Detecting Axion Dark Matter through the Radio Signal from Omega Centauri

Jin-Wei Wang

Astroparticle Physics, SISSA

JW Wang, XJ Bi, RM Yao, PF Yin, arXiv:2101.02585, PRD

JW Wang, XJ Bi, PF Yin, arXiv:2109.00877

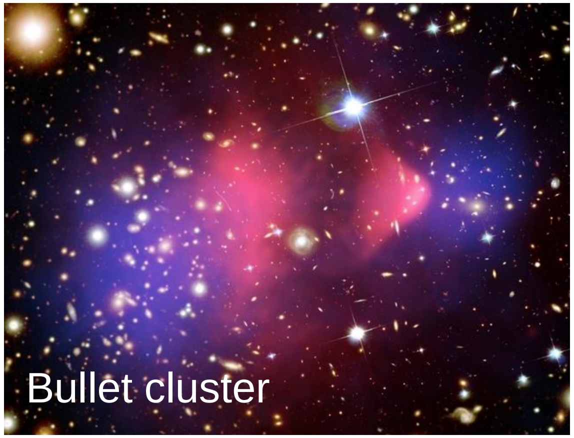
Barolo, September 9th, 2021

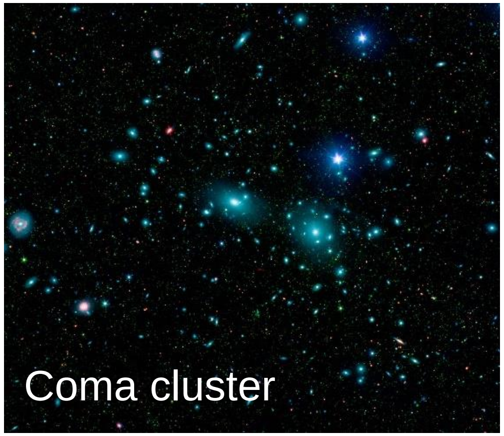
Outline

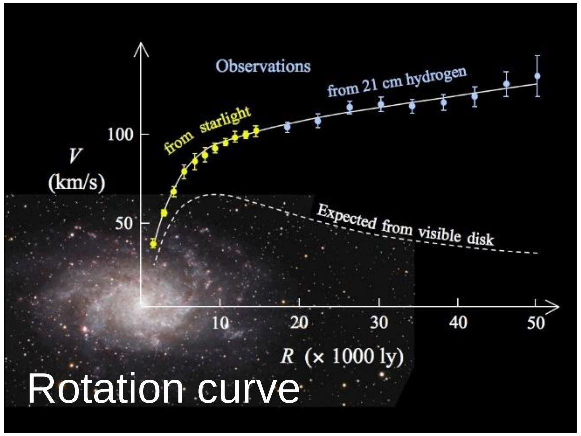
- Introduction and motivation
- The properties of Omega Centauri
- The properties of compact stars
- Detecting sensitivity on SKA 1 and LOFAR
- Summary

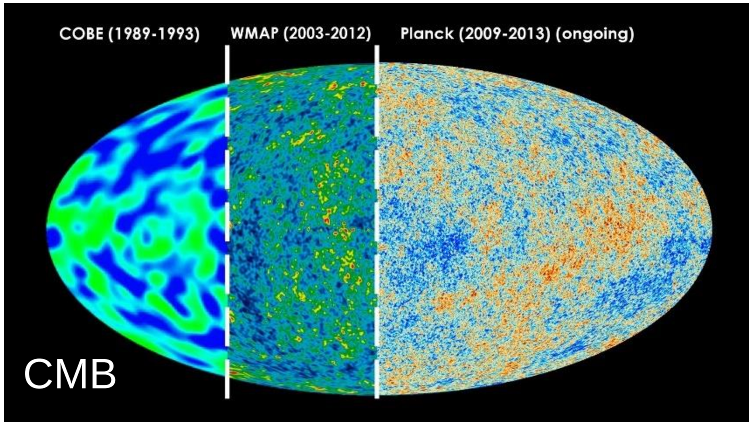
Dark matter in the Universe

- The astrophysical and cosmological observations have provided compelling evidences of the existence of **dark matter (DM)**.









Planck 2018 [1807.06209]

Cold DM (~26%)

$\Omega_c h^2 = 0.11933 \pm 0.00091$

Baryons (~5%)

$\Omega_b h^2 = 0.02242 \pm 0.00014$

Dark energy (~69%)

$\Omega_\Lambda = 0.6889 \pm 0.0056$

Axion dark matter

- **Strong CP problem**: the QCD Lagrangian can contain a **CP violating** term

$$\mathcal{L}_\theta = \bar{\theta}\frac{g_s^2}{32\pi^2}\varepsilon^{\mu\nu\alpha\beta}F^a_{\mu\nu}F^a_{\alpha\beta}$$

- Current limit from neutron EDM: $\bar{\theta} < 10^{-10}$

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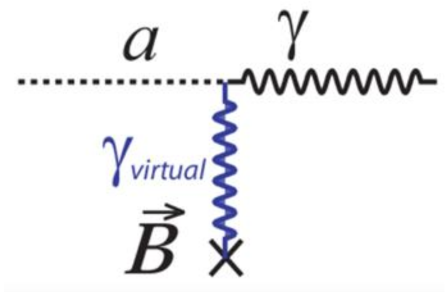
- Introduce a global U(1) **PQ symmetry**, promote $\bar{\theta}$ to a dynamical quantity instead of a constant parameter.
- The goldstone boson associated with U(1) PQ is called **axion**, with is a good DM candidate.

Axion-photon conversion

The coupling between axion and electromagnetic sector:

$$\mathcal{L}_{a\gamma\gamma} = -(1/4) g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$



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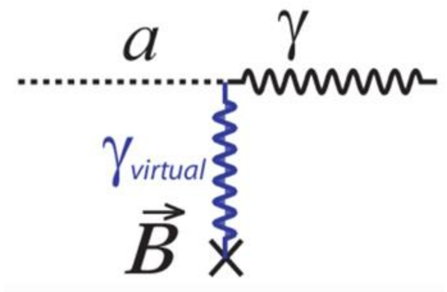

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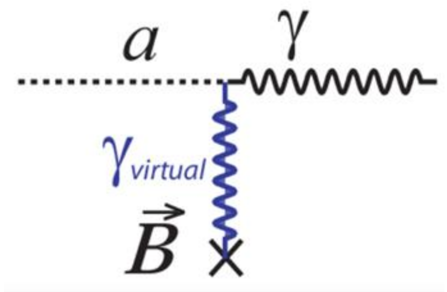
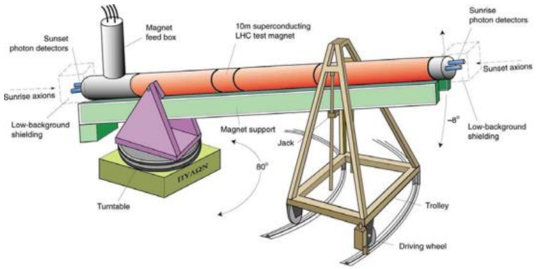


Axion-photon conversion in the external magnetic field

- **Axion helioscope** [1705.02290, 1401.3233 ⋯]



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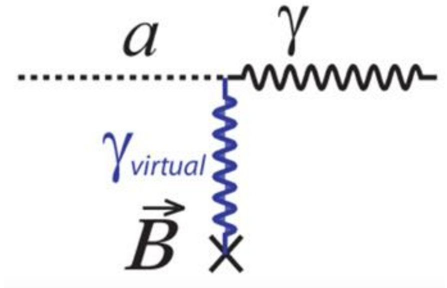

Axion-photon conversion in the external magnetic field

- **Axion helioscope** [1705.02290, 1401.3233 ···]
- **light shining through a wall** [1004.1313, 1302.5647 ···]

ALPS

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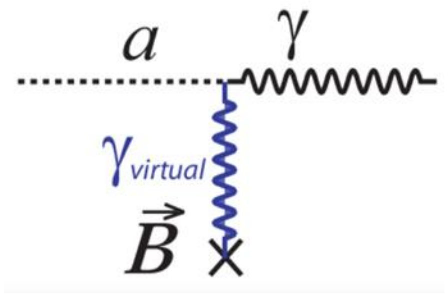
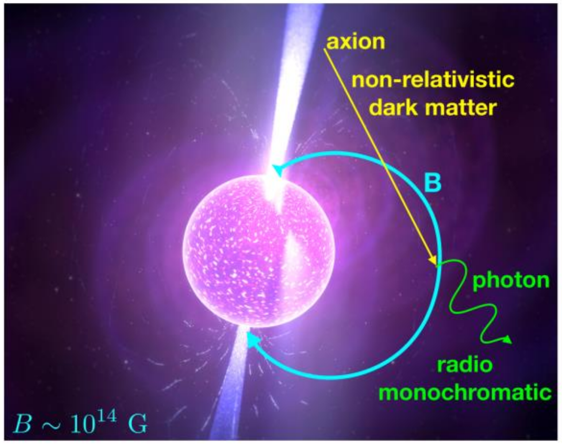


Axion-photon conversion in the external magnetic field

- **Axion helioscope** [1705.02290, 1401.3233 ⋯]
- **light shining through a wall** [1004.1313, 1302.5647 ⋯]
- **Neutron stars** [0711.1264, 1804.03145, 1803.08230, 2008.01877, 2011.05378, 2004.06486 ⋯]
- **Magnetic white dwarf stars** [2101.02585]



From Benjamin Safdi's talk

Single NS/MWD results

- The axion-photon mixing equations

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

with

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

- **Resonant conversion** condition $m_a=\omega_p$. When $\boldsymbol{\theta=\pi/2}$

Radio signal

$$P_{a\gamma}=\frac{1}{2v_c^2}g_{a\gamma}^2B^2(r_c)L, \quad \text{where } L=\begin{cases}\sqrt{\dfrac{2\pi k(r_c)r_c}{3m_A^2(r_c)}} & \text{for NS}\\ \sqrt{\dfrac{2\pi v_c H_{cor}}{m_A(r_c)}} & \text{for MWDs}\end{cases}$$

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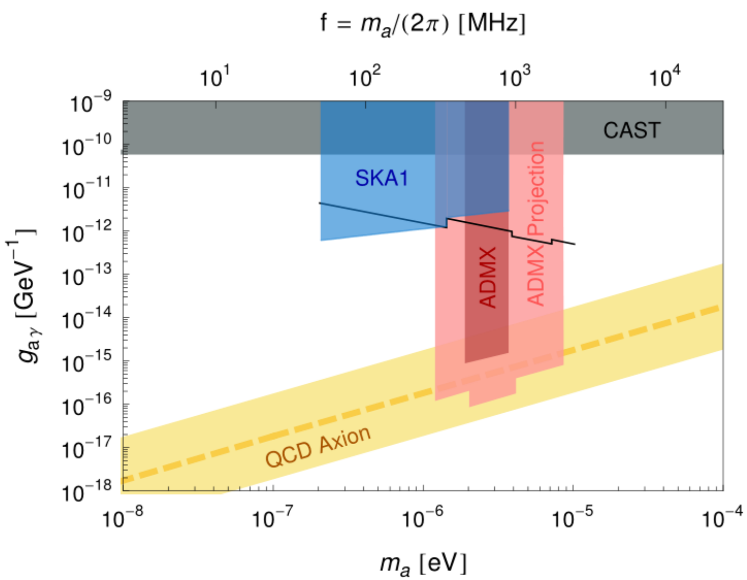
- $S_{a\gamma}^{\rm WD}\propto\rho_{\rm DM}v_0^{-1}g_{a\gamma}^2B_0^2m_a^{-1}d^{-2}$

$S_{a\gamma}^{\rm NS}\propto\rho_{\rm DM}v_0^{-1}g_{a\gamma}^2P^{7/6}B_0^{5/6}m_a^{4/3}d^{-2}$

Plasma model are different!



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The properties of Omega Centauri

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- The largest globular cluster in the Milky Way, and is suggested to be the remnant core of a dwarf galaxy;
- Amounts of CSs, larger DM density, and smaller velocity dispersion.

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- The DM profile: $\rho_{\rm NFW} = \rho_s \left(\frac{r}{r_s}\right)^{-1} \left(1 + \frac{r}{r_s}\right)^{-2}$ with $\rho_s = 7650.59\ M_\odot \mathrm{pc}^{-34}$, $r_s = 1.63\ \mathrm{pc}$

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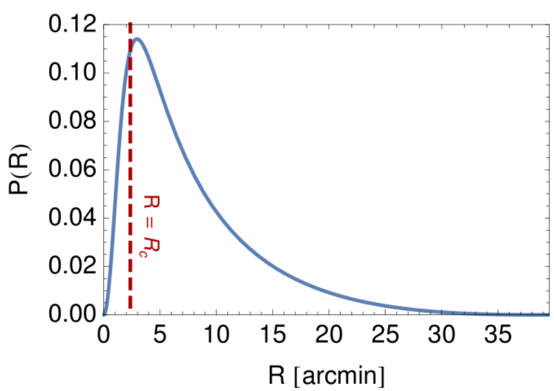
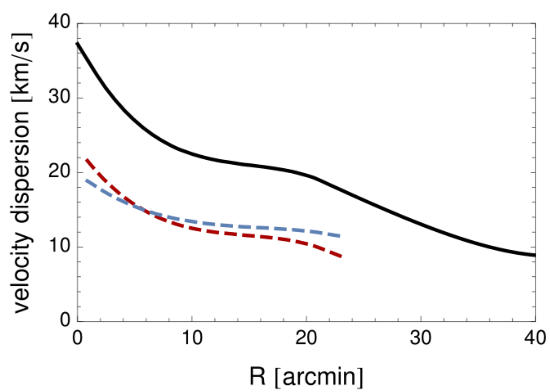
- The **King model** and position dependent **MB distribution**.





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- The **King model** and position dependent **MB distribution**.
- N-body simulations of GCs by using CMC code [**K. Kremer, etc, 2020**]

12531 NSs and 102990 MWDs with $B_0 > 0.1$ MG

The properties of compact stars

- **Dipole** magnetic field configuration, set $n_{e0} = 10^{10}\ \mathrm{cm}^{-3}$ and $T_{\mathrm{cor}} = 10^{6}\ \mathrm{K}$

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- **Dipole** magnetic field configuration, set For MWDs, the distribution of M_{WD} and B_0 are derived by using the current available MWDs data with linear interpolation, and R_{WD} is determined by EoS. and $T_{\rm cor} = 10^6$ K
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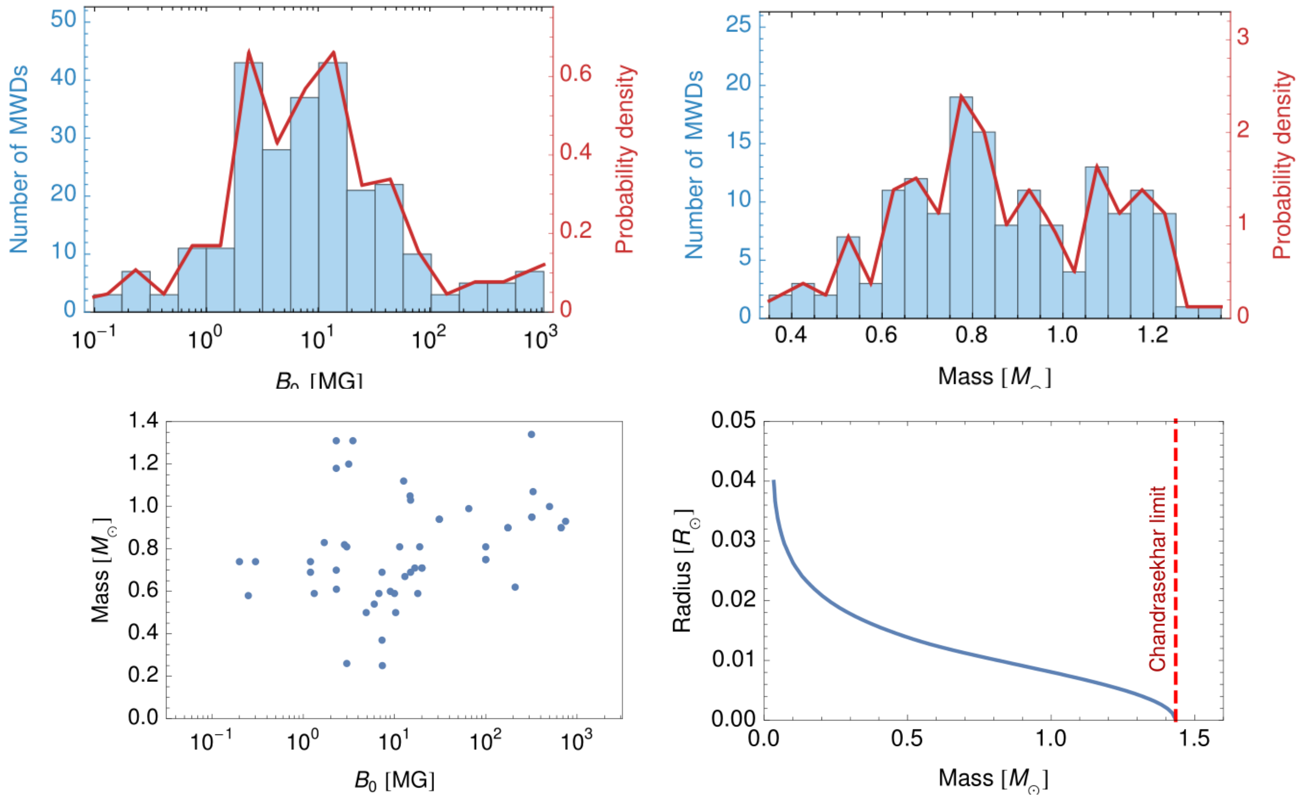

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- For NSs, the distribution of P_{NS}, α_{NS}, and B_0 are derived by the NS evolution models

$$P(t)P'(t) = \begin{cases} \frac{2}{3}\frac{P_{\rm in}^2}{\tau_{\rm in}} & \text{for active NSs} \\ \frac{2}{3}\frac{P_{\rm in}^2}{\tau_{\rm in}} \sin^2\alpha(t) & \text{for dead NSs} \end{cases},$$

$$B_0/P^2 > 0.34 \times 10^{12}\ {\rm G\ s^{-2}}$$

$$\frac{d}{dt}\log \sin\alpha(t) = -\frac{2}{3}\frac{\cos^2\alpha_{\rm in}}{\tau_{\rm in}}, \qquad \tau_{\rm in} = \frac{I}{\pi\mu^2 f_0^2} \approx 8904 \left(\frac{10^{12}\ {\rm G}}{B_0}\right)^2 \left(\frac{P_{\rm in}}{0.01}\right)^2 {\rm yr}$$

$$\frac{dB_0}{dt} = -B_0\left[\frac{1}{\tau_{\rm ohm}} + \left(\frac{B_0}{B_{\rm in}}\right)^2 \frac{1}{\tau_{\rm ambip}}\right], \qquad \tau_{\rm ohm} \sim \frac{1.8\times 10^9}{Q_{\rm imp}}{\rm yr}, \qquad \tau_{\rm ambip} \sim 3\times 10^9 \left(\frac{t_{\rm E}}{10^6\ {\rm yr}}\right)^{-1/3} \left(\frac{B_{\rm in}}{10^{12}\ {\rm G}}\right)^{-2} {\rm yr}$$

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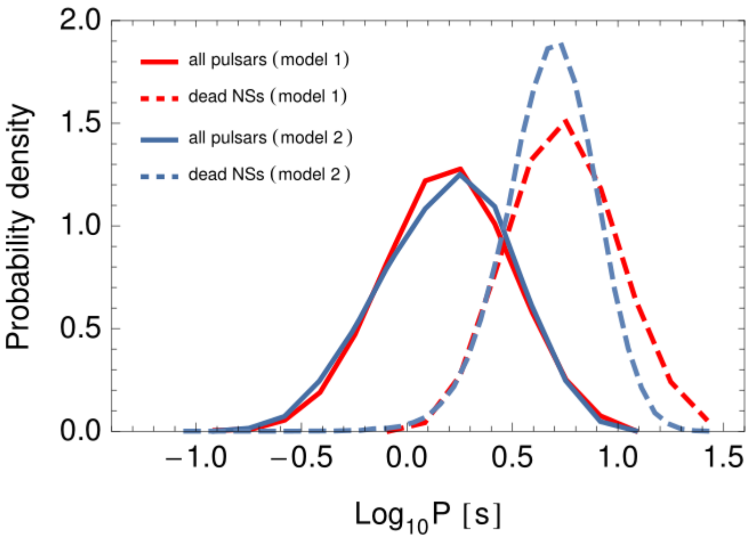
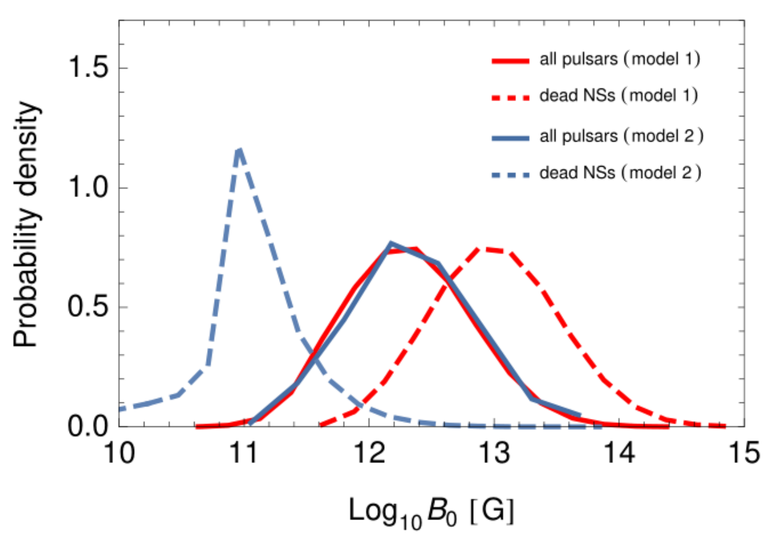




The sensitivity of SKA1 and LOFAR

Technical parameters of the SKA1 and LOFAR [13, 16]

Channel		Range [GHz]	Resolution [kHz]	FoV [arcmin]
SKA1 LOW		0.05∼0.35	1.0	327
SKA1 MID	B1	0.35∼1.05	3.9	109
	B2	0.95∼1.76	3.9	60
	B3*	1.65∼3.05	9.7	42
	B4*	2.80∼5.18	9.7	42
	B5a	4.6∼8.5	9.7	12.5
	B5b	8.3∼15.3	9.7	6.7
LOFAR LBA		0.03∼0.08	195	470.9
LOFAR HBA		0.11∼0.24	195	94.8

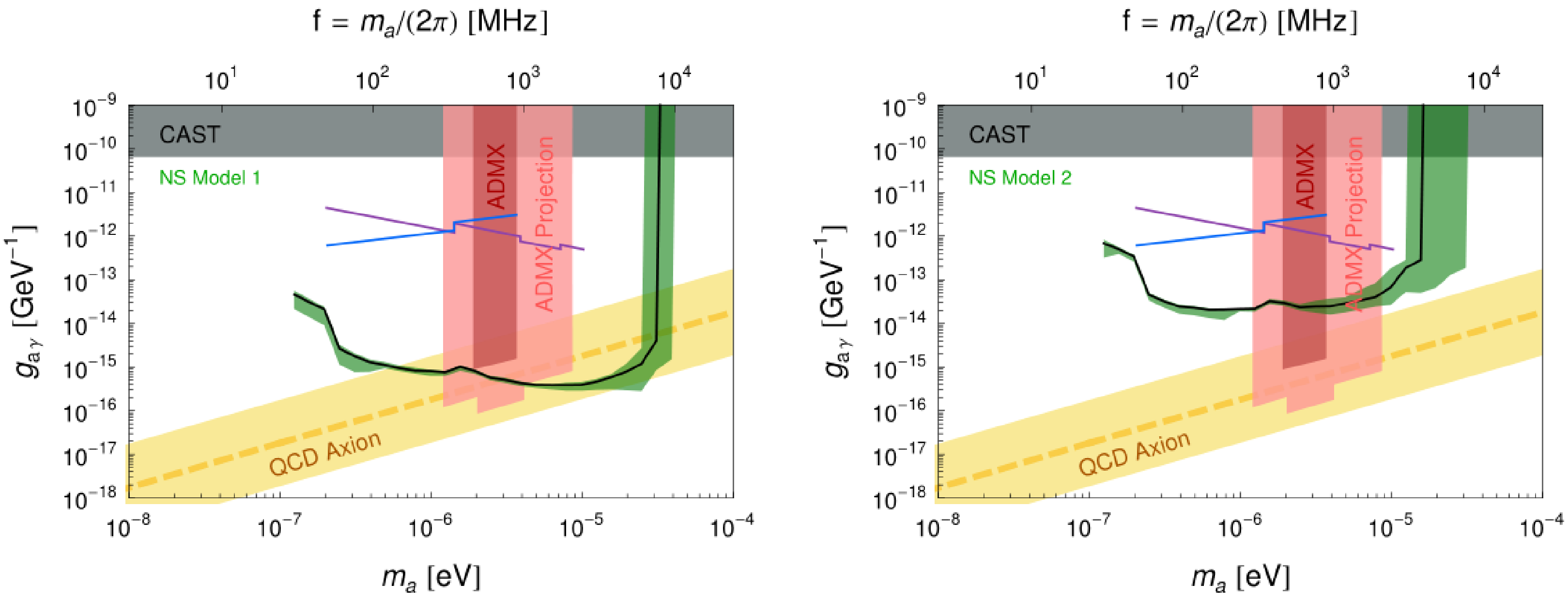
- The minimal detectable flux density:

$$S_{\rm min} = \frac{\rm SEFD}{\eta_s \sqrt{n_{\rm pol}\, \mathcal{B}\, t_{\rm obs}}}\,, \qquad {\rm SEFD} = \frac{2k_B}{A_{\rm eff}/T_{\rm sys}}$$

- The total flux density from Omega Centauri:

$$S_{a\gamma}^{\rm total} = \left(\sum_{N_{\rm NS}} S_{a\gamma}^{\rm NS} + \sum_{N_{\rm WD}} S_{a\gamma}^{\rm WD} \right) \times \Theta\left(\frac{\rm FoV}{2} - P_{\rm CS} \right)$$

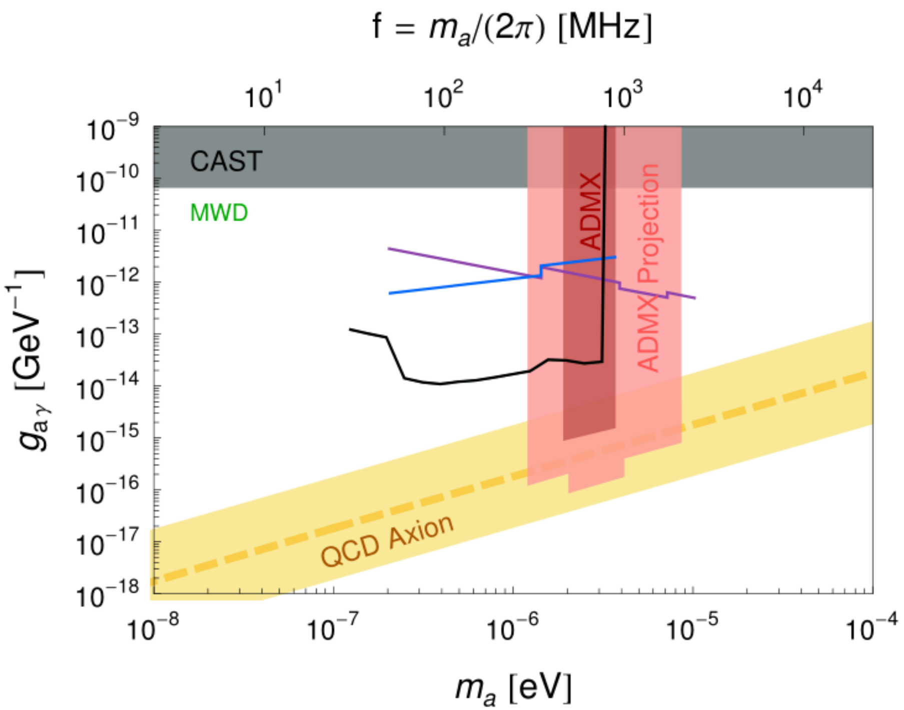
Result of pure NSs



- The largest detectable axion mass:

$$m_a^{\max} \approx 69.2 \times \left|3\cos^2\theta - 1\right|^{1/2} \sqrt{\frac{B_0}{10^{14}\ \mathrm{G}} \frac{1\ \mathrm{s}}{P}}\ \mu\mathrm{eV}$$

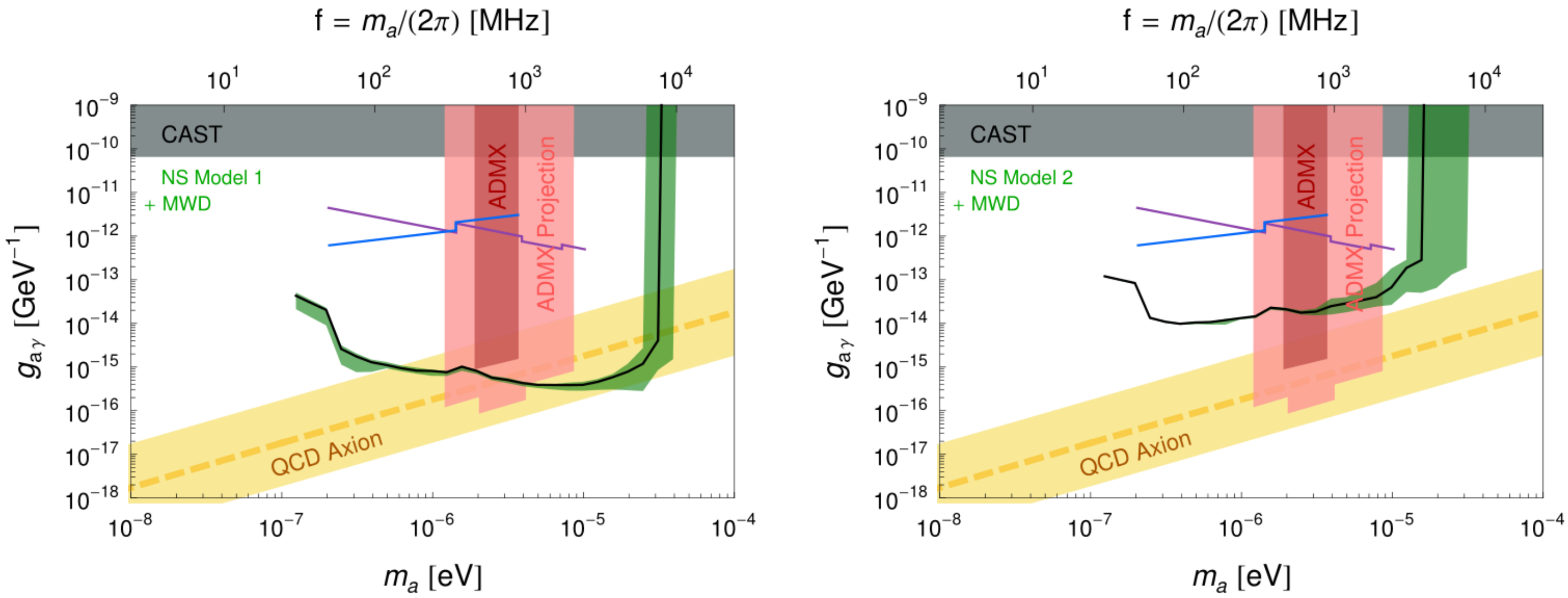
Pure MWDs results



- The largest detectable axion mass: $m_a^{\max} \approx 3.7\ \mu\text{eV}$

- The statistical fluctuation is quiet small (law of large numbers)

Combined results: NS+WMDs



- For NS model 1, the contribution of NS is dominant
- For NS model 2, the contribution of MWDs is relatively larger in the region of $m_a \lesssim 2\,\mu\mathrm{eV}$

Summary

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- **The axion-photon conversion provides a possible way to detect the axion dark matter, especially around objects with strong magnetic field;**
- **Compared with single CS, the Omega Centauri is a much more effective target. The constrains on $g_{a\gamma}$ can up to 10^{-14}~10^{-15} GeV^{-1}**

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Thank you