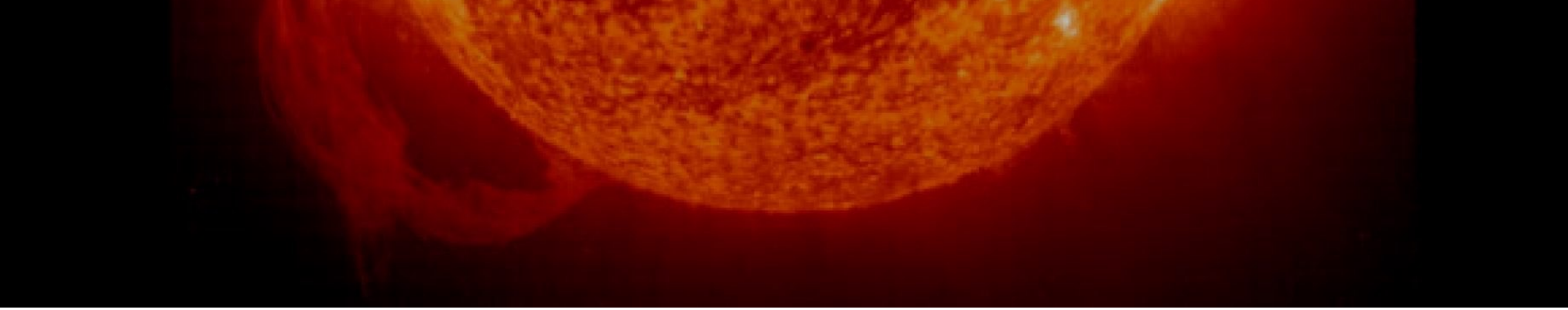
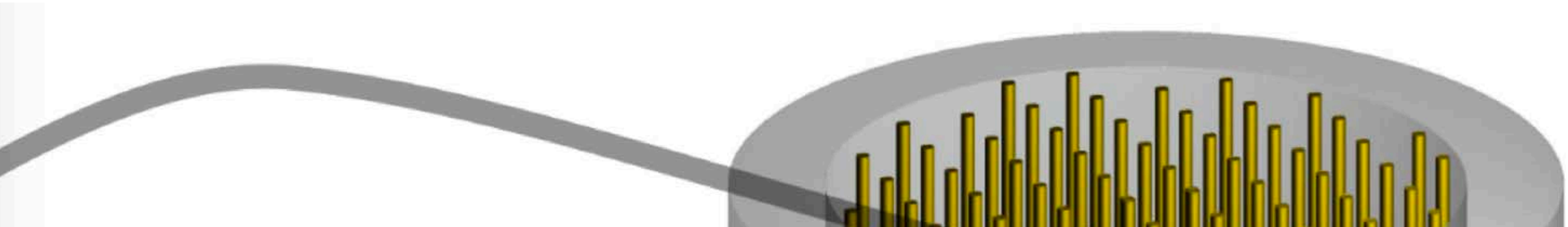


Light Dark Matter: Collective Effects in the Lab and in Stars

N3AS Seminar,
University of California, Berkeley (virtual)
March 29, 2022

Edoardo Vitagliano
edoardo@physics.ucla.edu
University of California, Los Angeles

UCLA



Credits: NASA, A.J. Millar

LDM: Collective Effects in the Lab and in Stars

I. Axion dark matter

- Solving the strong CP problem
- Why is the QCD axion a good DM candidate?

II. Plasma Haloscopes: axion detection

- From axion-photon coupling to axion-plasmon coupling
- Axion detection with nanowires: a classical calculation

III. Dark matter detection: a thermal field theory approach

- Axion detection with nanowires: TFT calculation
- Plasmon-axion mixing in stars

Conclusions

LDM: Collective Effects in the Lab and in Stars

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Time dependent

Conclusions

Axion dark matter

Axion dark matter (aka: two lessons about axions)

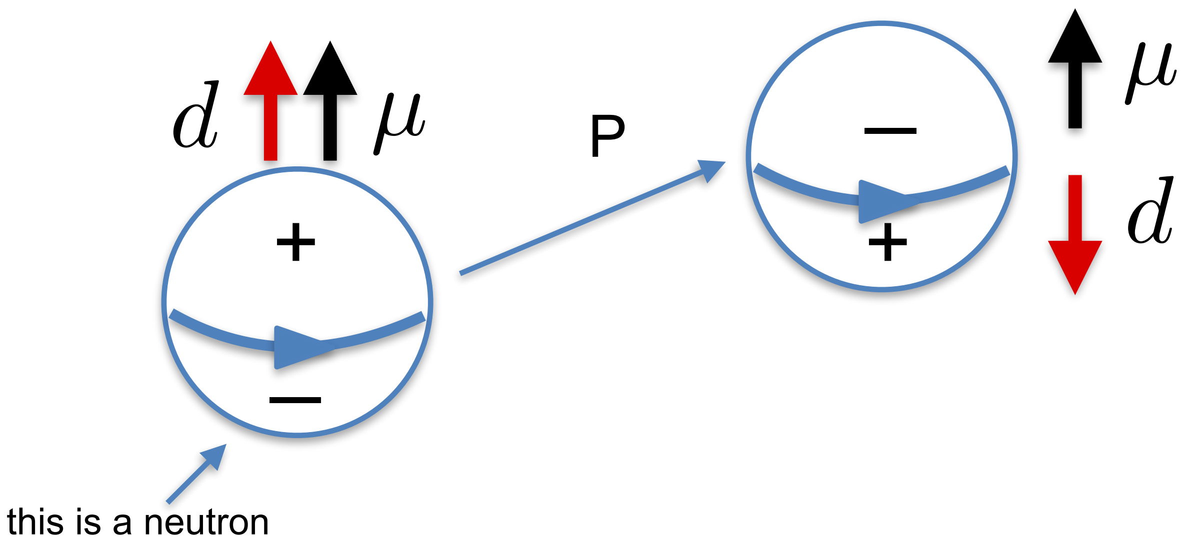
Axion dark matter (aka: two lessons about axions) (aka: how to kill two birds with one stone)

Strong CP ~~problem~~ hint

CP violation in neutrons: electric dipole moment

Strong CP ~~problem~~ hint

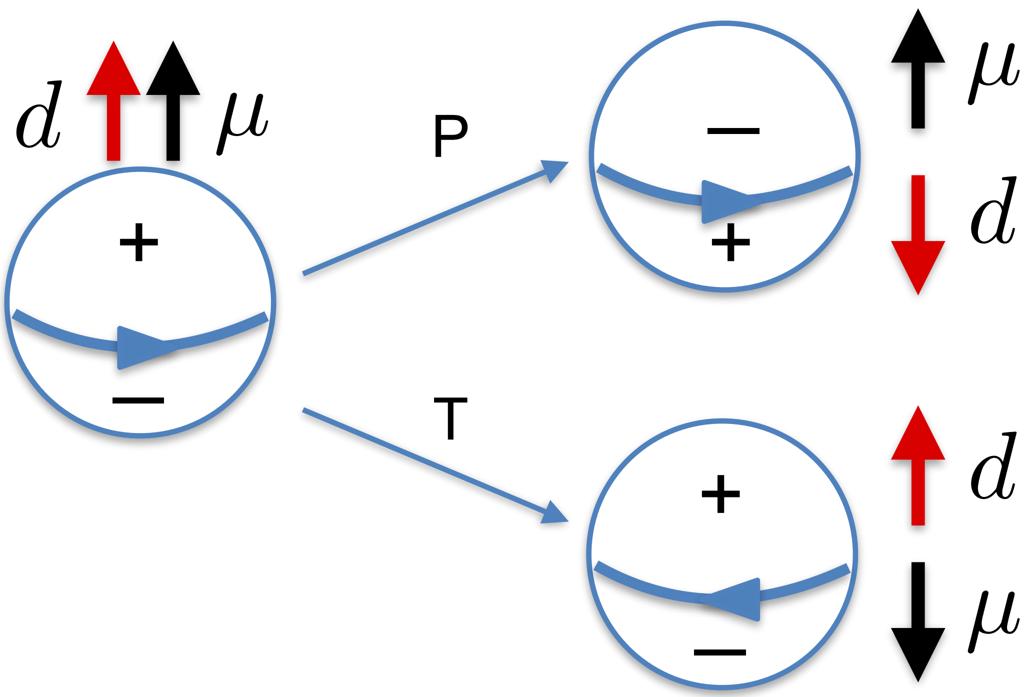
CP violation in neutrons: electric dipole moment



EDM would violate P…

Strong CP ~~problem~~ hint

CP violation in neutrons: electric dipole moment

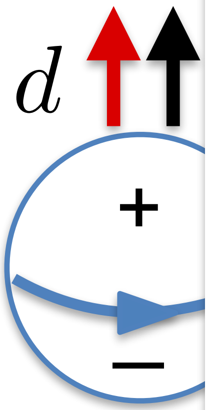


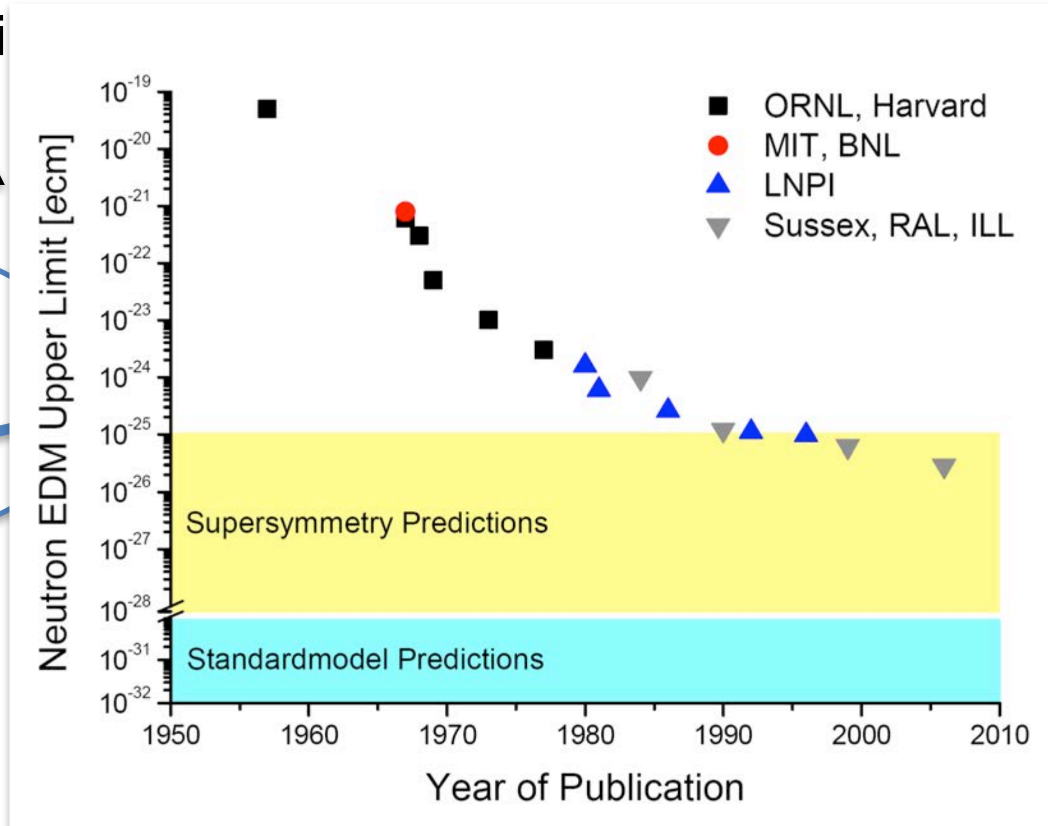
EDM would violate P…

But also T (i.e. CP)

Strong CP ~~problem~~ hint

CP violation i





ould violate P…

o T (i.e. CP)

$$|d_n| < 1.1 \times 10^{-26}\, q\,\mathrm{cm}$$

Physical Review Letters. ***124*** *(8): 081803*

It is small. Perhaps because it is not allowed…

Strong CP ~~problem~~ hint, cont'd

The Lagrangian describing hadrons is

$$\tilde{G}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}G_{\rho\sigma}$$

$$\mathcal{L}_{QCD} = \sum_q \overline{\psi}_q (i\not{D} - m_q e^{i\theta_q})\psi_q - \frac{1}{4}G^2 - \theta\frac{\alpha_s}{8\pi}G\tilde{G}$$

Real mass — Yukawa phase — CP odd

Strong CP ~~problem~~ hint, cont'd

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Remove phase by rotation finding

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$$|\bar{\theta}| < 10^{-11}$$

Strong CP ~~problem~~ hint, cont'd

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Why?

The (QCD) axion

UCLA

Introduce a global symmetry spontaneously broken at some high scale f_a, the Peccei-Quinn symmetry

$$\mathcal{L}_{QCD} = \sum_q \overline{\psi}_q (i\not{D} - m_q)\psi_q - \frac{1}{4}G^2 - \bar{\theta}\frac{\alpha_s}{8\pi}G\tilde{G}$$

$$\left.\begin{array}{l} \left.\begin{array}{l} q_L \to e^{-i\alpha/2} q_L \\ q_R \to e^{+i\alpha/2} q_R \end{array}\right\} U(1)_{\mathrm{chiral}} \\ m_q \to m_q e^{-i\alpha} \end{array}\right\} U(1)_{PQ}$$

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Lesson 1
After the SSB, we have a pseudo Goldstone boson rotating the angle away

STRONG CP PROBLEM SOLVED ✓

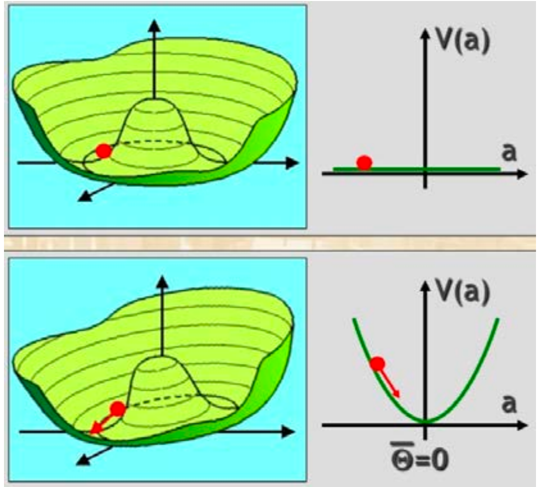
The (QCD) axion is massive

UCLA

Lesson 1, cont'd
The same rotation gives a mass to the axion (w/ two quarks)

$$m_a^2 = \frac{m_u m_d}{m_u + m_d} \frac{\langle \bar{u} u \rangle}{f_a^2}$$

In other words, give enough time to the universe and it relax to a CP conserving QCD Lagrangian*



*your mileage may vary

Axion cosmology in a nutshell

UCLA

Suppose PQ is broken before inflation. The axion field is homogeneous

$$\ddot{a} + 3H\dot{a} + \frac{\partial V}{\partial a} = 0 \qquad \text{where} \qquad H = \frac{\dot{R}}{R} \qquad V = m_a^2 a$$

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After being a damped harmonic oscillator, it becomes

$$\ddot{a} \simeq -m_a^2 a \quad \longrightarrow \quad a \simeq \left[\frac{R(H \sim m_a)}{R(t)}\right]^{3/2} a_0 \cos m_a t$$

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Including an additional temperature dependence

$$a \simeq \theta_0 f_a \sqrt{\frac{m_a(T_C)}{m_a(T)}} \left[\frac{R(H \sim m_a)}{R(t)}\right]^{3/2} a_0 \cos m_a t \qquad \rho_a = \frac{1}{2} m_a^2 a^2$$

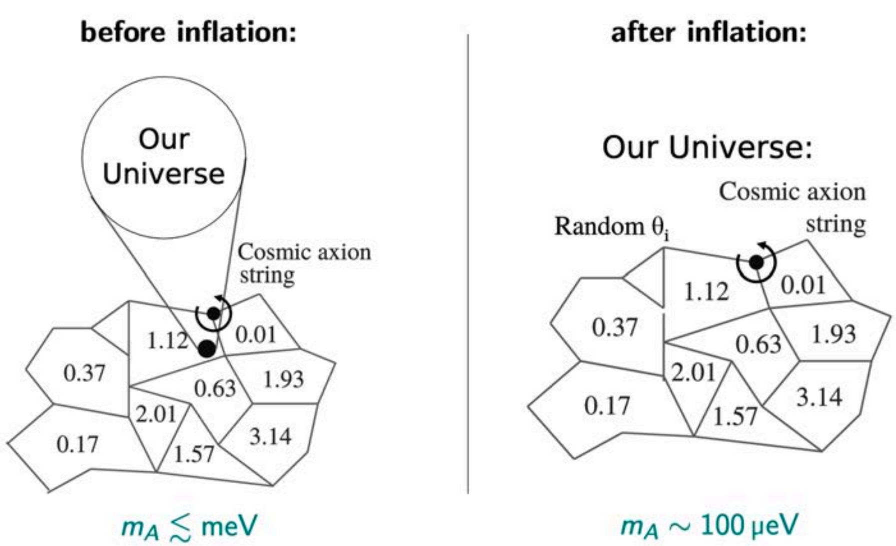
Lesson 2
Axion can be a dark matter candidate

DM MISTERY SOLVED ✓

QCD Axion cosmology in a nutshell

UCLA

(If broken after inflation, more axions produced from cosmic strings and domain walls)



Credit: S.Knirck

On QCD axion GW and axion production: Sikivie 1982, Chang et al. hep-ph/9808302, hep-ph/9807374, Hiramatsu et al 1002.1555, 1309.5001, 1207.3166. Ask for additional bibliography on the topic of axions from strings
On N=1 ALPs: Gorghetto et al. 2101.11007

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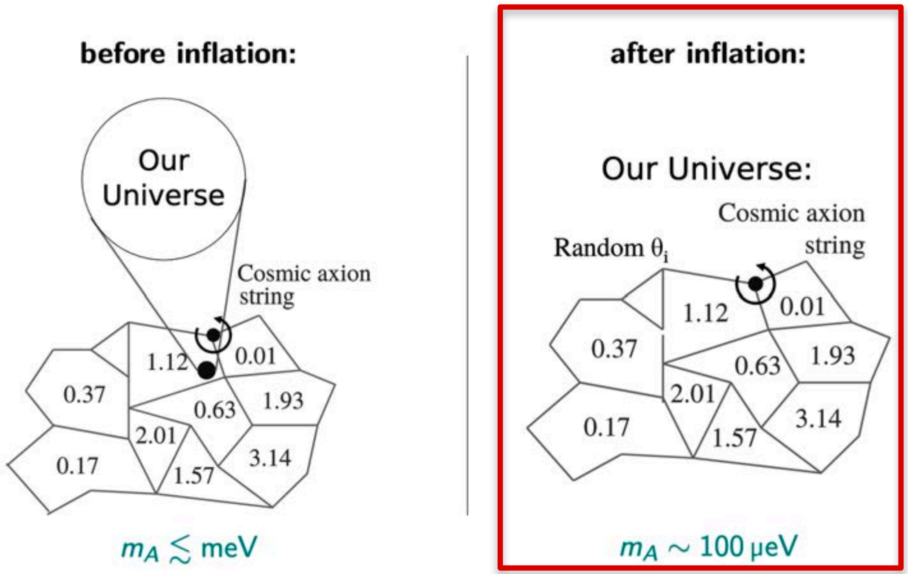

Credit: S.Knirck

New QCD axion detection ideas!

Examples:

- MADMAX, *Phys.Rev.Lett.* 118 (2017) 9, 091801
- Plasma haloscope (Lawson, Millar, Pancaldi, **EV**, Wilczek), *Phys.Rev.Lett.* 123 (2019) 14, 141802

On QCD axion GW and axion production: Sikivie 1982, Chang et al. hep-ph/9808302, hep-ph/9807374, Hiramatsu et al 1002.1555, 1309.5001, 1207.3166. Ask for additional bibliography on the topic of axions from strings
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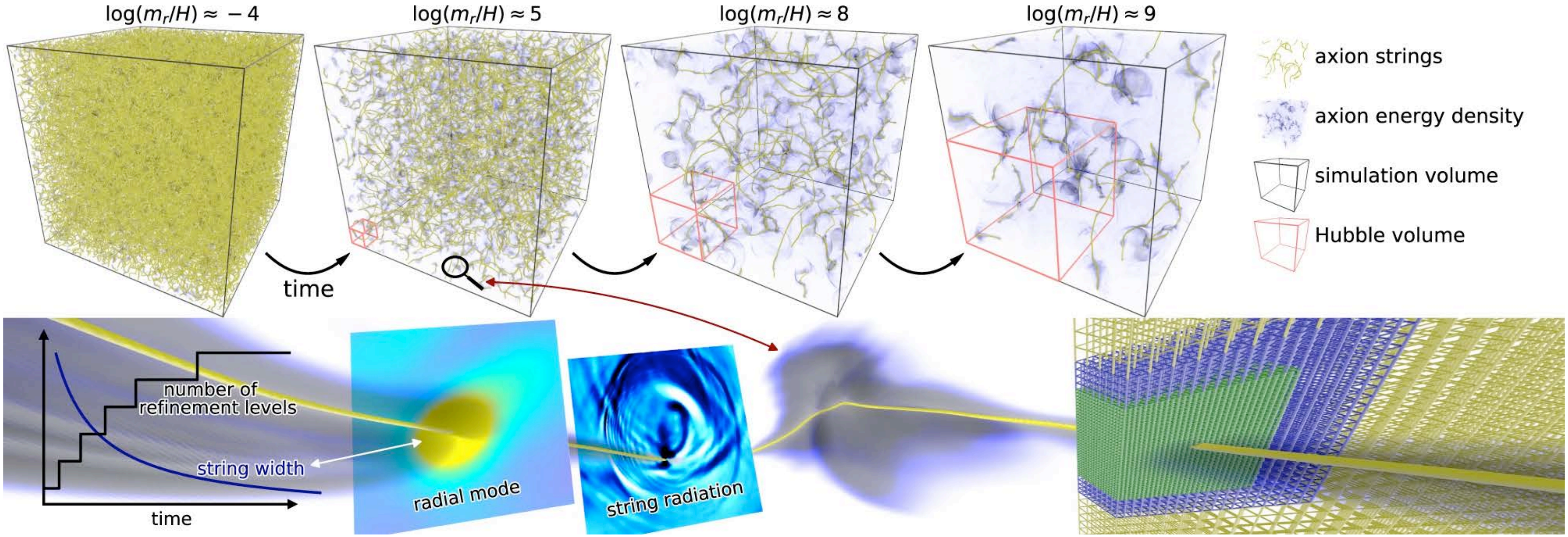


Buschmann et al., *Nature Communications* **volume 13**, Article number: 1049 (2022)

Latest results: $40 \lesssim m_a/\mu\text{eV} \lesssim 180$

How to detect the axion

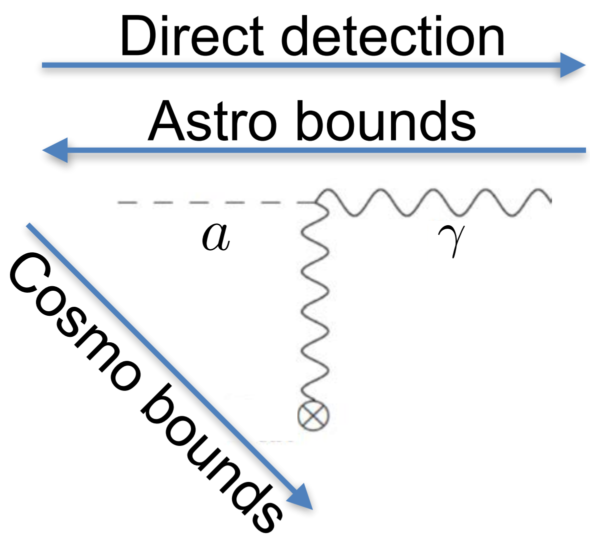
Axion searches (bird's eye)

UCLA

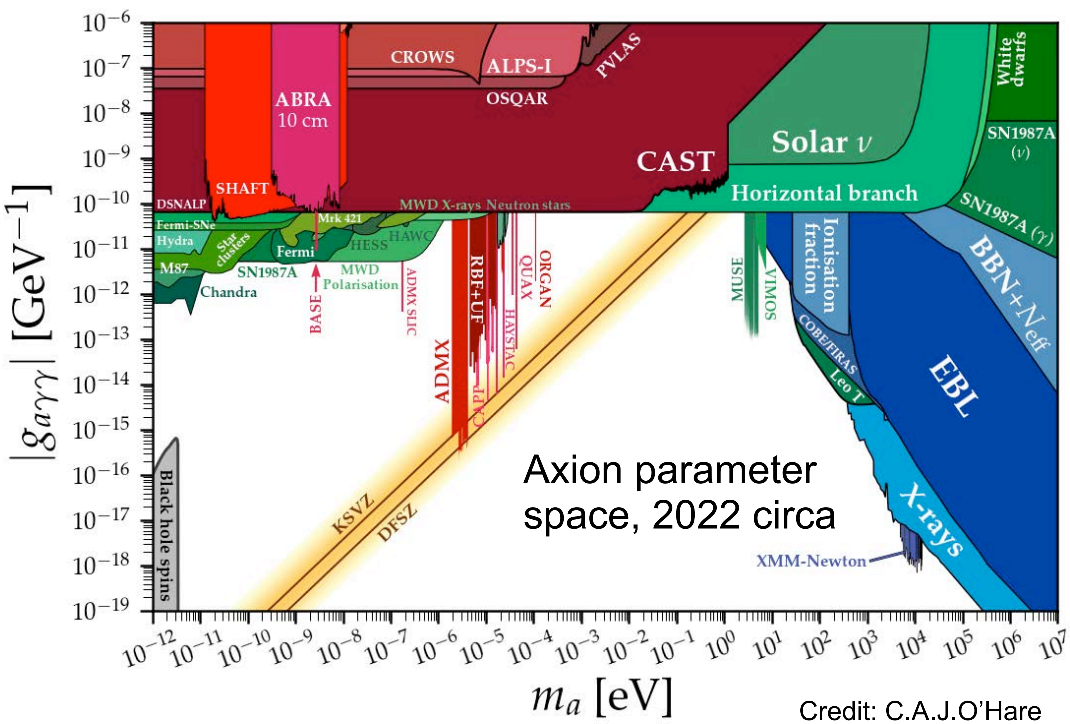
The QCD axion solves the strong CP problem and is a good DM candidate. How to detect it?

$$\mathcal{L} = -\frac{1}{4} g_{a\gamma} a F\tilde{F} = g_{a\gamma} a\, \mathbf{E}\cdot\mathbf{B}$$

(model dependent)



Primakoff effect



Credit: C.A.J.O'Hare

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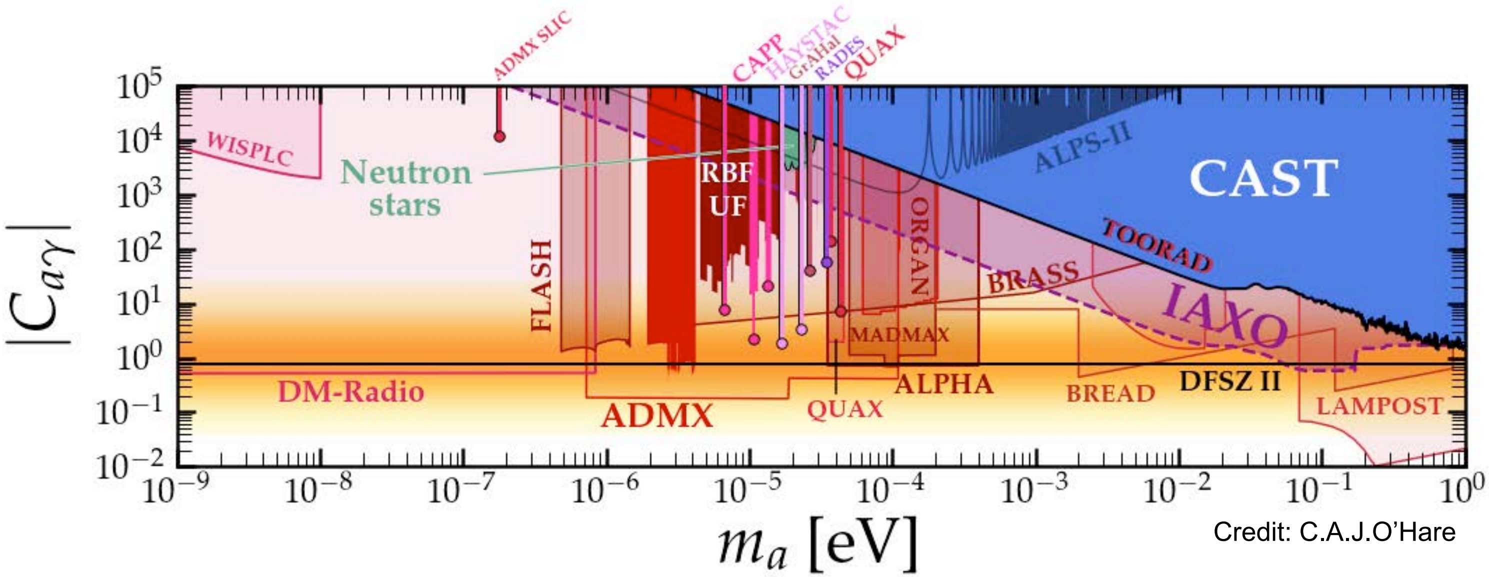

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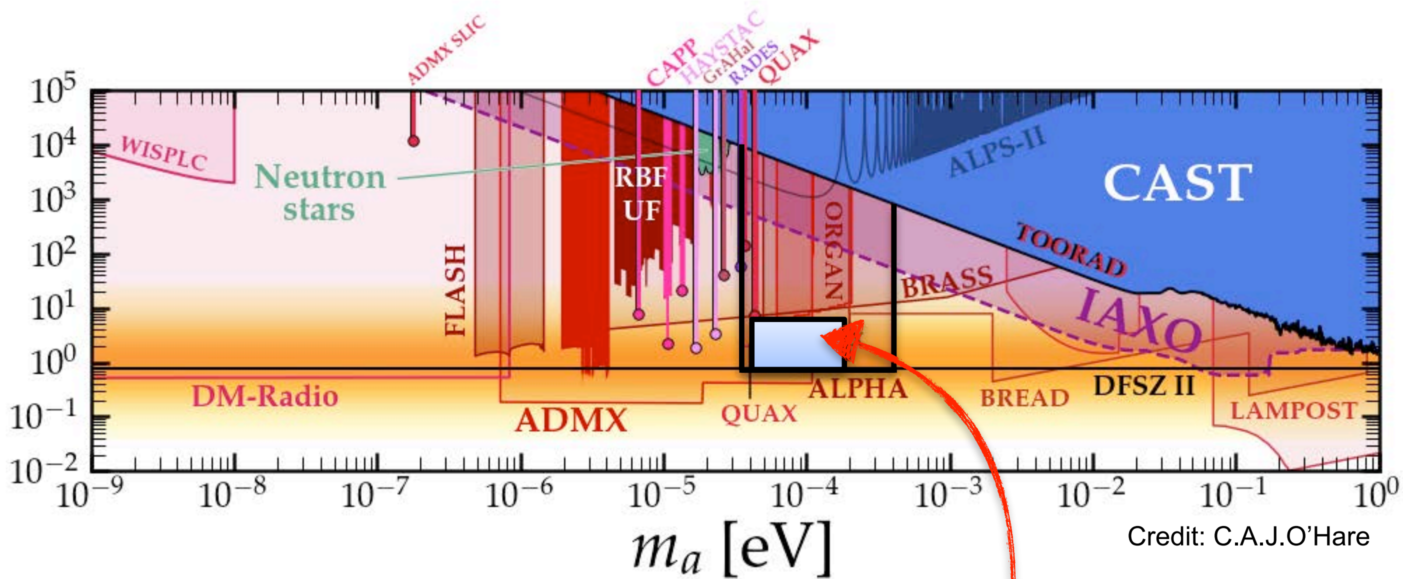


Credit: C.A.J.O'Hare

$$g_{a\gamma} = -\frac{\alpha}{2\pi f_a} C_{a\gamma}$$

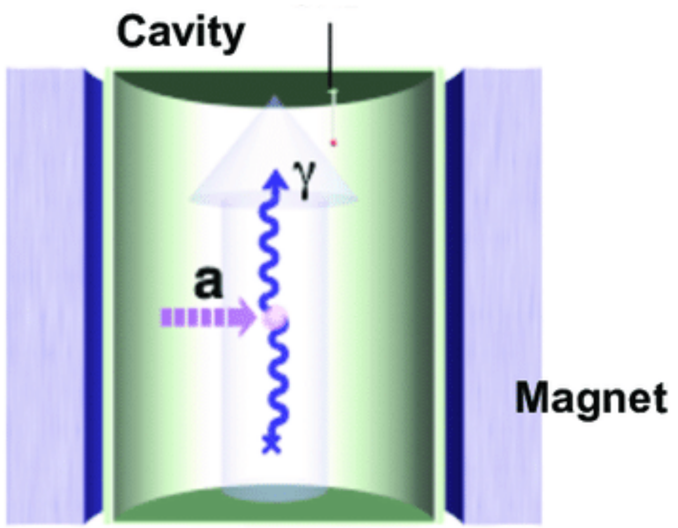
Latest predictions post-inflationary scenario

From axion-photon to axion-plasmon

UCLA

Axion DM is slow and massive. We need to correct for the energy-momentum conservation

In cavity searches,
the cavity size~Compton wavelength. But as they become more massive, it is prohibitive



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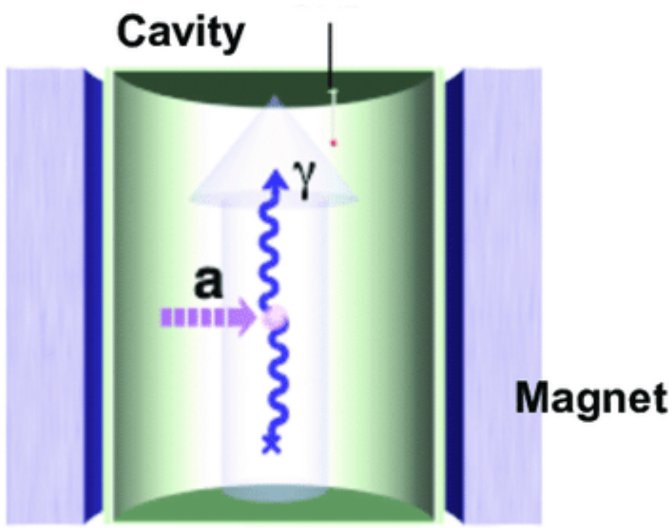

Alternative:

In a medium, photons are “massive” with mass=plasma frequency!
The basic idea of tunable plasma haloscopes:

$$\omega_{pl} = m_a$$

Axion detection in a medium

UCLA

Two equivalent descriptions:

- Maxwell equations in a medium
- Thermal field theory

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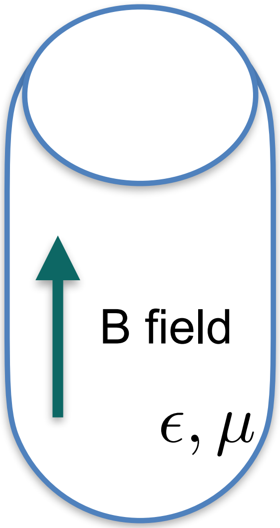
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - j^\mu A_\mu + \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}m_a^2 a^2 - \frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

The axion field is $a(t) = a_0 e^{-im_a t}$ which modifies the Maxwell equations

$$\nabla \times \mathbf{H} - \dot{\mathbf{D}} = g_{a\gamma}\mathbf{B}\dot{a}$$

$$\mathbf{D} = \epsilon \mathbf{E}$$
$$\mathbf{H} = \mathbf{B}/\mu$$



(Drude model)

Axion detection in a medium

Two equivalent descriptions:

- Maxwell equations in a medium
- Thermal field theory

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - j^\mu A_\mu + \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}m_a^2 a^2 - \frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

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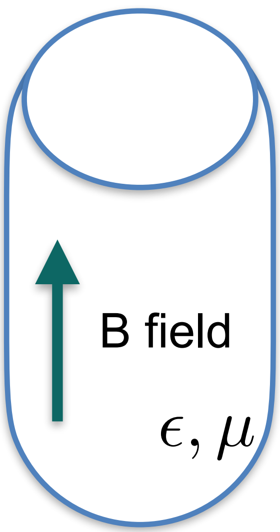

$$\mathbf{E} = -\frac{g_{a\gamma}\mathbf{B}a}{\epsilon} = -g_{a\gamma}\mathbf{B}a\left(1 - \frac{\omega_{pl}^2}{\omega_a^2 - i\omega_a\Gamma}\right)^{-1}$$

Dielectric function

Damping rate

Where we have used $\epsilon = 1 - \dfrac{\omega_{pl}^2}{\omega_a^2 - i\omega_a\Gamma}$ (Drude model)

Wire metamaterial

UCLA

We have a resonance! We need the damping (resistivity) to be low, and the plasma frequency must be tunable

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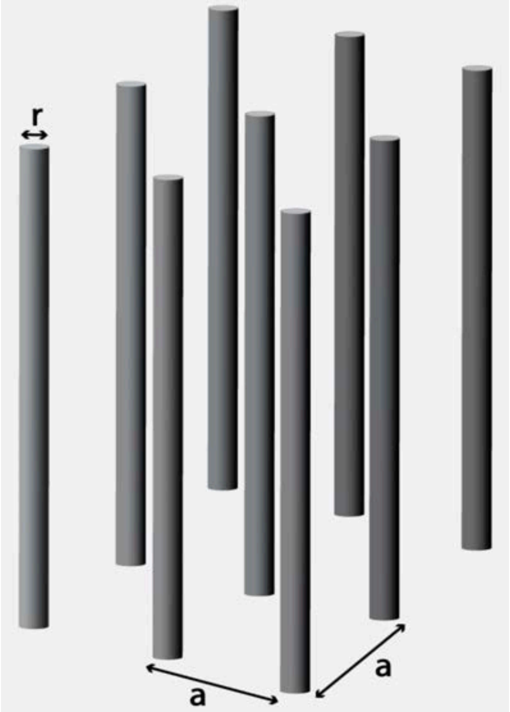
Pendry et al. J. Phys. Condens. Matter 10, 1998

Possible ideas: semiconductors, Josephson junctions, wire metamaterials



Credit: A. Millar

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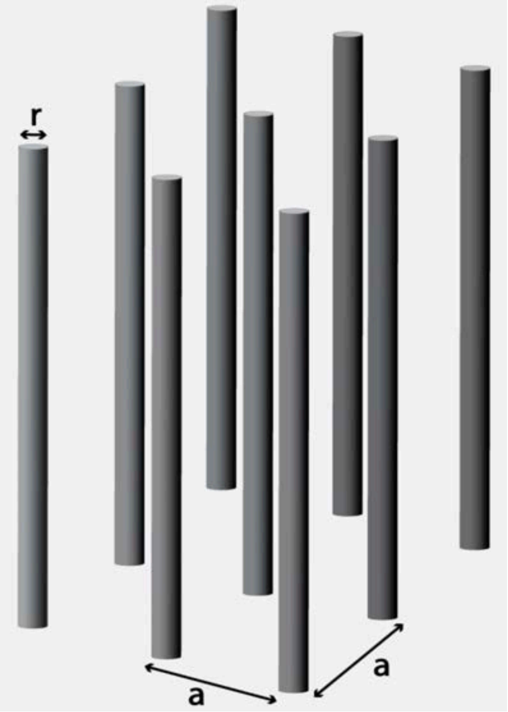
In a usual metal,

$$\omega_{pl}^2 = \frac{e^2 n_e}{m_e}$$



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Possible ideas: semiconductors, Josephson junctions, wire metamaterials

In a usual metal,

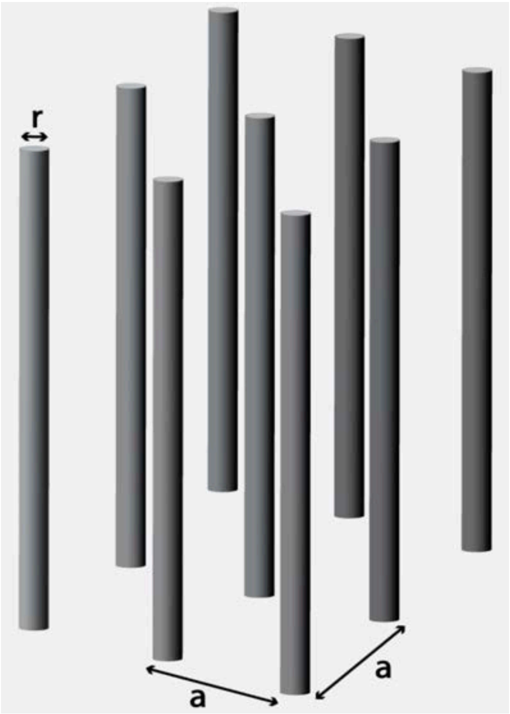
$$\omega_{pl}^2 = \frac{e^2 n_e}{m_e}$$

but in a nanowire system

$$n_e = \frac{n_{\text{metal}}\pi r^2}{a^2}$$ ← less charges

$$m_{eff} = \frac{e^2\pi r^2 n_{\text{metal}}}{2\pi}\log\frac{a}{r}$$ ← effective mass

$$\omega_{pl}^2 = \frac{e^2 n_e}{m_{\text{eff}}} = \frac{2\pi}{a^2\log a/r}$$



Credit: A. Millar

Setup

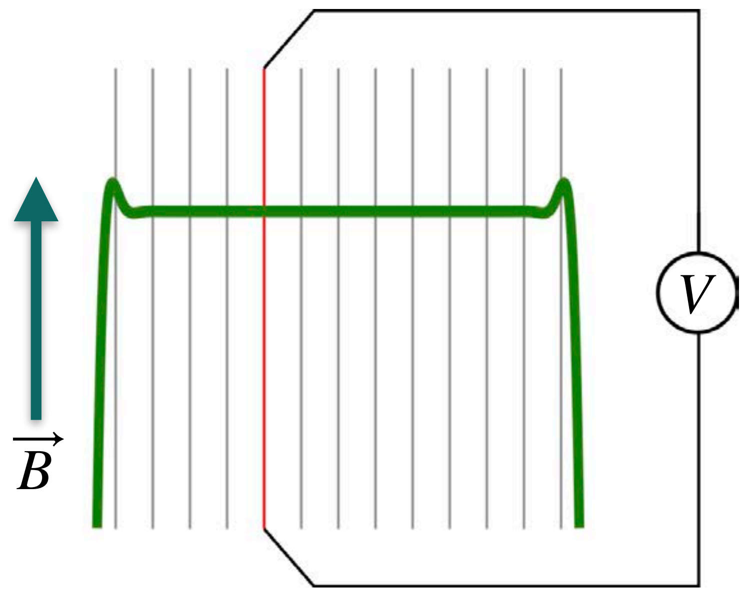
UCLA

The axion generates an electric field

$$\mathbf{E} = -\frac{g_{a\gamma}\mathbf{B}a}{\epsilon} = -g_{a\gamma}\mathbf{B}a\left(1 - \frac{\omega_{pl}^2}{\omega_a^2 - i\omega_a\Gamma}\right)^{-1}$$

$$\log a/r \gg 1 \begin{cases} r = 10\mu m \\ a = 3mm \end{cases}$$

$$\omega_{pl}^2 = \frac{e^2 n_e}{m_{\text{eff}}} = \frac{2\pi}{a^2 \log a/r} \simeq (100\,\text{GHz})^2$$



- Copper wires
- Strong magnetic field (solenoid is fine!)
- Not limited by size
- Tunability

Projected reach

UCLA

Loss rate

$$P = \Gamma U = \kappa \Gamma \frac{1}{4} \int \left(\frac{\partial(\epsilon\omega)}{\partial\omega} |\mathbf{E}|^2 + |\mathbf{B}|^2) \right) dV$$
$$= \kappa \mathcal{G} V \frac{Q}{m_a} \rho_a g_{a\gamma}^2 B^2$$

where we used

$Q = \frac{\omega}{\Gamma}$ Quality factor

$\mathcal{G} = \frac{\epsilon_z^2}{a_0^2 g_{a\gamma}^2 B_e^2 V} \frac{1}{2} \int \left(\frac{\partial(\epsilon_z\omega)}{\partial\omega} |\mathbf{E}|^2 + |\mathbf{B}|^2 \right) dV$ "geometric factor", goes to 1

κ signal coupling efficiency factor

$\rho_a = \frac{1}{2} m_a^2 a_0^2$

Scan rate

$$P = \Gamma U = \kappa \Gamma \frac{1}{4} \int \left(\frac{\partial(\epsilon\omega)}{\partial\omega} |\mathbf{E}|^2 + |\mathbf{B}|^2) \right) dV$$

$$= \kappa \mathcal{G} V \frac{Q}{m_a} \rho_a g_{a\gamma}^2 B^2$$

Dicke's equation

$$\frac{S}{N} = \frac{P}{T_{\rm sys}} \sqrt{\frac{\Delta t}{\Delta \omega_a}} > 3$$

We can use a set of reasonable parameters

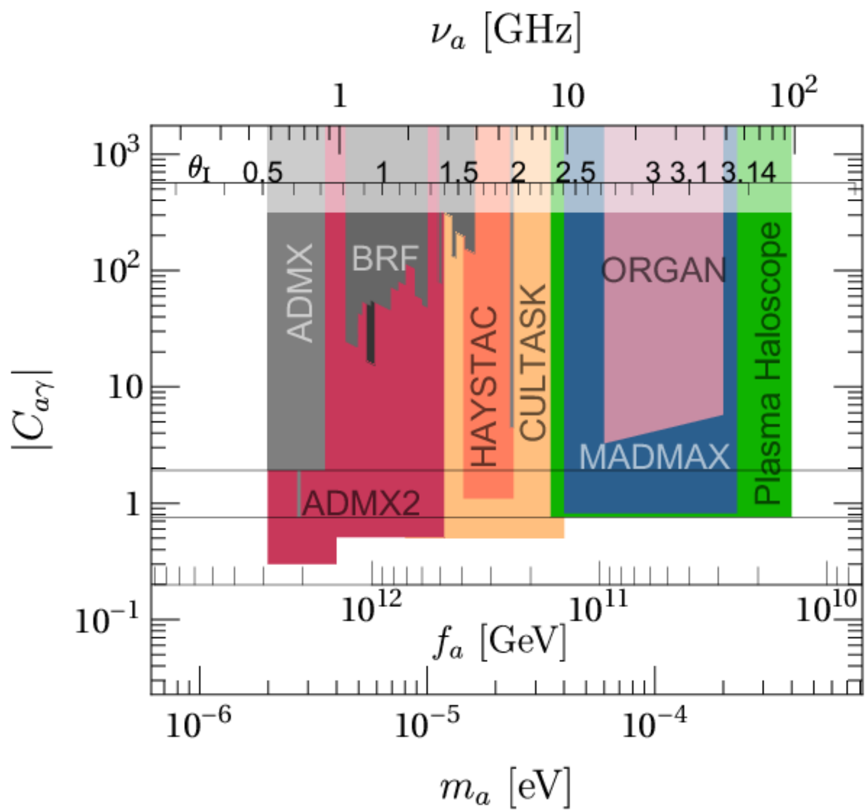
$$Q = 10^2$$

$$V = 0.8\, m^3$$

$$\Delta\omega_a = 10^{-6} m_a$$

$$B = 10\,\mathrm{T}$$

$$T_{\rm sys} = m_a$$



Lawson, Millar, Pancaldi, **Vitagliano**, Wilczek (2019)
Gelmini, Millar, Takhistov, **Vitagliano** (2020)

Featured in Physics | Editors' Suggestion | Open Access

Tunable Axion Plasma Haloscopes

Matthew Lawson, Alexander J. Millar, Matteo Pancaldi, Edoardo Vitagliano, and Frank Wilczek
Phys. Rev. Lett. **123**, 141802 – Published 1 October 2019

Physics See Synopsis: A New Plasma-Based Axion Detector

From coverage to the experiment

UCLA

TROVATO UN NUOVO MODO PER "SENTIRE" LA DARK MATTER

Sintonizzatevi su radio assione

I fisici dell'Università di Stoccolma e del Max Planck Institute for Physics

OCTOBER 9, 2019

Physicists report a way to 'hear' dark matter

WHAT'S THE FREQUENCY, KENNETH? —

Physicists propose listening for dark matter with plasma-based "axion radio"

Axions inside a strong magnetic field will generate a small electric field.

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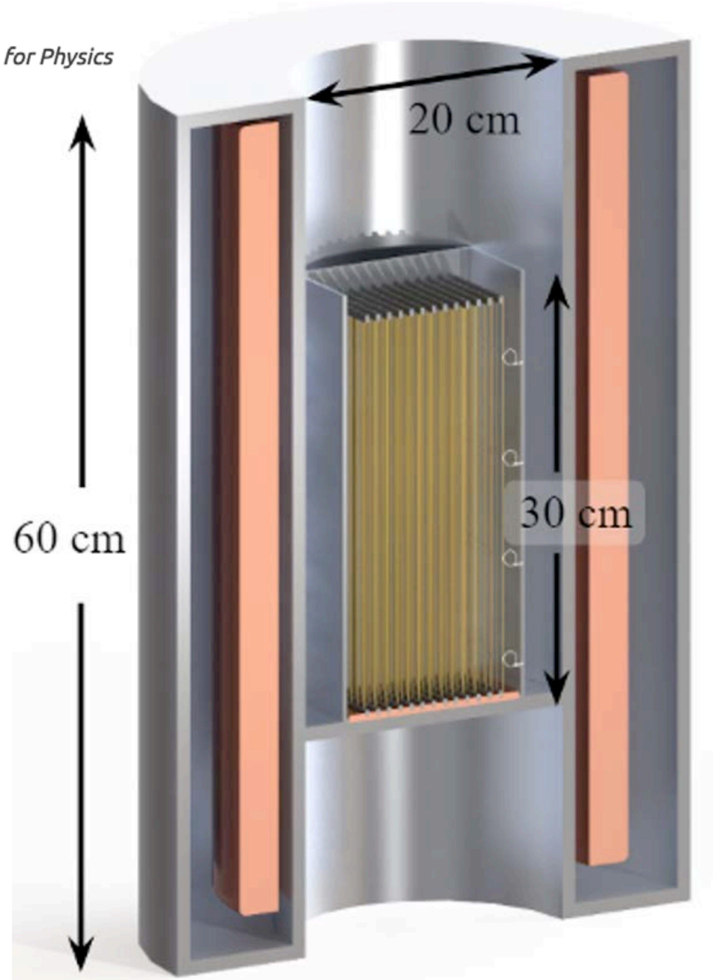
SYNOPSIS

A New Plasma-Based Axion Detector

October 1, 2019 • *Physics* 12, s111

A proposed device could detect the hypothesized dark matter particle in a mass regime not probed by other devices.



alpha

Axion **L**ongitudinal **P**lasmon **HA**loscope

Stockholm University, UC Berkeley, MIT,
ITMO, the University of Arizona, Cambridge,
the University of Maryland and UC Davis

https://axiondm.fysik.su.se/alpha/

Dark matter detection: a TFT approach

Crash course in thermal field theory

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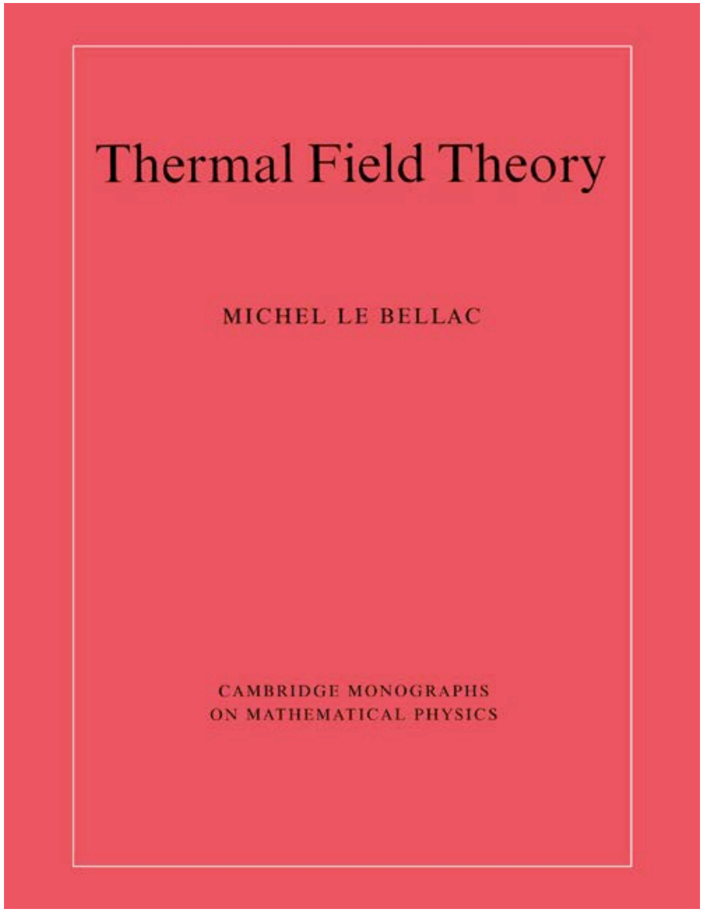


See also: Weldon (1983), Redondo and Raffelt (2013), An, Pospelov and Pradler (2013), Hardy and Lasenby (2016)

Crash course in thermal field theory

Thermal field theory is very similar to zero temperature QFT.

The imaginary part of a particle self energy

$$\mathrm{Im}\,\Pi = -\omega\Gamma$$

gives the rate with which a distribution of particles goes to equilbrium. For bosons

$$\Gamma = \Gamma_{\mathrm{abs}} - \Gamma_{\mathrm{prod}}$$

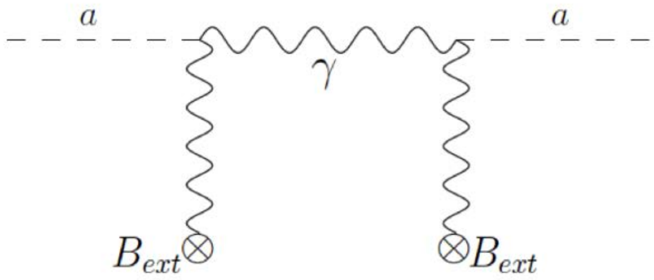
$$\frac{\partial f}{\partial t} = -f\Gamma_{\mathrm{abs}} + (1+f)\Gamma_{\mathrm{prod}}$$

This is analogous to the optical theorem in QFT, the imaginary part of the self energy is related to the decay rate

Crash course in thermal field theory

$$\frac{\partial f}{\partial t} = -f\Gamma_{\text{abs}} + (1+f)\Gamma_{\text{prod}}$$

Suppose we have two particles that can be converted into each other (so there is mixing)



Two cases:

- Many axions, no photons (laboratory)
- Many photons, no axions (stars)

DM detection w/ thermal field theory

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The power deposited in the detector is

$$P = V_d \int \frac{d^3\mathbf{k}}{(2\pi)^3}\, \omega \Gamma^X_{\rm abs}$$

The master equations for axions and plasmons are

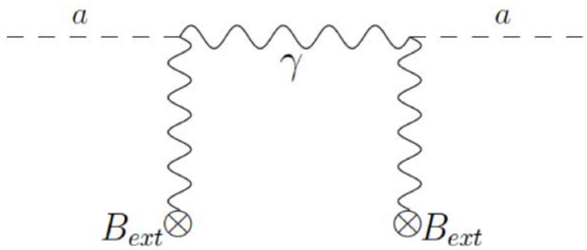
$$\frac{\partial f_a}{\partial t} \simeq -f_a \Gamma^{\rm axion}$$

$$\frac{\partial f_\gamma}{\partial t} = -f_\gamma \Gamma^{\rm axion}_{\rm prod} + (1+f_\gamma)\Gamma^{\rm axion}_{\rm abs}$$

Equilibrium is reached when $\Gamma^{\rm axion}_{\rm abs} \simeq (f_a - f_\gamma)\Gamma^{\rm axion} \simeq -f_a \frac{{\rm Im}\Pi_{\rm axion}}{\omega}$

SO we just need to compute the imaginary part of the polarization tensor!

DM detection w/ thermal field theory



The self energy of an axion is

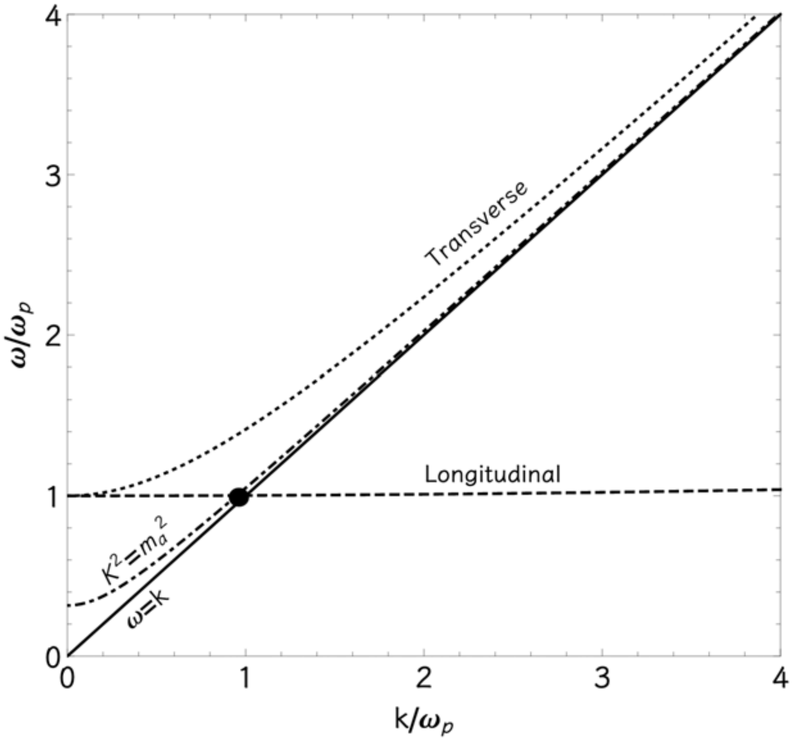
$$\Pi_{\rm axion} = m_a^2 + K^2 g_{a\gamma}^2 B_{||}^2 \frac{1}{K^2 - \Pi_{\gamma,L}(K)} + \omega^2 g_{a\gamma}^2 B_{\perp}^2 \frac{1}{K^2 - \Pi_{\gamma,T}(K)},$$

The dispersion relation of the plasmon is

$$\omega^2 - k^2 = {\rm Re}\,\Pi_{\rm T,L}$$

$${\rm Re}\,\Pi_T = \omega_p^2,$$

$${\rm Re}\,\Pi_L = \frac{K^2}{\omega^2}\omega_p^2, \qquad \omega_p = e^2 \frac{n_e}{m_e^2}$$



DM detection w/ thermal field theory

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The power deposited in the detector is

$$P = V_d \int \frac{d^3\mathbf{k}}{(2\pi)^3}\, \omega \Gamma_{\rm abs}^X$$

Using $\Gamma_T = \Gamma_L \equiv \Gamma_\gamma$ we have

$$\Gamma_{\rm abs}^{\rm axion} = f_a \frac{g_{a\gamma}^2 B^2}{\Gamma_\gamma} \qquad f_a = N(2\pi)^3 \delta^3(\mathbf{k})$$

$$P = V \int \frac{d^3\mathbf{k}}{(2\pi)^3} \omega \Gamma_{\rm abs}^{\rm axion} = g_{a\gamma}^2 B^2 \frac{Q}{\omega} V \rho_a$$

DM detection w/ thermal field theory

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Projected reach

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Loss rate

$$P = \Gamma U = \kappa\Gamma\frac{1}{4}\int\left(\frac{\partial(\epsilon\omega)}{\partial\omega}|\mathbf{E}|^2 + |\mathbf{B}|^2)\right)dV$$
$$= \kappa\mathcal{G}V\frac{Q}{m_a}\rho_a g_{a\gamma}^2 B^2$$

where we used

$Q = \frac{\omega}{\Gamma}$ Quality factor

$\mathcal{G} = \frac{\epsilon_z^2}{a_0^2 g_{a\gamma}^2 B_e^2 V}\frac{1}{2}\int\left(\frac{\partial(\epsilon_z\omega)}{\partial\omega}|\mathbf{E}|^2 + |\mathbf{B}|^2\right)dV$ "geometric factor", goes to 1

κ signal coupling efficiency factor

$\rho_a = \frac{1}{2}m_a^2 a_0^2$

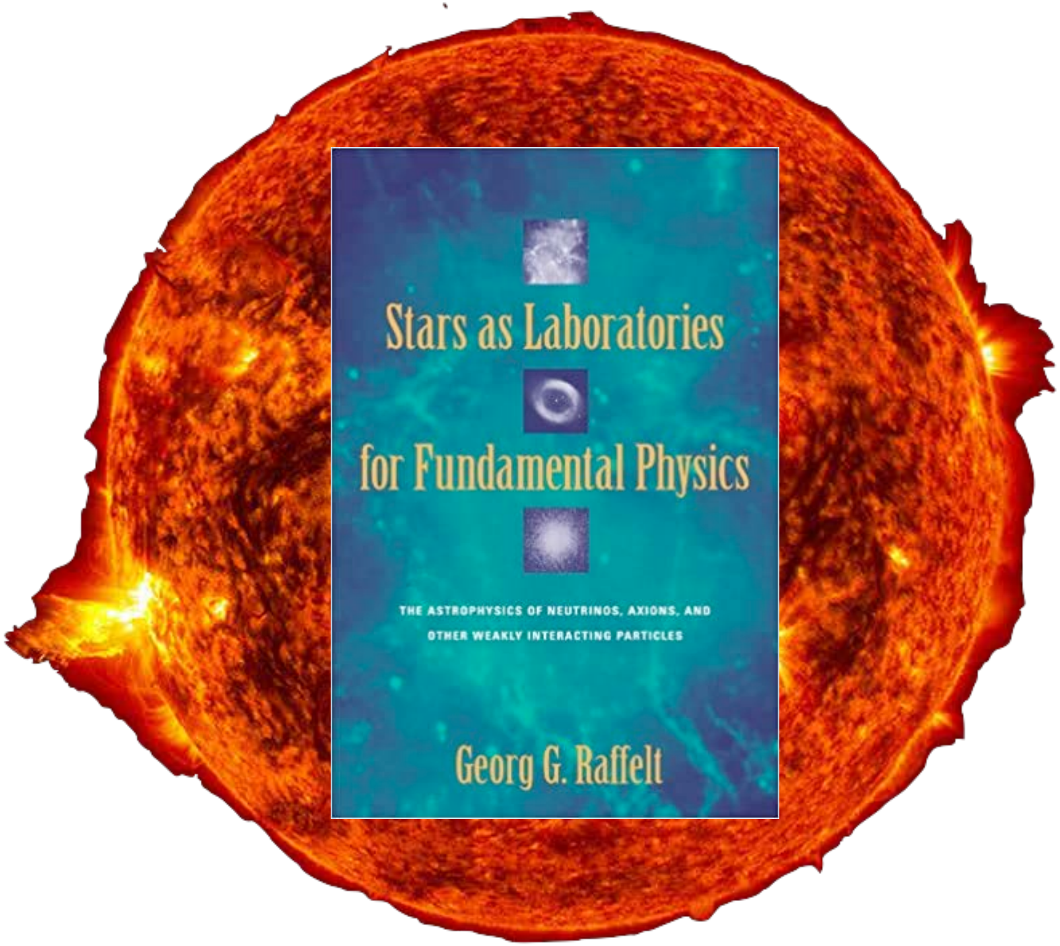
$\Gamma^{\mathrm{a}}_{\mathrm{a}}$

$$P = V\int\frac{d^3\mathbf{k}}{(2\pi)^3}\omega\Gamma^{\mathrm{axion}}_{\mathrm{abs}} = g_{a\gamma}^2 B^2\frac{Q}{\omega}V\rho_a$$

Collective effects in stars

In the **lab**: one can compute the signal in a plasma haloscope and obtain the classical result

In the **sky**: Energy loss in stars and supernovae, other signals



Collective effects in stars

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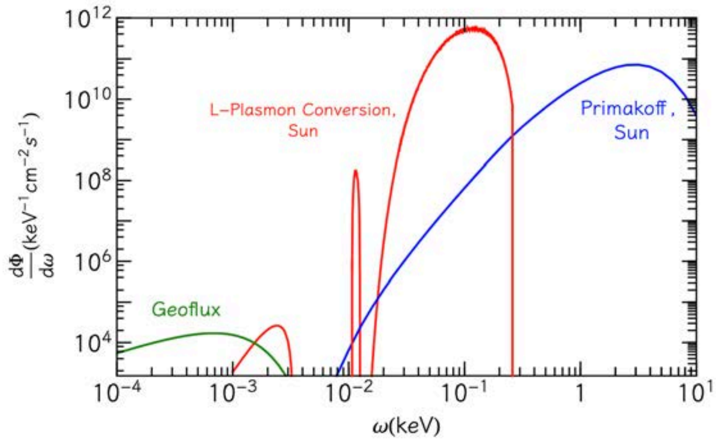
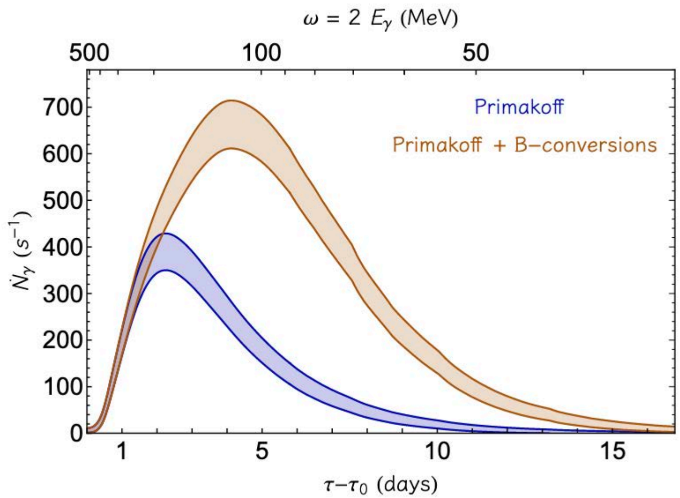
In the **sun**: a previously overlooked contribution to the axion flux in helioscopes



Caputo, Millar, **Vitagliano** (2020)
O'Hare, Caputo, Millar, **Vitagliano** (2020)

In **supernovae**: a previously overlooked contribution to (heavy) axion flux



Caputo, Carenza, Lucente, **Vitagliano** et al., *Phys.Rev.Lett*. 127 (2021) 18, 181102

Conclusions

Conclusions

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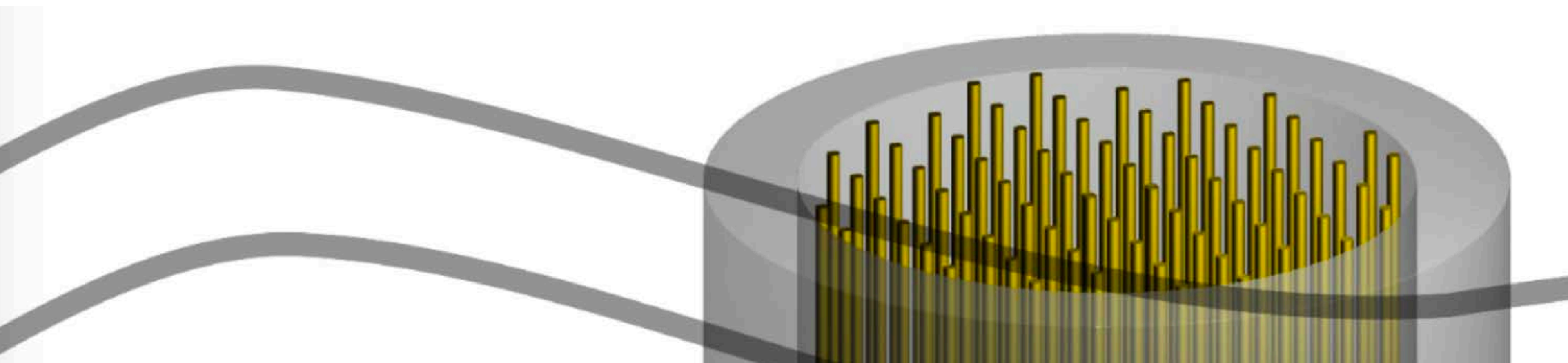
- The axion is a well-motivated dark matter candidate
- Plasma haloscopes are a promising new avenue
- We can probe larger mass axions
- We have competitive sensitivity, larger volumes, cheaper magnets (we can use a solenoid, and potentially probe any mass with the right metamaterial)
- The same process can be very important in stars and supernovae



Thank you

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