

An Axion Pulsarscope

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Axions in Stockholm

July 3, 2025

[image: NANOGrav]



Axion couplings to Standard Model

EM field

$$g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

Fermions

$$g_{a\psi\psi}(\partial_\mu a)\bar{\Psi}\gamma^\mu\gamma^5\Psi$$

Gluons

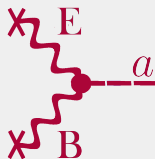
$$g_{agg}a\text{Tr}[G_{\mu\nu}\tilde{G}^{\mu\nu}]$$

Gravity

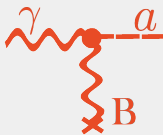
Axion coupling to EM field

$$g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

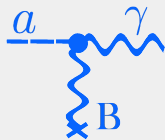
Emission



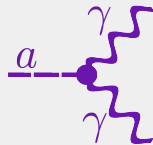
Primakoff effect



Inverse Primakoff



Decay



AXION DETECTION EXPERIMENTS

CAST

CERN Axion Solar Telescope
(helioscope)

- Solar axions
- Broad $\sim$ keV spectrum

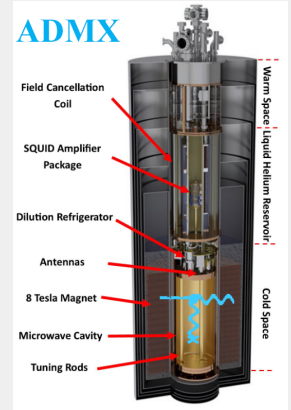
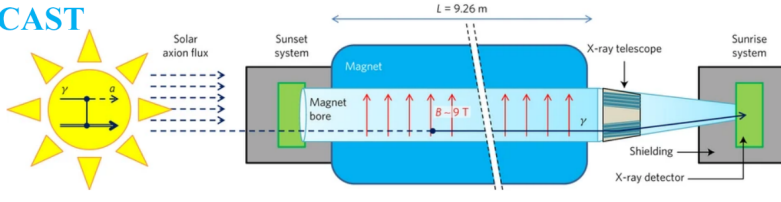
ADMX

Axion Dark Matter eXperiment
(haloscope)

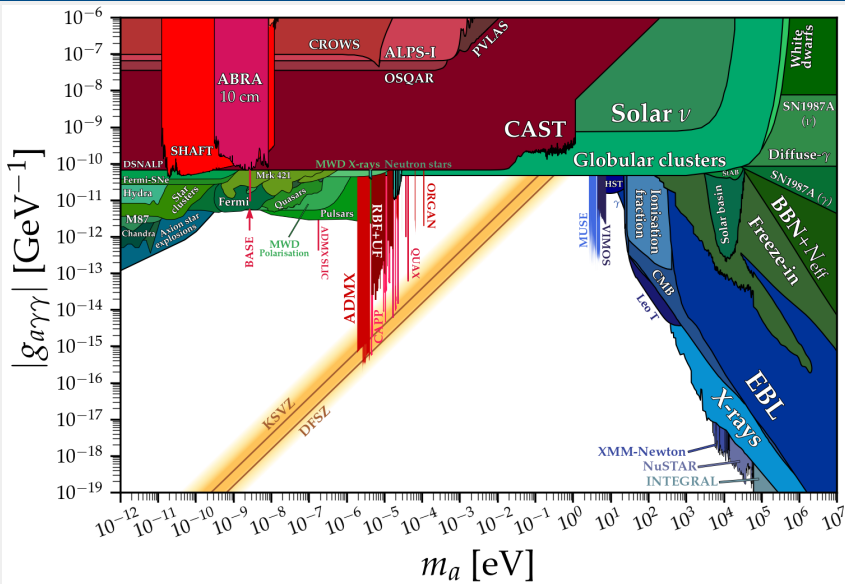
- Dark matter halo axions
- Resonant

[images: CAST Collaboration (2017), ADMX]

CAST



CURRENT BOUNDS ON THE AXION-PHOTON COUPLING CONSTANT

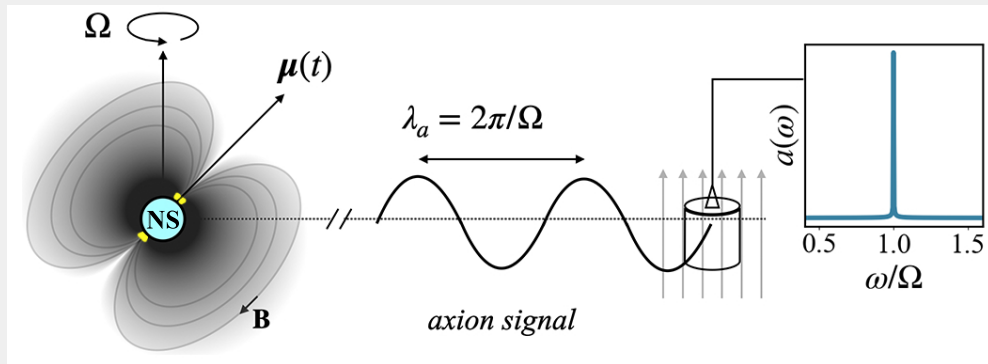


[Axion Limits maintained by **cajohare**]

Pulsarscope!!

Key advantages:

- known frequency
- monochromatic signal
- higher signal quality



PULSARS

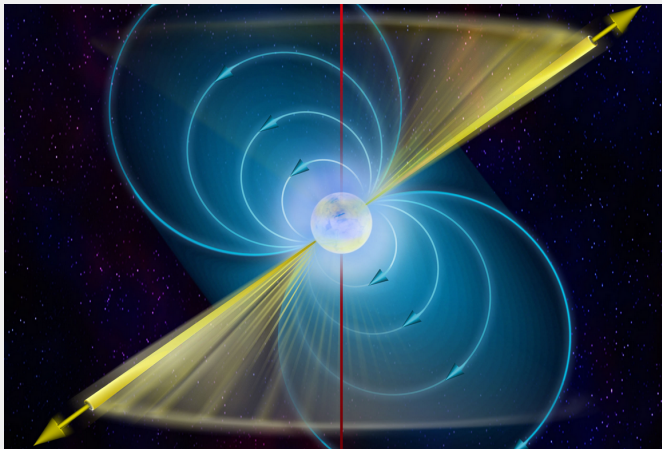
Pulsars are highly magnetized rotating **neutron stars**

Emit pulses of radiation at regular intervals

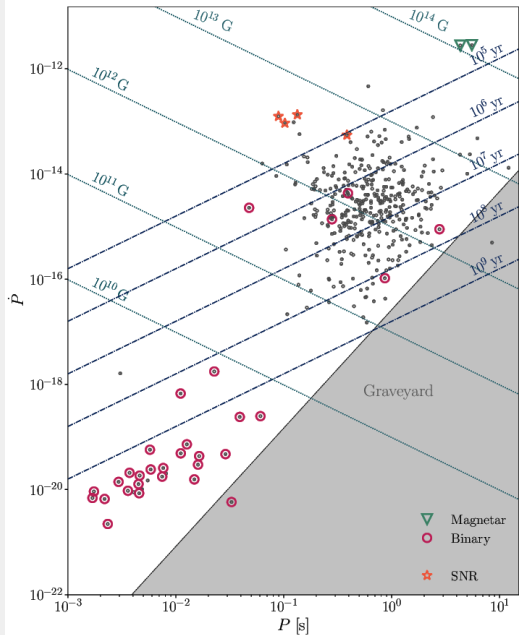
Rotation period: $T = 1.4\text{ms} - 76\text{s}$

Magnetic field: $B_0 \sim 10^8 - 10^{15}\text{G}$

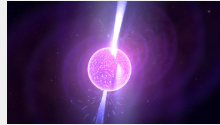
[image: NRAO webpage]



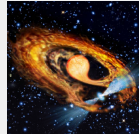
PULSAR POPULATION



■ Active



■ Millisecond

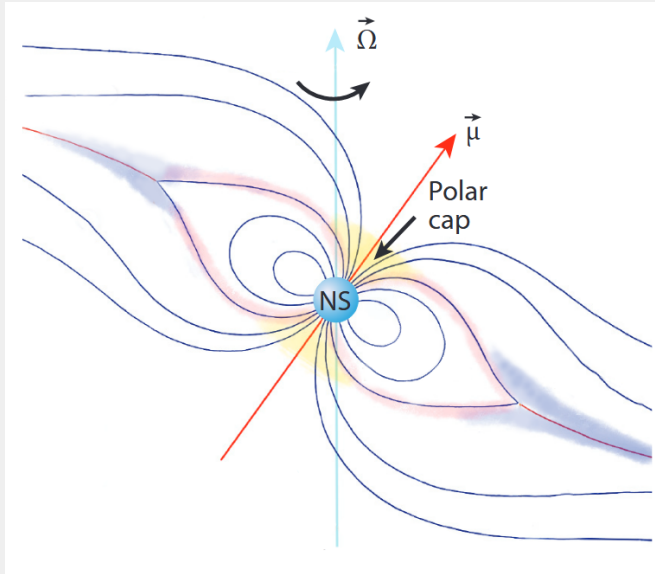


■ Magnetar



[Images: M. Lower et al. (2020), Kevin Gill, ESA, Francesco Ferraro, Carl Knox]

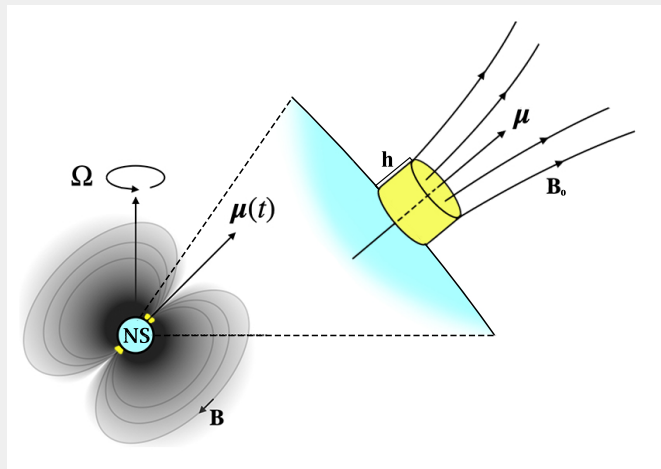
PULSARS' MAGNETOSPHERE



[Philipov & Kramer 2022]

THE POLAR CAP (PC) MODEL

Axions are emitted only from the small polar cap regions above the magnetic poles of a pulsar.



The equation of motion:

$$(\square + m^2)a = g_{a\gamma\gamma} \mathbf{E} \cdot \mathbf{B}$$

- **Monochromatic axion signal** on pulsar rotation frequency Ω

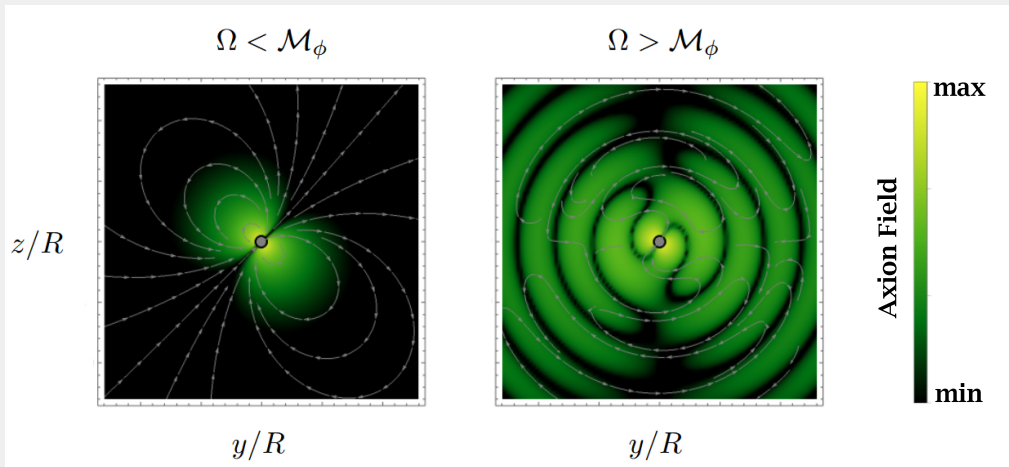
- Axion emission power:

$$P_a \propto g_{a\gamma\gamma}^2 B_0^4 \Omega^8 R_{\text{NS}}^8 h^4$$

[MK, M. Lisanti, A. Prabhu, B. Safdi (2024) arXiv:2402.17820]

THE VACUUM DIPOLE MODEL (VDM)

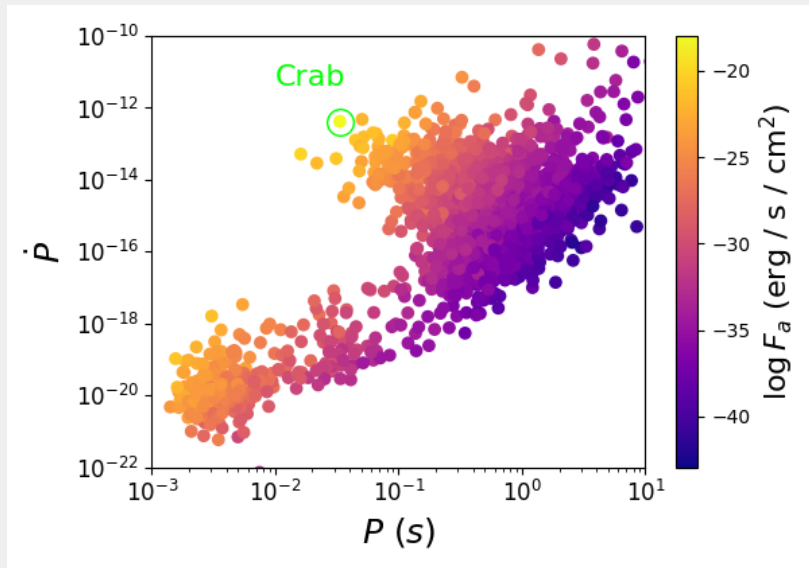
Axions are emitted from the entire volume of a pulsar's magnetosphere.



[Garbrecht, McDonald (2018)]

The axion emission power: $P_a \propto g_{a\gamma\gamma}^2 B_0^4 \Omega^6 R_{NS}^{10}$

BEST PULSAR AS AXIONS SOURCE

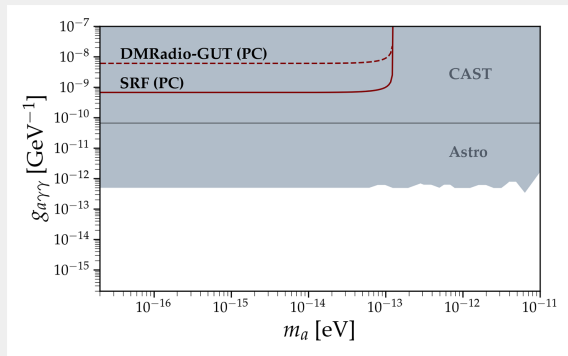


P - pulsar's
rotation period

$\dot{P}$ - pulsar's
spin-down rate

[MK, M. Lisanti, A. Prabhu, B. Safdi (2024) arXiv:2402.17820]

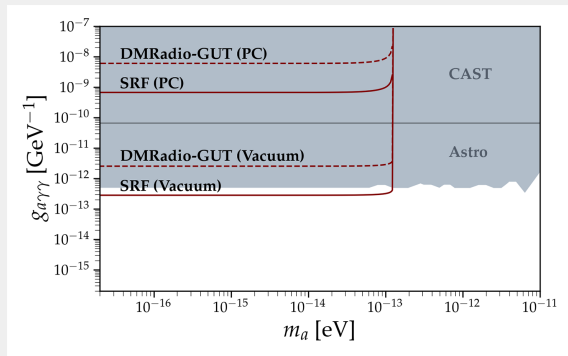
THE PROJECTED SENSITIVITY



Projected sensitivity for SRF, DMRadio-GUT and CASPEr experiments to axions emitted by Crab pulsar (polar gap and vacuum dipole magnetosphere model).

[MK, M. Lisanti, A. Prabhu, B. Safdi (2024) arXiv:2402.17820]

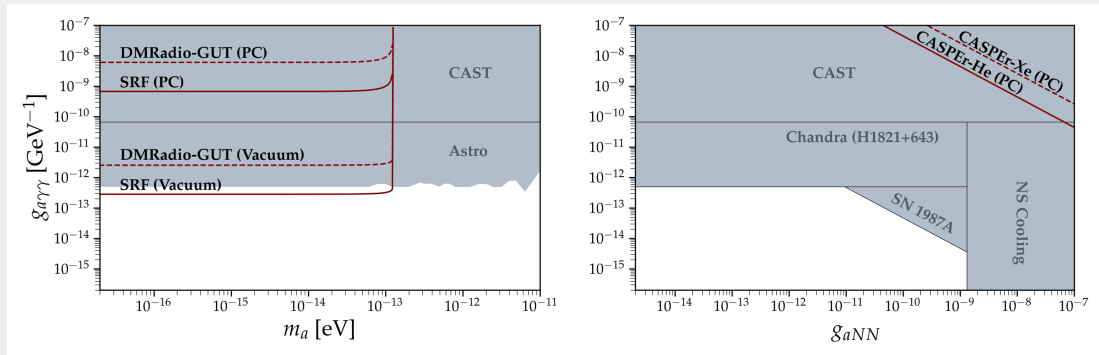
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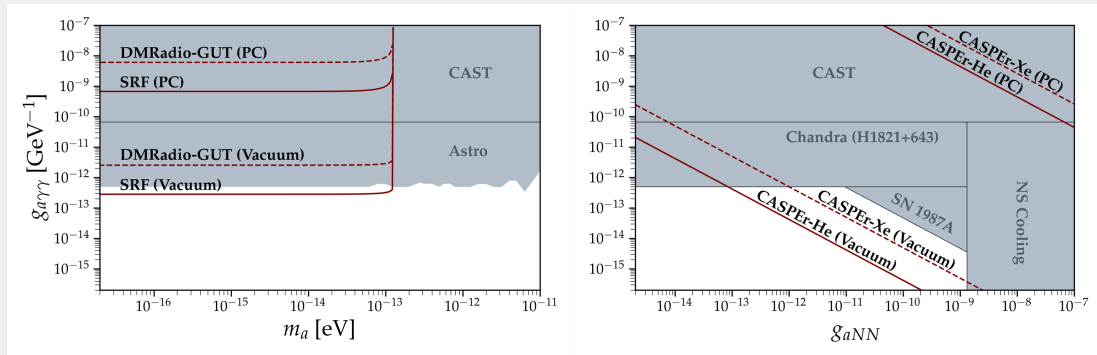
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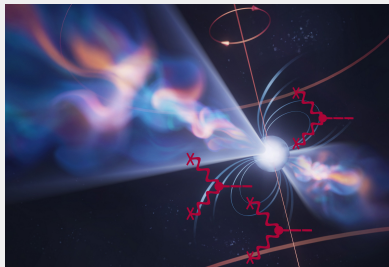
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Conclusions:

- A new target for axion detection is proposed – axions emitted by pulsars.
- Can potentially improve current laboratory constraints in mass range $m_a \lesssim 10^{-13}$ eV, depending on magnetosphere model.

Future work:

- Detailed PIC simulations of the pulsar's magnetosphere will provide a more precise estimation of axion emission power, refining targets for experiments.

[MK, M. Lisanti, A. Prabhu, B. Safdi (2024) arXiv:2402.17820]

THANK YOU!

UPCOMING AXION EXPERIMENTS PROJECTIONS

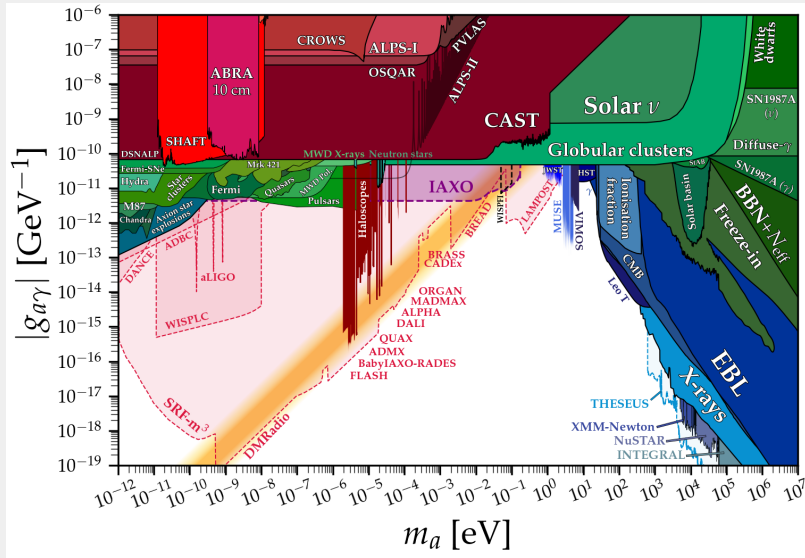
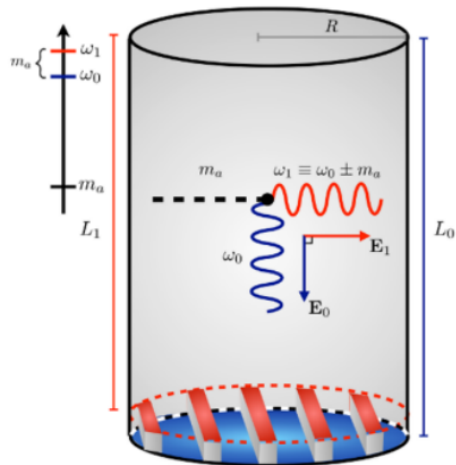


Figure 1: Axion-photon coupling bounds with projections [cajohare]



Cartoon of cavity setup.

SRF – Superconducting Radio Frequency cavity detector

- dark matter axions
- resonant

$$\omega_1 \approx \omega_0 + \omega_a$$

$$\text{quality factor } Q_0 \sim Q_1 \sim 10^{12}$$

Pulsarscope:

- quality factor $Q \sim 10^{12}$
- coherence time $\tau_{\text{coh}} \gg T_{\text{obs}}$

[Image: A. Berlin et al. (2020)]

EXPERIMENT SENSITIVITY SCALINGS

The experimental target can be modeled as resonator:

$$\ddot{x}(t) + \frac{\omega_0}{Q_0} \dot{x}(t) + \omega_0^2 x(t) = \frac{A}{\omega} \cos(\omega t + \varphi(t)) \quad (1)$$

Power extracted by oscillator from axion field:

$$\langle P \rangle = \frac{A^2 \omega_0 / Q}{2 [(\omega^2 - \omega_0^2)^2 + (\omega_0 \omega / Q)^2]} \quad (2)$$

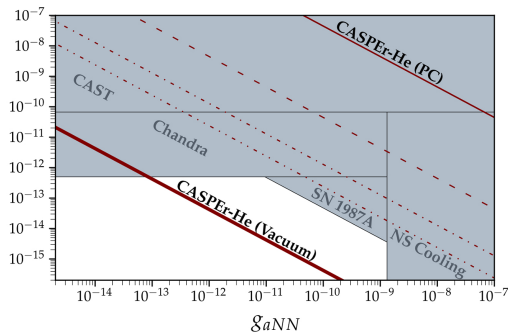
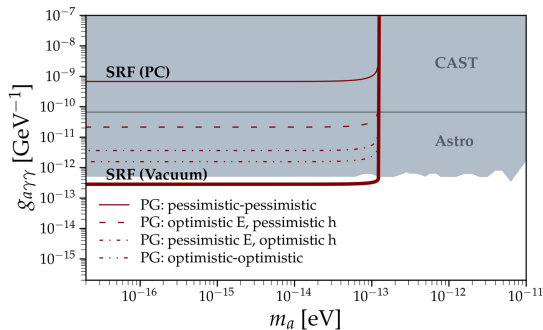
The signal-to-noise ratio for pulsar axions:

$$\text{SNR} \propto g_i^2 \rho_{\text{PS}} \left(\frac{\partial a}{\omega a} \right)^2 (TQ)^{1/2} \quad (3)$$

POLAR CAP MODELS

		Polar gap height, h	
		positive	negative
Polar Gap electric field, E	positive	$h = r_{pc}$ $E = E_{vac} = \Omega R_{NS} B$	$h = h_{Rud}$ $E = E_{vac} = \Omega R_{NS} B$
	negative	$h = r_{pc}$ $E = E_{Rud} = 2\Omega h B = 2\Omega r_{pc} B$	$h = h_{Rud}$ $E = E_{Rud} = 2\Omega h B = 2\Omega h_{Rud} B$

PROJECTIONS



Projected sensitivity for SRF and CASPER experiments to axions emitted by Crab pulsar (vacuum dipole magnetosphere and several different polar gap models).