Toward a Realization of Bose-Einstein Condensation of Positronium

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ICEPP The University of Tokyo
AIST NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE AND TECHNOLOGY (AIST)
APSA Advanced Photon Science Alliance

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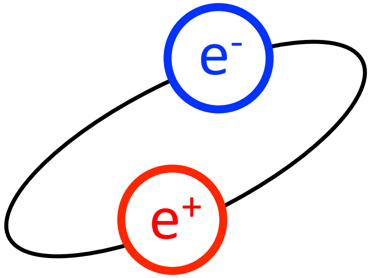
Positronium:
Probe on Fundamental Physics



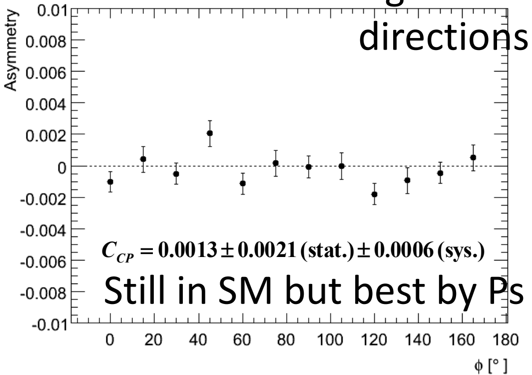
◆ Sensitive probe on fundamental physics

- ✓ Exotic atom with anti-particle
    - ➢ Suit for exploring the mystery of anti-matter
- ✓ Pure leptonic system
    - ➢ Experiments and theory calculations can be compared in high precision (*ppm* level)

Our works:

CP violation in lepton sector

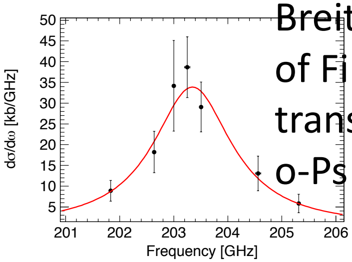
By search asymmetry of annihilation gammas directions



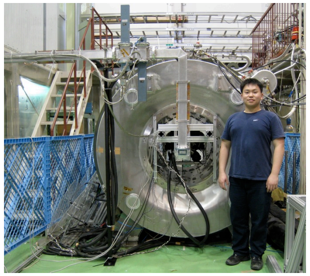
$C_{CP} = 0.0013 \pm 0.0021\,(\text{stat.}) \pm 0.0006\,(\text{sys.})$

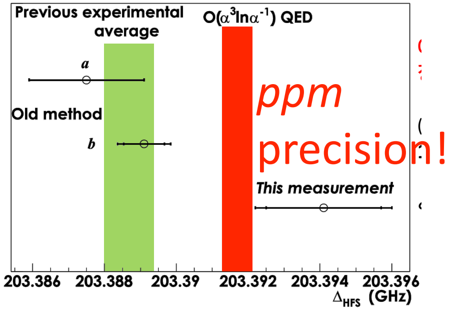
Still in SM but best by Ps

Hyperfine structure ($E_{o\text{-}Ps}$-$E_{p\text{-}Ps}$)



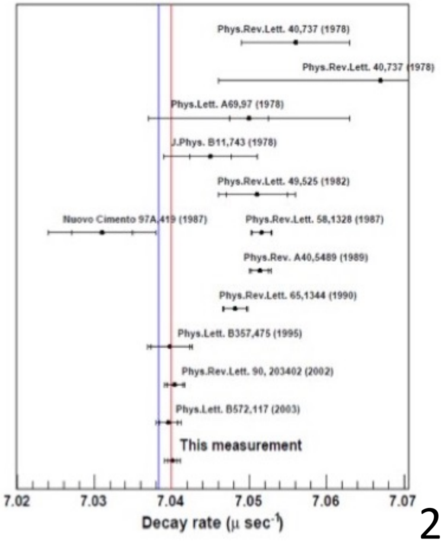
Breit-Wigner curve of First direct transition o-Ps → p-pS





ppm precision!

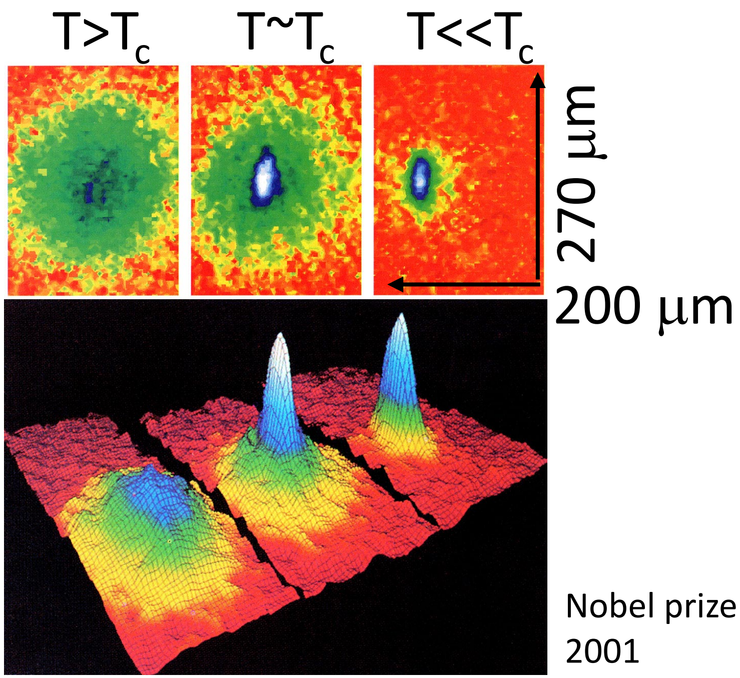
o-Ps life



Next target :
Positronium Bose-Einstein condensation

Bose-Einstein condensation (BEC)

- ➢ Almost all of atoms in a cloud occupy a single quantum state
- ➢ Atoms must be dense and cold



Nobel prize 2001

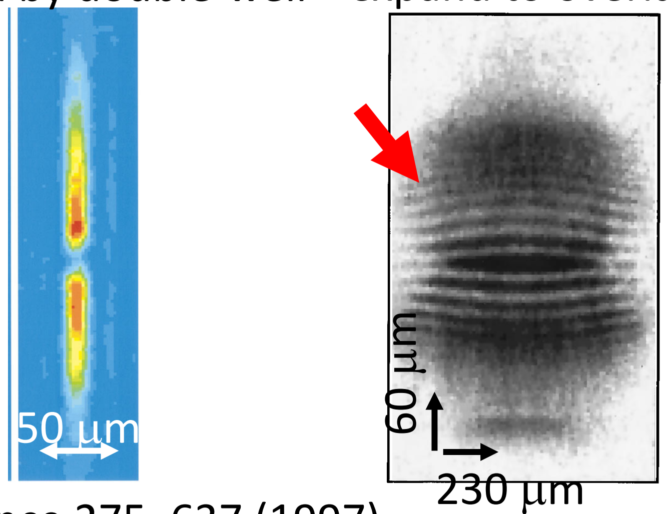
Spatial image of dense rubidium-87 around T_c (critical temperature) of BEC

Important feature

- ● BEC is "Atom laser"
- ● Quiet and coherent: Microscopic quantum effect in macroscopic such as matter-wave interference
- ● Breakthrough to study microscopic world

Before release trapped by double-well

After release expand to overlap



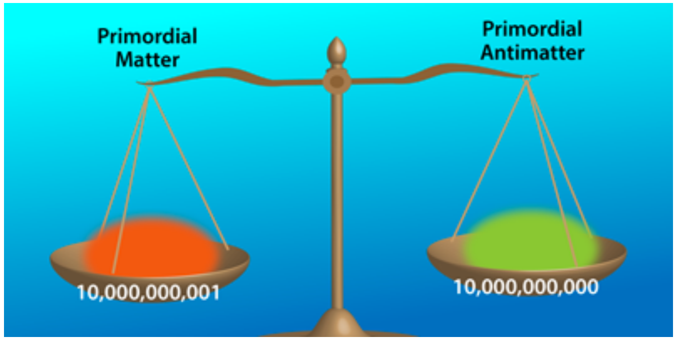
Science 275, 637 (1997)

Why BEC of "Positronium"

◆ Because Ps has anti-matter! First BEC with anti-matter.

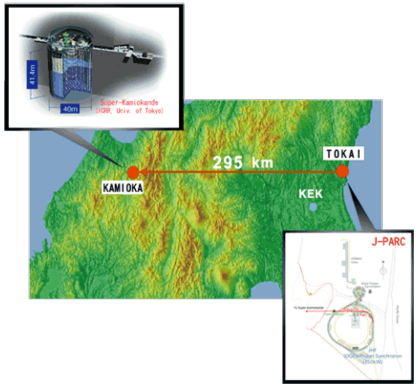
- Hot topics in particle physics and cosmology

- Anti-matter should not be same as matter to explain why matters left in the universe



From Alan Stonebraker

- Many experiments are searching on matter anti-matter symmetry



T2K experiment in neutrino mixing

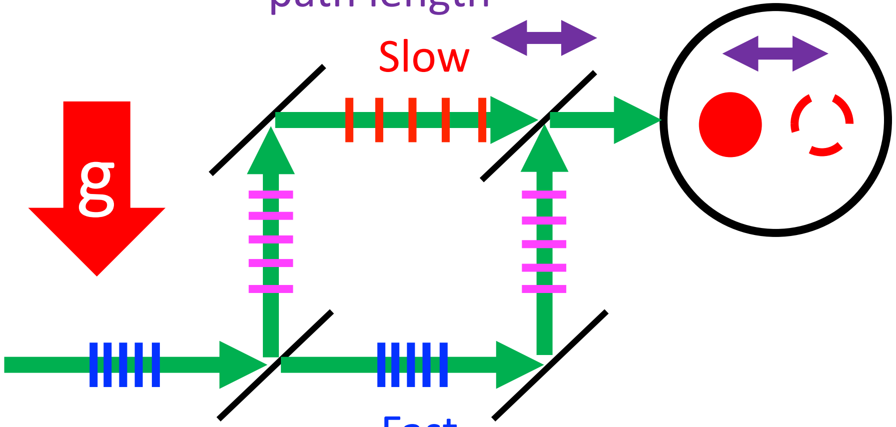
The antiproton decelerator at CERN
Produce atoms with antiproton such as $\bar{H}$

- BEC with anti-matter can be good tool to search on this hot topic by using coherency

What we can do with Ps-BEC

1. Measure anti-matter gravity by atom-interferometer

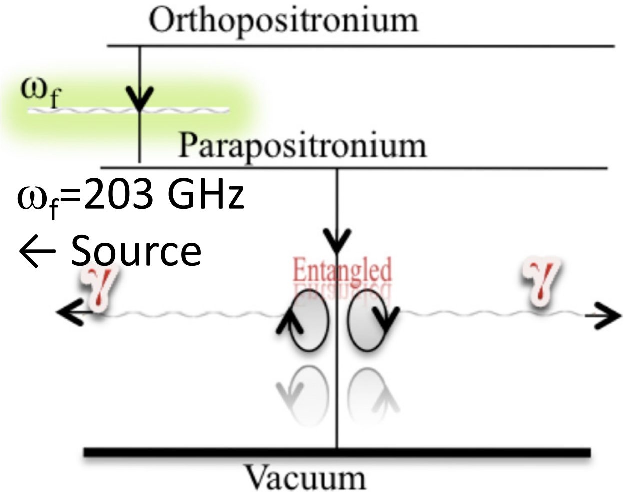
Intensity of Ps blinks by changing path length



- 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. 511 keV gamma-ray laser



ω_f=203 GHz

← Source

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

Challenges to realize Ps-BEC

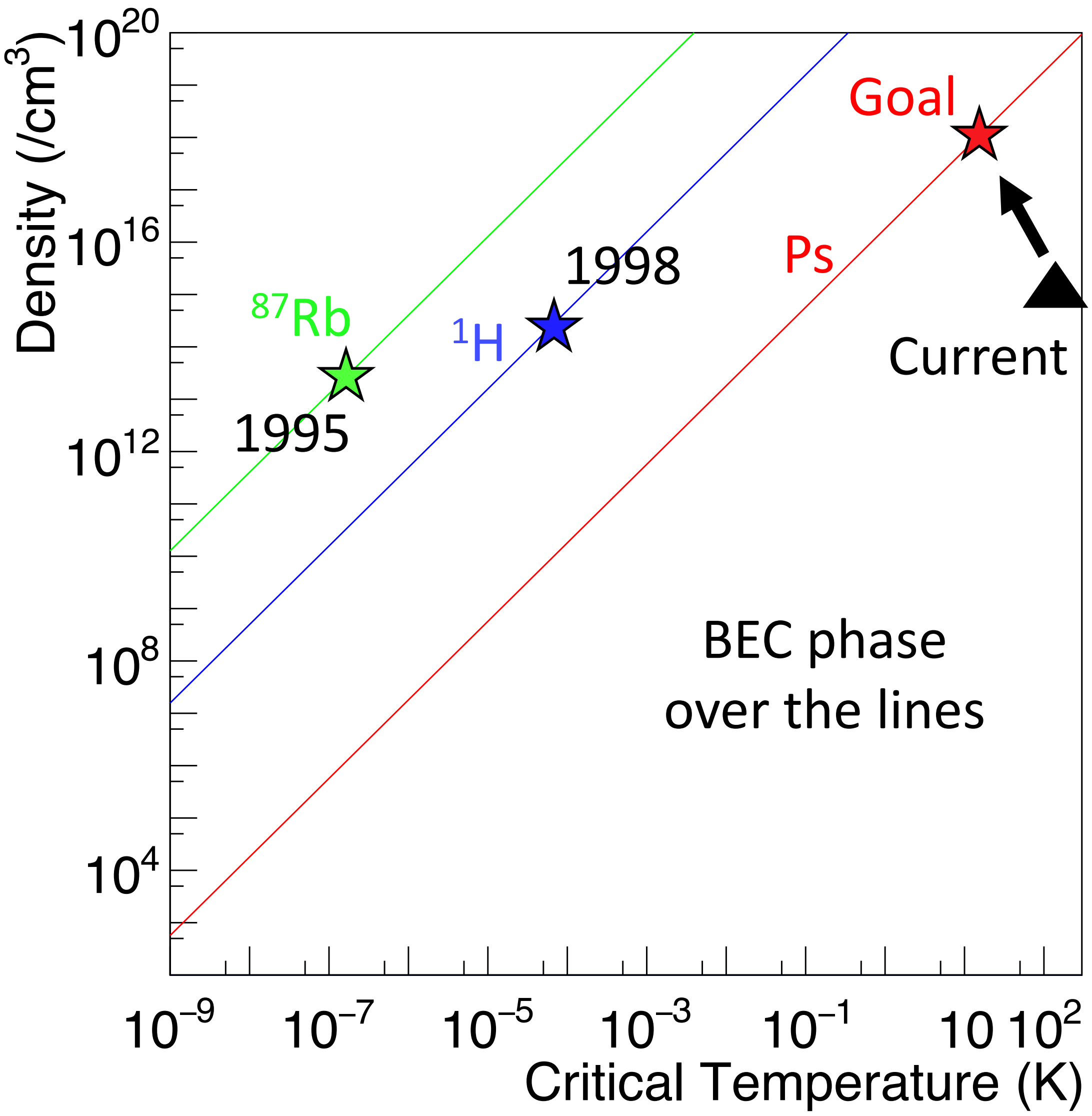
Conditions to realize Ps-BEC

- High density
- Low temperature
- ➢ For Ps, 14 K at 10^{18} cm^{-3}

- Critical temperature (T_C) is very high due to Ps light mass
- × Ps annihilation life time is only 142 ns

Necessary techniques

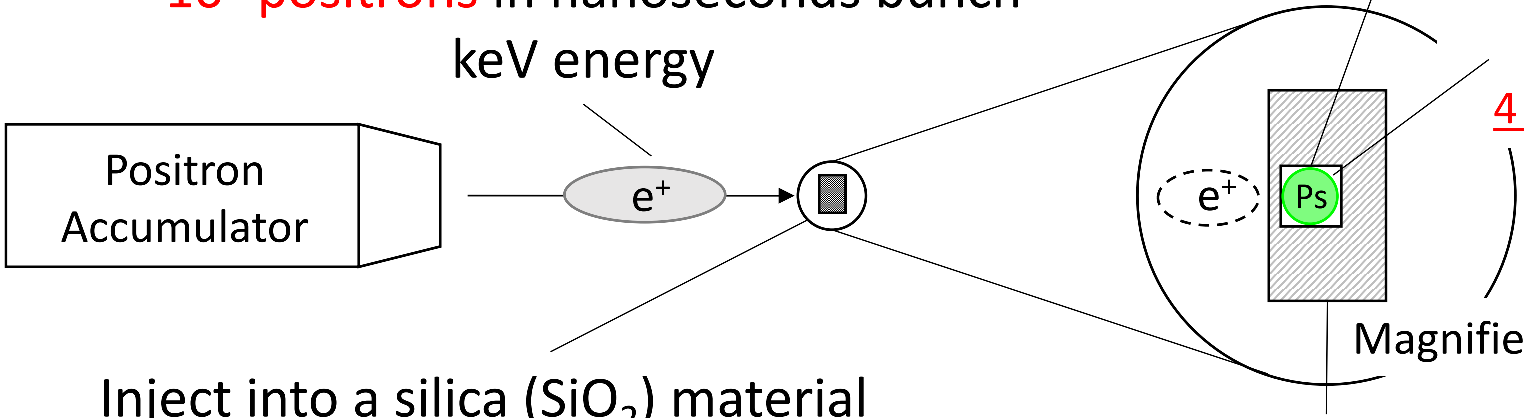
1. Instance (around 10 ns) creation of dense Ps
2. Fast cooling of Ps to 10 K in around 100 ns



Method to realize Ps-BEC

New method: K. Shu *et al.* J. Phys. B 49, 104001 (2016)

1. Create dense positrons and convert into dense Ps at once



Internal void = trap cavity
~150 nm × 150 nm × 150 nm

~10^8 positrons in nanoseconds bunch
keV energy

13,500 Ps
created
4×10^{18} cm^{-3}

Magnified view

Inject into a silica (SiO_2) material
with ~100 nm beam waist by focusing

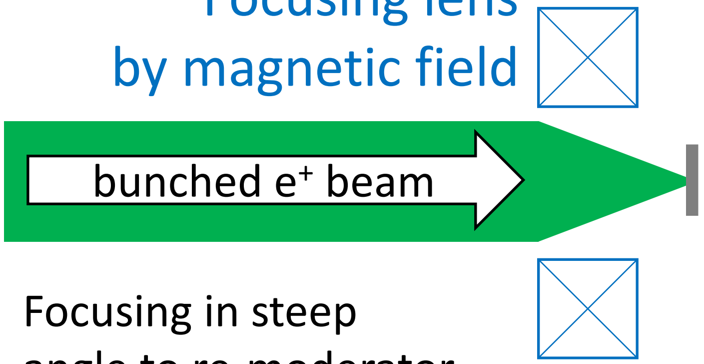
Silica as Ps converter
~50% prob.

- 10^9 positron accumulation was achieved elsewhere. We will construct new focusing system to achieve 100 nm beam waist

Positron focusing

Currently, a few μm waist is achieved to probe fine structures of a surface

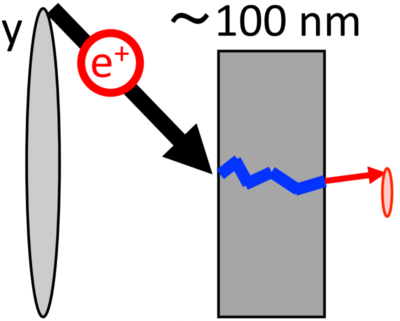
Principle of positron focusing (brightness enhancement):



Focusing lens
by magnetic field

bunched e^+ beam

Focusing in steep
angle to re-moderator



Thin metal (W, Ni) moderator

keV energy

e^+

～100 nm

re-emitted in eV energy
= positron negative
work function

Thermalize and diffuse
to rear surface

N. Oshima *et al.* J. Appl. Phys. 103, 094916 (2008).

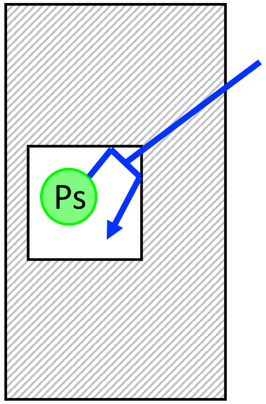
◆ Narrow beam with low emittance can be acquired!

Plan to use this method for many stages, but <u>repulsive force</u> between positrons themselves can be problem because it is dense

➢ <u>Now studying and designing beam optics</u>

Method to realize Ps-BEC

2. Cooling by thermalization process



1st step

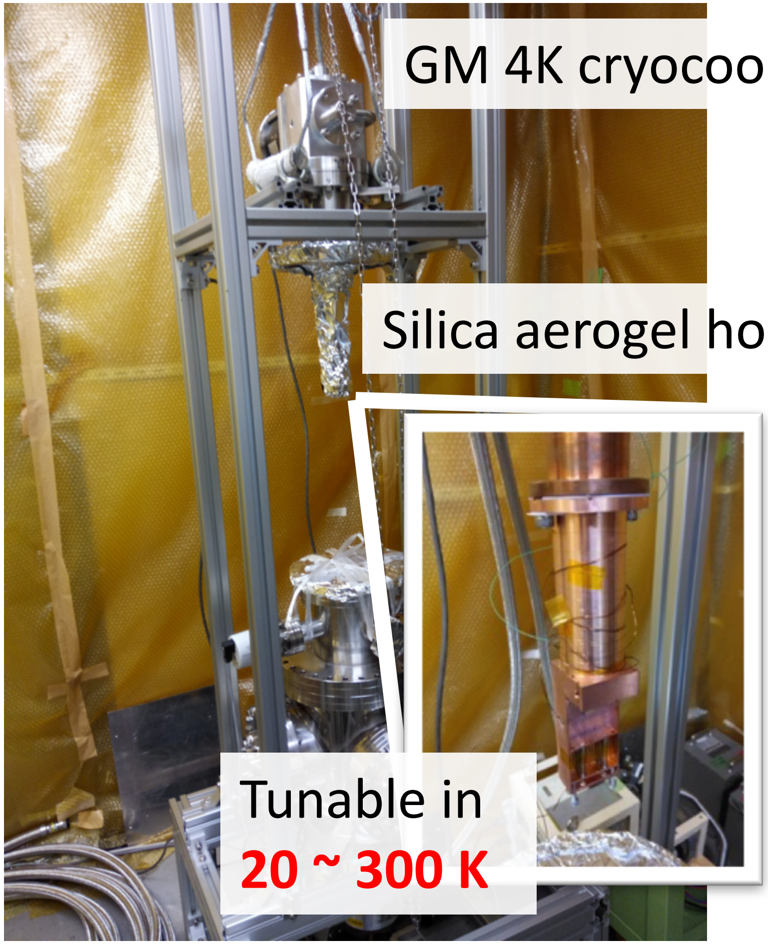
By collisions with cold silica cavity wall

= Thermalization process

Cold Silica < 10 K

First observation of thermalization process in cryogenic environment

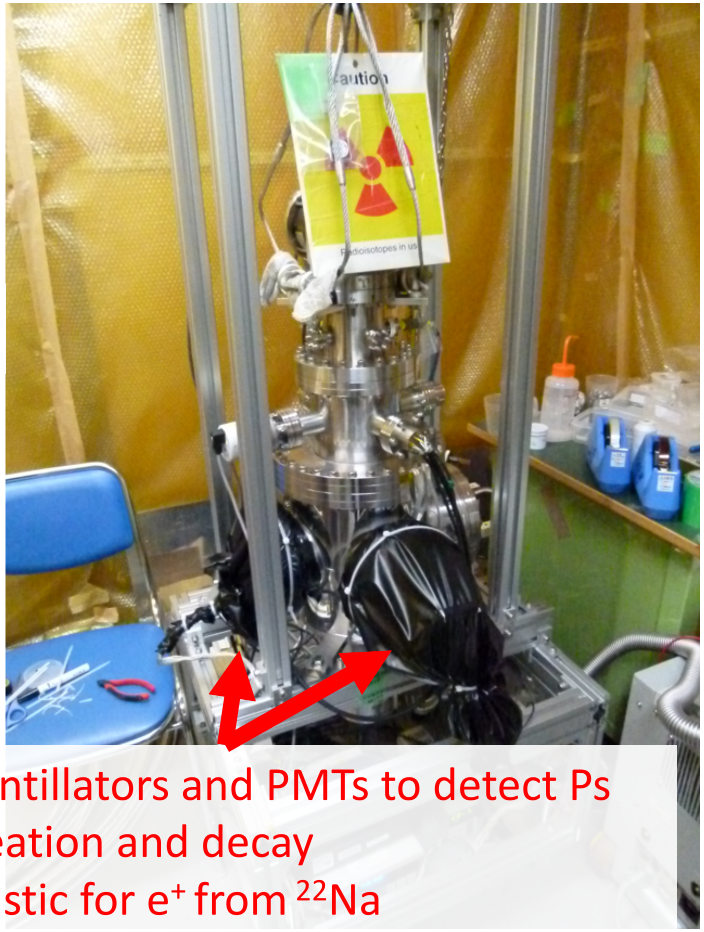
We newly measured thermalization process in cryogenic silica aerogel (=porous material made by SiO_2) to confirm how they are cooled



GM 4K cryocooler

Silica aerogel holder

Tunable in
20 ~ 300 K



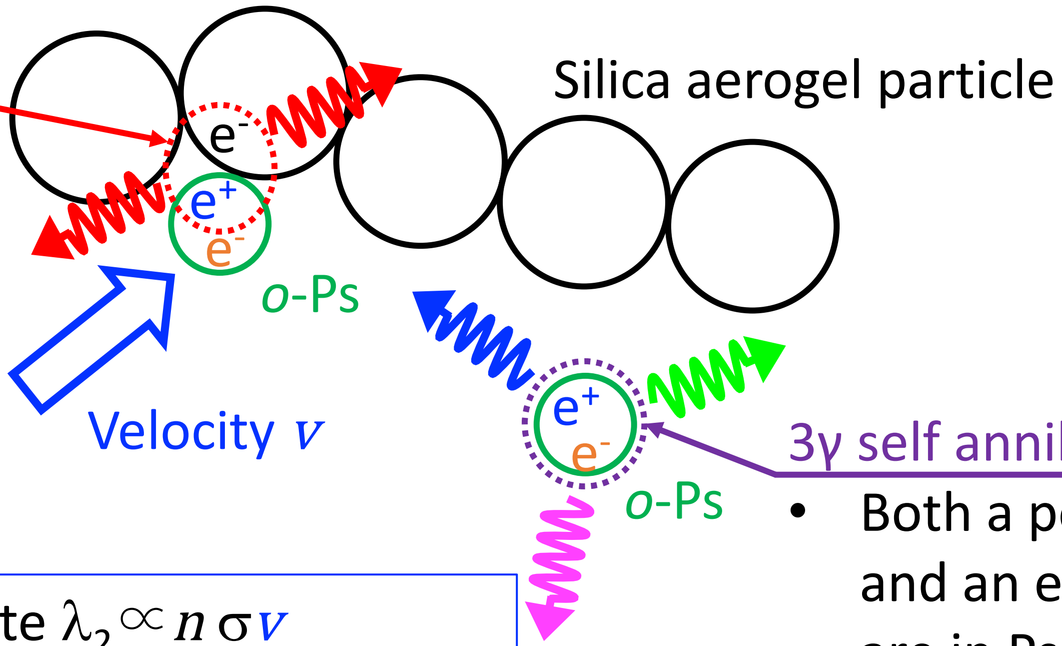
Scintillators and PMTs to detect Ps creation and decay

Plastic for e^+ from ^{22}Na

$LaBr_3$ for annihilation gammas

Method to measure thermalization process
Use Pick-off annihilation

- Measure rate of collisions between Ps and silica particle



Pick-off 2γ annihilation

- A positron in Ps and an electron in silica by collisions
- 511 keV mono energy

3γ self annihilation

- Both a positron and an electron are in Ps
- 0 ~ 511 keV continuous energy spectrum

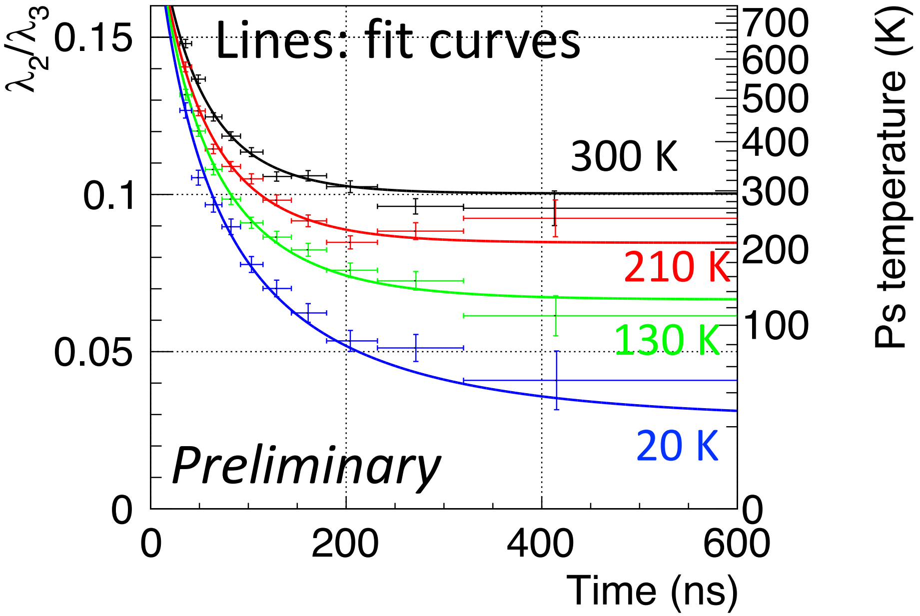
Pick-off annihilation rate $\lambda_2 \propto n \sigma v$

n: Density of electrons in silica particle

σ: Cross section of Pick-off annihilation

→ By measuring λ_2 vs Ps life, temperature evolution of Ps can be measured

Result of the measurement



Thermalization curves of Ps in various silica temperature

- Thermalization into cryogenic temperature was clearly observed

Temperature evolutions of Ps are modeled by elastic collision model

$$\frac{dE}{dt} = -\frac{2}{LM}\, v\,\left(E - \frac{3}{2}k_B T\right),$$

$$v = \sqrt{\frac{2E}{m_{Ps}}},$$

$$\lambda_2(t) = \frac{C}{L}\times v$$

Important parameter is M:

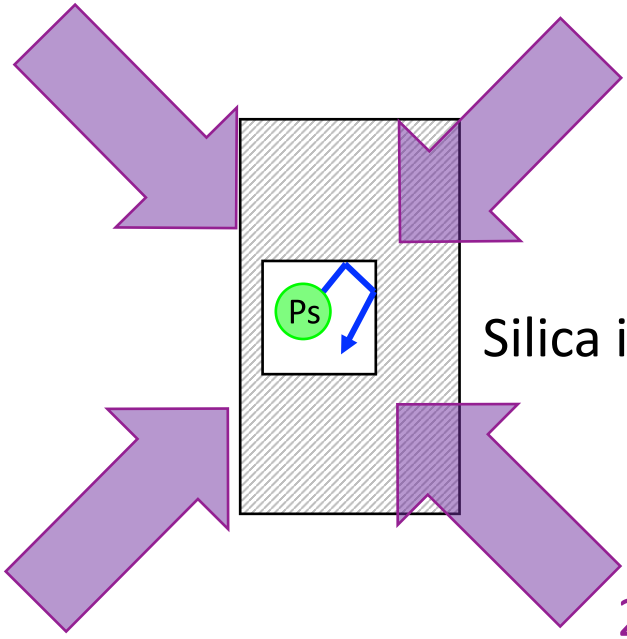
Effective mass of silica for elastic collision with Ps

Measured M = 170±10 a.m.u

✓ Smaller (thermalize faster) than other experiments in high T or with gases

Method to realize Ps-BEC

2. Cooling by laser



2nd step

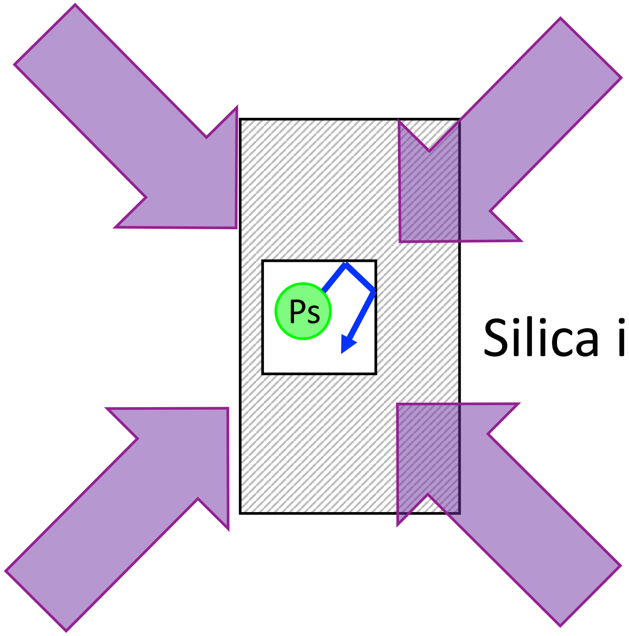
Irradiate 243 nm UV laser to cool Ps down to 10 K

Silica is transparent in UV

243 nm UV laser

Method to realize Ps-BEC

2. Cooling by laser



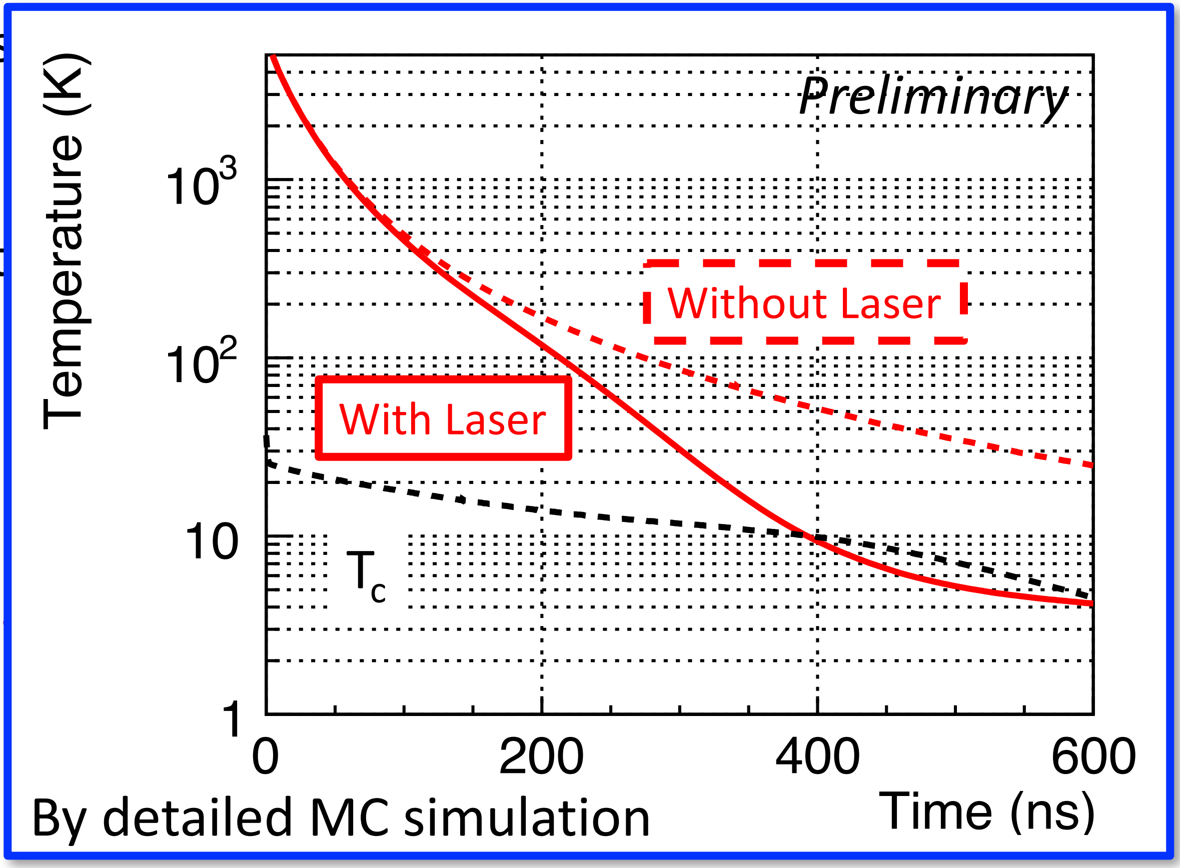
2nd step

Irradiate 243 nm UV laser to cool

Ps

Silica is t

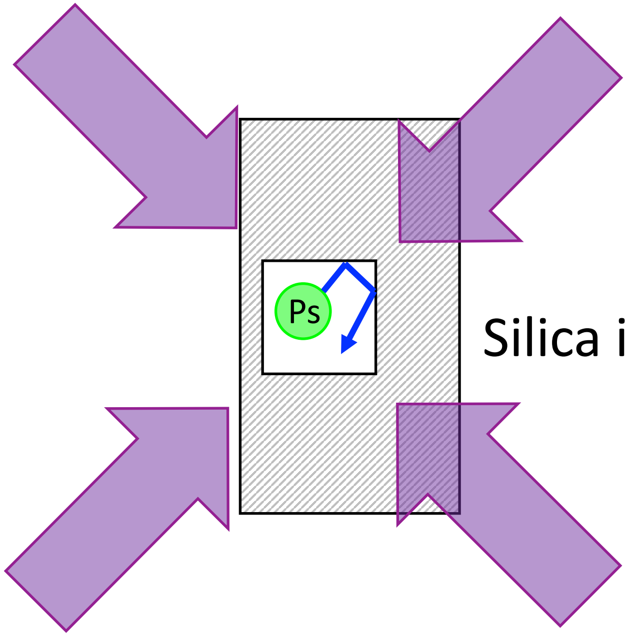
24



By detailed MC simulation

Method to realize Ps-BEC

2. Cooling by laser



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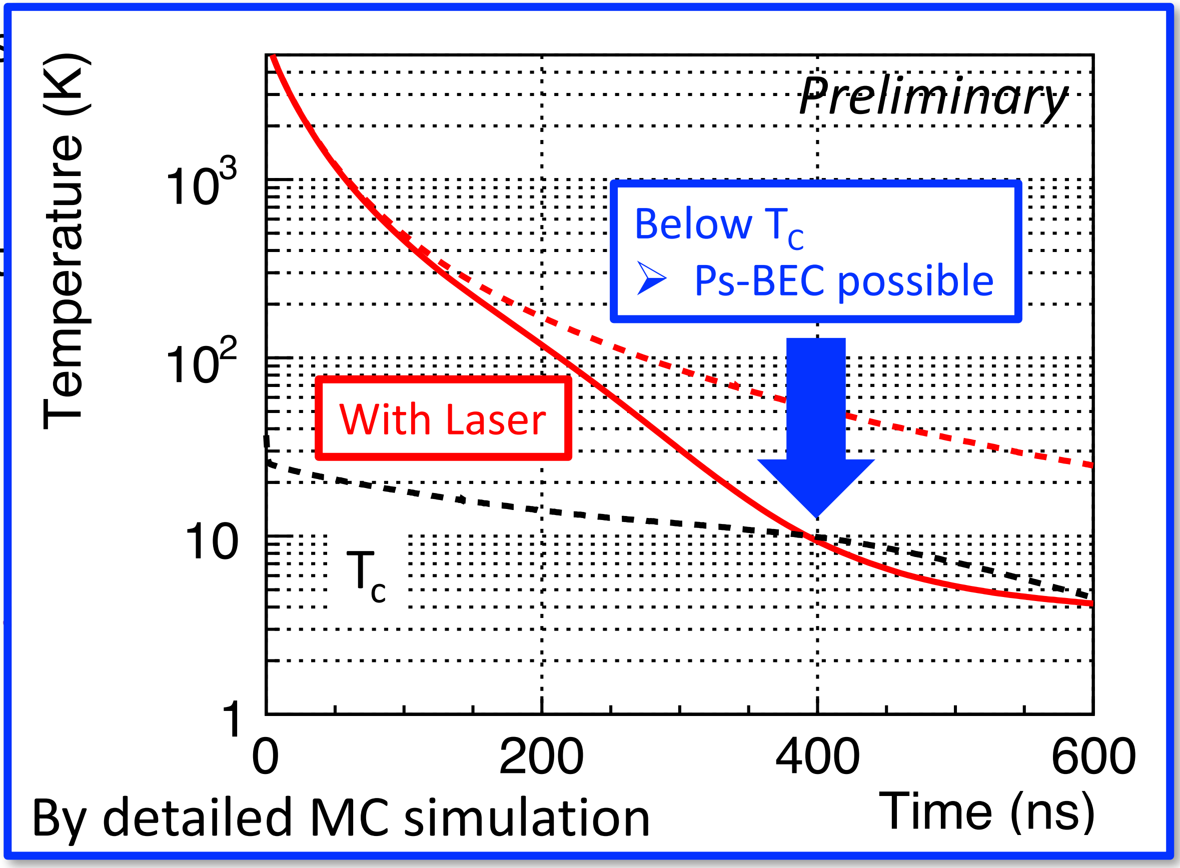
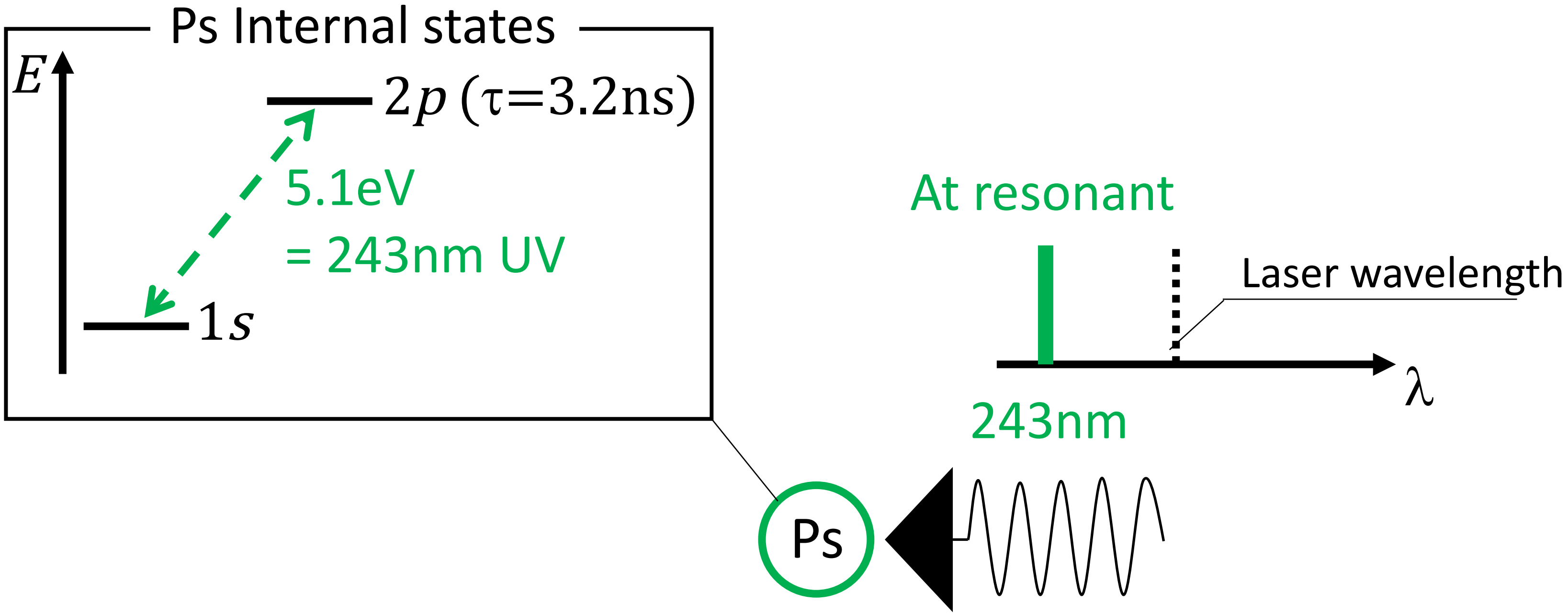


By detailed MC simulation

Principle of Laser Cooling

Laser cooling: Cool atoms by absorptions of photons' momentum



Ps Internal states

E

$2p$ (τ=3.2ns)

5.1eV

= 243nm UV

$1s$

At resonant

Laser wavelength

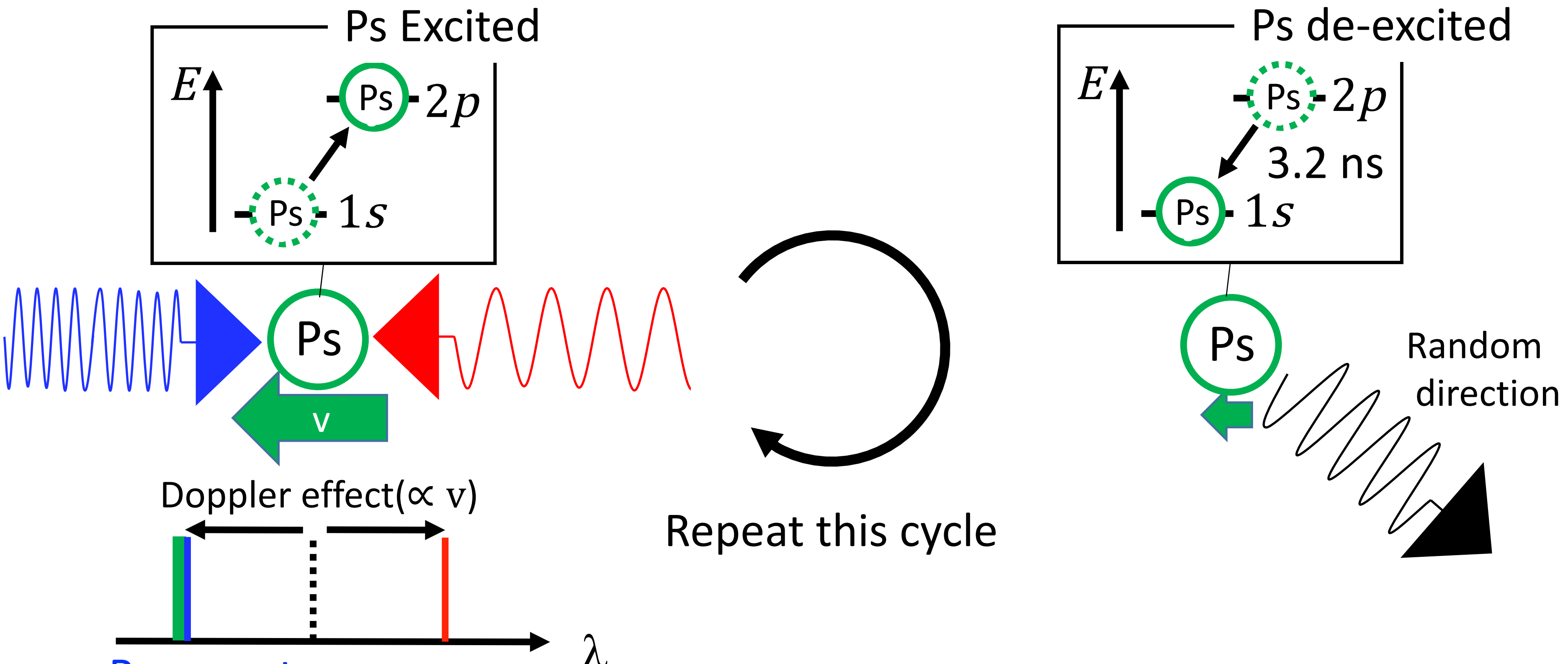
λ

243nm

Ps

- To let Ps absorb photon, use 1s - 2p transition
- Incident laser wavelength is detuned slightly longer than resonance

Principle of Laser Cooling



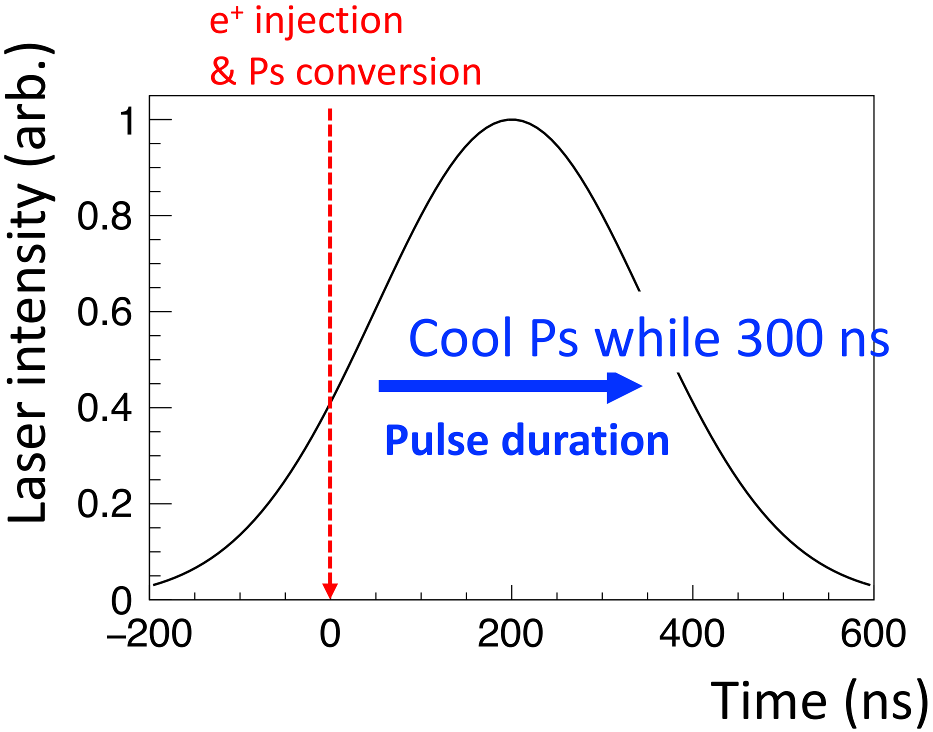
1. Only counter-propagating photons are absorbed by Doppler effect
2. Decelerate by photon‘s momentum
3. Spontaneously de-excite in 3.2 ns with random direction photon
(no effect on Ps temperature)

Requirements for Cooling Laser

No laser cooling of Ps (anti-matter systems)

For Ps, several special features are necessary

1. Long time duration pulse
   - ➢ Cooling of Ps takes around 300 ns (~ Ps life)



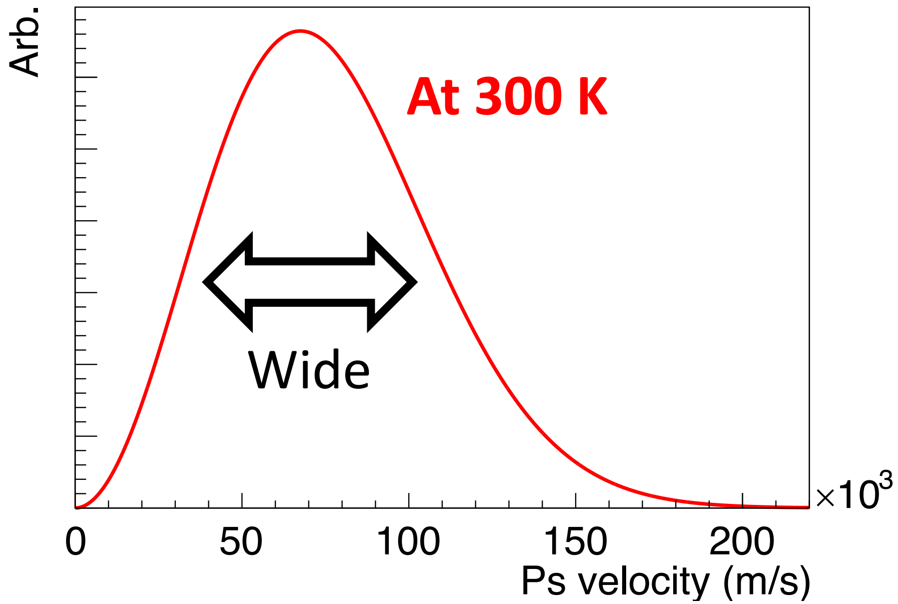
e^+ injection
& Ps conversion

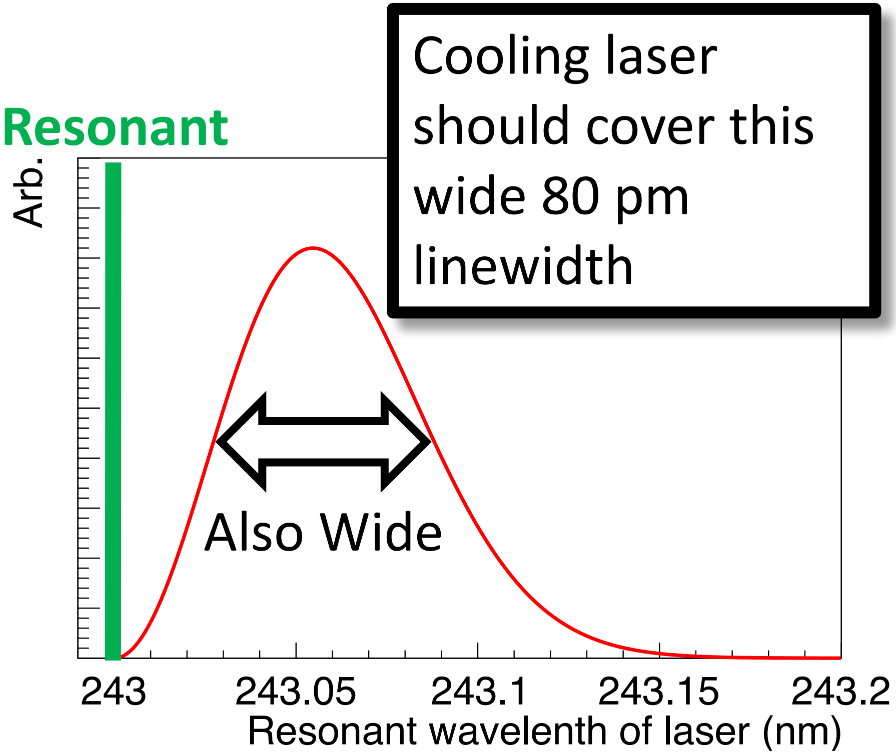
Cool Ps while 300 ns

Pulse duration

Requirements for Cooling Laser

2. Wide linewidth
   - Doppler effect is large due to Ps light mass, so laser linewidth must cover wide Doppler width

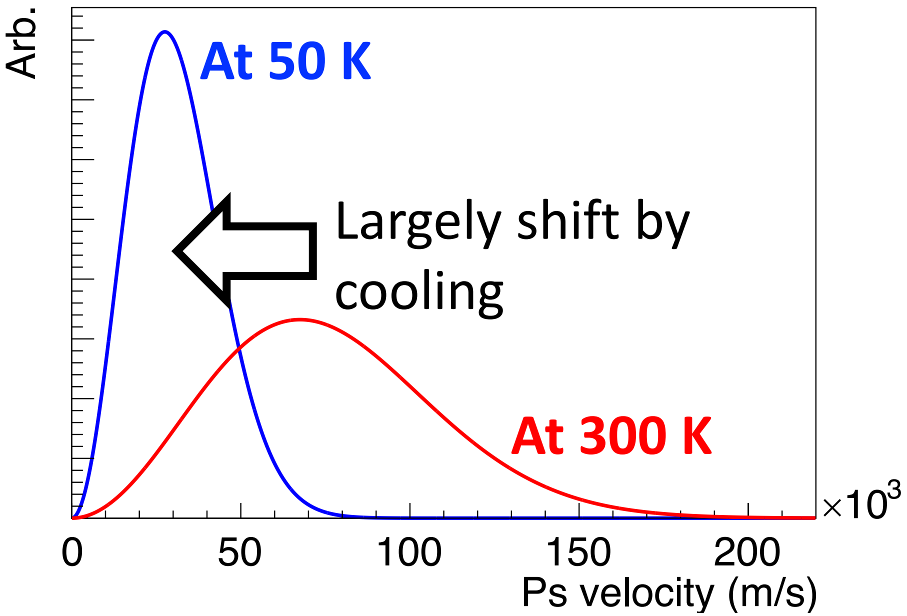




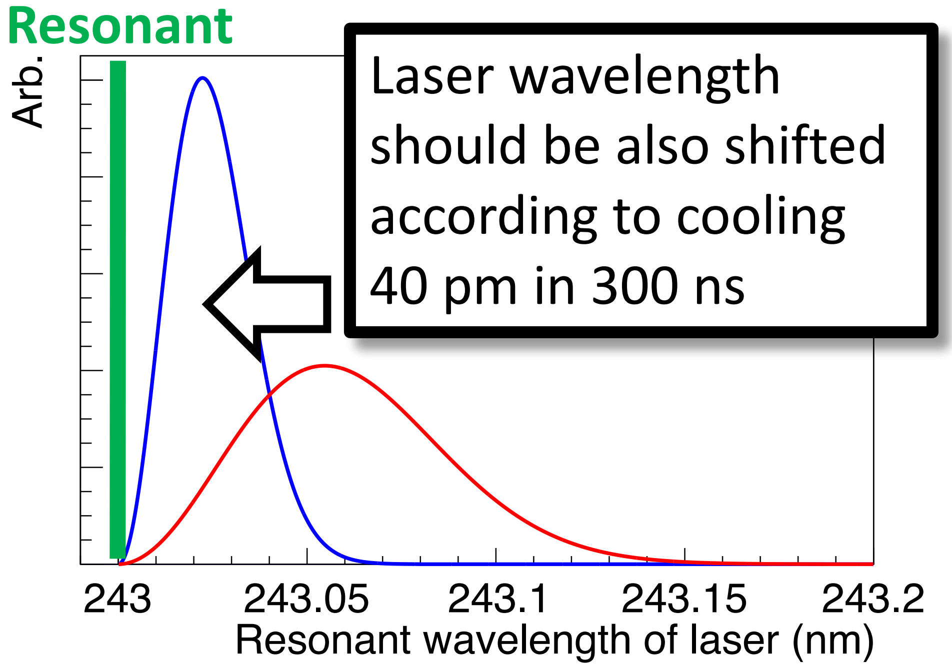
Cooling laser should cover this wide 80 pm linewidth

Requirements for Cooling Laser

3. Fast shift of wavelength
   - ➢ Resonant wavelength shifts as Ps atoms get cold
   - ✓ Fast shift (40 pm in 300 ns) of pulse laser has never been achieved



Largely shift by cooling



Laser wavelength should be also shifted according to cooling 40 pm in 300 ns

Requirements for Cooling Laser How special?

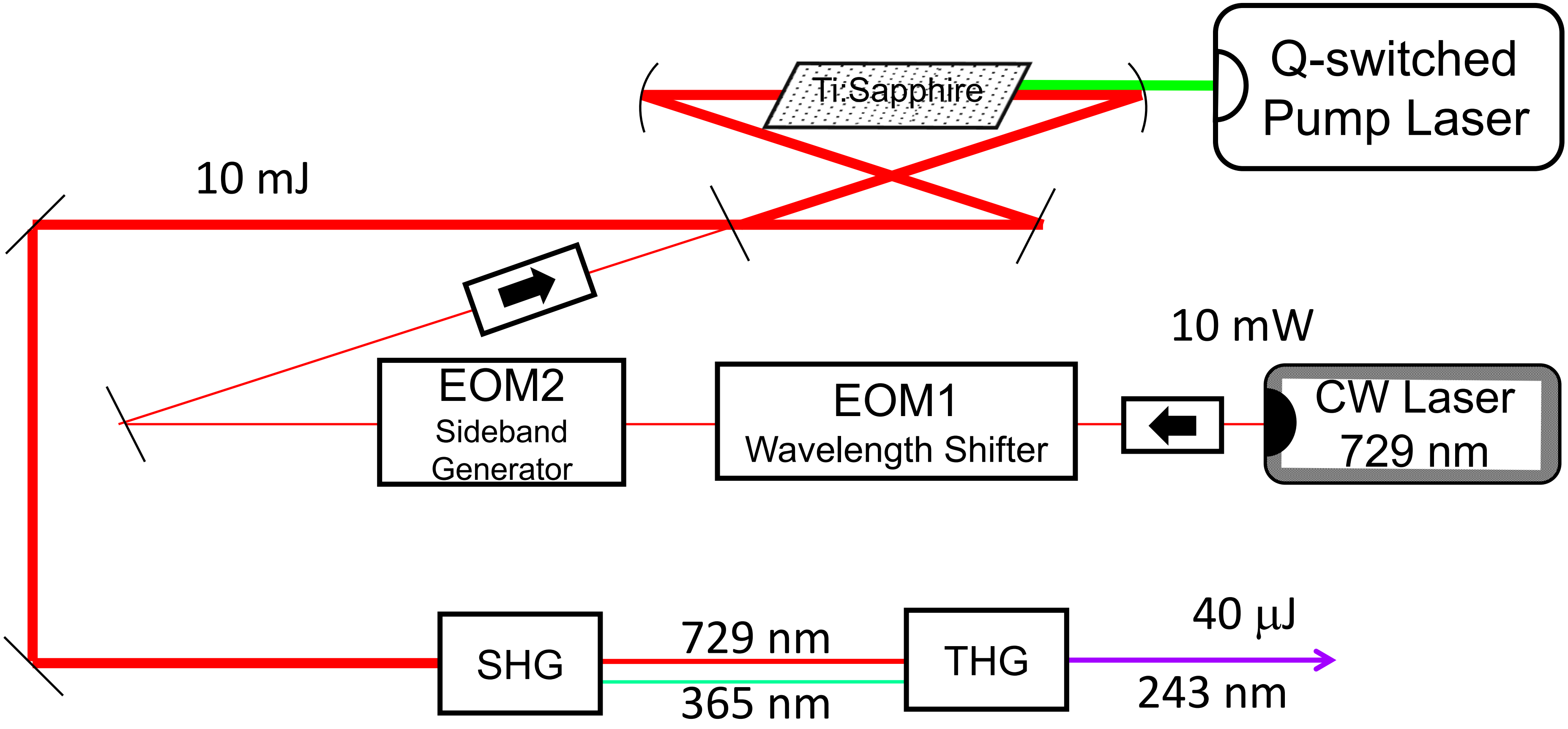
	Ps cooling laser	**Common laser**
Time duration	300 ns	CW or Pulse with 10ns or 100 fs
Linewidth	80 pm	< 2 pm or > 10 nm
Wavelength shift	40 pm in 300 ns	No example in my knowledge

- Even though laser optics are deeply developed, many features which Ps requires are special because laser cooling of Ps is a new challenge

- New design has been considered by combining sophisticated the-state-of-the-arts optics technologies

Special home-made laser system

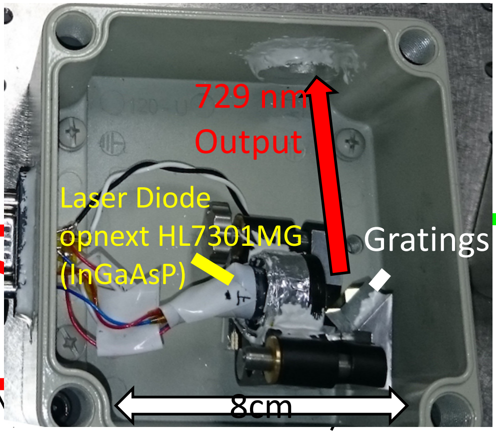
- Schematic diagram of the system

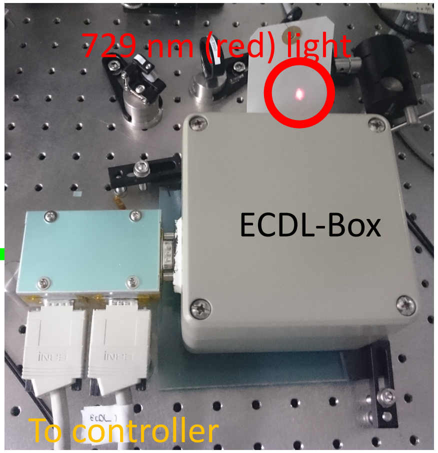


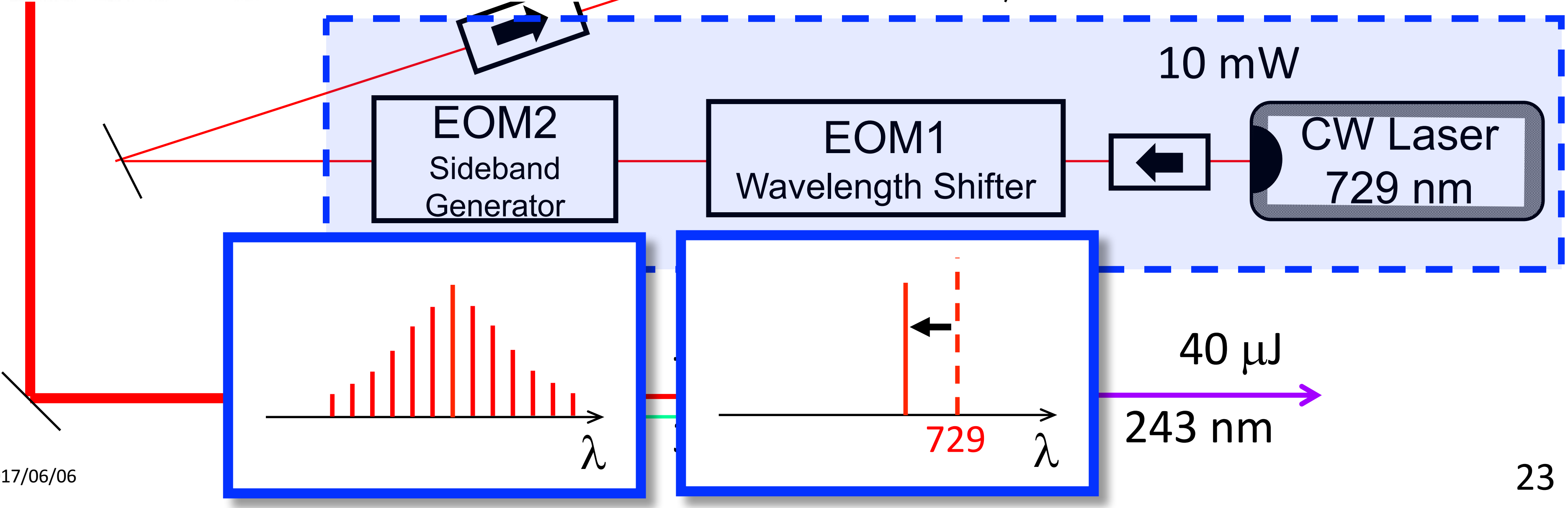
Special home-made laser system

1. Wavelength control : shift and broadening in 729 nm CW by EOMs

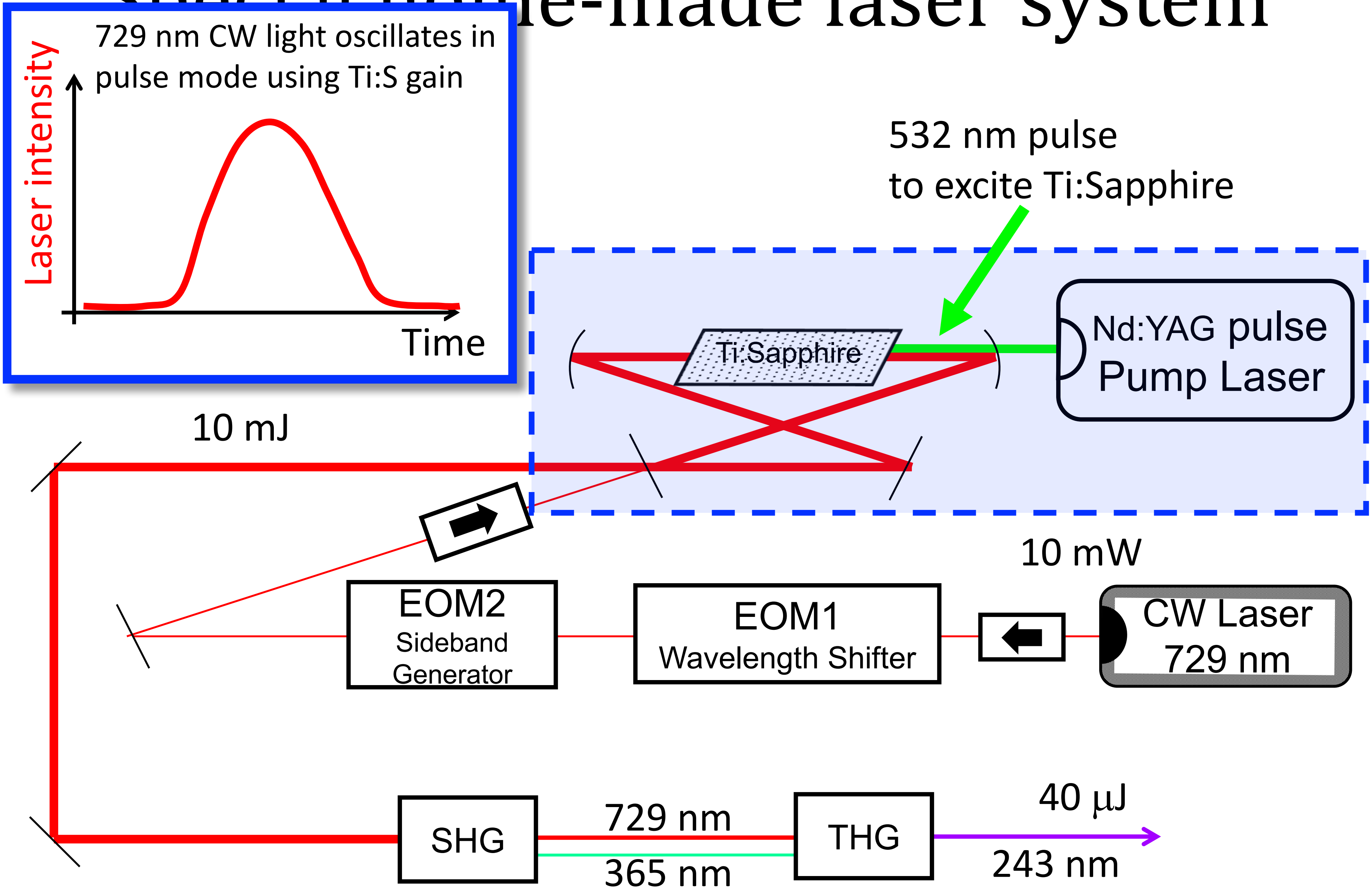
EOMs can generate wavelength modulated light by applying RF for CW red light







Special home-made laser system



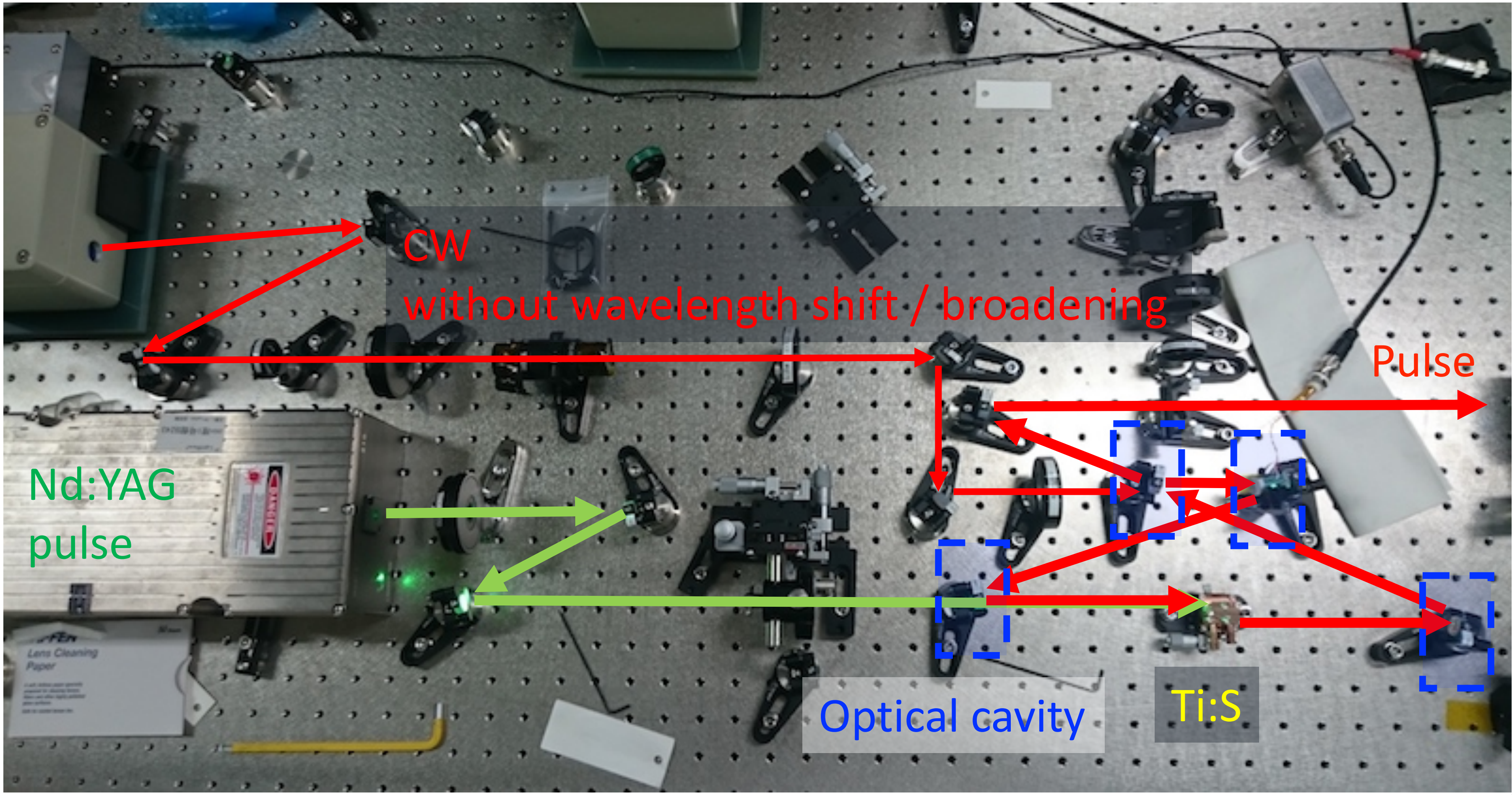
729 nm CW light oscillates in pulse mode using Ti:S gain

532 nm pulse to excite Ti:Sapphire

Development : Prototype long pulse

Developed a bit short cavity with high reflectivity mirrors

Expected pulse time duration : 200 ns



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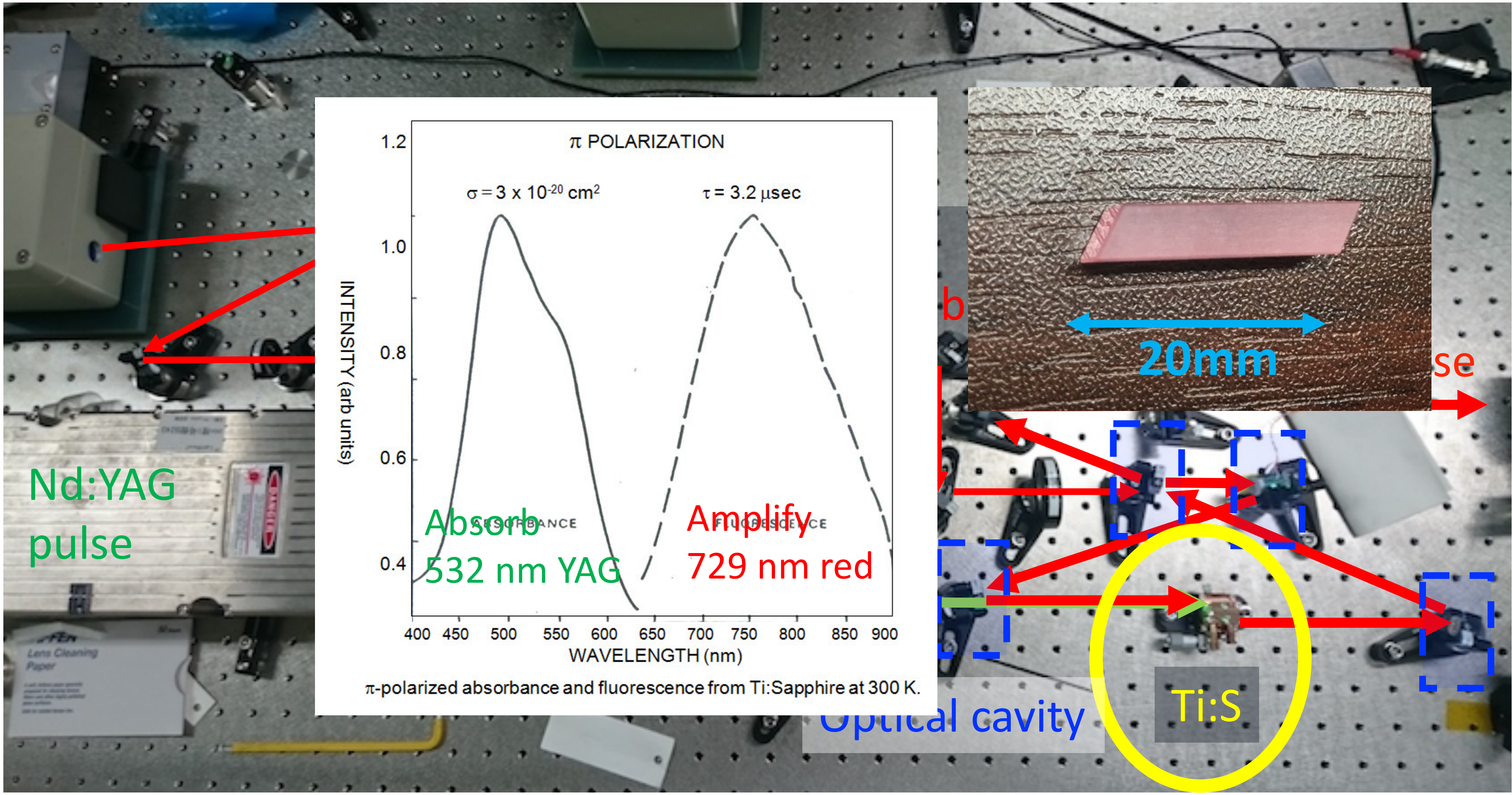
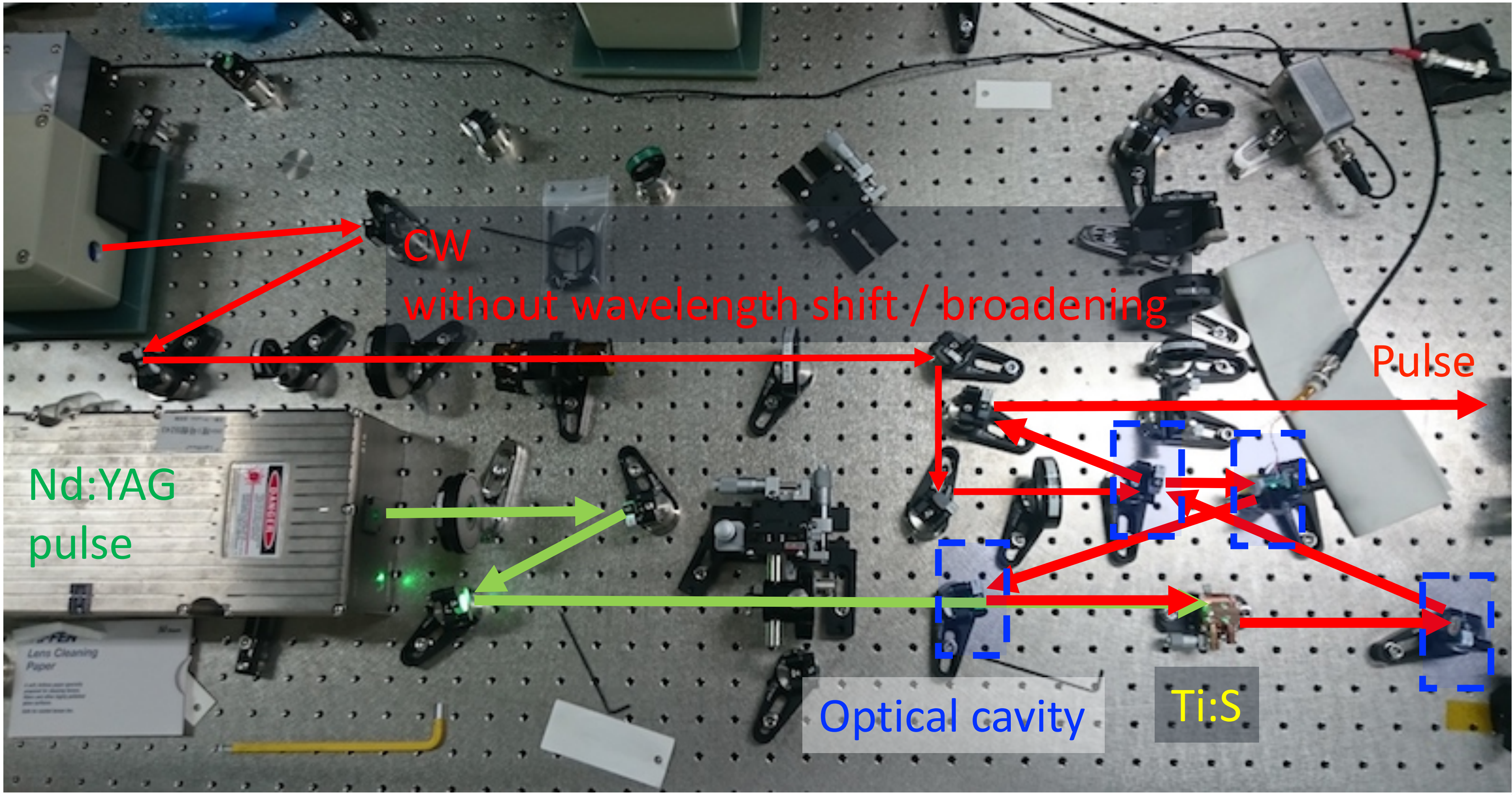


π-polarized absorbance and fluorescence from Ti:Sapphire at 300 K.

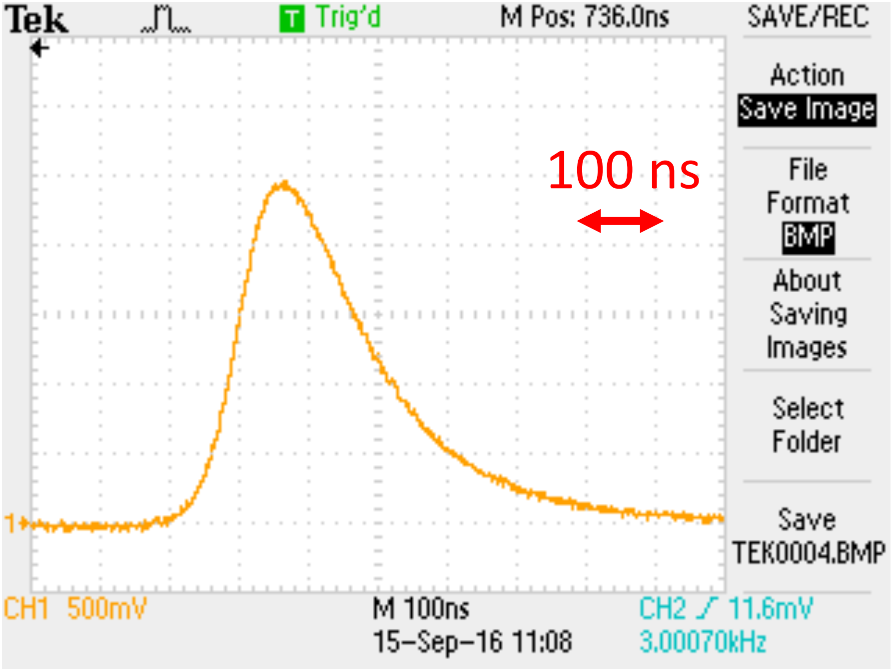
Development : Prototype long pulse

Developed a bit short cavity with high reflectivity mirrors

Expected pulse time duration : 200 ns



Confirmed 200 ns long pulse at 729 nm



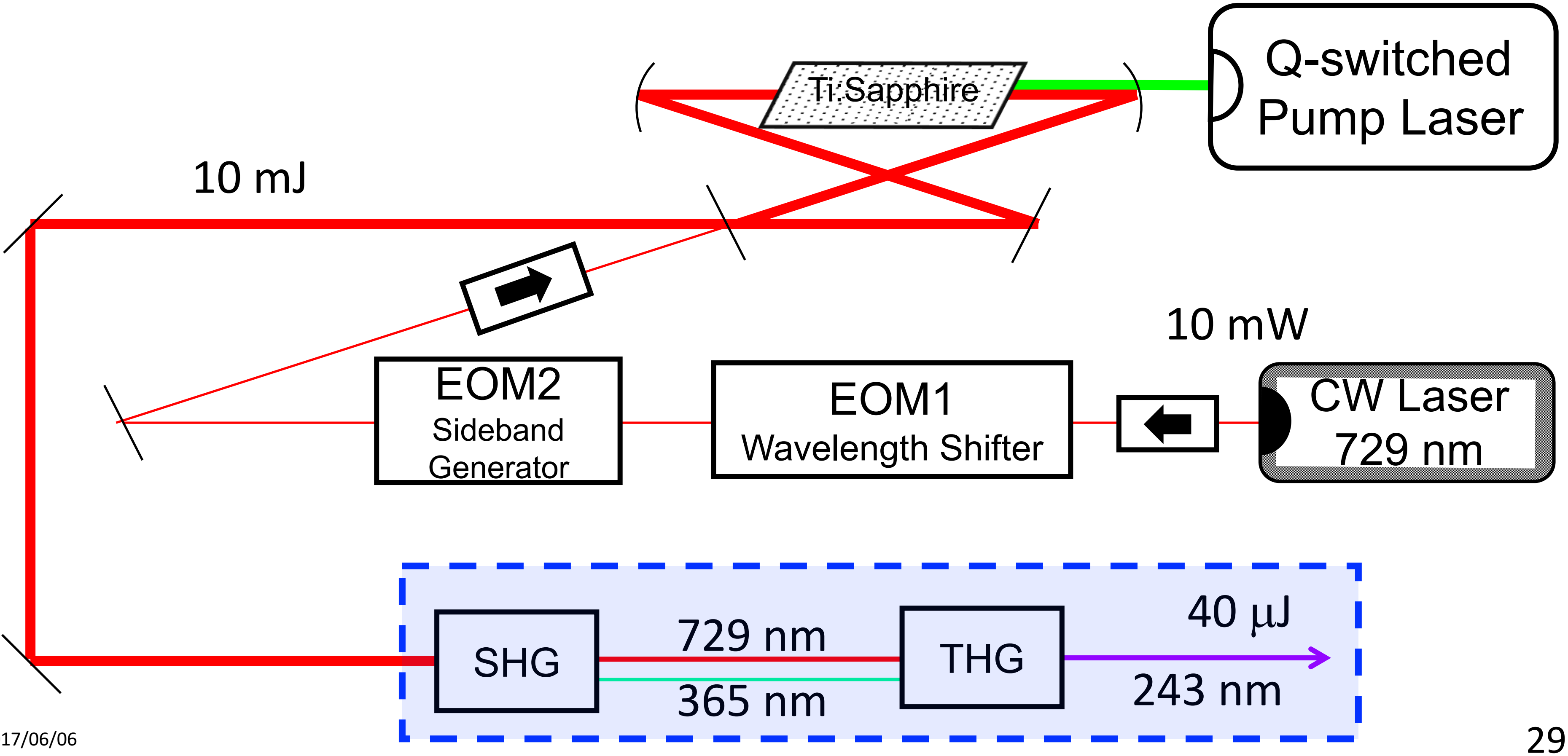
Pulse shape detected by photo diode detector

- ✓ Long pulse consisted with prototype design is achieved!
- ➢ Make larger cavity (L~4 m) to store light for longer time to achieve 300 ns time duration

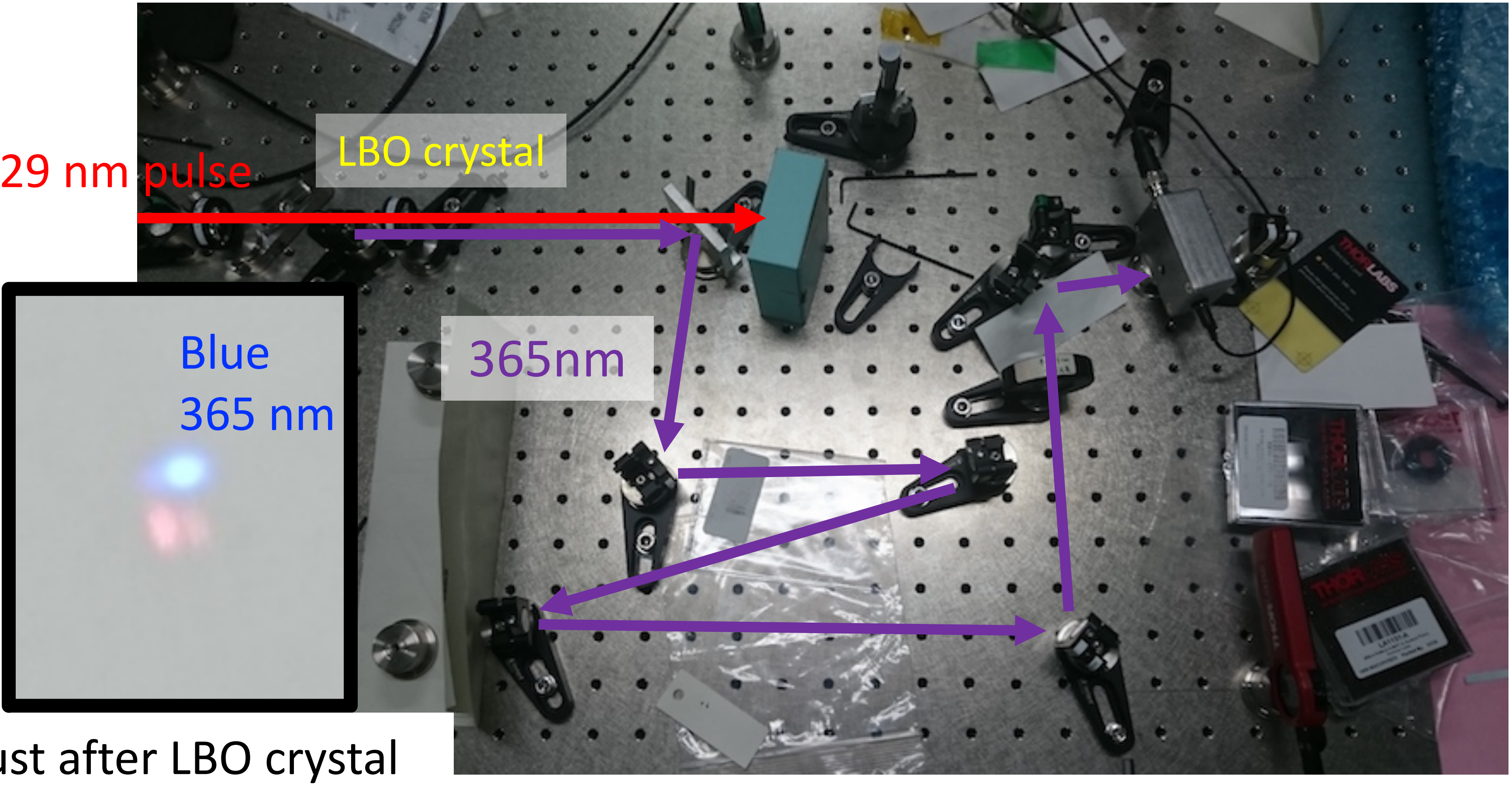
Special home-made laser system

Wavelength conversion using non-linear optics

- ✓ Complete!



SHG 729 nm → 365 nm is also done



Just after LBO crystal on paper

- Plan to complete other parts around one year, then conduct laser cooling experiment with modest Ps density

Summary

- Ps-BEC is a good candidate of the first BEC with anti-matter, which has a rich potentials on both fundamental and application physics

- New method has been proposed using dense positrons and cooling by the thermalization process and laser cooling. Thermaliztion process in cryogenic temperature has been measured for the first time, and it is efficient enough to realize BEC with laser cooling

- Cooling laser for Ps requires very special optics, so new system is currently under development. Prototype long pulse mode is confirmed to be possible.

- Developments on creating dense, focused positrons is also under study in parallel

- We will do laser cooling first and then go to BEC!

Backup

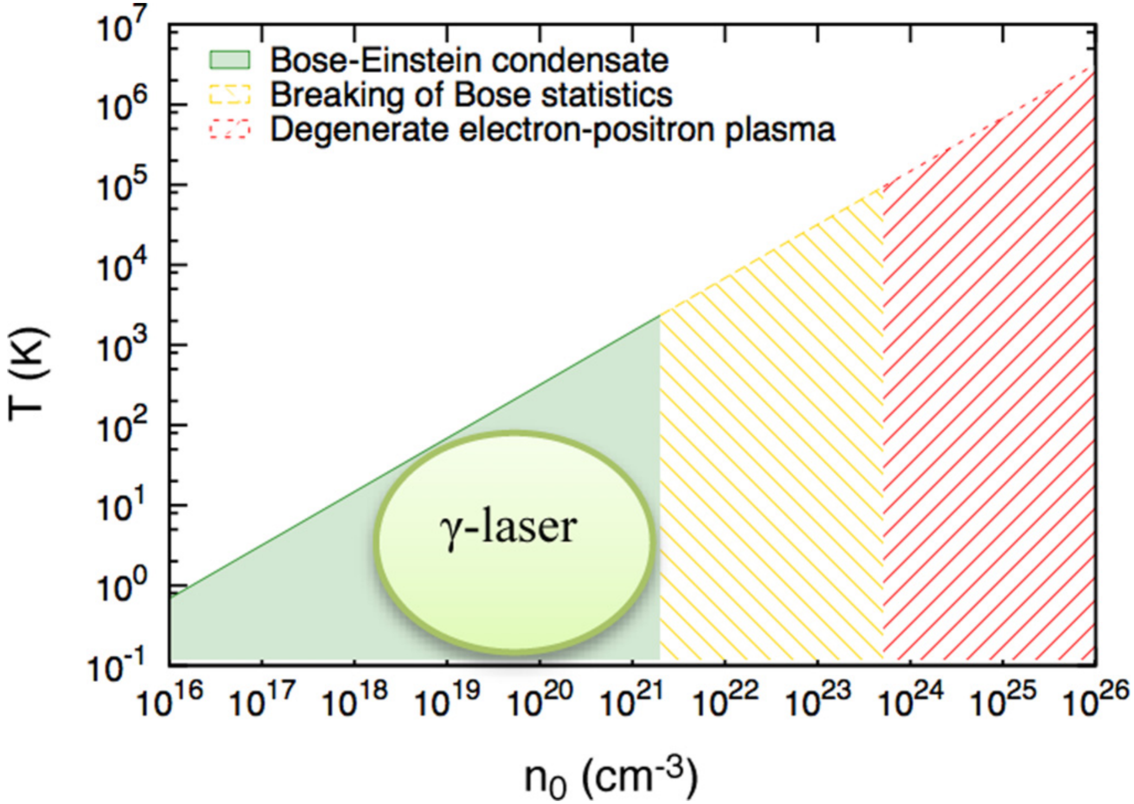
511 keV gamma-ray Laser

Decay from the BEC state (macroscopically occupied) enhances corrective decay

- Directive
- Coherent

BEC shape should be long in one direction (cigar shape) to have long interacting time between Ps and 511 keV photons

Ps-BEC will be formed in *ortho*, then stimulated into *para* by 203 GHz photon



511 keV photon density vs BEC density from Ref

1.5 cm x ϕ10 μm 長い Ps-BEC

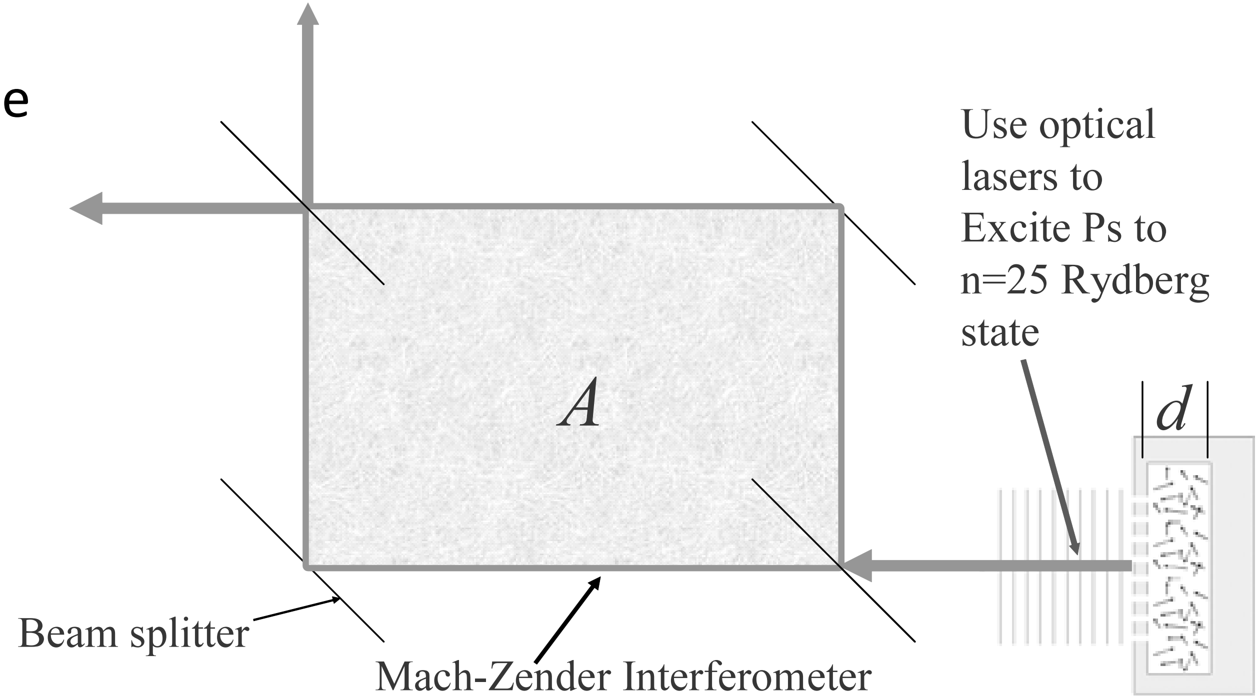
H. K. Avetissian *et al.* Phys. Rev. A 92, 023820 (2015).

Anti-matter Gravity Measurement

Difference of the paths will rotate relative phase between splited beams

It is said that in Ref: 20 cm legs would be enough to see anti-matter gravity's effect

Ps must be excited into Rydberg state to be long-lived (~miliseconds)



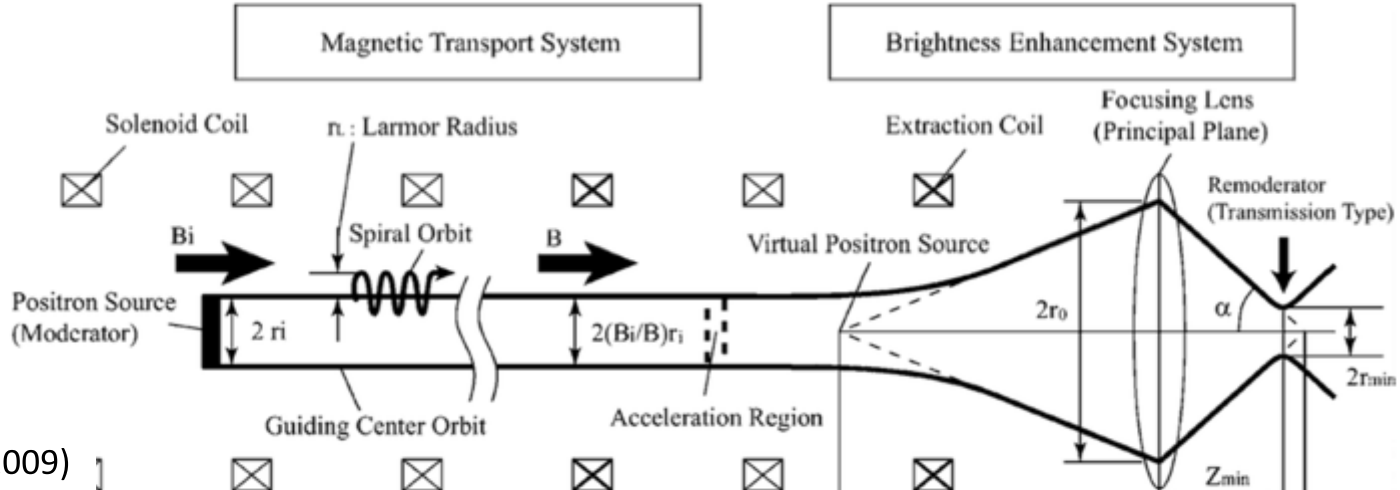
Interferometer experiment with Ps-BEC from Ref.

D. B. Cassidy et al. phys. stat. sol. (c) 4, No. 10 (2007)

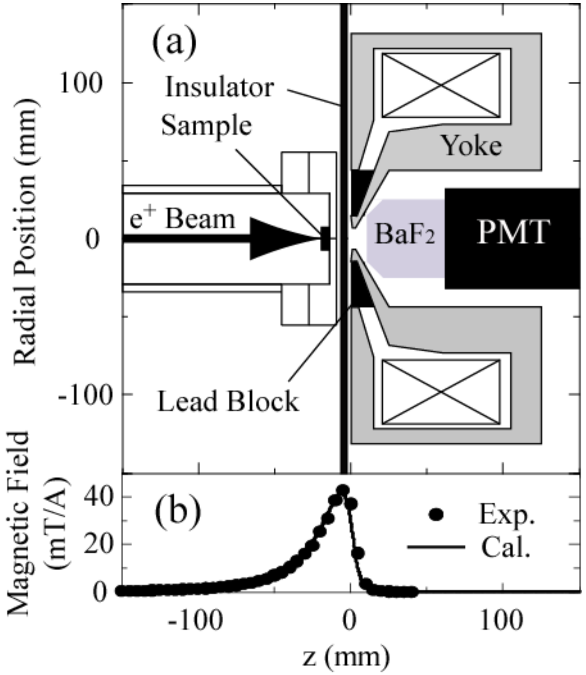
Focusing positrons

- Positron beam can be guided & focused by magnetic fields

From N. Oshima et al. J. Appl. Phys. 103, 094916(2008)



From Mat. Sci. Forum 607, 238(2009)



←↑ Positron Probe Microanalyzer system at AIST

- Multi-stage enhancements of intensity:
  1. Focusing by large gradient of mag-field
  2. Transmit moderator to reduce emittance

- This system has achieved 25μm(FWHM)
- Improvements are under studying for:
  1. Magnetic lenses
  2. Moderators

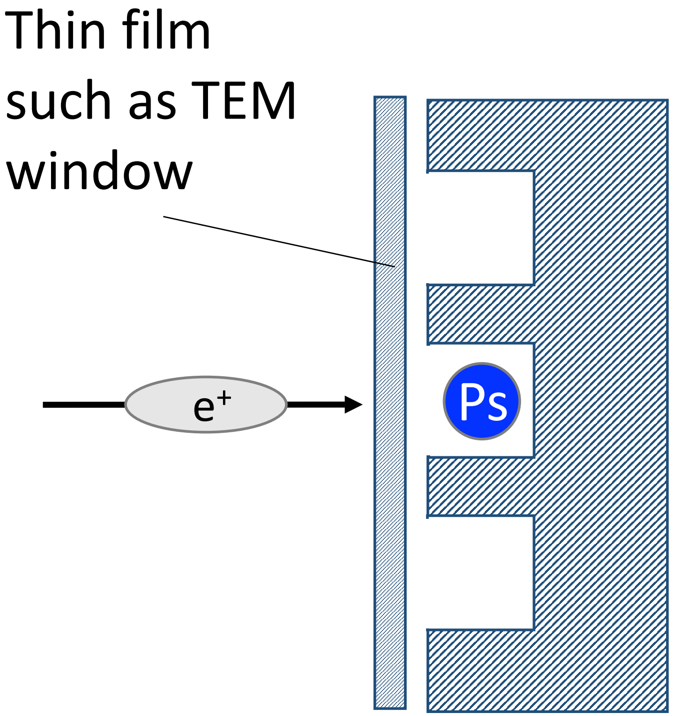
光透明シリカキャビティの開発

次のステップはレーザー冷却
光に透明なPs生成・閉じ込めキャビティが必要

- 100 nm 微細加工可能な機能性シリカガラスが候補

必要要求

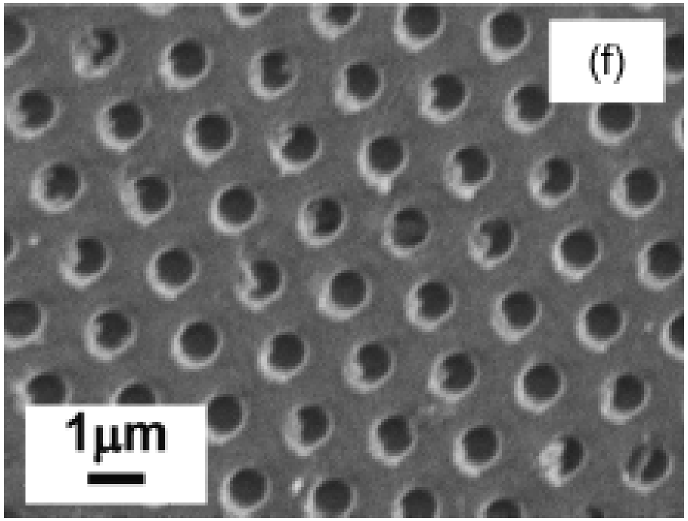
1. 高いポジトロニウム生成率



表面穴加工した
シリカガラス

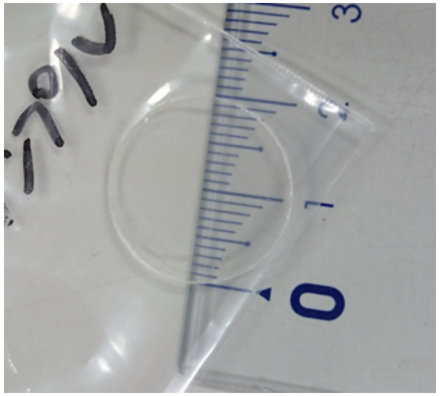
100 nmオーダーの穴加工できる

（表面）



S. Fujino *et al.* J. Am. Ceram. Soc., Vo.94[8] 2319-2322 (2011)

機能性シリカガラスの性質

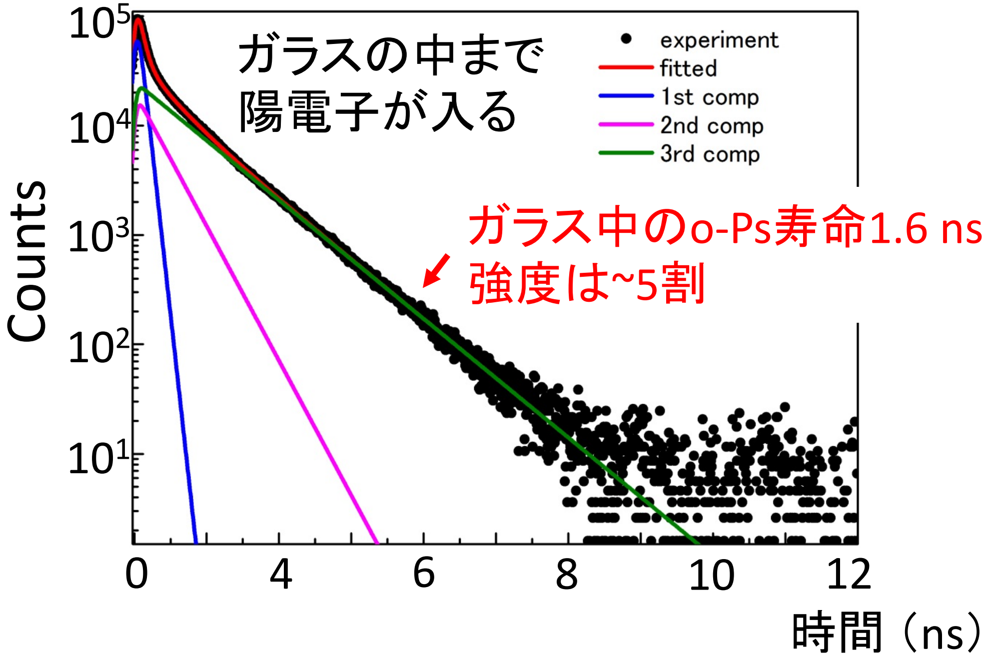


作ったガラス

透過スペクトル

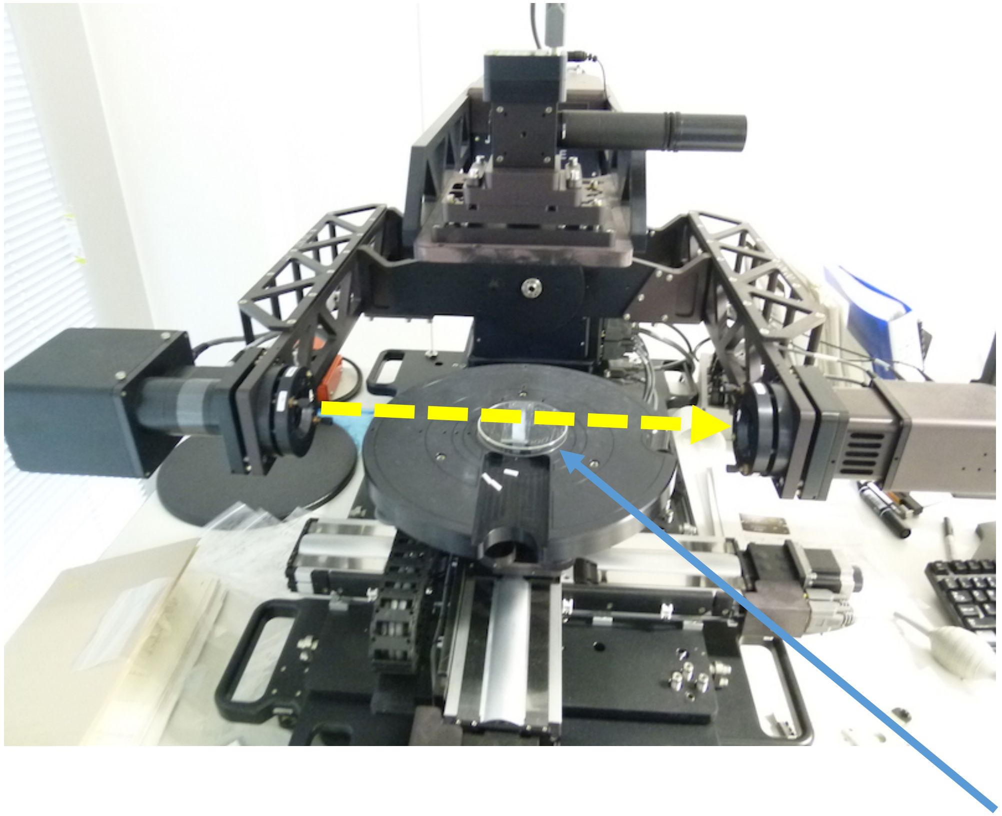
常温では光透過率OK
極低温でも実測する

- ^{22}Na由来の陽電子（数百 keV）を入射したときの崩壊寿命



通常のシリカガラスと同程度の高いo-Ps生成率（5割以上）を確認
現在、産総研にて、低速陽電子（数keV）を入射して、ガラス表面から飛び出すPs生成の確認実験を実施中

エリプソメーターによる透過率測定



白色入射光
190~1600nm

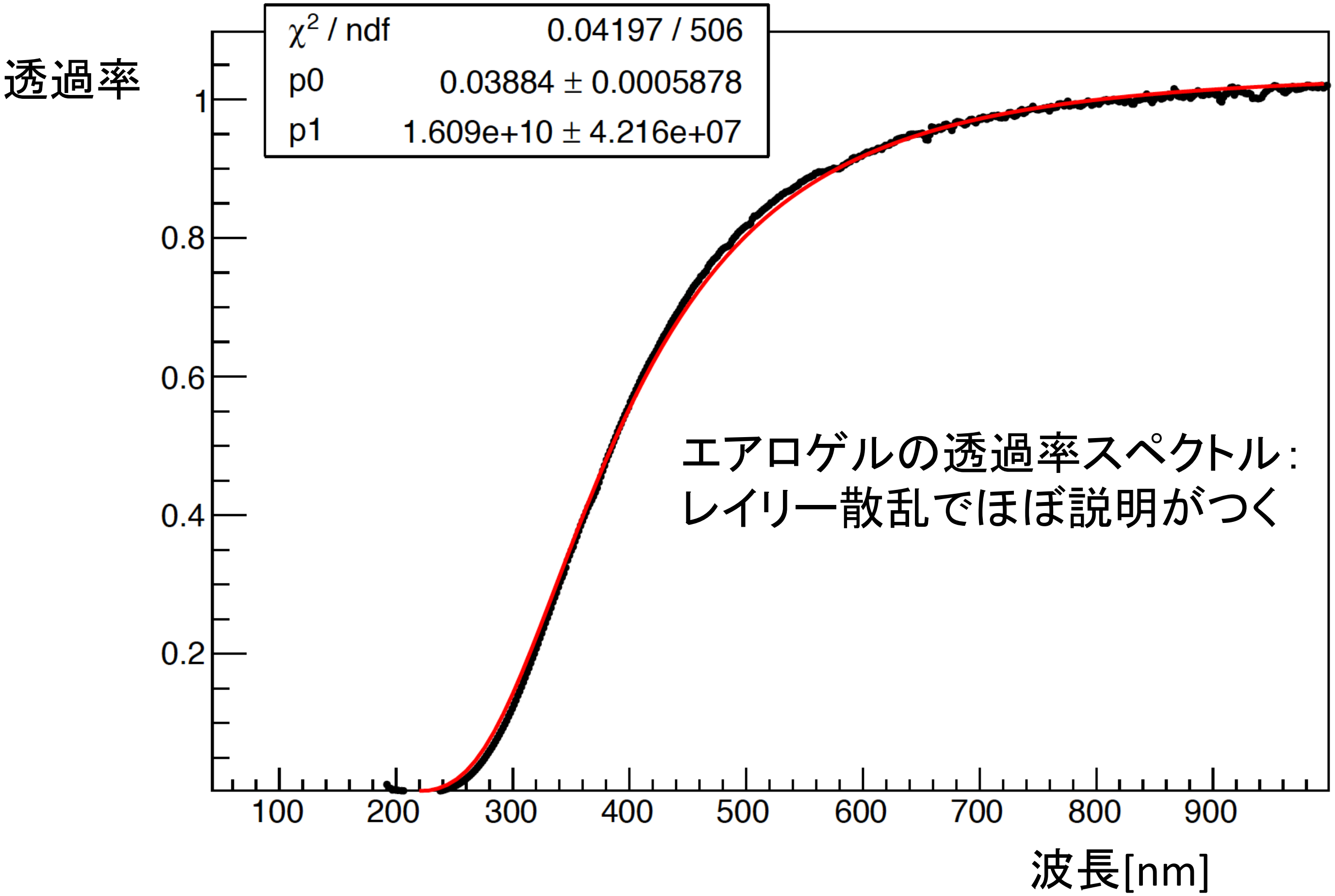
受光面

試料（エアロゲル）

試料なしの時とありの時とで、
波長ごとに受光面に入る光量の比を測定
→透過率スペクトル

エリプソメーターによる透過率測定

- 測定結果の一例：ほぼレイリー散乱でFit可能
  - ➢現時点でエアロゲルでの光の吸収は確認されていない



エアロゲルの透過率スペクトル：
レイリー散乱でほぼ説明がつく

低温での Ps 生成率とレーザー

H. Saito and T. Hyodo, "Quenching of positronium by surface paramagnetic centers in ultraviolet- and positron-irradiated fine oxide grains", Phys. Rev. B **60**, 11070 (1999).

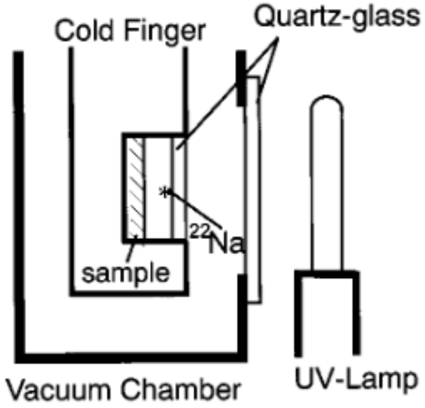
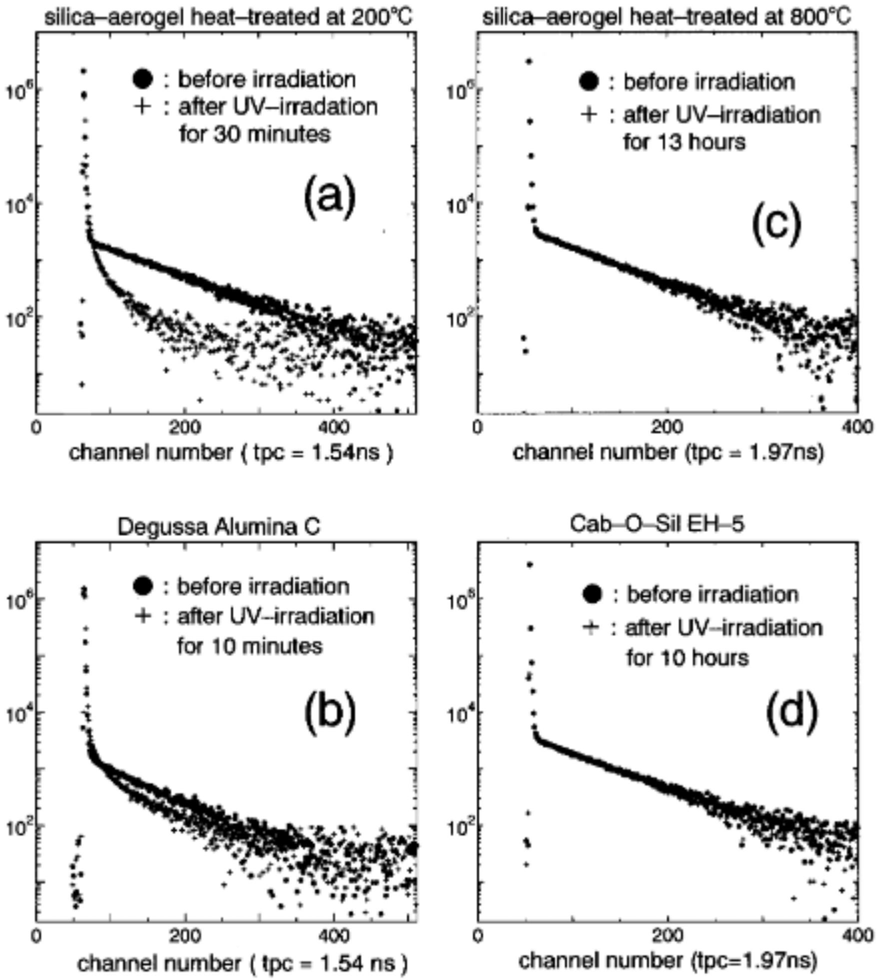


FIG. 1. Schematic diagram of the sample chamber for positron lifetime and Doppler broadening measurements under UV irradiation.


silica–aerogel heat–treated at 200℃

silica–aerogel heat–treated at 800℃

Degussa Alumina C

Cab–O–Sil EH–5

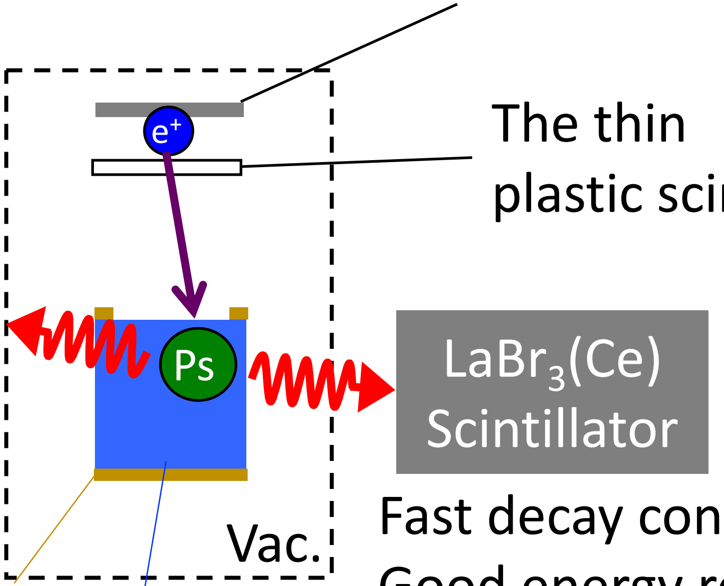
FIG. 3. Positron-lifetime spectra before and after UV irradiation for (a) silica aerogel heat treated at 200 °C, (b) Degussa Alumina C, (c) silica aerogel heat treated at 800 °C, and (d) Cab-O-Sil.

Components for the measurement

- Positron comes from ^{22}Na RI
- Detected by a thin plastic scintillator
- Acquire t = 0 (Ps creation timing)

- Get electron from silica and form Ps in pore
- Ps collides many times with the silica with various temp.
- Annihilate into γ rays by Pick-off / self annihilation

- Detect γ rays by $LaBr_3(Ce)$ scintillator
- Count Pick-off annihilation events vs Ps life



^{22}Na radio isotope

The thin
plastic scintillator

$LaBr_3(Ce)$
Scintillator

Fast decay constant : 20 ns
Good energy resolution :
4% at 511 keV (FWHM)

Cold stage

Silica aerogel : porous material made by silica
Density: 0.11 g/cm^3 → Mean free path 60 nm

Deducing Pick-off annihilation rate

Use difference between energy spectra of Pick-off 2γ/Self 3γ

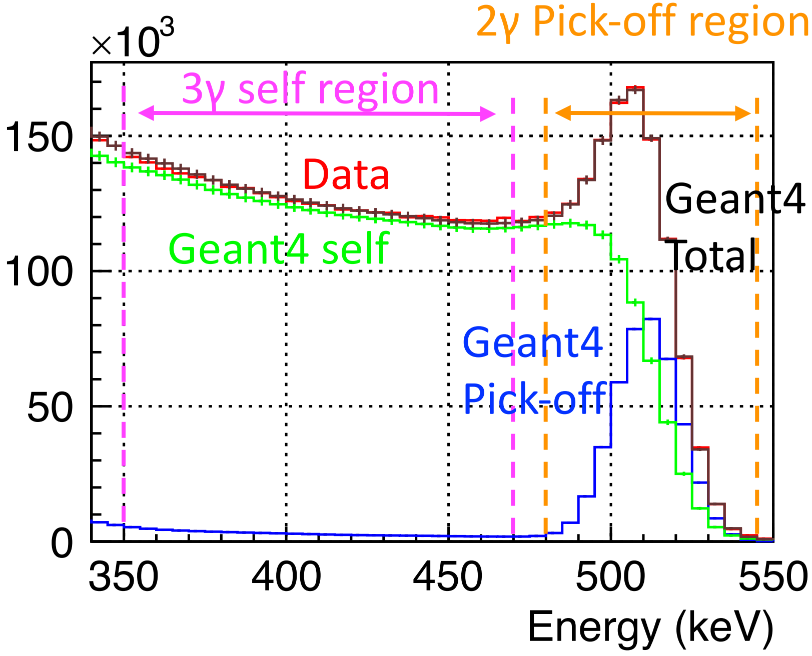
Pick-off 2γ : 511 keV peak
Self 3γ : Continuous
Define energy regions to enhance each annihilation event

Self annihilation rate λ_3 is constant
$N_{in\,3\gamma}$: Remained number of Ps
$N_{in\,2\gamma}$: Pick-off rate

$$N_{in\,3\gamma} = \varepsilon_3\lambda_3\int dt\; N_{Ps} + 2\gamma\ \text{Contamination}$$

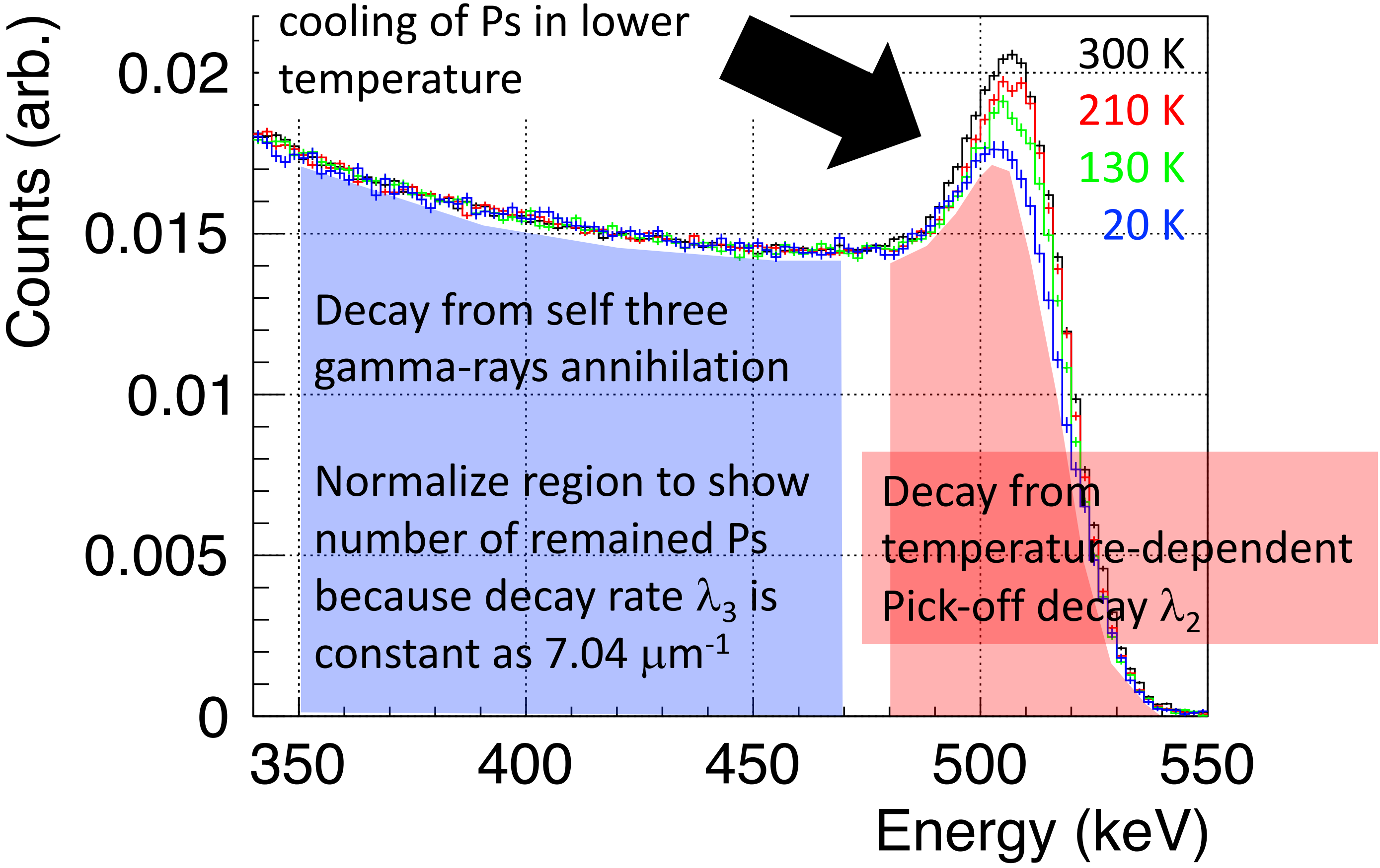
$$N_{in\,2\gamma} = \int dt\; \varepsilon_2\lambda_2(t)N_{Ps} + 3\gamma\ \text{Contamination}$$

$$\Rightarrow \quad \frac{\langle\lambda_2(t)\rangle}{\lambda_3} = \frac{\varepsilon_3 N_{in\,2\gamma}}{\varepsilon_2 N_{in\,3\gamma}}$$



Recorded energy spectrum
(Ps life 30 - 300 ns)
Accidental events are subtracted by energy spectrum in 1200 - 1500 ns

After rejecting contamination
Detection efficiencies are by Geant4



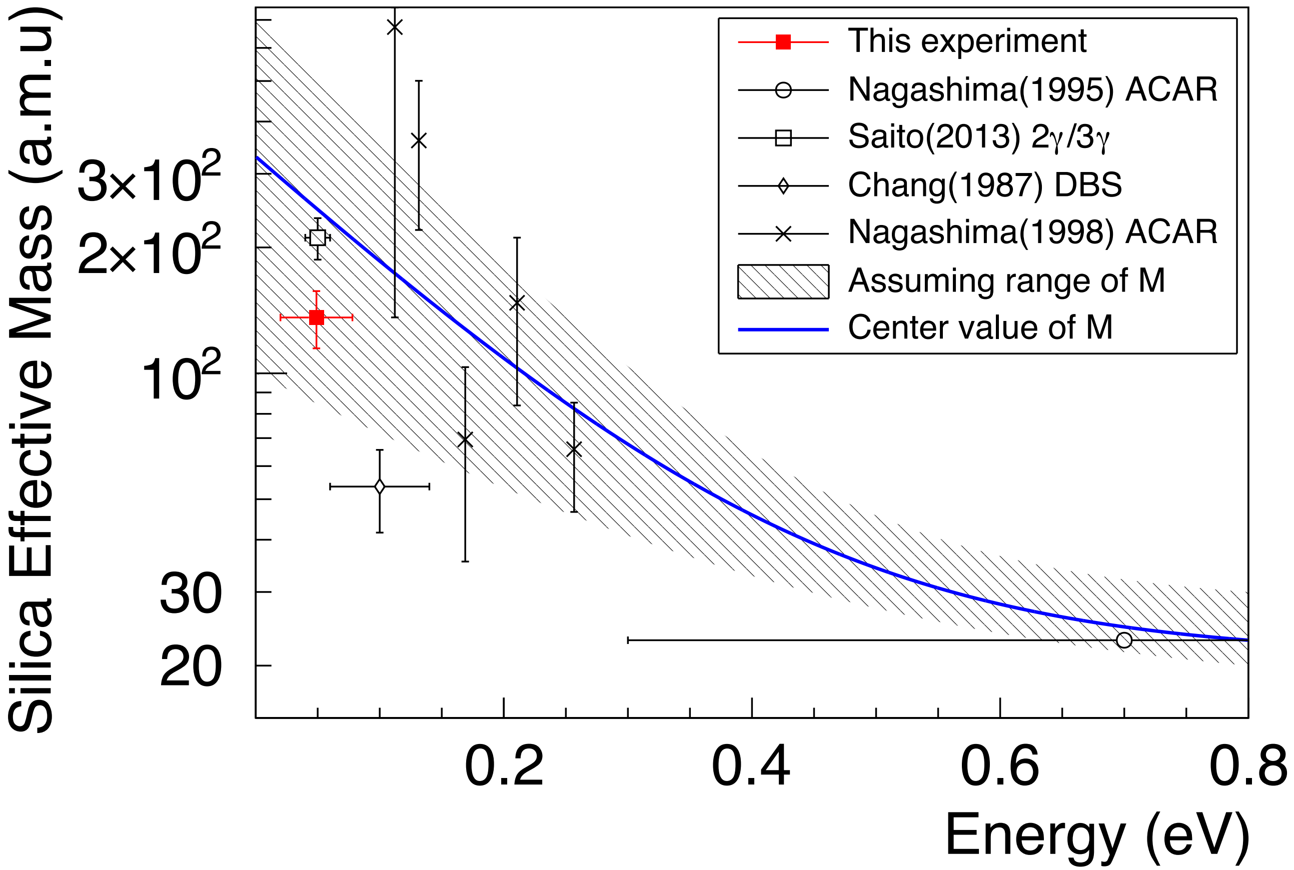
Less Pick-off by further cooling of Ps in lower temperature

Decay from self three gamma-rays annihilation

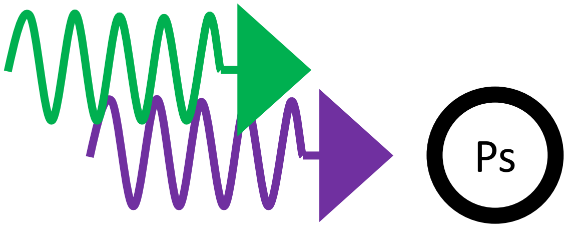
Normalize region to show number of remained Ps because decay rate λ_3 is constant as 7.04 μm^{-1}

Decay from temperature-dependent Pick-off decay λ_2

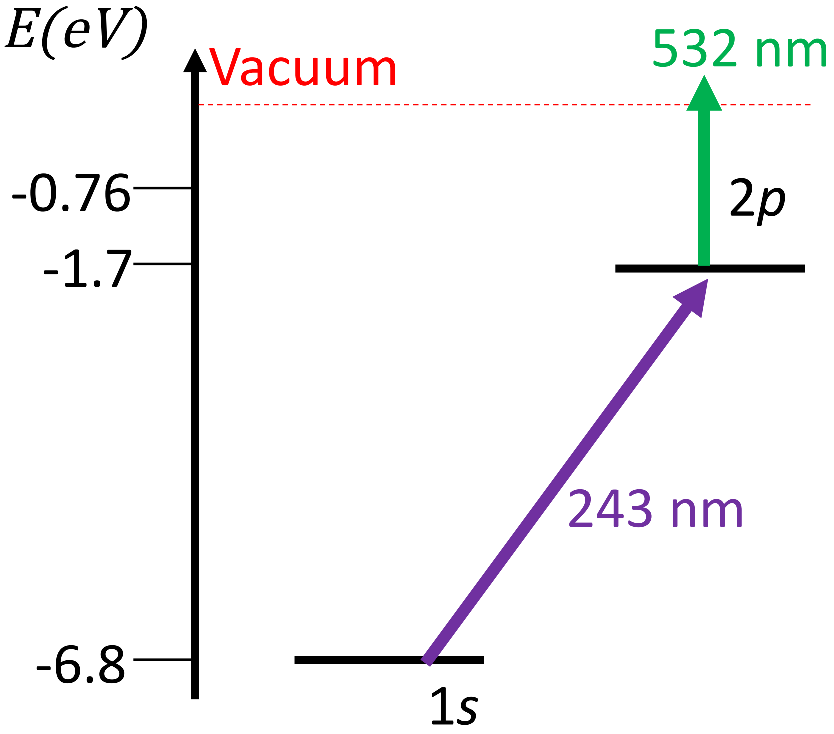
Acquired energy spectrum of annihilation gamma-rays in 30 - 600 ns from Ps creation

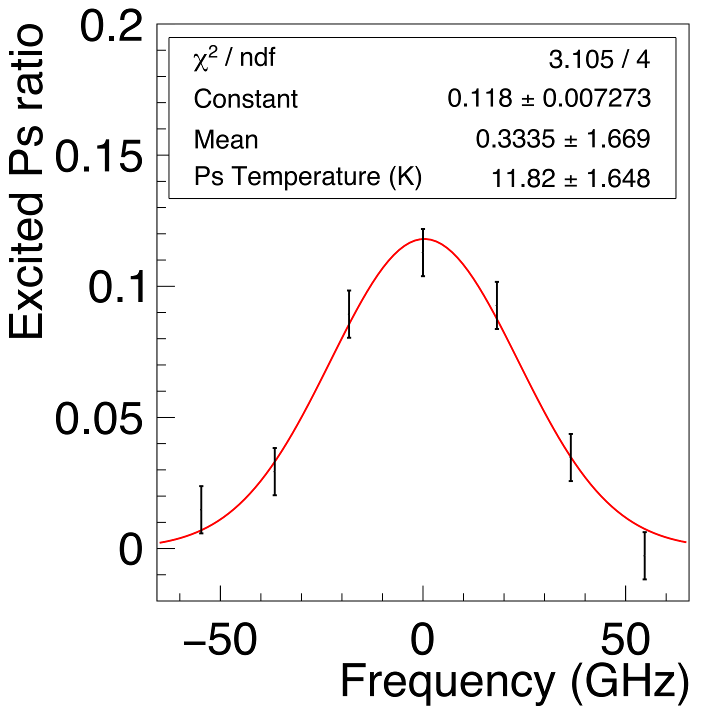

Silica Effective Mass (a.m.u)
3×10²
2×10²
10²
30
20
0.2
0.4
0.6
0.8
Energy (eV)
This experiment
Nagashima(1995) ACAR
Saito(2013) 2γ/3γ
Chang(1987) DBS
Nagashima(1998) ACAR
Assuming range of M
Center value of M

Doppler Spectroscopy

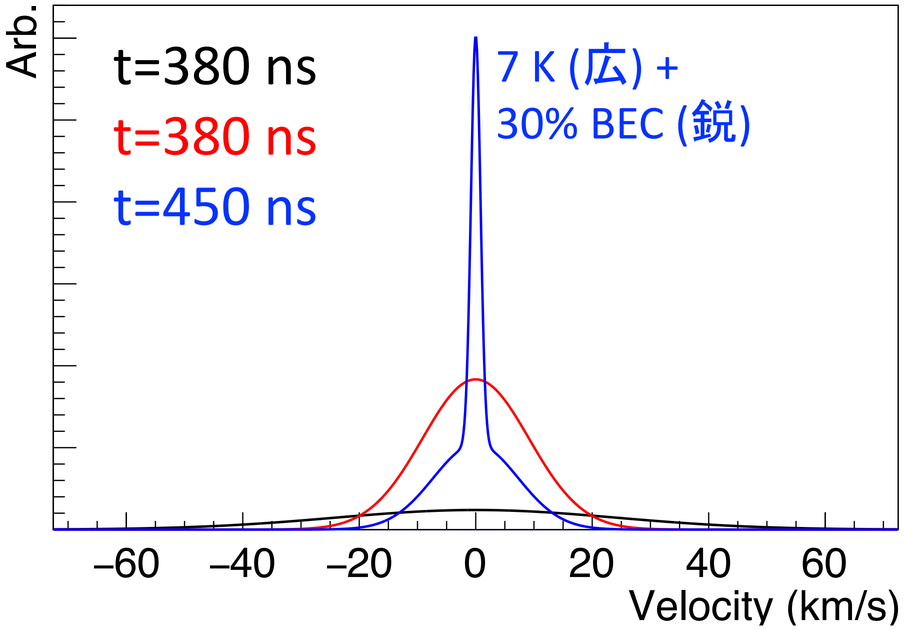


243 nm & 532 nm pulsed laser

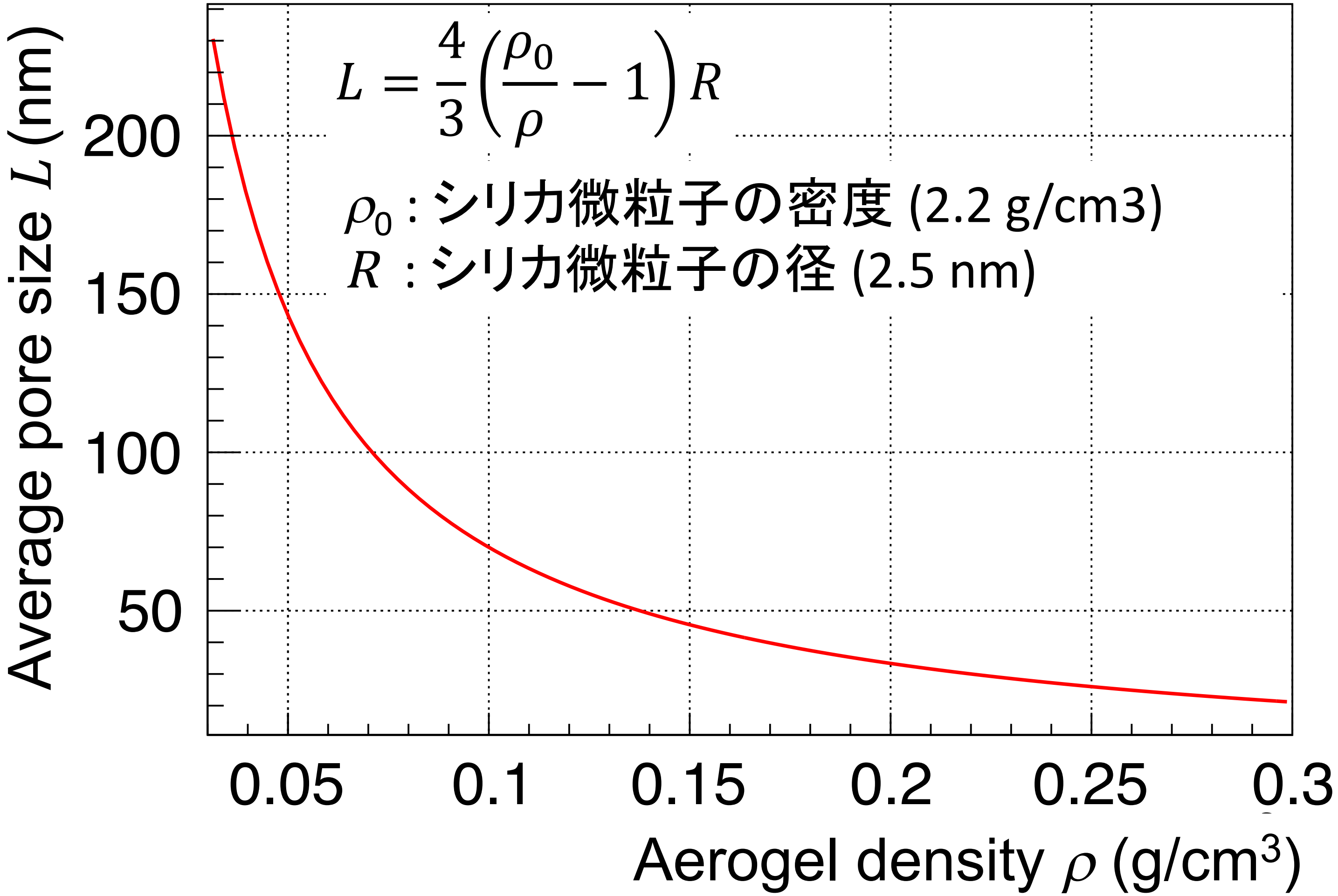




Expected resonance curve for 10 K Ps with 10^7 Ps in total, at t=300 ns


Arb.
t=380 ns
t=380 ns
t=450 ns
7 K (広) +
30% BEC (鋭)
−60
−40
−20
0
20
40
60
Velocity (km/s)

シリカエアロゲルの空孔径

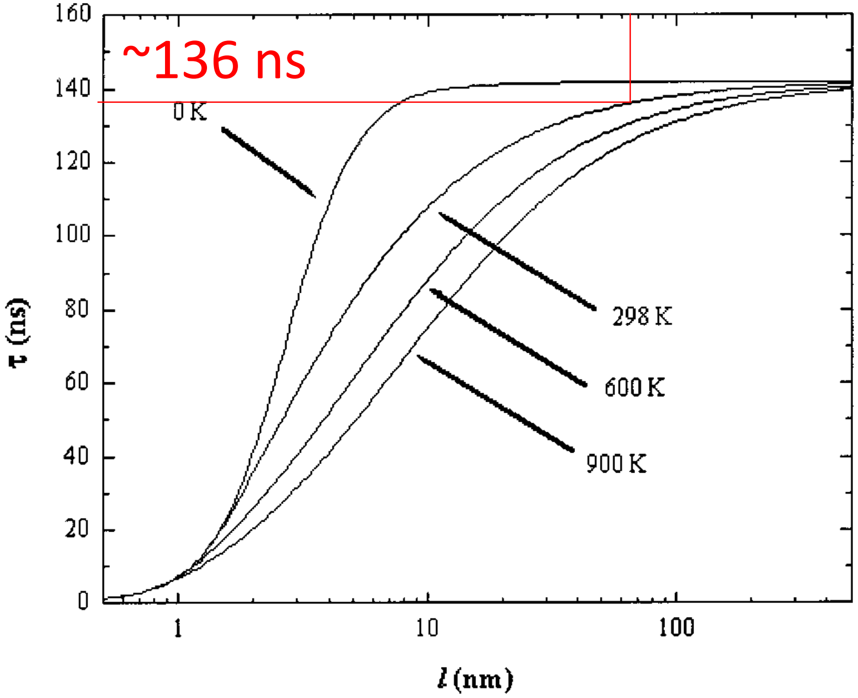


$$L = \frac{4}{3}\left(\frac{\rho_0}{\rho} - 1\right) R$$

ρ_0 : シリカ微粒子の密度 (2.2 g/cm3)
R : シリカ微粒子の径 (2.5 nm)

Phys. Rev. A 52, 258 (1995)

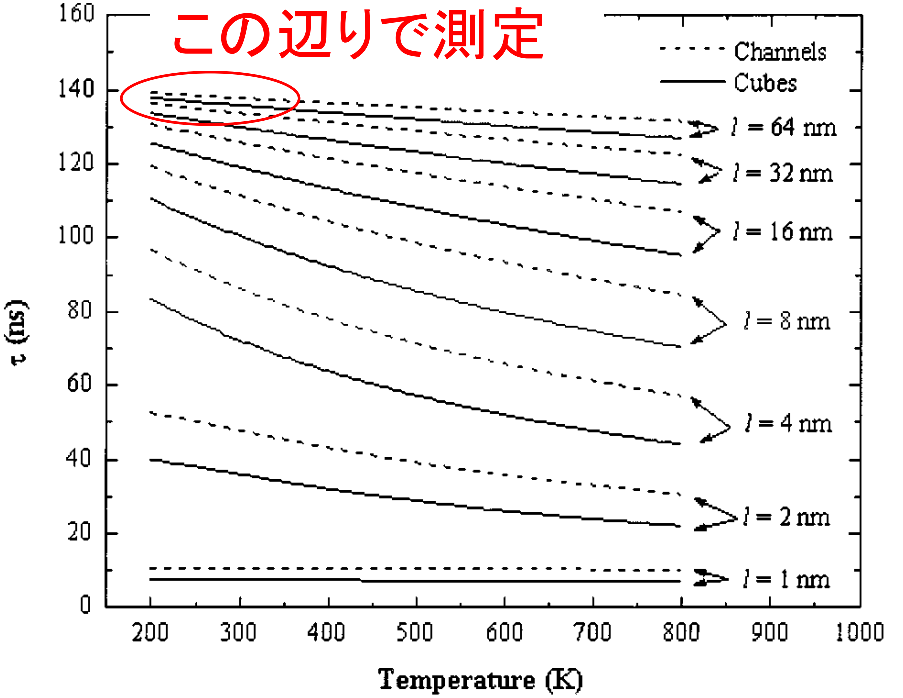
空孔中での陽電子寿命



使ったシリカゲル：63 nm

~136 ns

Figure 3. Temperature dependence of the Ps lifetime for cubical pores in the RTE calculation. The mean free path, *l*, is related to the cube side length by $l = {}^{2}/_{3}\mathrm{a}$.



この辺りで測定

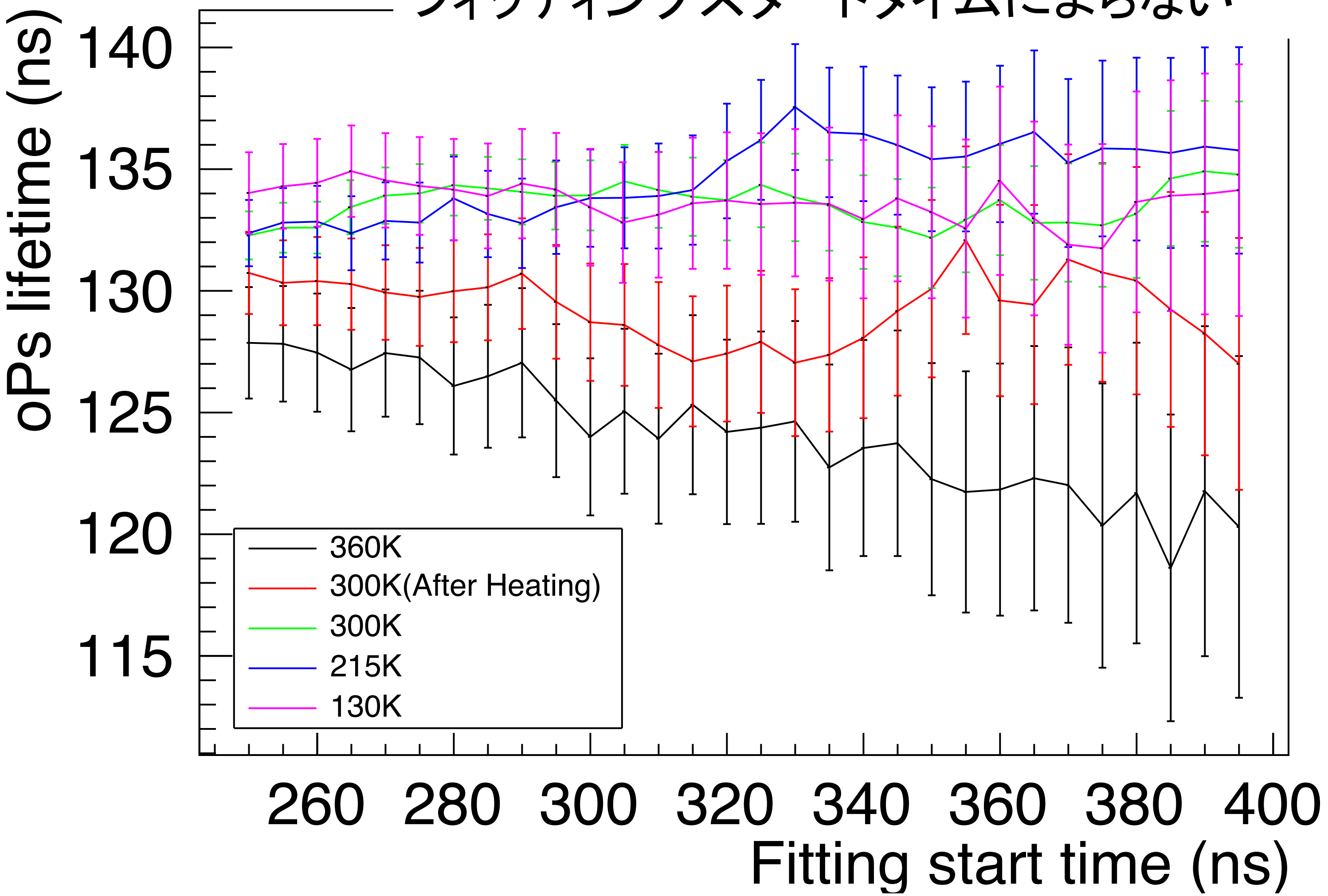
Figure 4. Ps lifetime vs temperature for a variety of mean free paths using both 2D and 3D pores in the calculation.

Rectangular Tao-Eldrup model =RTE (J. Phys. Chem. B **2001**, 105, 4657-4662)

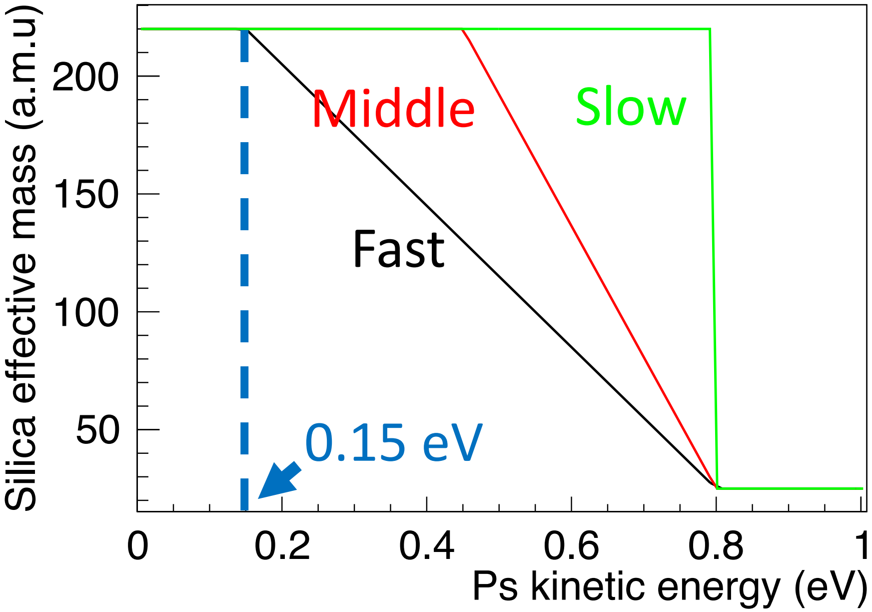
熱化後のPs寿命

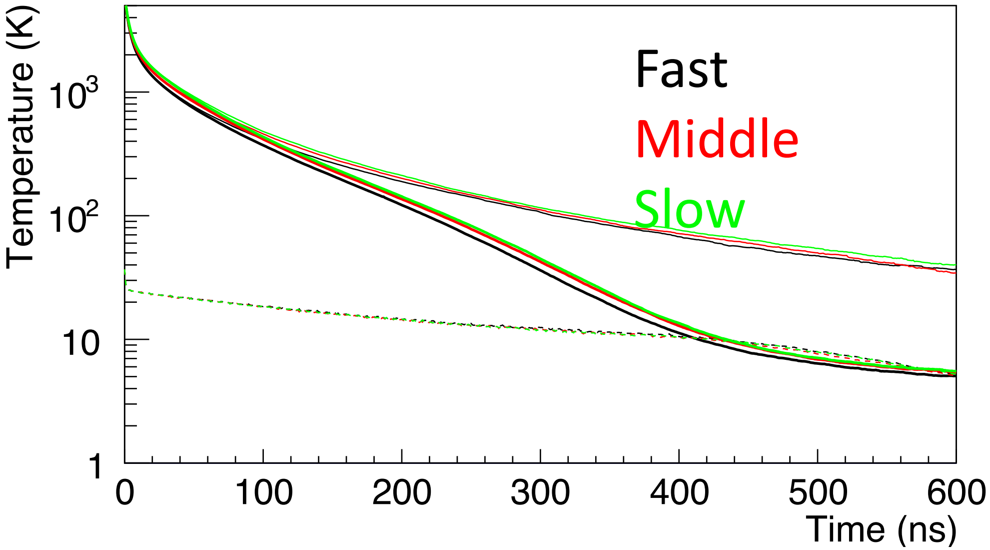
カット：QLa<540 keV

エラーの範囲内で
フィッティングスタートタイムによらない



E_{Ps}が高いときの効果





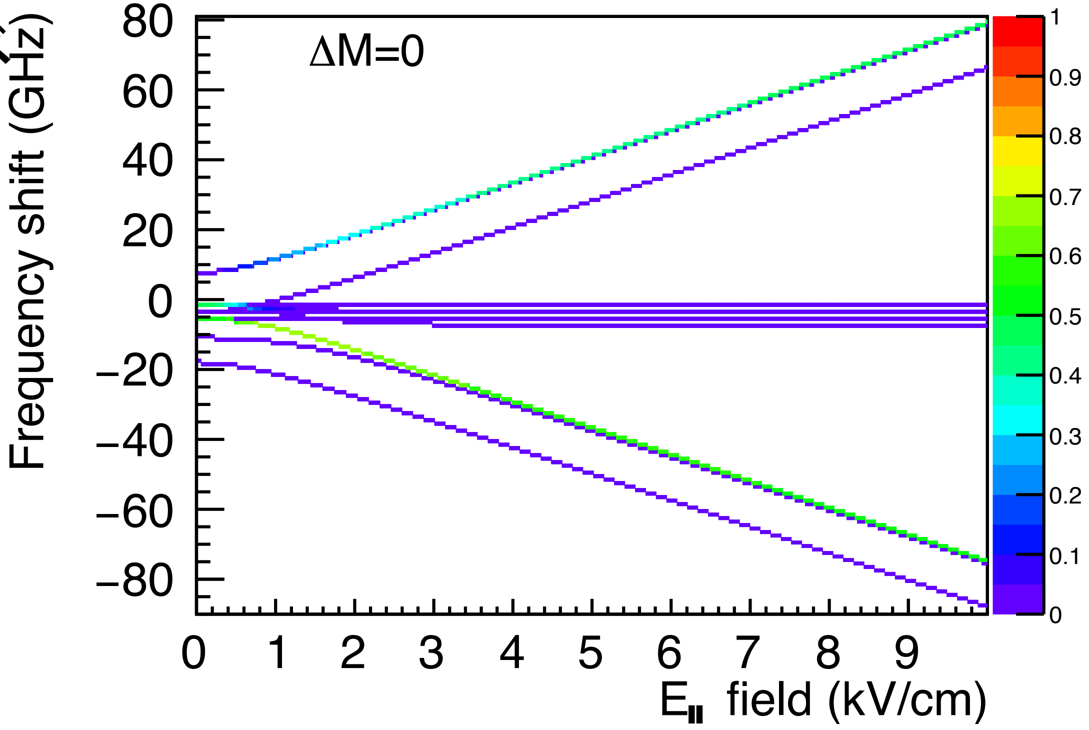
10 ns 弱，0.15 eVへの到達時間が変わる（割合では30%）
Psはエネルギー分布が広いため，0.15 eV以下の平均エネルギーでも熱化関数の形は異なる

電場($E_{//}$)の効果
エネルギーレベル

電場があるとエネルギー　レベルが変化してしまい，　レーザー冷却ができない

このシフトは
離調-周波数幅(2σ)
=240GHz – 140GHz
=100GHz
以下に抑えたい

エネルギーレベルからの要請
→ 電場 $E_{//}$<10 kV/cm



z軸は遷移確率を表す
ΔMは遷移の種類
(レーザー偏光に依存)

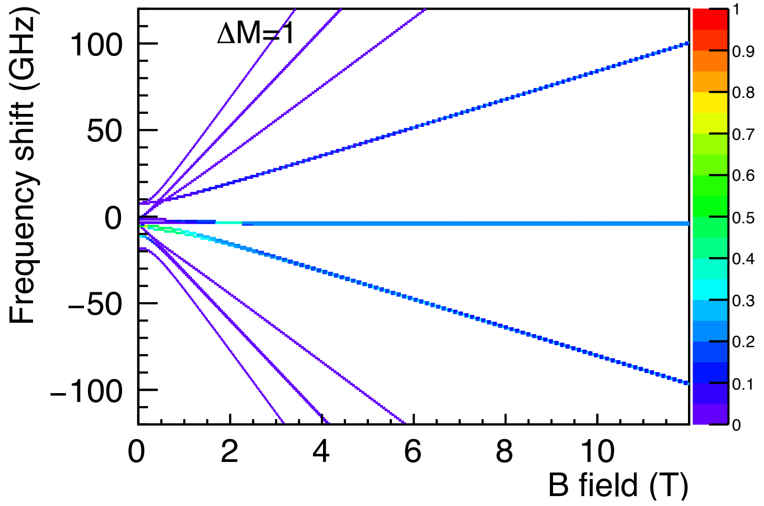
磁場(B)の効果
エネルギーレベル

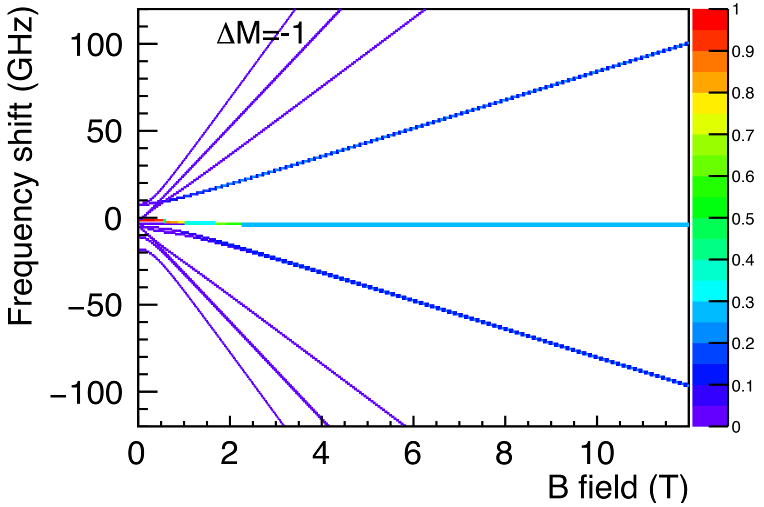
動的シュタルクを通して
エネルギーレベルを変化

Ps 500Kの速度と仮定
(>500K, レーザー冷却不要)

このシフトも100GHzに抑える

エネルギーレベルからの要請
→ 磁場 B<12T



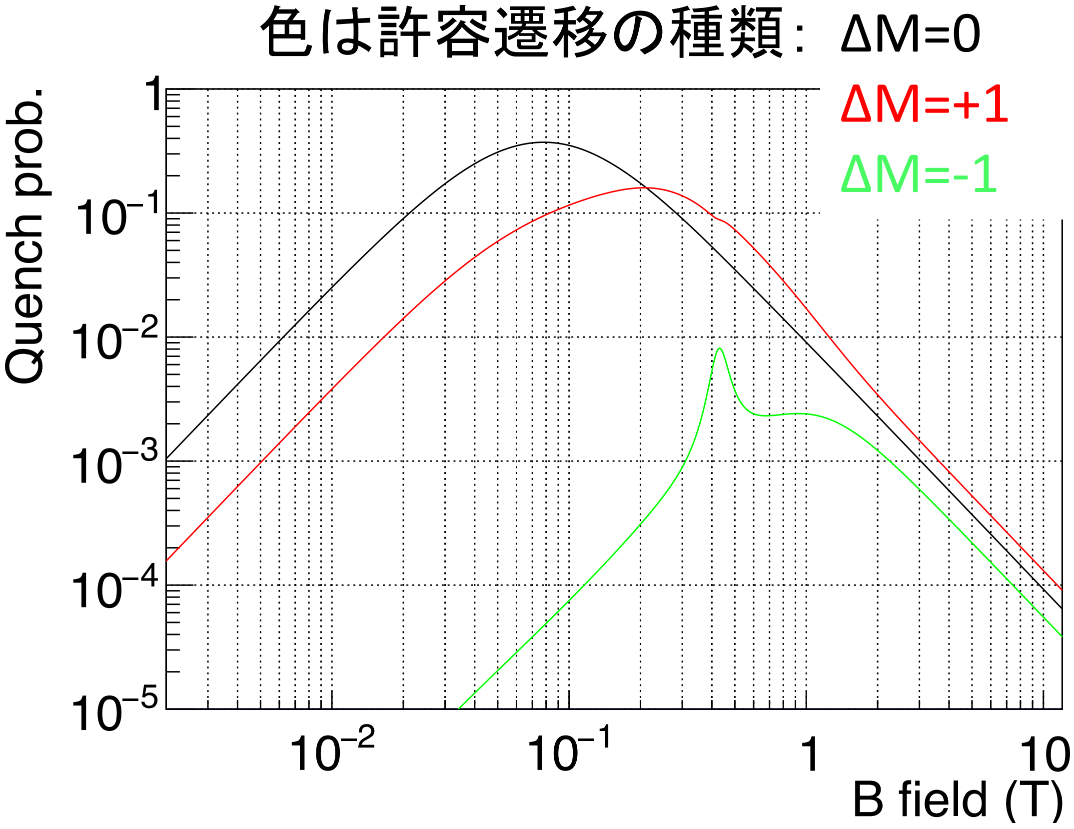


電磁場中でのクエンチ

以降もPs 500Kの速度と仮定

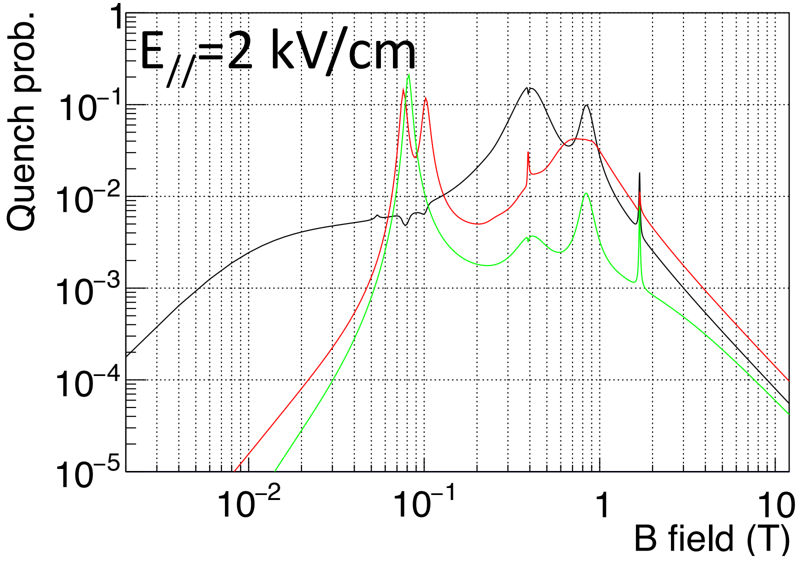
400nsの冷却期間で,
約300回1*s*↔2*p*繰り返す

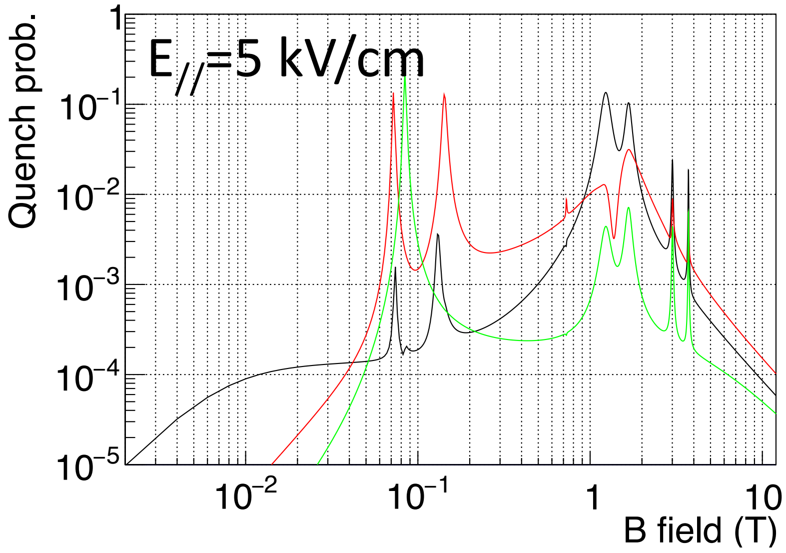
クエンチ確率	生き残り
0.002 (2x10^{-3})	55%
0.001 (1x10^{-3})	74%
0.0005 (5x10^{-4})	86%

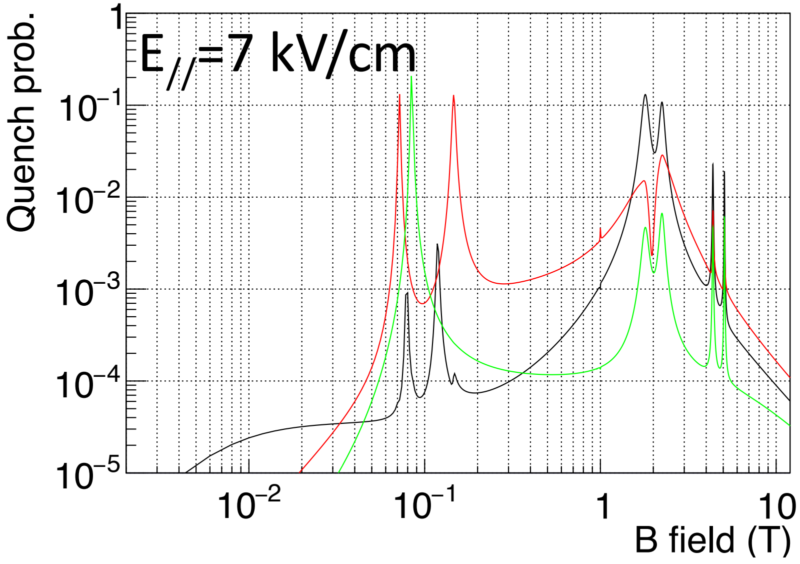

色は許容遷移の種類:

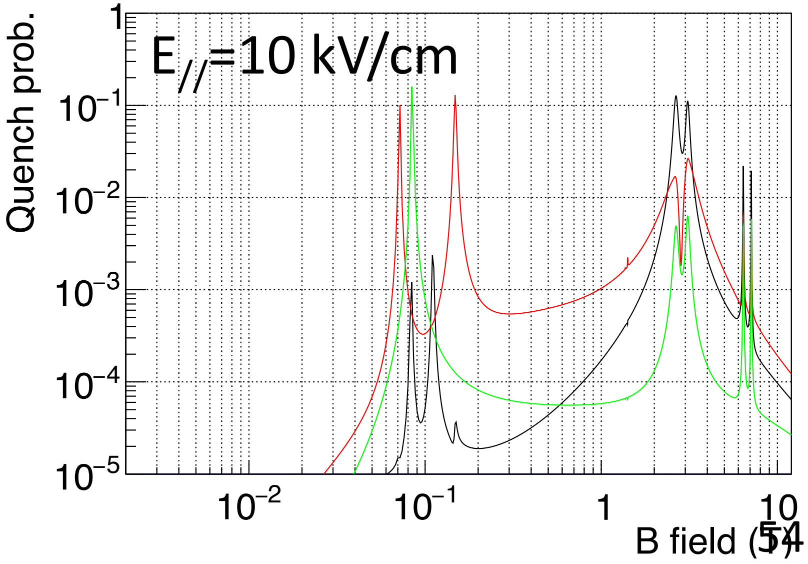
1*s* ↔ 2*p* 1サイクルあたりの
クエンチ確率 at $E_{//}$=0kV/cm

電場（$E_{//}$）の効果・クエンチ

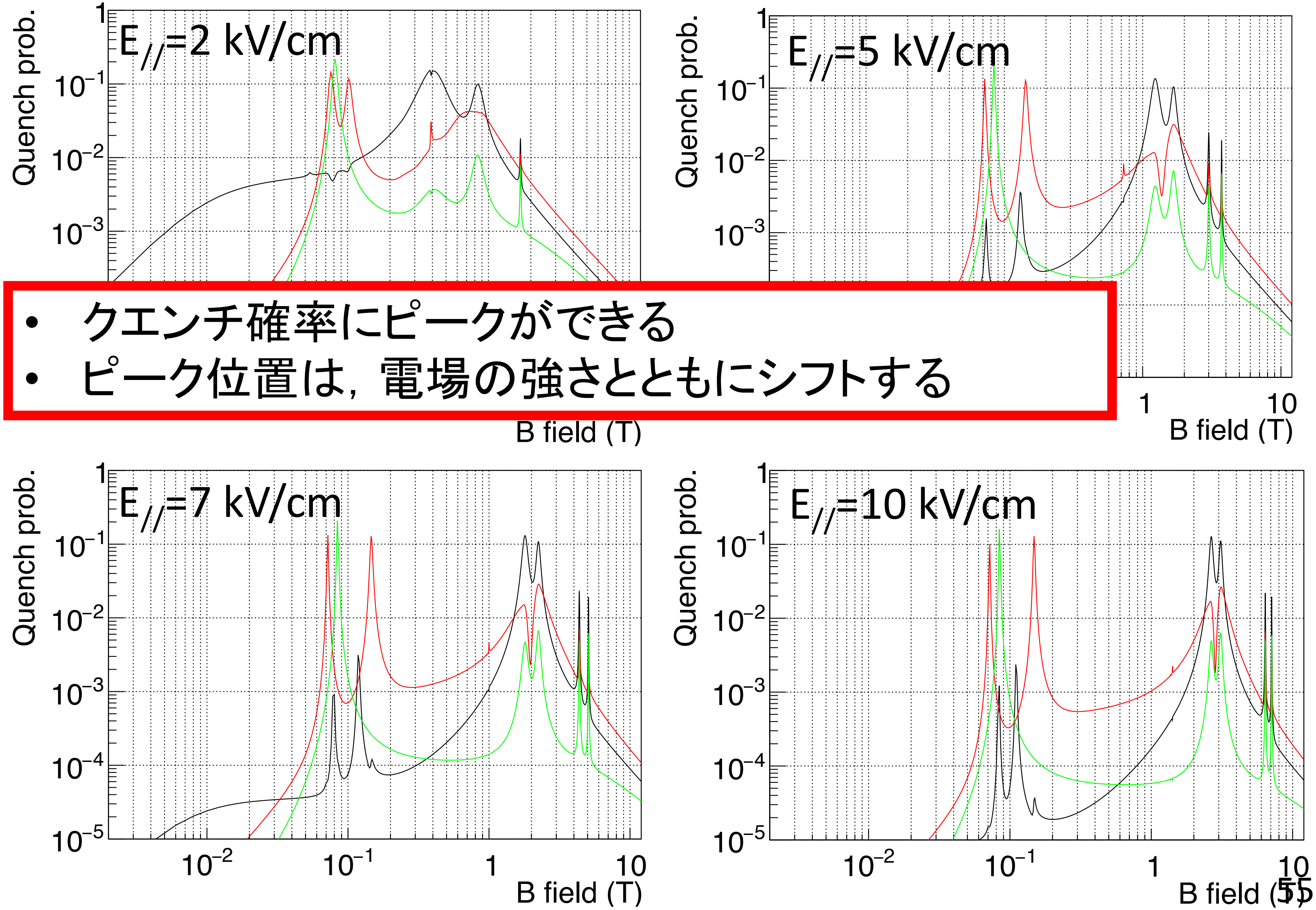

E//=2 kV/cm
Quench prob.
1
10−1
10−2
10−3
10−4
10−5
10−2
10−1
1
10
B field (T)


E//=5 kV/cm
Quench prob.
1
10−1
10−2
10−3
10−4
10−5
10−2
10−1
1
10
B field (T)


E//=7 kV/cm
Quench prob.
1
10−1
10−2
10−3
10−4
10−5
10−2
10−1
1
10
B field (T)


E//=10 kV/cm
Quench prob.
1
10−1
10−2
10−3
10−4
10−5
10−2
10−1
1
10
B field (T)

電場（$E_{//}$）の効果・クエンチ



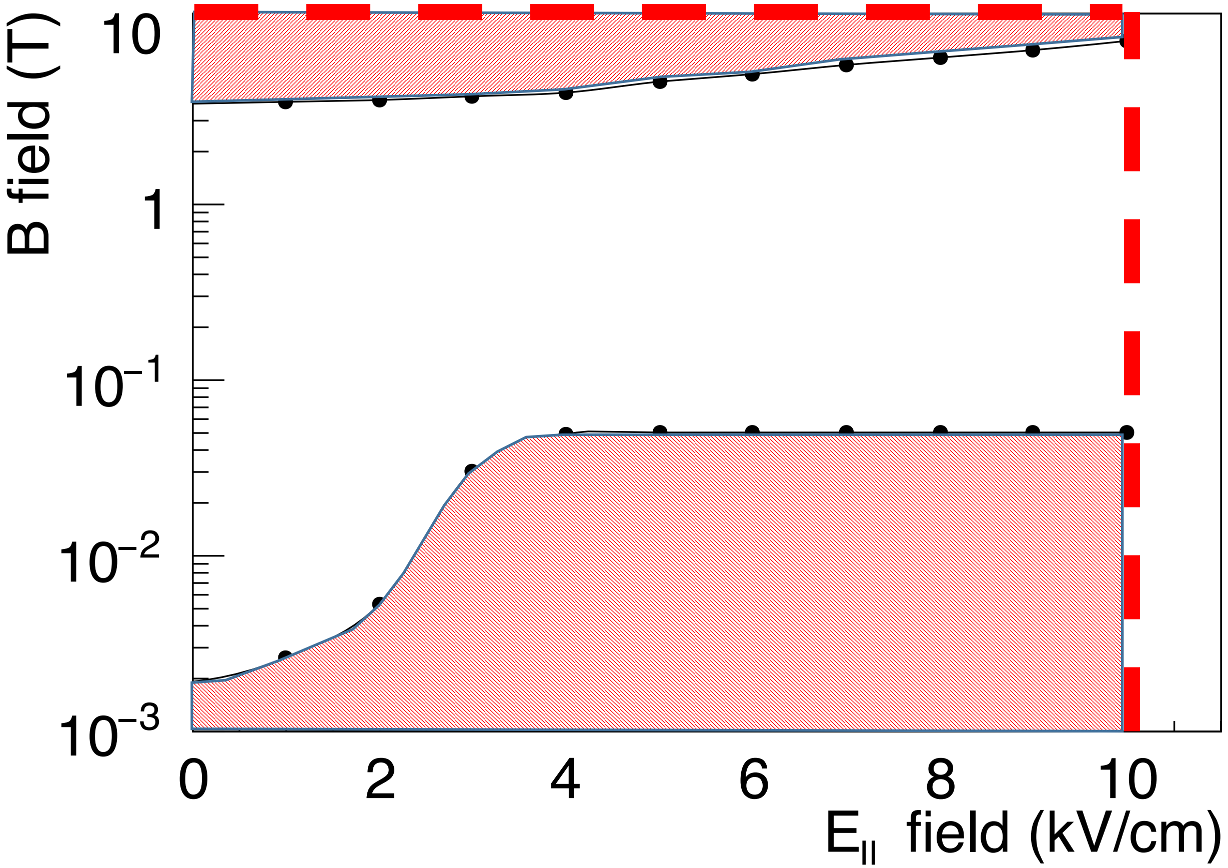
- クエンチ確率にピークができる
- ピーク位置は，電場の強さとともにシフトする

必要な電場 ($E_{//}$) vs 磁場 (B)

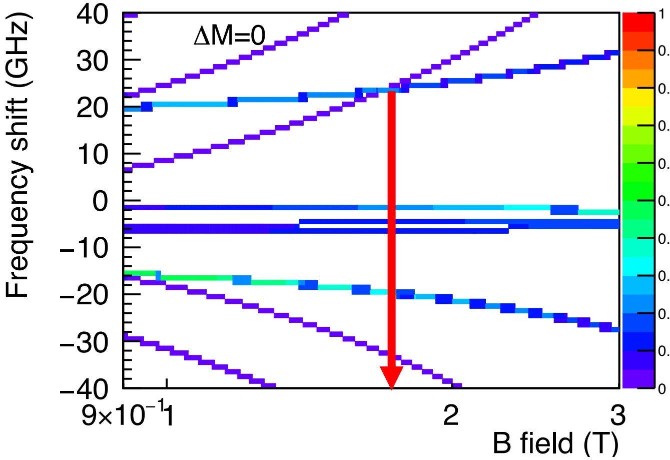
$P_{\text{Quench}} < 1\text{x}10^{-3}$
となる領域

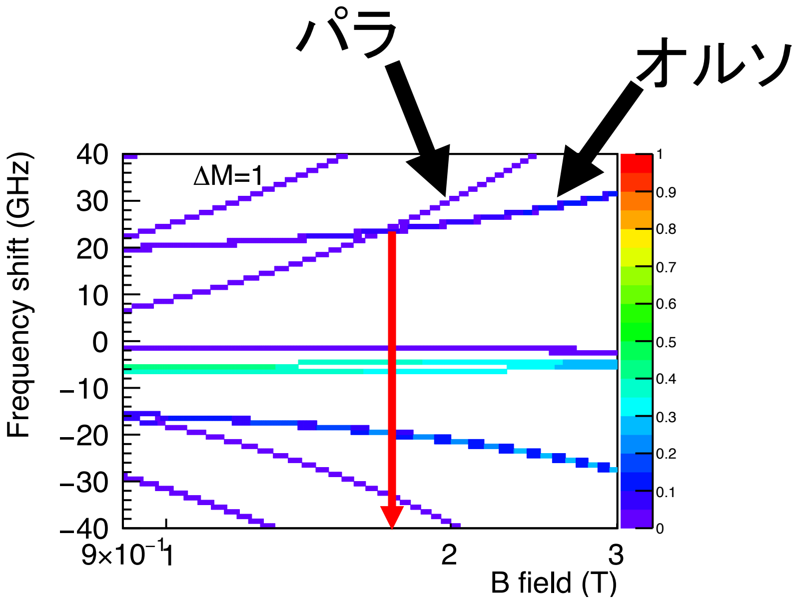
$E_{//}$, Bともに小だと エネルギーレベルへの 影響の面で好ましい

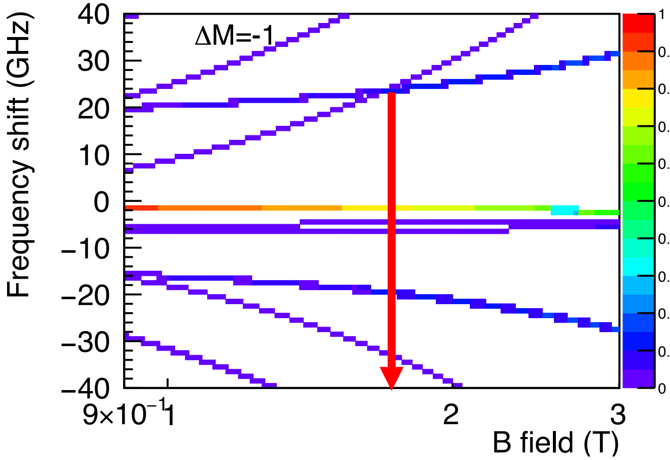
$E_{//}$, Bそれぞれのエネルギーレベルへの寄与
1T ≒ 1kV/cm

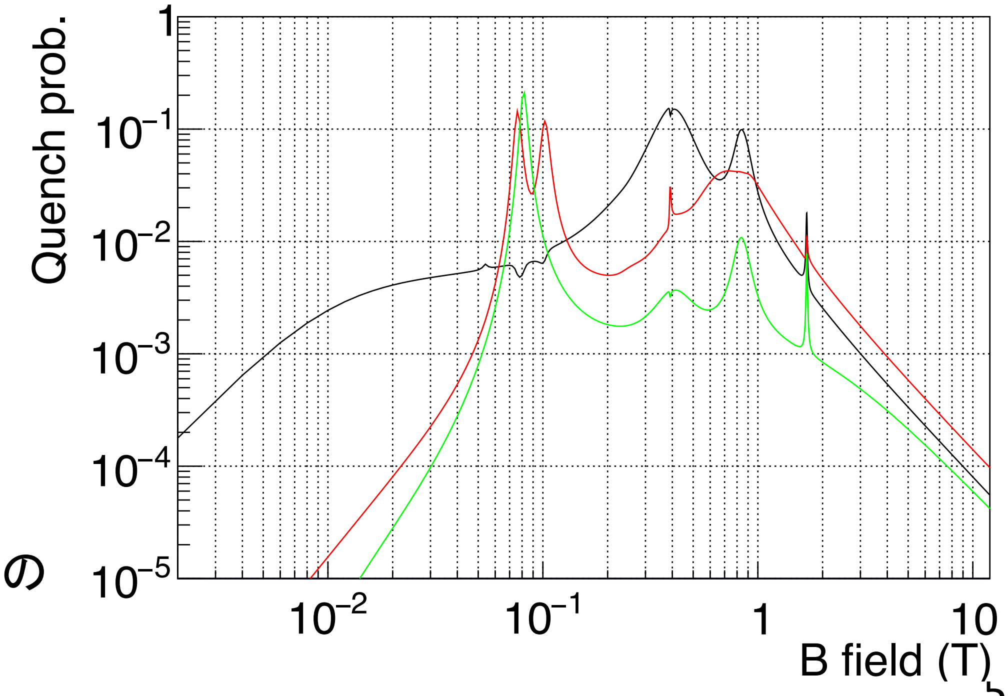


$E_{//}$=2 kV/cm









ピーキングするのは，準位が交差する所

$E_{//}$によってB=0でのエネルギーが変化するので，

クエンチピークでの磁場がずれる