Searching for Wavelike Dark Matter: The Interactions

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Axion Interactions

- Axions cool… so how do we look for them?
- First step is always working out the interactions
- See arXiv:1801.08127 for a good review

Collage by MIT News

Fun Facts About Goldstone Modes

- Pure Goldstone modes only have derivative couplings (shift symmetry)
- Mass and non-derivative couplings only come from explicit symmetry breaking
- If you know the explicit and spontaneously symmetry breaking scales you know most of the couplings to $\mathcal{O}(1)$
- None of this applies to HP

Axion Interactions

- Lots of details depend on the model… can potentially have CP conserving and violating interactions (following notation of arXiv:1801.08127)

$$
\begin{aligned}
\mathcal{L}_{\mathrm{ALP-int.}} &= -\frac{g_{a\gamma}}{4} F_{\mu\nu}\widetilde{F}^{\mu\nu} a - a\sum_{\psi} g_{a\psi}(i\bar{\psi}\gamma^5\psi) - aF_{\mu\nu}\sum_{\psi}\frac{g_{a\psi\gamma}}{2}(i\bar{\psi}\sigma^{\mu\nu}\gamma^5\psi) + \ldots \\
&\quad -\frac{\bar{g}_{a\gamma}}{4} F_{\mu\nu}F^{\mu\nu} a - a\sum_{\psi}\bar{g}_{a\psi}(\bar{\psi}\psi)
\end{aligned}
$$

- QCD axion has a potential from QCD

$$
\mathcal{V}_{\mathsf{QCD}}(\theta) = -(m_\pi f_\pi)^2\sqrt{1 - 4\frac{m_u m_d}{(m_u+m_d)^2}\sin^2\left(\frac{\theta}{2}\right)},
$$

The QCD Axion

- Pseudo-Goldstone modes mass is determined by the explicit symmetry breaking
- QCD anomalous means non-perturbative effects give the axion a mass

$$m_a^2 f_a^2 = \frac{\partial^2 V_{\mathrm{QCD}}}{\partial^2 \theta}$$

- This can be directly calculated from QCD susceptibility
- $$m_a = 5.70(7)\mu\mathrm{eV}\left(\frac{10^{12}\mathrm{GeV}}{f_a}\right)$$
- Goldstone ALPS have similar kinds of scalings, but depends on the explicit breaking scales

Dimensionless Couplings

- Often written in a dimensionless form

$$
\begin{aligned}
g_{Af} &\equiv \frac{C_{Af} m_f}{f_A} &&= 1.75 \times 10^{-13} C_{Af} \frac{m_f}{\mathrm{GeV}} \frac{m_A}{\mu\mathrm{eV}}, \\
g_{A\gamma} &\equiv \frac{\alpha}{2\pi} \frac{C_{A\gamma}}{f_A} &&= 2.0 \times 10^{-16} C_{A\gamma} \frac{m_A}{\mu\mathrm{eV}}\ \mathrm{GeV}^{-1}, \\
g_{A\gamma n} &\equiv \frac{C_{A\gamma n}}{m_n f_A} &&= 6.4 \times 10^{-16} \frac{m_A}{\mu\mathrm{eV}} \mathrm{GeV}^{-2},
\end{aligned}
$$

- This scaling is intentional: all pseudo-Goldstone modes have couplings suppressed by the symmetry breaking scale

Model Independent couplings

- QCD axion must mix with the neutral mesons

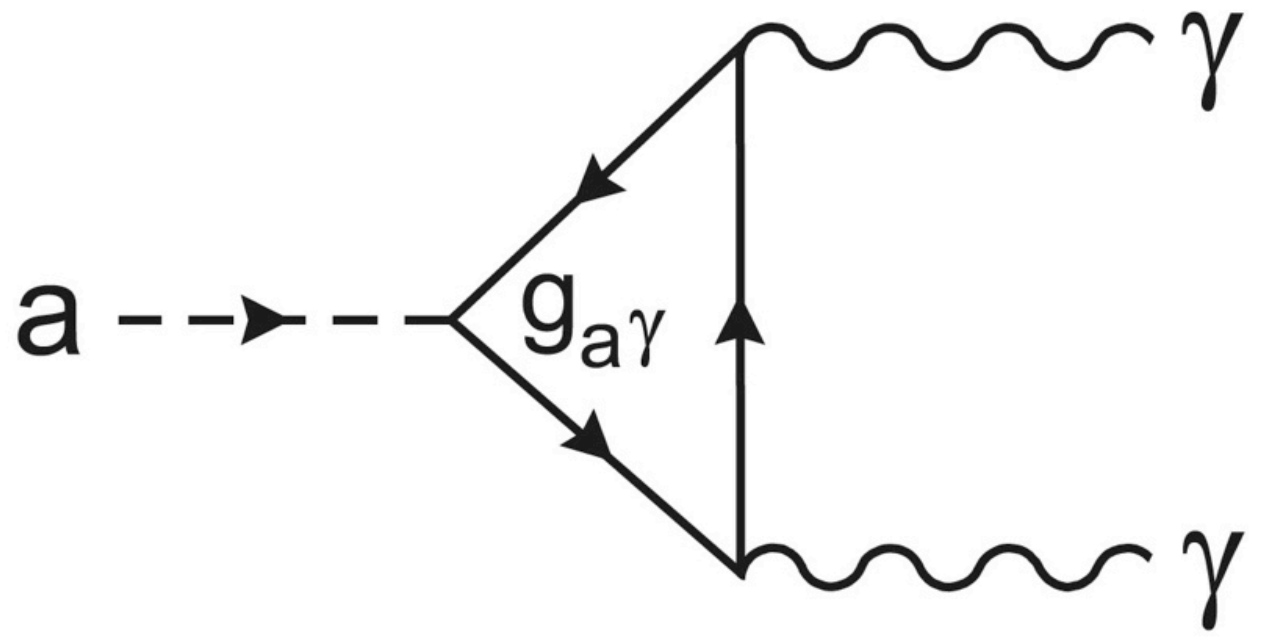
$$
\begin{aligned}
C_{Ap} &= -0.47(3) + 0.88(3)C_{Au} - 0.39(2)C_{Ad} - K_{Ah} \\
C_{An} &= -0.02(3) - 0.39(2)C_{Au} + 0.88(3)C_{Ad} - K_{Ah} \\
K_{Ah} &= 0.038(5)C_{As} + 0.012(5)C_{Ac} + 0.009(2)C_{Ab} + 0.0035C_{At} \\
C_{A\gamma} &= \frac{E}{N} - 1.92(4)
\end{aligned}
$$

- E is electromagnetic anomaly, N colour anomaly (domain wall number)

Axion Electrodynamics

- Axions and ALPs interact with photons through an anomaly term
- This coupling is tiny, but still important
- Mixes with the photon in an external magnetic field

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



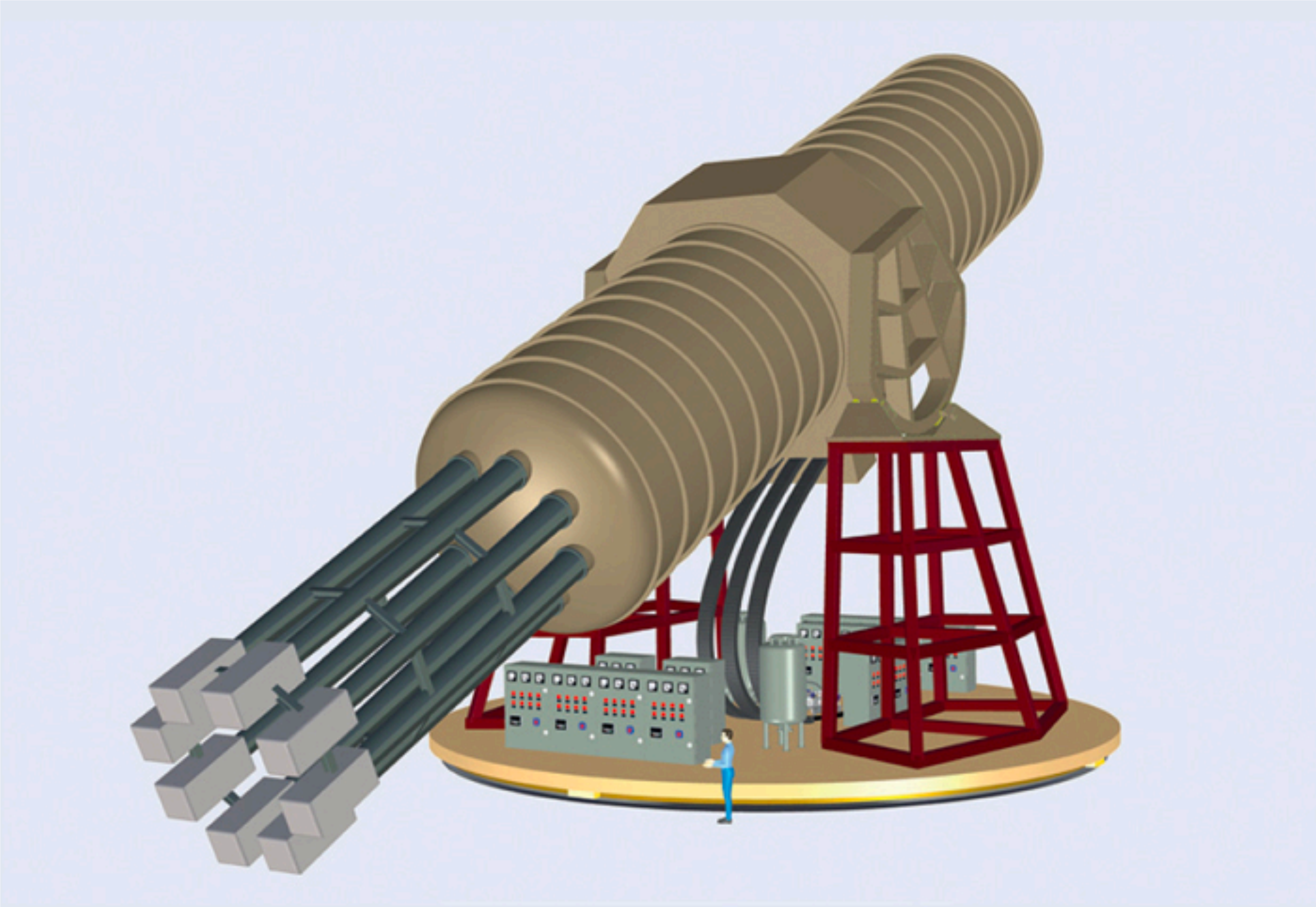
Axion-Maxwell Equations

- Turns up everywhere! Very useful
- Also can appear in condensed matter systems which break T

$$
\begin{aligned}
\boldsymbol{\nabla} \cdot \mathbf{E} &= \rho - g_{a\gamma} \mathbf{B} \cdot \boldsymbol{\nabla} a \,, \\
\boldsymbol{\nabla} \times \mathbf{B} - \dot{\mathbf{E}} &= \mathbf{J} + g_{a\gamma} \left(\mathbf{B}\, \dot{a} - \mathbf{E} \times \boldsymbol{\nabla} a \right) \,, \\
\boldsymbol{\nabla} \cdot \mathbf{B} &= 0 \,, \\
\boldsymbol{\nabla} \times \mathbf{E} + \dot{\mathbf{B}} &= 0 \,, \\
\ddot{a} - \boldsymbol{\nabla}^2 a + m_a^2 a &= g_{a\gamma} \mathbf{E} \cdot \mathbf{B} \,.
\end{aligned}
$$

Search Strategies

- Astrophysical
- Dark matter detection
- Cosmology
- Non-DM laboratory experiments



Astrophysical Limits

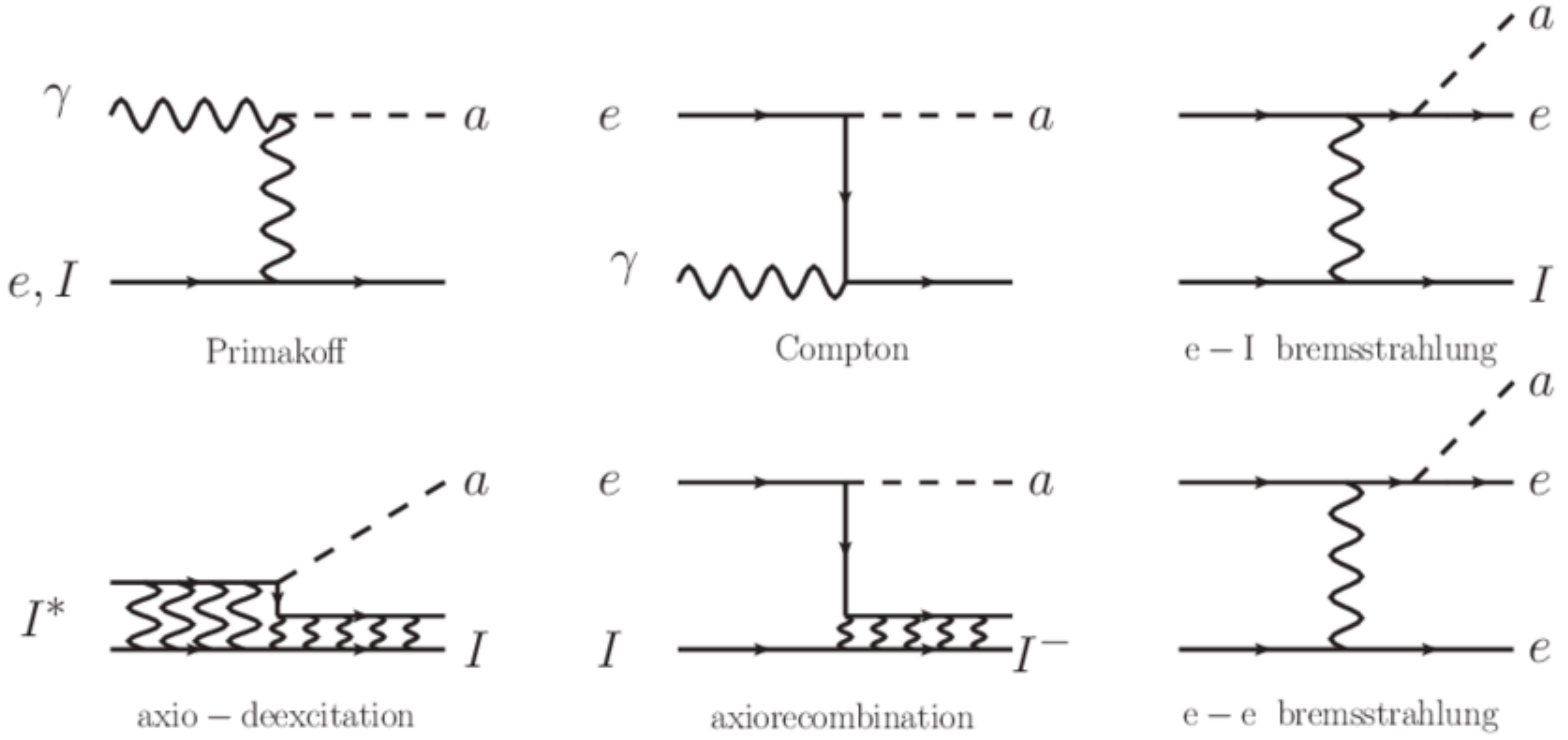
- Light and weakly interacting particles can be produced in stellar environments
- “Energy loss” similar to neutrinos
- Red Giants, supernovas, WD etc are all very sensitive to this energy loss
- Some of the strongest bounds on axions!

Astrophysical Limits

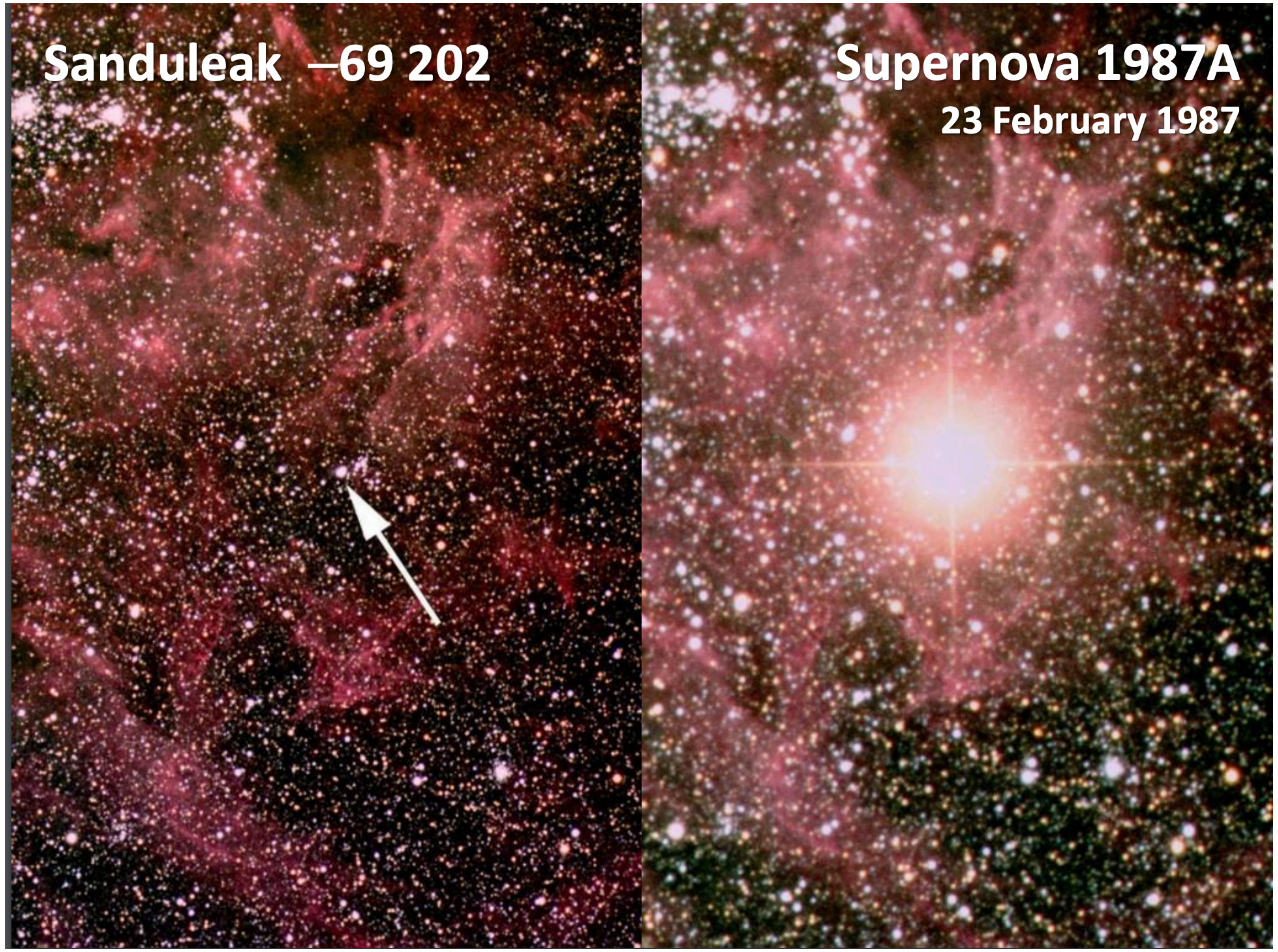
- Supernova 1987A is still one of the strongest bounds ever
- ALP conversion in galactic magnetic fields
- Black hole super radiance
- Axion DM converting to radio lines in NS
- Looking from axions from the Sun
- Magnetic WD
- …

Axion Production in Astrophysical Environments

- Primakov effect
- Axion bremsstrahlung
- Pion conversion
- Plasmon conversion
- ...



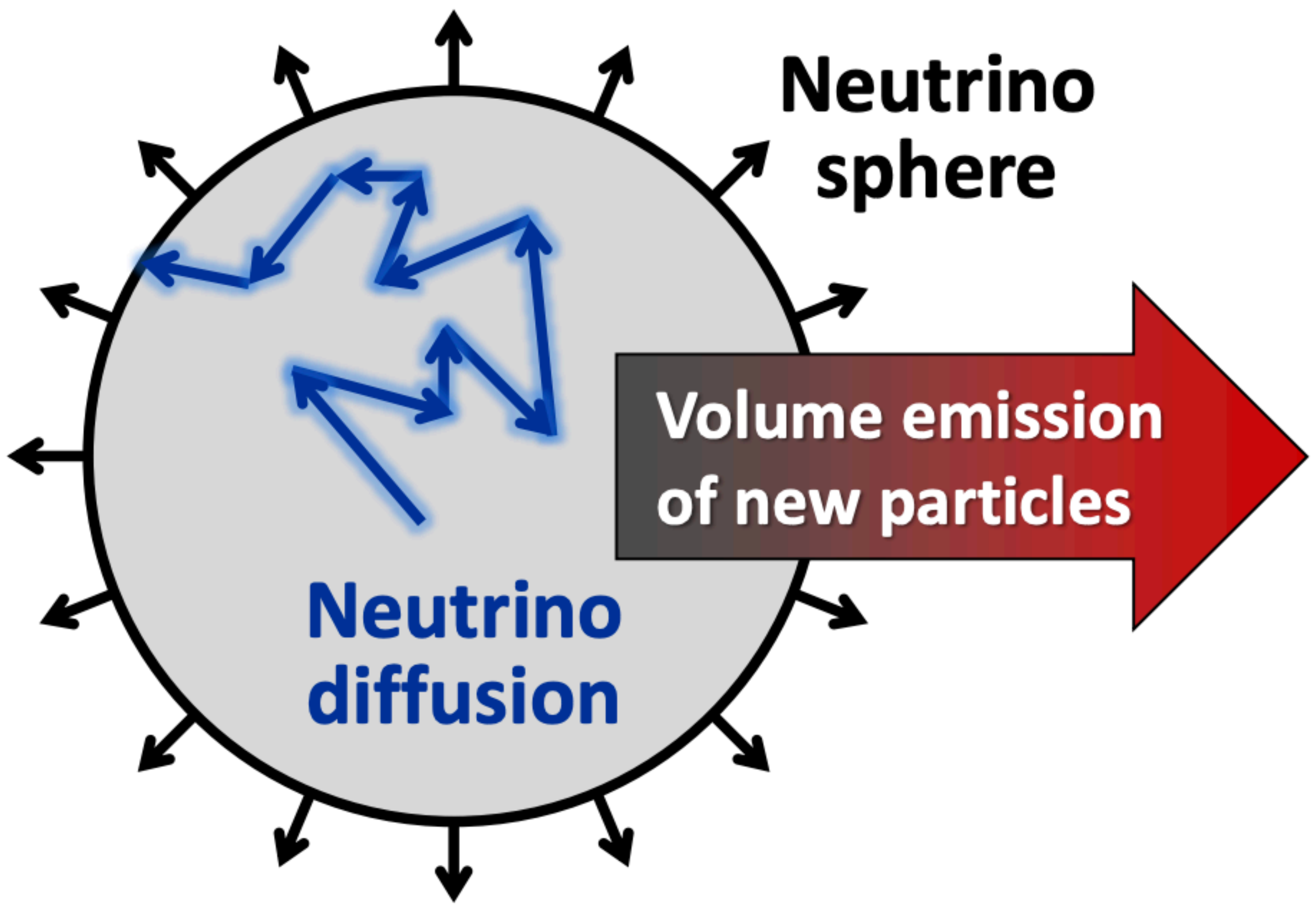
Supernova 1987A



Stolen from Georg Raffelt

Supernova 1987A

- Core collapse supernova
- Occurs when fusion gets up to Fe
- Very complicated dynamics
- Dominated by energy transport
- So dense even neutrinos can be trapped
-

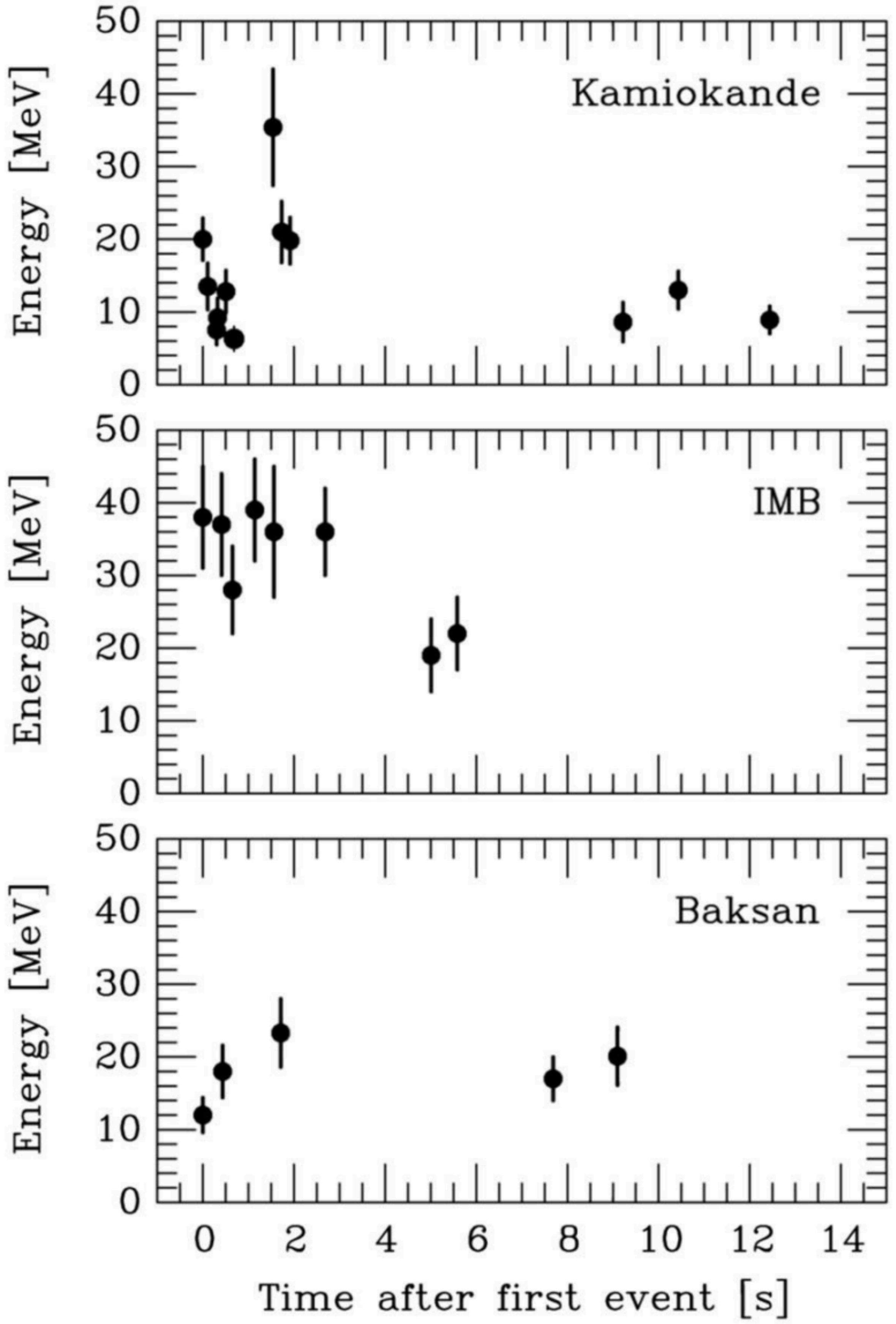


Stolen from Georg Raffelt

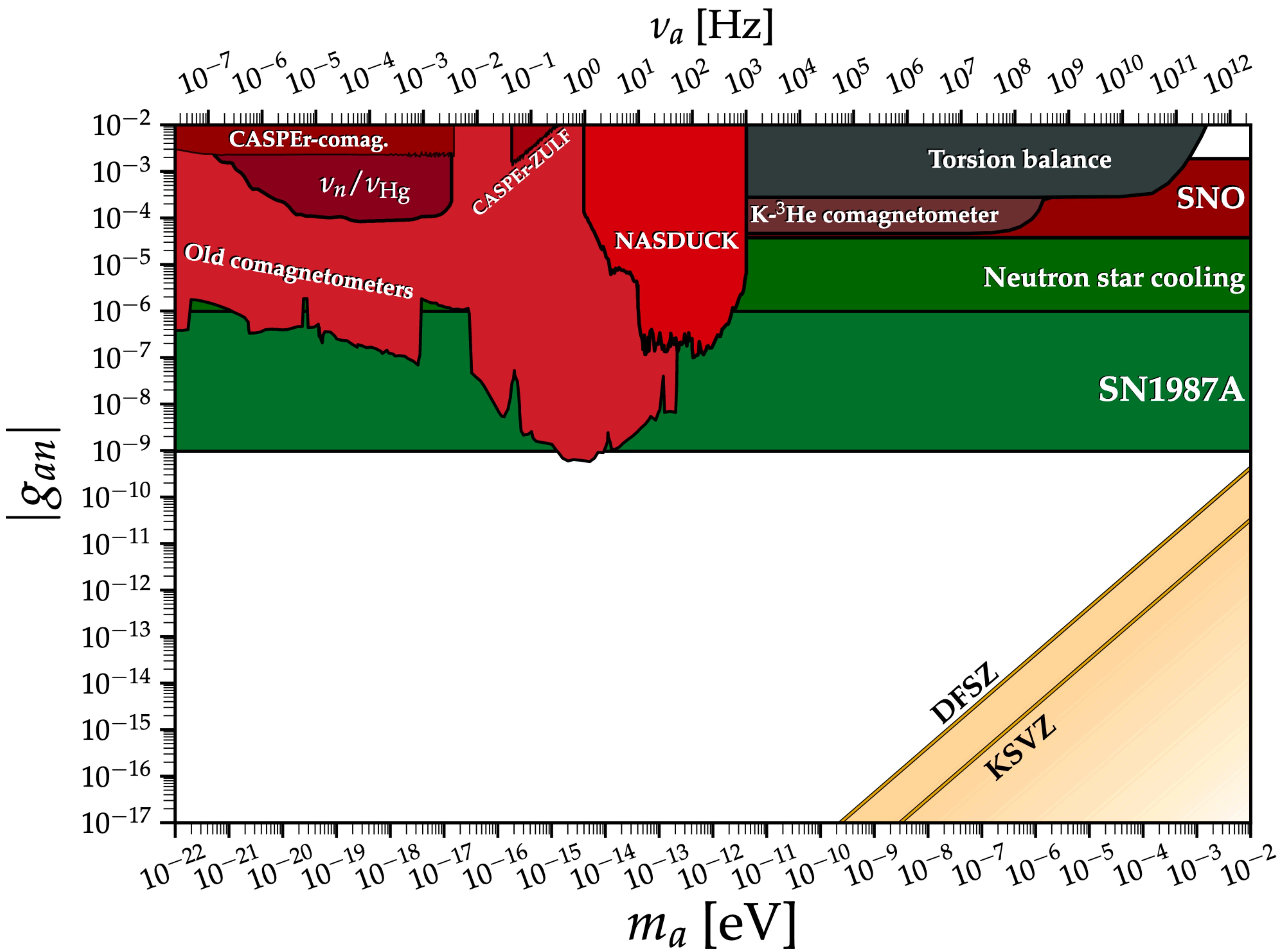
Supernova 1987A

- Weak interactions the only way to transport energy
- Cooling of the proto-neutron star produces (measured) neutrinos
- Only about half the energy could have gone to axions

SN 1987A neutrino signal



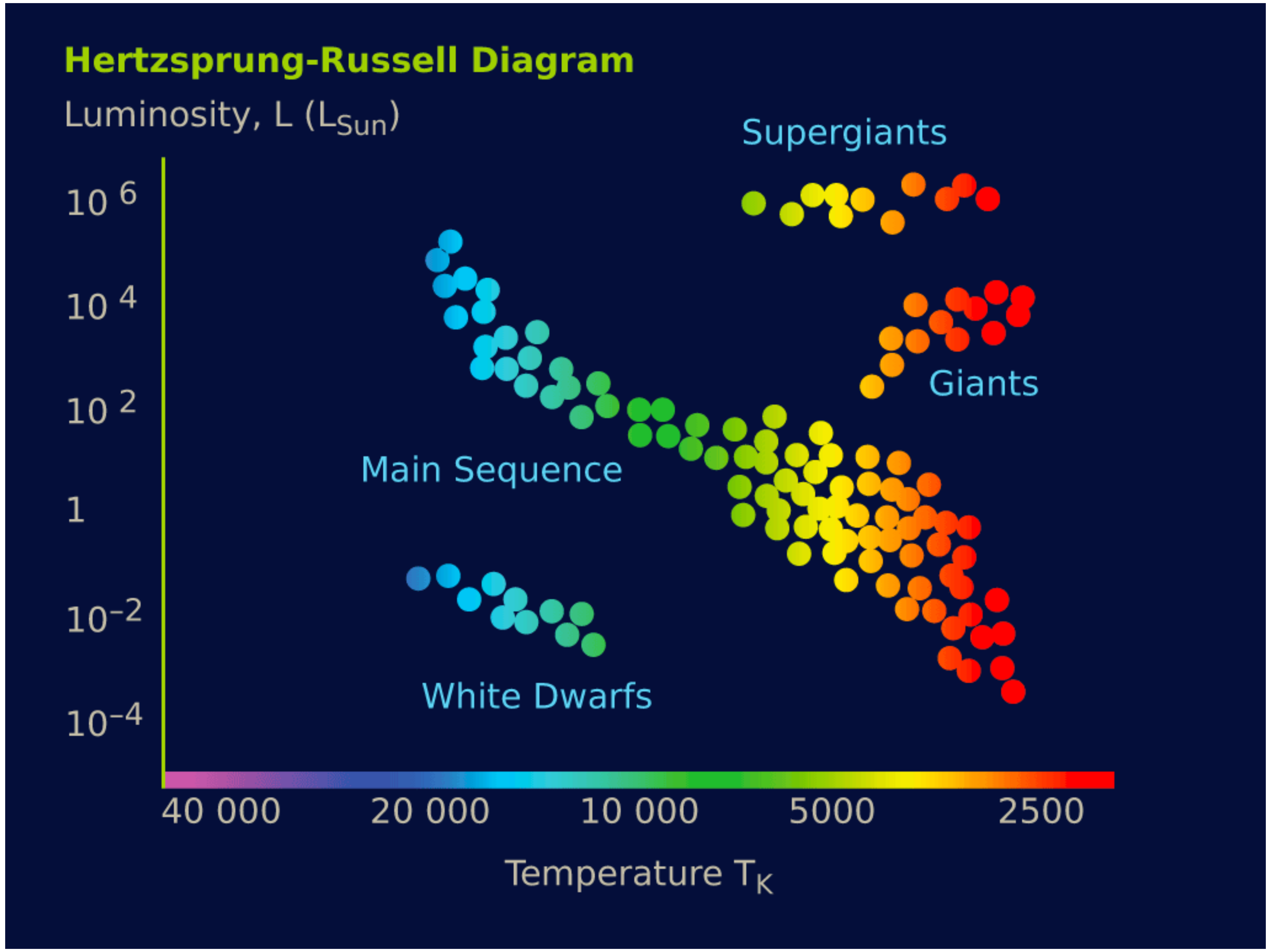
Axion-Neutron Coupling



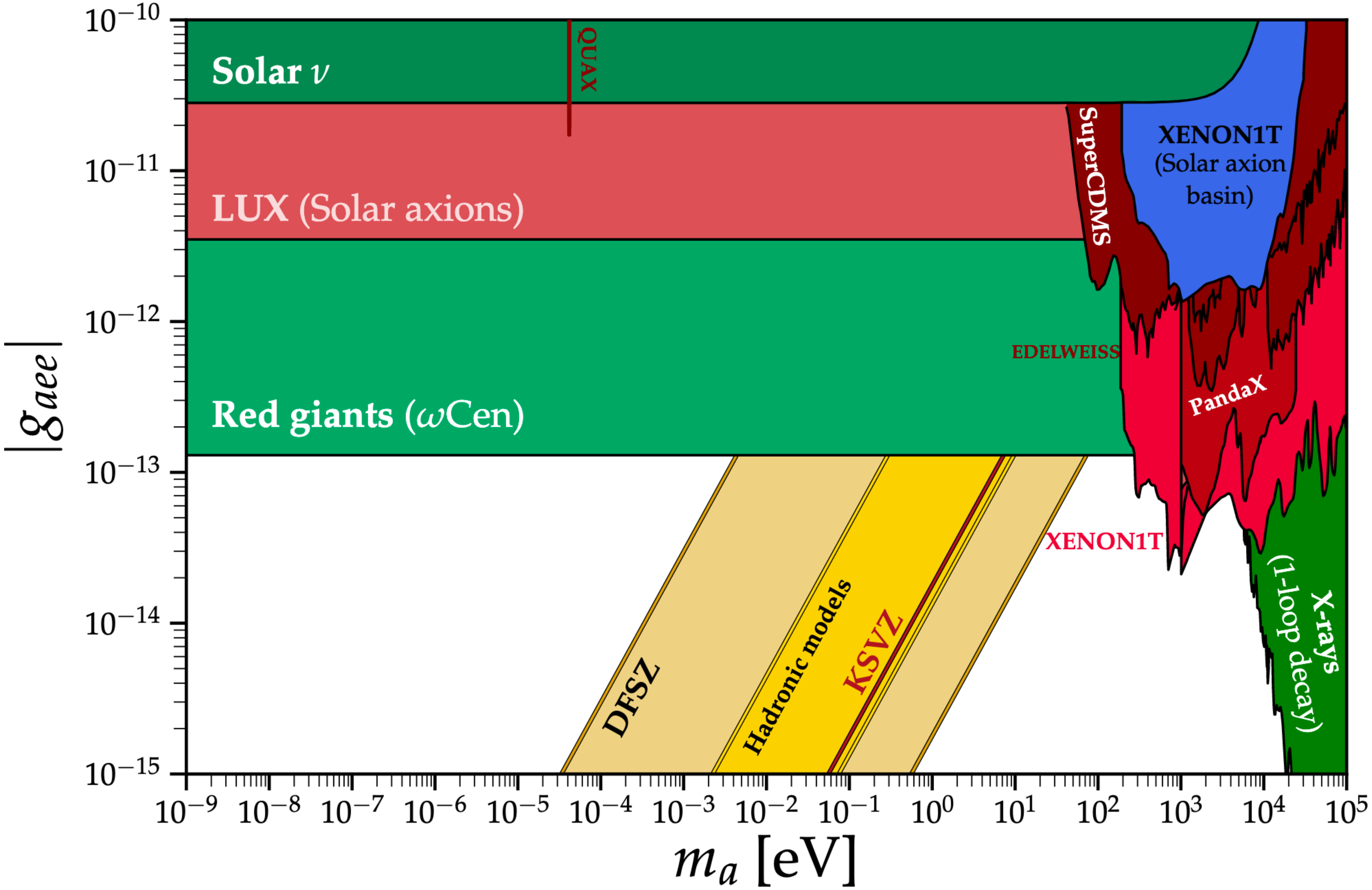
https://github.com/cajohare

Stellar Evolution

- Energy loss actually increases the rate of stellar fusion
- Biggest stars have the shortest lifetime!
- Measuring the ratio of different life stages or the tip of different parts tells you the energy loss
- Super sensitive bound on light particles!



Axion-Electron Limits



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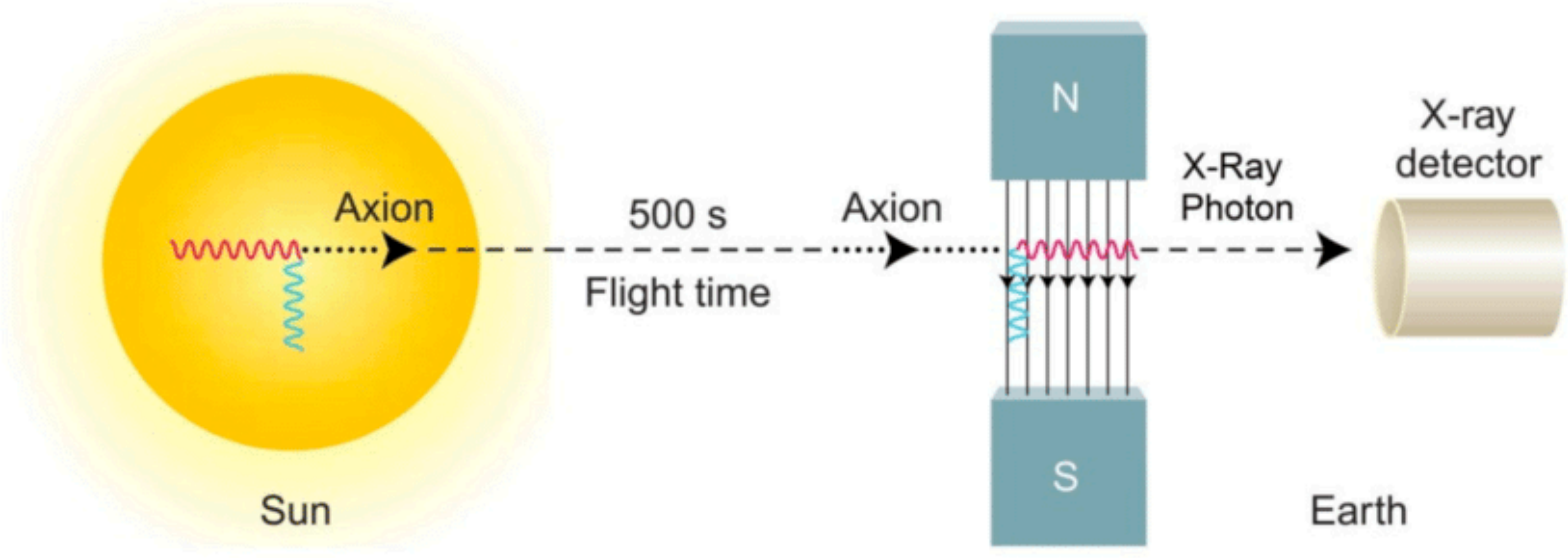
Helioscopes

- If the Sun shines axions, can't we just see them?

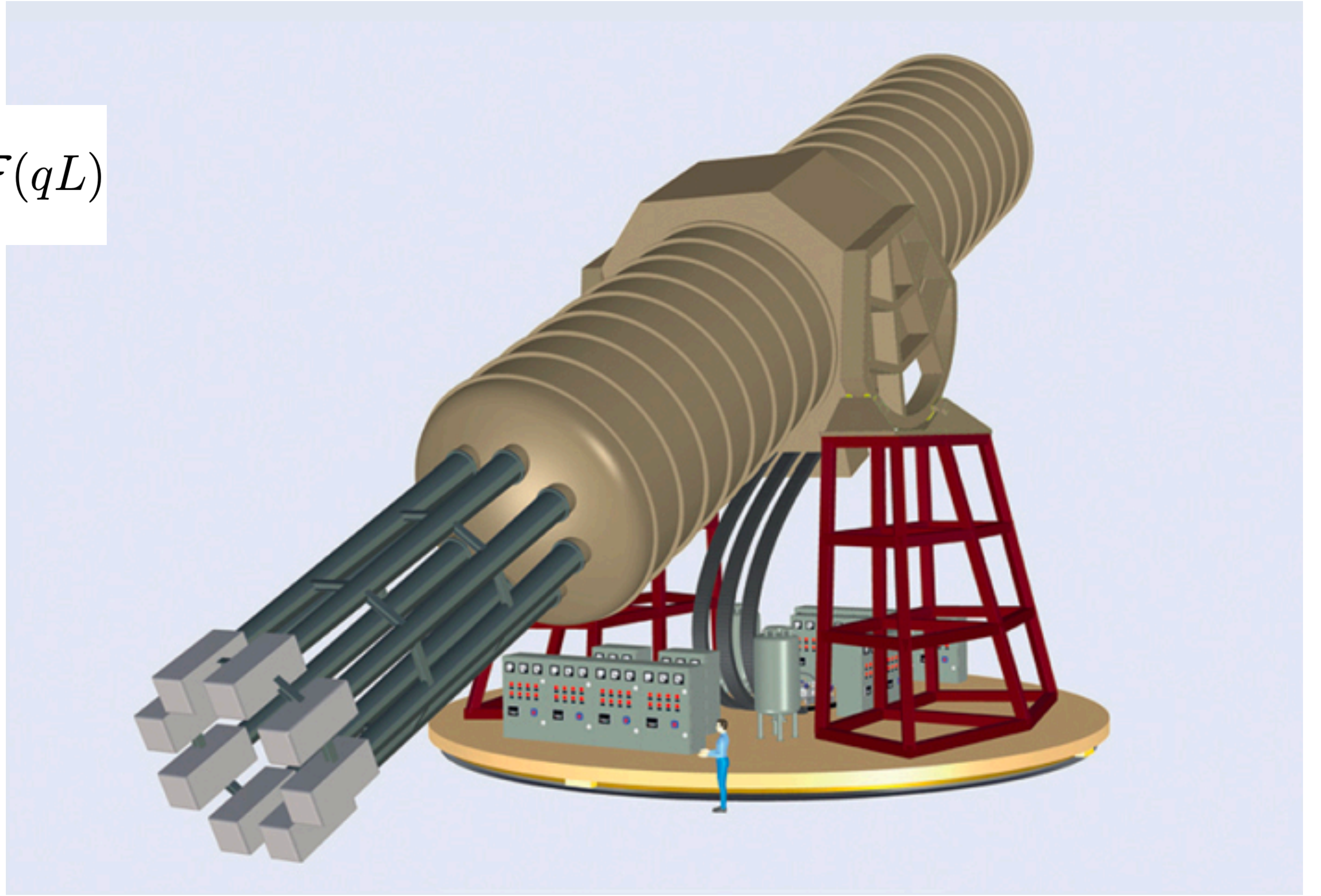


Helioscopes

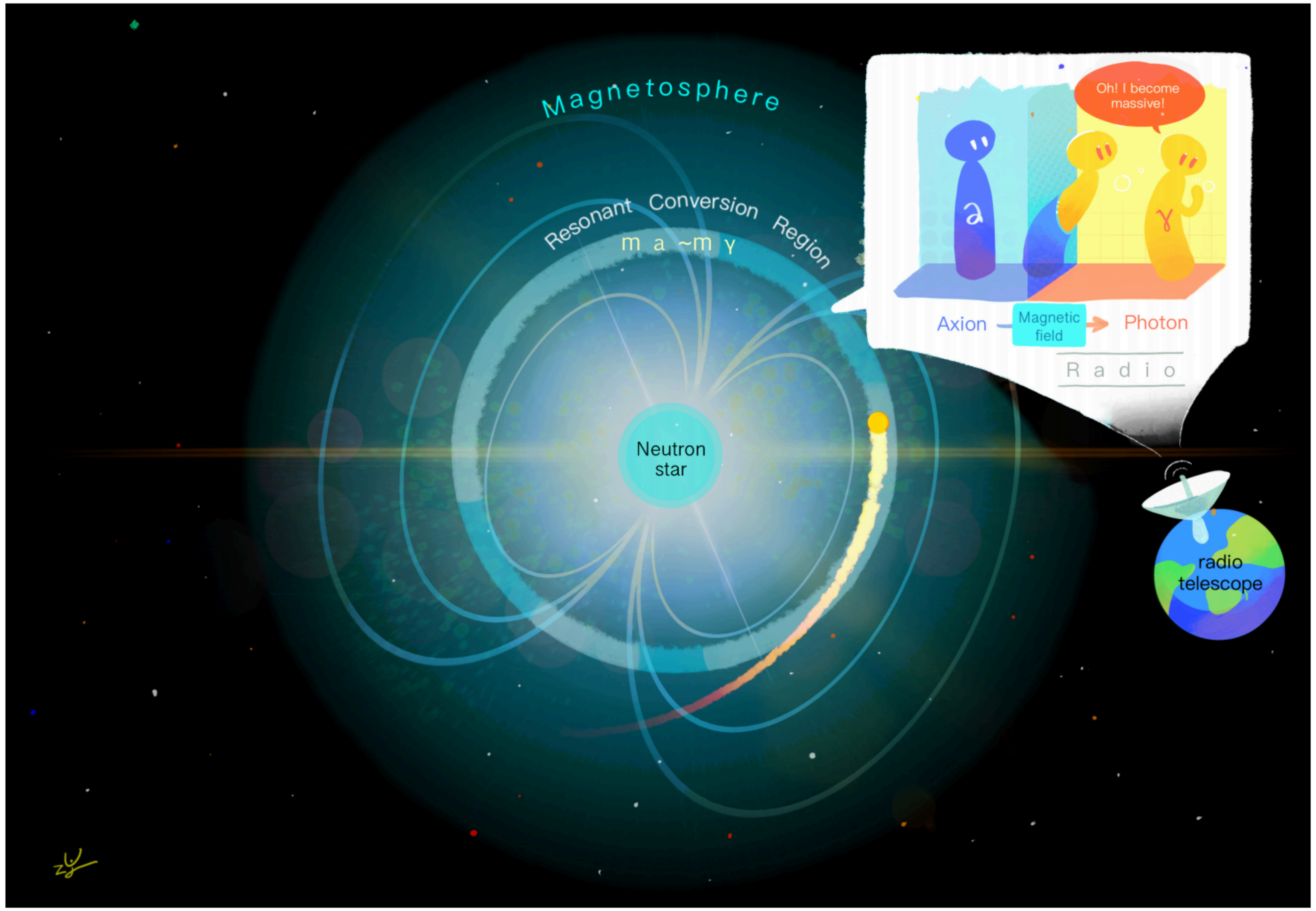
- Magnet converts axions into X-rays

$$\mathcal{P}(a \to \gamma) = 2.6 \times 10^{-17} \left(\frac{g_{a\gamma}}{10^{-10}\mathrm{GeV}^{-1}} \right)^2 \left(\frac{B_e}{10\ \mathrm{T}} \right)^2 \left(\frac{L}{10\ \mathrm{m}} \right)^2 \mathcal{F}(qL)$$

- CAST gave very strong limits (recycled LHC dipole magnet)
- Next gen (babyIAXO, IAXO) should be able to do much better
- Very clean system, no assumption about DM



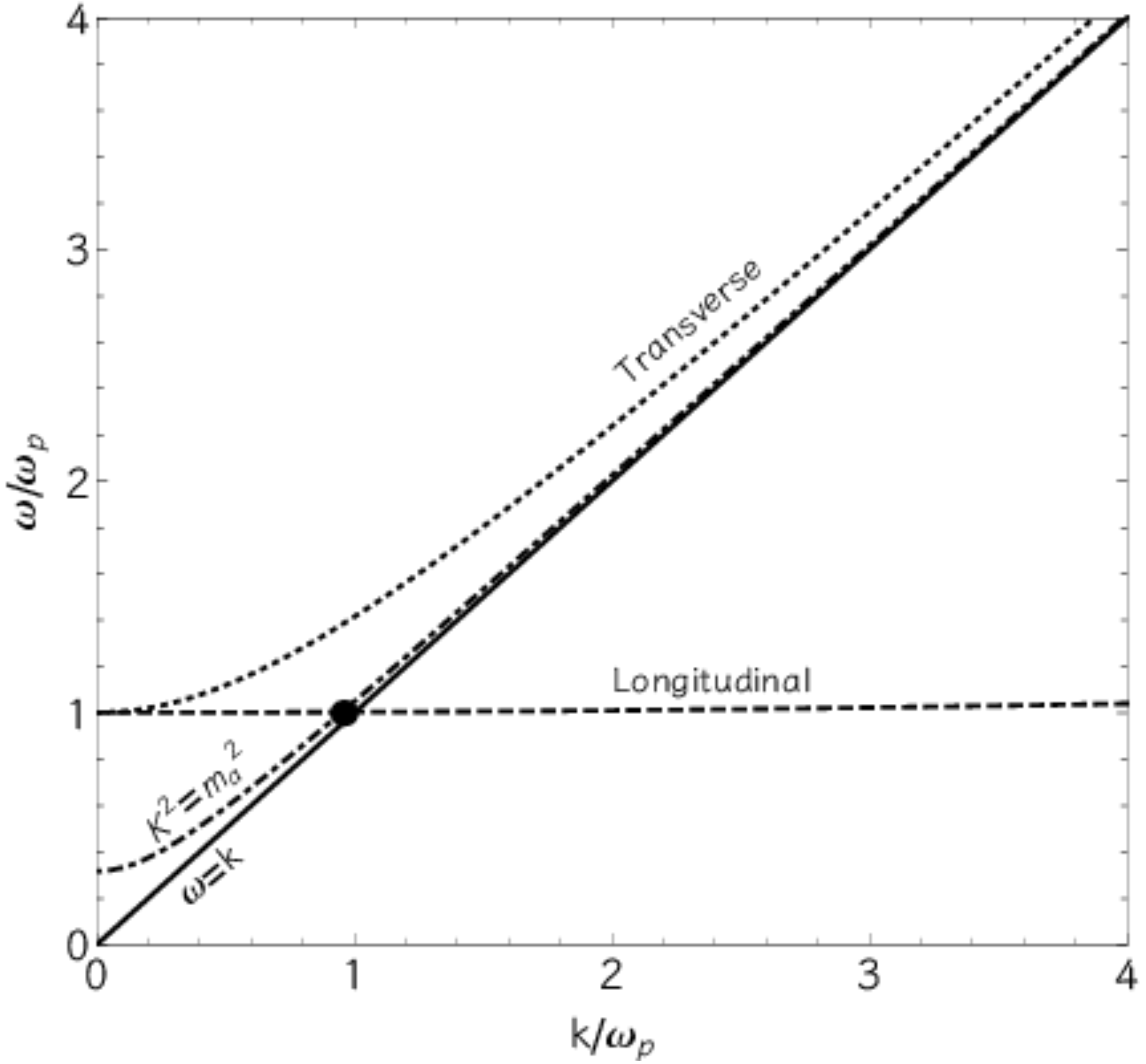
Axion Conversion in Neutron Stars



arXiv:2004.06486

Axion Conversion in Neutron Stars

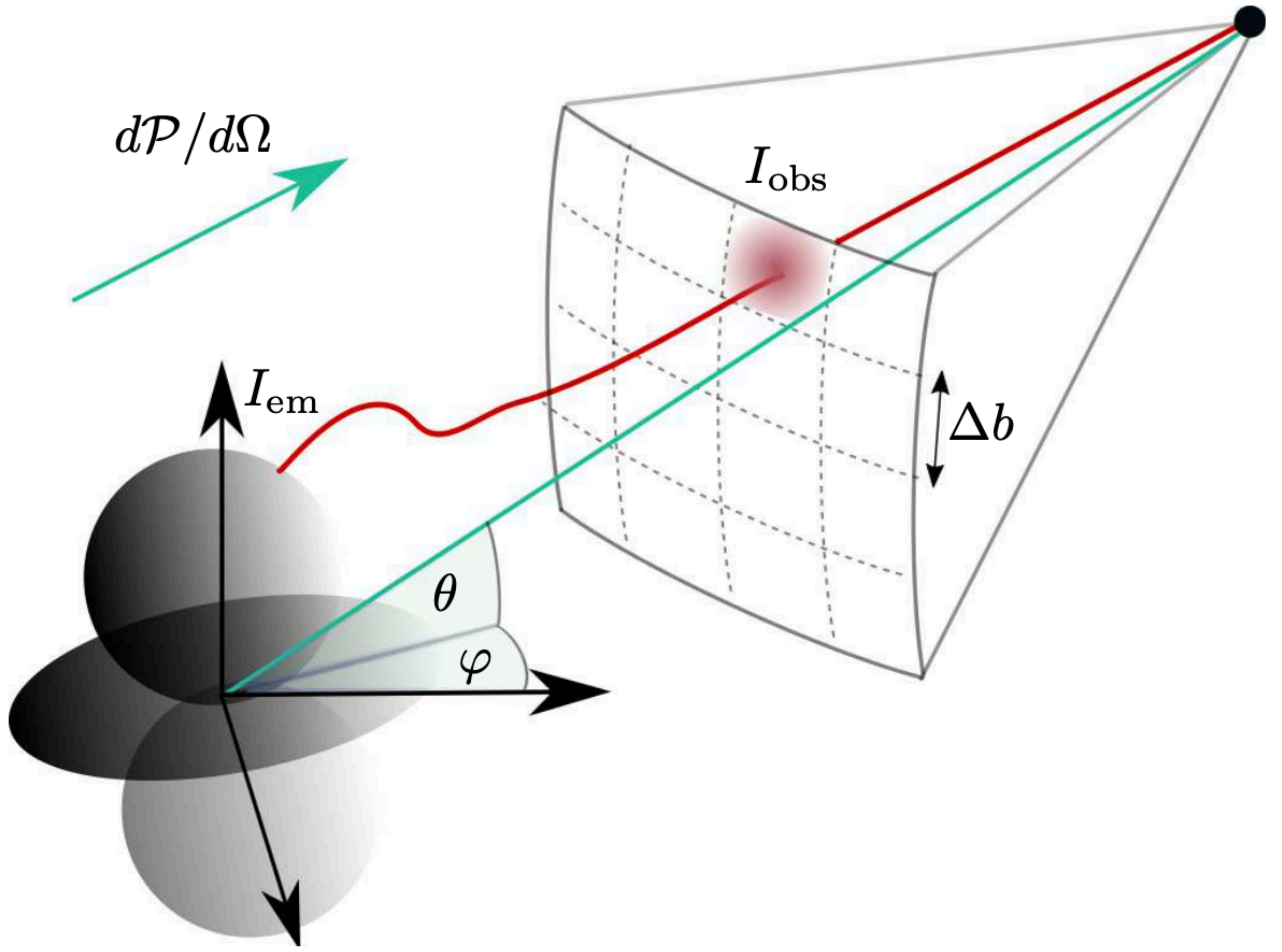
- NS have the largest known B-fields
- DM axions fall into the star
- Convert in the plasma surrounding the star
- Need to match energy and momentum
- Photon mass ~ plasma frequency
- Complicated anisotropic plasma



arXiv:2005.00078

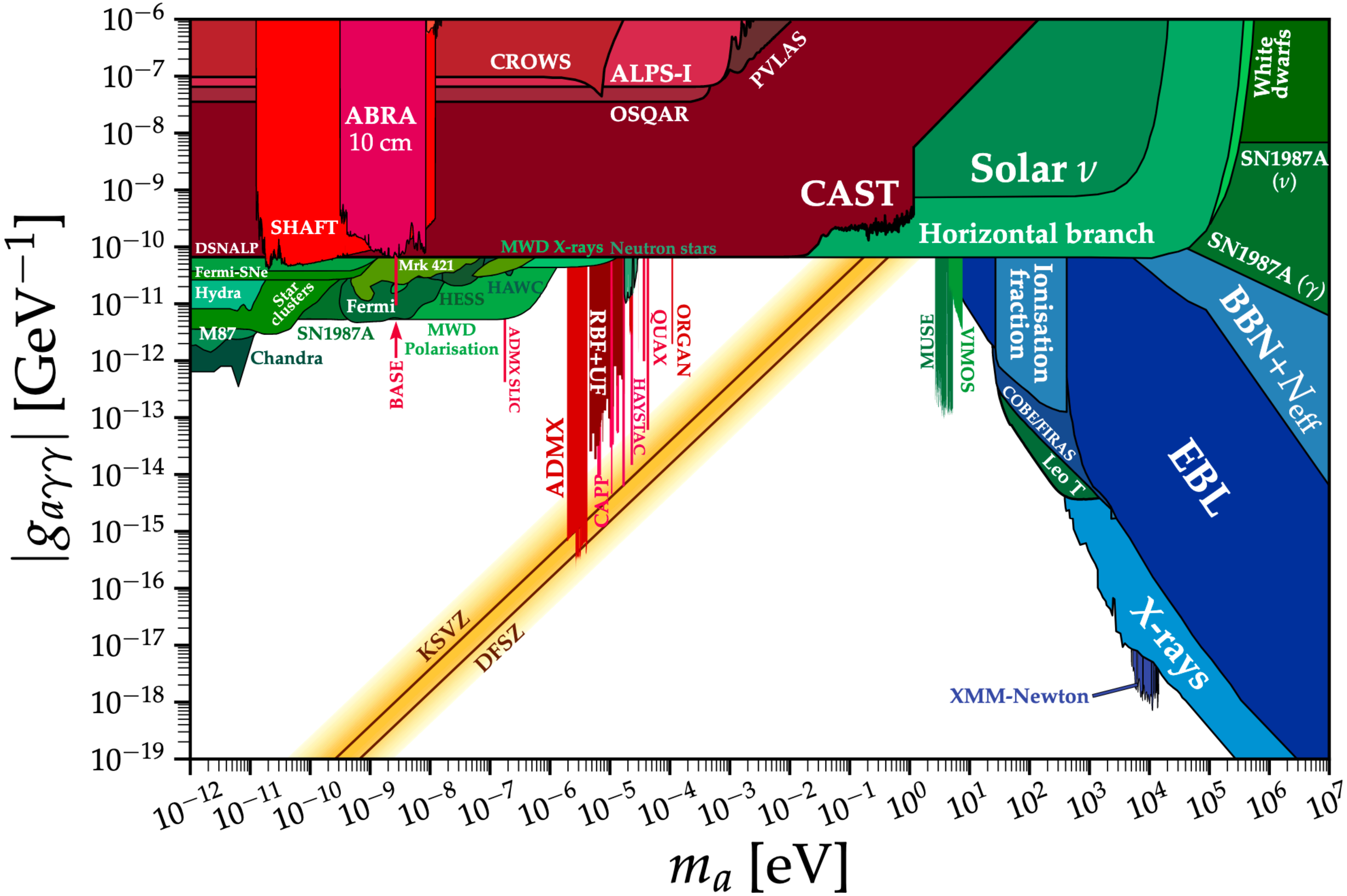
Axion Conversion in Neutron Stars

- Potentially detectable radio line
- Also need to ray-trace the photon to an observer
- Huuuuge systematic uncertainties
- Generally better for discovery than limits



arXiv:2104.08290

Axion-Photon Limits



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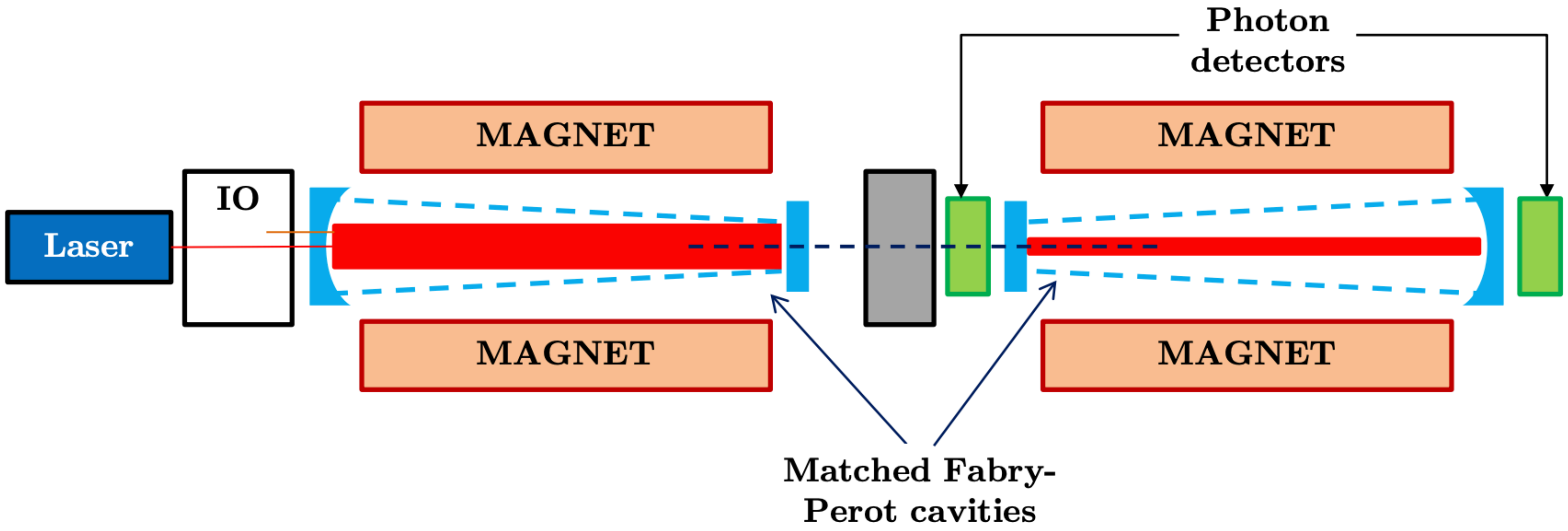
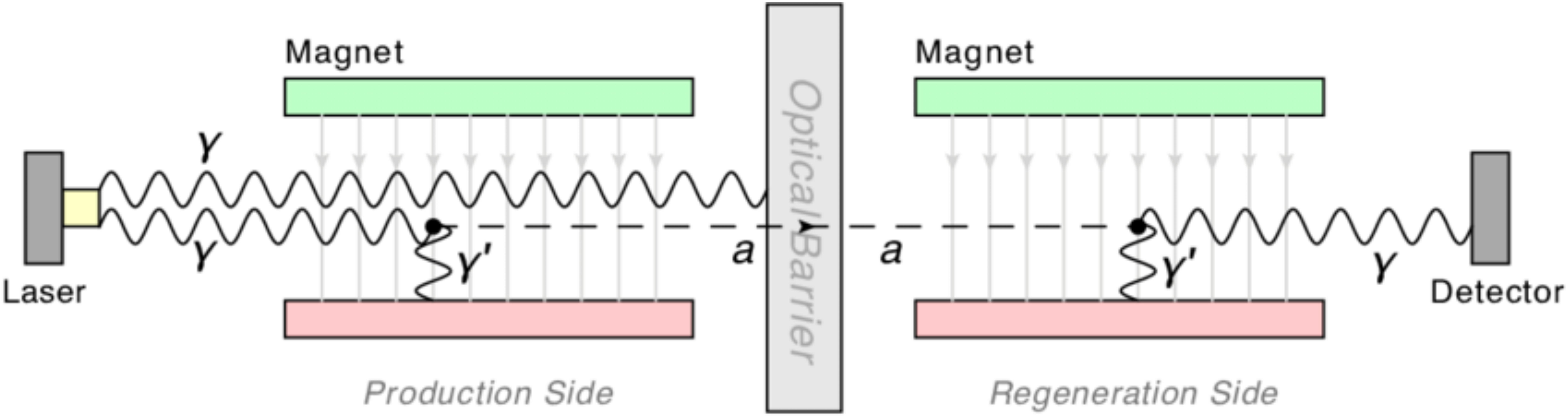
Lab Experiments

- Why not produce axions ourselves?
- Light shining through wall
- 5th force experiments (ARIADNE)

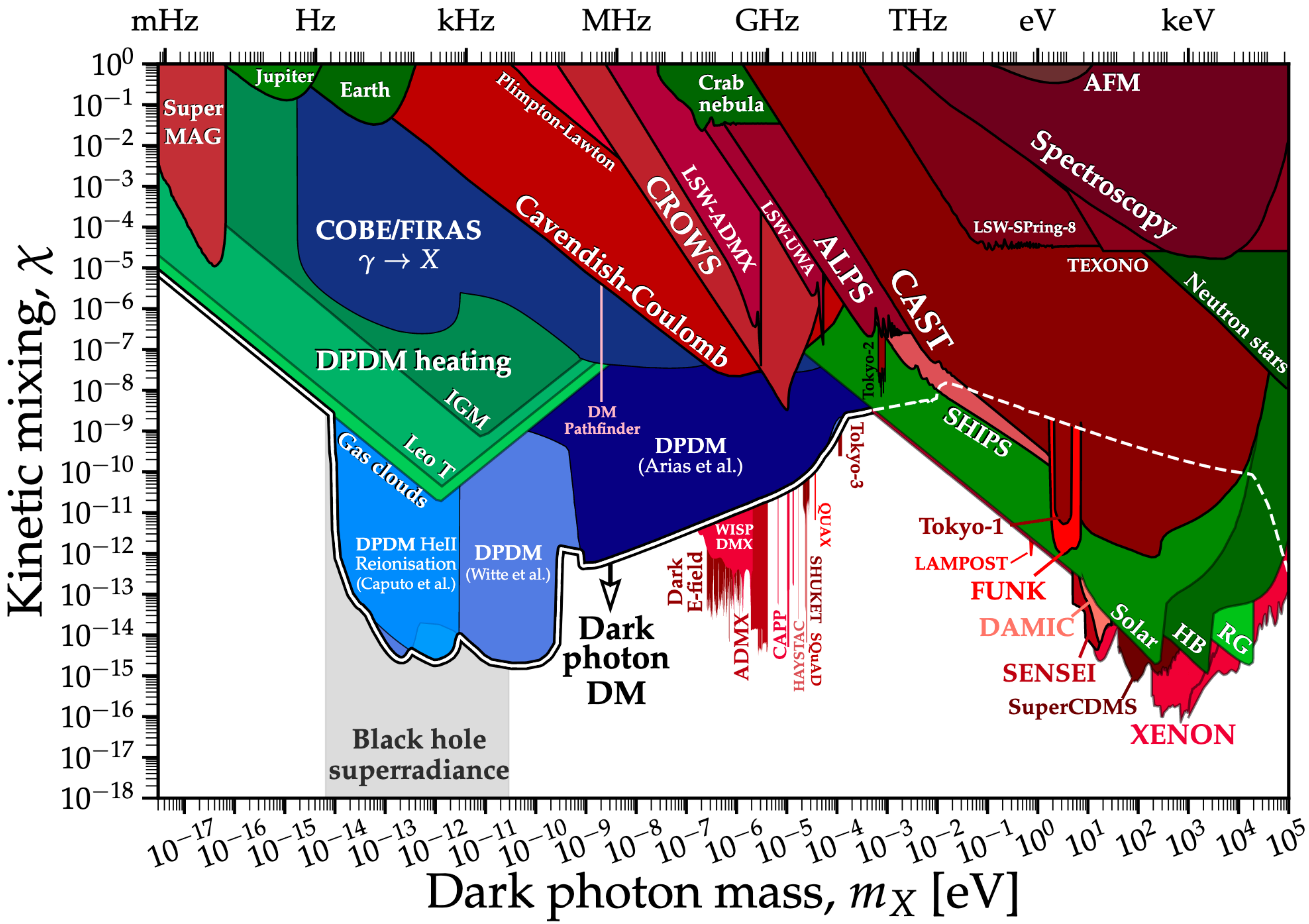


Light Shining Through Wall

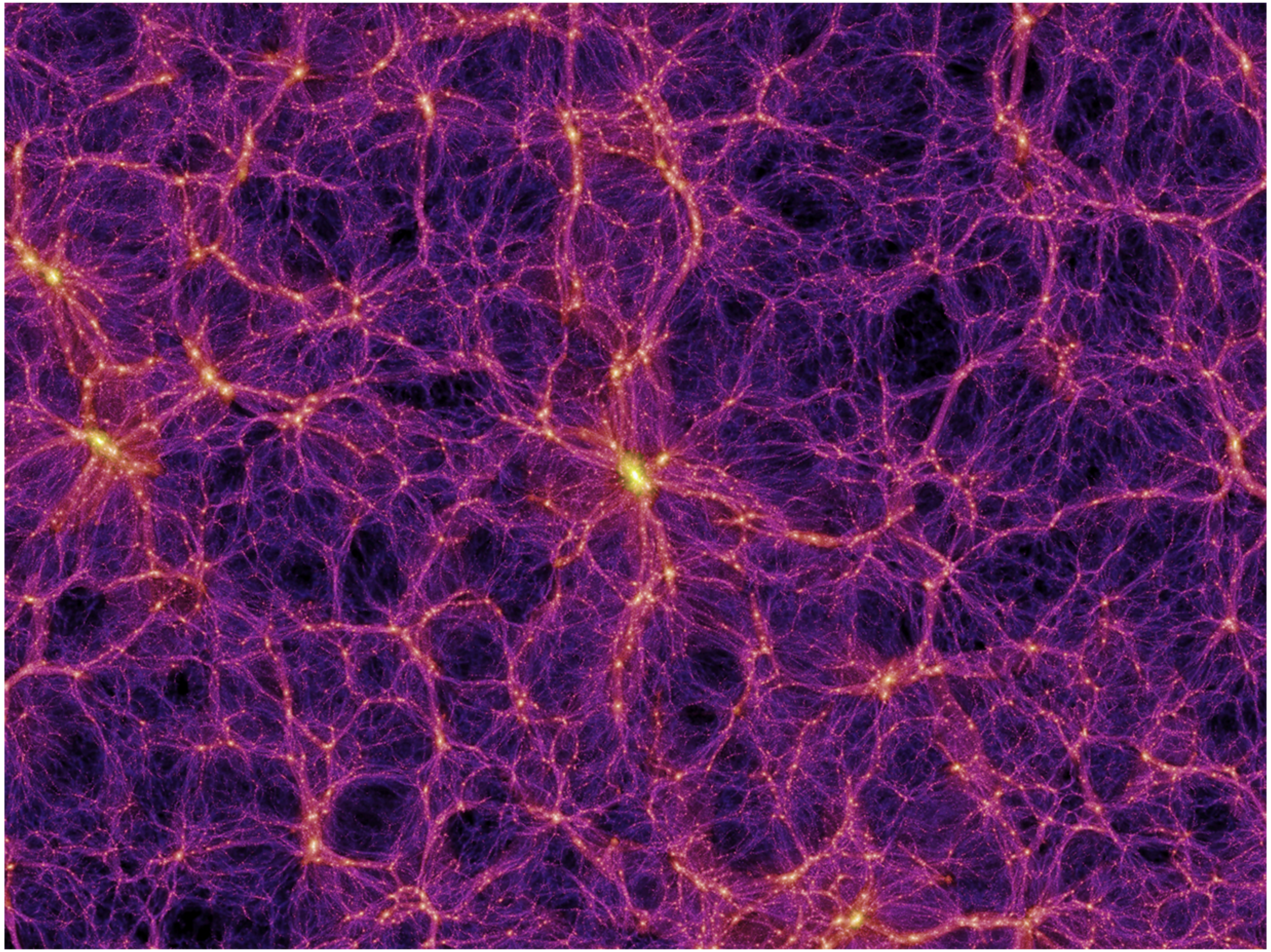
- Least systematic uncertainties
- Usually worst limits (four powers of coupling)
- Recent ideas including superconducting cavities with microwaves



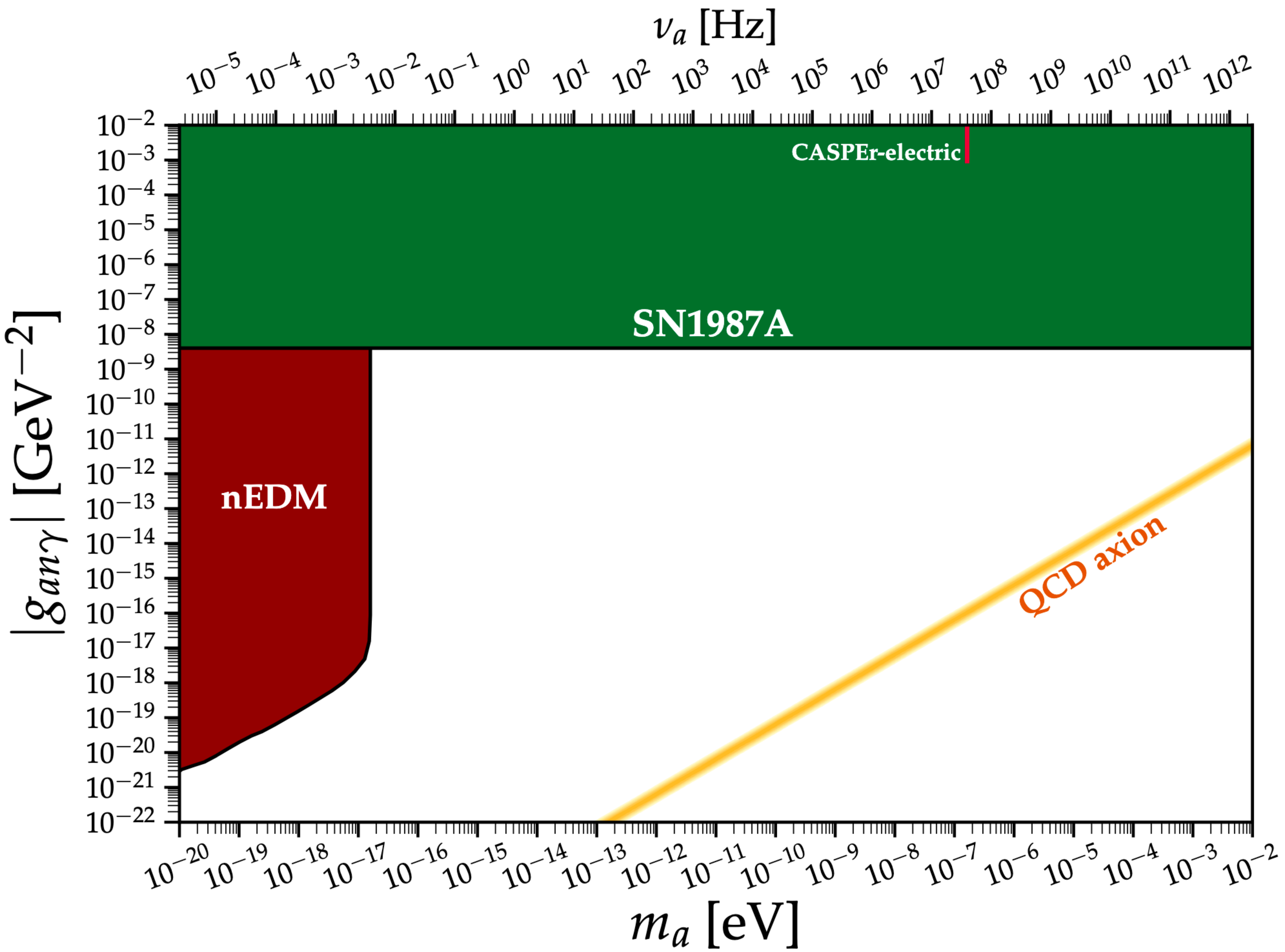
Dark Photon Limits



Next Time: DM Searches



Axion-EDM



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