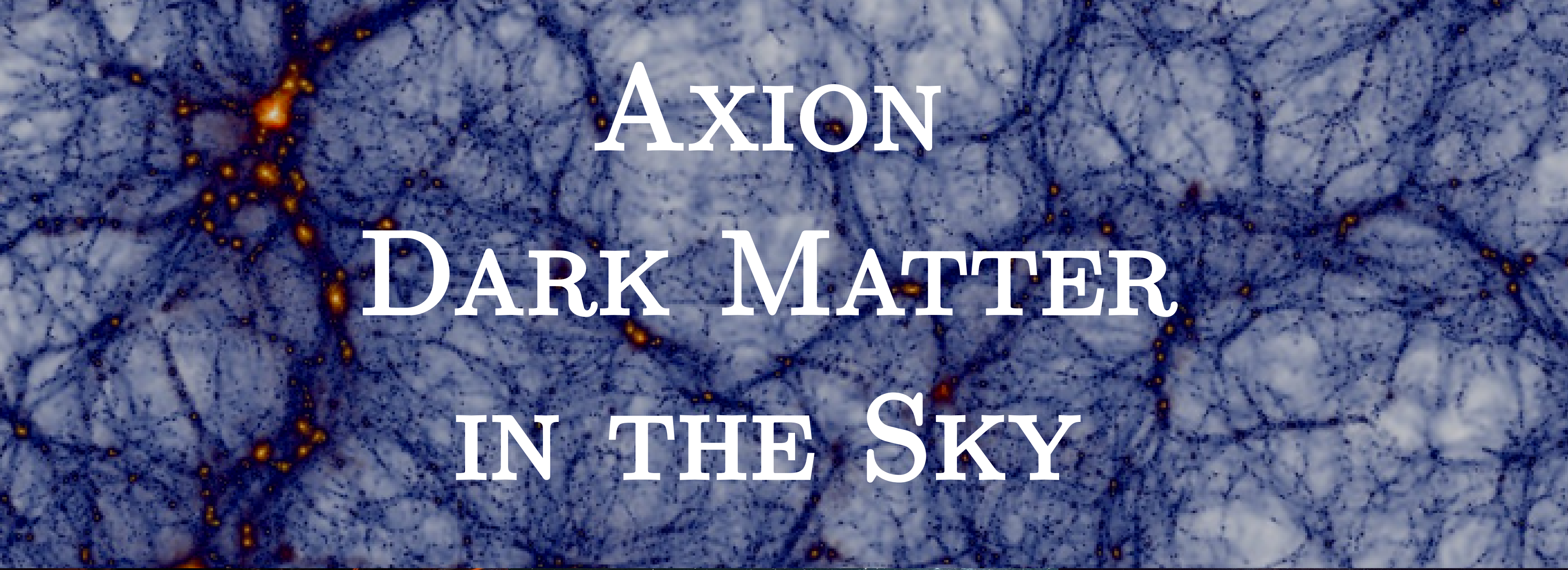
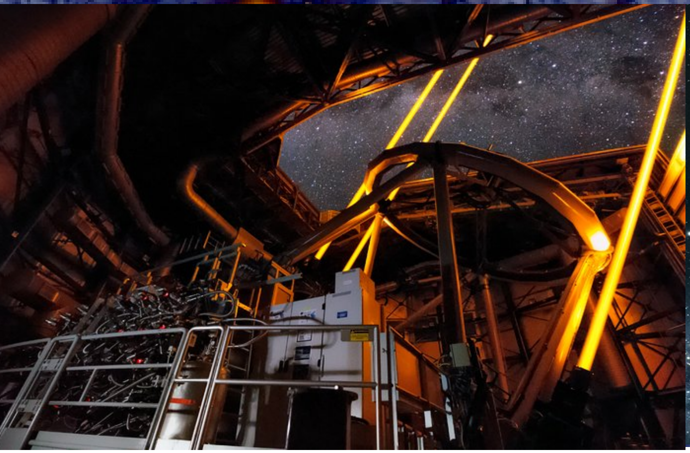
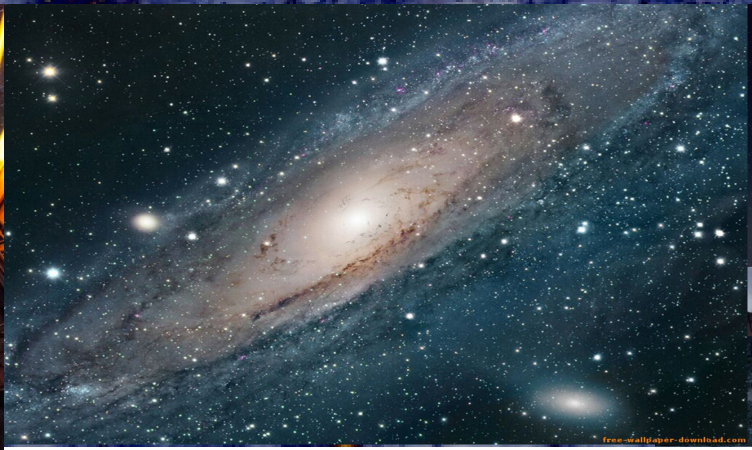


Axion Dark Matter in the Sky





UNIVERSITÀ DI TORINO

Marco Regis

INFN Istituto Nazionale di Fisica Nucleare

Which solution?

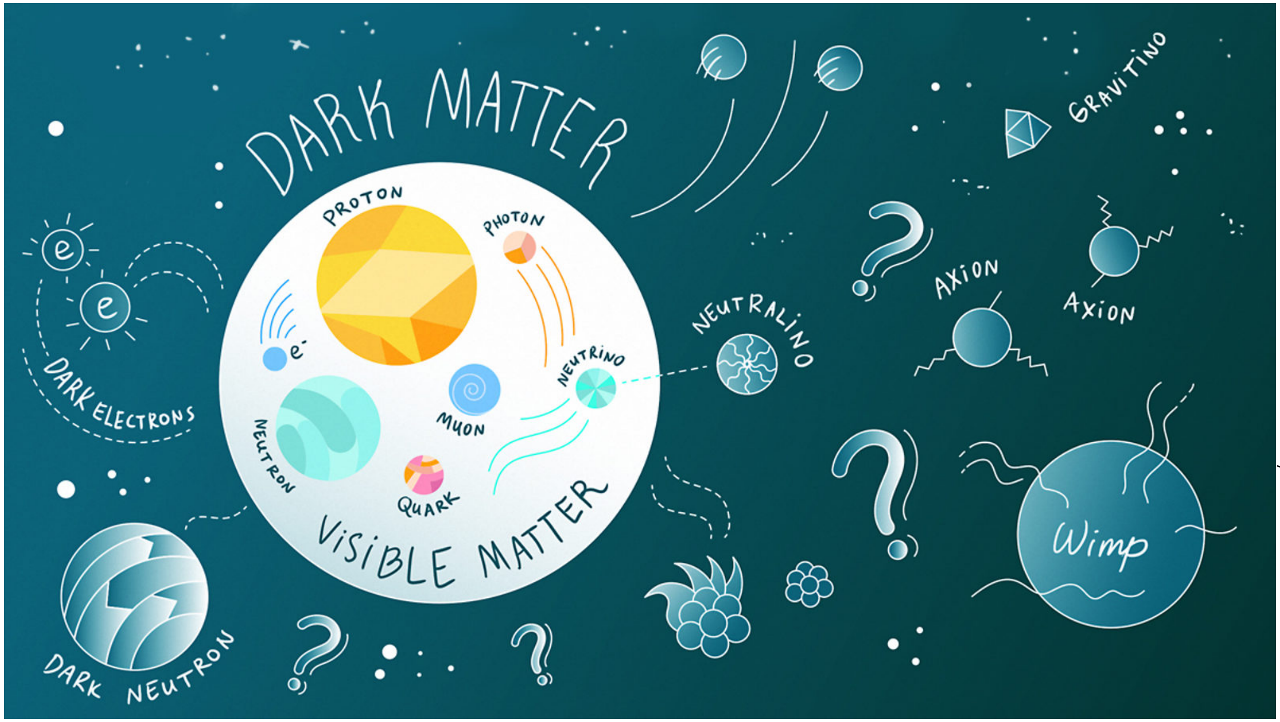
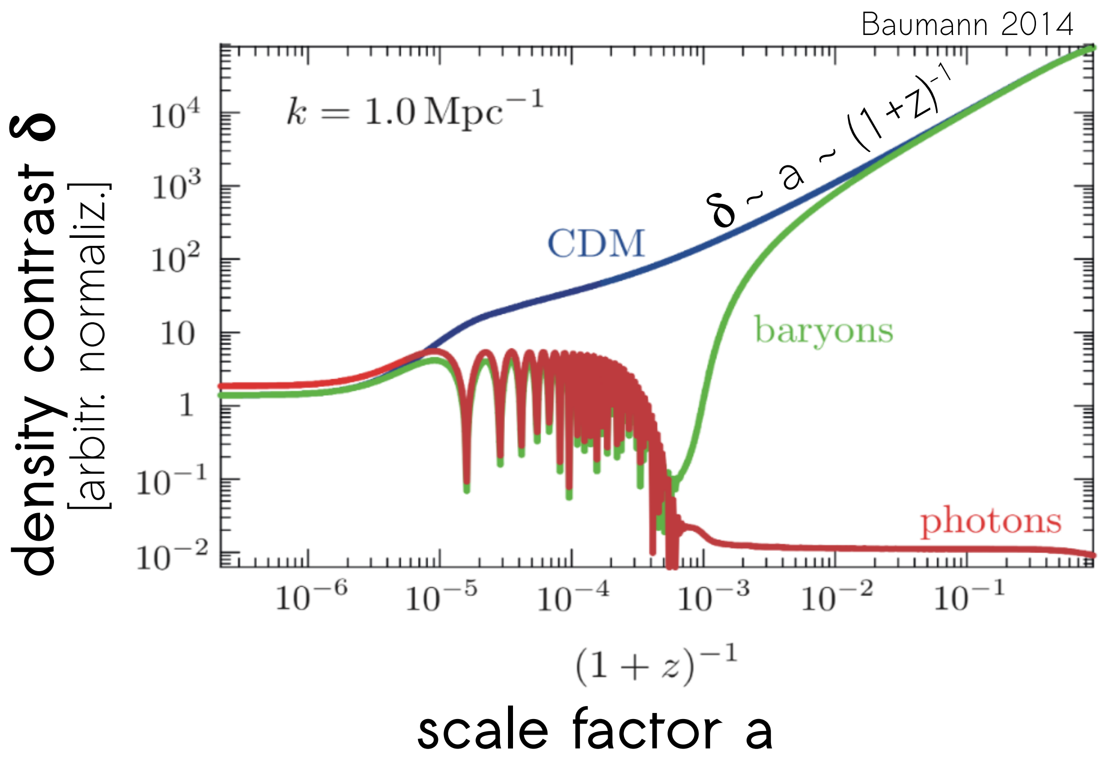


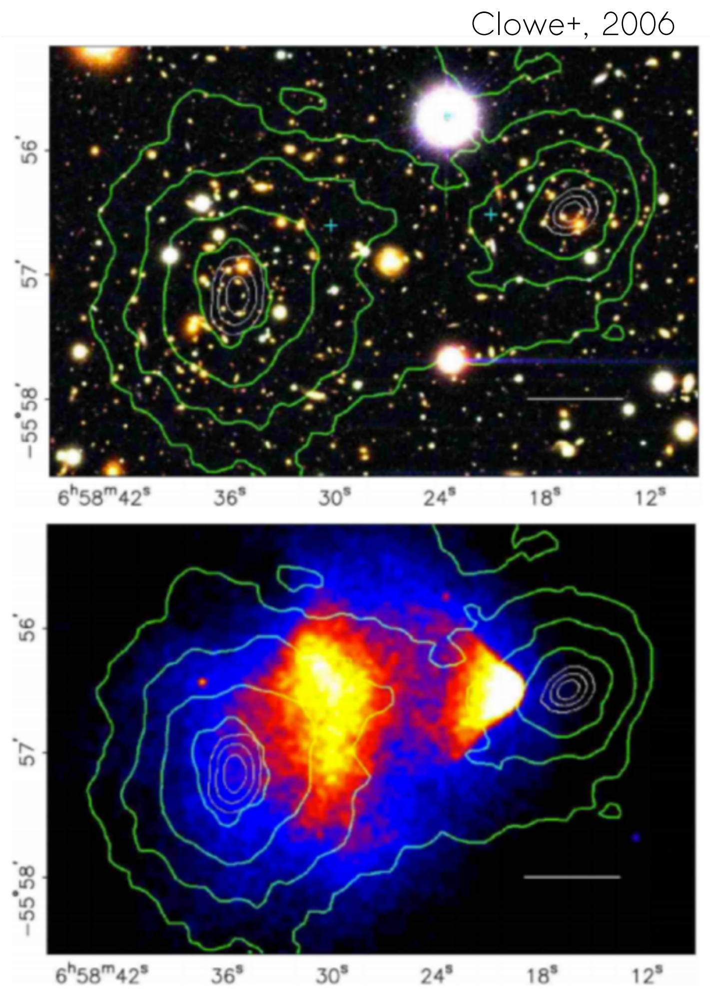
Illustration by Sandbox Studio

- Modified Gravity
- New Particle beyond the Standard Model
- Baryonic Dark Matter

MODIFIED GRAVITY

Remarkable successes on galactic scales
Difficult to make it working on larger scales



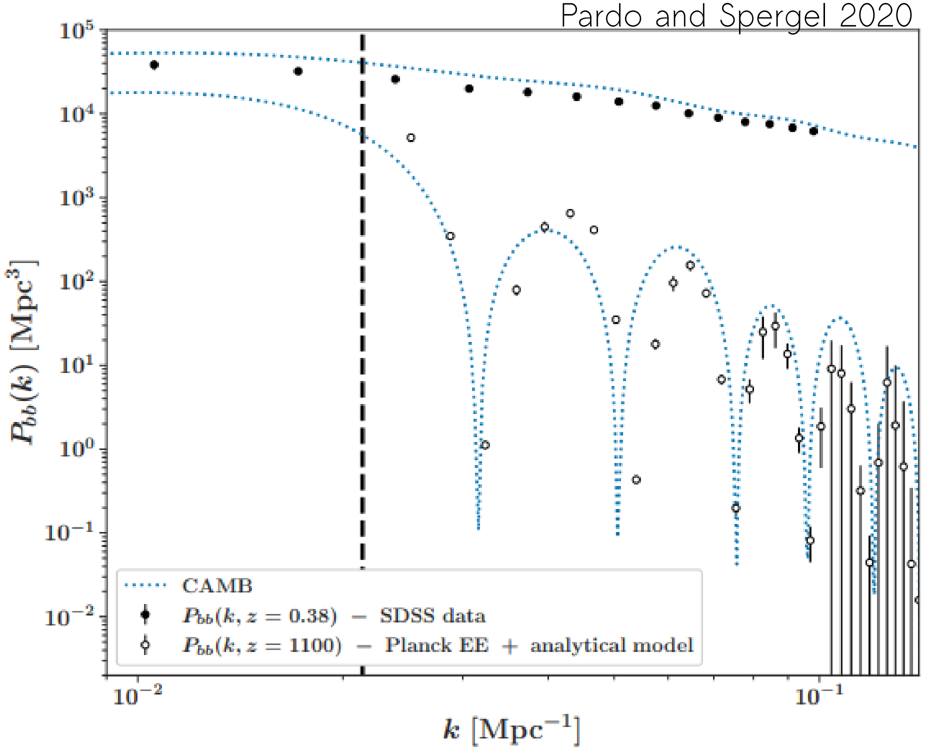


MODIFIED GRAVITY

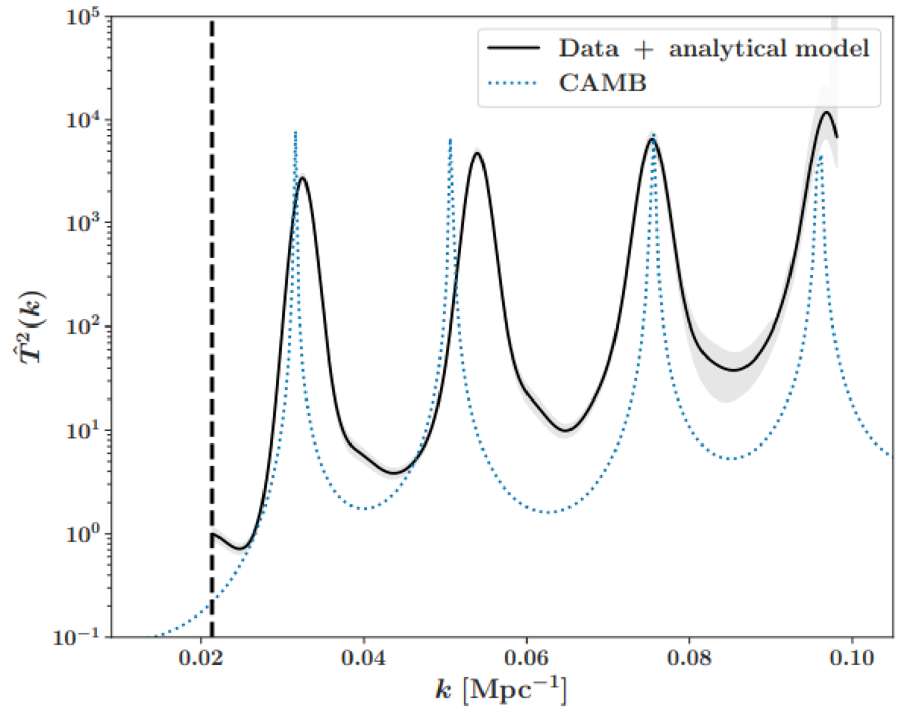
Remarkable successes on galactic scales

Difficult to make it working on larger scales

Pardo and Spergel 2020



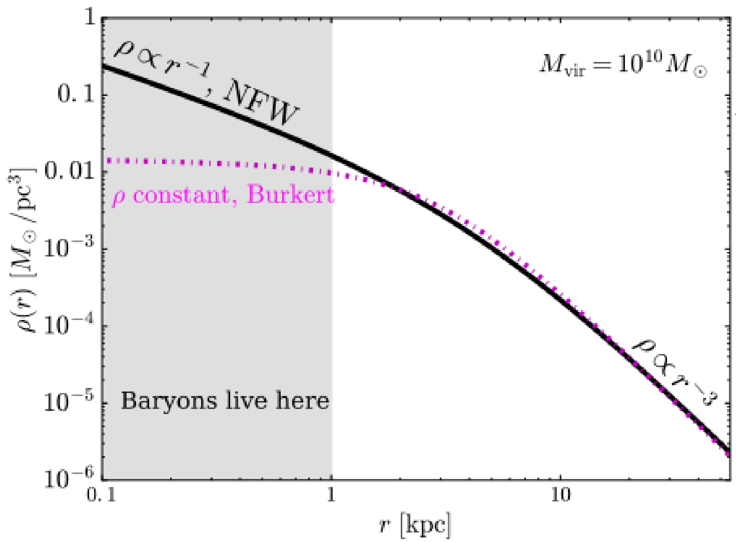
$$\hat{T}_b^2(k) = \frac{P_{bb}(k, z \sim 0)}{P_{bb}(k, z = 1100)}$$



NEW PARTICLE
BEYOND the STANDARD MODEL

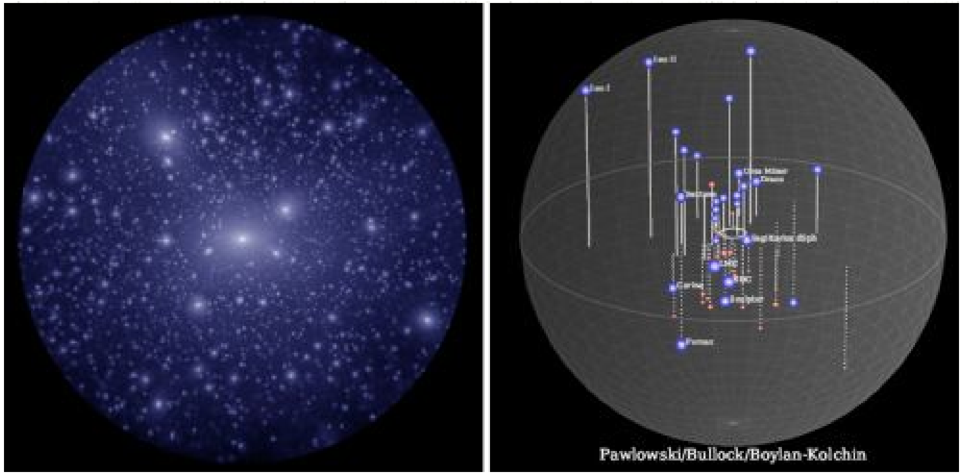
some "gastrophysics" is needed
to make it fully working at small scales

CUSP-CORE



Buckley&Peter 2017

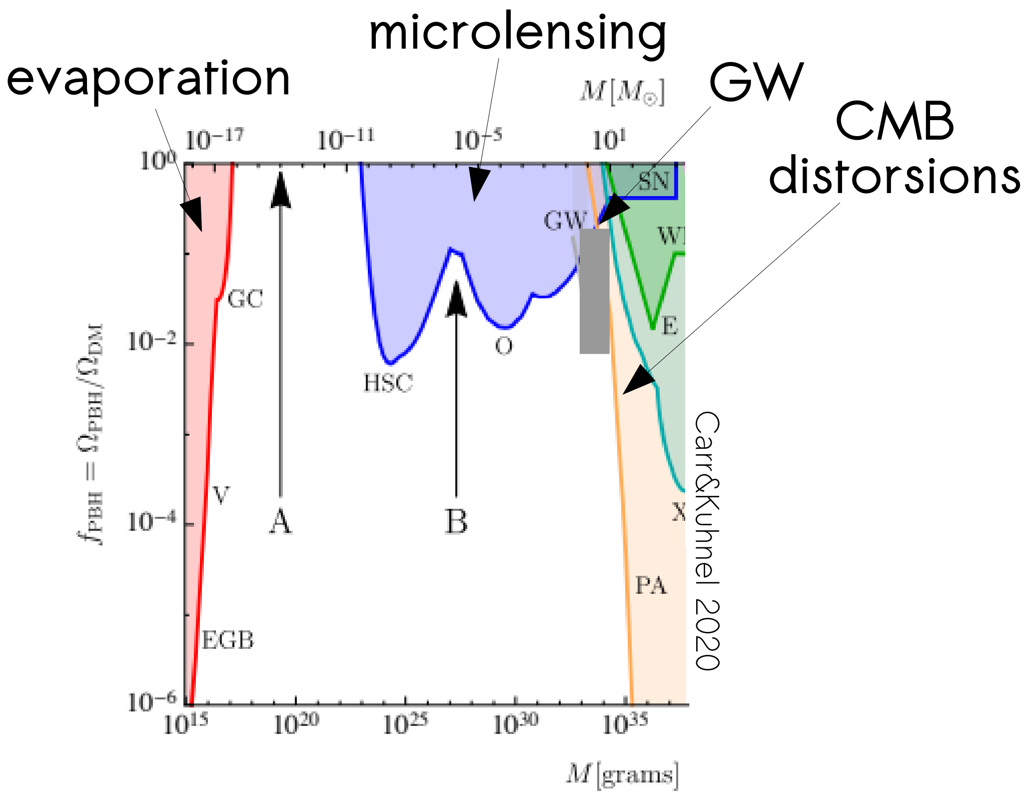
MISSING SATELLITES (too-big-to-fail)



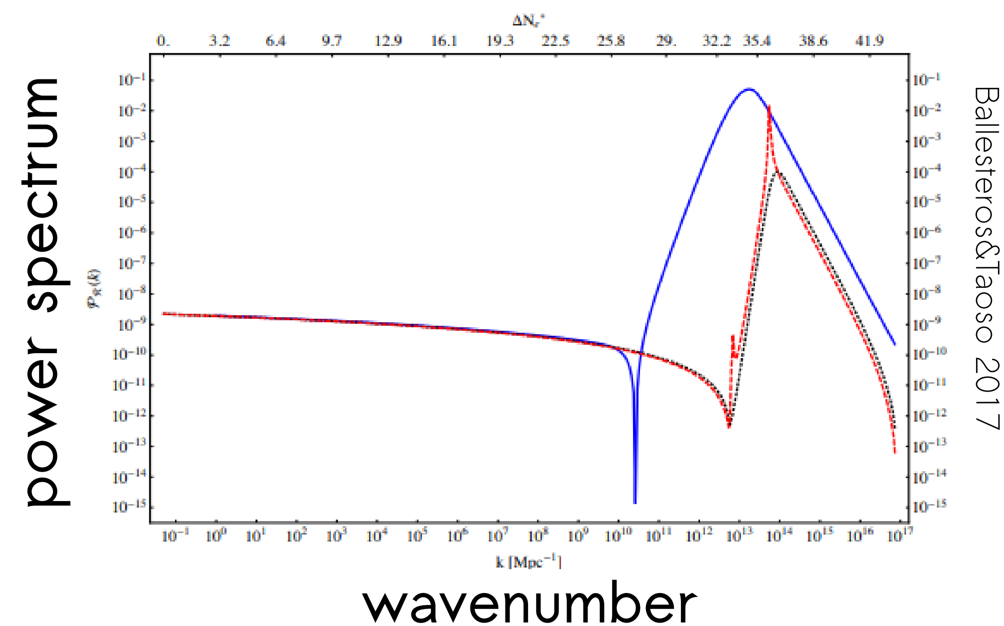
BARYONIC DARK MATTER

needs to be decoupled before BBN

- very compact primordial objects: **primordial black holes**
- **new composite states** made of standard model particles



Production mechanism?

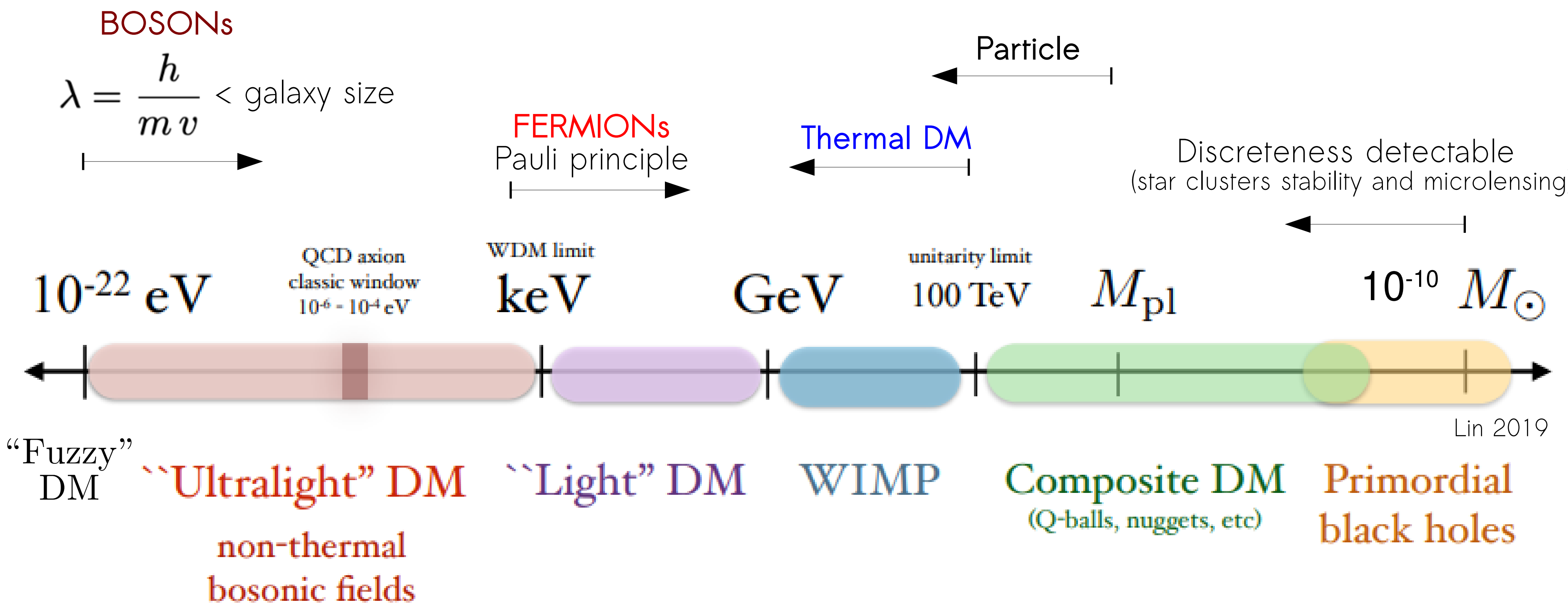


DM fundamental properties

A successful DM candidate:

- Dark and dissipationless (usually neutral)
- Collisionless (or with $\sigma/m < cm^2/g$)
- Cold (or Warm)
- Stable or long lived (lifetime > age of the U. ~ 13 Gyr)
- Produced in the early Universe
- Not too light / not too heavy

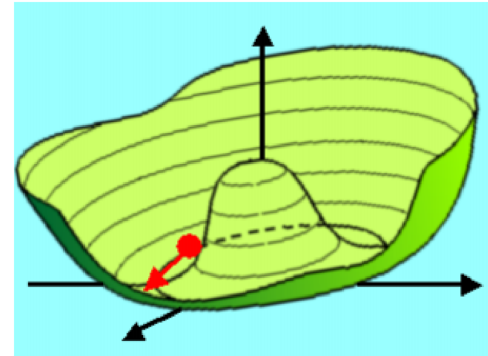
DM fundamental properties - mass



Not too light - Not too heavy
but still quite a wide range of possibilities!

ALPs (Axion-Like Particles)

(pseudo-)scalar particles
mainly pseudo-Nambu-Goldstone bosons
(QCD axion, many "stringy" axions, ...)

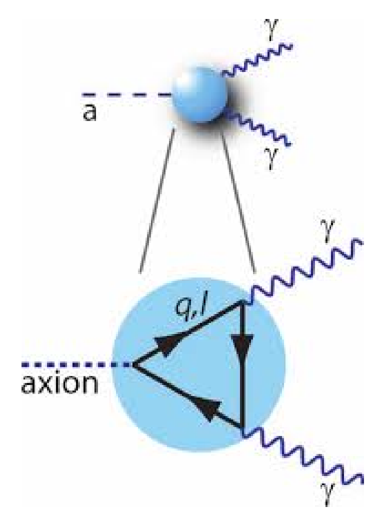


assumption:
ALPs constitute (a fraction of) the DM content in the Universe

photon coupling:
ALP-photon coupling
described by the low-energy
effective Lagrangian:

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

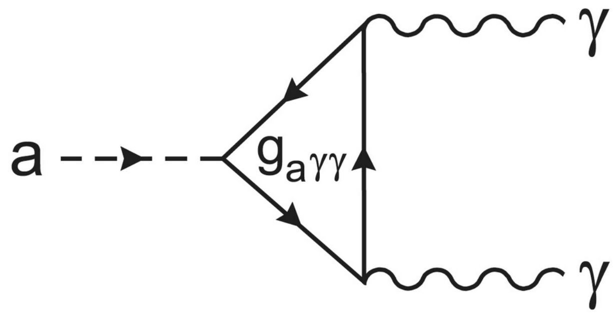
→ decay/conversion
into photon(s)
→ "monochromatic"
emission



ALP phenomenology (photons)

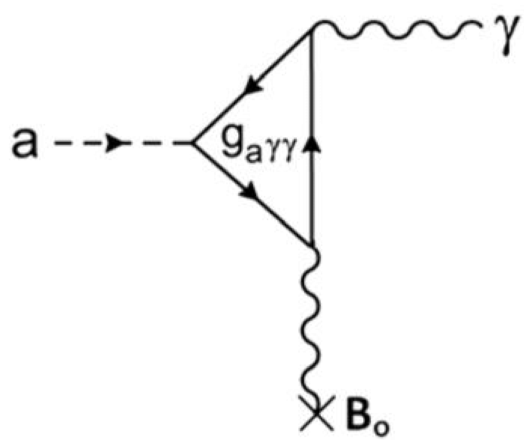
The ALP-photon coupling → phenomenology related to

decay



discussed in this talk

conversion

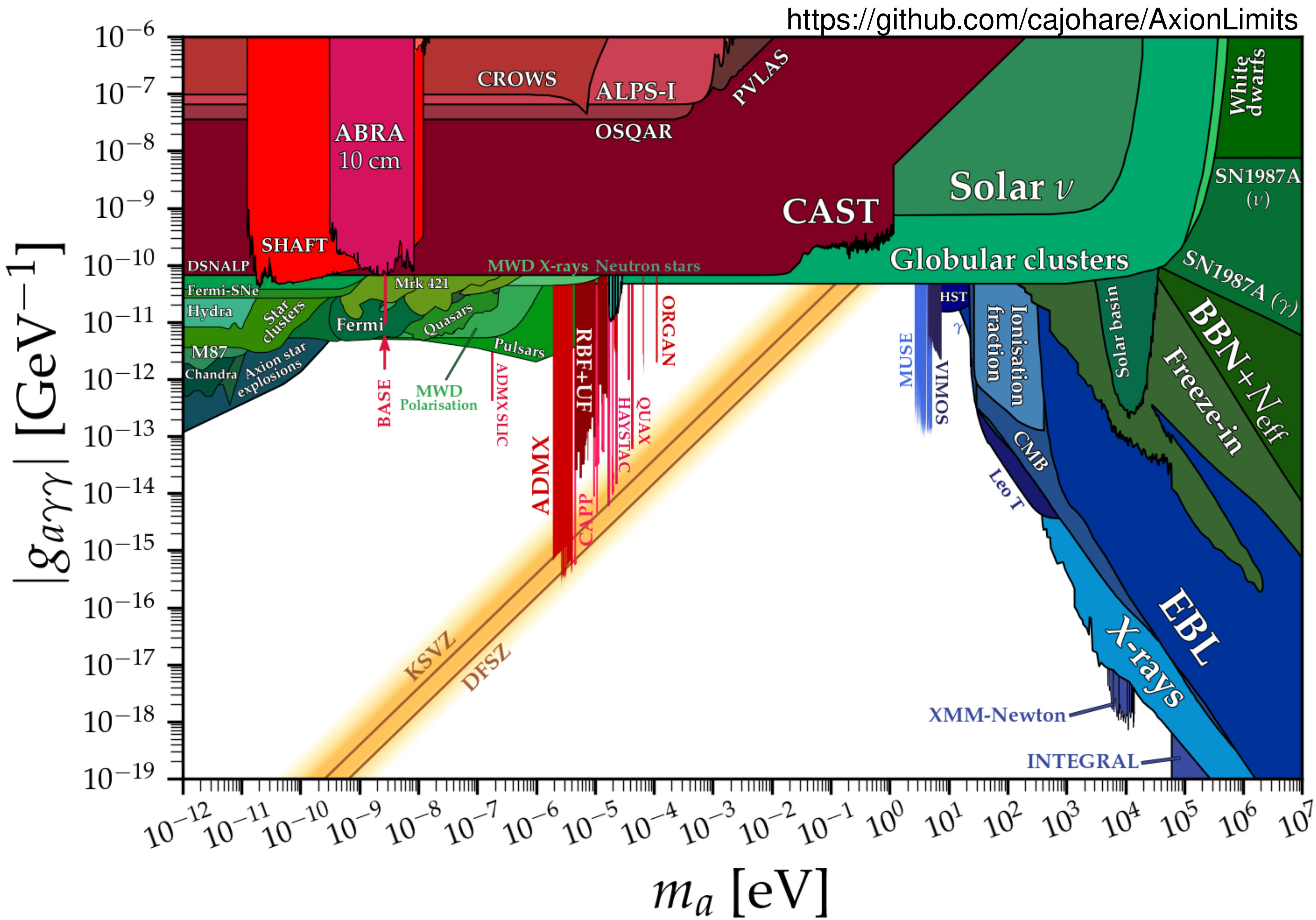


needs large magnetic field

- created in lab (haloscopes)
- extreme astro objects (e.g. neutron stars)

Or **inverse processes** (γ-ray tansparency, stellar cooling, ...)

Bounds on ALPs



Outline

Looking for a photon monochromatic emission at $E_\gamma \sim m_a/2$
given by ALP decay
from regions with high dark-matter density

For a good story:

Who? What? When? Where? Why?

Outline

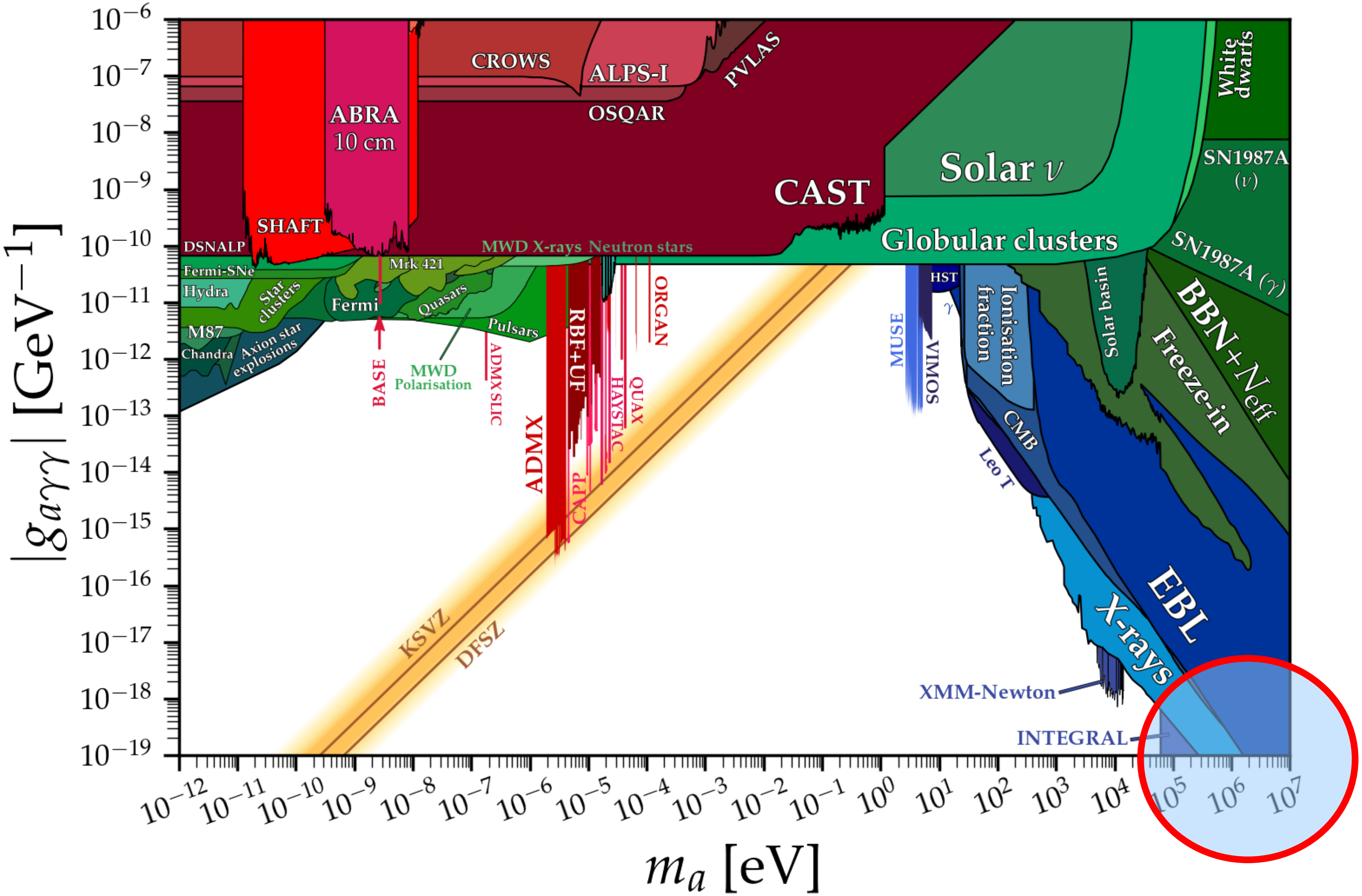
Looking for a photon monochromatic emission at $E_\gamma \sim m_a/2$
given by ALP decay
from regions with high dark-matter density

For a good story:

Who? What? When? Where? Why?

... let's take a journey across
different mass ranges and astrophysical targets
to see current bounds and near-future prospects

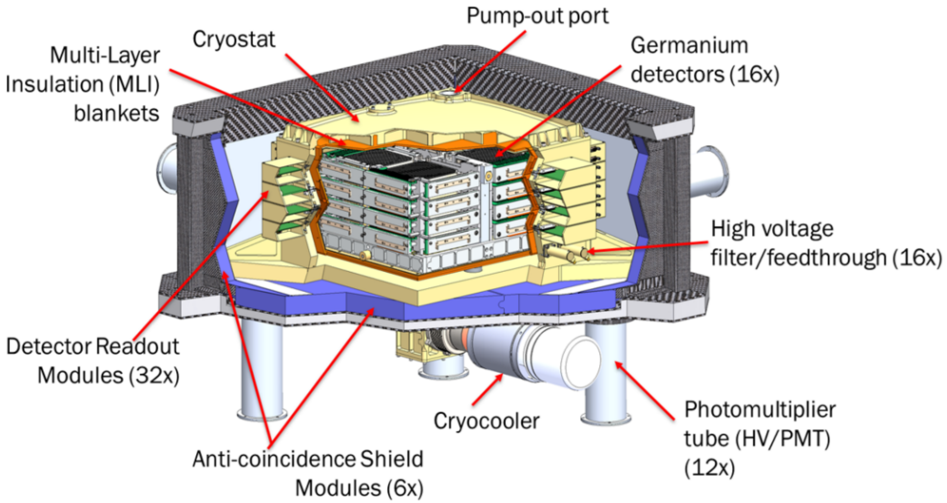
MeV ALPs (gamma-rays)

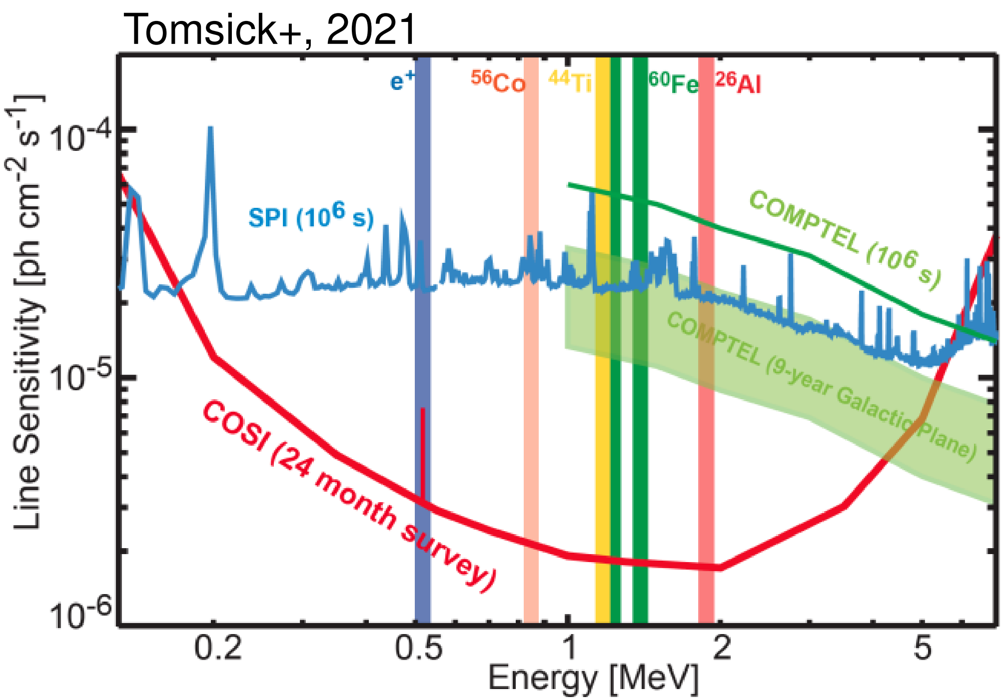


COSI telescope

Compton Spectrometer and Imager (COSI)
wide-FOV telescope designed to survey the γ-ray sky at 0.2-5 MeV
→ Imaging with high-resolution spectroscopy ($\Delta E/E \sim$ few x 10^{-3})

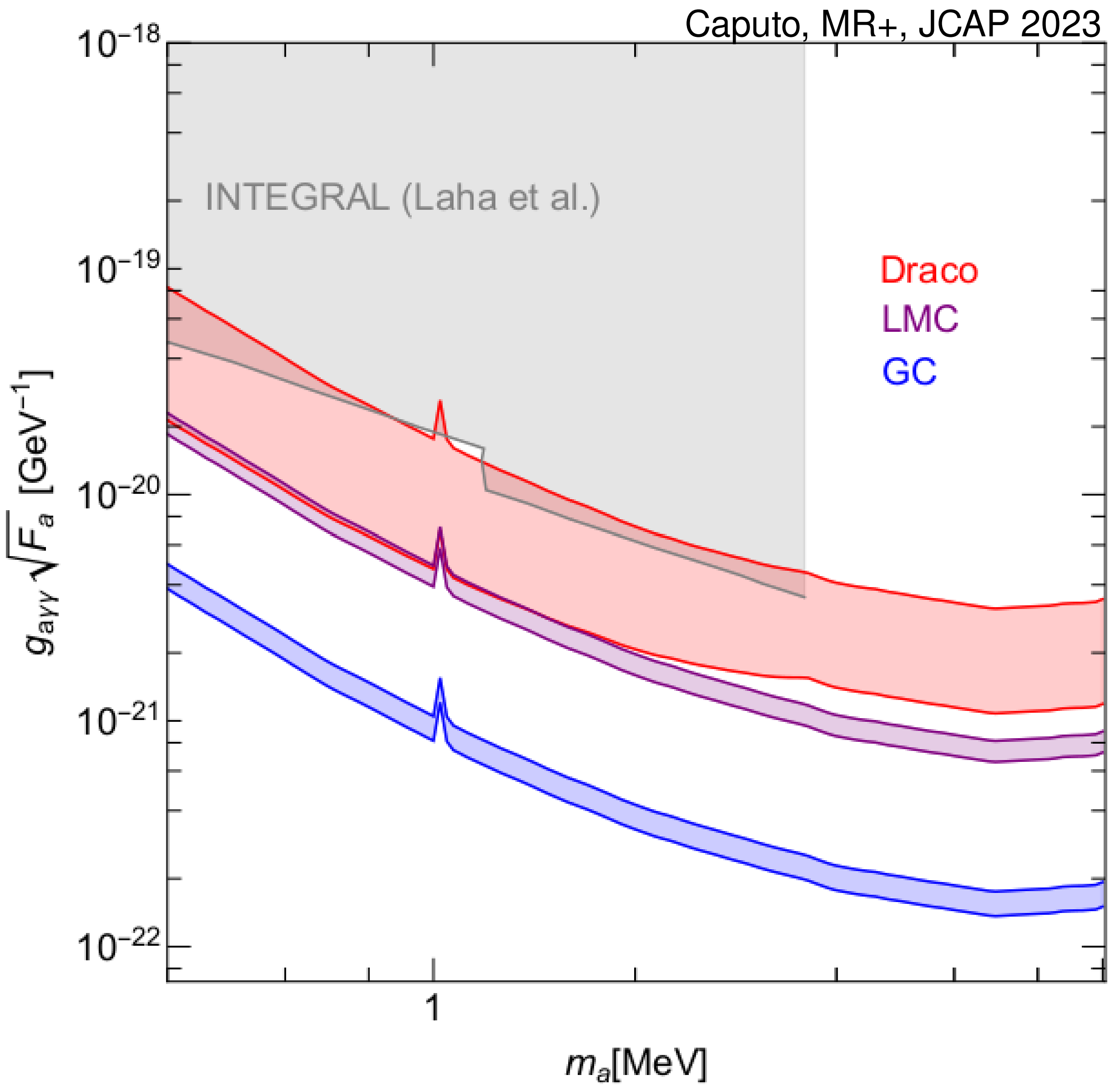
selected by NASA in October 2021, to be launched in 2027



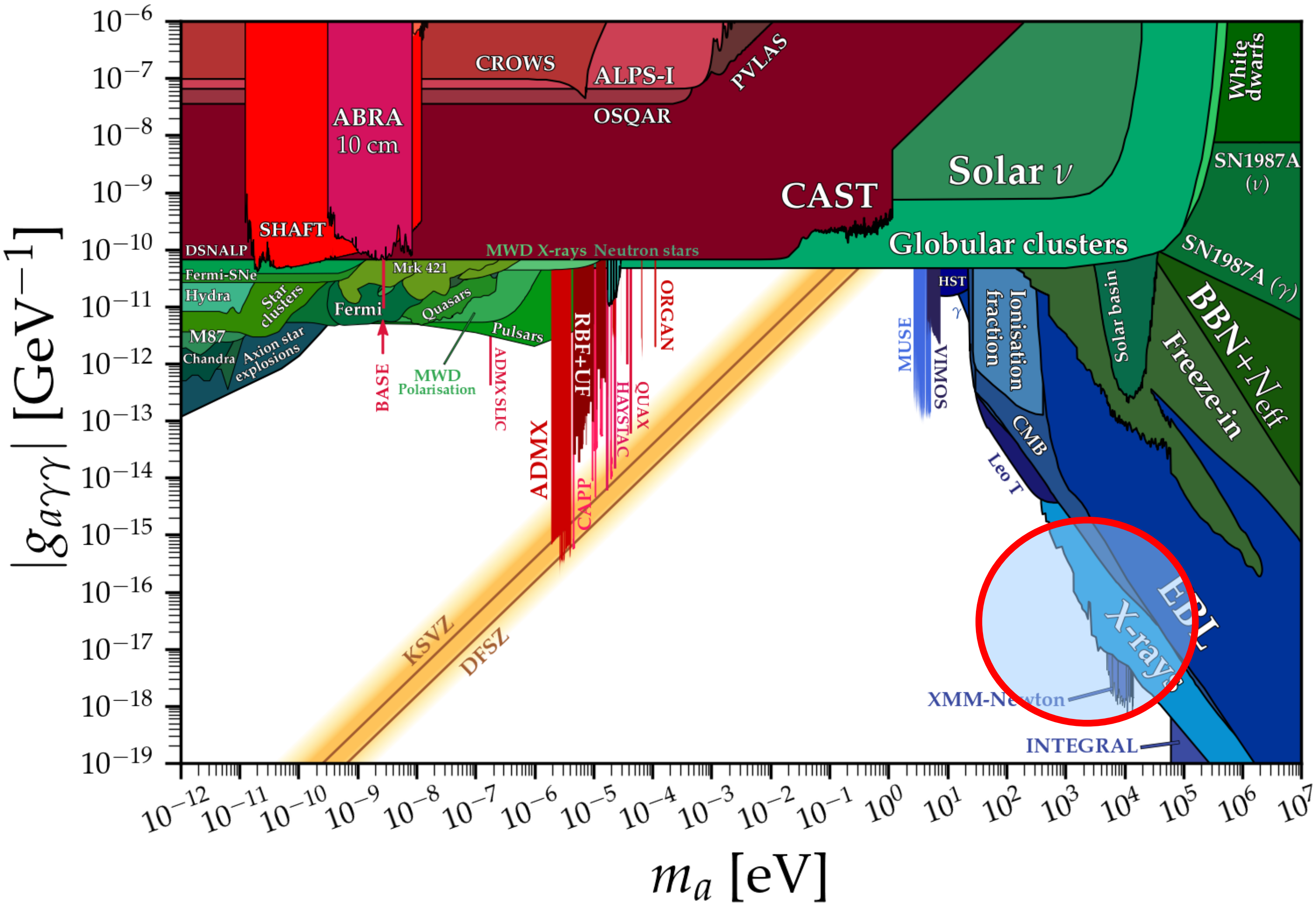


COSI sensitivity to MeV ALPs

Projected sensitivity compared to current bounds



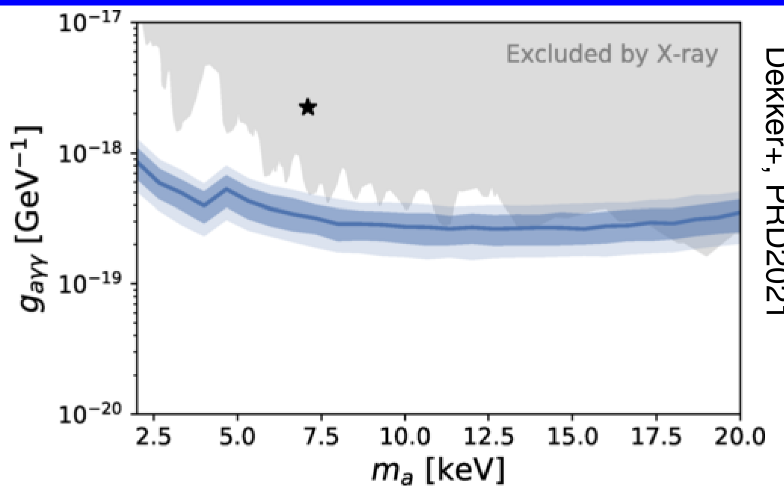
keV ALPs (X-rays)



X-rays and ALPs

eROSITA [0.2-8 keV]

data from Dec. 2019 to Feb. 2022
(about half-way)



Dekker+, PRD2021

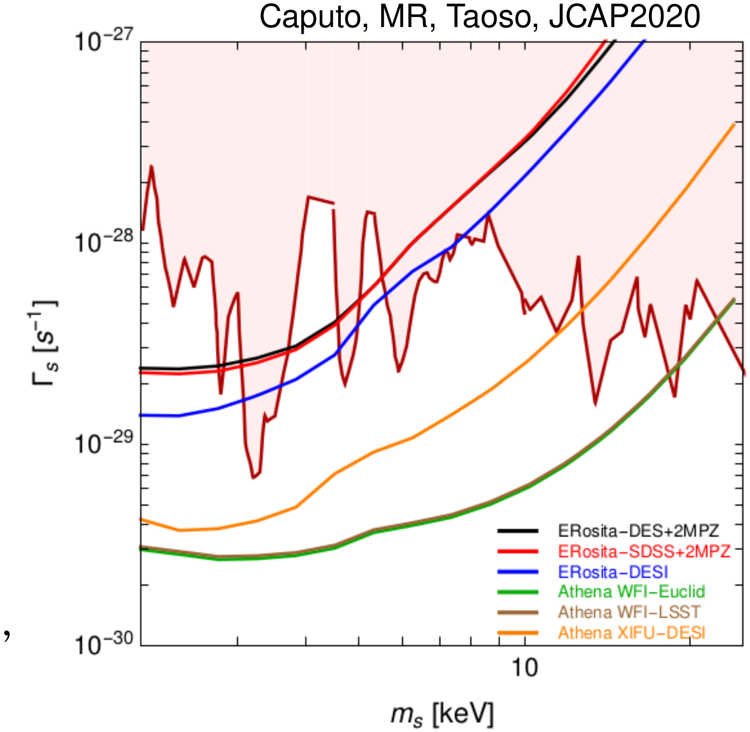
Line Intensity Mapping

ALP decay → photons at $E_e = m_a/2$ in the rest frame
If the ALP is at redshift z_e, we see $\mathbf{E_{obs} = m_a/2/(1+z_e)}$

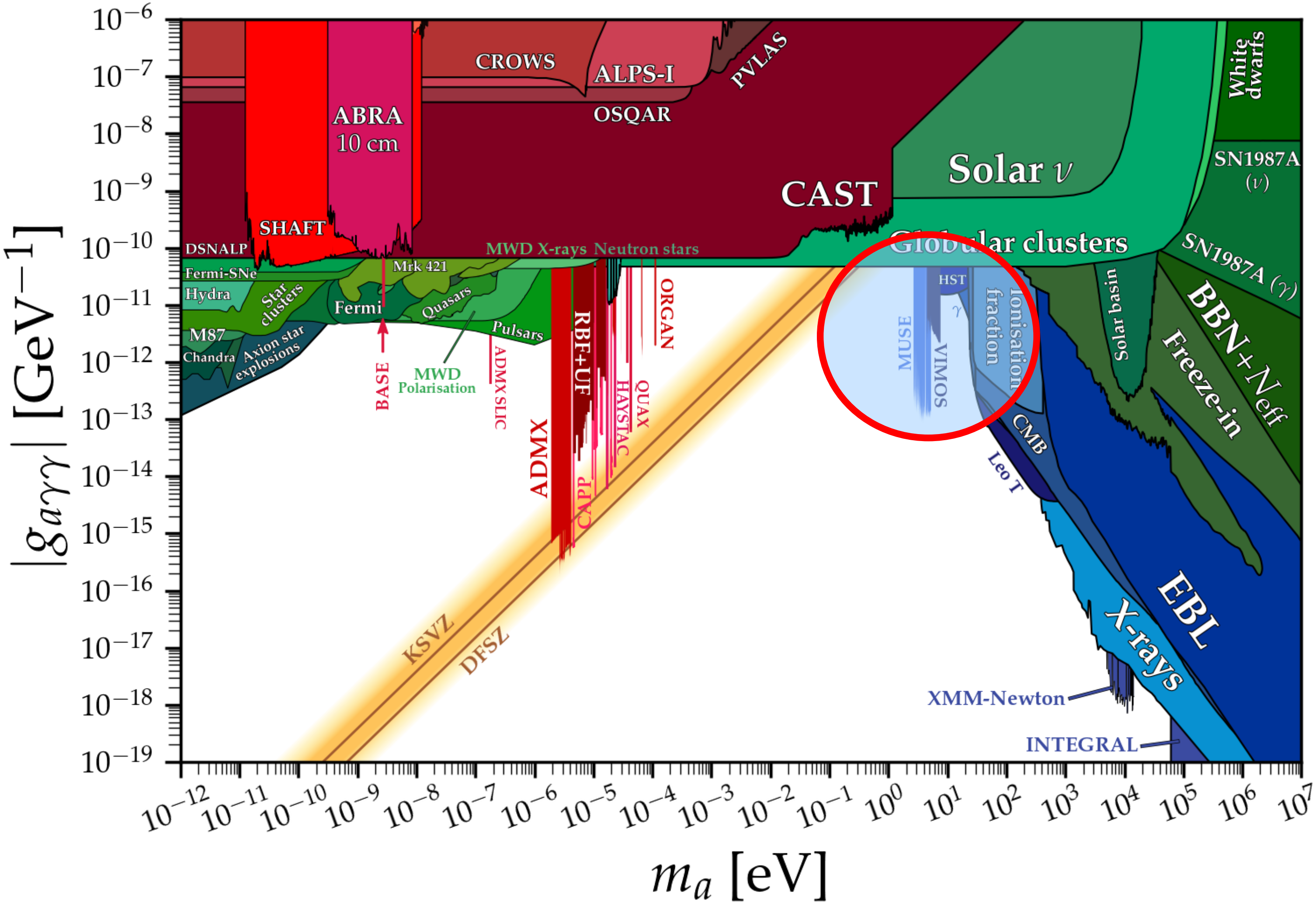
→ The ALP emission should show a **correlation with large-scale structures** at redshift $z = z_e$ and no correlation with LSS at $z \neq z_e$.

If DM is made of ALPs
→ line intensity mapping competing with lensing, galaxy counts, etc.. in cosmological searches

Caputo, MR, Taoso, JCAP2020



eV ALPs (optical)



ALP signal

To observe photons from ALP decays we need an experiment with:
- good frequency resolution
- decent FoV
- good angular resolution
- good sensitivity

... and observing the DARKNESS!

→ muse

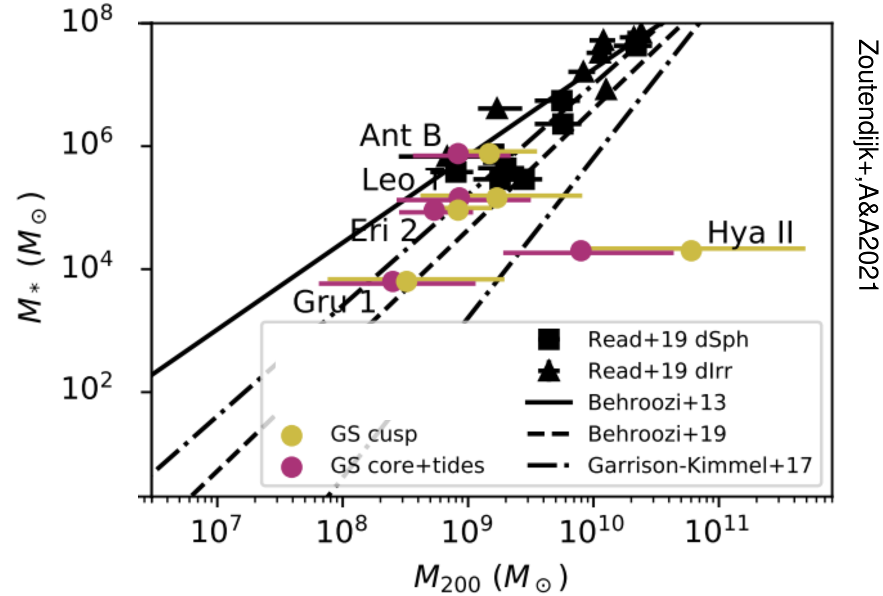
multi unit spectroscopic explorer

on the VLT at Paranal Observatory (ESO)

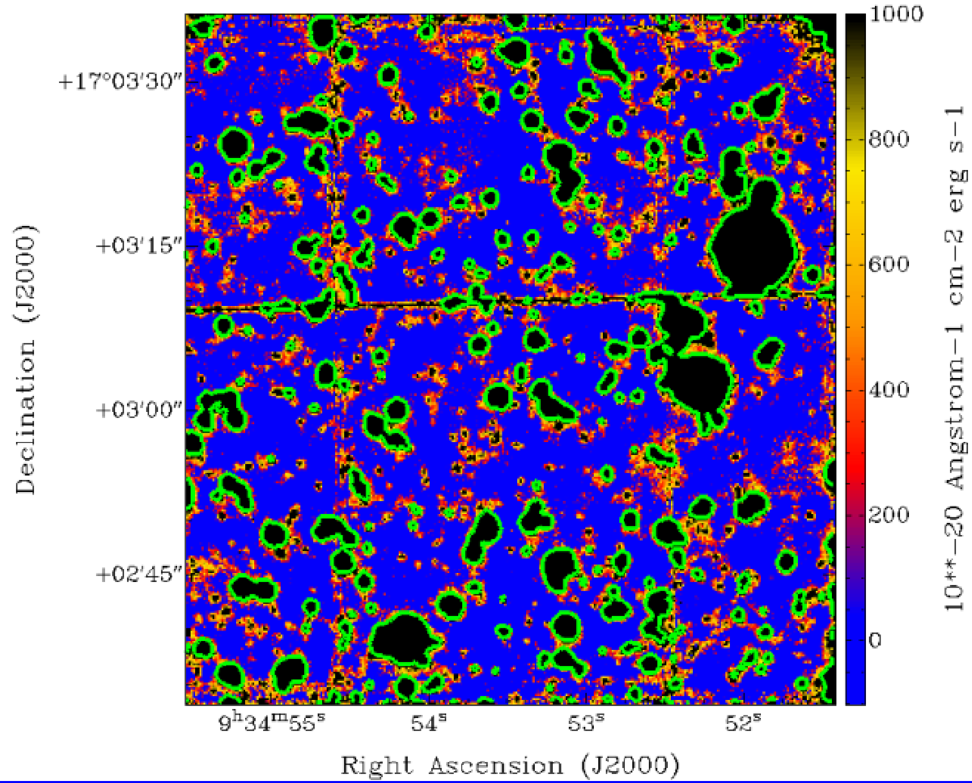
λ = 465-930 nm
ang. res. < 1 arcsec
spectr. res. $\Delta E/E < 10^{-3}$

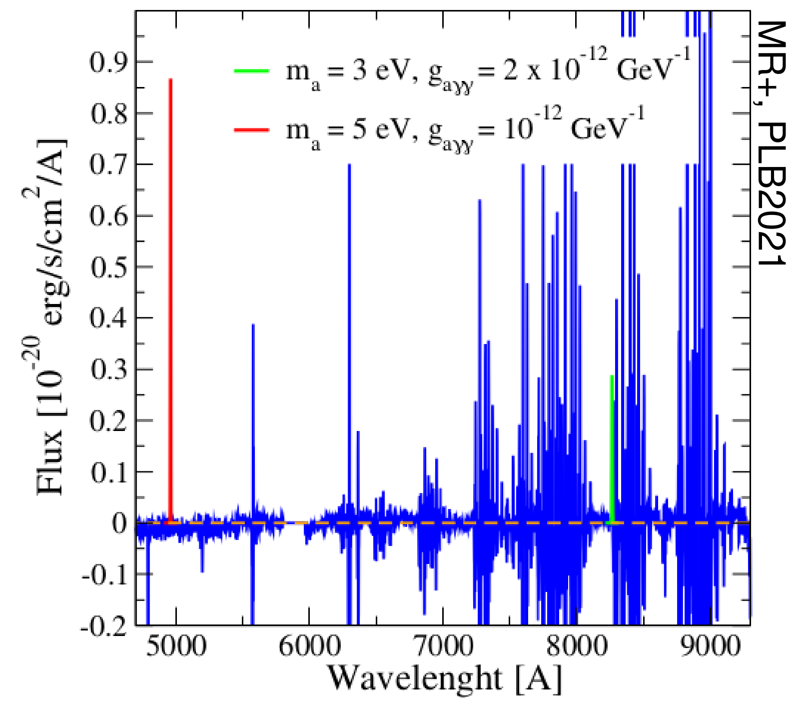
Credit: Roland Bacon/ESO

MUSE observations of five dwarf spheroidal galaxies:



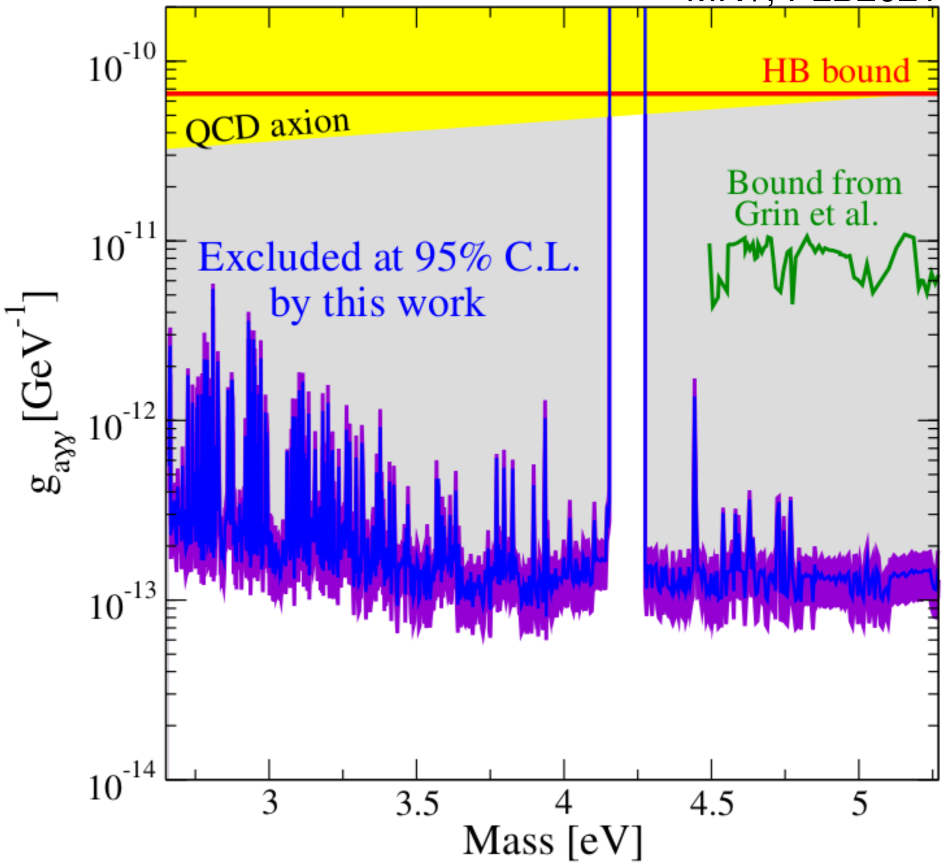
Example: LeoT



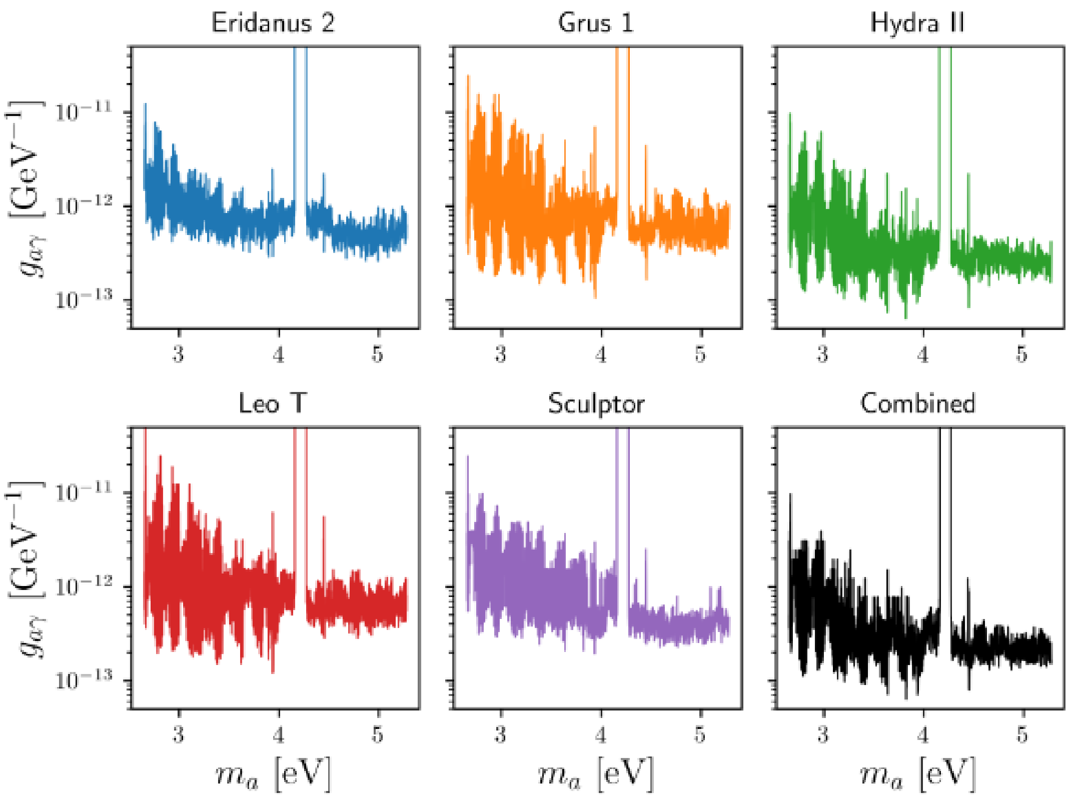


Bounds on ALPs

MR+, PLB2021

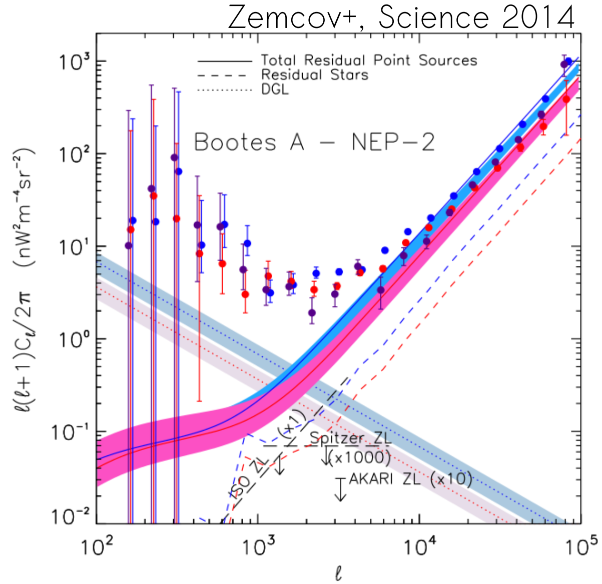


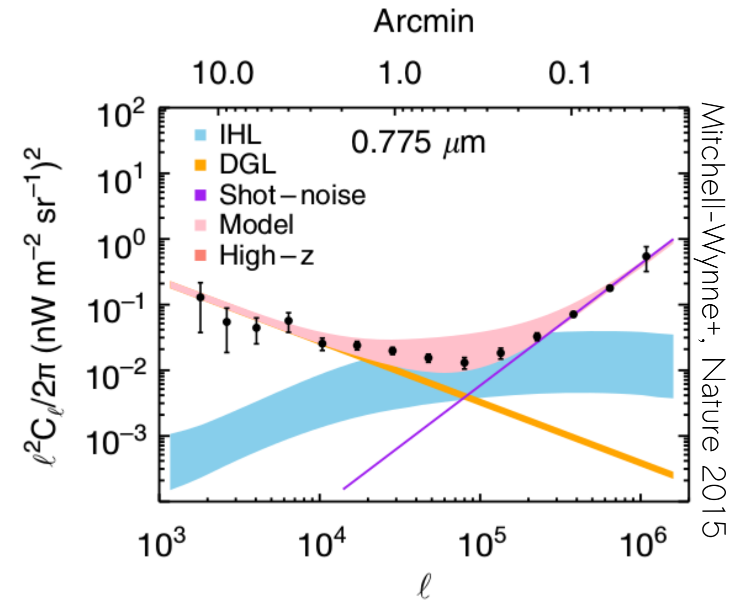
Todarello, MR+, in preparation



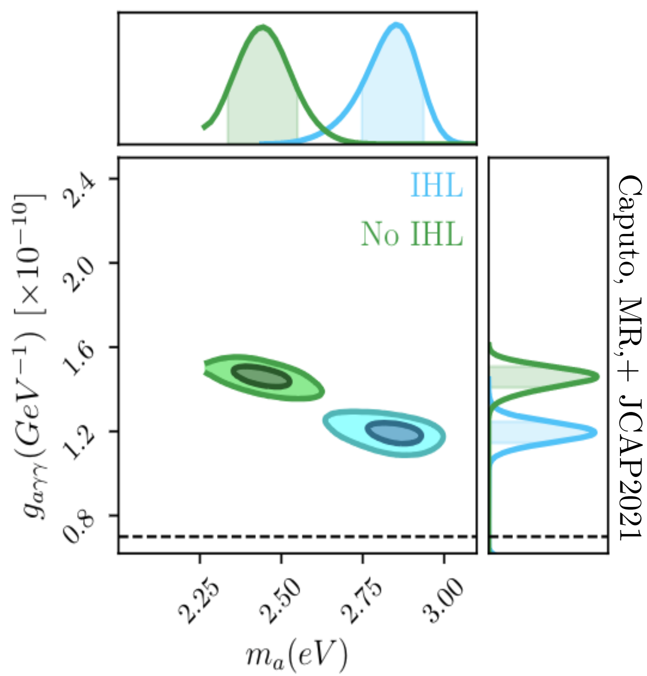
NIRB and Axion-like Particles

Excess in the NIRB autocorrelation angular power spectrum (0.6-4.5 μm)



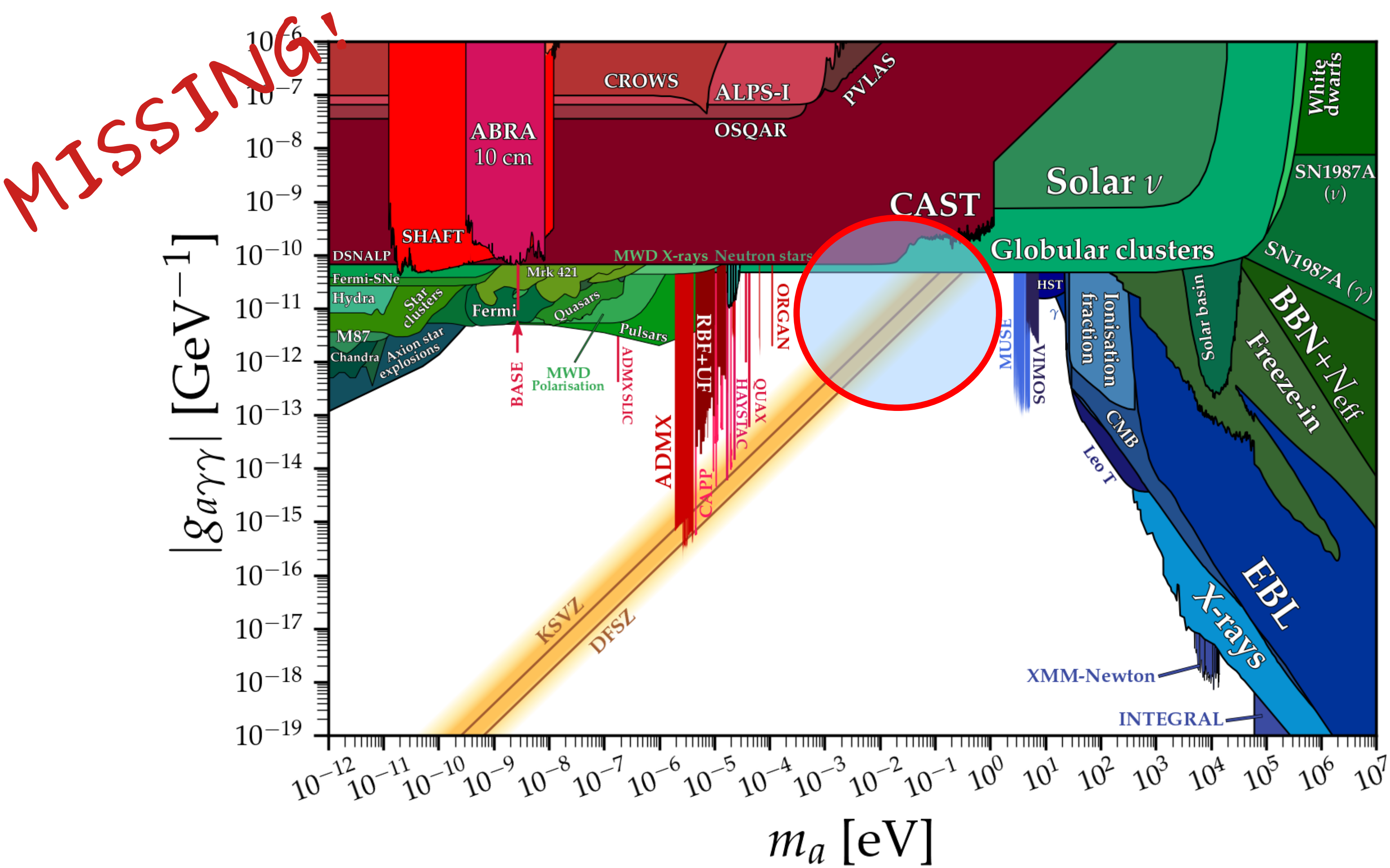


ALP interpretation of the NIRB excess **revisited**:

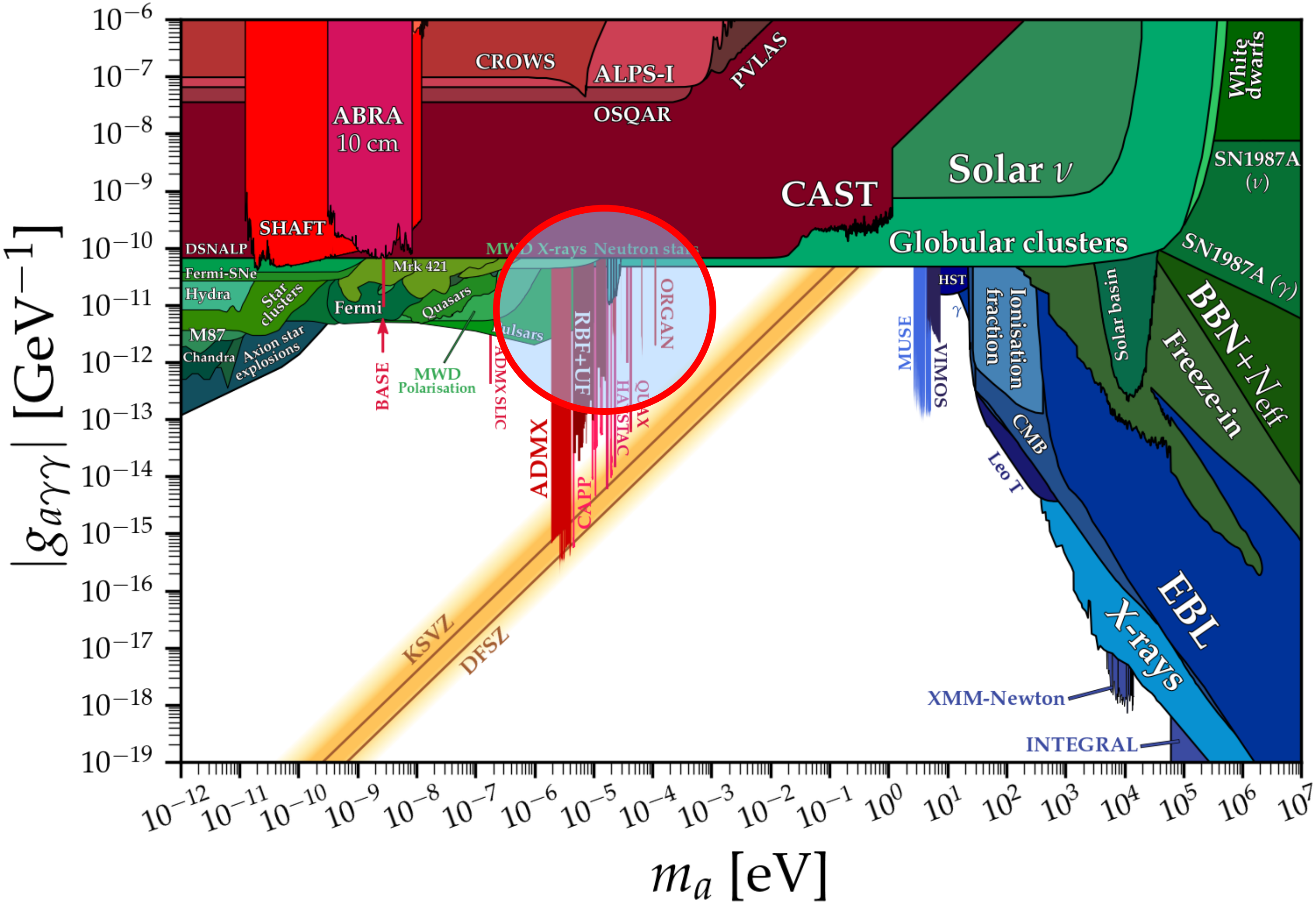


→ more from JWST

few meV ALPs (far infrared)

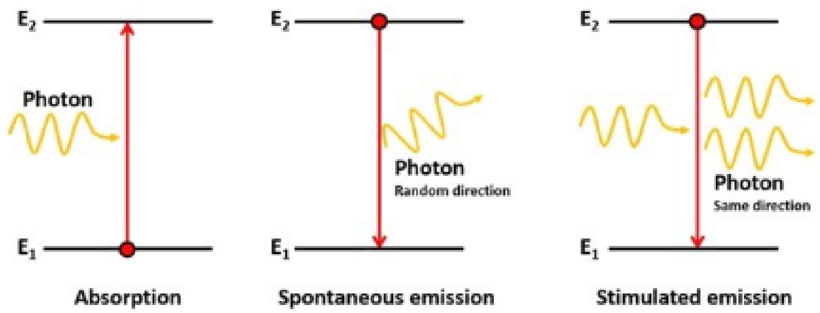


μeV ALPs (radio)



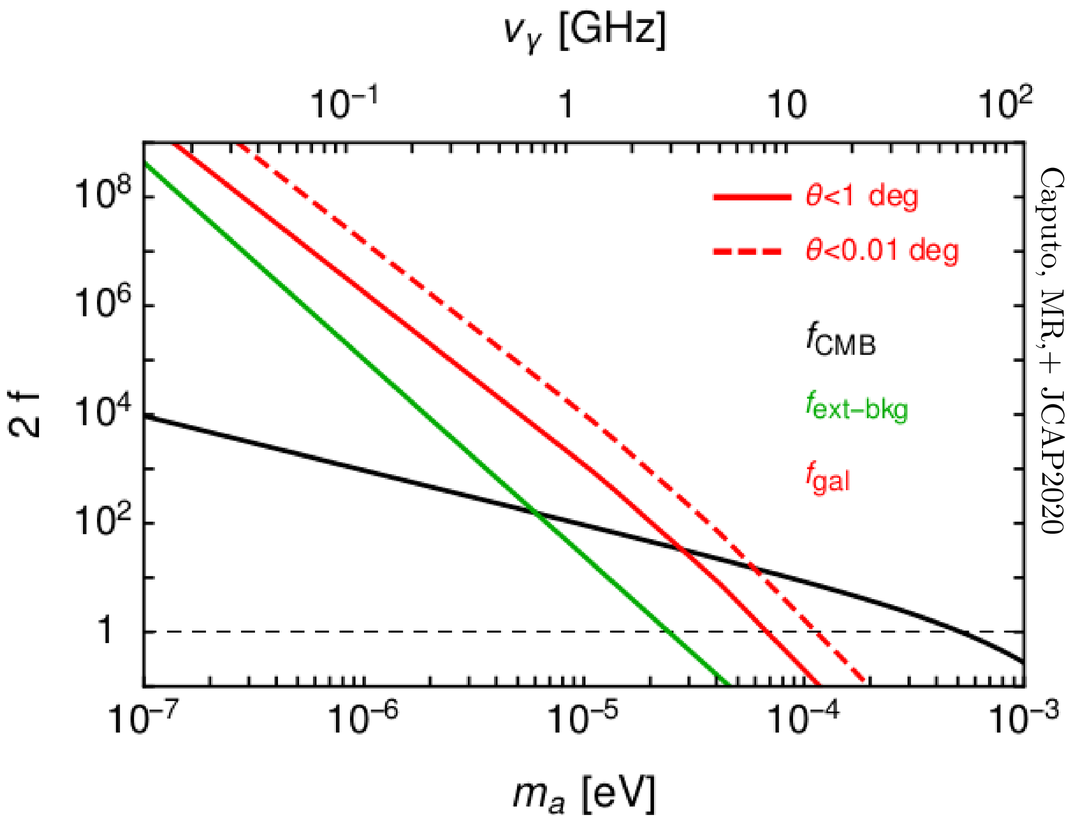
ALP stimulated decay

Stimulated decay



$$2f = \frac{\text{stimulated emission}}{\text{spontaneous emission}}$$

$$f_\gamma = \frac{\pi^2 \rho_\gamma}{E_\gamma^3}$$



Decay rate: $\Gamma_a \equiv g^2_{a\gamma\gamma} m_a^3/(64\pi)$

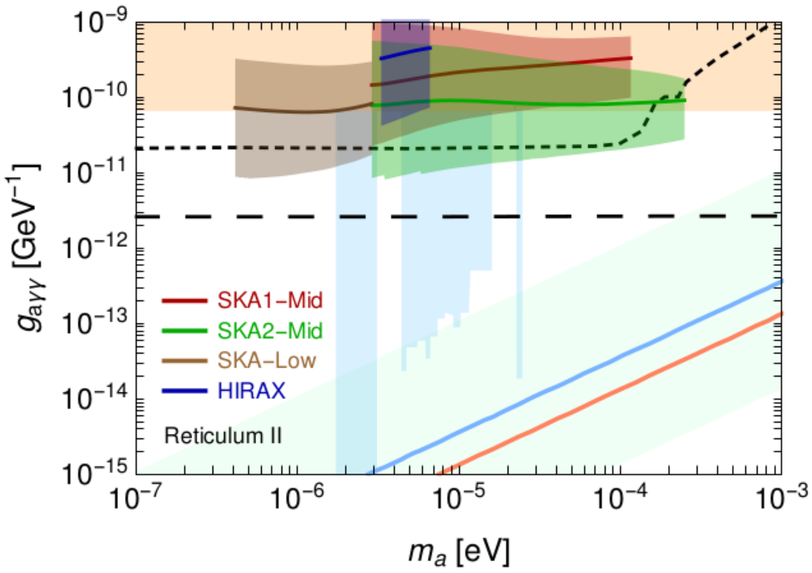
Flux: $S_{\rm decay} = \frac{\Gamma_a}{4\pi\Delta\nu}\int d\Omega\, d\ell\, \rho_a(\ell,\Omega)\,[1 + 2f_\gamma(\ell,\Omega,m_a)]$

ALP stimulated decay - projected limits

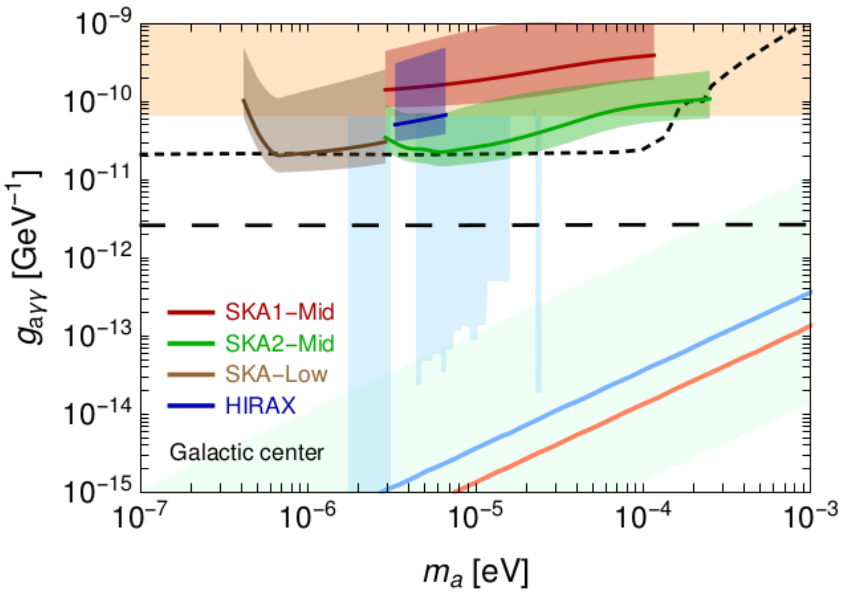
Stimulated emission within the source

Caputo, MR,+ JCAP2019

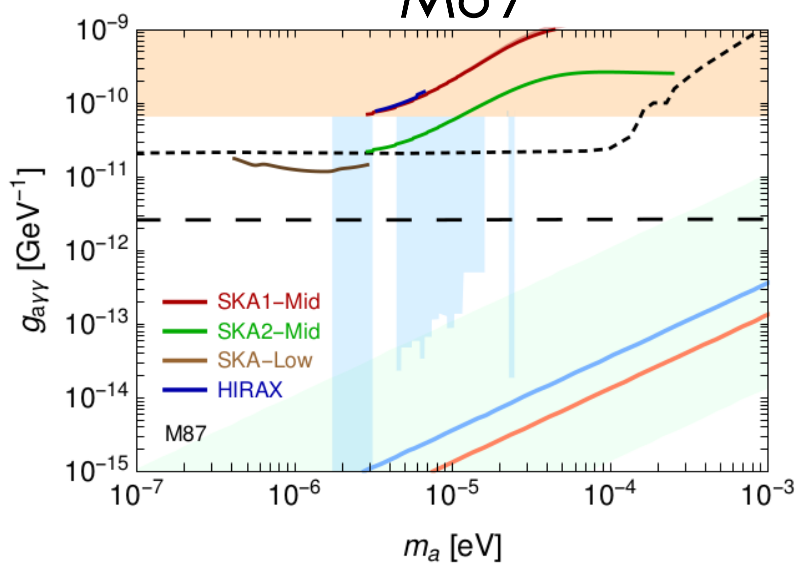
Dwarf spheroidal galaxy



Galactic Center



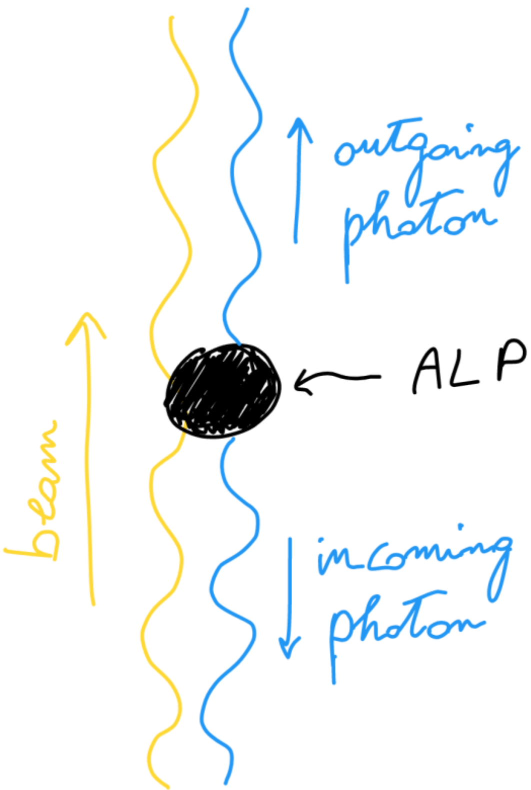
M87



See also
Caputo+ PRD2018
Battye+ PRD2020
Ayad&Beck JCAP2022

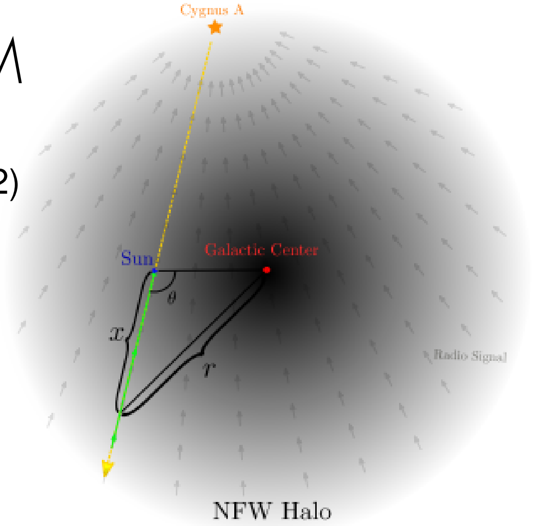
ALP stimulated decay - echo

The ALP stimulated decay can be used to
listen for the echo of a powerful radio beam
(i.e. faint radio line traveling in the ~opposite direction)



ARTIFICIAL BEAM
(Arza&Sikivie PRL2019, Arza&Todarello PRD2022)

ASTRO BEAM
(Ghosh+ 2020
Sun+ PRD2022
Buen-Abad+ PRD2022)

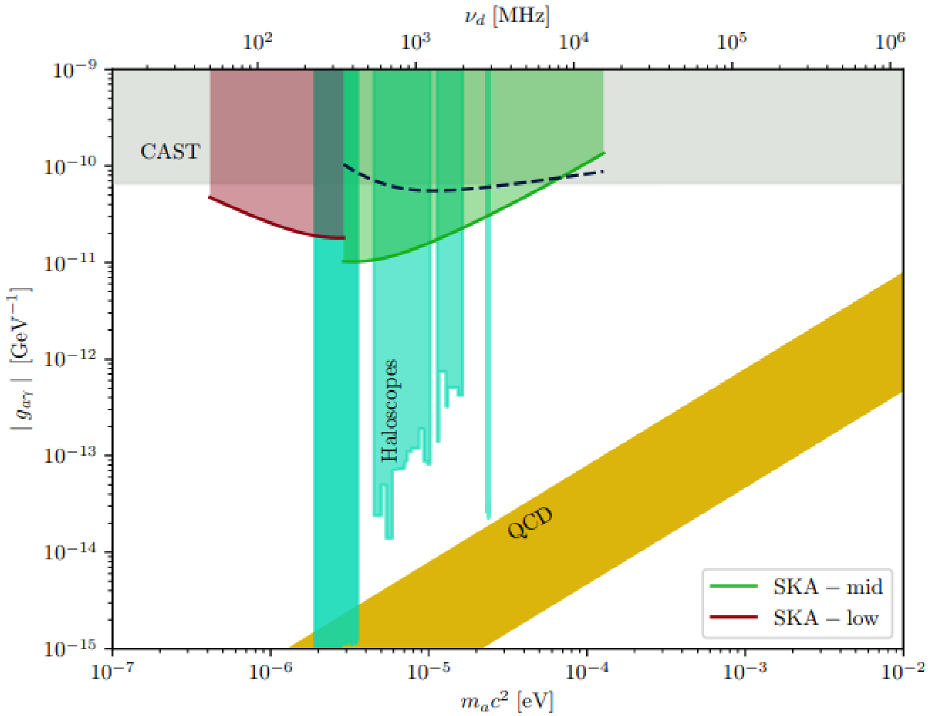


$$S_g = \frac{g_{a\gamma\gamma}^2}{16} S_{\nu,0}(\nu_a) \int \rho(x_d)\, \mathrm{d}x_d$$

Stimulated emission from a beam going through the Milky Way halo

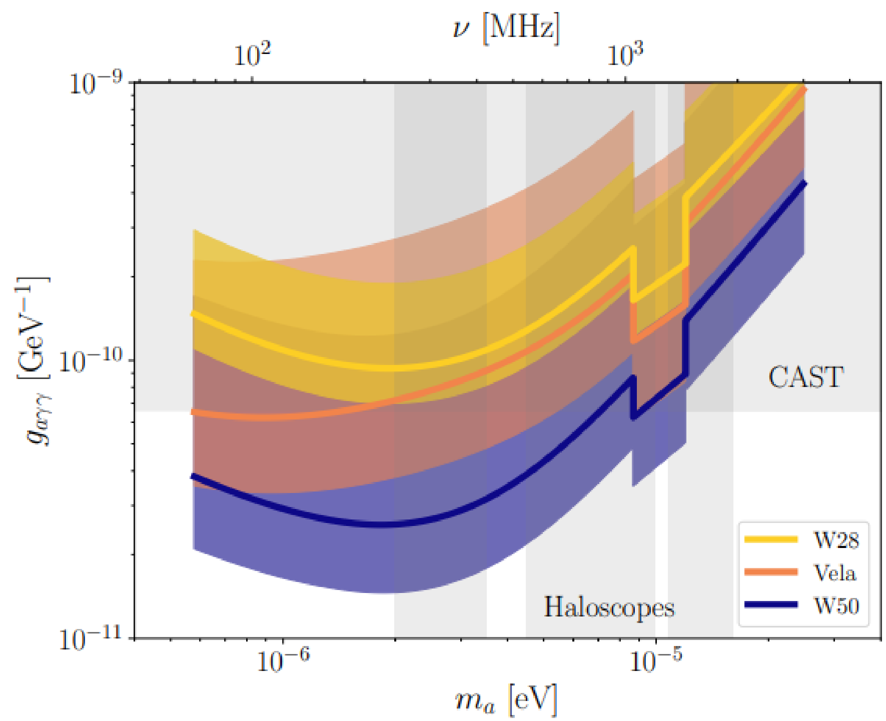
(Ghosh+, 2020)

Source: Cygnus A



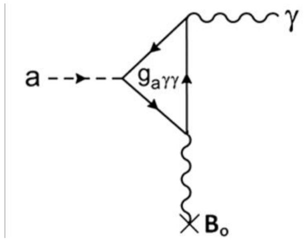
(Sun+ PRD2022, Buen-Abad+ PRD2022)

Source: Galactic SN remnants



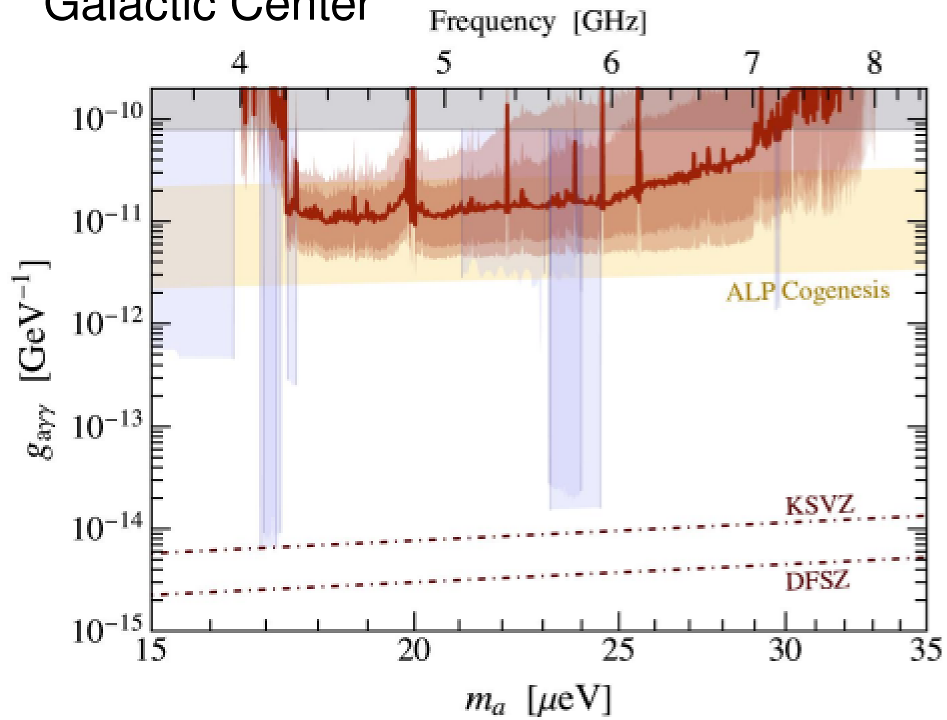
ALP conversion

ALPs may convert to radio-frequency electromagnetic radiation in the strong magnetic fields around **neutron stars**



GBT
Galactic Center

Foster+, 2022



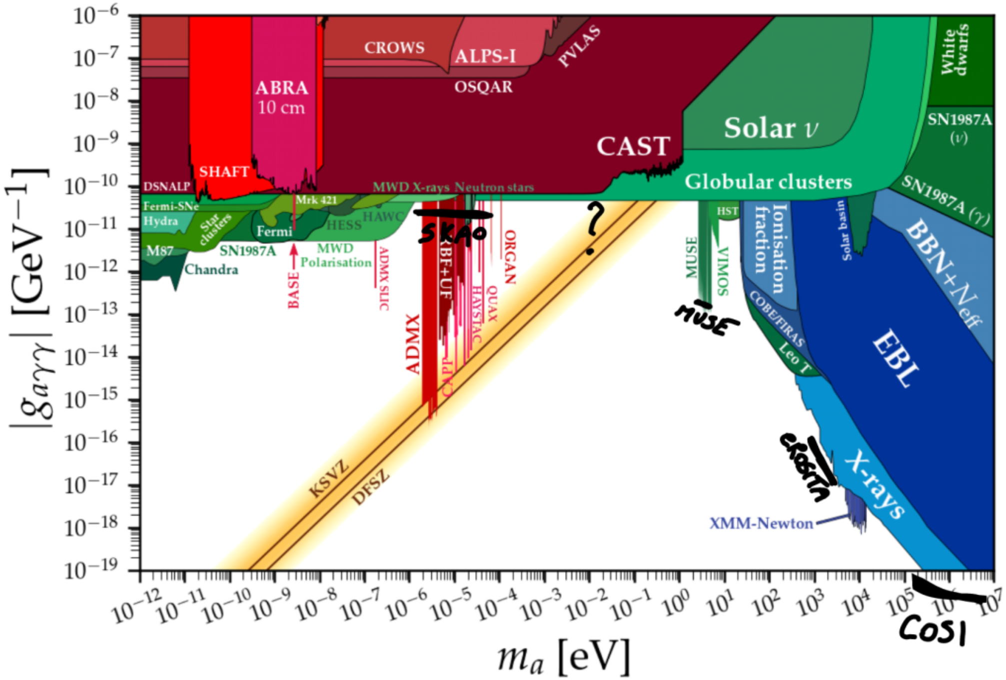
Very promising technique but with quite uncertain predictions.

$$\frac{d\mathcal{P}}{d\Omega} \simeq 5.7\times10^{9}\ \mathrm{W}\left(\frac{g_{a\gamma\gamma}}{10^{-12}\,\mathrm{GeV}^{-1}}\right)^{2}\left(\frac{r_{\mathrm{NS}}}{10\,\mathrm{km}}\right)^{5/2}\left(\frac{m_a}{\mathrm{GHz}}\right)^{4/3}$$
$$\times\left(\frac{B_0}{10^{14}\,\mathrm{G}}\right)^{5/6}\left(\frac{P}{\mathrm{sec}}\right)^{7/6}\left(\frac{\rho_{\mathrm{DM}}^{\infty}}{0.45\,\mathrm{GeV\,cm^{-3}}}\right)\left(\frac{M_{\mathrm{NS}}}{\mathrm{M}_{\odot}}\right)^{1/2}$$
$$\times\left(\frac{200\,\mathrm{km\,s^{-1}}}{v_0}\right)\frac{3\,(\hat{\mathbf{m}}\cdot\hat{\mathbf{r}})^{2}+1}{\left|3\cos\theta\,\hat{\mathbf{m}}\cdot\hat{\mathbf{r}}-\cos\theta_{\mathrm{m}}\right|^{7/6}},$$

Summarizing

It is a period with no strong bias concerning the particle dark matter mass
→ **multi-wavelength approach**

Searching for ALP decays in the sky will likely play a crucial role in shaping the allowed fraction of the ALP parameter space



ALP stimulated decay - projected limits

A “**golden era**” for **radio astronomy** has been starting with the **SKAO** and its precursors

SKA1-Low: 100 hours @ 100 MHz
→ 180 μJy/beam
(line sensitivity for $\Delta\nu/\nu = 10^{-4}$)

Credit: SKA Organisation

stimulated decay inside the source

$$S \simeq 100\,\mu\mathrm{Jy} \left(\frac{g_{a\gamma\gamma}}{10^{-11}\,\mathrm{GeV}^{-1}}\right)^2 \left(\frac{10^{-4}}{\sigma}\right) \left(\frac{m_a}{\mu\mathrm{eV}}\right)^{3-1} \frac{2f}{10^7} \frac{D}{10^{19}\,\frac{\mathrm{GeV}}{\mathrm{cm}^2}}$$

echo from stimulated decay

$$S \simeq 10\,\mu\mathrm{Jy} \left(\frac{g_{a\gamma\gamma}}{10^{-11}}\right)^2 \left(\frac{10^{-3}}{\sigma}\right) \left(\frac{\mu\mathrm{eV}}{m_a}\right) \left(\frac{S_0}{10^4\,\mathrm{Jy}}\right) \left(\frac{\rho}{0.4\,\frac{\mathrm{GeV}}{\mathrm{cm}^3}}\right) \left(\frac{x_d^{max}}{20\,\mathrm{kpc}}\right)$$