NNU · 南京师范大学
NANJING NORMAL UNIVERSITY

Need Ideas to Probe Ultra-light Dark Matter with Radio Telescopes

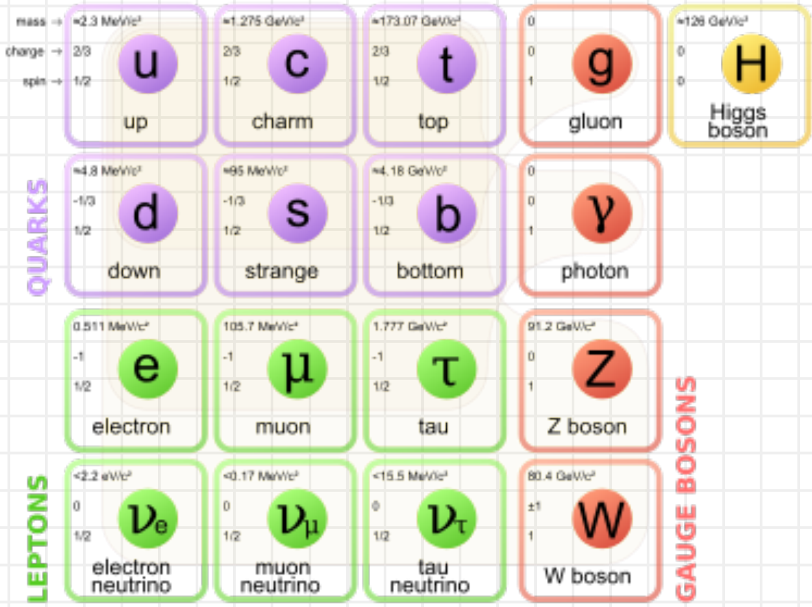
(Dark Matter and Neutrino Focus Week, Tsung Dao Lee Institute, Shanghai Jiao Tong University, Shanghai, China)

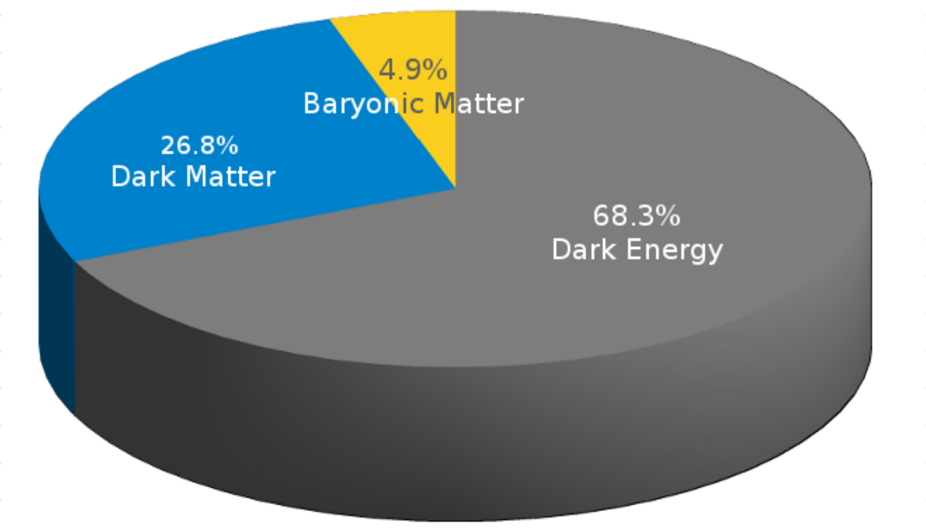
Ariel Arza

School of Physics and technology, Nanjing Normal University, Nanjing, China.

Introducción

Standard model of particles can only explain the baryonic content of the universe

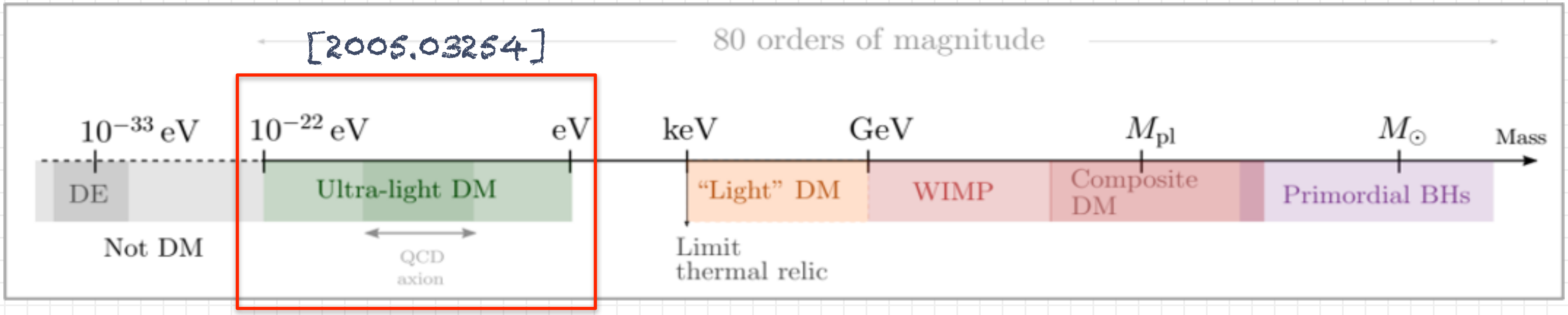




There is enough evidence that dark matter exists, from rotation go galaxies at lower scale to structure formation at larger scale

Introducción

There is large variety of dark matter candidates, whose masses ranging along more than 80 orders of magnitude



this is my preferred range

This range includes:

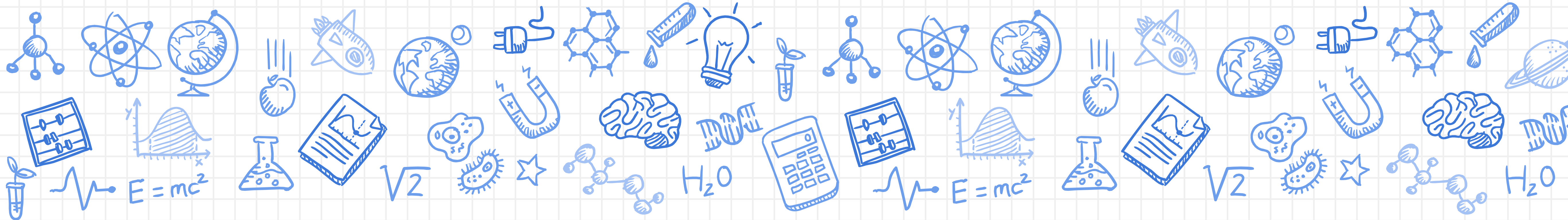
- axions
- axion-like particles
- dark photons
- millicharged bosons
- others

Introducción

Ultralight dark photons are good dark matter candidates if they were produced in the early universe by non thermal mechanisms

Production mechanisms for dark photons:

- Misalignment mechanism [1105.2812, 1201.5902]
- Inflationary fluctuations [1504.02102, 1810.07208]
- Tachyonic instabilities from axion-like particles [1810.07196, 1810.07188]
- Parametric resonance from dark Higgs decay [1810.07195]



Dark photon phenomenology

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \underbrace{\frac{\chi}{2}F_{\mu\nu}F'^{\mu\nu}}_{\text{Kinetic mixing term}} + \frac{1}{2}m_{\gamma'}^{2}A'_{\mu}A'^{\mu} \underbrace{- J_{\mu}A^{\mu}}_{\text{Electromagnetic interaction}}$$

$\chi << 1$ Kinetic mixing parameter

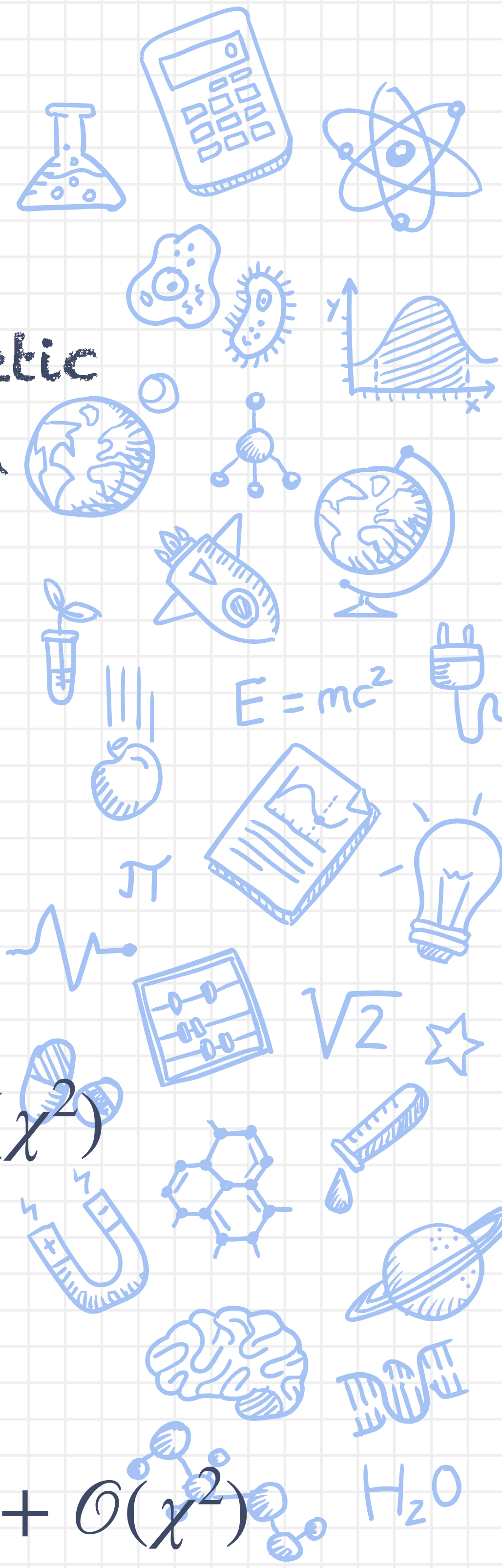
We can have a better picture of the physics if we get rid of the kinetic mixing term:

- Propagation basis: $A_\mu \to A_\mu + \chi A'_\mu$

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{\gamma'}^{2}A'_{\mu}A'^{\mu} - J_{\mu}A^{\mu} - \underbrace{\chi J_{\mu}A'^{\mu}}_{\text{New force}} + \mathscr{O}(\chi^{2})$$

- Interaction basis: $A'_\mu \to A'_\mu + \chi A_\mu$

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{\gamma'}^{2}A'_{\mu}A'^{\mu} + \underbrace{\chi\, m_{\gamma'}^{2}A_{\mu}A'^{\mu}}_{\text{Photon-dark photon oscillation}} - J_{\mu}A^{\mu} + \mathscr{O}(\chi^{2})$$



Dark photon phenomenology

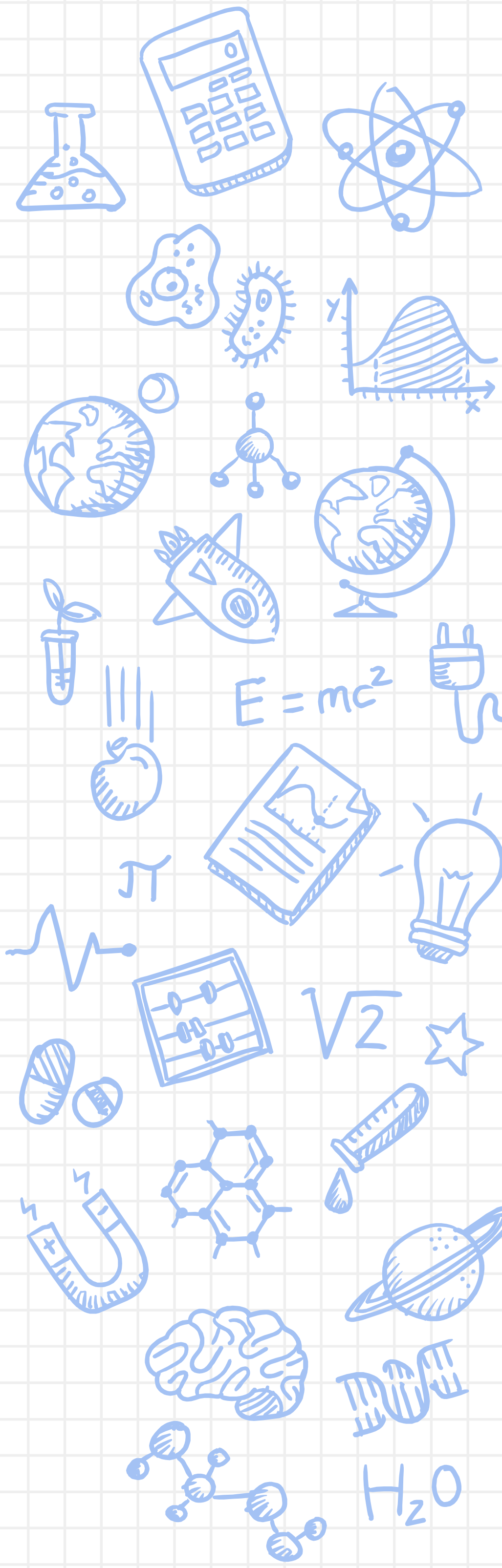
Axion experiments work well to probe dark photons:

$$\vec{\nabla} \times \vec{B} - \partial_t \vec{E} = \vec{J}_{eff}$$ Modified Ampere's law

$$\vec{J}_{eff} = -\, g\, B_0\, \partial_t\, a$$ Axions

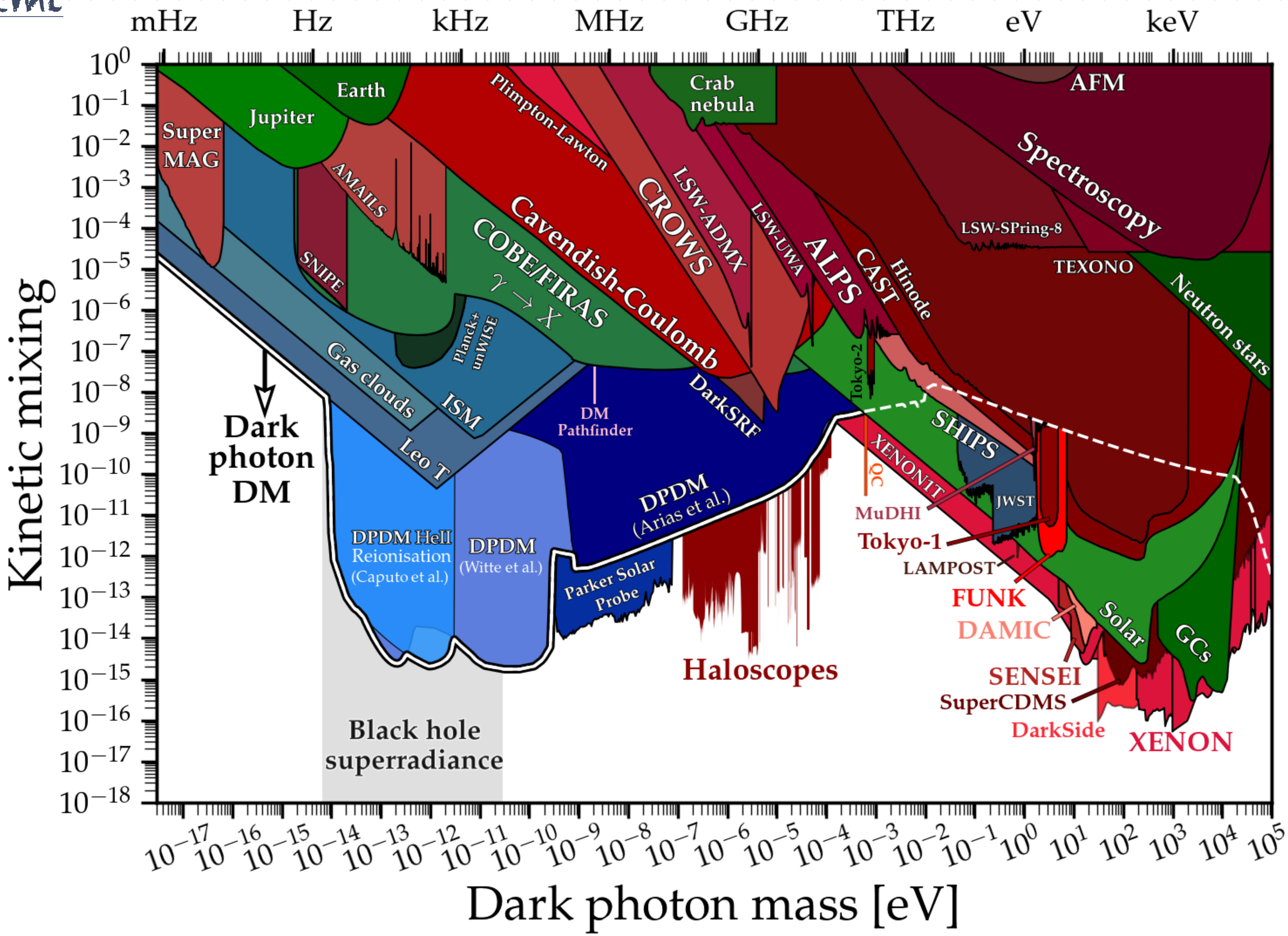
$$\vec{J}_{eff} = -\, \chi m_{\gamma'}^2\, \vec{A}'$$ Dark photons

$$\chi m_{\gamma'}^2 \leftrightarrow g B_0$$ Mapping from axion dark matter

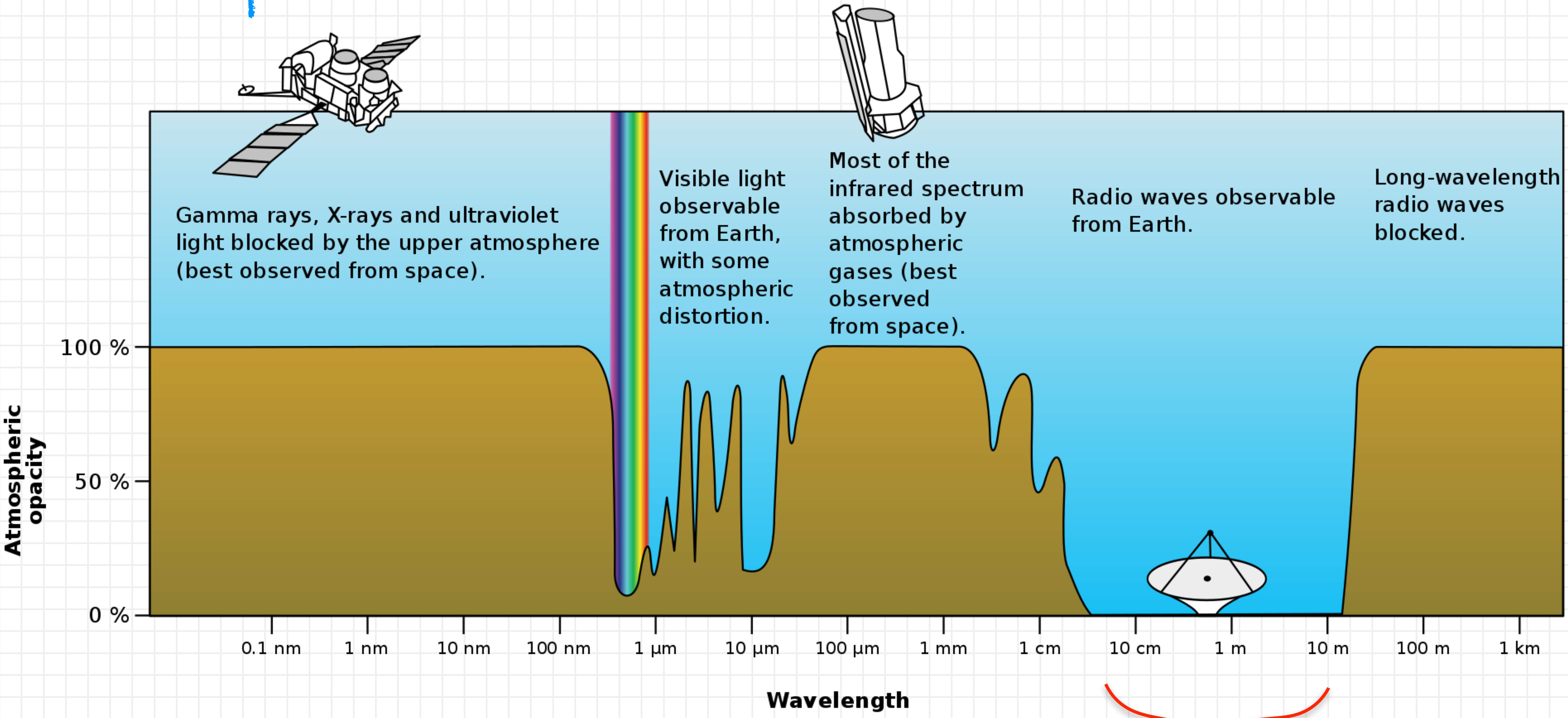


Dark photon phenomenology

Ciaran O'Hare data basis: https://cajohare.github.io/AxionLimits/docs/ap.html



Radio observations of axions and dark photons



$\nu = 10\,\mathrm{MHz} - 1\,\mathrm{THz}$ ➡ $m_{dm} = 4\times10^{-8} - 4\times10^{-3}\,\mathrm{eV}$

Radio window

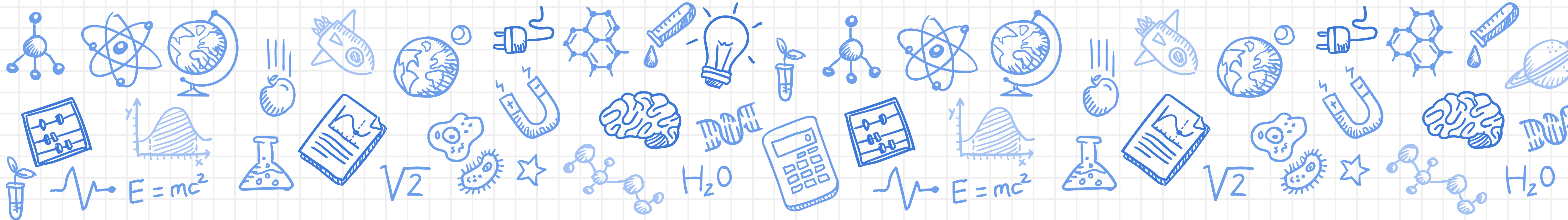
Radio observations of axions and dark photons

Axions:

- Radio emission from neutron stars magnetospheres [2004.00011, 2407.13060]
- Axion spontaneous and stimulated decay [astro-ph/0611502, 2502.08913]

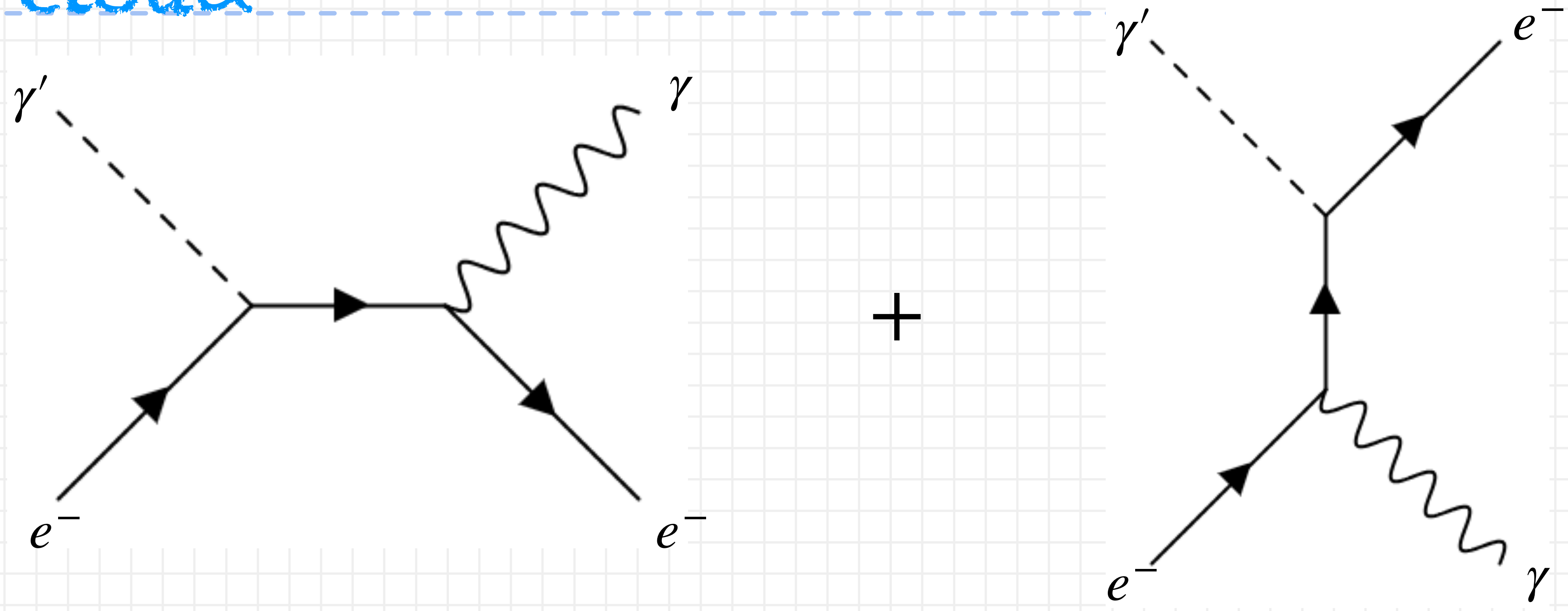
Dark photons:

- CMB distorsions [2004.00011, 2002.05165]
- Effect on radio telescopes [2207.05767]
- Galactic center [2212.09756]
- Solar corona [2301.03622, 2304.01056]



Radio signal from de Milky Way electron cloud

$\mathcal{M} =$

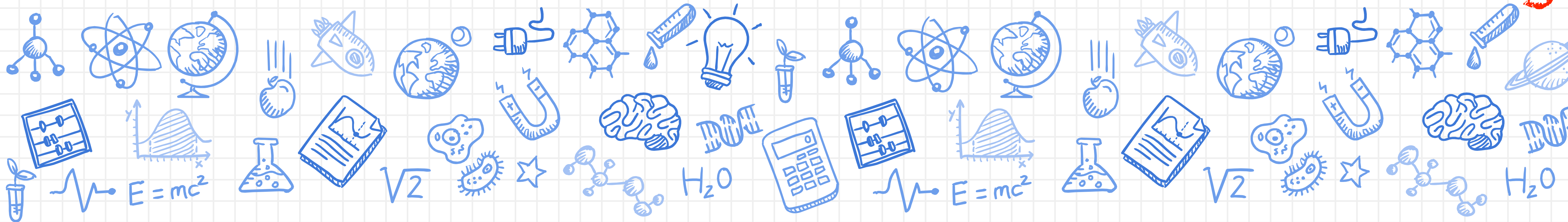


$$\sigma v = \begin{cases} \frac{8\pi}{3}\frac{\alpha^2\chi^2}{m_e^2}, & m_{\gamma'} \ll m_e \\ \frac{2\pi}{3}\frac{\alpha^2\chi^2}{m_e^2}, & m_{\gamma'} \gg m_e \end{cases}$$

Interesting

$\Gamma_{\gamma'\to 2e^-} \gg n_e \sigma v$

Not interesting



Radio signal from de Milky Way electron cloud

Signal characteristics:

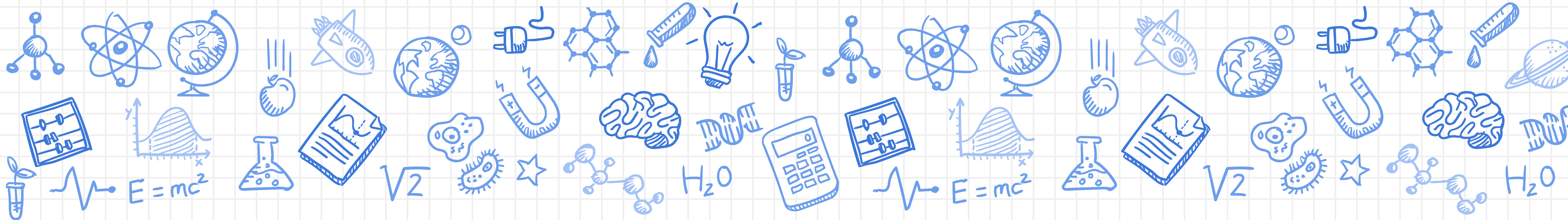
- Should be present at any location of the Galaxy
- It is anisotropic, since it is stronger to directions where the electron and DM densities are bigger
- It is a spectral line with angular frequency equal to the dark photon mass
- The bandwidth is determined by the electron velocity dispersion, of the order of 10^{-3} c.

Signal frequency: →

$$\nu = \frac{m_{\gamma'}}{2\pi}$$

Signal bandwidth: →

$$\delta\nu = \frac{m_{\gamma'}}{2\pi}\delta v_e \sim 10^{-3}\,\nu$$



Boltzmann equation: $\dot{\rho}_\gamma = \langle \sigma v \rangle n_e \rho_{\mathrm{dm}}$

$$\langle \sigma v \rangle = 2.07 \times 10^{-16} \chi^2 \, \mathrm{cm^2\, m/s}$$ averaged cross section

$$I_\nu = \frac{\langle \sigma v \rangle}{4\pi \delta \nu} \int_0^{\ell_T} d\ell \int_{\Omega_{\mathrm{fov}}} d\Omega \, n_e(\ell, \Omega) \, \rho_{\mathrm{dm}}(\ell, \Omega)$$

$\ell_T = 28.3\,\mathrm{kpc}$	Total line of sight of the observation	Ω_{fov}	Field of view of the radio telescope
ρ_{dm}	Dark matter energy density	n_e	Electron density

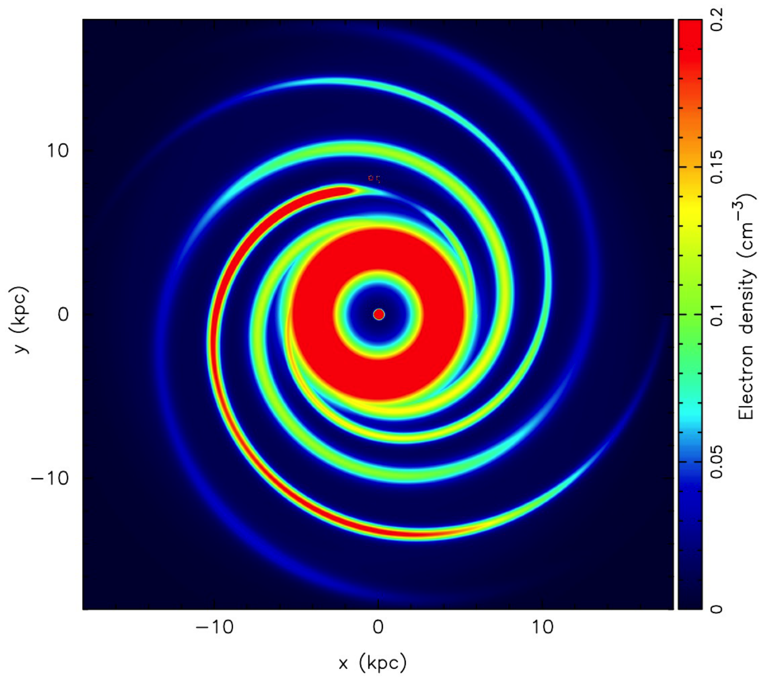
YMW16 electron density model

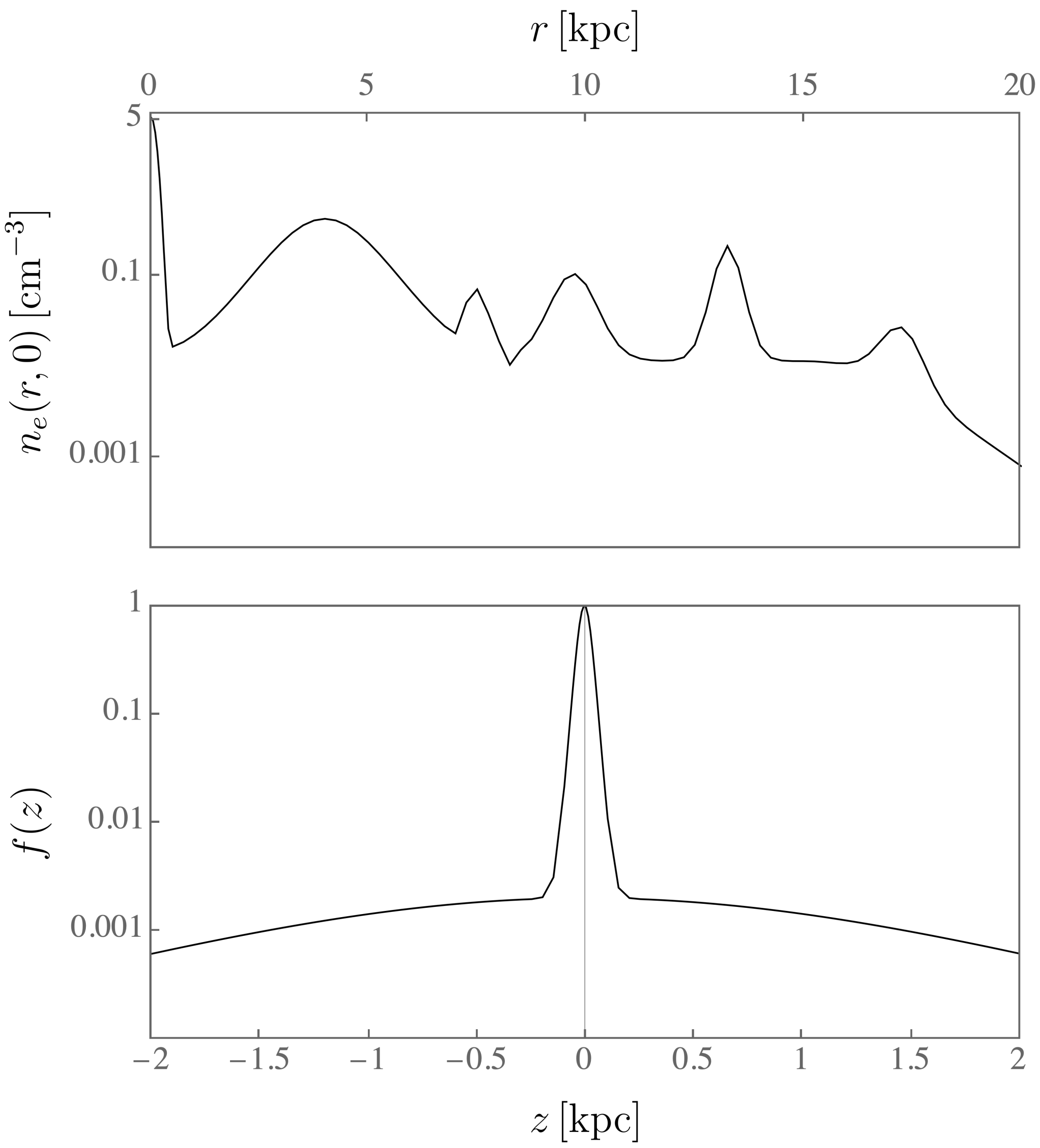
J. M. Yao, R. N. Manchester and N. Wang, Astrophys. J. 835 (2017) 29.

$$n_e(r,z) = f(z)n_e(r,0)$$

$z = 0$ Sun plane

$$\bar{n}_e = 0.144\,\mathrm{cm}^{-3}$$





https://www.atnf.csiro.au/research/pulsar/ymw16/

Dark matter halo models

Navarro-Frenk-White (NFW)

$$\rho_{\rm dm}(r) = \rho_s \frac{r_s}{r} \frac{1}{\left(1+\frac{r}{r_s}\right)^2}$$

Moore

$$\rho_{\rm dm}(r) = \rho_s \left(\frac{r_s}{r}\right)^{1.16} \frac{1}{\left(1+\frac{r}{r_s}\right)^{1.84}}$$

Einasto

$$\rho_{\rm dm}(r) = \rho_s \exp\left(-18.2\left(\left(\frac{r}{r_s}\right)^{0.11} - 1\right)\right)$$

Best motivated model by recent observations [1012.4515]

Model	ρ_s [GeV/cm^3]	r_s [kpc]	I_ν [mJy]
NFW	0.184	24.42	0.238
Moore	0.105	30.28	0.476
Einasto	0.021	35.24	0.61

typical flux density

Radio signal

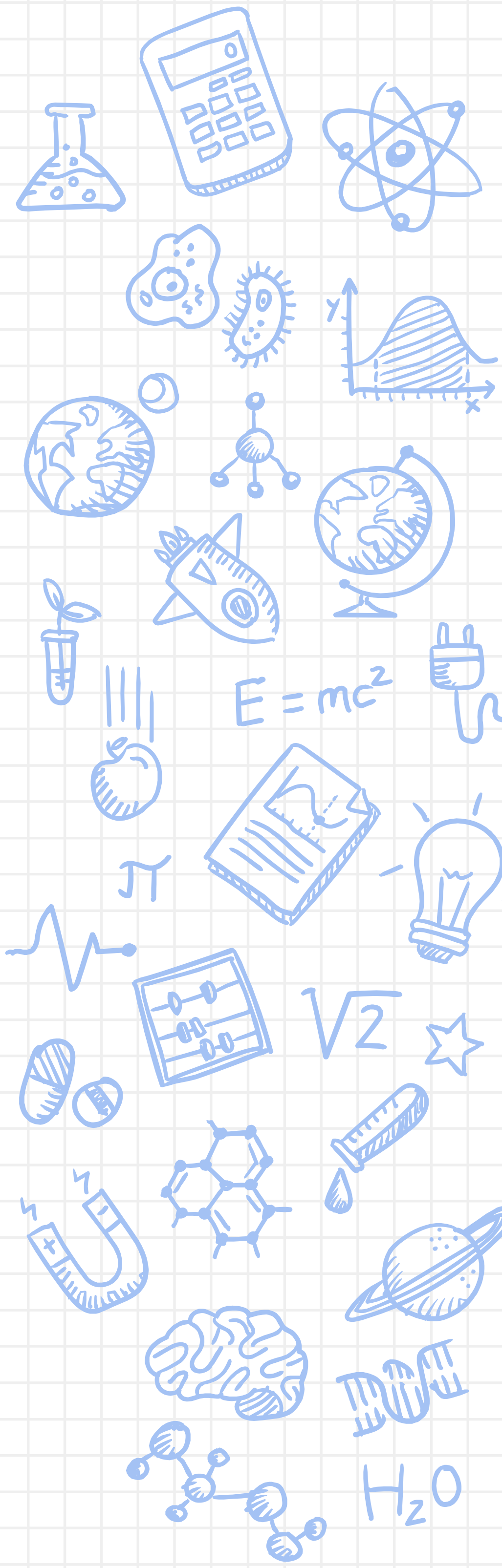
Single dish observation:

$$P_i = \delta\nu\, I_\nu\, S_i \qquad (s/n)_i = \frac{P_i}{T_{\mathrm{sys}}}\sqrt{\frac{t_{\mathrm{obs}}}{\delta\nu}}$$

S_i	Area of the dish
t_{obs}	Total time of observation
T_{sys}	System noise temperature

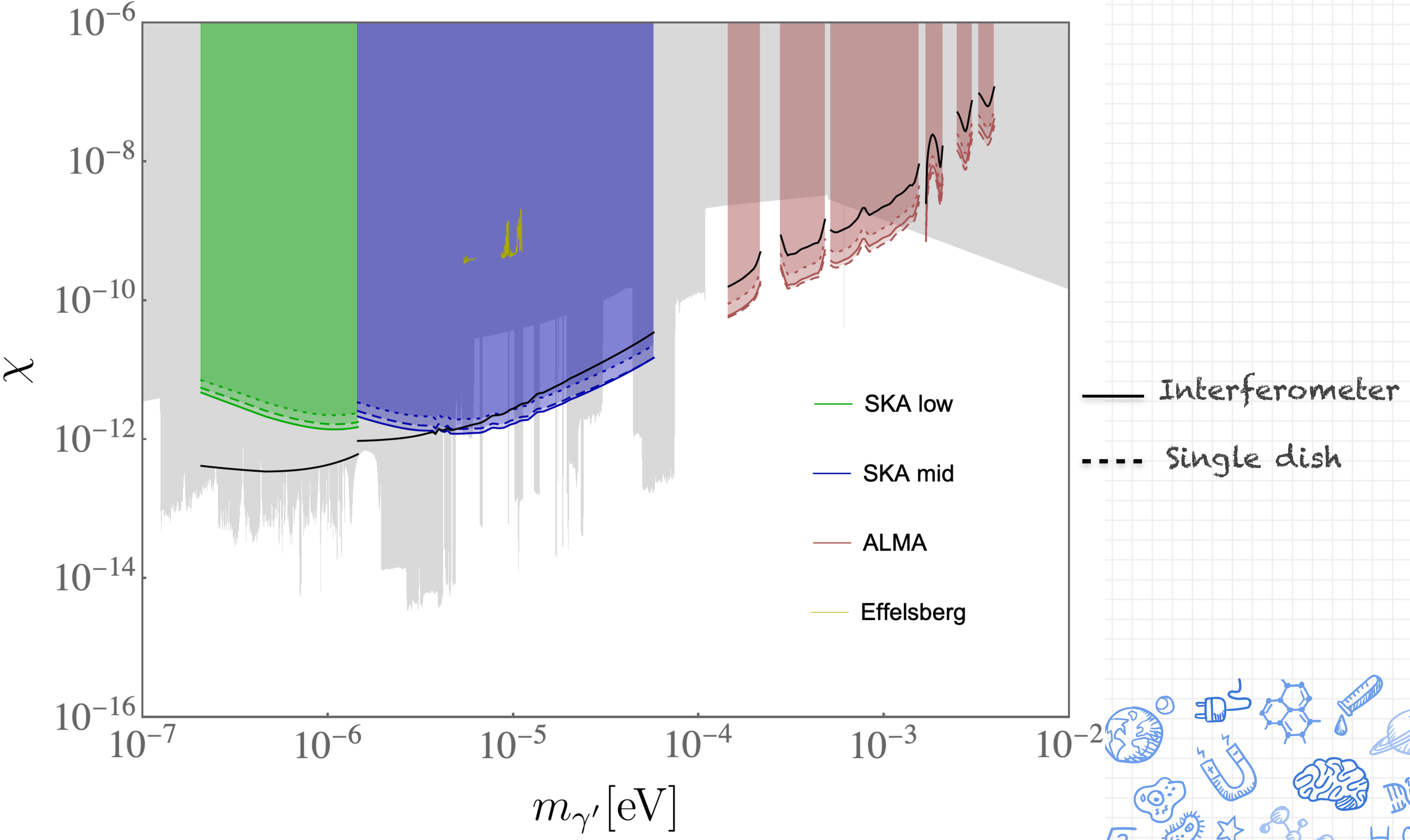
For n dishes:

$$s/n = \sqrt{\sum_{i=1}^{n} (s/n)_i^2}$$



Radio signal

Sensitivity projections with ALMA and SKA [2406.12797]



Conclusions

This work:

- We considered Thomson-like scattering from dark matter dark photons and Milky Way free electrons
- Interesting for radio observations
- Current and future radio telescope arrays are sensitive enough to probe dark photon dark matter in unconstrained parameter space

Next?

- Use real data from real observations
- Planning a dedicated observation
- Study this signal from other sources, Like neutron stars or nearby galaxies?

Thanks for your attention!