Exploring the axion dark matter through radio signals from magnetic white dwarf stars

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Outline

- Motivation
- Axion-photon conversion in the magnetic field
- Radio signals induced by axion dark matter in the corona of the magnetic white dwarf
- conclusion

Motivation

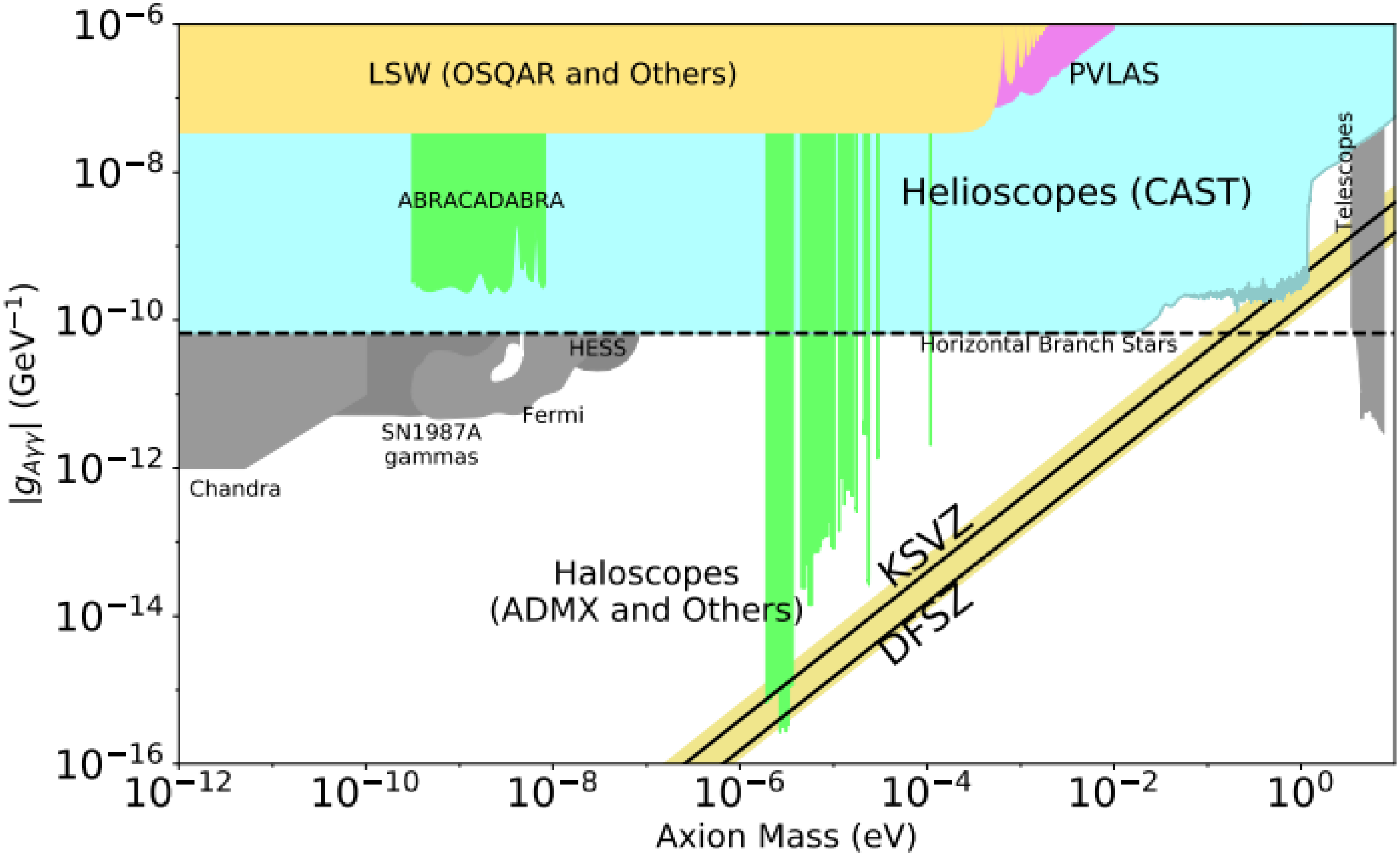
- (QCD) Axion is predicted by the Peccei-Quinn model, which naturally explains the strong CP problem in the standard model.

- Axion-like particle (ALP): light pseudo-scalar with similar interactions as QCD axion. Well motivated by the string theory.

- Axion is a good candidate of cold dark matter and is produced by the misaligned mechanism at the early universe.

- Axions can also be produced via many high energy astrophysical processes and provide many detectable signals at astrophysical observations.

Current limit



PDG 2020

Axion-photon interaction

- Effective Lagrangian：

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - A_\mu j^\mu - \frac{1}{4}g_{a\gamma\gamma}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- Equation of emotion：

For more detais, see Raffelt, Stodolsky, PRD, 1988

Hook et. al, 1804.03145

$$\ddot{a} - \nabla^2 a + m_a^2 a \;=\; -g_{a\gamma\gamma}\,\dot{\boldsymbol{A}}\cdot(\boldsymbol{\nabla}\times\boldsymbol{A})$$

Equation of emotion of axion with “source”

$$\ddot{\boldsymbol{A}} - \nabla^2\boldsymbol{A} + \boldsymbol{\nabla}(\boldsymbol{\nabla}\cdot\boldsymbol{A}) \;=\; \boldsymbol{j} + g_{a\gamma\gamma}\,\dot{a}\,\boldsymbol{\nabla}\times\boldsymbol{A} - g_{a\gamma\gamma}\,\boldsymbol{\nabla}a\times\dot{\boldsymbol{A}}$$

“Ampere’s law”

$$-\boldsymbol{\nabla}\cdot\dot{\boldsymbol{A}} \;=\; \rho - g_{a\gamma\gamma}\,\boldsymbol{\nabla}a\cdot(\boldsymbol{\nabla}\times\boldsymbol{A})$$

“Gauss’ law”

- The cases of interest are the linearized perturbations around static background fields.

$$a(\boldsymbol{x},t) = \bar{a}(\boldsymbol{x}) + \delta a(\boldsymbol{x},t) \qquad \boldsymbol{A}(\boldsymbol{x},t) = \bar{\boldsymbol{A}}(\boldsymbol{x}) + \delta\boldsymbol{A}(\boldsymbol{x},t)$$

e.g. oscillating axion-photon wave propagates in the plasma with the external magnetic field.

Mixing equation for axion-photon wave

- For strong external magnetic field $\bar{A} \gg \delta A$

  $\nabla \times A \to B$, **B** is the external magnetic field

  -$\dot{A} \to E$, **E** is the electric field of the propagating photon wave

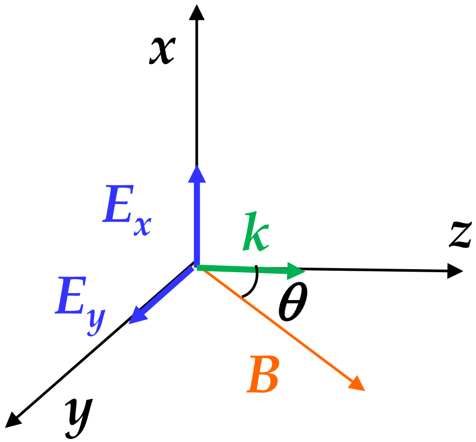
$$-\partial_t^2 a + \nabla^2 a = m_a^2 a - g_{a\gamma\gamma}\mathbf{E}\cdot\mathbf{B}$$

$$-\nabla^2\mathbf{E} + \nabla(\nabla\cdot\mathbf{E}) = \omega^2\mathbf{D} + \omega^2 g_{a\gamma\gamma} a\mathbf{B}$$

- Assume the radial plane wave solution

$$a(r,t) = ie^{i\omega t - ikr}\tilde{a}(r) \qquad A_y(r,t) = e^{i\omega t - ikr}\tilde{A}_y(r)$$

$$k = \sqrt{\omega^2 - m_a^2}$$



- Only $\mathbf{E}_y$ couples to axion and propagates.

- Electric displacement **D** includes the medium effect.

Mixing equation for axion-photon wave

- With the WKB approximations $|\tilde{A}''_{\parallel}(r)| \ll k|\tilde{A}'(r)|$ and $|\tilde{a}''(r)| \ll k|a'(r)|$,
  the second-order mixing equation can be reduced to the first-order

$$\left[-i\frac{d}{dr}+\frac{1}{2k}\begin{pmatrix} m_a^2-\xi\omega_p^2 & -\Delta_B \\ -\Delta_B & 0 \end{pmatrix}\right]\begin{pmatrix} \tilde{A}_y \\ \tilde{a} \end{pmatrix}=0$$

$$\xi=\frac{\sin^2\tilde{\theta}}{1-\frac{\omega_p^2}{\omega^2}\cos^2\tilde{\theta}} \qquad \Delta_B=Bg_{a\gamma}\omega\frac{\xi}{\sin\tilde{\theta}}$$

- Mixing is dominantly determined by the external magnetic field **B** and the coupling between the axion and photon $g_{a\gamma}$.

- The interaction between the electrons/ions and photons in the plasma changes the dispersion relation in the vacuum.

  Thus the photon propagating in the plasma gets an “effective mass”.

$$\omega_p=\sqrt{4\pi\alpha_{\rm em}n_e/m_e}$$

Conversion probability

- For initial incoming axion flux, define the energy transfer fraction after a propagating distance.

  $$p_{a\gamma}(r) = |\tilde{A}_y(r)|^2/|a_0|^2$$

  This function can also denote the conversion probability.

- An approximation is

  $$P(a \to \gamma) \sim \sin^2\Theta \sin^2(\Delta k L)$$

  $\tan\Theta \sim B g_{a\gamma\gamma}\omega/(m_a^2 - m_\gamma^2)$ denotes the mixing angle,

  Δk denotes the momentum difference between two particles,

  L denotes the propagating distance.

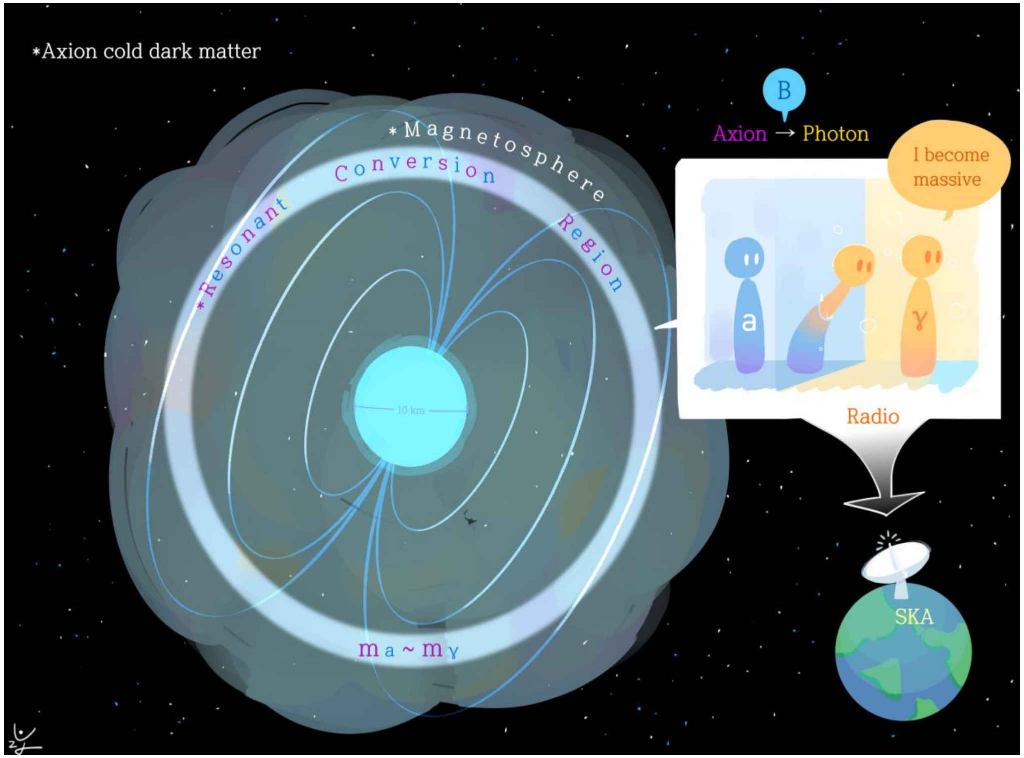
- The resonant conversion takes place when $m_a \sim m_\gamma$

Conversion in the neutron star's magnetosphere

- For significant conversion, we need strong magnetic field and resonant conversion with $m_a \sim m_\gamma$.

- **Neutron star (NS)** is an ideal target with B~10^{10}-10^{14}G .

- The photons become massive in the magnetosphere and can satisfy the resonant condition in a shell region with a narrow width.



From F. P. Huang

- For the typical mass of the DM axion ~μeV, the emission photon has a frequency ~GHz.

  Can be detected by the radio telescope.

Pshirkov, Popov, 0711.1264

Huang et. al, 1803.08230

Hook et. al, 1804.03145

Conversion in the magnetic white dwarf's corona

- We propose that the conversion may also significantly take place in the **magnetic white dwarf's (MWD's) corona**.

- **NS**: B~10^{10}-10^{14}G and r~10km

  MWD: B~10^{6}-10^{9}G and r~10^{4}km

  Although the magnetic field of the MWD is much weaker than the NS, it has a larger geometrical size and thus a larger conversion region.

- There are some MWDs near the Earth which provide an advantage for detection.

Corona of the MWD and its magnetic field structure

- The NS magnetosphere has been studied for a long time and can be described by the GJ model

Goldreich, Julian, APJ, 1969

$$n_c = \frac{2\mathbf{\Omega}\cdot\mathbf{B}}{e}\frac{1}{1-\Omega^2 r^2 \sin^2\theta}$$

- The corona of MWD is suggested by several theories, but it has not been observed yet. Its properties are constrained by x-ray observations

- We take the corona density with a fixed temperature~10^6K.

$$n_e(r) = n_{e0}\exp\left(-\frac{r-R_{\rm WD}}{H_{\rm cor}}\right)$$

Zheleznyakov et. al, Astro. Rep, 2004

$$H_{\rm cor} = \frac{2k_{\rm B}T_{\rm cor}}{m_{\rm p}g} = 21.90\left(\frac{T_{\rm cor}}{10^6\ {\rm K}}\right)\left(\frac{M_{\rm WD}}{M_\odot}\right)\left(\frac{R_{\rm WD}}{10^4\ {\rm km}}\right)^{-2}\ {\rm km}$$

Corona of the MWD and its magnetic field structure

- Using the resonant conversion condition, the radius of the resonant conversion region for the MWD is

$$r_c = R_{\rm WD} + 21.90 \times \left[2.634 + \ln\left(\frac{n_{e0}}{10^{10}\ {\rm cm}^{-3}}\right) + \ln\left(\frac{\mu{\rm eV}^2}{m_a^2}\right)\right] \times \left(\frac{T_{\rm cor}}{10^6\ {\rm K}}\right)\left(\frac{M_{\rm WD}}{M_\odot}\right)\left(\frac{R_{\rm WD}}{10^4\ {\rm km}}\right)^{-2}\ {\rm km}$$

- For NS

$$r_c(\theta, \theta_m, t) = 224\ {\rm km} \times \left(\frac{r_0}{10\ {\rm km}}\right) \times \left[\frac{B_0}{10^{14}\ {\rm G}}\ \frac{1\ {\rm sec}}{P}\left(\frac{1\ {\rm GHz}}{m_a}\right)^2\right]^{1/3}$$

- The magnetic field structure is take to be dipole configuration

m is the magnetic diploe moment

$$\boldsymbol{B} = \frac{B_0}{2}\frac{R_{\rm WD}^3}{r^3}\left(3(\hat{\boldsymbol{m}} \cdot \hat{\boldsymbol{r}})\hat{\boldsymbol{r}} - \hat{\boldsymbol{m}}\right) \quad {\rm for}\ r > R_{\rm WD}$$

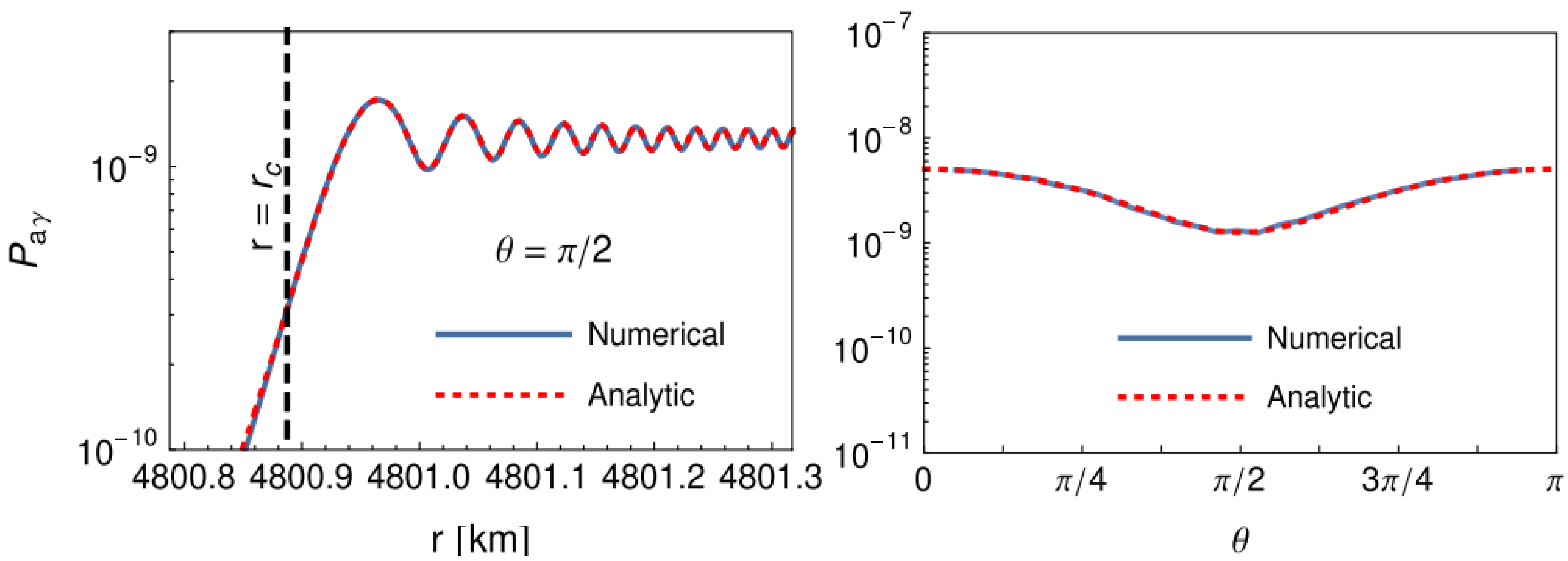
Conversion probability for MWD

- An approximate solution of the mixing equation is

$$p_{a\gamma}^{\infty} = \lim_{r\to\infty} p_{a\gamma}(r) \approx \frac{\xi(r_c)^2}{2v_c^2 \sin^2\tilde{\theta}} g_{a\gamma\gamma}^2 B(r_c)^2 L^2$$

This function depends on the angle with respect to the magnetic field

$$p_{a\gamma}^{\infty} \approx \frac{1}{2v_c^2} g_{a\gamma\gamma}^2 B(r_c)^2 L^2 \qquad L = \sqrt{2\pi v_c H_{\rm cor}/m_a}$$ for $\theta = \pi/2$



Radio flux density

- The outgoing photons may be scattered in the corona due to the inverse bremsstrahlung and Compton scattering.

$$P_s \simeq \exp\left[-\int_{r_c}^{\infty} dr(\Gamma_{\rm inv} + \Gamma_{\rm Com})\right]$$

The survival probability is ~1 for the MWD candidates of interest.

- The DM density near the compact star is larger than the average value.

$$\rho_{\rm DM}^{r_c} = \rho_{\rm DM}^{\infty} \frac{2}{\sqrt{\pi}} \frac{v_c}{v_0}$$

- The radiated power and the flux density are

$$\frac{d\mathcal{P}}{d\Omega} \approx 2 \times p_{a\gamma}^{\infty} \rho_{\rm DM}^{r_c} v_c r_c^2 \qquad S_{a\gamma} = \frac{d\mathcal{P}}{d\Omega} \frac{1}{\mathcal{B} d^2}$$

- Results for some nearby MWDs

	$M_{\rm WD}$ $[M_\odot]$	$R_{\rm WD}$ $[R_\odot]$	$T_{\rm eff}$ [K]	B [MG]	$d_{\rm WD}$ [pc]	$S_{a\gamma}$ [μJy]
WD 09487 – 2421	0.84	0.0098	14530	670	36.53	85.33
WD 2010 + 310	1.14	0.00643	19750	520	30.77	110.02
WD 1031 + 234	0.937	0.00872	20000	200	64.09	2.97
WD 1043 – 050	1.02	0.00787	16250	820	83.33	33.51
WD 1743 – 520	1.13	0.00681	14500	36	38.93	0.33

Radio flux density

- Approximate result for the MWD

$$S_{a\gamma}^{\rm WD} \simeq 29.11\ \mu{\rm Jy} \left(\frac{\rho_{\rm DM}^{\infty}}{0.3\ {\rm GeV/cm^3}}\right) \left(\frac{M_{\rm WD}}{M_{\odot}}\right)^{3/2} \times \left(\frac{v_0}{200\ {\rm km/s}}\right)^{-1} \left(\frac{R_{\rm WD}}{10^4\ {\rm km}}\right)^{-1/2} \left(\frac{T_{\rm cor}}{10^6\ {\rm K}}\right) \times \left(\frac{g_{a\gamma}}{10^{-12}\ {\rm GeV^{-1}}}\right)^2 \left(\frac{B_0}{10^8\ {\rm G}}\right)^2 \left(\frac{m_a}{1\ \mu{\rm eV}}\right)^{-1} \times \left(\frac{d}{10\ {\rm pc}}\right)^{-2} \left(\frac{\mathcal{B}}{1\ {\rm kHz}}\right)^{-1}$$

- For the NS

$$S_{a\gamma}^{\rm NS} \simeq 71.97\ \mu{\rm Jy} \left(\frac{\rho_{\rm DM}^{\infty}}{0.3\ {\rm GeV/cm^3}}\right) \left(\frac{M_{\rm NS}}{M_{\odot}}\right)^{1/2} \left(\frac{v_0}{200\ {\rm km/s}}\right)^{-1} \times \left(\frac{R_{\rm NS}}{10\ {\rm km}}\right)^{5/2} \left(\frac{P}{1\ {\rm sec}}\right)^{7/6} \left(\frac{g_{a\gamma}}{10^{-12}\ {\rm GeV^{-1}}}\right)^2 \times \left(\frac{B_0}{10^{14}\ {\rm G}}\right)^{5/6} \left(\frac{m_a}{1\ \mu{\rm eV}}\right)^{4/3} \left(\frac{d}{100\ {\rm pc}}\right)^{-2} \left(\frac{\mathcal{B}}{1\ {\rm kHz}}\right)^{-1}$$

- The main differences are caused by different plasma distributions

Experimental sensitivity

- The minimum detectable flux density of a radio telescope is given by

$$S_{\rm min} = \frac{\rm SEFD}{\eta_s \sqrt{n_{\rm pol} \mathcal{B} t_{\rm obs}}}$$

The system-equivalent flux density depends on the effective area and temperature of the telescope

$$\mathrm{SEFD} = \frac{2k_B}{A_{\rm eff}/T_{\rm sys}}$$

- We calculate the sensitivity for SKA1.

Name	f [MHz]	$B_{\rm res}$ [kHz]	$A_{\rm eff}/T_{\rm sys}$ [m^2/K]	SEFD [Jy]	$S_{\rm min}$ [μJy]
SKA1-Low	(50, 350)	1.0	1000	2.76	140.0
SKA1-Mid B1	(350, 1050)	3.9	779	3.54	91.0
SKA1-Mid B2	(950, 1760)	3.9	1309	2.11	54.2
SKA1-Mid B3	(1650, 3050)	9.7	1309	2.11	34.3
SKA1-Mid B4	(2800, 5180)	9.7	1190	2.32	37.8
SKA1-Mid B5	(4600, 13800)	9.7	994	2.78	45.2

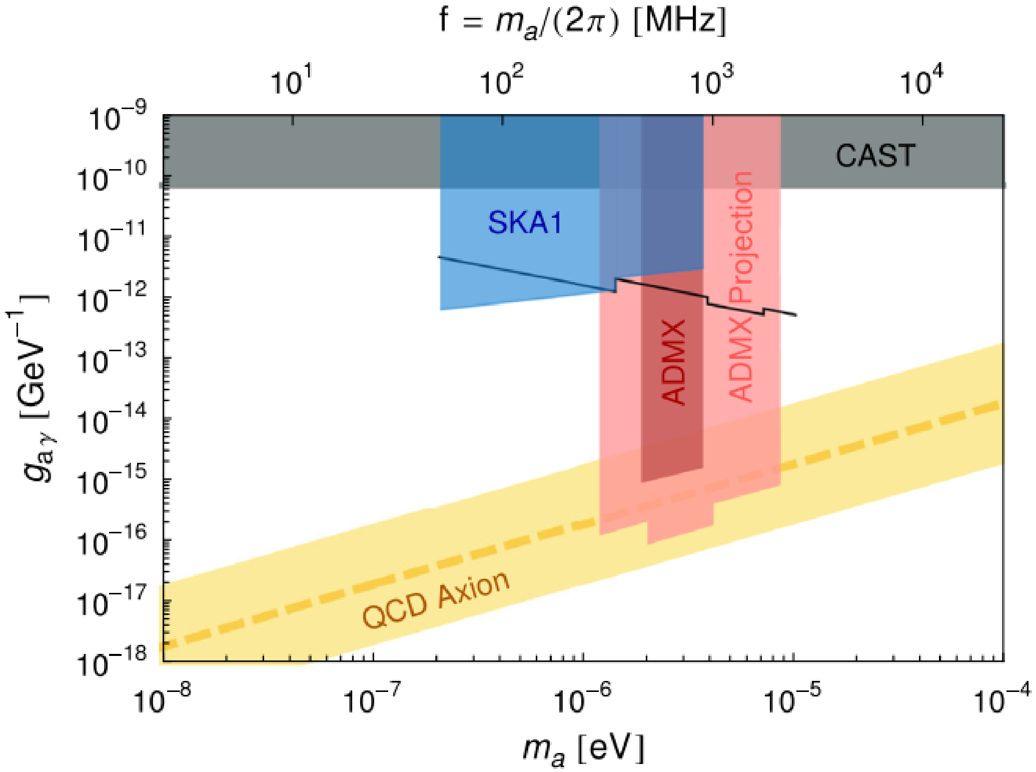
Experimental sensitivity

- We calculate the sensitivity for the nearby MWD **WD** 2010+310, with **B=5.2X10^{8}G** and **d=30.8 pc**

- Due to the limit on the plasma density of the WD, the mass of the converted axion has a upper-limit.

  We only consider the first two frequency bands SKA1-Low and SKA1-B1

- For comparison, we also calculate the sensitivity for the **NS** RX J0806.4-4123 , with **B=2.5X10^{13}G** and **d=250 pc**



Summary

- Axion is a good candidate for cold dark matter.
- Axion-photon mixing may induce many detectable astrophysical signals
- We propose to search for the radio signals converted by the axion dark matter from magnetic white dwarfs
- There are many extended topics, e.g. searching the signals from compact stars in the globular cluster.

Thank you