Search for X-ray photon-photon elastic scattering with a Laue-case beam collider

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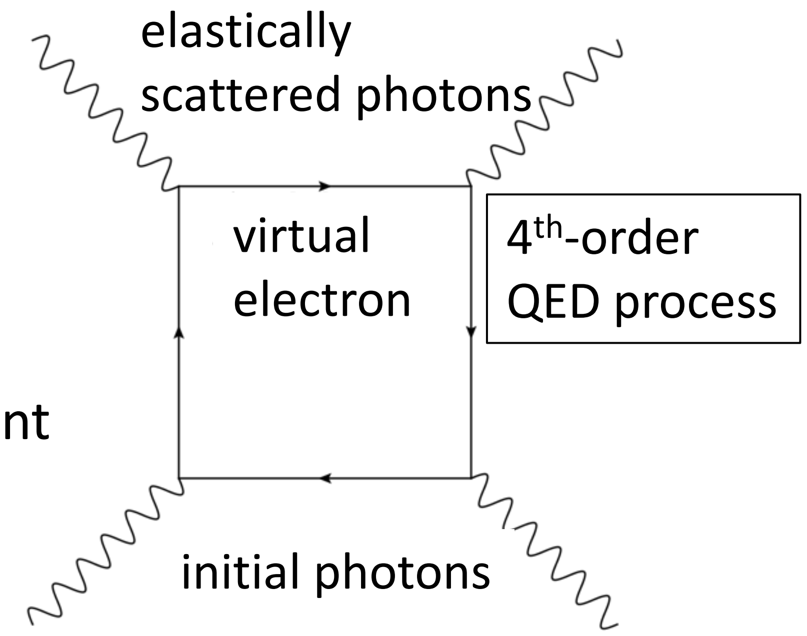
Photon-photon scattering

◆Photon-photon scattering

・Quantum ElectroDynamics(QED) predicts elastic scattering of photons in vacuum (1936) =nonlinear effect of vacuum

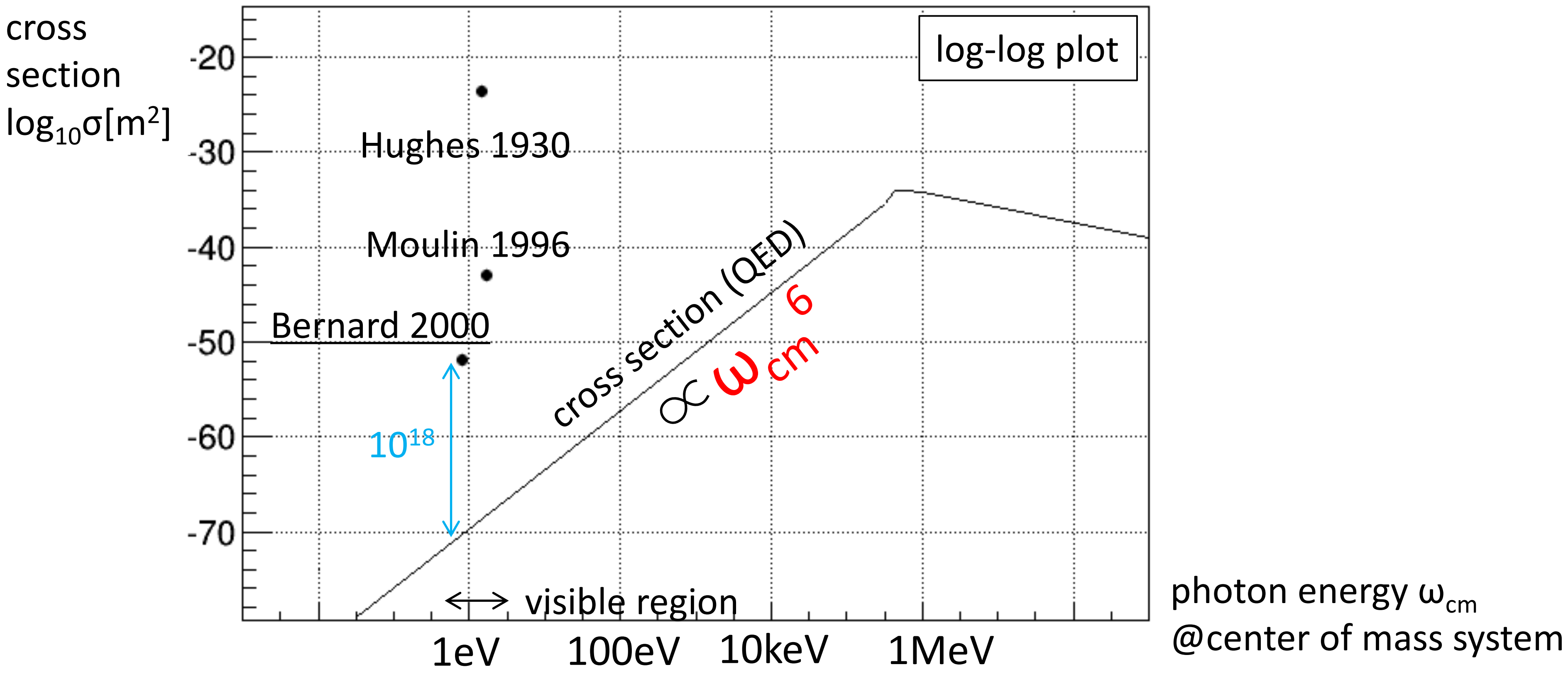
・The contribution of virtual photon scattering is inclusively observed: Delbruck scattering, e/μ anomalous magnetic moment

・The scattering of real photons has not ever been observed
→important verification of QED



・If unknown particles which mediate the scattering exist, scattering cross section can be enhanced by the prediction of QED
→new physics
ex)Axion Like Particles(ALP)

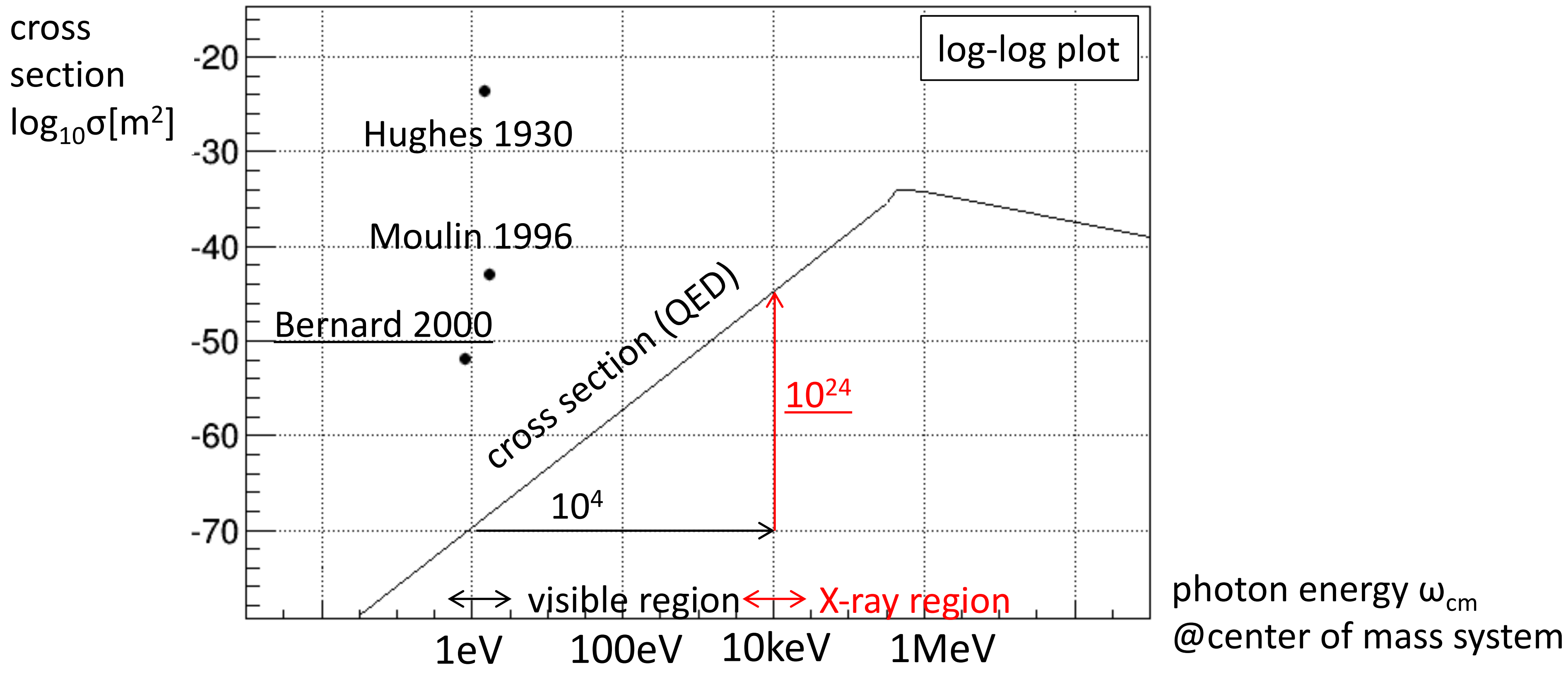
Summary of previous experiments



- cross section (QED) is proportional to 6th power of photon energy

- All previous experiments use visible or infrared sources
- The best upper limit is 18 orders of magnitude worse than the prediction of QED

New experiment using X-ray source



- X rays have 4 orders of magnitude higher energy than visible photons
  →Cross section is enhanced by 24 orders of magnitude
- X-ray detectors with high energy precision improve S/N ratio
- X rays have smaller diffraction limit → beams can be focused more strongly
- X-ray region (~10keV) is new to particle physics experiments→interesting!

X-ray source : SACLA

・the strongest X-ray Free Electron Laser(XFEL) in the world

◆Specs

・pulsed source with the photon flux of ~6×10^{11}photon/pulse and the duration of < 10fs

・beam width: 200μm(FWHM), and 1μm coherent focusing is available

→suitable for scattering experiments with high luminosity

・repetition: 30 Hz @ 2015 November

・X-ray energy: 10.985keV with the bandwidth of 80 eV

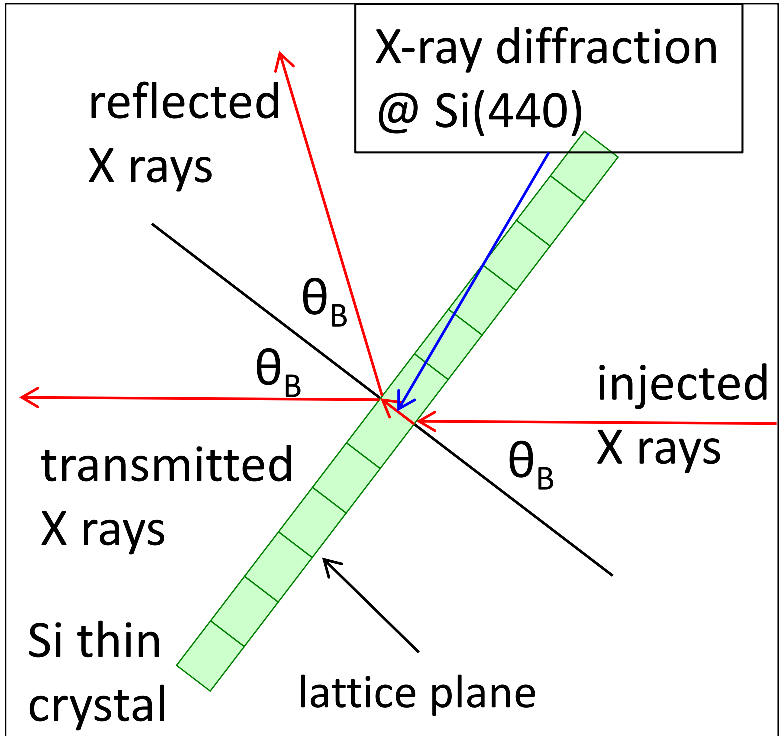
X-ray collision system (1/2)

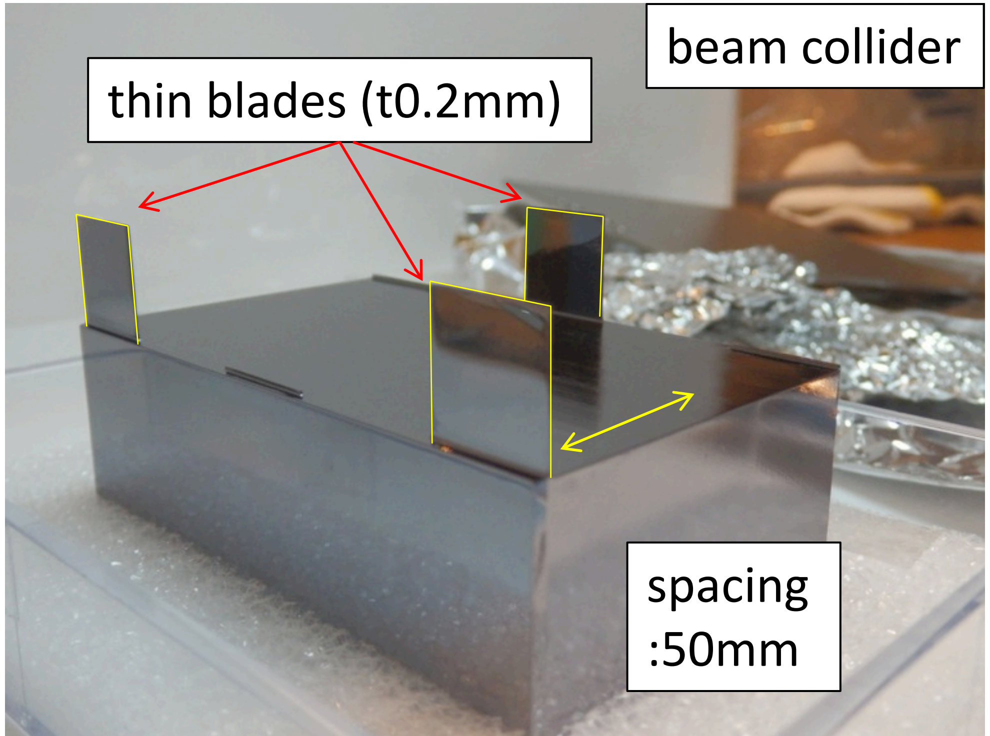
▪X-ray diffraction is used to split X-ray beams and to make them collide
This technique is developed in X-ray interferometry region

◆X-ray beam collider

▪Laue-case X-ray diffraction at silicon crystal is used

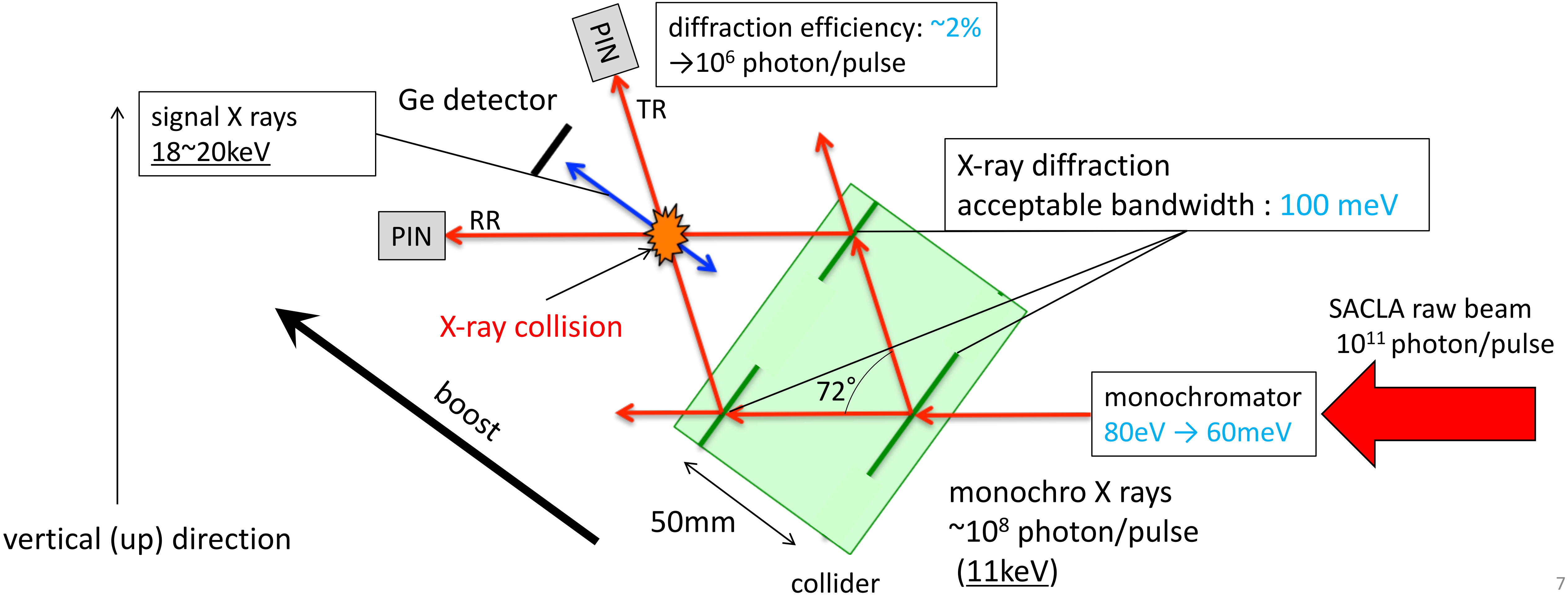
▪The collider consists of three blades (t 0.2mm) manufactured on a single mono-crystal





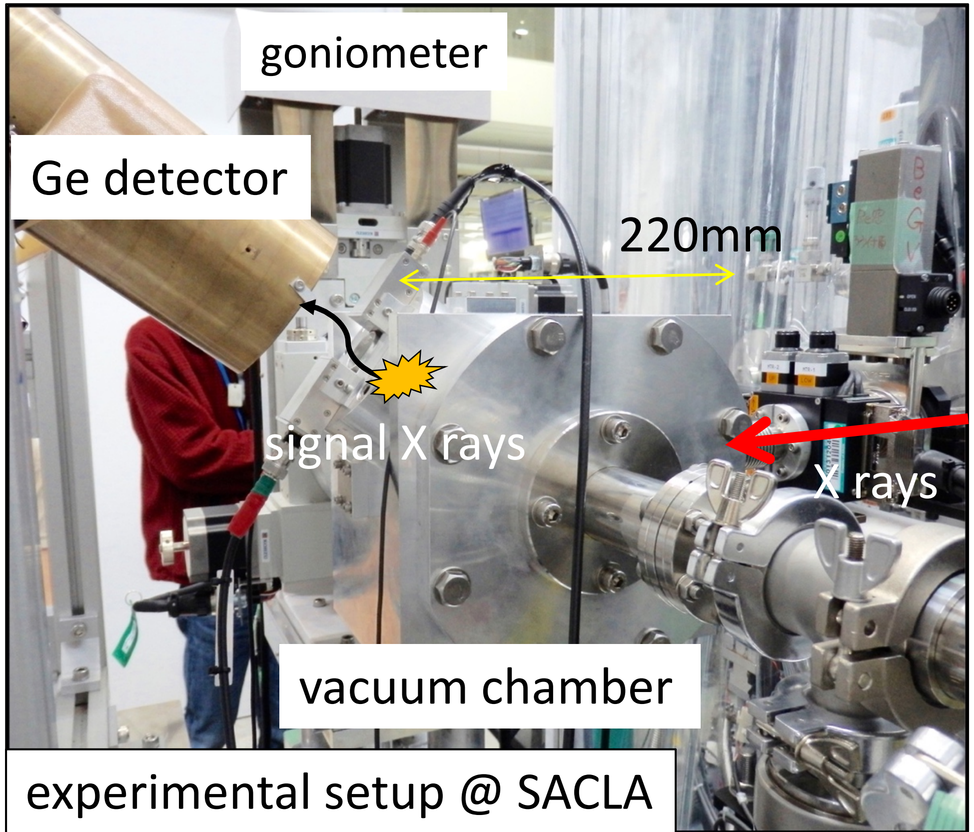
X-ray collision system (2/2)

- X-ray collision is spatially and temporally guaranteed by a geometrical symmetry
- The pulse-by-pulse intensity of colliding beams are measured by PIN photodiodes

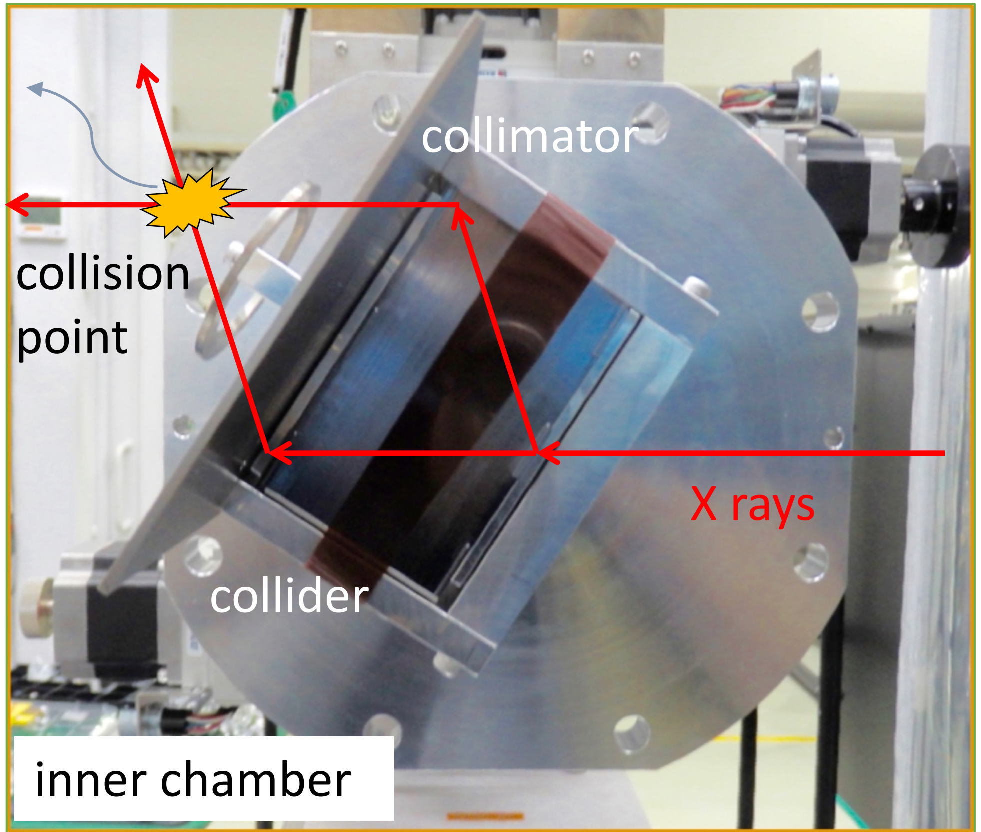


Suppression of stray X rays: vacuum chamber

- Signals are very weak even if they exist → suppression of stray X rays is essential!
- To suppress stray X rays from atmospheric molecules, collider is installed into a vacuum chamber
- Collimators are installed along the X-ray path to cut the path of stray X rays scattered by the collider
  →The detection rate of stray X rays is reduced to 10^{-13} of injected X rays,
  and measurement without pseudo signals is achieved!



experimental setup @ SACLA

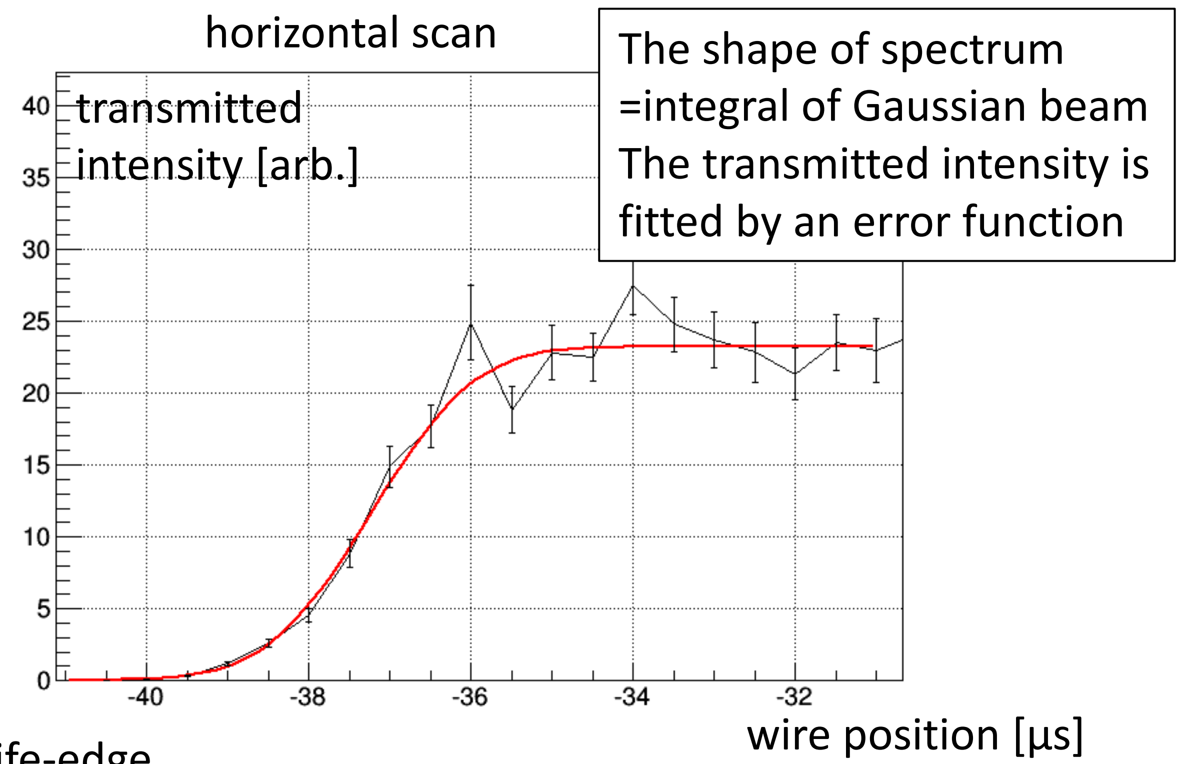


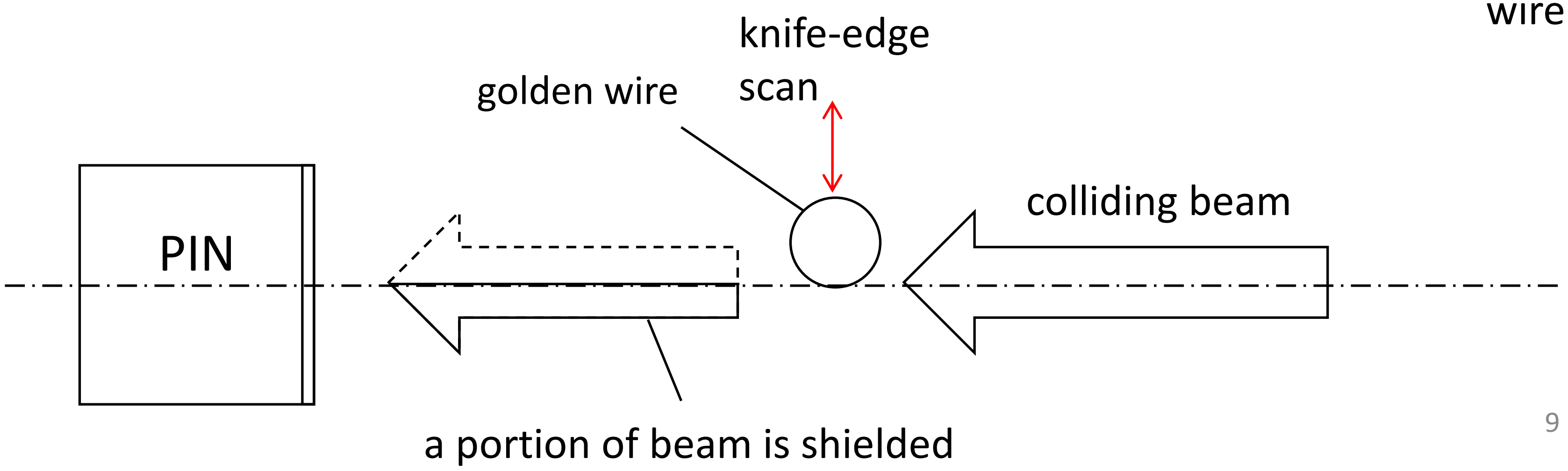
inner chamber

Measurement of beam widths

- Beam widths is measured by edge scan
  1)vertical (not focused) : a stainless rod
  2)horizontal (1μm focused) : ϕ200 μm golden wire

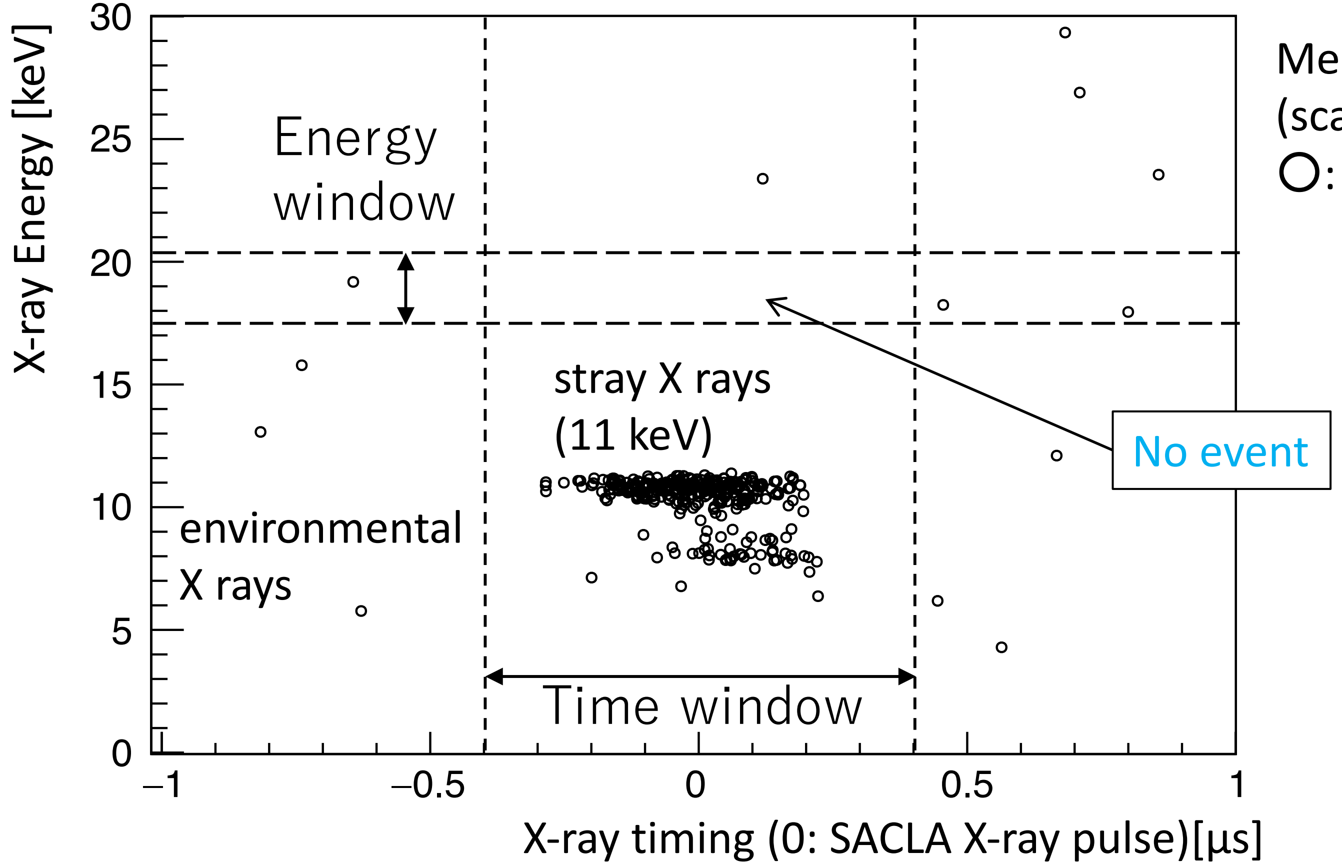
- horizontal width (σ): 0.962±0.037μm (RR)
  0.992±0.044μm (TR)
  vertical widths : 144±12μm (RR)
  124±7μm (TR)





Measured X-ray spectrum

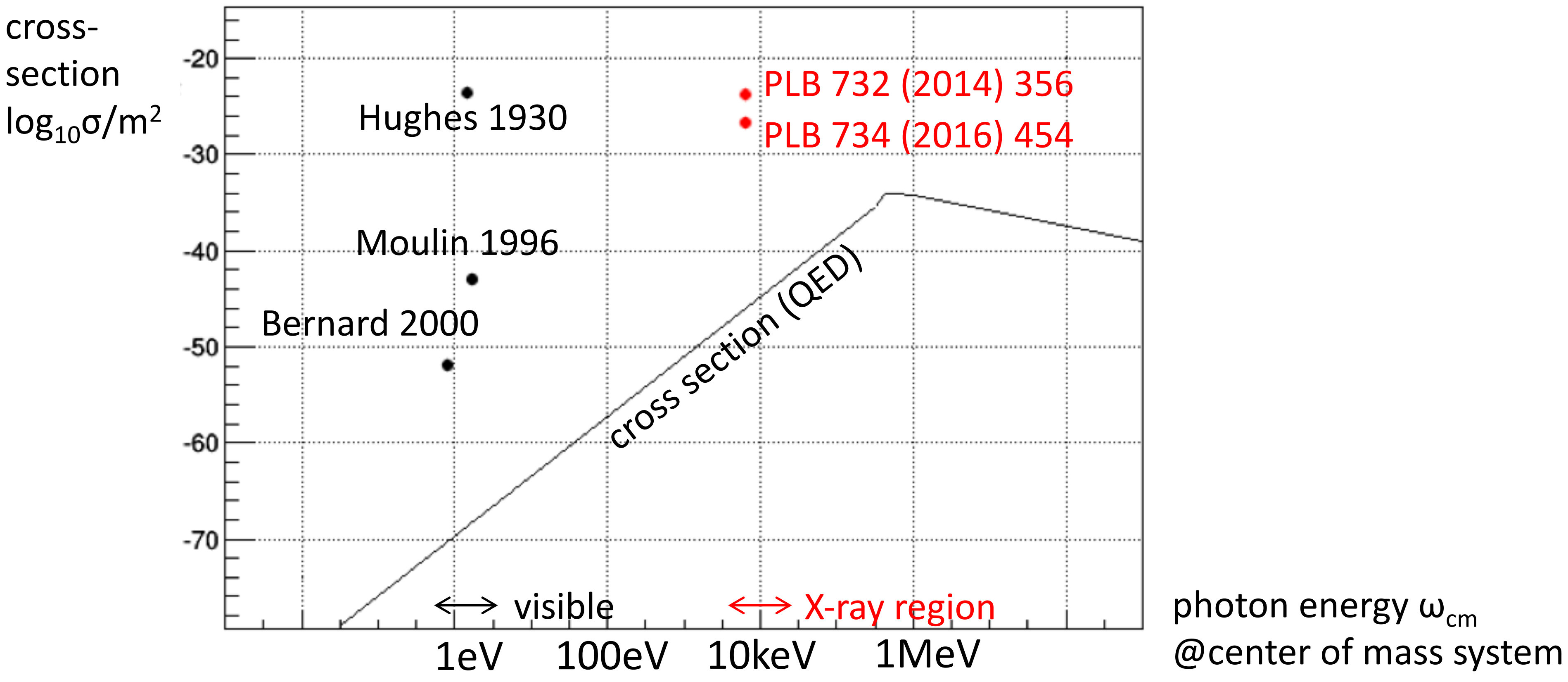
- newest measurement (*Phys. Lett. B 763 (2016) 454*)
- measurement period: 30 Hz ×~38 hour DAQ = 4.1 × 10^6 X-ray pulses
- timing window: detector timing resolution ±5σ=±0.4 μs
- No significant signal is observed



Measured X-ray spectrum
(scatter plot)
○: 1 event

◆Potential source of pseudo signals
1)pileups of two stray X rays (<22keV)
2)accidental coincident of
environmental X rays (18~20keV)
- pseudo signals are expected to
<u>< 1 event</u>

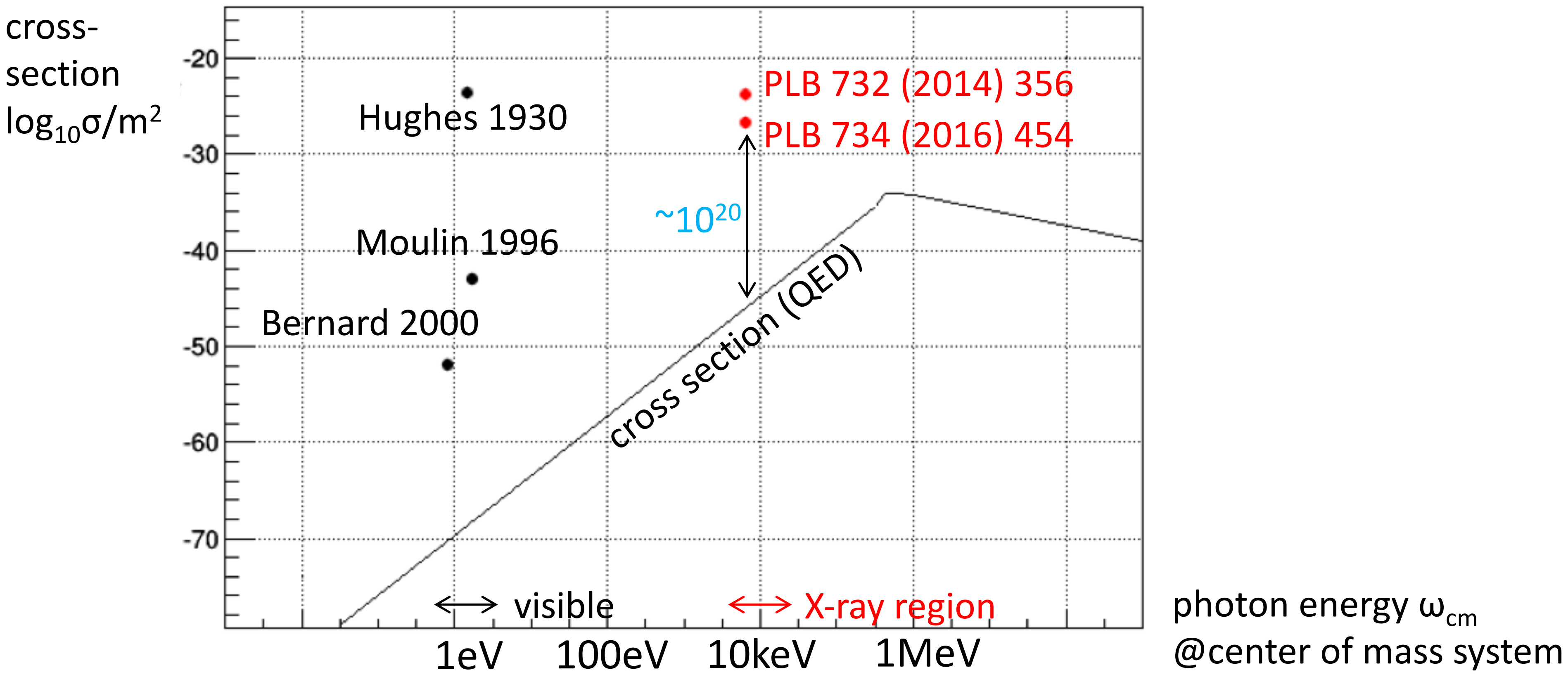
Results



- upper limit (PLB 2016) on the cross section : 1.9×10^{-27} [m^2] @ 6.5keV (95% C.L.)

- This is the unique/most stringent upper limit in X-ray region

Results



- The upper limit is 20 orders of magnitude worse than QED prediction
- In order to enhance the sensitivity and approach to the QED prediction, it is essential to change the experimental setup drastically
- Diffraction efficiency is very small (~10^{-5} of raw beam → 10^{-10} sensitivity reduction)

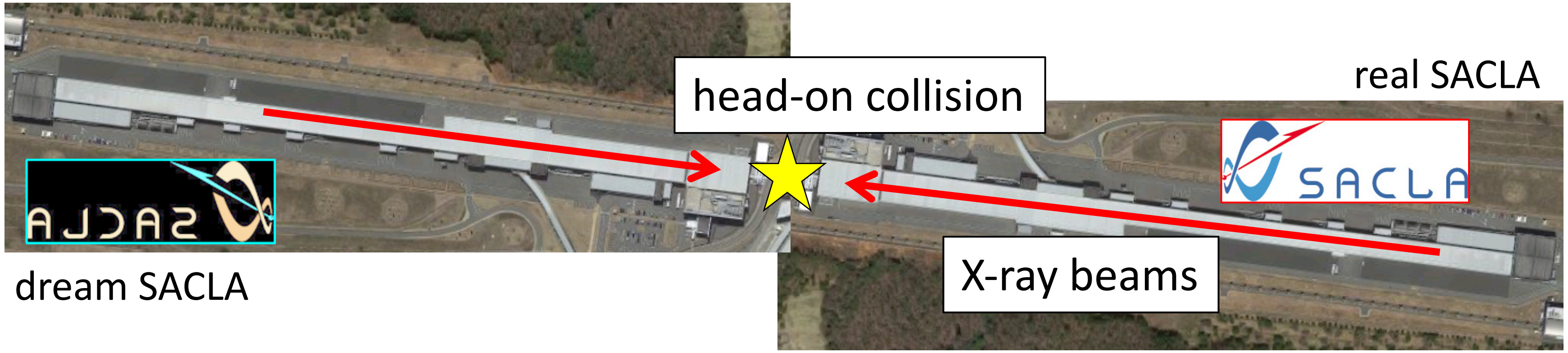
→Experiment without diffraction is needed!

dream plan : SACLA+SACLA head-on collision

- Experiment without diffraction requires an additional X-ray source
- If another SACLA exists in front of SACLA,
can photon-photon scattering be observed? (thought experiment)

- head-on collision of X-ray pulses with 10^{12} photon/pulse
- 50nm focusing (horizontal/vertical) can be used for head-on collision
  →1 photon-photon scattering per 60Hz 2 day DAQ

- In principle, X-ray collision can be observed by head-on collision of 2 XFELs
→ultimate goal of scattering experiments in X-ray region

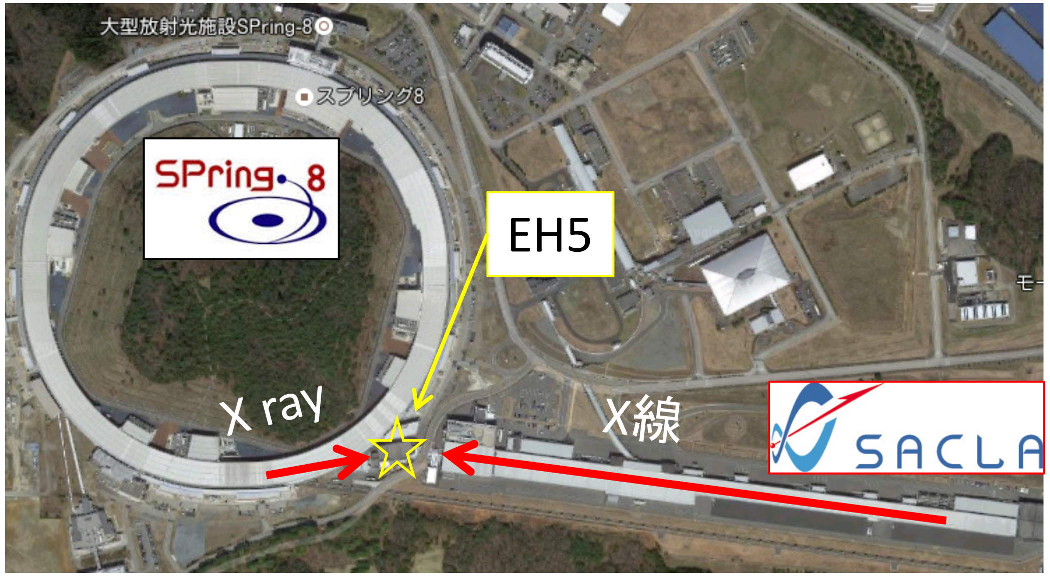


realistic setup : SACLA+SPring-8

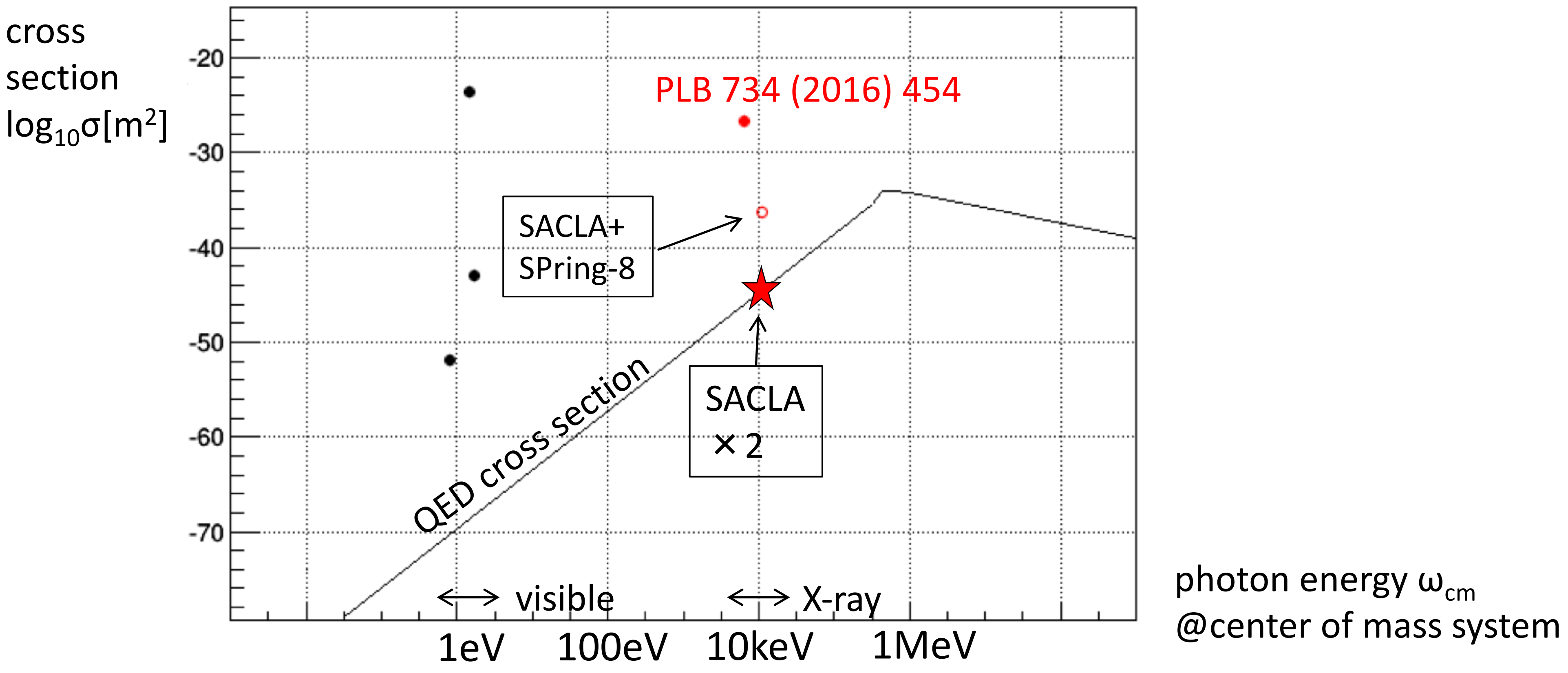
◆SACLA+SPring-8 head-on collision

- SACLA EH5: simultaneous usage of SACLA and SPring-8 BL32
  Synchronized operation will be developed in the near future → realistic setup
- SPring-8 : ~10^3 photon/pulse, 40MHz, 40ps (pulse intensity is 10^{-9} of SACLA)

- The head-on collision experiment with 50nm focusing at EH5
  →sensitivity enhancement of 10^{11} by 60 Hz 2 day DAQ (10^9 worse than QED prediction)
- more realistic than SACLA+SACLA : next step



Summary of prospects



・current upper limit : 20 orders of magnitude worse than QED prediction

・SACLA+SACLA: QED prediction can be verified (in principle)

: ultimate goal of photon-photon scattering experiment in the X-ray region

・head-on collision of SACLA and SPring-8 : sensitivity can be enhanced by 10^{11}

Summary

- We are performing particle experiments using photons
- Photon-photon scattering of real photons has not ever been observed
  : important verification of QED
- We have performed first scattering experiment in X-ray region
- X-ray diffraction is used to split X rays and make them collide
- Background X rays are suppressed to perform 0-pileup experiment
- The upper limit on cross section is 10^{20} worse than QED prediction
  : drastic change of experimental setup is necessary

- SACLA+SACLA: sensitivity can approach to QED prediction in principle
  : ultimate goal of X-ray photon-photon scattering experiment
- head –on collision of SACLA and SPring-8 : sensitivity is enhanced by 10^{11}
  :next step

backups

SACLA optical Laser systems

- SACLA has TW/PW optical Laser systems

- Now 2.5TW Laser is available

- PW (500TW ×2) Laser system is under installation
→strong source with ~10^{20}photon/pulse
suitable for photon-photon scattering

THALES PW Lase (under installation)

specs	Hidra-100 2.5TW	THALES 500TW×2
wavelength	800nm	
pulse intensity	100 mJ =4×10^{17} photon/pulse	12.5 J =5×10^{19} photon/pulse
duration	40fs	10fs
repetition	10Hz	1Hz

photon^2 scattering with 4 wave mixing

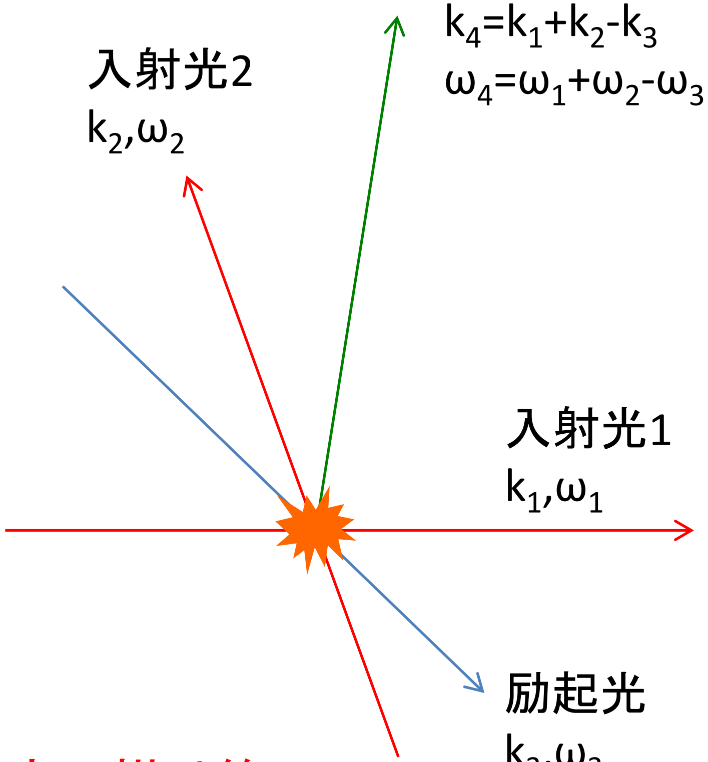
◆four wave mixing(nonlinear effect of vacuum)

・stimulating beams are injected to the cross point

・signal intensity is enhanced by the photon num of stimulating beam → huge enhancement ~10^{20}

・photon-photon scattering can be observed by three PW Lasers + 1 day DAQ

・the suppression of stray photons is problematic



四光波混合信号数

ビーム強度の掛け算

$$N_{4,QED} = \epsilon_{PM}\epsilon_{Spec}\epsilon_{Osc}\frac{16}{2025}\left(\frac{2}{\pi\sqrt{3}}\right)^3 \frac{\omega_4 \underline{E_1 E_2 E_3}}{m_e^4}\frac{r_e^4}{\omega^2\tau^2}K^2$$

sensitivity loss of current setup

◆losses/disadvantages due to X-ray diffraction

1)small acceptable bandwidth + diffraction efficiency (~10^{-5})

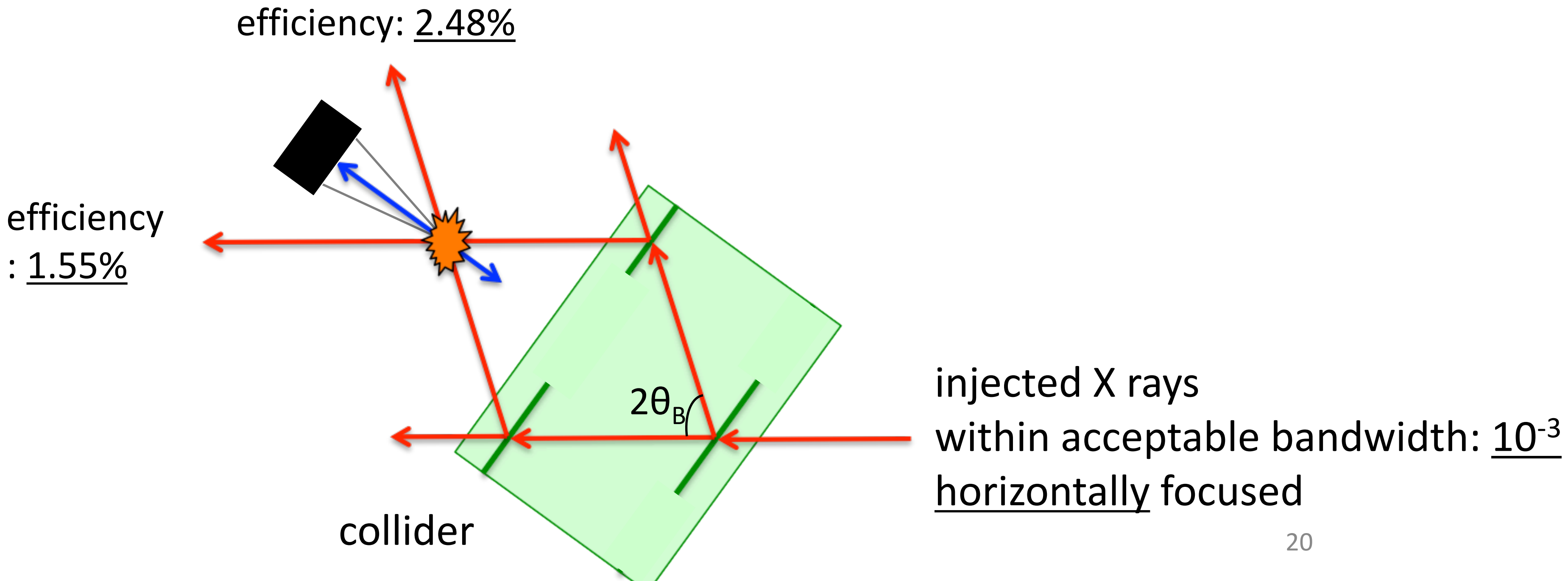
→sensitivity is reduced by 10^{-10}

2)X-ray beams cannot be focused in the diffraction plane→luminosity is reduced by 10^{-2}

→reduction factors are combined to be 10^{-12}

3)energy sweeping is impossible due to diffraction condition

→scattering experiments without X-ray diffraction is needed!



Background X rays

▪ <u>suppression of background X rays is inevitable for high sensitivity</u>

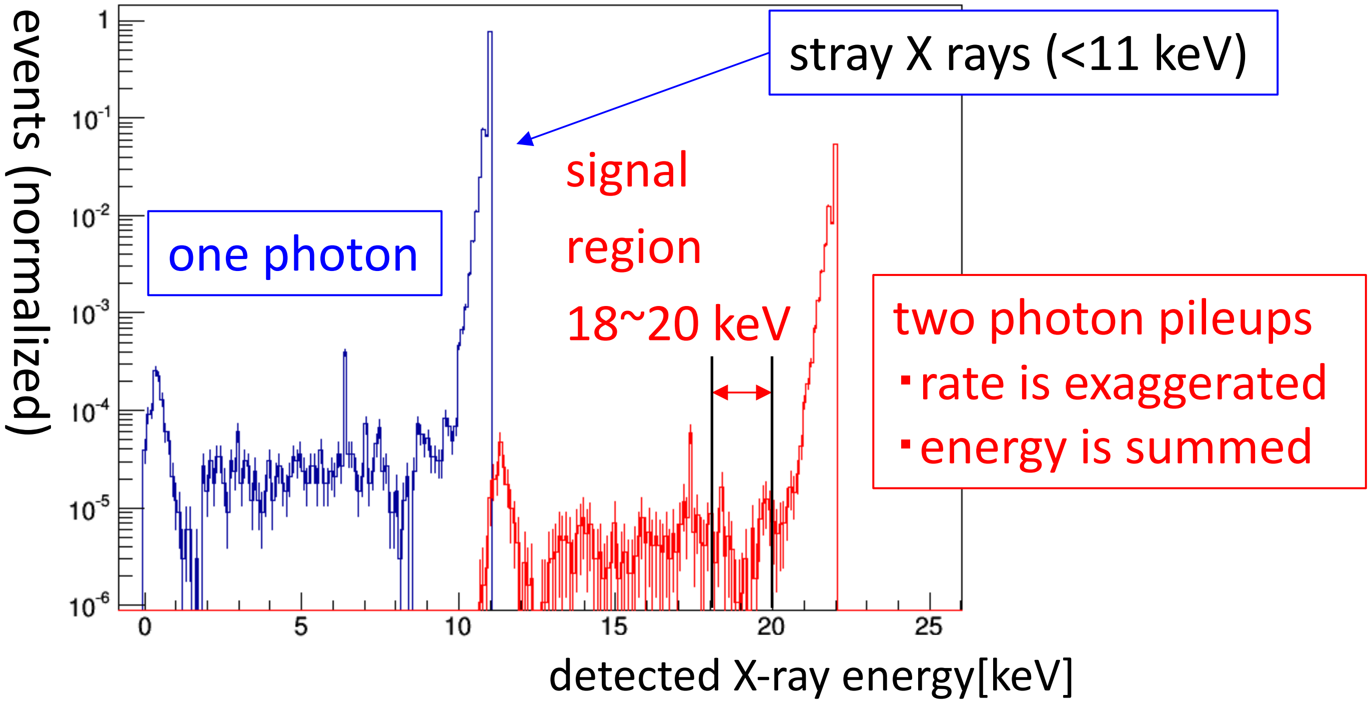
◆Background sources

▪ Environmental X rays: easily excluded by timing measurement

▪ <u>stray X rays (Rayleigh/Compton) scattered by atmospheric molecules/collider</u>

→pileups of stray photons can be misidentified as signals

Geant4 Monte Carlo simulation



sensitivity loss of current setup

◆losses/disadvantages due to X-ray diffraction

1)small acceptable bandwidth + diffraction efficiency (~10^{-5})

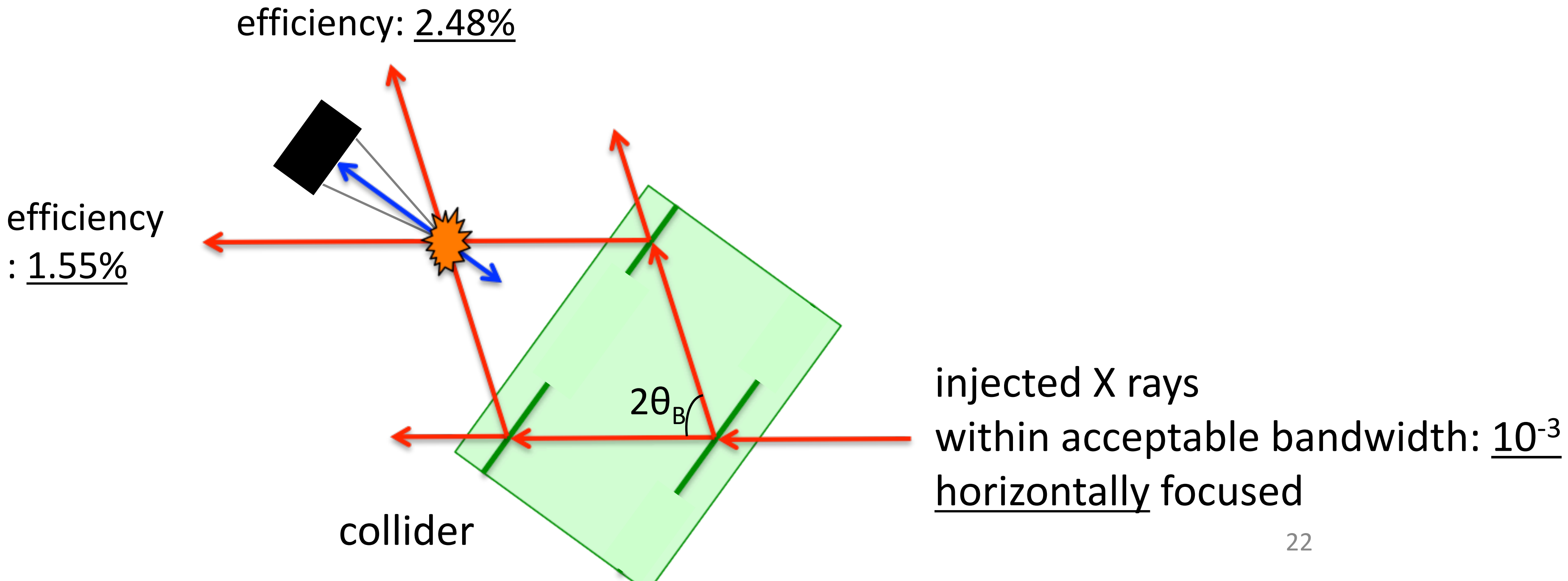
→sensitivity is reduced by 10^{-10}

2)X-ray beams cannot be focused in the diffraction plane (vertical) →luminosity is reduced by 10^{-2}

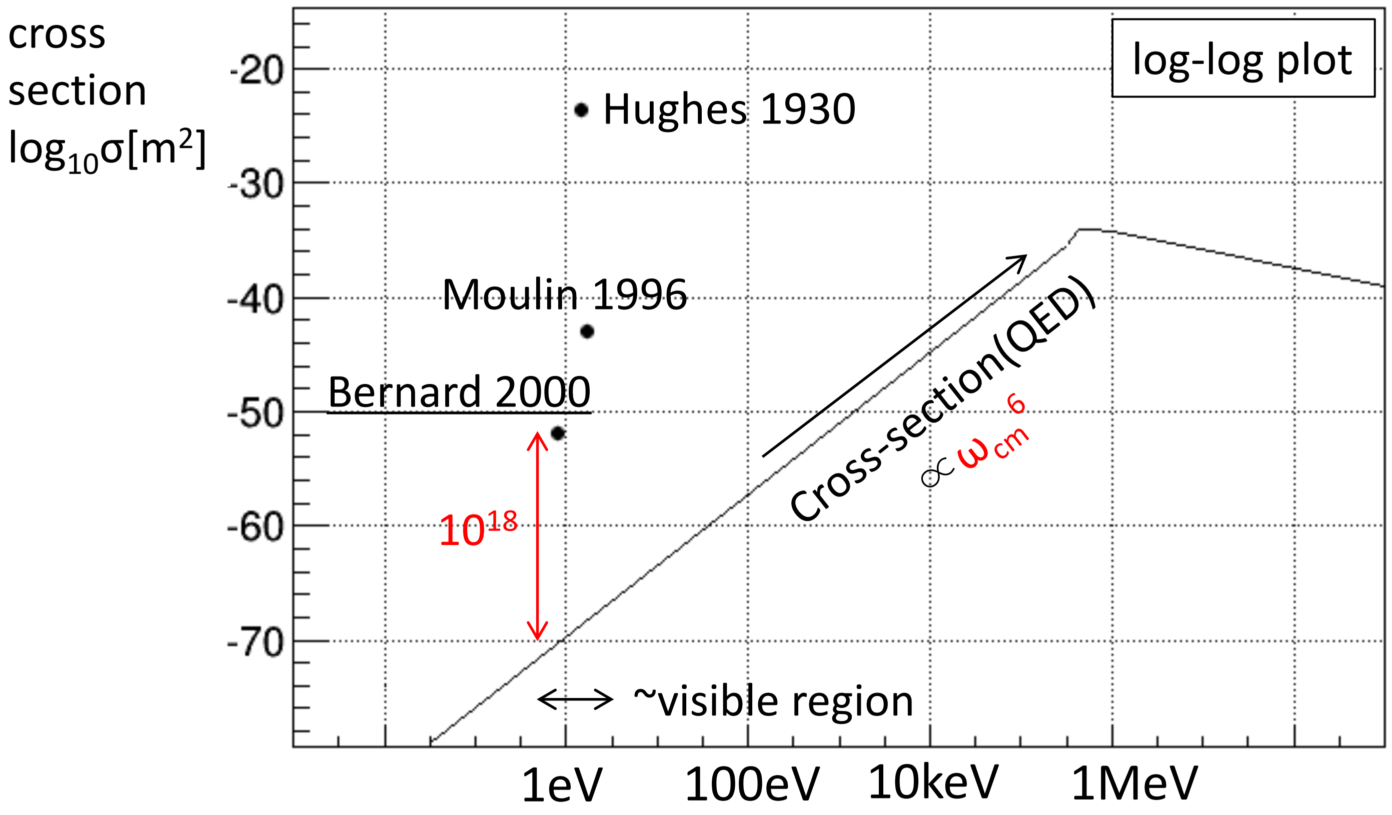
→reduction factors are combined to be 10^{-12}

3)the photon energy in cms system is fixed by the diffraction condition (sweeping is incapable)

→scattering experiments without X-ray diffraction is needed!



Summary of previous experiments



・cross-section (QED prediction) for photons with the same linear polarization state (ω_{cm} < 700 keV)

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{linear,same}} = \frac{\alpha^4 \omega_{\text{cm}}^6}{(180\pi)^2 m_e^8}(260\cos^4\theta + 328\cos^2\theta + 580)$$

$$\sigma_{\text{linear,same}} = 3.5 \times 10^{-70}(\omega_{\text{cm}}[\text{eV}])^6[\text{m}^2]$$

($\propto$ photon energy^6)

photon energy ω_{cm} @center of mass system

・All previous experiments use visible or infrared sources

・The best upper limit is 10^{18} higher than the prediction of QED

◆disadvantages in using visible/infrared sources

・Cross section in the visible region is strongly suppressed($\propto$ photon energy^6)

・White stray photons generated within optics deteriorate S/N ratio and sensitivity

Particle experiments using Photons

- There are many phenomena which cannot be explained by the Standard Model(SM)
  ex) dark matter/energy, the asymmetry of matter and antimatter
  →We need new physics beyond SM, but
  the energy scale is much higher than energy accelerators can generate

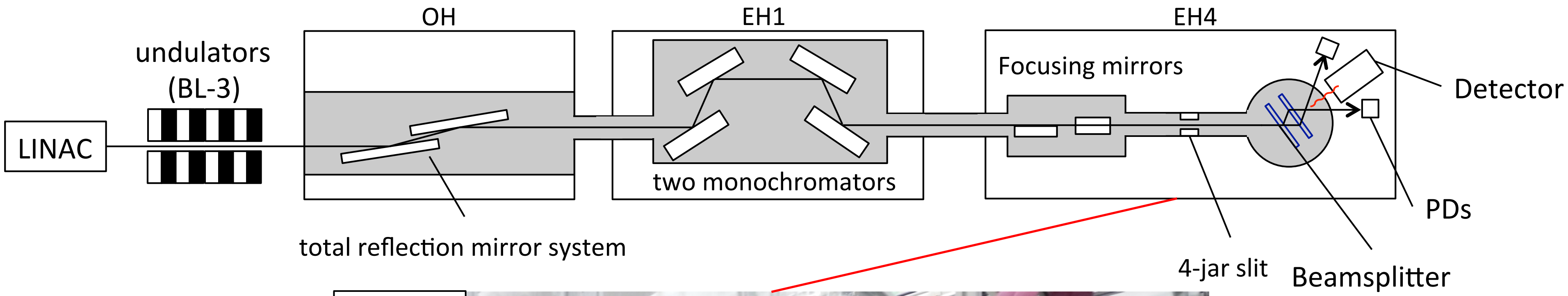
◆Particle experiments using photons

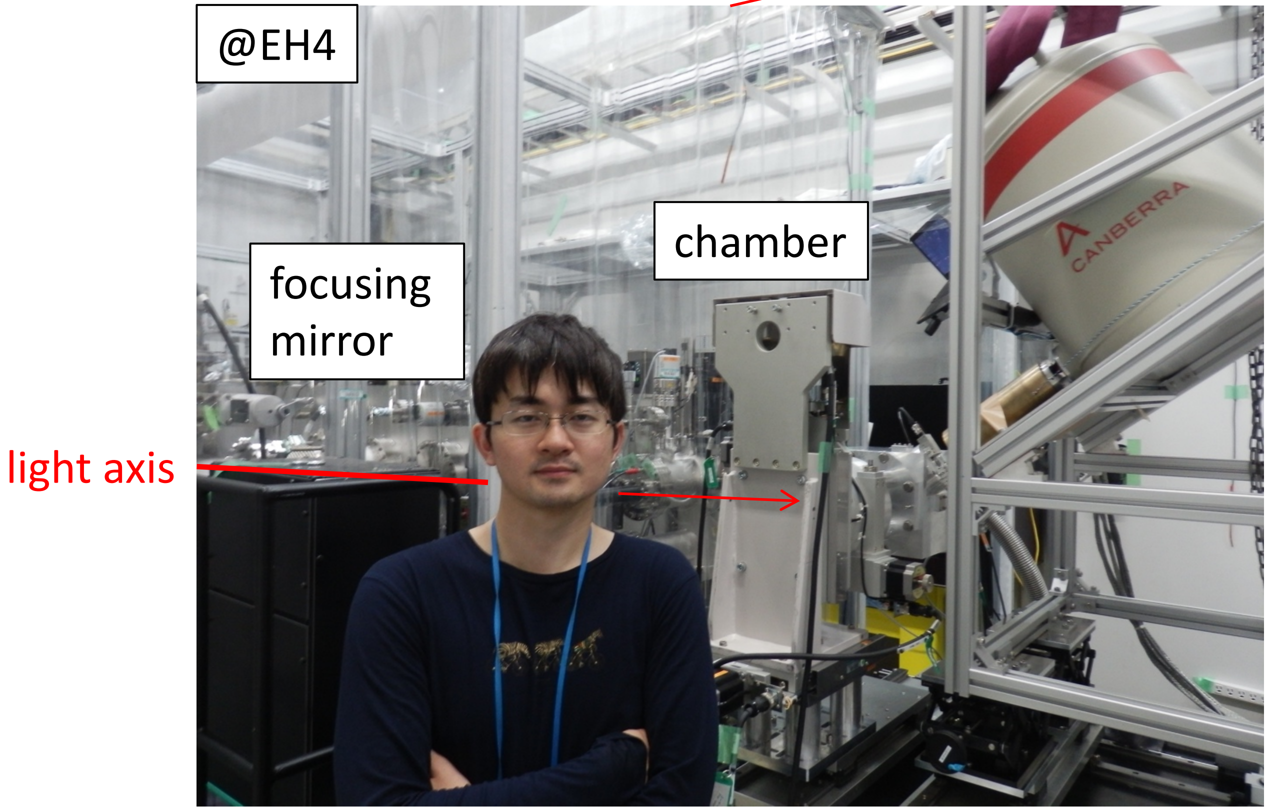
- strong and dense field can be more easily produced by strong light sources
  →searches for new physics with higher energy scale

- To search variety of new physics,
  searches using various photon sources
  are effective

  1)Laser + magnetic field: S. Kamioka (11:35~)
  2)Laser + X-ray: Y. Seino (11:55~)
  3)X-ray + X-ray: This talk

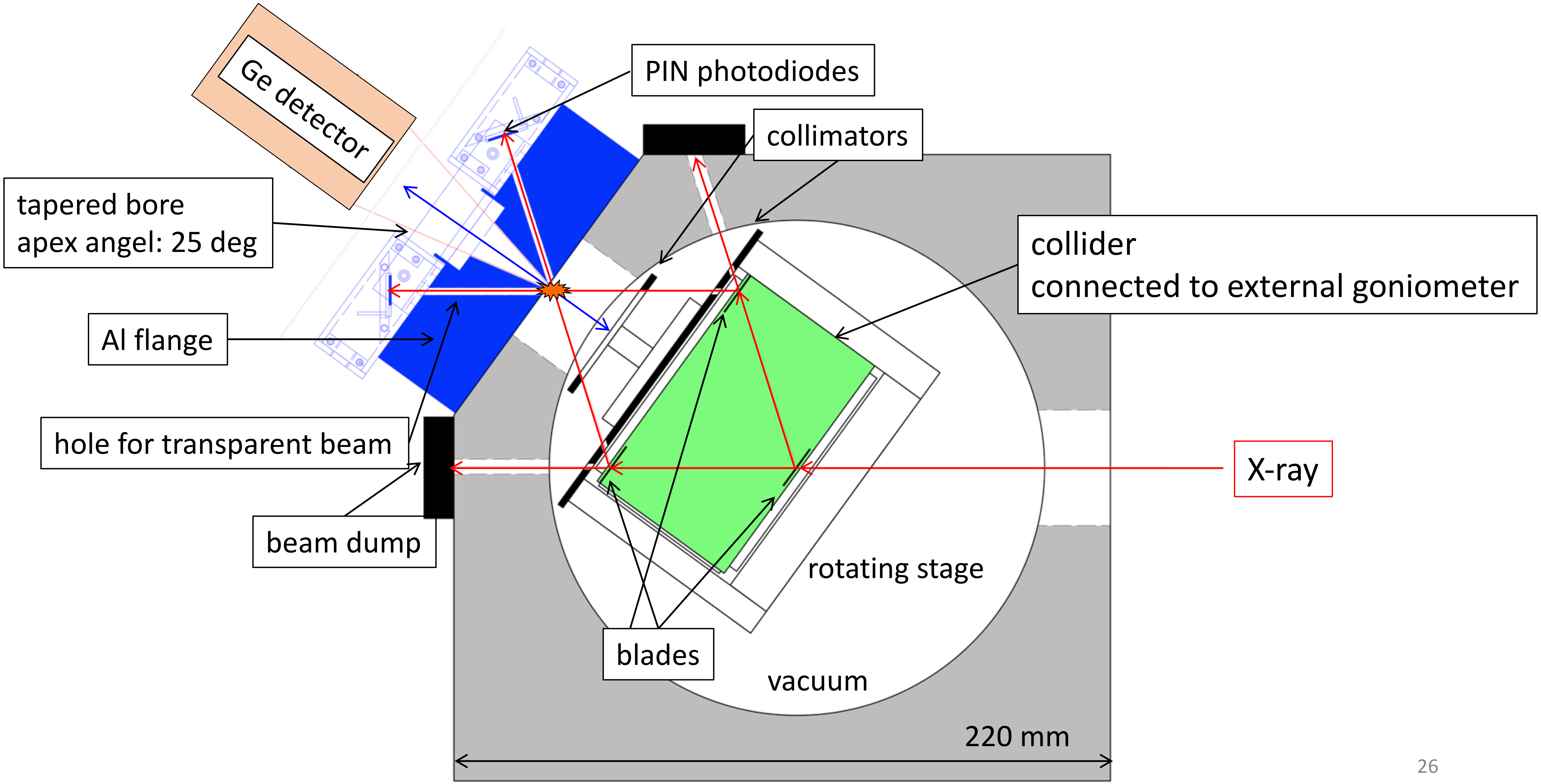
Optics





Ge detector
-inclined by 36 deg

Vacuum chamber schematics



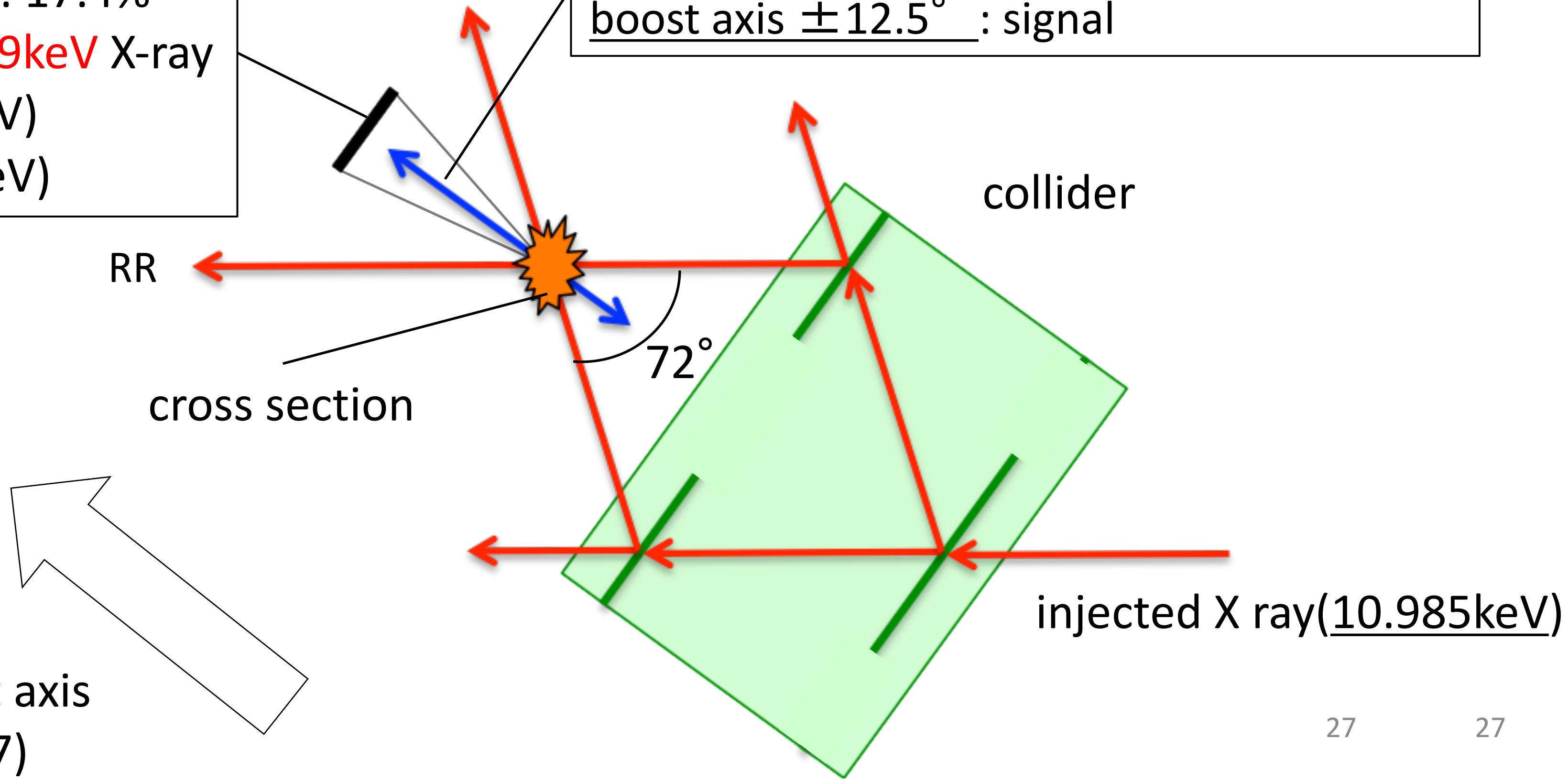
Kinematics

-X-ray diffraction uses Si(440) lattice plane
crossing angle : $2\theta_B$=72° for 10.985 keV→ ω_{CM}＝6.46keV

◆ブースト系での散乱実験

Ge detector
signal coverage: 17.4%
signal: 18.1-19.9keV X-ray
(center: 19.9keV)
(edge : 18.1keV)

signals : concentrated around the boost axis
boost axis ±12.5° : signal



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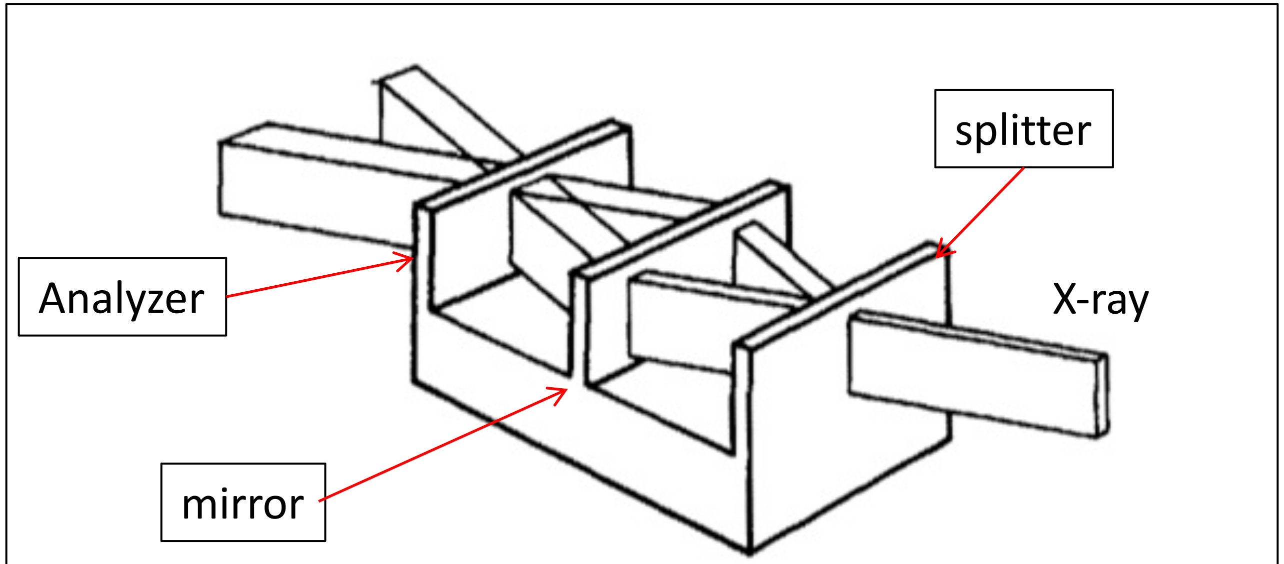
X-ray interferometer

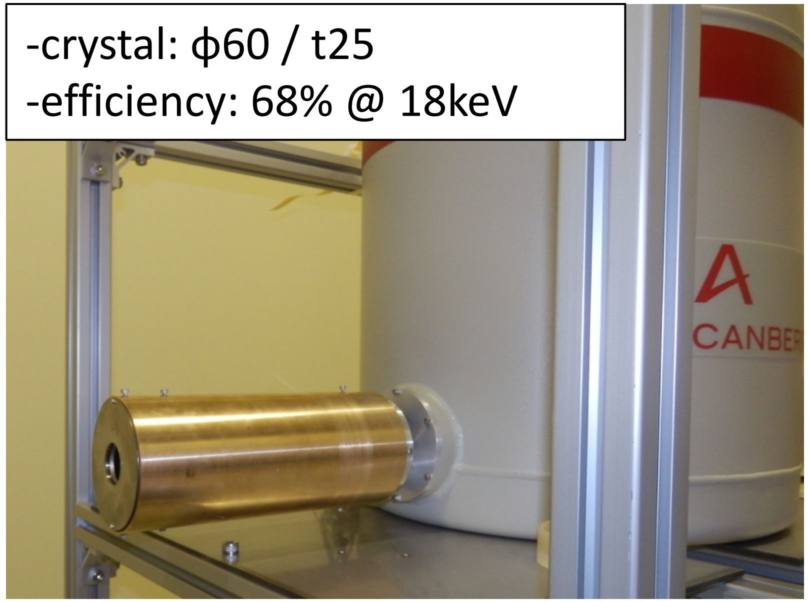
U. Bonse and W. Graeff, X-ray Optics, Springer-Verlag, 93 (1977)
A. Appel, et al, Phys. Rev. Letters, 67, 1673 (1991)
・Interferometry fringe can be seen by the analyzer blade
→collision is guaranteed



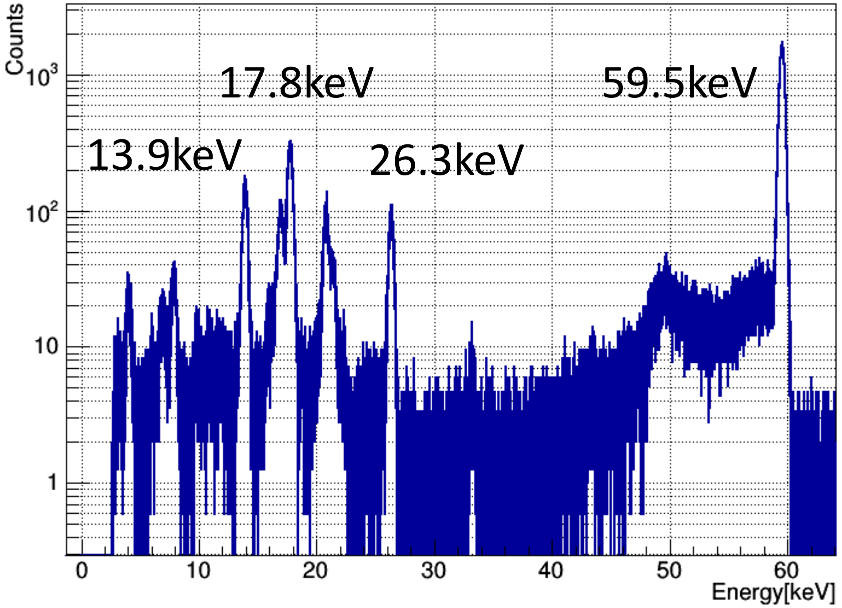
interferometer made from mono-crystal

Ge detector

Canberra BE2825



Am241 spectrum

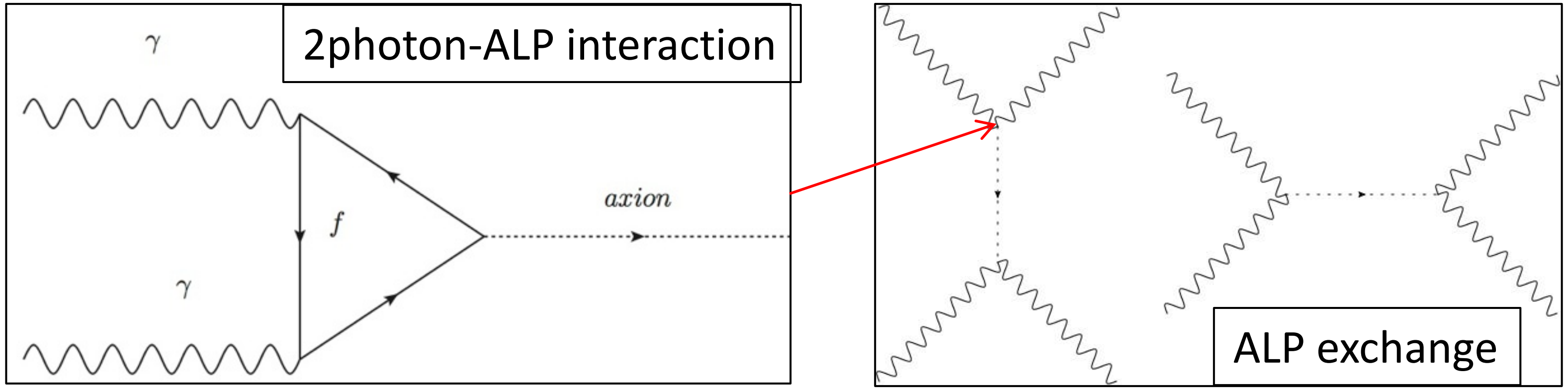


-resolution(σ): <u>0.2 keV</u>@ 26.3keV
 calibration change during measurement: < <u>0.1keV</u>@ 17.7keV ~ 26.3keV
-signal energy (raw): 18.1-19.9keV
 calibration: 0.1keV, 2σ=0.4keV is included to the energy region
 →energy region: 17.6 -20.4keV

-detection efficiency of signal X rays: 13.2±0.3%(Geant4)

enhancement of cross section by new physics

- ALP(Axion Like Particle)
  interact with two photons by anomaly

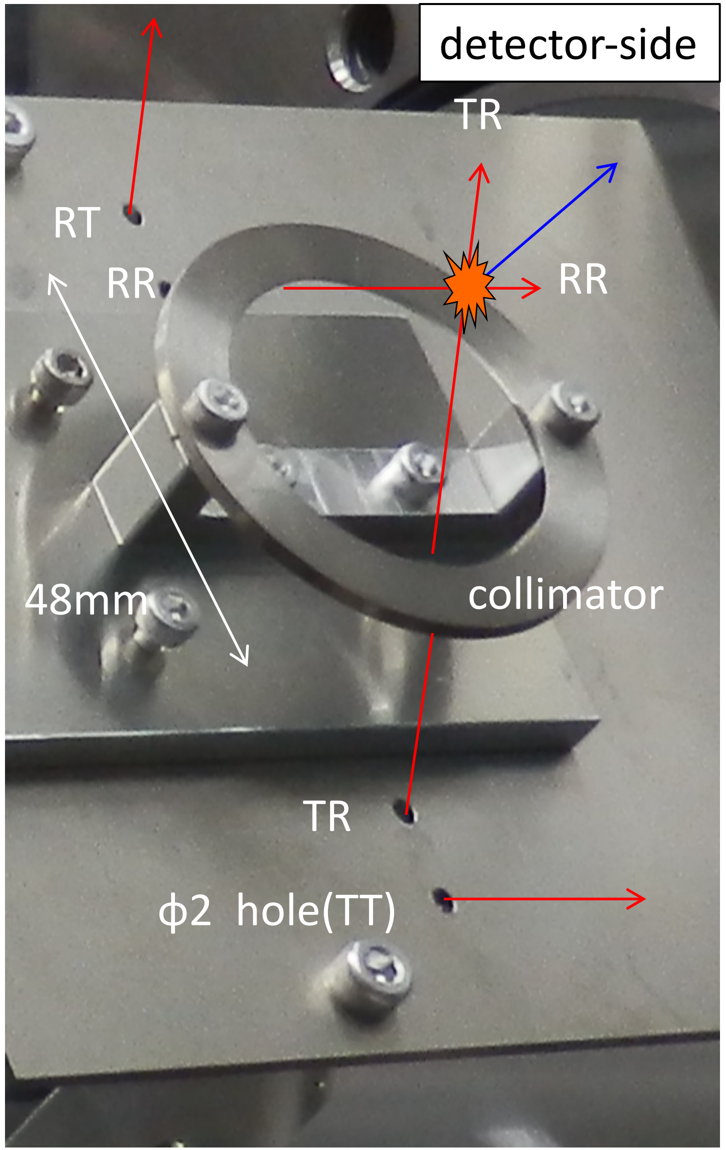


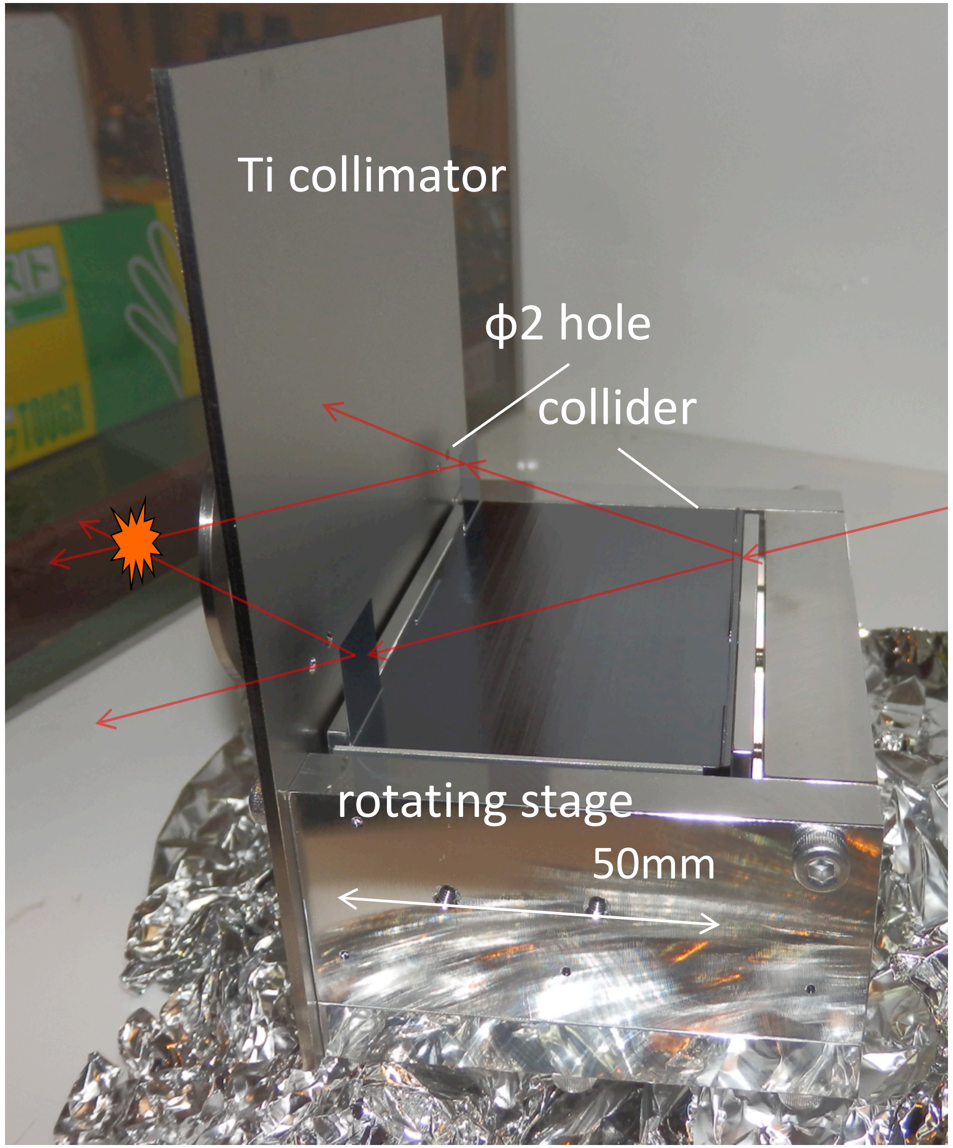
- cross section
  D. Bernard, Nuovo Cimento, A 110, 1339(1997)
  - non-resonant : less than QED
  - huge enhancement on the mass pole (determined by Breit-Wigner formula)

$$\sigma_{BW} = \frac{\pi}{4k^2}\frac{\Gamma^2}{(2k-m_a)^2+\frac{\Gamma^2}{4}}$$

maximum : π/k^2 2.9×10^{-21} [m^2] @ 6.46keV

chamber inner side





detector-side flange