Search for the electron EDM in ACME III

2022.12.09

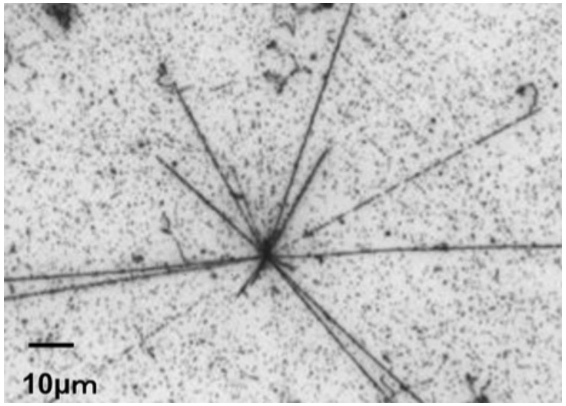
Ayami Hiramoto (Okayama Univ.)
for the ACME collaboration

Introduction

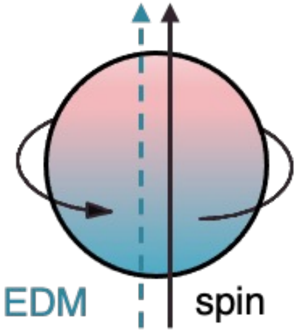
Ayami Hiramoto

- ~2021.3 Kyoto University (Ph.D.)

  "Measurement of Neutrino Interactions on Water using Nuclear Emulsion Detectors"



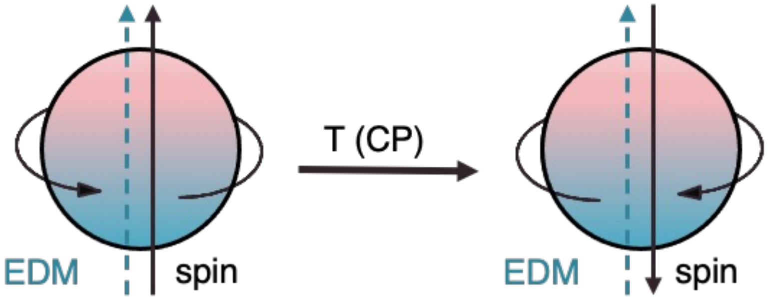
- 2021.4~ Okayama University (PD)
  - ACME electron EDM
  - Buffer-gas cooling (Cold molecule)

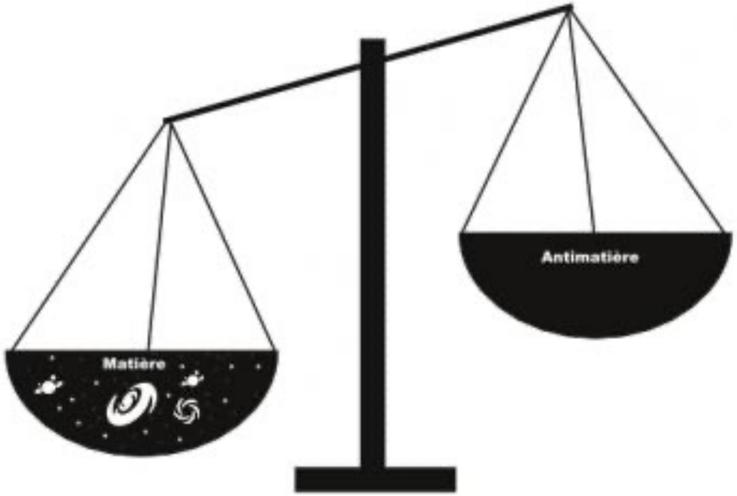


Electric Dipole Moment

- Separation of charge (e·cm)
- Non-zero EDM requires T-violation

  => EDM is sensitive to CP violation





Credits: GANIL

EDM @Standard Model is very small…

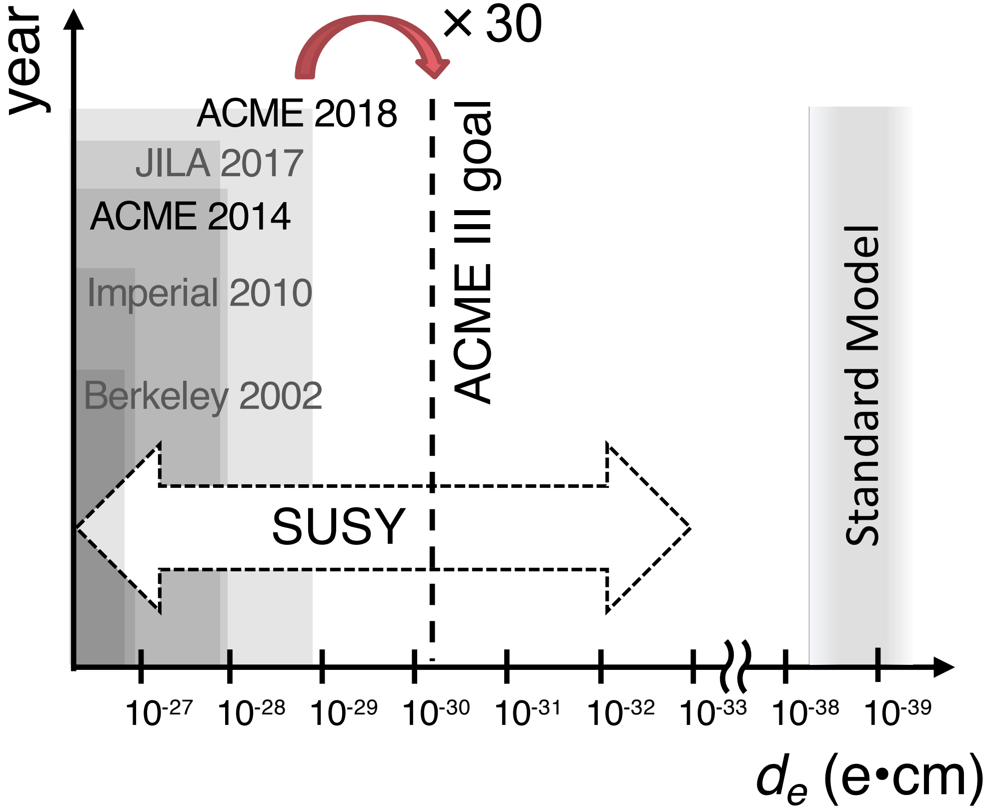
- Matter-antimatter asymmetry?
- Particles beyond the SM?

EDM is a powerful probe to physics beyond the SM.

Electron Electric Dipole Moment (eEDM)

- ACME (Advanced Cold Molecule Electron EDM) experiment:

  => Setting the most stringent limits on eEDM.



<u>ACME II result (2018):</u>

$|d_e| < 1.1 \times 10^{-29}$ ecm (90%C.L.)

ACME Collaboration, Nature 562, 355-360 (2018).

<u>ACME III goal:</u>

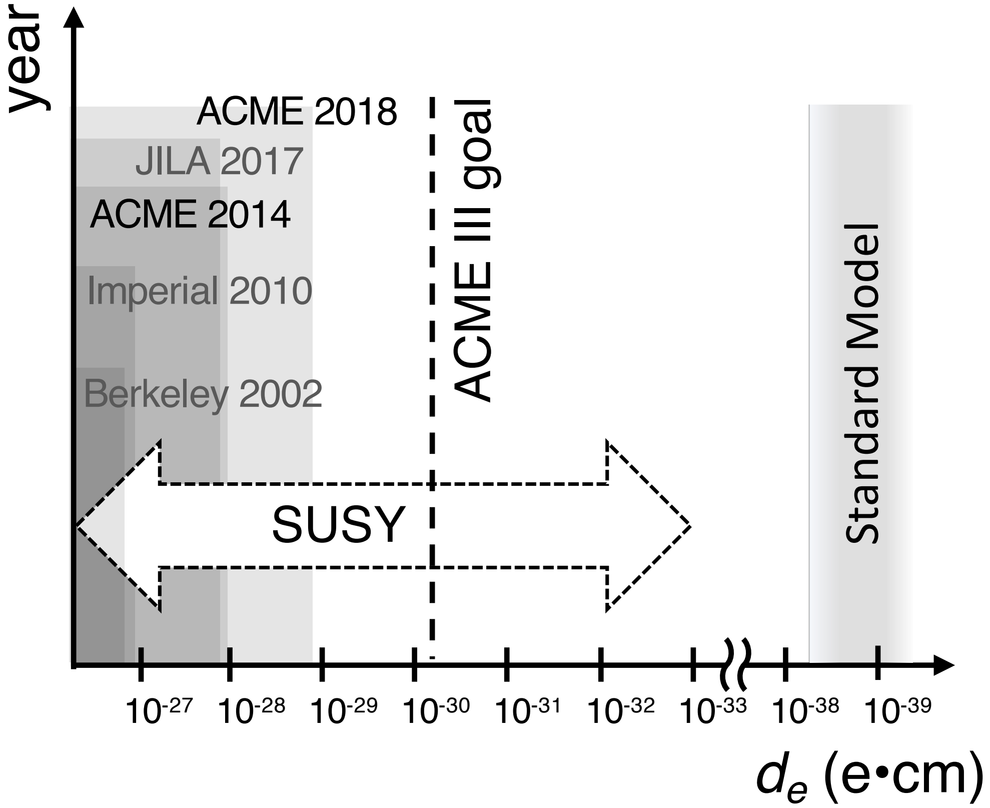
× 30 improvement

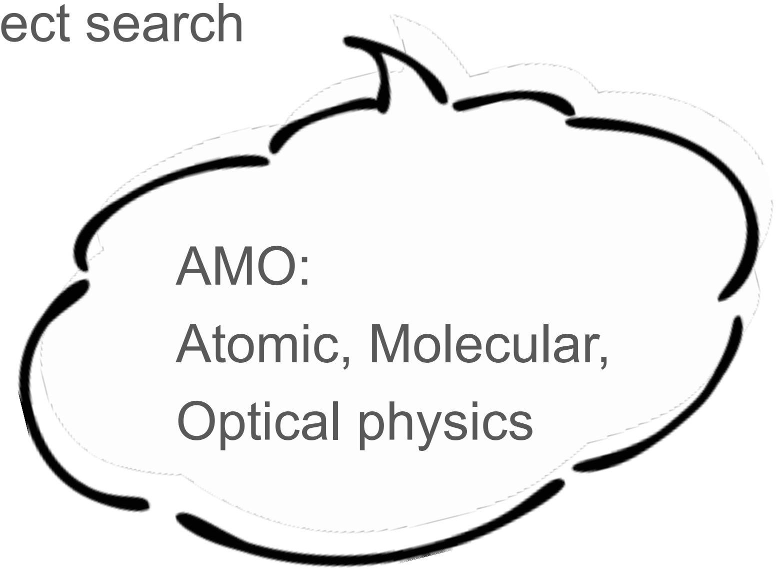
This talk is about the current status of the ACME III upgrade

AMO and particle physics

Searching for a new particle

- High energy physics (Accelerator): Direct search
- Low energy physics (Tabletop): Indirect search





AMO:
Atomic, Molecular,
Optical physics

One of the important approaches in particle physics.

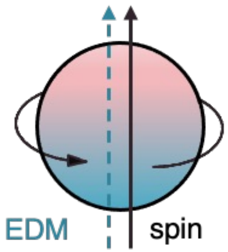
Outline

① How to measure the eEDM in ACME

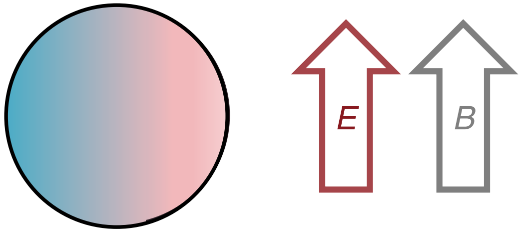
② Apparatus upgrades towards higher statistics

③ Suppressing systematic uncertainties

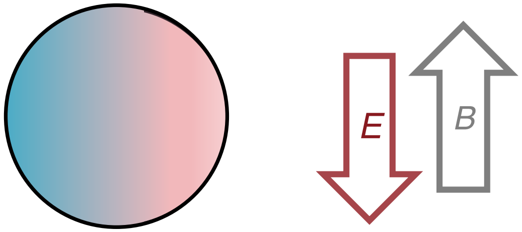
eEDM measurement



- Spin precession measurement
- EDM (d) changes precession frequency depending on E field reversal



$$\omega_+ = 2\frac{\mu B + \boxed{dE}}{\hbar}$$



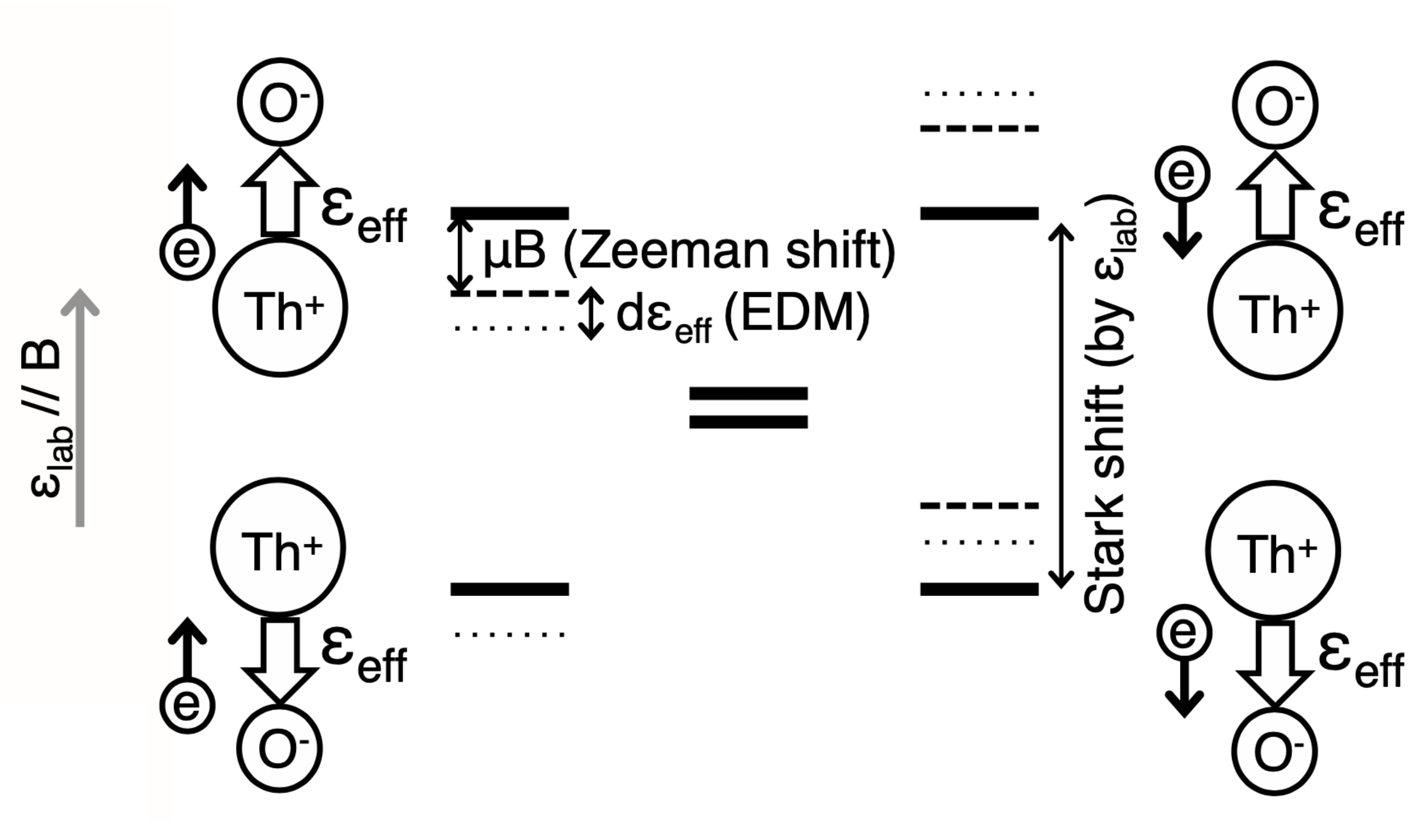
$$\omega_- = 2\frac{\mu B - \boxed{dE}}{\hbar}$$

~50 Hz ~20 μHz

Strong E field is required to measure small EDM (d)

ACME experiment

- Cold polar molecule ThO, H ($^3\Delta_1$)
- Large E_{eff} field, completely polarized in laboratory fields (~10 V/cm)



ThO molecule, H state

- Large effective E field: $\varepsilon_{eff} = 78$ GV/cm

  L.V.Skripnikov, J.Chem. Phys. **145** 214307 (2016).
  M.Denis and T.Fleig, J.Chem. Phys. **145** 214307 (2016).

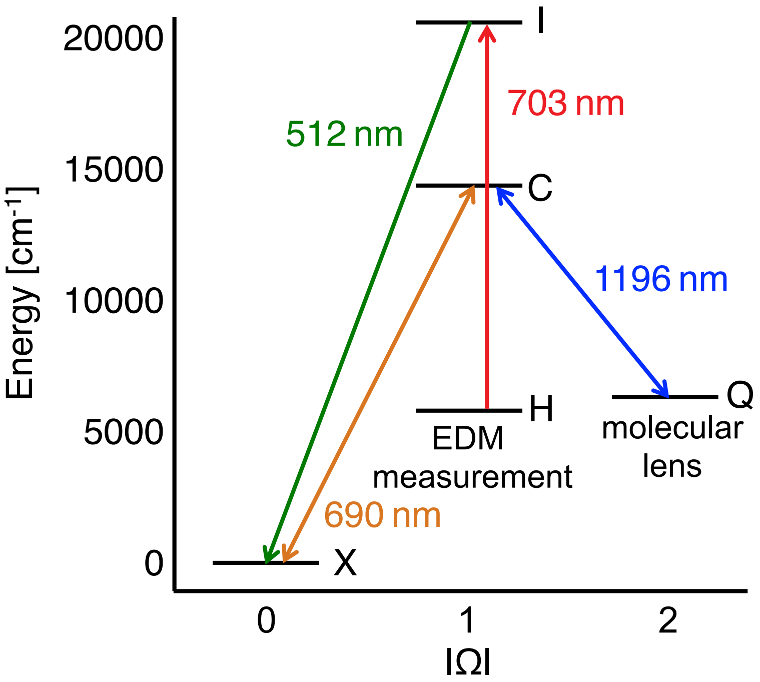
- Small magnetic moment: $\mu = 0.0044\ \mu_B$

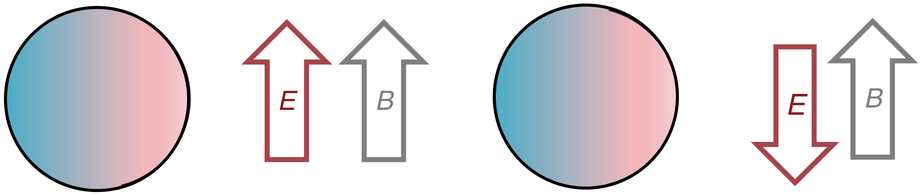
  L.V.Skripnikov *et al.*, J. Chem. Phys. **139** 221103 (2013).

- Easily polarized by $\varepsilon_{lab} = 80, 140$ V/cm

- Relatively long lifetime: $\tau_H = 4.2$ ms

  D.G.Ang *et al*, Phys. Rev. A (2022).



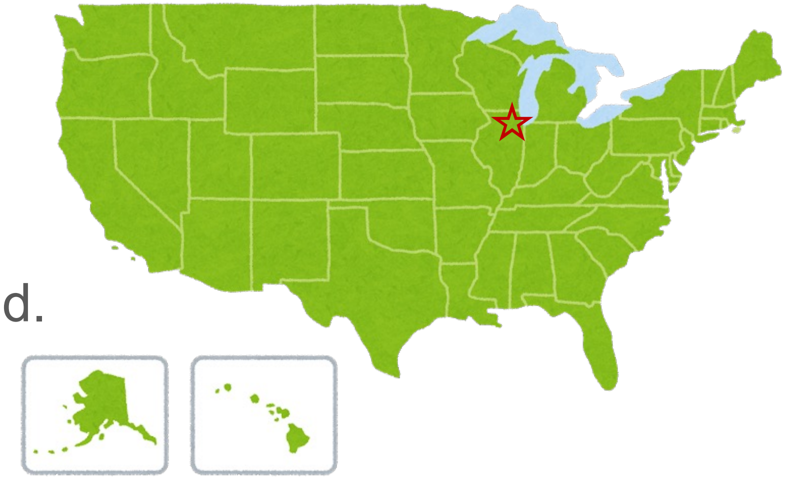


$$\omega_+ = 2\frac{\mu B + \boxed{dE}}{\hbar} \qquad \omega_- = 2\frac{\mu B - \boxed{dE}}{\hbar}$$

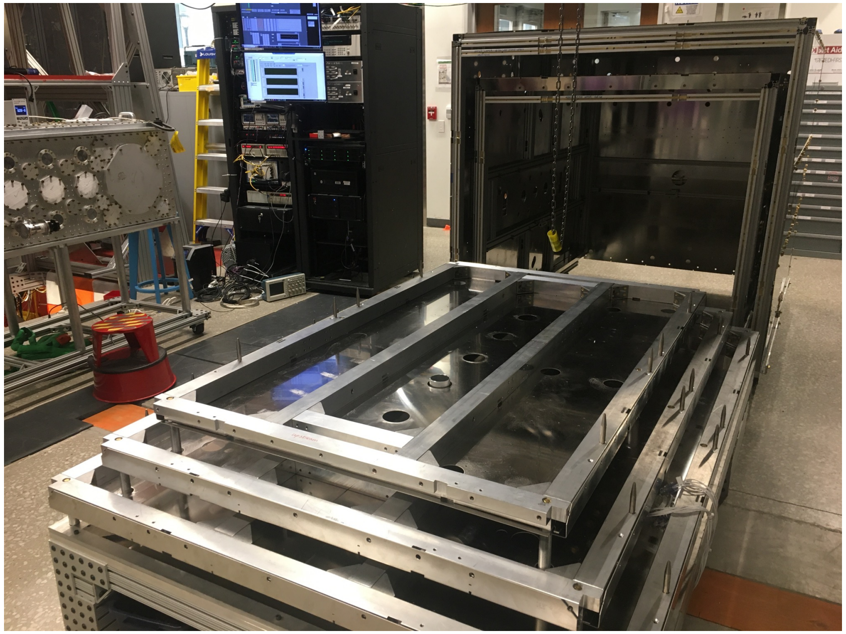
ACME III experimental site

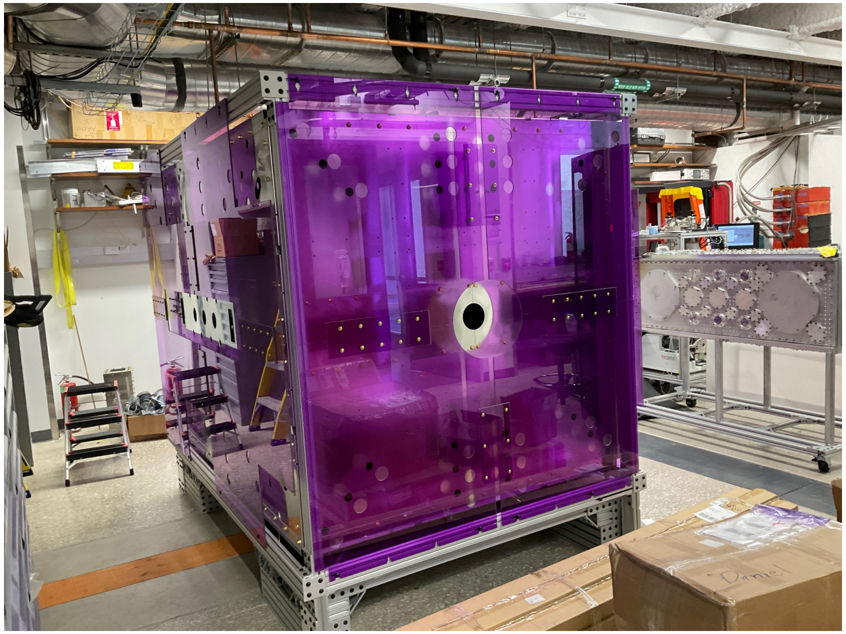
- Experimental site:

  Northwestern University (US)

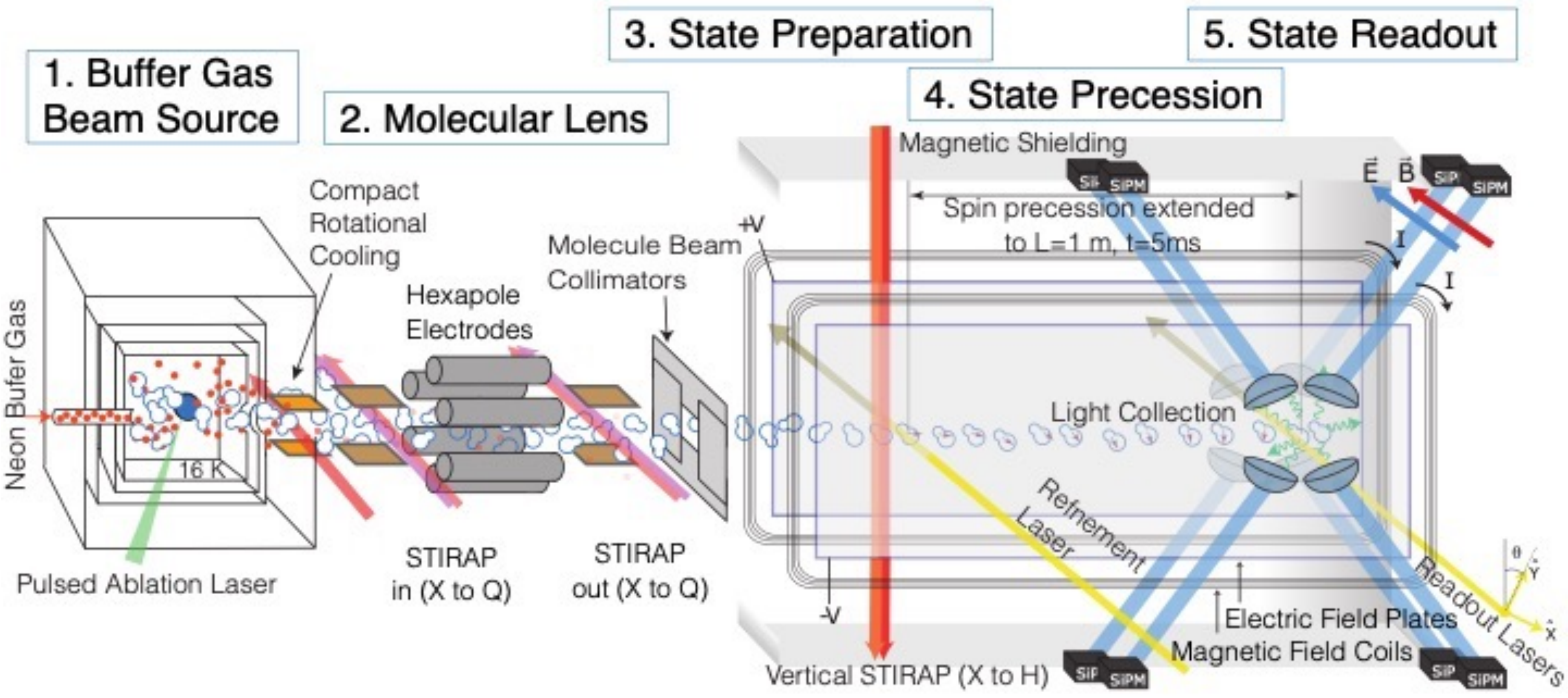


- Almost all the parts are newly constructed.





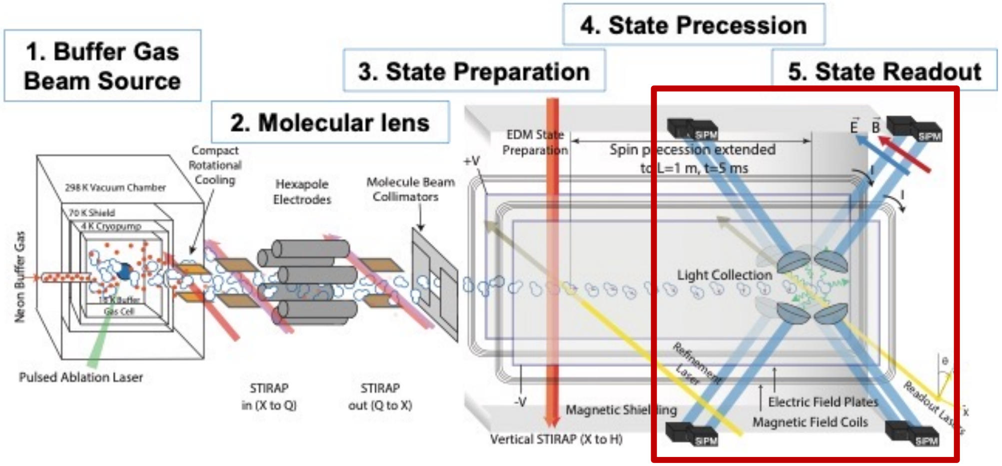
ACME III apparatus



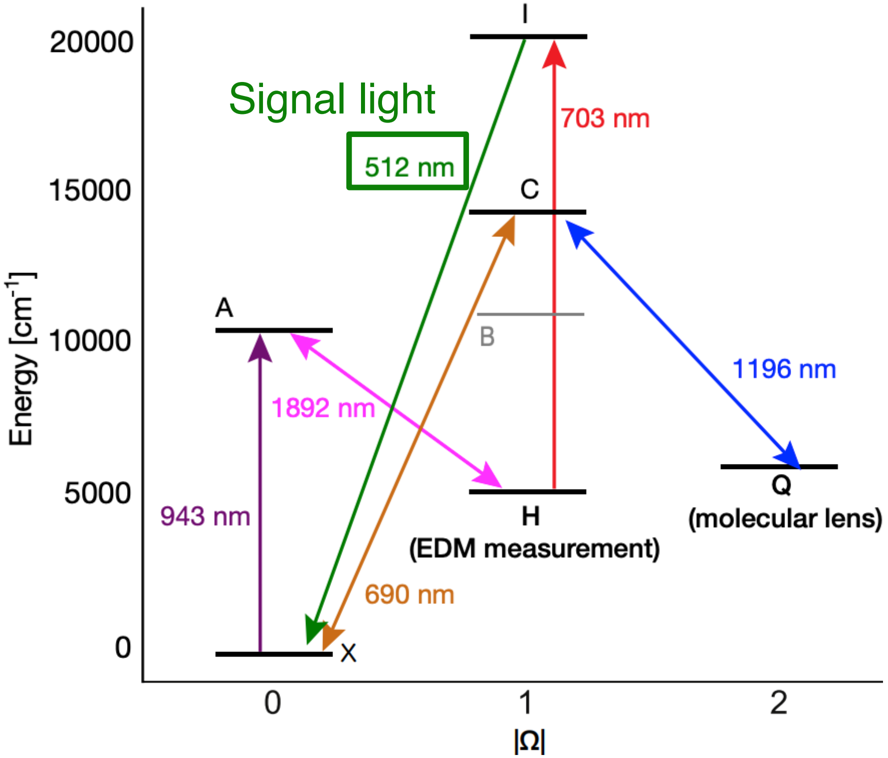
$$d_e = (4.3 \pm 3.1_{stat} \pm \boxed{2.6_{syst}}) \times 10^{-30} ecm$$ （ACME II）

ACME signal

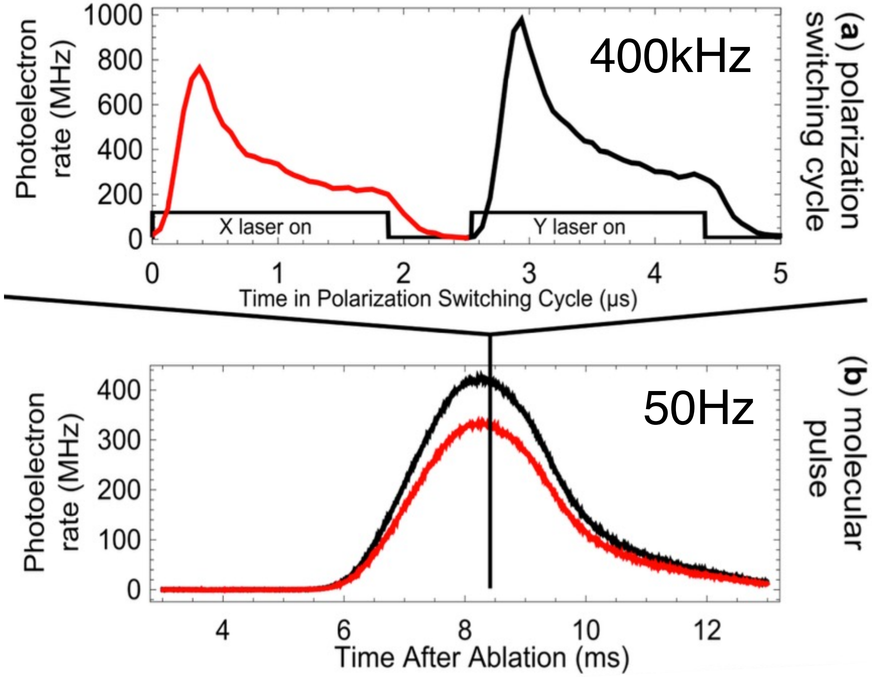
- 512 nm fluorescence light
- Signal asymmetry probed by X-Y lasers



ThO states

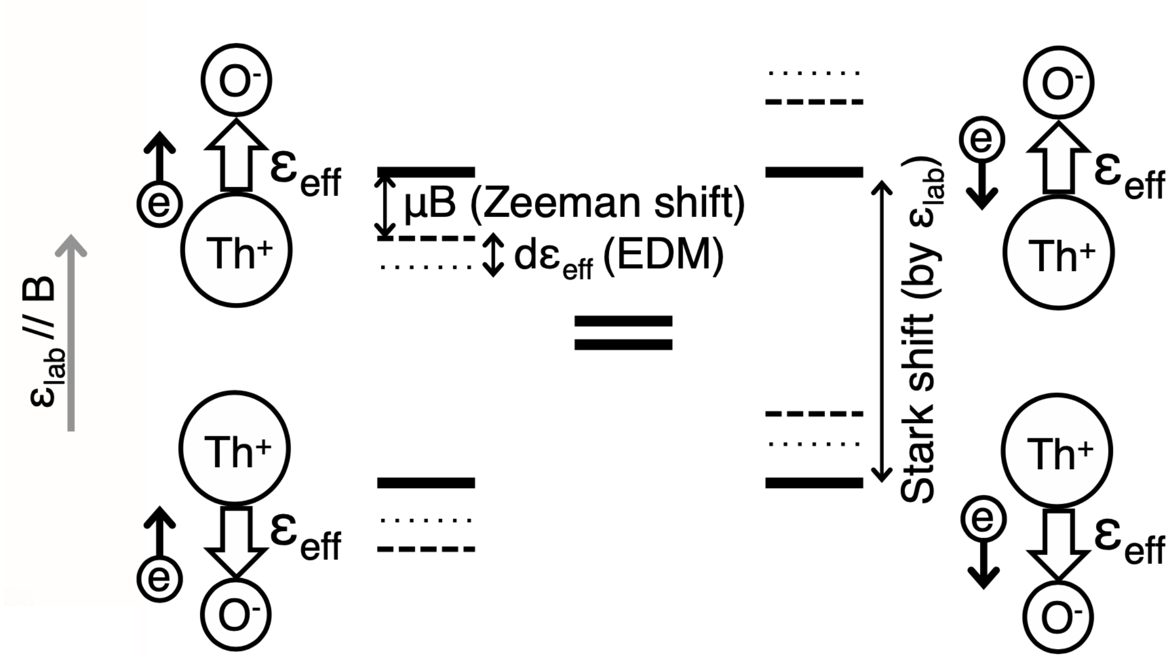


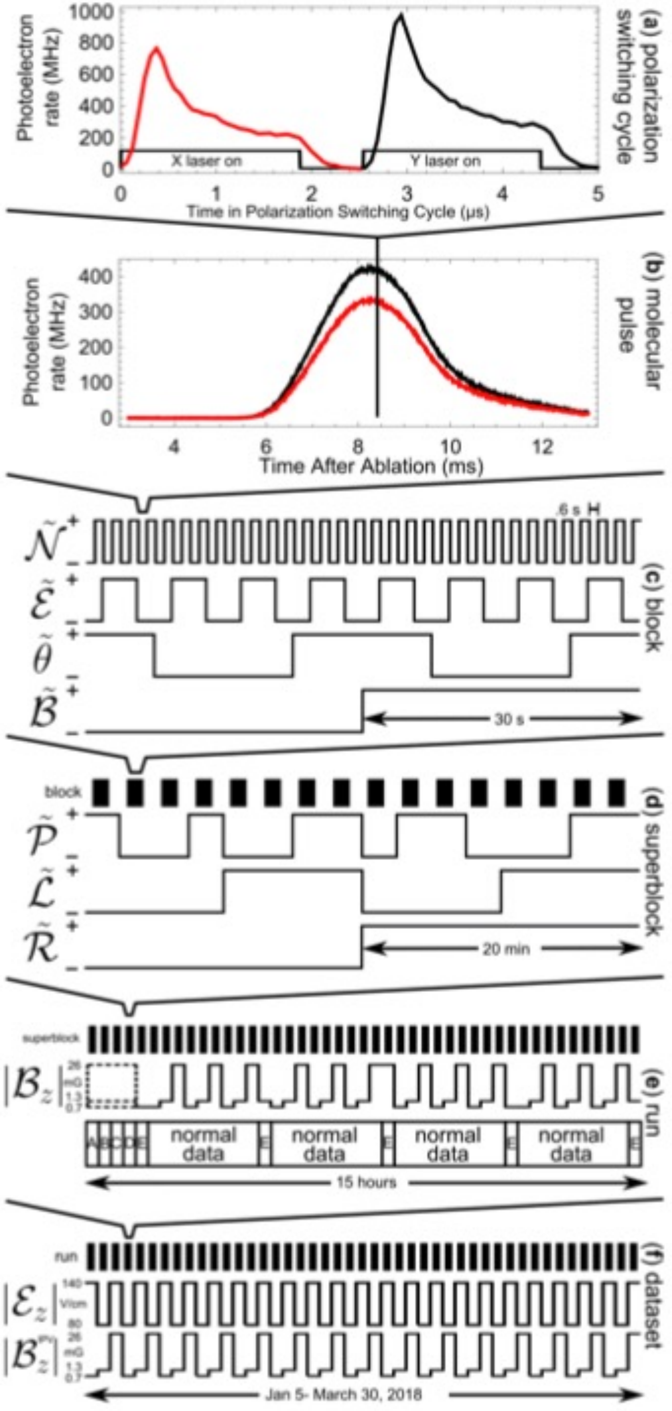
ACME signal & molecualr pulse



Switching

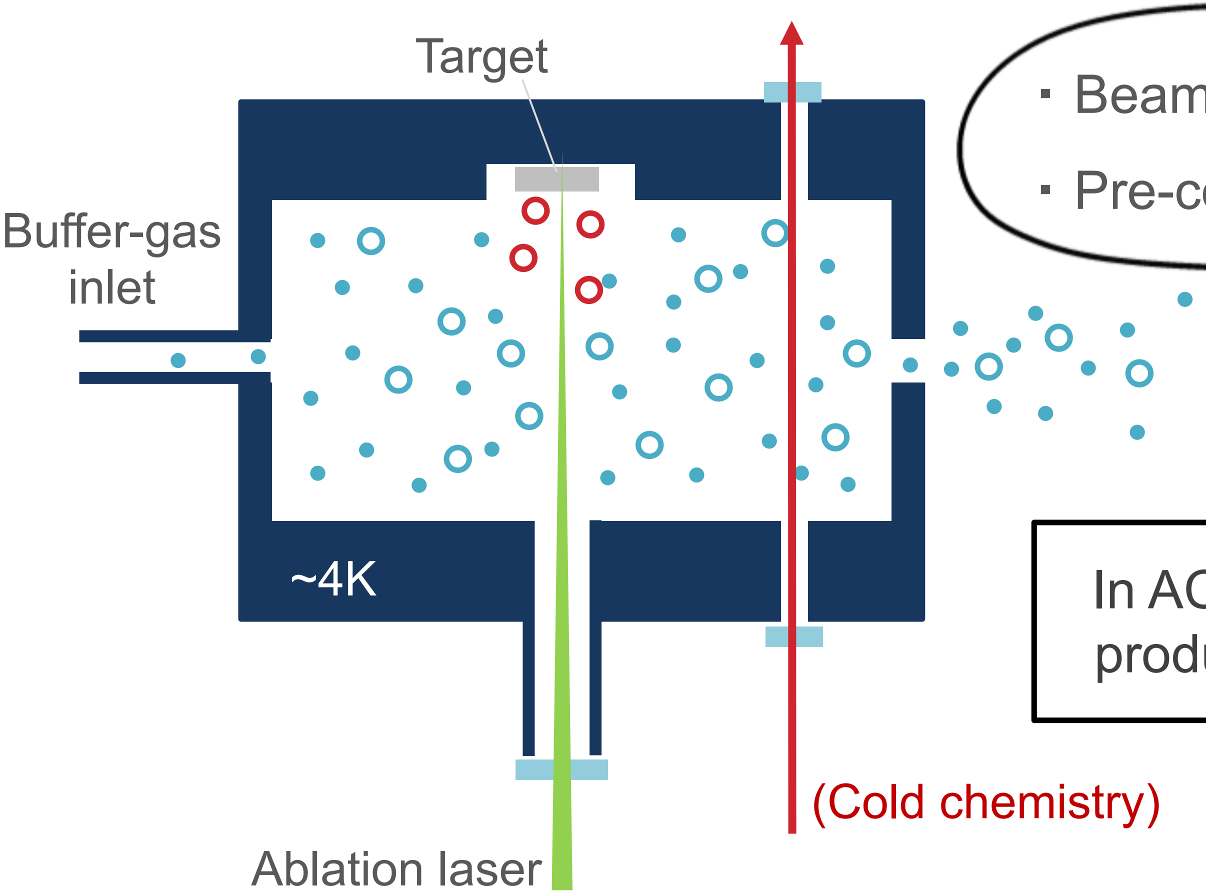
- Measurements under multiple conditions ("switching")





Buffer-gas cooling

- Universal cooling technique for atoms and molecules.
- Hot target species are cooled by collision with ultracold buffer gas.



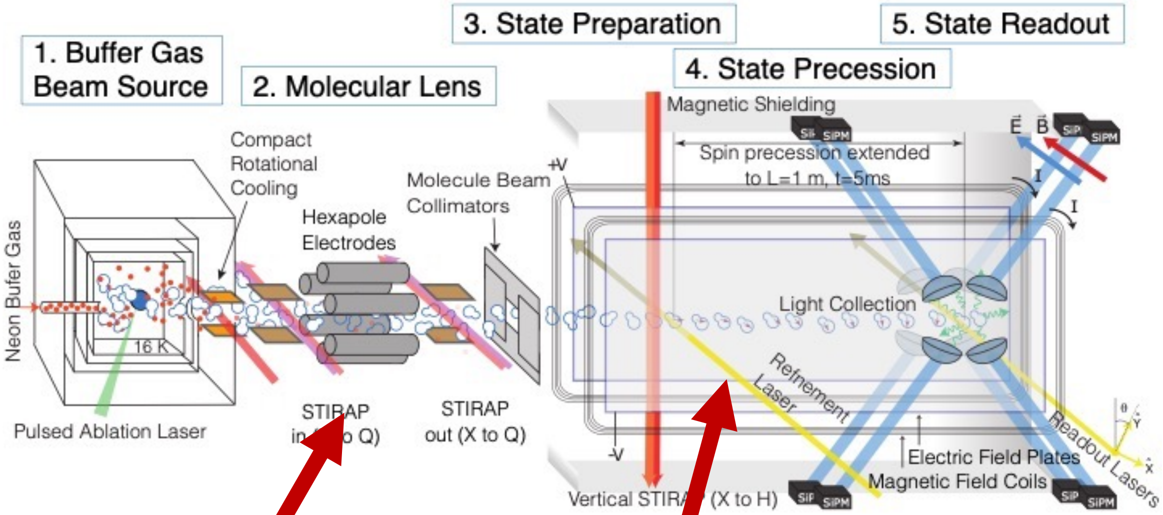
- Beam for fundamental physics
- Pre-cooling for trapping

In ACME, cold ThO beam is produced by this technique.

Improvements

Sensitivity

$$\Delta d_e \sim \frac{\hbar}{E_{\mathrm{eff}}\tau}\,\frac{1}{\sqrt{\dot{n}_{\mathrm{mol}}T}}\,\sqrt{\frac{F}{\varepsilon_{\mathrm{det}}}}$$

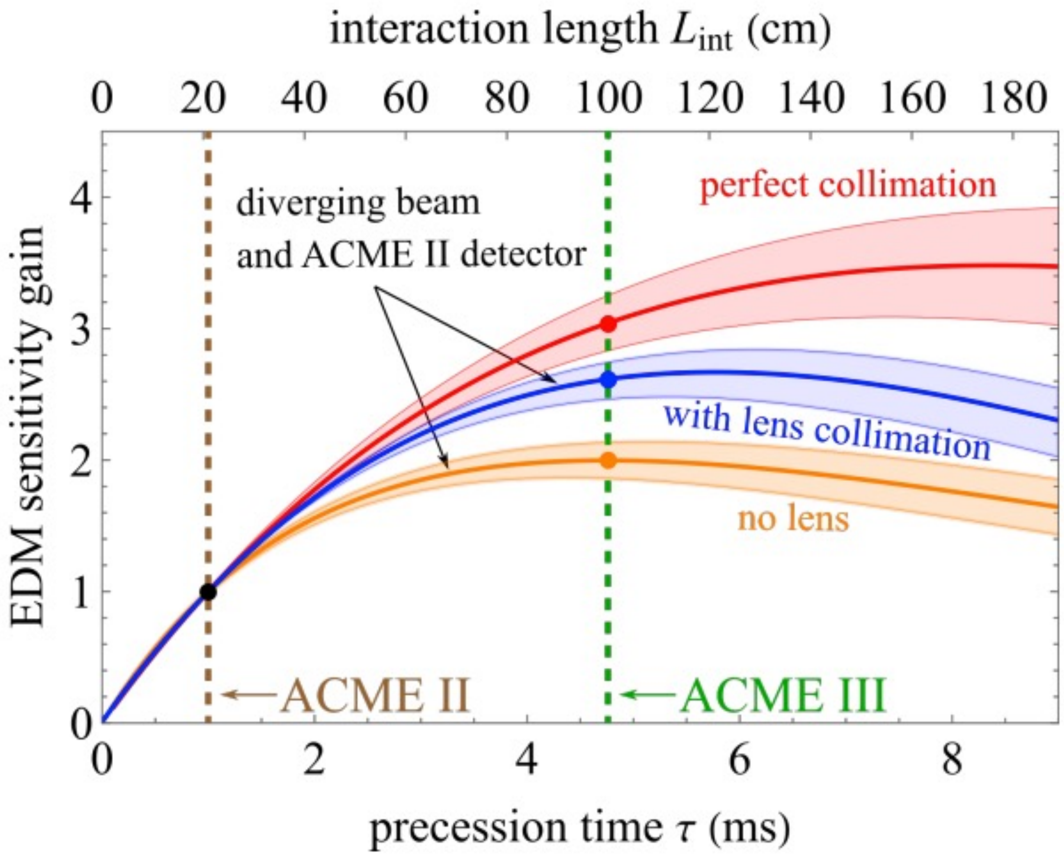


Projected Improvement	Signal gain	EDM sensitivity
Longer precession time	0.27	2.6
Molecular lens	12.0	3.4
Photon detector upgrade	2.7	1.6
Improved collection optics	1.6	1.3
Timing jitter noise	1.0	1.7
Total	14.0	31.2

D.G.Ang *et al*, Phys. Rev. A (2022).

Longer precession time

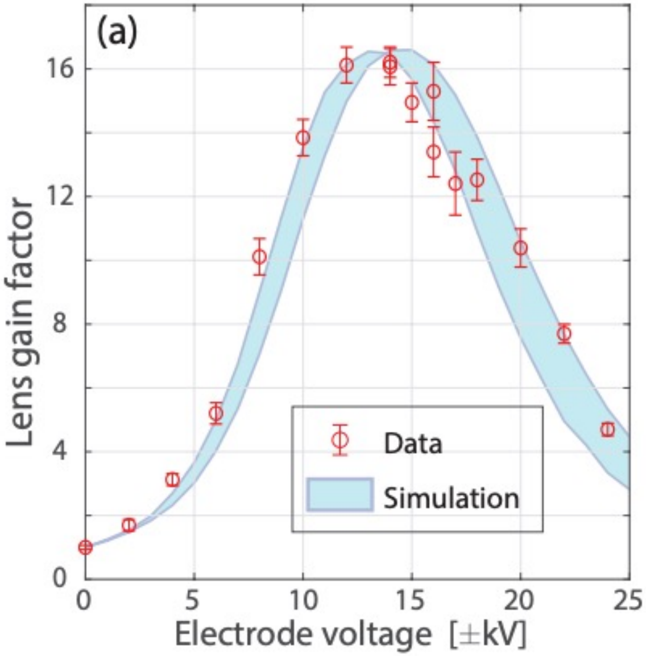
- Recently measured H-state lifetime: 4.2±0.5ms
- Longer precession region (1ms => 5ms) to match the H state lifetime



X. Wu *et al*, *New J. Phys.* **24** 073043 (2022).

Molecular lens

- Electrostatic hexapole lens to focus the ThO beam
  - Reduce losses from the beam divergence
  - Boost the overall number of ThO
- Demonstration with ACME II beamline shows × 16 flux



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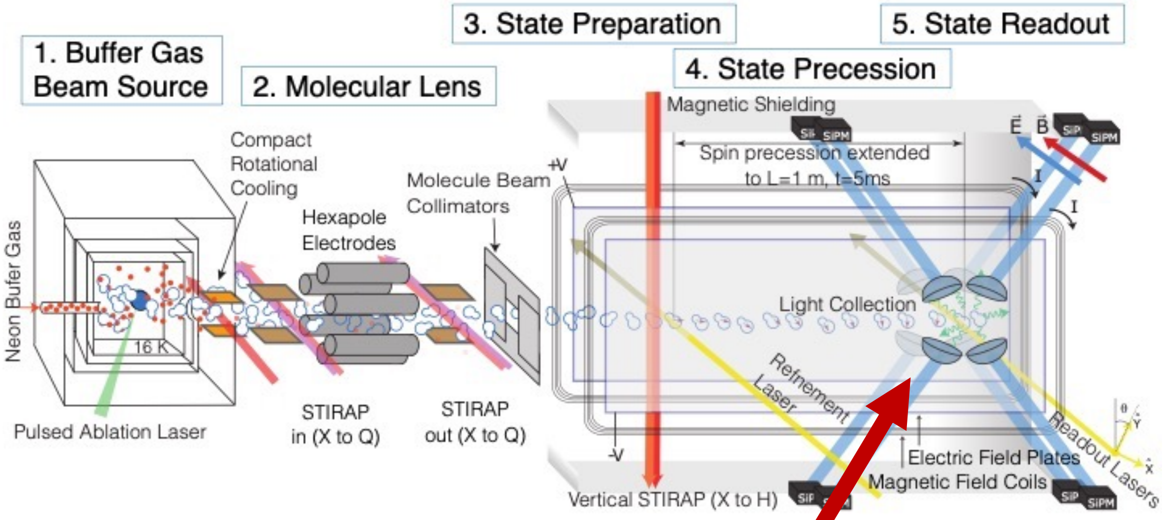

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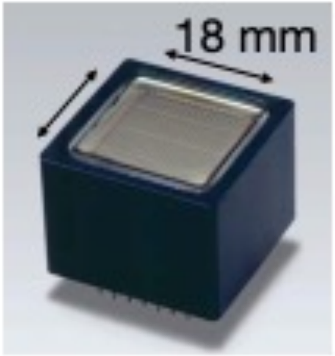
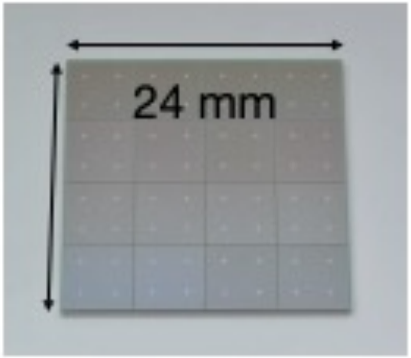
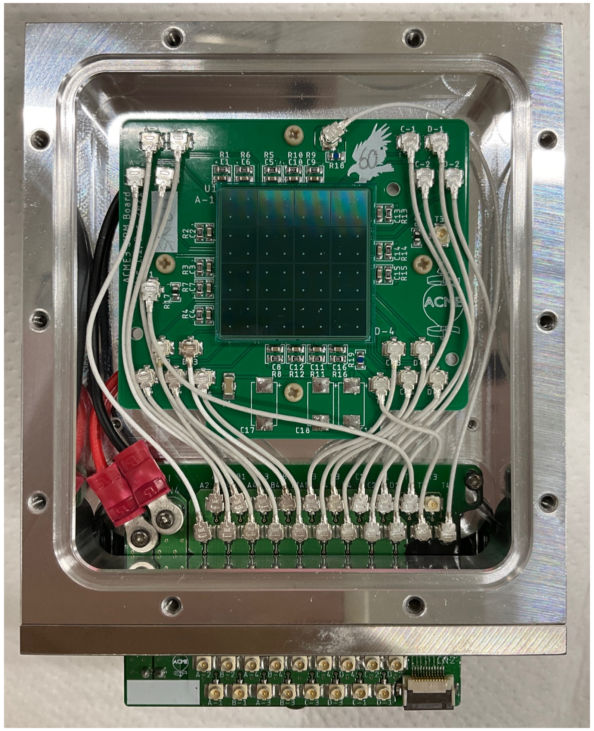
Photodetector upgrade

PMT



SiPM





Q.E.@512nm (signal): 25% => 45%

Q.E.@703nm (background): 0.6% => 20%

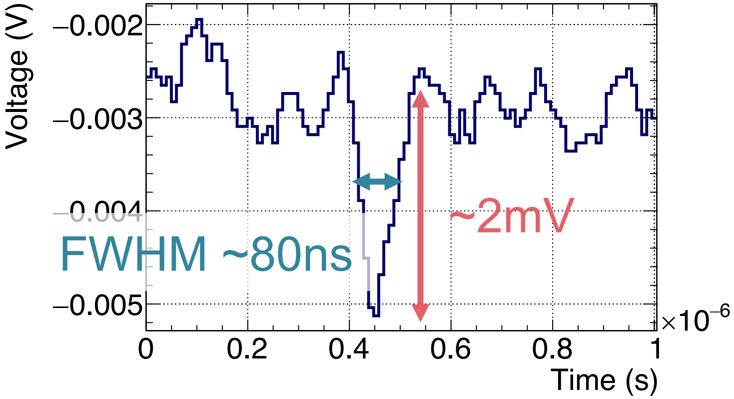
Three Band-pass filters for suppression

Dark count rate: 3kcps = > 2Mcps/ch

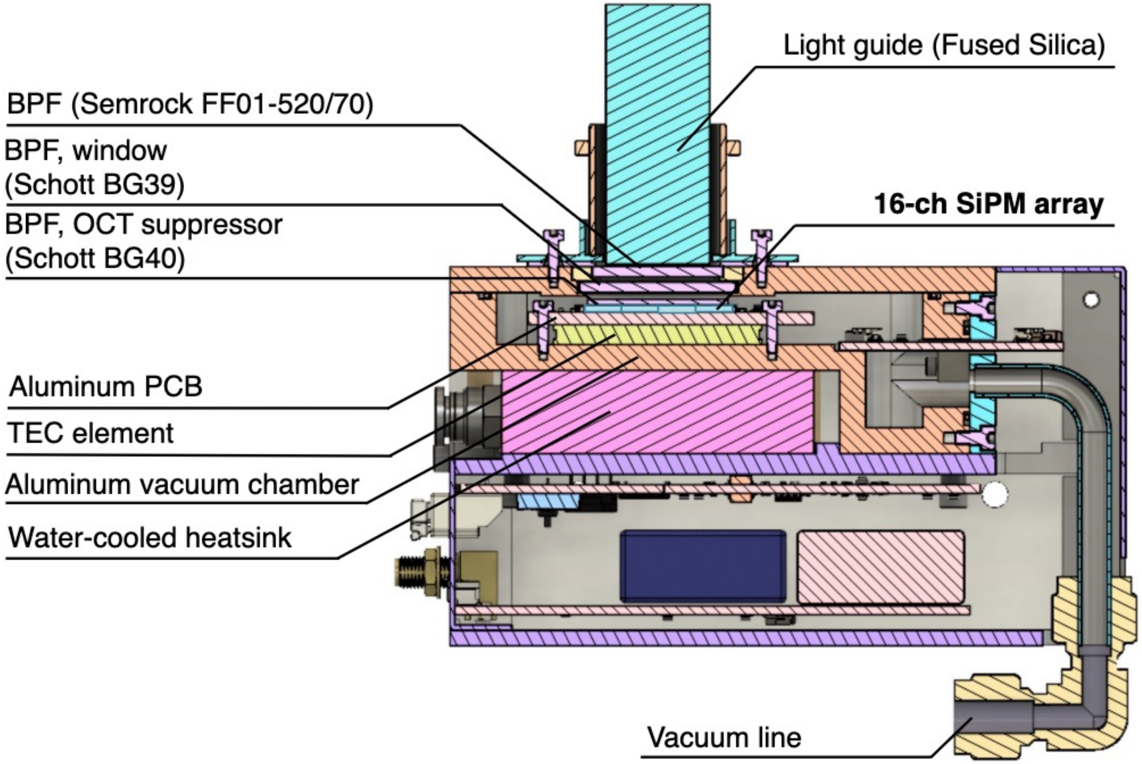
(requirement: 80kcps/ch)

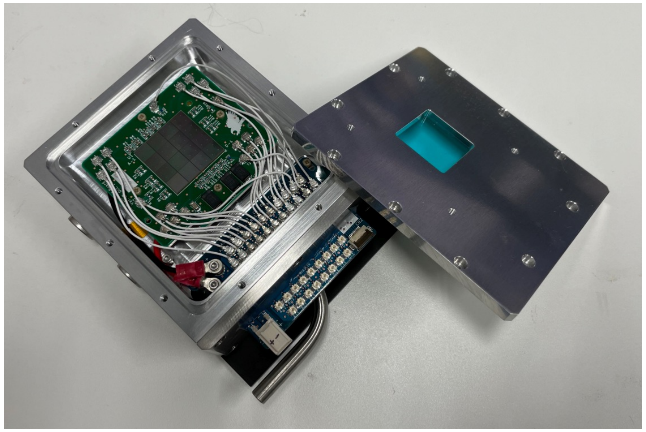
SiPM is cooled down to -15℃

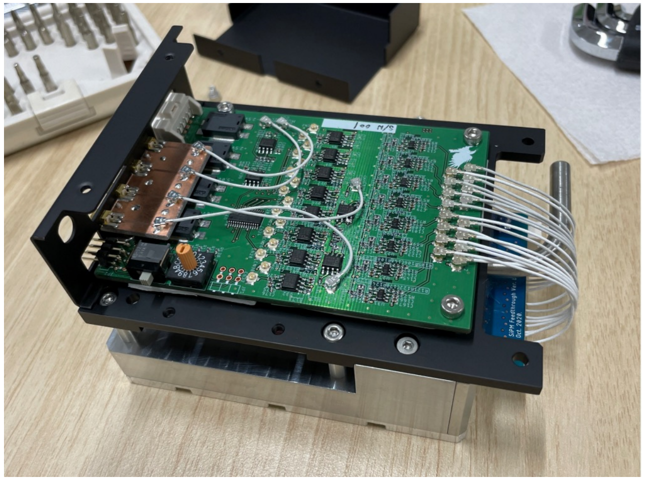
single photon



SiPM module design





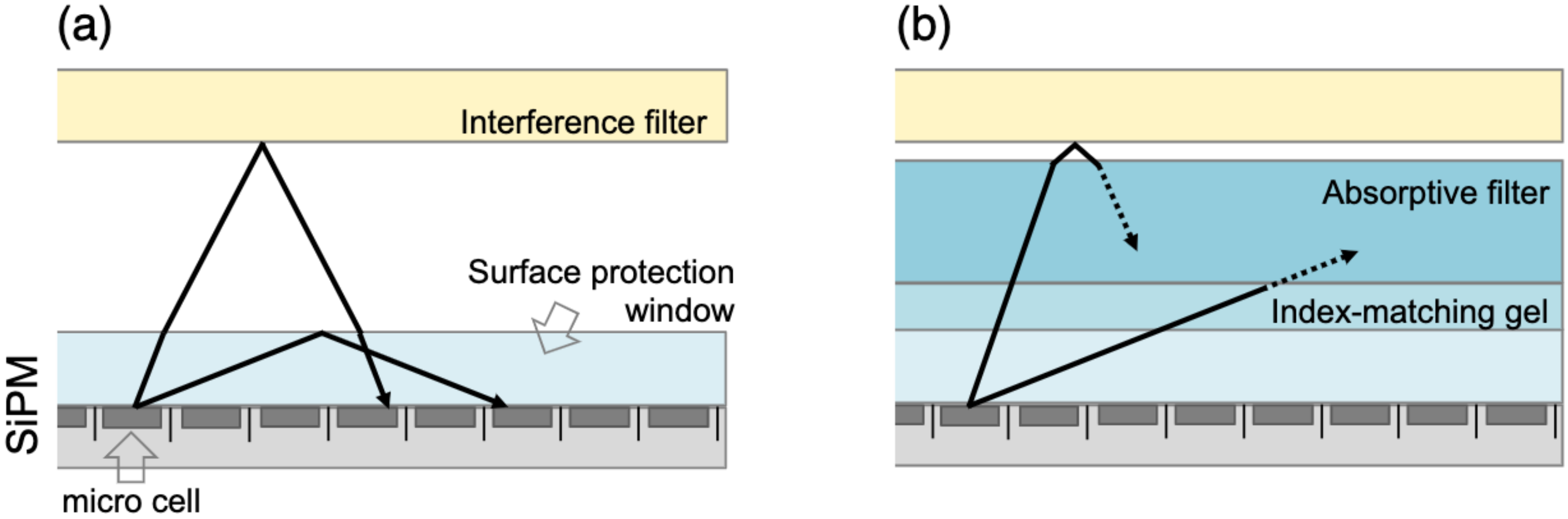


Designed in Okayama University

=> 10 modules shipped to the USA this summer.

Optical Crosstalk (OCT)

- OCT limits the resolution of the SiPM photon counting
- OCT is caused by secondary photons in the SiPM avalanche process
- The 3-filter configuration suppresses the OCT: ~25% => ~4% level
- Excess noise factor F~1.1, including delayed crosstalk and afterpulse



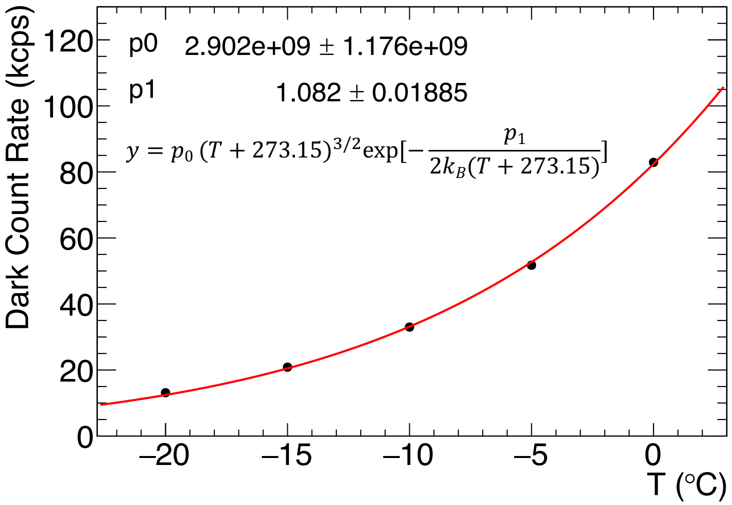
T. Masuda *et al.*, Opt. Express **29** (11), 16914 (2021).

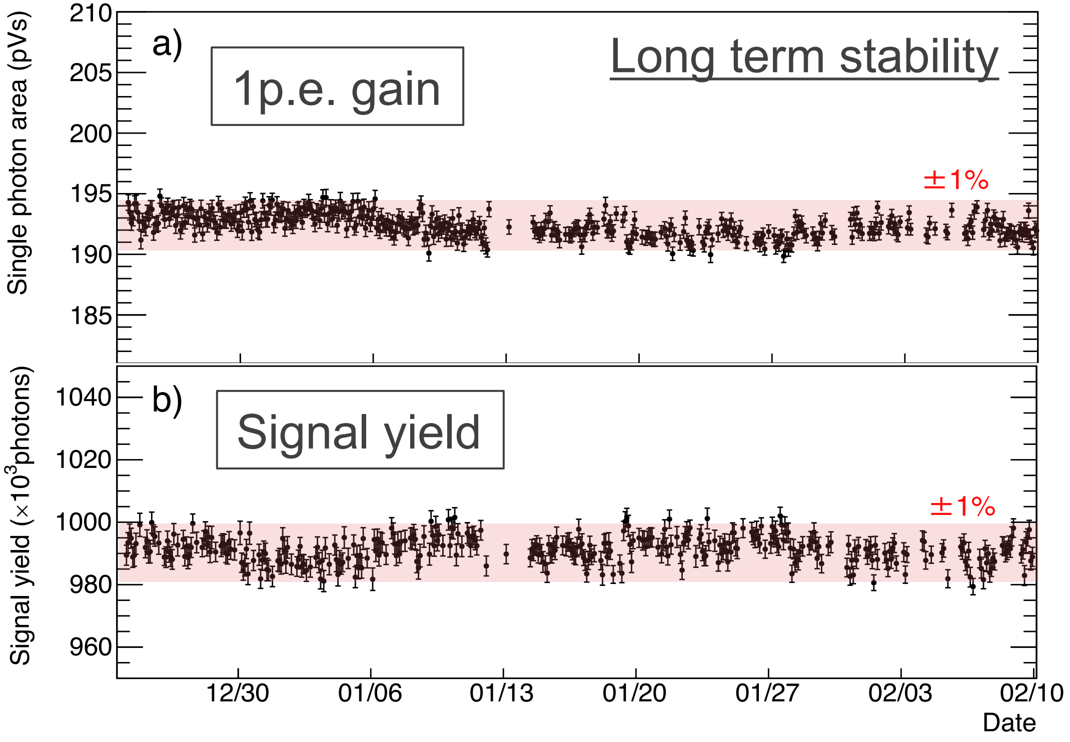
SiPM module status

A. Hiramot *et al*., NIMA **1045**, 167513 (2022).
Accepted by Optics Express (2022).

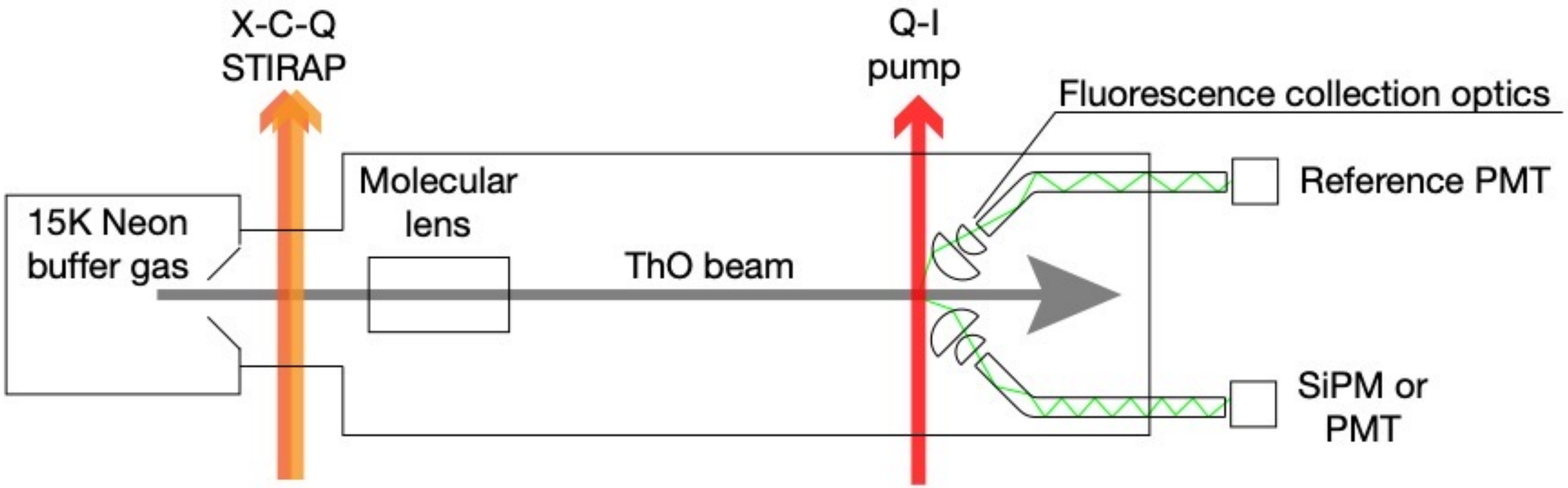
- Constructed 10 modules (8 + 2 spares) were tested before shipping
- DCR is well suppressed by cooling TEC
- Long term stability of the SiPM 1p.e. gain and signal yield: ±1% over 7 weeks (= 10^{14} photons)

DCR vs temperature





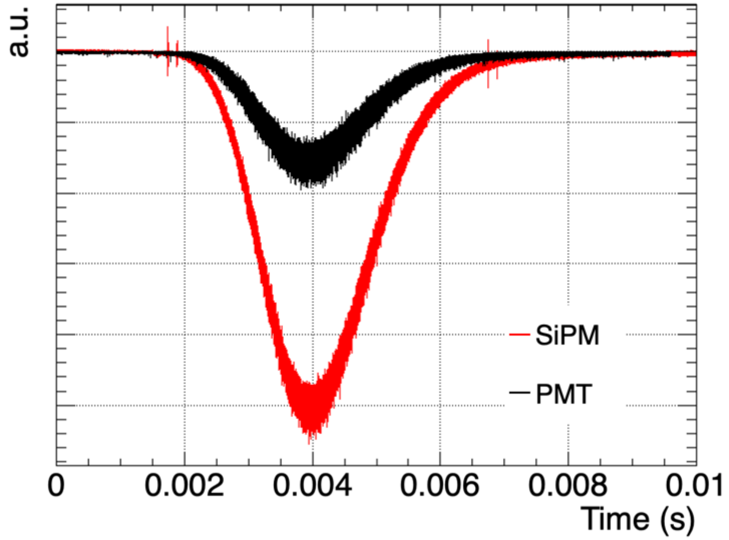
Test with ThO beam @Harvard



- First detection of the ACME ThO beam using SiPM (2021 summer)
- The SiPM module has ~3 times higher detection rate than the PMT.

+ New collection optics gain additional x 1.6

ThO signal



Improvements

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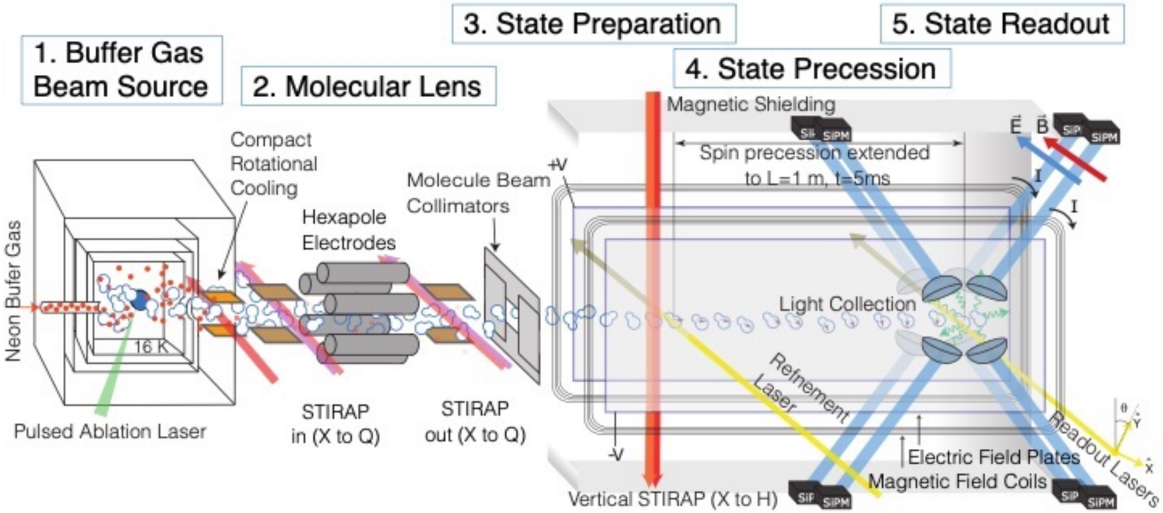

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Systematic uncertainty (ACME II)

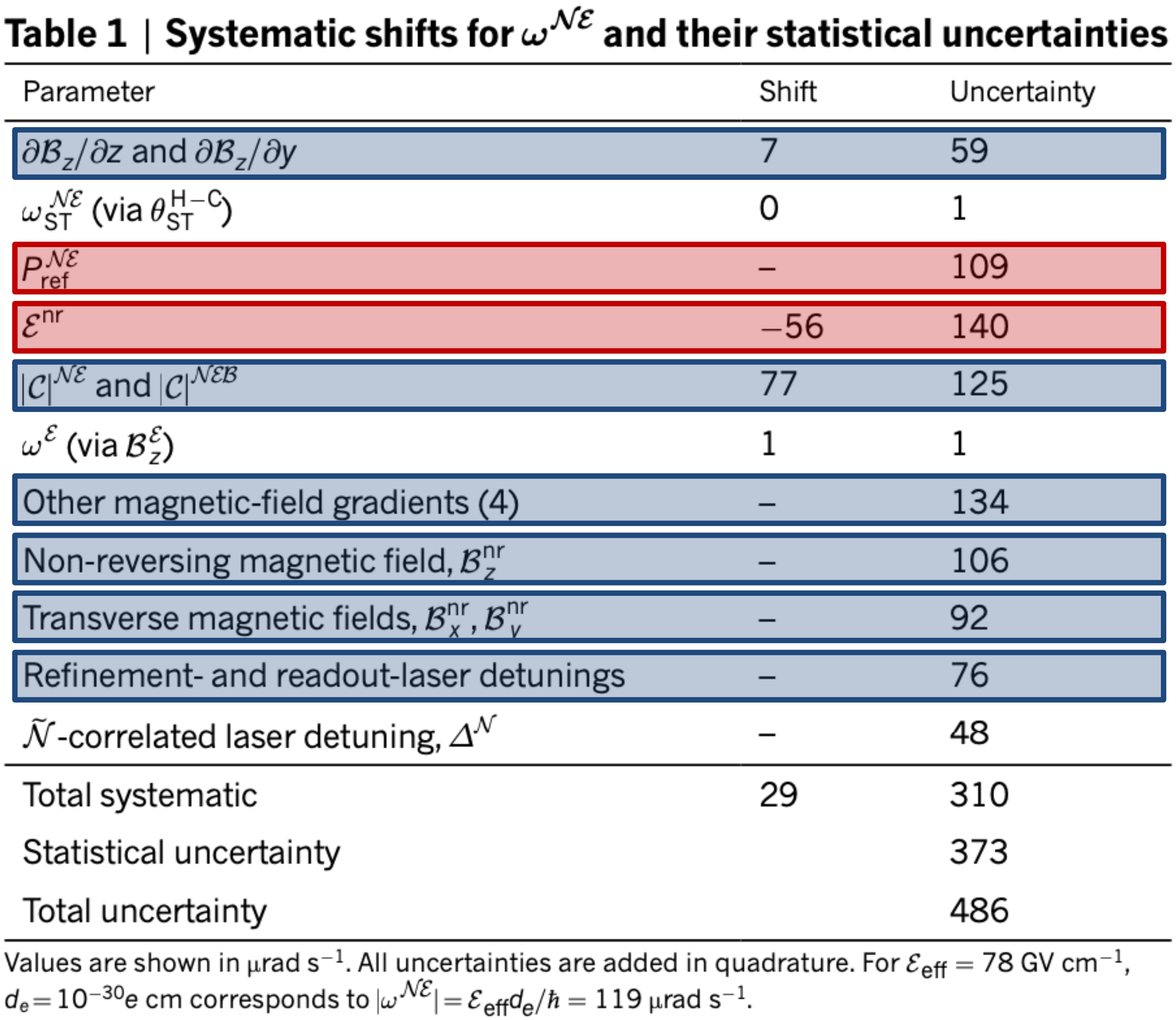


Table 1 | Systematic shifts for $\omega^{\mathcal{NE}}$ and their statistical uncertainties

Parameter	Shift	Uncertainty
$\partial\mathcal{B}_z/\partial z$ and $\partial\mathcal{B}_z/\partial y$	7	59
$\omega_{\mathrm{ST}}^{\mathcal{NE}}$ (via $\theta_{\mathrm{ST}}^{\mathrm{H-C}}$)	0	1
$P_{\mathrm{ref}}^{\mathcal{NE}}$	–	109
$\mathcal{E}^{\mathrm{nr}}$	−56	140
$\lvert\mathcal{C}\rvert^{\mathcal{NE}}$ and $\lvert\mathcal{C}\rvert^{\mathcal{NEB}}$	77	125
$\omega^{\mathcal{E}}$ (via $\mathcal{B}_z^{\mathcal{E}}$)	1	1
Other magnetic-field gradients (4)	–	134
Non-reversing magnetic field, $\mathcal{B}_z^{\mathrm{nr}}$	–	106
Transverse magnetic fields, $\mathcal{B}_x^{\mathrm{nr}}$, $\mathcal{B}_y^{\mathrm{nr}}$	–	92
Refinement- and readout-laser detunings	–	76
$\tilde{\mathcal{N}}$-correlated laser detuning, $\Delta^{\mathcal{N}}$	–	48
Total systematic	29	310
Statistical uncertainty		373
Total uncertainty		486

Values are shown in μrad s^{-1}. All uncertainties are added in quadrature. For $\mathcal{E}_{\mathrm{eff}} = 78$ GV cm^{-1}, $d_e = 10^{-30}e$ cm corresponds to $|\omega^{\mathcal{NE}}| = \mathcal{E}_{\mathrm{eff}} d_e/\hbar = 119$ μrad s^{-1}.

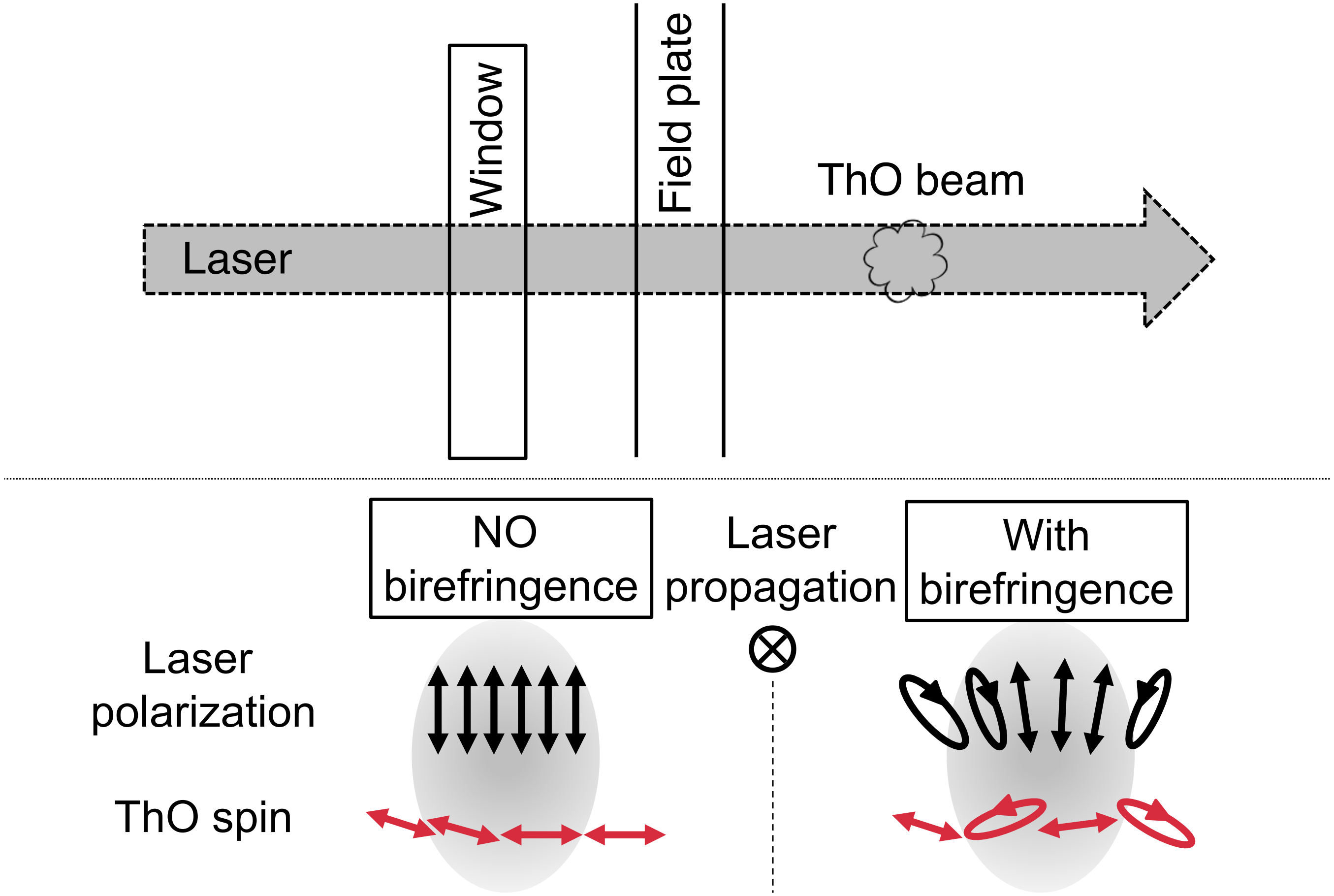
Imperfection of …

Laser polarization

Magnetic field

Birefringence

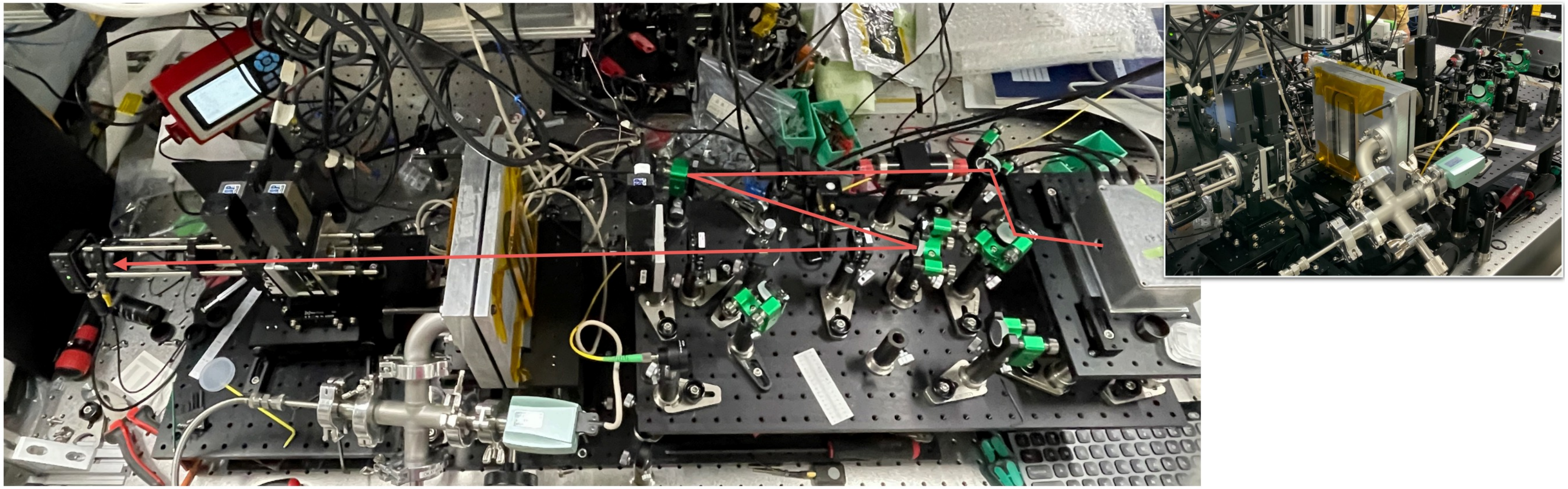
- Imperfection of laser polarization due to birefringence
- Need to suppress mechanical stress of any optical elements

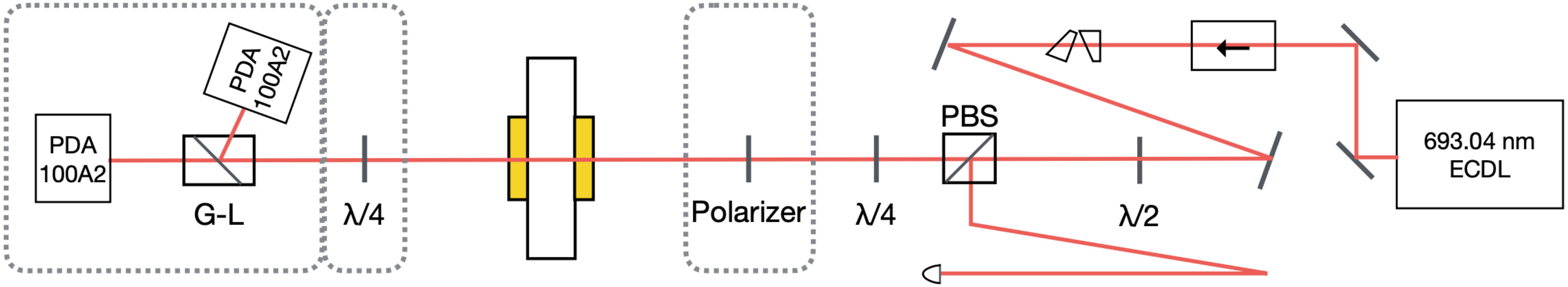


Birefringence

V. Wirthl *et al.*, OSA Continuum **4**, 2949 (2021).

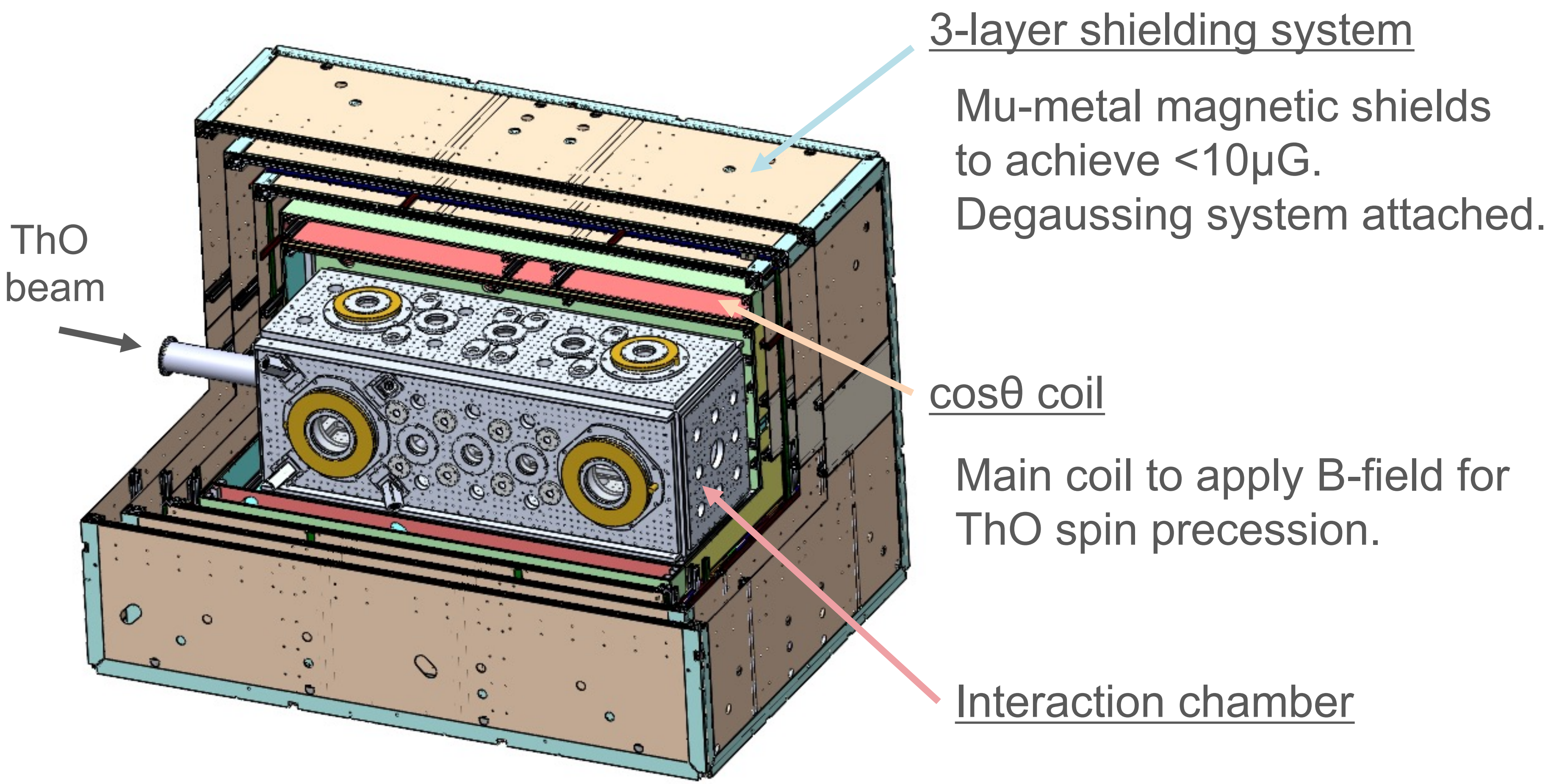
- Glass birefringence measurement with a simple polarimeter





Evaluation on-going!

B-field



ThO beam

3-layer shielding system

Mu-metal magnetic shields to achieve <10μG.
Degaussing system attached.

cosθ coil

Main coil to apply B-field for ThO spin precession.

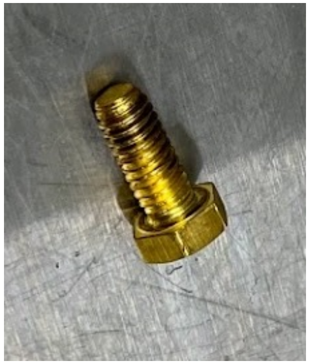
Interaction chamber

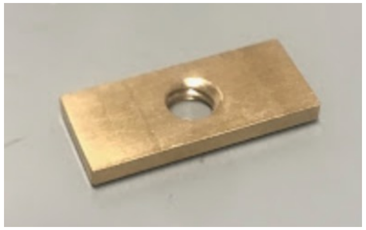
B-field

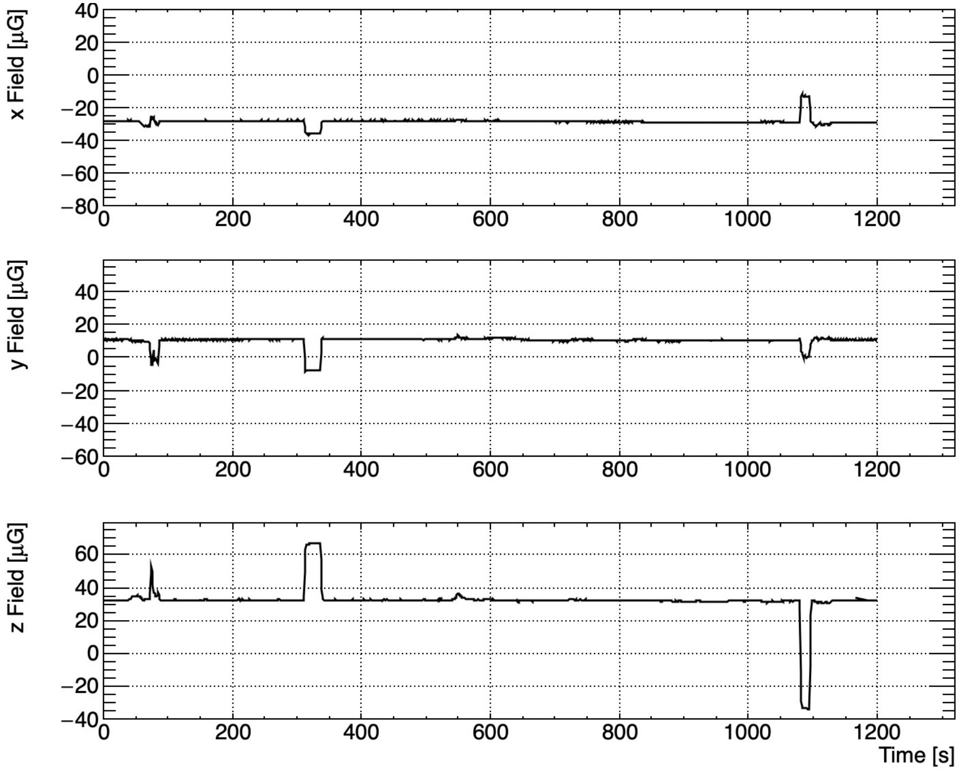
Are they really “non-magnetic?”

- All parts were magnetized and measured using magnetometer

  => some parts need to be replaced to achieve <10μG







Summary

- ACME measures eEDM using cold ThO molecules.
- The next generation ACME goal: × 30 improvement
- Statistical upgrades:
  - Longer precession time, Molecular lens
  - Photodetector upgrade (PMT=>SiPM)
- Systematics suppression:
  - Glass birefringence
  - Residual B-field
- All parts will be assembled in Northwestern University soon!

Thank you!

The ACME Collaboration

OKAYAMA UNIV.


David DeMille


John Doyle

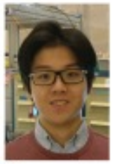

Gerald Gabrielse


Xing Fan


Daniel Ang


Xing Wu


Cole Meisenhelder


Zhen Han


Collin Diver


Siyuan Liu


Zack Lasner


Satoshi Uetake


Koji Yoshimura


Naboru Sasao


Peiran Hu


Maya Watts


Cris Panda


Nick Hutzler


Takahiko Masuda


Ayami Hiramoto

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科研費 KAKENHI

eEDM and SUSY

$$\frac{d_e}{e} \sim \kappa \left(\frac{\alpha_{\rm eff}}{2\pi}\right)^n \left(\frac{m_e c^2}{\Lambda^2}\right) \sin(\phi_{\rm T})(\hbar c),$$

Λ: rest-mass energy of a new particle

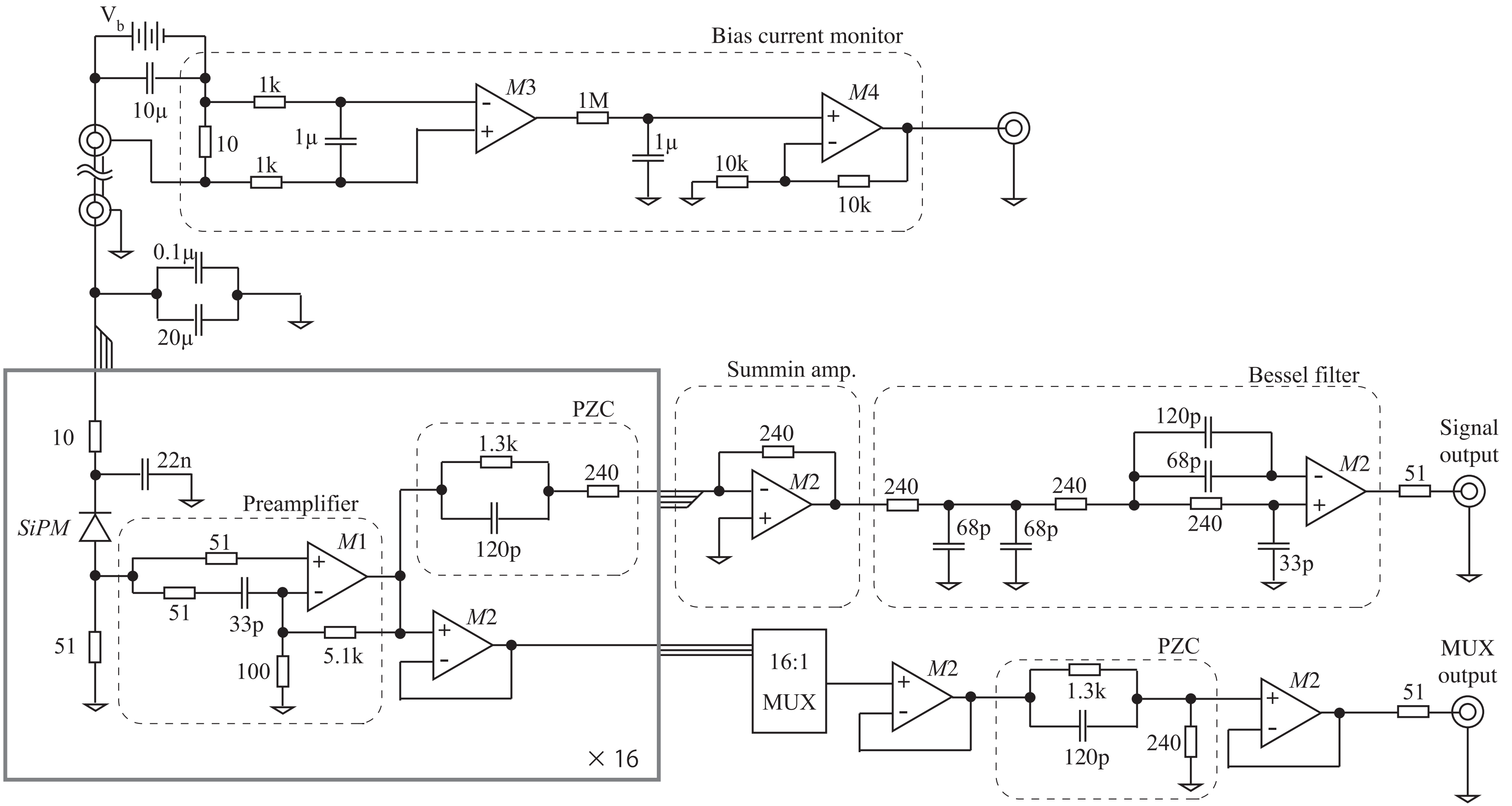
κ: 0.1-1 depending on models

φ_T: T-violating phase

n: the number of loops in an Feynman diagram

sin φ_T ~ 1, Λ ~ 1-100TeV => 10^{-28}-10^{-30} e▪cm

Readout circuit



- 16 channels are summed up
- Pulse shape optimization by PZC and LPF