Axion Searches with X-ray Free-Electron Lasers

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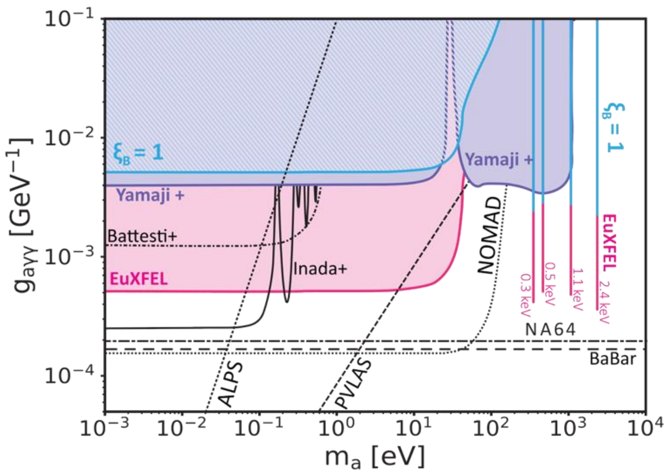
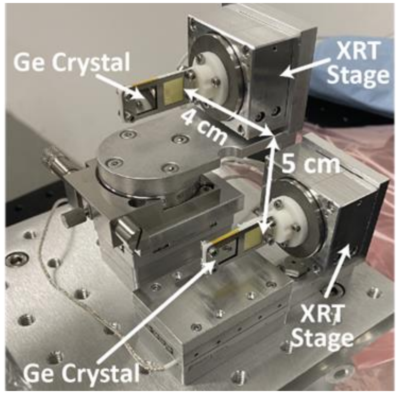
This project was begun with the collaboration of Prof. Ian Shipsey – to whom this talk is dedicated

Overview

- Introduction to Axions / ALPS and overview of search strategies
- Experimental design for a light shining through a wall experiment with an X-Ray Free Electron Laser (XFEL)
- Experimental data for initial experiments on EuXFEL
- Follow-up work at SACLA (QCD sensitivity)
- Fundamental physics with high powered lasers

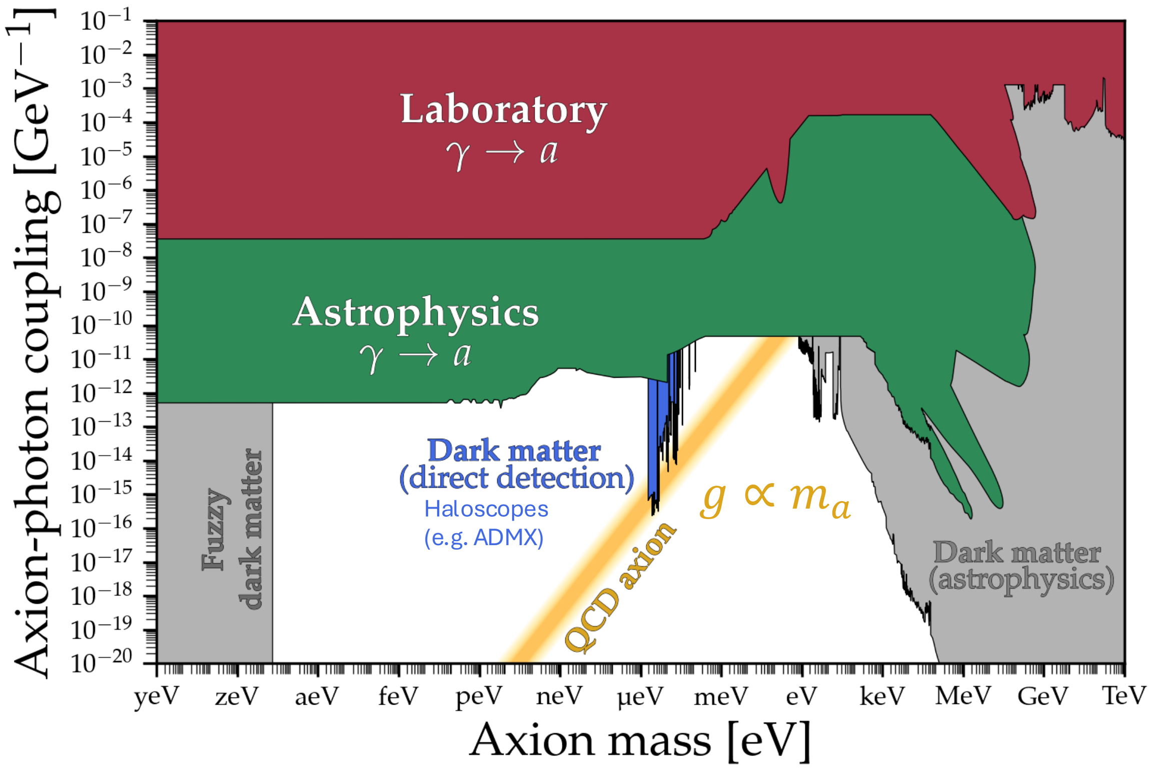




Axions solve the strong CP problem and are a cold dark matter candidate

- Postulated to explain the *absence* of CP-violation in strong interactions (which would otherwise generate an electric dipole moment for the neutron)
- The axion arises from spontaneous breaking of the Peccei-Quinn (PQ) symmetry
- Axion-like particles (ALPs) also arise generically in string theory
- Light axions ($m_a \sim 10^{-6} - 10^{-4}$ eV) are a natural candidate for cold dark matter
- Laboratory searches target this light axion window

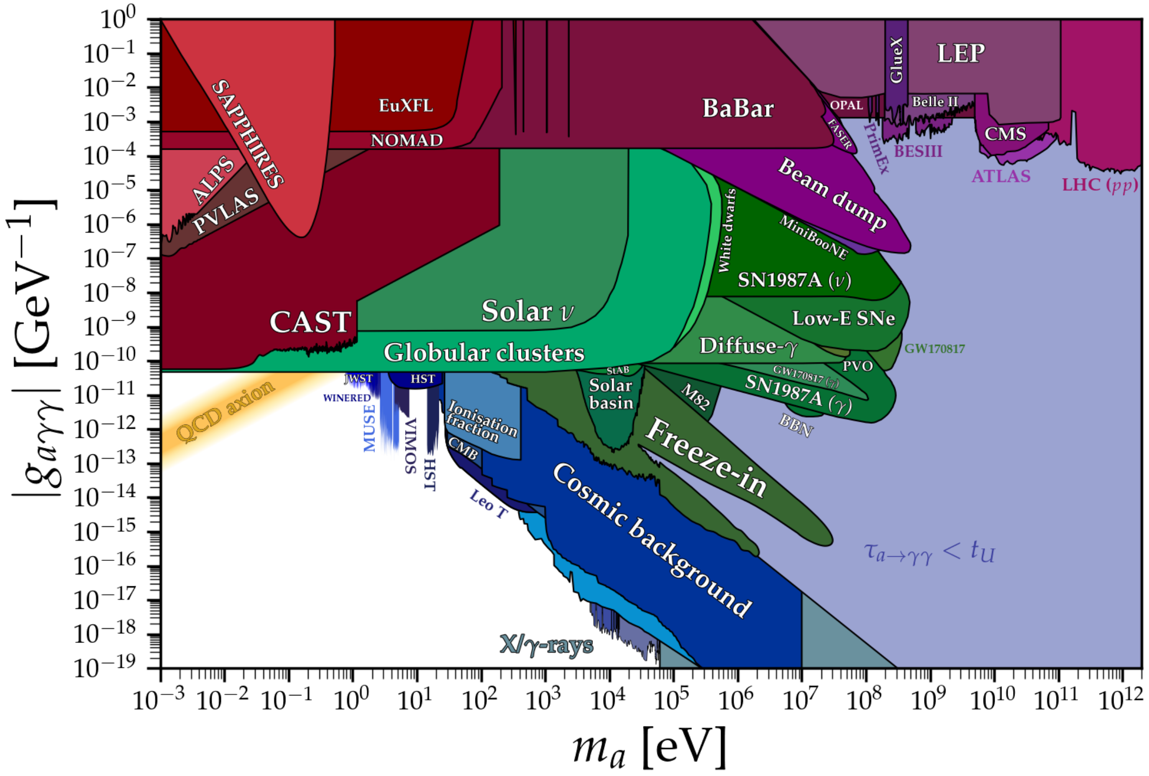
F. Chadha-Day *et al.* "*Axion dark matter: What is it and why now?*" *Sci. Adv.* **8**, eabj3618 (2022).



Credit: Ciaran O'Hare (github.com/cajohare/AxionLimits)

There has recently been interest in heavier axions, which motivates our study

- Recent suggestion: When PQ symmetry is broken *after* cosmological inflation, axions are also produced in the decay of axion domain walls
- Taking this additional contribution into account requires axions which make up dark matter to have a **mass above 10^{-2} eV**



Credit: Ciaran O'Hare (github.com/cajohare/AxionLimits)

A. Ringwald & K. Saikawa, "*Axion dark matter in the post-inflationary Peccei-Quinn symmetry breaking scenario*". Phys. Rev. D **93**, 085031 (2016).

K. Beyer & S. Sarkar, "*Ruling out light axions: The writing is on the wall*", SciPost Phys. **15**, 003 (2023).

There are a variety of complimentary axion search strategies

Increased sensitivity

Astrophysical

Axion losses in stellar models

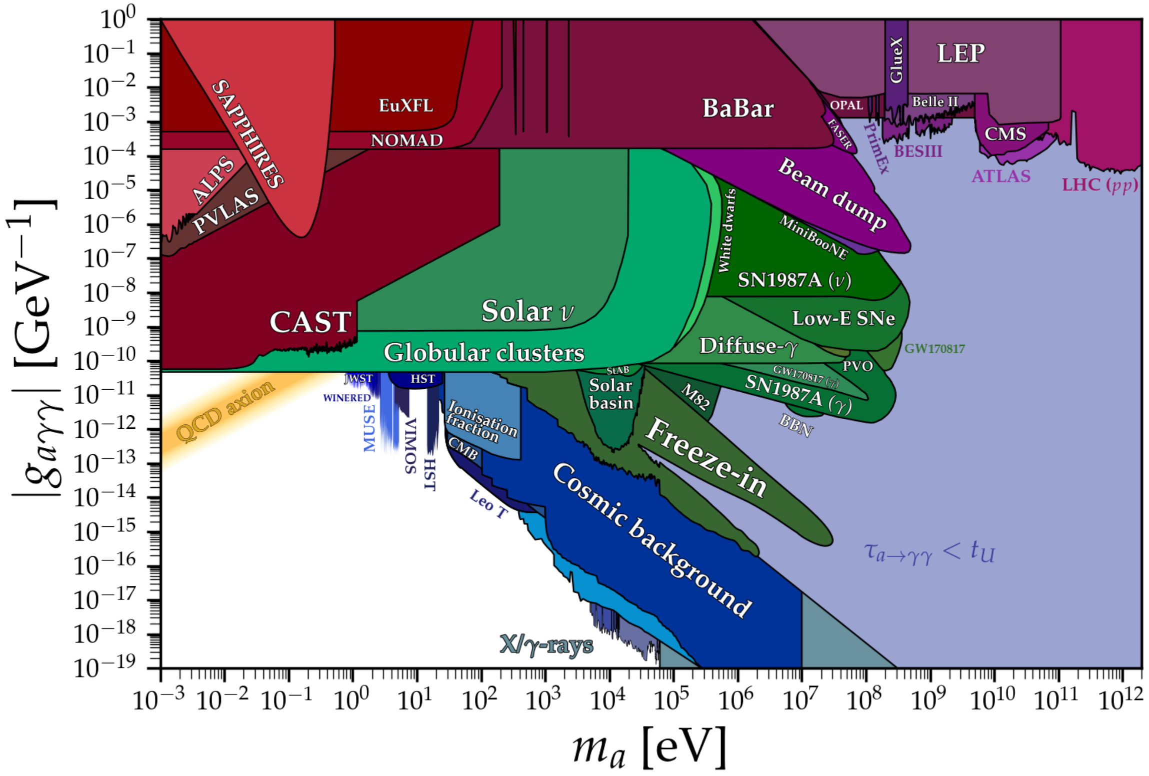
Lab detection

Helio/haloscopes

Lab generation

Generate (& detect) terrestrially

Reduced model dependence



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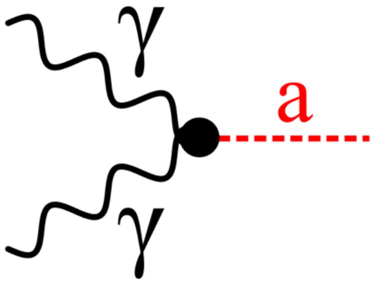
Yannis K. Semertzidis & SungWoo Youn, "*Axion dark matter: How to see it?*", Sci. Adv. **8**, eabm9928 (2022).

A. Caputo & G. Raffelt, *"Astrophysical Axion Bounds: The 2024 Edition",* Proceedings of Science **454**, 041 (2024).

For $m_a \leq 1$ eV, stringent bounds are imposed by the CERN Axion Telescope (CAST)

- <u>Helioscope</u>: Axions produced in the sun convert into photons via the Primakoff effect:

$$\mathcal{L}_{\text{axion}} = g_{a\gamma\gamma}\boldsymbol{E} \cdot \boldsymbol{B}a$$

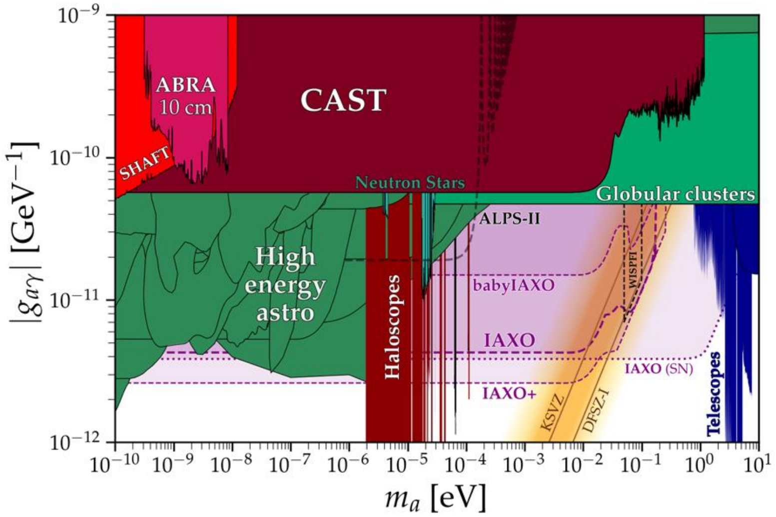


- Geometry suppresses sensitivity to axions with $m_a > 1$ eV

- Some model dependence due to high temperature and ω_p in Solar plasma

CAST Collaboration, "*New CAST limit on the axion–photon interaction*" Nature Phys. **13**, 584 (2017).

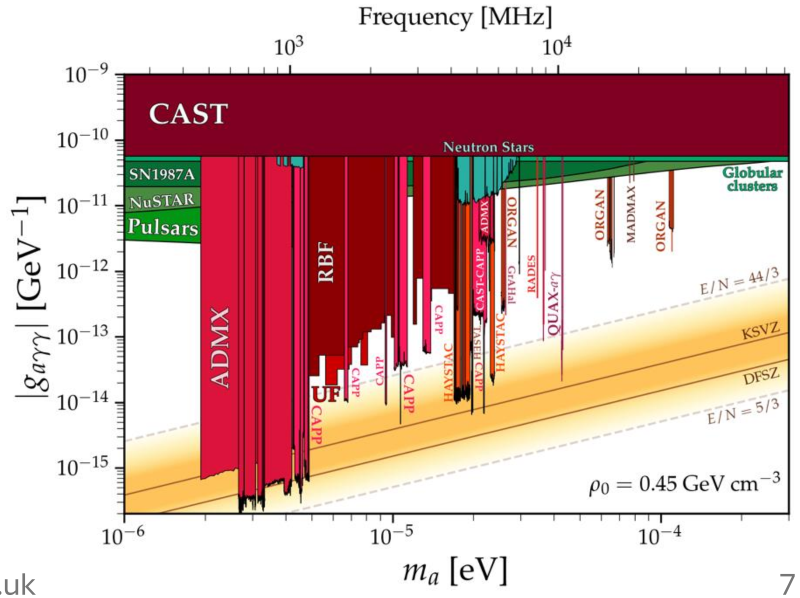
J. Jaeckel *et al.* "*Need for purely laboratory-based axionlike particle searches*", Phys. Rev. D **75,** 013004 (2007)



In the $m_a \sim$ μeV region, haloscopes, including ADMX, probe down to the QCD axion coupling.

- Axion Dark Matter eXperiment (ADMX), at the University of Washington
- Haloscope: Axions from (local) Galactic halo convert to microwaves in cavity surrounded by a super-conducting electromagnet ($B = 7.6$ T)
- Tune cavity Q-factor to scan through different axion masses
- Probes down to QCD axion couplings for $m_a = 1 - 100$ μeV

C. Goodman *et al, "Axion dark matter experiment around 3.3 eV with Dine-Fischler-Srednicki-Zhitnitsky discovery ability"*, Phys. Rev. Lett. – in press (2025)



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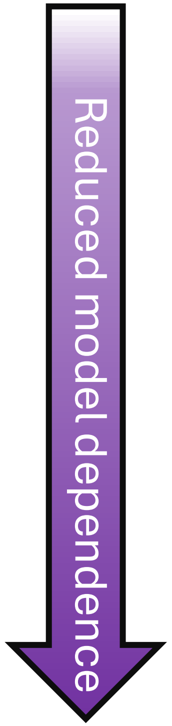

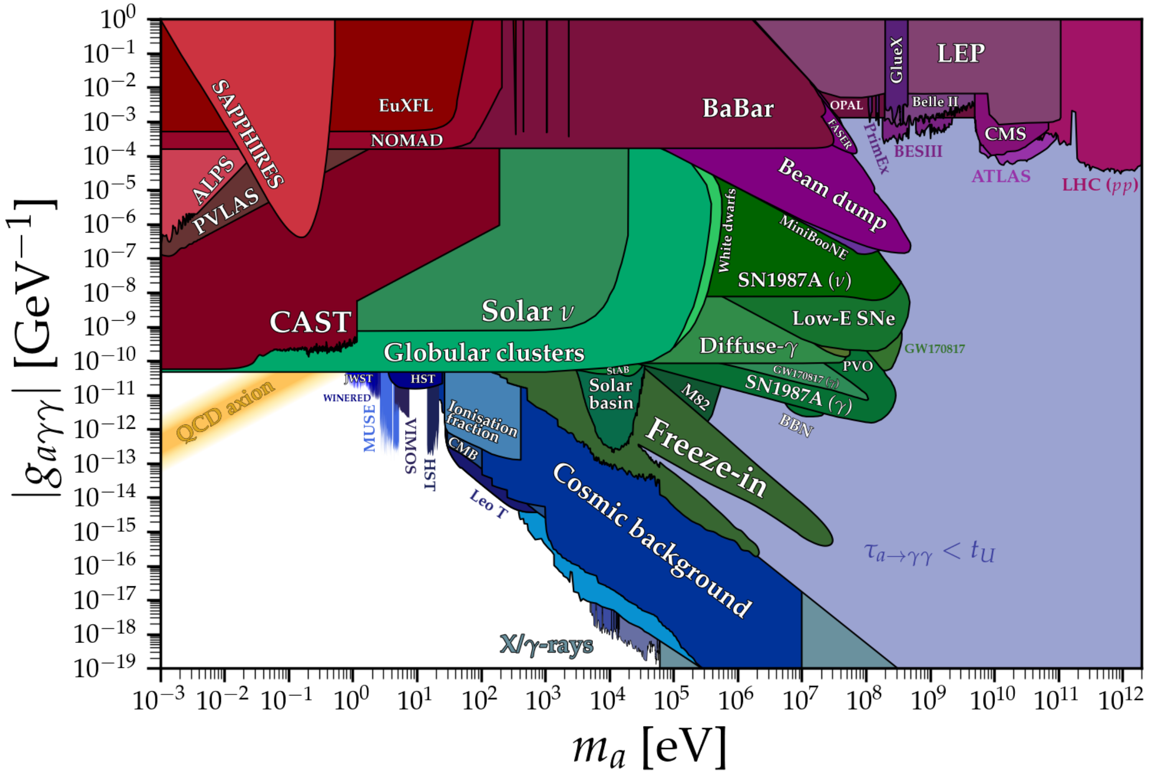

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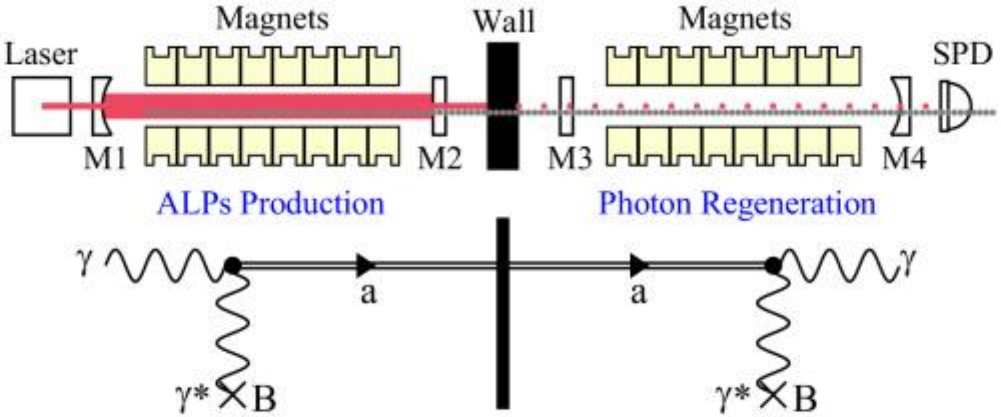
Light shining through wall (LSW) experiments are an example of direct detection searches

- Generating axions in the lab removes any model dependence
- But sensitivity suppressed by a factor of $\sim g_{a\gamma\gamma}$
- No sensitivity to $m_a > 1$ eV (uses visible photons)
- Photo taken from ALPS-II, current experiment at DESY which recycles magnets from HERA



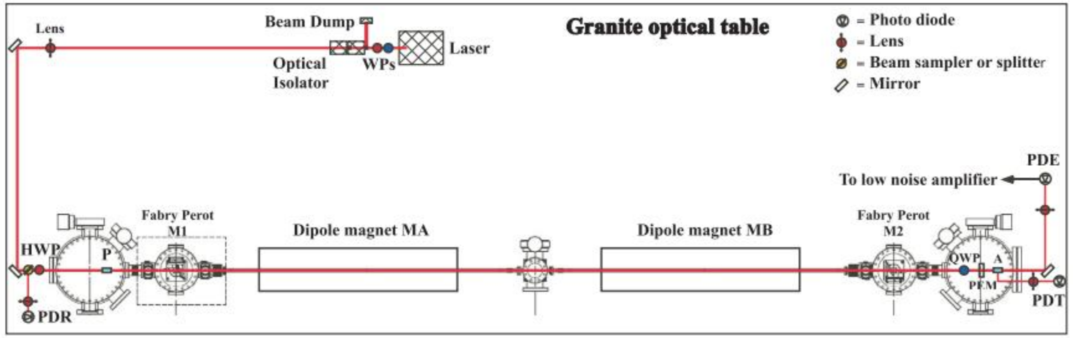
C. Robilliard *et al, "No light shining through a wall",* Phys Rev. Lett. **99**, 190403 (2007).

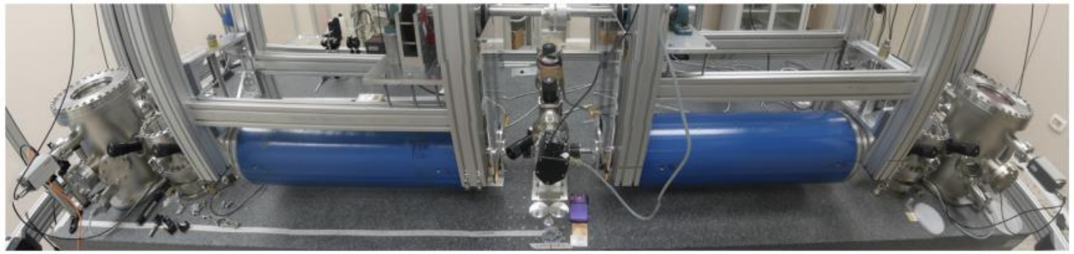
Klaus Ehret *et al, "New ALPS results on hidden-sector lightweights",* Phys. Lett. B **689**, 149 (2010).

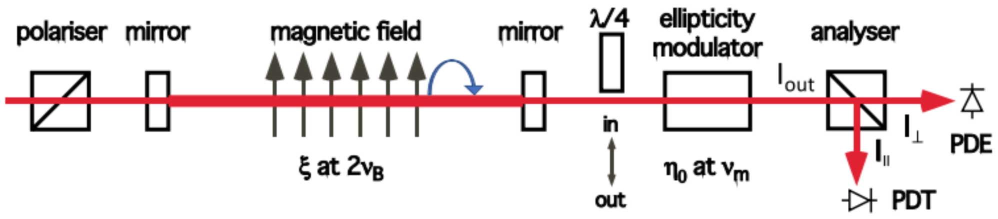
QSQAR collaboration, *"New exclusion limits on scalar and pseudoscalar axionlike particles"* Phys. Rev. D**92**, 092002 (2015).

Vacuum birefringence experiments, including PVLAS, are also sensitive to axions generated terrestrially

- Vacuum birefringence – induce ellipticity in laser propagating though magnetic field
- Sensitive to a variety of QED effects (e.g. photon-photon scattering)
- Axion-photon coupling can also induce ellipticity
- Sensitive to <u>generation</u> of axions, *not* <u>regeneration</u> of photons:
  - $P_{a\leftrightarrow\gamma} \propto (g_{a\gamma\gamma})^1$ – Vacuum birefringence
  - $P_{a\leftrightarrow\gamma} \propto (g_{a\gamma\gamma})^2$ – LSW experiments
- Hard limit on sensitivity due to QED effects







A. Ejlli *et al*, *"The PVLAS experiment: A 25 year effort to measure vacuum magnetic birefringence"* Phys. Rep. **871**, 1 (2020).

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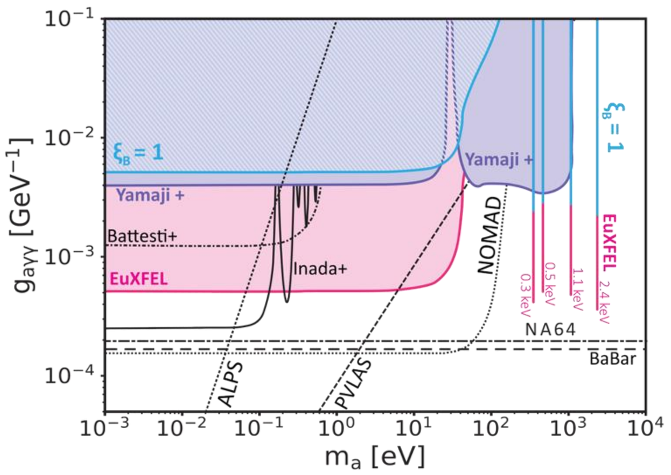
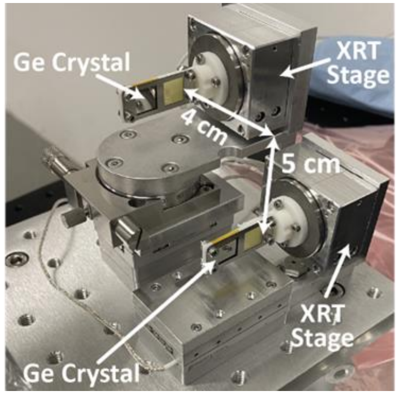


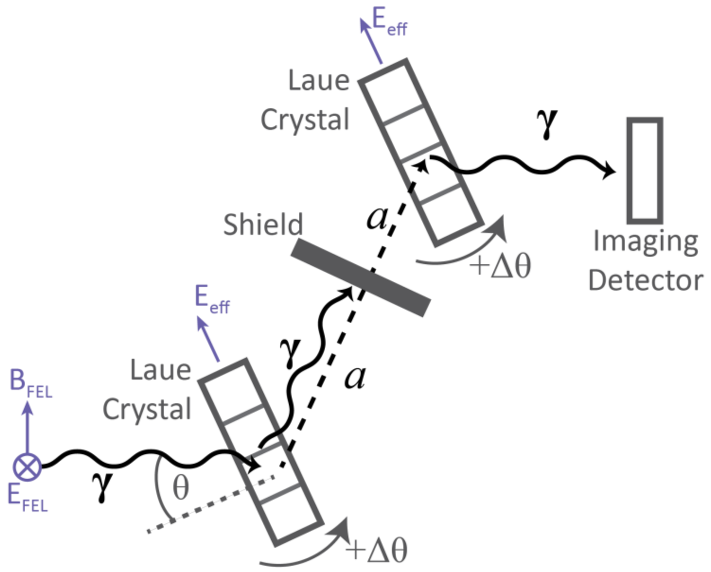


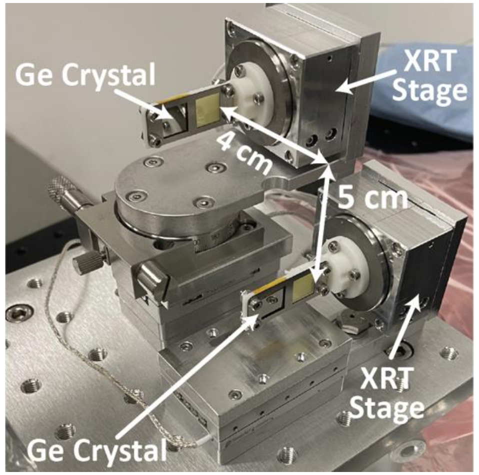
X-ray light sources enable the extension of light shining through wall experiments to search for heavy axions

- Again, rely on Primakoff effect:

$$\mathcal{L}_{\text{axion}} = g_{a\gamma\gamma}\boldsymbol{E}\cdot\boldsymbol{B}a$$

- Magnetic field from (σ-polarised) X-Ray beam
- Electric field normal to planes in crystalline material:
  - $E{\sim}10^{11}$ V/m (equivalent to $B{\sim}1$ kT)
  - Germanium crystal, thickness $L = 500$ μm
  - Path integrated field ~ 25 Tm
- Previous experiments [Yamaji+] on Synchrotron light source
- Our study is the *first* to use an X-Ray Free Electron Laser





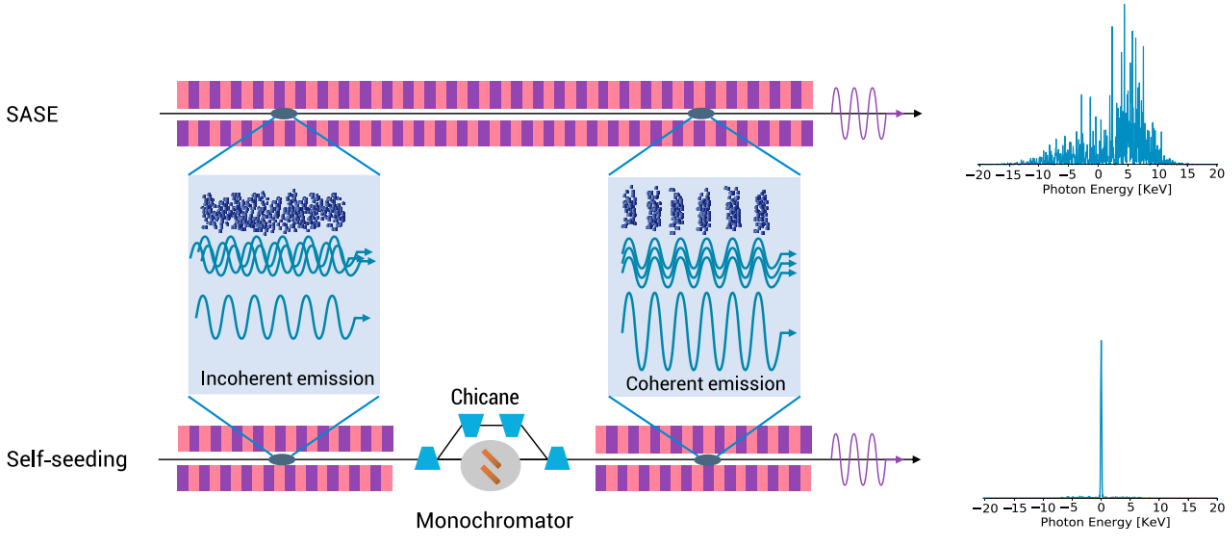
Buchmüller & Hoogevee, *"Coherent production of light scalar or pseudoscalar particles in Bragg scattering"*, Phys. Lett. B **267**, 2 (1990).

T. Yamaji *et al*, *"Search for Axion like particles using Laue-case conversion in a single crystal"* Phys. Lett. B **782**, 526 (2018).

An X-ray Free Electron Laser (XFEL) is a light source, based on an electron LINAC

- LINAC accelerates electrons to $\sim 10\ \mathrm{GeV}$
- Undulators (periodic dipole magnets) cause beam to oscillate → radiation emitted
- **SASE** (Self Amplified Spontaneous Emission):
  - Emitted radiation interacts with beam causing microbunching
  - Microbunching amplifies light (coherent emission)
  - Very short pulse-duration ($\sim$10 fs)
- **Self-seeding –** monochromator in beamline imposes preferred length scale for microbunches → monochromatic light
- Extremely high "brilliance"

  $(N_\gamma / \mathrm{s} / \mathrm{mm}^2 / \mathrm{mrad}^2 / 0.1\%\mathrm{BW})$
- High impact science from drug discovery to fundamental physics with access decided in extremely competitive calls



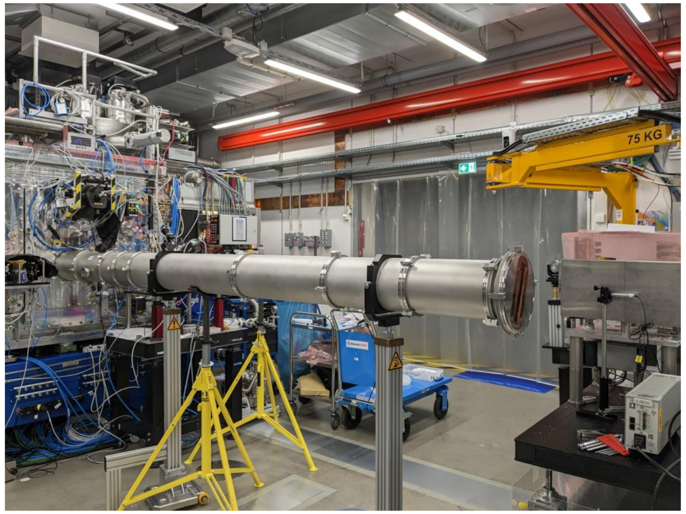
Facility	Beam energy [GeV]	Photon energy [eV]	Pulse duration [fs]
EuXFEL	8.5 – 17.5	240 – 25,000	3-150
LCLS-II	4 – 15	200 – 25,000	1 – 500
SACLA	5.1 – 8.9	400 – 12,800	2 – 10

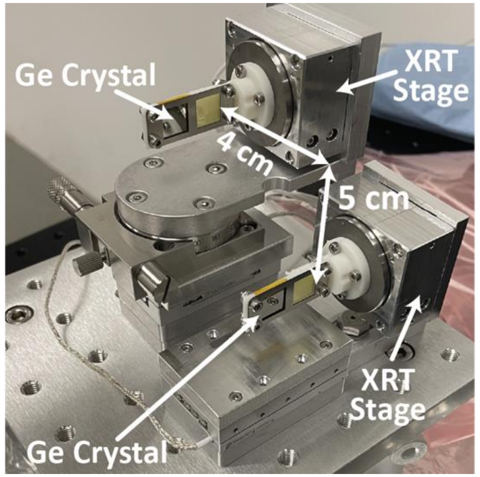
N. Huang *et al. "Features and futures of X-ray free-electron lasers"*. The Innovation. **2**, 2 (2021)

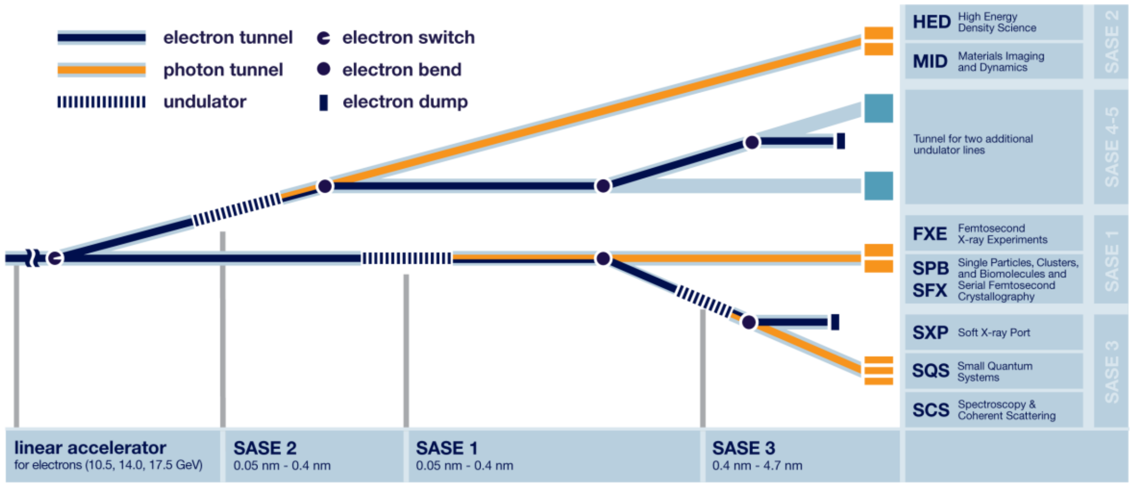
Configuration used for our experiment at The European XFEL (EuXFEL)

- Our search used the HED/HiBEF instrument at EuXFEL, Hamburg
- Three days (72 hrs) of beamtime awarded over the Easter bank holiday 2023
- Operated in a self-seeded mode

Parameter	Value
Photon energy / wavelength	9.8 keV / 1.3 Å
Bandwidth ($\Delta E/E$)	5×10^{-5}
Pulse duration	$\sim 10^{-14}$ s
Repetition rate	10 Hz
Spot size	$400 \times 400\ \mu m^2$
Total photons on-target	1×10^{17}



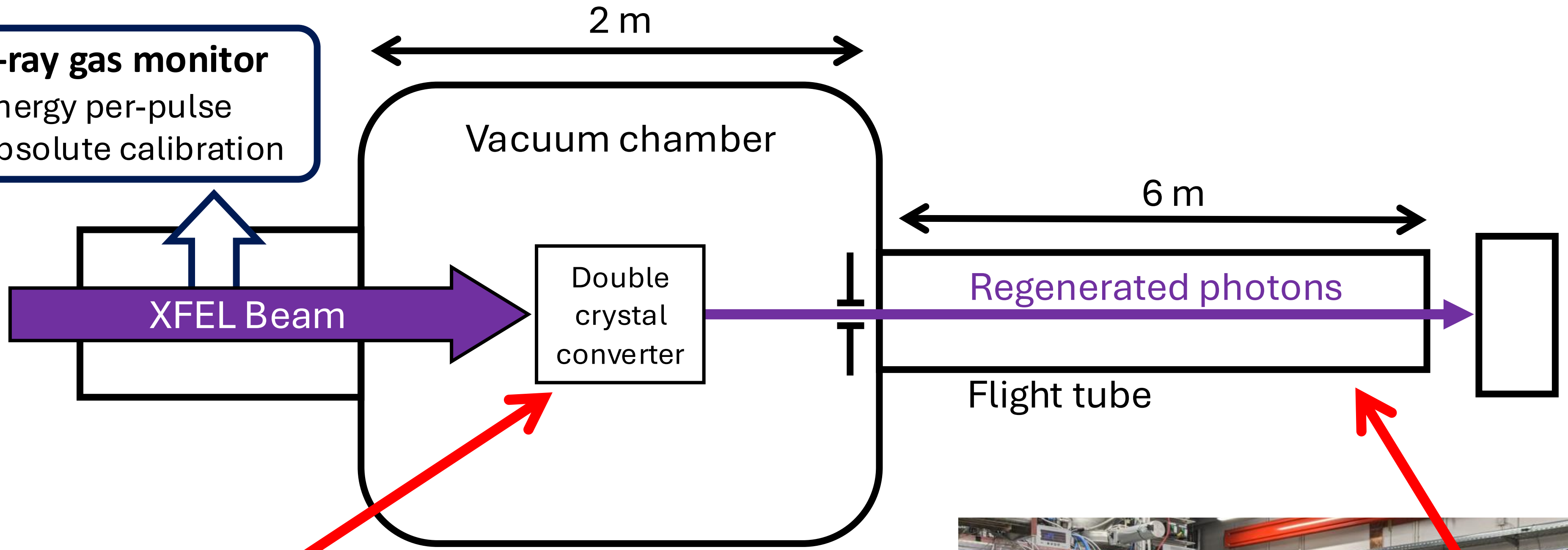


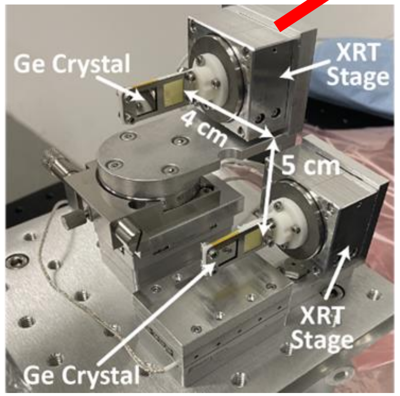


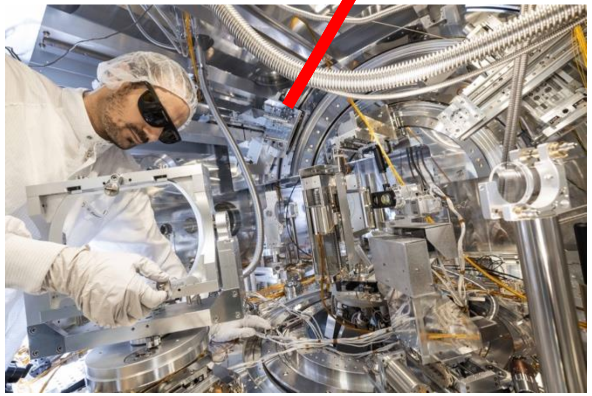
The HED/HiBEF instrumentation enabled an accurate constraint to be placed on input / output X-ray flux

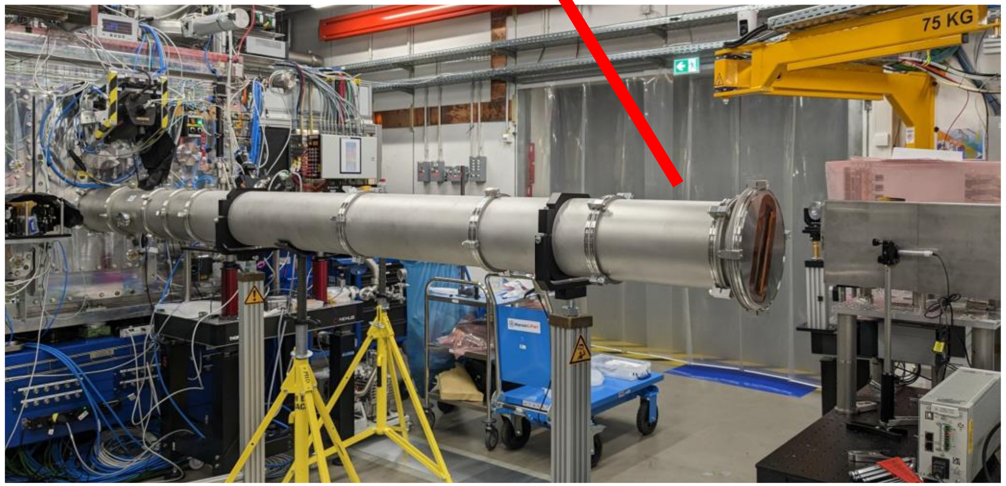
X-ray gas monitor
- Energy per-pulse
- Absolute calibration

Jungfrau-4
- Hybrid pixel detector
- Acquisitions gated to 2 µs
- Energy resolution ~ 0.5eV









The sensitivity of the scan is a function of the interaction-length, while the mass range is tuned by adjusting θ

Probability of conversion:

$$P(a \leftrightarrow \gamma) = \left(\frac{1}{4} g_{a\gamma\gamma} E_{\text{eff}}\, L_{\text{eff}} \cos\theta_B\right)^2$$

$$L_{\text{eff}} = 2L^B_{\text{att}}\left[1 - \exp\left(-\frac{L_x}{2L^B_{att}}\right)\right], \quad L_x = \ell/\cos(\theta_B + \Delta\theta)$$

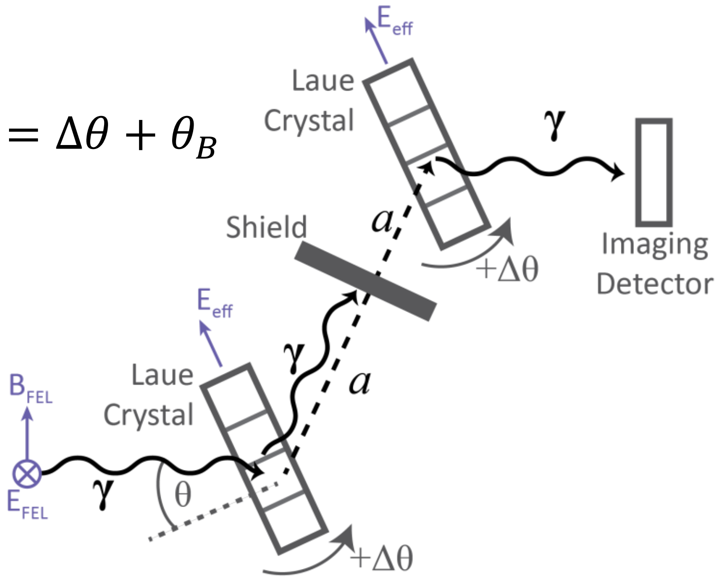
Mass range for the search:

$$\left|m_a^2 - m_\gamma^2\right| \le \frac{4k_\gamma}{L_{eff}} \qquad (\Delta\theta = 0)$$

$$m_a = \sqrt{m_\gamma^2 + 2q_T k_\gamma \cos(\theta_B)\Delta\theta} \qquad (\Delta\theta \neq 0)$$

T. Yamaji *et al, "Theoretical calculation of coherent Laue-case conversion between x-rays and ALPS for an X-ray LSW experiment"* Phys. Rev. D **96**, 15001 (2017).

$$\theta = \Delta\theta + \theta_B$$



Reciprocal lattice spacing (q_T)	6.2 keV
Plasma frequency (m_γ)	44 eV
Crystalline field (E_{eff})	7.3×10^{10} V/m
Attenuation length (L^B_{att})	1.5 mm
Crystal thickness (ℓ)	500 μm

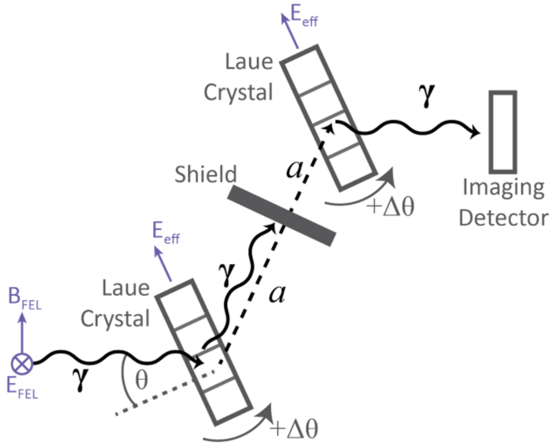
The Borrmann effect increases the extinction length by $\sim 10^3$ for Laue-case diffraction

- Conversion probability - $P(a \leftrightarrow \gamma) \propto L_{ext}^2$
- **Laue-case diffraction**
  - Scatter off planes normal to crystal surface
  - Anomalous extinction, $L_{\text{ext}}^B = 1500\ \mu\text{m}$
  - Due to the Borrmann effect
- **Bragg case diffraction**
  - Scatter off planes parallel to crystal surface
  - Extinction, $L_{\text{ext}} = 1\ \mu\text{m}$
- In both cases diffraction follows Bragg's law

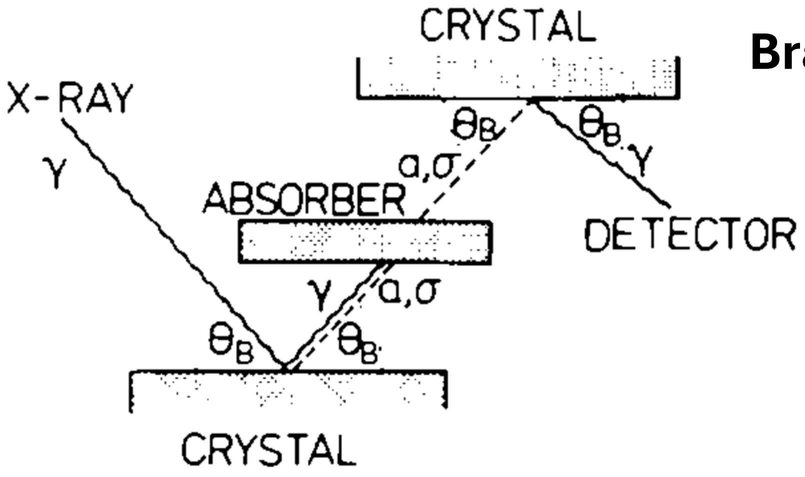
$$2d\sin\theta_B = n\lambda$$

G. Borrmann *"Über Extinktionsdiagramme von Quarz"* Physikalische Zeitschrift **42** (1941).

Laue



Bragg



[Buchmüller & Hoogeveen – 1990]

For XFEL experiments, the pulse duration is short compared to the timescale associated with diffraction

- Consider 2 measures of angular spread of transmitted X-rays:

Rocking curve width ($\Delta\theta_{RC}$): *Actual* angular spread

Darwin width ($\Delta\theta_D$): *Predicted* spread using a theory that neglects time dependence

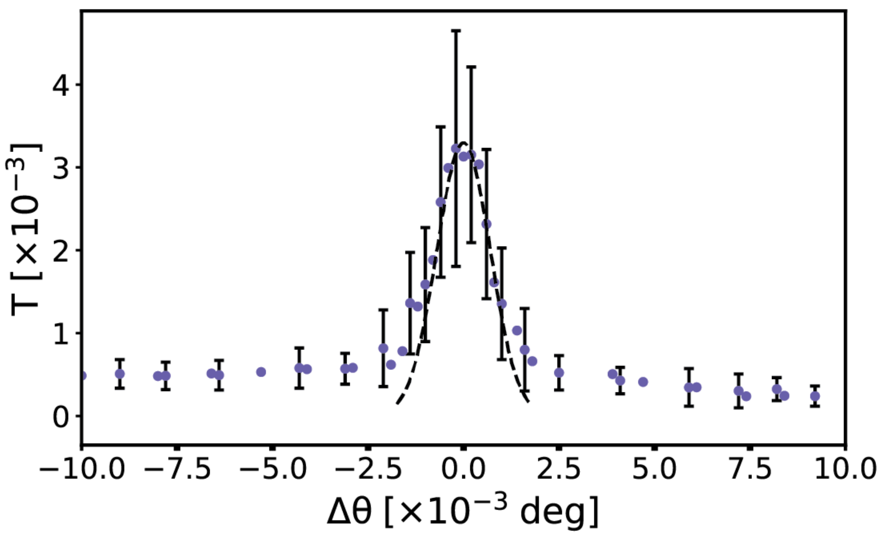
- For a transform limited pulse:

$$\Delta\theta_{RC}\Delta t \approx \frac{\lambda_x \tan\theta_B}{c}$$

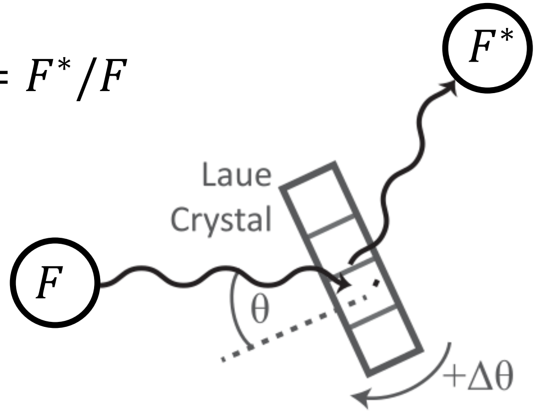
- The timescale for diffraction is:

$$\Delta t = (2\ell/c)\tan\theta_B \sin\theta_B$$

Wark & Lee, "*Simulations of femtosecond X-ray diffraction from unperturbed and rapidly heated single crystals*", Journal of Applied Crystallography **32** (1999).



$T = F^*/F$



Probability for photon-axion conversion should account for this short pulse-duration

- There is an implicit assumption in theory from Yamaji *et al.* that $\Delta\theta_{RC} = \Delta\theta_D$
- Expression for conversion probability modified to account for this:

$$P(a \leftrightarrow \gamma) \approx \left(\frac{1}{4} g_{a\gamma\gamma} \xi_B E_{\text{eff}}\ L_{\text{eff}} \cos\theta_B\right)^2$$

$$\xi_B = \Delta\theta_D / \Delta\theta_{RC}$$

- Time-bandwidth product – expression accurate to factor of order unity
- Physical interpretation: increase in refractive index of crystal

T. Yamaji *et al, "Theoretical calculation of coherent Laue-case conversion between x-rays and ALPS for an X-ray LSW experiment"* Phys. Rev. D **96**, 15001 (2017).

Rocking curve width ($\Delta\theta_{RC}$): *Actual* angular spread of transmitted X-rays

Darwin width ($\Delta\theta_D$): *Predicted* spread using a theory that neglects time dependence

Rocking curve width ($\Delta\theta_{RC}$)	$\sim 0.4\ \mu\text{rad}$
Darwin width ($\Delta\theta_D$)	$44\ \mu\text{rad}$
ξ_B	~ 110

"Brilliance" of XFEL amplifies conversion probability

$(N_\gamma /\ \text{mm}^2 /\ \text{s}/\text{mrad}^2 /\ 0.1\%\text{BW})$

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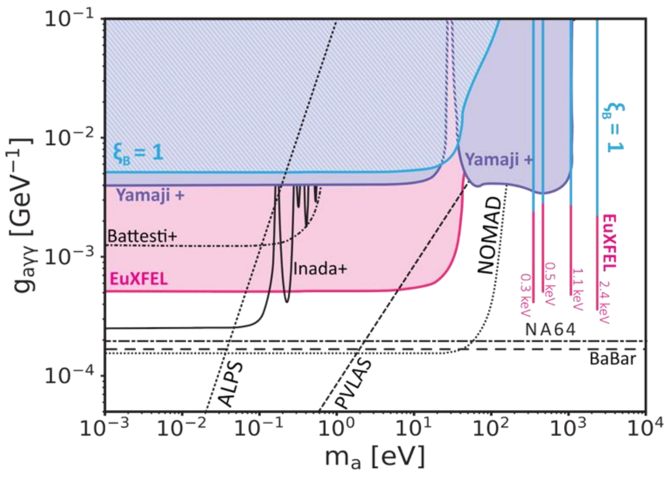
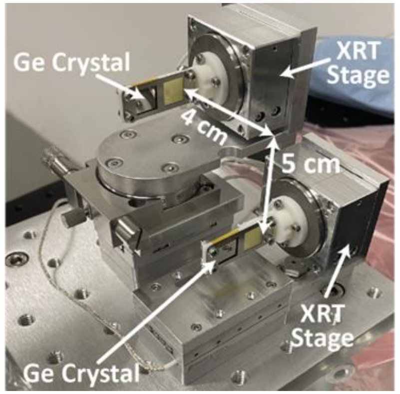
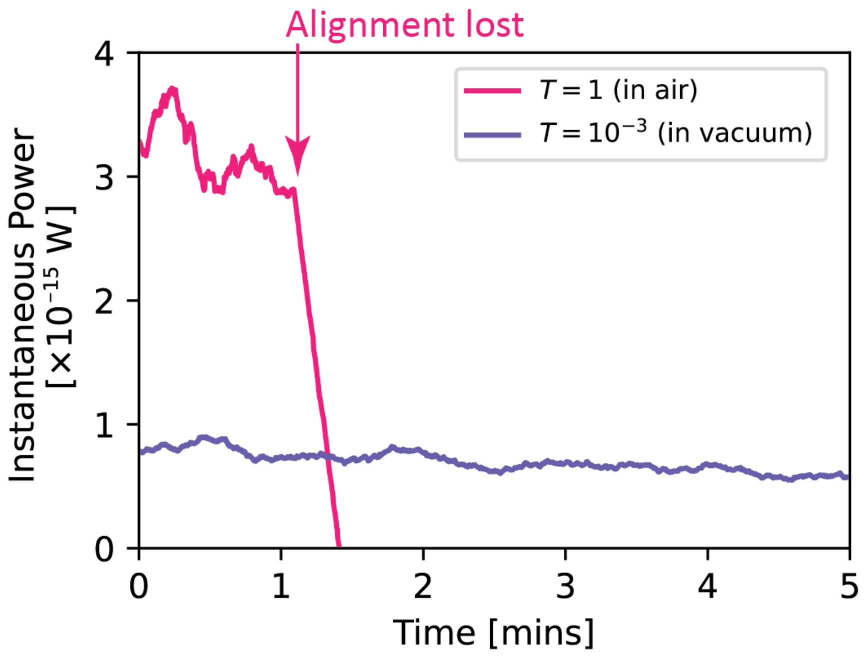
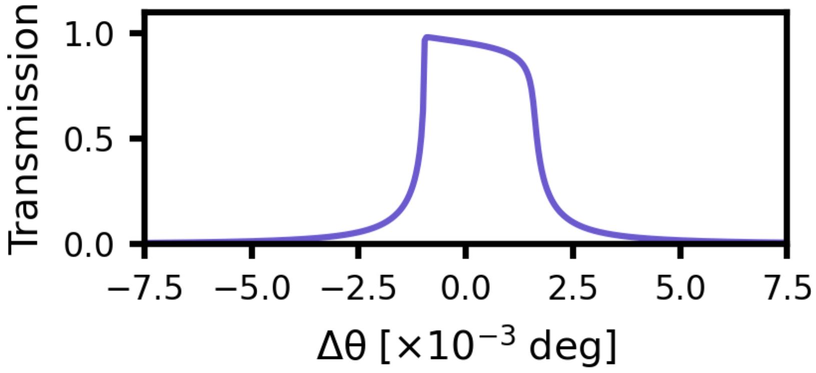




Crystal heating was a major problem during the beamtime

- Maintaining alignment is challenging as the heat load distorts the crystal lattice
- Rocking curve width for Germanium $\sim 5 \times 10^{-3}$ degrees
- Able to maintain stable alignment with 10^3 attenuation applied to the XFEL beam
- Limited search to acquiring data at θ_B and at 4 discrete values of $\Delta\theta$
- In future experiments can mitigate:
  - Active cooling of conversion crystal





Due to crystal heating, a multi-step process was used for data collection

- Process for data collection:
  1. Stages tuned to θ_B and radiation shield removed. ~2 mins characterization data collected.
  2. Stages tuned to search angle & radiation shield returned. ~10 mins search data collected.
  3. Stages tuned back to θ_B and shield removed. ~2 mins characterization data collected.
- For the i'th run calculate:

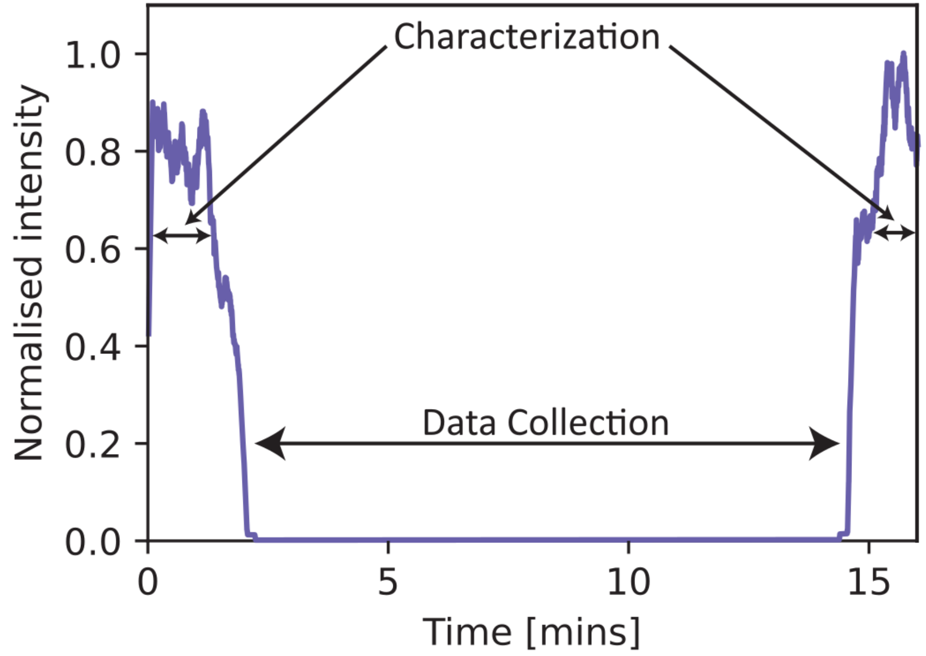
$$\eta_i = \frac{1}{T_{\rm Ge}^2}\frac{E_i^{\rm JF,ch}}{E_i^{in,ch}}$$

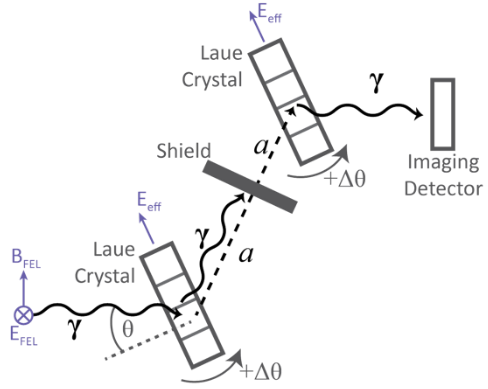
- Then, for all runs at a given $\Delta\theta$:

$$\eta N_{in} = \sum_i \eta_i E_i^{\rm in,aq}/k_\gamma$$

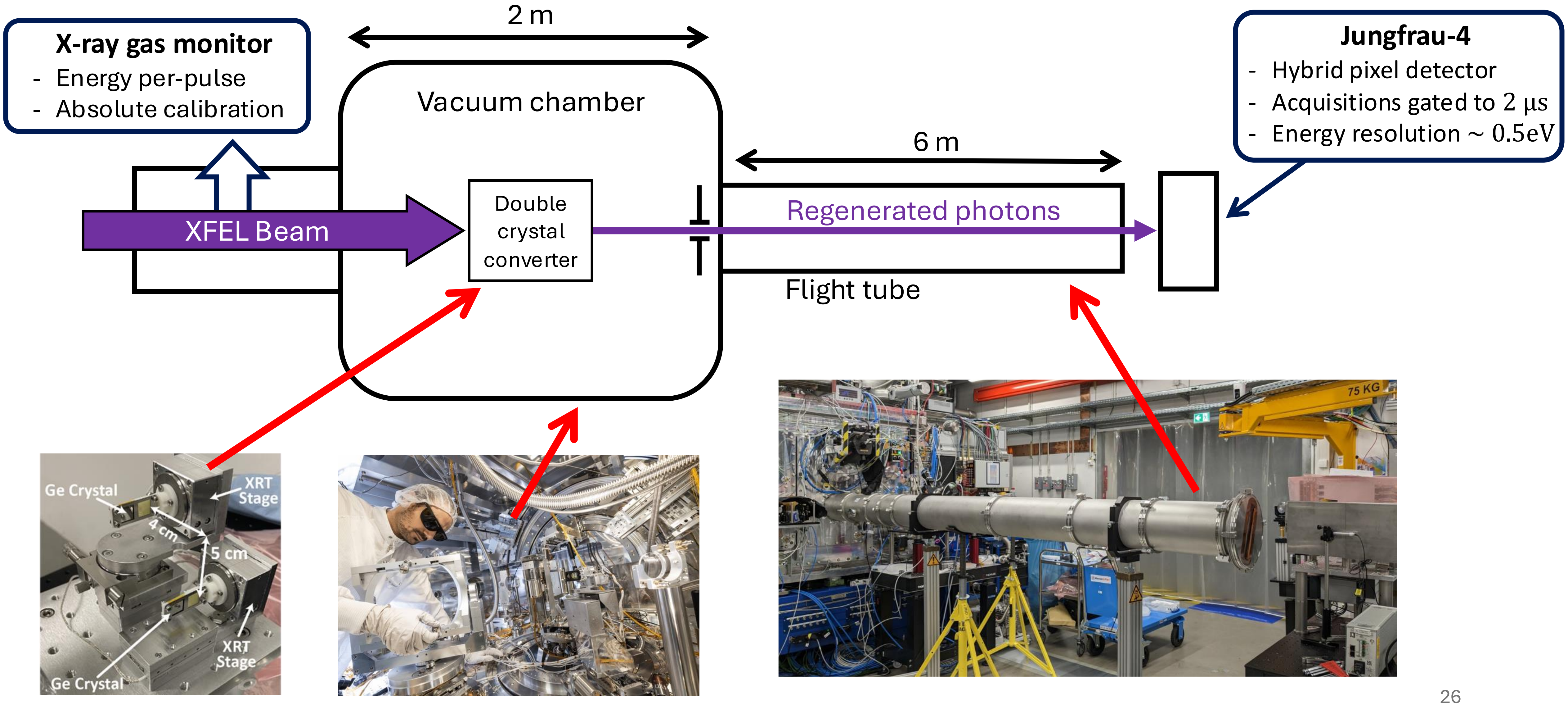
- Measured probability of axion generation then:

$$P(a \leftrightarrow \gamma)^2 = \frac{N_{\rm det}}{\eta N_{in}}$$

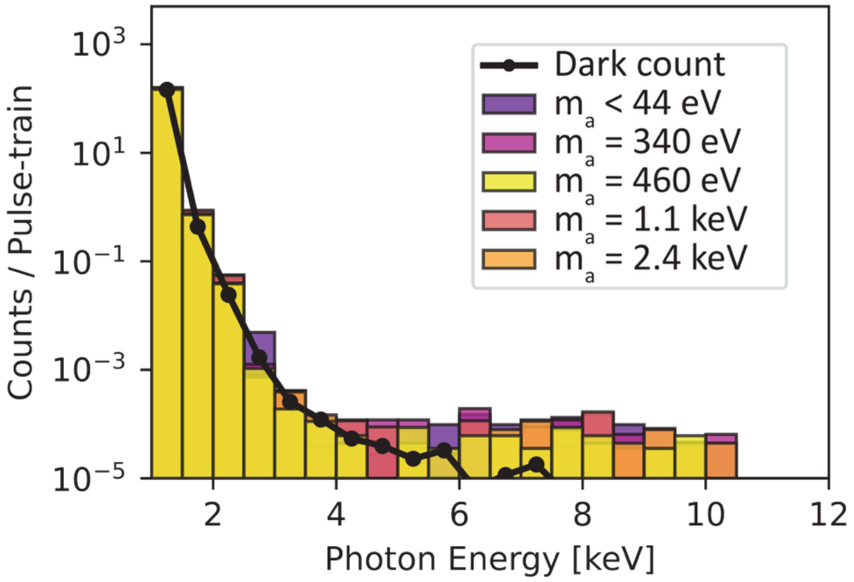


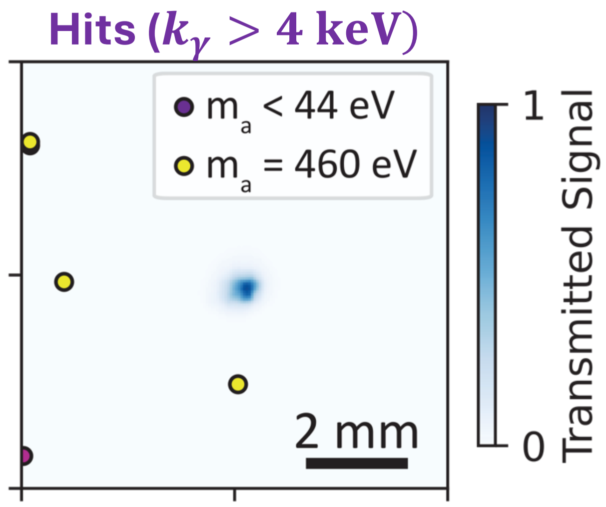


The HED/HiBEF instrumentation enabled an accurate constraint to be placed on input / output X-ray flux



No events consistent with axion production were detected during the experiment





Events consistent with axion production have $k_\gamma = 9.8\,\mathrm{keV}$.

They should also lie on the X-Ray spot observed on the Jungfrau when in characterisation mode.

Bounds on the coupling strength were calculated taking a 90% confidence interval

- Measured probability of axion generation:

$$P(a \leftrightarrow \gamma)^2 = \frac{N_{\text{det}}}{\eta N_{in}}$$

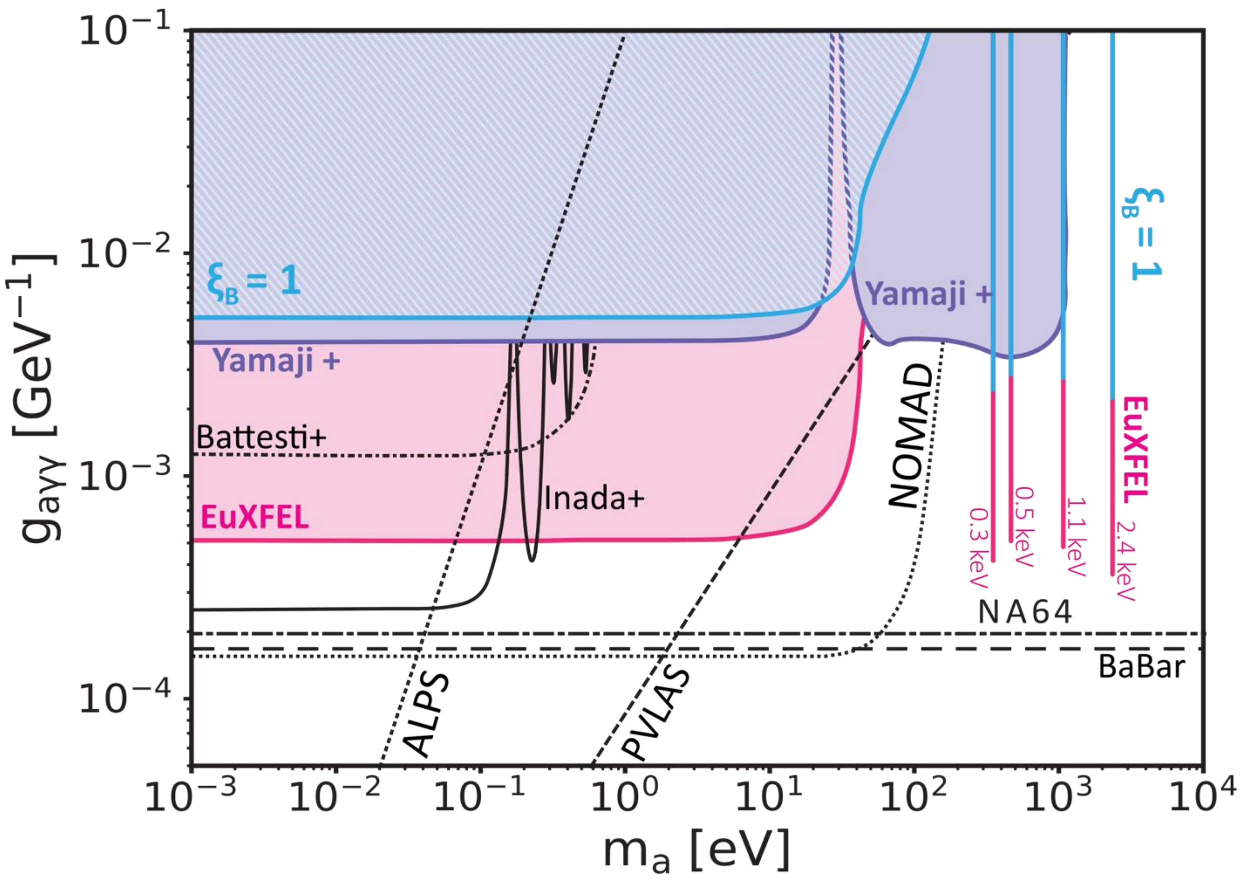
- Take $N_{\text{det}} = 2.3$ events (assume events Poisson distributed, 90 % confidence interval with $\mu = 0$)
- Upper bound on axion-photon coupling:

$$g_{a\gamma\gamma} < \left(\frac{1}{4} E_{\text{eff}} L_B \xi_B \cos\theta_B\right)^{-1} P(a \leftrightarrow \gamma)^{1/2}$$

$\Delta\theta$ [mrad]	m_a [eV]	$g_{a\gamma\gamma}$ [Gev^{-1}]
0.0	< 44	3.91×10^{-4}
1.0	3.4×10^{2}	3.10×10^{-4}
1.8	4.6×10^{2}	3.87×10^{-4}
10.0	1.1×10^{3}	3.69×10^{-4}
50.0	2.4×10^{2}	2.76×10^{-4}

T. Junk *"Confidence level computation for combining searches with small statistics"* Nucl. Instrum. Meth. A **434,** 435 (1999)

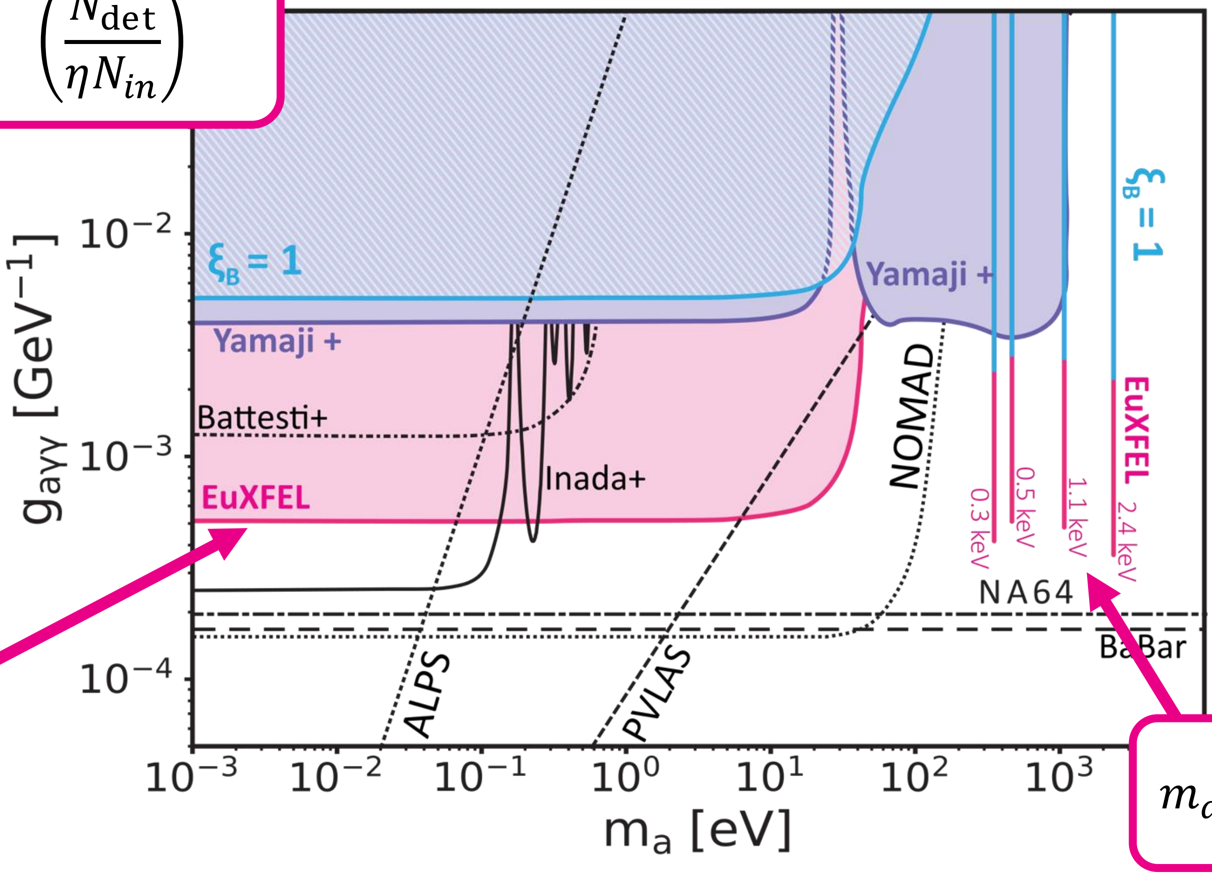
Bounds obtained in this work are competitive with existing studies - using a complementary search technique



J. W. D. Halliday *et. al.* *"Bounds on Heavy Axions with an X-Ray Free Electron Laser"* Phys. Rev. Lett. **134**, 055002 (2025)

Bounds obtained in this work are competitive with existing studies - using a complementary search technique

$$g_{a\gamma\gamma} < \left(\frac{1}{4} E_{\mathrm{eff}} L_B \xi_B \cos\theta_B\right)^{-1} \left(\frac{N_{\mathrm{det}}}{\eta N_{in}}\right)^{-1/4}$$



$$|m_a^2 - m_\gamma^2| \leq \frac{4k_\gamma}{L_{eff}}$$

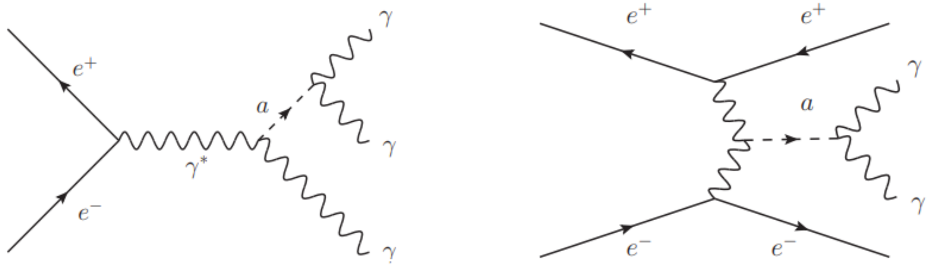
$$m_a = \sqrt{m_\gamma^2 + 2q_T k_\gamma \cos(\theta_B)\Delta\theta}$$

J. W. D. Halliday *et. al.* *“Bounds on Heavy Axions with an X-Ray Free Electron Laser”* Phys. Rev. Lett. **134**, 055002 (2025)

Our bounds are complimentary to those imposed from searches using accelerators

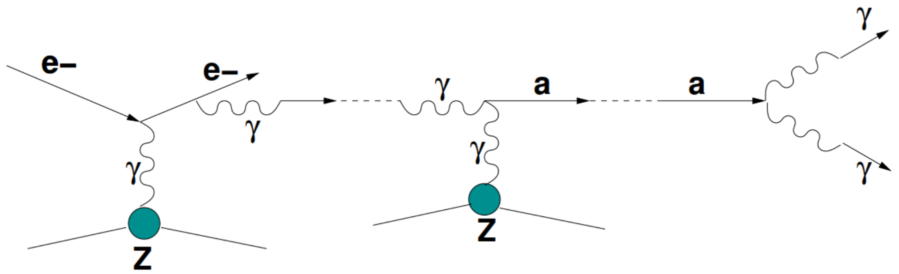
BaBar

- Bounds on dark photon detection [BaBar Collaboration] recast by Dolan *et al.* to obtain a bounds on $g_{a\gamma\gamma}$.
- Probes spontaneous axion decay



NA64

- Target-Bremsstrahlung photons generated by 100 GeV electrons in NA64 beam dump produce axions via the Primakoff effect
- Search for both spontaneous axion decay and missing energy in calorimetry data



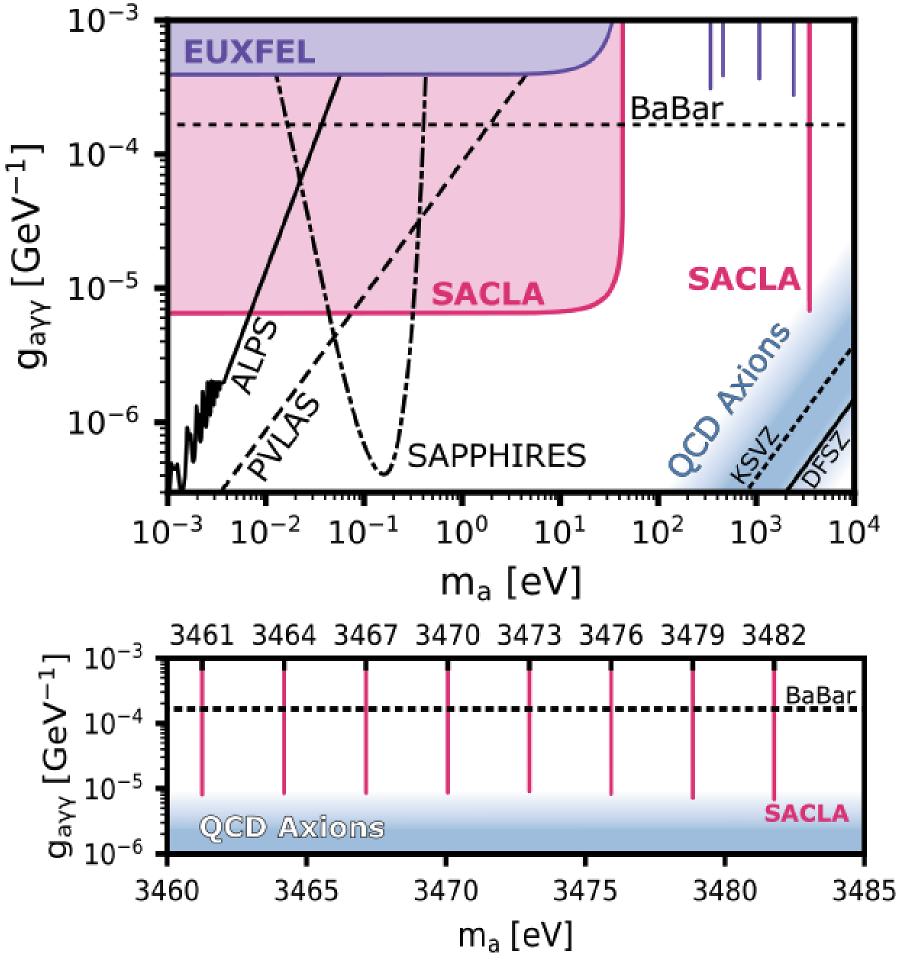
The BaBar collaboration. *"Search for Invisible Decays of a Dark Photon Produced in e^+e^- Collisions at BaBar"*, Phys. Rev. Lett. **119** (2017)

J. Dolan *et al. "Revised constraints and Belle-II sensitivity for visible and invisible axion-like particles"*, J. High Energ. Phys. 94 (2017)

The NA64 Collaboration, "Search for Axionlike and Scalar Particles with the NA64 Experiment" Phys. Rev. Lett. **125** (2020)

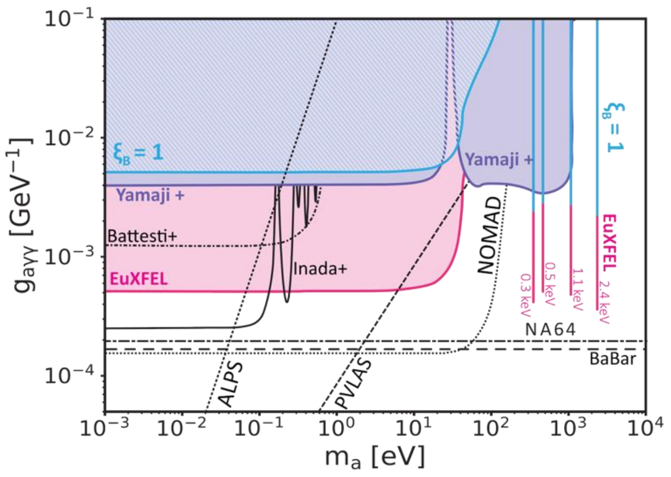
Follow-up SACLA measurements yield preliminary bounds approaching the QCD axion band

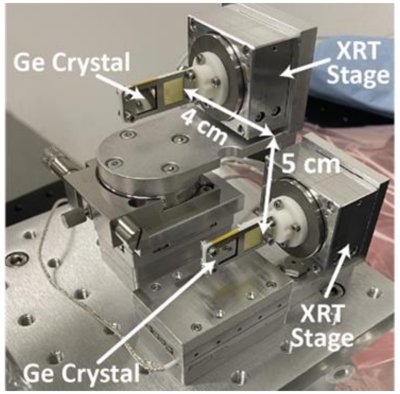
- Follow-up axion search performed at SACLA building directly on the EuXFEL configuration
- Operation in air enabled passive crystal cooling, allowing a deliberate trade-off of increased photon flux (~10^4) against reduced per-photon SNR
- Sensitivity was further improved through the use of thicker Germanium samples $(\ell \sim L_{\text{ext}}^{B} = 1.5\ \text{mm})$
- Preliminary axion–photon coupling bounds extracted from 3 days of data collection (in October 2025)
- Sensitivity approaches the QCD axion band at discrete masses (off-Bragg scans)
- Future prospects: improved signal-to-noise and implementation of continuous mass scans via photon-angle tuning



Overview

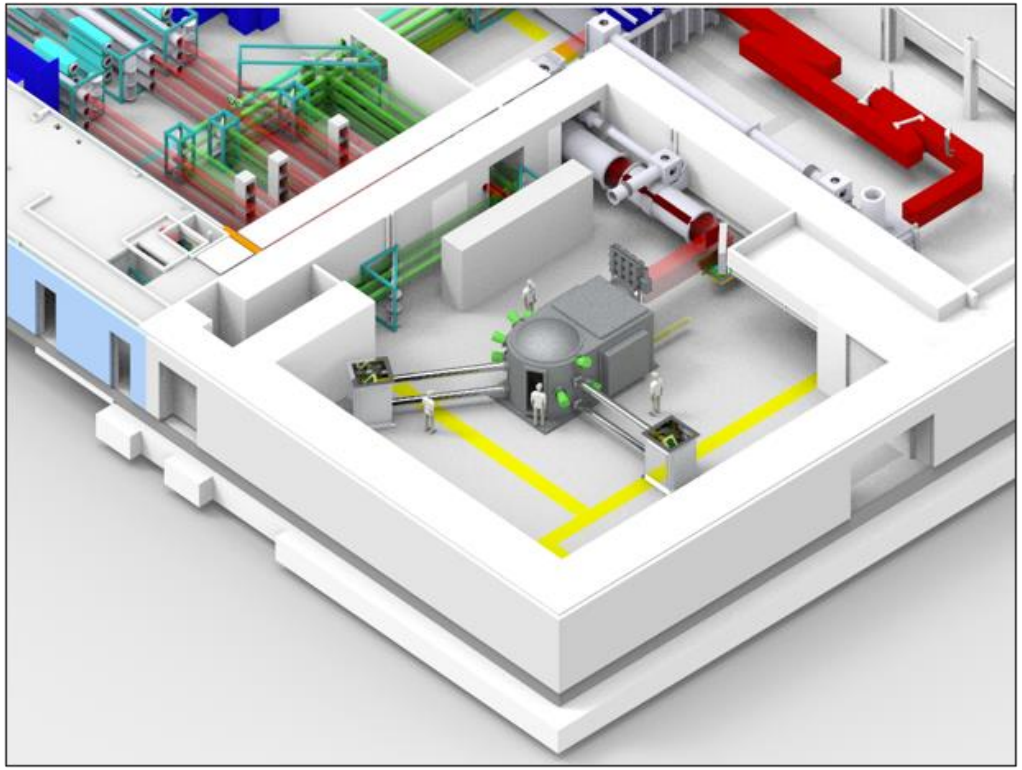
- Introduction to Axions / ALPS and overview of search strategies
- Experimental design for a light shining through a wall experiment with an X-Ray Free Electron Laser (XFEL)
- Experimental data for initial experiments on EuXFEL
- Follow-up work at SACLA (QCD sensitivity)
- **Fundamental physics with high powered lasers**





Vulcan 2020: Extreme Optical Fields for Strong-Field Experiments

- Optical laser system ($\lambda \sim 1\ \mu\text{m}, \varepsilon_\nu \sim 1\ \text{eV}$)
- Primary beam will deliver 20 PW peak power in a 20 fs pulse
- Large-aperture beam ($\sim 650\ \times\ 650\ \text{mm}^2$) focused to $\sim$ $5\ \mu m$, enabling peak intensities $\text{I} \gtrsim\ 10^{23}\ W/cm^2$
  ($\text{I}_{\text{Sch}} \sim 10^{29}\ \text{W/cm}^2$ but strong-field QED and perturbative non-linear vacuum effects accessible in targeted setups)
- Facility design explores splitting the primary beam into two equal arms, enabling dual-beam geometries
  (e.g. photon–photon interactions)
- Complemented by VOPPEL (1 PW-class) laser, optimised for laser-wakefield acceleration
  ($\sim 1\ GeV$ electron beams synchronised to the optical pulse with comparable spot size and duration)



There are a growing number of PW and multi-PW laser systems globally

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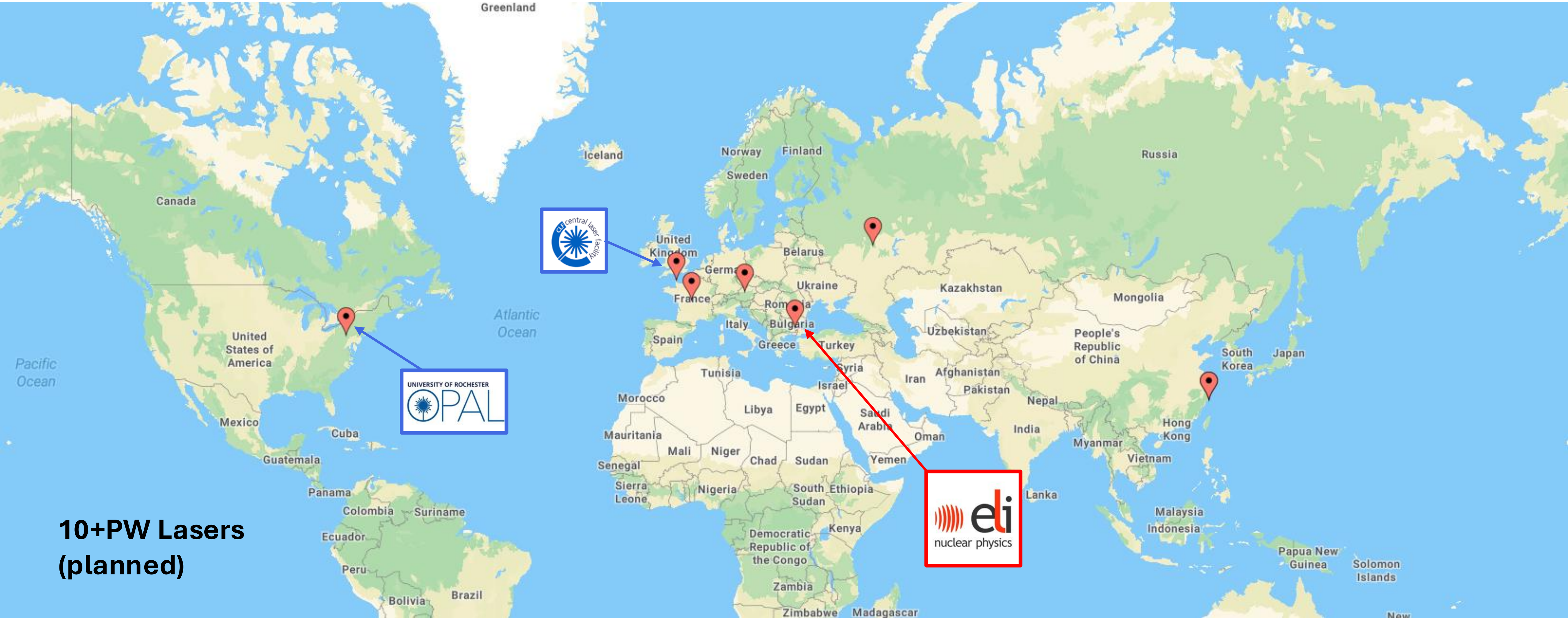
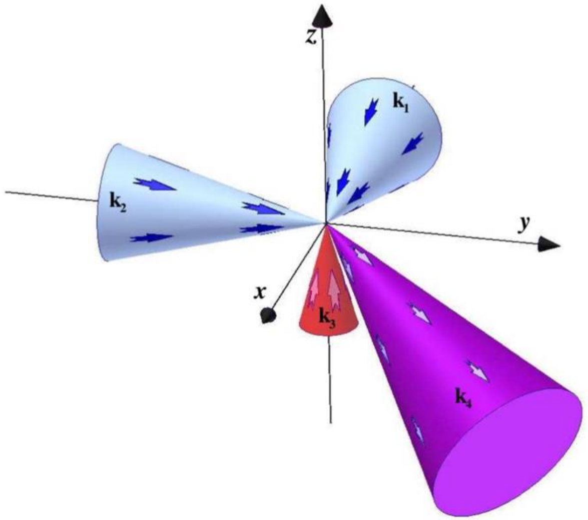
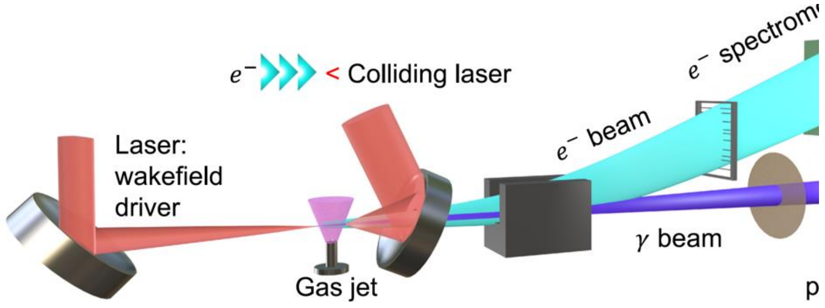


10+PW Lasers (planned)

Selected Fundamental-Physics Experiments to Explore with Multi-PW Lasers

- **Simulated photon-photon scattering:** four-wave mixing scheme to detect elastic photon–photon scattering in vacuum using multi-PW lasers [E. Lundström *et al.*, "Using high-power lasers for detection of elastic photon–photon scattering," *Phys. Rev. Lett.* **96**, **083602** (2006).]
- **Quantum radiation reaction:** high-significance ($> 5\sigma$) experimental validation of quantum radiation-reaction models in laser-electron collisions at strong fields [E. E. Los *et al.*, "Observation of quantum effects on radiation reaction in strong fields," *Nat. Commun.* **17**, 1157 (2026).]
- **Axion photon / axion electron coupling:** exploratory experimental concepts discussed in the following slides
- **Longer-term directions:** Exotic atoms; Post Newtonian gravity; high-frequency gravitational wave detection…





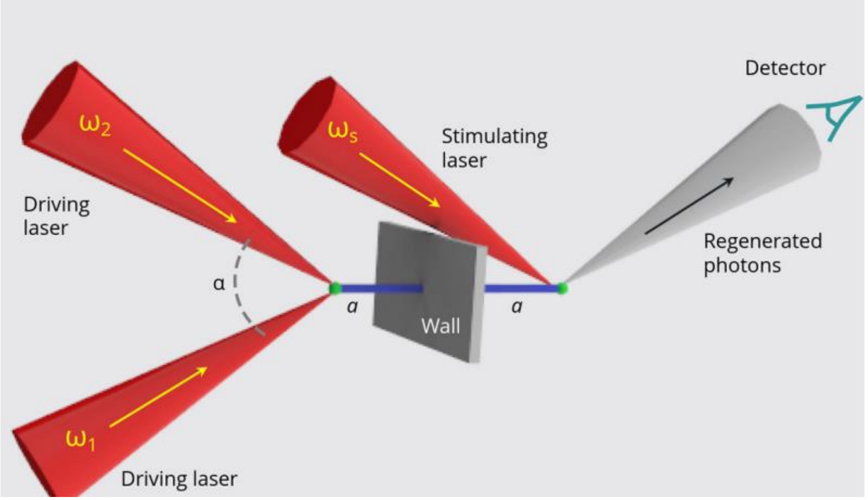
E.g. consider an axion search, with optical lasers, sensitive to $m_a = 1 - 10\ \mathrm{eV}$

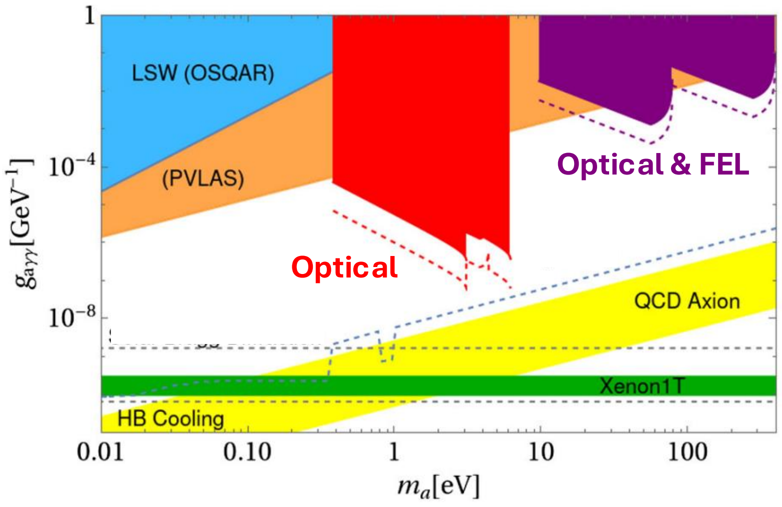
- Two short-pulse optical laser beams with orthogonal polarisations crossed in vacuum
- Axion production via the axion–photon interaction:

$$L_{\text{axion}} = g_{a\gamma\gamma}\boldsymbol{E}\cdot\boldsymbol{B}a$$

- Axions reconverted to photons via the inverse process using a third (stimulating) beam (LSW geometry)
- Projected sensitivity shown for the Aton-4 laser (ELI, Czech Republic) in the 1-10 eV mass range
- The same experimental concept is directly adaptable to multi-PW optical facilities including Vulcan-2020

K. Beyer *et al.* *"Light-shining-through-wall axion detection experiments with a stimulating laser"* Phys. Rev. D **105**, 035031 (2022)

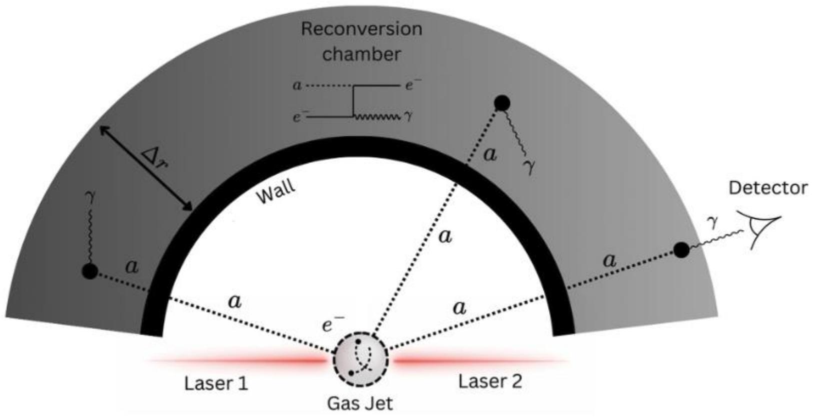


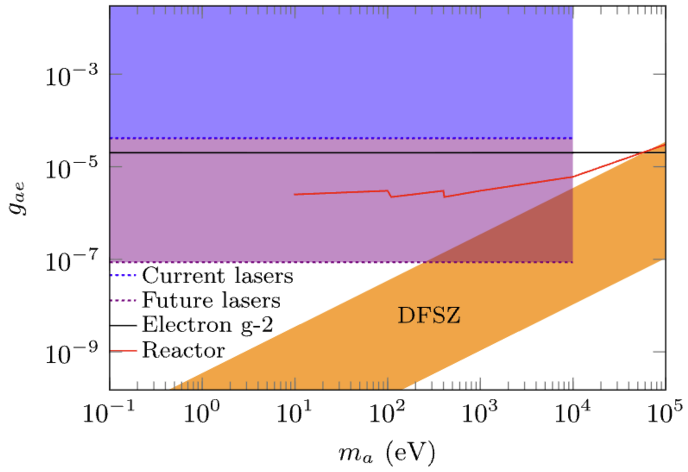


Laser-driven schemes targeting the axion–electron coupling have also been proposed

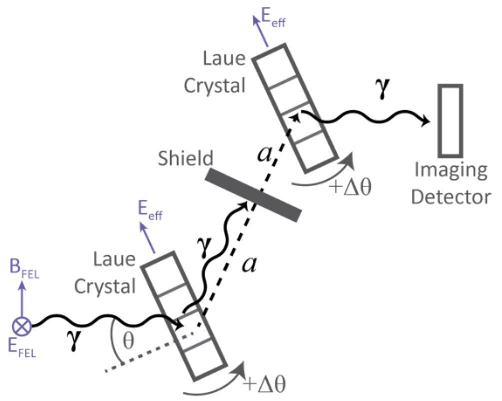
- Two counter-propagating laser pulses form a standing wave in a gas jet, directly accelerating electrons via the oscillating electric field.
- Accelerated electrons have a probability to emit axions during this direct acceleration process (by analogy with radiation from an accelerated charge)
- Axions traverse through a wall and interact with electrons in the material, enabling reconversion via a Compton-like process ($a + e^- \rightarrow \gamma + e^-$)
- Projected sensitivities for multi-PW laser facilities are competitive with existing accelerator searches

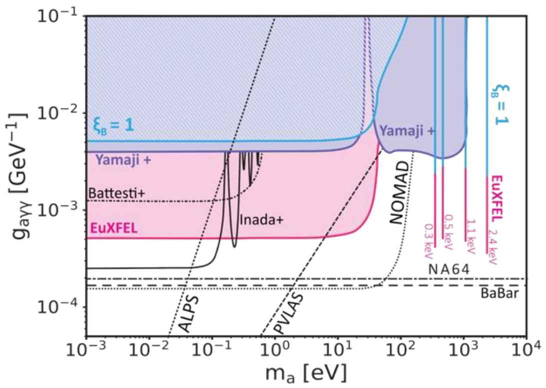
G. Vacalis, A. Higuchi, R. Bingham, and G. Gregori, *Proposal to use laser-accelerated electrons to probe the axion–electron coupling*, **Phys. Rev. Lett. 135**, 195003 (2025).

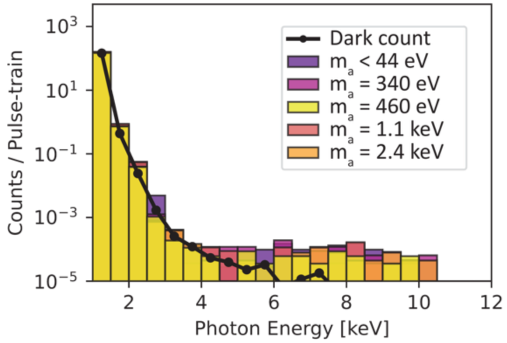


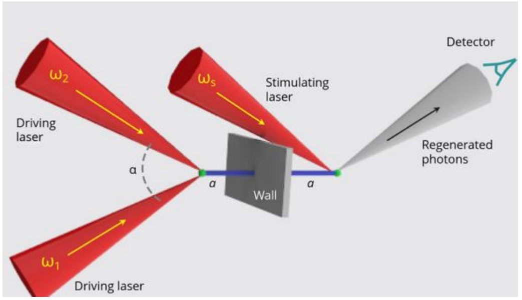


Conclusions









- Axions explain the absence of CP-violation in strong interactions and are a cold dark matter candidate
- We performed a search for heavy axions on EuXFEL
- Had issues with crystal heating, but we could still impose competitive bounds on $g_{a\gamma\gamma}$ using a search technique complimentary to collider-based experiments
- Follow up experiment at SACLA demonstrated sensitivity approaching the QCD axion band
- High powered lasers have potential uses for fundamental physics, including in axion searches.

J. W. D. Halliday *et. al.* *"Bounds on Heavy Axions with an X-Ray Free Electron Laser"* Phys. Rev. Lett. **134**, 055002 (2025)