ACME

Advanced Cold Molecule Electron EDM Search

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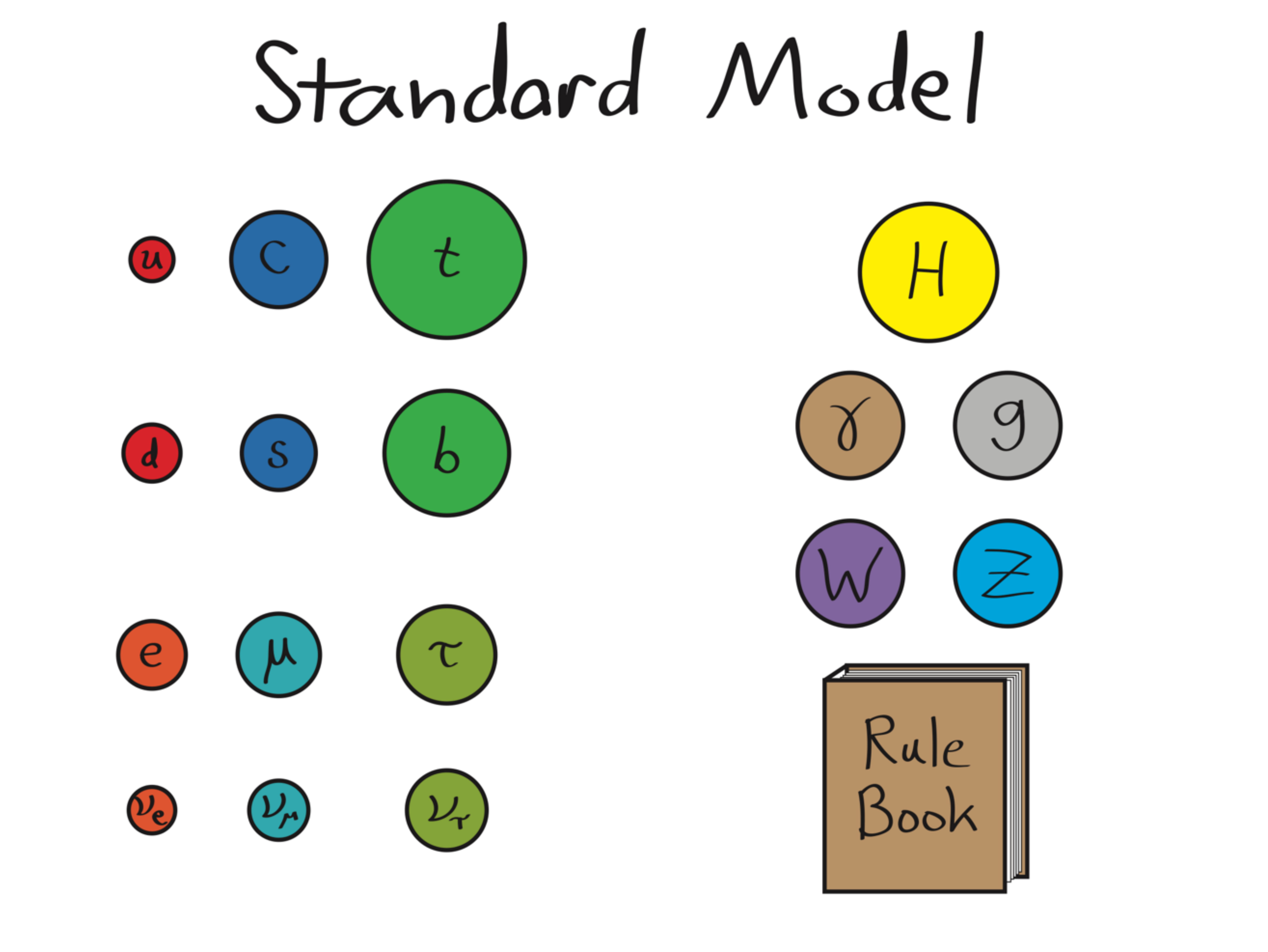
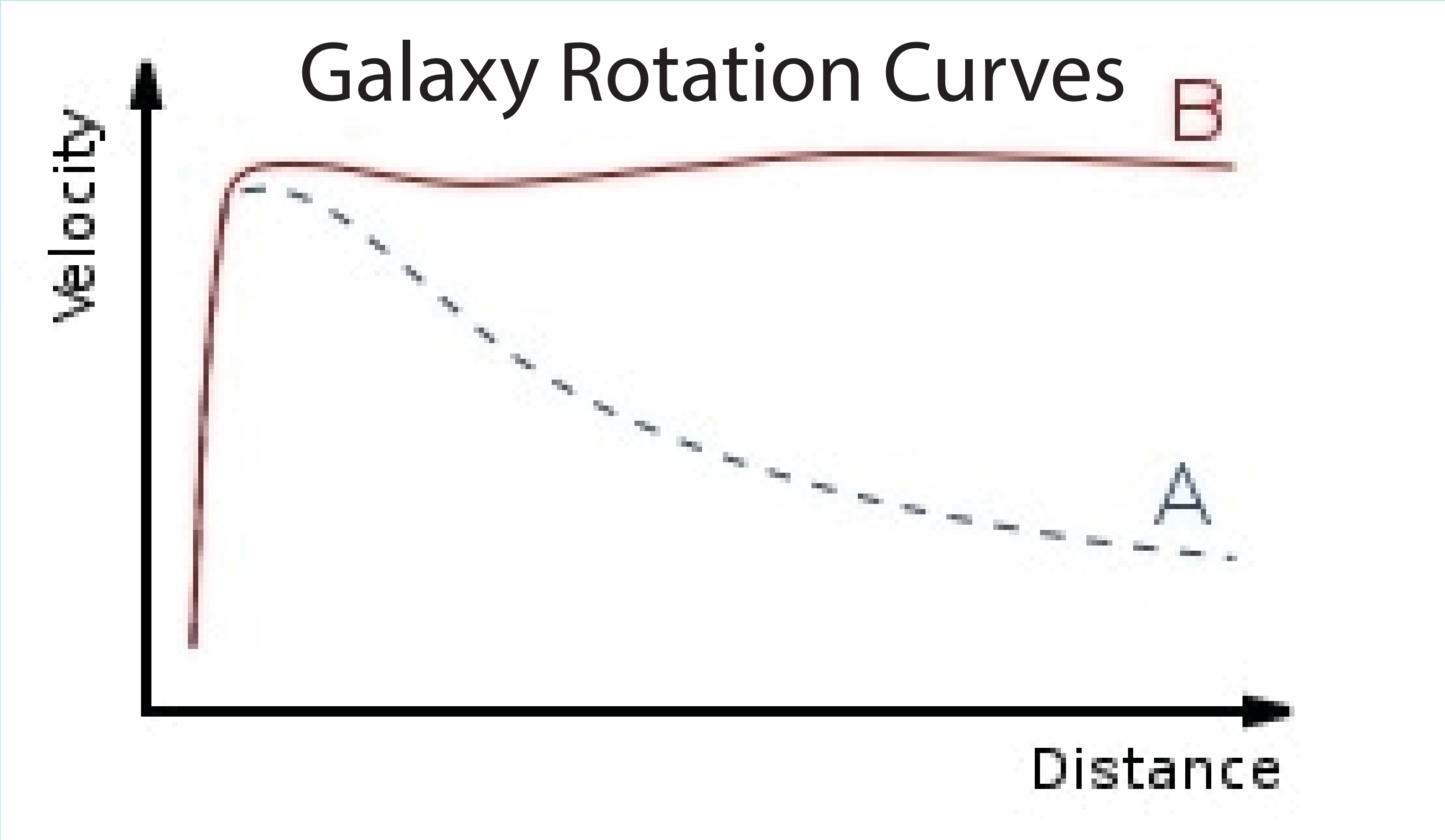
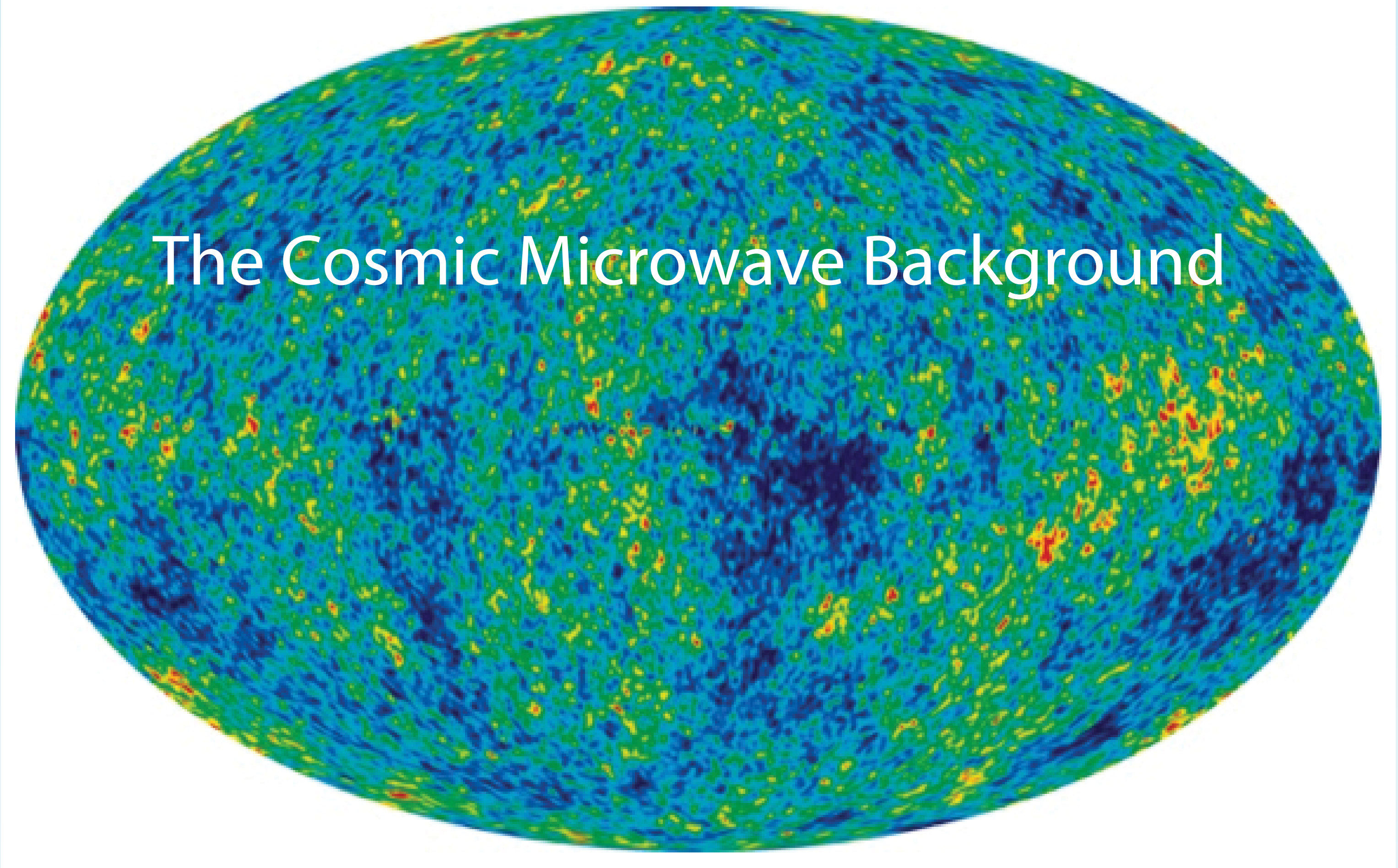
Max Parsons (U) - Harvard Graduate Student, Greiner Group
Yulia Gurevich (G) - Yale PD, Lamoreaux Group
Remi Louf (VS) - IPhT Scientist
Amar Vutha (G) - Professor, University of Toronto
Wes Campbell (G) - Professor, UCLA
Chris Overstreet (U) - Stanford Graduate Student, Kasevich Group
Nick Hutzler (G) - Harvard Postdoc, Ni Group (and ACME collaborator)
Ben Spaun (G) - JILA Postdoc, Ye Group
Paul Hess (G) - JQI Postdoc, Monroe Group

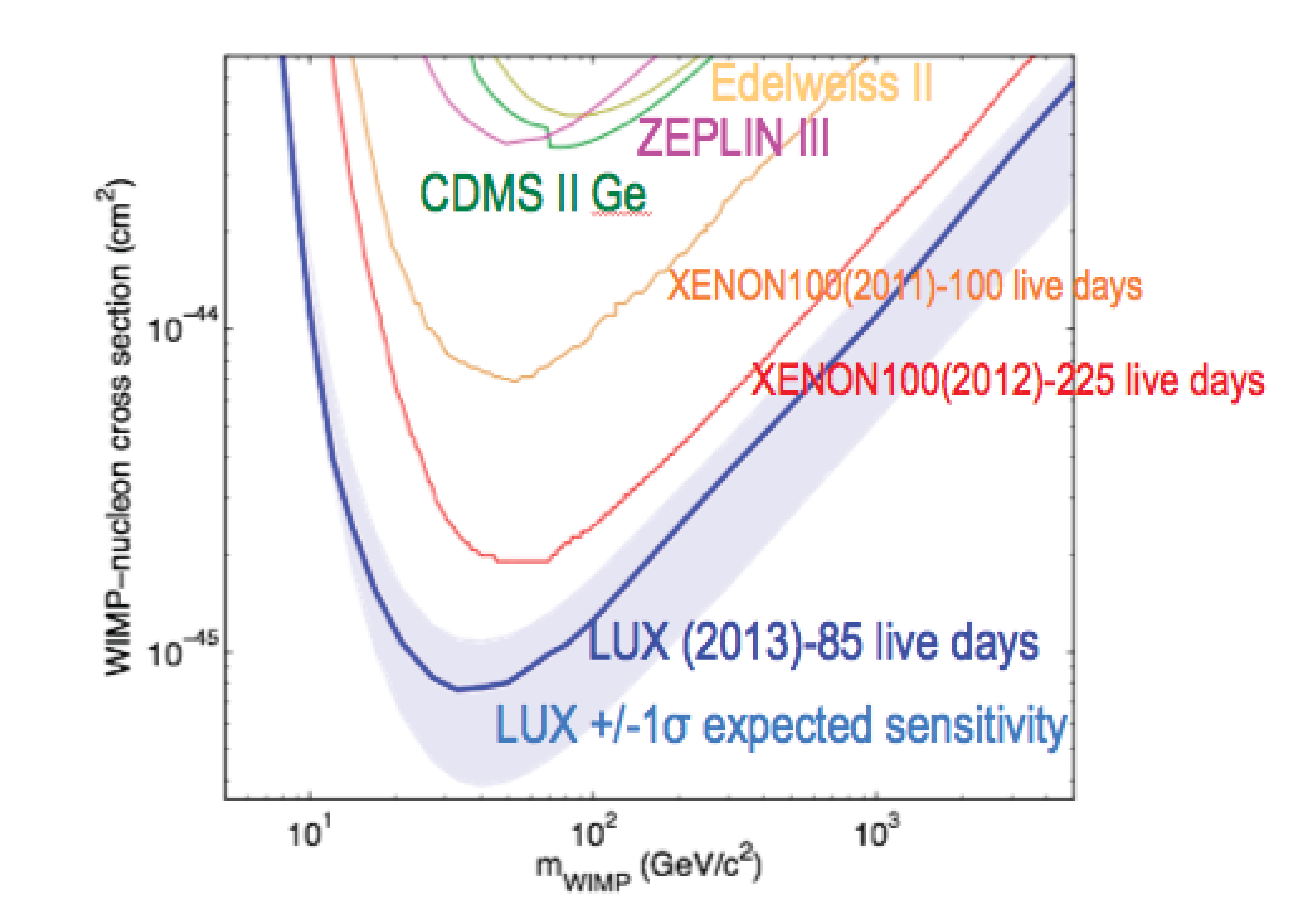
The "Standard Model" Does Not Explain Everything about Particle Physics



Observed Dark Matter — UNEXPLAINED

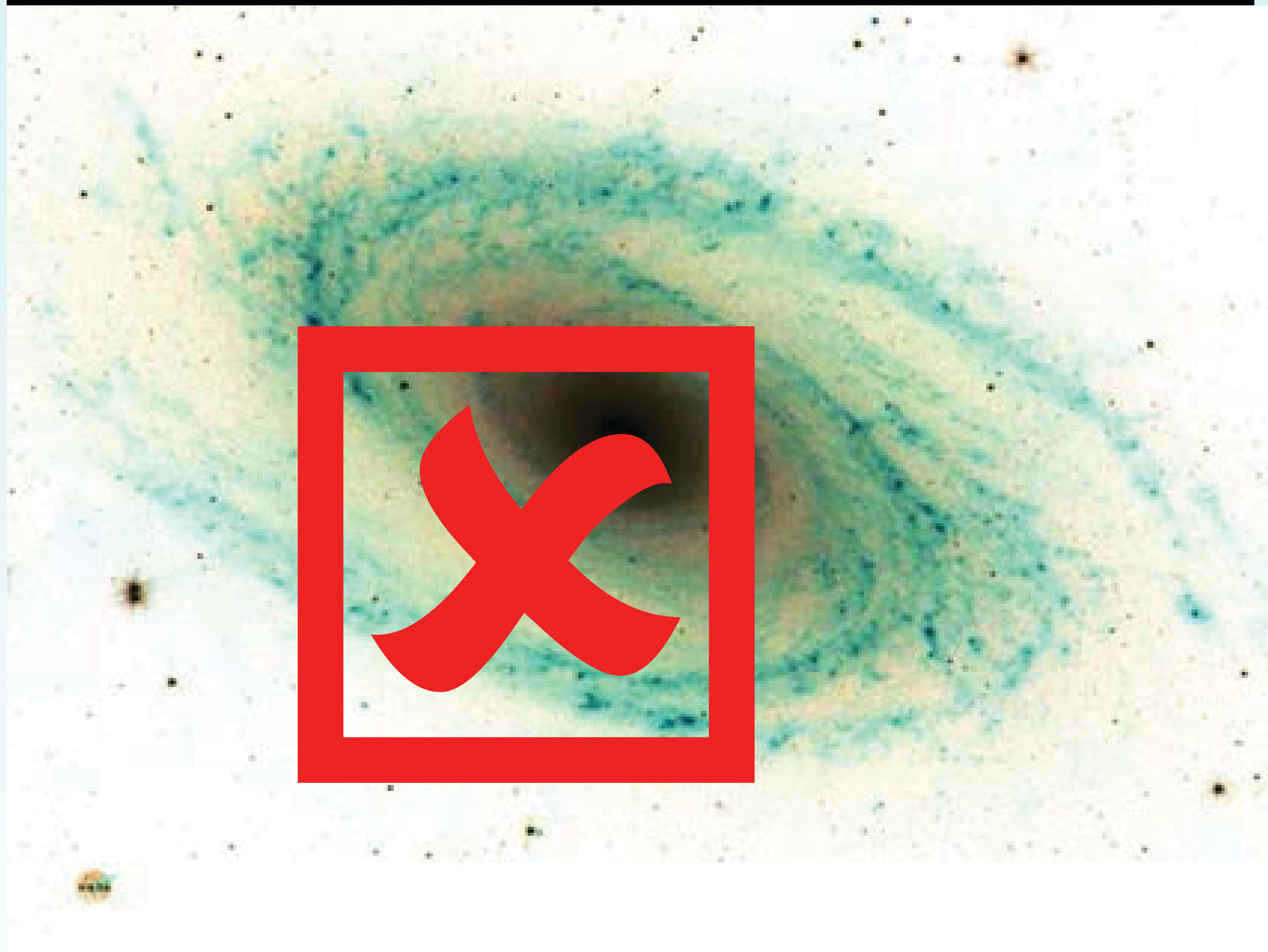






Direct Detection — so far, no dice

Matter/AntiMatter Asymmetry — UNEXPLAINED



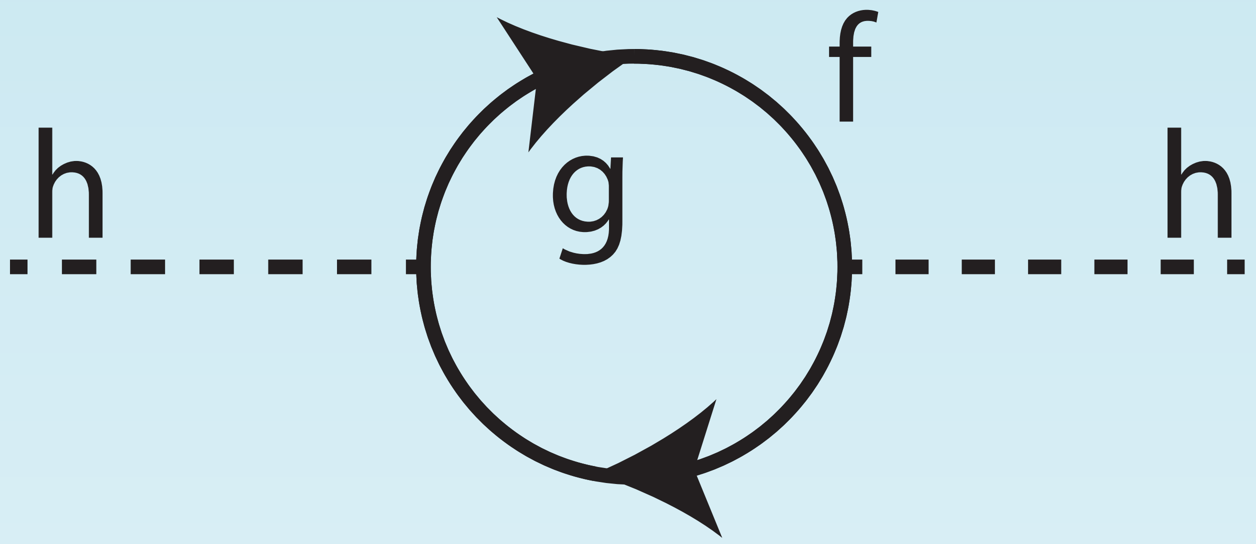
- One key requirement: CP Violation
- CP Violation exits in SM
- Not enough SM $\not{CP}$ to explain our Universe

Observed M/AM asymmetry
REQUIRES T-violation
and
REQUIRES new sources beyond the SM

A. D. Sakharov, JETP Lett. 5, 27 (1967)

Naturalness of the Higgs Mass — *Uncomfortable*

Problem



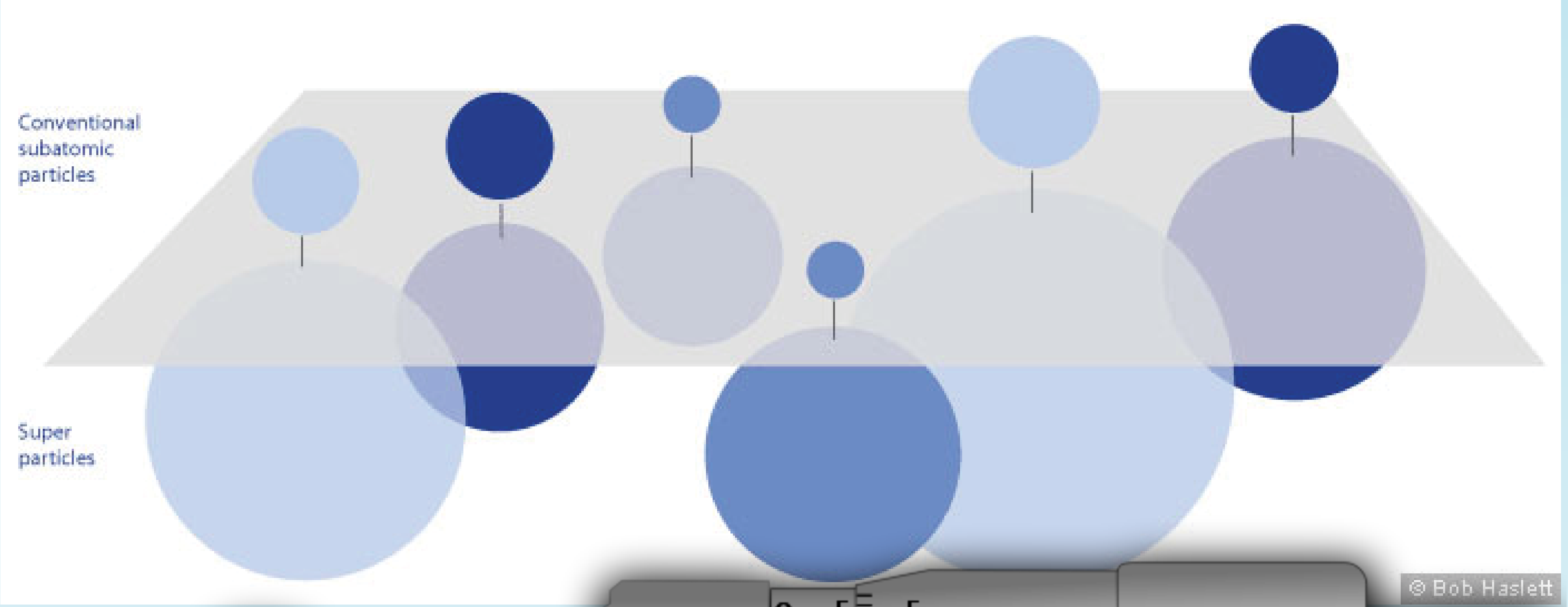
$$m_h \approx \frac{g}{4\pi}\Lambda$$

$$m_h = 125\ \text{GeV}$$

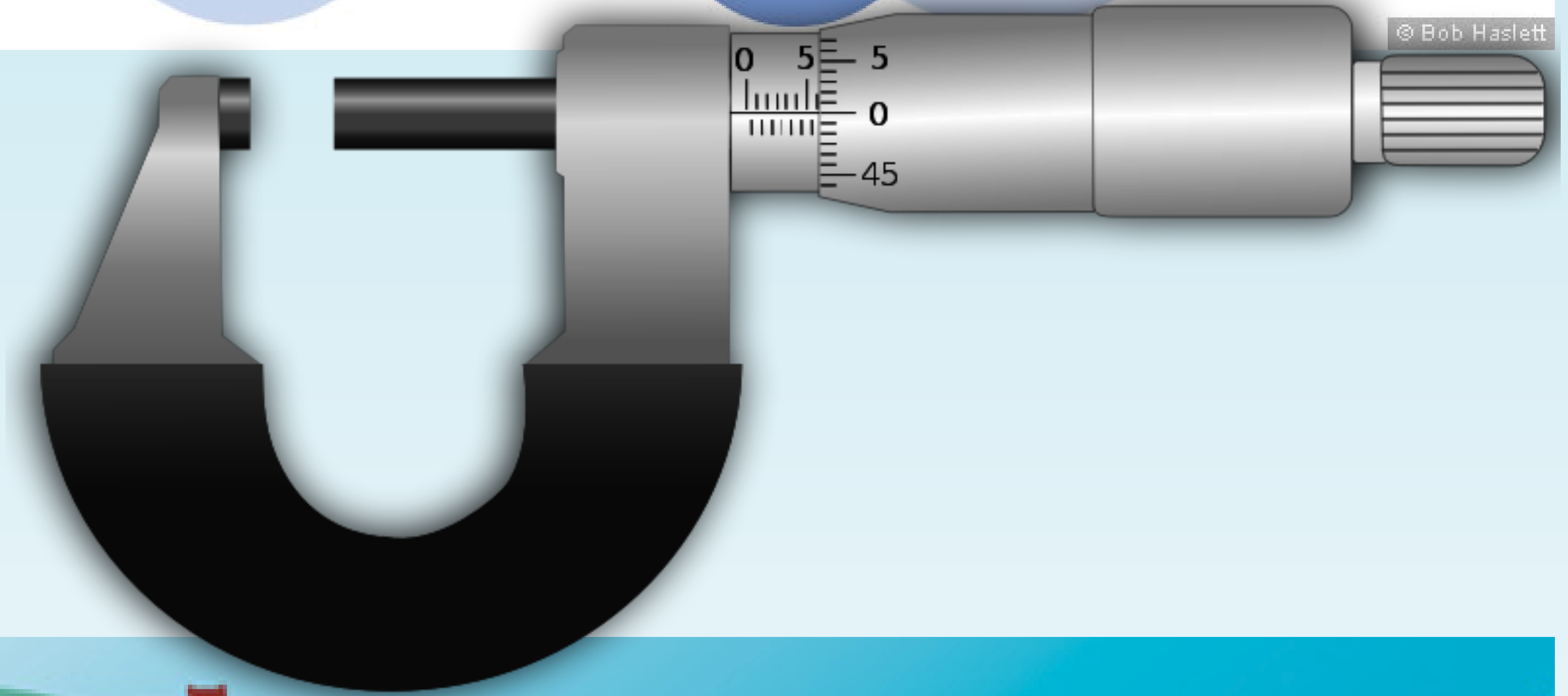
The Higgs Mass^2 is Quadratically Divergent
to Radiative Corrections
So "Naturally" lies near **Lambda,**
UV (New Physics) cutoff

Possible Solutions

Super Particles

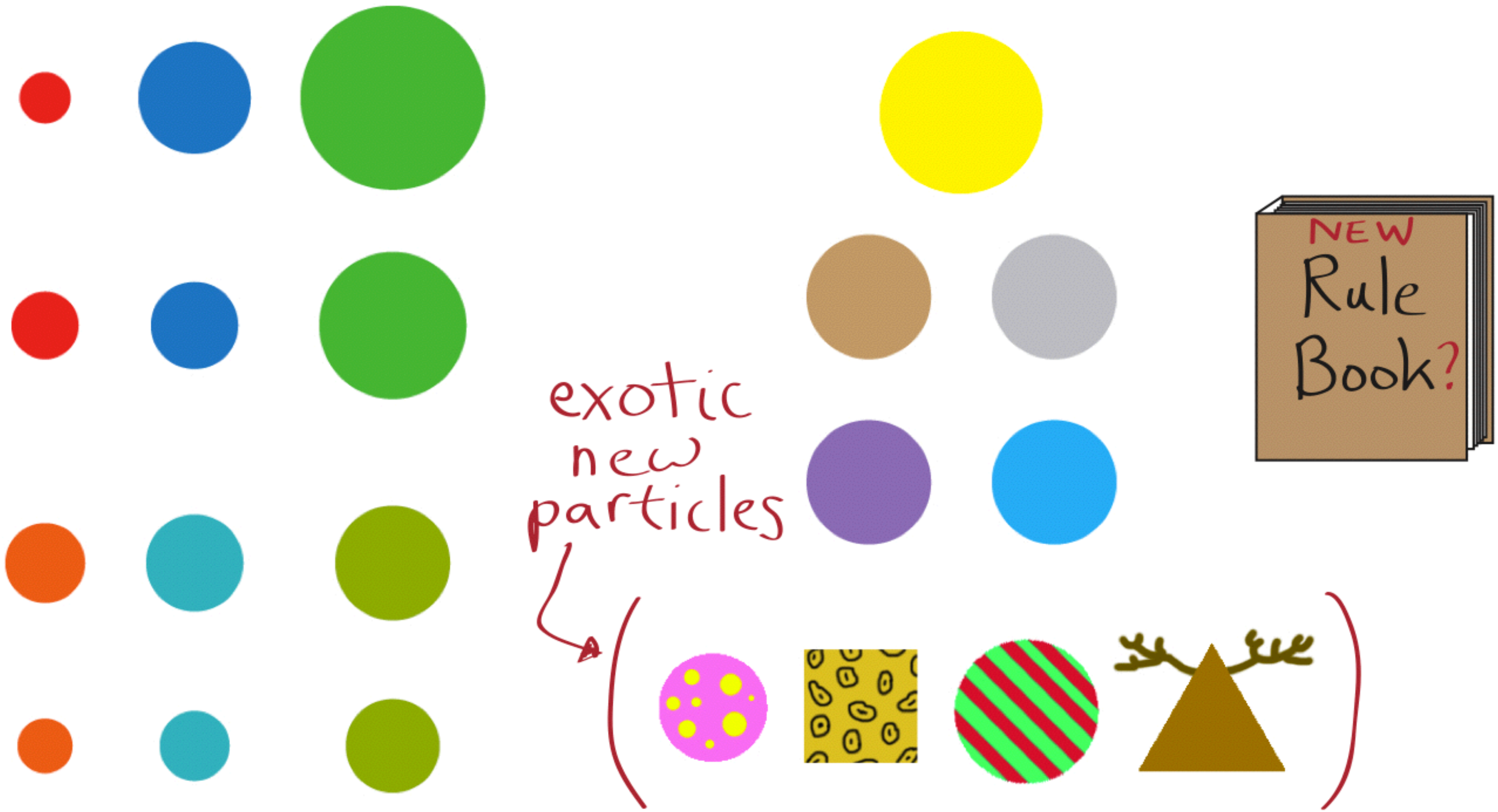


Fine Tuning



Extra Dimensions

Possible Solution

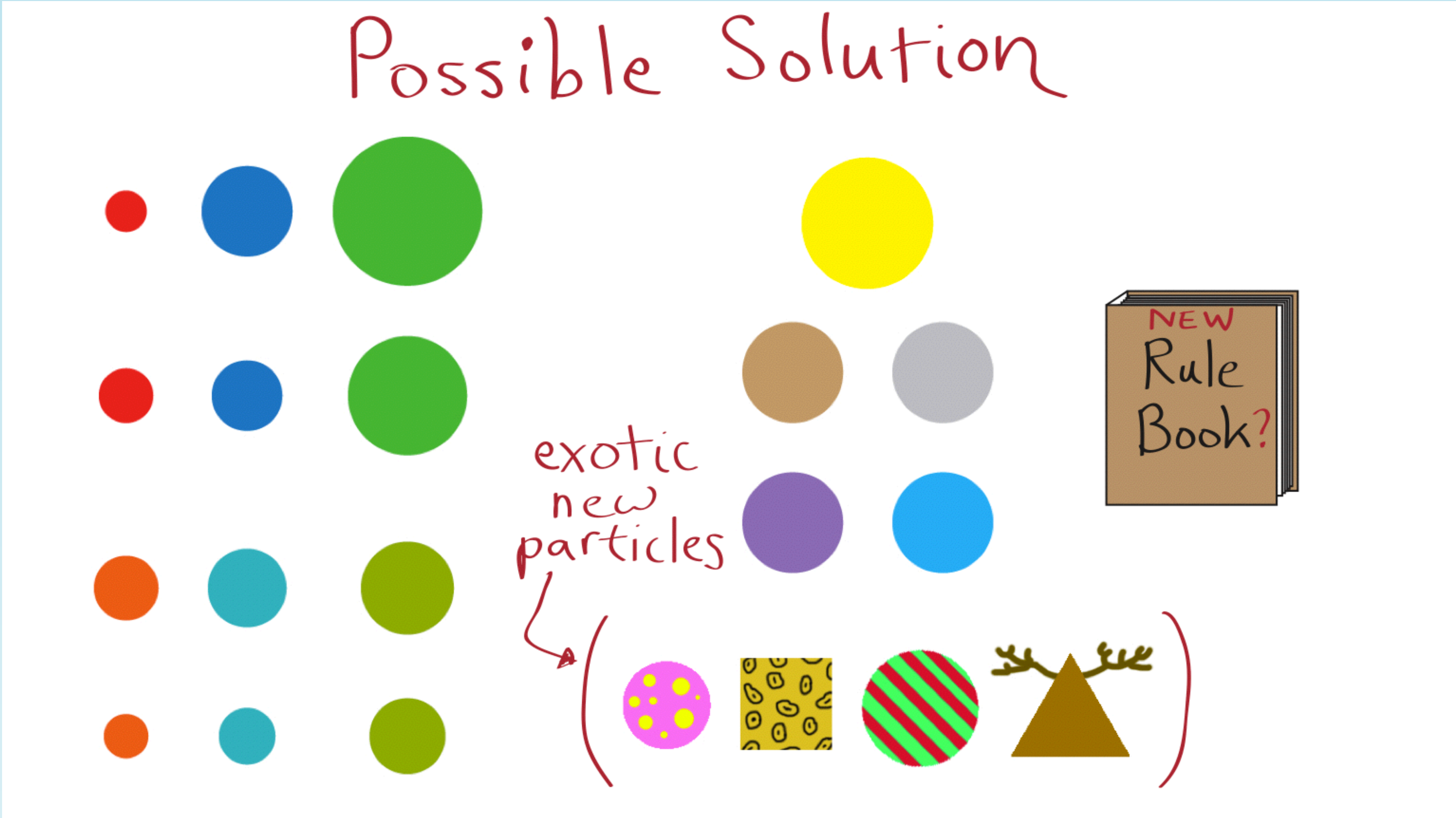


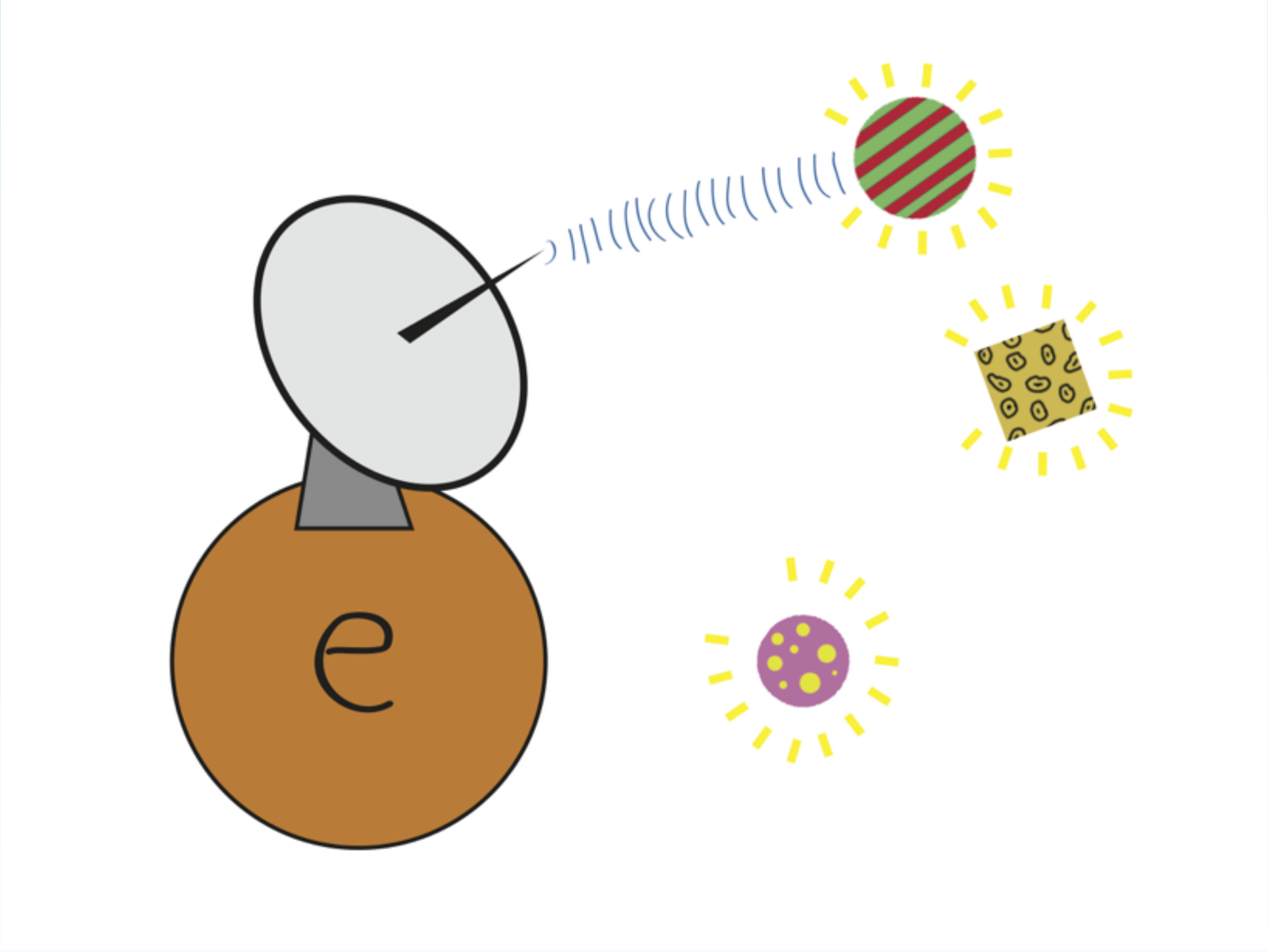
Several SUSY Theories Solve all Problems

☆ Matter/Antimatter
-naturally provides needed T-violation

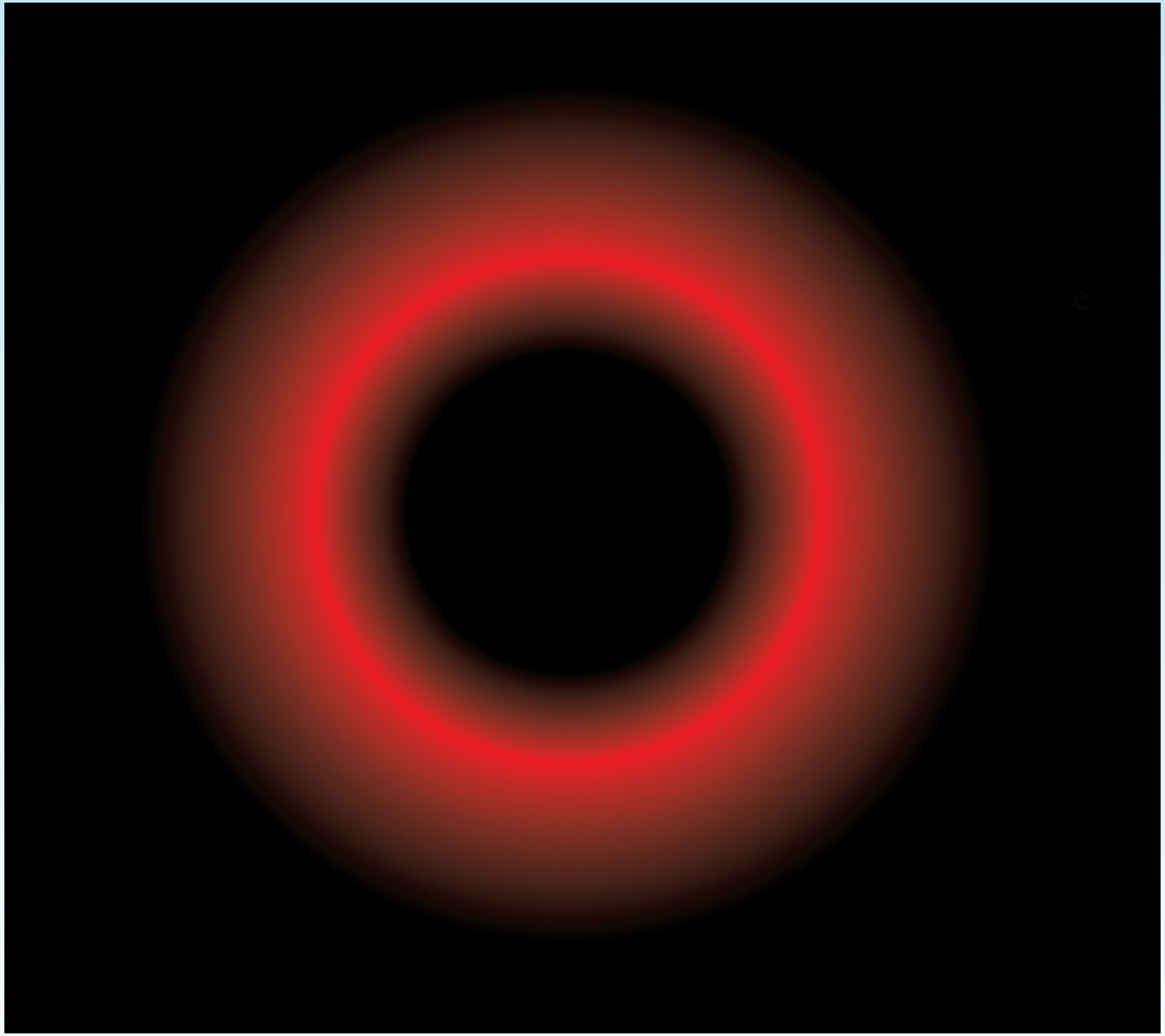
☆ Unification/Hierarchy
- provides needed particles

☆ Dark Matter
- provides candidate particle





Electron is dressed by Virtual Particles — g-2



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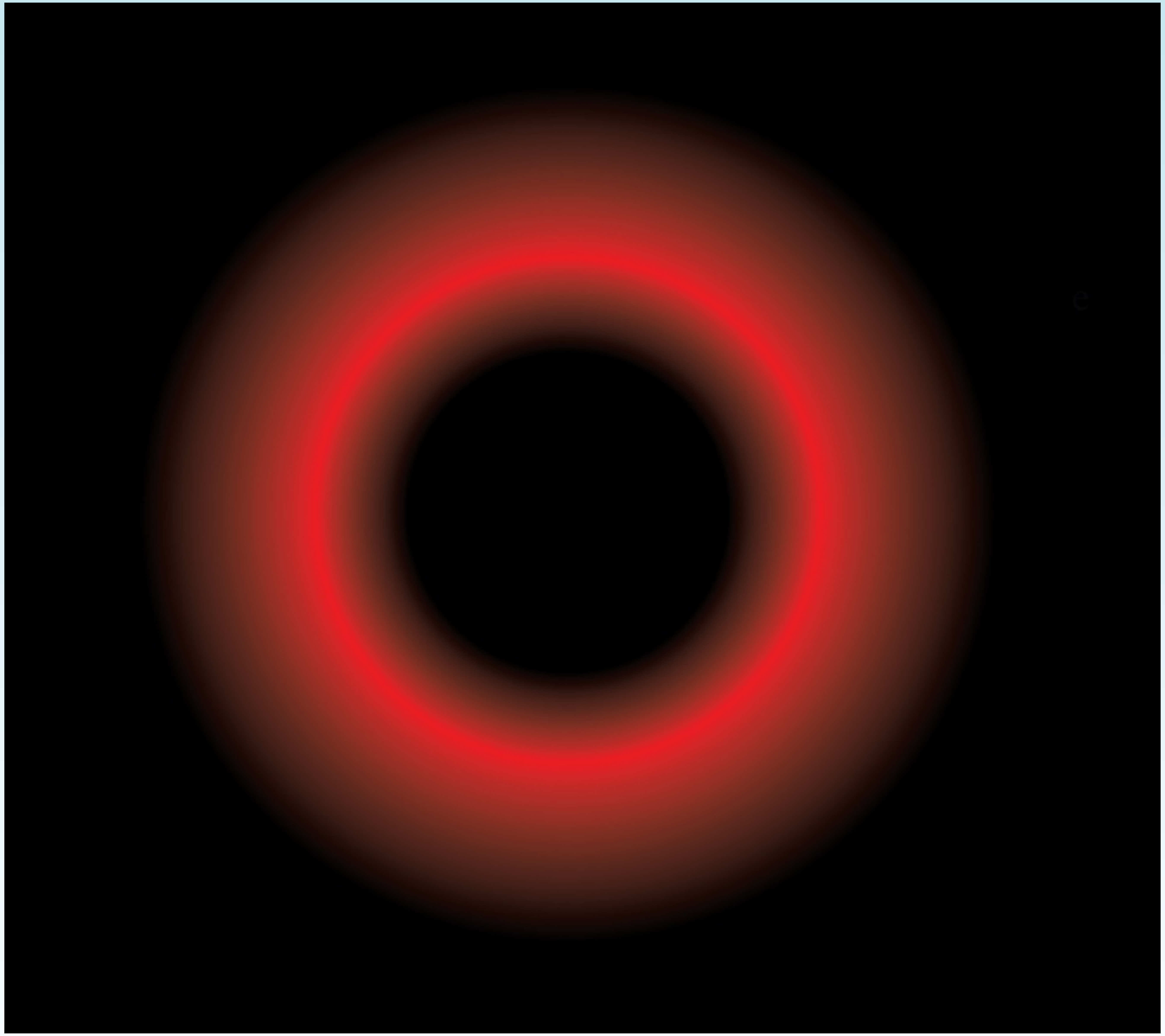

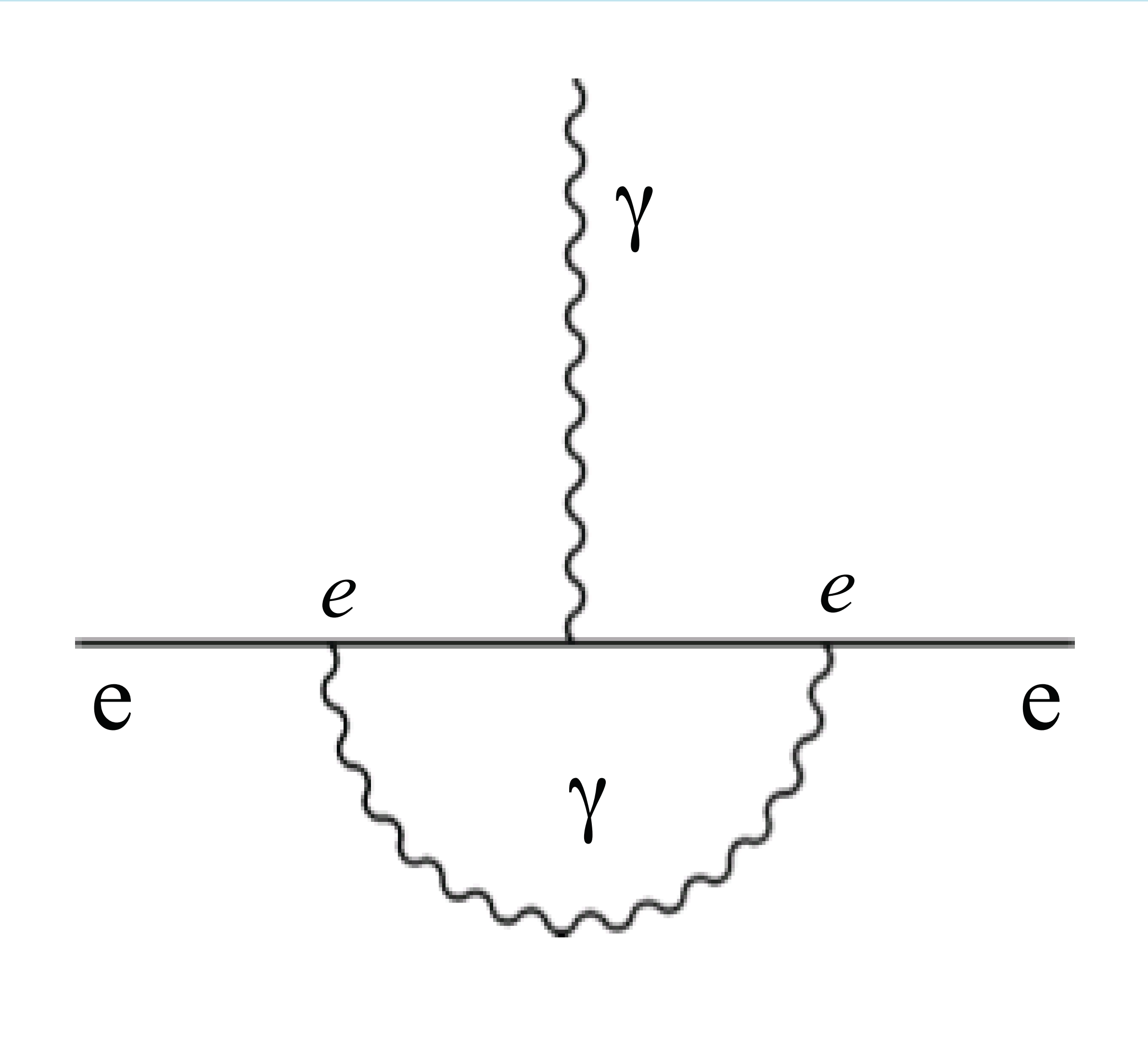

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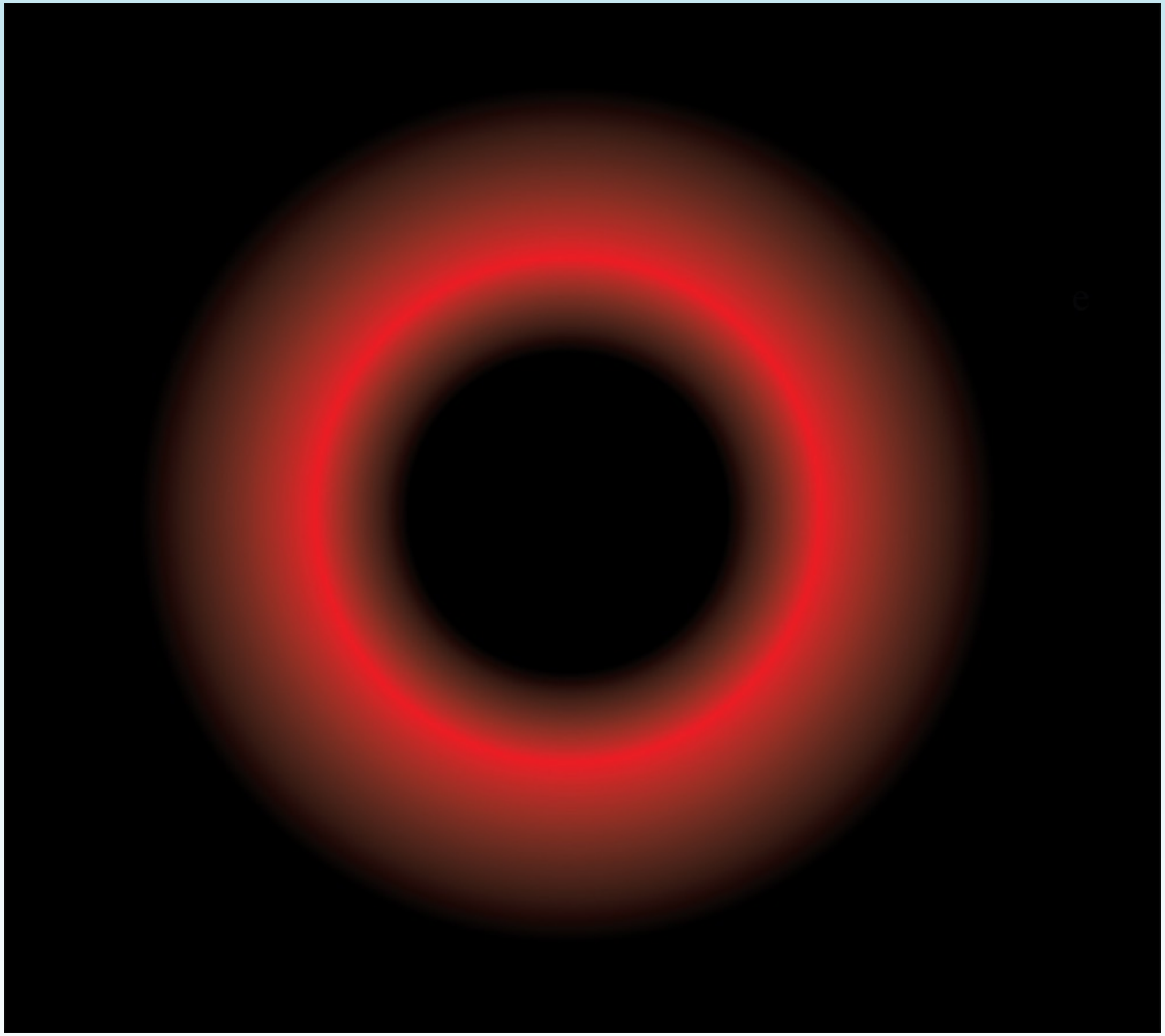
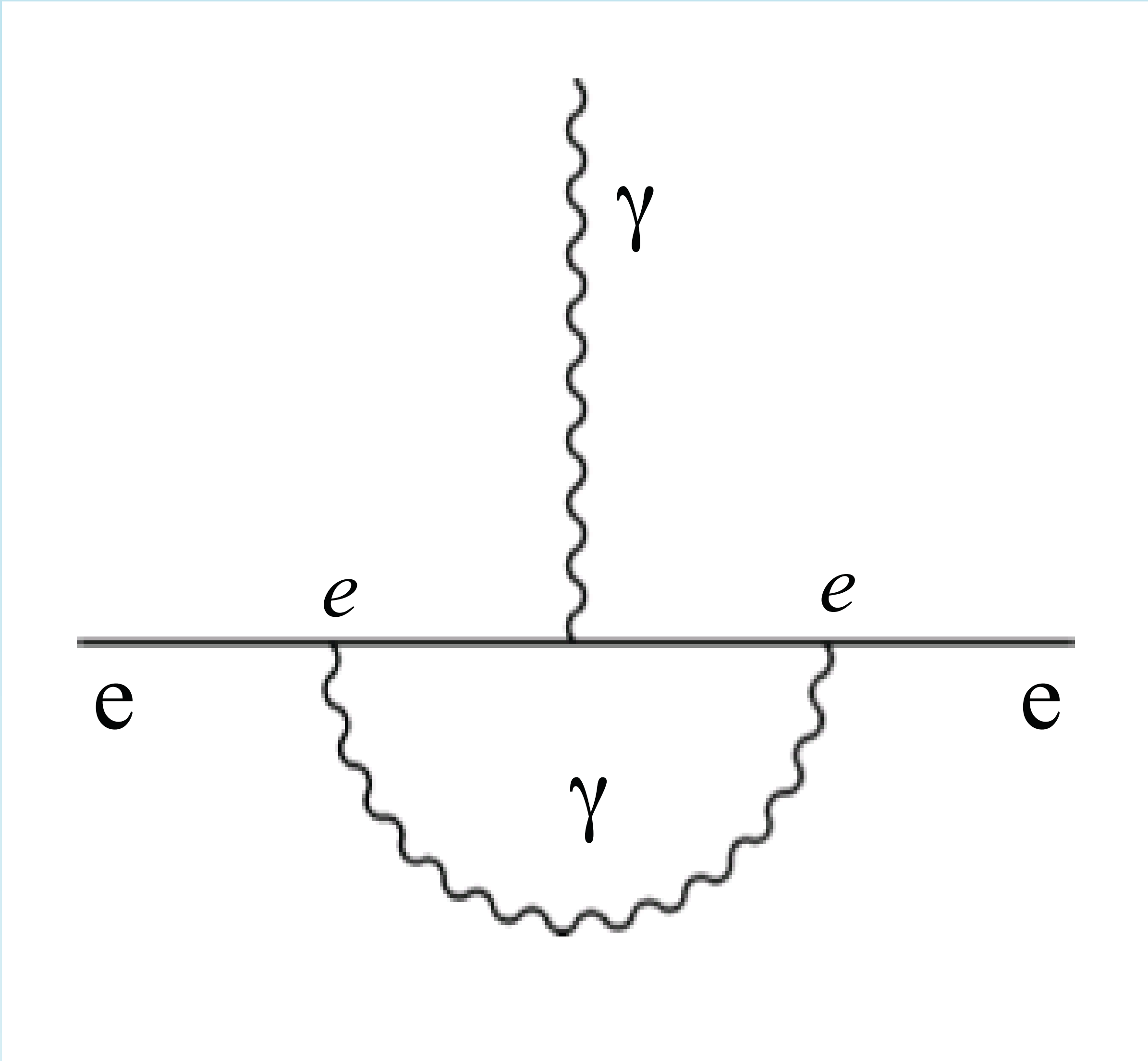
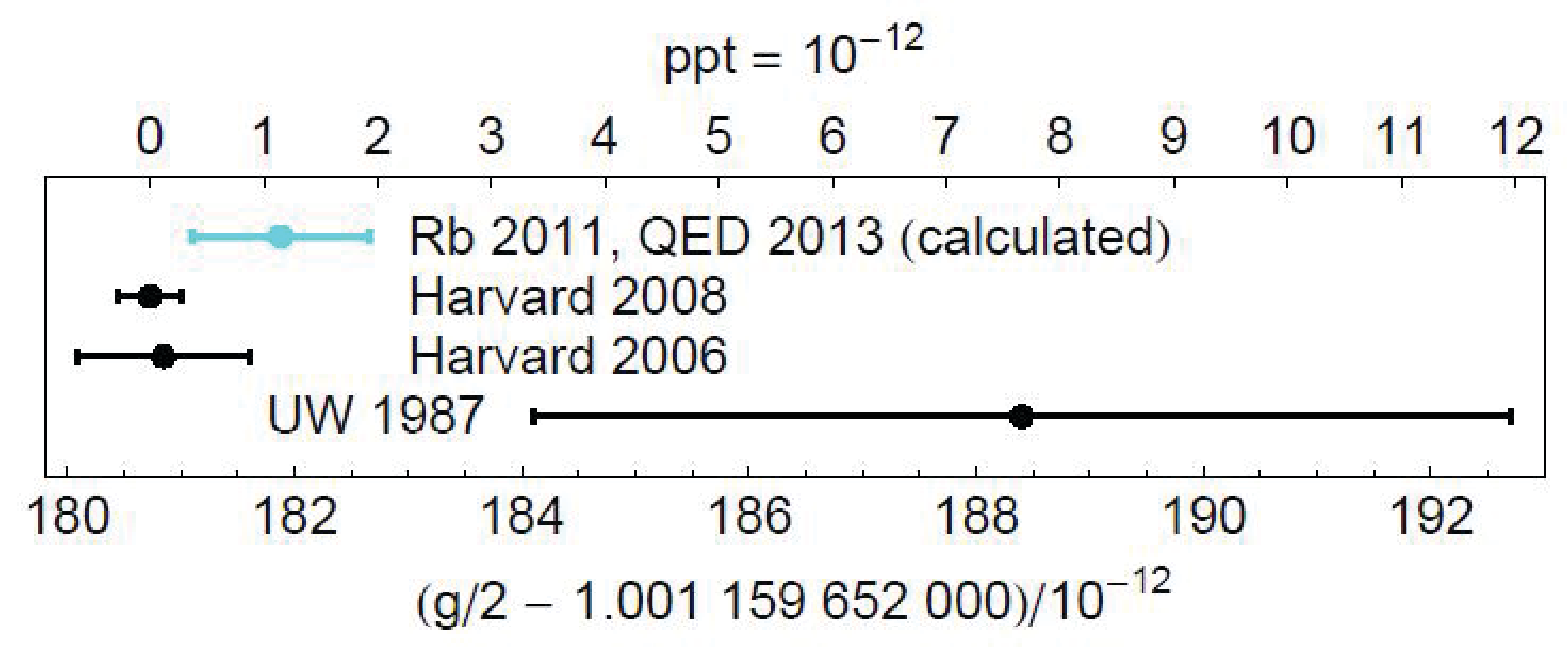
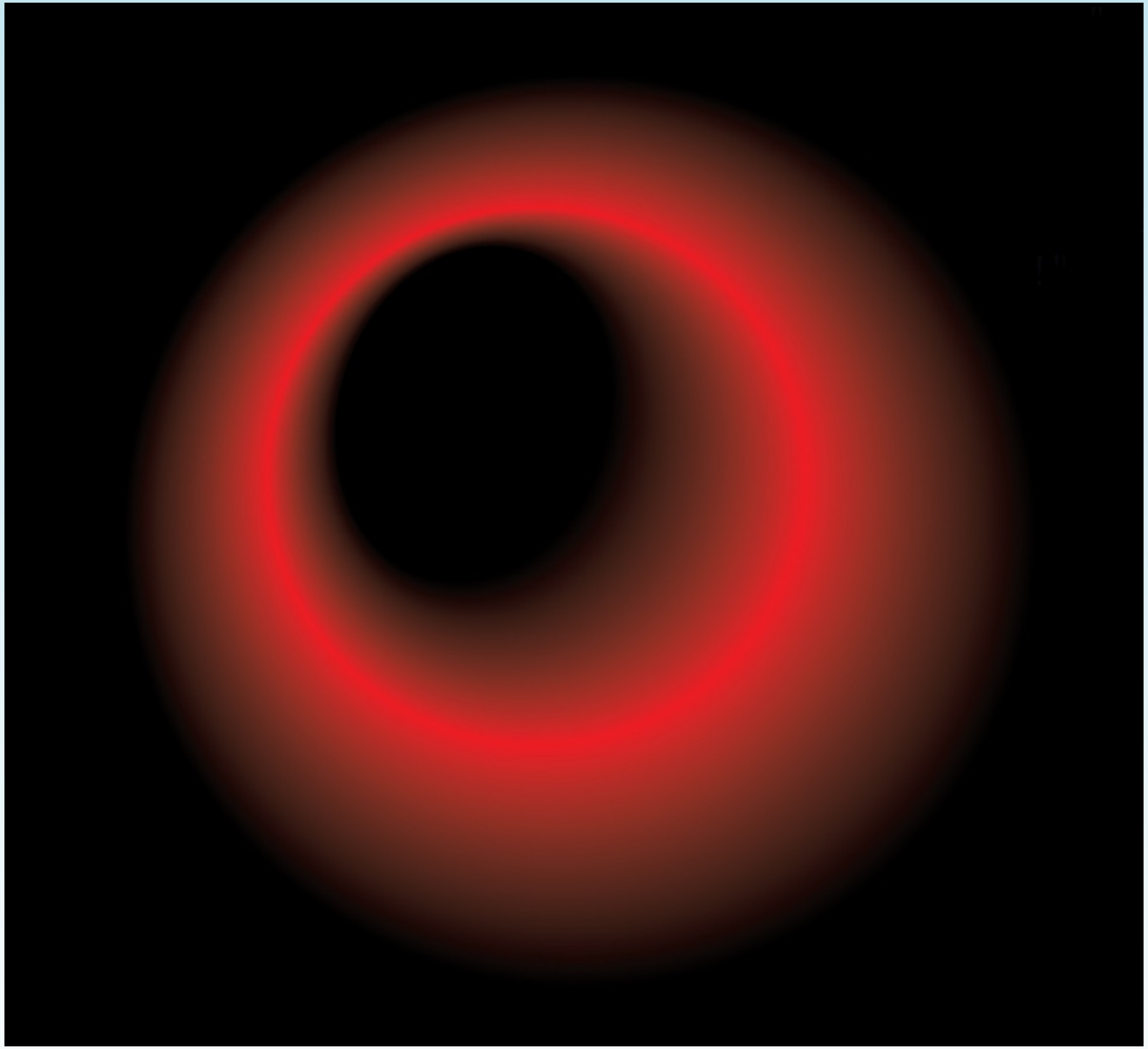


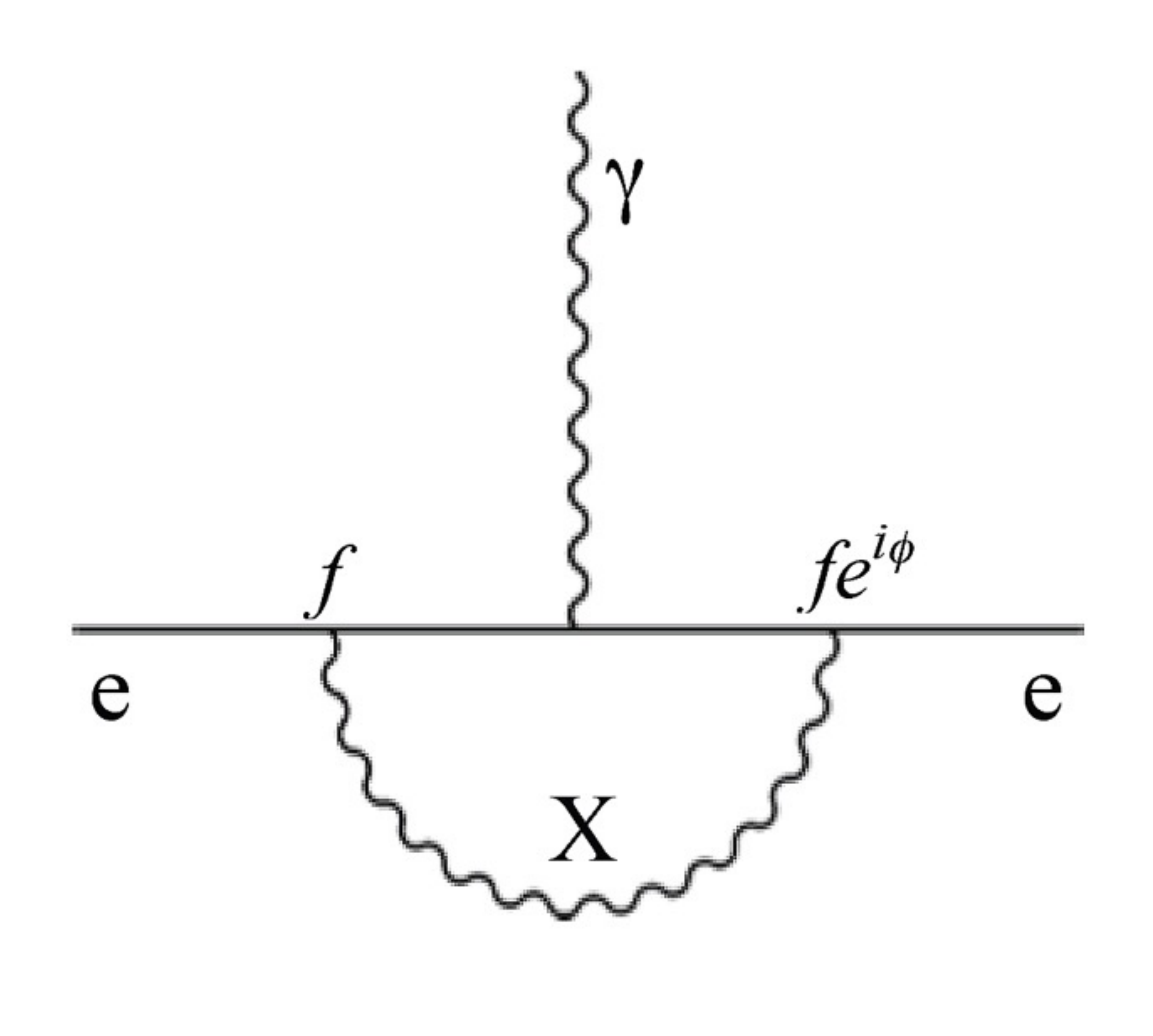


Gabriesle group confirms SM QED ppt



Electron is dressed by Virtual Particles — New Physics





SUSY
1st order perturbation
cancellations not inherent
T-violating phase natural

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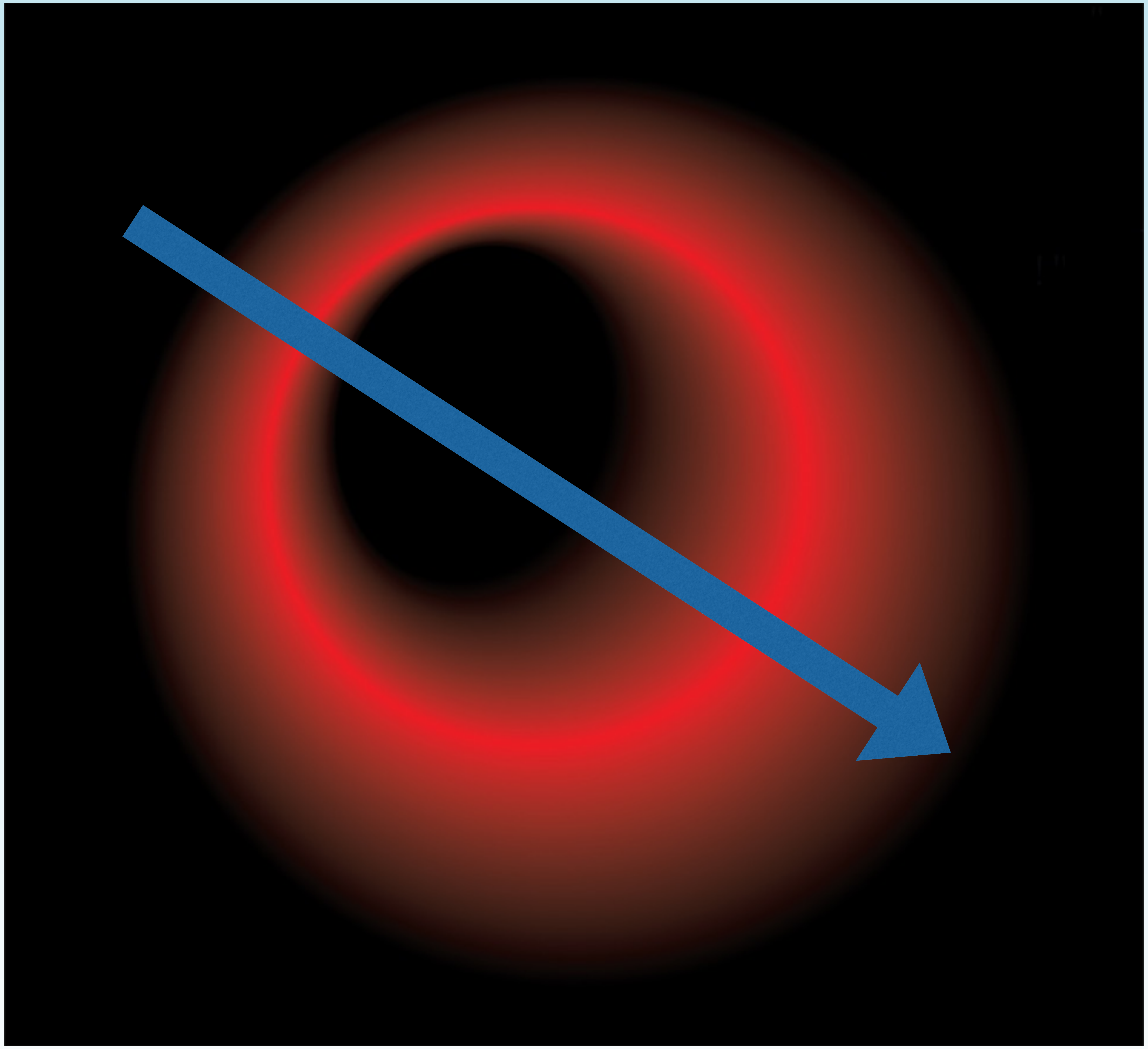

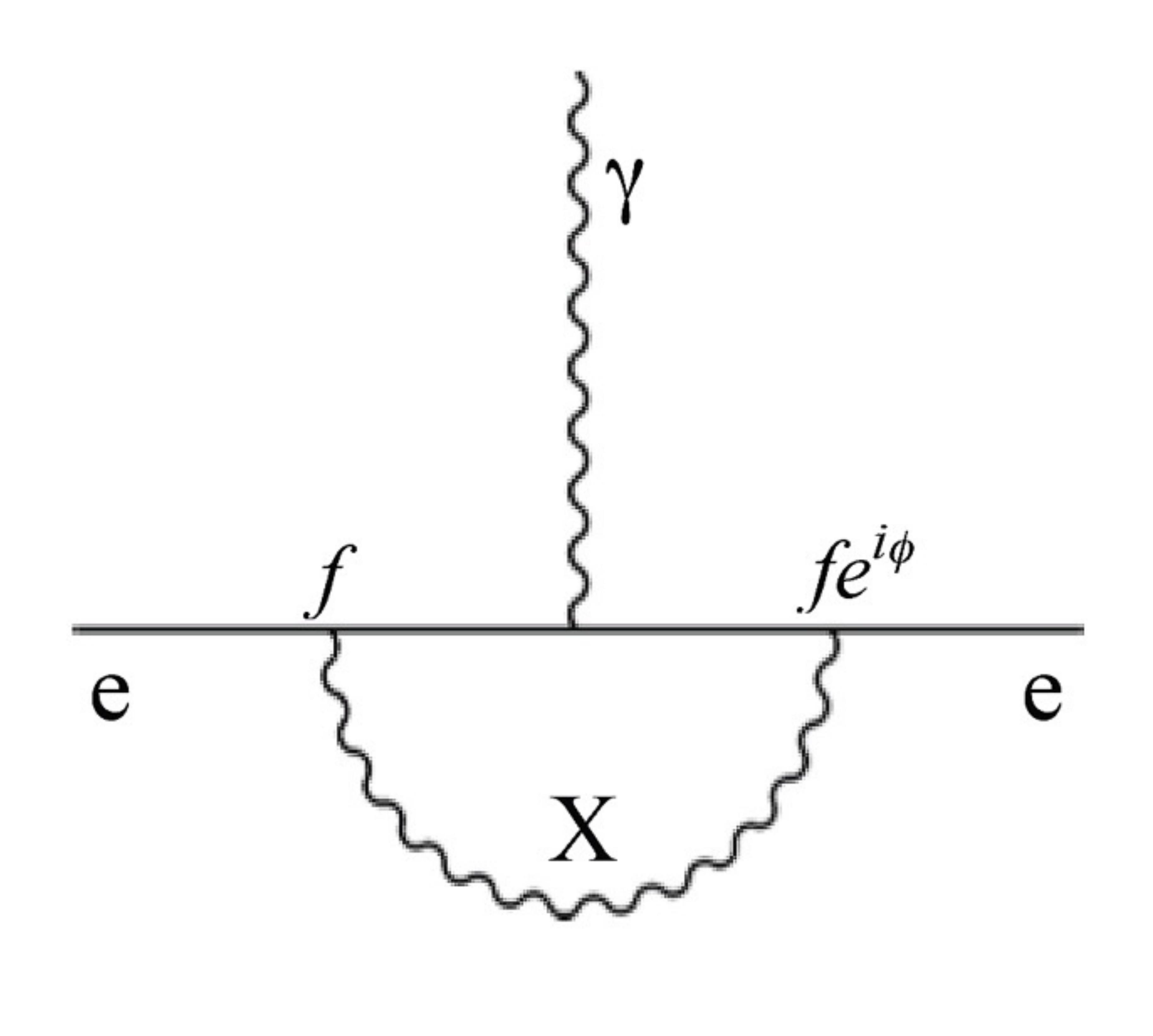

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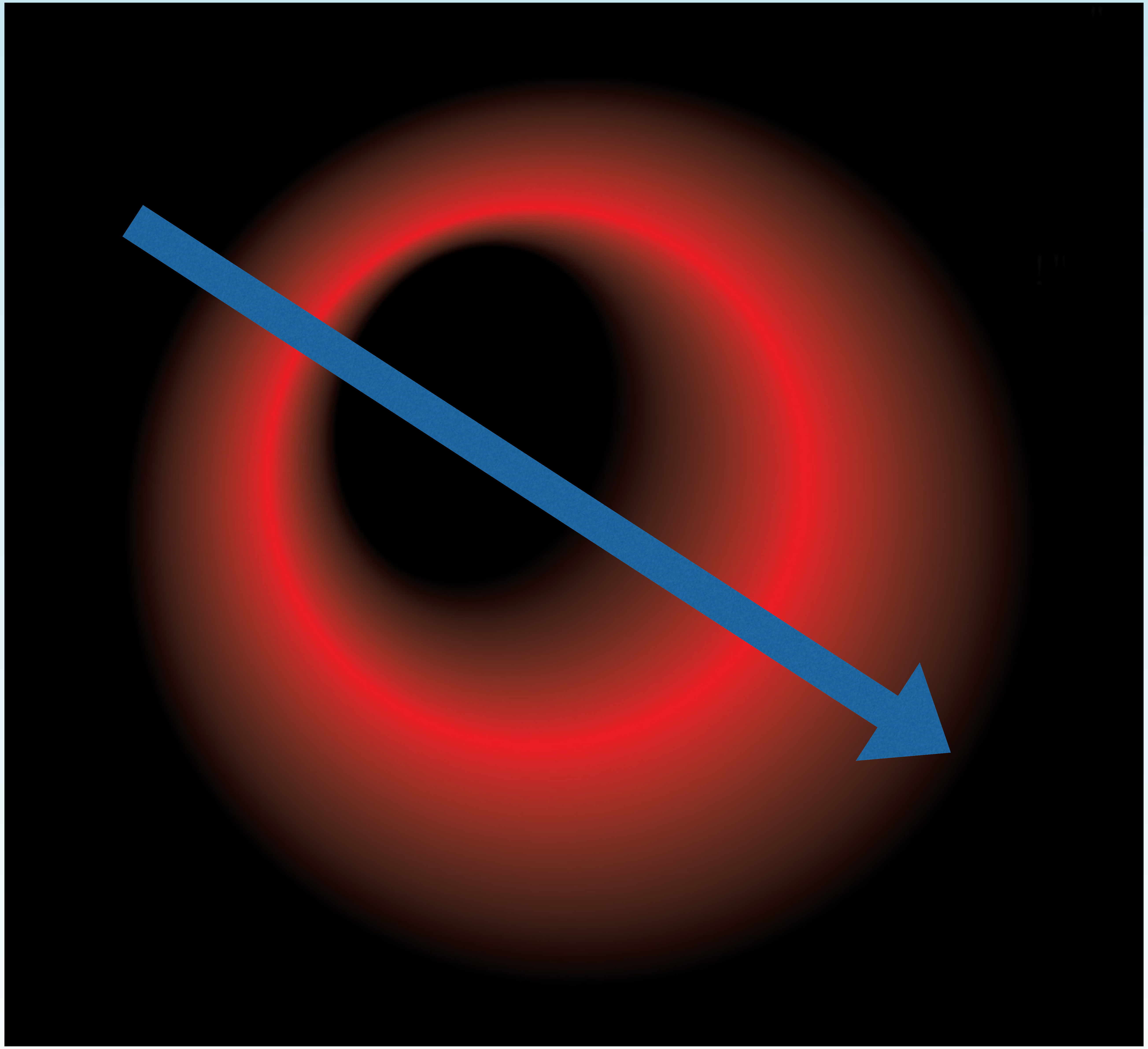
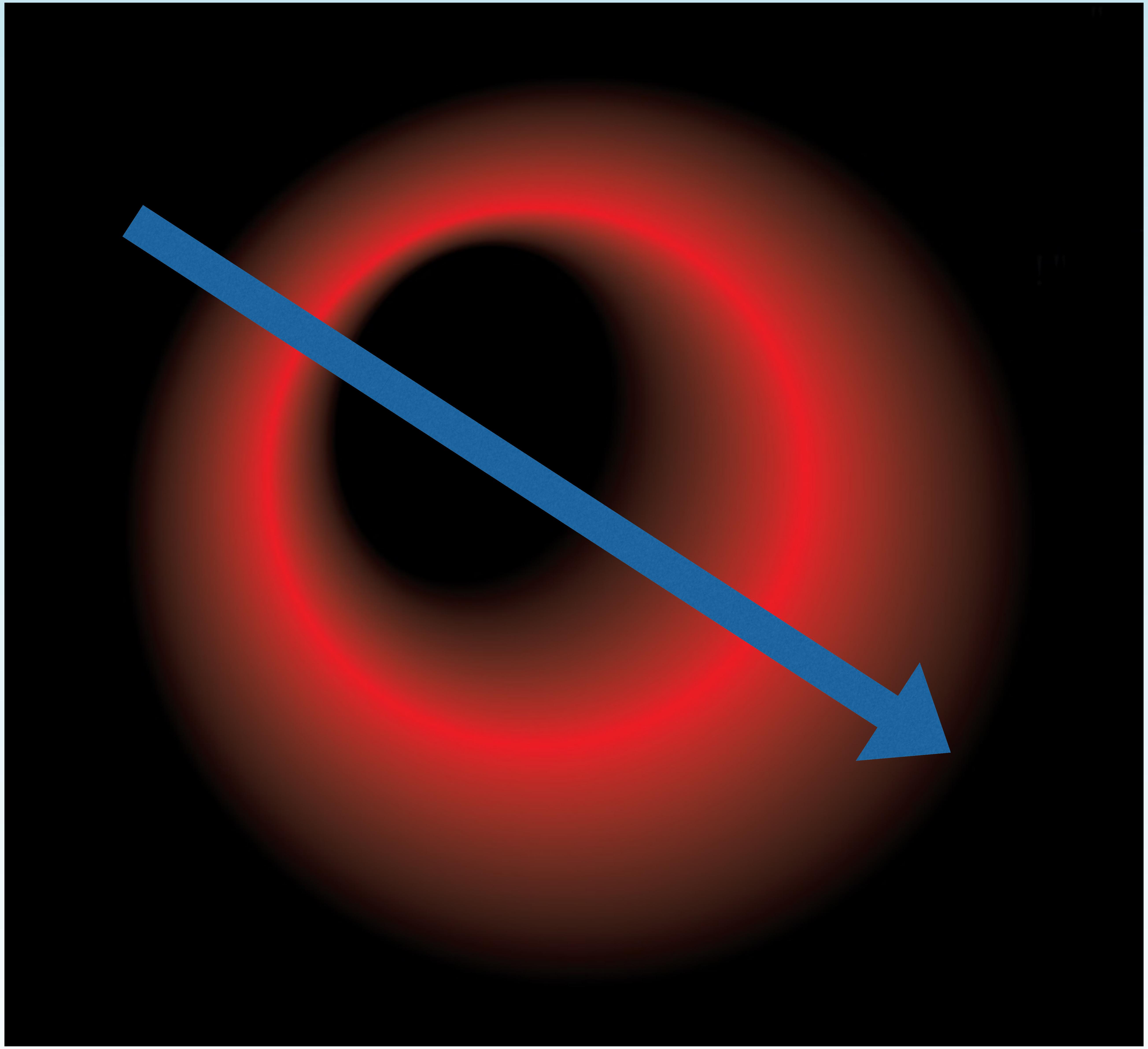


EDM is inherently T-violating

Electron is dressed by Virtual Particles — New Physics



EDM is inherently T-violating

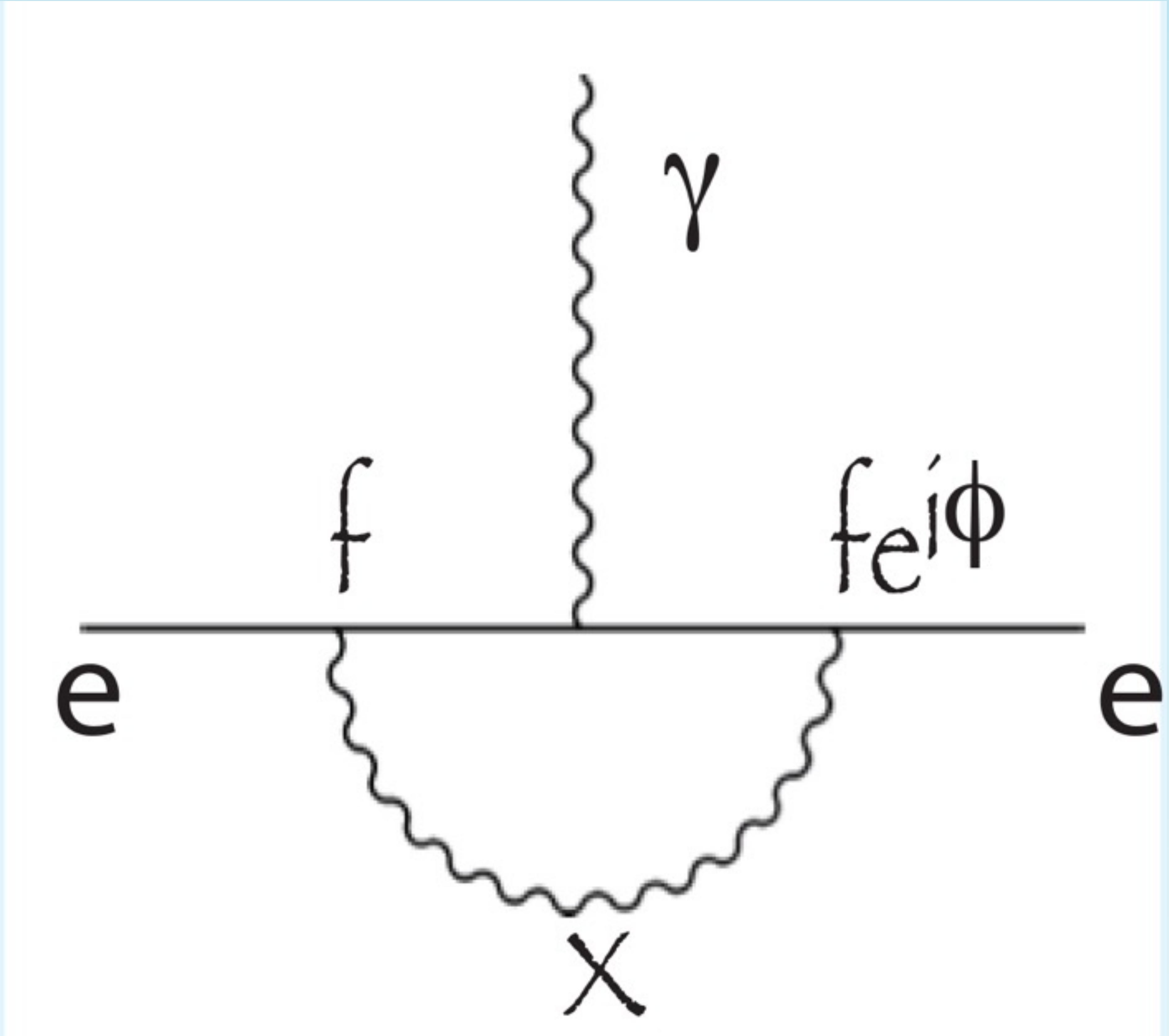
EDM in our experimental range would have enough T-violation to explain Matter/Antimatter asymmetry, indicate new 1-1000 TeV particle

EDM Too Small??

Assume $f^2/hc \approx \alpha$

$$\sin(\Phi) \approx 1$$

$$m_\chi \approx 100 \text{ GeV}$$



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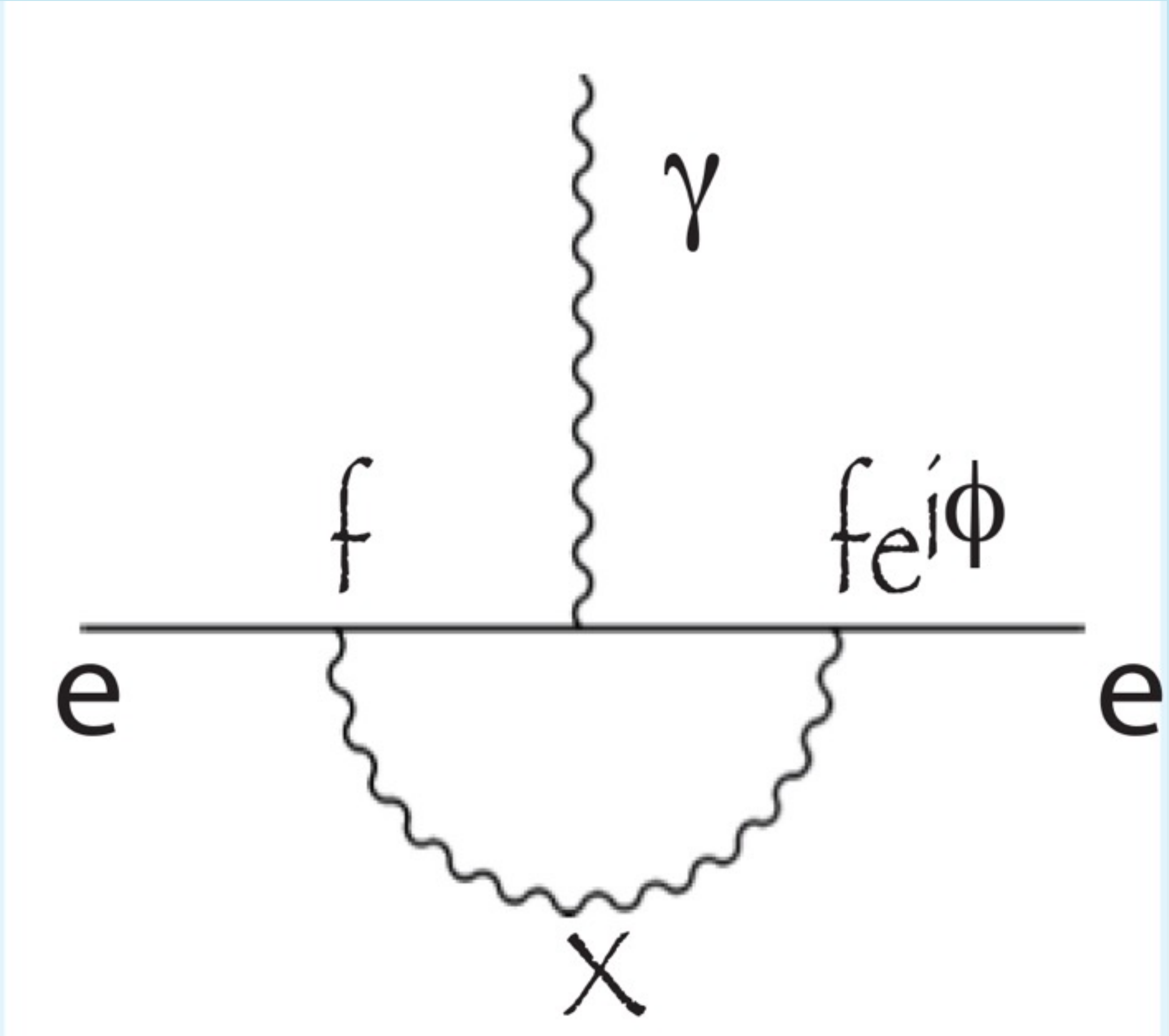
$$\text{EDM} \approx \mu_B\, (\alpha/\pi)^N\, (m_e/m_\chi)^2 \sin(\Phi)$$



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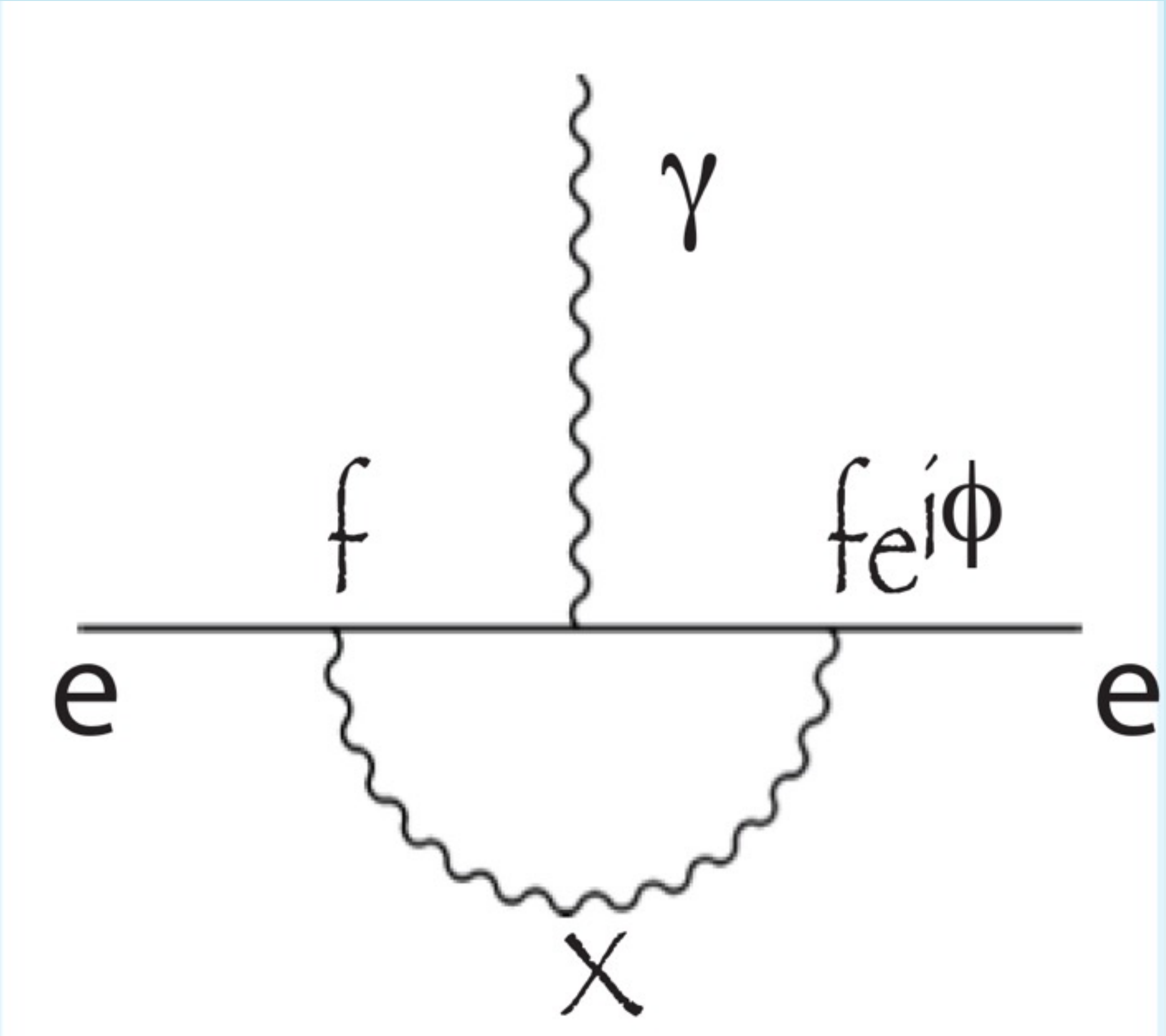

number of loops ↓ N

$$\text{EDM} \approx \mu_B \, (\alpha/\pi)^N \, (m_e/m_\chi)^2 \sin(\Phi)$$

$$\text{EDM} \approx 10^{-25} \text{ e cm}$$

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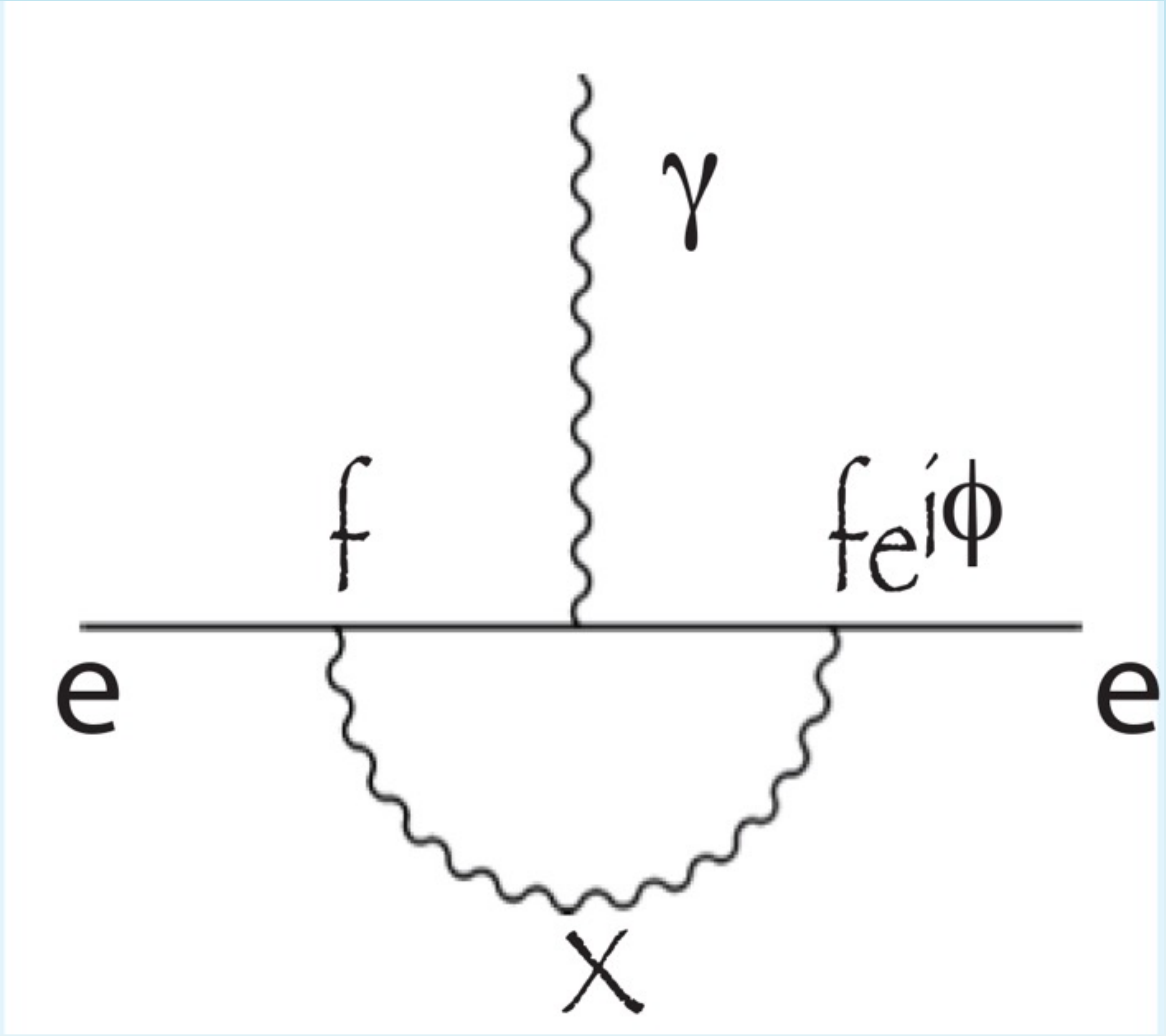
EDM ≈ 100x previous limit



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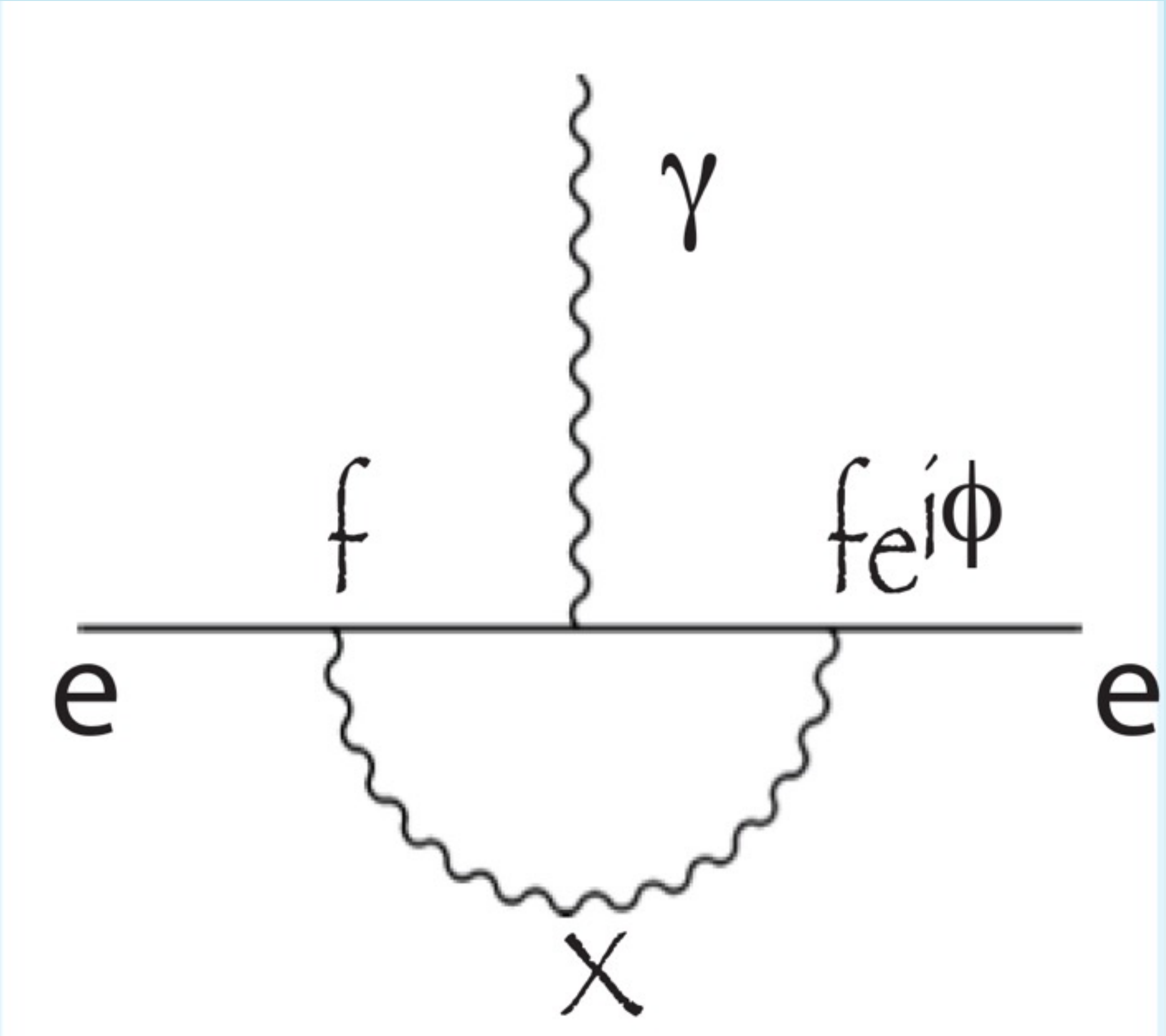


What the heck is going on?

ADMA RITZ TALK 2014

Summary

EDMs are an important class of flavour-diagonal CP-odd observables, testing/limiting new physics (motivated by the need for baryogenesis)

- Disentangling multiple CP-odd operators at 1 GeV requires multiple observables

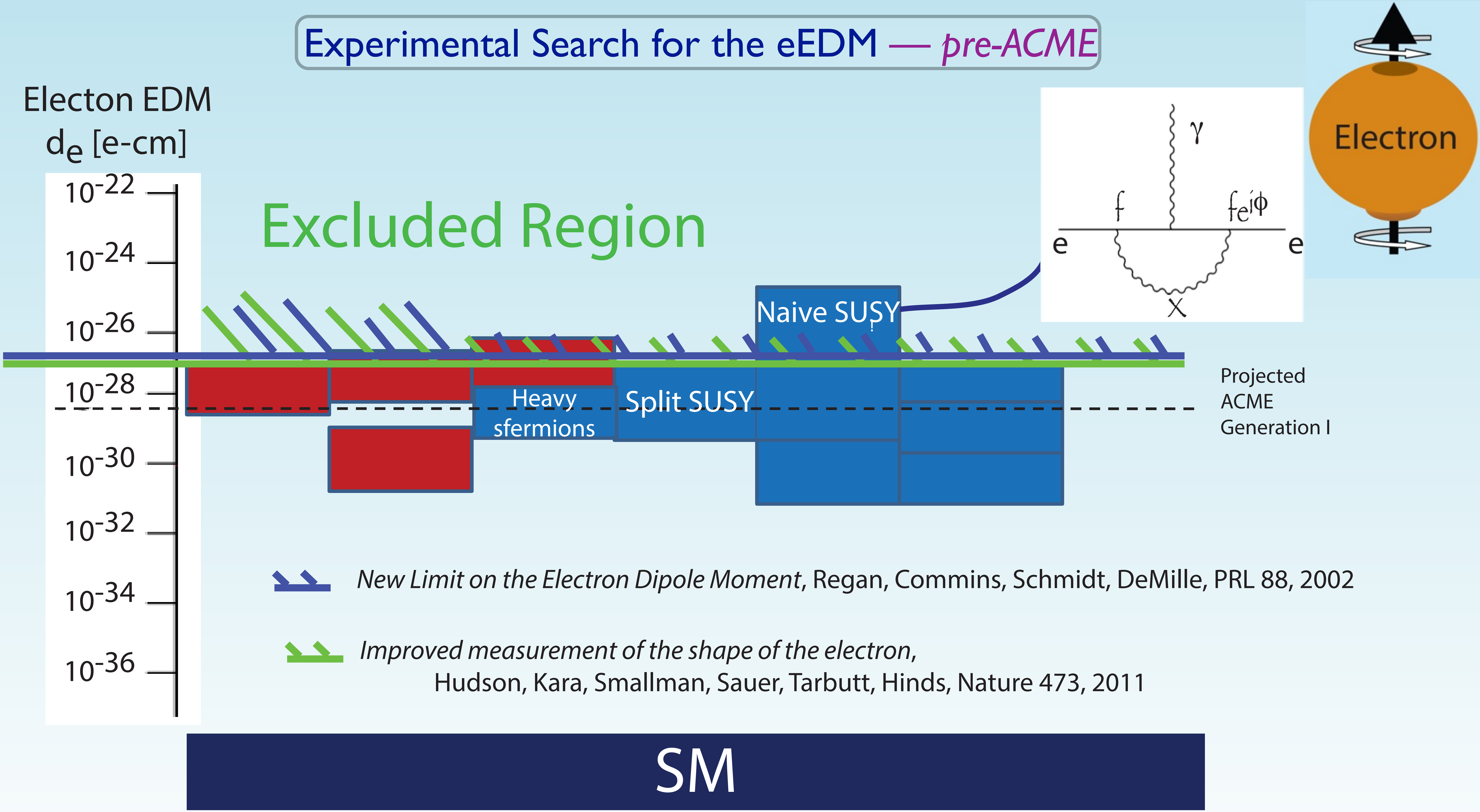
recent applications

- Useful interplay between EDM constraints and precision

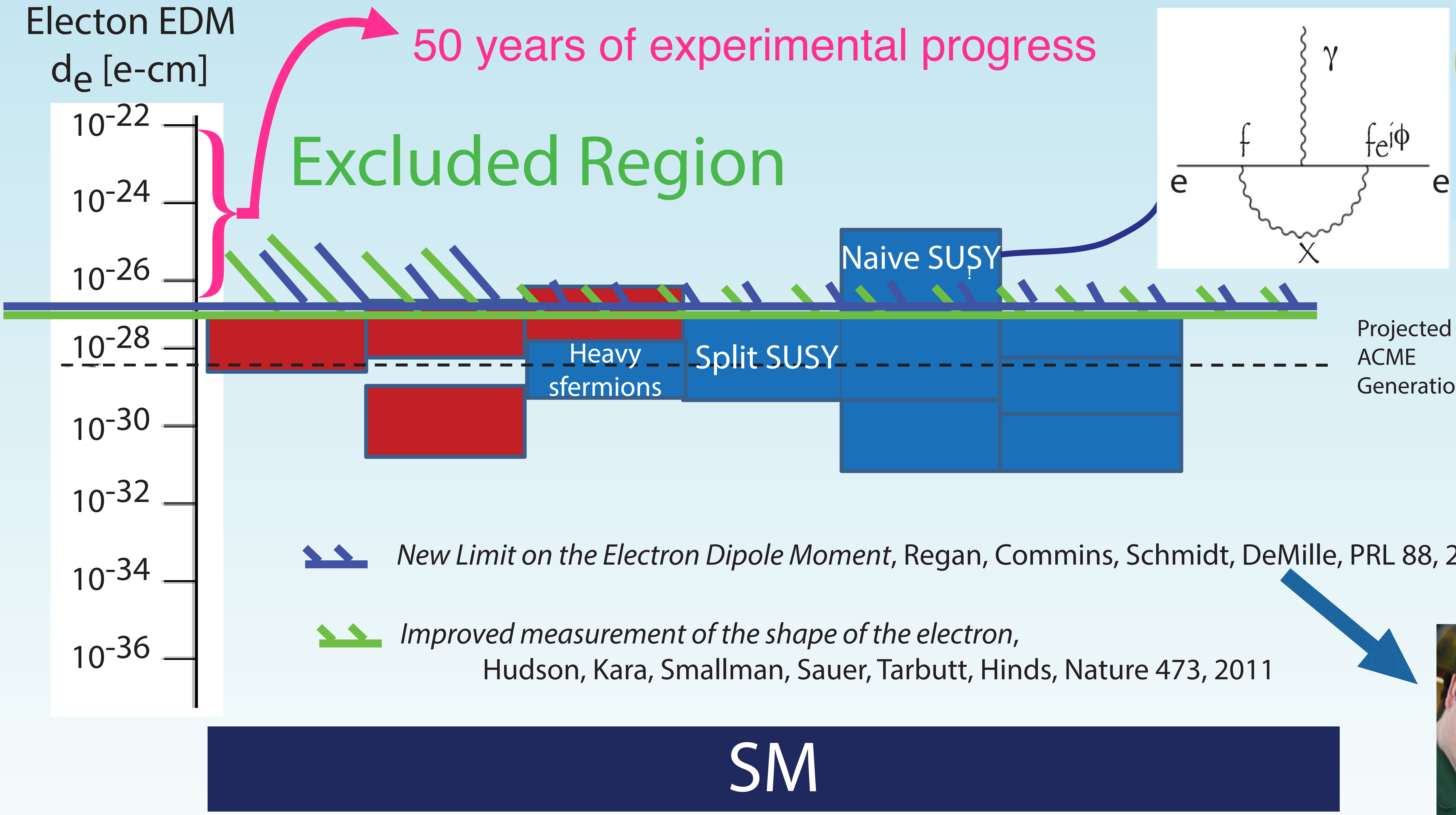
- The SUSY CP problem, hinted at by (1-loop) EDMs for more than 20 years, has been “confirmed” by the LHC, with no squarks seen near the weak scale (thus far). EDMs probe the very high (PeV) sfermion scales characteristic of the “large” observed Higgs mass

but is it at much higher scales? Or possibly at low scales (< GeV)?

Experimental Search for the eEDM — *pre-ACME*



Experimental Search for the eEDM — *pre-ACME*



Experiment	One Day Statistical Sensitivity e-cm $day^{-1/2}$	Published Limit $\lvert d_e \rvert <$ in e-cm
Berkeley Tl	0.5×10^{-27}	1.6×10^{-27}
Imperial YbF	2×10^{-27}	1.5×10^{-27}

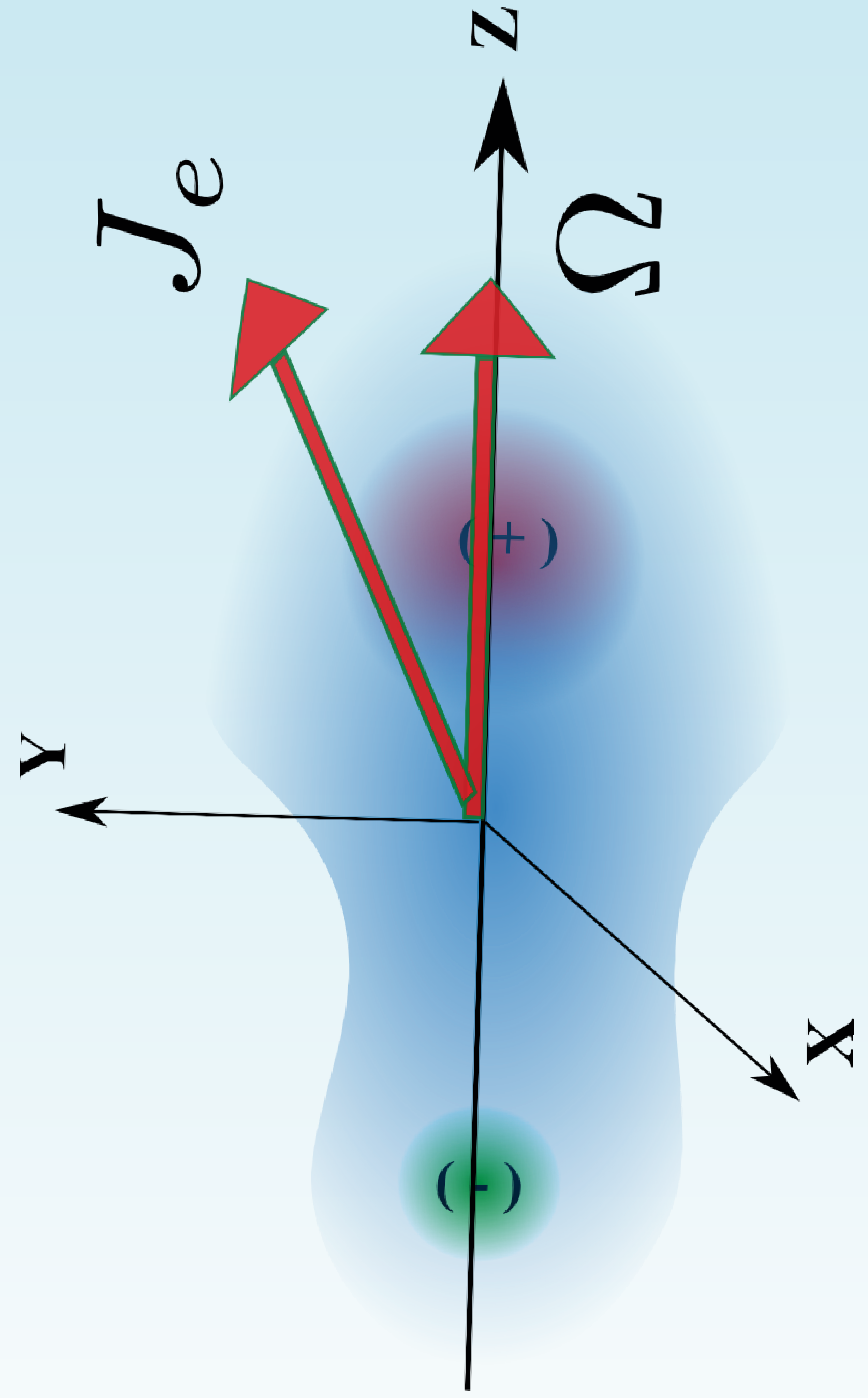
Improvement 1	Improvement 2	Improvement 3	EDM Sensitivity Gain over Previous Experiment
used a	molecule		~1

Our “Lab” — the ThO Molecule

ThO “H state”

$$^3\Delta_1$$

90 $^3F_2$	**8** $^3P_2$
Th	**O**
Thorium	Oxygen
232.0381	15.9994
$[Rn]6d^27s^2$	$1s^22s^22p^4$

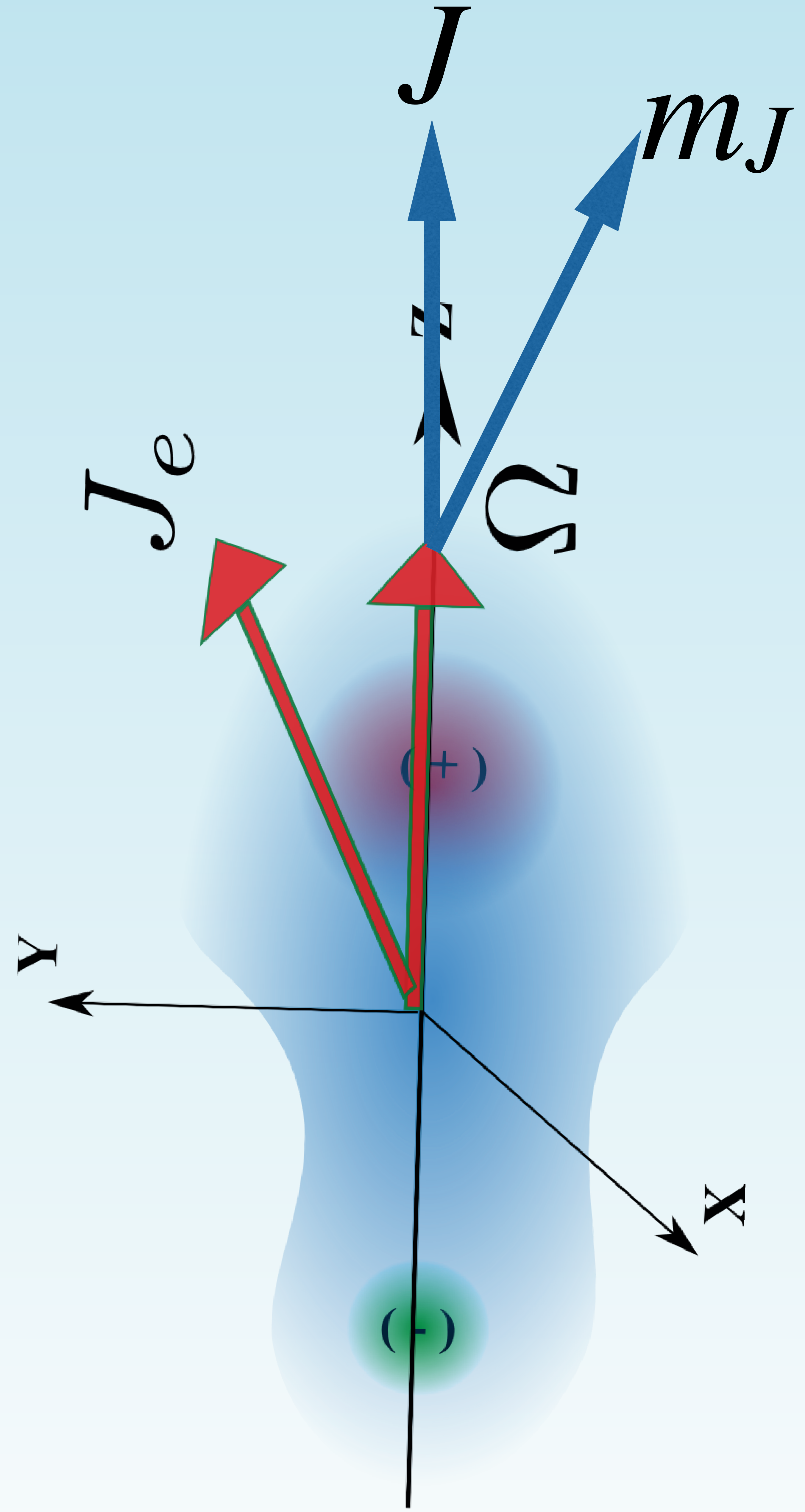


Our “Lab” — the ThO Molecule

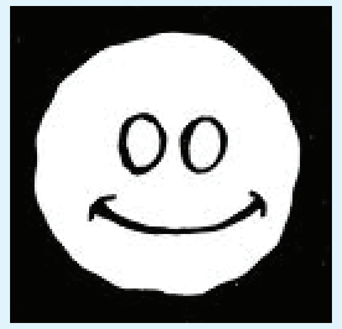
ThO “H state”

$$^{3}\Delta_{1}$$

90 $^{3}F_{2}$	8 $^{3}P_{2}$
Th	**O**
Thorium	Oxygen
232.0381	15.9994
$[Rn]6d^{2}7s^{2}$	$1s^{2}2s^{2}2p^{4}$

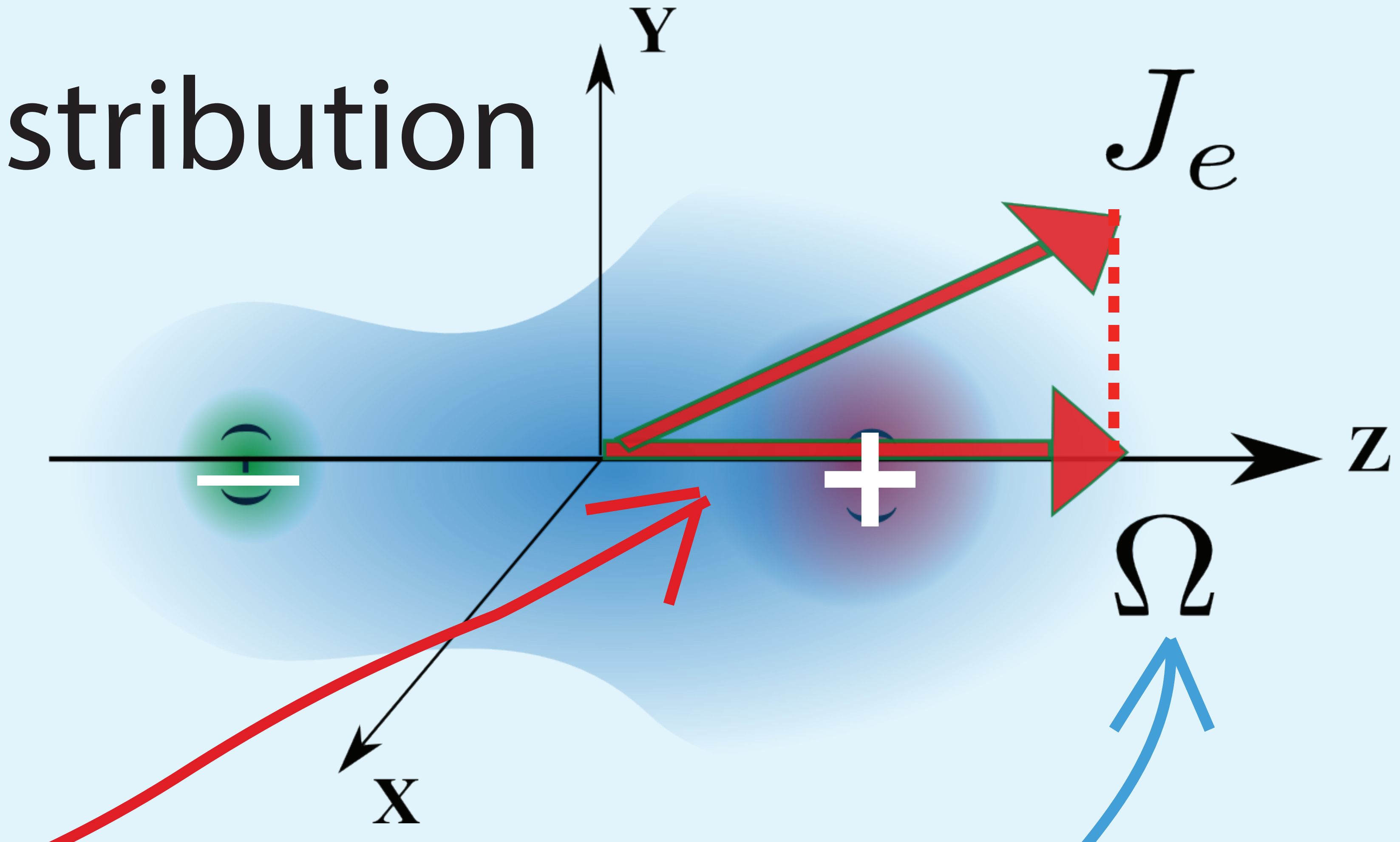


Using Molecules to Search for the EDM

Molecules -- the Good 

-"Natural" Asymmetric Electric Field Distribution

(due to chemical bonding)



Strong Electric Field in There

New Quantum Number

Using Molecules to Search for the EDM

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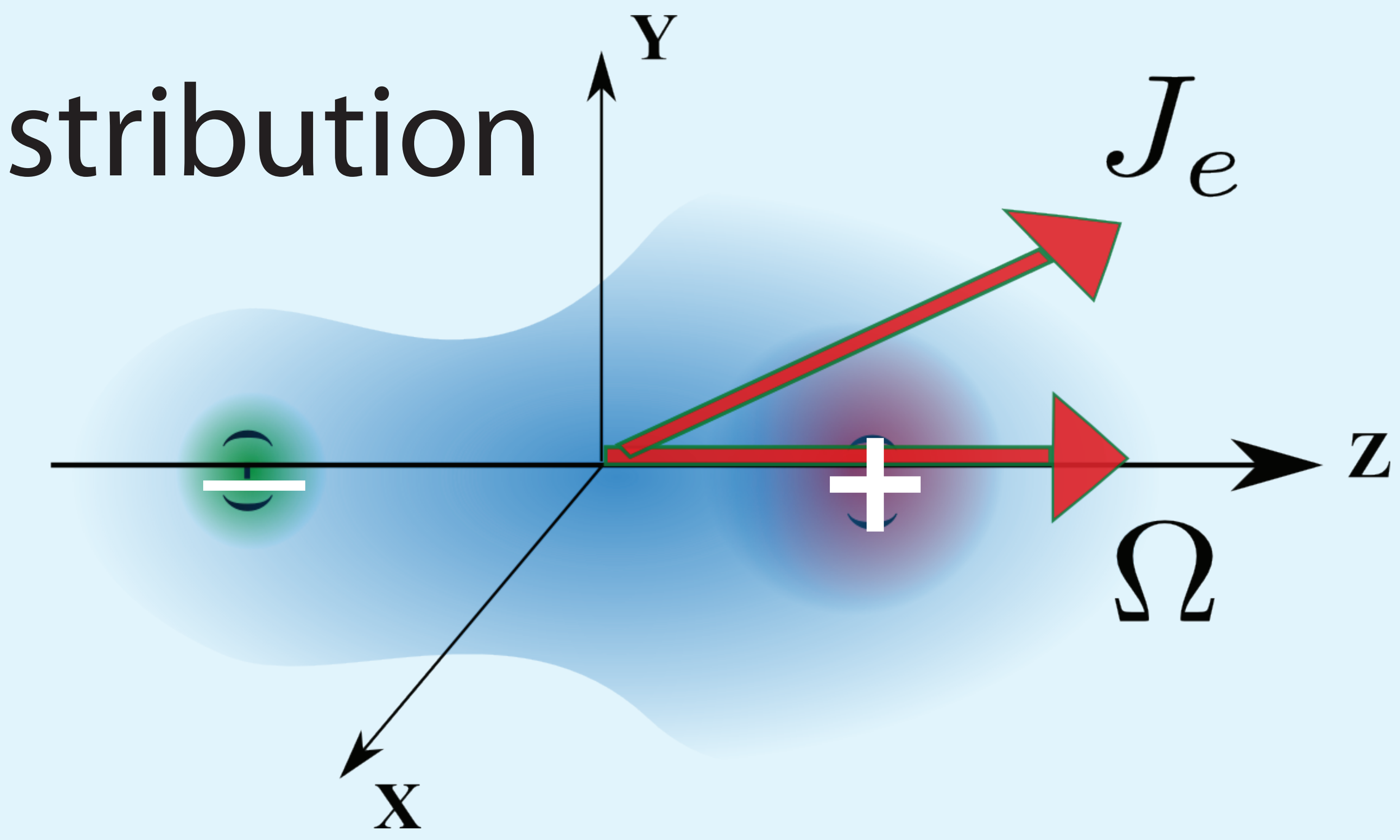
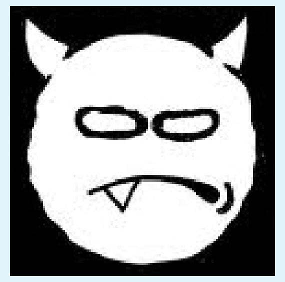


Molecules -- the Bad 

-Go ahead, make my Hamiltonian*...

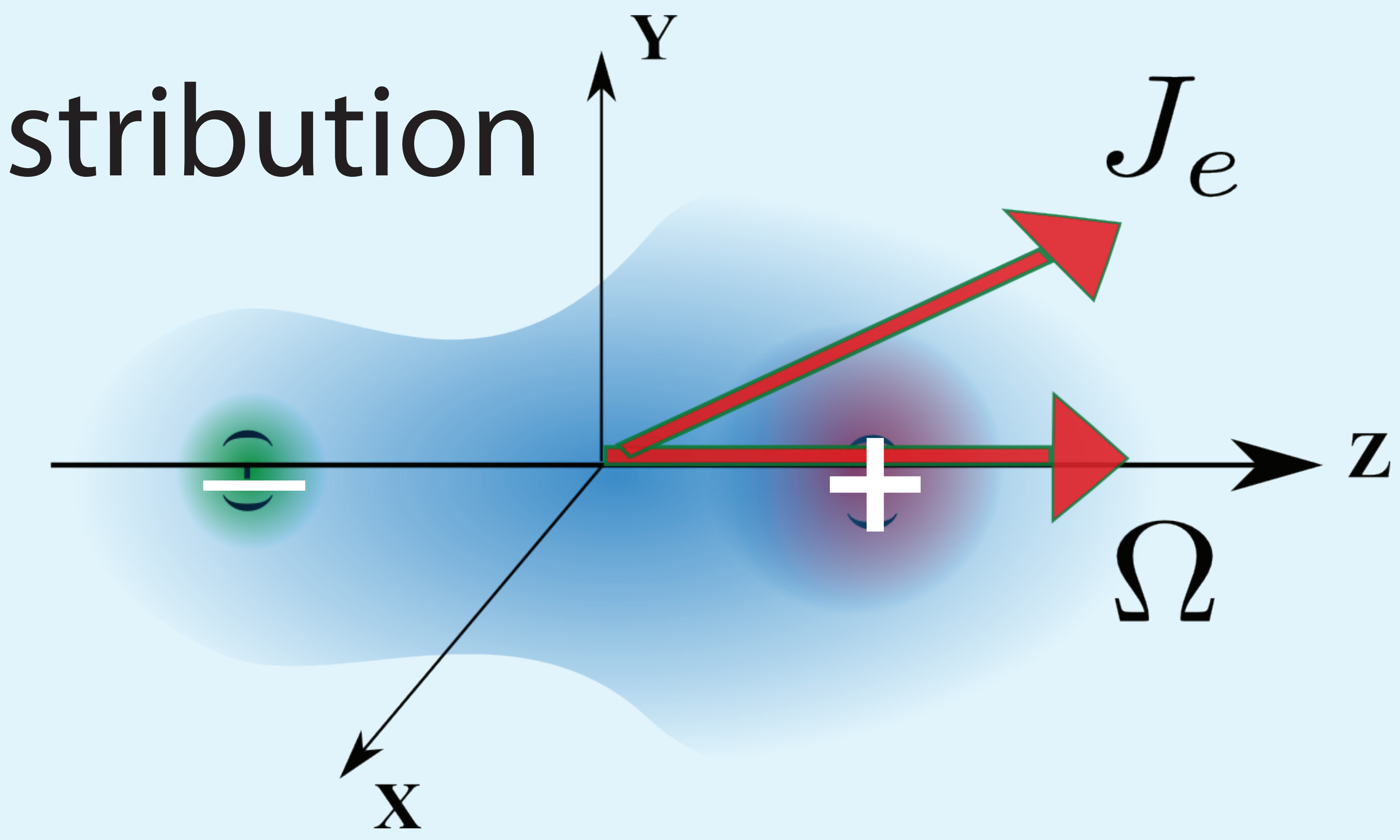
$$
\begin{aligned}
\hat{H} = {} & B(J^2 - J_z^2) - B(J_-L_+ + J_+L_-) + A_z L_z S_z + \frac{1}{2}\left(A_\perp + 2B - \gamma\right)\left(L_+S_- + L_-S_+\right) + \left[\frac{2}{3}(B + \lambda_z - 2\gamma) + \lambda_0\right] S^2 - \frac{1}{3}\left(B - 2\lambda - 2\gamma\right)\left(3S_z^2 - S^2\right) \\
& + \left(\lambda_\perp - \frac{1}{4}\gamma_\perp\right)\left(T_+S_zS_- + T_+S_-S_z + T_-S_+S_z + T_-S_zS_+\right) + \lambda_{\perp\perp}\left(T_+^2S_-^2 + T_-^2S_+^2\right) - \frac{1}{4}\gamma_\perp\left(L_+T_- + L_-T_+ + T_+L_- + T_-L_+\right) - (2B - \gamma)(J \cdot S - J_zS_z) \\
& + \frac{1}{2}\gamma_\perp(J_+T_- + J_-T_+)S_z + \sum_{i=\alpha,\beta}\Big[\frac{eQ_i}{2I_i(2I_i - 1)} q^e_{zi} I^2 f_{Lzi} L_z I_{zi} + \frac{1}{2} f_{Lz\perp i}(I_{+i}I_{-i} + L_-I_{+i}) + f_{Szi} S_z I_z + \frac{1}{2}(f_{S\perp i} - c_i)(S_+I_i + S_-I_{+i}) + \frac{1}{2} f_{S\perp zi}(S_+T_- + S_-T_+)I_{zi} \\
& + \frac{1}{2} f_{Sz\perp i}(I_{+i}T_- + I_iT_+)S_z + \frac{1}{4} f_{S\perp\perp i}(S_+T_-^2I_{+i} + S_-T_+^2I_{-i}) + c_i(J \cdot I - J_zI_{zi})\Big] + d(I_\alpha \cdot I_\beta - 3I_{z\alpha}I_{z\beta}) + \delta I_\alpha \cdot I_\beta + \mu_B(g_{lz} - \sigma_{lz})L_z\mathcal{B}_z + \frac{1}{2}\mu_B(g_{l\perp} + g_z - \sigma_{l\perp})(L_+\mathcal{B}_- + L_-\mathcal{B}_+) \\
& + \frac{1}{4}\mu_B\sigma_{sz\perp}\left[\mathcal{B}_z(S_+T_- + S_-T_+) + (T_-S_+ + T_+S_-)\mathcal{B}_z + (\mathcal{B}_+T_- + \mathcal{B}_-T_+)S_z + S_z(T_-\mathcal{B}_+ + T_+\mathcal{B}_-)\right] + \frac{1}{4}\mu_B\sigma_{s\perp\perp}(\mathcal{B}_+S_+T_-^2 + \mathcal{B}_-S_-T_+^2 + T_-^2S_+\mathcal{B}_+T_+^2S_-\mathcal{B}_-) \\
& - g_z(J \cdot \mathcal{B} - J_z\mathcal{B}_z) - \sum_{i=\alpha,\beta}\left\{g_{Ii}\left[(1 - \sigma_{iz})I_{zi}\mathcal{B}_z + \frac{1}{2}(1 - \sigma_{i\perp})(I_{+i}\mathcal{B}_- + I_{-i}\mathcal{B}_+)\right] + \frac{1}{4}\sigma_{i\perp\perp}(\mathcal{B}_+I_{+i}T_-^2 + \mathcal{B}_-I_{-i}T_+^2 + T_-^2I_{+i}\mathcal{B}_+ + T_-^2I_{+i}\mathcal{B}_+ + T_+^2I_{-i}\mathcal{B}_-)\right\} \\
& + (\text{terms nondiagonal in } S)
\end{aligned}
$$

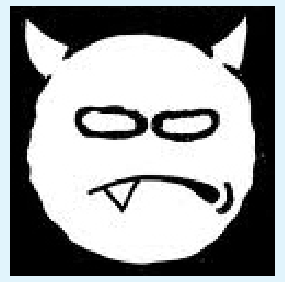
*thanks to Roman Krems

Using Molecules to Search for the EDM

Molecules -- the Good

-"Natural" Asymmetric Electric Field Distribution
(due to chemical bonding)



Molecules -- the Bad 

-Go ahead, make my Hamiltonian*...

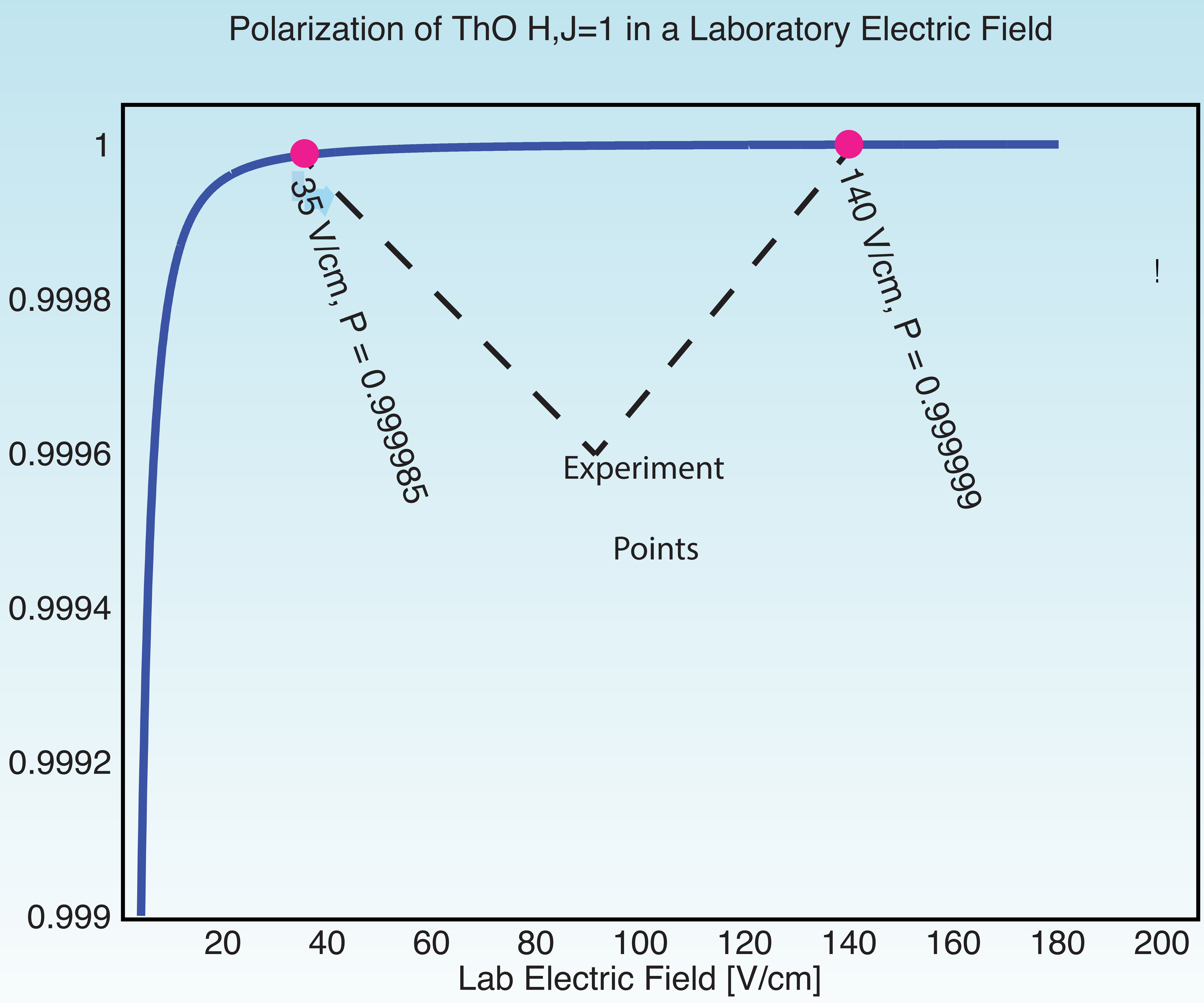
What would possess a person
to
make a precision measurement in such a complicated
"laboratory"
?
?

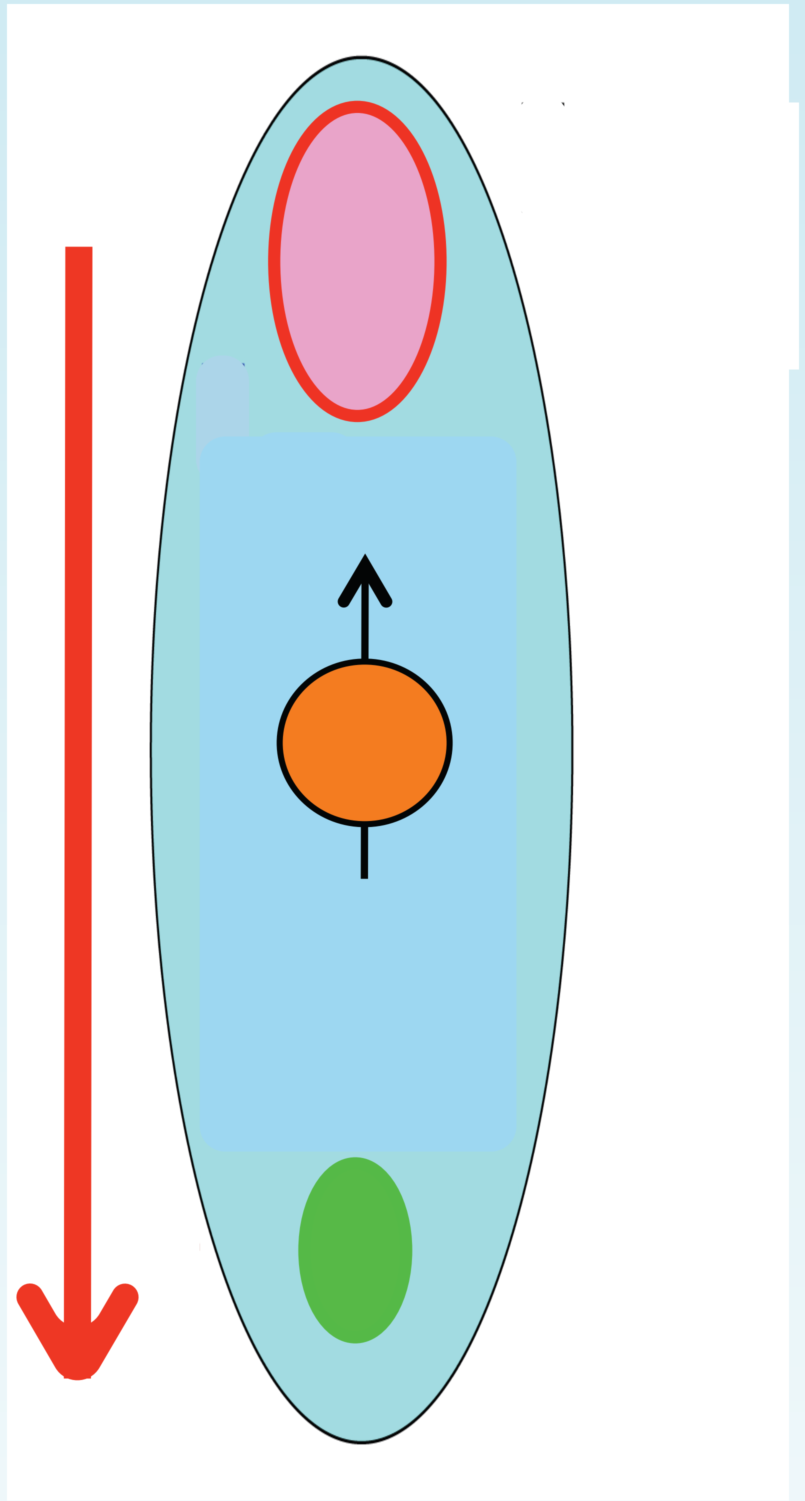
*thanks to Roman Krems

Lets start with the BASICS

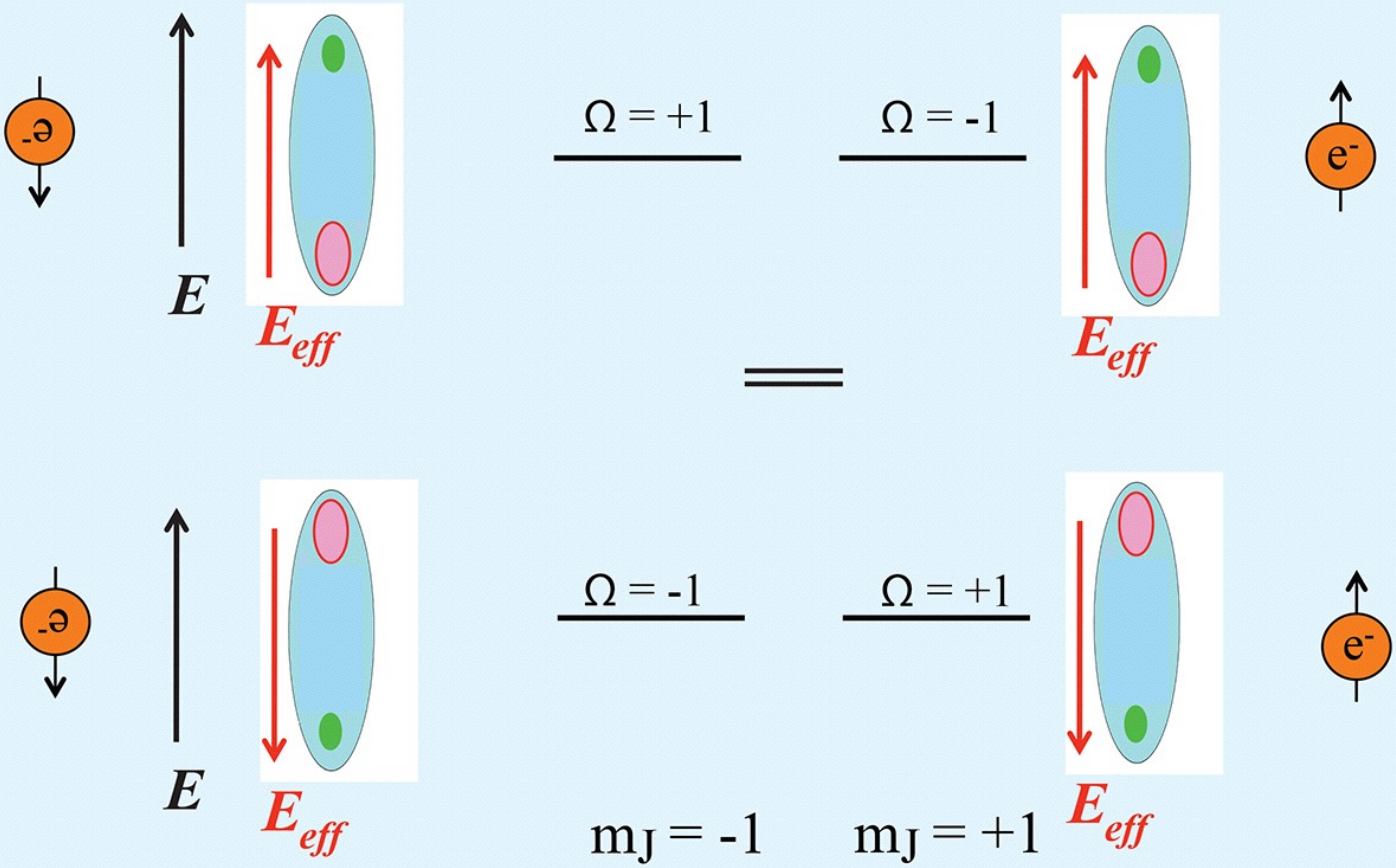
OK, lets put the molecules in an electric field

Fully Polarized ThO - "Easy"



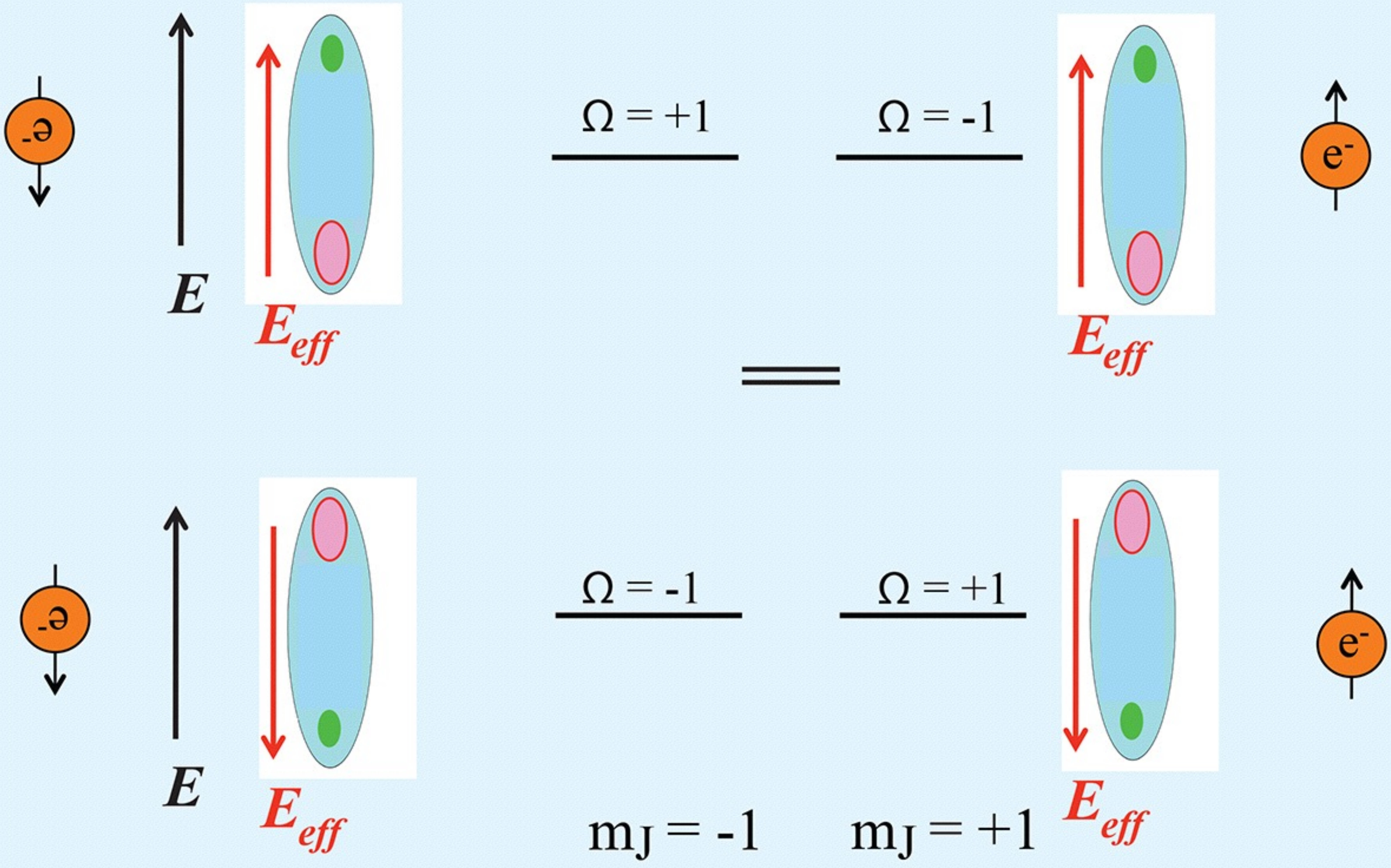


ThO H state in an Electric Field



ThO H state in an Electric Field

Frequency Selection



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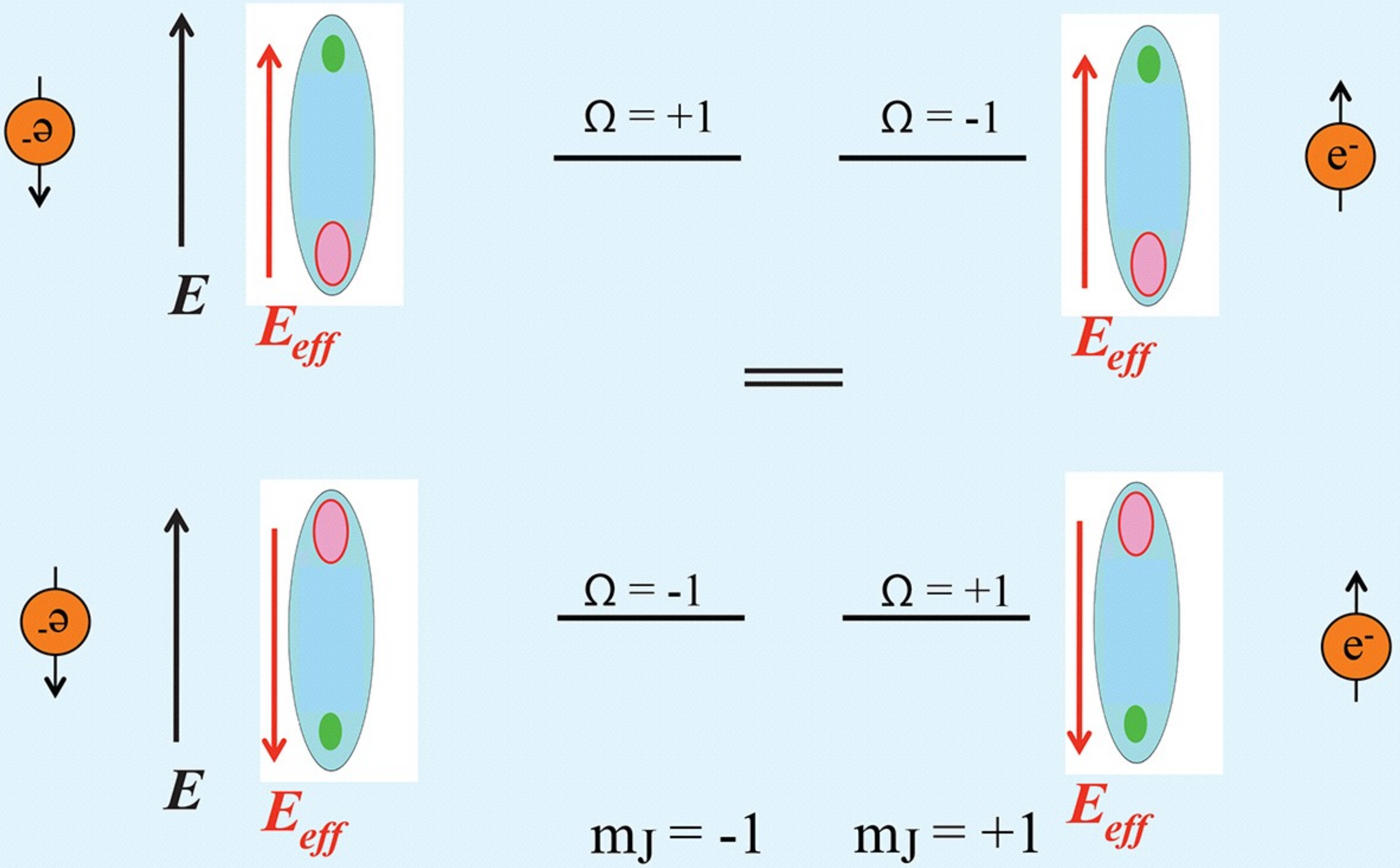

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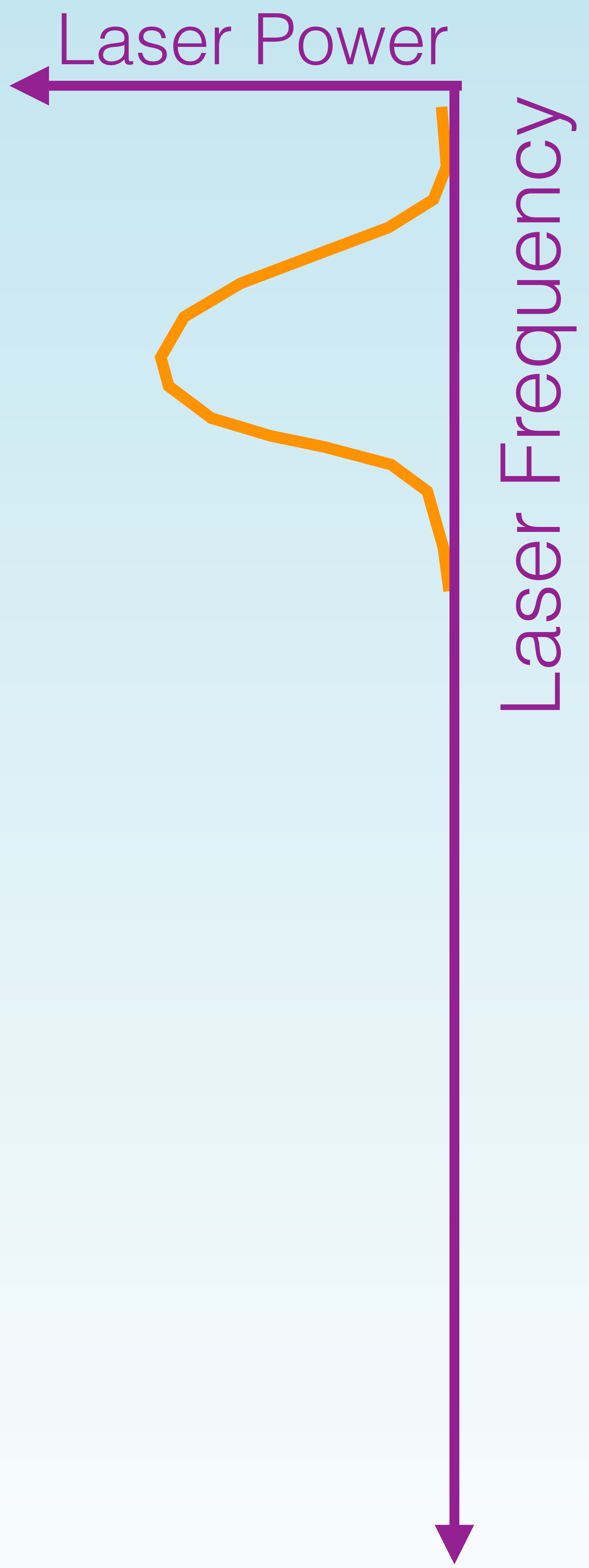

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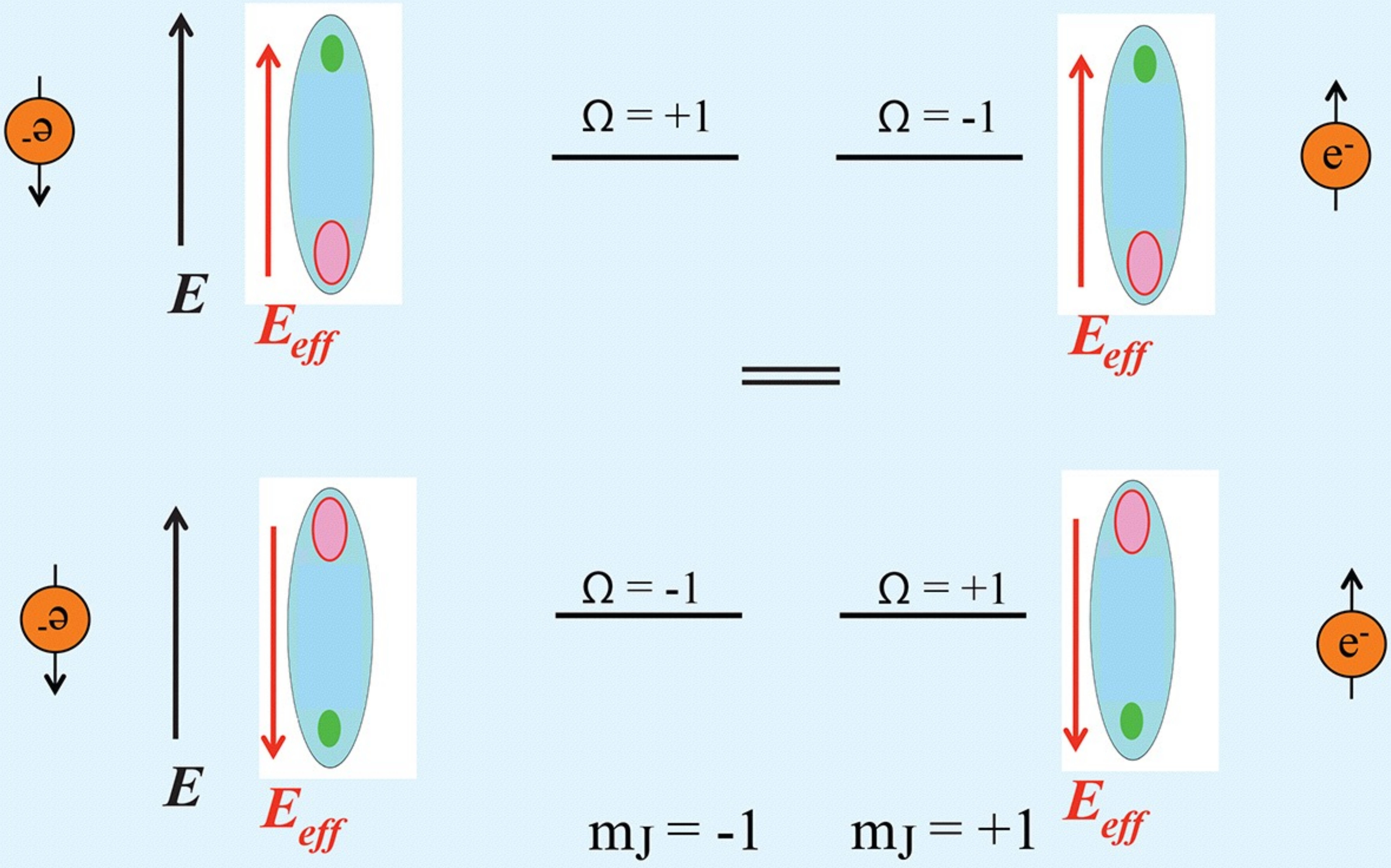

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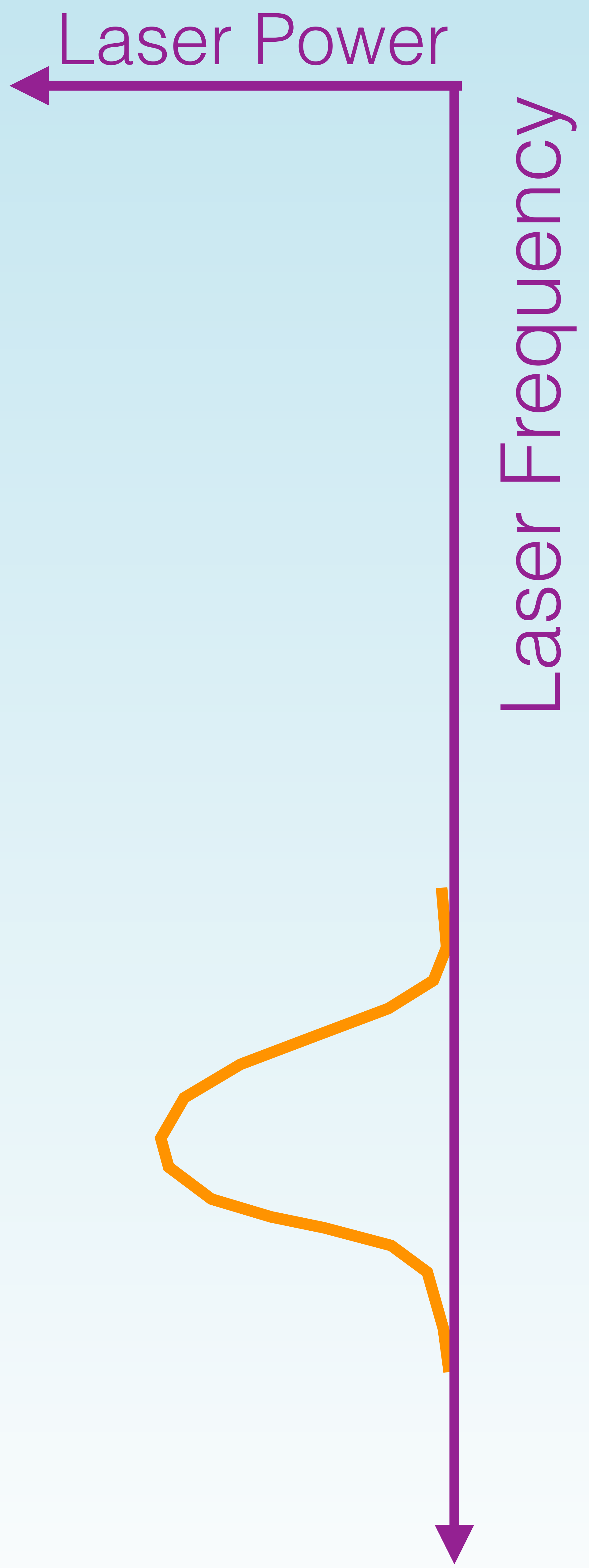

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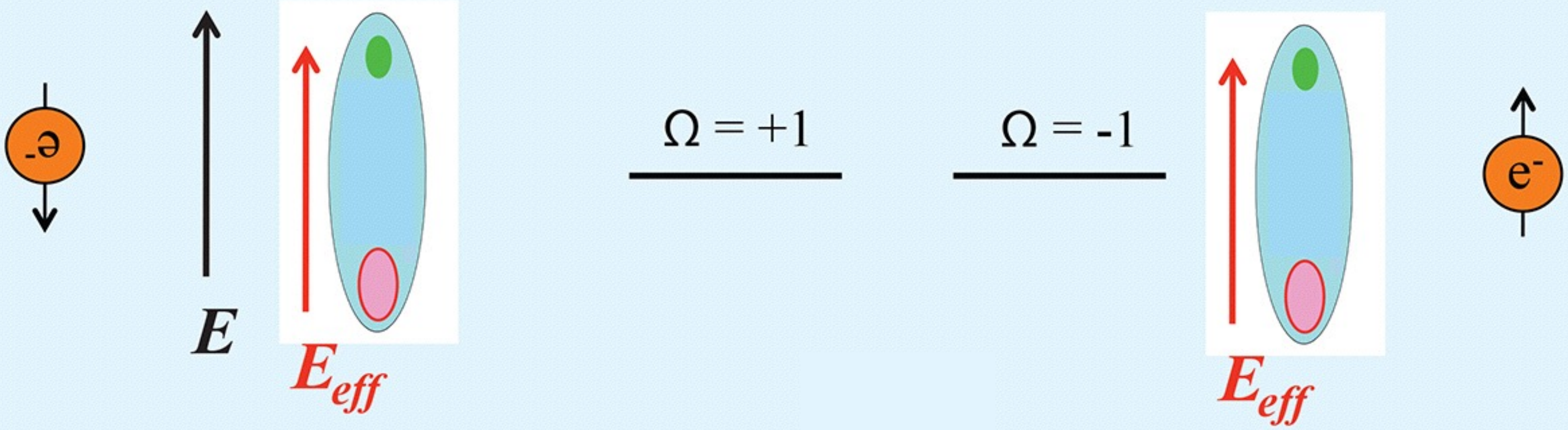
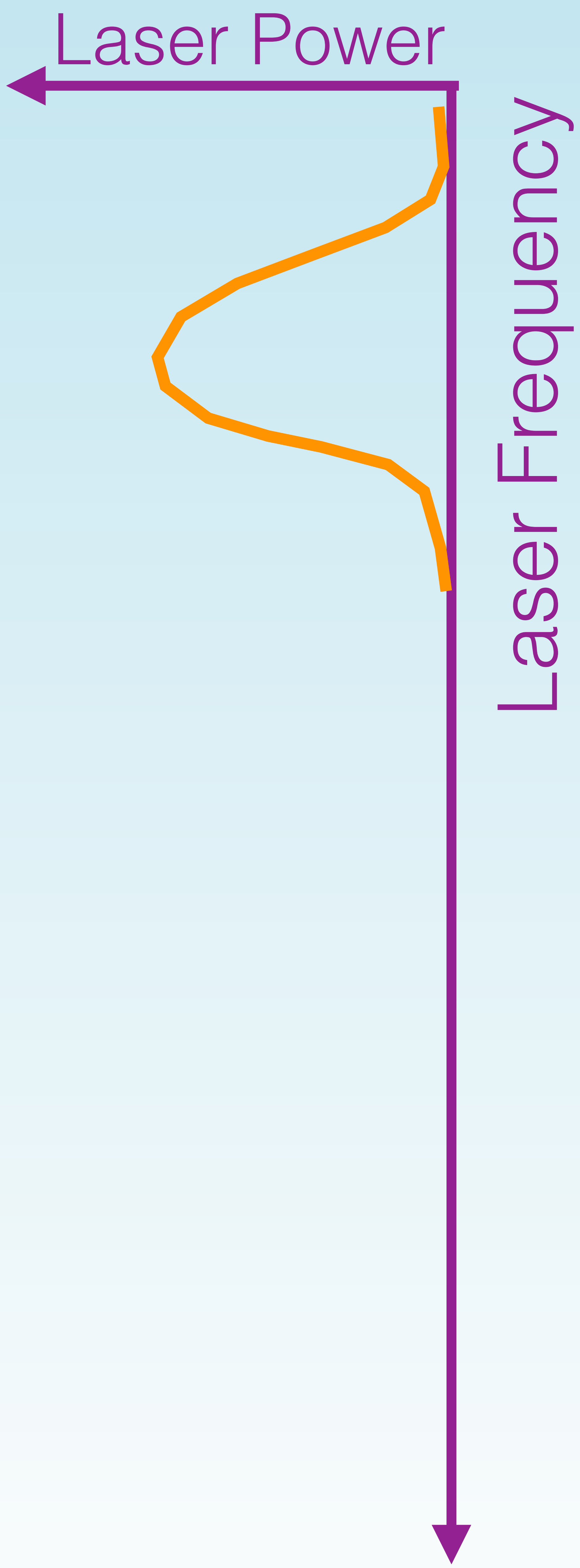


Ignore these levels for the moment…

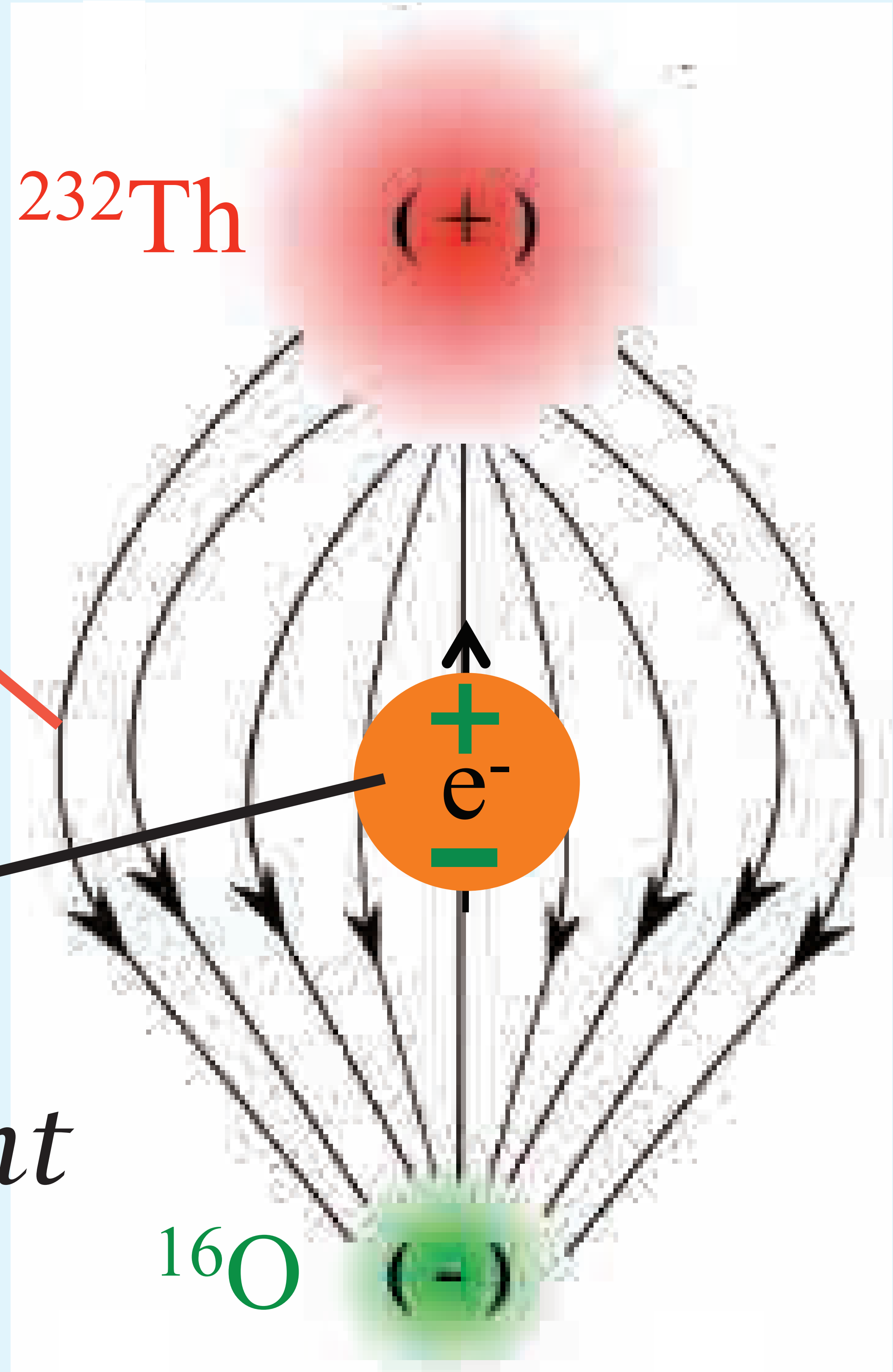
Frequency Selection



Add the eEDM -- Effective Field Interaction

$\mathcal{E}_{eff}$

Effective
Electric Field
Inside the Molecule



$$H'_{de} = - d_e \bullet \mathcal{E}_{eff}$$

d_e

Electric Dipole Moment
of the Electron

d_e interacts with $\mathcal{E}_{eff}$

$\mathcal{E}_{lab} \sim 100$ V/cm

$\mathcal{E}_{eff} \sim 10^{11}$ V/cm

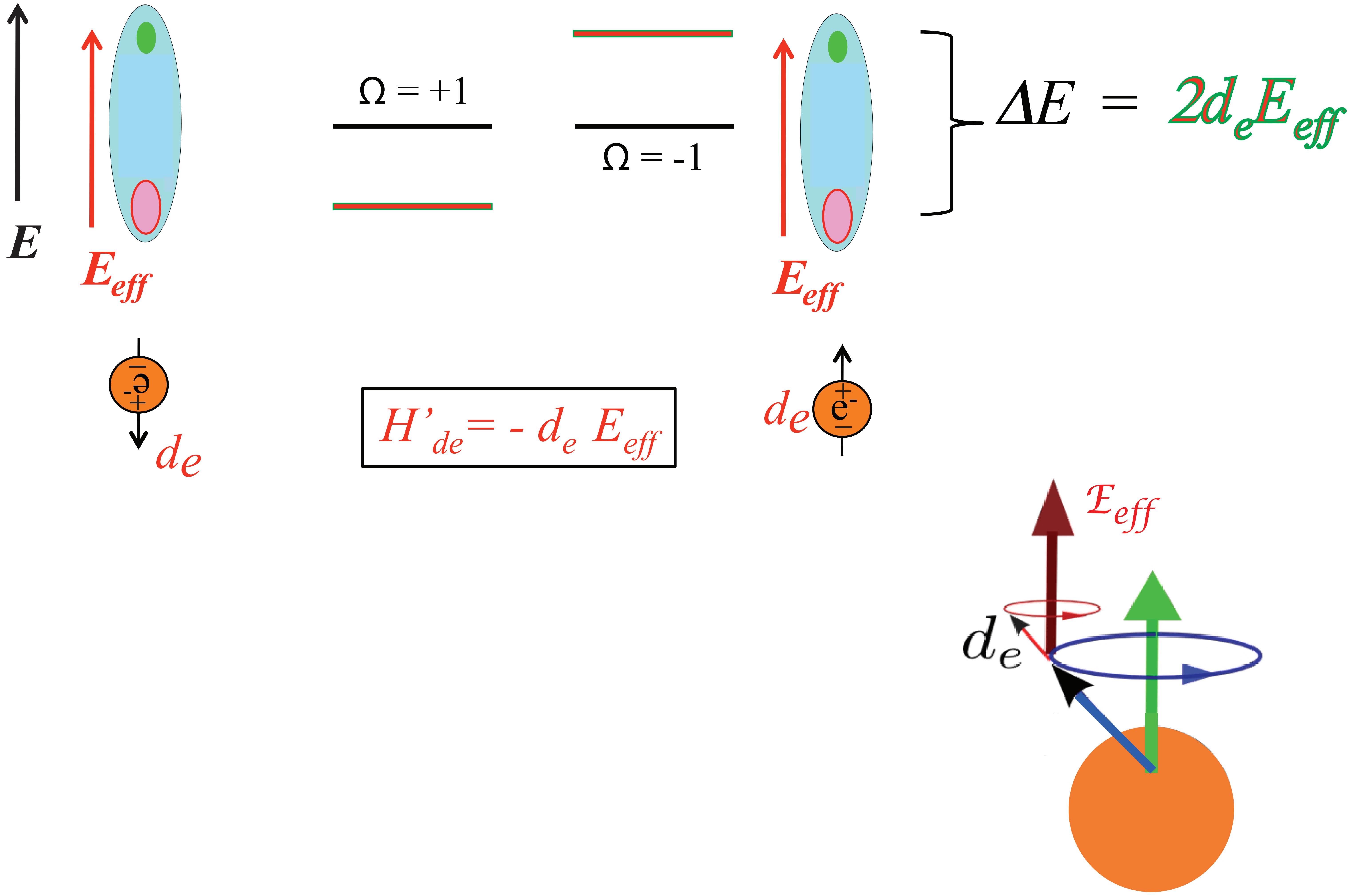
THE JOURNAL OF CHEMICAL PHYSICS **139**, 221103 (2013)

Communication: Theoretical study of ThO for the electron electric dipole moment search

L. V. Skripnikov,[1,2,a)] A. N. Petrov,[1,2] and A. V. Titov[1,2,b)]
[1] *Federal State Budgetary Institute "Petersburg Nuclear Physics Institute," Gatchina, Leningrad district 188300, Russia*

Later, more detailed calculation

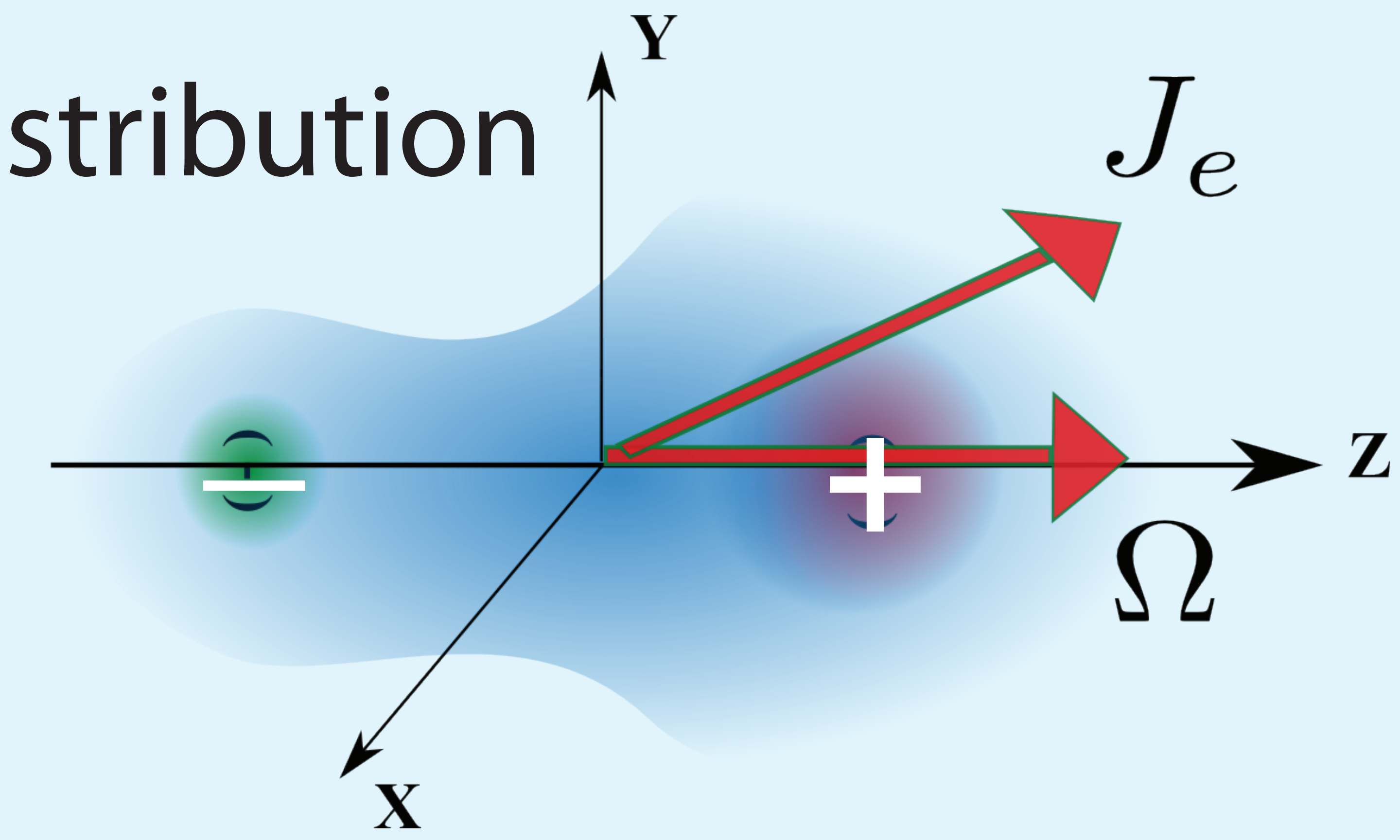
Add the eEDM - Levels Shift, Electron Spin Precesses

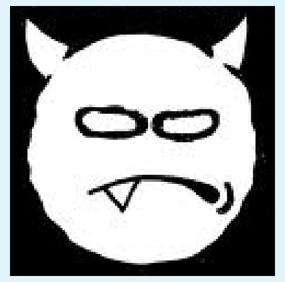


Using Molecules to Search for the EDM

Molecules -- the Good

-"Natural" Asymmetric Electric Field Distribution
(due to chemical bonding)



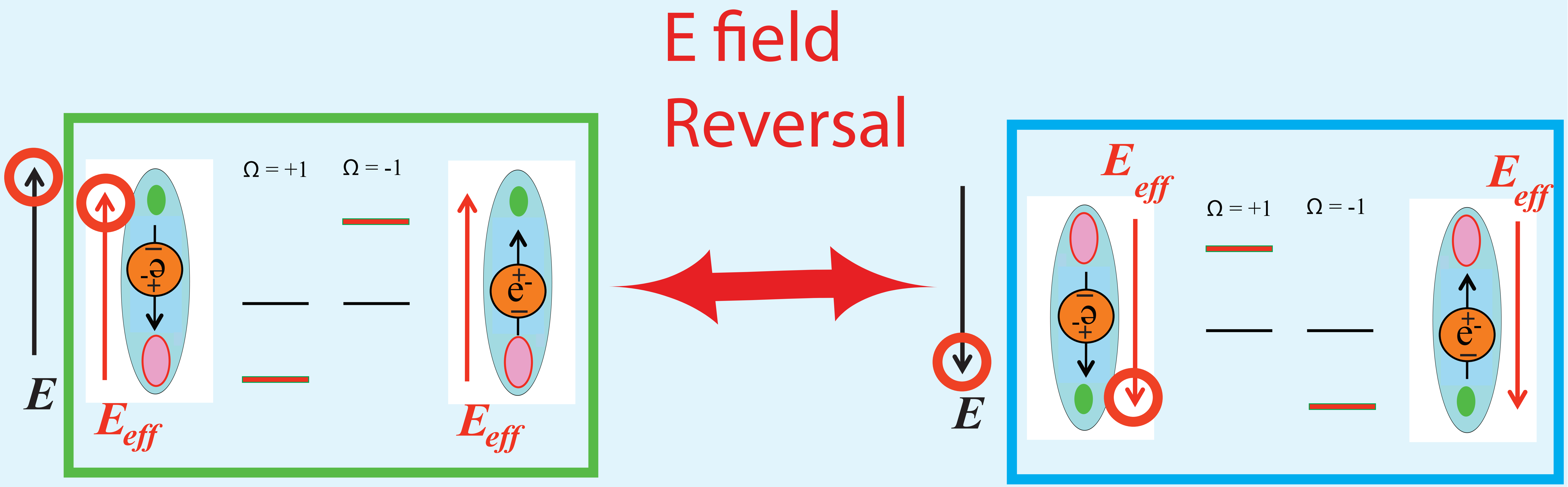
Molecules -- the Bad 

-Go ahead, make my Hamiltonian*...

Here is how we handle these complications…

*thanks to Roman Krems

Reverse Direction of E field, Keep Laser Frequency Fixed



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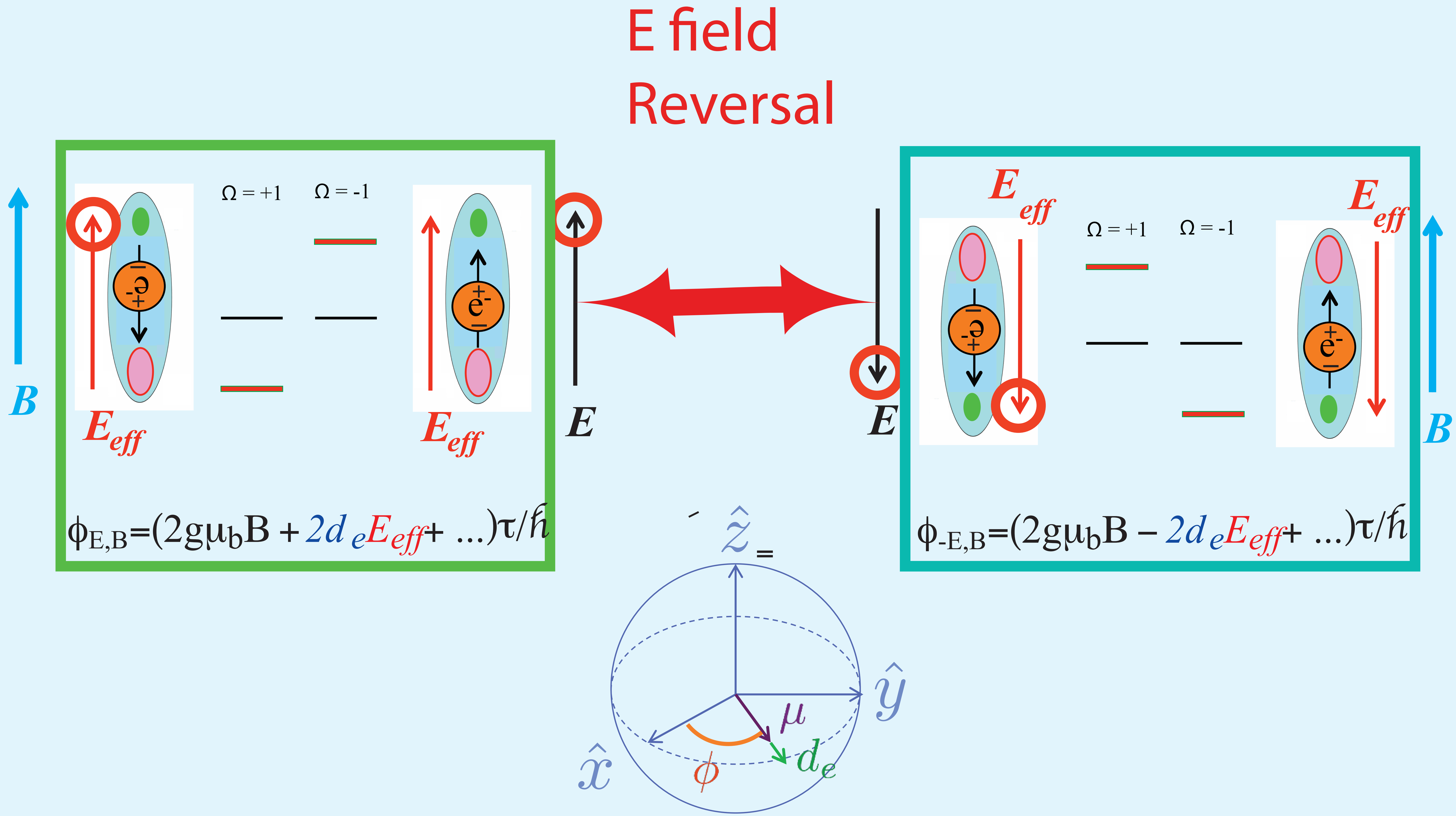
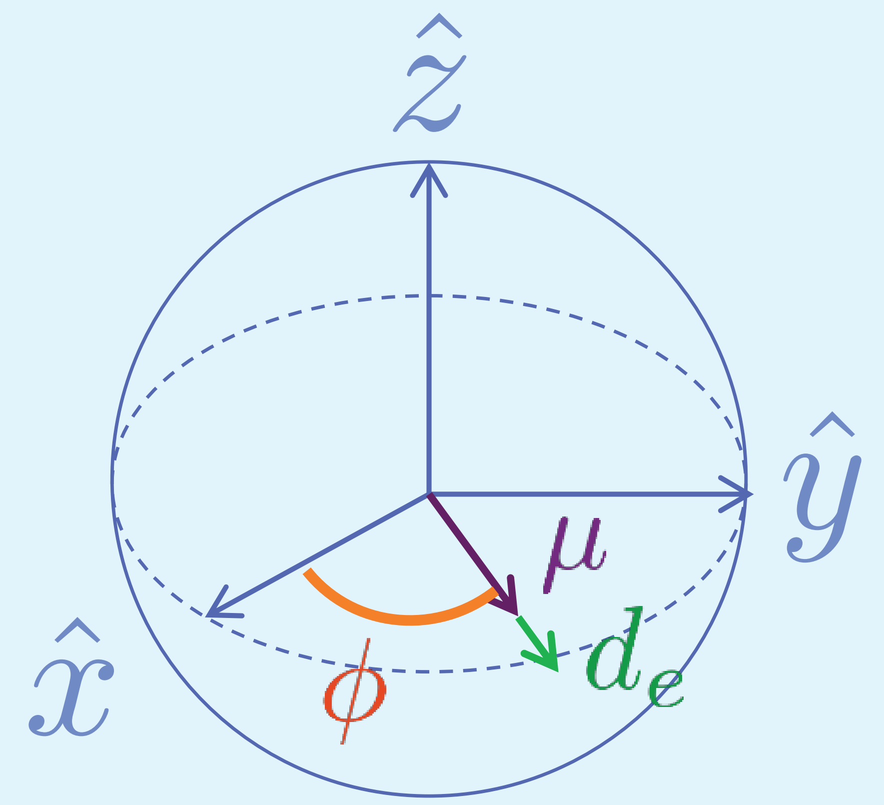
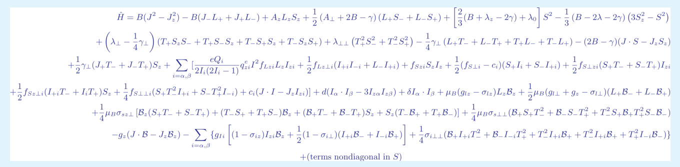


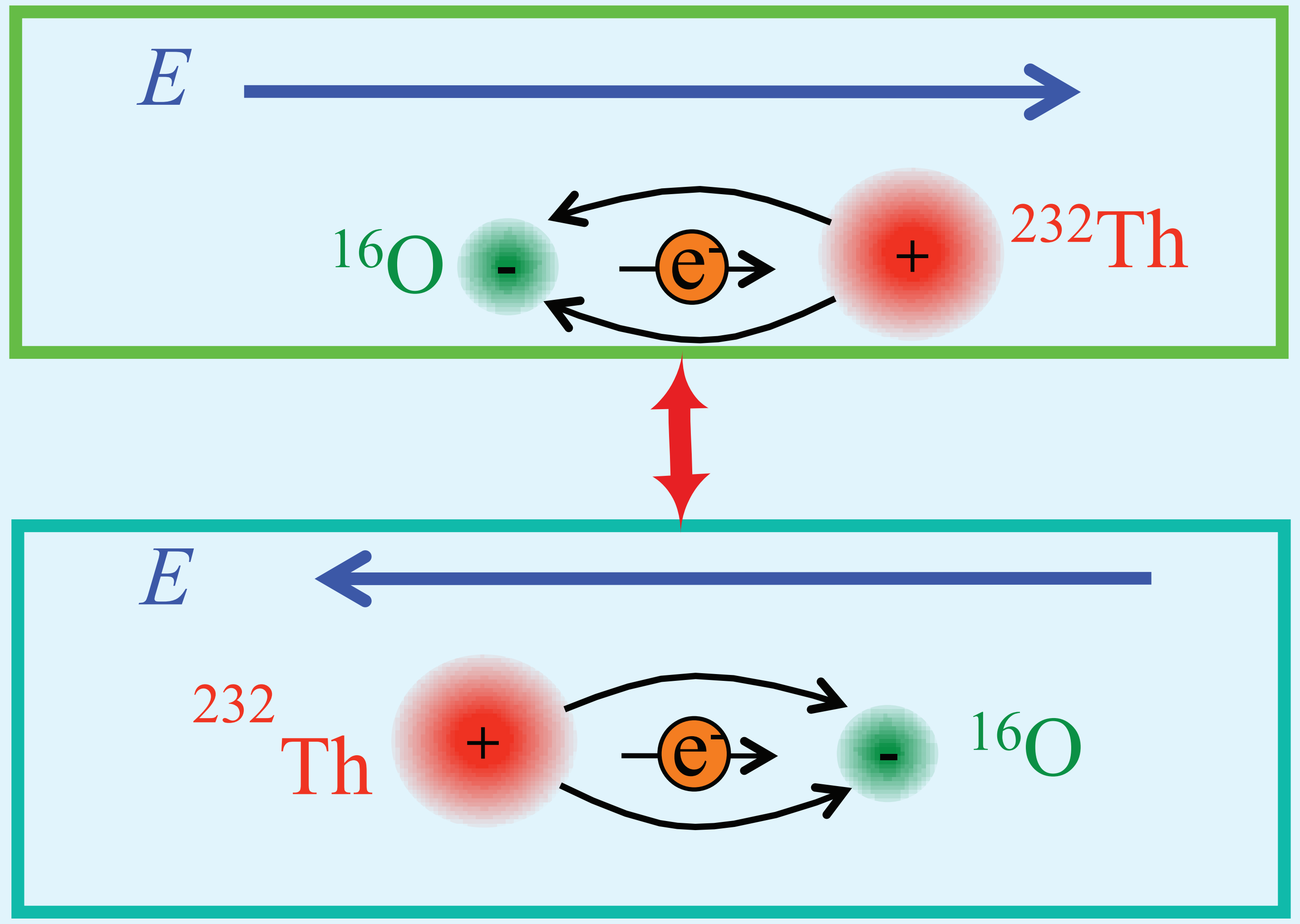
$$P_- \equiv \boxed{\phi_{E,B}=(2g\mu_b B + 2d_e E_{eff} + \ldots)\tau/\hbar} - \boxed{\phi_{-E,B}=(2g\mu_b B - 2d_e E_{eff} + \ldots)\tau/\hbar} = (4d_e E_{eff} + \ldots)\tau/\hbar$$

Determining eEDM, now with Efield Reversal

Measure the precession of the spin with E field reversal, subtract the two values







$$P_- = (4 d_e E_{eff} + g\mu_b B_{E\text{-}corr} + \eta \mu_b E_{nr}|B| + \ldots)\tau/\hbar$$

B field correlated with E reversal

Need $B_{E\text{-}corr} < 10^{-7}$ gauss, for 10^{-28} e-cm

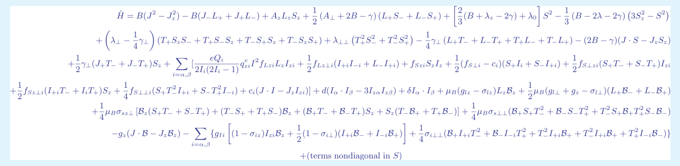
$B_{E\text{-}corr}$ measured with fluxgates, $<10^{-8}$ gauss sensitivity

"Non-reversing E field"

-- g factor is linear in E, due to rotational mixing
-- Need $E_{nr} < 1$ V/cm,
-- E_{nr} measured by raman spectroscopy , ~ few mv/cm
-- *AND η determined from N, B reversals (1 nm/volt)*

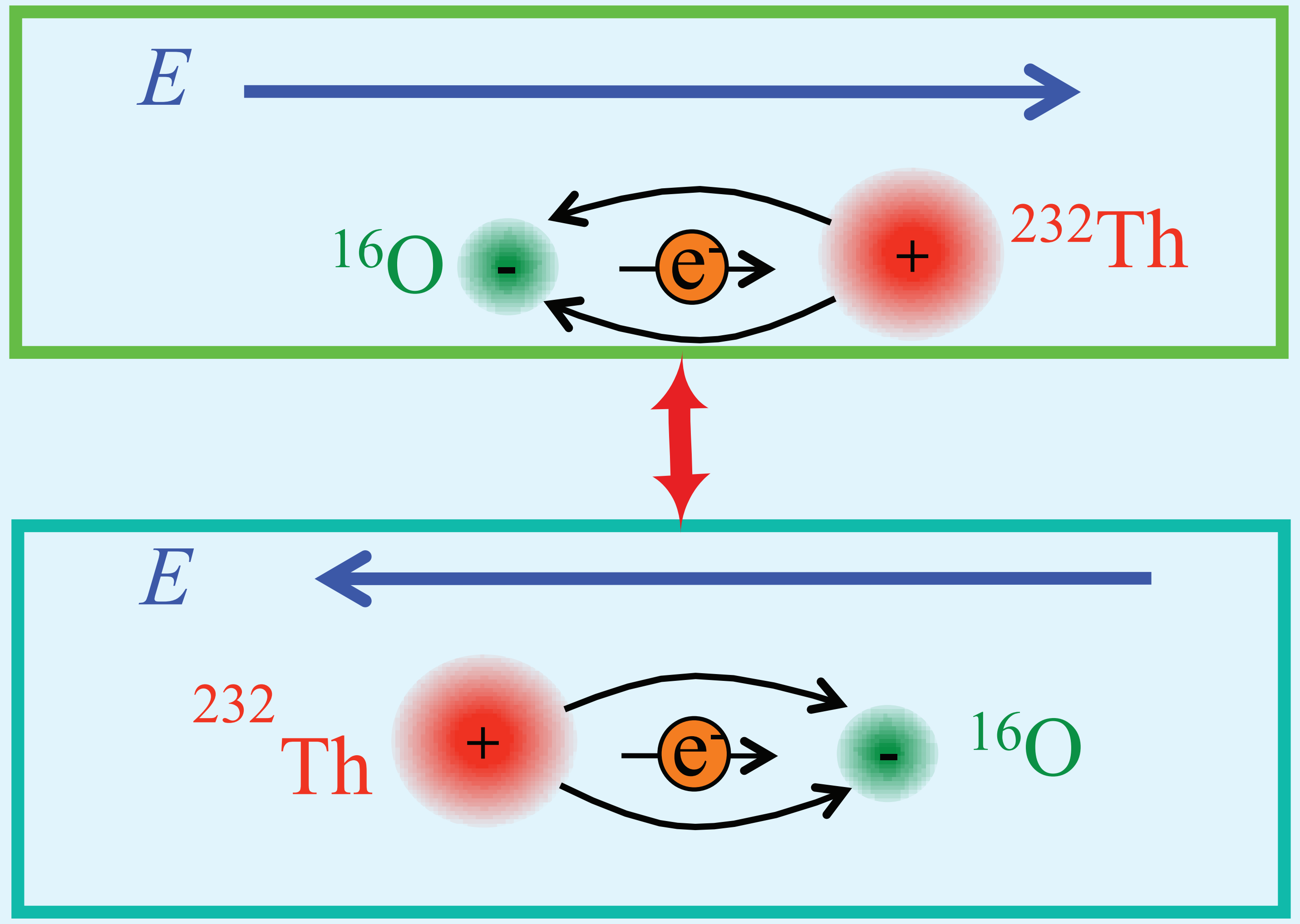
E field reversal alone could give greatly improved measurement of eEDM
But we don't do just E reversals.....

Determining eEDM, now with Efield Reversal



+ terms due to applied fields + EDM terms

Measure the precession of the spin with
E field reversal, subtract the two values



$\hat{z}$

EDM term now Dominates!

$$P_- = (4 d_e E_{eff} + g\mu_b B_{E\text{-}corr} + \eta\mu_b E_{nr}|B| + \ldots)\tau/\hbar$$

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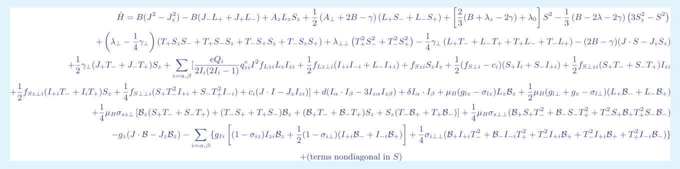
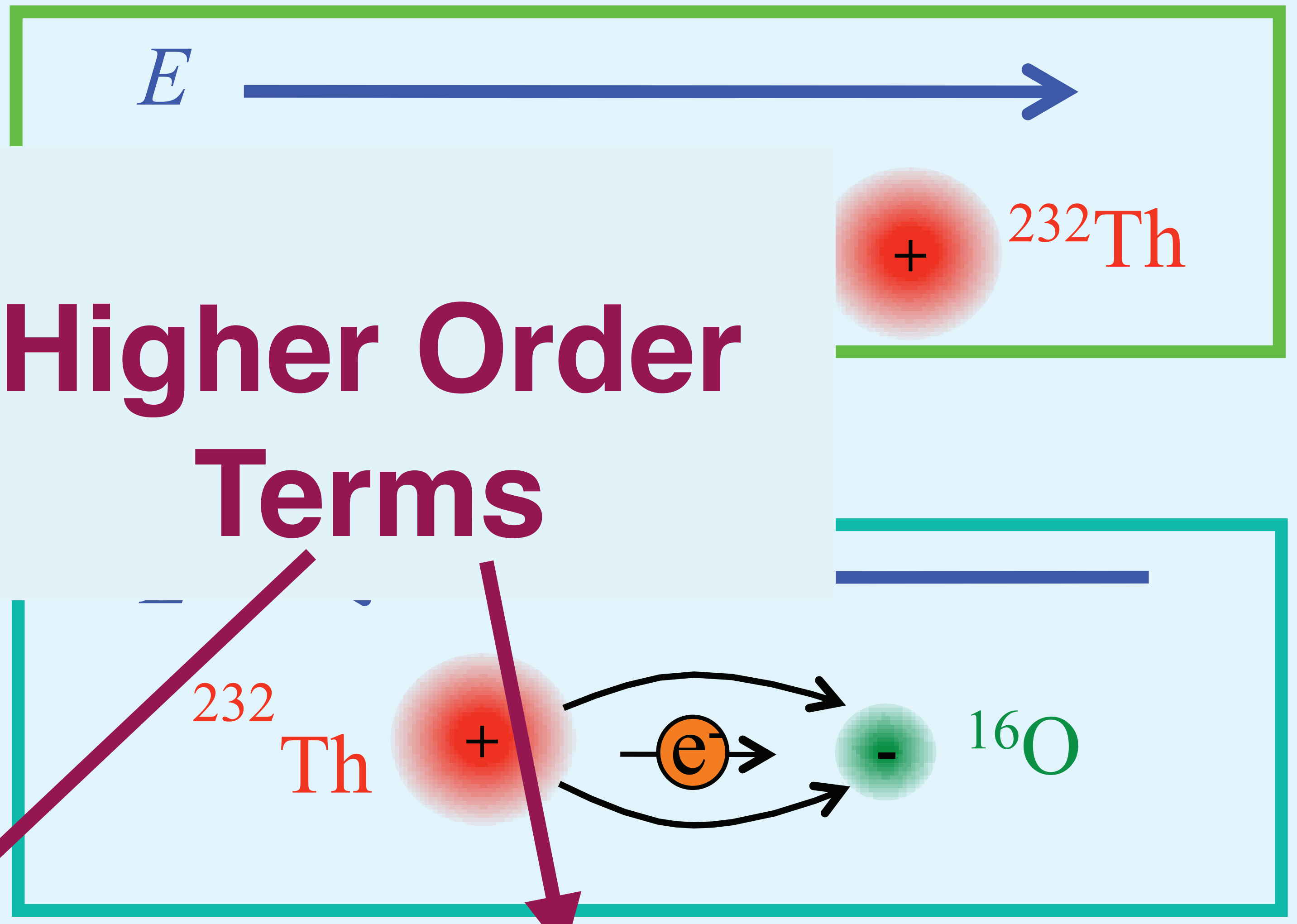


+ terms due to applied fields + EDM terms

EDM term now Dominates!



Higher Order Terms

$$P_- = (4 d_e E_{eff} + g\mu_b B_{E\text{-corr}} + \eta \mu_b E_{nr}|B| + \ldots)\tau/\hbar$$

B field correlated with E reversal

Need $B_{E\text{-corr}} < 10^{-7}$ gauss, for 10^{-28} e-cm

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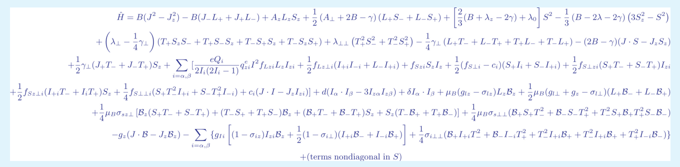
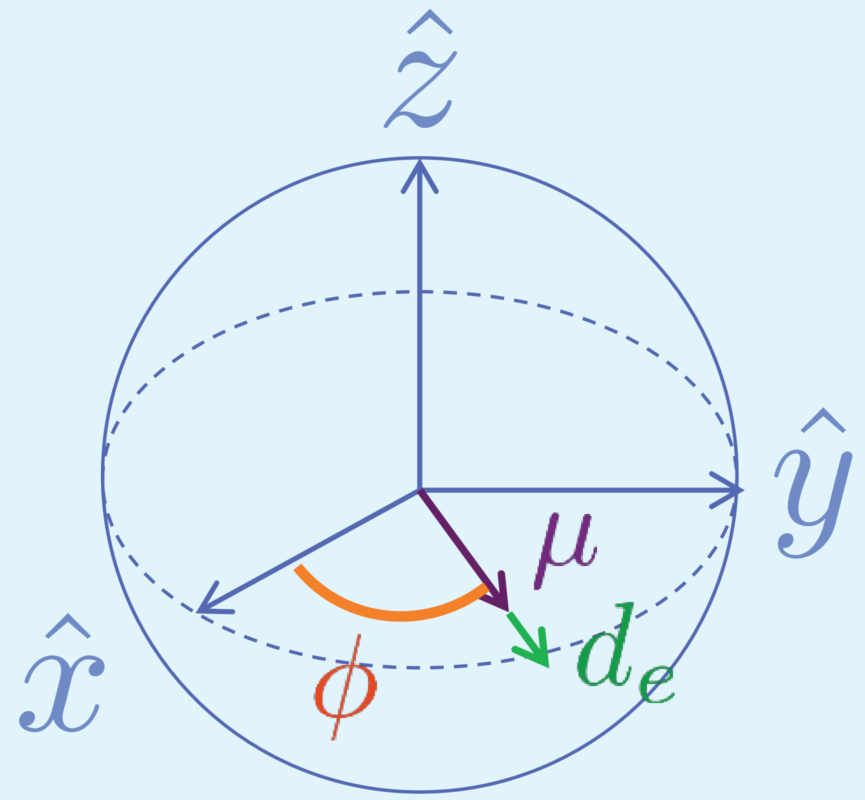
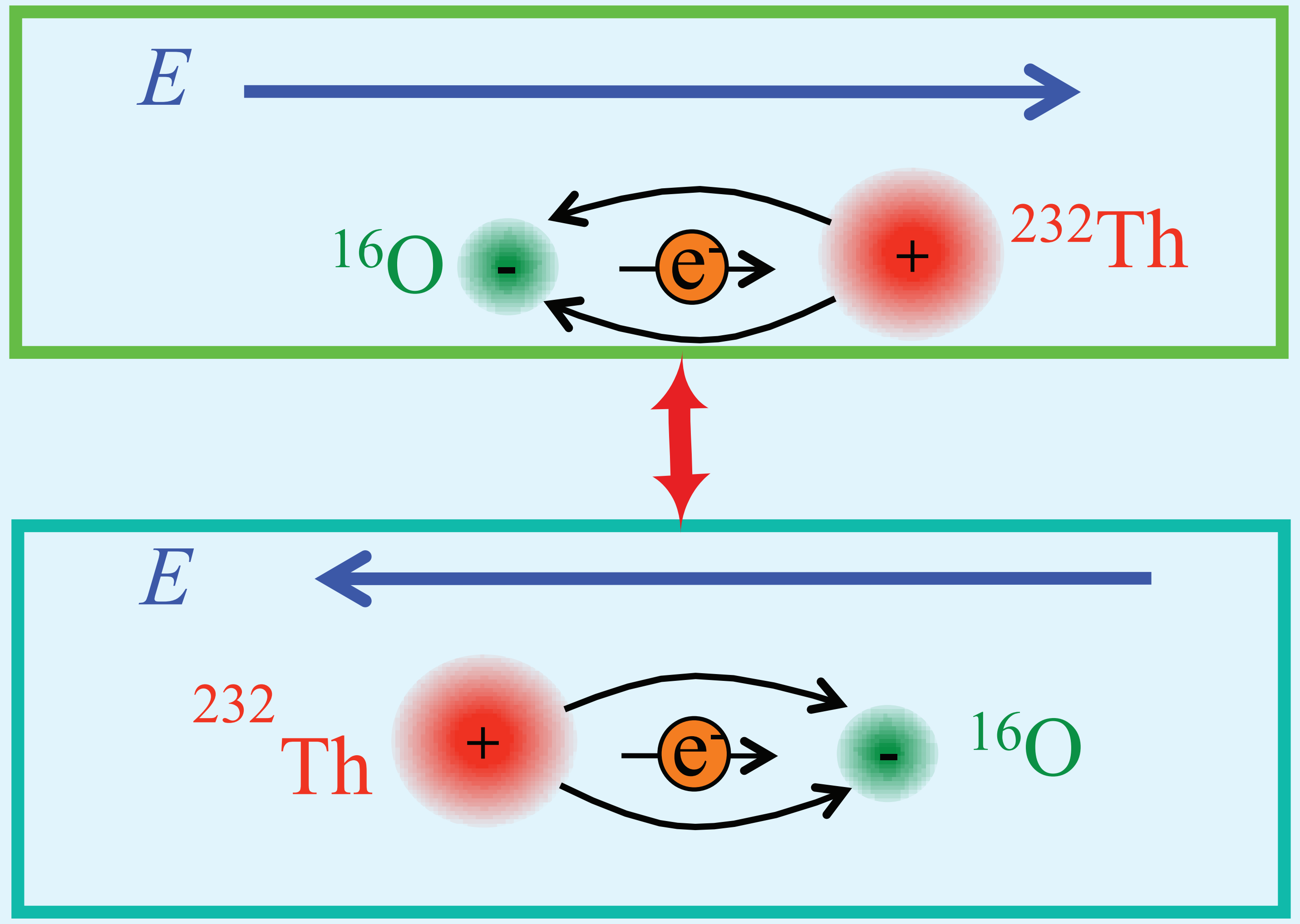
Determining eEDM, now with Efield Reversal

Measure the precession of the spin with
E field reversal, subtract the two values



+ *terms due to applied fields + EDM terms*





We call this a "parity sum"

$$P_- = (4 d_e E_{eff} + g\mu_b B_{E\text{-corr}} + \eta\mu_b E_{nr}|B| + \ldots)\tau/\hbar$$

B field correlated with E reversal

Need $B_{E\text{-corr}} < 10^{-7}$ gauss, for 10^{-28} e-cm

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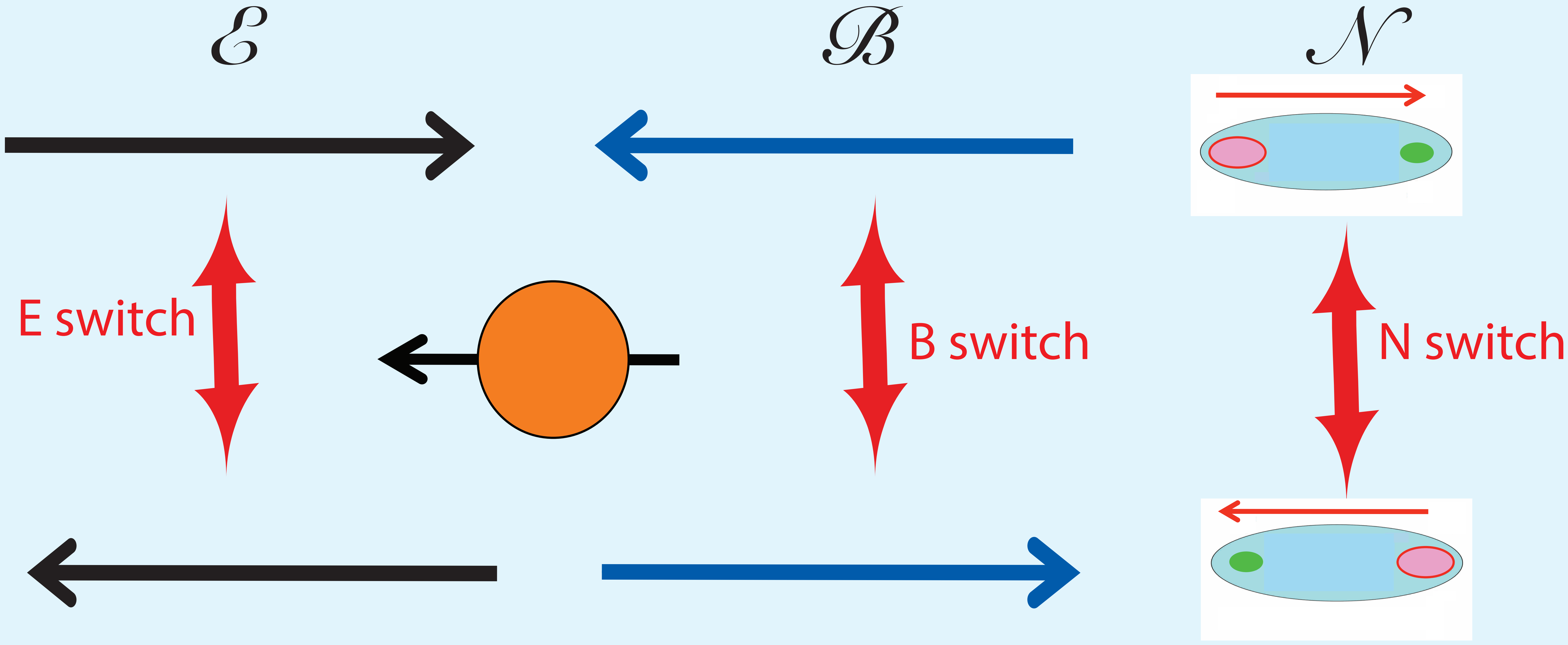
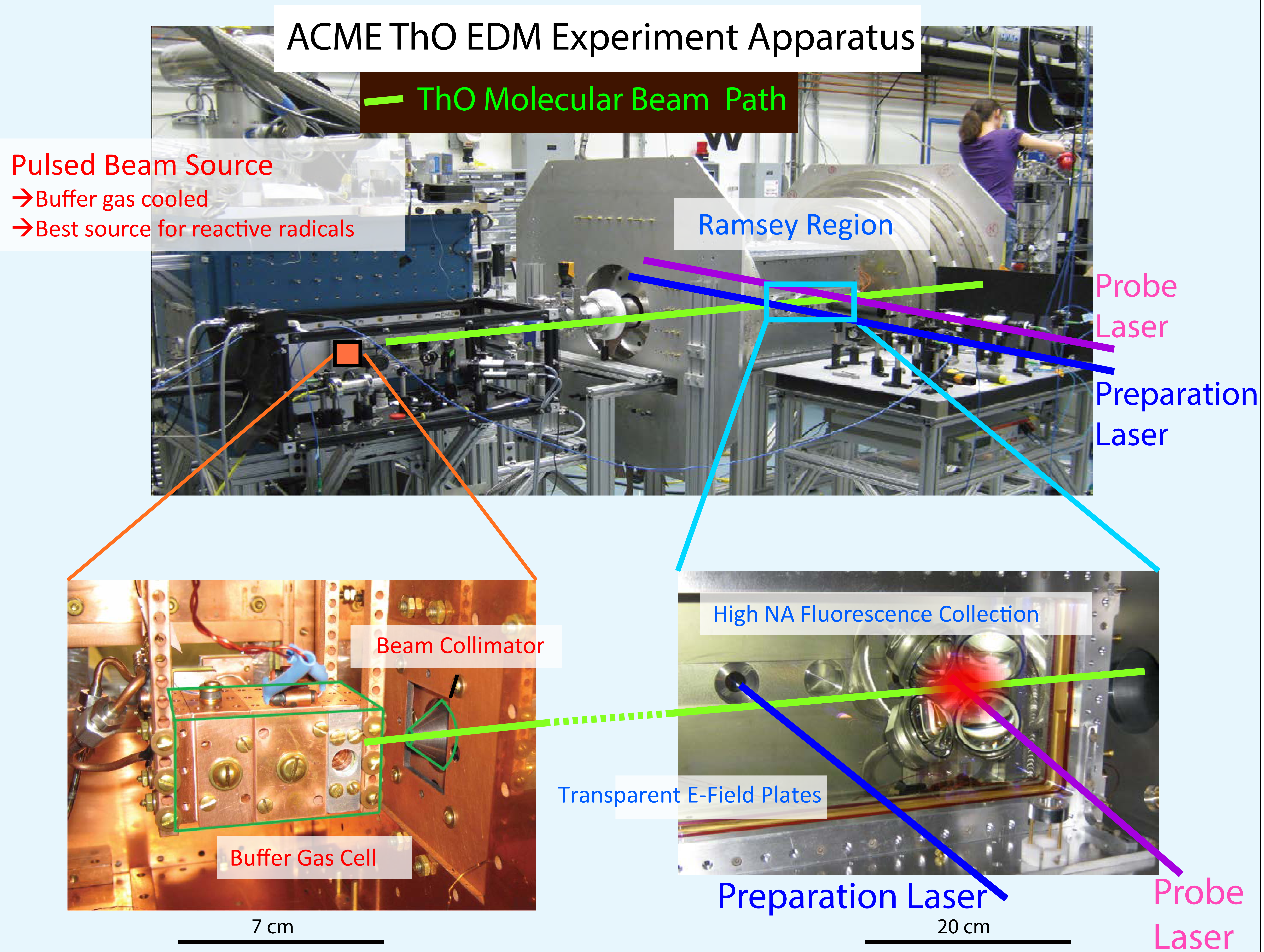
E field reversal alone could give greatly improved measurement of eEDM
But we don't do just E reversals.....

THREE reversals -- EIGHT combinations



These reversals together generate 8 parity sums

Each contain information about the system


ACME ThO EDM Experiment Apparatus
ThO Molecular Beam Path
Pulsed Beam Source
→Buffer gas cooled
→Best source for reactive radicals
Ramsey Region
Probe Laser
Preparation Laser
Beam Collimator
Buffer Gas Cell
7 cm
High NA Fluorescence Collection
Transparent E-Field Plates
Preparation Laser
Probe Laser
20 cm

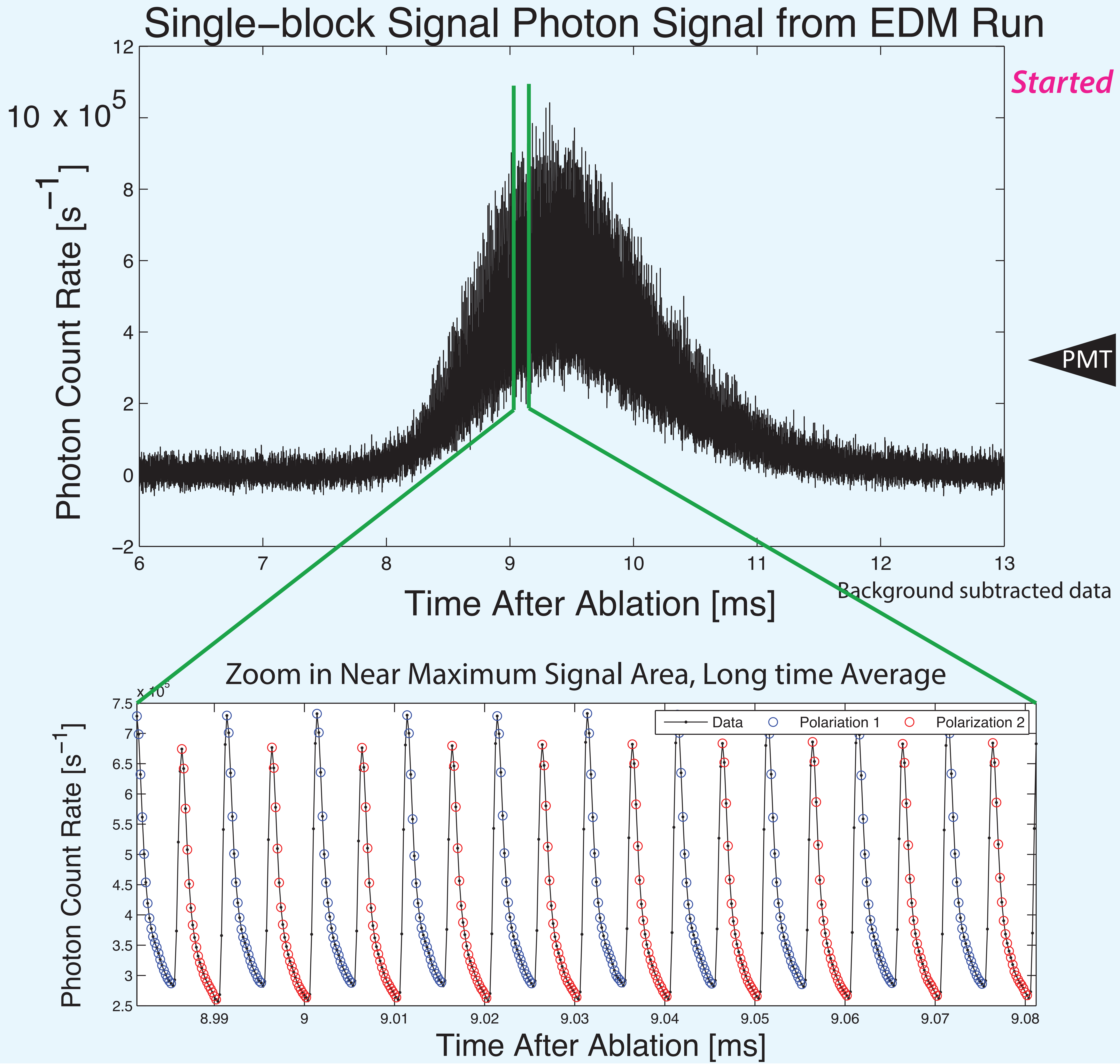
ACME

Advanced Cold Molecule Electron EDM

Harvard University

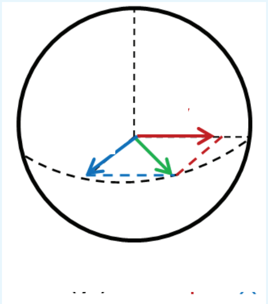
Yale University

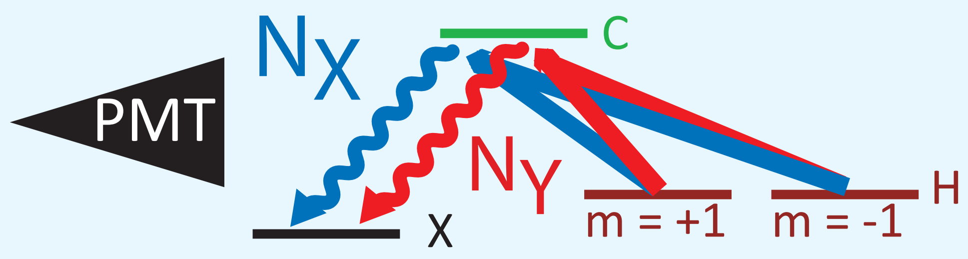
Typical EDM Data -- Pulses of Molecules Through the Ramsey Region



Started Taking EDM Data May 2012

Read out quantum state

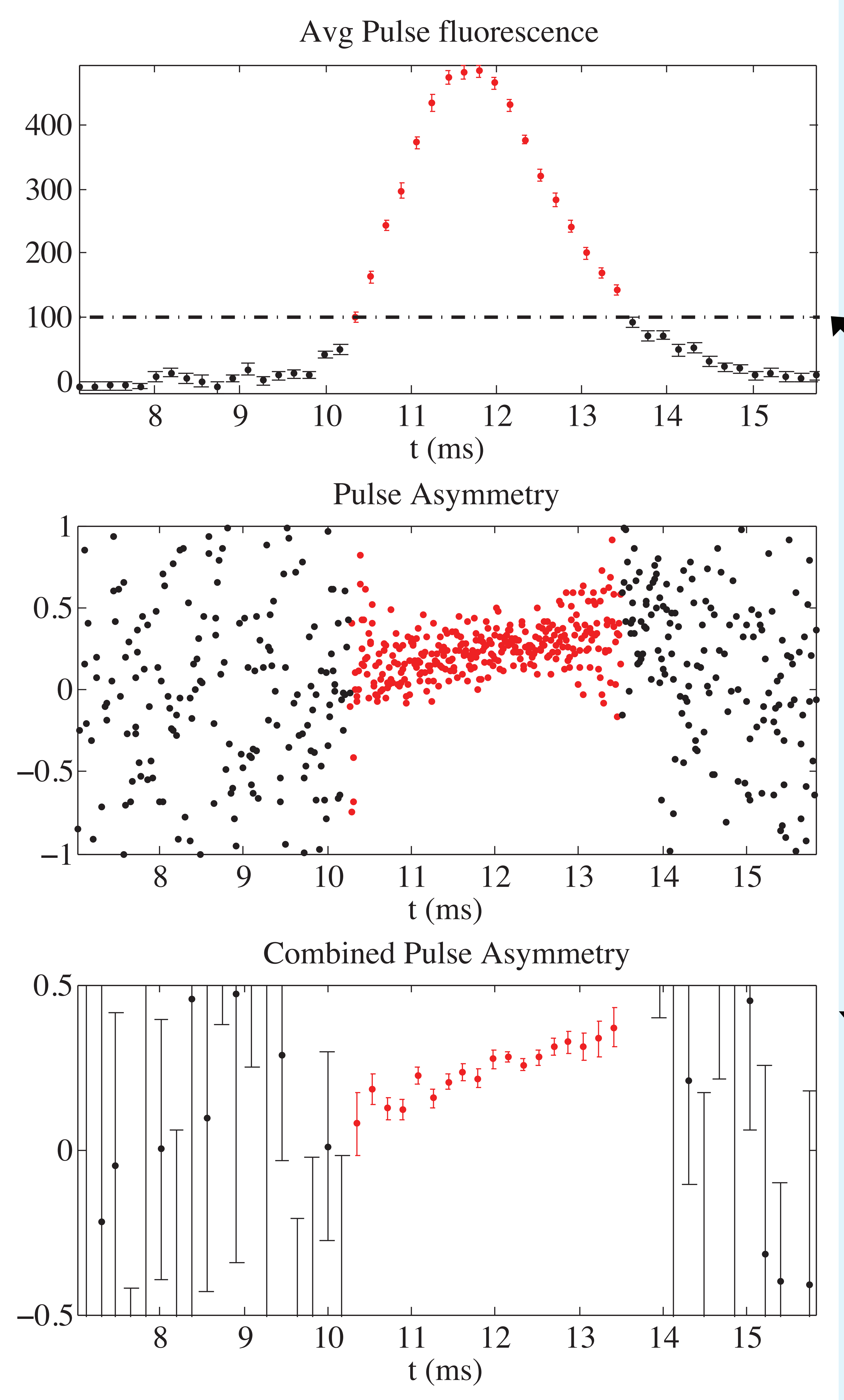




Red and Blue indicate fluorescence collected under application of orthogonal polarizations of probe light.

Ratio of Red to Blue areas gives phase angle ϕ

Data Analysis



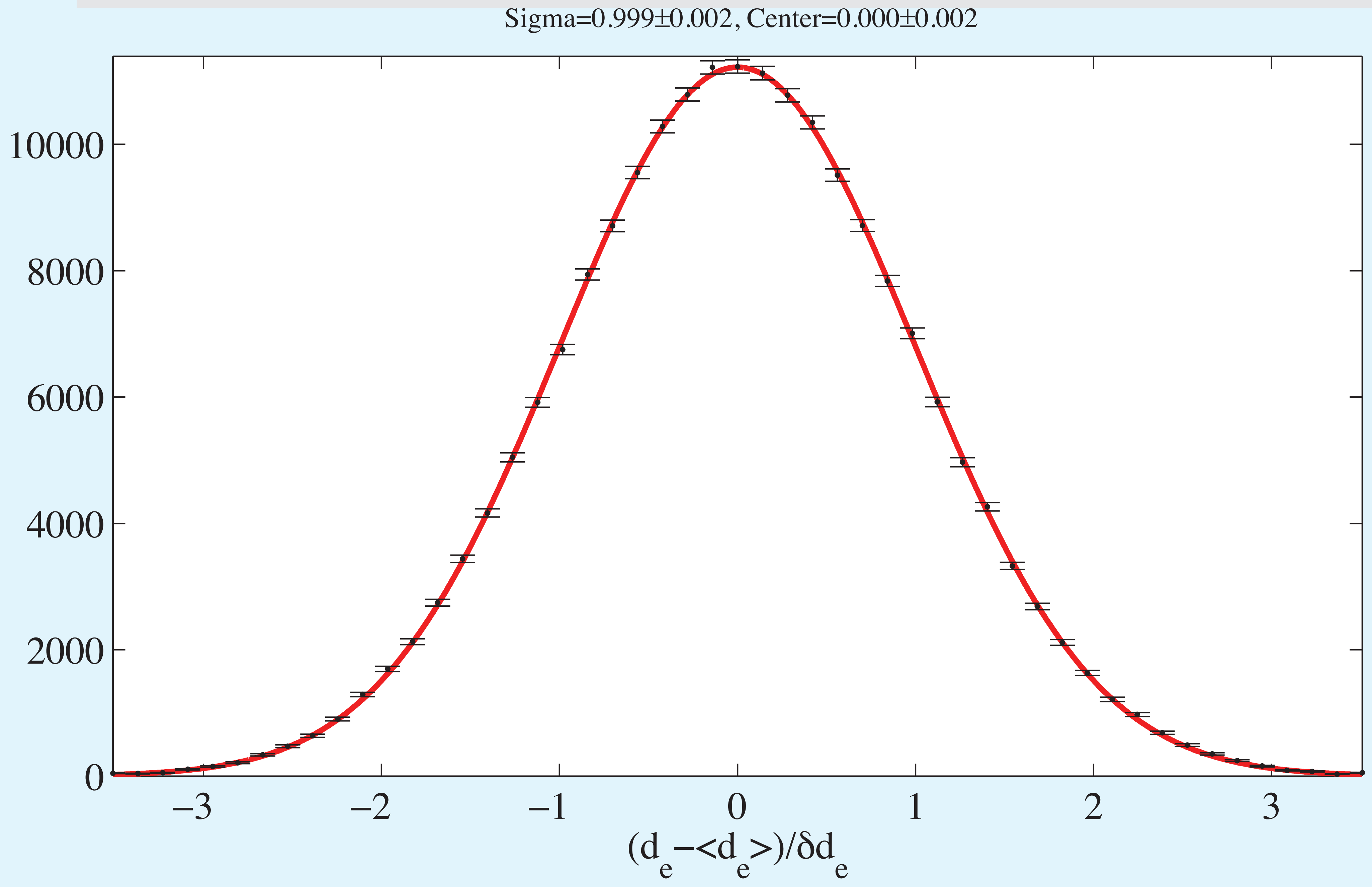
signal threshold cut ensures gaussian asymmetry

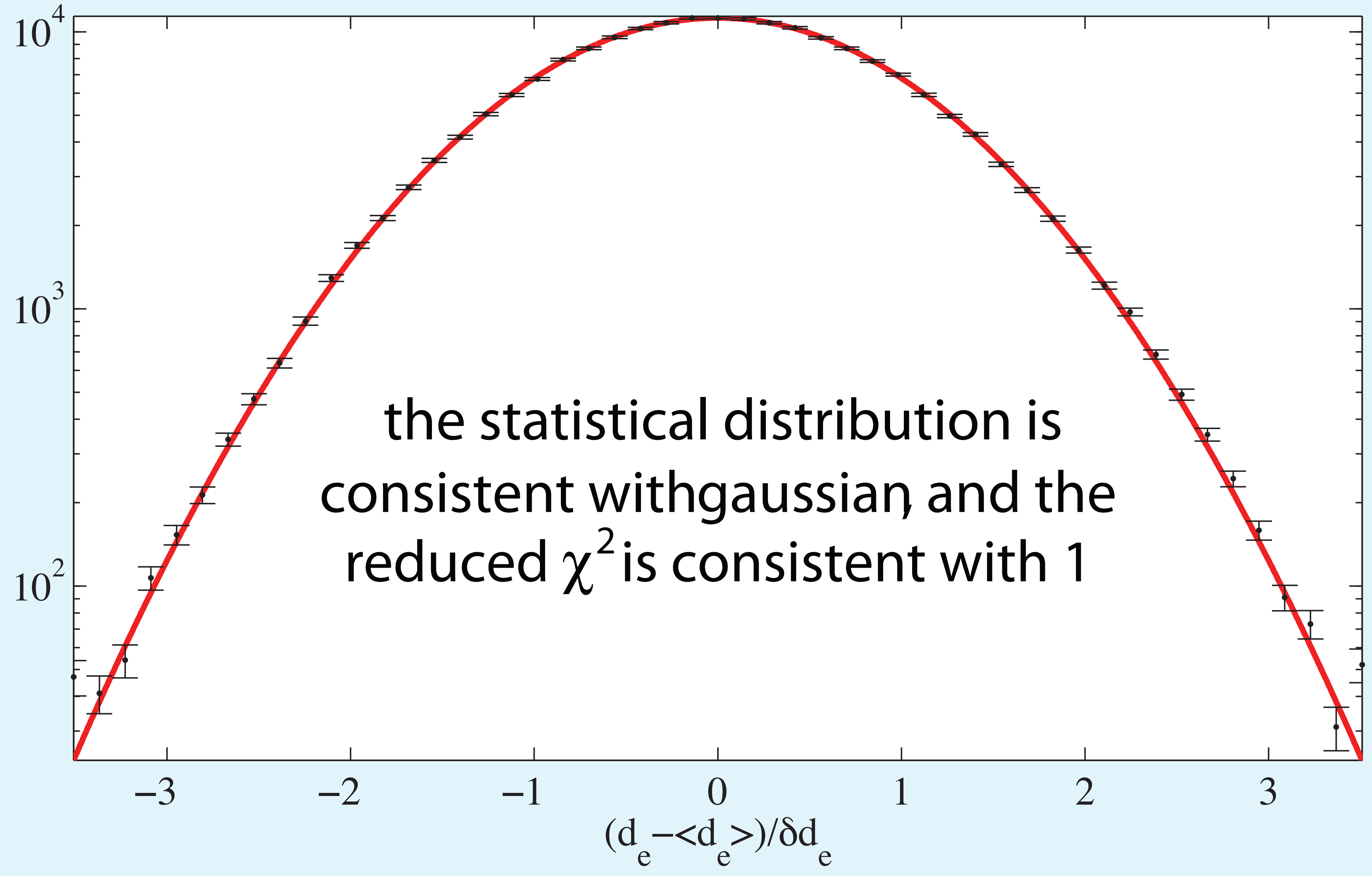
binning of asymmetries (18-30 pts)

compute the standard error in the mean, and use standard error propagation to obtain the result.

- Computation of Uncertainty
- Uncertainty propagation
- Statistical Distribution
- Blind Offset
- Feldman-Cousins Confidence Intervals

Data Analysis





- Computation of Uncertainty
- Uncertainty propagation
- **Statistical Distribution**
- Blind Offset
- Feldman-Cousins Confidence Intervals

the uncertainty is limited by photon shot noise in the photodetectors

$$\delta\omega^{NE} \approx 1.15\times \frac{1}{C\tau\sqrt{N}}$$

Statistical Sensitivity to the eEDM

Shot noise limited error in measurement of the electron EDM using our method

$$\delta d_e = \frac{1}{2\,E_{eff}}\,\frac{\hbar}{\tau\sqrt{\dot{N}T}}$$

Effective Electric Field

Coherence Time

(Photon) Counting Rate

Integration Time

= (molecular flux) X (detection efficiency)

Statistics OK
+-4 x 10^{-29} e-cm

best previous measurements $d_e < 1 \times 10^{-27}$ e-cm

Statistics OK

$\pm 4 \times 10^{-29}$ e-cm

best previous measurements $d_e < 1 \times 10^{-27}$ e-cm

Got Systematics ?

Systematic Error Search - I

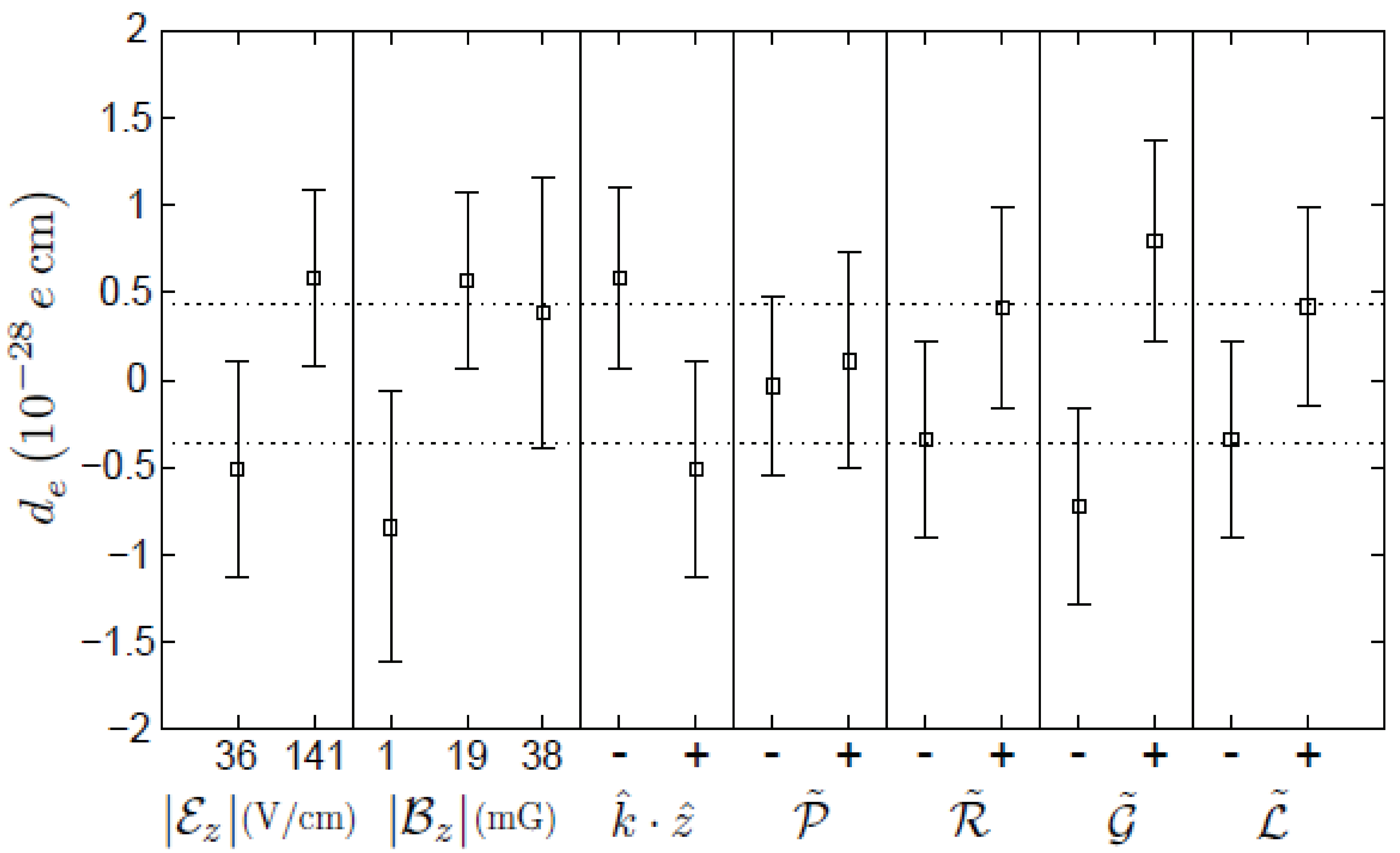
Turn Knobs -- see what happens

These Knobs Should NOT change EDM, but let`s check!

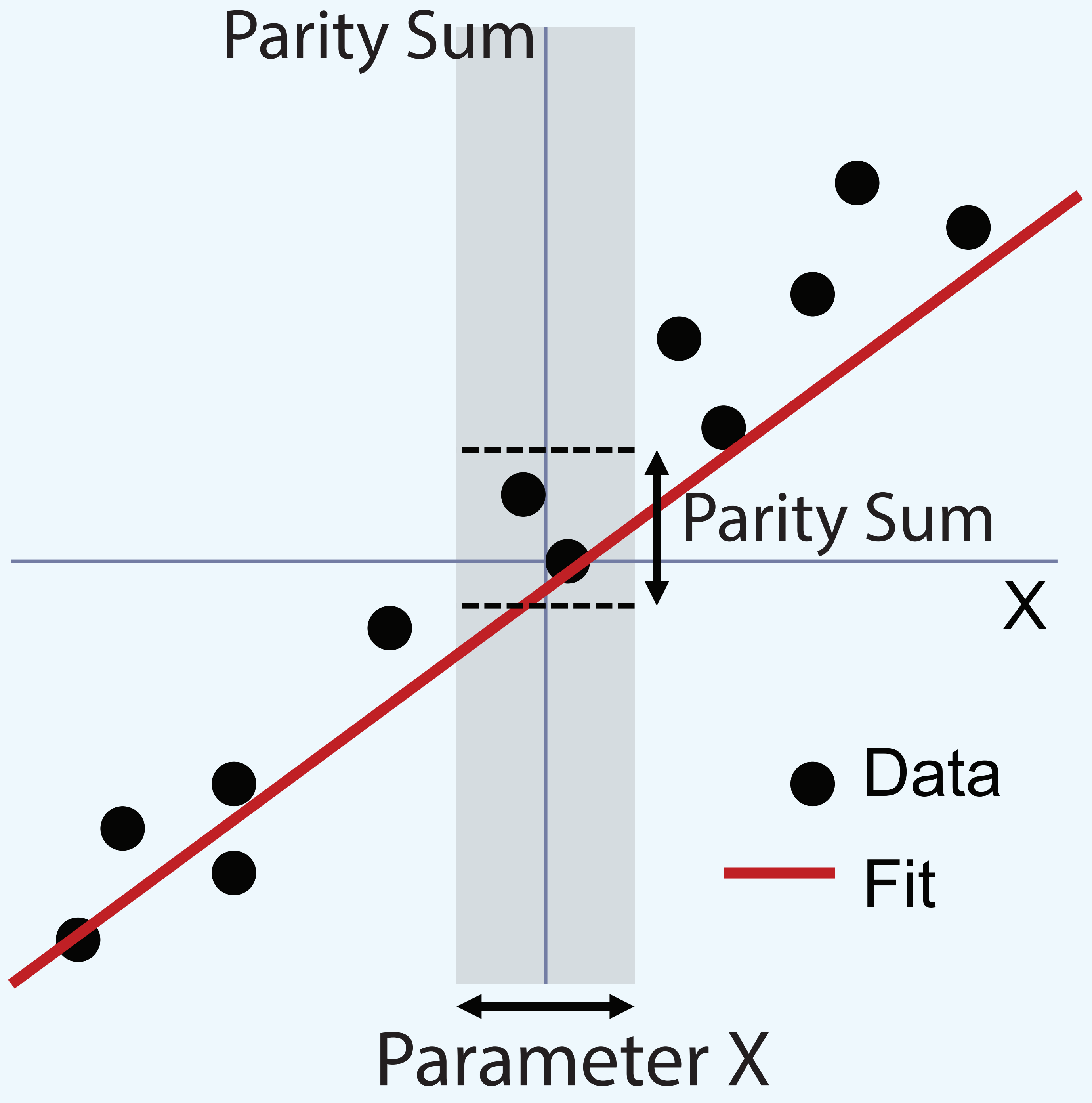
Extra "Switches"

TWO Different
Pump-probe
-relative polarizations
-global polarizations
Efield plate lead positions
Laser propogation directions
Probe upper states
Electric field (E) magnitudes

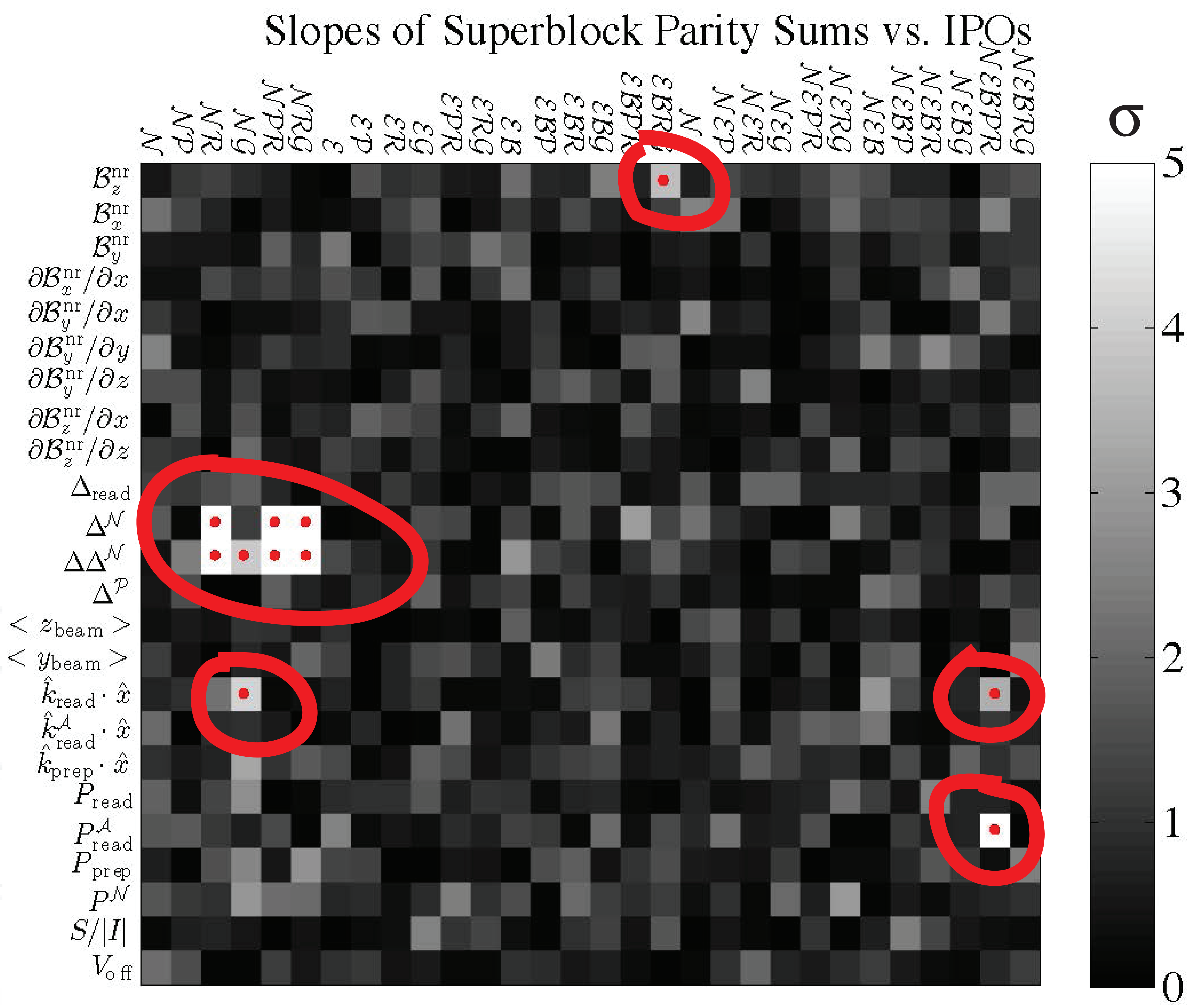
THREE different
Magnetic field (B) values



Systematic Checks - III, Correlation Search Method

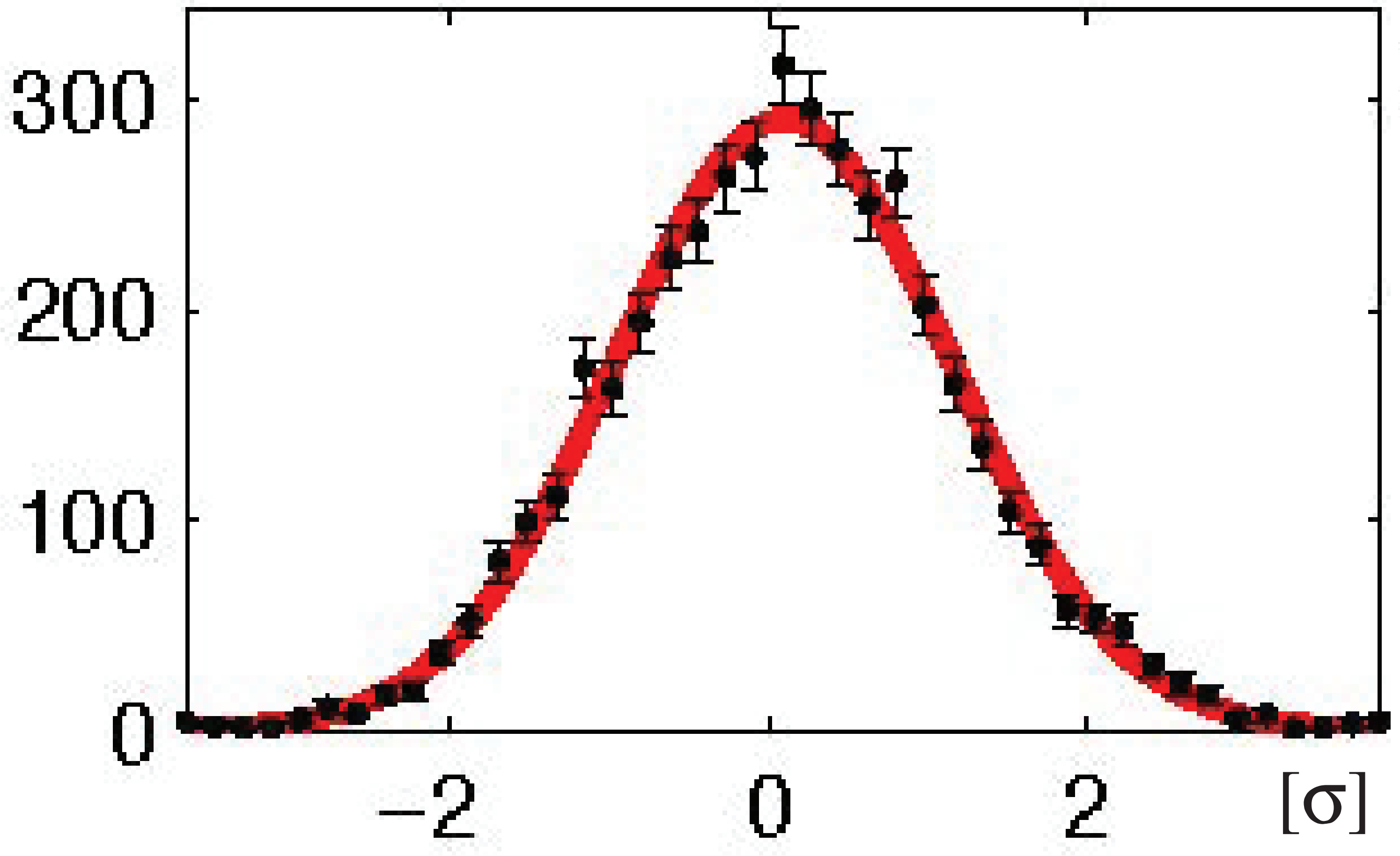


Pixel Plot Identifies Correlations



ω Parity Sums IPO Slopes
Red Dots: > 3.39σ. Expect 0.5 by chance

Statistical Distribution of Diagnostic Signals from Systematic Error Search

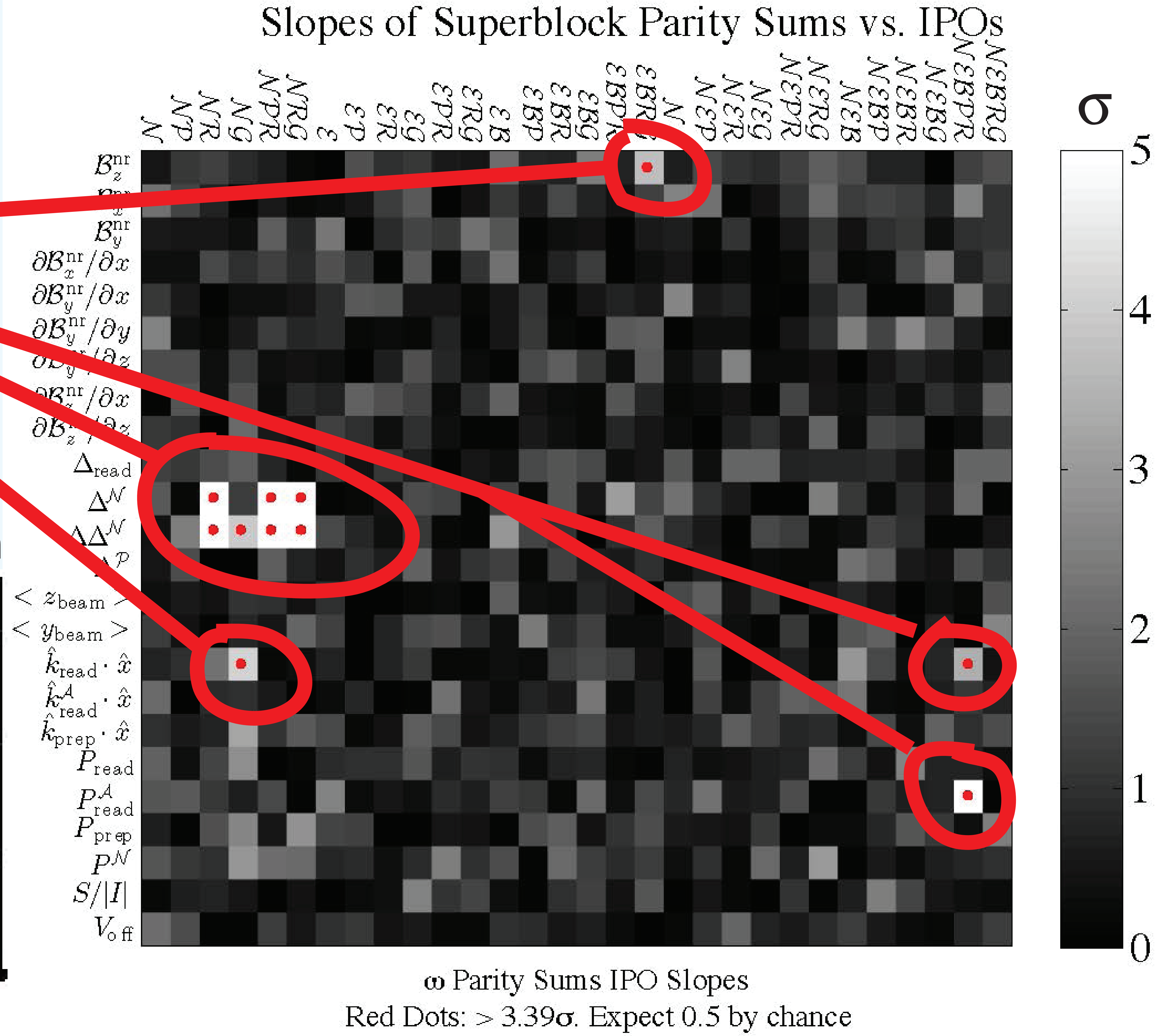


Systematic Checks - III, Correlation Search Method

Few "outliers",
one "switch" (or so)
from the EDM channel

All understood and/or controlled

Pixel Plot Identifies Correlations



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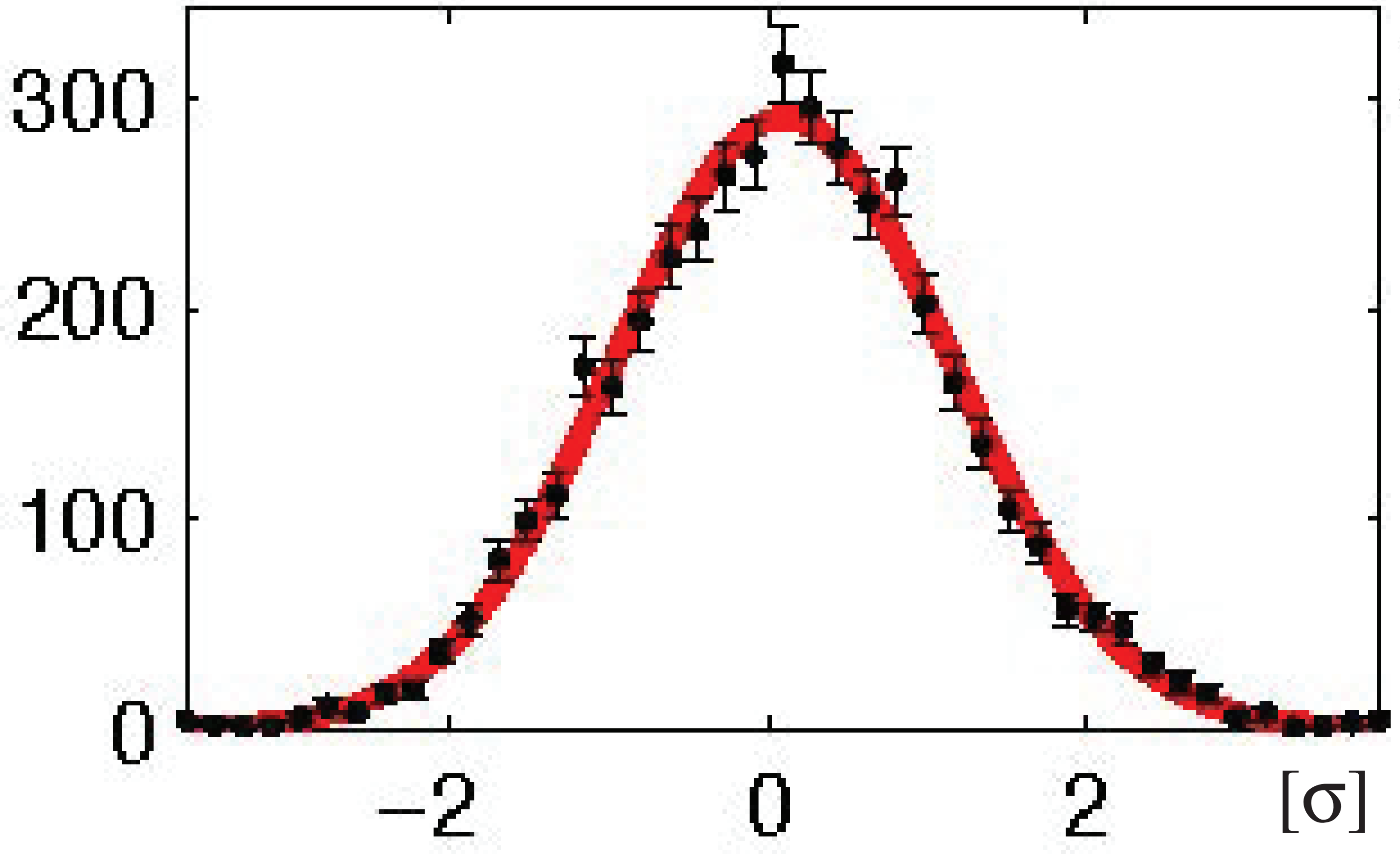

EDM Measurement Error Budget Sheet

Systematic and statistical errors for rate of angular precession of the electron spin in units of mrad/second.

1 mrad/s ~ 10^{-29} e cm

Parameter	Shift	Uncertainty
$\mathcal{E}^{\rm nr}$ correction	−0.81	0.66
$\Omega_r^{\mathcal{N}\mathcal{E}}$ correction	−0.03	1.58
$\phi^{\mathcal{E}}$-correlated effects	−0.01	0.01
$\phi^{\mathcal{N}}$ correlation		1.25
Nonreversing $\mathcal{B}$-field ($\mathcal{B}_z^{\rm nr}$)		0.86
Transverse $\mathcal{B}$-fields ($\mathcal{B}_x^{\rm nr}$, $\mathcal{B}_y^{\rm nr}$)		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

Systematics

Statistics

$$d_e = (\quad \pm 3.7_{\rm stat} \pm 2.5_{\rm syst}) \times 10^{-29} e{\cdot}{\rm cm}$$

using Eeff = 84 GV/cm, calculated by Skripnikov, Petrov and Titov JCP (2013) and Meyer and Bohn PRA (2008)

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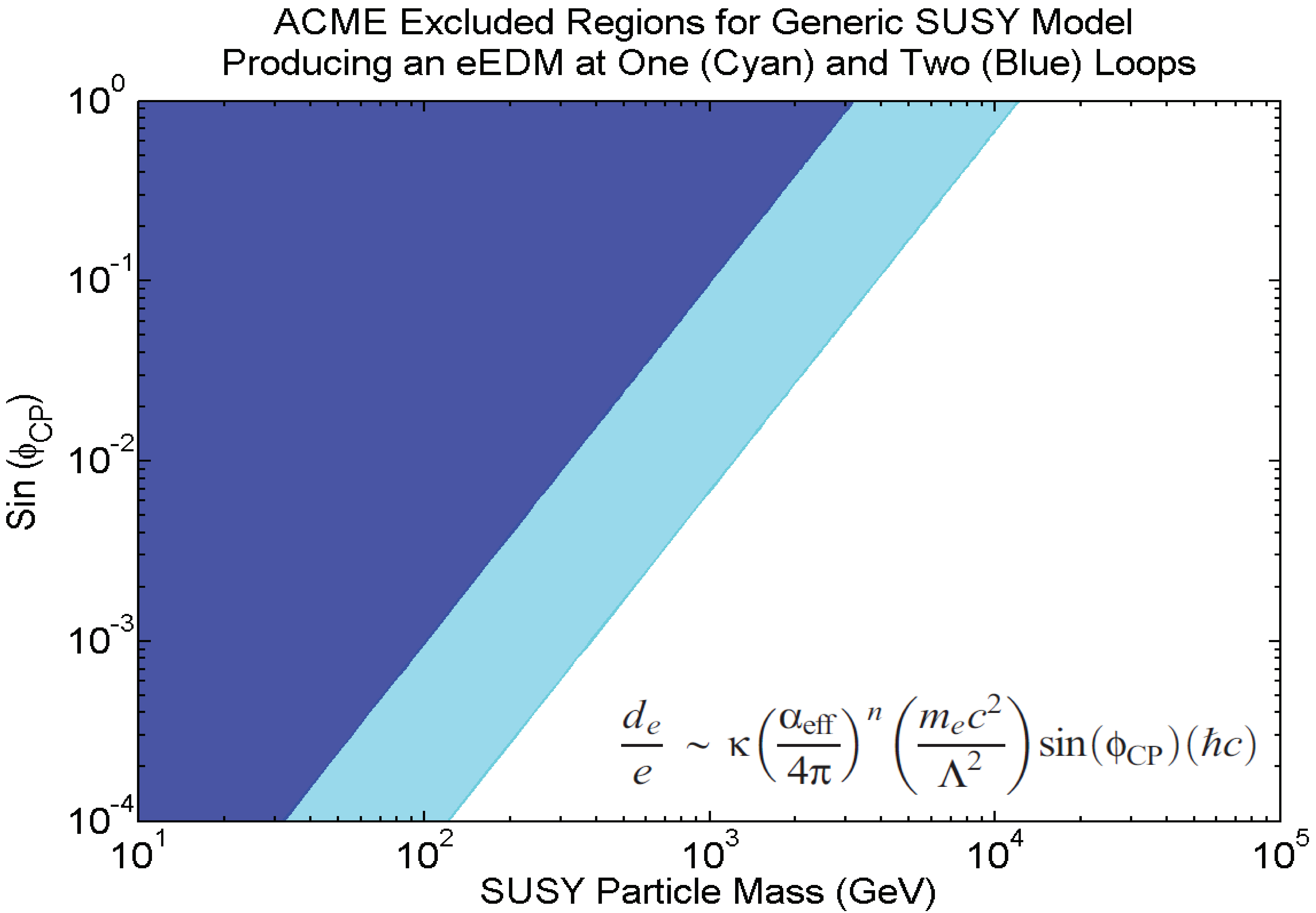
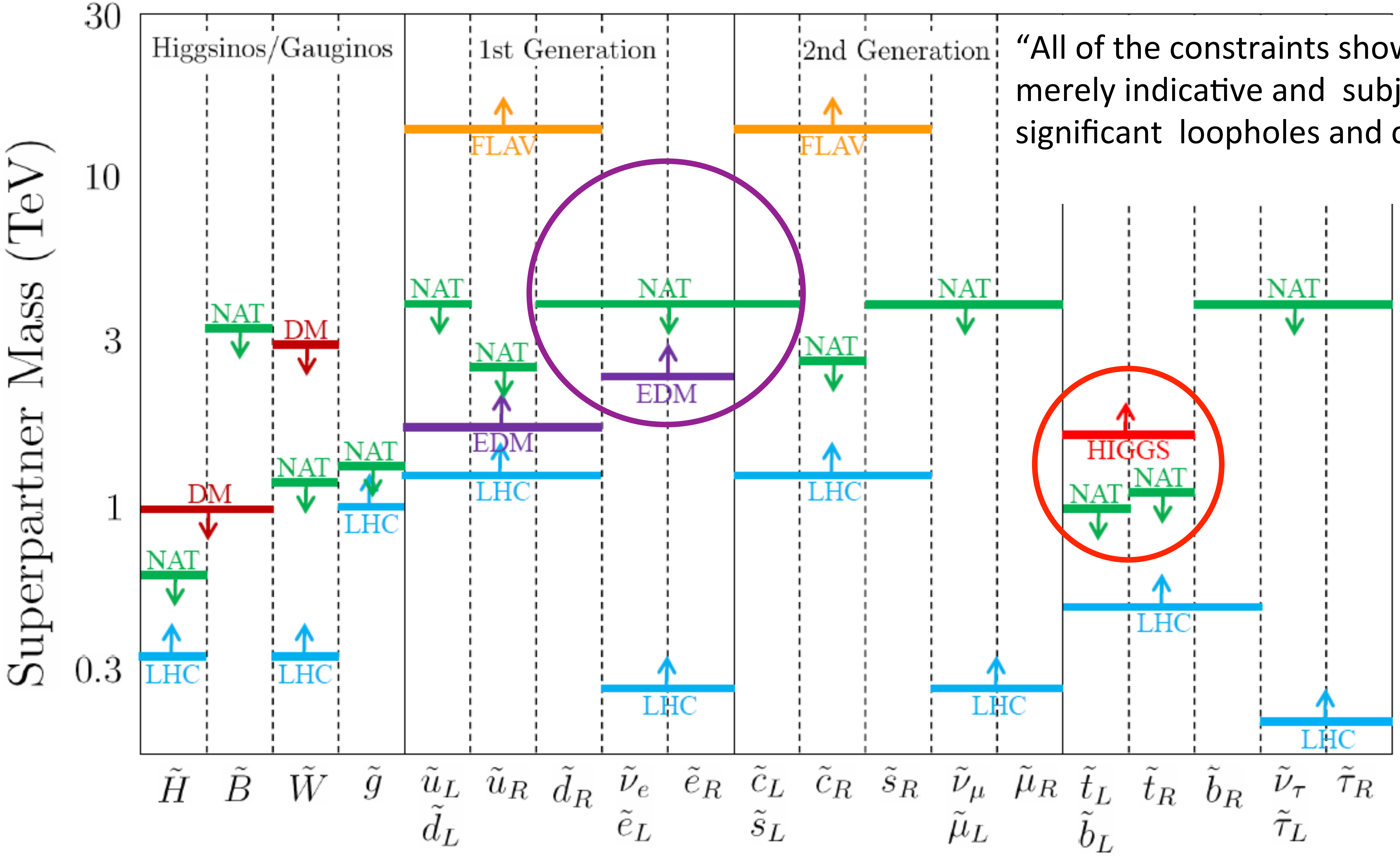


ACME Excluded Regions for Generic SUSY Model
Producing an eEDM at One (Cyan) and Two (Blue) Loops
Sin (ϕ_{CP})
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
SUSY Particle Mass (GeV)
$\frac{d_e}{e} \sim \kappa \left(\frac{\alpha_{\mathrm{eff}}}{4\pi}\right)^n \left(\frac{m_e c^2}{\Lambda^2}\right) \sin(\phi_{\mathrm{CP}}) (\hbar c)$

What does our limit mean for particle physics?

J. Feng: "Naturalness and the status of SUSY", Ann. Rev. Nucl. Part. Sci. (2013)



"All of the constraints shown are merely indicative and subject to significant loopholes and caveats"

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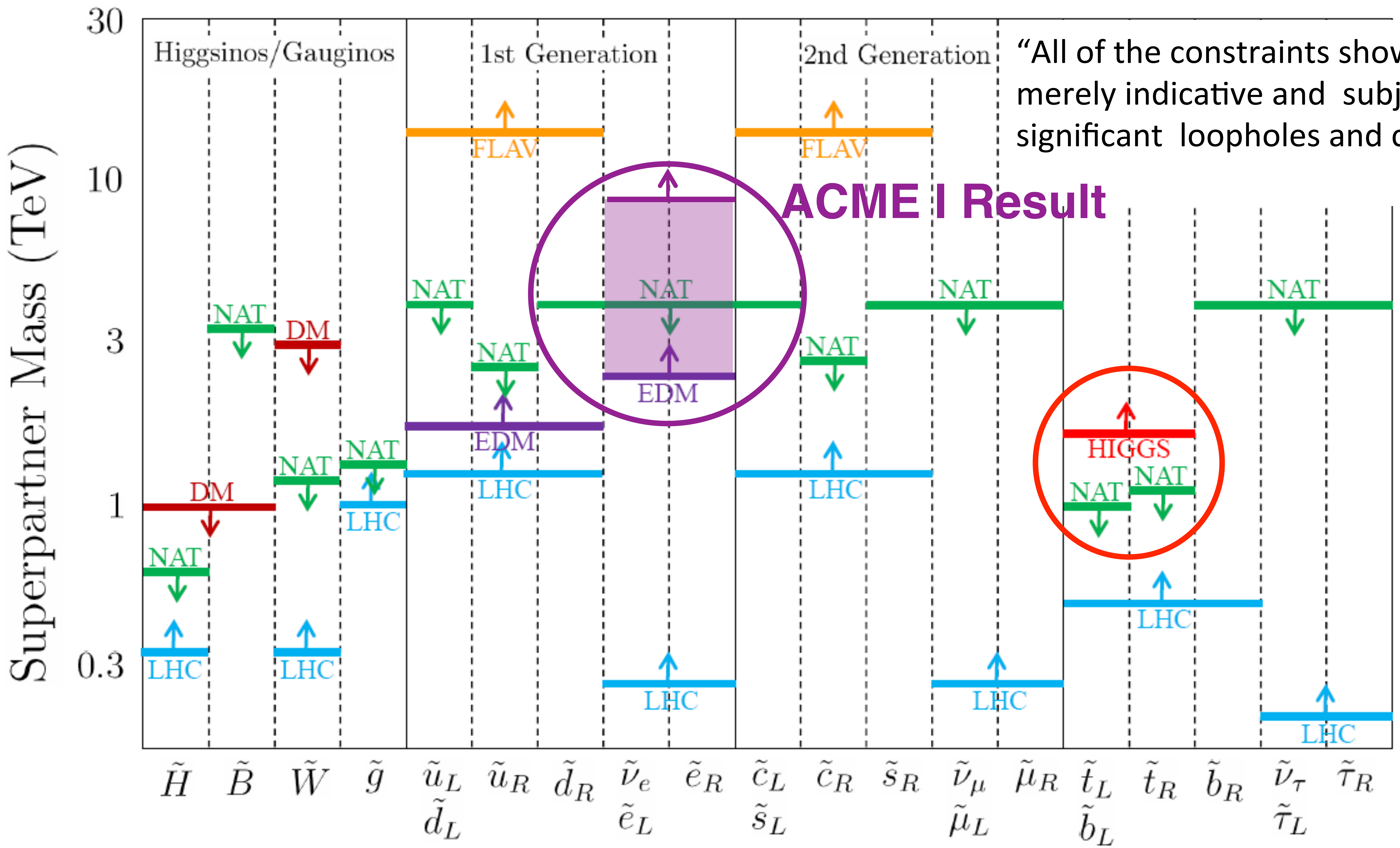
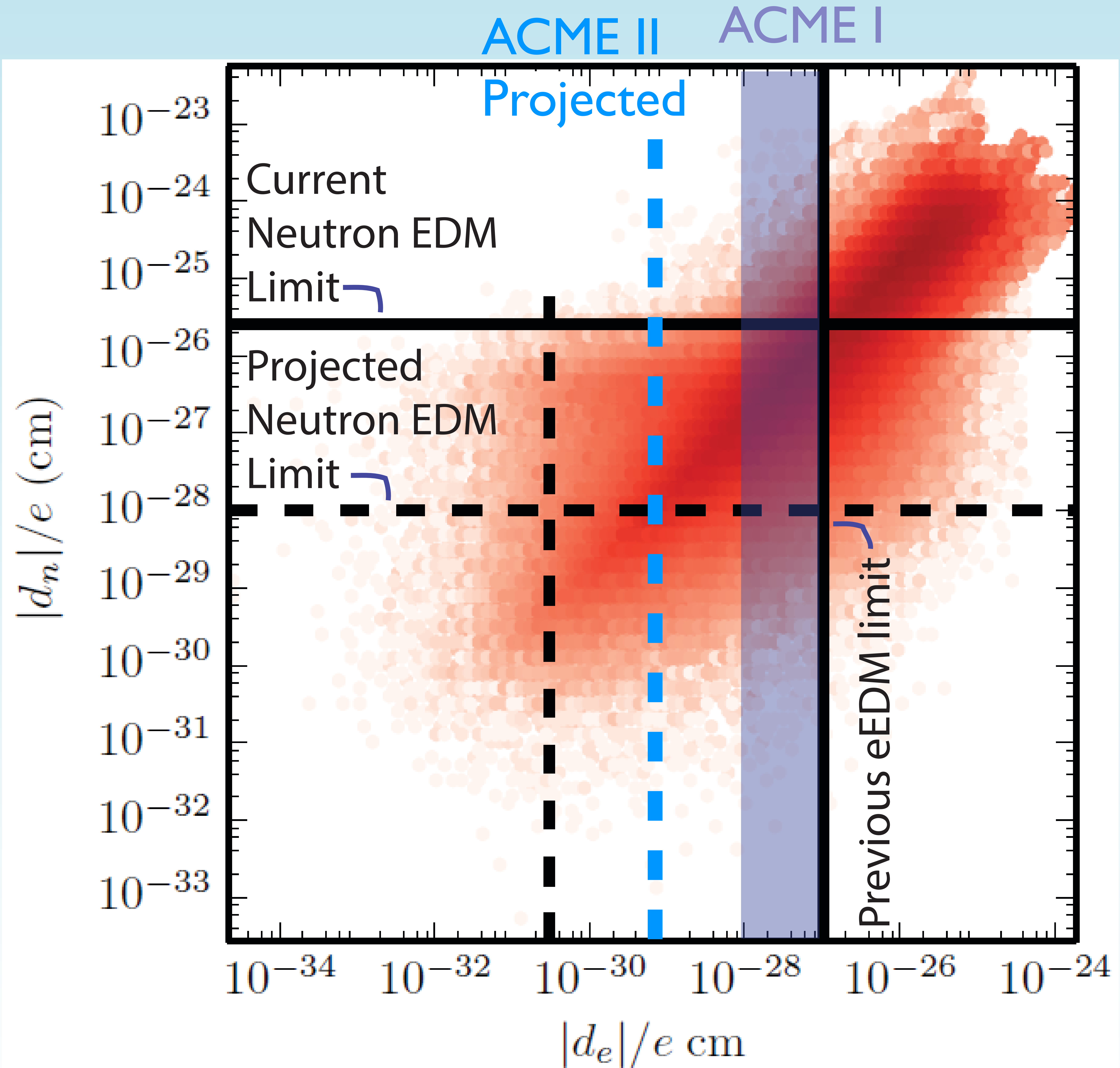


"All of the constraints shown are merely indicative and subject to significant loopholes and caveats"

MSSM Parameter Scatter Plot



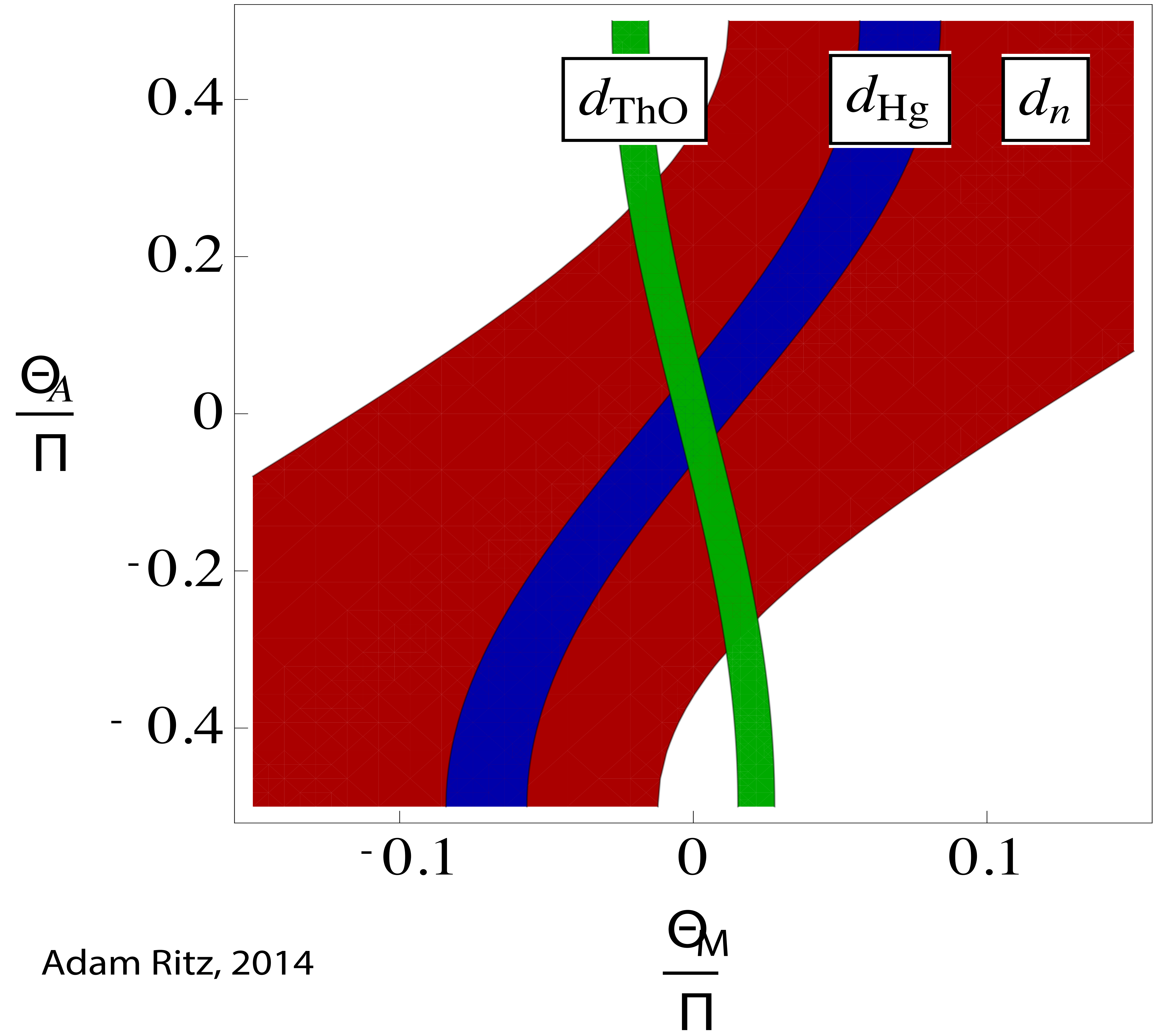
Color Scale indicates 10^4 Range of "Probability Density"

2/3 of parameter space excluded by *previous* EDM limits

ACME I excluded 2/3 of Remaining

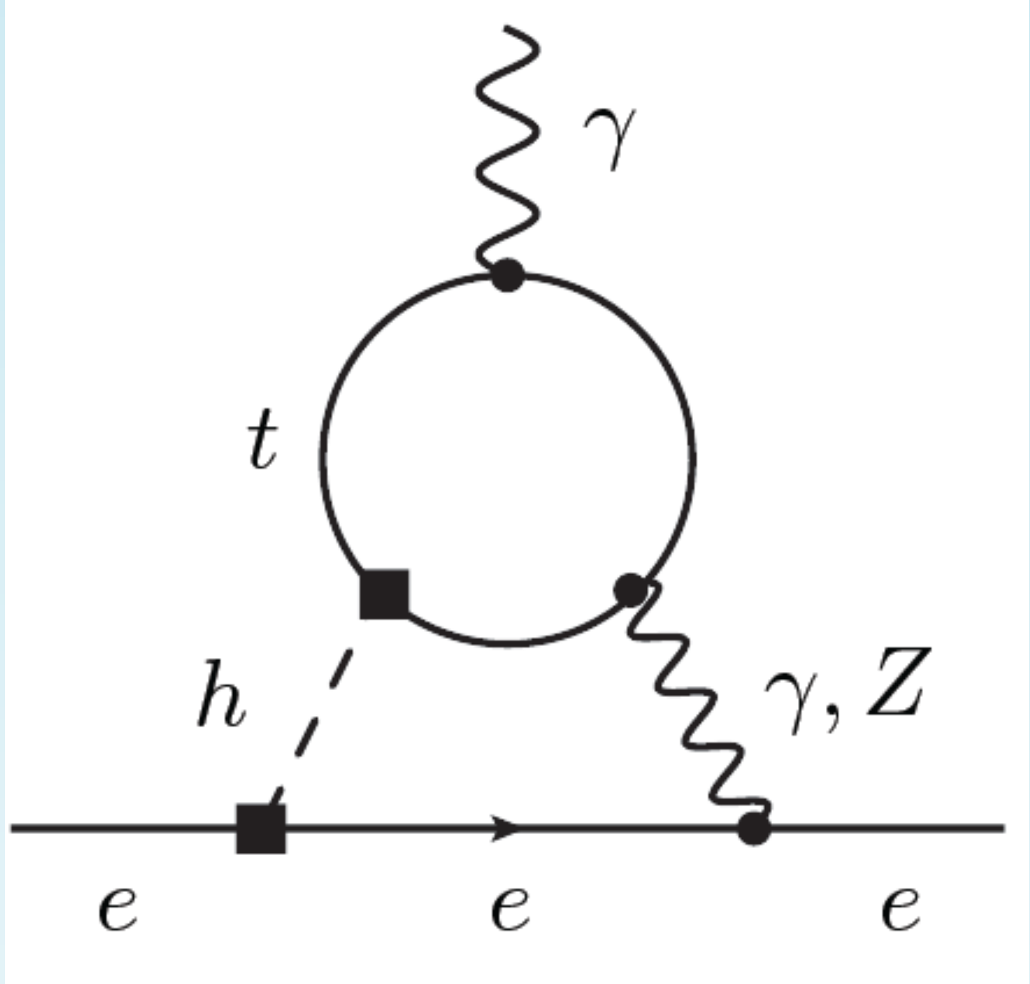
Flat log distribution of SUSY CP Phases

J. Berger et al., 1309.7653 (2013)



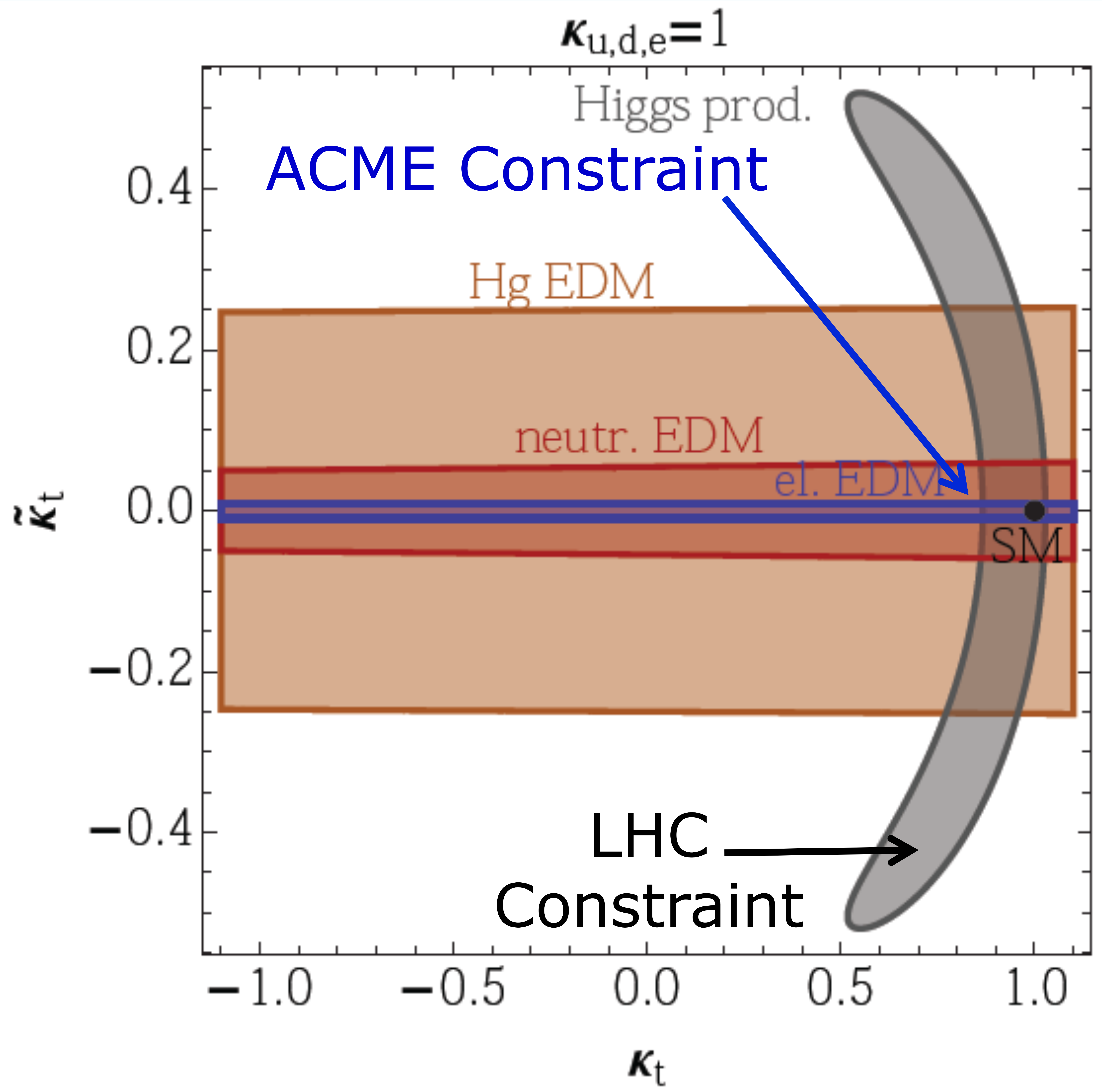
Adam Ritz, 2014

Diagrams with
known SM particles
can rule out
non-SM couplings



Example:
CP-violating
Higgs-top coupling

Brod *et al.*,
arXiv: 1310.1385

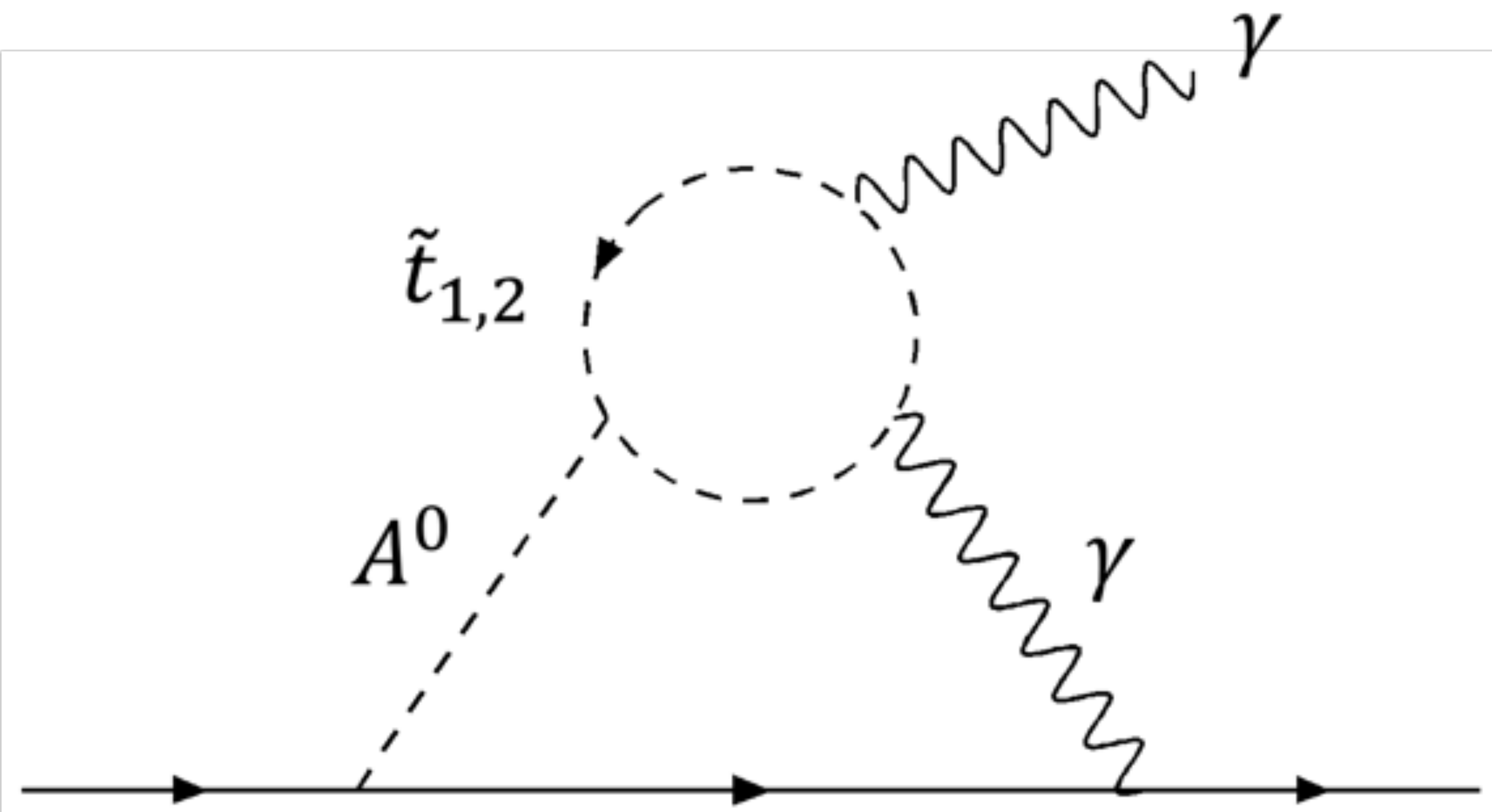


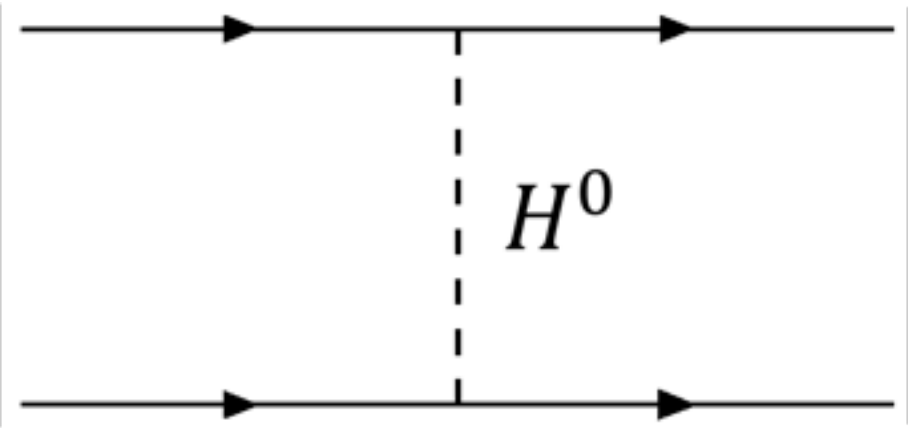
CP-odd/CP-even Higgs-top coupling <1% from ACME

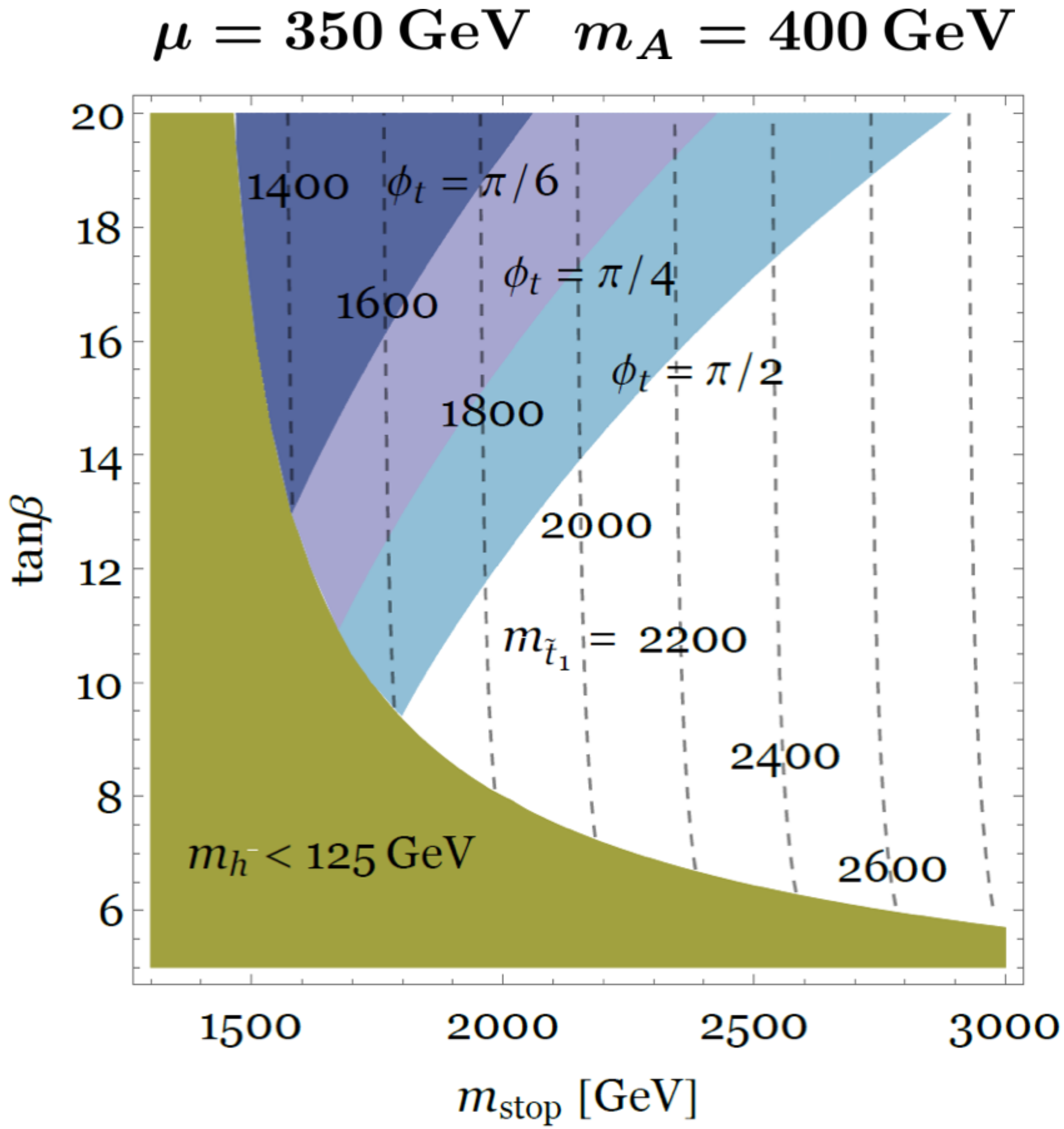
Present bounds on stop masses in the MSSM

Yuichiro Nakai and Matthew Reece: **preliminary!**

Superpartners of top quarks (stops),
essential for the natural EWSB,
can generate a sizable EDM.







For the maximal CP phase $\phi_t = \arg(A_t \mu)$

$$m_{\tilde{t}_1} > 1.6 \text{ TeV}$$

t
experimentally excluded
unconstrained
Imperial 2010
ACME I
2014
Berkeley 2002
Berkeley 1994
Berkeley 1990
standard model
SUSY variants
generic models
Multi-
Higgs
Left-Right
Symmetric
Extended
Technicolor
Lepton Flavor
Changing
Standard
Model
Split
SUSY
SO(10)
GUT
Alignment
Seesaw Neutrino Yukawa Couplings
Accidental
Cancellation
Approx.
CP
Approx.
Universality
Exact
Universality
Naive SUSY
Heavy
sFermions
10-25
10-26
10-27
10-28
10-29
10-30
10-31
10-32
10-33
10-40
10-41
de (e cm)

What led to statistical sensitivity improvements in ThO over YbF?

1) ThO (change of molecule)

÷1.5	÷2 radiative decay of metastable EDM state
x6	x6 higher effective field
2.5	6.5 lower state preparation
= x2 better	

2) Hydrodynamic Buffer Gas Beam Source (New Source)

÷3.7	x14 useful molecular flux
x1.7	x1.7 coherence time
= x6.5 better	

3) Technical Changes

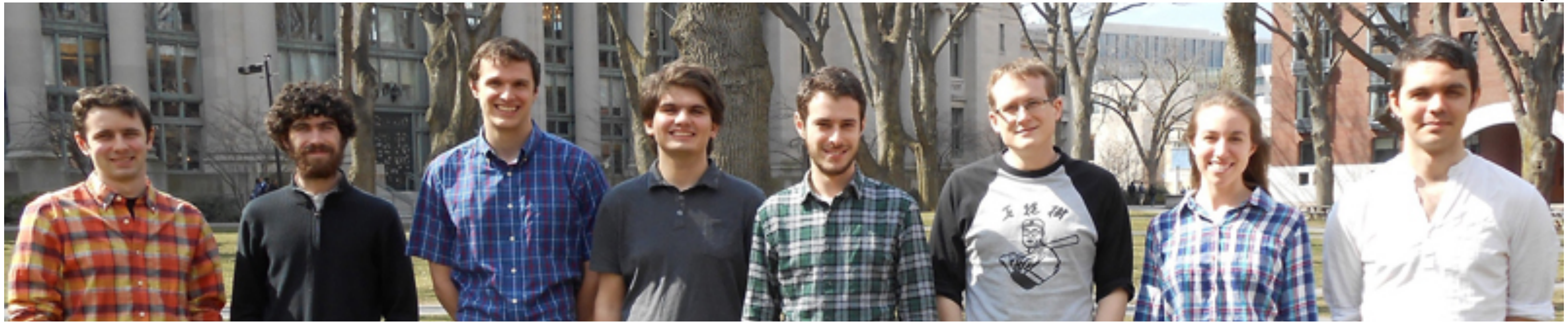
÷1.2	1.5 longer length
x1.7	x3 higher collection efficiency
÷1.4	÷2 shorter running time
x1.4	x2 optical rotational cooling
=x1.5 better	

x15, better overall statistical sensitivity

Experiment	One Day Statistical Sensitivity e-cm day$^{-1/2}$	Published Limit $\lvert d_e \rvert <$ in e-cm
Berkeley Tl	0.5×10^{-27}	1.6×10^{-27}
Imperial YbF	2×10^{-27}	1.5×10^{-27}
ACME I ThO	1×10^{-28}	0.9×10^{-28}

Improvement 1	Improvement 2	Improvement 3	EDM Sensitivity Gain over Previous Experiment
used a	molecule		~x1
Beam Source x6.5	Molecule to ThO x2	Technical x1.5	**x15**

The ACME team

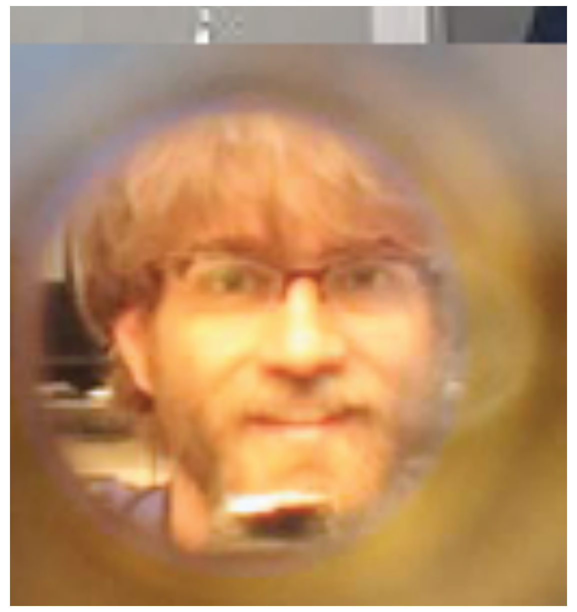


Paul Hess | Brendon O'Leary | Ben Spaun | Cris Panda | Jacob Baron | Nick Hutzler | Elizabeth Petrik | Adam West

Emil Kirilov

Amar Vutha

Yulia Gurevich



Wes Campbell

Ivan Kozyryev

Max Parsons

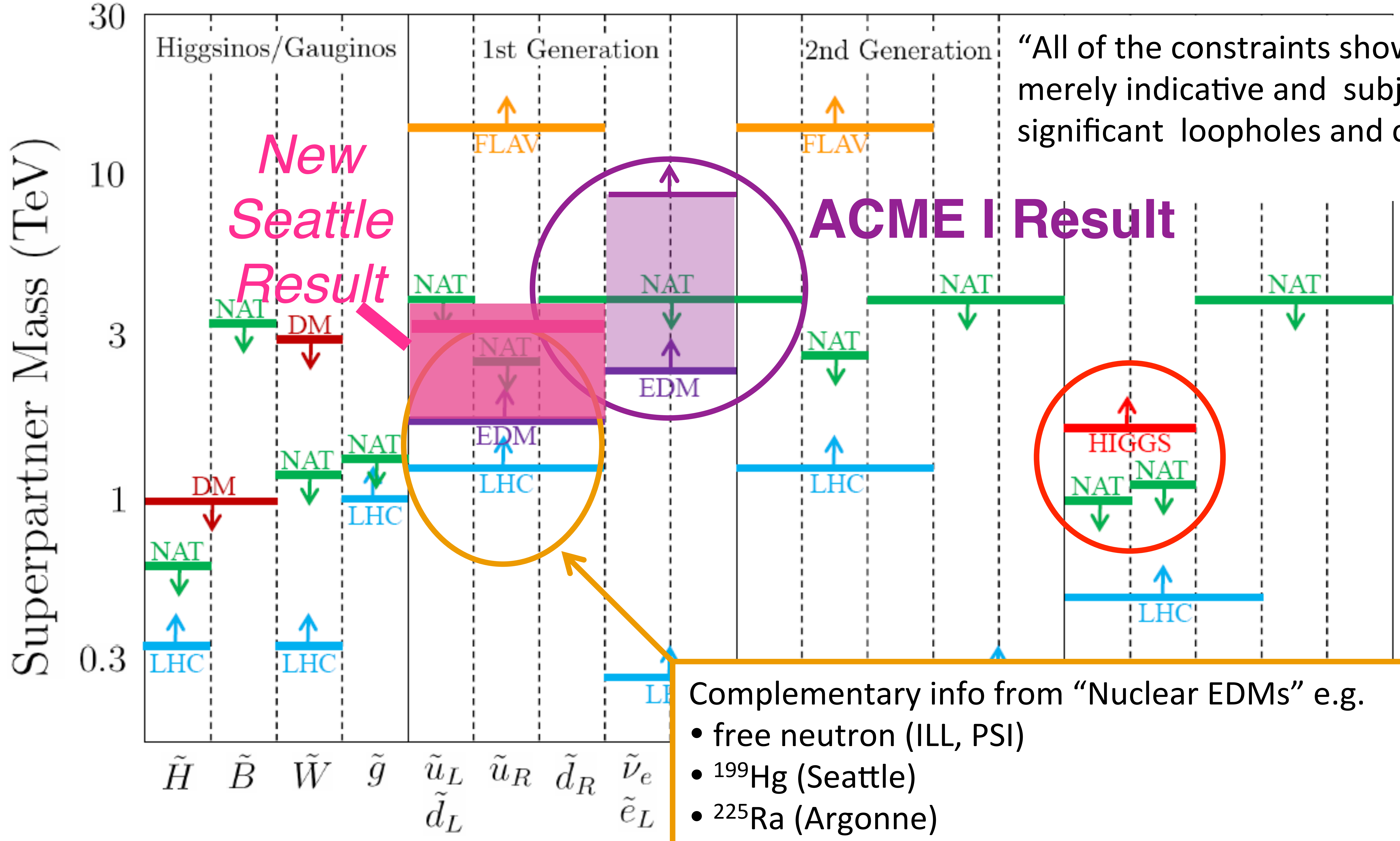
JMD

Gabrielse

DeMille

Nuclear EDMs and Naturalness

J. Feng: “Naturalness and the status of SUSY”, Ann. Rev. Nucl. Part. Sci. (2013)



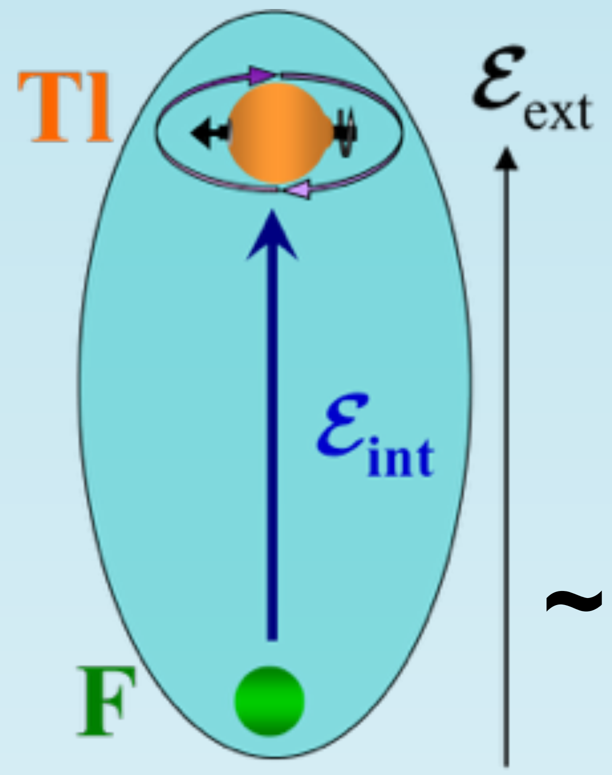
“All of the constraints shown are merely indicative and subject to significant loopholes and caveats”

Complementary info from “Nuclear EDMs” e.g.

- free neutron (ILL, PSI)
- ^{199}Hg (Seattle)
- ^{225}Ra (Argonne)
- ^{129}Xe (TUM/Mich/PTB): Mo-127, Tu-126
- ^{129}Xe (Mainz)
- ^{221}Ra (Michigan)

ACME method will be applied to Nuclear EDM search

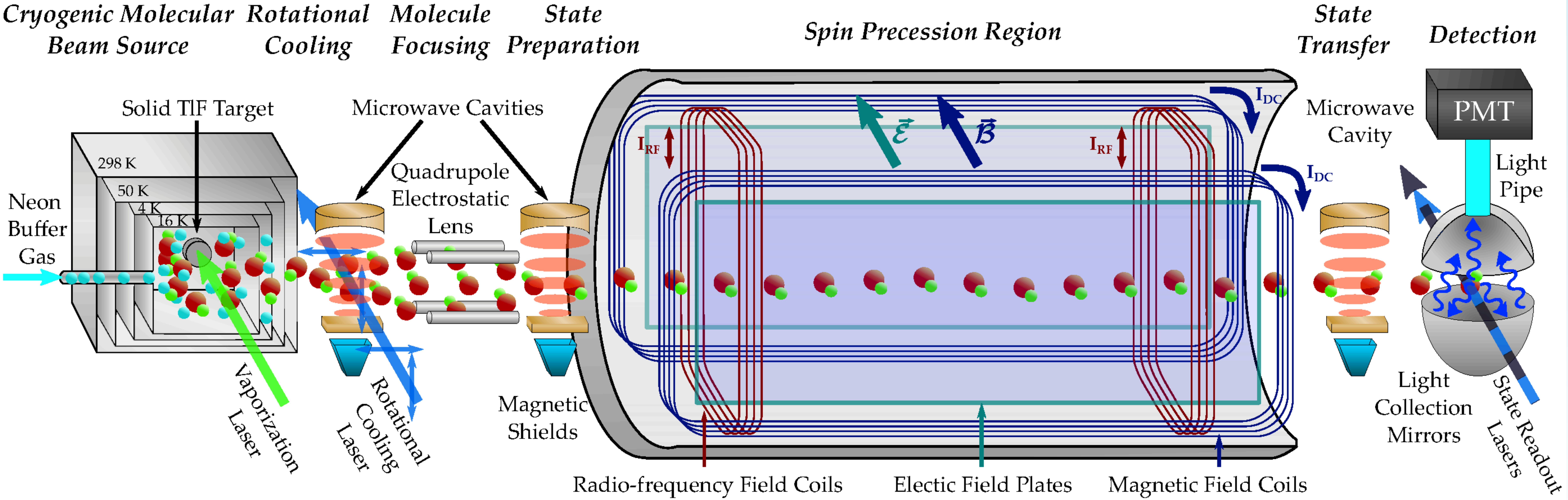
Current state-of-the-art Schiff moment limit from ^{199}Hg atom experiment (Seattle):
Already sensitive to new physics at >TeV scale



CeNTREX

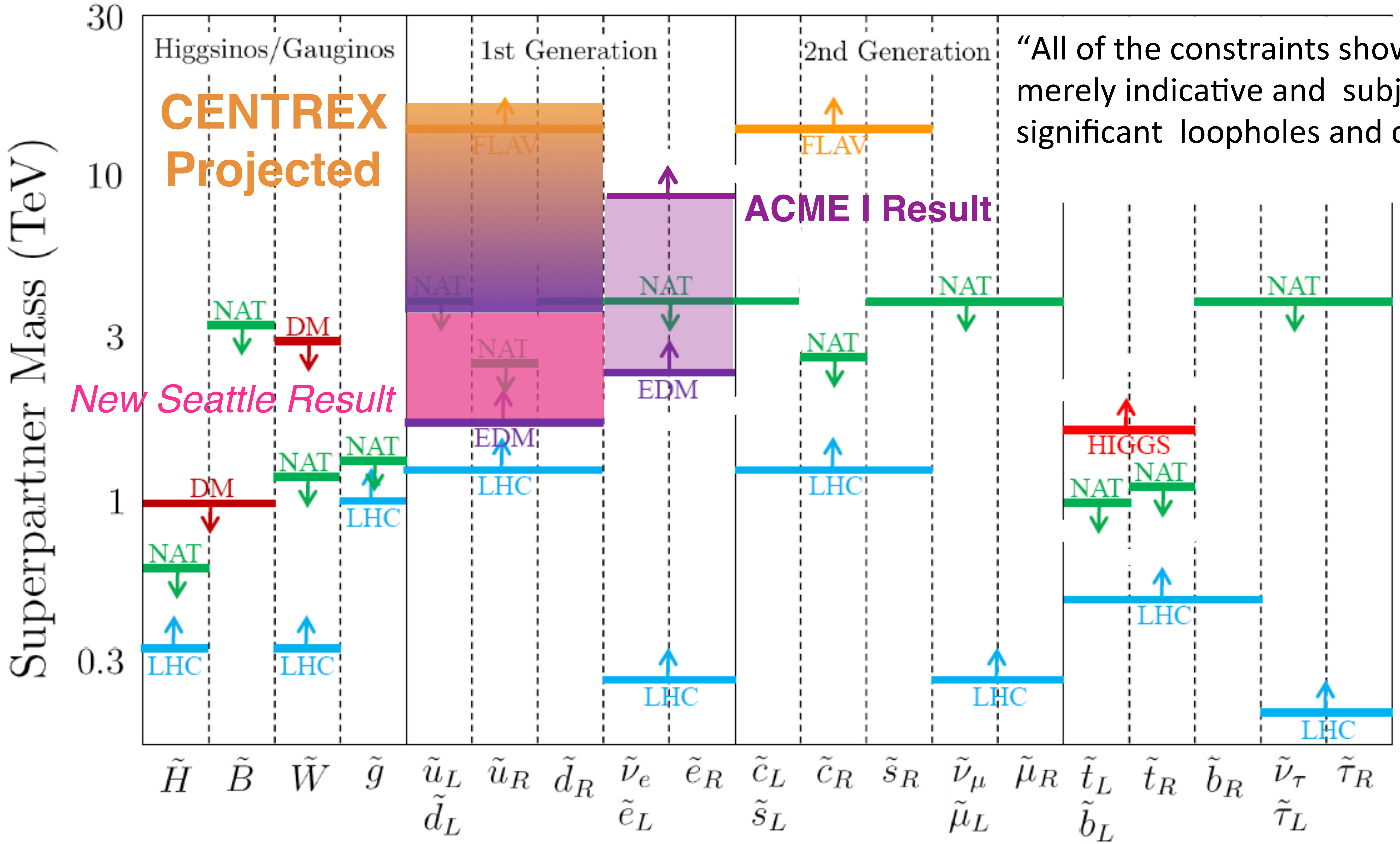
Similar to *e*-EDM, huge intra-molecular E-field
⇒nuclear spin precession rate
~10^4× larger than in ^{199}Hg atoms

D. DeMille, D. Kawall, S. Lamoreaux, T. Zelevinsky



Nuclear EDMs and Naturalness

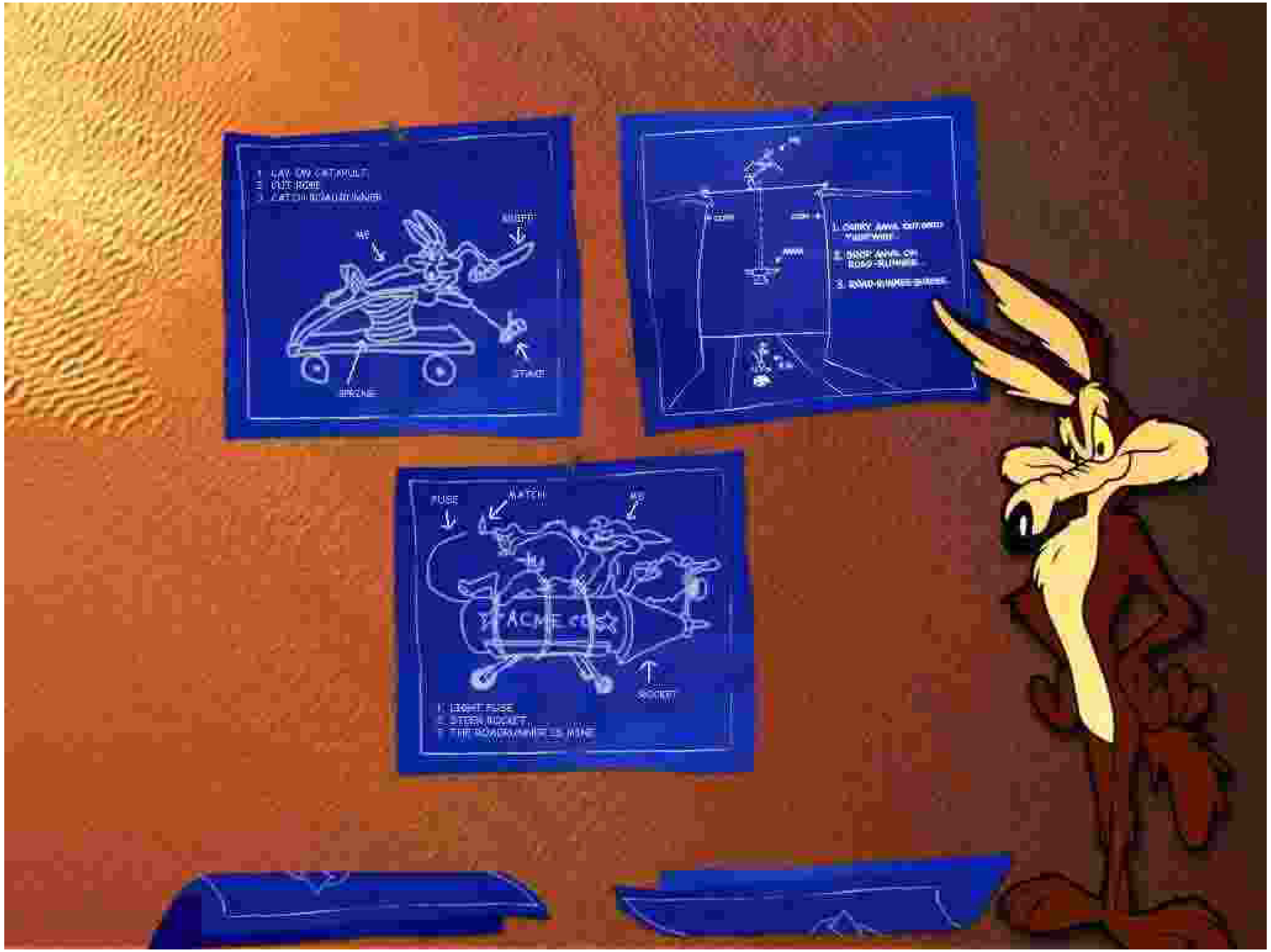
J. Feng: “Naturalness and the status of SUSY”, Ann. Rev. Nucl. Part. Sci. (2013)



“All of the constraints shown are merely indicative and subject to significant loopholes and caveats”

We are still hard at work....

.....with ACME II !




t
experimentally excluded
unconstrained
Imperial 2010
ACME I
2014
Berkeley 2002
Berkeley 1994
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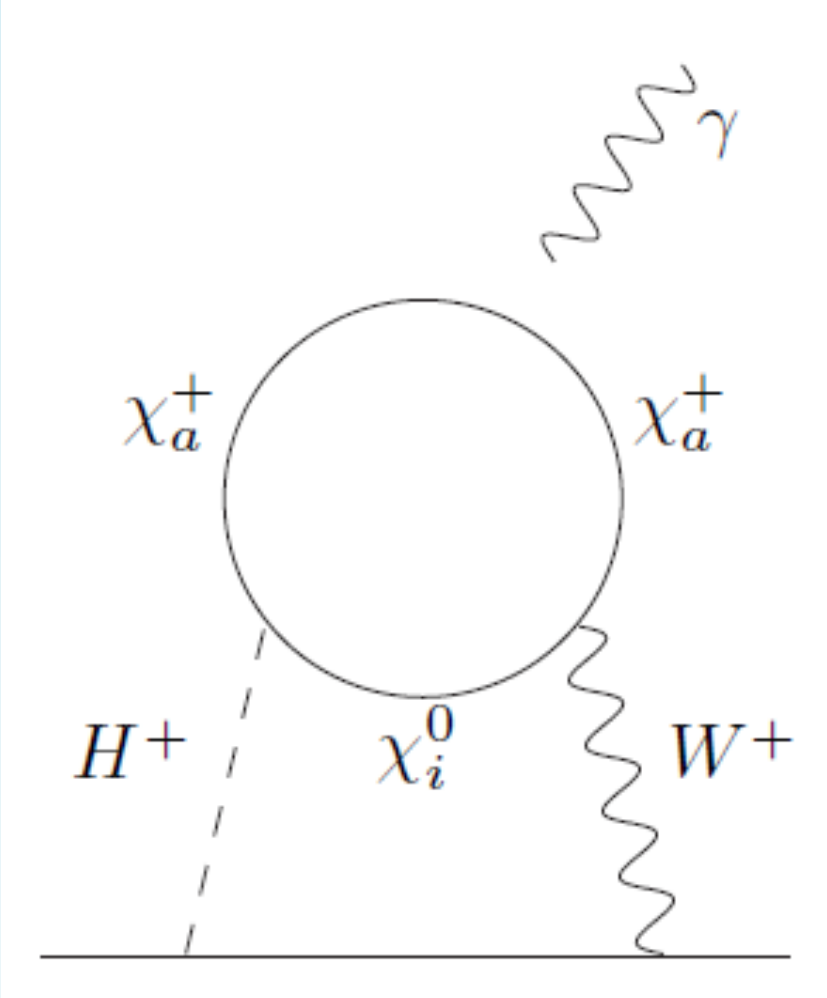
standard model
SUSY variants
generic models
Multi-Higgs
Left-Right Symmetric
Extended Technicolor
Lepton Flavor Changing
Some of these Theories Seem Reasonable :-)
Standard Model
Split SUSY
SO(10) GUT
Alignment
Seesaw Neutrino Yukawa Couplings
Accidental Cancellation
Approx. CP
Approx. Universality
Exact Universality
Naive SUSY
Heavy sFermions
10^-25
10^-26
10^-27
10^-28
10^-29
10^-30
10^-31
10^-32
10^-33
10^-40
10^-41
de (e cm)

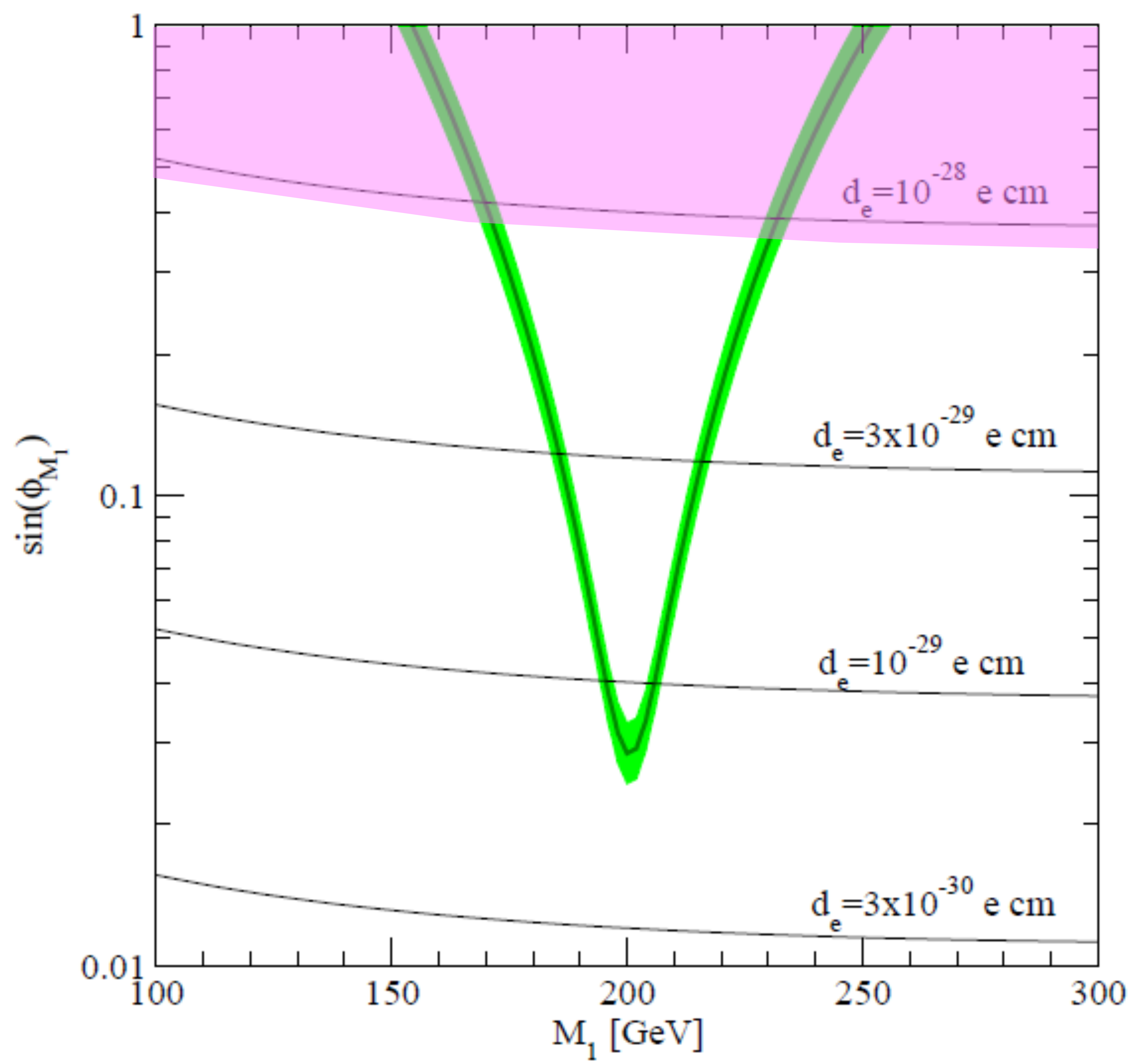
Implications for baryon asymmetry…?

Last viable corner for
Electroweak Baryogenesis
(a testable model for
matter/antimatter asym)…?

"Bino-driven EWBG"
can elude ACME limit, but…



requires non-universal
SUSY CP phases (φ_2=0)

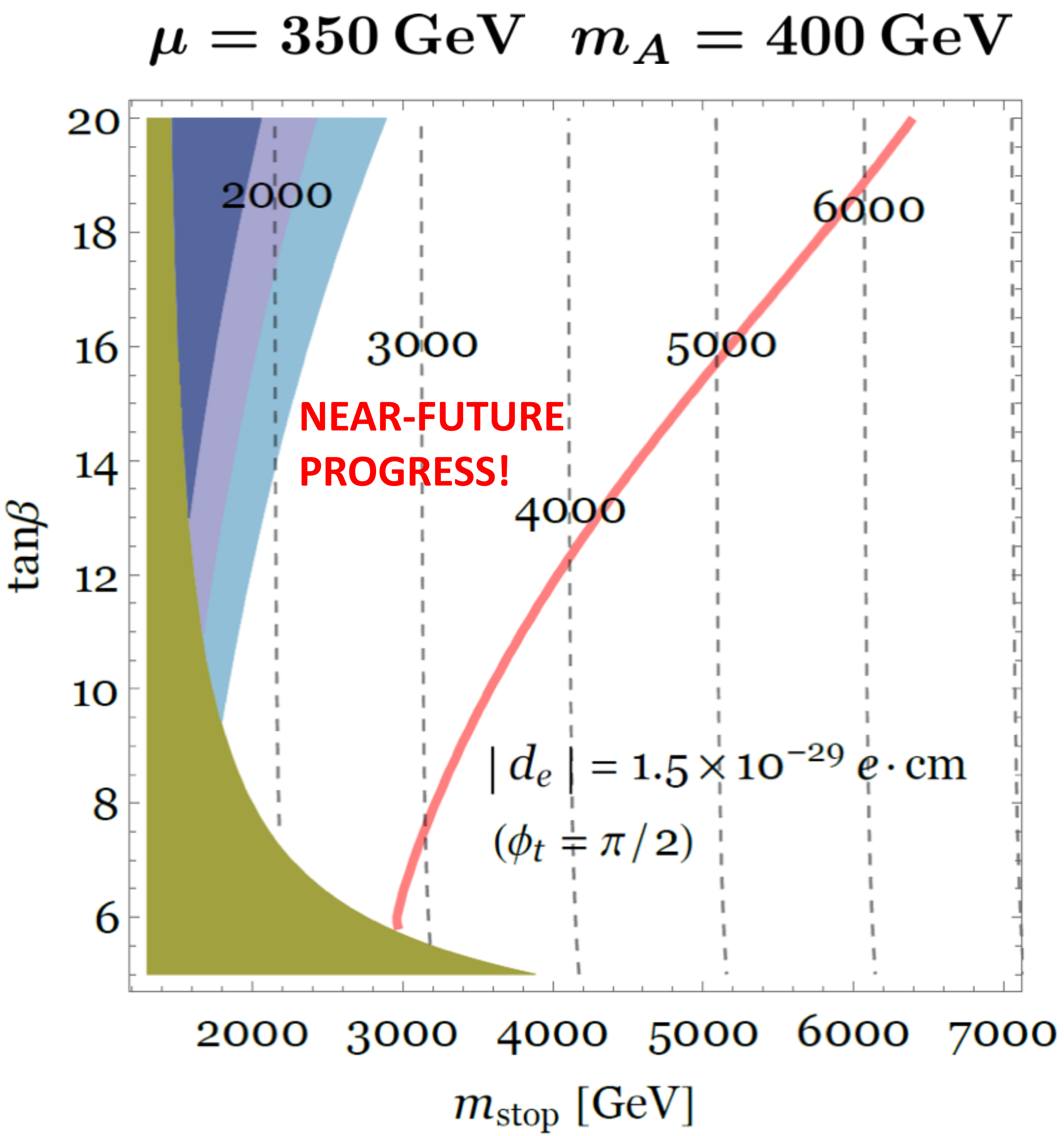


Li *et al.*, Phys. Lett. (2009)

~10x improvement may rule out Electroweak Baryogenesis…?

Future prospects

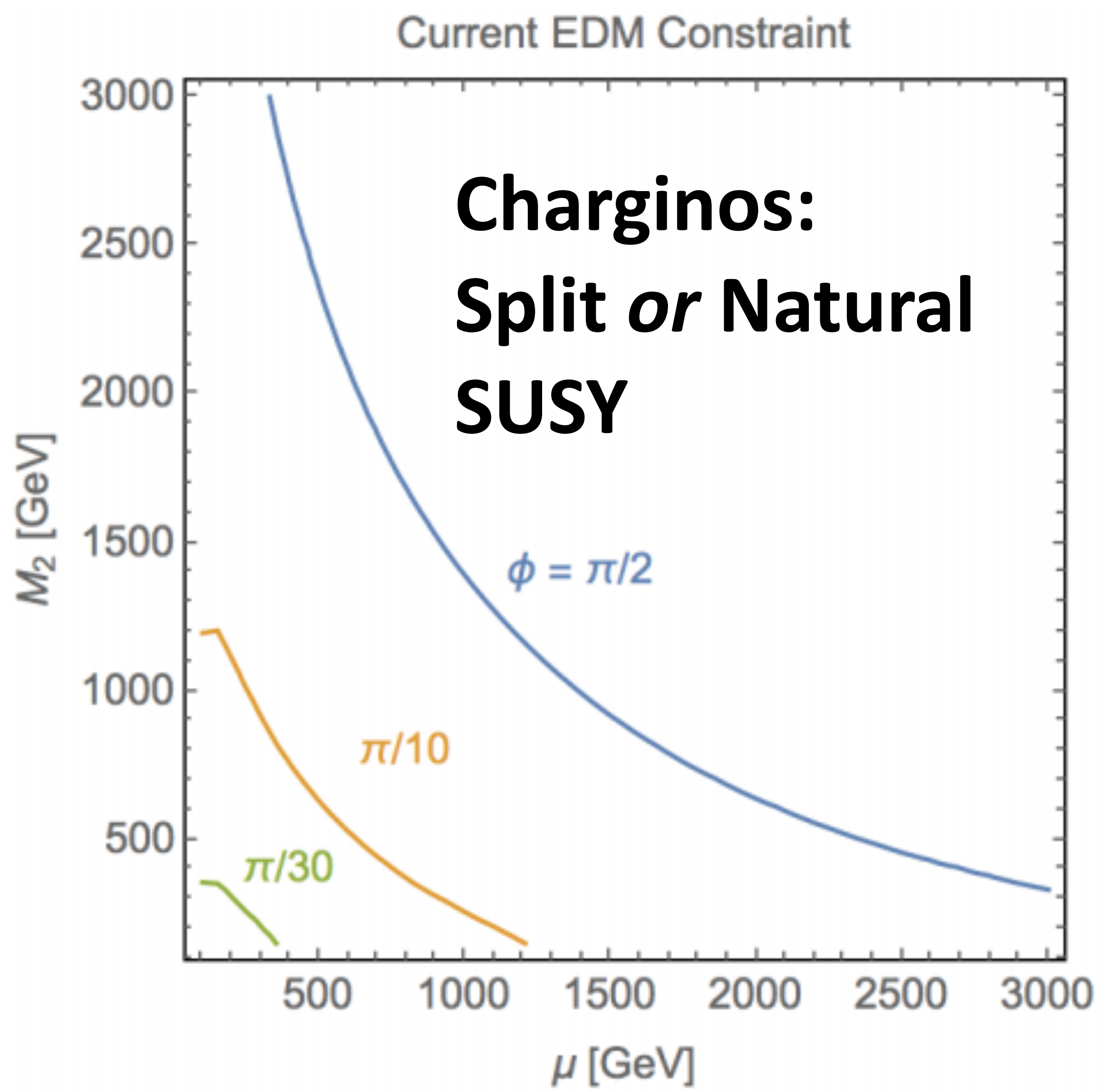
Yuichiro Nakai and Matthew Reece: **preliminary!**



Large parameter space of stop masses unconstrained by the Higgs mass can be explored. Factor of 10 improvement will cover large part of interesting parameter space w/ CP phase.

More to the story: charginos, Higgs physics beyond MSSM, …

Under study



ACME I —> ACME II Upgrades

Beamline geometry

State preparation

Light collection/ readout

State readout

The Path to Improvements

This slide is about five years old….

BEFORE

the ACME I result

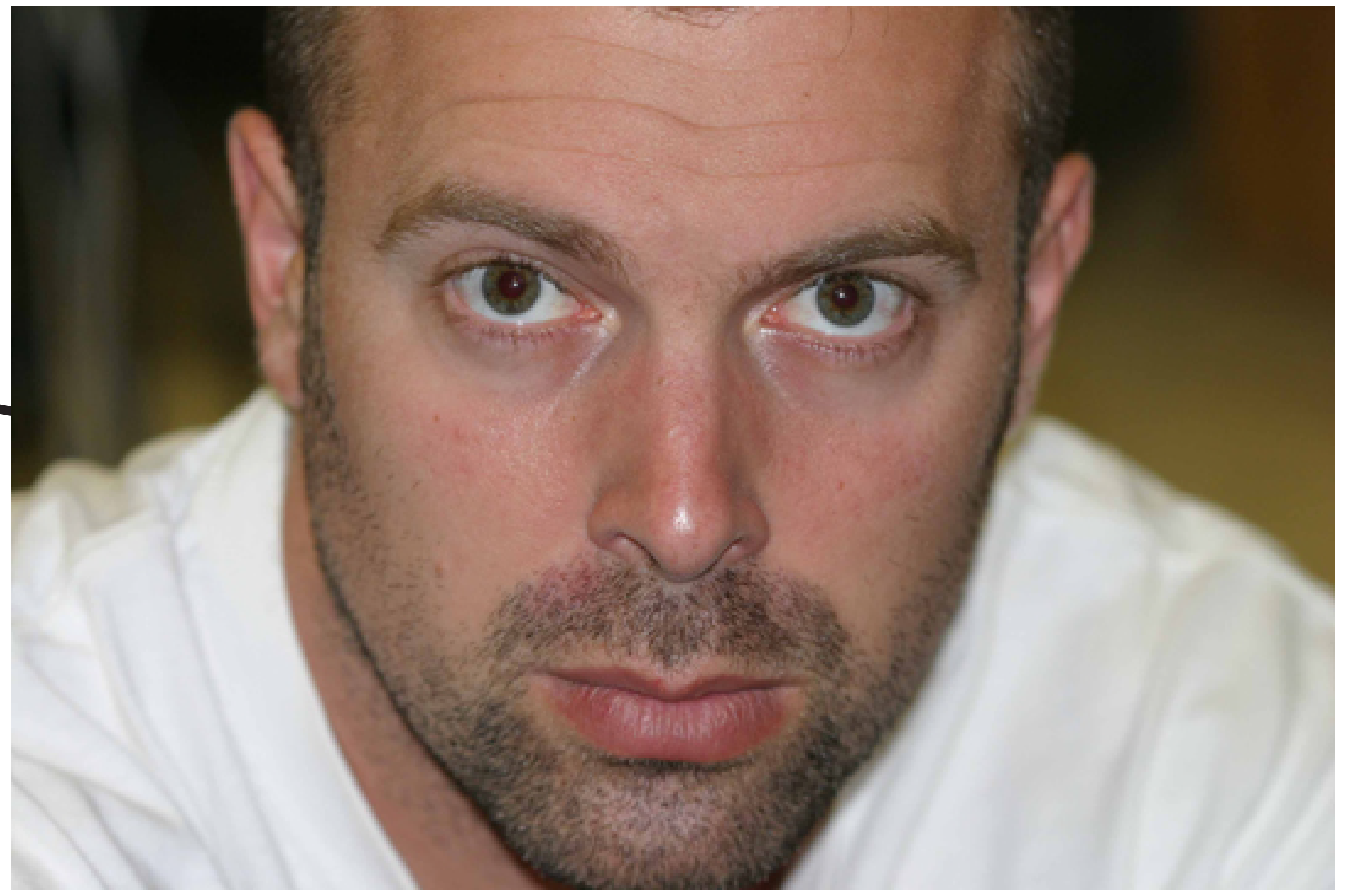
Increases in statistical sensitivity already demonstrated

Fully Demonstrated:

✓ Electrostatic Focussing
✓ Rotational Cooling } 10x
✓ STIRAP State Preparation 5x

Mostly Demonstrated:

✓ Photon Cycling/collection geometry
(photon shot noise ---> molecule shot noise) 10x
✓ Thermochemical Production 10x



Emil Kirilov

Not Demonstrated:

More cryogenic cooling 4x
PMT-->Cooled Photodiode or PMT 2x

Possible combined increase in signal: 100 -- 10,000

Possible combined increase in statistical sensitivity: 10 -- 100

The Path to Improvements

This slide is about five years old….

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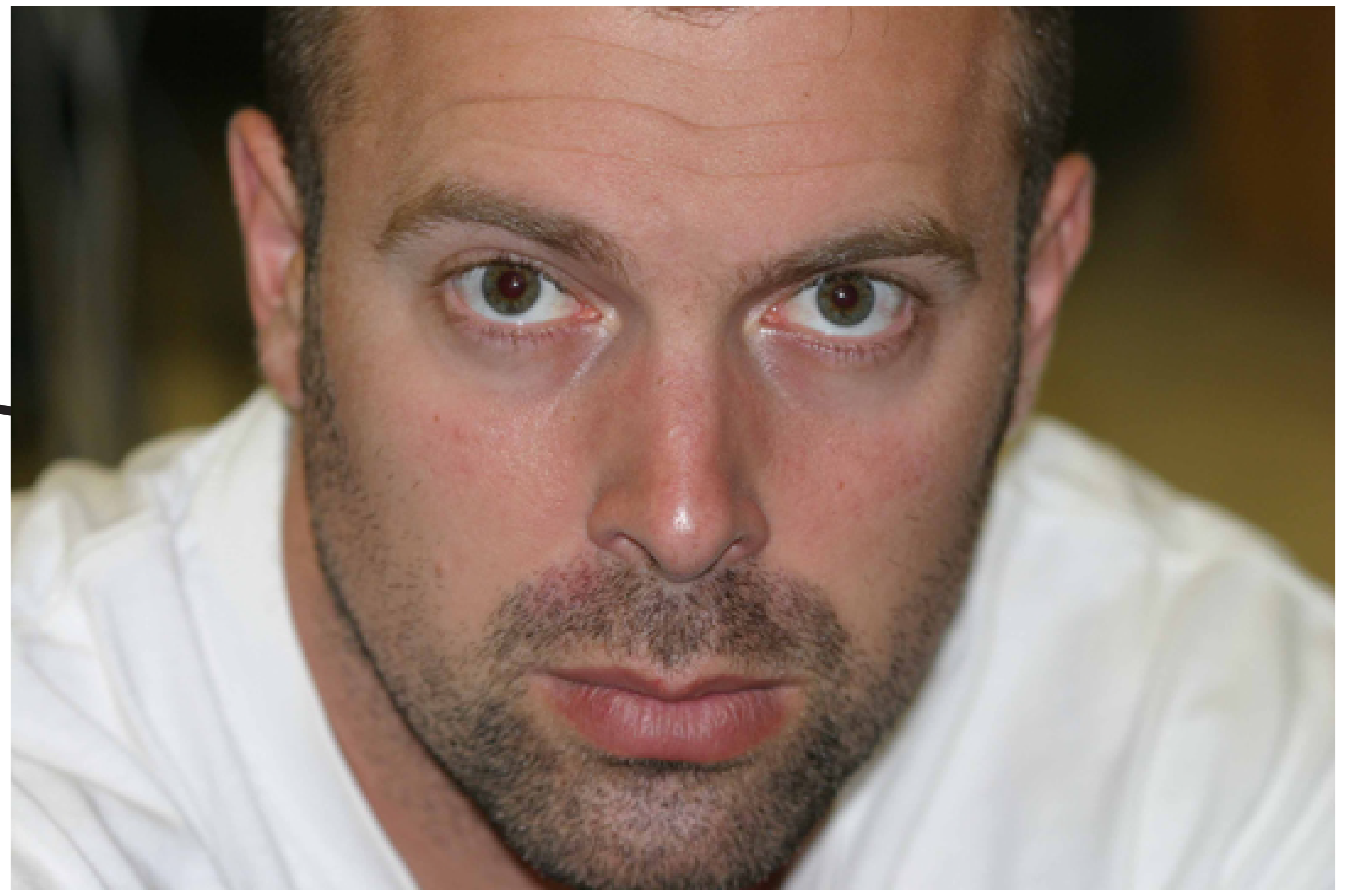

Emil Kirilov

Not Demonstrated:

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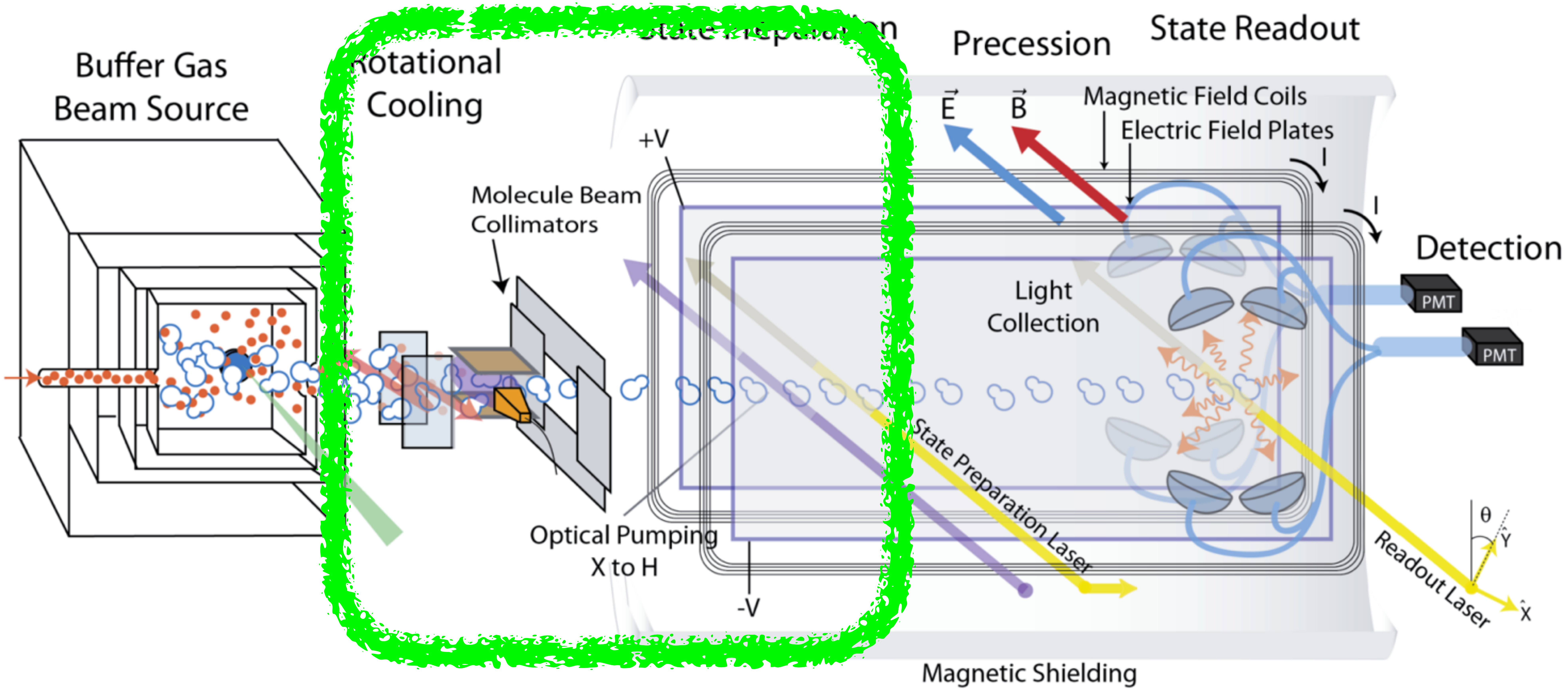
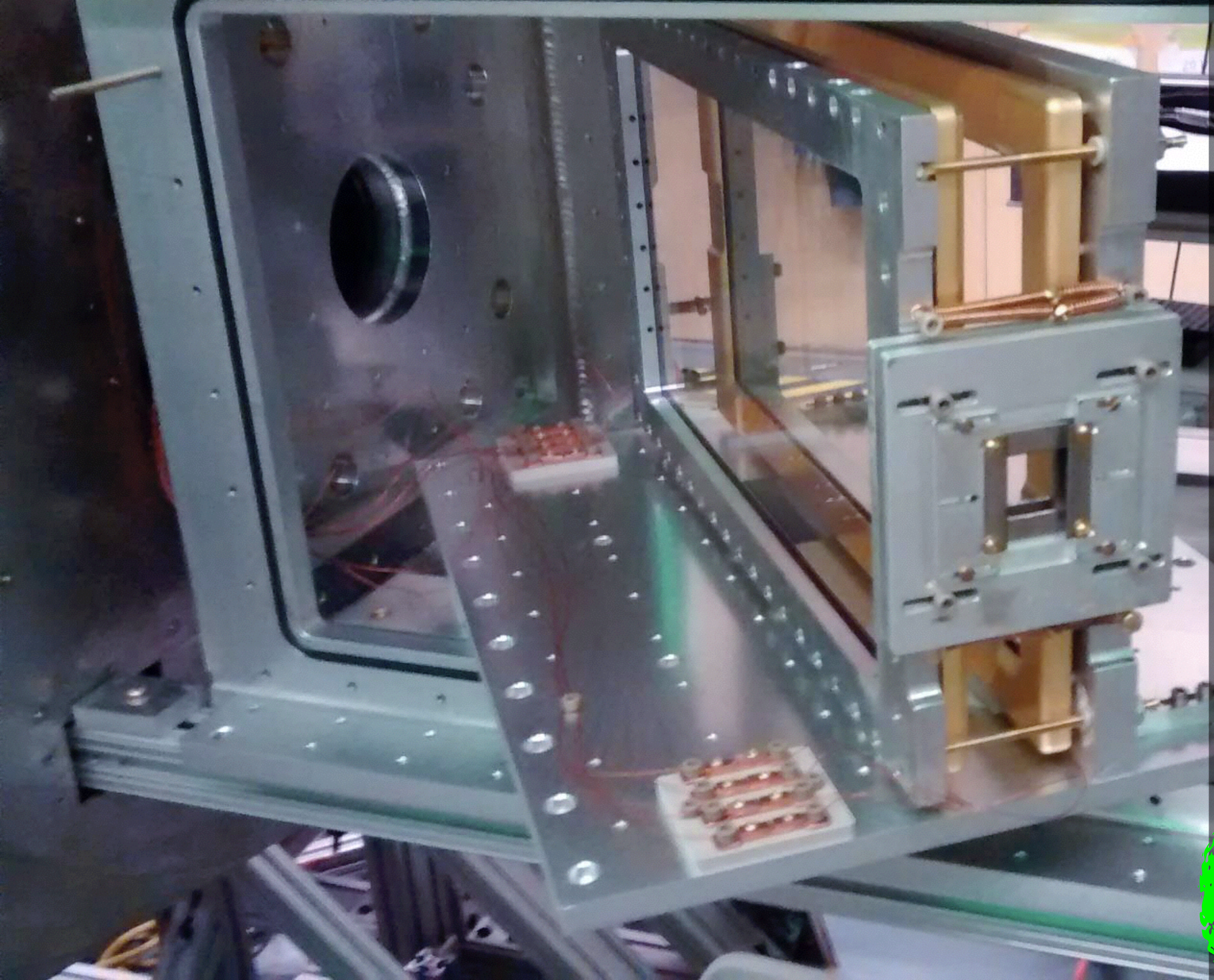
Possible combined increase in statistical sensitivity: 10 -- 100

ACME Generation II Apparatus Improvements



Increasing Detected Solid Angle of Molecule Beam

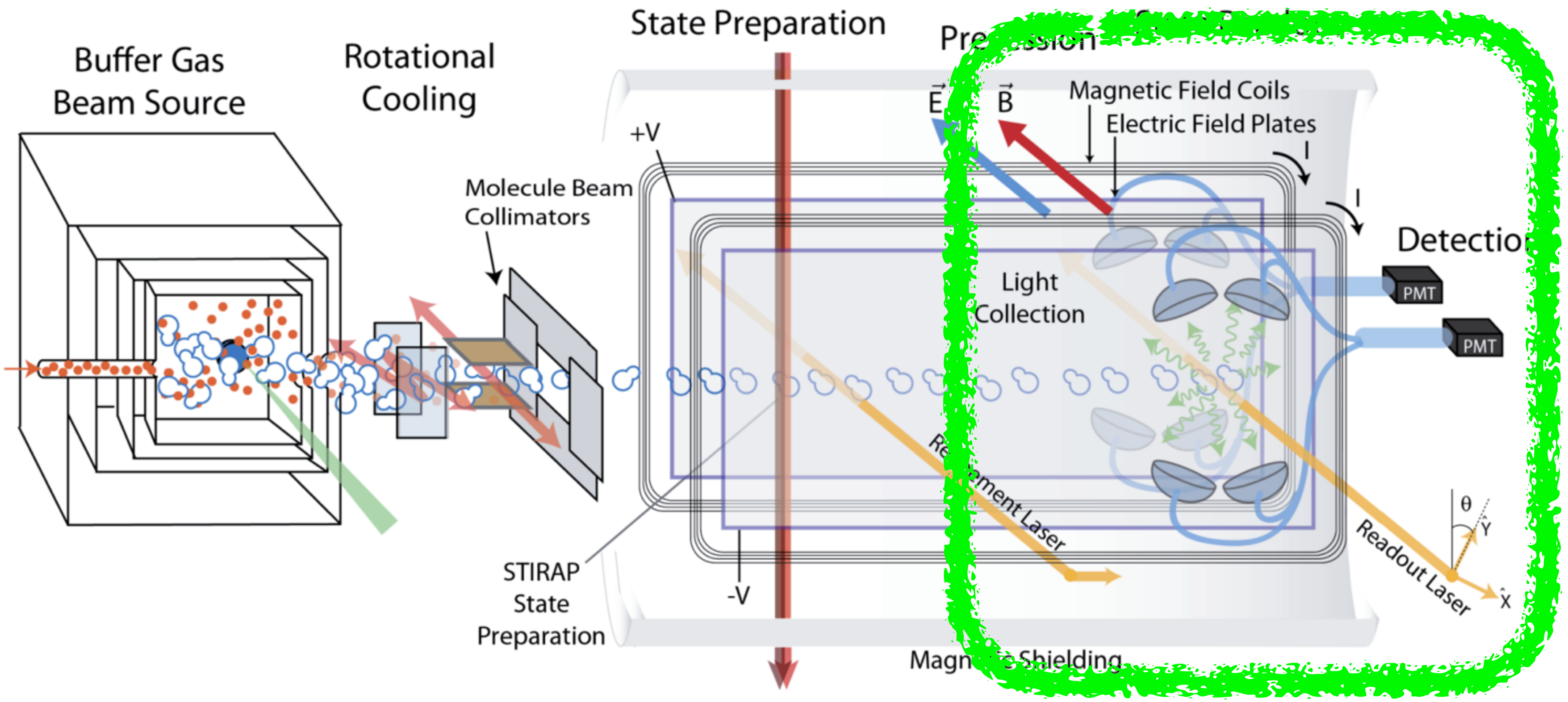


More molecules in detection region

- Shortening beamline by 1.2x
- Increasing separation between field plates, increasing fixed collimator size 2.4x

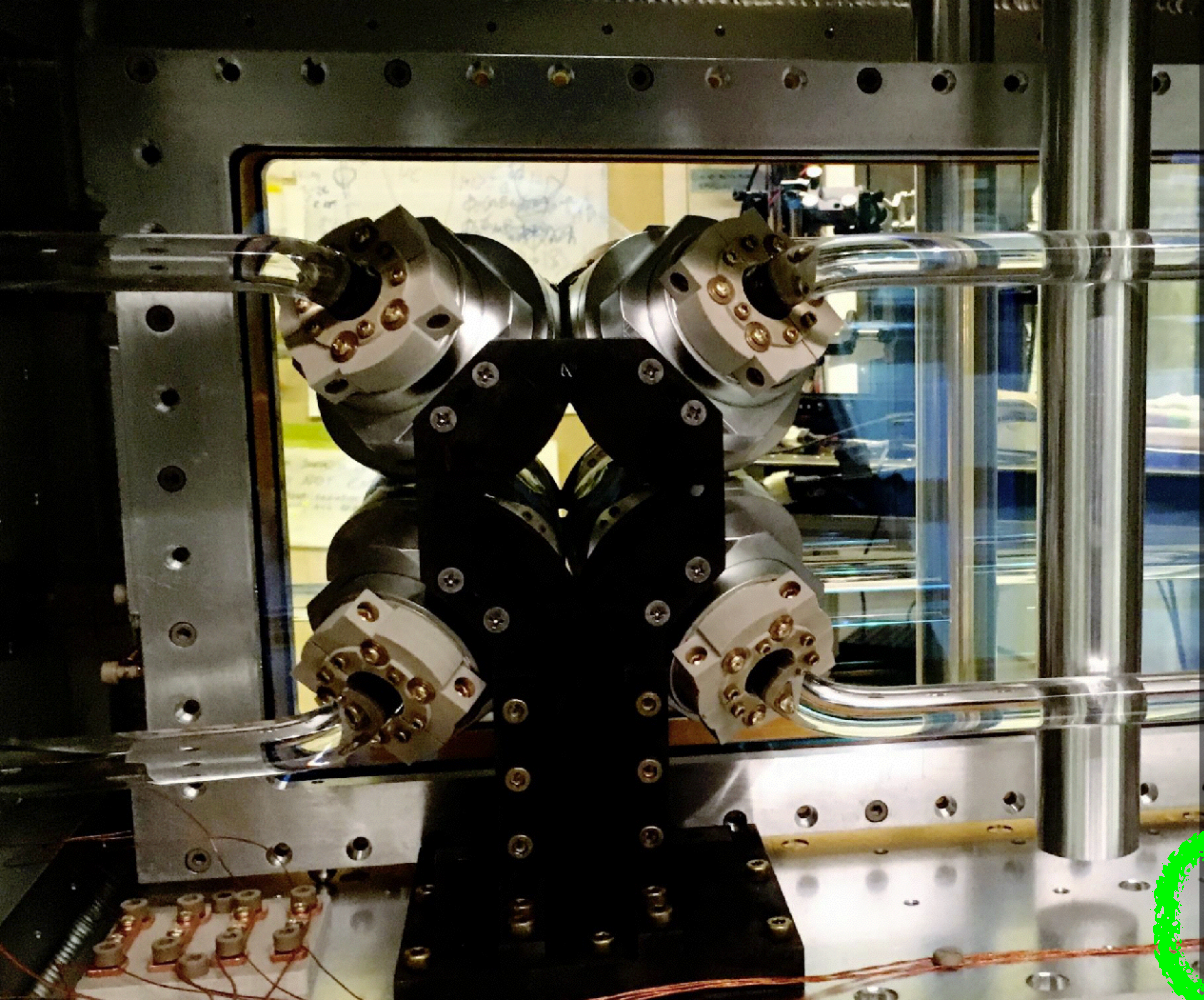
ABOUT 8x SIGNAL GAIN

ACME Generation II Apparatus Improvements



Increasing Molecule Detection Efficiency with New Transition

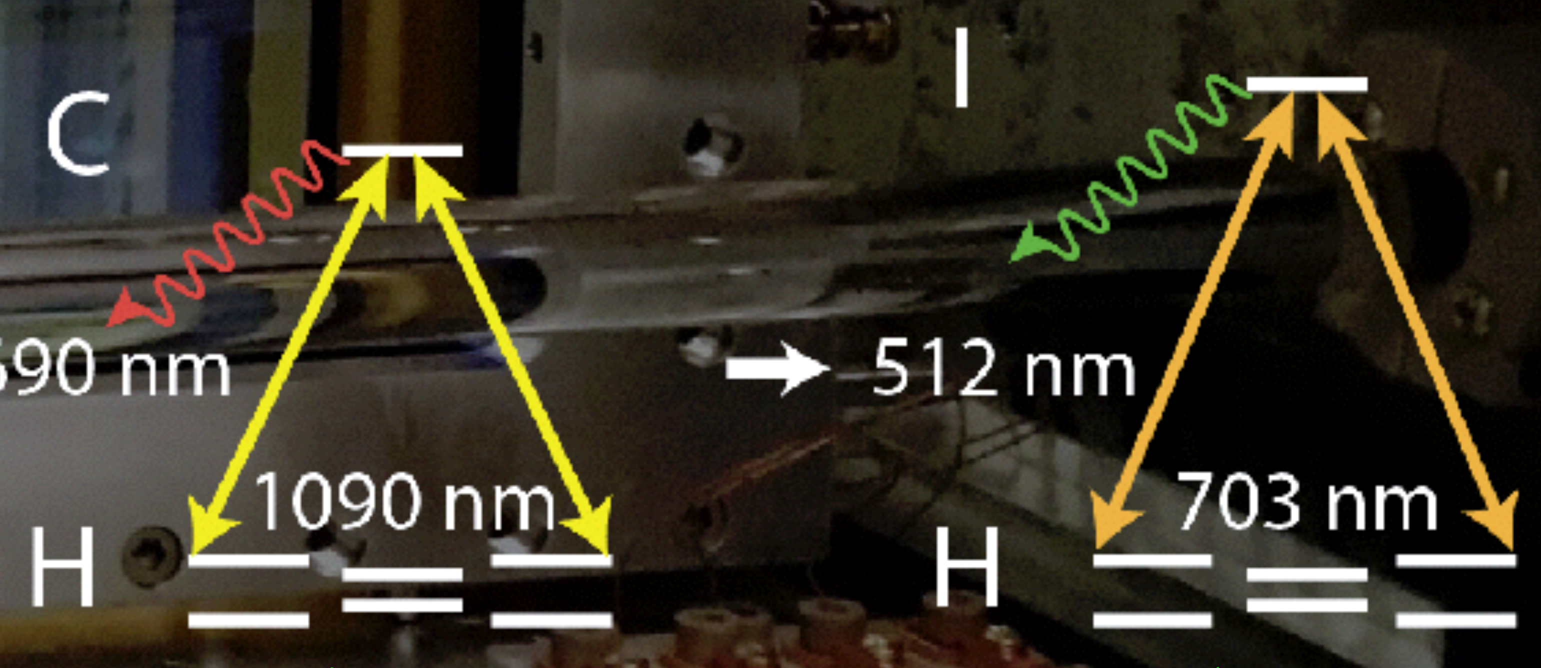
Improving Detection Efficiency



Curved light pipes and other light collection optimizations
About 1.8x Gain

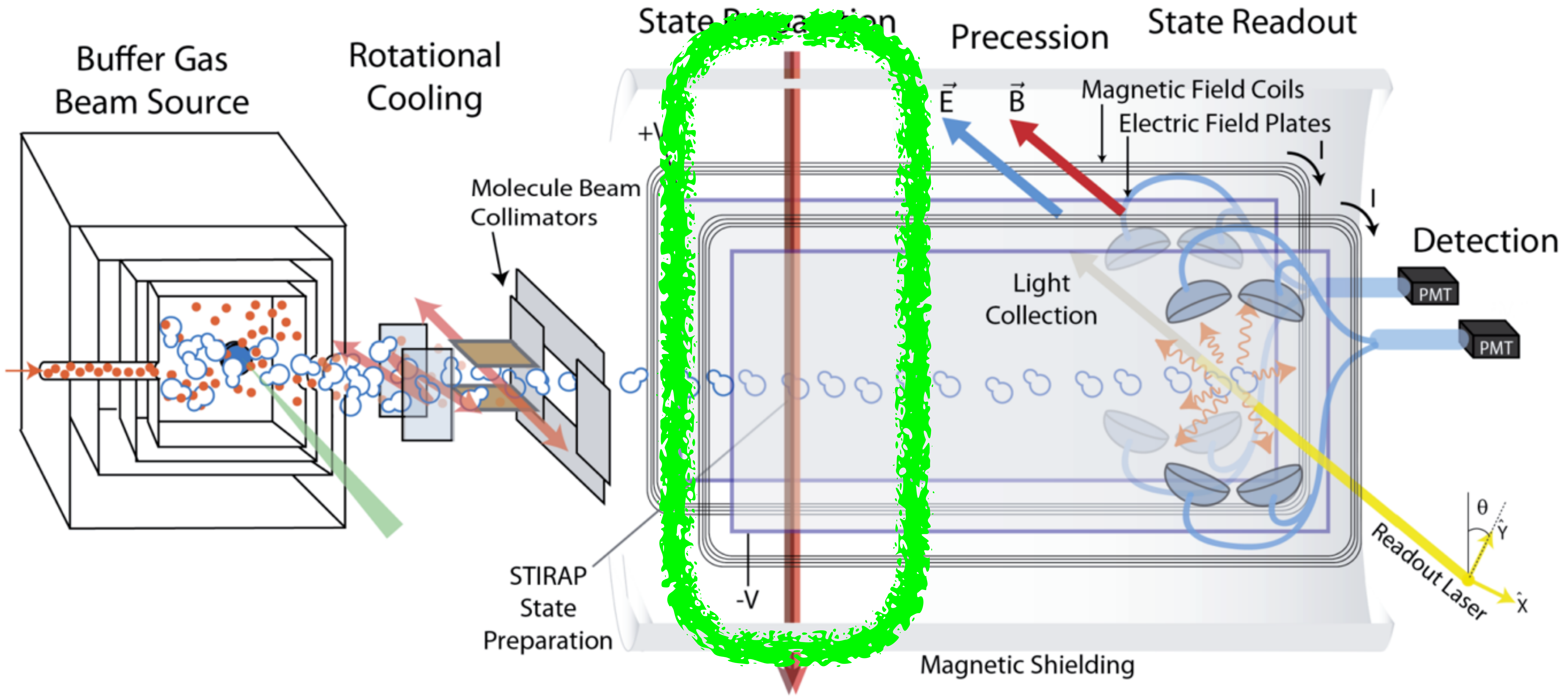
Detecting on new transition provides more light/molecule due to larger branching ratio, About 1.2x Gain

Higher quantum efficiency at new detection wavelength 512 nm, About 2.5x Gain



ABOUT 5x SIGNAL GAIN

ACME Generation II Apparatus Improvements

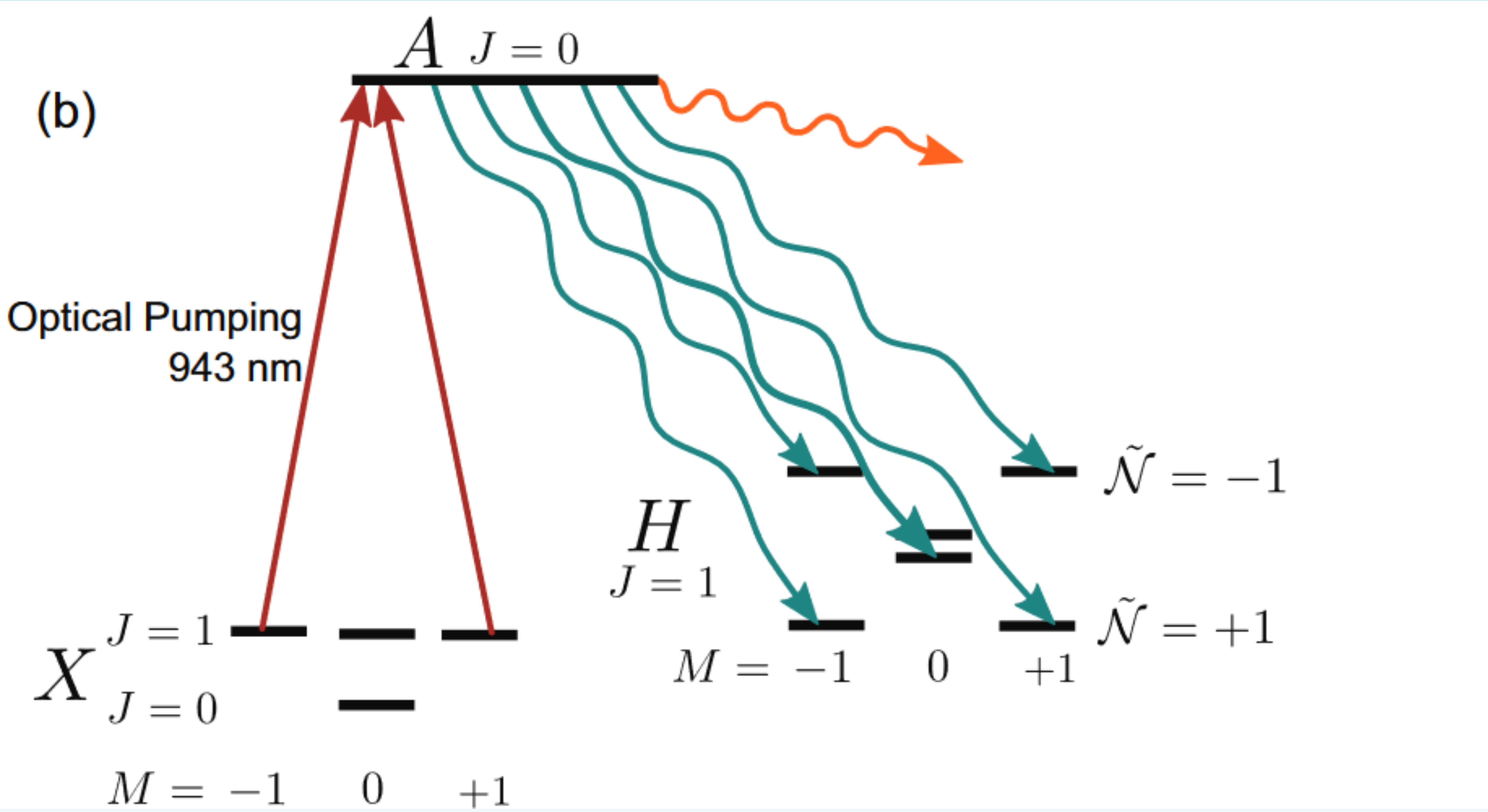


Increasing the Efficiency of State Preparation

ACME I —> ACME II

STIRAP State Preparation

ACME I

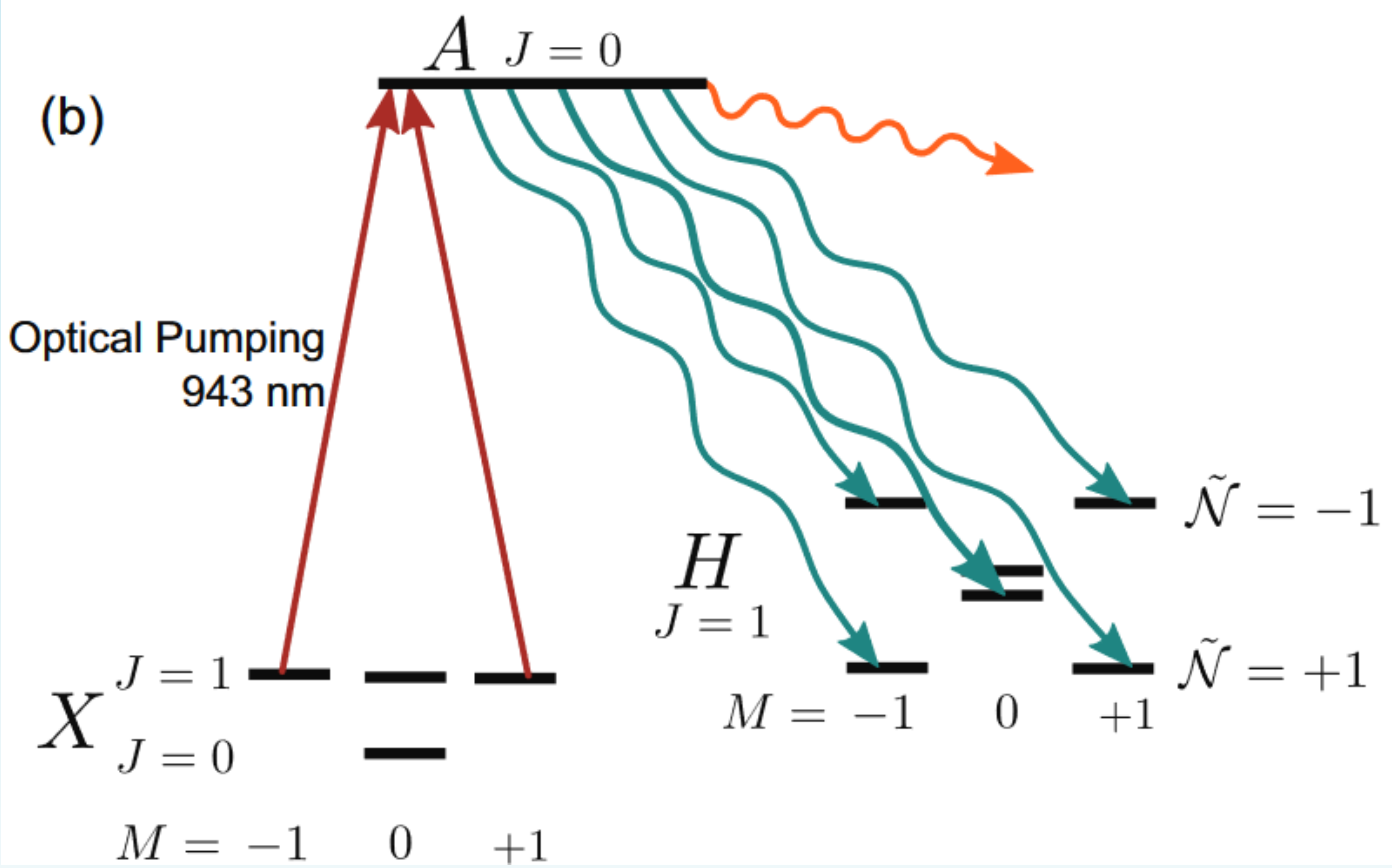


Optical Pumping (incoherent)

ACME I —> ACME II

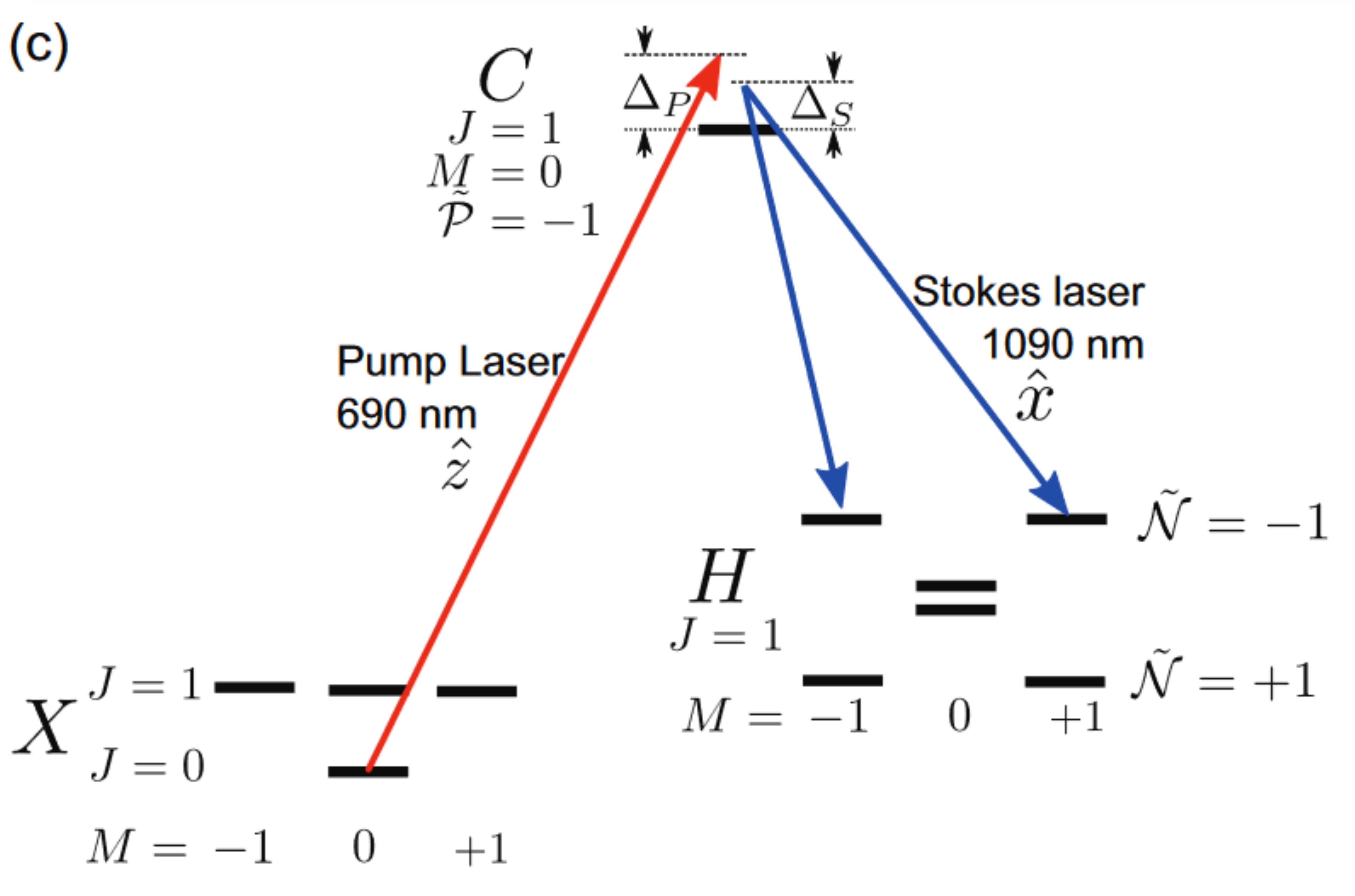
STIRAP State Preparation

ACME I



Optical Pumping (incoherent)

ACME II



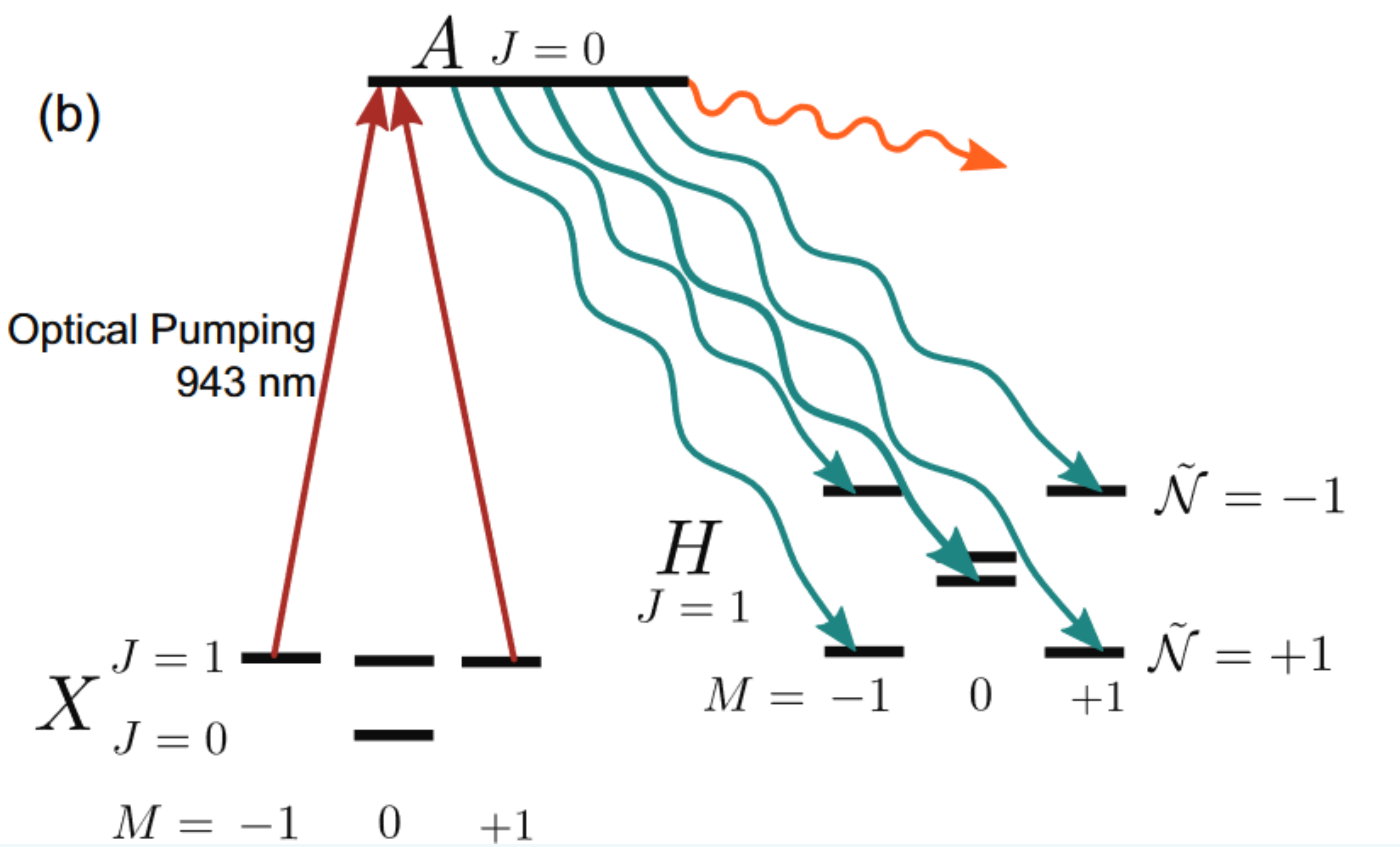
STIRAP (coherent)

ACME I —> ACME II

Known Technique

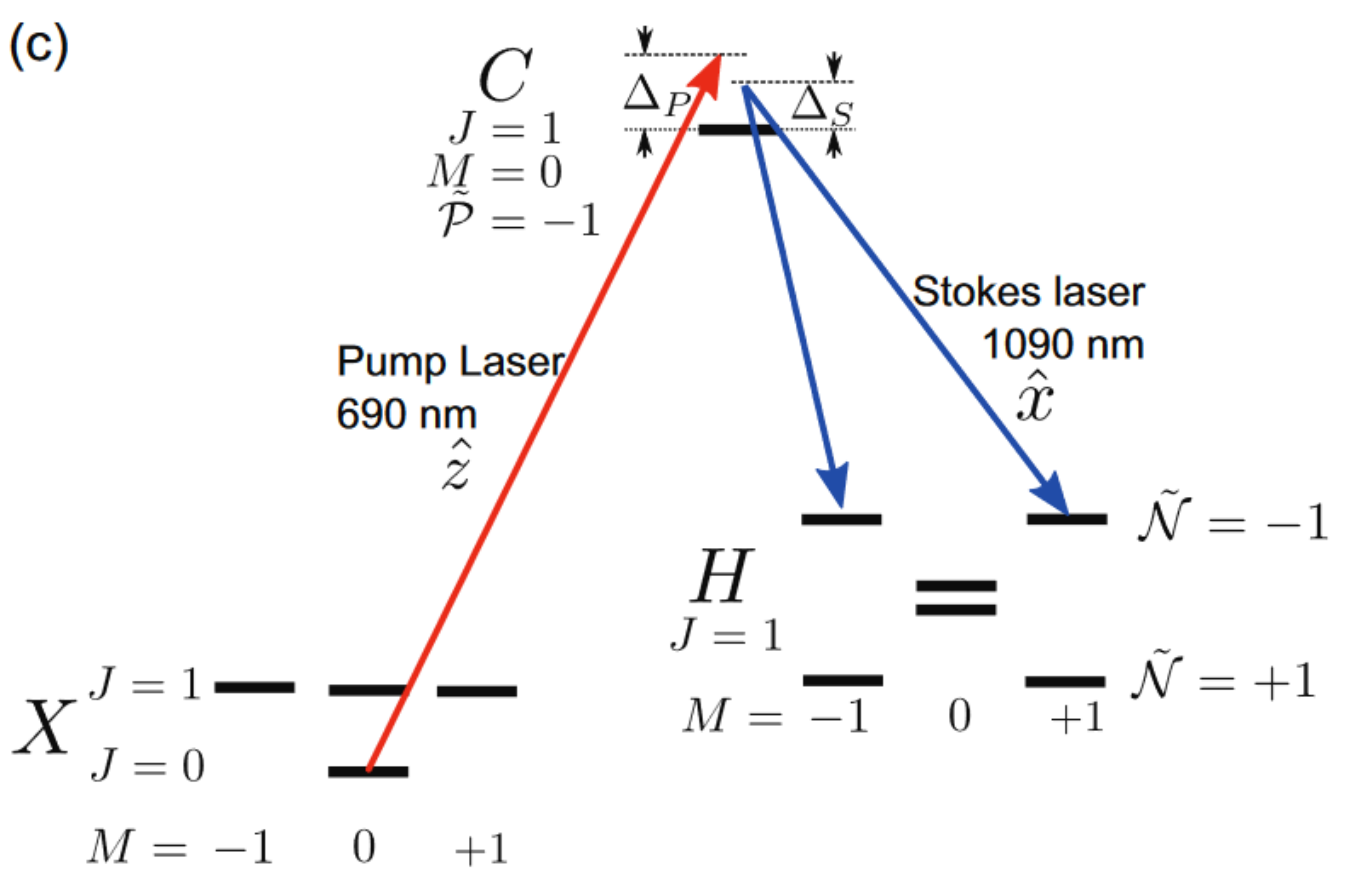
STIRAP State Preparation

ACME I



Optical Pumping (incoherent)

ACME II



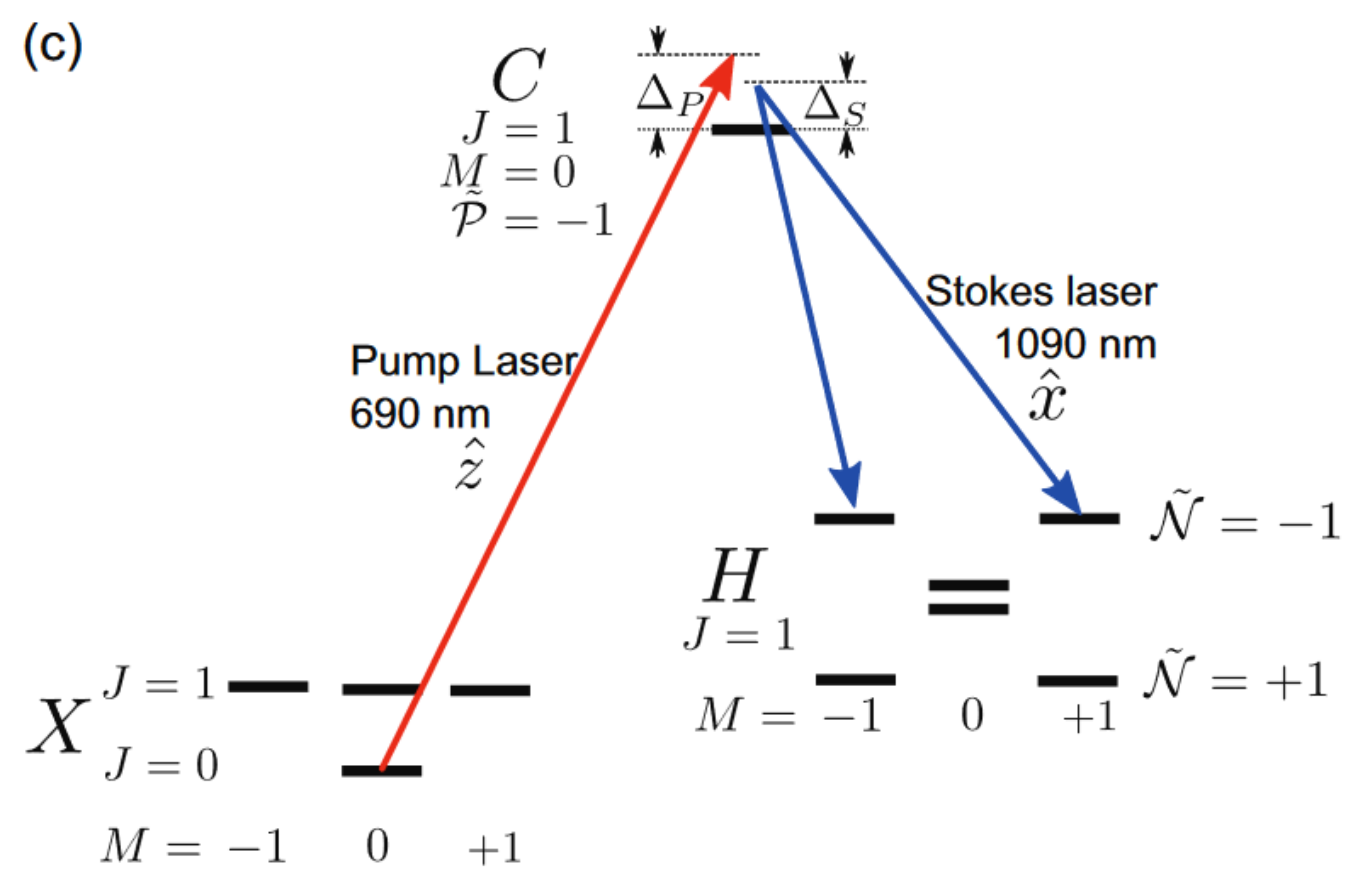
STIRAP (coherent)

ACME I —> ACME II

STIRAP State Preparation

Known Technique

ACME II

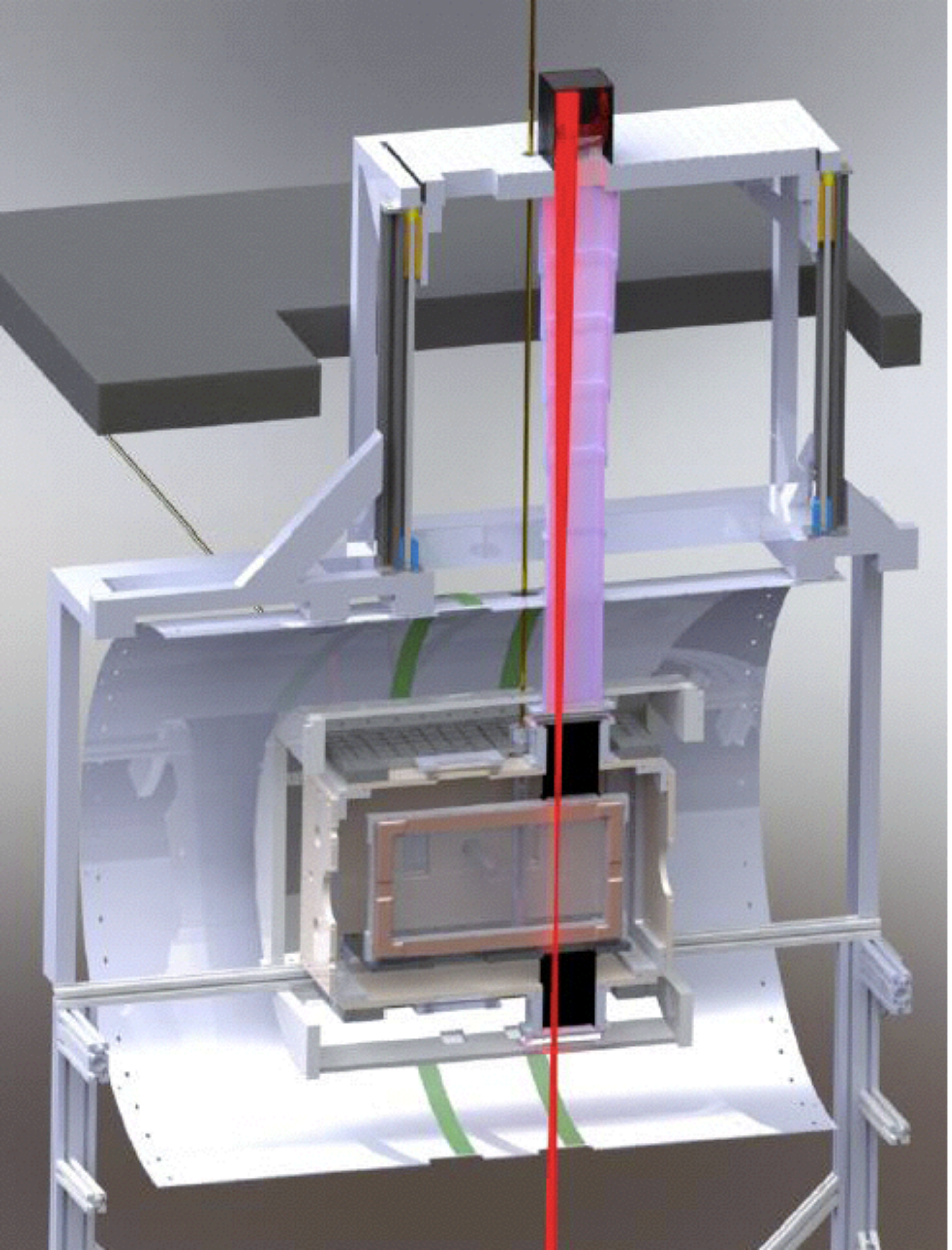


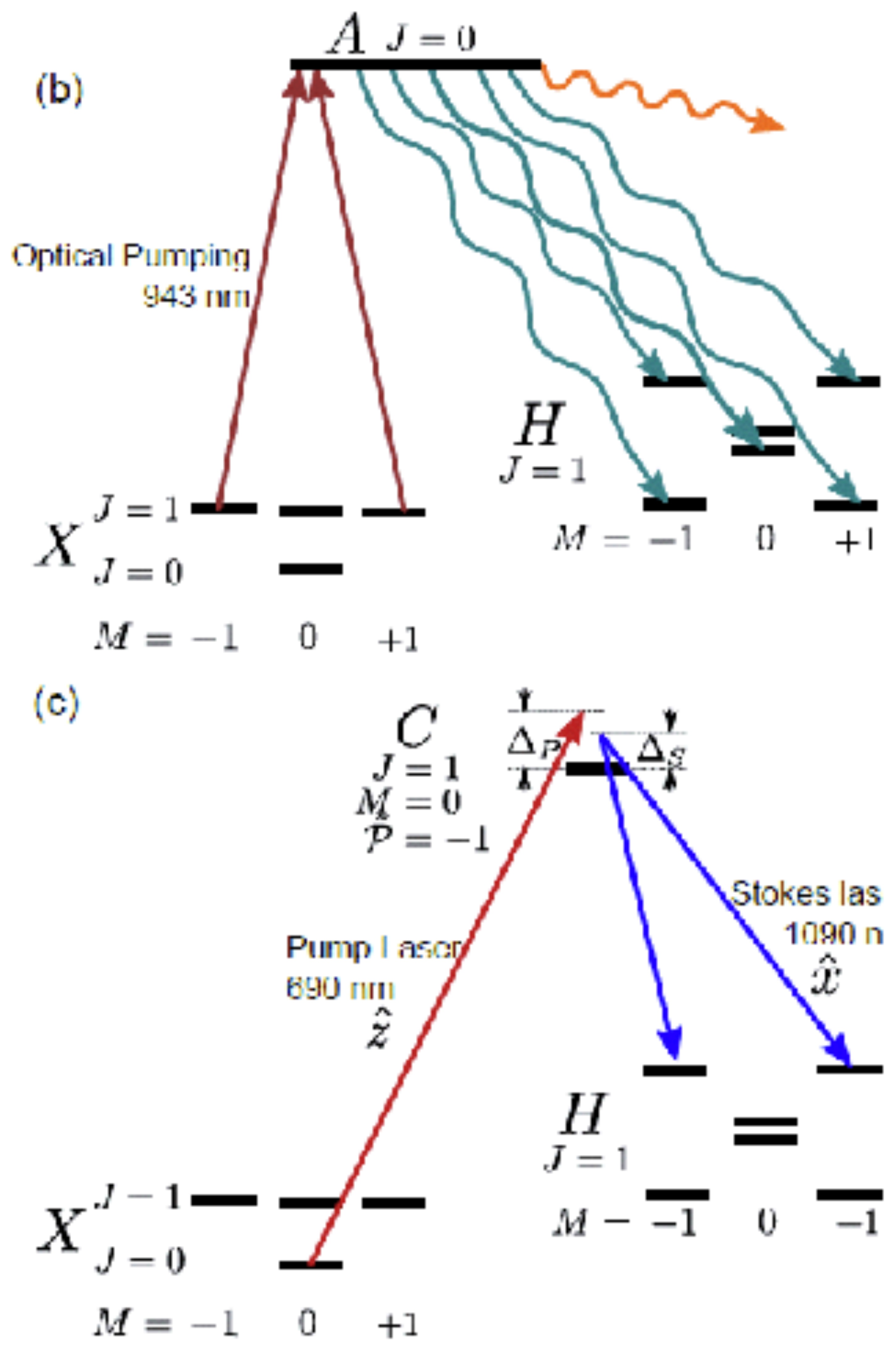
STIRAP (coherent)

BUT Challenges

- Weak transition
- Wavelengths differ by x2
- Large doppler width
- Large diameter molecular beam
- Interaction region about 1 m away

More Efficient Molecule Manipulation





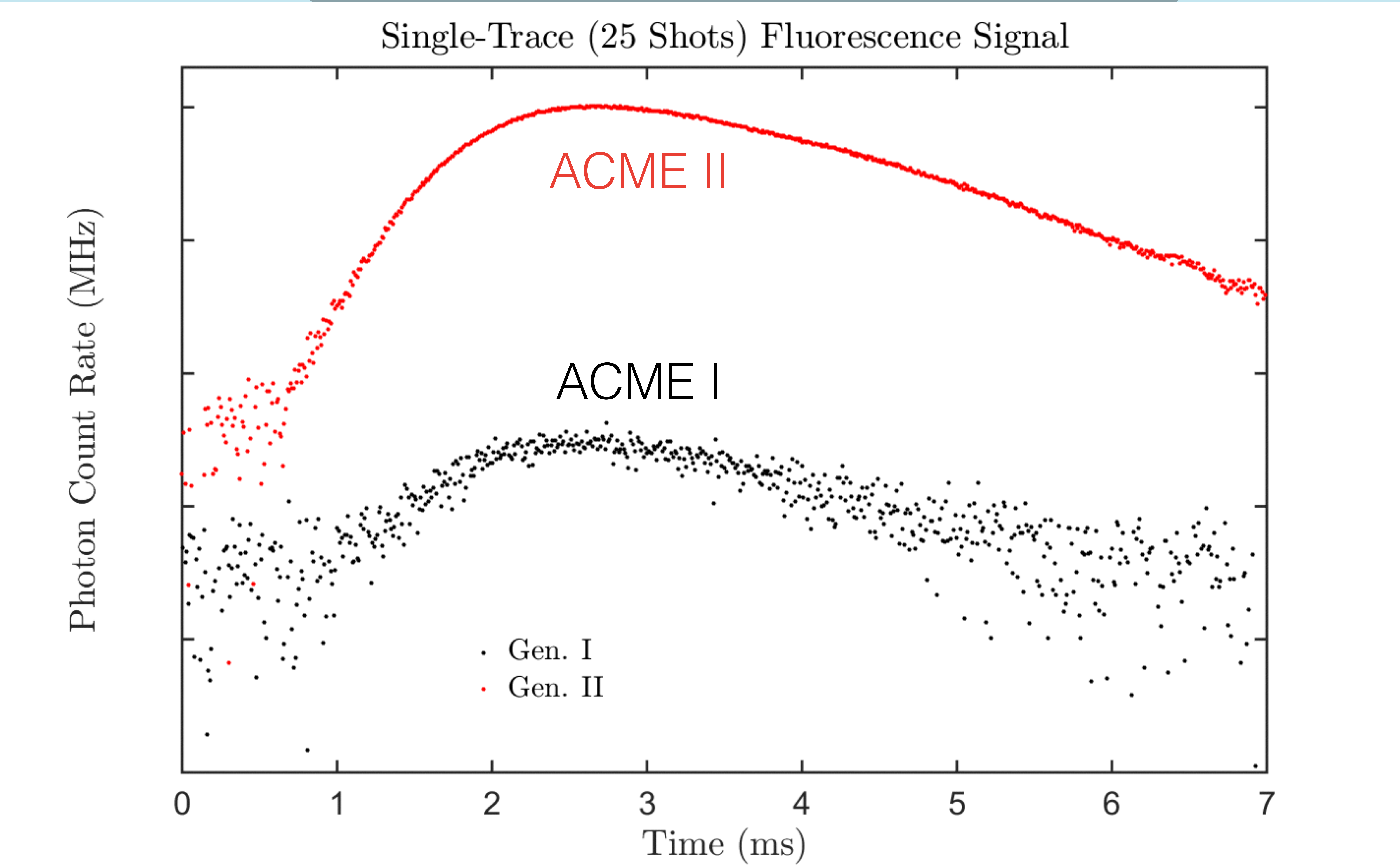
- Demonstrated STIRAP with 75% efficiency
- Compare to Optical Pumping with 6% efficiency
- New systematic errors require refinement beam
- Requires vertical launch of lasers

ABOUT 12x SIGNAL GAIN

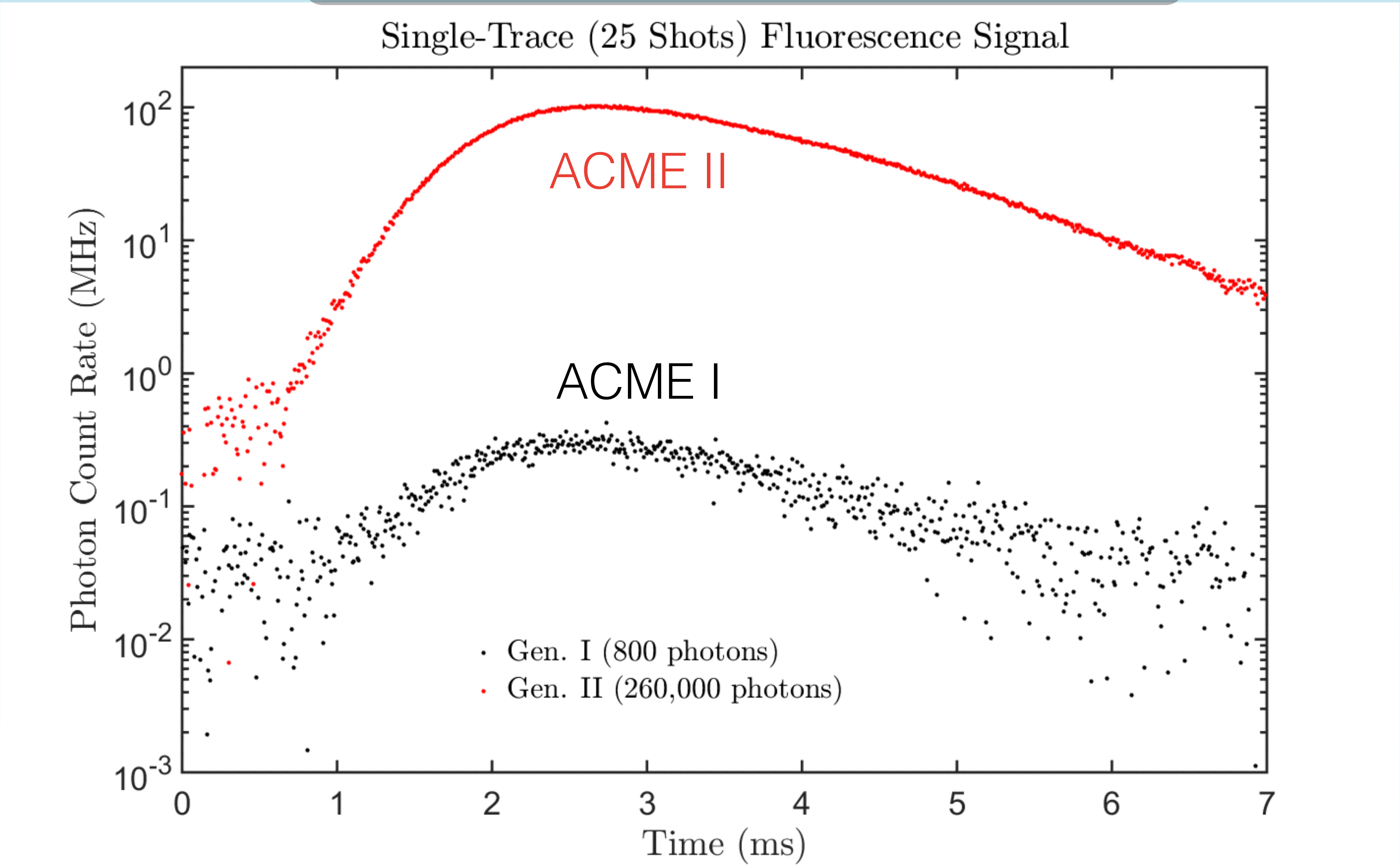
STIRAP State Preparation

C. Panda et al. Phys. Rev. A. 93 052110 (2016)

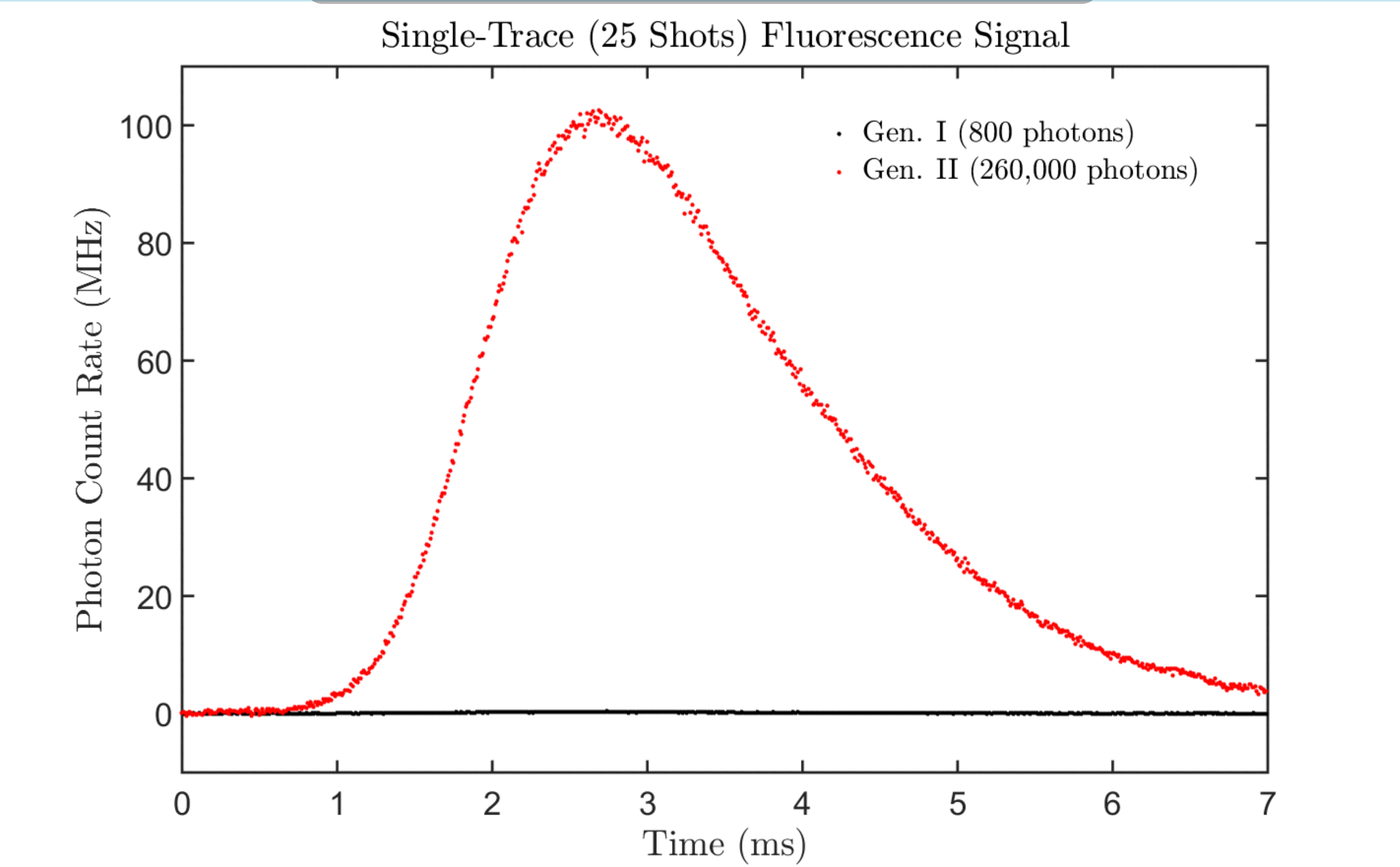
ACME II Preliminary Signals



ACME II Preliminary Signals



ACME II Preliminary Signals



Experiment	One Day Statistical Sensitivity e-cm day$^{-1/2}$	Published Limit $\lvert d_e \rvert$ < in e-cm
Berkeley Tl	0.5×10^{-27}	1.6×10^{-27}
Imperial YbF	2×10^{-27}	1.5×10^{-27}
ACME I	1×10^{-28}	0.9×10^{-28}
ACME II	*0.5×10^{-29}*	*Projected*

Improvement 1	Improvement 2	Improvement 3	EDM Sensitivity Gain over Previous Experiment
used a	molecule		~x1
Beam Source x6.5	Molecule to ThO x2	Technical x1.5	x15
Geometry x3	STIRAP x3.5	Detection x2.2	*x20 Projected*

t
experimentally excluded
ACME II Projected
unconstrained
Imperial 2010
ACME I 2014
Berkeley 2002
Berkeley 1994
Berkeley 1990
standard model
SUSY variants
generic models
Multi-Higgs
Left-Right Symmetric
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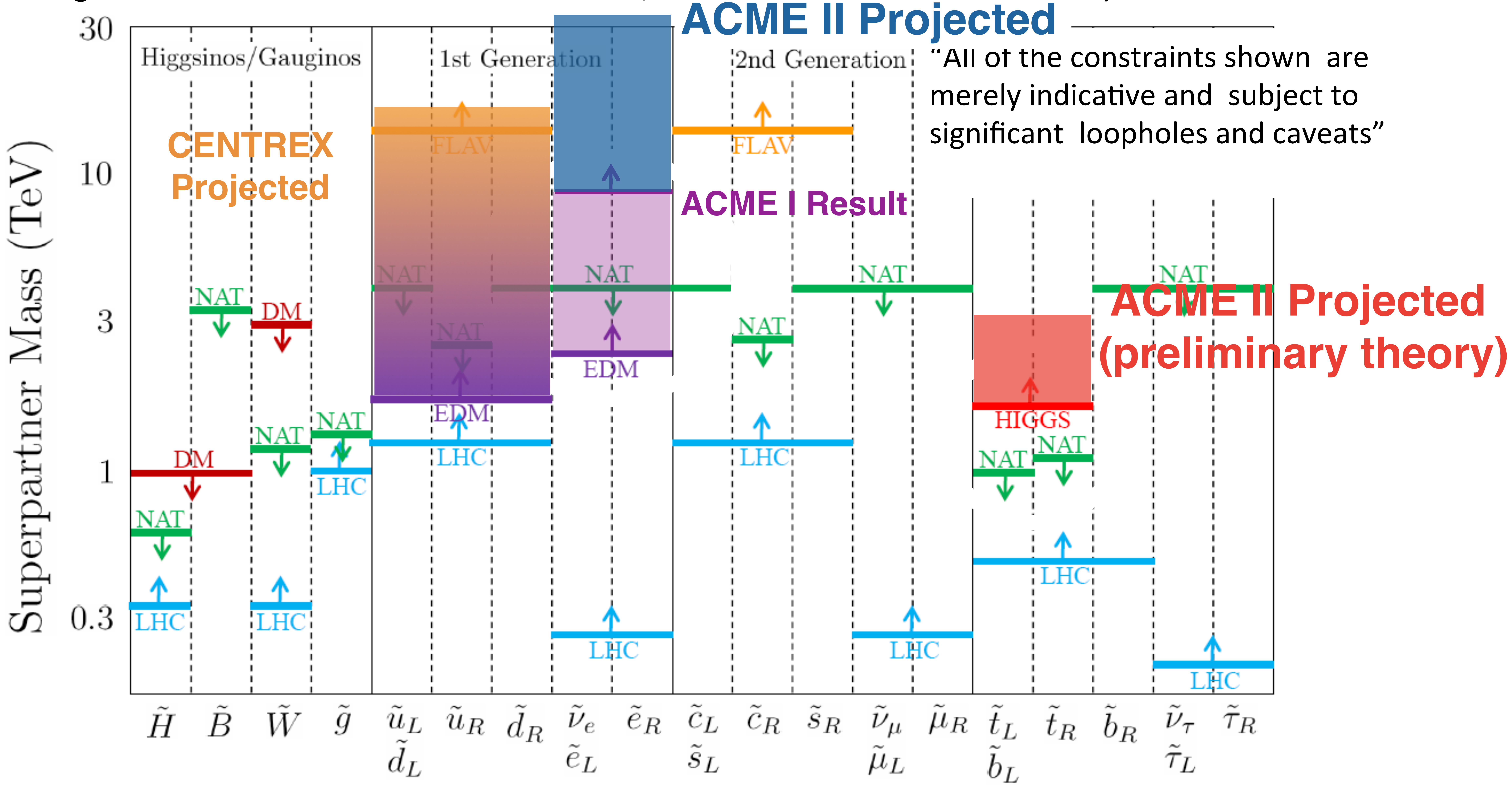
Approx. CP
Approx. Universality
Exact Universality
Naive SUSY
Heavy sFermions
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-40}
10^{-41}
d_e (e cm)

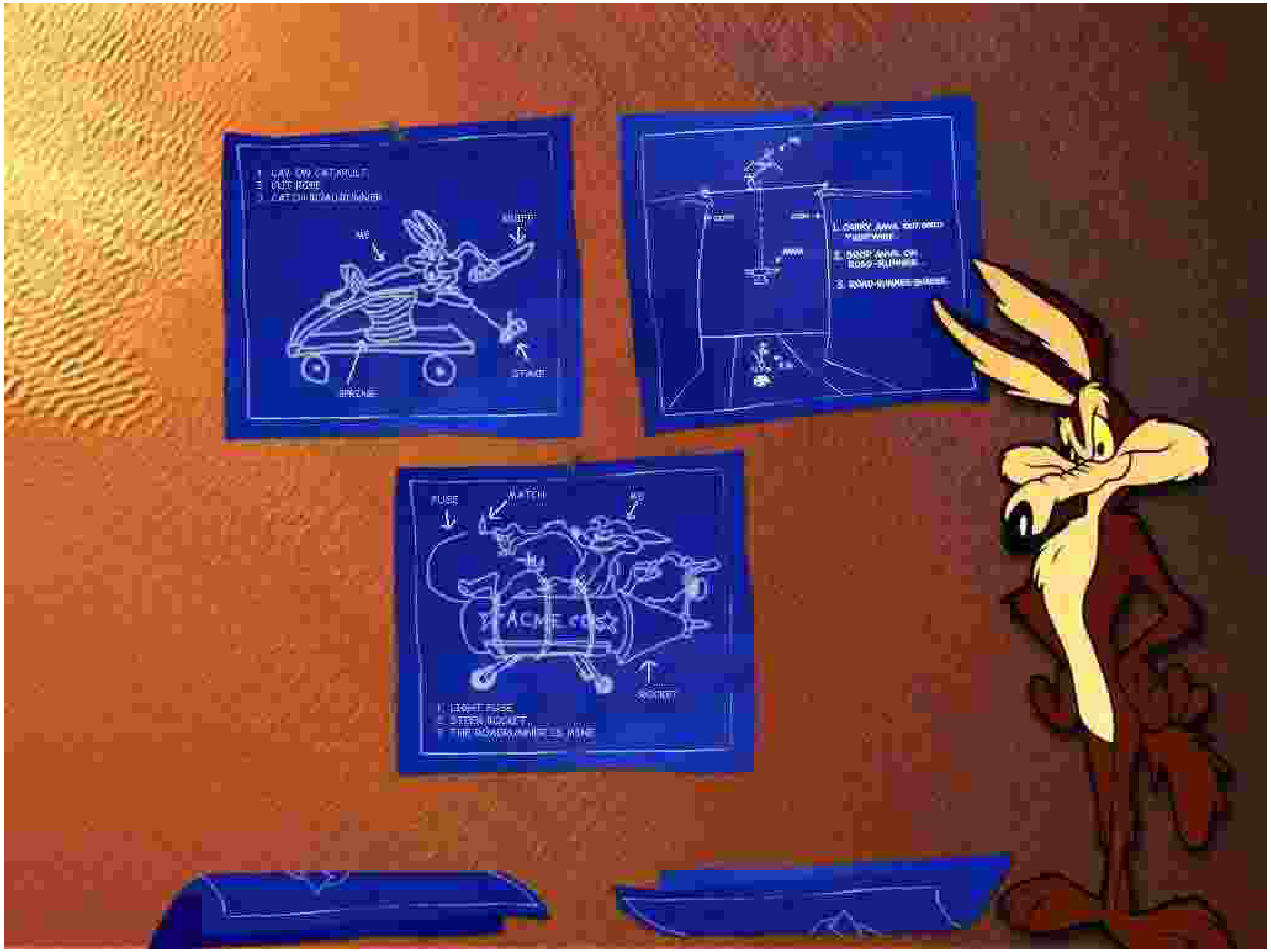
ACME II Projected Impact - 2017

J. Feng: “Naturalness and the status of SUSY”, Ann. Rev. Nucl. Part. Sci. (2013)



We are still hard at work....

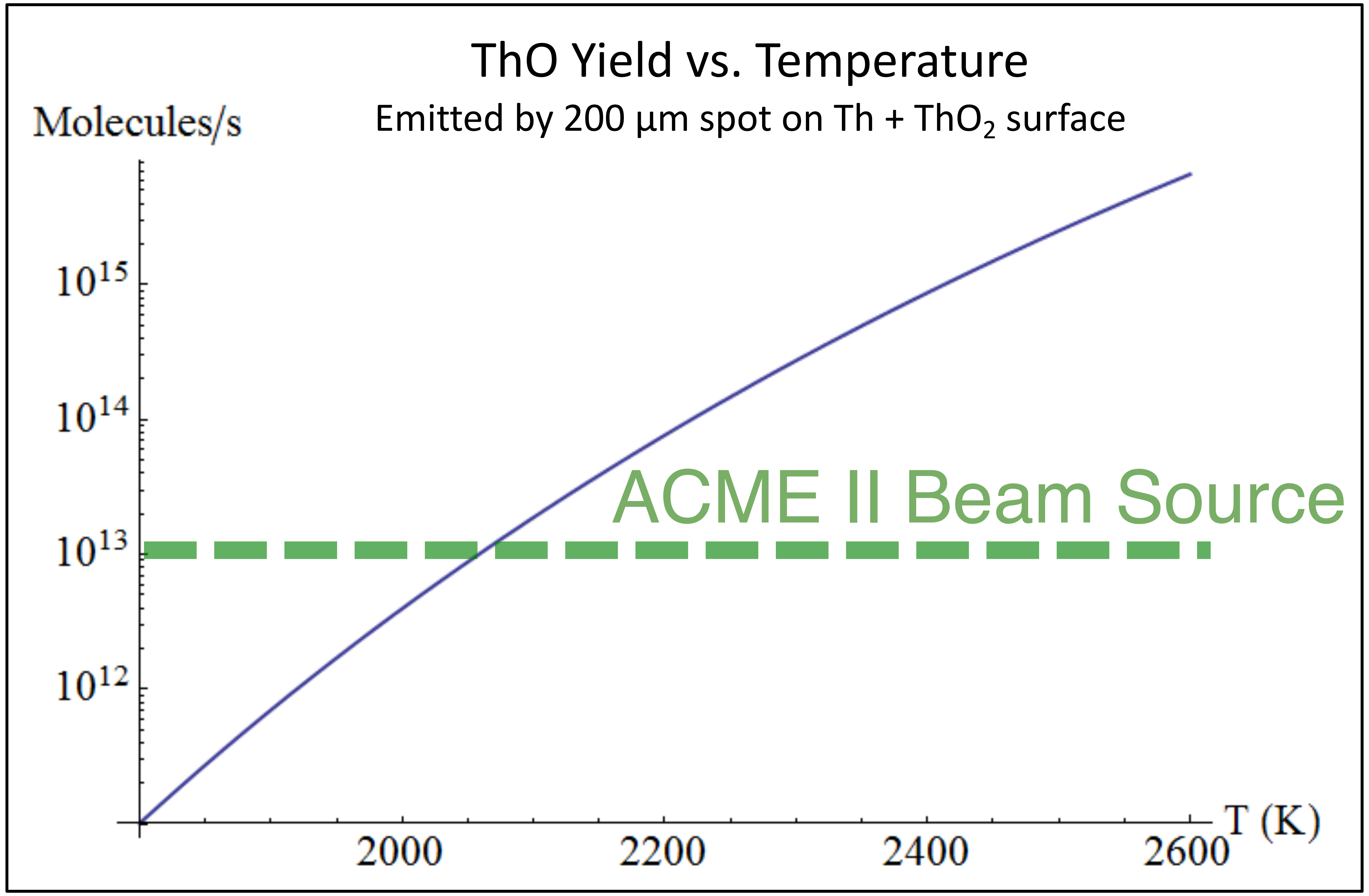
.....with ACME II ! And ACME III !



High-Temperature Thorium-Oxygen Chemistry

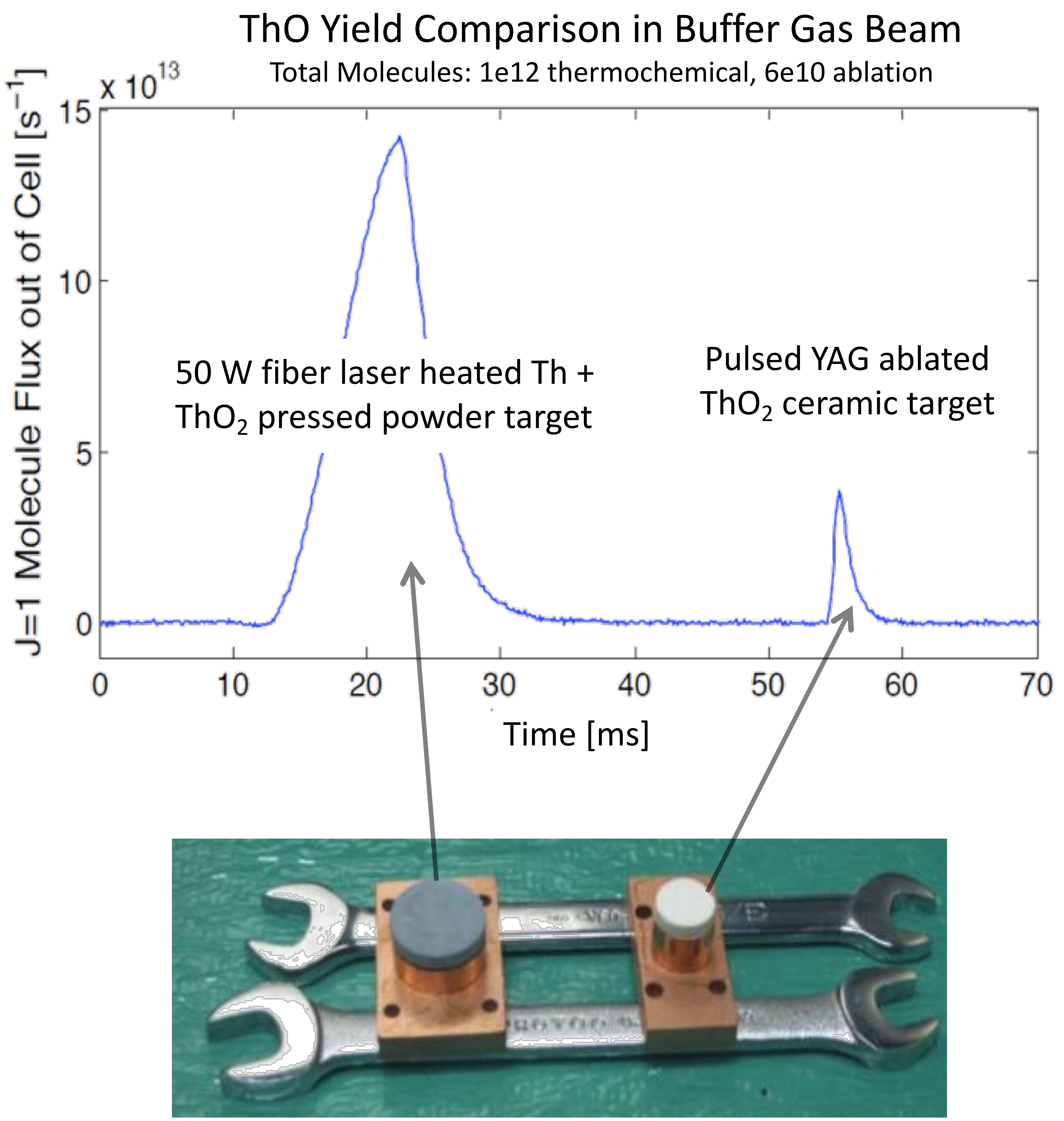
Chemical reaction with favorable yields >2000 K

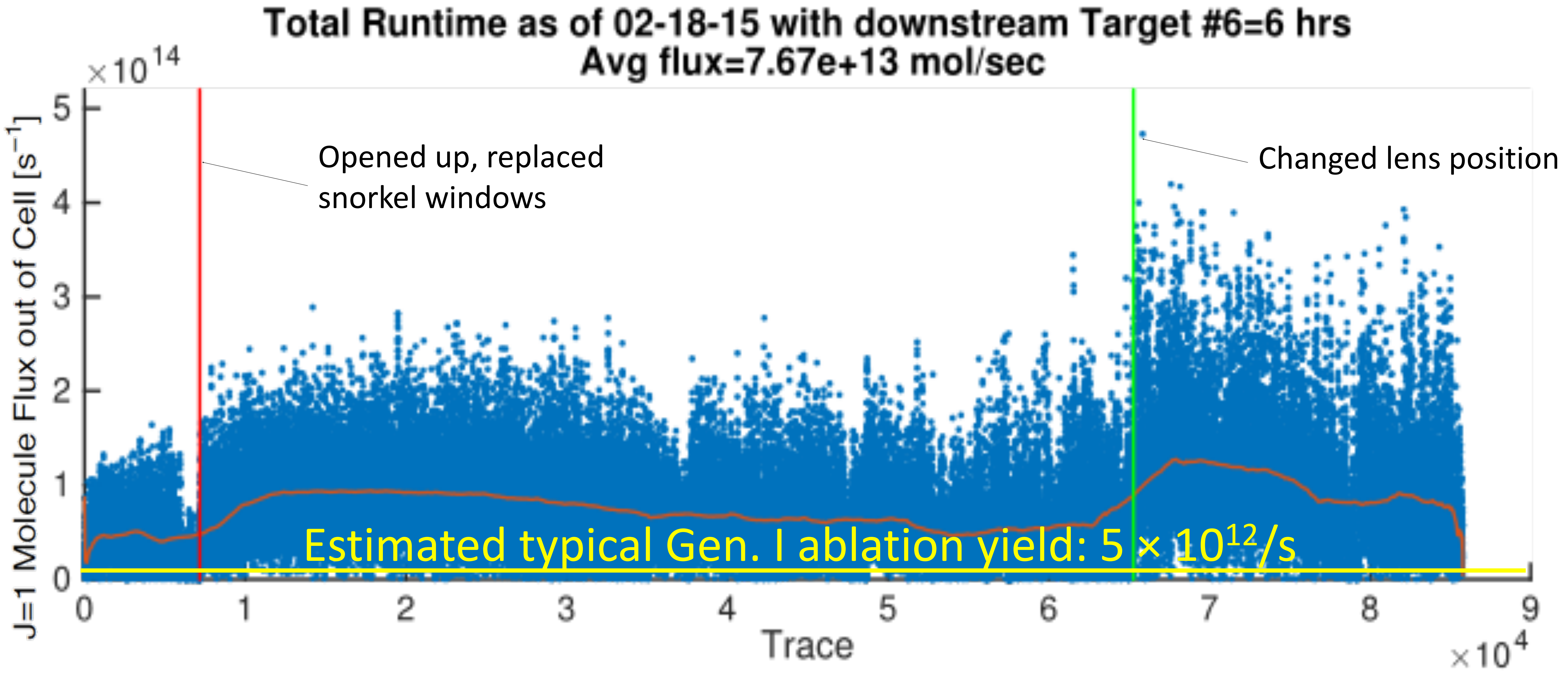
$$Th(s) + ThO_2(s) \xrightarrow{\text{Heat}} 2ThO(g)$$



1. Darnell and McCollum, "High Temperature Reactions of Thorium and Thoria and the Vapor Pressure of Thoria," *Atomics International*, September 1961.
2. Hildenbrand and Murad, "Mass Spectromectric Studies of Gaseous ThO and ThO_2," *J. Chem. Phys.*, August 1974.
3. Rand et al., *Chemical Thermodynamics of Thorium*, OECD 2007.

Thermochemical Source Yields

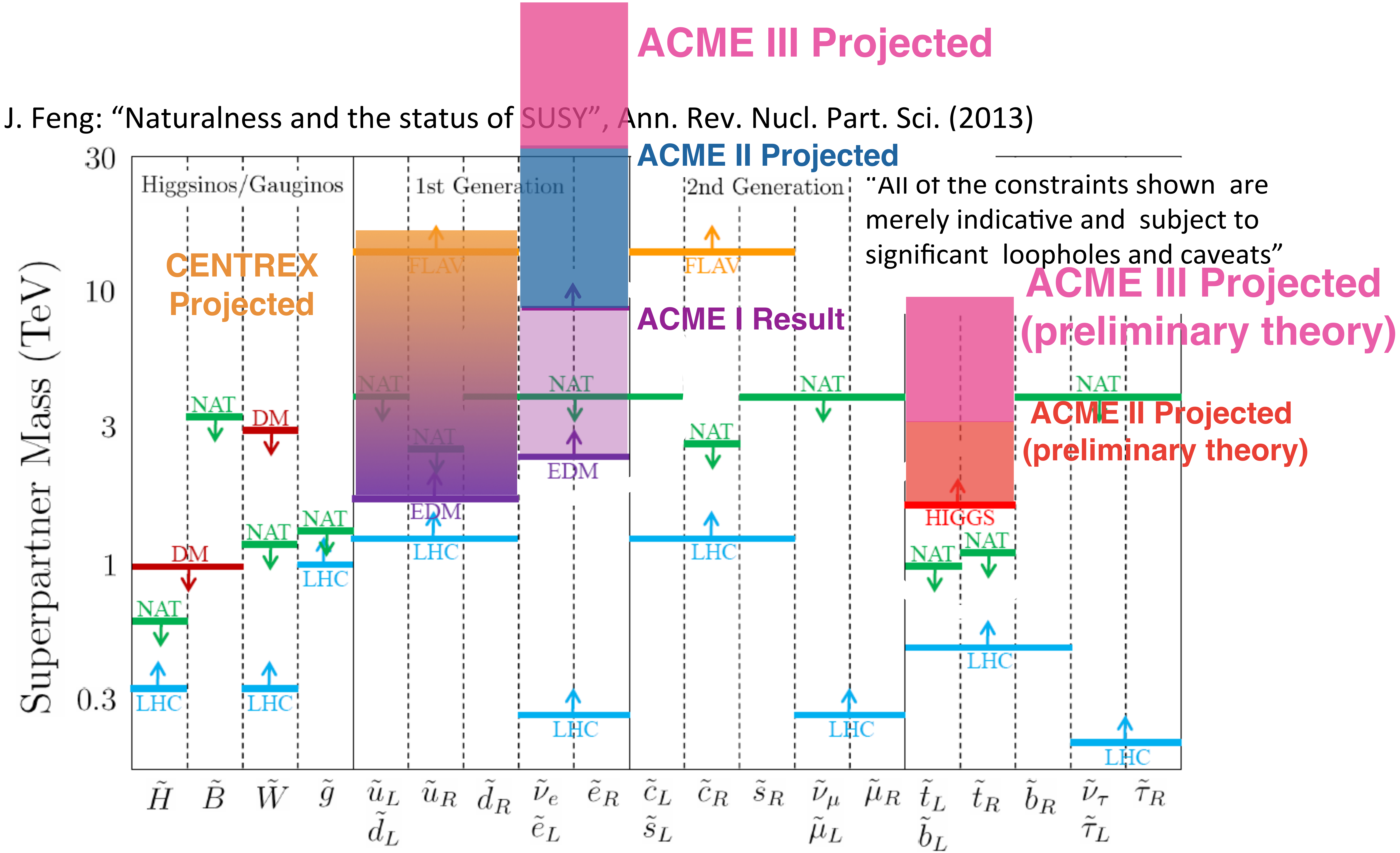




$\sim 10\times$ larger flux than ablation source

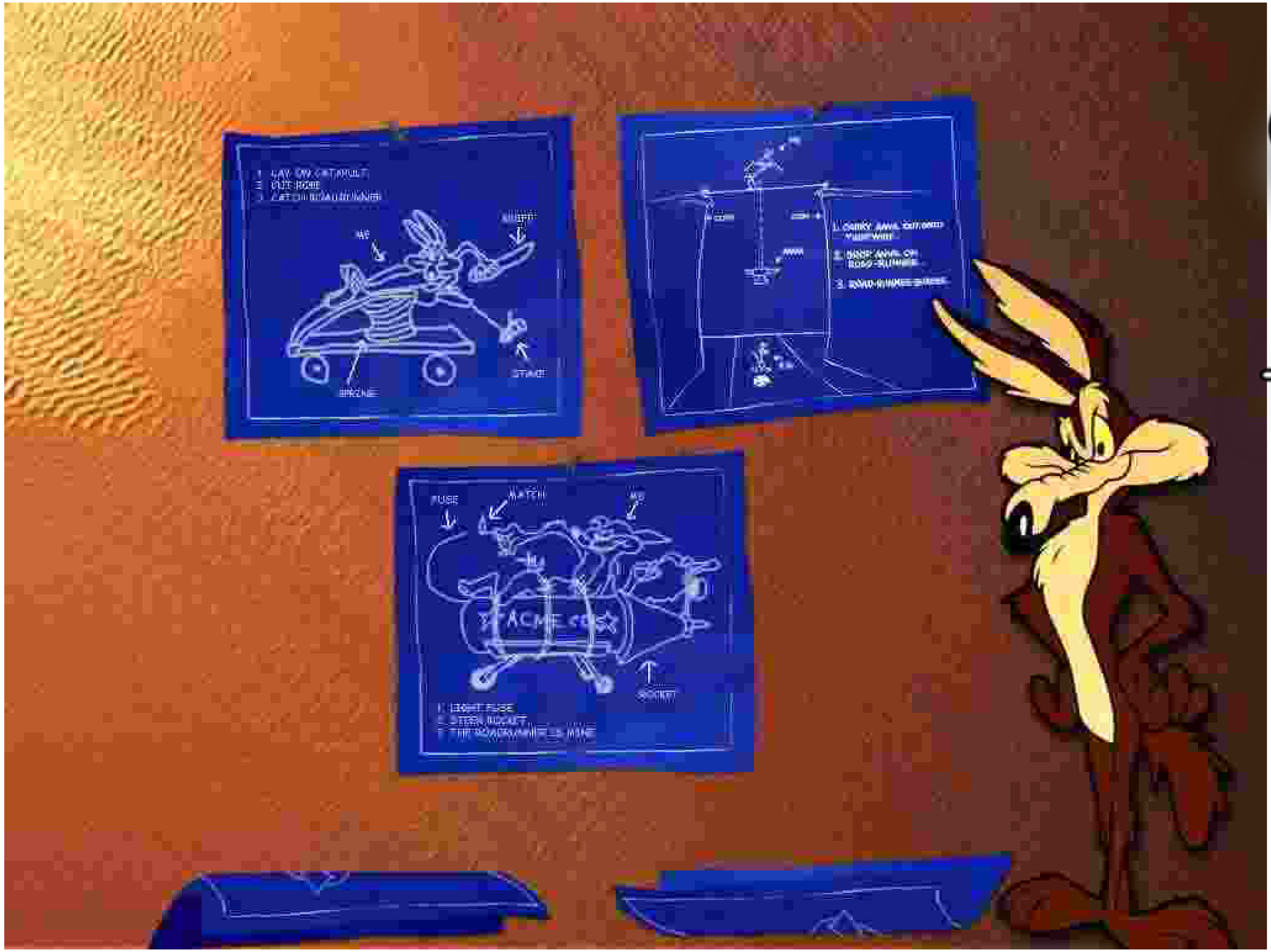
Experiment	One Day Statistical Sensitivity e-cm day$^{-1/2}$	Published Limit $\|d_e\| <$ in e-cm
Berkeley Tl	0.5×10^{-27}	1.6×10^{-27}
Imperial YbF	2×10^{-27}	1.5×10^{-27}
ACME I	1×10^{-28}	0.9×10^{-28}
ACME II	*0.5×10^{-29}*	*Projected*
ACME III	*0.3×10^{-30}*	*Projected*

Improvement 1	Improvement 2	Improvement 3	EDM Sensitivity Gain over Previous Experiment
used a	molecule		~x1
Beam Source x6.5	Molecule to ThO x2	Technical x1.5	x15
Geometry x3	STIRAP x3.5	Detection x2.2	*x20 Projected*
Thermochemical Source x3	*Electrostatic Lens x1.5*	*Detection x5*	*x20 Projected*


ACME III Projected
J. Feng: “Naturalness and the status of SUSY”, Ann. Rev. Nucl. Part. Sci. (2013)
ACME II Projected
“All of the constraints shown are merely indicative and subject to significant loopholes and caveats”
ACME III Projected (preliminary theory)
ACME I Result
ACME II Projected (preliminary theory)
CENTREX Projected
Superpartner Mass (TeV)
30
10
3
1
0.3
Higgsinos/Gauginos
1st Generation
2nd Generation
FLAV
NAT
DM
EDM
LHC
HIGGS
$\tilde{H}$ $\tilde{B}$ $\tilde{W}$ $\tilde{g}$ $\tilde{u}_L$ $\tilde{d}_L$ $\tilde{u}_R$ $\tilde{d}_R$ $\tilde{\nu}_e$ $\tilde{e}_L$ $\tilde{e}_R$ $\tilde{c}_L$ $\tilde{s}_L$ $\tilde{c}_R$ $\tilde{s}_R$ $\tilde{\nu}_\mu$ $\tilde{\mu}_L$ $\tilde{\mu}_R$ $\tilde{t}_L$ $\tilde{b}_L$ $\tilde{t}_R$ $\tilde{b}_R$ $\tilde{\nu}_\tau$ $\tilde{\tau}_L$ $\tilde{\tau}_R$

We are still hard at work....

.....with ACME II ! And ACME III !



and
ACME
Super-duper!

Experiment	One Day Statistical Sensitivity e-cm day$^{-1/2}$	Published Limit $\|d_e\|$ < in e-cm
Berkeley Tl	0.5 x 10^{-27}	1.6 x 10^{-27}
Imperial YbF	2 x 10^{-27}	1.5 x 10^{-27}
ACME I	1 x 10^{-28}	0.9 x 10^{-28}
ACME II	*0.5 x 10^{-29}*	*Projected*
ACME III	*0.3 x 10^{-30}*	*Projected*
ACME SD	*1 x 10^{-32}(?)*	*Projected*

Improvement 1	Improvement 2	Improvement 3	EDM Sensitivity Gain over Previous Experiment
used a	molecule		~x1
Beam Source x6.5	Molecule to ThO x2	Technical x1.5	x15
Geometry x3	STIRAP x3.5	Detection x2.2	*x20 Projected*
Thermochemical Source x3	*Electrostatic Lens x1.5*	*Detection x5*	*x20 Projected*
Advanced Beam Phase Space	*Optimized Detection x1.5*	*?*	*?*

t
experimentally excluded
ACME II
Projected
ACME III
Projected
ACME
2014
Imperial 2010
Berkeley 2002
Berkeley 1994
Berkeley 1990
standard model
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generic models
Multi-
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= 1 PeV sensitivity
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Changing
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SUSY
SO(10)
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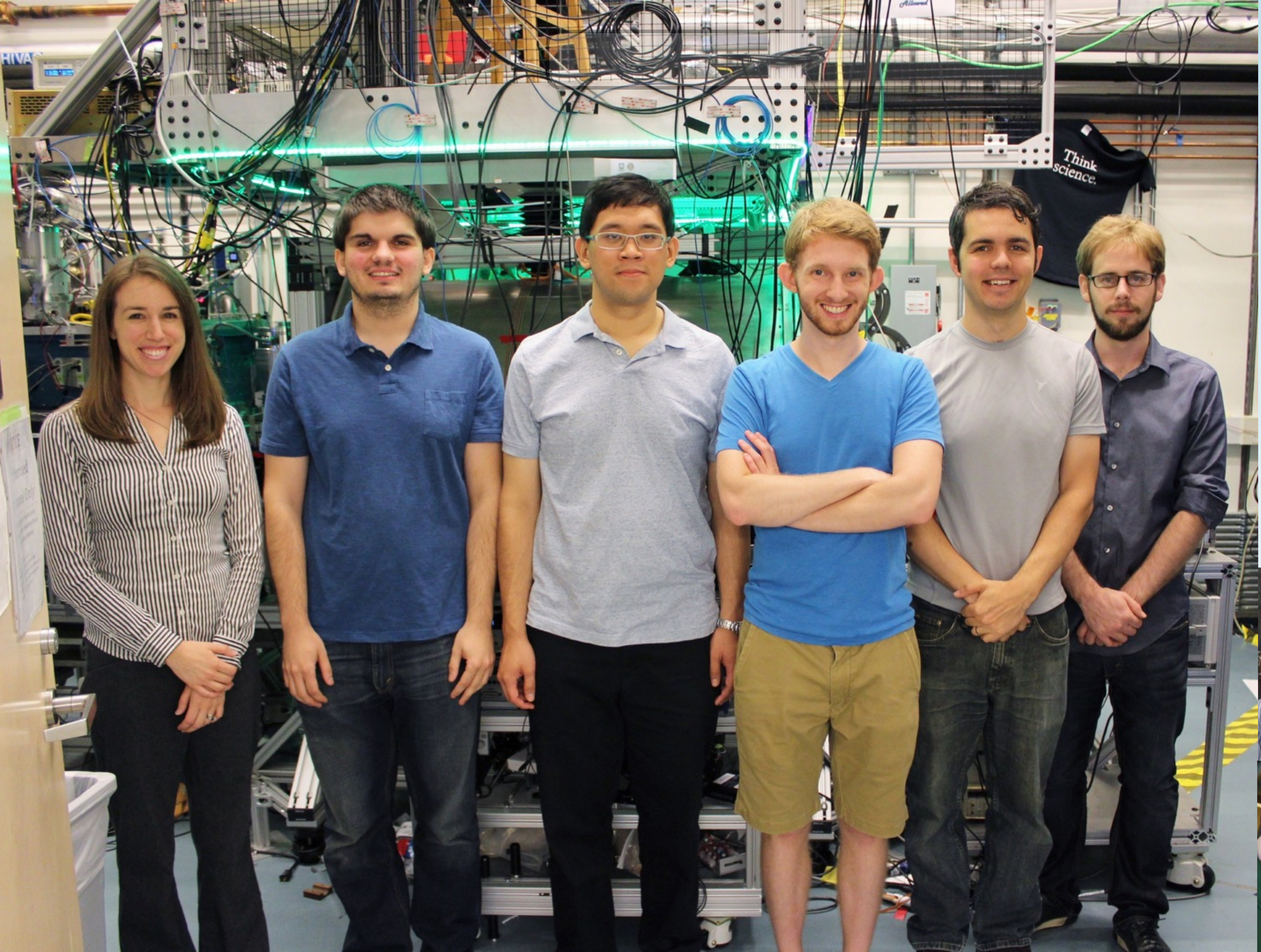
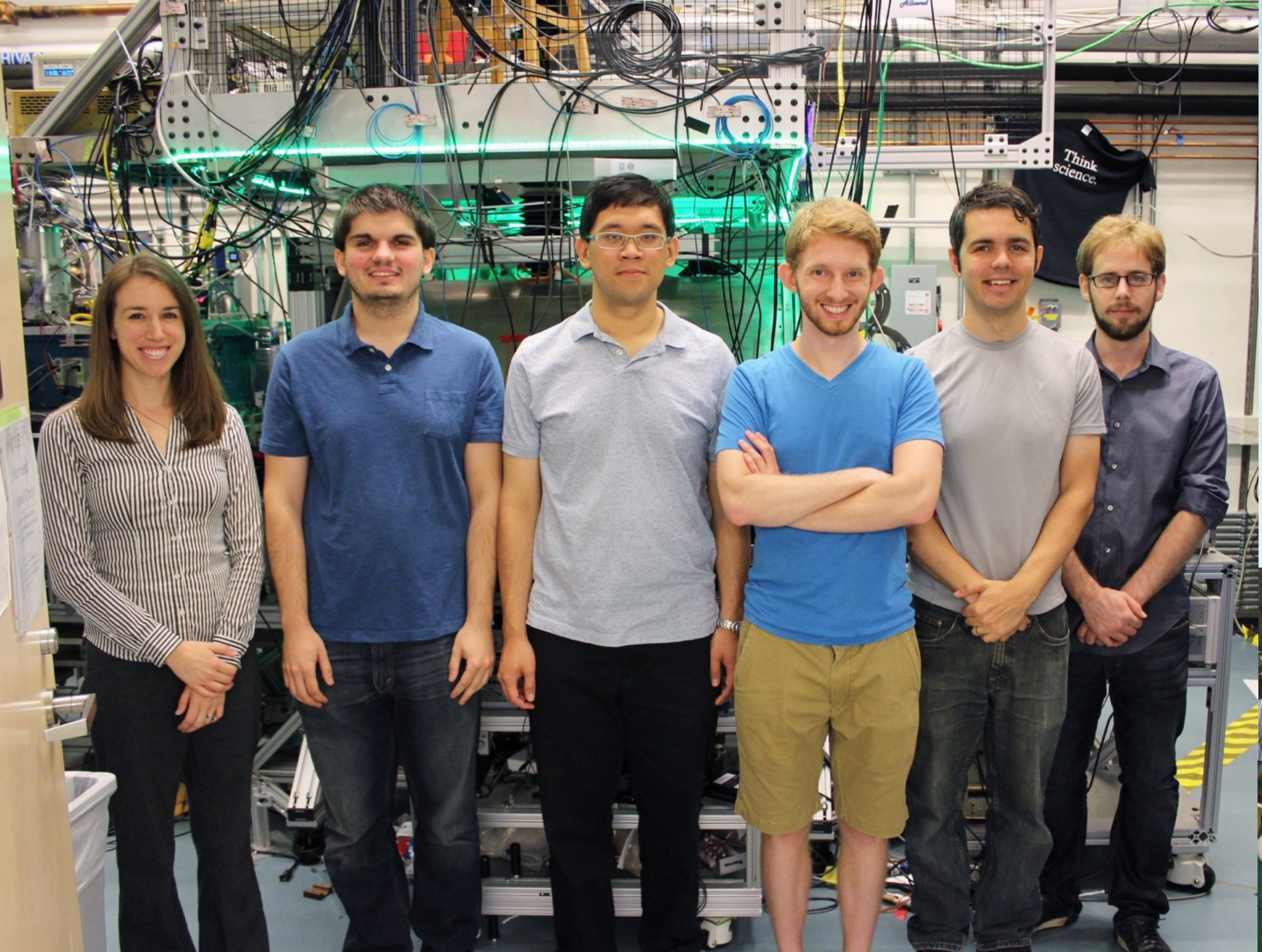
Alignment
Seesaw Neutrino Yukawa Couplings
Accidental
Cancellation
Approx.
CP
Approx.
Universality
Exact
Universality
Naive SUSY
Heavy
sFermions
10^{-25} 10^{-26} 10^{-27} 10^{-28} 10^{-29} 10^{-30} 10^{-31} 10^{-32} 10^{-33} 10^{-40} 10^{-41}
d_e (e cm)



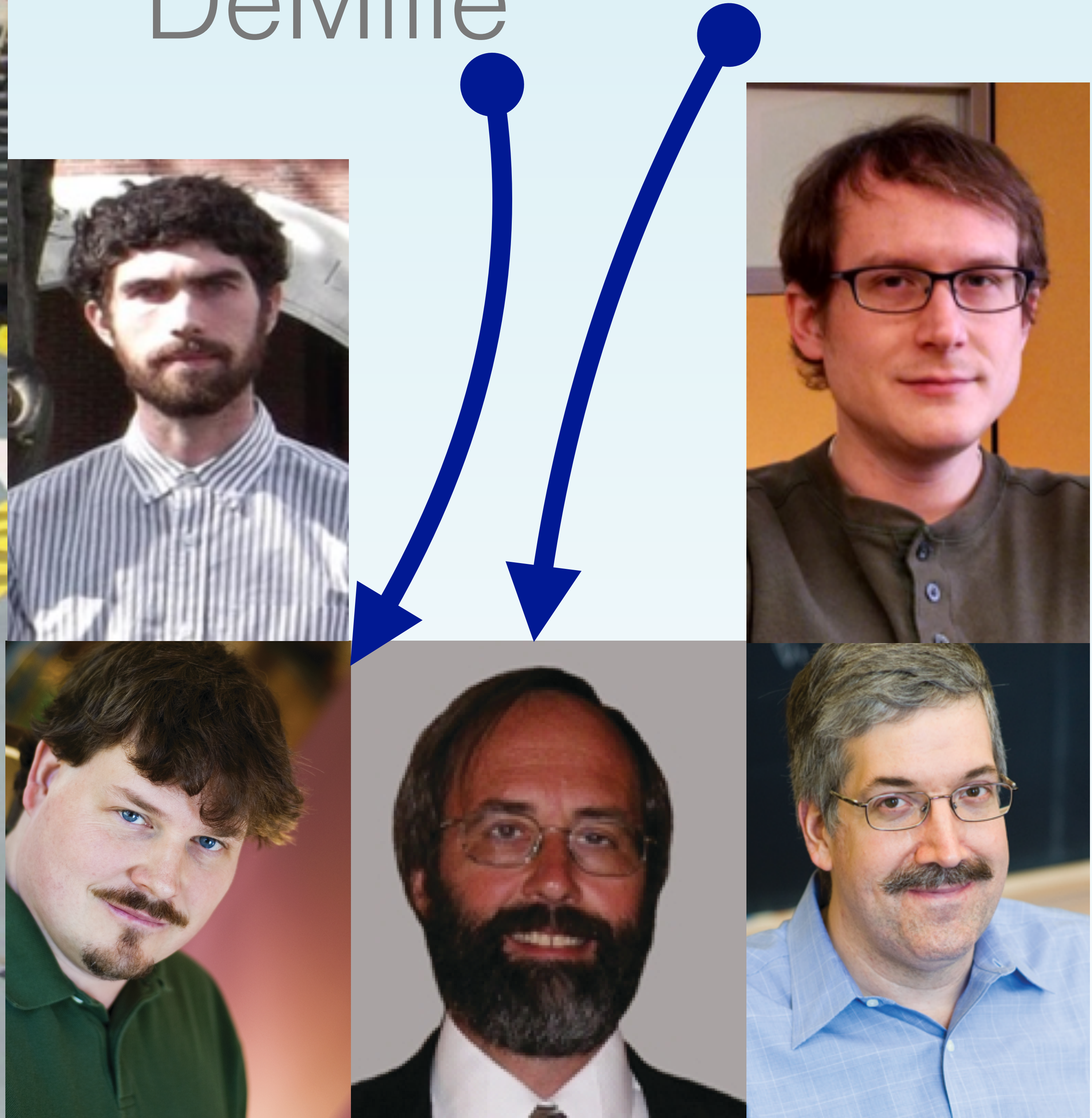
Brendon
O’Leary

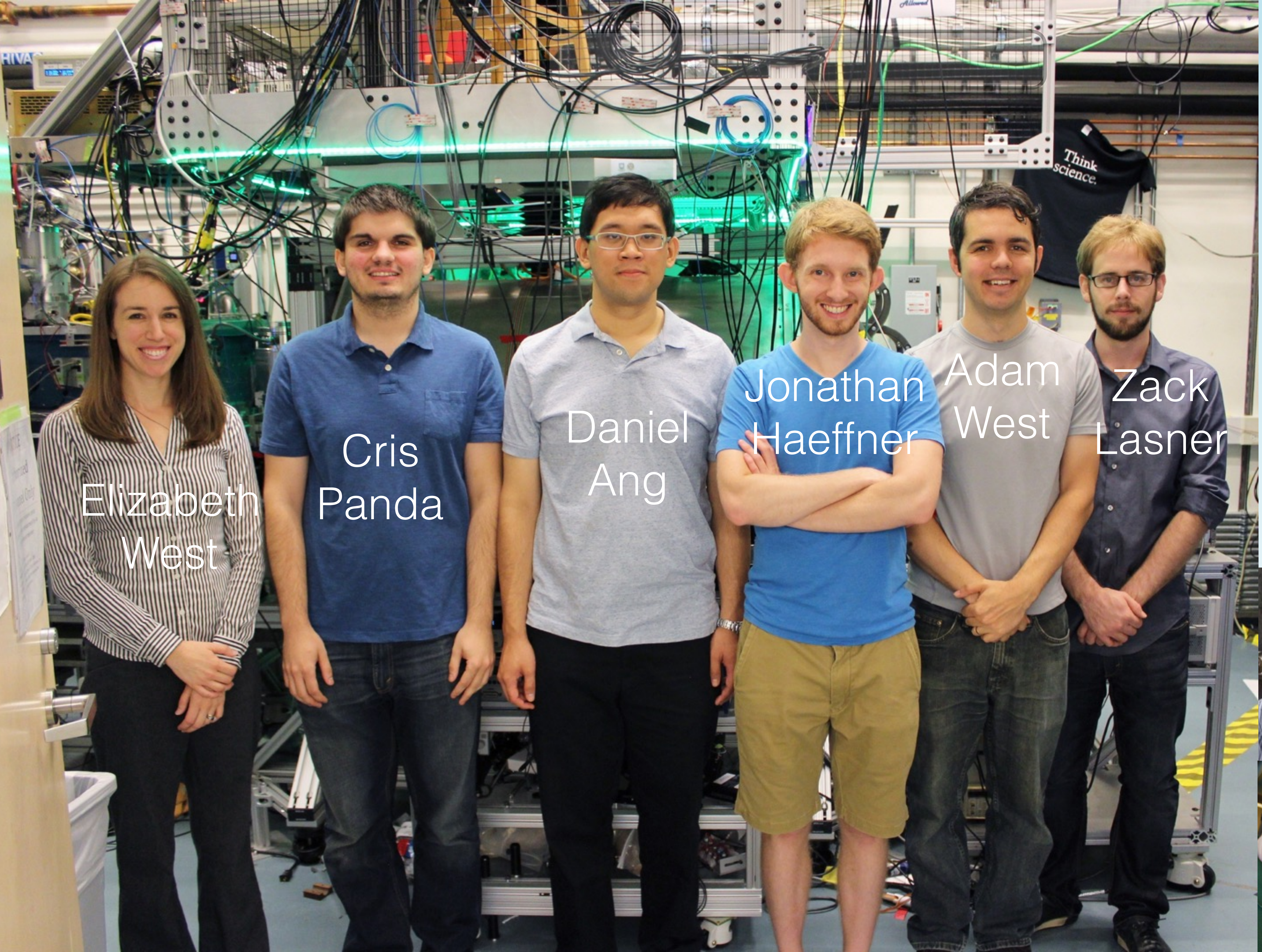
Nick
Hutzler



Dave
DeMille

Gerald
Gabrielse

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