AXION in Japan

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in Tohoku University

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Revealing the history of the universe

with underground particle and nuclear research 2019

Contents

Strong CP Problem

☆ QCD Lagrangian:

$$\mathcal{L}_{\rm QCD} = \overline{Q_i}(i\gamma^\mu D_\mu - m_{ij})Q_j - \frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + \boxed{\frac{g^2\theta}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}}$$

CP-violation term

☆ Neutron Electron Dipole Moment (nEDM):

$$\rightarrow \mathcal{L}_{\rm nEDM} = \frac{1}{2}d_n\overline{n}i\gamma_5\sigma_{\mu\nu}nF^{\mu\nu}$$

$$d_n \sim \theta \cdot 10^{-16} e\,{\rm cm}$$

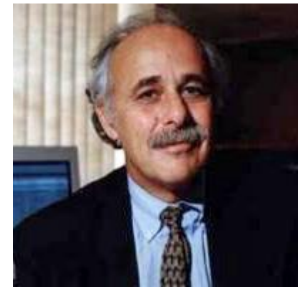
Why so small value?
→ Strong-CP problem

From experiment:

$|d_n| < 3.0 \times 10^{-26}$ e·cm. ⇨ $|\theta| < 10^{-10}$

J. M. Pendlebury, *et al.*
Phys. Rev. D 92 092003. a (2015)

Peccei, Quiin mechanism (1977)




1. Assume U(1) $_{PQ}$ symmetry

2. Spontaneously broken

3. Nambu-Goldstone boson → axion (Pseudo-Scalar particle 0^-)

$$\mathcal{L}_{\text{axion}} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{g^2}{32\pi^2}\frac{a}{f_a}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

4. The minimum point of the effective potential:

$$\theta - \frac{a}{f_a} = 0$$

a : axion field

f_a : axion decay constant

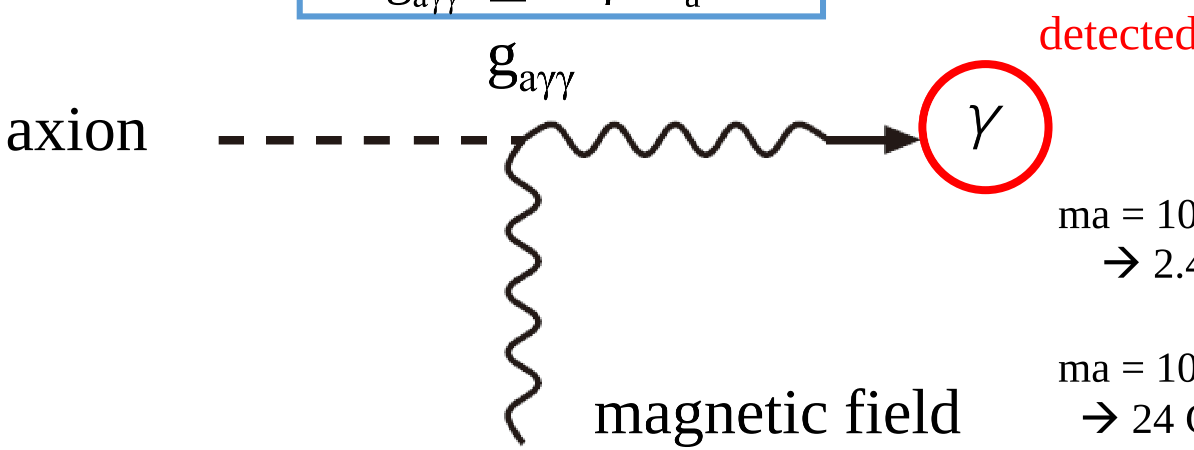
θ-term is dynamically cancelled out !

How to search axion

- Axion mass is very small (μeV - eV) and very weakly interact (< $1/10^{10}$ of EM) → Candidate of DM
- Axion weakly couples to two photons.

→ Convert axions (around us, or coming from sky) to photons in the strong magnetic field (Primakoff effect)

Conversion efficiency
$\propto g_{a\gamma\gamma}^{2} \underline{B}^{2} V \rho m_a$



ma = 10 μeV
→ 2.4 GHz

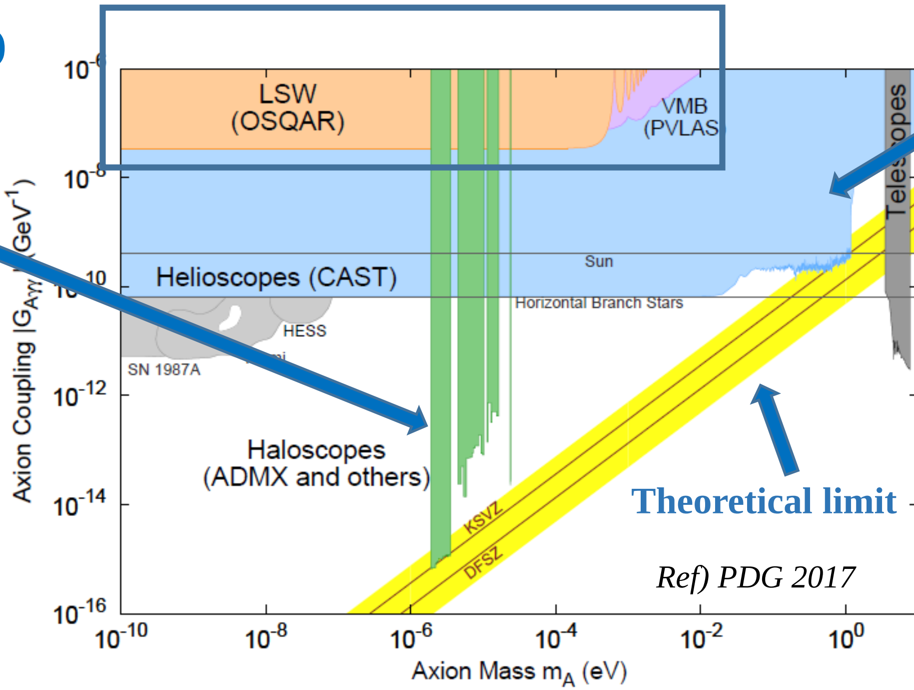
ma = 100 μeV
→ 24 GHz

Main BG
Black body radiation

→ Low temperature experiment (< 1 K)

Summary of the search result

Laser experiment



DM-axion (O (10) μeV)

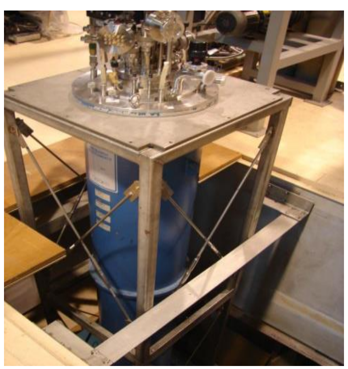
Frequency of
converted photon : ~GHz

→ Cavity experiment

ex)
- ADMX @ Washington Univ.

- CARRACK @ Kyoto Univ.
  → single-photon counting
  → establish the method

New-CARRACK @ Osaka Univ.
(Tokiyasu et al.)
last part of this talk



Solar-axion(> meV)

Production in the sun

→ Solar telescope

ex)
- CAST @ CERN

- SUMICO @ Tokyo Univ.
  → Data taken was completed.
  Phys. Lett. B 668 (2008) 93
  → Hidden photon search etc.

axion-window from cosmology

$$10^{-15} < g_{a\gamma\gamma} < 10^{-12}$$
$$10^{-6}\ \mathrm{eV} < m_a < 10^{-3}\ \mathrm{eV}$$

Other region: ALPs(Axion-like particles)

Contents

Cf)
In the program of JPS meeting
Search “アクシオン, axion”
7 talks
4 talks : search experiment

(Total > 3000 talks.)

- Introduction
  - Strong-CP problem
  - Search method
  - Current Search status
- Recent axion search result in Japan
  - XMASS — Physics Letters B 787 (2018) 153–158
  - LSW @ SPring-8 — T. Inada *et al.*, Phys. Rev. Lett 118 (2017) 071803; T. Yamaji *et. al*, Phys. Lett. B 782 (2018) 523–527

    m_a > eV
- Future plan of axion search in Japan
  - New-CARRACK project

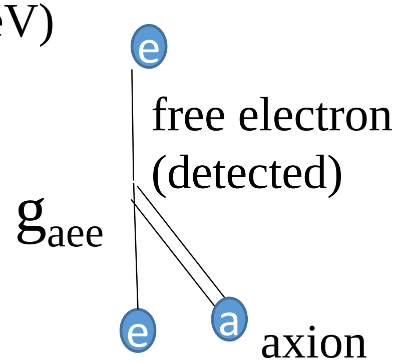
axioelectonic process

Physics Letters B 787 (2018) 153–158

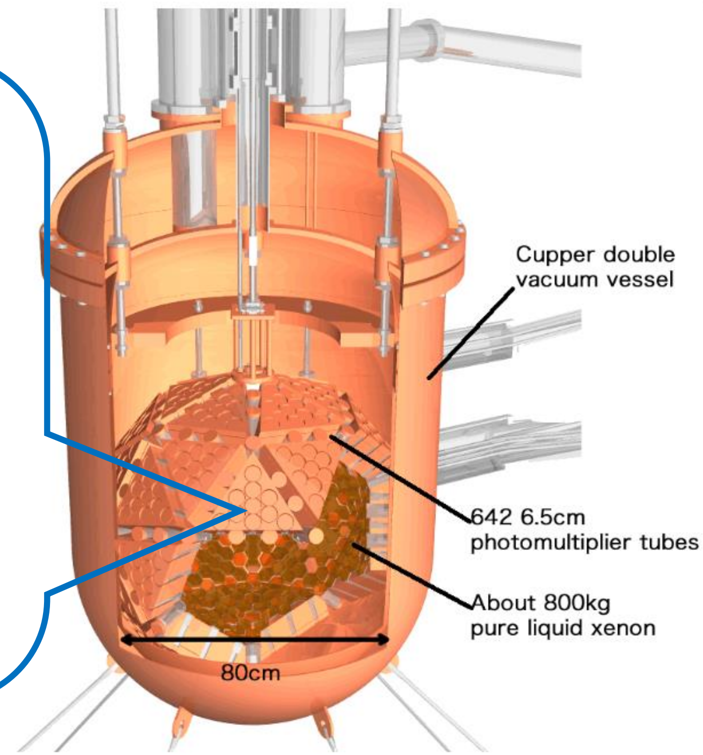
Liq Xe 835kg
Dense, large A
Low threshold

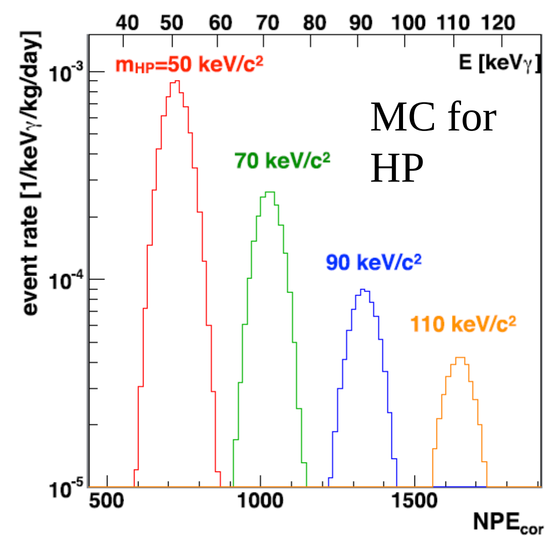
→ Suitable for axion via axioelectonic process

axioelectronic process
(~keV)



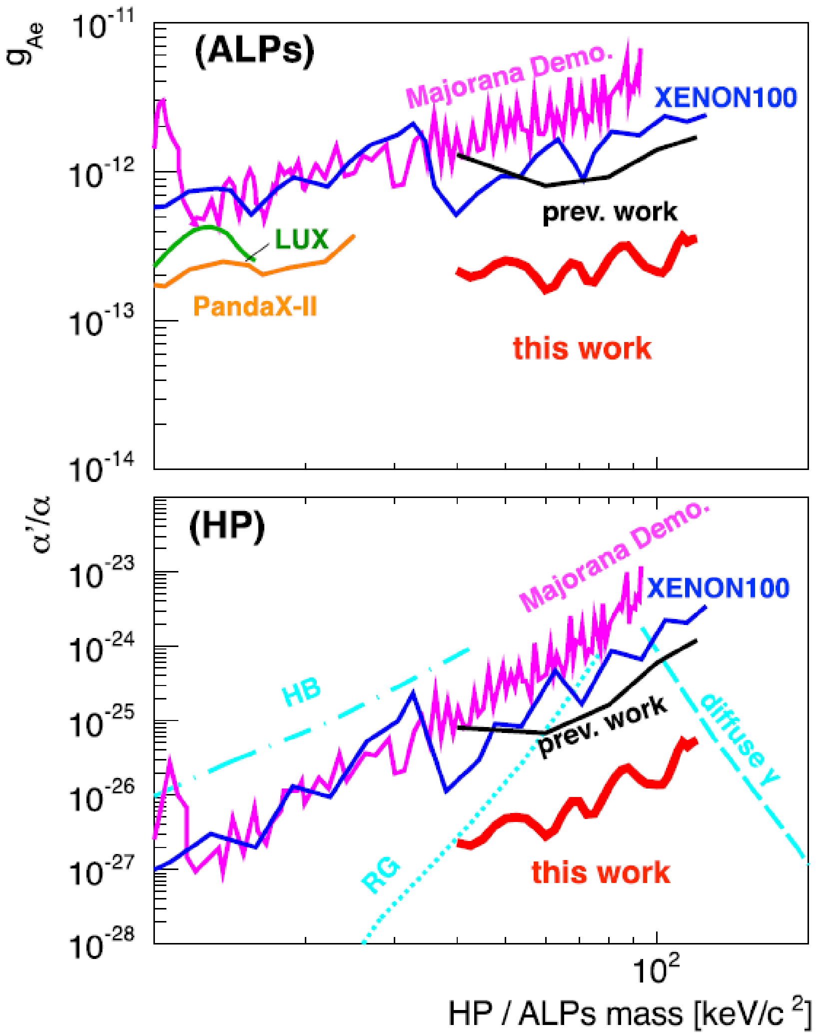
Bound electron

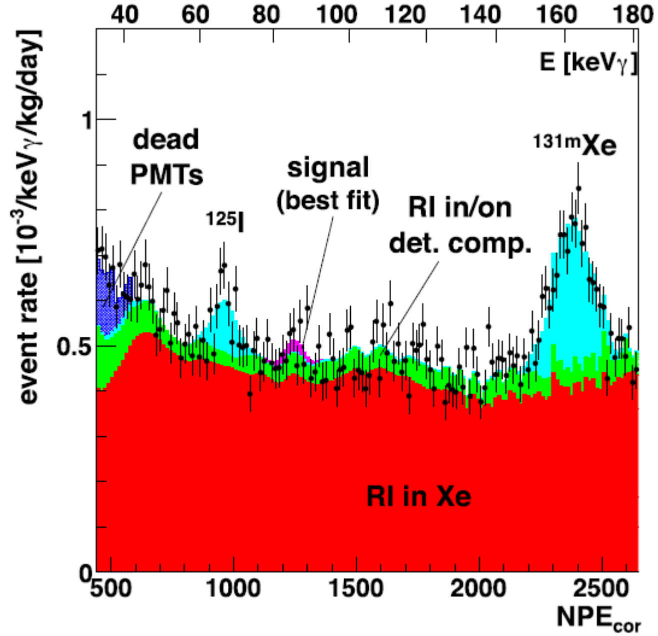




$$R_{ALP}[1/\mathrm{kg/day}] = \frac{1.2\times 10^{19}}{A} g_{Ae}^2 \sigma_{pe}[\mathrm{barn}] \cdot m_{ALP}[\mathrm{keV}],$$

Search Result





$40\ \text{keV} < m_a > 120\ \text{keV}$

$g_{Ae} = 10^{-13}$

LSW experiment @ SPring-8

Super
Photon
ring -8GeV
X-ray beam

Light Shining through the Wall experiment
by Tokyo University group.

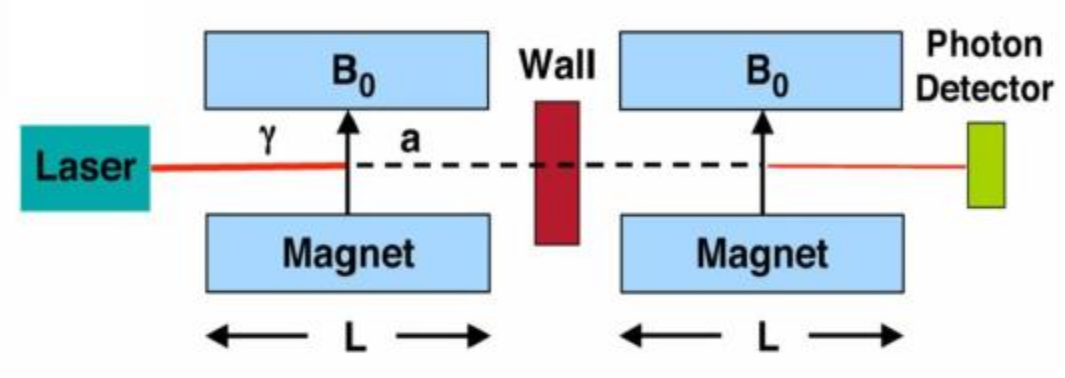
→ Pulsed magnetic field

T. Inada *et al.*, Phys. Rev. Lett 118 (2017) 071803

→ Laue-case conversion

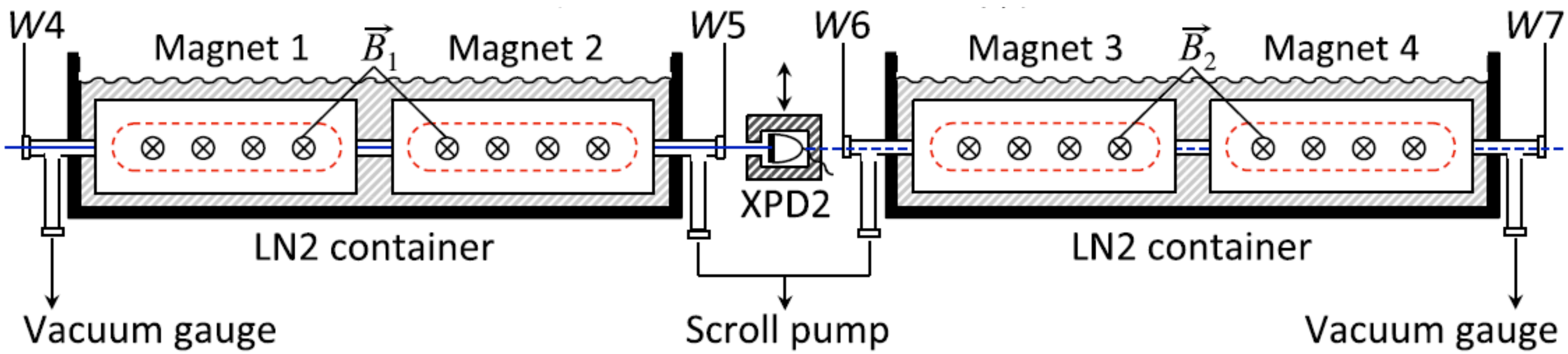
T. Yamaji *et. al*, Phys. Lett. B 782 (2018) 523–527

Pulsed magnetic field



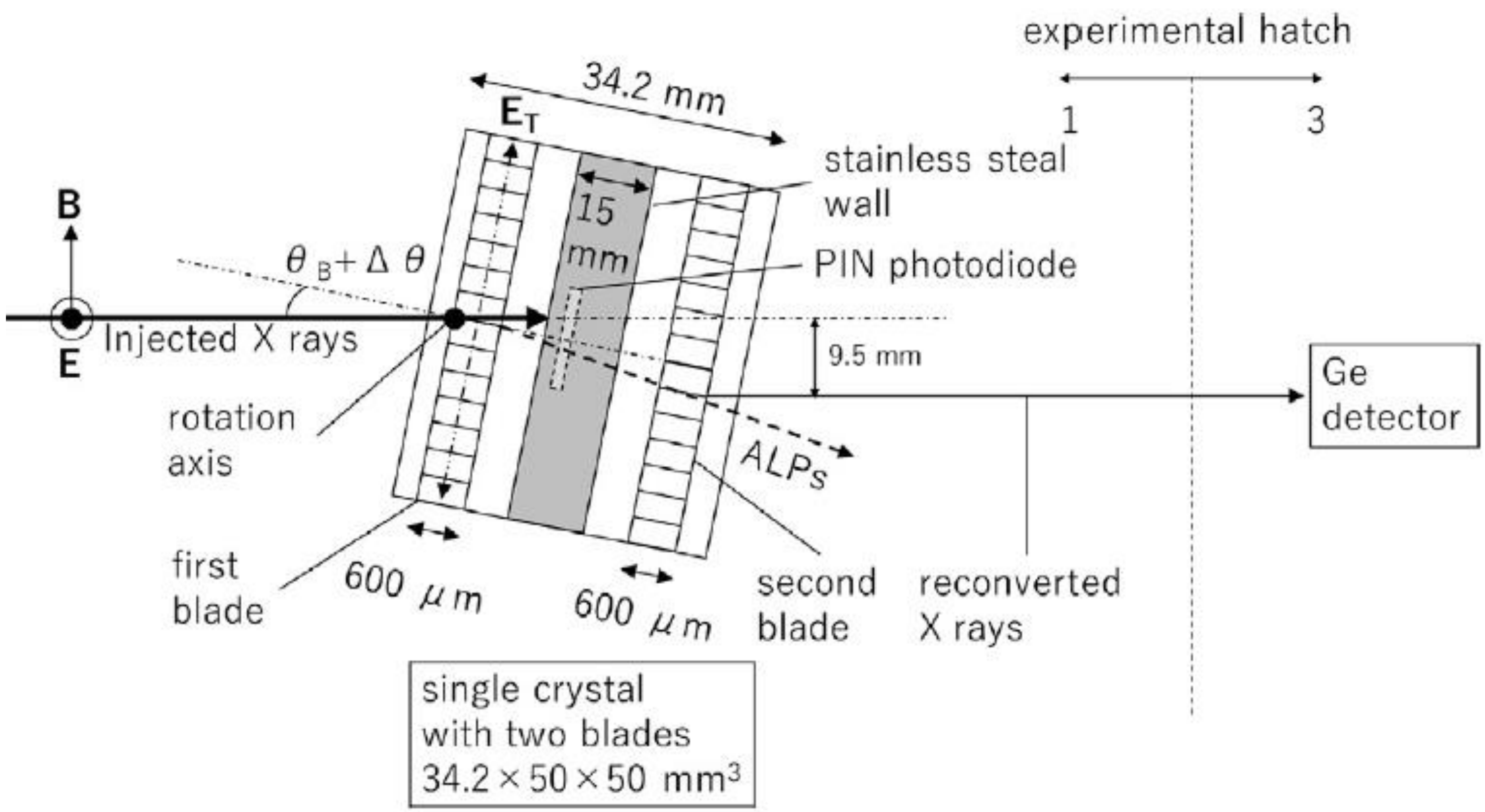
merit: model-independent search
demerit :low efficiency
(γ → a, a → γ)

pulsed magnet
10 T, 0.8 m, 0.2 Hz



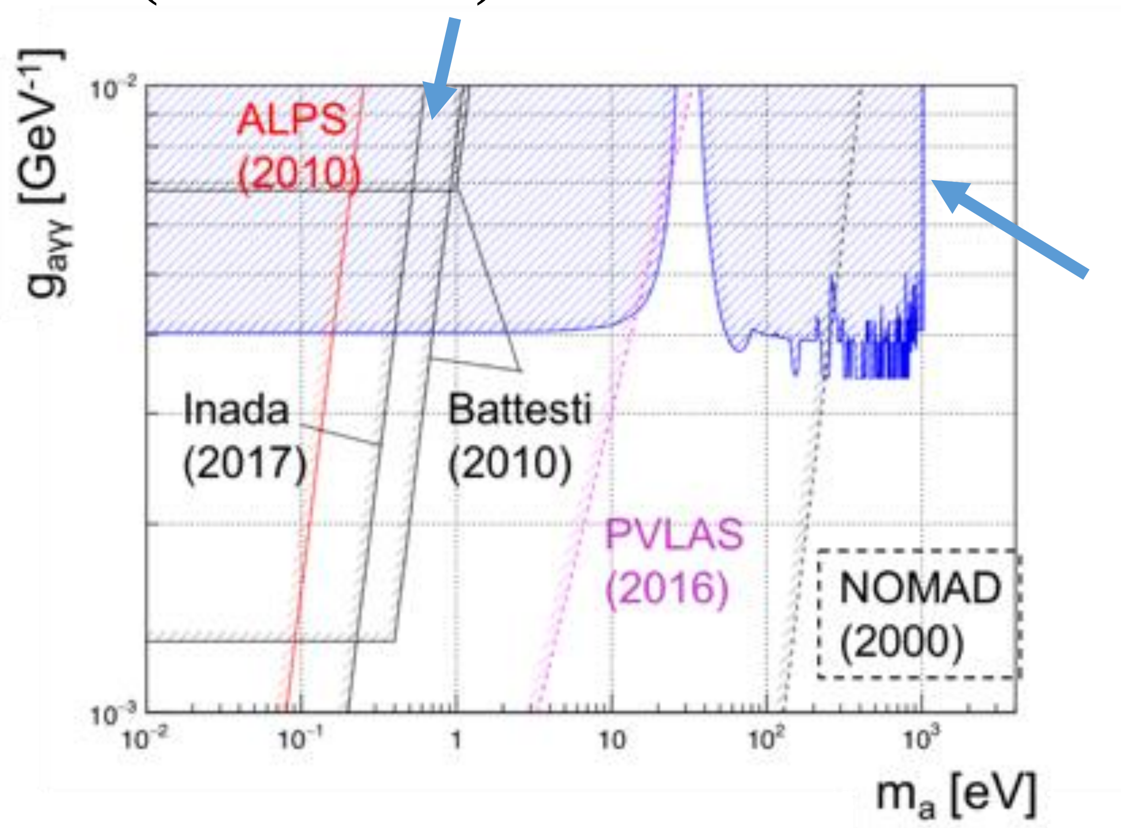
Laue-case conversion

- atomic electric field : 10^{11} V/m → 10^{3} T
- by rotating the crystal, different mass region can be searched.
- Sensitive to Heavy axion as 10 keV



Search result

$g_{a\gamma\gamma} < 2.51 * 10^{-4}$ GeV^{-1}
(ma < 0.1 eV)



$g_{a\gamma\gamma} < 4.2 * 10^{-3}$ GeV^{-1}
(ma < 10 eV)

$g_{a\gamma\gamma} < 5.0 * 10^{-4}$ GeV^{-1}
(46 eV < ma < 1020 eV)

The most stringent upper limit in the world. → SACLA

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- Introduction
  - Strong-CP problem
  - Current Search status
- Recent axion search result in Japan
  - XMASS
  - LSW @ SPring-8
- Future plan of axion search in Japan
  - New-CARRACK project

New-CARRACK project

- DM center in Kyoto University was closed in 2016.
- CARRACK was moved to Osaka University
- 2017 ~ Project in Research Center for Nuclear Physics

  "Search for Axions to Resolve

  the Strong-CP and Dark Matter Problems"

- Collaborators
  - A. O. Tokiyasu (Tohoku Univ.), I. Ogawa (Fukui Univ.), K. Nakajima (Fukui Univ.), H. Funahashi (Kyoto Univ.) A. Matsubara (Kyoto Univ.) , K. Imai (JAEA), S. Matsuki (RCNP), T. Nakano (RCNP)

- Target mass : ~10μeV → ~100 μeV

Why 100 μeV?

☆ Prediction from cosmology after Planck, BICEP2

（Phys. Rev. Lett 113(2014)011801, Phys. Rev. Lett. (2014)011802
, Phys. Rev. D 90 (2014) 043534 etc）

- Precise measurement of CMB→ information on the early universe
- m_a : 70 — 120 μeV

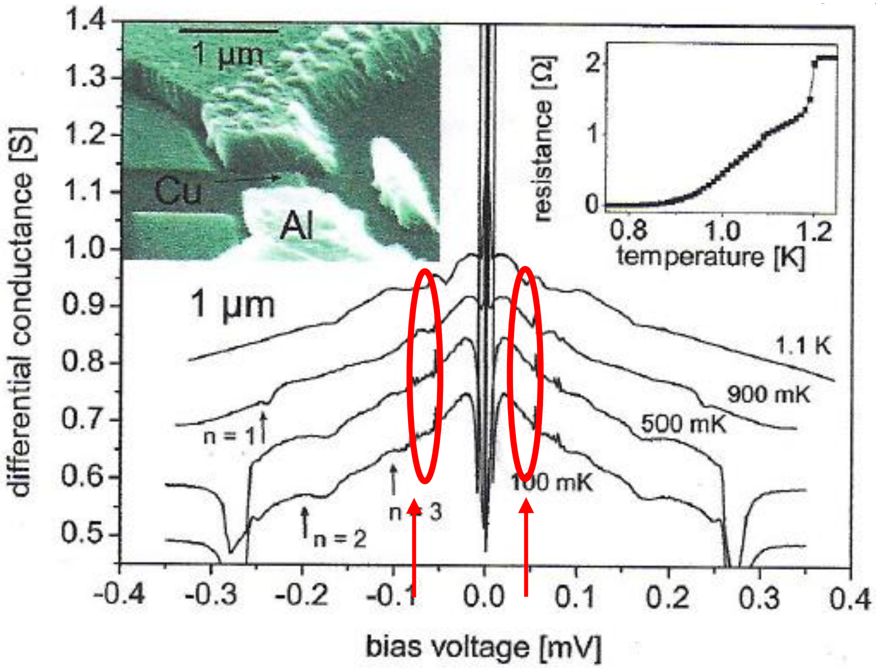
☆ Prediction from lattice-QCD (S. Borsanyi, Nature 539 69-71)

- Calculate the axion potential in the early universe and rate of expansion of the universe
- m_a : 50 — 1,500 μeV

- Theoretical models predict the mass region around 100 μeV.

Axion signal?

C. Hoffmann, F. Lefloch, M. Sanquer, B. Pannetier, Phys. Rev. B 70, 180503(R) (2004)



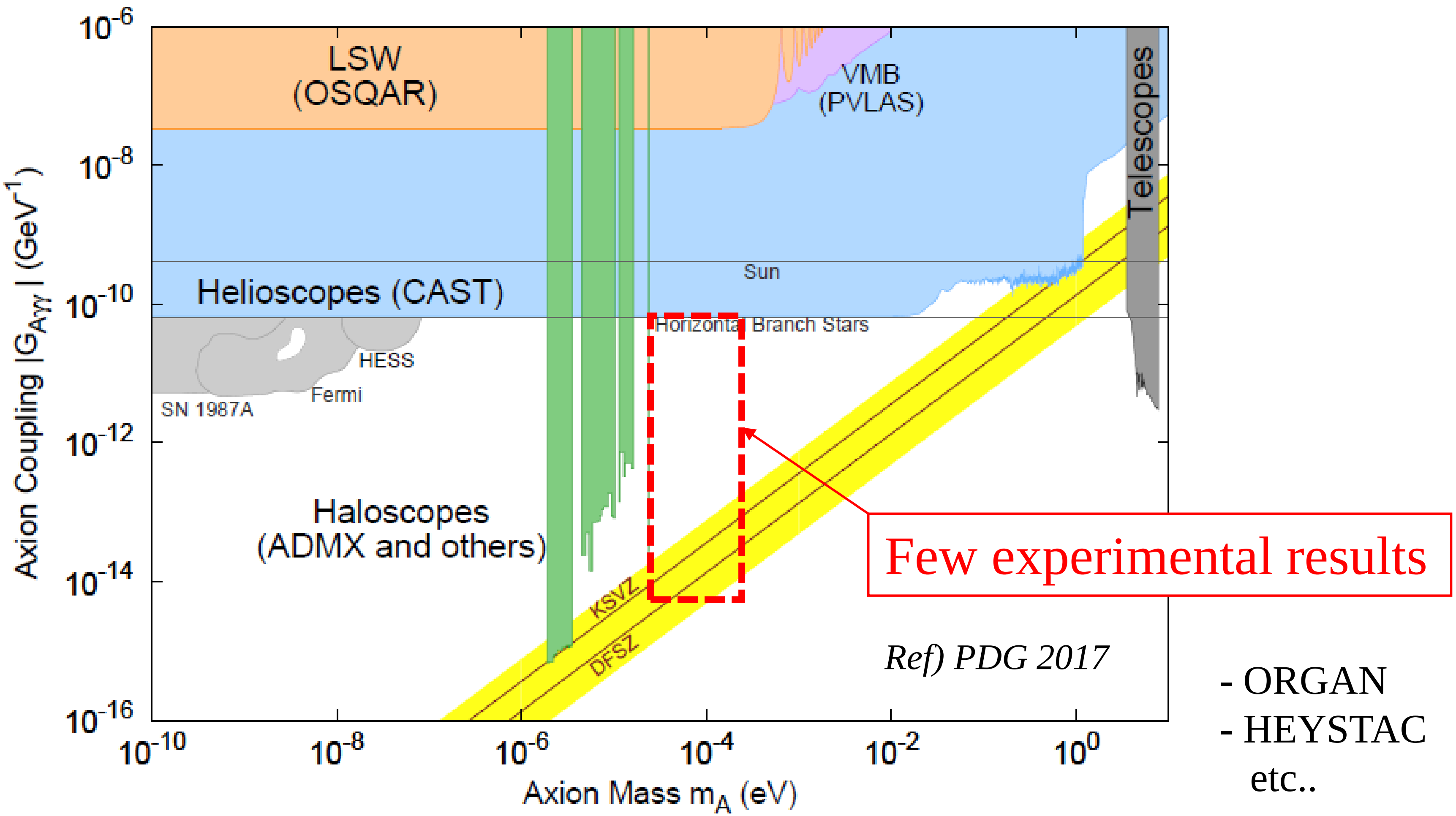
Peak structure in G-V curve of Josephson Junction (Al-Cu-Al)

$m_a = 110\ \mu eV$
$\rho_a = 0.051\ GeV/cm^3$

C. Beck PRL 111, 231801 (2013)

- Verification experiments are being considered.
  by A. Tokiyasu *et al.* in Tohoku University
  or T. Naka *et al.* in Nagoya University

Summary of search result



- ORGAN
- HEYSTAC
  etc..

Why difficult?

m_a = 100 μeV → 24 GHz photon

Sensitivity of Cavity experiment deteriorate

$$\frac{S}{N} = \frac{P_{sig}}{kT_s} \cdot \sqrt{\frac{t}{\Delta\nu}}$$

$$P_{sig} \sim B^2 V Q m_a \rho_a$$

1. SQL BG becomes large
(10 μeV → 0.116K, 100μ eV → 1 K)

2. Volume size
become small (~ $1/f^2$)

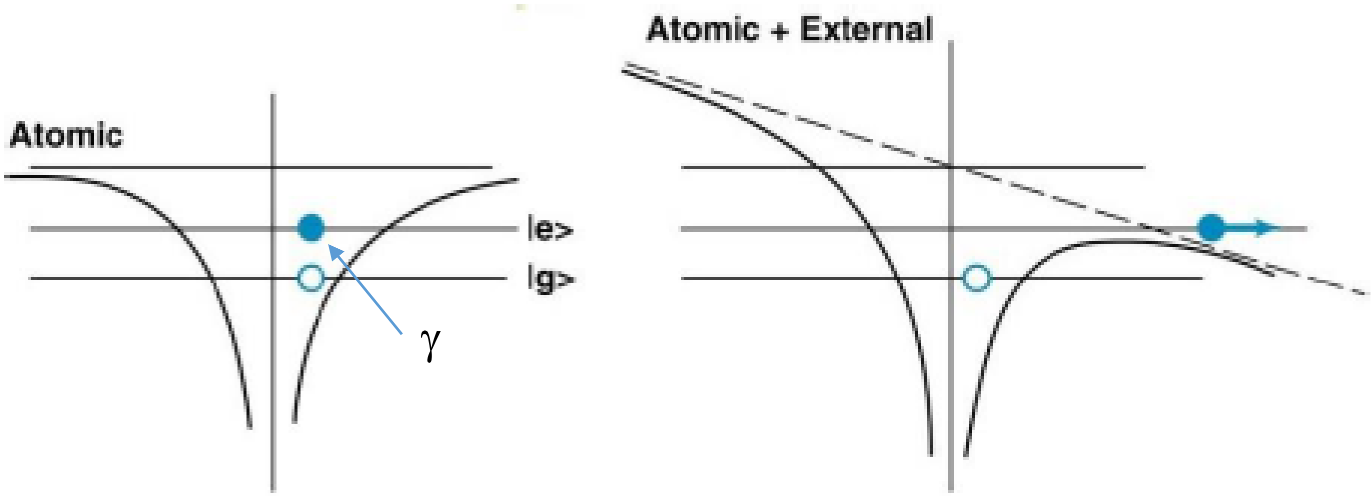
1. single photon measurement
by using Rydberg atom

2. multi-mode cavity

Rydberg atom

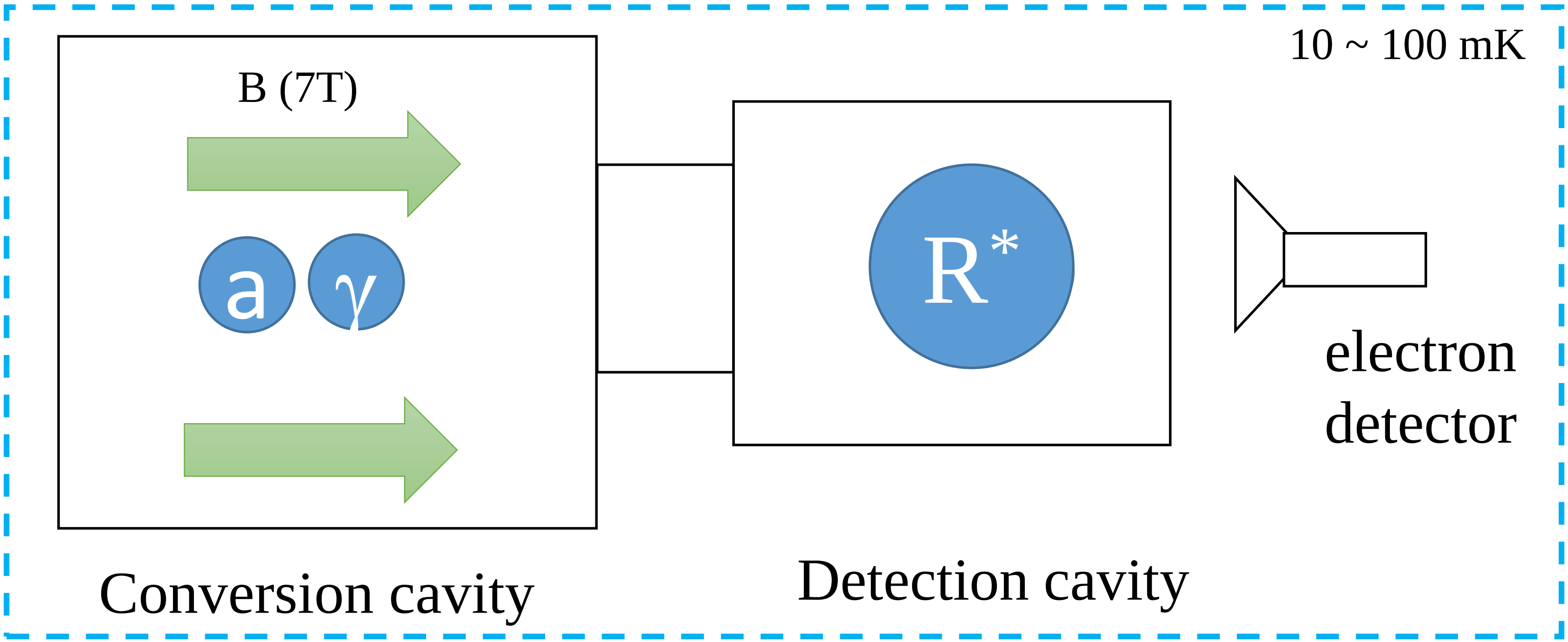
☆Rydberg atom : Atom with high principle number (n=100)
- Rb or K beam
- excited with two laser (λ = ~766.6, ~455.4nm).
- large cross section with microwave photon.

☆Selective field ionization

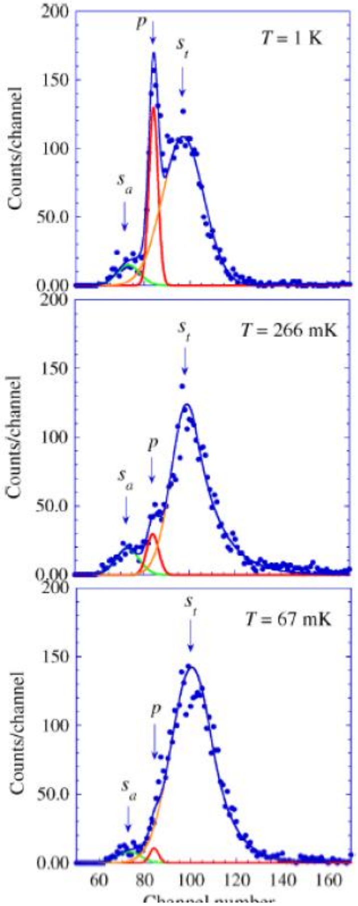


New-CARRACK overview

1. axion is converted to microwave photon
   by the strong magnetic field in the conversion cavity.
2. photon is guided to the detection cavity.
3. photon is absorbed by Rydberg atom
4. field ionized, and electron is detected.



BR measurement



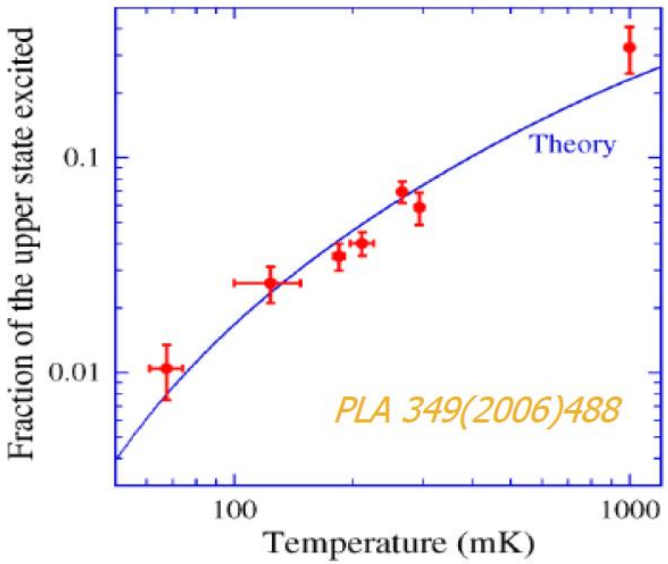


Fig. 4. Temperature dependence of the fraction of the 111 $p_{3/2}$ states excited by the blackbody-photon absorption in the cavity. The dependence was measured with the present Rydberg-atom single photon detector. Solid line is a theoretical prediction (see text in detail) in the over-damped regime.

$111s_{1/2} \Rightarrow 111p_{3/2}$

2527 MHz SQL: 121 mK

Ref) Phys. Lett. A349, Issue 6, 23 (2006)488

Why difficult?

m_a = 100 μeV → 24 GHz photon

Sensitivity of Cavity experiment deteriorate

$$\frac{S}{N} = \frac{P_{sig}}{kT_s} \cdot \sqrt{\frac{t}{\Delta \nu}} \qquad P_{sig} \sim B^2 V Q m_a \rho_a$$

1. SQL BG becomes large
 (10 μeV → 0.116K, 100μ eV → 1 K)

2. Volume size
 become small (~ $1/f^2$)

1. single photon measurement
 by using Rydberg atom

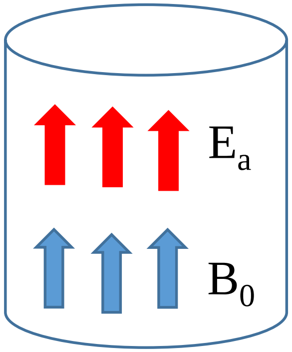
2. multi-mode cavity

Multi-mode Cavity

Form factor: Effective conversion volume

$$C = \frac{\left(\int dV\, \boldsymbol{E_a} \cdot \boldsymbol{B_0}\right)^2}{B_0^2 V \int dV\, \boldsymbol{E_a} \cdot \boldsymbol{E_a}} \quad (0 < C < 1)$$

TM mode

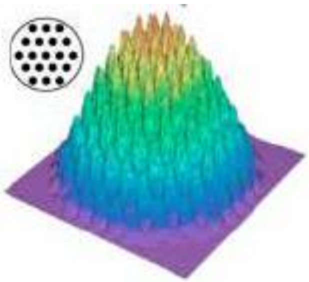


TM_{030} mode

→ High freq but small C. (1/10 of TM_{010})

→ increase detection efficiency: bunched Rydberg atom beam.

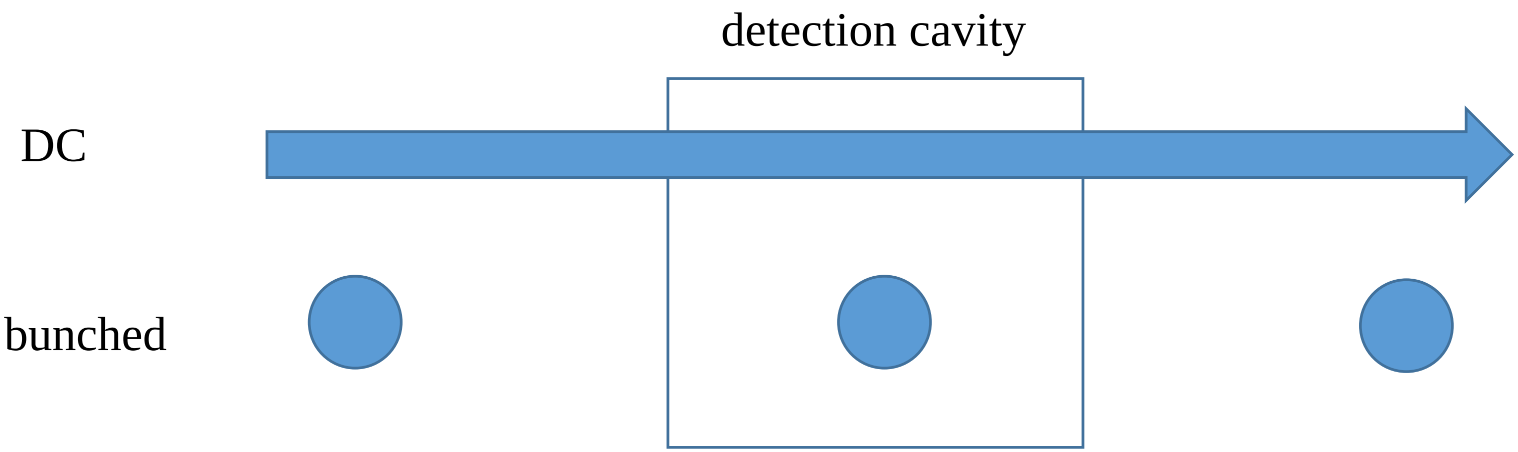
(cf) Photonic Bandgap Resonators (periodical array of metal post)



Lect. Notes. Phys. 741 (2008)

Being developed
by Y. Kishimoto (Tokyo Univ.),
I. Ogawa (Fukui Univ.) *et al.*

Bunched Rydberg beam



By using bunched beam:

we can know when and where the Rydberg atom exists.

Synchronize the electric field for the field ionization.

→ Maximize efficiency

→ Reduce the noise component

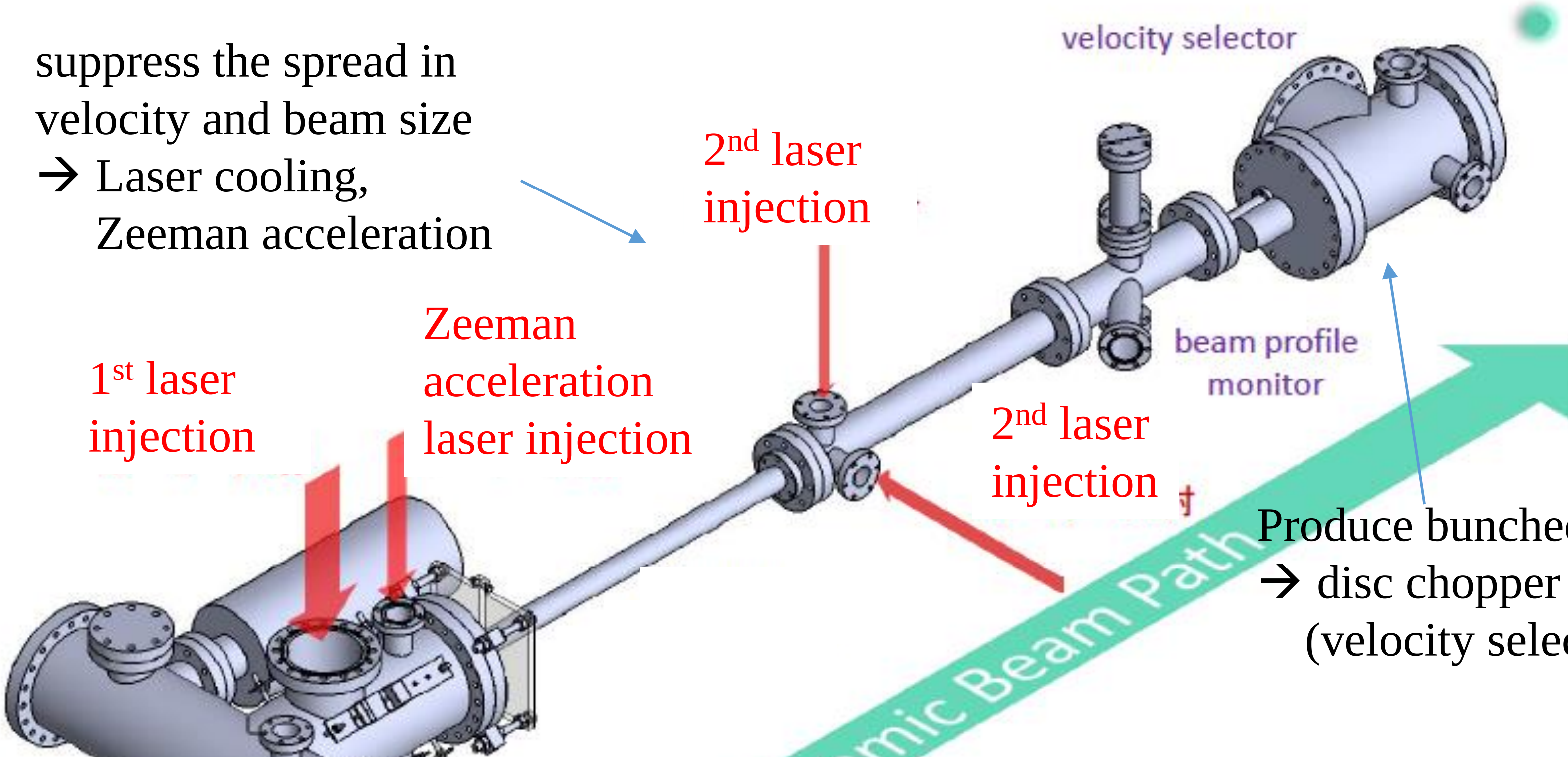
→ Cancel out the stray field inside the magnet.

(deodorize the sensitivity of field ionization)

S/N → x10
compared to
CARRACK

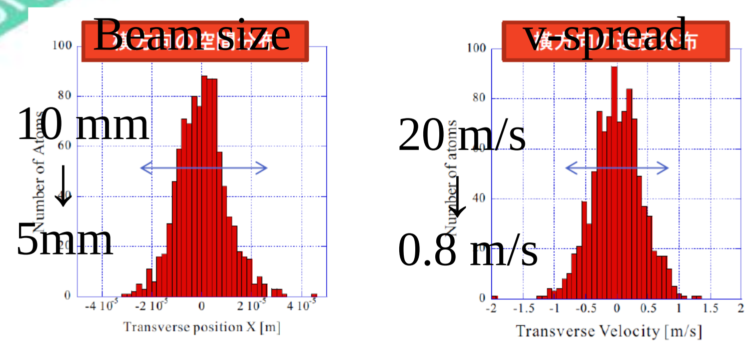
Bunched Rydberg beam

suppress the spread in velocity and beam size
→ Laser cooling,
Zeeman acceleration



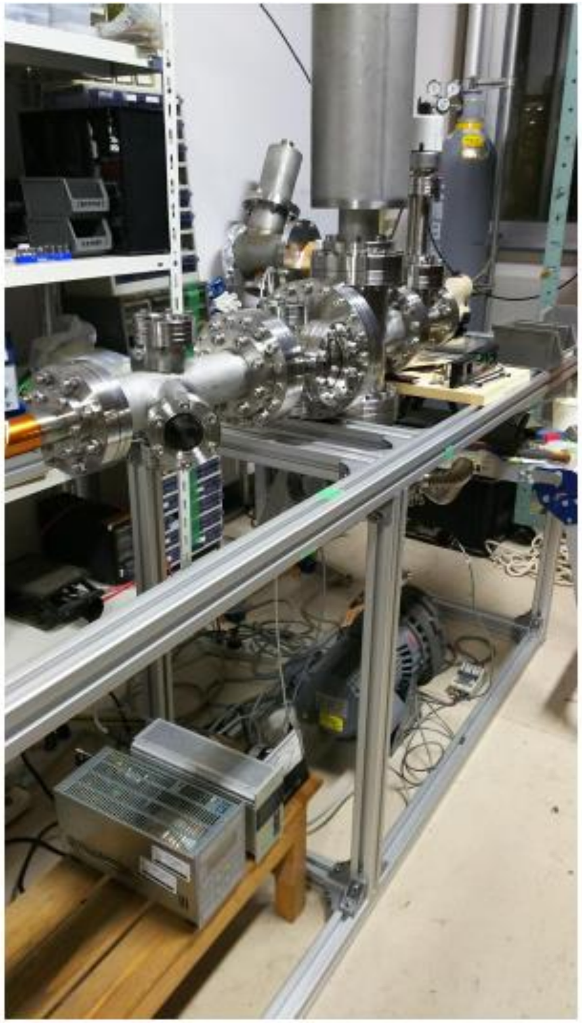
Produce bunched beam
→ disc chopper
(velocity selector)

atomic beam oven



Simulation result

Bunched Rydberg beam



Design was finished.

Assembled in Kyoto University.

Beam size measurement is planned in next FY.

Summary of New-CARRACK

- Target mass : ~100 μeV (CARRACK : ~10μeV)
- New Cavity: TM_{030} will be constructed.
- Bunched Rydberg beam: test in next FY.
- Experimental setup is now stored in Osaka University.
- We are aiming to start the experiment (within a few year).
- We welcome your collaboration!

Summary

- Axion ← Strong CP problem, DM problem
- Recent axion search result in Japan
  - XMASS $g_{Ae} = 10^{-13}$ (40 < ma <120 keV)
  - LSW @ SPring-8 $g_{a\gamma\gamma} < 2.51 * 10^{-4}$ GeV^{-1} (ma < 0.1 eV)

    $g_{a\gamma\gamma} < 4.2 * 10^{-3}$ GeV^{-1} (ma < 10 eV)

    $g_{a\gamma\gamma} < 5.0 * 10^{-4}$ GeV^{-1} (46 eV < ma < 1020 eV)
- New-CARRACK project (m_a =100 μeV)
  - Kyoto → Osaka
  - New setup is being developed.