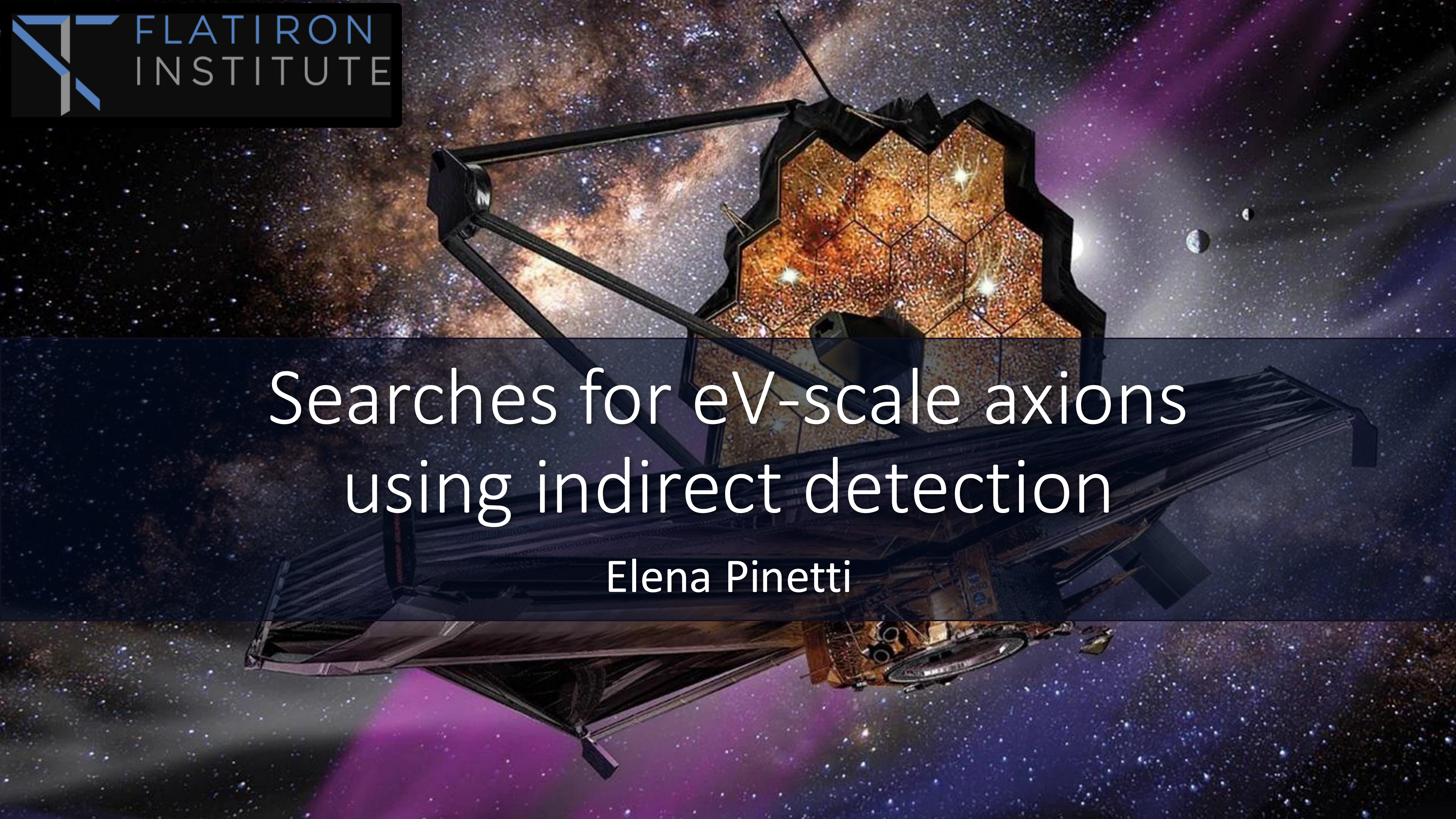


FLATIRON INSTITUTE

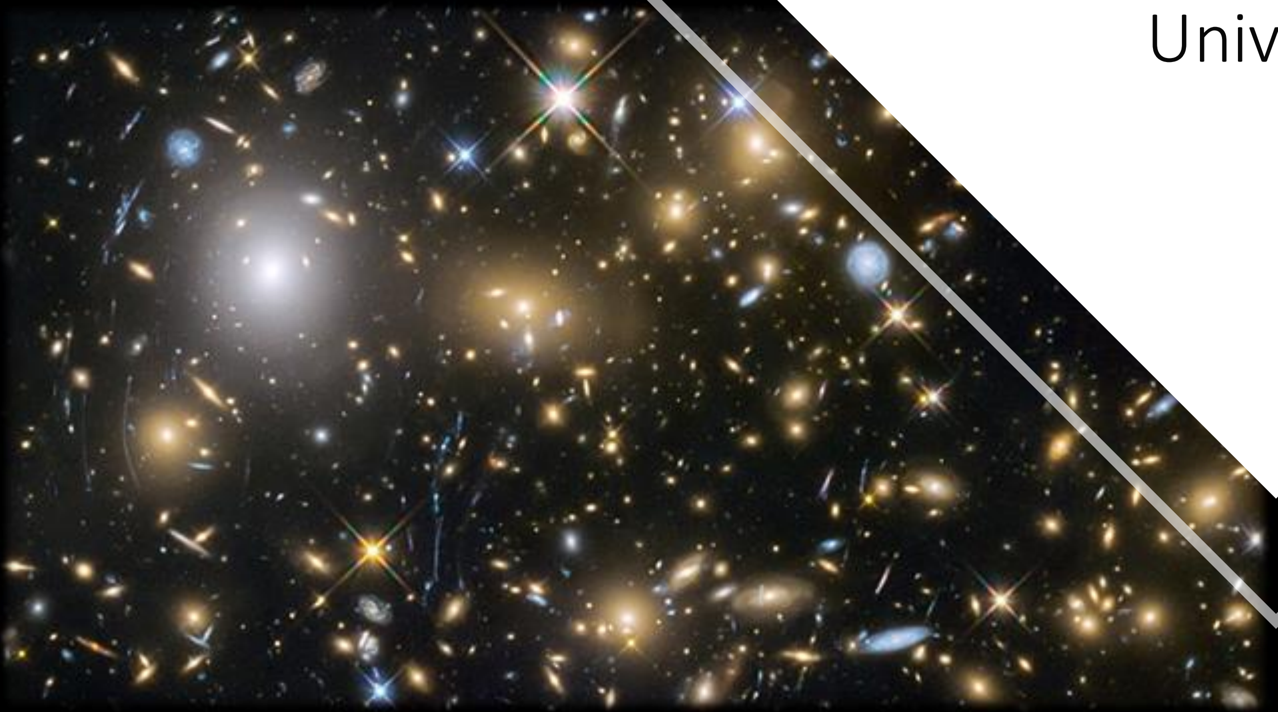
Searches for eV-scale axions using indirect detection

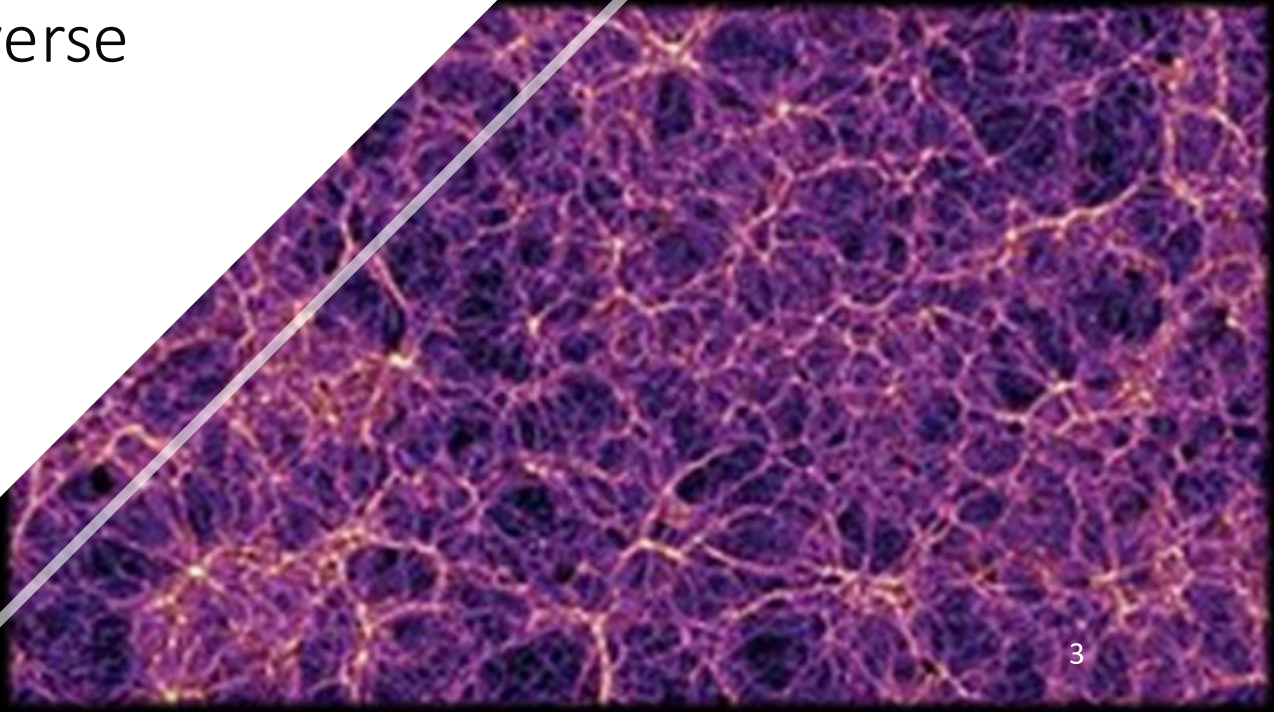
Elena Pinetti

Outline

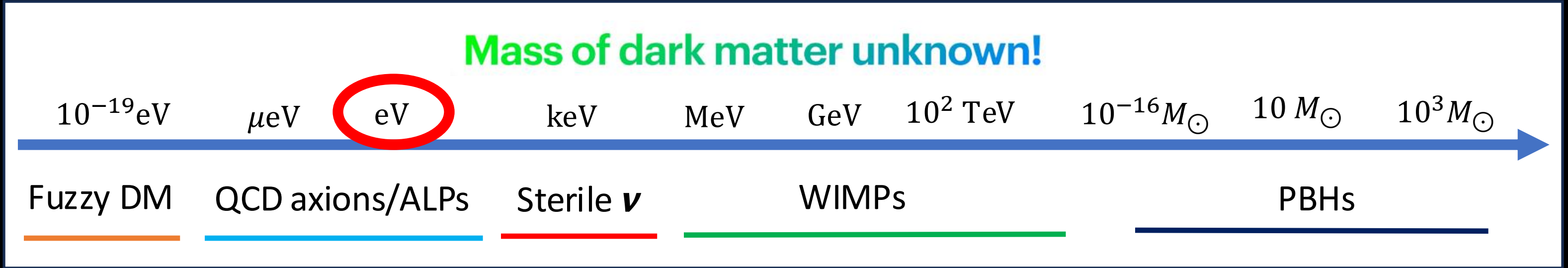
- ❑ Axion Dark Matter
- ❑ Infrared Observations
- ❑ Results & Prospects

Dark matter in the Universe





Dark Matter candidates



QCD axions & axion-like particles

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

axion-gluon coupling

Gluons

axion-photon coupling

axion field

EM field

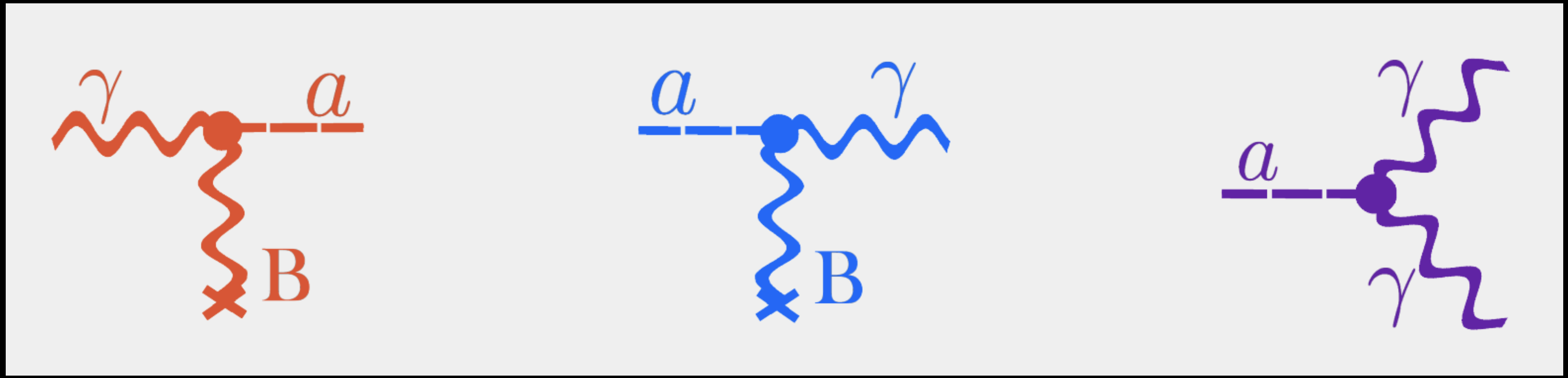
Strong CP problem

Interaction with photons

Interaction with fermions

Axion-photon interactions

1. Primakov production in stars: $\gamma \to a$
2. Conversion $a \leftrightarrow \gamma$ in laboratory and astrophysical B-fields
3. Axion decay $a \to \gamma\gamma$



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*
Fermi National Accelerator Laboratory, Theoretical Astrophysics Department, Batavia, Illinois, 60510, USA

Elena Pinetti†
Fermi National Accelerator Laboratory, Theoretical Astrophysics Department, Batavia, Illinois, 60510, USA and University of Chicago, Kavli Institute for Cosmological Physics, Chicago, IL 60637, USA

PRL 134, 0710002 (2025) Editor’s Suggestion

First constraints on QCD axion dark matter using James Webb Space Telescope observations

Elena Pinetti[1, 2, 3, 4, *]

arXiv:2503.14582v1, submitted to PRL

Shedding Infrared Light on QCD Axion and ALP Dark Matter with JWST

Akash Kumar Saha (Bangalore, Indian Inst. Sci.), Subhadip Bouri (Bangalore, Indian Inst. Sci.), Anirban Das (Saha Inst. and HBNI, Mumbai), Abhishek Dubey (Bangalore, Indian Inst. Sci.), Ranjan Laha (Bangalore, Indian Inst. Sci.)
Mar 18, 2025

arXiv:2503.14582v1

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. Galactic Center
2. Dwarf galaxies
3. Galaxy clusters

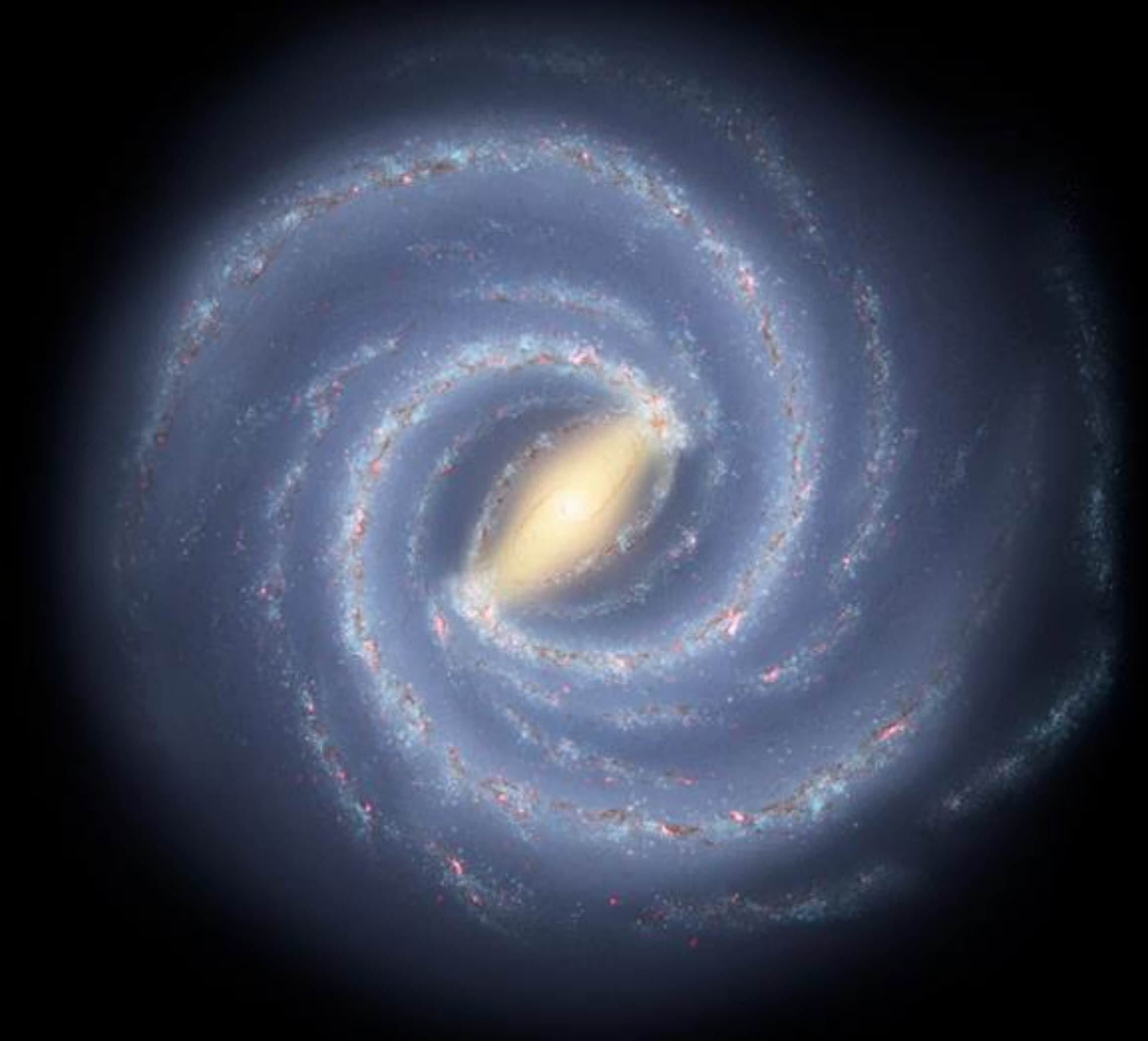
Galactic Center

Pros:

- Highest DM density in the Milky Way
- Largest DM signal
- Multi-wavelength observations (GCE in gamma-rays with Fermi-LAT)

Cons:

- Large astrophysical backgrounds
- Large uncertainties on the DM distribution



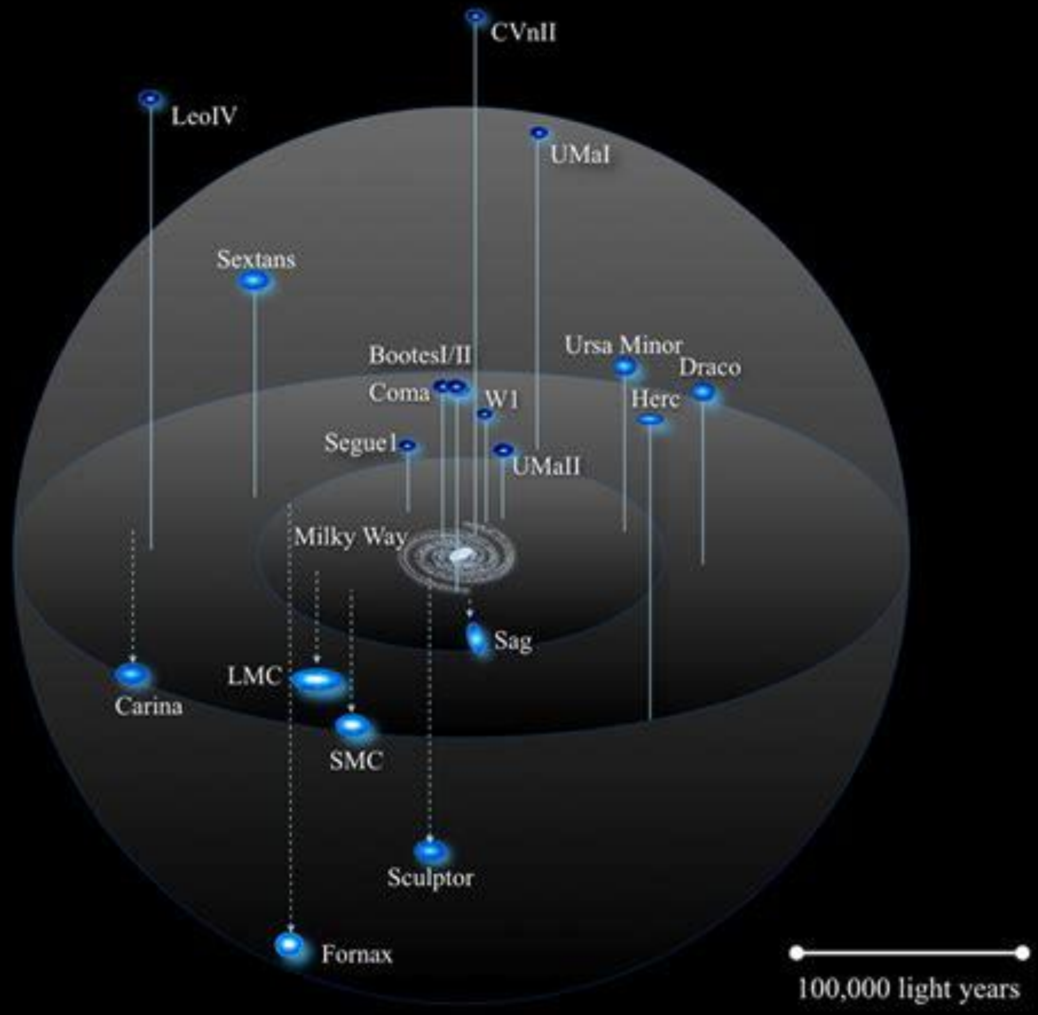
Dwarf galaxies

Pros:

- DM dominated
- Favourable signal-to-background ratio
- Complementary searches in other wavelengths (Fermi and MAGIC in gamma-rays, MUSE in optical, etc)

Cons:

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



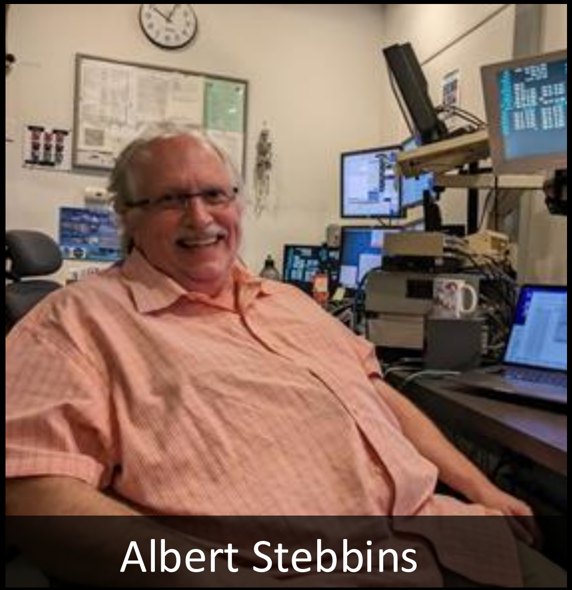
Galaxy clusters

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

Blank-sky observations

Kitt Peak Observatory (Arizona)



Albert Stebbins

Lily Robinthal, myself, Albert Stebbins

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

Axion signal

Axion signal

Emission rate

$$\frac{d\phi_a}{dE\,d\Omega} = \frac{\Gamma_\gamma}{4\pi\, m_a} \frac{dN}{dE} D$$

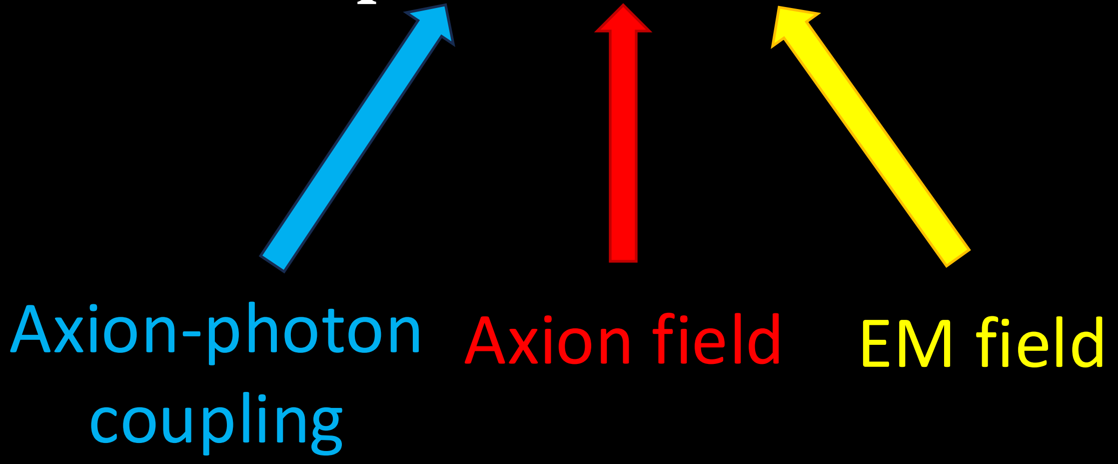
Axion mass

Emission spectrum

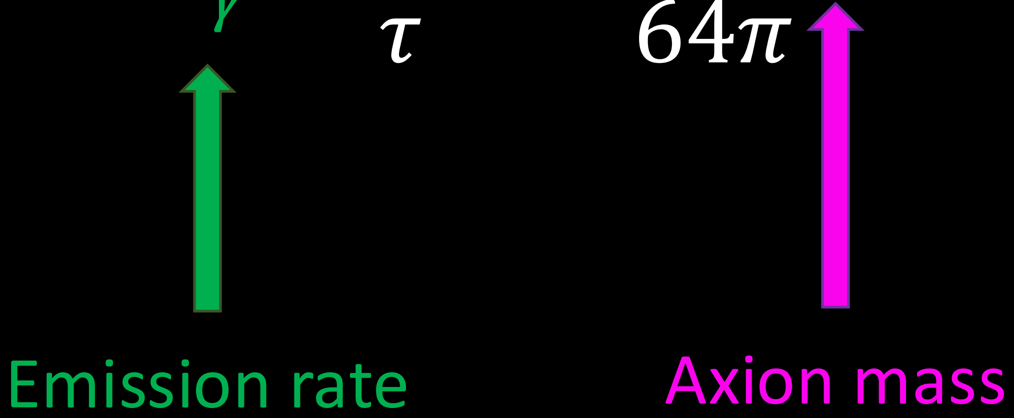
D-factor

Axion-photon coupling

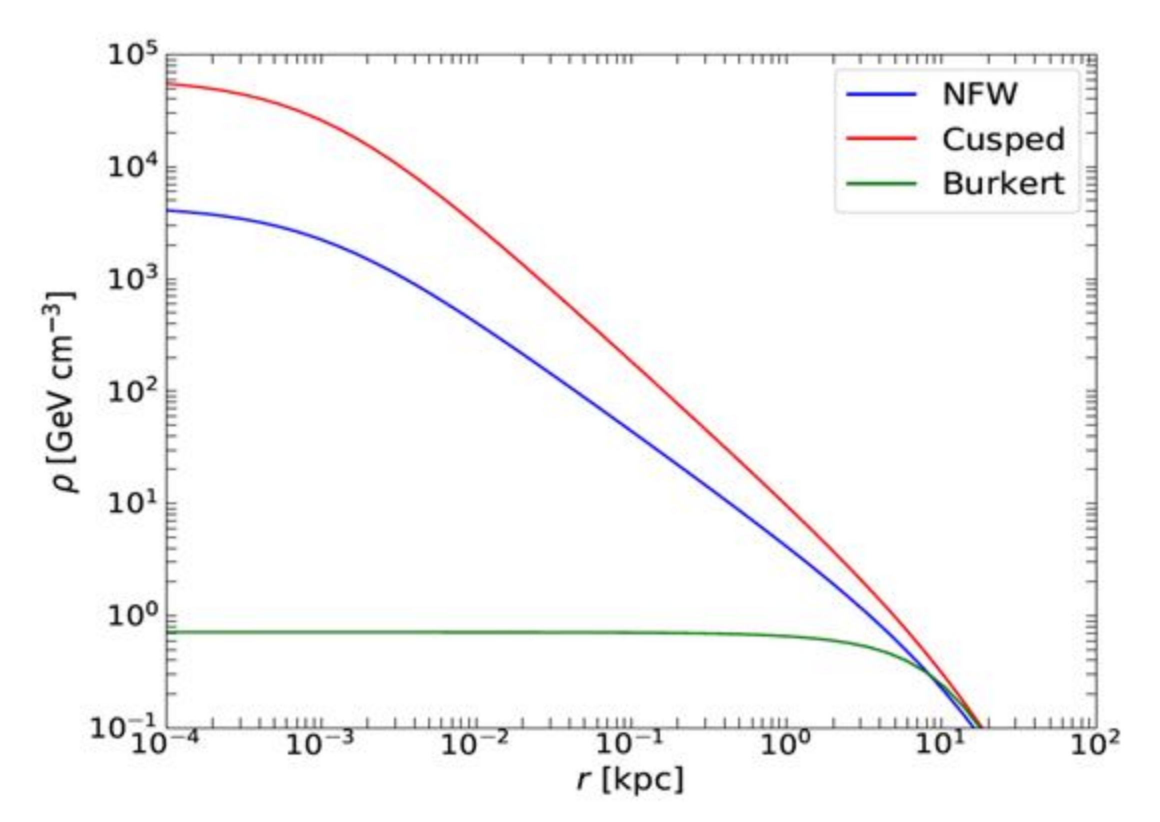
$$\mathcal{L} = -\frac{1}{4} g_{a\gamma\gamma}\, a\, F_{\mu\nu}\tilde{F}_{\mu\nu}$$



$$\Gamma_\gamma = \frac{1}{\tau} = \frac{g_{a\gamma\gamma}^2\, m_a^3}{64\pi}$$



D-factor



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

$$\rho_0 = 0.3\ \mathrm{GeV/cm^3}$$

Photon emission spectrum

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

$$\frac{df}{dv} * W$$

Doppler effect

Instrumental response

James Webb Space Telescope

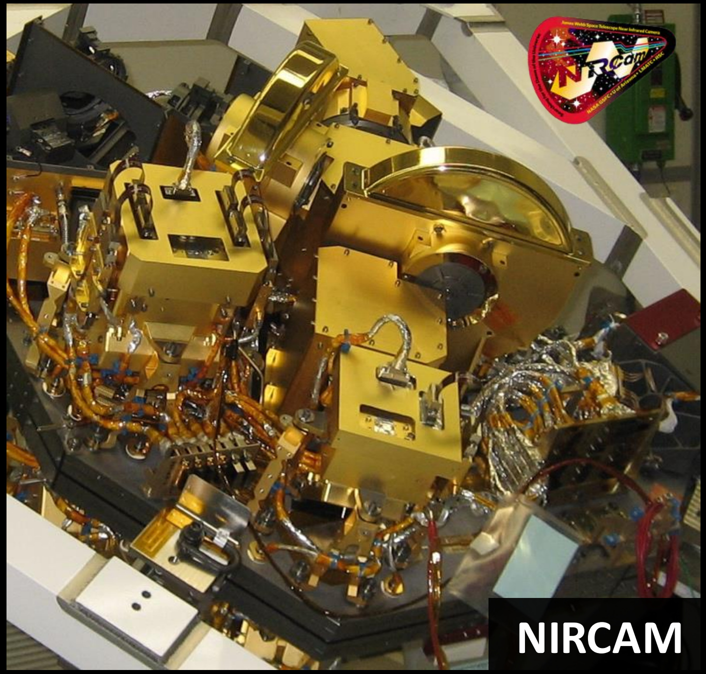
JWST launch

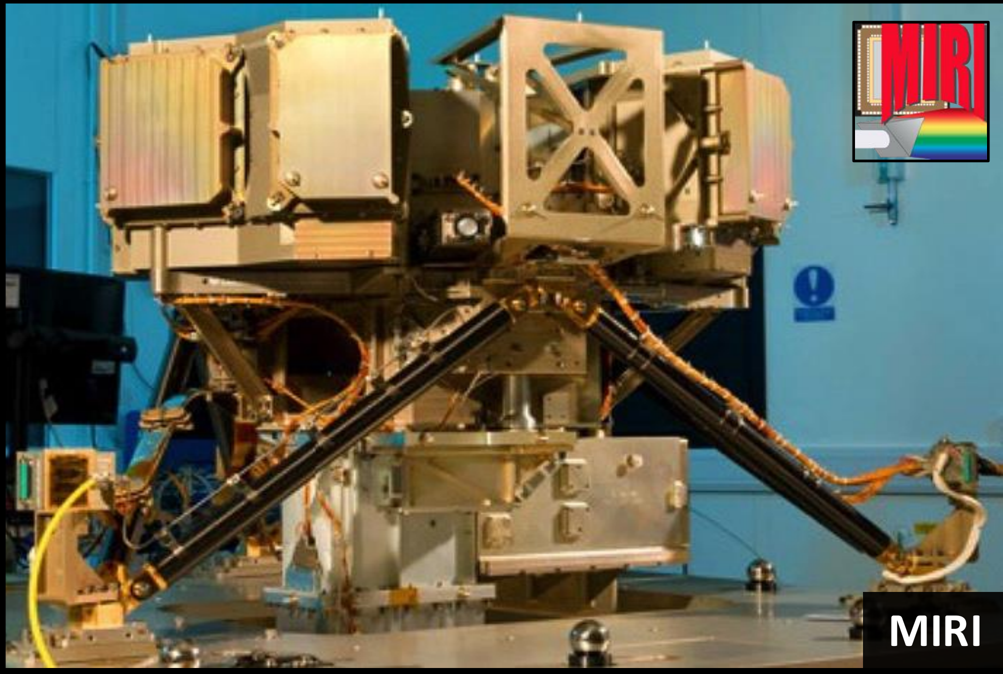
Launch: 25 December 2021 from French Guiana

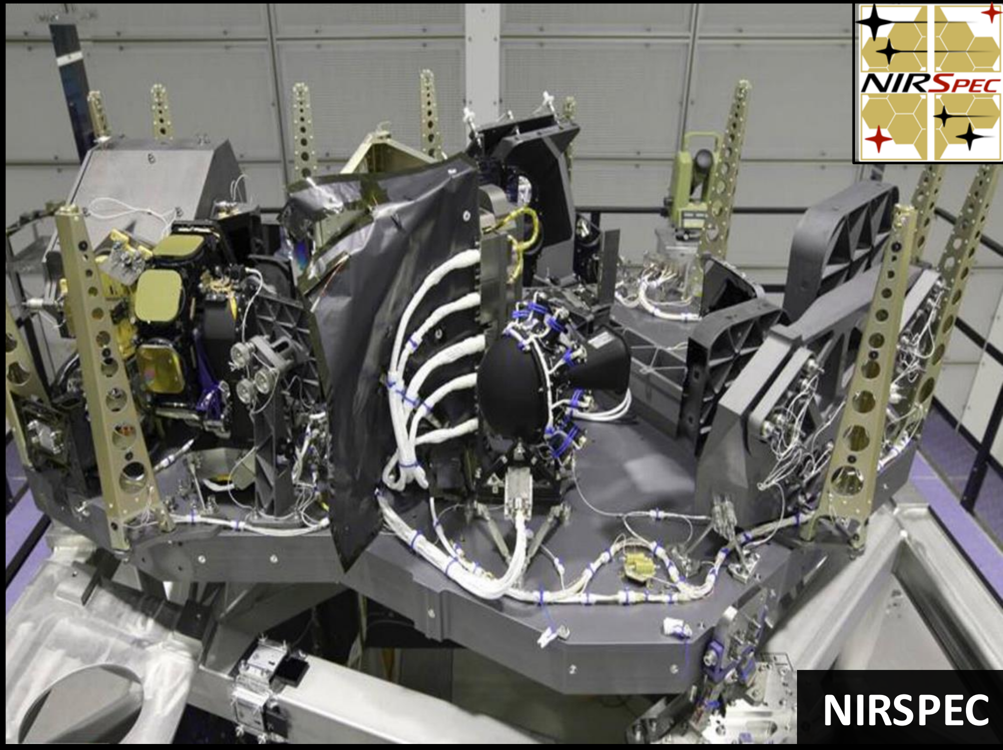
Arianespace Ariane 5 rocket

It does not orbit around the Earth like the Hubble Space Telescope, it orbits the Sun 1.5×10^6 km away from Earth at L2 (2nd Lagrange point)

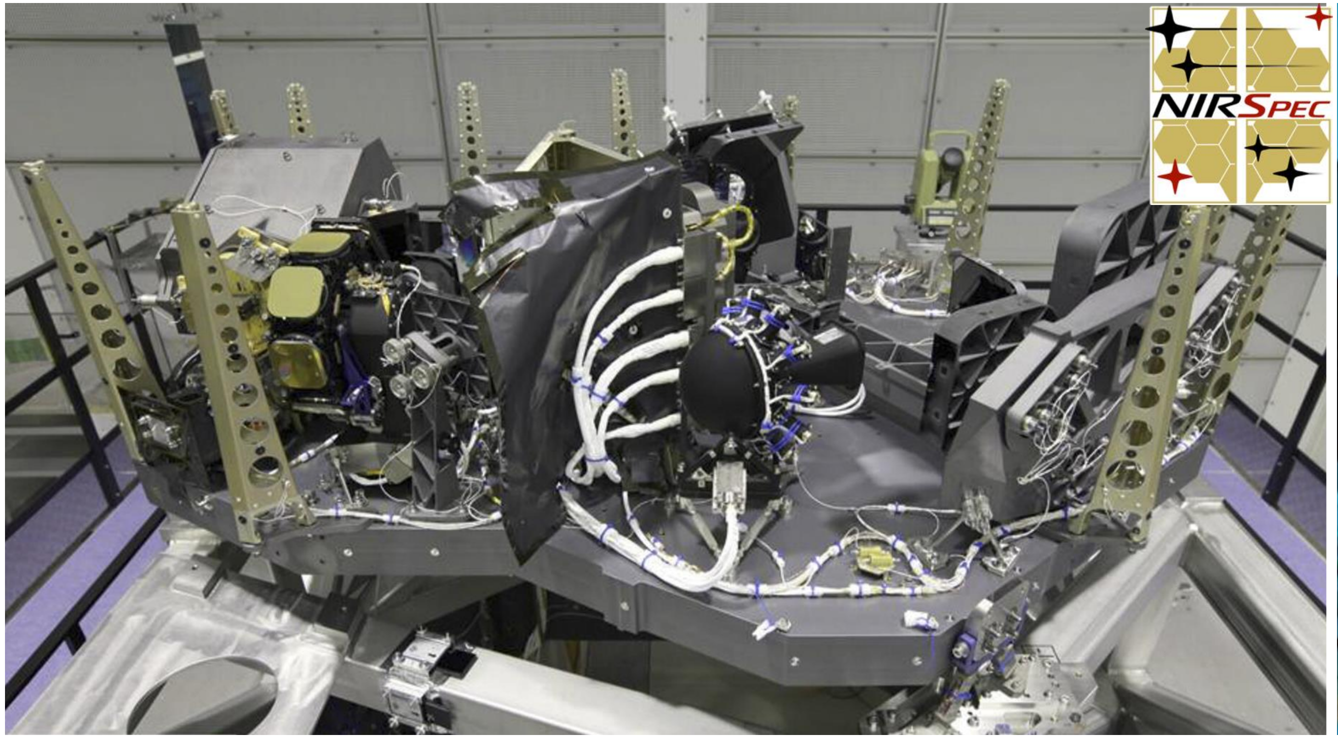
JWST Instruments

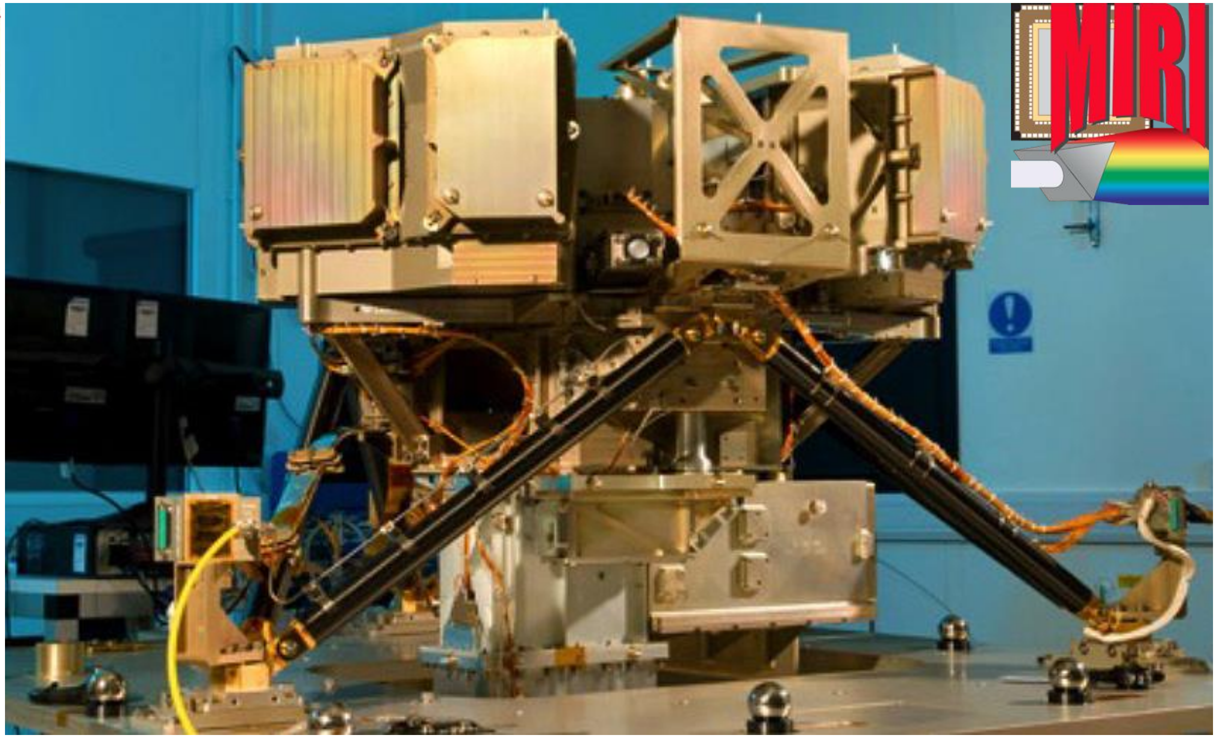






NIRSPEC and MIRI





NIRSpec: Near-Infrared Spectrograph

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

MIRI: Mid-Infrared Instrument

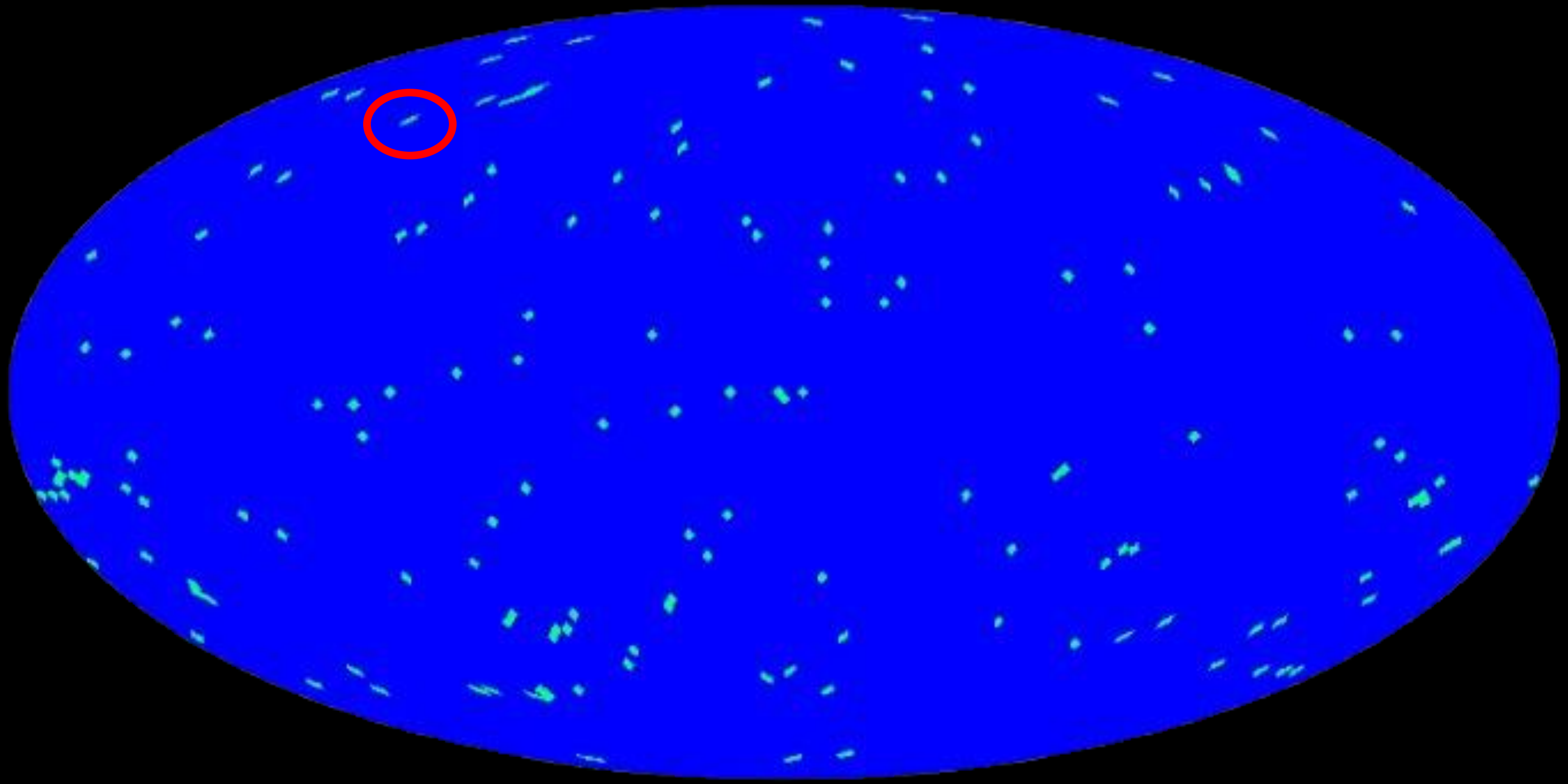
$\Delta\lambda = 4.9 - 27.9\ \mu m$

Observations

GN-z11

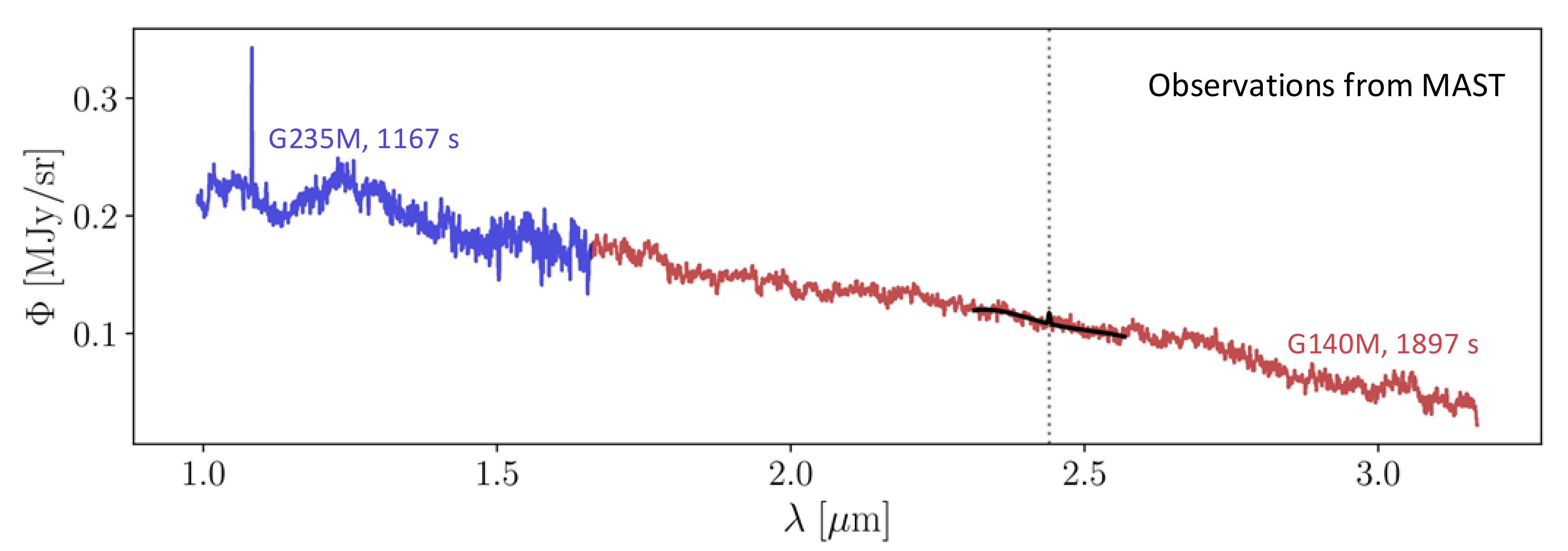
- High-redshift galaxy (z=10.6) in the constellation of Ursa Major
- Most distant known galaxy until 2022 (when JWST discovered JADES-GS-z13-0)
- Fun fact: Maiolino et al (2024) discovered that GN-z11 contains the most distant (aka earliest) black hole known in the Universe

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

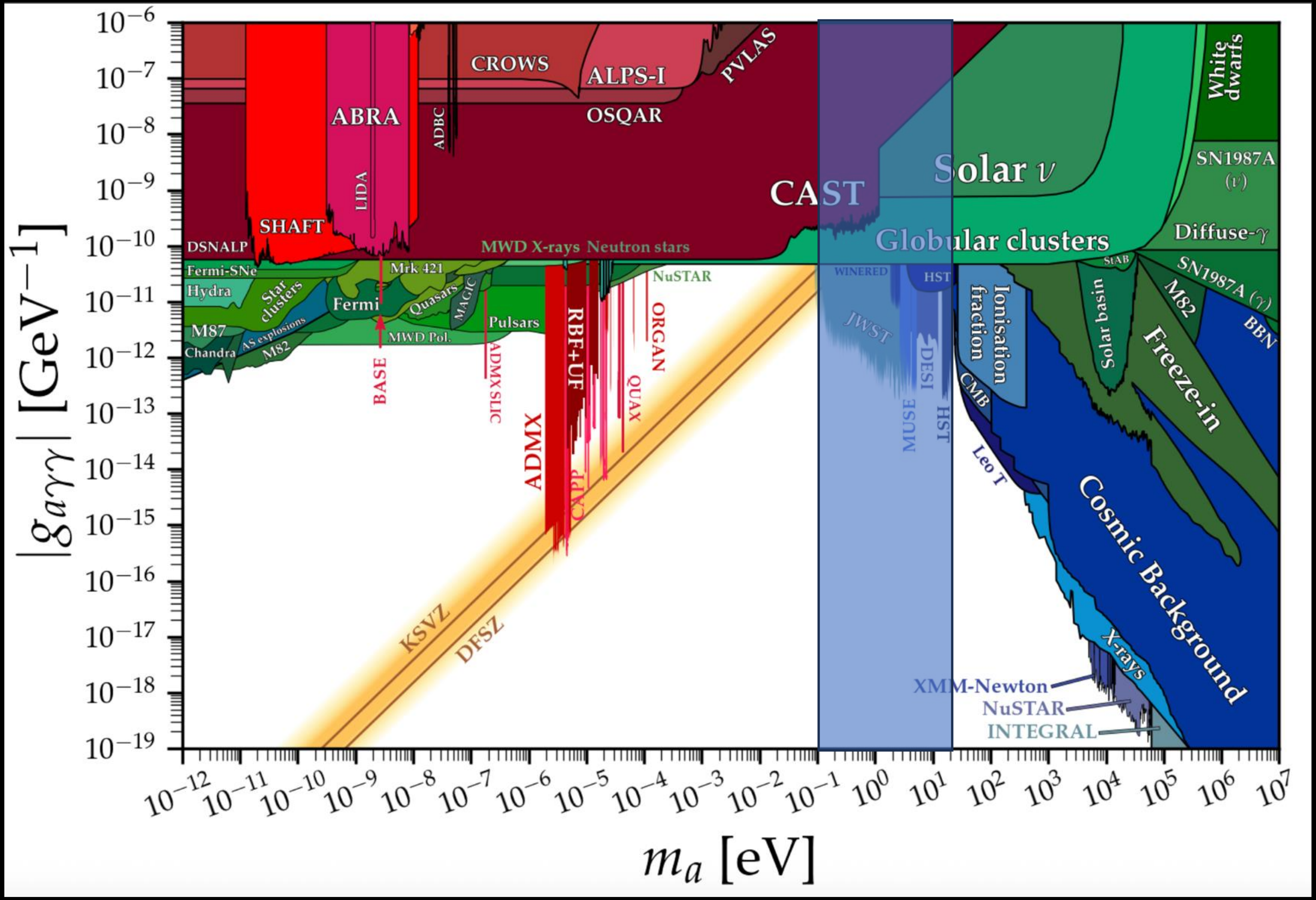


$m_a = 1\ \text{eV}$ $\quad g_{a\gamma\gamma} = 1.1\times10^{-11}\text{GeV}^{-1}$

Janish & **EP**, PRL 134, 071002 (2025)

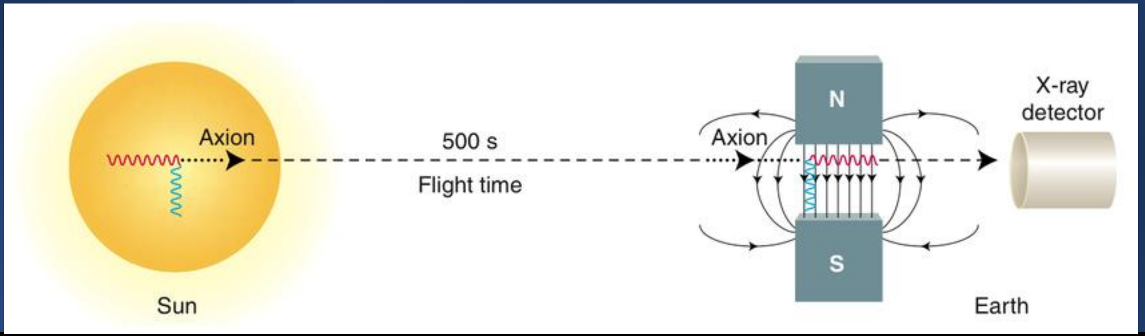
Results

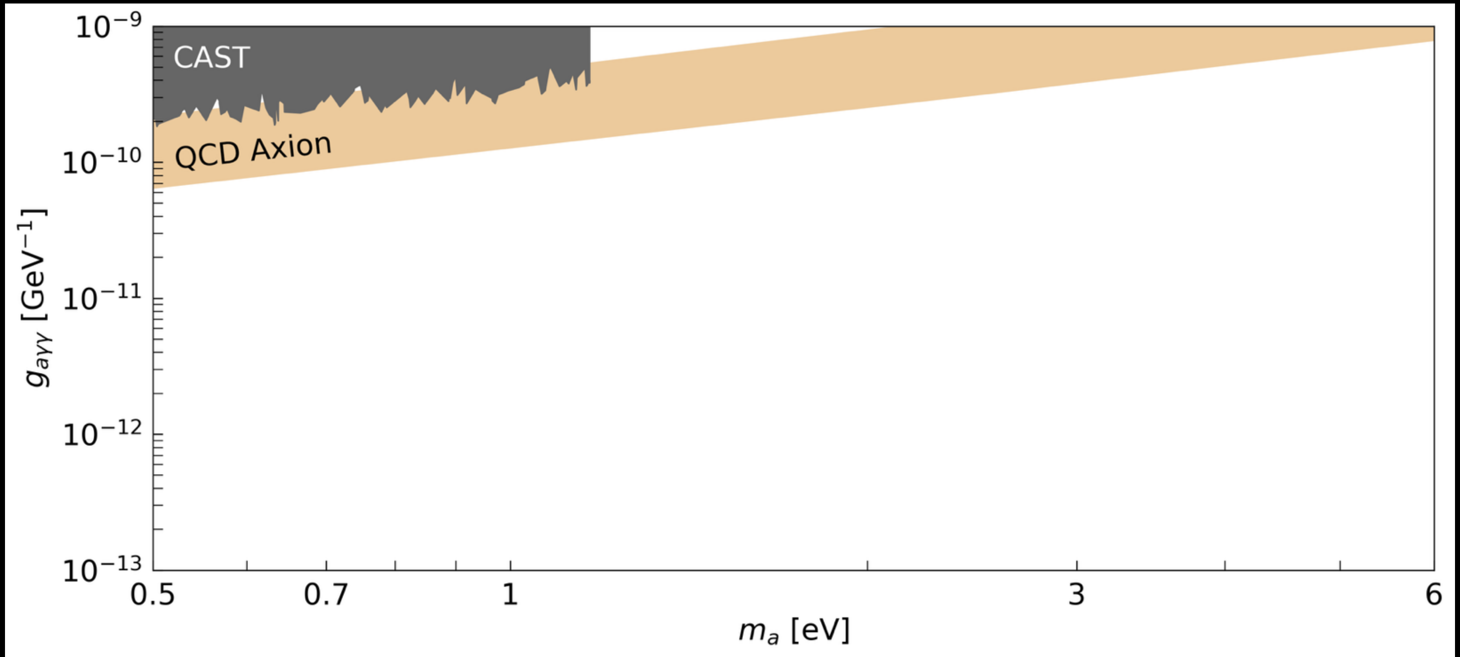
Bounds



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 Milky Way


Messier 2

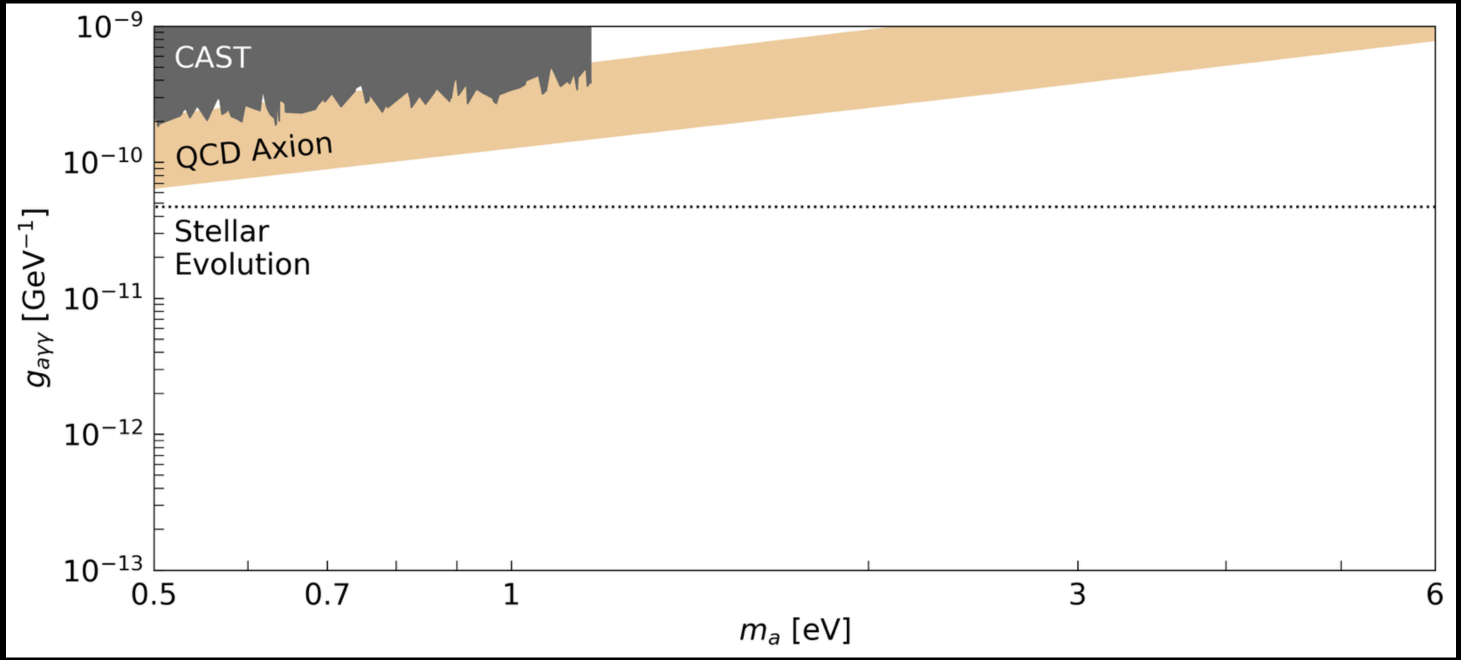
Axions could be produced in stellar interiors via the Primakoff process, freely escape and drain energy from its interior

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



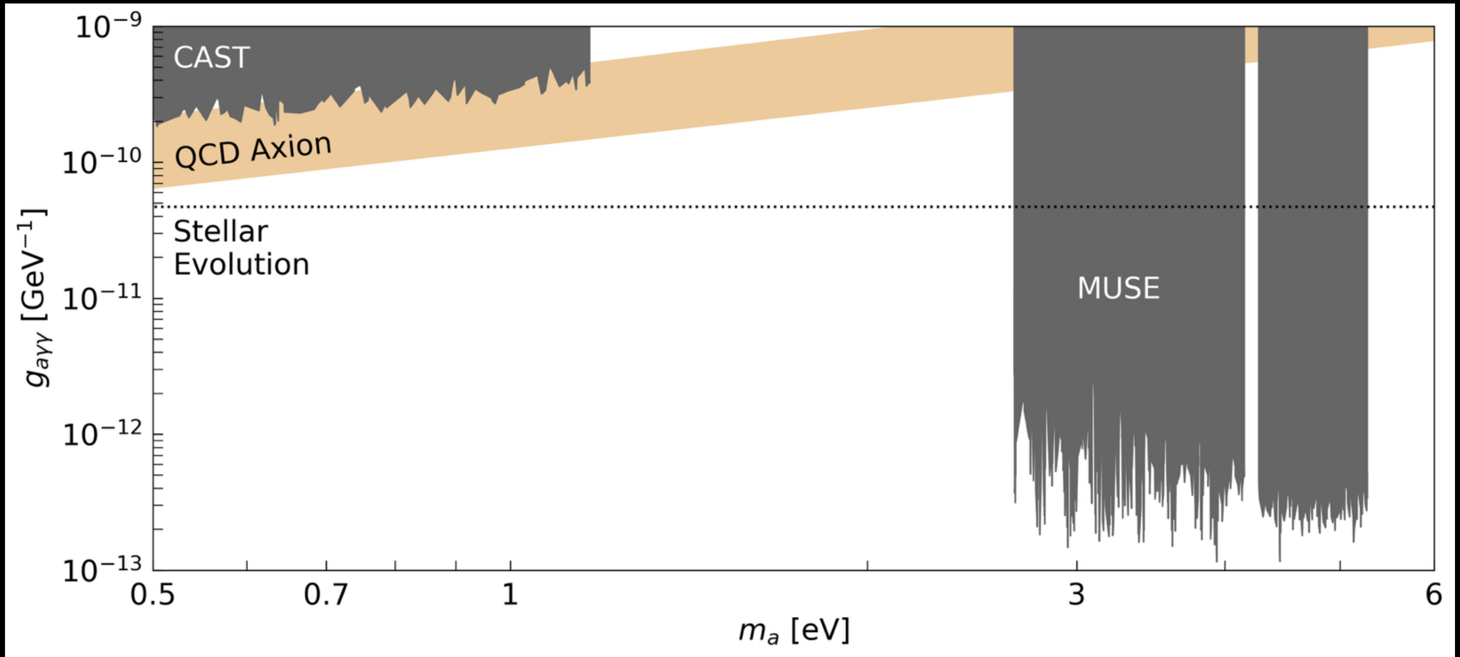
48 globular clusters observed with the Hubble Space Telescope

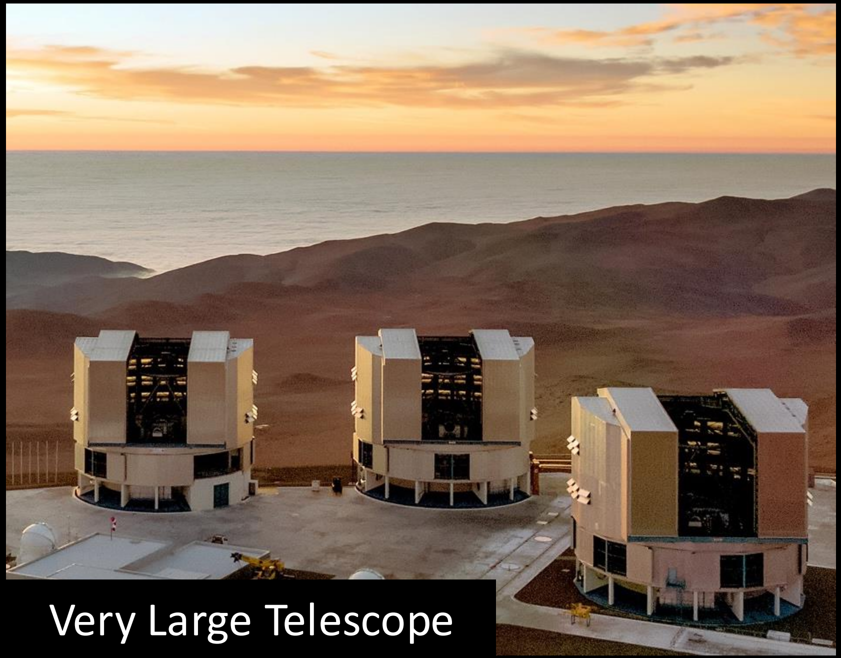
$k_B T_{core} = O(\text{keV}) \Longrightarrow$ if $m_a \ll k_B T_{core}$, the axion is massless from the star perspective

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

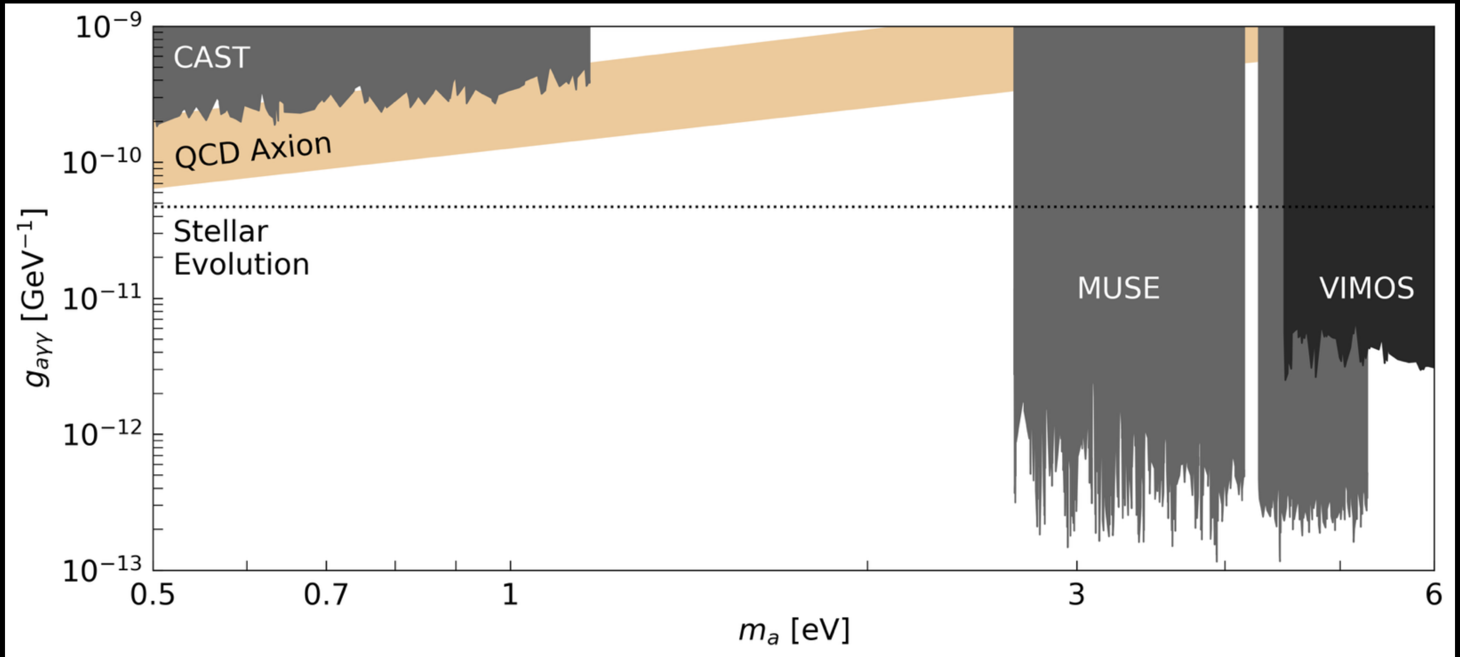
5 dwarf spheroidal galaxies: Leo T, Sculptor, Eridanus 2, Grus 1, Hydra II

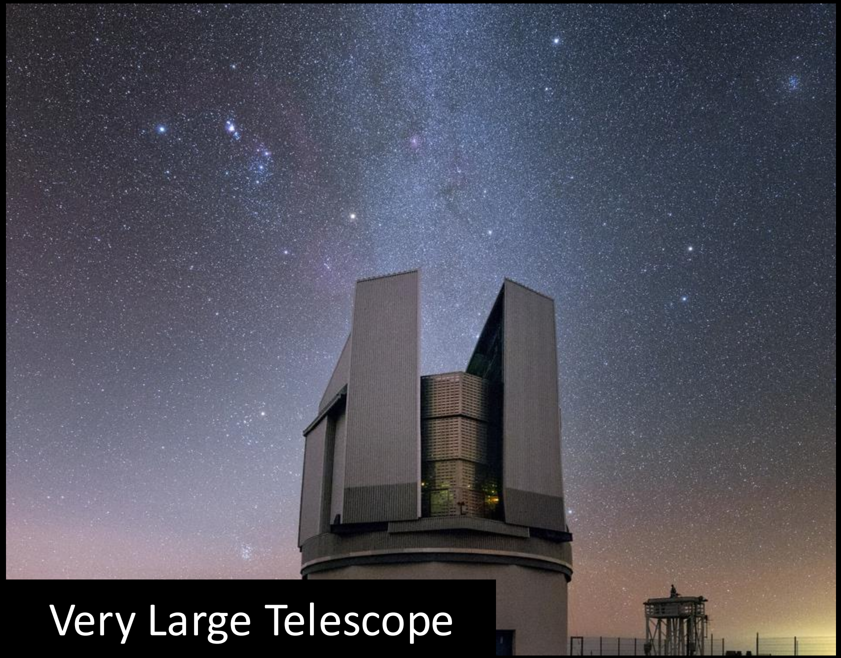
MUSE (Multi-Unit Spectroscopic Explorer) at the Very Large Telesocope: wavelength 4800 – 9350 Å, resolution 1.25 Å, observation time 3-22h

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

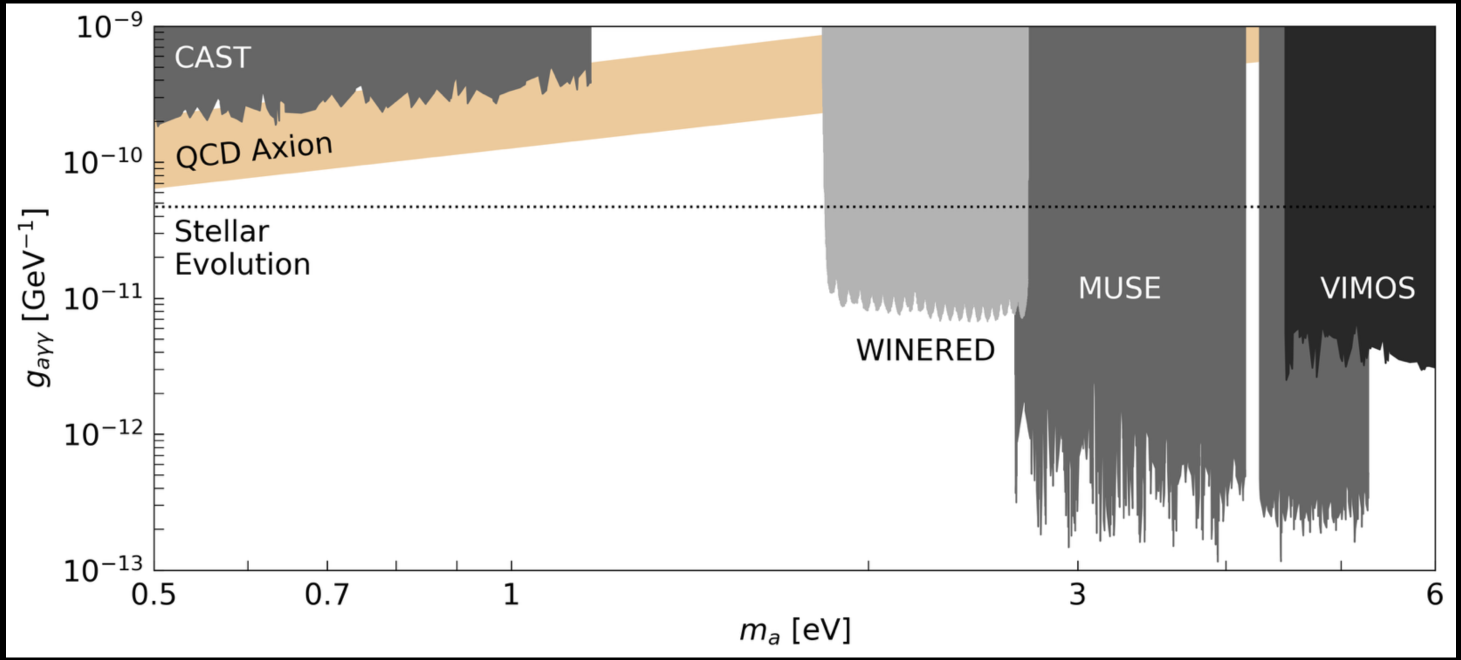
Target: Galaxy clusters Abell 2667 and 2390

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



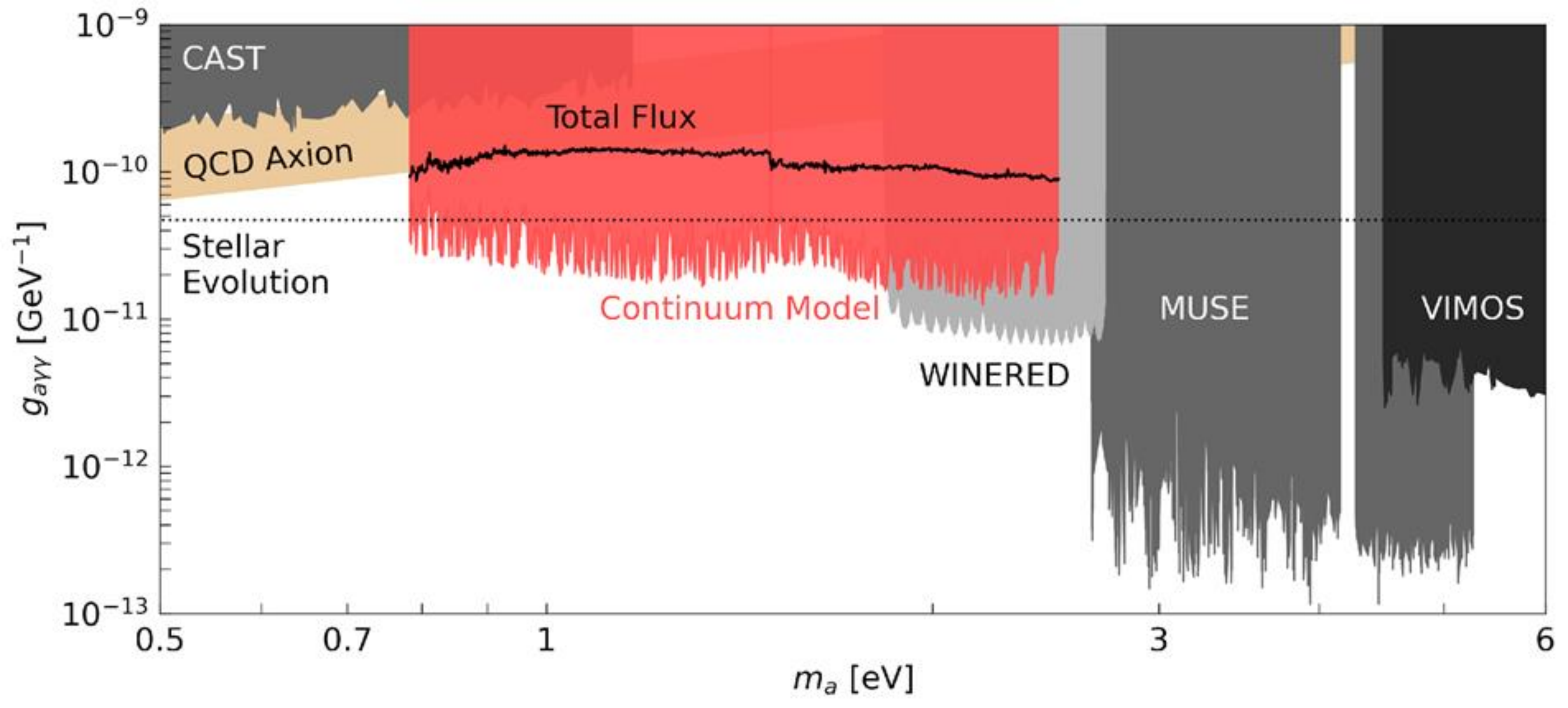
Target: Dwarf galaxies Leo V and Tucana II

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 – Pilot study



Janish & **EP**, PRL 134, 071002 (2025), **Editor's Suggestion**

Two Key Questions

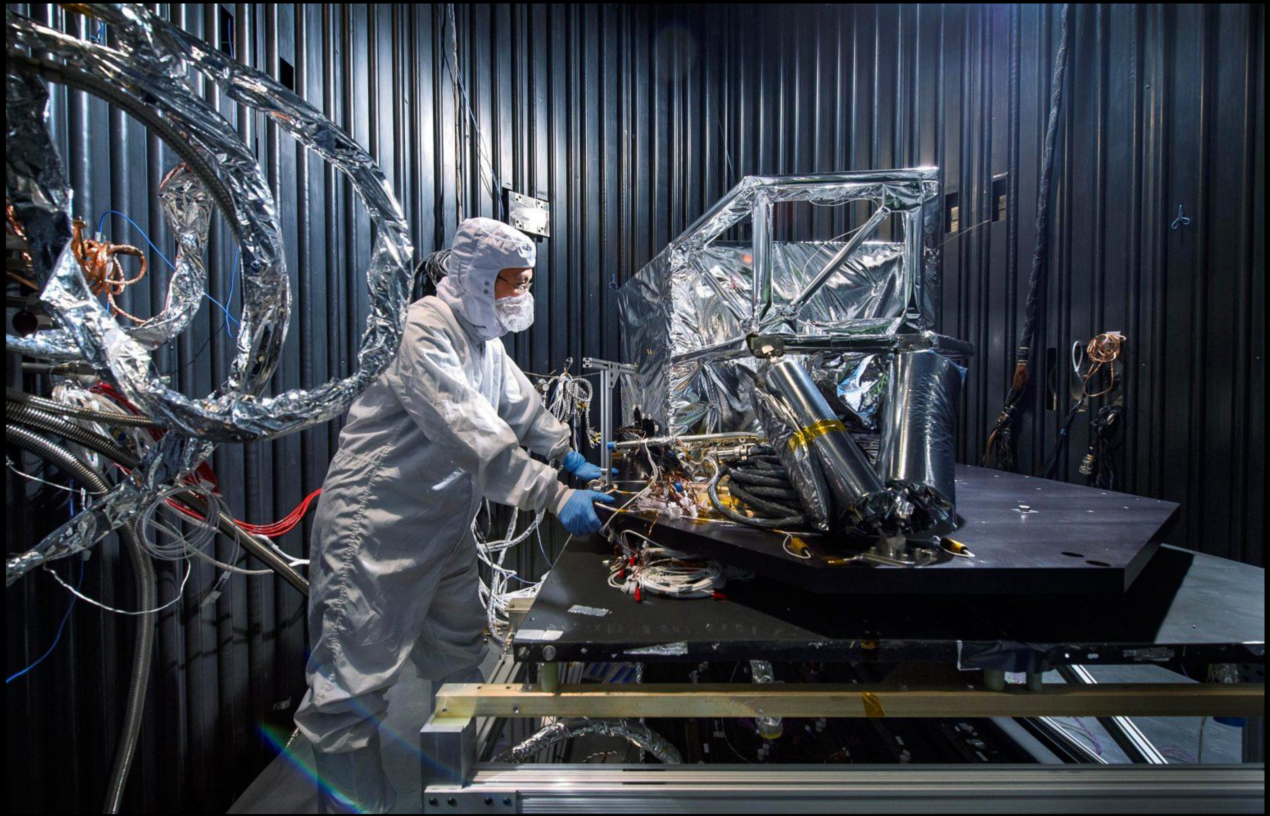
1. Can we safely assume that the background is a continuum?

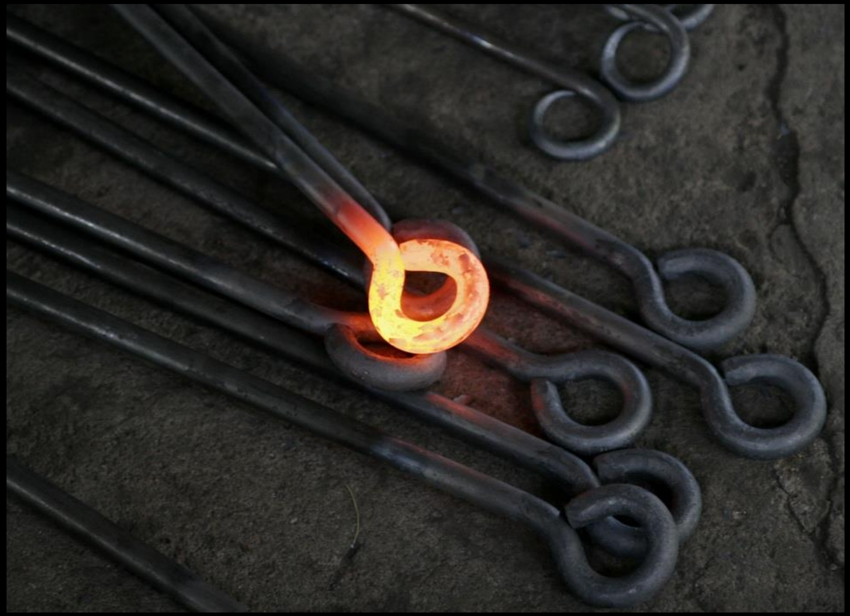
2. Can we do better with more targets?

Astrophysical backgrounds

Thermal self-emission

Thermal self-emission: instruments, or even the spacecraft itself, can emit infrared light because of thermal radiation (i.e. thermal motion of the particles in matter above 0 K)





NASA testing the Webb telescope's MIRI thermal shield in a thermal vacuum chamber at NASA's Goddard Space Flight Center in Greenbelt, MD. Credit: NASA

Stray light

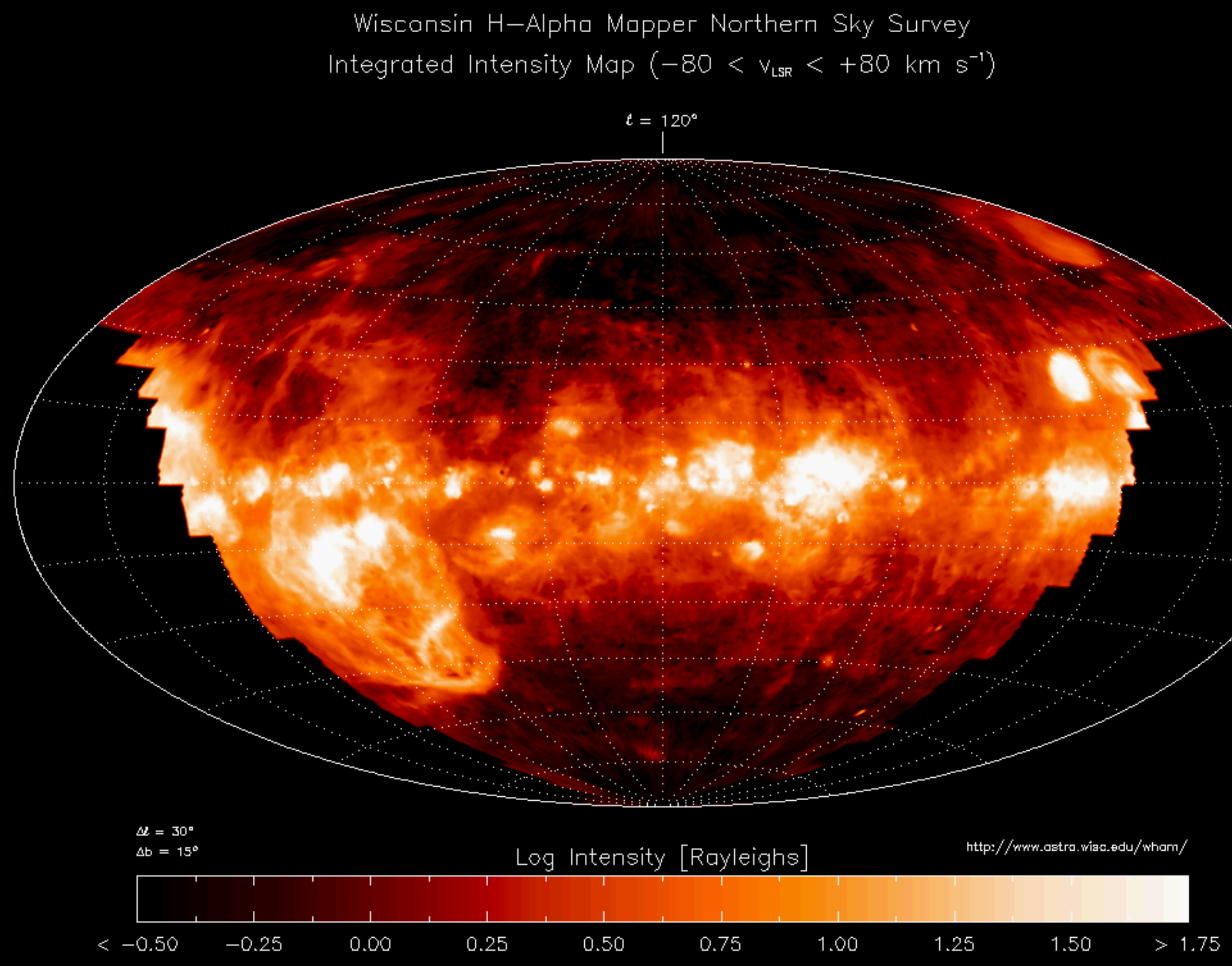
Stray light: unwanted light that reaches a detector but does not originate from the intended source of observation (light from outside the fov, reflections within the telescope)

Insterstellar medium

ISM: interstellar medium background associated with the dust emission within our Galaxy

Examples:

- Interstellar dust grains absorb starlight and then re-emit the energy in infrared
- Spectral lines from highly excited states of hydrogen



Zodiacal light

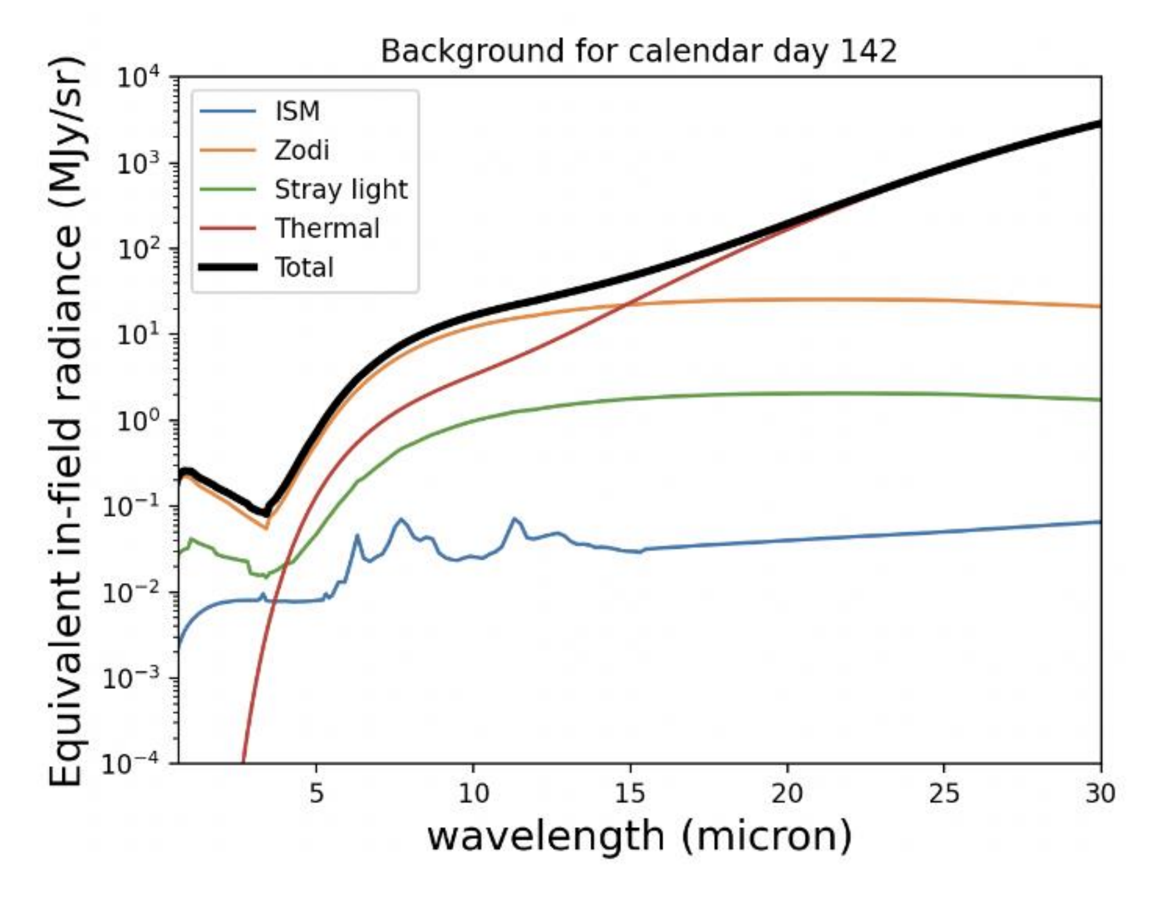
Zodiacal light ("false dawn") originates from sunlight scattered by dust particles in the Solar System

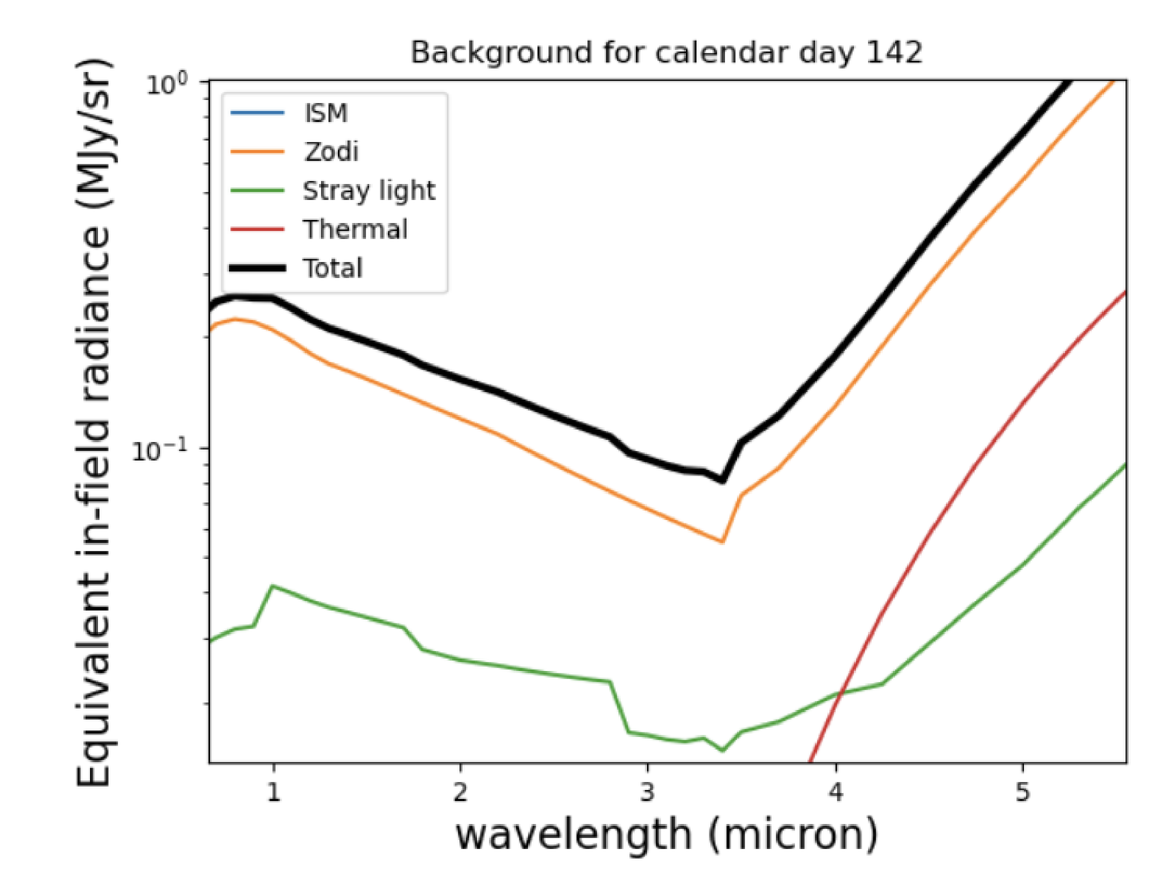
Moon, Apollo 15

Brian May, guitarist of Queen

Very Large Telescope, Atacama Desert (Chile)

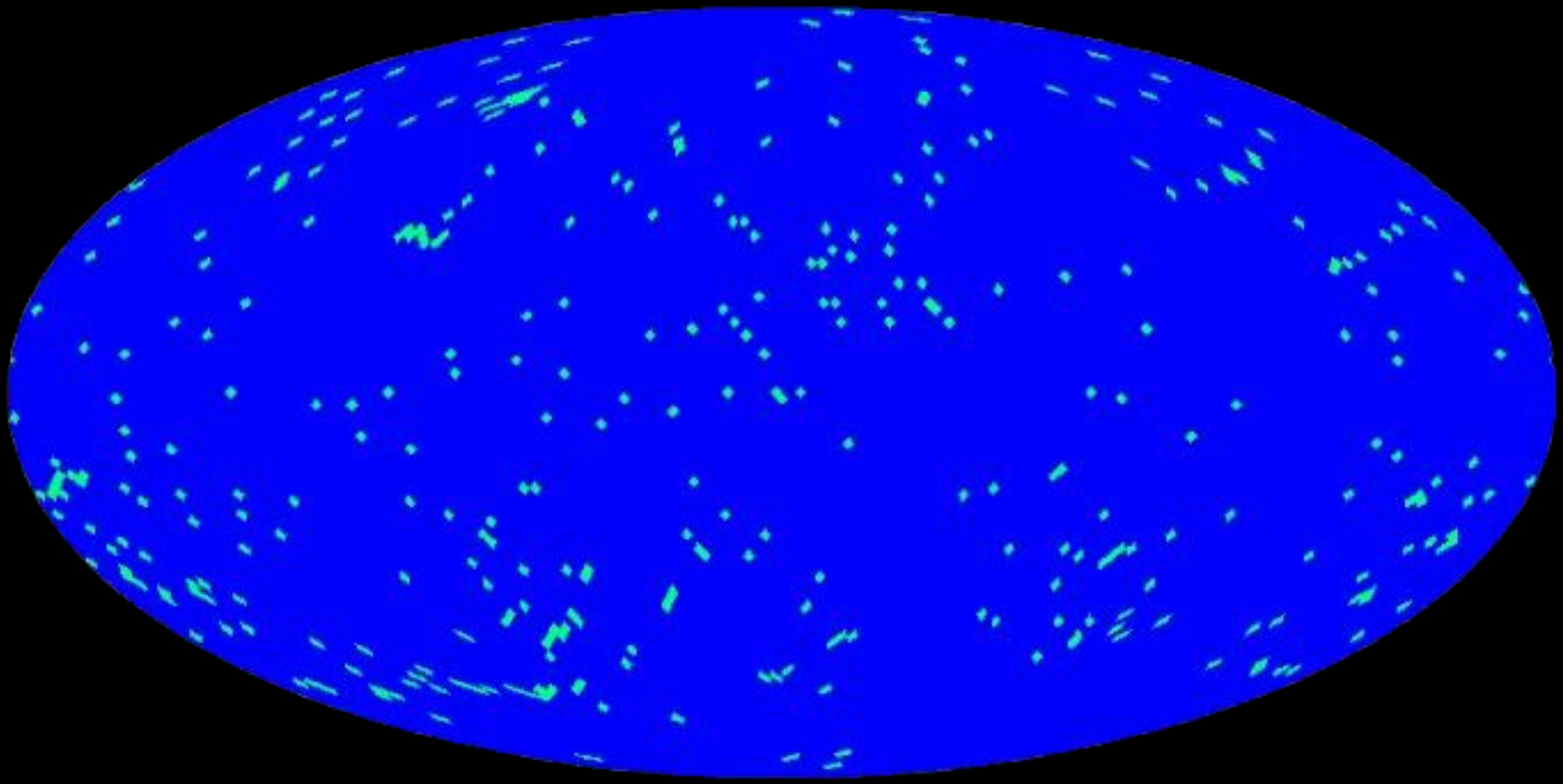
Astrophysical backgrounds





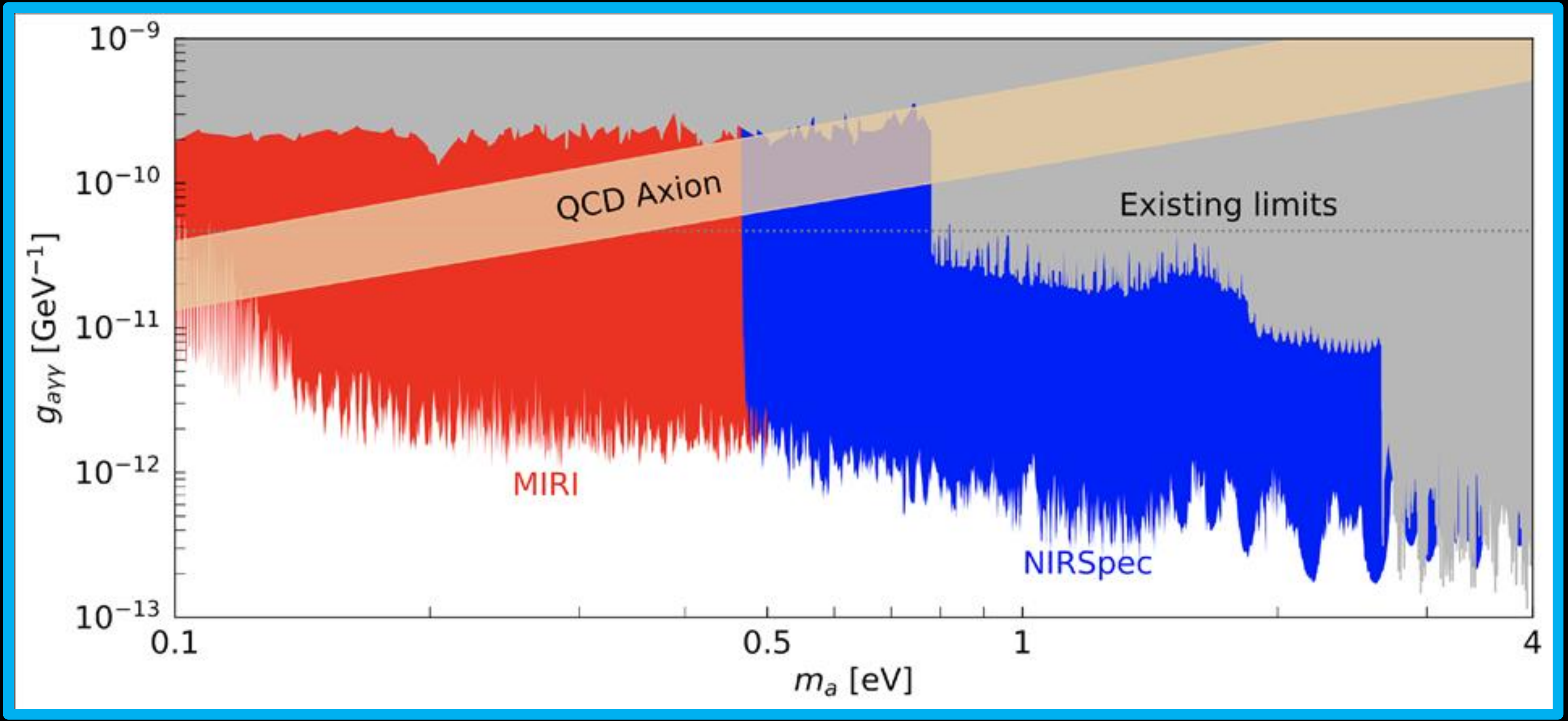
Backgrounds from: https://jwst-docs.stsci.edu/jwst-other-tools/jwst-backgrounds-tool#gsc.tab=0

More JWST observations



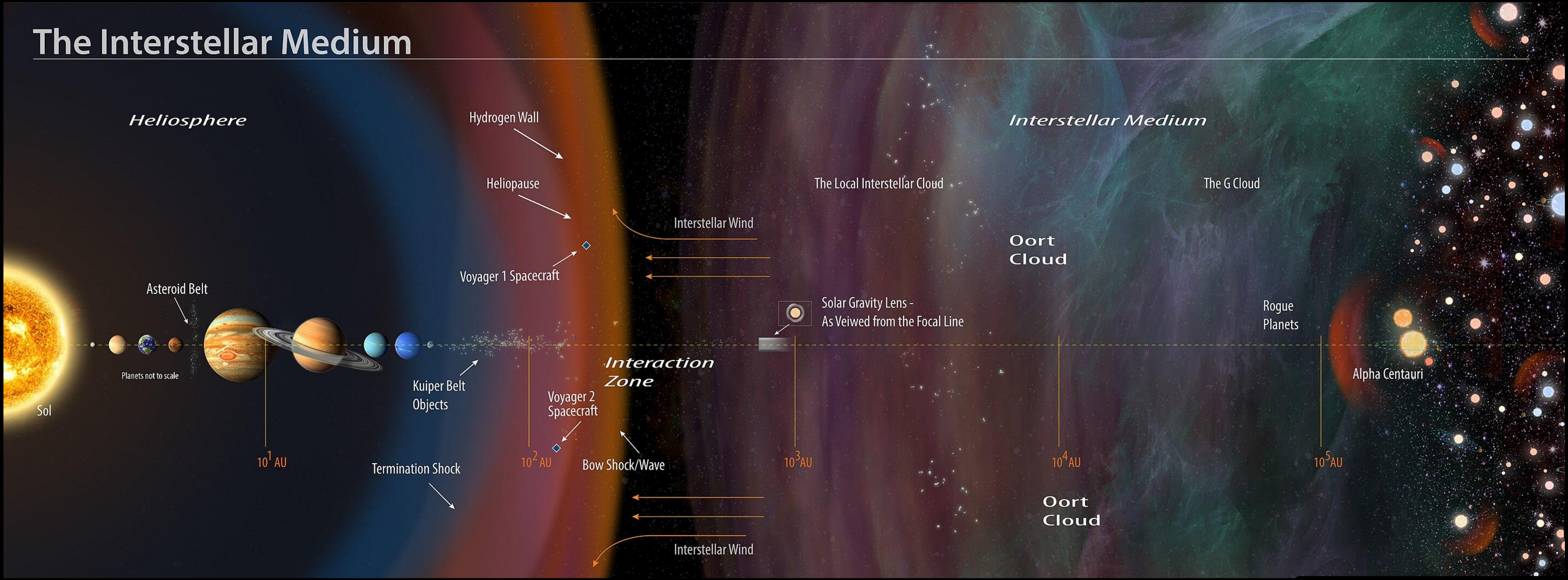
- Over 400 targets and ~ 5,000 hr of observing time
- Both NIRSpec and MIRI
- More statistics, better targets and broader mass coverage

JWST bounds



EP, arXiv:2503.11753, Submitted to PRL

An eye toward the future



1. Build a template for the ISM
2. Fit a dark matter signal

Karin Sandstrom

Aurelio Amerio

EMIR @ Gran Telescopio Canarias

EMIR: Espectrógrafo Multi-objeto Infra-Rojo, Infrared Multiobject Spectrograph

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

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

Wavelength: near-infrared (0.9-2.5 μm)

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

Summary & Conclusions

1. Indirect detection is a powerful way to probe dark matter

2. Telescopes like JWST, MUSE, VIMOS provide competitive bounds

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!

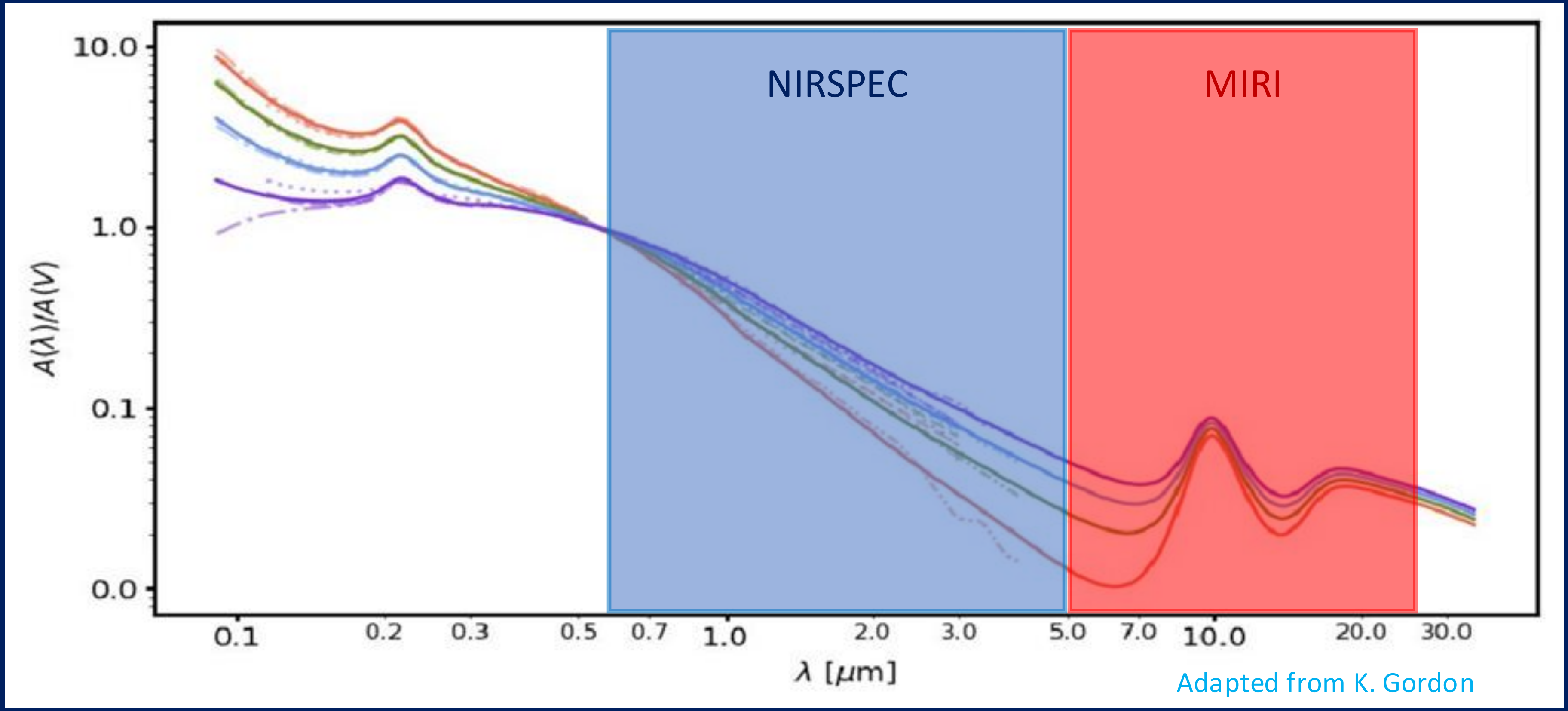
1. Indirect detection is a powerful way to probe dark matter

2. Telescopes like JWST, MUSE, VIMOS provide competitive bounds

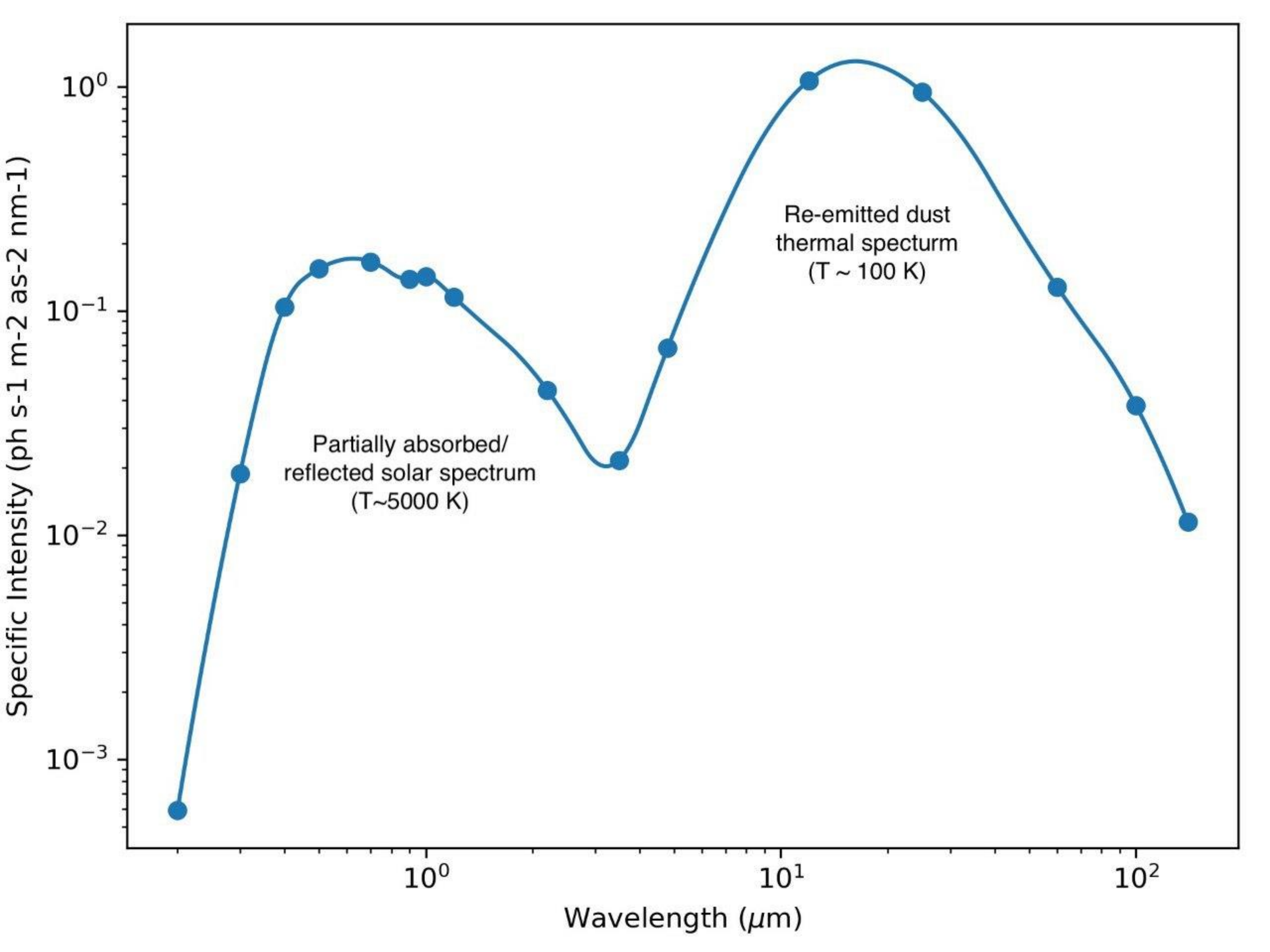
3. Numerous observations are already available and more data are on their way: This is just the beginning!

Back-up slides

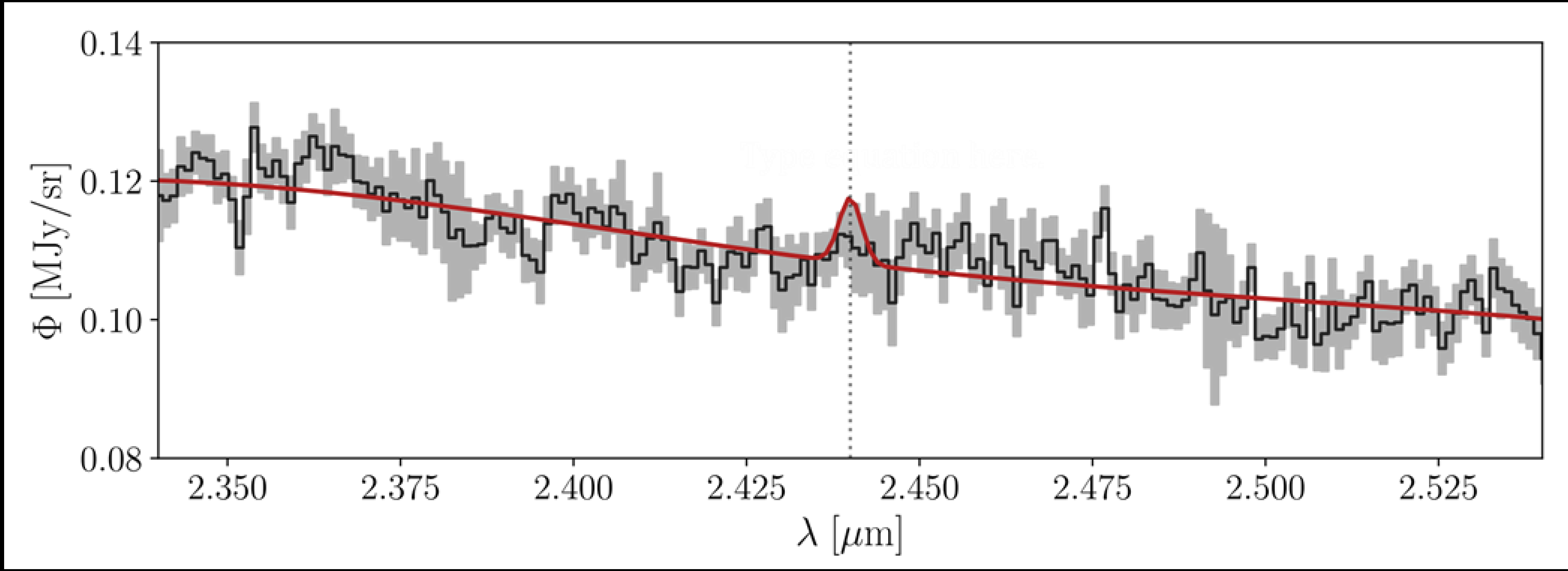
Galactic dust extinction



Zodiacal light



Blank-sky flux + dark matter



$m_a = 1\,\mathrm{eV}$ $\qquad g_{a\gamma\gamma} = 1.1\times10^{-11}\mathrm{GeV}^{-1}$

Cosmological bounds

	PlanckTTTEEE	PlanckTTTEEE+lensing	PlanckTTTEEE+BAO
$T_{RH} = 10\,\mathrm{MeV}$	< 391	< 393	< 391
$T_{RH} = 20\,\mathrm{MeV}$	< 39.2	< 36.6	< 36.0
$T_{RH} = 30\,\mathrm{MeV}$	< 6.72	< 6.55	< 6.31
$T_{RH} = 40\,\mathrm{MeV}$	< 3.23	< 3.22	< 3.05
$T_{RH} = 50\,\mathrm{MeV}$	< 2.09	< 2.05	< 1.89
$T_{RH} = 80\,\mathrm{MeV}$	< 0.912	< 0.906	< 0.901
$T_{RH} = 100\,\mathrm{MeV}$	< 0.691	< 0.696	< 0.688
$T_{RH} = \infty$	< 0.837	< 0.639	< 0.259

Table 1. 95% CL upper bounds on axion mass m_a (in eV) from different datasets, for the values of the reheating temperature T_{RH} indicated in the first column.

Carenza, Lattanzi, Mirizzi, Forastieri, JCAP 07 (2021) 031