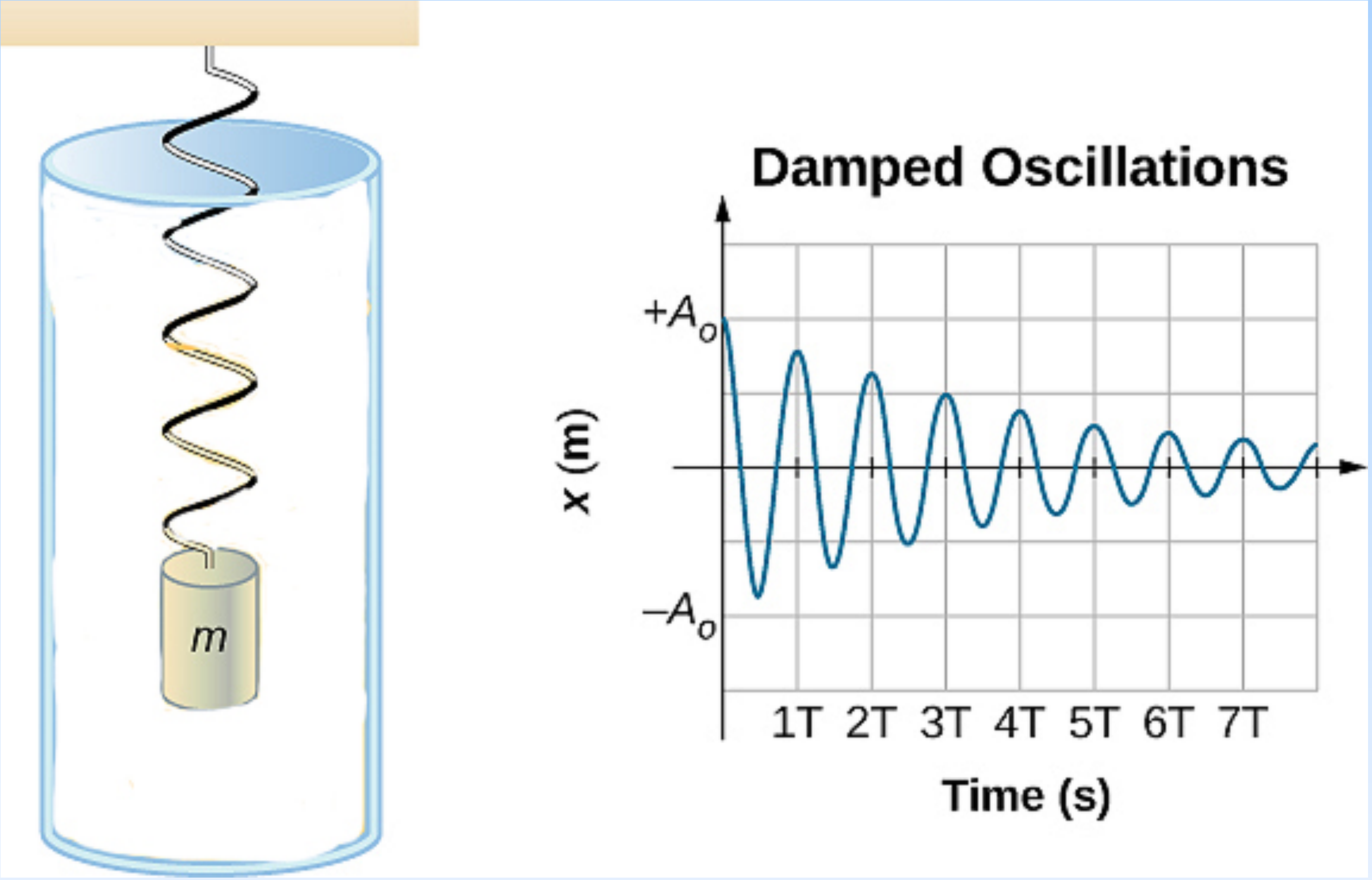
"Quantum Sensing for Particle Physics"

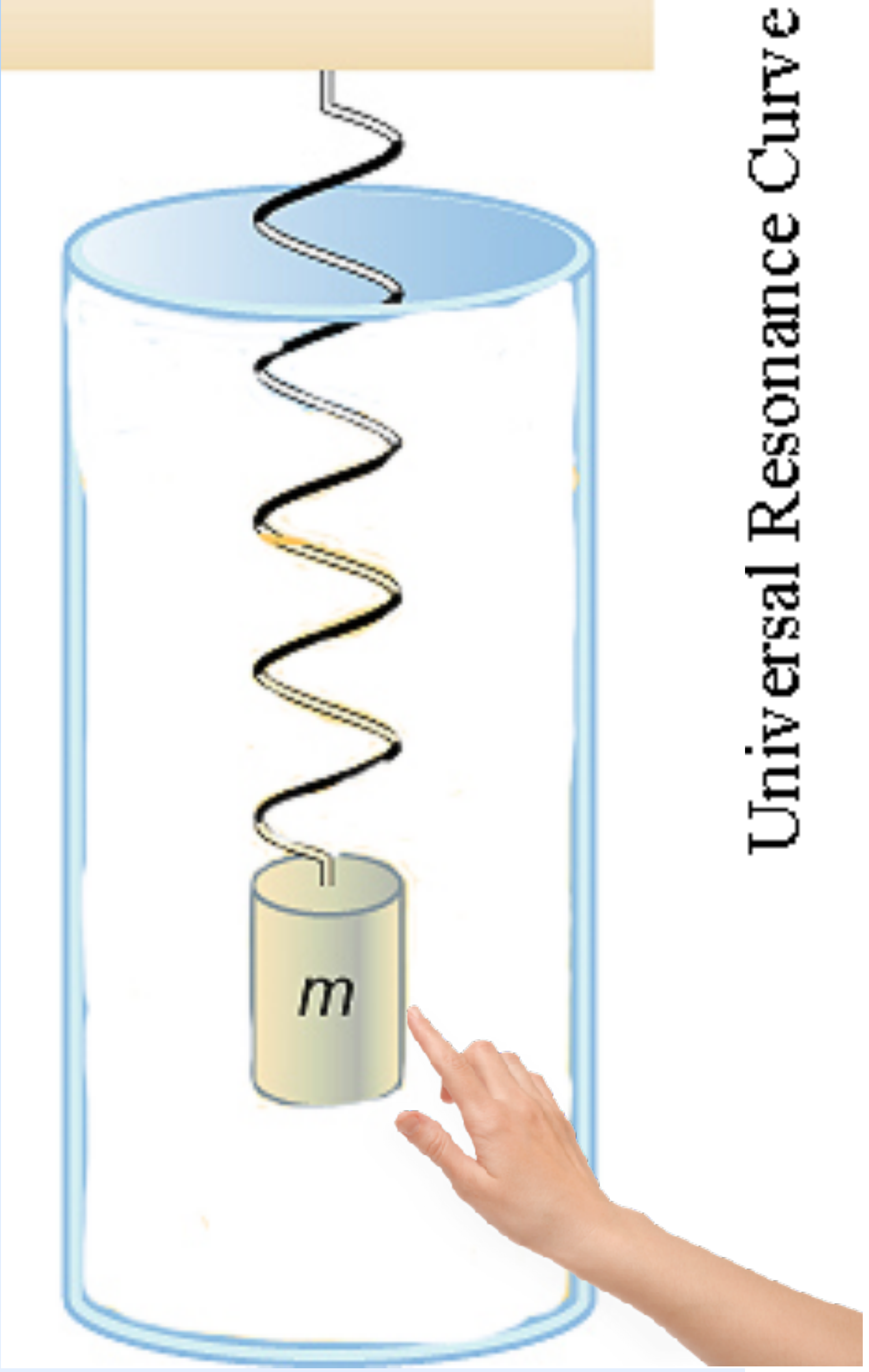
Some Basic Theory - Some Basic Experiment - Overview - Example

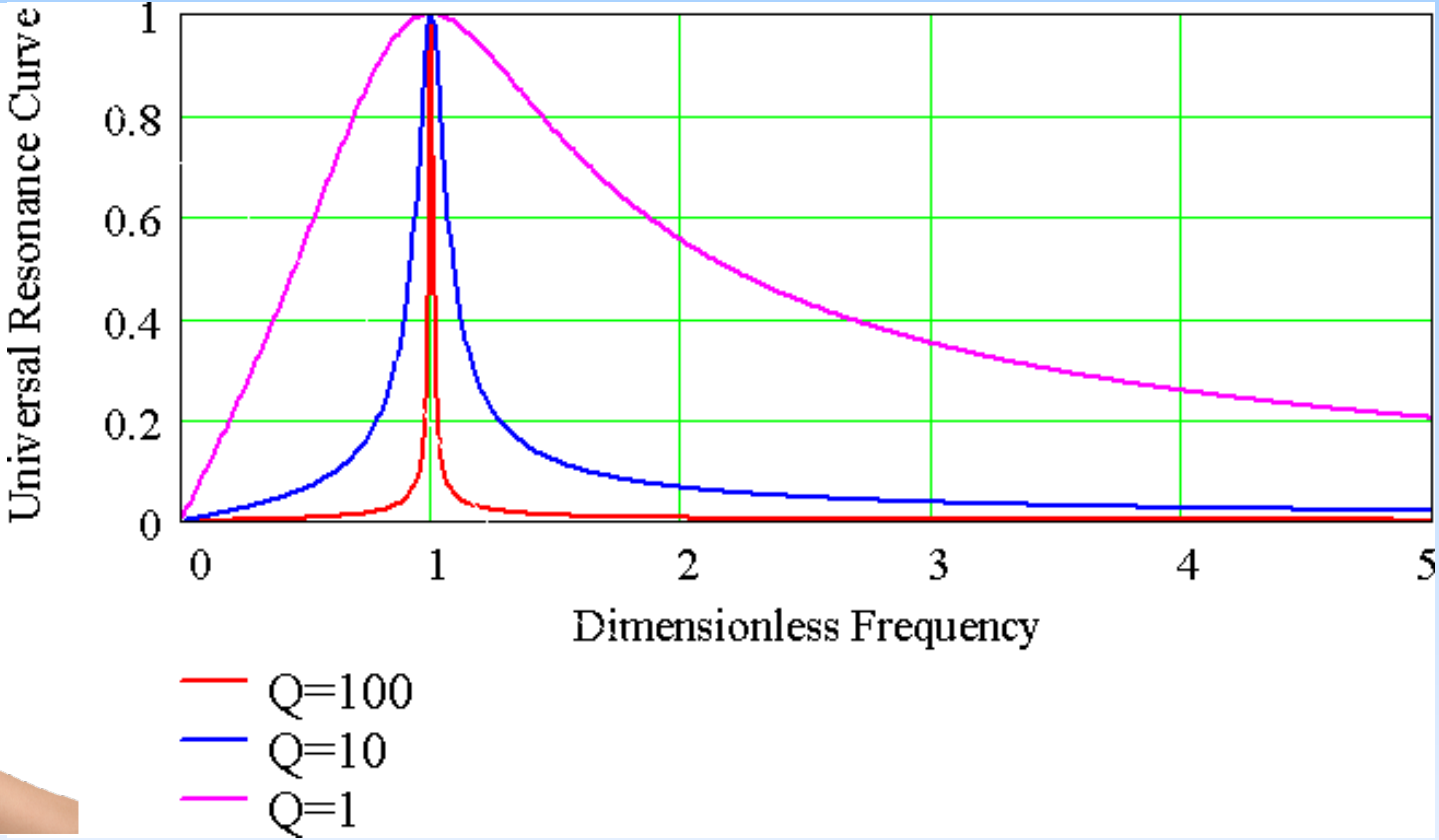
John Doyle
Harvard University

Resonance

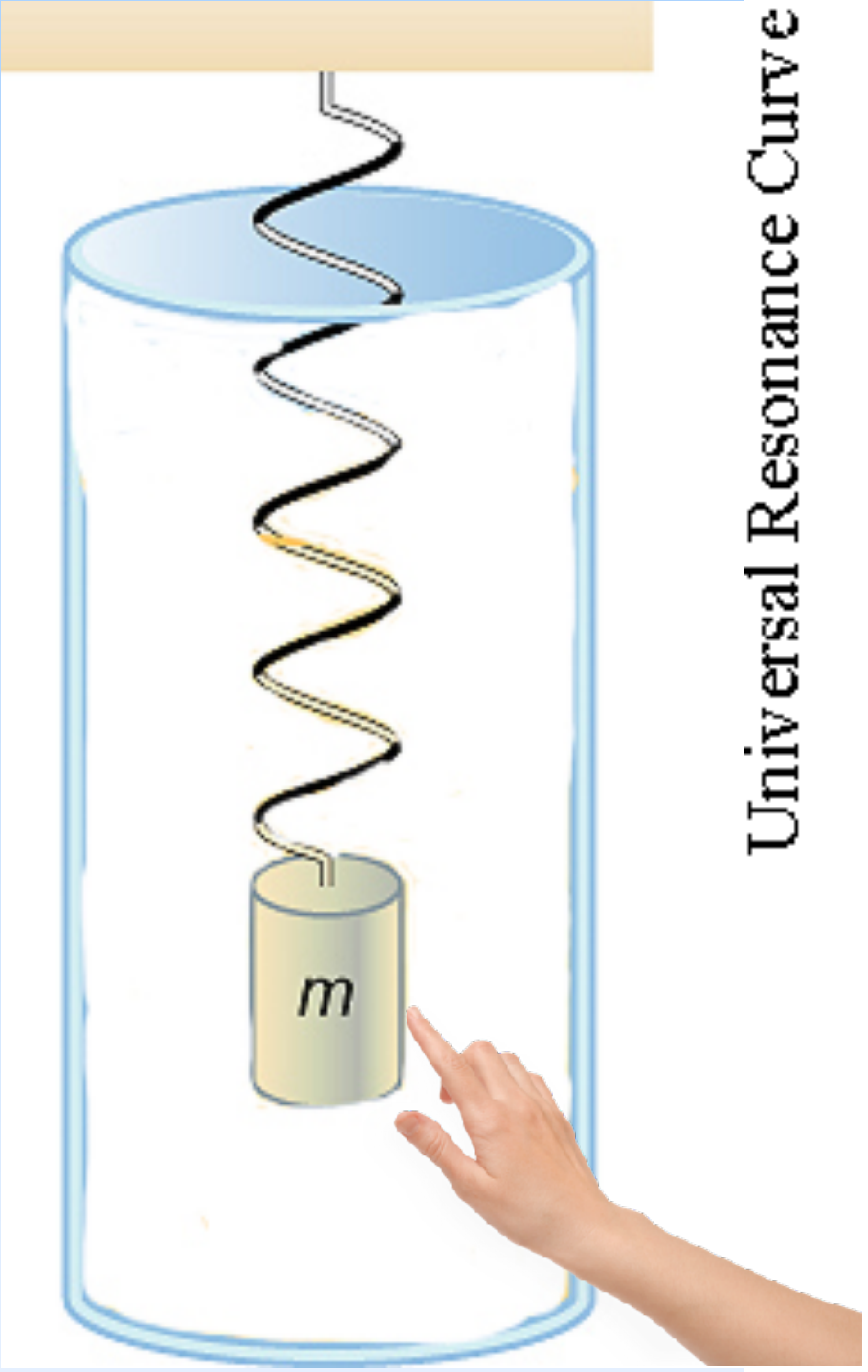


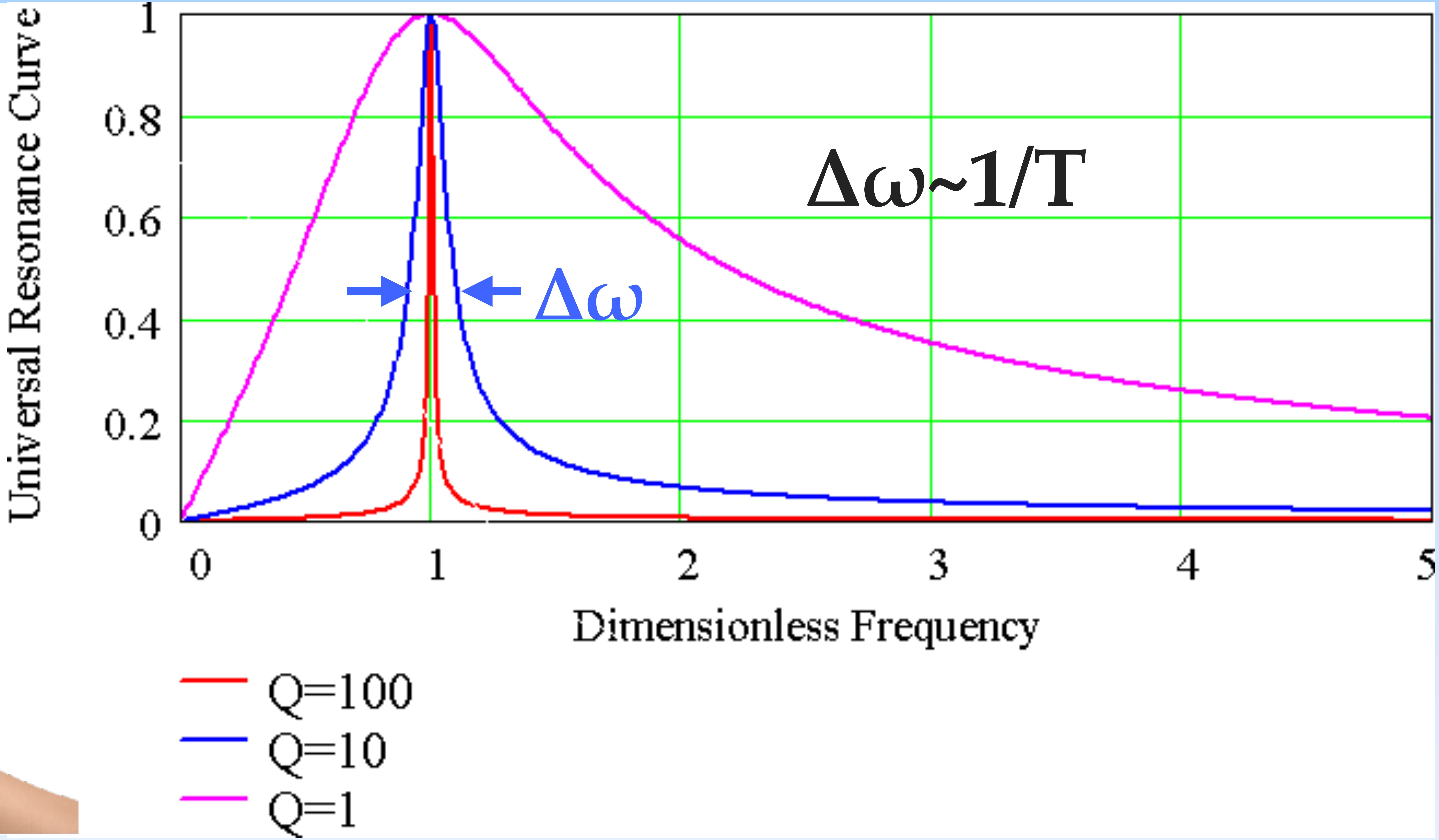
Resonance


m

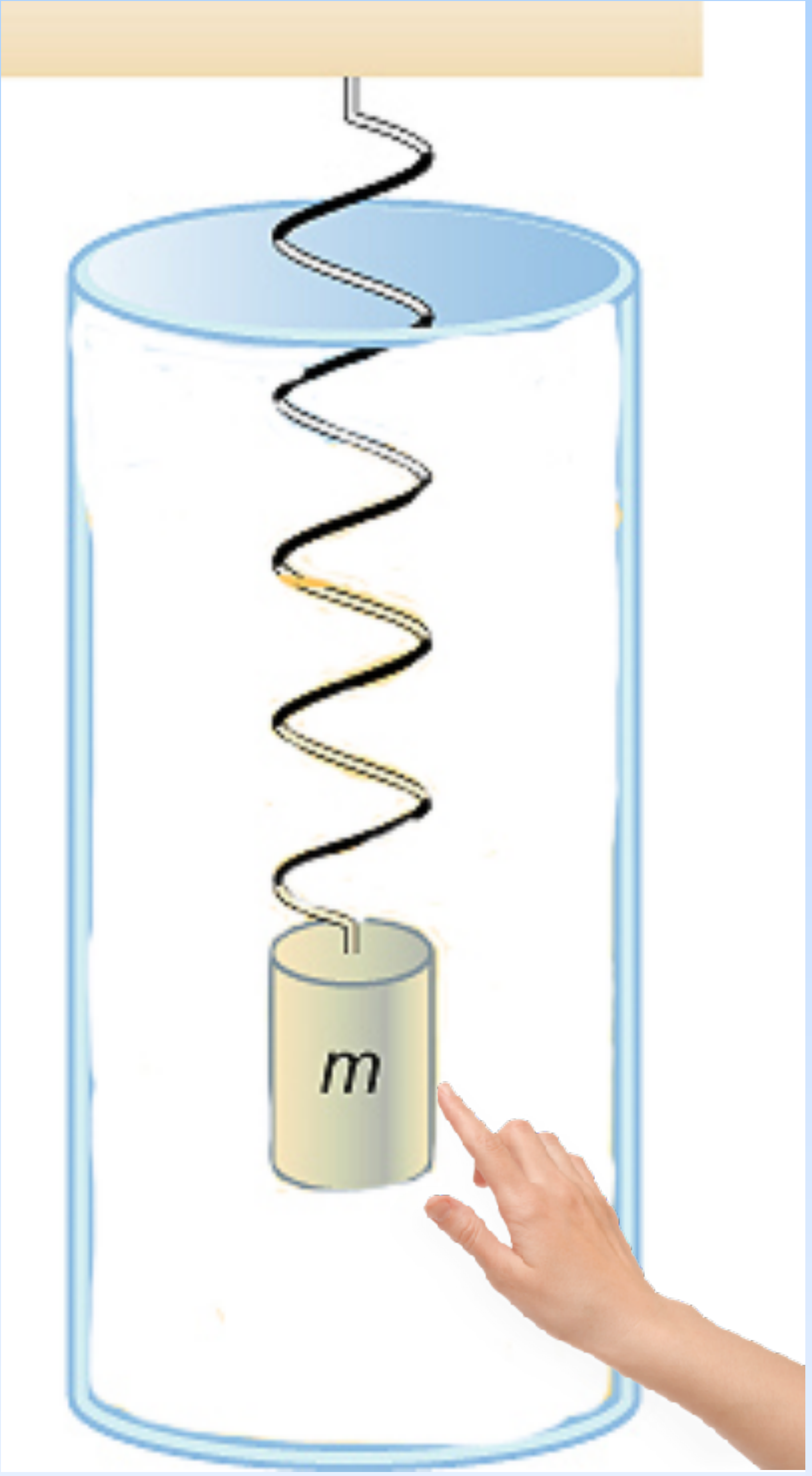

Universal Resonance Curve
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
Dimensionless Frequency
Q=100
Q=10
Q=1

It takes time…

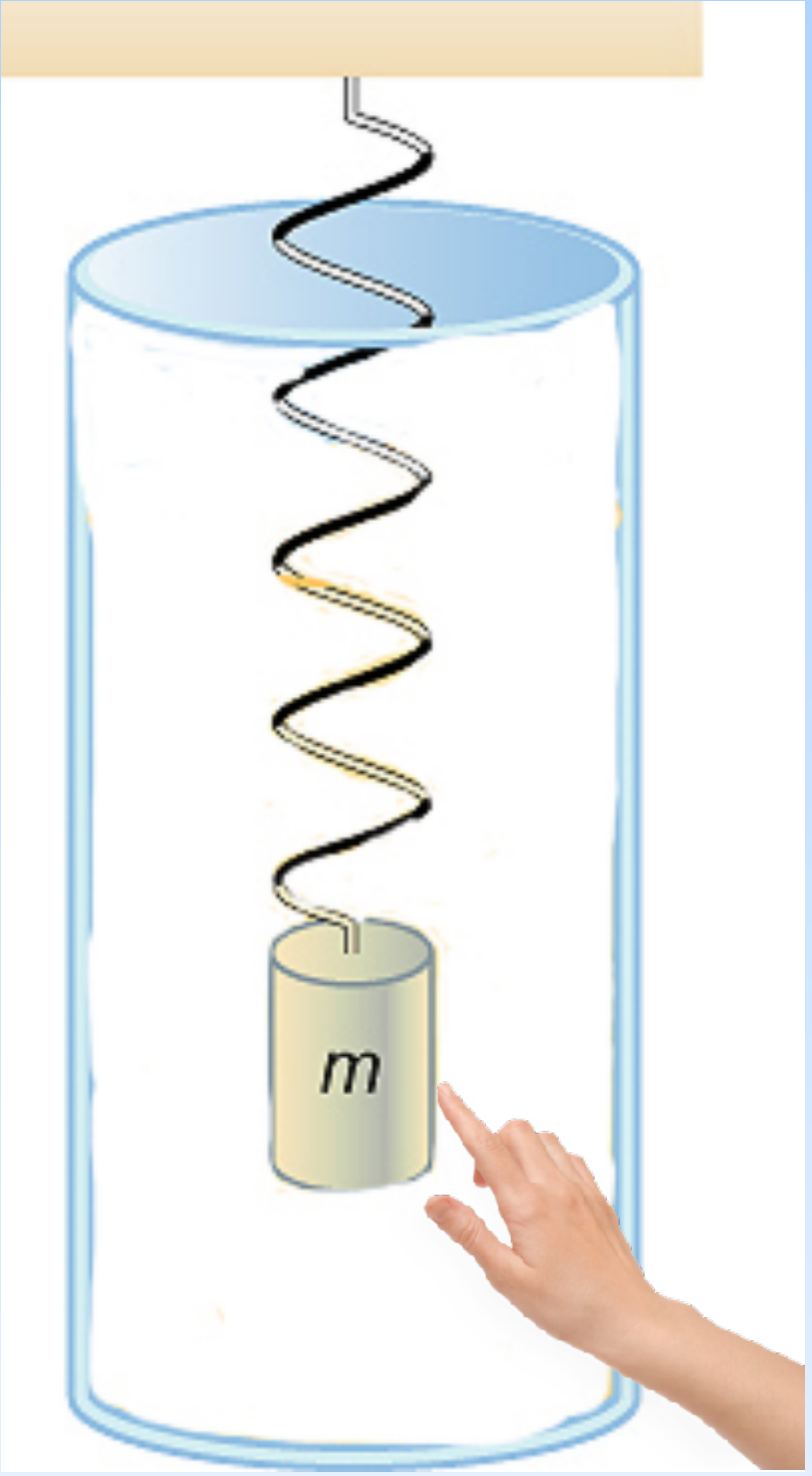




Make a Clock

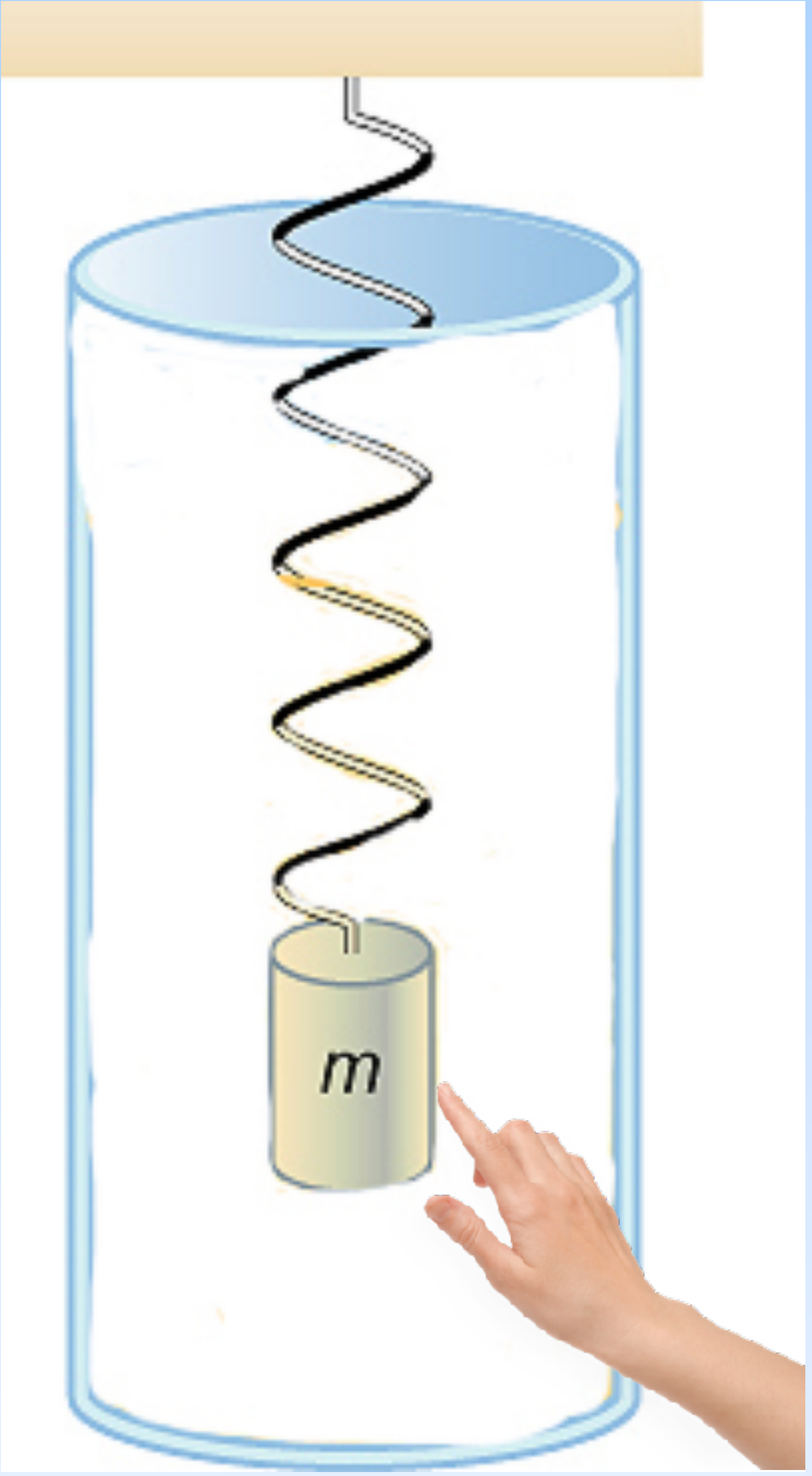


Make a Clock



Why?

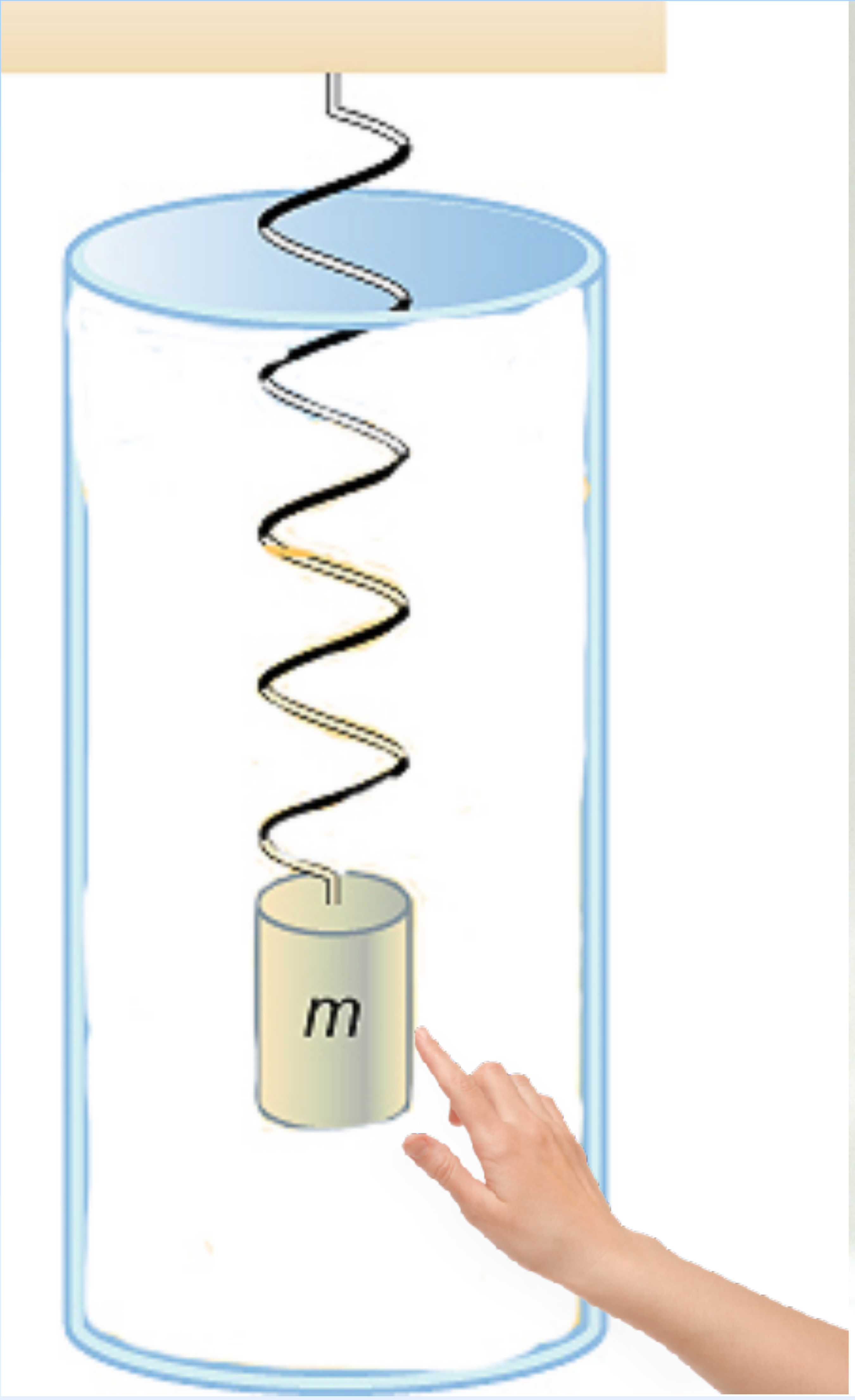
Make a Clock



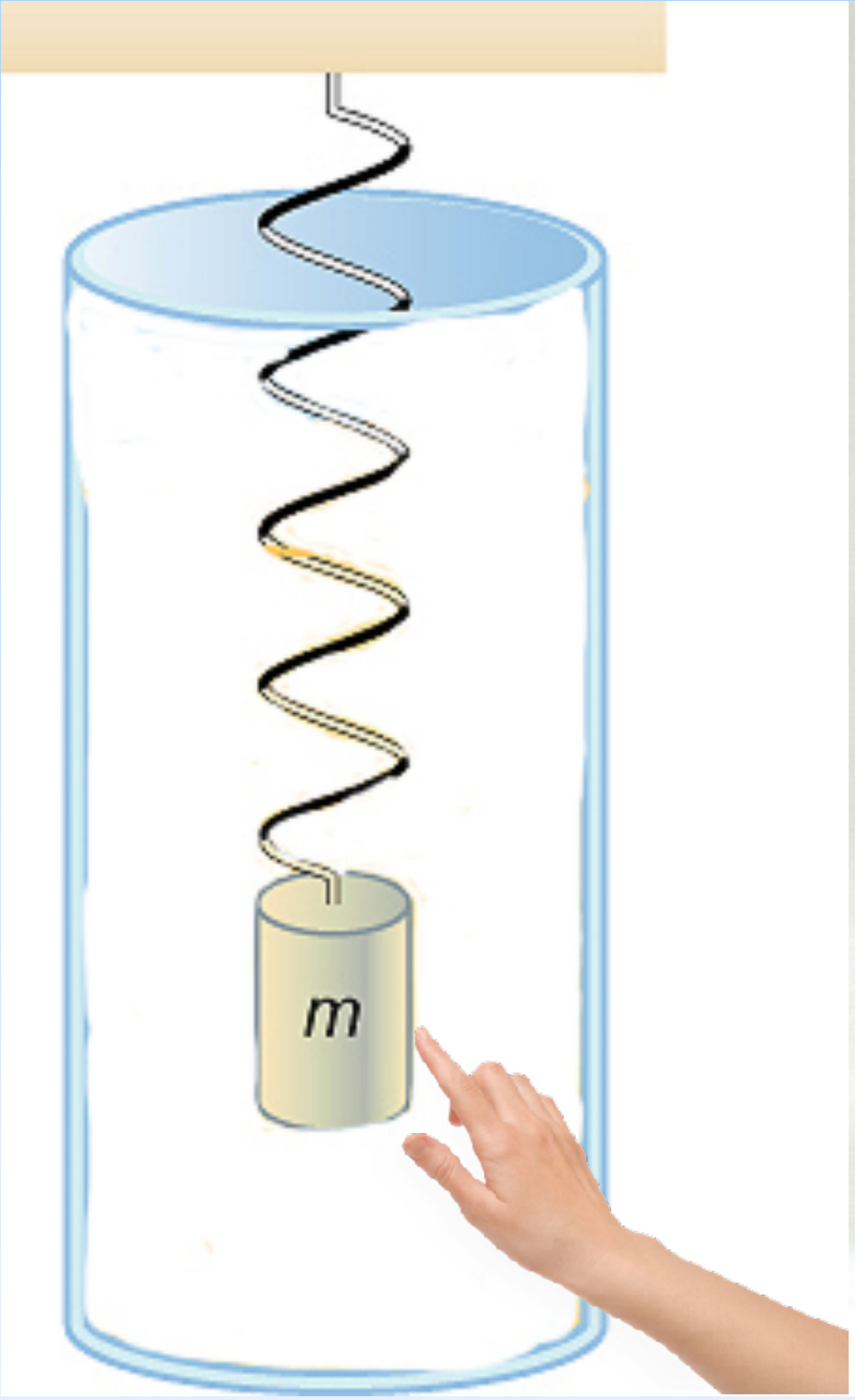
Why?

- Need to measure frequencies
- Clock rates can depend on certain physics

Make a Clock



Make a Clock

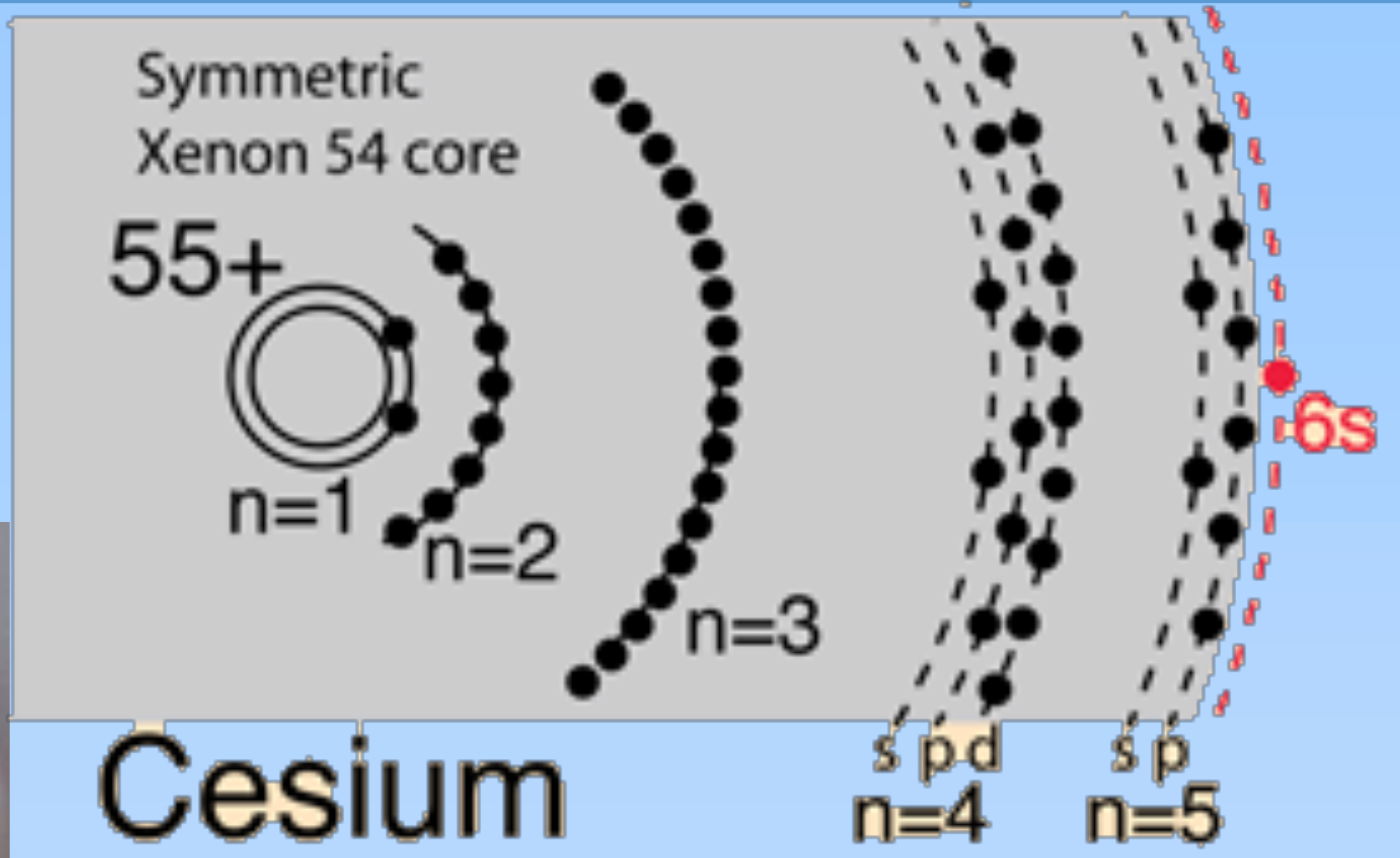

m

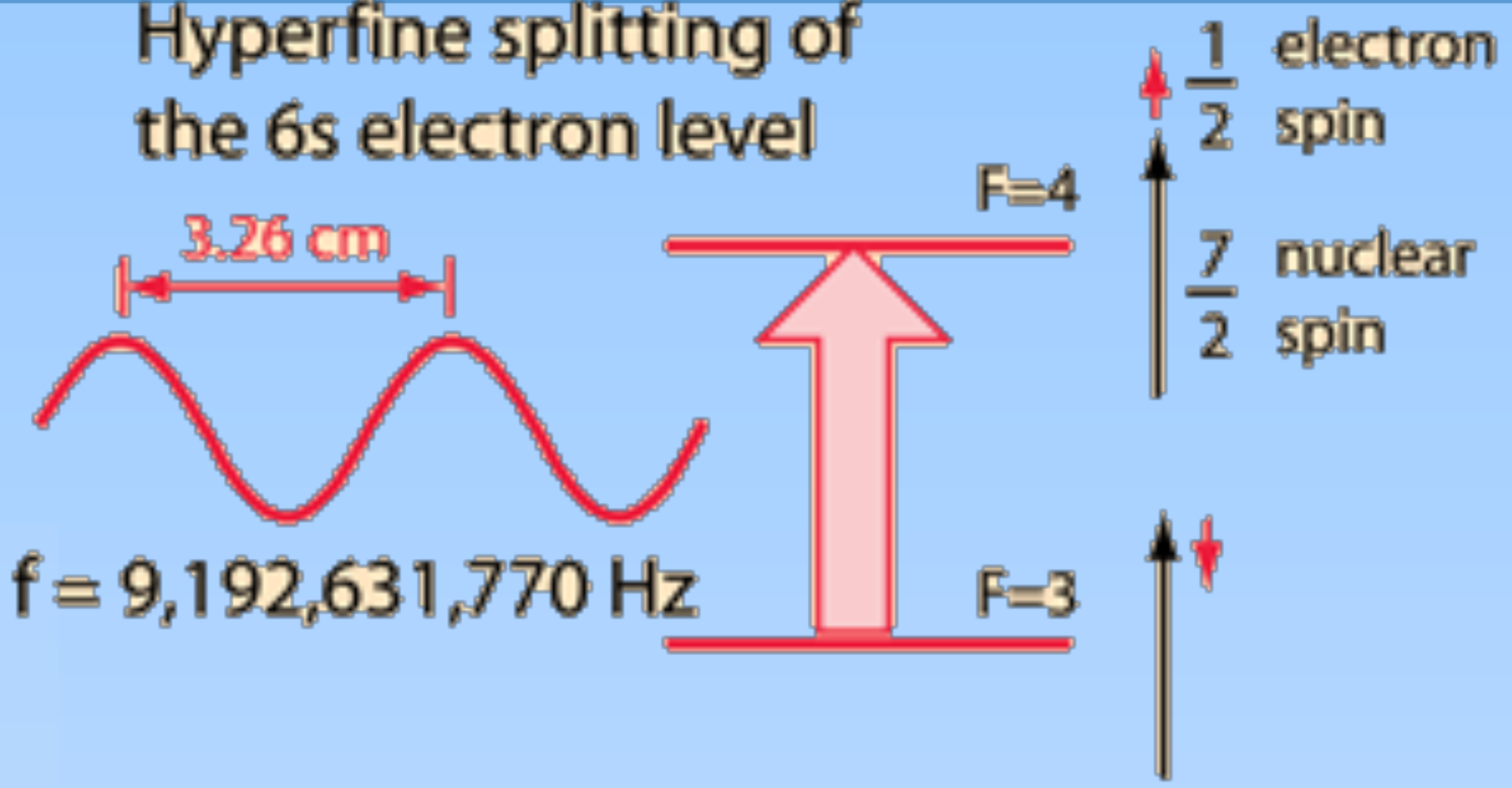

E.PORCELLOTTI
ANNO 1877
FIRENZE


29GA
BELL SYSTEM
STANDARD
1950

Make a Clock

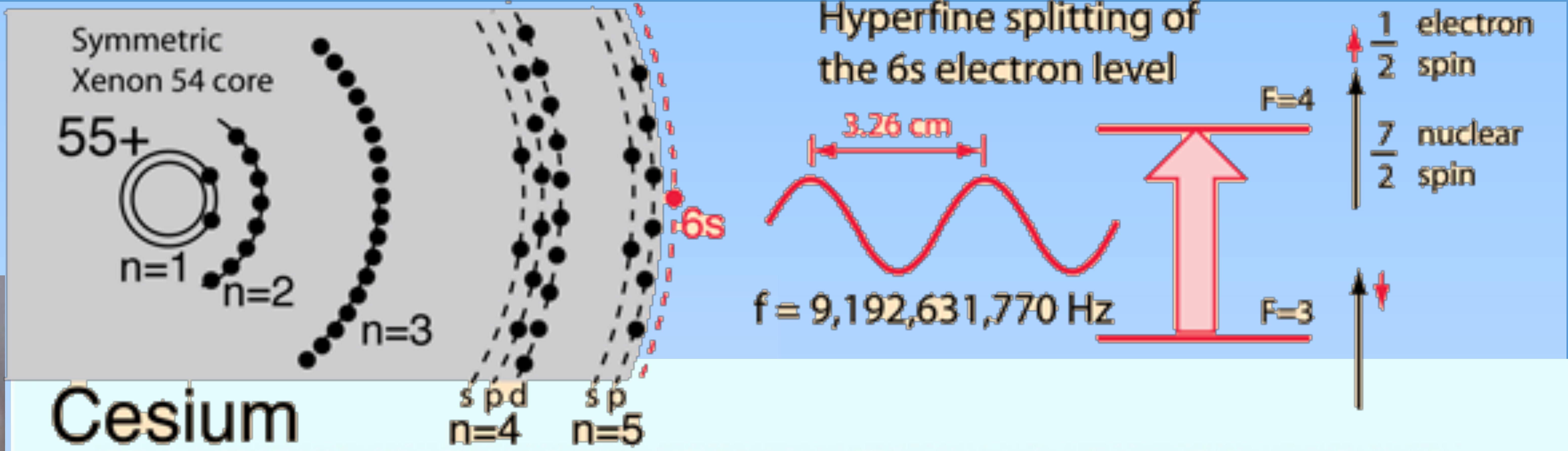

29GA
BELL SYS
STANDA
1950


Symmetric
Xenon 54 core
55+
n=1
n=2
n=3
s p d
n=4
s p
n=5
6s
Cesium


Hyperfine splitting of
the 6s electron level
3.26 cm
f = 9,192,631,770 Hz
F=4
F=3
1/2 electron spin
7/2 nuclear spin

Make a Clock

E.PORCELL
FIREN
29GA
BELL SYS
STANDA
1950



Symmetric
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Hyperfine splitting of
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3.26 cm
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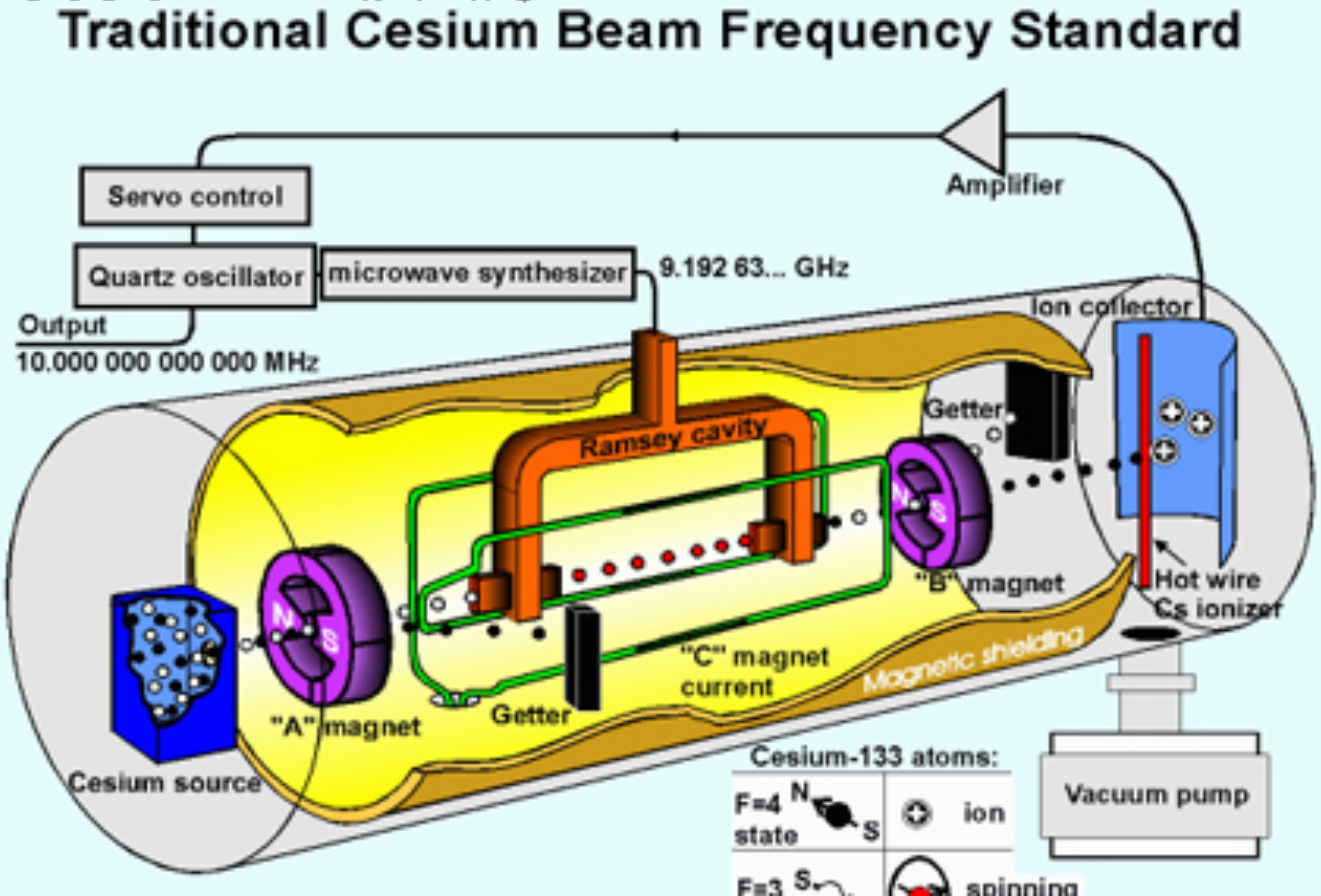
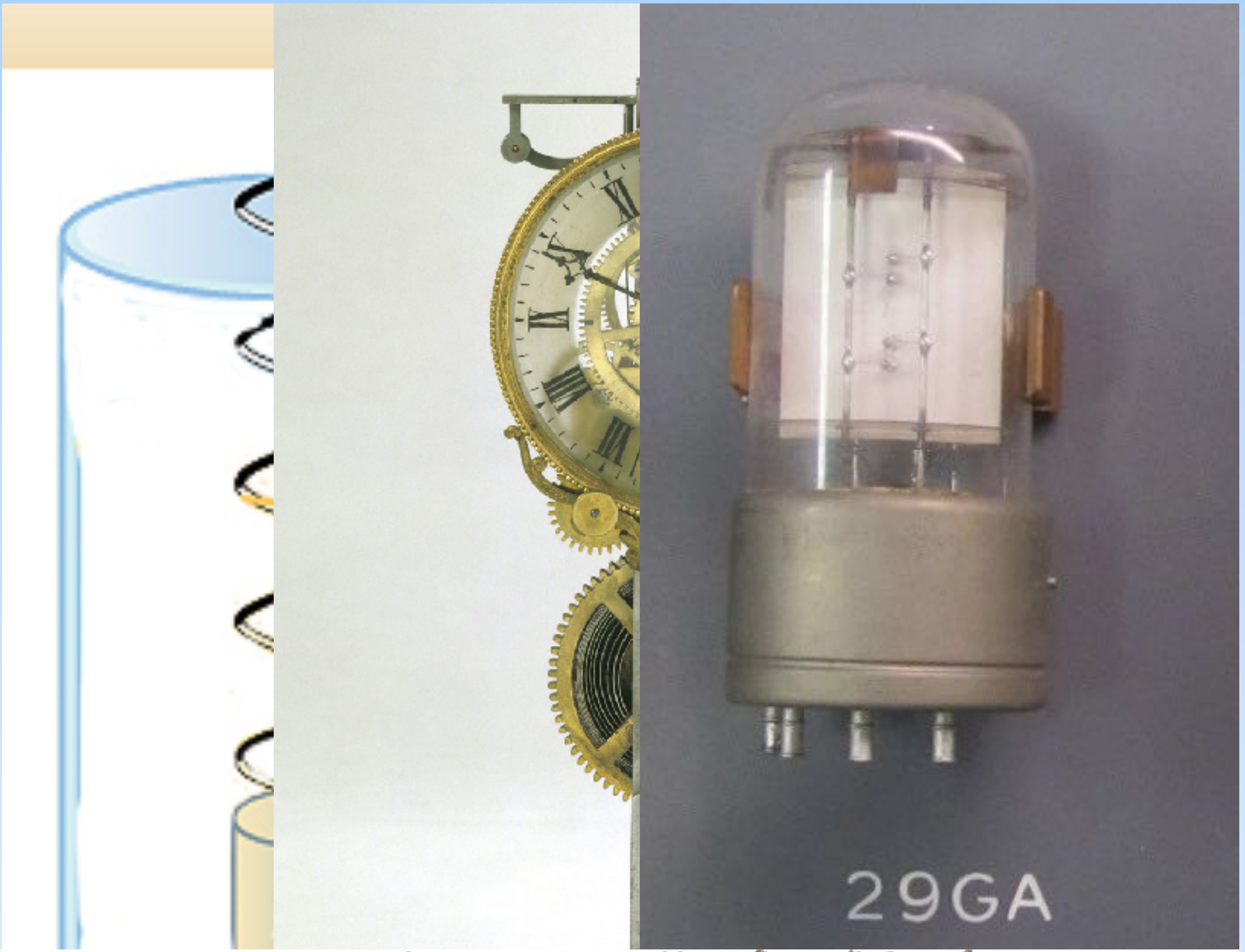
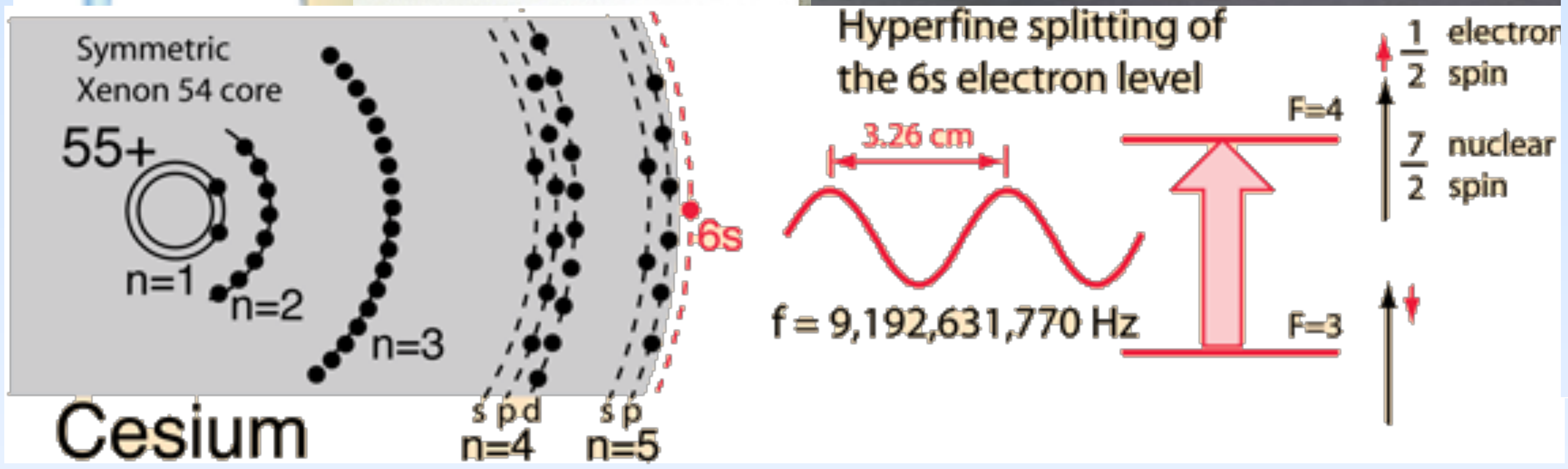
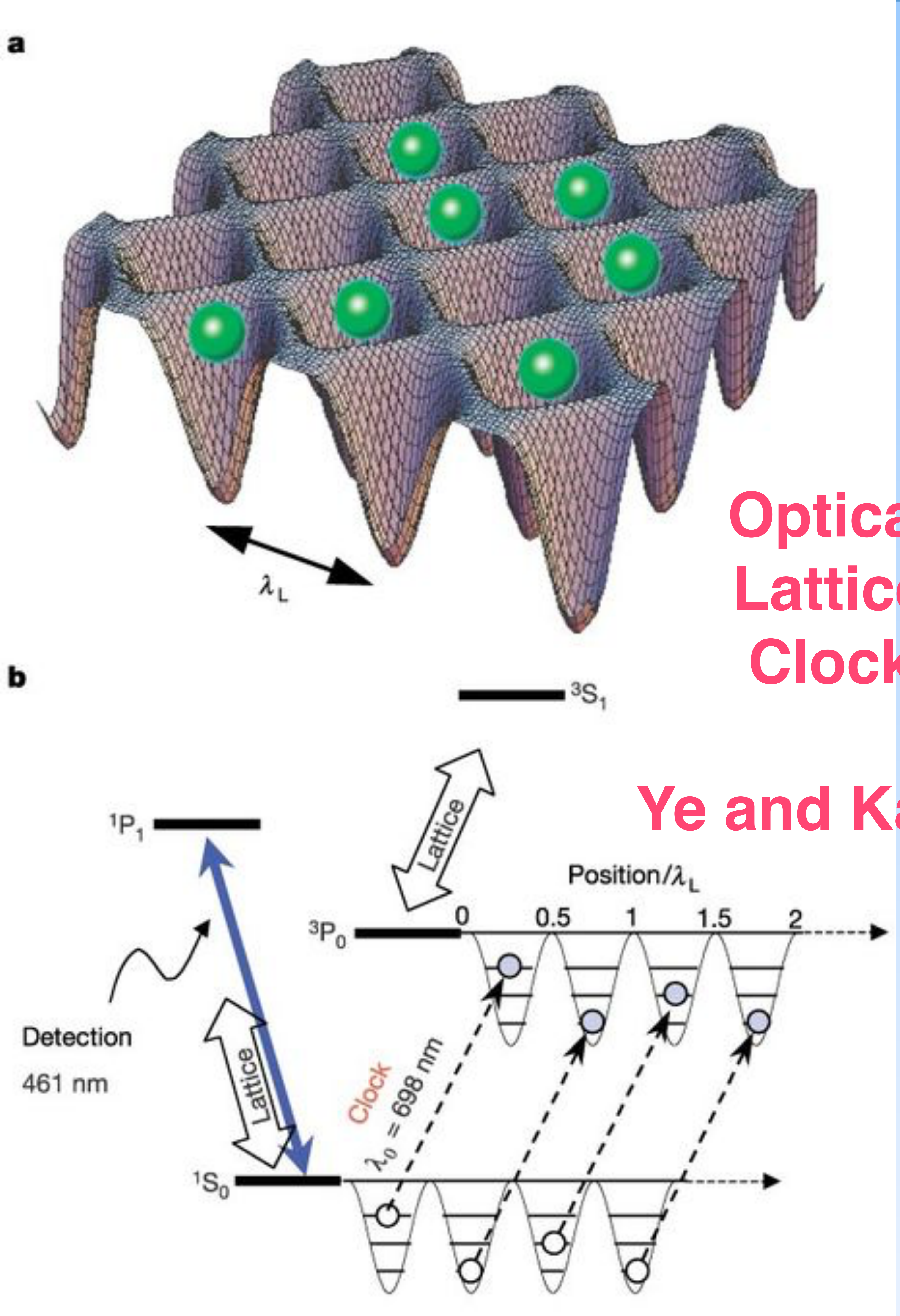


Traditional Cesium Beam Frequency Standard
Servo control
Amplifier
Quartz oscillator
microwave synthesizer
9.192 63... GHz
Output
10.000 000 000 000 MHz
Ion collector
Getter
Ramsey cavity
"B" magnet
Hot wire
Cs ionizer
"C" magnet
current
Magnetic shielding
"A" magnet
Getter
Cesium source
Cesium-133 atoms:
F=4 state
ion
Vacuum pump

Make a Clock



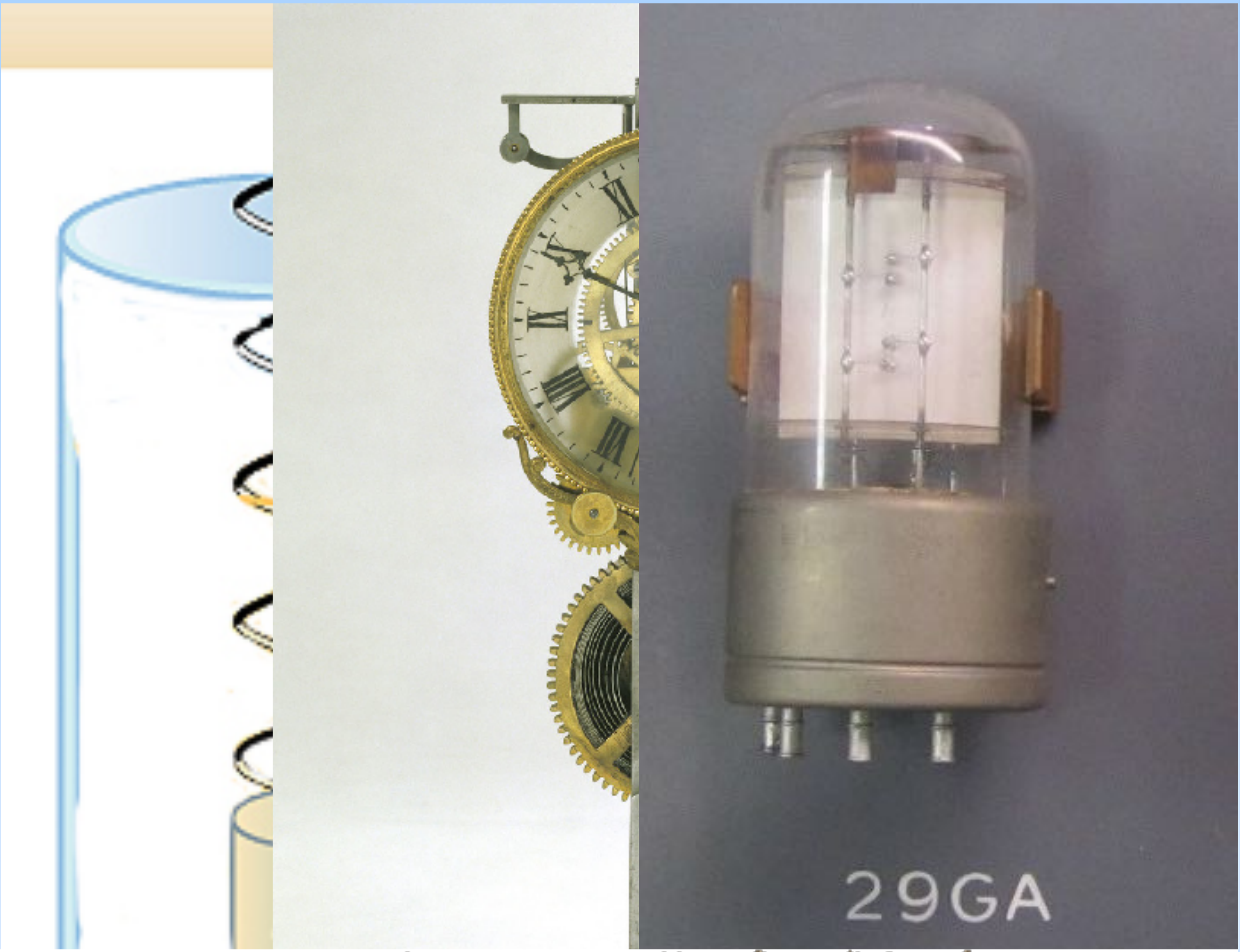


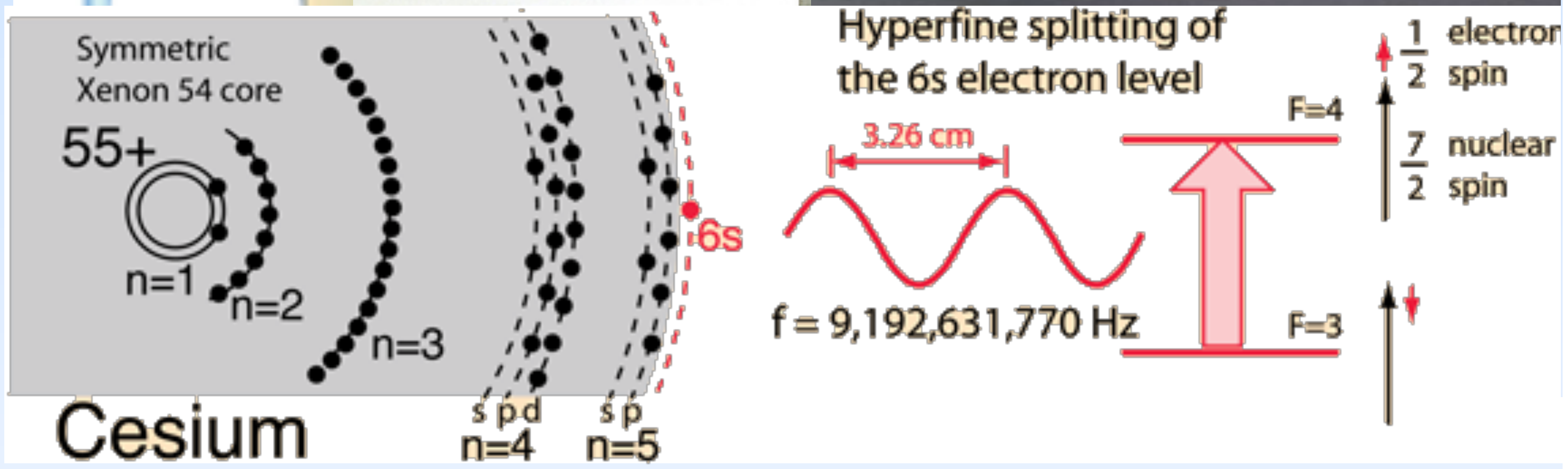


Optical Lattice Clock

Ye and Katori

Make a Clock


29GA


Symmetric
Xenon 54 core
55+
n=1
n=2
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s p d
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6s
Cesium
Hyperfine splitting of
the 6s electron level
3.26 cm
f = 9,192,631,770 Hz
F=4
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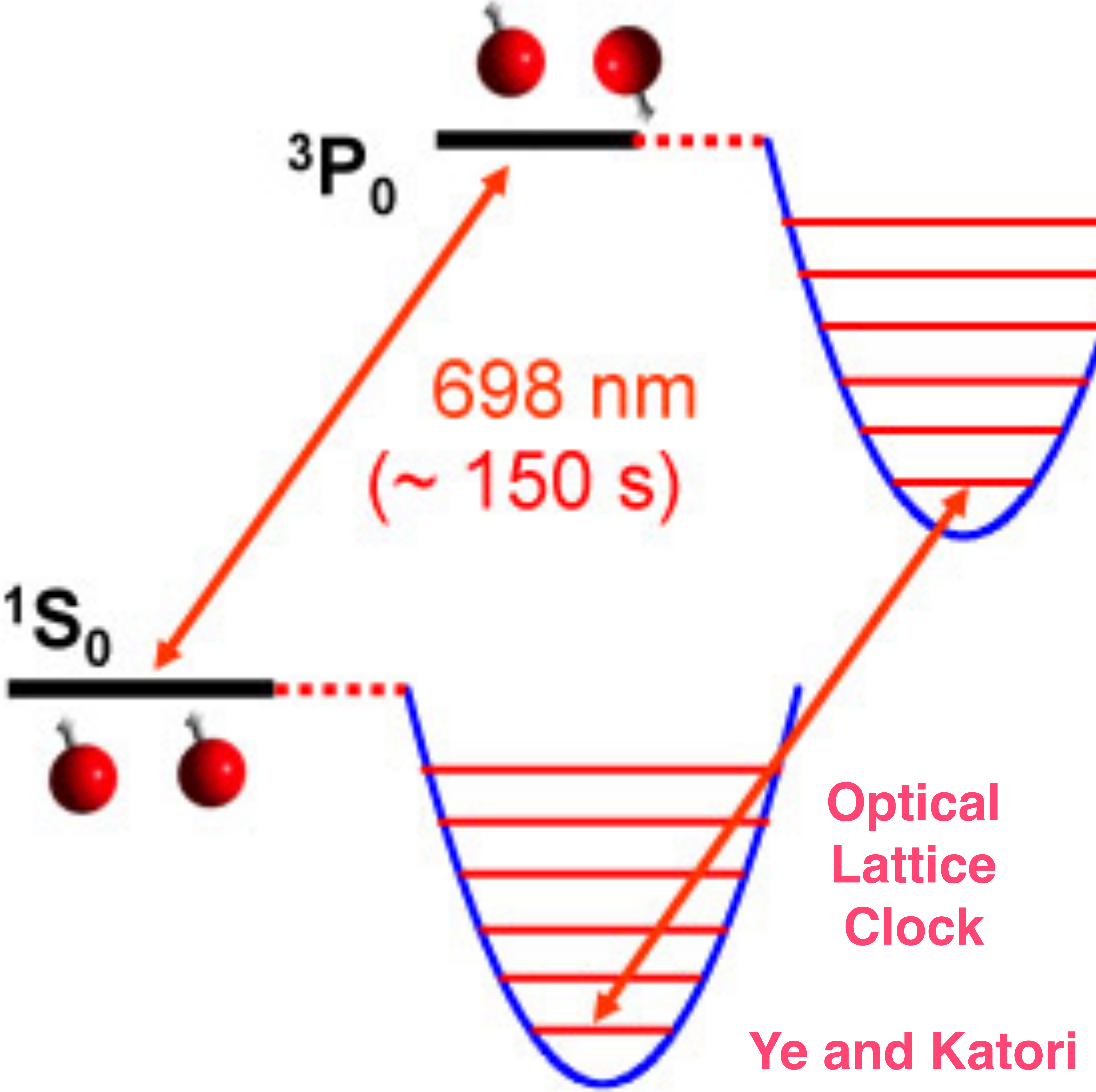
1/2 electron spin
7/2 nuclear spin


$^3P_0$
698 nm
(~ 150 s)
$^1S_0$
Optical
Lattice
Clock
Ye and Katori

Resonance

Resonance

Noise
m
0.4
0.2
0
0
1
2
3
4
5
Dimensionless Frequency
Q=100
Q=10
Q=1
Noisy Resonance Line

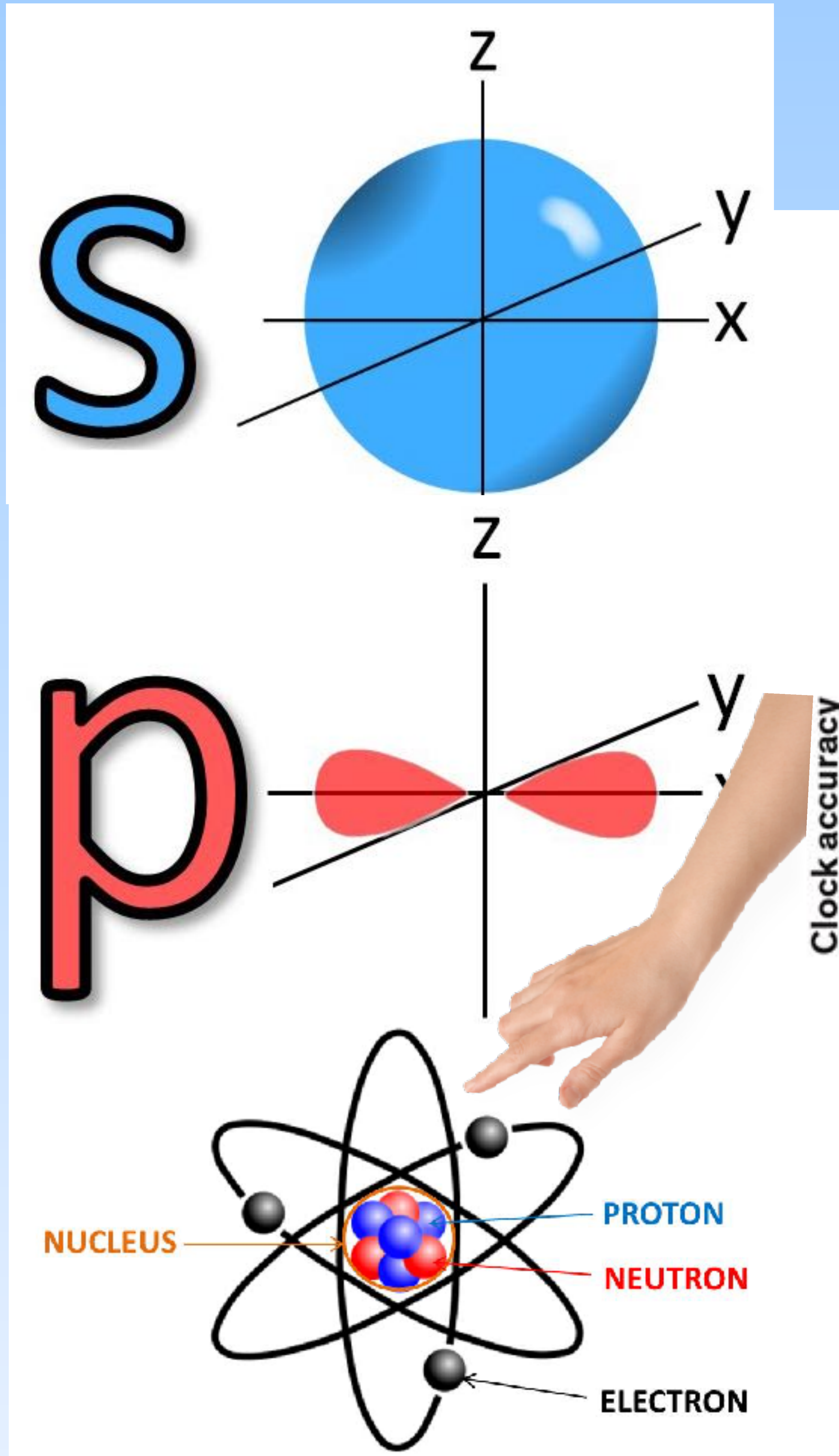
Resonance Reality

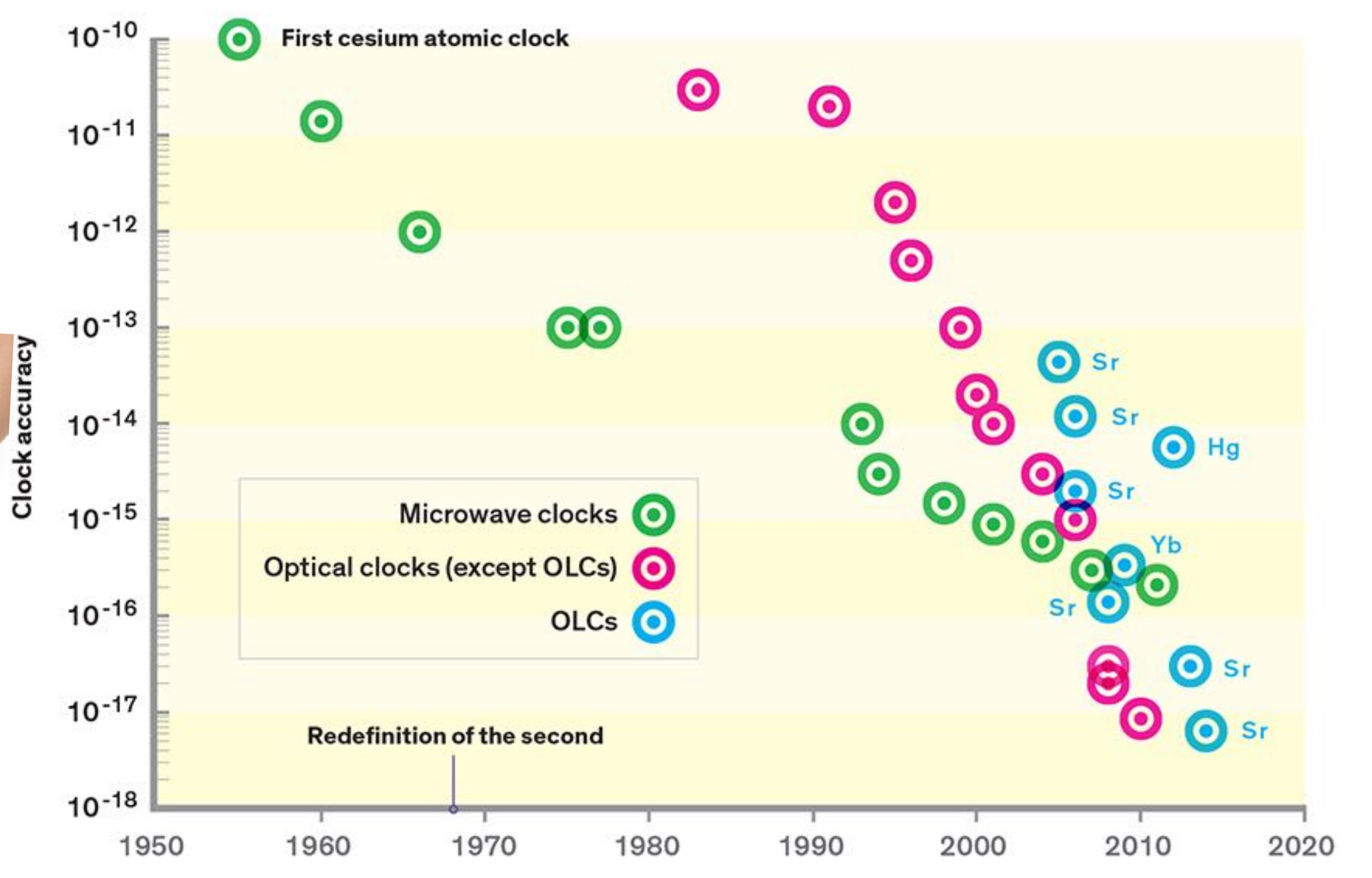
In "Real Life" Line Splitting can be done to ~ 10^6 Level

Heckel, UWash, Nuclear EDM Expt 3×10^7

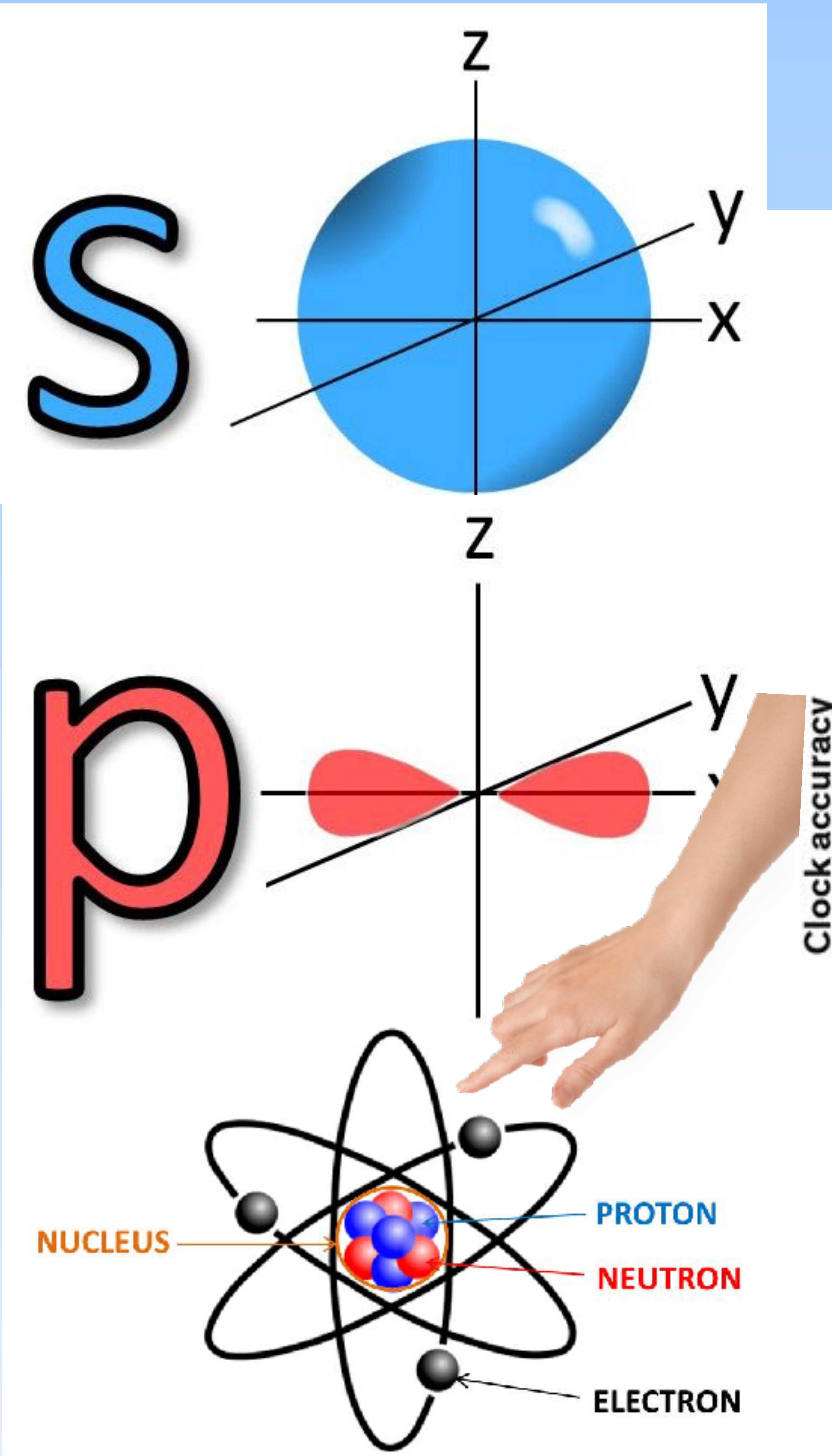
Cesium Beam Clocks 10^6

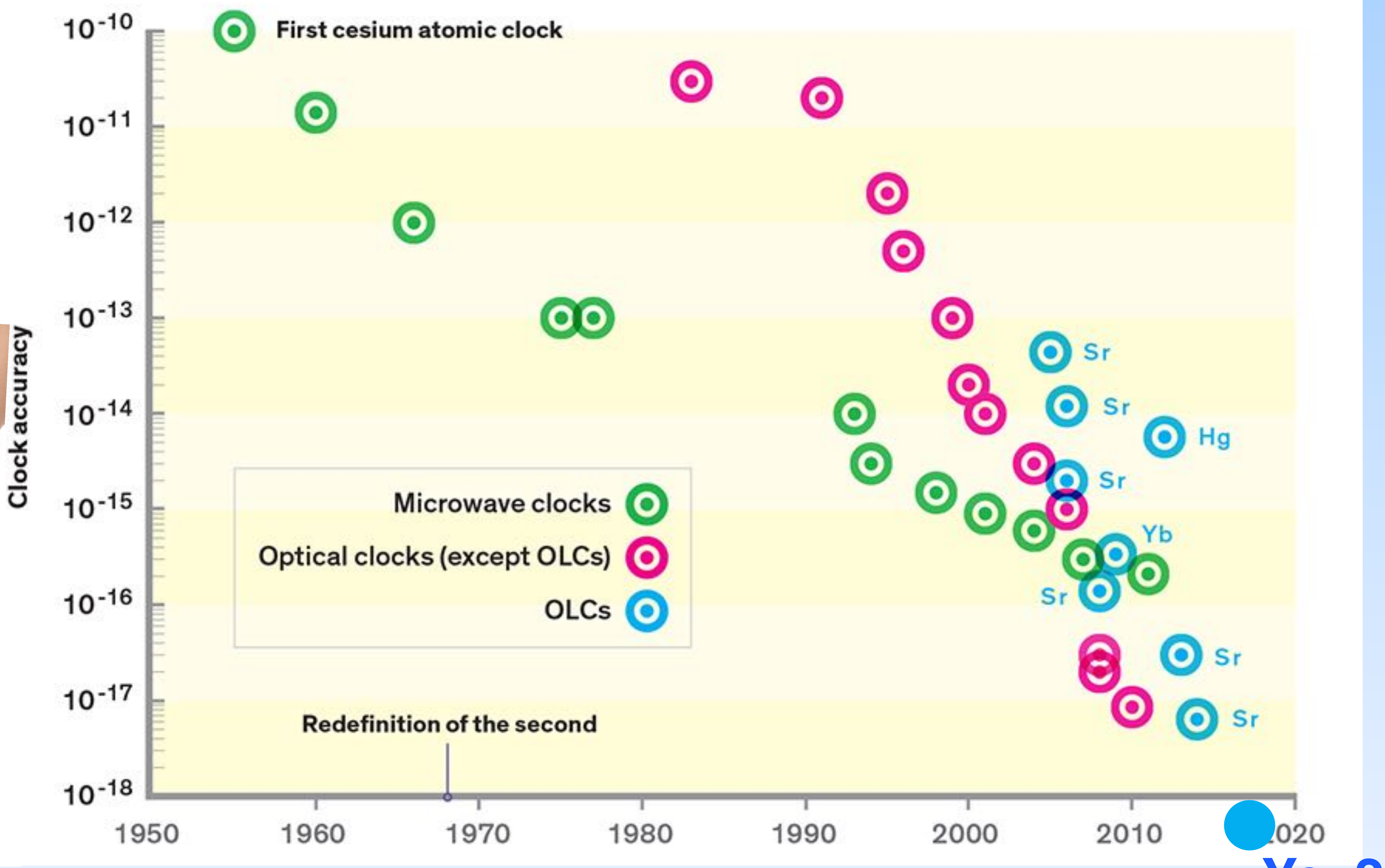
Atomic Clock History





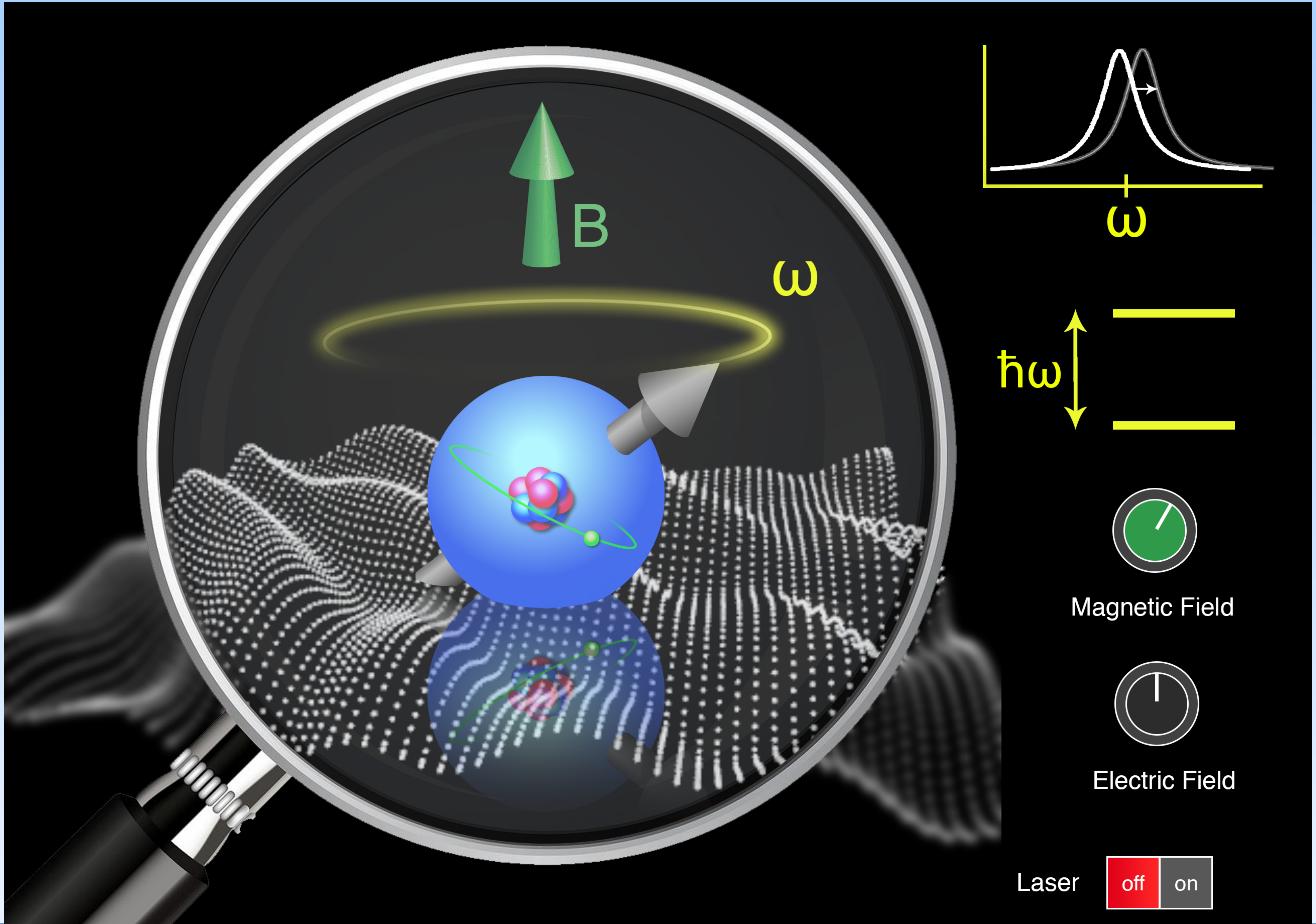
Atomic Clock History





Ye, 2017

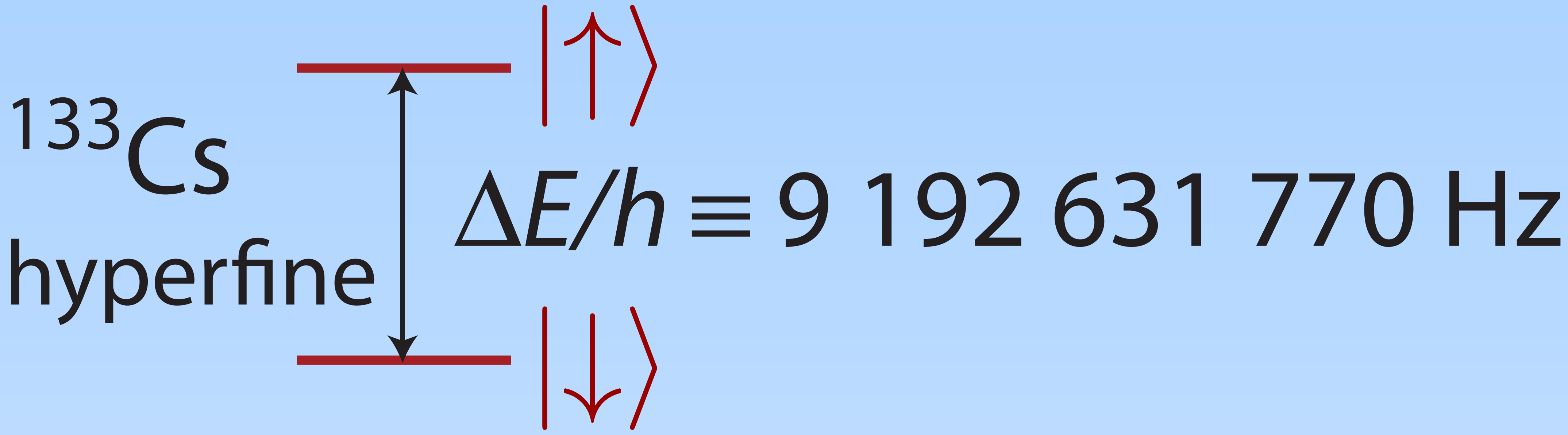
Spin Precession



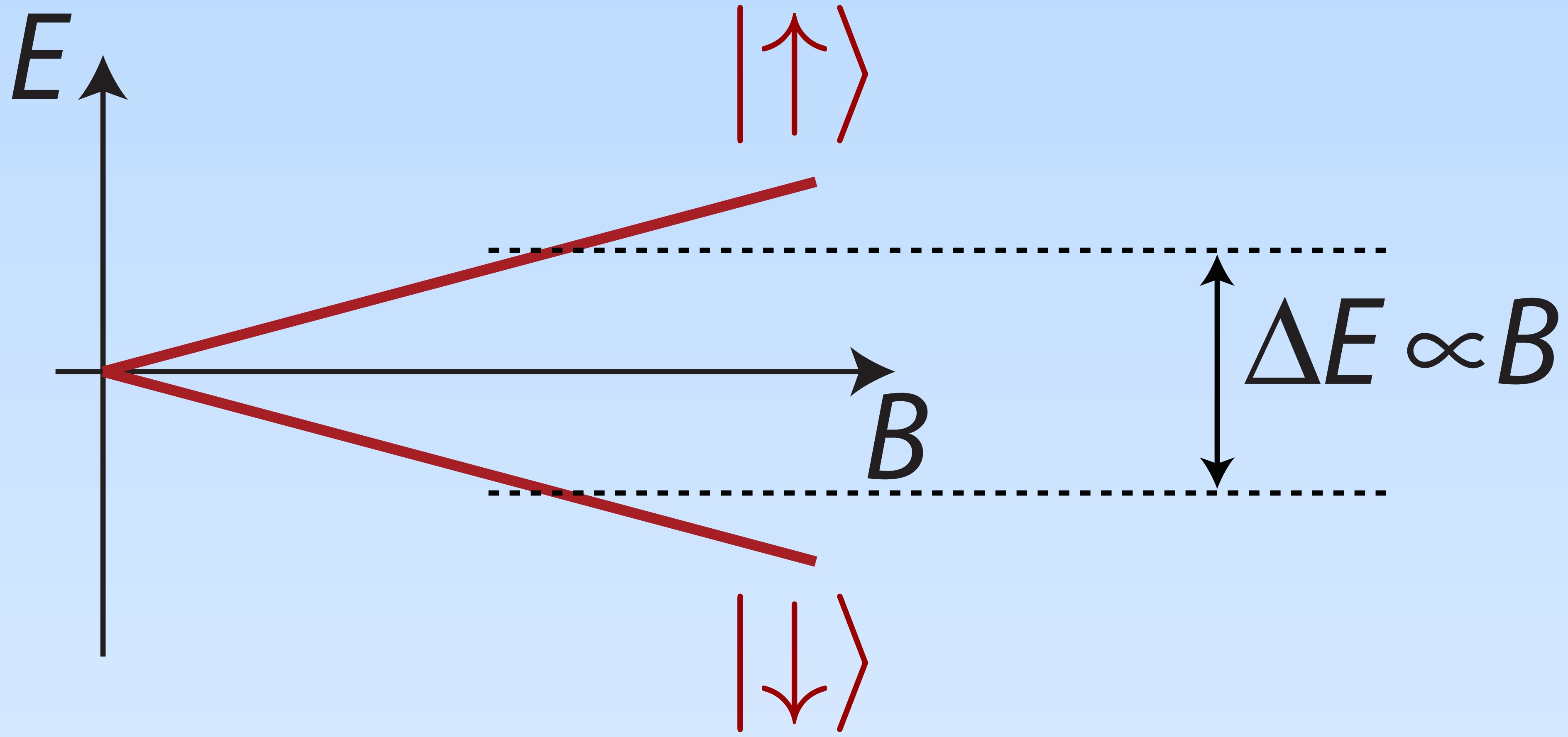
"Spin" Precession

Two level systems —> Spin Systems

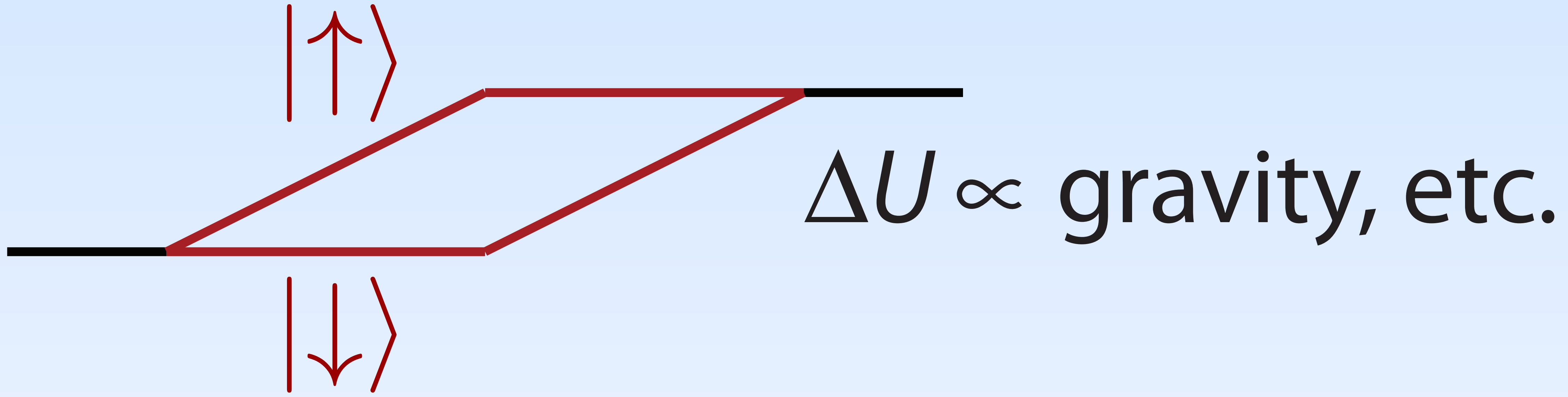
- Atomic clock



- Magnetometer

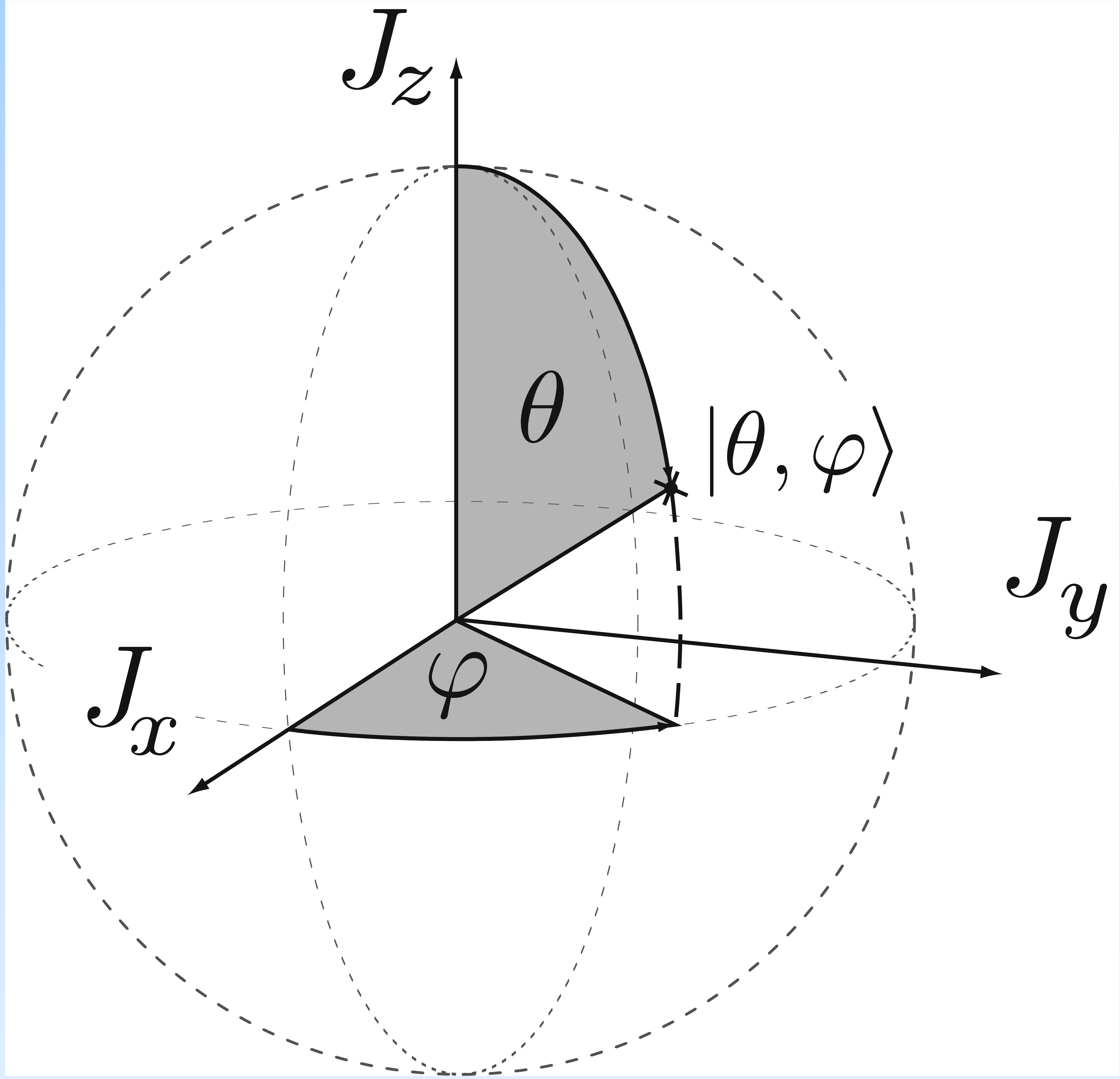


- Interferometer



M. Schleier-Smith

Bloch Sphere

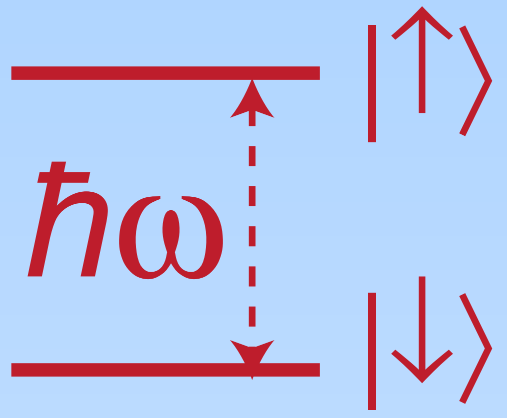


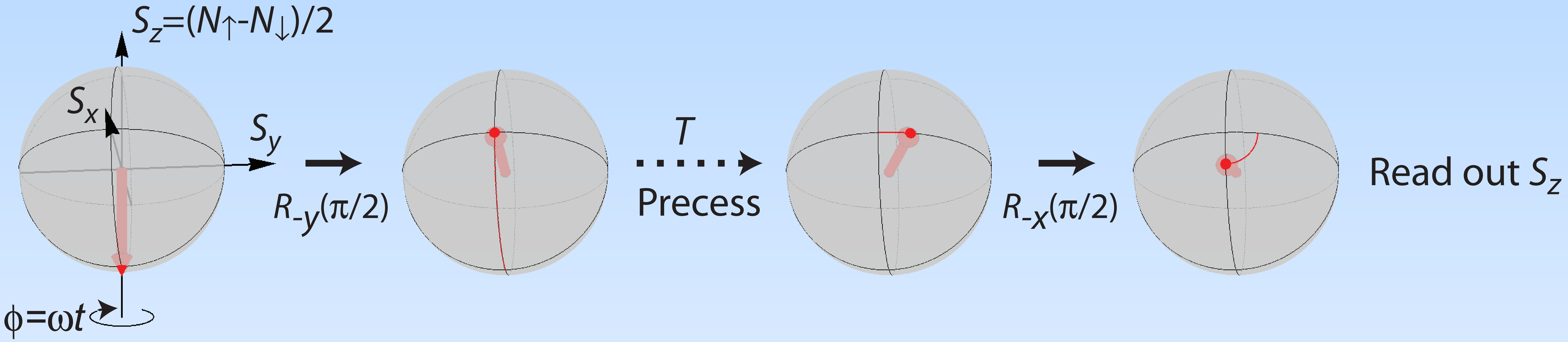
$|\theta, \varphi> = \sin(\theta/2)\ |\uparrow> + \cos(\theta/2)e^{i\varphi}\ |\downarrow>$

We are interested in measuring ϕ

Phase Precession Measurement from Population Measurement

Ramsey spectroscopy with an ensemble of *N* two-level atoms:

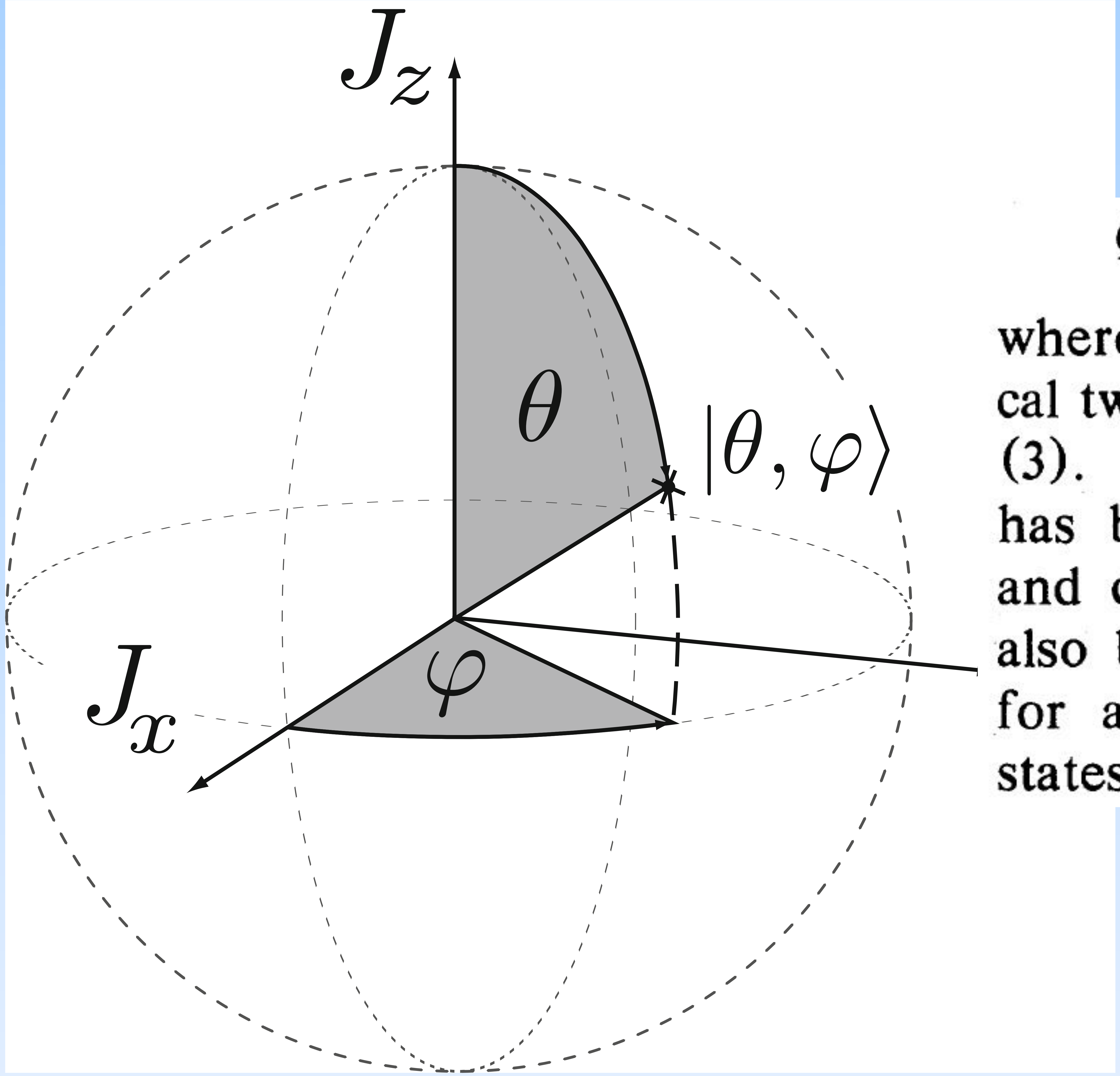




$$S_z \propto N_\uparrow - N_\downarrow$$

M. Schleier-Smith

Q-function



$$Q(\theta, \phi) \equiv [(2r+1)/4\pi] \langle \theta, \phi | \rho | \theta, \phi \rangle$$

where ρ is an arbitrary density matrix for a system of identical two-level atoms; it can be a ρ_D of Eq. (2) or a ρ_B of Eq. (3). Except for the factor $(2r+1)/4\pi$, the same function has been discussed by Gilmore, Bowden, and Narducci,[7] and called the Q function or the Q representation; it has also been used by Lieb[8] to discuss the "classical" entropy for a quantum system described in Bloch coherent spin states.

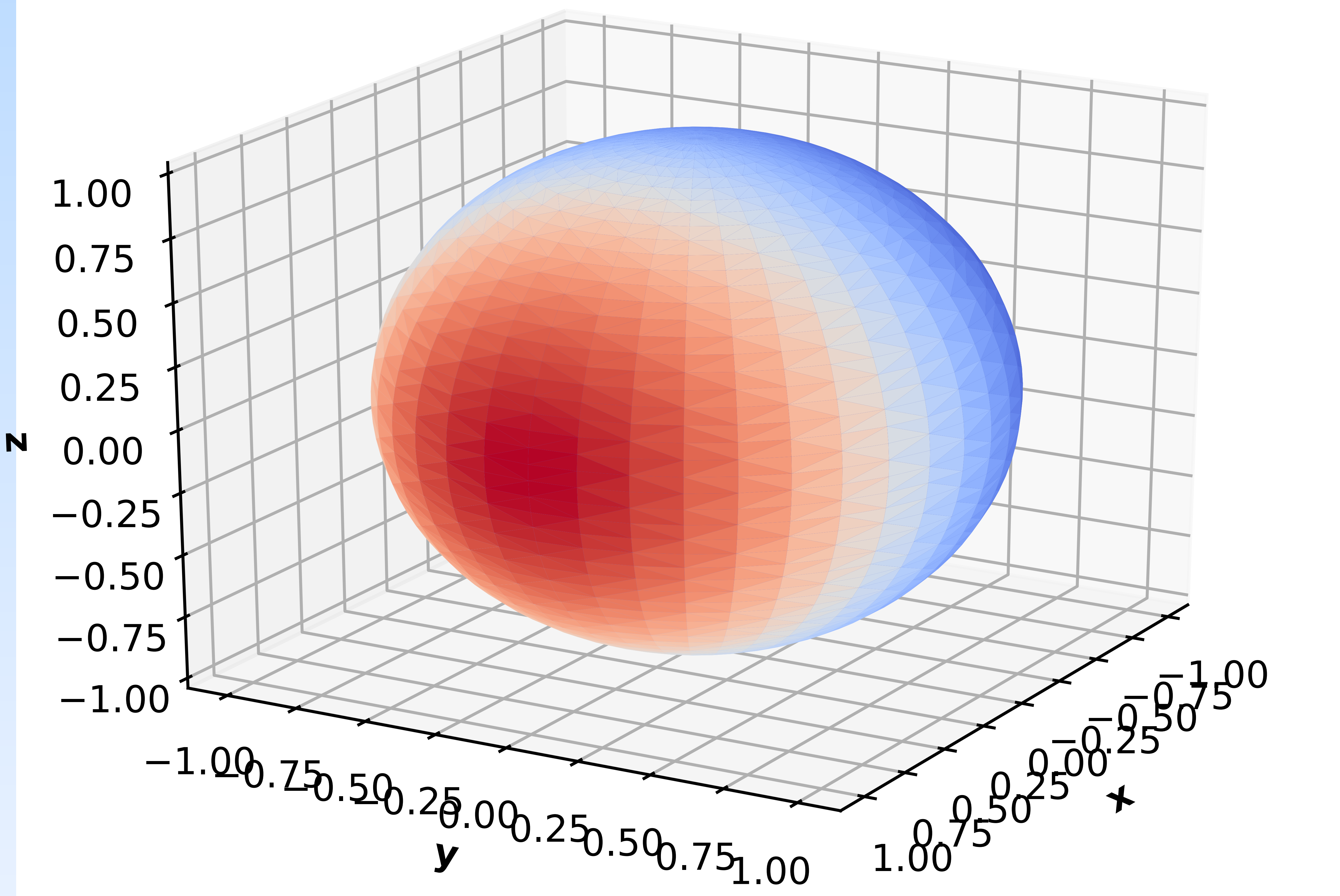
C.T. Lee, PRA, v30, n6, 1984

Bloch Sphere - N uncorrelated spins

$$|\psi\rangle = \alpha|\uparrow\rangle + \beta|\downarrow\rangle. \quad (1)$$

When this particle's spin is measured, the answer is $\uparrow$ with probability $P_\uparrow = |\alpha|^2$, and $\downarrow$ with probability $P_\downarrow = |\beta|^2$. When this measurement is repeated N times (or equivalently, with N uncorrelated spins), the statistics are binomial: the average number of $\uparrow$s is $\langle N_\uparrow \rangle = N|\alpha|^2$ and the variance is $\left\langle N_\uparrow^2 \right\rangle = N|\alpha|^2(1 - |\alpha|^2)$.

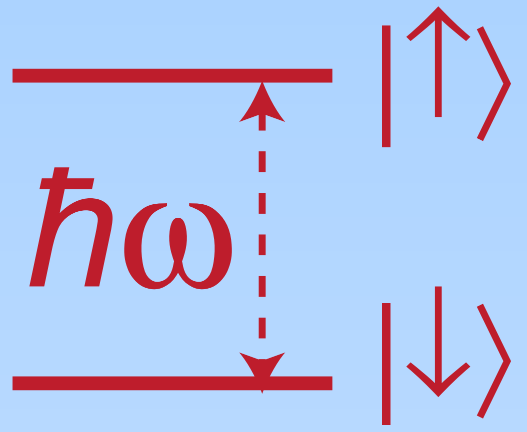
$\Delta\Phi \sim 1/N^{1/2}$

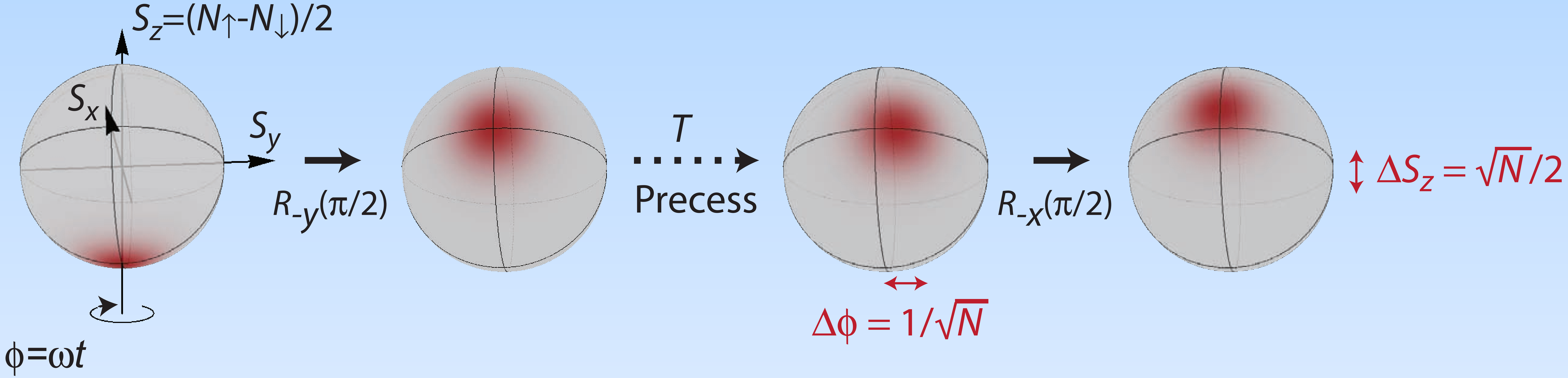


A. Vutha

Phase Precession Measurement from Population Measurement

Ramsey spectroscopy with an ensemble of N two-level atoms:





M. Schleier-Smith

Take Home Message for All Precision Measurements So Far

Energy Shift $\Delta\omega \sim 1/(T \bullet N^{1/2})$ Signal

Coherence Time

Typical line split $\sim 10^{-6}$

A. Vutha

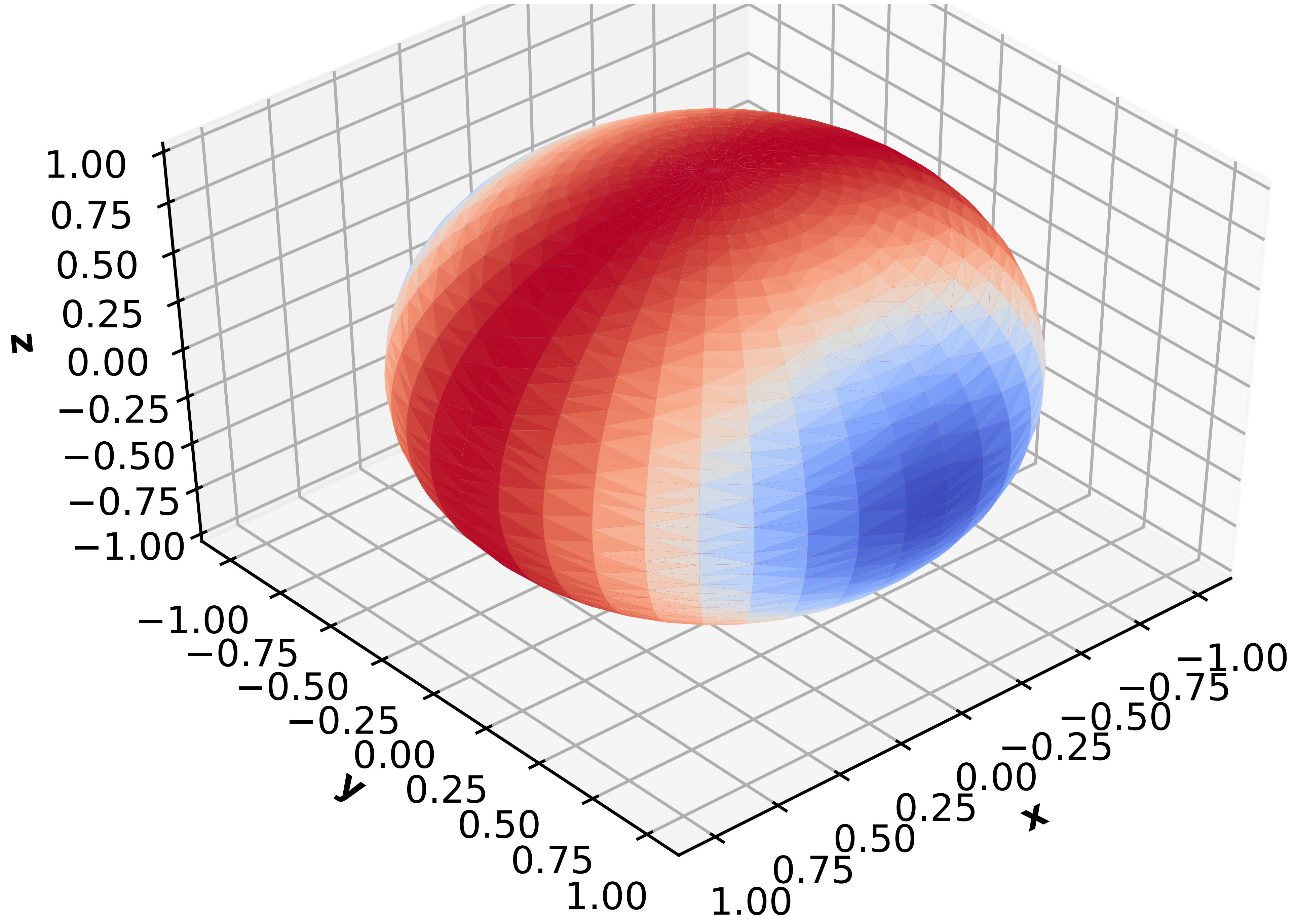
Bloch Sphere - N/2 correlated spins pairs

$$|\Psi\rangle = \alpha|\uparrow\uparrow\rangle + \beta|\downarrow\downarrow\rangle. \quad (2)$$

When this pair of particles is measured, the answer is $\uparrow\uparrow$ with probability $P_{\uparrow\uparrow} = |\alpha|^2$, and $\downarrow\downarrow$ with probability $P_{\downarrow\downarrow} = |\beta|^2$. When the measurement is repeated $N/2$ times (or equivalently, with $N/2$ uncorrelated spin pairs), the average number of $\uparrow$s is $\langle N_\uparrow \rangle = 2\frac{N}{2}|\alpha|^2 = N|\alpha|^2$ as before. But the variance is now $\left\langle N_\uparrow^2 \right\rangle = 4\frac{N}{2}|\alpha|^2(1-|\alpha|^2) = 2N|\alpha|^2(1-|\alpha|^2)$. (Basically, this is a binomial random walk with half the number of steps and twice the step length.)

Linear Combination of Fully Stretched N Particles

$\Delta\Phi$~1/N



SPIN SQUEEZING APPLIED TO FREQUENCY STANDARDS.
JJ Bollinger, DJ Wineland, WM Itano, DJ Heinzen
Proceedings of the Fifth Symposium on Frequency Standards

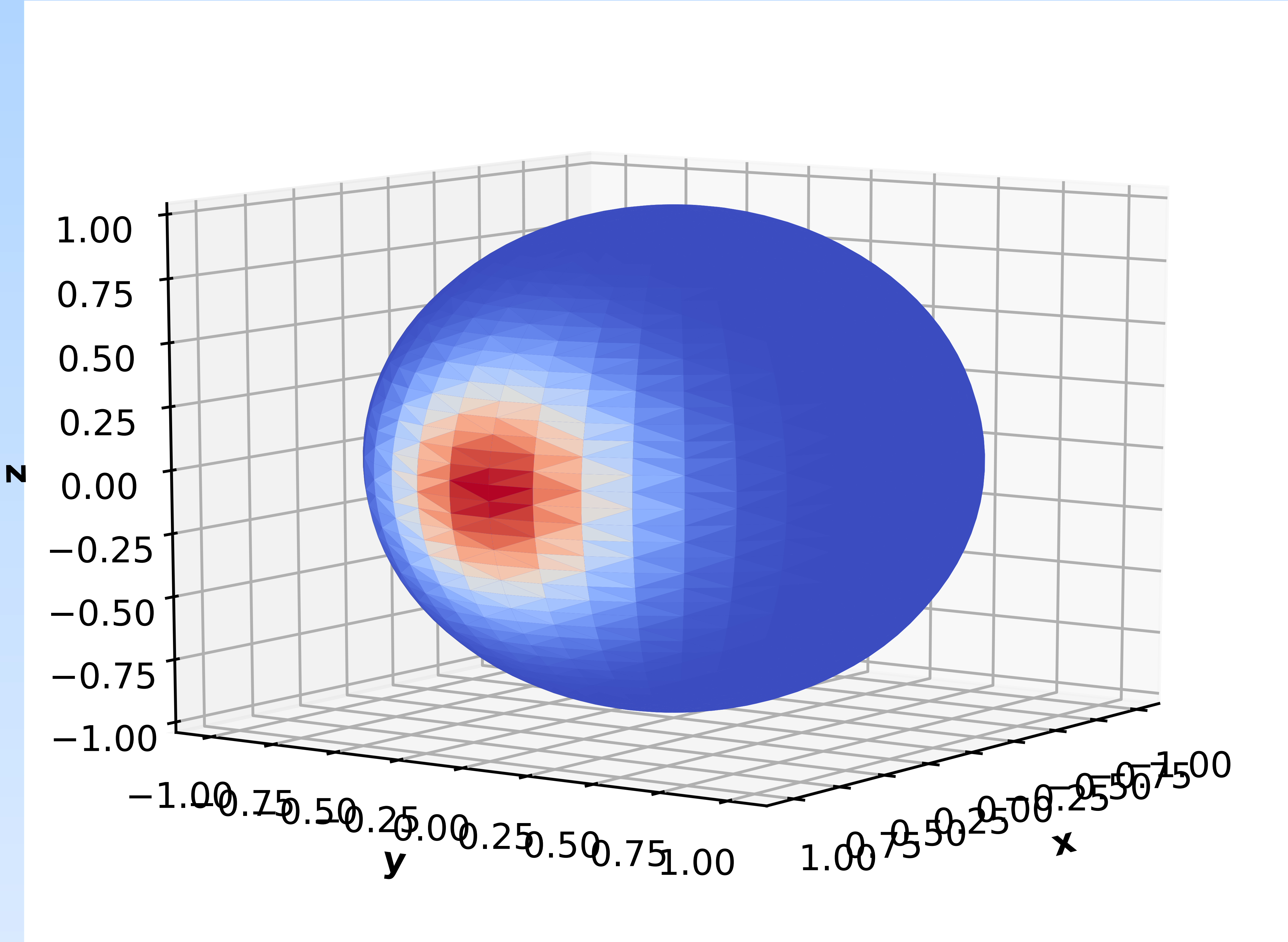
A. Vutha

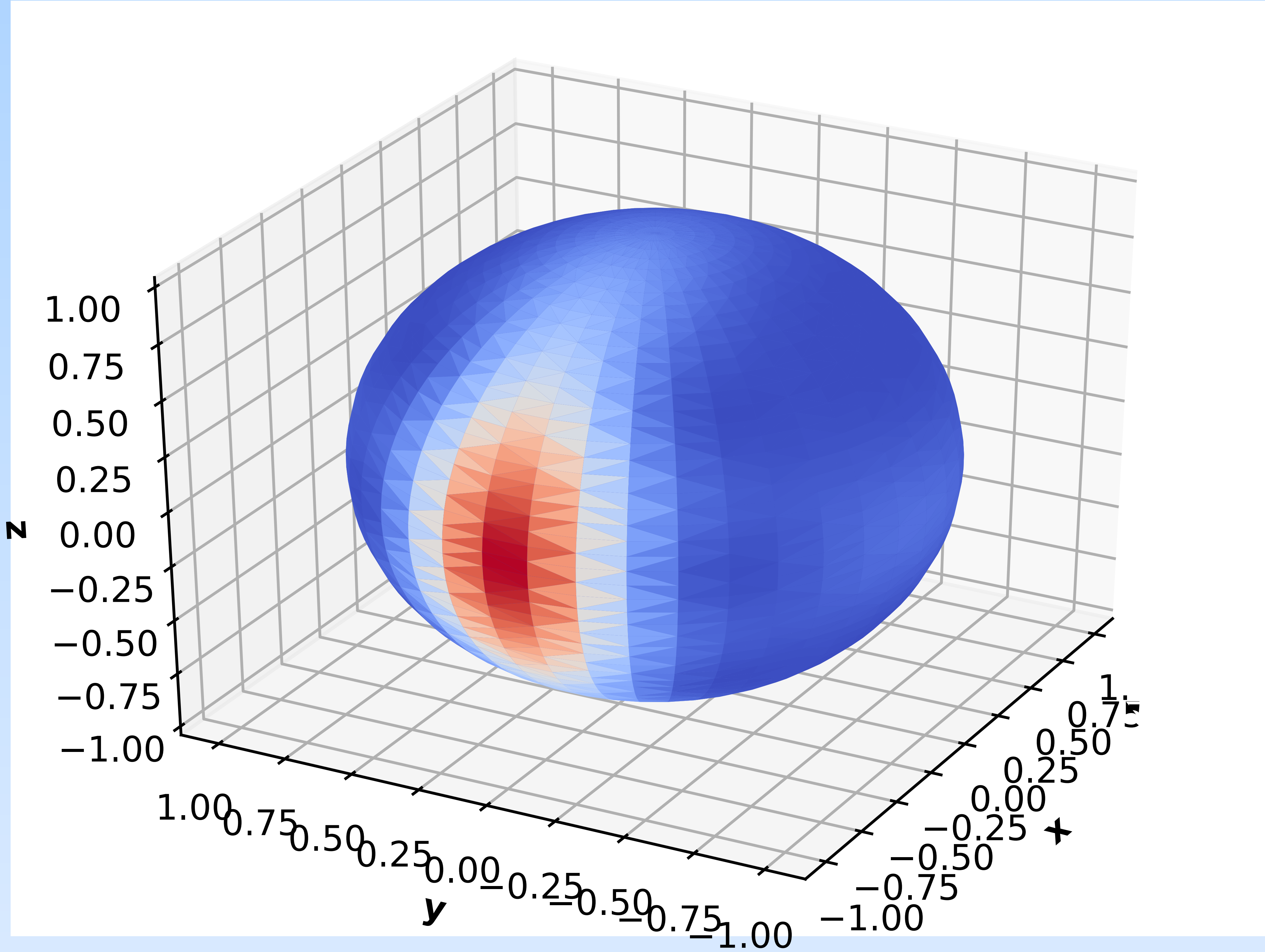
Bloch Sphere - Squeezed State

20 Spins

$\Delta\Phi \sim 1/N^{1/2}$

$\Delta\Phi < 1/N^{1/2}$

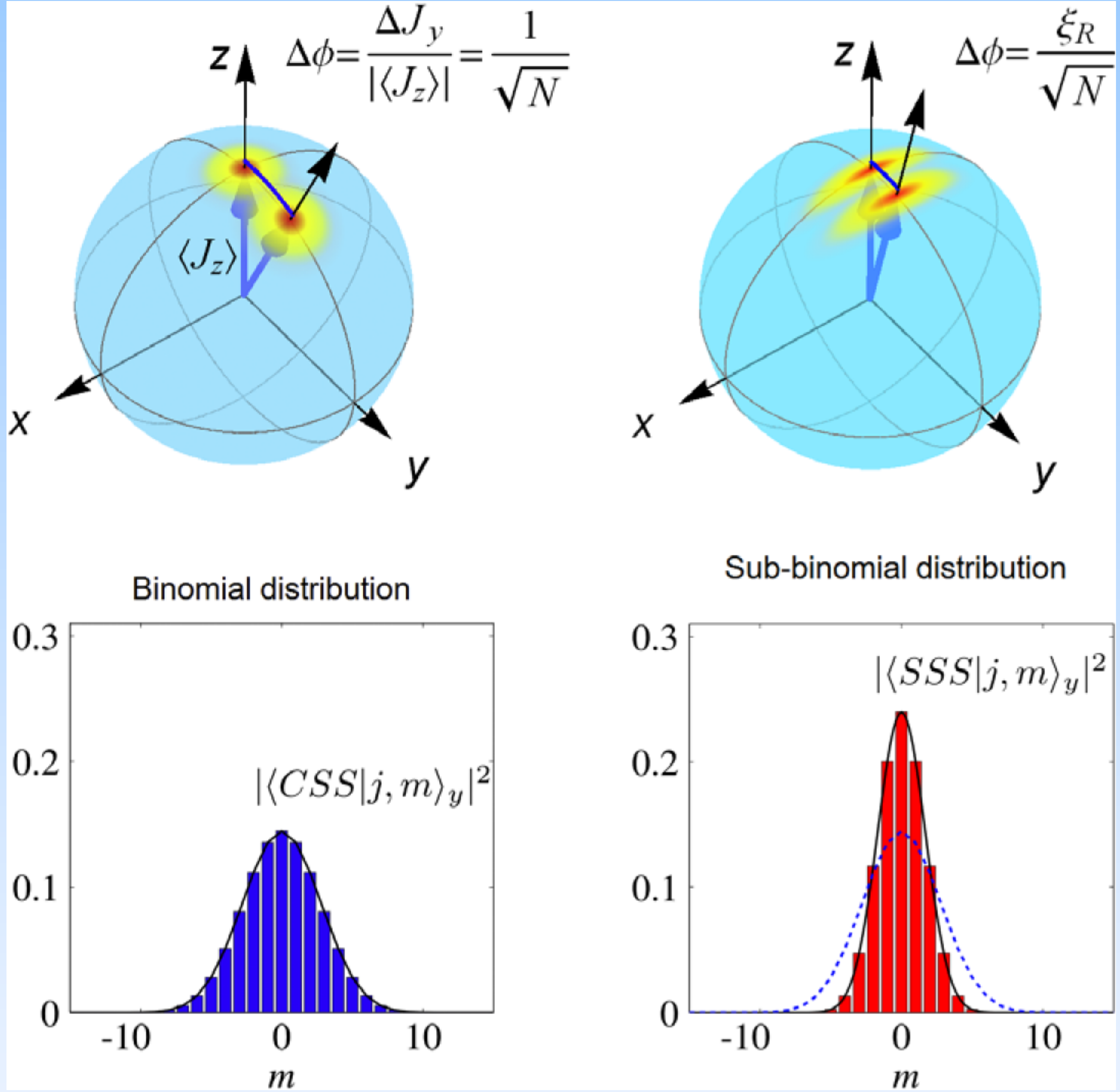




A. Vutha

Squeezed atomic states and projection noise in spectroscopy
D. J. Wineland, J. J. Bollinger, W. M. Itano, and D. J. Heinzen
Phys. Rev. A **50**, 67 – Published 1 July 1994

Squeezed spin states
Masahiro Kitagawa and Masahito Ueda
Phys. Rev. A **47**, 5138 – Published 1 June 1993

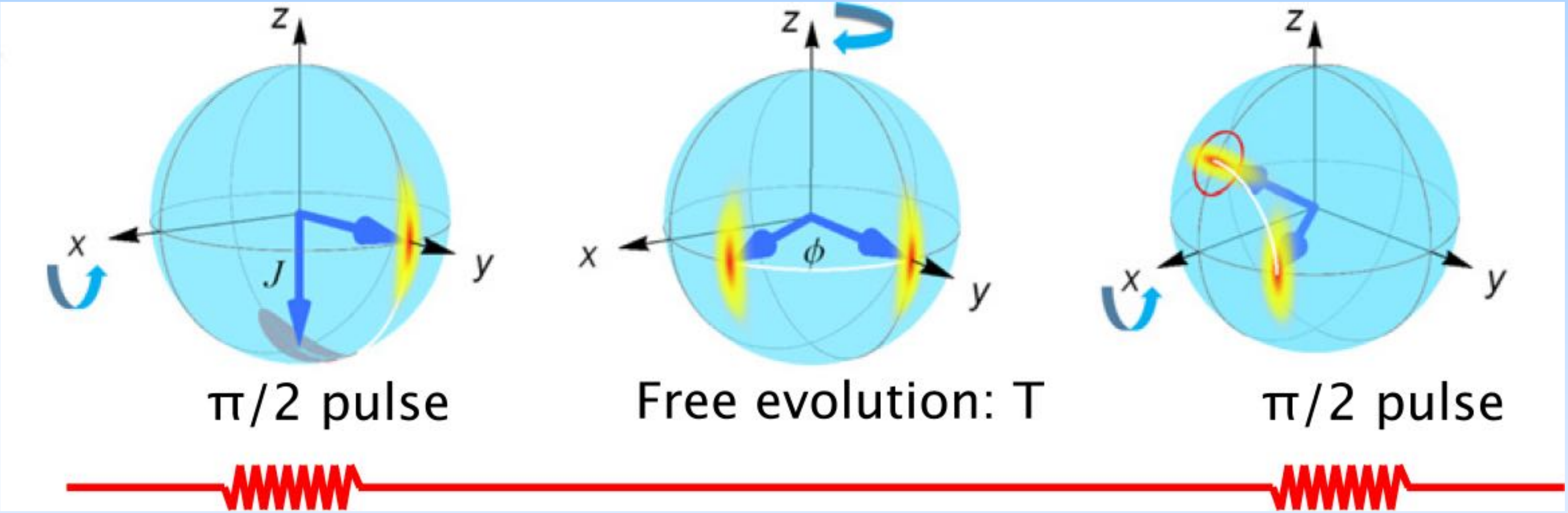


Bloch Sphere - Squeezed State

SSS = squeezed spin state
CSS = coherent spin state

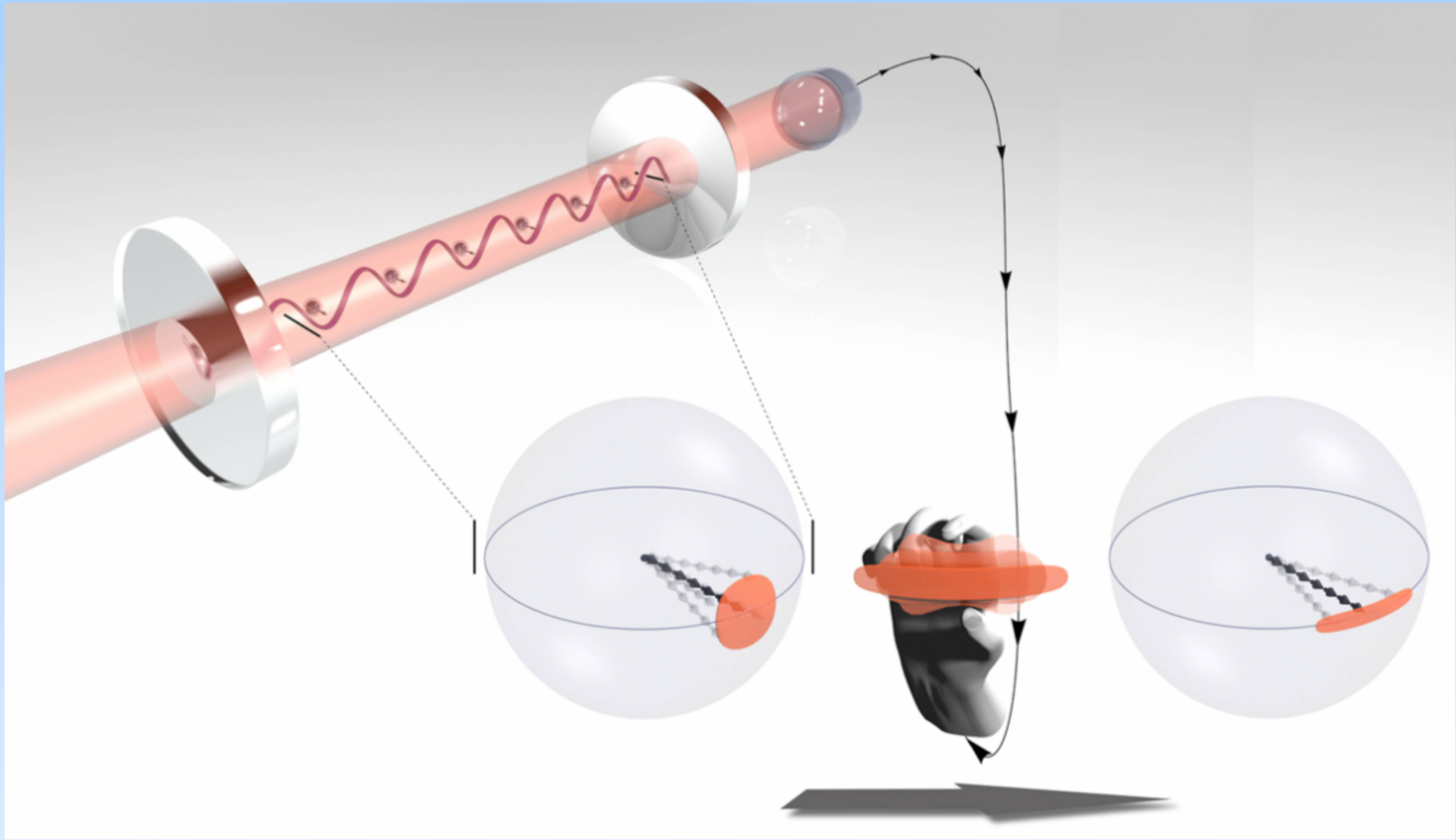
Quantum spin squeezing
Jian Ma, Xiaoguang Wang, C.P. Suna, Franco Nori,
Physics Reports, 2011

Phase Precession Measurement from Population Measurement



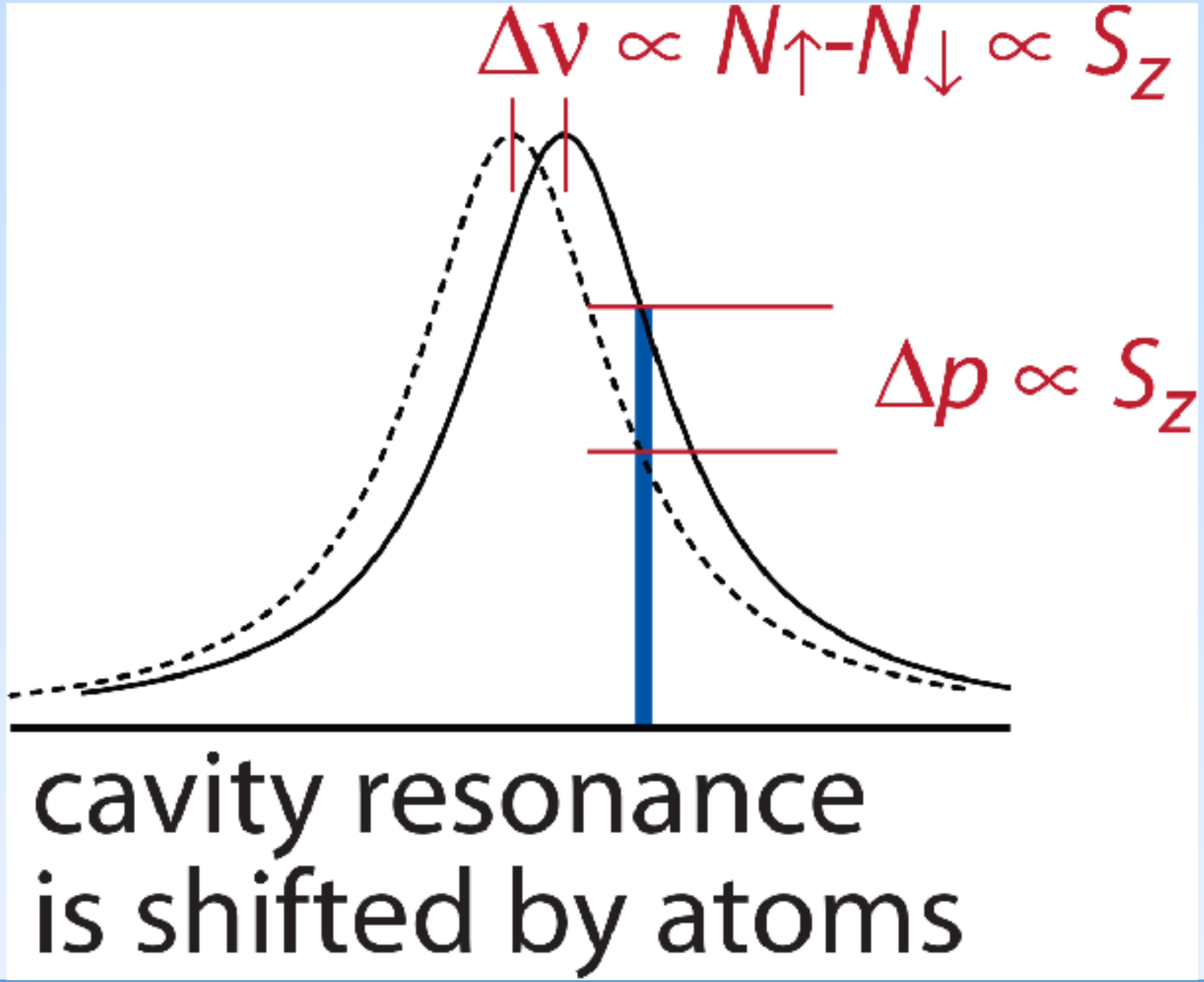
F. Nori

One slide on how one can spin squeeze



J. Thompson

Make measurement that
- measures S_z
- population (collective)
- not single atoms
- …
- cavity resonance shift



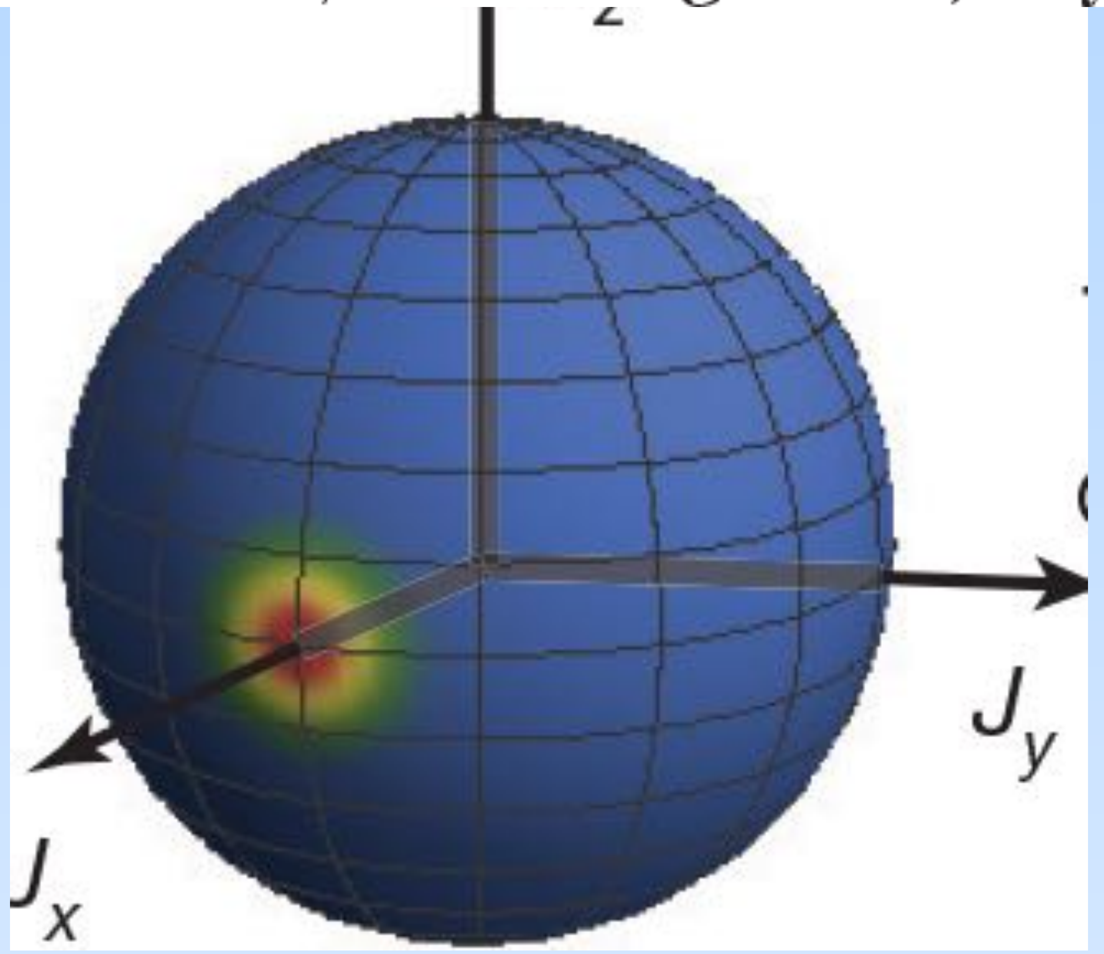
M. Schleier-Smith

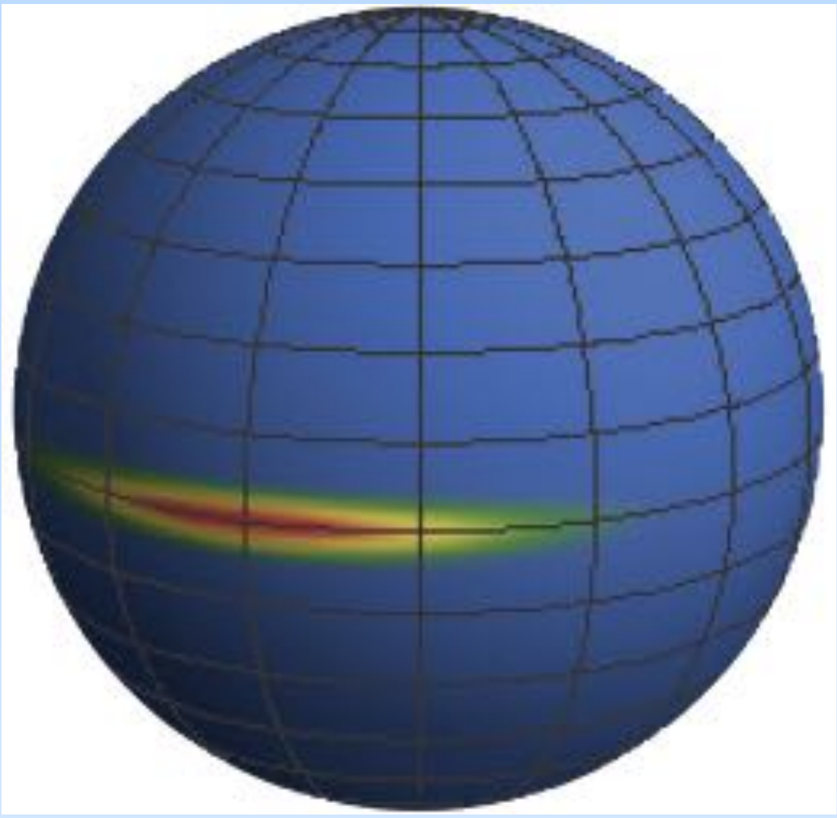
Help by Squeezing

Measurement noise 100 times lower than the quantum-projection limit using entangled atoms

Onur Hosten[1], Nils J. Engelsen[1], Rajiv Krishnakumar[1] & Mark A. Kasevich[1]

Nature 2016





Equivalent to Factor of 10 Increase in Counts

Help by Squeezing

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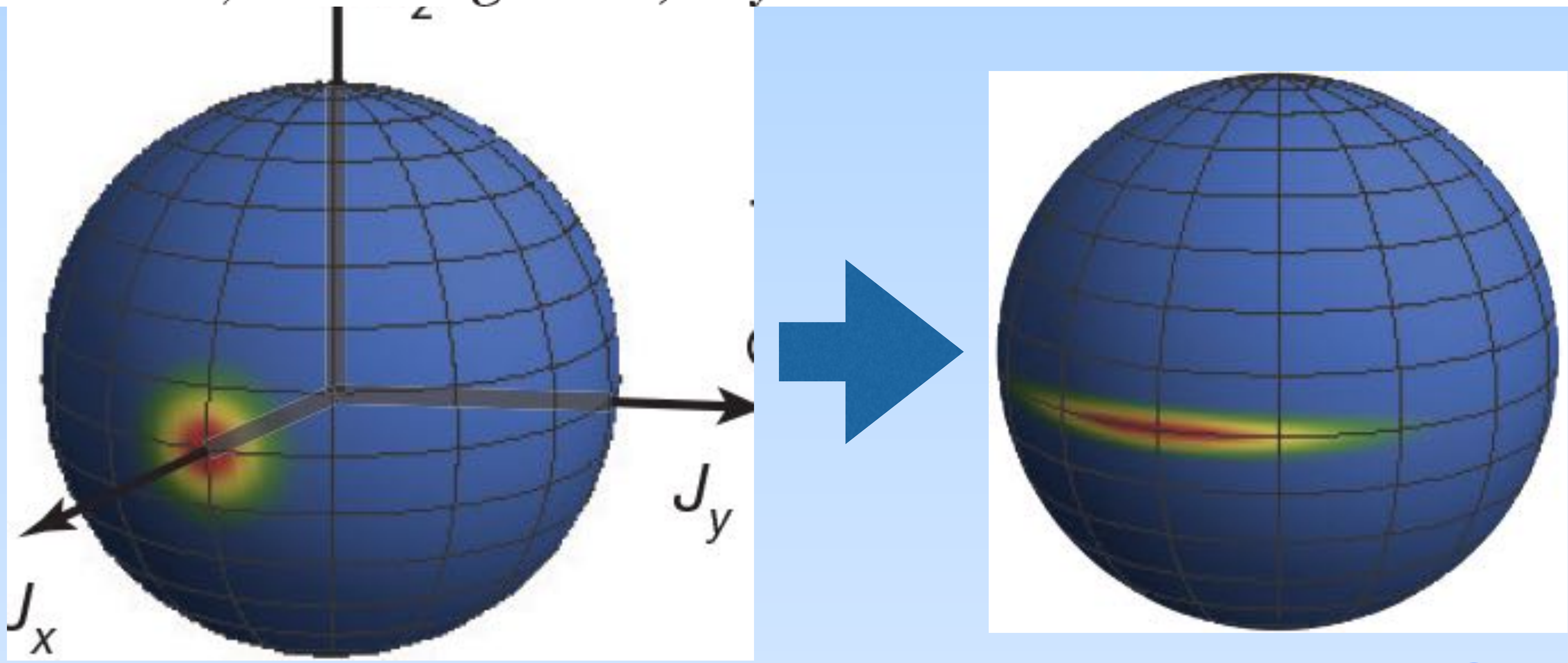

Equivalent to Factor of 10 Increase in Counts

Also see Mitchell, Vuletic, Schleier-Smith, Takahashi, others….

Help by Squeezing

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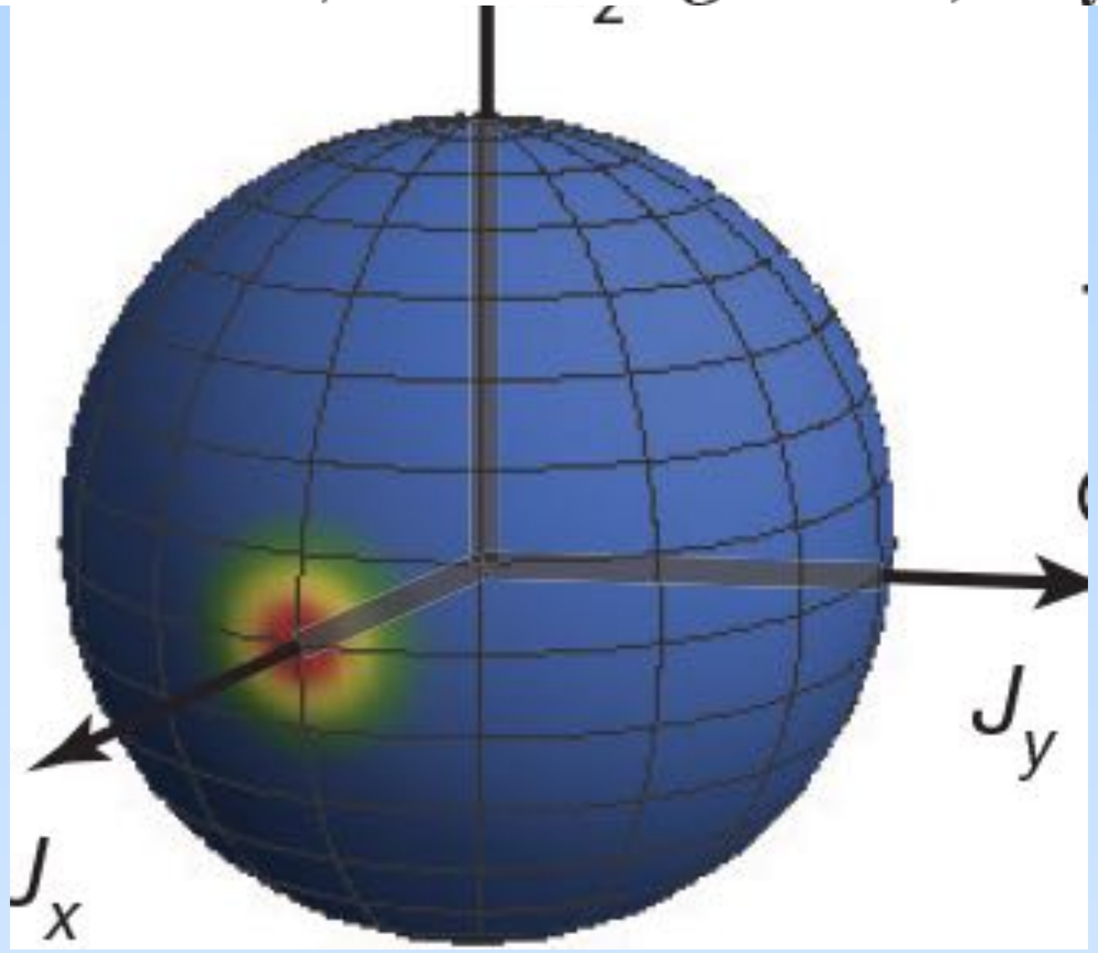
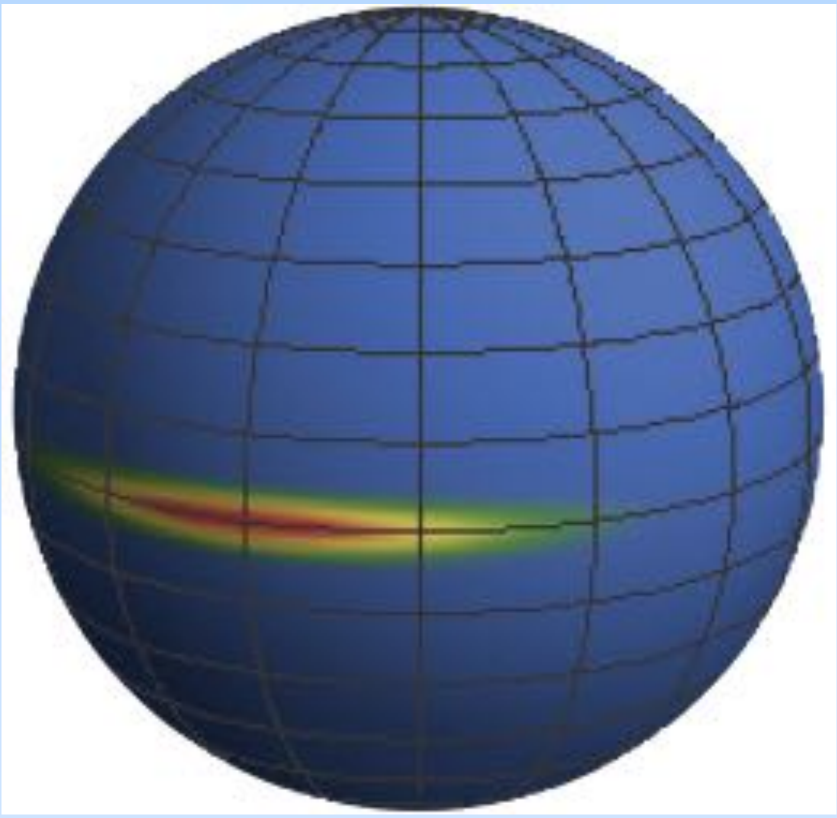
Onur Hosten[1], Nils J. Engelsen[1], Rajiv Krishnakumar[1] & Mark A. Kasevich[1] Nature 2016





Equivalent to Factor of 10 Increase in Counts

Also see Mitchell, Vuletic, Schleier-Smith, Takahashi, Thompson, others….

Spin Squeezing of a Cold Atomic Ensemble with the Nuclear Spin of One-Half
T. Takano, M. Fuyama, R. Namiki, and Y. Takahashi
Phys. Rev. Lett. **102**, 033601 – Published 22 January 2009

Can a Quantum Nondemolition Measurement Improve the Sensitivity of an Atomic Magnetometer?
M. Auzinsh, D. Budker, D. F. Kimball, S.M. Rochester, J. E. Stalnaker,A.O. Sushkov, and V.V. Yashchuk

Simultaneous tracking of spin angle and amplitude beyond classical limits
Giorgio Colangelo, Ferran Martin Ciurana, Lorena C. Bianchet, Robert J. Sewell & Morgan W. Mitchell

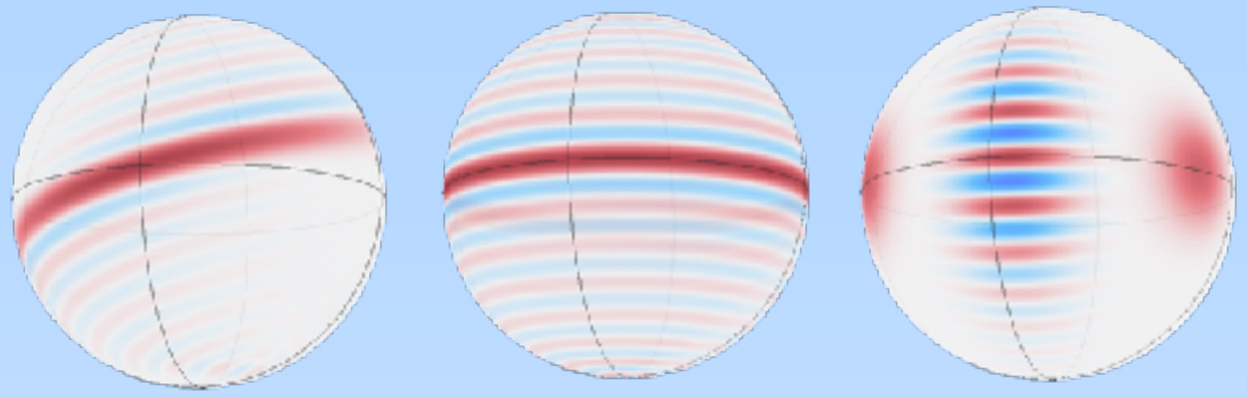
Deterministic Squeezed States with Collective Measurements and Feedback
Kevin C. Cox, Graham P. Greve, Joshua M. Weiner, and James K. Thompson
JILA, NIST, and University of Colorado, 440 UCB, Boulder, Colorado 80309, USA

Magnetic Sensitivity Beyond the Projection Noise Limit by Spin Squeezing
R. J. Sewell, M. Koschorreck, M. Napolitano, B. Dubost, N. Behbood, and M. W. Mitchell
Phys. Rev. Lett. **109**, 253605 – Published 19 December 2012

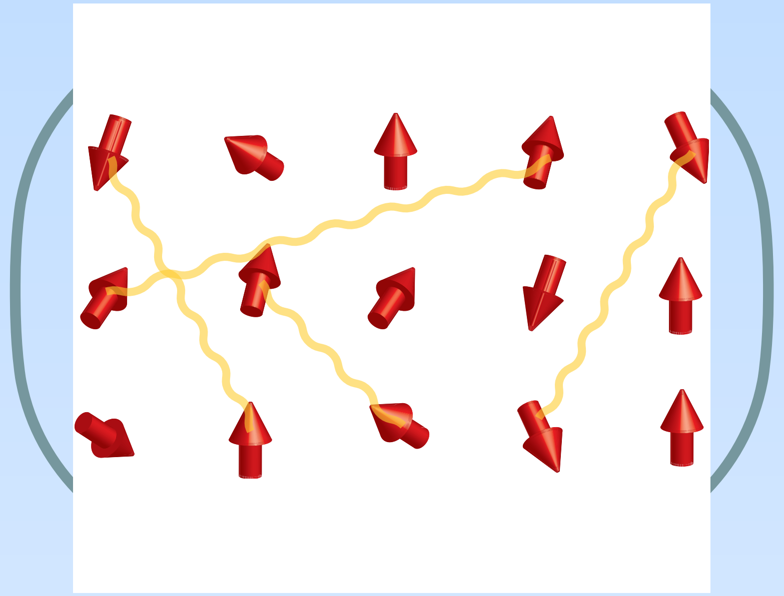
Monika's Talk

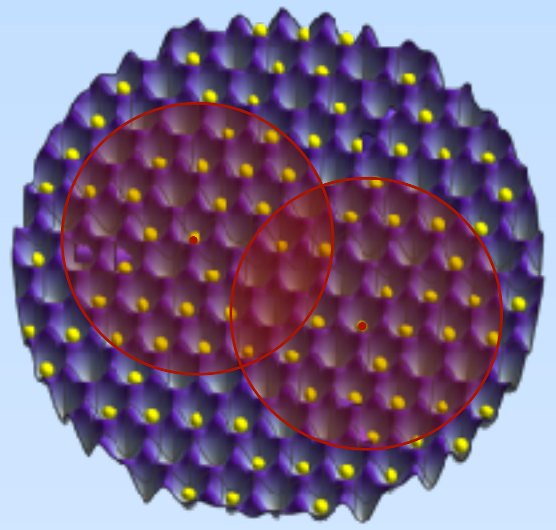
Quantum Engineering with Cold Atoms

Which many-particle entangled states
are useful for precision measurements?

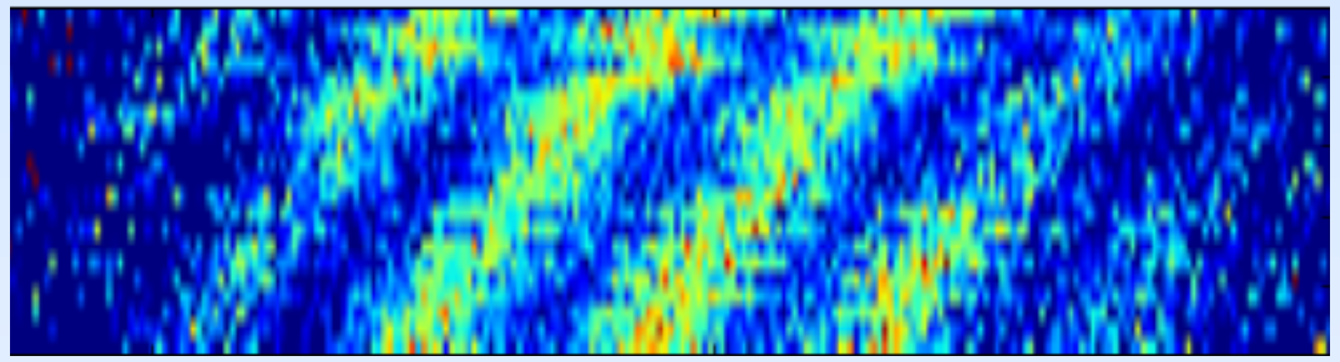


How can we engineer interactions
to generate and harness entanglement?





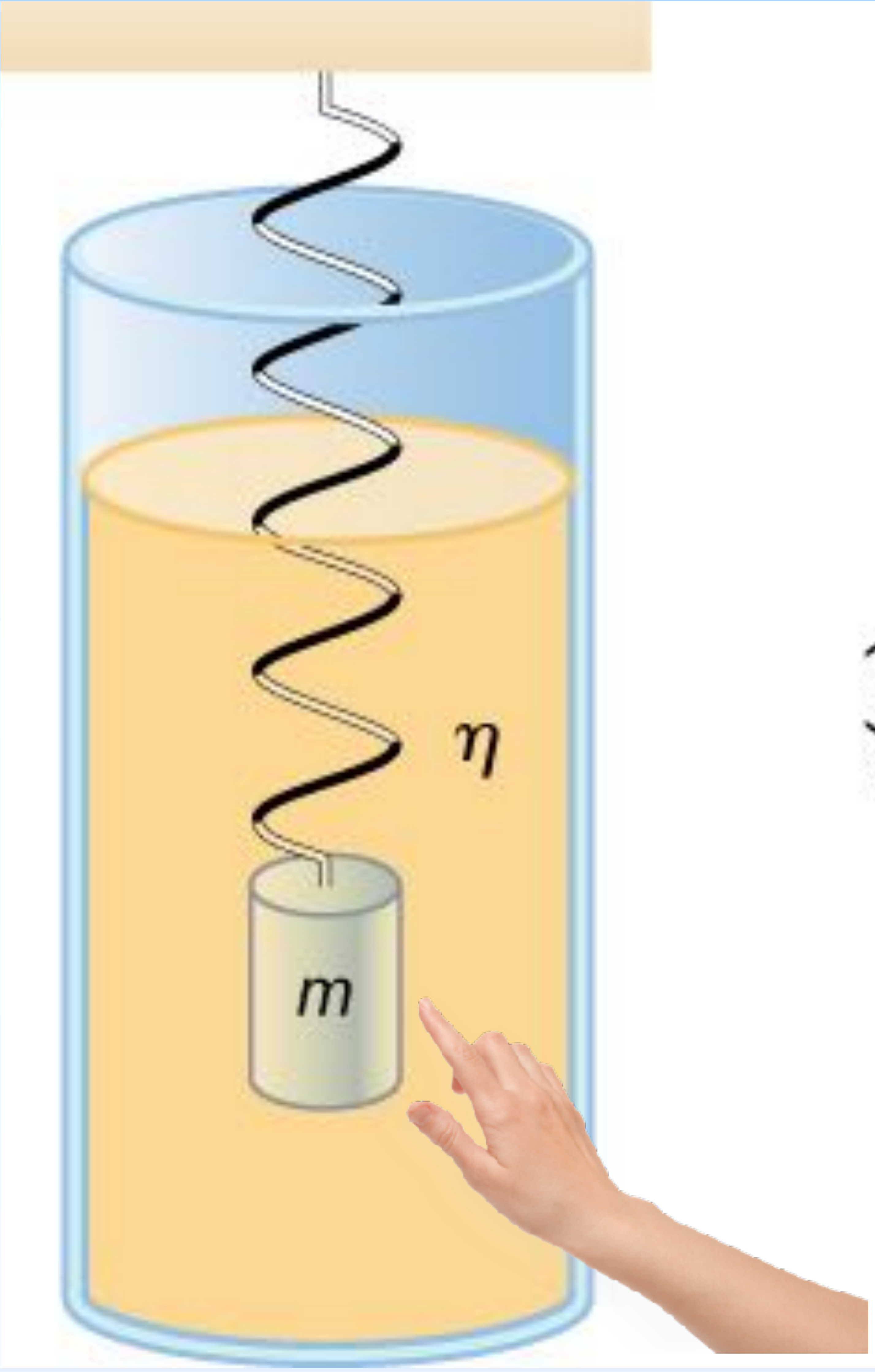
How will we push quantum sensors
to their fundamental limits?

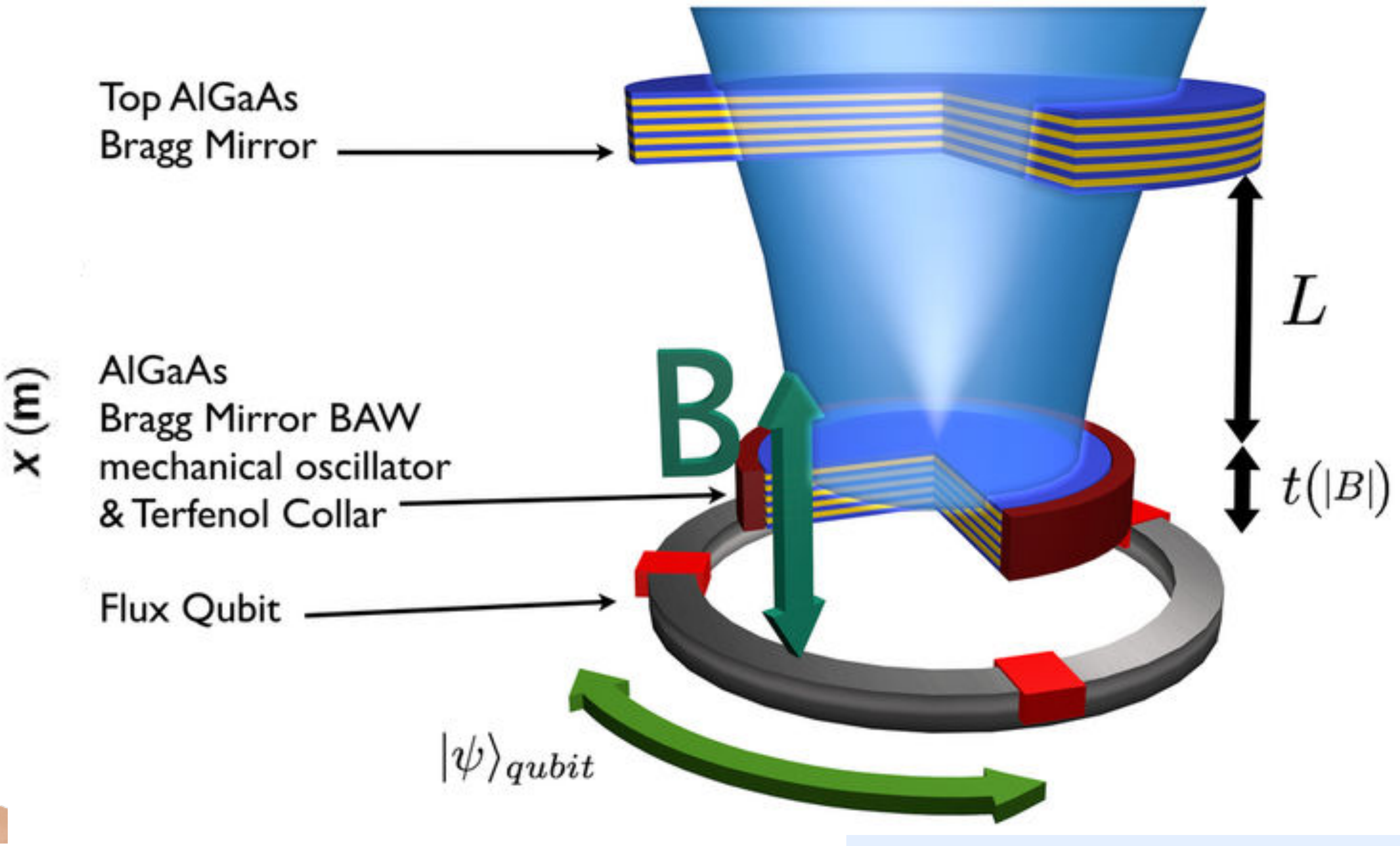


M. Schleier-Smith

Resonance is Useful for Finding New Physics

Different Kinds of Resonant Objects





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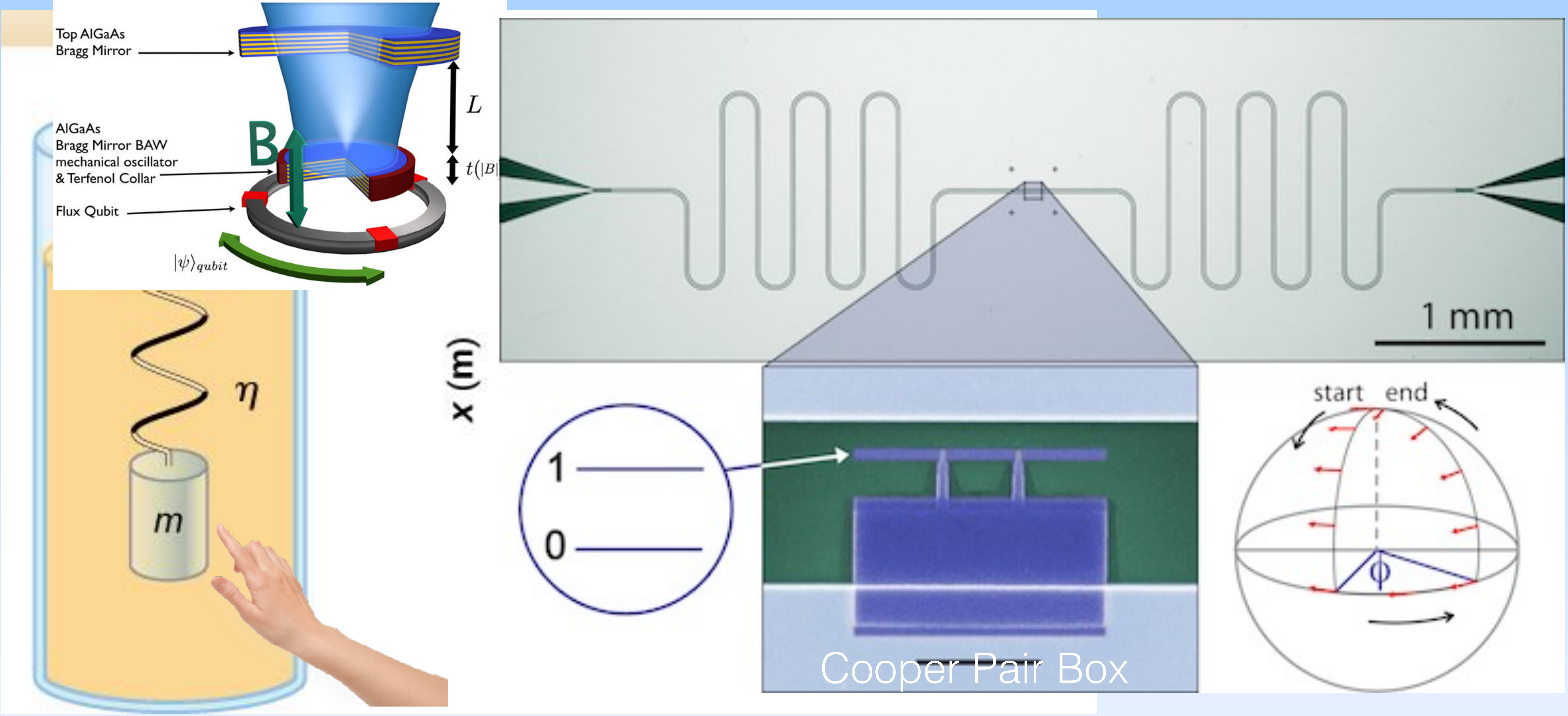

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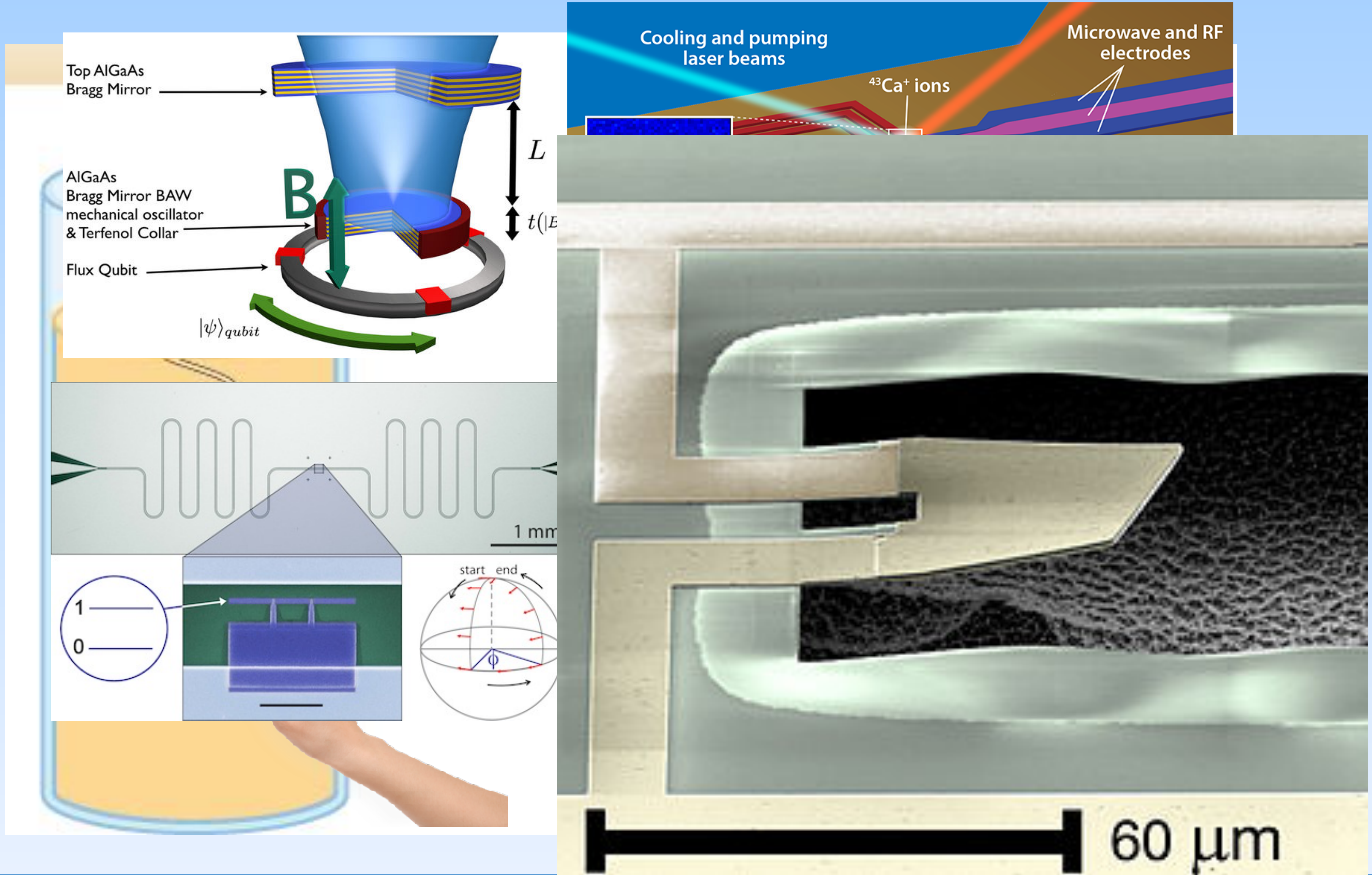

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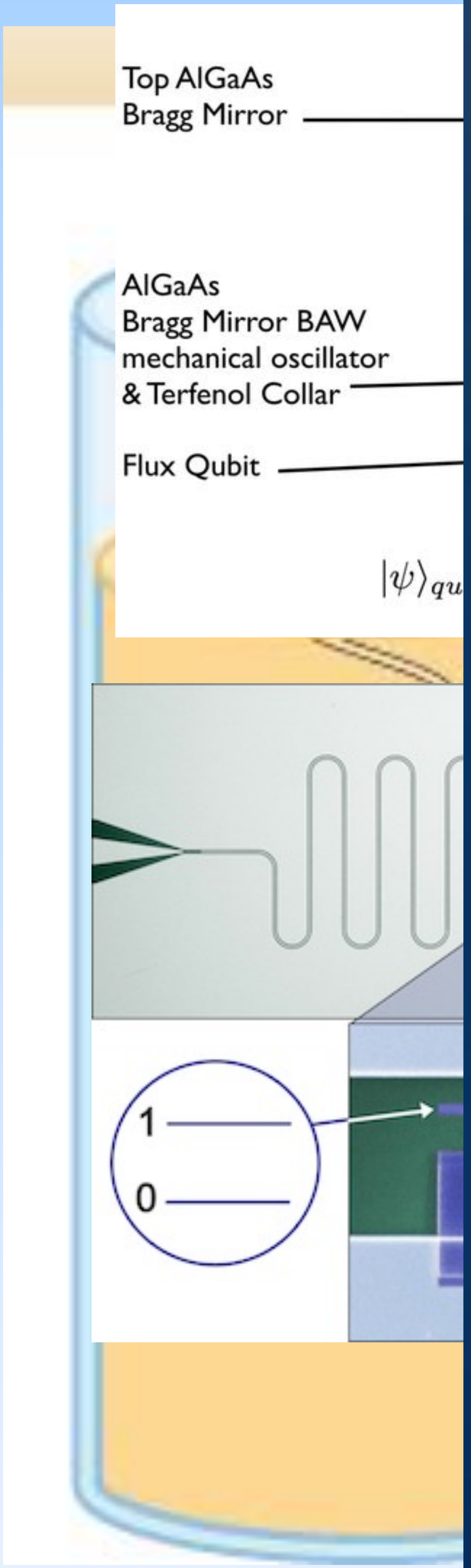

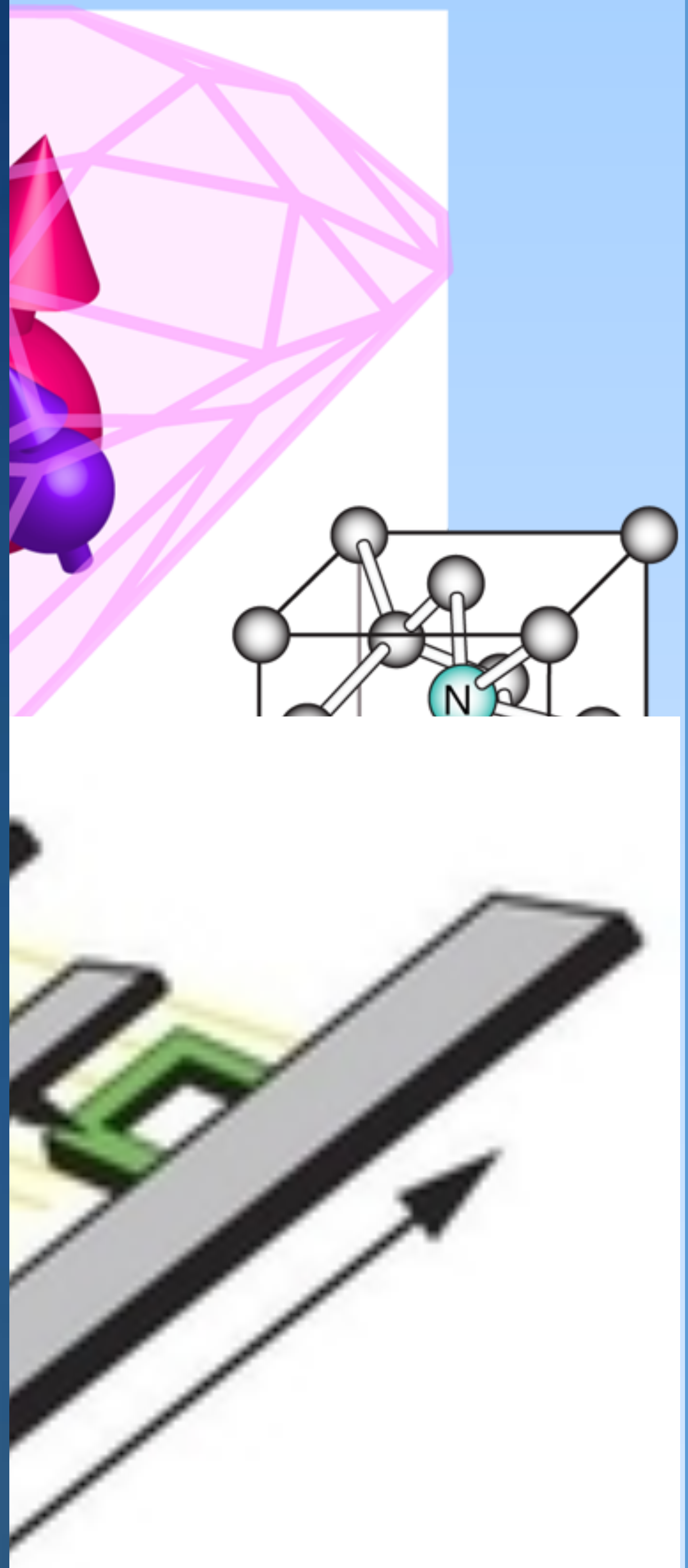

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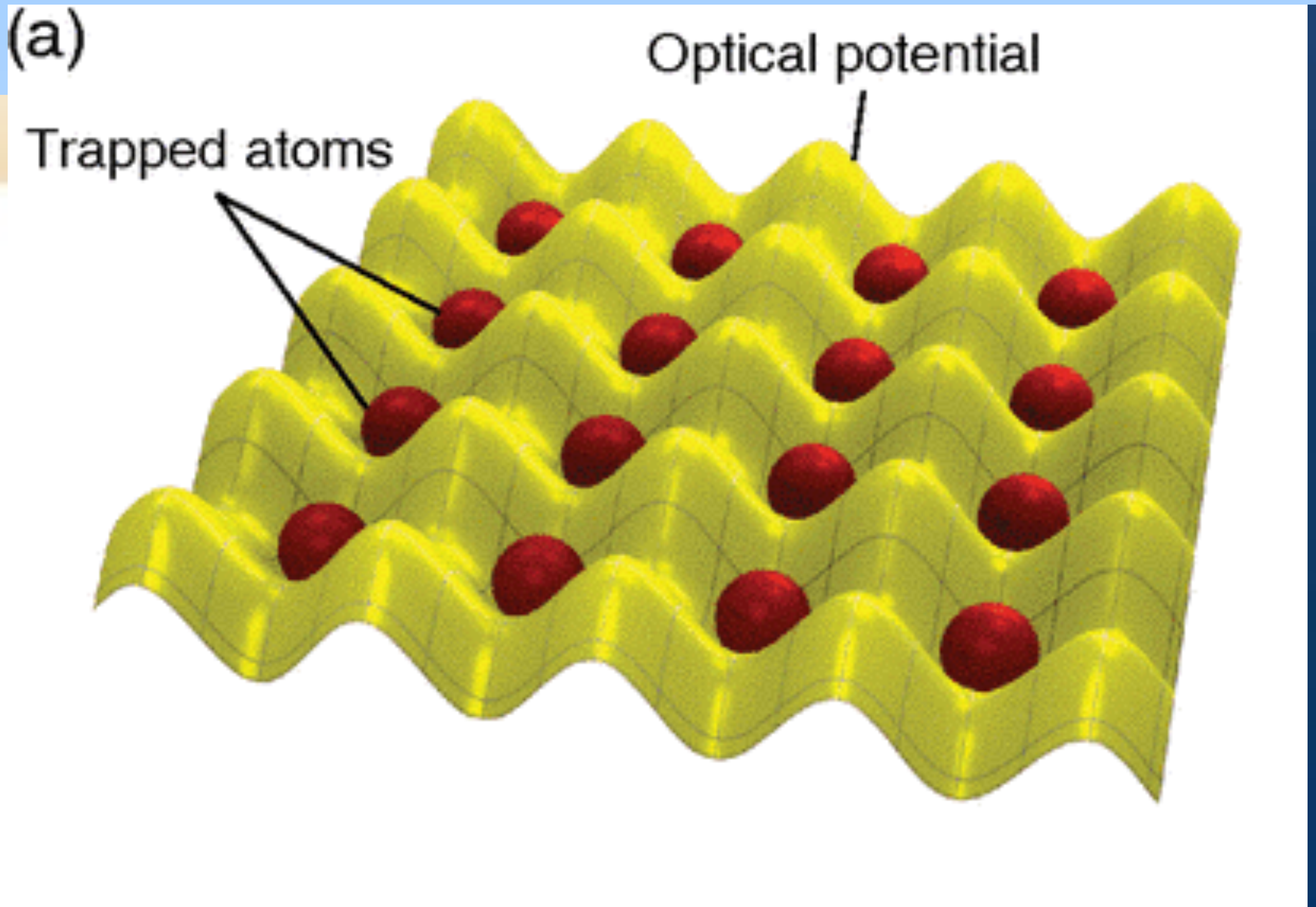
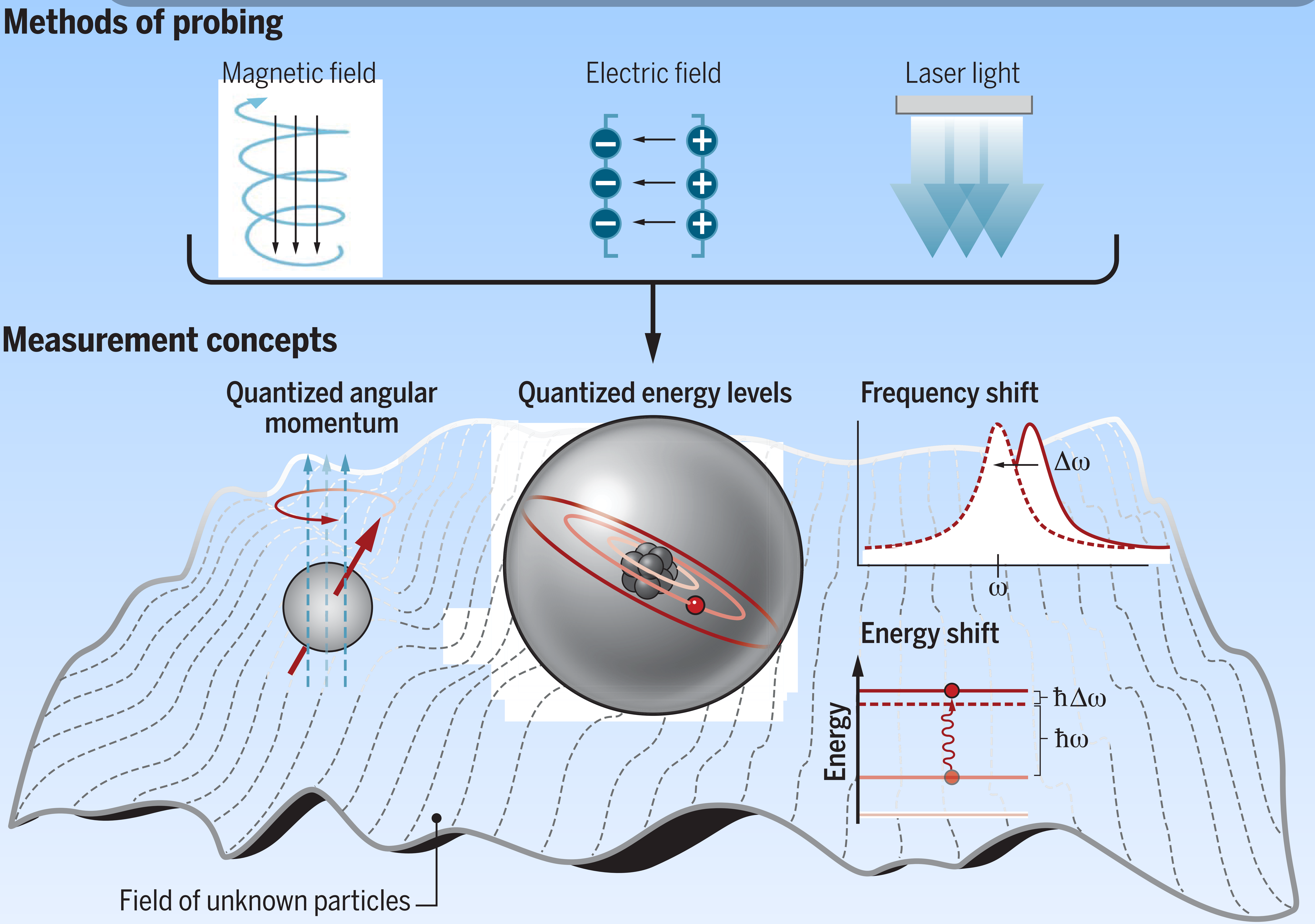
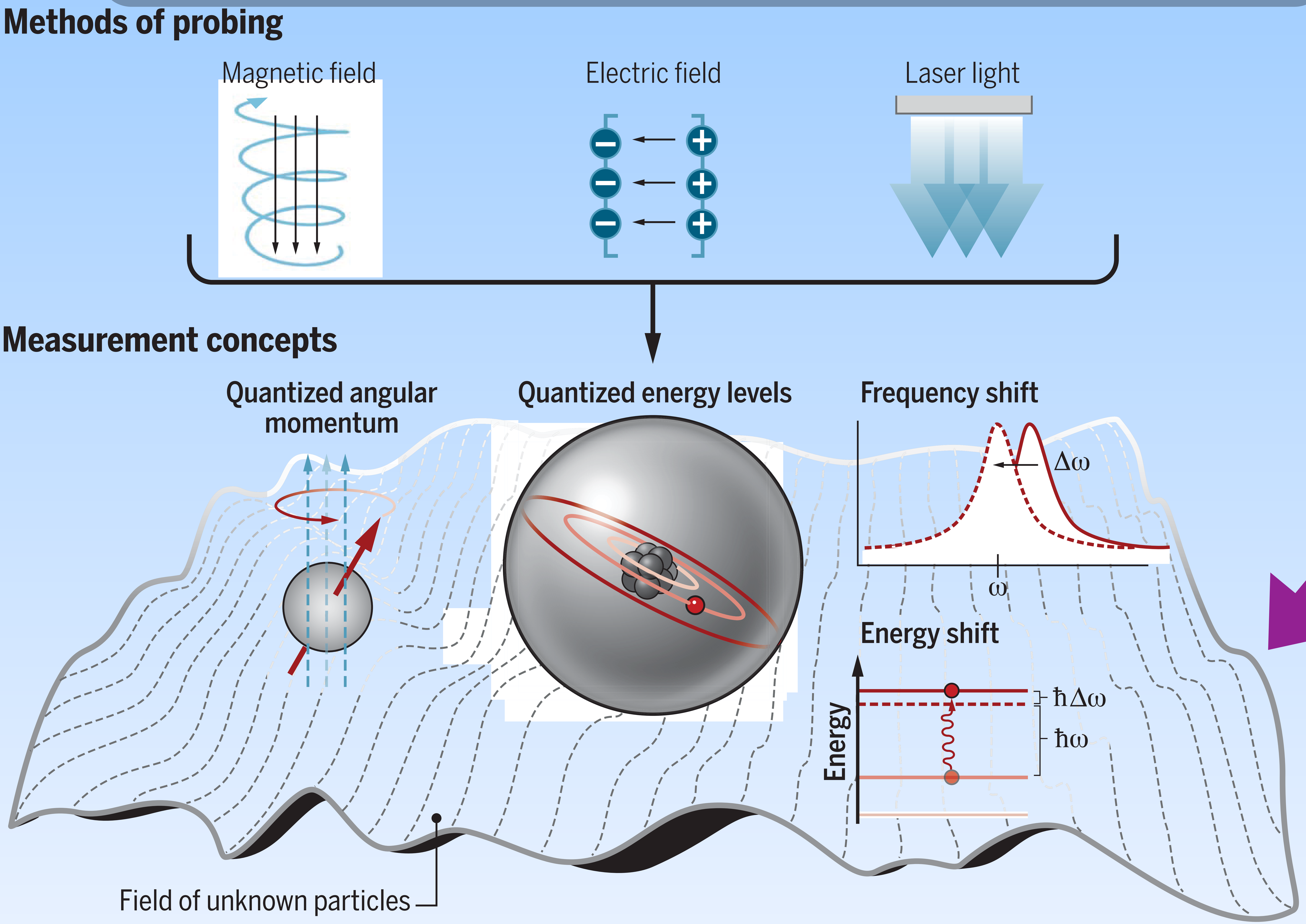


Atoms/Molecules
are
All the Same

Often Couple to these systems by EM



New Physics Couples in Many Ways



Gravity
Nuclear
EM
everything!

DeMille, Sushkov, JMD, Science 2017

Gravity Waves

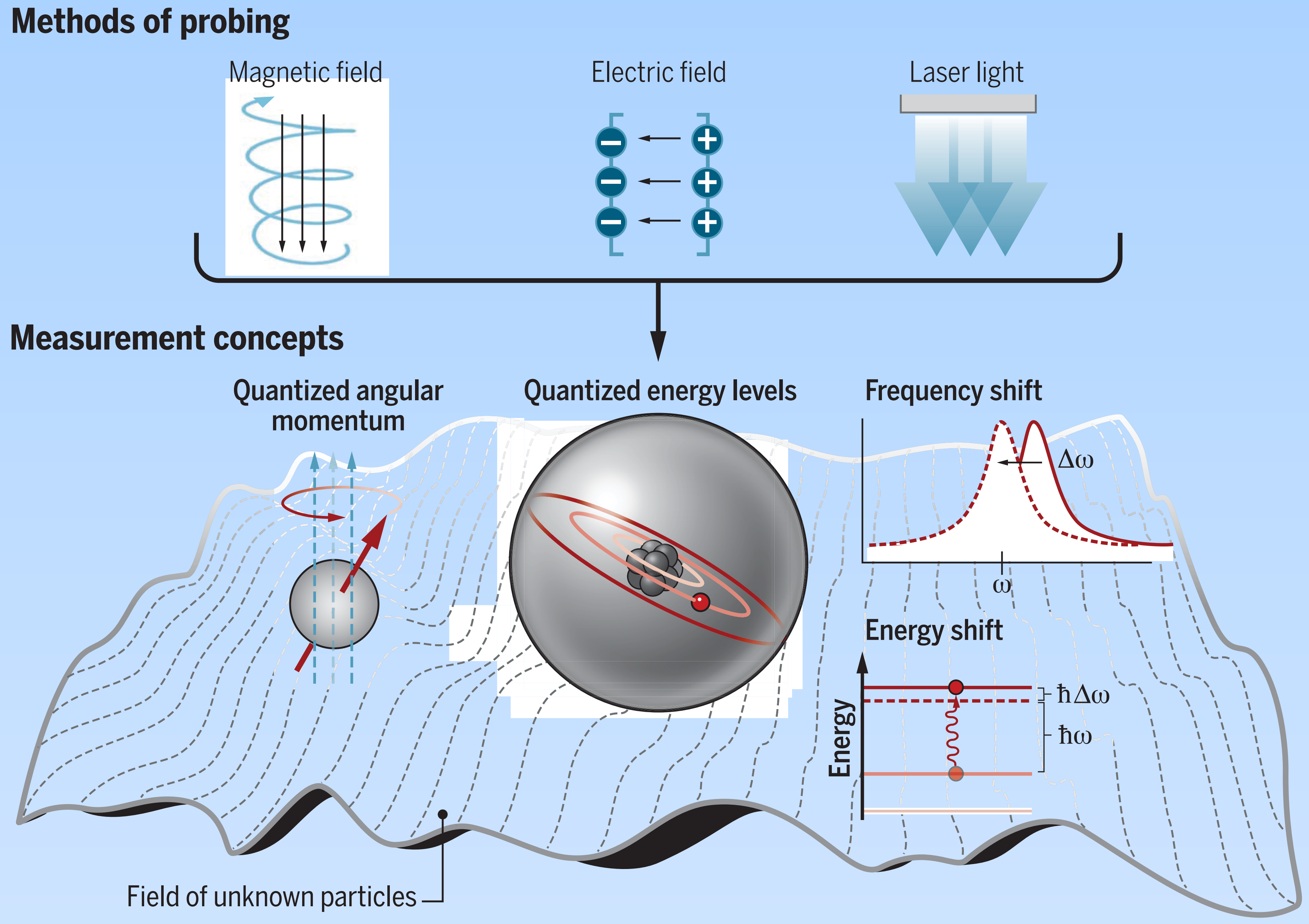
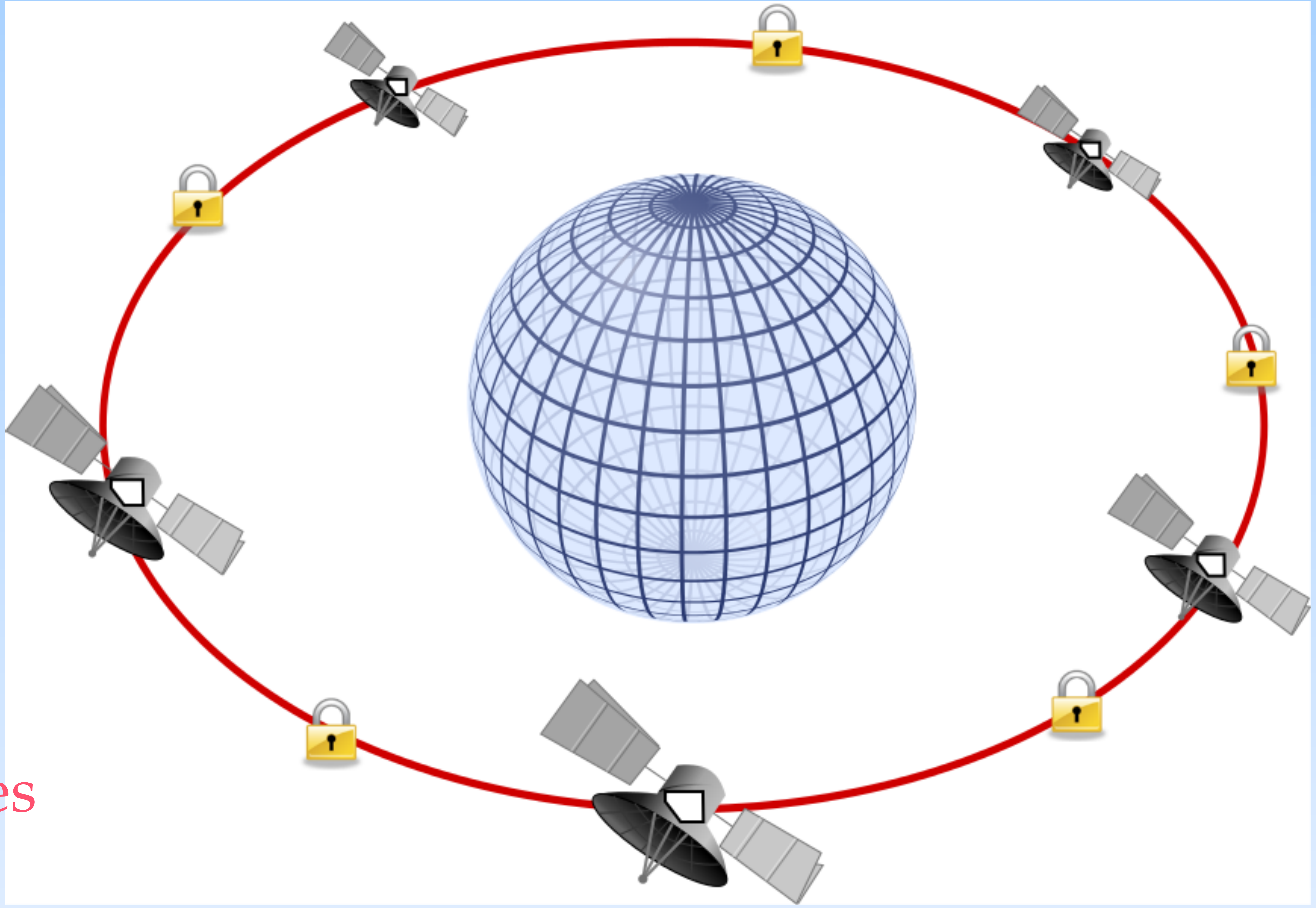


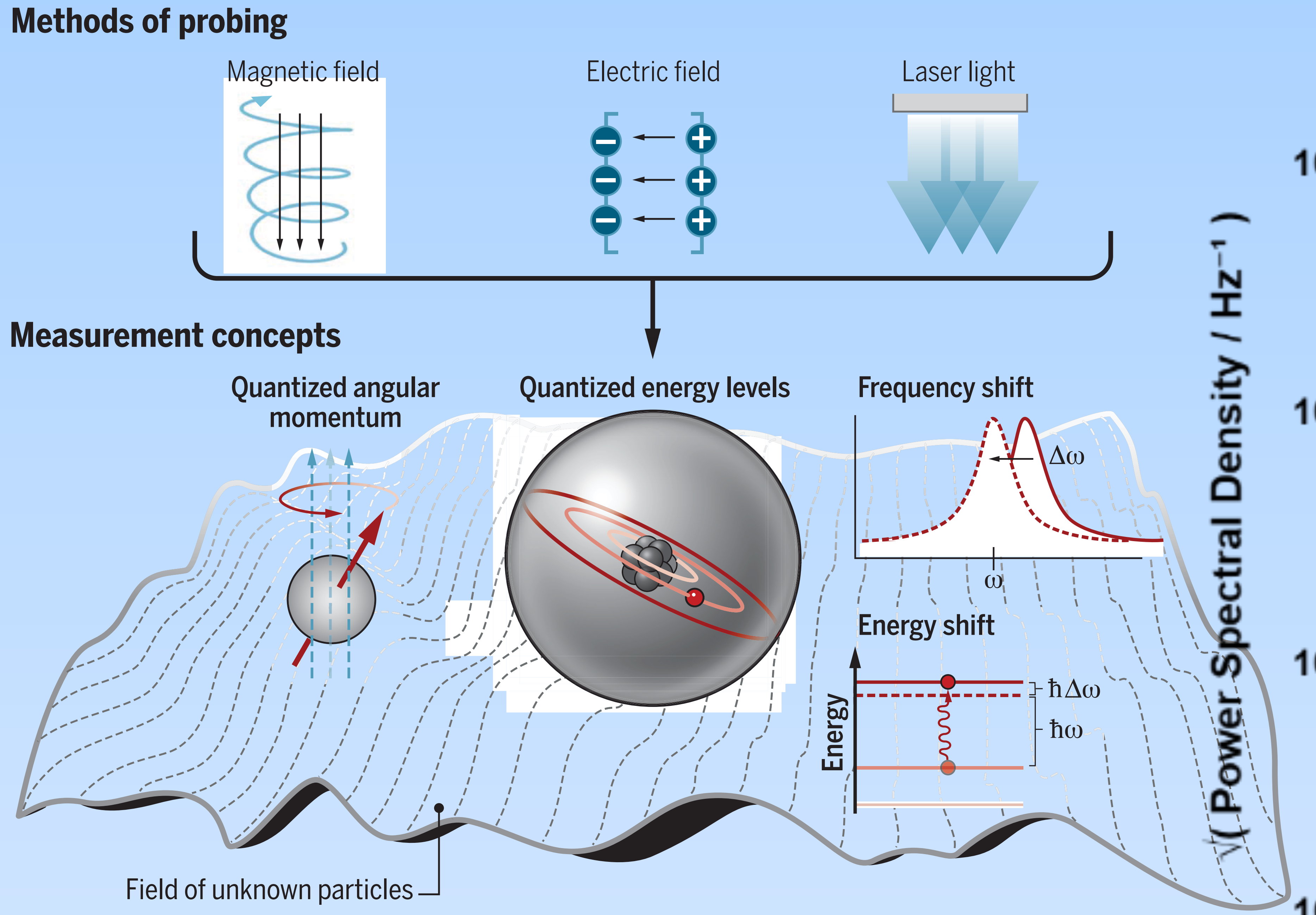
Fig. 1. Probing fundamental physics with resonance experiments.



Using spins to detect gravity waves
Lukin and Walsworth (Harvard),
Hogan (Stanford), Ye (JILA),
Many others

J. Ye

Gravity Waves



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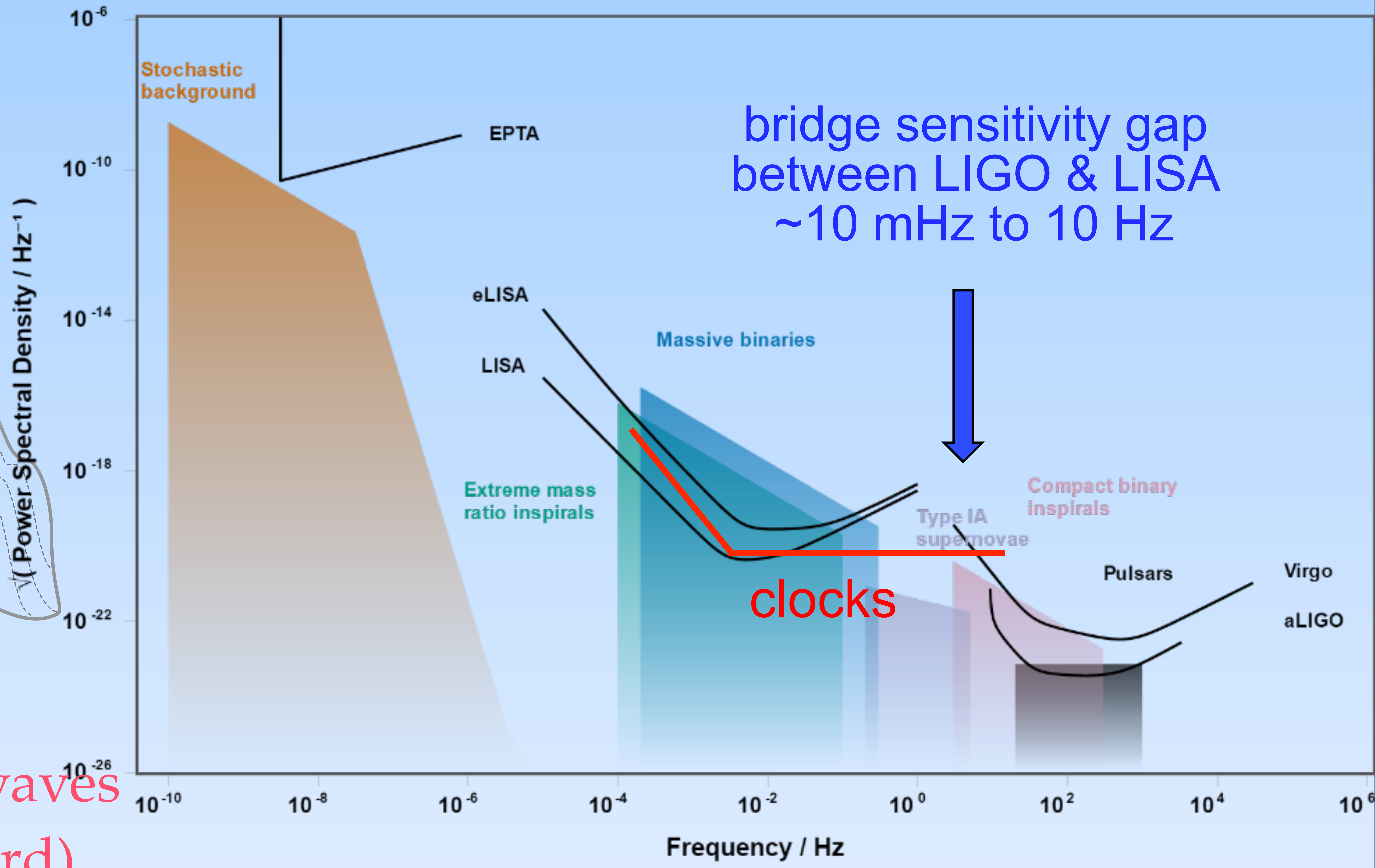


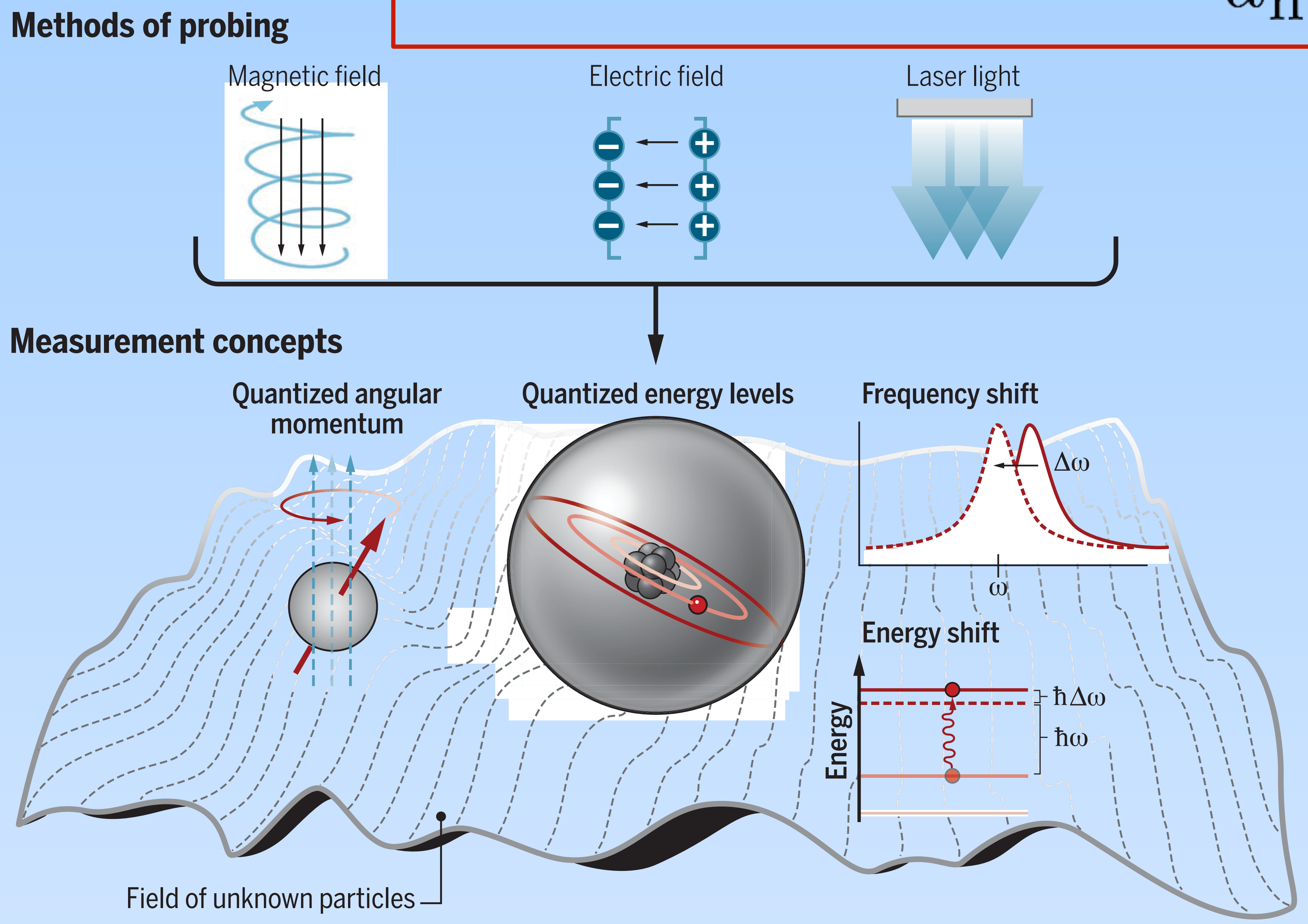
Using spins to detect gravity waves
Lukin and Walsworth (Harvard),
Hogan (Stanford), Ye (JILA),
Many others

R. Walsworth

Axions

axion dark matter ⇒ oscillating nuclear EDM: $d_n \propto a \cos \omega_a t$

$\omega_a = m_a c^2/\hbar$ axion Compton frequency



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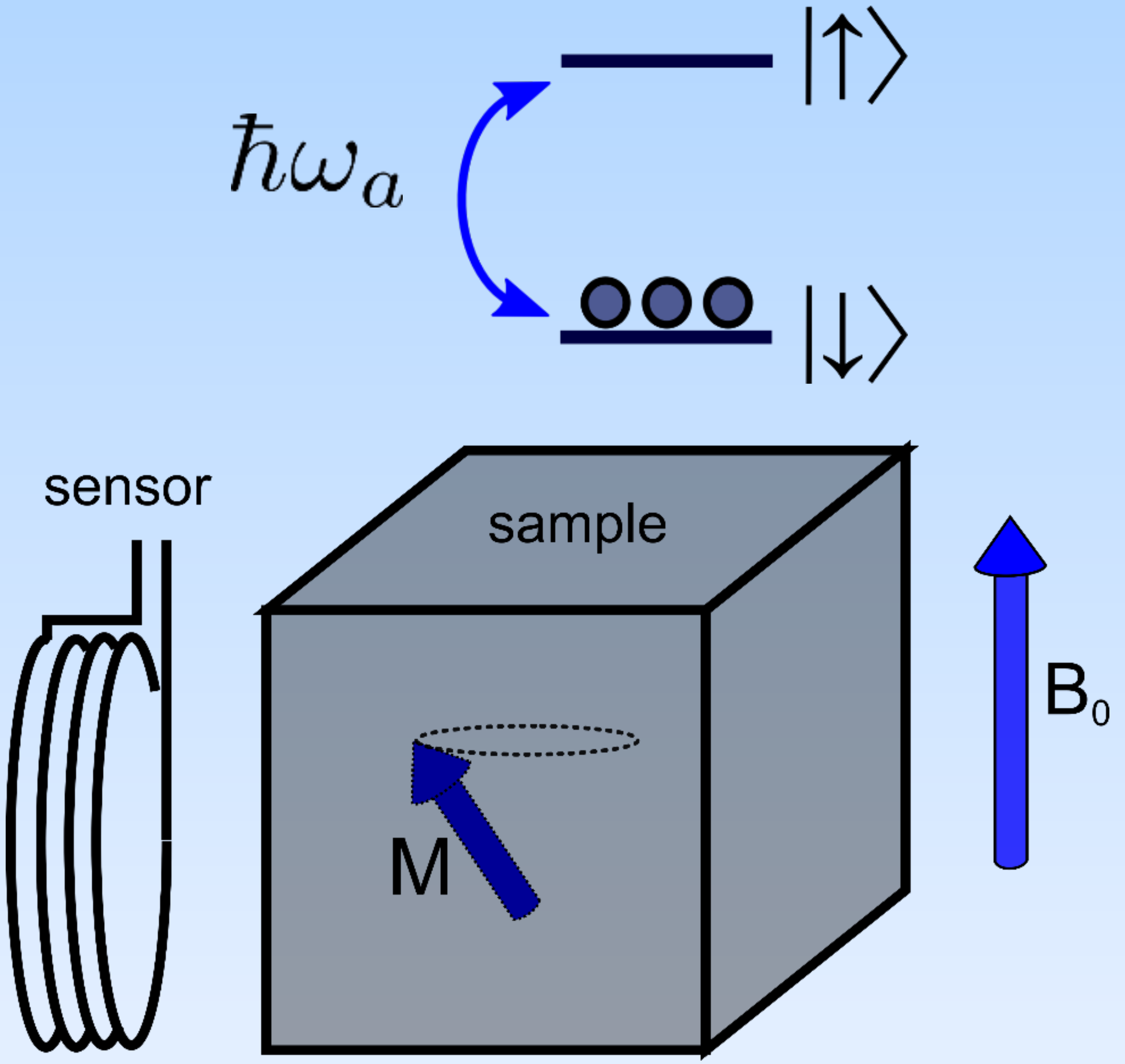


Using spins to search for ultra-light dark matter

CASPEr

Sushkov (BU), Budker (UCB/Mainz), Graham (Stanford), Rajendra (UCB)

A. Sushkov

Directional Detection of Low-Mass WIMPs

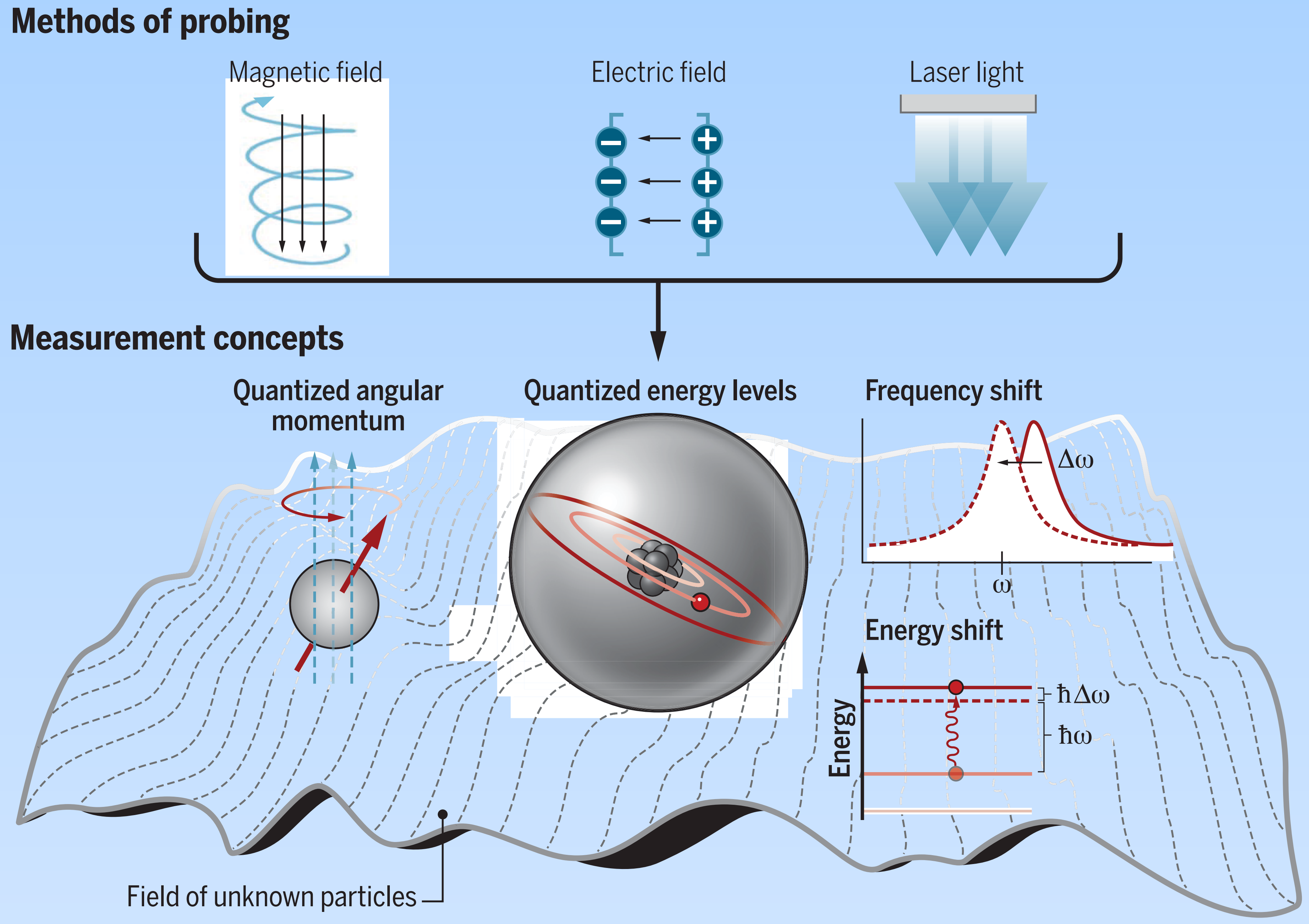
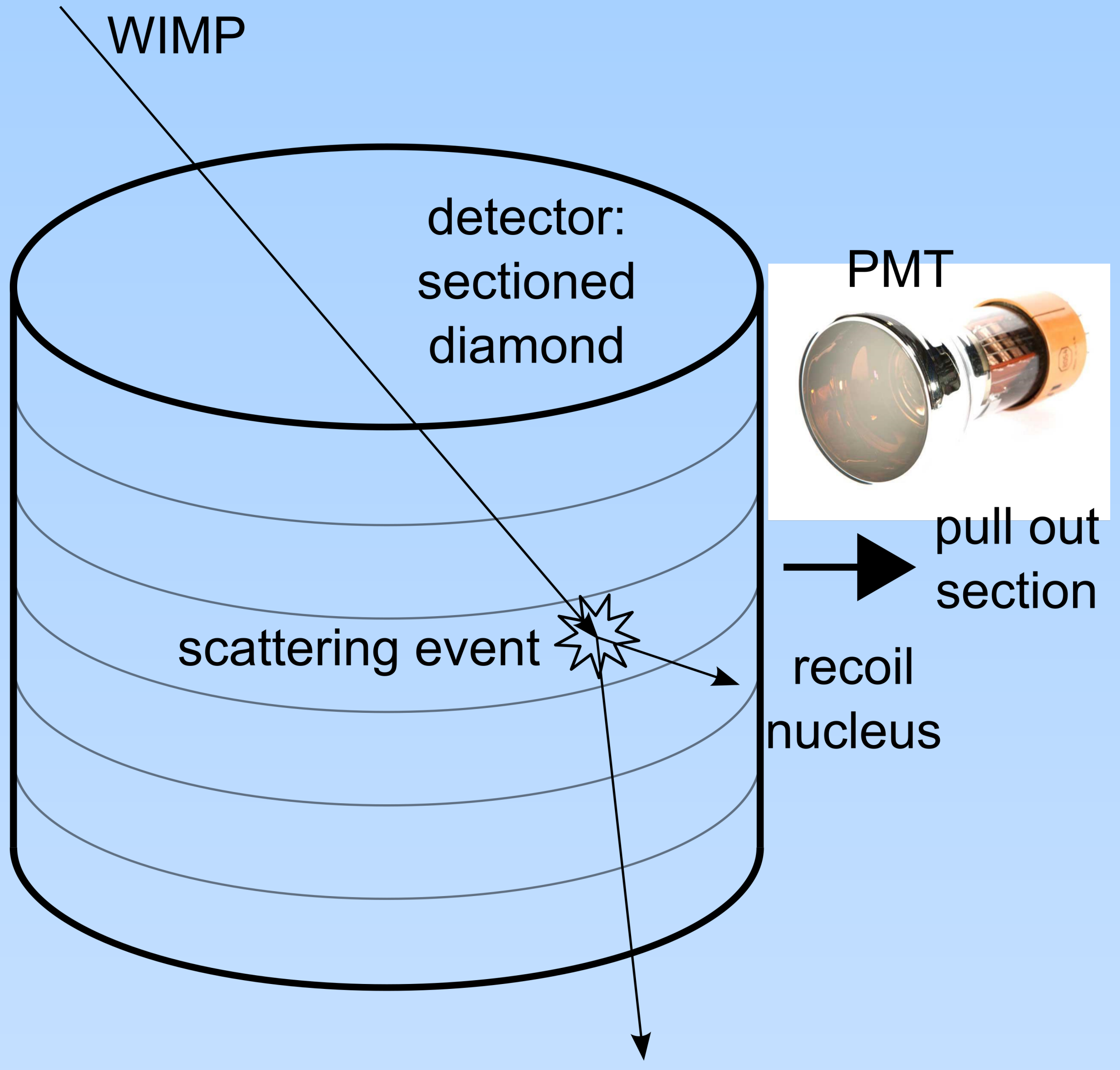
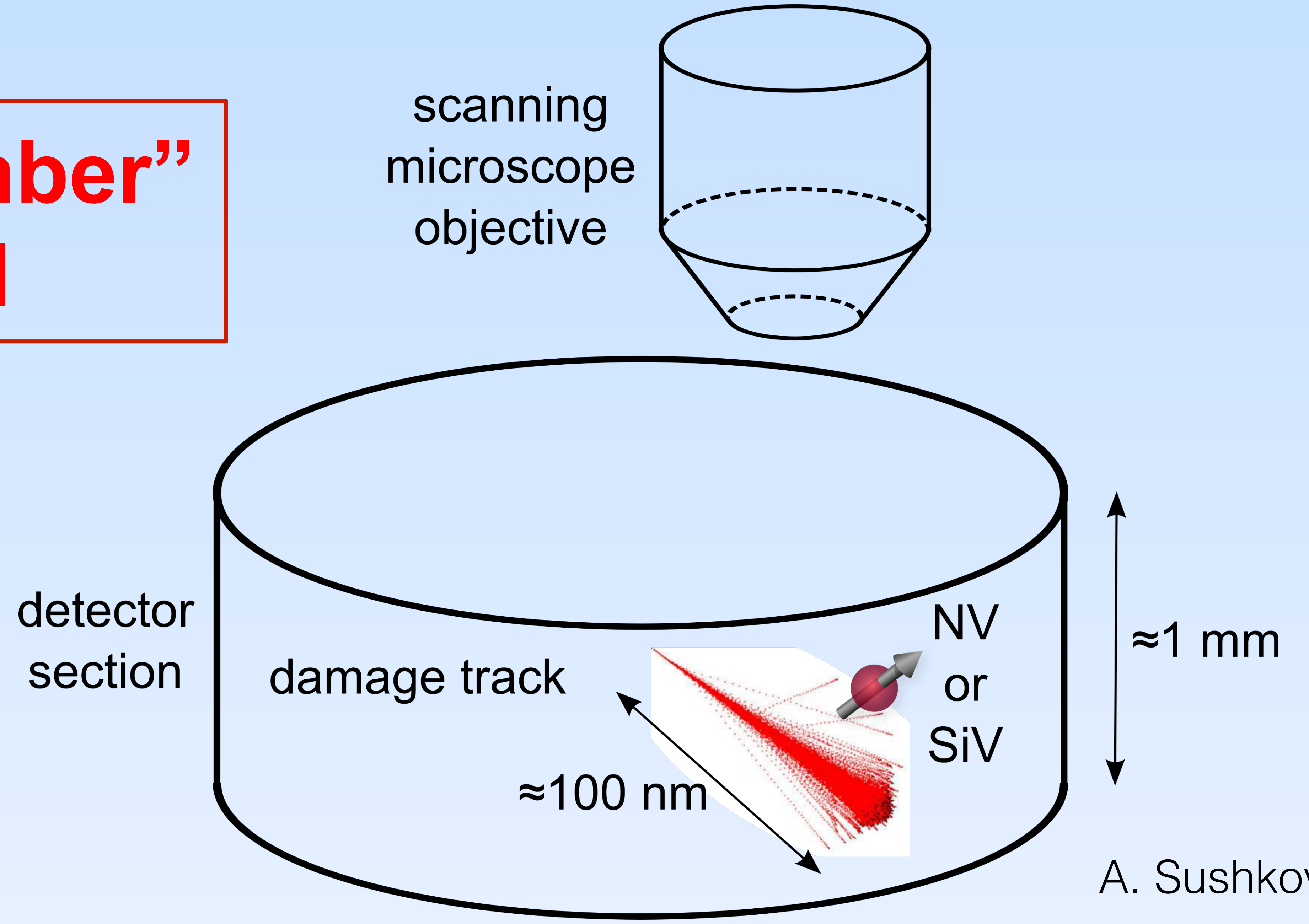


Fig. 1. Probing fundamental physics with resonance experiments.



a “bubble chamber” in diamond



A. Sushkov

Ron Walsworth (Harvard)
Alex Sushkov (Boston University)
Surjeet Rajendran (UC Berkeley)
Misha Lukin (Harvard)

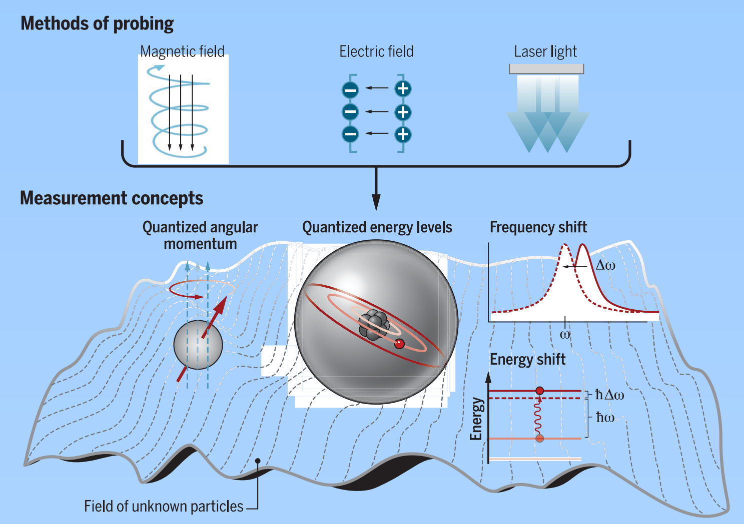
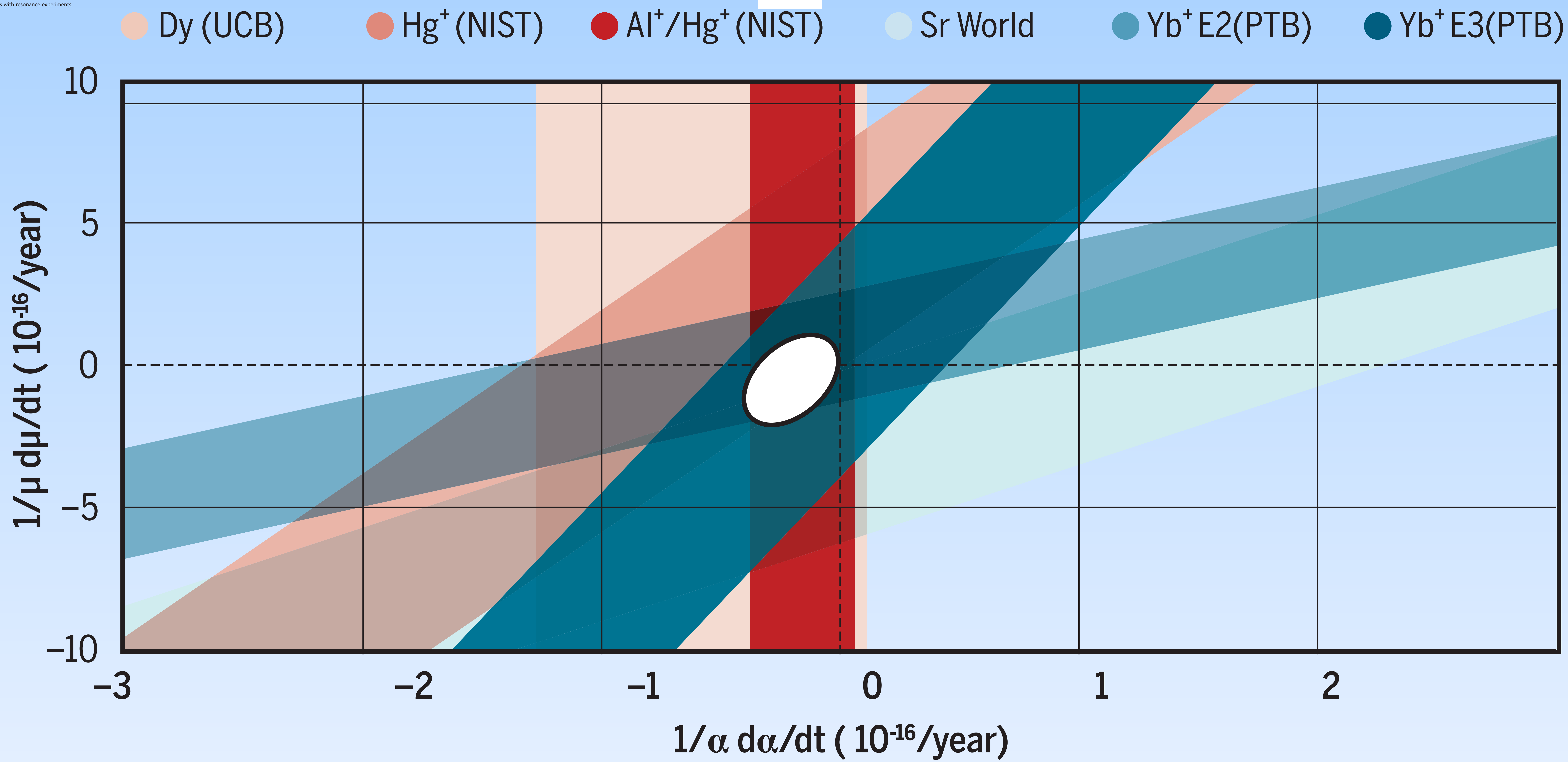


Fig. 1. Probing fundamental physics with resonance experiments.

Dark Energy through Fundamental Constants



Review Papers

Search for New Physics with Atoms and Molecules

M.S. Safronova[1,2], D. Budker[3,4,5], D. DeMille[6], Derek F. Jackson Kimball[7], A. Derevianko[8] and C. W. Clark[2]

[1]University of Delaware, Newark, Delaware, USA,
[2]Joint Quantum Institute, National Institute of Standards and Technology and the University of Maryland, College Park, Maryland, USA,
[3]Helmholtz Institute, Johannes Gutenberg University, Mainz, Germany,
[4]University of California, Berkeley, California, USA,
[5]Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA
[6]Yale University, New Haven, Connecticut, USA,
[7]California State University, East Bay, Hayward, California, USA,
[8]University of Nevada, Reno, Nevada, USA

arXiv:1710.01833v1 [physics.atom-ph] 5 Oct 2017

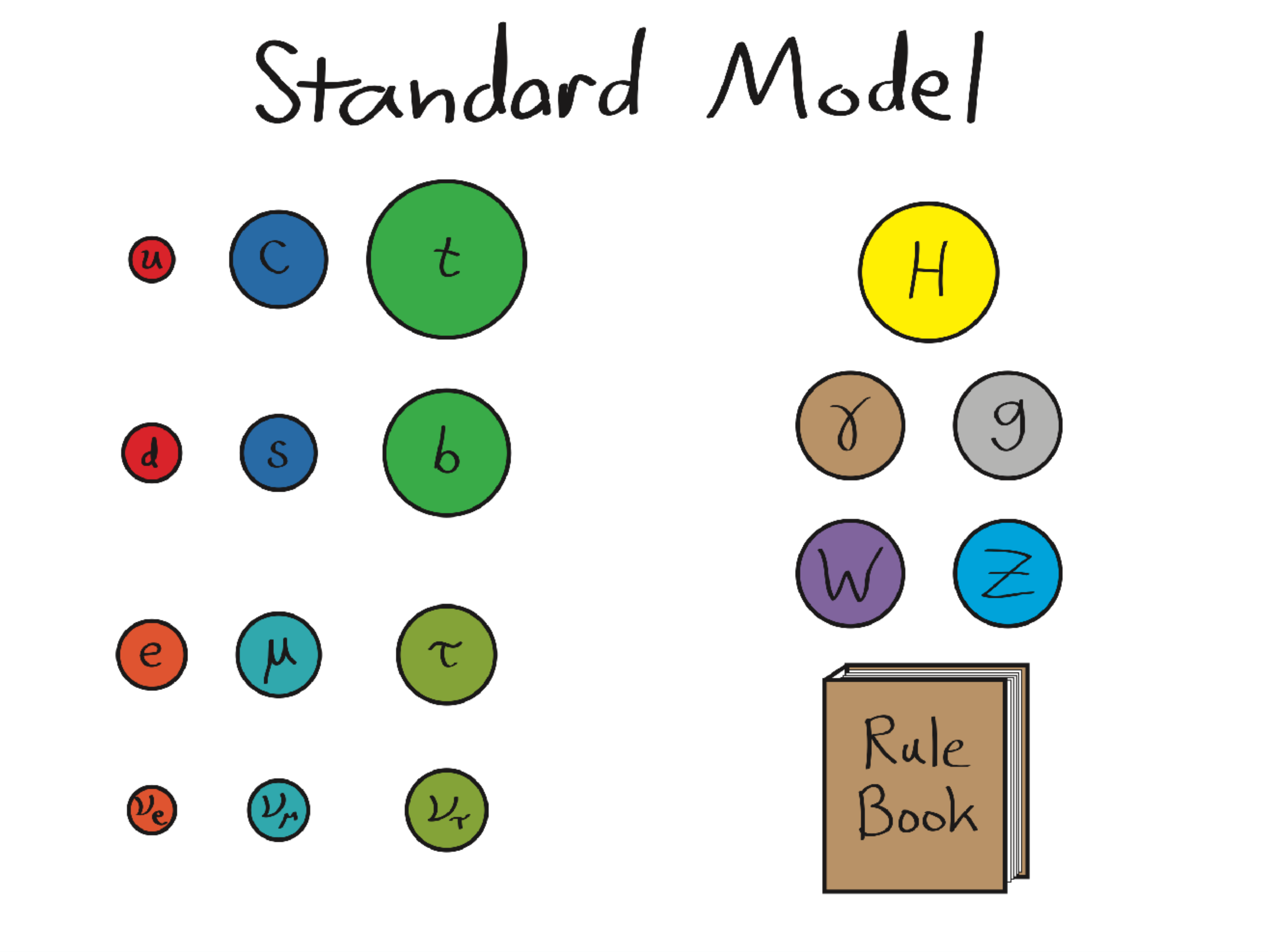
REVIEW

Probing the frontiers of particle physics with tabletop-scale experiments

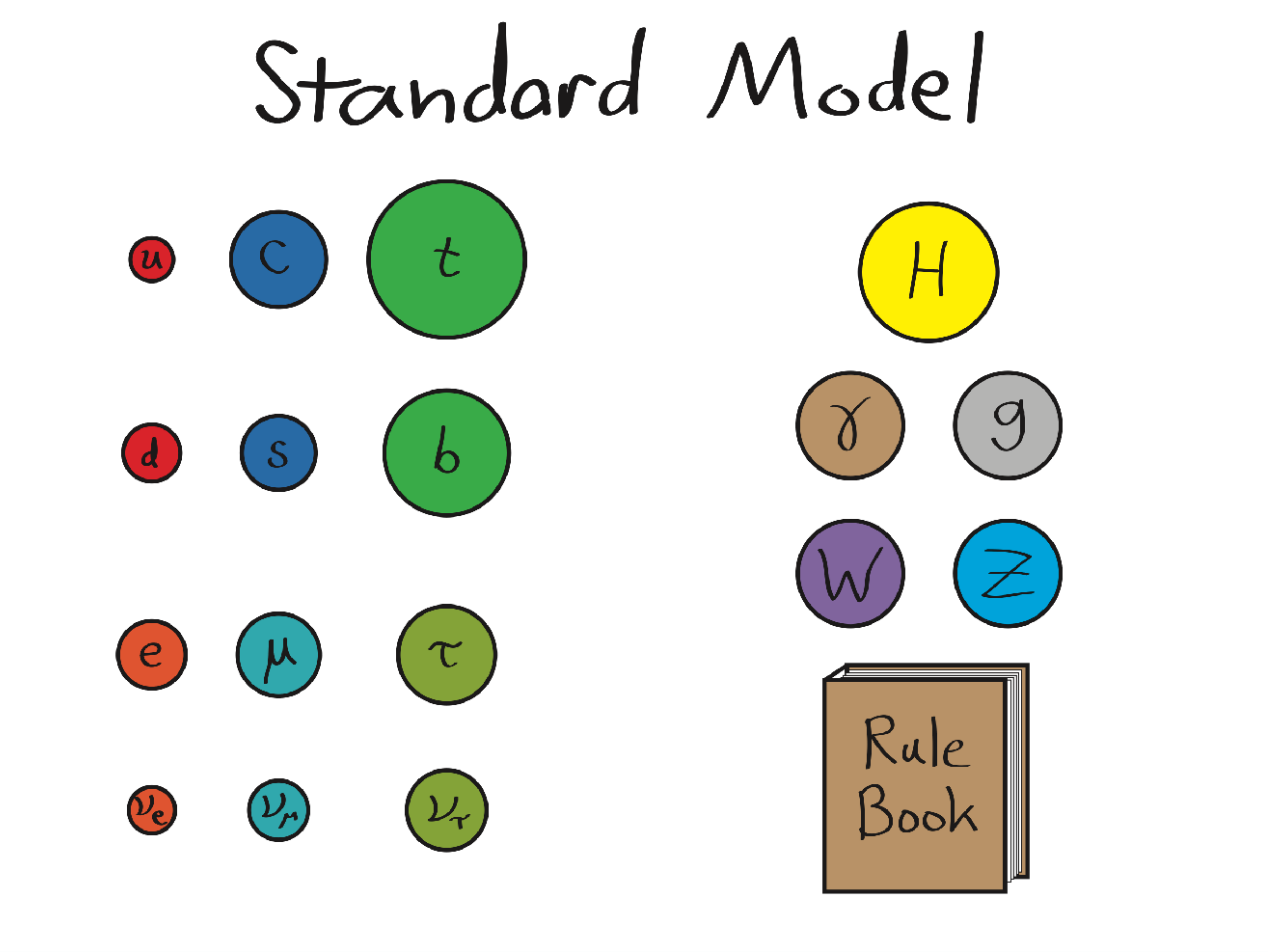
David DeMille,[1]* John M. Doyle,[2]* Alexander O. Sushkov[3,4]*

Science 2017

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

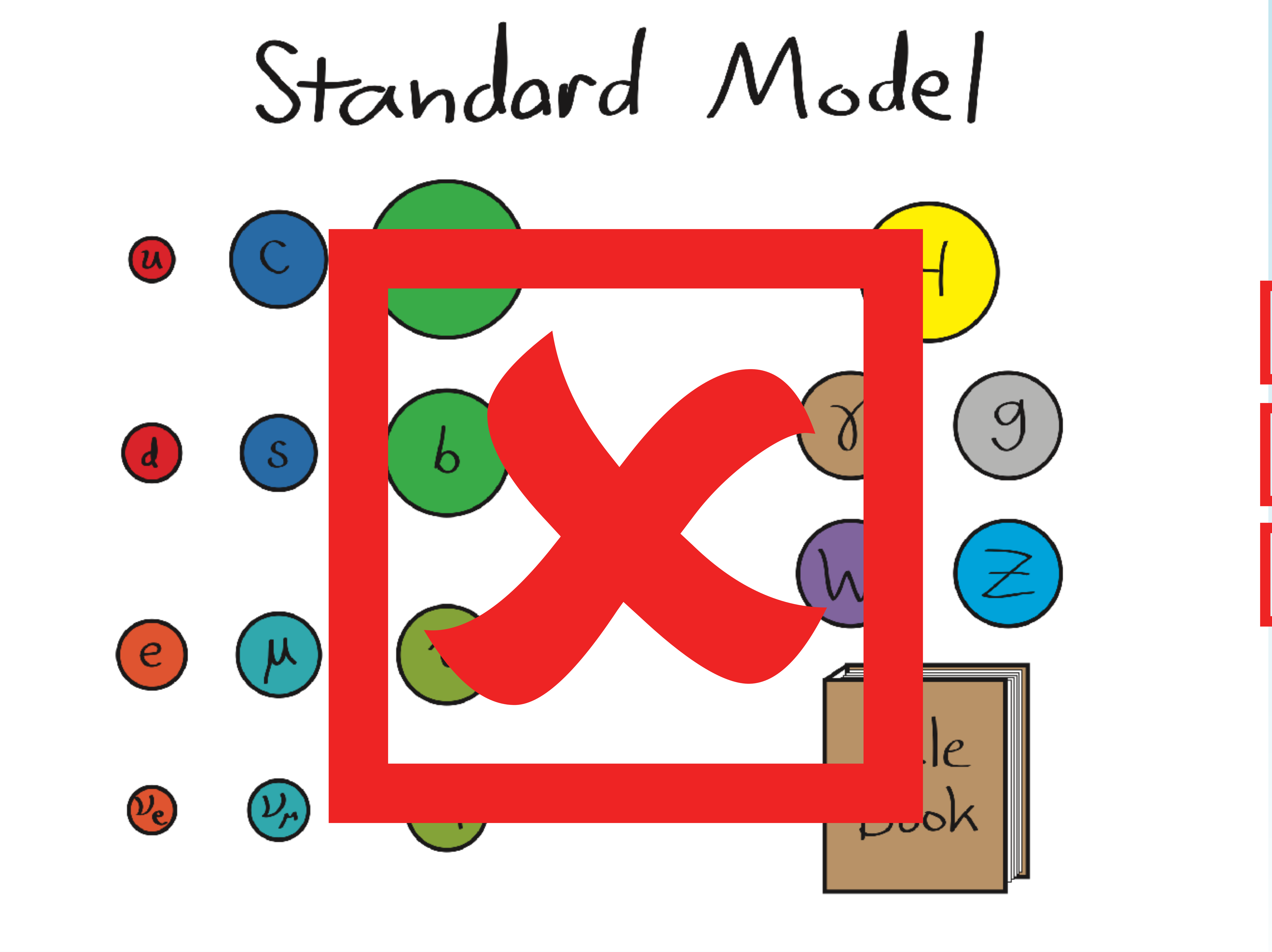


The "Standard Model" Does Not Explain Everything about Particle Physics



Key Unresolved Questions

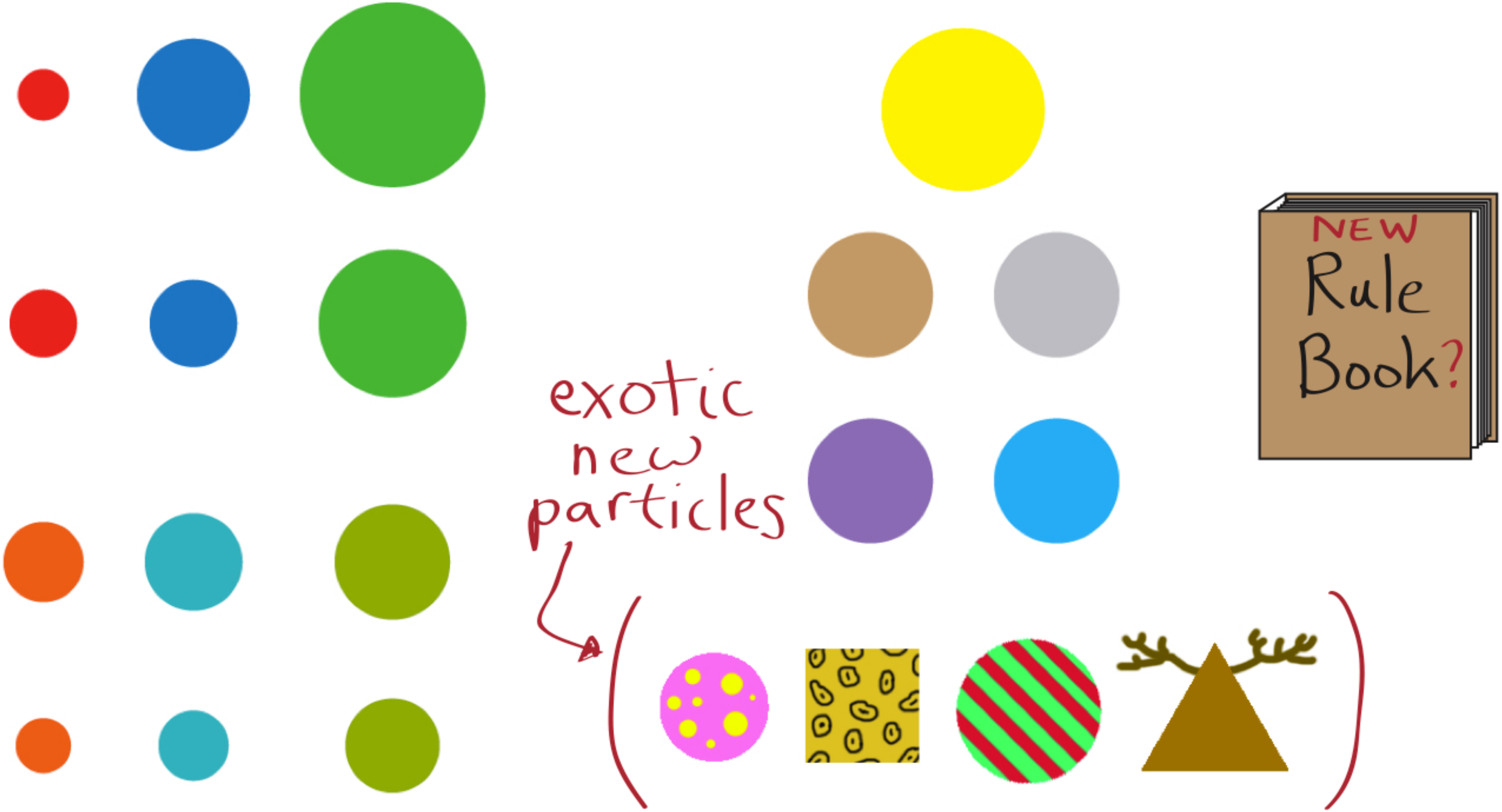
The “Standard Model” Does Not Explain Everything about Particle Physics



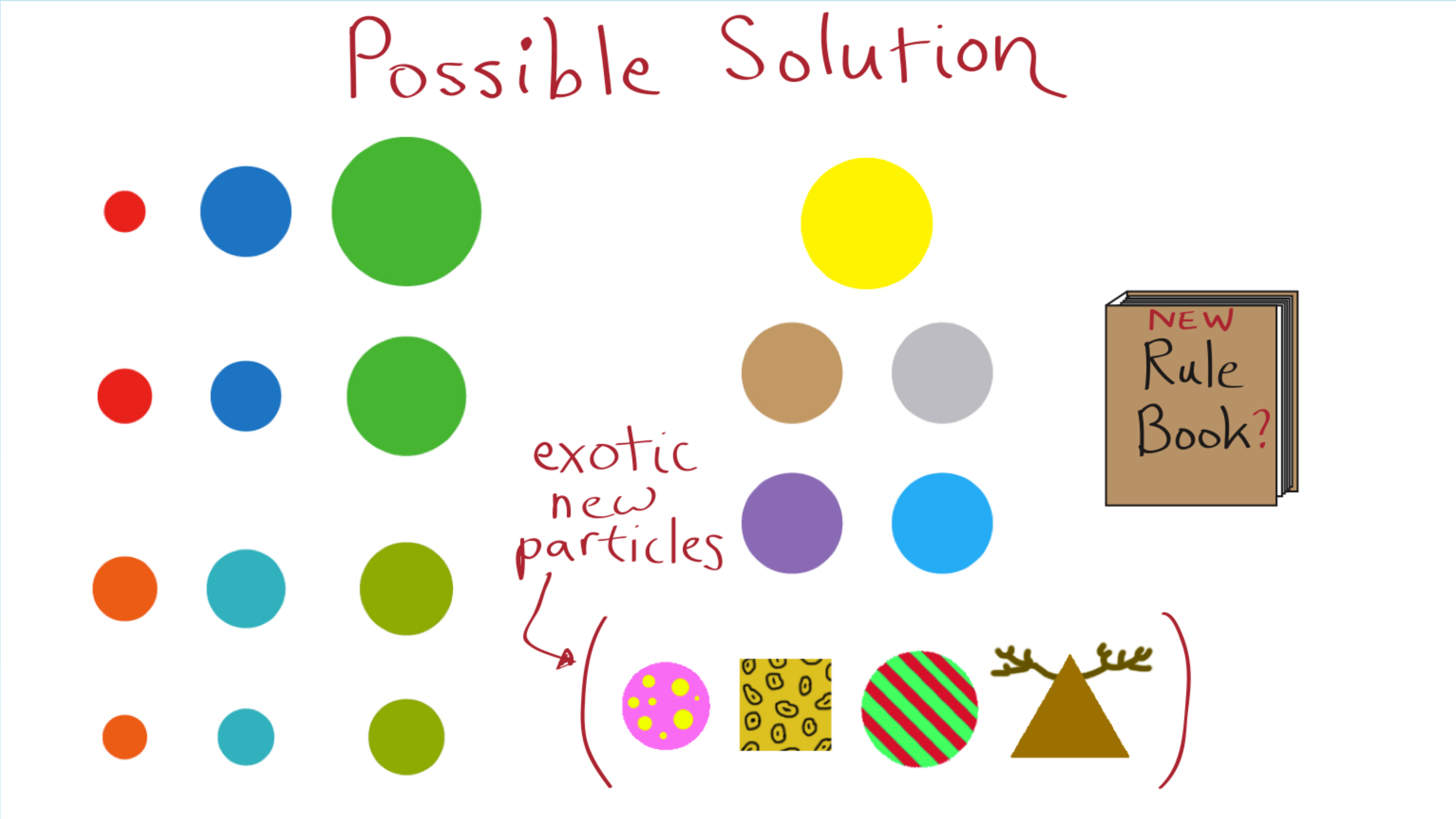
Key Unresolved Questions

- Dark Matter
- Matter-Anti Matter
- Hierarchy “Problem”

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

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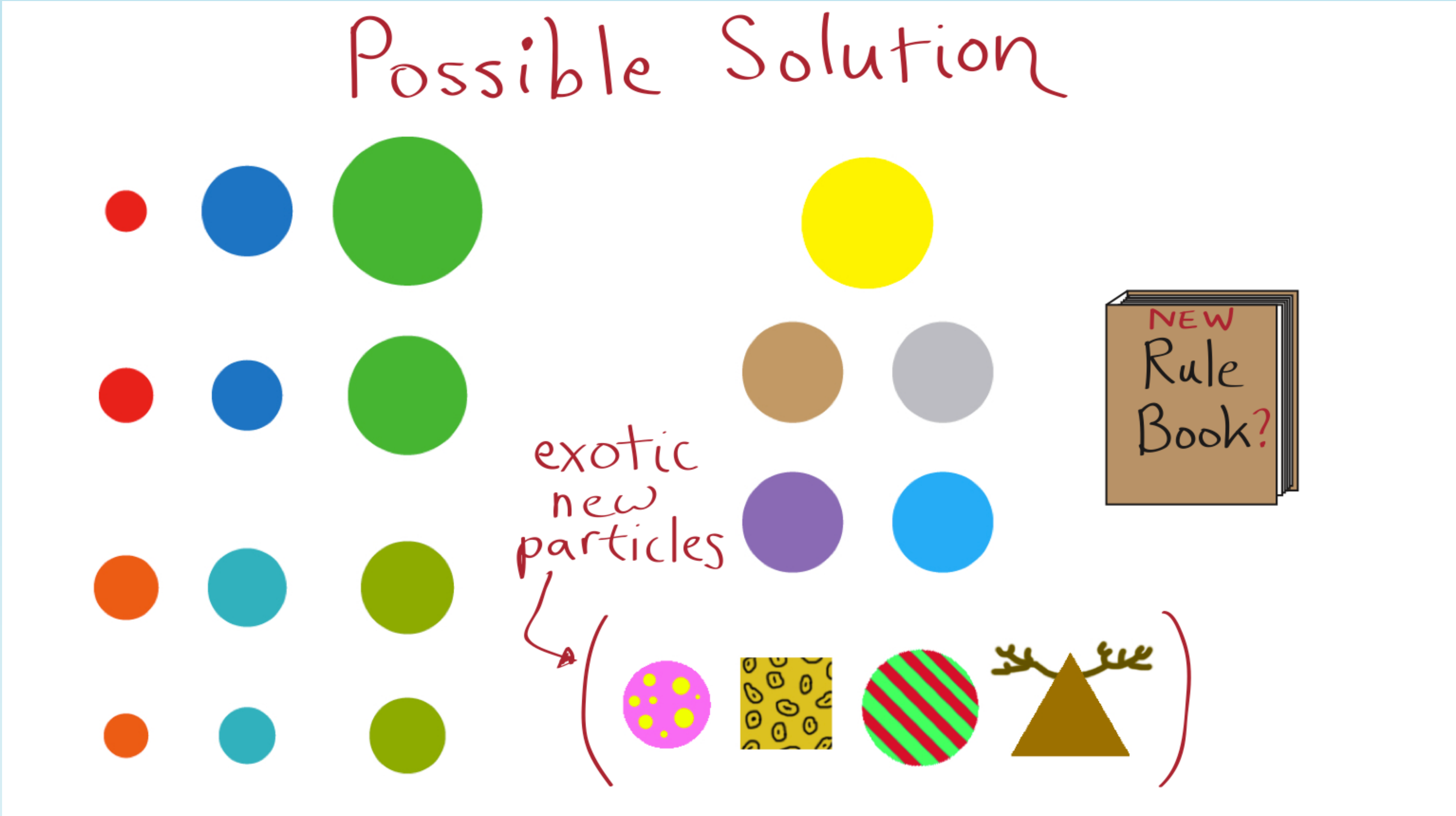

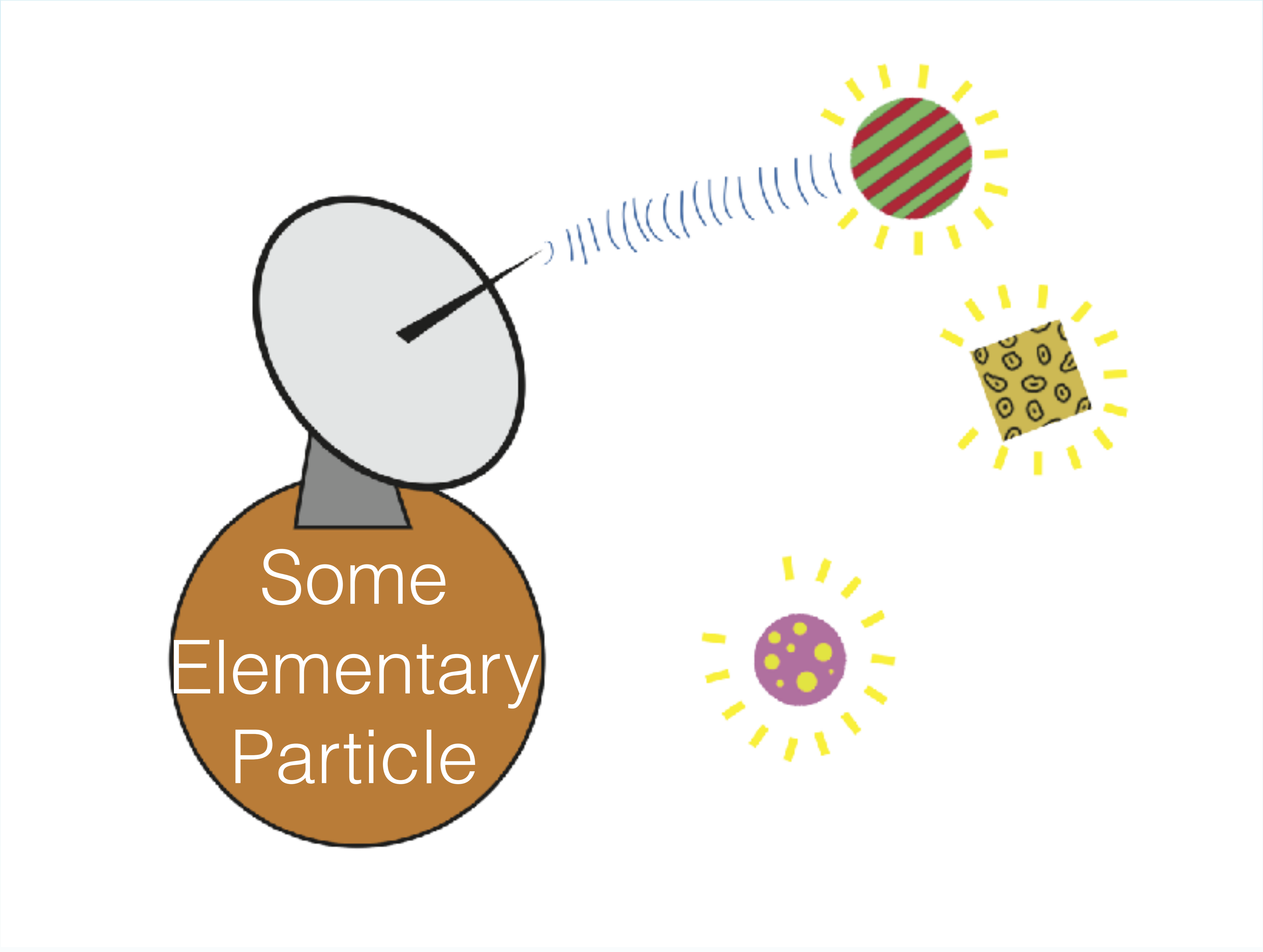

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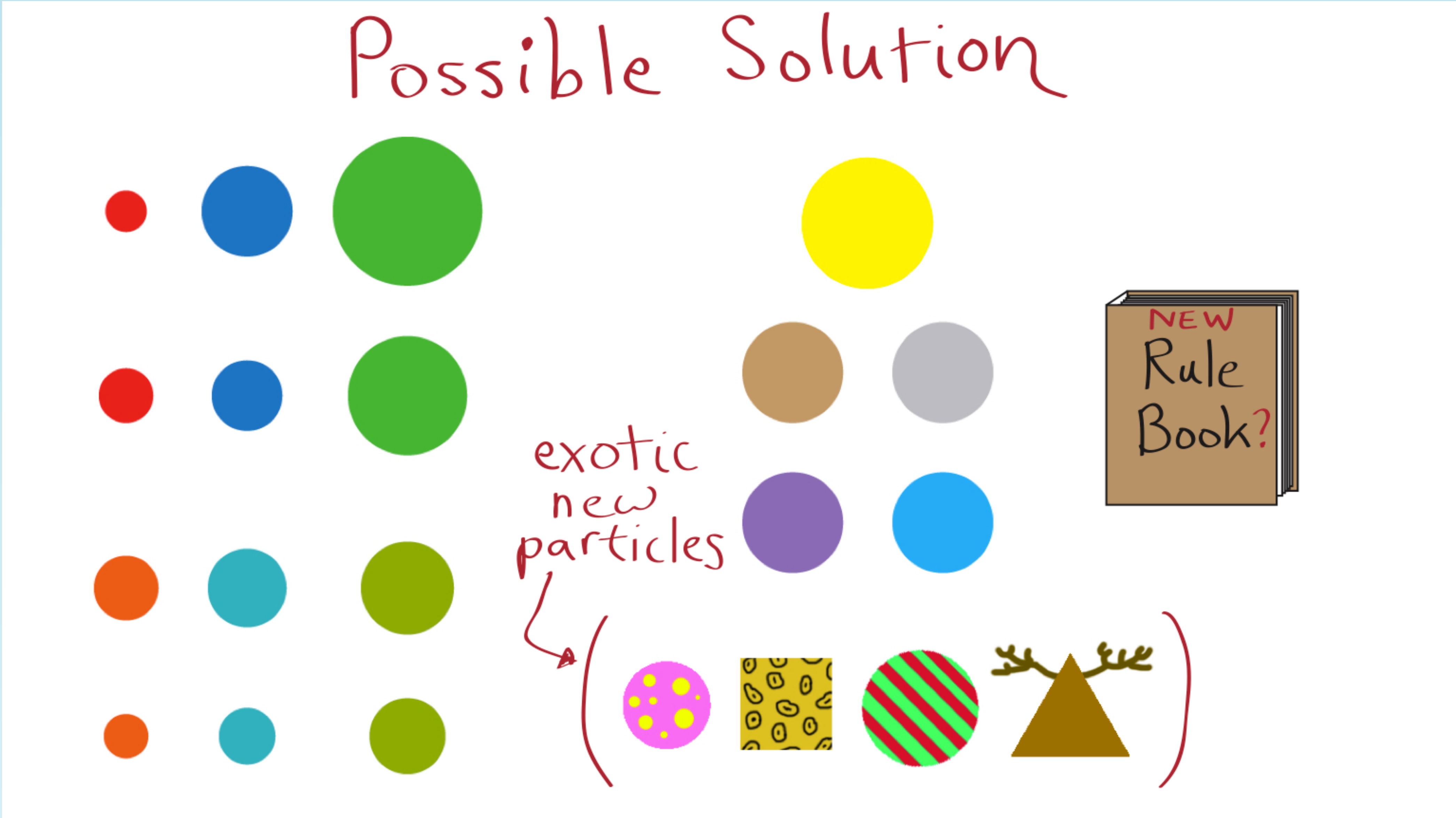
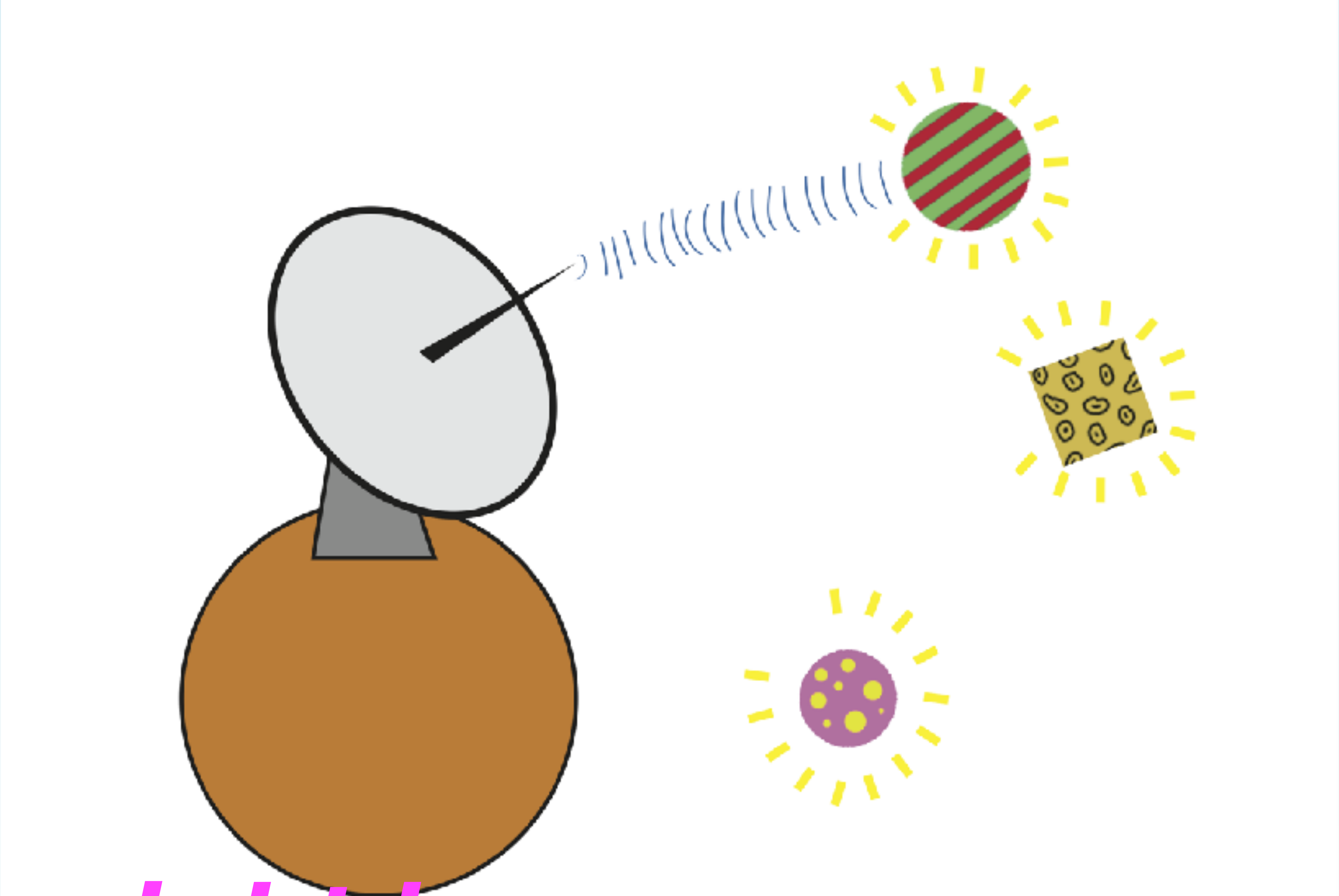
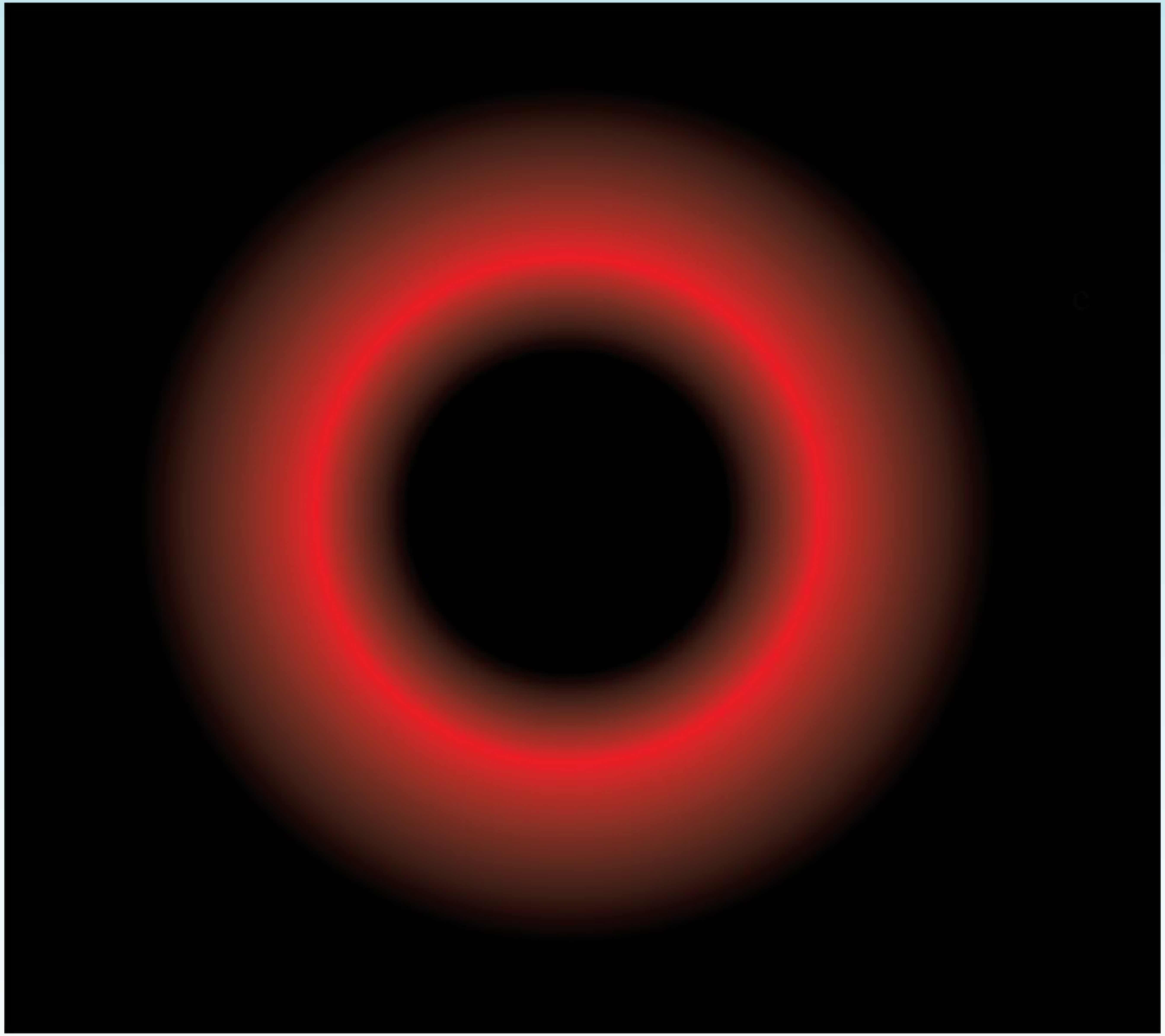




Those new particles are right here, now.

Electron is dressed by Virtual Particles — g-2



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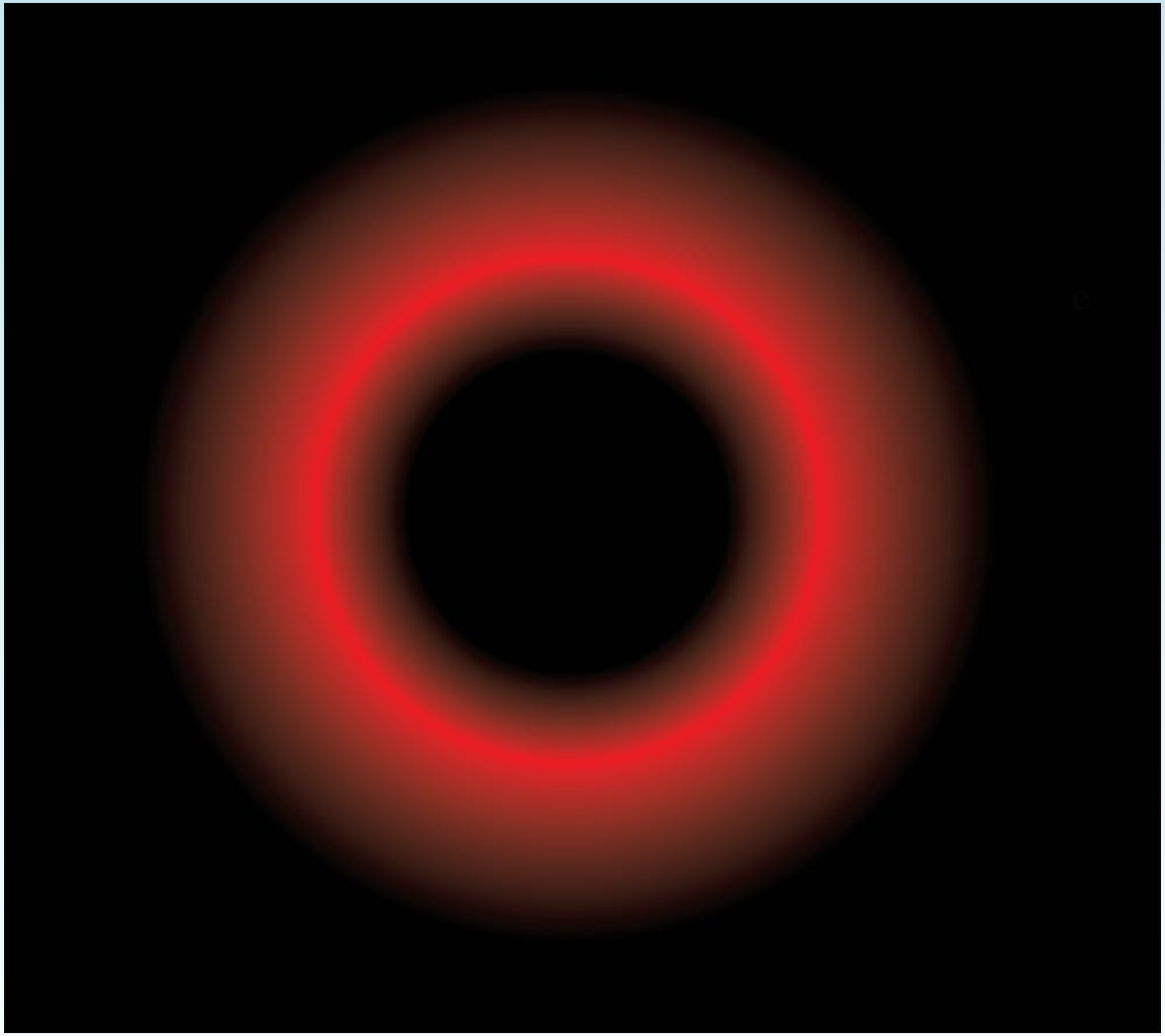

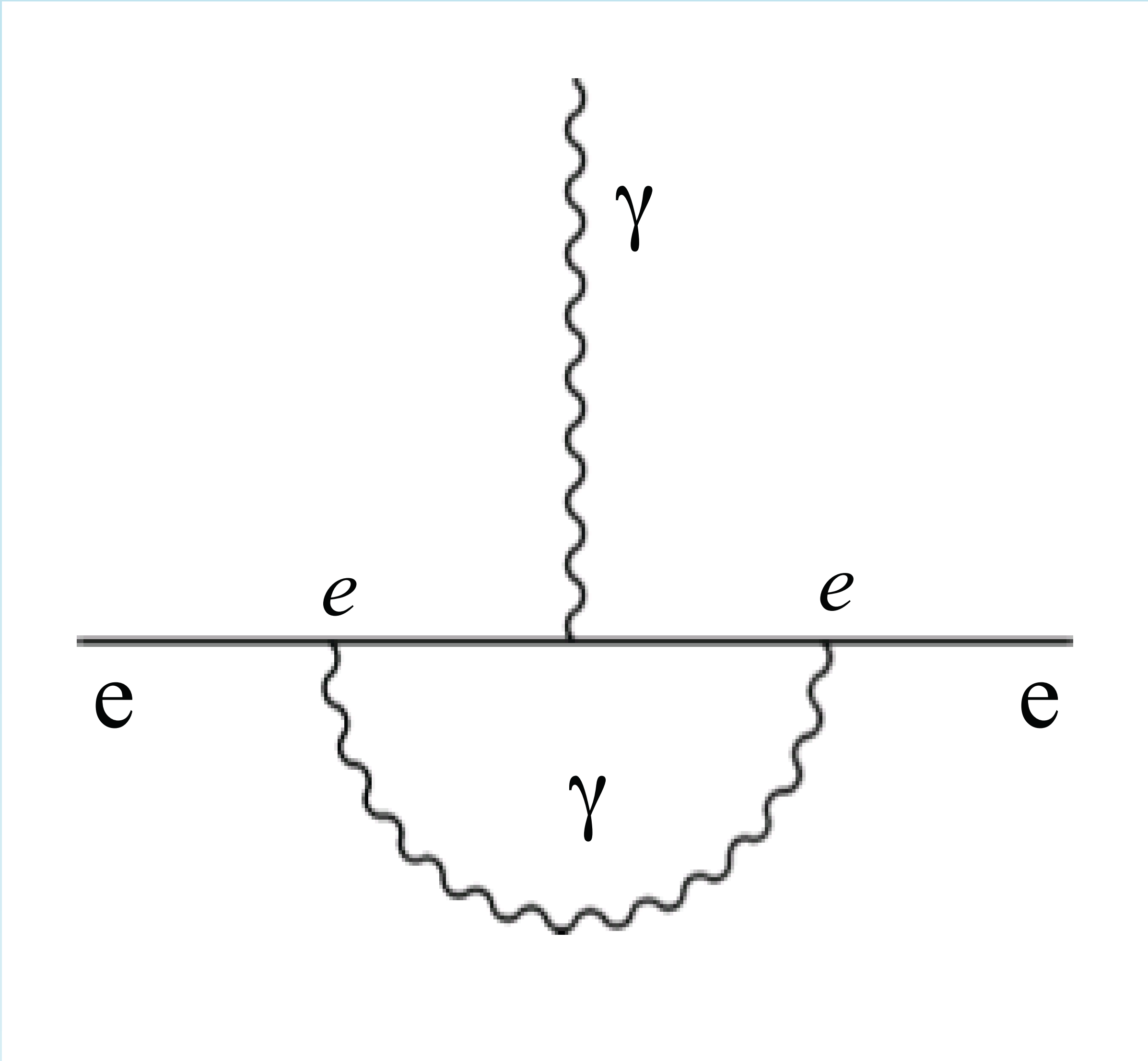

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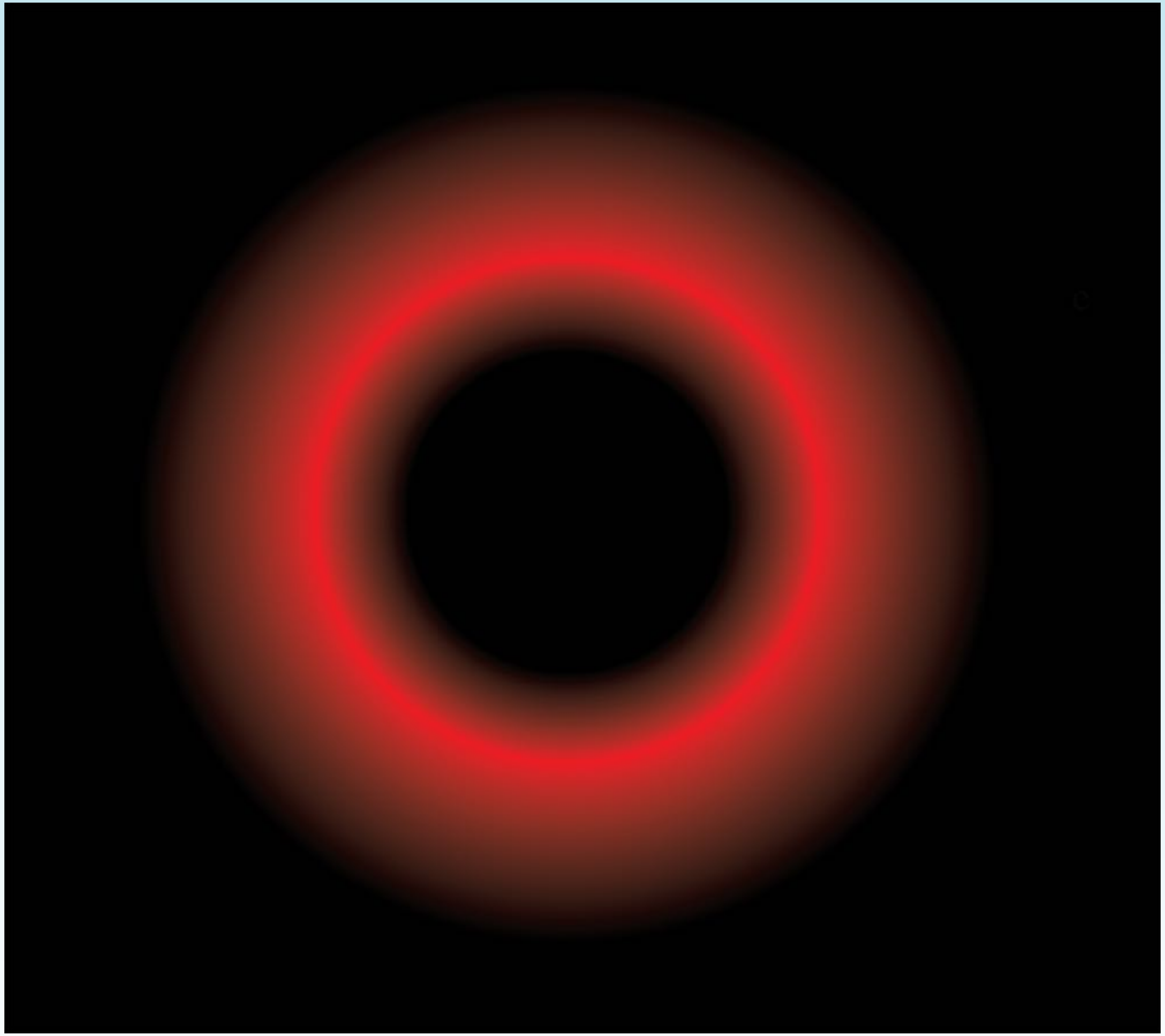
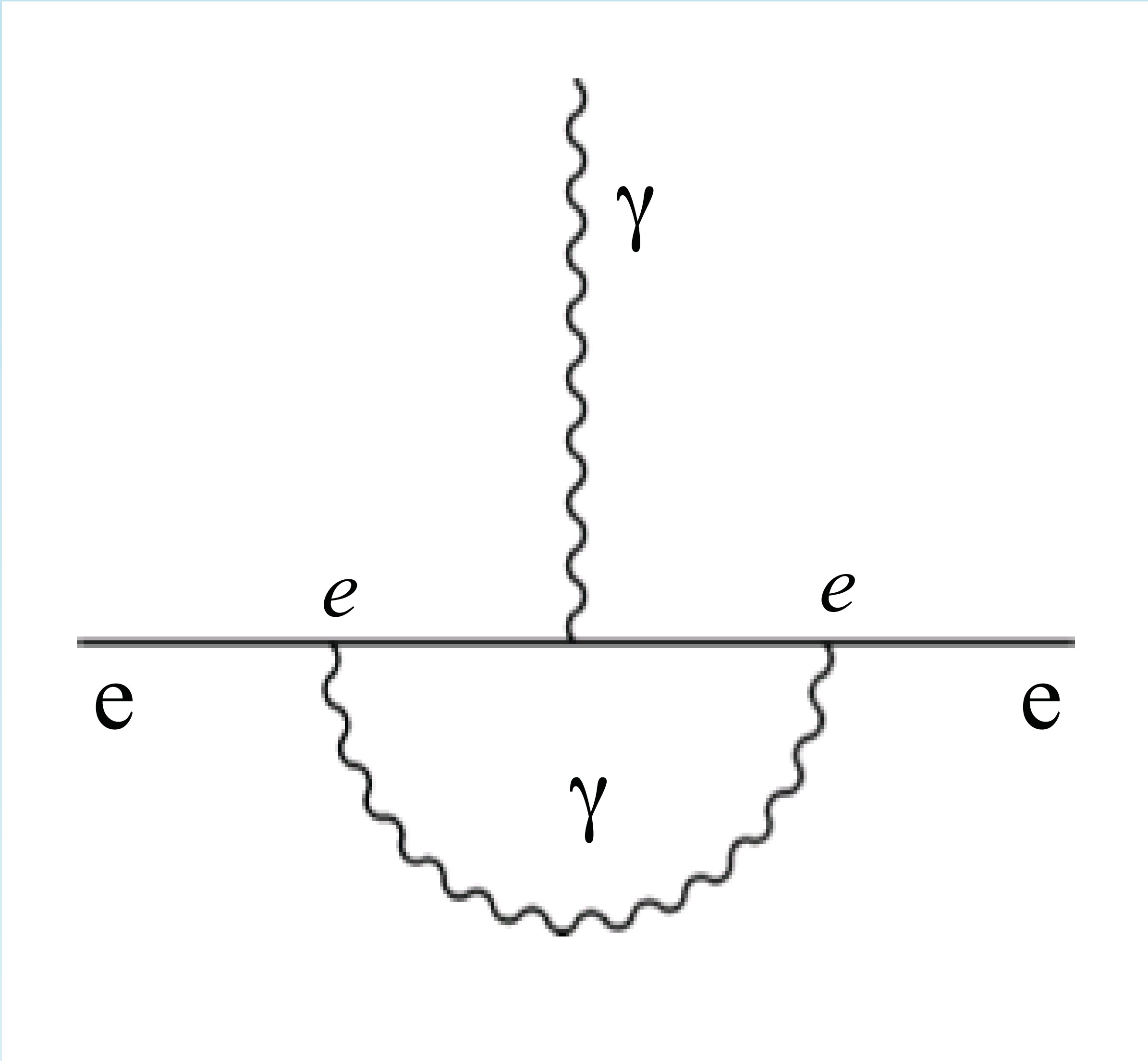
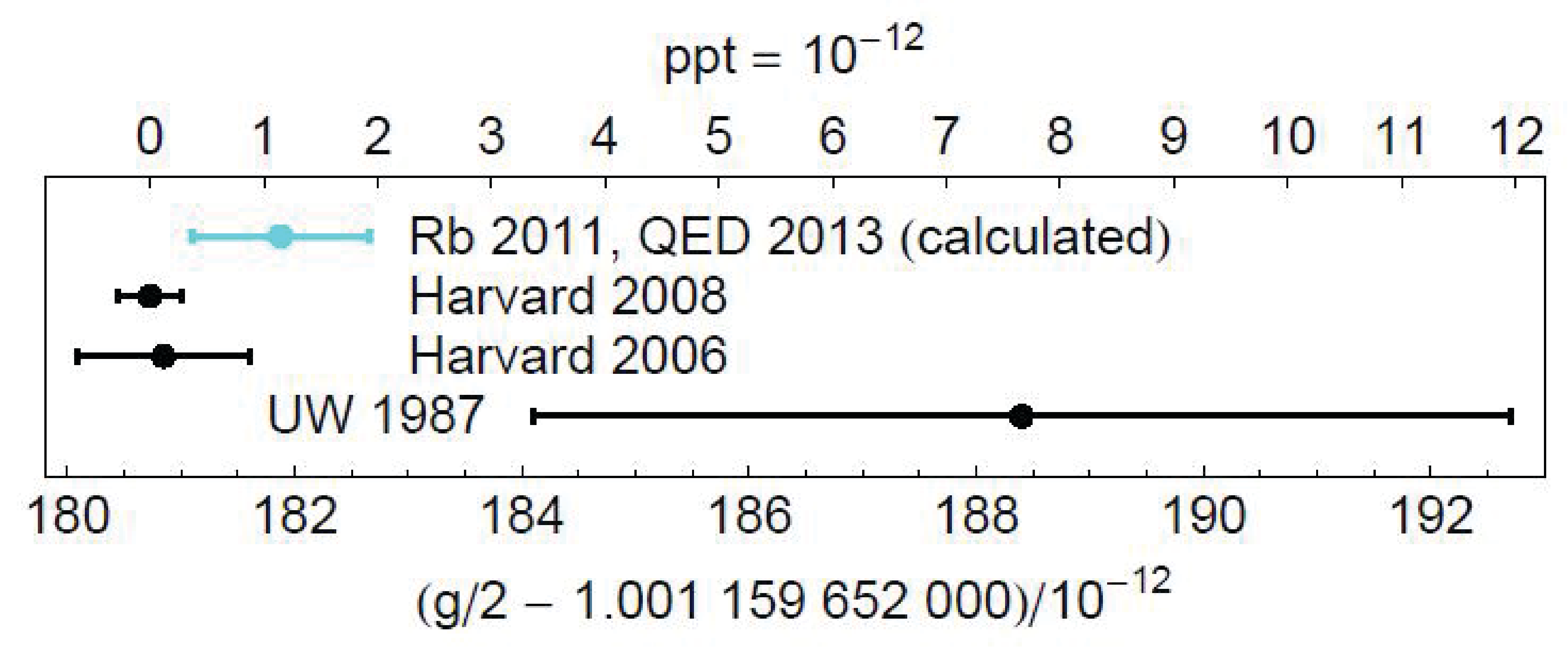




Gabriesle group
confirms SM QED
ppt



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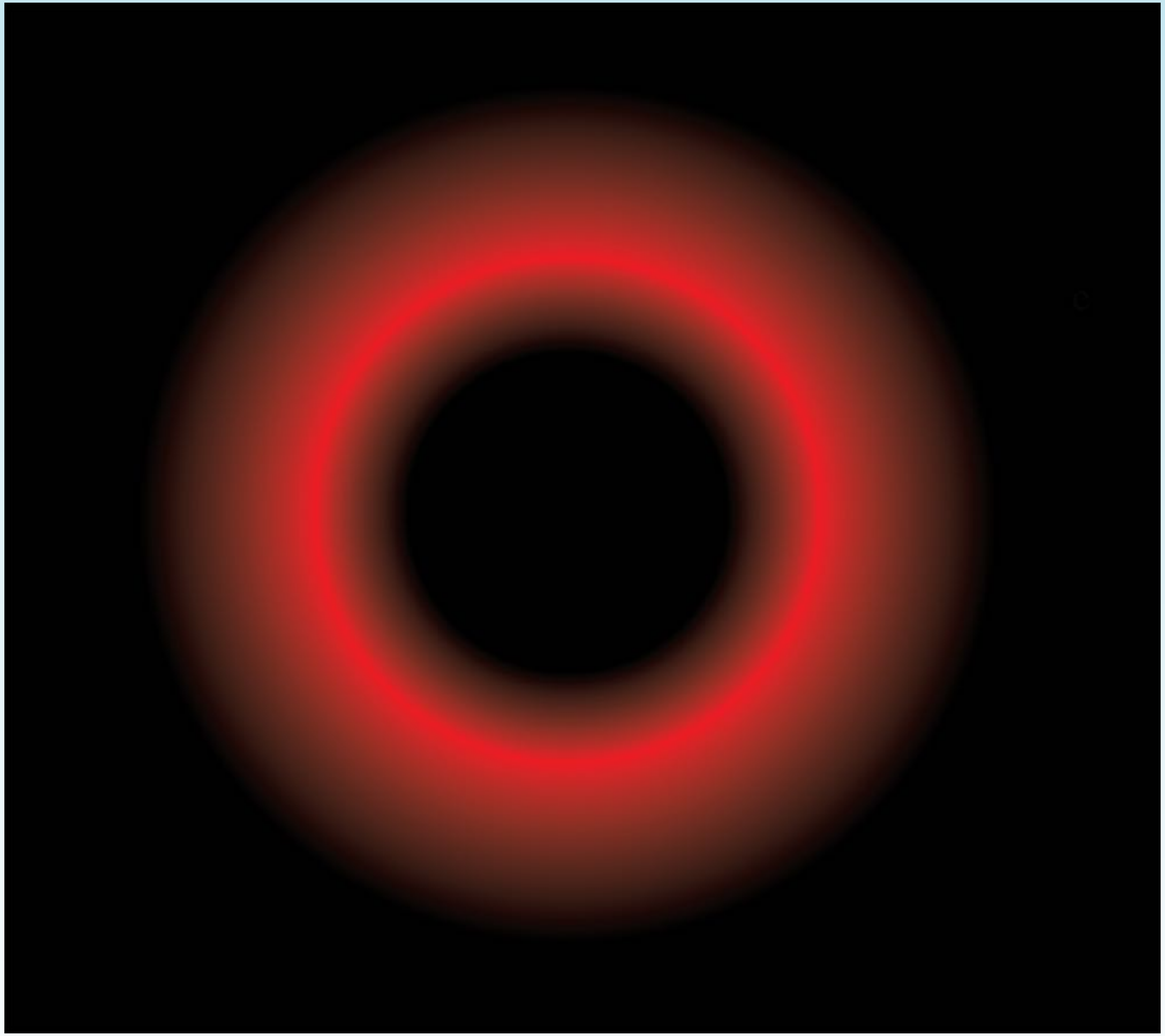
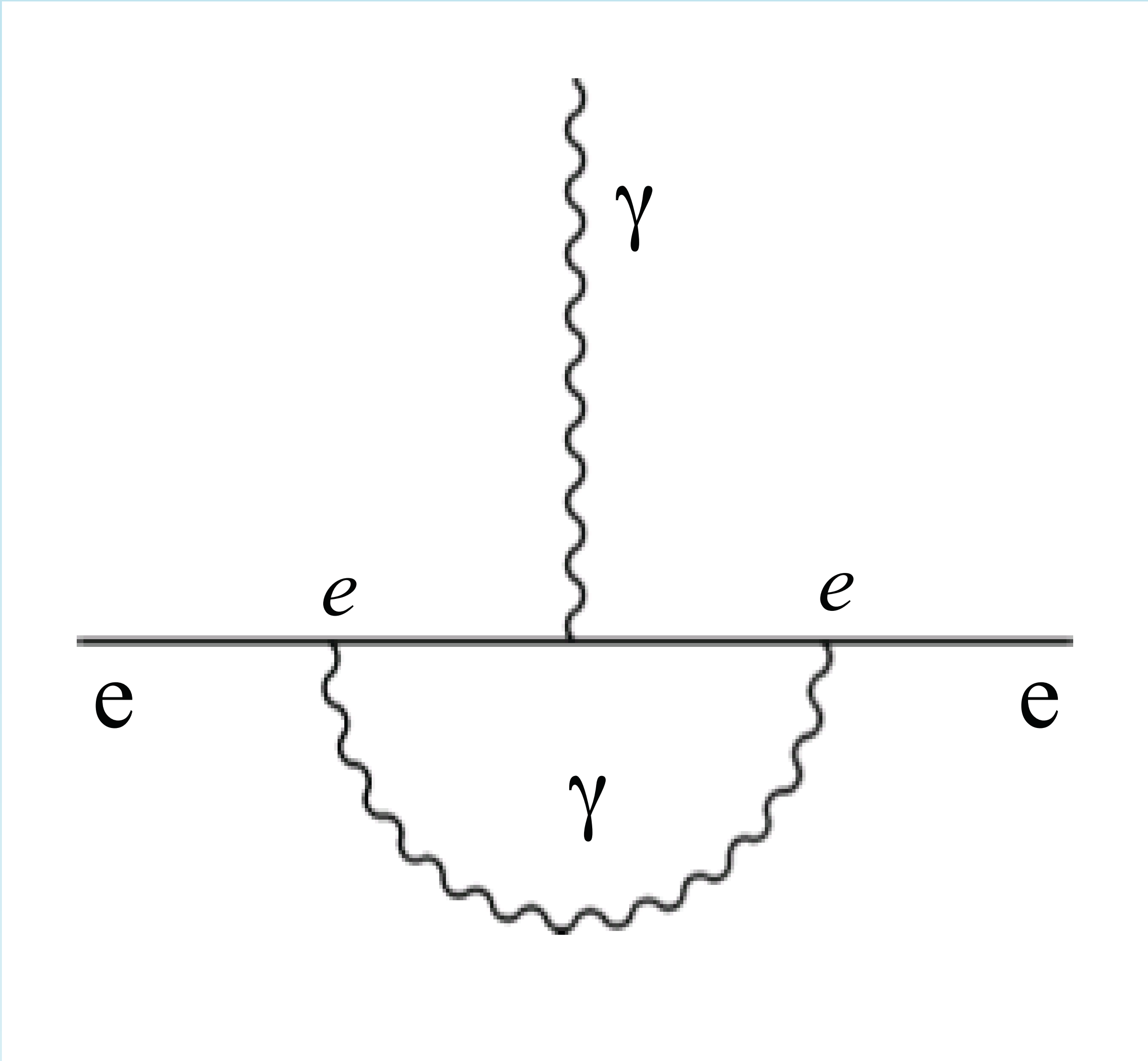
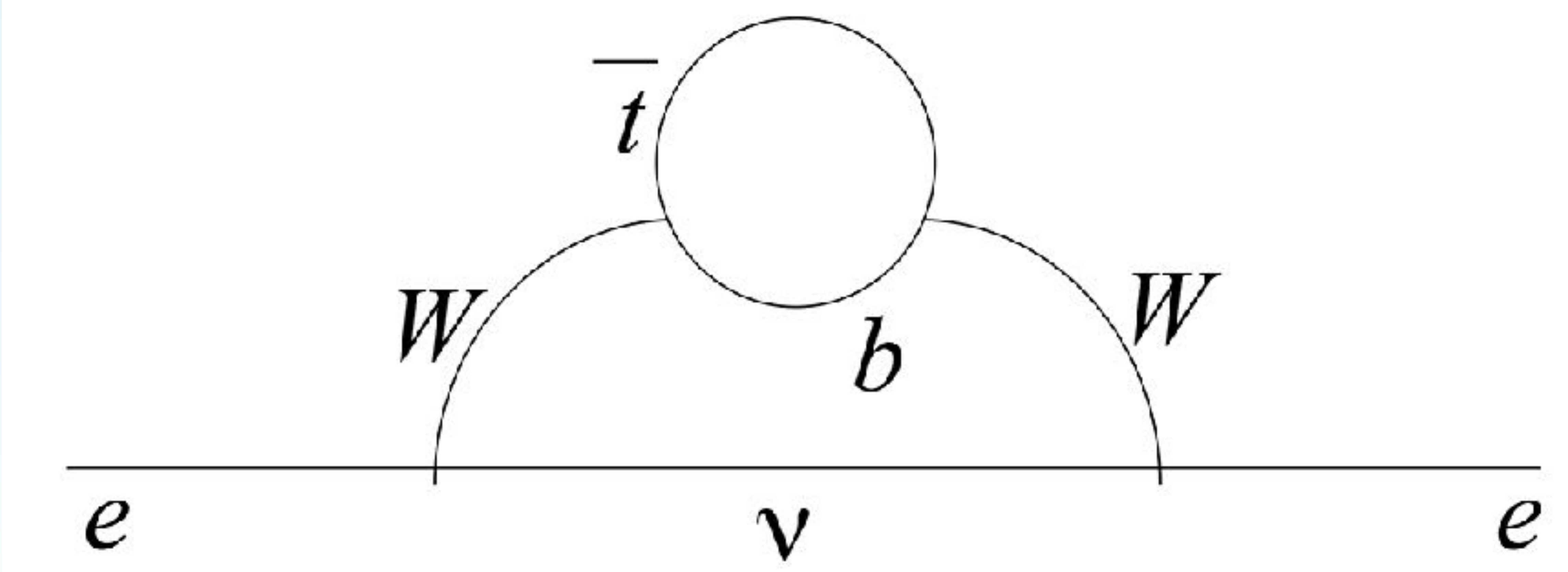


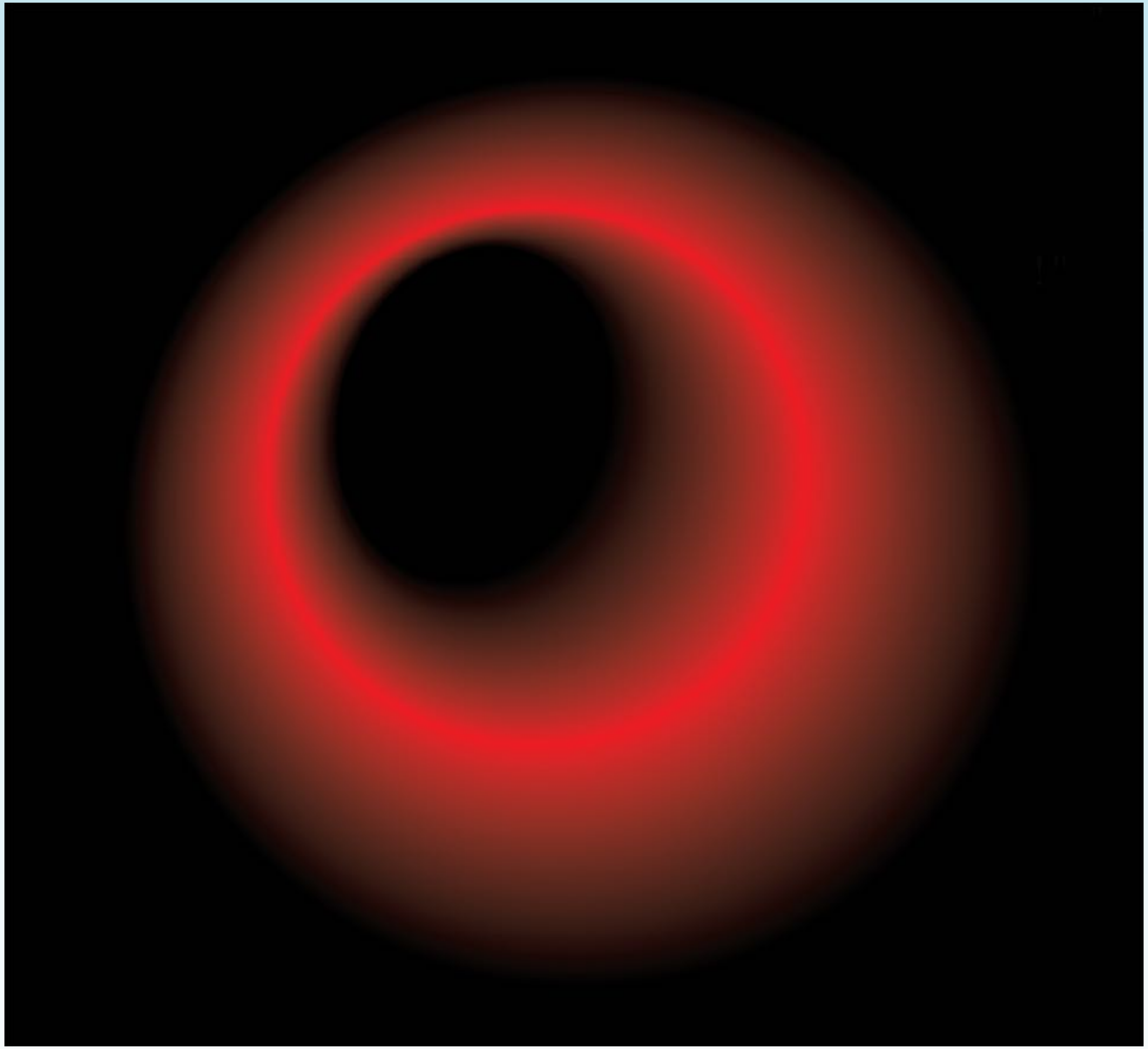


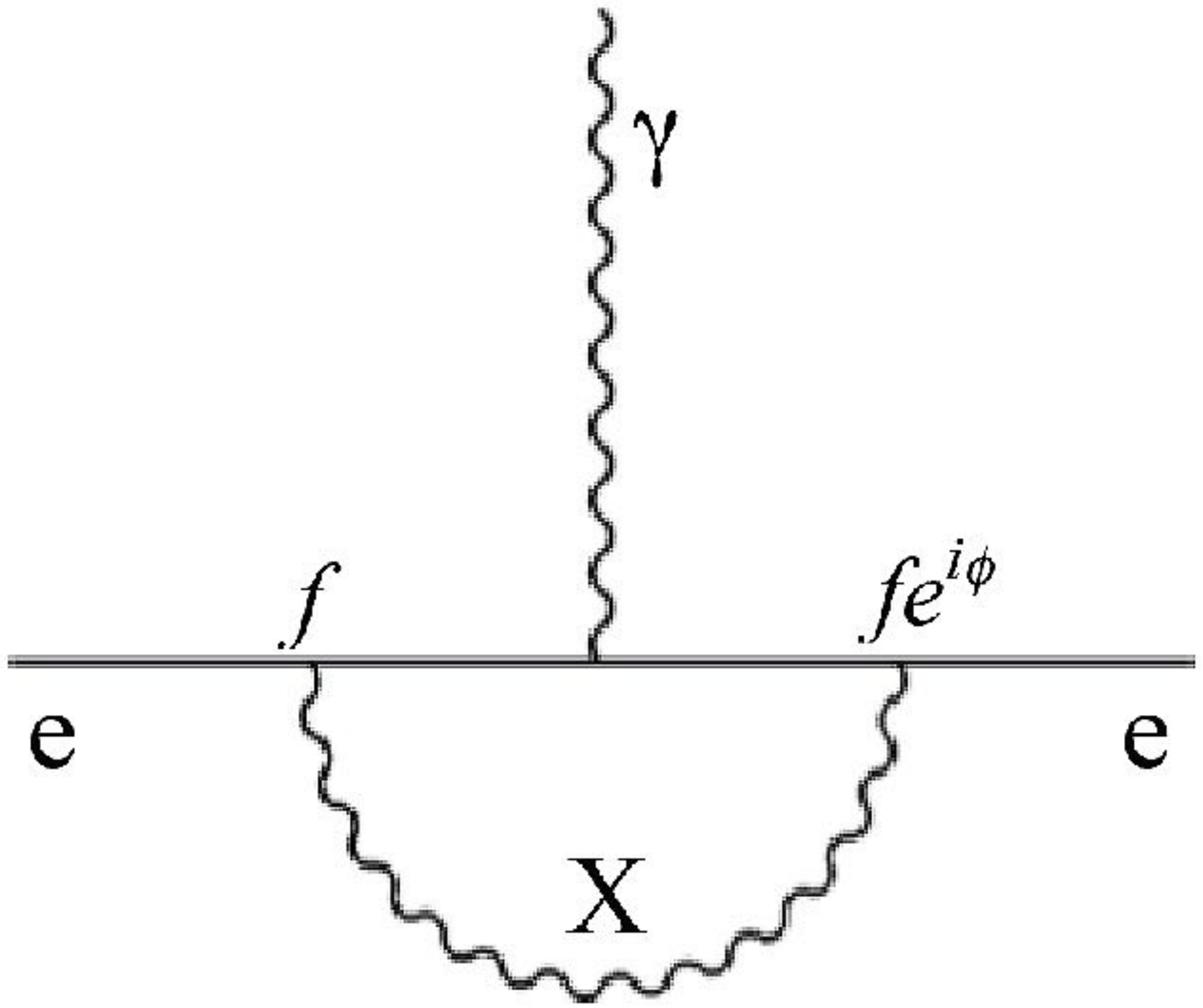
Effect ∝ $1/M^2$

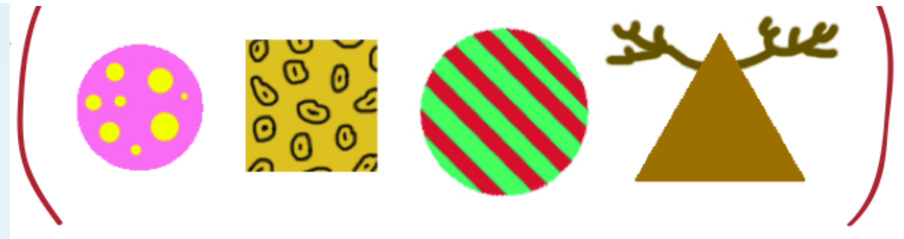
More Loops, higher order perturbation



Electron is dressed by Virtual Particles — New Physics







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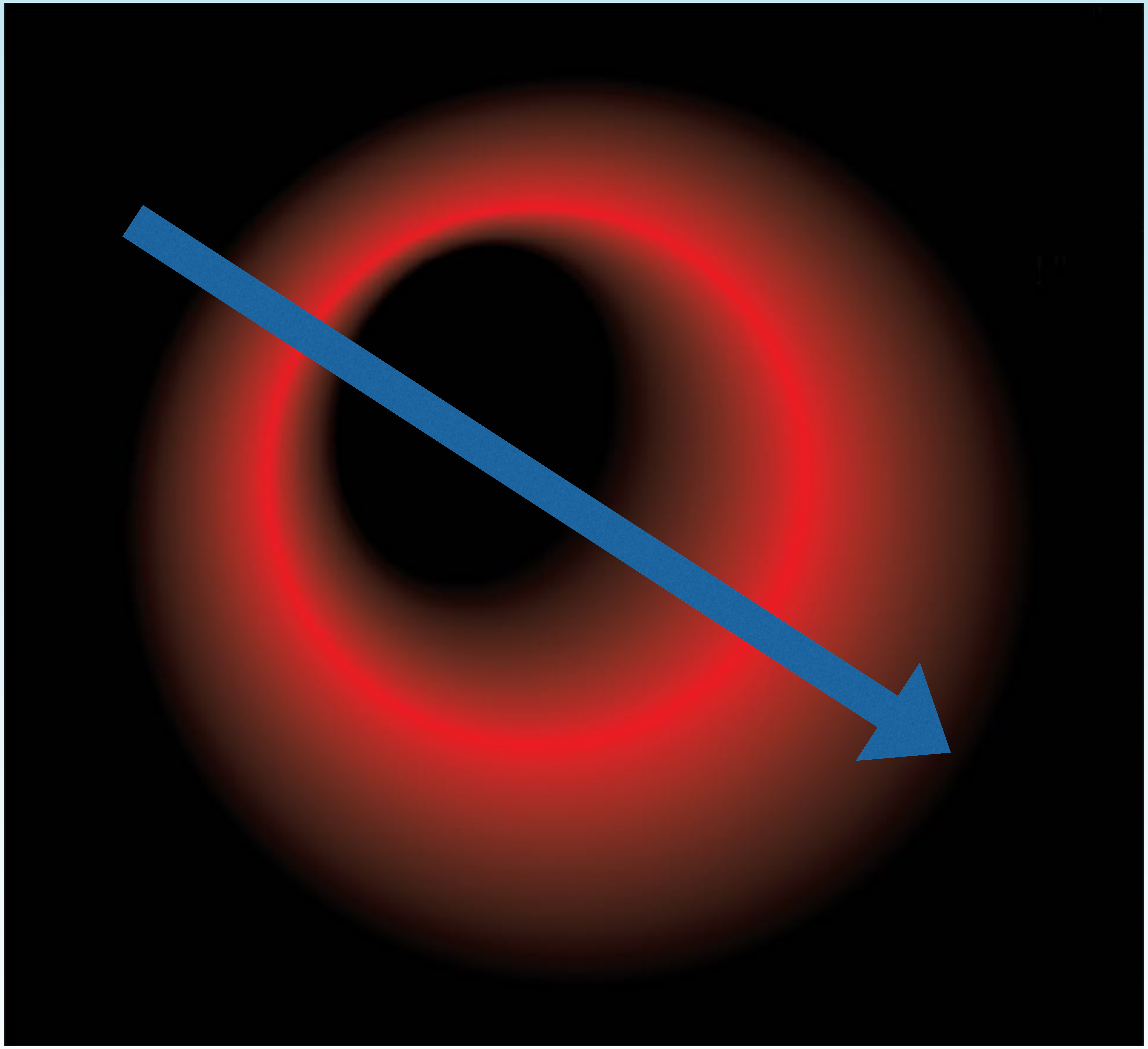
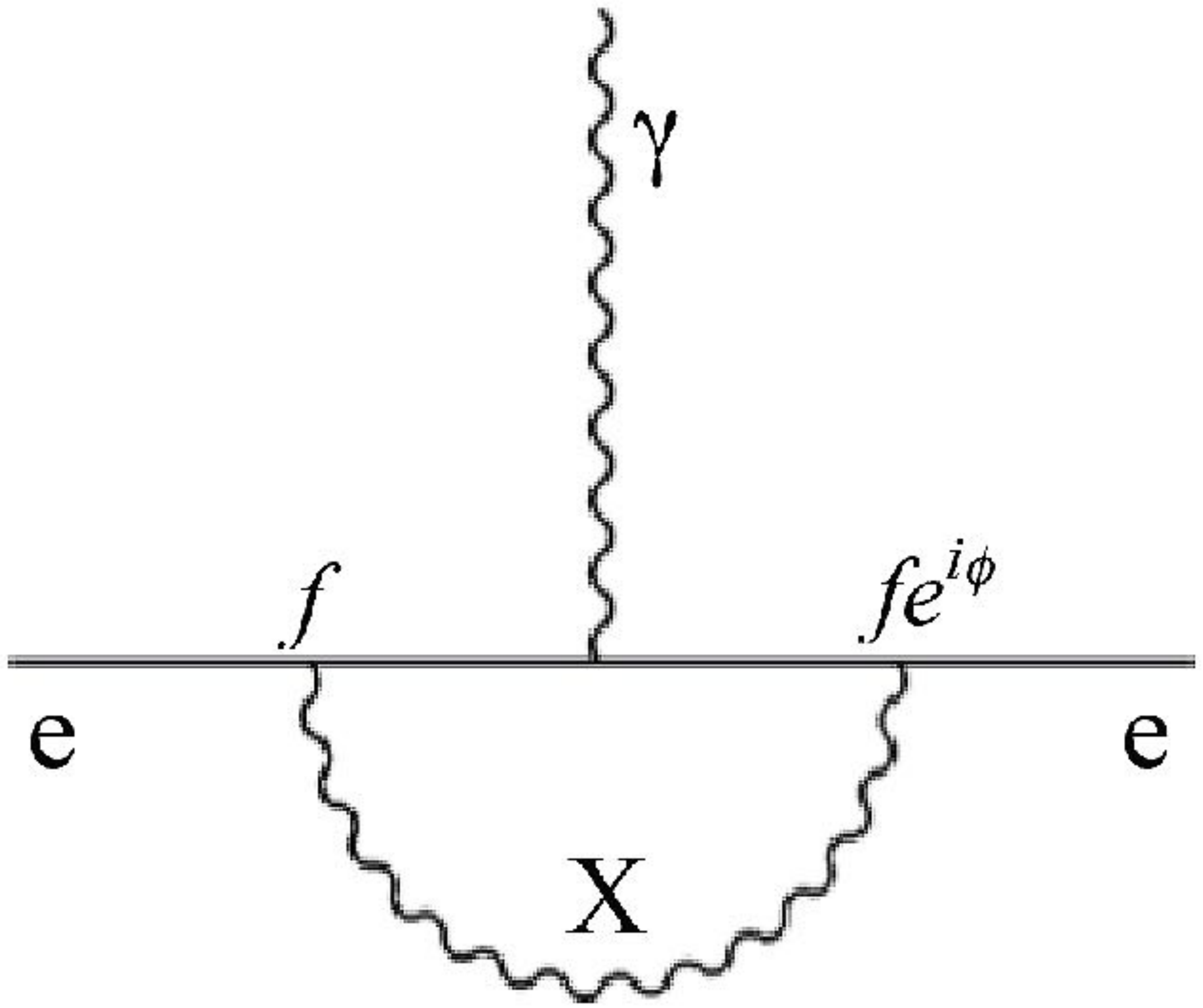
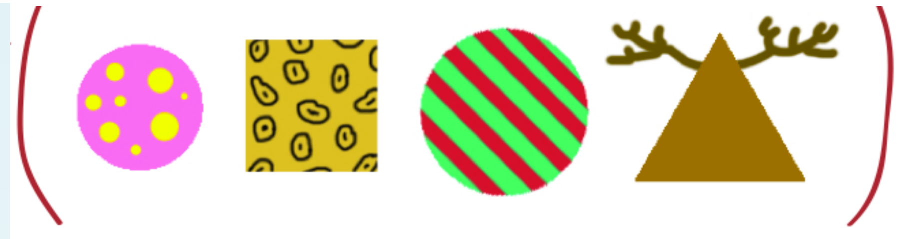






SUSY
1st order perturbation
Cancellations not inherent
T-violating phase natural

EDM is SM Background Free!

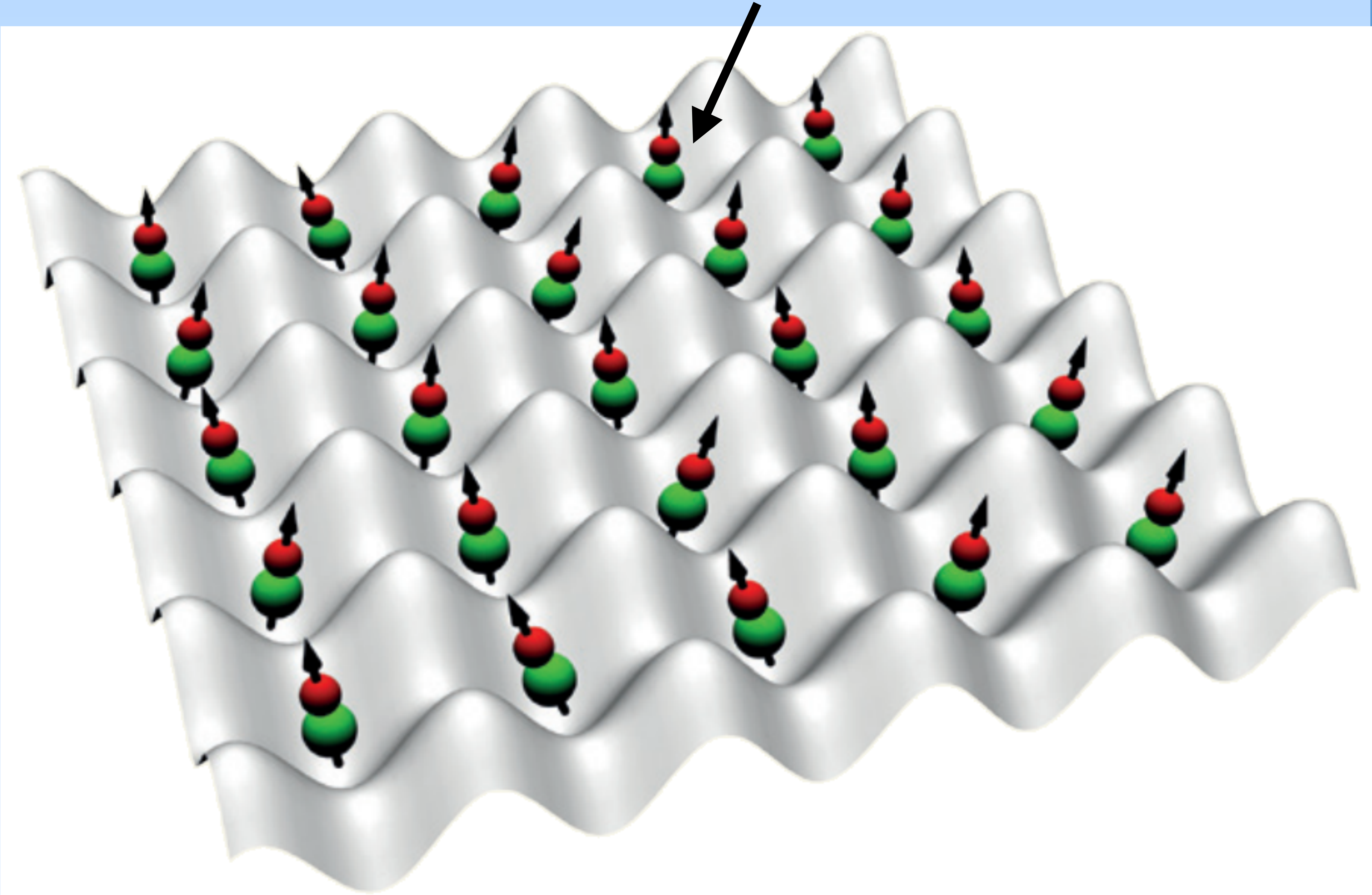
Where we are going with precision measurement… one PREVIEW

EDMs — Beyond the Standard Model Particle Physics

EDMs are capable of probing high energy scales, with a sensitivity unmatched by any signals from the LHC, within the framework of a very broad range of theoretical models—and particularly in the most widely-studied and broadly predictive models, such as SUSY.

- 10^6 molecules
- 10 s coherence
- Large enhancement(s)
- 1 day averaging

$M_{new\ phys}$ ~ 1,000 TeV



N. Hutzler

Numerical Value of the electron EDM from New Particle Dimensional Analysis

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

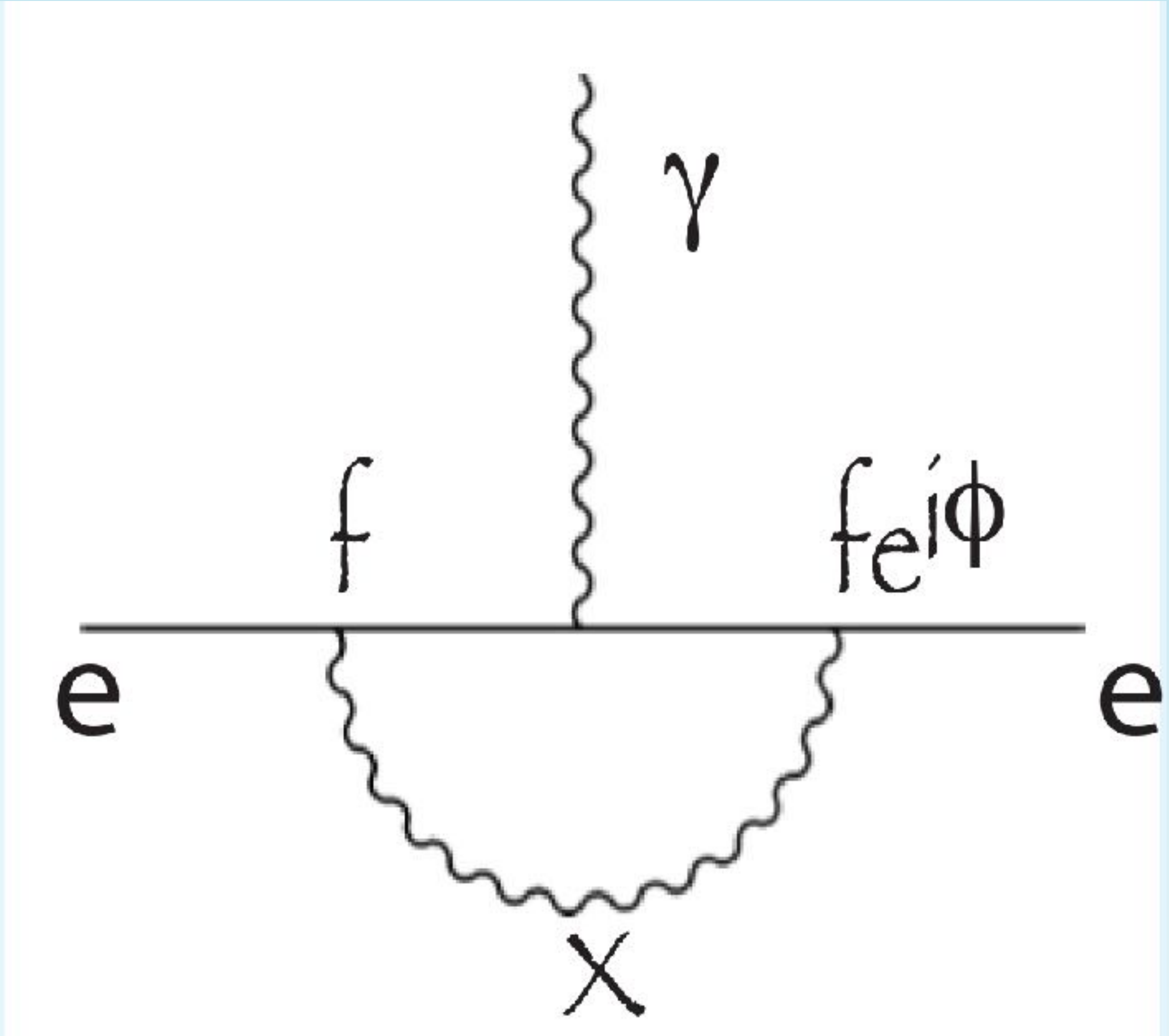
$$\sin(\Phi) \approx 1$$

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

number of loops ↑

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

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



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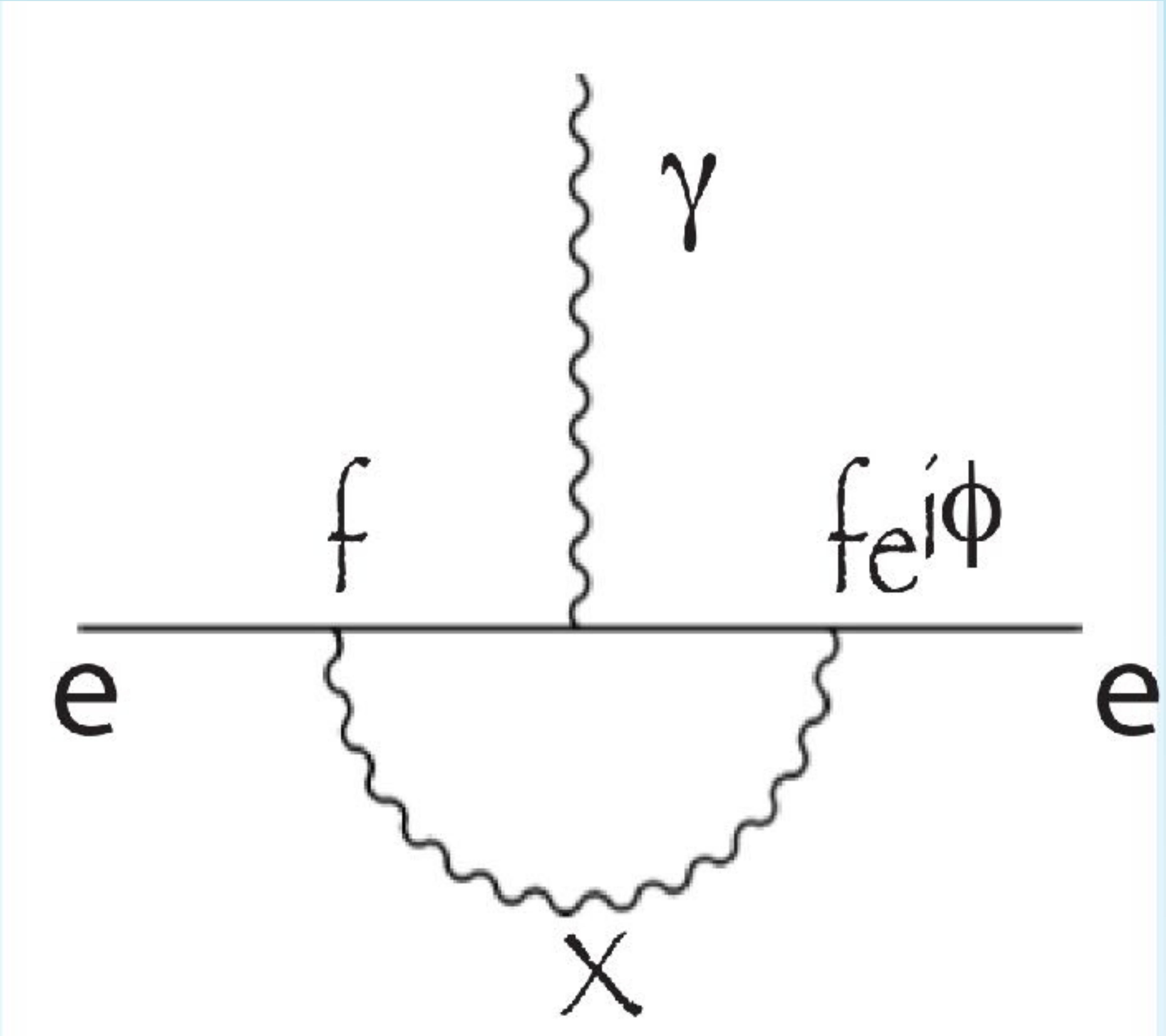


$$\text{EDM} \approx \mu_B\,(\alpha/\pi)^N\,(m_e/m_\chi)^2\,\sin(\Phi)$$

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

calculated 1-loop

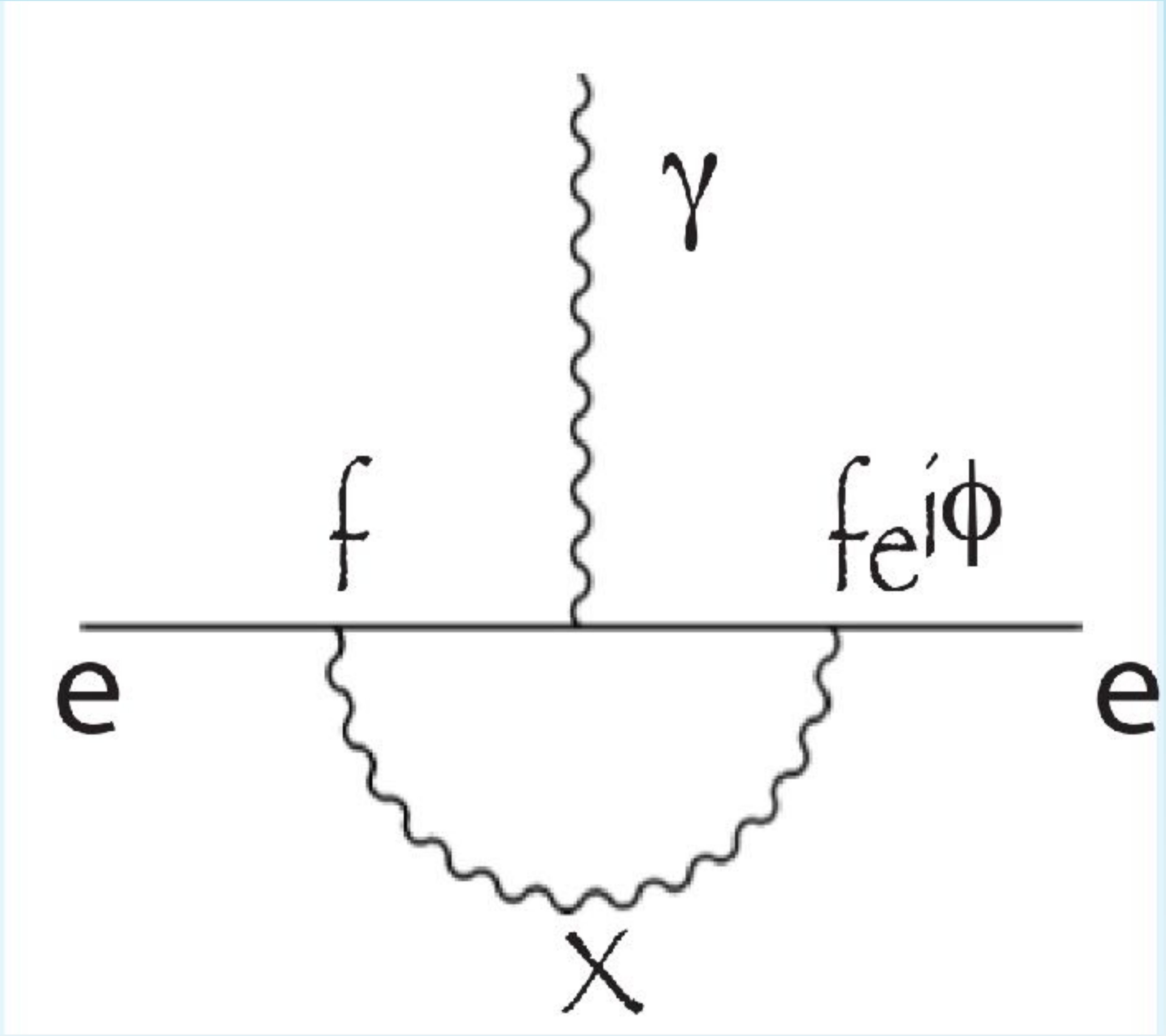
EDM ≈ 100x 20 year old limit

EDM Too Small??

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

$\sin(\Phi) \approx 1$

$m_\chi \approx 100$ GeV



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

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

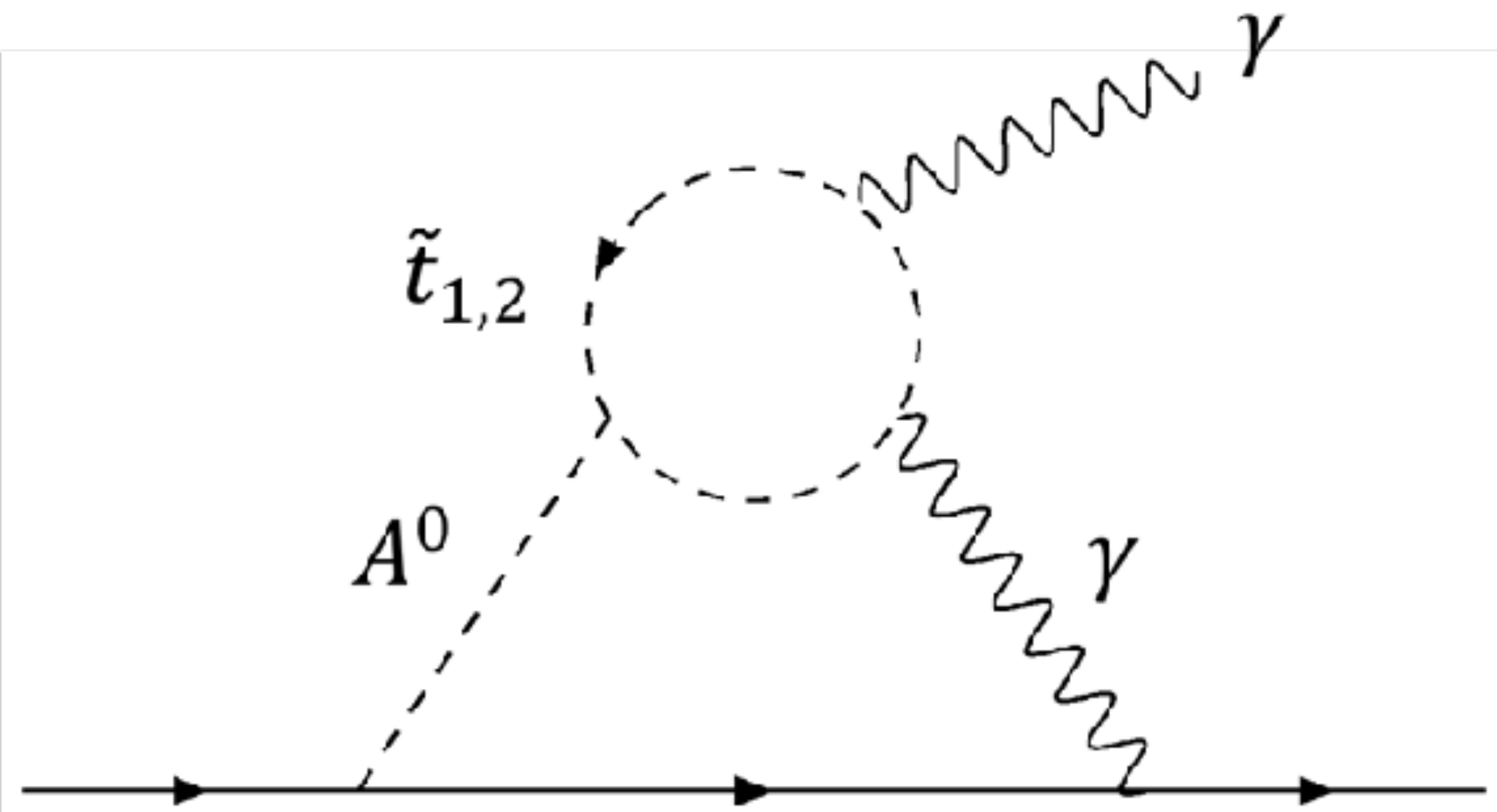
calculated 1-loop
EDM ≈ 100x previous limit

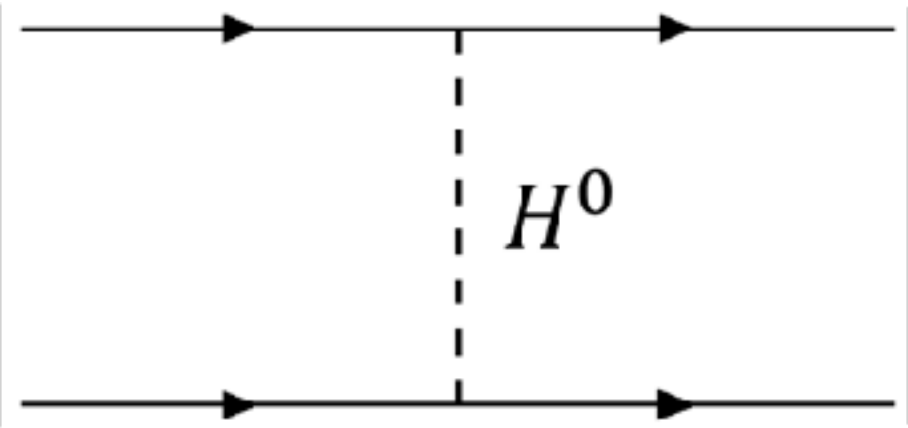
SUSY was constrained near 1 TeV level before the LHC was built.
Escape clause: very small Φ possible.

eEDM probes *Stop particle*

Yuichiro Nakai and Matthew Reece

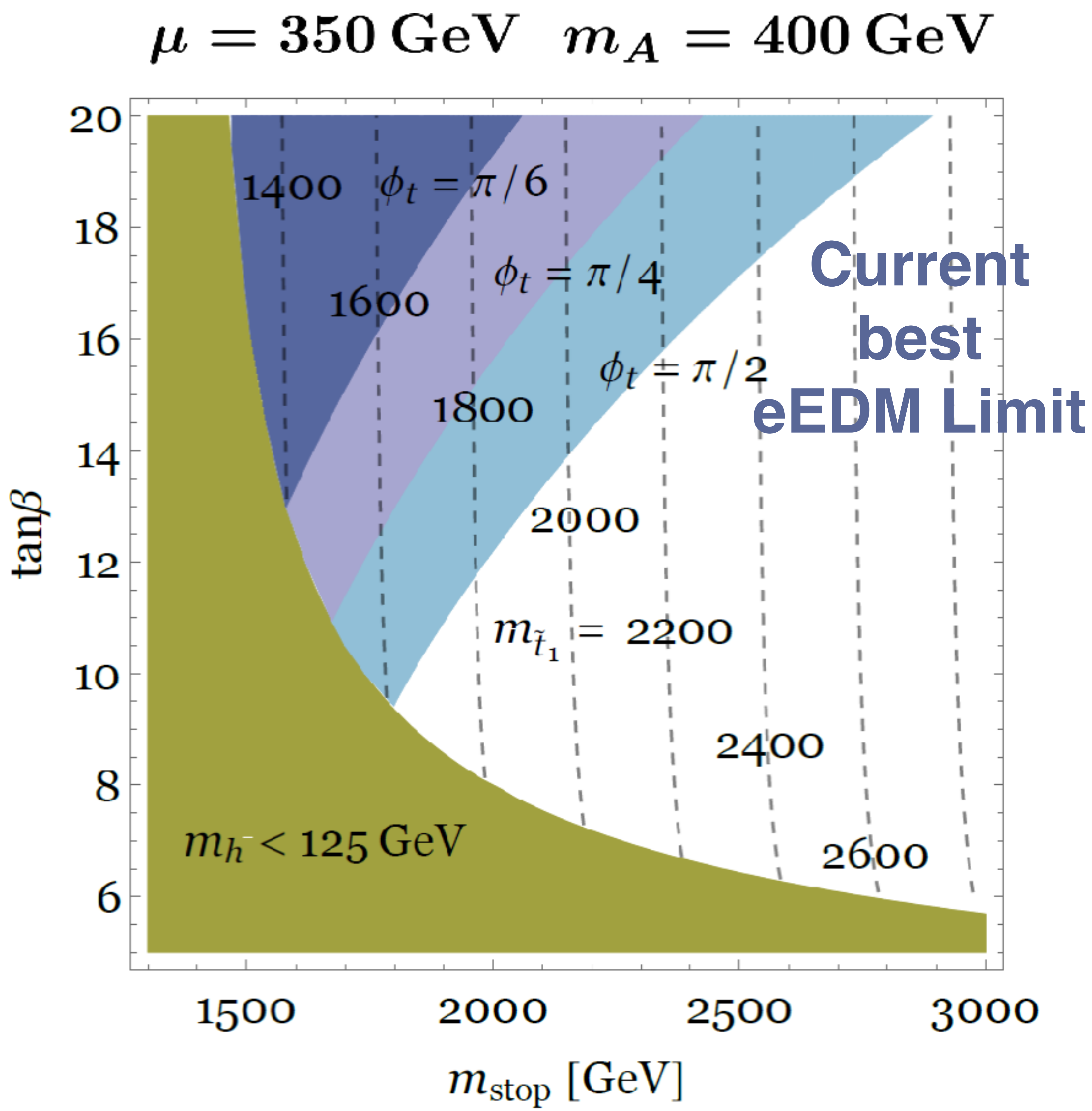
Superpartners of top quarks (stops),
essential for the natural EWSB,
can generate a sizable EDM.





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

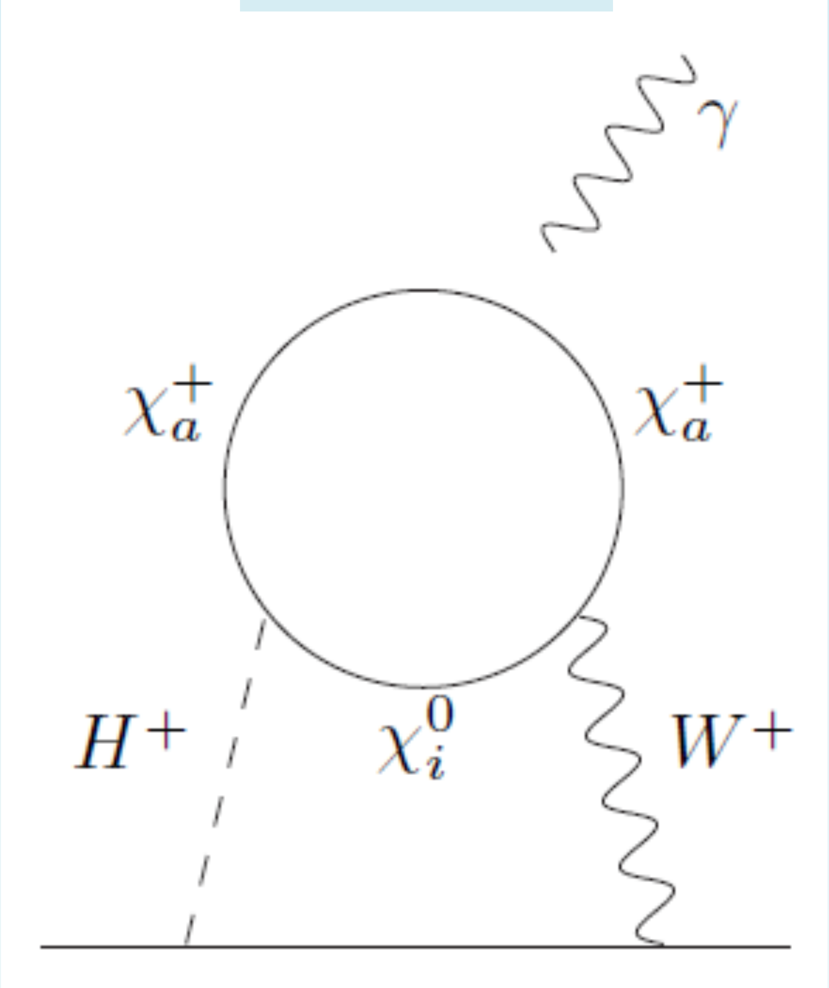
$m_{\tilde{t}_1} > 1.6$ TeV



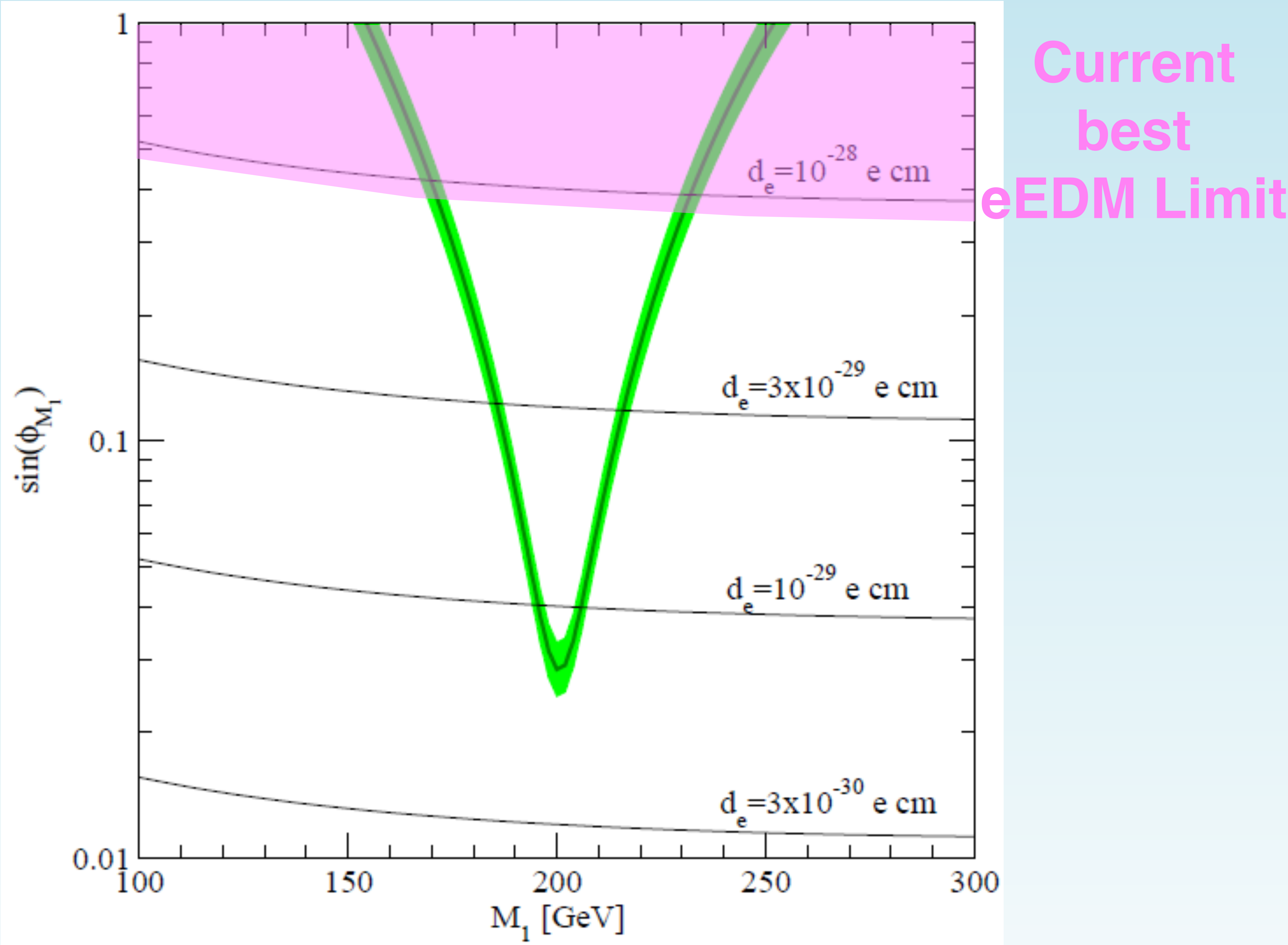
Implications for baryon asymmetry…?

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

"Bino-driven EWBG" can elude **EDM** limit, but…



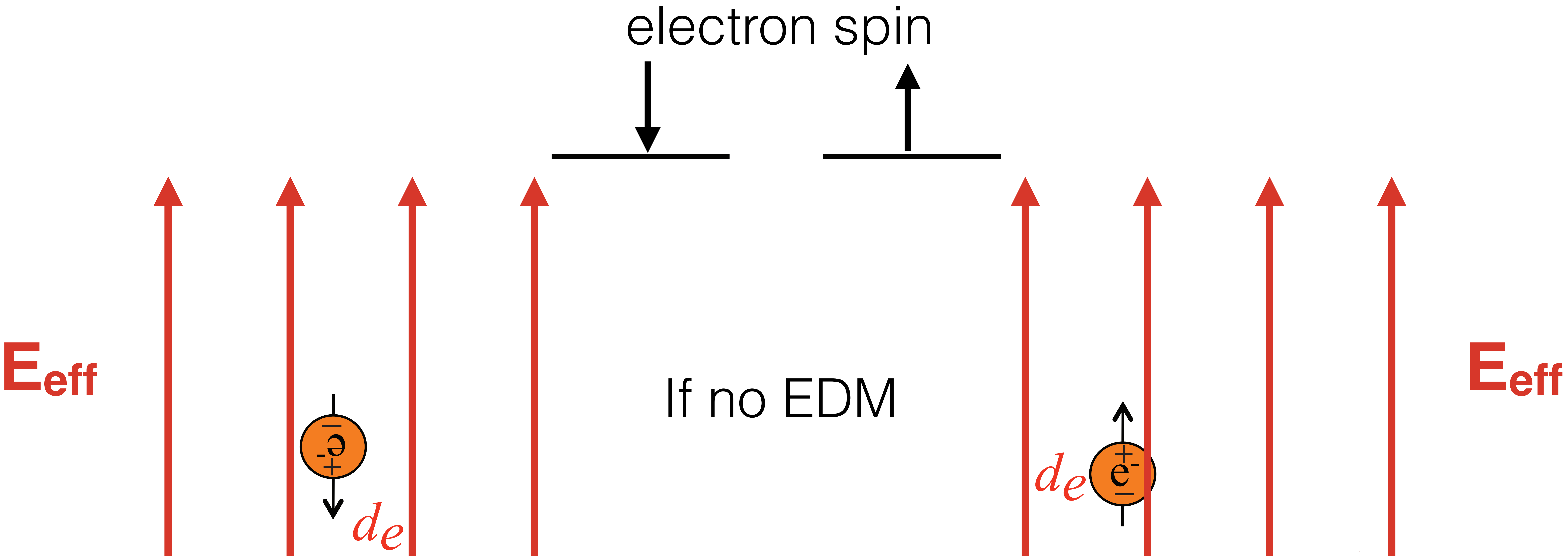
requires non-universal SUSY CP phases (φ_2=0)



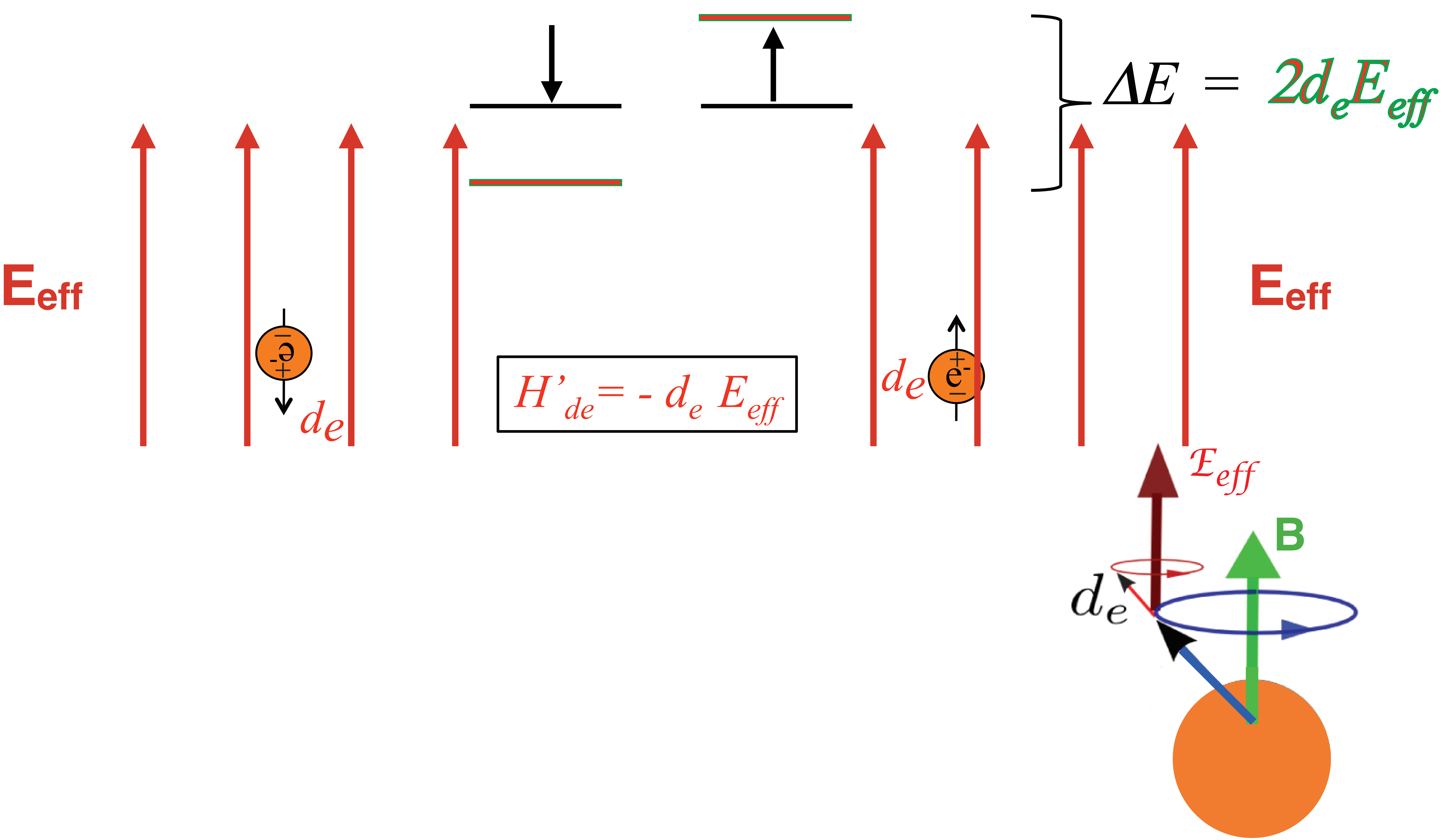
Li *et al.*, Phys. Lett. (2009)

~10x improvement may rule out Electroweak Baryogenesis…?

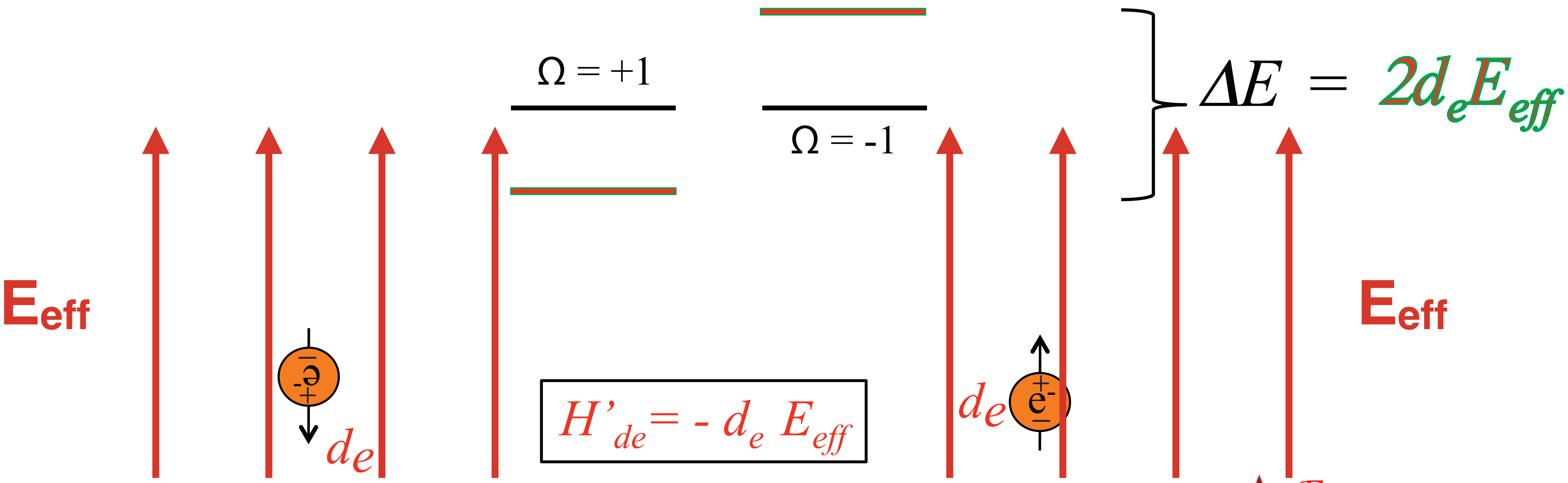
How to do an EDM experiment - Generic

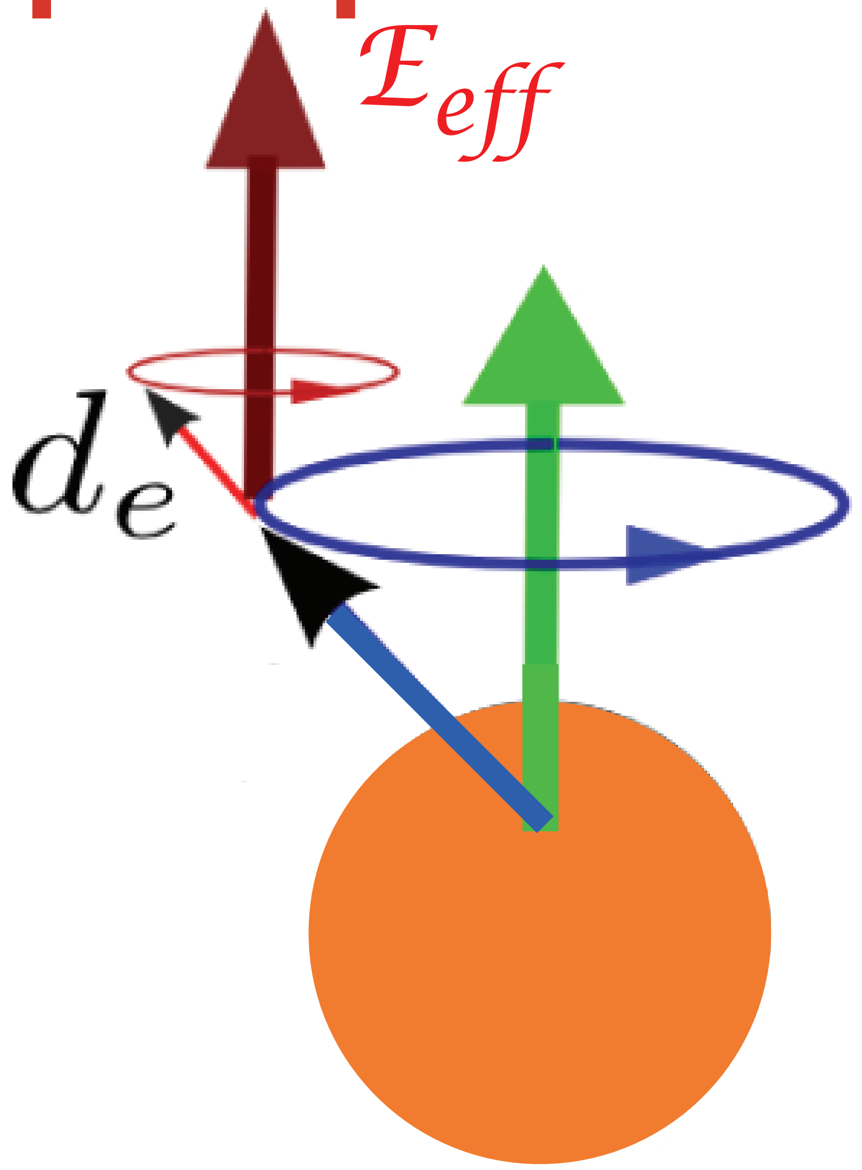


EDM Shift - Generic



Add the eEDM - Levels Shift, Electron Spin Precesses



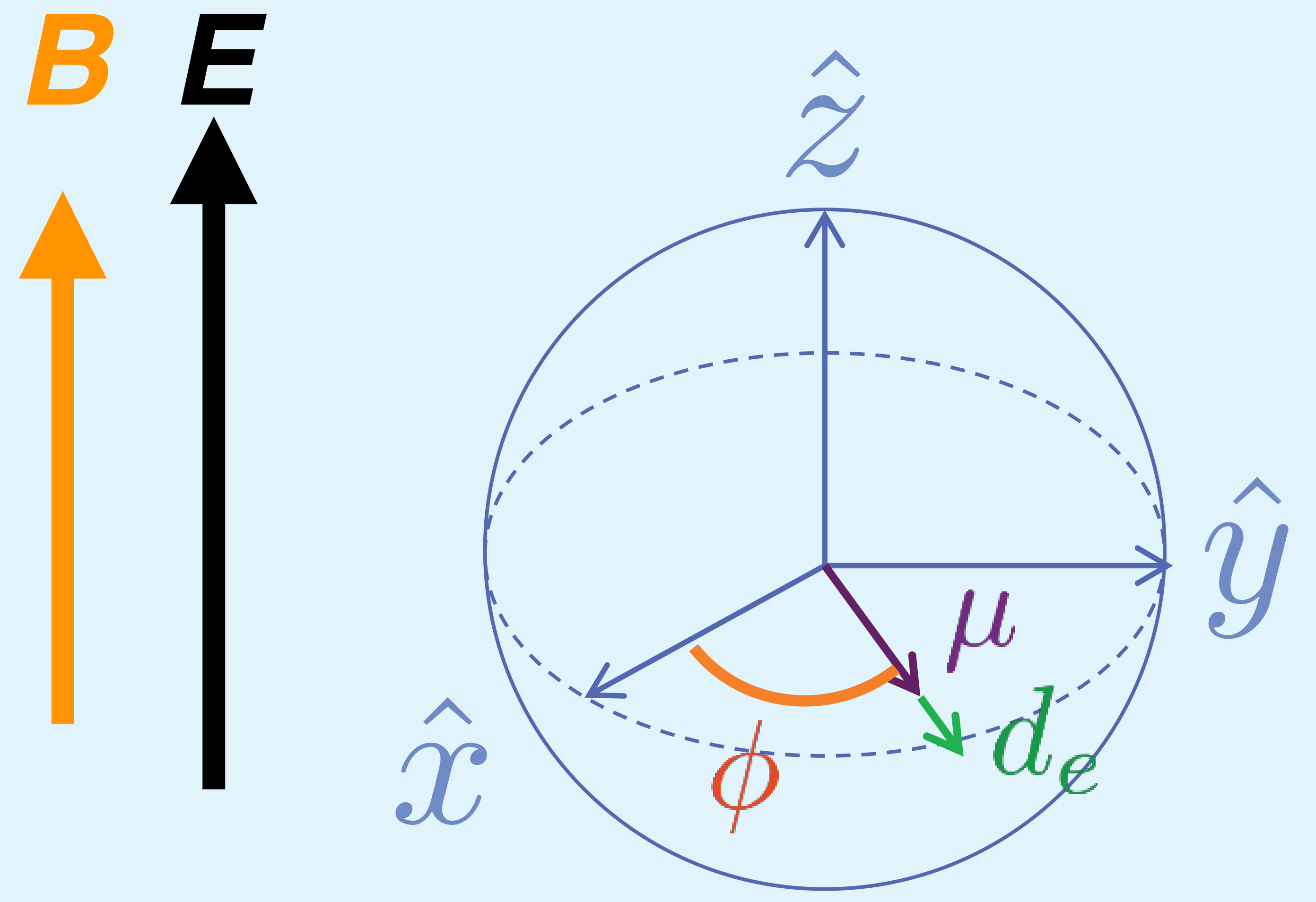


How to measure the eEDM:

Ramsey Spin Precession

Zeroth Order EDM Measurement

Just measure the precession of the spin?



$$\phi = 2(\mu B + d_e \mathcal{E}_{eff})\tau/\hbar + \textit{other pertubations, phase shifts}$$

$(\tau = 1 \text{ ms})$

How to measure eEDM:

1) Polarize spin

2) Place E and B field

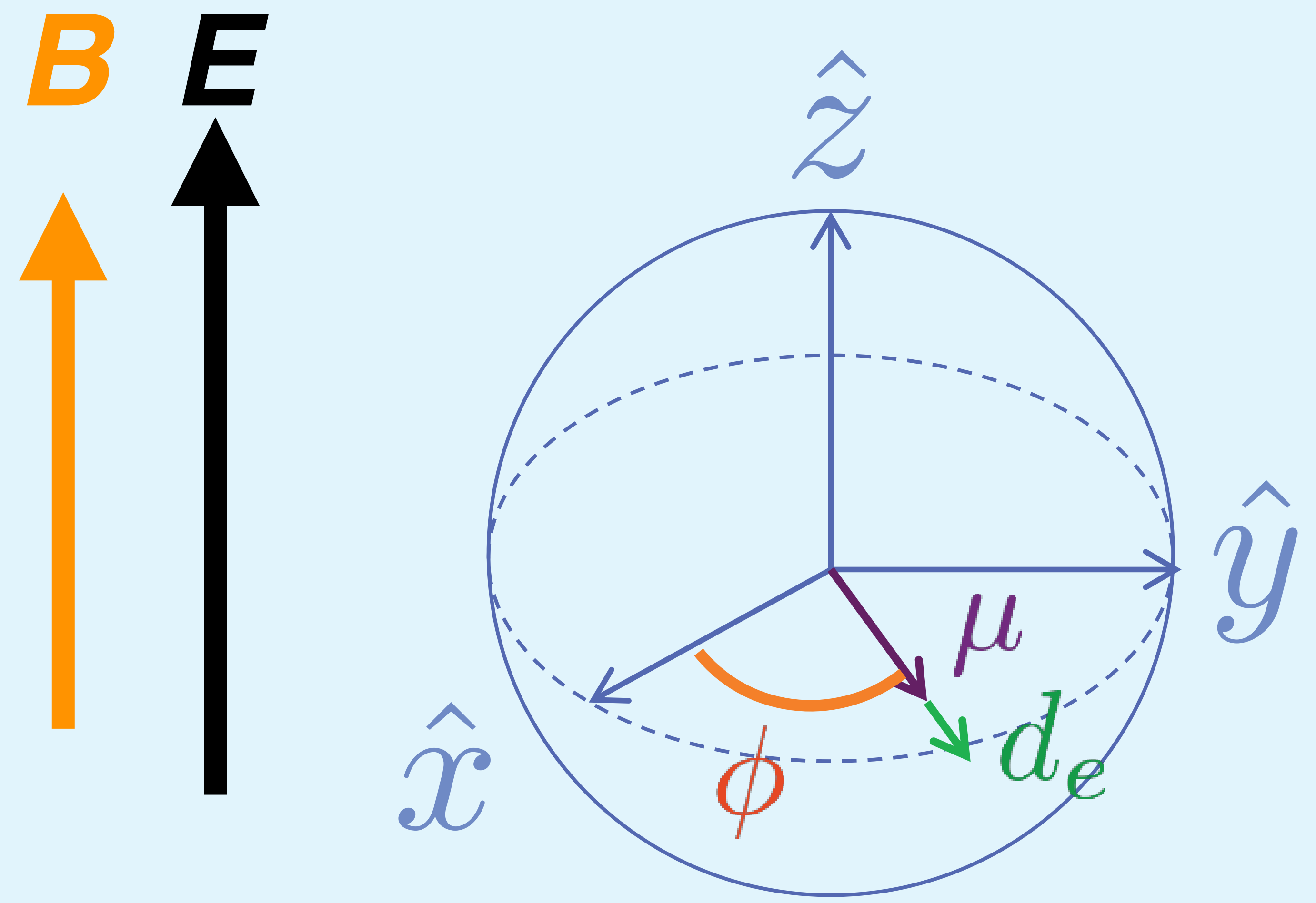
3) Wait a time τ

4) Measure phase

Standard Procedure
AMO
Spin Projection
Measurement

Zeroth Order EDM Measurement

Just measure the precession of the spin?



$$\phi = 2(\mu B + d_e \mathcal{E}_{eff})\tau/\hbar + \textit{other pertubations, phase shifts}$$

$(\tau = 1\text{ ms})$

To determine

$$\phi_{edm} = 10\ \mu\text{ rad for } d_e = 10^{-28}\text{ e-cm}$$

One would need

- magnetic field absolute value to 10^{-7} gauss (but known to only around 10^{-5} gauss)

and

- magnetic moment to the 10^{-6} fractional level

How to measure eEDM:

1) Polarize spin

2) Place E and B field

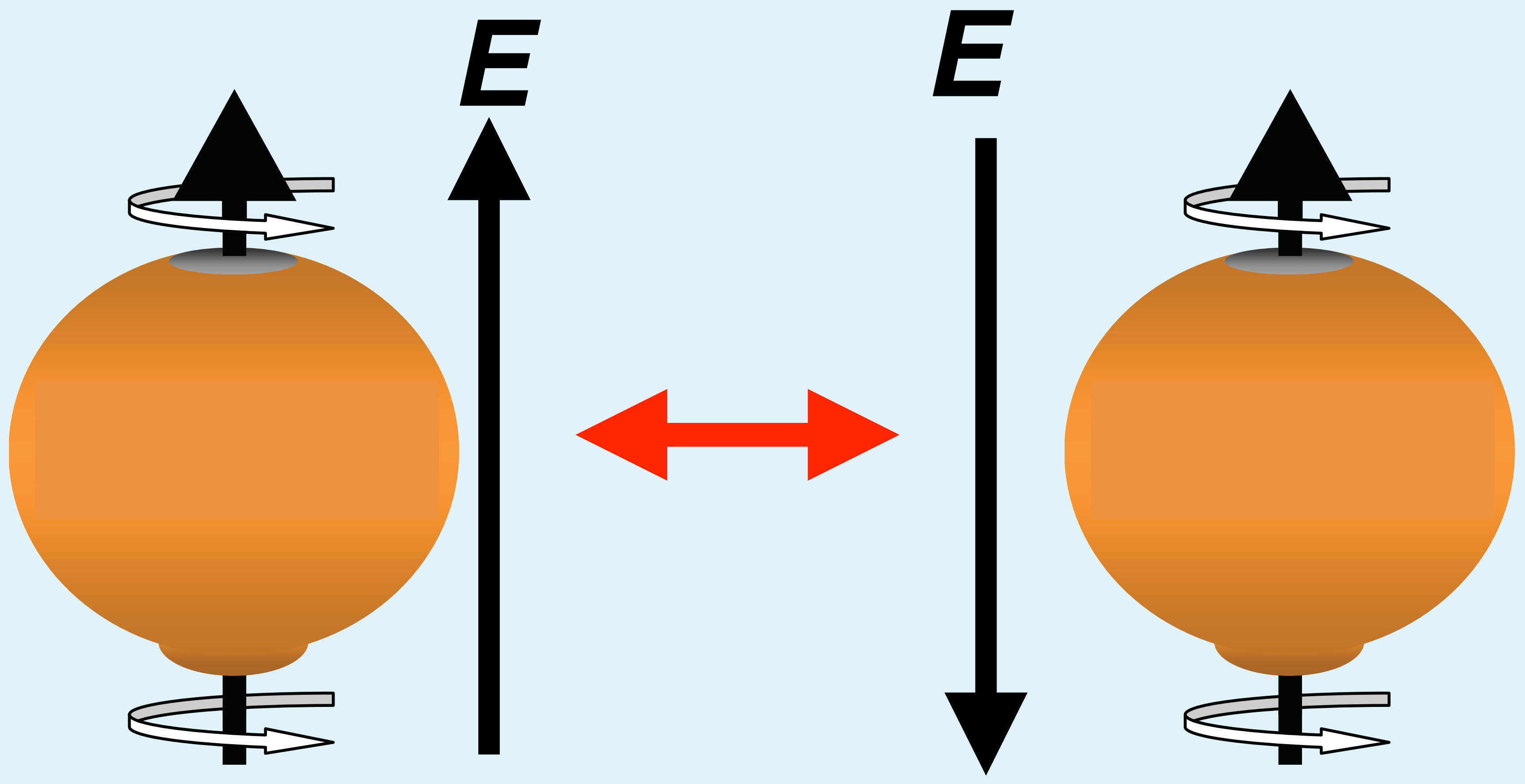
3) Wait a time τ

4) Measure phase

Standard Procedure AMO Spin Projection Measurtement

What is a "Switch" ?

Do the experiment twice with an electric field "switch"



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

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

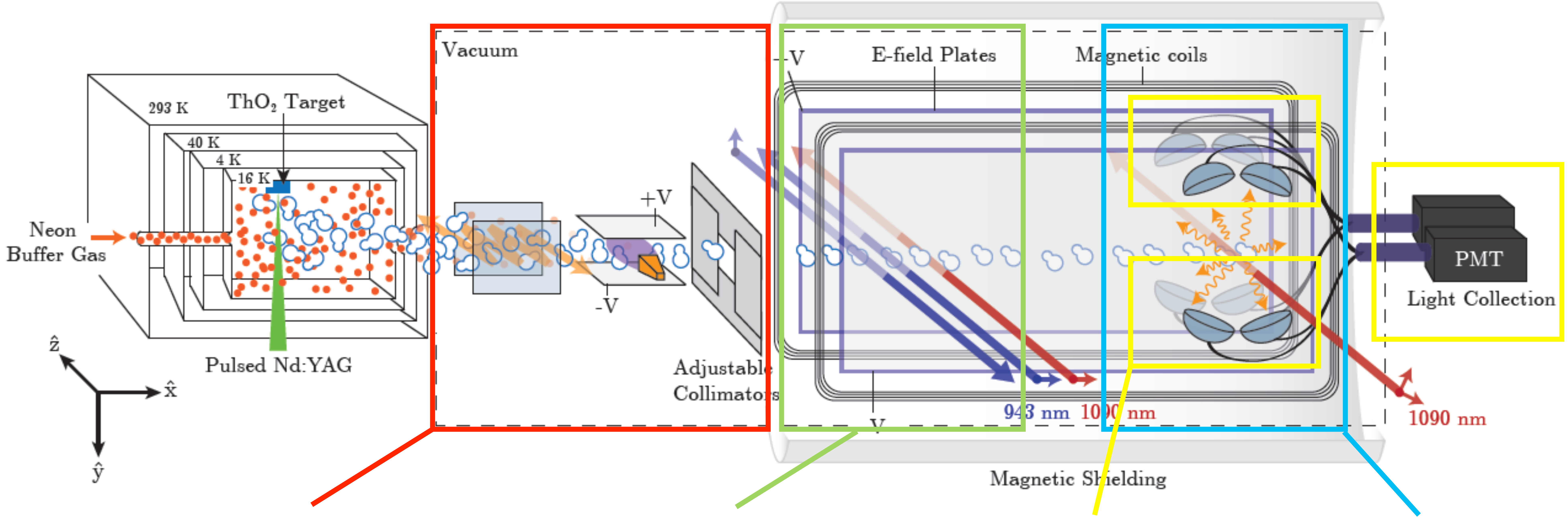
ACME Electron EDM

Beam

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

Effective Electric Field — Coherence Time — (Photon) Counting Rate — Integration Time

ACME
Coherence time ~ 10^{-3} s
Number of counted spins ~ 10^{5} s^{-1}
Molecule -> Huge E_{eff}



Beamline geometry
State preparation
Light collection/
State readout

JILA Electron EDM

Ion Trap

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

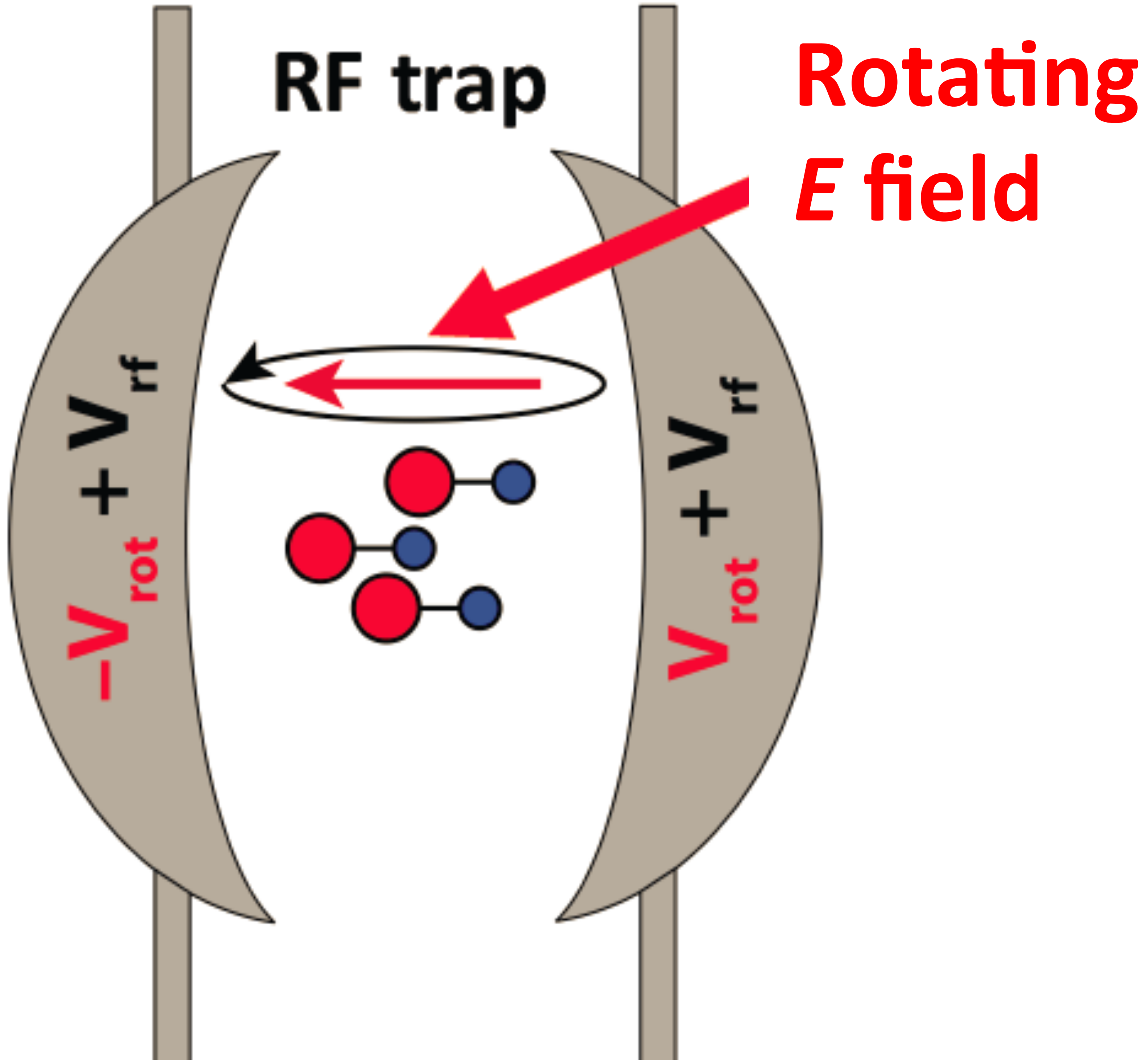
Effective Electric Field

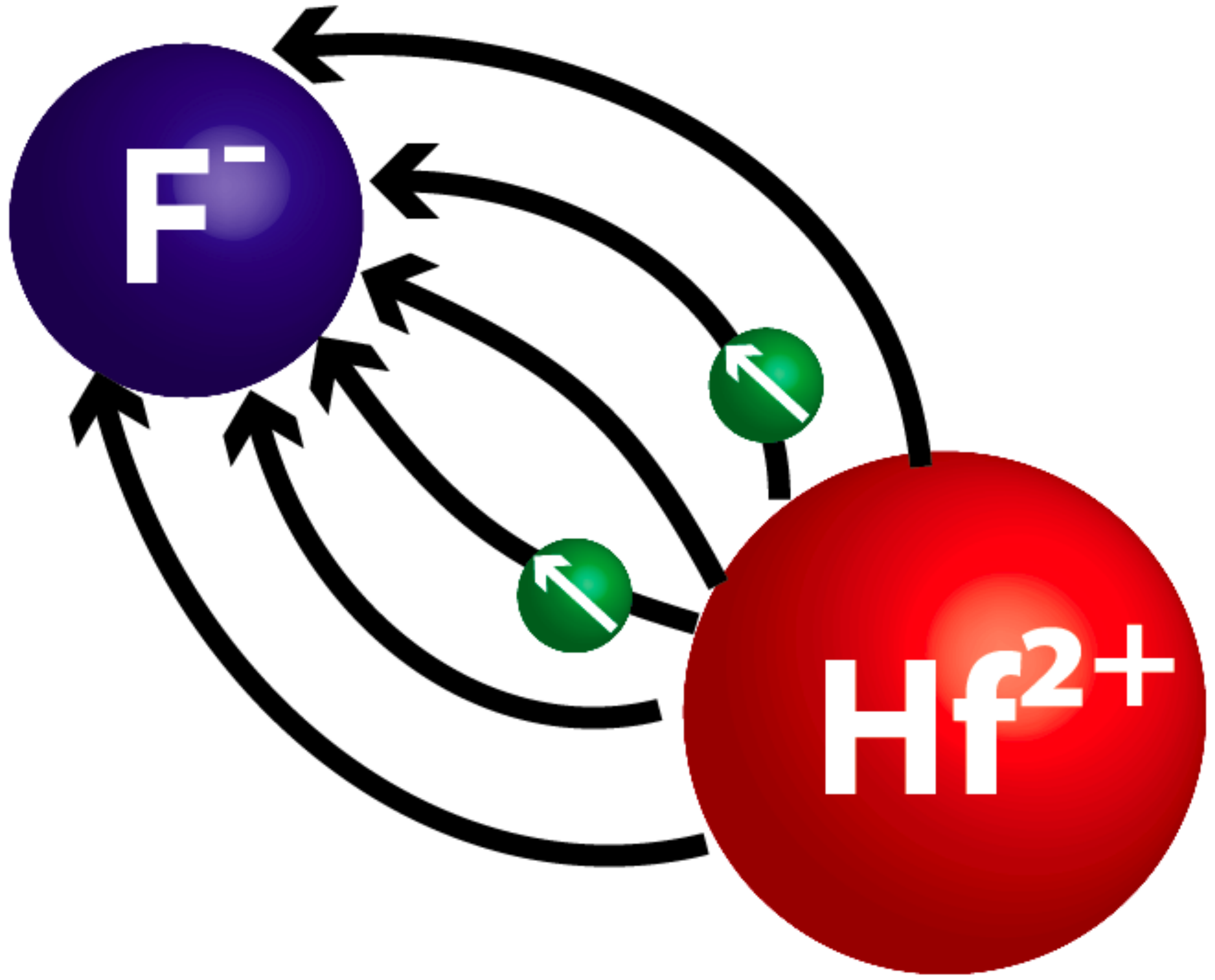
Coherence Time

(Photon) Counting Rate

Integration Time

JILA
Coherence time ~ 1 s
Number of counted spins ~10 s^{-1}
Molecule -> Huge E_{eff}





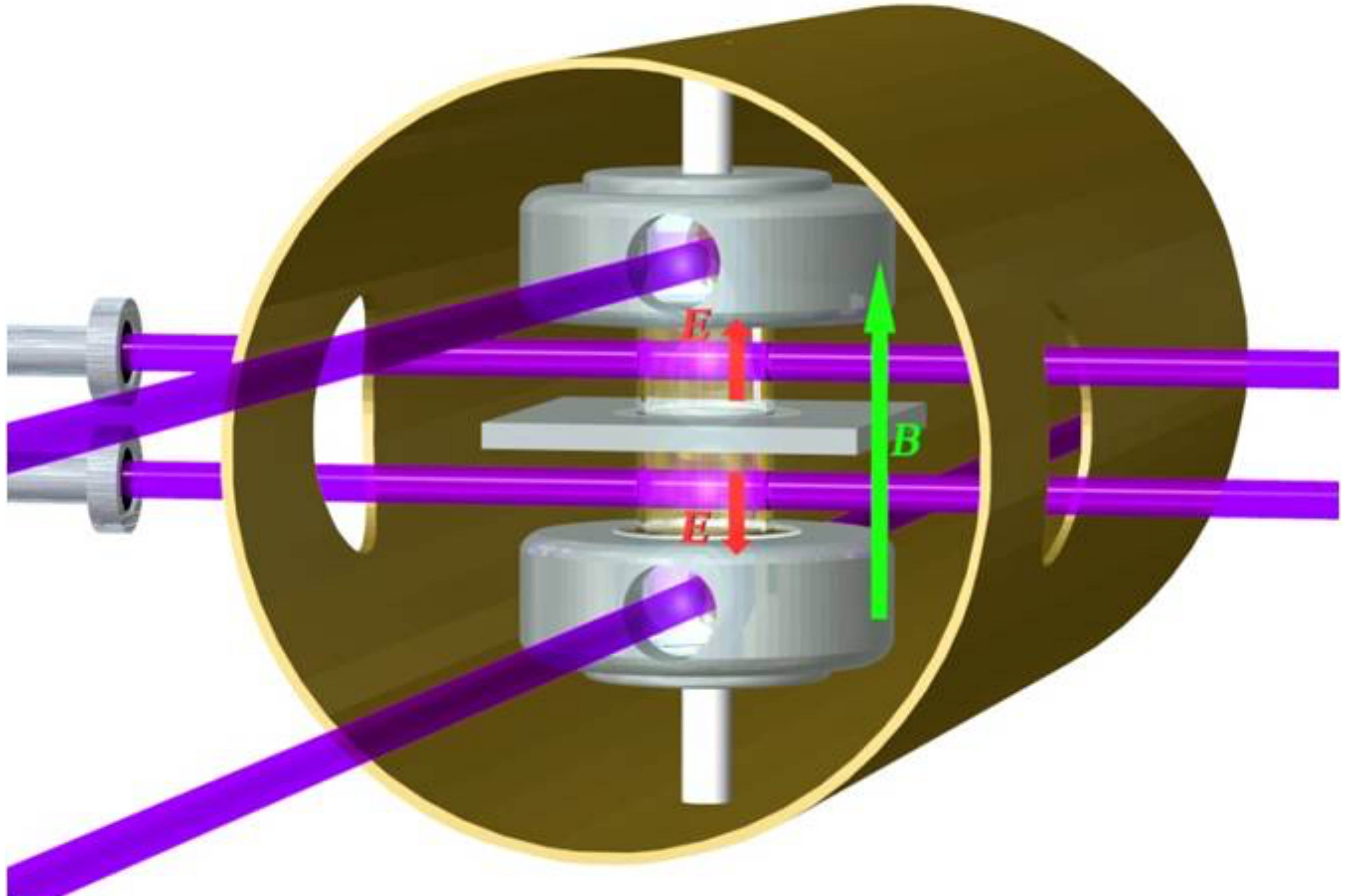
UWash Nuclear EDM

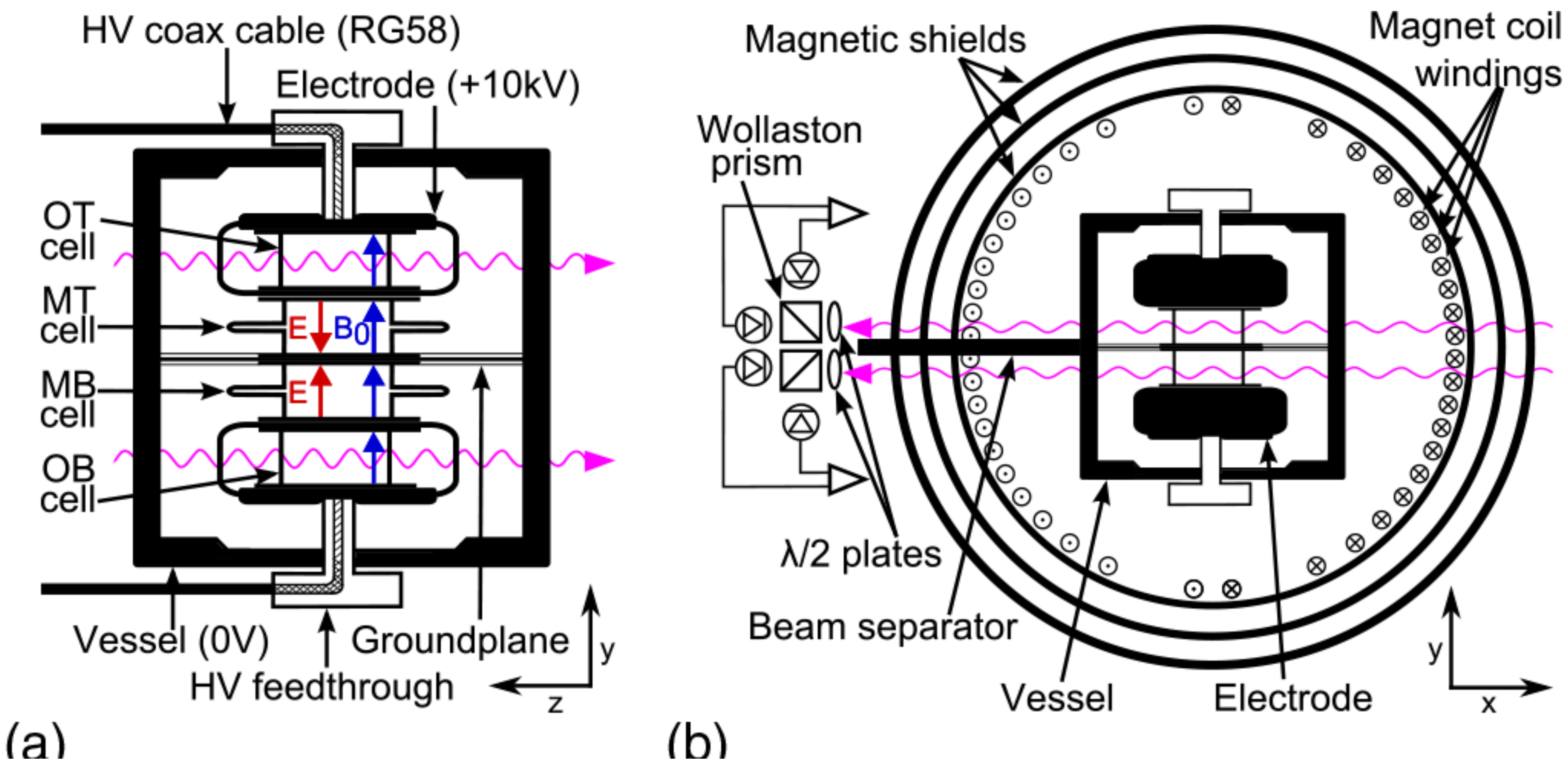
Cell

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

Effective Electric Field — Coherence Time — (Photon) Counting Rate — Integration Time

UWash
Coherence time = 100 s
Number = $10^{12}\ s^{-1}$
(Atom -> note lower E_{eff})





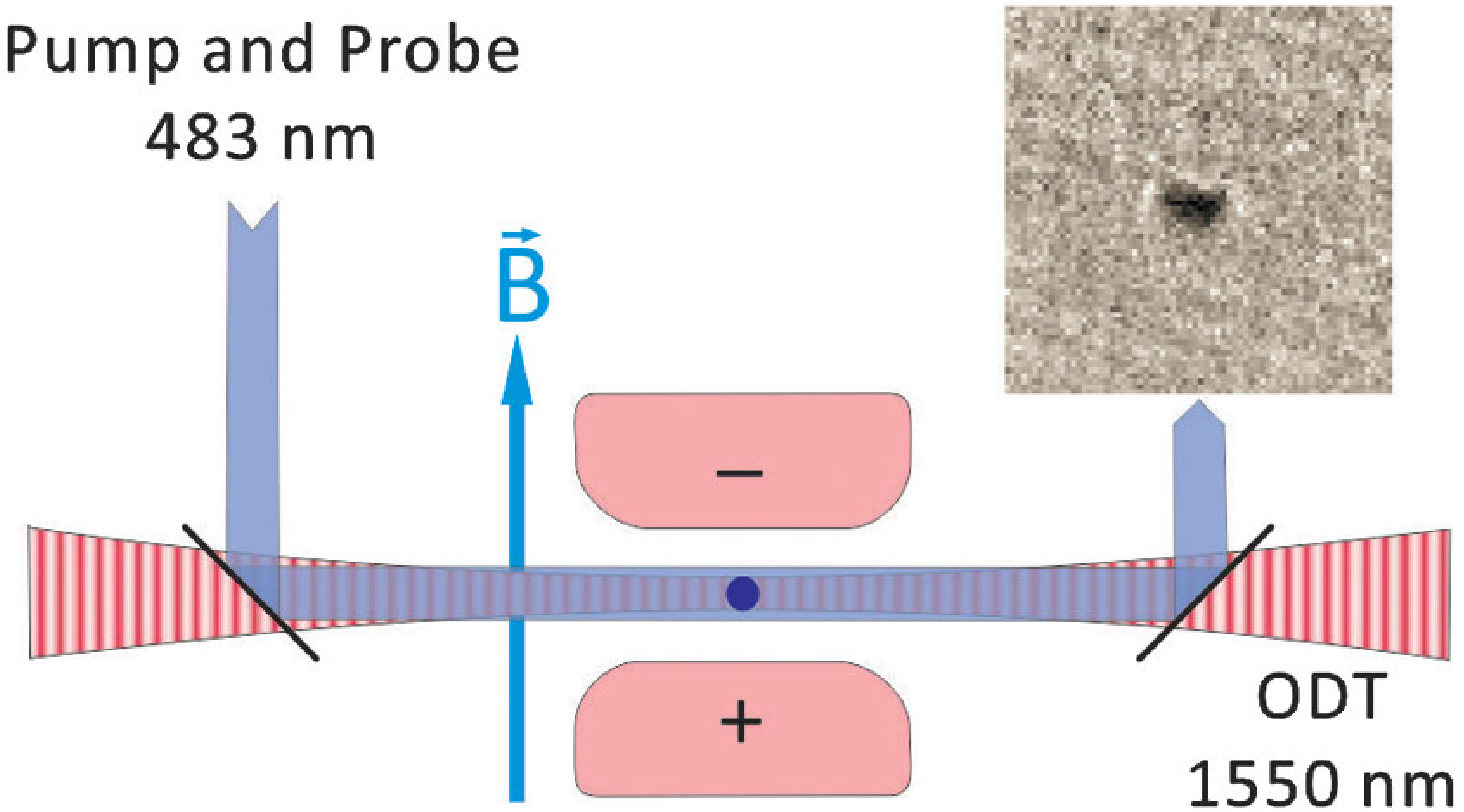
Argonne Nuclear EDM

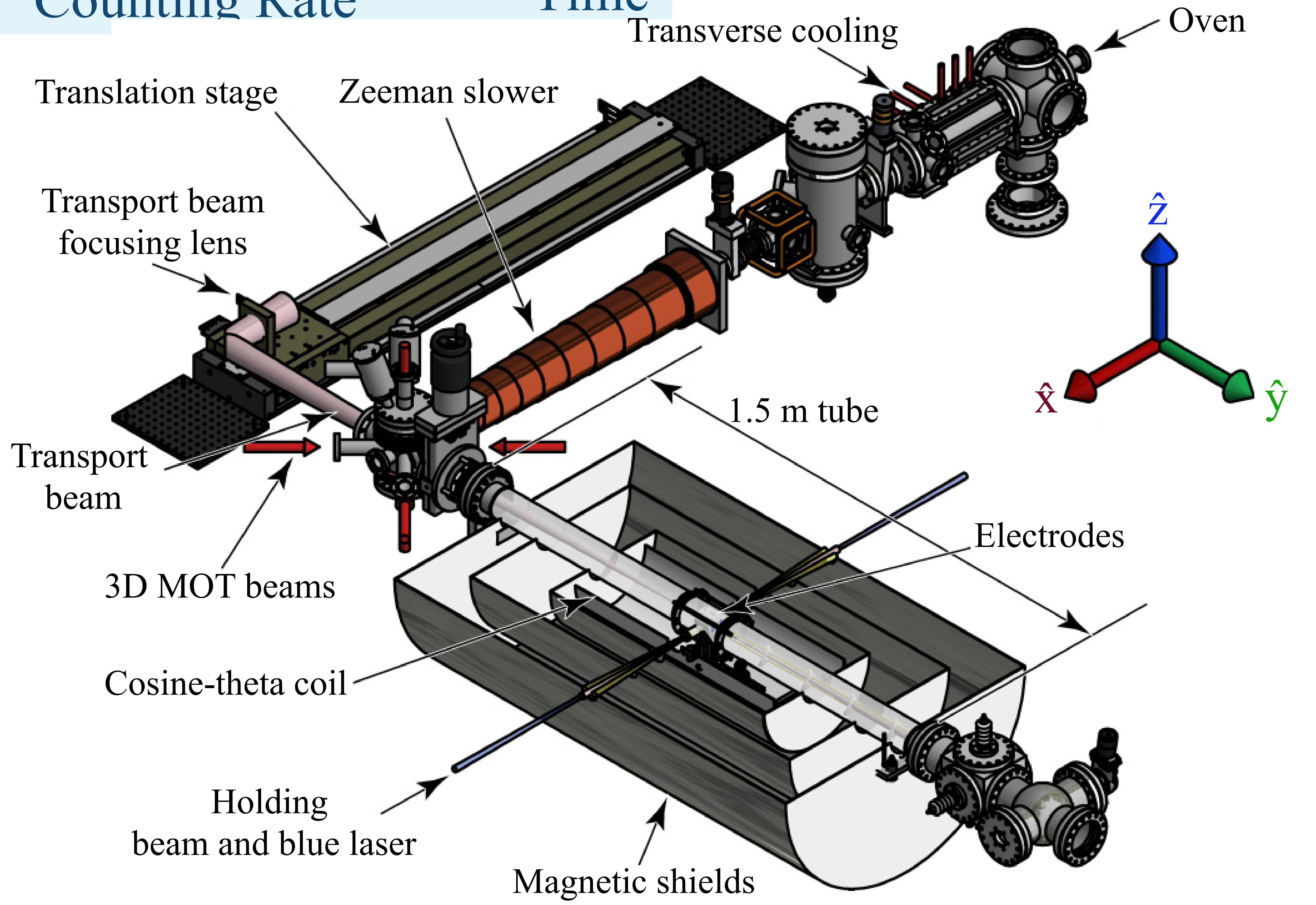
Optical Trap

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

Effective Electric Field — Coherence Time — (Photon) Counting Rate — Integration Time

Argonne
Coherence time = 20 s
Number = $10^2\ s^{-1}$
(note atom -> lower E_{eff},
but octopole enhancement!)





What sets EDM sensitivity?

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

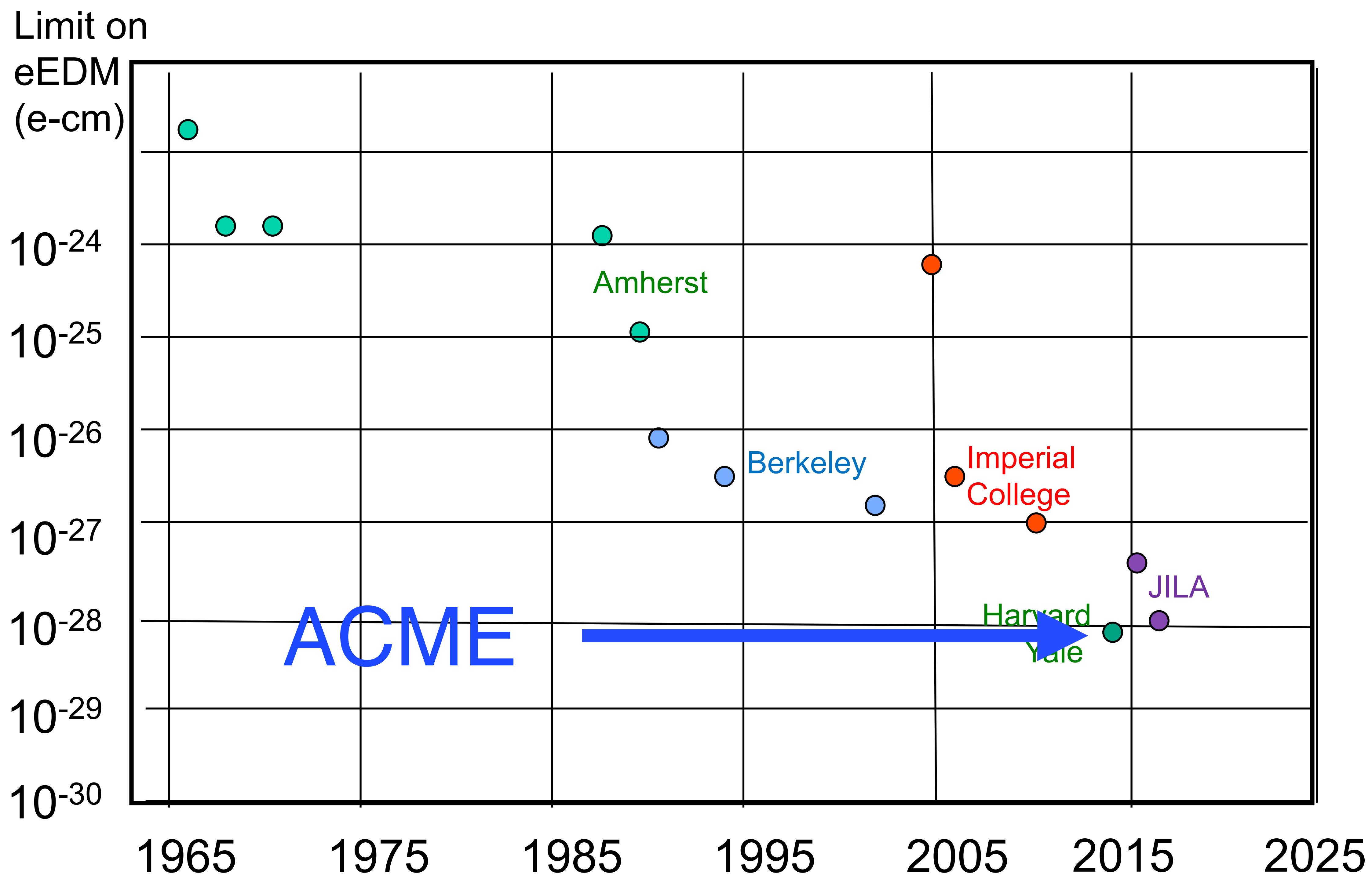
Effective Electric Field — Coherence Time — (Photon) Counting Rate — Integration Time

electron edm - d_e

Imperial $d_e < 1.05 \times 10^{-27}$ e·cm, 2011

ACME, $d_e < 8.7 \times 10^{-29}$ e·cm, 2013

JILA $d_e < 1.3 \times 10^{-28}$ e·cm, 2017



d_e

E. Cornell

Experiment	One Day Statistical Sensitivity e-cm $day^{-1/2}$	Published Limit $\lvert d_e \rvert$ < in e-cm	Year
Berkeley Tl	0.5×10^{-27}	1.6×10^{-27}	2002
Imperial YbF	2×10^{-27}	1.5×10^{-27}	2010
ACME I ThO	**1×10^{-28}**	**0.9×10^{-28}**	2013
JILA HfF+	**2×10^{-28}**	**1.3×10^{-28}**	2017

Reality Check!

Point of Interest

Experiment	One Day Statistical Sensitivity e-cm day$^{-1/2}$	Published Limit $\|d_e\|$ < in e-cm	Year
Berkeley Tl	0.5×10^{-27}	1.6×10^{-27}	2002
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JILA HfF+	**2×10^{-28}**	**1.3×10^{-28}**	2017

Reality Check!

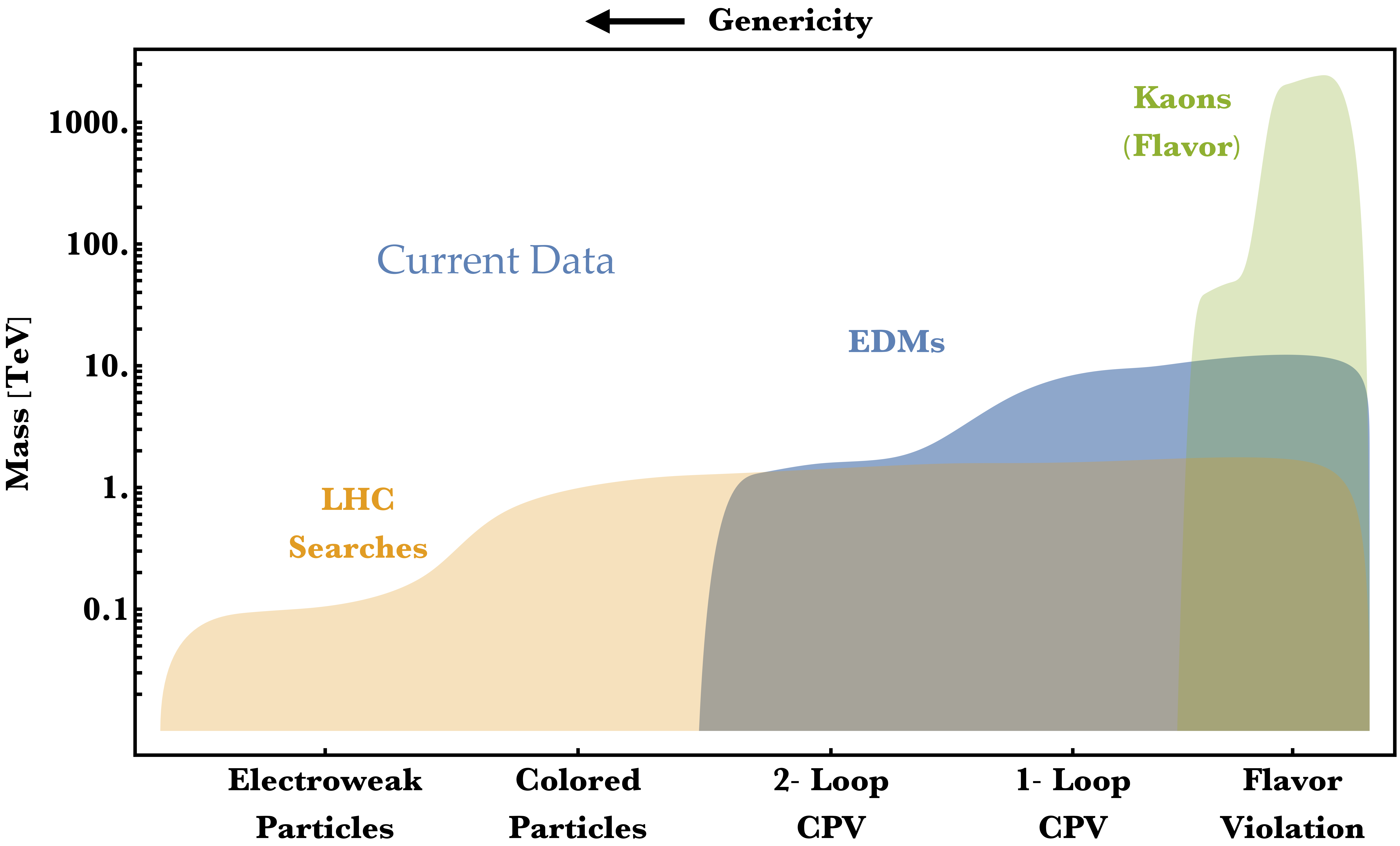
Point of Interest

One day sensitivity quotes are the same, historically, to eventual published limits!!

Feng, J. L. (2013). Naturalness and the Status of Supersymmetry. Annual Review of Nuclear and Particle Science, 63(1), 351–382.

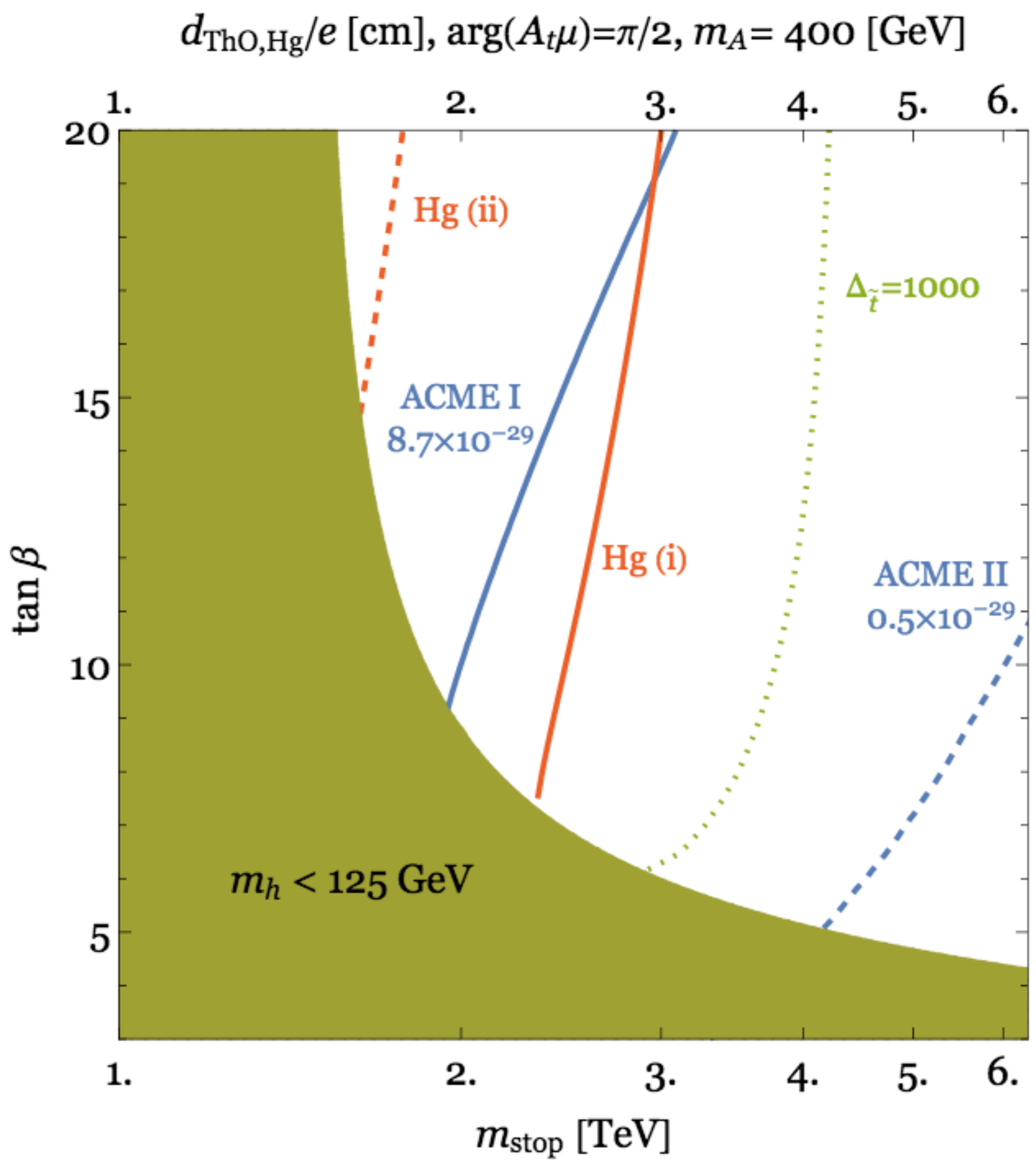

t
experimentally excluded
unconstrained theory
Electron EDM Search
ACME I Result
JILA 2017
ACME I 2013
Imperial 2010
Berkeley 2002
Berkeley 1994
Berkeley 1990
standard model
SUSY variants
generic models
Multi-Higgs
Left-Right Symmetric
Extended Technicolor
Lepton Flavor Changing
Standard Model
Split SUSY
SO(10) GUT
Alignment
Seesaw Neutrino Yukawa Couplings
Accidental Cancellation
Approx. CP
Approx. Universality
Exact Universality
Naive SUSY
Heavy sFermions
~10 TeV
~100 TeV
~1000 TeV
d_e (e cm)
10^{-25} 10^{-26} 10^{-27} 10^{-28} 10^{-29} 10^{-30} 10^{-31} 10^{-32} 10^{-33} 10^{-40} 10^{-41}

Breadth of new physics versus depth of mass reach



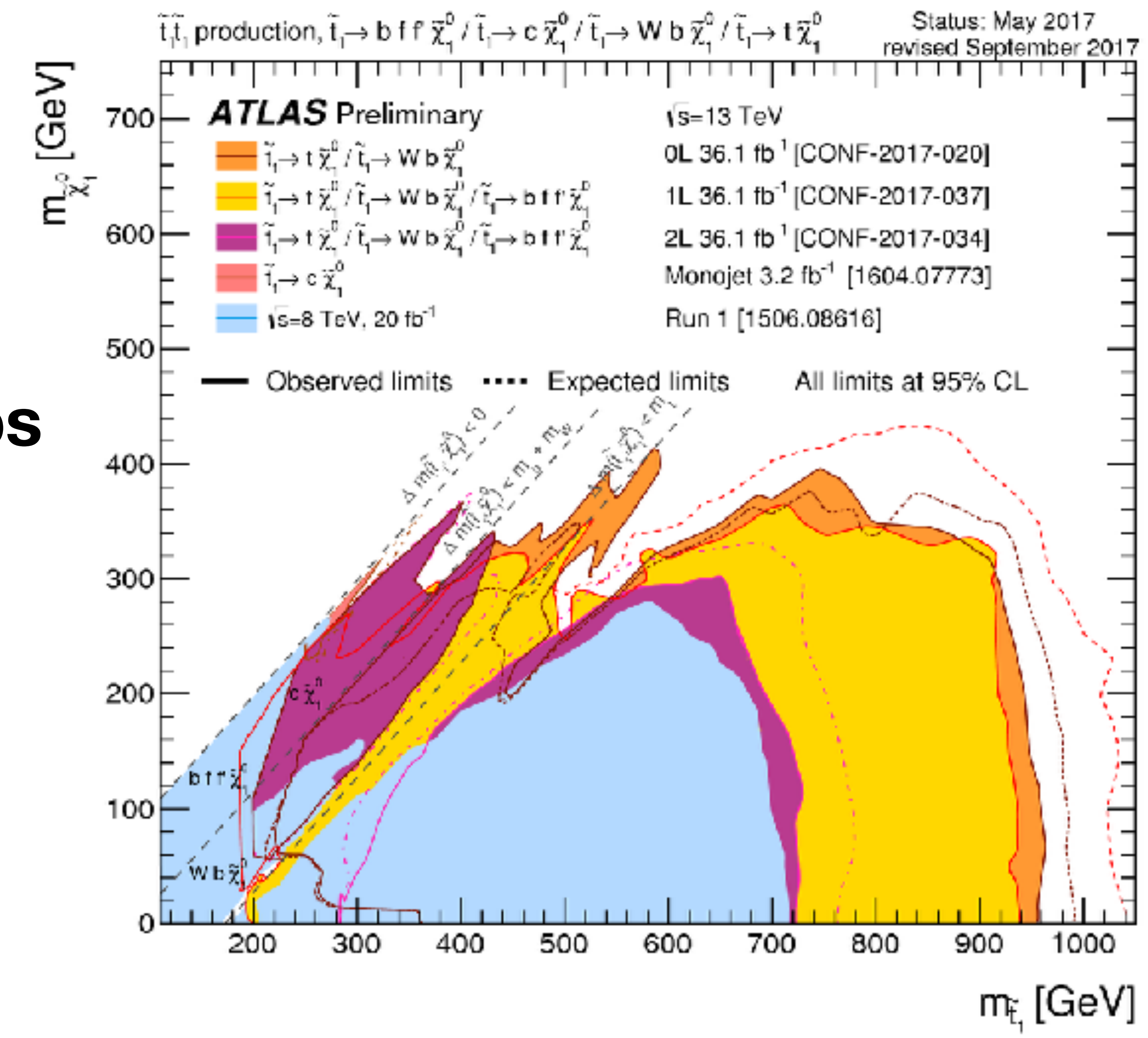
M. Reece

Probing New Physics: How do EDMs Compare?



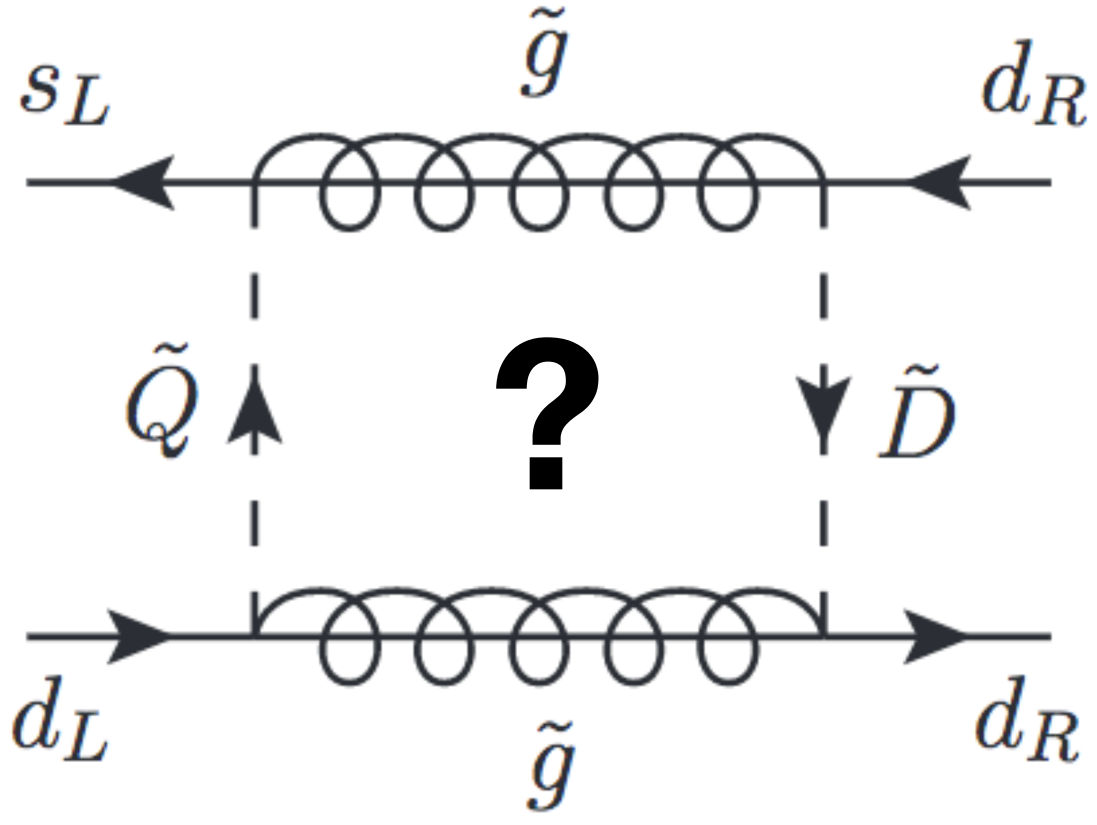
EDMs: exclude stops at 2-3 TeV, with order-1 CPV, m_A = 400 GeV (Nakai, Reece)

LHC: Exclude stops at 1 TeV for typical decay chains



EDM signal would be *clean*, i.e. no background.

Flavor Physics: strong constraints from kaons, *but* 2.8σ hint of new physics in ε'/ε

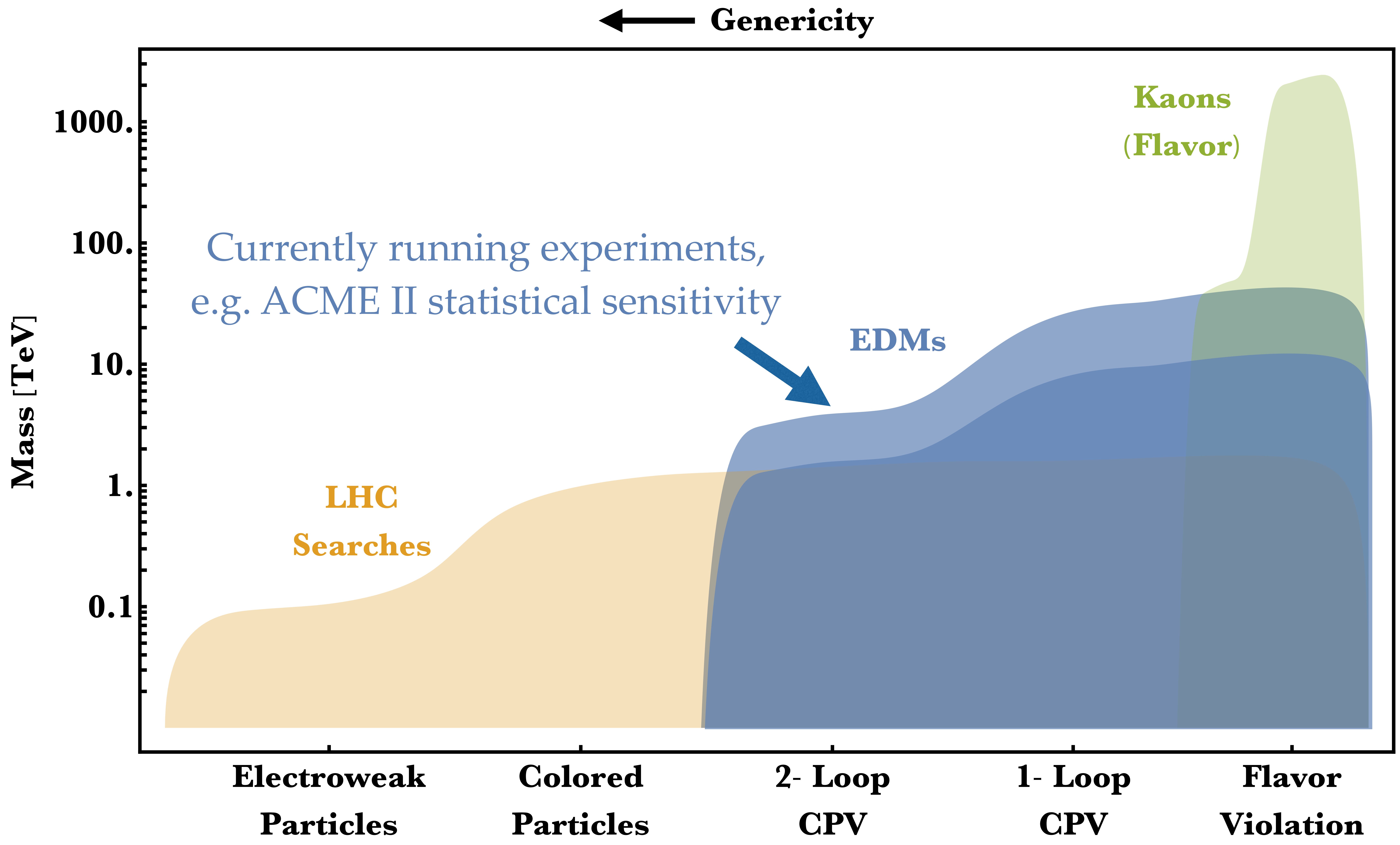


Not clean: unclear how seriously we take this! (Difficult lattice QCD calculations.)

SUSY interpretation: e.g. Crivellin, D'Ambrosio, Kitahara, Nierste '17

M. Reece

Breadth of new physics versus depth of mass reach



M. Reece

How to do better?

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

Effective Electric Field (E_{eff})

Coherence Time (τ)

(Photon) Counting Rate ($\dot{N}$)

Integration Time (T)

Planned improvements at Argonne, JILA, ACME, Imperial….

My Personal Perspective

- Right now we are improving statistical sensitivity. **Hard work, need smart people, requires serious resources…**
- Progress toward next x10 improvement is good for many AMO based EDM experiments.
- But what about the future? What about 1000 TeV??

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

Effective Electric Field — Coherence Time — (Photon) Counting Rate — Integration Time

My Personal Perspective

- Right now we are improving statistical sensitivity. **Hard work, need smart people, requires serious resources…**

- Progress toward next x10 improvement is good for many AMO based EDM experiments.

- But what about the future? What about 1000 TeV??

10^3 improvement in EDM sensitivity possible for some experiments…

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

Effective Electric Field — Coherence Time — (Photon) Counting Rate — Integration Time

…but needs new molecule AND using T < mK methods

My Personal Perspective

- Right now we are improving statistical sensitivity. **Hard work, need smart people, requires serious resources…**

- Progress toward next x10 improvement is good for many AMO based EDM experiments.

- But what about the future? What about 1000 TeV??

10^3 improvement in EDM sensitivity possible for some experiments…

10^2 improvement in eEDM sensitivity possible…

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

Effective Electric Field

Coherence Time

(Photon) Counting Rate

Integration Time

…but needs new molecule AND using T < mK methods

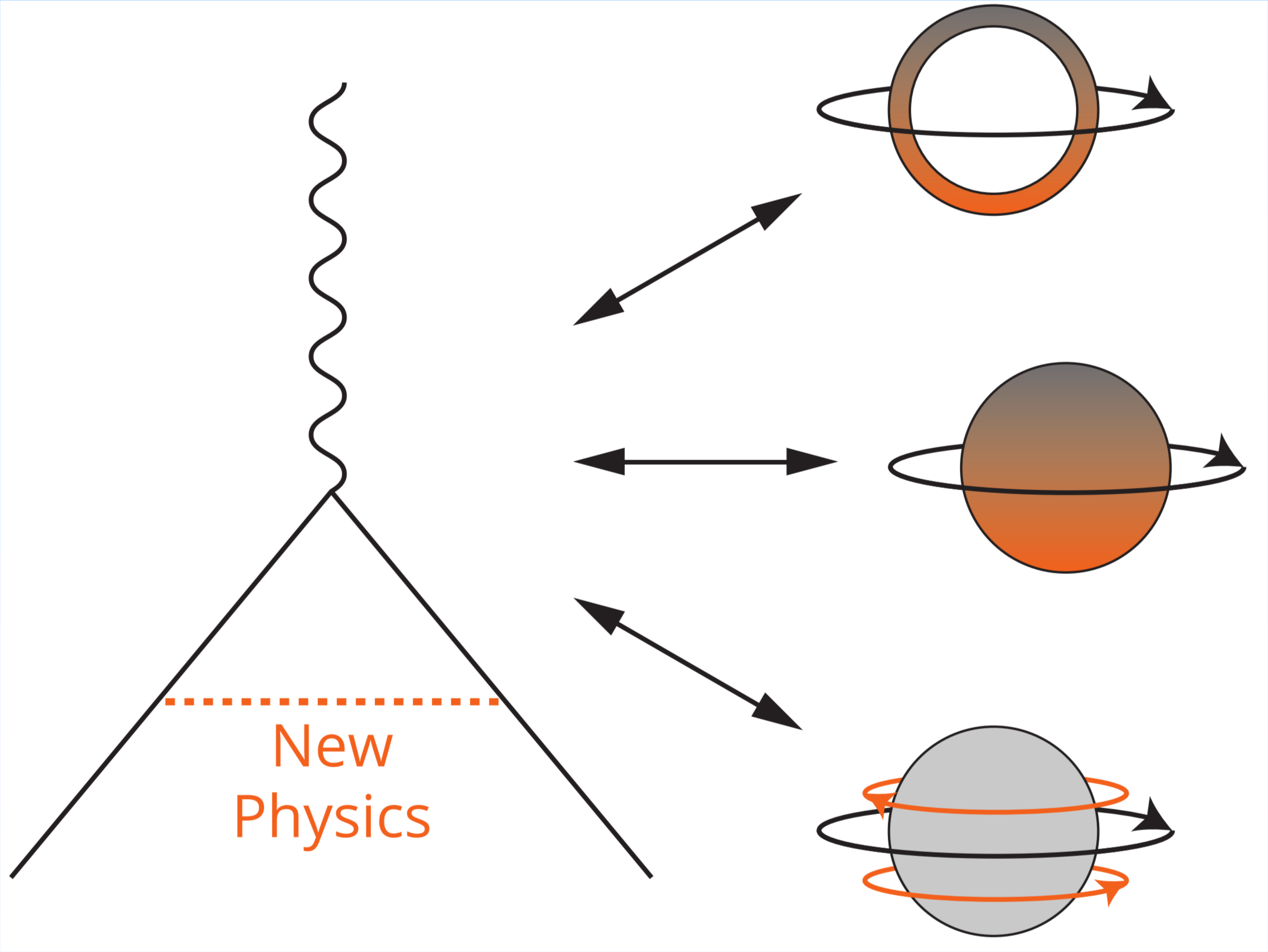
…but needs new, creative methods

My Advice to You

The Graduate
1967, starring
Dustin Hoffman,
dir. Mike Nichols

Symmetry violation in Molecules

- Molecules have enhanced sensitivity to *many* BSM sources
  - Electron EDM
  - Nuclear Schiff moment
  - Nuclear magnetic quadrdupole moment (MQM)
  - PV/anapole moments
  - … and more!
- Let's apply our methods to new sources



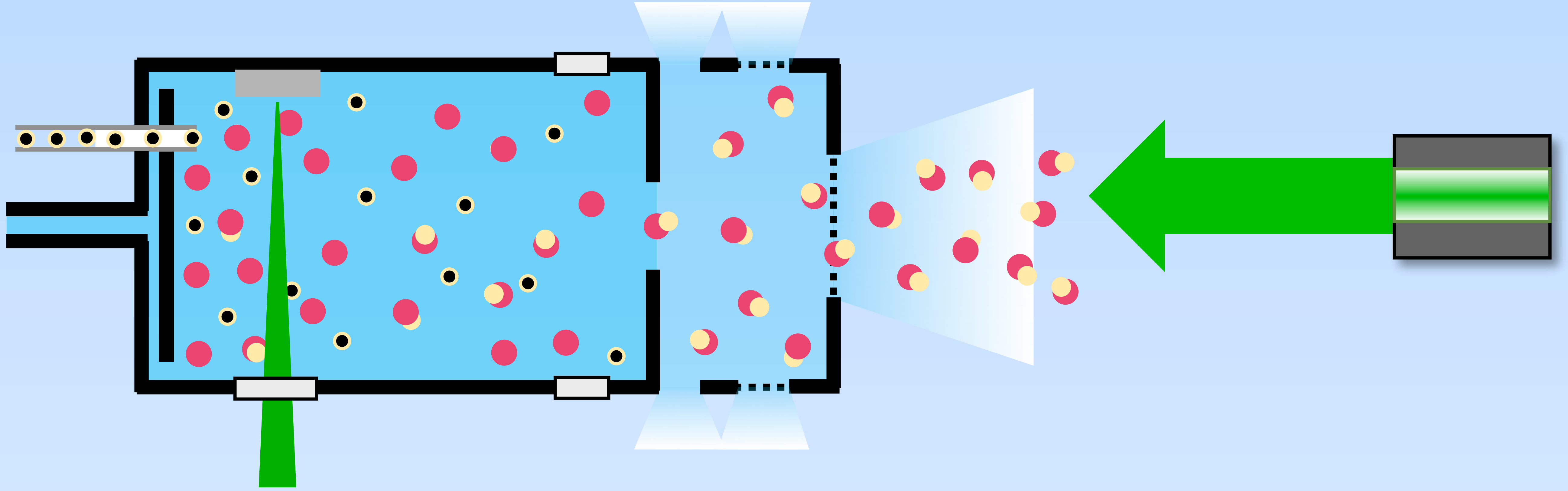
N. Hutzler

CaF

Very Recent Developments

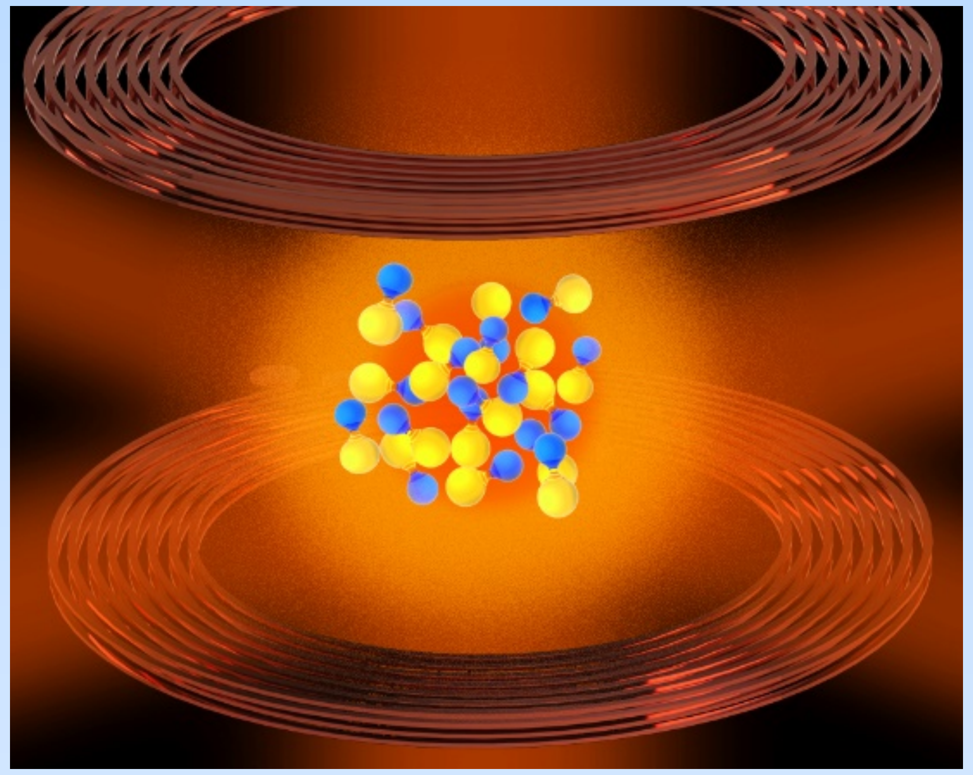
Creating Cold Molecules

CaF Source
(Buffer gas cooling)

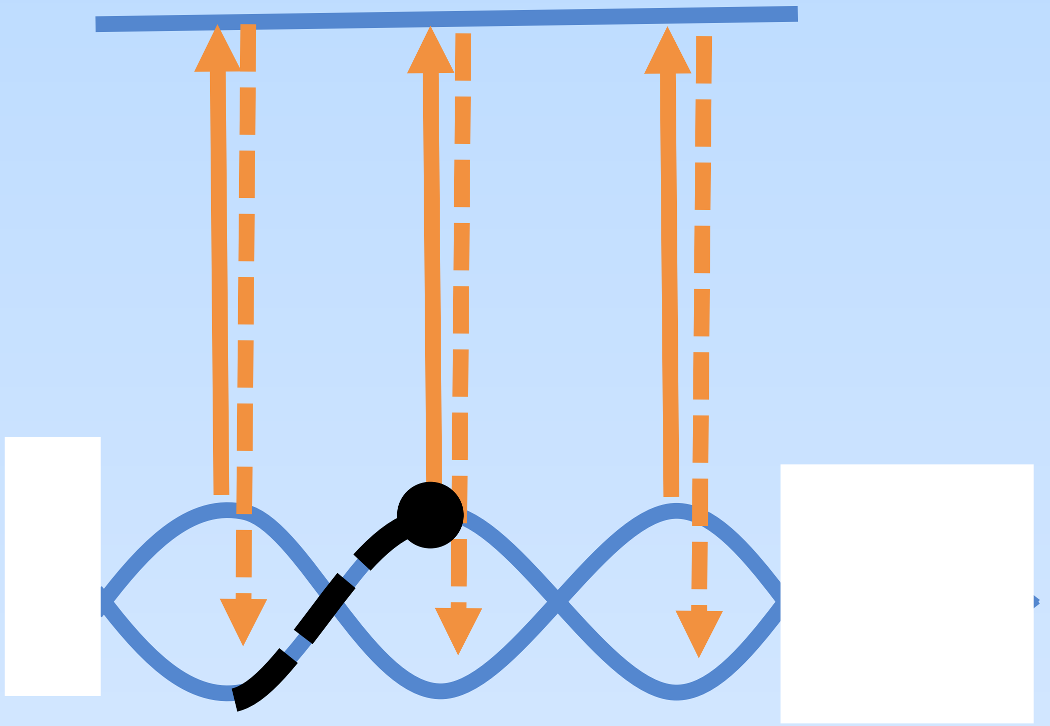


Laser Slowing

RF MOT



Sub - Doppler Cooling



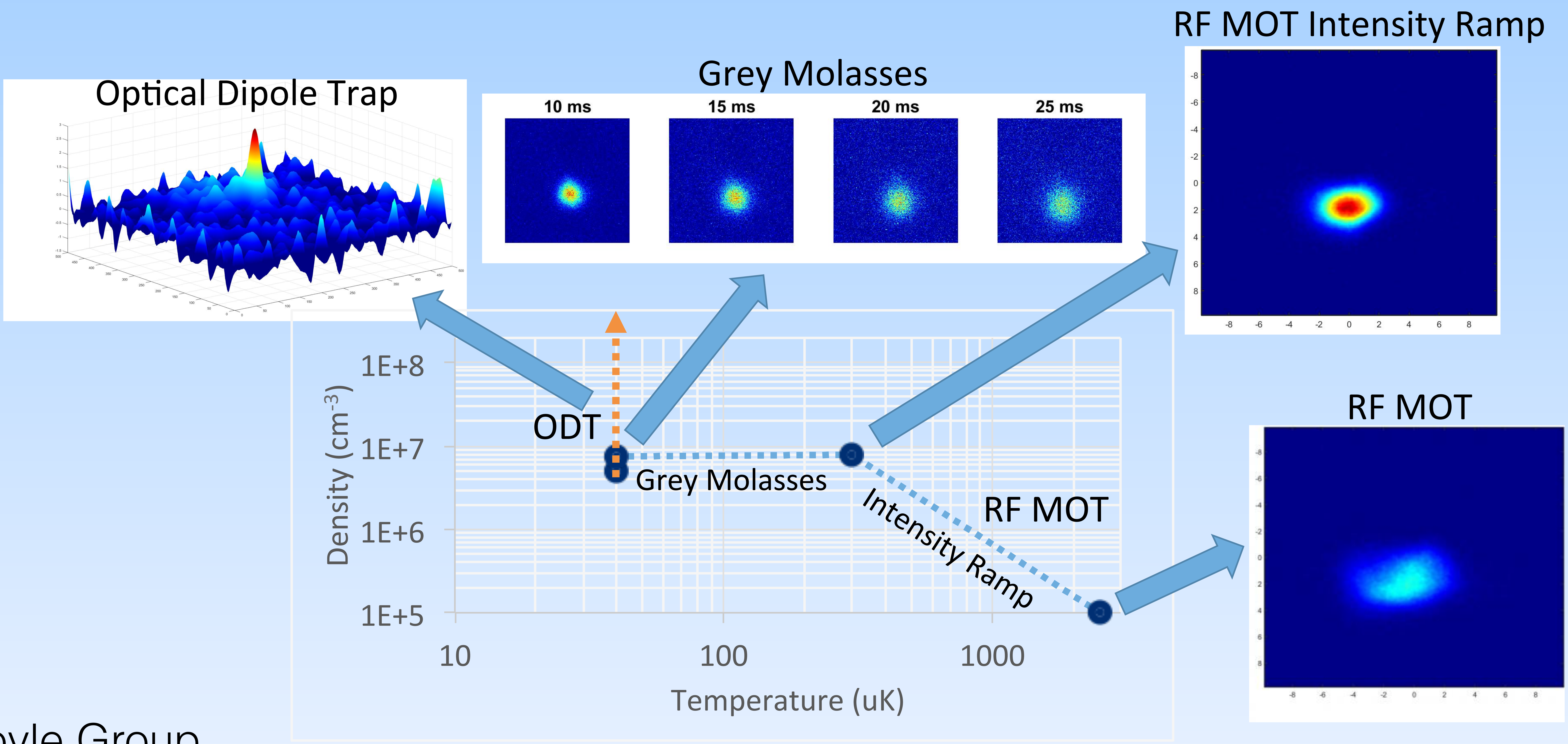
2K **300 uK** **40uK**

Tarbutt, DeMille, Doyle

CaF

Ultracold "Real" Molecules now Available

Increasing Phase space Density

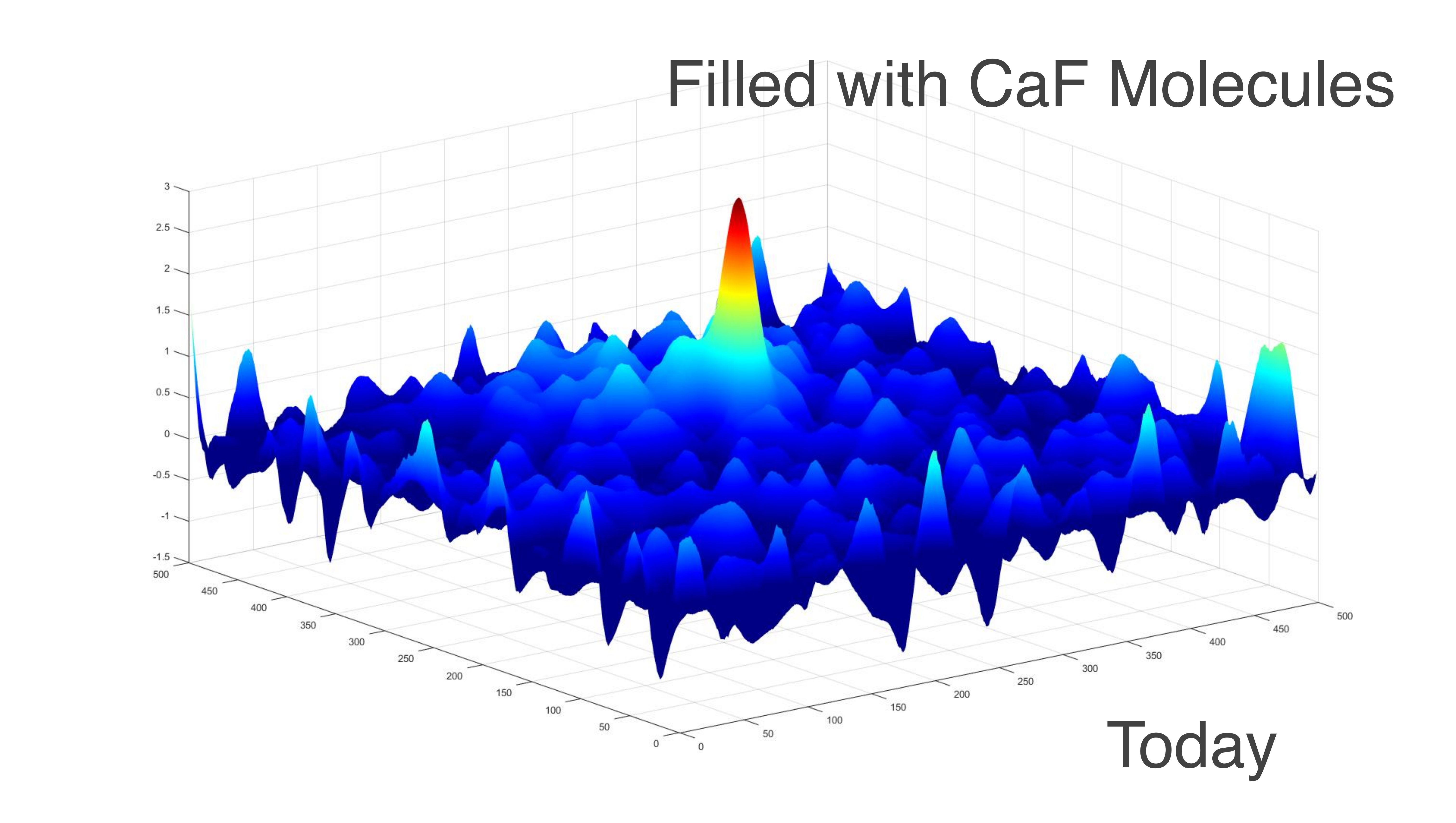


Doyle Group

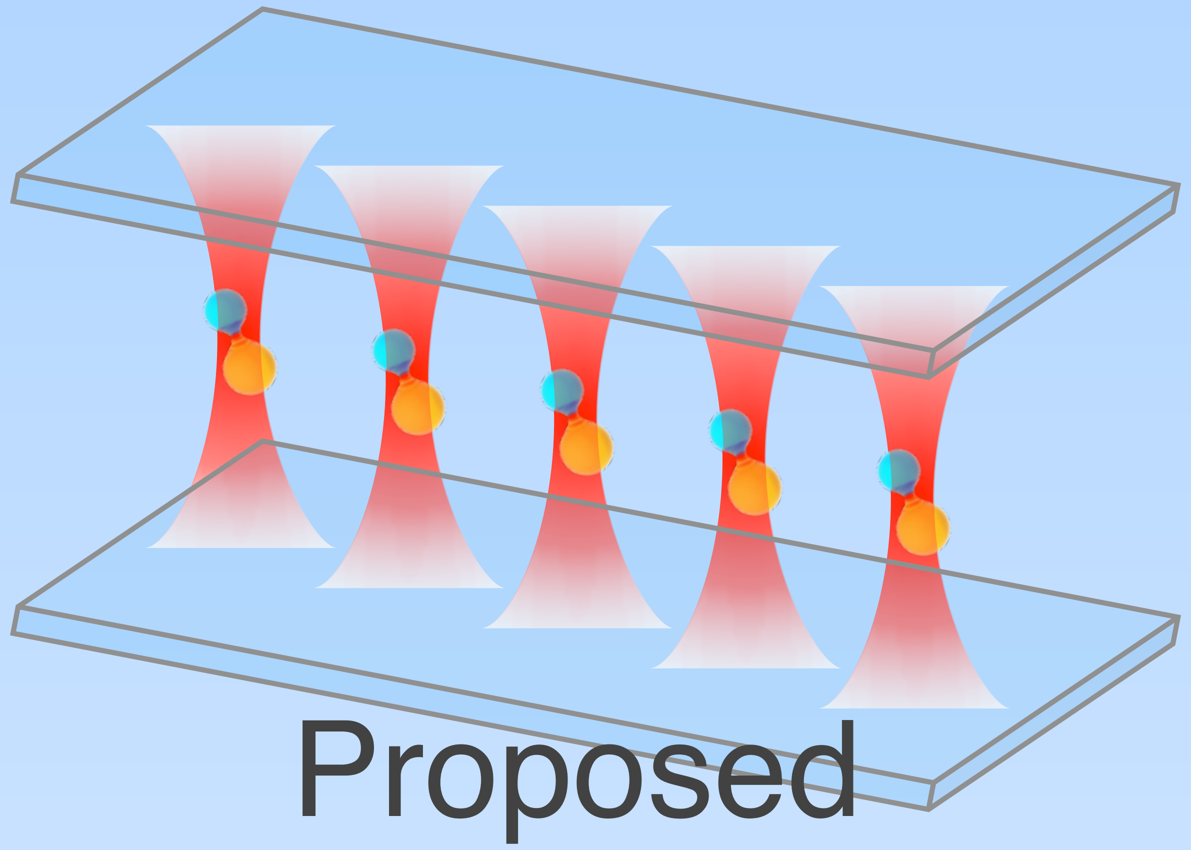
CaF Molecules Can Be Held in "Clock" Type Trap

Towards Quantum Simulation and Computation

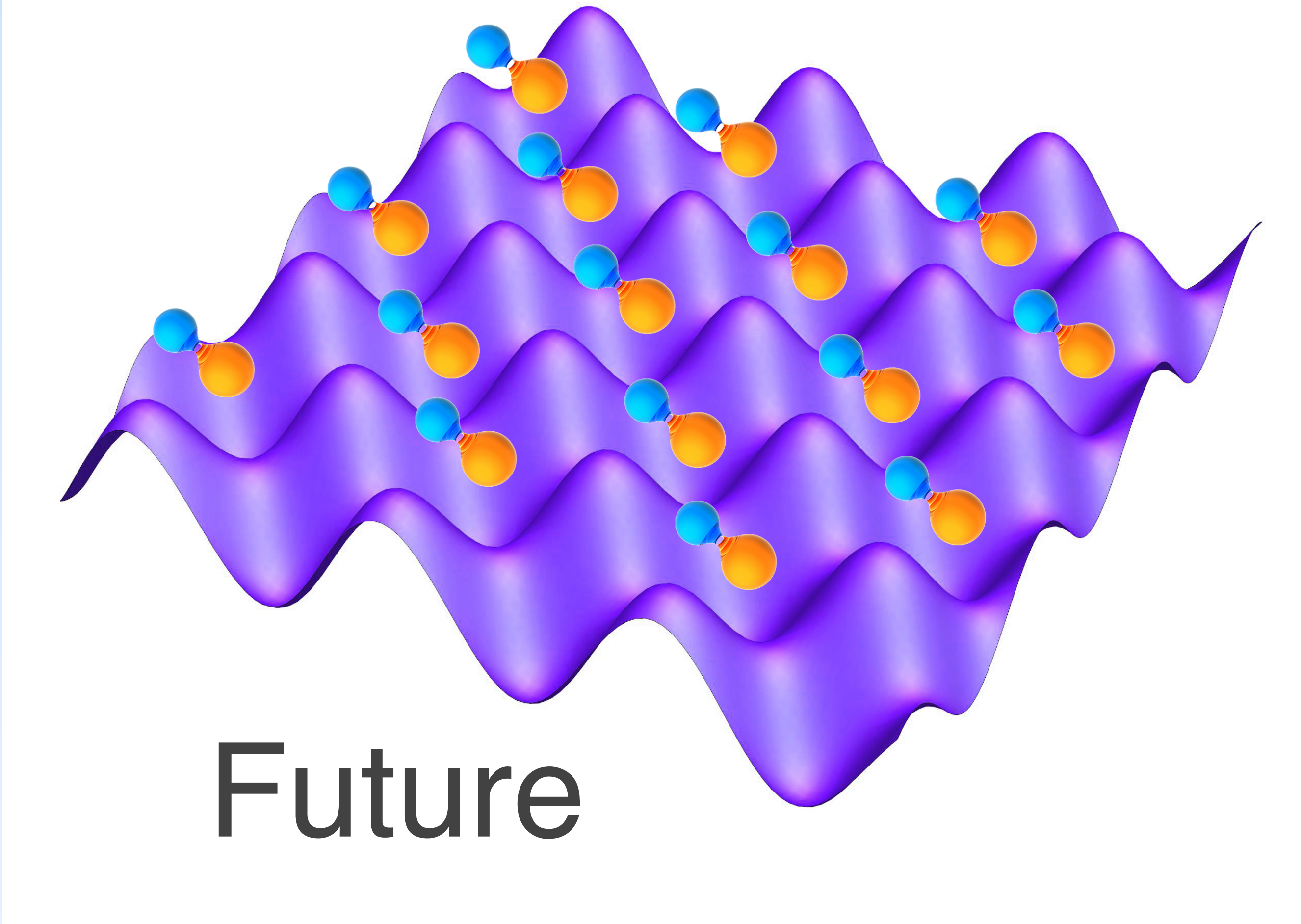
Optical Dipole Trap



1D Optical Tweezer Array



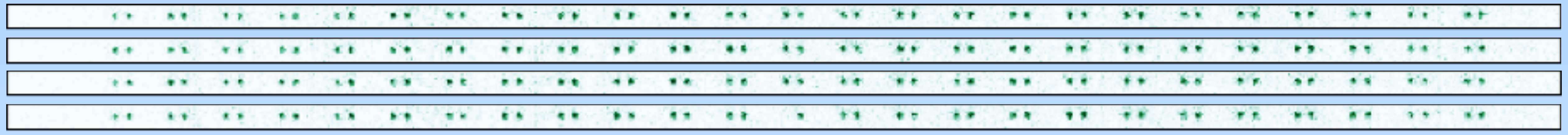
Optical Lattice



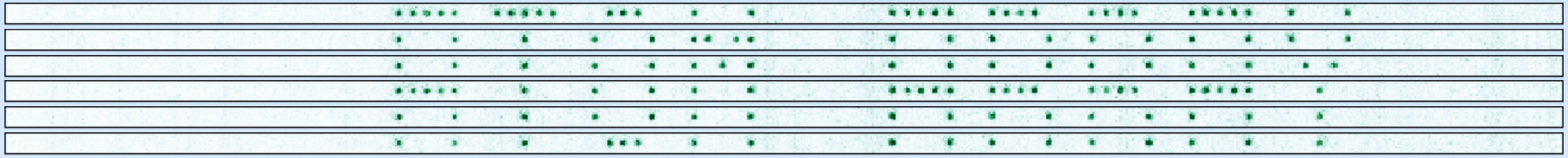
Doyle Group

Atom Array

Clusters of 2

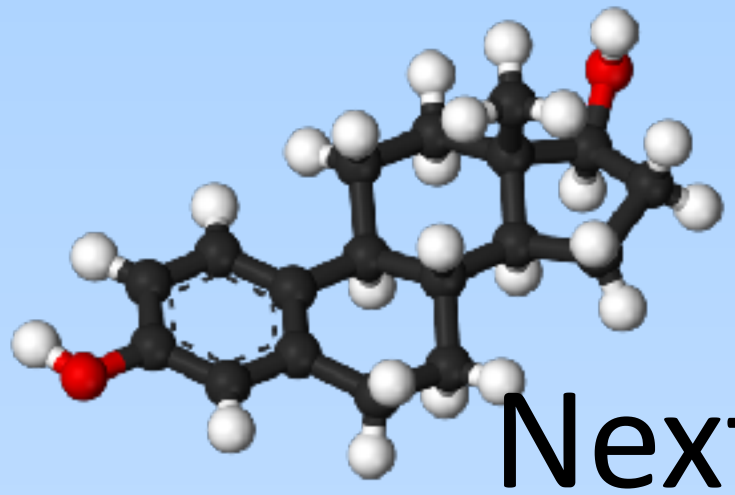


Clusters of 10

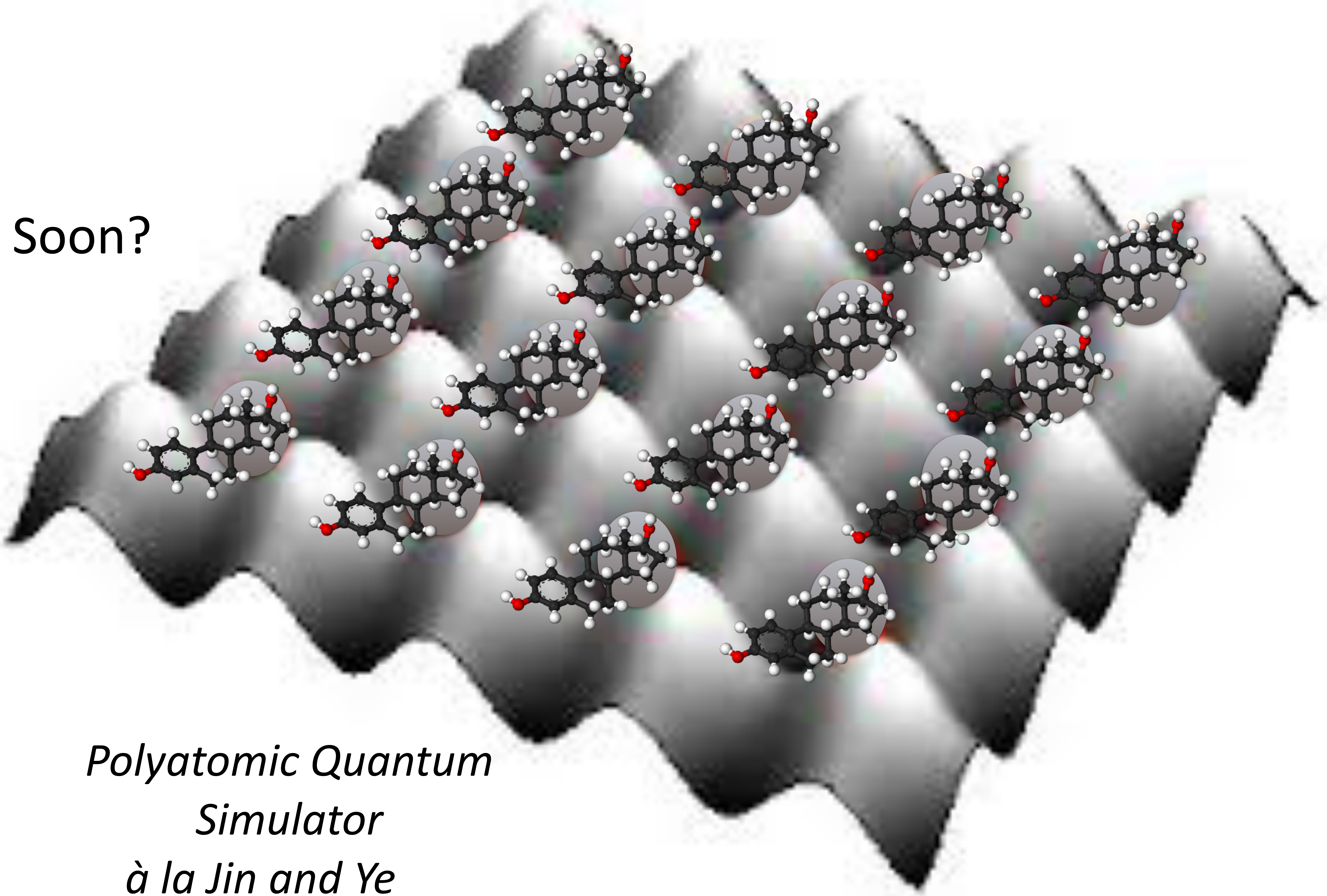


Manuel Endres, Hannes Bernien, Crystal Senko, Alexander Keesling, Harry Levine, Eric Anschuetz,
CUA collaboration of Lukin, Greiner & Vuletic groups;

- Molecular Quantum Simulation and Clocks Possible



Next? Soon?



Polyatomic Quantum Simulator
à la Jin and Ye

What do Polyatomic Molecules Have to do with Particle Physics ?

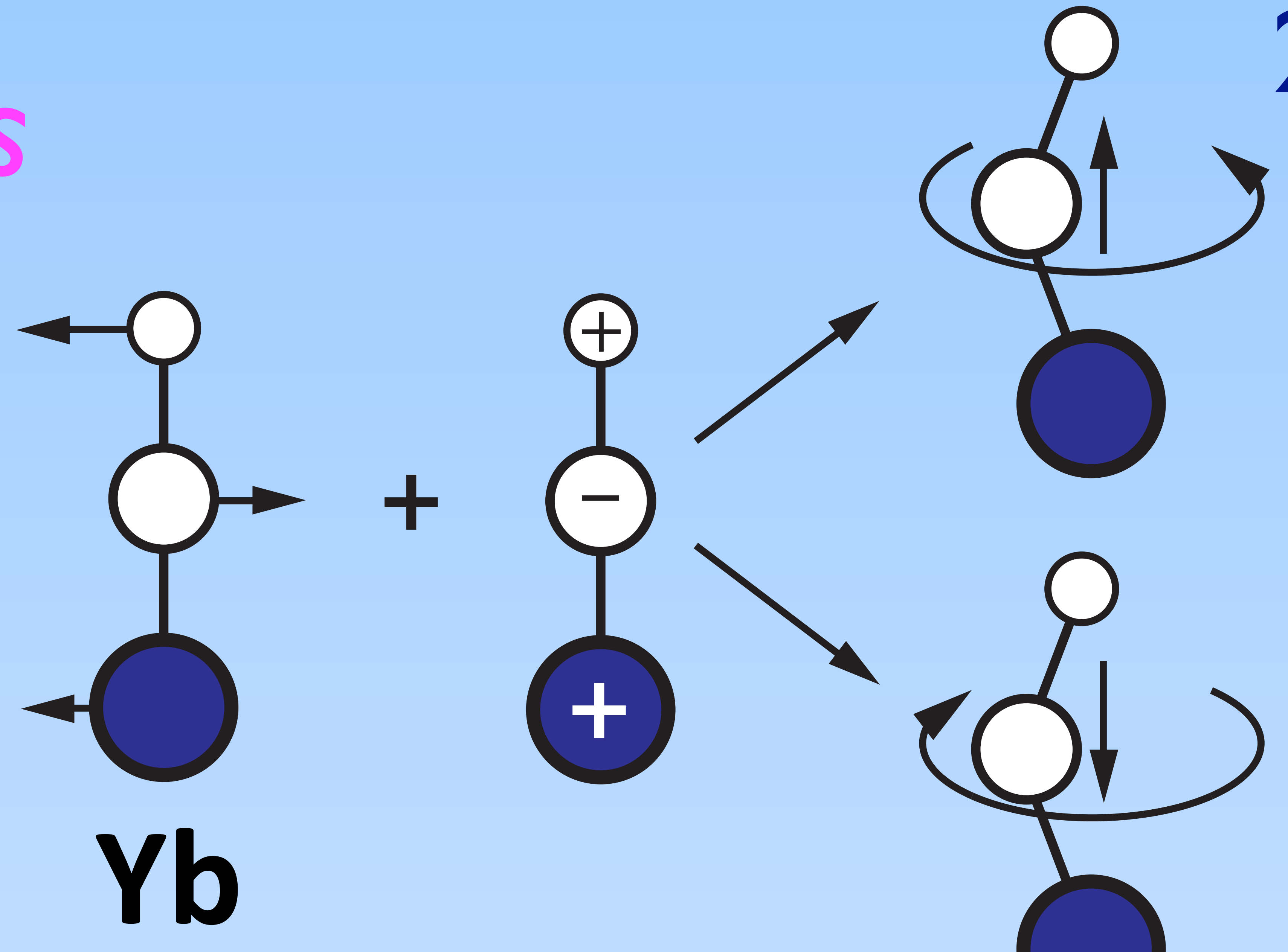
What do Polyatomic Molecules Have to do with Particle Physics ?

Quite a bit, it turns out….

Phys. Rev. Lett. ***119****, 133002, September 2017, Hutzler and Kozyryev*

2017

Embrace the Complexity - Particle Physics



Two GENERIC Handles

Needs for an EDM Molecule

Must orient in lab frame

- need a "handle"

Must have heavy atom

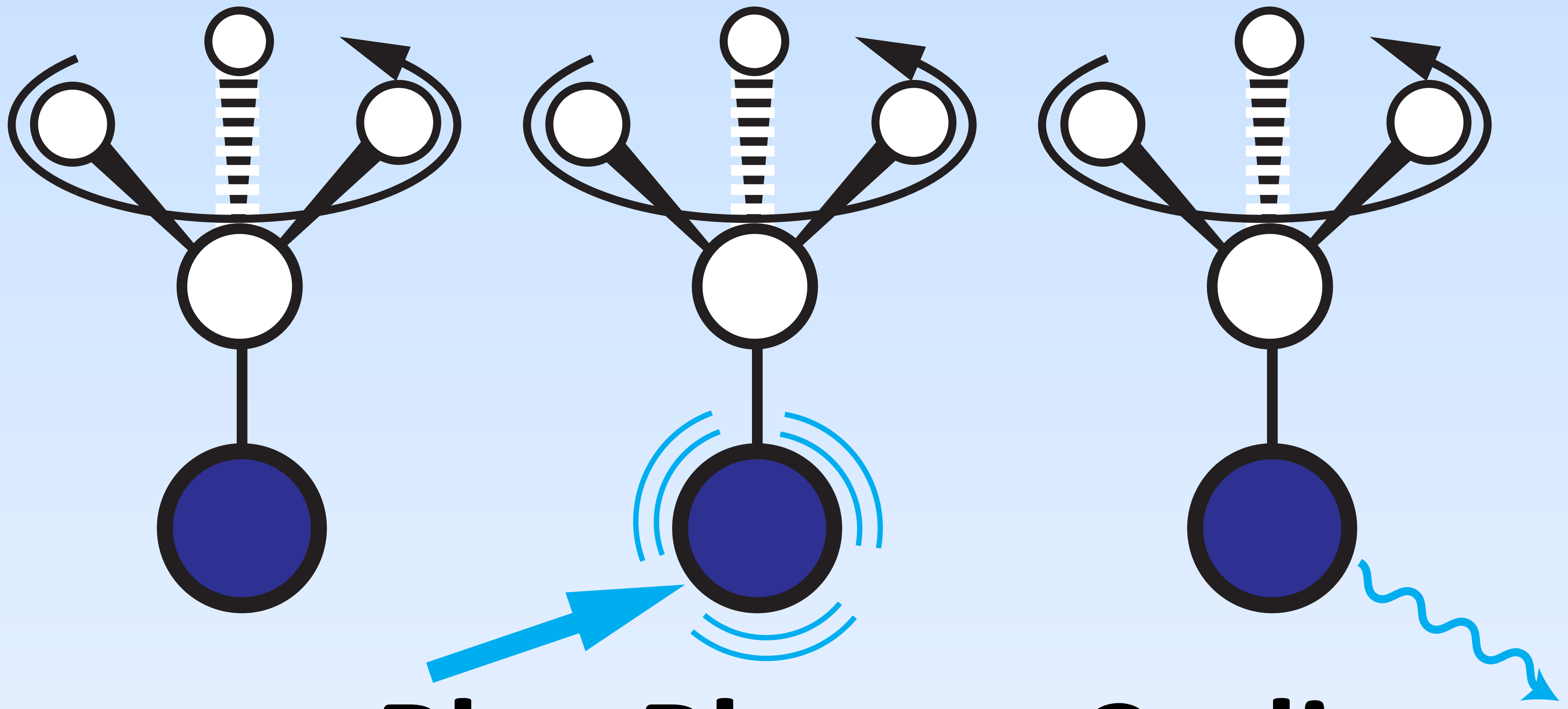
- need relativistic enhancement

WANT photon cycling

- laser cool
- 100% detection

Long Lifetime (> 1s)

A whole class of polyatomics have it ALL.

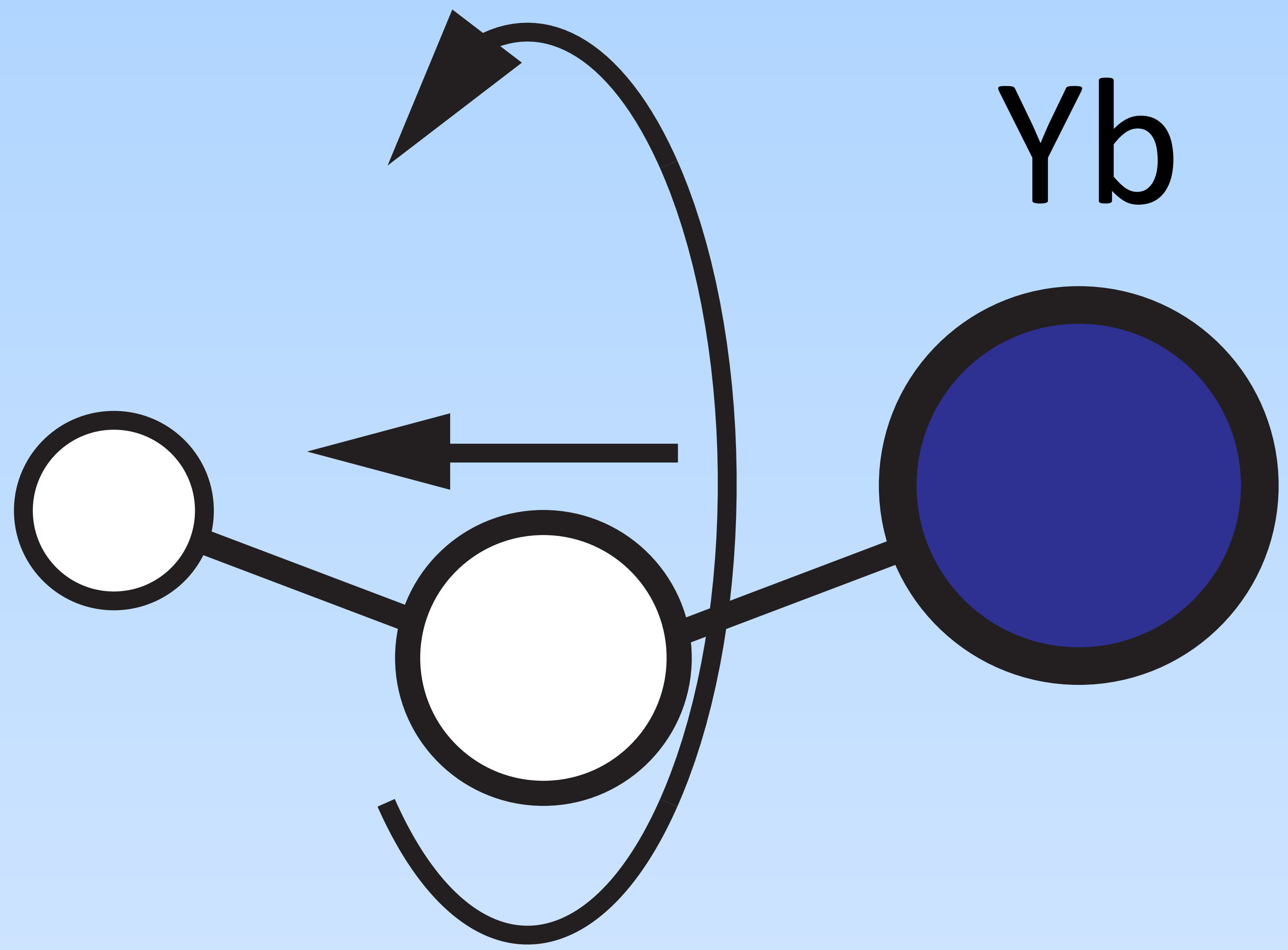


Plus Photon Cycling

Phys. Rev. Lett. ***119****, 133002 – Published 28 September 2017*

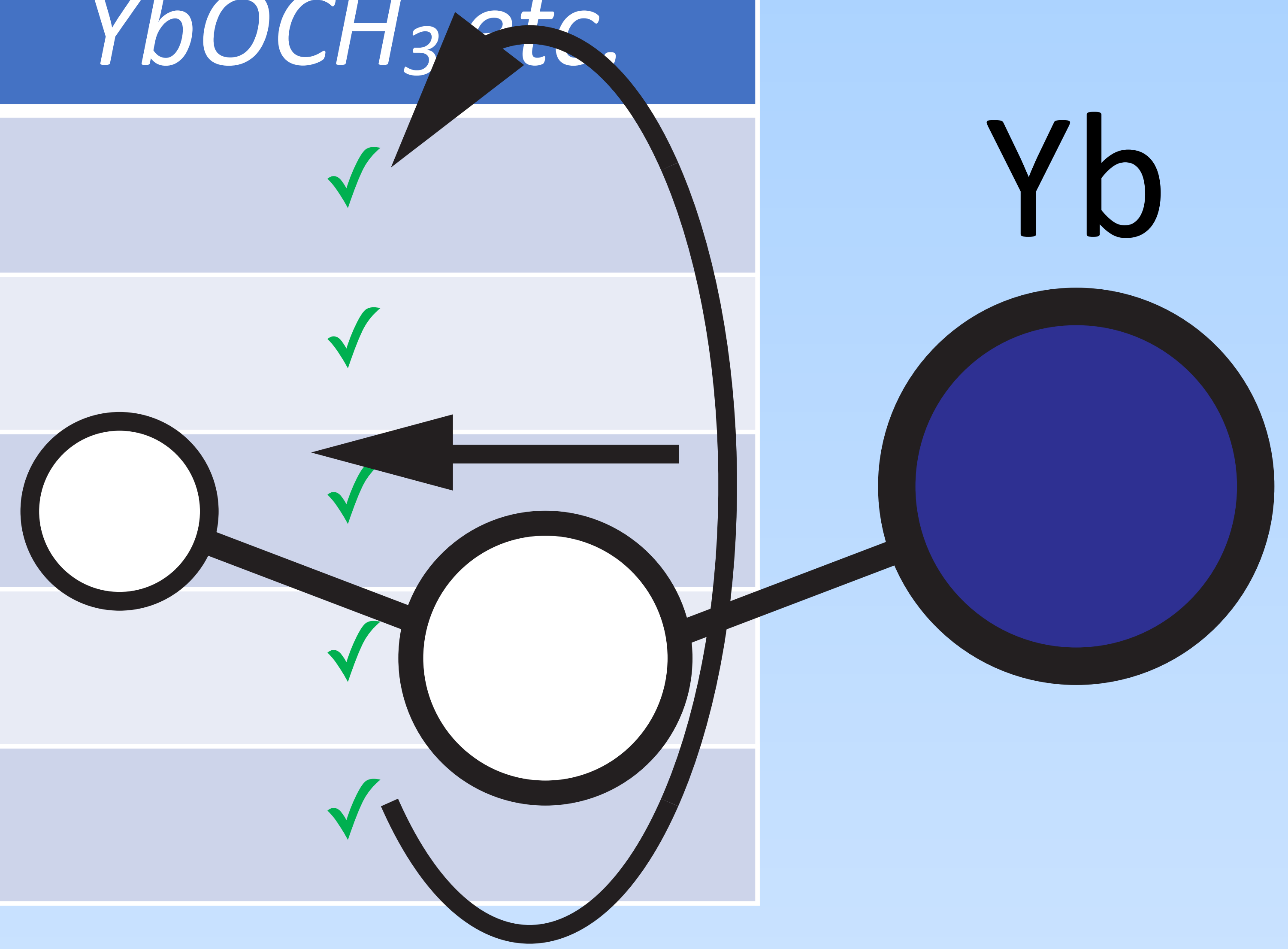
Polyatomic EDM

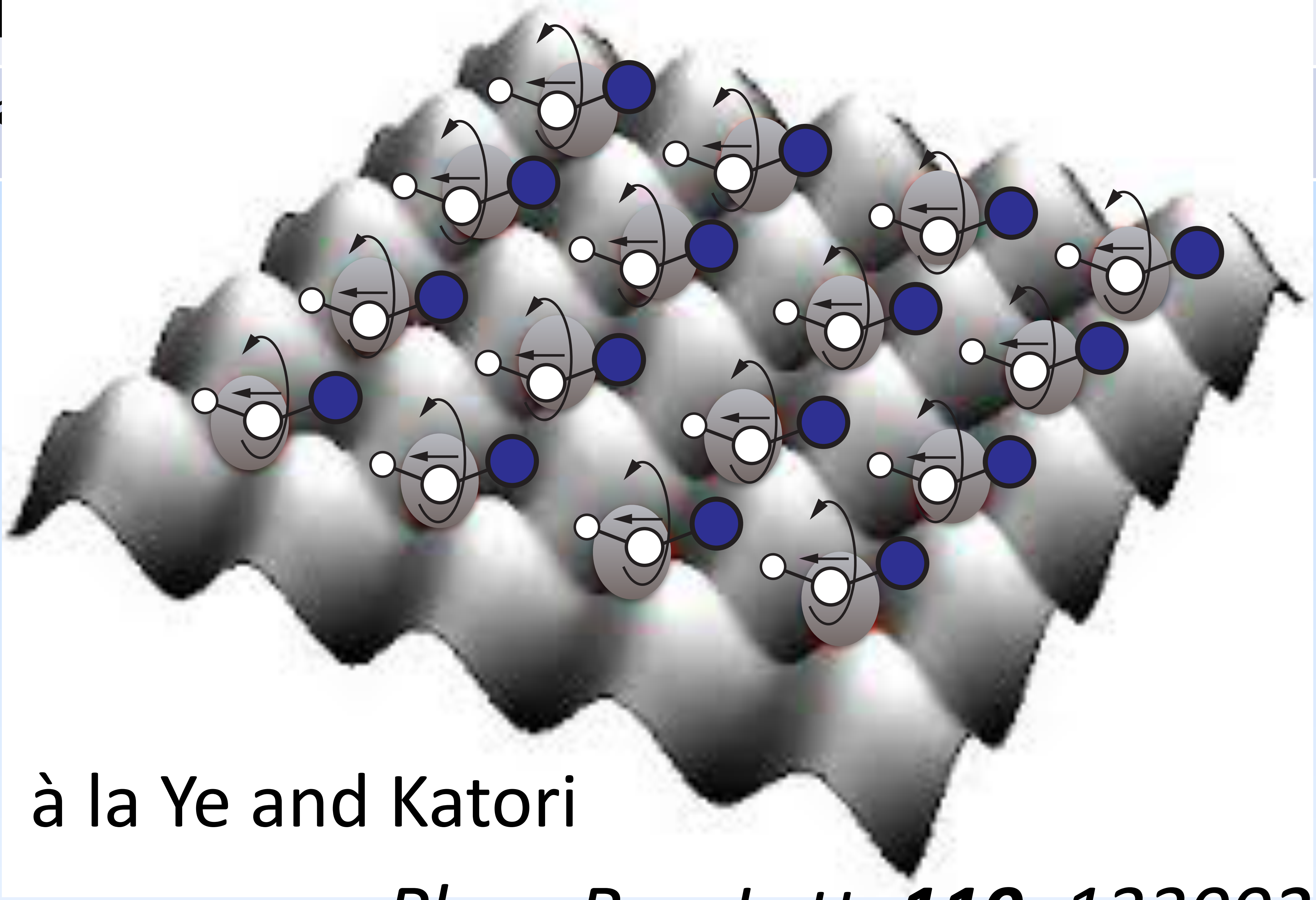
Feature	**ThO, ACME**	(Yb,Ba, Ra)F	WC	**(Hf,Th)F⁺, JILA ION**	*YbOH, $YbOCH_3$, etc.*
Laser cooling	✗	✓	✗	✗	✓
Full polarization	✓	✗	✓	✓	✓
Internal co-mag.	✓	✗	✓	✓	✓
>1 s lifetime	✗	✓	✓	✓	✓
Scalable (Large #)	✓	✓	✓	✗	✓



Polyatomic EDM

Feature	ThO, ACME	(Yb,Ba,Ra)F	WC	$(Hf,Th)F^+$, JILA ION	*YbOH, $YbOCH_3$ etc.*
	Diatomics			Poly-atomics	
Laser cooling	✗	✓	✗	✗	✓
Full polarization	✓	✗	✓	✓	✓
Internal co-mag.	✓	✗	✓	✓	✓
>1 [illegible]	✗	✓	✓	✓	✓
Sc[illegible]	[illegible]	[illegible]	[illegible]	✗	✓

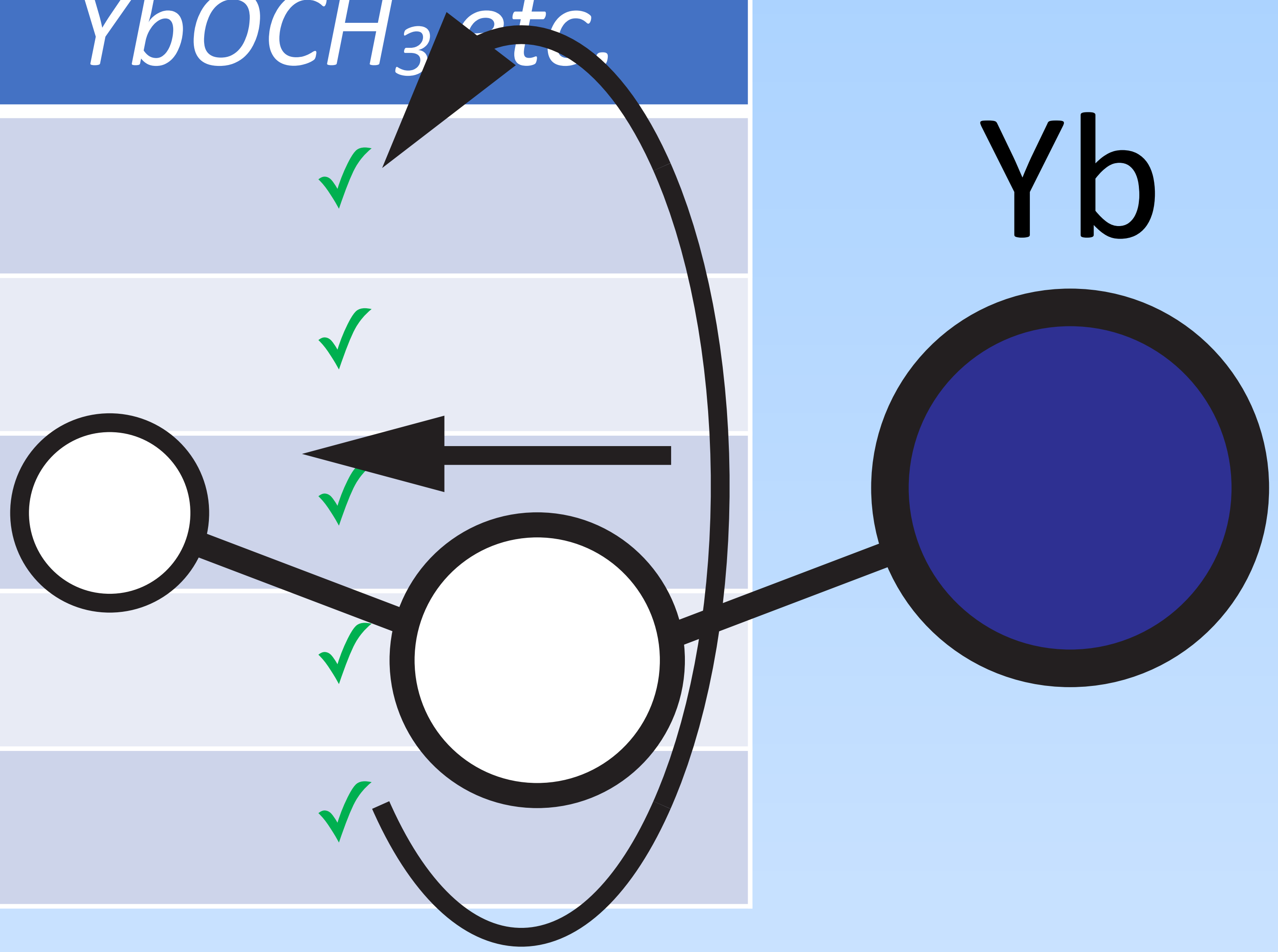


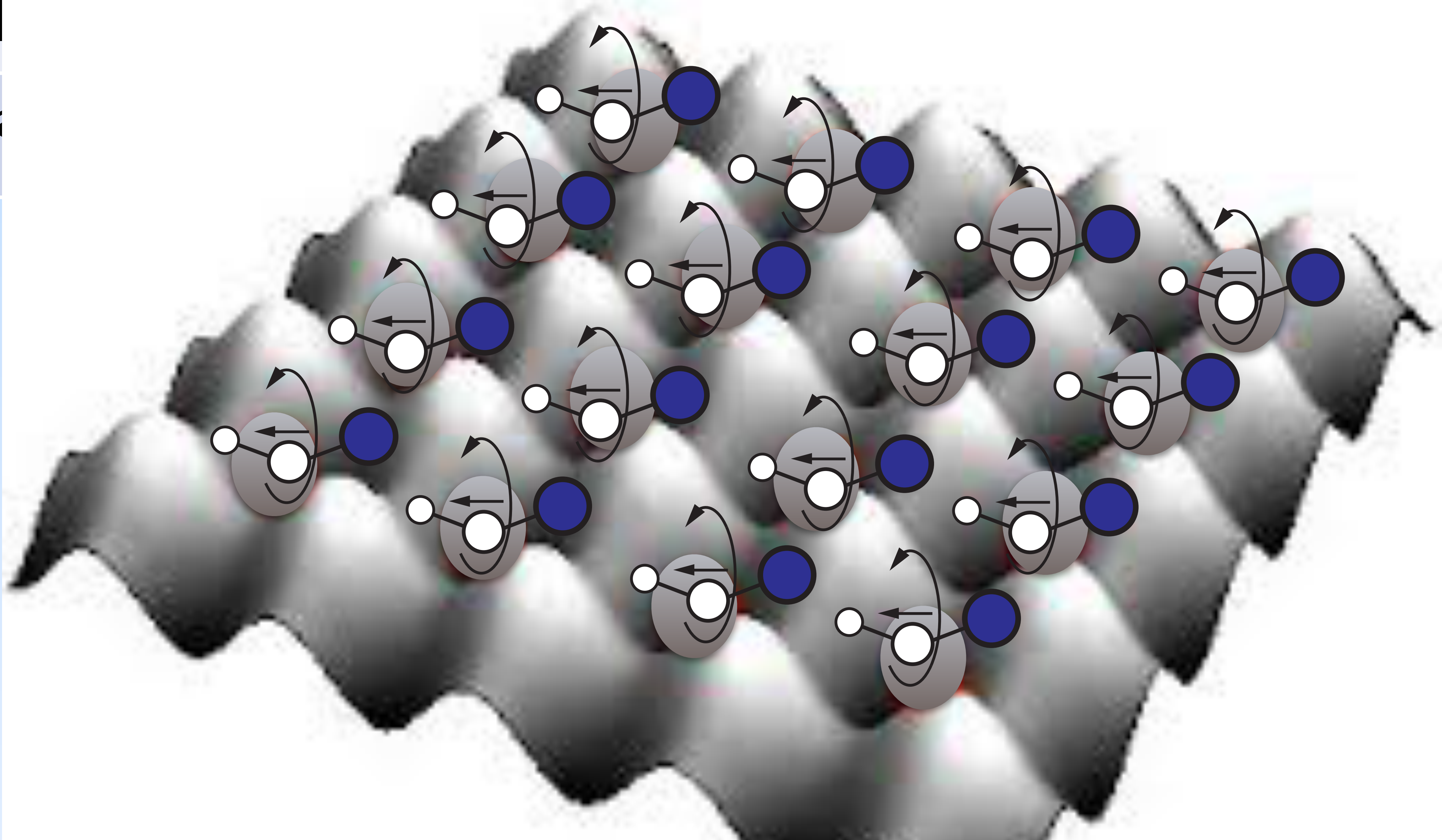


Phys. Rev. Lett. ***119***, *133002 – Published 28 September 2017*

Polyatomic EDM

Feature	ThO, ACME	(Yb,Ba,Ra)F	WC	(Hf,Th)F^+, JILA ION	*YbOH, $YbOCH_3$ etc.*
	Diatomics			Poly-atomics	
Laser cooling	✗	✓	✗	✗	✓
Full polarization	✓	✗	✓	✓	✓
Internal co-mag.	✓	✗	✓	✓	✓
>1[illegible]	✗	✓	✓	✓	✓
Sc[illegible]	[illegible]	[illegible]	[illegible]	✗	✓





à la Ye and Katori

5x10^6 molecules

E_eff=25 GV/cm

10 s coherence

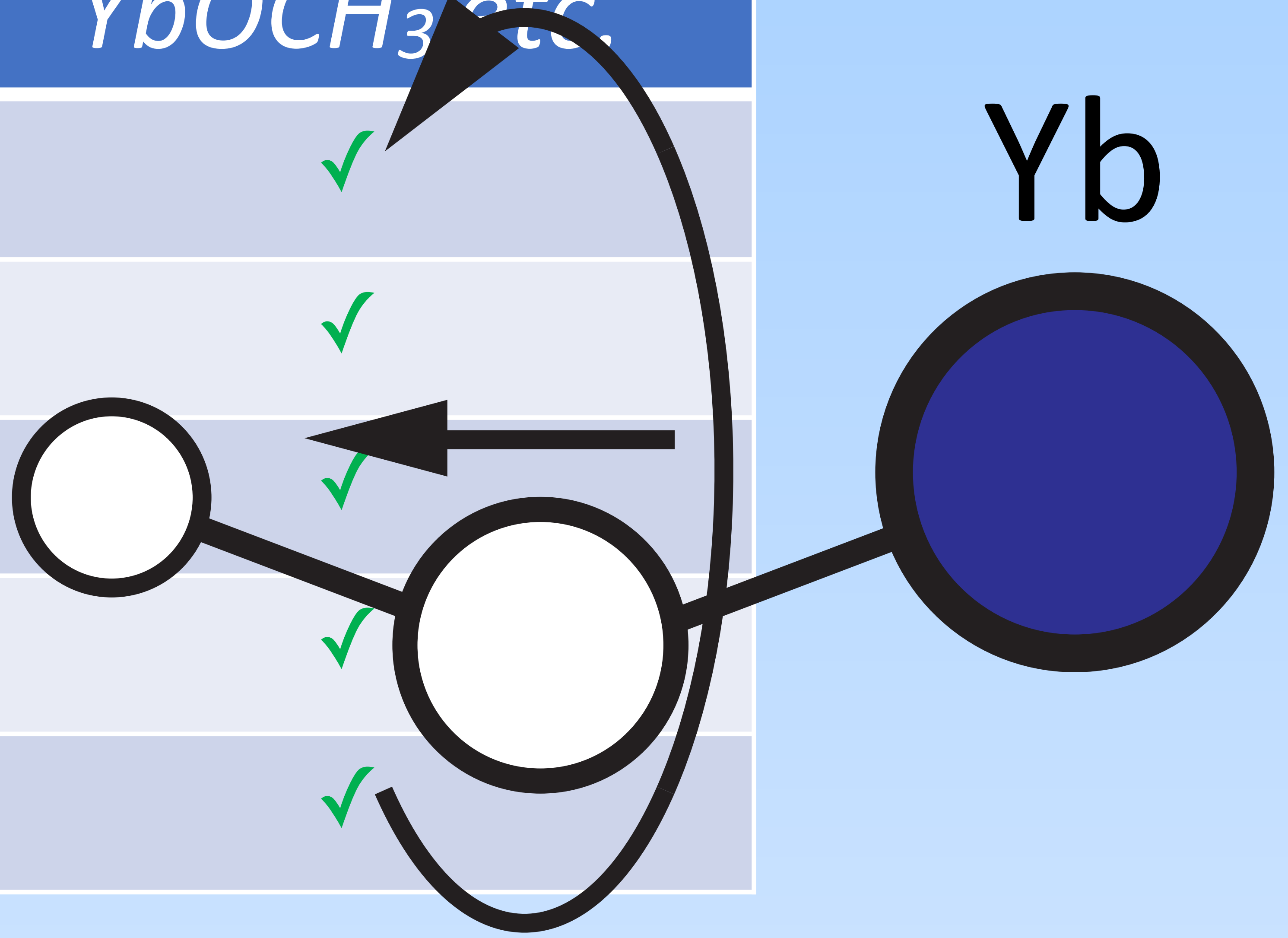
1 day of data taking

Phys. Rev. Lett. ***119****, 133002 – Published 28 September 2017*

Polyatomic EDM

Diatomics | Poly-atomics

Feature	ThO, ACME	(Yb,Ba,Ra)F	WC	(Hf,Th)F^+, JILA ION	*YbOH, $YbOCH_3$ etc.*
Laser cooling	✗	✓	✗	✗	✓
Full polarization	✓	✗	✓	✓	✓
Internal co-mag.	✓	✗	✓	✓	✓
>1 s lifetime	✗	✓	✓	✓	✓
Scalable (Large #)	✓	✓	✓	✗	✓



5×10^6 molecules

E_eff=25 GV/cm

10 s coherence

1 day of data taking

Sensitivity to EDM 10^{-32} e cm

Phys. Rev. Lett. ***119****, 133002 – Published 28 September 2017*

Polyatomic EDM

Diatomics | Poly-atomics

Feature	ThO, ACME	(Yb,Ba,Ra)F	WC	**(Hf,Th)F^{+}, JILA ION**	YbOH, $YbOCH_3$ etc.
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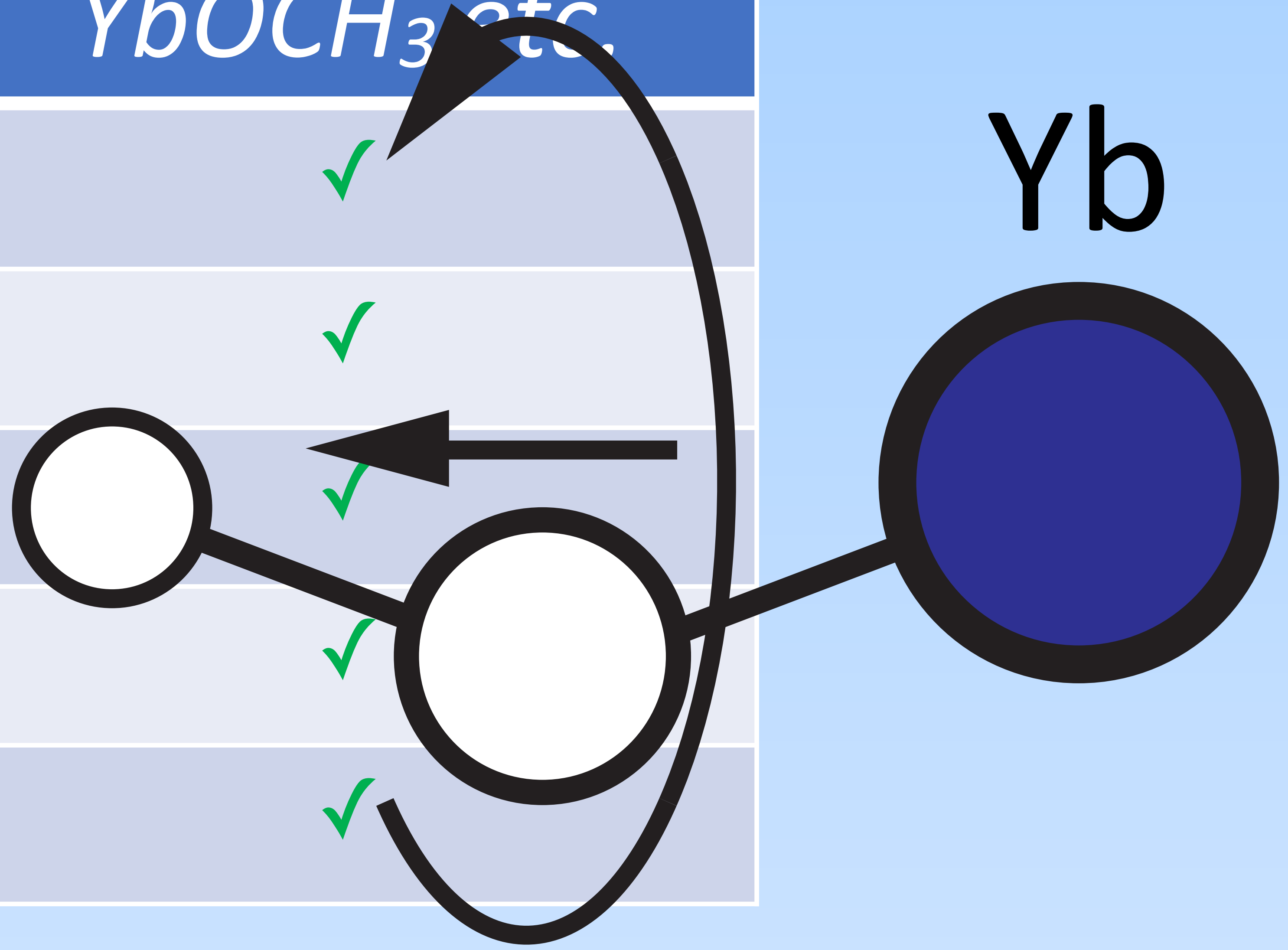
Full polarization	✓	✗	✓	✓	✓
Internal co-mag.	✓	✗	✓	✓	✓
>1 s lifetime	✗	✓	✓	✓	✓
Scalable (Large #)	✓	✓	✓	✗	✓

In a FORT experiment



5x10^{6} molecules

E_eff=25 GV/cm

10 s coherence

1 day of data taking

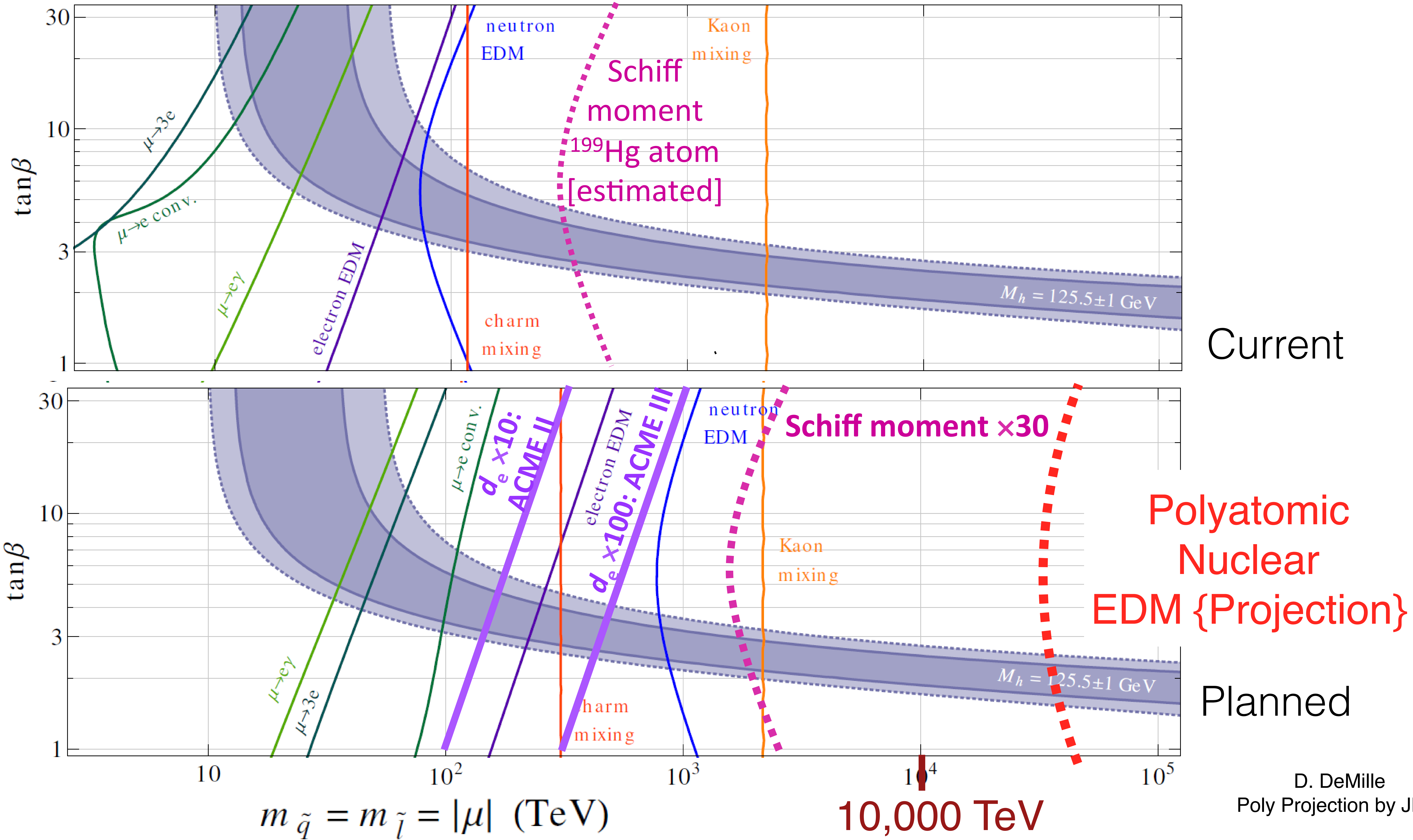
Sensitivity to EDM 10^{-32} e cm

WHAT DOES THIS MEAN TO PARTICLE PHYSICS?

Phys. Rev. Lett. ***119****, 133002 – Published 28 September 2017*

A particle physics future?
1000 TeV
Poly-EDM Projected
Kozyryev and Hutzler, PRL, 2017
30
10
3
1
0.3
Superpartner Mass (TeV)
Higgsinos/Gauginos
1st Generation
2nd Generation
"Al… onstraints shown are me… ative and subject to sigr… oopholes and caveats"
Order Unity SUSY Phases
ACME II Projected with ThO
Seattle Hg
FLAV
NAT
DM
EDM
LHC
HIGGS
SQUARK SLEPTON
STOP

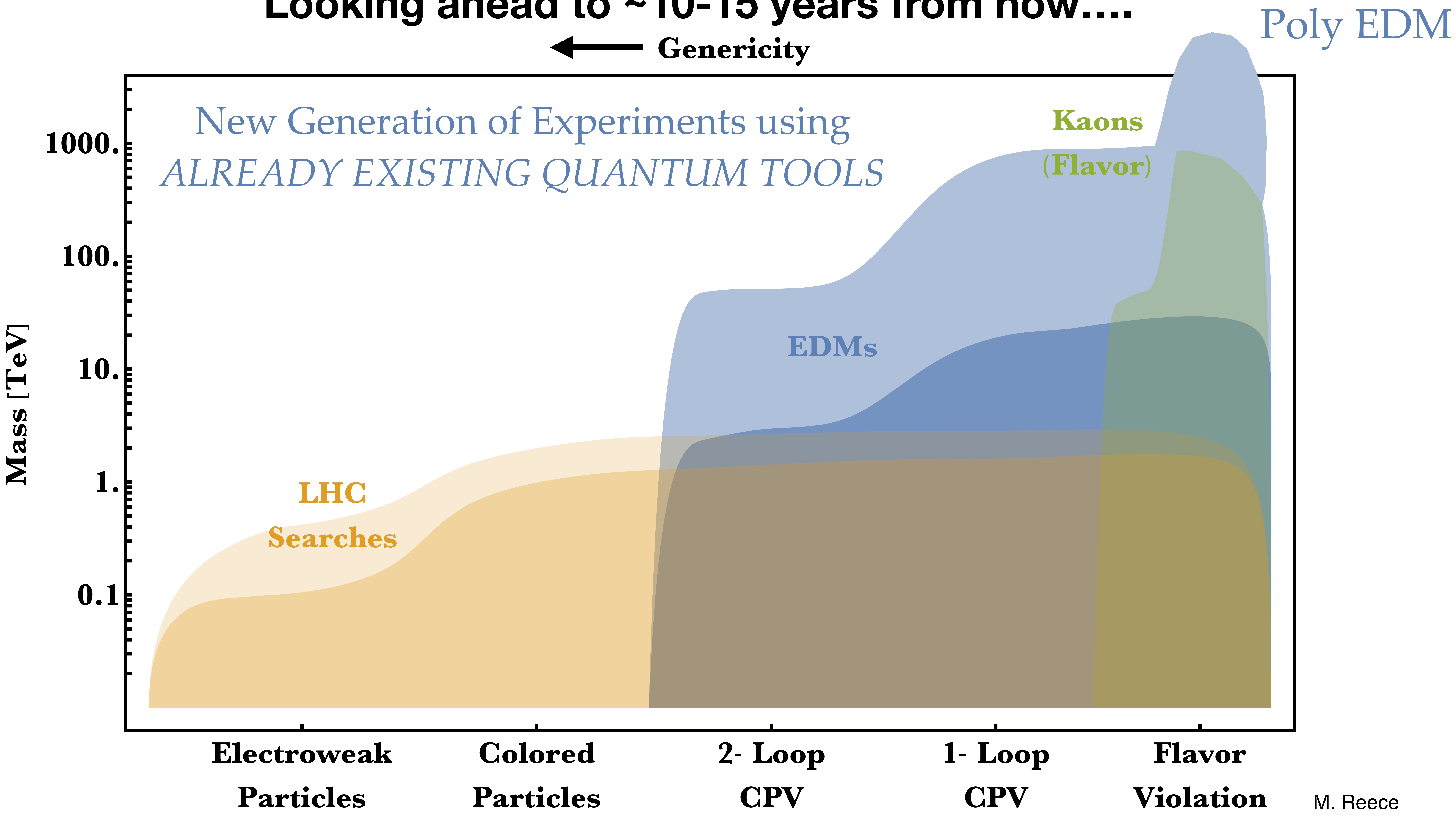
EDMs accompanying new flavor violation



W. Altmannshofer, *et al.*, Low energy probes of PeV scale sfermions. JHEP **2013**(11), 202 (2013).

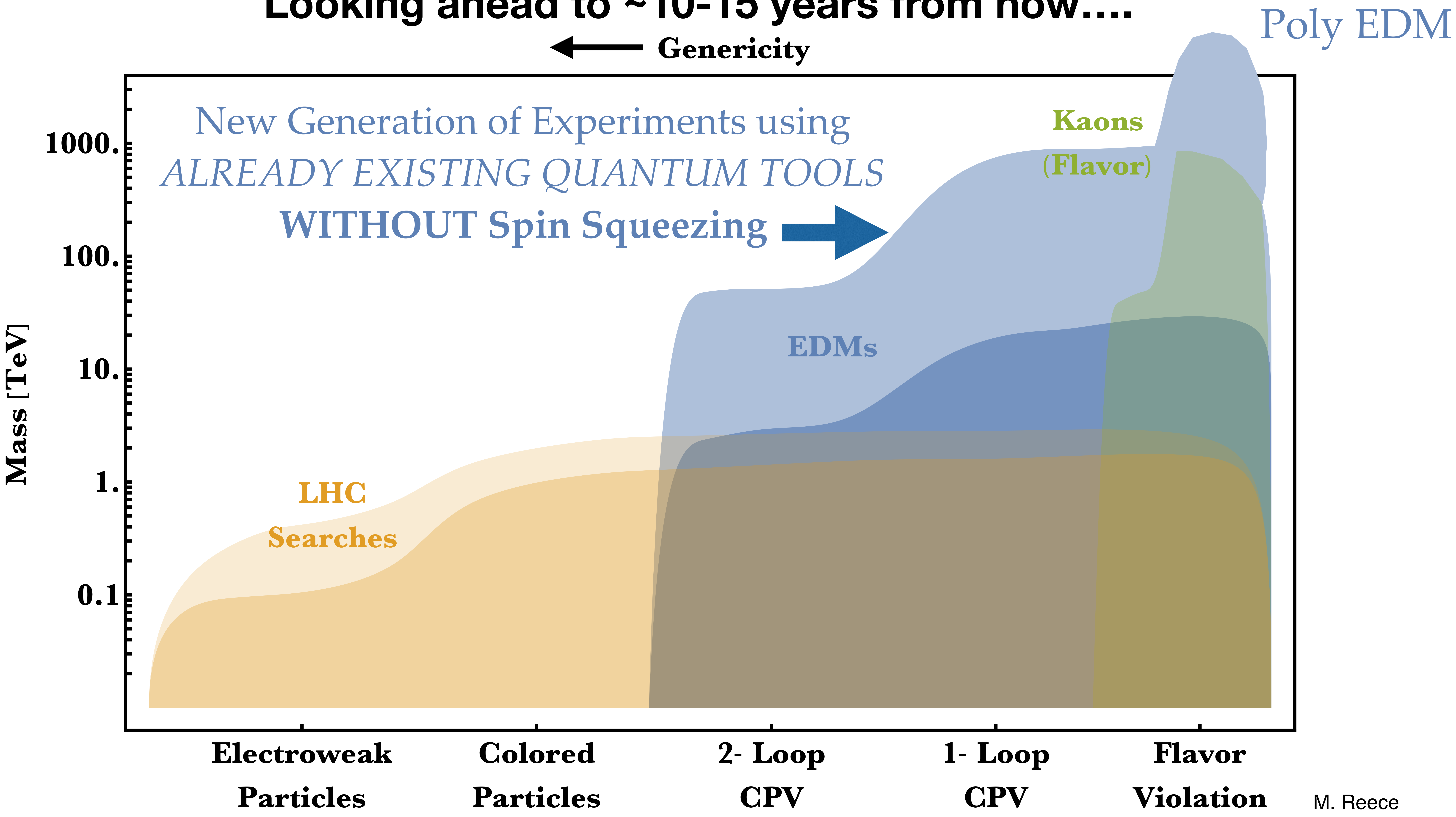
D. DeMille
Poly Projection by JMD

Looking ahead to ~10-15 years from now....



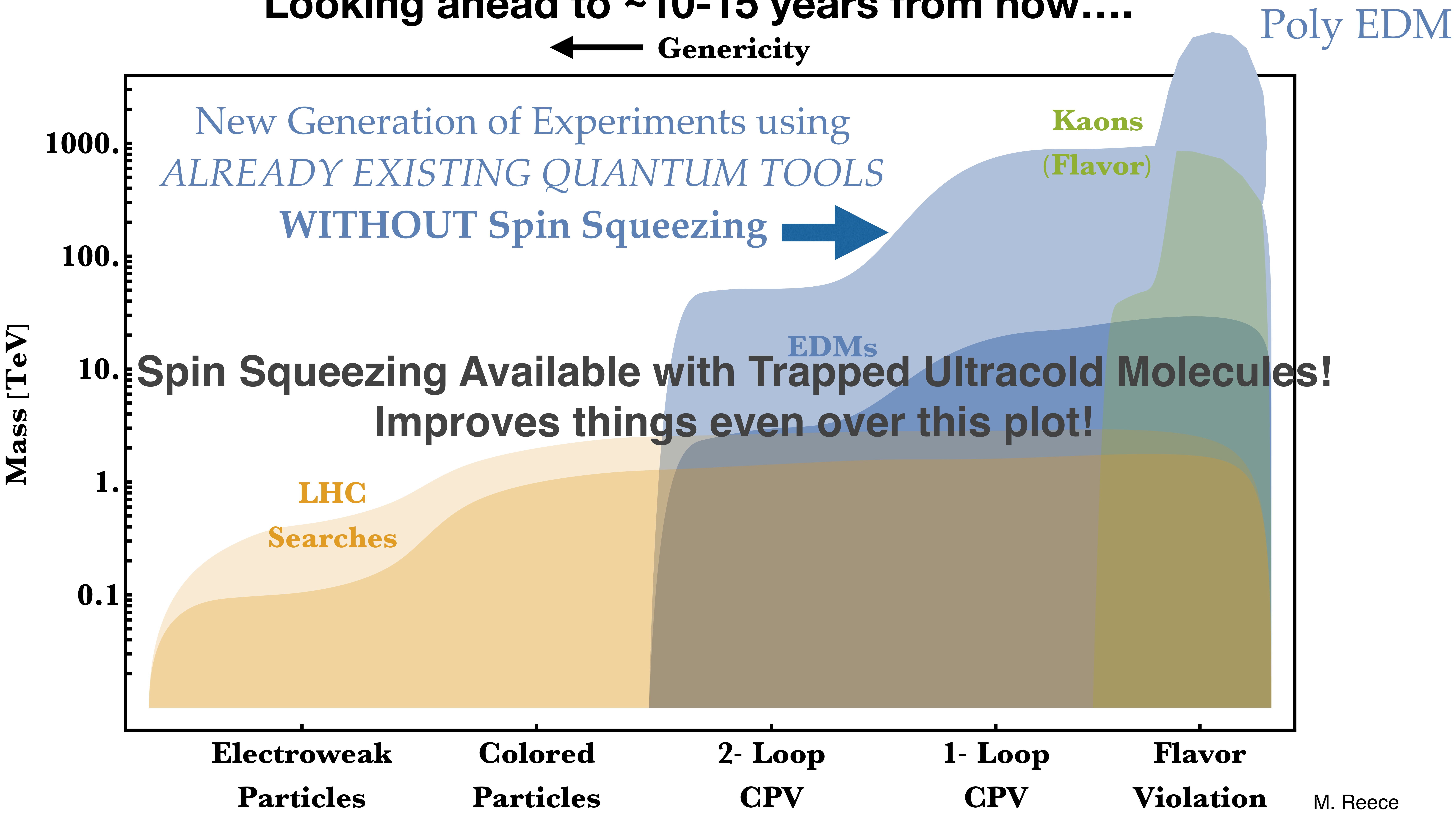
M. Reece
~10-15 year Projection by JMD

Looking ahead to ~10-15 years from now....



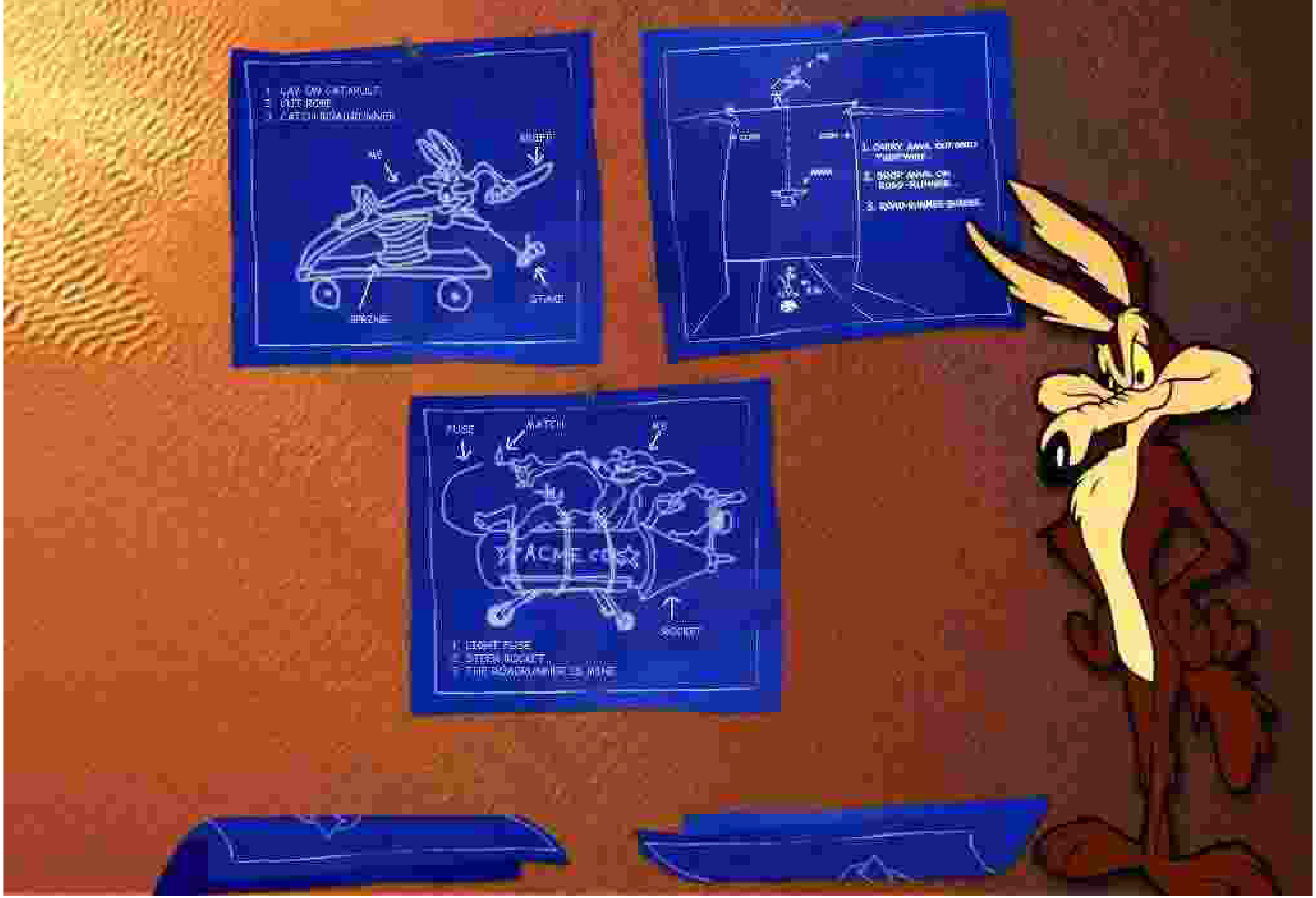
M. Reece
~10-15 year Projection by JMD

Looking ahead to ~10-15 years from now….



M. Reece
~10-15 year Projection by JMD

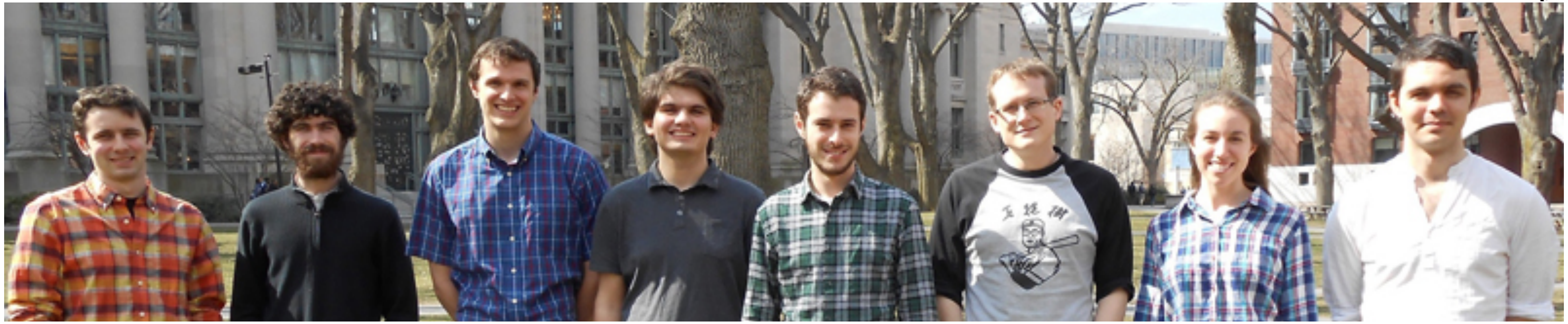
Finally, a word from our sponsors about ACME



DeMille
Doyle
Gabrielse

t
experimentally excluded
ACME II
Projected
Currently running
ACME II statistical sensitivity
Imperial 2010
ACME
2014
Berkeley 2002
Berkeley 1994
Berkeley 1990
standard model
SUSY variants
generic models
Multi-
Higgs
Left-Right
Symmetric
Extended
Technicolor
Lepton Flavor
Changing
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}
d_e (e cm)

The ACME team

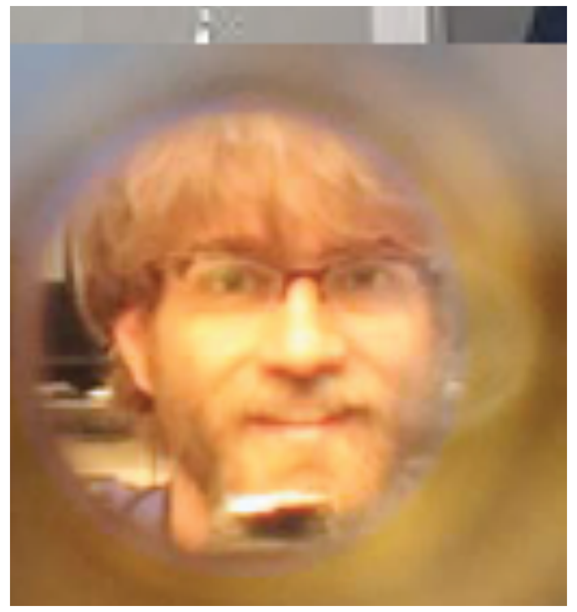


Paul Hess | Brendon O'Leary | Ben Spaun | Cris Panda | Jacob Baron | Nick Hutzler | Elizabeth Petrik | Adam West

Emil Kirilov

Amar Vutha

Yulia Gurevich



Wes Campbell

Ivan Kozyryev

Max Parsons

VE RI TAS
HARVARD

JMD

Gabrielse

DeMille

LUX ET VERITAS

Status of ACME

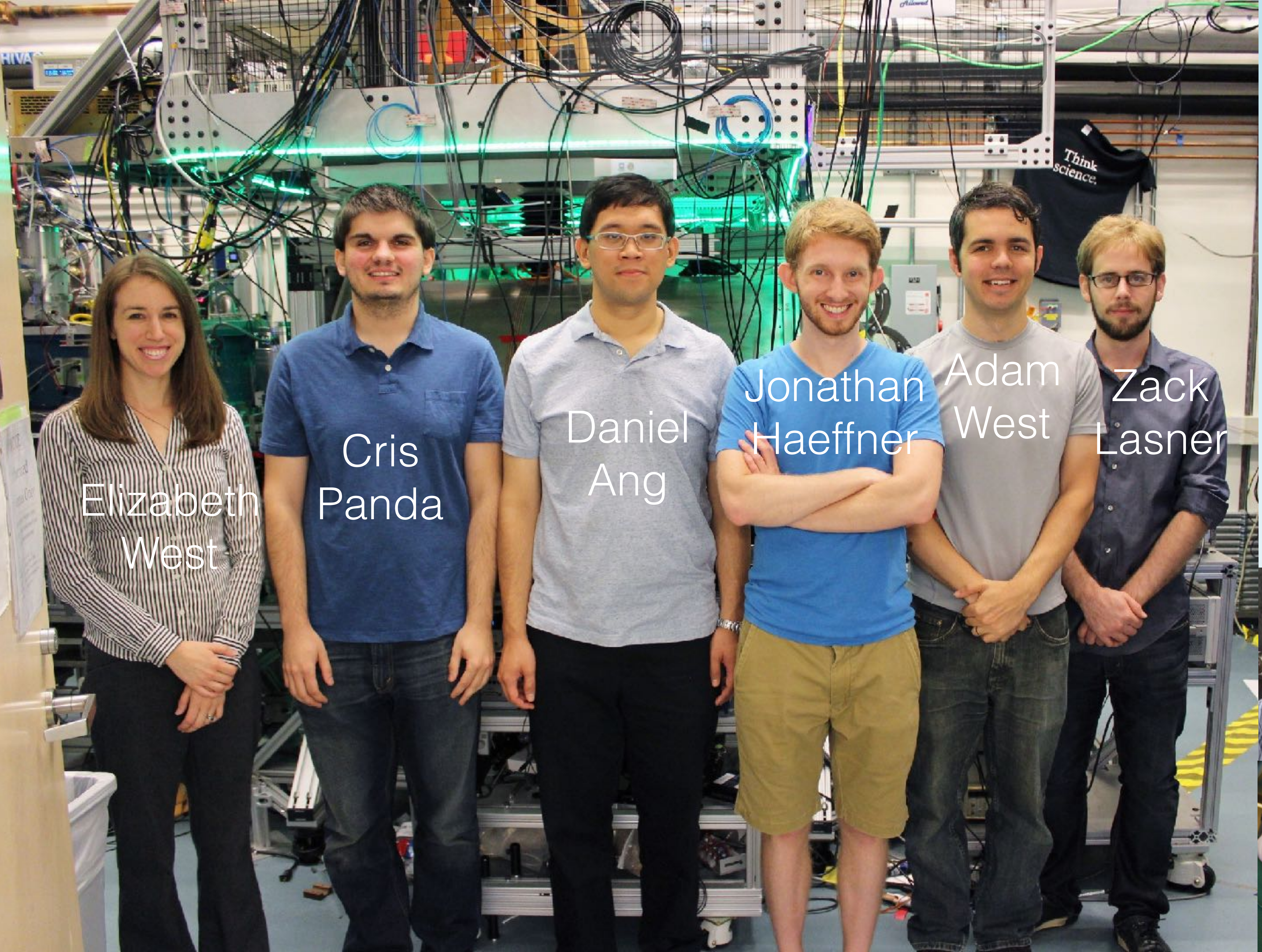
ACME Collaboration
12/9/2017

Status of ACME II

- 1 year of systematic checks data
- >200 runs, 50000 blocks, 3000 superblocks
- 15 TB of systematic check data
- 40 parameters checked for systematic dependence
- 3 systematics understood and under control with contributions significantly under statistical sensitivity
- Many additional measurements such as:
  - Suppression of E-correlated phases by the N switch
  - Measurement of leakage current
  - STIRAP phases investigations
  - Magnetic and electric field gradients
- Still to do:
  - Finalize systematic investigations.
  - Final data set under ideal conditions.
  - Molecular beam clipping check.
- Expected sensitivity:
  - Better than 10^{-29} e cm
  - 10 times better than the ACME II result

Systematic category	Systematic check	Units
Lasers: Pointing and position	Probe: applied pointing	mrad
	Cleanup: applied pointing	mrad
	Cleanup: position	mm
Lasers: Detuning	Cleanup detuning*	MHz
	Delta P	MHz
	Ti Sapph detuning (both cleanup a	MHz
	Delta N*	MHz
Lasers: Power	Low probe power	unitless (fraction of typ
	X,Y beams power asymmetry	unitless (Px-Py)/(Px+I
	I state power asymmetry	unitless (Plp-Plm)/(Plp
Lasers: Polarization	Cleanup ellipticity	S/I
	Probe ellipticity	S/I
	Probe polarization rotation	deg of lambda/2
Electric Field	E_mag large	V/cm
	E_mag small	V/cm
	Floating field plates*	V
Magnetic Field: Offsets	Bz_nr*	mGauss
	Bx_rev	mGauss
	By_rev	mGauss
	Bx_nr*	mGauss
	By_nr*	mGauss
Magnetic Field: Gradients	dBx/dx_nr*	mGauss/cm
	dBy/dy_nr*	mGauss/cm
	dBy/dz_nr*	mGauss/cm
	dBy/dx_nr*	mGauss/cm
	dBz/dx_nr*	mGauss/cm
	dBx/dx_rev	mGauss/cm
	dBy/dx_rev	mGauss/cm
	dBy/dy_rev	mGauss/cm
	dBy/dz_rev	mGauss/cm
	dBz/dx_rev	mGauss/cm
	dBz/dz_rev	mGauss/cm
DAQ parameters	Block switches settling times	fraction of typical
	Polarization switching frequency	kHz
	Waveplate dither angle	degrees of pol rotation

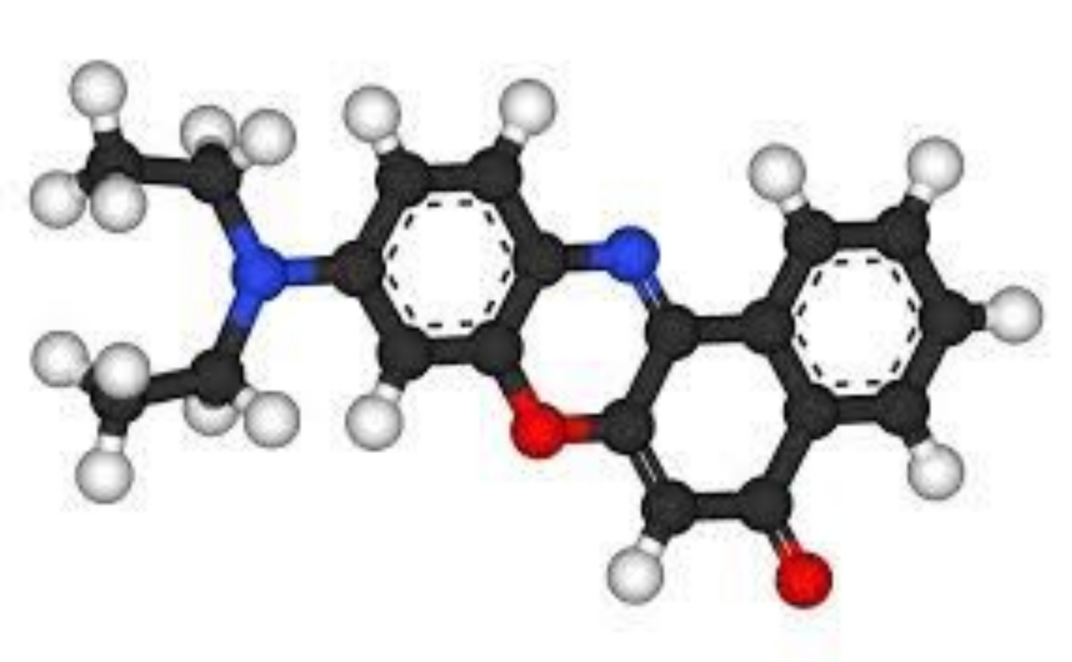
Blue: limited range of IPV (<10x)
Yellow: larger range of IPV (>10x)
* part of systematic error bar


Think science.
Elizabeth West
Cris Panda
Daniel Ang
Jonathan Haeffner
Adam West
Zack Lasner


NSF
VE RI TAS
Cris
Panda
HARVARD PHYSICS
Cole
Meisenhelder
Zack
Lasner
Daniel
Ang
Xing
Wu
Jonathan
Haeffner
Nick
Hutzler
CalTech

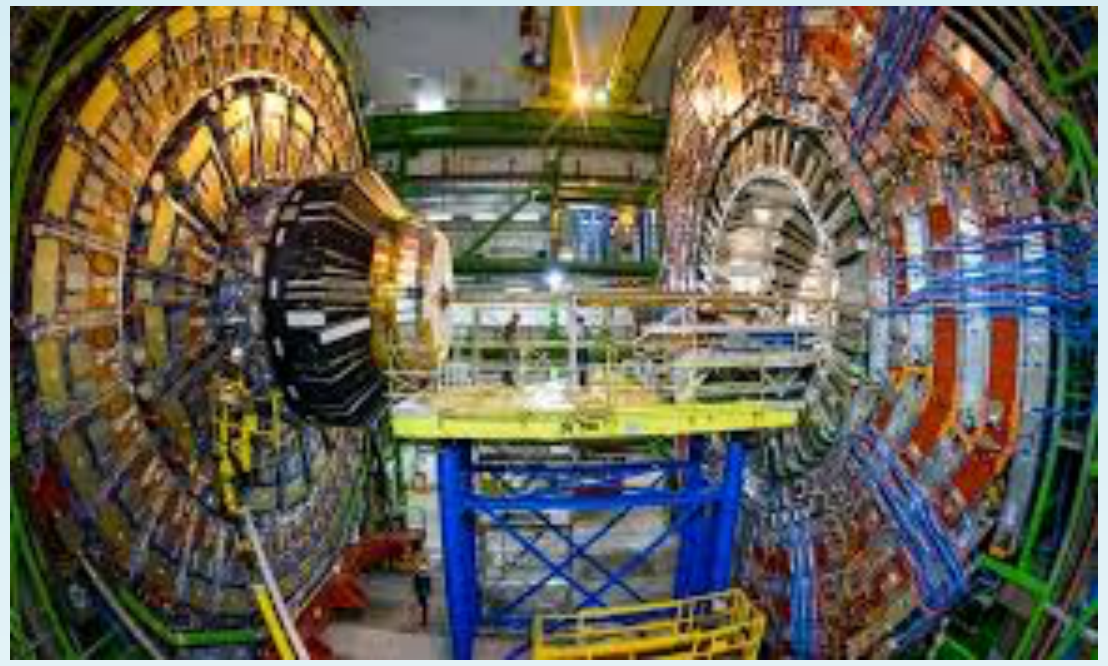
The future of particle physics is ...

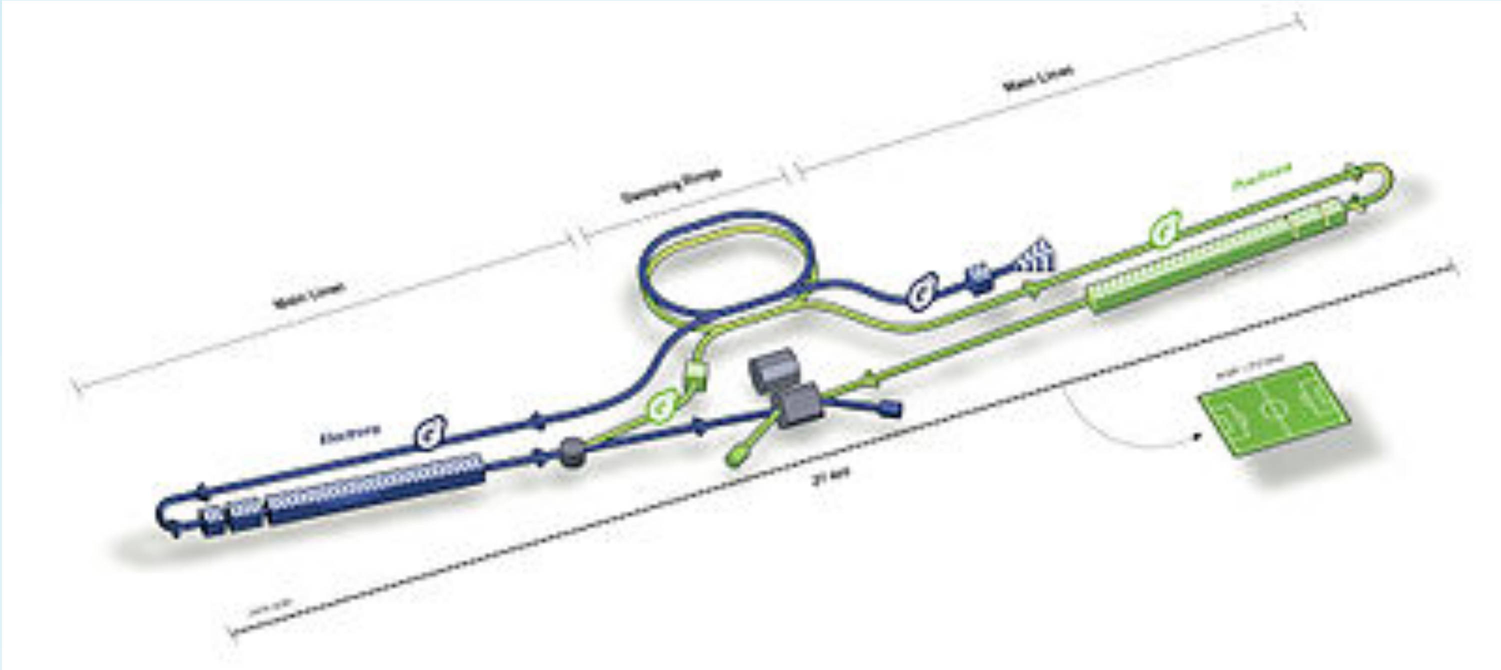
this



? Experiment fits in a room, currently TeV, PeV possible

or this





? Currently TeV, ~10 TeV possible

or both?