Indirect Detection of Axion Dark Matter with Neutron Stars

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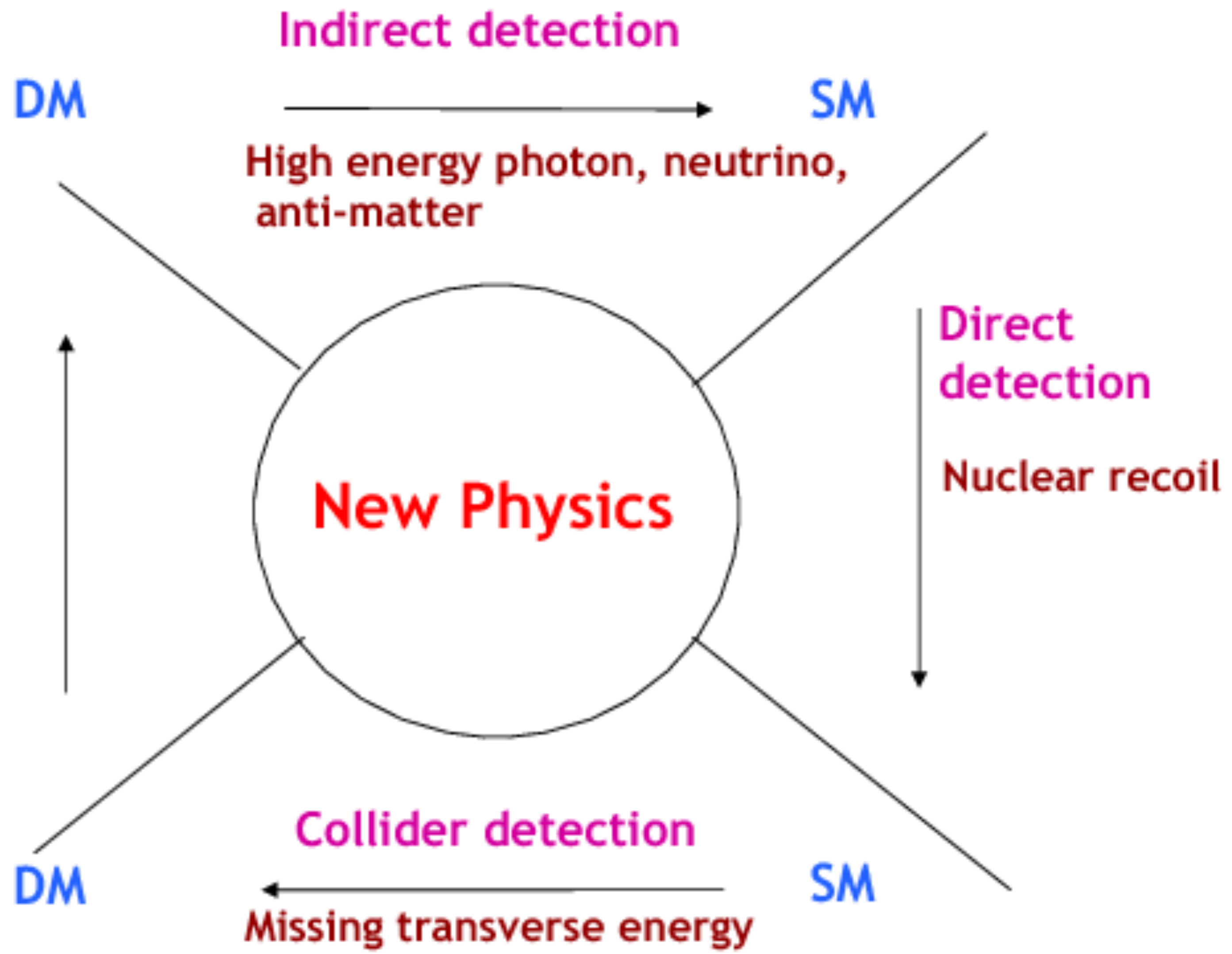
BNL “Dark Interactions” conference, 10/3/18

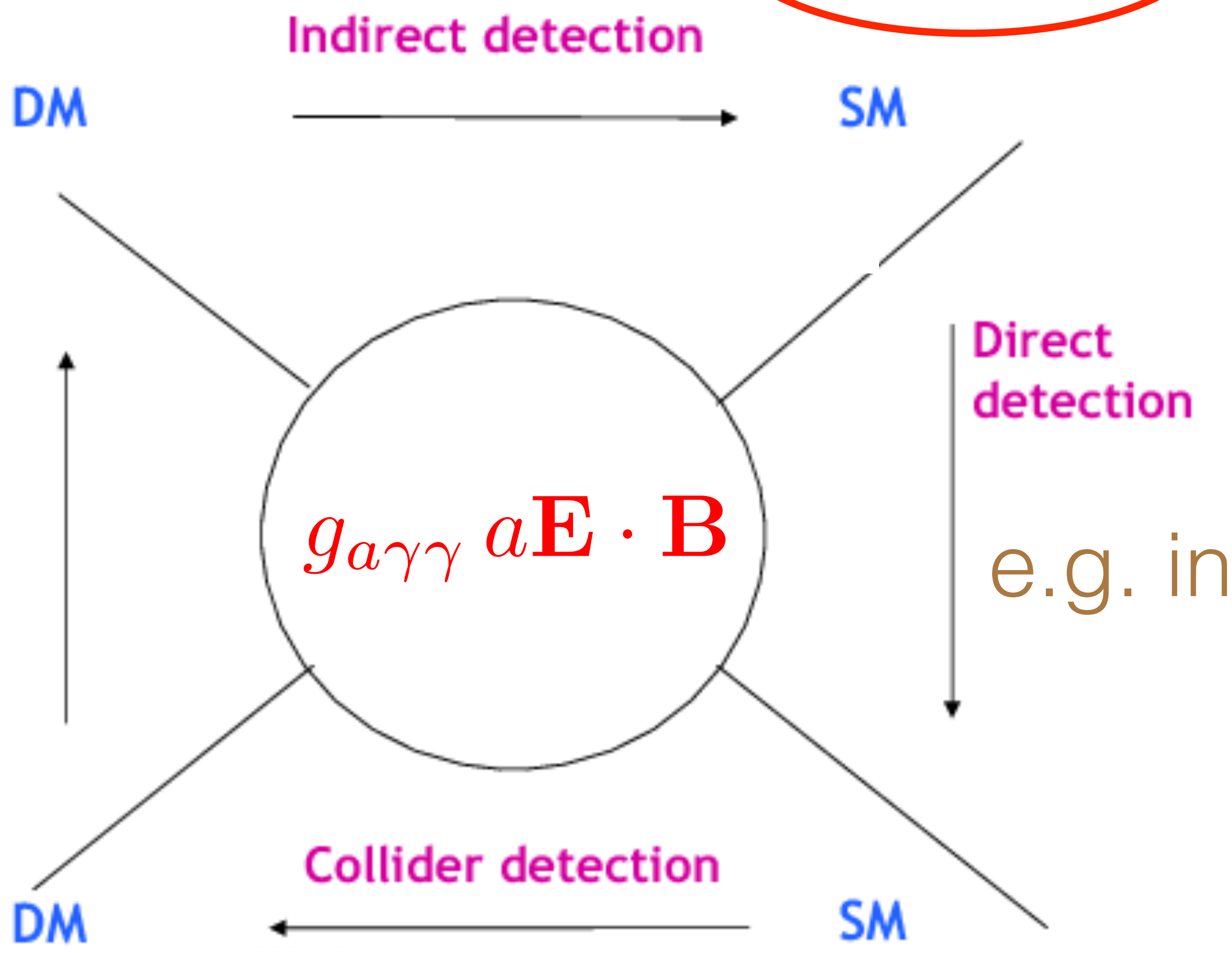
WIMP DM "holy trinity"



Analogue for axions??

Axion DM "holy trinity"

axion emission and/or conversion



e.g. interferometry

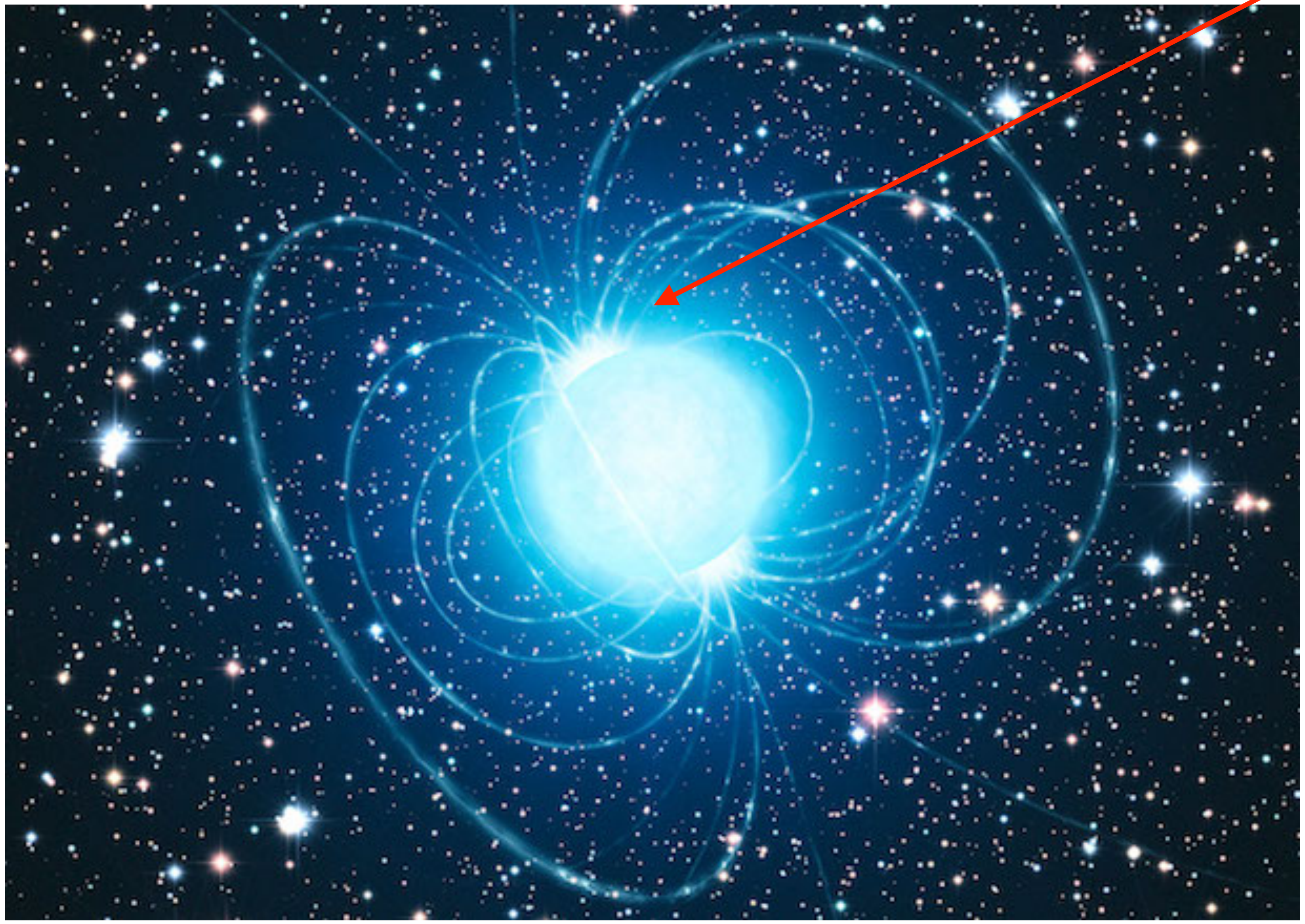
light shining through walls

(analogy isn't perfect: 2 -> 1 rather than 2 -> 2)

Where to look?

Magnetar - largest B-fields in the known universe!

$B_{\text{max}} \sim 10^{11}$ T

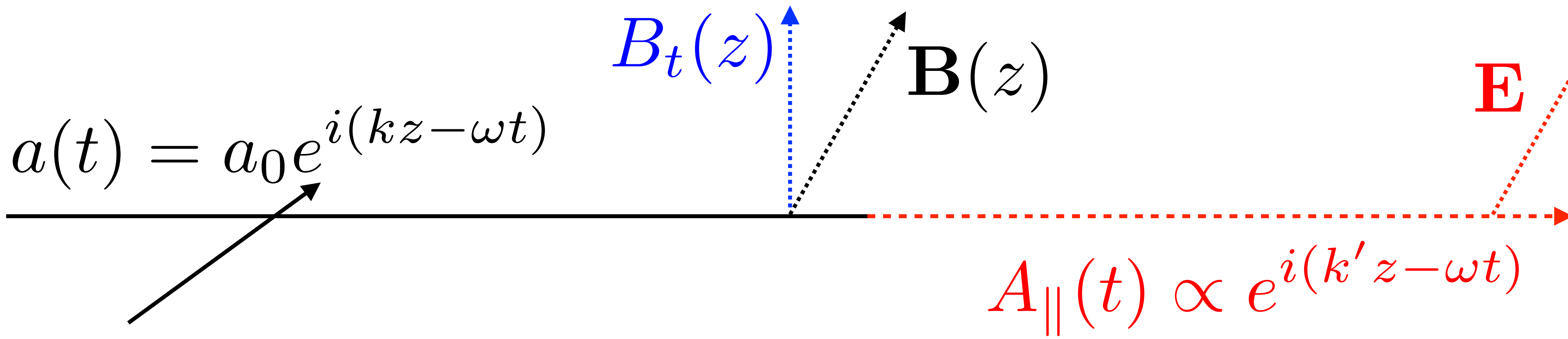


Also strong gravity:

$v_{\text{esc}} \sim 0.2c$

DM accelerates toward star along radial trajectories - axion velocity is crucial

Axion-photon mixing



$$-\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \widetilde{F}^{\mu\nu} \implies$$

$$\left[\omega^2 + \partial_z^2 + \begin{pmatrix} -\omega_p^2 & -g_{a\gamma\gamma} B_t \omega \\ -g_{a\gamma\gamma} B_t \omega & -m_a^2 \end{pmatrix}\right] \begin{pmatrix} A_\parallel \\ a \end{pmatrix} = 0$$

plasma frequency

only transverse field contributes

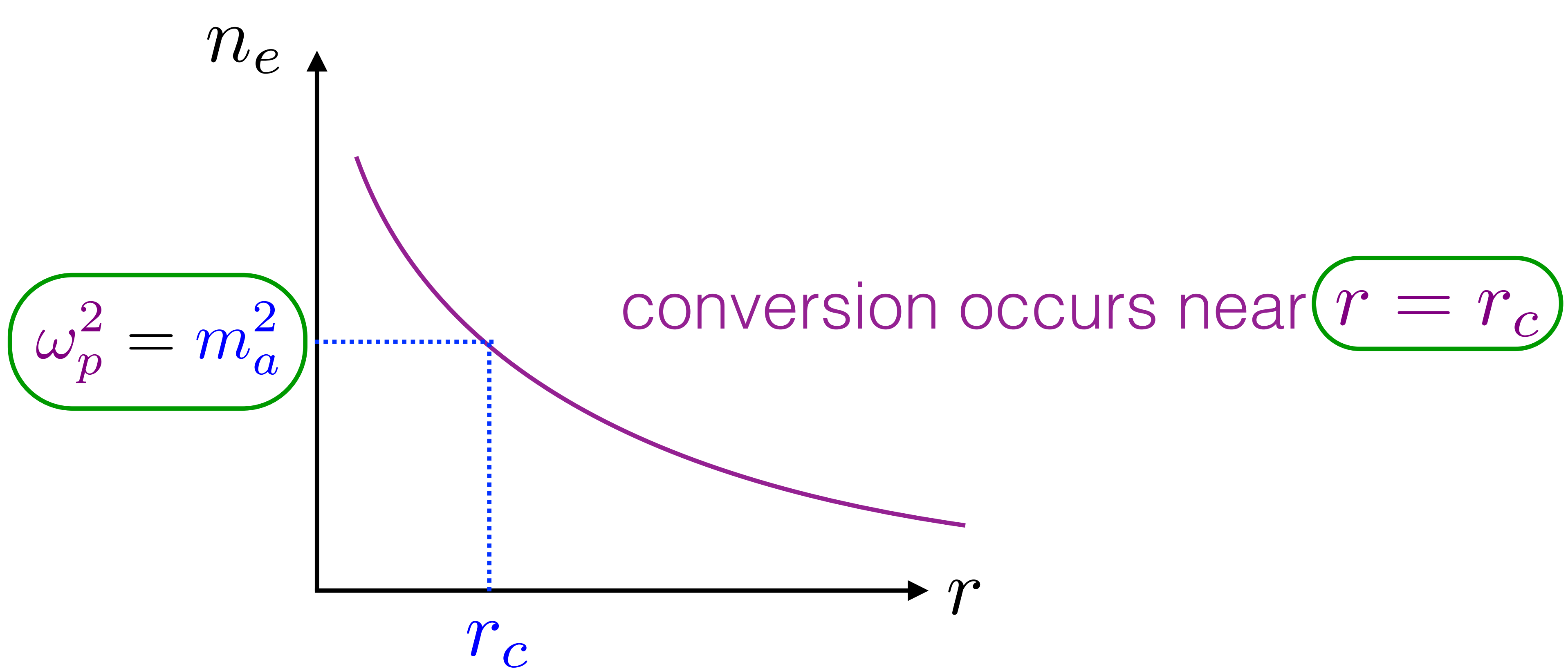
only mixes with one polarization

Resonant conversion

Need momentum matching

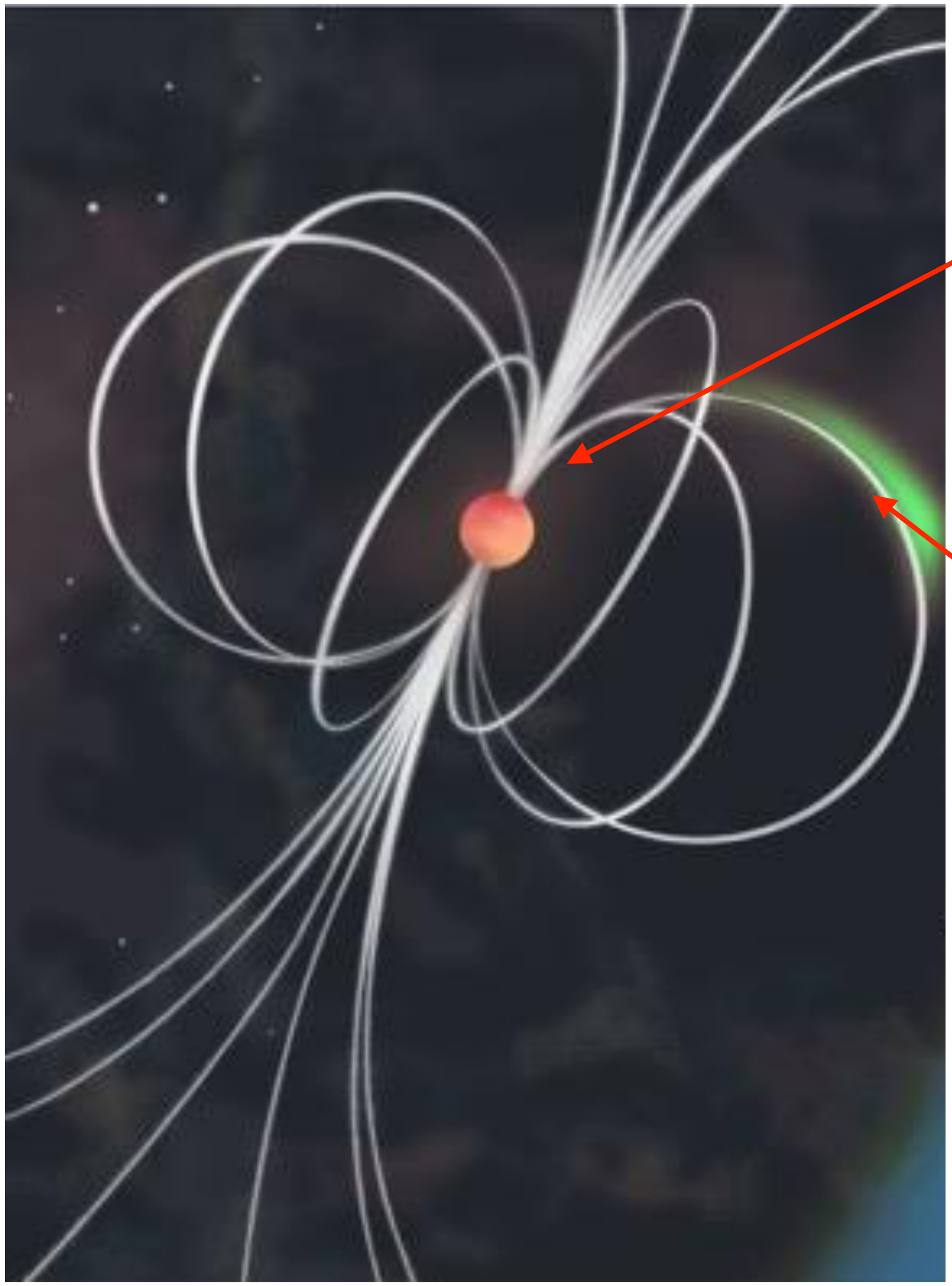
Option 1: B-field has significant spatial variations at axion wavelength (hard to obtain: $m_a = 10^{-6}\ \text{eV} \implies \lambda_a \sim\ \text{m}$)

Option 2: B-field is approximately homogeneous, photon dispersion changes with plasma density



Neutron stars: ideal candidates!

2 key (related) ingredients for axion indirect detection:



1. Strong B-fields

$$B_\theta = \frac{B_0}{2}\left(\frac{r_{\rm NS}}{r}\right)^3 \sin\theta$$

$$B_0 \sim 10^{10}\ \mathrm{T}$$

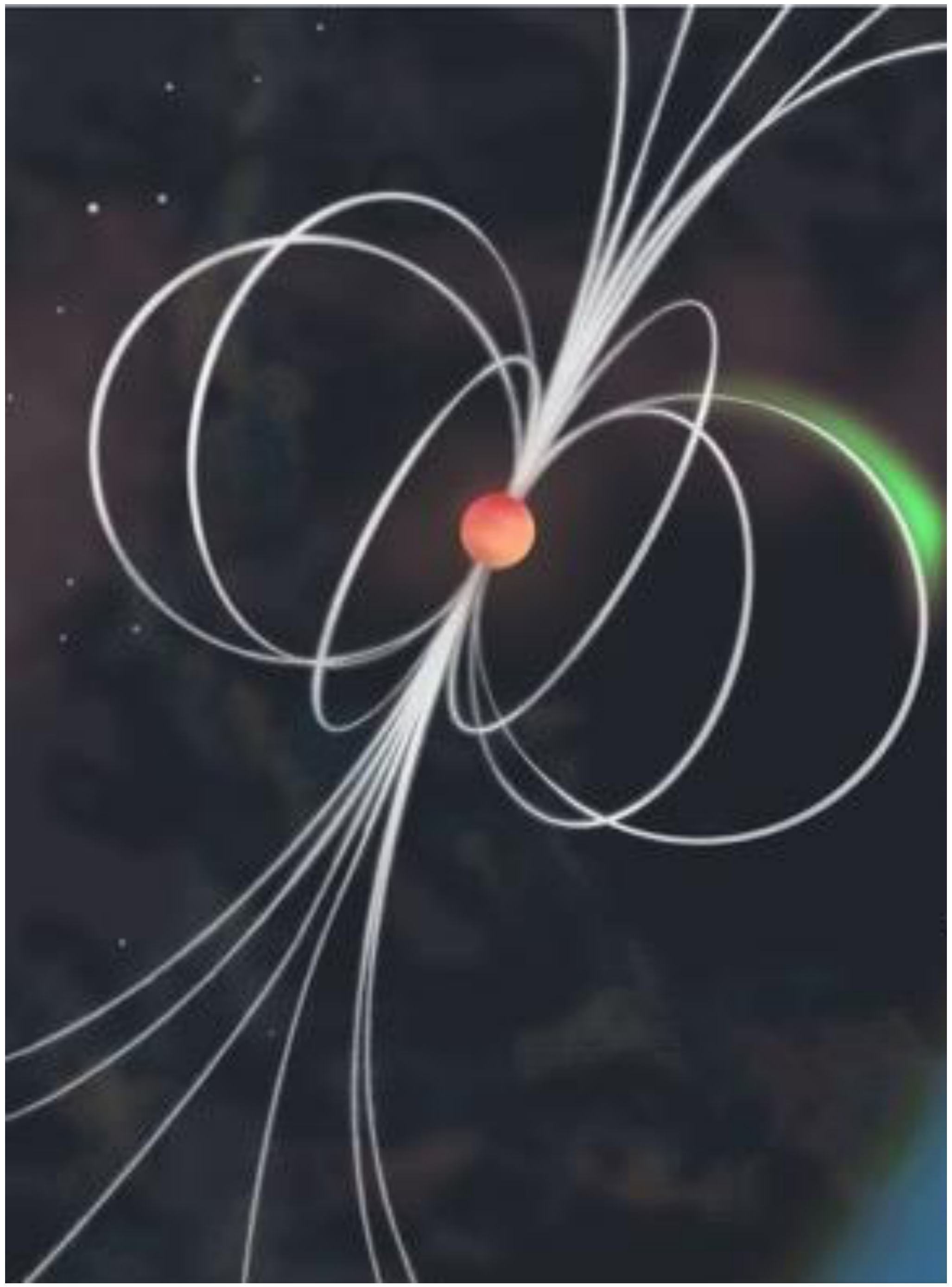
2. Goldreich-Julian model relates plasma frequency in "lobes" to dipole B-field:

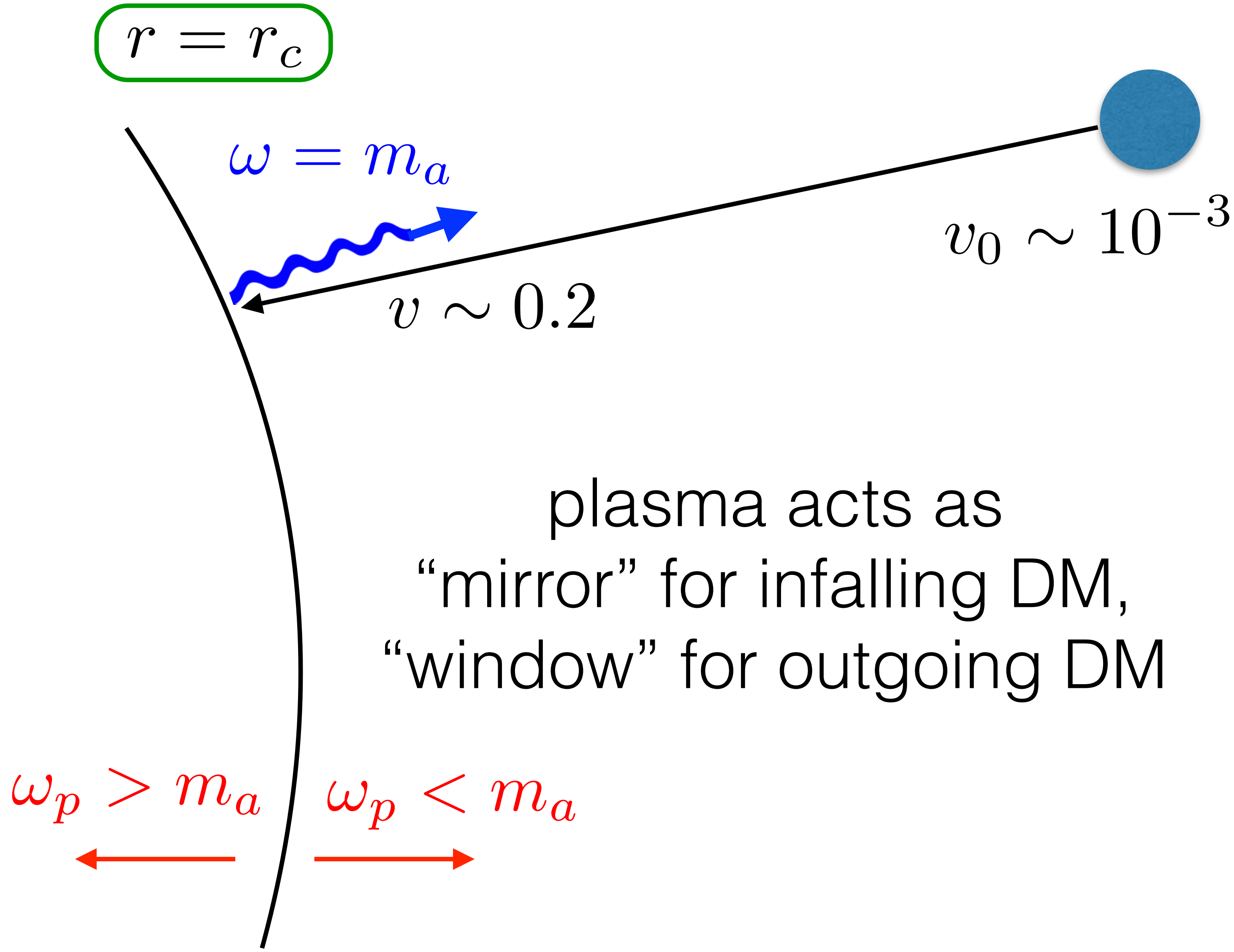
$$\omega_p \propto \sqrt{n_e} \propto \sqrt{B_0 \left(\frac{r_{\rm NS}}{r}\right)^3 (3\cos^2\theta - 1)}$$

Monotonically decreasing, can always solve $\omega_p = m_a$.

[Hook, **YK**, Safdi, Sun, arXiv:1804.03145]

Infalling axion DM conversion



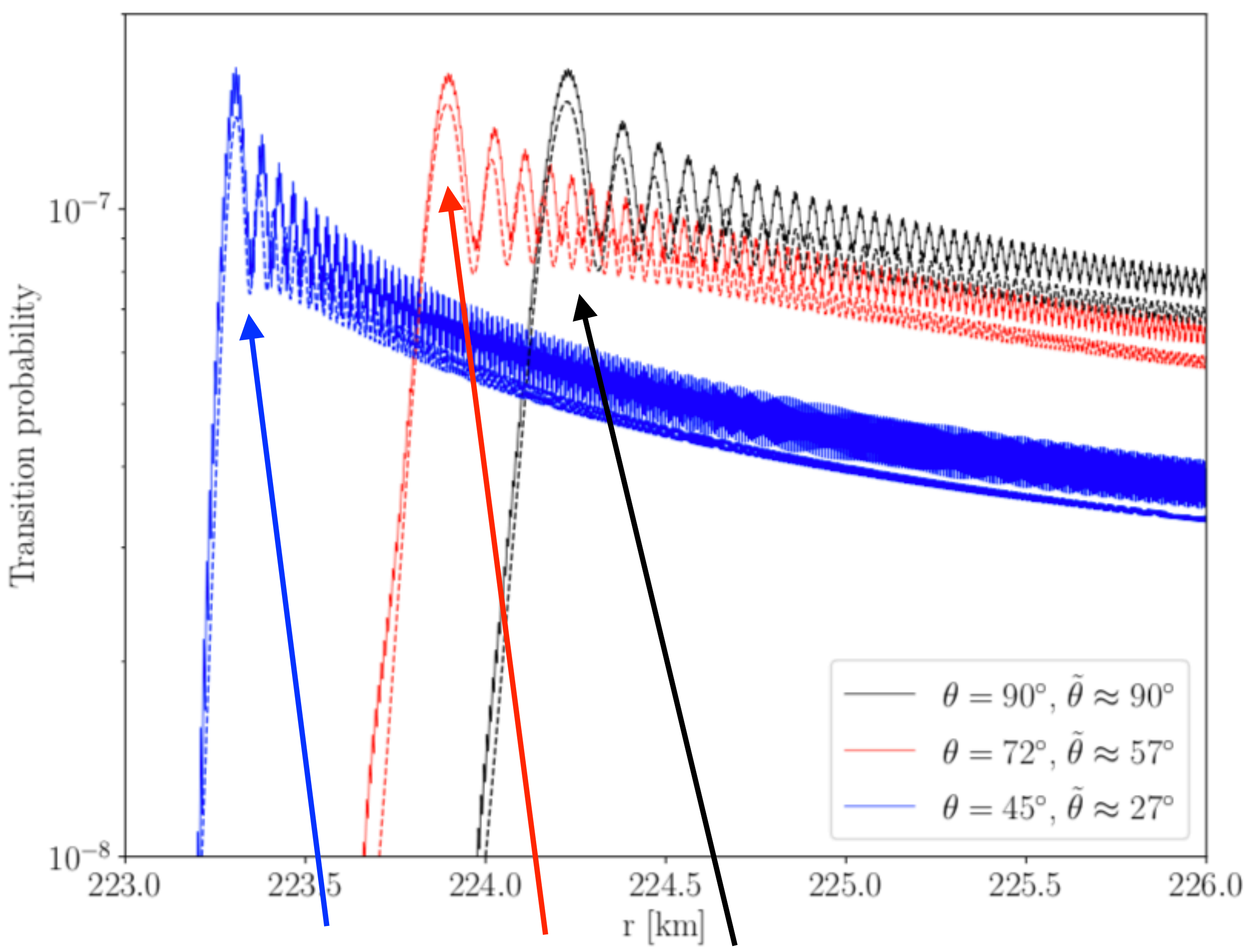


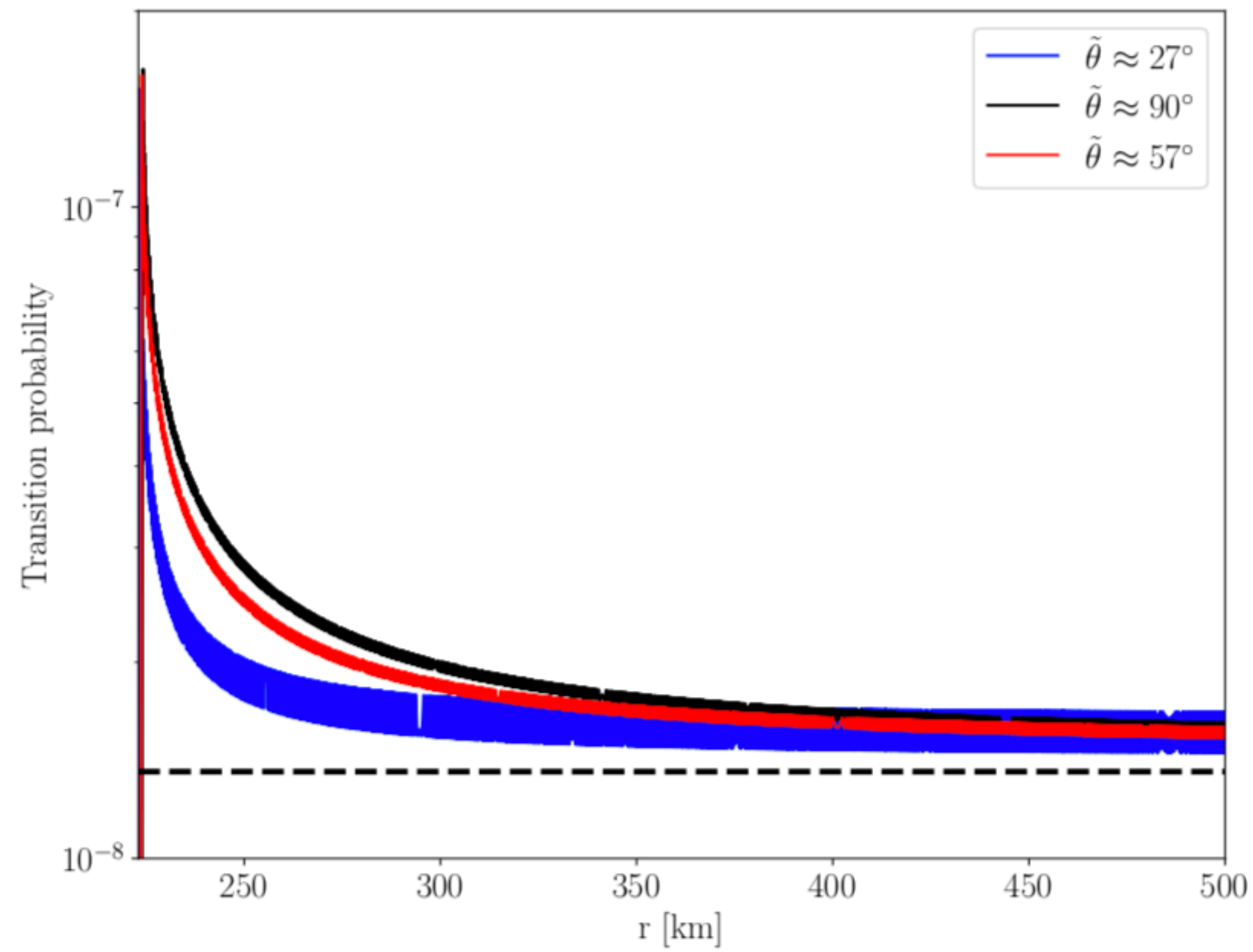
$$m_a = 1 \text{ GHz } (\sim 10^{-6} \text{ eV}), \;\; B_0 = 10^{10} \text{ T}$$
$$\Longrightarrow \;\; r_c \sim 220 \text{ km at } \theta = \pi/2$$

gravitational acceleration + Liouville = enhanced DM density

 [Hook, **YK**, Safdi, Sun, arXiv:1804.03145]

Photon transition probability





transition prob. peaks at conversion radius, happens over distance

$$L = \sqrt{\frac{2\pi r_c v_c}{3m_a}}$$

outgoing photon wave damped by plasma (like ocean waves):

$$p^{\infty}_{a\gamma} \approx \frac{1}{2v_c} g^2_{a\gamma\gamma} B(r_c)^2 L^2$$

Expected photon flux

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

incoming+outgoing

$$= \rho_{\rm DM}^{\infty} \frac{2}{\sqrt{\pi}} \frac{1}{v_0} \sqrt{\frac{GM}{r_c}}$$

$$\approx \sqrt{\frac{2GM_{\rm NS}}{r_c}}$$

$$\frac{d\mathcal{P}(\theta, \theta_m, t)}{d\Omega} = \frac{d\mathcal{P}(\theta = \frac{\pi}{2}, \theta_m = 0)}{d\Omega} \times \frac{3\,(\hat{\mathbf{m}} \cdot \hat{\mathbf{r}})^2 + 1}{\left|3 \cos\theta\, \hat{\mathbf{m}} \cdot \hat{\mathbf{r}} - \cos\theta_m\right|^{4/3}}$$

time-dependent! misalignment angle

Total power ~ 10^{10} W for QCD axion, local DM density

Radio bump hunt

$$\frac{F}{B} \sim \frac{P}{4\pi d^2} \frac{1}{10^{-6}\omega}$$

$$2\ \text{Jy} \sim \frac{2 \times 10^{15}\,\text{W}}{\text{kHz}\,\text{kpc}^2}$$

$$S_{\text{min}} = \text{SNR}_{\text{min}} \frac{\text{SEFD}}{\sqrt{n_{\text{pol}} B \Delta t_{\text{obs}}}}$$

$$\sim 10^{-6}\omega$$

[Arecibo]

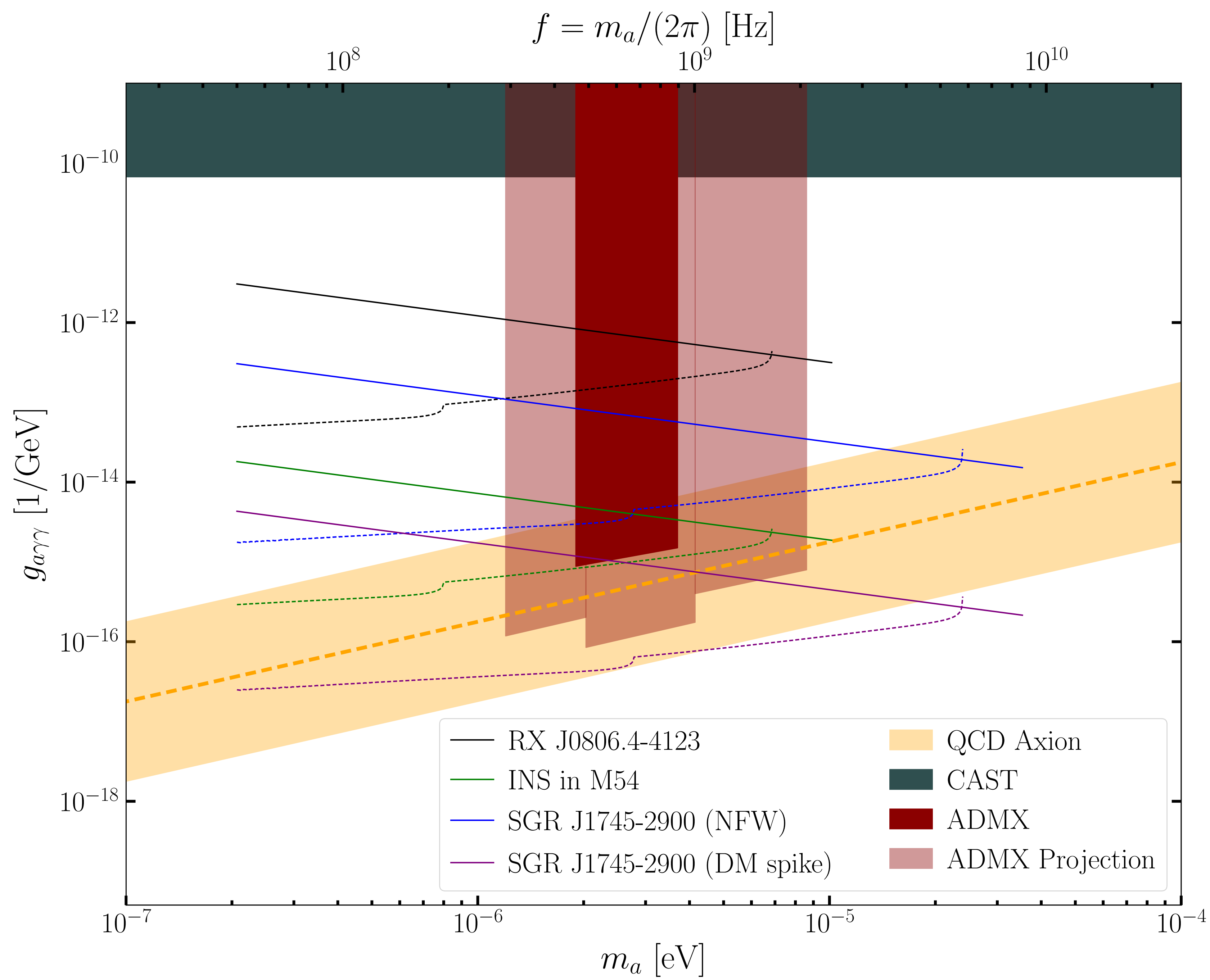
Desired characteristics:

- Radio-quiet (negligible foreground)
- Low DM velocity dispersion (dwarfs)
- Close by (< kpc), **or**
- DM-rich (Galactic center, dwarfs)

Added bonus: energy conservation keeps line narrow

Projections: individual NS's

Neutron star menagerie:

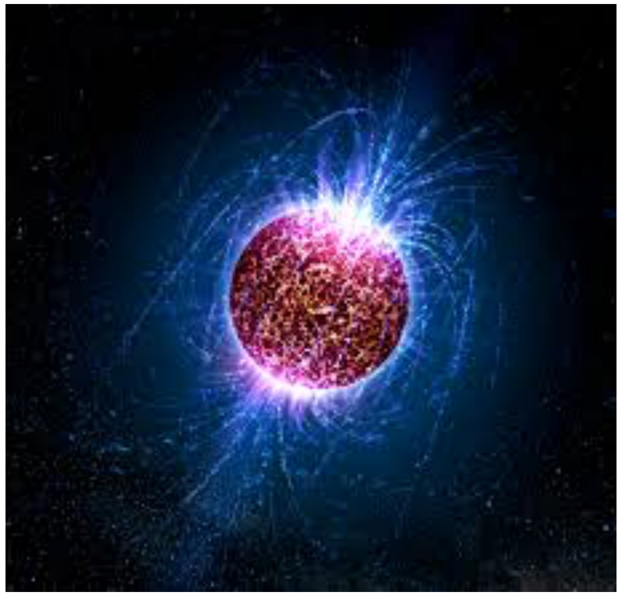


Solid = equator, dashed = best-case

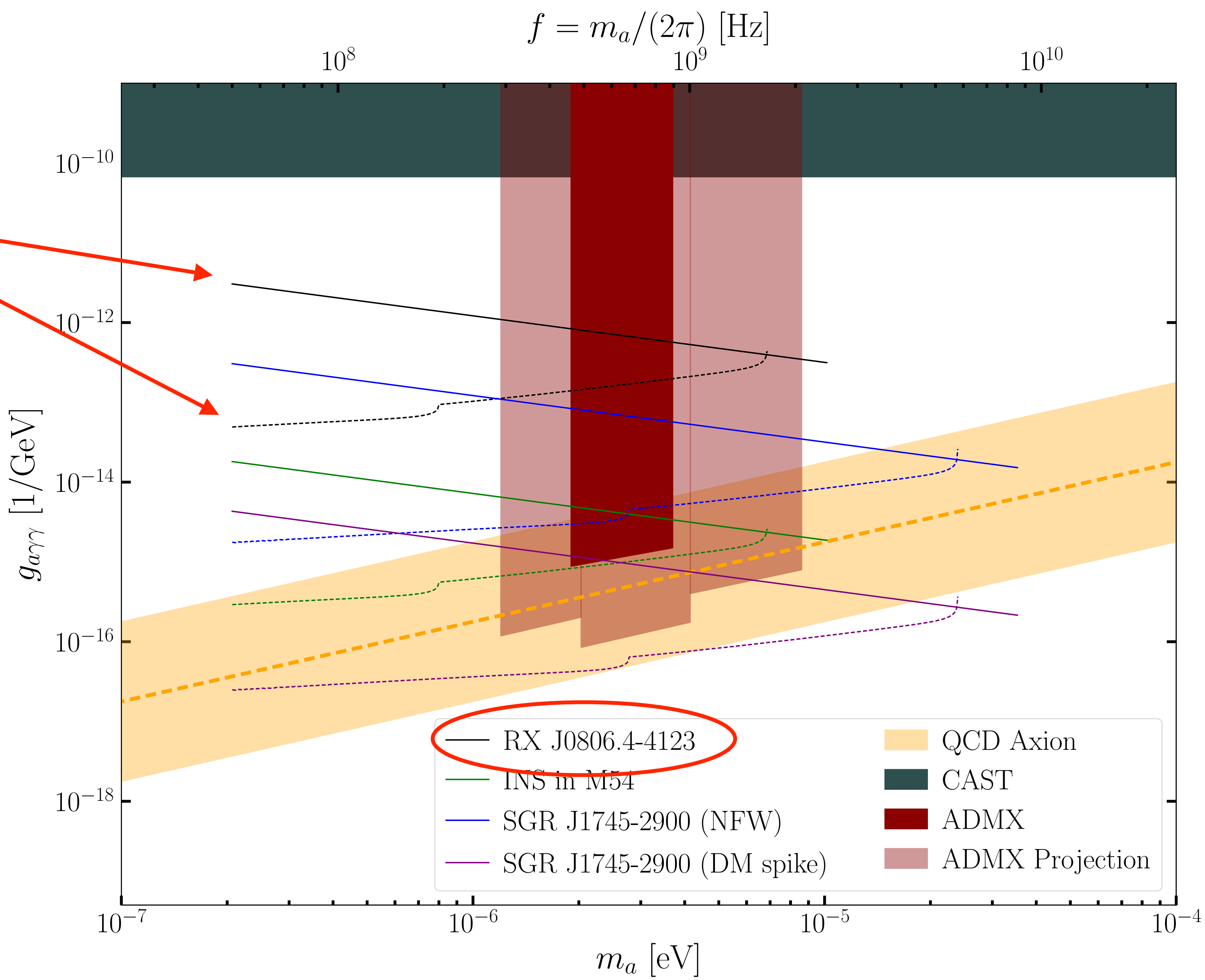
Projections: individual NS's

Neutron star menagerie:

RX J0806.4-4123



- Isolated
- Nearby (250 pc)
- Radio-quiet
- Non-pulsed



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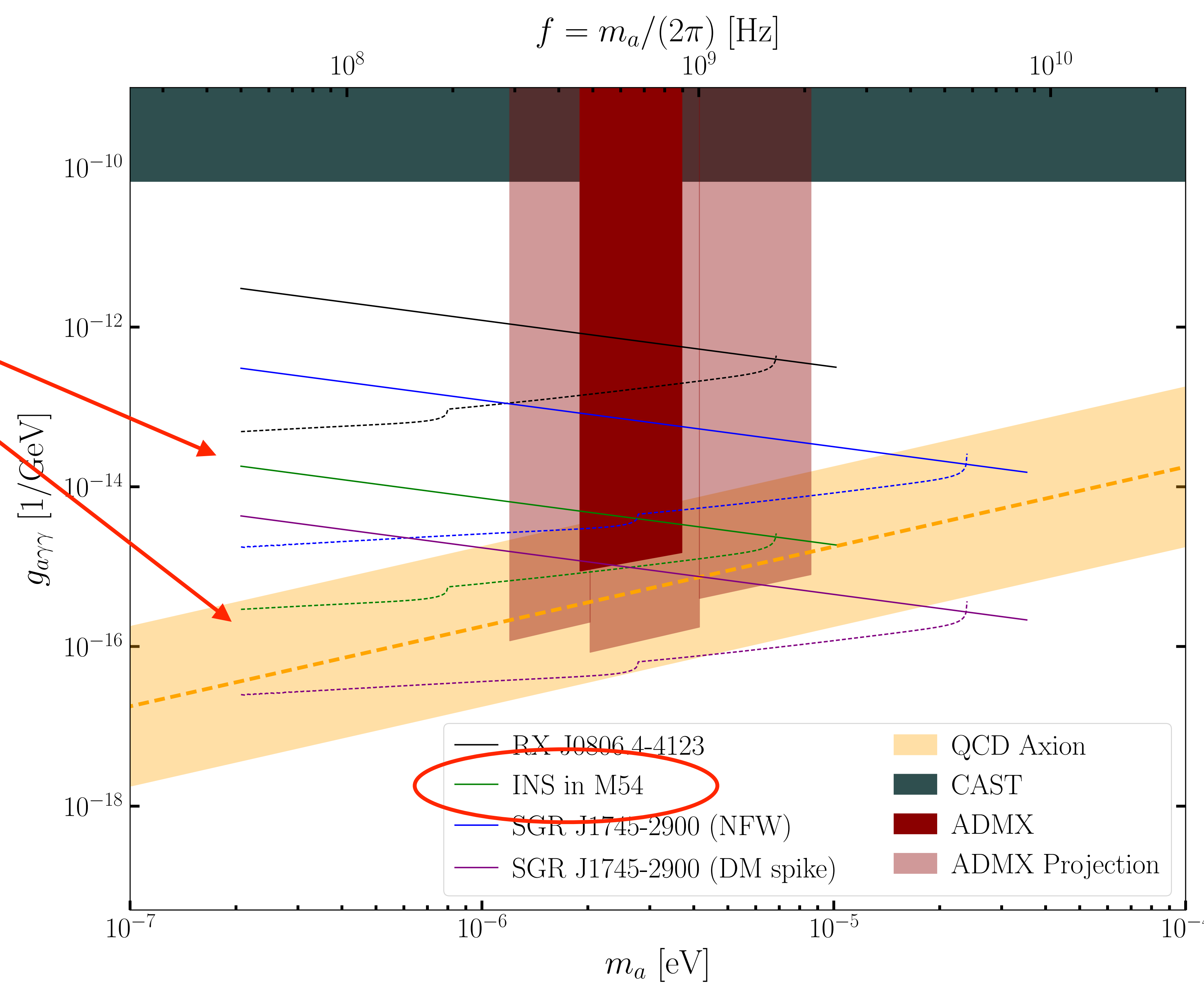
Projections: individual NS's

Neutron star menagerie:

Hypothetical NS's in M54

- 21 kpc away, but…
- High DM density
- Lots of NS emissions within angular res.



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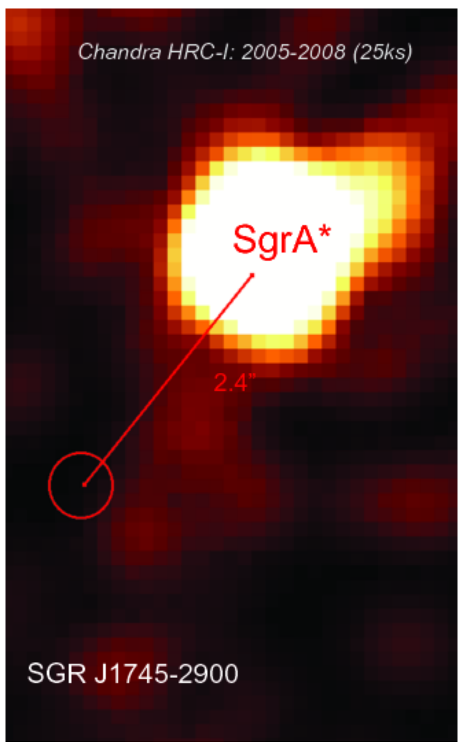
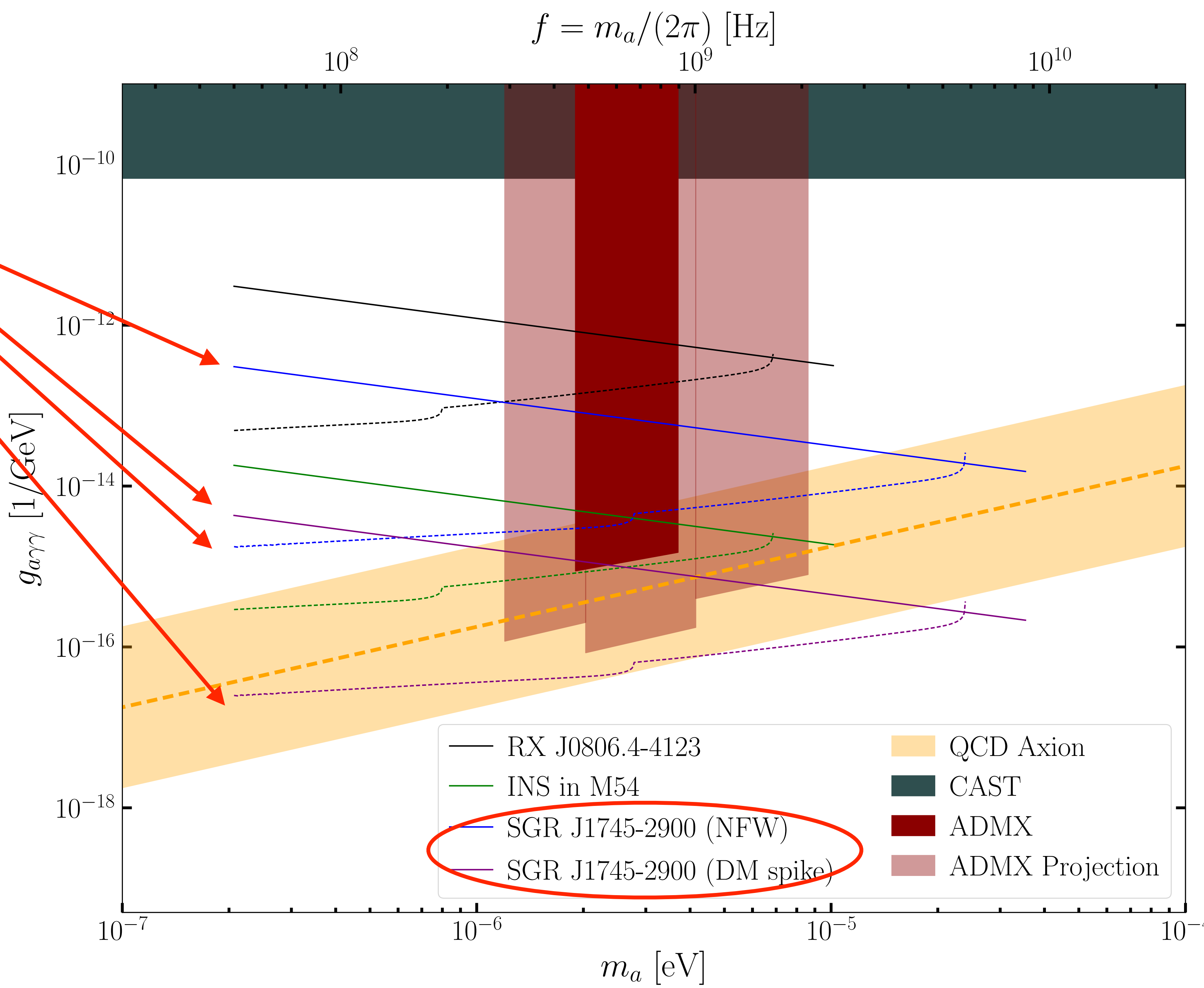
Projections: individual NS's

Neutron star menagerie:

SJR J1745-2900



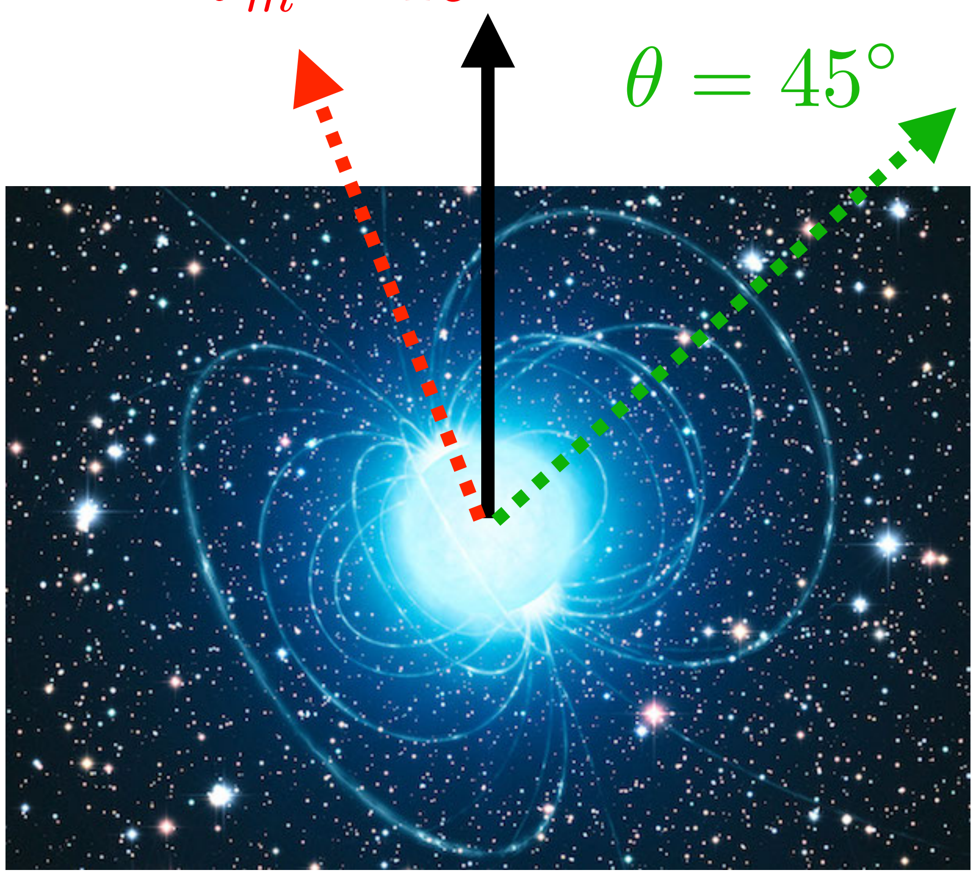
- Magnetar! $B_0 \approx 10^{10}$ T
- 0.1 pc from GC
- Potentially enormous DM density



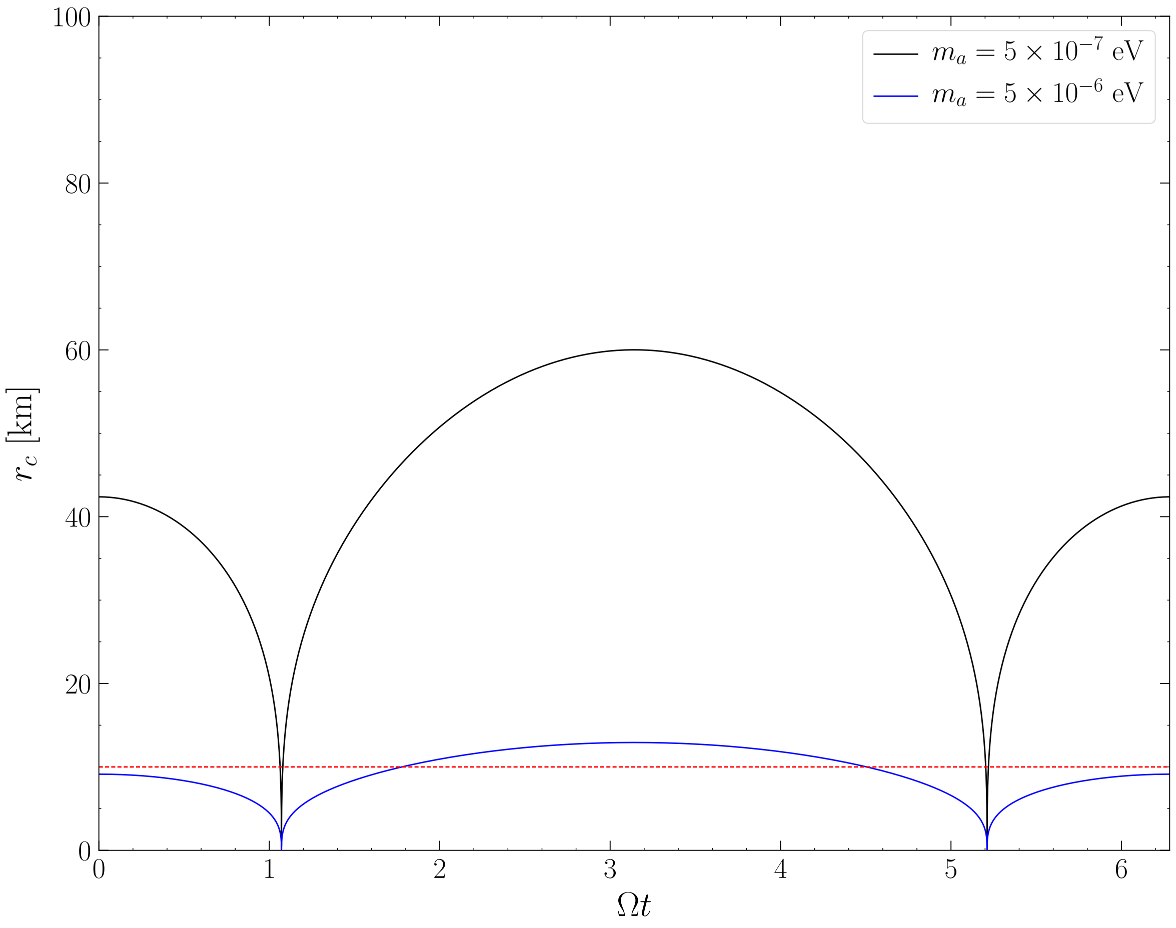
Solid = equator, dashed = best-case

Time-dependent signal

Misaligned neutron stars have rotation axis misaligned from magnetic poles: strong time dependence of plasma freq. in GJ model



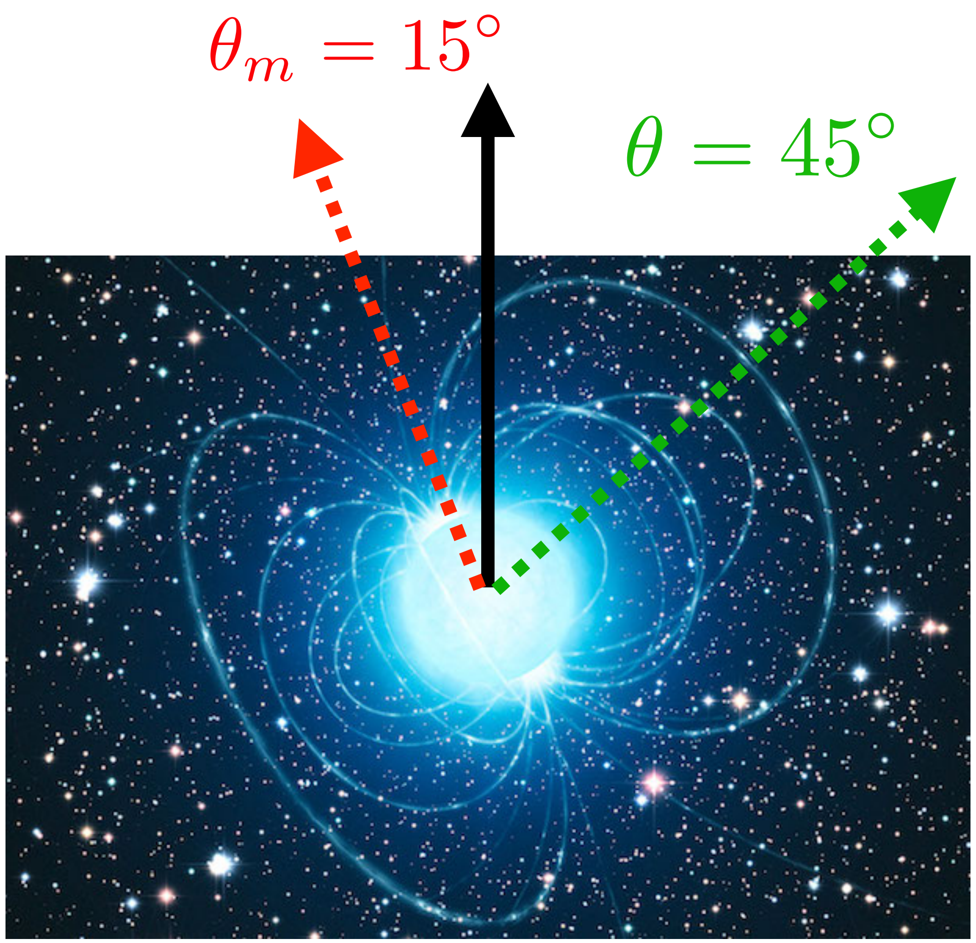
Critical radius



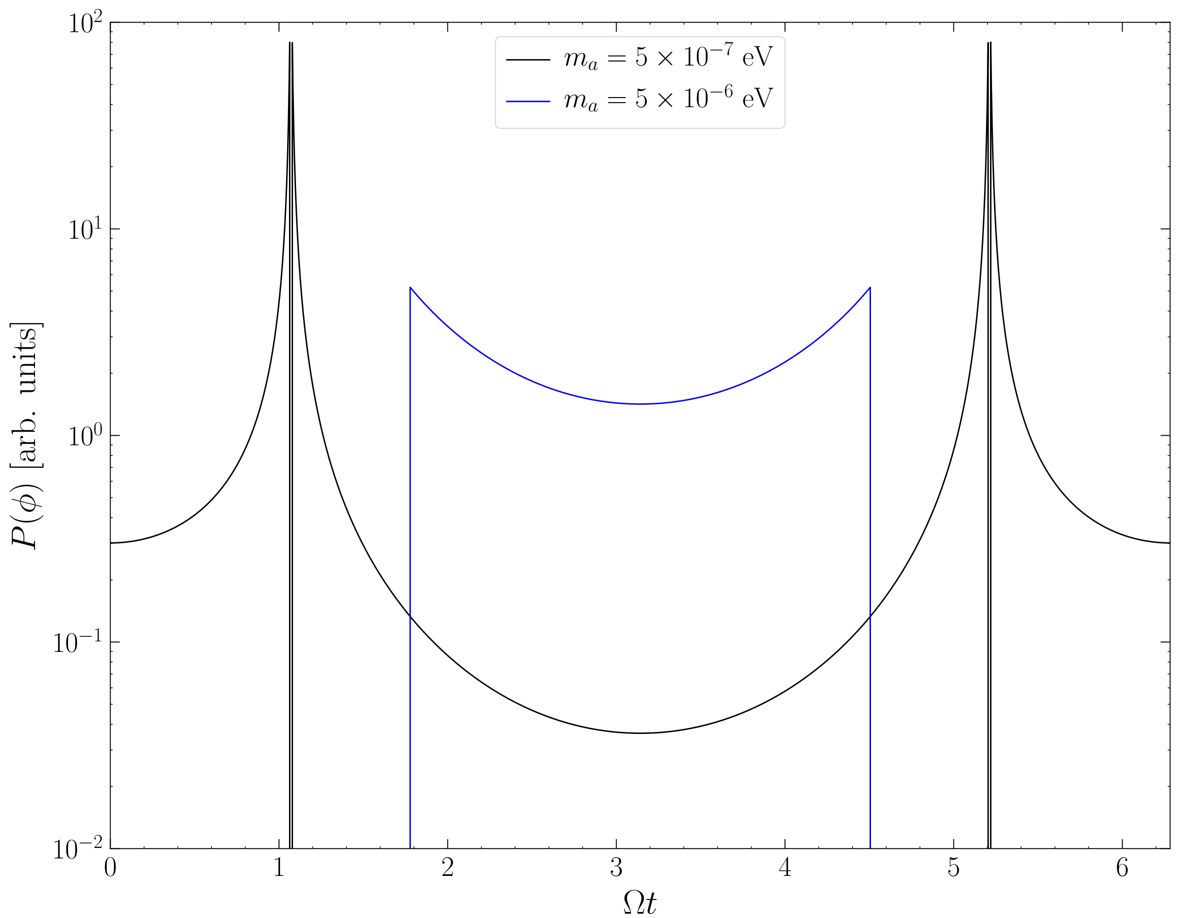
[Hook, **YK**, Safdi, Sun, arXiv:1804.03145]

Time-dependent signal

Misaligned neutron stars have rotation axis misaligned from magnetic poles:
strong time dependence of plasma freq. in GJ model



Light curve

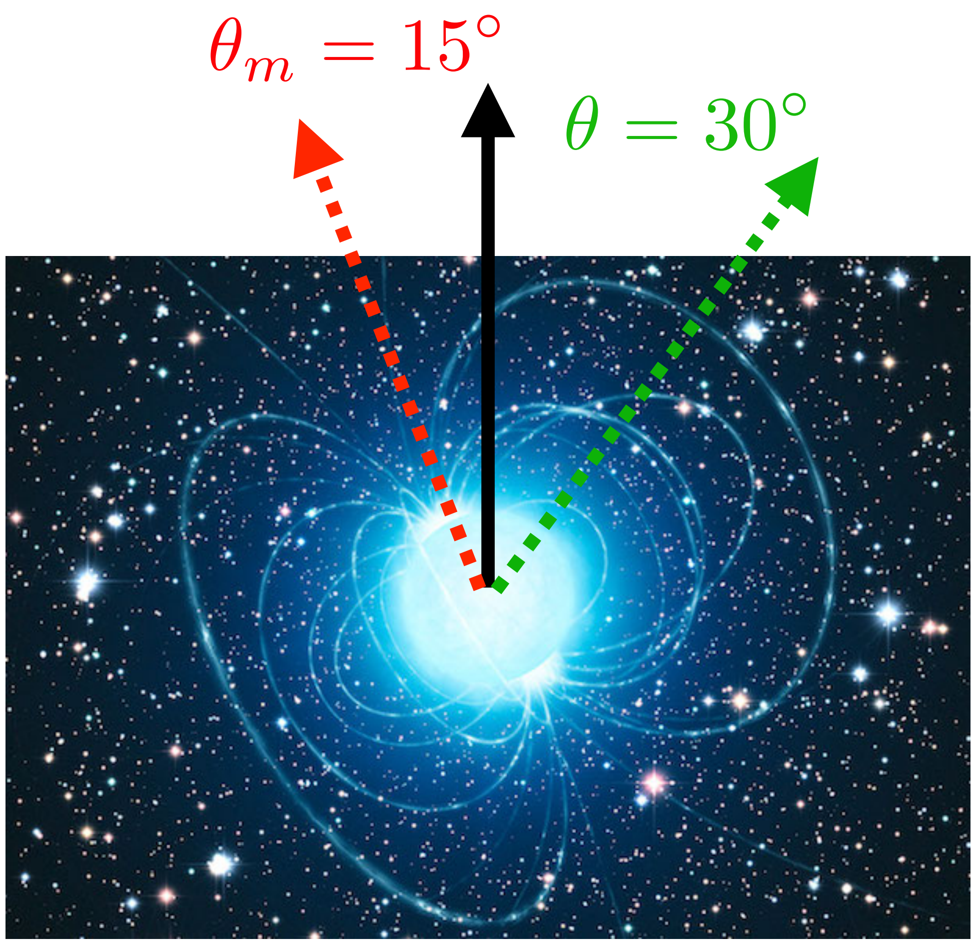


Striking signal: looks promising!

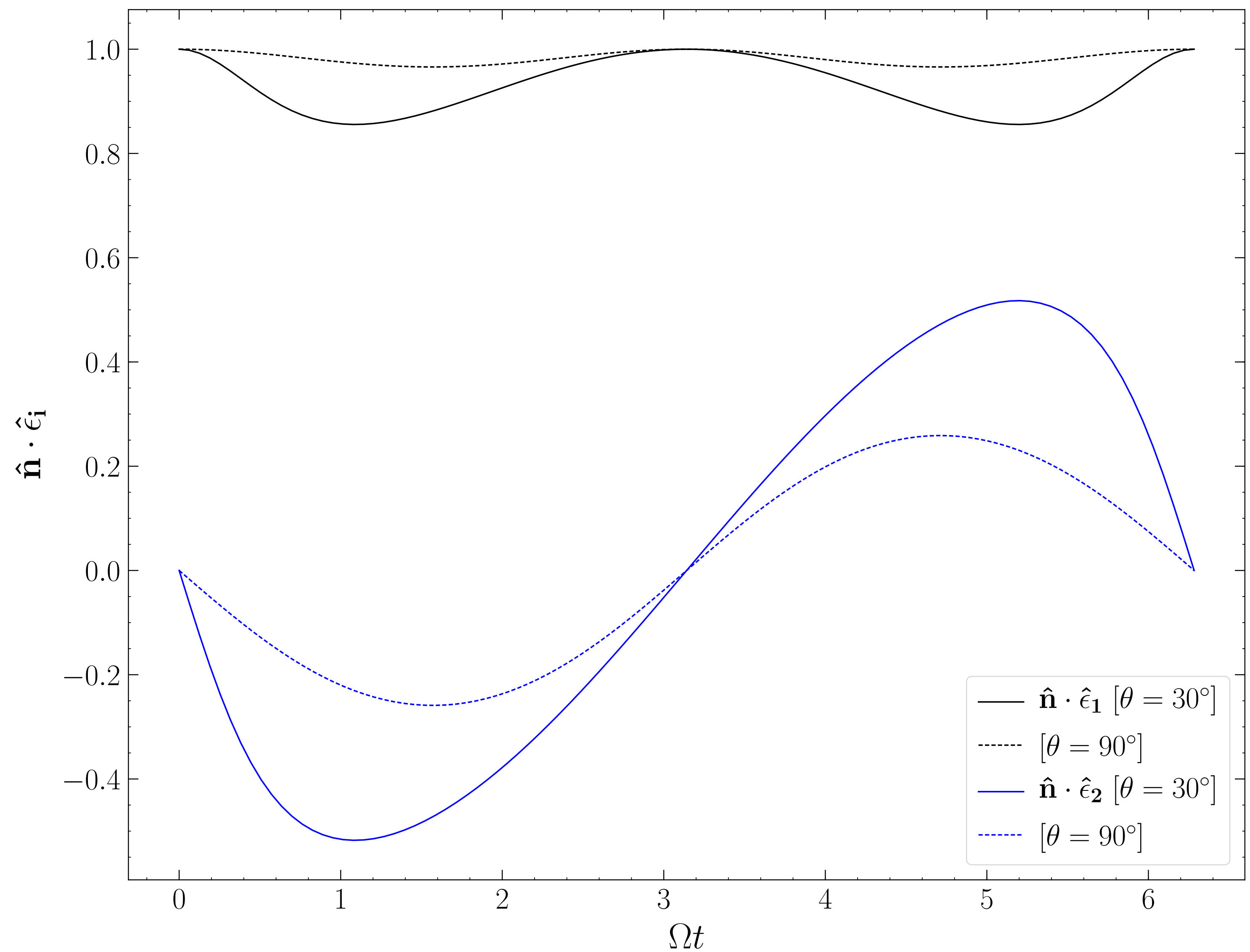
[Hook, **YK**, Safdi, Sun, arXiv:1804.03145]

Polarization signal

EM wave always polarized along
direction of B-field at conversion radius



$$(\hat{\epsilon}_1 = \hat{\theta},\ \hat{\epsilon}_2 = \hat{\phi})$$



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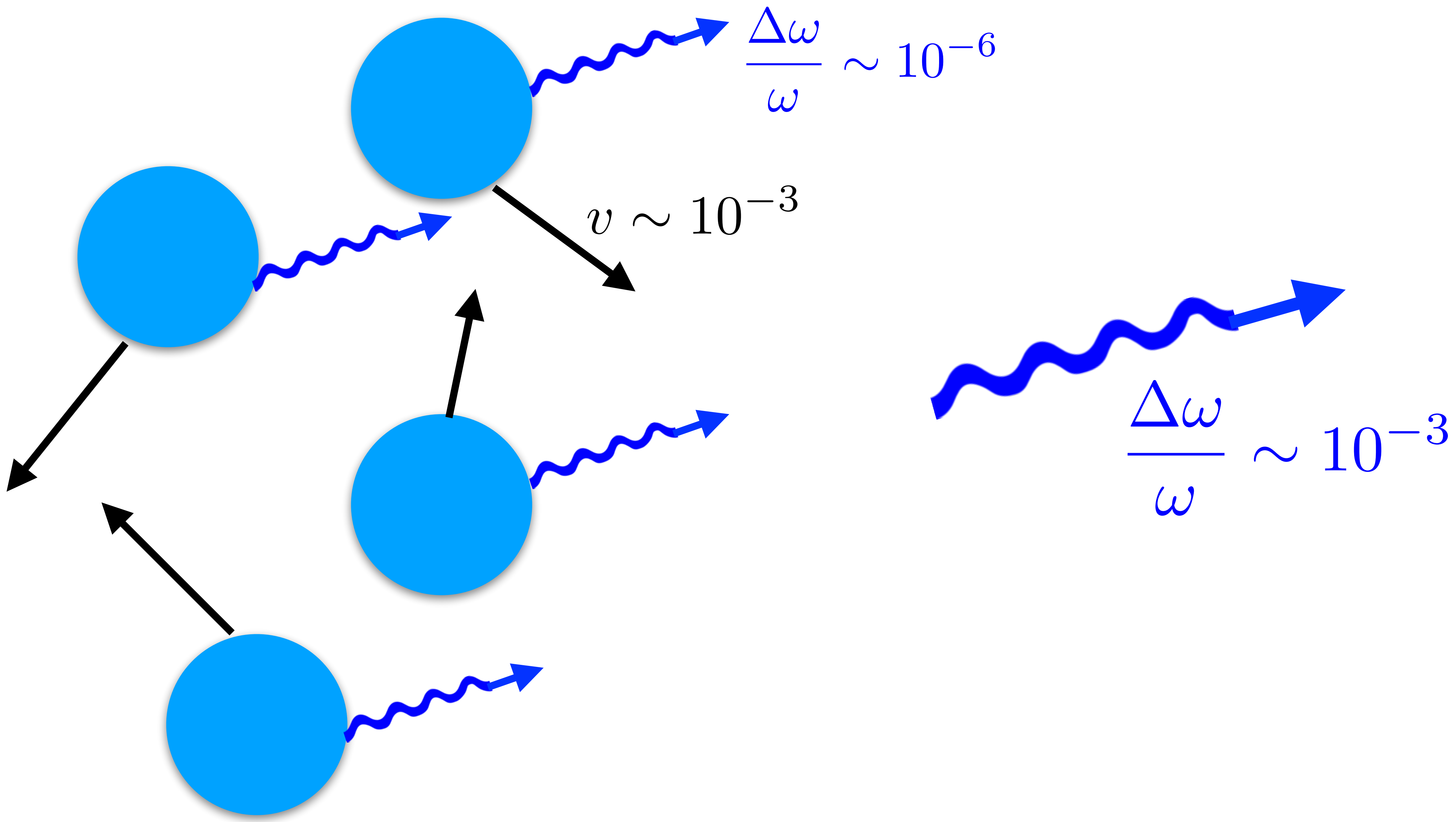
Neutron star populations



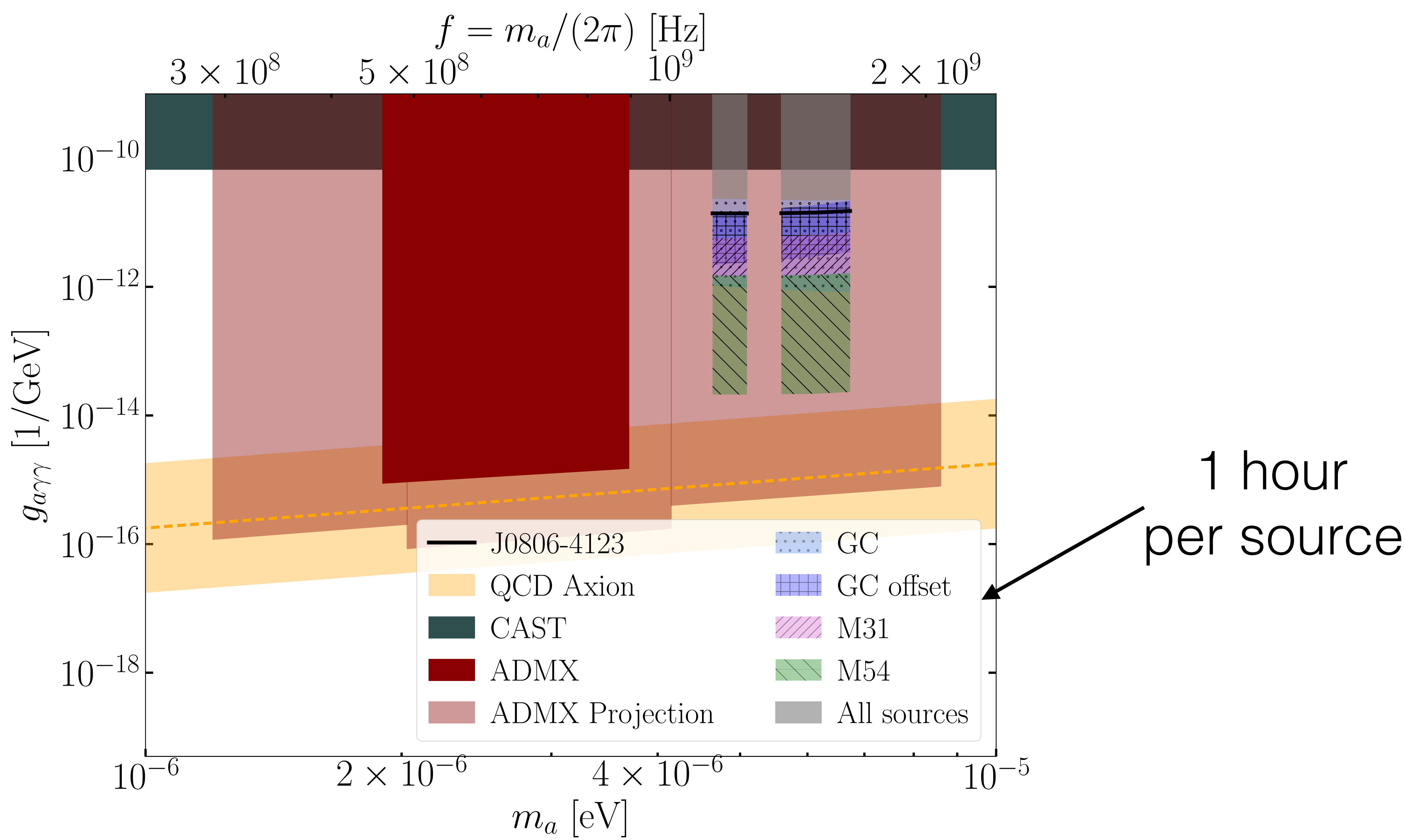
Doppler broadening: larger bandwidth

But signal adds incoherently!

If N_{NS} > 1000, still win

[Chen, Safdi, Sun, to appear]

NS populations at Green Bank Telescope



Can be competitive with ADMX with 1 hour of observation!