Searching for axion dark matter: from the lab to the stars

KCL Seminar 10 Nov 2021

Jamie McDonald

CP3 Université Catholique de Louvain

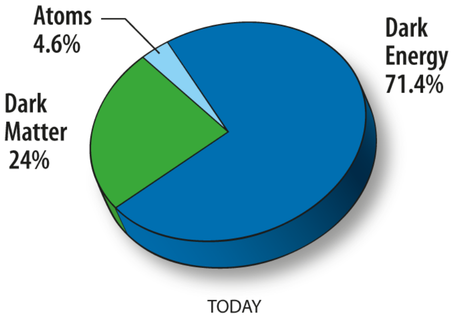
UCLouvain

Based on **Phys.Rev.D 102 (2020) 2, 023504** and **JHEP 09 (2021) 105** and 2107.01225 and 2108.13894

Outline

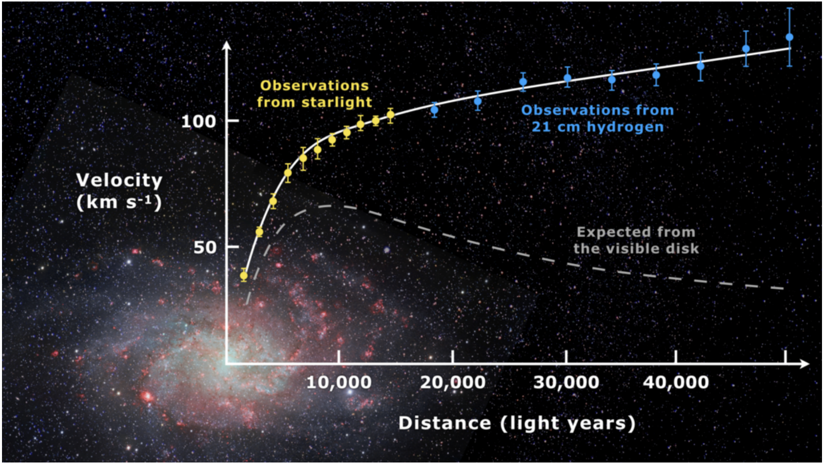
1. Axions and Dark Matter
2. Detecting Axion Dark Matter
3. Harnessing the power of Neutron Stars as Dark Matter detectors
4. State of the art in stellar dark matter detection
5. Axion dark matter in the lab - computer designed detectors and gradient descent
6. Looking forward

Unable to explain most of the matter/energy content of the universe

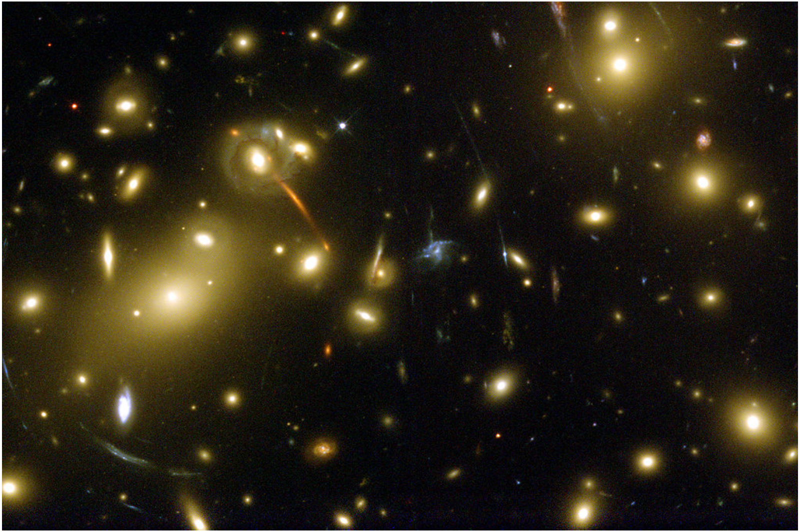


Dark Matter

Velocity Rotation Curves

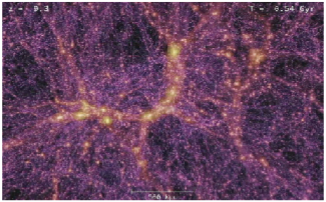


Gravitational Lensing by Dark Matter

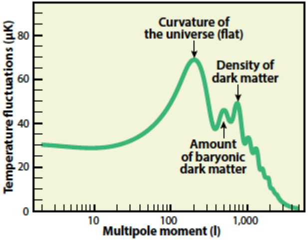


Needed To Explain Cosmology

Structure Formation



CMB



Many Explanation of Dark Matter

Light bosons

- axions

- axion-like particles

- fuzzy cold dark matter

sterile neutrinos

weak scale

-supersymmetry

-extra dimensions

-little Higgs

Primordial black holes

Massive compact halo objects (MaCHOs)

Modifying gravity...

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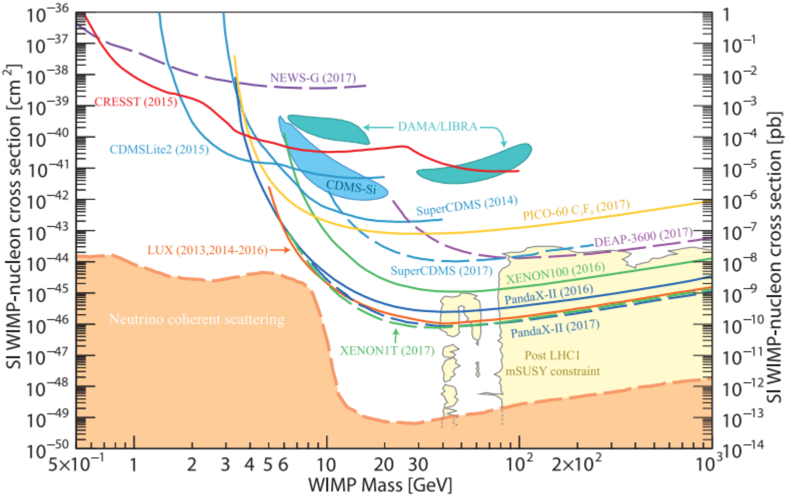
Modifying gravity...

One popular scenario $m_{\rm DM} \sim$ GeV (WIMPS)



PDG 2017

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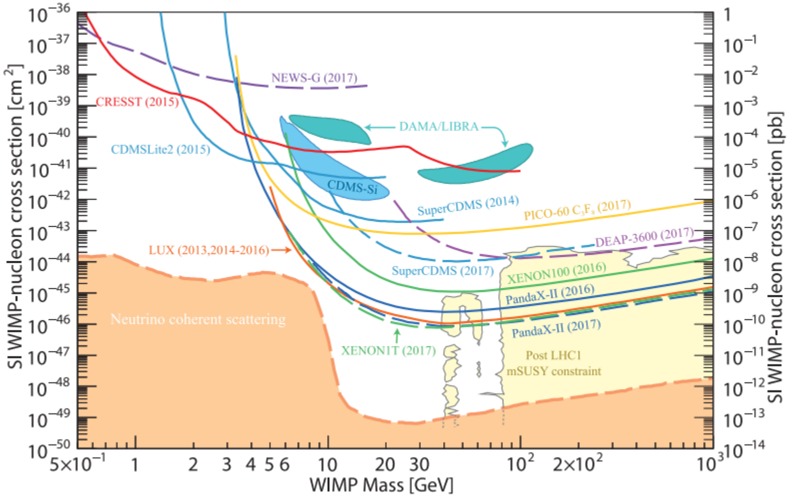

PDG 2017

But so far they haven't shown up...

Many Explanation of Dark Matter

Light bosons $\rightarrow$

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sterile neutrinos

weak scale

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Modifying gravity...

Axions

Generic class of Particle: light (pseudo) scalar: a

$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a \partial^\mu a + V(a)$$

Typically couples to many particles in standard model

$$\mathcal{L}_{SM} = \frac{g_{a\gamma\gamma}}{2} a \underbrace{F_{\mu\nu}\tilde{F}^{\mu\nu}}_{\text{electromagnetism}} + g_{aN}\partial_\mu a \underbrace{(\bar{N}\gamma^\mu\gamma_5 N)}_{\text{nucleons}} + g_{ae} \underbrace{\partial_\mu a(\bar{e}\gamma_\mu\gamma_5 e)}_{\text{electrons}}$$

Main motivations:

- **Occurs in many extensions of the SM** (e.g. "string axiverse"
- **Strong CP Problem** Peccei, Quinn (1977)

$$\mathcal{L}_\theta = \frac{\theta_{QCD}}{32\pi} \mathrm{Tr} G_{\mu\nu}\tilde{G}^{\mu\nu} \qquad \theta \lesssim 10^{-10}$$

- **DM Candidate** - halos made from scalar fields Hui et al (2016)

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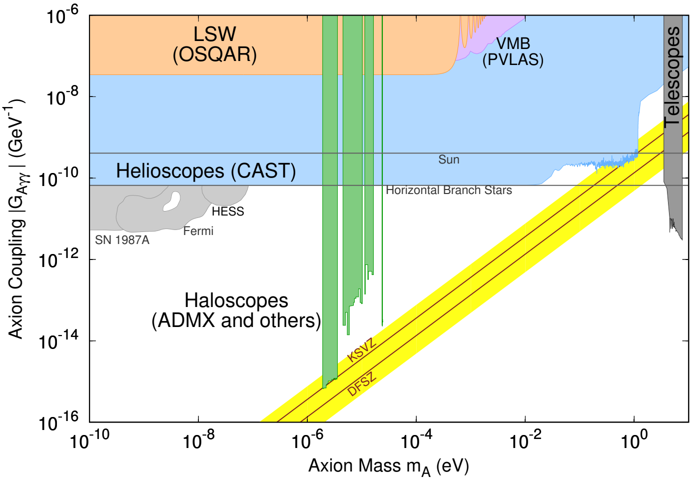
Renewed interest in axion dark matter $m_a \sim \mathcal{O}(\mu eV)$



Axion coupling to electromagnetism

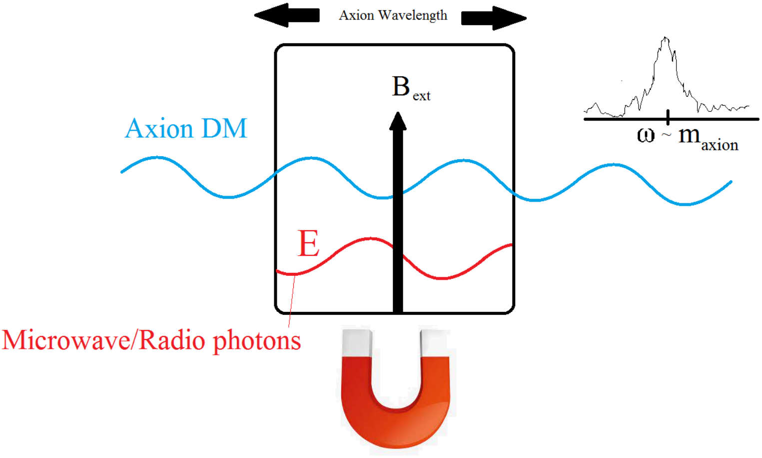
$$L_{axion} = \frac{1}{2}\partial_\mu a \partial_\mu a - g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Axion Electrodynamics

$$\begin{aligned}
\nabla \cdot \mathbf{E} &= \rho - g_{a\gamma\gamma} \mathbf{B} \cdot \nabla a \,, \\
\nabla \times \mathbf{B} - \dot{\mathbf{E}} &= \mathbf{J} + g_{a\gamma\gamma} \dot{a} \mathbf{B} - g_{a\gamma\gamma} \mathbf{E} \times \nabla a \,, \\
\nabla \cdot \mathbf{B} &= 0 \,, \\
\dot{\mathbf{B}} + \nabla \times \mathbf{E} &= 0 \,.
\end{aligned}$$

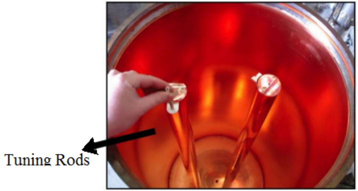
Detect axion DM with EM coupling (Sikivie 1980s)

$$\partial^2 \mathbf{E}(t,x) = g_{a\gamma\gamma}\mathbf{B}_{\rm ext}\ \underbrace{\ddot{a}(t,x)}_{\text{axion DM field}}\ , \qquad a \sim a_0\, e^{-i m_a t}$$

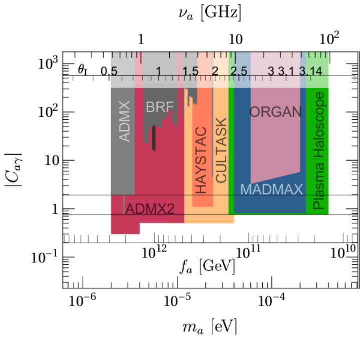


Resonant Cavity Searches

The detector must be tuned for each axion mass



ADMX collab.



Proj. Sesnsitivity. 6 yr Data

Lawson et al. 2019

Searching for axion DM in the lab is like tuning a radio

tune → listen (take data) → repeat

Narrow band search taking 10s of years to scan

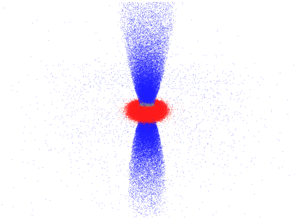
Can stars get us there quicker?

Plasma: $\omega_{\rm p}^2 = n_e/m_e$

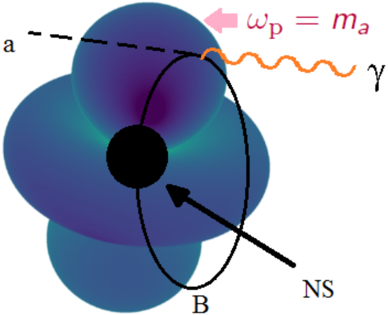
$$\partial^2\,\mathbf{E}(t,x) + \omega_{\rm p}^2\mathbf{E}(t,x) = g_{a\gamma\gamma}\mathbf{B}_{\rm ext}\underbrace{\ddot{a}(t,x)}_{\text{axion DM field}}\quad,\qquad a \sim a_0\,e^{-im_a t}$$

Resonant enhancement when $\omega_{\rm p} = m_a$.

Neutron Stars Are Surrounded by Plasma



Resonant Conversion Around Neutron Stars

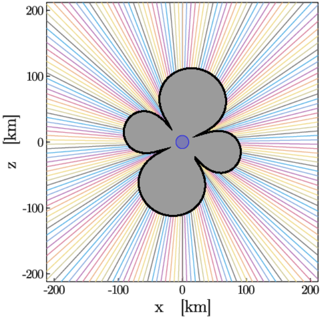


$$P_{a\to\gamma} \sim \frac{g_{a\gamma\gamma}^2 B^2}{\frac{d}{dz}(\omega_p(x_{res}))}$$

Goldreich-Julien (1960s)

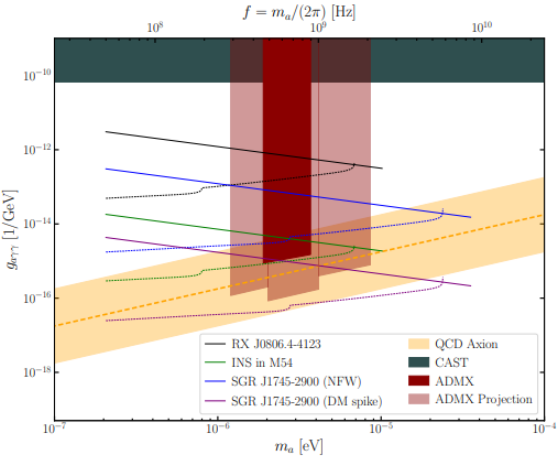
$$n_{GJ}(\mathbf{r}) = \frac{2\,\mathbf{\Omega}\cdot\mathbf{B}}{e}\frac{1}{1-\Omega^2\, r^2\, \sin^2\theta}\,, \qquad \omega_p = \sqrt{\frac{4\pi\,\alpha_{EM}\,|n_{GJ}|}{m_e}},$$

The renaissance of interest (2018) Hook et al



Radial Trajectories

One gets the following theory prediction for the sensitivity



Hook et al 2018

Very compelling

deep + broad + immediate reach in parameter space!

The race is on to properly model + take radio data

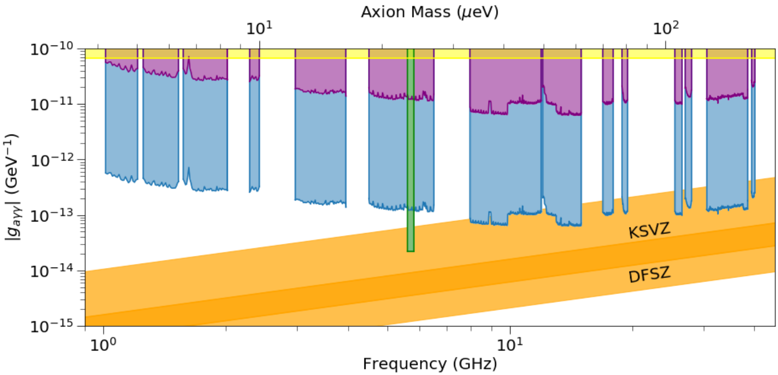
Green Bank (US)

Foster et al.
Phys.Rev.Lett. 125 (2020) 17, 171301

J. Darling
Phys.Rev.Lett. 125 (2020) 12, 121103
& Astrophys.J.Lett. 900 (2020) 2, L28

Karl J Jansky VLA

Effelsberg (Ger)



J. Darling Astrophys.J.Lett. 900 (2020) 2, L28

PSR J17452900 the first-discovered magnetar. Orbits black hole Sagittarius A^*

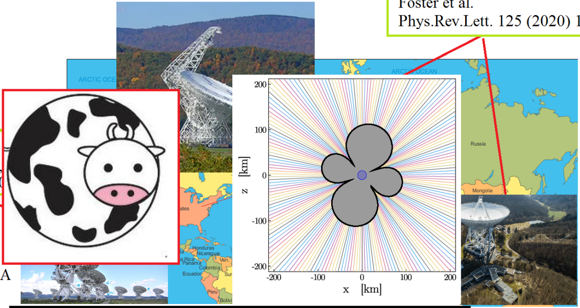
$$B \sim 10^{14} \text{Gauss}$$

State of the art theory yet to be applied!

Green Bank (US)

Foster et al.
Phys.Rev.Lett. 125 (2020) 17, 171301

J. Darling
Phys.Rev.Lett. 125 (2020) 12,
& Astrophys.J.Lett. 900 (202



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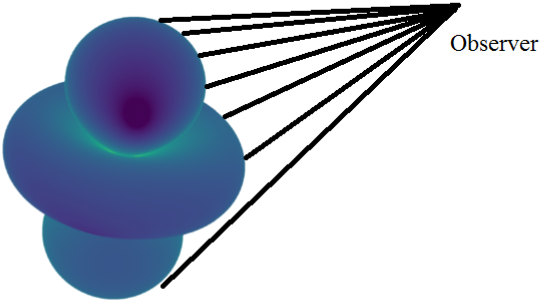
Better Modelling Needed

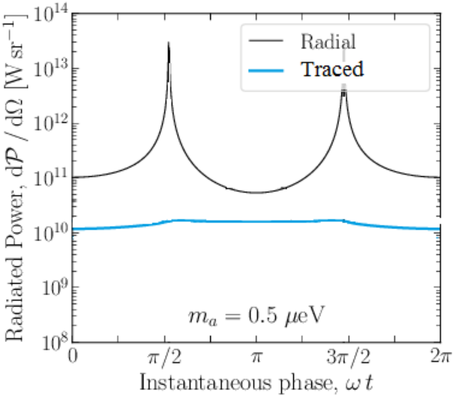
“Radio signal of axion-photon conversion in neutron stars: A ray tracing analysis”

Leroy et al Phys. Rev. D 101, 123003 (2020)



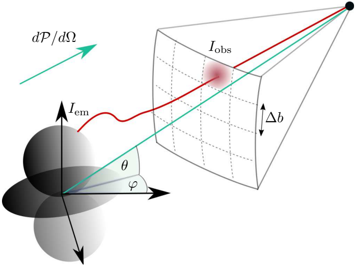
Trace straight line rays to line of sight

Pulse Profiles



Leroy et al Phys. Rev. D 101, 123003 (2020)

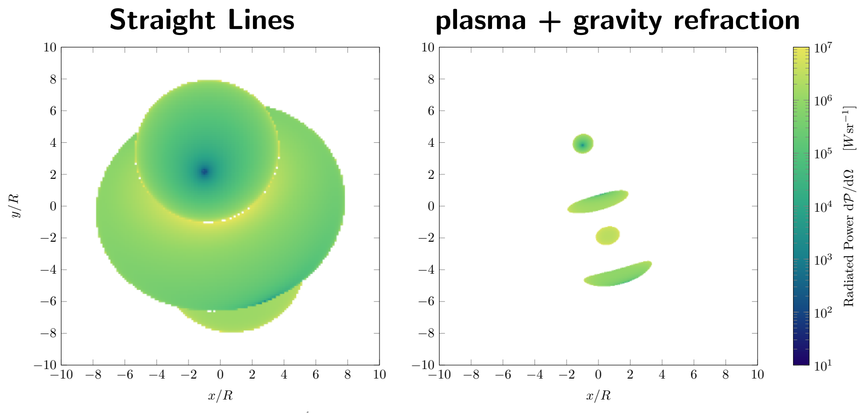
Rays are not straight lines! (this work)



Dispersion Relation: $\underbrace{g_{\mu\nu}}_{\text{gravity}} k^\mu k^\nu + \omega_{\rm p}^2 \underbrace{(t, \mathbf{x})}_{\text{inhomogeneous}} = 0$

$$\frac{d^2 x^\mu}{d\lambda^2} + \Gamma^\mu_{\nu\rho} \frac{dx^\nu}{d\lambda} \frac{dx^\rho}{d\lambda} = -\frac{1}{2} \partial^\mu \omega_{\rm p}^2 \,,$$

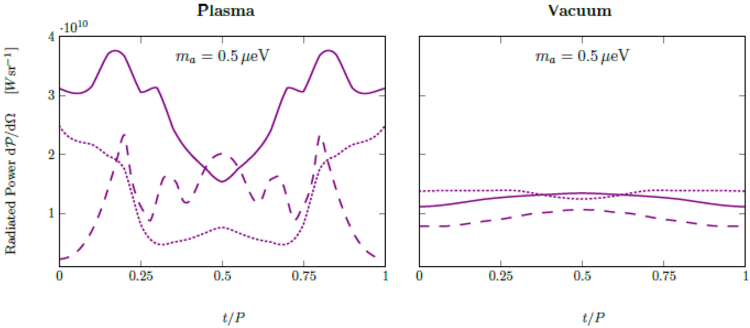
$$\frac{dx_\mu}{d\lambda} = k_\mu$$



(this work)

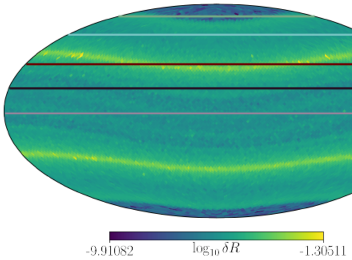
Dark matter radio emission from the star strongly lensed!

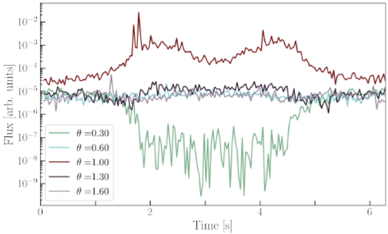
Pulse Profiles



See also...

Witte et al (hep-ph/2104.07670)





Line Shape

Naively,by conservation

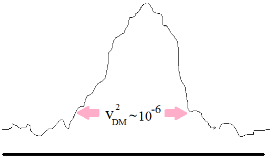
$$\omega_\gamma = E_a \simeq m_a + \frac{1}{2} m_a v_{\rm DM}^2$$

So the signal naively has

Central Frequency : $\omega_c = m_a$ **width:**$\Delta\omega/\omega_c \sim \underbrace{\Delta v_{\rm DM}^2}_{\text{vel. spread of DM}}$

So

$$f_{\rm DM}(v) \sim e^{-v^2/v_0^2}, \qquad v_0 \sim 100 \text{km/s}$$

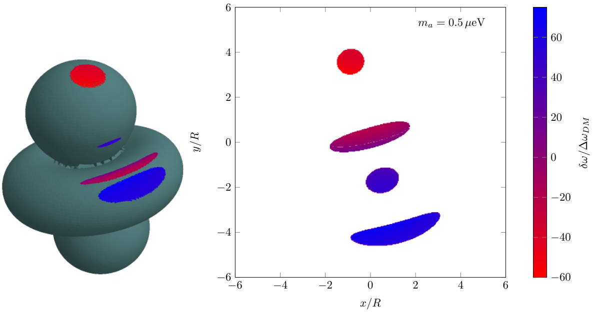


Narrower signals are easier to find

So good understanding of freq. dependence is crucial!

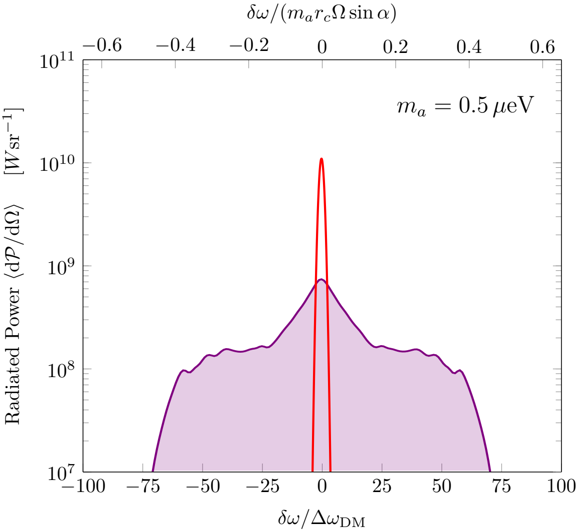
Doppler Broadening - time-dependent effects

$$\frac{d\omega(x(t),t)}{dt} = \frac{1}{2\omega}\underbrace{\partial_t \omega_{\rm p}^2(t,\mathbf{x}(t))}_{\rm t-dep\,plasma}$$



$$\delta\omega \simeq \frac{1}{2\omega}\int dt' \partial_t \omega_{\rm p}^2(t',\mathbf{x}(t'))$$

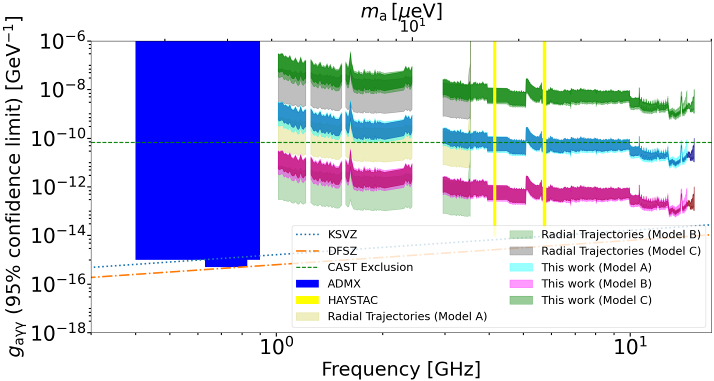
Line Shape



$\leftarrow$ **frequency** $\rightarrow$

First Constraints with Ray-Tracing from galactic centre magnetar

Battye, Darling, McDonald, Srinivasan (2021)

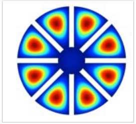


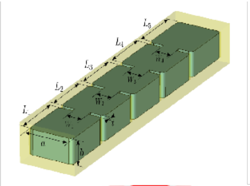
main uncertainty: DM density near galactic centre

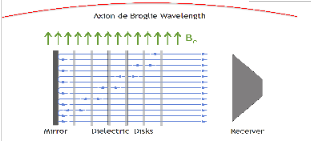
(also more work needed to better understand constraint sensitivity to magnetosphere structure)

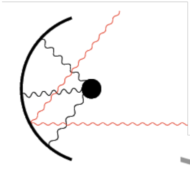
Axion Dark Matter Detection in the Lab

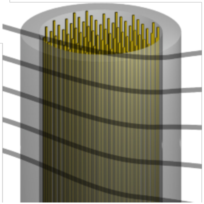
Dark Matter Detection in the Lab











There is a large **zoo** of axion dark matter detectors

Current Design Process: trial and error, flashes of inspiration?

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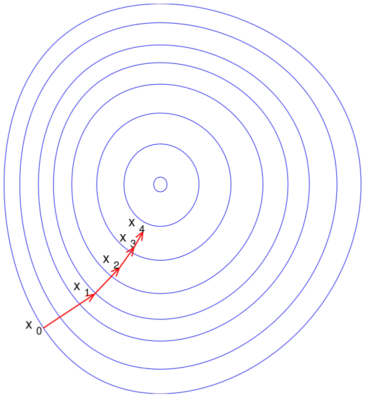
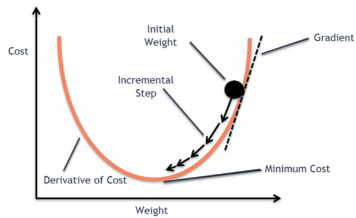
Better Design process? computer-led/gradient descent?

(**McDonald** 2108.13894)



Gradient Descent



Material Properties (X_n): permittivity, geometry, boundary conditions...

$$X_{n+1} = X_n - \gamma_n \nabla_X F(X_n)$$

Designs : X_n

learning rate : γ_n

cost/objective function: $F(X_n)$ (i.e. DM signal)

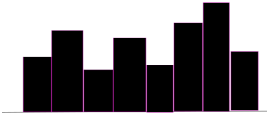
$$\nabla \cdot \mathbf{D} = -g_{a\gamma\gamma}\mathbf{B} \cdot \nabla a\,,$$
$$\nabla \times \mathbf{B} - \dot{\mathbf{D}} = g_{a\gamma\gamma}\dot{a}\mathbf{B} - g_{a\gamma\gamma}\mathbf{E} \times \nabla a\,,$$
$$\nabla \cdot \mathbf{B} = 0\,,$$
$$\dot{\mathbf{B}} + \nabla \times \mathbf{E} = 0\,,$$

$$\boxed{-\nabla^2\mathbf{E} + \nabla(\nabla \cdot \mathbf{E}) + \varepsilon \cdot \ddot{\mathbf{E}} = g_{a\gamma\gamma}\ddot{a}\mathbf{B}.}$$

Cost function F(X) : $U\Big[\Big\{\omega_{\rm p}^{(i)}\Big\}\Big] = \int dV\,\left[\partial_\omega(\omega \mathrm{Re}[\varepsilon])\,\mathbf{E}^2 + \mathbf{B}^2\right].$

X_n **designs :** $\varepsilon(\mathbf{x})$

N layer design in 1D



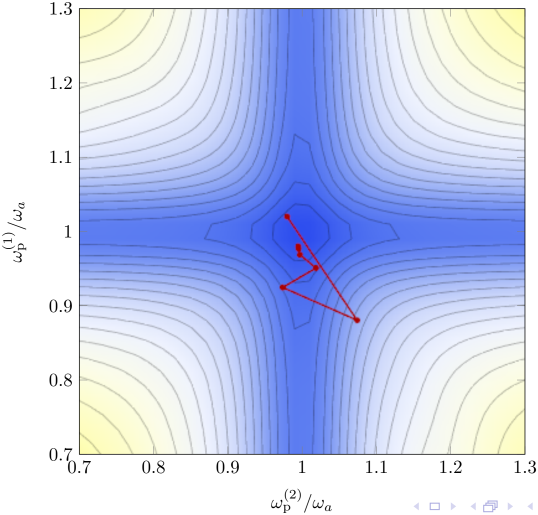
$$\varepsilon^{(i)} = 1 - \frac{\omega_{\rm p}^{(i)\,2}}{\omega^2 + i\Gamma^{(i)}\omega}, \qquad 1 \le i \le N,$$

$$-\frac{d^2 E_{\|}}{dx^2} + \omega^2 \varepsilon E_{\|} = g_{a\gamma\gamma}\omega^2 a_0 B_0,$$

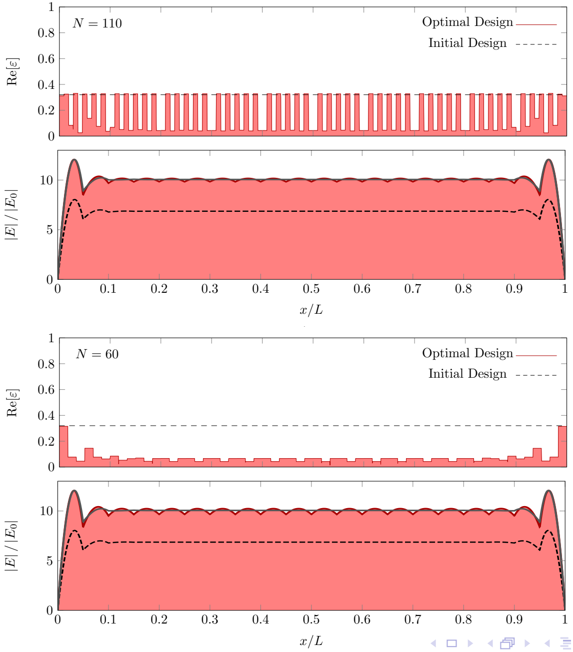
Cost Function and coordinates:

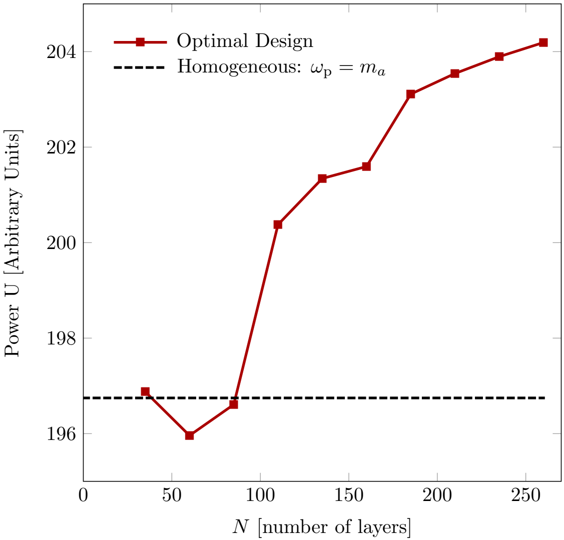
$$F[X] \equiv -U\Big[\,\Big\{\omega_{\rm p}^{(i)}\Big\}\,\Big], \qquad X = \Big\{\omega_{\rm p}^{(1)}, \cdots, \omega_{\rm p}^{(N)}\Big\}.$$

Two layer illustration



Larger Number of Layers





Optimal Design
Homogeneous: $\omega_p = m_a$
Power U [Arbitrary Units]
204
202
200
198
196
0
50
100
150
200
250
N [number of layers]

Obviously this just scratches the surface

1. Detector exterior geometry?
2. Other bulk properties: magneto-electric materials?
3. Tuneability?
4. higher dimensions?
5. more sophisticated gradient descent algorithms?

Conclusions

Neutron stars

- Good progress made in ray-tracing - future follow up work coming soon (Witte + McDonald)
- dark matter density remains uncertainty near galactic centre
- need to better understand sensitivity to magnetosphere structure

Detector designs

- extend to larger array of design properties and higher dimensions
- can one derive a mathematical upper bound?

Thanks for listening!