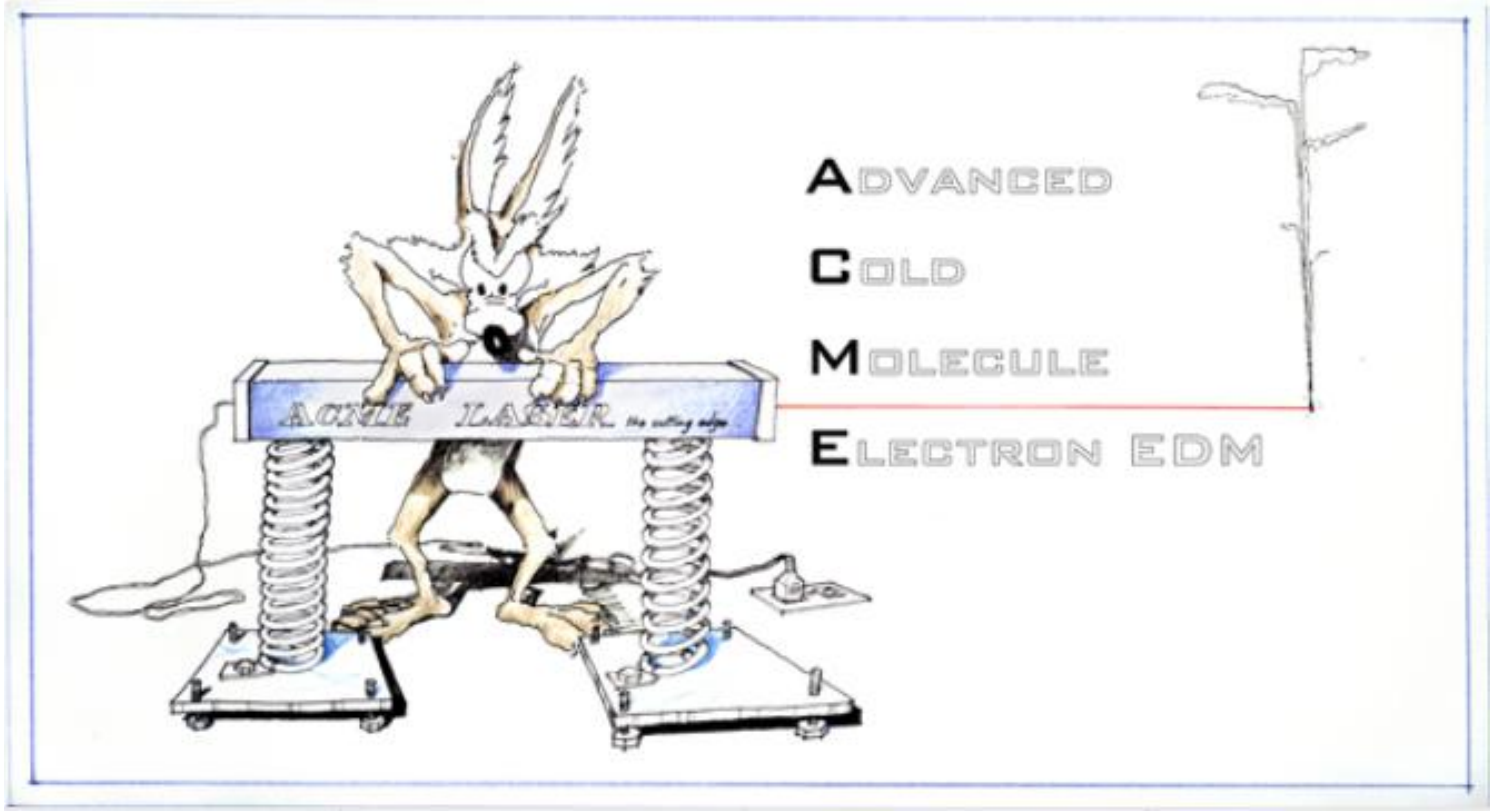
ACME III: electron EDM search using cold ThO molecular beam

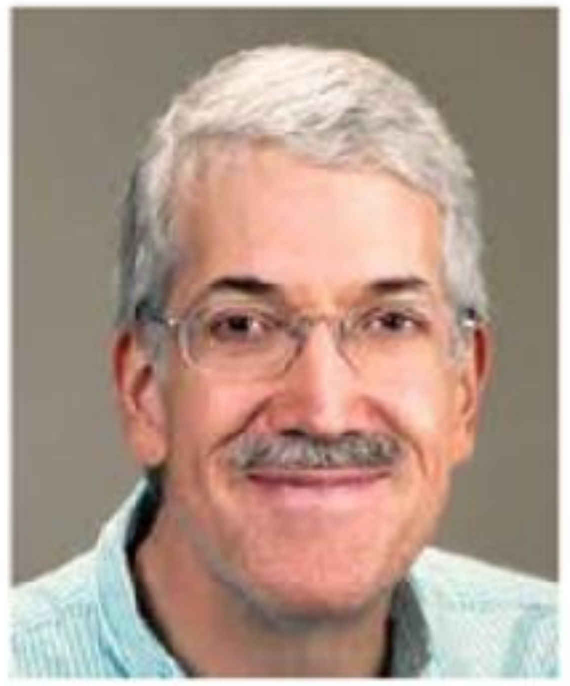


Takahiko MASUDA on behalf of the ACME collaboration

Research Institute for Interdisciplinary science,
Okayama University,

ACME Collaboration


David DeMille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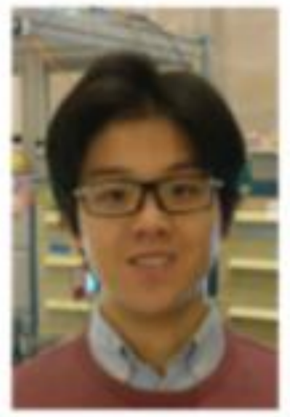
Northwestern University

THE UNIVERSITY OF CHICAGO

OKAYAMA UNIVERSITY

Caltech

Berkeley
UNIVERSITY OF CALIFORNIA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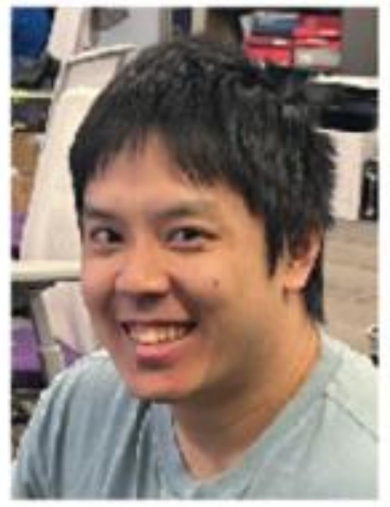
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JST SICORP
Matsuo Foundation

Outline

- Physics background and motivations
- Quick review of ACME:
  Experimental approach and prior results from ACME II
- Improvements with ACME III
  - Statistics improvements
  - Systematics improvements

Baryonic asymmetry

Matter universe

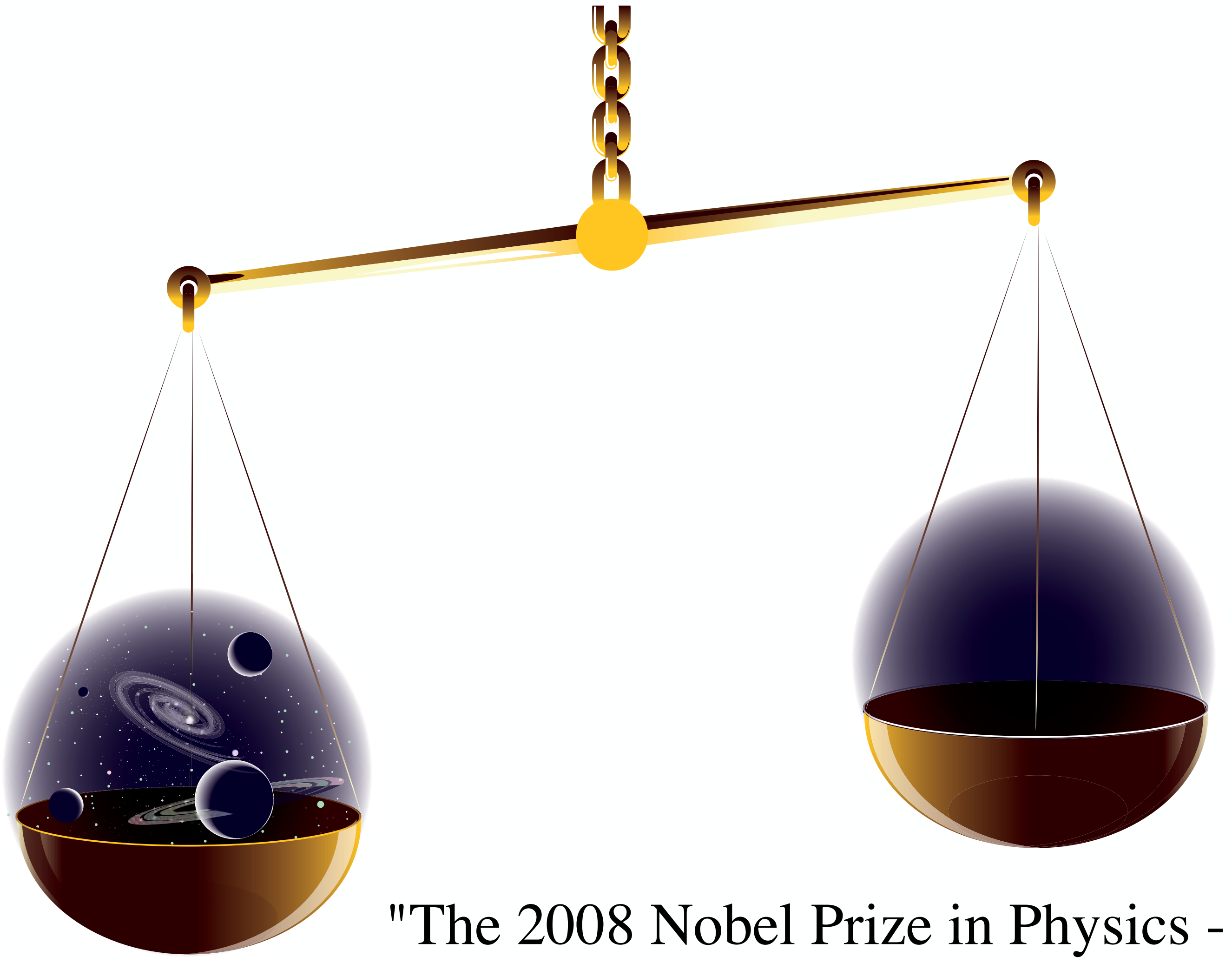
Why is the universe dominated by matter?

Observation : $n_B/n_\gamma \sim 6\times10^{-10}$

P.A. Zyla *et al*. (PDG), PTEP **2020**, 083C01 (2020).

Calculation : $n_B/n_\gamma \sim 10^{-18\text{-}20}$

8-10 orders different!



"The 2008 Nobel Prize in Physics - Popular Information". *Nobelprize.org*. Nobel Media AB 2013. Web. 25 Nov 2013. <http://www.nobelprize.org/nobel_prizes/physics/laureates/2008/popular.html>

Sakharov conditions

Sakharov A. D., JETP **5** pp.24-26 (1967)

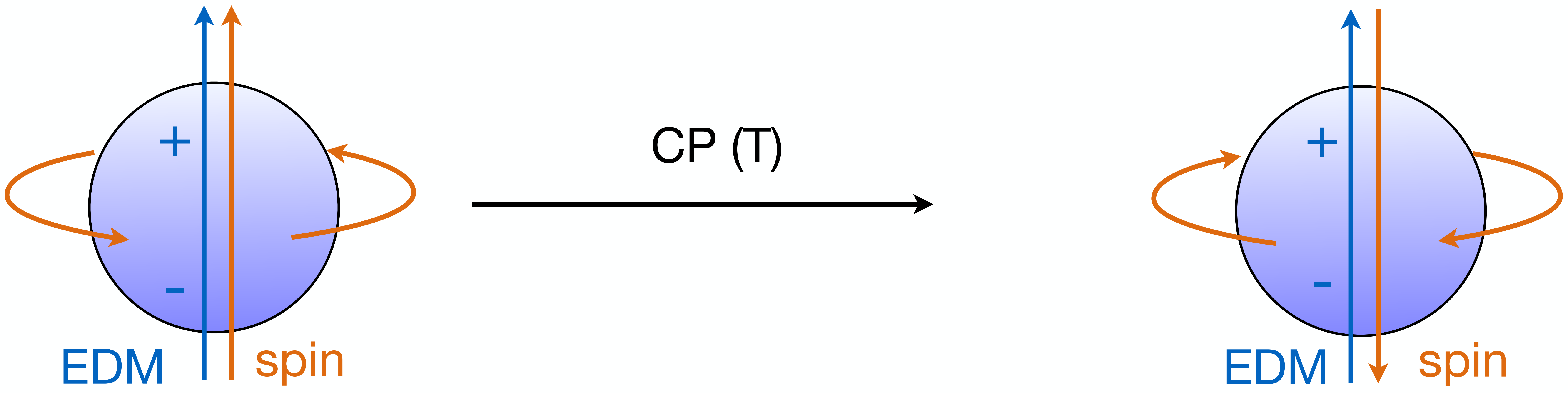
- **Baryon number *B* violation**
- ***C*-symmetry and *CP*-symmetry violation**
- **Out of thermal equilibrium**

→ There must be a term that violates *CP*-symmetry beyond the Standard Model

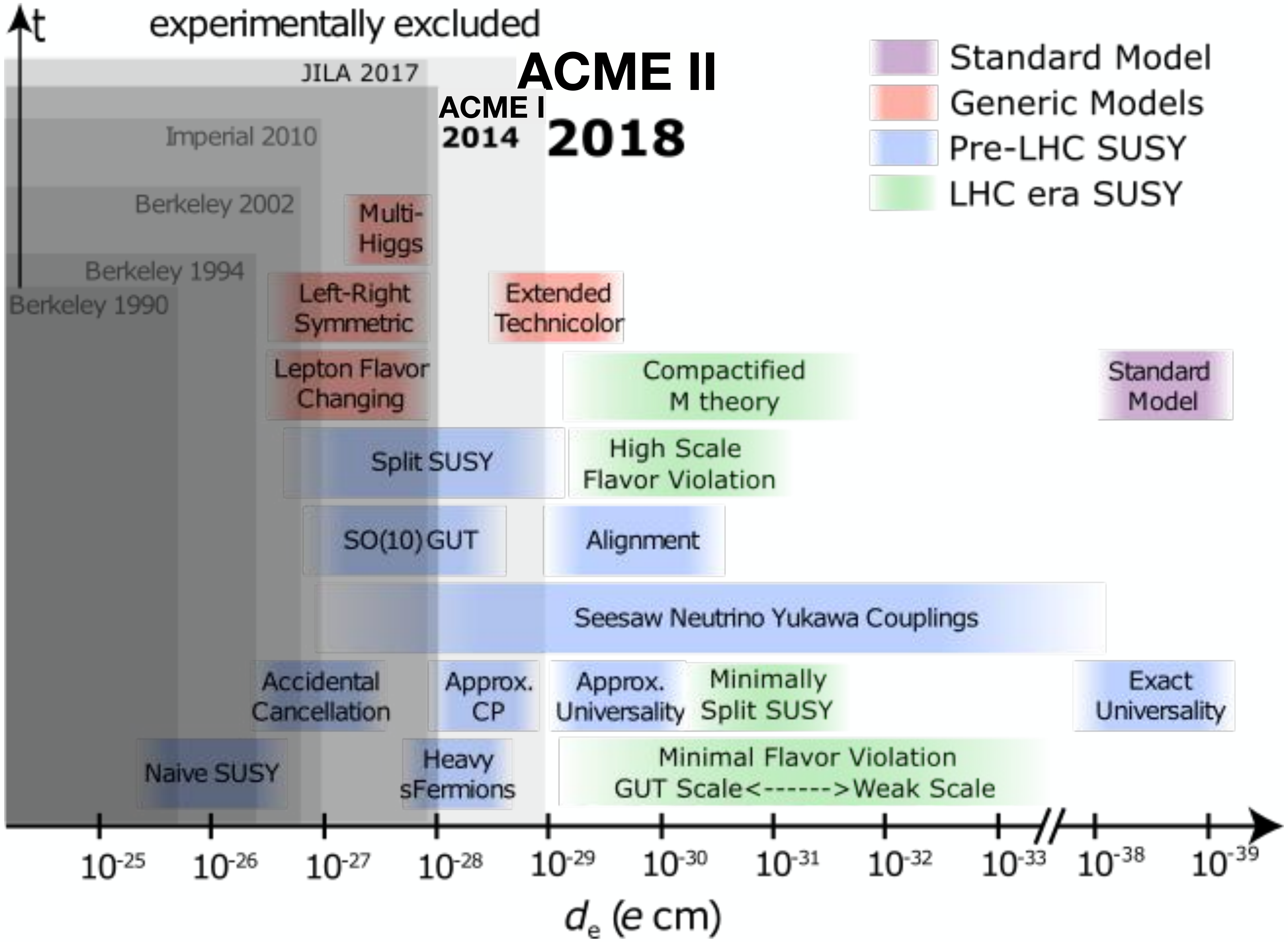
EDM : electric dipole moment

EDM : Permanent electric polarization of internal charge

If a spin 1/2 particle has finite EDM, it **violates** the *CP* symmetry.



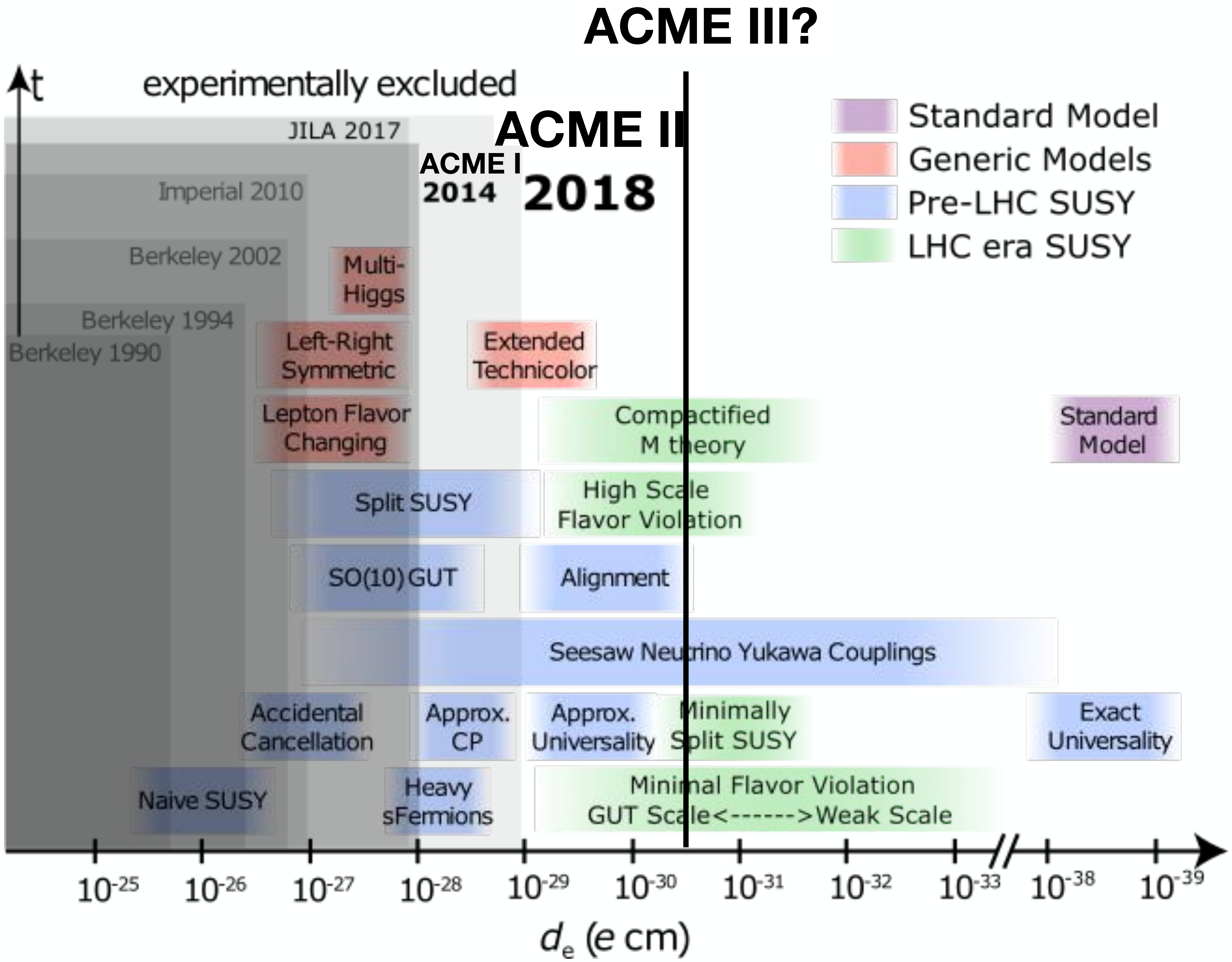
Electron EDM experiments



ACME II : $|d_e| < 1.1\times10^{-29}$ e cm

ACME Collab. Nature **562** (2018) 355.

Electron EDM experiments



ACME II : $|d_e| < 1.1\times10^{-29}$ e cm

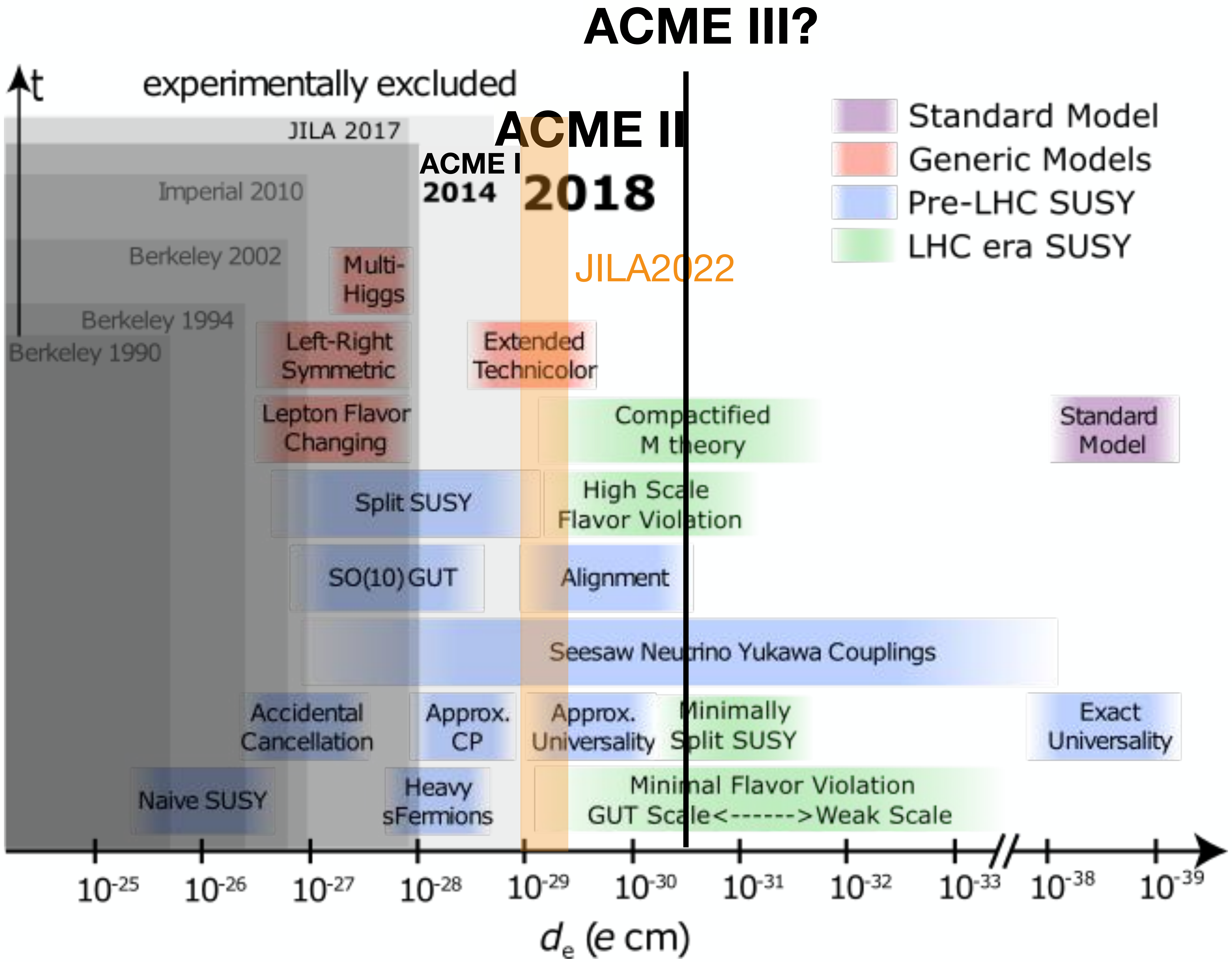
ACME Collab. Nature **562** (2018) 355.

ACME III goal:

× 30 improvement

Today's topic

Electron EDM experiments



JILA group has recently reported
$|d_e| < 4.1\times10^{-30}$ *e* cm
on arXiv:2212.11841

ACME II : $|d_e| < 1.1\times10^{-29}$ e cm

ACME Collab. Nature **562** (2018) 355.

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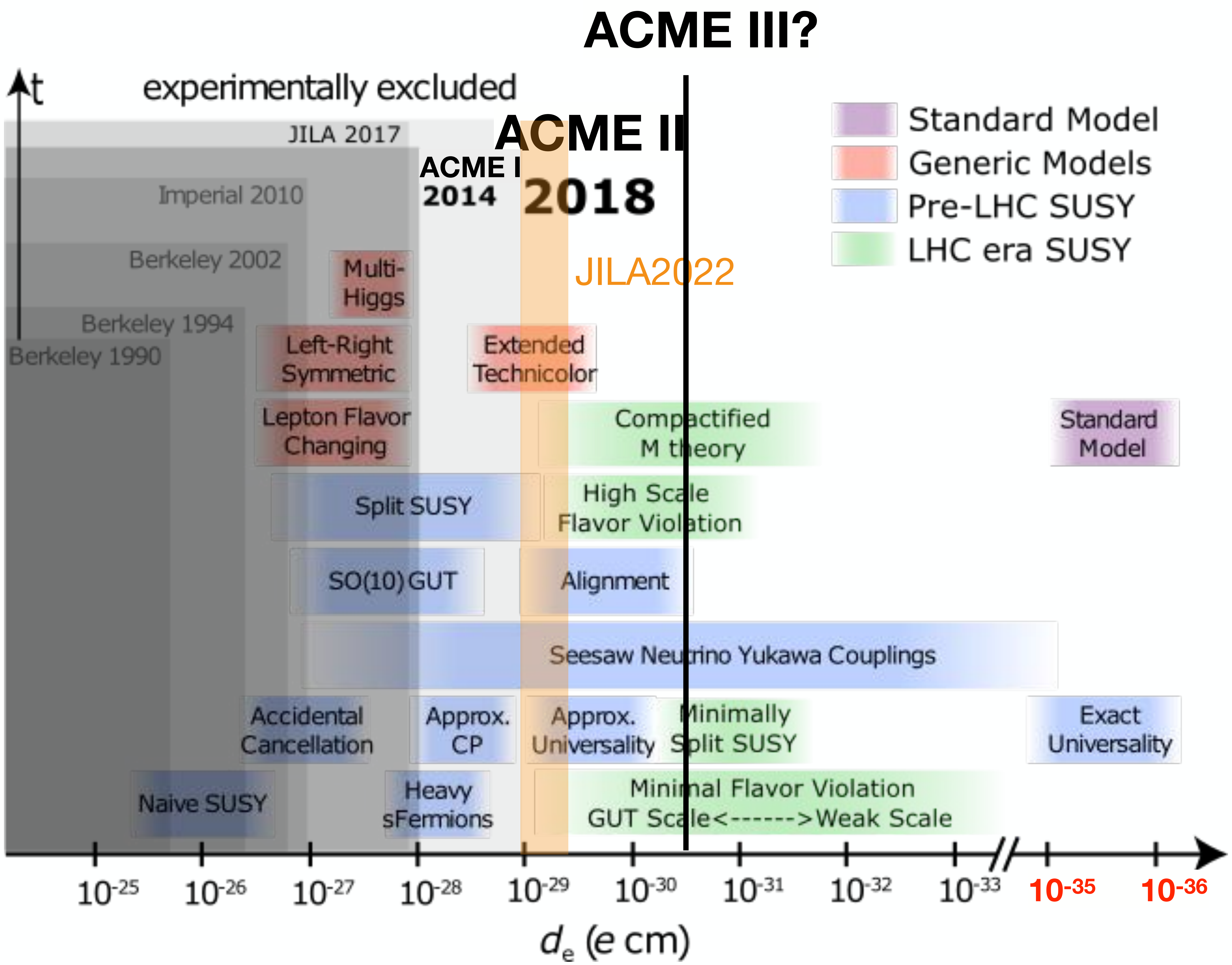

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ACME Collab. Nature **562** (2018) 355.

ACME III goal:

× 30 improvement

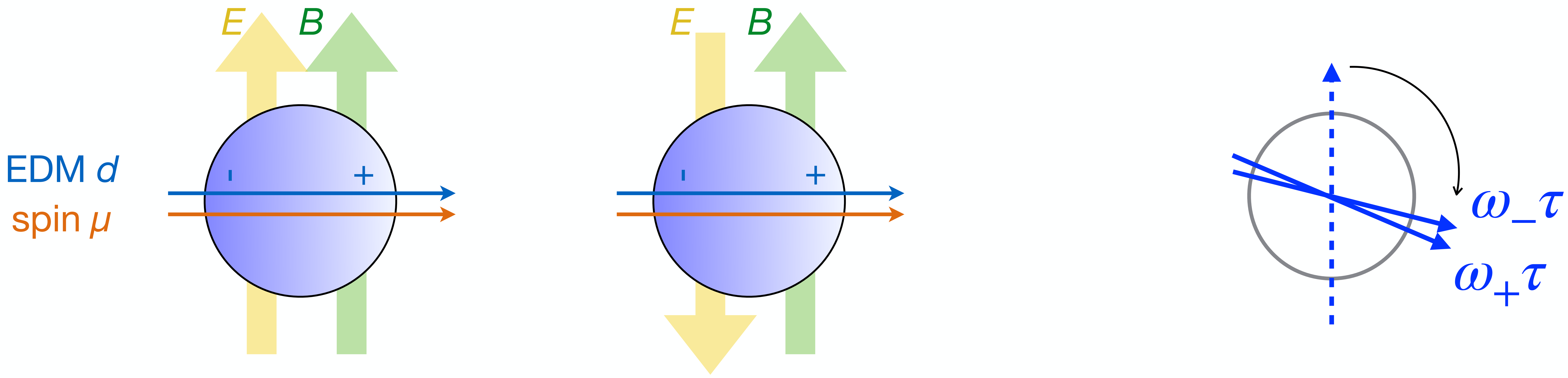
Today's topic

SM background has been updated.
Y. Ema *et al*., PRL**129**, 231801 (2022)

Principle of the EDM measurement

Spin precession measurement:

EDM changes precession frequency depending on E field reversal.



$$\omega_+ = 2\frac{\mu B + dE}{\hbar} \qquad \omega_- = 2\frac{\mu B - dE}{\hbar} \qquad \Rightarrow d = \frac{\hbar(\omega_+ - \omega_-)}{4E}$$

Statistical precision : $\Delta d_e \sim \frac{\hbar}{\boxed{E}\,\boxed{\tau}}\frac{1}{\sqrt{\boxed{\dot{n}T}}}$

Number of signals

Electric field

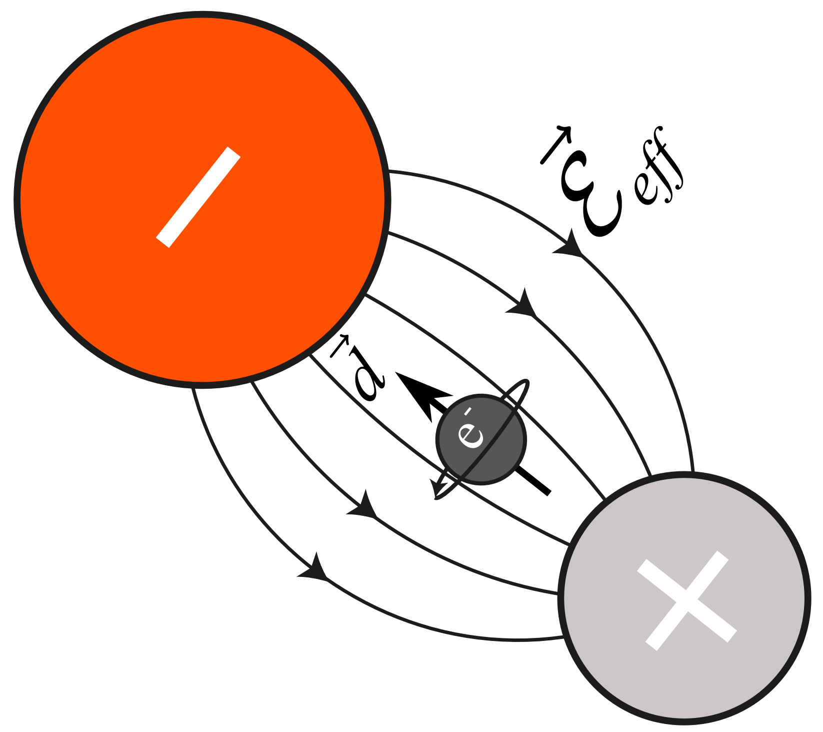
precession time

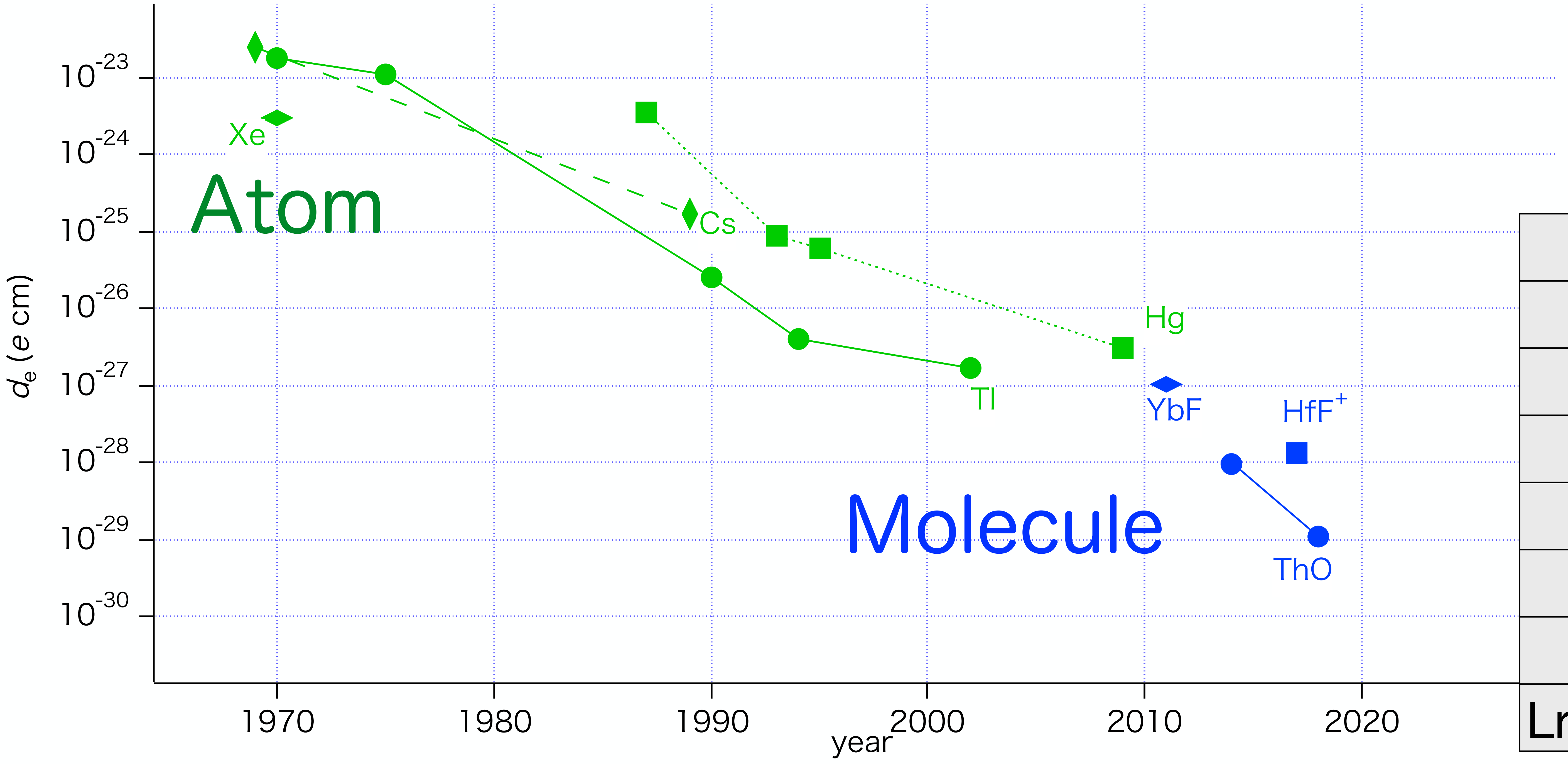
Electron EDM (eEDM, d_e)

eEDM measurement in **polar molecules.**

Sensitivity for d_e can be amplified in polar molecules due to its large internal field.

$$\Delta d_e \sim \frac{\hbar}{E\tau}\frac{1}{\sqrt{\dot{n}T}} \quad \Rightarrow \quad \Delta d_e \sim \frac{\hbar}{E_{\mathrm{eff}}\tau}\frac{1}{\sqrt{\dot{n}T}}$$





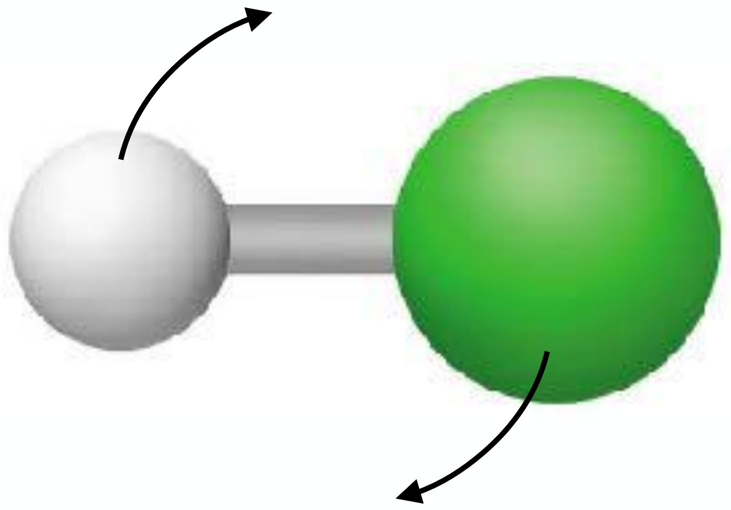
	E_{eff} [GV/cm]	Reference
YbF	25	J. Phys. B **30**, L607 (1997)
ThO	78	J. Chem. Phys. **145**, 214301 (2016)
HfF^+	23	Phys. Rev. A **96**, 040502 (2017)
ThF^+	35	New J. Pays. **17**, 043005 (2015).
PbO	25	Phys. Rev. Lett. **89**, 133001 (2002).
LrO, LrF^+, LrH^+	250-340	Phys. Rev. A **104**, 062801 (2021).

Advantage of ThO

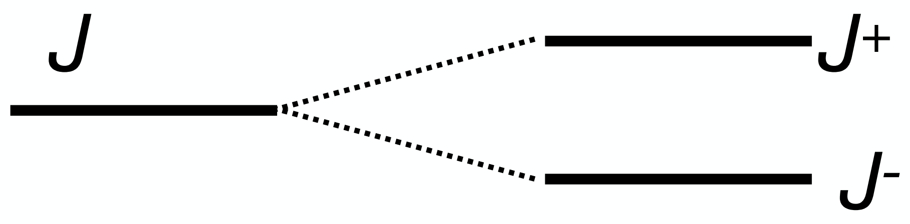
Ω-doublet *Nearly degenerated parity doublet*

Modest external E field can generate extremely **strong internal E field (GV/cm)**

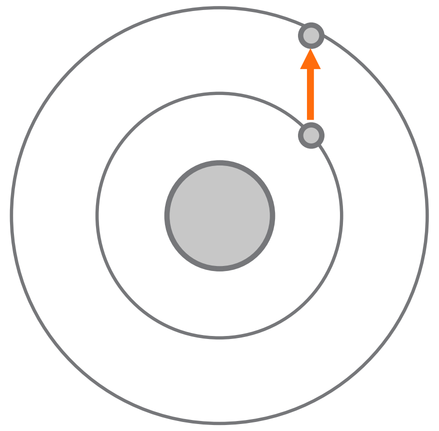
Rotational energy
ΔE ~ GHz
P ~ O(1) @ 10 kV/cm



Ω-doublet case
ΔE ~ MHz
P ~ O(1) @ 10 V/cm



(Ref.) Atom case
ΔE ~ THz
P ~ O(10^{-3}) @ 10 kV/cm

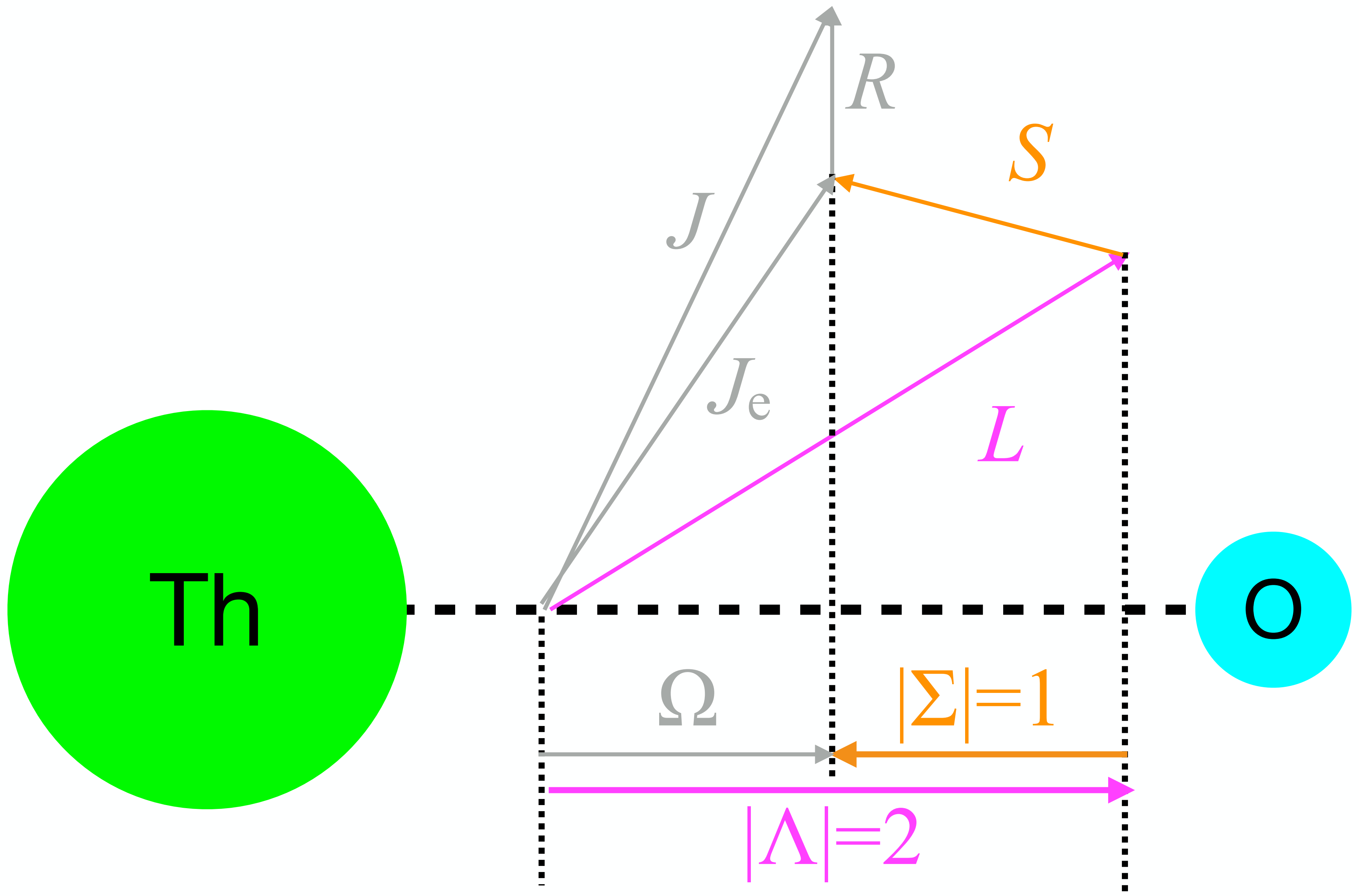


$^3\Delta_1$ *State without magnetic moment*

Electron's angular momentum (Λ=+2) and spin (Σ=-1) **vanish** the net magnetic moment

→ **Insensitive** to the magnetic field

$$\mu = \underset{2}{g_L \Lambda \mu_B} + \underset{-2}{g_s \Sigma \mu_B} \simeq 0$$



EDM in a ThO molecule

EDM measurement state : ***H*** $^3\Delta_1$ state

Strong internal E field (Ω doublet) : E_{eff} ~ 78 GV/cm

- 10 V/cm external field can saturate the polarization

L.V. Skripnikov, J. Chem. Phys. **145** 214307 (2016).

Tiny magnetic moment ($^3\Delta_1$): $\mu=0.0044\mu_B$

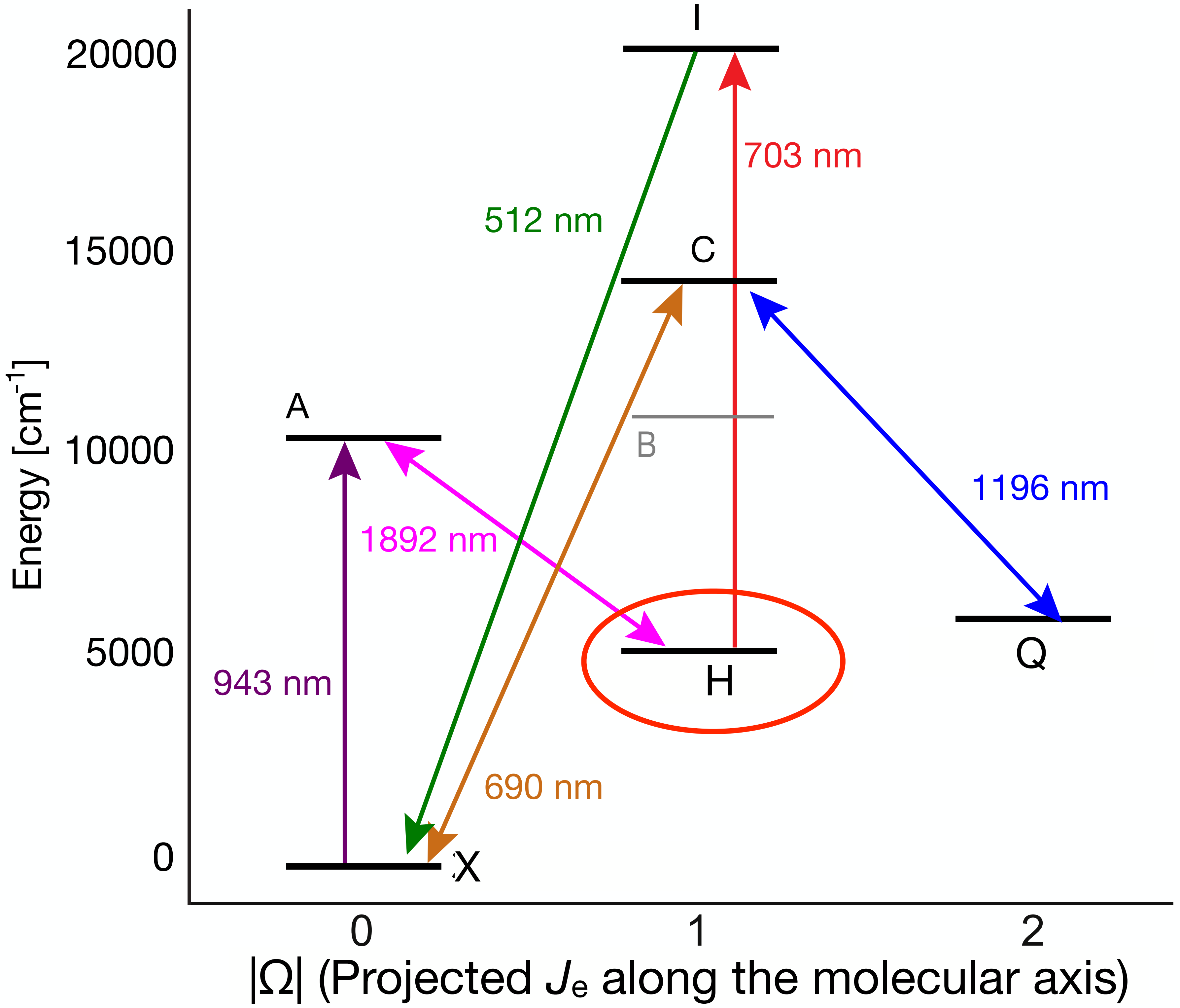
- Insensitive to the magnetic field

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

- Long lifetime (spin precession time) : $\tau = 4.2\pm0.5$ ms

D. Ang *et al*., PRA**106**, 022808 (2022).

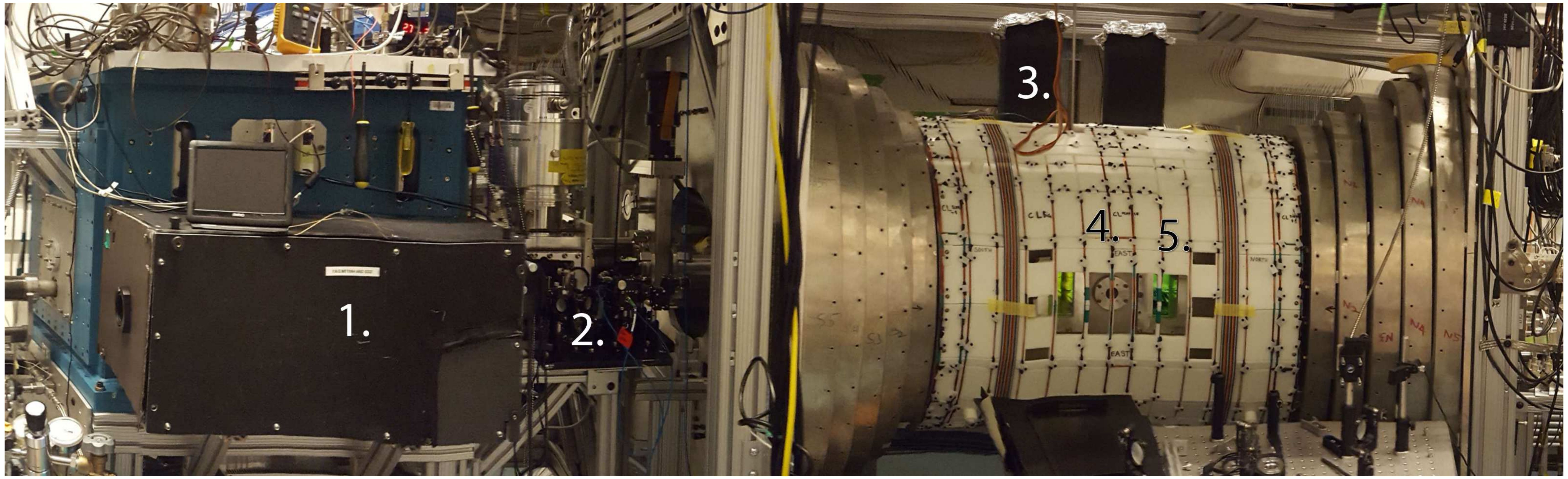
- Diatomic, Even nucleus, for spectroscopic simplicity
- Affordable laser : Red - NIR
- Efficiently producible in a beam by laser ablation
- $^{232}Th^{16}O$ Natural abundance >99.7%
  - etc.

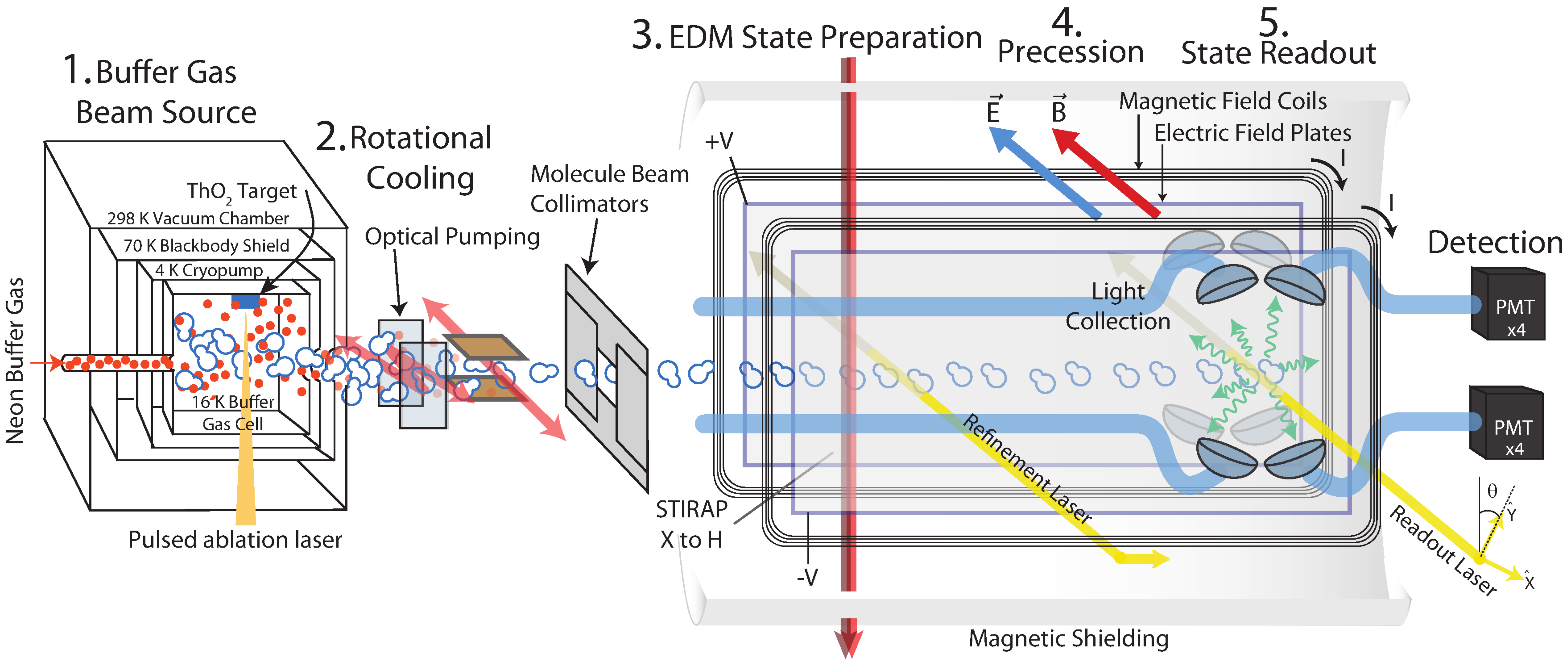


$$\Delta d_e \sim \frac{\hbar}{E_{\mathrm{eff}}\tau}\frac{1}{\sqrt{\dot{n}T}}$$

Quick review on ACME II (2018)

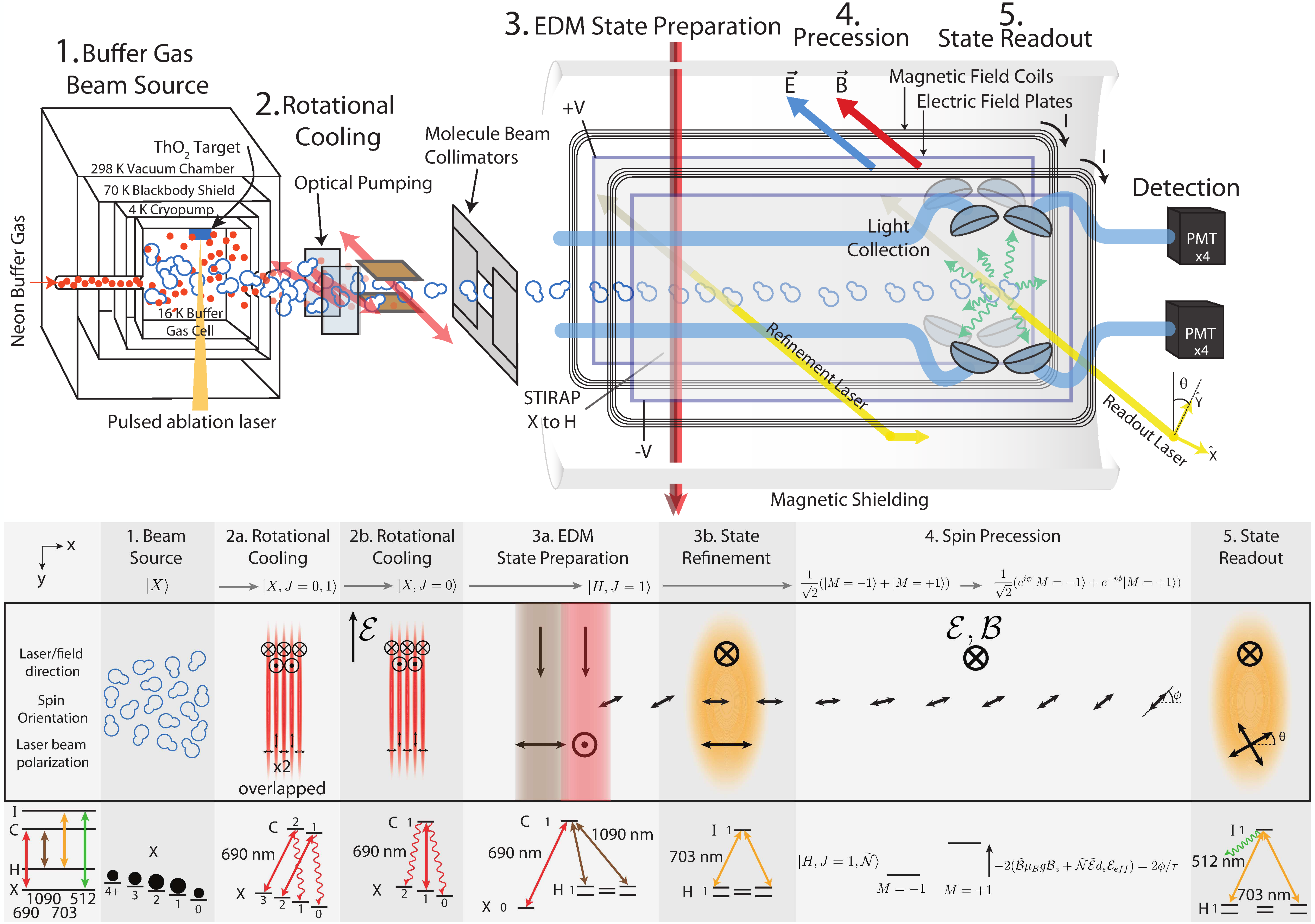
Zack Laser, Ph.D thesis. (2019)





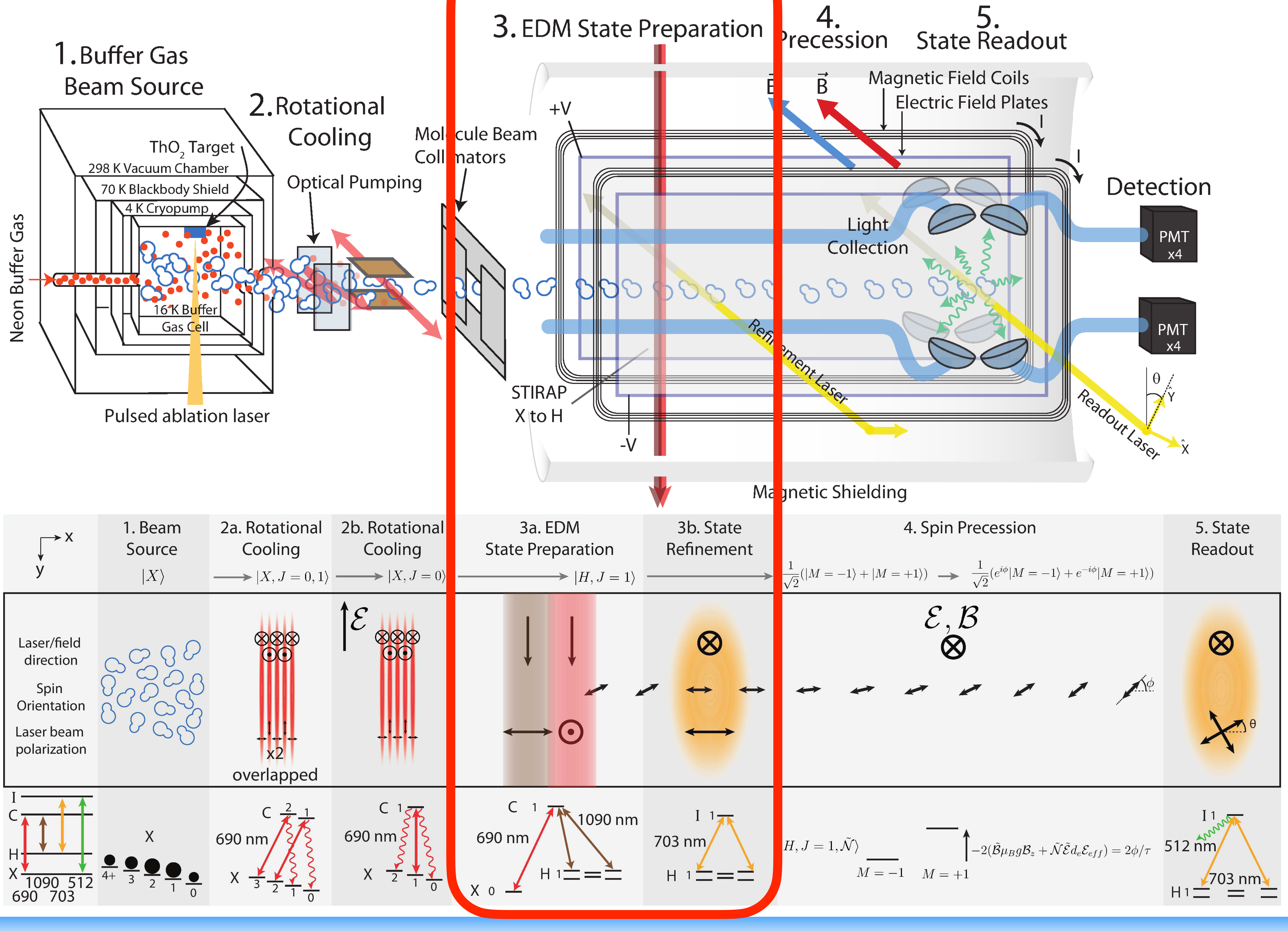
Quick review on ACME II (2018)

Zack Laser, Ph.D thesis. (2019)



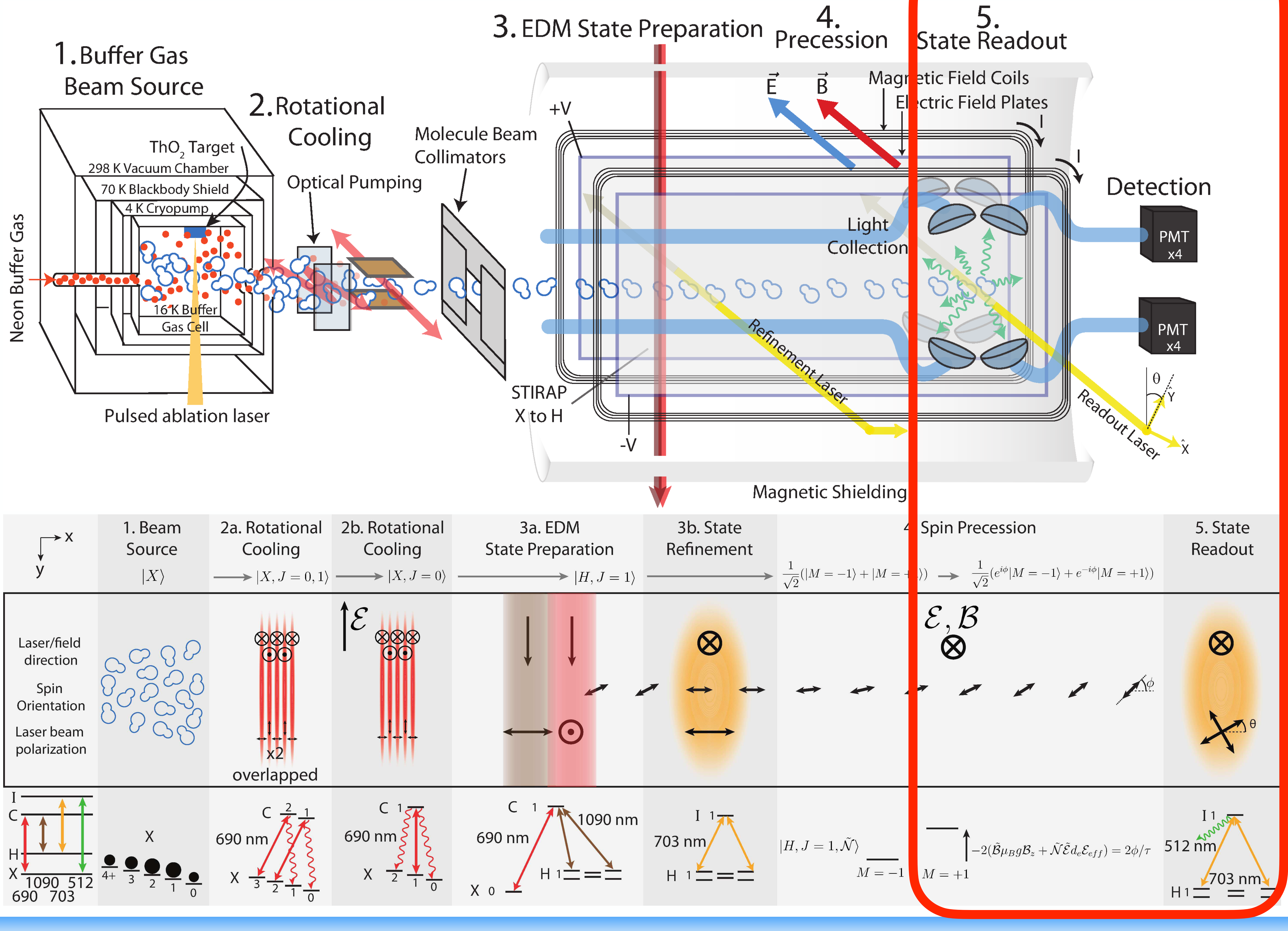
Quick review on ACME II (2018)

Zack Laser, Ph.D thesis. (2019)



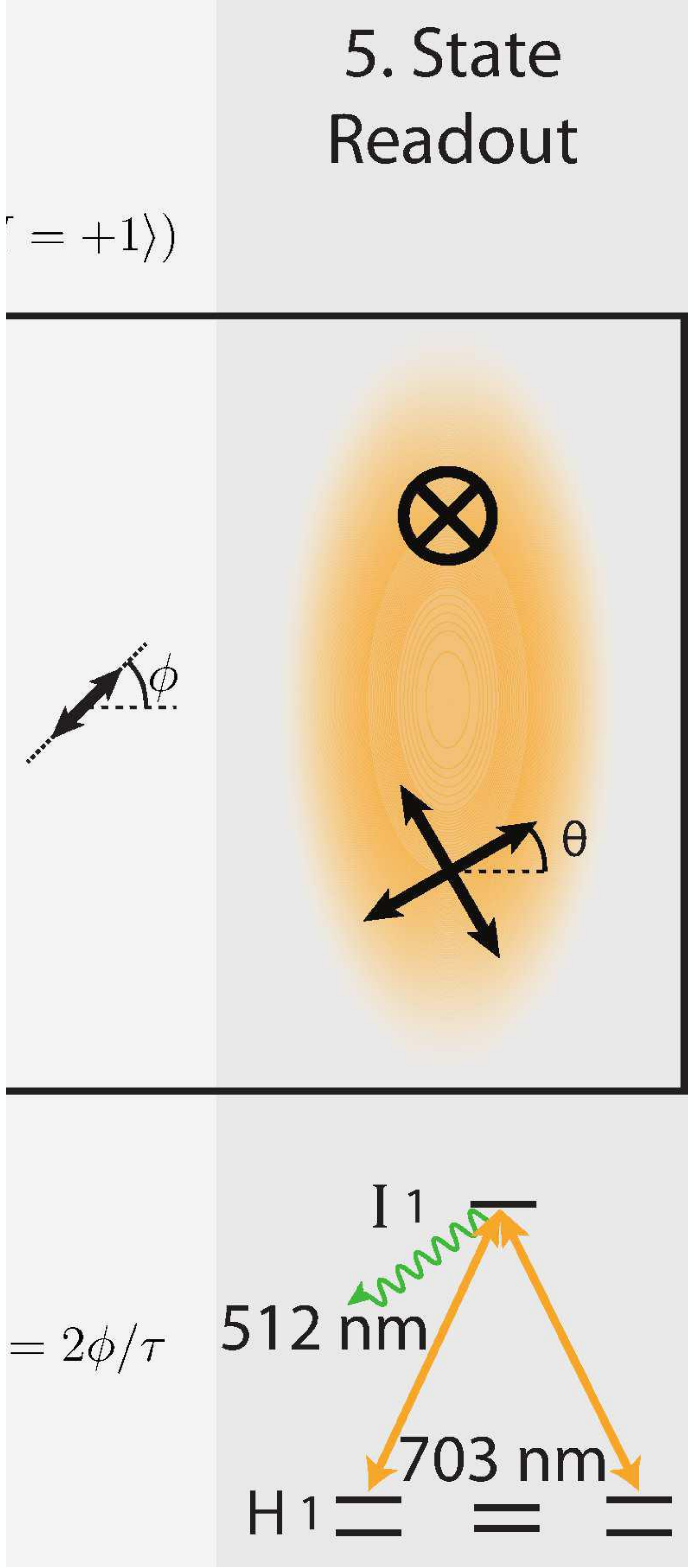
Quick review on ACME II (2018)

Z ck Laser, Ph.D thesis. (2019)

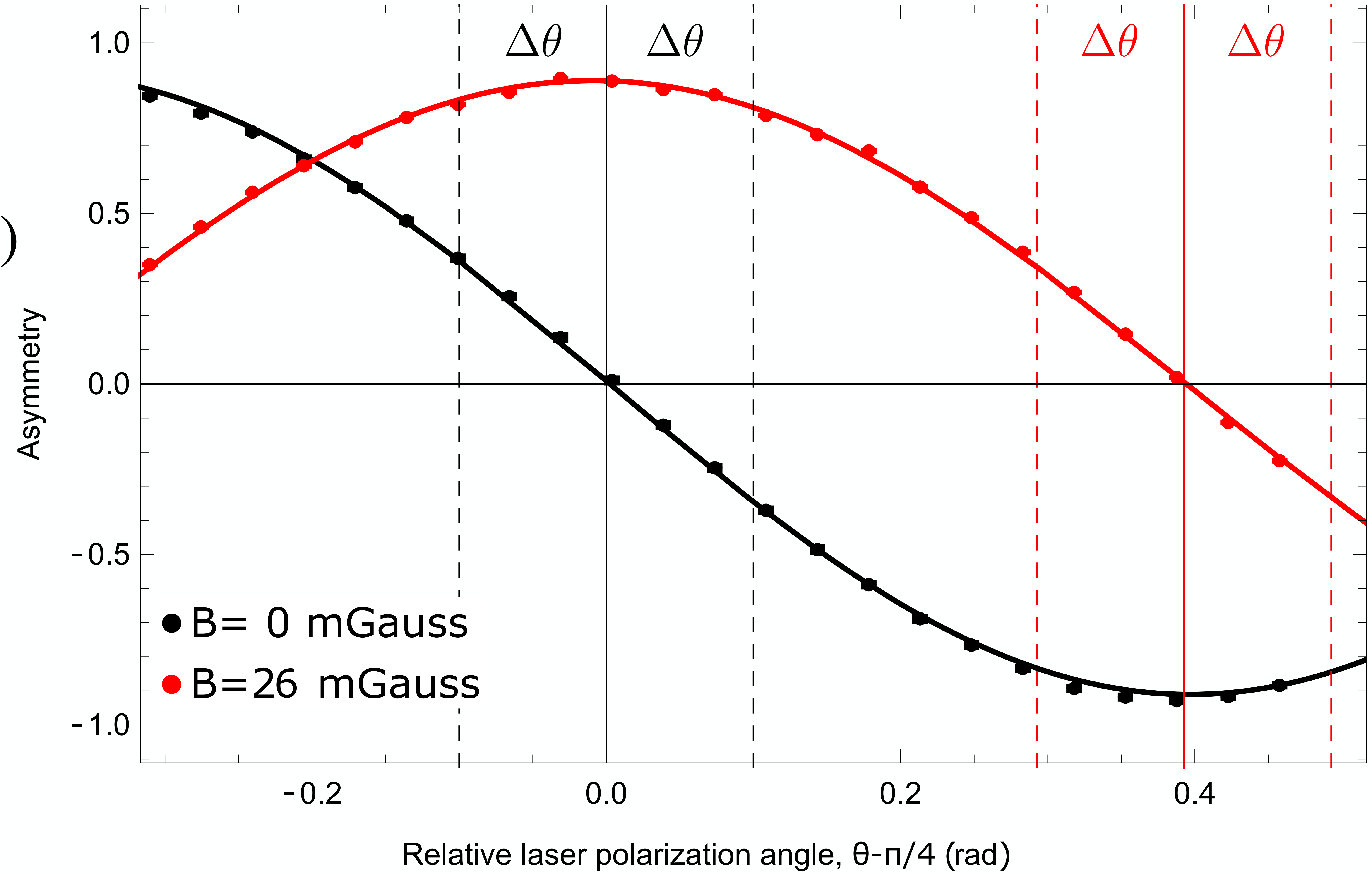


Example of spin rotation fringe

Cris Panda, Ph.D thesis. (2018)



$$A = \frac{F_x + F_y}{F_x - F_y}$$
$$\propto \cos 2(\phi - \theta)$$

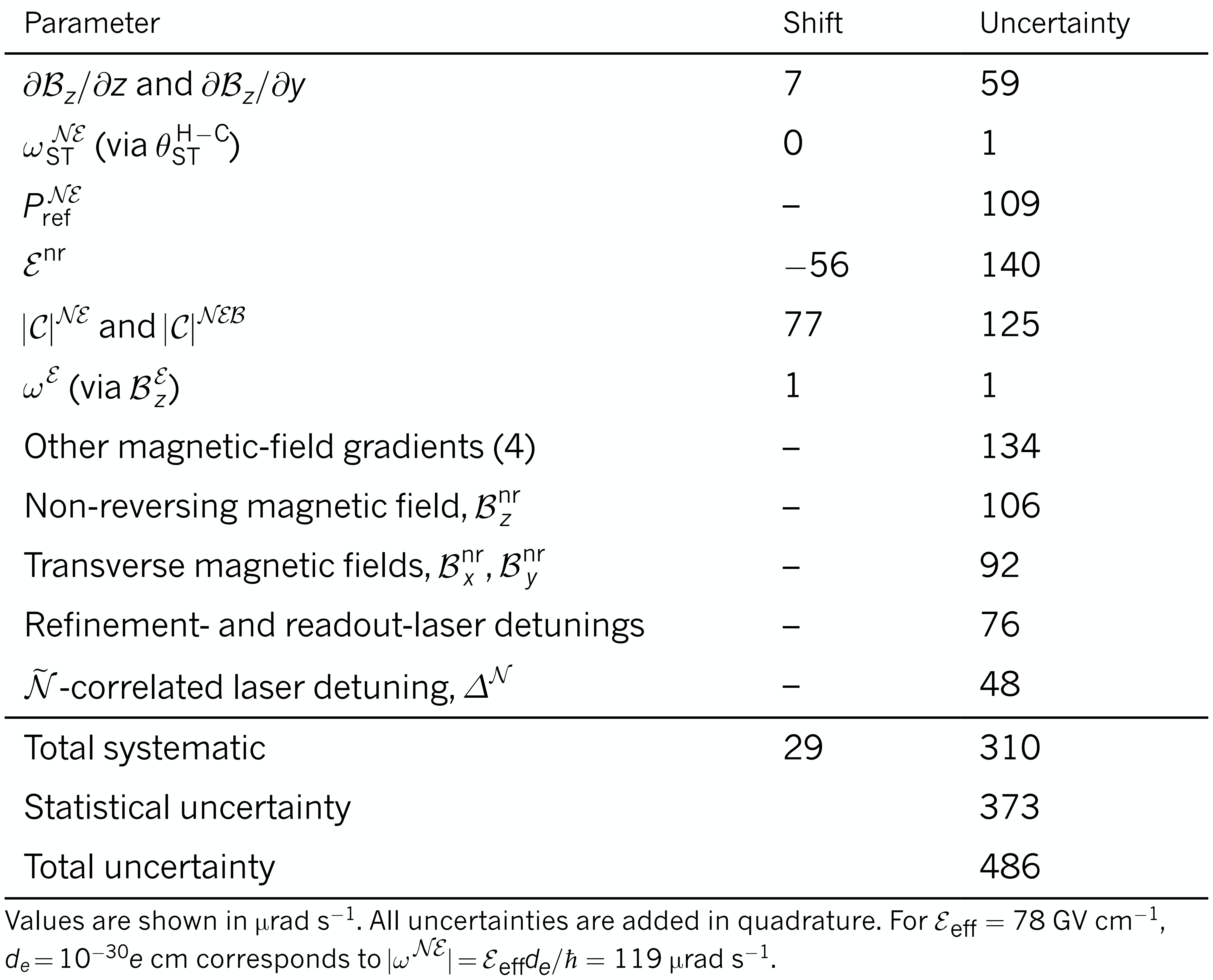


ACME II result

$$d_{\mathrm{e}} = (4.3 \pm 3.0_{\mathrm{stat}} \pm 2.6_{\mathrm{syst}}) \times 10^{-30}\ e \cdot \mathrm{cm}$$

based on

- 2×10^{14} ThO molecules detected
    - 6×10^{6} / pulse × 3×10^{7} pulses
    - 50Hz, 10 weeks
- 3×10^{5} p.e./pulse (5% eff.)

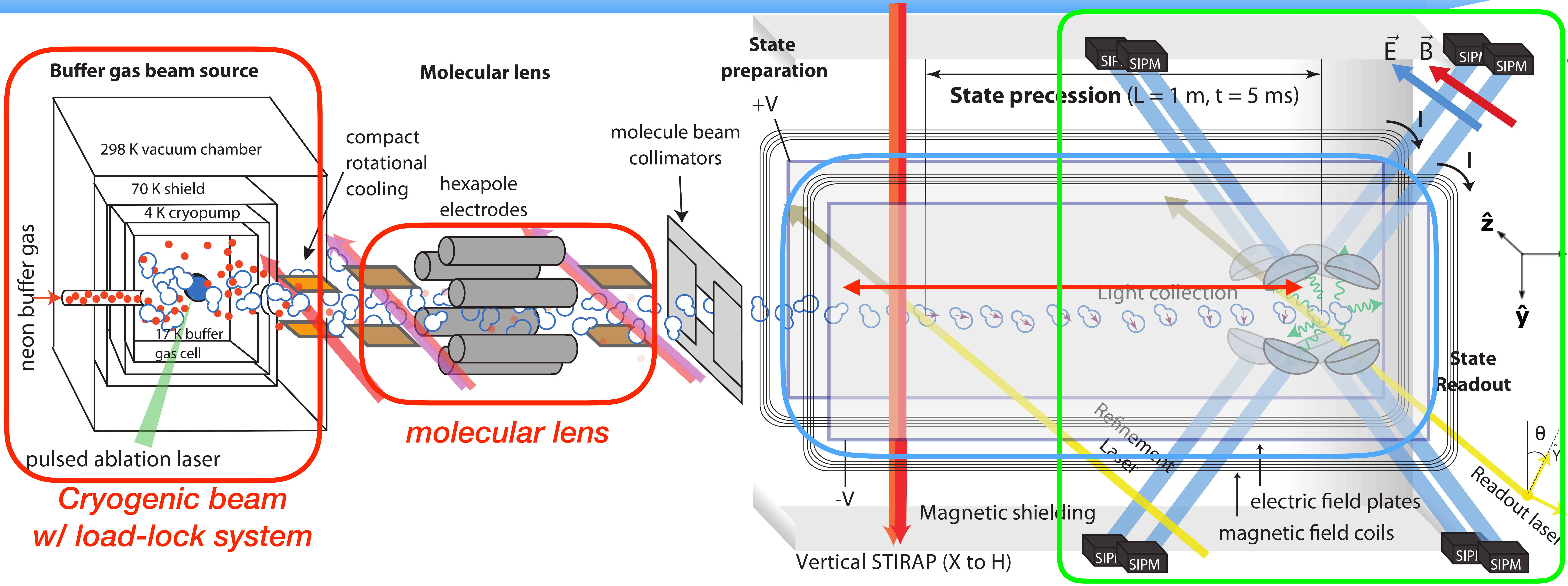


Parameter	Shift	Uncertainty
$\partial\mathcal{B}_z/\partial z$ and $\partial\mathcal{B}_z/\partial y$	7	59
$\omega_{\mathrm{ST}}^{\mathcal{NE}}$ (via $\theta_{\mathrm{ST}}^{\mathrm{H-C}}$)	0	1
$P_{\mathrm{ref}}^{\mathcal{NE}}$	–	109
$\mathcal{E}^{\mathrm{nr}}$	-56	140
$\lvert\mathcal{C}\rvert^{\mathcal{NE}}$ 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 $\mu\mathrm{rad\ s^{-1}}$. All uncertainties are added in quadrature. For $\mathcal{E}_{\mathrm{eff}} = 78\ \mathrm{GV\ cm^{-1}}$, $d_{\mathrm{e}} = 10^{-30} e\ \mathrm{cm}$ corresponds to $\lvert\omega^{\mathcal{NE}}\rvert = \mathcal{E}_{\mathrm{eff}} d_{\mathrm{e}}/\hbar = 119\ \mu\mathrm{rad\ s^{-1}}$.

ACME Collab. Nature **562** (2018) 355.

Statistics improvements in ACME III



Cryogenic beam
w/ load-lock system

molecular lens

High QE detector
+
Collection optics

5x long precession time (length)

Improved DAQ
w/ low time variance

C.D. Panda *et al.*,
J. Phys. B, **52** (2019) 235003

Statistical sensitivity:

$$\Delta d_{\rm e} \sim \frac{\hbar}{E_{\rm eff}\boxed{\tau}}\frac{1}{\sqrt{\boxed{\dot{n}_{\rm mol}}T}}\sqrt{\frac{\boxed{F}}{\boxed{\varepsilon_{\rm det}}}}$$

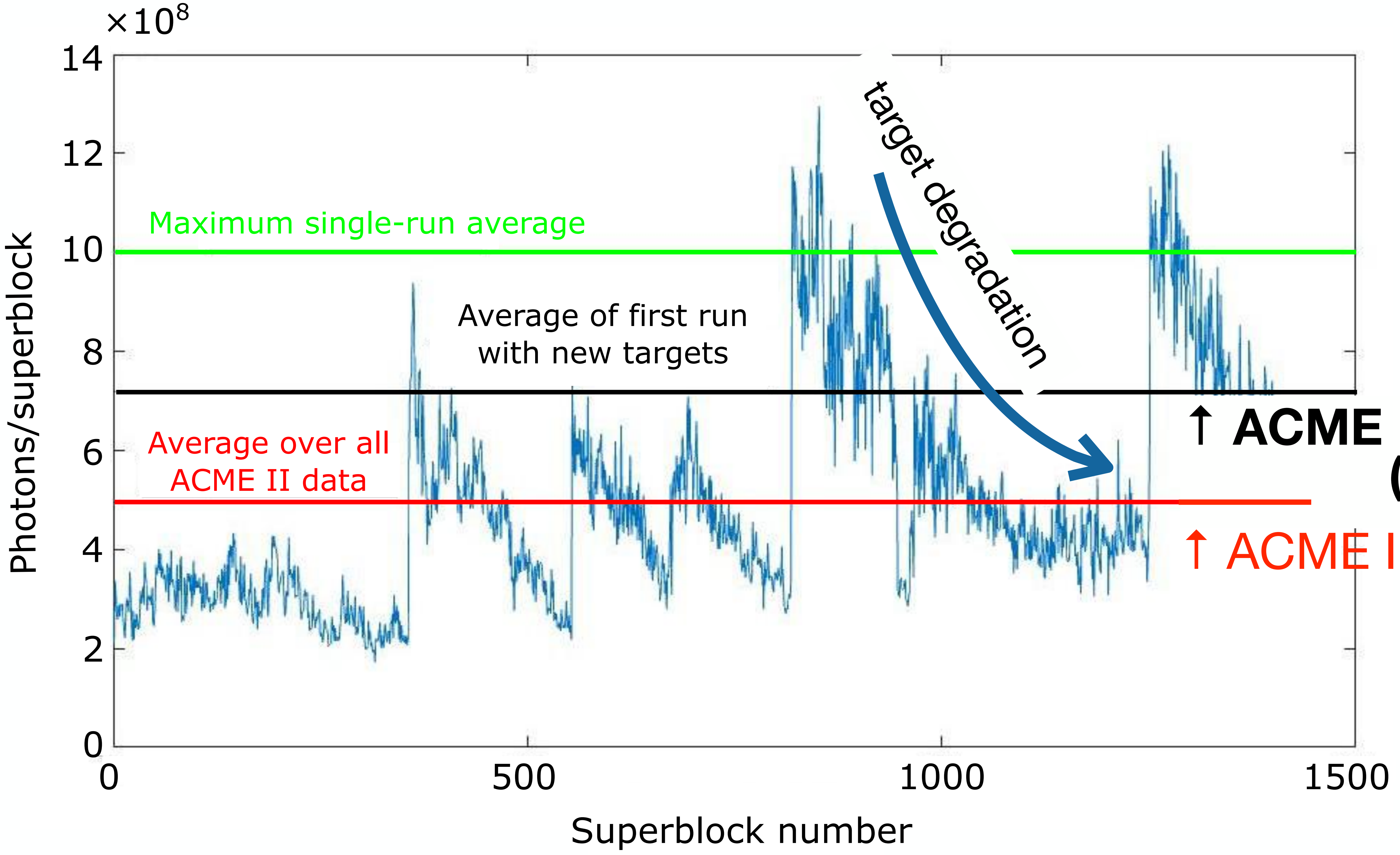
Improvement	Signal gain	EDM sensitivity gain
New beam source	1.5	1.2
Electrostatic lens	12	3.5
Longer precession time	0.3	2.6
Detector upgrade	2.7	1.6
Collection optics	1.7	1.3
Timing jitter reduction	1	1.7
Total	25	39

New cryogenic beam source w/ load-lock

Ablation target Load-lock system : enabling daily *in-situ* target replacement

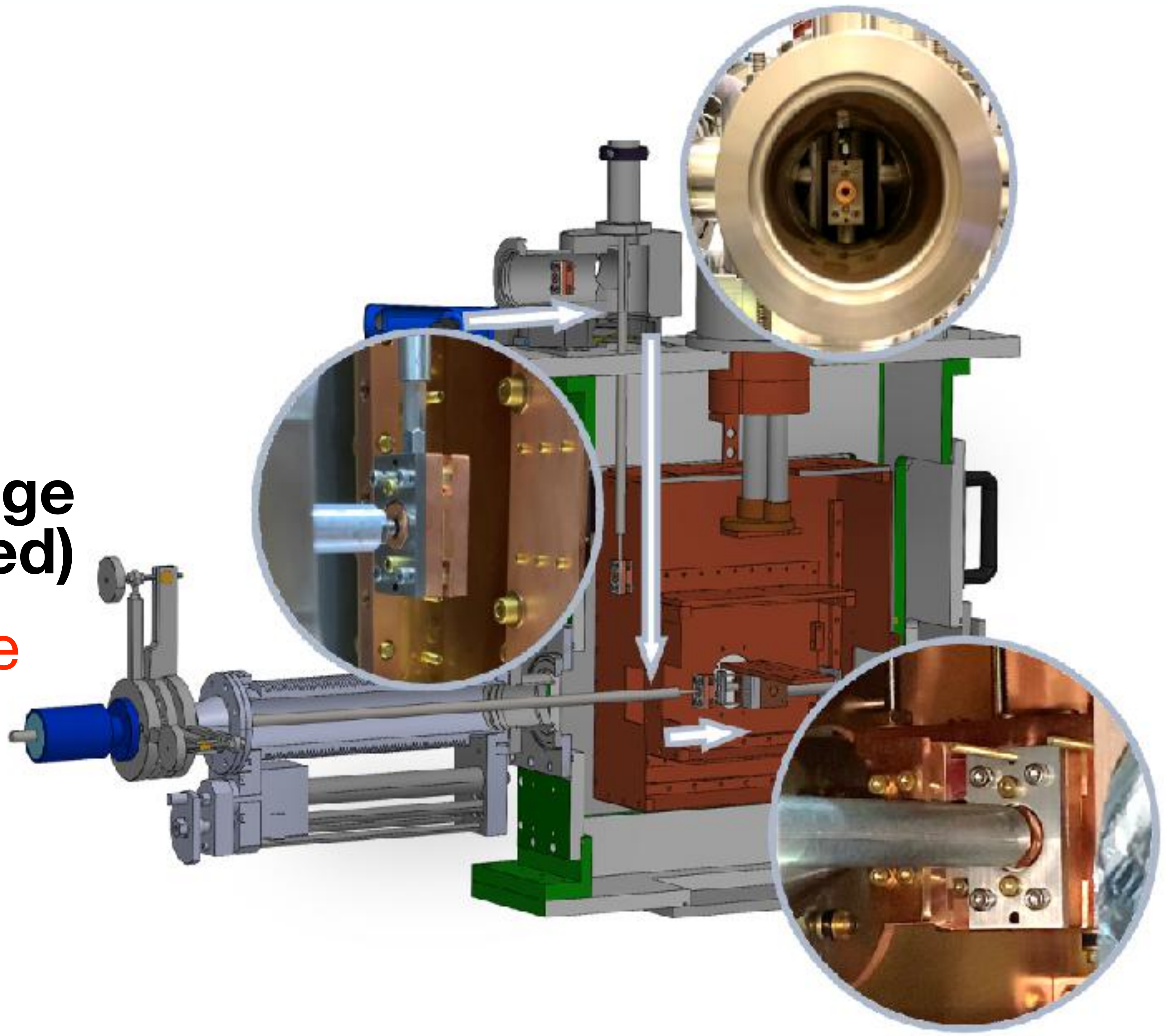
- Ablation targets were usually replaced after ~2 weeks in ACME II.
- Replacement takes more than one day (warm up, vacuum break, radioactive work, cool down)

→ Load-lock system can increase the average statistics.

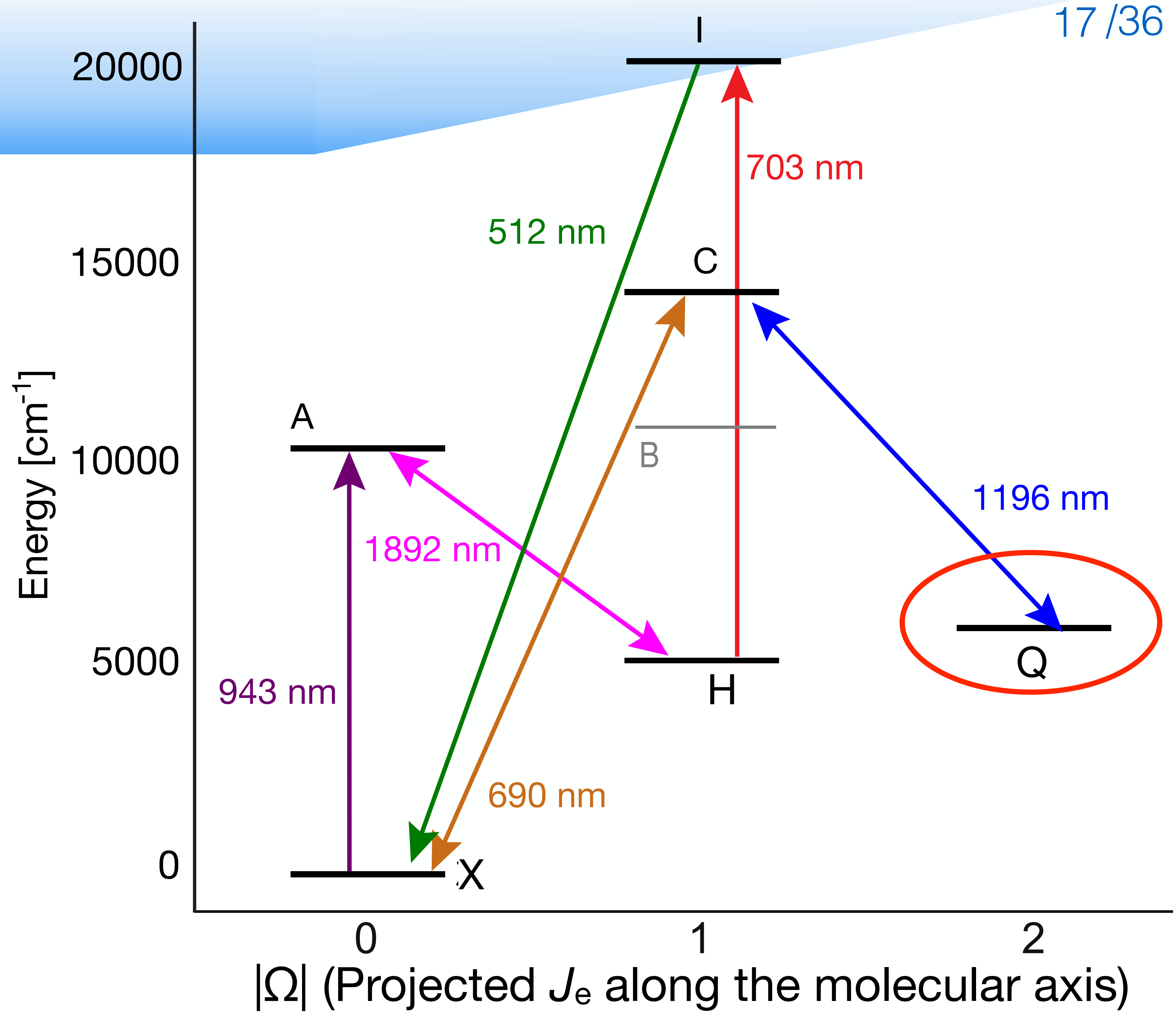


↑ ACME III average (projected)

↑ ACME II average



Electrostatic molecular lens



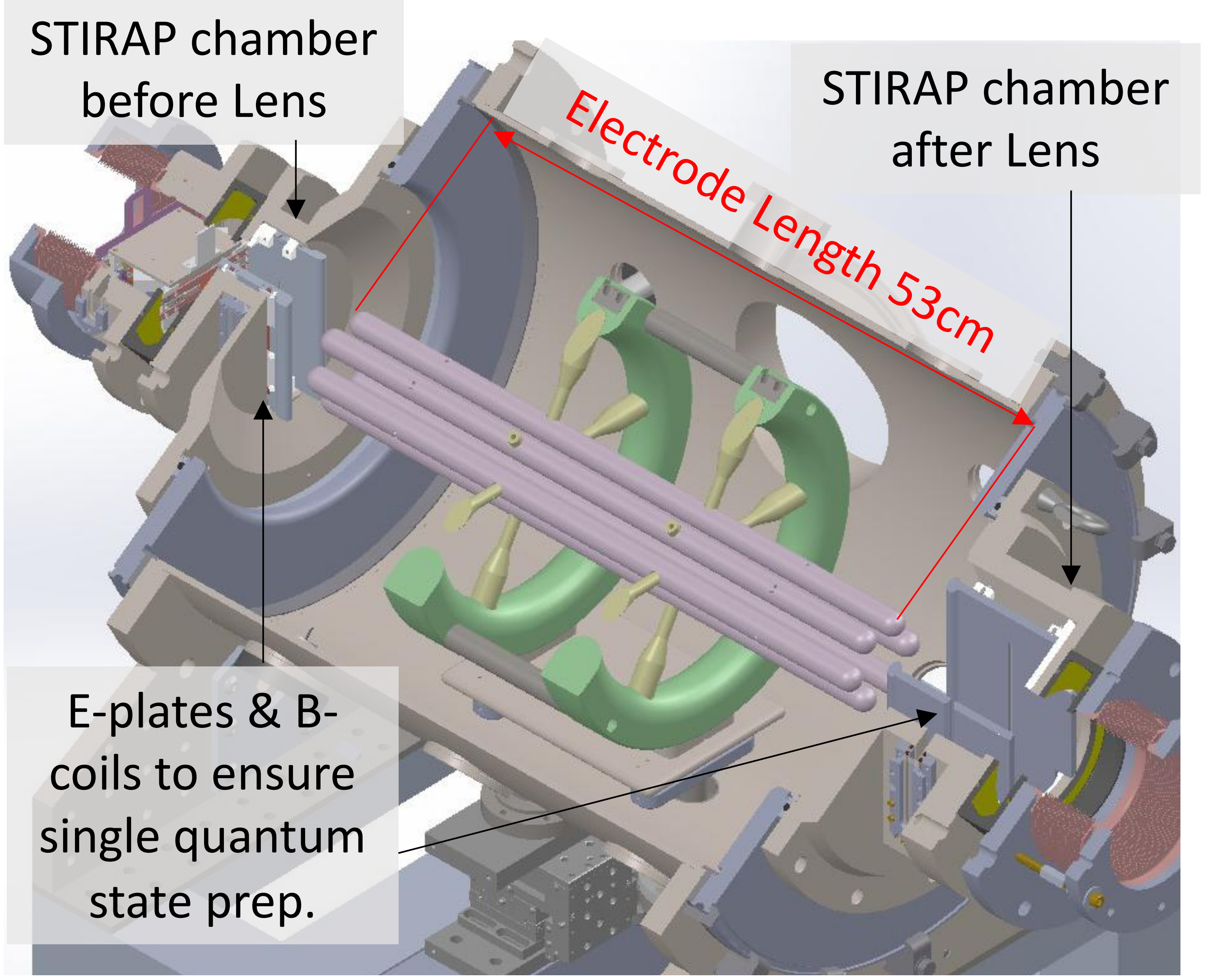
ThO beam is collimated by electrostatic potential

- Increasing the number of available ThO
- Reducing the loss of extended flight distance

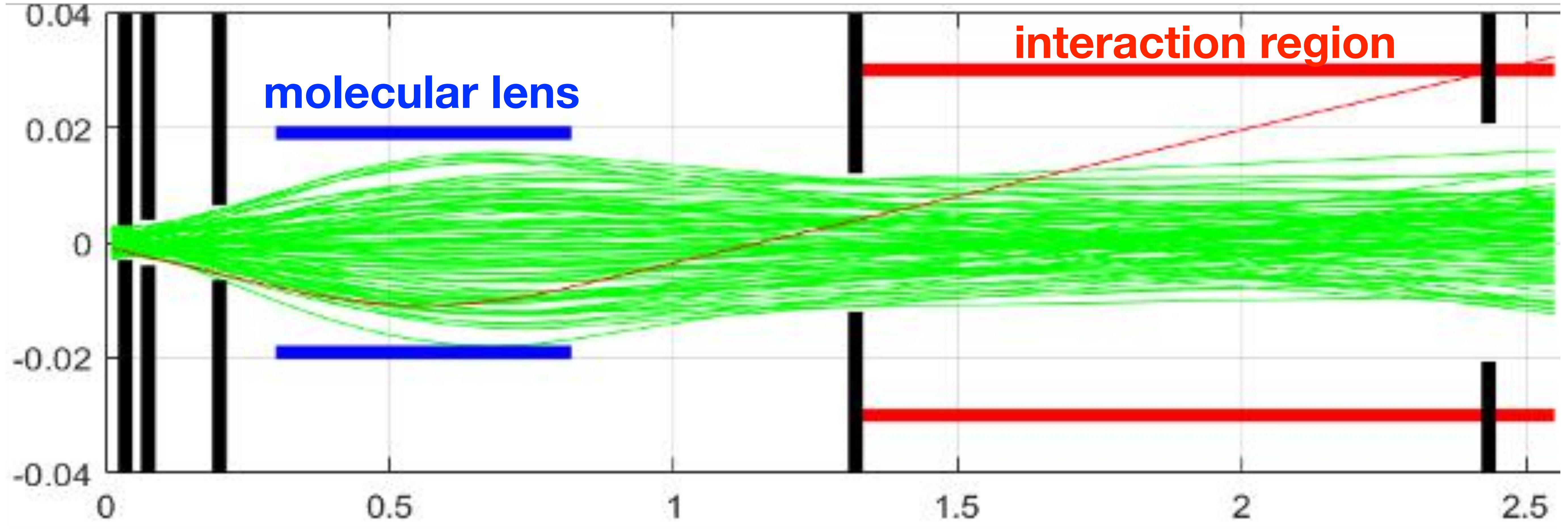
Q state

X. Wu *et al.*, New J. Phys. **22** (2020) 023013.

- Large Stark shift: $D_Q = 4.1$D *deep electric potential is available*
- Transition strength: $d_{Q\text{-}C} = 1.0$ D *~100% transfer $C \rightleftarrows Q$ is feasible*
- Life time: $\tau > 62$ ms *lossless during the collimation*



Trajectory simulation



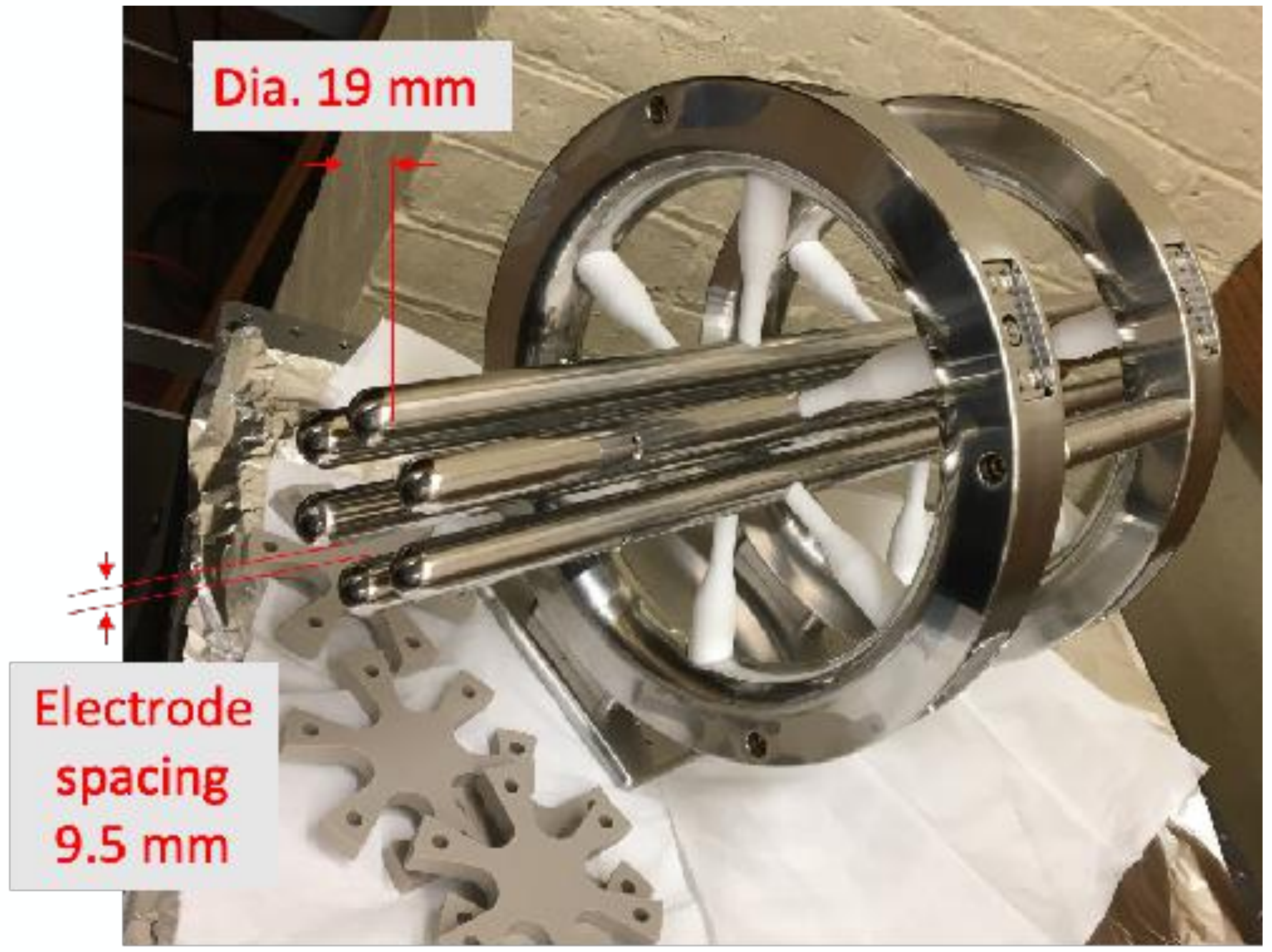
Xing Wu (Harvard/Chicago), DAMOP2021

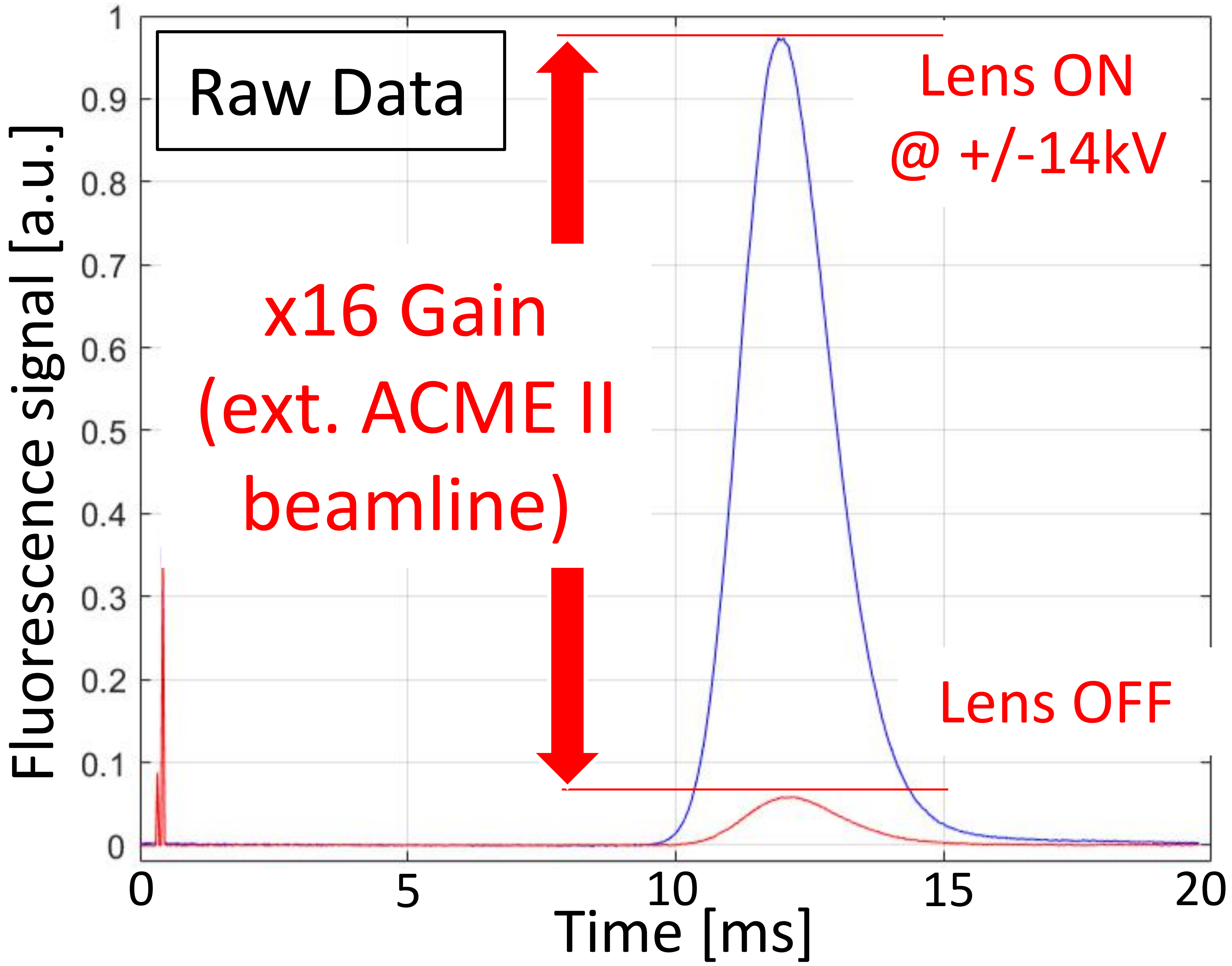
Electrostatic molecular lens

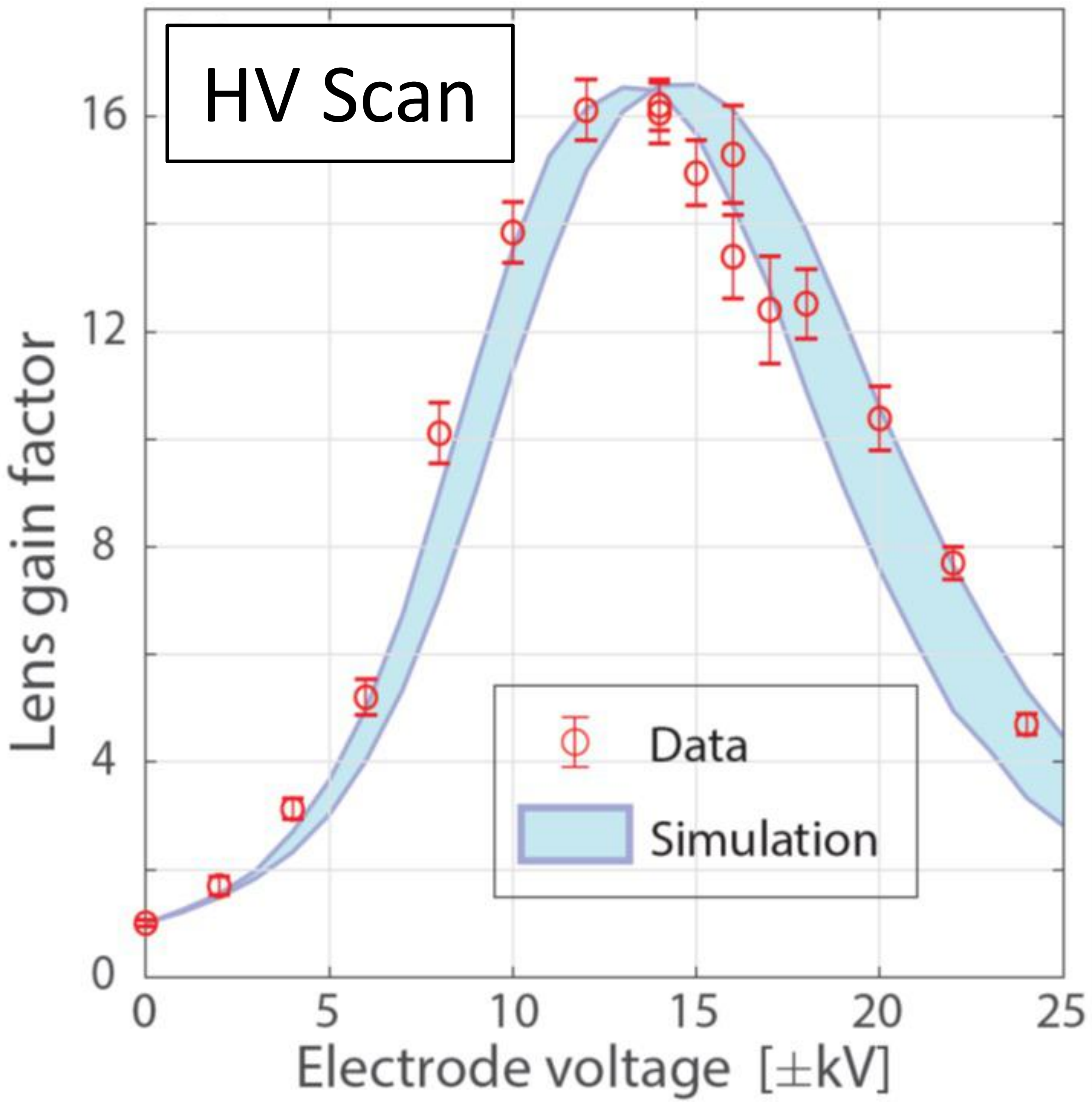
X. Wu et al., New J. Phys. **24** 073043 (2022).

×16 improvements has been demonstrated.

(consistent with expectations from the simulations)







Longer precession time : 1 → 5 ms

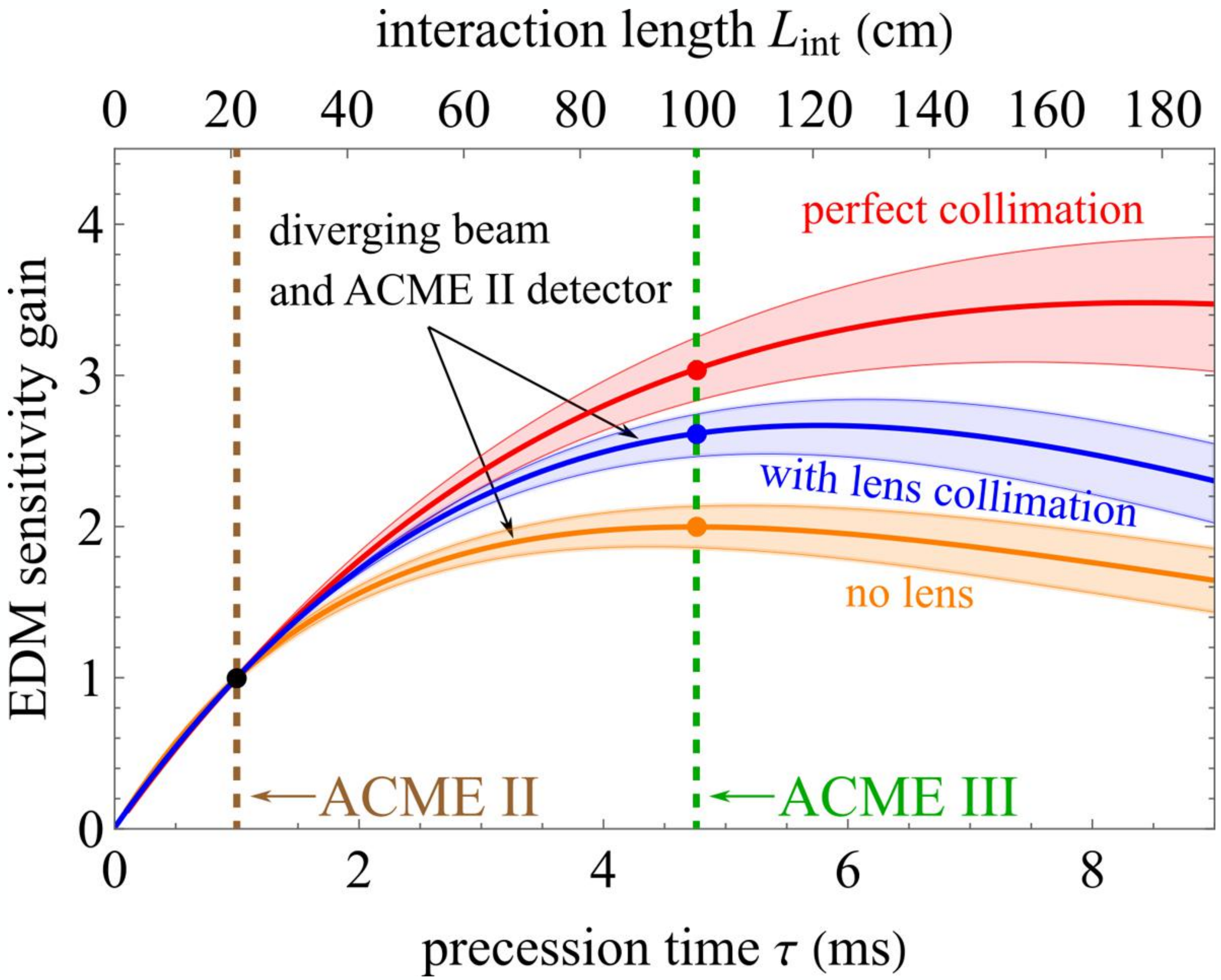
D. Ang et al., PRA **106**, 022808 (2022).

Possible precession time is limited by the lifetime of the H state τ_H

- Previous measurement : $\tau_H > 1.8$ ms → ACME II used τ=1 ms

  (A. Vutha et al., J. Phys. B 43 (2010) 074007.)

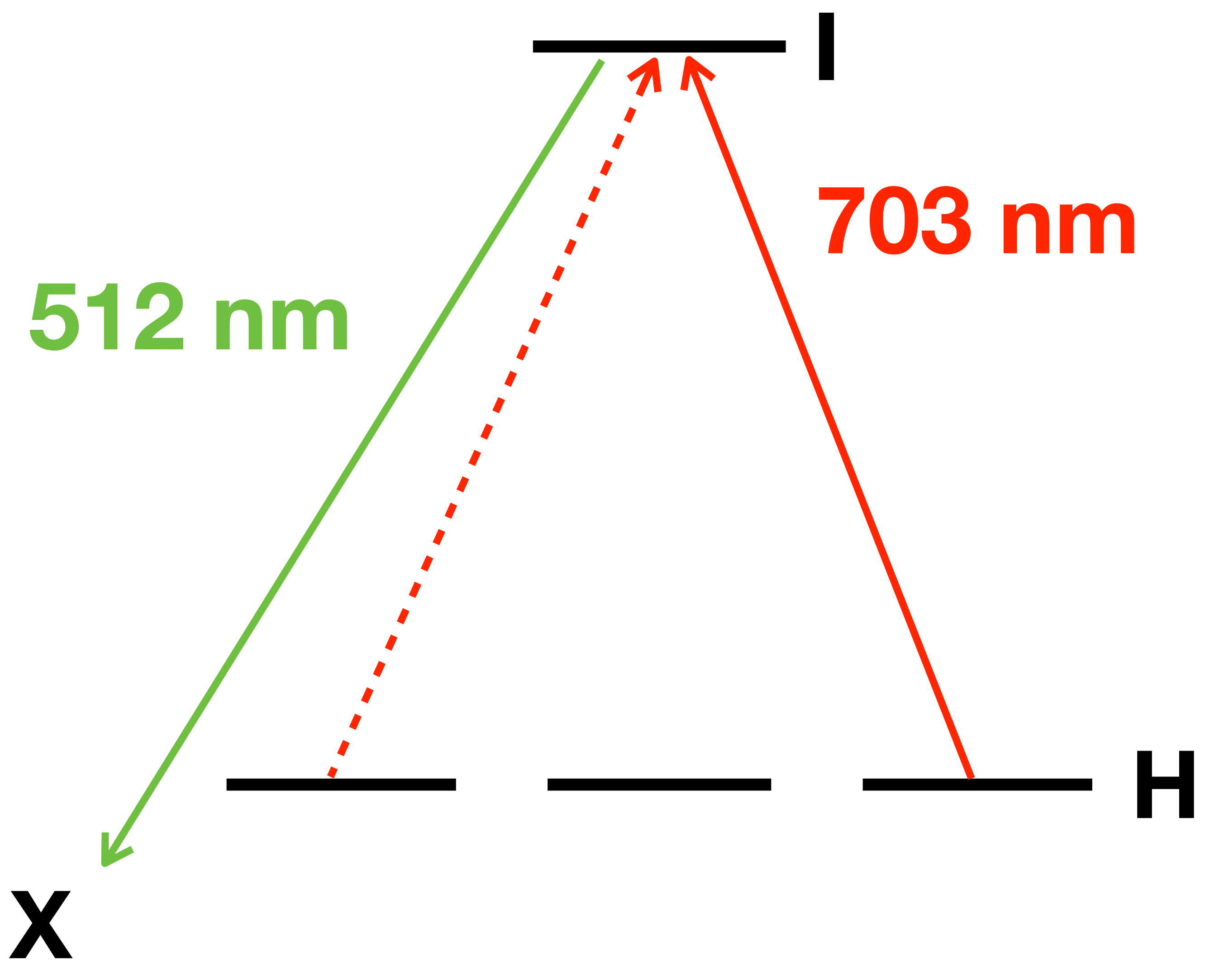
- Recent measurement : $\tau_H = 4.2$ ms → ACME III will use τ=5 ms

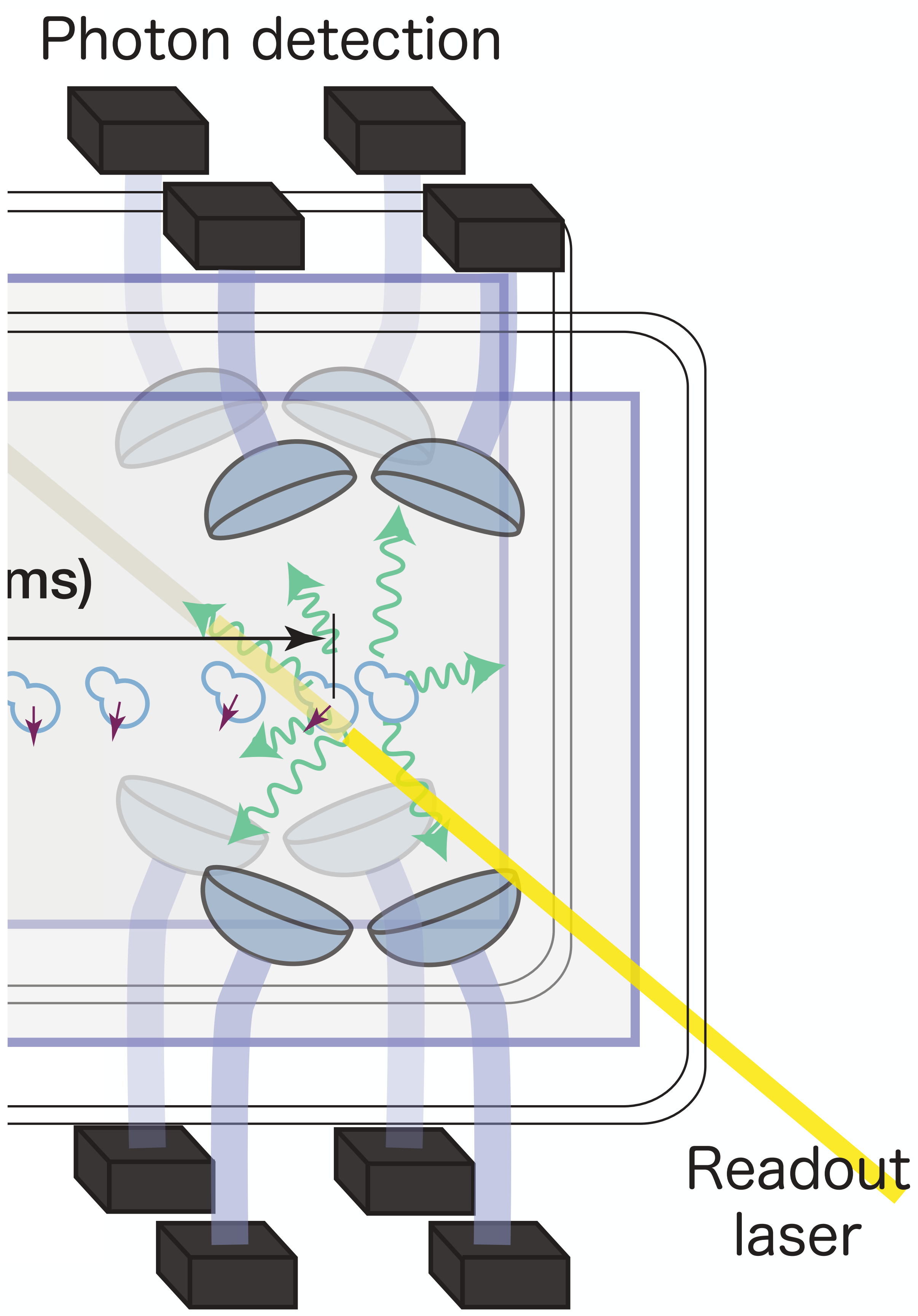


$$\Delta d_e \sim \frac{\hbar}{E_{\mathrm{eff}}\,\tau}\frac{1}{\sqrt{\dot{n}_{\mathrm{mol}}\,T}}\sqrt{\frac{F}{\varepsilon_{\mathrm{det}}}}$$

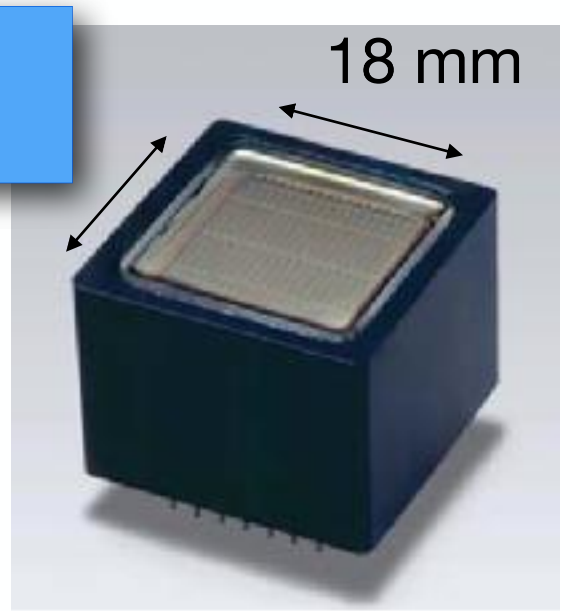
Photodetector upgrade : PMT → SiPM

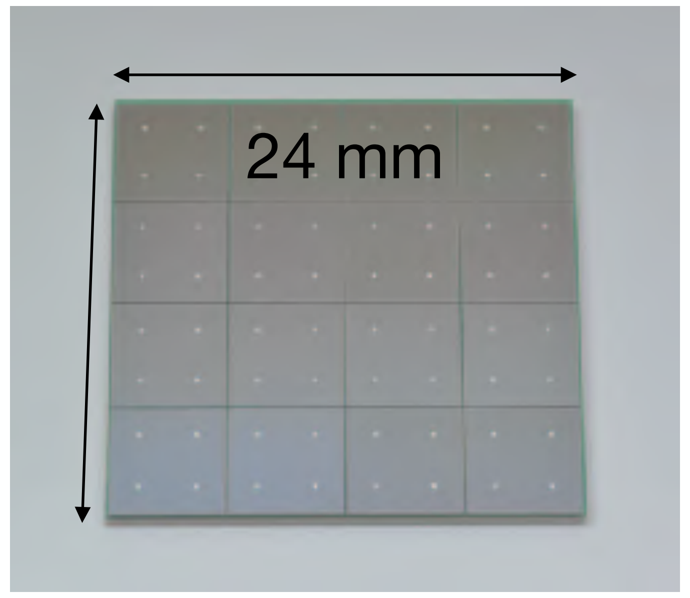
Final state readout





PMT vs. SiPM





	ACME II PMT	Advanced ACME SiPM	
Part No.	R7600U-300	S13361-6075NE-04	
Sensitive area	18×18 mm^2	24×24 mm^2 (16 ch.)	*pros*
Q.E. @ 512 nm	**~25%**	**~45%**	
Excess noise *F*	~1.2	~1.2 (depend on CT & AP)	
Q.E. @ 703 nm	~0.6%	~ 20%	
Dark count @ 25°C	~ 3 kcps	~ 2 Mcps/ch	*cons*
Capacitance	few pF	1.4 nF	

Changing from PMTs to SiPMs will increase the PDE by a factor of ~2 and sensitive area as well.

SiPM module

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

Suppress DCR

Cooling (-20°C), Vacuum (<10 Pa)

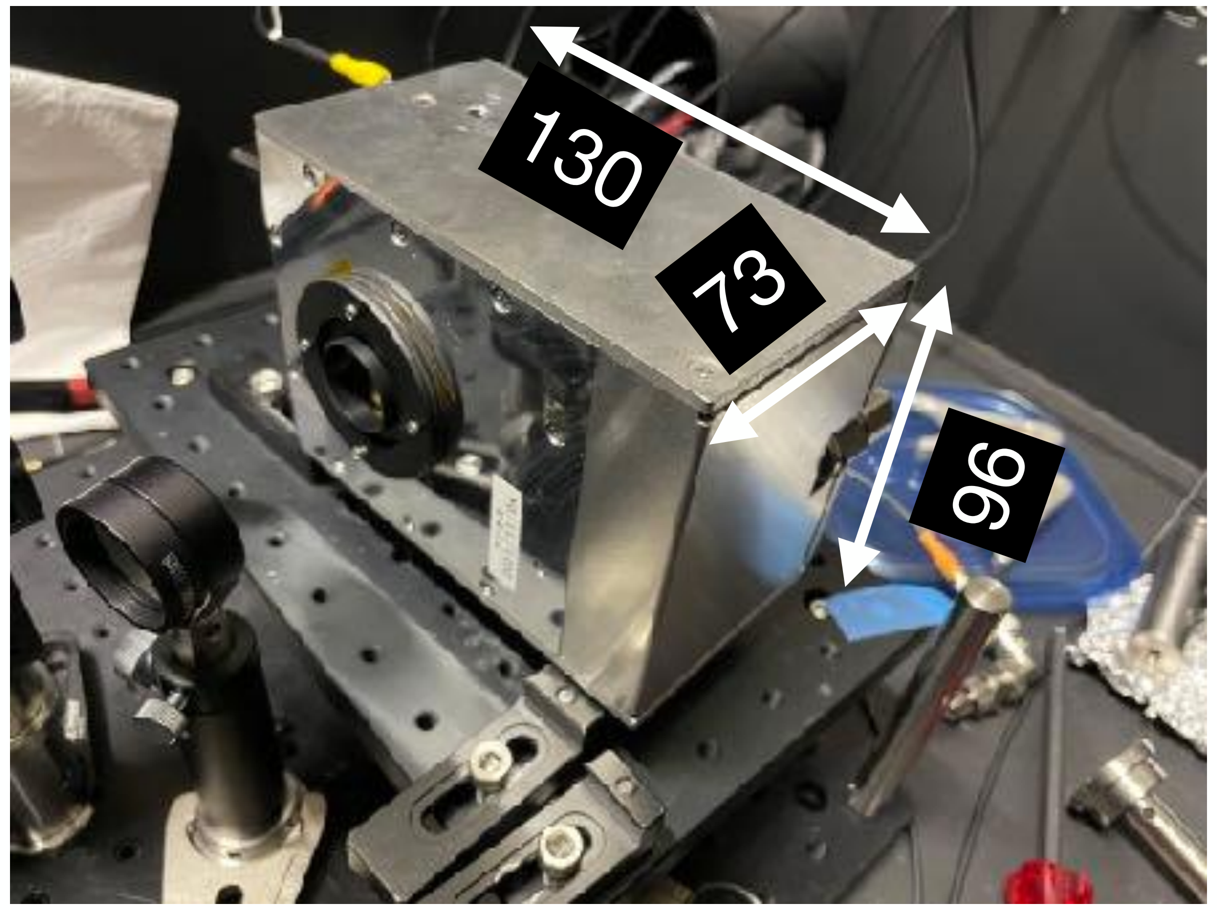
Suppress Optical Crosstalk and Stray light

Optimized triple filtering scheme

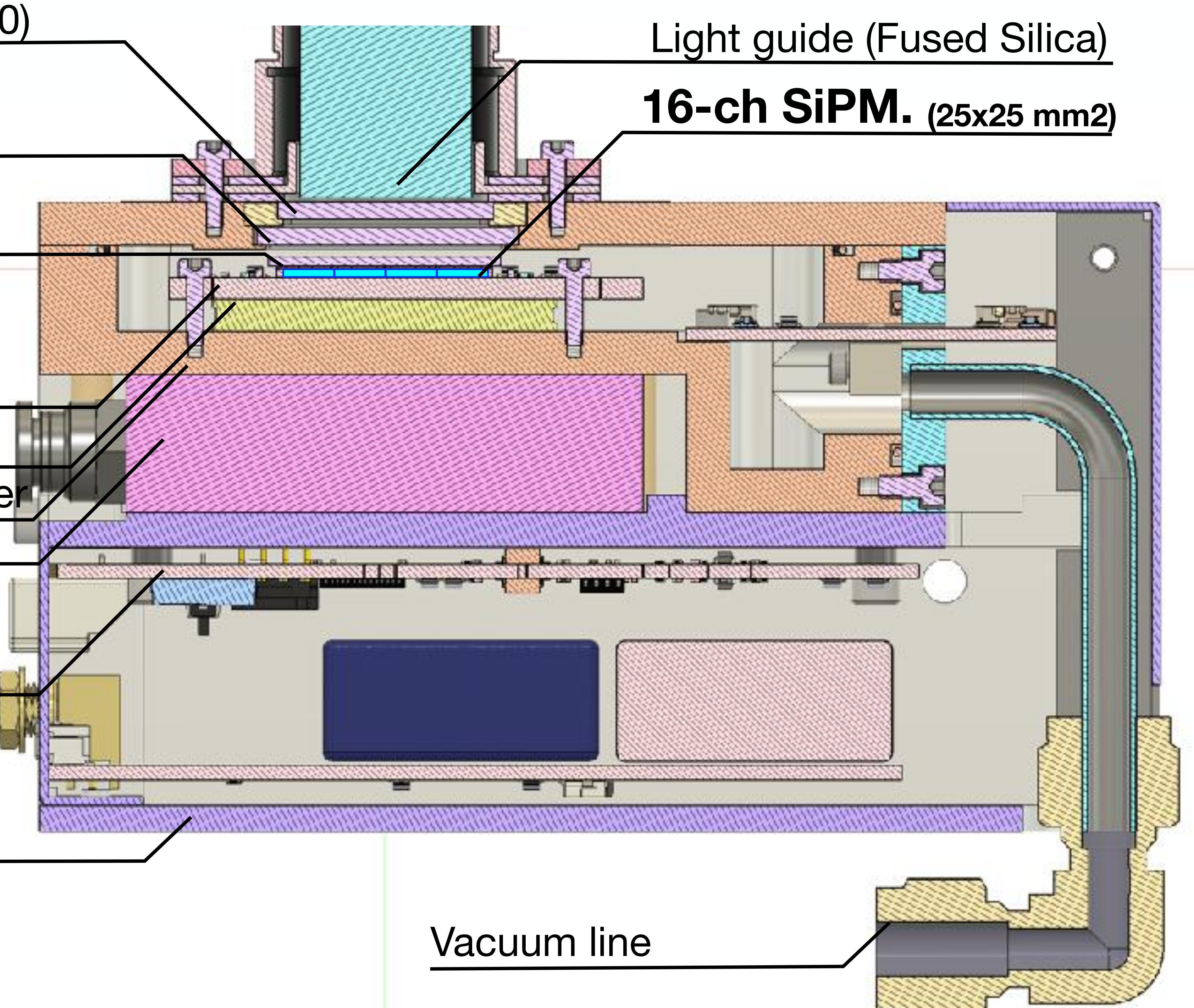
Dedicated electronics

Molecular pulse duration	~ 4 ms
Readout laser pulse duration	~ 1 us
I state lifetime	115 ns

16ch analog summing



Cut-out view



BPF (Semrock FF01-520/70)

BPF, window
(Schott BG39)

BPF, OCT suppressor
(Schott BG40)

Aluminum PCB

TEC element

Aluminum vacuum chamber

Water-cooled heatsink

Preamplifier PCB

Electronics box

Light guide (Fused Silica)

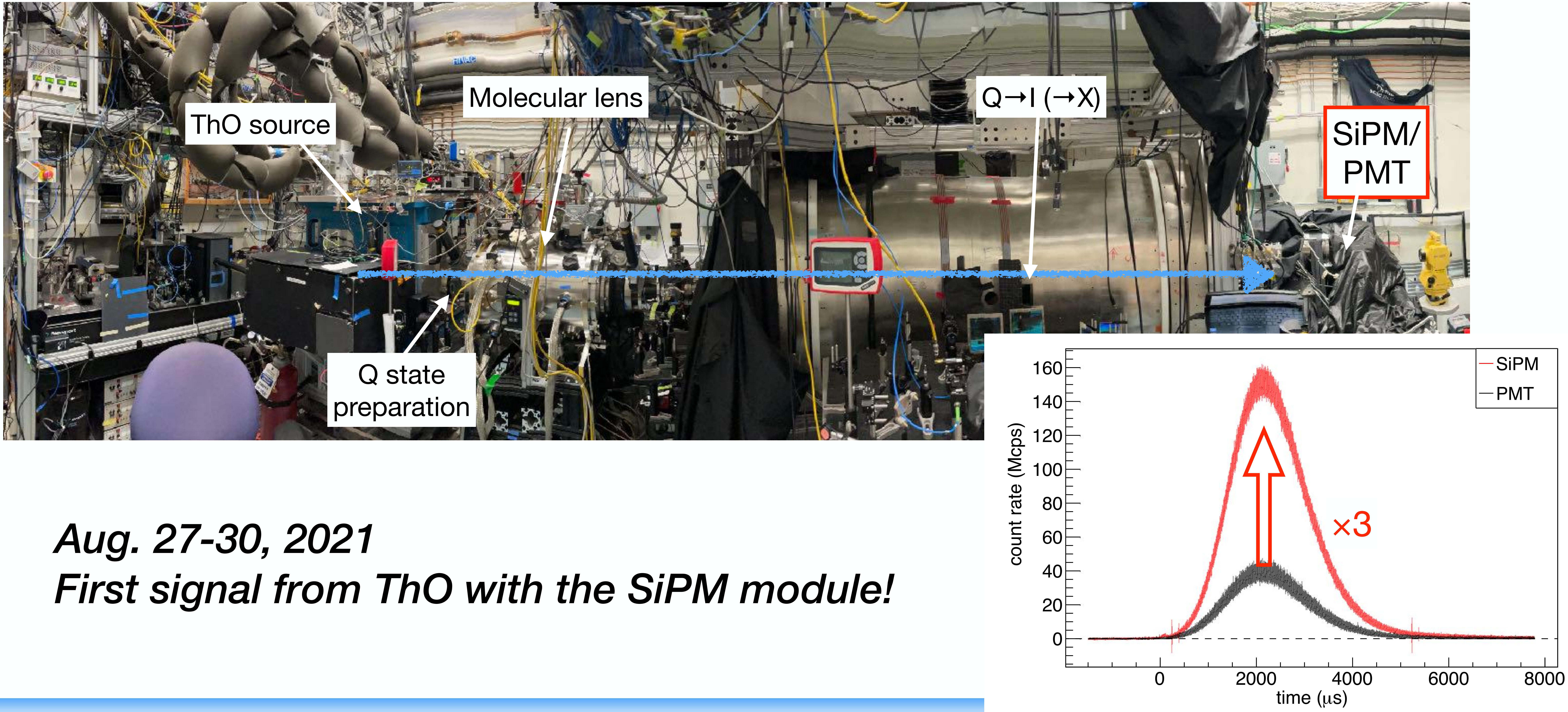
16-ch SiPM. (25x25 mm2)

Vacuum line

Beam test (2021 August)

A. Hiramoto et al., Nucl. Instrum. Meth. A, **1045** (2023) 167513.
T. Masuda *et al*., Opt. Express **31** 1943 (2023).

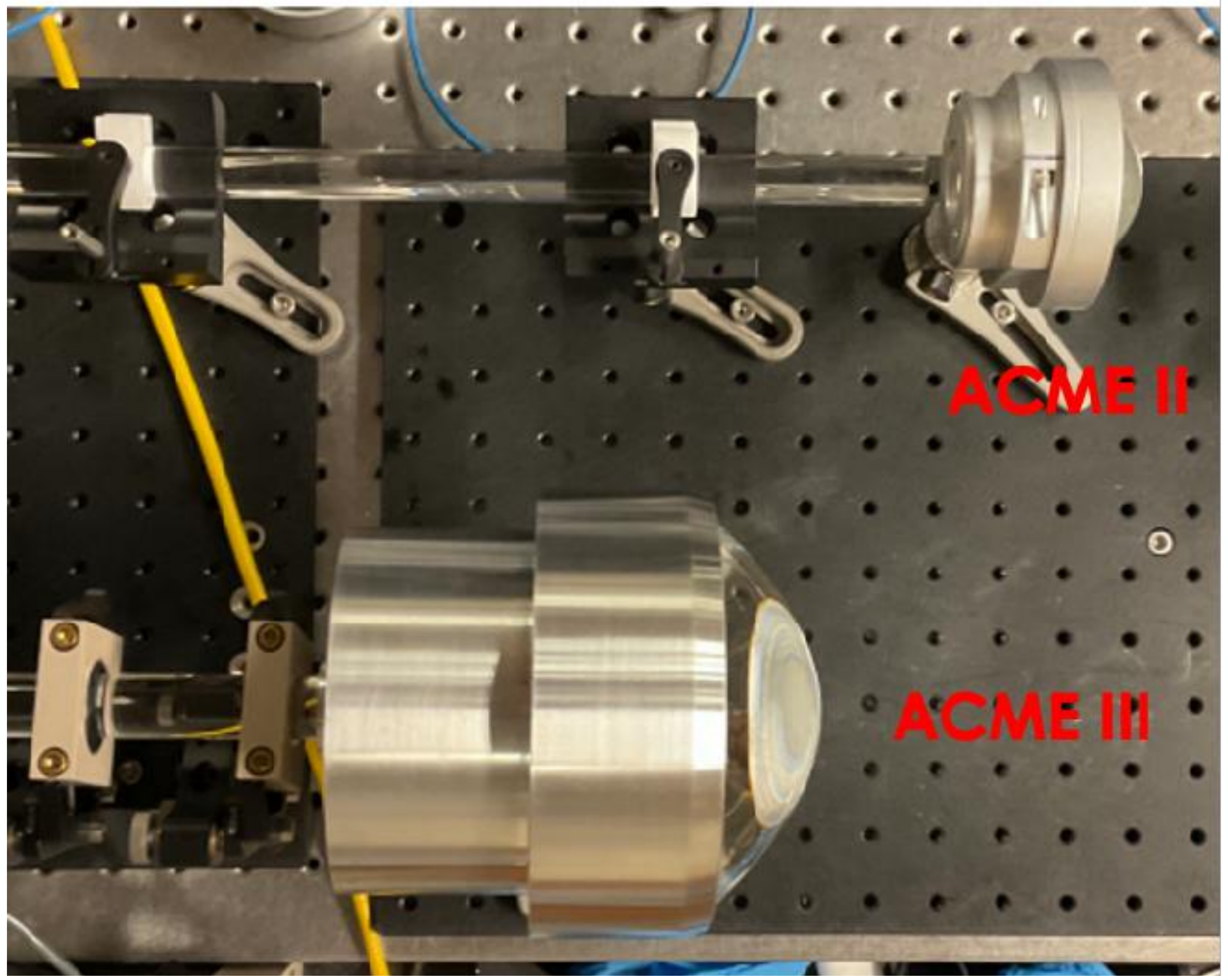
ThO fluorescence detection test @ ACME II beam line

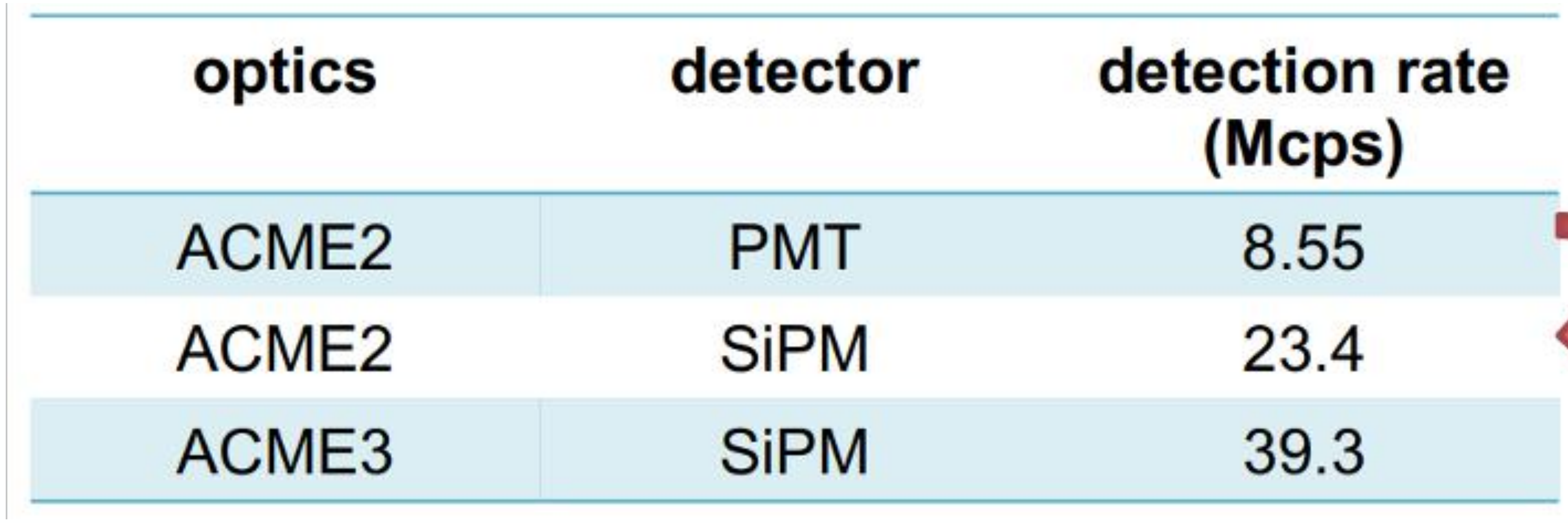


Aug. 27-30, 2021
First signal from ThO with the SiPM module!

Collection optics

Bigger lens increases the collection efficiency: 5% → 8%





optics	detector	detection rate (Mcps)
ACME2	PMT	8.55
ACME2	SiPM	23.4
ACME3	SiPM	39.3

×2.74: detector effect

×1.68: optics effect

Summary of the statistics improvements

Improvement	Signal gain	EDM sensitivity gain	Reference
New beam source	1.5	1.2	
Electrostatic lens	12	3.5	X. Wu *et al*., New J. Phys. **22**, 023013 (2020) X. Wu *et al*., New J. Phys. **24**, 073043 (2022)
Longer precession time	0.3	2.6	D.G. Ang *et al*., Phys. Rev. A **106**, 022808 (2022)
Detector upgrade	2.7	1.6	T. Masuda *et al*., Opt. Exp. **29**, 16914 (2021) T. Masuda, A. Hiramoto *et al*., Opt. Exp. **31**, 1943 (2023)
Collection optics	1.7	1.3	
Timing jitter reduction	1	1.7	C.D. Panda *et al*., J. Pays. B **52**, 235033 (2019)
Total	**25**	**39**	

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

ACME III anticipated statistical sensitivity

$$\delta d_{\mathrm{e}} \sim 3 \times 10^{-31}\ e \cdot \mathrm{cm}/\sqrt{\mathrm{day}}$$

Systematics improvements in ACME III

Parameter	Shift	Uncertainty
$\partial\mathcal{B}_z/\partial z$ and $\partial\mathcal{B}_z/\partial y$	7	59
$\omega_{\mathrm{ST}}^{\mathcal{N}\mathcal{E}}$ (via $\theta_{\mathrm{ST}}^{\mathrm{H-C}}$)	0	1
$P_{\mathrm{ref}}^{\mathcal{N}\mathcal{E}}$	–	109
$\mathcal{E}^{\mathrm{nr}}$	-56	140
$\lvert\mathcal{C}\rvert^{\mathcal{N}\mathcal{E}}$ and $\lvert\mathcal{C}\rvert^{\mathcal{N}\mathcal{E}\mathcal{B}}$	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, $\mathit{\Delta}^{\mathcal{N}}$	–	48
Total systematic	29	310
Statistical uncertainty		373
Total uncertainty		486

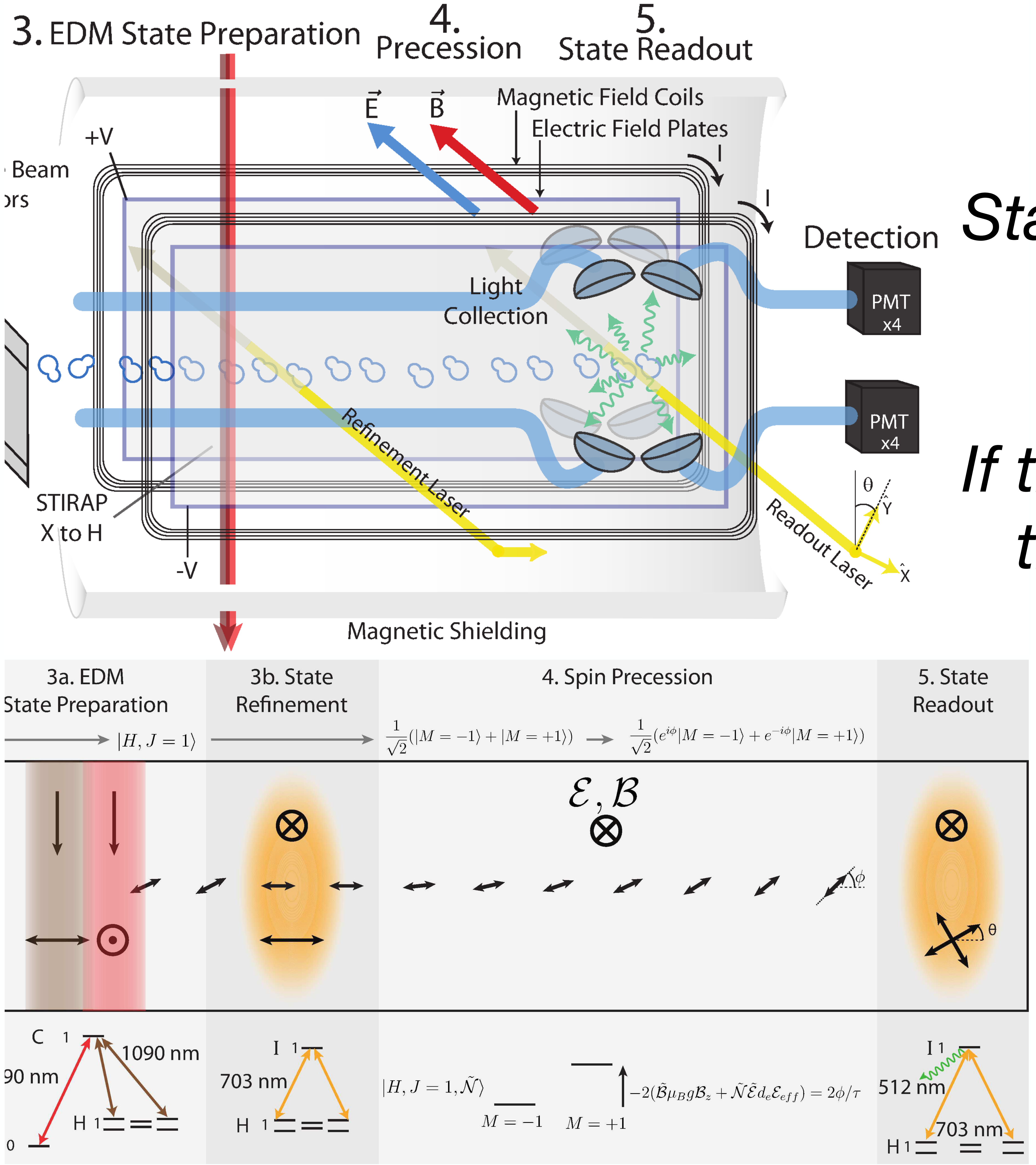
Values are shown in μrad s^{-1}. All uncertainties are added in quadrature. For $\mathcal{E}_{\mathrm{eff}} = 78$ GV cm^{-1}, $d_e = 10^{-30}e$ cm corresponds to $|\omega^{\mathcal{N}\mathcal{E}}| = \mathcal{E}_{\mathrm{eff}} d_e/\hbar = 119$ μrad s^{-1}.

Imperfection of laser polarization

Imperfection of the magnetic field

ACME Collaboration, Nature **562** (2018) 355.

Ellipticity gradients in the laser polarization



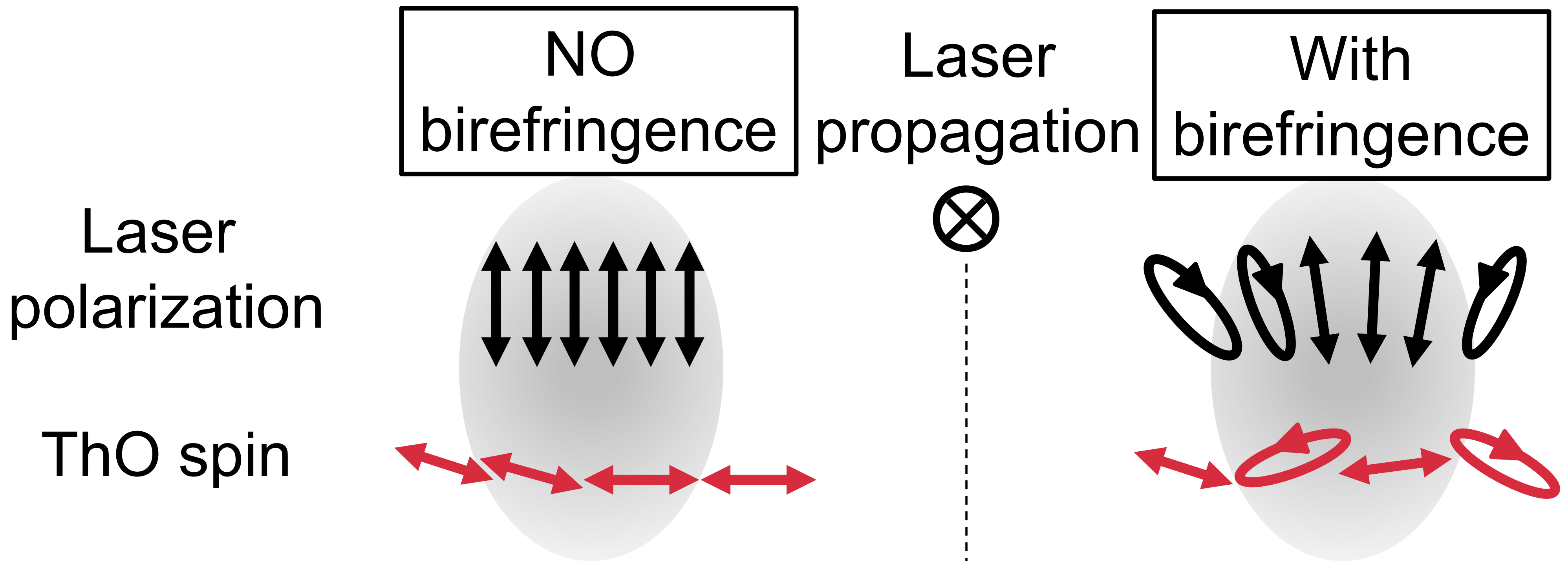
State preparation and readout are depending on the ***laser polarization.***

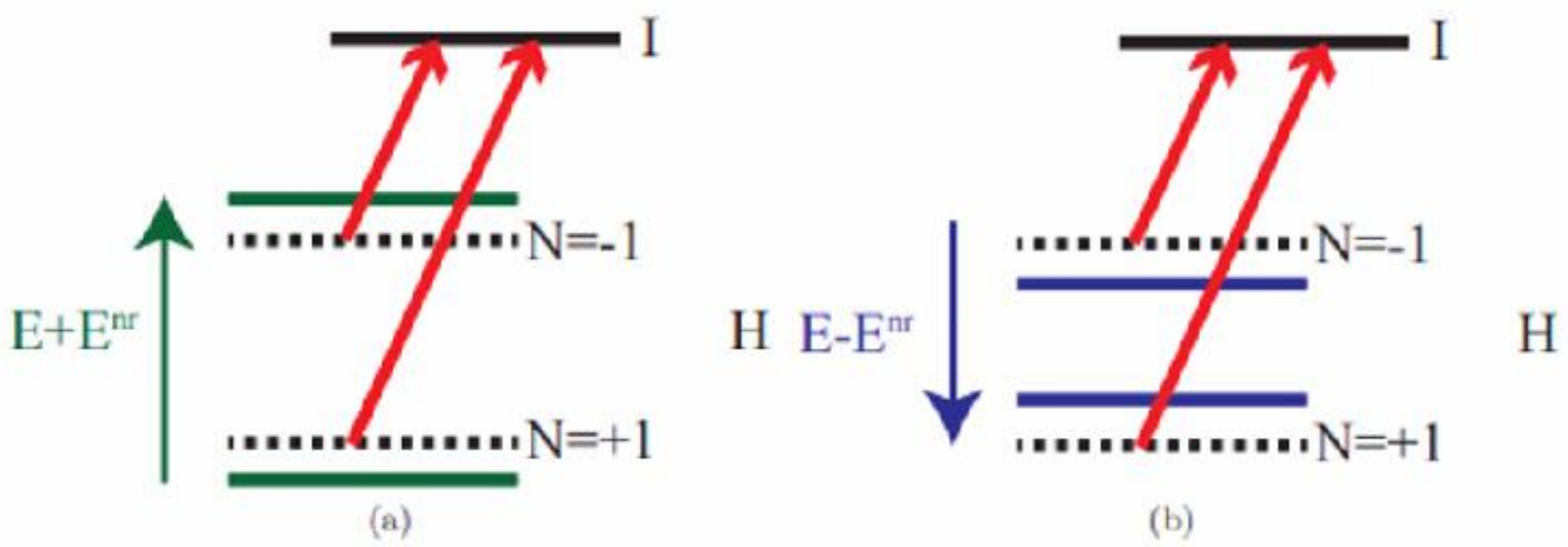
↓

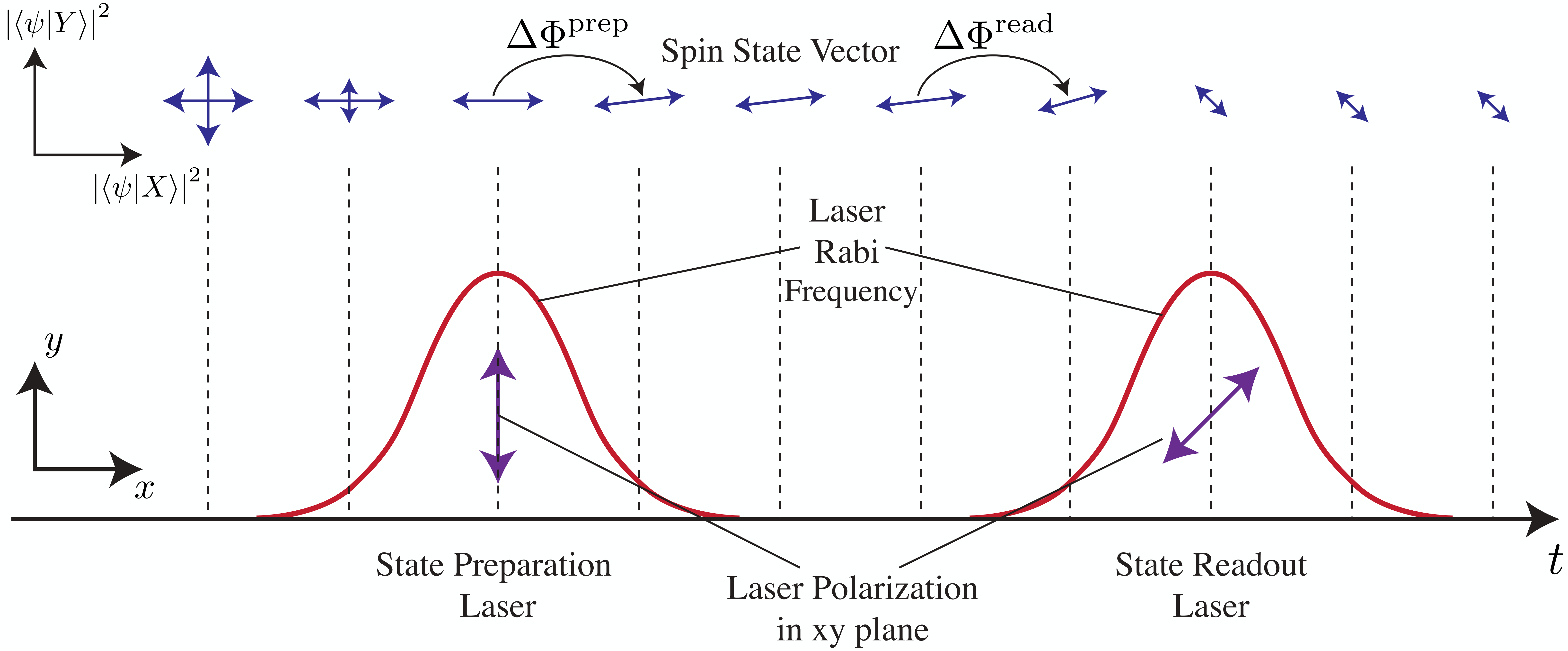
If the laser polarization is not perfect, the spin precession could be disturbed.

Cause of systematics

False EDM : Ellipticity gradient (laser imperfection)
+ AC-Stark shift gradient (E-field imperfection)







Ellipticity gradient due to glass

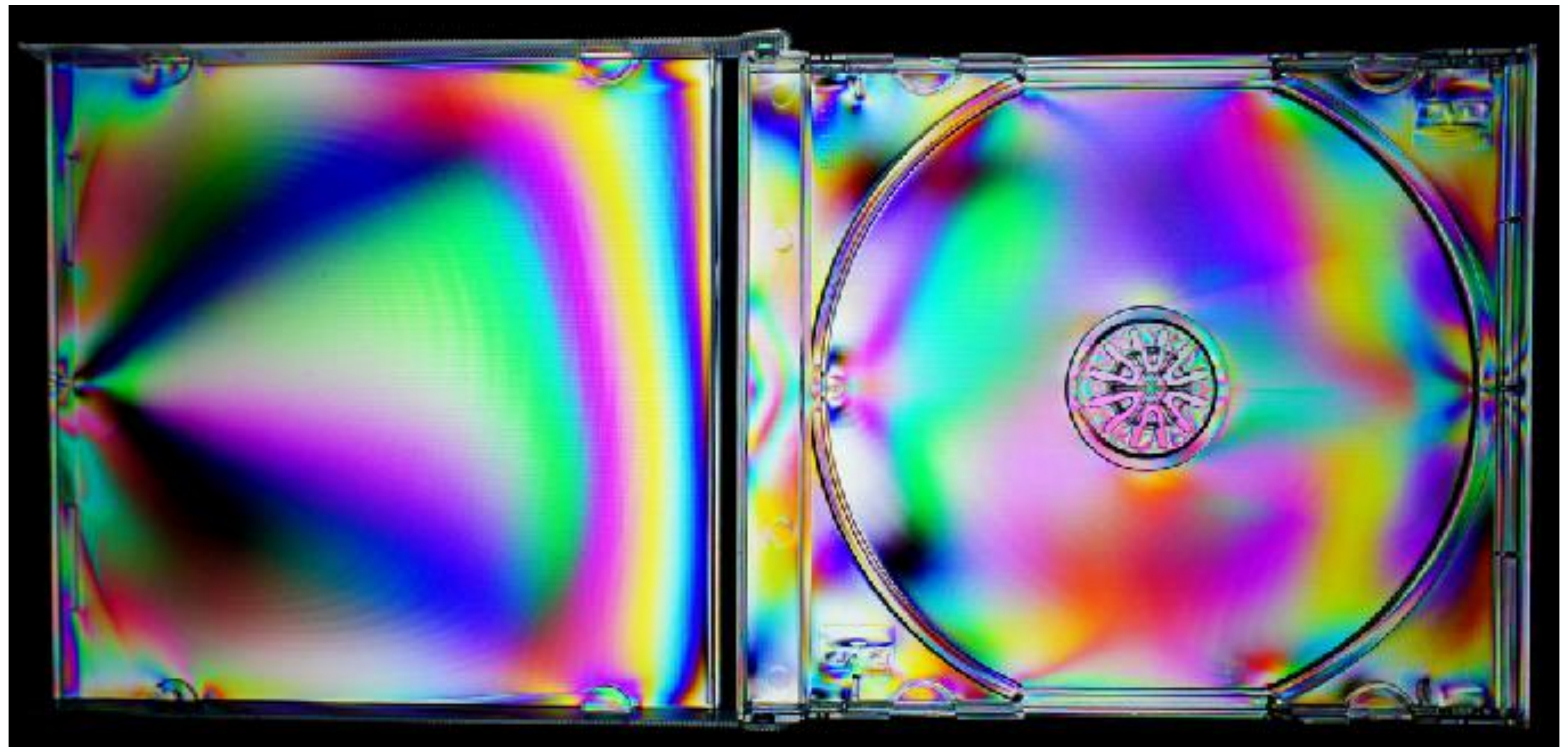
Laser polarization is varying
due to birefringence gradient of the optical components along the laser pass.

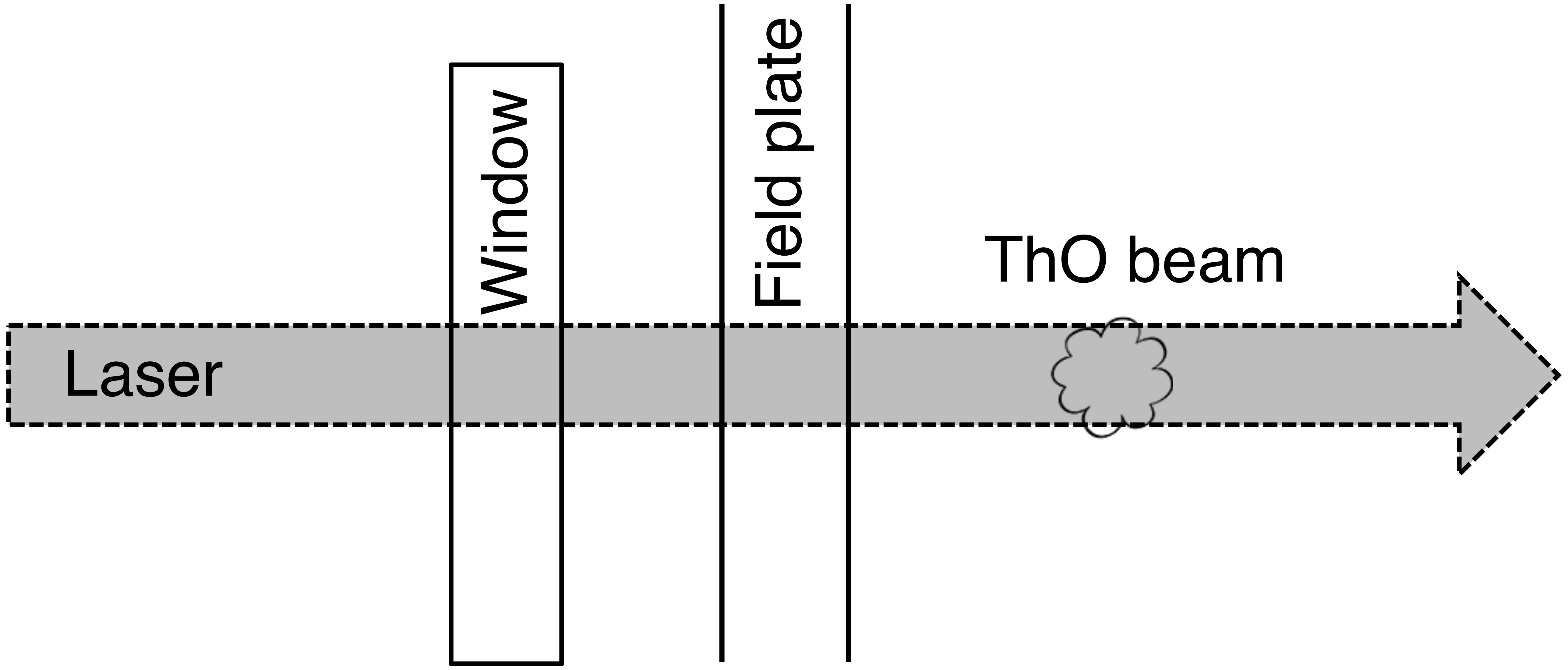
Birefringence Gradients in ***Vacuum window*** *&* ***Field plate****:*

ACME II. 0.1%/mm
ACME III. 0.01%/mm

mainly caused by stress

wikipedia



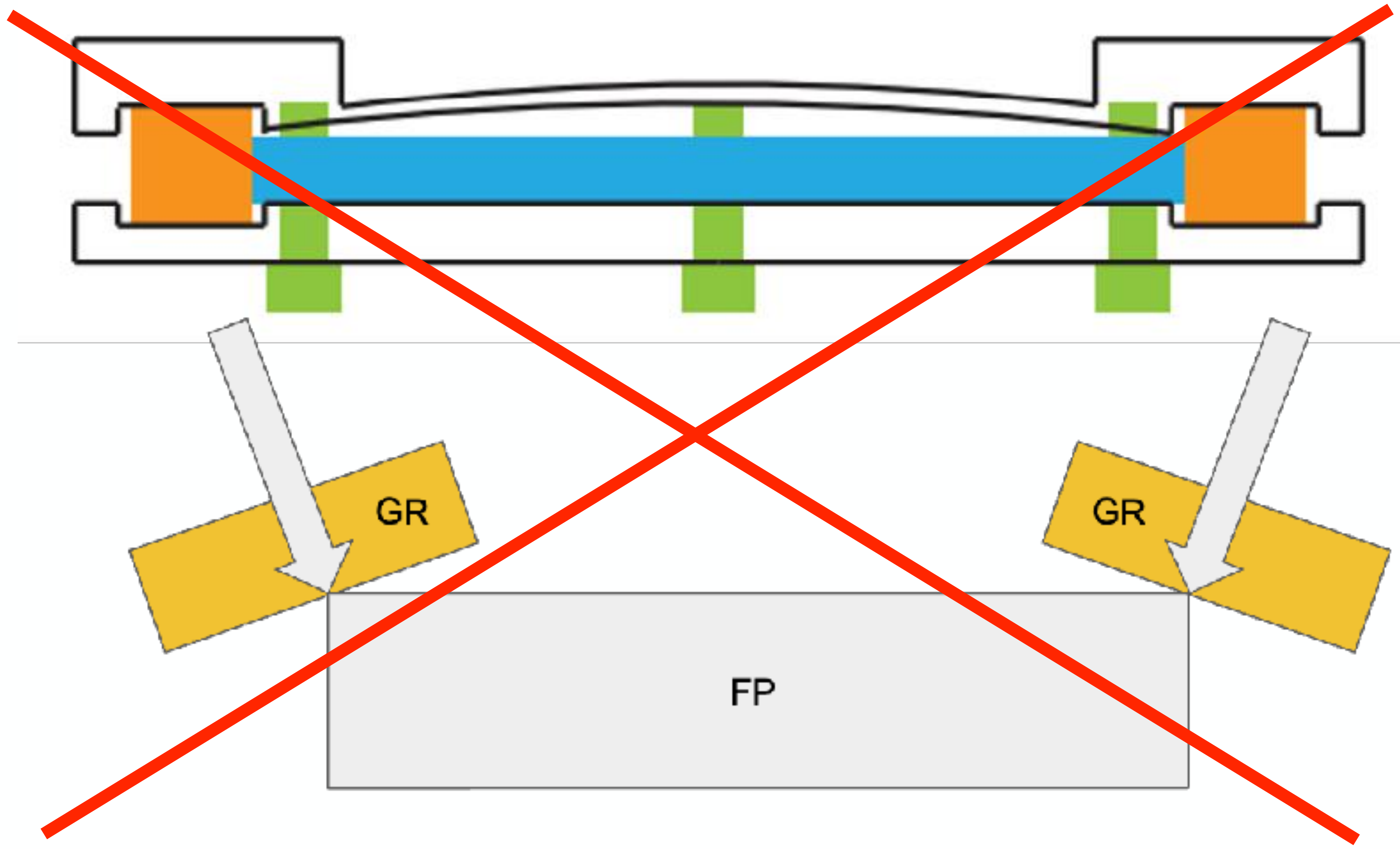


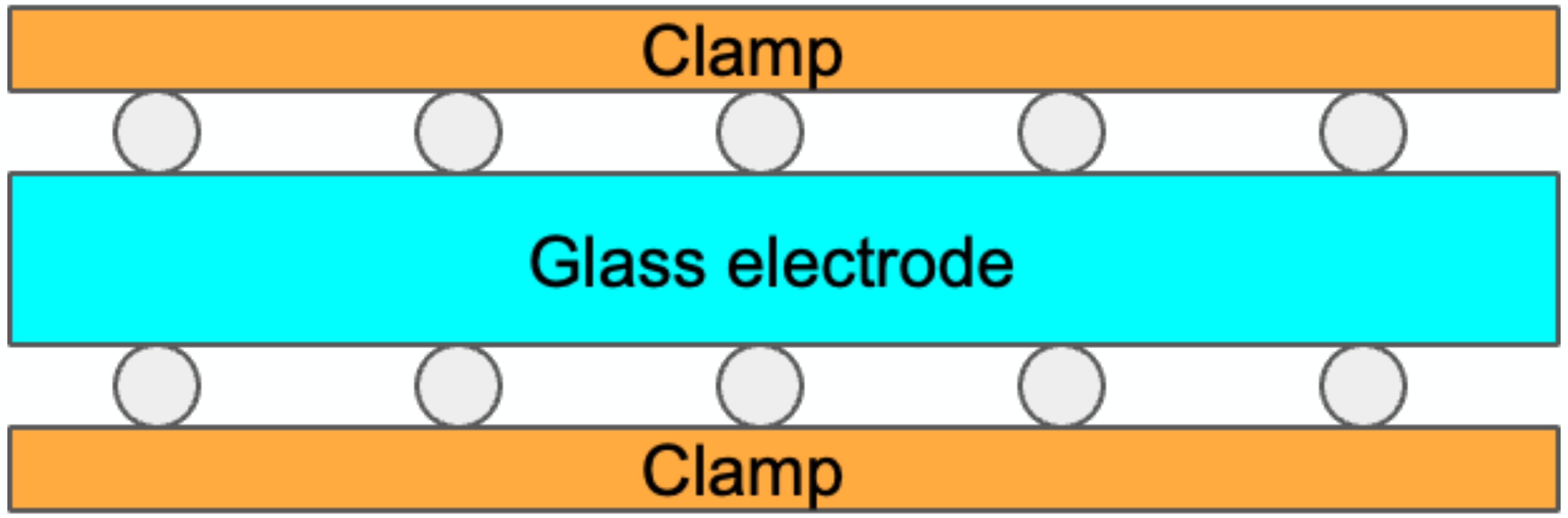
Field plate

Birefringence gradients in ACME II field plates were dominated by tangential **clamping stress**.

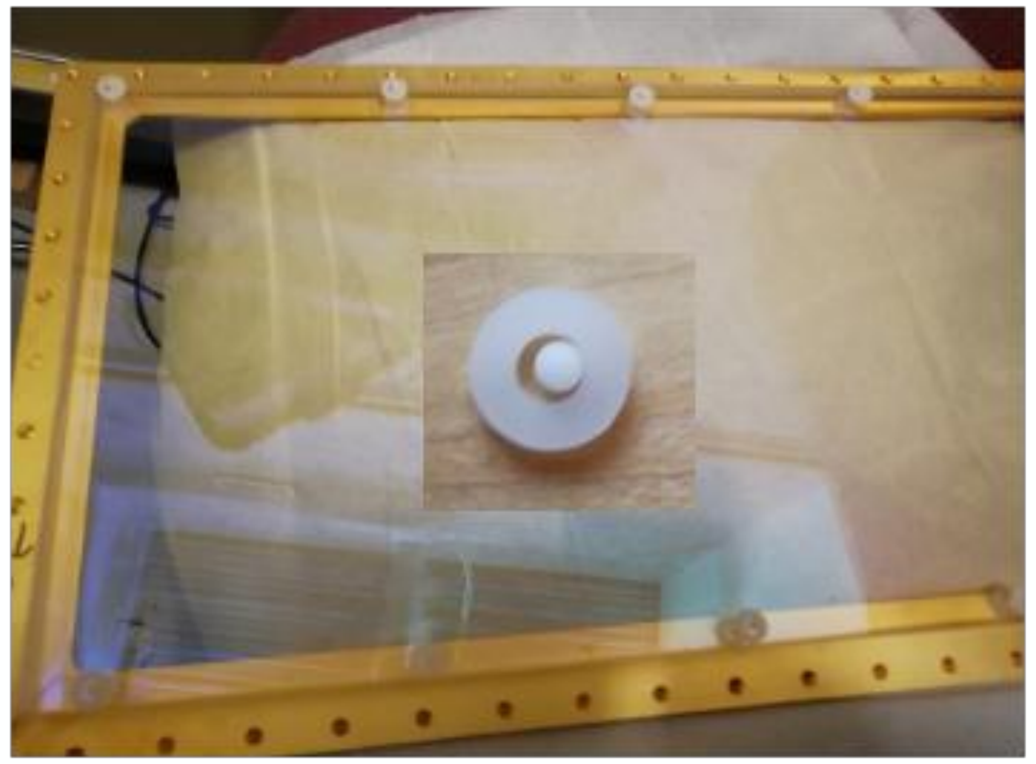
↓

Stress-free mounting has been designed.





Birefringence free mounting scheme



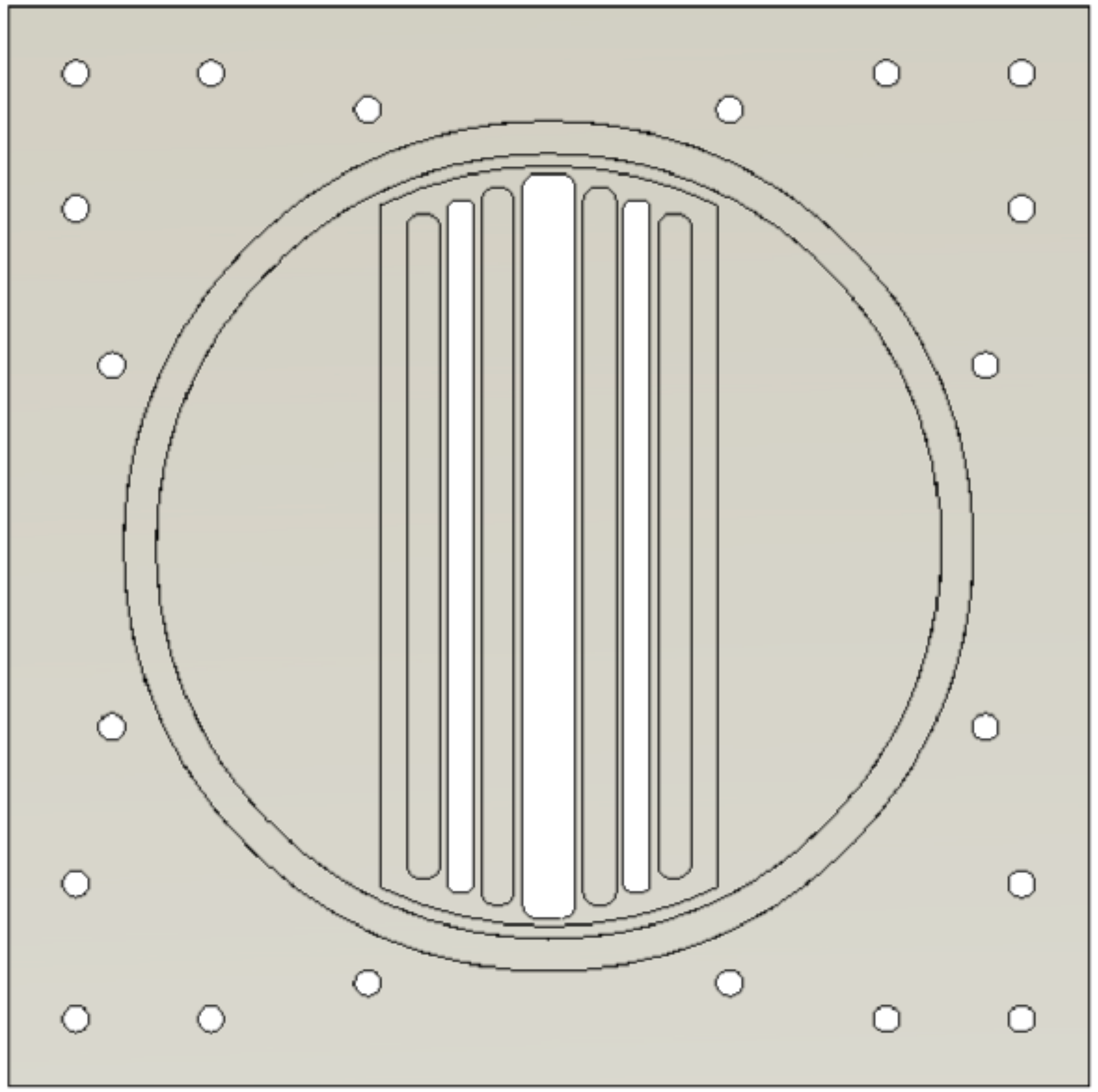
Proof of principle clamping modification on ACME II

clamping test

Vacuum window

Vacuum window is suffered huge stress due to atmospheric pressure.
→ Use ***ultra-low stress-optic glass*** as window material
& ***Thin slit*** vacuum opening to minimize vacuum stress

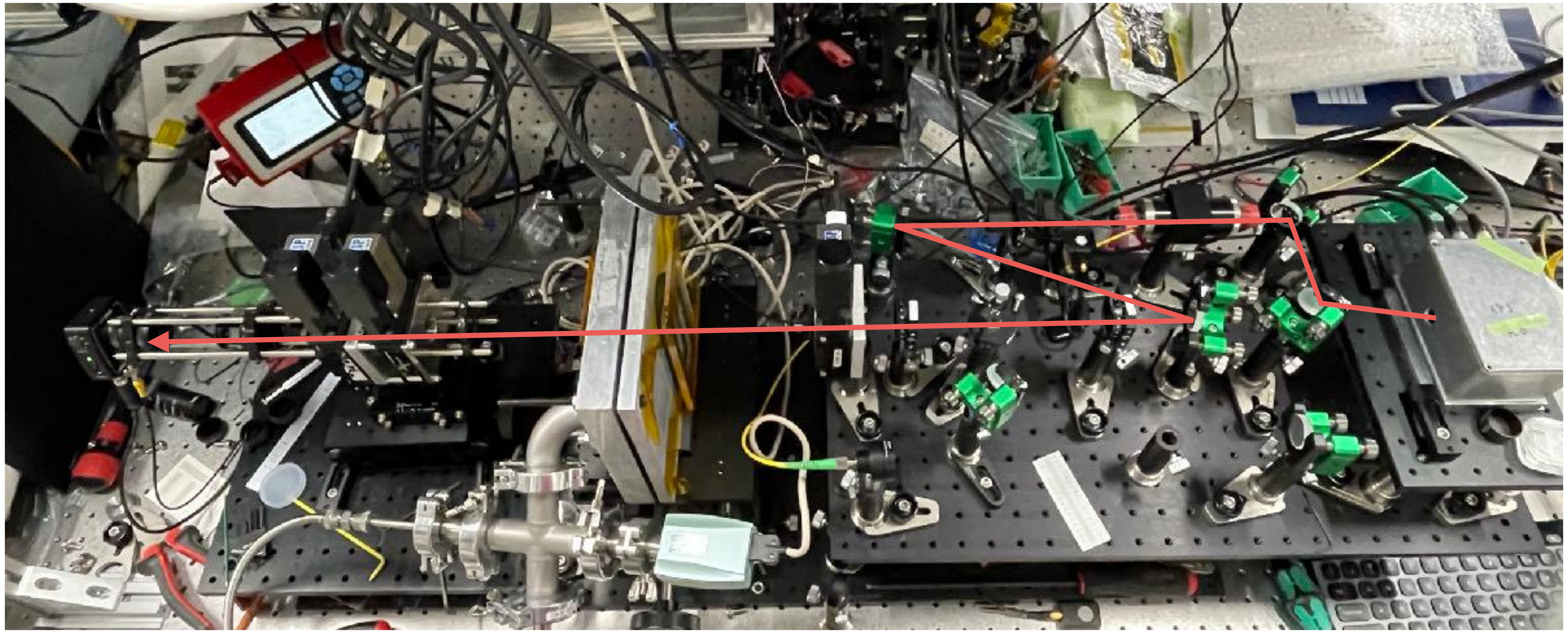
Glass	Stress-optical coeff. (10^{-3} /GPa)
Borofloat	4.0
N-BK7	2.77
Corning 7980 (Fused silica)	3.5
Shott SF57HTultra	**0.07**

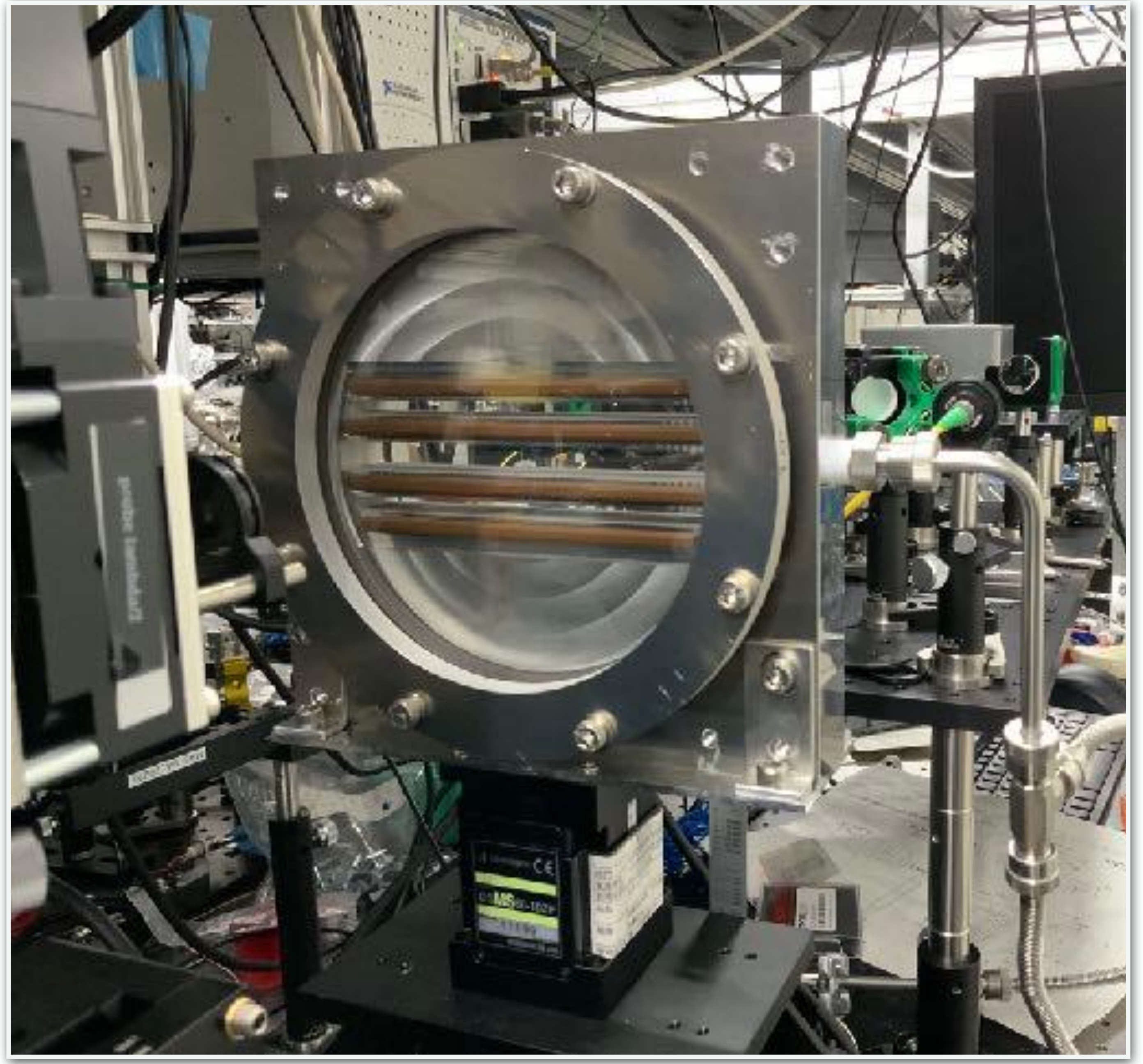


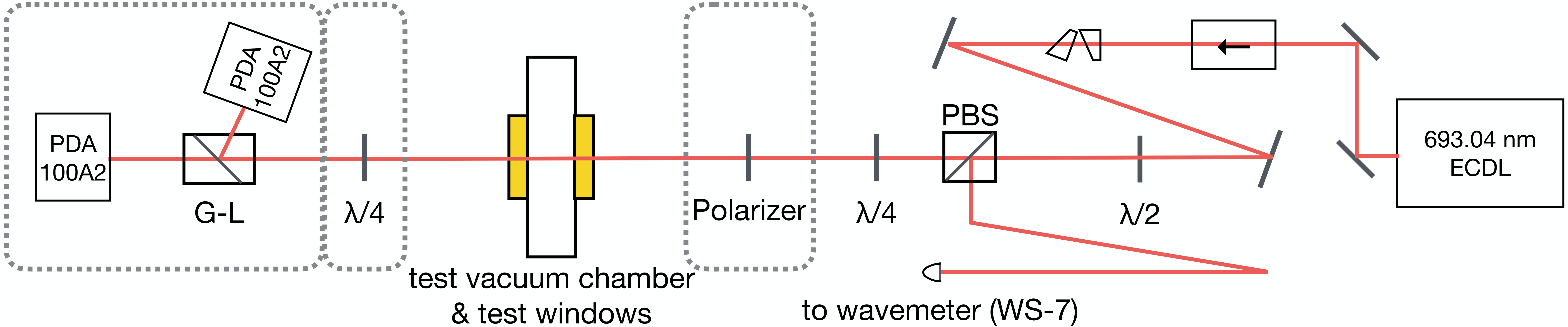
Birefringence measurement @ Okayama

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

Evaluation is on-going w/ a dedicated polarimeter.

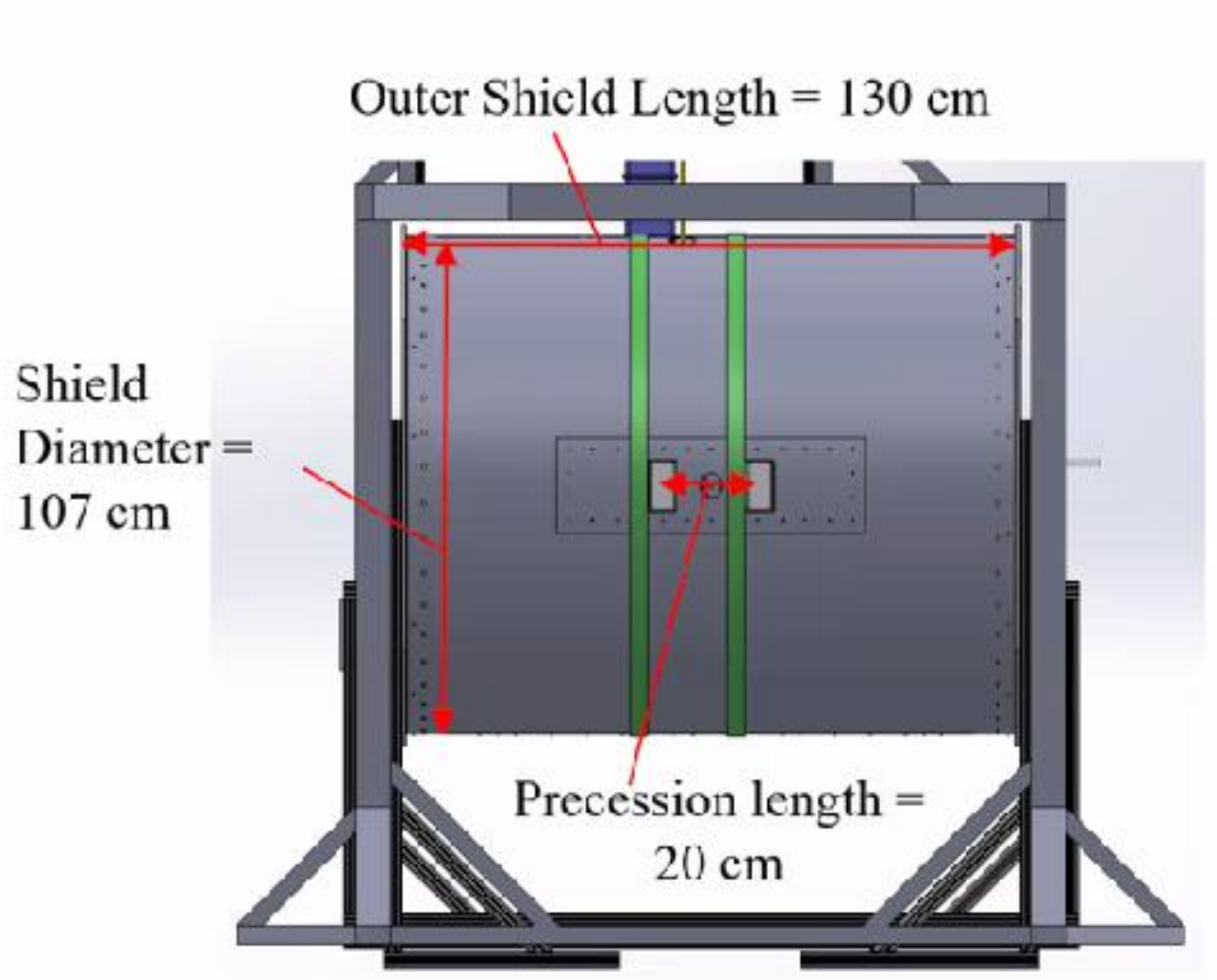


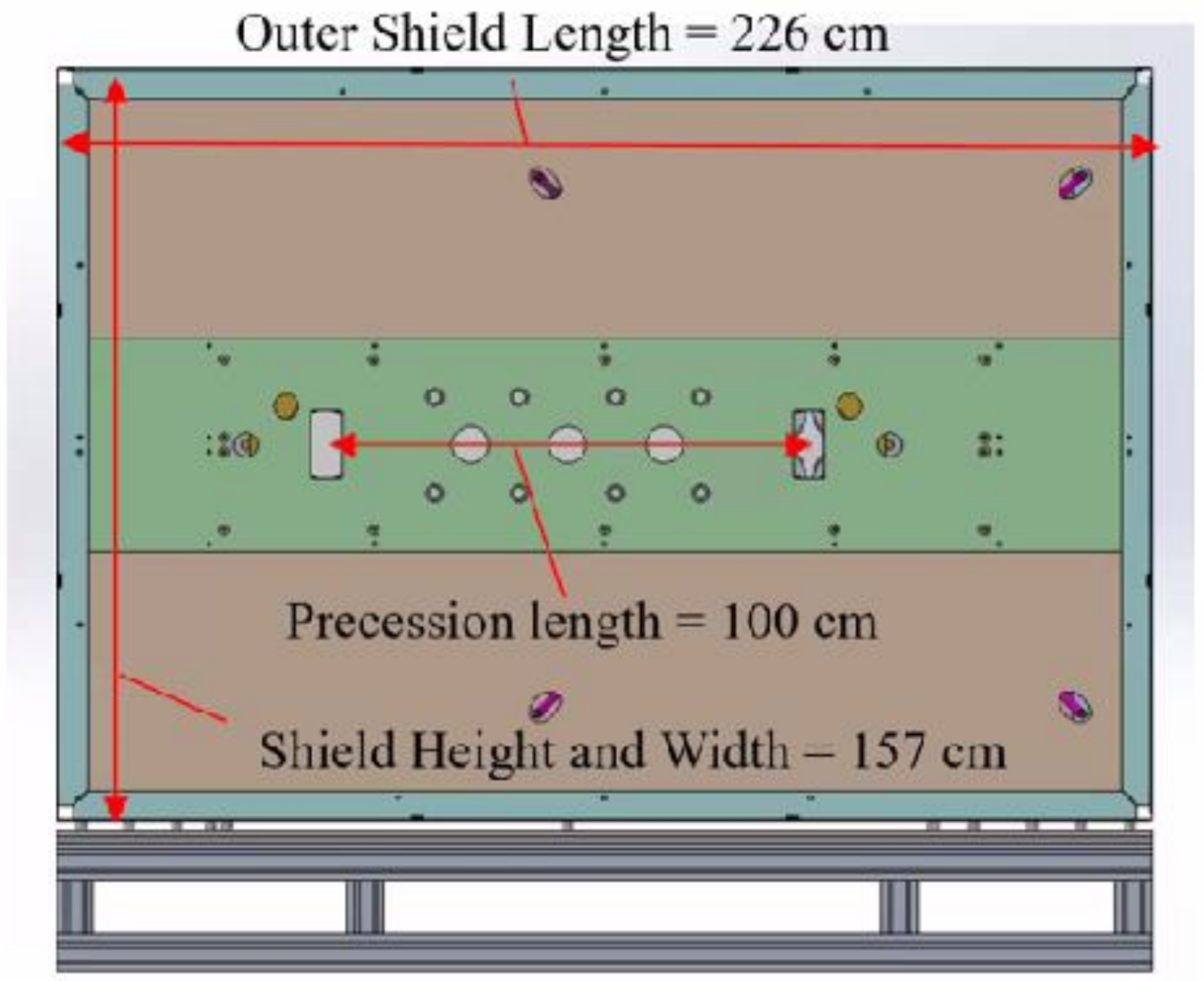




magnetic field

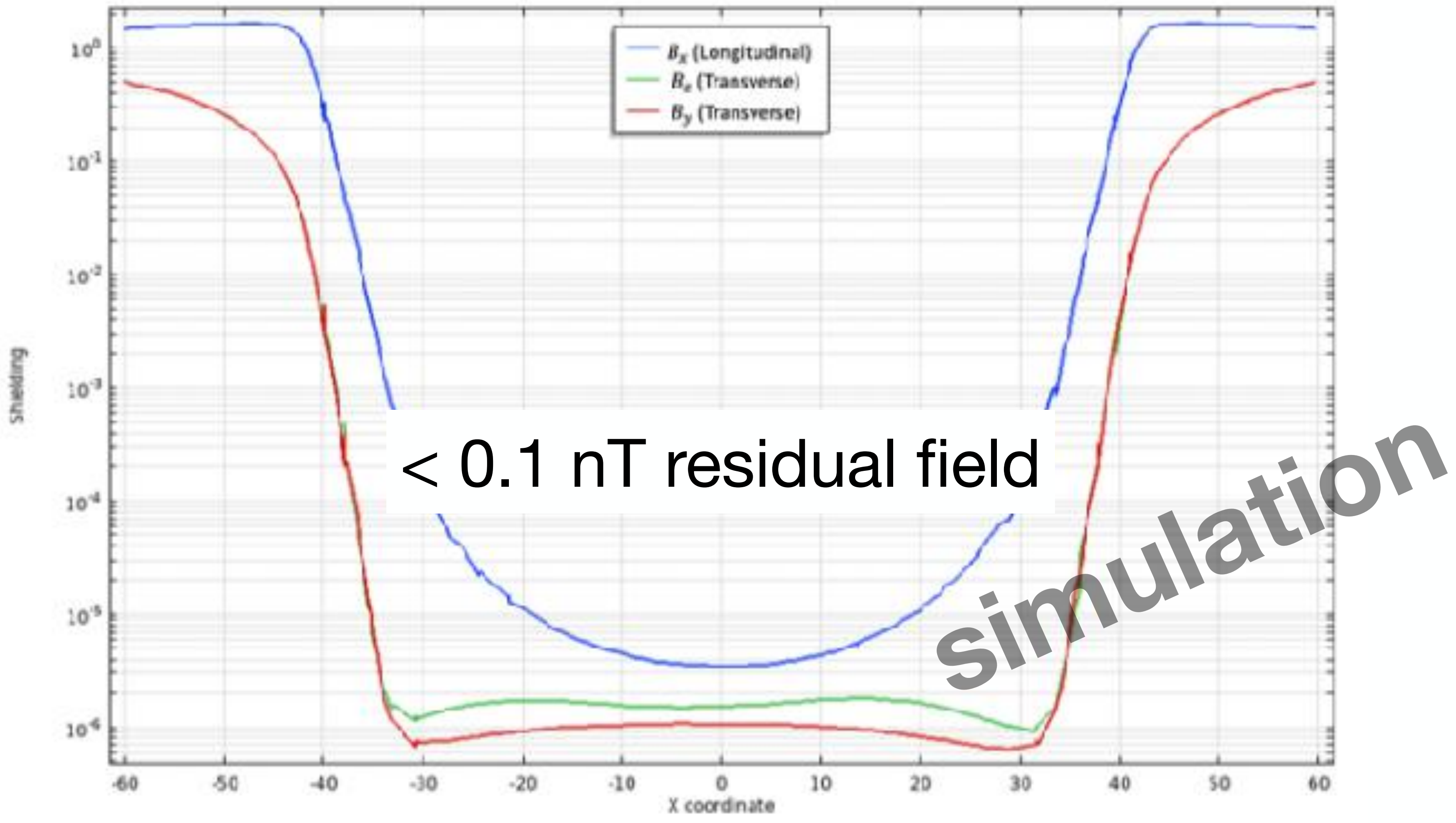
- Enlarged magnetic shield
- Applied magnetic field ~10 nT
- Required residual field
  & field gradient
  < 0.1 nT, < 0.1 nT/cm



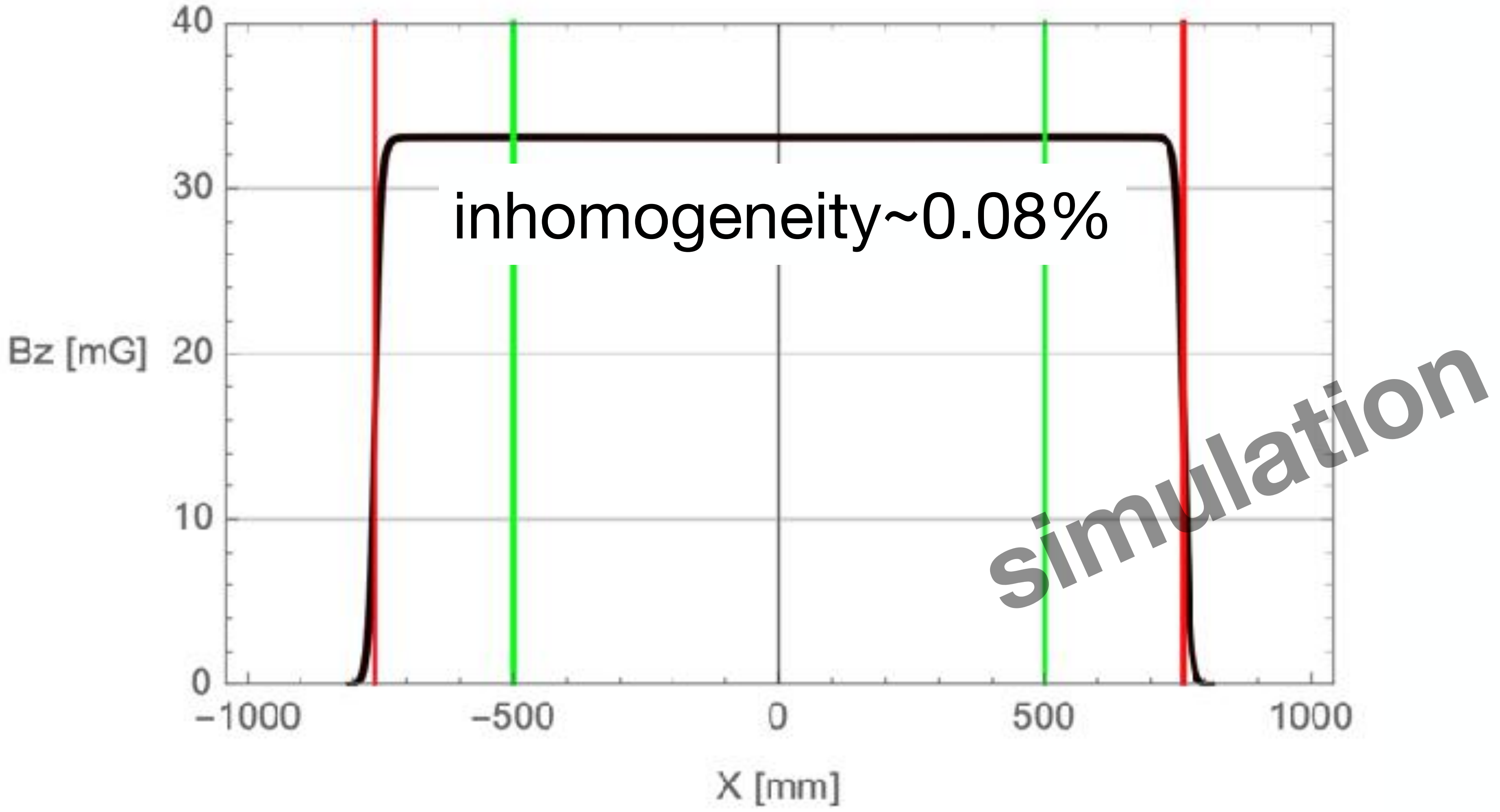


- 3-layer mu-metal shield + 108 degaussing coils + Self shielded Cosθ coils

Siyuan Liu (Northwestern), DAMOP2022



< 0.1 nT residual field



inhomogeneity~0.08%

Magnetic shield

Assembly work and performance evaluation on-going at Northwestern.

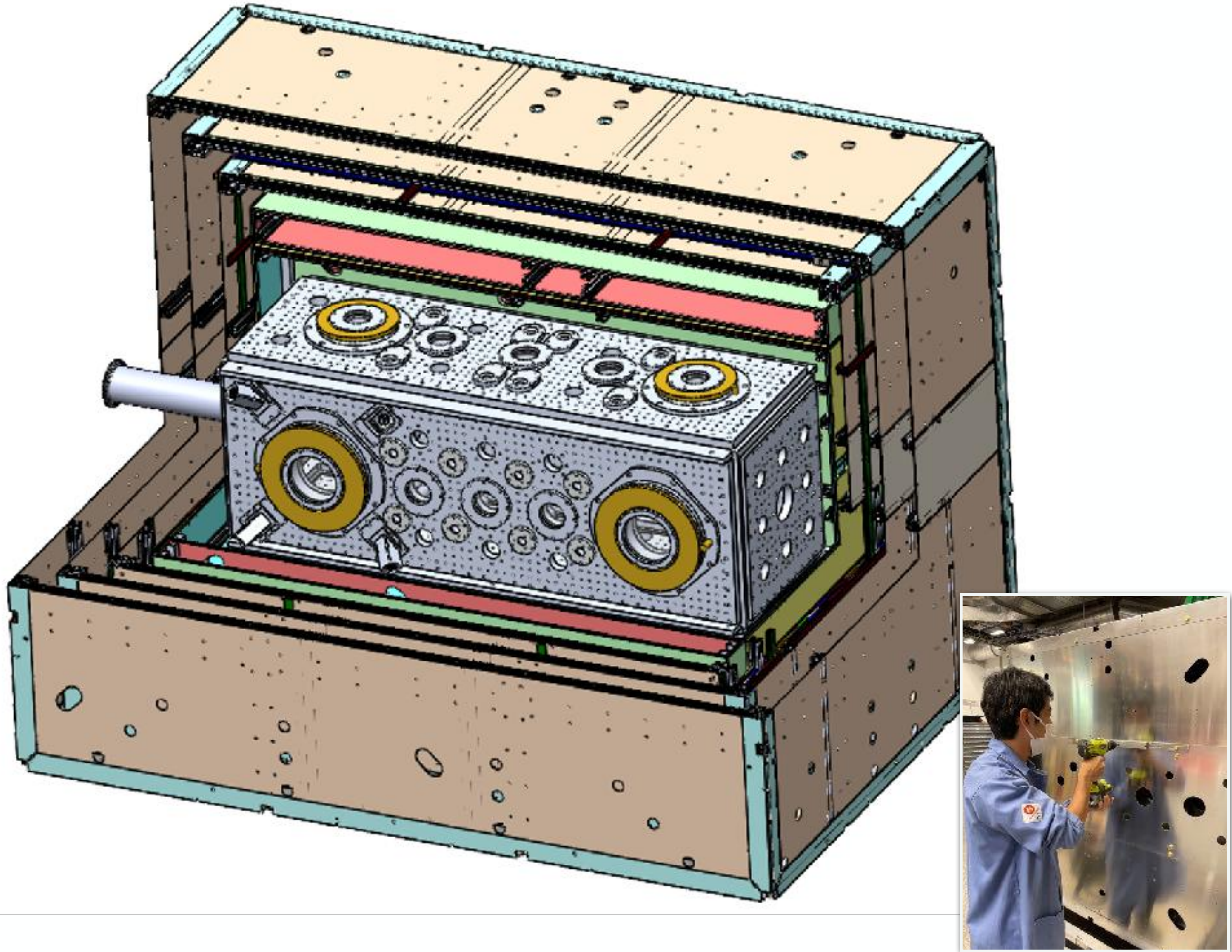
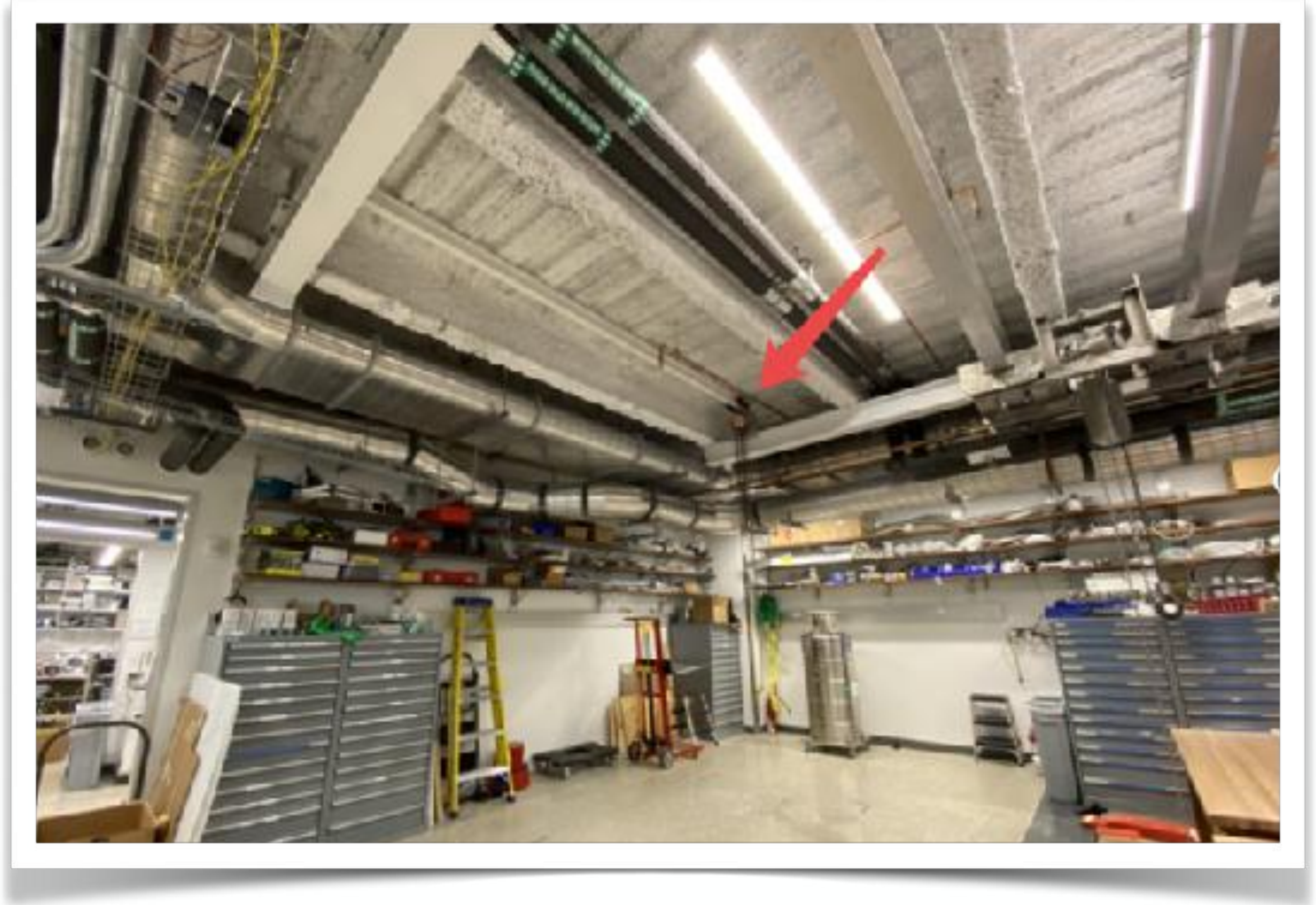


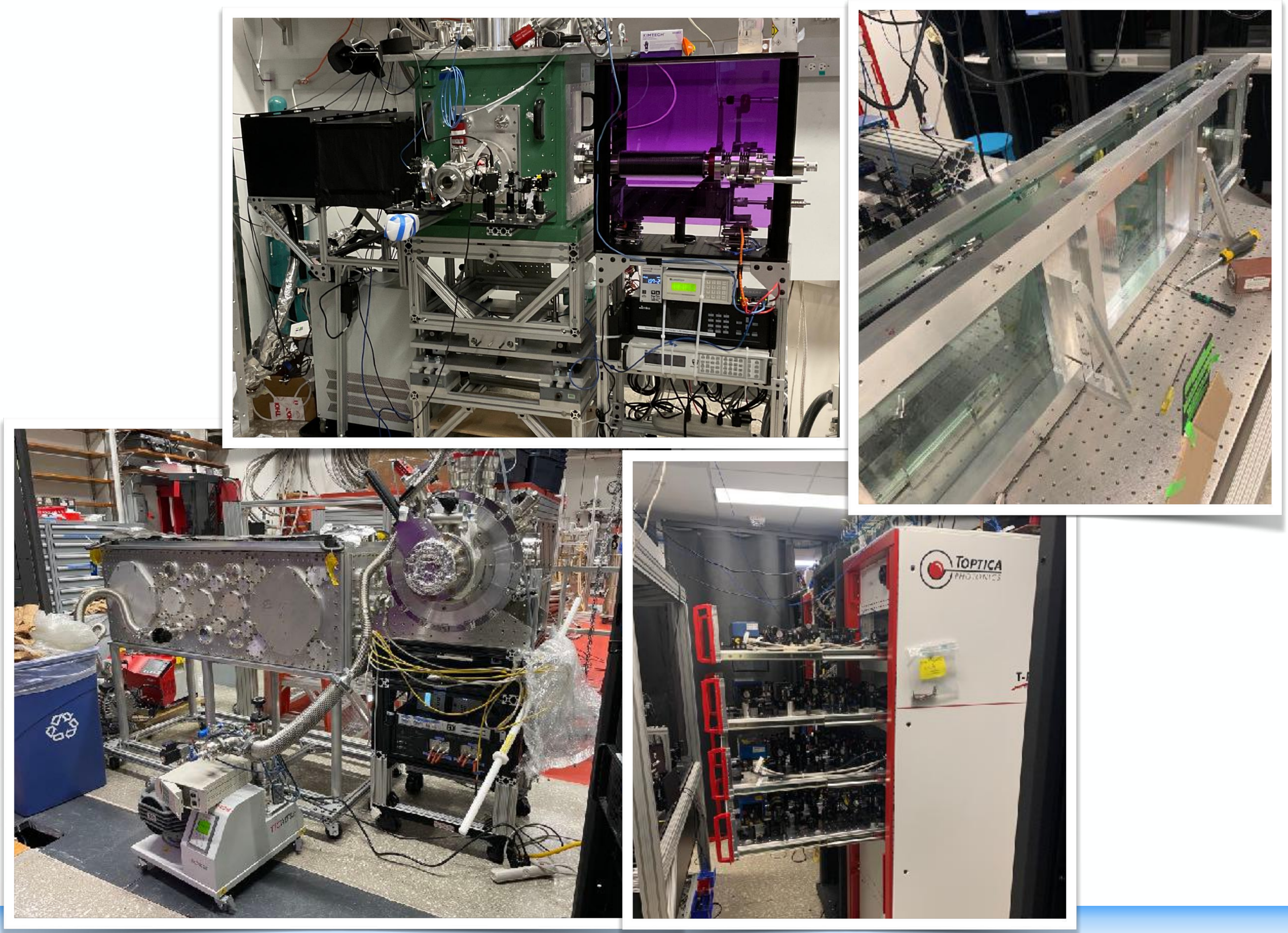
Photo gallery at Northwestern

2022-2023

March 2021

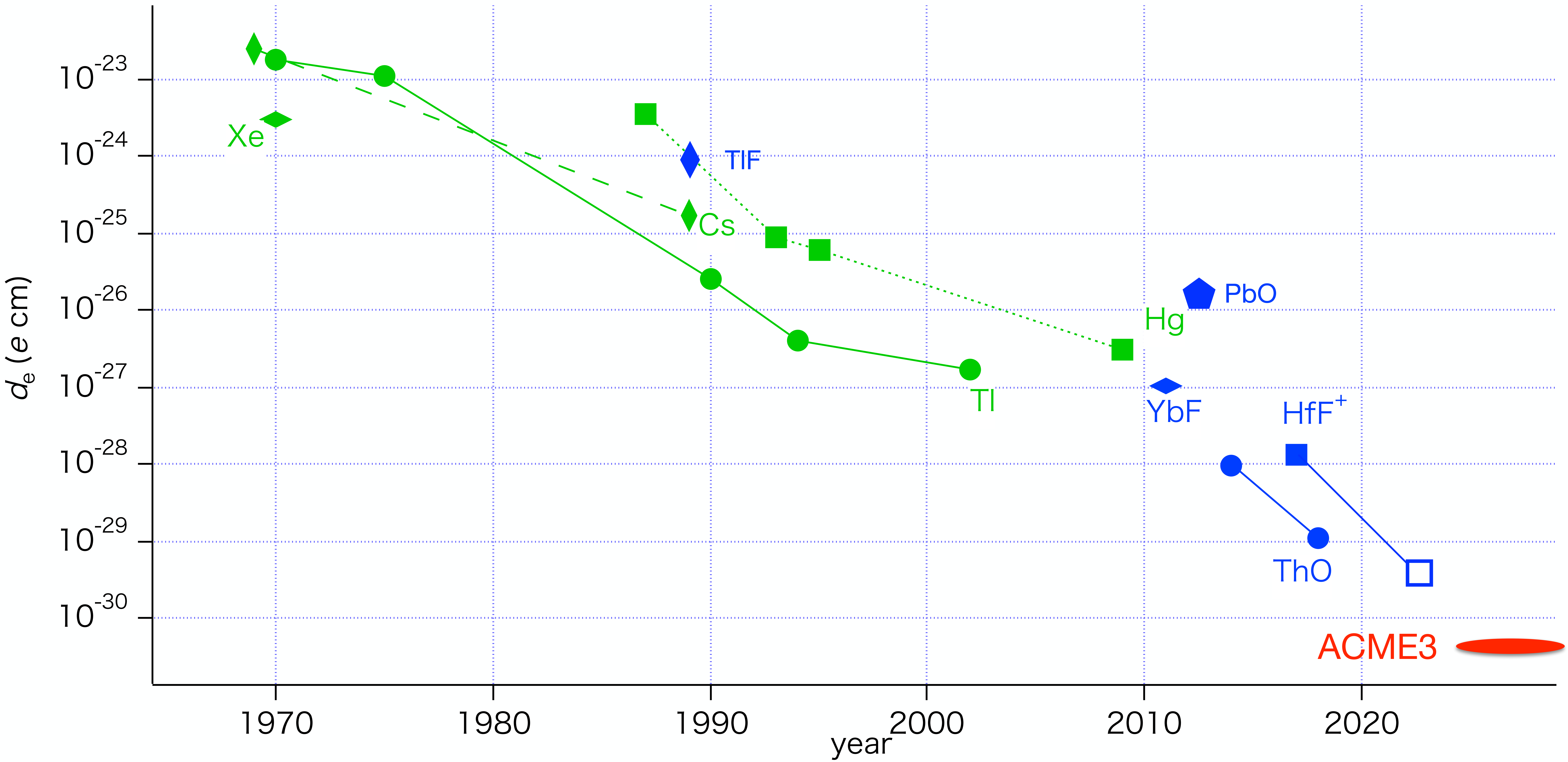
Clean up the ACME space





ACME construction in progress !

Outlook


d_e (e cm)
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
Xe
TlF
Cs
Hg
PbO
Tl
YbF
HfF$^+$
ThO
ACME3
1970
1980
1990
2000
2010
2020
year

Summary

- Electron EDM (eEDM) is a powerful tool to search for a new physics beyond the standard model.
- Many R&D works for ACME3 are going to improve the current upper limit of eEDM by a factor of ~30.