Hunting dark matter lines with JWST

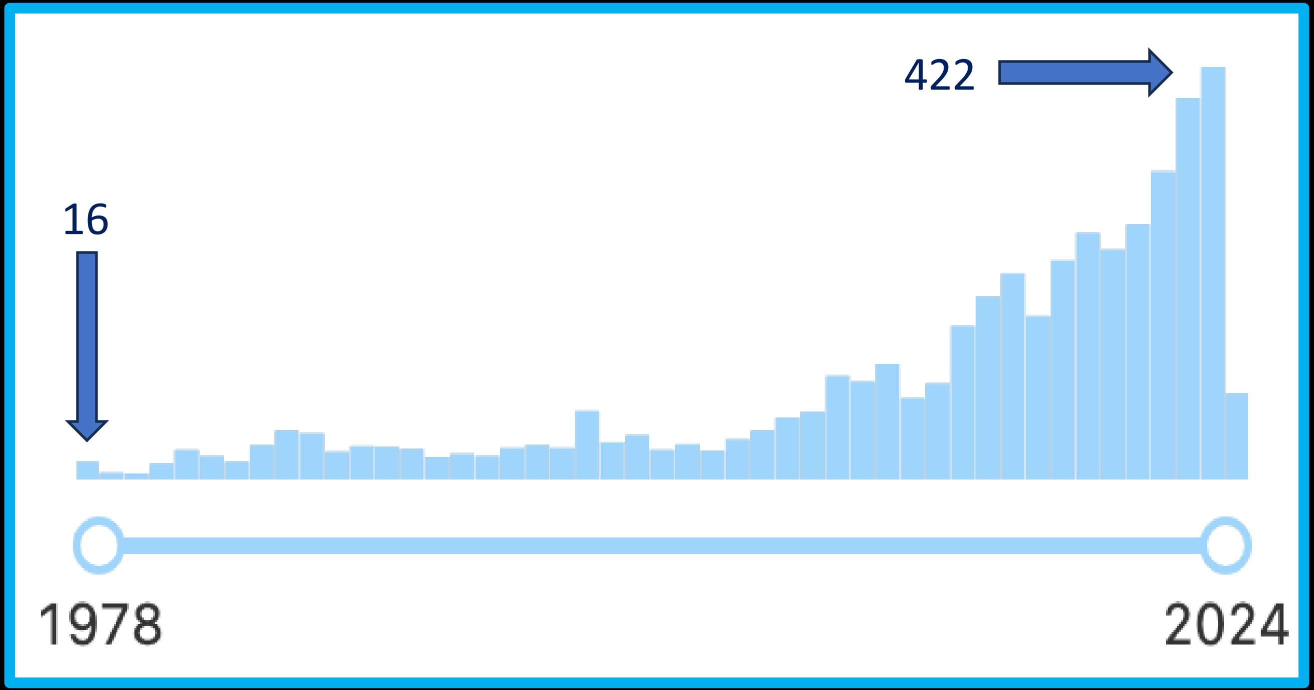
Elena Pinetti

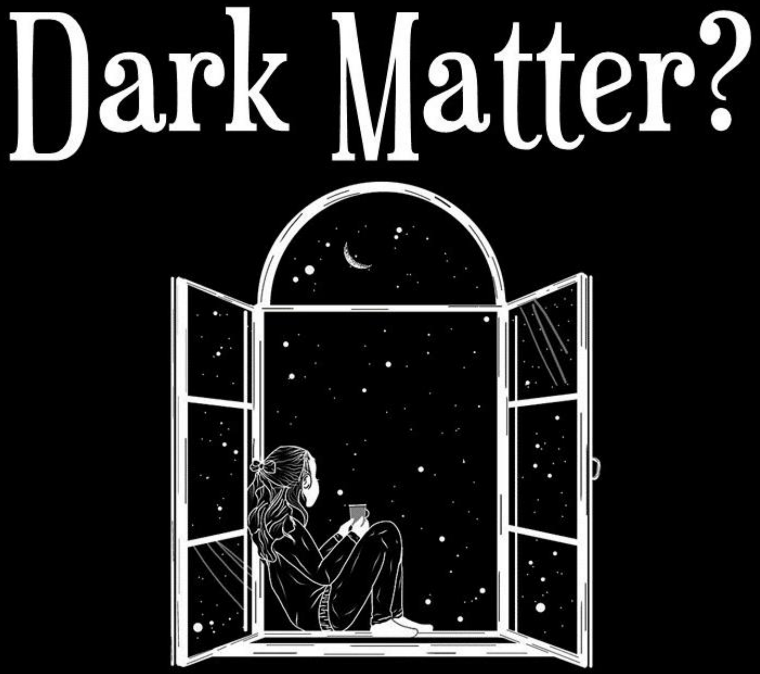
Cosmic WISPers – 5th September 2024

Dark matter in the Universe

Dark Matter candidates

Favorite imaginary friends: axions



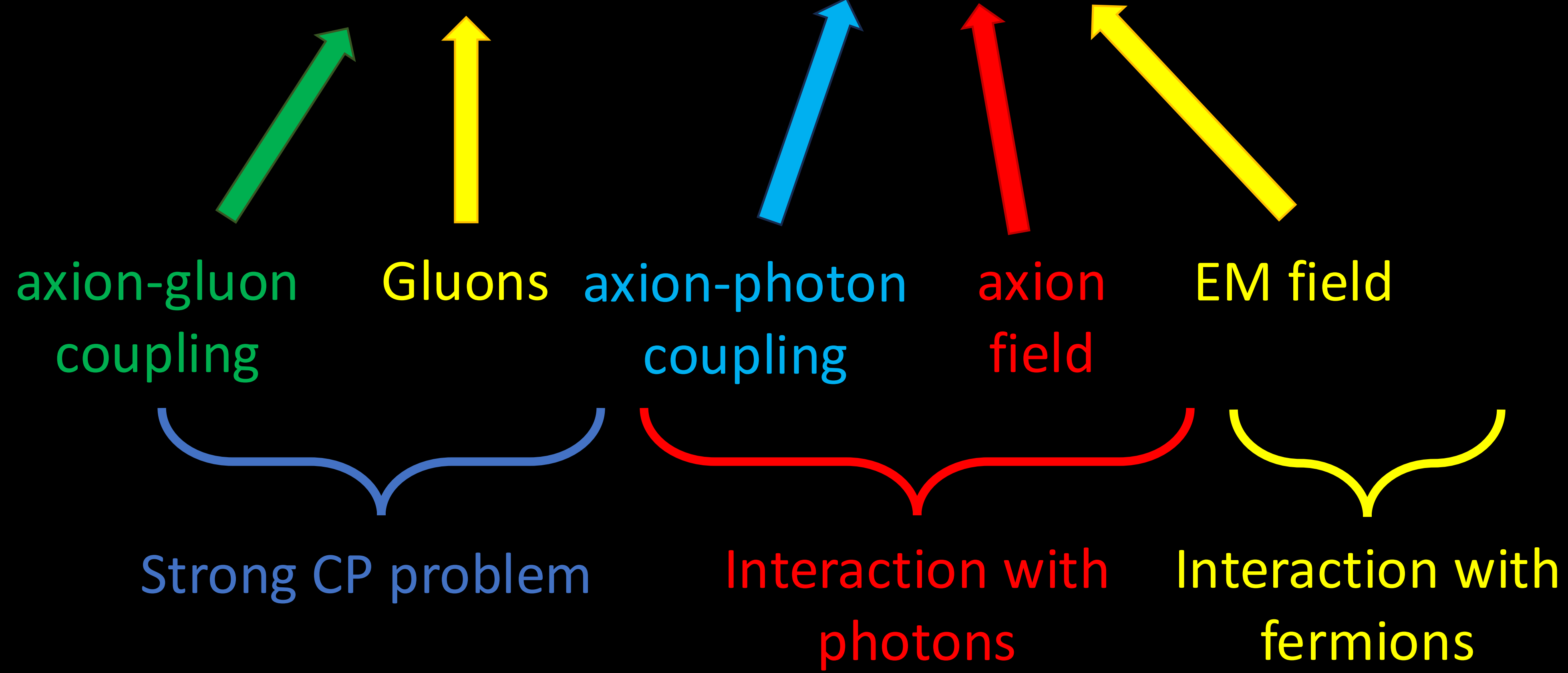


Outline

- ☐ Dark matter flux
- ☐ JWST Observations
- ☐ Results & Prospects

QCD axions & axion-like particles

$$\mathcal{L}_a \supset -\frac{\alpha_s}{8\pi}\frac{a}{f_a} G_{\mu\nu}\tilde{G}_{\mu\nu} - \frac{1}{4} g_{a\gamma\gamma}\, a F_{\mu\nu}\tilde{F}_{\mu\nu} + (\dots)$$



axion-gluon coupling

Gluons

axion-photon coupling

axion field

EM field

Strong CP problem

Interaction with photons

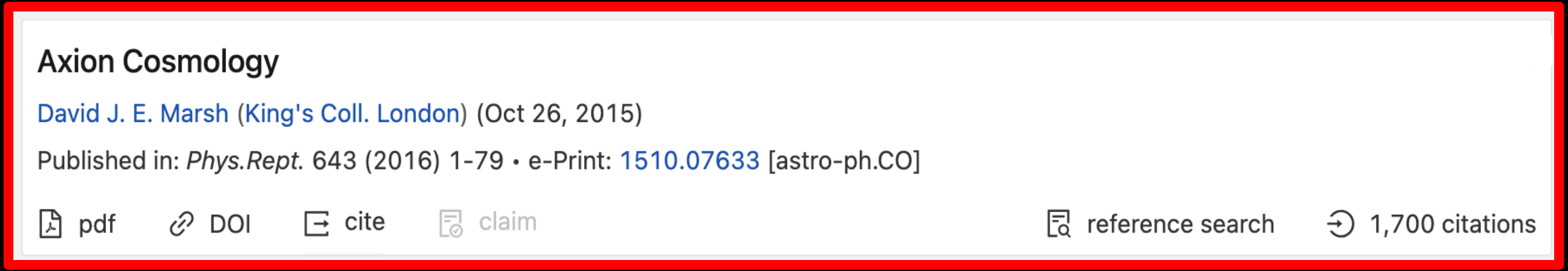
Interaction with fermions

For more on axions

Axion Cosmology

Pierre Sikivie (CERN and Florida U.) (Oct, 2006)

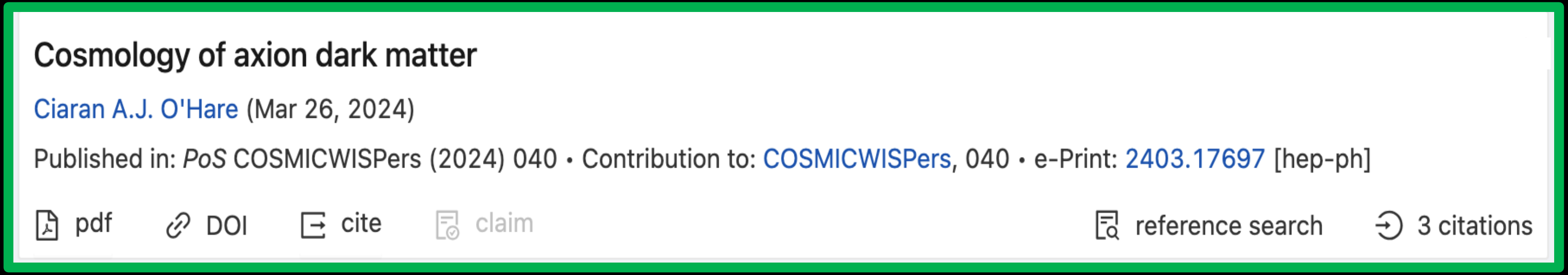
Published in: *Lect.Notes Phys.* 741 (2008) 19-50 • Contribution to: Joint ILIAS-CAST-CERN Axion Training at CERN, 19-50 • e-Print: astro-ph/0610440 [astro-ph]



Axion Cosmology

David J. E. Marsh (King's Coll. London) (Oct 26, 2015)

Published in: *Phys.Rept.* 643 (2016) 1-79 • e-Print: 1510.07633 [astro-ph.CO]



Cosmology of axion dark matter

Ciaran A.J. O'Hare (Mar 26, 2024)

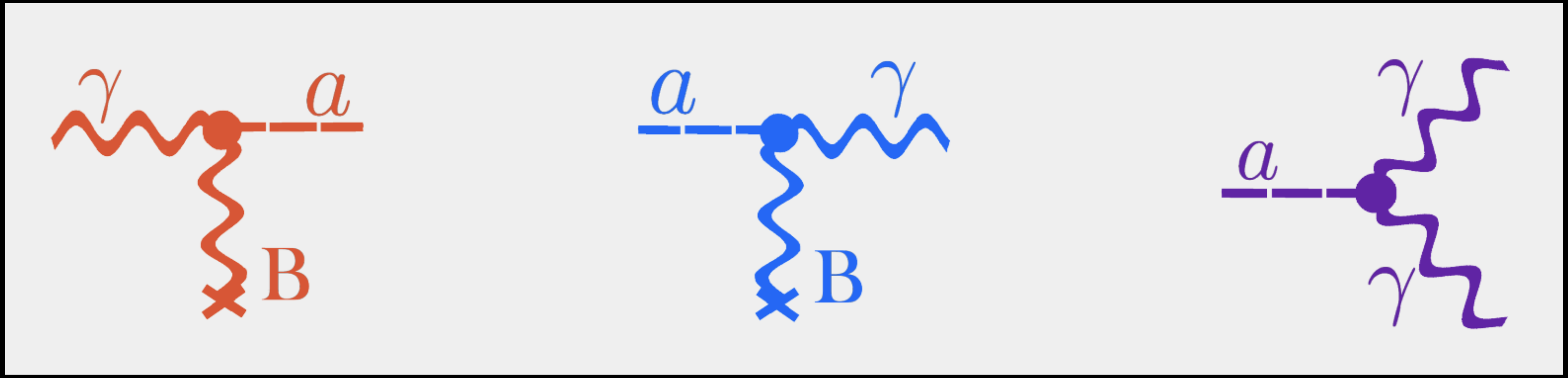
Published in: *PoS* COSMICWISPers (2024) 040 • Contribution to: COSMICWISPers, 040 • e-Print: 2403.17697 [hep-ph]

Axion-photon interactions

① Primakov production in stars: $\gamma \rightarrow a$

② Conversion $a \leftrightarrow \gamma$ in laboratory and astrophysical B-fields

③ $\boxed{\text{Axion decay } a \rightarrow \gamma\gamma}$

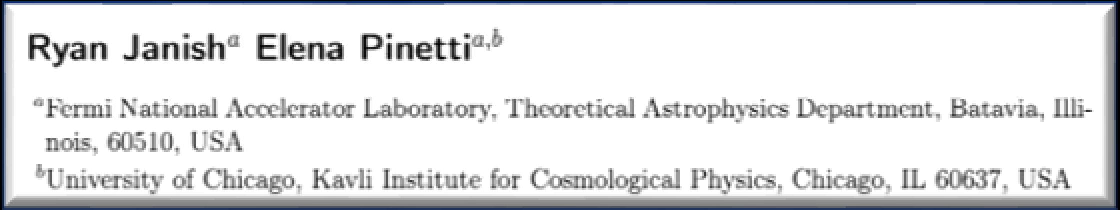


① ② ③

eV-scale axions

$m_a \sim 1$ eV → Infrared photons

Hunting Dark Matter Lines in the Infrared Background with the James Webb Space Telescope



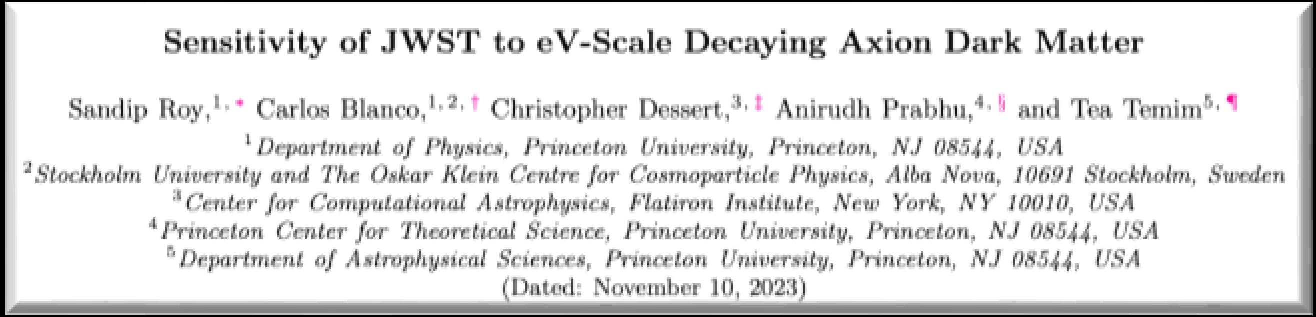
Ryan Janish[a] **Elena Pinetti**[a,b]

[a] Fermi National Accelerator Laboratory, Theoretical Astrophysics Department, Batavia, Illinois, 60510, USA

[b] University of Chicago, Kavli Institute for Cosmological Physics, Chicago, IL 60637, USA

arXiv:2310.15395, submitted to PRL

+ Follow-up paper with more JWST data!



Sensitivity of JWST to eV-Scale Decaying Axion Dark Matter

Sandip Roy,[1,*] Carlos Blanco,[1,2,†] Christopher Dessert,[3,‡] Anirudh Prabhu,[4,§] and Tea Temim[5,¶]

[1] *Department of Physics, Princeton University, Princeton, NJ 08544, USA*

[2] *Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden*

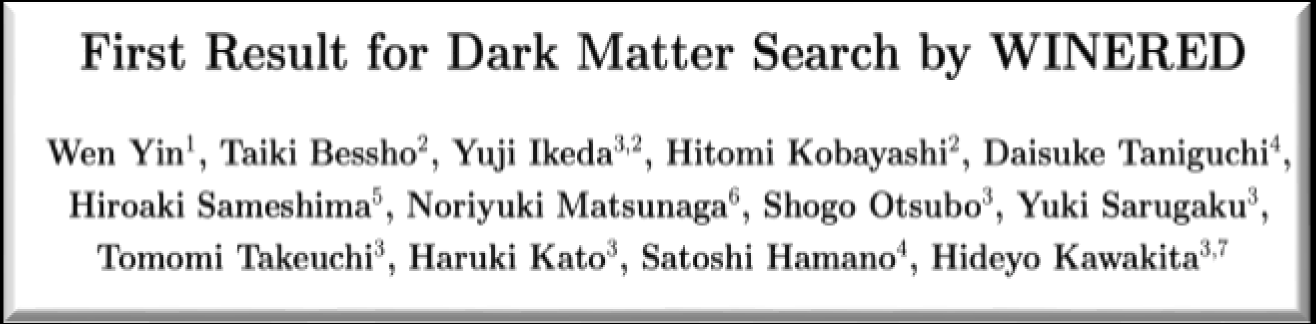
[3] *Center for Computational Astrophysics, Flatiron Institute, New York, NY 10010, USA*

[4] *Princeton Center for Theoretical Science, Princeton University, Princeton, NJ 08544, USA*

[5] *Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA*

(Dated: November 10, 2023)

arXiv:2311.04987v1



First Result for Dark Matter Search by WINERED

Wen Yin[1], Taiki Bessho[2], Yuji Ikeda[3,2], Hitomi Kobayashi[2], Daisuke Taniguchi[4], Hiroaki Sameshima[5], Noriyuki Matsunaga[6], Shogo Otsubo[3], Yuki Sarugaku[3], Tomomi Takeuchi[3], Haruki Kato[3], Satoshi Hamano[4], Hideyo Kawakita[3,7]

arXiv:2402.07976v1

Interesting targets

Where to look?

① Blank-sky observations

② Dwarf galaxies

③ Galaxy clusters

Blank-sky observations (diffuse)

Pros:

- Tons of archival data
- No need to apply for time on the telescope
- DM signal-to-background more favourable

Cons:

- The DM signal might be low if the location is far from the GC
- Less deep than target observations

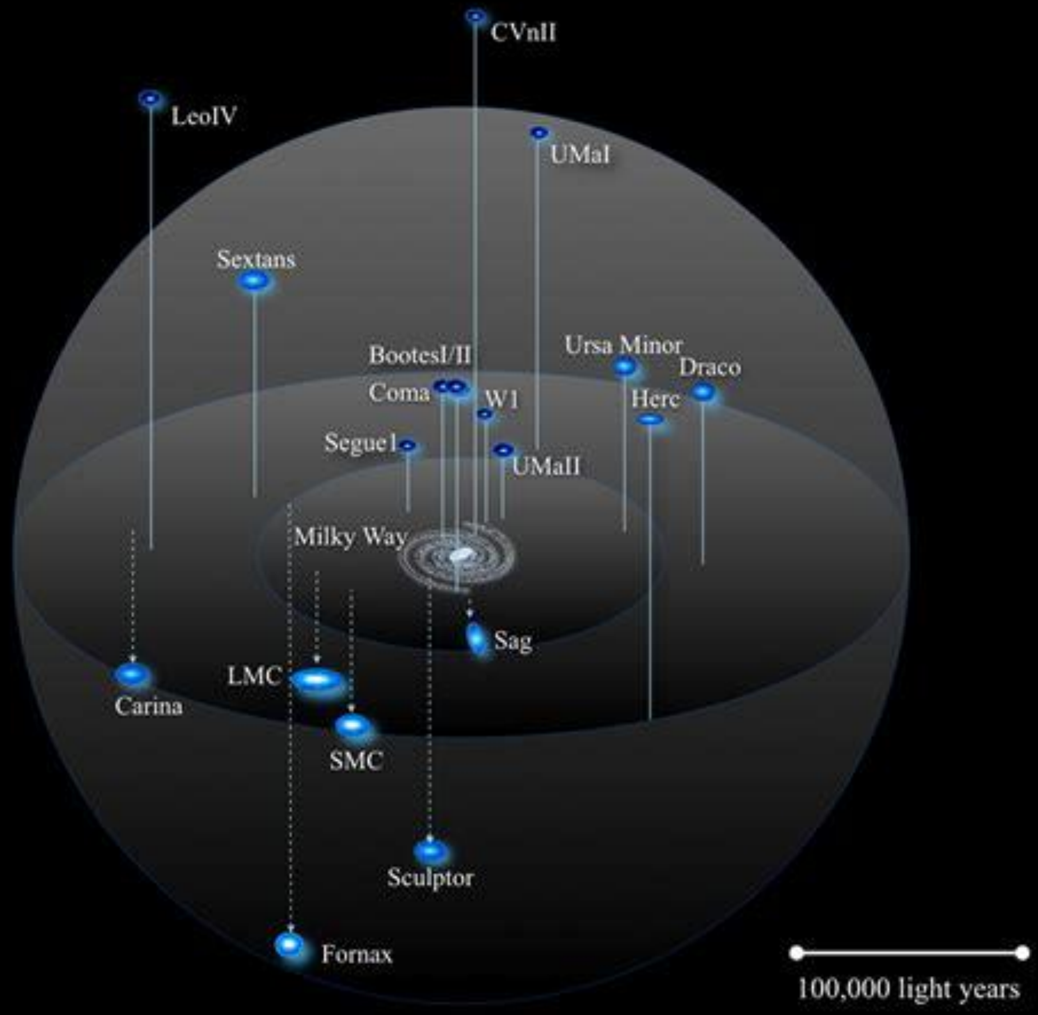
Dwarf galaxies

Pros:

- DM dominated
- Favourable signal-to-background ratio
- Close to us
- Complementary searches in other wavelengths (Fermi and MAGIC in gamma-rays)

Cons:

- Low signal
- Some dwarfs have large uncertainties on the D-factor and J-factor



Galaxy clusters

Pros:

- Strong DM signal
- Expected to host a large population of subhalos which boost the signal

Cons:

- Far away from us
- The contributions of the substructures is uncertain
- Large uncertainties

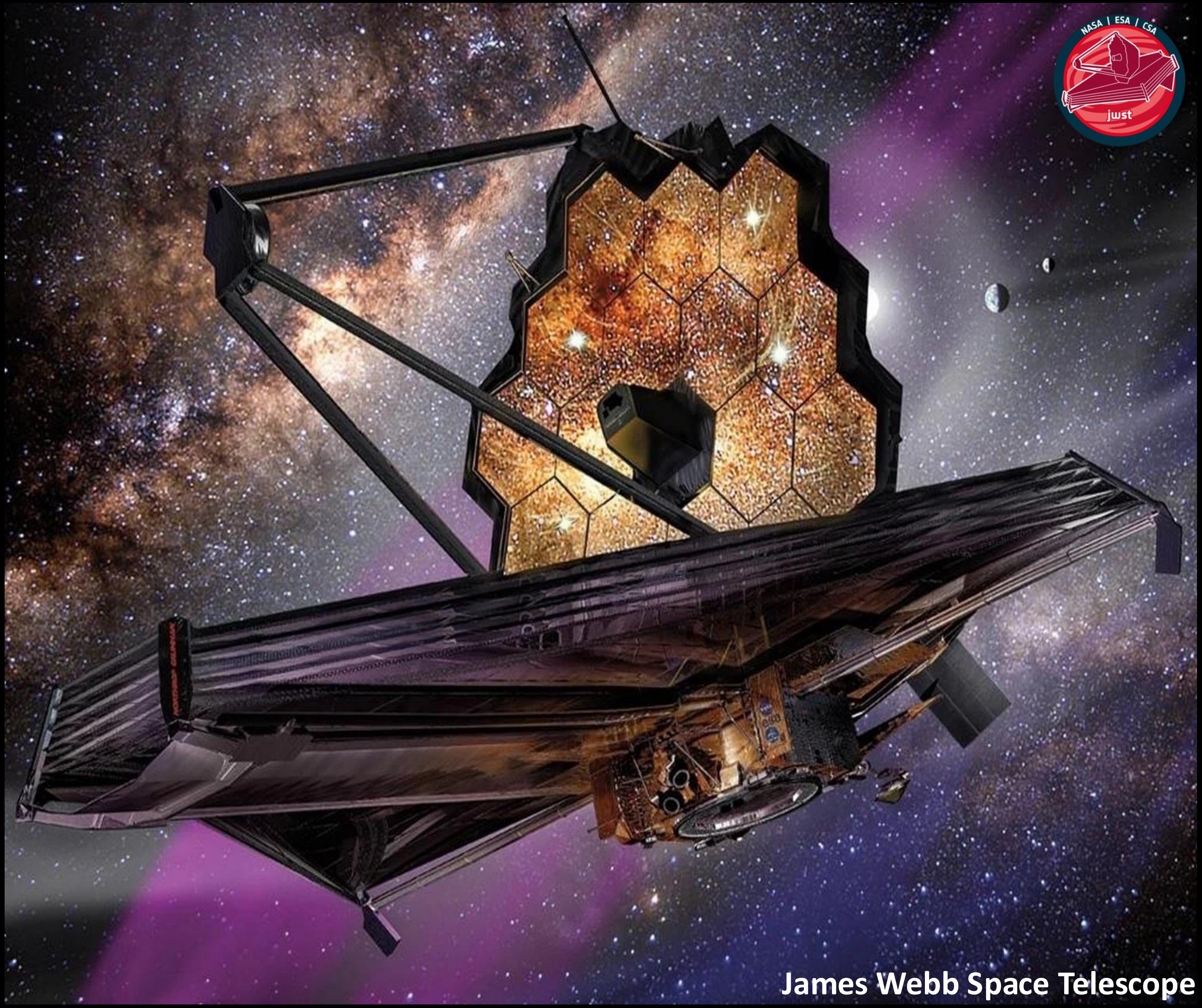
© Nasa/Hubble Space Telescope

Observed dark matter signal

Dark matter signal

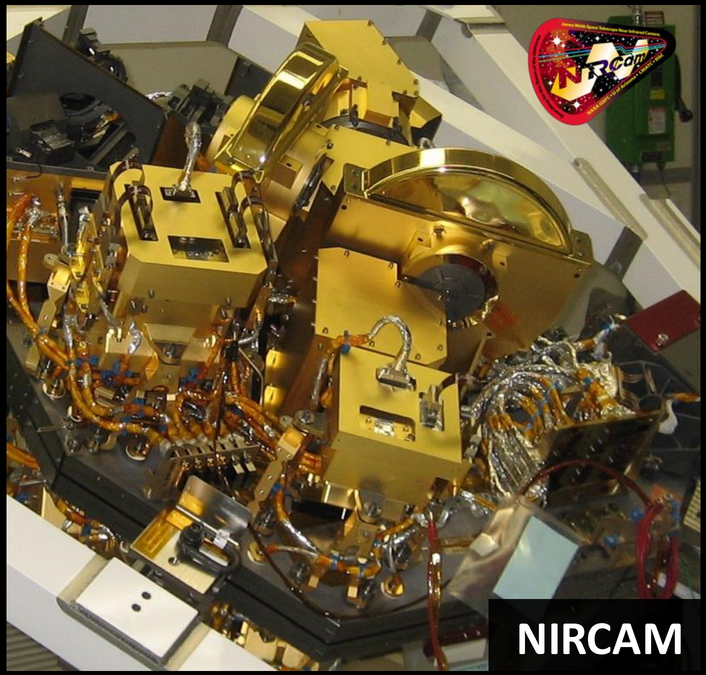
$$\frac{d\phi_{DM}}{dE\,d\Omega} = \frac{\overbrace{\Gamma_\gamma}^{\text{Emission rate}}}{4\pi\, \underbrace{m_a}_{\text{Axion mass}}} \underbrace{\frac{dN}{dE}}_{\text{Emission spectrum}} \underbrace{D}_{\text{D-factor}}$$

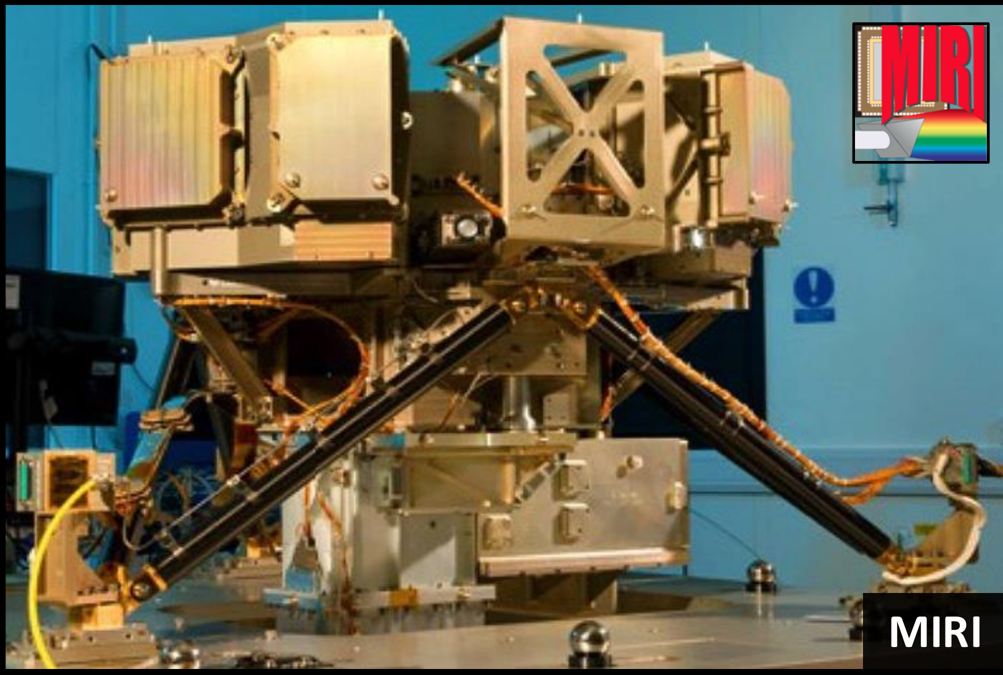
James Webb Space Telescope



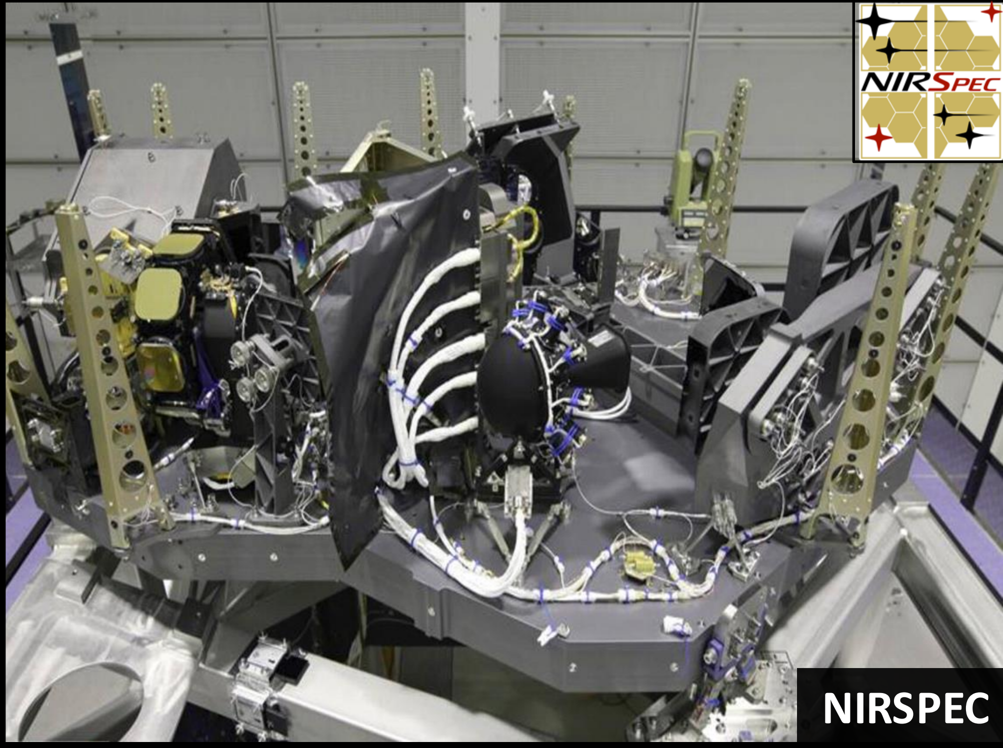
James Webb Space Telescope

JWST Instruments

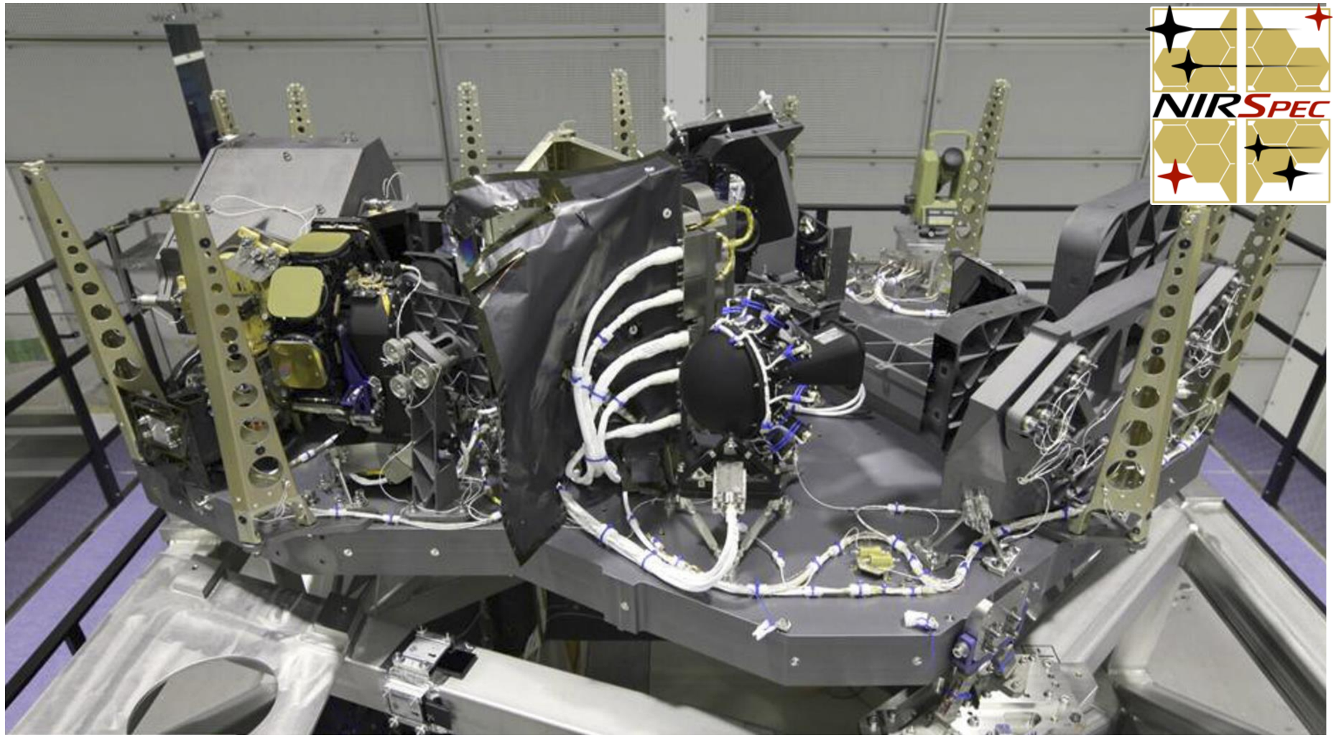

NIRCAM

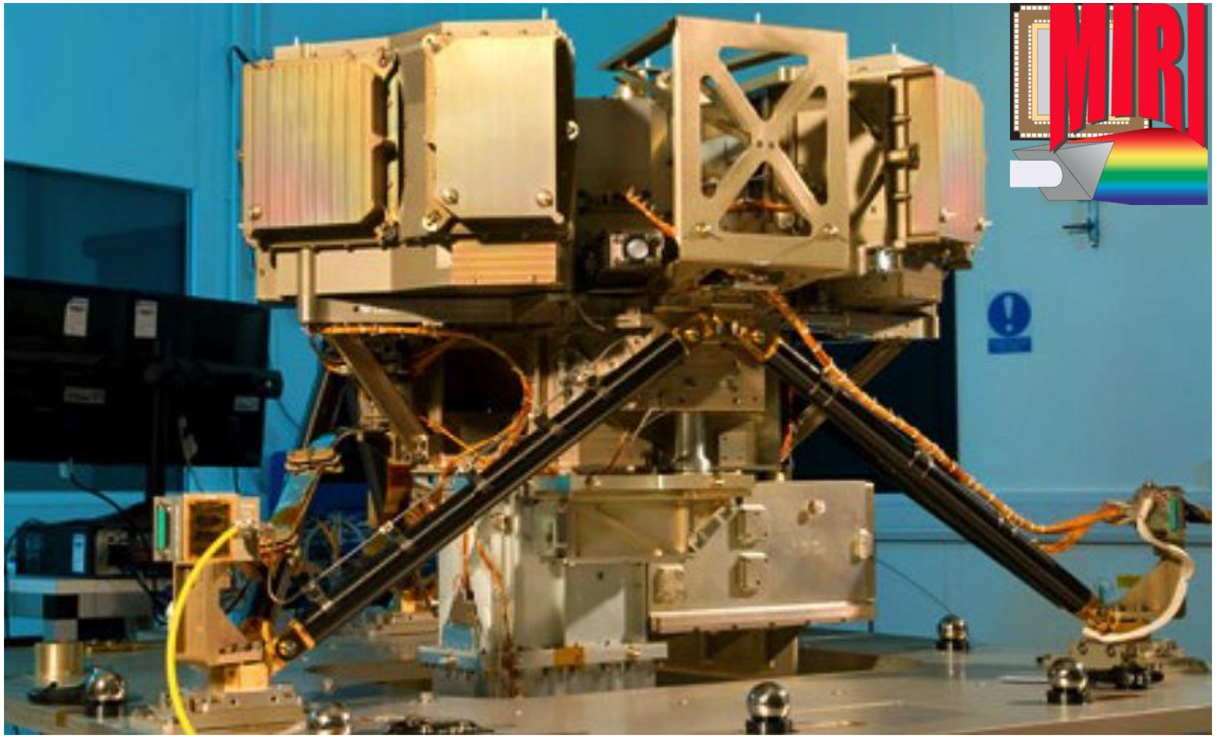

MIRI


NIRISS


NIRSPEC

NIRSPEC and MIRI





NIRSpec: Near-Infrared Spectrograph

$\Delta\lambda = 0.6 - 5\ \mu m$

MIRI: Mid-Infrared Instrument

$\Delta\lambda = 4.9 - 27.9\ \mu m$

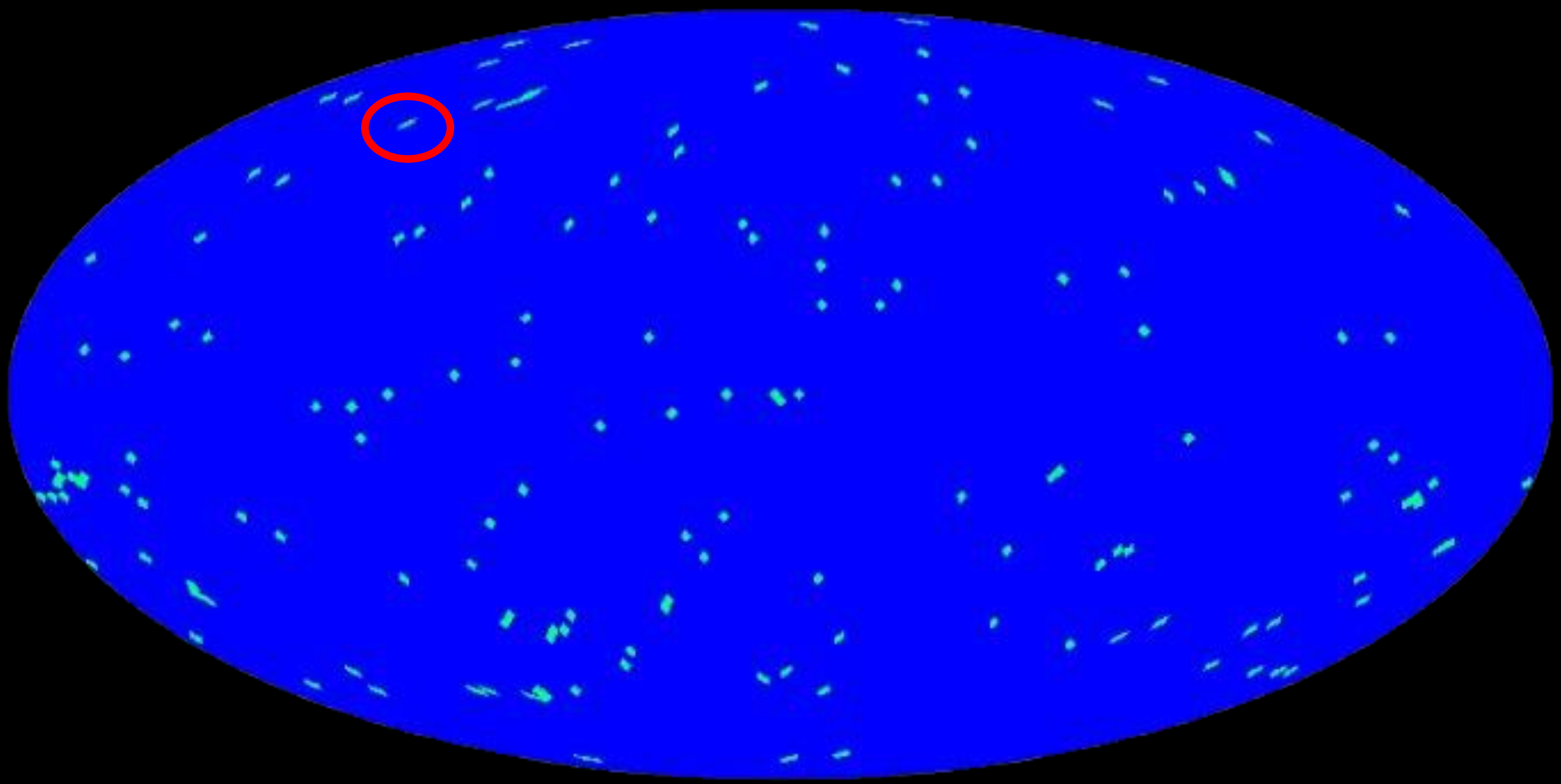
JWST collaboration

Observations

GN-z11

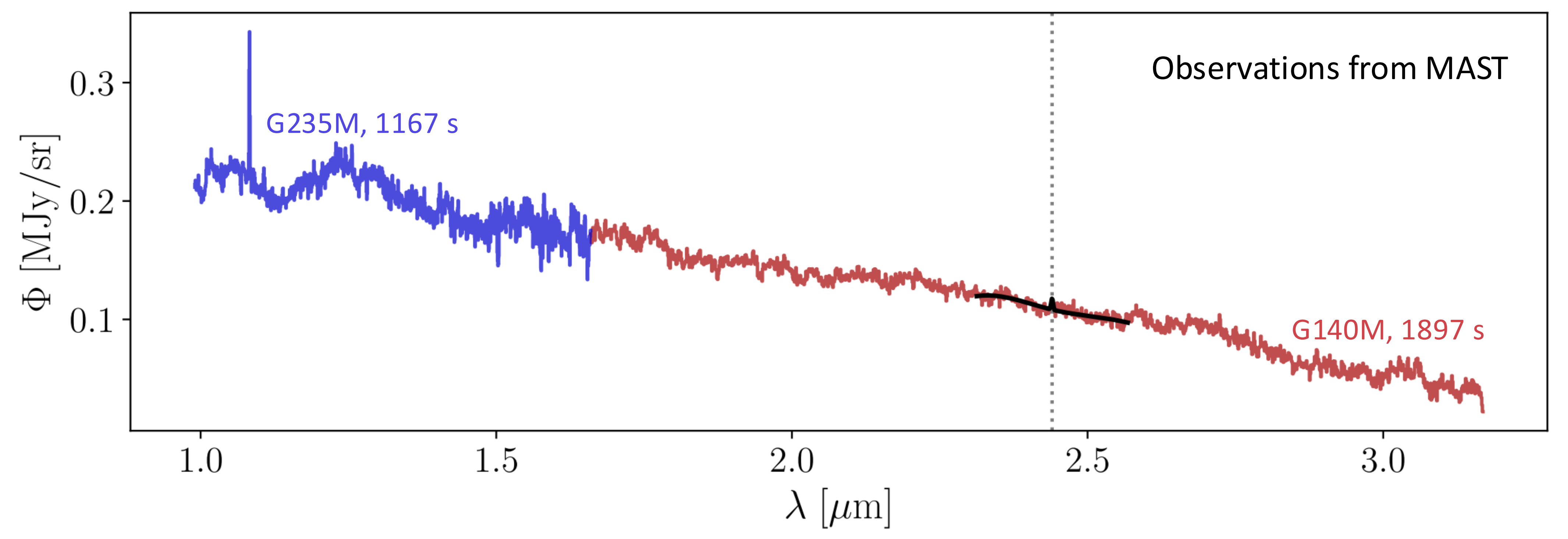
- High-redshift galaxy (z=10.6) in the constellation of Ursa Major
- Most distant known galaxy until 2022 (when JWST discovered JADES-GS-z13-0)
- Fun fact: Maiolino et al (2024) discovered that GN-z11 contains the most distant (aka earliest) black hole known in the Universe

GN-z11



- $(b, \ell) = (54.8°, 126°)$
- $D = 2.3 \times 10^{22}\ \mathrm{GeV/cm^2}$
- 2 observations: 1167s and 1897 s (less than 1h)

Blank-sky flux

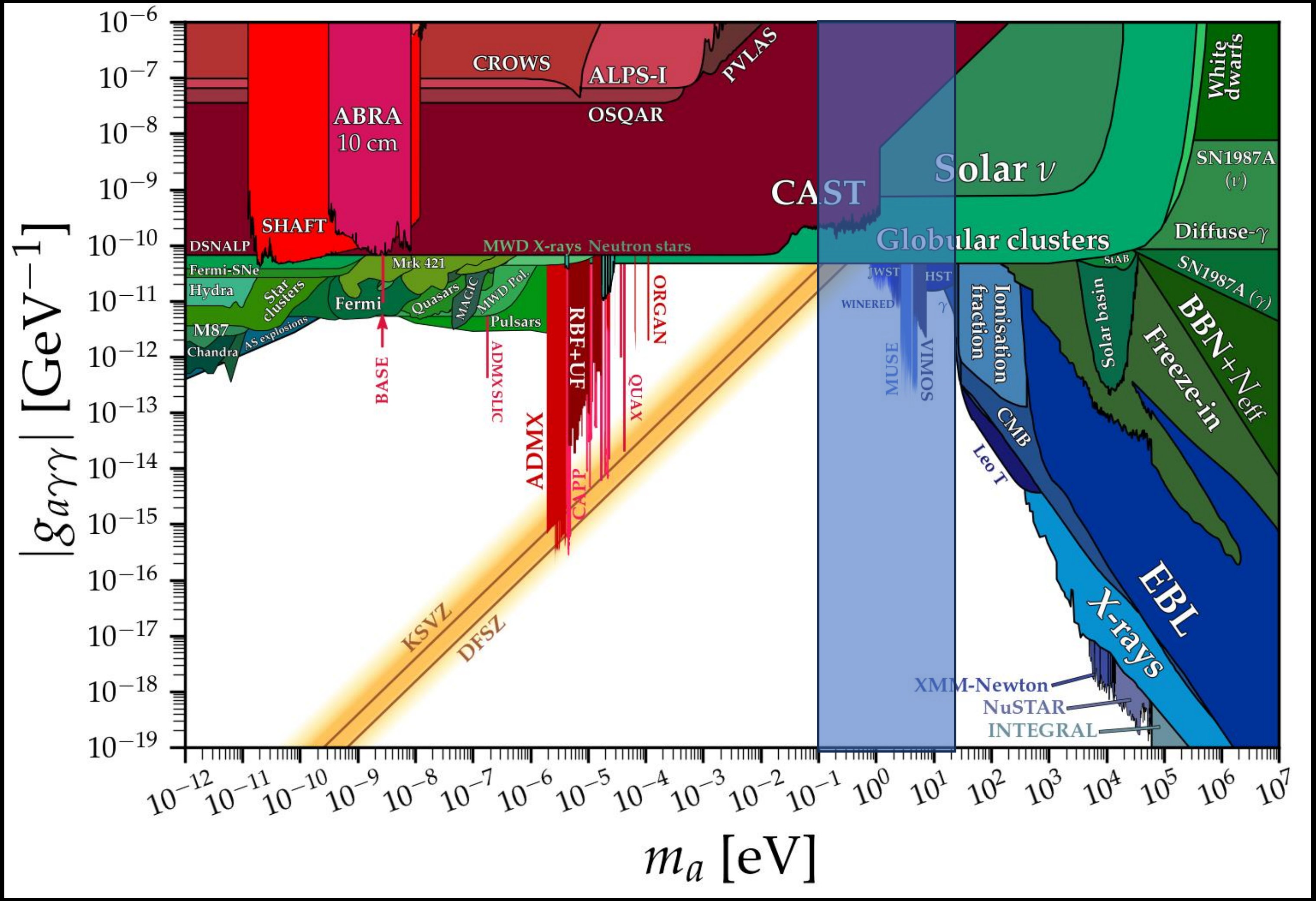


$m_a = 1\,\mathrm{eV}$ $\quad$ $g_{a\gamma\gamma} = 1.1 \times 10^{-11}\mathrm{GeV}^{-1}$

Janish & EP, arXiv:2310.15395, submitted to PRL

Dark matter bounds

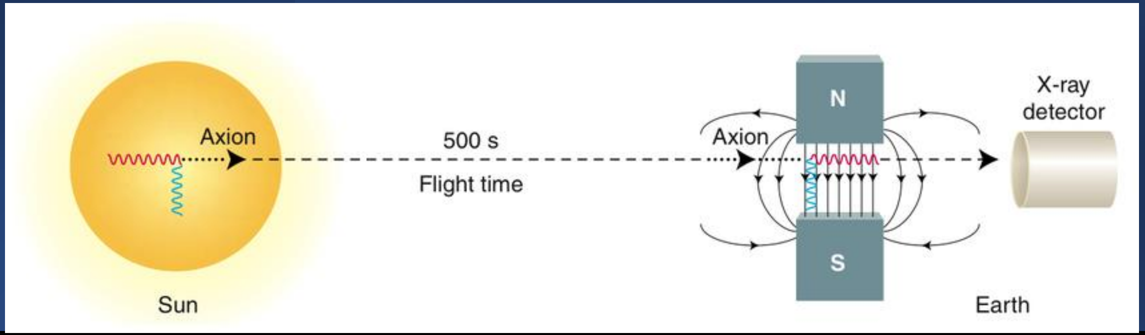
Bounds

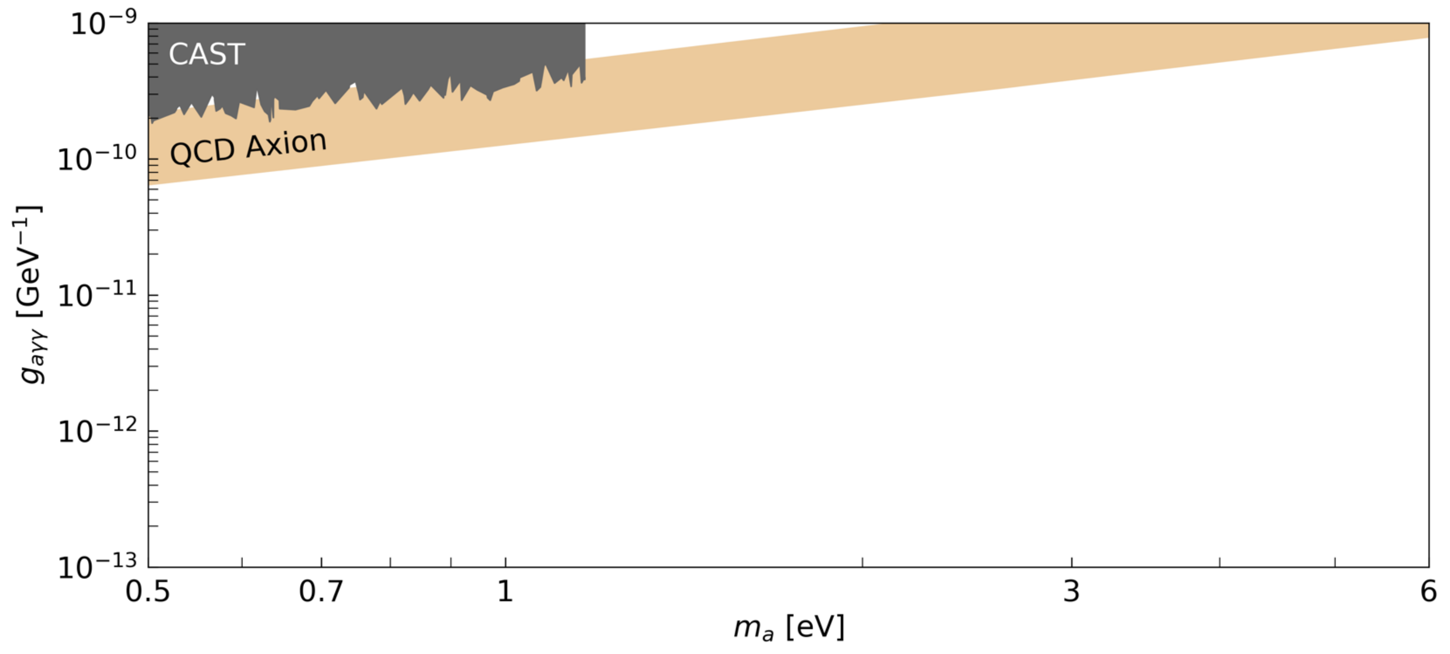


See Maurizio Giannotti's review

Credit: Ciaran O'Hare

CAST Bounds





CERN Axion Solar Telescope

Target: Sun → Conversion of photons in the Sun into axions due to EM fields (Primakoff effect)

CAST (Cern Axion Solar Telescope) use the reverse process of axion-photon conversion (magnetic telescope): solar axions may be converted into photons inside **B** (9 T)

Dark matter mass range: < 2 eV

CAST Collaboration, JCAP 04 (2007) 010,
CAST Collaboration, Nature Phys. 13 (2017)

Stellar cooling due to axions

Globular Clusters: Gravitationally bound systems of stars, among the oldest systems in the MW


Messier 2

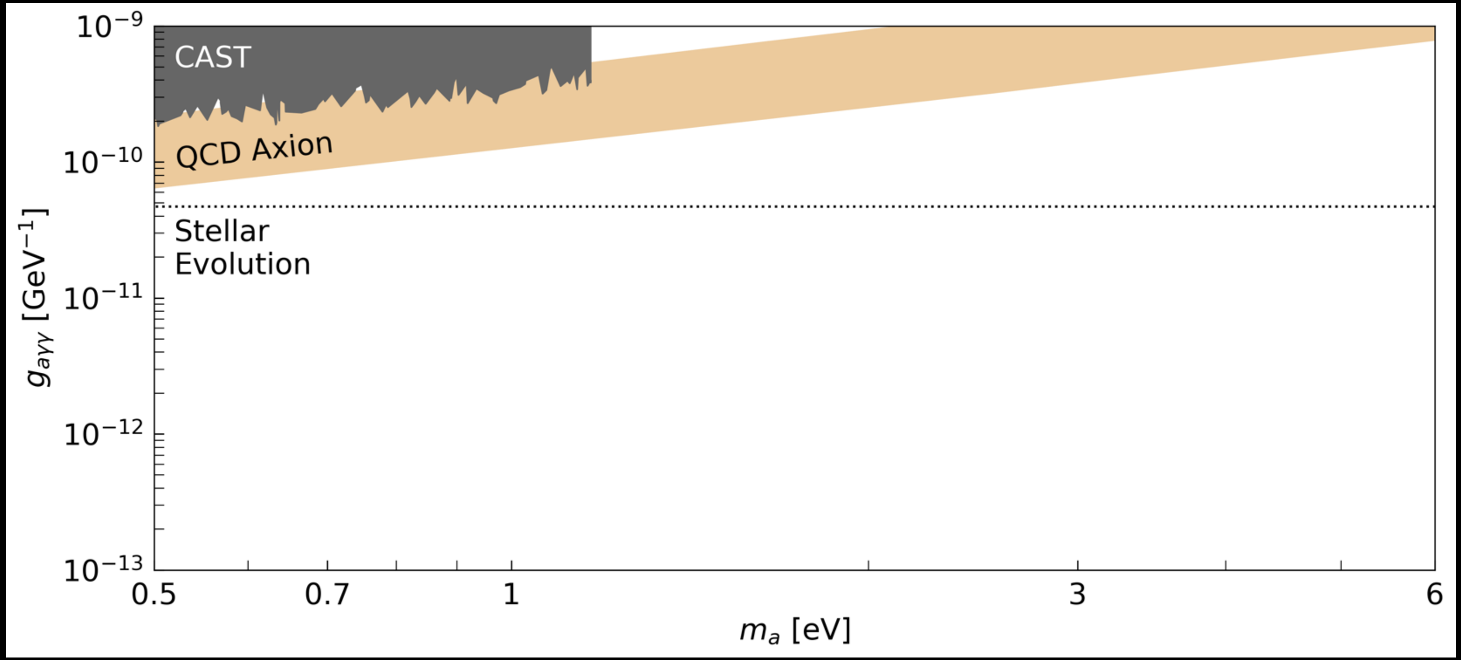
Axions could be produced in stellar interiors via the Primakoff process, freely escape and drain energy from its interior

Higher energy losses → Contractions → Nuclear burning

Higher rate of nuclear burning expedites the stellar evolution

Evolution phases: main sequence (core H burning), red-giant branch (RGB, H burning shell), horizontal branch (HR, core He burning), asymptotic giant branch (AGB, helium-burning shell)

Stellar Evolution Bounds



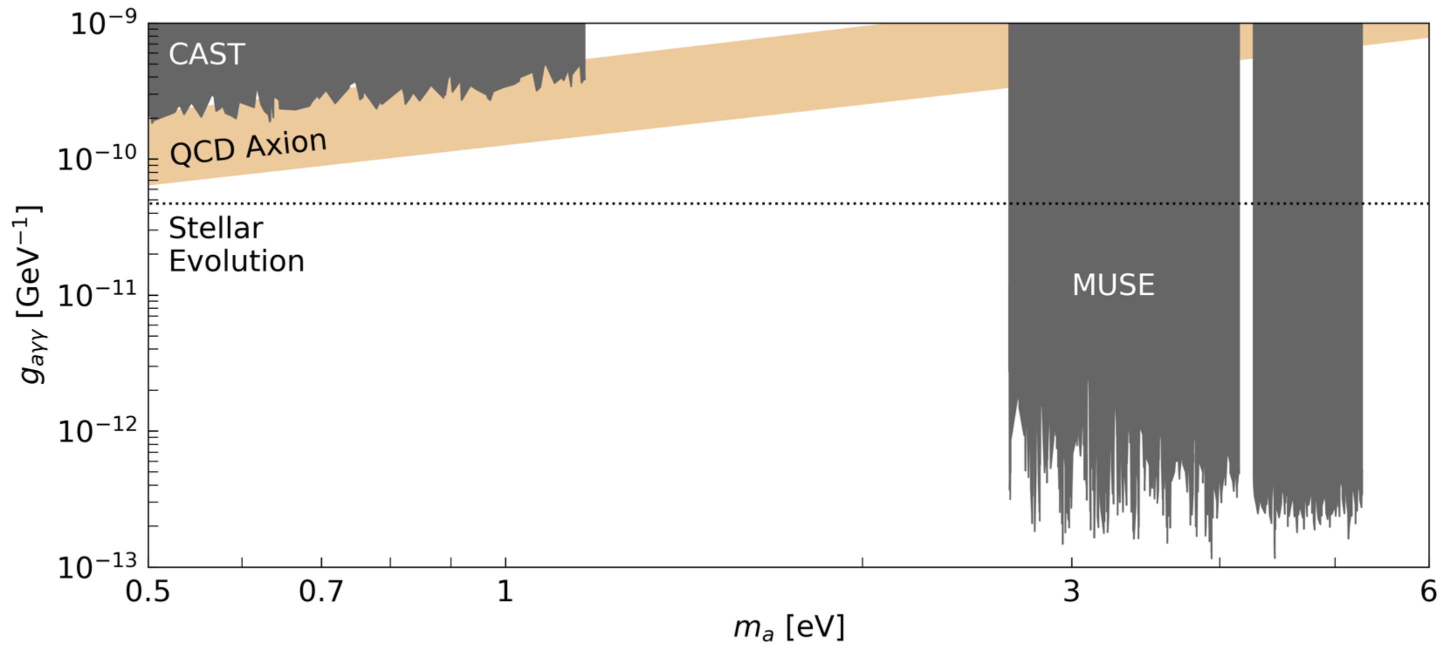
48 globular clusters observed with the Hubble Space Telescope

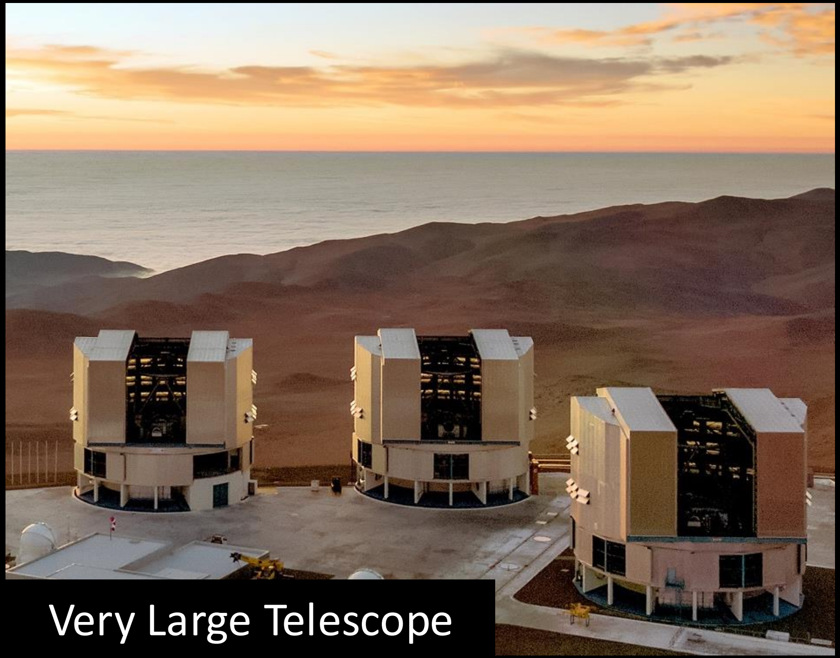
$k_B T_{core} = O(\text{keV}) \Longrightarrow$ if $m_a \ll k_B T_{core}$, the axion is massless from the star perspective

Dark matter mass range: < 10 keV

Ayala et al, PRL 113 (2014) 191302,
Dolan et al, JCAP 10 (2022) 096
Severino et al, APJ 943 (2023) 95

MUSE Bounds





Very Large Telescope

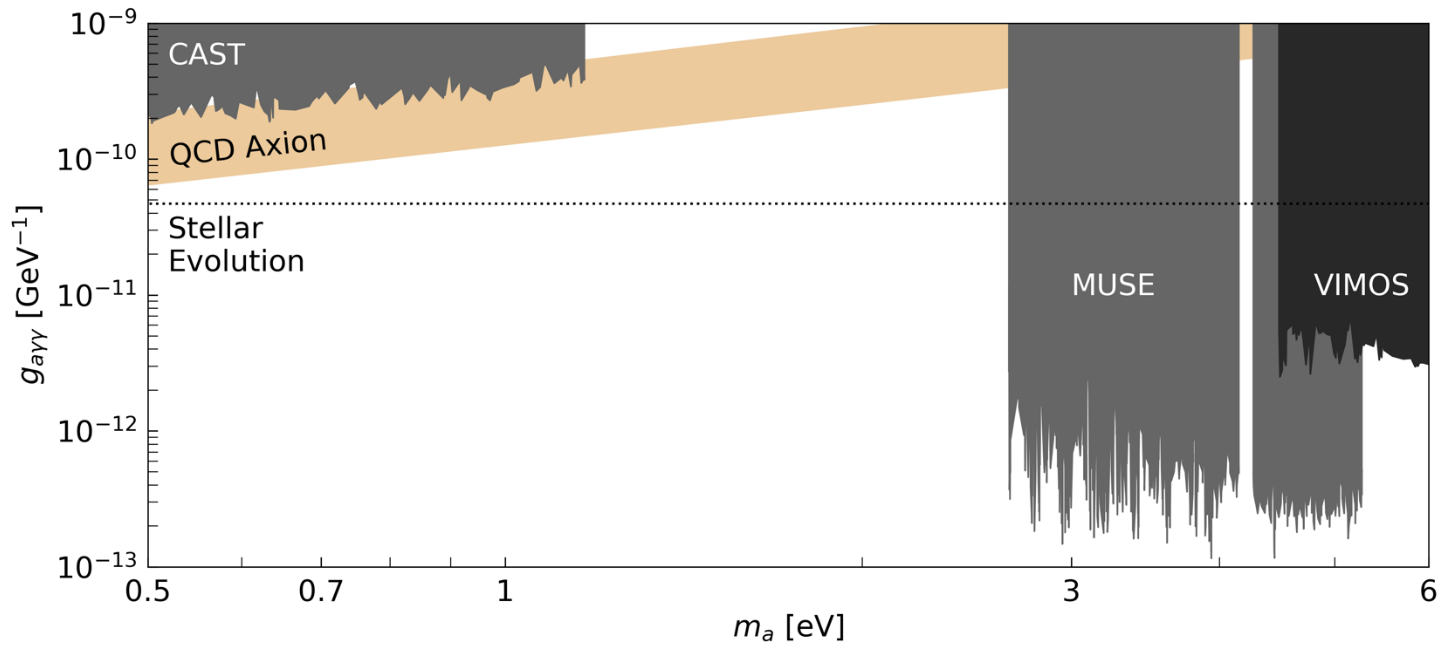
5 dwarf spheroidal galaxies: Leo T, Sculptor, Eridanus 2, Grus 1, Hydra II

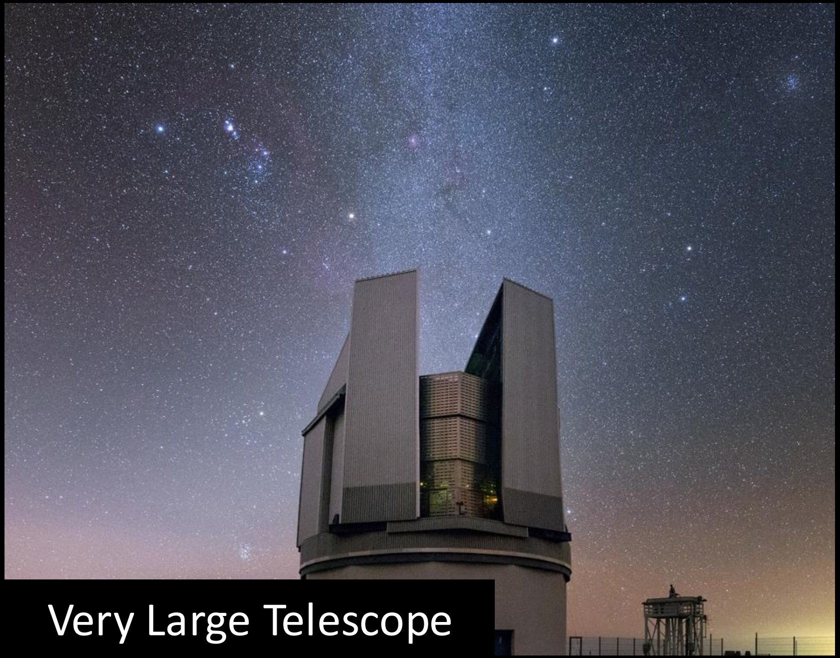
MUSE (Multi-Unit Spectroscopic Explorer) at the Very Large Telesocope: wavelength 4800 – 9350 Å, resolution 1.25 Å, observation time 3-22h

Dark matter mass range: 2.7-5.3 eV

Regis et al, Phys. Lett. B 814 (2021) 136075,
Todarello et al, arXiv:2307.07403

VIMOS Bounds




Very Large Telescope

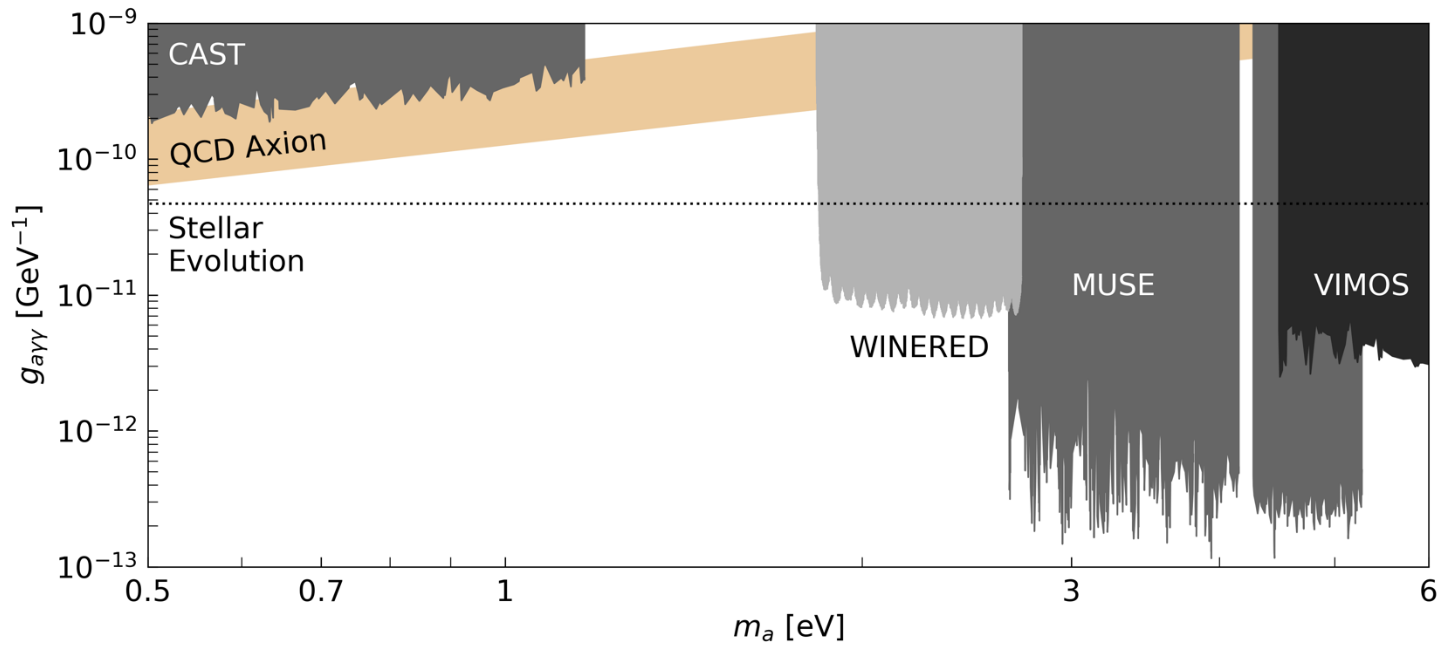
Target: Galaxy clusters Abell 2667 and 2390

VIMOS (Visible Multi-Object Spectrograph) at the Very Large Telescope: wavelength 3500 – 7000 Å, resolution 18 Å, exposure time 10.8ks

Dark matter mass range: 4.5-7.7 eV

Grin et al, Phys. Rev. D75 (2007) 105018

WINERED Bounds



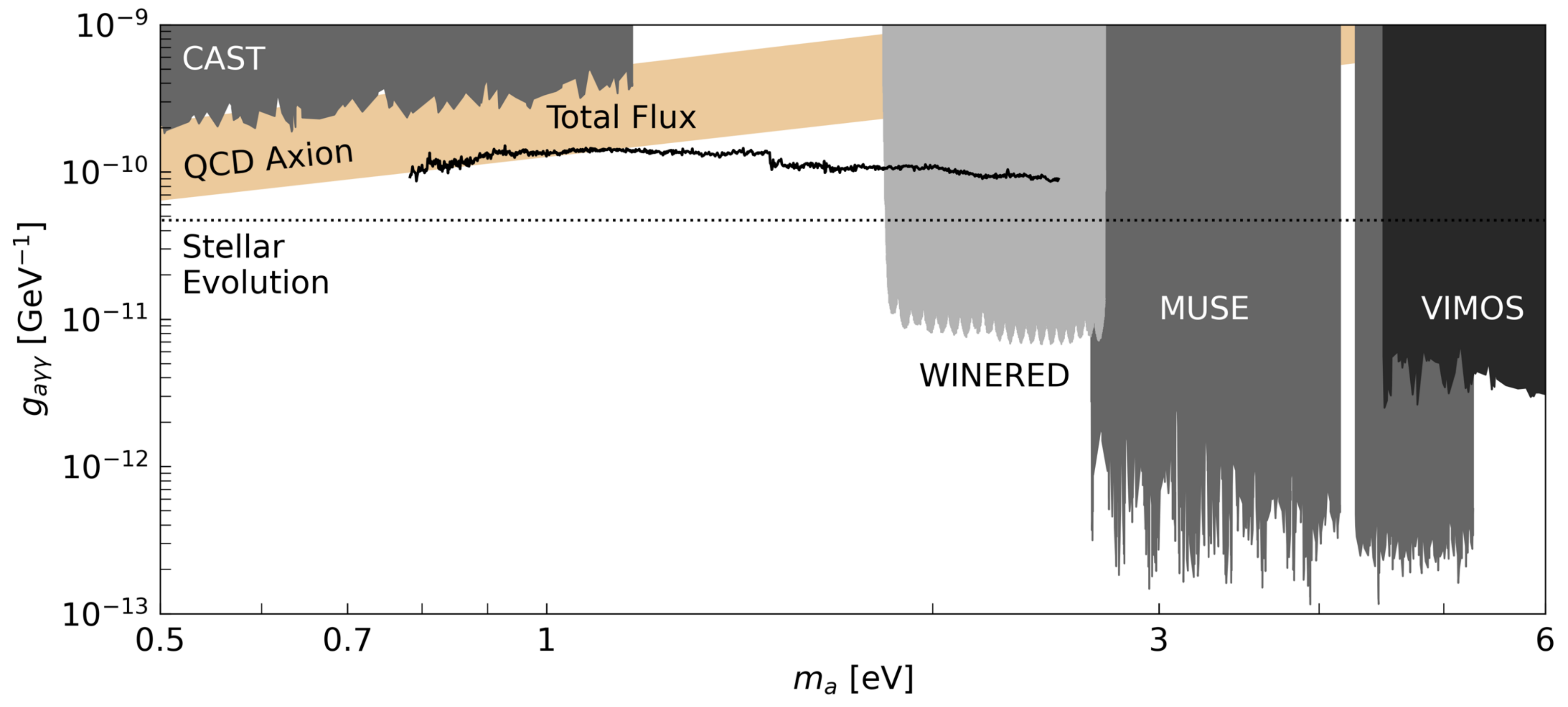
Target: Dwarf galaxies Leo V and Tucana II

WINERED (Warm Infrared Echelle spectrograph for Realizing Extreme Dispersion) at the Magellan Clay Telescope: 0.9 – 1.35 μm, R 28,000, exposure time 1hr and 1.2hr

Dark matter mass range: 1.8-2.7 eV

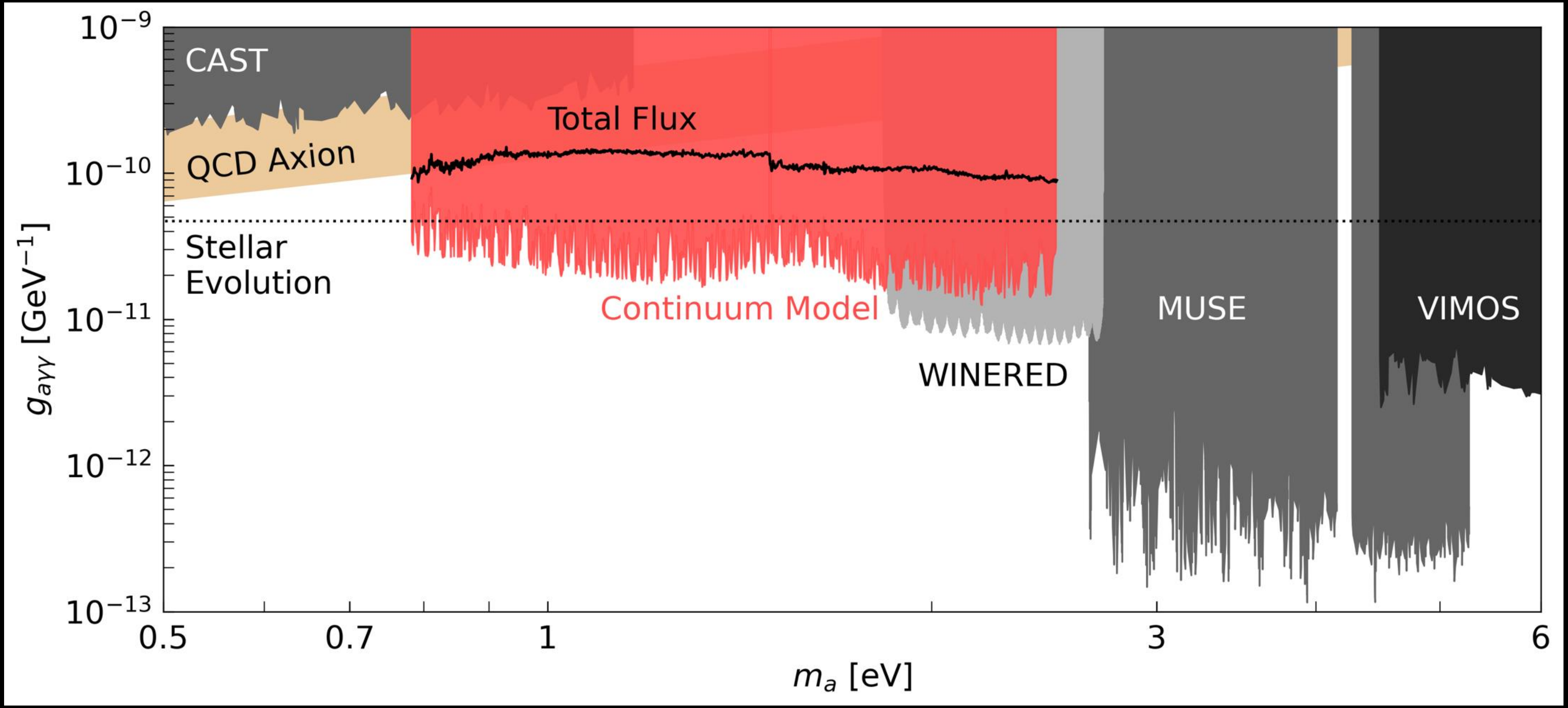
Yin et al, arXiv:2402.07976v1

JWST Bounds: Total Flux



Janish & **EP**, arXiv:2310.15395, submitted to PRL

JWST Bounds: Continuum Model



Janish & **EP**, arXiv:2310.15395, submitted to PRL

Decay lifetime

$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2\ m_a^3}{64\pi}$$

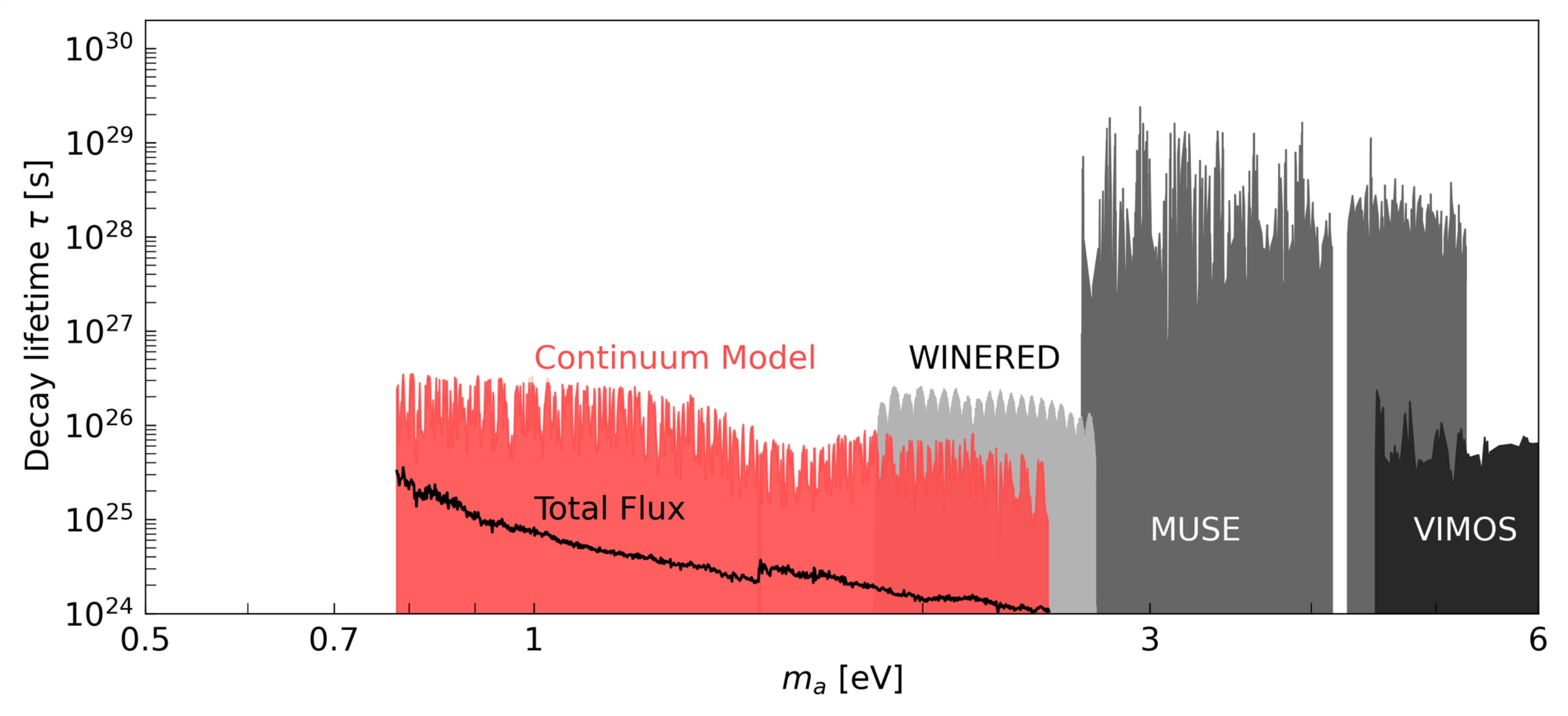
Emission rate

Axion mass

$$\tau_{a\to\gamma\gamma} = \frac{1}{\Gamma_{a\to\gamma\gamma}}$$

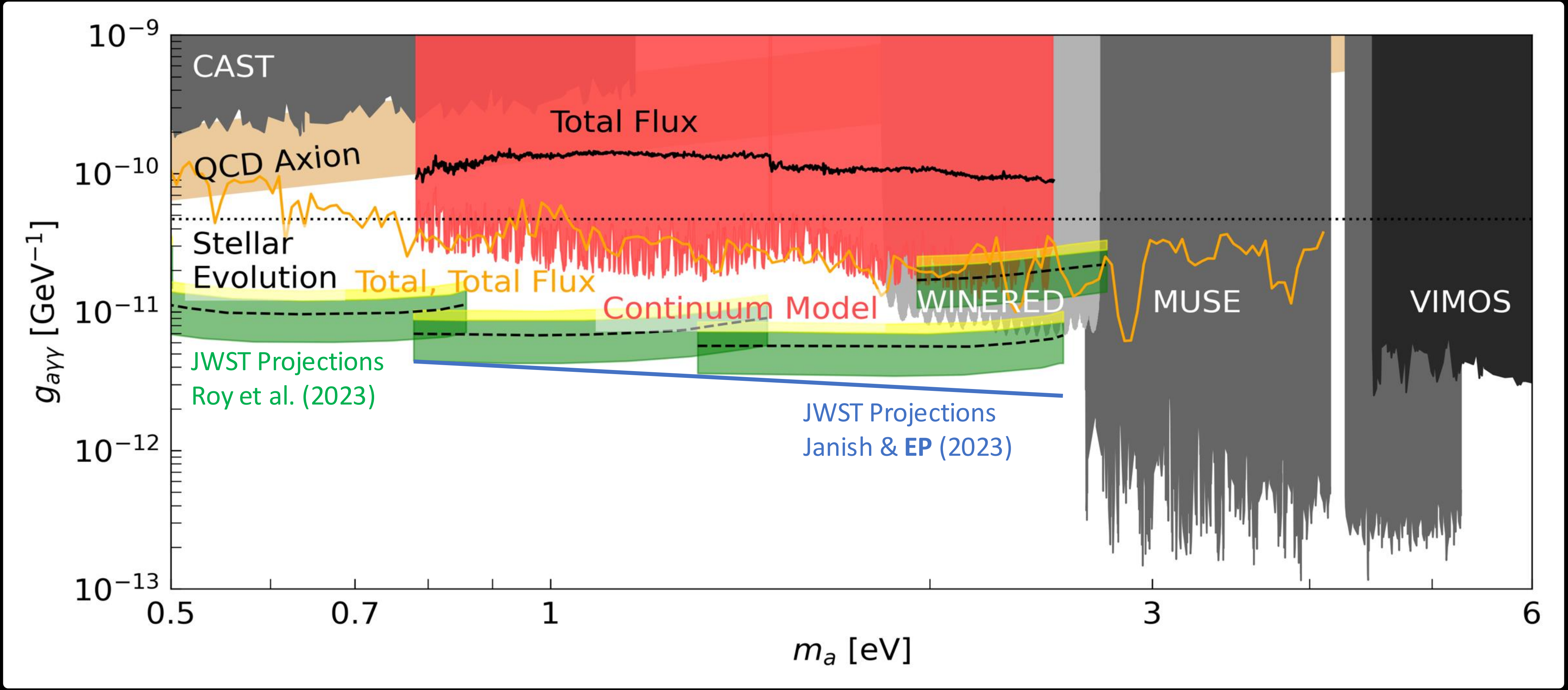
$$\left(5.5\times10^{-7}\,\mathrm{GeV}^{-1}\right)^2 \left(1\,\mathrm{eV}\right)^3$$

Bounds on the decay lifetime



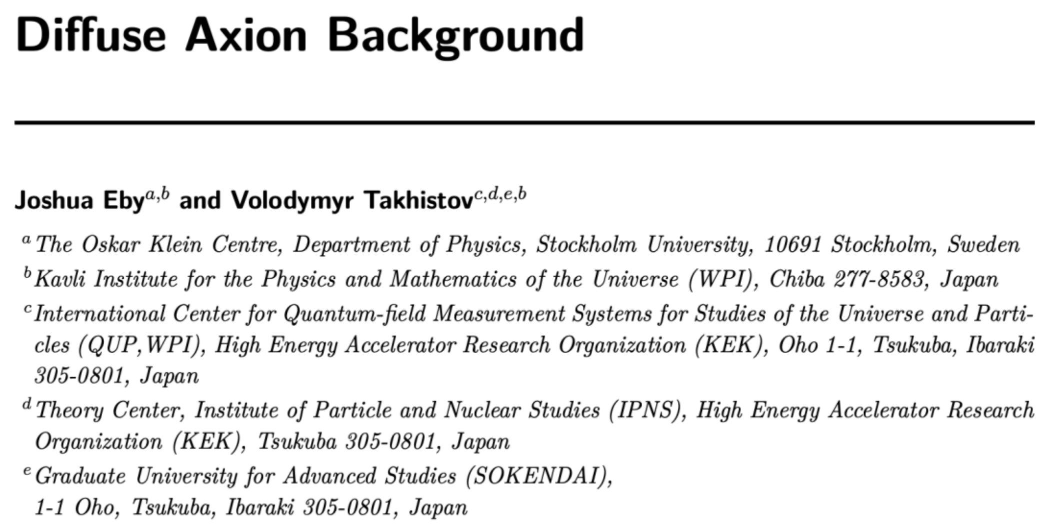
Janish & **EP**, arXiv:2310.15395, submitted to PRL

Projections for end-of-mission JWST



MORE IDEAS ON DARK MATTER SEARCHES WITH JWST

Diffuse axion background with JWST



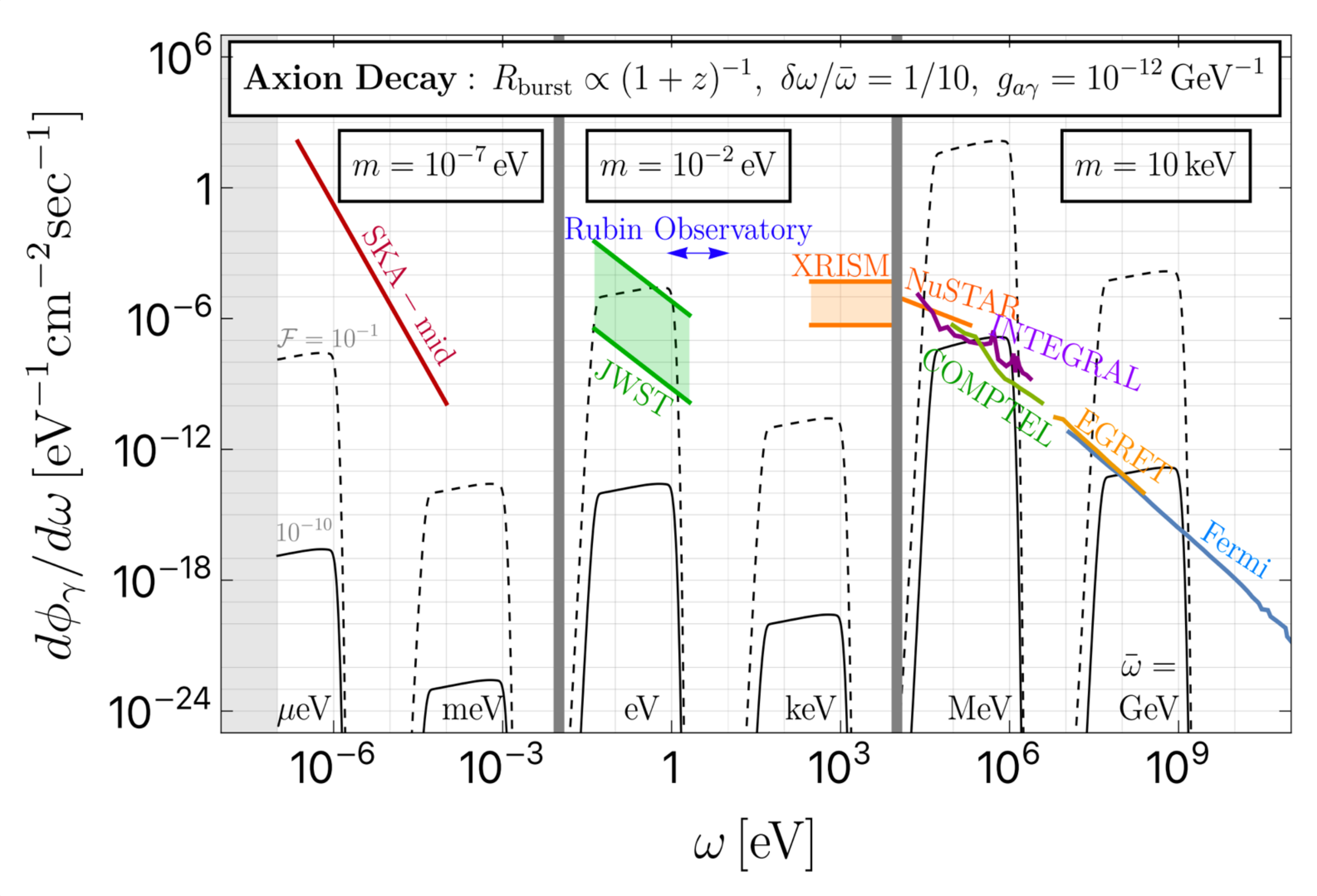
Diffuse Axion Background

Joshua Eby^{a,b} **and Volodymyr Takhistov**^{c,d,e,b}

[a] *The Oskar Klein Centre, Department of Physics, Stockholm University, 10691 Stockholm, Sweden*
[b] *Kavli Institute for the Physics and Mathematics of the Universe (WPI), Chiba 277-8583, Japan*
[c] *International Center for Quantum-field Measurement Systems for Studies of the Universe and Particles (QUP,WPI), High Energy Accelerator Research Organization (KEK), Oho 1-1, Tsukuba, Ibaraki 305-0801, Japan*
[d] *Theory Center, Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*
[e] *Graduate University for Advanced Studies (SOKENDAI), 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*

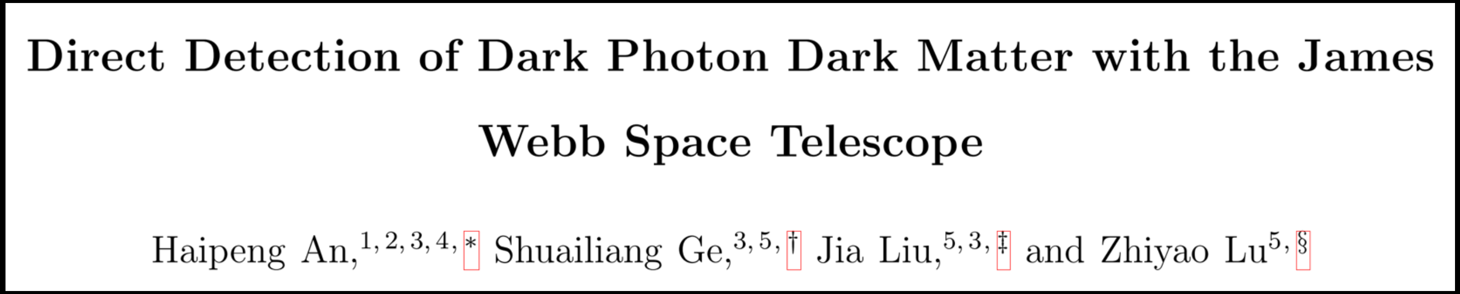
Main idea: relativistic axions can be produced in transient sources (e.g. supernovae and mergers of neutron stars) and then decay/convert into photons

Multi-wavelength analysis to probe a wide range of axions masses with present and future telescopes (including JWST)



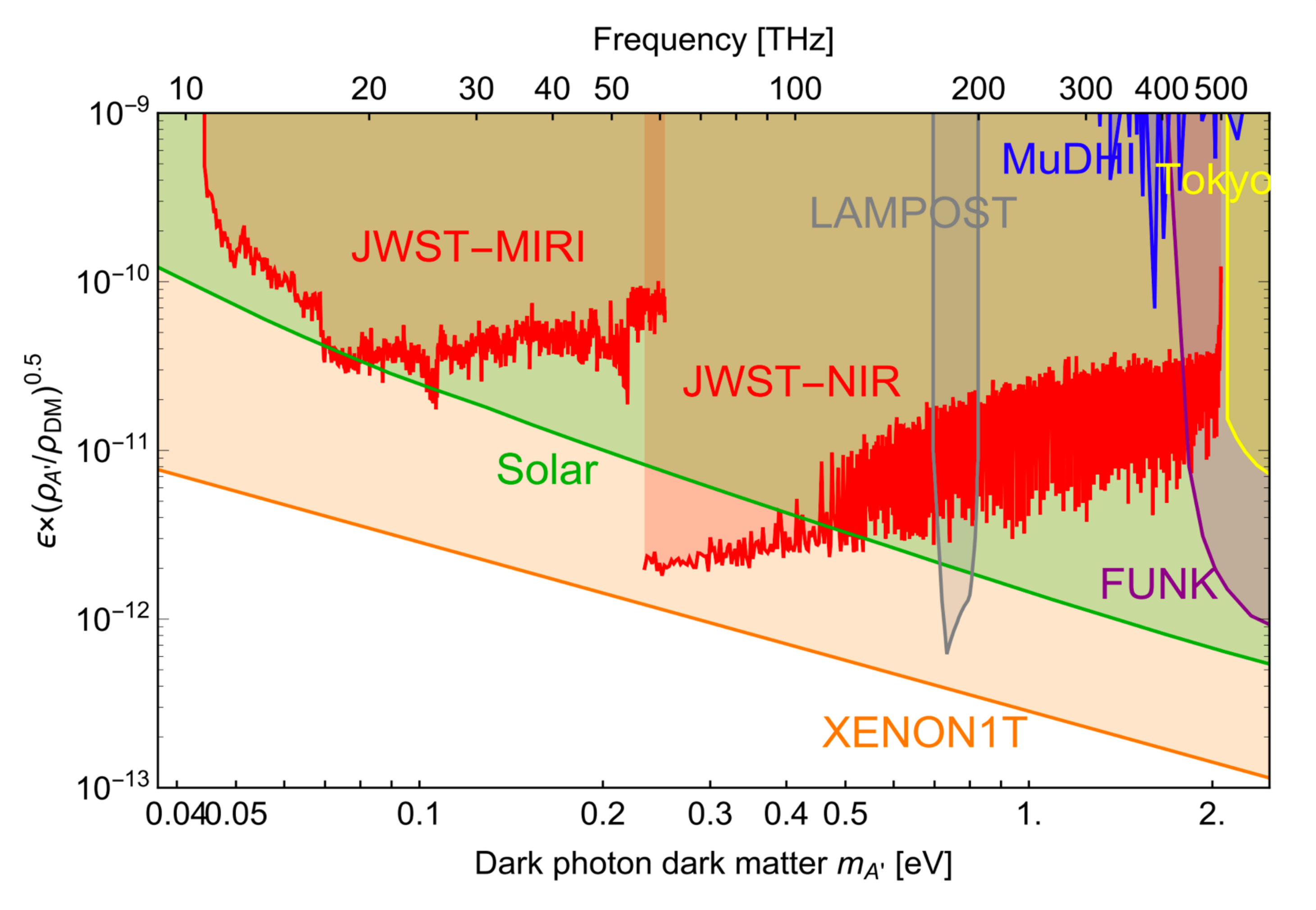
Eby & Takhistov, arXiv:2402.00100v2

Dark photon with JWST



Direct Detection of Dark Photon Dark Matter with the James Webb Space Telescope

Haipeng An,[1, 2, 3, 4, *] Shuailiang Ge,[3, 5, †] Jia Liu,[5, 3, ‡] and Zhiyao Lu[5, §]



An et al, arXiv:2402.17140

Exoplanets as dark matter detectors

Target: Exoplanets (planets outside the solar systems)

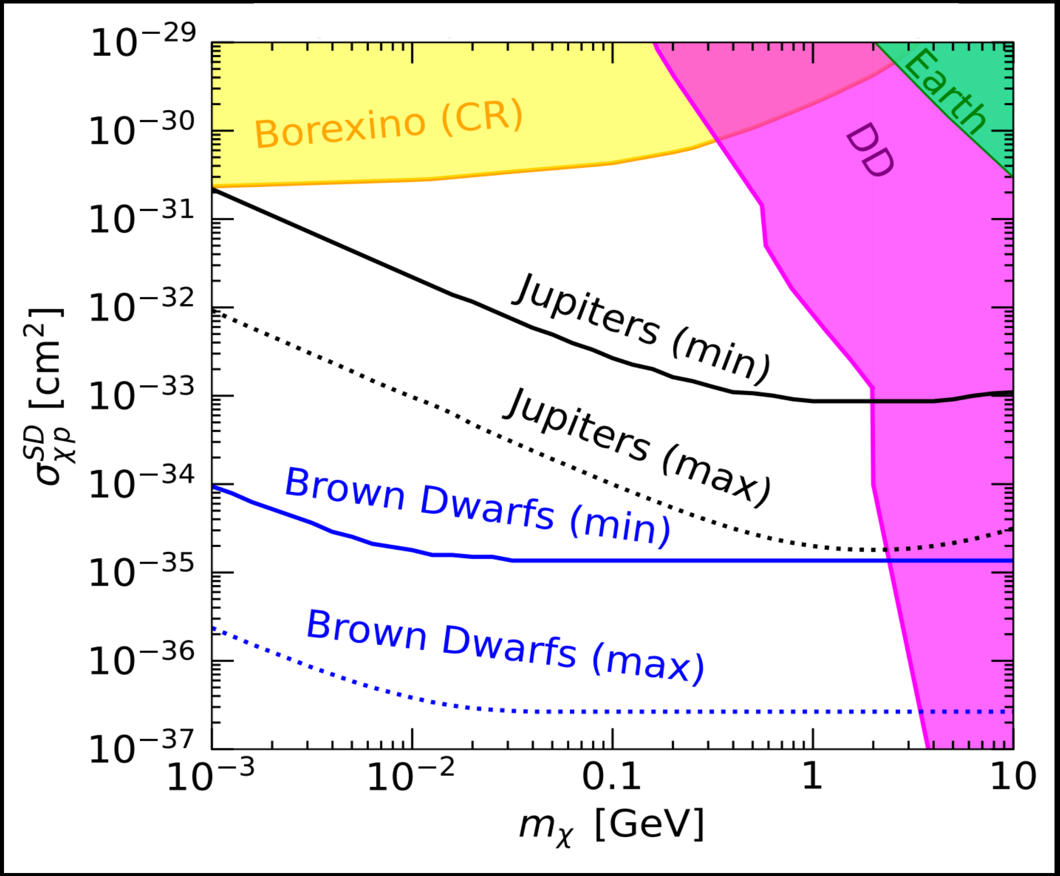
Main idea: dark matter can scatter with nucleons in the exoplanets and become gravitationally captured by the exoplanet. The captured dark matter accumulates, annihilates and heats exoplanets.

Exoplanets can be very cold (T ~ 100 K , i.e. infrared) → Low temperatures allows for a clearer signal over background for dark matter heating

5000+ exoplanets discovered (mostly discovered in the past decade)

Estimated 300 billion exoplanets in our Galaxy

Best telescopes: JWST, Roman Telescope, Rubin Telescope/LSST



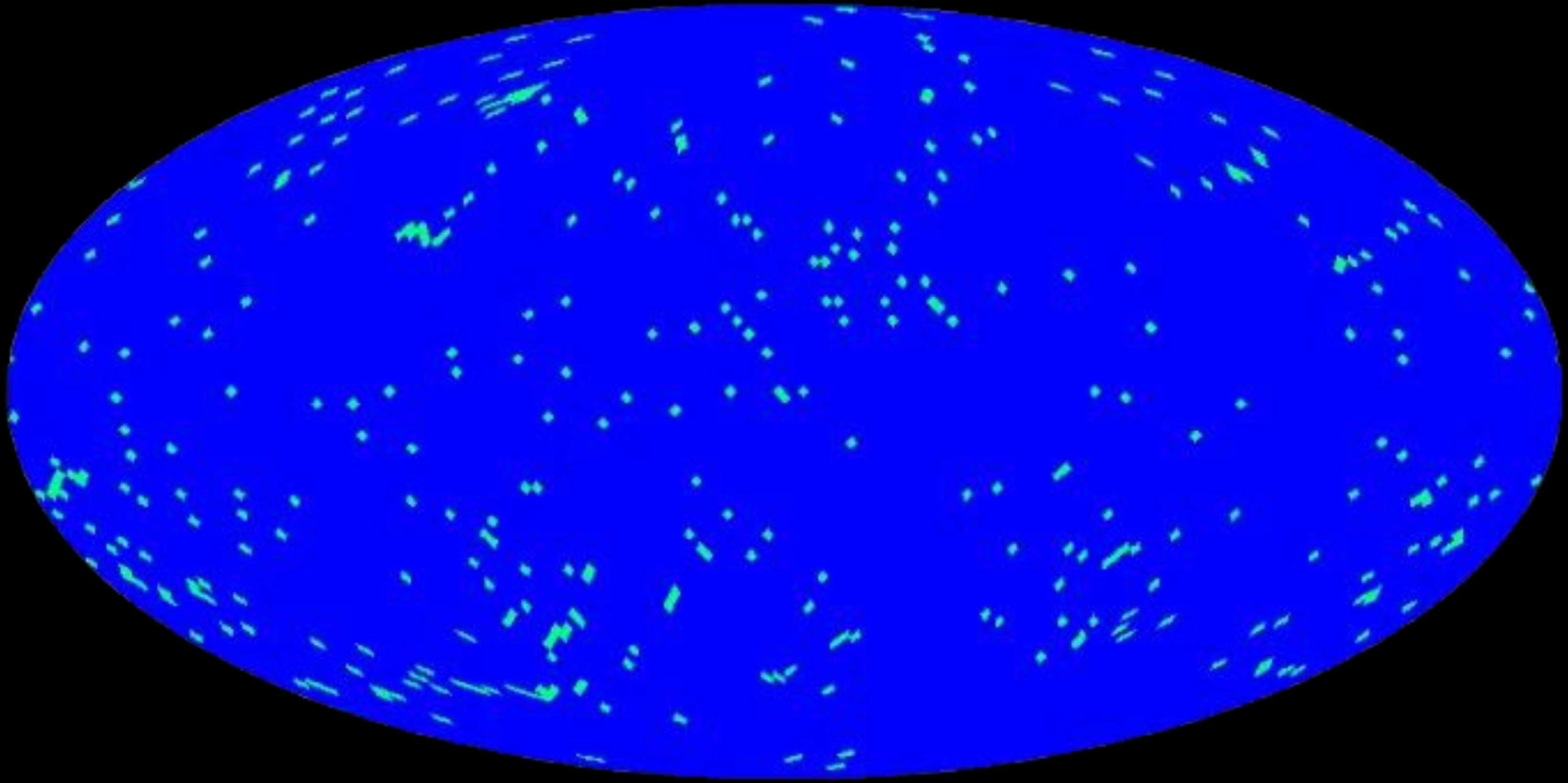
Leane & Smirnov, arXiv:2010.00015

Acevedo et al, arXiv:2405.02393

Leane & Tong, arXiv:2405.05312

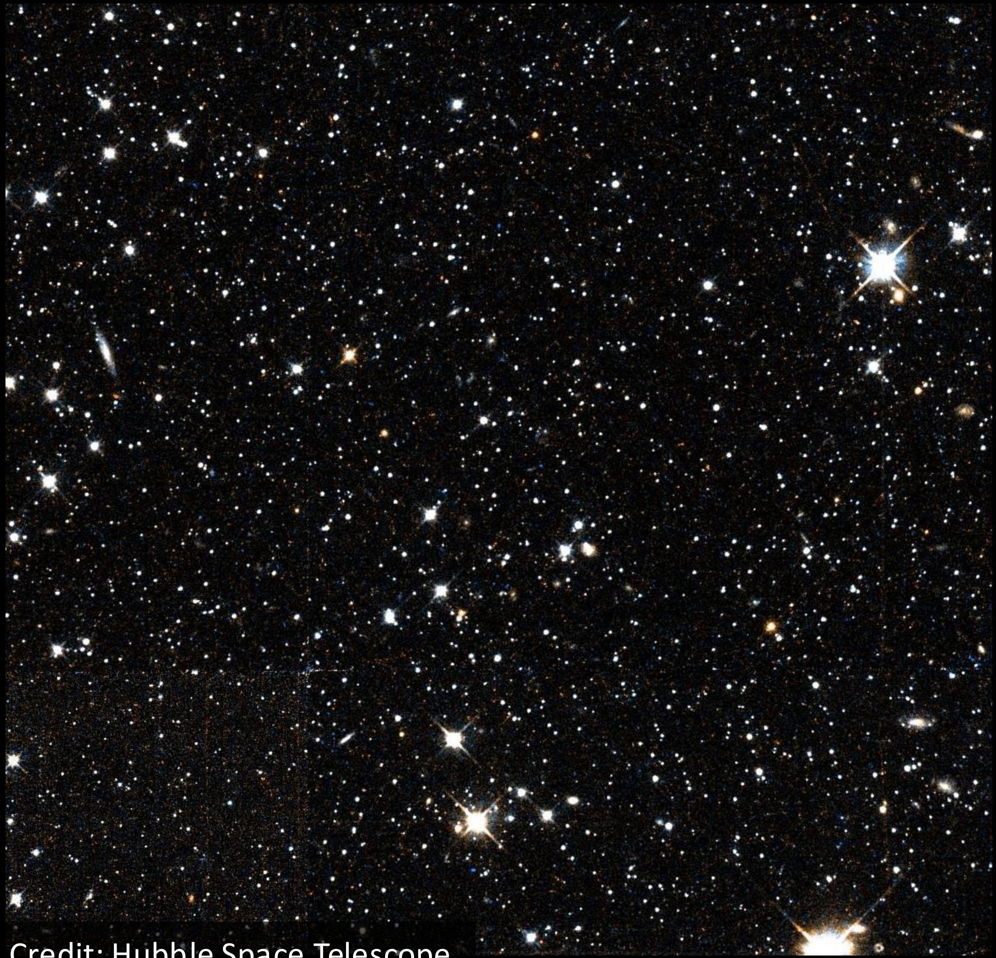
An eye toward the future

More JWST observations



- 900+ targets
- Both NIRSPEC and MIRI
- More statistics & Better targets

Observations with EMIR+


Credit: Hubble Space Telescope

Multi-object medium-resolution spectrograph and wide-field imager

Wavelength: near-infrared (0.9-2.5 μm)

Location: Roque de los Muchachos Observatory (La Palma, Canary Islands)

Target: Draco/Coma Berenice dwarf galaxy

Data taking expected in September

IAC collaborators: Jorge Terol Calvo, Jorge Camalich, and Francisco Garzon Lopez

Infrared & Optical observations

Infrared observations: Spitzer, KECK, Herschel, …

Optical observations: HST, VLT, DESI, HETDEX…

Summary & Conclusions

① Infrared observations from different targets are a powerful way to probe dark matter

② With JWST, we derive competitive bounds on eV-scale dark matter

③ Numerous observations are already available and more data are on their way: This is just the beginning!

Summary & Conclusions

Thank you for your attention!

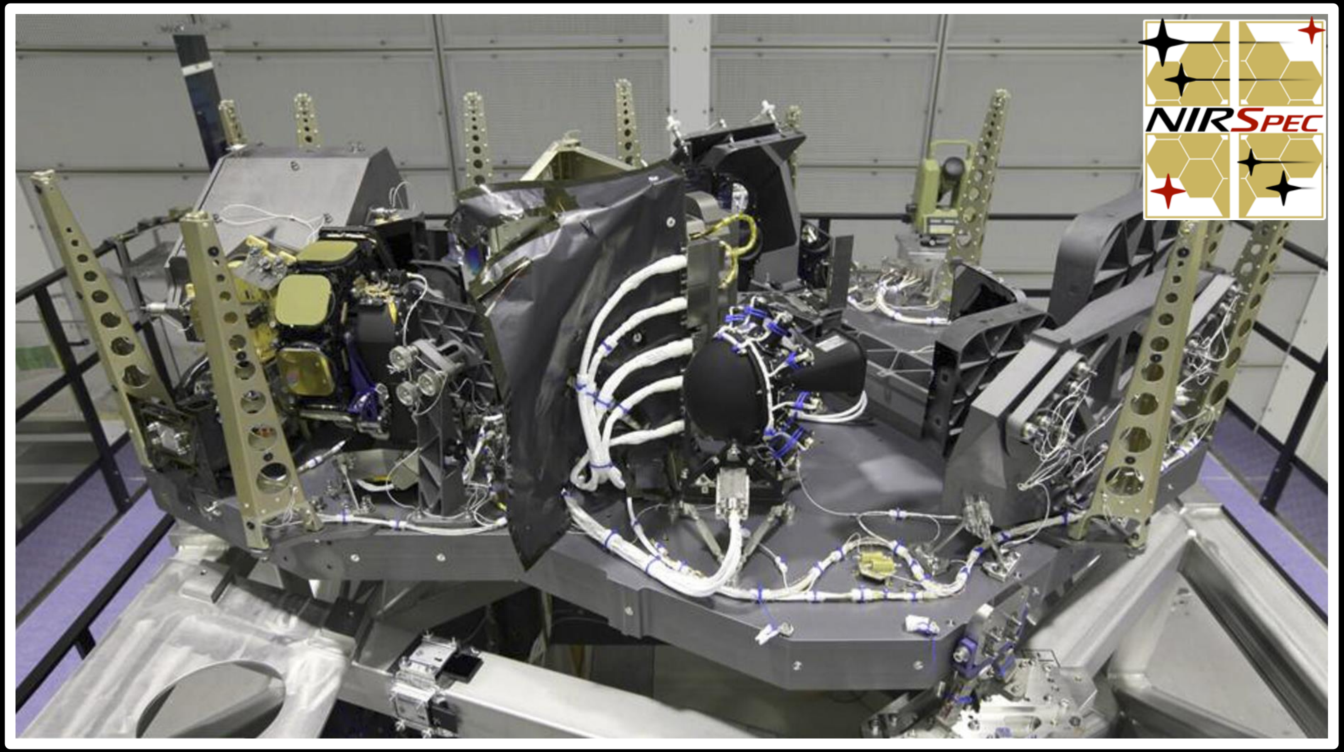
① Infrared observations from different targets are a powerful way to probe dark matter

② With JWST, we derive competitive bounds on eV-scale dark matter

③ Numerous observations are already available and more data are on their way: This is just the beginning!

Back-up slides

NIRSPEC



NIRSpec: Near Infrared Spectrograph

$$\Delta\lambda = 0.6 - 5\ \mu m$$

Three observing modes:

- Low-resolution mode using a prism
- R~1000 multi-object mode
- R~2700 integral field unit

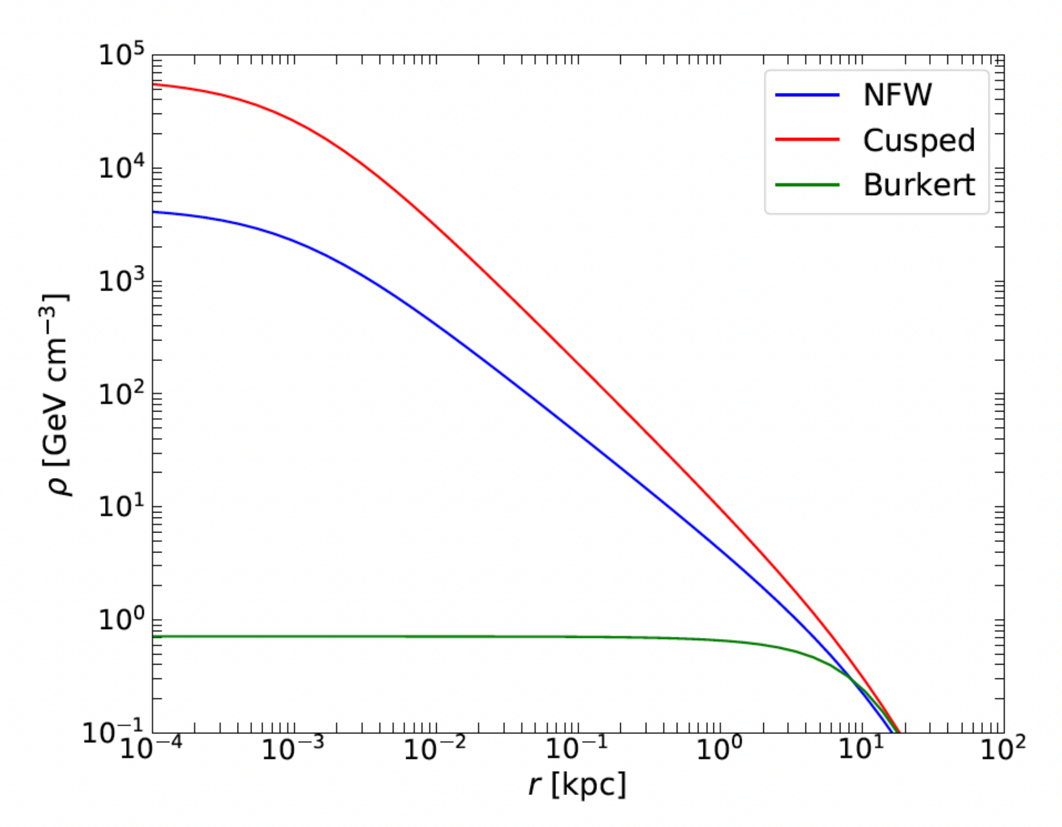
D-factor

$$D(\theta) = \int_0^\infty ds\, \rho\big(r(s,\theta)\big)$$

$$\rho(r) = \frac{\rho_s}{\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)}$$ NFW profile

$$\rho_s = 0.18\ \mathrm{GeV/cm^3}$$

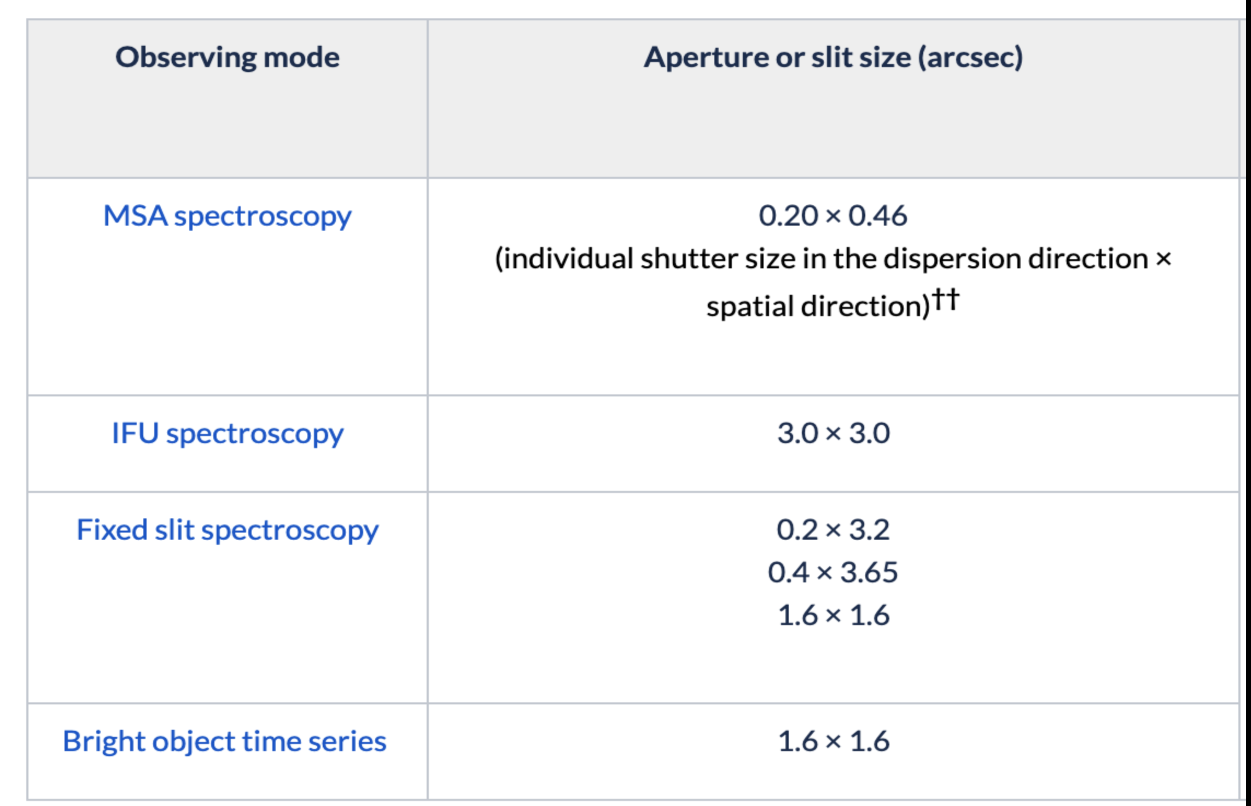
$$r_s = 24\ \mathrm{kpc}$$



NIRSPEC

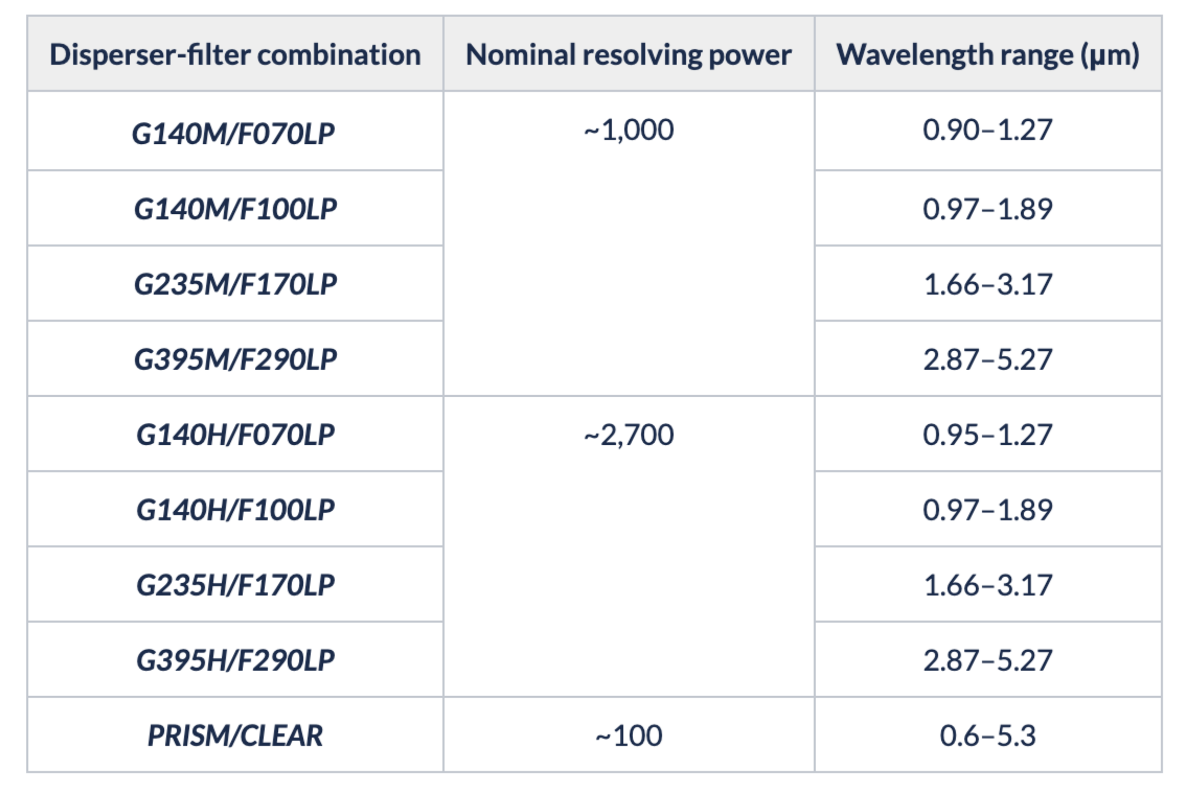
NIRSpec: Near Infrared Spectrograph

$$\Delta\lambda = 0.6 - 5.3\ \mu m$$



Observing mode	Aperture or slit size (arcsec)
MSA spectroscopy	0.20 × 0.46 (individual shutter size in the dispersion direction × spatial direction)††
IFU spectroscopy	3.0 × 3.0
Fixed slit spectroscopy	0.2 × 3.2 0.4 × 3.65 1.6 × 1.6
Bright object time series	1.6 × 1.6

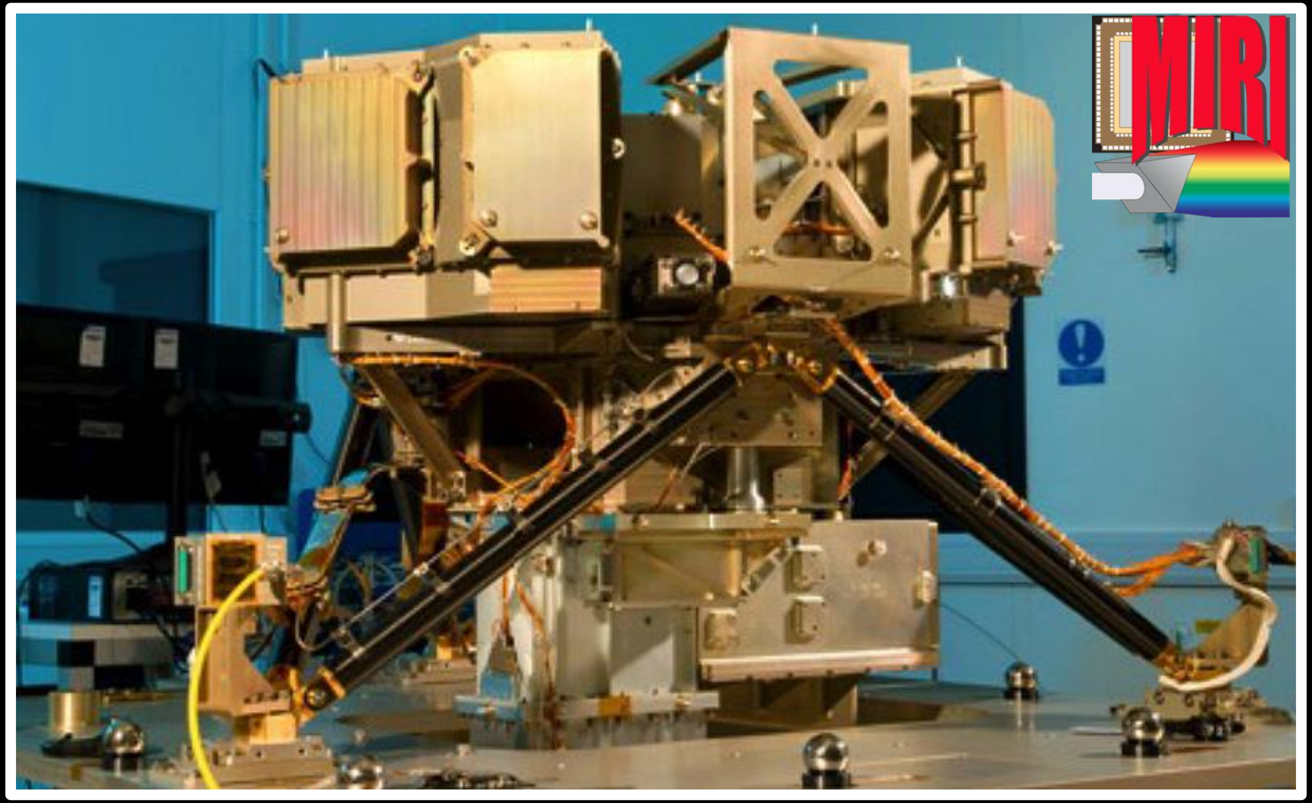
https://jwst-docs.stsci.edu/jwst-near-infrared-spectrograph#gsc.tab=0



Disperser-filter combination	Nominal resolving power	Wavelength range (μm)
G140M/F070LP	~1,000	0.90–1.27
G140M/F100LP		0.97–1.89
G235M/F170LP		1.66–3.17
G395M/F290LP		2.87–5.27
G140H/F070LP	~2,700	0.95–1.27
G140H/F100LP		0.97–1.89
G235H/F170LP		1.66–3.17
G395H/F290LP		2.87–5.27
PRISM/CLEAR	~100	0.6–5.3

https://jwst-docs.stsci.edu/jwst-near-infrared-spectrograph/nirspec-observing-modes/nirspec-ifu-spectroscopy#gsc.tab=0

MIRI



MIRI: Mid-Infrared Instrument

$\Delta\lambda = 4.9 - 27.9\ \mu m$

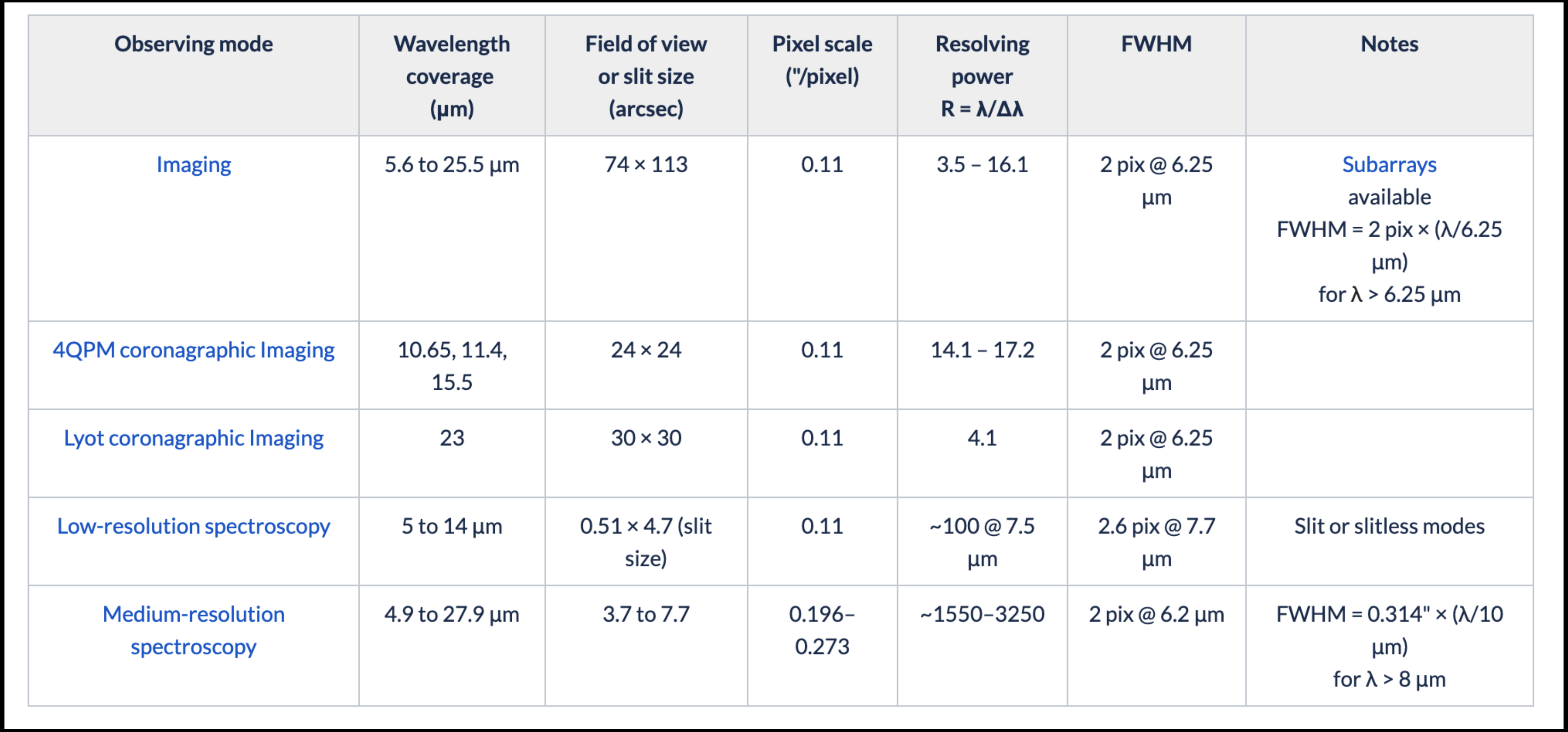
Four observing modes:

- Imaging
- 4QPM coronographic imaging
- Low-resolution slitted and slitless spectroscopy
- Medium-resolution integral field unit spectroscopy

MIRI

MIRI: Mid-Infrared Instrument

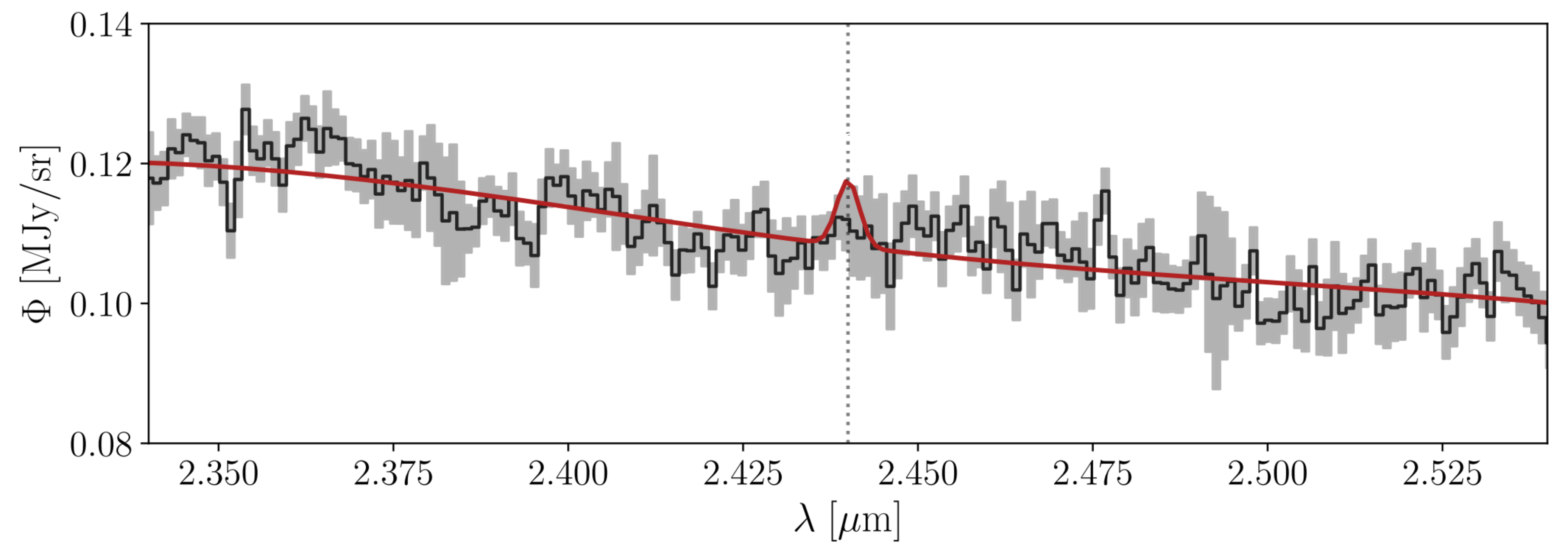
$$\Delta\lambda = 4.9 - 27.9\ \mu m$$



Observing mode	Wavelength coverage (µm)	Field of view or slit size (arcsec)	Pixel scale ("/pixel)	Resolving power R = λ/Δλ	FWHM	Notes
Imaging	5.6 to 25.5 µm	74 × 113	0.11	3.5 – 16.1	2 pix @ 6.25 µm	Subarrays available FWHM = 2 pix × (λ/6.25 µm) for λ > 6.25 µm
4QPM coronagraphic Imaging	10.65, 11.4, 15.5	24 × 24	0.11	14.1 – 17.2	2 pix @ 6.25 µm	
Lyot coronagraphic Imaging	23	30 × 30	0.11	4.1	2 pix @ 6.25 µm	
Low-resolution spectroscopy	5 to 14 µm	0.51 × 4.7 (slit size)	0.11	~100 @ 7.5 µm	2.6 pix @ 7.7 µm	Slit or slitless modes
Medium-resolution spectroscopy	4.9 to 27.9 µm	3.7 to 7.7	0.196–0.273	~1550–3250	2 pix @ 6.2 µm	FWHM = 0.314" × (λ/10 µm) for λ > 8 µm

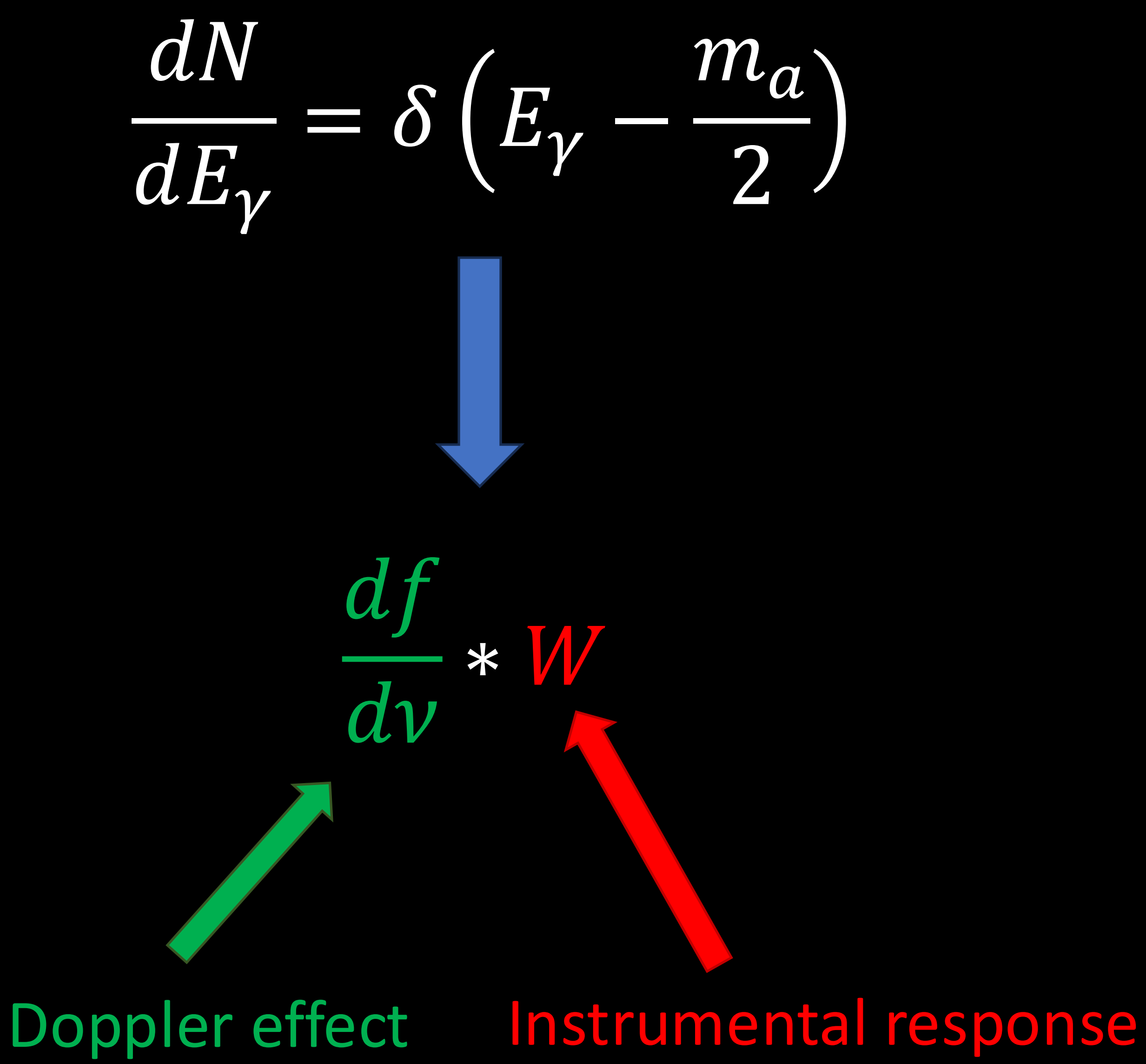
https://jwst-docs.stsci.edu/jwst-mid-infrared-instrument#gsc.tab=0

Blank-sky flux + dark matter



$m_a = 1\ \mathrm{eV}$ $\qquad g_{a\gamma\gamma} = 1.1 \times 10^{-11} \mathrm{GeV}^{-1}$

Photon emission spectrum



$$\frac{dN}{dE_\gamma} = \delta\left(E_\gamma - \frac{m_a}{2}\right)$$

$$\frac{df}{d\nu} * W$$

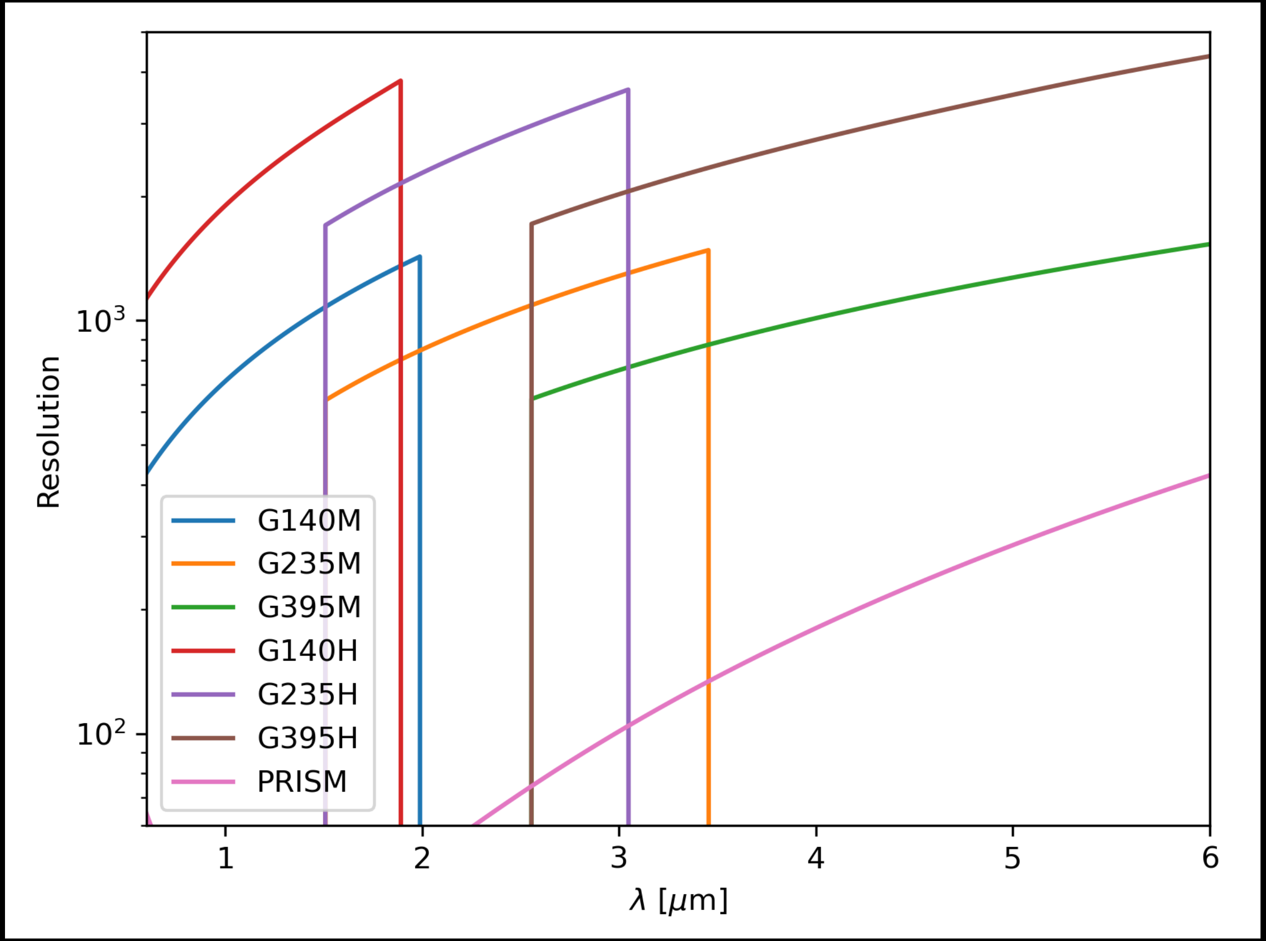
Doppler effect

Instrumental response

Instrumental response function

$$W(\lambda) = \frac{1}{\sqrt{2\pi\sigma_\lambda^2}} e^{-\lambda^2/2\sigma_\lambda^2}$$

$$\sigma_\lambda = \frac{\Delta\lambda}{2\sqrt{2\ln 2}}$$



Spectral resolution

$$W(\lambda) = \frac{1}{\sqrt{2\pi\sigma_\lambda^2}} e^{-\lambda^2/2\sigma_\lambda^2}$$

$$\sigma_\lambda = \frac{\Delta\lambda}{2\sqrt{2\ln 2}}$$

Doppler effect

$$\frac{df}{dv} = \frac{v}{2v_0^2} \int \frac{f(v)}{v} dv$$

$$f(v) = \frac{4\pi v^2}{(2\pi\sigma_v^2)^{3/2}} e^{-v^2/2\sigma_v^2}$$

$$\sigma_v = 160\ km/s$$

Evans et al, PRD 99 (2019) 023012