Probing Axion-Photon Conversion in PSR J1745-2900 Magnetosphere with ALMA Observation

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Presented by

Nutnicha Masoongnoen

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Auditorium (Center for Information Technology and Communication Services (CITCOMS))
Naresuan University

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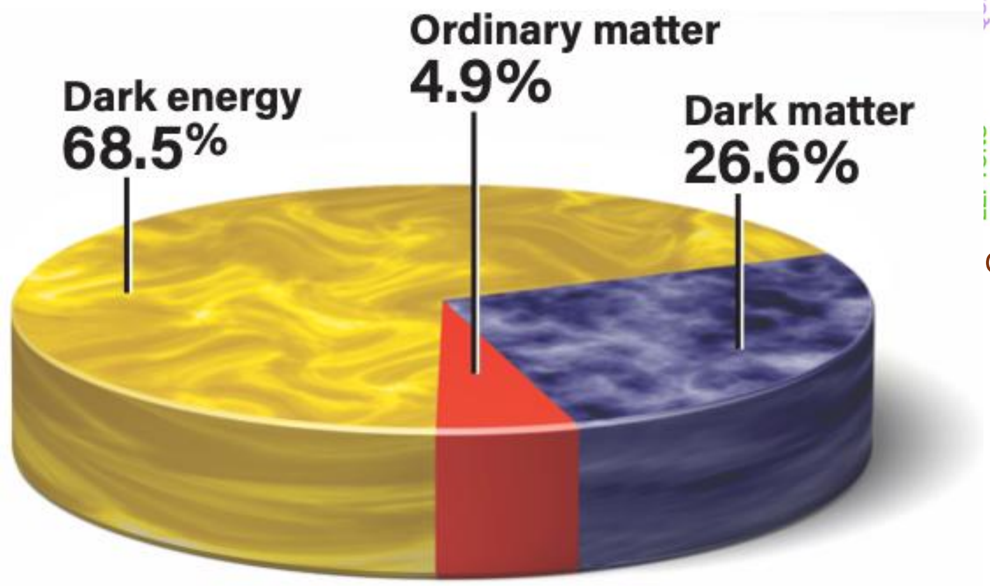
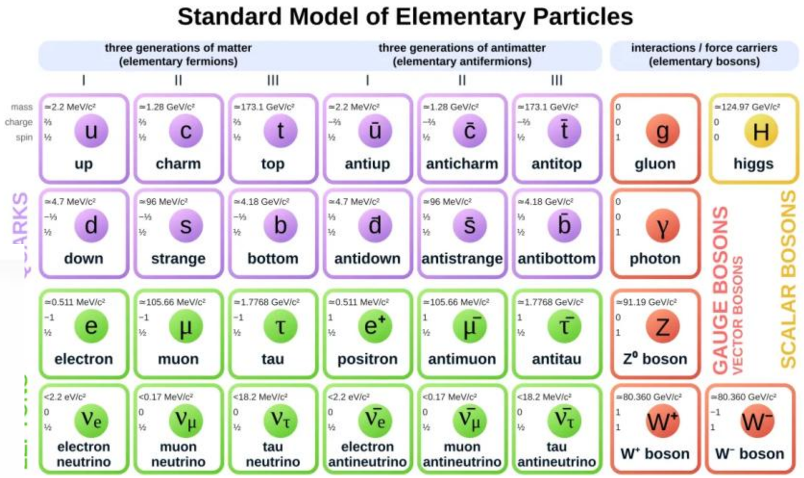
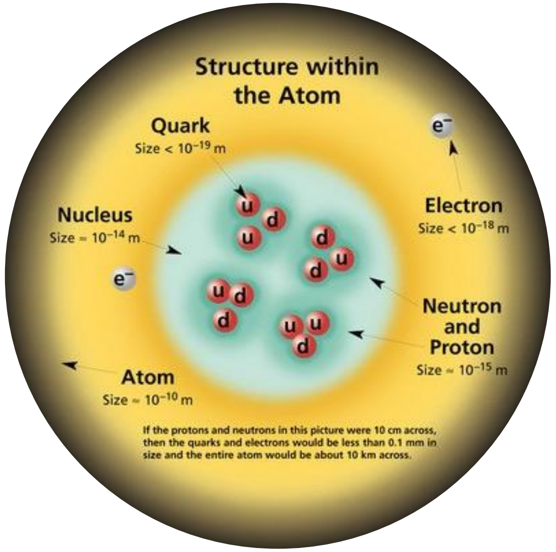
Dark Matter



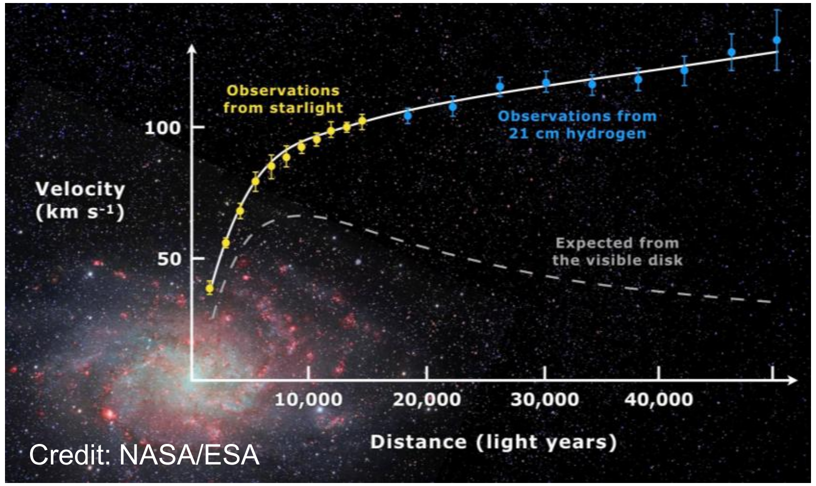
Credit: https://www.astronomy.com



Credit: Particle Data Group, Standard Model chart



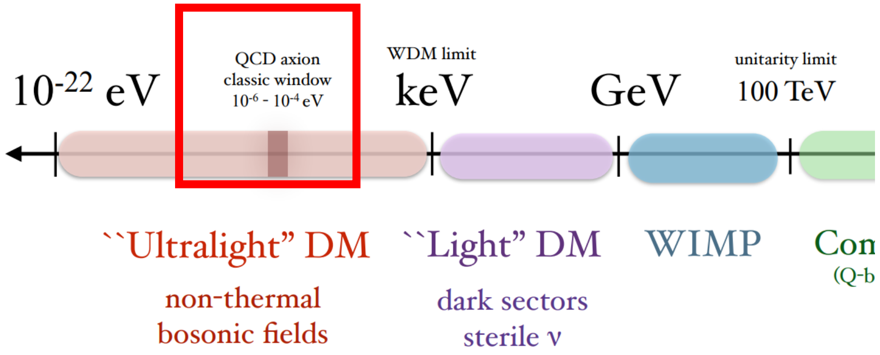
Credit: https://prancer.physics.louisville.edu



Rotation Curve

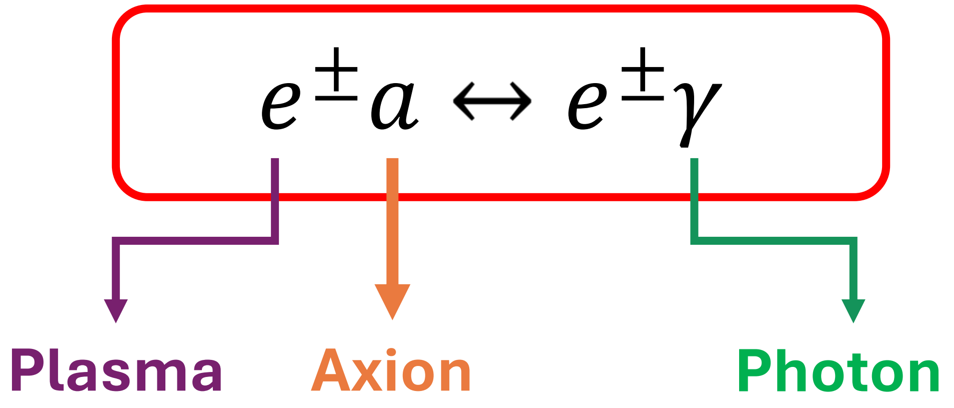
Structure of the Universe

Axion Dark Matter

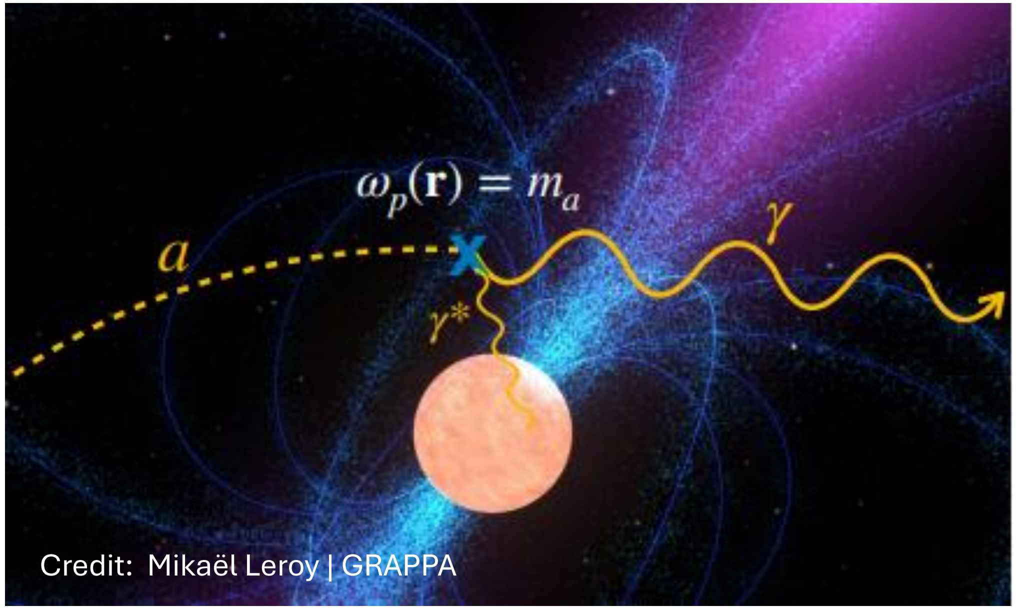


Credit: T. Lin, TASI Lectures

- A well-motivated dark matter candidate
- An ultralight dark matter (mass: μeV – meV)
- Can **convert into photons** under the presence of the **strong magnetic field**.



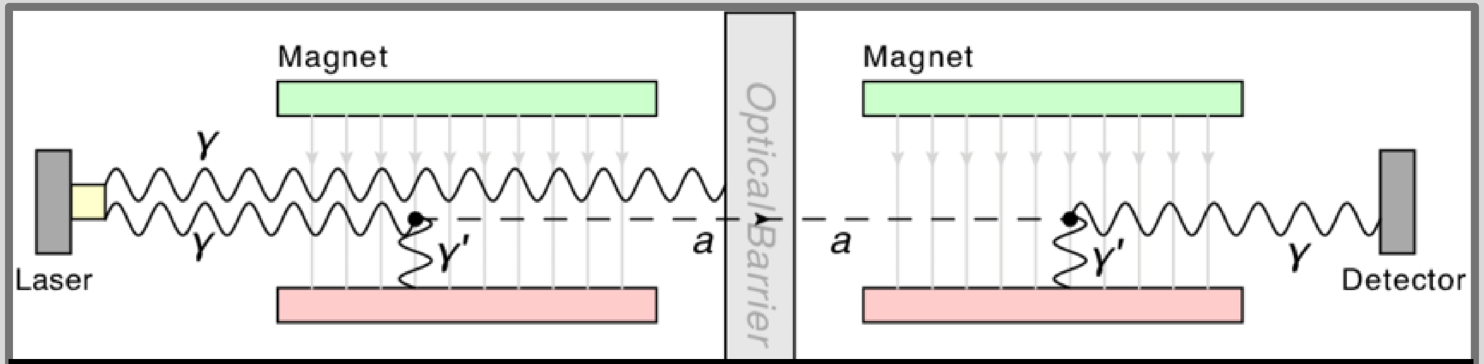
Credit: Langhoff, K., Outmezguine, N. J., & Rodd, N. L. (2022).



Credit: Mikaël Leroy | GRAPPA

Axion Detections

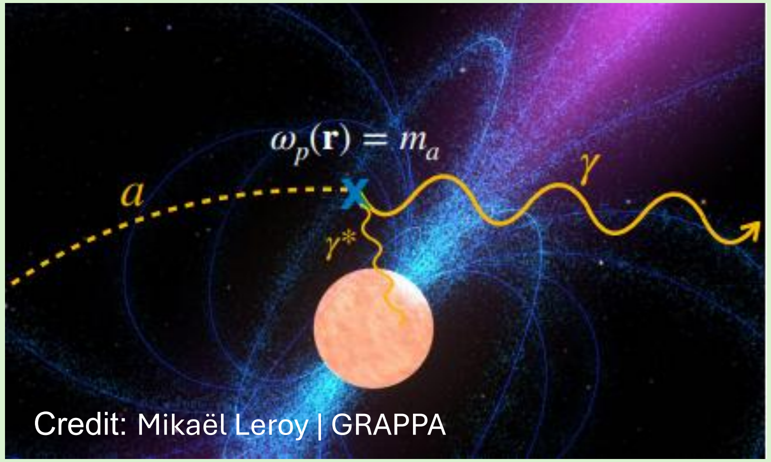
Credit: CERN Axion Solar Telescope (CAST)



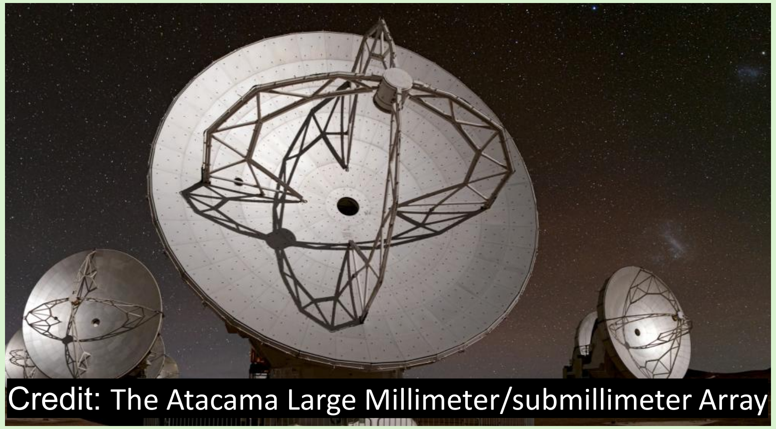
Credit: The light-shining-through-a-wall (LSW) experiment, Battesti et al., Physics Reports (2018).

Direct Detection & Experiments

No confirmation



Credit: Mikaël Leroy | GRAPPA



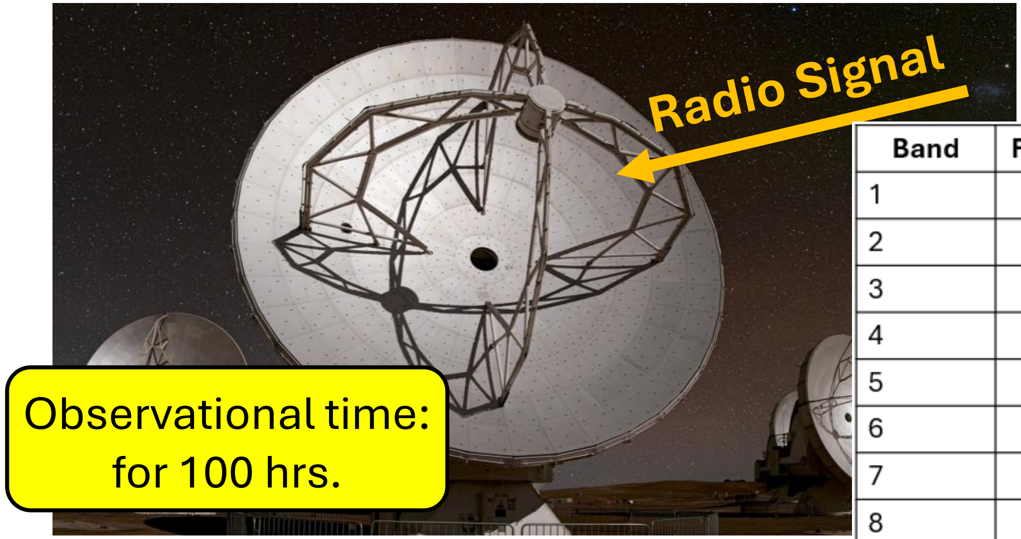
Credit: The Atacama Large Millimeter/submillimeter Array

Indirect Detection

THIS WORK!!!

The Atacama Large Millimeter/submillimeter Array

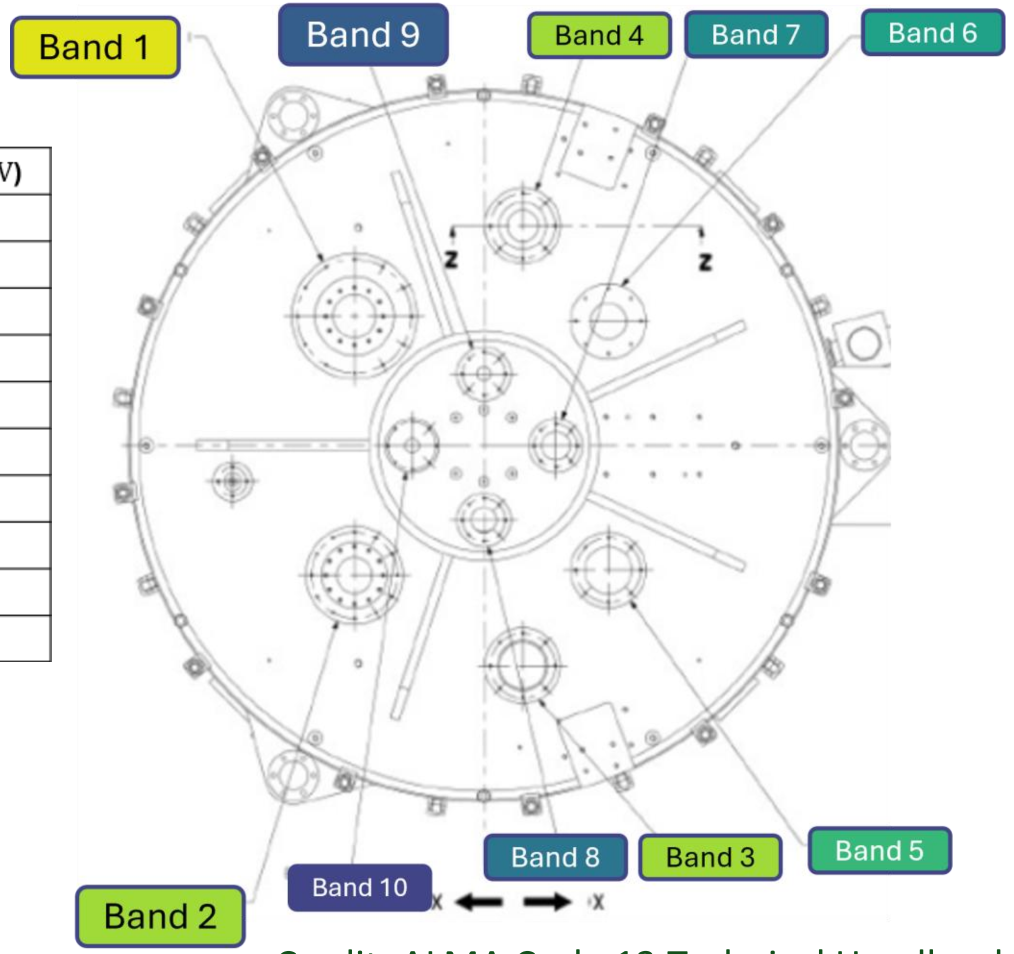
ALMA Observation



The Atacama Large Millimeter/submillimeter Array

$$h\nu = m_a c^2$$

Band	Frequency (GHz)	Axion mass (meV)
1	35-50	0.14-0.21
2	67-84	0.28-0.35
3	90-116	0.37-0.48
4	125-157	0.52-0.65
5	163-210	0.67-0.87
6	211-275	0.87-1.14
7	276-373	1.14-1.54
8	385-500	1.59-2.07
9	602-720	2.49-2.98
10	787-950	3.25-3.93



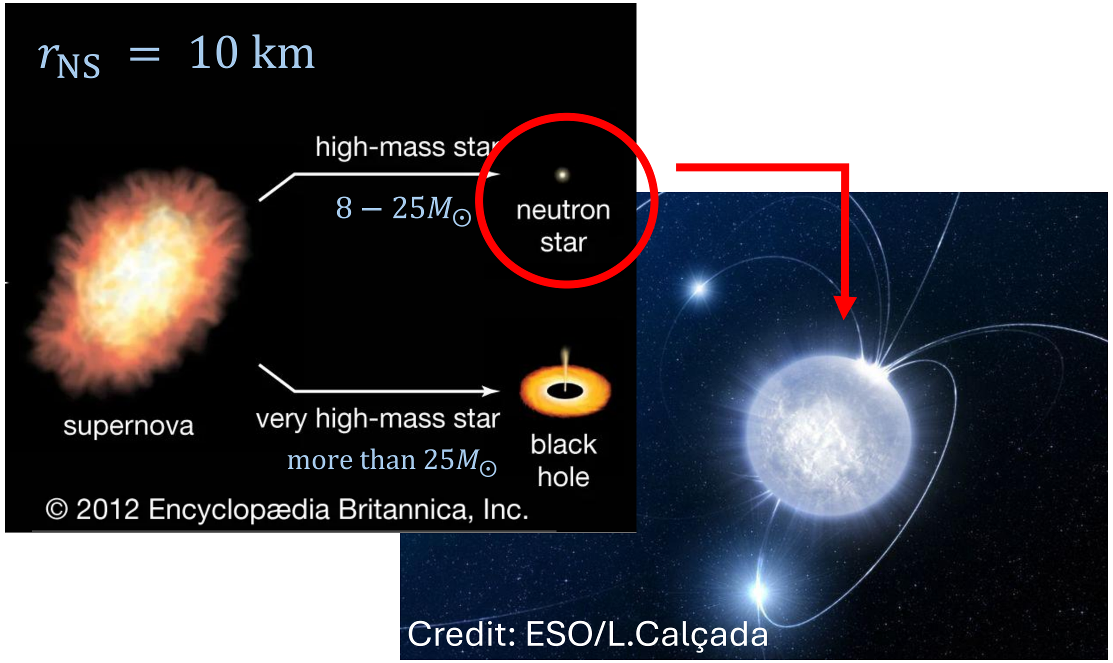
Credit: ALMA Cycle 13 Technical Handbook

- **Frequency** matches **axion mass** window **in meV**
- **Ultra-high sensitivity for weak signals: 0.739-87.9 μJy**
- **High angular resolution: up to 0.004 to 0.005 arcseconds**
- **Dry high-altitude site: about 5,000 m altitude reduces atmospheric noise**
- **Southern Hemisphere location provides better visibility of the Galactic Center with lower interference.**

Which source is suitable for this conversion?

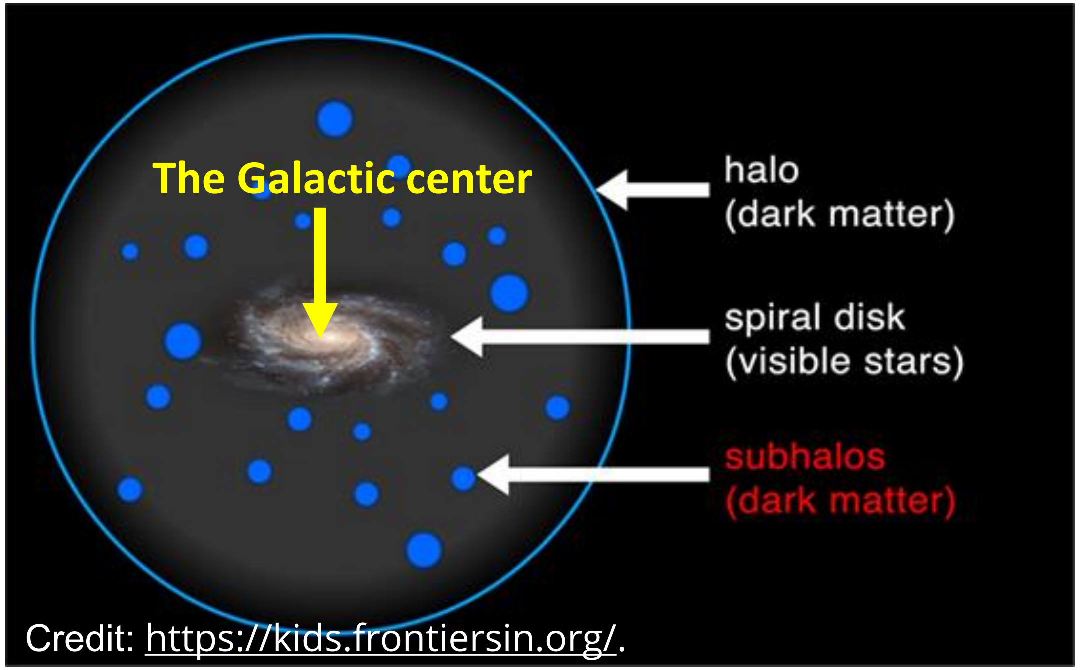
Magnetar ≡ Strong magnetic field neutron star

with Extremely strong magnetic field above 10^{14} G

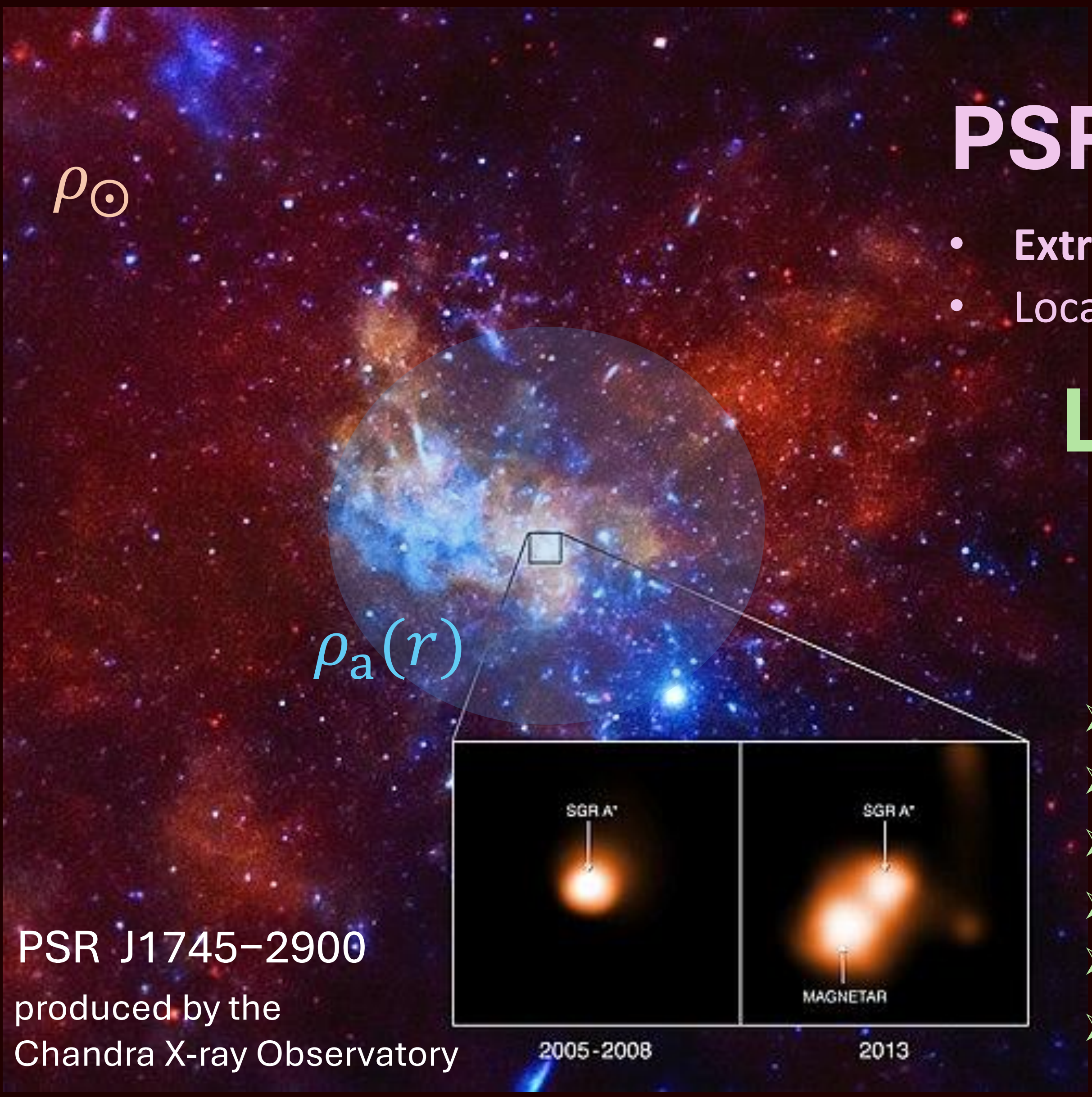


High DARK MATTER DENSITY region

- ➢ Imply to the sufficiently axion dark matter density



Magnetar...The Strongest Magnetic Star



PSR J1745-2900

- **Extremely magnetic field** $\boldsymbol{B_0 = 2.4 \times 10^{14}\ G}$
- Located near **Galactic Center**

Local Axion Density (ρ_a)

$$\rho_a(r) = \frac{2\rho_\infty}{\sqrt{\pi}} \frac{v_a(r)}{v_0}$$

- $\rho_a(r)$ is the local axion density
- ρ_∞ is the dark matter density near the star: $\rho_\infty = 10^9 \rho_\odot$
- $\rho_\odot$ is local dark matter density around the Sun.
- v_0 is the dispersion velocity: $v_0 = 236$ km/s
- $v_a(r)$ is the axion dark matter velocity: $v_a(r) = \sqrt{\frac{2GM}{r}}$
- r is the radius, M is magnetar mass, G is the gravitational constant

Magnetar magnetosphere

- Plasma around Magnetosphere

$$n_e(r) = \boldsymbol{\kappa} \frac{|\Omega B_z(r)|}{2\pi e c},$$

Minimum plasma density in Neutron Star

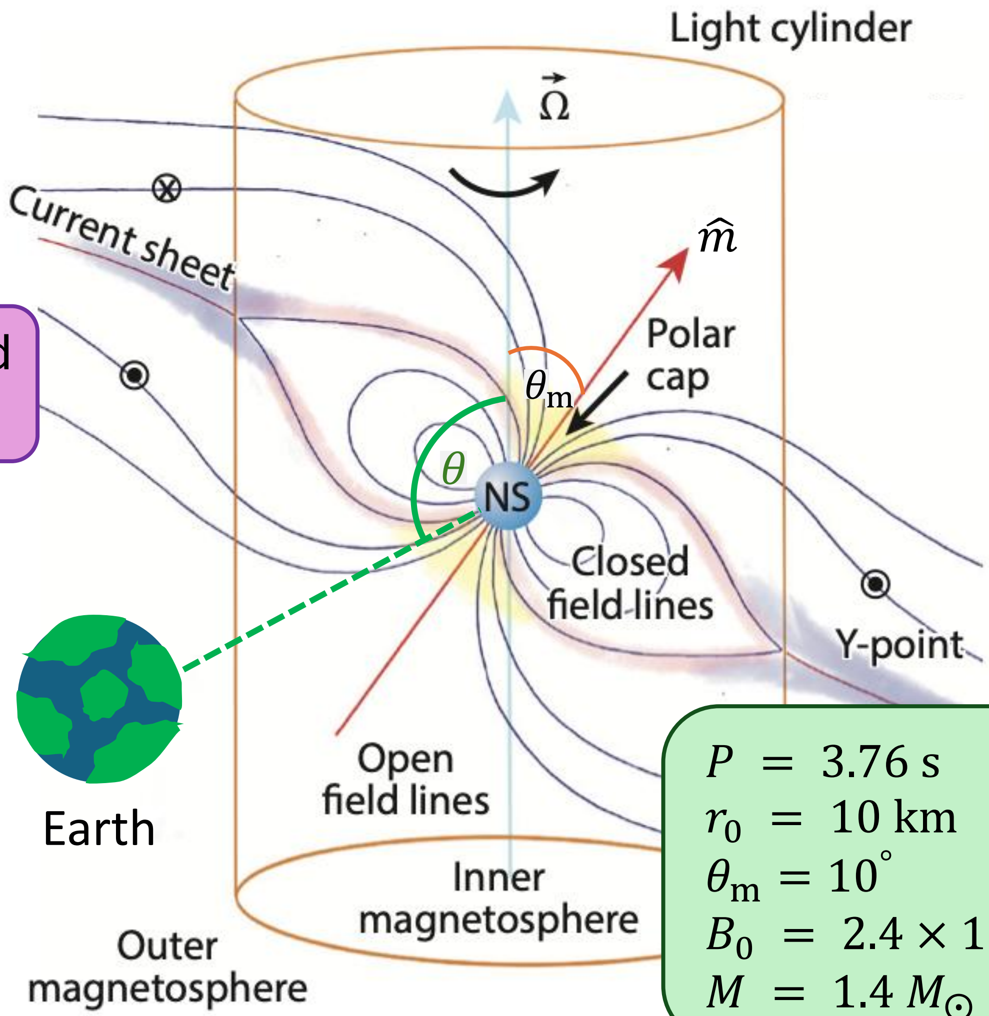
- $\Omega = 2\pi/P$, P is the spin period
- r is the radius
- $\boldsymbol{\kappa}$ is the effective multiplicity
- e is electron charge, c is the speed of light

must be tuned correctly!!!

- The misaligned rotating magnetic dipole:

$$B_z(r) = \frac{B_0}{2}\left(\frac{r_0}{r}\right)^3 [3\cos\theta\, \hat{\mathrm{m}}\cdot\hat{\mathrm{r}} - \cos\theta_{\mathrm{m}}],$$

- B_0 is the magnetic field strength at magnetar surface
- r_0 is the magnetar radius, r is the radius
- θ is the viewing angle
- θ_{m} is the misalignment angle



$P = 3.76$ s
$r_0 = 10$ km
$\theta_{\mathrm{m}} = 10^{\circ}$
$B_0 = 2.4 \times 10^{14}$ G
$M = 1.4\, M_{\odot}$

Credit: A. Philippov and M. Kramer, 2022

Axion-Photon Conversion

Probability ($P_{a\to\gamma}$)

$$P_{a\to\gamma} = \frac{\pi}{3}\frac{(B(r_c))^2 r_c}{v_a(r_c)}\frac{g_{a\gamma\gamma}^2}{m_a}$$

Astrophysics **Particle Physics**

DON'T KNOW YET

- $g_{a\gamma\gamma}$ is the axion-photon-photon coupling
- r_c is the conversion radius
- $B(r_c)$ is the total magnetic field strength
- $v_a(r_c)$ is the axion dark matter velocity
- m_a is the axion dark matter mass
- $\rho_a(r_c)$ is the local axion density

Needs to be CONSTRAINED

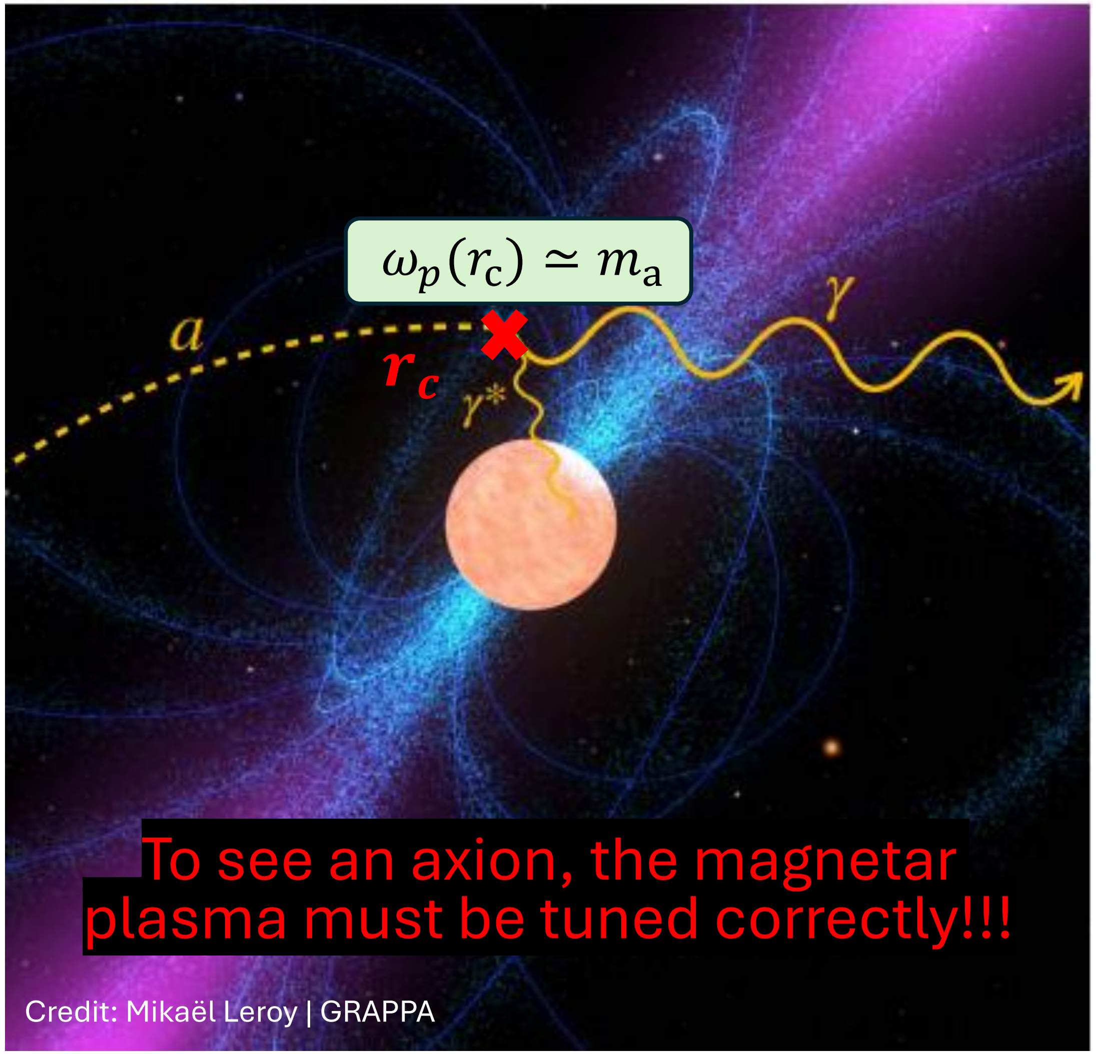
within the parameter space accessible to ALMA observations

- How heavy the axion mass : m_a
- How strongly it must couple : $g_{a\gamma\gamma}$
- How dense the minimum plasma density : $\boldsymbol{\kappa}$

Objective

- To predict the possibility to detect axion dark matter
- To see ALMA's potential to probe axion-induced signatures
- To constrain the axion parameters within the parameter space accessible to ALMA observations

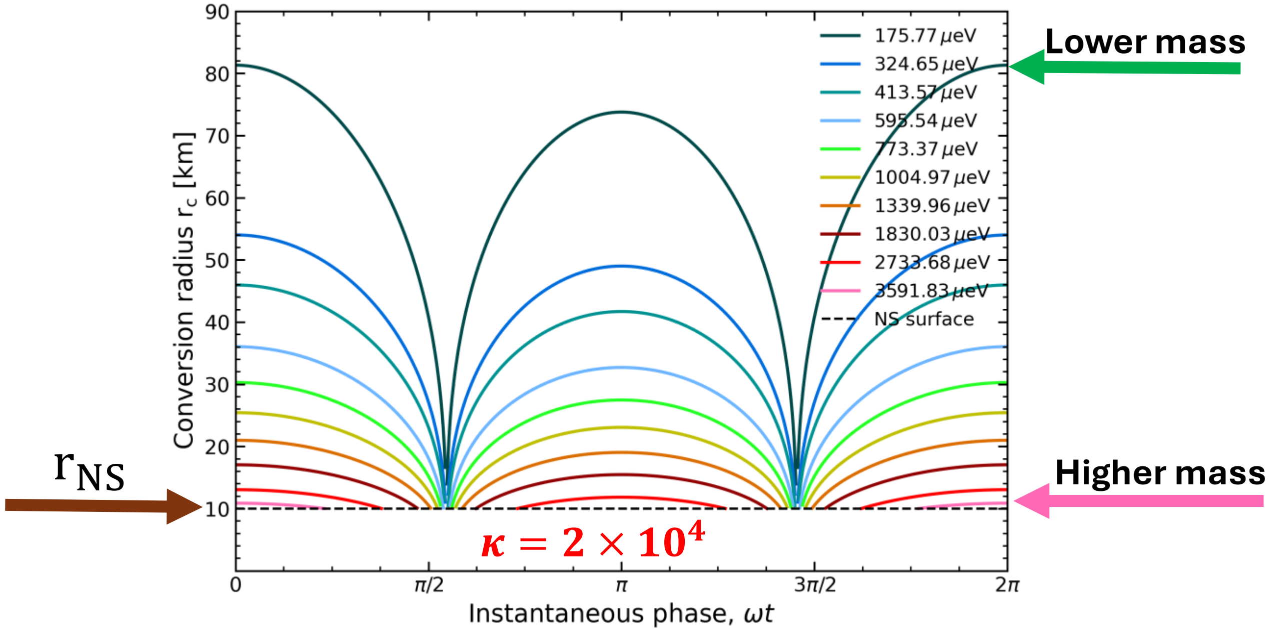
Axion-Photon Conversion



At Conversion Radius

$$\omega_p(r_c) = \sqrt{\frac{4\pi\alpha n_e(r_c)}{m_e}}$$

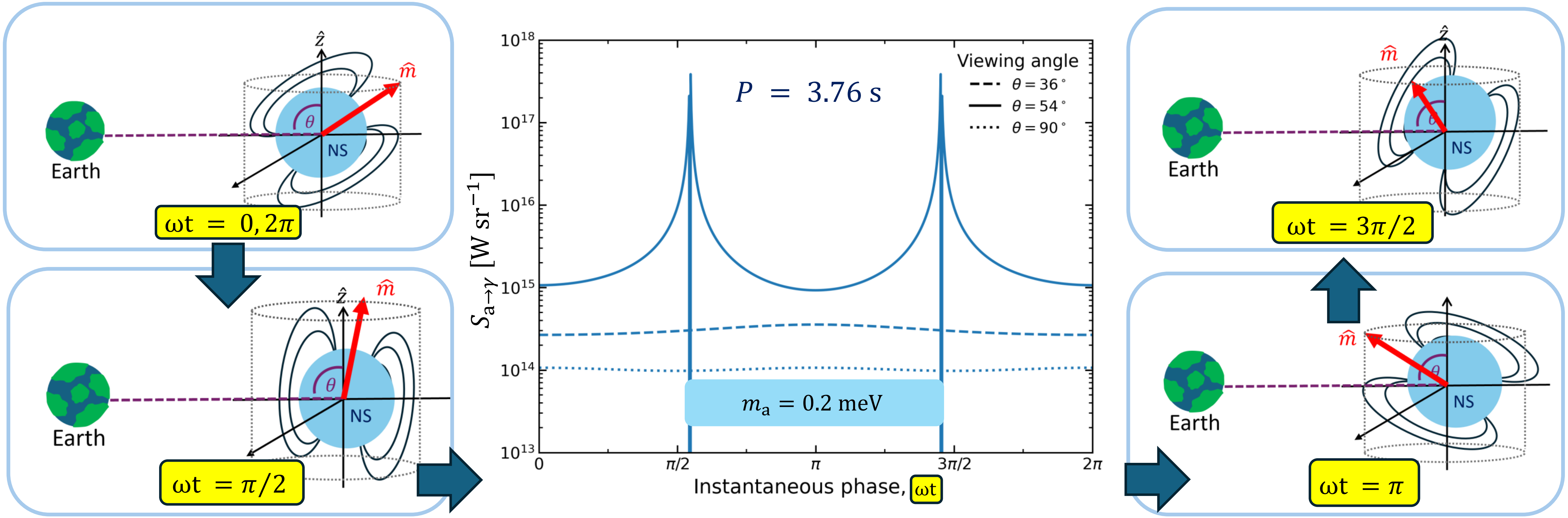
- ω_p is the plasma frequency
- r_c is the conversion radius
- α is the fine-structure
- m_e is the electron mass
- $n_e(r_c)$ is the plasma number density



Minimum multiplicity coverage **all bands**

Radiated Power per solid angle

$$S_{a\to\gamma} = 2P_{a\to\gamma}\rho_a(r_c)v_a(r_c)r_c^2 \,,$$



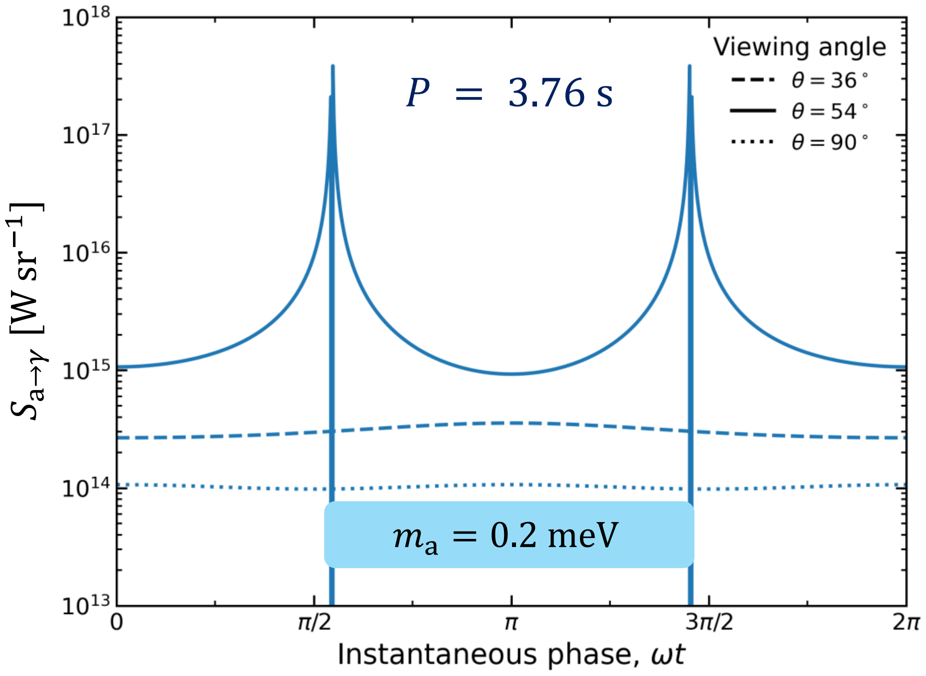
$P_{a\to\gamma}(g_{a\gamma\gamma})$ = axion-photon conversion probability, $\rho_a(r_c)$ = the local axion density, $v_a(r_c)$ is the escape axion velocity, r_c is the conversion radius, $g_{a\gamma\gamma}$ is the axion-photon-photon coupling

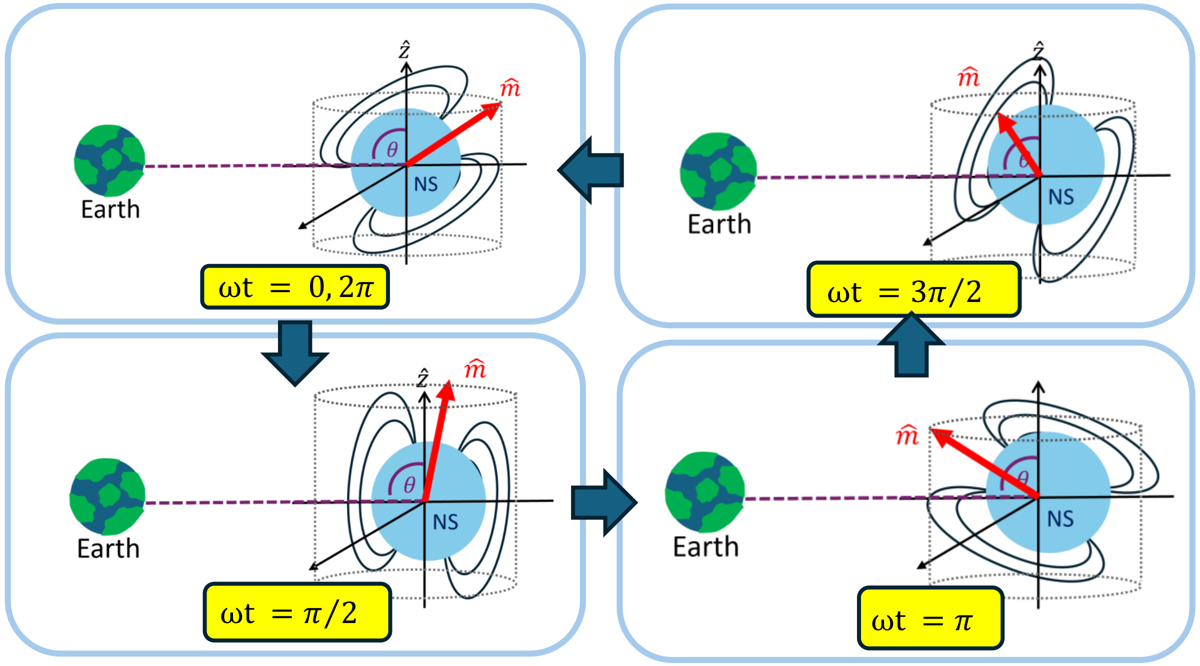
Predicted Signal ($S_{a\to\gamma}$)

Consider the variance over magnetar rotation $\sigma_T = \frac{\langle S_{a\to\gamma}^2\rangle - \langle S_{a\to\gamma}\rangle^2}{\langle S_{a\to\gamma}\rangle^2}$.

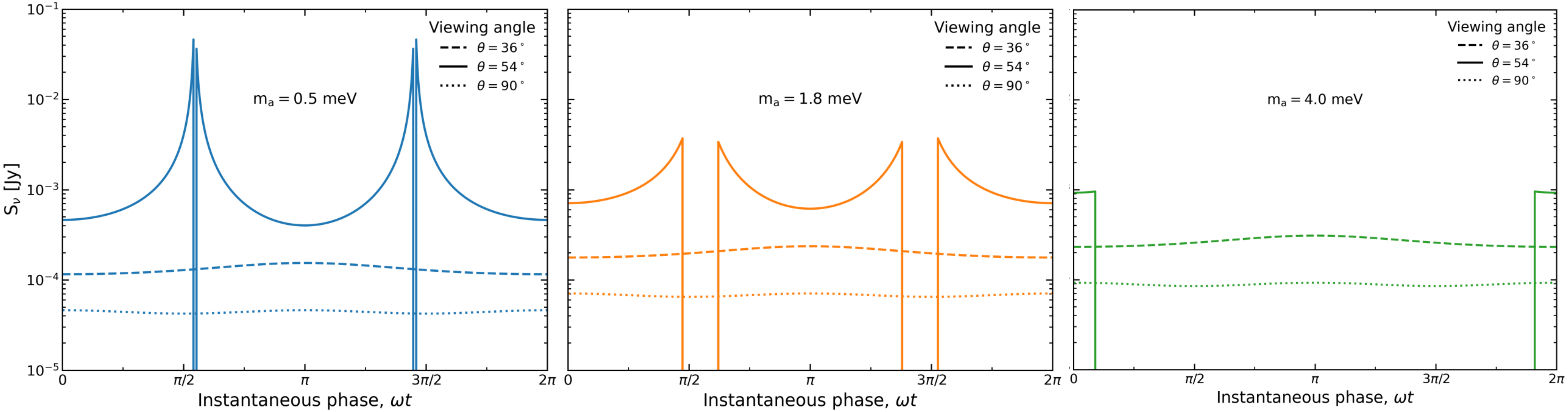
Therefore,

$$S_{a\to\gamma} \to \sqrt{\sigma_T} S_{a\to\gamma}$$





Predicted Signal ($S_{a\to\gamma}$)



Gap of vanishing signal depends on mass!

Signal or Noise?

Signal-to-Noise Ratio

$$\mathrm{SNR} = \frac{S_{a\to\gamma}}{\sigma_s}$$

Signal

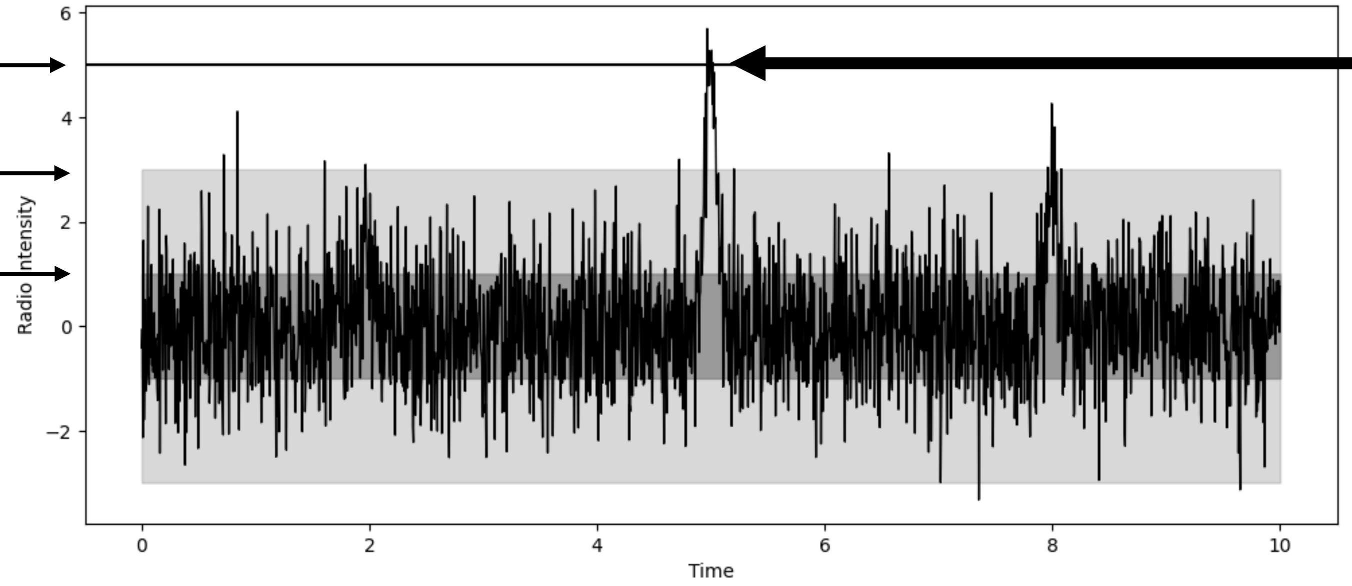
Systematic Noise $\sigma_s(T_{sys})$

A robust discovery typically requires SNR ≥ 5 (5σ) corresponding to ≈ 99.99994% confidence (1 in 3.5 million)

$S_{a\to\gamma} = 5\sigma$

3σ

1σ



Astrophysical Signal?

Noise

Constraints

Astrophysics | Particle Physics

Probability ($P_{a\to\gamma}$)

$$P_{a\to\gamma} = \frac{\pi}{3} \frac{(B(r_c))^2 r_c}{v_a(r_c)} \frac{g_{a\gamma\gamma}^2}{m_a} \quad (1)$$

$h\nu = m_a c^2$

Calculate from ALMA's parameters

Unmodulated signal

$$S_{a\to\gamma} = 2P_{a\to\gamma}\rho_a(r_c)v_a(r_c)r_c^2 \quad (2)$$

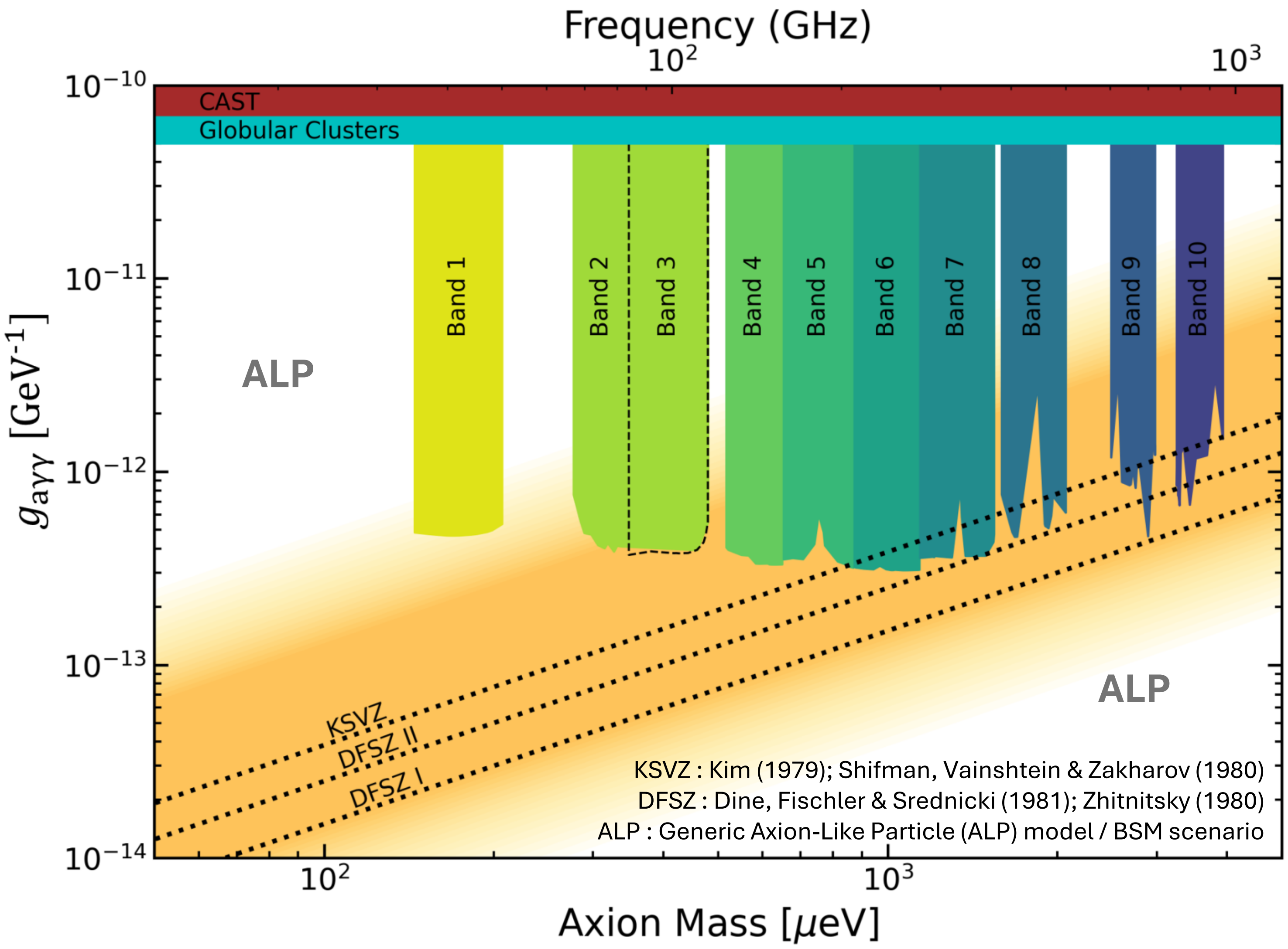
Predicted Signal

$$S_{a\to\gamma} \to \sqrt{\sigma_T} S_{a\to\gamma} \quad (3)$$

Therefore,

$$S_{a\to\gamma} \propto \frac{g_{a\gamma\gamma}^2}{m_a} \quad (4)$$

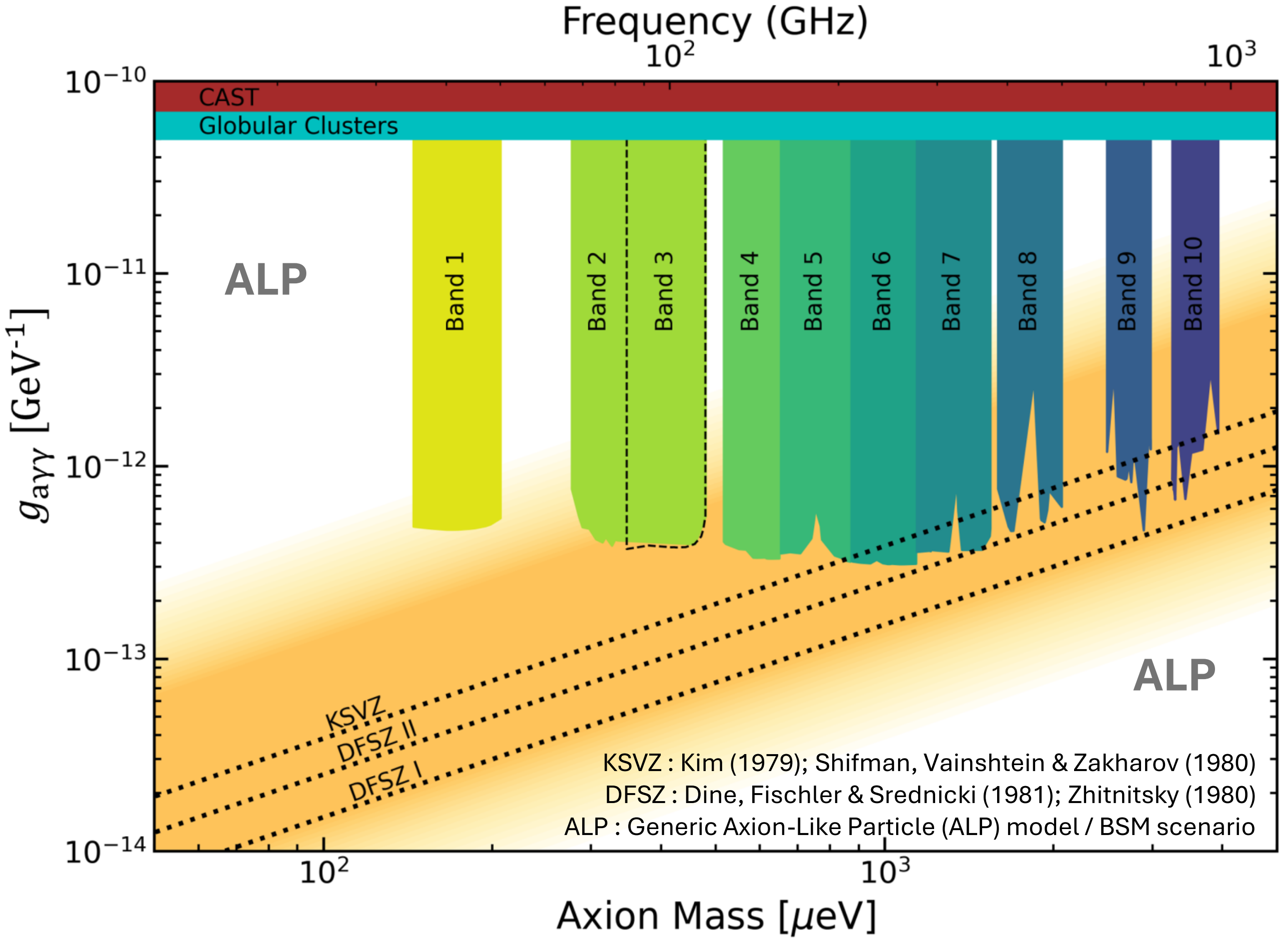
Result & Conclusion

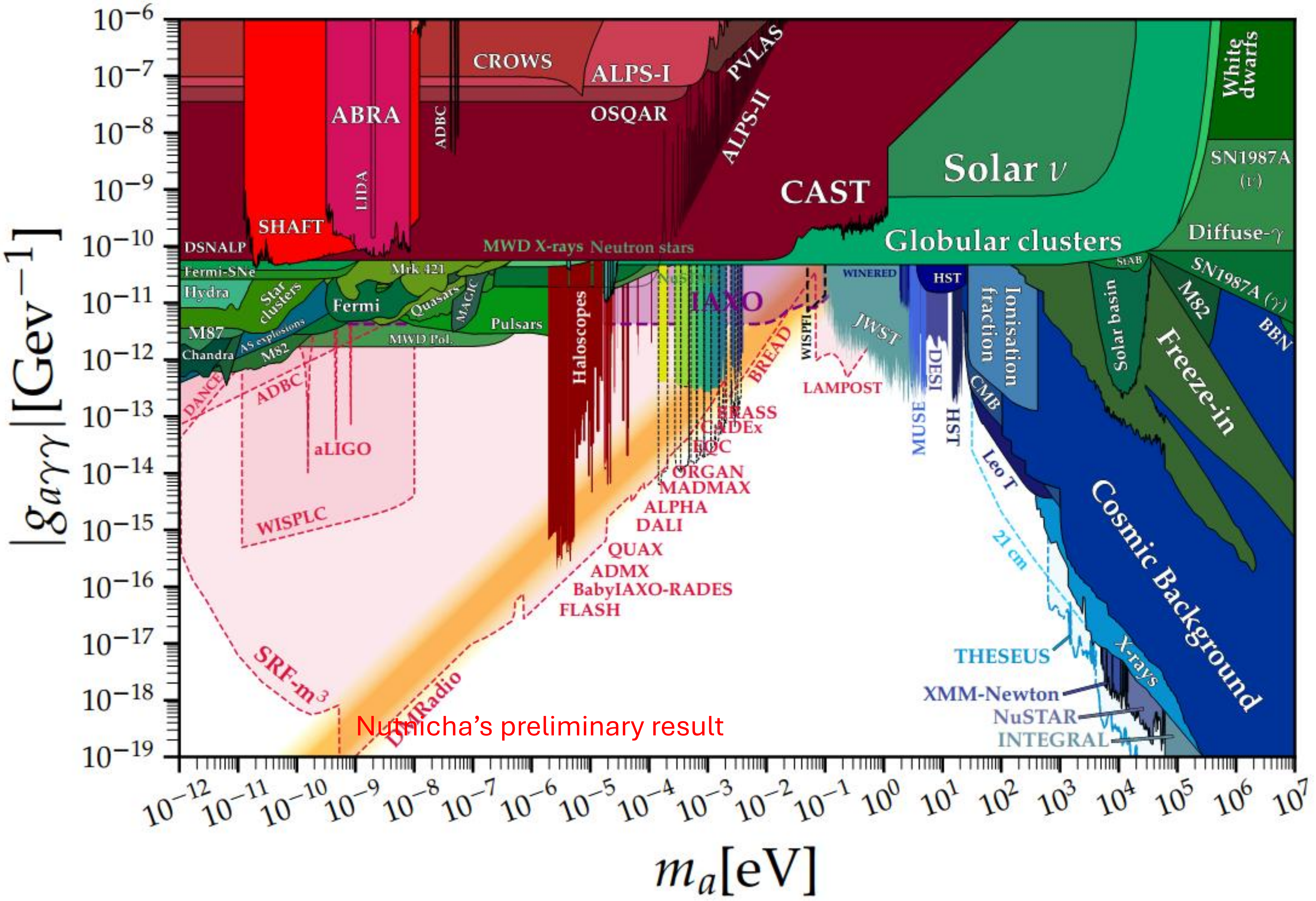


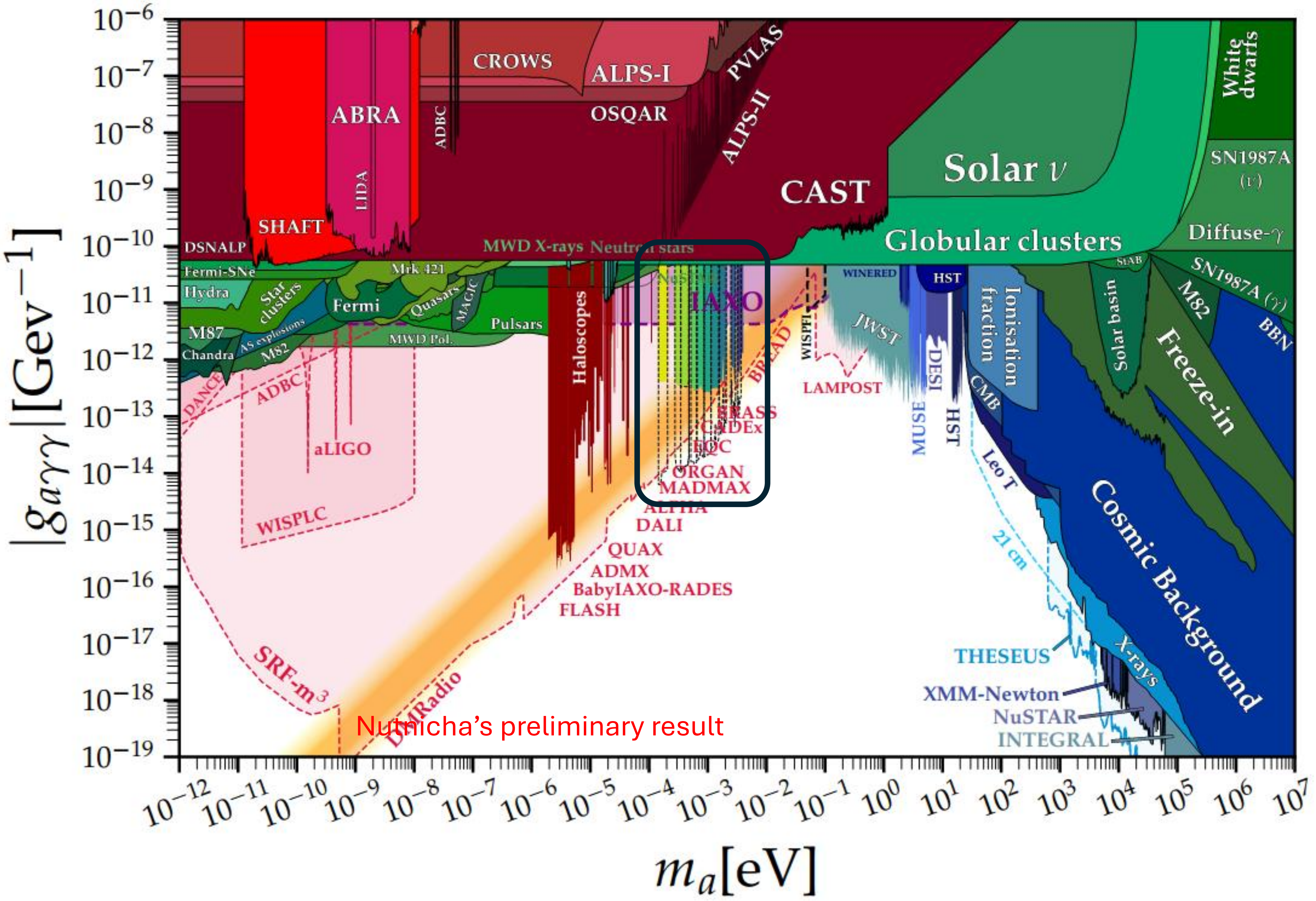
- ALMA explores a **range of axion masses** since 0.14-3.93 meV .
- **ALMA observations** are a **viable** method to detect Axion-Like Particle **(ALP)** from the conversion signals .
- ALMA band 6–10 provide the **possibility** to detect radio photon **from QCD axion** .
- Demonstrates ALMA's potential to probe axion parameter space **near QCD axion models**.

Result & Conclusion

- **PSR J1745–2900** provides a promising environment to probe axion dark matter.
- **Strong magnetic fields** and **high plasma density** enhance axion–photon conversion.
- Minimum multiplicity for axion-conversion detection in all ALMA bands: $\boldsymbol{\kappa = 2 \times 10^4}$.
- ALMA band 6–10 **has potential** to probe axion parameter space near QCD axion models.




CROWS
ALPS-I
PVLAS
ABRA
OSQAR
ALPS-II
ADBC
LIDA
CAST
Solar ν
White dwarfs
SN1987A
SHAFT
DSNALP
MWD X-rays
Neutron stars
Globular clusters
Diffuse-γ
Fermi-SNe
Mrk 421
Hydra
Star clusters
Fermi
Quasars
MAGIC
Pulsars
M87
AS explosions
Chandra
M82
MWD Pol.
Haloscopes
IAXO
WISPFI
WINERED
HST
JWST
Ionisation fraction
Solar basin
SN1987A (γ)
M82
BBN
Freeze-in
DANCE
ADBC
aLIGO
WISPLC
BREAD
LAMPOST
DESI
MUSE
HST
CMB
Leo T
BRASS
CADEx
LOC
ORGAN
MADMAX
ALPHA
DALI
QUAX
ADMX
BabyIAXO-RADES
FLASH
Cosmic Background
21 cm
X-rays
THESEUS
XMM-Newton
NuSTAR
INTEGRAL
SRF-m³
DMRadio
Nutnicha's preliminary result
$|g_{a\gamma\gamma}|[\text{GeV}^{-1}]$
$m_a[\text{eV}]$



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$|g_{a\gamma\gamma}|$[Gev^{-1}]
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m_a[eV]

Next Process

- Modify the plasma multiplicity
- Develop a more realistic magnetosphere model
- Compare the results with observational data

Reference

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