Beyond the Standard Model with high power lasers and XFELs

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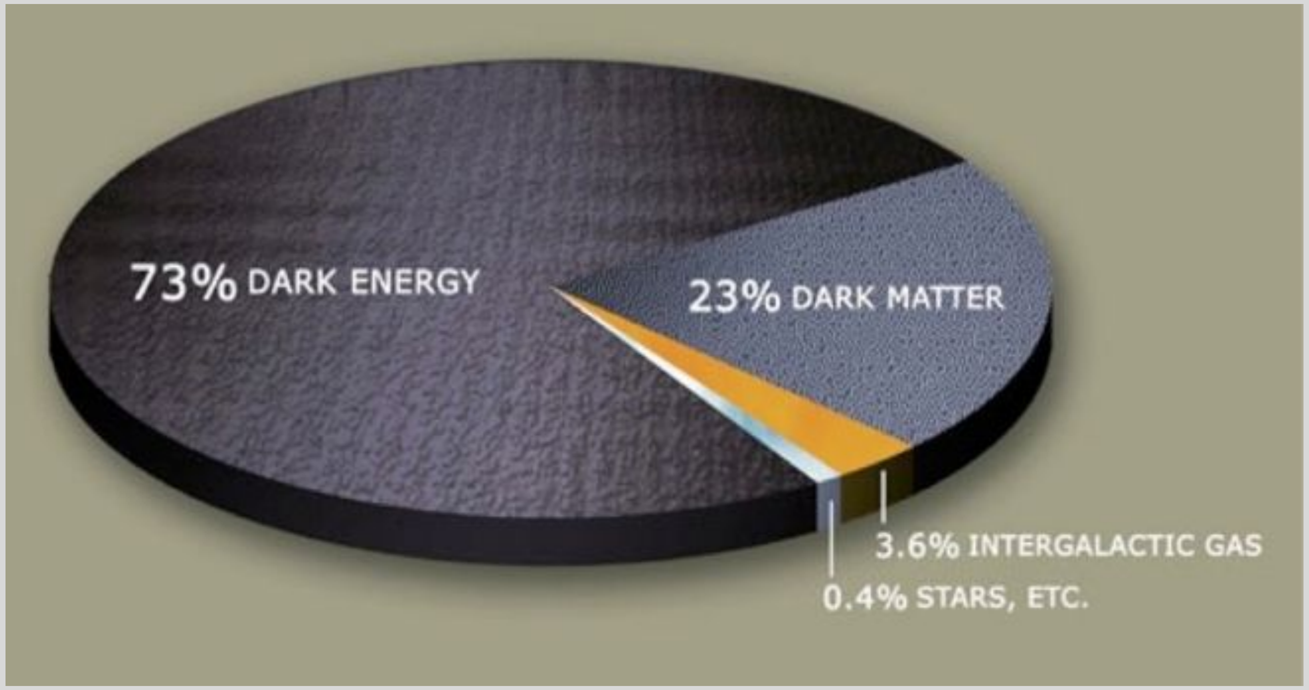
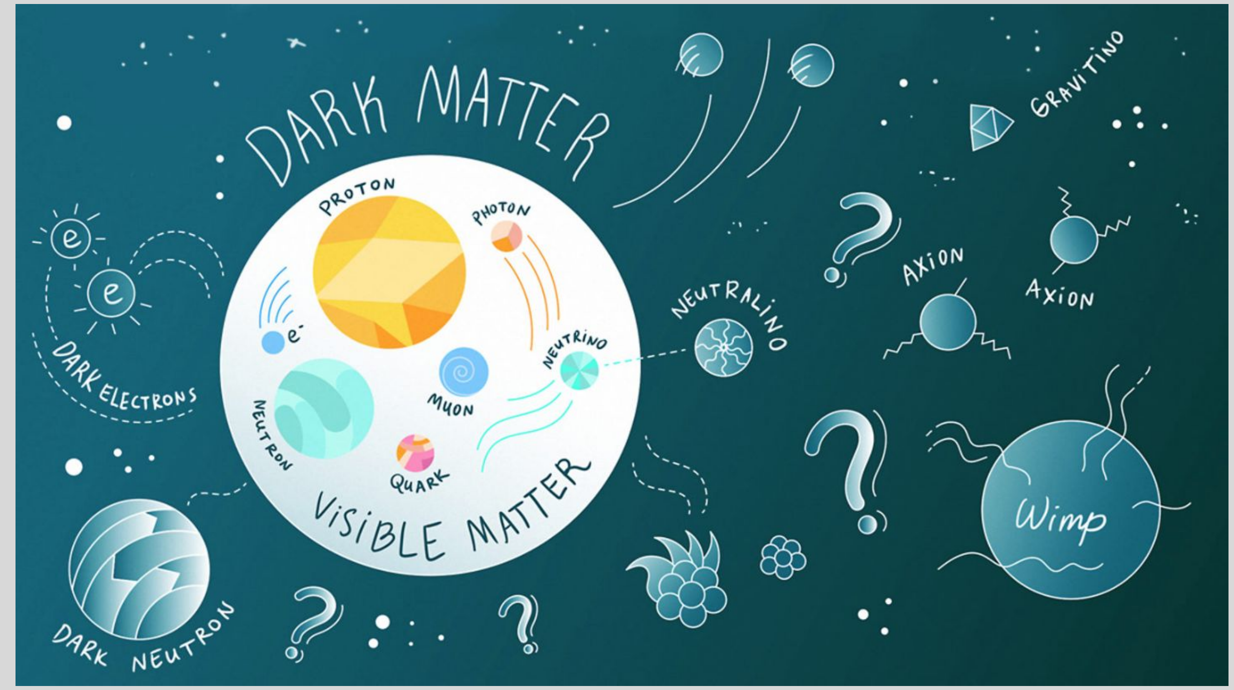
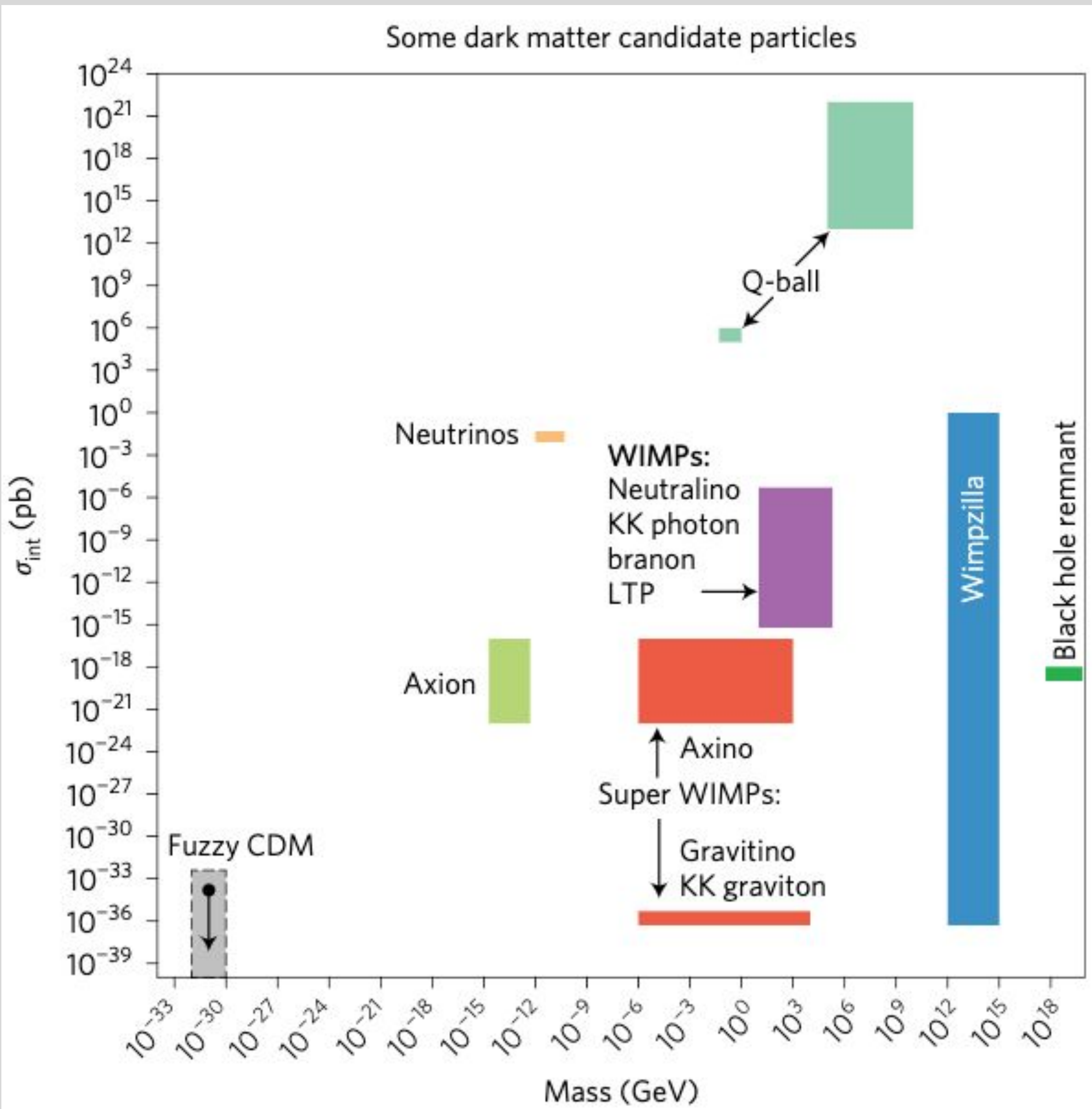
Our understanding of the Universe is limited to only the luminous matter





- The existence of dark matter is inferred from:
  - Rotation curves of galaxies (but evidence is debatable as distance galaxies are dim background light from Milky Way needs to be subtracted)
  - Micro-lensing
- Dark energy is believed to explain the acceleration of the Universe
- *So far there is no direct experimental evidence of neither dark matter or dark energy*
- *Experimental laboratory searches are important*

Many possibilities for dark matter candidates



Conrad & Reimer, Nature Phys. 2017

- ➜ Many possibilities spanning an enormous range of energies/masses
- ➜ Some theories are more developed than others
- ➜ Searches with particle accelerations have mostly concentrated on the higher mass regions (WIMPs) but no positive detection has been made
- ➜ Astrophysical observations provide some indirect bounds

Axions are required to fix the Standard Model

- Axions are pseudo-scalar particles postulated to exist to explain the absence of CP violation by the strong interaction $\mathcal{L}_{QCD} = \ldots + \theta_{QCD}\mathbf{G}\tilde{\mathbf{G}}$

- Experimental limit on neutron electric dipole moment implies $\theta_{QCD} \ll 10^{-10}$

- Promote θ_{QCD} to dynamical variable which can relax to zero (Peccei & Quinn 1977)

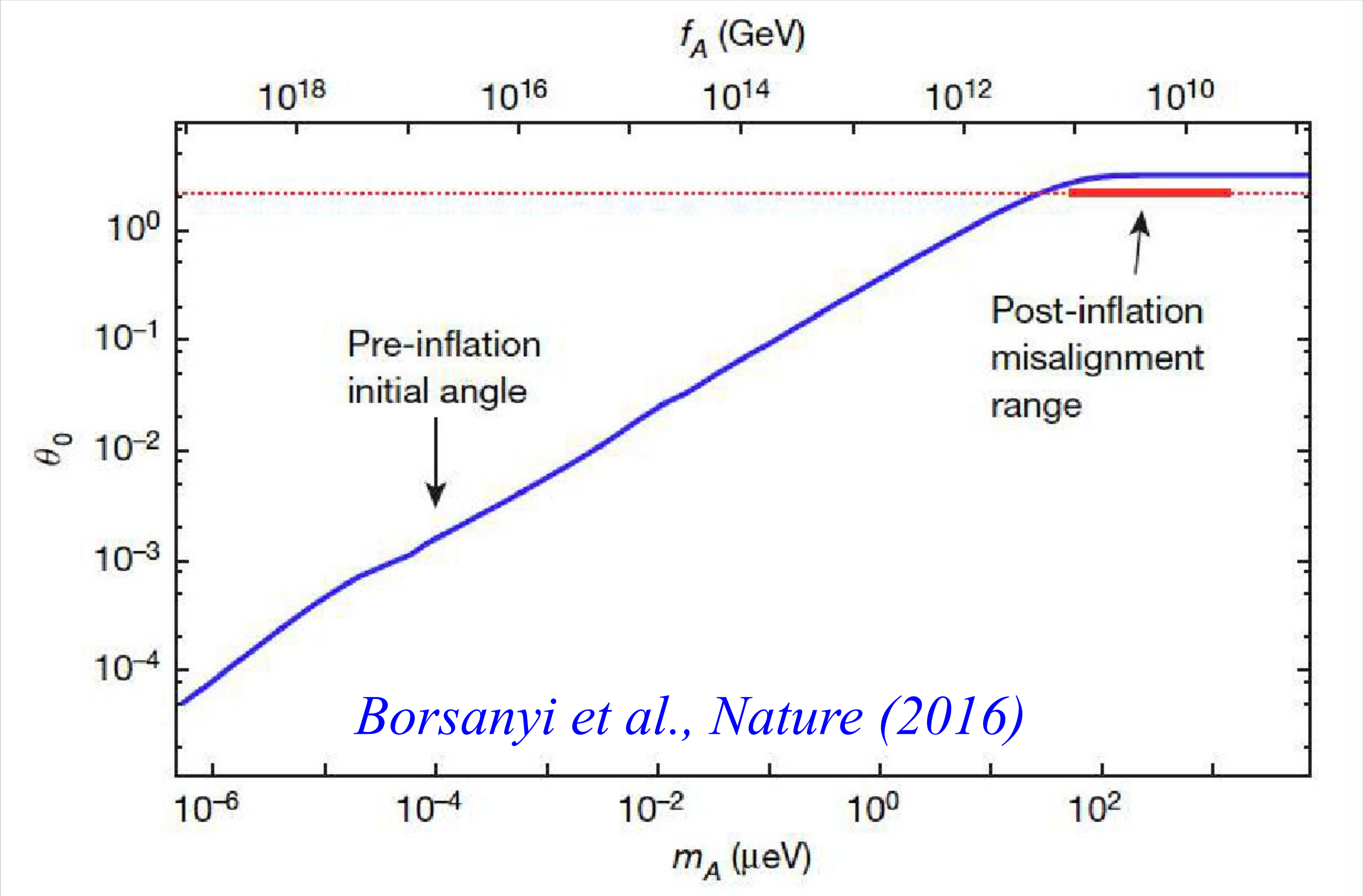
- Axion is Nambu-Goldstone boson of the high energy breaking of $U(1)_{PQ}$ symmetry

- String theory compactification leads to (pseudo)scalar particles that do not necessarily couple to the QCD fields. These are axion-like particles (ALPs) are less prescribed by theory

Light axions are predicted by lattice QCD calculations

- Axions can naturally be the dark matter (for $f_a \sim 10^{10-12}\ \mathrm{GeV}$)

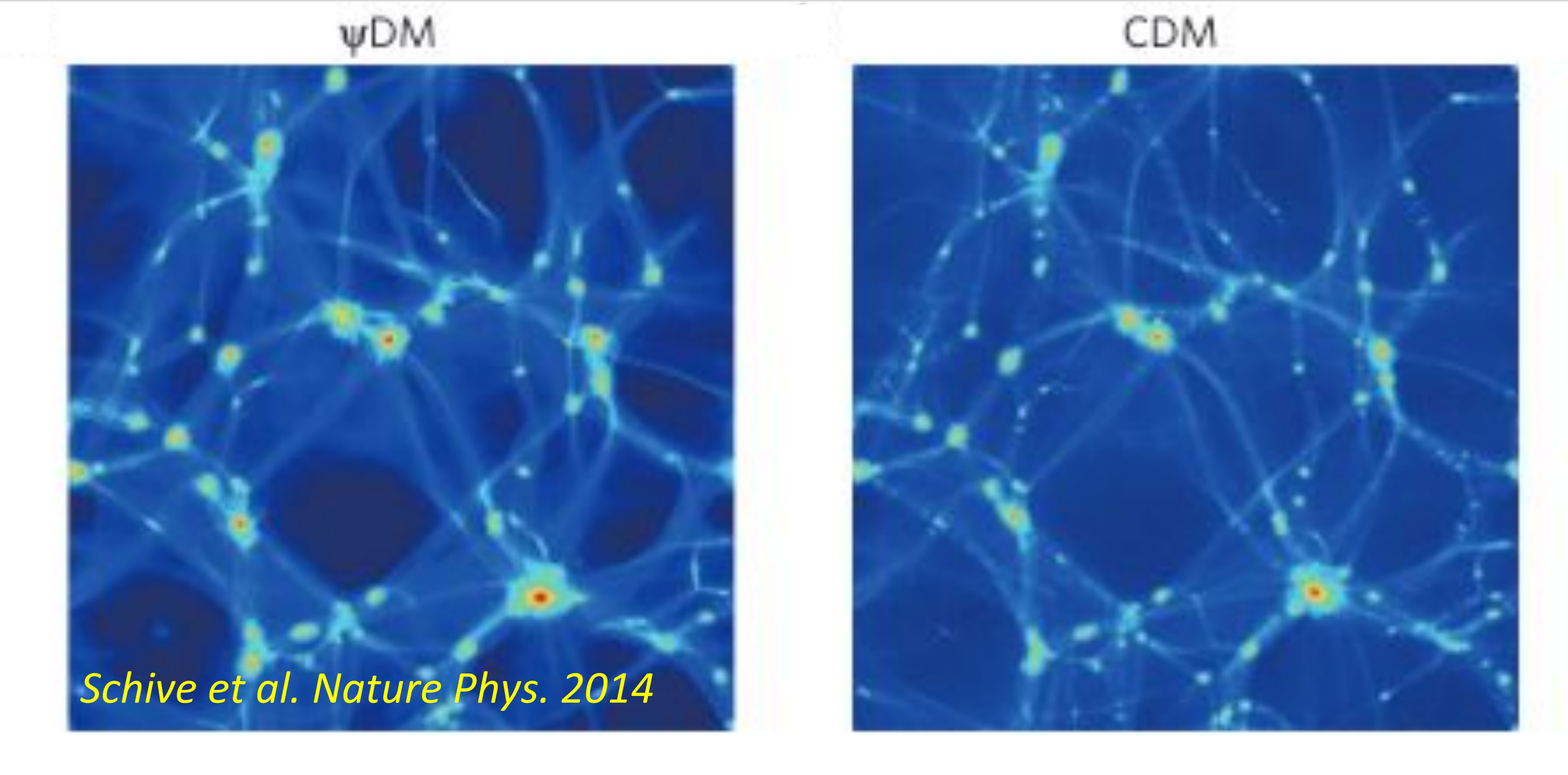
- Lattice calculations pin down m_a (f_a) for QCD axions to be the major constituent of dark matter

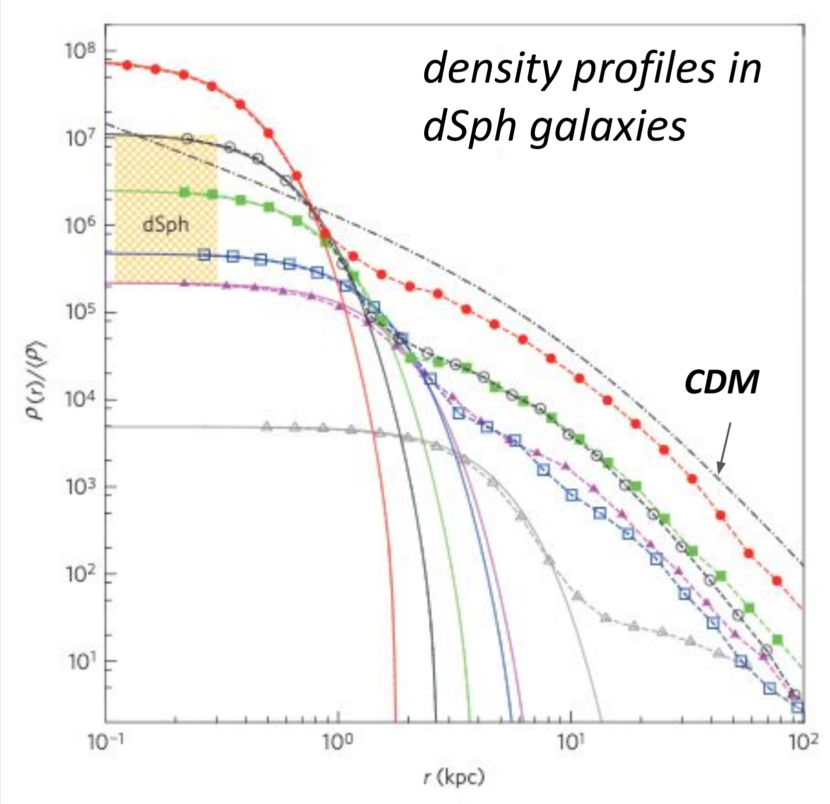


- Assuming dark matter is made of axions, the axion field is:

$$a(R) = (2\rho^0_{\mathrm{DM}})^{1/2}/R^{3/2}m_a \qquad \rho^0_{\mathrm{DM}} = 9.6 \times 10^{-12}\ \mathrm{eV}^4$$

Ultra-light axions could explain the large-scale structure of the Universe





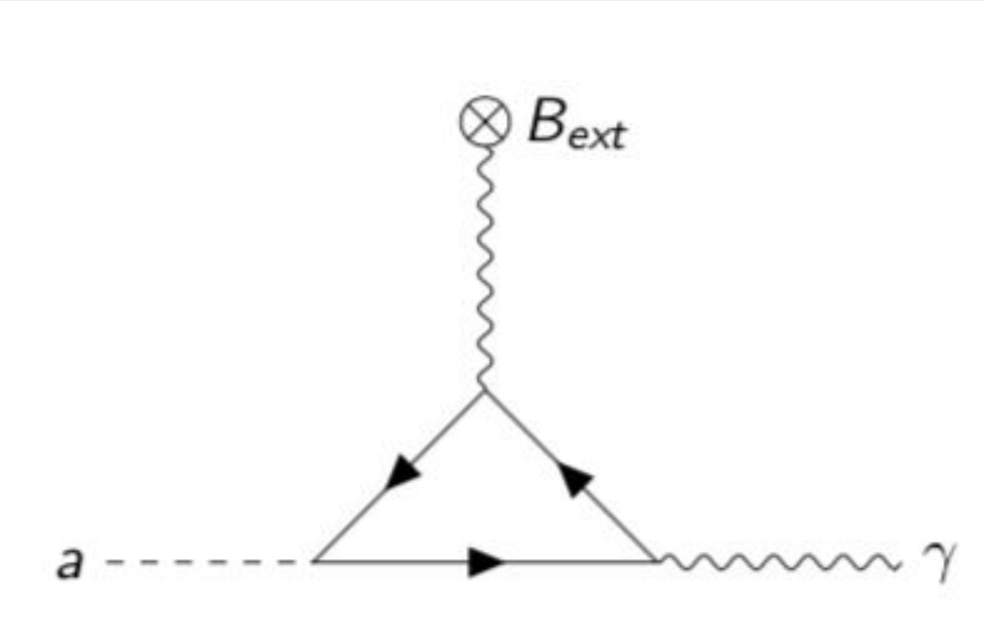
- ➜ Structure formation simulations with and without axion-like dark matter show difference in the visible matter distribution around spheroidal dwarf galaxies
- ➜ Simulations with axion-like dark matter agree with observational data if the axion mass is ~10^{-22} eV (i.e., with a Compton wavelength of the same order as the size of the galaxy)
- ➜ Similar masses are also inferred from the solution to Friedmann's equation in presence of a pseudo-scalar field (*Gregori et al. ApJ 2019*)

QCD axions and ALPs

- QCD axions and pions share the same quantum numbers. Mixing with the pion gives it a small mass

$$m_a = m_\pi (f_\pi / f_a)$$

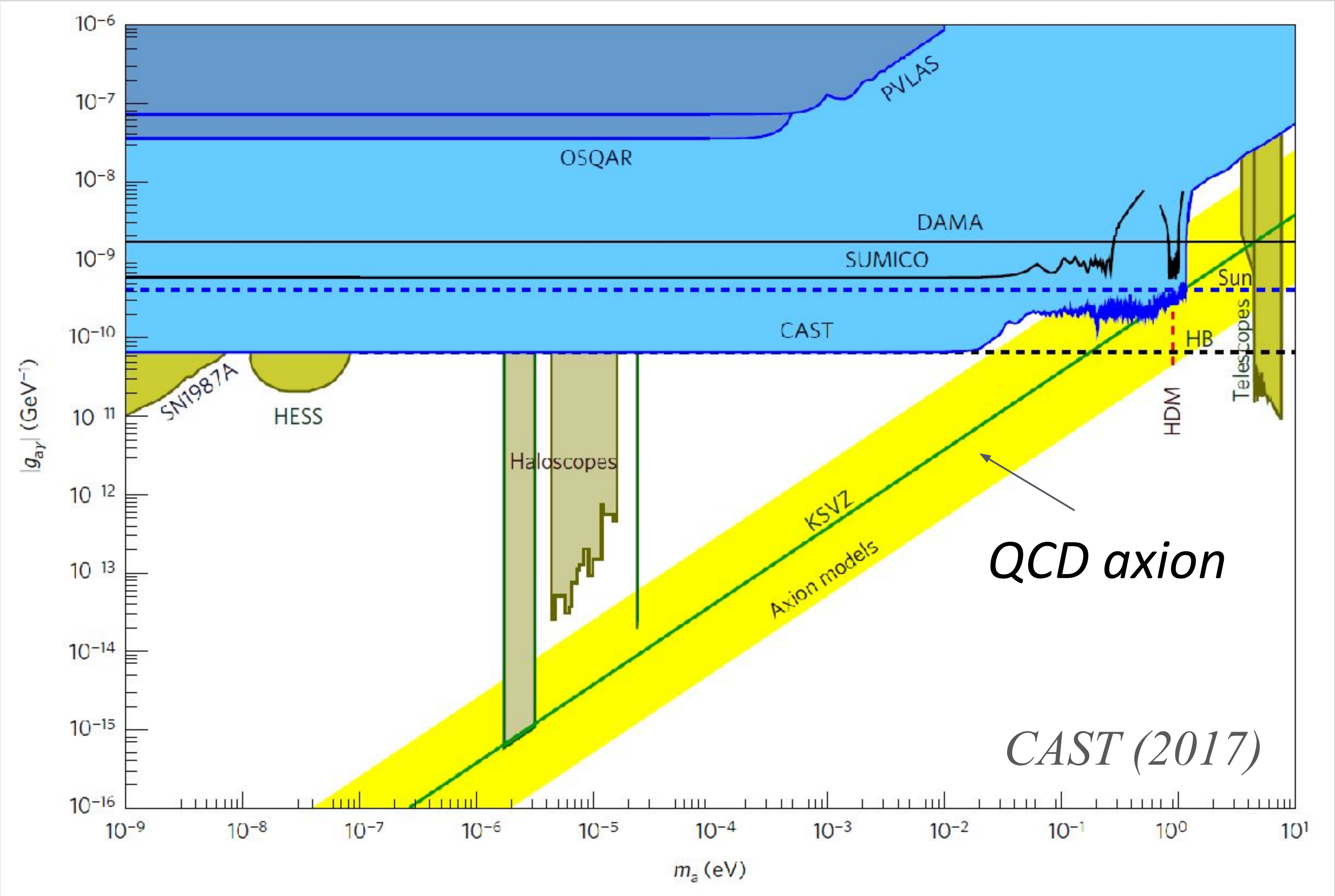
- Hence, axions couple to QED via a loop-induced two-photons diagram
- In presence of an external field, this is an effective mass mixing between axions and photons



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

$$g_{a\gamma\gamma} \approx 2 \times 10^{-22} (m_a / \mathrm{meV})^{-1} \ \mathrm{eV}^{-1}$$

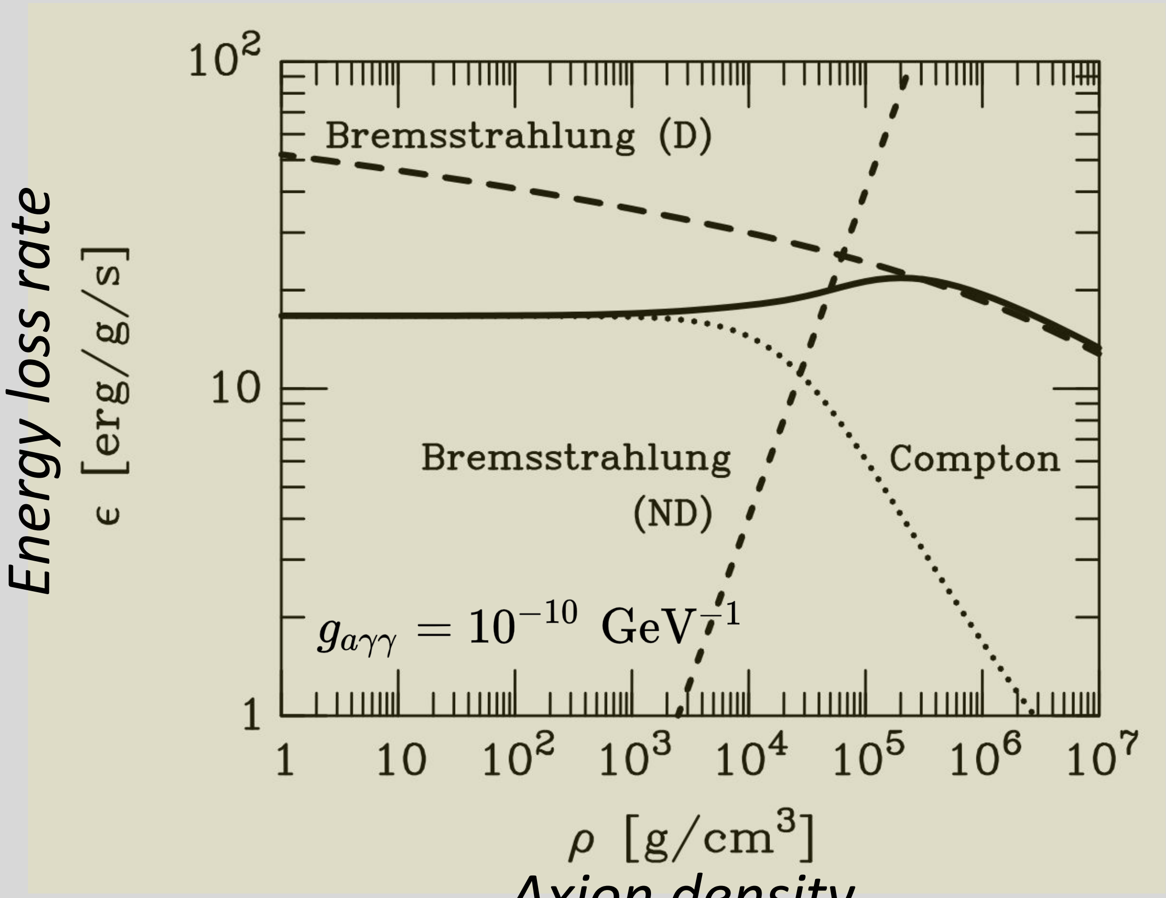
Experimental and astrophysical constraints on axion/ALPs



- Astrophysical bounds are based on stellar evolutionary models
- Helioscopes (e.g., CAST) constraints rely on solar models
- Haloscopes (e.g., ADMX) assumes axions/ALPs constitutes a large fraction of dark matter
- Laser bounds (e.g., PVLAS) are far from QCD predictions

Experimental and astrophysical constraints on axion/ALPs

Helium plasma at 10 keV



Energy loss rate

Axion density

Raffelt and Weiss, 1995

➜ Axions with energies ~10 keV can be produced in stars (Primakoff effect)

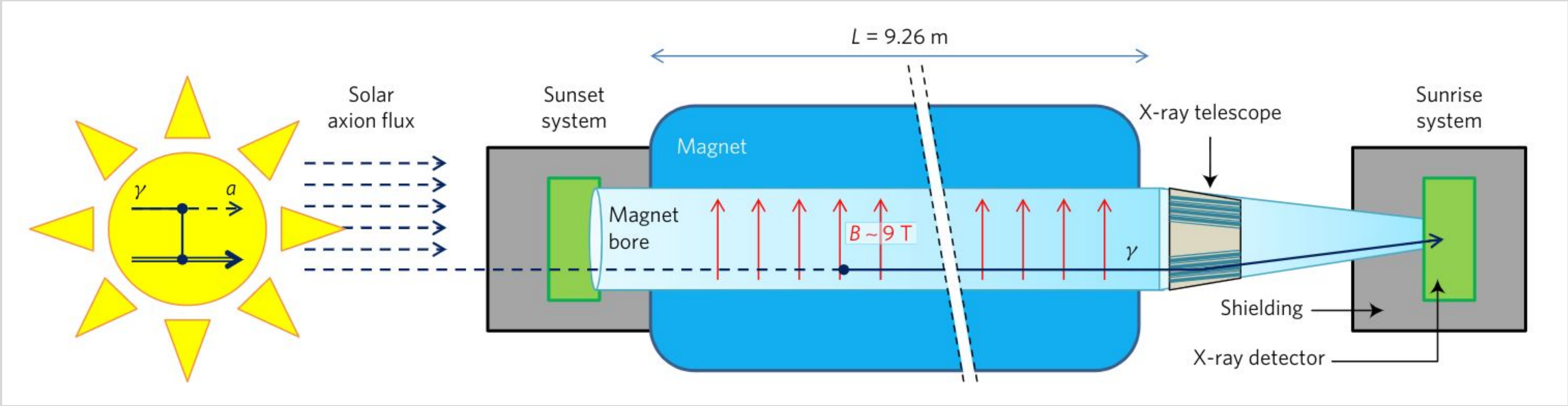
➜ Axions provides an extra energy loss mechanism: this leads to faster cooling

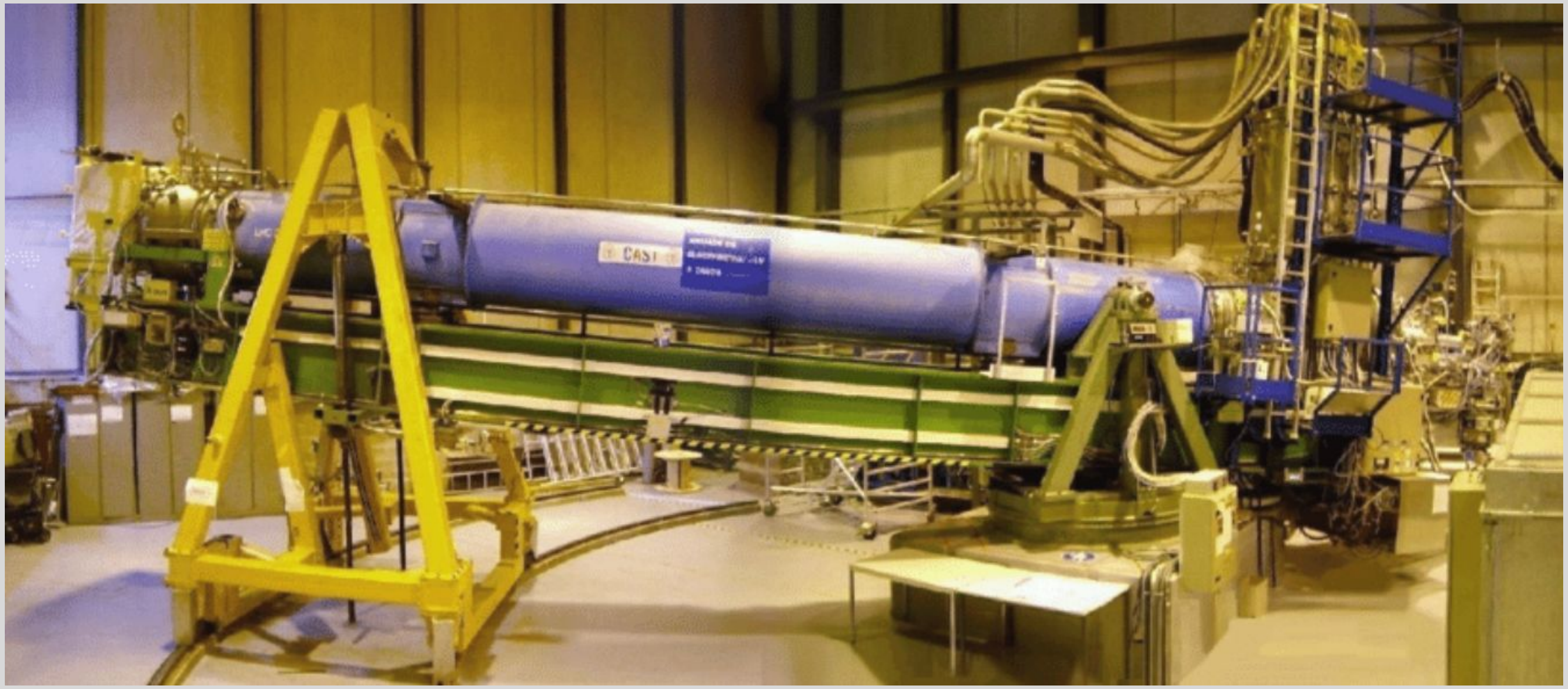
➜ Plasma screening effects must be included and this complicates the estimates of the axion flux

➜ The lifetime of horizontal branch stars sets:

$$g_{a\gamma\gamma} < 10^{-10} \ \mathrm{GeV}^{-1}$$

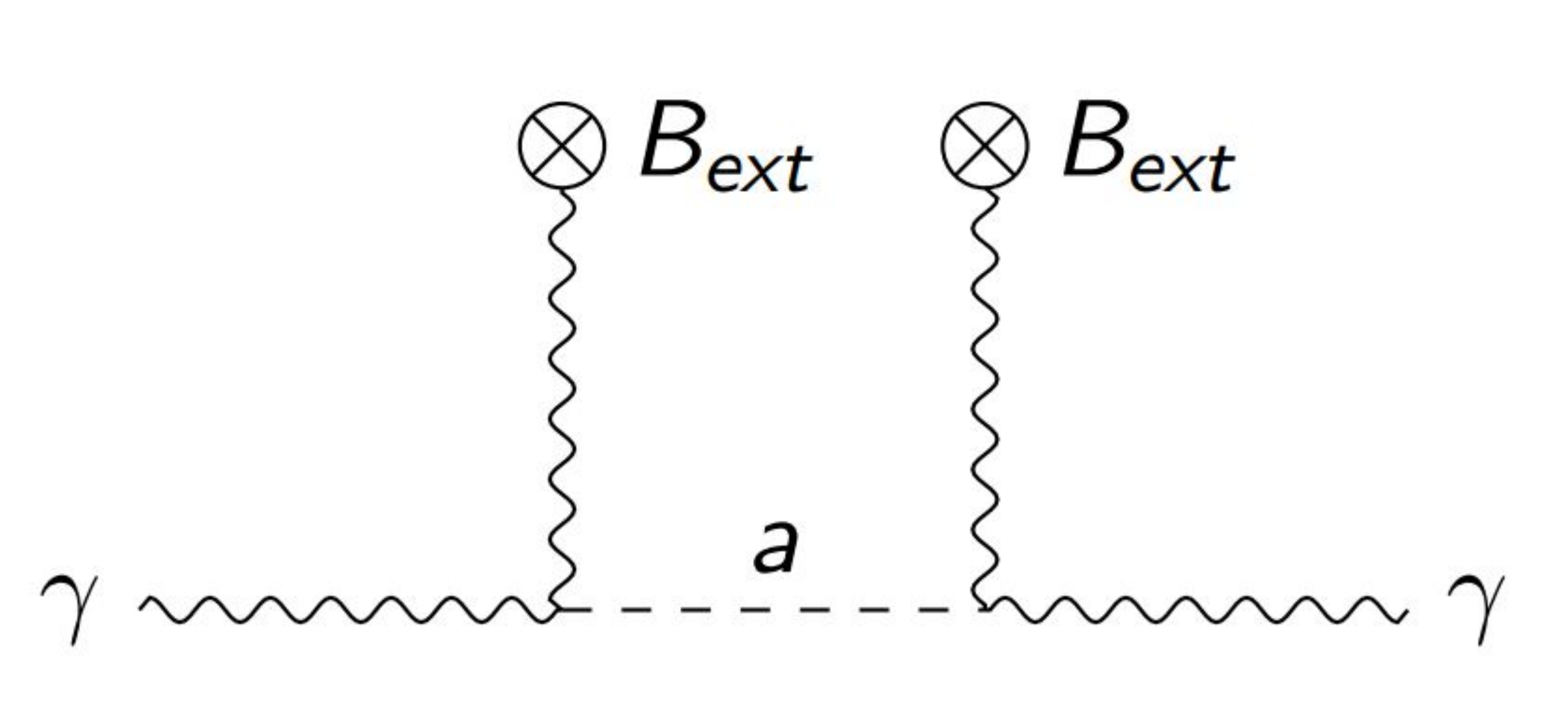
CAST telescope at CERN provides state-of-art axion constraints





- ➜ CERN Axion Solar Telescope (CAST) looks at the solar axions by converting them into X-ray photons with a magnetic field
- ➜ Provides one of the best bounds at higher axion masses
- ➜ Assumptions needed to estimate axion production in the Sun

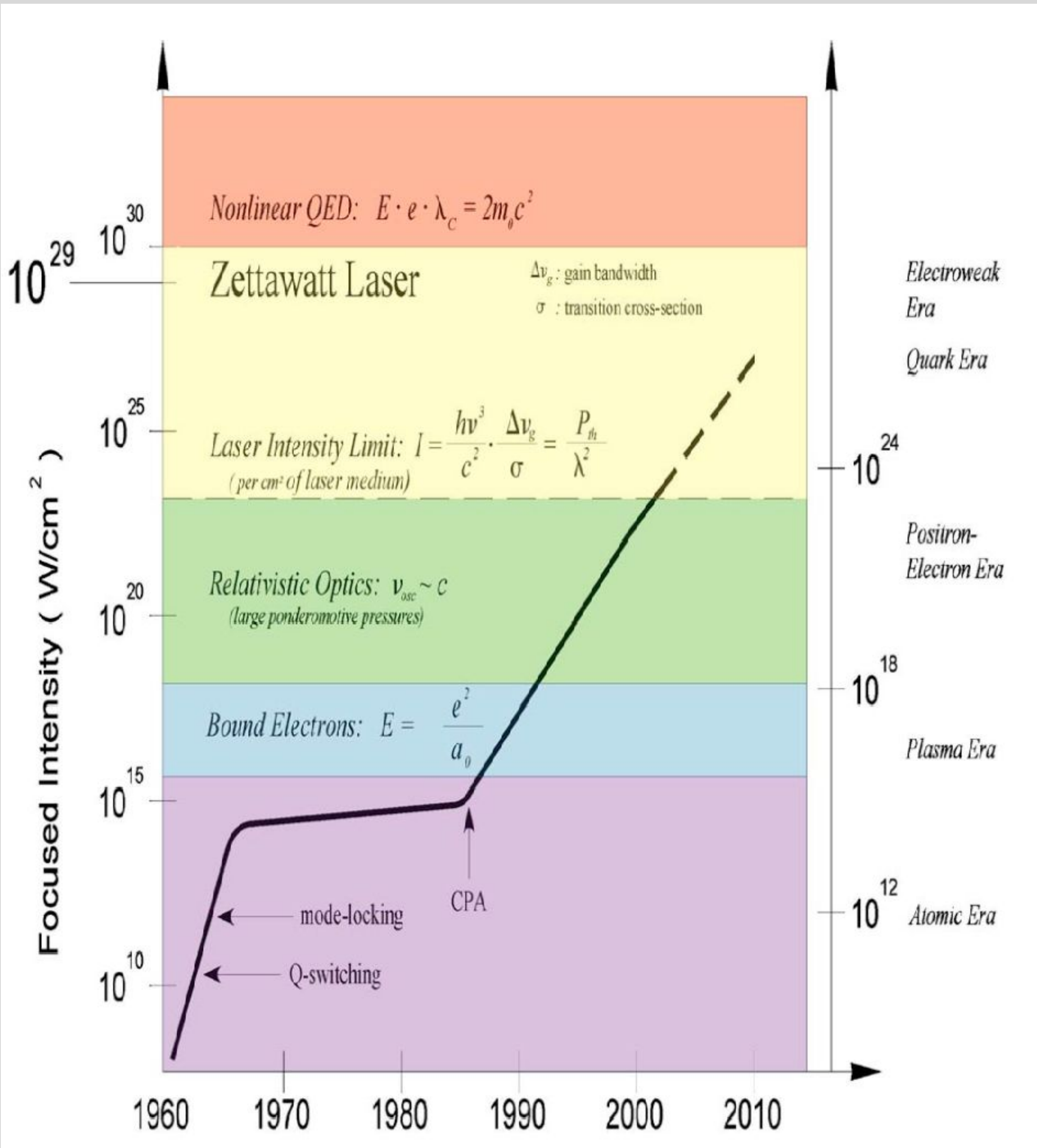
Detection techniques use regeneration of axions into photons



$$p_a = g^2_{a\gamma\gamma}\left(\frac{\alpha BL}{2\pi f_a}\right)^2 \frac{\sin^2\left(\frac{m_a^2 L}{4\omega}\right)}{\left(\frac{m_a^2 L}{4\omega}\right)^2}$$

- The probability of regeneration is maximized when $L \sim 4\omega\,(m_a)^{-2}$, which sets the length of the magnet with the axion mass

Optical photons have energies that naturally match those of the axions



- Progress enabled by CPA technique
- Normalized vector potential:

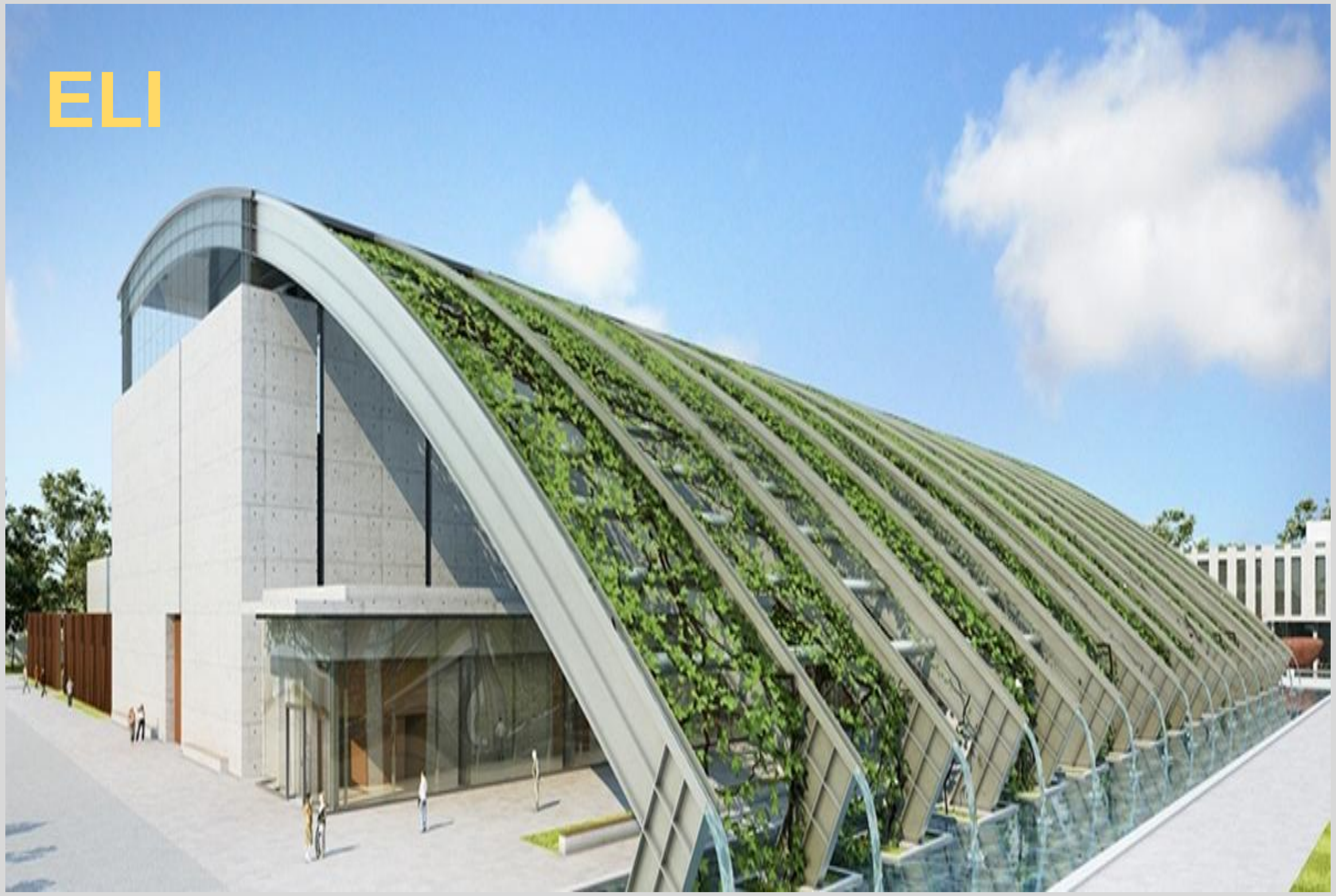
$$a_0 = \frac{eE}{mc\omega} = 0.6\left(\frac{I}{10^{18}W/cm^2}\right)^{1/2}\left(\frac{\lambda}{\mu m}\right)$$

- $a_0 > 1$ implies relativistic motion for the electron
- Quantum non-linearity parameter:

$$\eta = \frac{2\,a_0^2\hbar\omega}{mc^2} = 0.18\left(\frac{I}{10^{23}W/cm^2}\right)\left(\frac{\lambda}{\mu m}\right)$$

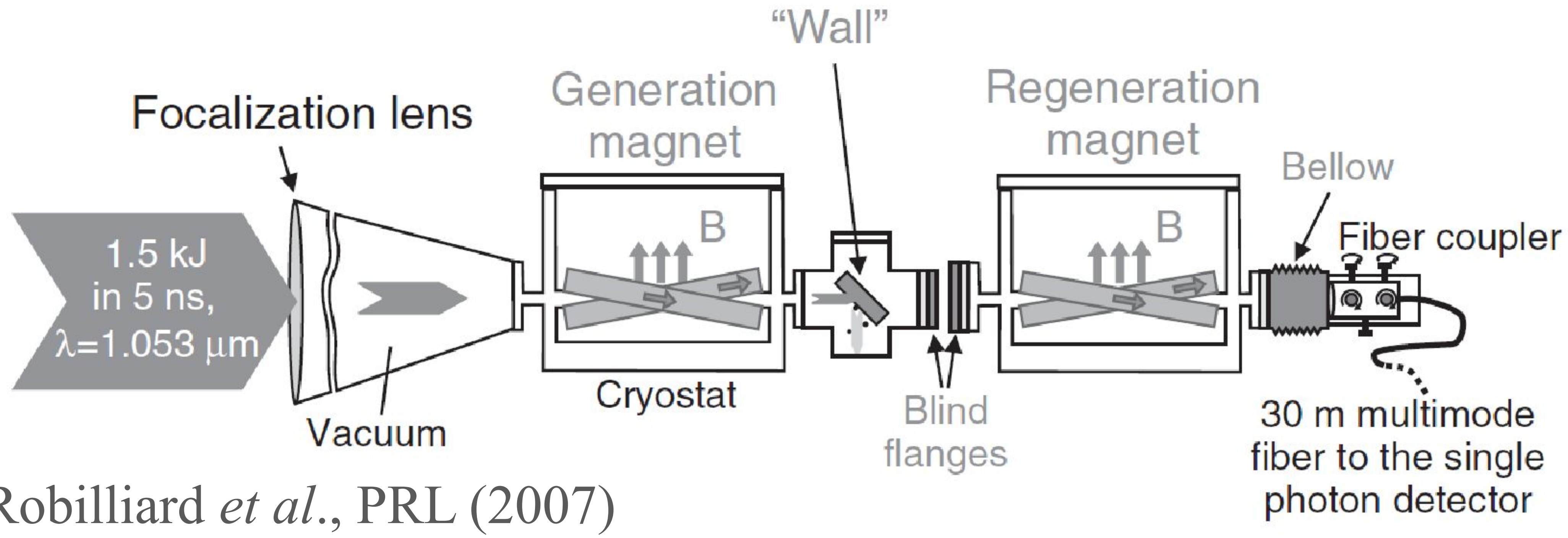
- $\eta > 1$ means that pair production is important

Optical and Free Electron Lasers can be used for axion searches



- ELI laser will achieve intensities $>10^{23}$ W/cm^2, much higher than any current laser system
- XFEL.EU has achieved highest brightness in X-rays than any other sources
- **A combination of these facilities may be envisioned for fundamental physics research**

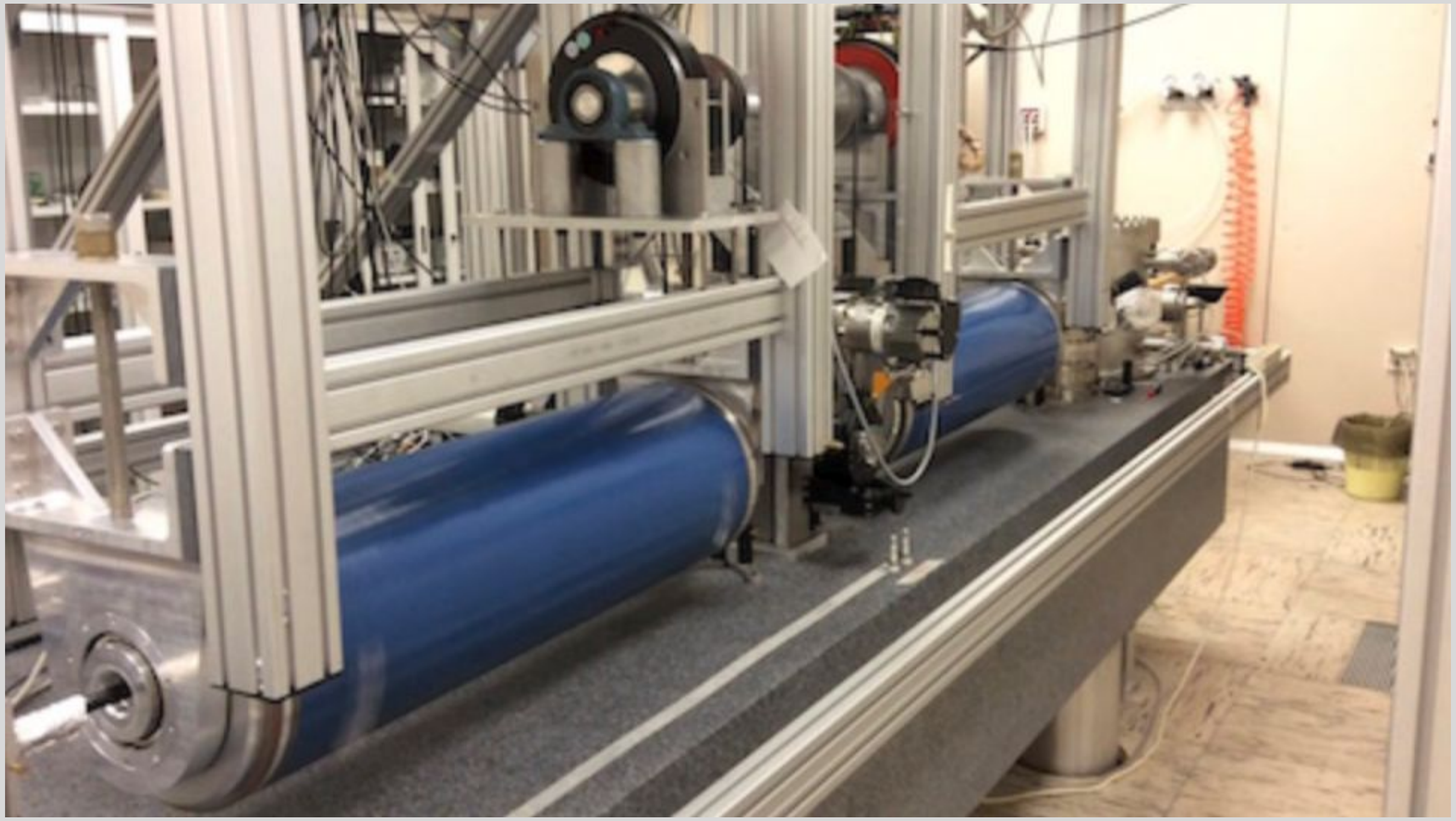
Light-through-wall experiments have provided model-free bounds

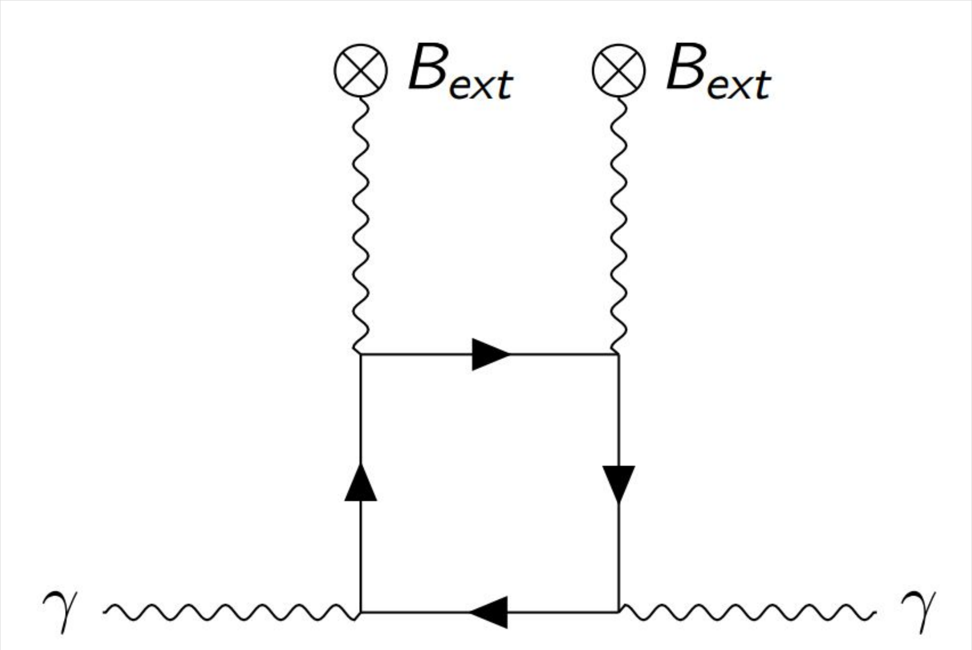


Robilliard *et al*., PRL (2007)

- No need to rely on model-dependent axion production mechanisms
- Light-through-wall experiments suffer from low sensitivity - due to conversions from axions to photons and back
- Used to look for ALPs with large coupling ($g_{a\gamma\gamma} > 10^{-4}$)

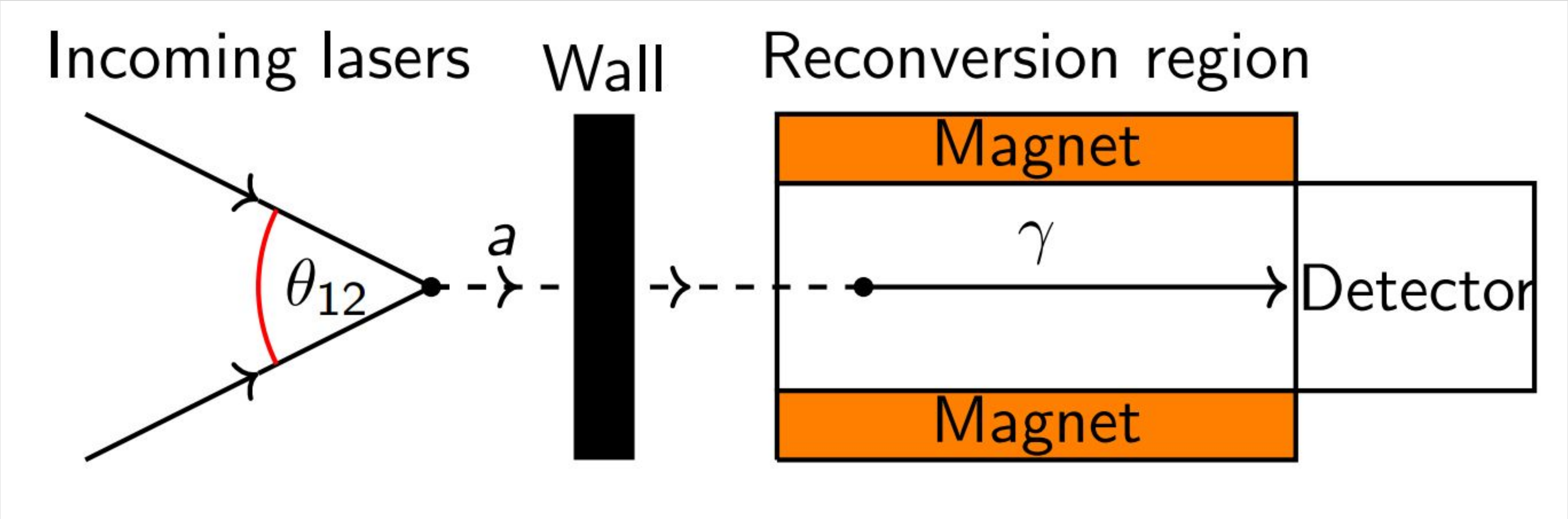
PVLAS can achieve higher sensitivity but limited by QED effects

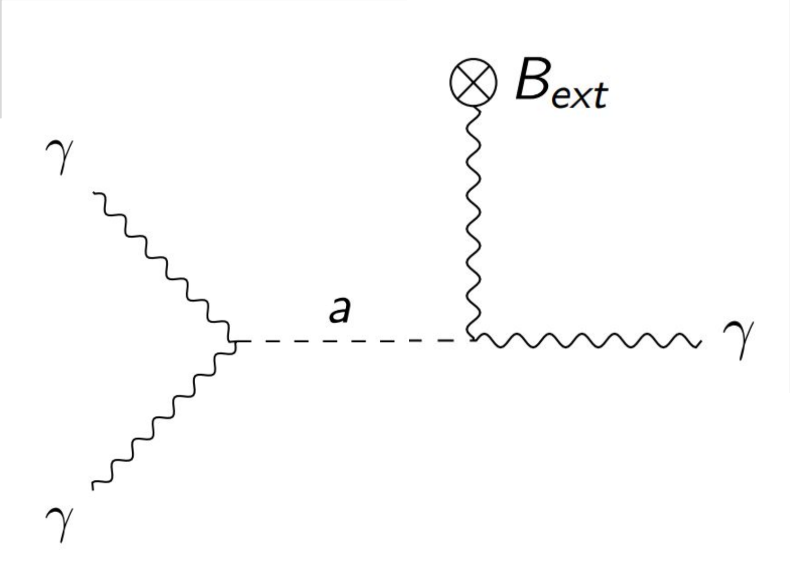




- PVLAS (Polarizzazione del Vuoto con LASer) aims at measuring the birefringence and dichroism induced by the axion contribution to the effective photon mass
- Birefringence goes as $(g_{a\gamma\gamma})^2$ instead of $(g_{a\gamma\gamma})^4$
- However, the same effect can occur via the QED box diagram (from the Heisenberg-Euler Lagrangian)

An alternative proposal: resonant scattering with on-shell axions





- Real axions are produced by two-photon scattering
- To detect a real axion, we must reconvert it at a macroscopic distance from production region
- No QED background, but effect goes as $(g_{a\gamma\gamma})^4$
- However, lower efficiency can be compensated by using laser substructures (patterns) within beam, enhancing scattering - analogous to Bragg scattering

How can improve the mass range and sensitivity of the bounds?

- Light-through-wall experiments suffer from double conversion (low sensitivity)
- The same problem occurs with on-shell photon scattering
- We have been working on an alternative proposal whereby axions are excited from the Unruh vacuum seen by an electron accelerated by a laser beam
- These axions can then convert into photons in an external magnetic field
- The advantage over light-through-wall experiments is that axion (re)generation happens only once

Motion of electrons in a laser field

- Assume electron is accelerated by laser electric field. If the motion remains non-relativistic, the Hamiltonian can be simplified by considering non-relativistic motions, $a_0 < 1$,

$$H = [(\boldsymbol{p} - e\boldsymbol{A})^2 + m_e^2]^{1/2} \approx \left(p^2 + \gamma^2 m_e^2\right)^{1/2}$$

- Now, consider an electron moving into a space-time defined by a metric $g_{\mu\nu} = h^2(x)\,\eta_{\mu\nu}$ (variable mass metric). The Hamiltonian is

$$H = \left(p^2 + h^2 m_e^2\right)^{1/2}$$

- The dynamics of the charged particle oscillating in the laser field in flat space-time may be equivalently described by the variable mass metric Hamiltonian of a free particle

Crowley *et al*., Sci. Rep. (2012)

Gregori *et al*., Class. Quantum Grav. (2016)

Axion generation in the accelerated frame

- We use the quantum Vlasov equation to calculate the rate of massive pseudo-scalar, spinless particle production as seen by an accelerated electron

$$\frac{dN_k}{dt} = \frac{\dot{\omega}_k}{2\omega_k}\int_{t_0}^{t} du\,\frac{\dot{\omega}_k(u)}{2\omega_k(u)}[1 + 2N_k(u)]\cos[2\theta_k(t) - 2\theta_k(u)]$$

$$\omega_k^2 = k^2 + m^2h^2 - \frac{\ddot{h}}{h} \qquad \theta_k(t) = \int du\,\omega_k(u)$$

- Because the electron is accelerated, it sees itself surrounded by a bath of pseudo-scalar particles
- We also assume the following Lagrangian:

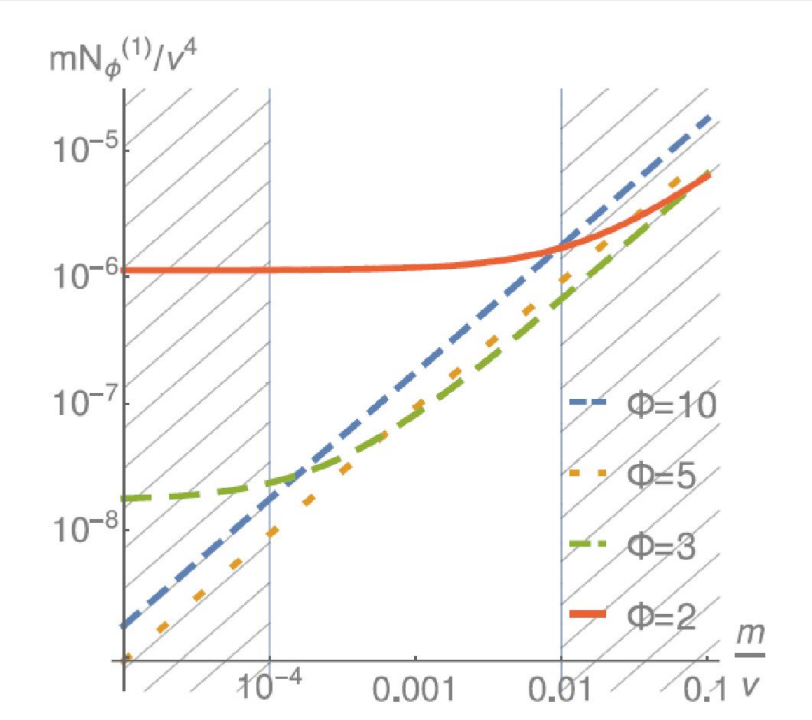
$$L = \frac{1}{2}\sqrt{\det g_{\mu\nu}}\left[g^{\mu\nu}(\partial_\mu\varphi)(\partial_\nu\varphi) - m^2\varphi^2 + g_{a\gamma\gamma}\boldsymbol{E}\cdot\boldsymbol{B}_{\text{ext}}\varphi\right]$$

Wadud *et al*., PLB (2018)

Number of axions produced by the time-varying metric is large

- In the accelerated vacuum, the observer (electron) sees itself surrounded by a thermal bath of particles
- Axions (if they exist) are produced by the same process that produces the Unruh/Hawking radiation
- By solving the quantum Vlasov equation, the number density of axions is obtained ($\xi \sim \mathcal{O}(1)$)

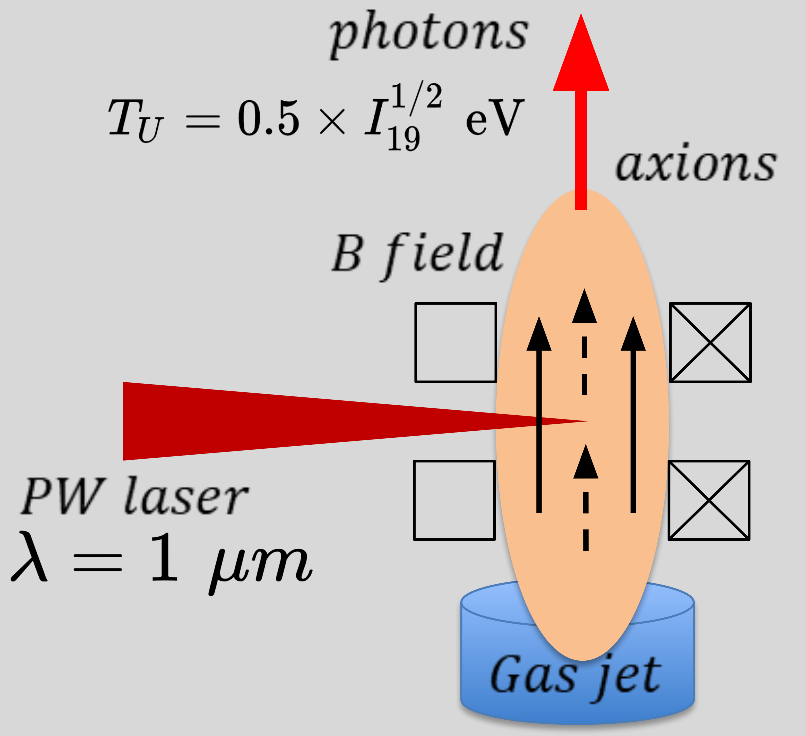
$$n_a \sim \xi a_0^4 \omega^4 \tau_L$$



Wadud *et al.*, PLB (2018)

Axion search with high power lasers can probe the low-mass range

- Low-Z gas-jet (e.g., H, He) with density 10^{21} cm^{-3}
- ELI: 1 kJ, 100 fs, high-repetition rate
- Unruh temperature in the 0.5 eV range (optical emission near 2 μm)
- Difficulty lies on separating axion-photon emission with other classical emission processes near the laser wavelength

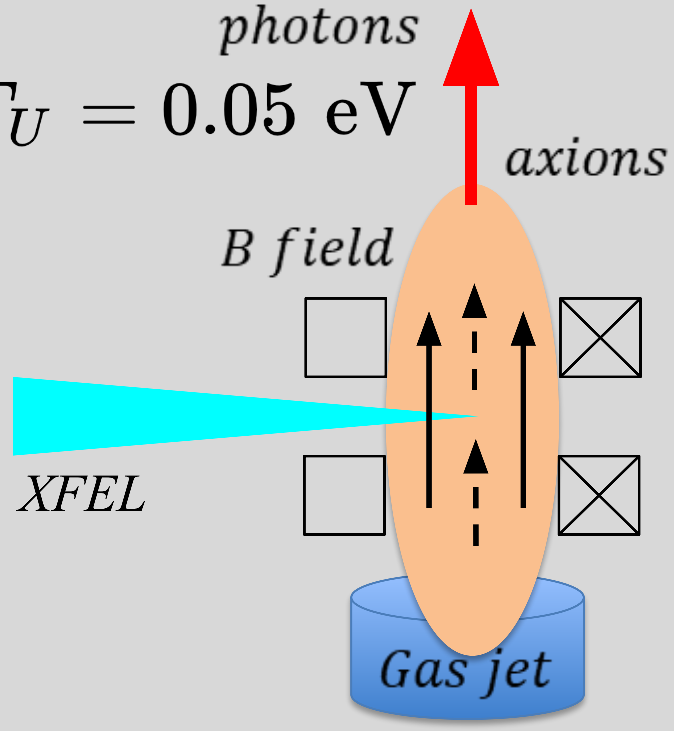


$$N_\gamma \sim n_a g_{a\gamma\gamma}^2 \frac{B^2}{m_a^2} N_e (\tau_L w_L^2)$$

$$N_\gamma \sim 2\left(\frac{g_{a\gamma\gamma}}{10^{-11}\ \mathrm{GeV}^{-1}}\right)^2 \left(\frac{m_a}{\mathrm{meV}}\right)^{-2} \left(\frac{N_e}{10^{15}}\right) \left(\frac{B}{50\ \mathrm{kG}}\right)^2 \left(\frac{w_L}{0.1\ \mathrm{mm}}\right)^2 \left(\frac{\tau_L}{100\ \mathrm{fs}}\right)^2 \left(\frac{I_L}{10^{19}\ \mathrm{W/cm}^2}\right)^2$$

Axion search with XFELs allow for separation between drive and signal

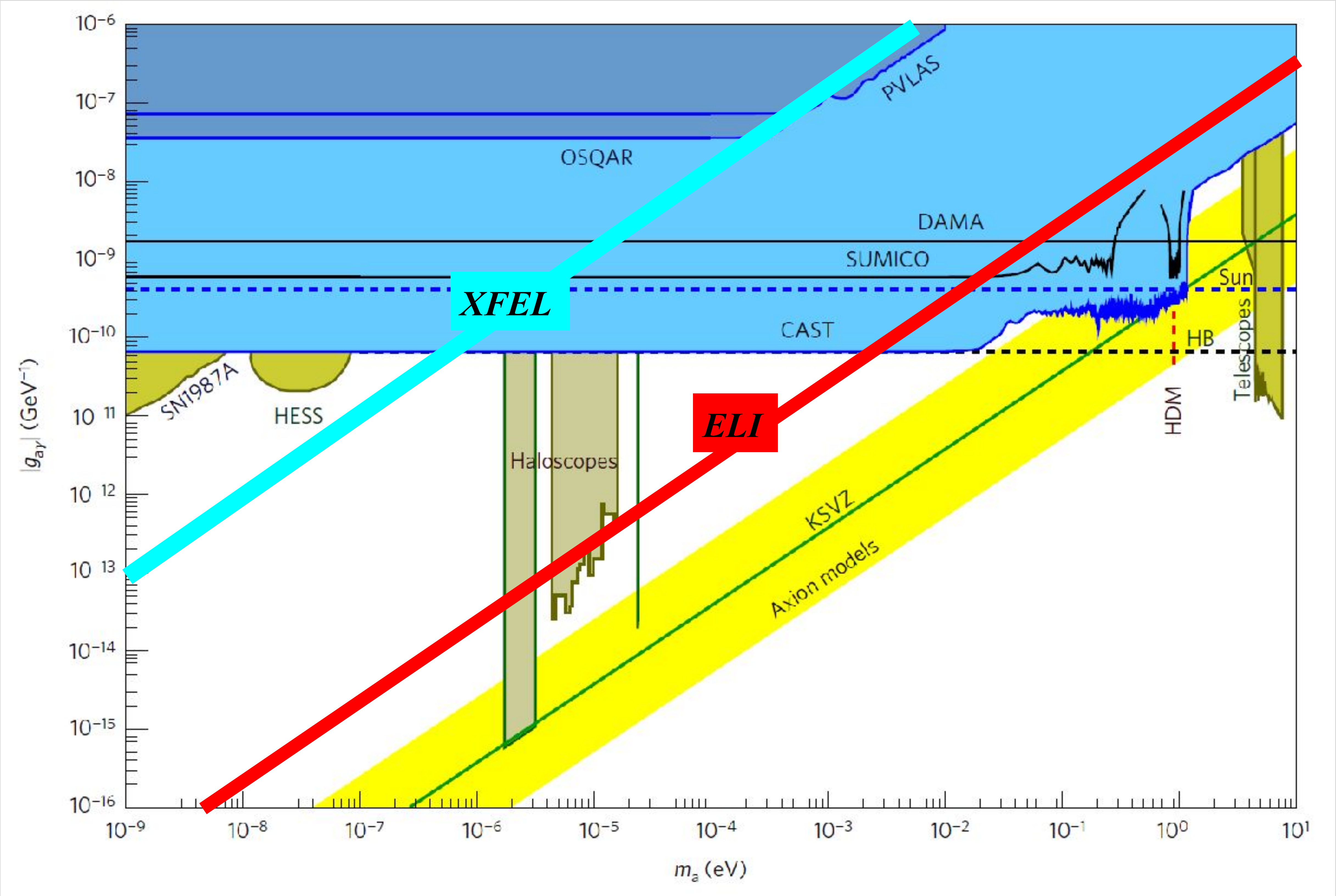
- Low-Z gas-jet (e.g., H, He) with density 10^{21} cm^{-3}
- FEL: 1 mJ, 100 fs focussed on <1 μm spot size, high-repetition rate
- Expect emission wavelength near 25 μm
- Lower constraints on axion coupling, but easy to separate axion signal (in the infra-red) from the x-ray drive



$$N_\gamma \sim n_a g_{a\gamma\gamma}^2 \frac{B^2}{m_a^2} N_e (\tau_L w_L^2)$$

$$N_\gamma \sim 2\left(\frac{g_{a\gamma\gamma}}{10^{-7}\ \mathrm{GeV}^{-1}}\right)^2 \left(\frac{m_a}{\mathrm{meV}}\right)^{-2} \left(\frac{N_e}{10^{11}}\right) \left(\frac{B}{50\ \mathrm{kG}}\right)^2 \left(\frac{w_{FEL}}{1\ \mu\mathrm{m}}\right)^2 \left(\frac{\tau_{FEL}}{100\ \mathrm{fs}}\right)^2 \left(\frac{I_{FEL}}{10^{17}\ \mathrm{W/cm}^2}\right)^2$$

Proposed axion searches using ELI or XFEL can complement current ones



Thank you for your attention!