# Tokyo axion helioscope experiment

## and

## other axion experiments


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for the Sumico Collaboration


Rencontres de Moriond EW2011, 18 March 2011, La Thuile, Italy

# Collaborators


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Logo designed by ⟶

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# Outline

- Introduction
  - What & how we are going to detect?
- Tokyo axion helioscope
  - Hardware, results & prospects
- Other experiments
  - CAST
  - Crystalline detectors
  - Microwave cavity (axion haloscope)
- Conclusions

# Introduction

# Strong CP problem

Two *independent* sources of CP violation in QCD:

$$\mathscr{L}_{\bar\theta} = \frac{\bar\theta}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}, \qquad \bar\theta = \theta + \arg\det \mathcal{M}_q,$$

$$\text{where} \begin{cases} \theta & \leftarrow \text{initial QCD ground state} \\ \mathcal{M}_q & \leftarrow \text{quark mass matrix (EW scale physics)} \end{cases}$$

$$\Updownarrow$$

Neutron EDM:

$$d_n < 2.9 \times 10^{-26}\, e\,\mathrm{cm} \qquad (\bar\theta < 10^{-10})$$

# Peccei–Quinn mechanism

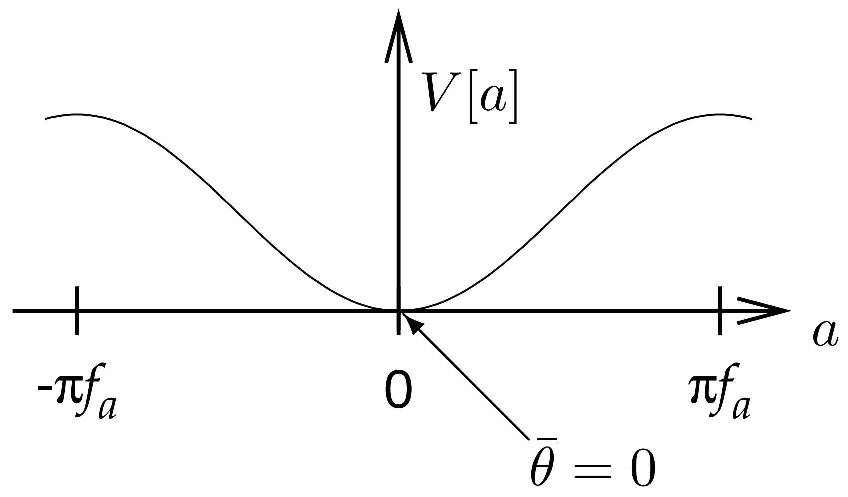
Global chiral $\mathrm{U(1)_{PQ}}$ + SSB $\longrightarrow$ **Axion** (NG boson)

+ Making $\bar{\theta}$ into a dynamic parameter which should fall into the potential minimum:

$$\bar{\theta} = \theta + \arg\det \mathcal{M}_q + \boxed{\frac{a}{f_a}}$$

Axion mass:

$$m_a = \frac{\sqrt{z}}{1+z}\frac{f_\pi m_\pi}{f_a}$$



# Axion-photon coupling

The axion couples to two photons:

$$\mathscr{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu} = g_{a\gamma} a \vec{E} \cdot \vec{B}$$

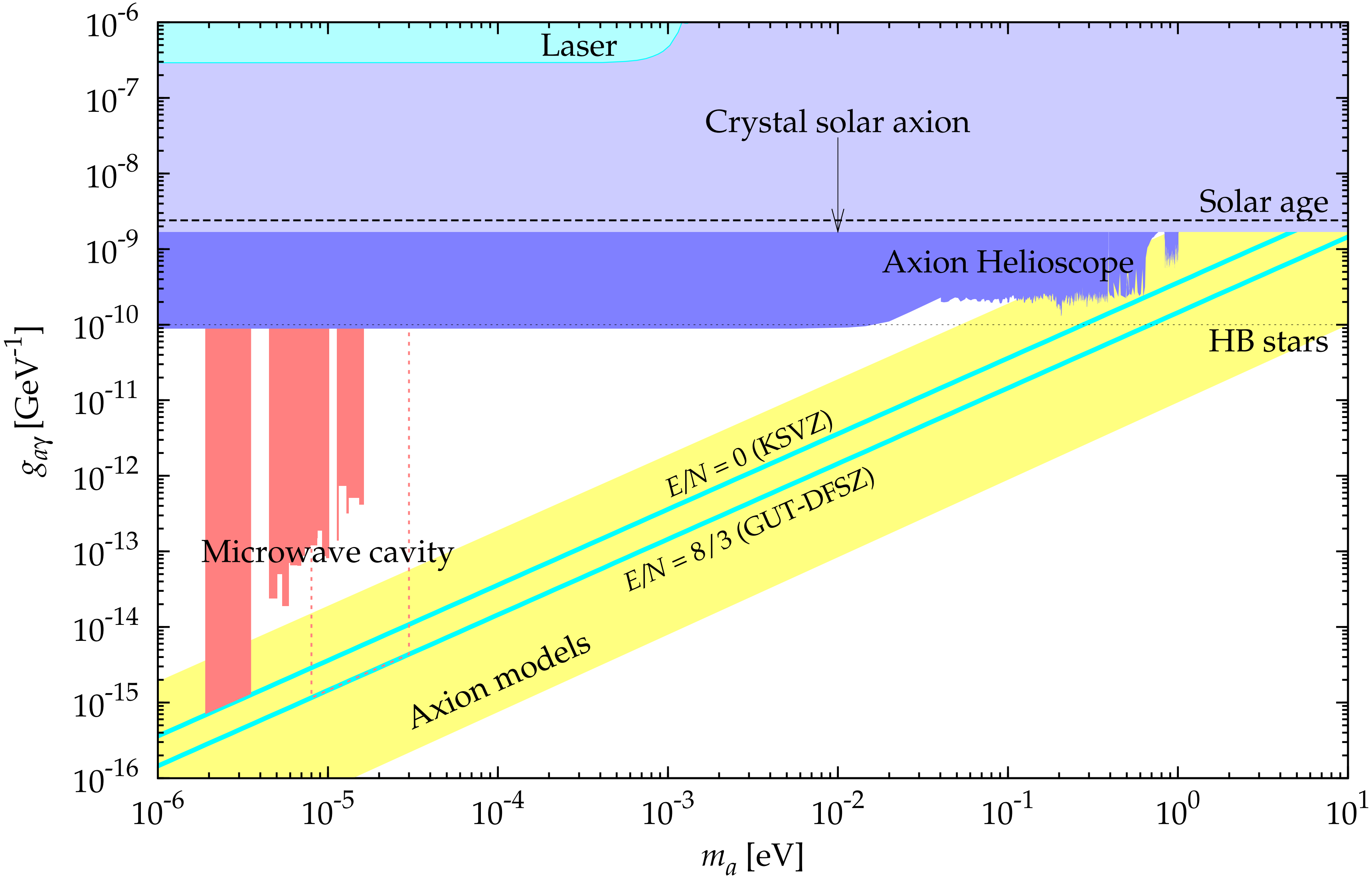
$$\begin{aligned} g_{a\gamma} &= \frac{\alpha}{2\pi f_a} \left[ \frac{E}{N} - \frac{2(4+z)}{3(1+z)} \right] \\ &= 1.9 \times 10^{-10} \left( \frac{m_a}{1\,\mathrm{eV}} \right) [E/N - 1.92] [\mathrm{GeV}^{-1}] \end{aligned}$$

Model dependent factor:

$E/N = 0$ (std. KSVZ), $\quad$ $8/3$ (GUT DFSZ).

$$E = \mathrm{Tr}(Q_{\mathrm{PQ}} Q_{\mathrm{em}}^2), \quad N = \mathrm{Tr}(Q_{\mathrm{PQ}} Q_{\mathrm{c}}^2)$$

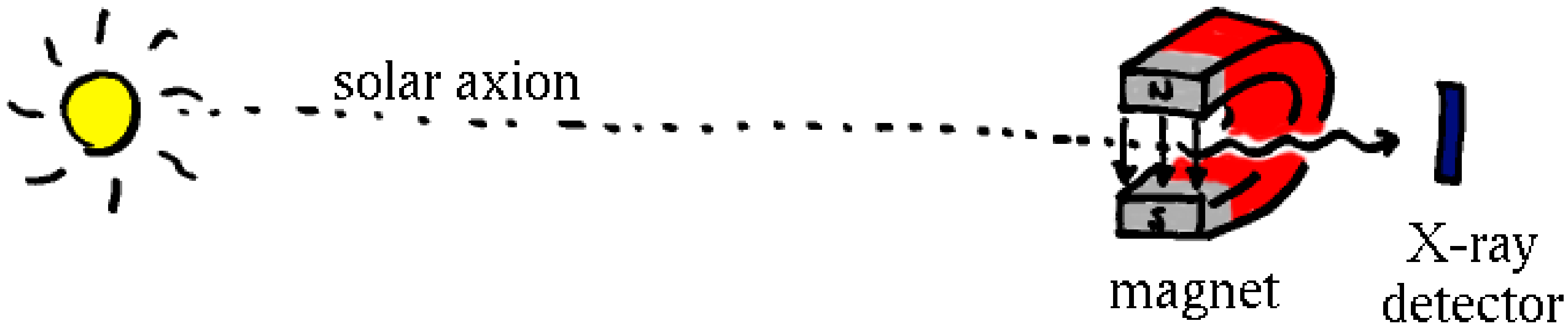
# Exclusion plot ($g_{a\gamma}$–$m_a$)



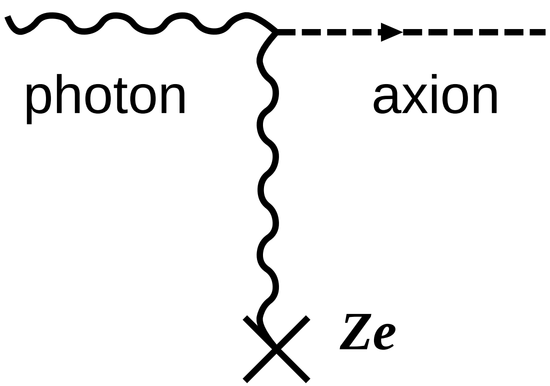
# Axion helioscope

[P.Sikivie, PRL51,1415(1983)]

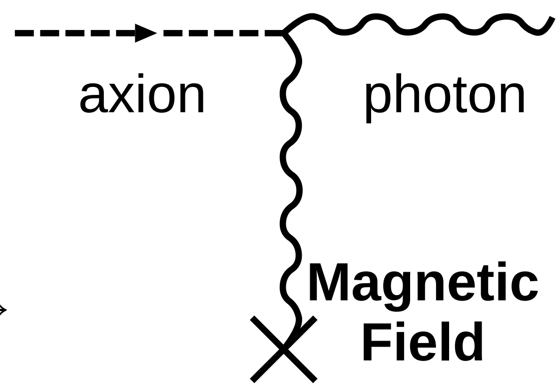
The sun can be a powerful source of axions.




Primakoff process

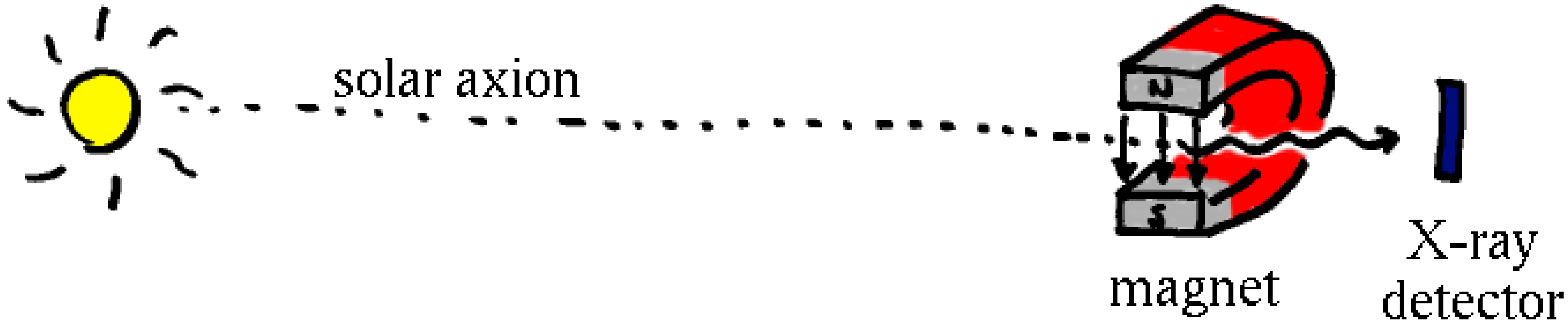


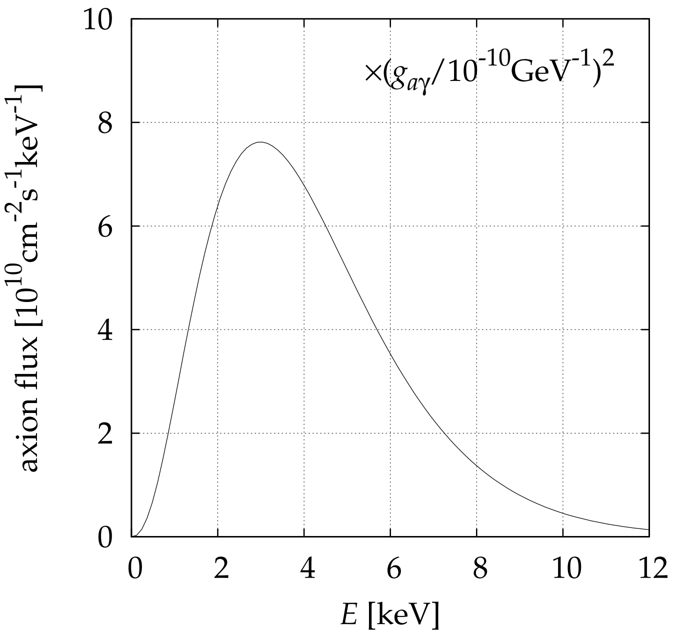

$$\longleftarrow \boxed{\mathscr{L}_{a\gamma\gamma} = g_{a\gamma} a \vec{E} \cdot \vec{B}} \longrightarrow$$



# Axion helioscope

[P.Sikivie, PRL51,1415(1983)]




Conversion rate:

$$P_{a\to\gamma} \lesssim \frac{1}{4} g_{a\gamma}^2 B^2 L^2$$

Sensitivity:

$$g_{a\gamma} \propto (BL)^{-\frac{1}{2}} \left( \frac{\text{bg rate}}{\text{time} \times \text{area}} \right)^{\frac{1}{8}}$$

# Buffer gas — to reach out for heavier axions

Conversion rate:

$$P_{a\to\gamma} = \frac{g_{a\gamma}^2}{2}\left|\int_0^L B e^{iqz} dz\right|^2 \quad \lesssim \quad \frac{g_{a\gamma}^2 B^2 L^2}{4},$$

$$q = k_\gamma - k_a \approx \frac{m_\gamma^2 - m_a^2}{2E}.$$

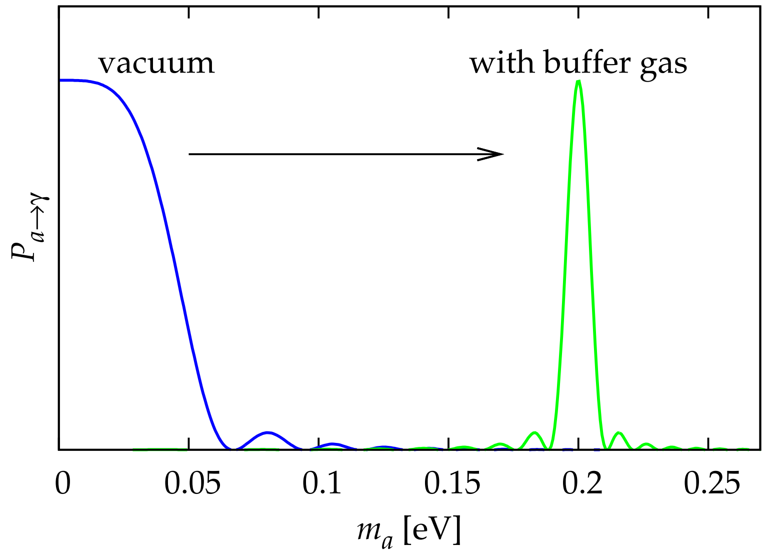
In vacuum, coherence is lost for $m_a \gtrsim \sqrt{\pi E/L}\ldots$

$\Downarrow$

The effective photon mass in buffer gas:

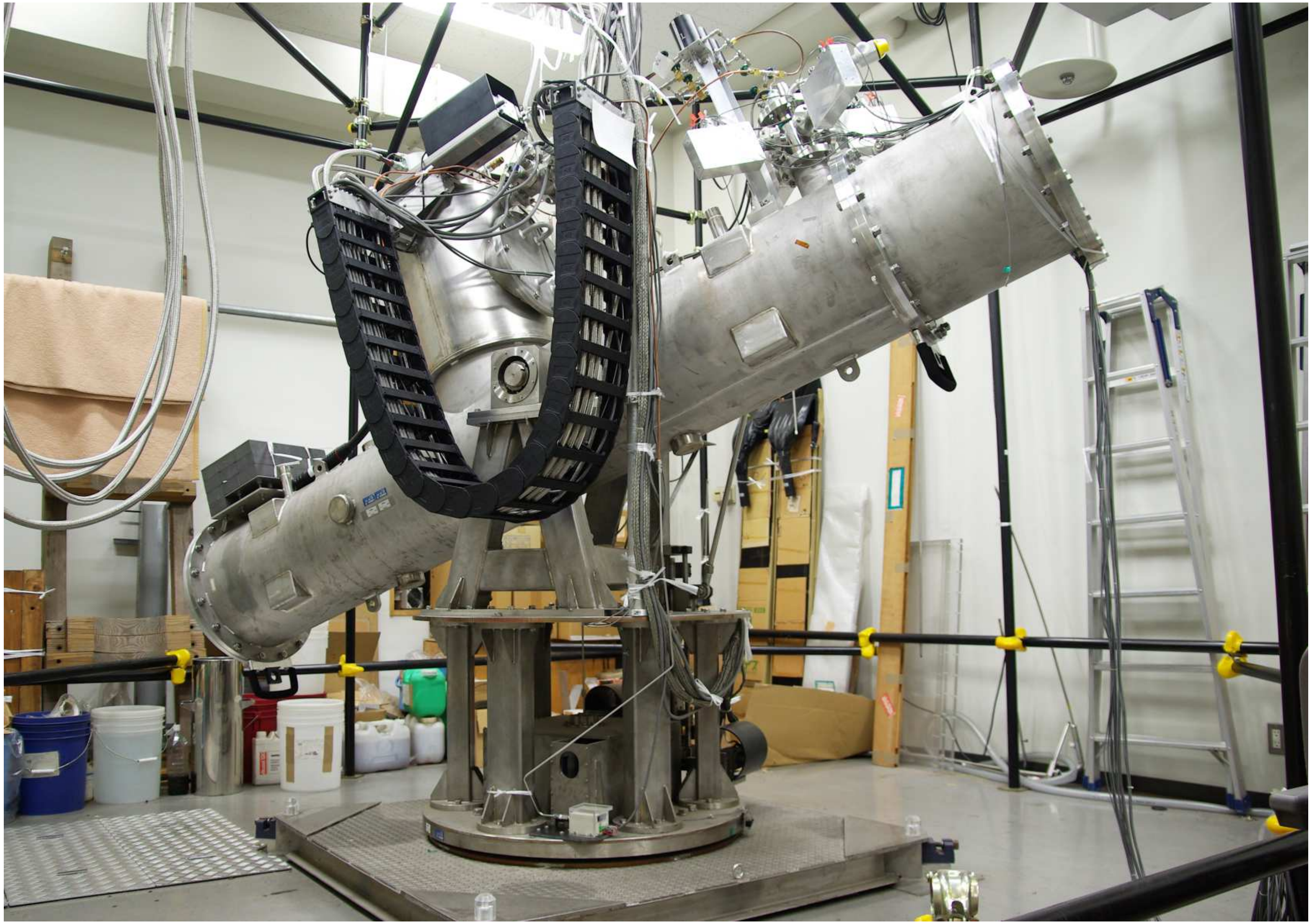
$$m_\gamma = \sqrt{\frac{4\pi\alpha N_e}{m_e}}.$$

$N_e$: electron density

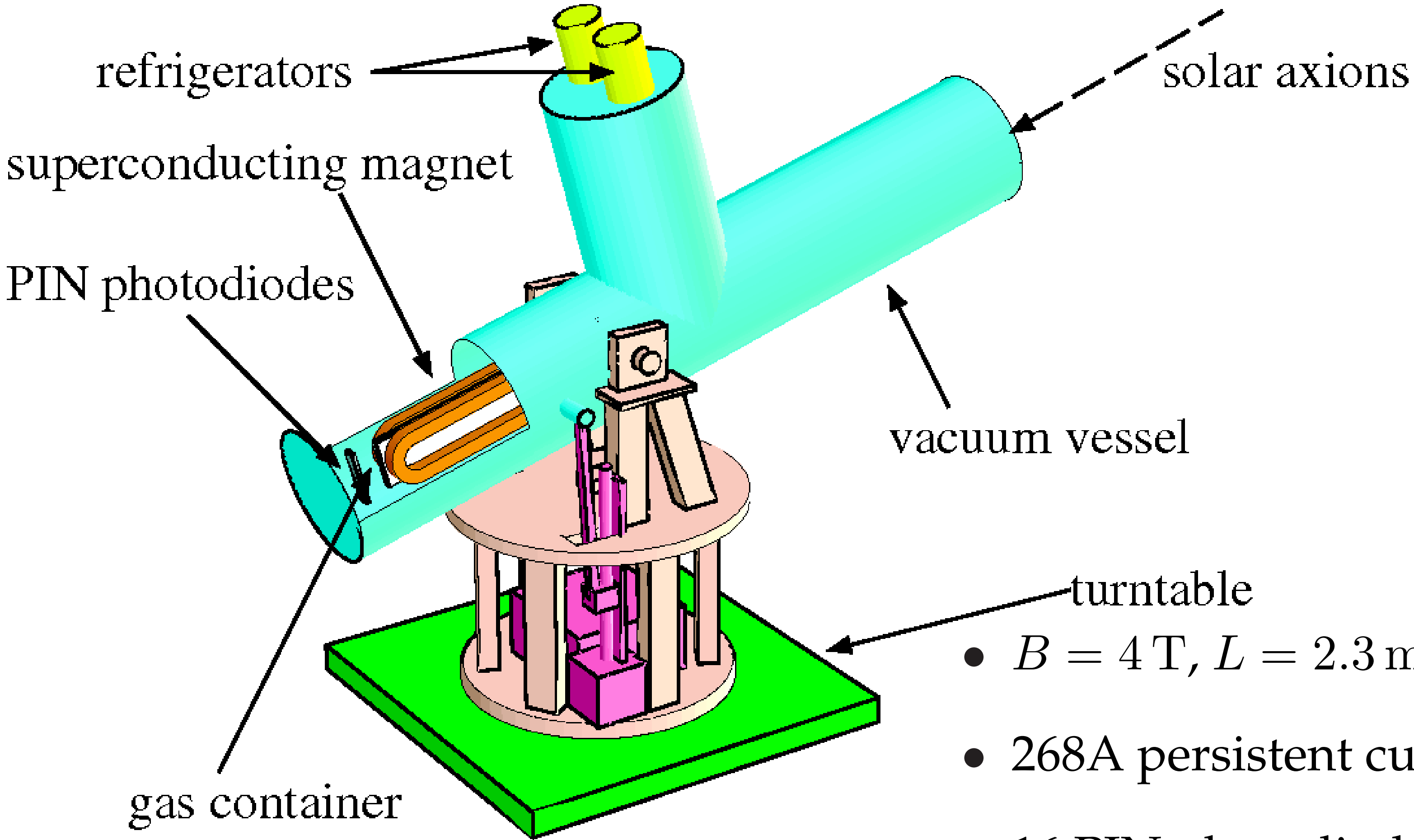


# Tokyo axion helioscope

# Tokyo axion helioscope (Sumico)

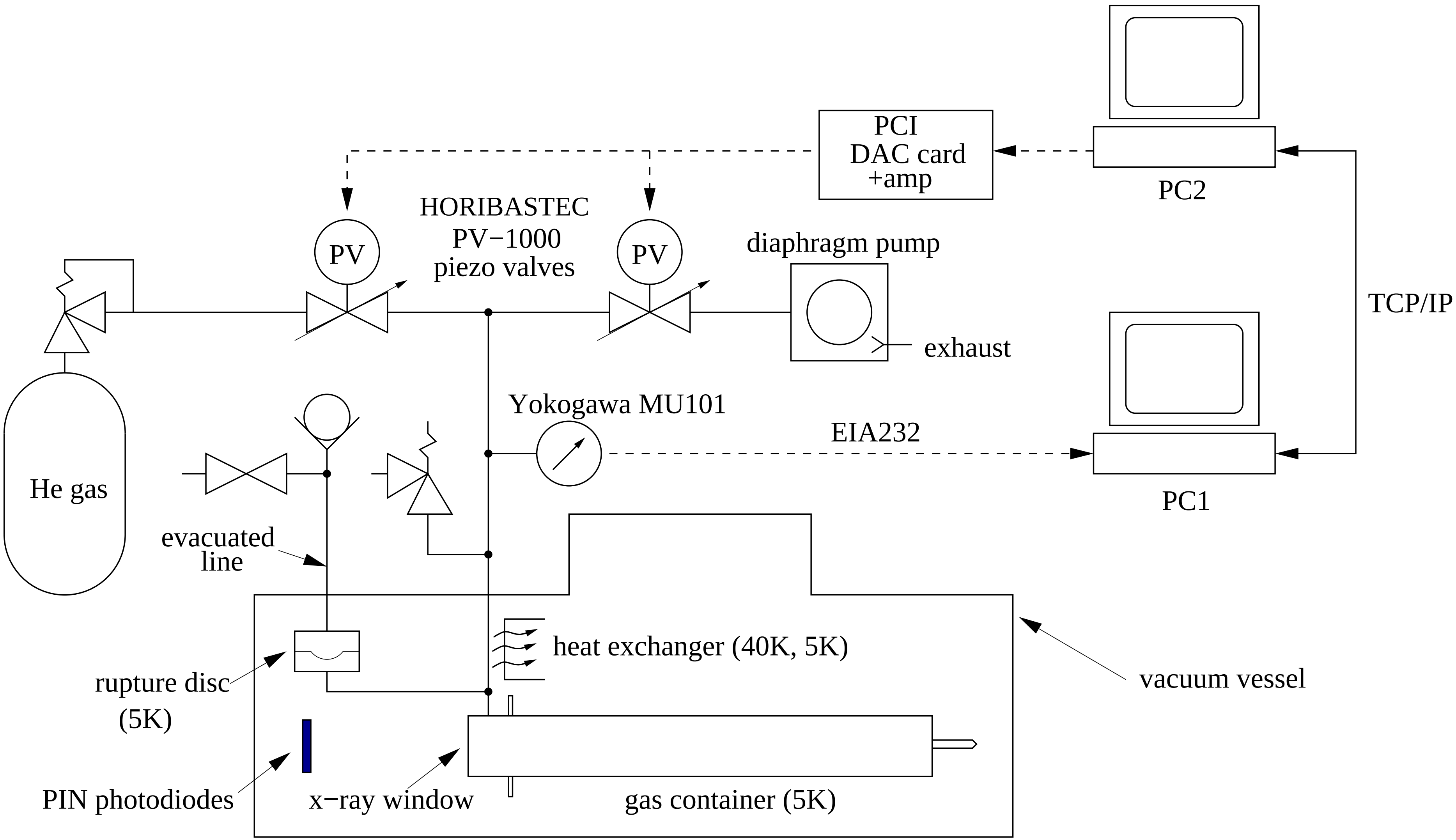


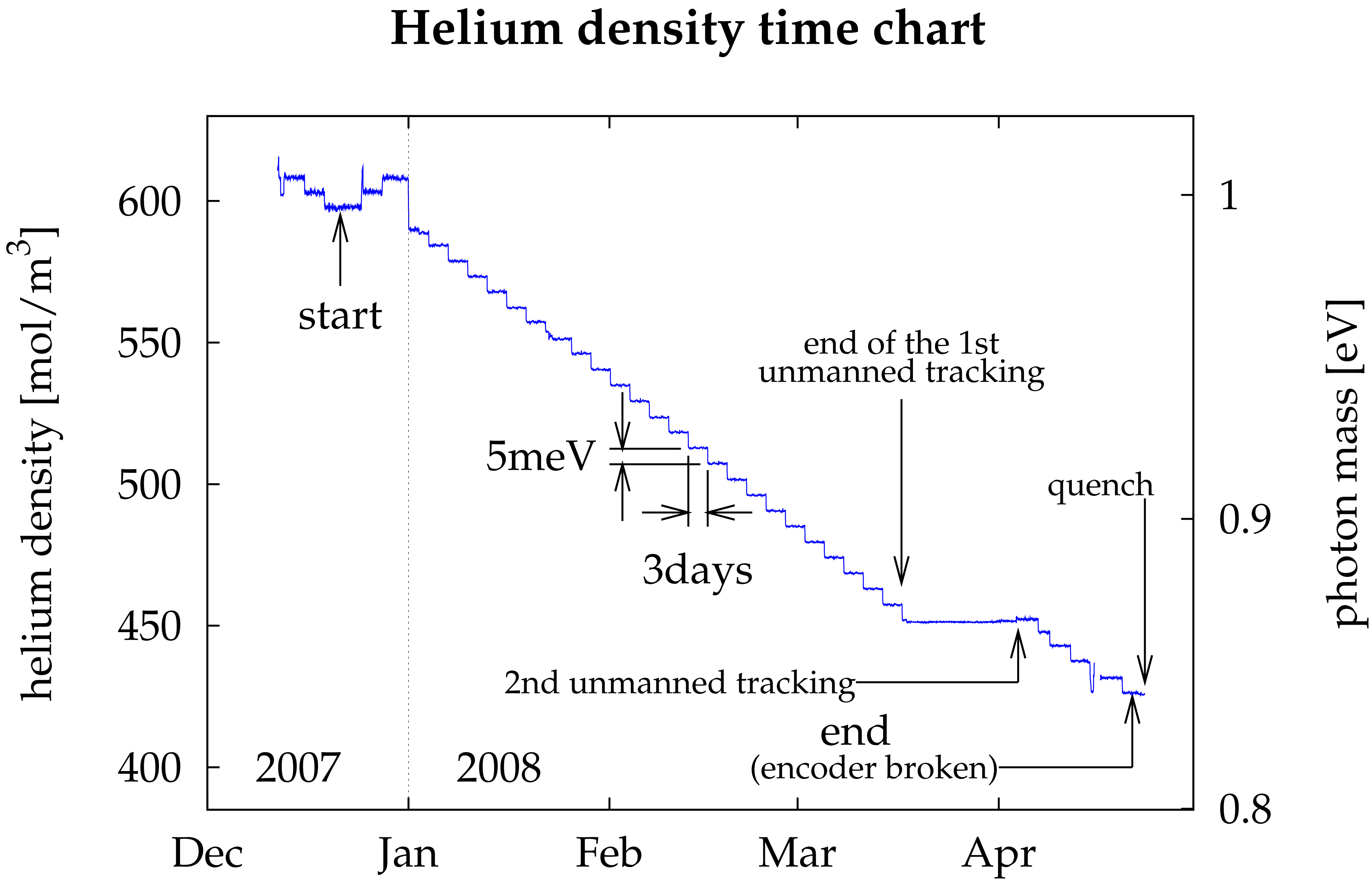
# Sumico V detector



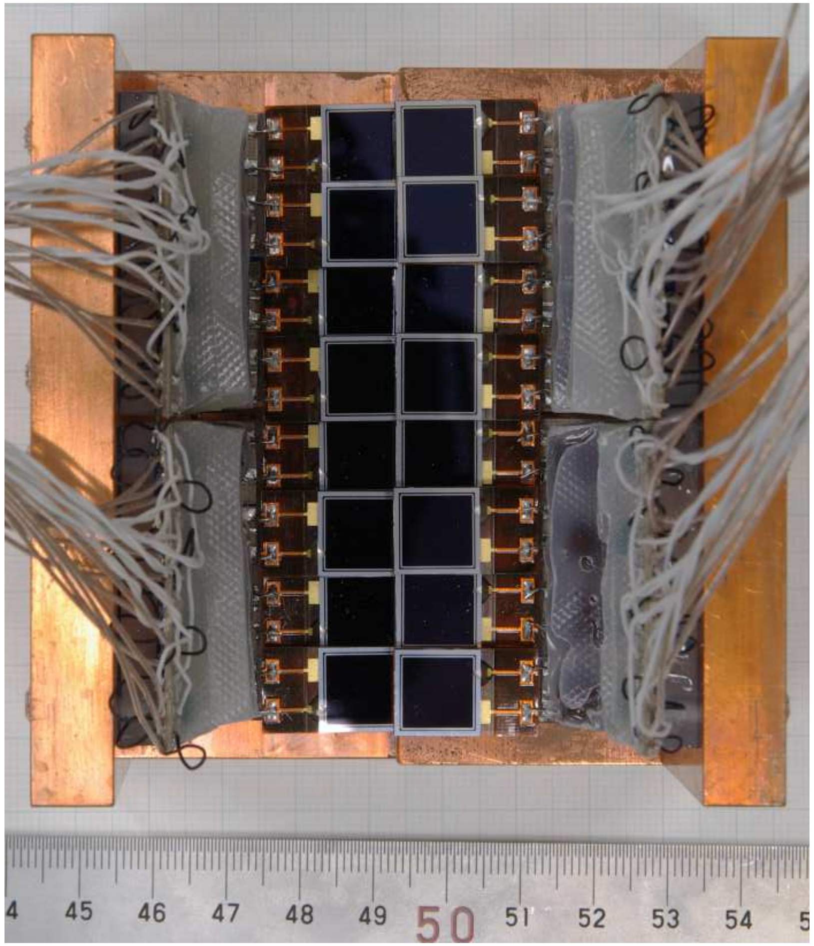

- $B = 4\,\mathrm{T}$, $L = 2.3\,\mathrm{m}$
- 268A persistent current
- 16 PIN photodiodes
- Track the sun $\sim 12\,\mathrm{hours/day}$

# Gas handling system




Helium density time chart
helium density [mol/m3]
photon mass [eV]
600
550
500
450
400
1
0.9
0.8
Dec
Jan
Feb
Mar
Apr
2007
2008
start
5meV
3days
end of the 1st
unmanned tracking
quench
2nd unmanned tracking
end
(encoder broken)

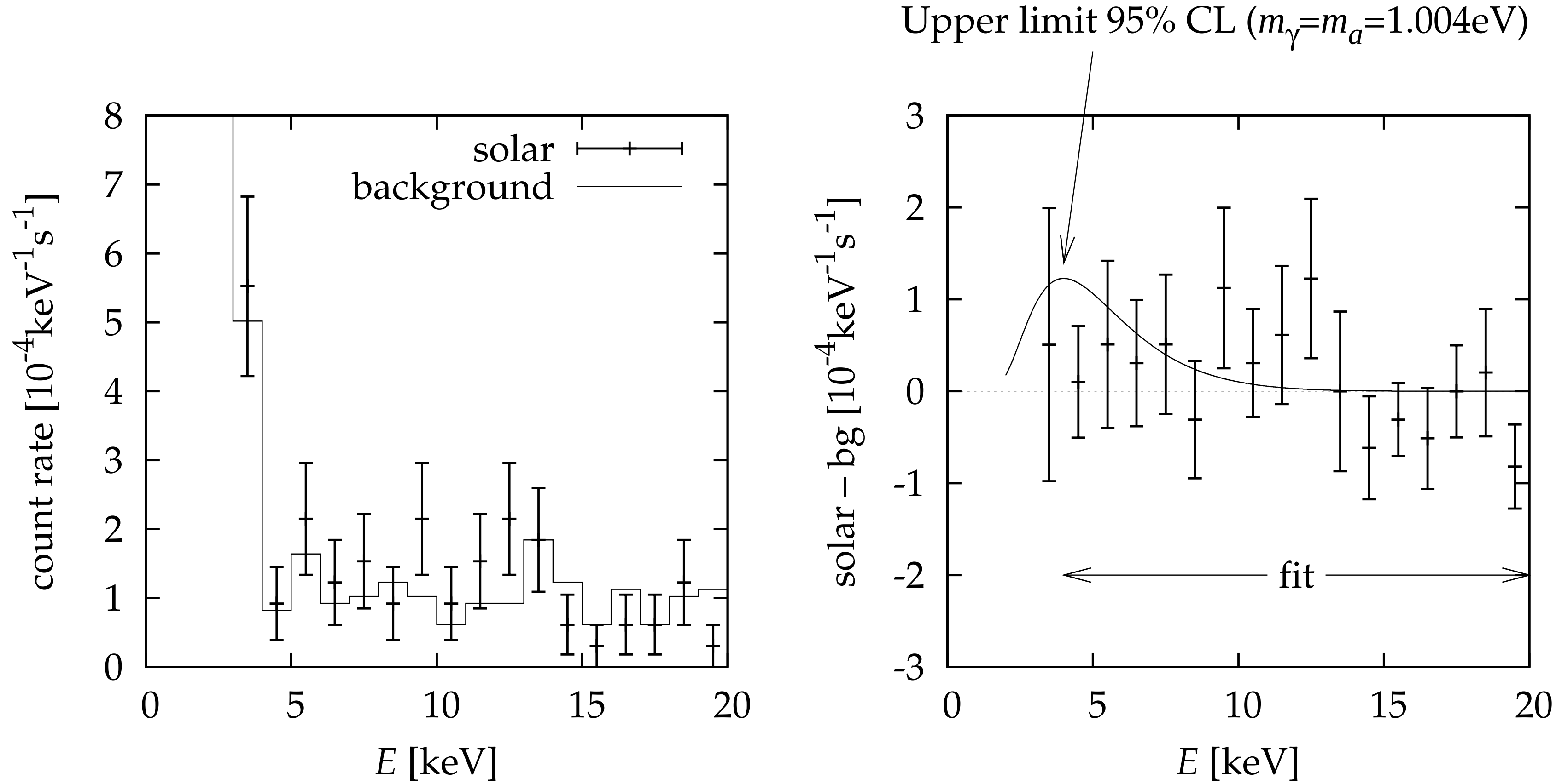
# PIN photodiode X-ray detector




- Inside OFHC shield @ $T = 60\,\mathrm{K}$
- 16 PIN photodiodes
  4 PIN/module
- chip:
  Hamamatsu S3590-06-SPL
- size:
  $11 \times 11 \times 0.5\,\mathrm{mm}^3/\mathrm{PIN}$
- active area $> 9 \times 9\,\mathrm{mm}^2/\mathrm{PIN}$
- inactive surface $< 0.35\mu\mathrm{m}$

[T.Namba *et al.*, NIMA489(2002)224]
[Y.Akimoto *et al.*, NIMA557(2006)684]

# Energy spectrum

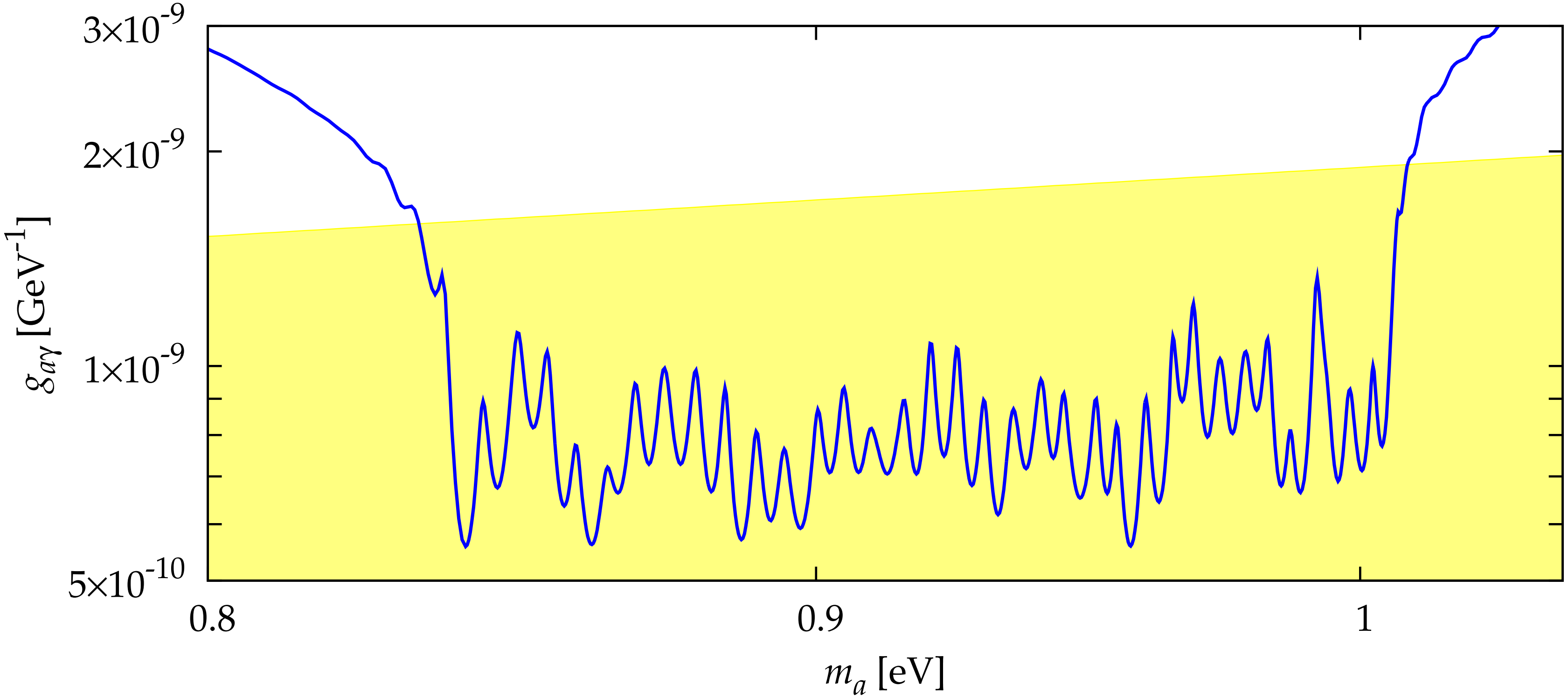



$$\chi^2(m_a) = \sum_{m_\gamma = m_{\gamma,\mathrm{min}}}^{m_{\gamma,\mathrm{max}}} \sum_{E=4\,\mathrm{keV}}^{20\,\mathrm{keV}} \left[ \frac{N_{\mathrm{solar}}(E, m_\gamma) - N_{\mathrm{bg}}(E, m_\gamma) - N_{\mathrm{theo}}(E, q)}{\sigma(E, m_\gamma)} \right]^2$$

# Exclusion plot

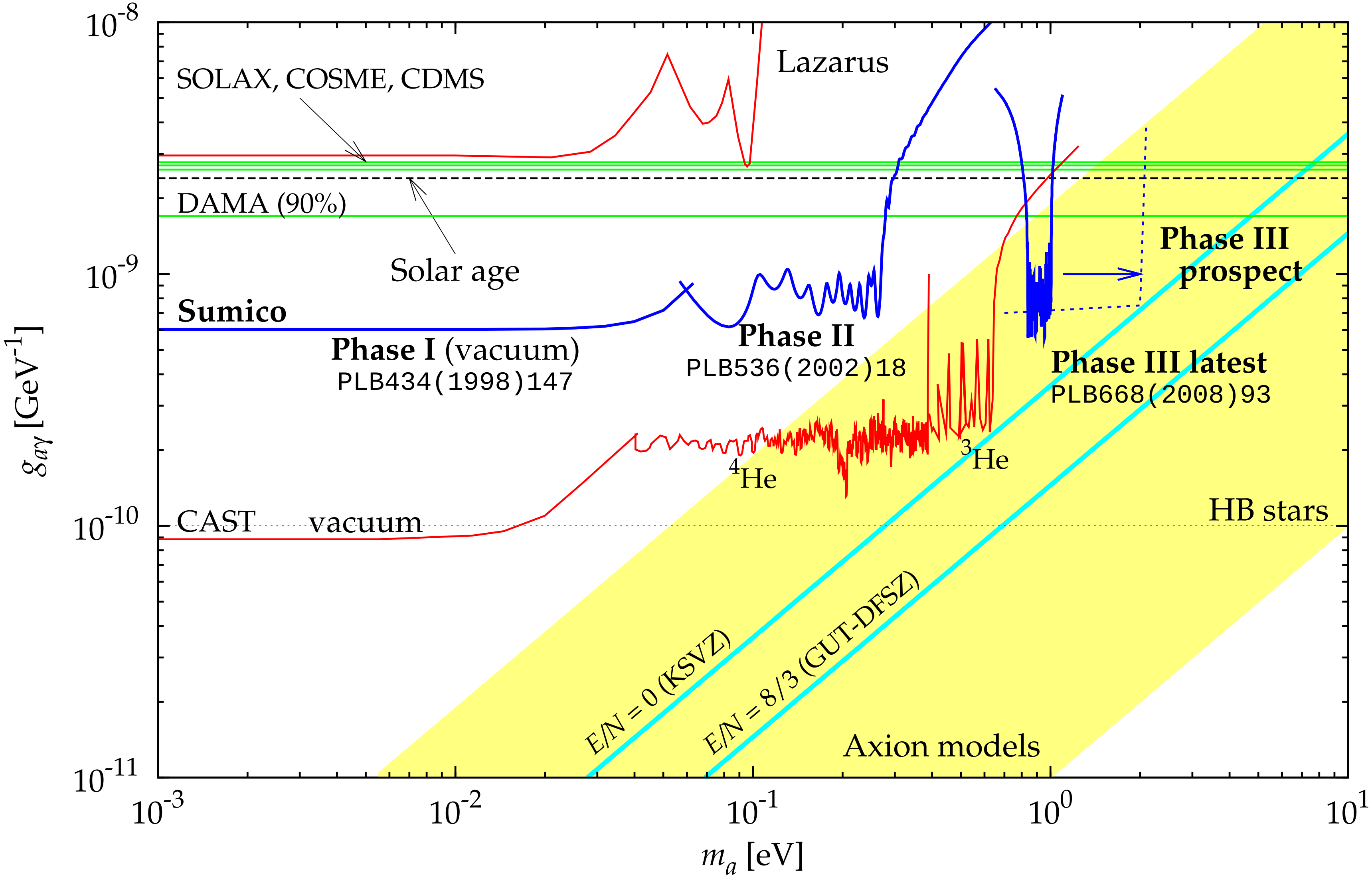
[Y.Inoue *et al.*, PLB668(2008)93]

Upper limit (95% CL)




$$\chi^2(m_a) = \sum_{m_\gamma = m_{\gamma,\mathrm{min}}}^{m_{\gamma,\mathrm{max}}} \sum_{E=4\,\mathrm{keV}}^{20\,\mathrm{keV}} \left[ \frac{N_{\mathrm{solar}}(E, m_\gamma) - N_{\mathrm{bg}}(E, m_\gamma) - N_{\mathrm{theo}}(E, q)}{\sigma(E, m_\gamma)} \right]^2$$

# Sumico results & prospect



# Phase III upgrades, troubles & status

✓ Introduced a cryogenic rupture disk (Done)

✓ Automated gas density control (Done)

——— Sumico 2007–2008 run ———

✓ Reworked He pipelines for quicker evacuation (Done)

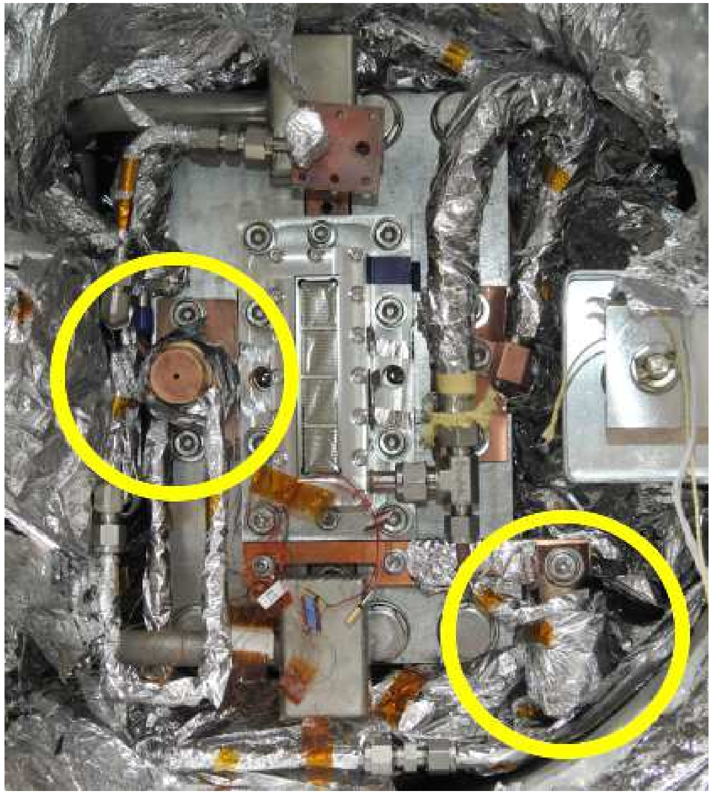
✓ Thermoacoustic oscillation at higher $\rho_{\mathrm{He}}$
$\rightarrow$ Introduced a blind-end bellows at $T_{\mathrm{room}}$ section (Resolved)

- Thermal non-uniformity at higher $\rho_{\mathrm{He}}$
$\rightarrow$ Introduced new heat exchangers (Testing)

✓ 1st X-ray window got a puncture/crack
$\rightarrow$ Repaired by the manifacturer (Test passed)

✘ 2nd Spare window broken entirely by thermal stress (Alas!)

# **Phase III upgrades, troubles & status** (gallery)



New heat exchangers

1st X-ray window
repaired
with epoxy

Light shinning
through the
2nd X-ray window

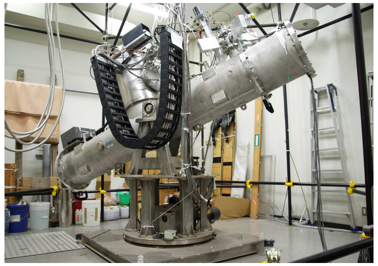
# Other experiments

## **CAST** (CERN Axion Solar Telescope)

[K.Zioutas *et al.*, PRL94,121301(2005)]

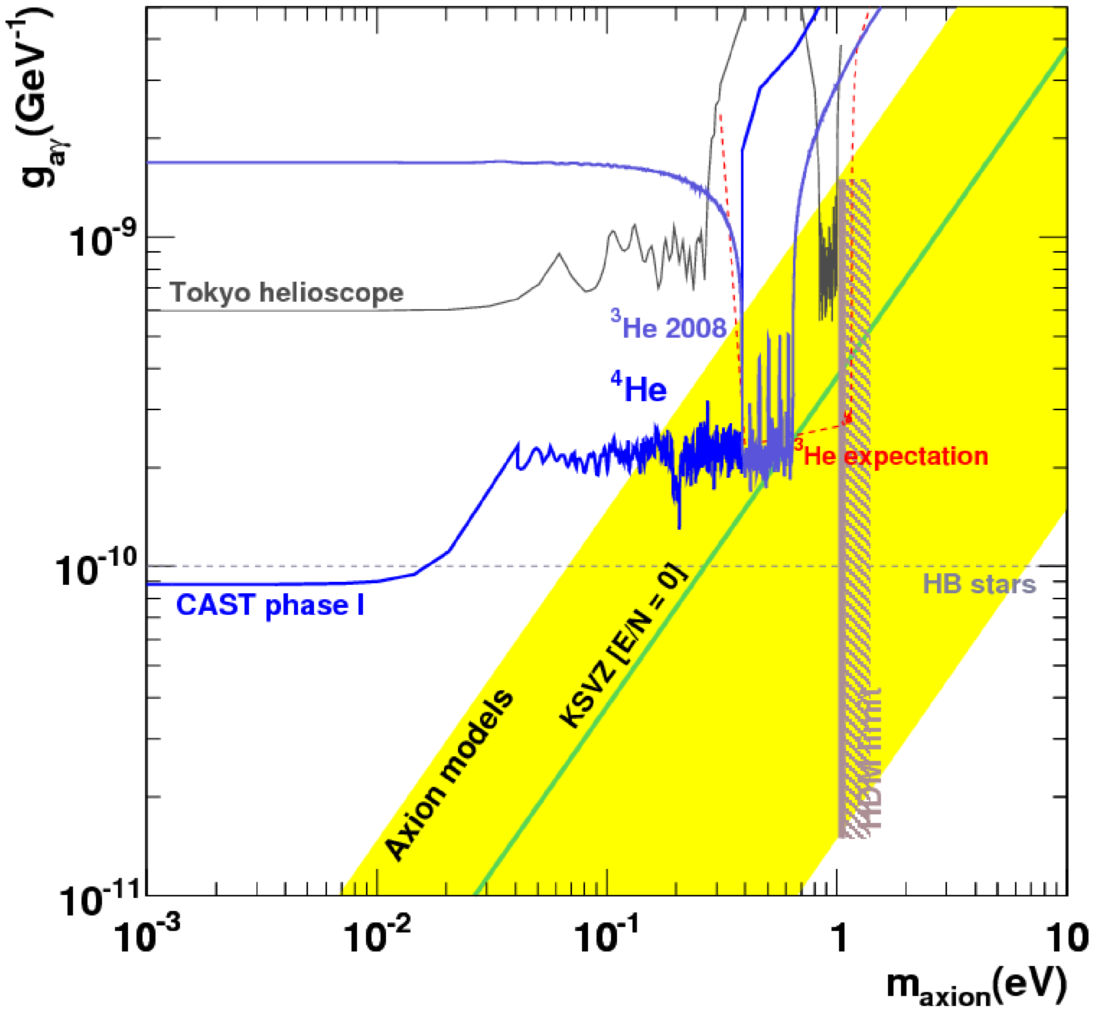
- $B = 9\,\mathrm{T}$, $L = 9.26\,\mathrm{m}$ (LHC test magnet)
- Vertical $\pm 8^\circ$, horizontal $\pm 40^\circ$
- TPC, Micromegas, CCD X-ray telescope

# Sumico & CAST side-by-side



| Sumico | CAST |
|---|---|
| Tokyo | CERN |
| $4\,\mathrm{T} \times 2.3\,\mathrm{m}$ | $9\,\mathrm{T} \times 9.26\,\mathrm{m}$ |
| 12 hours/day | $2 \times 1.5$ hours/day |
| $^4$He @ $5\,\mathrm{K}$ ($m_a \lesssim 2\,\mathrm{eV}$) | $^4$He,$^3$He @ $1.9\,\mathrm{K}$ ($m_a < 1.1\,\mathrm{eV}$) |

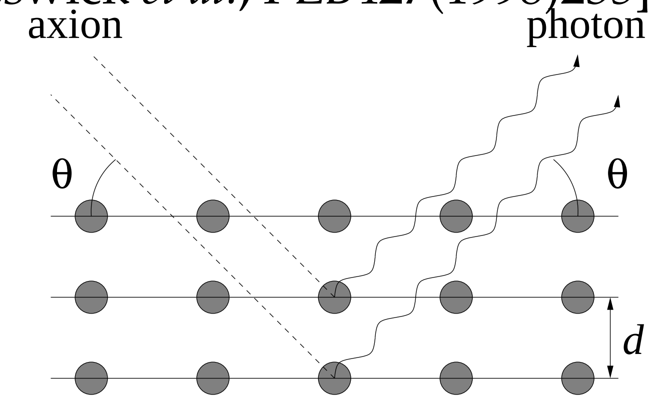
# CAST result




From
[J.Galan, arXiv:1102.1406]

# Crystal detectors

- Primakoff conversion in a lattice [R.J.Creswick *et al.*, PLB427(1998)235]




- Bragg condition:

$$2d \sin\theta = n\lambda$$

- SOLAX — Ge [A.O.Gattone *et al.*, NPB-PS70(1999)59]
  $g_{a\gamma} < 2.7 \times 10^{-9}\mathrm{GeV}^{-1}$ (95%)

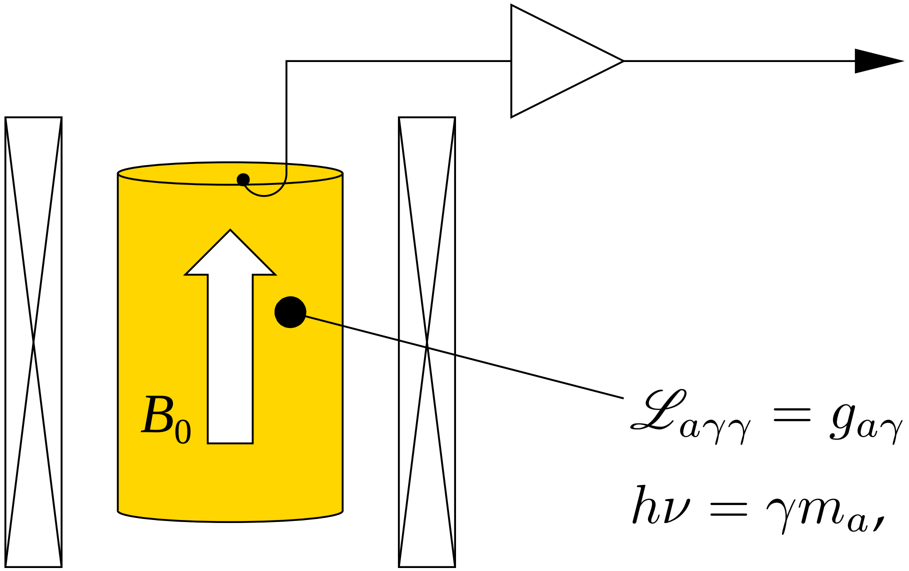
- COSME — Ge [A. Morales *et al.*, Astropart. Phys. 16(2002)325]
  $g_{a\gamma} < 2.78 \times 10^{-9}\mathrm{GeV}^{-1}$ (95%)

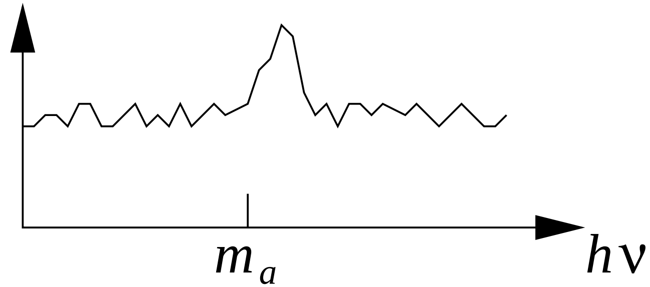
- DAMA — NaI(Tl) [R.Bernabei *et al.*, PLB515(2001)6]
  $g_{a\gamma} < 1.7 \times 10^{-9}\mathrm{GeV}^{-1}$ (90%)

- CDMS — Ge [Z.Ahmed *et al.*, PRL103,141802(2009)]
  $g_{a\gamma} < 2.6 \times 10^{-9}\mathrm{GeV}^{-1}$ (95%)

# Microwave cavity (axion haloscope)

[P.Sikivie, PRL51,1415(1983)]




$1\,\mathrm{GHz} = 4.14\,\mu\mathrm{eV}$

$$\mathscr{L}_{a\gamma\gamma} = g_{a\gamma} a \vec{E} \cdot \vec{B}$$

$$h\nu = \gamma m_a, \quad \langle \beta^2 \rangle \sim 10^{-6}$$

$$\mathrm{Power} = \frac{g_{a\gamma}^2 V B_0^2 \rho_{\mathrm{halo}} C_{\mathrm{mode}}}{m_a} \min(Q_{\mathrm{cavity}}, Q_{\mathrm{halo}})$$

$$g_{a\gamma} \propto B_0^{-1} V^{-1/2} T_{\mathrm{noise}}^{1/2}$$

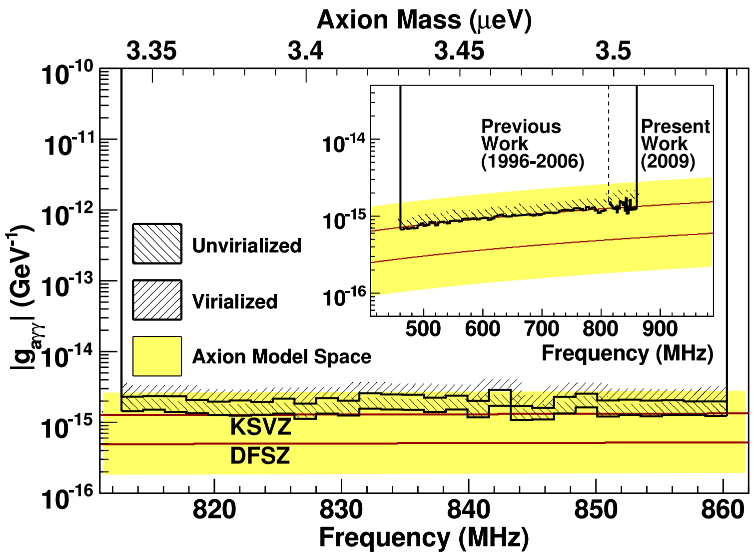
Pioneers: Rochester-BNL-FNAL (RBF), Florida (UF)

# **ADMX** (Axion Dark Matter eXperiment)

[S.J.Asztalos *et al.*, PRL104,041301(2010)]

http://www.flickr.com/photos/llnl/4305091276

- LLNL
- $B_0 = 7.6\,\mathrm{T}$
- GaAs HFET $(T_s \sim 2\,\mathrm{K})$
  $\rightarrow$ dc SQUID $(T_s = 47\,\mathrm{mK}\ @\ 700\,\mathrm{MHz})$
- Scanned $m_a = 1.9$–$3.53\,\mu\mathrm{eV}$
- Next upgrade: $T_{\mathrm{cavity}} \sim 2\,\mathrm{K} \rightarrow 100\,\mathrm{mK}$



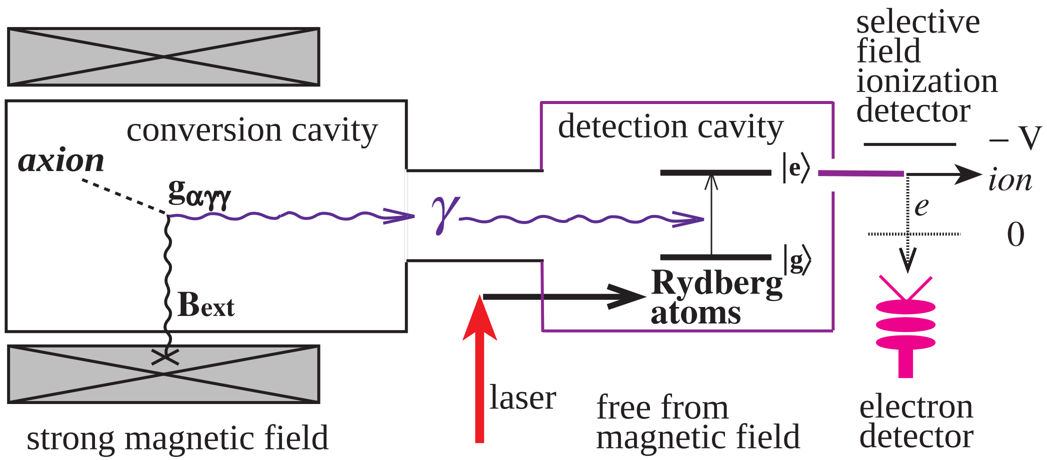
# CARRACK

(Cosmic Axion Research with Rydberg Atoms in resonant Cavity in Kyoto)

[M.Tada *et al.*, NPB-PS72(1999)164]

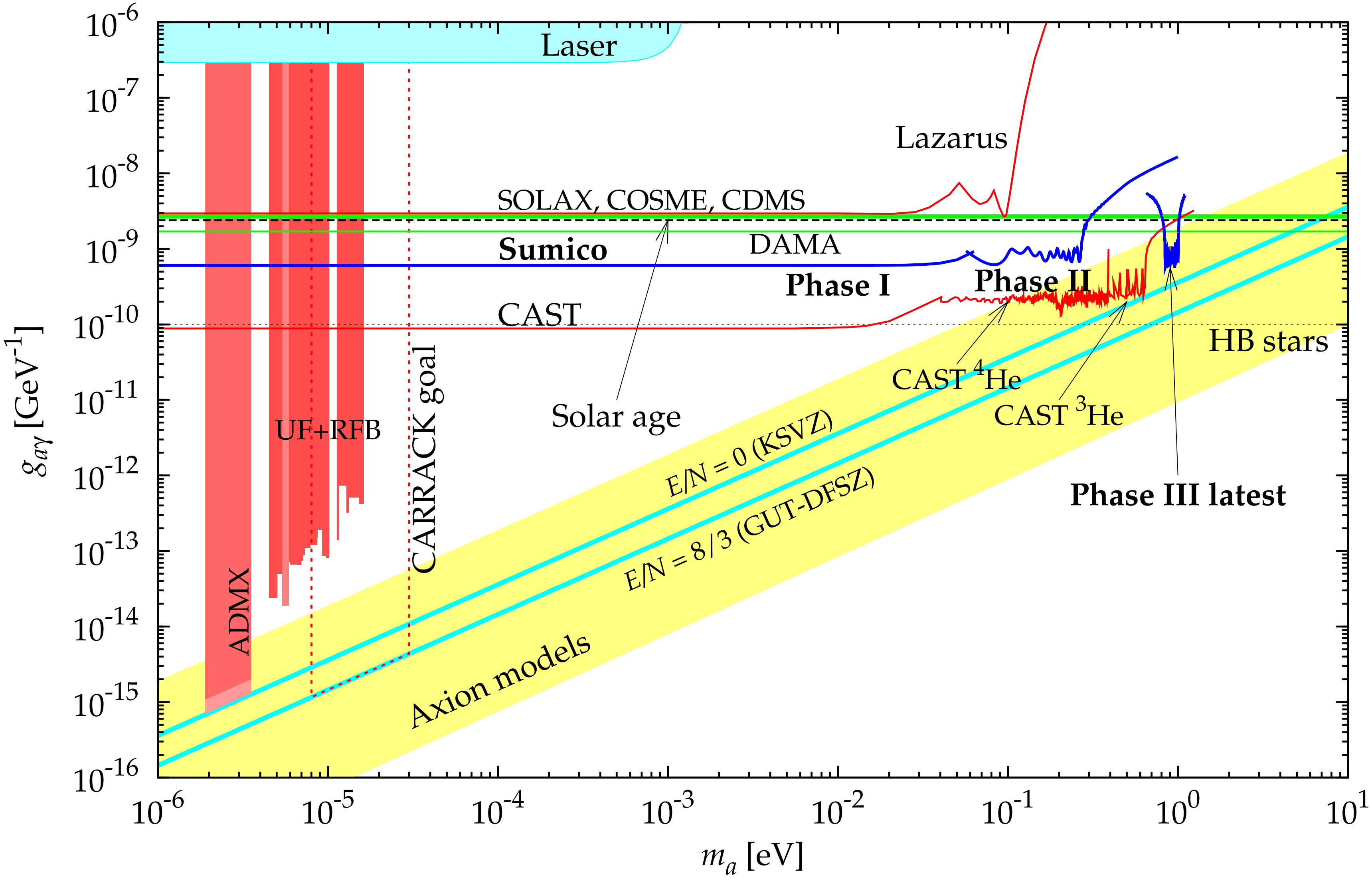
- Microwave photon counting using Rydberg atoms
  $^{39}$K, $^{85}$Rb, etc.; $ns \to np, n = O(100\text{–}200)$
- $B = 7\,\mathrm{T}, T_{\mathrm{cavity}} = 10\,\mathrm{mK}$
- Goal: cover $m_a =$ 8–30 $\mu$eV up to $g_{a\gamma} \sim$ DFSZ prediction.

http://www.ltm.kyoto-u.ac.jp/newcarrack/




[M.Tada *et al.*, arXiv:physics/0101028]

# Exclusion plot



# Conclusions

- 2 Fronts of experimental axion searches:
  - Solar axion $m_a \sim O(\mathrm{eV})$
    Sumico, CAST, crystals
  - Dark matter axion $m_a \sim O(\mu\mathrm{eV})$
    ADMX, CARRACK

- Sumico Phase III
  - Sumico 2007–2008 result:

    $$g_{a\gamma} < 5.6\text{–}13.4 \times 10^{-10}\mathrm{GeV}^{-1} \quad (0.84 < m_a < 1.00\,\mathrm{eV})$$

  - Upgrading toward $m_a \lesssim 2\,\mathrm{eV}$

# Backup

# Axion-photon oscillation

[Raffelt & Stodolsky, PRD37(1988)1237]

Wave equation for $(A_\perp, A_\parallel, a)$ plane wave propagating along the $z$ axis:

$$\begin{pmatrix} \omega^2 + \partial_z^2 - m_\gamma^2 & 0 & 0 \\ 0 & \omega^2 + \partial_z^2 - m_\gamma^2 & g_{a\gamma} B\omega \\ 0 & g_{a\gamma} B\omega & \omega + \partial_z^2 - m_a^2 \end{pmatrix} \begin{pmatrix} A_\perp \\ A_\parallel \\ a \end{pmatrix} = 0.$$

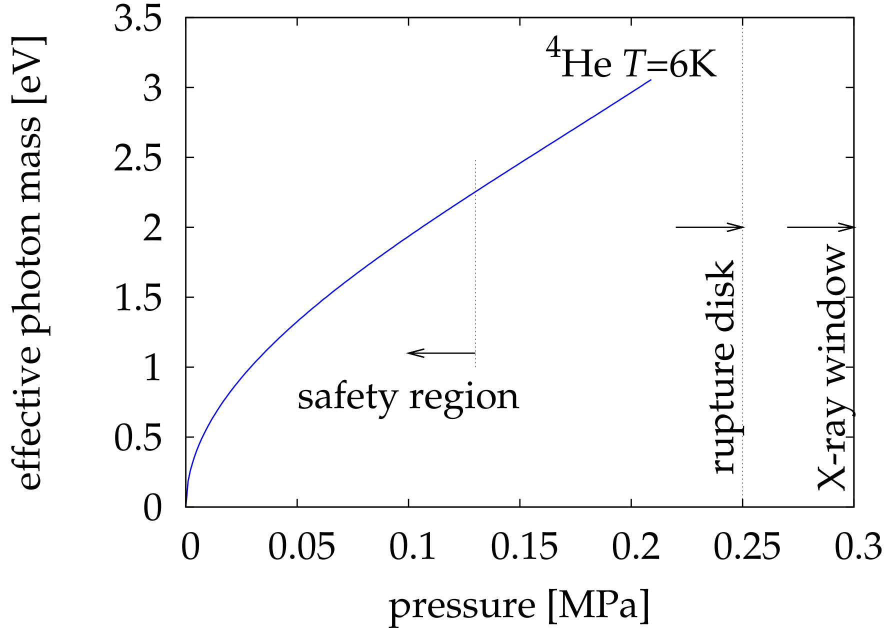
$$\downarrow$$

$A_\parallel \rightleftharpoons a$ mixing

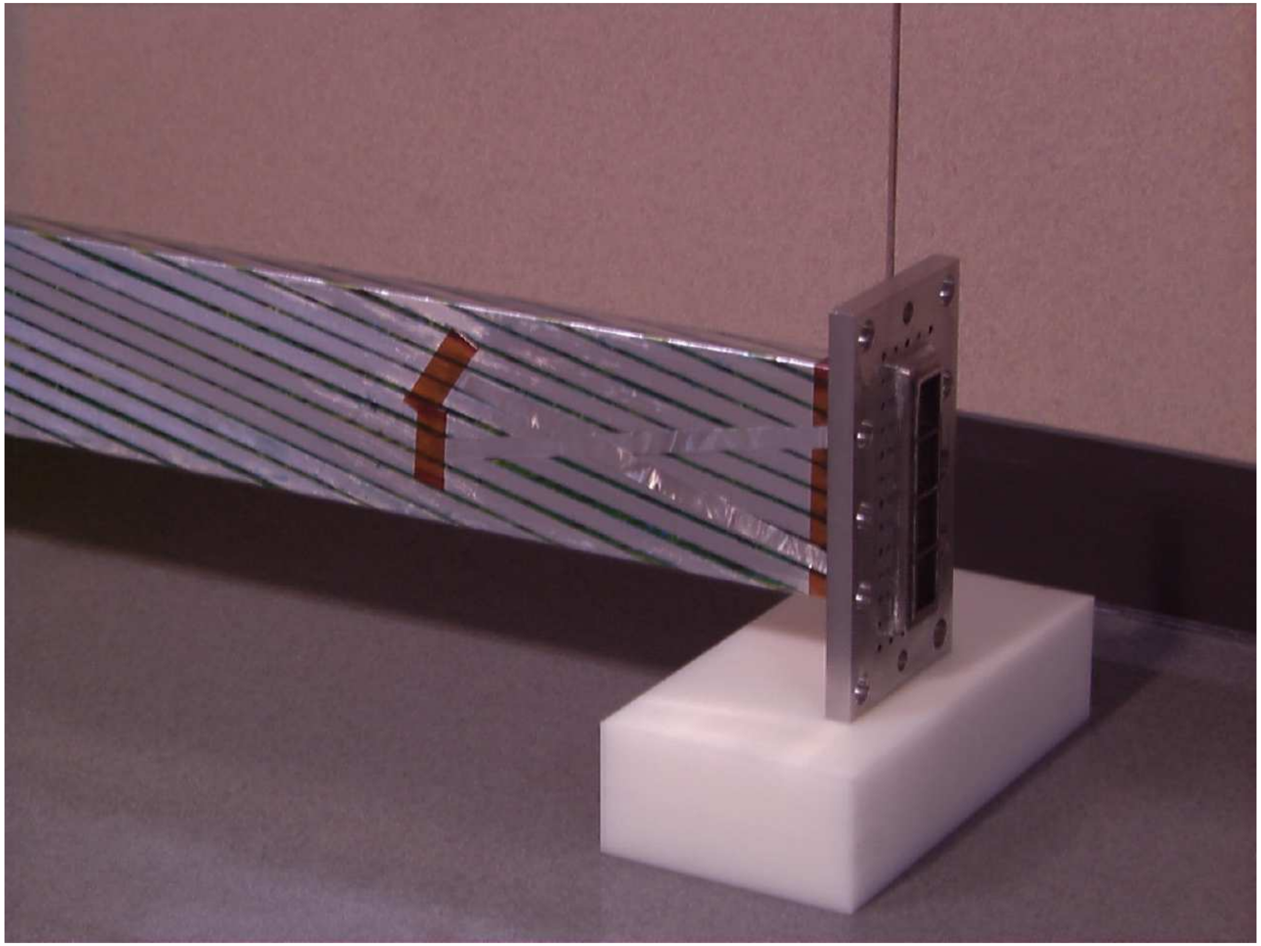
# Notes on buffer gas

- $^4$He is used $\iff$ CAST is using $^3$He
- Temperature is kept high enough above the critical point ($p_c = 0.227\,\mathrm{MPa}$, $T_c = 5.1953\,\mathrm{K}$)
- X-ray absorption and decoherence due to gravity are not fatal even at $m_\gamma \sim 2\,\mathrm{eV}$

$$m_\gamma = \sqrt{\frac{4\pi\alpha N_e}{m_e}} \longrightarrow$$

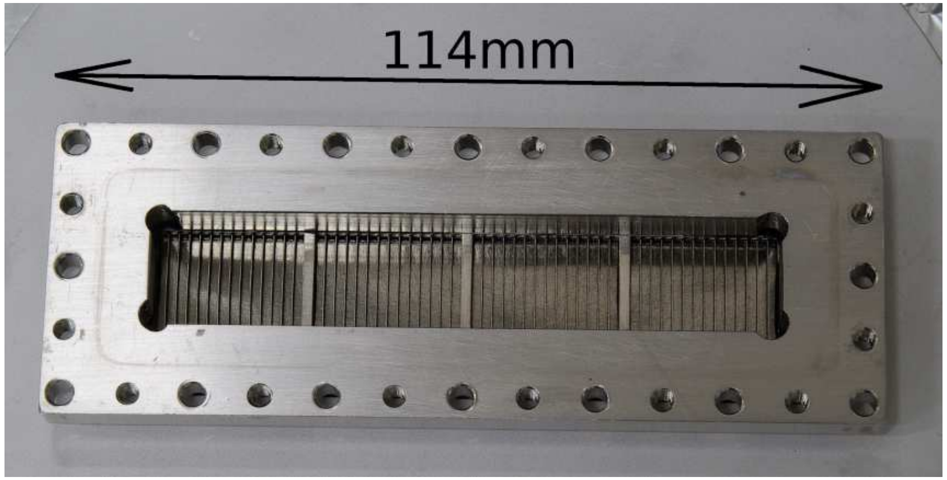


# Buffer gas container



- Welded 4 × st. steel 304 $21.9 \times 17.9 \times 2300\,\mathrm{mm}^3$ square pipes
- Wrapped with 99.999% pure Al 0.1-mm thick × 2 layers
- Thermal conductivity (measured) $\gtrsim 10^{-2}\mathrm{W/K}$ @ 5 K, 4 T

# X-ray window

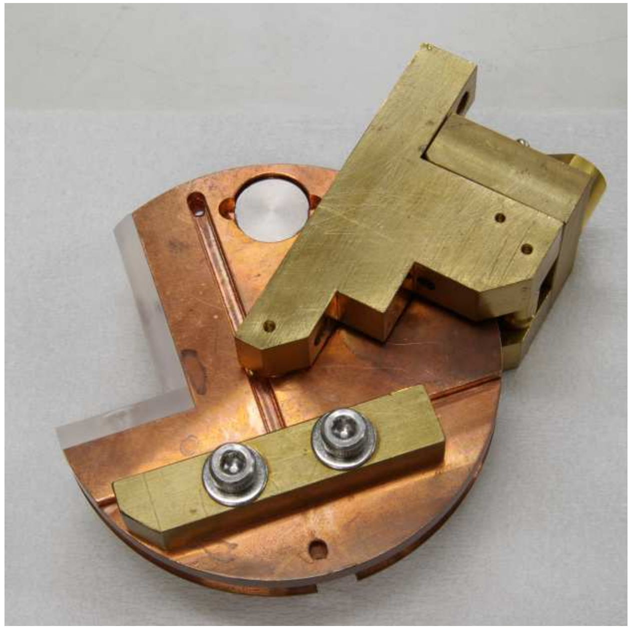



Metorex C10 window
(custom)

- $25\mu$m Be foils with $1\mu$m polyimide coating
- Supported by Ni grid
- Withstands up to 0.3 MPa
- Transmits $\gtrsim 80\%$ for $E > 3$keV

# Internal calibration source

$^{55}$Fe (5.97 keV)



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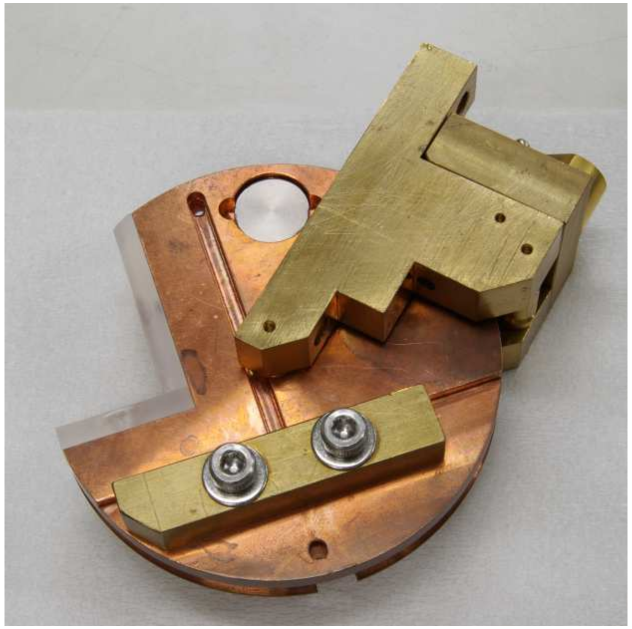
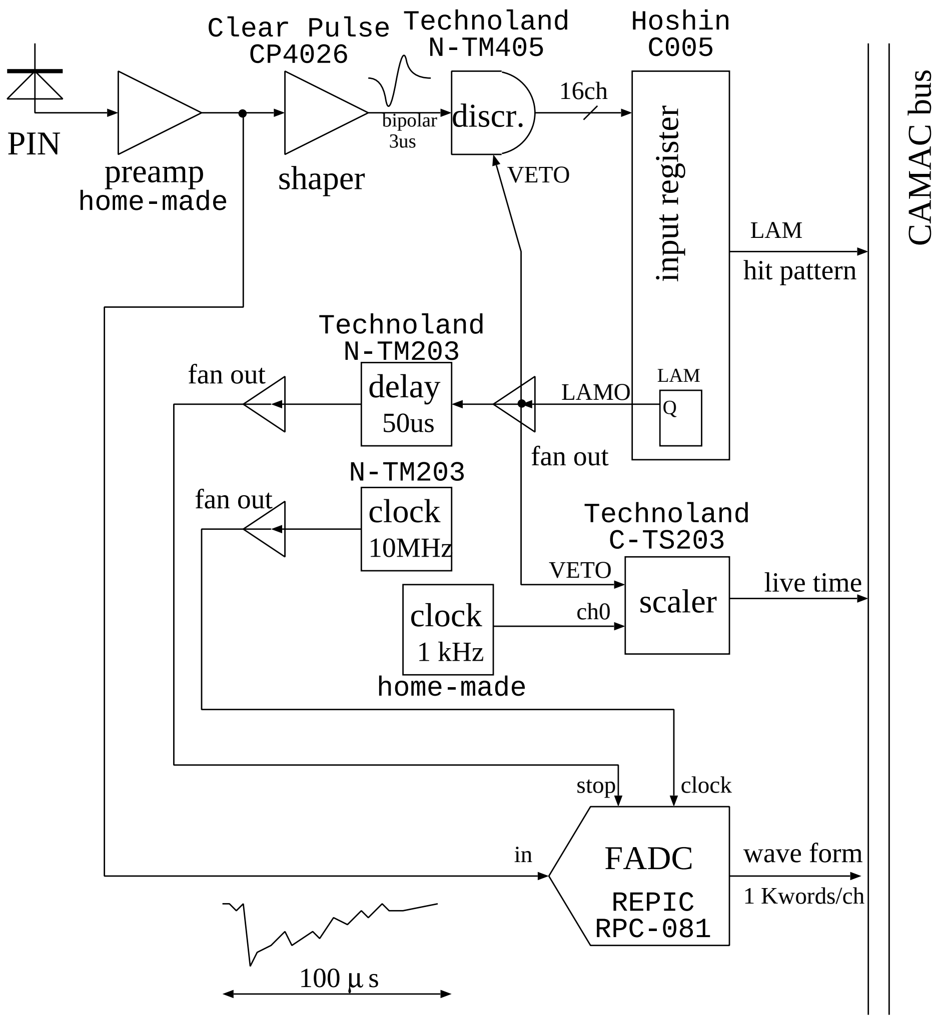
$^{55}$Fe (5.97 keV)



# Data acquisition system




- 16 input channels
- Waveform recording:
  PIN photodiode
  ↘ Charge sens. preamp.
  ↘ Flash ADC
- Offline shaping
- Trigger:
  shaper + leading edge discr.
- Precise live time
- Control: CAMAC

# Sumico results & prospect

✓ Phase I — vacuum

Sumico 1997 run: [S.Moriyama *et al.*, PLB434(1998)147]

$$g_{a\gamma} < 6.0 \times 10^{-10}\mathrm{GeV}^{-1} \qquad (m_a < 0.03\,\mathrm{eV})$$

✓ Phase II — low density $^4$He $(\rho_{\mathrm{He}} \lesssim 10^5\mathrm{Pa}/298\,\mathrm{K})$

Sumico 2000 run: [Y.Inoue *et al.*, PLB536(2002)18]

$$g_{a\gamma} < 6.8\text{–}10.9 \times 10^{-10}\mathrm{GeV}^{-1} \quad (0.05 < m_a < 0.27\,\mathrm{eV})$$

☞ Phase III — high density $^4$He

Sumico 2007–2008 run: [Y.Inoue *et al.*, PLB668(2008)93]

$$g_{a\gamma} < 5.6\text{–}13.4 \times 10^{-10}\mathrm{GeV}^{-1} \quad (0.84 < m_a < 1.00\,\mathrm{eV})$$

Upgrades are continuing…

Goal: $p \lesssim 0.1\,\mathrm{MPa}$ @ $T = 6\,\mathrm{K}$ $\quad \rightarrow m_a \lesssim 2\,\mathrm{eV}$

# Pioneering axion helioscope

[Lazarus *et al.*, PRL69,2333(1992)]

- BNL-Rochester-FNAL
- $B = 2.2\,\mathrm{T}$, $L = 1.8\,\mathrm{m}$, fixed dipole magnet
- He gas (0, 50, 100 Torr)
- Proportional chamber (Ar 90% $CH_4$ 10%)
- 15 minutes/day (sunset)
- $g_{a\gamma} < 3.6 \times 10^{-9}\mathrm{GeV}^{-1}$ for $m_a < 0.03\,\mathrm{eV}$,
  $g_{a\gamma} < 7.7 \times 10^{-9}\mathrm{GeV}^{-1}$ for $0.03\,\mathrm{eV} < m_a < 0.11\,\mathrm{eV}$.

cf. Solar age: $g_{a\gamma} < 2.4 \times 10^{-9}\mathrm{GeV}^{-1}$