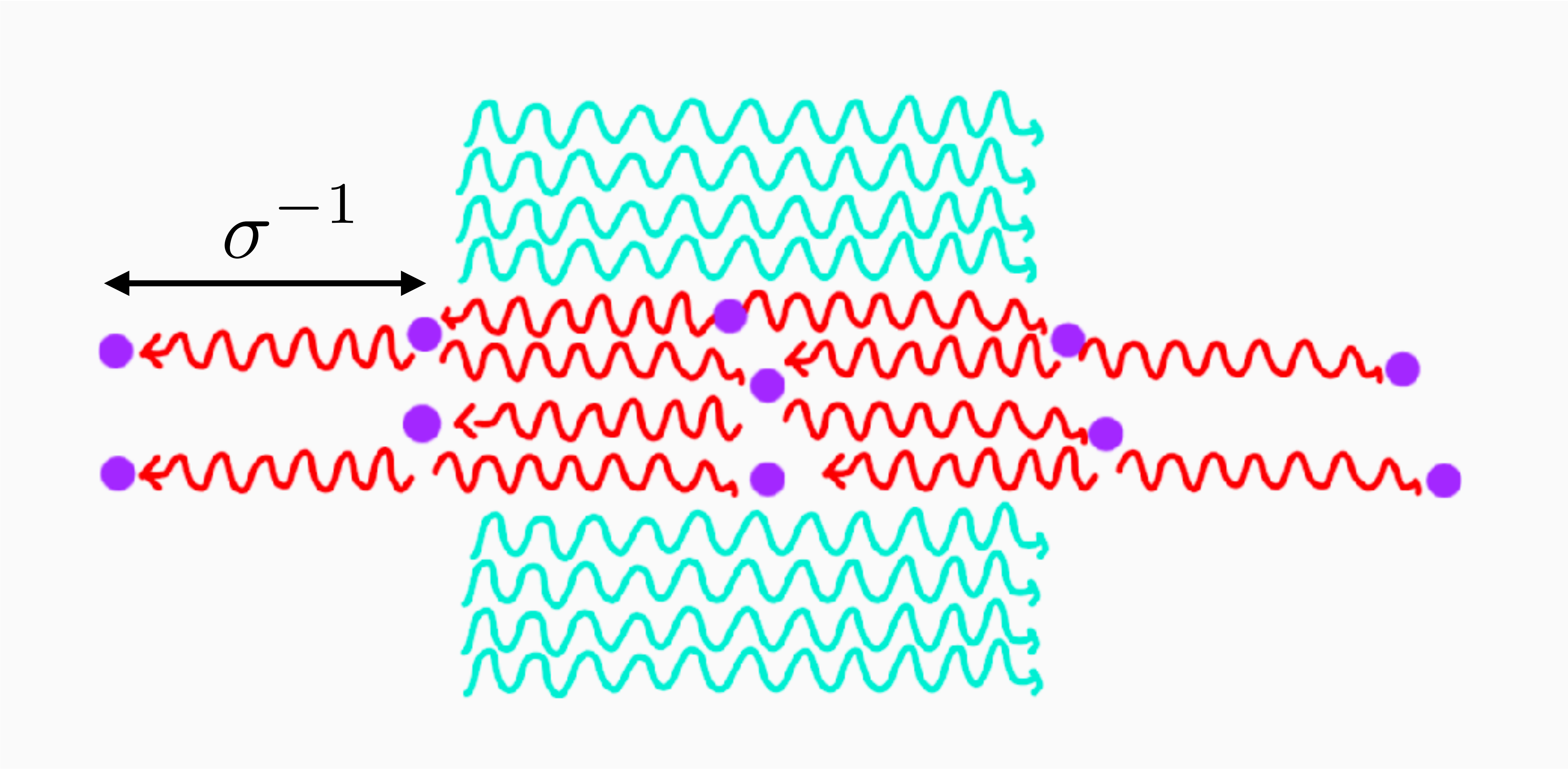
$$E = 10\,\mathrm{MW\,yr} \quad s/n = 5 \quad T_n = 20\,\mathrm{K} \quad R = 50\,\mathrm{m} \quad R_c = 100\,\mathrm{m}$$

Parametric Resonance



Levkov et al., PRD 102 (2020)

Exponential growth



$$\sigma = \frac{g}{2}\sqrt{\frac{\rho}{2}} \simeq 6 \times 10^{-24}\,\mathrm{eV}\left(\frac{g}{10^{-11}\,\mathrm{GeV}^{-1}}\right)\left(\frac{\rho}{0.4\,\mathrm{GeV/cm^3}}\right)^{1/2}$$

$$\sigma^{-1} \simeq 3.5\ \mathrm{yr} \simeq 1\ \mathrm{pc}$$

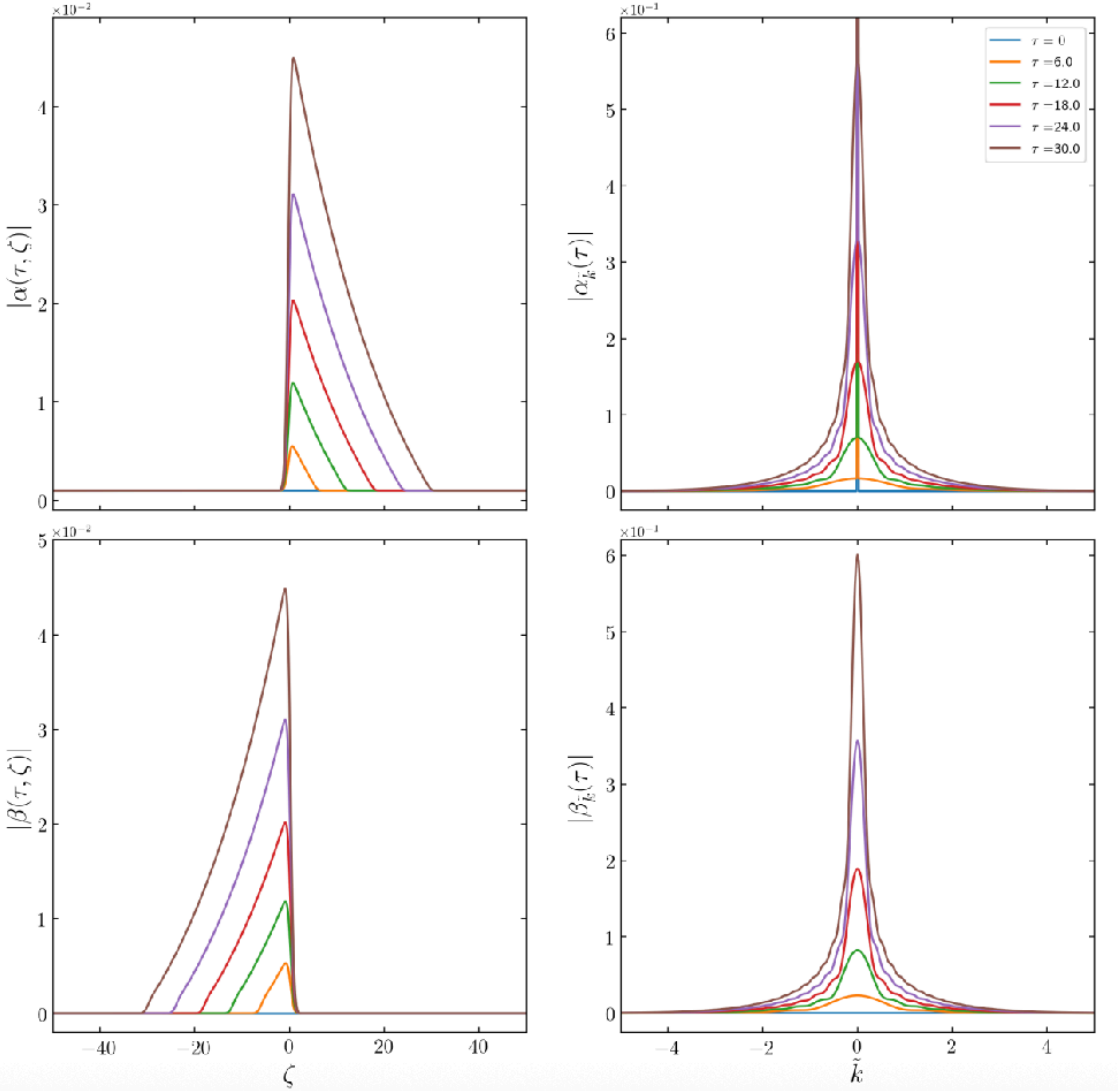
Resonance band

$$-2\sigma < \epsilon < 2\sigma \qquad\qquad \epsilon = 2\omega - p_{\|} - m$$

$$\omega = \frac{m}{2}(1 + v_{\|})$$

Easily detuned by change in velocity or gravitational potential!

$$m = 10^{-5}\ \mathrm{eV} \qquad \Delta v \lesssim 10^{-17} \qquad \Delta\varphi \lesssim 10^{-15}$$



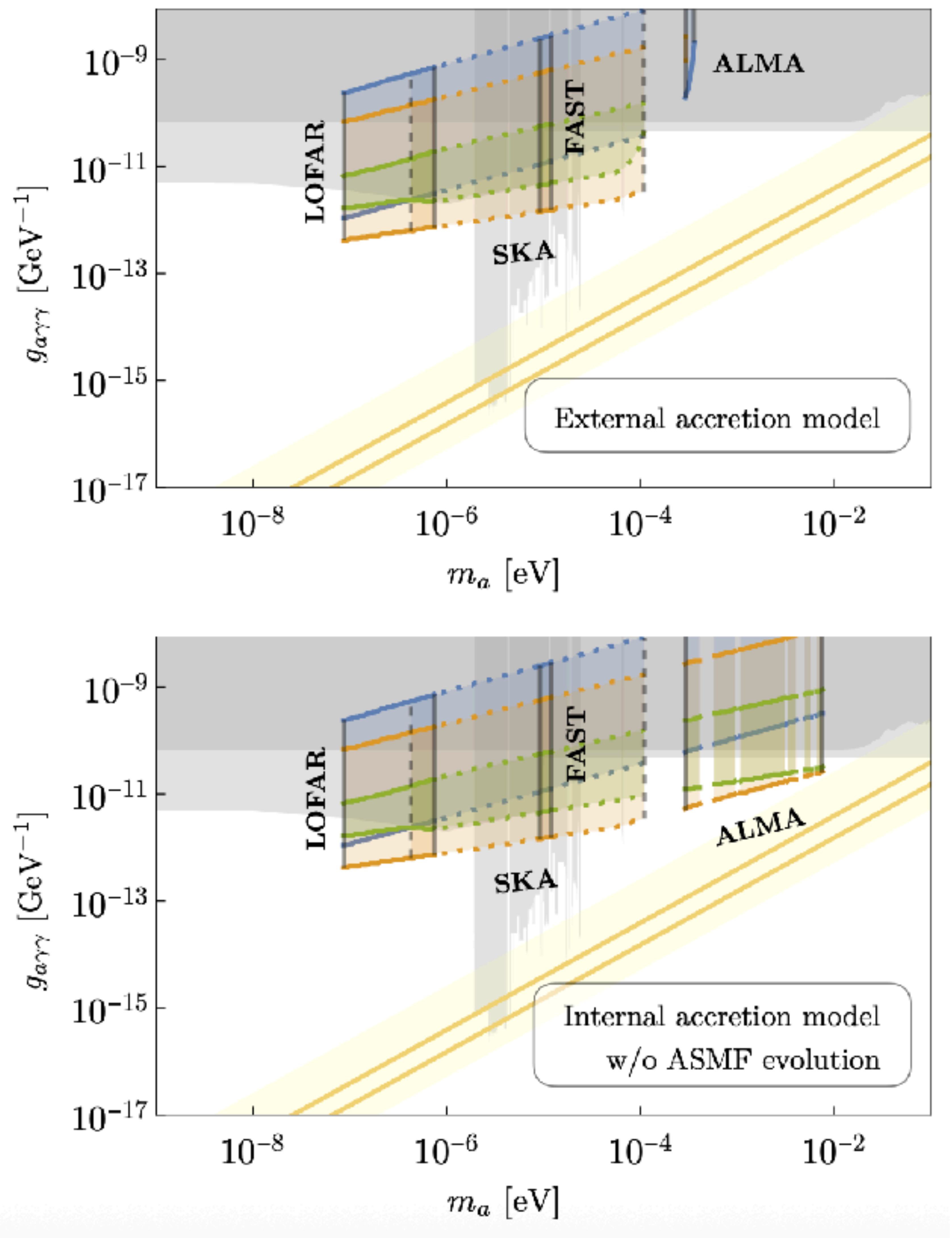
Arza et al., JCAP 10 (2020) 013

Resonance develops if

$$\sigma R > 1$$

(Tkachev, Phys. Lett. B191 (1987))

Axion Stars



Maseizik et al., *"Radio lines from accreting axion stars"*, JCAP 05 (2025) 033

- One axion star per minicluster
- Minicluster mass function -> core-halo relation -> axion star mass function
- Axion star unstable above critical mass
- Accretion from surrounding halo or minicluster

See also Escudero et al., *"Axion Star Explosions: A New Source for Axion Indirect Detection"*, Phys.Rev.D 109 (2024) 4, 043018

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
- Parametric resonance for compact objects