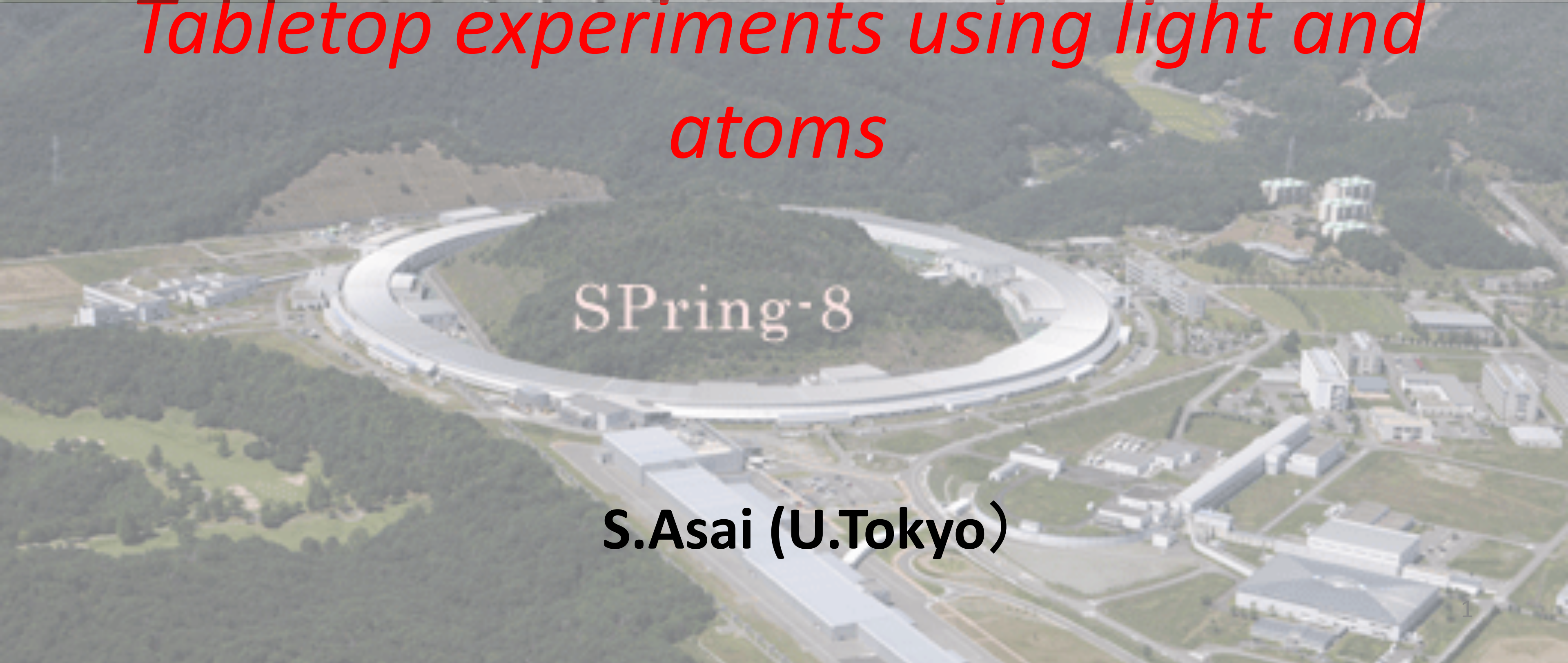
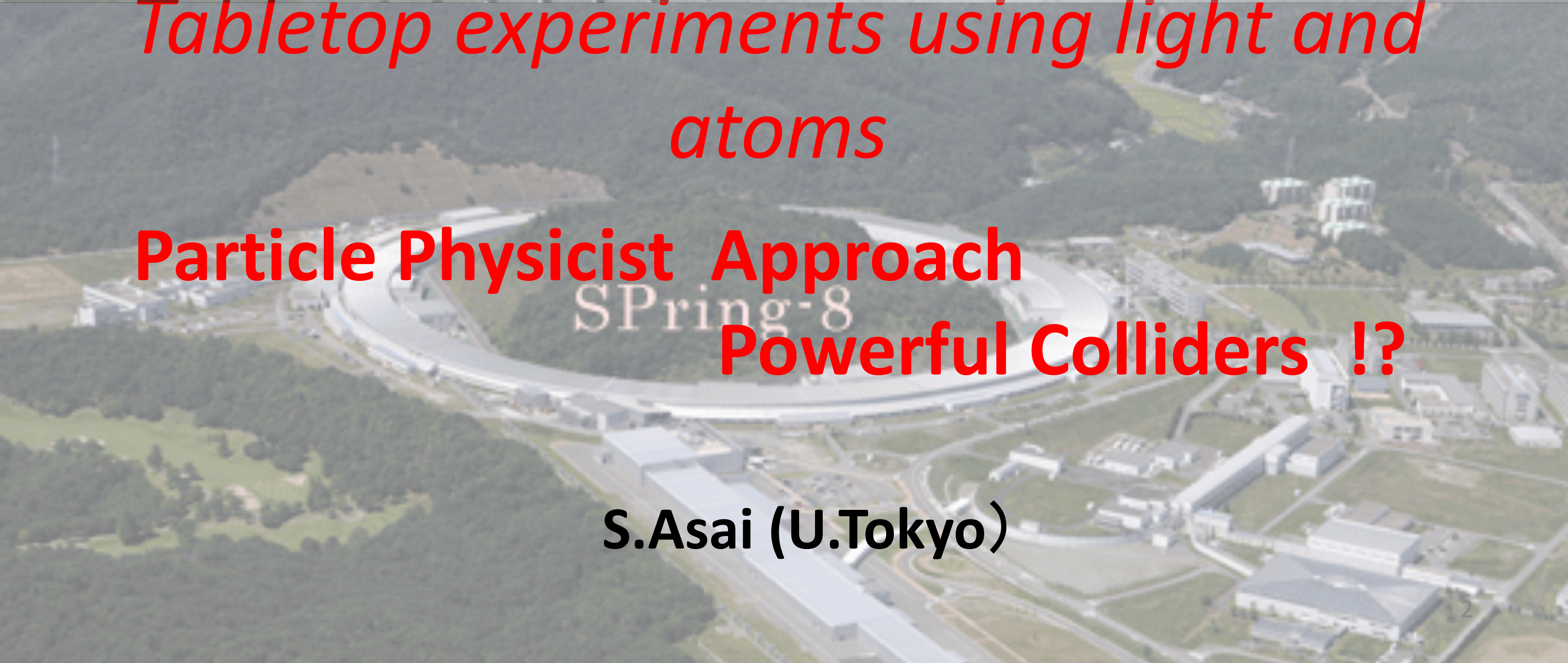
Tabletop experiments using light and atoms



S.Asai (U.Tokyo)

Tabletop experiments using light and atoms



Particle Physicist Approach

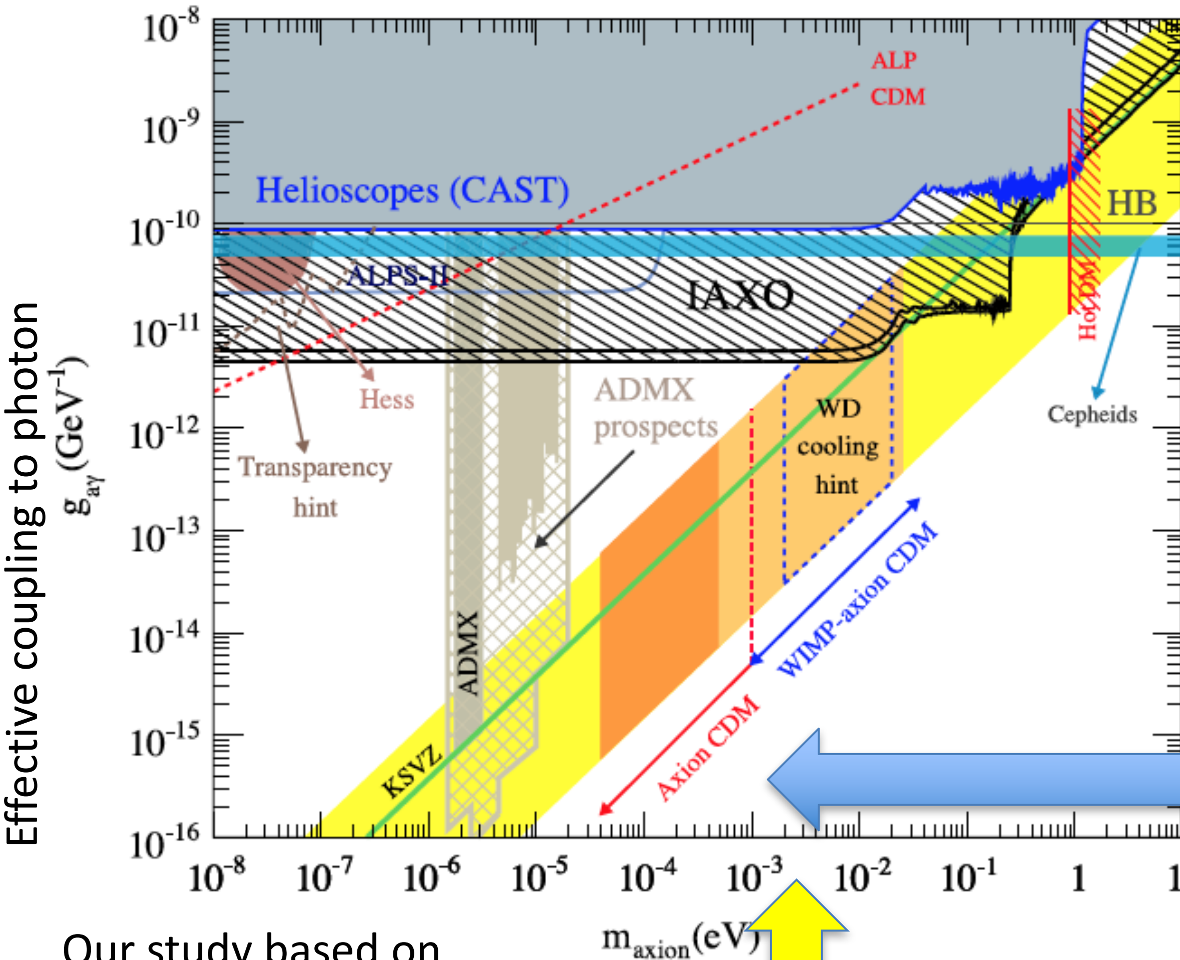
Powerful Colliders !?

S.Asai (U.Tokyo）

Our targets and table of contents

m(a)= meV - 1MeV (10^9 wide range)

arXiv:1303.4758



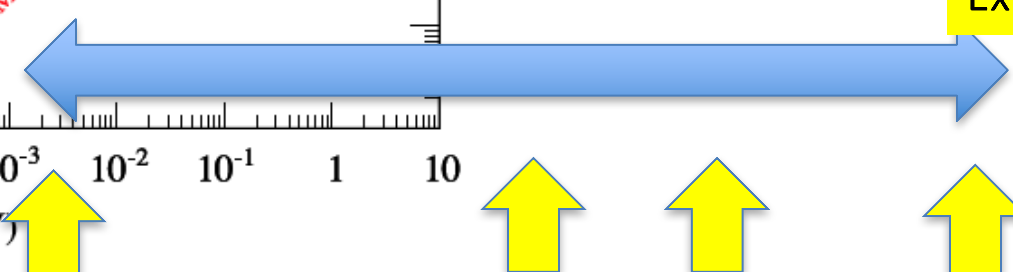
Extend upto 100MeV?

Thermal produced DM mass is 10 MeV-10 TeV

Our target is just below thermal production 10MeV

No rigid model exits except for axion for such a light region :

(5) Extend?

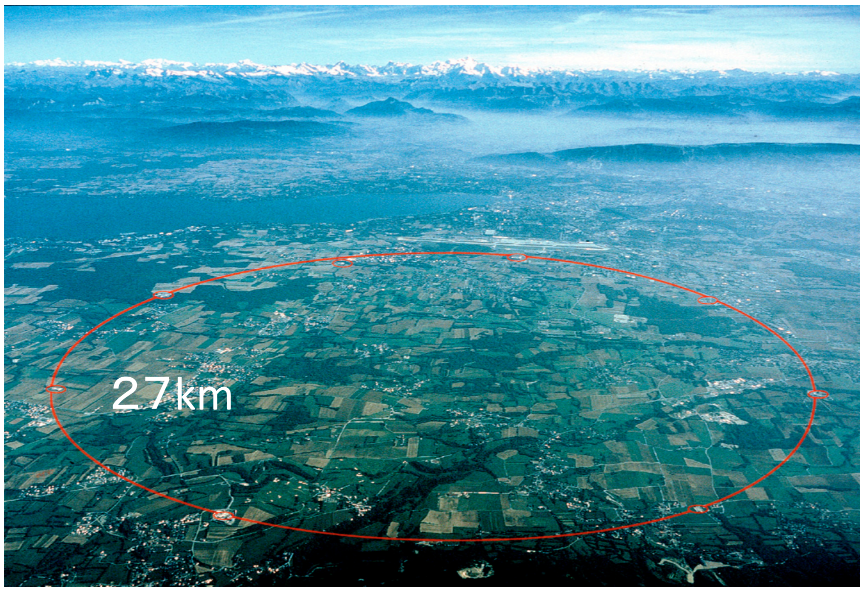


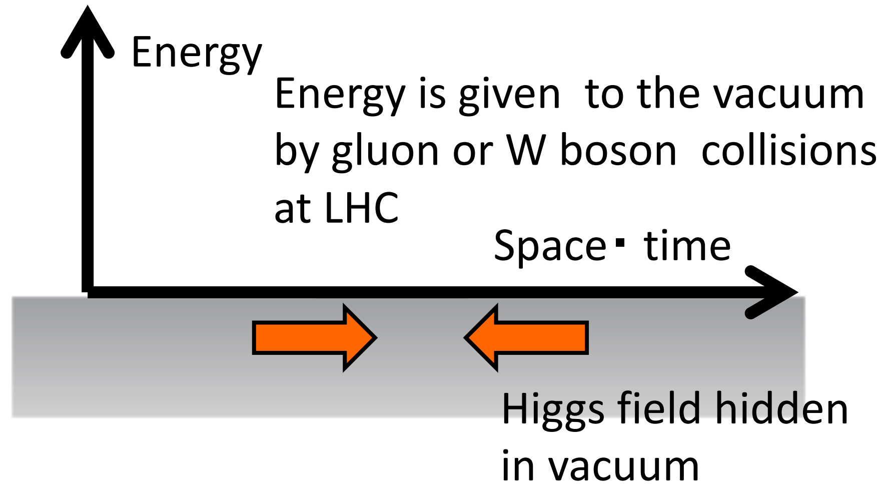
(1) (3) (2) (4)

Our study based on independently from DM model

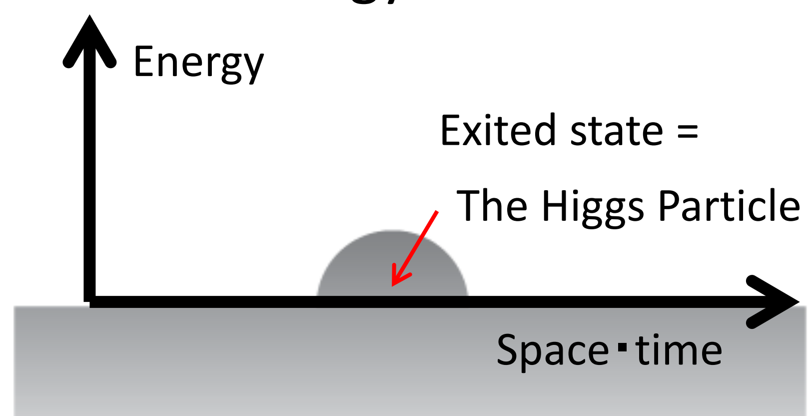
Introduction: Why is light used?

The Higgs Boson is discovered in 2012 at LHC



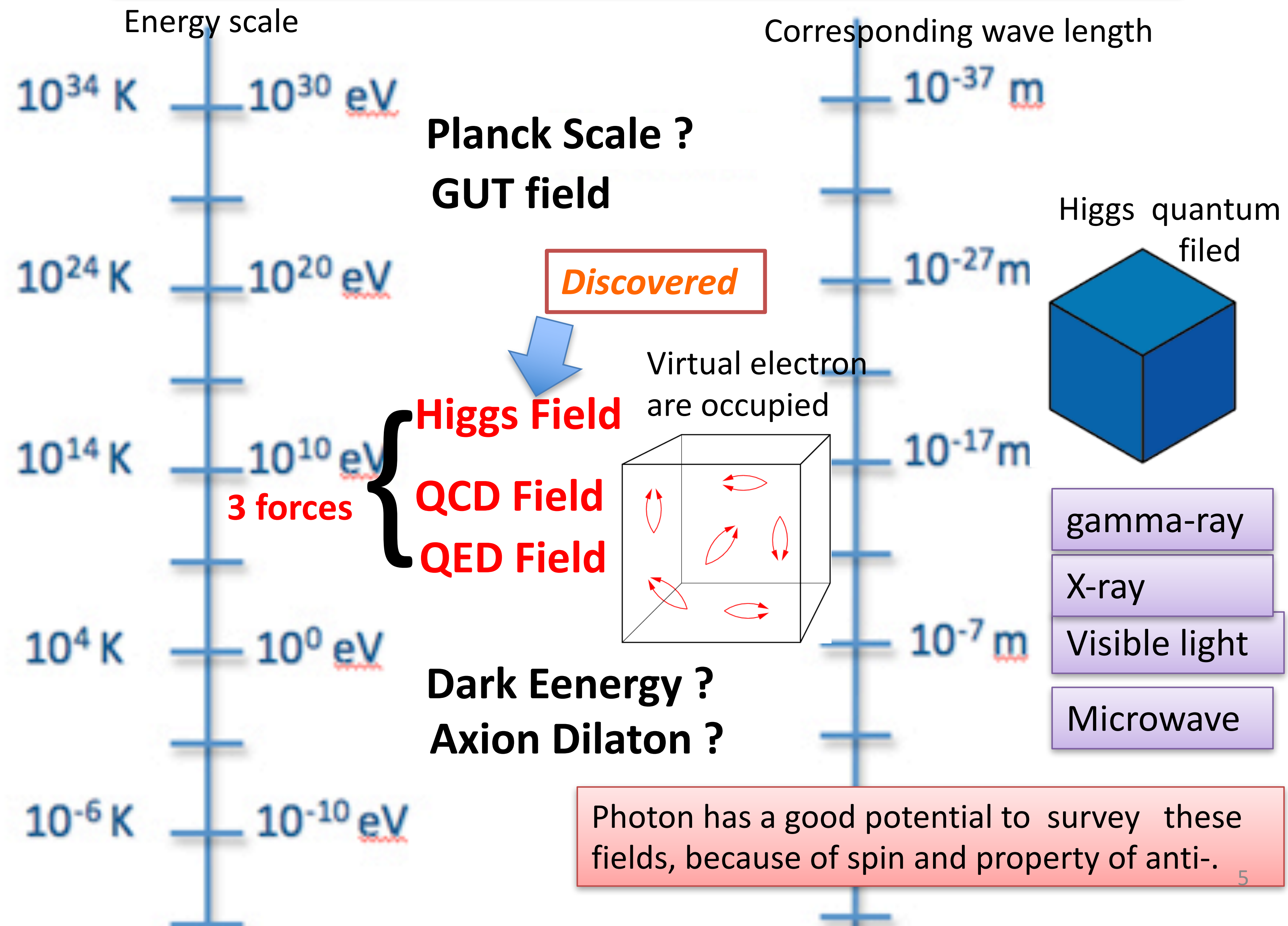


The energy excites the field.



Discovery of the Higgs boson shows that **our vacuum is filled with the strange quantum field** (in pool with Weak charge)
Higgs field is hidden in our vacuum.
We collide gluon and gluon
then excite this hidden filed.
This is the Higgs Boson. Photon can used instead of gluon.

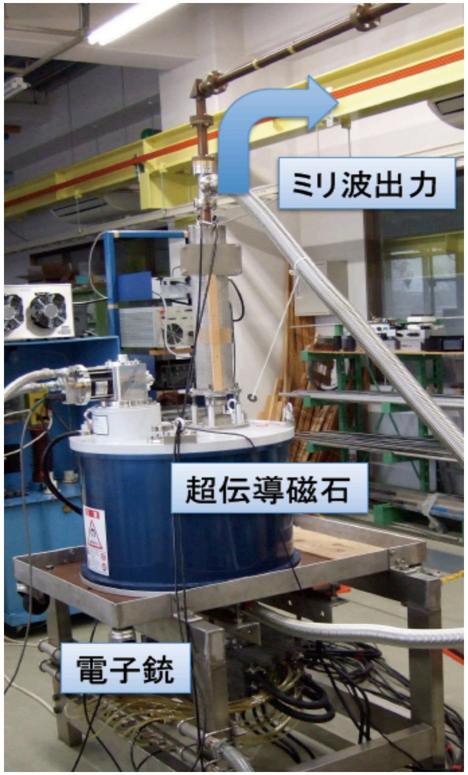
Various fields are hidden in our vacuum



Photon has a good potential to survey these fields, because of spin and property of anti-.

Wide range of Light Sources are developed/used

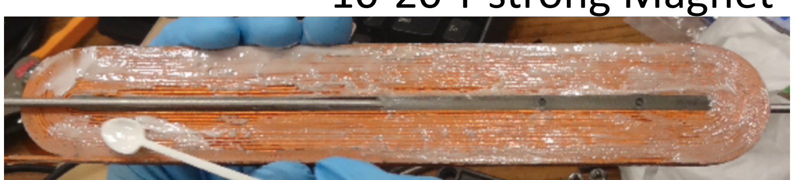
meV(THz)	eV (Laser)	KeV（X Ray）



Gyrotron + FP resonator
E>100kW 10^{26} Photon

F=450,000 FP resonator
500 TW Leaser

10-20 T strong Magnet

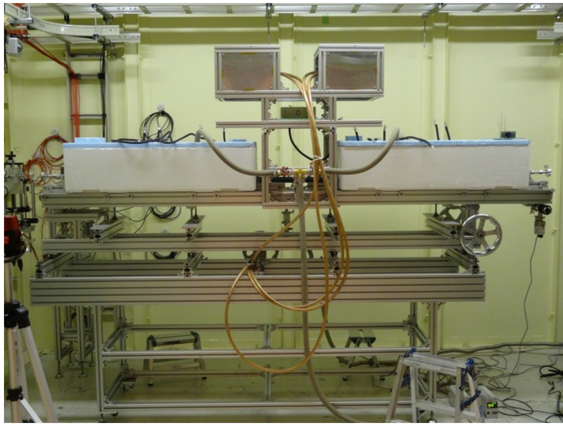


SACLA･Spring8

Various combinations
of these light sources
cover various ECM for survey

Rule violation?

Facility is big,
But the experimental setup/hall
is just on the table.

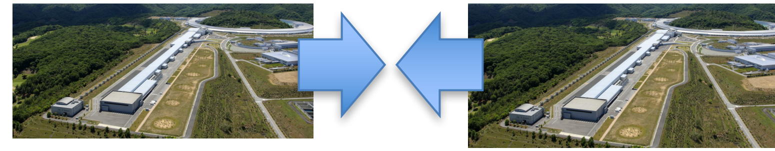


Light Shining through Walls (**LSW**) @ Spring8

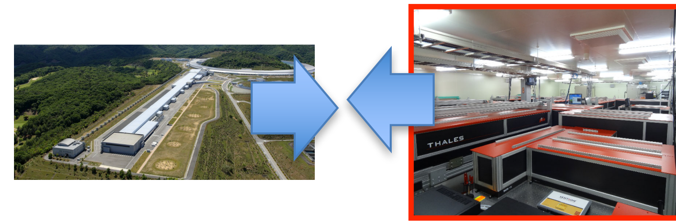
I hope Clear !!

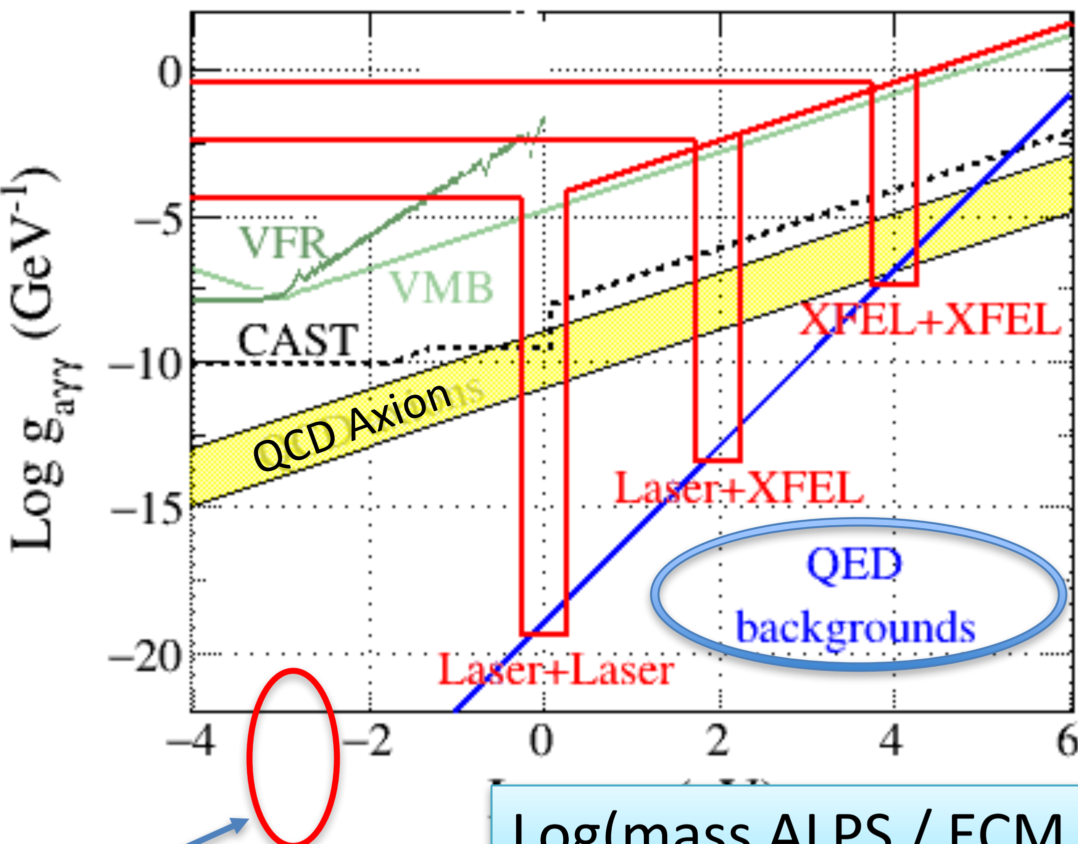
Particle Physicist View: Collider at various ECMs

1) X-ray + X-ray ECM~ 10keV



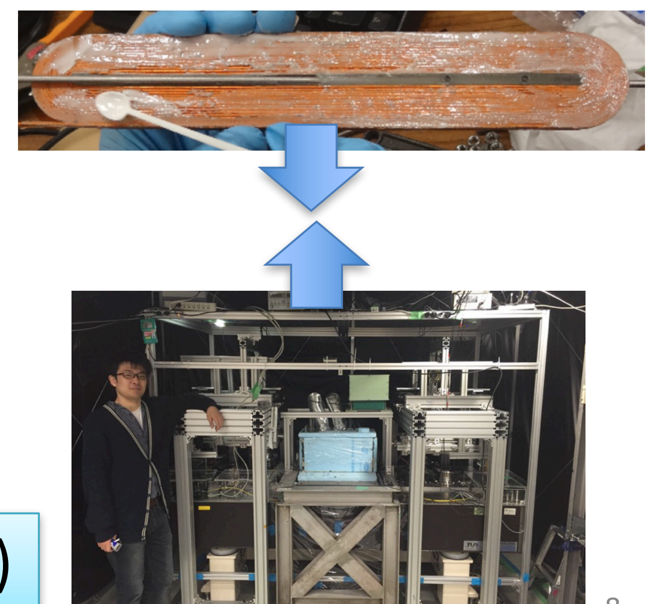
2) Visible Laser + X-ray ECM ~ 100 eV



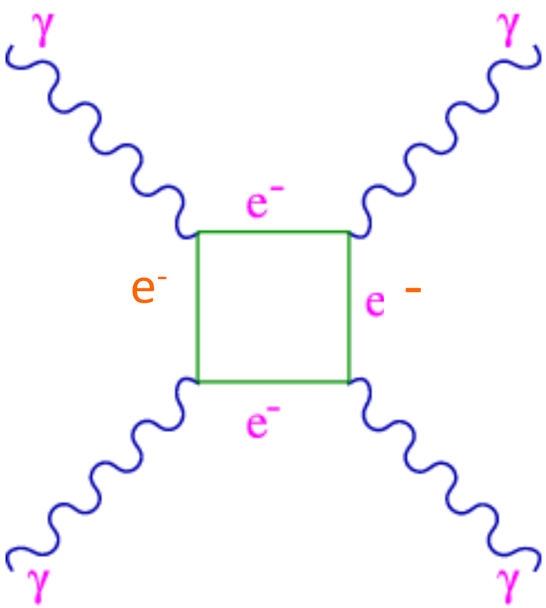


Log(mass ALPS / ECM eV)

3) Visible Laser + Strong Magnet ~ 1 meV



What is QED background?
Non-linear effect of the vacuum



Photon does not couple to photon itself.
But virtual electron-positron pair exists in our vacuum. (This is the QED vacuum)
Photon-photon scatter through this loop.

It is BG for hunting of a new field.
but It is also a very interesting target
Nobody see yet (ATLAS report recently)

QED prediction

$$\frac{d\sigma}{d\Omega} = \frac{139\alpha^4}{(180\pi)^2 m^2}\left(\frac{\omega}{m}\right)^6 (3+\cos^2\theta)^2$$

This process is seriously suppressed **by α^4 and highly suppressed by electron mass m^8**.

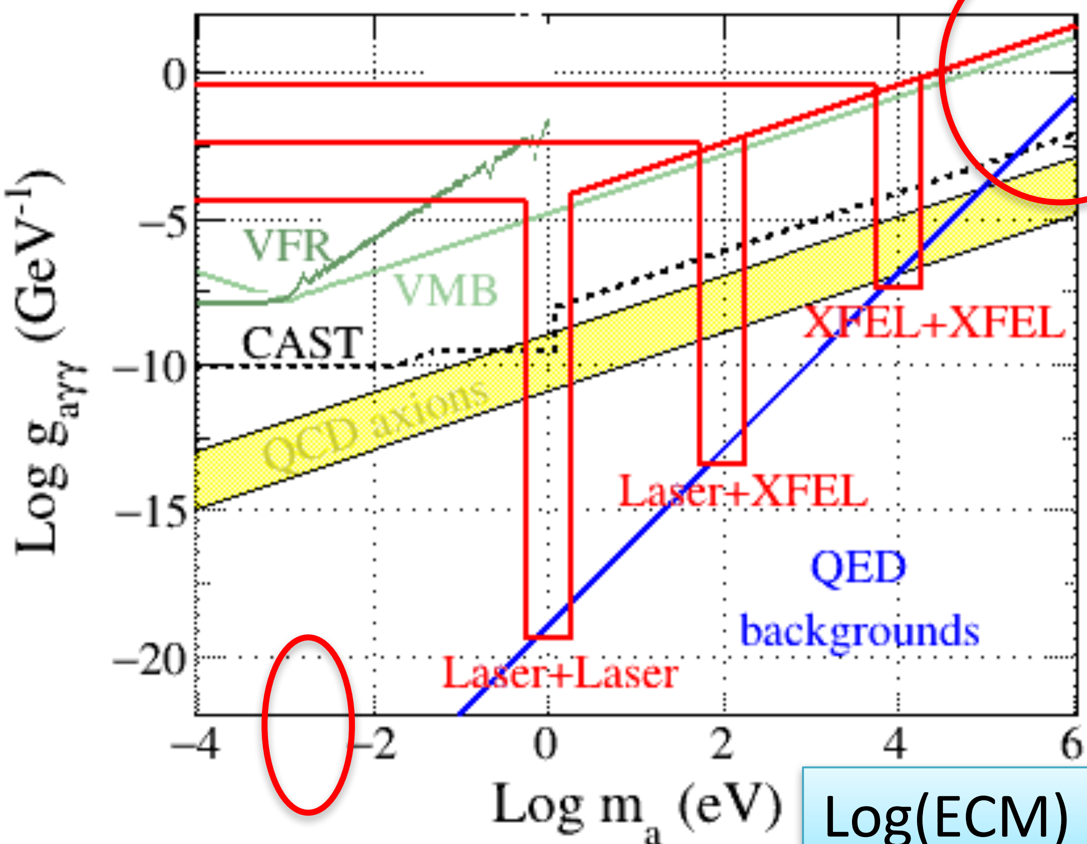
The expected cross section $\sigma = 1.8 \times 10^{-70}$ [m^2] for ω=eV Too small!!

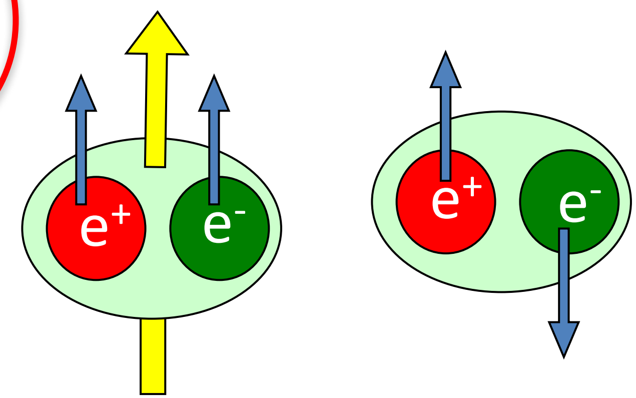
Enhanced by **24th order of magnitude for 10KeV X-ray** comparing to visible lights.

Particle Physicist View: Collider at various ECMs

4) Positronium

QED BG is serious
for √s > 100 KeV





Positronium is $e^+ e^-$ bound state
Ps is $e^+ e^-$ collider
(Low energy limit)

Log(ECM)

TeV region

14TeV-100TeV
gq collider

Thermal
WIMP can be
covered completely

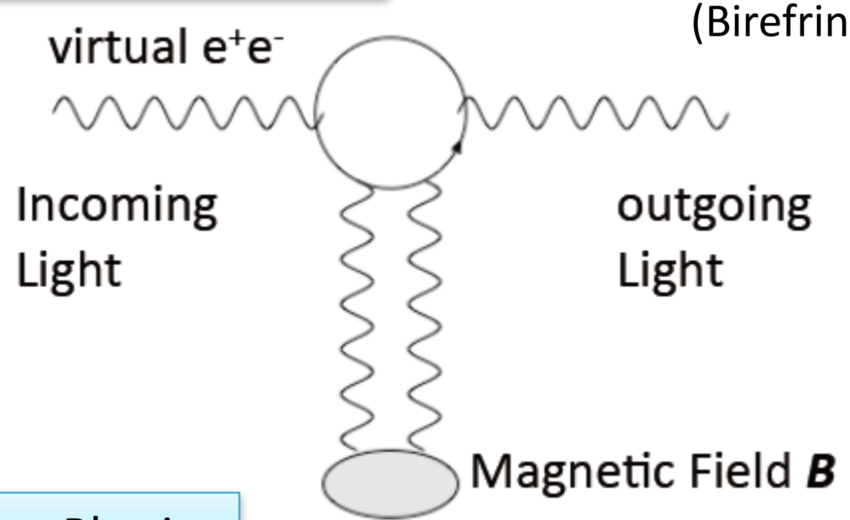
Photon collider

ee collider

arXiv:1901.02987

[1] Vacuum Magnetic Birefringence with Pulsed B √S~1meV

QED vacuum View



Refraction index n changes on the direction of the magnetic field B (Birefringence) -> Polarization is affected.

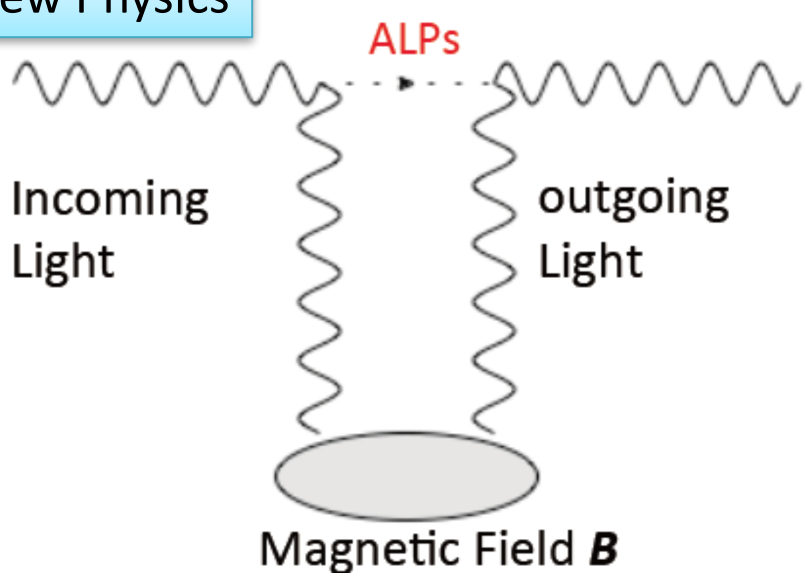
$$\Delta n = n_{||} - n_{\perp} = k_{CM} \times B^2$$

$$\mathbf{k_{CM}=4.0\times10^{-24}[T^{-2}]}$$

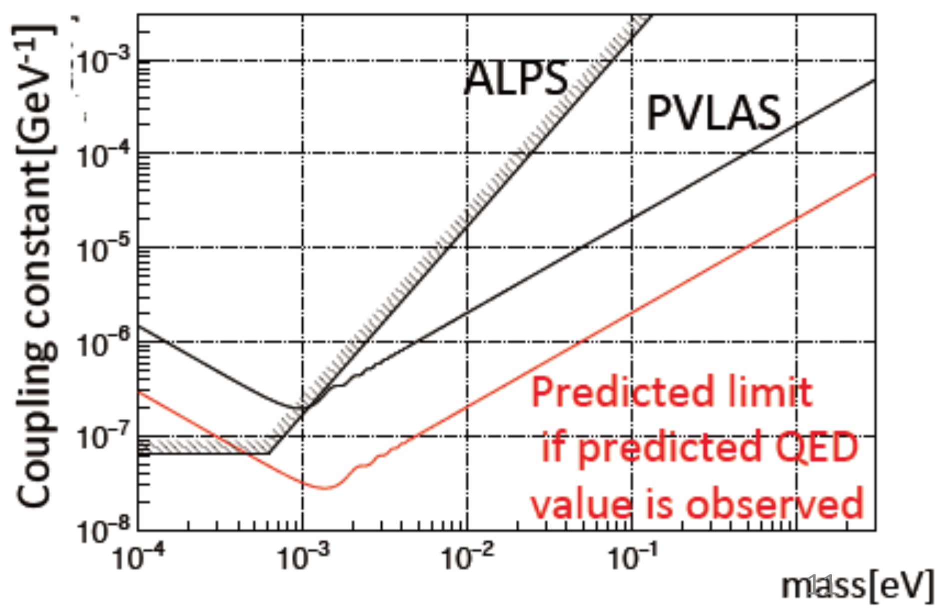
→ Evidence of QED vacuum

PLVAS try to discover VMB
Signal? Noise? is observed

New Physics



Sensitivity to Axion Like Particles



OVAL experiment at U. Tokyo

L: Light path length

Sensitivity $\Delta n \propto B^2 L_B$

Pulsed Magnets

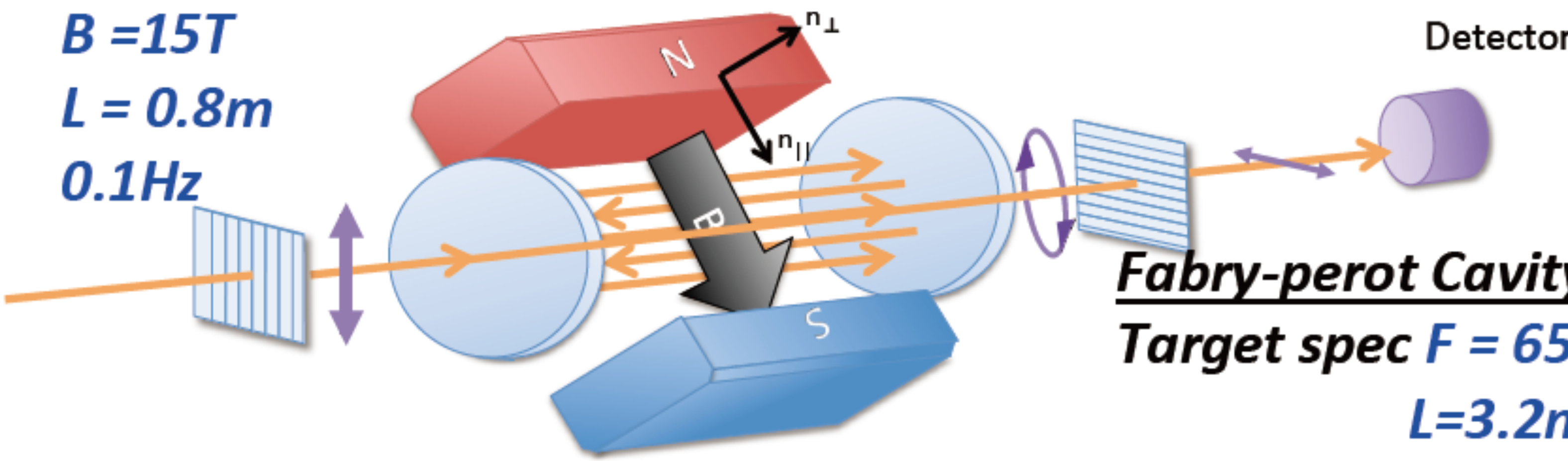
Target spec

B =15T

L = 0.8m

0.1Hz

Concept View



Fabry-perot Cavity

Target spec *F = 650,000*

L=3.2m, 5mW

Polari meter is
used to pickup signal

Strong Magnet (15T) is used
High repetition pulsed magnet is used.
It is different from PVLAS.

High Finesse Fabry-Perot Cavity
Effective L in B = 520 Km

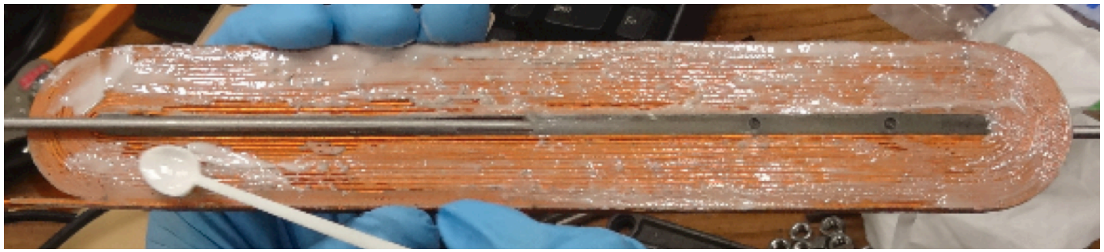
Noise control (similar to GW detector) is also crucial

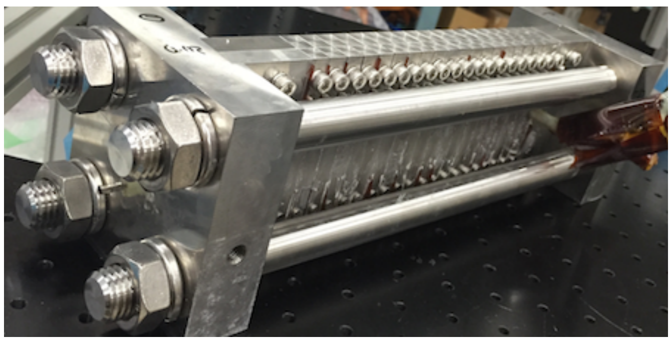
Pulsed Magnet

ϕ5.3mm: pipe: Light path

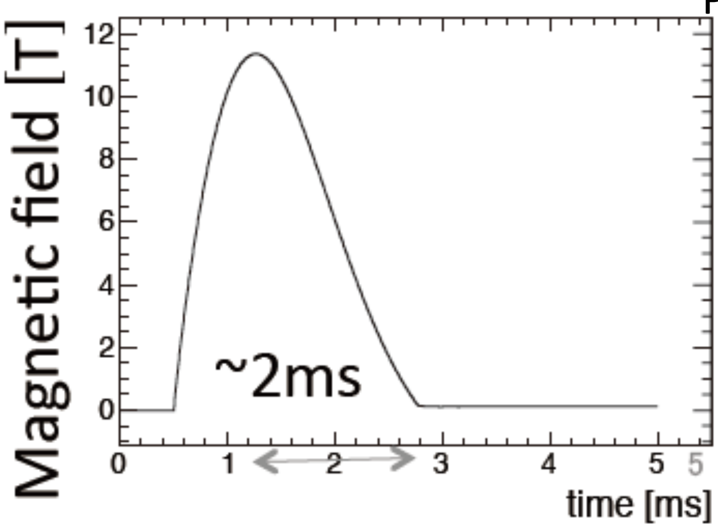
Racetrack magnet
with Cu

11 T 20cm OK → **Next 15T will be ready soon**



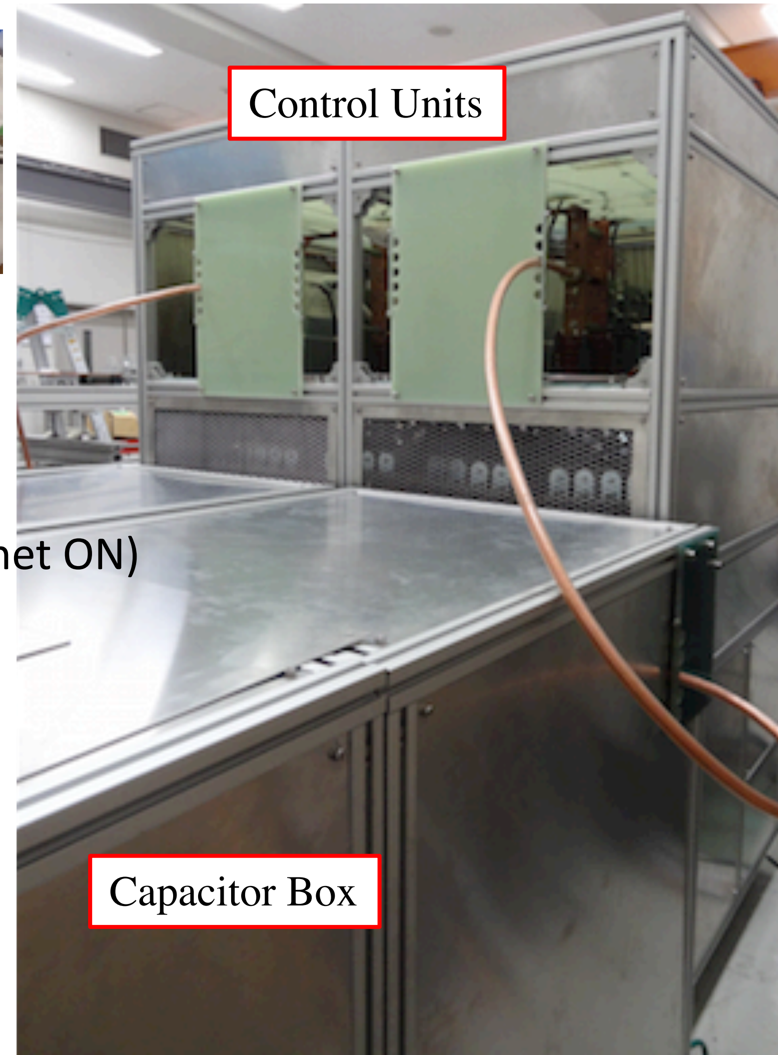


Magnet is reinforced
with Stainless case
(Force 40 Mpa is
generated at magnet ON)



Prototype has
been
tested well

Quick Recharge system
High repetition O(1)Hz



C=3.0mF, V=4.5kV, 15kVA

Everyone is surprised with Pulsed Magnet ?!?

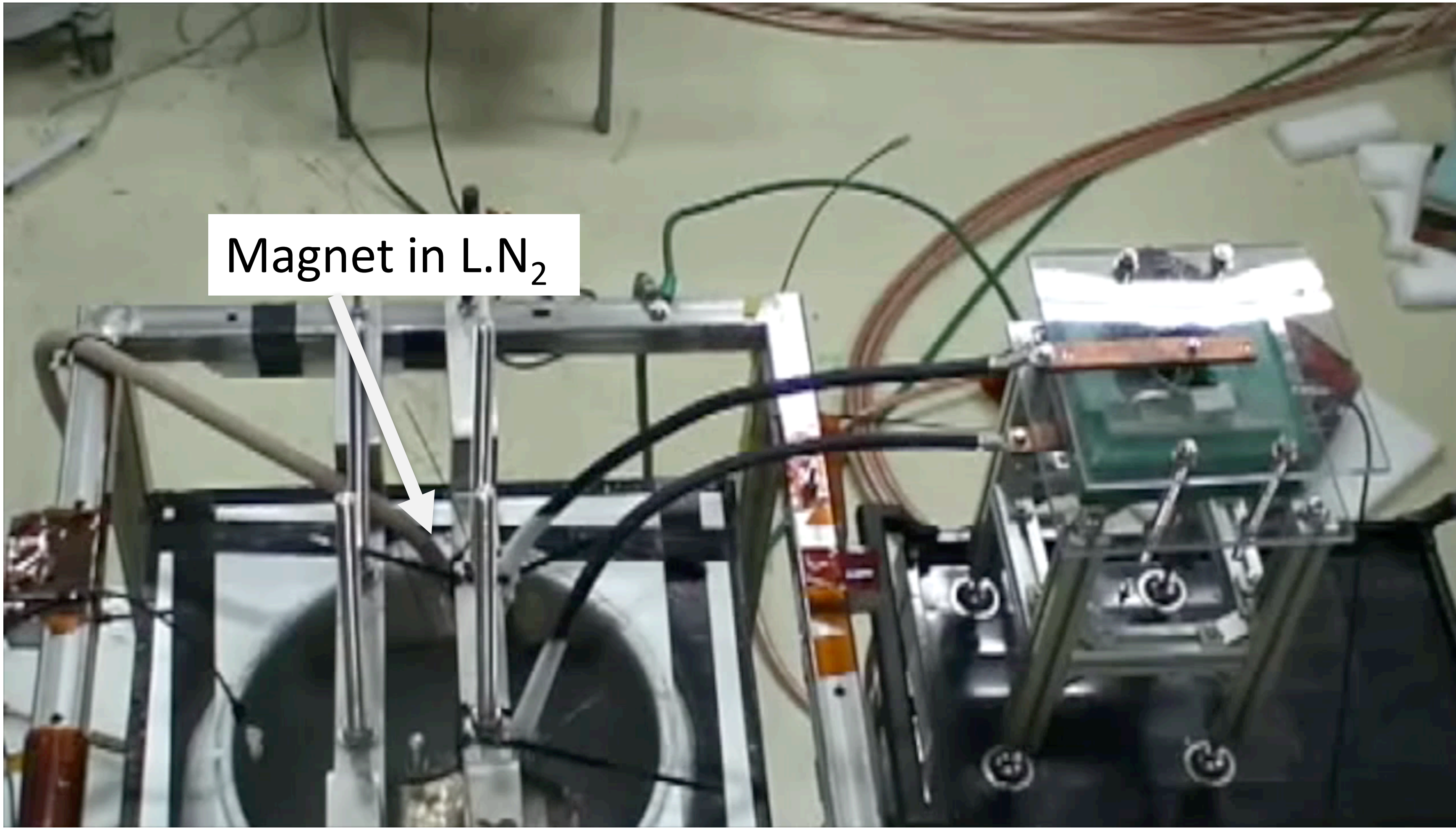
I=20kA Cable

Magnet is operated in L. N_2 for cooling 77K

Let’s turn ON

Large vibration & sound

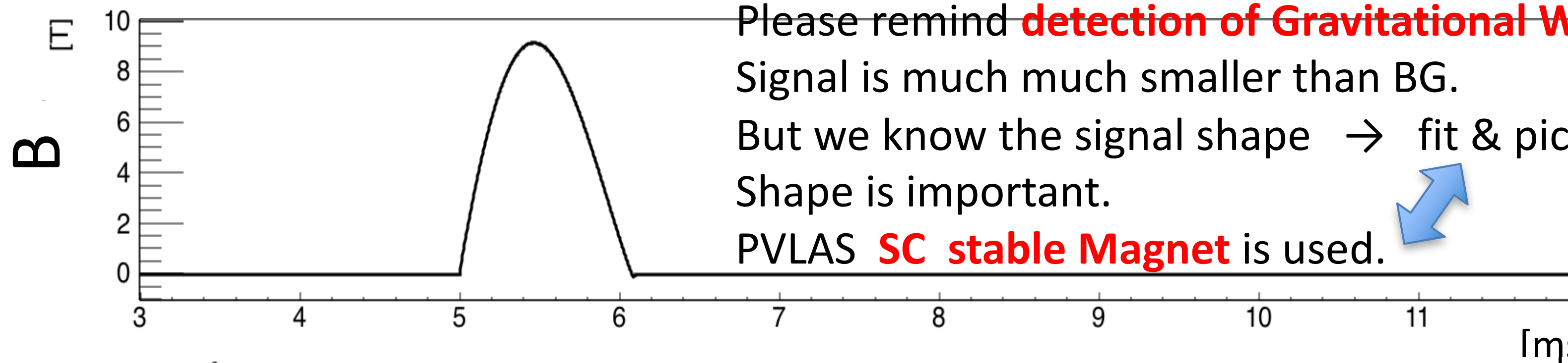
Do not be ambitious !!!



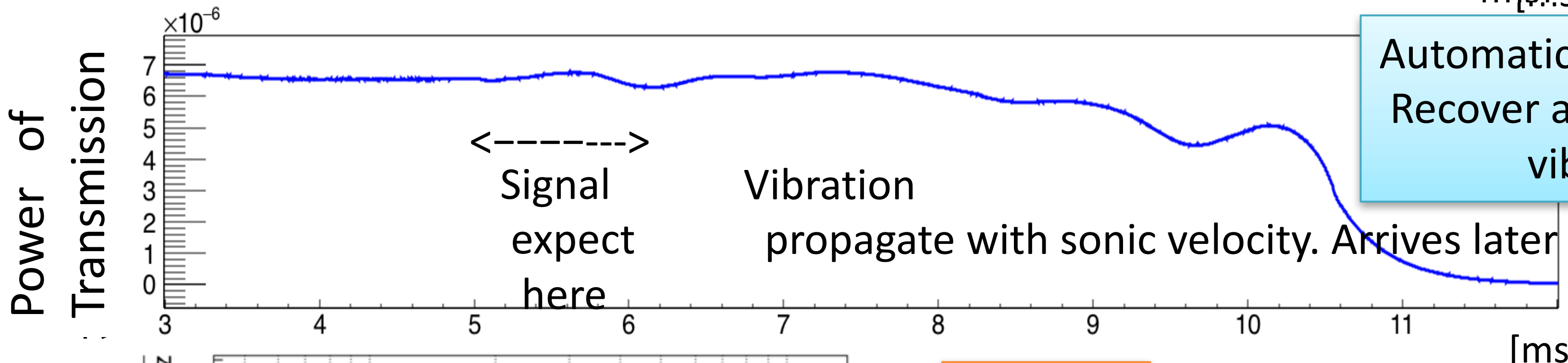
Why do we choose the pulsed magnet?

Benefit 1

Please remind **detection of Gravitational Wave**.
Signal is much much smaller than BG.
But we know the signal shape → fit & pickup signal
Shape is important.
PVLAS **SC stable Magnet** is used.

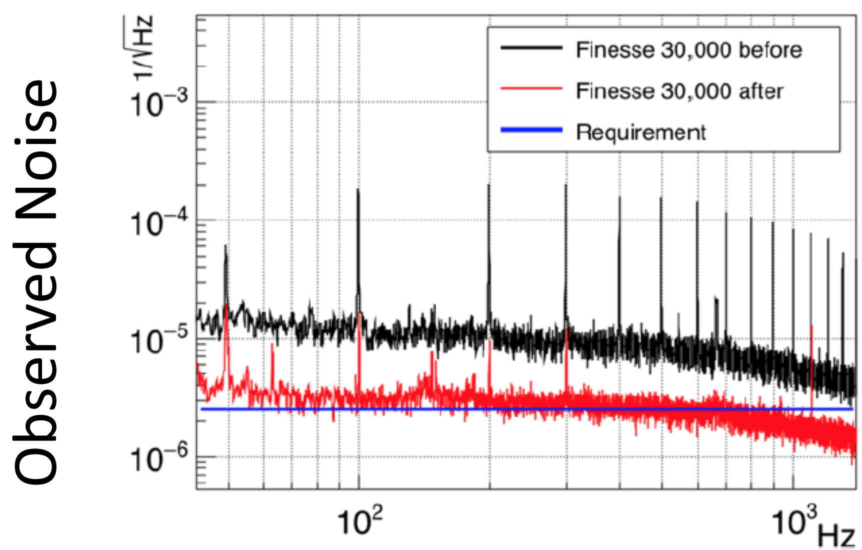


Automatic Recover after vibration



<------->
Signal expect here

Vibration propagate with sonic velocity. Arrives later



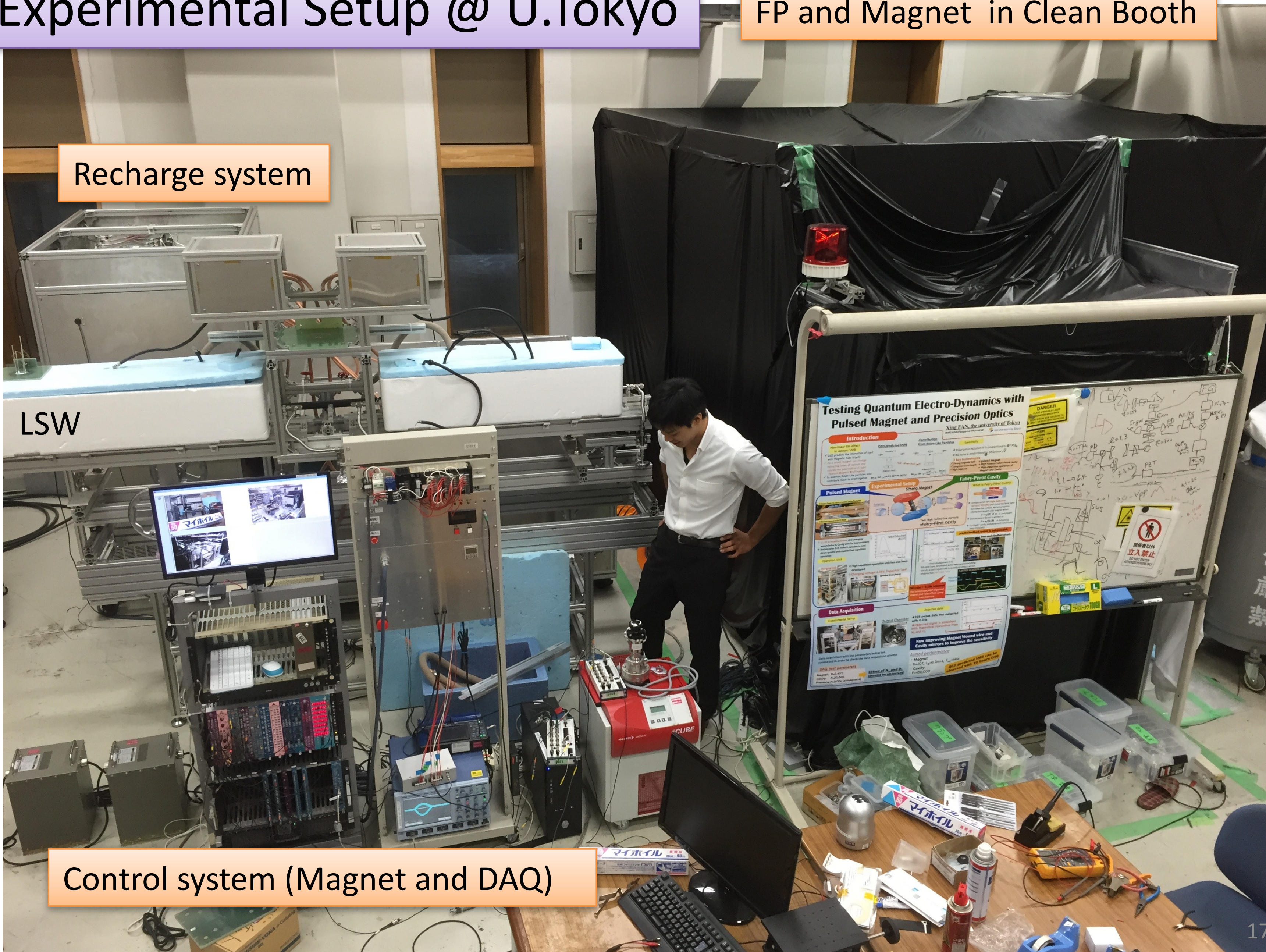
Benefit 2

Fast pulse -> High Frequency

High Noise background @ low Frequency

F=30,000 Cavity Noise OK
Next Study with F=300,000

Experimental Setup @ U.Tokyo

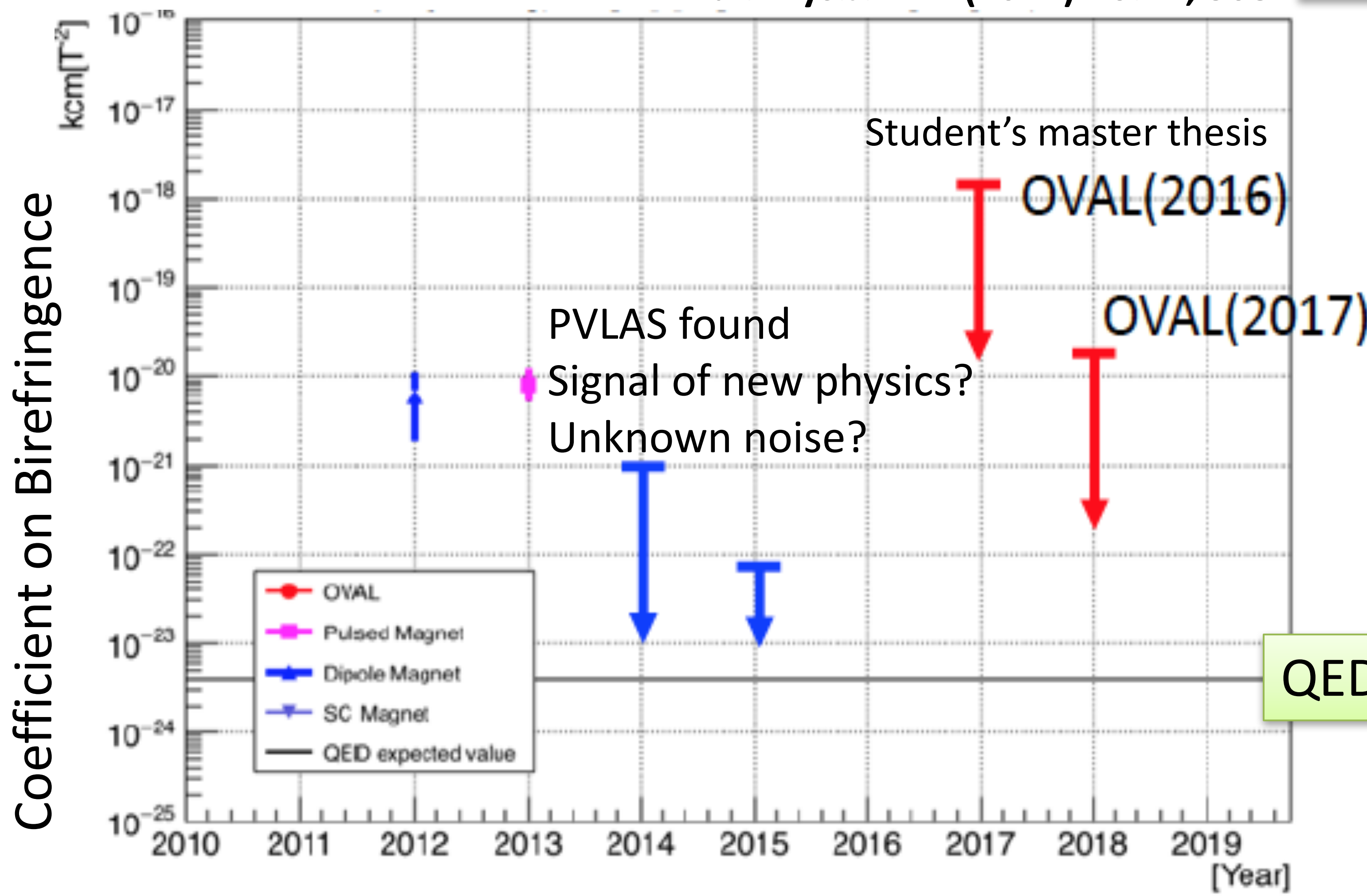


Current Status

The first test result
with just 100 pulses is published

Eur.Phys.J. D71 (2017) no.11, 308

No signal
was observed



Factor
300 less
sensitive
to PVLAS

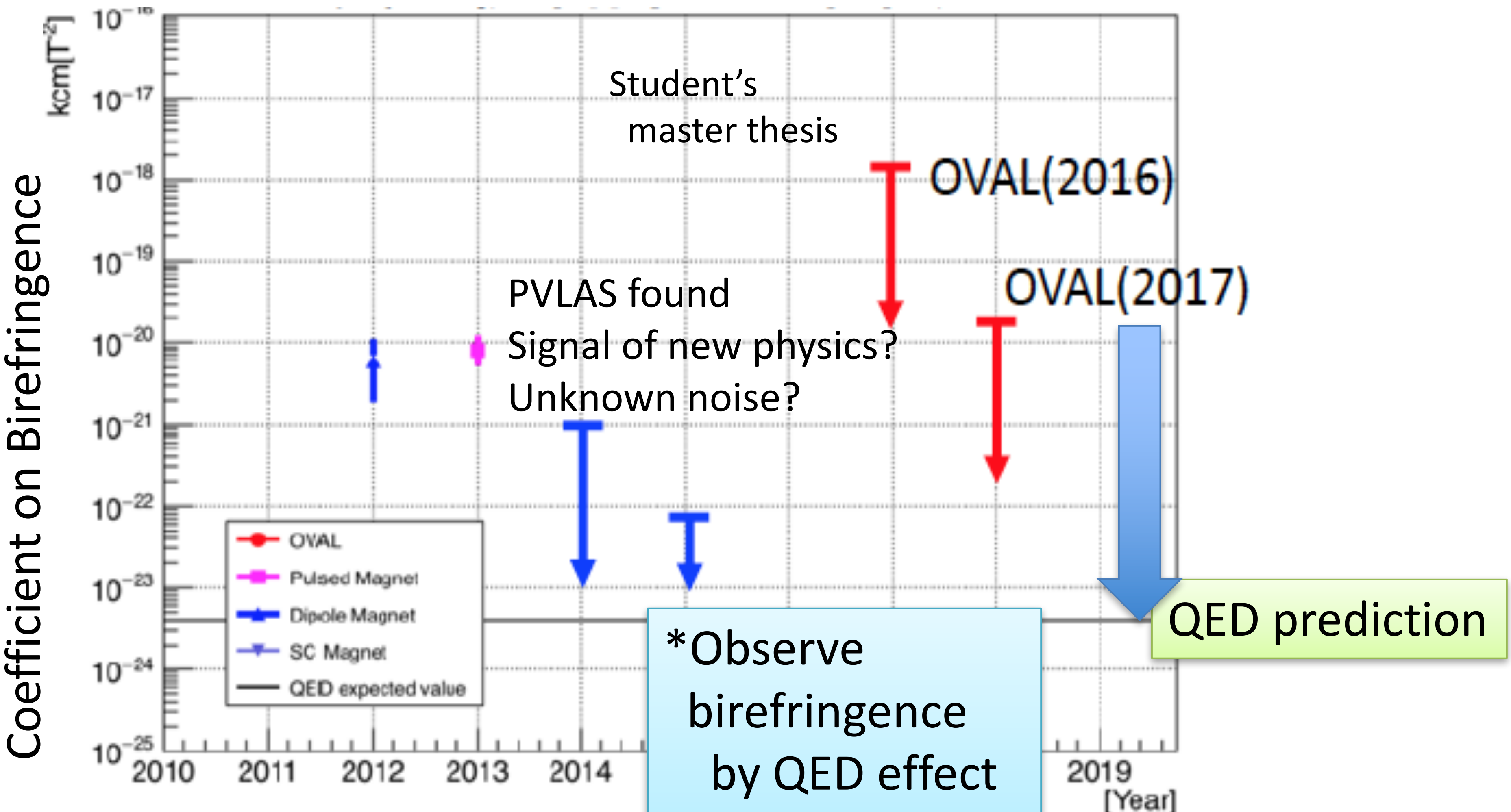
QED prediction

Status of Preparation for the Next Step

	2017	**Goal**	**Gain**	**Status for Goal**
Magnet	9[T]	15[T]	3	Soon [Cu->CuAg]
Length	0.2[m]	0.8[m]	4	Easy
Pulse length	1.2[msec]	4.8[msec]	2	Upgrade power unit (Add Capa.)
Finesse	350,000	650,000	2	Ready
Run time	100 [pulse]	200 [days]	14	Stability test Yet.

Factor ~3000 can be gained.

Status @2020



*Observe birefringence by QED effect
*Confirm / reject Excess @ PVLAS

[2] Search for the photon scatter at SACLA √S~10keV

We performed to search for photon-photon collision at SACLA(X-ray FEL).

Just collide? Not so easy!!

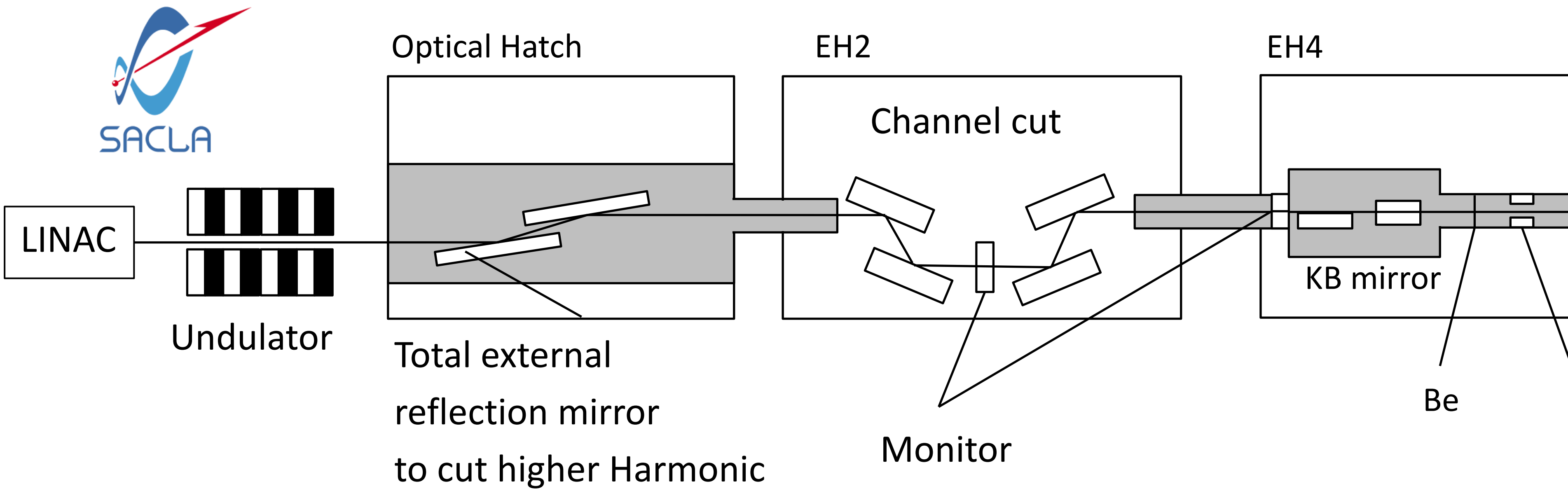
3 challenges

A） Photon Luminosity is crucial.

B） To collide photon to photon, control the optical path accurately in space and in timing.

C） Understand background events and reject them drastically.
Signal is very very small. On the other hand, BG is huge.

A) How to gain Photon Intensity; Upstream



- ✧ **6×10^{11}photons/pulse**@11keV, Pulse frequency is **30-60Hz**.
- ✧ Beam width is **200μm × 200μm** (FWHM), and a pulse length is short as **10fs(=3μm)**
- ✧ Monochromatic spectrum (bandwidth 80eV ->63meV) is obtained using the channel cut in which Si (4,4,0) Lattice is used. E=10.985keV
- ✧ Using the KB mirrors, beam is squeezed into **1 μm** (Horizontal)

→ High Intensity is obtained.

B) How to Split and Collide X-rays

Laue diffraction is used;

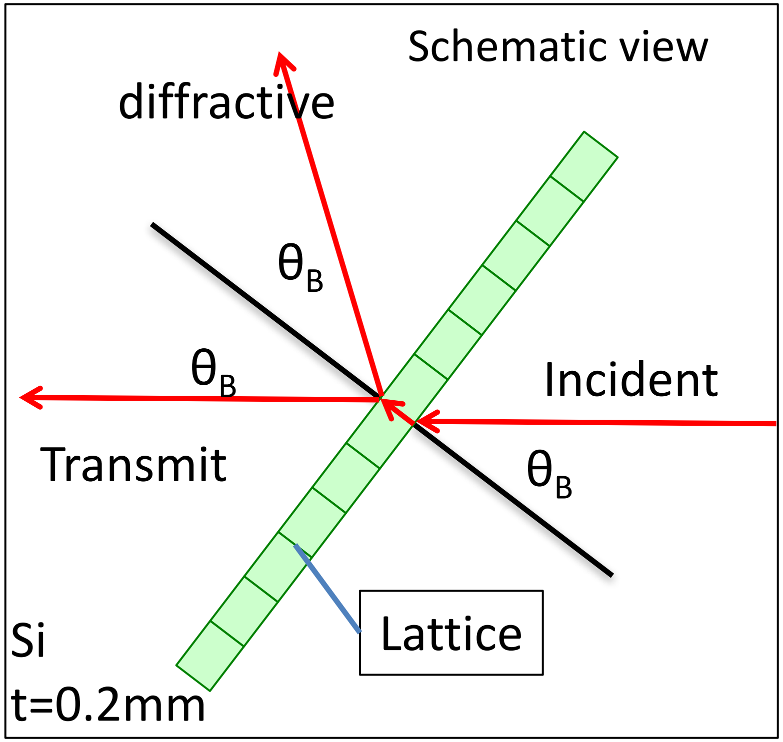
Si (4,4,0) Crystal Lattice is used.

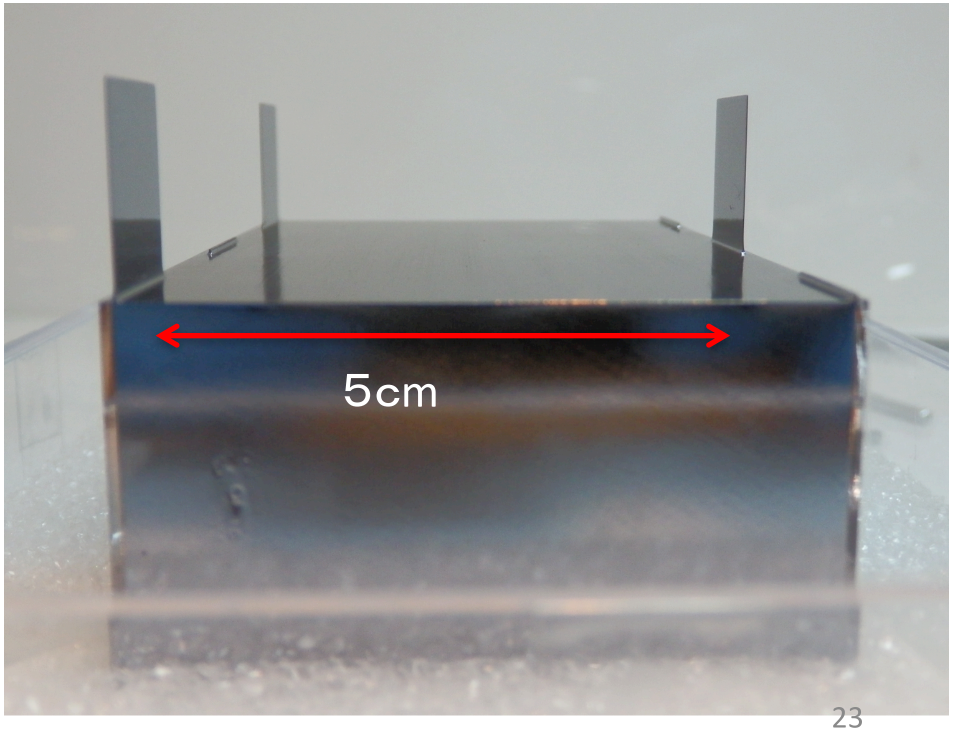
θ_B=36° for 10.985keV incident X-ray

Injected X-ray is split into transmit and diffractive. Both efficiencies are about 10%

Laue-Type interferometer is used;

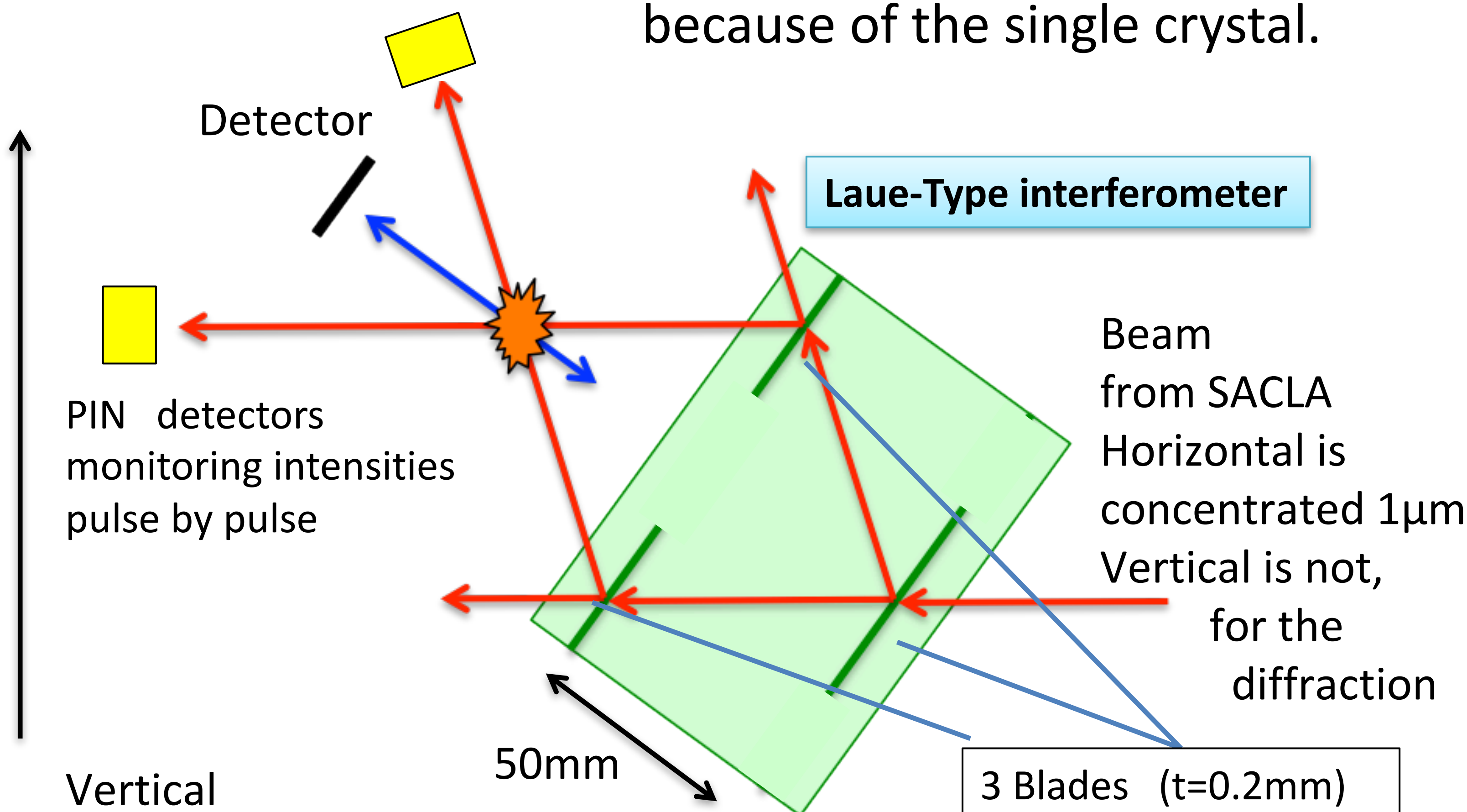
3 blades (t=200μm) are cut from a single crystal of Silicon.





B') How to collide X-rays

Beam splits into two using the blades, and collide here.
Optical path (both in space and time) is guaranteed,
because of the single crystal.

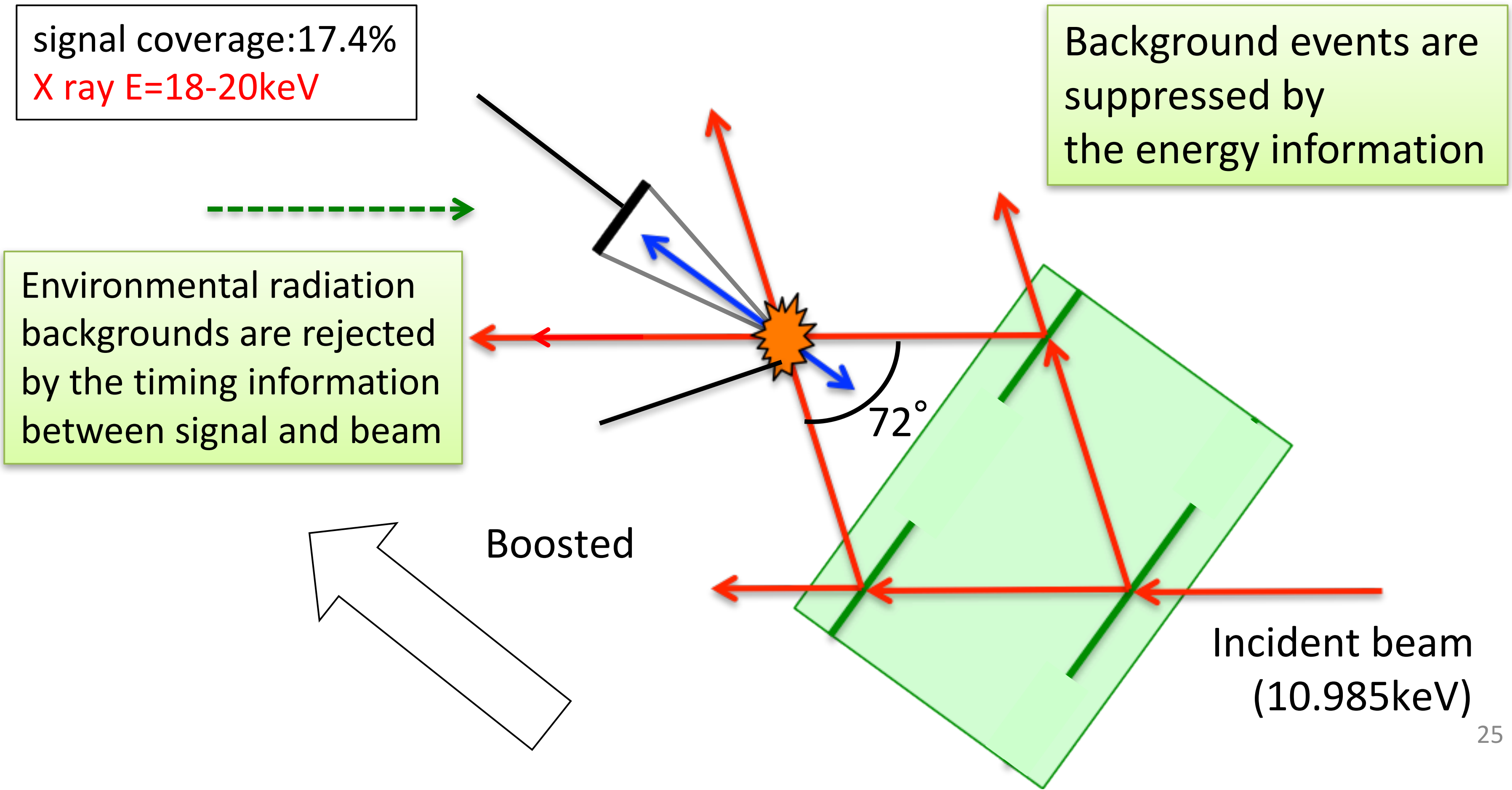


Nice idea

C) Background suppression (Energy information)

Dominant background is the stray photon of the incident X-ray. (E~11KeV)

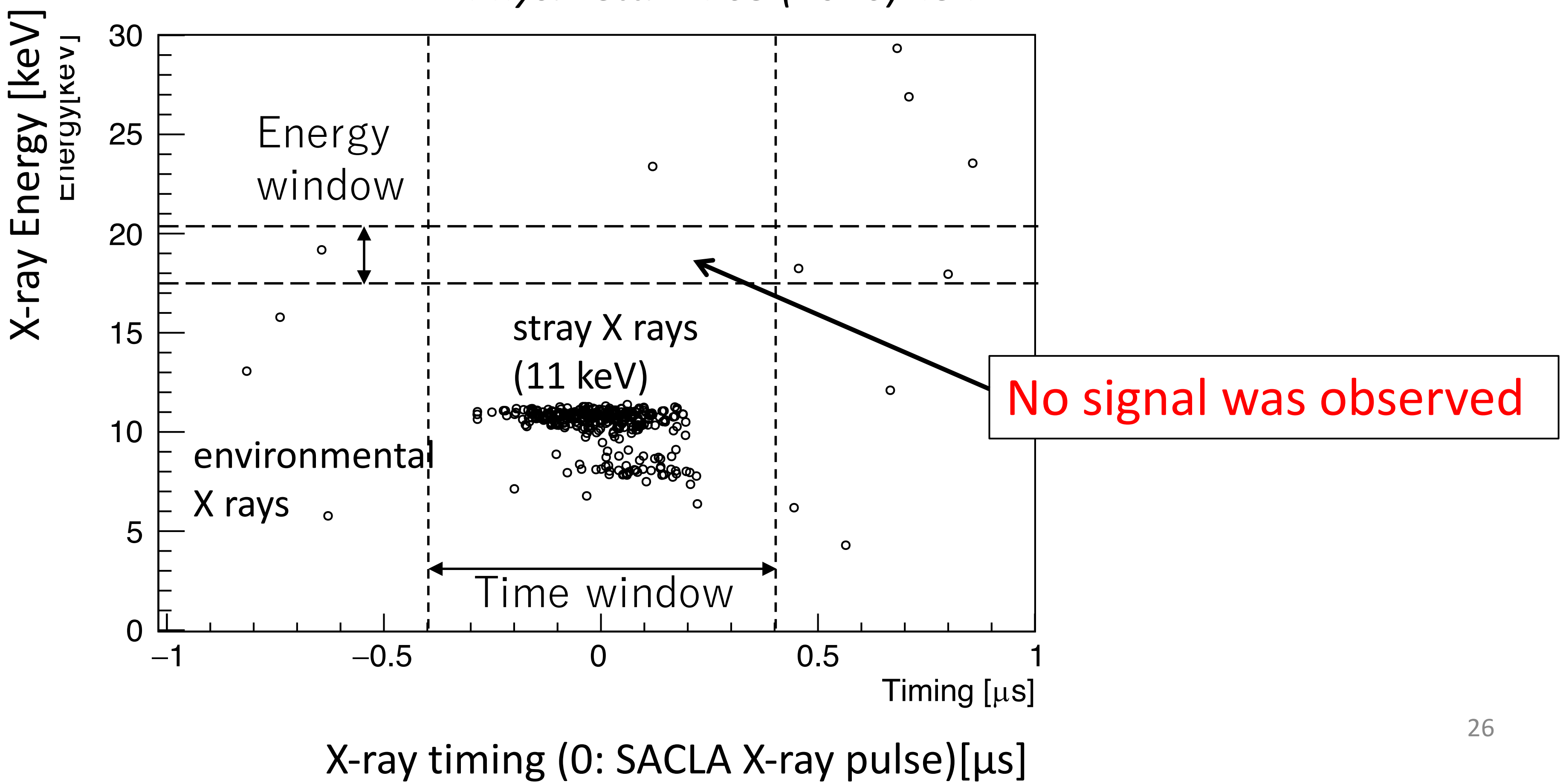
Collision is not Head-on (the collision angle is 72 degree), then the CM system is boosted forward. The energy of signal photon becomes 18-20 keV.



Result

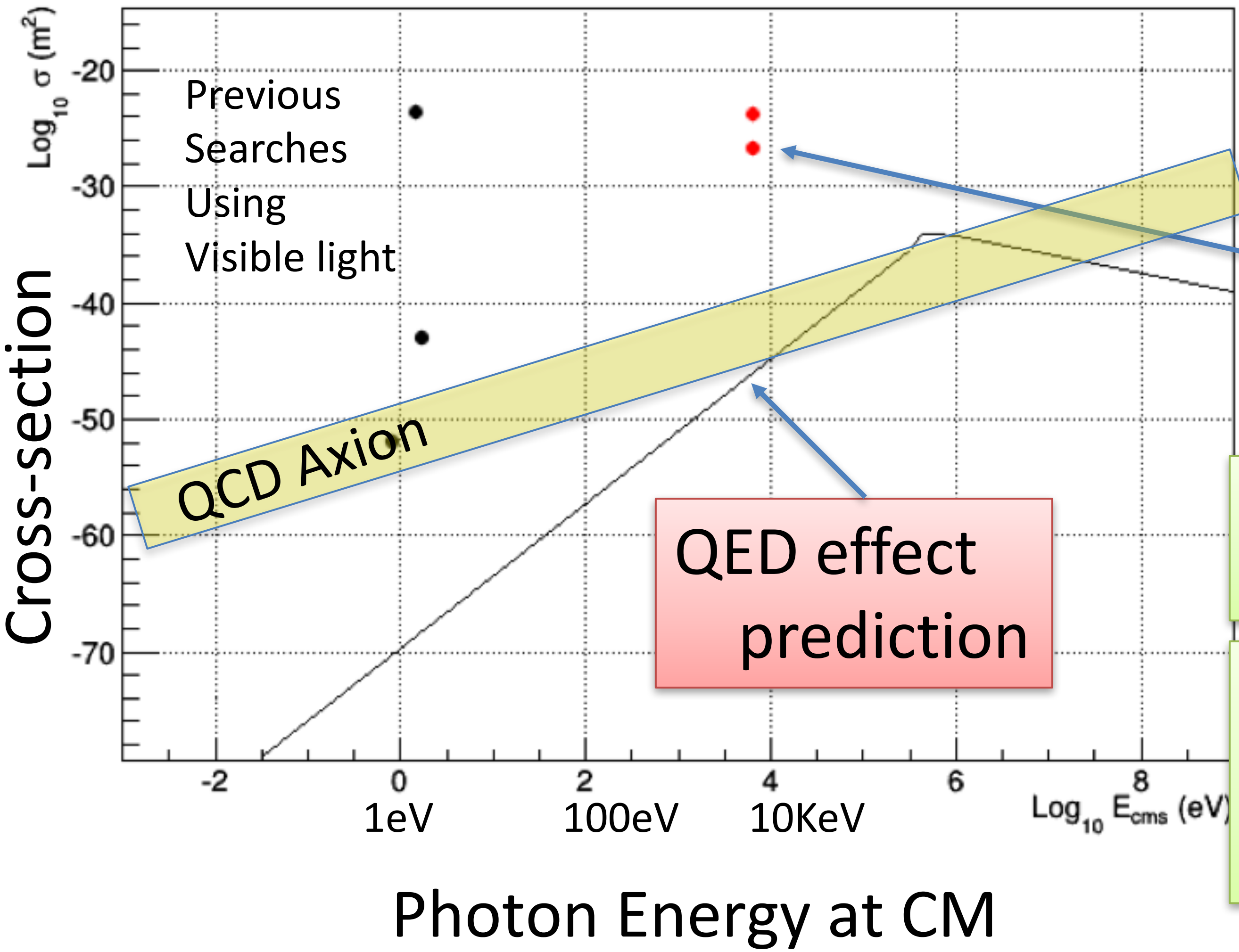
◆Potential source of pseudo signals
1)pileups of two stray X rays
: ~0.01 pileups are expected
2)accidental coincident of environmental X rays
:0.43 ± 0.03 BGs are expected

Phys. Lett. B 763 (2016) 454



No signal was observed

Upper-limit on the cross-section(95%CL)



1.9×10^{-27} [m^2]
~ 10^{14} fb

We have performed twice in 2014 and 2016

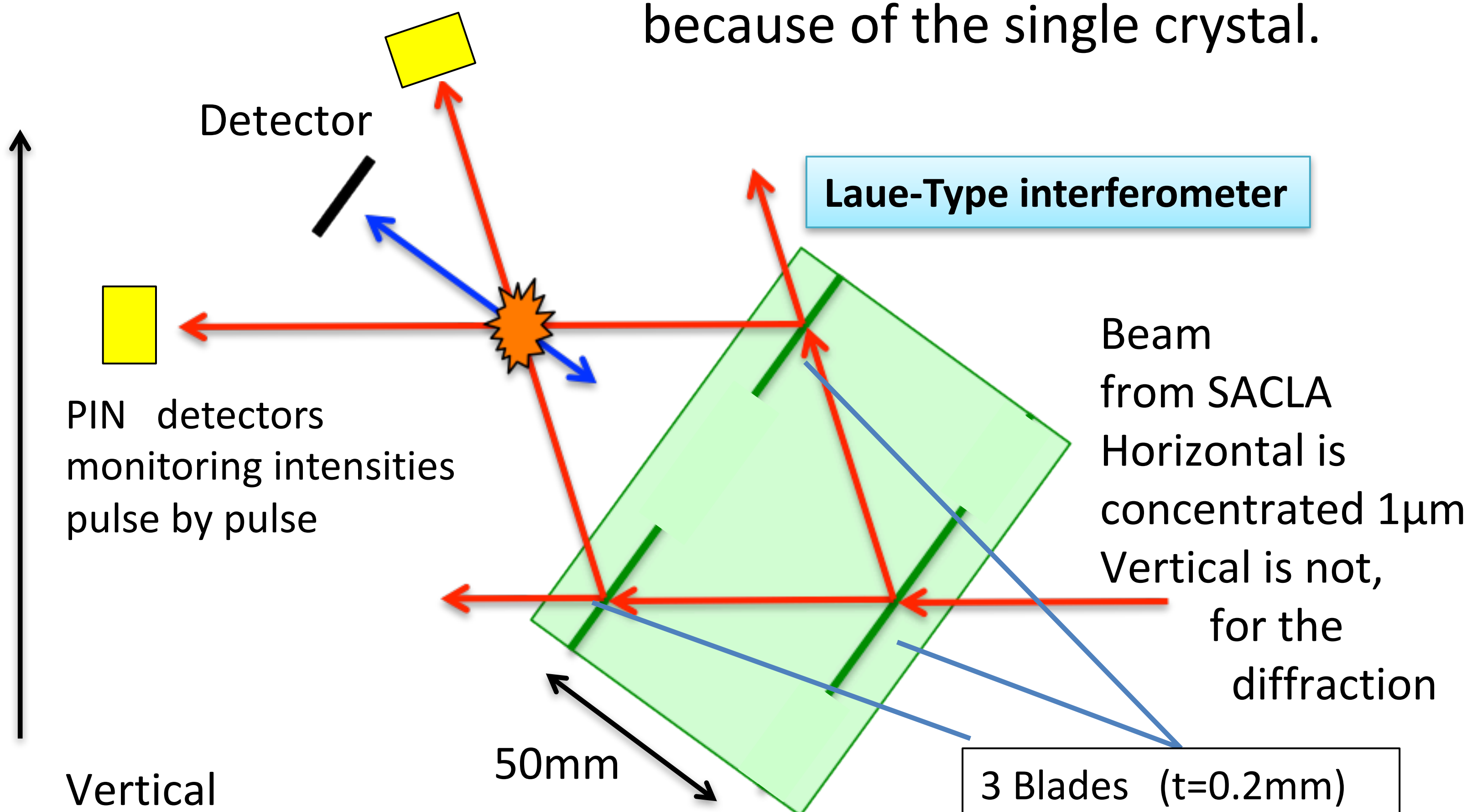
The first results at X ray region.

But still need sensitivity of 10^{15}-10^{20} to observe the QCD Axion / QED vacuum

Why so becomes worse? Arrowed E Width of “Laue scatter” is too narrow
80eV -> 63meV 1/1000 * 2% (2 Laue scatter) -> 10^{-5} photon loss / each

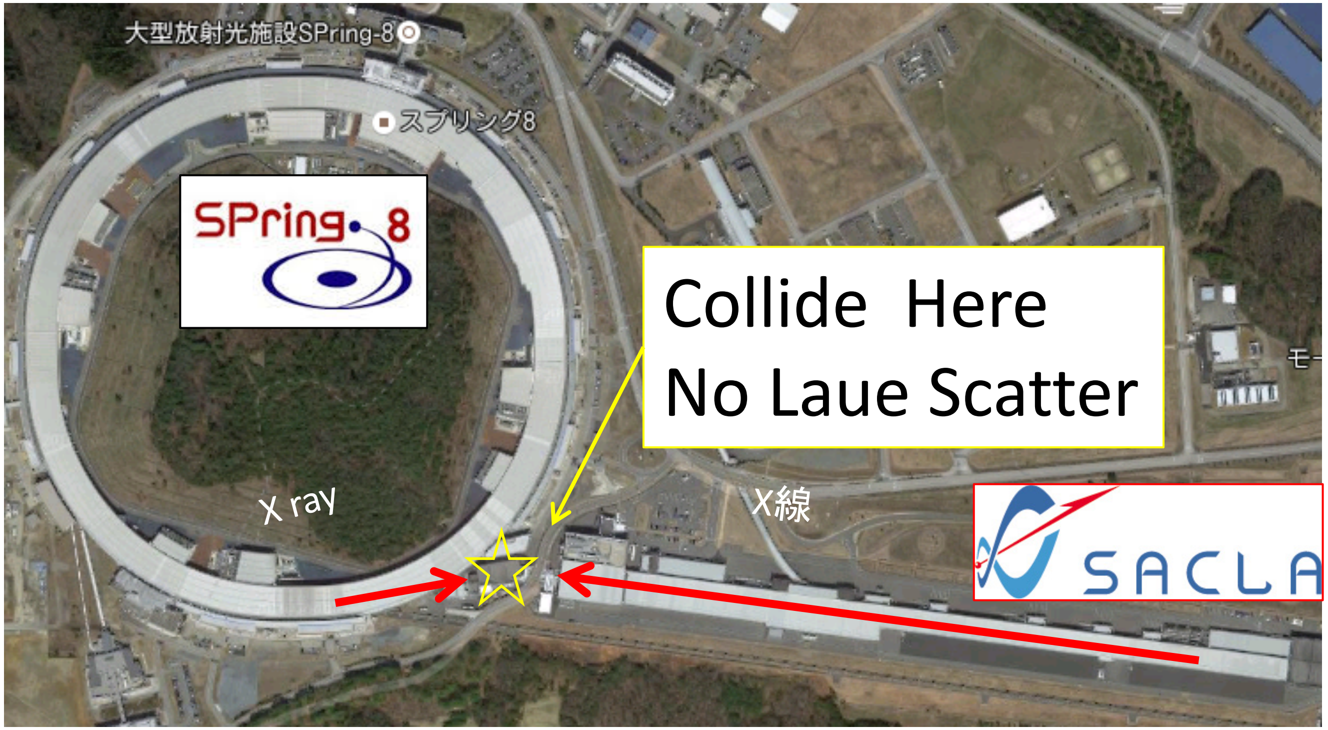
B') How to collide X-rays

Beam splits into two using the blades, and collide here.
Optical path (both in space and time) is guaranteed,
because of the single crystal.



Not Nice idea

Next Step : SACLA+SPring-8 head-on collision

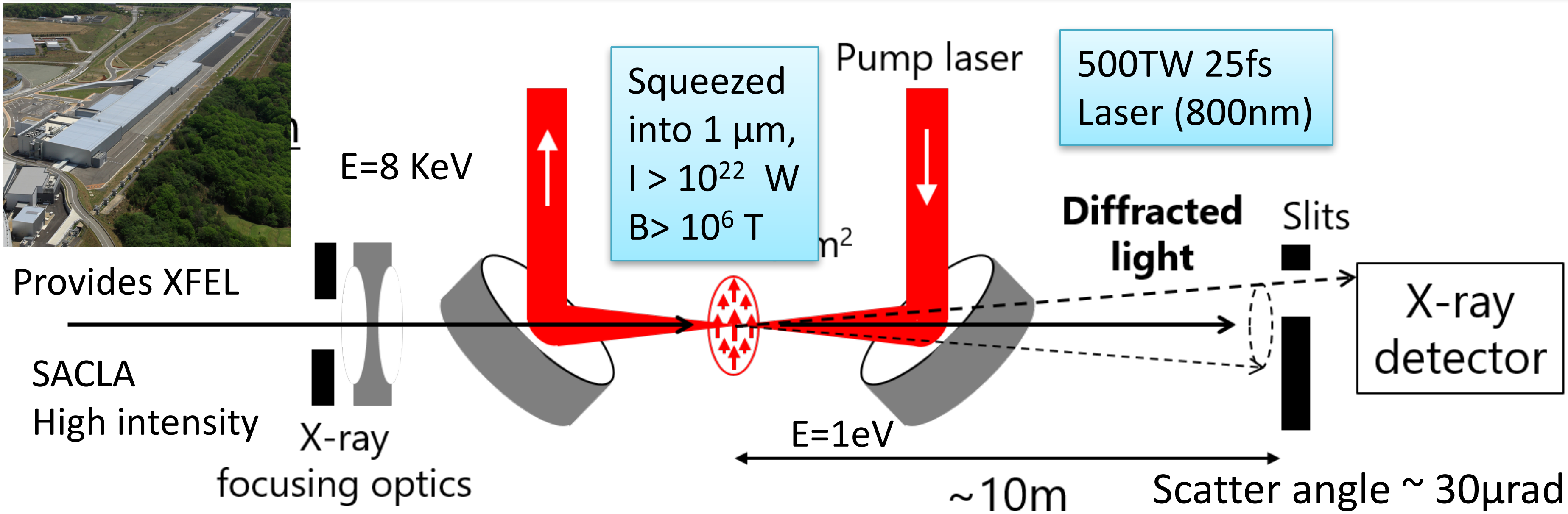


Riken has a plan for material science.

We are developing the methods to collide with each other.

Control path and timing is in progress.

[3] X-ray - Laser scatter at SACLA √S~100eV



Performance of the SACLA

- Photon number : 6×10^{11} photons/pulse @10 keV
- Pulse width : <10 fs
- Beam size after focusing -> 1 μm

Performance of the 500 TW laser

- Wave length : 800 nm
- Pulse energy : 10 J
- Pulse width : 30 fs
- Rate : 1 Hz
- beam size is squeezed upto 1μm

500 TW laser
(in commissioning now)

How to detect?

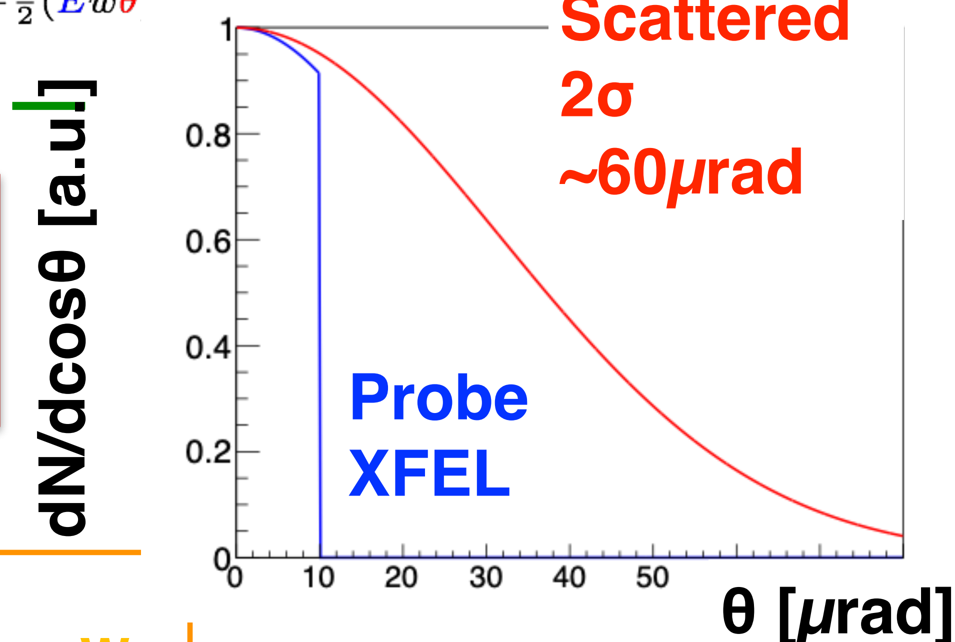
X-ray is scattered (small angle)

$$\frac{dN_{\mathrm{diffracted}}}{d\cos\theta} \sim \frac{JE^2W^2}{w_L^2(w_L^2+2w_X^2)} \times (Ew)^2 e^{-\frac{1}{2}(Ew\theta}$$

$$w^2 = \frac{w_L^2 w_X^2}{w_L^2 + 2w_X^2}$$

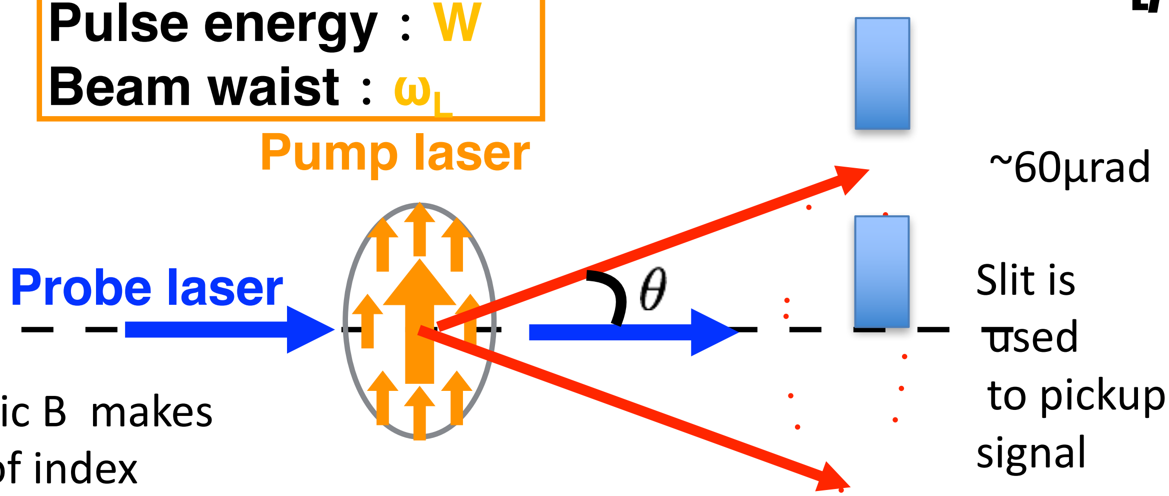
PRD 94, 013004 (2016)

High Energy E
Squeezed both
High Flux J
High Power W



Probe X-ray laser (Gaussian beam)
Photon flux : J
Photon energy : E
Beam waist : ω_X

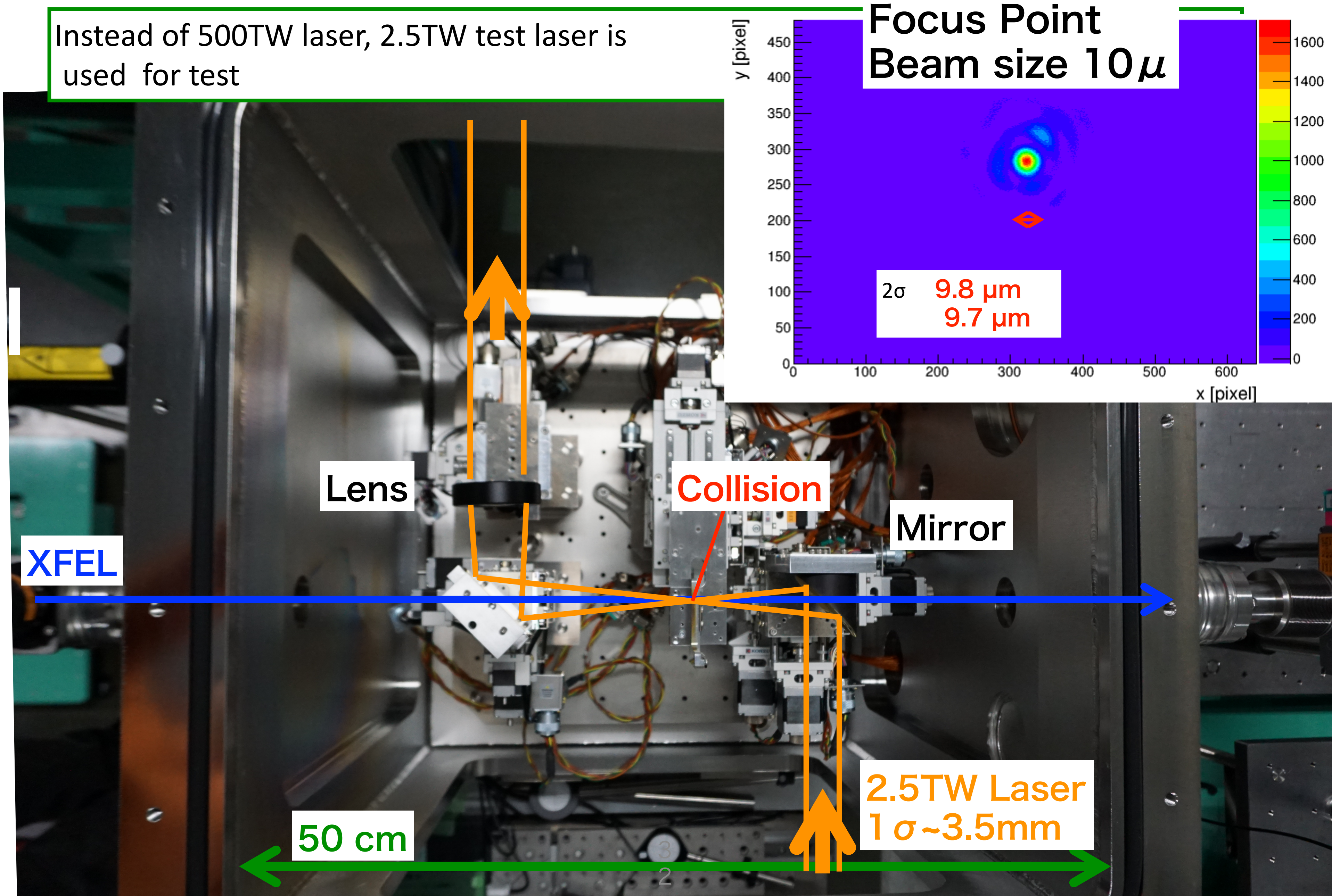
Pump laser
Pulse energy : W
Beam waist : ω_L



QED view: Strong Magnetic B makes Inuniformity of index

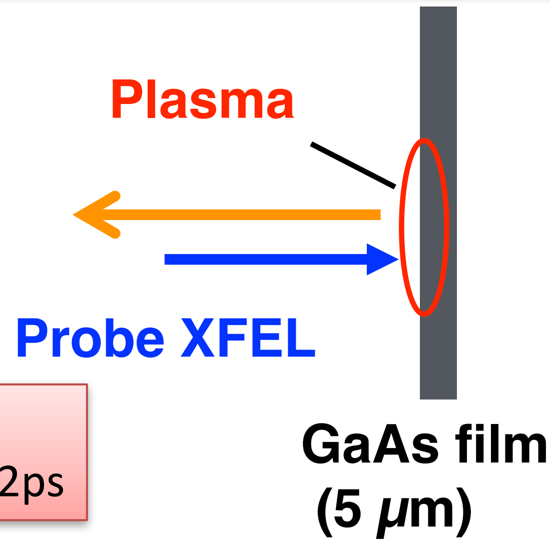
The first test experiment has been performed at SACLA (2017)

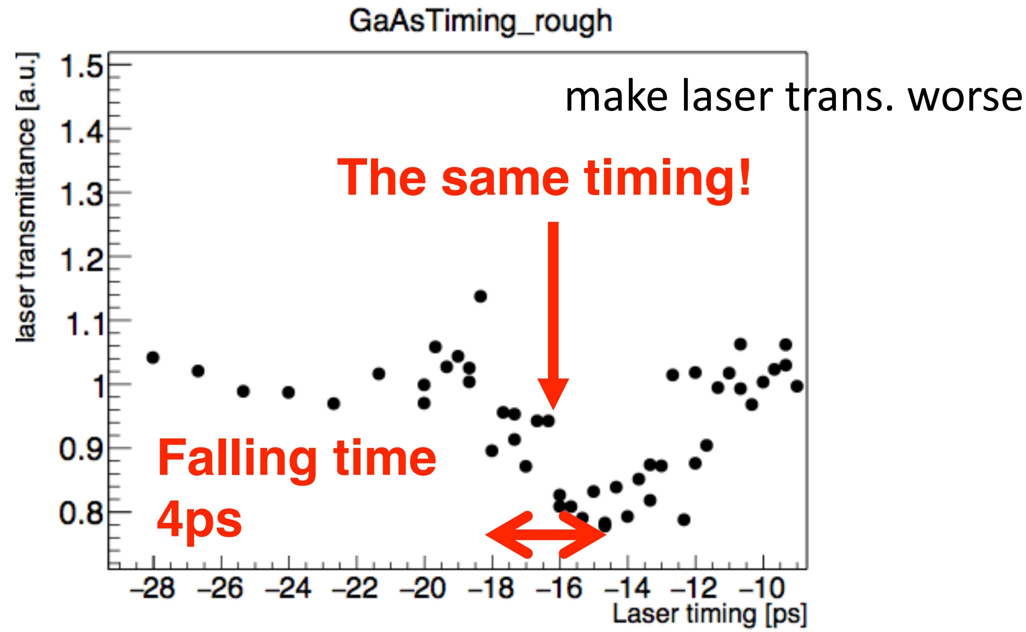
Instead of 500TW laser, 2.5TW test laser is used for test



Timing is estimated with GaAs film

X-ray hits GaAs film
Plasma is produced

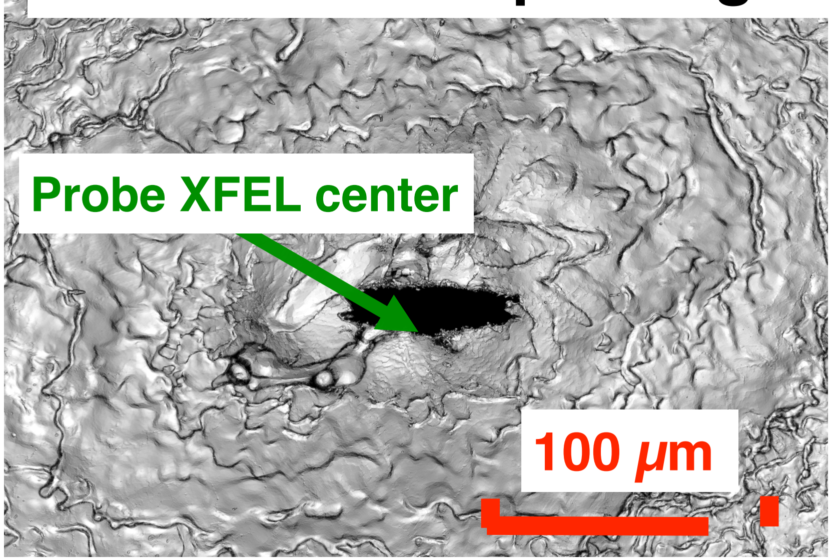




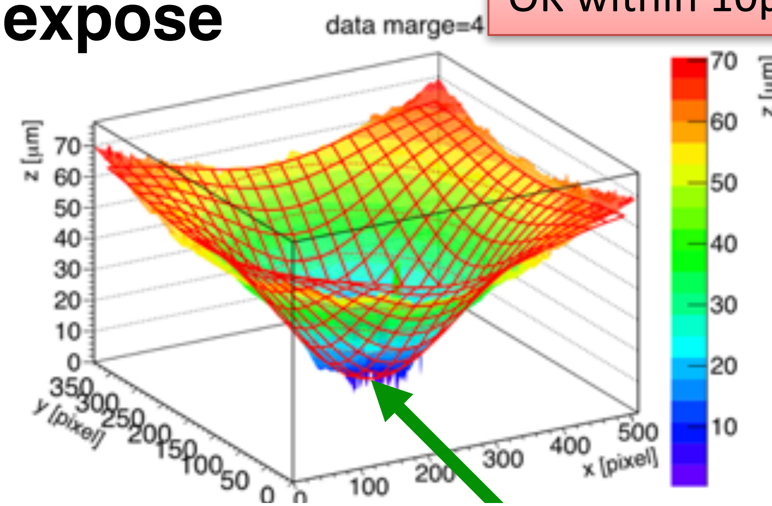
timing is OK within 2ps

Position is estimated with Zn thin film

Laser microscope image after expose



Center is OK within 10μm

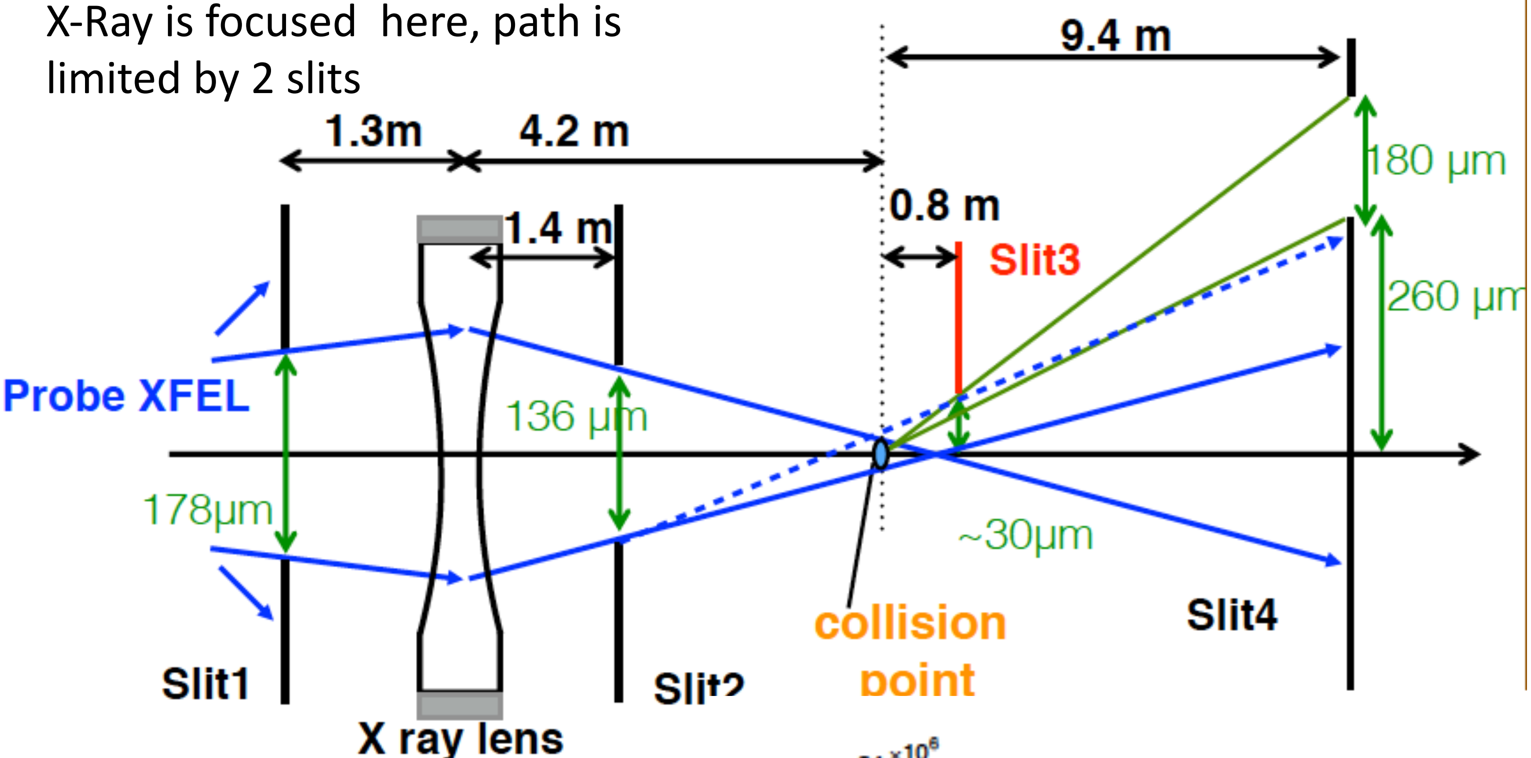


Pump laser center

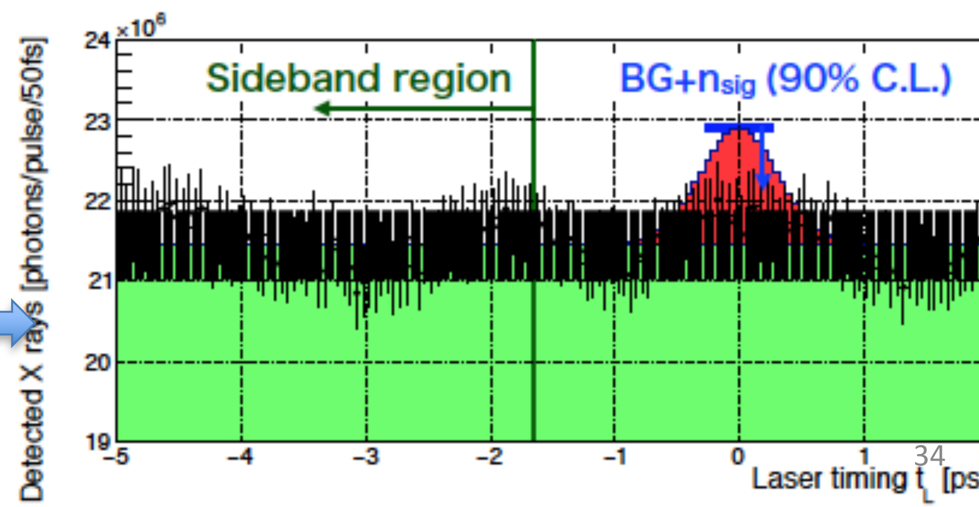
But Background level is still high

Layout of setup

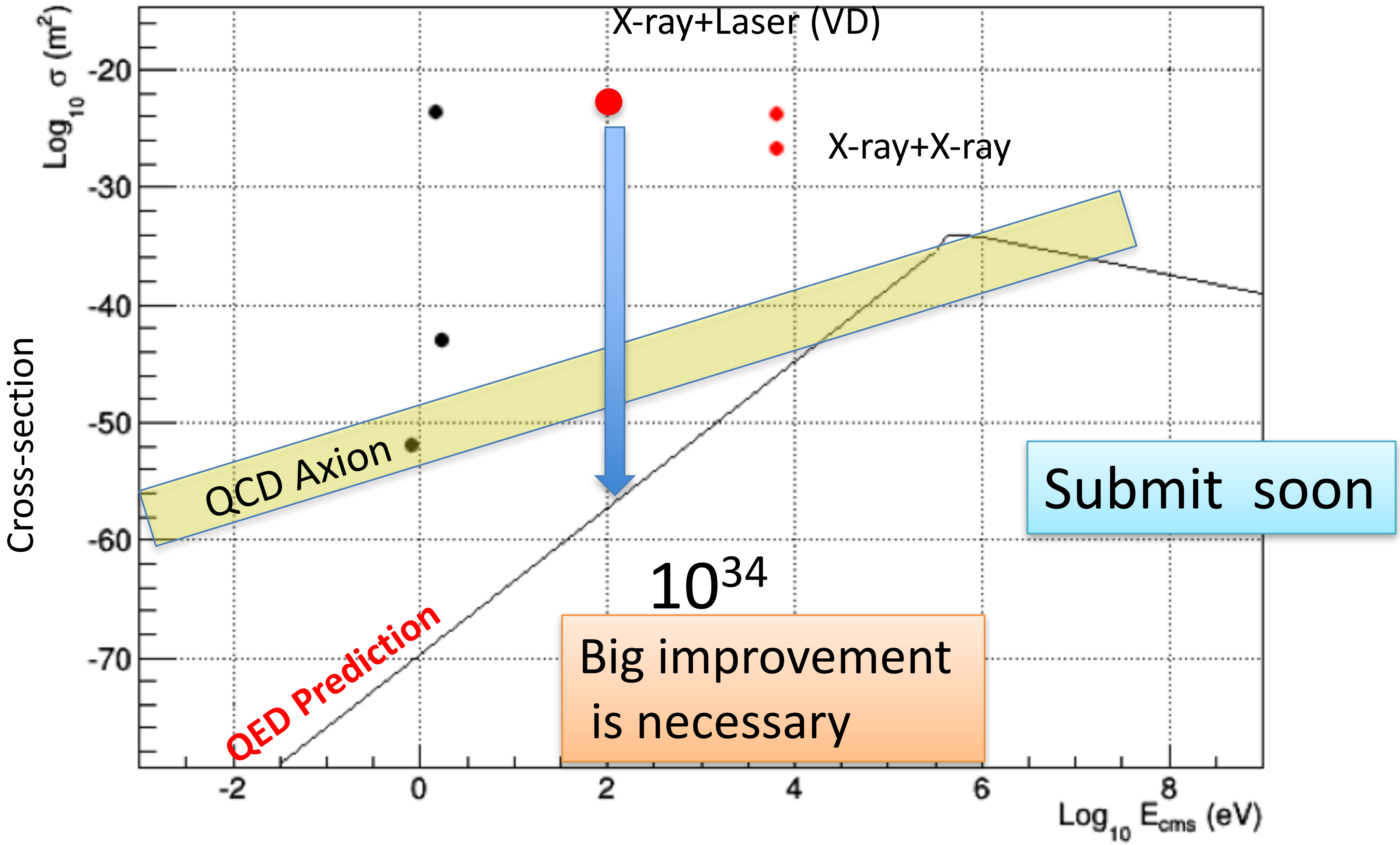
X-Ray is focused here, path is limited by 2 slits



Scattered X-ray is suppressed By the Slits (S3, S4).
10^{-16} suppression is necessary,
But still about 10^{-4},
diffraction at the edges contributes to BG.



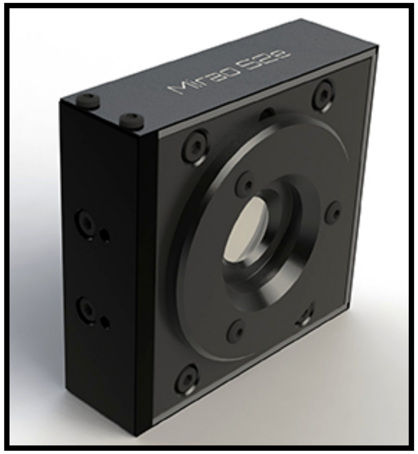
The first search has been performed with 2.5TW laser + SACLA
Focusing size ~ 10μm (This is the first result for X-ray+Laser)

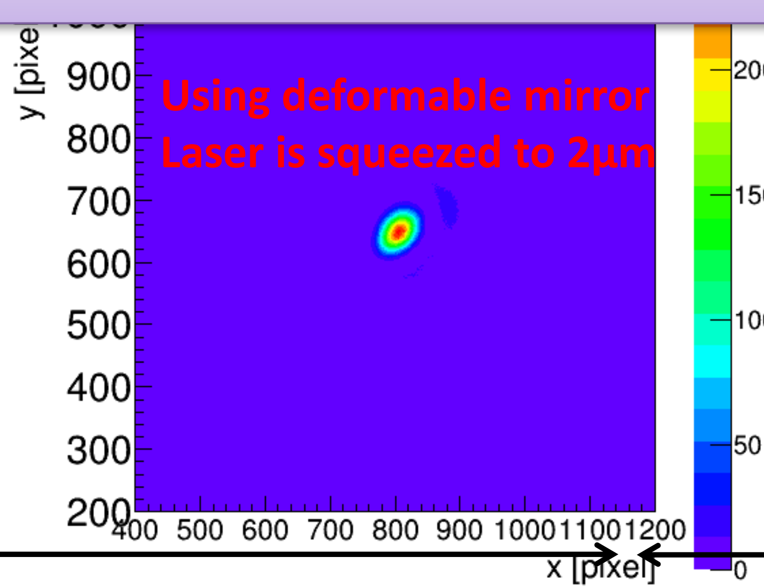


Log (Center of Mass Energy of gamma gamma system)

Next Step for Optics

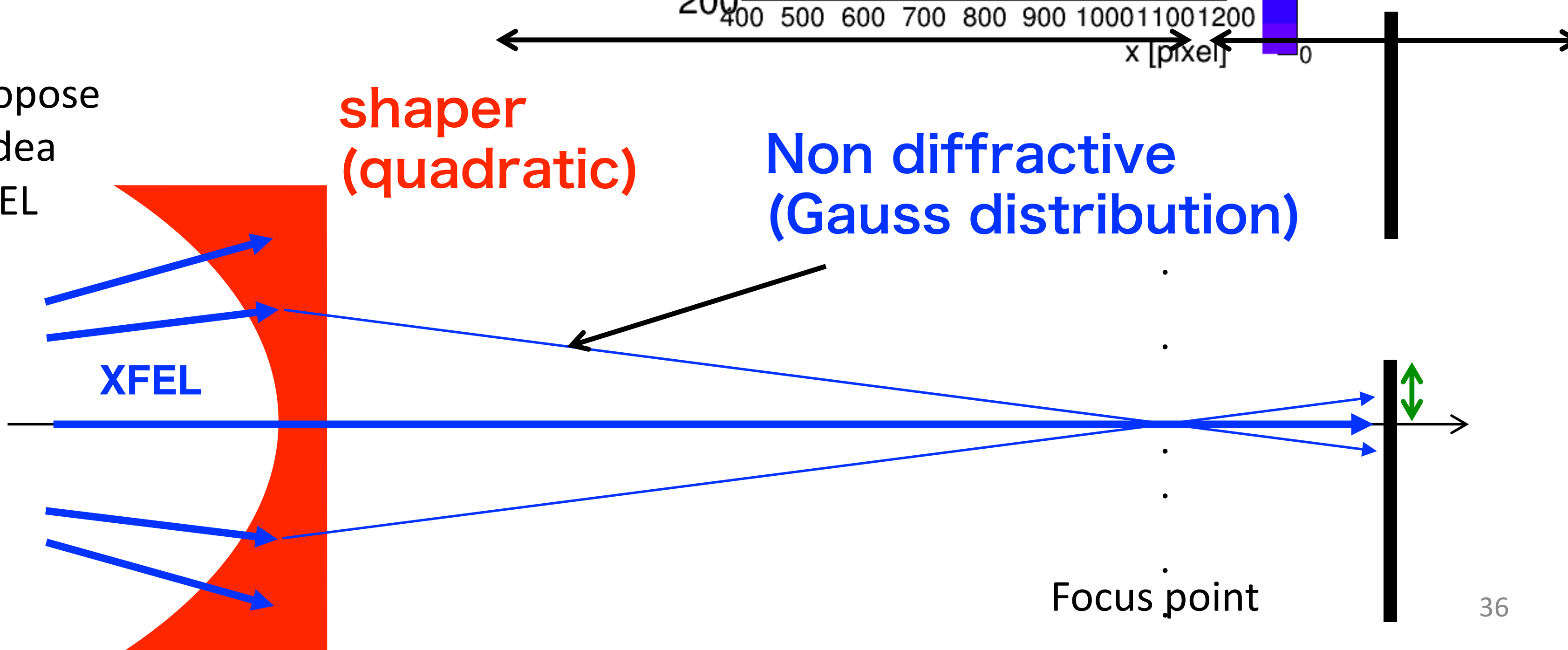
Laser





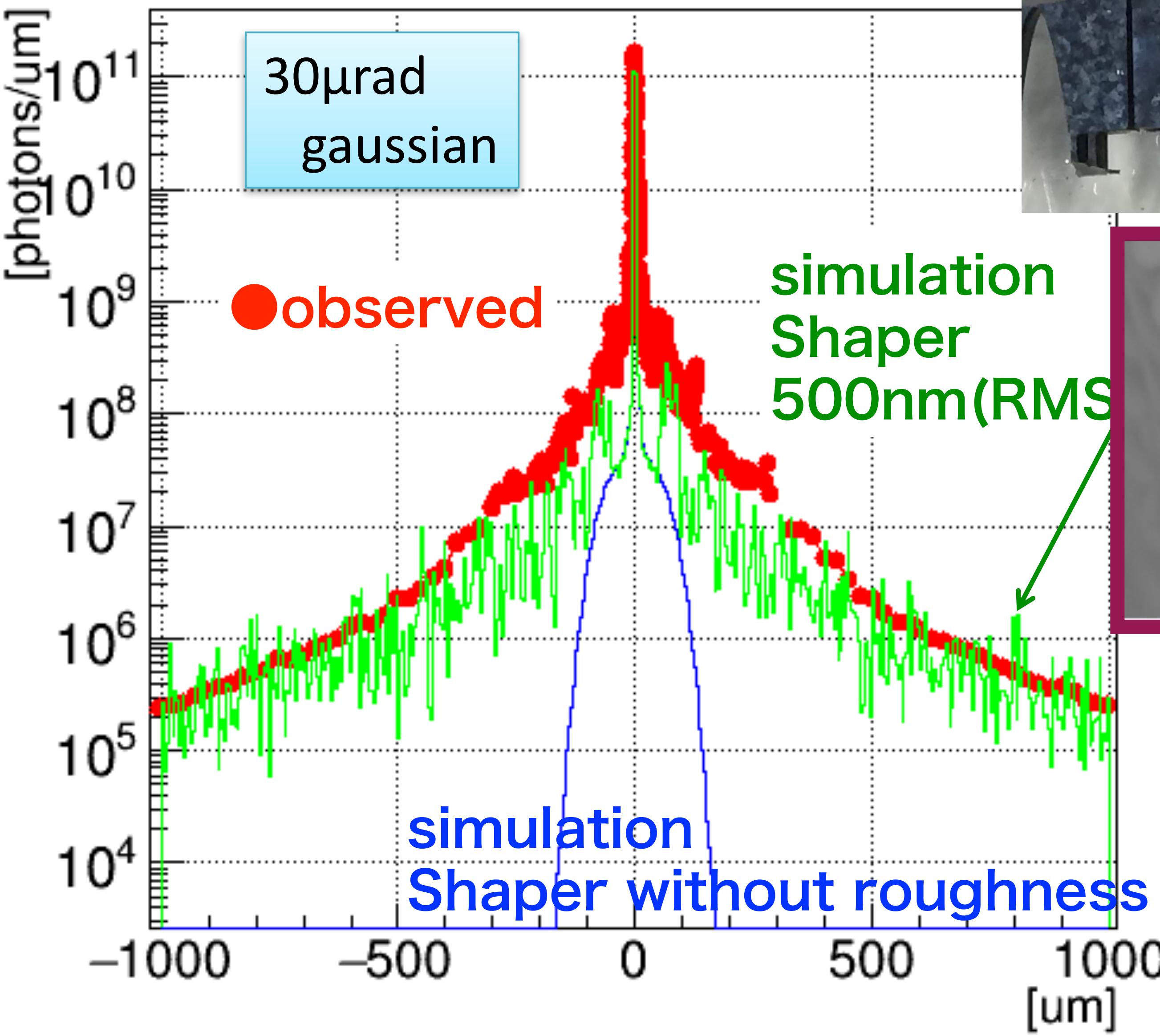
Close to Diffraction limit Clear

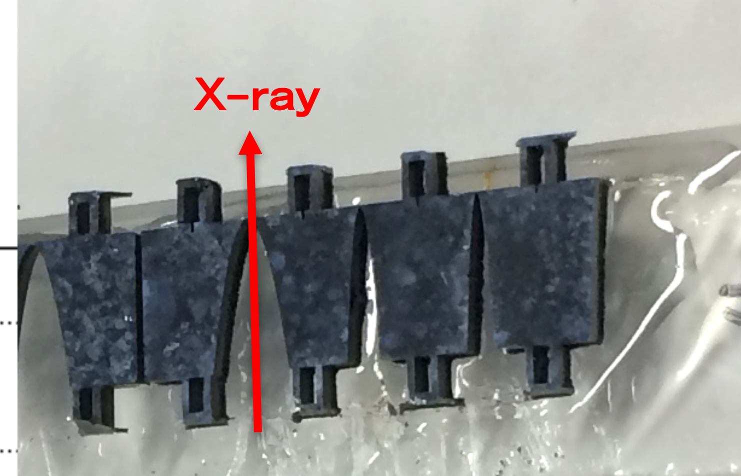
We propose new idea for XFEL

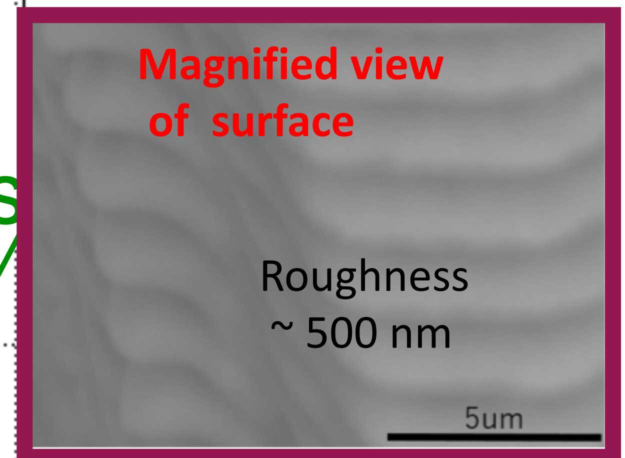


Shaper is made with Si
(Ion etching)

30μrad gaussian





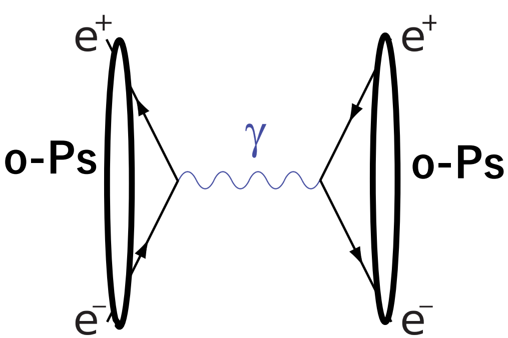


Roughness ~ 20 nm
then BG suppress
by 10^{-10}

[4] Using Atom (Positronium)

Positronium is quite different from the other Hydogen-like atom

C) Energy Level

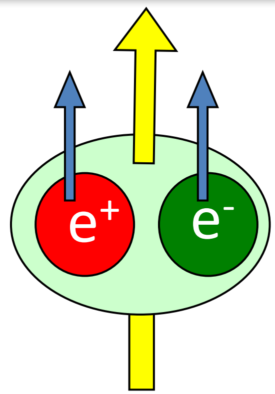


Mix with photon
87GHz

A) Rare decay
$\gamma' \rightarrow \gamma X$(ALPS)

B) Decay rate

Triplet State

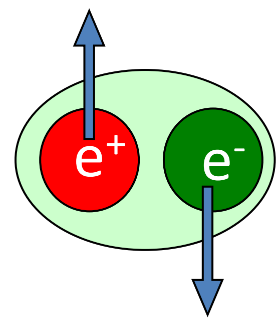


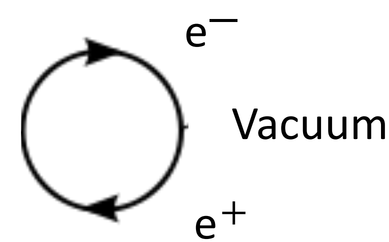
Orthopositronium

o-Ps has the same quantum number as photon.
It is the excited photon

Dominant decay mode
o-Ps → 3γ
λ=7.039979 μ s^{-1}

Singlet State





Parapositroniim

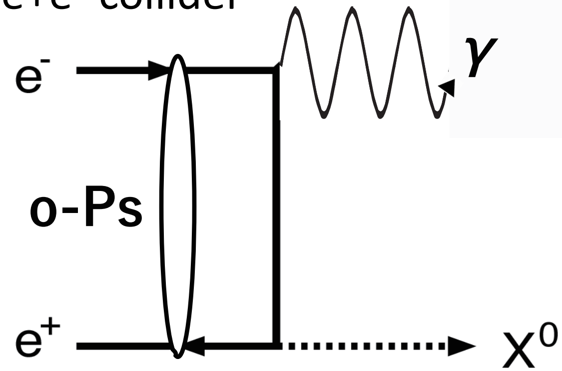
p-Ps has the similar quantum number to vacuum. (Higgs field not)
It is the excited vacuum.

Dominant decay mode
p-Ps → 2γ
λ=8032.50 μ s^{-1}

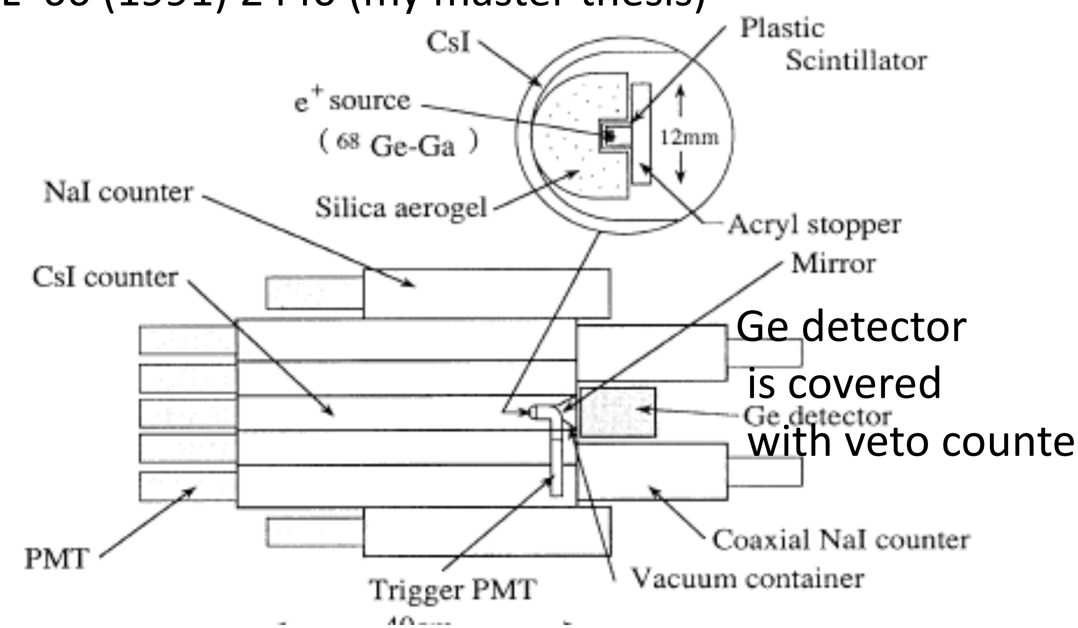
A) Exotic decay

PRL 66 (1991) 2440 (my master thesis)

e+e- collider



X: Scalar, PsudoScalar, Axial Vector

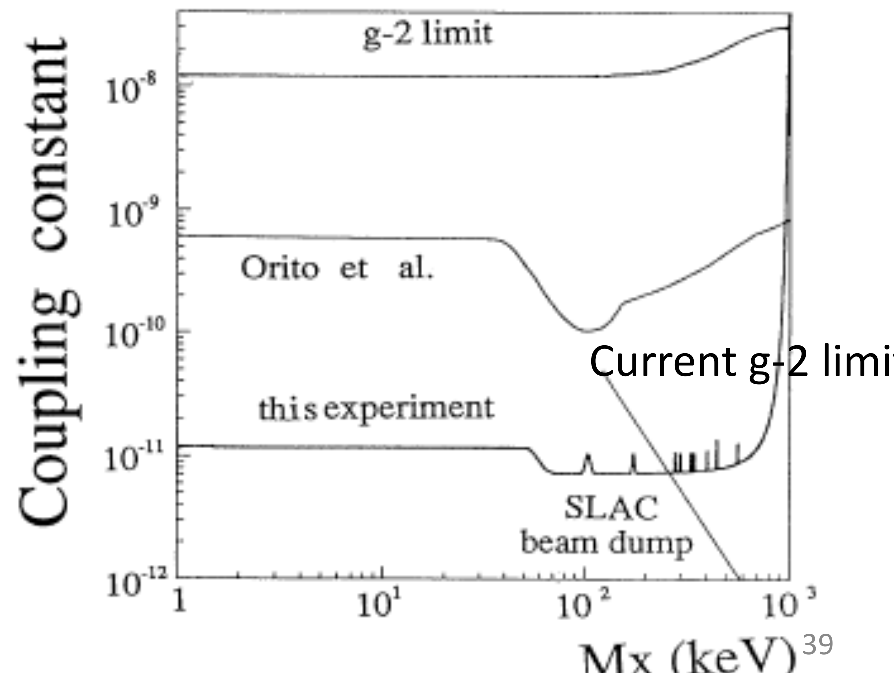


Basic decay mode

o-Ps => 3 γ is seriously suppressed due to many vertex of α and Phase space.

Sensitivity to α(eeX) becomes high.
coupling to electron

Search for event in which
o-Ps looks like to decay into single γ



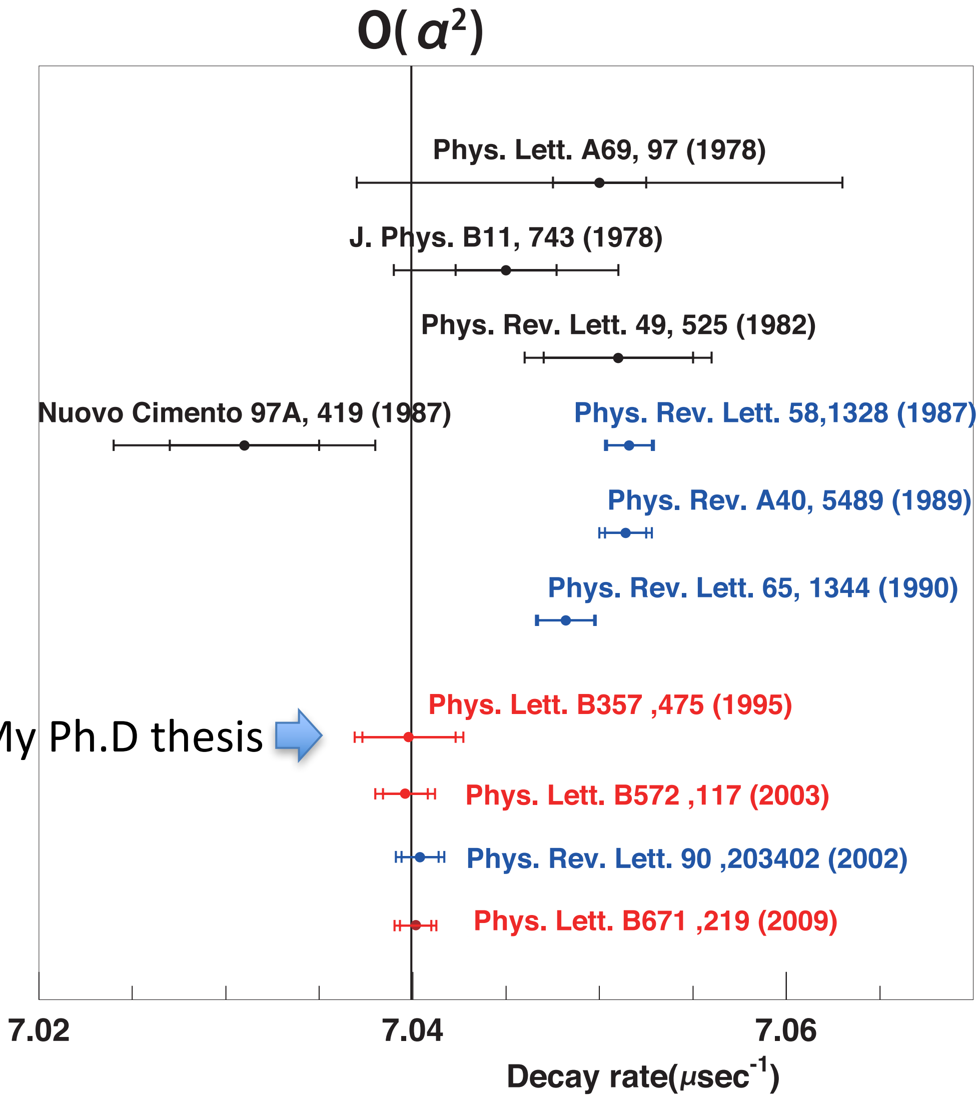
Sensitive to upto 1MeV
α(eeX) < 10^{-11}
For Heavier region
Beam dump is maybe better

B) Decay rate

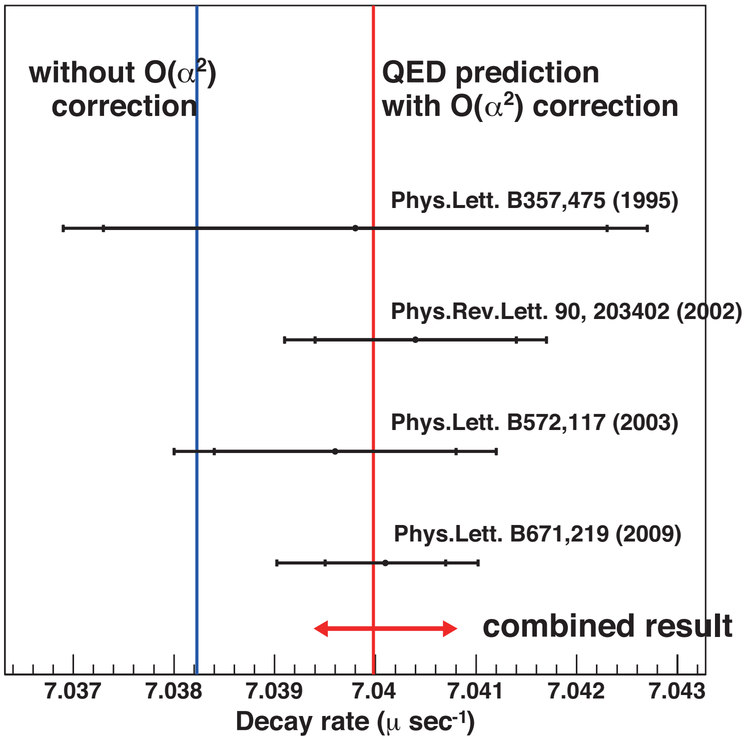
o-Ps →3γ decay rate
Measure values were much shorter than QED prediction 25 years ago (Positronium lifetime puzzle)
-> Now we solve this problem (thermalization)

Red shows our results and consist with QED

My Ph.D thesis



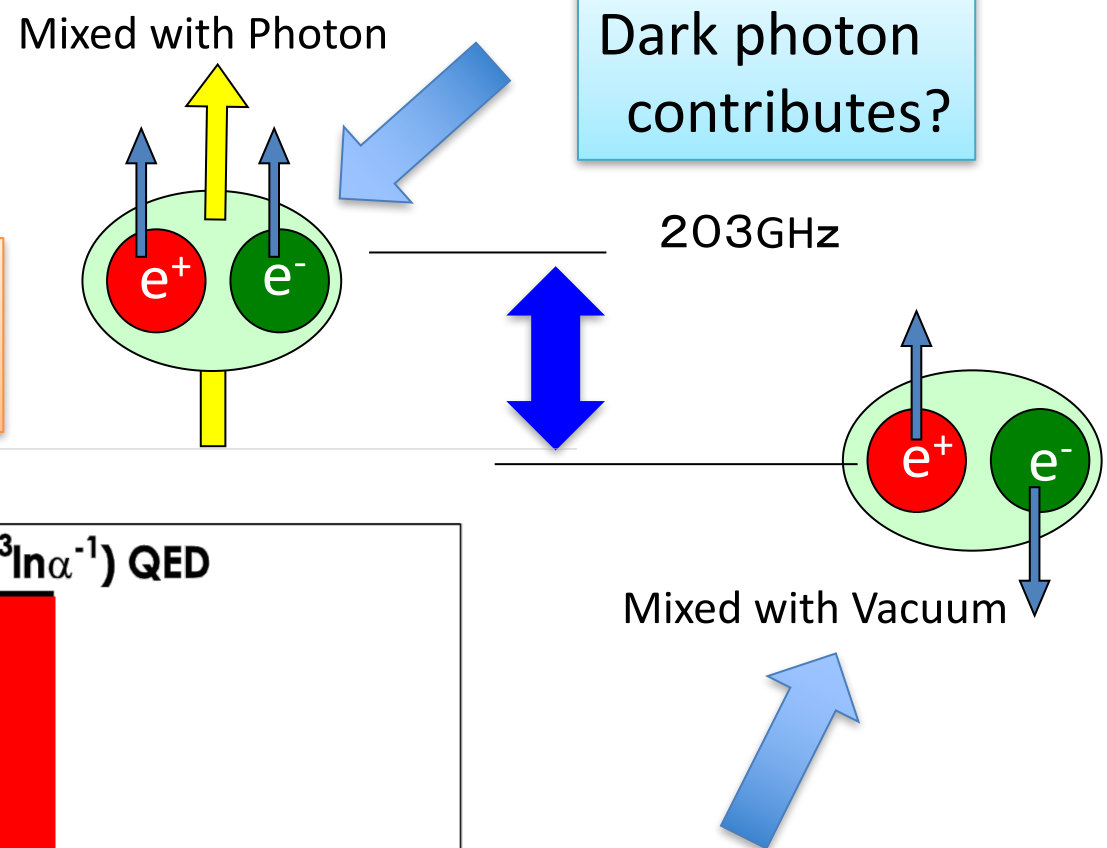
Now accuracy is O(α^2)



Please remind that o-Ps is Bound state, QED prescription is different from Free particle. NRQED

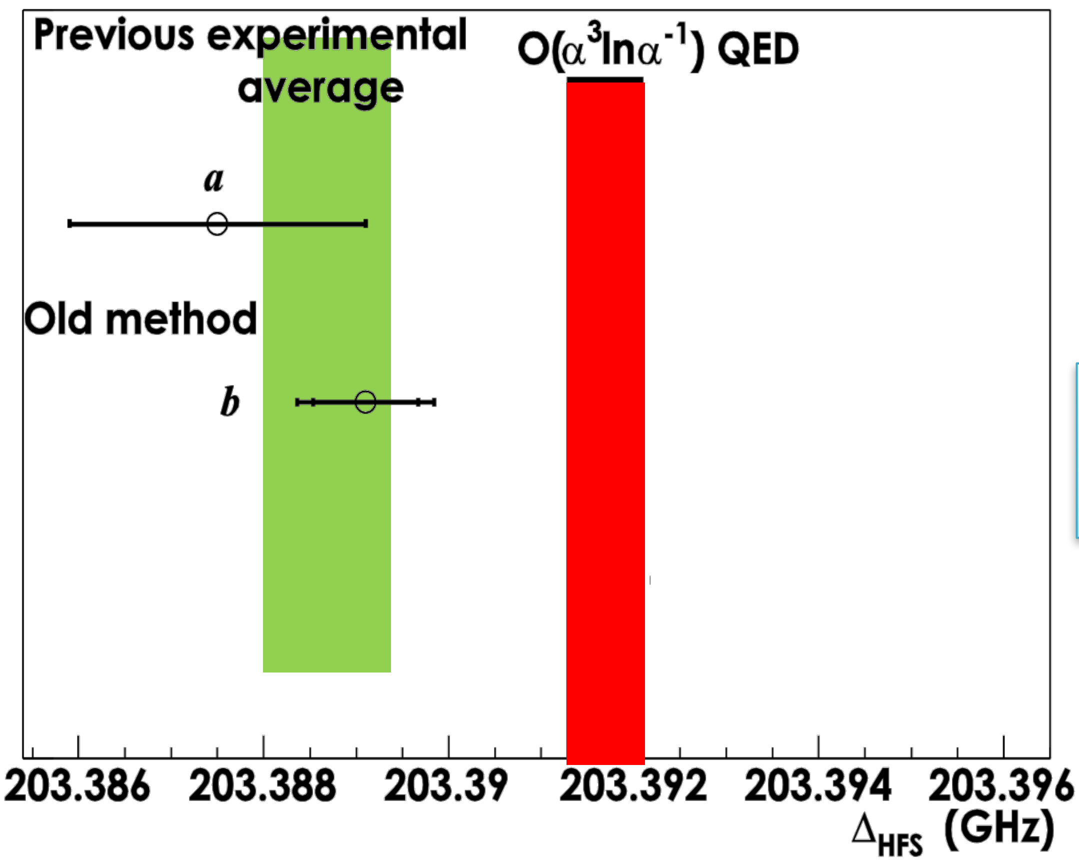
C) Energy Level

There was 15ppm(4σ) discrepancy between QED prediction and measurements



Dark photon contributes?

Mixed unknown filed contributes?

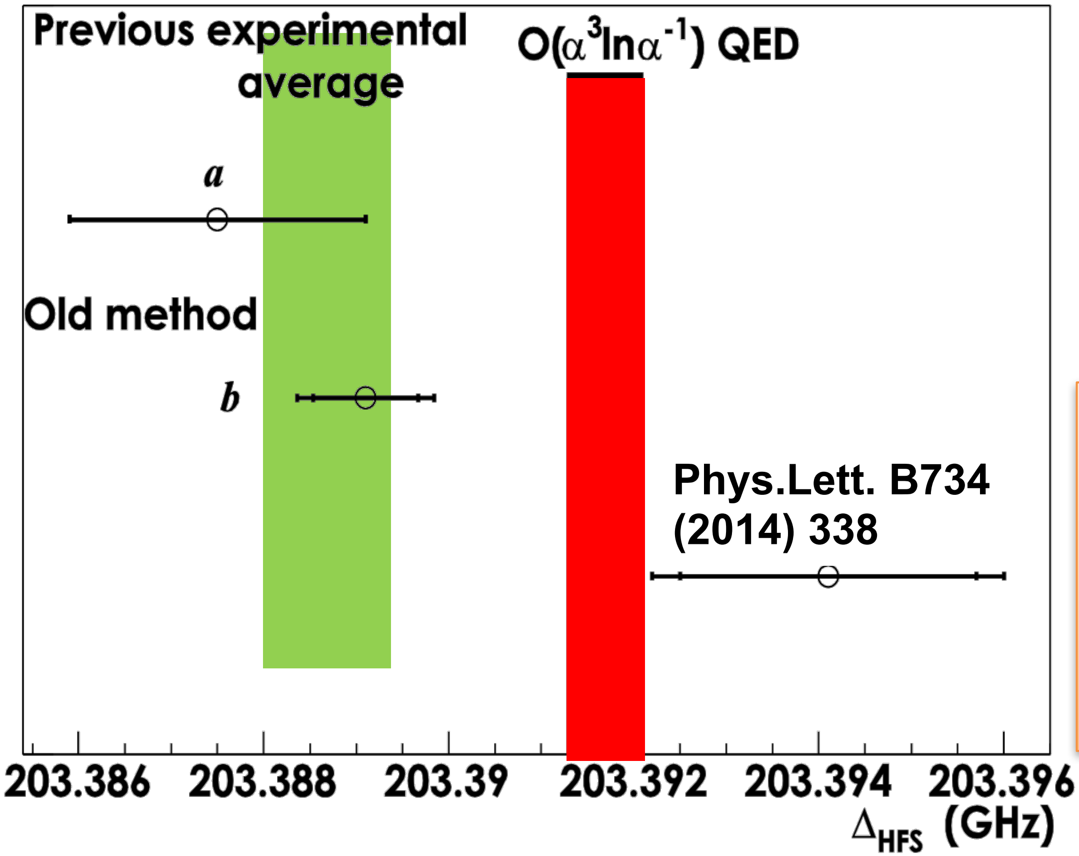


C) Energy Level new results

We perform new measurement with new method.
The result is consistent with QED and reject previous results. **(Unfortunately!!!)**

Now accuracy is $O(\alpha^2)$

obtain tight constrain on ALPS



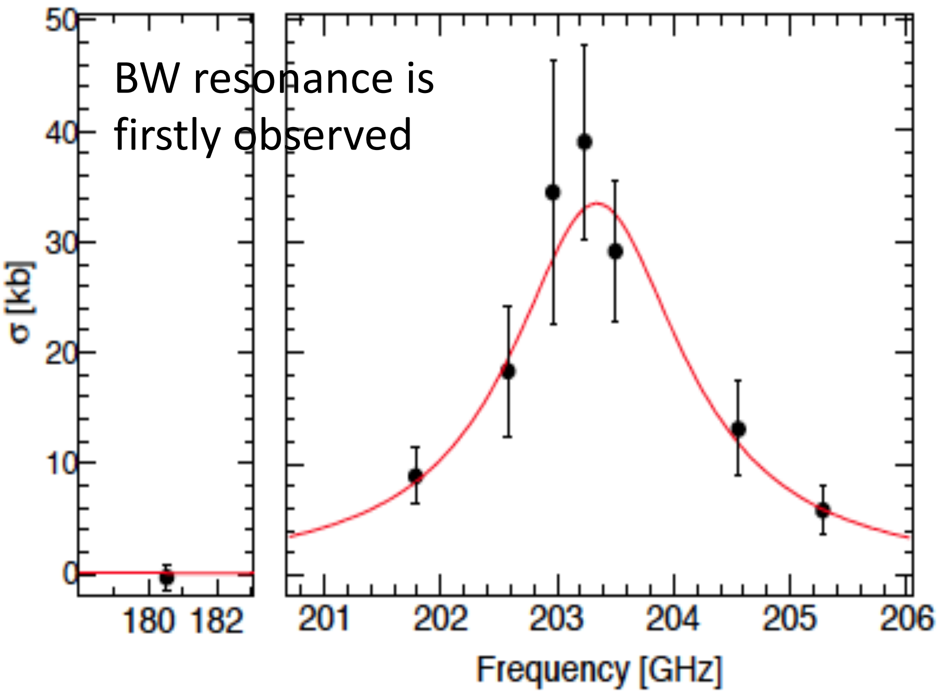
????
$\alpha(eeX) < 10^{-16}$
using QM
????

Need calculation with Quantum Field Theory (QFT)
Not Quantum Mechanics(QM)
They are mixing with Photon and Vacuum, also unknown new particle.

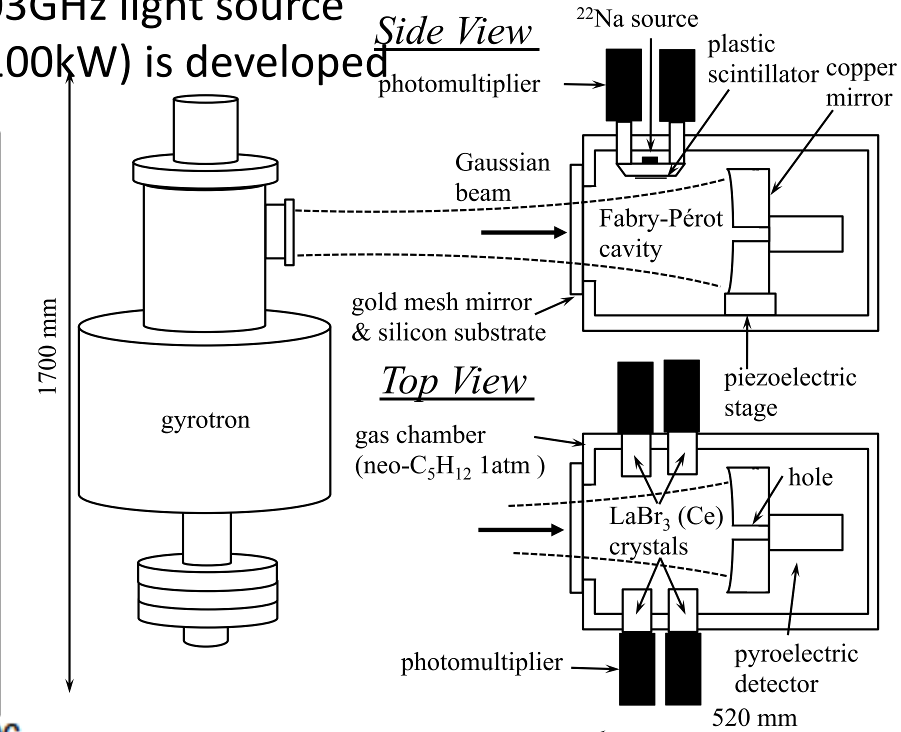
First transition between o-Ps -> p-Ps with M1 transition

Excited Photon -> excited vacuum + Photon(203GHz)
Forbidden in the relativistic limit

BW resonance is firstly observed



203GHz light source (100kW) is developed



Phys.Rev.Lett. 108 (2012) 253401
PTEP 2015 (2015) no.1, 011C01

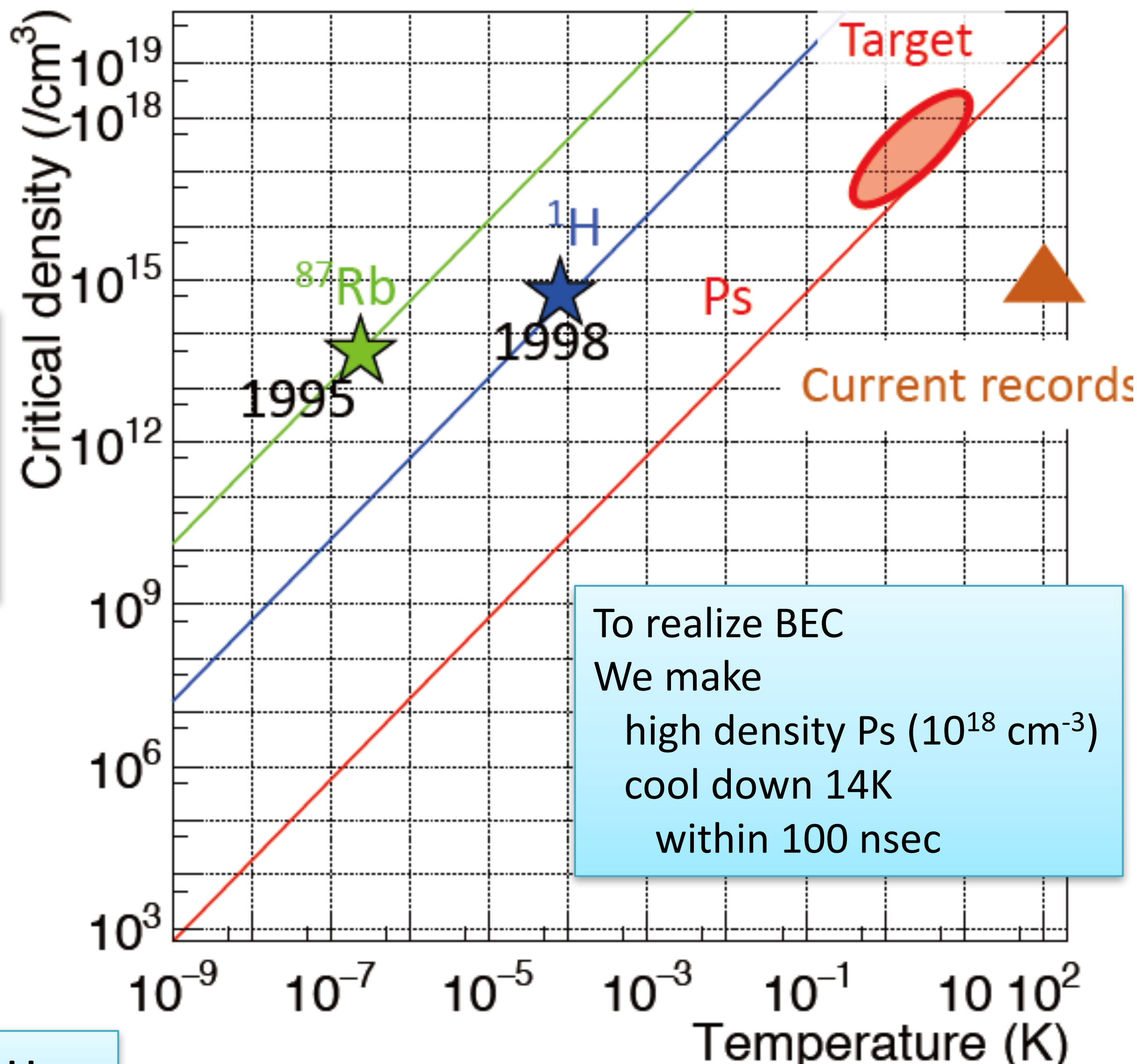
HFS = 203.39 ± 0.18 GHz
width = 11.2 ± 2.3 /nsec
A= (3.7 ±0.5) * 10^{-8} /sec

Accuracy will be improved
with positron beam to form Ps
powerful Gyrotorn

Next step

Ps BEC

1) High intensity positron beam
2) Silica nano processing
 with cooling
3) Laser cooling
 with new optics



To realize BEC
We make
 high density Ps (10^{18} cm^{-3})
 cool down 14K
 within 100 nsec

In progress
Within a few(several?) years

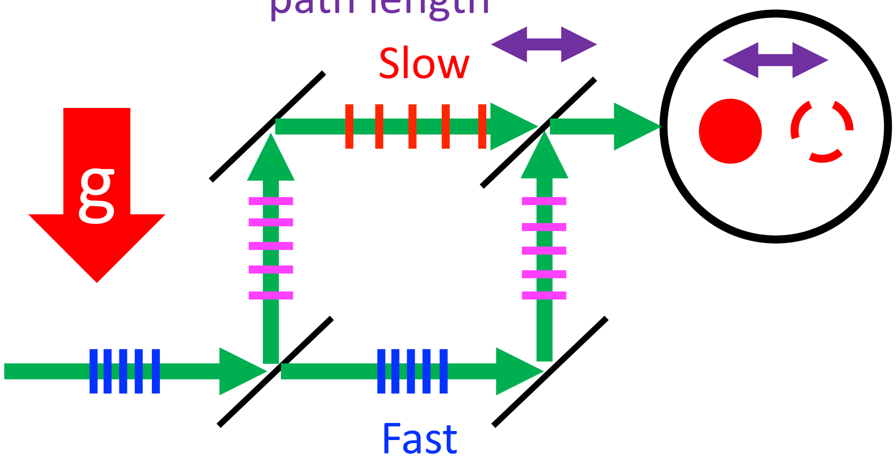
* First BEC with anti matter
* Massive Photon Laser?

J.Phys.Conf.Ser. 791 (2017) no.1, 012007

Why? Ps-BEC

1. <u>Measure anti-matter gravity by atom-interferometer</u>

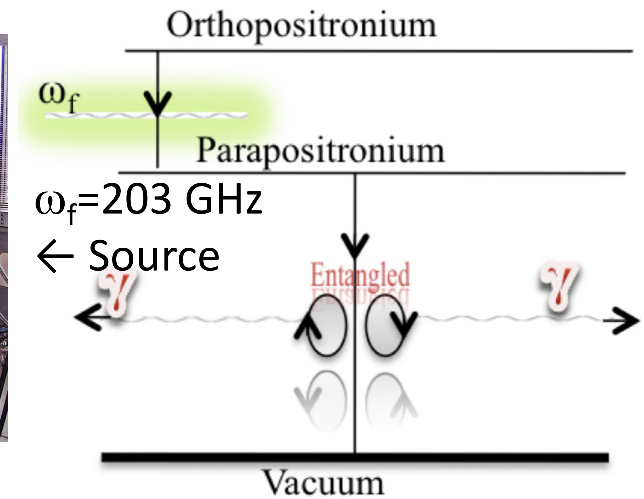
Intensity of Ps blinks by changing path length



- Deceleration by gravity shift phase of Ps in different paths
- Path length 20 cm to see gravity effects with weak-equivalent principle

Phys. stat. sol. 4, 3419 (2007)

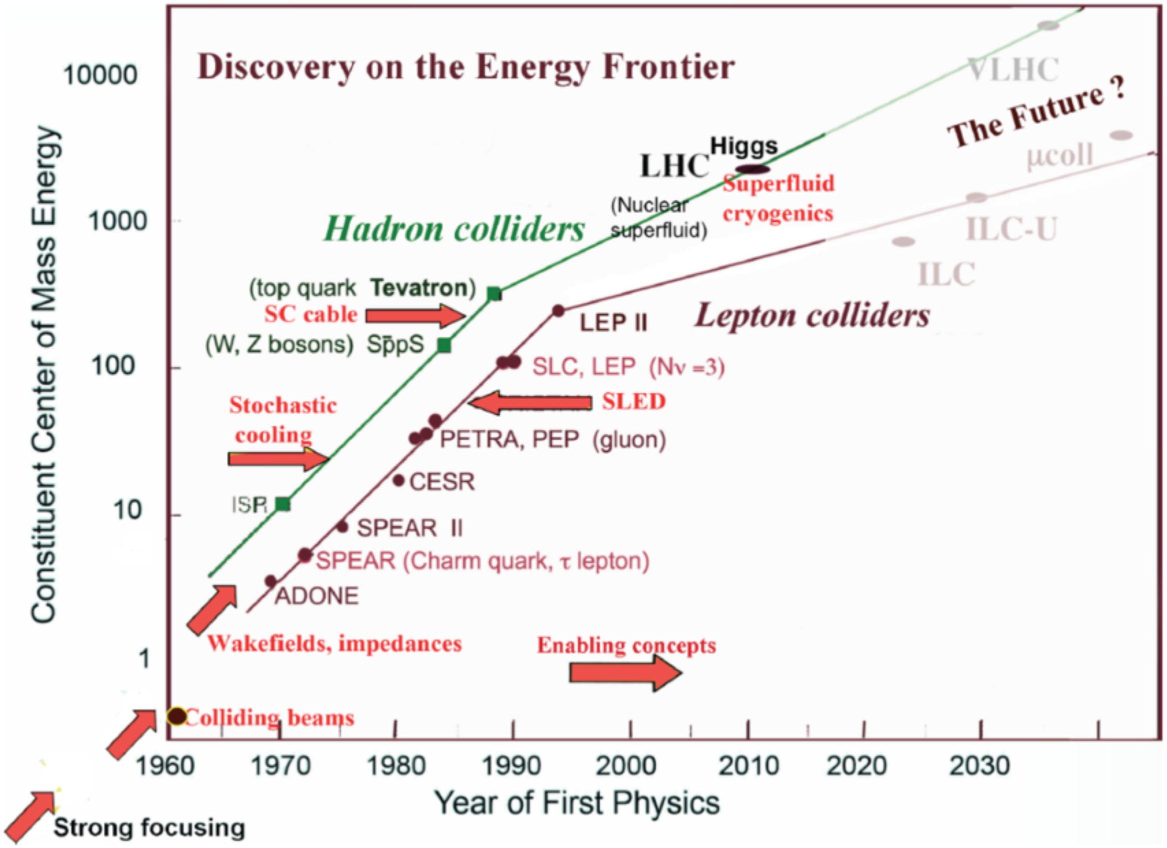
2. <u>511 keV gamma-ray laser</u>



Phys. Rev. A 92, 023820 (2015)

- *o*-Ps BEC to *p*-Ps by 203 GHz RF
- *p*-Ps BEC collectively decays into coherent 511 keV gamma-rays
- ☐ Probe with x10 shorter wavelength than current x-rays
- ☐ Macroscopic entanglement

[5] Extend to 10-100 MeV collider?



$\sqrt{S}$ = 10-200 MeV Collider is interesting?

1) No collider at this ECM in Histiroy
2) Also difficult to cover by beam dump
-> Next European Project

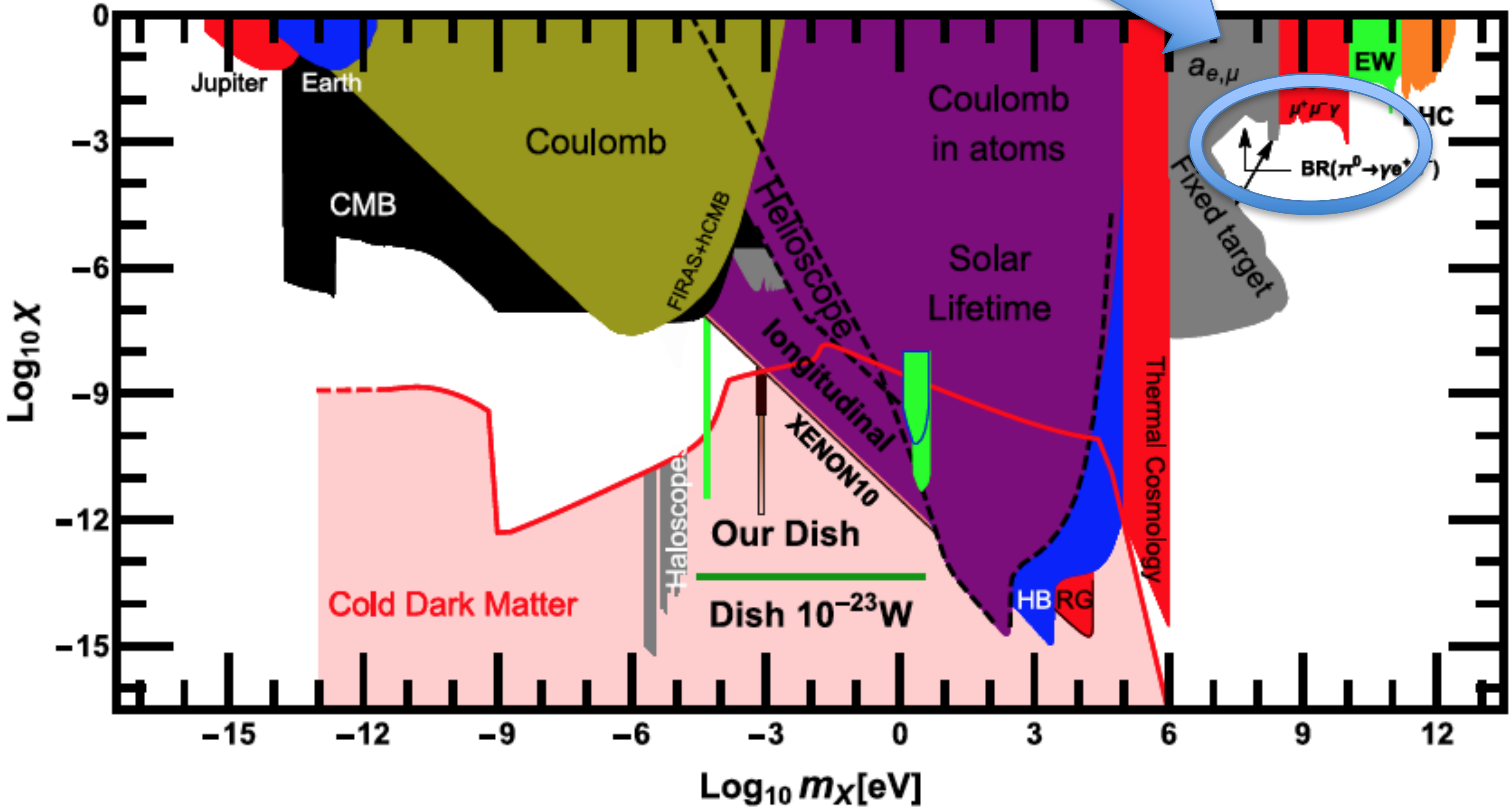
Problem on α_s
QCD Vacuum
(vacuum polarization)

* Emittance is important for such a low energy e+e- collider
- Linear Collider Technology can be used:

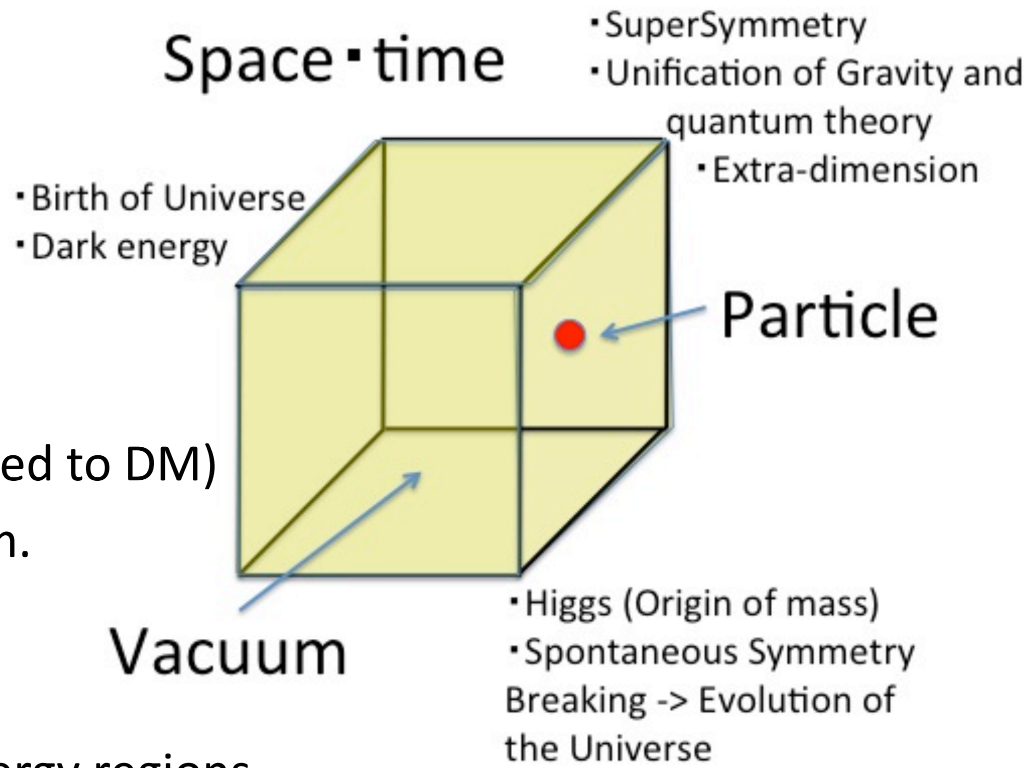
15 Years Ago, I consider with an accelerator expert at KEK
Using asset of ILC

Tabletop size
About 10M USD
Not so expensive

Many proposal are submitted for European Strategies
to cover here



Summary



- After Higgs Boson discovery, "Vacuum" becomes one of the frontier field (maybe related to DM)
- Many fields are hidden in vacuum. Photon is key technology to probe the vacuum.
- Using Photon, three different energy regions (10KeV, 100eV, 1meV) are explored with the different technologies.
- Positronium is also good tool to probe light new particles.

- Space/time (Gravity for particle) is also exciting (Next time)

Only some part of our researches are shown:
http://tabletop.icepp.s.u-tokyo.ac.jp/Tabletop_experiments/English_Home.html

Collaborators

Particle Physics

U. of Tokyo ICEPP

S.Asai, T.Namba A.Ishida T.Inada, K.Shu, Y.Seino, S.Kamioka, K.Yamada, K.Narita, K.Hashidate

Laser

APSA
Advanced Photon Science Alliance

U. of Tokyo Photon Science Center

K.Toshioka、J.Oomach,E.Chae **M.Gonokami (President)**

X ray SACLA, Spring8

Riken

K.Tamasaku, K.Sawada, Y.Inubushi, M.Yabashi, T.Yanai,T.Yabuuchi, T.Togashi, **T.Ishikawa**

Pulse Magnet

U .of Tokyo （ISSP）＋U. of Tohoku（IMR）

A. Matsuo, H.Nojiri, K.Kindo

Positron beam

AIST and KEK/QST

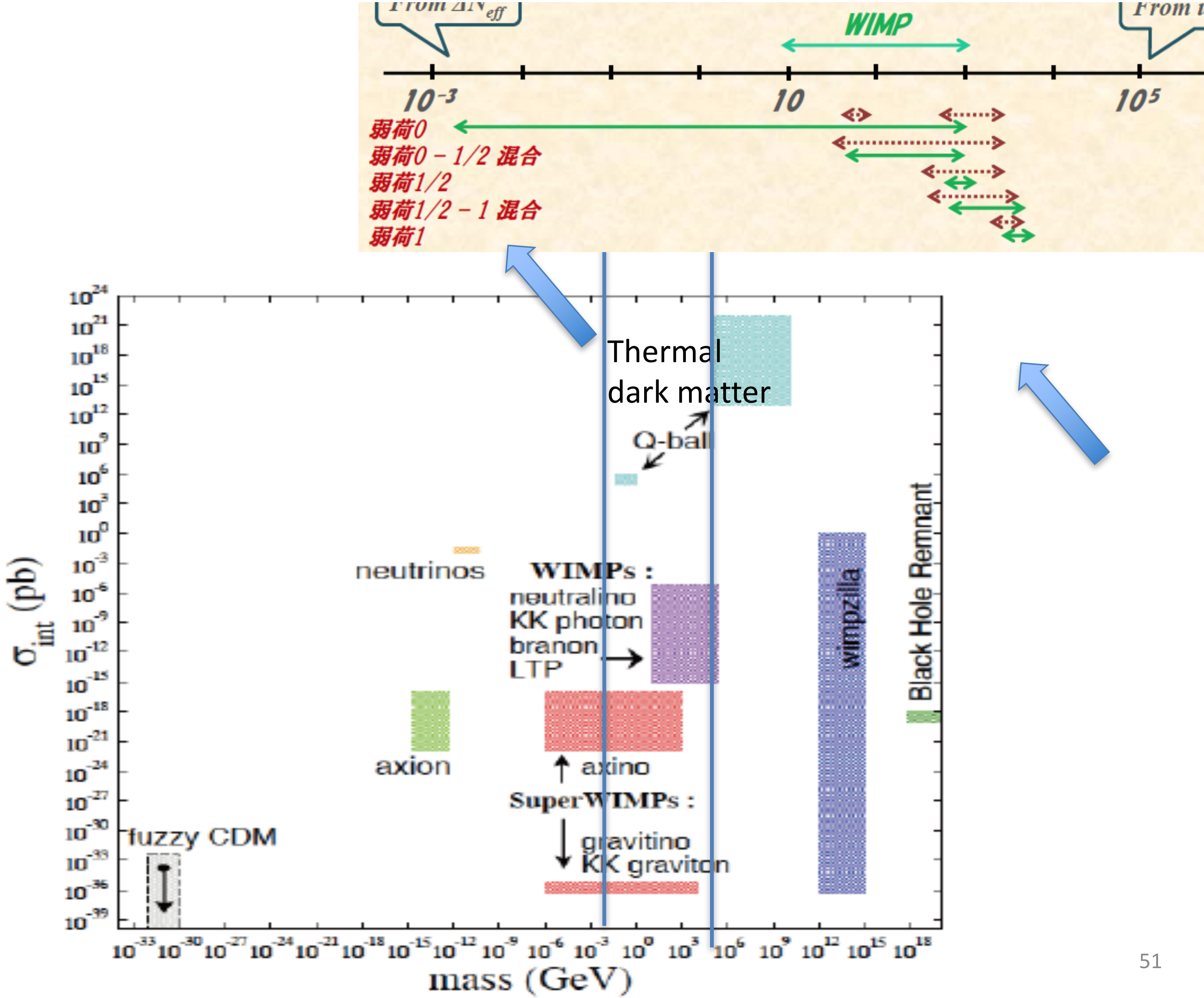
N.Oshima, B.O'Rourke, K.Michishio, K.Ito, K.Kumagai, R.Suzuki, T.Hyodo,I Mochizuki, K.Wada

THz light Source

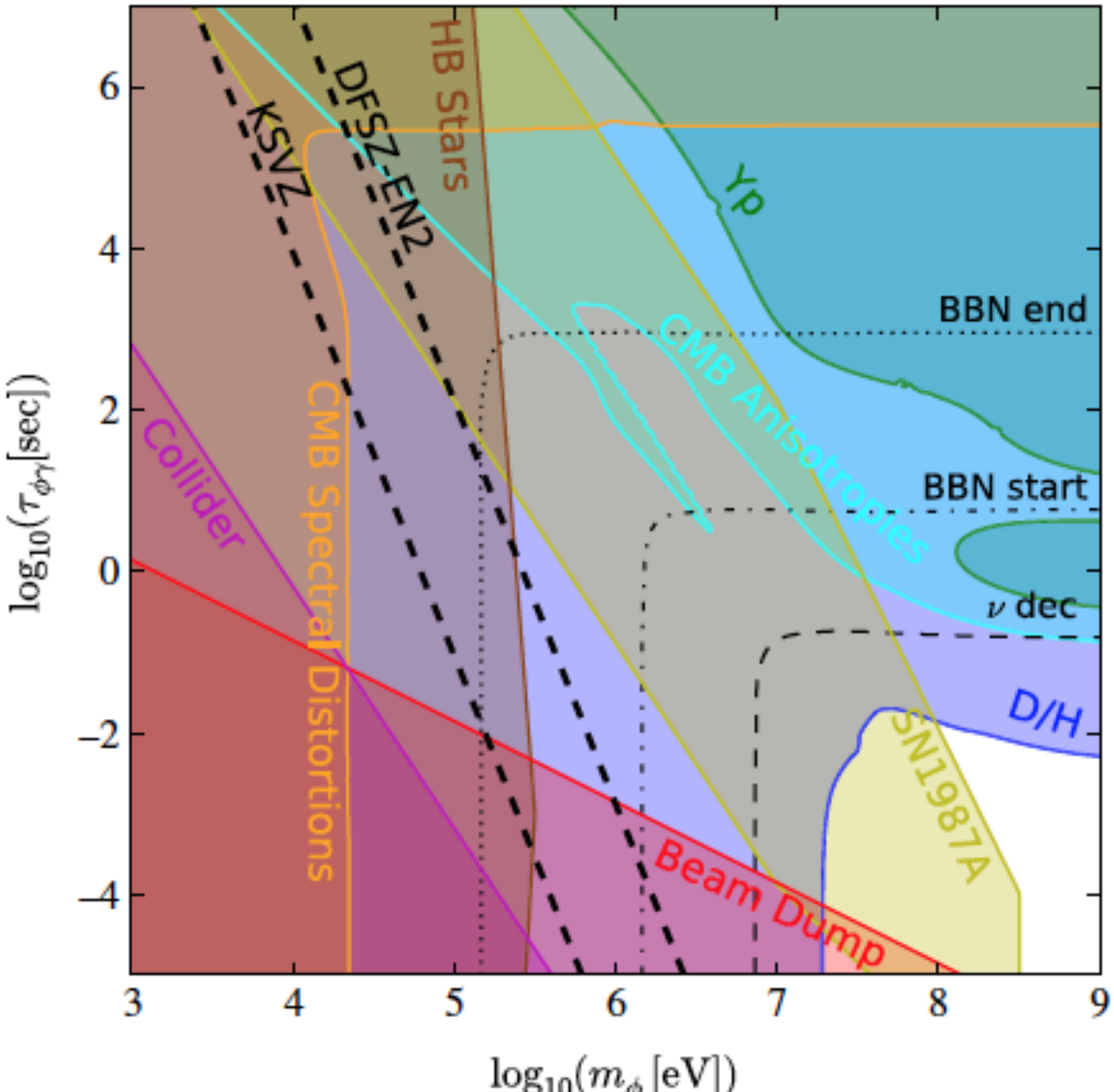
U.of Fukui FIR-UF

T.Idehara, I. Ogawa, Y.Tatematsu

おまけ

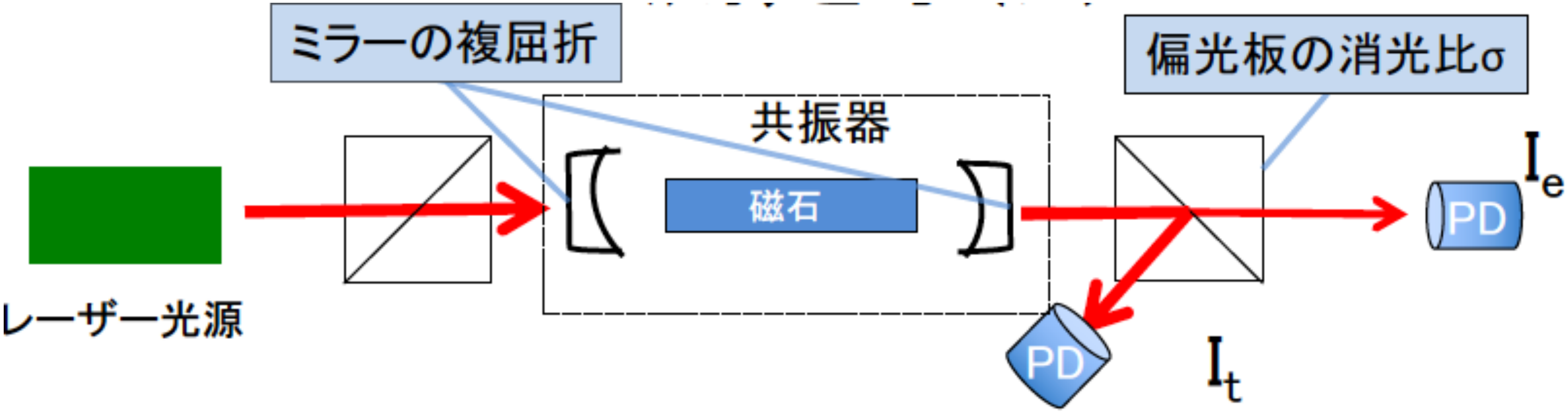


From ΔN_{eff}
WIMP
10^{-3}
10
10^{5}
弱荷0
弱荷0 − 1/2 混合
弱荷1/2
弱荷1/2 − 1 混合
弱荷1
Thermal dark matter
Q-ball
neutrinos
WIMPs :
neutralino
KK photon
branon
LTP
axion
axino
SuperWIMPs :
gravitino
KK graviton
fuzzy CDM
wimpzilla
Black Hole Remnant
σ_{int} (pb)
mass (GeV)

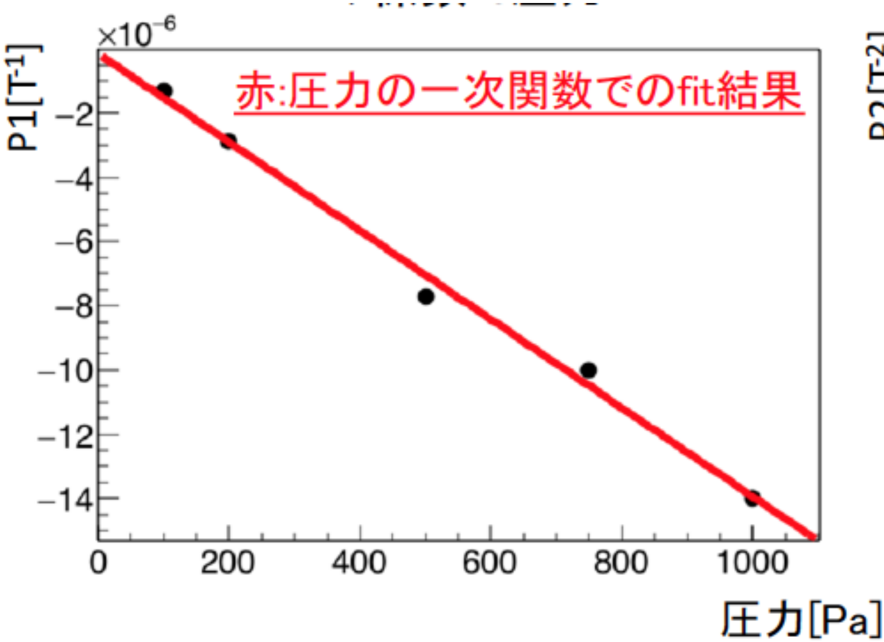


HB Stars
DFSZ-EN2
KSVZ
Yp
BBN end
CMB Anisotropies
BBN start
ν dec
D/H
SN1987A
Beam Dump
Collider
CMB Spectral Distortions
$\log_{10}(\tau_{\phi\gamma}[\text{sec}])$
$\log_{10}(m_\phi\,[\text{eV}])$

テスト実験(Calib.): 窒素いれて実験



Ie=透過：偏光が変わった成分　It=反射：もともとの偏光成分
Ie/It = P0+P1*B(ファラデー回転)+P2*B^2 (ファラデー回転＋複屈折成分)
同時フィットして、窒素の圧力を　100-1000 Paかえて測定



P2[T-2]

Calibration OK！

真空でテスト (100回だけ磁石)

$$Kc = 3*10^{-17}\ [T^{-2}]$$

7桁不足→4桁は今のセットアップで可能
PVLASと同感度の測定が可能

磁石　強化　＋　3ヶ月の測定で→　QED

X-ray has advantages to probe the QED vacuum

✧ Cross-section has the strong dependence on ω; $(\omega/m_e)^6$ 6^{th} power!!

Enhanced by 24^{th} order of magnitude for 10KeV X-ray comparing to visible lights.

✧ Previous searches have been performed using visible/infrared light.

Many filed may be hidden in the vacuum.

Let's use different ω, and Explore a new regions.

✧ X-ray is vey interesting

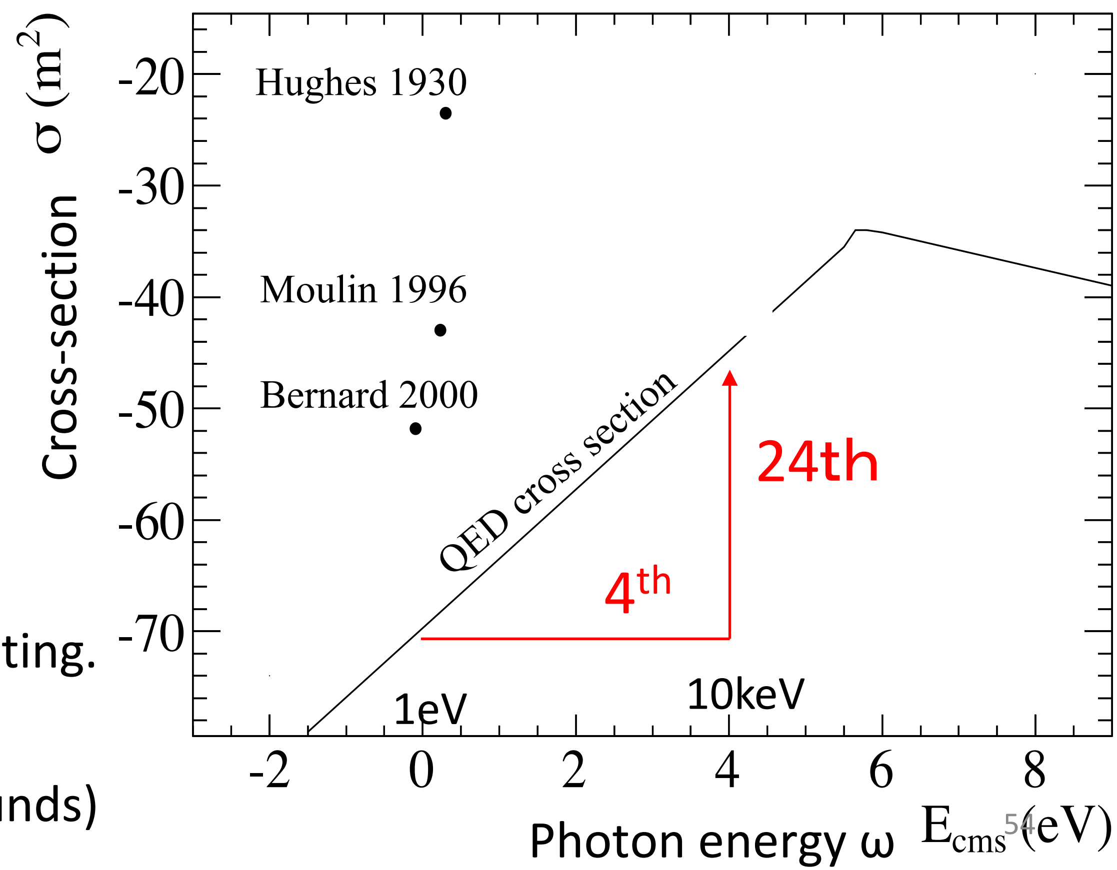
(1) Squeeze upto ~ O(1) nm

(2) Go straight

(3) Easy a single photon counting.

((1)-> intensity

(2)(3) -> to control backgrounds)



Next Step : Soft mirroring?
SACLA+SPring-8 head-on collision

If Laue/Bragg scatter is used, very narrow Energy width is necessary(63meV). Can we use more loose mirroring valid for the wide width (like mosaic crystal or multi-Layer Bragg)? New idea / New Optics are necessary to use all photons(10^{12}) from the XFEL.

SACLA+SPring-8 co-operation

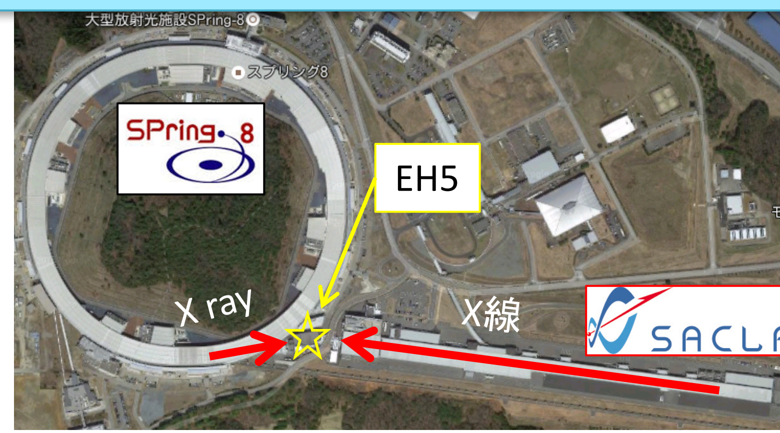
In EH5: SACLA and SPring-8 will be synchronized in near future.

From Spring8 ~10^3 photon/pulse 40ps (pulse intensity is 10^{-9} weaker than SACLA)

All photons from SACLA/Spring8 can be used.

・50nm focusing can be used in head-on collision

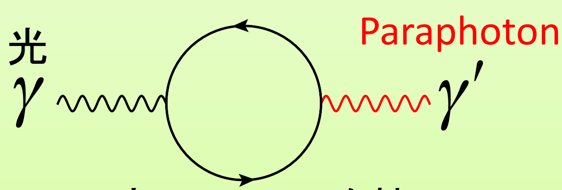
→sensitivity 10^{11} is enhanced.



Then we can reach the QED vacuum or discover a new unknown field(Axion, Dilaton).

Paraphoton (Hidden photon)

- Extra U(1) Gauge Bosonは理論的に不可欠
- スピン1
- MeVだと**暗黒物質の候補**
- 光子と paraphoton の混合



両方の charge を持つ重いフェルミオン

Axion

- QCD vacuum should v PQ 対称性
- **暗黒物質のよい候補**
- スピン　０　パリティー負

$$F_{\mu\nu}\tilde{F}^{\mu\nu}a = g_{\alpha\gamma\gamma}\vec{E}\cdot\vec{B}a$$

Bの向きと光の偏極面が一致すると　光→axion

Dilaton

- 重力理論で不可欠
- **インフレーションのタネ**？
- スピン　０　パリティー正 スカラー粒子

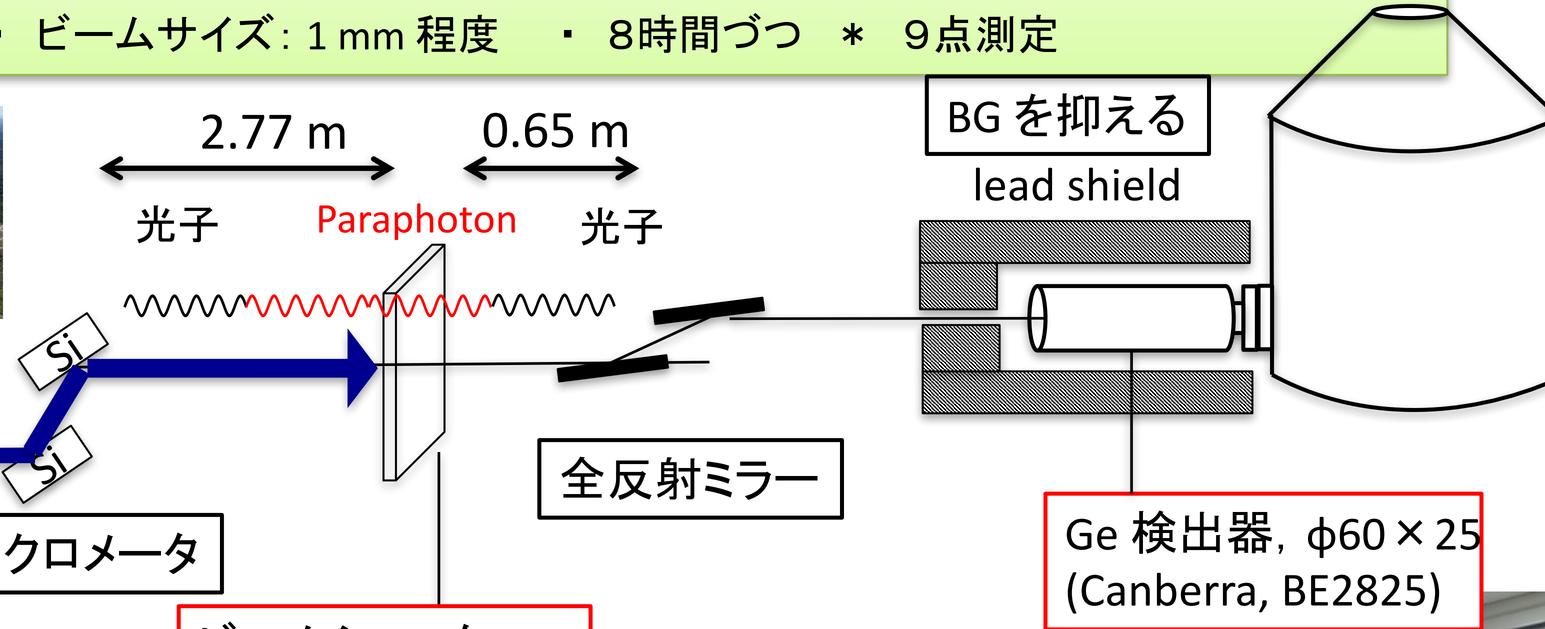
$$F_{\mu\nu}F^{\mu\nu}d$$

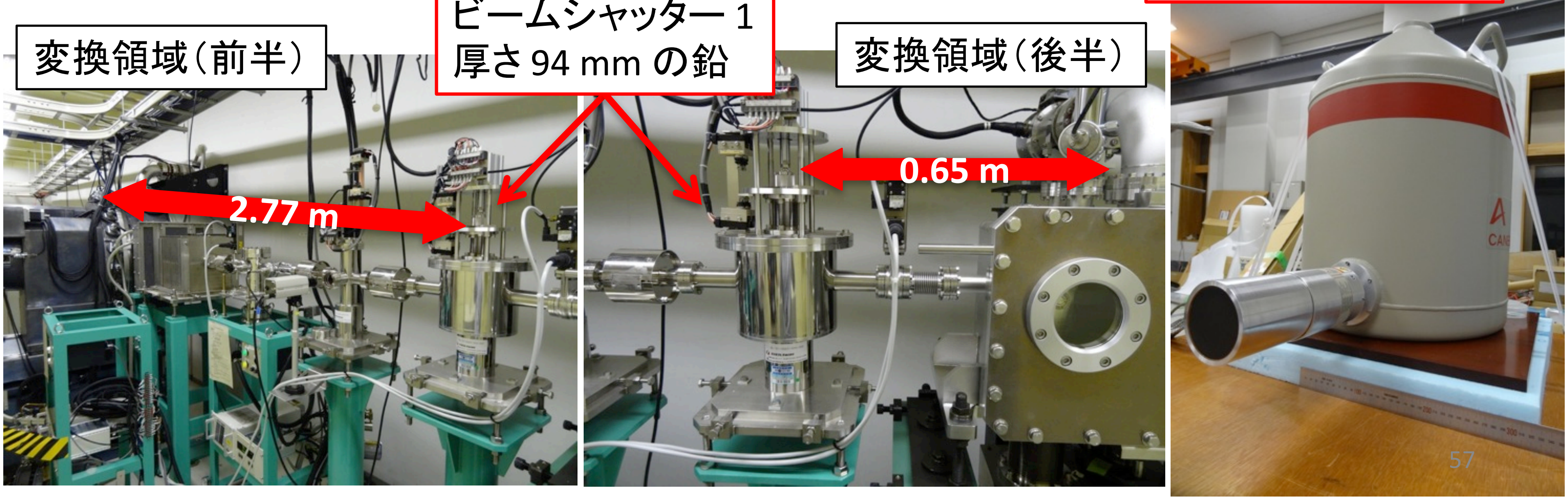
$$= g_{d\gamma\gamma}(B^2 - E^2)d$$

Bの向きと光の偏極面が直交すると　光→dilaton

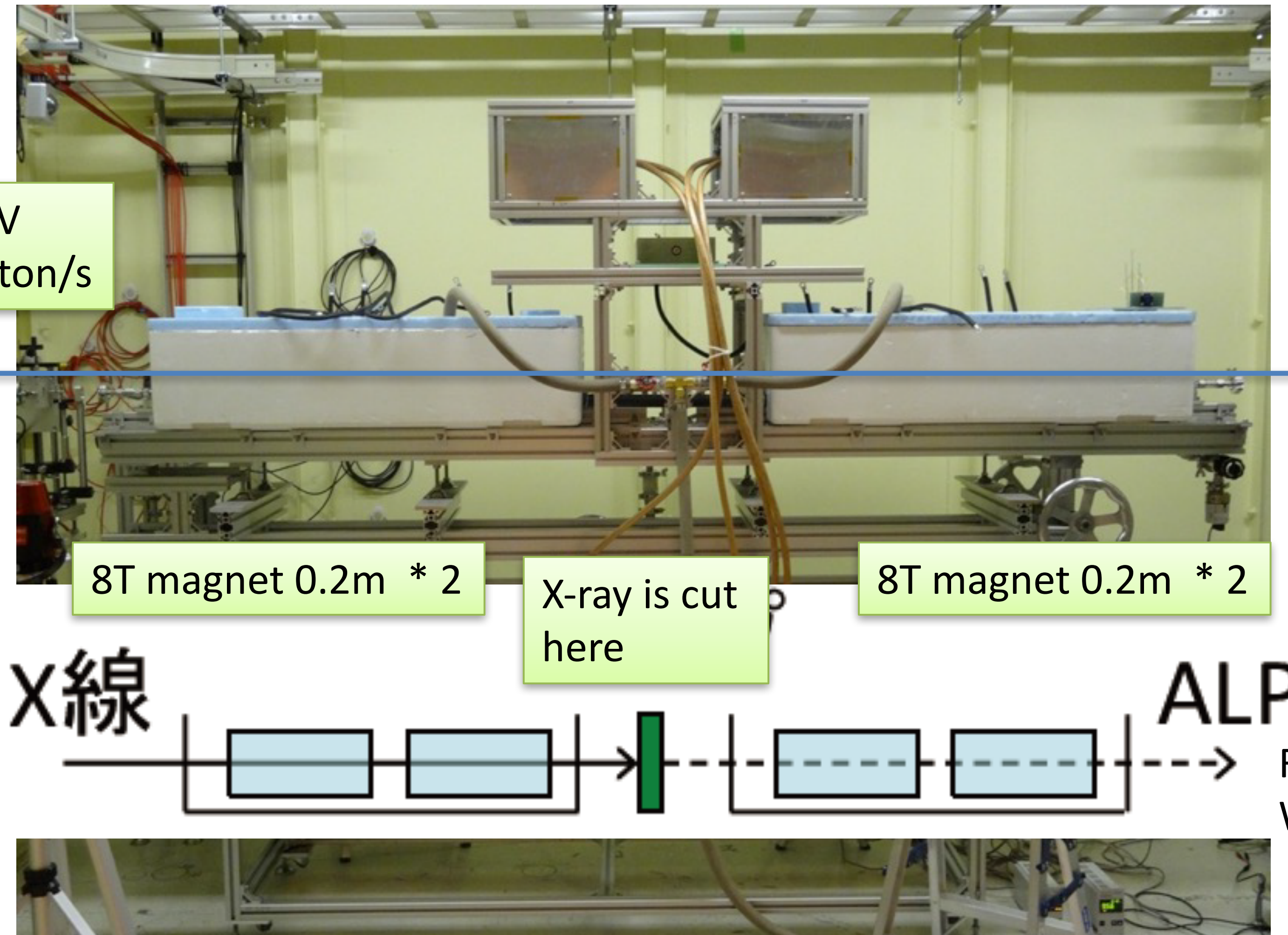
BL19LXU　@ SPring8　やってみた。

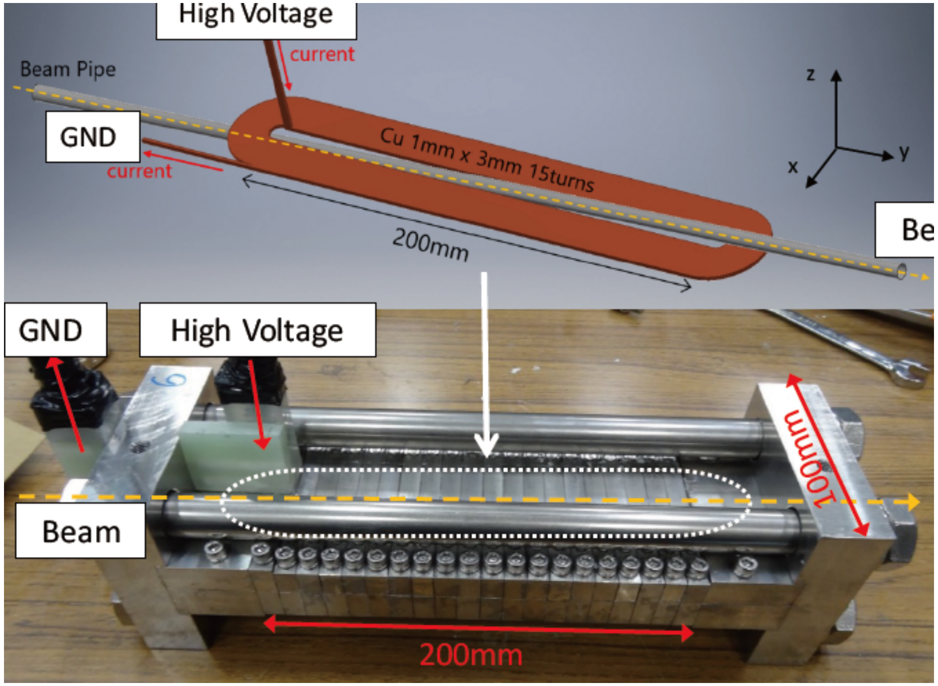
- エネルギー領域：　7.2 – 51 keV　　・ビーム強度　10^{13} – 10^{14} photon/s @ 7.2 – 30 keV
- 線幅：数 eV　　・ ビームサイズ：1 mm 程度　　・ 8時間づつ　＊　9点測定





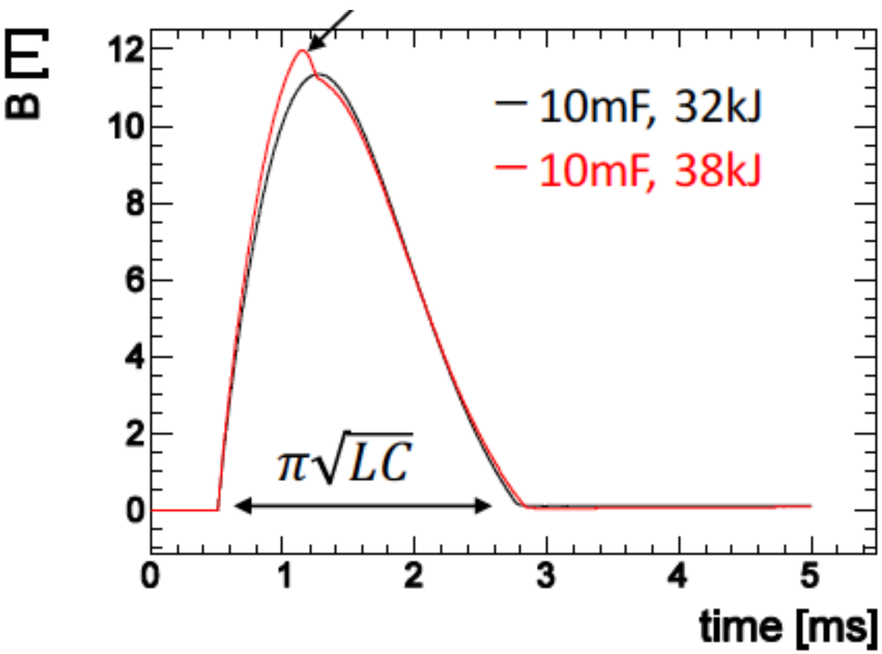
5. [C] Using collision of X-ray and Strong Magnet at Spring-8 (Axion/Dilaton like particle)





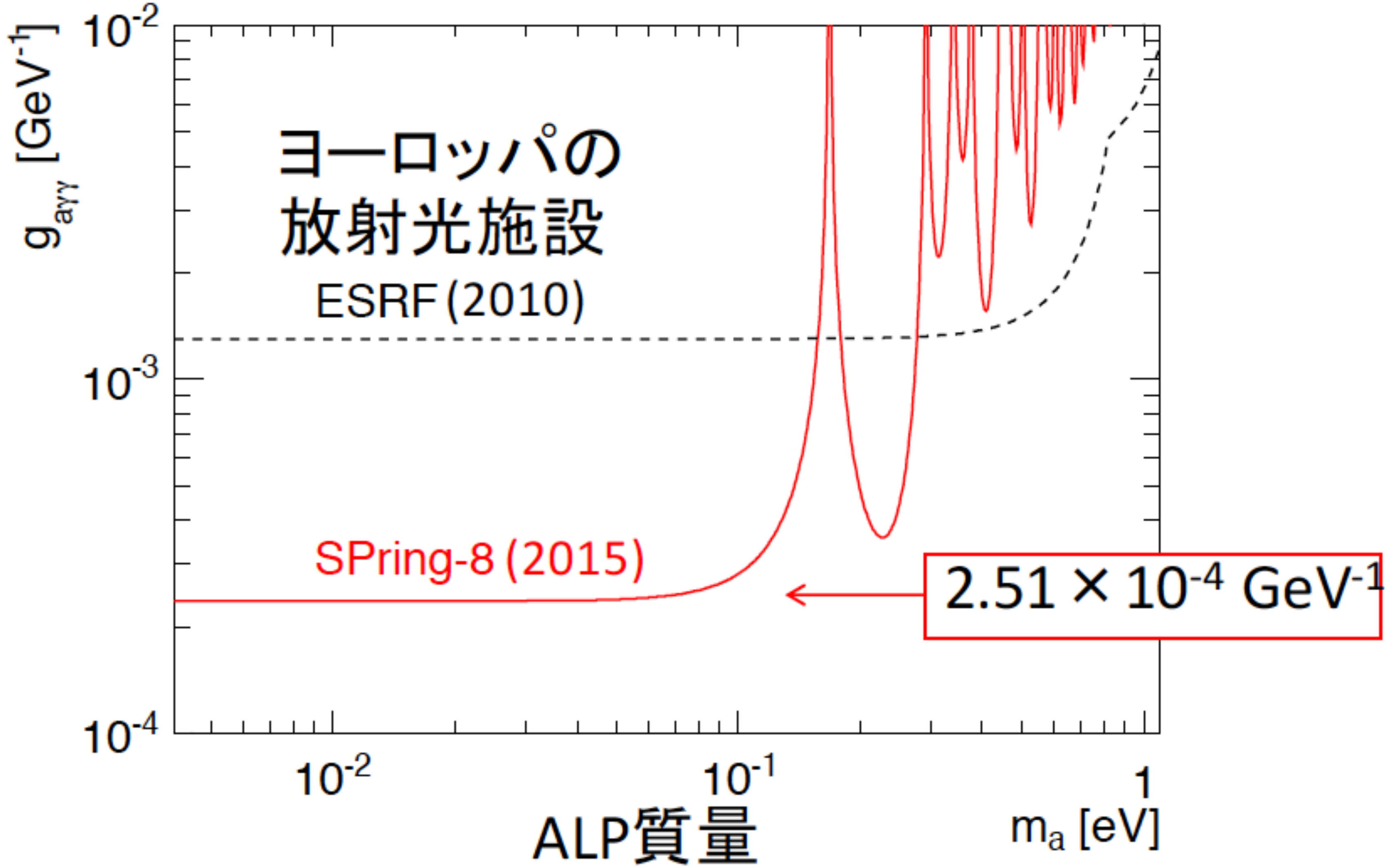
10T Magnets are used (4 units)

L.Ne is used to cool magnet down
100L/h is exhosted.

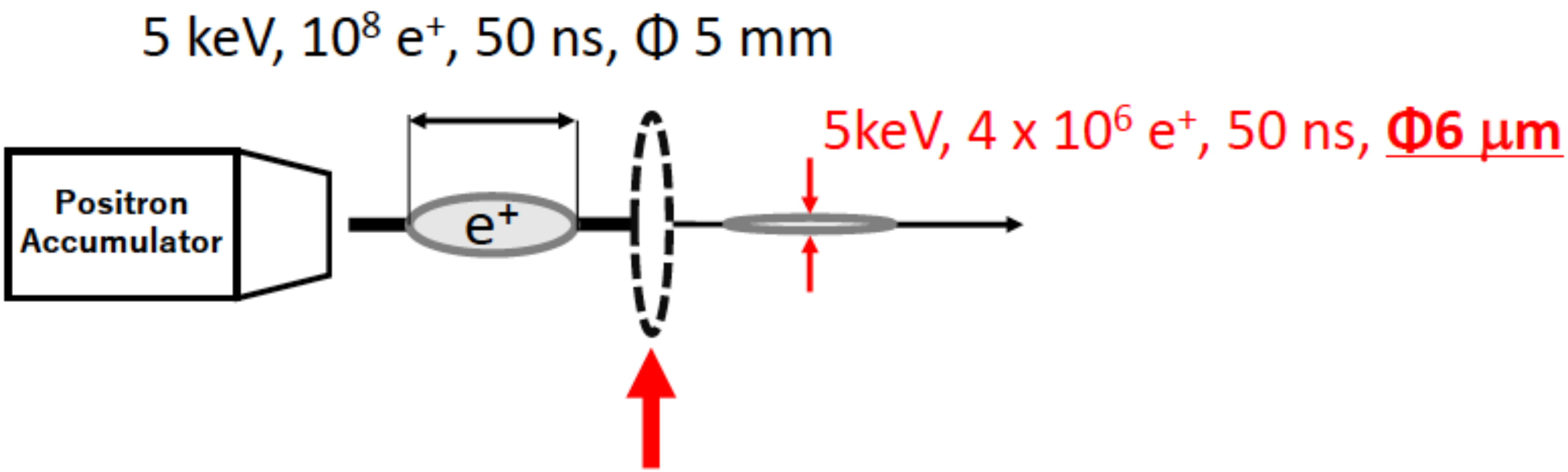


3mF Condenser bank
30KJ (1HZ rep.)

Sensitivity is for 0.1 eV



High intensity positron beam is in progress in Sansoken

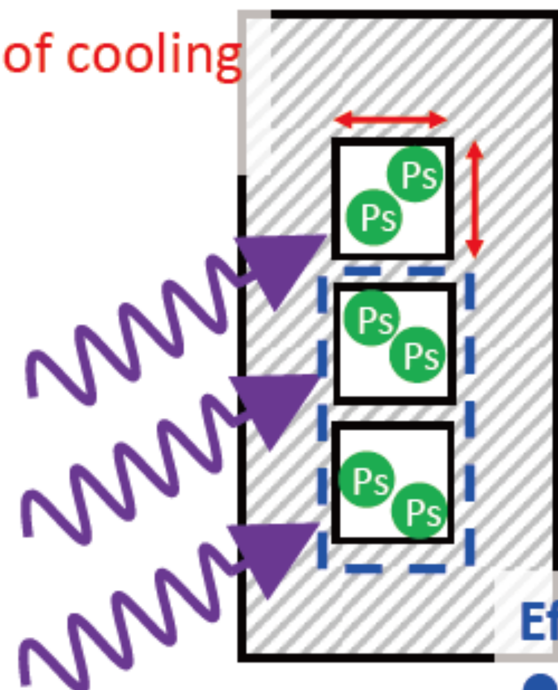


Many-stages brightness enhancement
Details in the next and N. Oshima's talk

Ps is made and cool down to 100K with

Optimized void size 50-100 nm to

- Make thermalization rapid
- Reduce pick-off annihilation
- Avoid quantum limit of cooling and Dicke narrowing

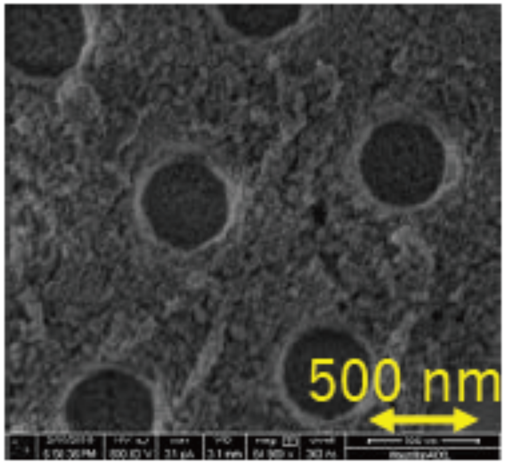


High transparency at UV

Efficient Ps trap by

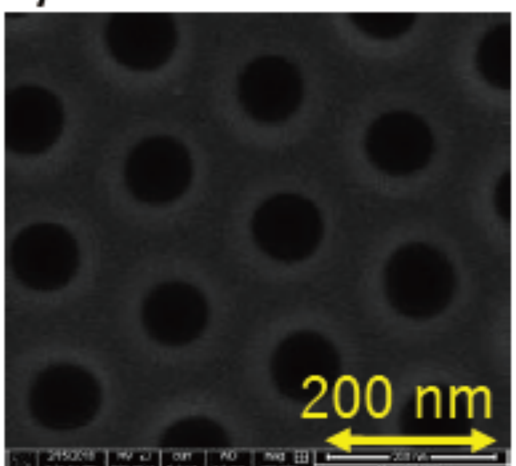
- Material of high Ps conversion efficiency
- High porosity

Idea 2 : Nano-processing



By imprinting on SiO_2-PVA composite and sintering

By electron beam lithography



Laser Cooling (Special optics have to be developed)

Ps laser cooling requires some special features
we are developing original system. Will be available in 2018.

1. Long pulse duration : Already done.
2. Broad linewidth : Elements are ready, now in testing.