Axion-like particle searches at SPring-8 synchrotron facility

ICEPP, the university of Tokyo
tabletop experiments group
Toshio NAMBA

New particle searches with X rays

UT tabletop experiments group (only related to today's talk)

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Core members

- RIKEN, JASRI (SPring-8&SACLA):

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X-ray experts

- UT ISSP & Tohoku Univ.:

Pulsed magnet experts

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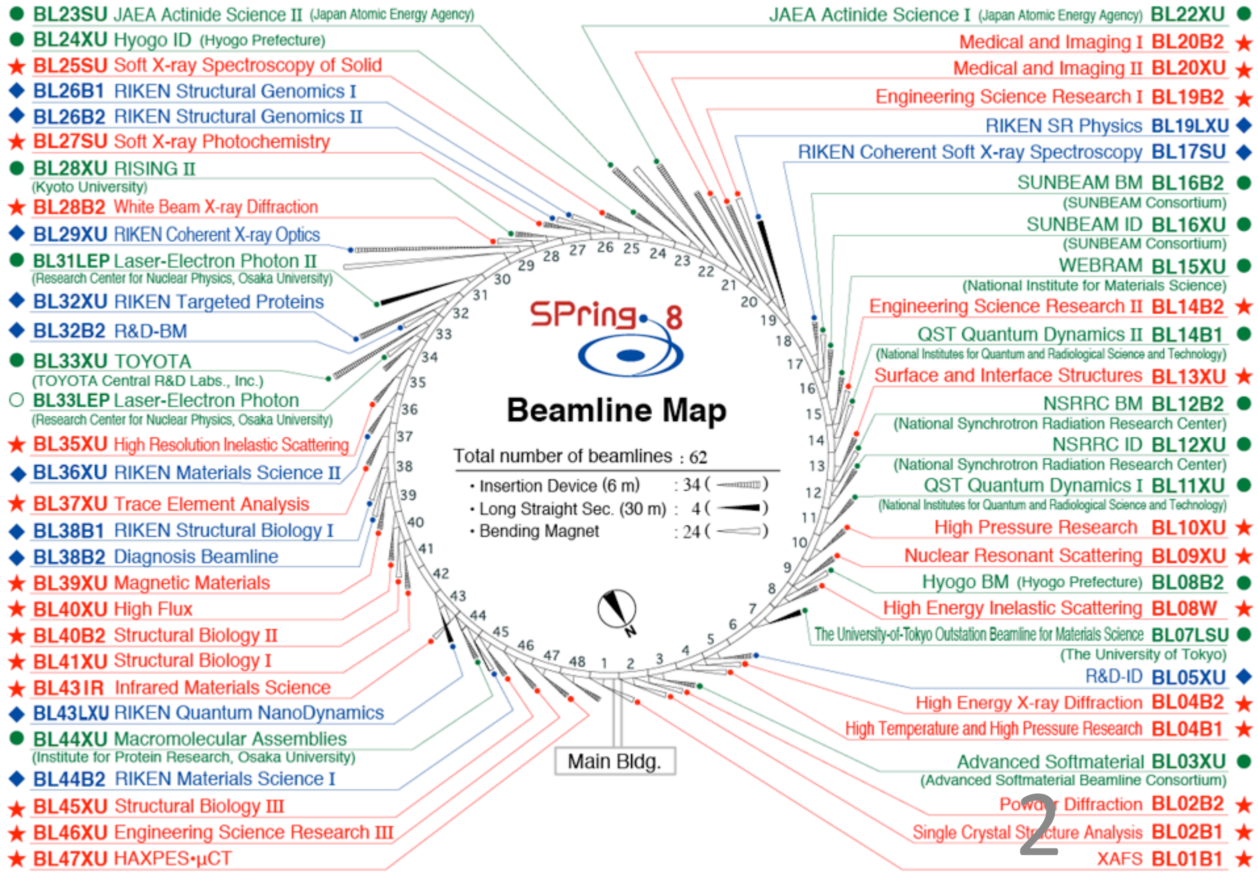
SPring-8 synchrotron facility

- One of the largest synchrotron radiation facility in the world
- 8 GeV electron storage ring whose circumference is 1436m
- 62 beamlines available (IR, soft X-ray, hard X-ray, polarized X-ray, ...)



BL19LXU @SPring-8

- 27m long undulator beamline
- Energy range: 7.2~18 keV (1st harmonics), 22~37 keV (3rd harmonics)
- Photon flux: ~2×10^{14} photons/s (@14keV)

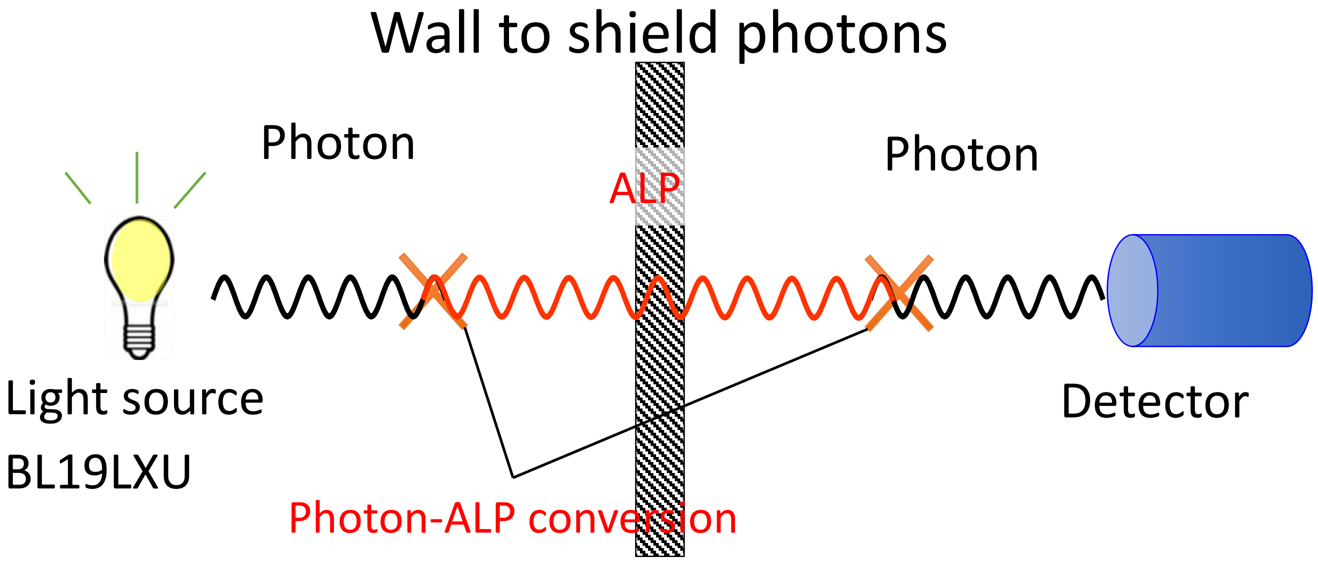
  (40 ps bunch with 23.6ns interval)
- X-ray size: $0.8(V) \times 1.5(H)$ mm^2

  can be focused with X-ray mirrors

With this high-intensity X-ray beam, our group performed pure laboratory-base ALP searches in keV region.

Light Shining through a Wall (LSW) method

- Convert photons to ALPs ⇒ Shield photons at a wall ⇒ Re-convert ALPs to photons ⇒ Detect photons



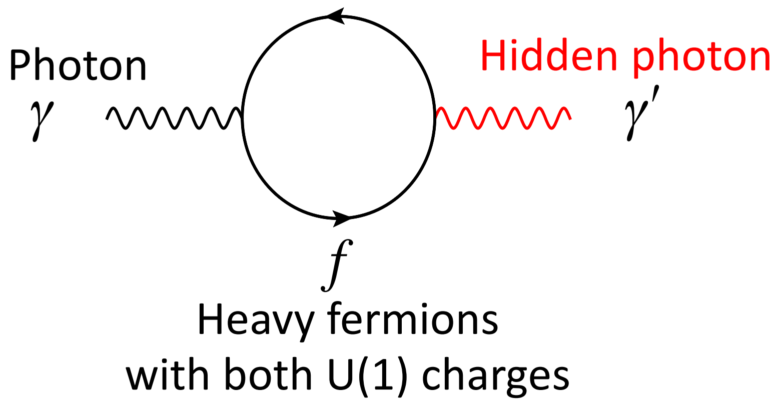
- Purely laboratory search: No cosmological/astrophysical assumptions are required
- LSW with X-rays: Relatively heavier ALPs can be searched compared with optical/IR photons.

Our LSW searches

3 searches performed in BL19LXU will be shown:

1. Hidden photon search
2. ALP search with pulsed magnets
3. ALP search with crystalline electric fields

1st target: Hidden photons



- Extra gauge bosons of hypothetical U(1) symmetry
- One candidate of the cold dark matter
- Tiny kinetic mixing χ with ordinary photons

$$\mathcal{L}_{\mathrm{int}} = -\frac{\chi}{2} F_{\mu\nu} X^{\mu\nu}$$

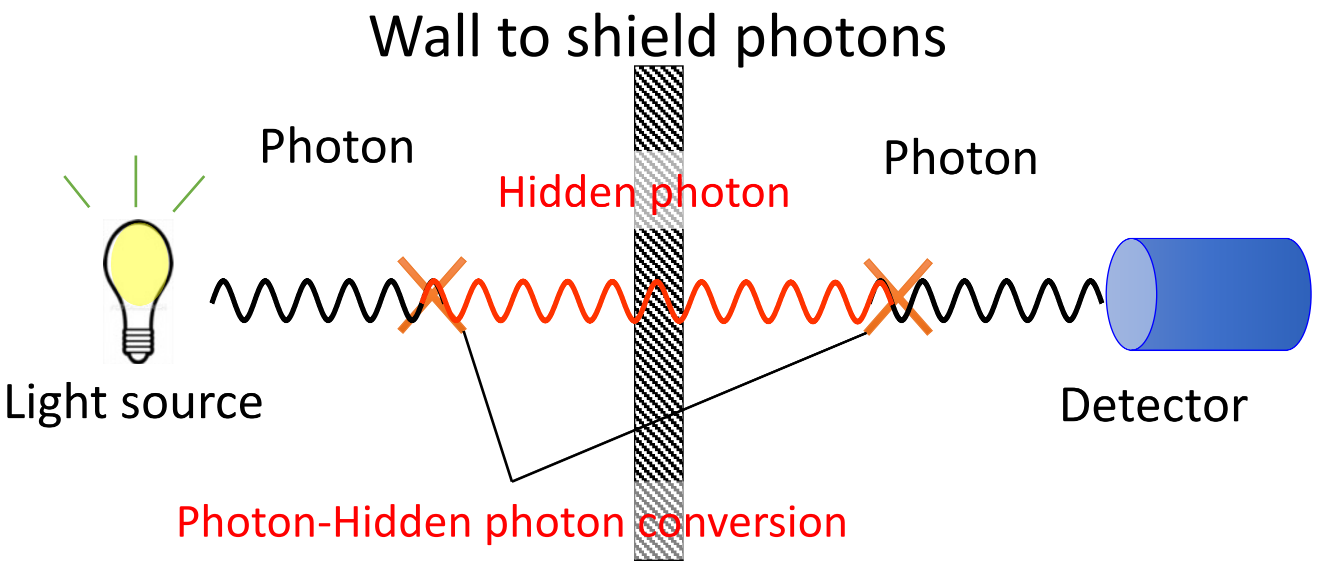
  - Neutrino like flavor oscillation

Hidden photon search with LSW method

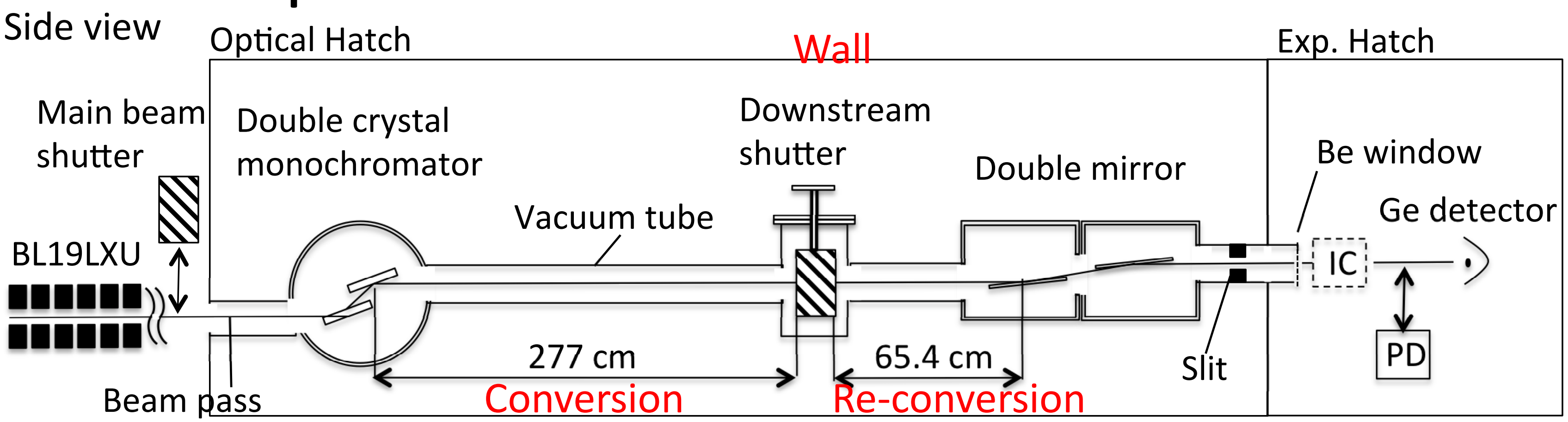
- Photon/hidden photon oscillation in vacuum is used for the conversions

$$P_{\gamma\to\gamma'} = 4\chi^2 \sin^2\left(\frac{m_{\gamma'}^2}{4\omega}L\right)$$

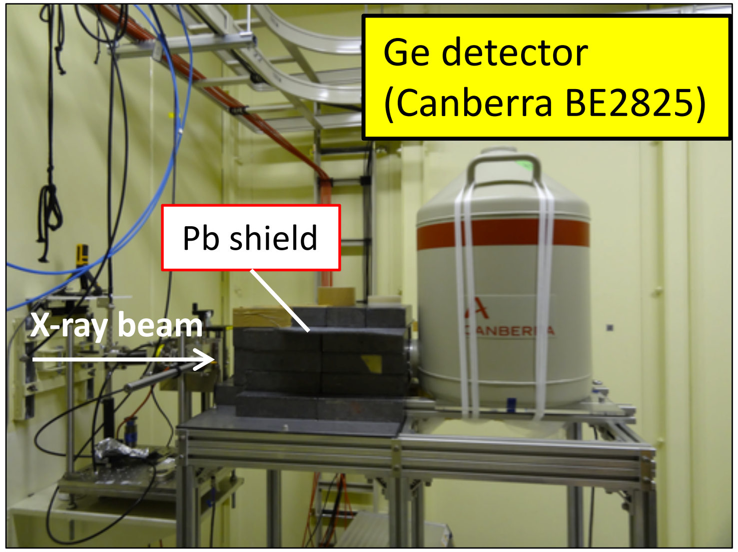
- Just prepare vacuum paths and a shutter, it can be searched.



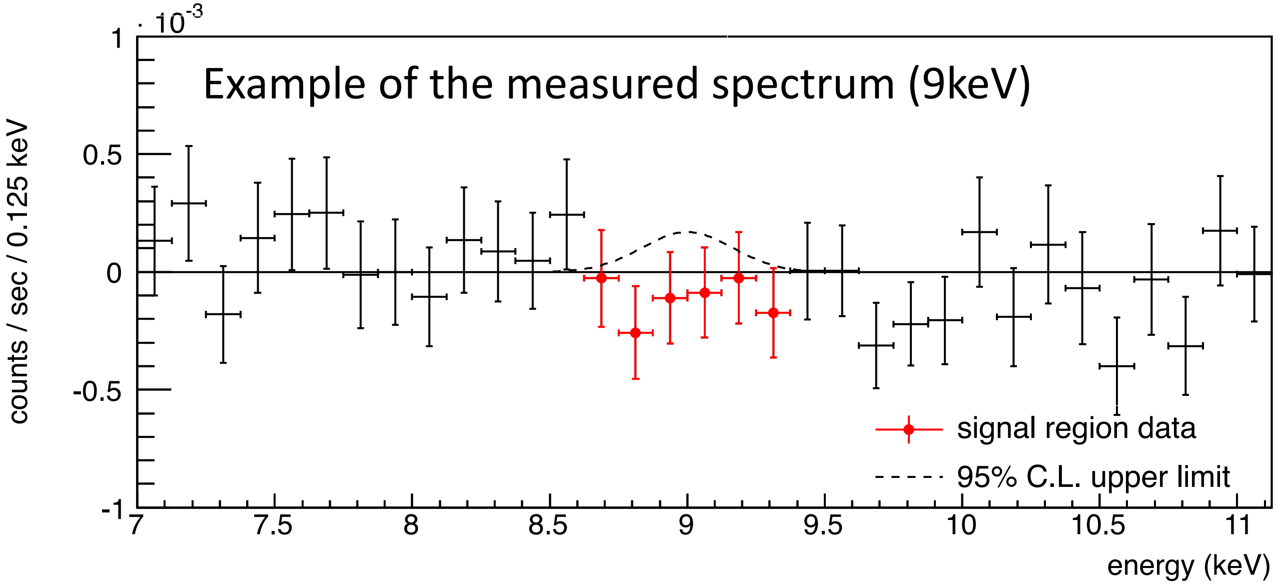
Search setup in the beamline



- Permanent apparatuses in the beamline were used for the LSW setup
- The search was performed in June 2012 for 2 days.
- X-ray energies were changed 9 times from 7.27 keV to 26 keV.
- A germanium detector was used to detect re-converted X-rays.

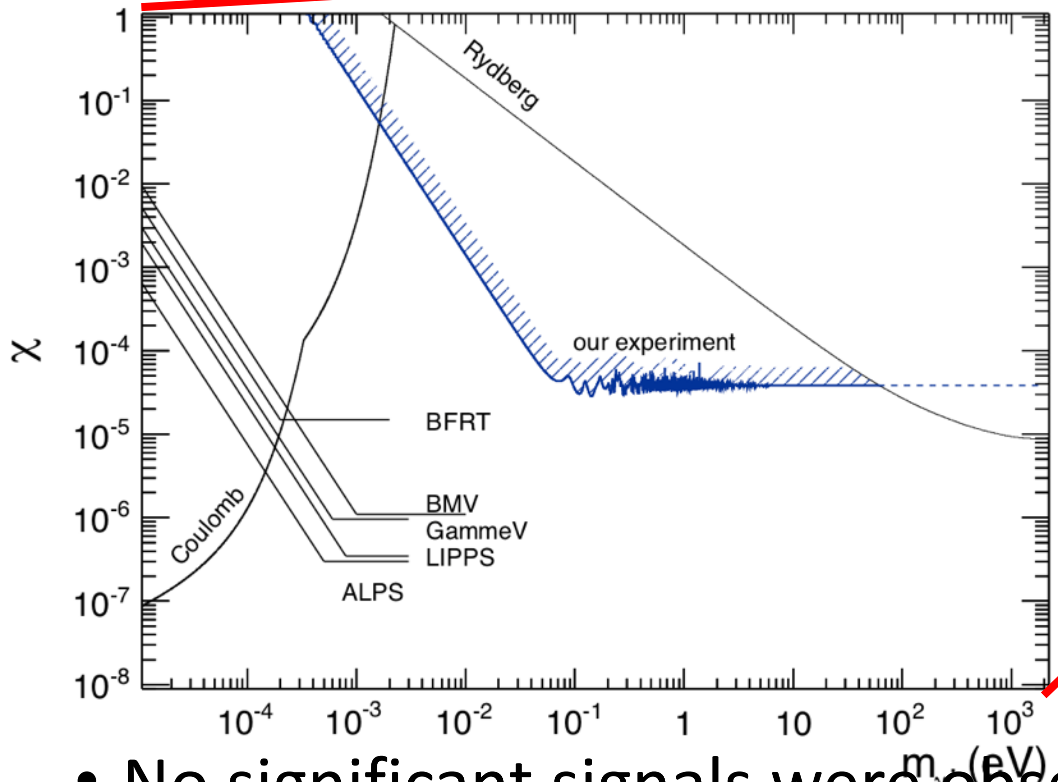


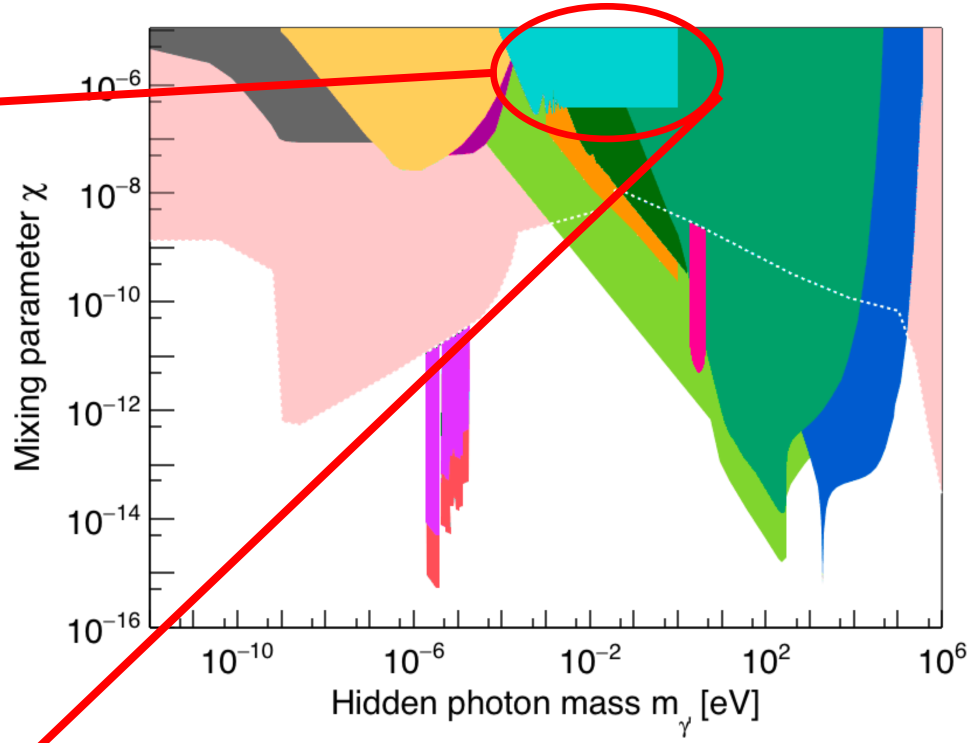
Search Results



- No significant signals were observed in all data.
- The spectra for other energies had also no peaks.

Search Results

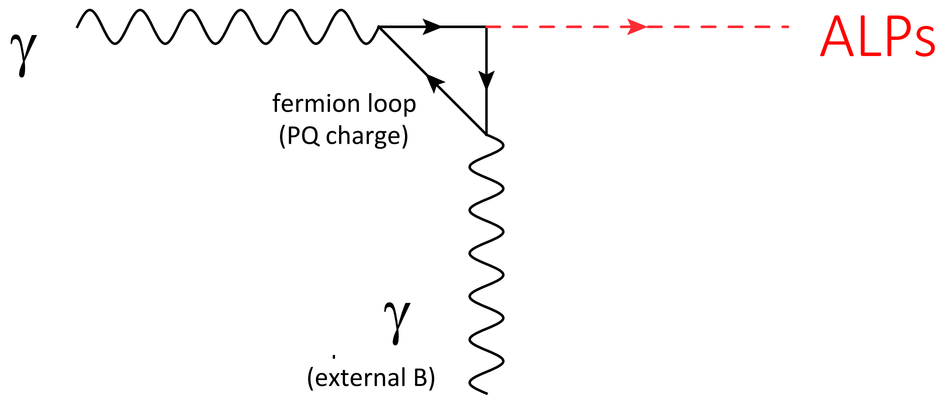




- No significant signals were observed in all data.
- Constraints of $\chi < 8.06\times10^{-5}$ for (0.04 eV < m_{HP}< 26 keV) were obtained (95% C.L.)
- Phys. Lett. B722(2013)301.

The most sensitive laboratory search at 0.1~100eV region

Next target: Axion Like Particles (ALPs)



- Originally motivated by the strong CP problem
  - CPV caused by θ vacuum can be cancelled by SSB of PQ symmetry → New NG boson, axion
- More generally, axion like particles are predicted by string theory or SUSY/SUGRA
  (No constraints on mass-coupling relations)
- ALPs interact with two photons (Primakoff process)

$$\mathcal{L}_{a\gamma\gamma}=-\frac{g_{agg}}{4}F_{\mu\nu}\tilde{F}^{\mu\nu}a = g_{a\gamma\gamma}\vec{E}\cdot\vec{B}a$$

or are converted to photons under EM field

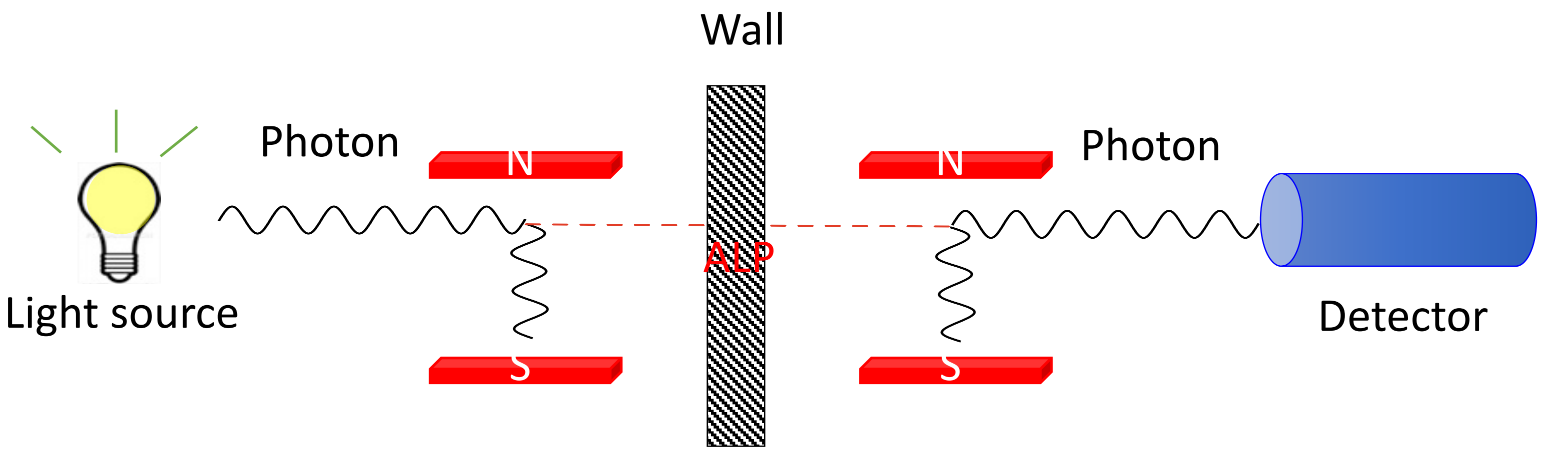
- Also are good candidate of CDM

Magnetic field is required

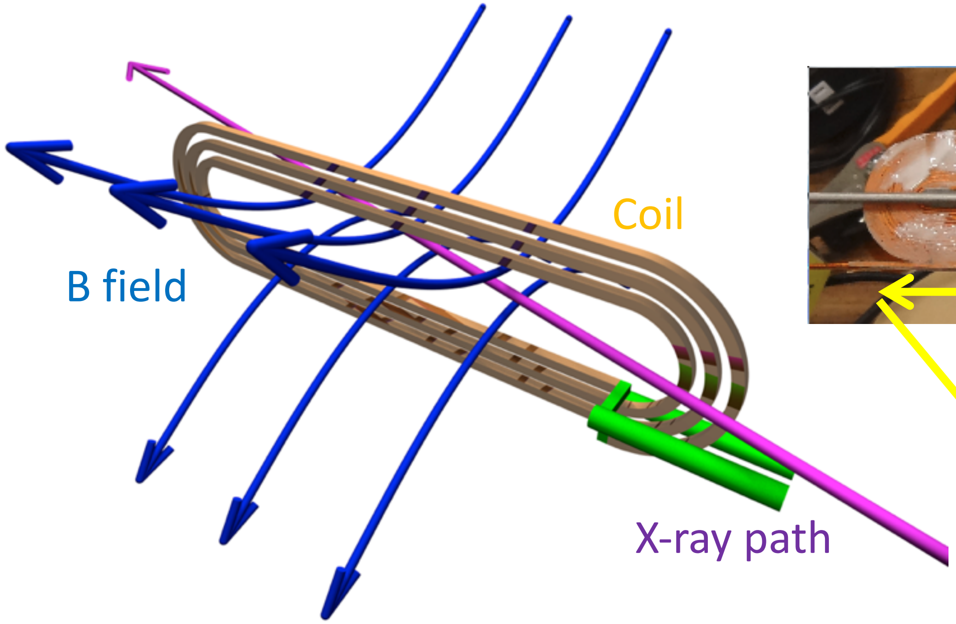
- We want to do ALP search similar as hidden photon search, but dedicated magnets are required for the conversion.

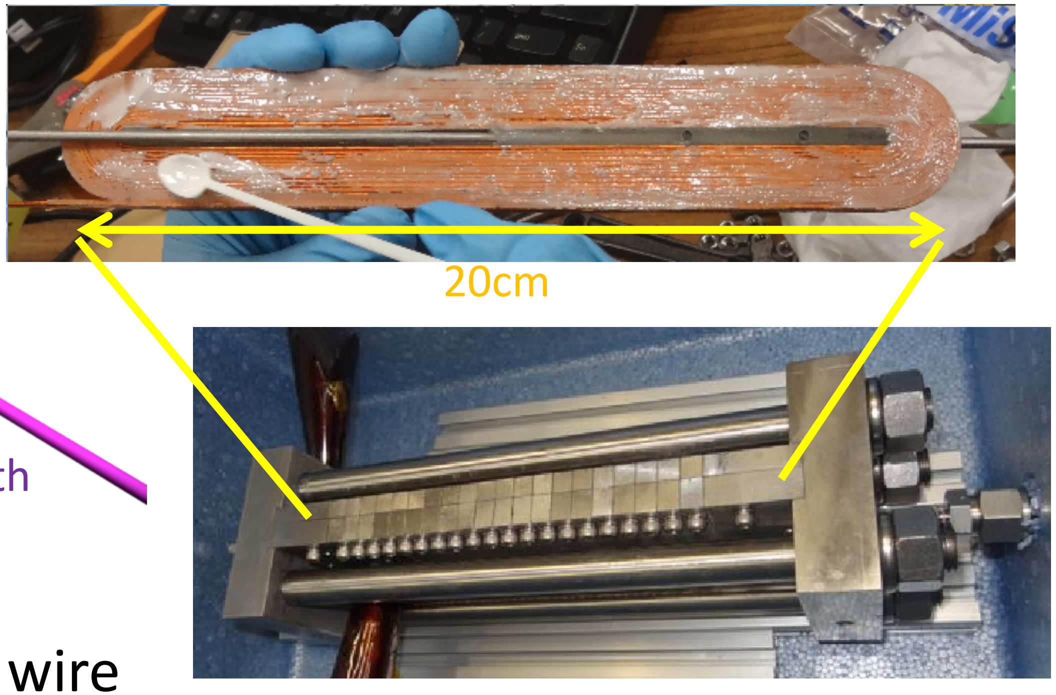
$$P = \left(\frac{g_{\alpha\gamma\gamma} BL}{2} \frac{\sin\theta}{\theta} \right)^2, \qquad \theta = \frac{m_\alpha^2 l}{4\omega}$$

- Since the magnetic field should be applied perpendicular to the light path, and the conversion depends on $(BL)^2$, usual solenoid magnets are not suitable.



Our magnet for ALP search

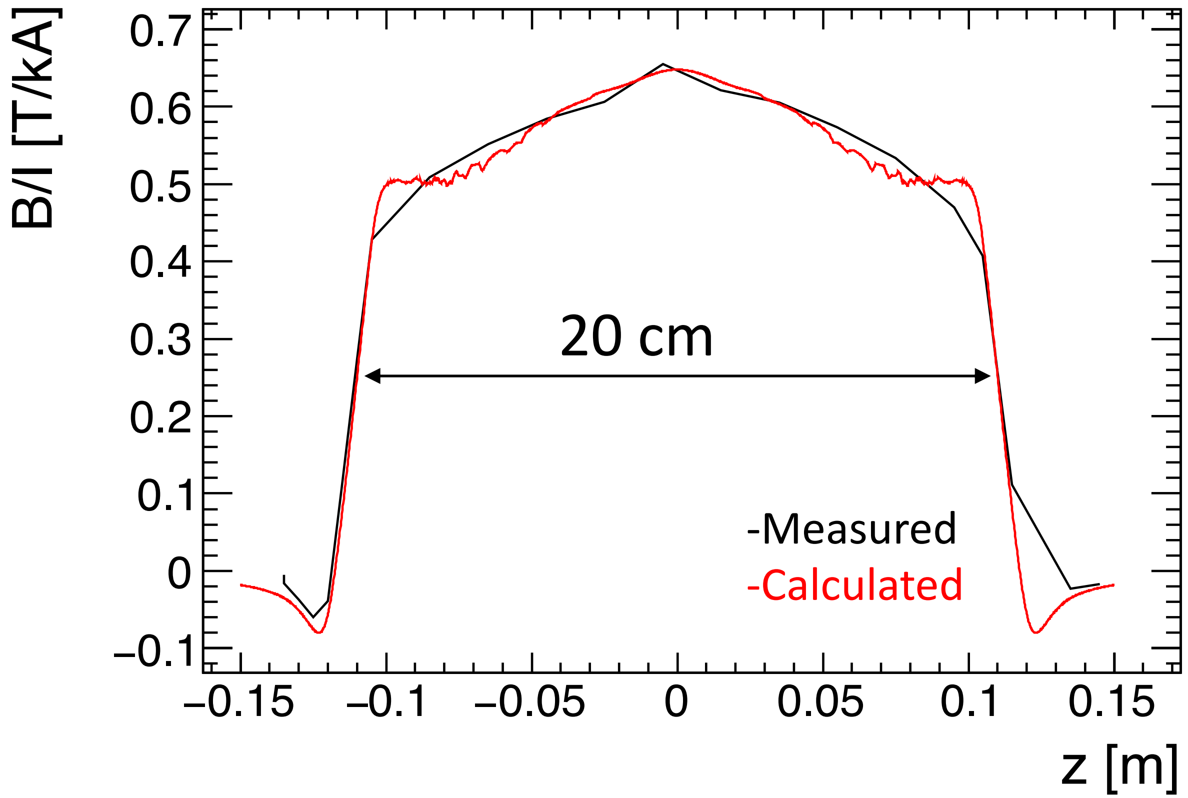




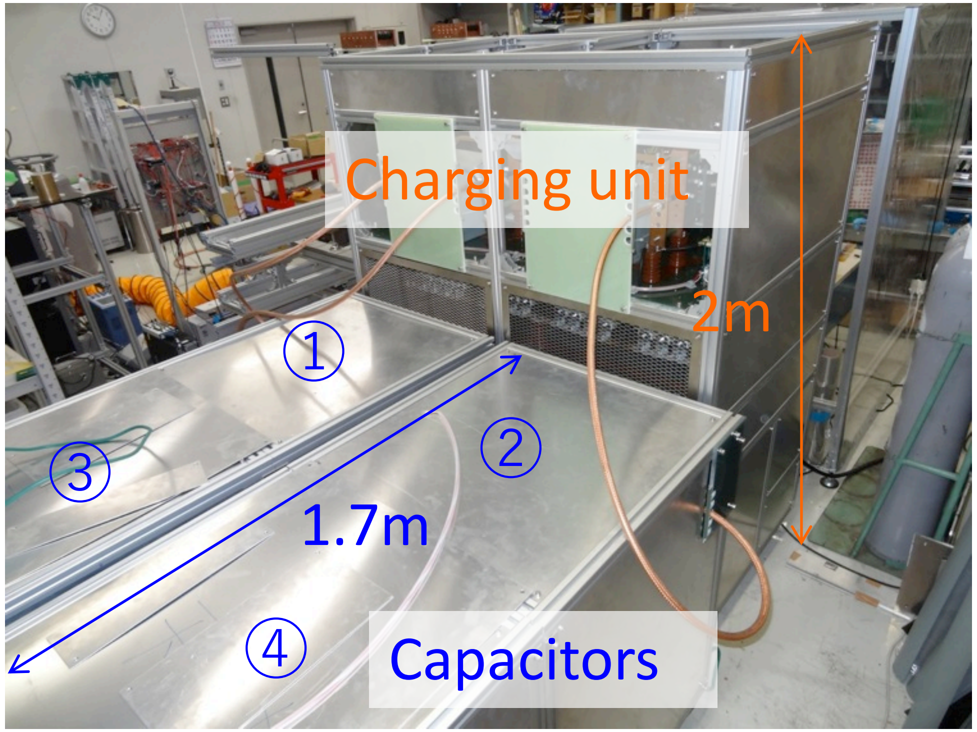
- Racetrack shape coils made of copper wire
- Its length is L=20cm
- Capsulated in a stainless frame to endure the magnetic field stress
- Designed to be operated at pulse mode, 14.1T max, ~1ms duration (Good for S/N separation)
- Cooled by Liq. Nitrogen

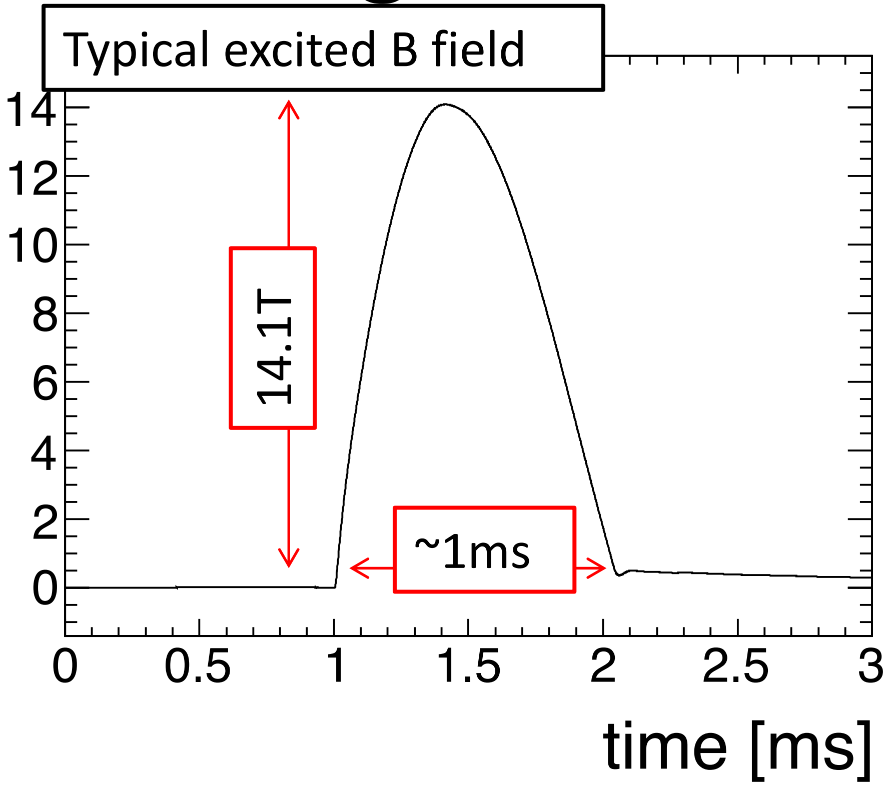
Magnetic field map of the coil

- The magnetic field at the center path of the beam pipe (ϕ5.3mm) agrees with calculations.
- The magnetic field at the edge is ~20% smaller than the center.



Power supply for the pulsed magnet



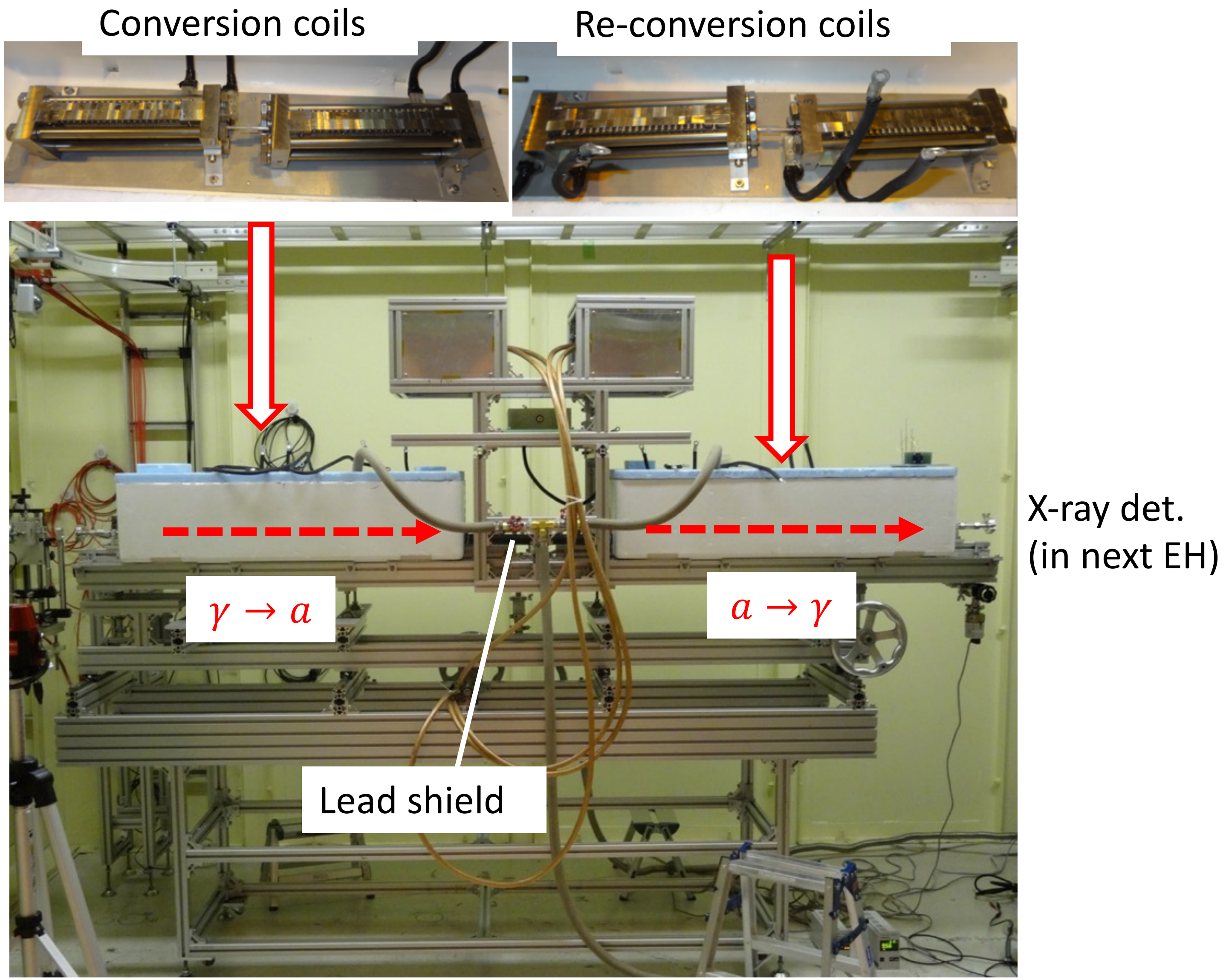


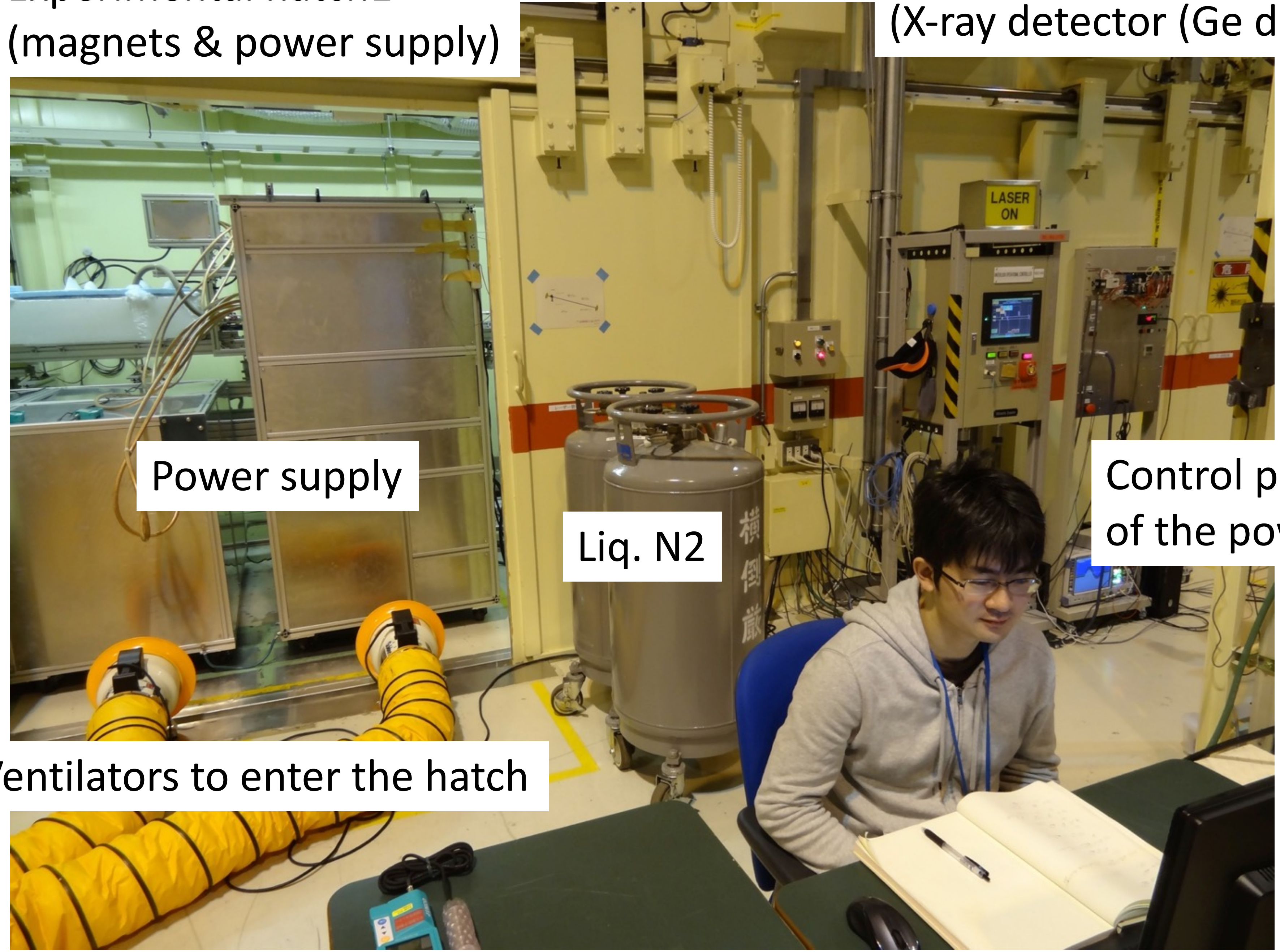
- Total 3mF capacitance (0.25mFx12capacitors) is charged to 4.5kV (30kJ power).
- The rapid charging system enables 0.5Hz repetition rate.
- Total 2 ton weight (can be carried by motortrucks).
- NIM A 833(2016)122

ALP search in BL19LXU

- Performed in Nov. 2015
- 4 coils were placed at the X-ray path in the experimental hatch
- 2 for (X-ray → ALP) conversion
- 2 for(ALP → X-ray) re-conversion
- X-ray energy was set to 9.5 keV
- Net 2 days operation

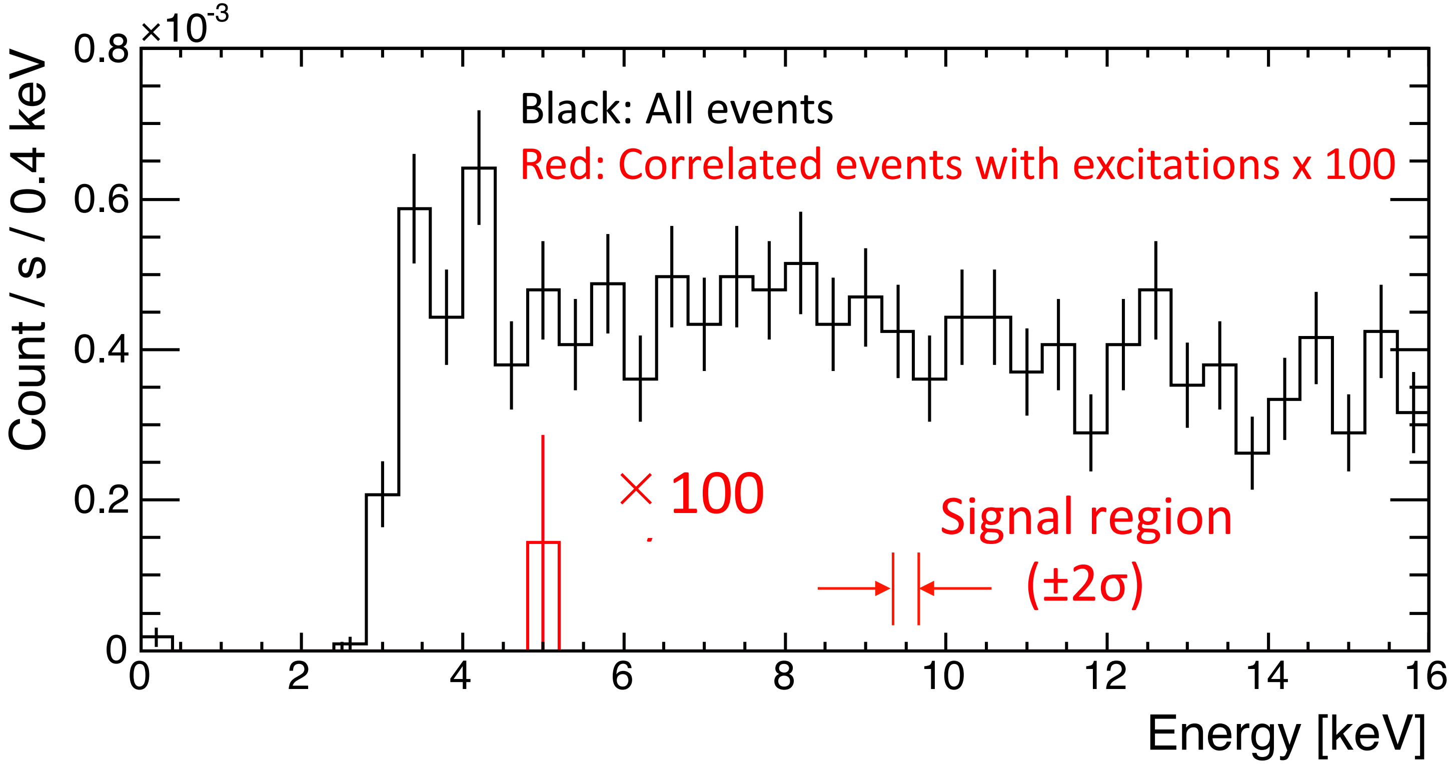
(total 28,000 excitations)





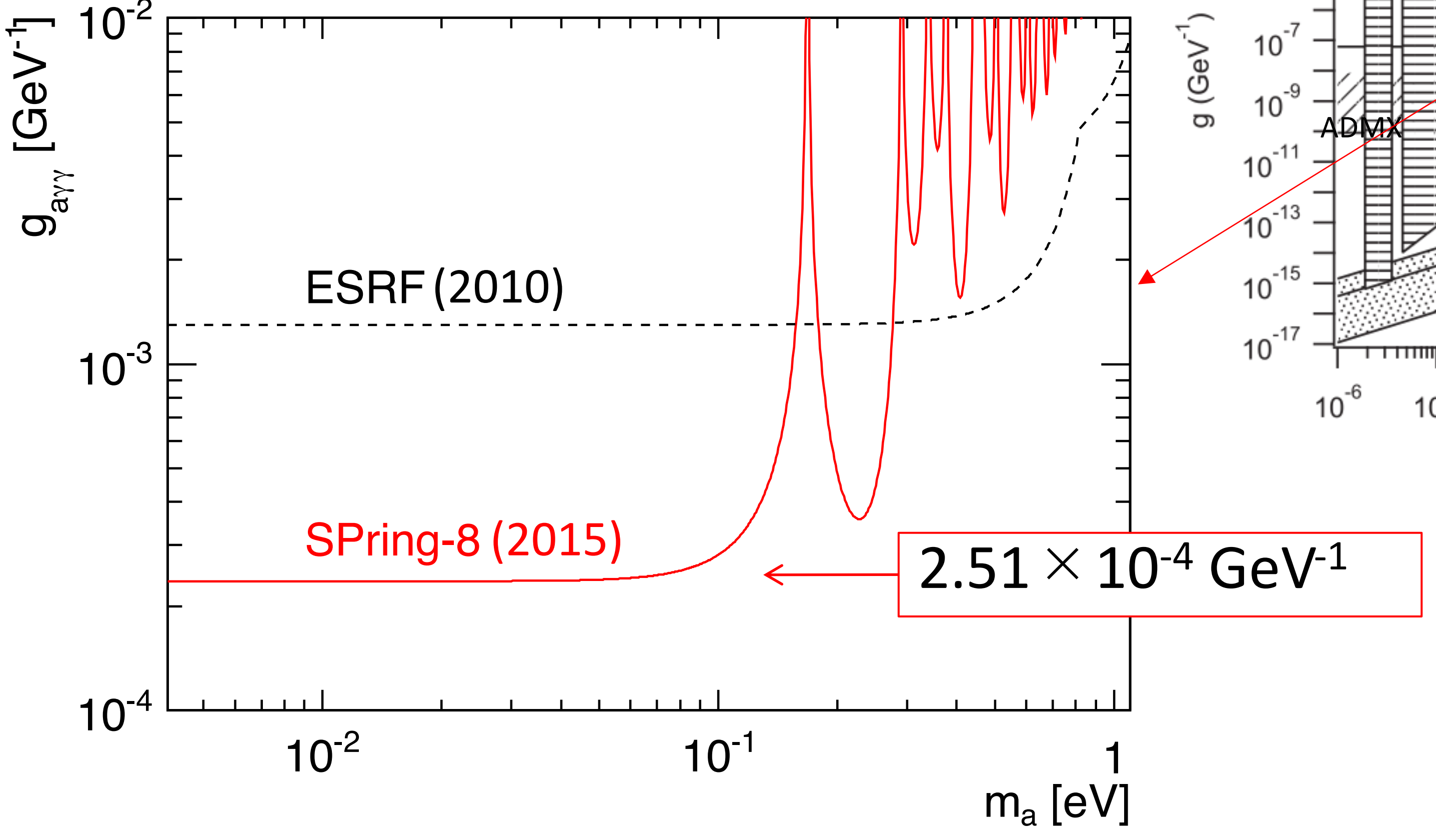
Many risks
- High voltage
- High magnetic field
- Strong X rays
- Suffocation

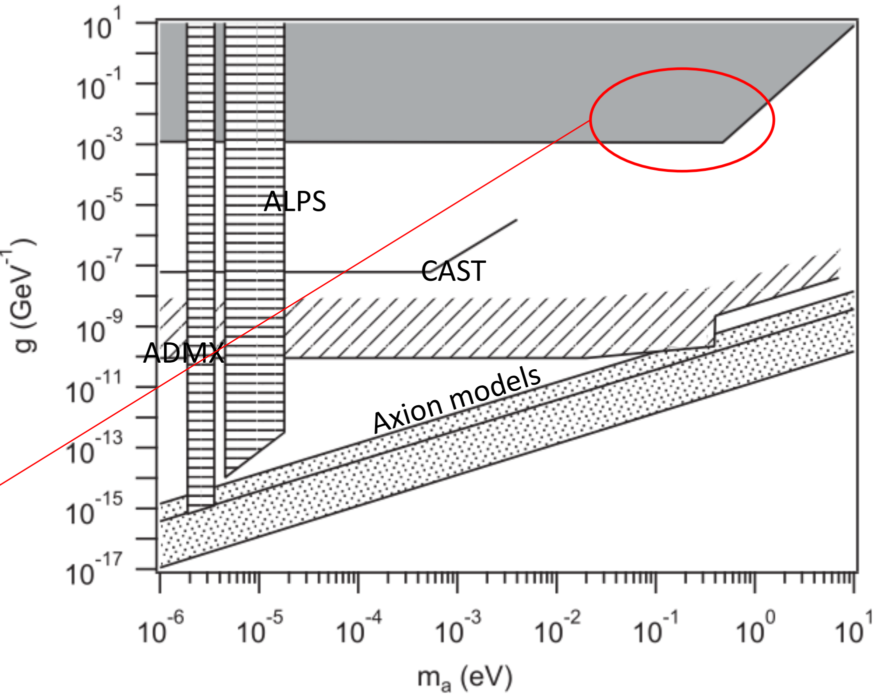
Event distribution



- No significant events correlated to the magnet excitations were observed.
- BG rate is consistent with the one observed event.

Search result



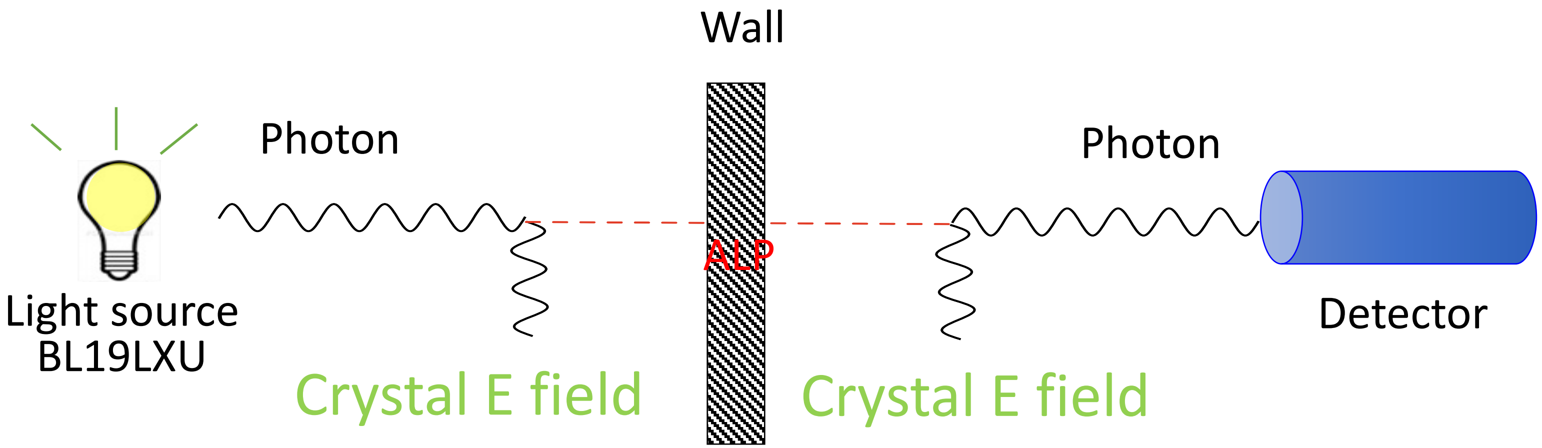


- Most stringent X-ray LSW limit

  $g_{a\gamma\gamma} < 2.51 \times 10^{-4}$ GeV^{-1} (95%C.L.) was obtained below m_a~0.1eV
- More sensitive search will be performed with upgraded magnets or using SACLA (XFEL).
- PRL 118(2017)071803

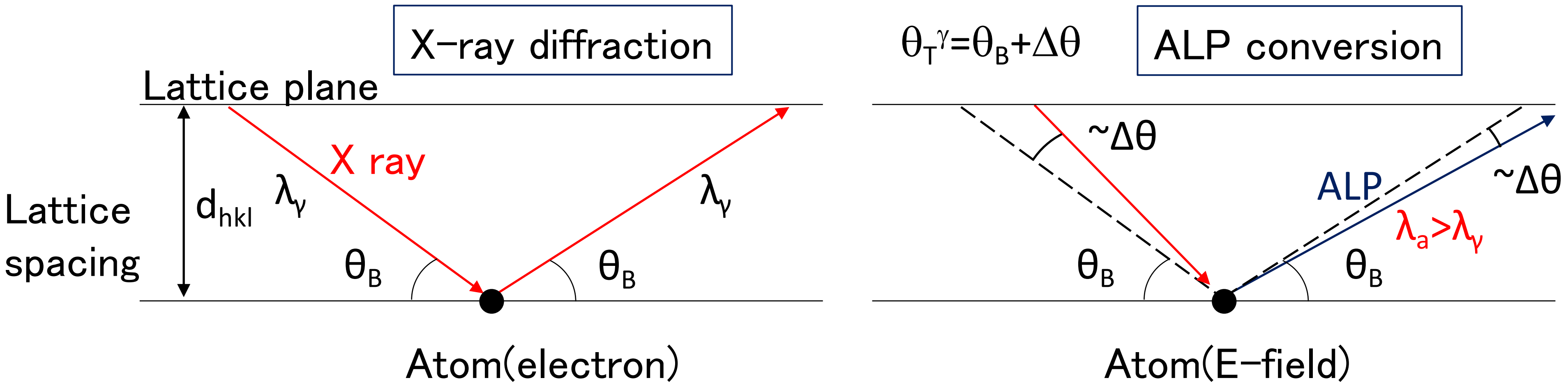
Another ALP search using crystal diffractions

- An electric field can convert ALPs to photons. $(BL)^2 \Rightarrow (EL)^2$
- LSW experiments can be performed by using electric fields in materials.



ALP-photon conversion by X-ray diffraction in crystals

- Periodic electric fields in crystals (10^{10}V/m~10^{11}V/m) can be used for photon-ALP conversion (similar power as 10^{2}~10^{3} T).
- Relatively heavier ALPs can be converted if the incident angle of X-rays is tuned.



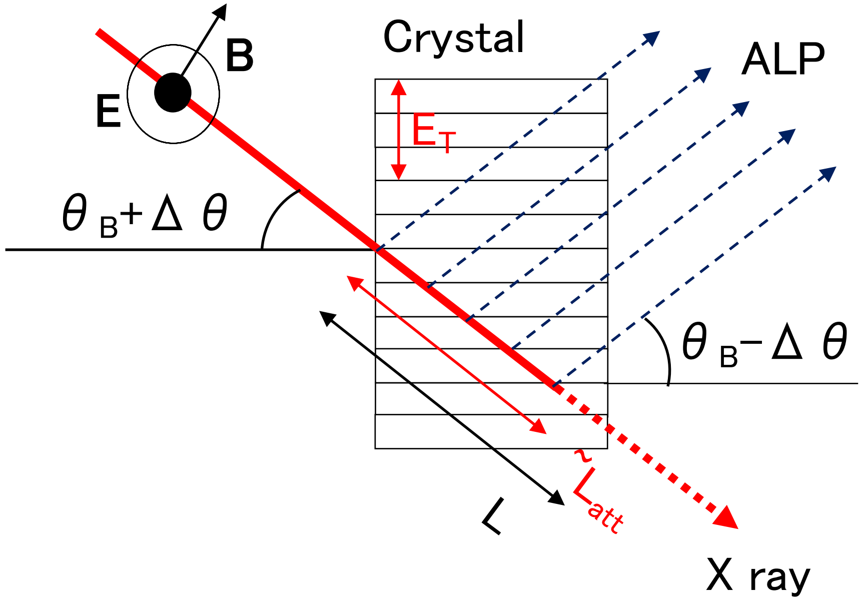
Coherence matching condition: $$\left|m_a^2 - m_\gamma^2 - 2q_T\left(k_\gamma \sin\theta_T^\gamma - \frac{q_T}{2}\right)\right| \lesssim \frac{4k_\gamma}{L}$$

$q_T=2\pi/d_{hkl}$: Reciprocal lattice spacing

Depending on the incident angle

Calculation for Laue case diffraction

- T. Yamaji et al., Phys. Rev. D 96(2017)115001



$$P_{a\to\gamma} = \left(\frac{1}{2} g_{a\gamma\gamma} E_T L_{\rm eff} \cos\theta_{\rm B}\right)^2,$$

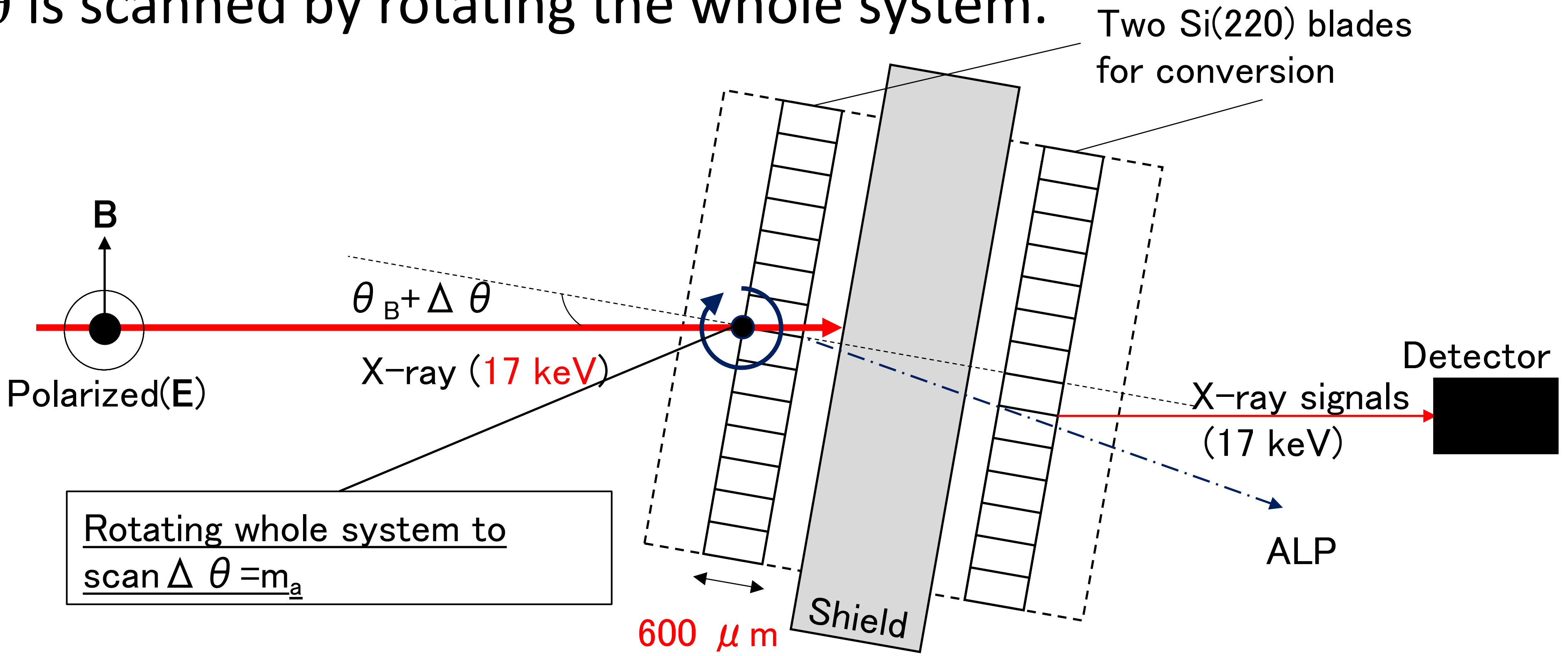
$$L_{\rm eff} = 2L_{\rm att}\left(1-\exp\left(-\frac{L}{2L_{\rm att}}\right)\right)$$

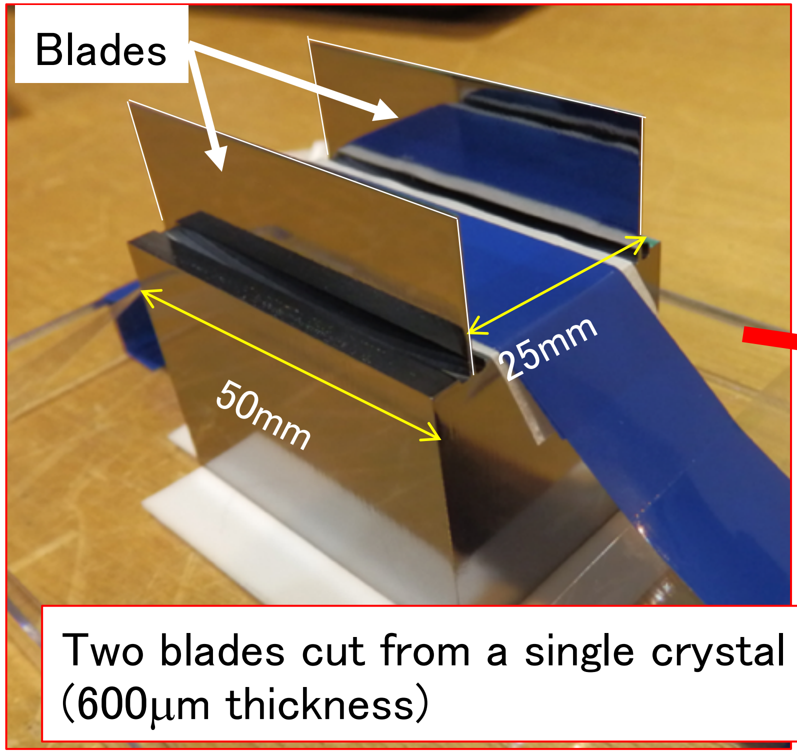
In the case of Silicon: 600μm, 17keV X rays

- E_T=4.1x10^{10}V/m
- L_{eff}=488μm
- Until m_a～10keV can be converted

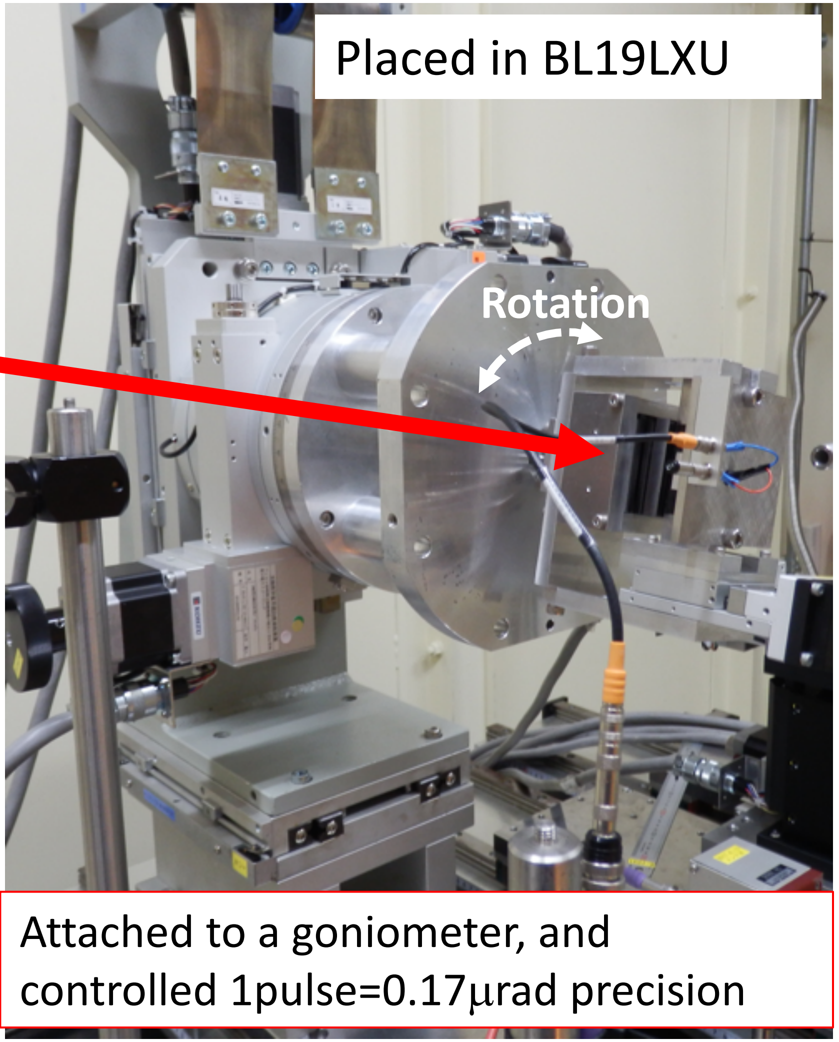
The silicon crystal for the search

- Two blades cut from a single silicon crystal were used for search. (Lattice planes of two blades are guaranteed as parallel)
- $\Delta\theta$ is scanned by rotating the whole system.





Two blades cut from a single crystal (600μm thickness)

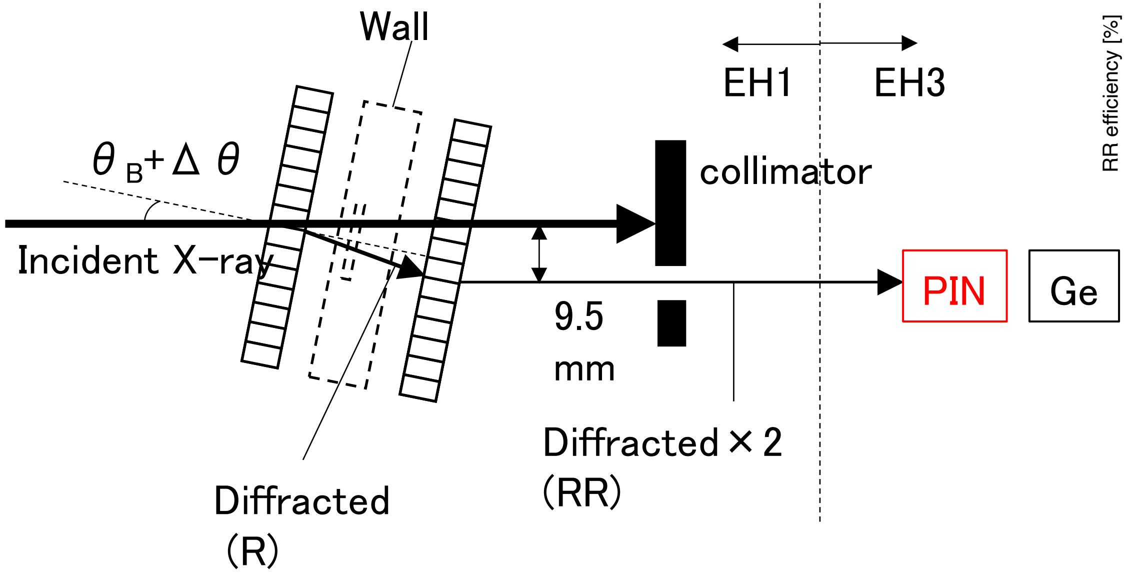


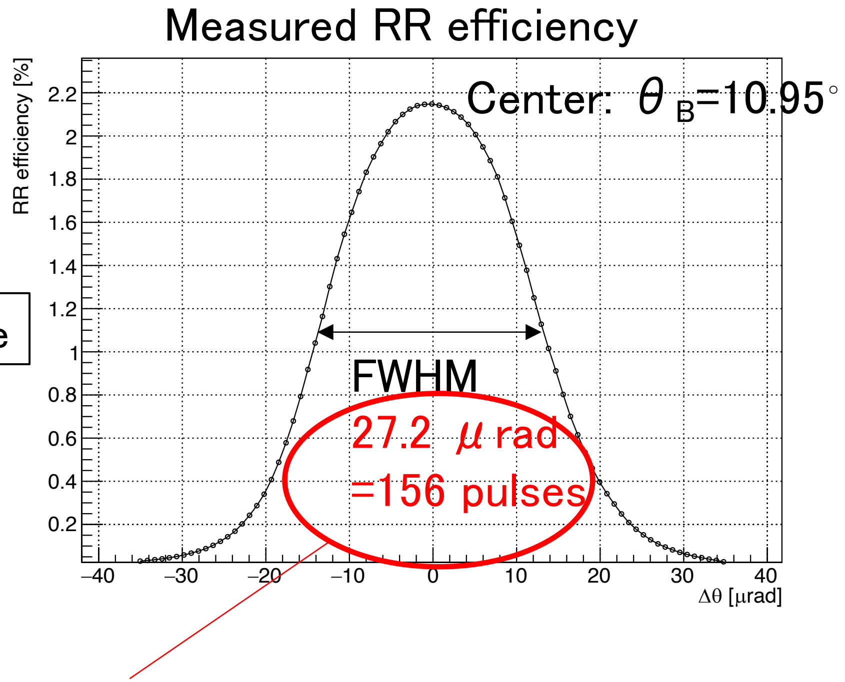
Attached to a goniometer, and controlled 1pulse=0.17μrad precision

- Performed in Oct. 2017, for 2 days.
- Scanned from Bragg angle to $\Delta\theta$=4.6mrad
  (Corresponding to $0<m_a<1$keV)

Rocking curve measurement
(Confirmation of the successive Laue diffraction)

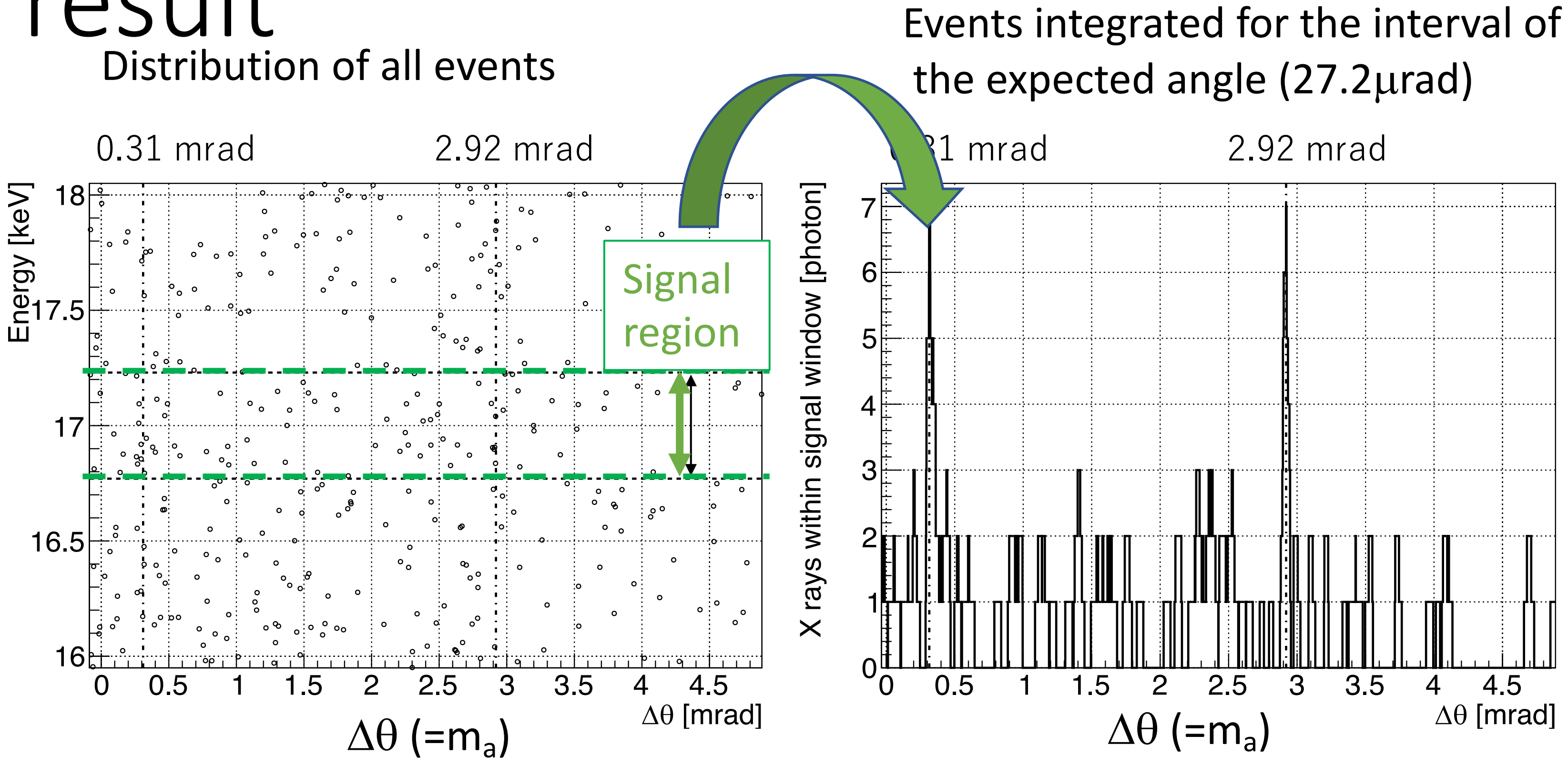
- The successive Laue diffraction efficiency is measured by removing the shield wall.
- The efficiency agrees with the calculation within 2%.





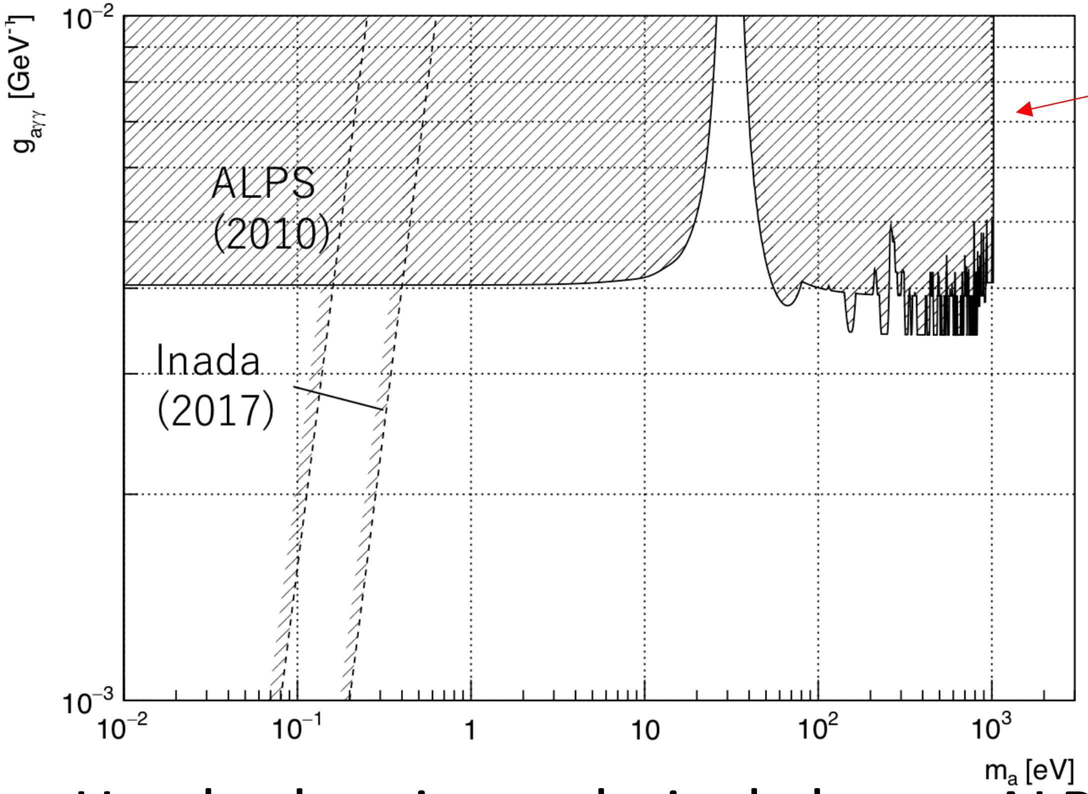
Diffraction width of the crystal: 10.8μrad
X-ray angle dispersion: 6.1μrad
X-ray energy width: 2.1eV

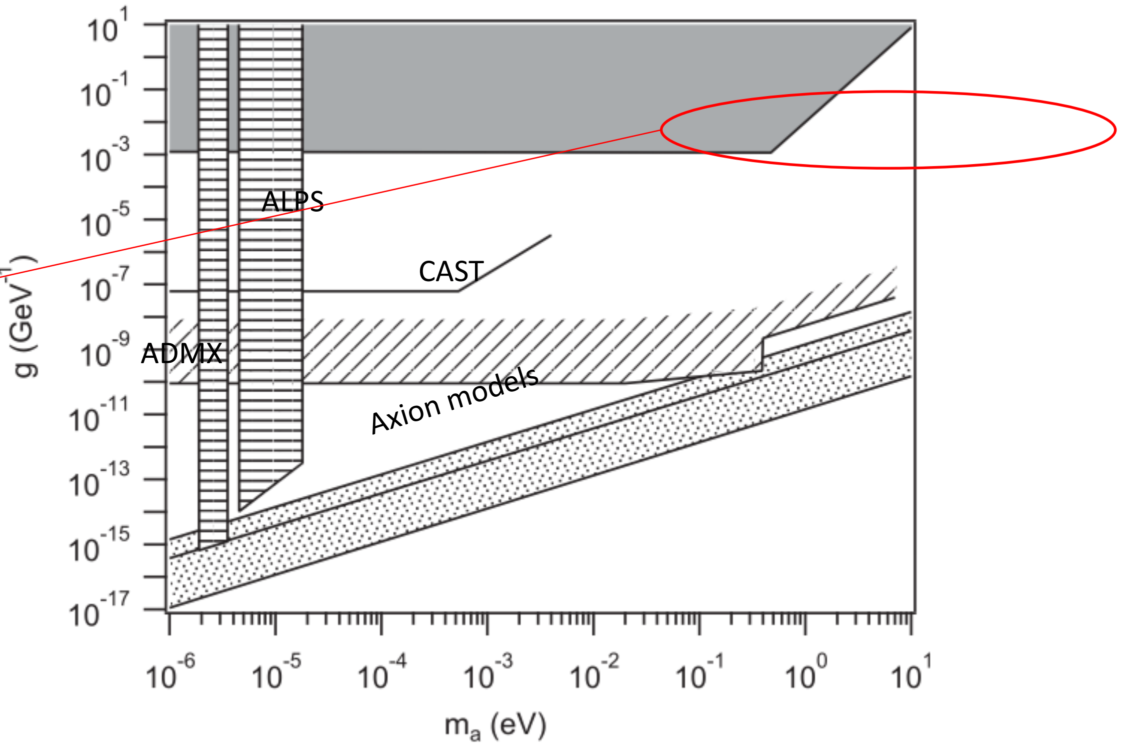
Scan result



- Scans were repeated 4 times.
- ALP signals are expected to distribute for 27.2μrad, but no significant excesses were found.

Obtained limit





- Hatched region, relatively heavy ALPs, are excluded.
- Phys. Lett. B 782(2018)523.

$$g_{a\gamma\gamma} < 4.2 \times 10^{-3}\ \mathrm{GeV}^{-1}\ (\text{for } m_a < 10\ \mathrm{eV}),$$
$$g_{a\gamma\gamma} < 5.0 \times 10^{-3}\ \mathrm{GeV}^{-1}\ (\text{for } 46\ \mathrm{eV} < m_a < 1020\ \mathrm{eV}).$$

- Sensitivity upgrade will be expected another crystal (Carbon, ...)

Summary

- UTokyo tabletop experiments group searches ALPs with various methods at SPring-8. (In niche? regions)
  - Hidden photon laboratory search
  - ALP search with dedicated pulsed magnets
  - ALP search with crystal diffraction

- Unfortunately, we have not found ALPs yet, but we will continue to search ALPs with our original ideas & methods.