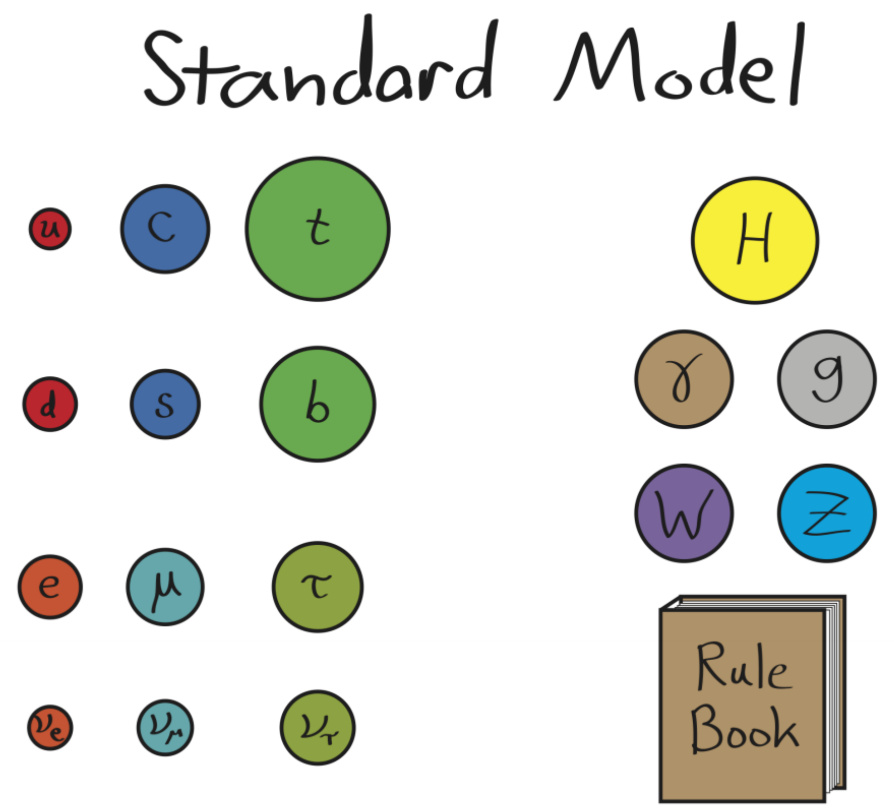
STIRAP and the electron EDM search in ThO

Cris Panda
Gabrielse Lab/ACME Collaboration
STIRAP International Symposium
Semptember 23 2015

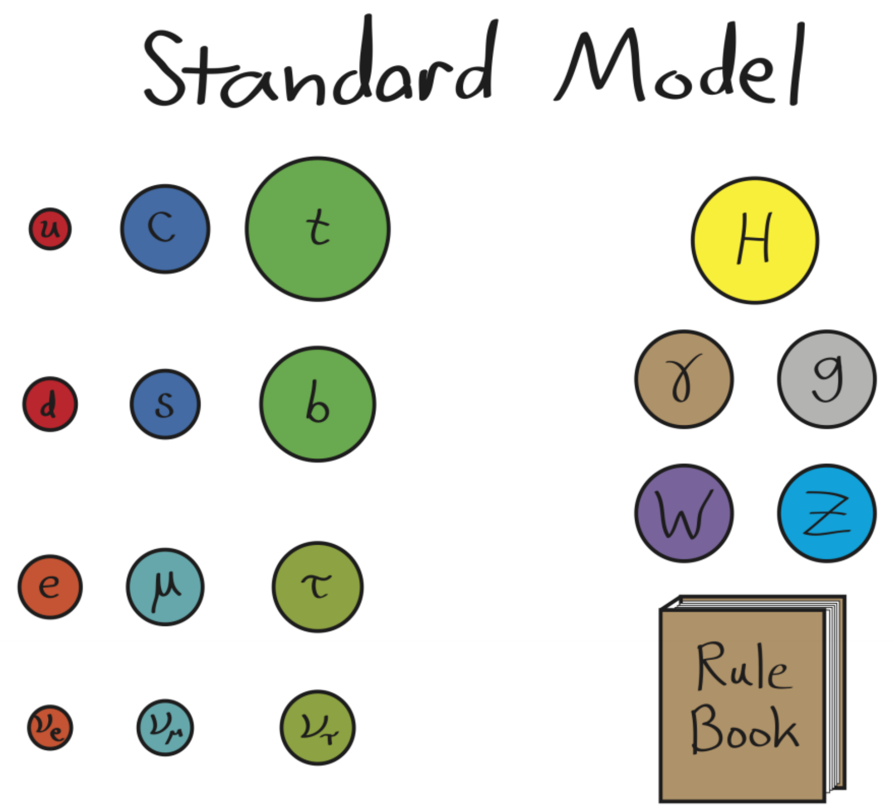
Questions that motivate us



Questions that motivate us

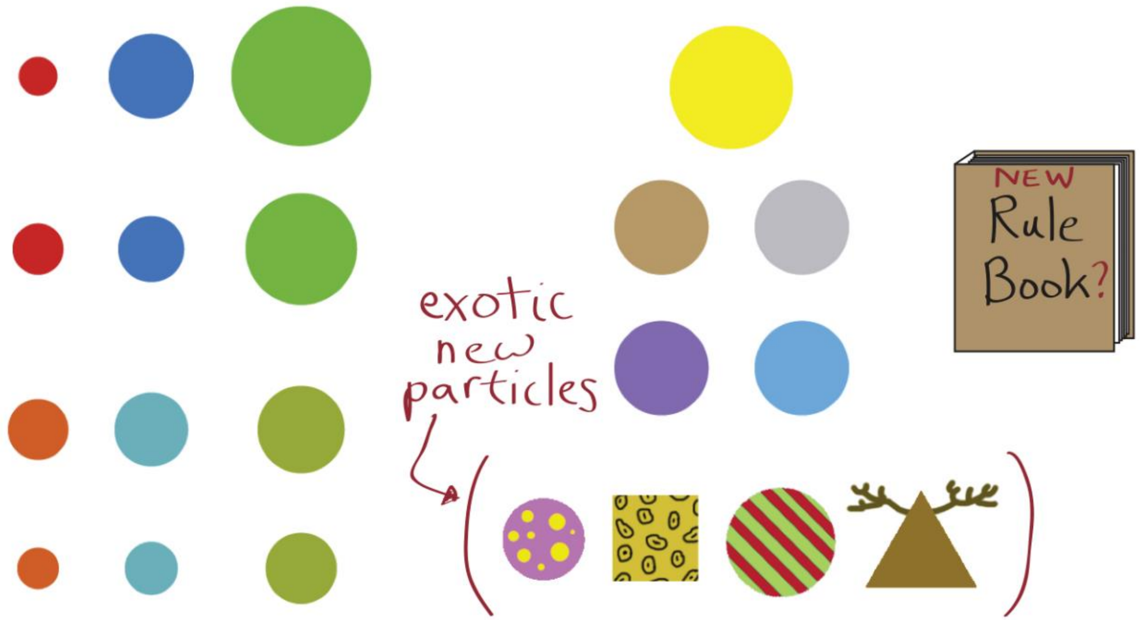
Standard Model doesn't tell us

- What is dark matter?

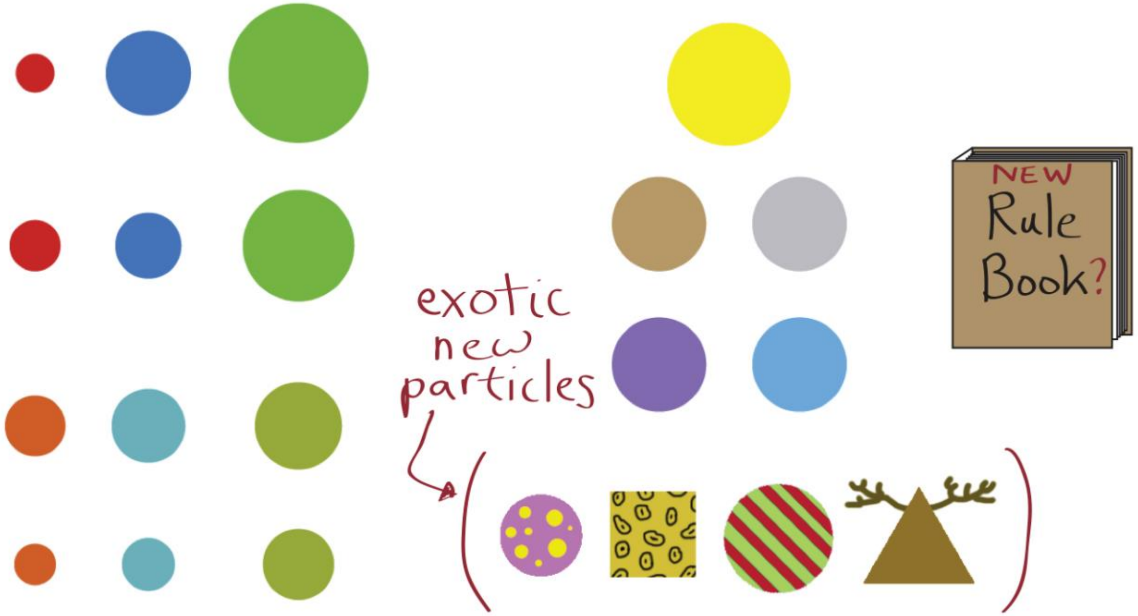


Possible solutions

- What is dark matter?
  - Heavy particles that interact weakly with known matter (WIMPs)?



Questions that motivate

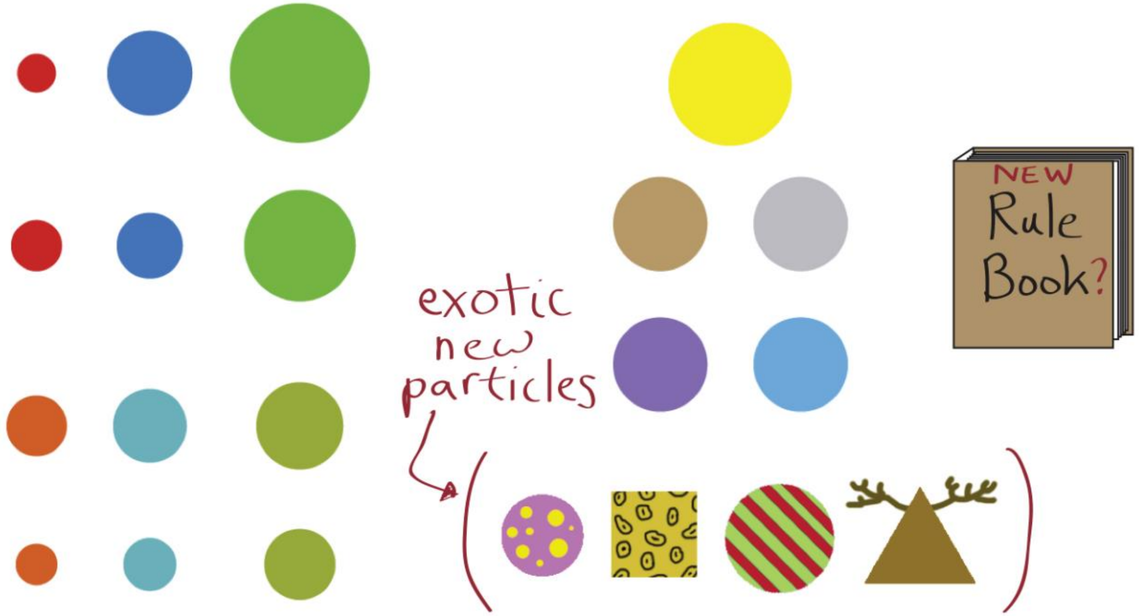


- What is dark matter?
  - Heavy particles that interact weakly with known matter (WIMPs)?

- Why do we see more matter than antimatter in the universe?

[1] A. D. Sakharov, JETP Lett. **5**, 27 (1967).

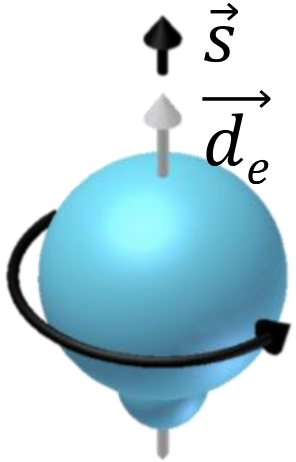
Possible solutions



- What is dark matter?
  - Heavy particles that interact weakly with known matter (WIMPs)?
- Why do we see more matter than antimatter in the universe?
  - Assuming equal initial amounts of matter and antimatter Sakharov[1] derived that CP violating processes are required to explain this.
  - This (assuming CPT invariance) implies T violating phases.
  - The Standard Model does account for some T-violation (CKM matrix), but not enough.

[1] A. D. Sakharov, JETP Lett. **5**, 27 (1967).

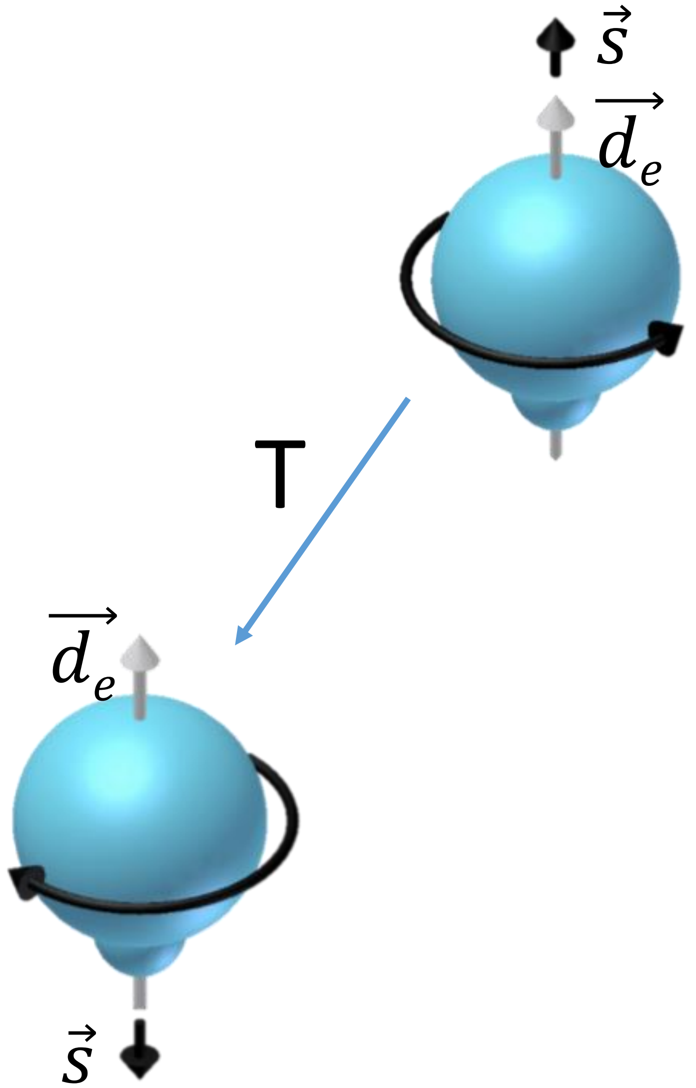
Electric dipole moments and fundamental symmetries



- Permanent EDMs of fundamental particles violate T-symmetry.

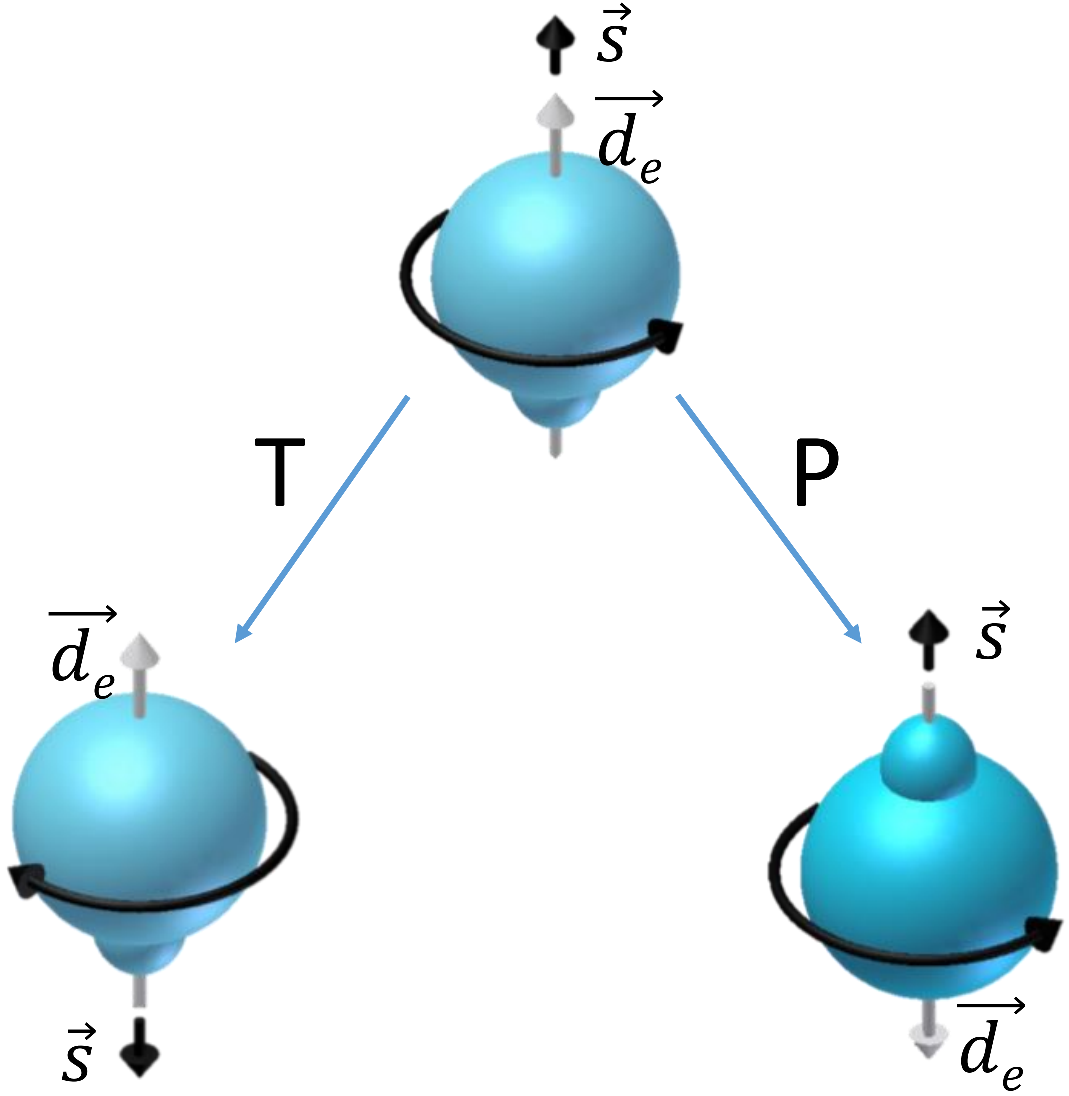
Electric dipole moments and fundamental symmetries

- Permanent EDMs of fundamental particles violate T-symmetry.



Electric dipole moments and fundamental symmetries

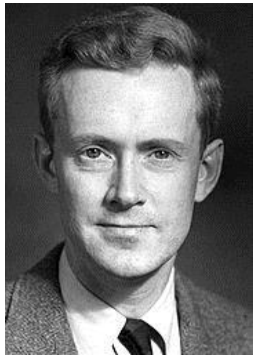
- Permanent EDMs of fundamental particles violate T-symmetry.
- EDMs are also not symmetric under parity inversion.

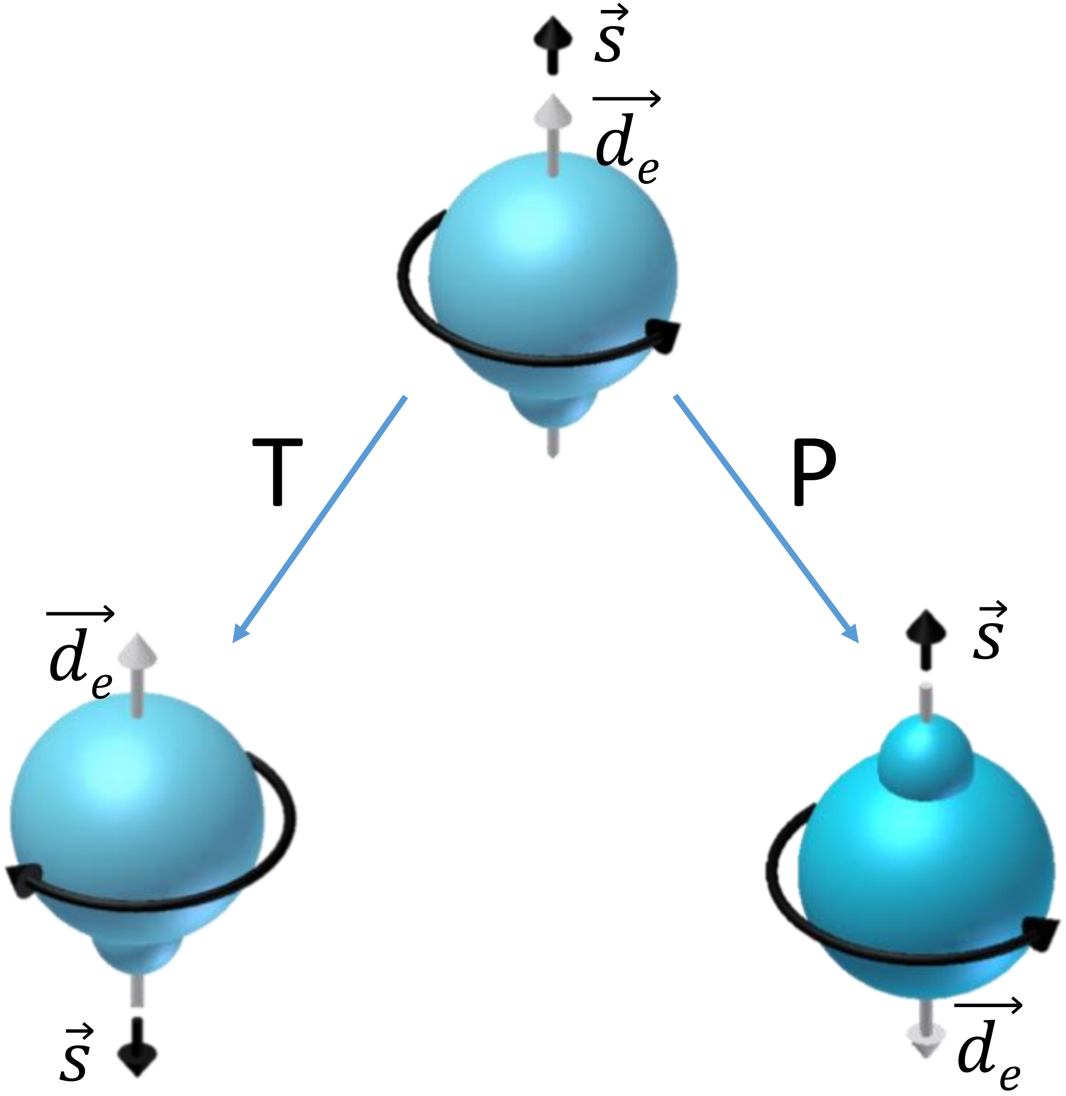


[1] Purcell, E. & Ramsey, N., *Phys. Rev.*, *78*(6), 807 (1950)

Electric dipole moments and fundamental symmetries

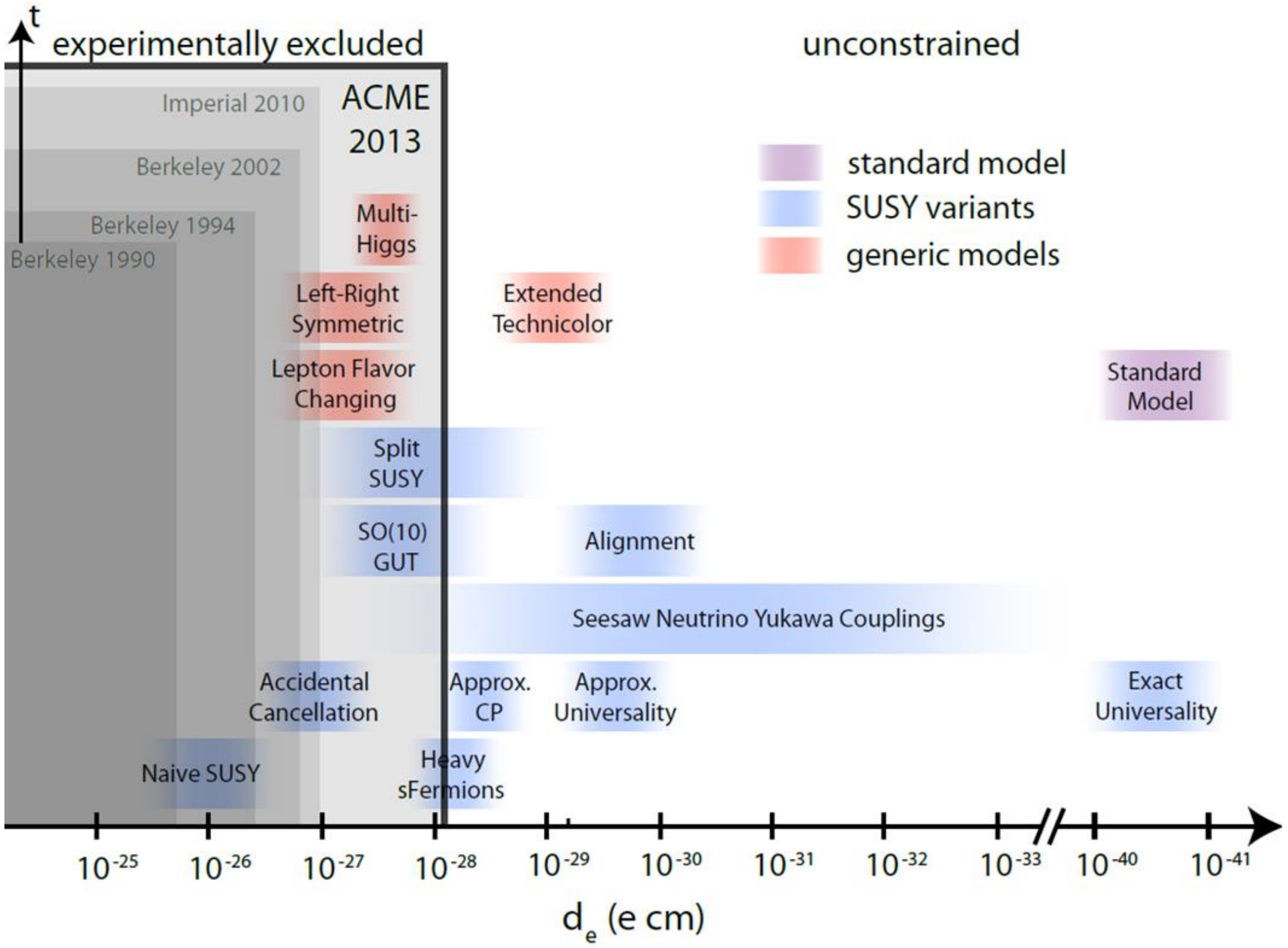
- Permanent EDMs of fundamental particles violate T-symmetry.
- EDMs are also not symmetric under parity inversion.
- No permanent EDMs have yet been observed, despite 60 years of searching[1].





[1] Purcell, E. & Ramsey, N., *Phys. Rev.*, *78*(6), 807 (1950)

EDMs and Physics beyond the standard model



Typical scaling for eEDM Feynman diagrams (n-loop):

Coupling constant (assume g ~0.1)

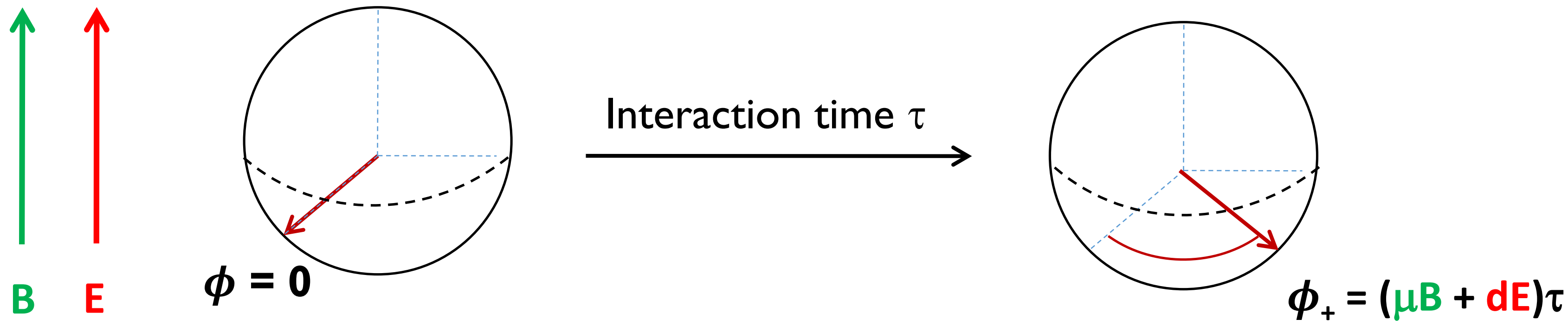
CP violating phase (assume ~0.1-1)

$$d_e \approx \mu_B \left(\frac{g^2}{4\pi}\right)^n \left(\frac{m_e}{m_X}\right)^2 \sin(\theta_{CP})$$

Mass scale of new particles

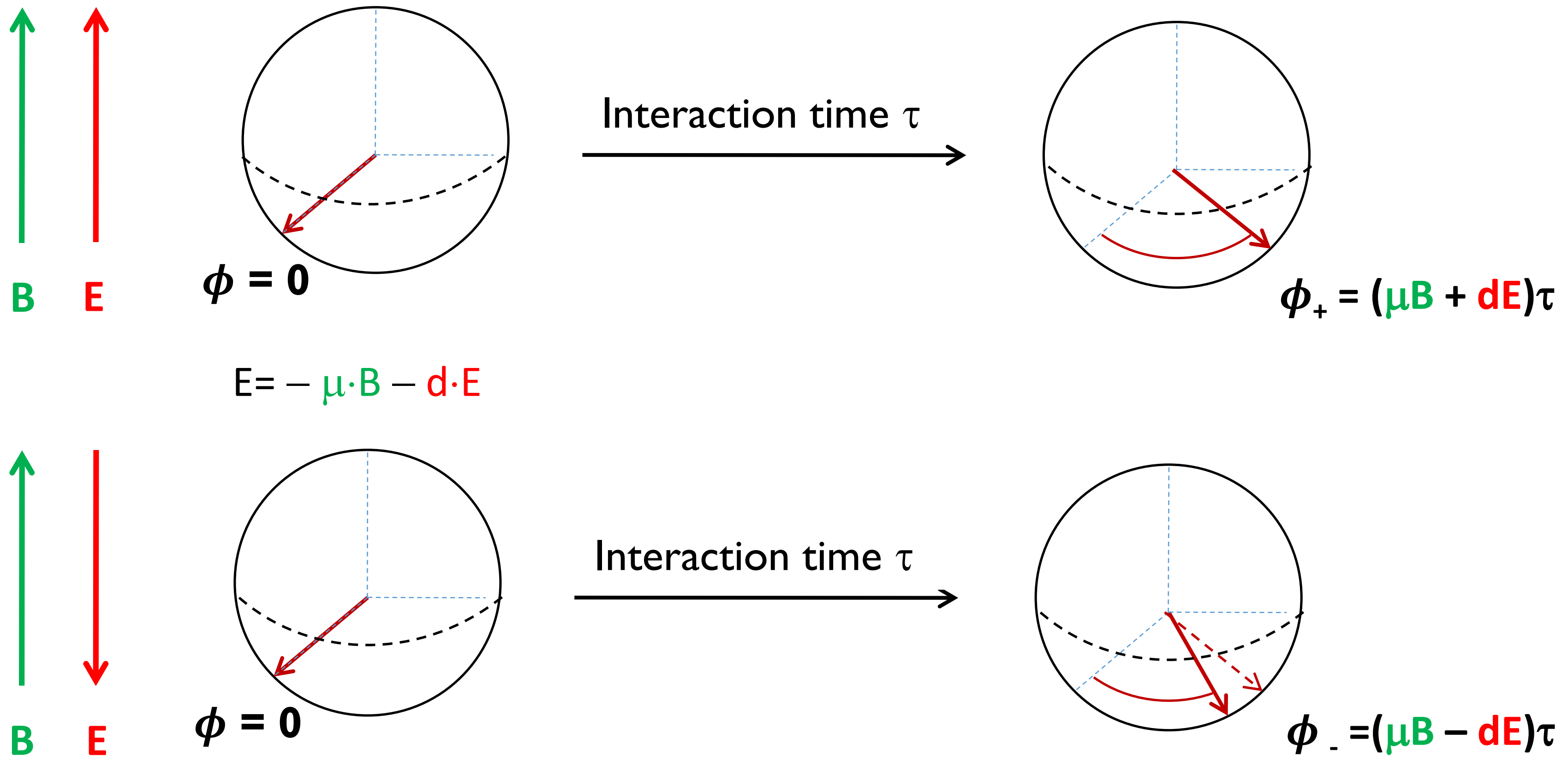
EDM experiments sensitive to ~TeV mass scales at 2-loop , complement LHC

How to Measure an EDM

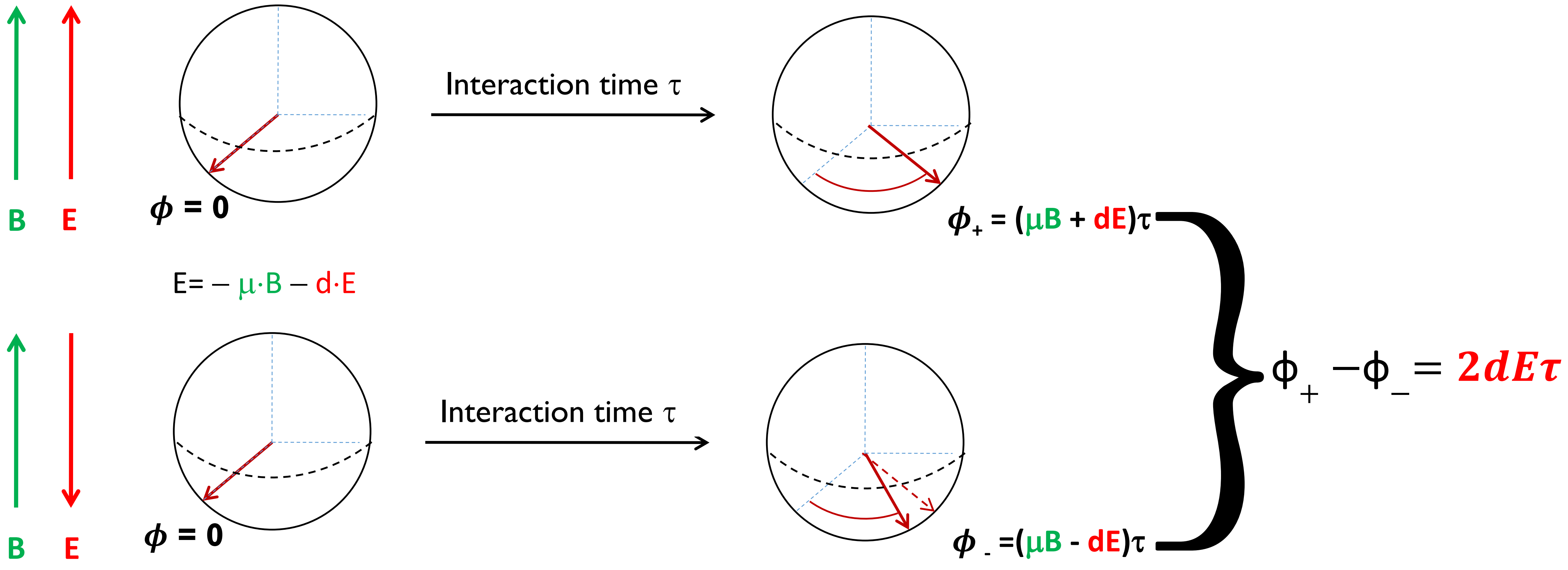


$E = -\mu \cdot B - d \cdot E$

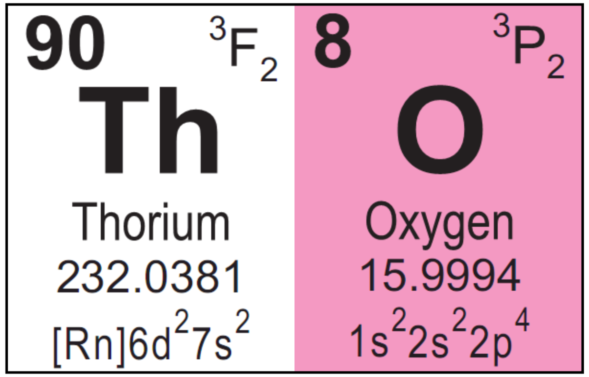
How to Measure an EDM



How to Measure an EDM



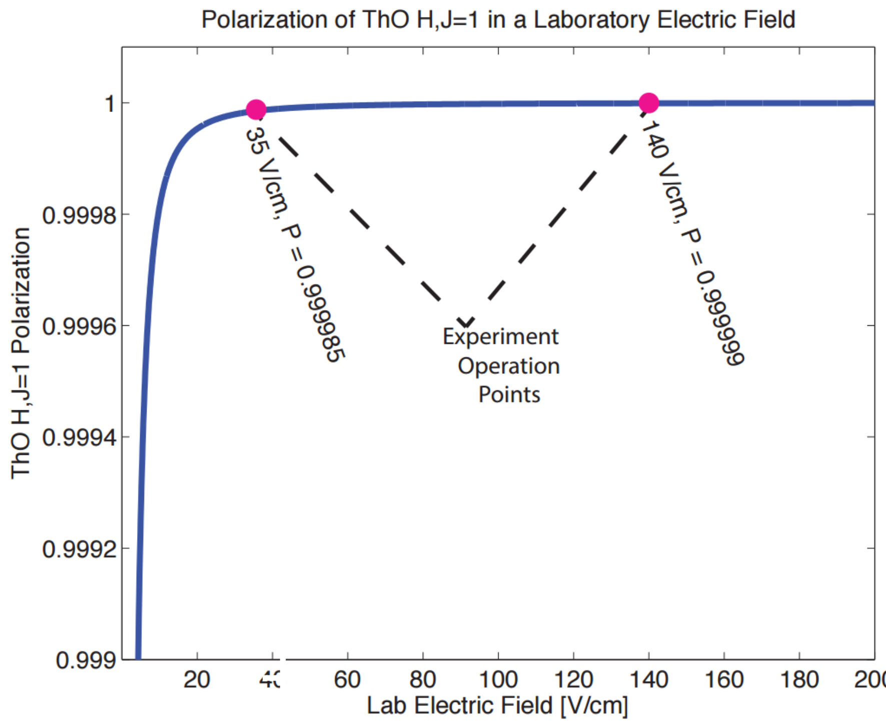
Advantages of ThO Molecule



$$1/\Delta d_e \propto \mathcal{E}\tau\sqrt{\dot{N}T}$$

- Diatomic molecules have large internal electric fields:
  - For us E_{eff} = 84 GV/cm[1].
  - Three orders of magnitude larger than atoms.
- Easily polarized
  - Lab fields of 10 V/cm fully align the molecule.
- Spectroscopy available and optical transitions accessible with standard robust diode and fiber lasers.
- Sufficient coherence time: 2 ms.

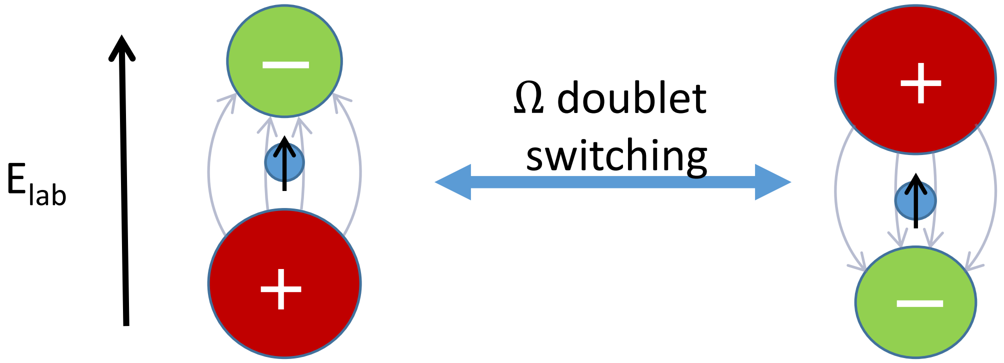
$$1/\Delta d_e \propto \mathcal{E}\tau\sqrt{\dot{N}T}$$



[1] L.V. Skripnikov, A.N.Petrov, A.V. Titov, arXiv:1308.0414 (2013)

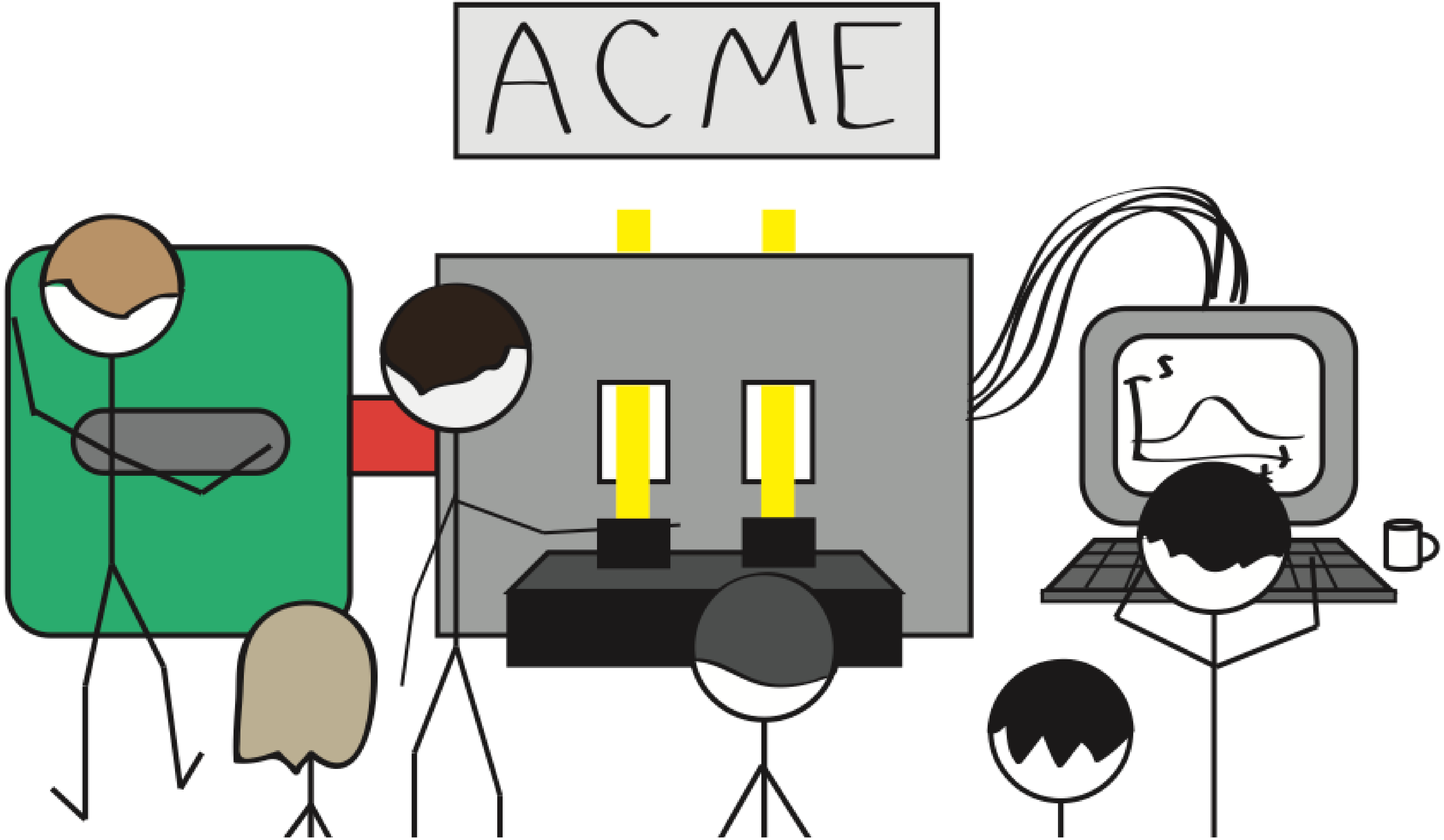
Advantages of ThO Molecule

- H State - Omega doublet structure
  - Allows us to reverse the internal electric field of the molecule without switching the lab electric field by tuning our laser.
- Magnetically insensitive, reduces B field systematics
  - Magnetic moment is 0.004 $\mu_{B.}$
- Bright molecular beams
  - Can make cold, slow, high flux beams using buffer gas technique.



$$1/\Delta d_e \propto \mathcal{E}\tau\sqrt{\dot{N}T}$$

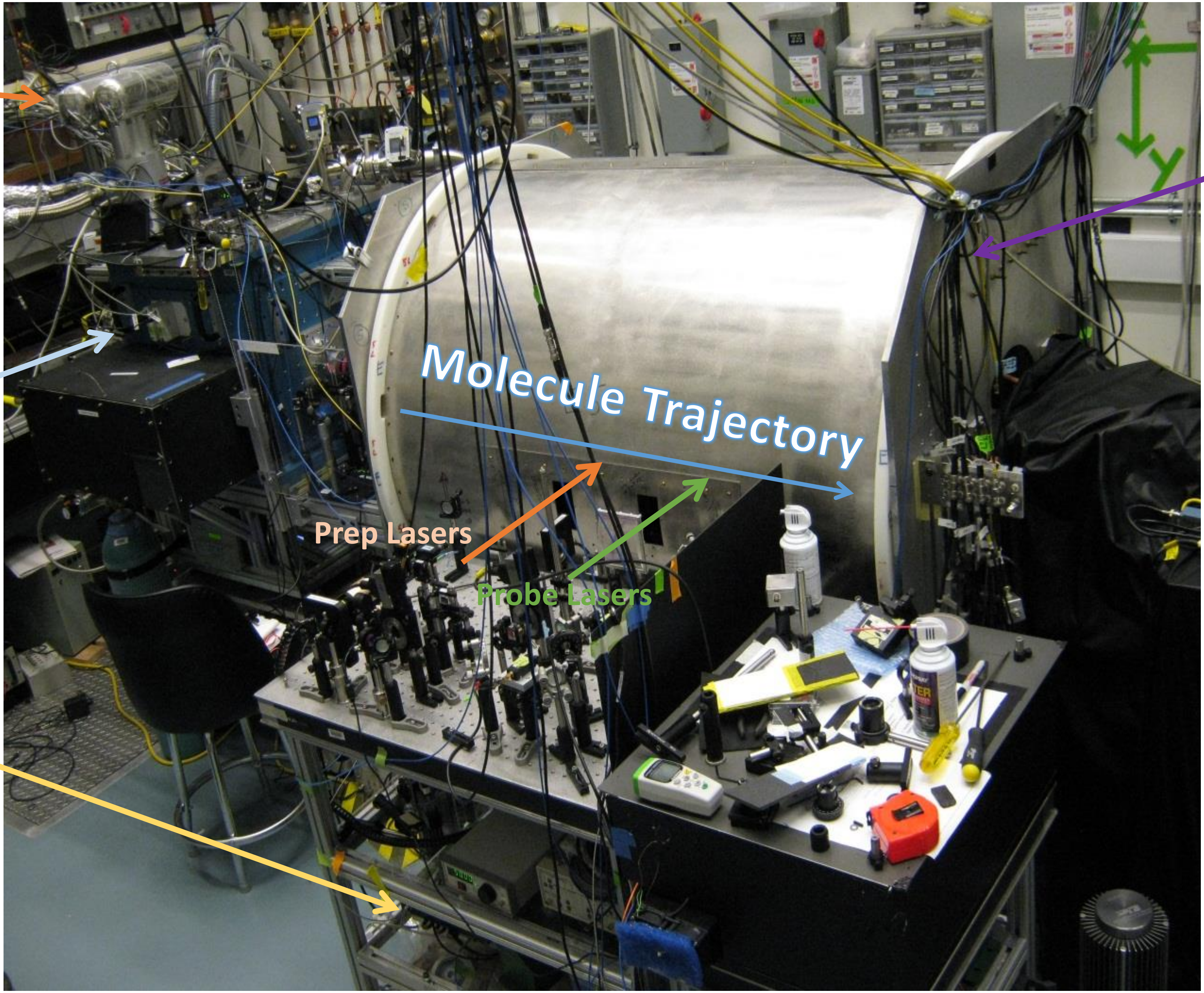
The Experimental Apparatus



Pulse tube
Cryo
refrigerator

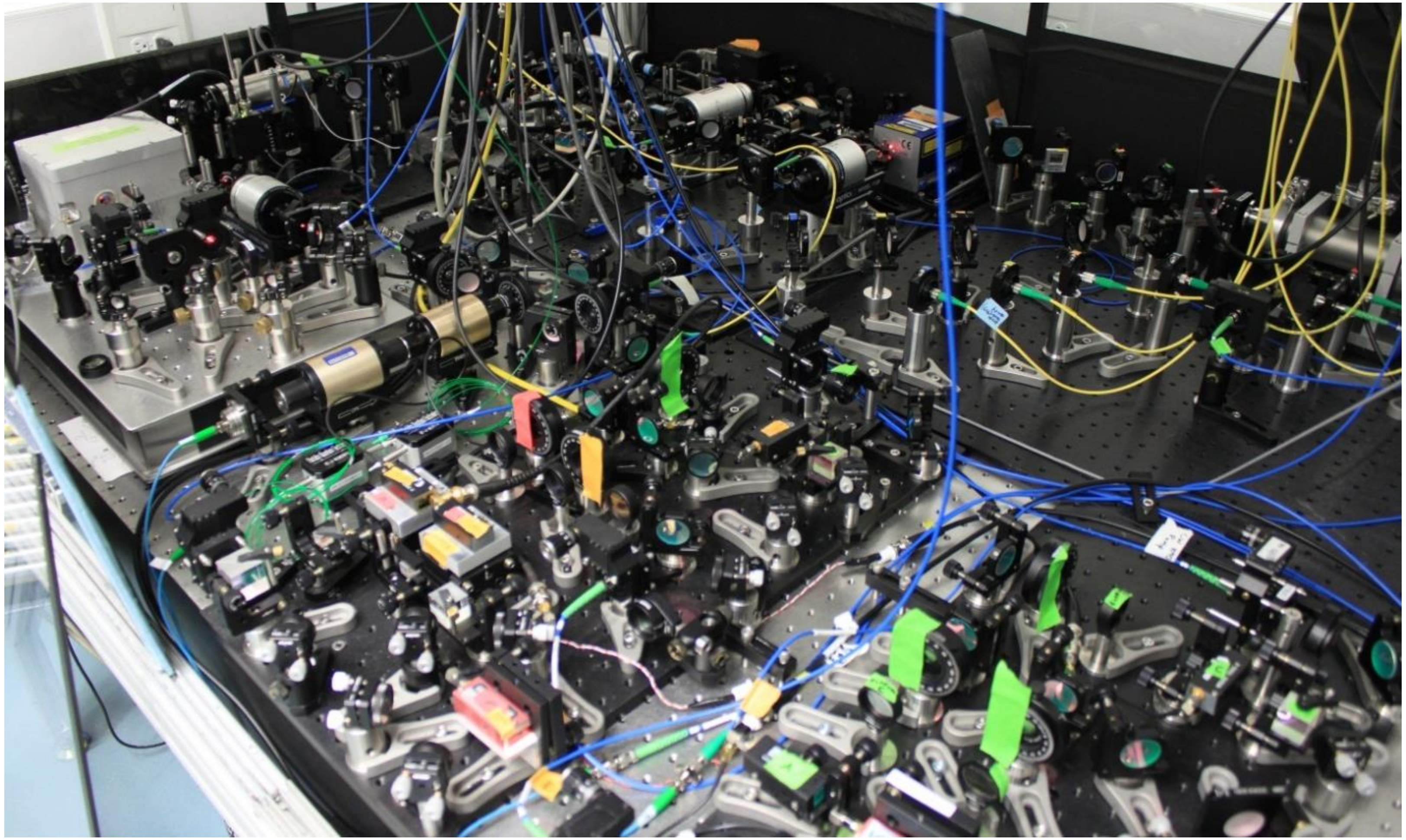
5 layers of
mu-Metal
shields

ThO Buffer
Gas Beam
source

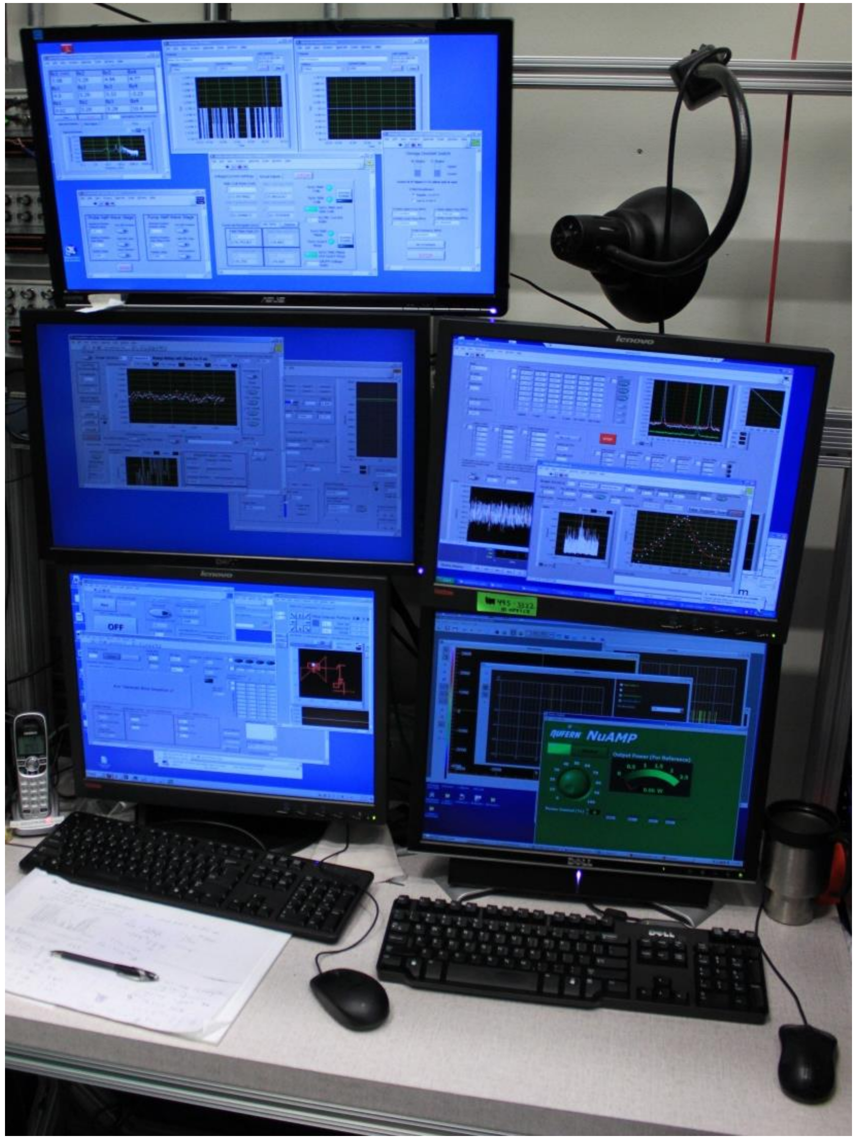


Laser fiber
amplifier
(10 Watt)

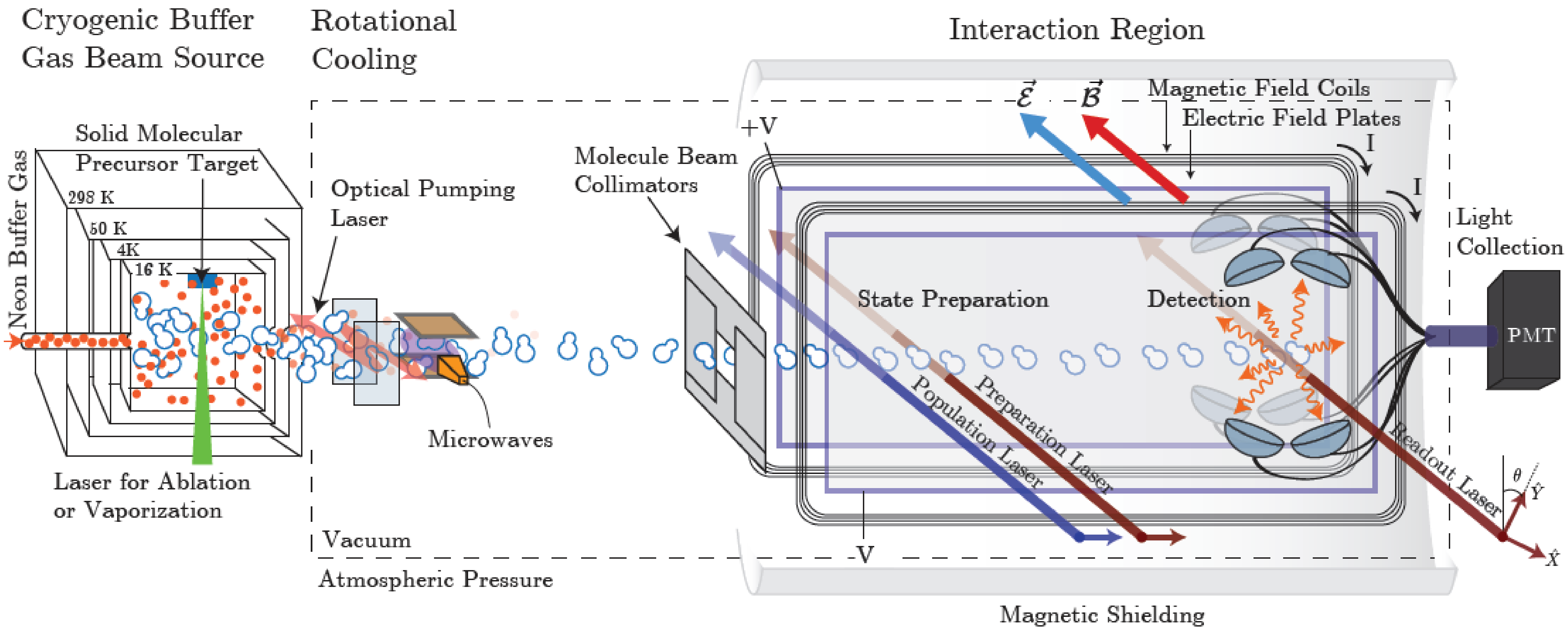
One of several optical tables w/ ~15 lasers, modulators, locking electronics, fibers spanning across two buildings



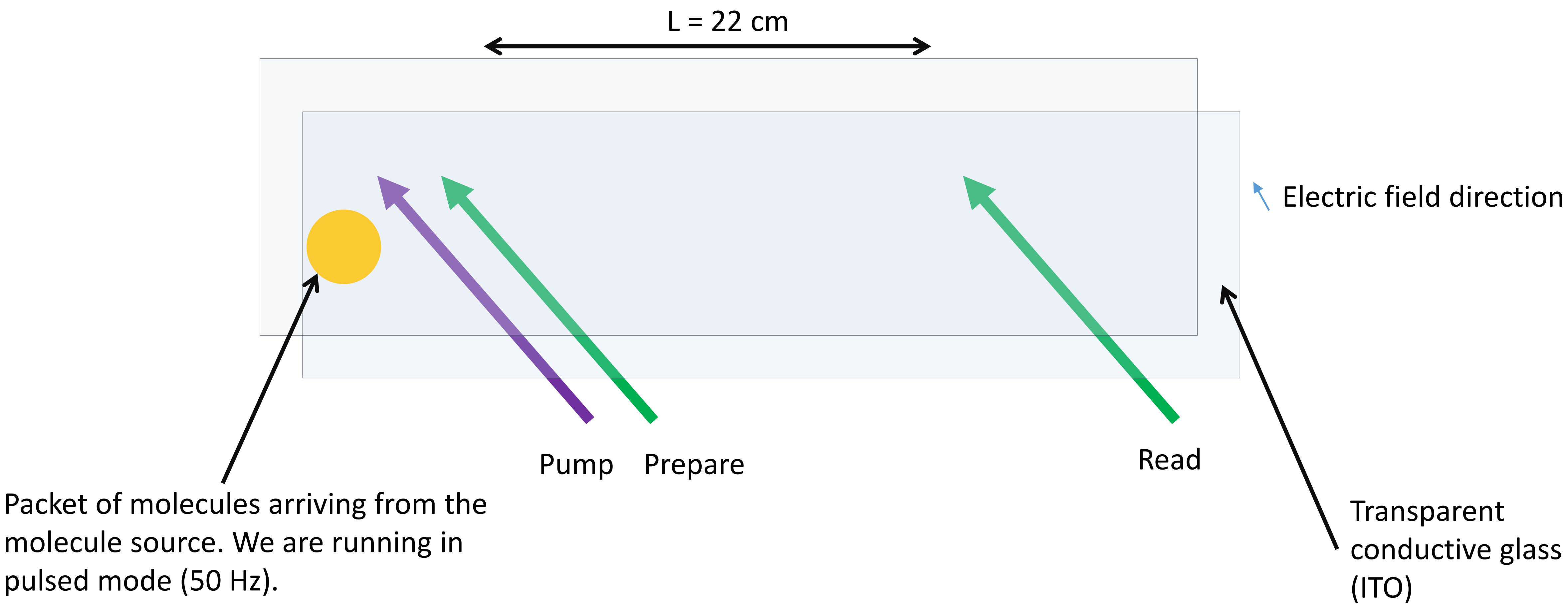
“control room”



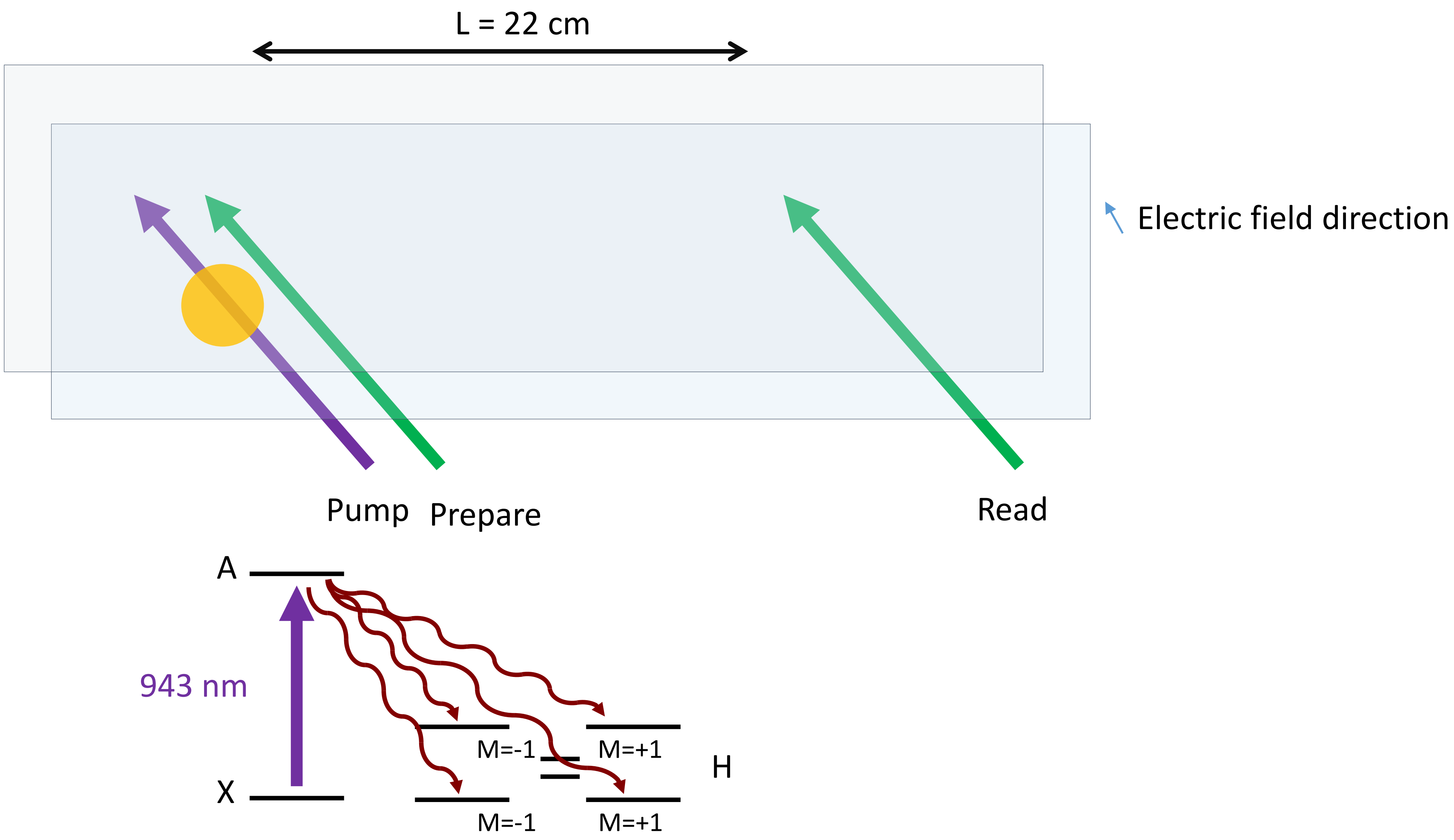
GEN I experiment



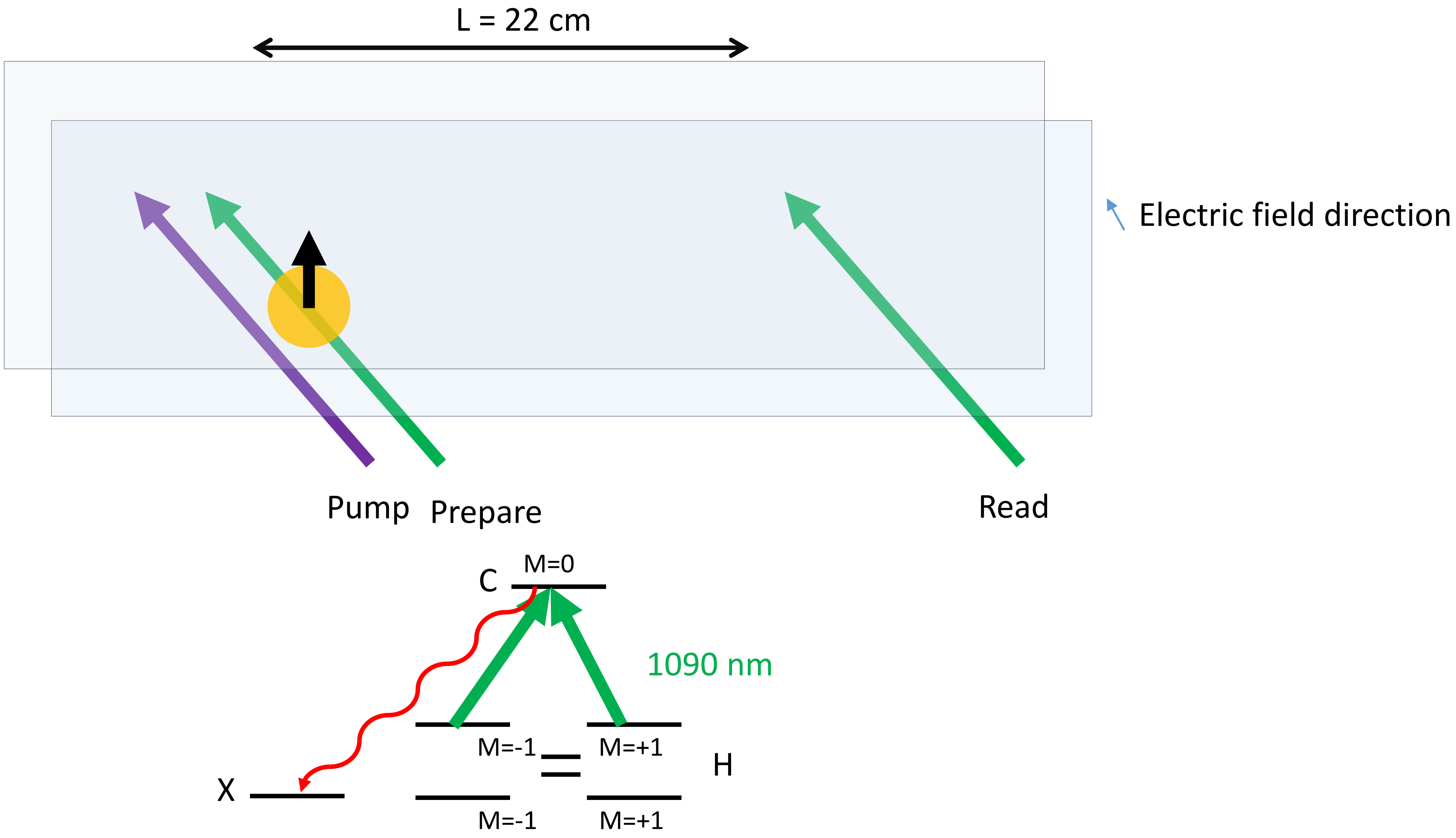
Phase Measurement Scheme



Populate experiment state (H)

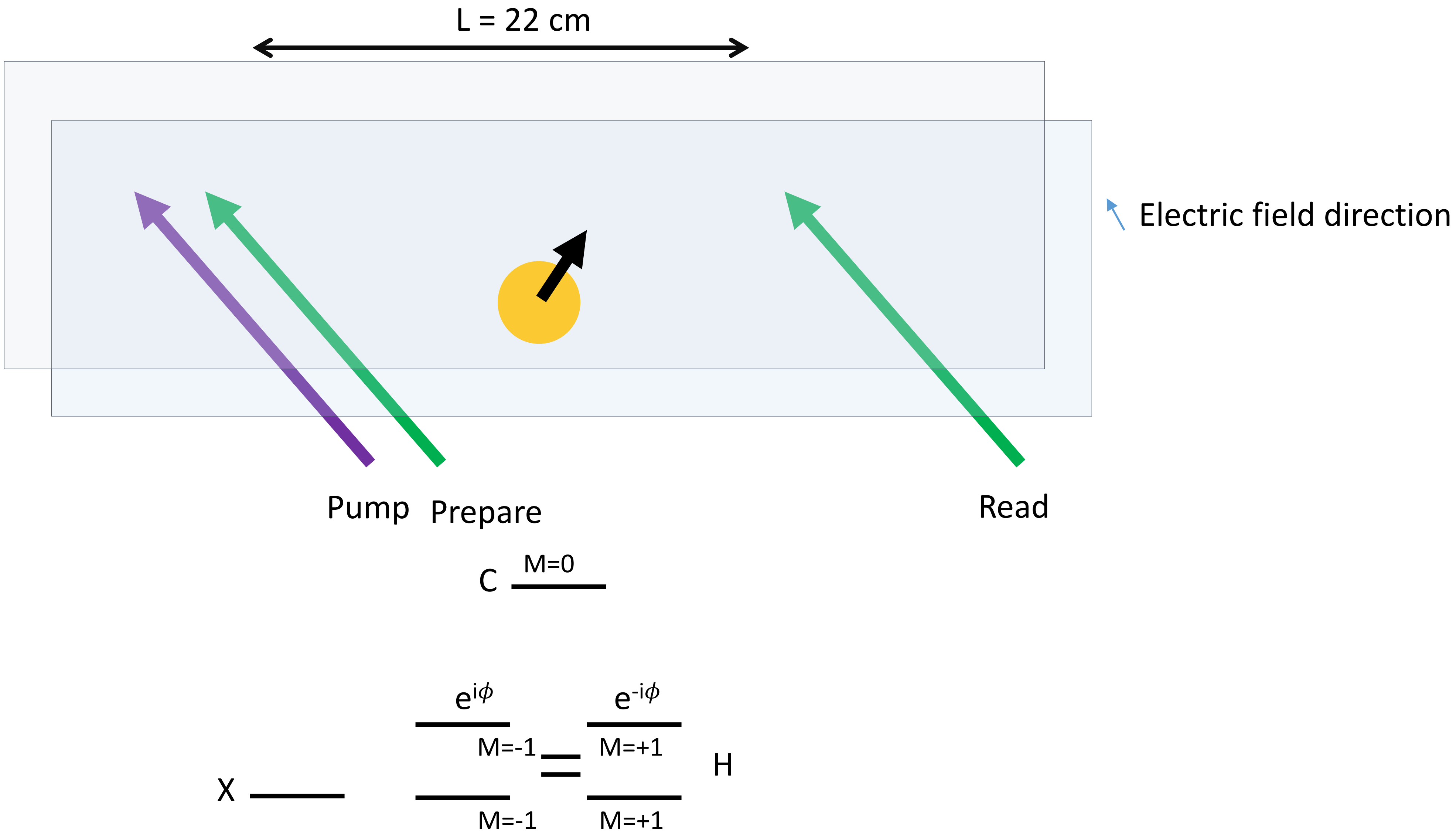


Align spin

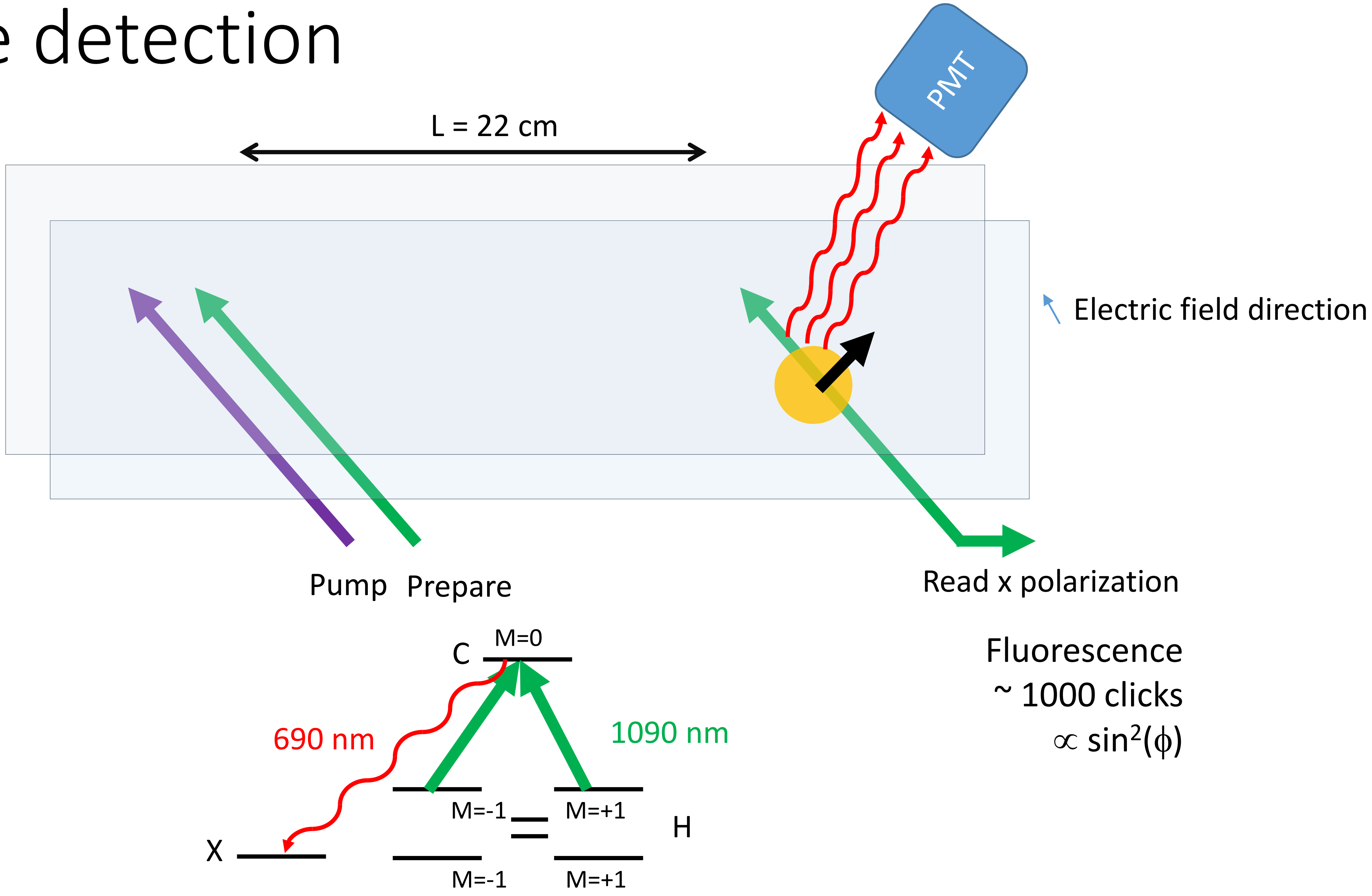


L = 22 cm
Electric field direction
Pump
Prepare
Read
C
M=0
1090 nm
M=-1
M=+1
H
X
M=-1
M=+1

Spin precession

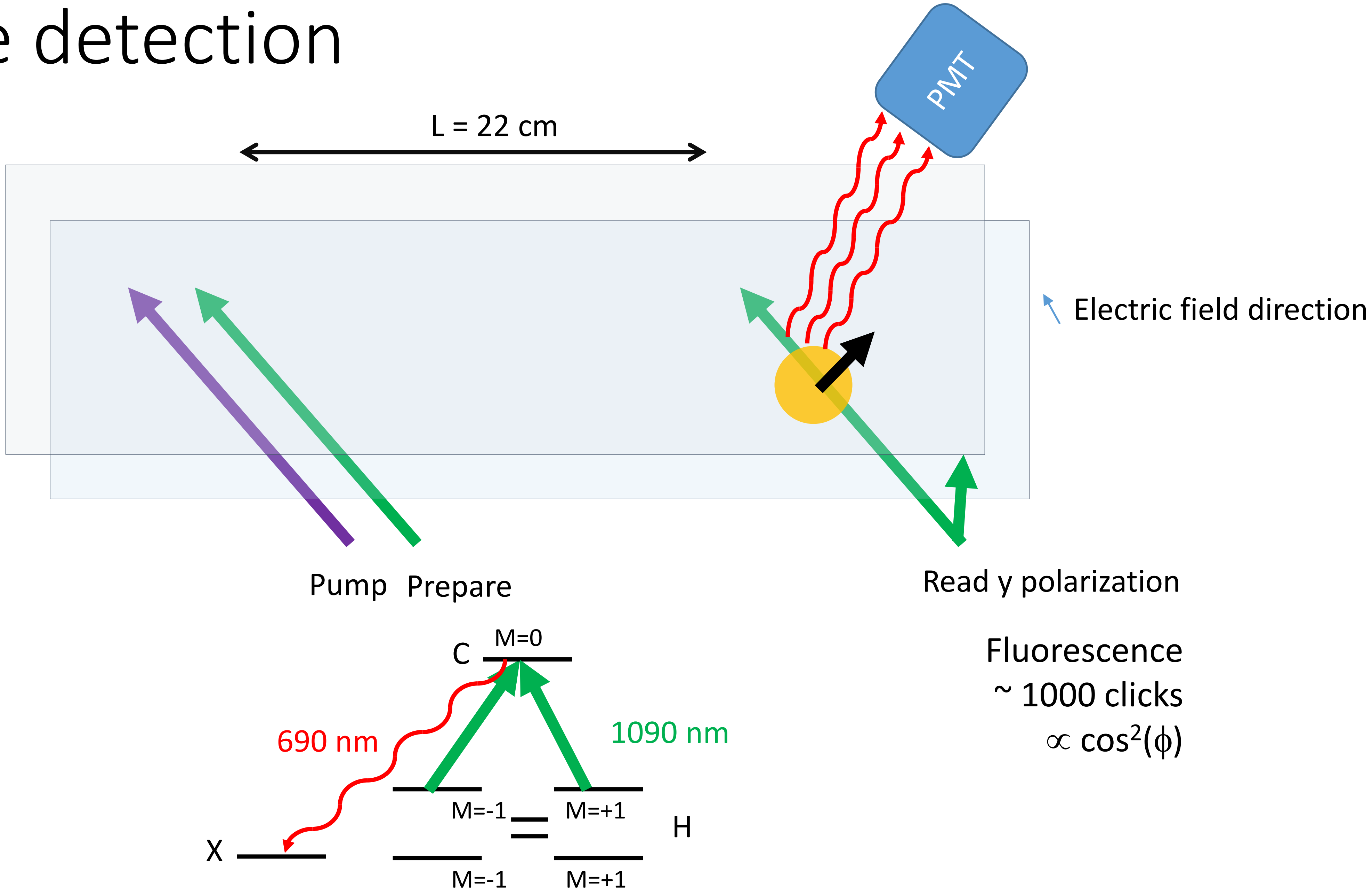


Phase detection



Fluorescence
~ 1000 clicks
$\propto \sin^2(\phi)$

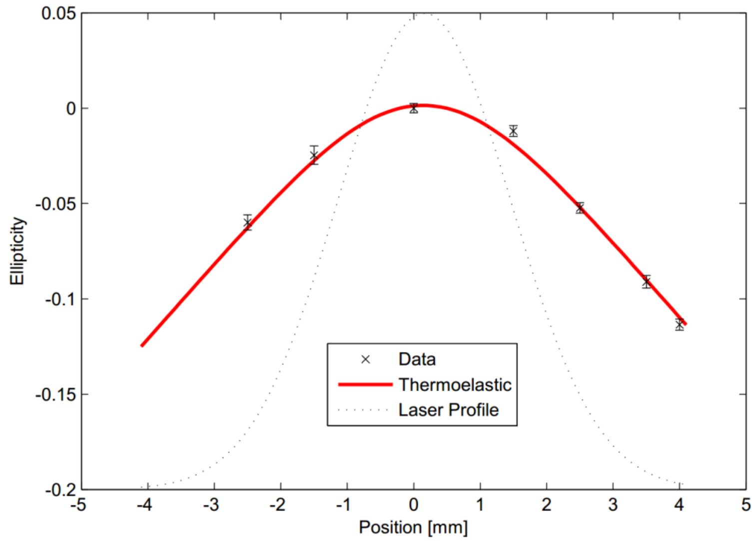
Phase detection

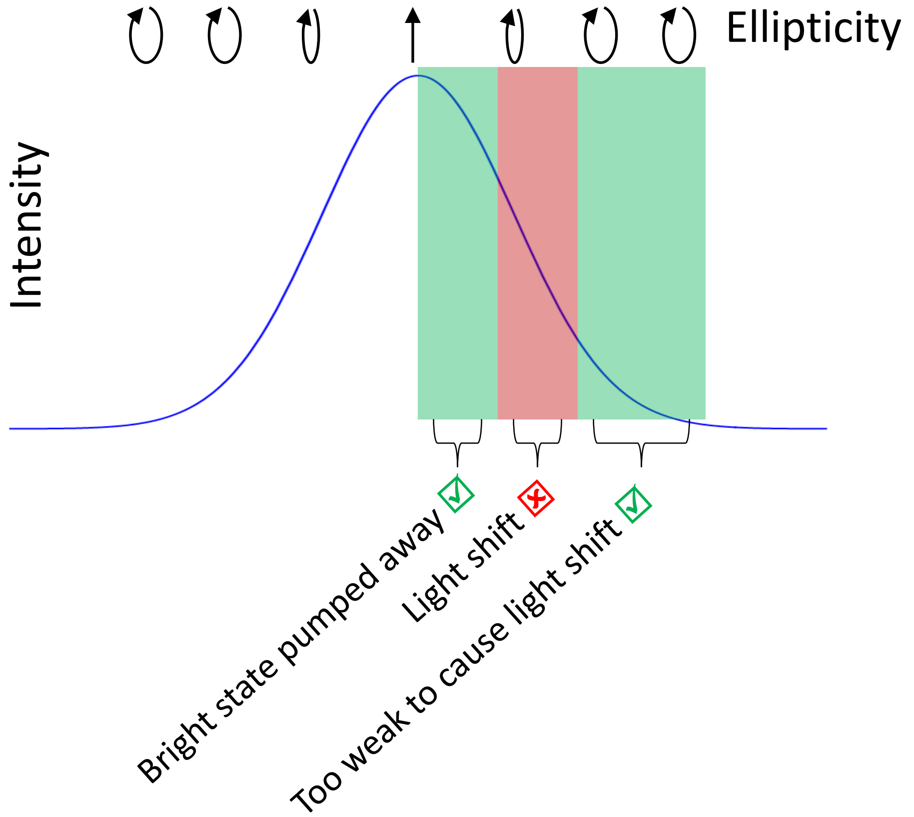


Fluorescence
~ 1000 clicks
$\propto \cos^2(\phi)$

Systematic Study: E_{nr}

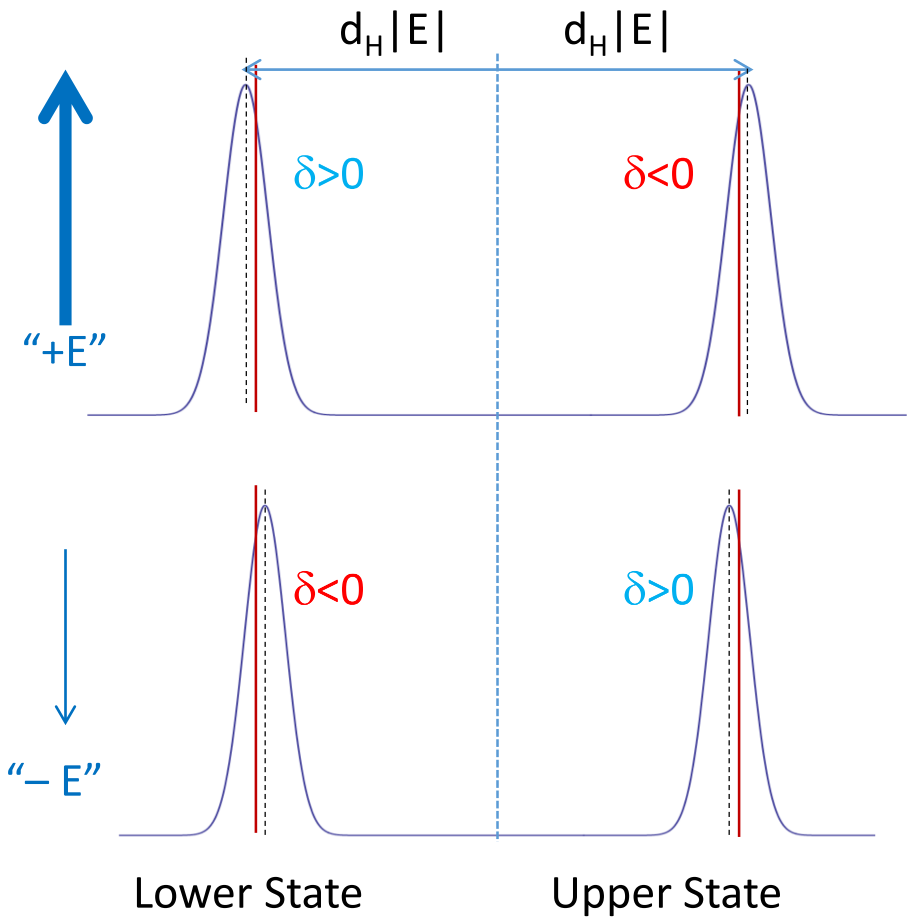
- Ellipticity profile caused by thermal stress in E-field plates
  - ITO absorption → Heat
  - Heat → Stress
  - Stress → Birefringence
- Varying ellipticity across the laser wavefront
  - Dark state acquires bright component
  - Bright component acquires light shift
  - Ellipticity → M=±1 differentially shifted
- Just a light shift shouldn't cause a false EDM…





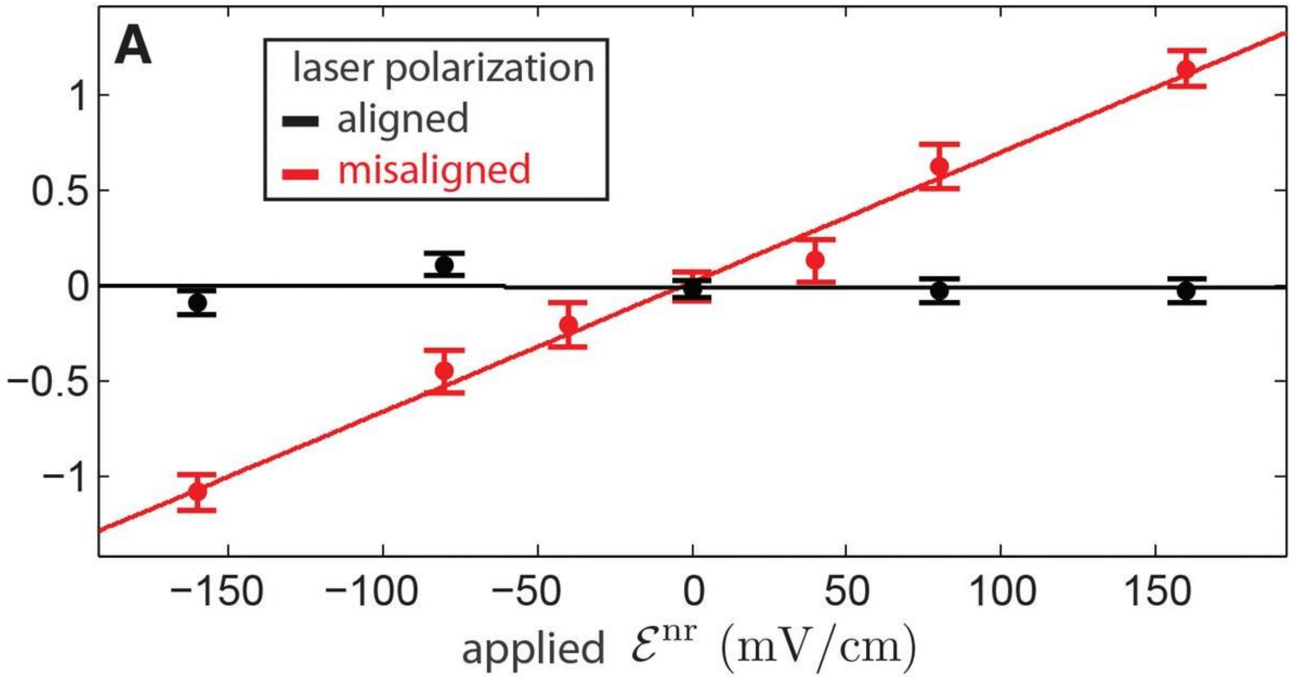
Correlated Detuning

- A non-reversing E-field (E_{nr}) leads to detuning
  $\delta \propto \mathrm{sgn}(\mathcal{N})\mathrm{sgn}(\mathcal{E})$
  - Non-reversing electric field means “+E” ≠ “–E”
  - Same parity as EDM
- Couples to linear light shift to cause a false EDM



Solutions

- Can't do anything about patch potentials, but we can suppress light shift
  - Align laser polarizations along optical axes
  - Use chopper wheel to reduce heat load
  - Shape beams to have sharp cutoff in Ramsey region
- We suppress the effect by a factor of ~100
  - Next-generation field plates should give another ~100



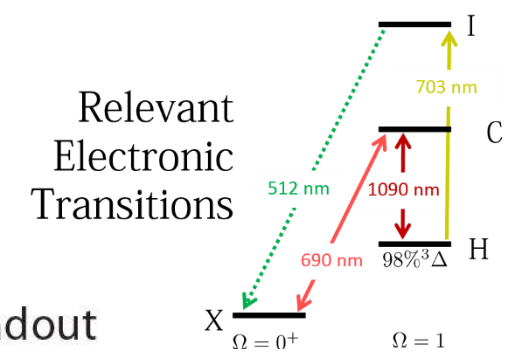
GEN I result

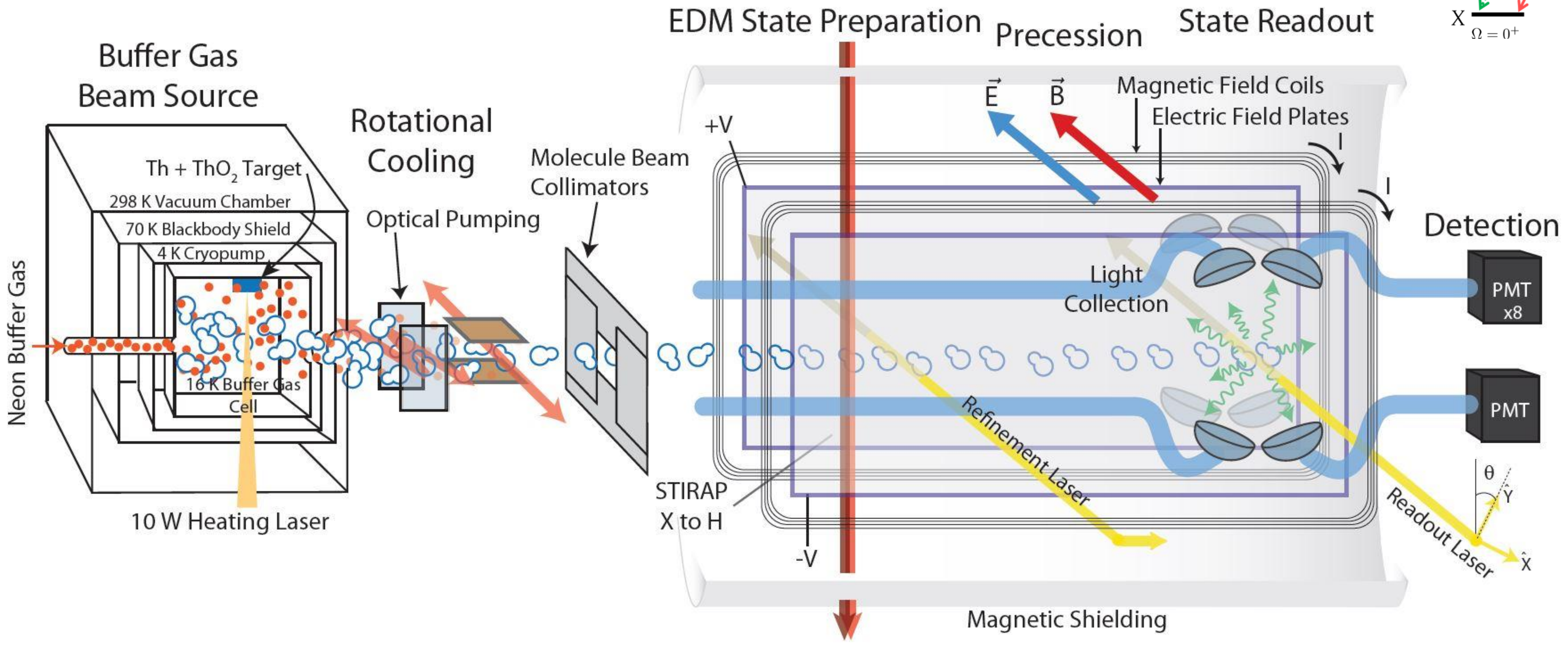
- Measured d_e=(-2.1±3.7$_{stat}$±2.5$_{syst}$) x 10^{-29} e cm.
- Consistent with 0!

$|d_e| < 8.7 \times 10^{-29}$ e cm (90 % Confidence).

Parameter	Shift	Uncertainty
$\mathcal{E}^{\rm nr}$ correction	-0.81	0.66
$\Omega_{\rm r}^{\mathcal{N}\mathcal{E}}$ correction	-0.03	1.58
$\phi^{\mathcal{E}}$ correlated effects	-0.01	0.01
$\phi^{\mathcal{N}}$ correlation		1.25
Non-Reversing $\mathcal{B}$-field ($\mathcal{B}_z^{\rm nr}$)		0.86
Transverse $\mathcal{B}$-fields $\left(\mathcal{B}_x^{\rm nr}, \mathcal{B}_y^{\rm nr}\right)$		0.85
$\mathcal{B}$-Field Gradients		1.24
Prep./Read Laser Detunings		1.31
$\tilde{\mathcal{N}}$ Correlated Detuning		0.90
$\mathcal{E}$-field Ground Offset		0.16
Total Systematic	-0.85	3.24
Statistical		4.80
Total Uncertainty		5.79

Present and future: GEN II





2. Thermochemical beam source (up to x10)

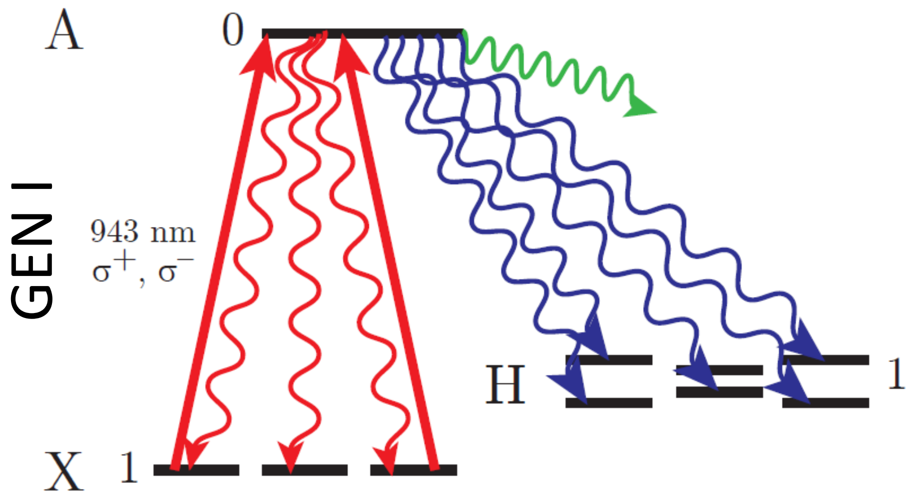
3. Geometric Improvements (x7)

1. STIRAP state preparation (up to x17)

4. Readout/collection improvements(x4)

1. STIRAP state preparation

- Currently, state preparation using incoherent optical pumping is ~6% efficient.

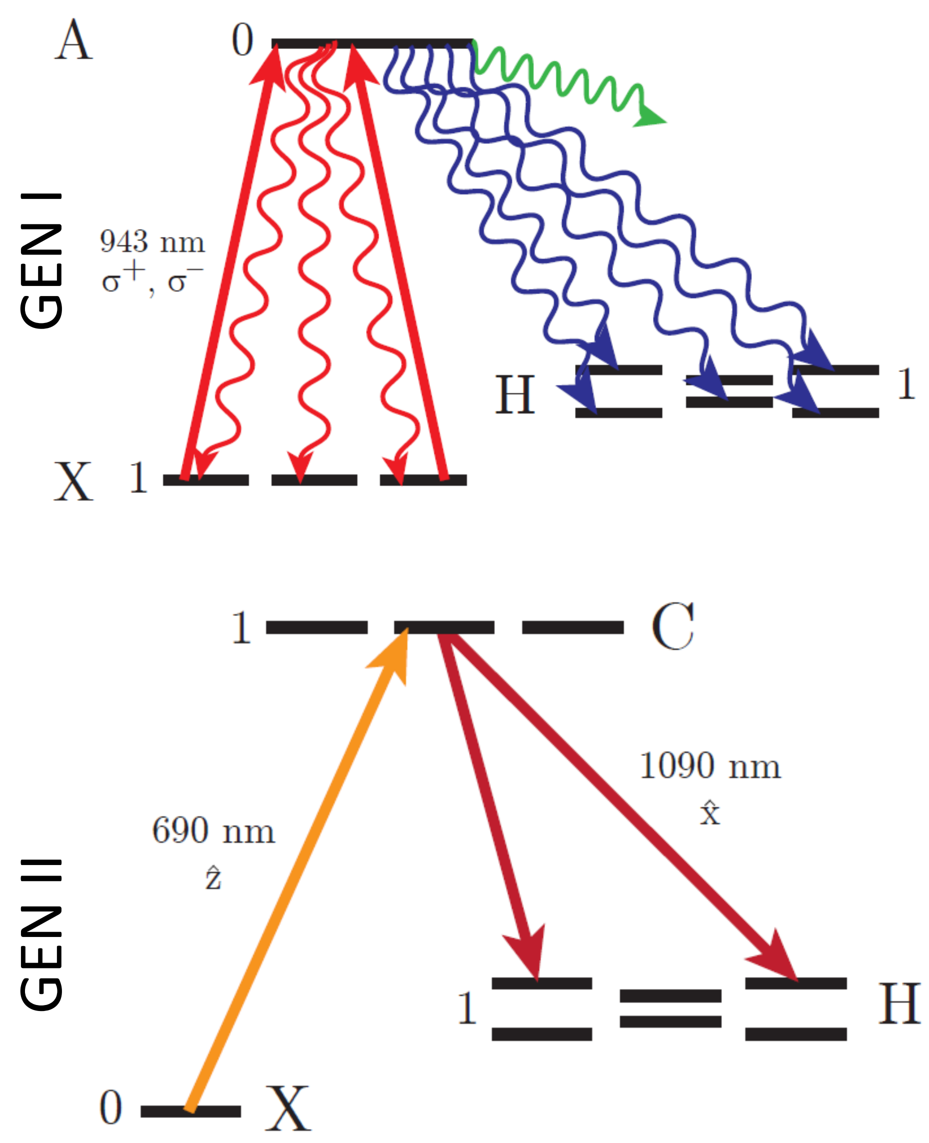


1. STIRAP state preparation

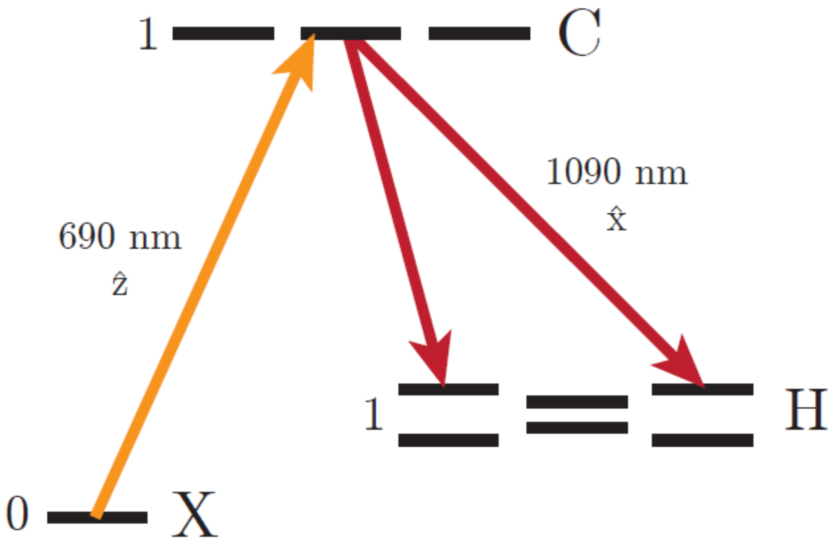
- Currently, state preparation using incoherent optical pumping is ~6% efficient.

↓

- STIRAP can coherently transfer population into the desired state superposition with close to 100% efficiency.



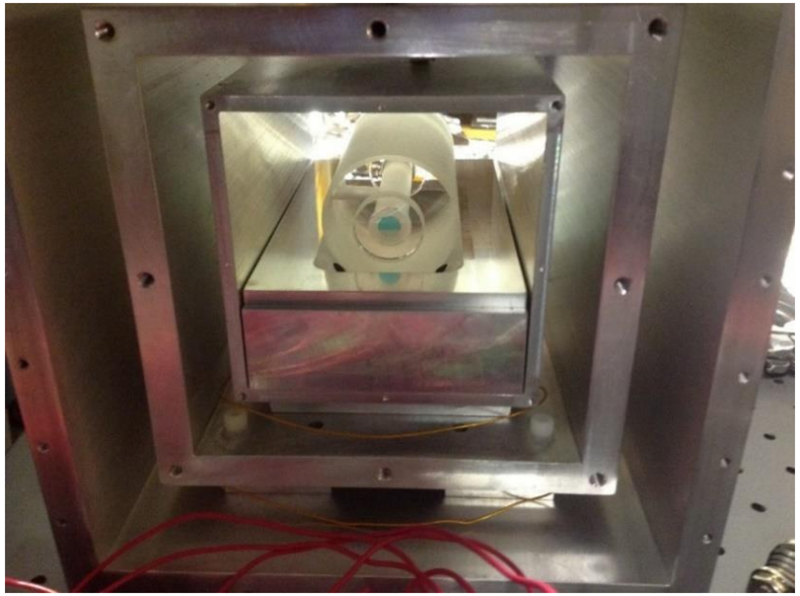
STIRAP in ThO

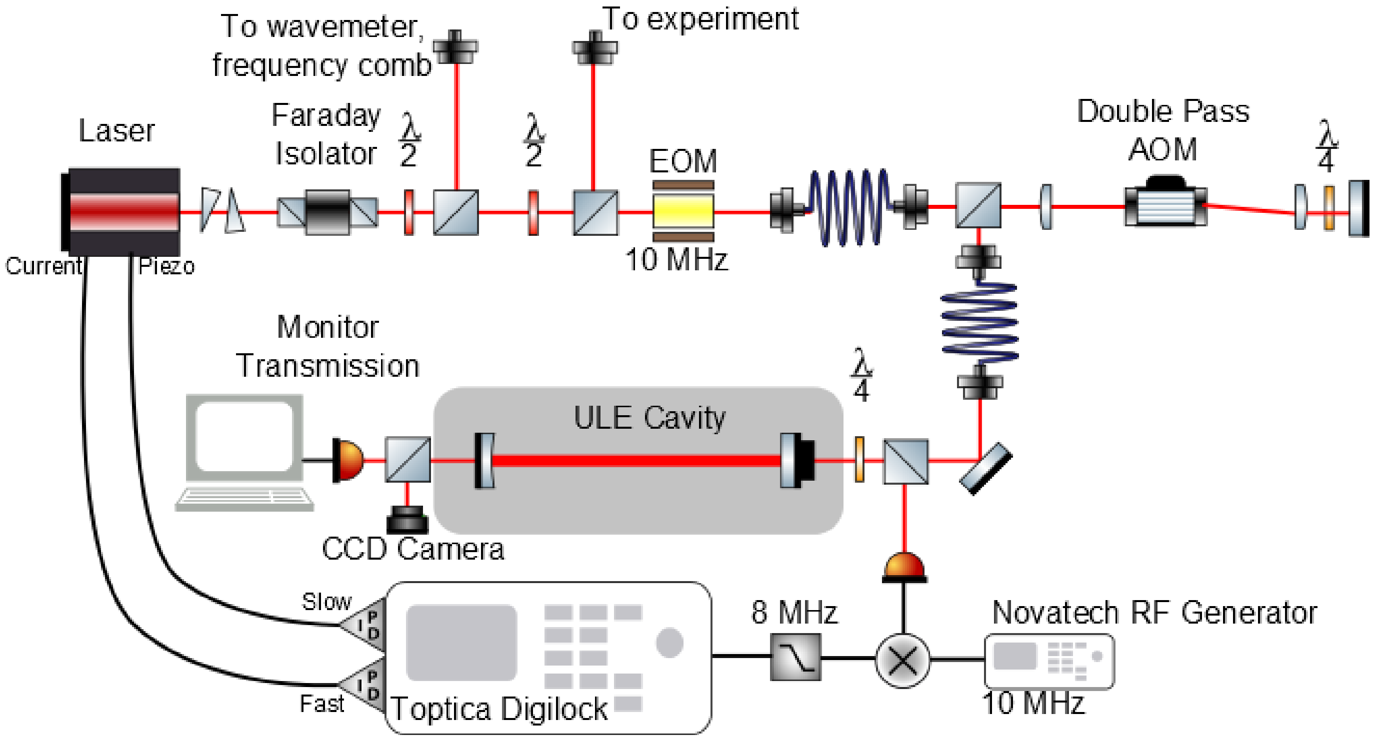


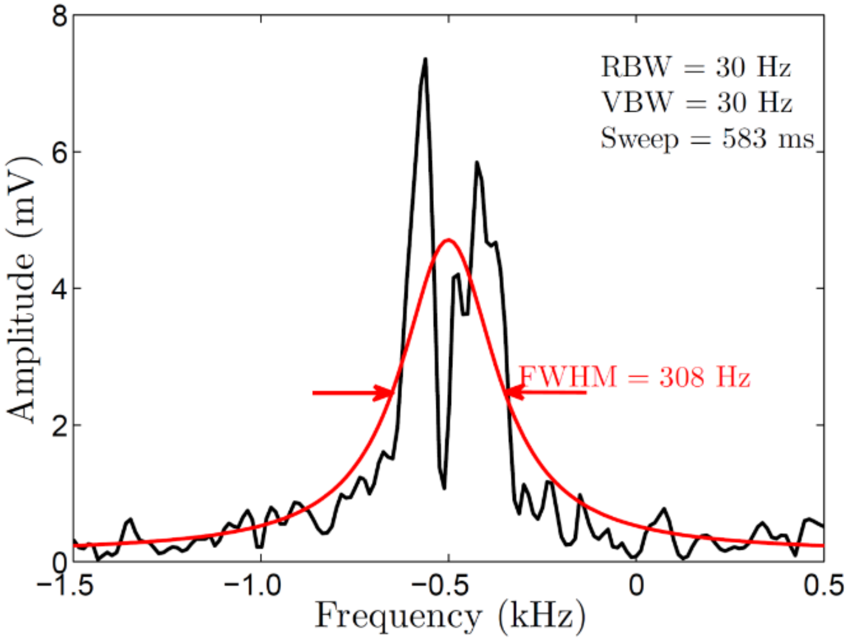
- Well understood and established technique – STIRAP in molecular beam done by Klaas Bergmann 25 years ago in Na_2.
  - Robust, reliable, have to be able to run many hours a day for months.
- But…
  - ThO transitions not strong (d_{HC}=0.01 ea0) -> Need lots of intensity ->More power or focus more
  - Two photons almost a factor of two in frequency apart (690 and 1090 nm), large transversal Doppler velocity distribution (1 m/s) -> large Doppler two photon detunings ->Even more intensity to saturate
  - Large diameter of the molecular beam to be addressed (25 mm), 5 layers of mu metal shielding, robust vacuum chamber, field plates -> Laser beamshaping might not be trivial.

Narrow laser system

- Lasers locked to ULE cavities for linewidth reduction.
- Frequency comb used for absolute frequency reference.

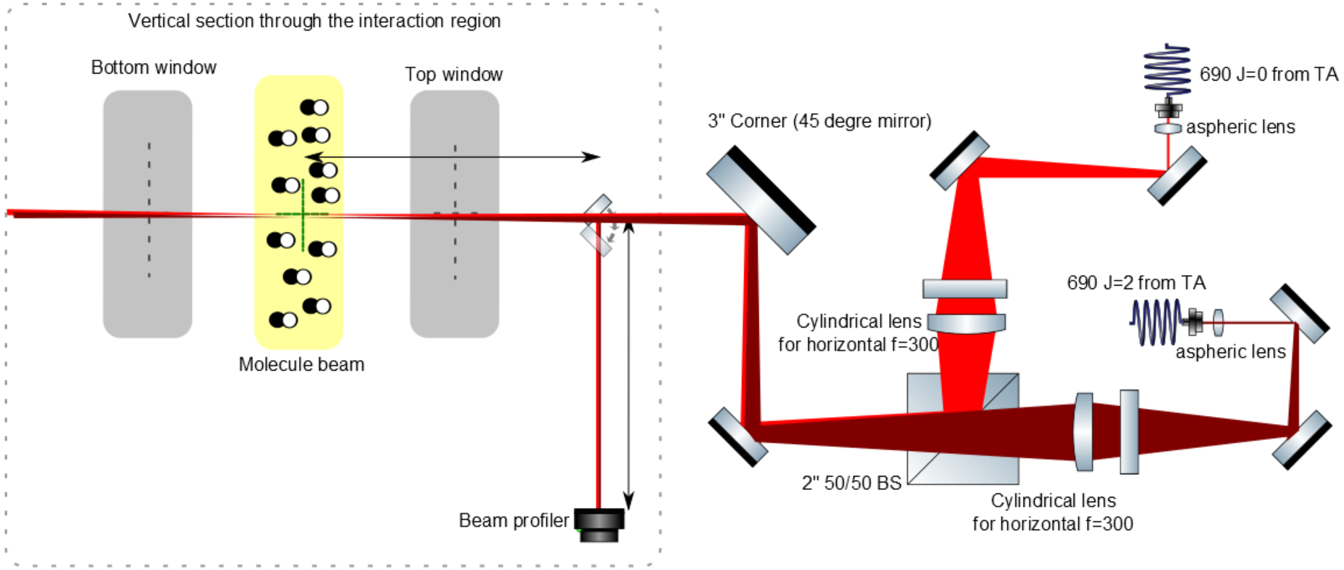


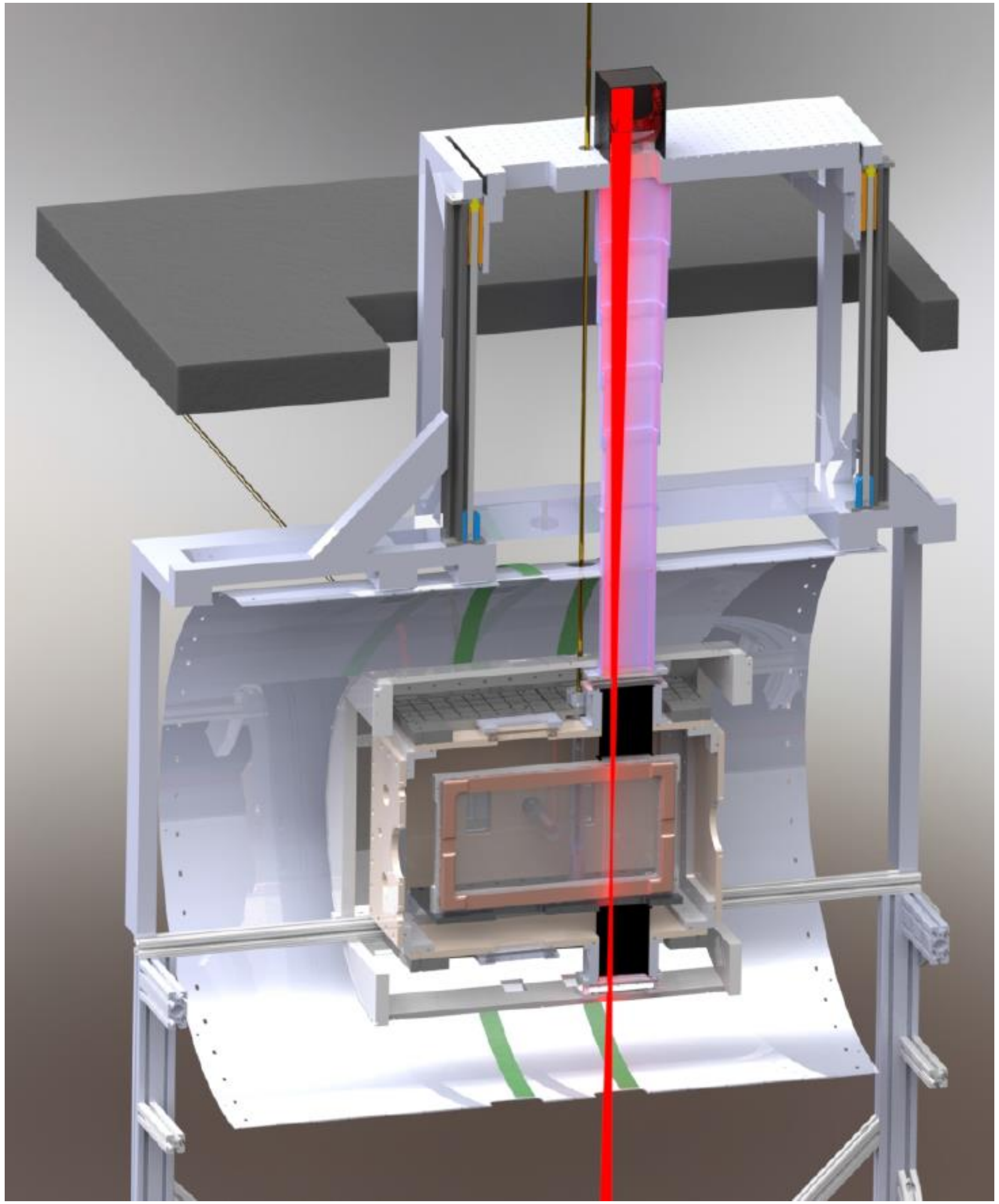




Vertical access for STIRAP

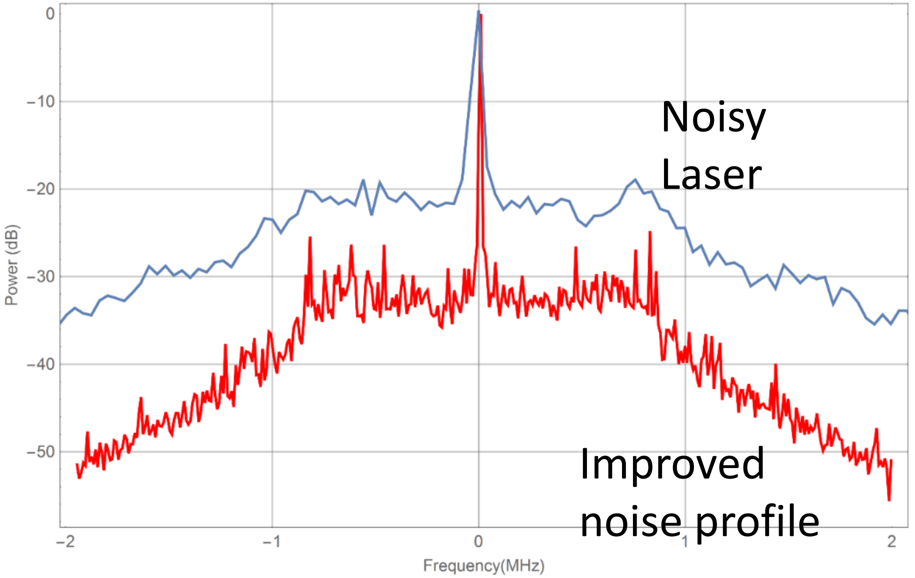
- Vertical STIRAP beams to avoid shining high intensity lasers on the ITO field plates.
- Laser beamshaping and relative pointing alignment vital to ensure optimal overlap across the molecular beam.

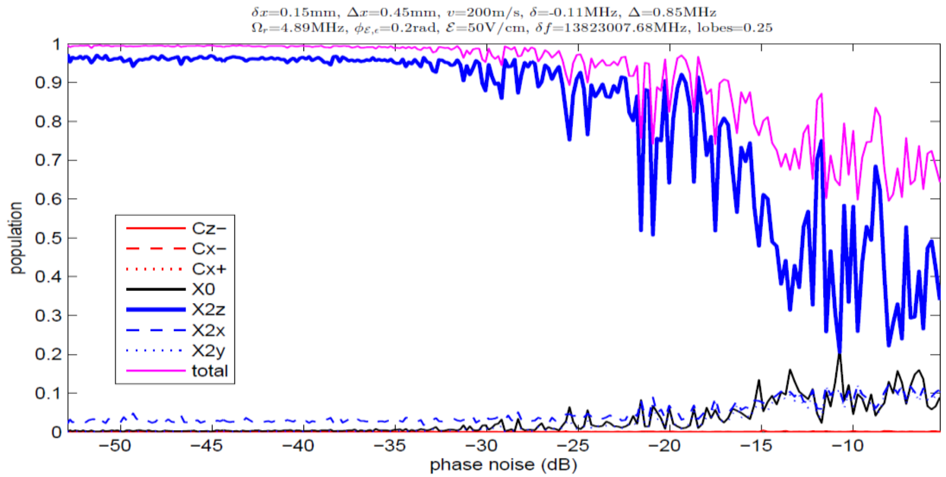




Laser phase noise decreases transfer efficiency

- Two photon linewidth of ~2 MHz.
- ECDL phase noise outside of the two photon linewidth decoheres the STIRAP process and populates the bright state.
- Population remains in initial state or decays away. Observed initial transfer rates of ~35%.
- Narrower, quieter lasers alleviate problems.





PHYSICAL REVIEW A **89**, 013831 (2014)

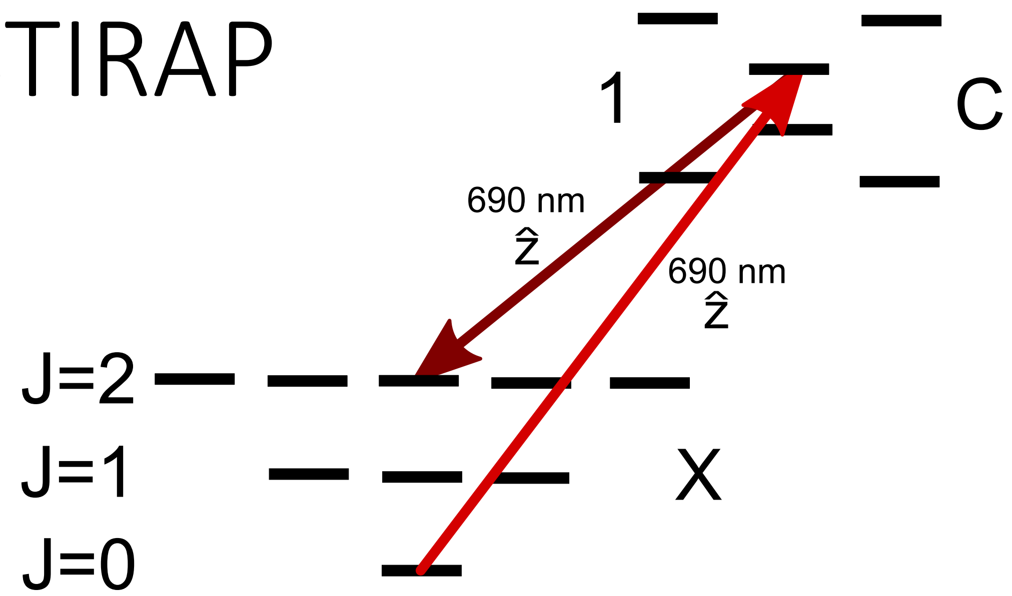
Detrimental consequences of small rapid laser fluctuations on stimulated Raman adiabatic passage

L. P. Yatsenko*
Institute of Physics, National Academy of Sciences of Ukraine, prospect Nauki 46, Kiev-39, 03650, Ukraine

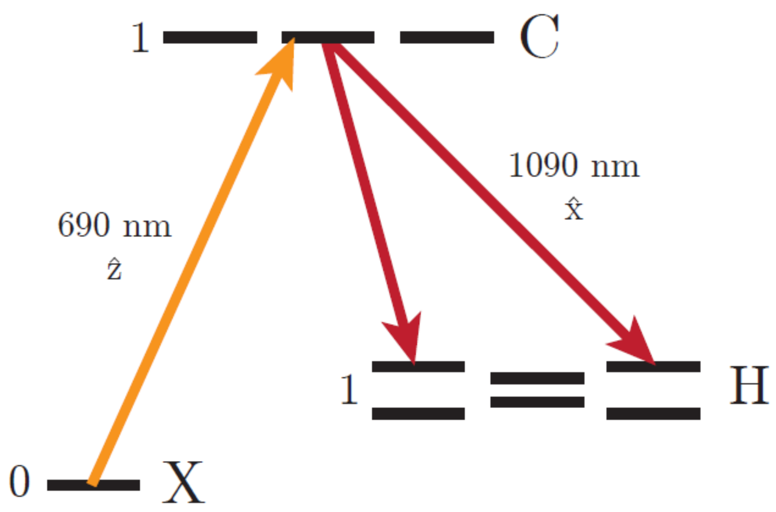
B. W. Shore
618 Escondido Circle, Livermore, California 94550, USA

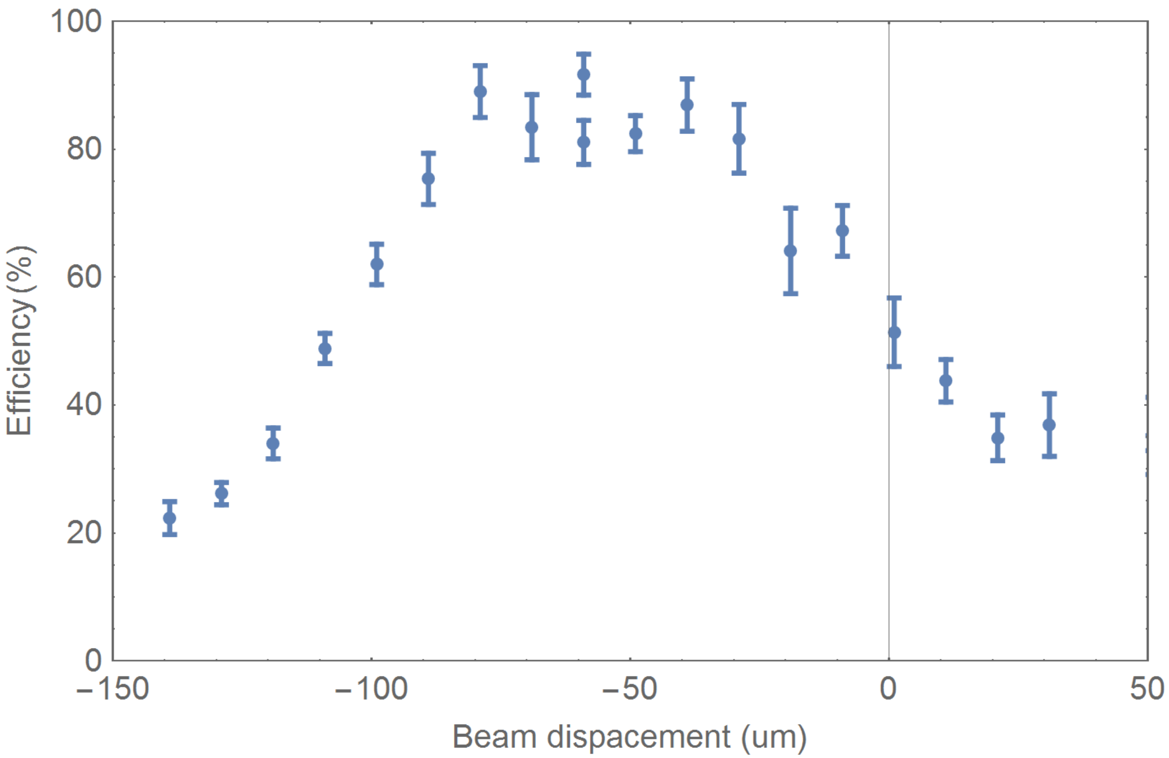
K. Bergmann
Department of Physics and OPTIMAS Research Center, Technical University Kaiserslautern, 67653 Kaiserslautern, Germany
(Received 6 November 2013; published 23 January 2014)

Efficient rotational cooling STIRAP and future



- Tests with transferring population between rotational levels completed successfully.
- Observed transfer efficiencies of ~90%!
- Transfer to experiment state (H state) STIRAP tests are now underway.





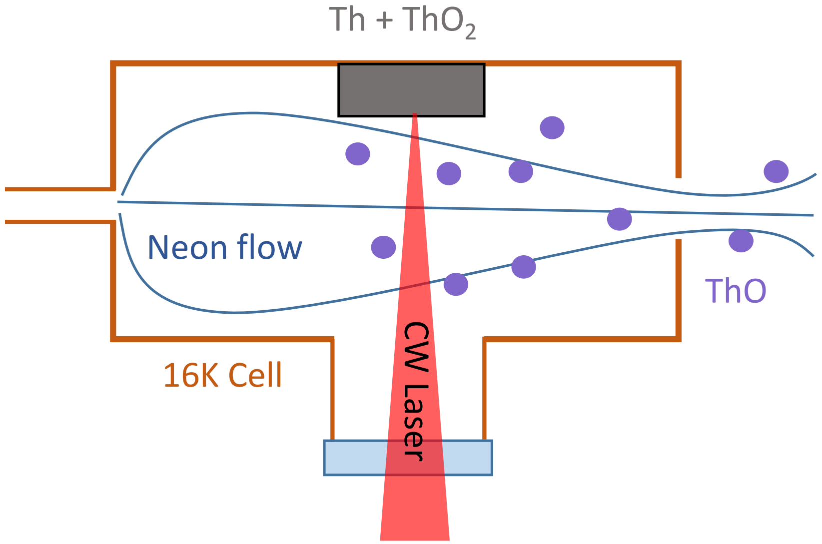
2. Thermochemical beam source

- Chemically favorable reaction (2000K):
  - Th(s)+ThO2(s)-> 2ThO (g)

2. Thermochemical beam source

- Chemically favorable reaction (2000K):
  - Th(s)+ThO2(s)-> 2ThO (g)

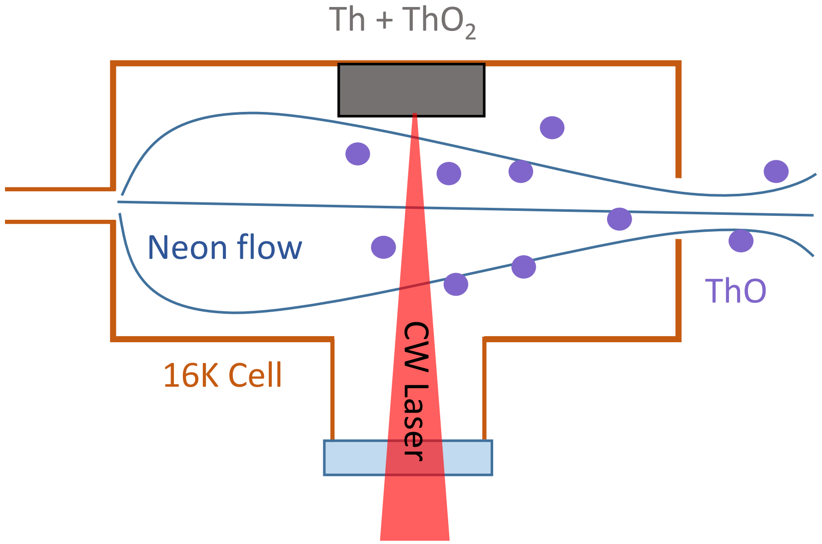
Thermochemical Cell



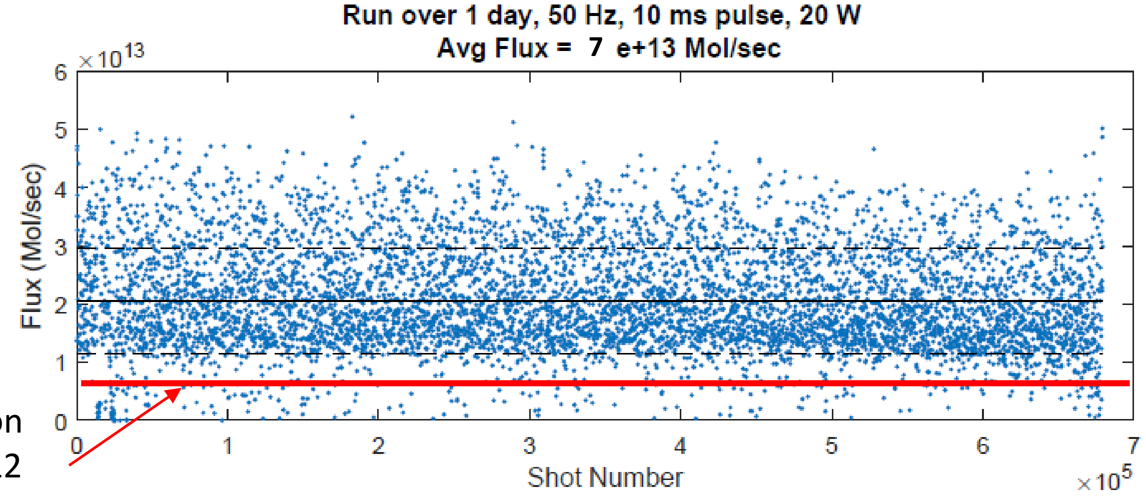
2. Thermochemical beam source

- Chemically favorable reaction (2000K):
  - Th(s)+ThO2(s)-> 2ThO (g)
- Currently working on characterization, optimization.

Thermochemical Cell

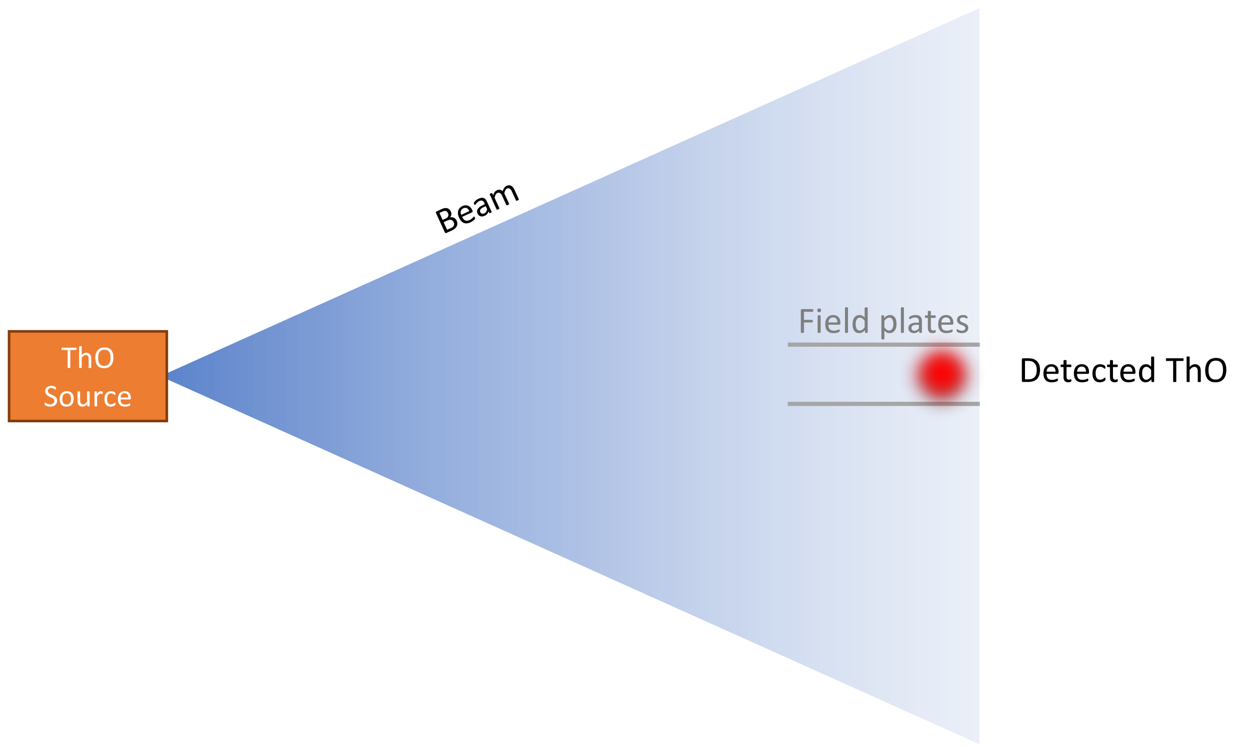


Typ. ablation yield: 5 e+12 Mol/sec



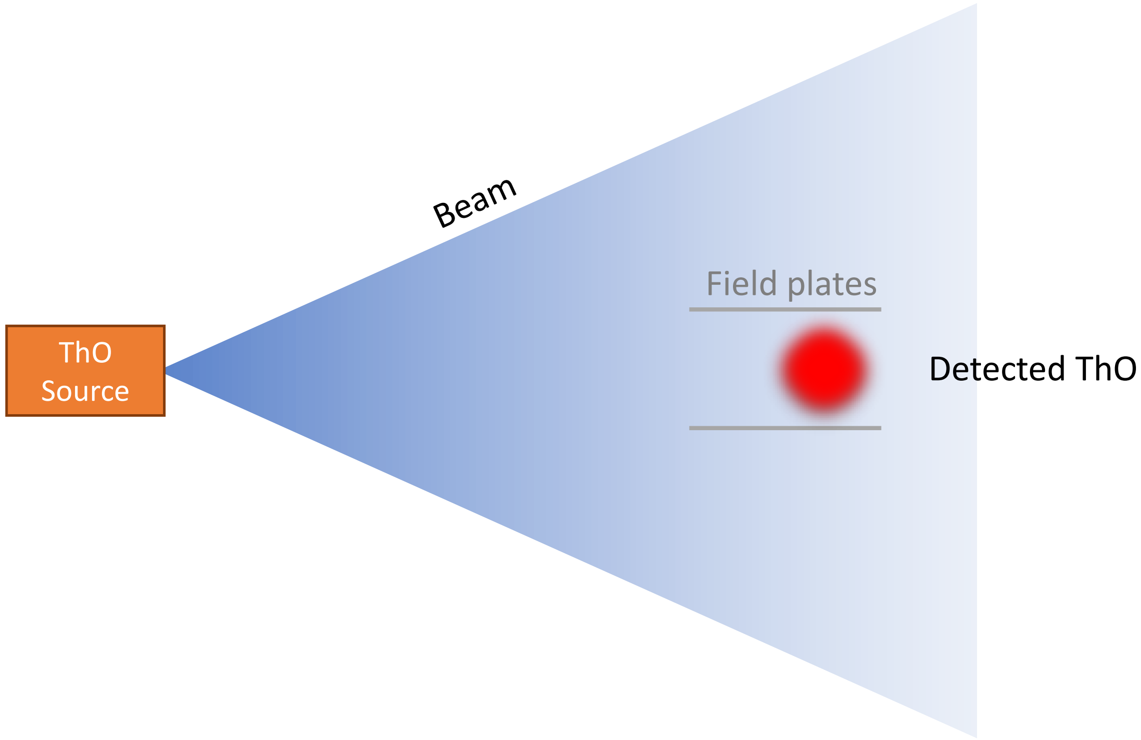
3. Improved experiment geometry

- Molecular beam divergence is 45^{o} FWHM, so only 1 in 10^{5} of produced molecules reaches probe area



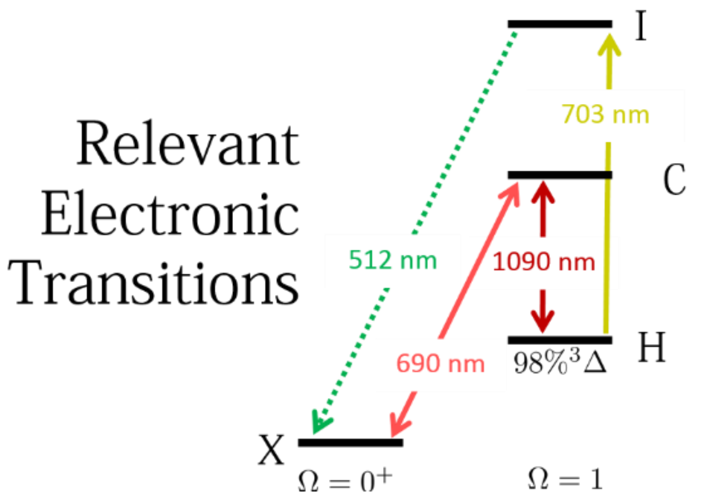
3. Improved experiment geometry

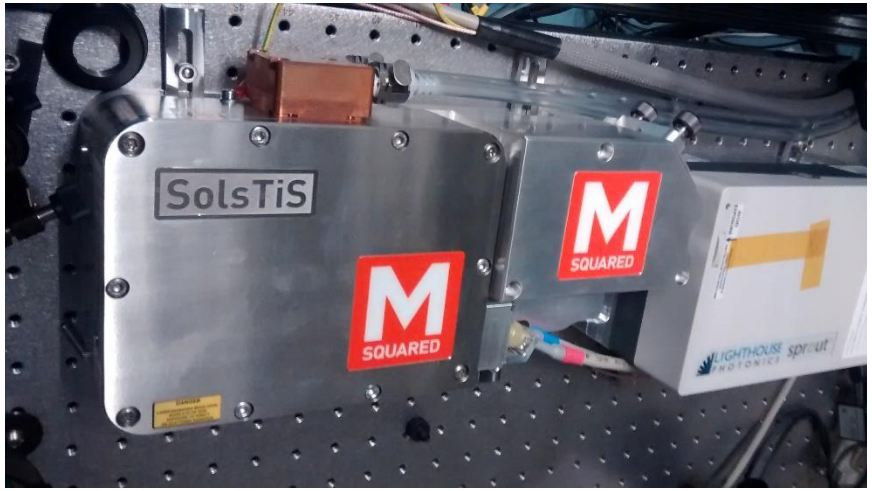
- Molecular beam divergence is 45^o FWHM, so only 1 in 10^5 of produced molecules reaches probe area
- Shorten beamline by a factor of ~1.2 and increase detection region by a factor of ~2.5 to enhance captured solid angle
- Gain ~6-8



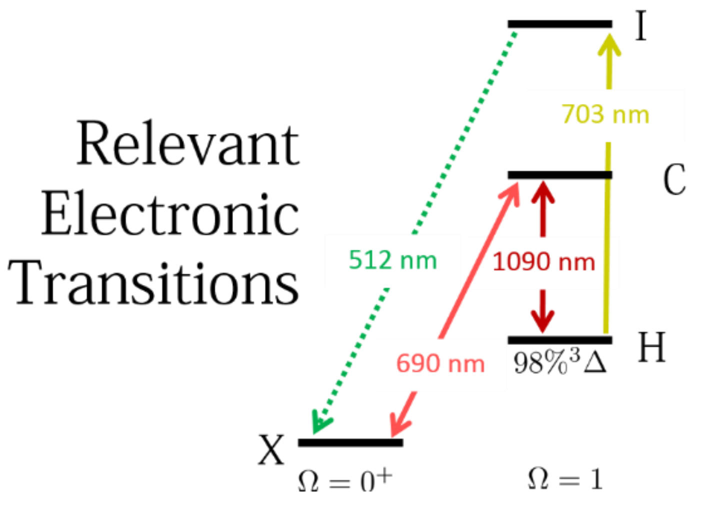
4. Readout/collection efficiency improvements

- I state has two benefits:
  - Eliminate light contamination from STIRAP/probing at the same wavelength (690 nm).
  - Gain of 2.5 in PMT quantum efficiency at shorter wavelength.

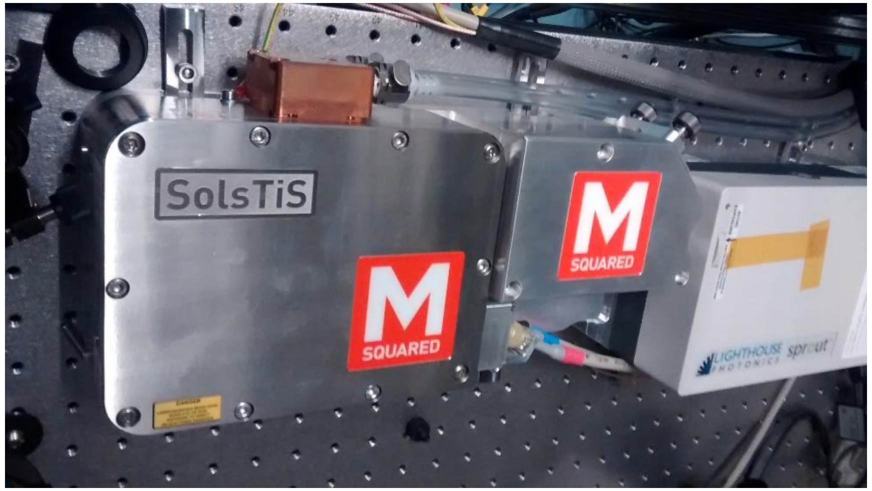


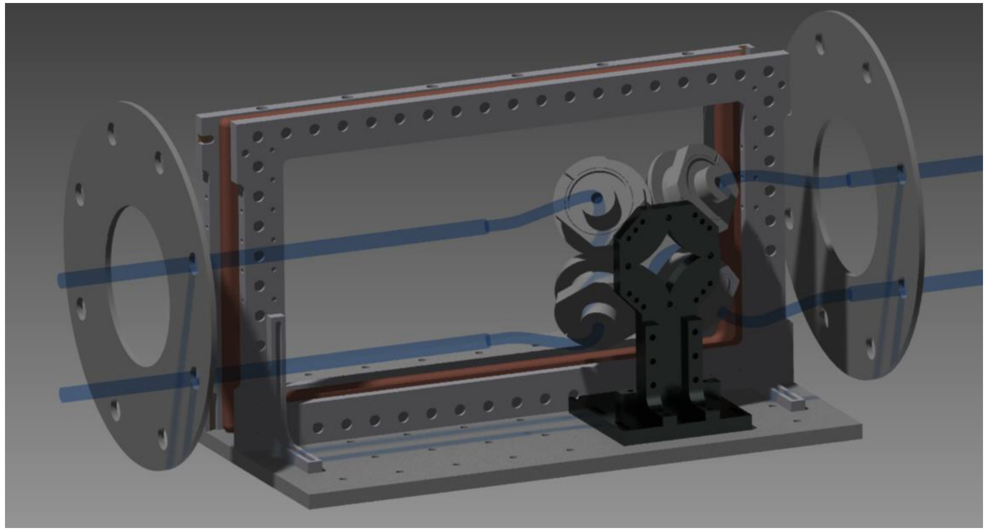


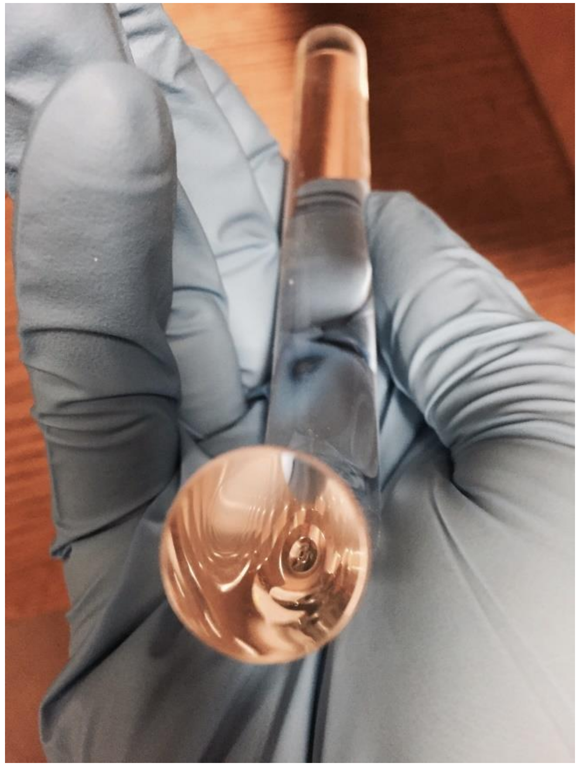
4. Readout/collection efficiency improvements



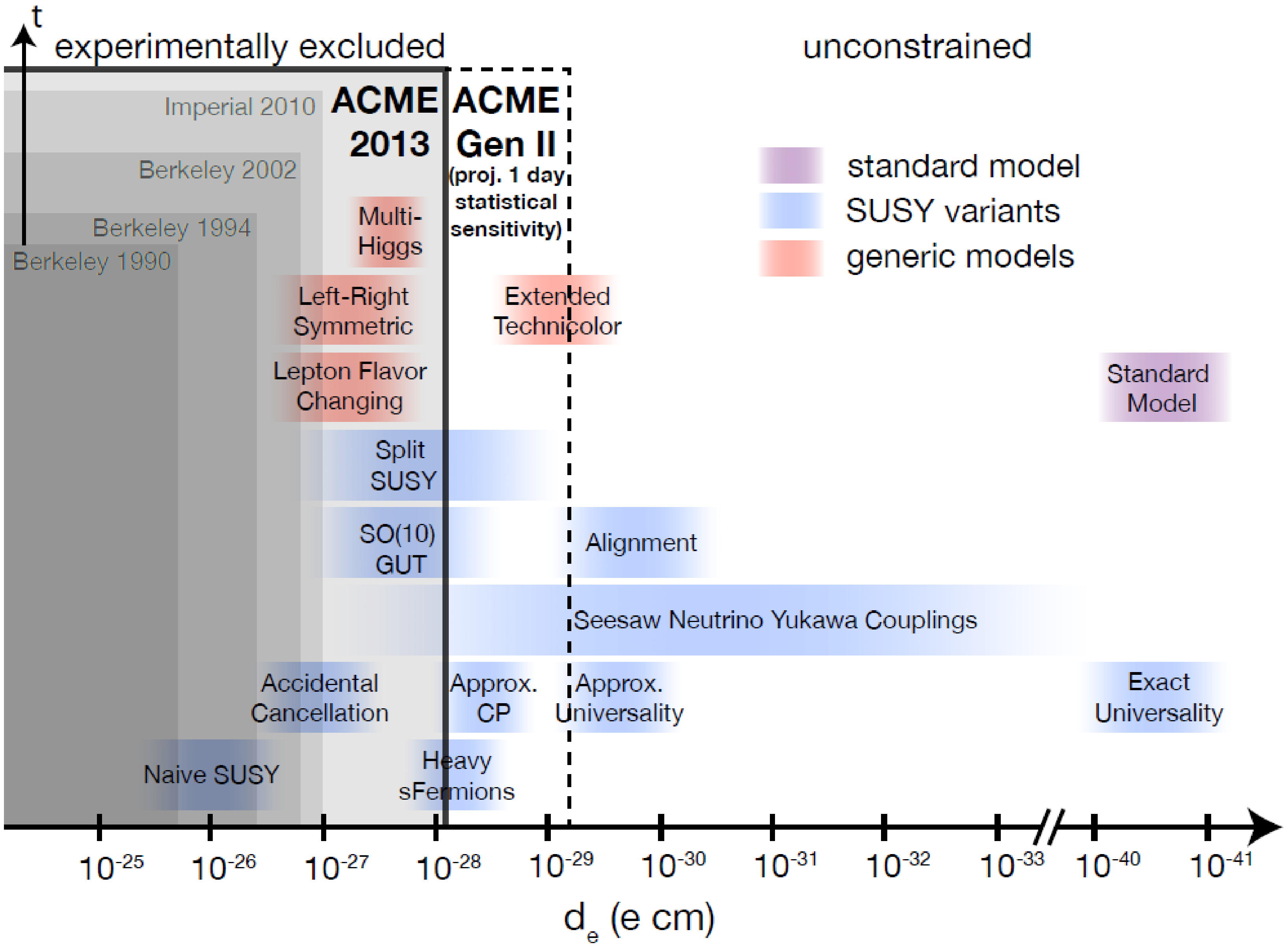
- I state has two benefits:
  - Eliminate light contamination from STIRAP/probing at the same wavelength (690 nm).
  - Gain of 2.5 in PMT quantum efficiency at shorter wavelength.
- Switching from using fiber bundles to bent lightpipes eliminates fiber bundles packing fraction loss.







ACME GEN II Target



ACME Collaboration

Back row:

PI’s (left to right)
John Doyle
Gerald Gabrielse
David DeMille

Alumni:
Wes Campbel
Yulia Gurevich
Paul Hess
Nicholas Hutzler
Emil Kirilov
Ivan Kozyryev
Ben Spaun
Amar Vutha

Graduate students (left to right)
Elizabeth Petrik
Jacob Baron
Cris Panda
Brendon O’Leary
Zack Lasner

Postdoc (far right)
Adam West

New students, not pictured:
Daniel Ang
Vitaly Andreev
Grey Wilburn