Theory Meets Experiments 2025:
Direct Detection across Dark Matter mass ranges
Wave Dark Matter Experiments

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Me + disclaimers

My research:

- ABRACADABRA → DMRadio
- BREAD
- Qubit-based sensors for axions, low-mass particle DM, CEvNS

UC Berkeley

BERKELEY LAB

Disclaimers:

- Content is subject to my bias
- Few references included – please ask me if you would like more references on any topic
- Several topics/images reproduced from others'. Thank you to many, including: Karl van Bibber, Julia Vogel, Bianca Giaccone, Axel Lindner, Lindley Winslow, Ben Safdi, Kevin Zhou

Expectations

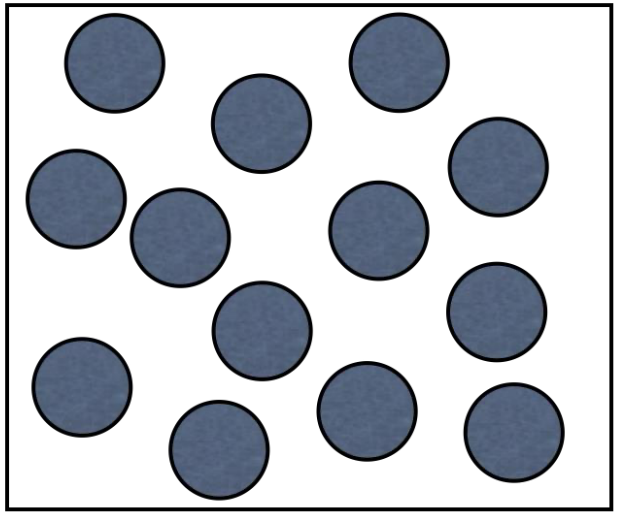
- Please ask lots of questions!
- I’m happy to have the discussion be guided by people’s interests (within reason)
    - If there is a topic that sparks a lot of interest, we can add it to the last lecture to go more in-depth

Lecture 1: axion-photon experiments overview

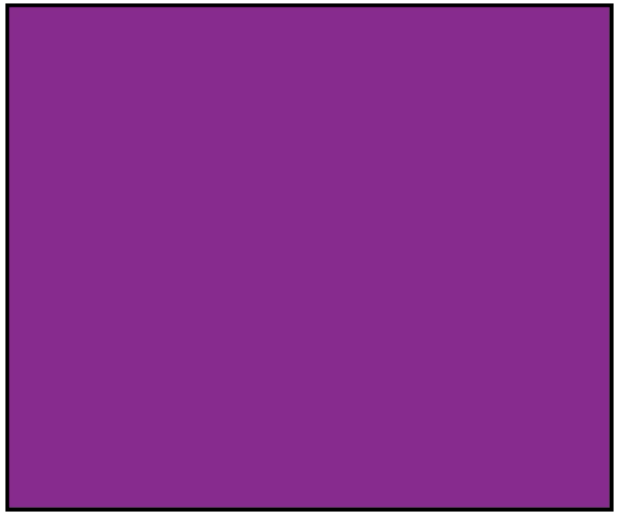
- Wave dark matter detection
- Axion interactions with photons
- Sources of axions and their implications for experiments

Wave vs particle dark matter

- **A definition for wave DM:**
  - de Broglie wavelength > average particle separation
  - Equivalently, occupation number > 1



Particle dark matter



Wave dark matter

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de Broglie Wavelength - $\lambda_{dB} \approx \frac{2\pi}{mv}$ **Occupancy Number -** $N \approx \frac{\rho_{DM}}{m}\lambda_{dB}^3$

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•Axion ($m \sim 10^{-9}$ eV): $\lambda_{dB} \sim 10^4$ km with $N \sim 10^{44}$

•WIMP ($m \sim 100$ GeV): $\lambda_{dB} \sim 10^{-16}$ km with $N \sim 10^{-36}$

where $\rho_{DM} = 0.4$ GeV/cm³

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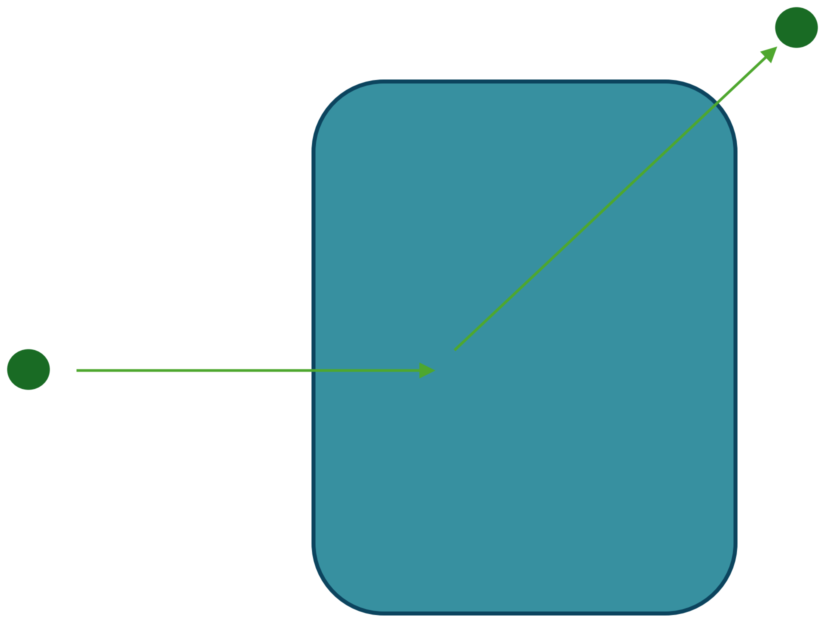
What does this mean for how we build our DM detectors? Compare to detectors from last week!

What does this mean for detection?

- Coherent and very high occupation number: can describe dark matter in terms of classical waves
- In a detector, we should think of the collective interactions of the field of DM instead of the individual particle interactions

Not a normal scattering experiment



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- Too light to use standard particle detectors

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- Too light to use standard particle detectors
- But very numerous!

Wave DM candidates

- QCD axions ⭐
- Axion-like particles (ALPs)
- Dark photons

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same way to detect, just different coupling strengths

QCD axions: coupling dependent on m_a
ALPs: coupling independent of m_a

Wave DM candidates

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same way to detect, just different coupling strengths

- Dark photons

many axion detectors also have dark photon sensitivity, but not all!

Axion interactions

$$\mathcal{L} = \underbrace{-\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}}_{\text{coupling to photons}} \underbrace{-\frac{i}{2}g_{d}a\bar{N}\sigma_{\mu\nu}\gamma_5 N F_{\mu\nu} + g_{aNN}(\partial_\mu)\bar{N}\gamma^\mu\gamma_5 N}_{\text{coupling to nucleons}} + \underbrace{g_{aee}(\partial_\mu)\bar{e}\gamma^\mu\gamma_5 e}_{\text{coupling to electrons}}$$

All interactions are feeble! ($g \propto 1/f_a$)

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most experiments

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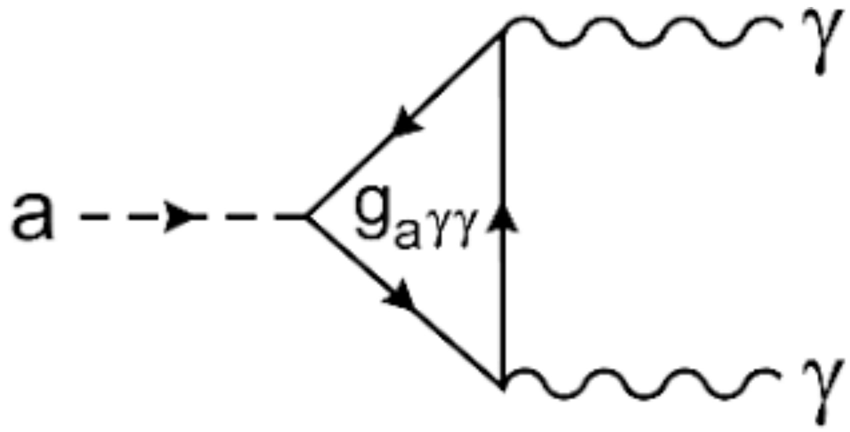
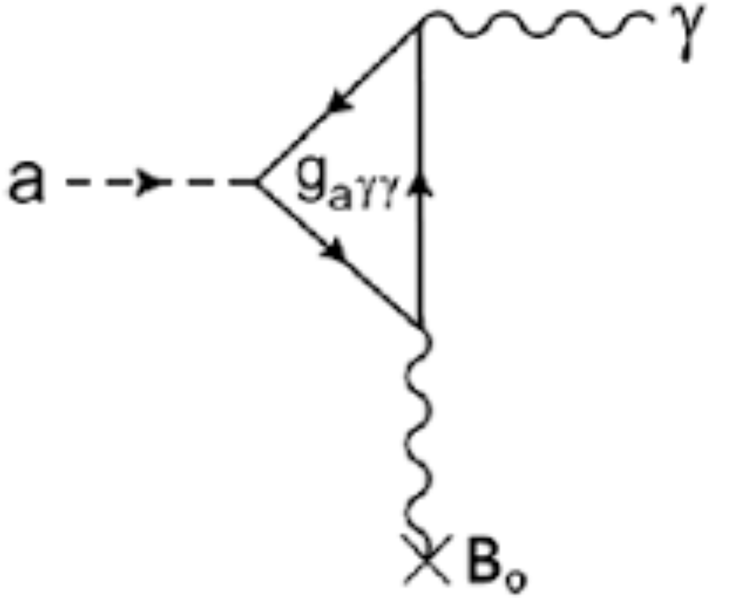
Primakoff effect

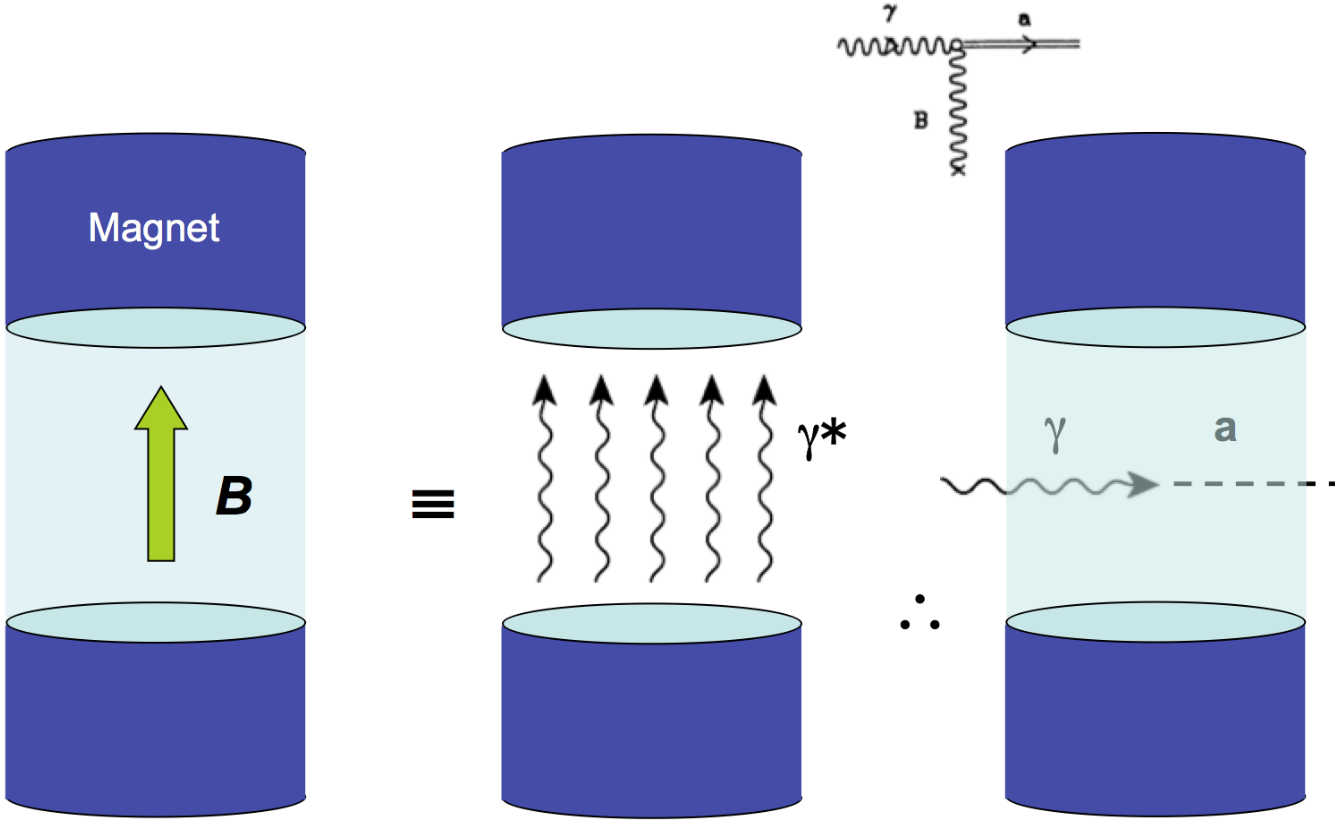
Axion couples to 2 photons through loop



Primakoff effect

Often drawn with one virtual photon from B field





Classical EM field *Sea of virtual photons* *Primakoff Effect*

Modified E&M

Modified QED Lagrangian

$$\mathcal{L}_{QED} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

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Modified Source-Free Maxwell Equations

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

$$\nabla\cdot\mathbf{B} = 0$$

$$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t}$$

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

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$$= g_{a\gamma\gamma}\sqrt{2\rho_{DM}}\cos{(m_a t)}\mathbf{B}$$

$$a(t) = \frac{\sqrt{2\rho_{DM}}}{m_a}\sin{(m_a t)}$$

- Time-varying axion field acts as an effective current (or displacement current) in the presence of a magnetic field
- Frequency is the mass of the axion

Axion-photon experiment ingredients

1. Strong magnetic field* (axion-to-photon converter)

$$\mathbf{J}_{\text{eff}} = g_{a\gamma\gamma}\sqrt{2\rho_{DM}}\cos(m_a t)\mathbf{B}$$

*can use DC field or RF field

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Axion-photon experiment ingredients

1. Strong magnetic field (axion-to-photon converter)
2. Coupling system (couple photons/EM signal into detector)
3. Very sensitive detector (amplify a tiny signal)

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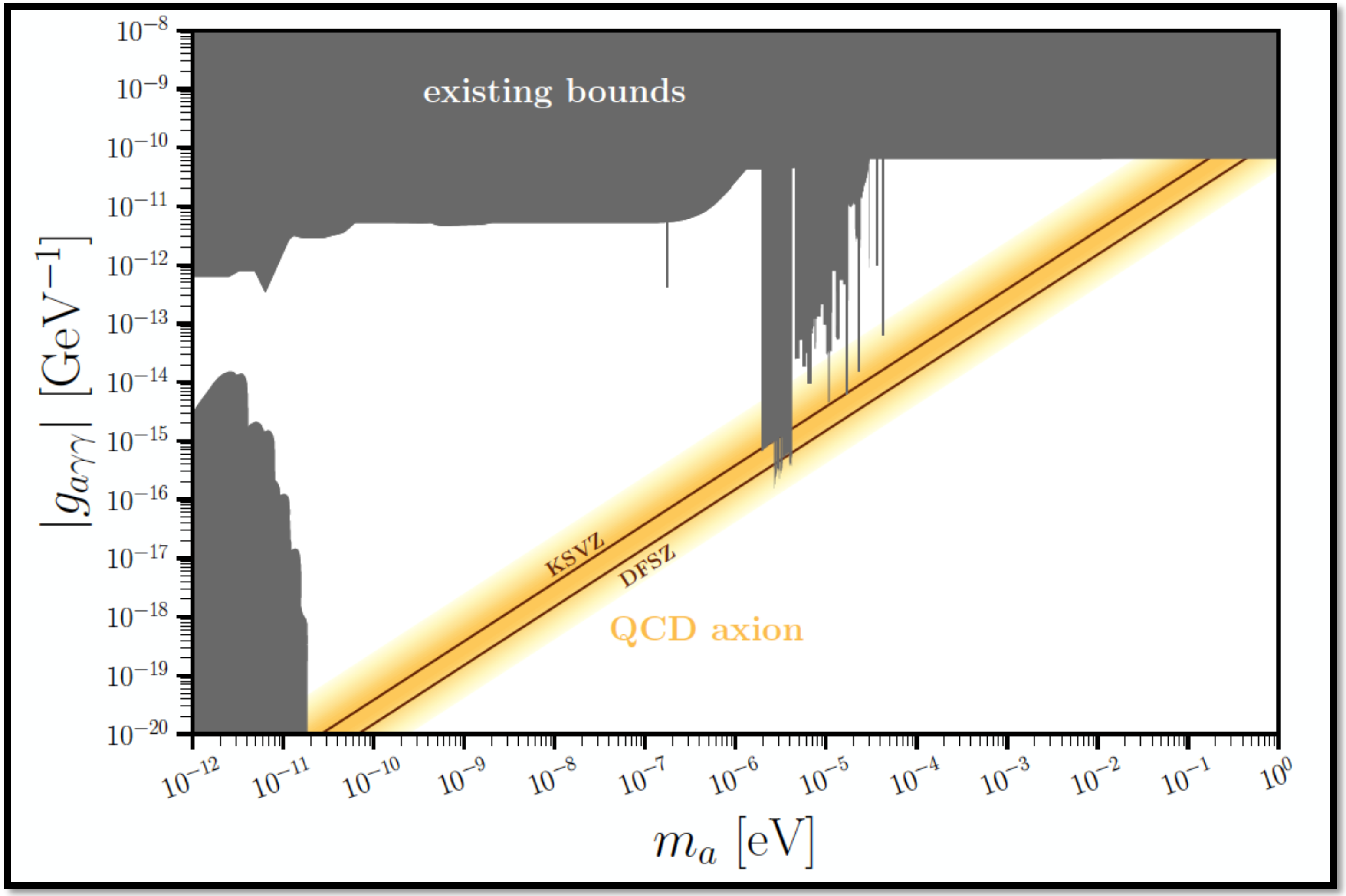
Parameter space to search



A. Berlin and others

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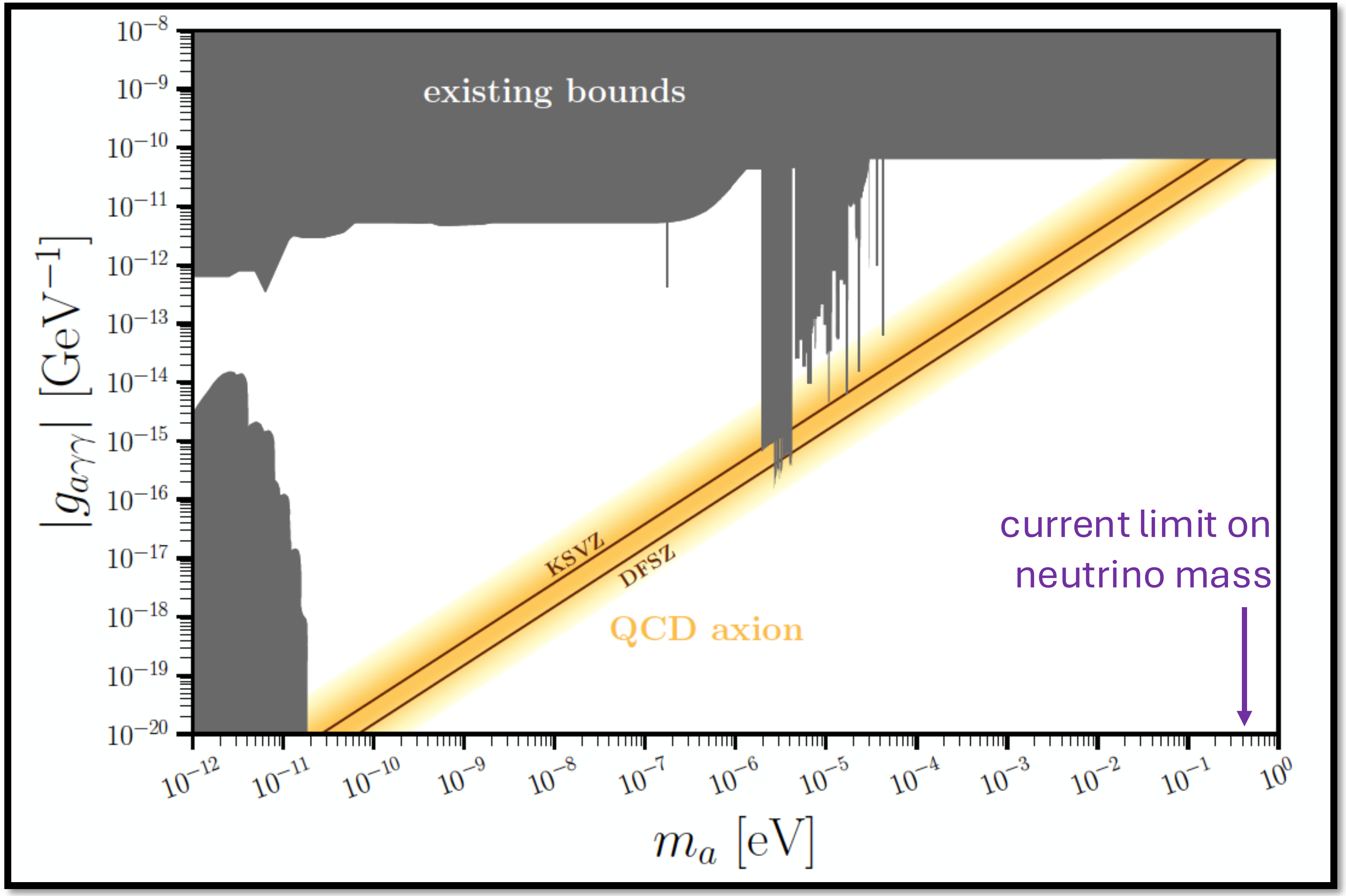

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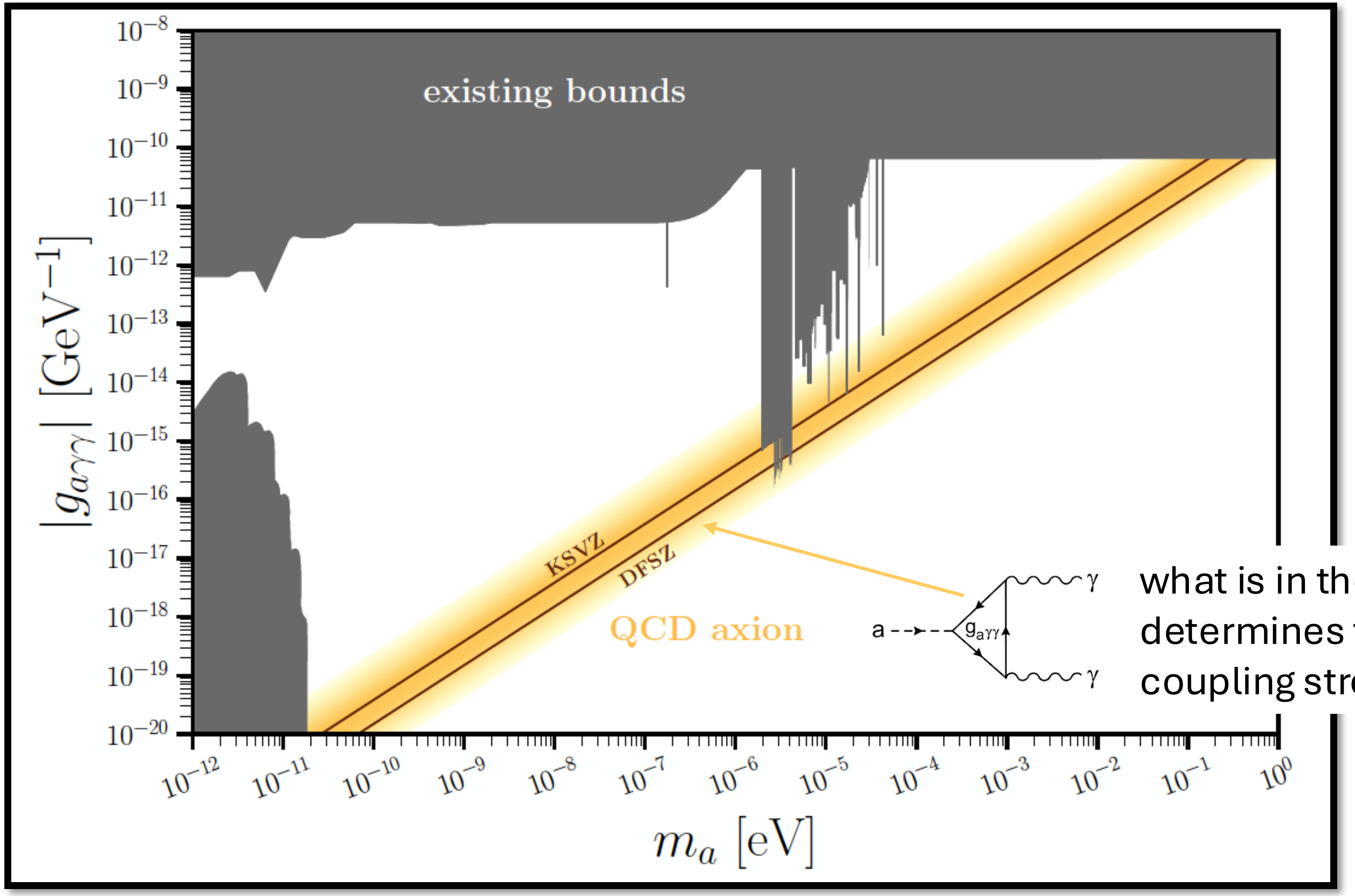
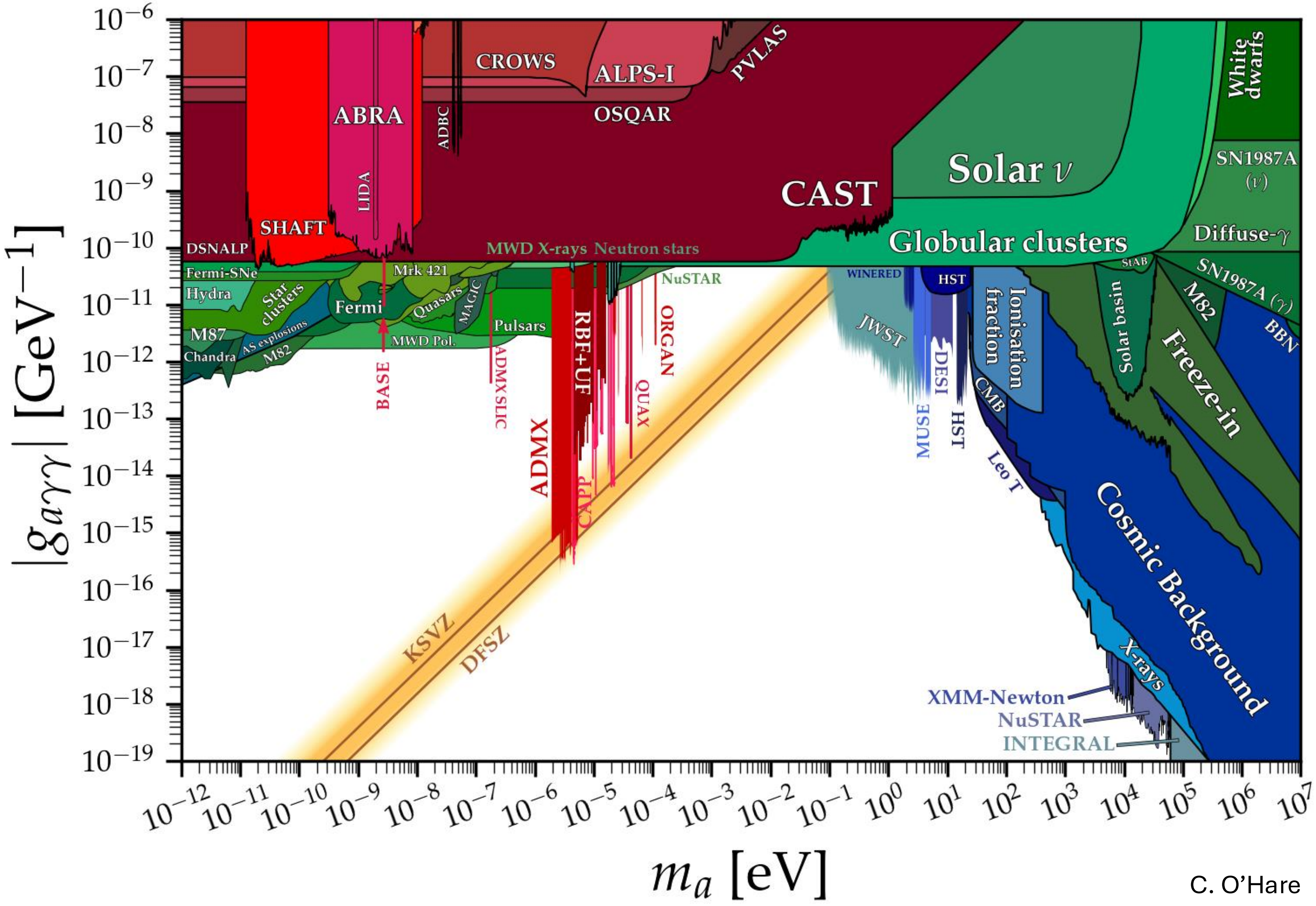


what is in the loop determines the coupling strength

A. Berlin and others

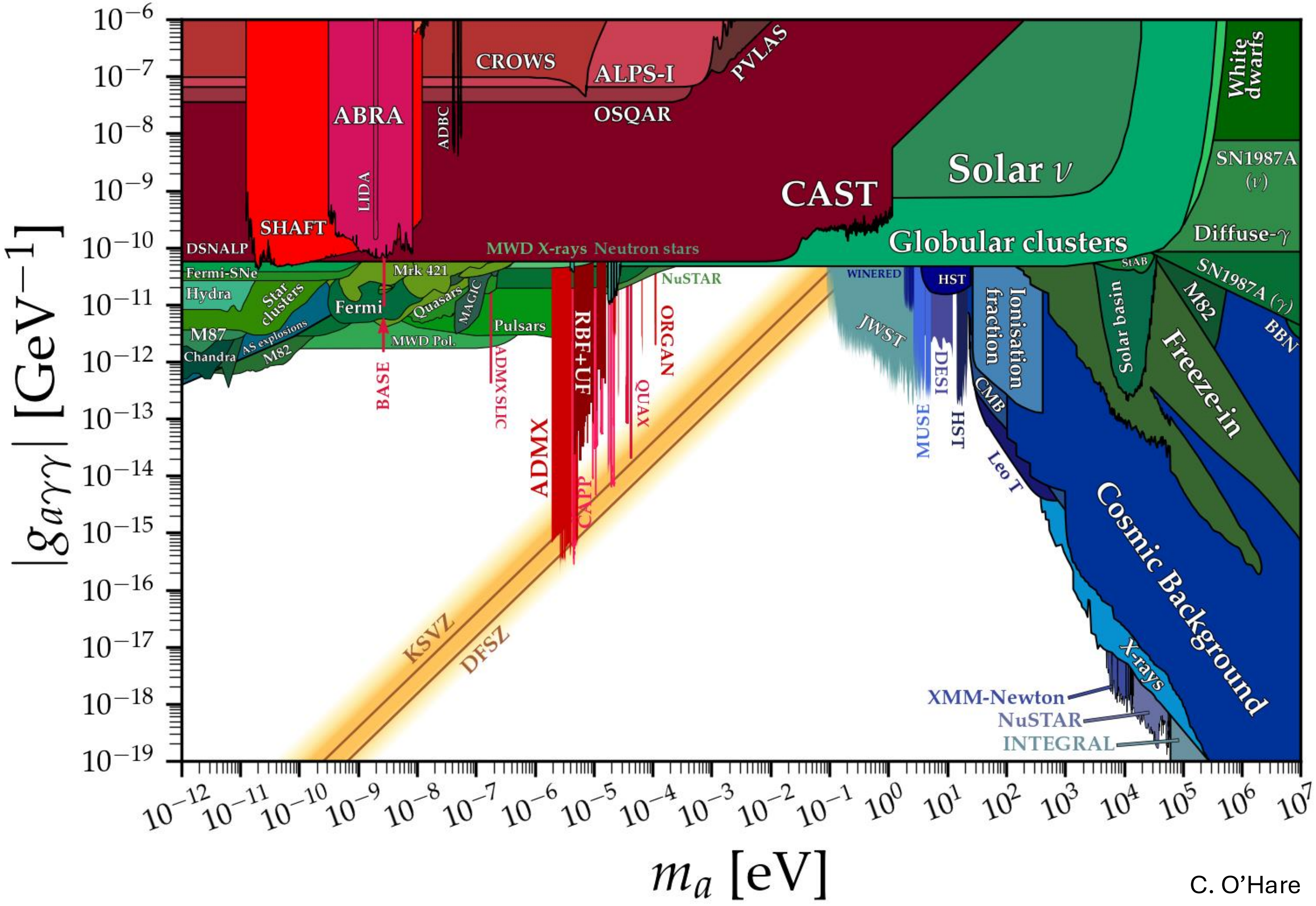
Existing bounds



C. O'Hare

Existing bounds

* Many different sources of axions (not all dark matter)
* Many different experimental techniques
→ must recognize different assumptions and systematics



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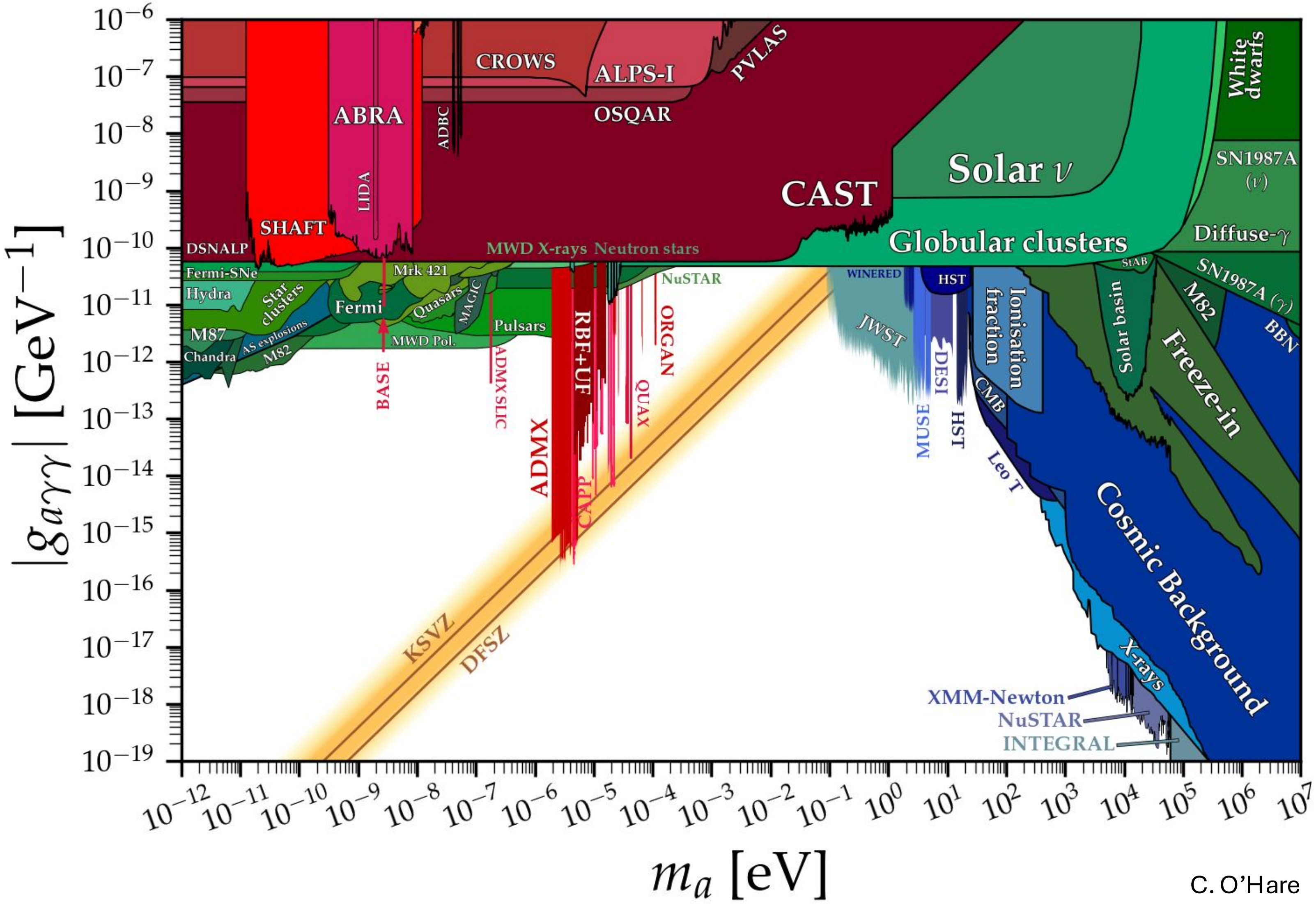

C. O'Hare

Sources of axions: astrophysical "indirect" searches

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- Entire cosmos is the laboratory
- But… astrophysics is *hard:* lots of systematics
- Many targets and methods

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a few examples…
(many details under the hood)

Stellar cooling

- **Basic principle:**
  - Axions should be produced inside stars
  - Once created, they will stream out, removing energy from stellar core
  - If they take away too much energy, the process would affect stellar evolution

Stellar cooling in globular clusters

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  - O(millions) stars
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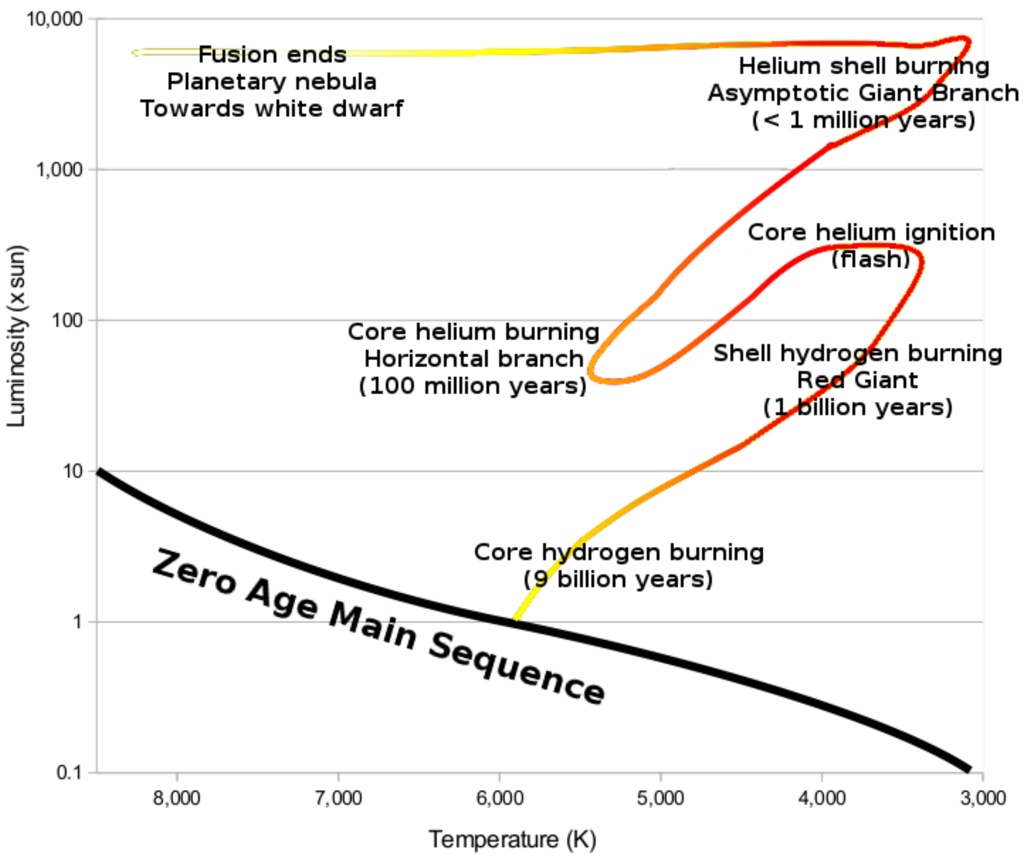

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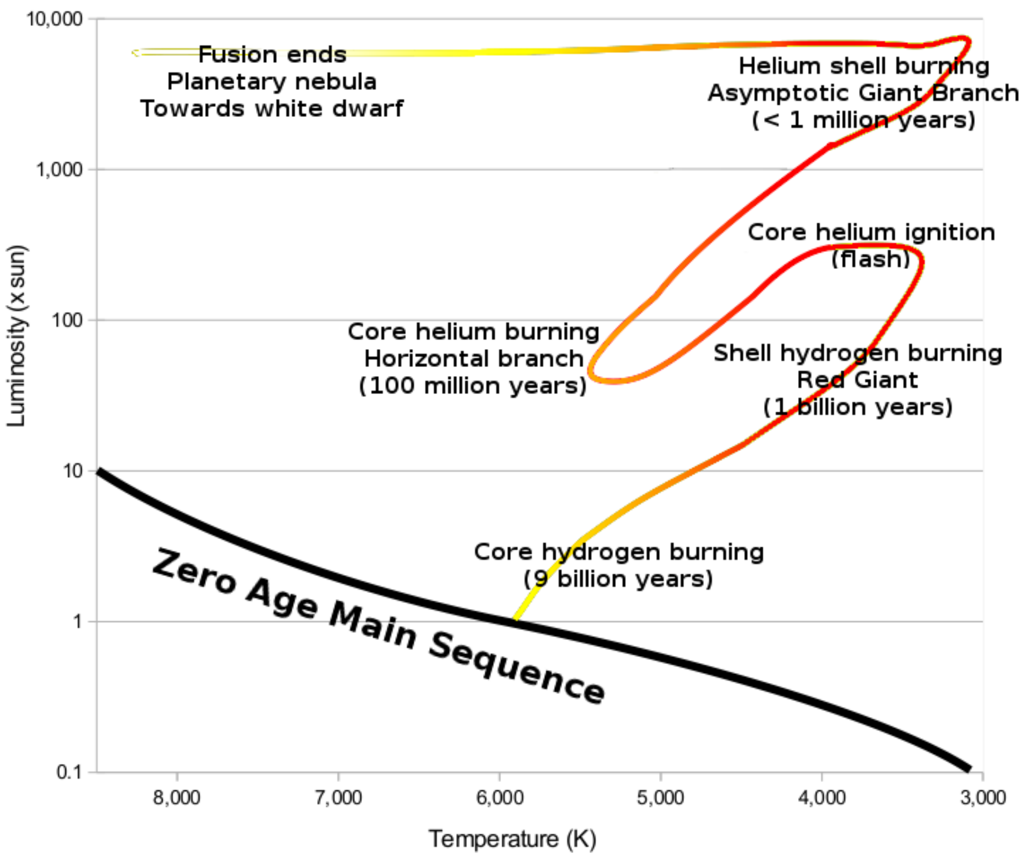

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  - Red giant branch: H burning shell ← minimal loss to axions via photon coupling
  - Horizontal branch: core He burning ← significant loss to axions via photon coupling
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Axion conversion in plasma

- Photons propagate through dense plasma inside the stars
- EM waves cannot propagate in plasma below the plasma frequency

$$\omega_p \approx \sqrt{\frac{4\pi\alpha_{\rm EM} n_e}{m_e}} \approx 1 \times 10^{-12}\ {\rm eV}\sqrt{\frac{n_e}{10^{-3}/{\rm cm}^3}}$$

- Conversion probability after traveling distance L in Coulomb field E

$$p_{\gamma\to a} \sim g_{a\gamma\gamma}^2 E^2 L^2$$

Back to globular clusters

- **RGB:** plasma frequency > temperature (no photon propagation)
- **HB:** plasma frequency < temperature (photon propagation)
- Only get axion conversion if we have propagating photons!
- Calculate ratio:

$$R = \frac{n_{\mathrm{HB}}}{n_{\mathrm{RGB}}}$$

Look for gamma ray bursts from supernovae

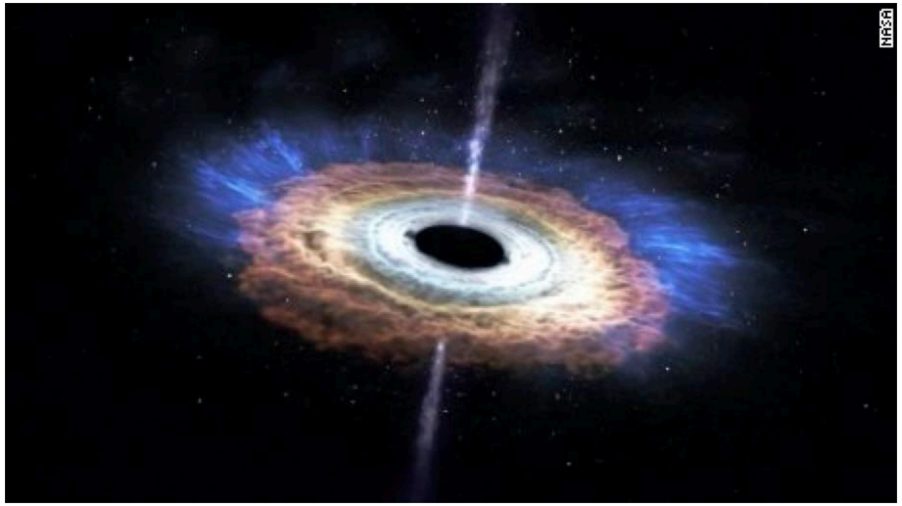
- **SN1987a:** Type II (core collapse) supernova 50kpc from Earth
- Hot photons propagating in core-collapse B-fields create axions
- Axion reconvert to gamma rays in galactic B-fields
- No gamma ray burst found in Gamma-Ray Spectrometer (Solar Maximum Mission)
- Limits:

$$g_{a\gamma} \lesssim 5.3 \times 10^{-12}\ \mathrm{GeV}^{-1},\ \text{for}\ m_a \lesssim 4.4 \times 10^{-10}\ \mathrm{eV},$$

Payez et al. 2015

Totally different method: black hole superradiance

- Axions with Compton wavelength ~ black hole size can extract angular momentum from the black hole, spinning it down
- If a rapidly spinning black hole exists with a given mass, that strongly constrains axions with the corresponding wavelength



Note: exponential process-– axions don't have to be a large fraction of the DM!

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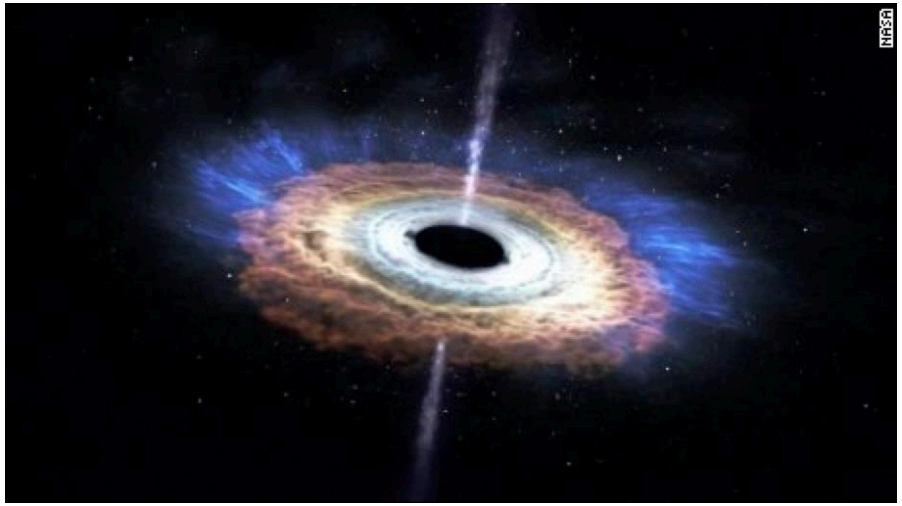
Note: can also look for gravitational wave signatures from "gravitational atom"



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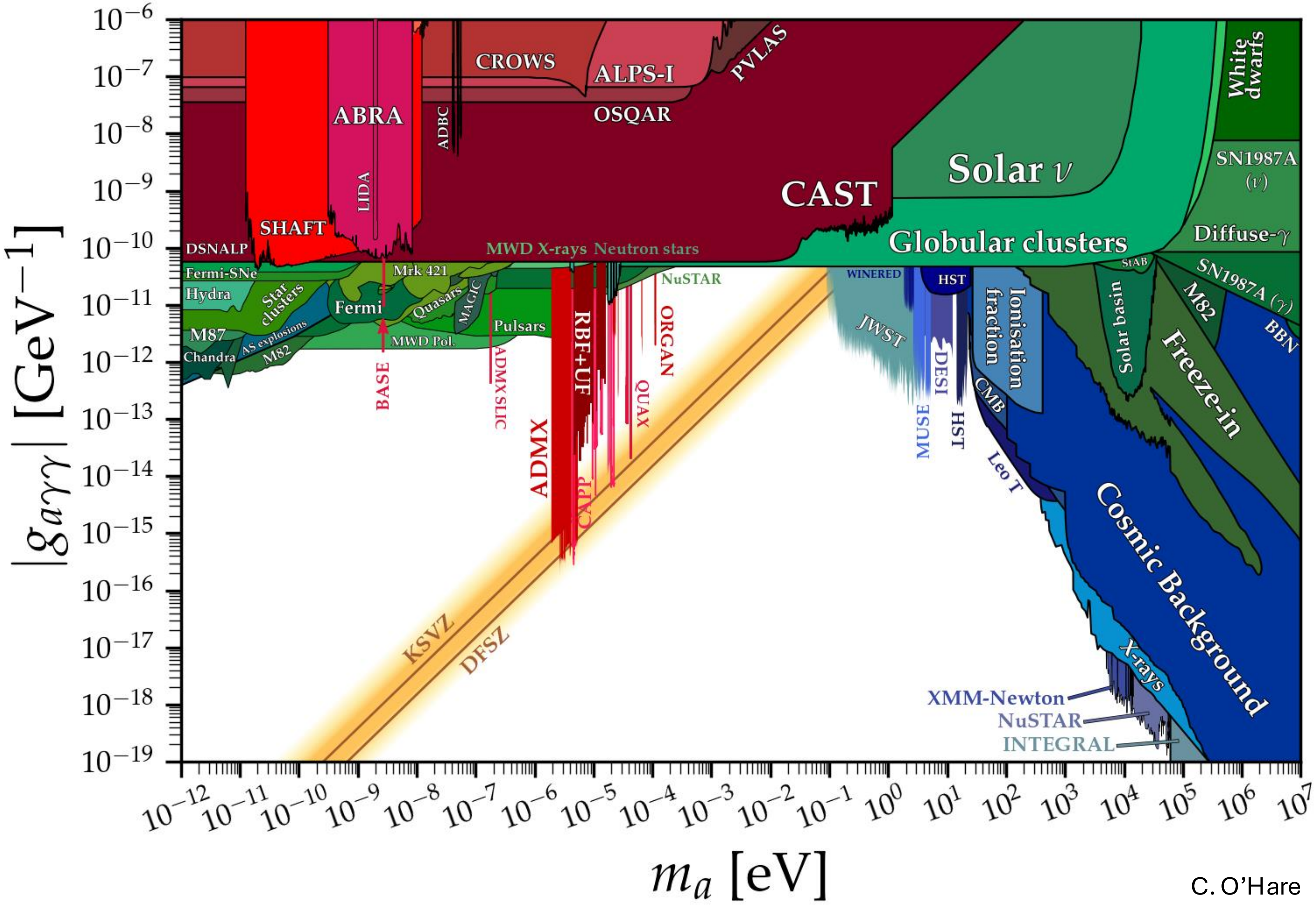
Small group activity!

link to github generating this plot:

- Pick one of the blue or green exclusions from Ciaran's plot
- Lightning lit review: figure out the basic concept and discuss as a small group
- At the end, elect someone to briefly summarize the concept to everyone



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