Study on Cooling of Positronium for Bose-Einstein Condensation

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Ps - BEC

- Ps: A bound state of e^+e^-
  The lightest atom
  Very high critical temperature of BEC
  e.g.) ~10K @ 10^{18}/cm^3

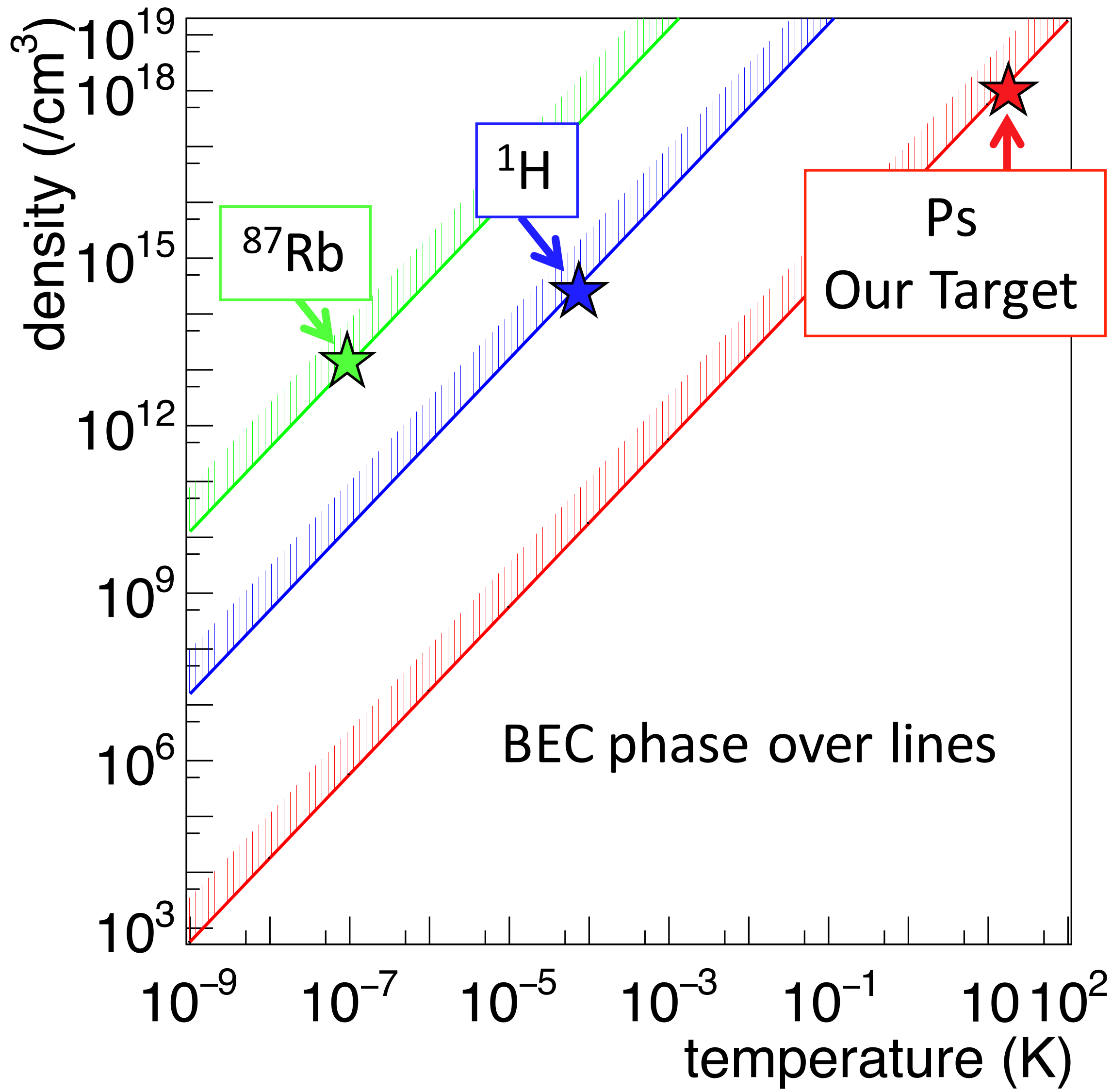
◆ Until now,
NO BEC with anti-matter system

➢ Ps is a good candidate for anti-matter BEC

Goals of Ps - BEC:

☐ Precise measurements of anti-matter gravity

☐ 511keV laser using decaying gamma rays



To achieve Ps - BEC

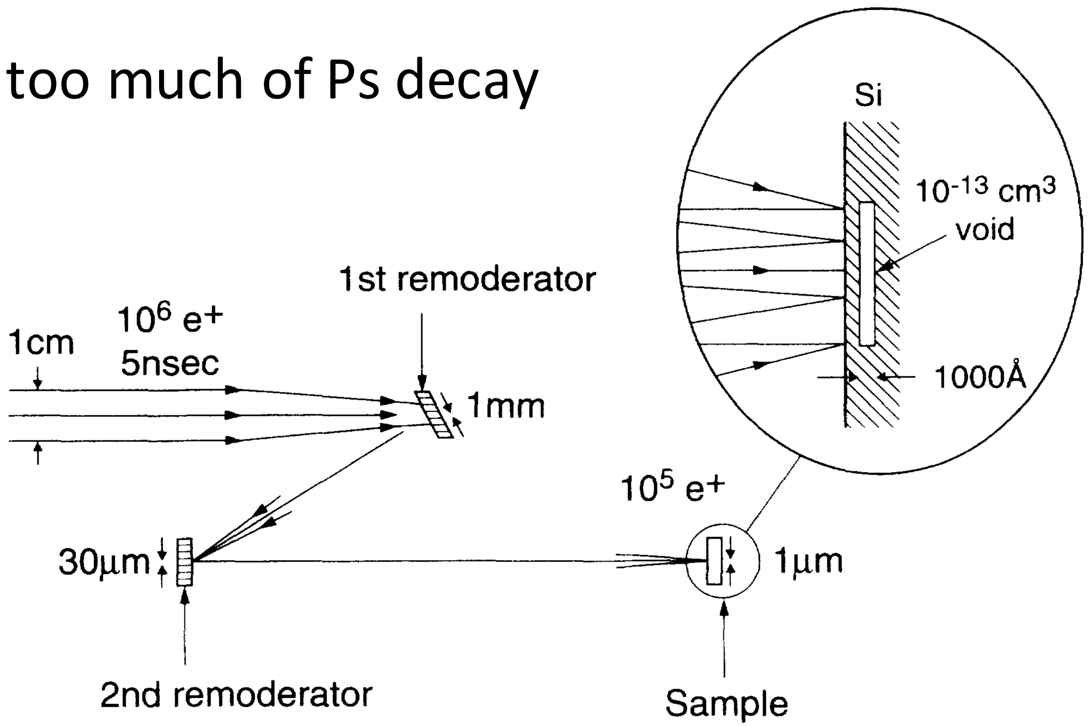
To achieve Ps - BEC, short decaying life time(142ns) requires:

- ☐ Highly focused slow positrons
  - Make a high density of Ps by injecting them at once in some material
- ☐ Rapid cooling of Ps
  - To be cooled to ~1K before too much of Ps decay

Using cold Si cavity was proposed in 1994 for trapping and cooling Ps

- However, recent measurements showed the thermalization process is very slow

➢ Examine cooling

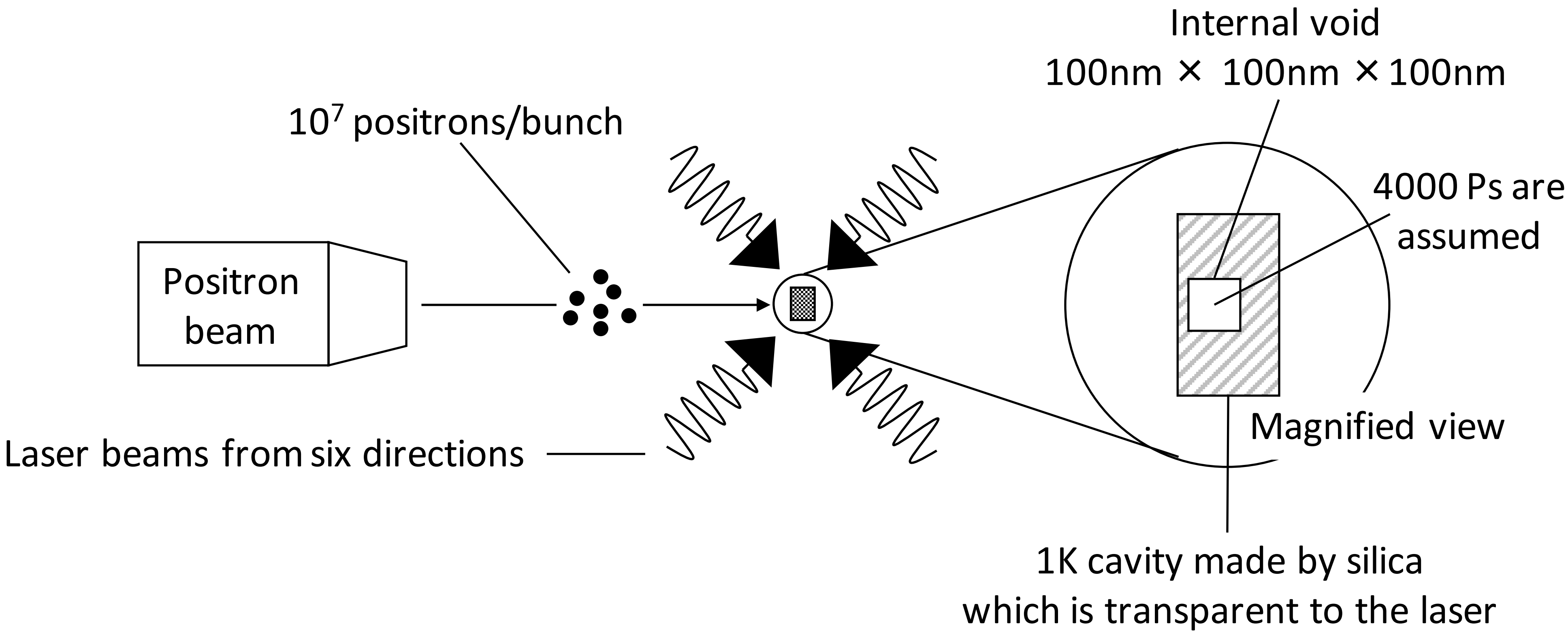


The original Idea of an experimental setup for Ps - BEC
(P. M. Platzman and A. P. Mills, Jr, Phys. Rev. B 49, 454(1994))

Conceptual view of the setup

- We propose a new scheme as cooling by 2 steps
  (Submitted to Journal of Physics B, arXiv:1511.07924)

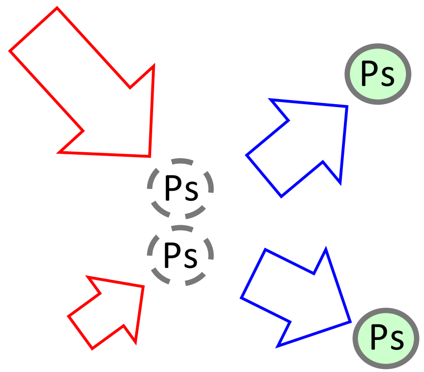
1. Down to ~300K: by thermalization process with silica
2. Down to ~1K: by a laser cooling (1s – 2p optical molasses)



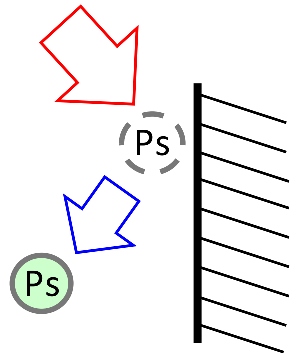
Interactions

Three interactions are considered:

- Ps - Ps two-body scatterings
  - Crucial for the high density
  - Elastic collisions
- Interactions with the walls of the cavity
  - Ps initial kinetic energy: 0.8eV(mono)
  - Cooling by collisions with the walls
- Doppler cooling by laser photons
  - Cooling by photon recoils



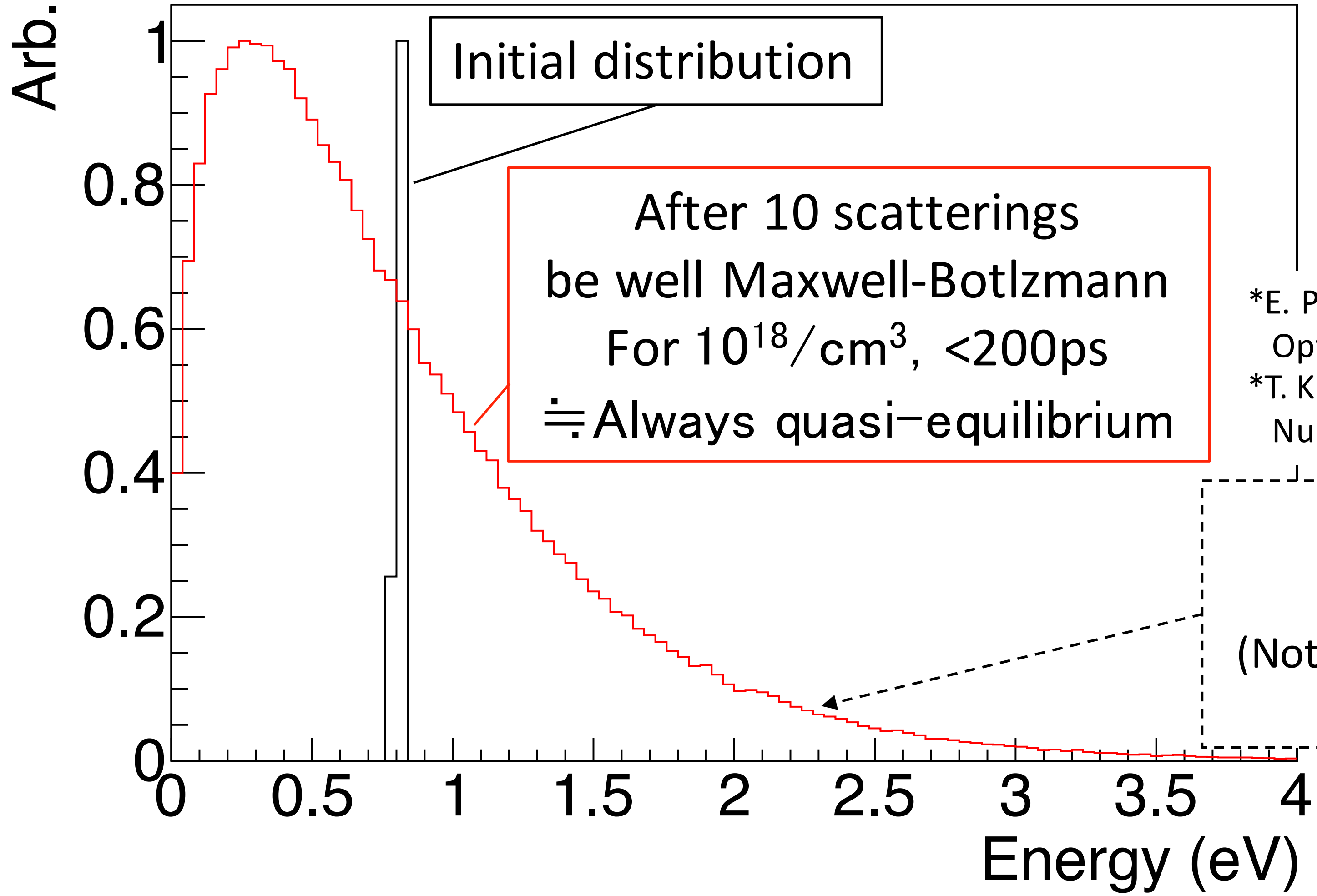
Ps - Ps scatterings



Interaction with a wall

Ps – Ps two-body scatterings

- The cross section: 32Å^2
  from Journal of the Physical Society of Japan 70, 1549(2001)
  Phys. Rev. A 65, 022704(2002)



*E. P. Liang and C. D. Dermer
Optics Communications 65, 419(1988)
*T. Kumita *et al.*
Nucl. Instrum. Meth. B 192 171(2002)

Crucial effects for
laser cooling
(Not taken into account in the
previous studies*)

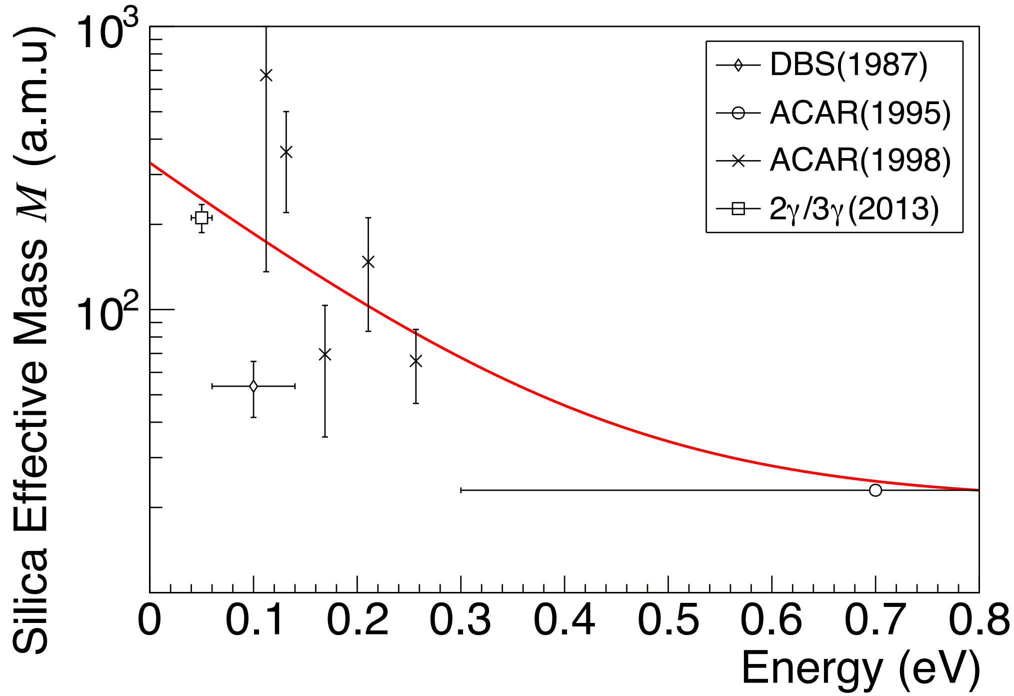
Thermalization

- Can be modeled by a classical model: describe by a differential eq.
  from Y. Nagashima *et al.* Phys. Rev. A, 52, 258(1995)

$$\frac{\mathrm{d}E_{\mathrm{av}}}{\mathrm{d}t} = -\frac{2}{LM}\sqrt{2m_{\mathrm{Ps}}E_{\mathrm{av}}}\left(E_{\mathrm{av}} - \frac{3}{2}k_B T\right)$$

E_{av} : Ps average kinetic energu, m_{Ps} : A Ps mass,
L : A mean free path of scatterings,
M : An effective of mass of scatteing bodies,
T : temperature

M has a dependence on kinetic energy of Ps
Y. Nagashima *et al.* J. Phys. B 31, 329(1998)



Measured values superimposed

- Estimation of the dependence:

$$M(E) = p_0 + p_1 \exp\left(\frac{E}{p_2}\right)$$

Legends:
DBS(1987): T. Chang *et al.* Phys. Lett. A 126, 189
ACAR(1995): Y. Nagashima *et al.* Phys. Rev. A 52, 258
ACAR(1998): Y. Nagashima *et al.* J. Phys. B 31, 329
2γ/3γ(2013): K. Shibuya *et al.* Phys. Rev. A 52, 258

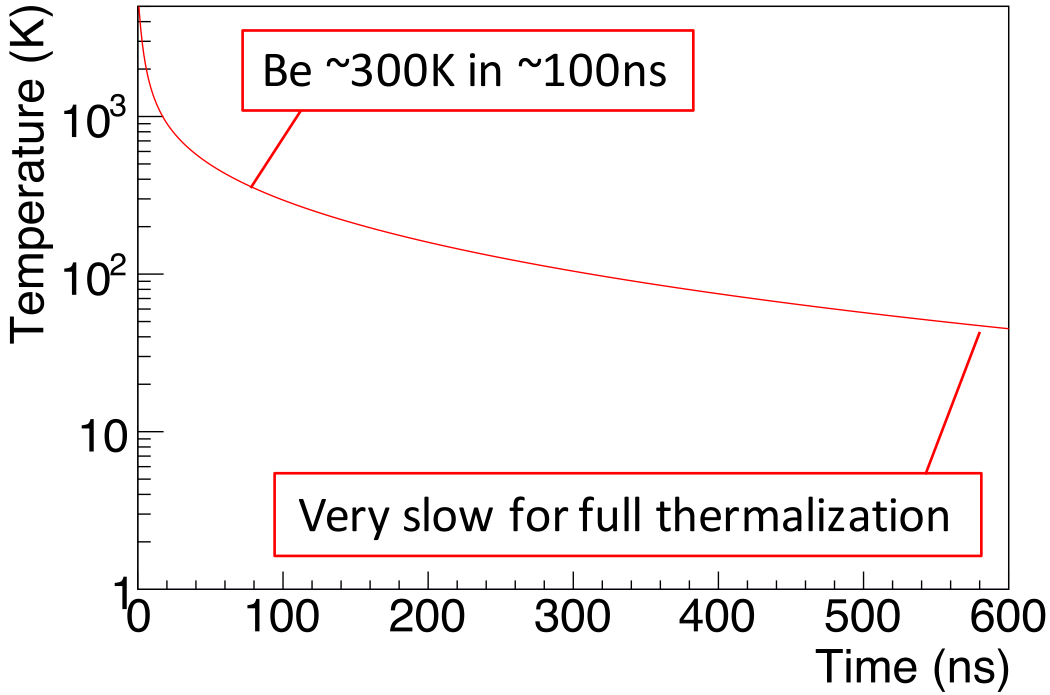
Evaluation of the thermalization process

Include

- Classical model with estimated parameter M
- The two body scatterings

An initial condition

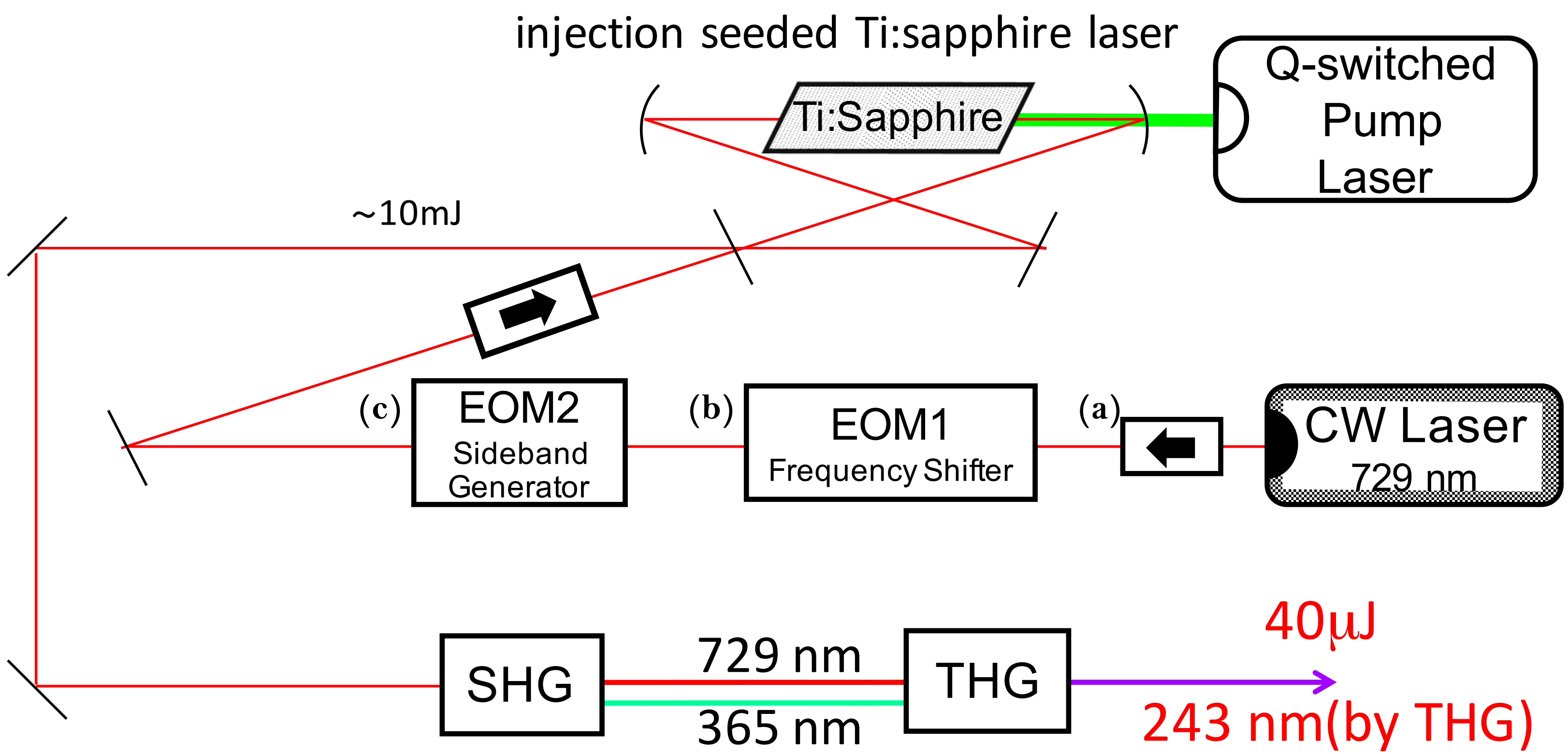
- ➢ Ps initial kinetic energy: 0.8eV
  from Y. Nagashima *et al.* Phys. Rev. A 52, 258(1995)
- ➢ An initial number of Ps: 4×10^3
- ➢ Silica cavity:
  100nm × 100nm 100nm, 1K



Time evolution of temperature

- Cooled to 300K in ~100ns
- Cannot be cooled to even 10K
- ➢ Cool by the laser after ~300K

Laser system



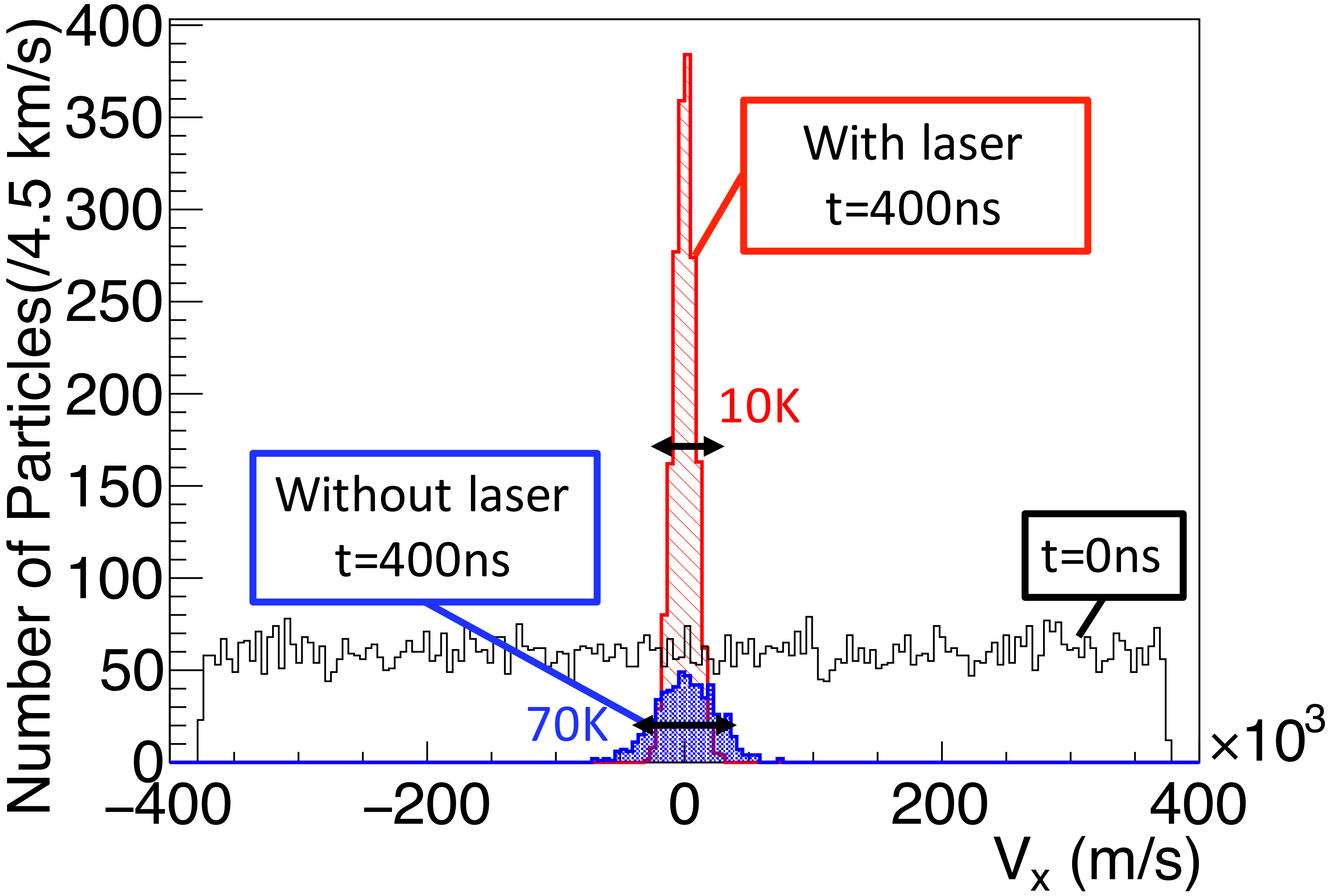
- Long time duration as lifetime of Ps
- Large bandwidth & frequency chirp to compensate large Doppler shift of Ps

➢ <u>A new trial for the laser cooling</u>

Time duration	300ns
Bandwidth	140GHz
Frequency chirp	60GHz

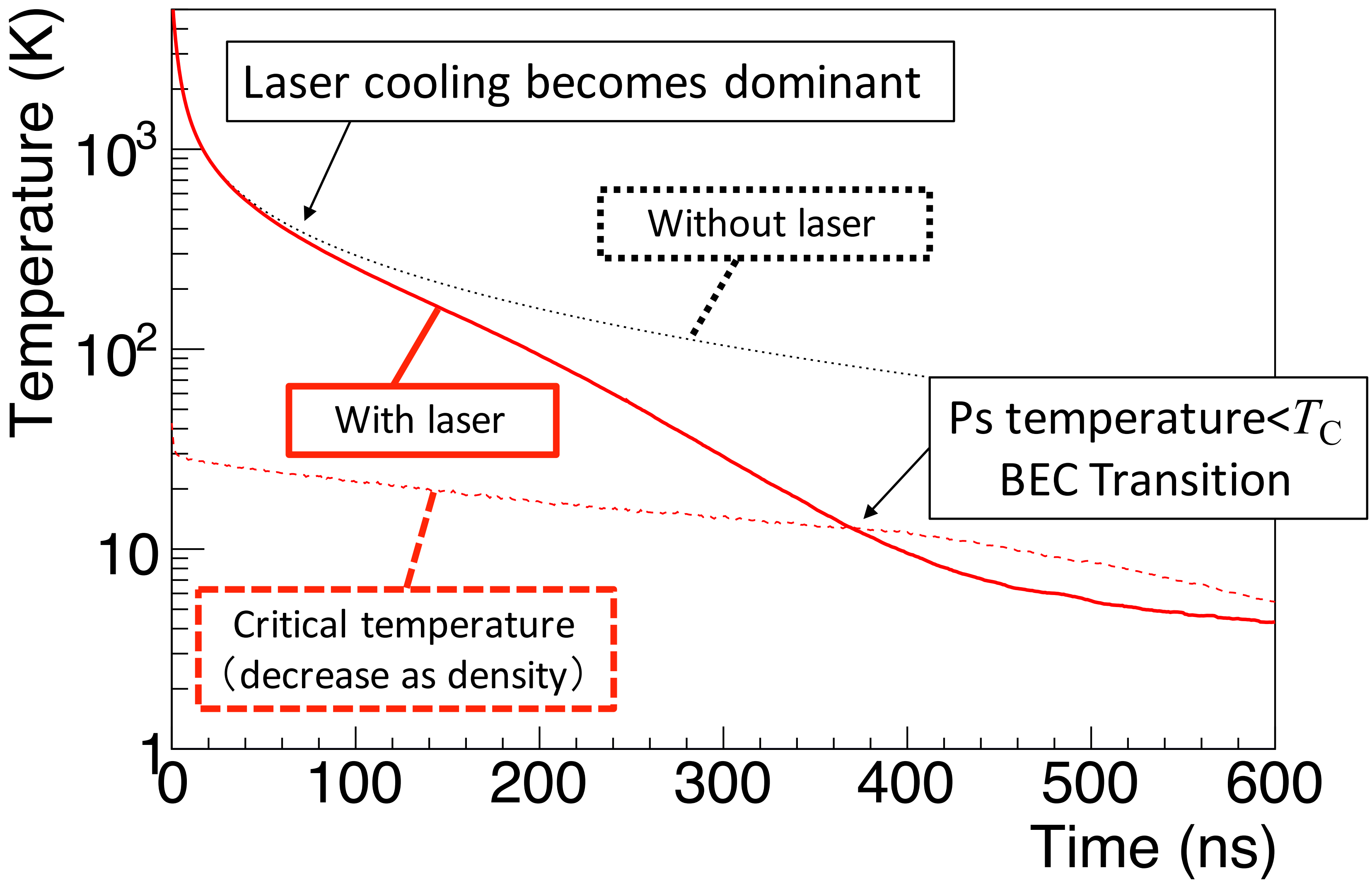
Specification of 243nm laser

Evaluation of the cooling



A distribution of the velocity(x-component)

Evaluation of the cooling



A time evolution of temperature

Laser - Frequency control

- Chirp as large as tens of GHz is challenging (usually <1GHz)

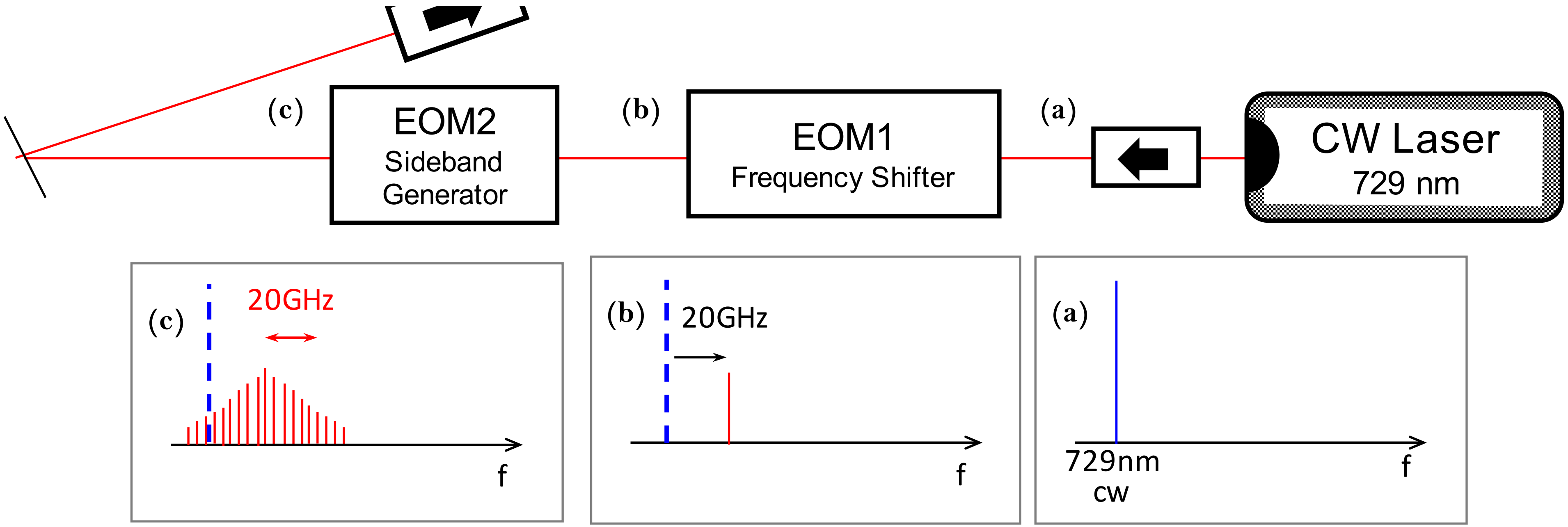
➢ Apply travelling-wave type Electric Optical Modulators(EOMs) for broadband communication to UV light → Stability & reproducibility

(a) Frequency stabilization for the seed light

(b) Frequency chirp of 20GHz by EOM1

(c) Sidebands generate by EOM2

*Chirp width and bandwidth are tripled by THG

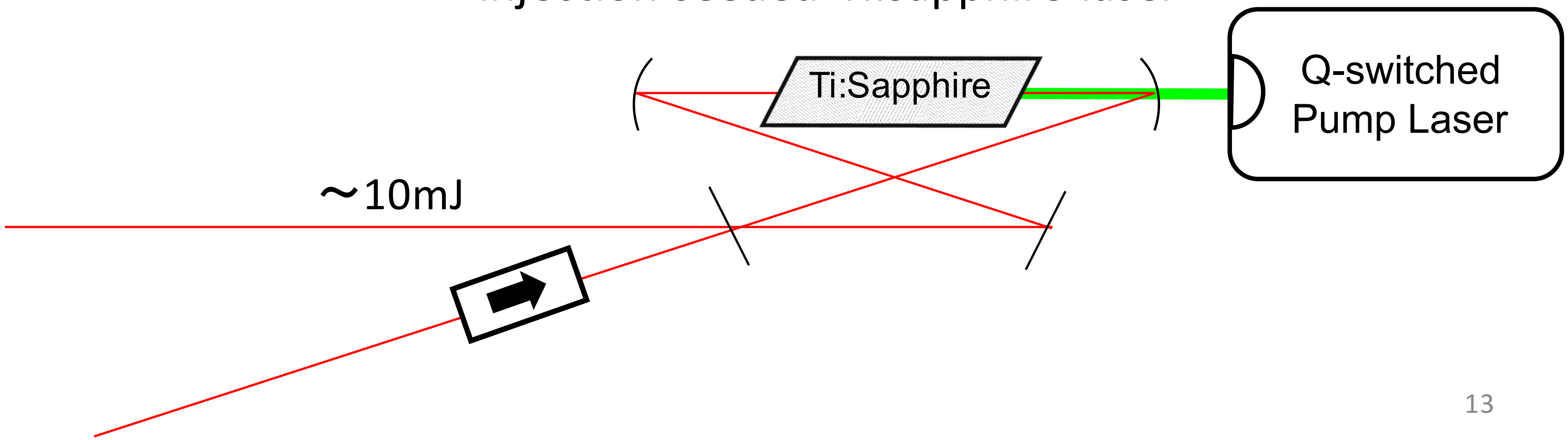


Laser - waveform shaping

- Waveform should be shaped to have a long time duration>100ns (Usually CW or <10ns)
- ➢ <u>By seed injection laser of Ti:Sapphire with gain controlled</u>

- Seeded by frequency controlled 729nm seed light
- Gain control by optimizing a coupling of a cavity → Long time duration
- ~10mJ output, enough for the THG

injection seeded Ti:sapphire laser



A Roadmap for Ps - BEC

1. Confirm the cooling by the thermalization process
   - ☐ Precision temperature measurement with cold material
   - ☐ Currently, measuring temperature of Ps with 100K silica by DBS

2. Develop laser system for cooling Ps down
   - ☐ Studying basic components and setup

3. Develop the focusing system of positrons
   - ☐ A number of 10^7 positrons in a bunch is already possible
   - ☐ However, focusing into 100nm is challenging
   - ☐ Currently focusing into 30μm* is possible by magnetic lenses so we consider improving this technique

*N. Oshima *et al.* Materials Science Forum 607, 238(2008)

Summary

- We propose a new scheme to cool Ps down for BEC with 2 steps:
    1. Down to ~300K: Thermalization with trapping cold cavity of silica
    2. Down to ~1K: Laser cooling(optical molasses)

- Evaluate the cooling with integrating:
    1. Ps – Ps two body scatterings (new with laser cooling)
    2. Thermalization
    3. Laser cooling effect

- BEC transition is possible with the special laser system

- Now develop the new system with the state-of-art optics technology:
    1. Large frequency manipulation(>10GHz) by broadband EOM
    2. Long time duration(>100ns) by adjusting amplification of seed injection laser