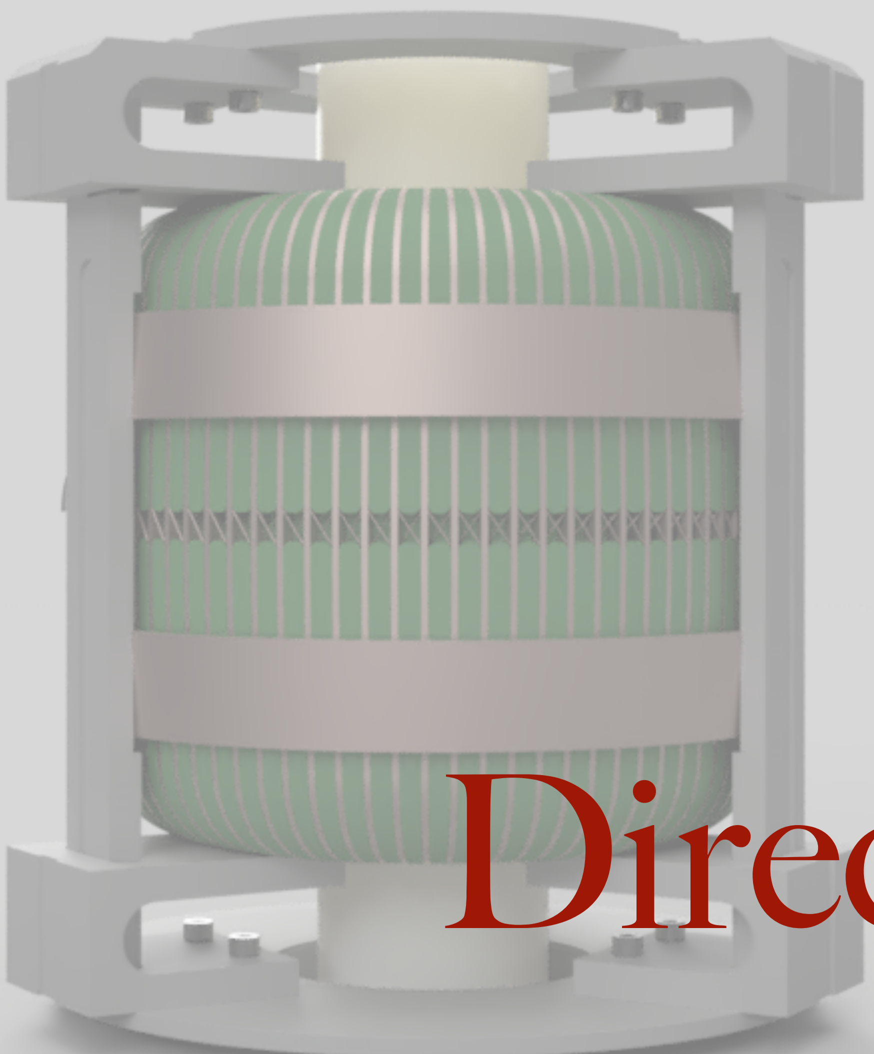
Axion Dark Matter Detection:



Direct and Indirect

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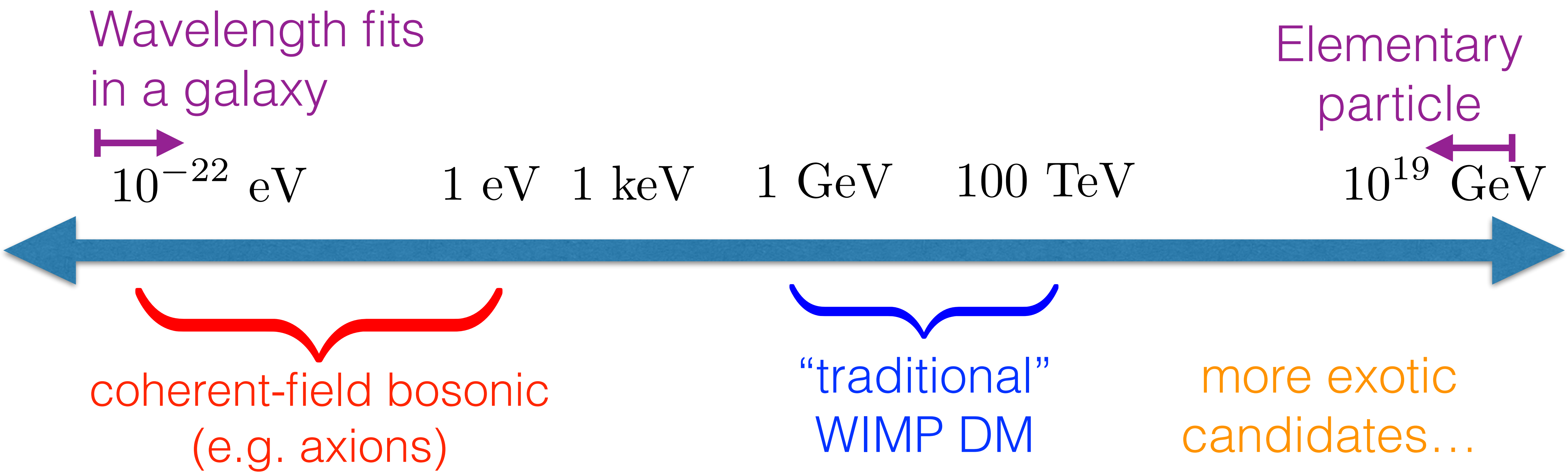
Kavli Institute
for Cosmological Physics
at The University of Chicago

TRIUMF workshop "Signals of Dark Matter in its Natural Habitat"

50 orders of magnitude



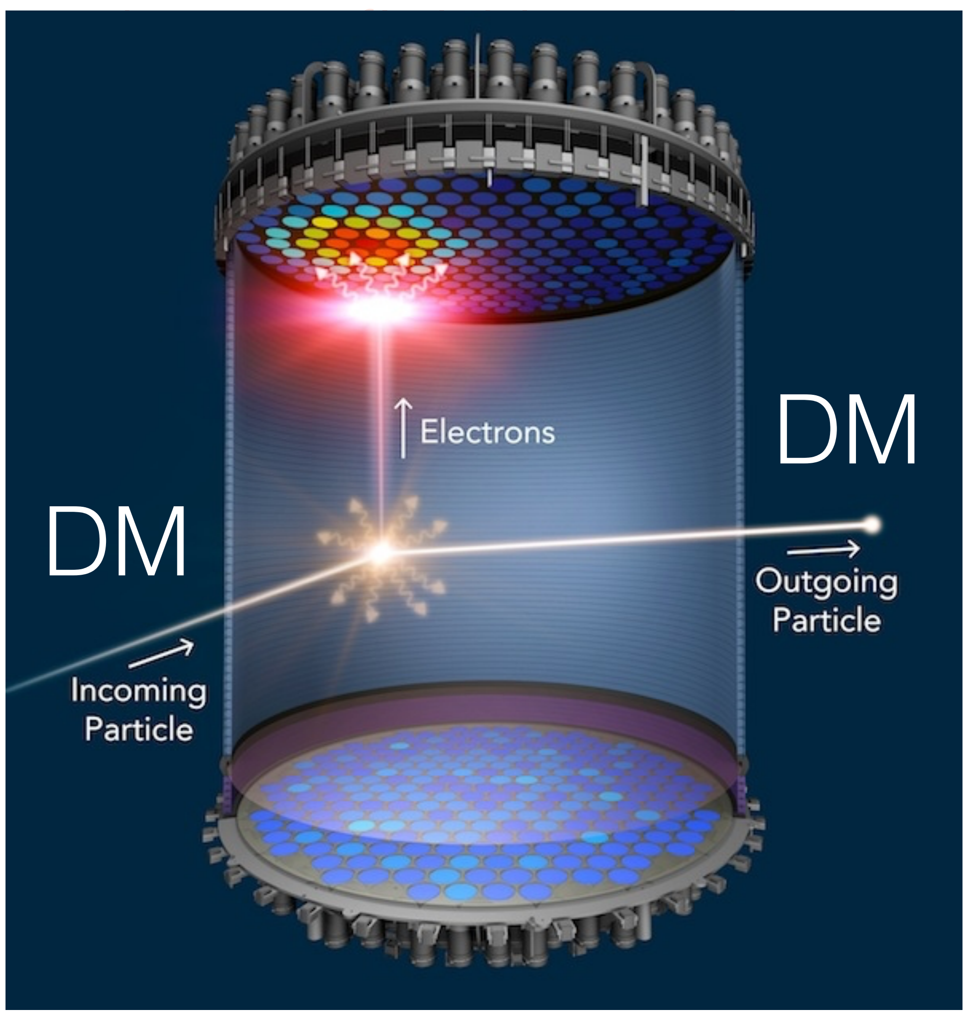
50 orders of magnitude

Wavelength fits in a galaxy

Elementary particle

10^{-22} eV 1 eV 1 keV 1 GeV 100 TeV 10^{19} GeV

"traditional" WIMP DM



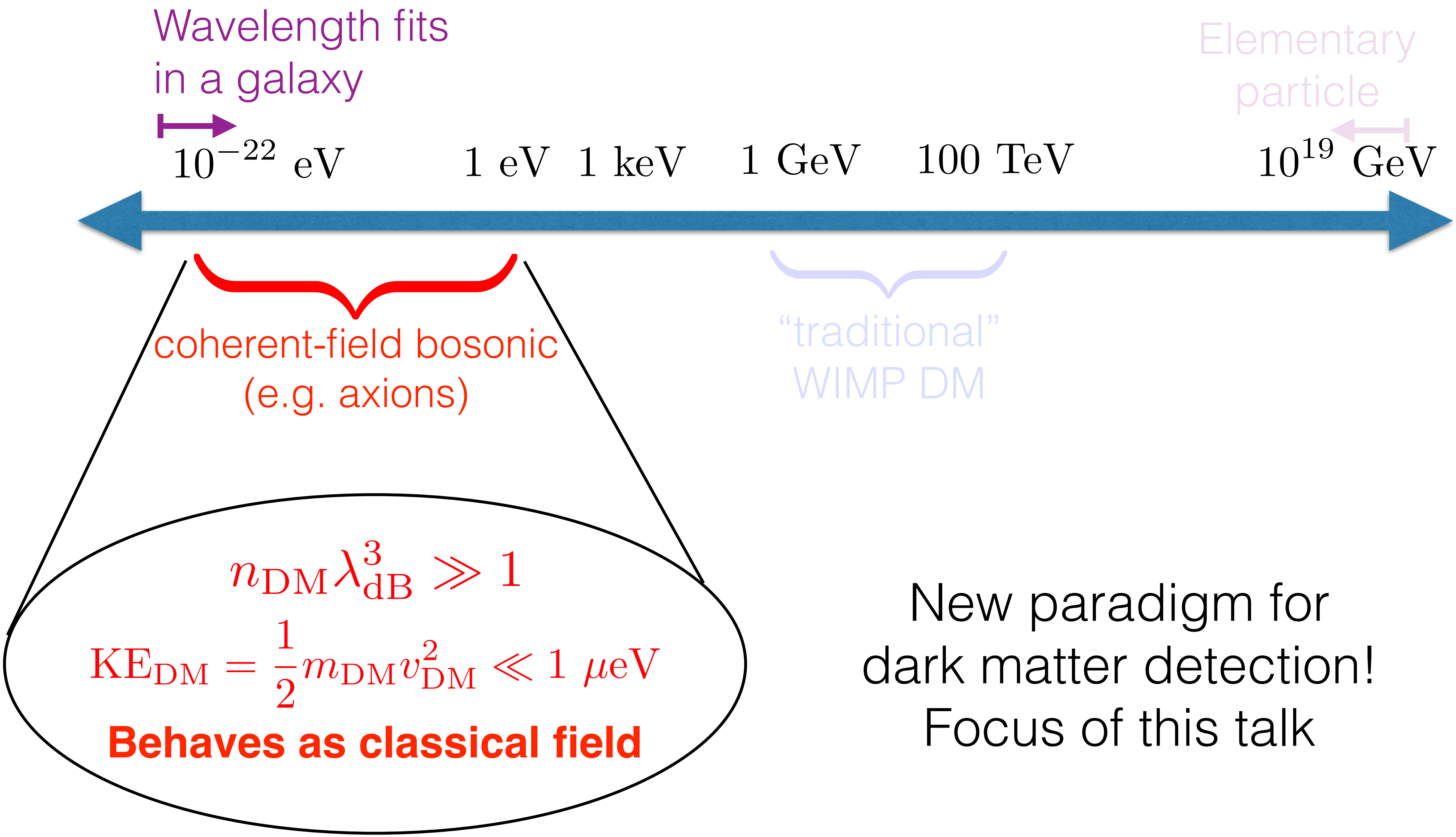
$$n_{\rm DM}\lambda_{\rm dB}^3 \ll 1$$

$$\text{KE}_{\rm DM} = \frac{1}{2} m_{\rm DM} v_{\rm DM}^2 > 1 \text{ keV}$$

Rare collisions

[Goodman & Witten PRD 1985; Drukier, Freese, Spergel PRD 1986; image credit LZ collab.]

50 orders of magnitude



New paradigm for
dark matter detection!
Focus of this talk

Axion DM: here and now

$$a(\mathbf{x},t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_a}\cos(m_a t + \mathcal{O}(v_{\rm DM})\mathbf{x})$$

amplitude set
by local DM density

oscillates at frequency
set by DM mass

e.g. $m_a = 10^{-9}\ \text{eV}$

$\lambda_{\rm Comp} \sim\ \text{km}$

$\tau_{\rm Comp} \sim \mu\text{s}$

Local DM velocity → Spatial coherence → Temporal coherence

$\Delta v_{\rm DM} \sim v_{\rm DM} \sim 10^{-3}$ $\quad \lambda_{\rm dB} = \frac{\lambda_{\rm Comp}}{v_{\rm DM}}$ $\quad \tau_{\rm coh} = \frac{\tau_{\rm Comp}}{v_{\rm DM}^2}$

Classical physics is fine: $m_a = 10^{-9}\ \text{eV} \implies N_a \sim 10^{18}/\text{cm}^3$

[Graham and Rajendran, Phys. Rev. D88 (2013)]

What should we measure?

$$a(\mathbf{x}, t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_a} \cos(m_a t + \mathcal{O}(v_{\rm DM})\mathbf{x})$$

In axion DM background, get oscillating observables:

$$\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma\gamma}\left(\mathbf{E}_0 \times \nabla a - \mathbf{B}_0 \frac{\partial a}{\partial t}\right)$$

$$\nabla \cdot \mathbf{E}_a = -g_{a\gamma\gamma}\mathbf{B}_0 \cdot \nabla a$$

Oscillating response from static fields

$$H_N \supset g_{aNN} \nabla a \cdot \vec{\sigma}_N$$

Spin-dependent force

$$d_n = g_d a$$

Time-varying EDM

Note: $\nabla a \sim v_{\rm DM} \sim 10^{-3}$ so some are easier than others

[Sikivie, Phys. Rev. Lett. (1983)]

Axion direct detection

$$\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma\gamma}\left(\mathbf{E}_0 \times \nabla a - \mathbf{B}_0 \frac{\partial a}{\partial t}\right)$$

Goal: detect axion DM **on Earth**
through interactions with laboratory B-fields

Axion searches with magnetic fields

$$\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

Cavity regime: $\lambda_{\rm Comp} \sim R_{\rm exp}$

e.g. ADMX

$$\nabla \times \mathbf{B}_a = \cancel{\frac{\partial \mathbf{E}_a}{\partial t}} - \underbrace{g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}}_{\mathbf{J}_{\rm eff}}$$

Quasistatic regime: $\lambda_{\rm Comp} \gg R_{\rm exp}$

e.g. ABRACADBRA

$$\nabla \cancel{\times \mathbf{B}_a} = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

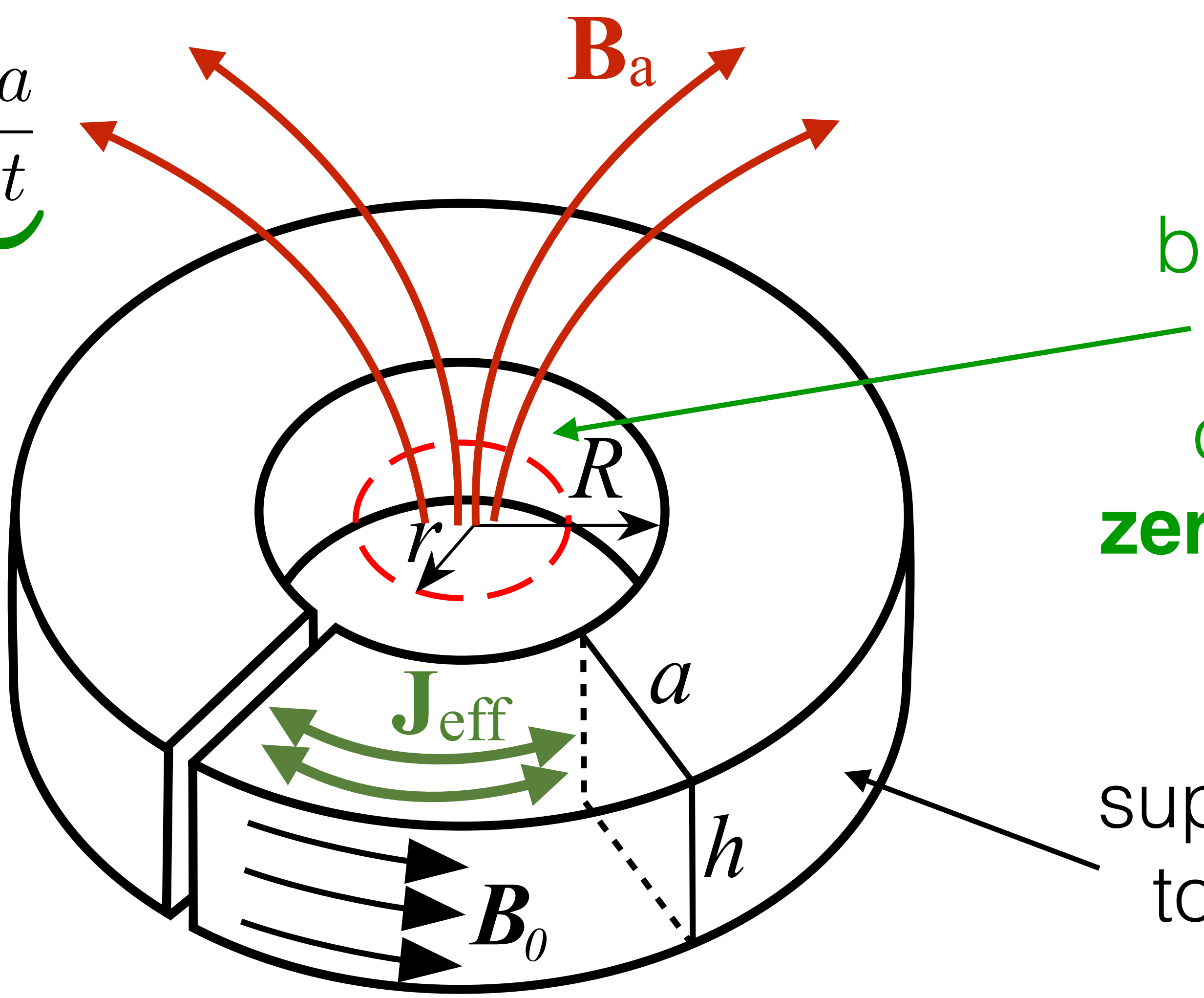
Radiation regime: $\lambda_{\rm Comp} \ll R_{\rm exp}$

e.g. MADMAX

Quasistatic regime: ABRACADABRA

A **B**roadband/**R**esonant **A**pproach to **C**osmic **A**xion **D**etection with an **A**mplifying **B**-field **R**ing **A**pparatus

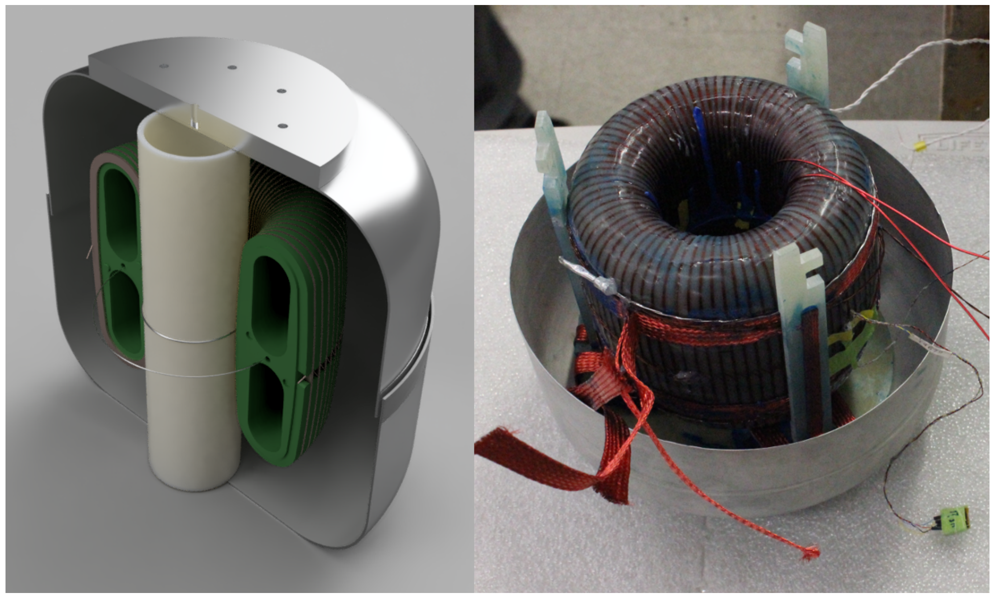
$$\nabla \times \mathbf{B}_a = \cancel{\frac{\partial \mathbf{E}_a}{\partial t}} - \underbrace{g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}}_{\mathbf{J}_{\text{eff}}}$$



$$\langle \Phi(t)^2 \rangle \sim g_{a\gamma\gamma}^2 \rho_{\text{DM}} B_0^2 V^{5/3}$$

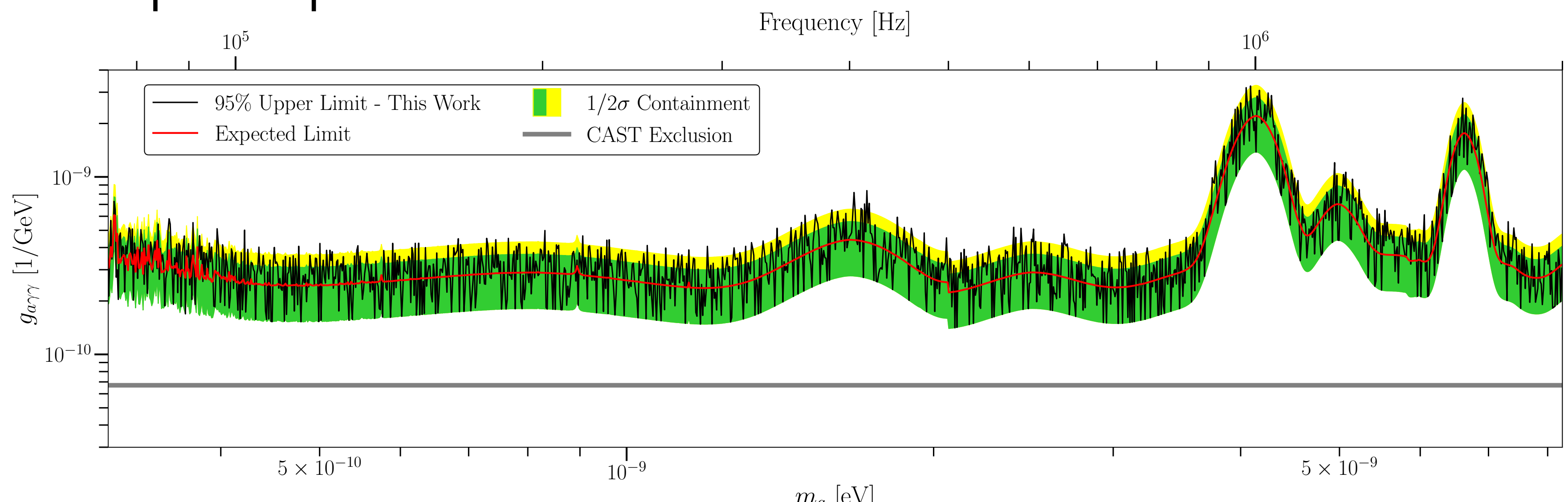
Volume enhancement at low masses

ABRACADABRA-10cm: hot off the presses



superconducting magnet
and pickup loop

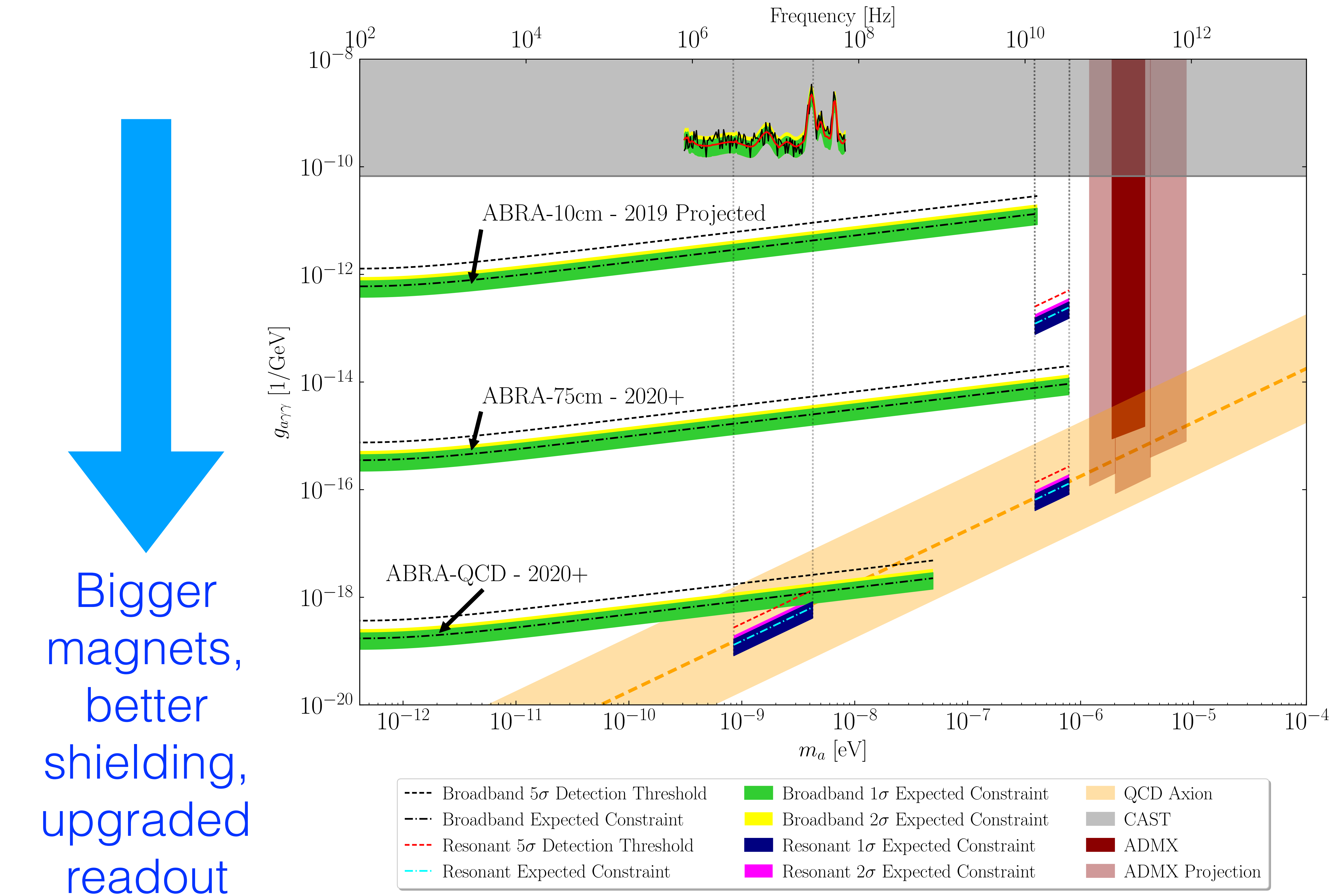
inside a 150 mK
dilution refrigerator



This is a theorist's dream: theory to experiment in 2 years flat!

[Ouellet, **YK**, et al., arXiv:1810.12257 and arXiv:1901.10652]

Future ABRA reach



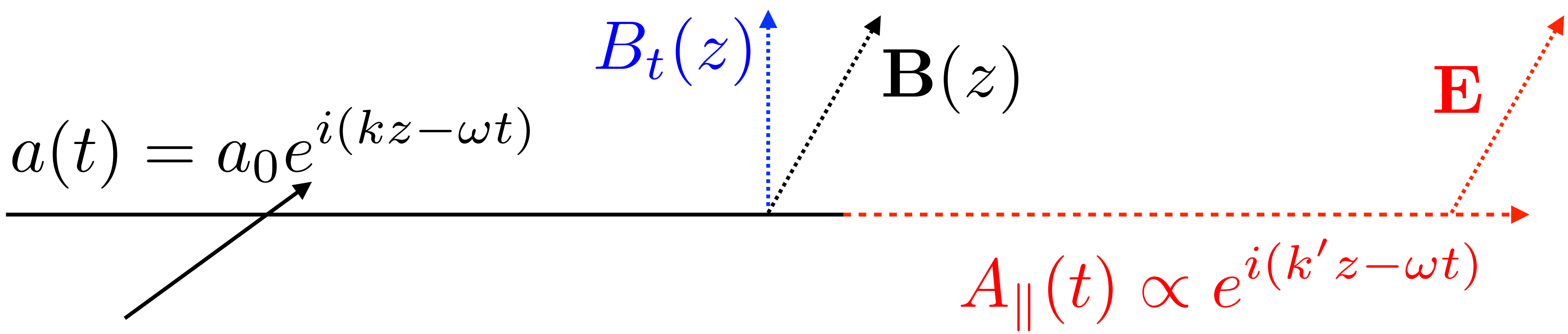
Bigger magnets, better shielding, upgraded readout

[**YK**, Safdi, Thaler, Phys. Rev. Lett. 2016; Ouellet, **YK**, et al., arXiv:1810.12257; J. Foster, ABRACADABRA collab.]

Axion indirect detection

Goal: detect photons produced by axions interacting with **astrophysical** B-fields

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

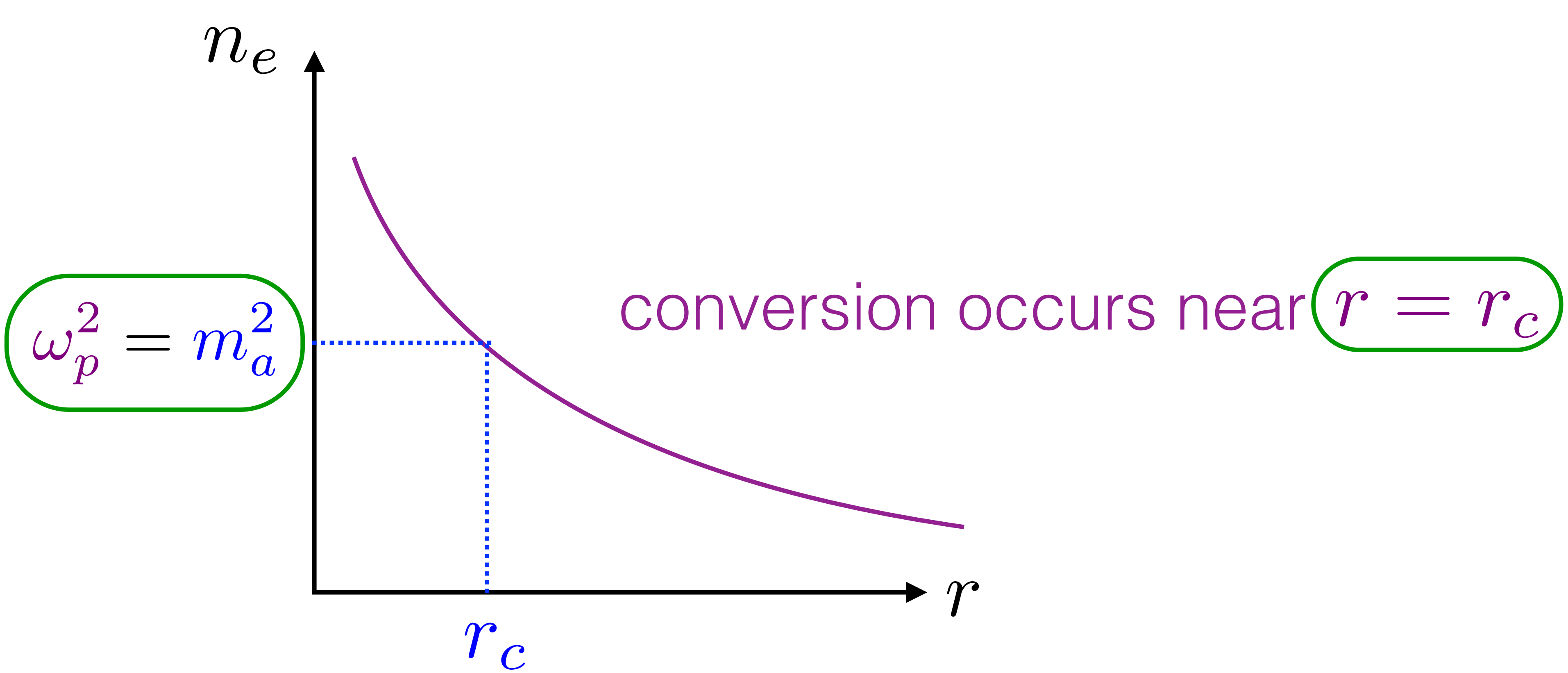
[Raffelt and Stodolsky, PRD 1988]

Resonant conversion

Need momentum matching

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

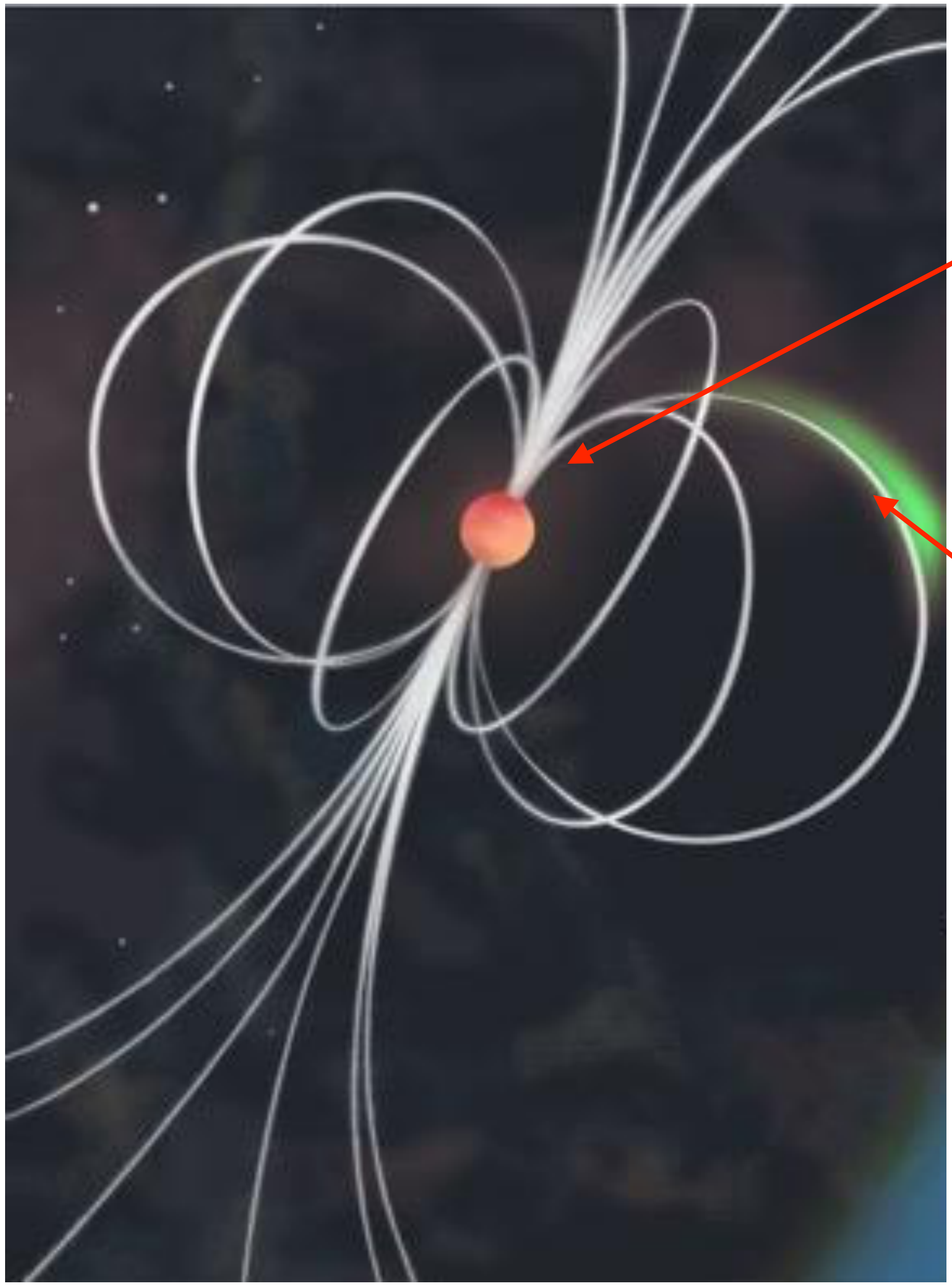
Option 2: B-field is approximately homogeneous, photon dispersion changes with plasma density



[Raffelt and Stodolsky, PRD 1988; Pshirkov and Popov, JETP 2009]

Neutron stars: ideal candidates!

2 key (related) ingredients for axion indirect detection:



1. Strong B-fields

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

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

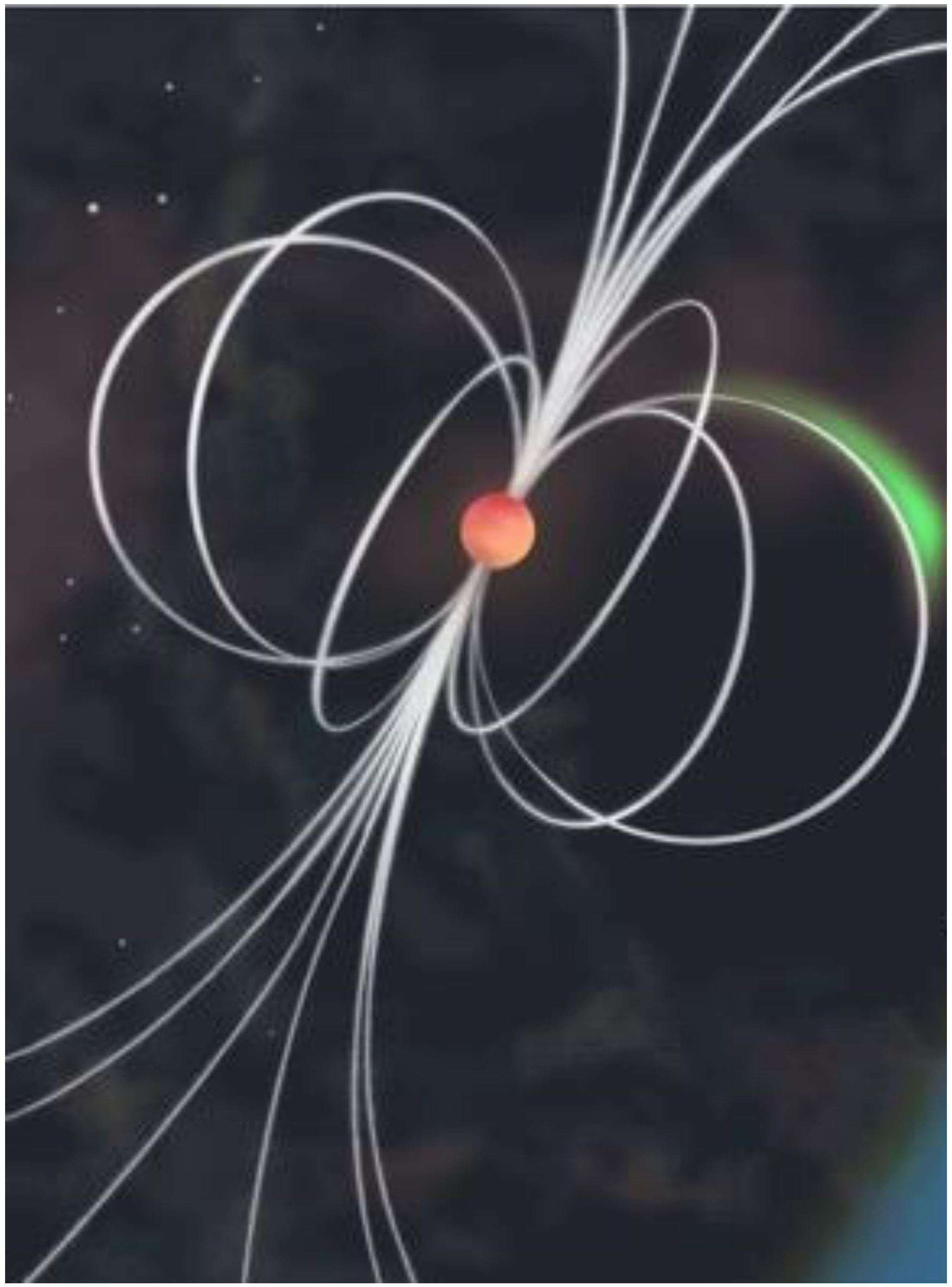
2. Goldreich-Julian model relates plasma frequency in "lobes" to dipole B-field:

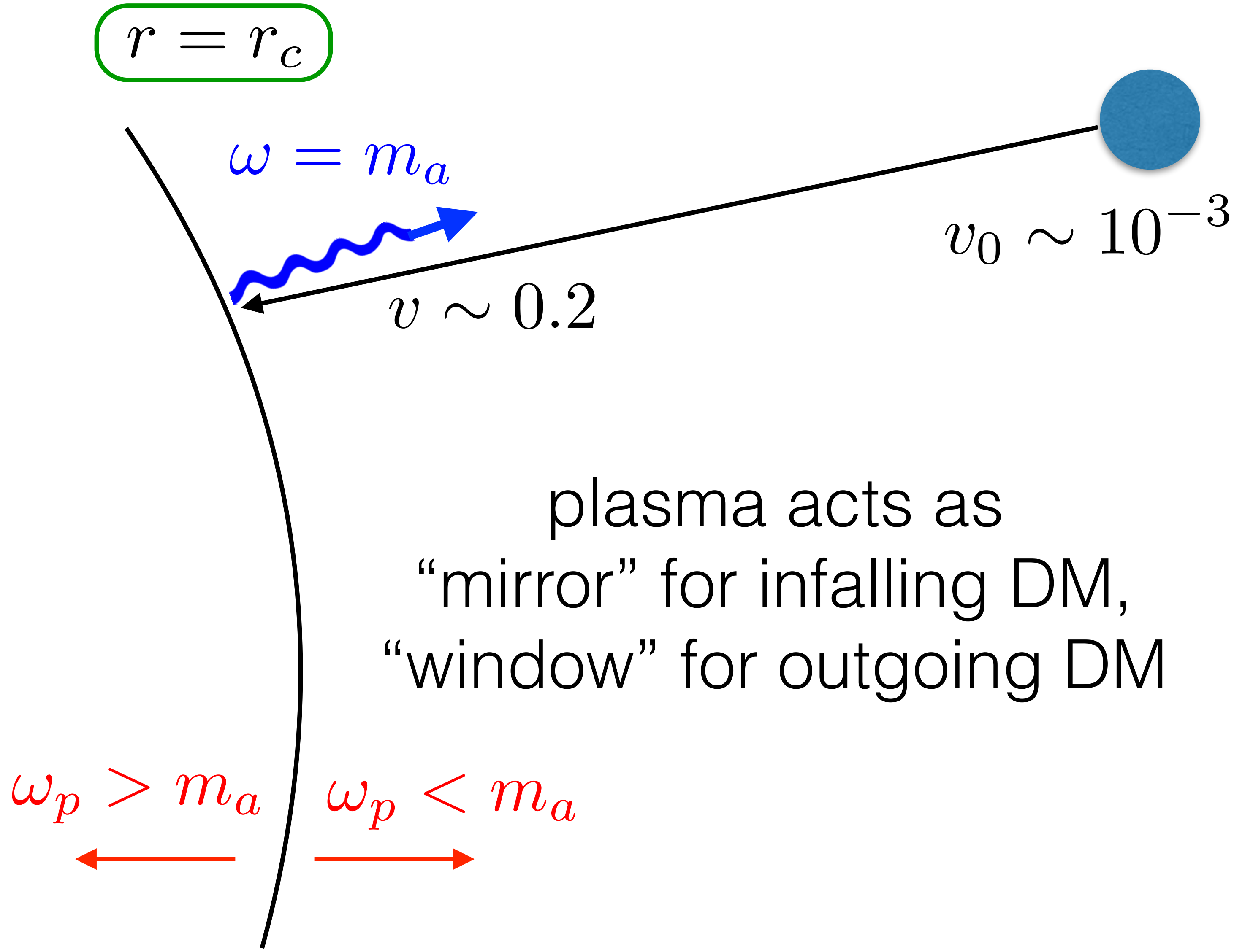
$$\omega_p \propto \sqrt{n_e} \propto \sqrt{B_0\left(\frac{r_{\rm NS}}{r}\right)^3 (3\cos^2\theta - 1)}$$

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

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

Infalling axion DM conversion





plasma acts as
"mirror" for infalling DM,
"window" for outgoing DM

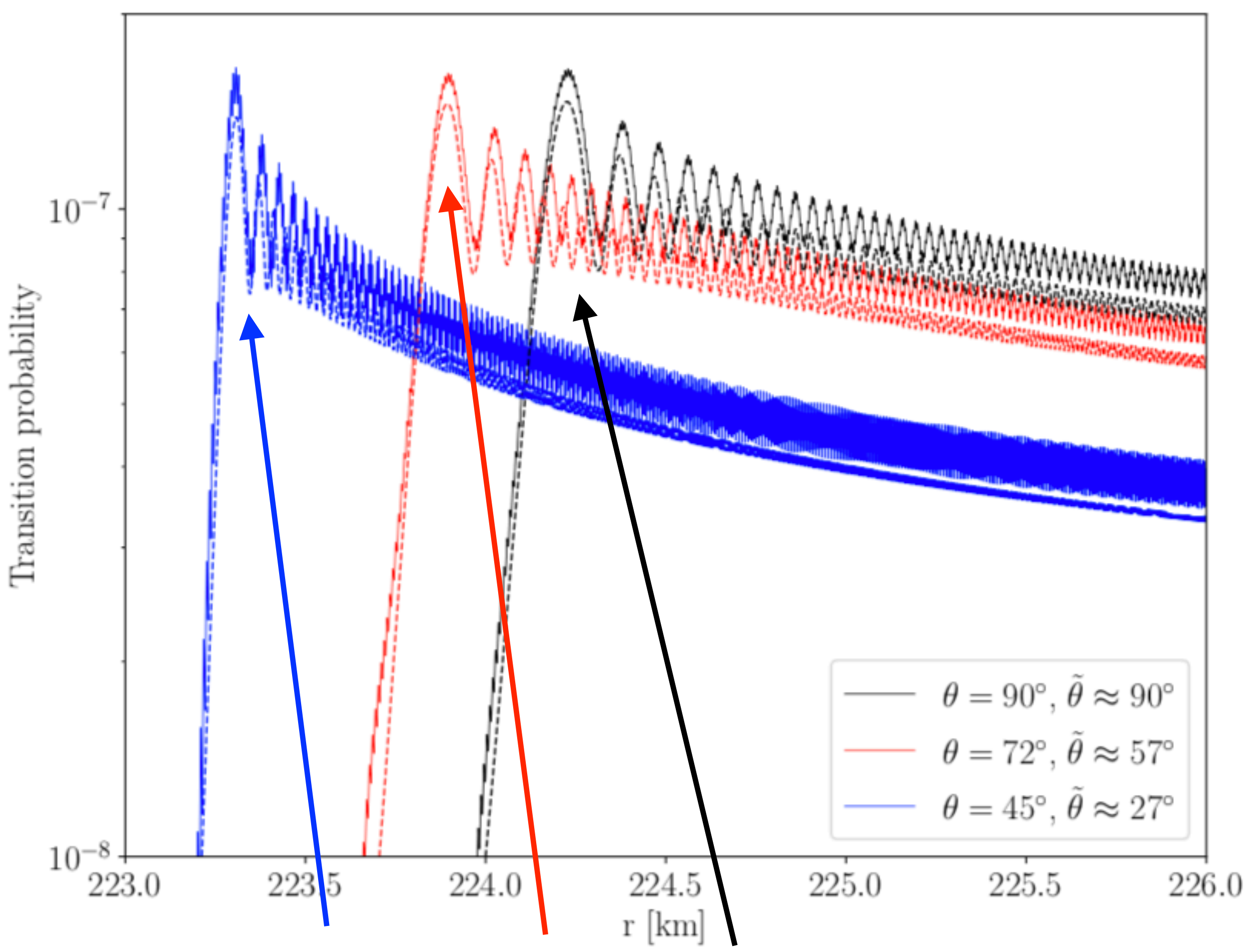
$$m_a = 1 \text{ GHz } (\sim 10^{-6} \text{ eV}), \;\; B_0 = 10^{10} \text{ T}$$

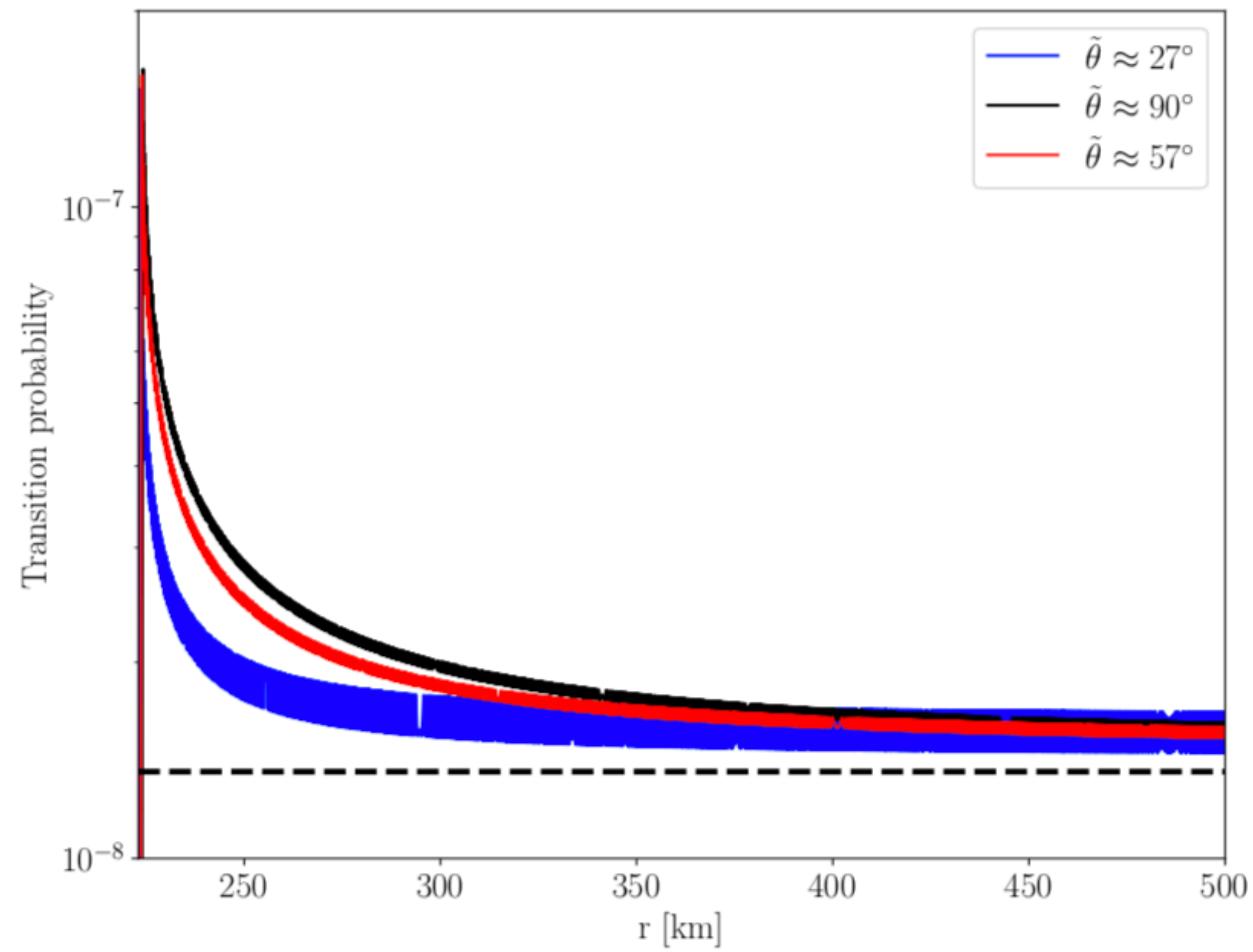
$$\Longrightarrow \;\; r_c \sim 220 \text{ km at } \theta = \pi/2$$

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):

$$p_{a\gamma}^{\infty} \approx \frac{1}{2v_c} g_{a\gamma\gamma}^2 B(r_c)^2 L^2$$

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

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

Radio bump hunt

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

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

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

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

[Arecibo]

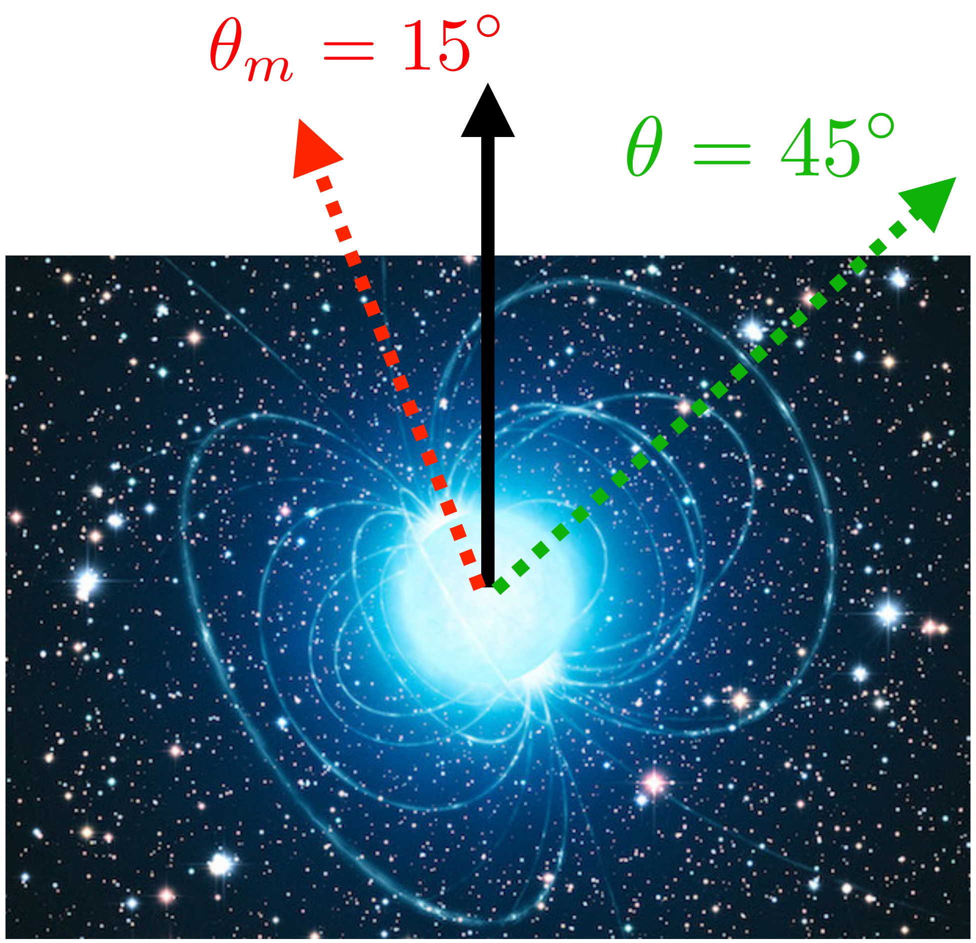
Desired characteristics:

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

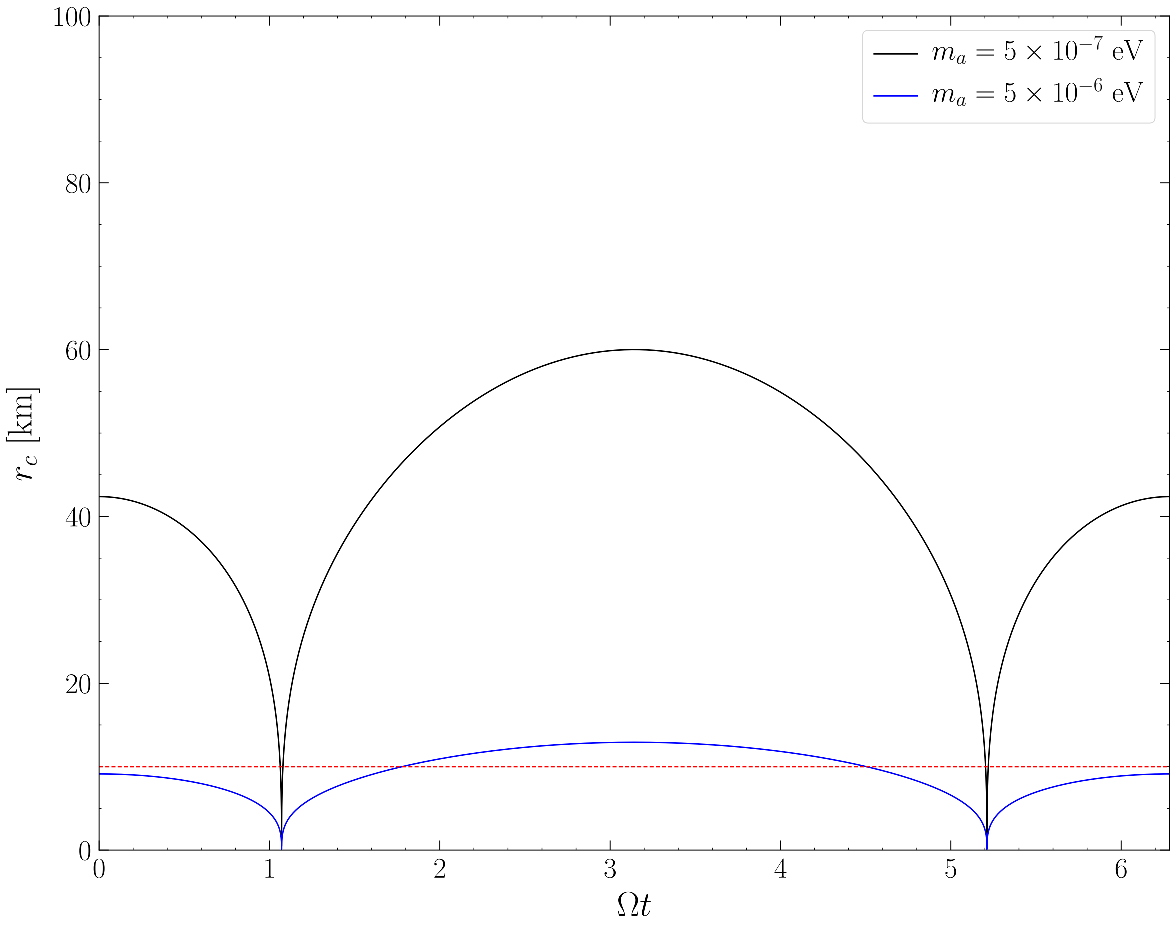
Added bonus: energy conservation keeps line narrow

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]

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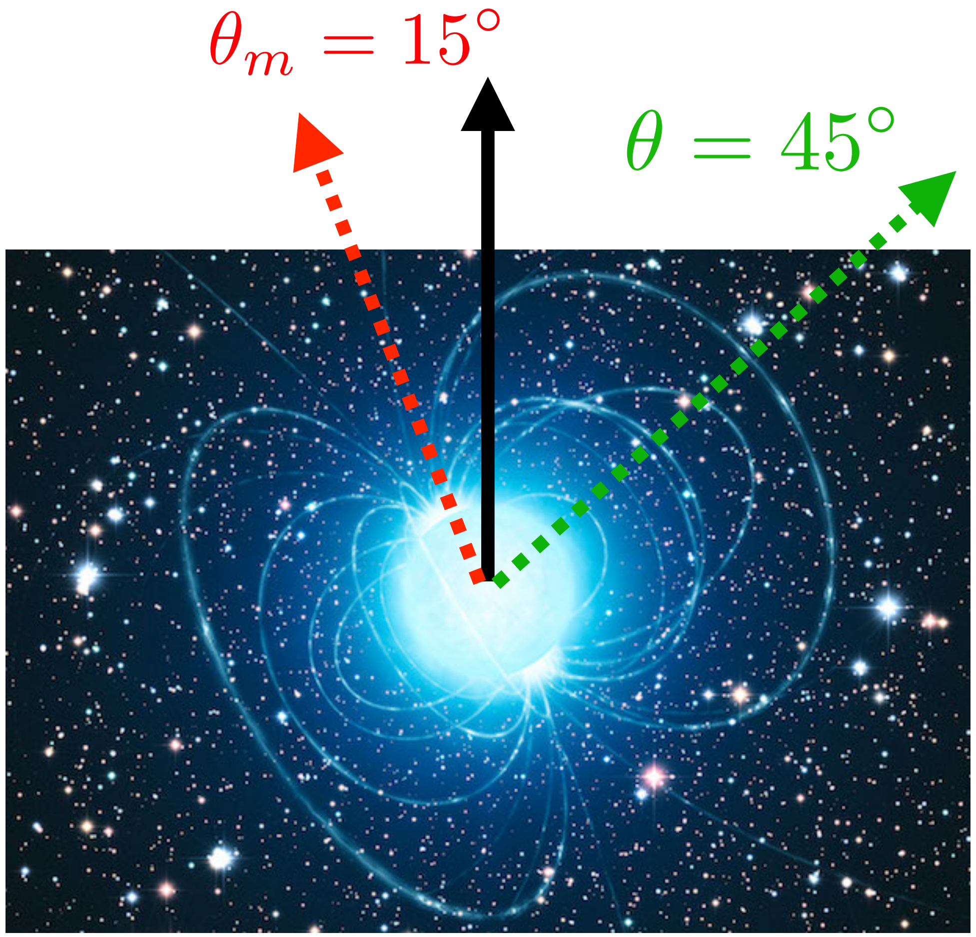
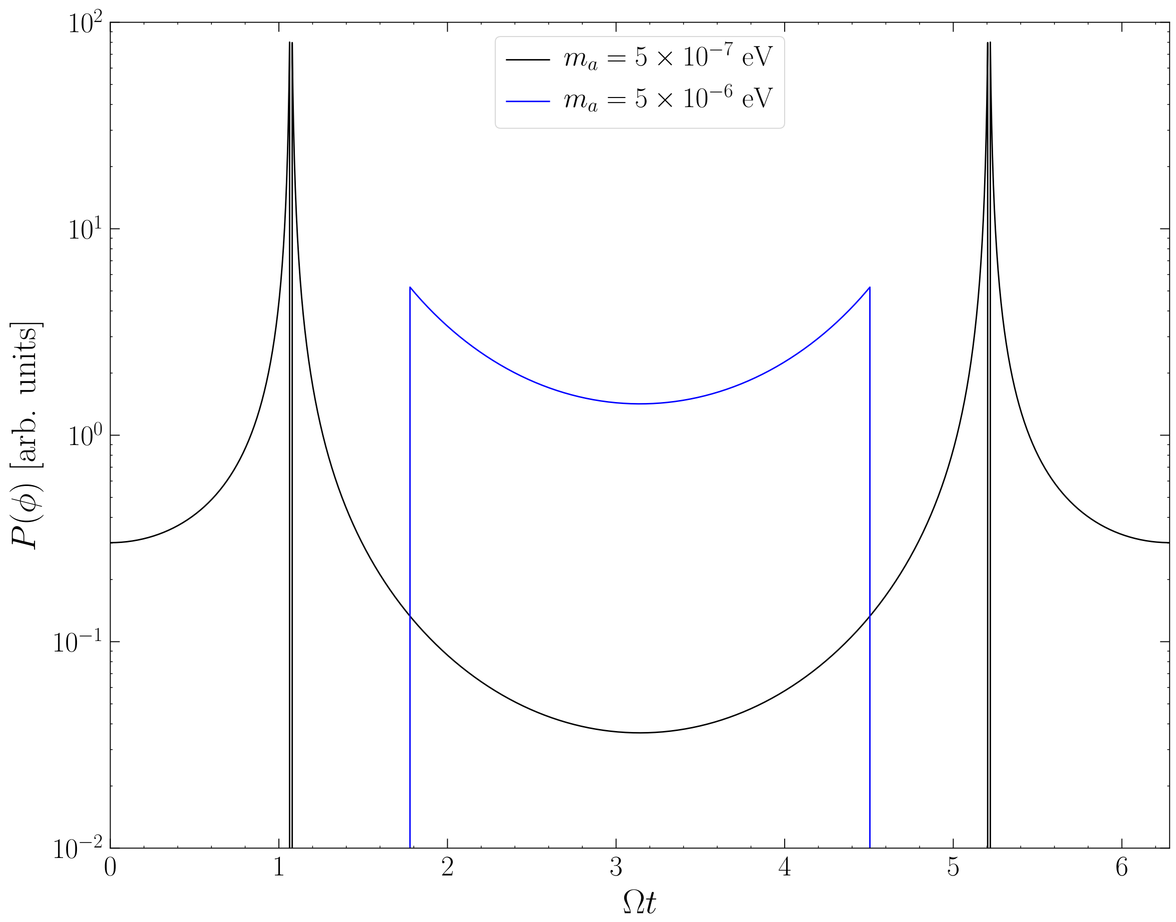


Light curve

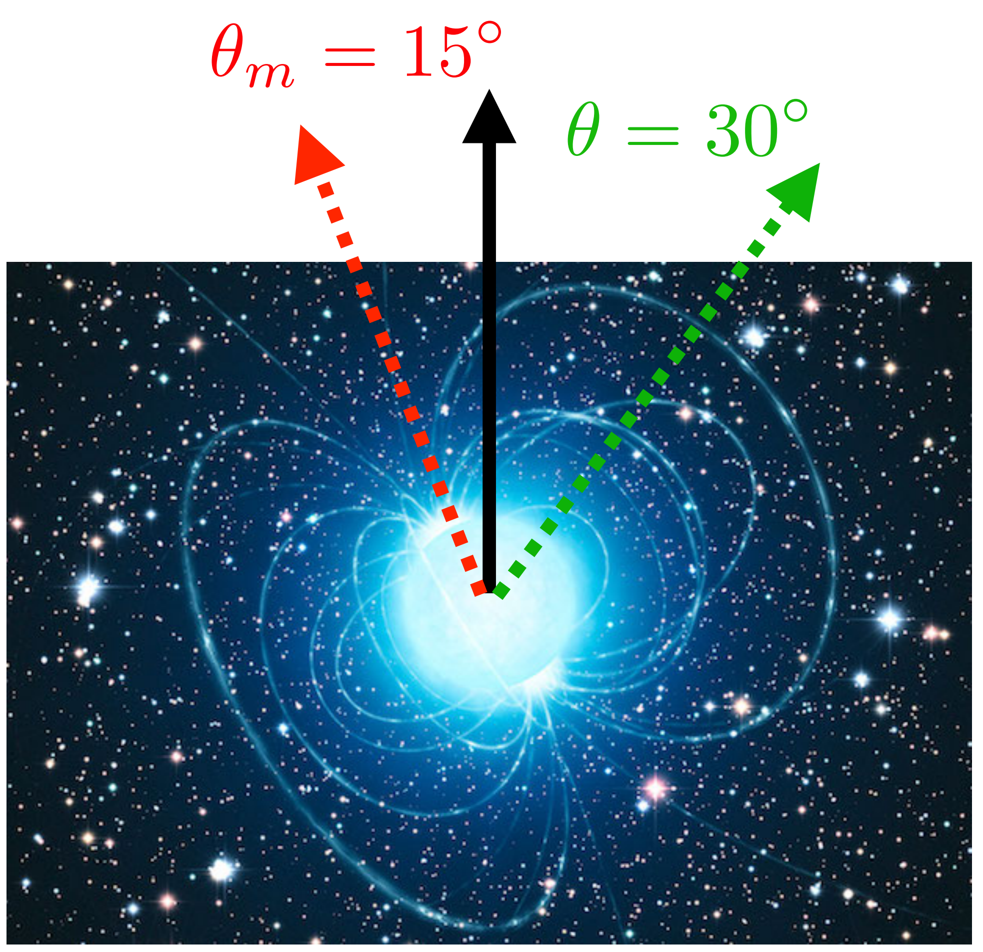


Striking signal: looks promising!

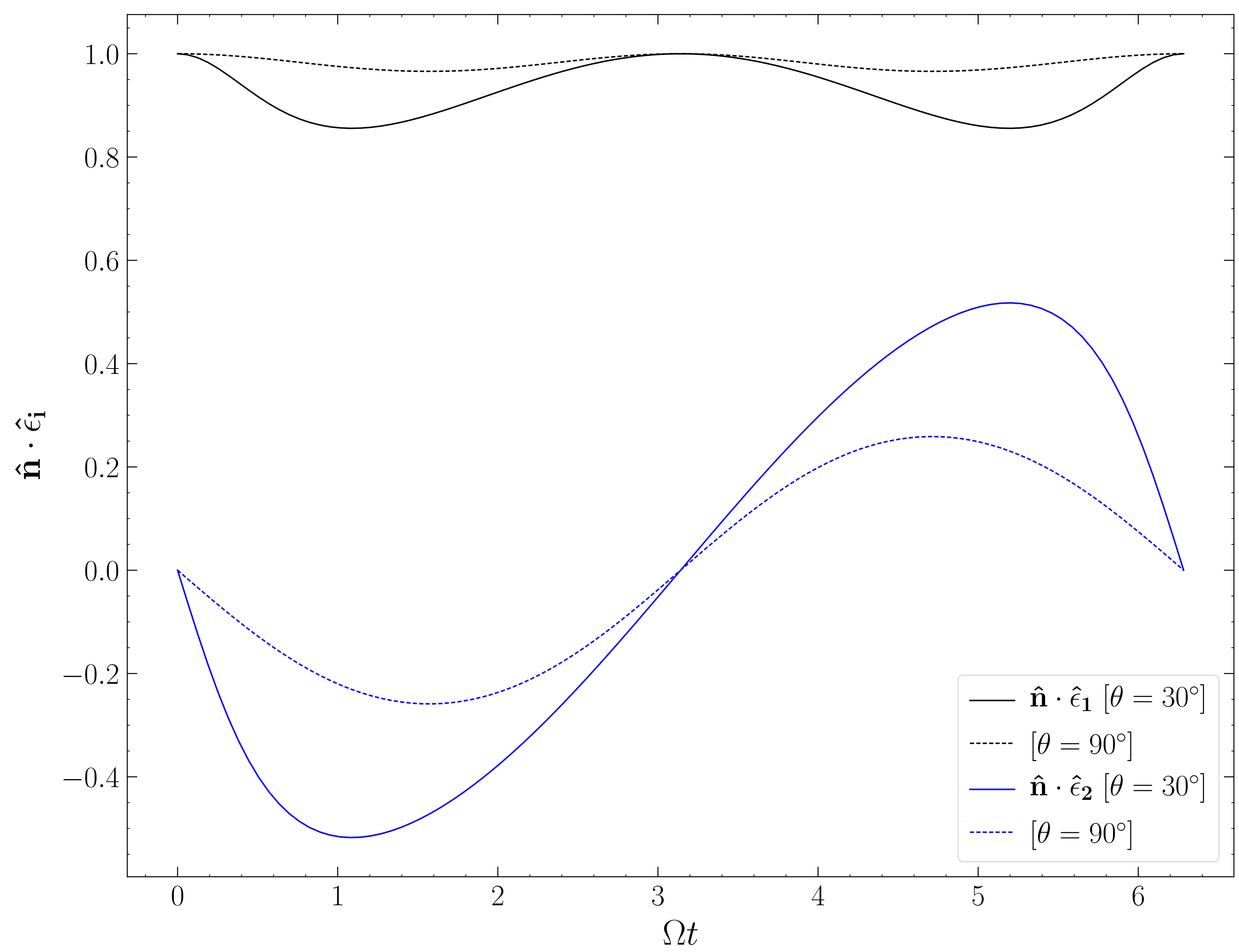
[Hook, **YK**, Safdi, Sun, arXiv:1804.03145]

Polarization signal

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

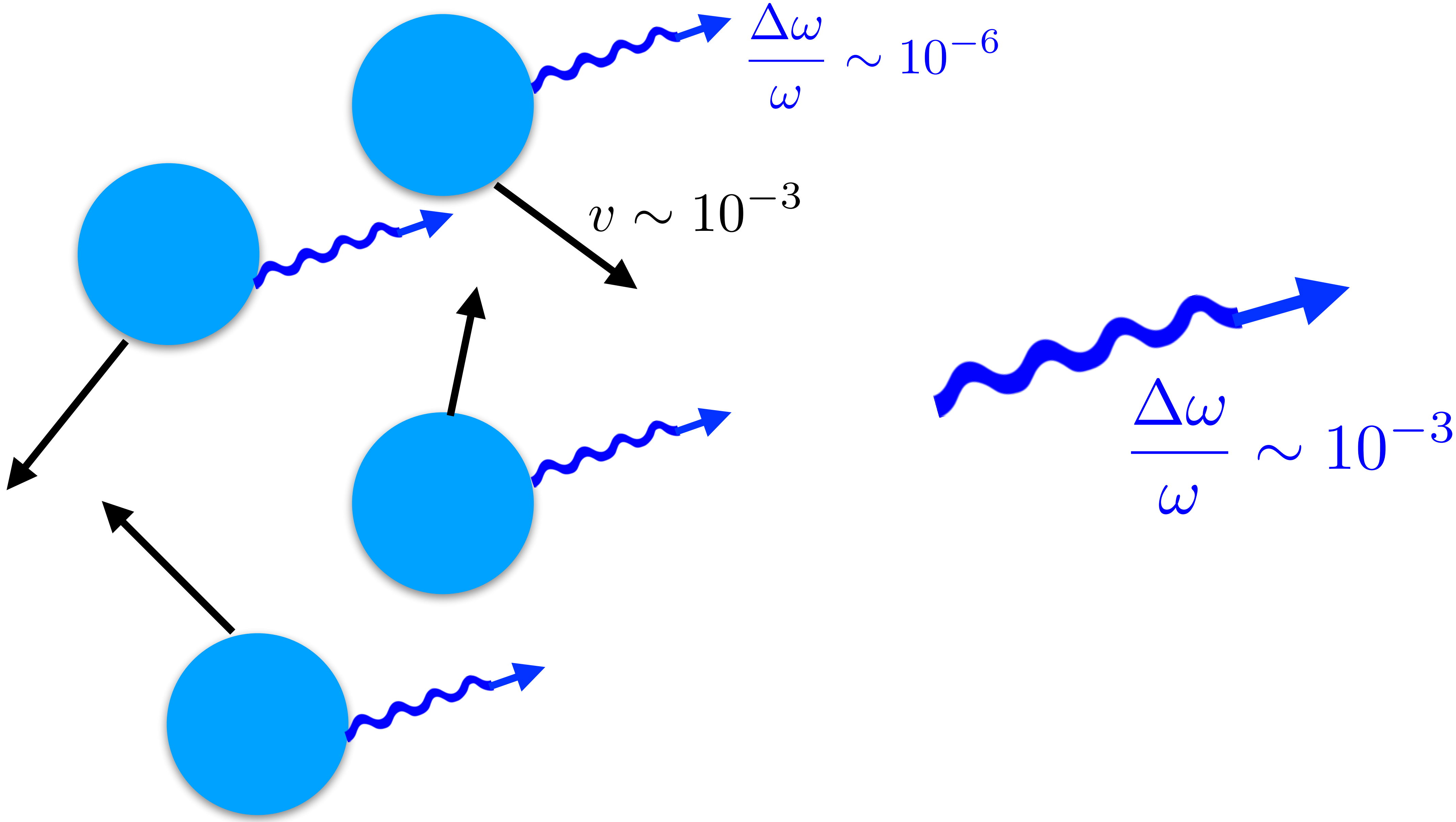


$$(\hat{\epsilon}_1 = \hat{\theta},\ \hat{\epsilon}_2 = \hat{\phi})$$



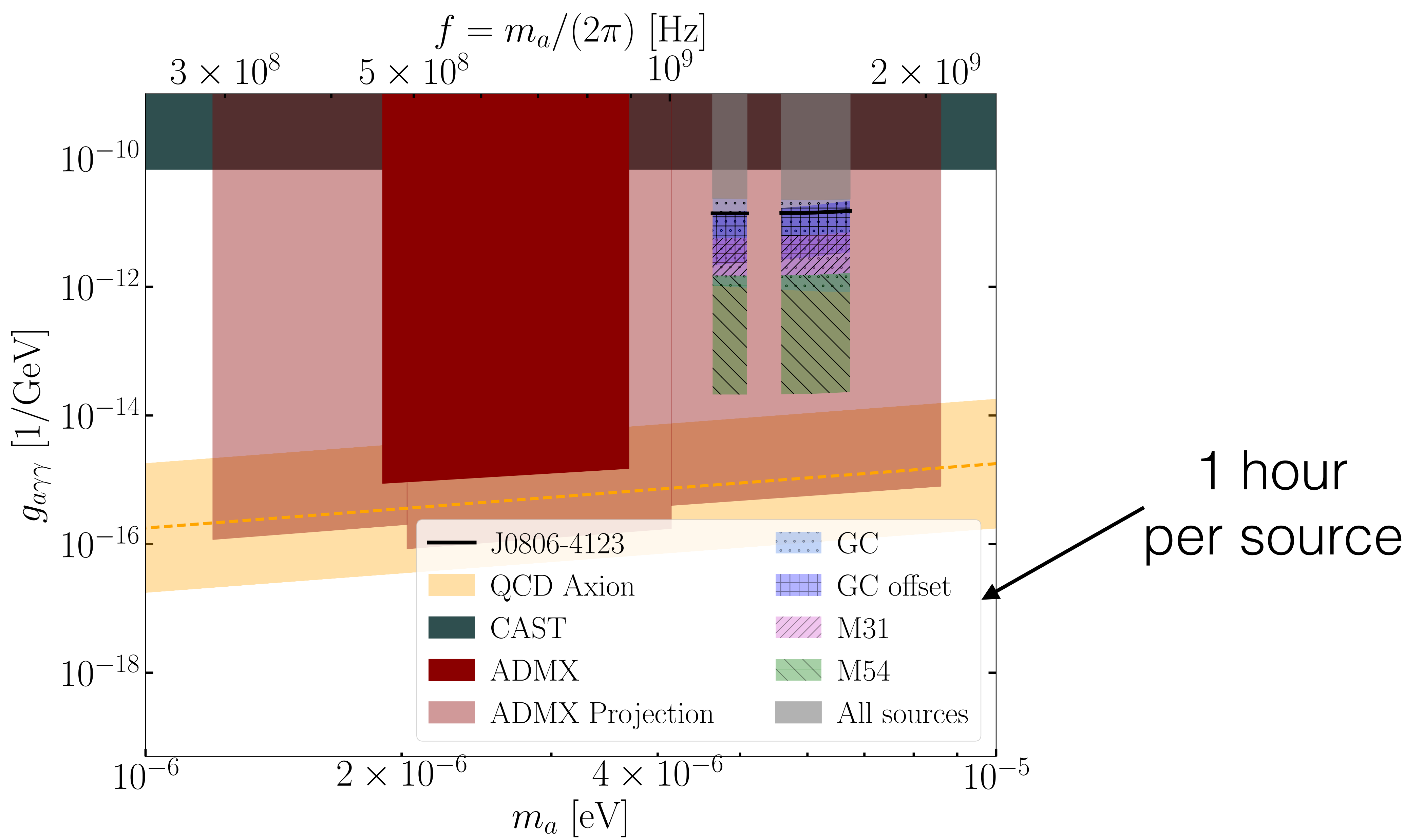
[Hook, **YK**, Safdi, Sun, arXiv:1804.03145]

Neutron star populations



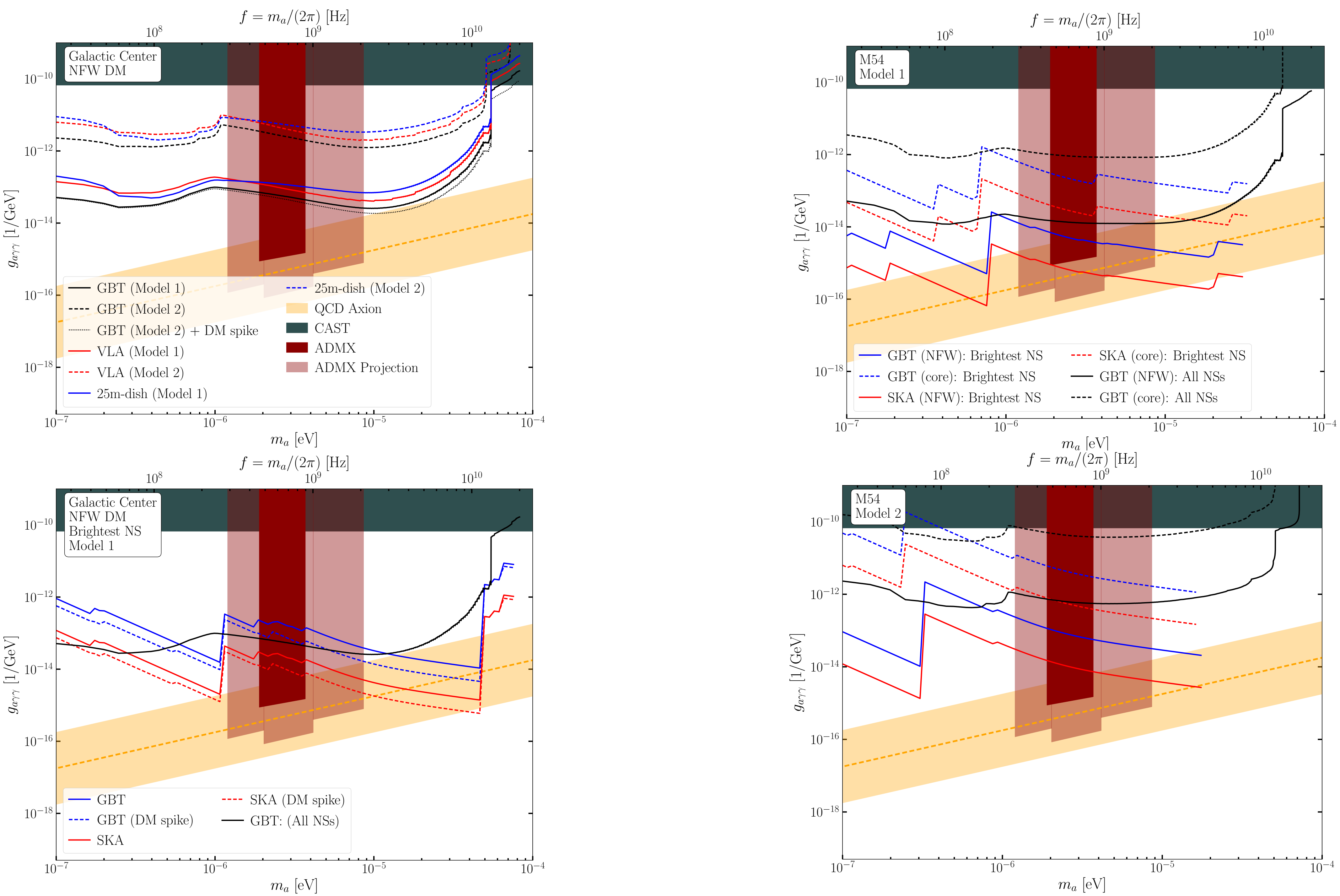
Doppler broadening: larger bandwidth
But signal adds incoherently!
If N_{NS} > 1000, still win

NS populations at Green Bank Telescope



Can be competitive with ADMX with 1 hour of observation!

Future radio searches



QCD axion might be within our reach!

[Chen, Safdi, Sun, arXiv:1811.01020]