

AMO experiments probing particle physics

Recent reviews

M.S. Safranova *et al.*, Rev. Mod. Phys. **90**, 025008 (2018)

DD, J.M. Doyle and A.O. Sushkov, Science **357**, 990 (2017);

Snowmass 2021 white papers

Quantum Sensors for HEP Science -- Interferometers, Mechanics, Traps, and Clocks arXiv:2203.07250

Tabletop experiments for infrared quantum gravity arXiv:2203.11846

Precision Studies of Spacetime Symmetries and Gravitational Physics arXiv:2203.09691

New Horizons: Scalar and Vector Ultralight Dark Matter arXiv:2203.08103

Electric dipole moments and the search for new physics arXiv:2203.08103

Axion Dark Matter arXiv:2203.14923

...

Dave DeMille

*Physics Department, University of Chicago
Physics Division, Argonne National Lab*



AMO experiments probing particle physics

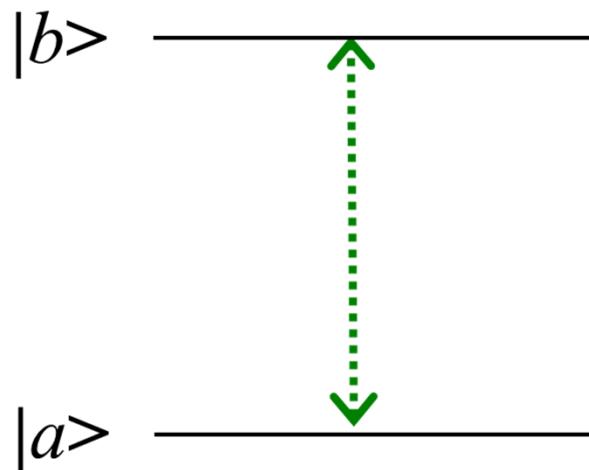
PHYSICS DRIVERS

- New probes of gravity
- Ultra-light dark matter
- Feebly-coupled light particles
- New physics at very high scales

BROAD CATEGORIES OF EXPERIMENTS/TECHNIQUES

- Clocks and Matter-wave interferometers: sensors of spacetime
- Sensors of external fields/forces
- Precision spectroscopy: deviations from established theory?
- Discrete symmetry violating signals: P, CPT, CP

Nearly all AMO precision measurements can be (re)cast as energy/frequency/time/phase



Intrinsic sensitivity
clever ideas,
backed by broad data

Coherence time
new techniques
& new systems

Figure of merit for statistical precision

$$Q \cdot \tau \cdot (S / N)$$

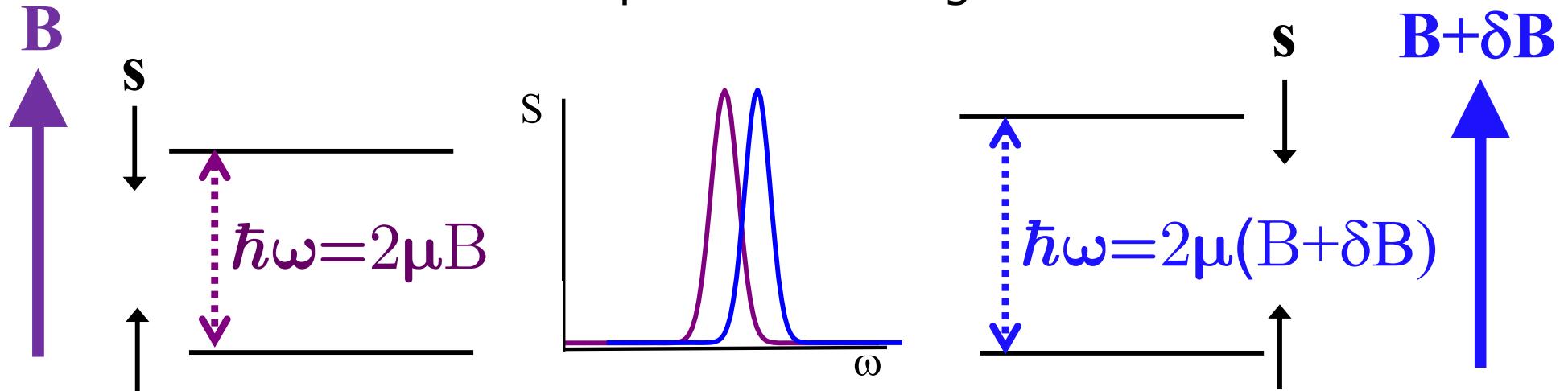
Backgrounds & detector noise & **intrinsic noise**
 \Rightarrow Std quantum limit $\propto \sqrt{N}$
 \Rightarrow Heisenberg limit $\propto N$

Novel/custom instrumentation often developed:
drives both science and technology

Perturbation-sensitive systems: sensors of fields

Measure shift in energy levels due to external influence

EXAMPLE: spin-based magnetometer



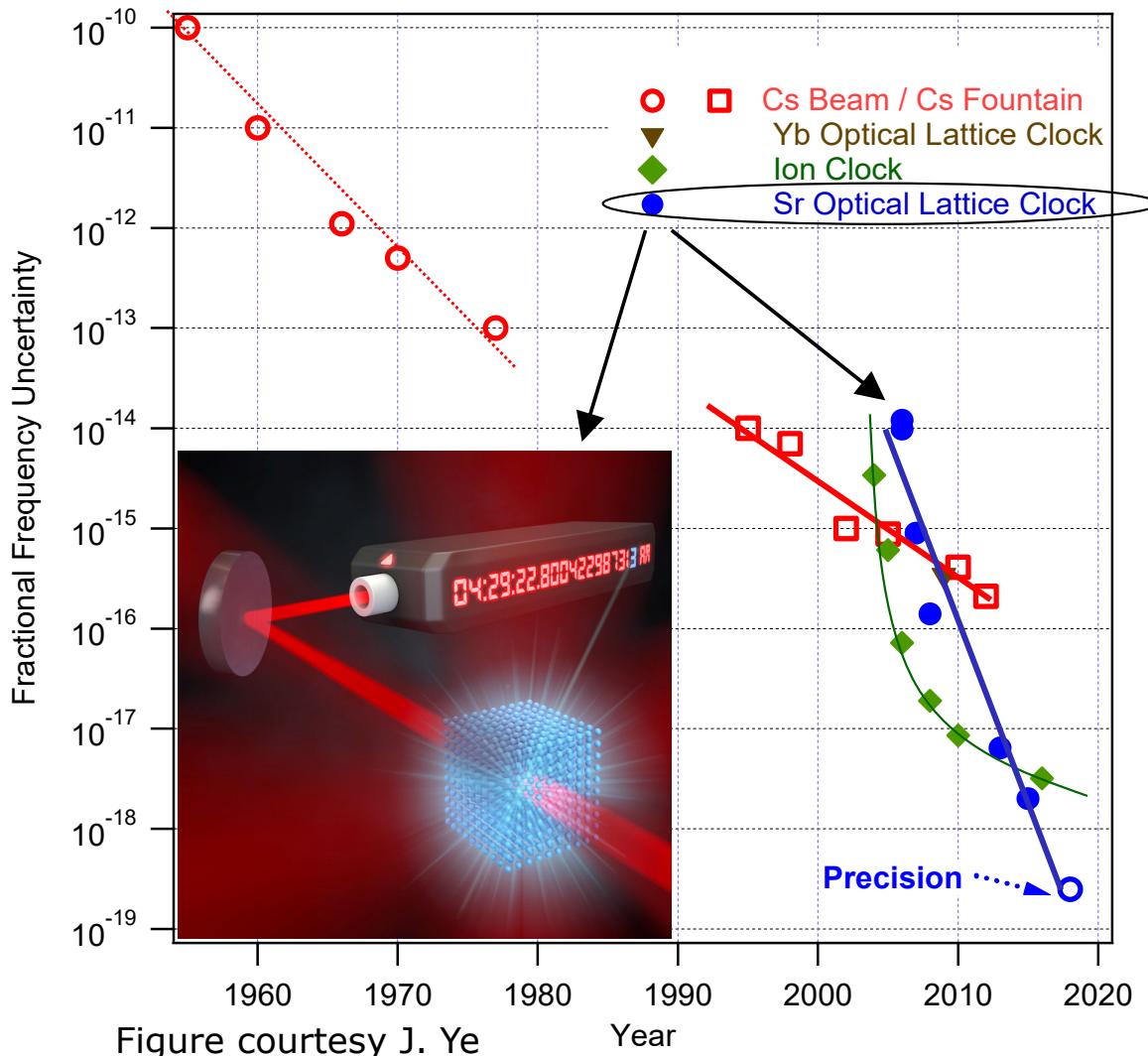
General concept used to detect “ordinary” electromagnetic fields
AND
effects from possible new interactions

Enabling ideas & techniques for ongoing progress:

- Systems with increased sensitivity to effects of fundamental physics interest
 - New physics goals identified at rapid pace
 - Increased coherence times & statistics for known important systems
 - Numerous technical innovations to suppress systematic shifts

Atomic clocks: sensors of (space)time

Clocks: THE original quantum technology, continued rapid progress



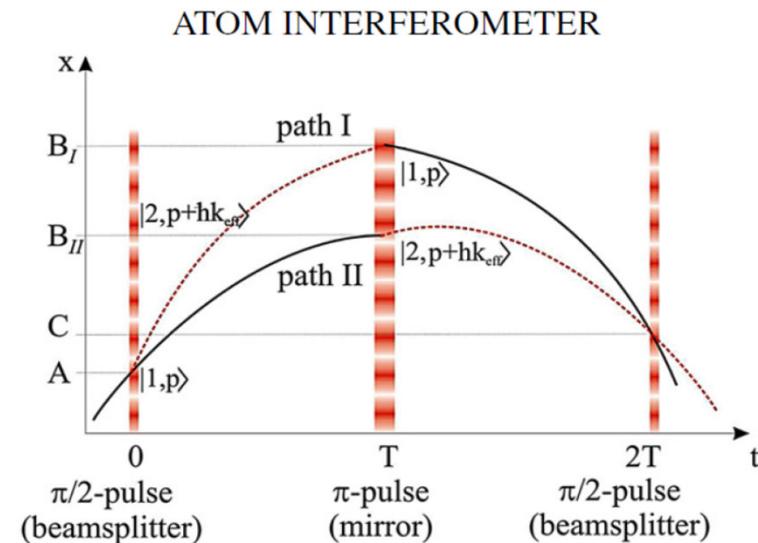
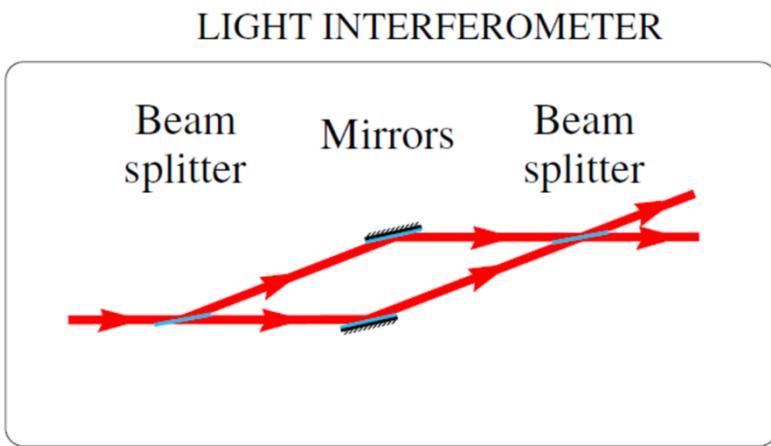
Enabling ideas & techniques
for ongoing revolution:

- Higher Q via **optical** transitions
- New laser stabilization methods:
 $\delta f < 100 \text{ mHz} @ f = 500 \text{ THz}$
- Ultracold neutral atoms trapped in
“magic wavelength” optical lattice:
high N , long τ , small perturbations
 - Optical frequency comb for transfer to “electronic device” range

- Current accuracy $\delta f/f \sim 10^{-19} = \text{grav. redshift} @ 1 \text{ mm!}$

Matter-wave interferometers: inertial sensors

Like optical interferometer, phase shift from path length difference



Figures:
M. de Angelis
et al.,
Meas. Sci.
Technol. **20**
022001
(2009)

Modern matter-wave interferometers:

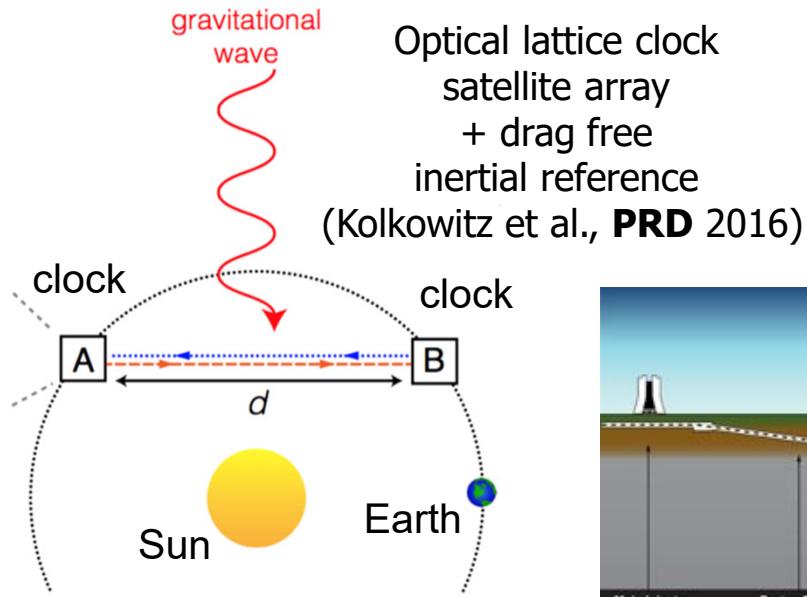
- Coherent beamsplitters using force from laser light
- Path length depends on motion of freely-moving atoms (vs. laser wavefronts)
 - Ultracold atoms: large coherence time/length → high sensitivity

Enabling ideas & techniques for ongoing revolution:

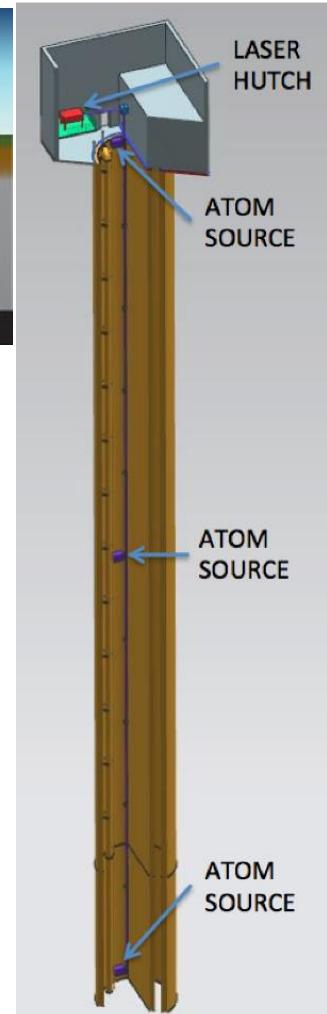
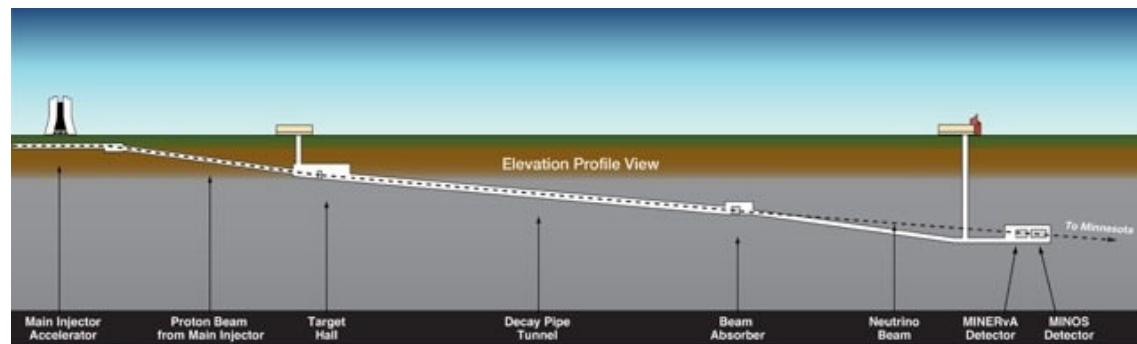
- High momentum-transfer beamsplitters enhance area & hence sensitivity
- Coldest atoms (picoKelvin) enable longer path length & enclosed area
 - Numerous technical innovations to suppress systematic errors

Proposed atomic sensors for gravitational wave detection

Atom = phase memory to detect optical path length change



MAGIS: Atom interferometry with clock atoms serving as both inertial reference + phase reference (Hogan, Kasevich, Kovachy, ...)

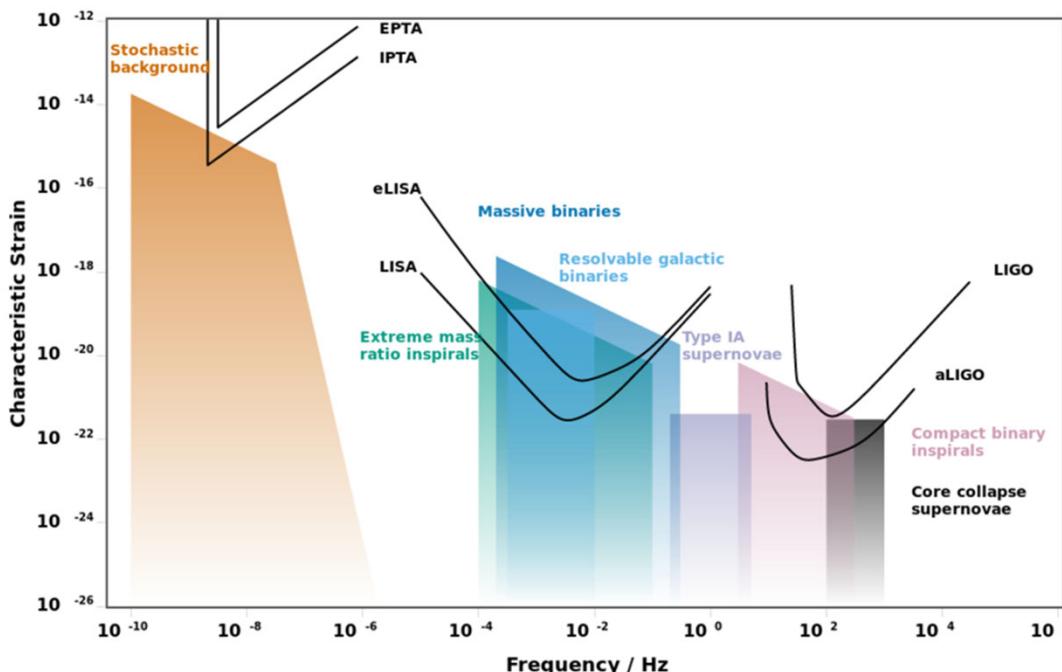


Atomic Clocks & Interferometers have **SAME** intrinsic sensitivity to gravitational waves

[M. Norcia, J. Cline, J. Thompson
Phys. Rev. A **96**, 042118 (2017)]

BUT:

Significant differences in technical details & advantages



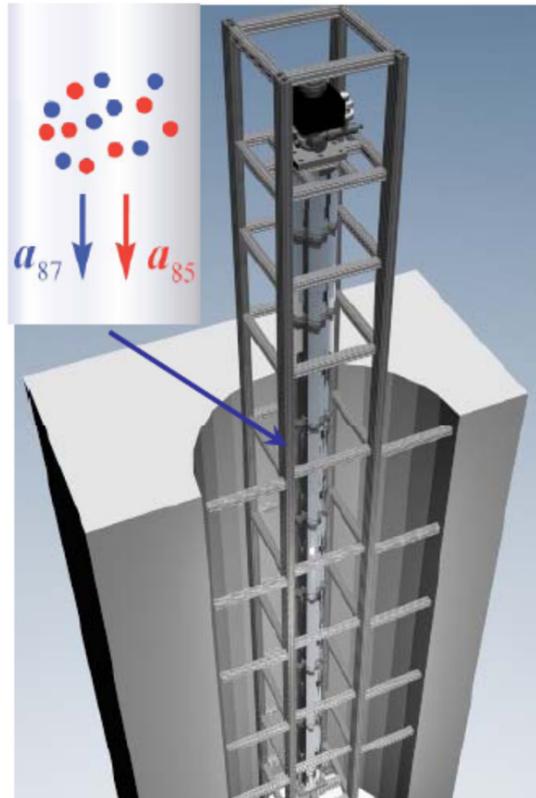
Courtesy

J. Hogan (Stanford)
& R. Walsworth (CfA)

Additional probes of gravity

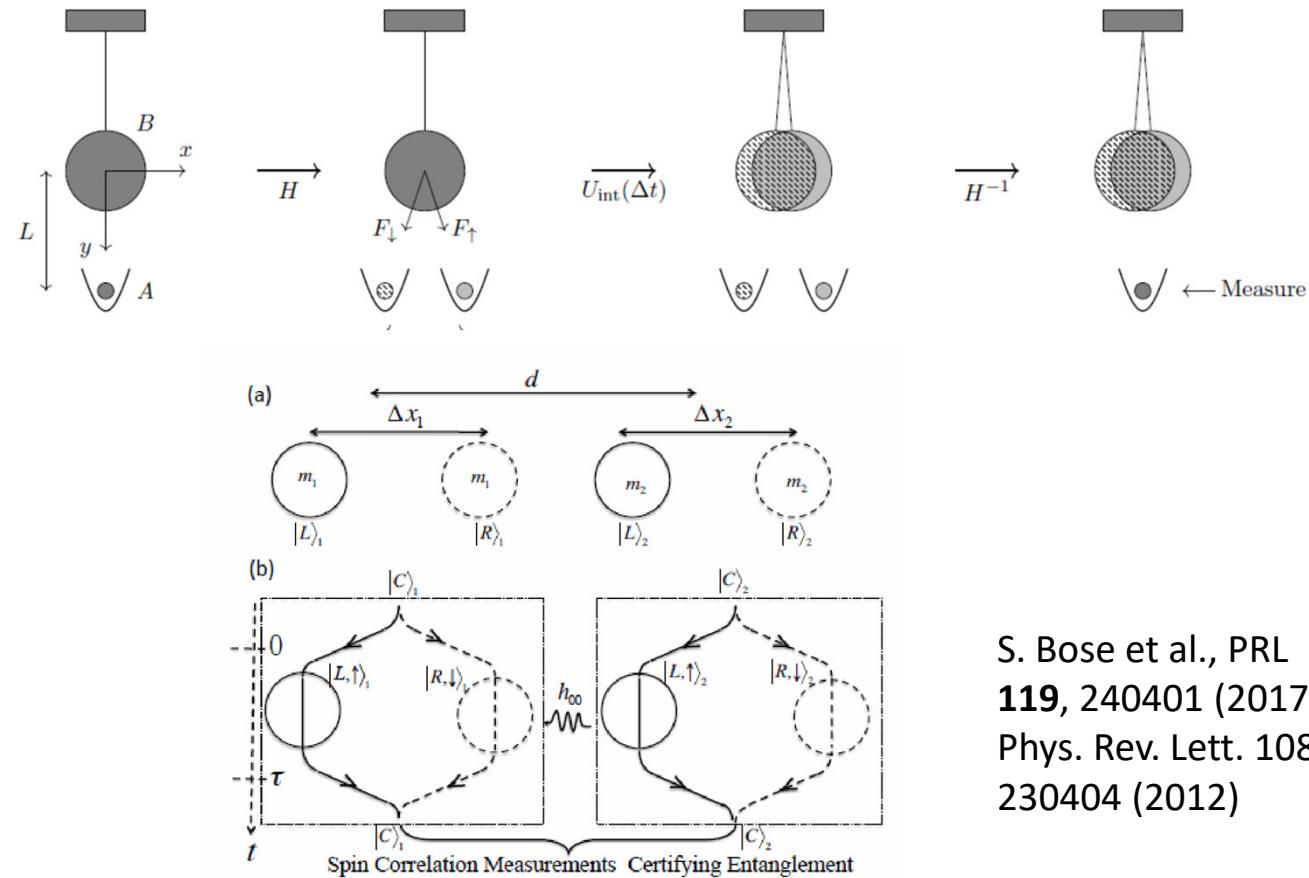
Weak equivalence principle

Towards quantum entanglement via gravity



CARNEY, MÜLLER, and TAYLOR

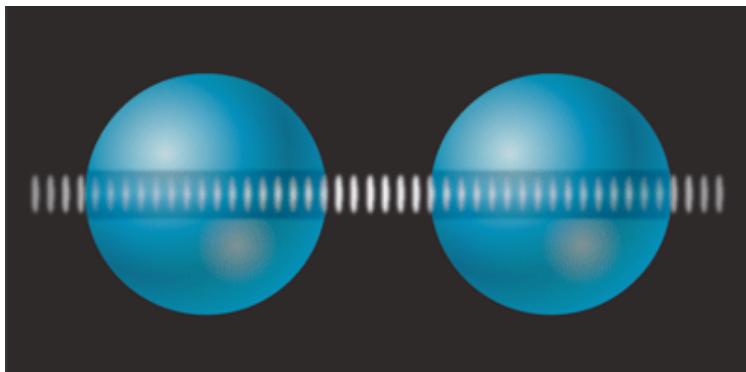
PRX QUANTUM 2, 030330 (2021)



S. Bose et al., PRL
119, 240401 (2017)
Phys. Rev. Lett. 108,
230404 (2012)

Gravitational Aharonov-Bohm effect

M.A. Hohensee et al, PRL 08, 230404 (2012);
C. Overstreet et al, Science 375, 226 (2022)



Rethinking discovery space in particle physics

- **Longstanding paradigm:** new physics at \sim TeV scale

--**BUT:** no discoveries at LHC, no detection of WIMP dark matter, no EDMs, ...

--Prospects to *directly* probe much higher scales decades away

--**Maybe** new physics instead in very weakly-coupled, lower-mass particles?

- **Many well-motivated examples of weakly coupled and/or low mass particles:**

--axions to explain absence of CP violation in QCD

--dilatons, moduli and axions from string theory, GUTs, extra dimensions, ...

--dark photon easily extends Standard Model

--all are viable dark matter candidates

- **ISSUE:** very little guidance from theory on mass or coupling scales!

⇒ **VERY BROAD SEARCH STRATEGIES NEEDED**

Dark matter: particles vs. fields

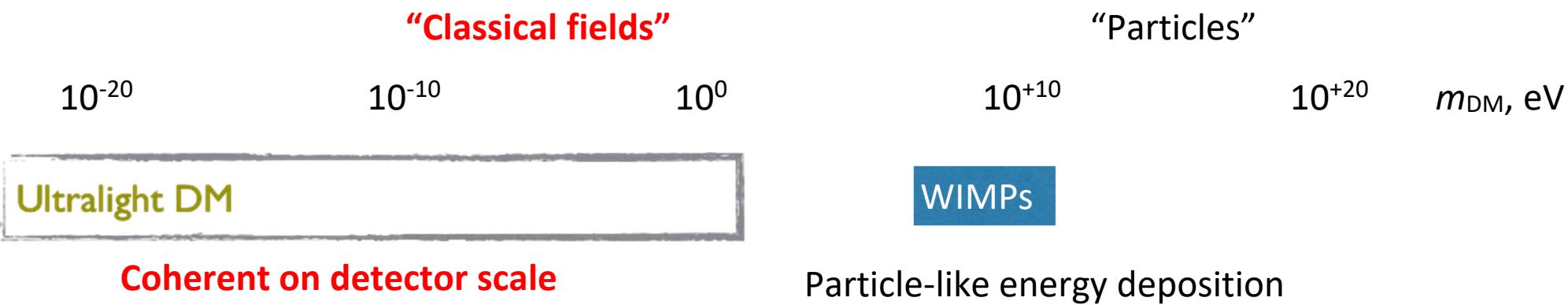
Compton wavelength:

$$\lambda_C \sim \frac{\hbar}{m_{DM}c}$$

$$\frac{\text{# of particles}}{\text{mode}} \sim \left(\frac{\rho_{DM}}{m_{DM}c^2} \right) \times \left(\lambda_{\text{de Broglie}} \right)^3$$

$\lambda_C >$ Schwarzschild radius $\Rightarrow m_{DM} \ll 10^{+28} \text{ eV}$

$\lambda_{vir} <$ Galactic size ($\sim 10 \text{ kpc}$) $\Rightarrow m_{DM} >> 10^{-22} \text{ eV}$



Simplest model: DM field oscillates at Compton frequency: $f_{DM} \sim 300 \text{ Hz} * [m_{DM}/10^{-12} \text{ eV}]$

Simplest model: DM field virialized \Rightarrow coherence $Q = \Delta f_{DM}/f_{DM} \sim 10^6$

Ultralight dark matter as background field

Different particle types couple to matter in different ways:

- **Vector bosons e.g. dark photon →**

--quasi-static fields electrically polarize, induce magnetic spin precession
--oscillating fields drive transitions

- **Pseudoscalar e.g. axion →**

--quasi-static field induces EDM along particle spin
--effective **B**-field along axion momentum **p**
--oscillating field can drive transitions

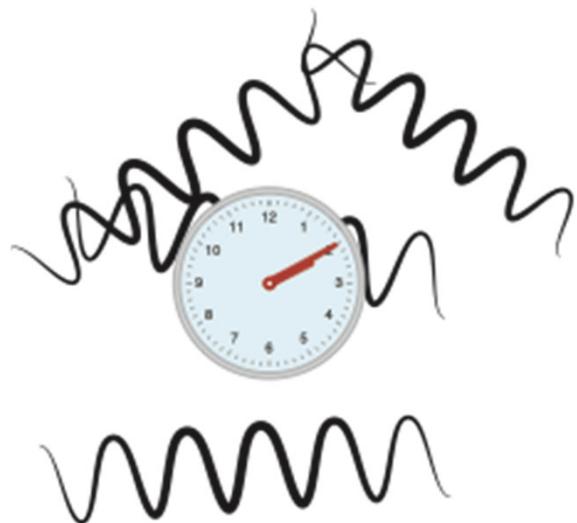
- **Scalar e.g. dilaton →**

--quasi-static field appears to modify fundamental constants of nature:
particle masses, fine structure constant α , etc.

Spatiotemporal variations in ~any AMO precision measurement
probes some version of ultralight dark matter

EXAMPLE: Ultralight scalar field detection via apparent time-variation of fundamental constants

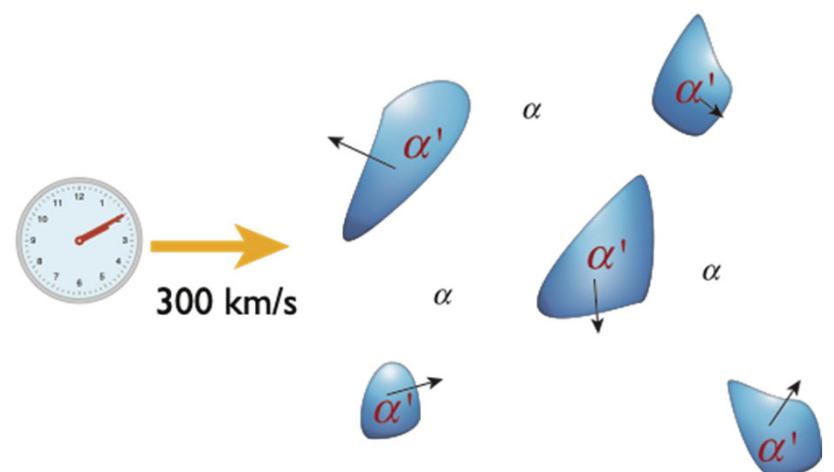
non-interacting fields



Oscillating or drifting fundamental consts

Arvanitaki *et al.* PRD **91**, 15015 (2015)

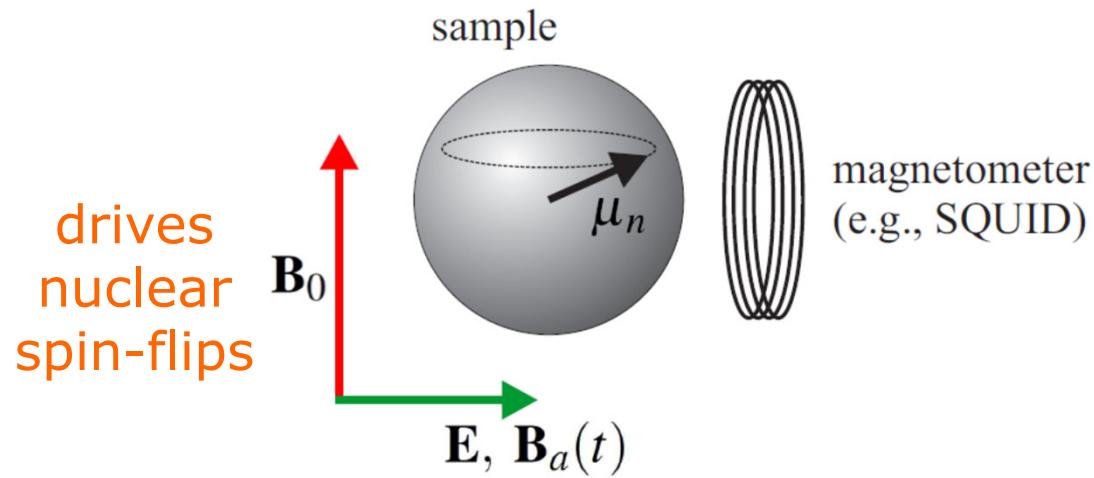
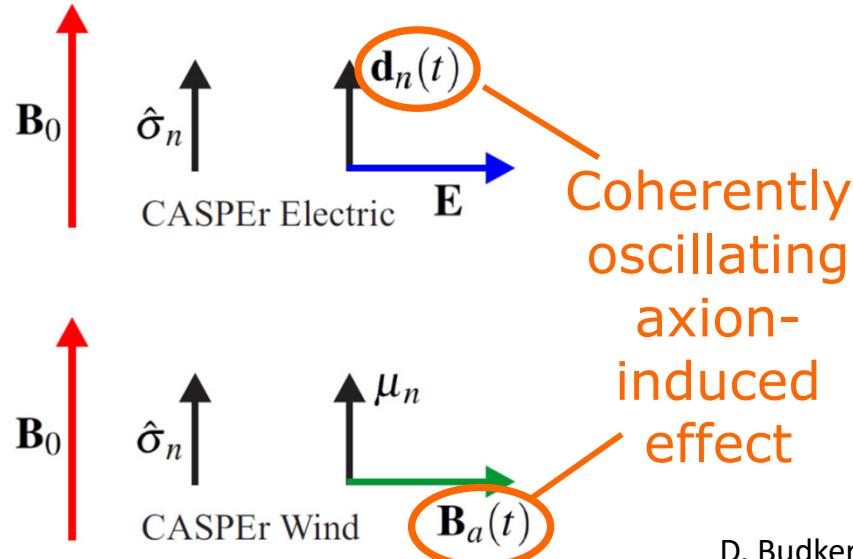
self-interacting fields



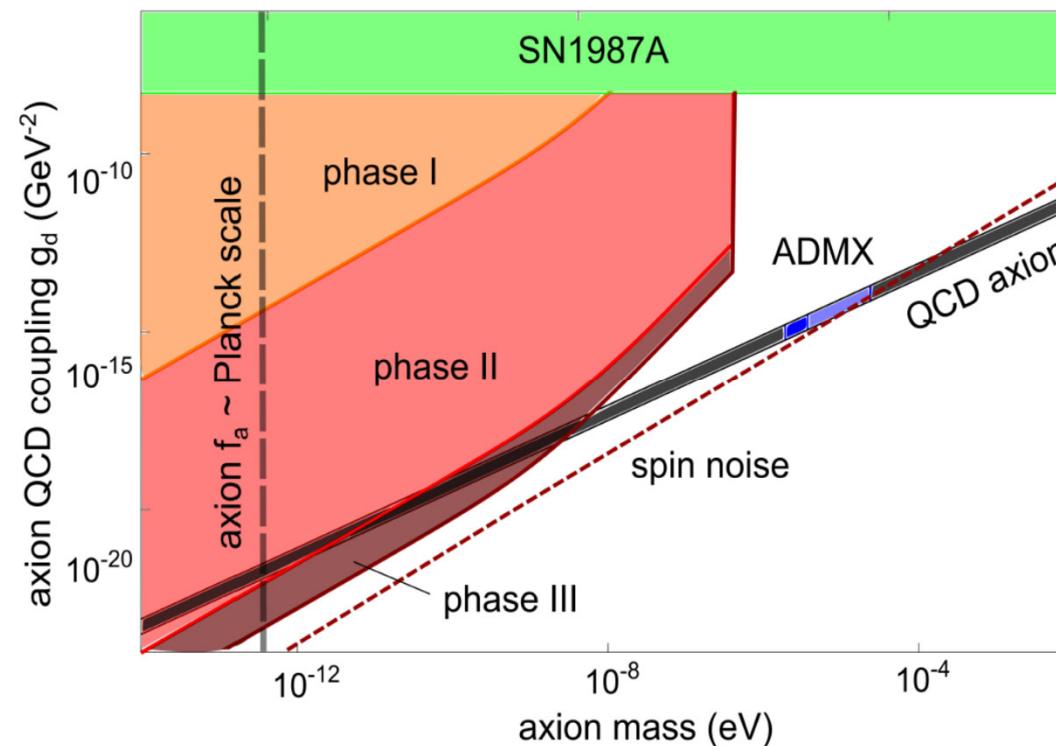
Transient variations of fundamental consts

Derevianko & Pospelov,
Nature Phys. **10**, 933 (2014)

EXAMPLE: Ultralight axion dark matter detection (CASPER)



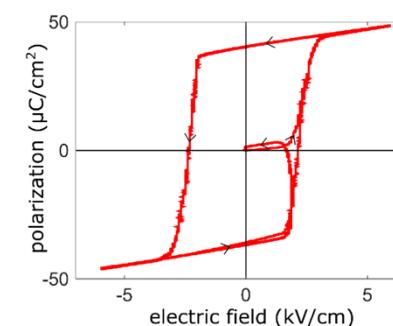
D. Budker, P. Graham, M. Ledbetter, S. Rajendran, and A. Sushkov PRX **4**, 021030 (2014)
D.F. Jackson Kimball *et al.*, arXiv:1711.08999



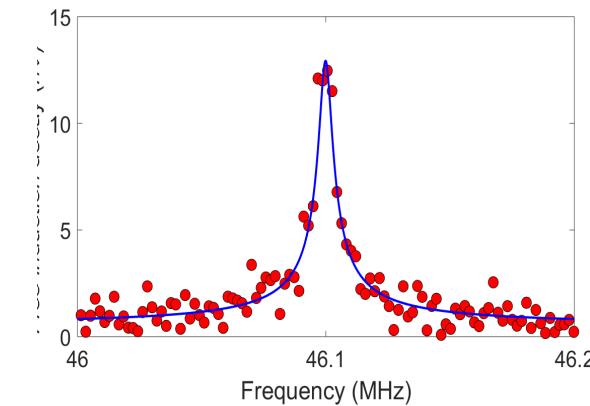
← Broad prospective reach
into theory-motivated region

Phase I under construction ↓

Ferroelectric material
→ large effective E-field on EDM



Sensitivity calibration
with ^{207}Pb NMR

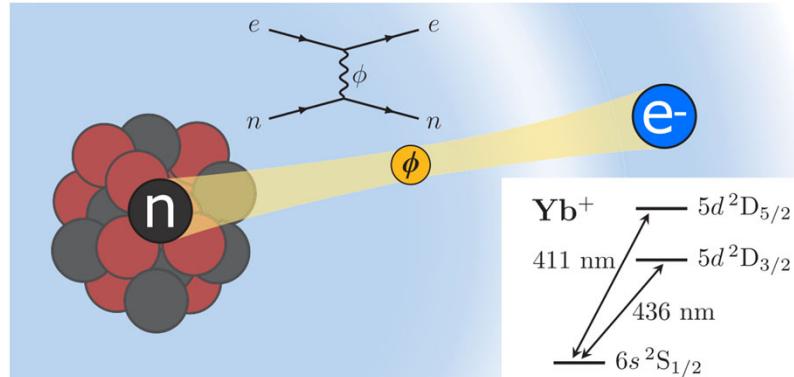


(Courtesy A. Sushkov, Boston Univ.)

Particle physics via precision measurements

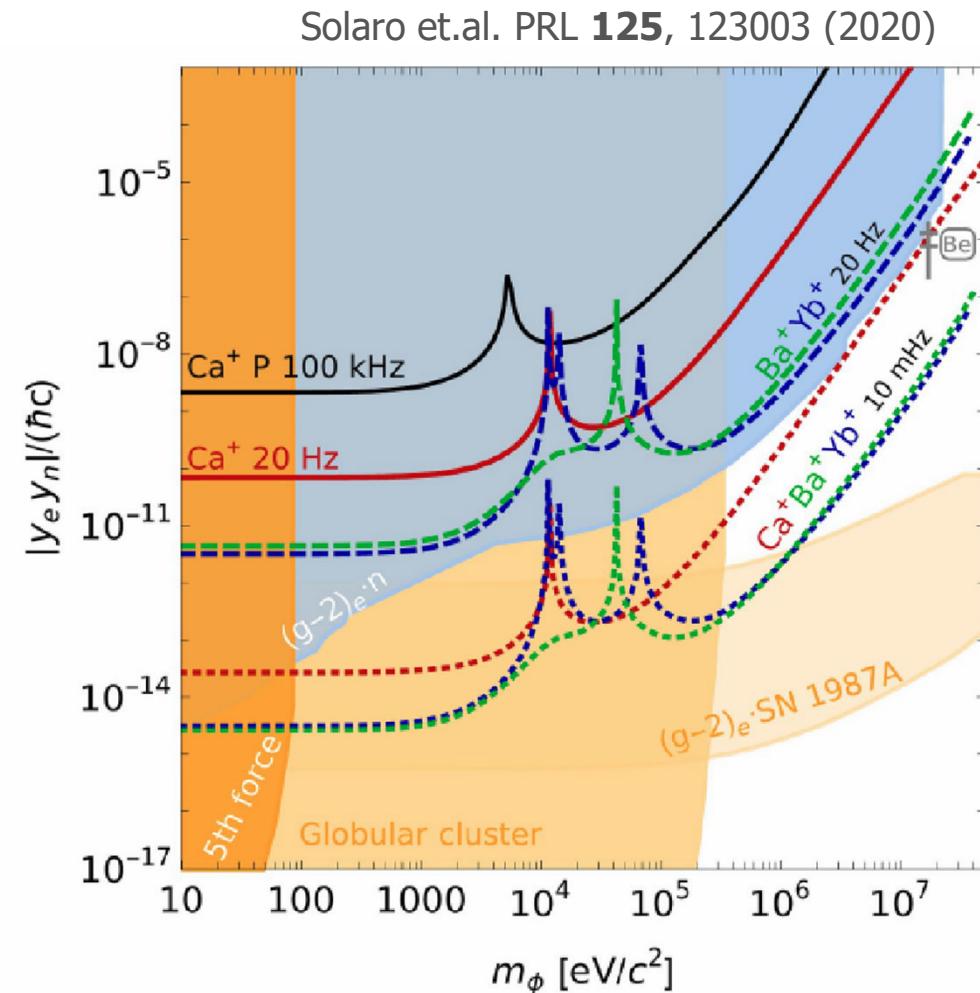
Compare experiment to well-understood theory

Example: new e-n coupling 5th force via isotope shifts



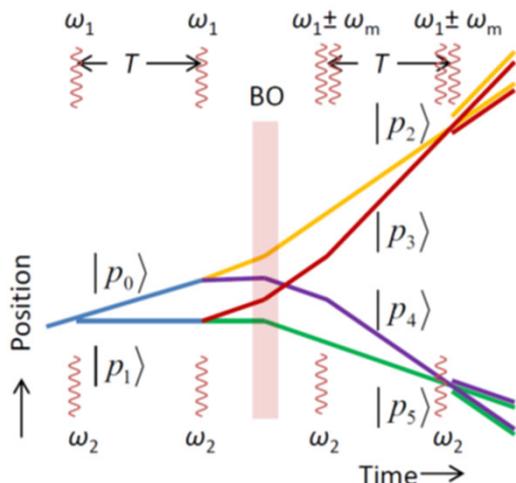
Energy shift due to new long-range interaction

$$V_{NP} = \frac{y_e y_n}{4\pi r} e^{-m_\phi r}$$



Also spin-dependent 5th forces, longer-range interactions, ...

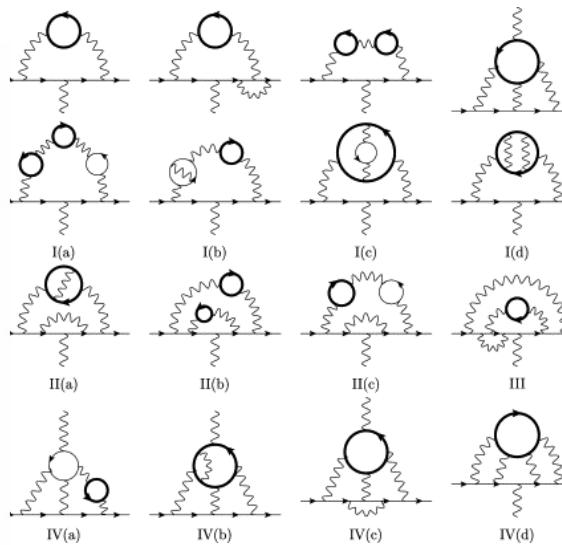
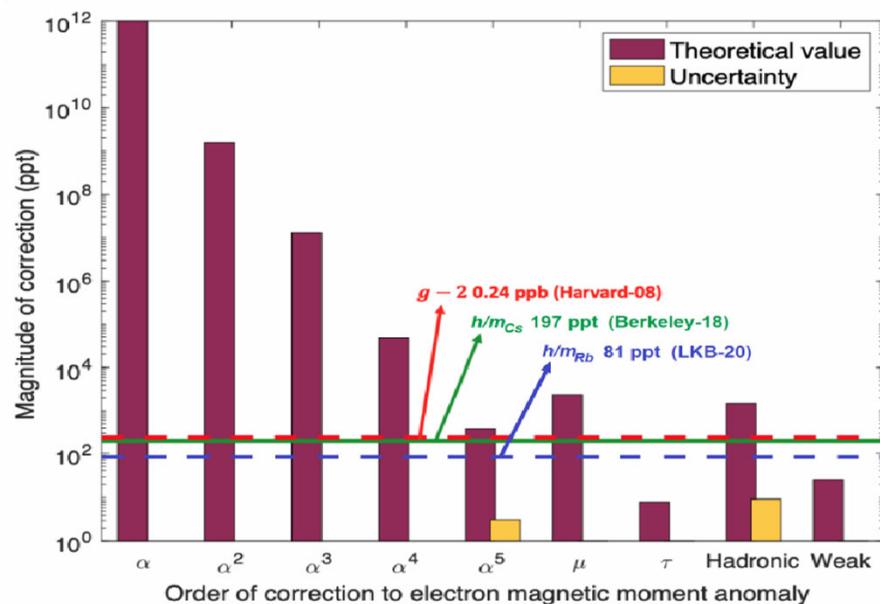
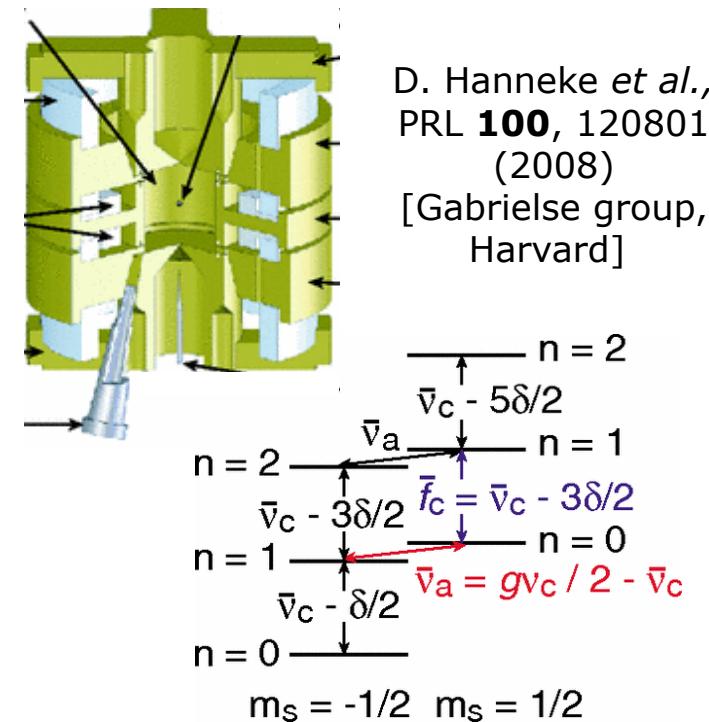
Fundamental physics: fine structure constant α



R. Parker et al.,
Science **360**, 191 (2018)
[Mueller group, UC Berkeley]

α from:
matter-wave interferometry
(atomic recoil momentum +
other precise data)

electron g-2 from:
 α + QED + hadronic



T.Aoyama et al.,
PRL **109**, 111807 (2012)

With improvements:
--shed light on hadronic
vacuum polarization?
--probe for ~MeV
dark photons

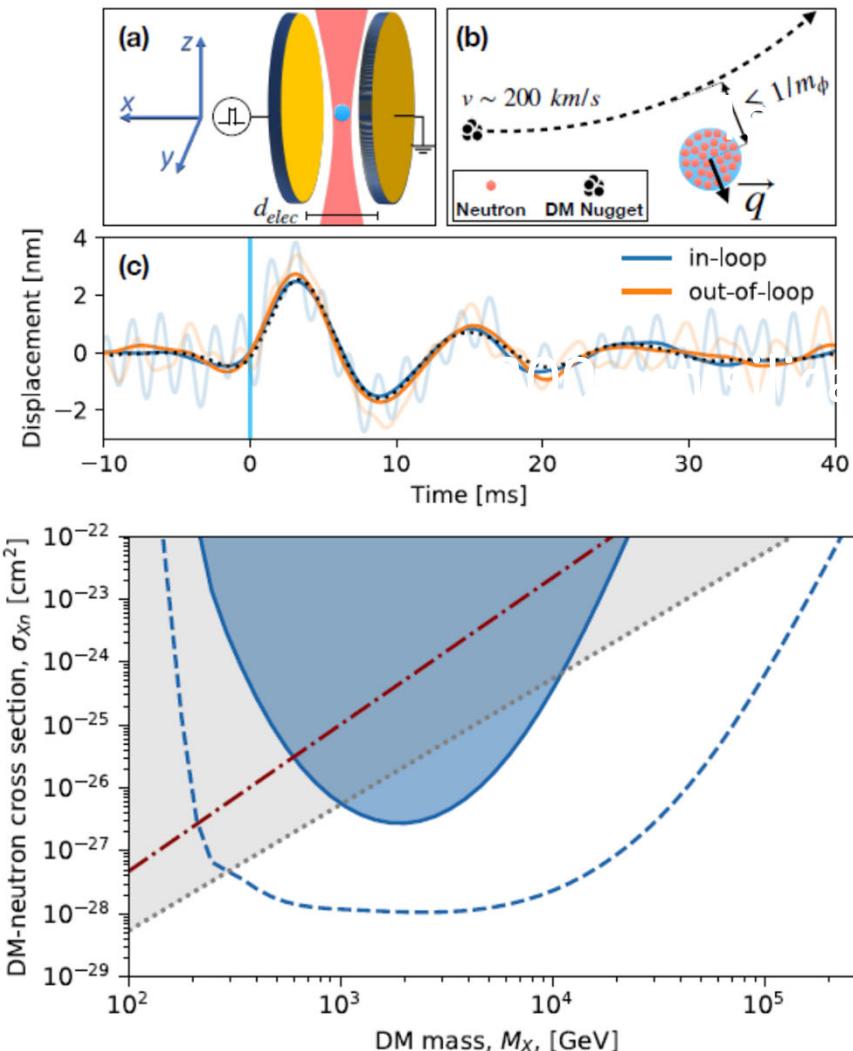
Optomechanical sensing

Cooling of a levitated nanoparticle to the motional quantum ground state
Science **367**, 892 (2020)

Uroš Delić^{1,2,*}, Manuel Reisenbauer¹, Kahan Dare^{1,2}, David Grass^{1,†}, Vladan Vuletić³, Nikolai Kiesel¹, ...

Search for Composite Dark Matter with Optically Levitated Sensors

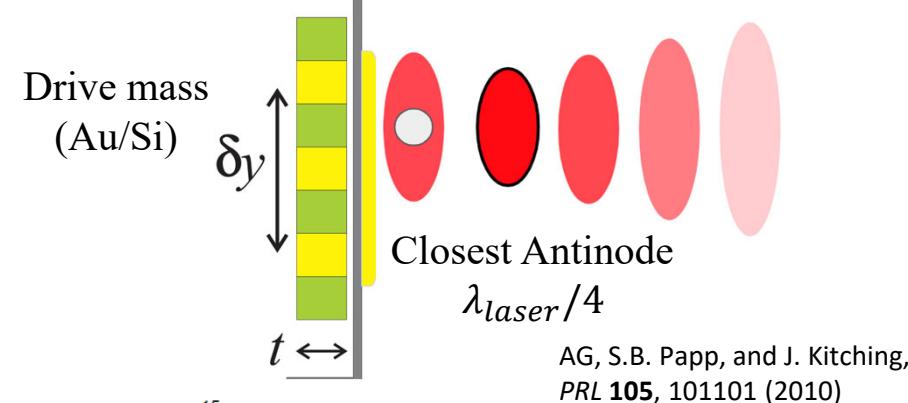
Fernando Monteiro, Gadi Afek, Daniel Carney, Gordan Krnjaic, Jiaxiang Wang, and David C. Moore
Phys. Rev. Lett. **125**, 181102 – Published 28 October 2020



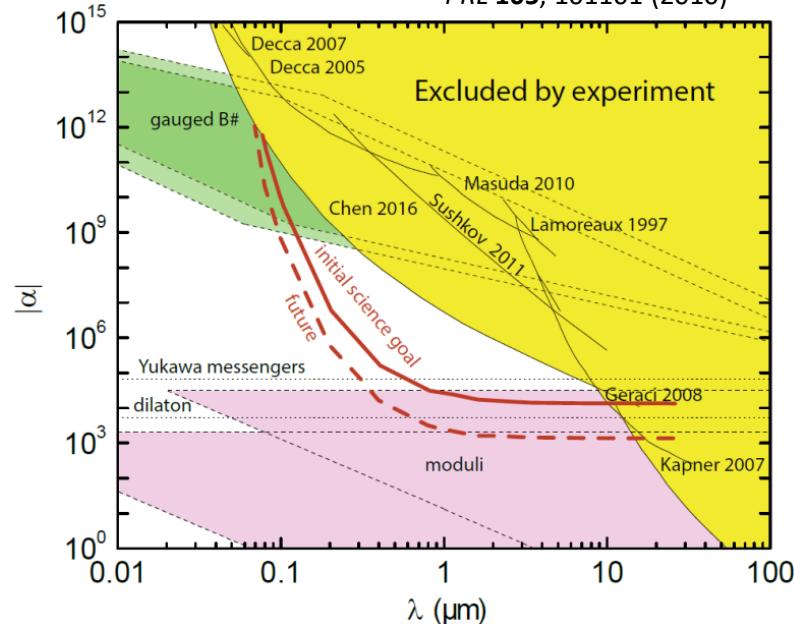
Quantum control of a nanoparticle optically levitated in cryogenic free space *Nature* **595**, 378–382 (2021)

Felix Tebbenjohanns, M. Luisa Mattana, Massimiliano Rossi, Martin Frimmer & Lukas Novotny

Micron-scale 5th forces



AG, S.B. Papp, and J. Kitching,
PRL **105**, 101101 (2010)



Northwestern, Stanford, Yale, ...

Particle physics via discrete symmetry violations

Powerful leverage:

electromagnetic interactions that define ordinary matter
obey discrete symmetries:

Parity P (mirror image)

Time-reversal T (\sim run time backwards)

Charge conjugation C (particle \leftrightarrow antiparticle)

BUT more exotic interactions break discrete symmetries

Symmetry-violating signals

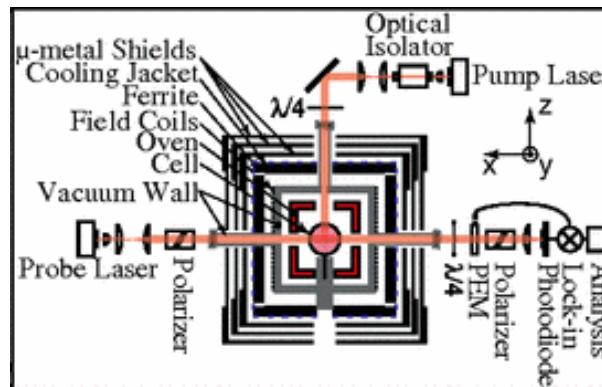
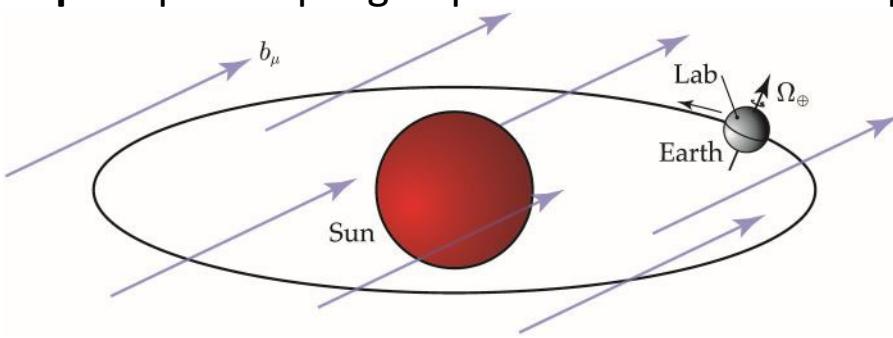
\Rightarrow “background free” probe of exotic physics

CPT violation & Local Lorentz Invariance (LLI)

- Combined symmetry CPT strongly linked to LLI
- Neither allowed in quantum field theory (most successful framework)
 - *Speculation:* both broken by quantum gravity...???
- Parameterization of effects (Kostelecky *et al.*) \Rightarrow compare experiments

Local Lorentz Invariance violation

Example: spin coupling to preferred direction in space



J. Brown *et al.*,
PRL 105 151604
(2010)

Example: magnetometer-based sensor

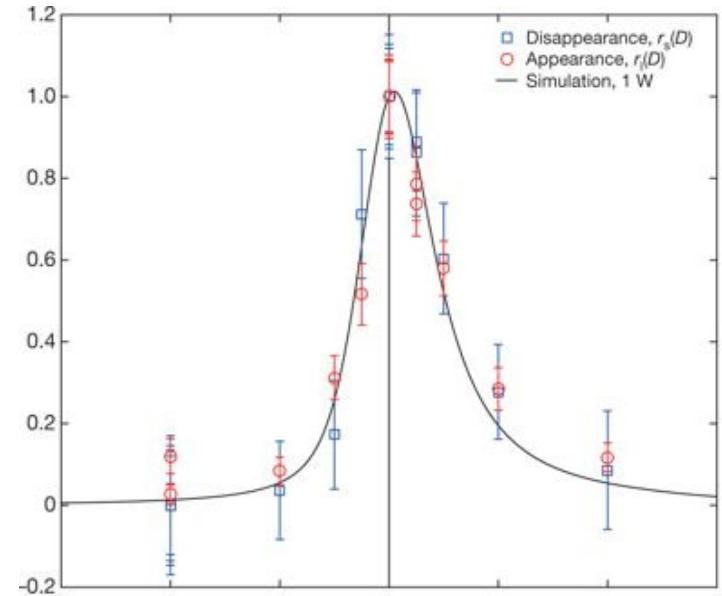
- Consistent with CPT/LLI

• Simple (1st order) models: Planck-scale breaking ruled out by ~ 14 orders of magnitude(!)

Direct CPT violation

Particle-antiparticle comparisons
(mass, magnetic moment, etc.)

Example: spectroscopy of anti-hydrogen atoms

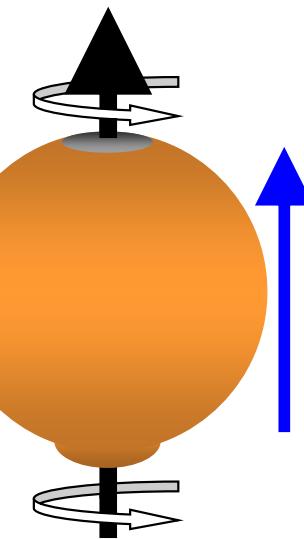


- Consistent with ordinary H atoms @ $\sim 10^{-12}$
- No CPT effect expected in simplest models!
- BUT: "Textbook" demonstration
 - Best CPT tests from LLI & particle physics (Kaon oscillations)

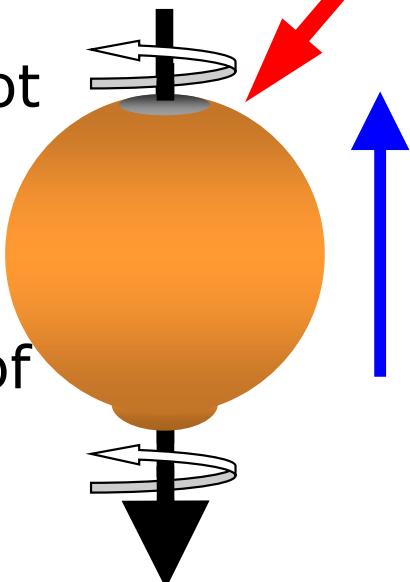
Charge asymmetry (EDM or Schiff moment) along spin violates time-reversal symmetry

Purcell
Ramsey
Landau

If every one of
some particle
(electrons, protons, etc.)
looks like this...



This does not
exist
↓
 T not good
symmetry of
nature

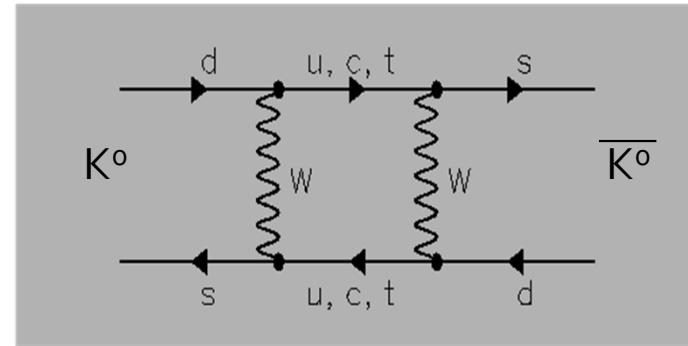


CPT conserved \Rightarrow T-violation = CP-violation

CP-violation: a window to new physics

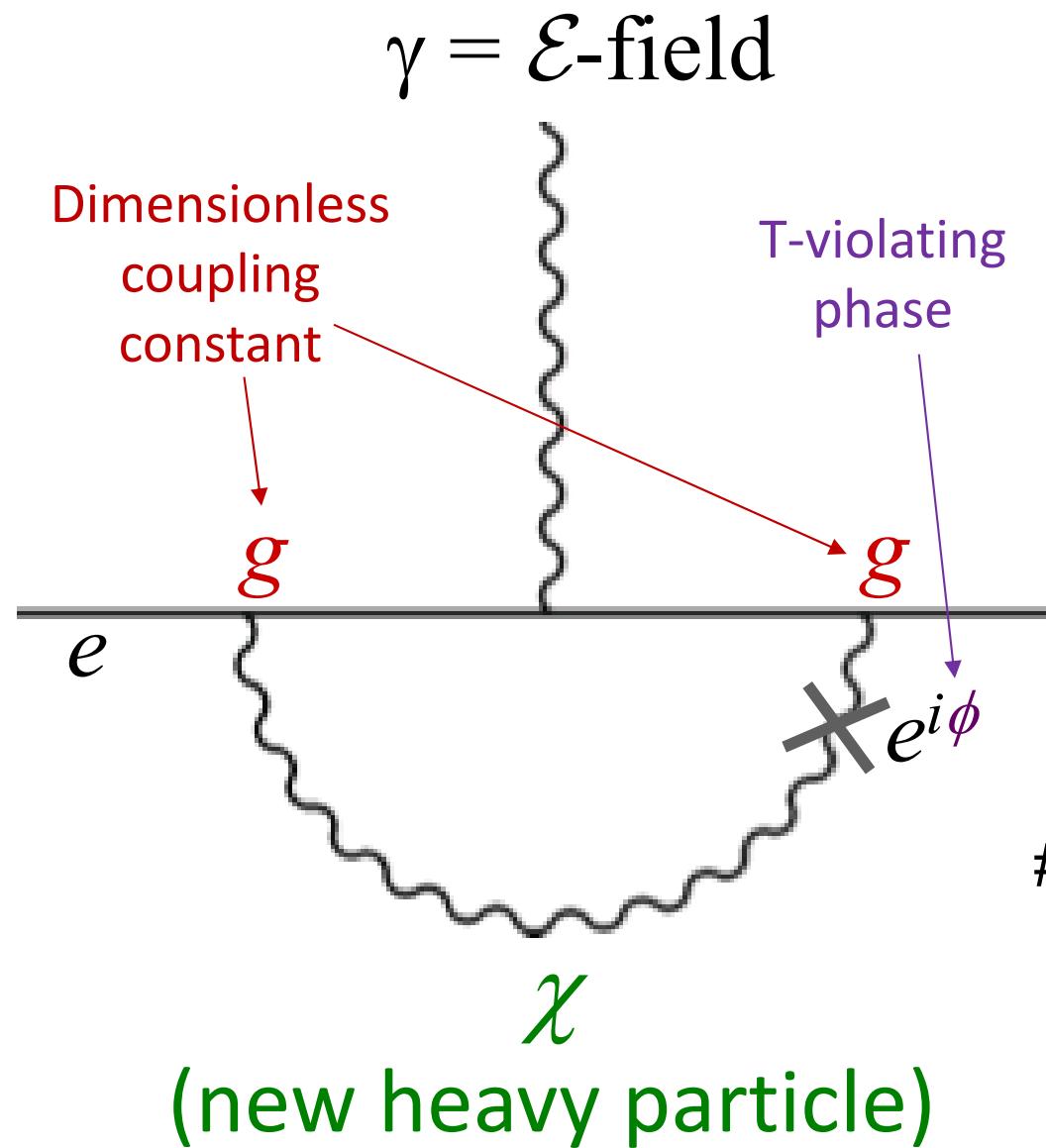
CPT theorem \Rightarrow CP-violation = T-violation

- CP-violation observed: K - and B -mesons
 \Rightarrow CP = T **NOT** conserved in nature
parameterized by complex phases
- Std. Model/CKM matrix phase $\delta_{\text{CP}} \sim 1$
- Observed cosmological matter-antimatter asymmetry
REQUIRES new sources of CPV beyond SM
- CPV-violation in SM: peculiar, suppressed by flavor structure
new sources of flavor-conserving T-violation
ubiquitous in SM extensions



Radiative corrections from new heavy particles \Rightarrow EDMs

Analogy: radiative correction “loop diagrams” modify magnetic moment



with “natural” assumptions

$$g^2/(\hbar c) \approx \alpha$$

$$\sin(\phi) \sim 1$$

typical electron EDM is

$$d_e \sim \mu_B \left(\frac{\alpha}{2\pi} \right)^N \left(\frac{m_e}{m_\chi} \right)^2 \sin \phi$$

$N =$
loops

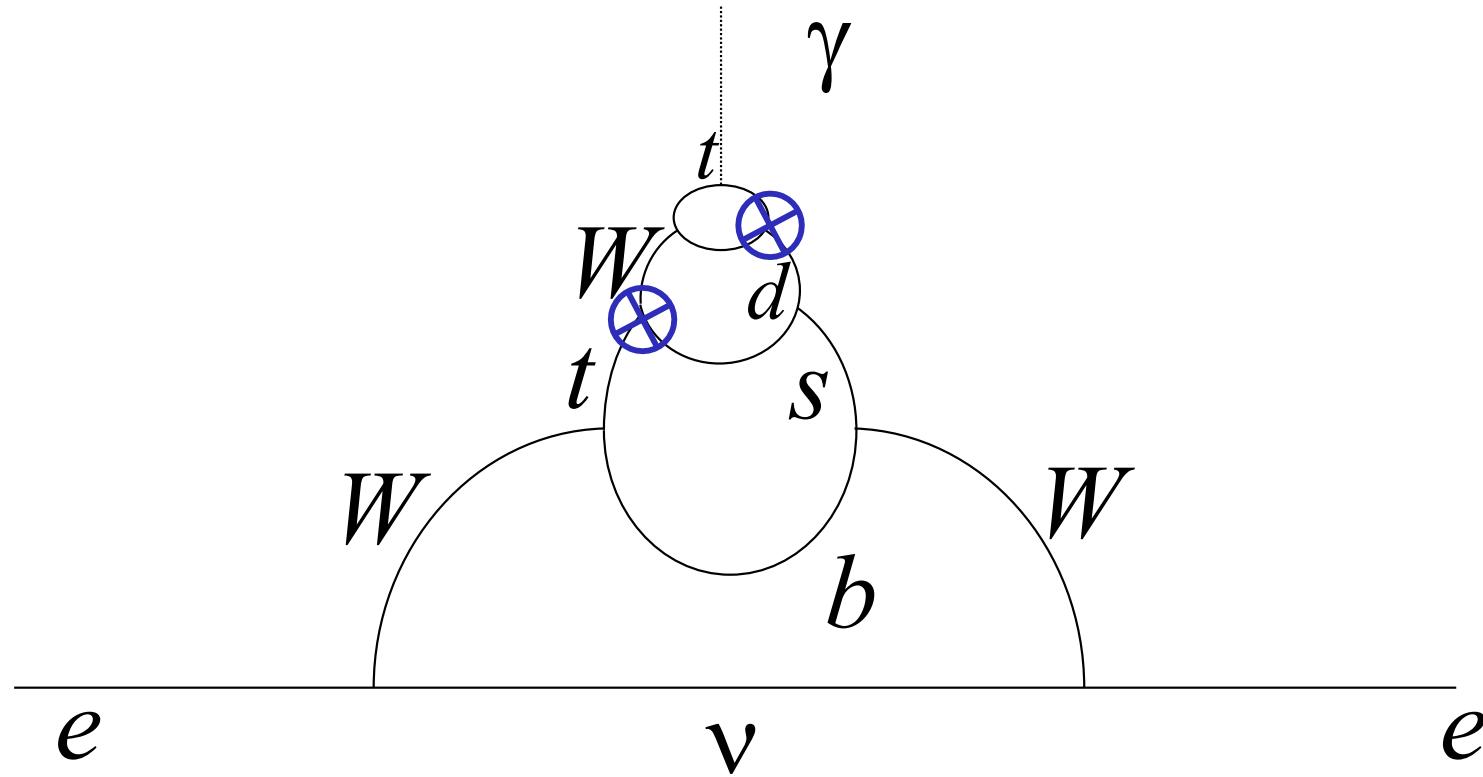
$d_e \sim$ current limit



$m_\chi \sim 30$ TeV
(for $N = 1$ loop)

EDMs nonzero, but DEEPLY suppressed in Std. Model

typical lowest-order Standard Model diagram giving electron EDM



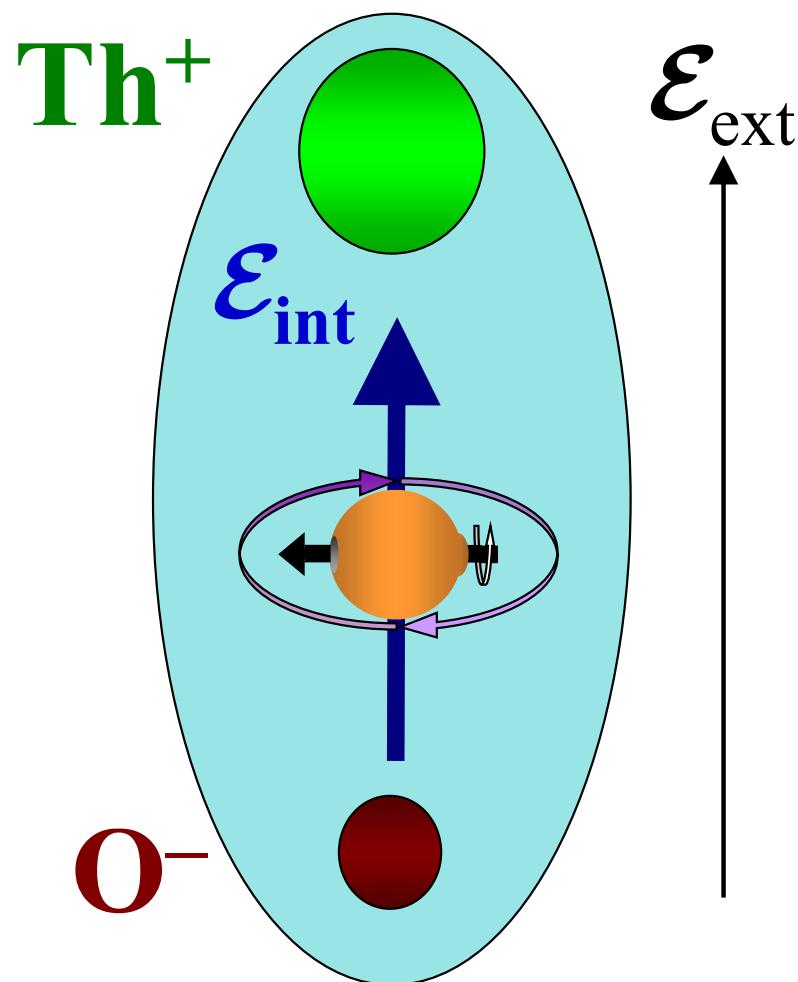
AND severe cancellations in sum over all diagrams
(from flavor structure of CP violation in Std. Model)

BOTTOM LINE:

many orders of magnitude “headroom” for discovery with EDMs

EDM detection: magnetometer principle, but with \mathcal{E} vs. \mathbf{B} -field

Largest effective \mathcal{E} -fields: internal to polarized molecules



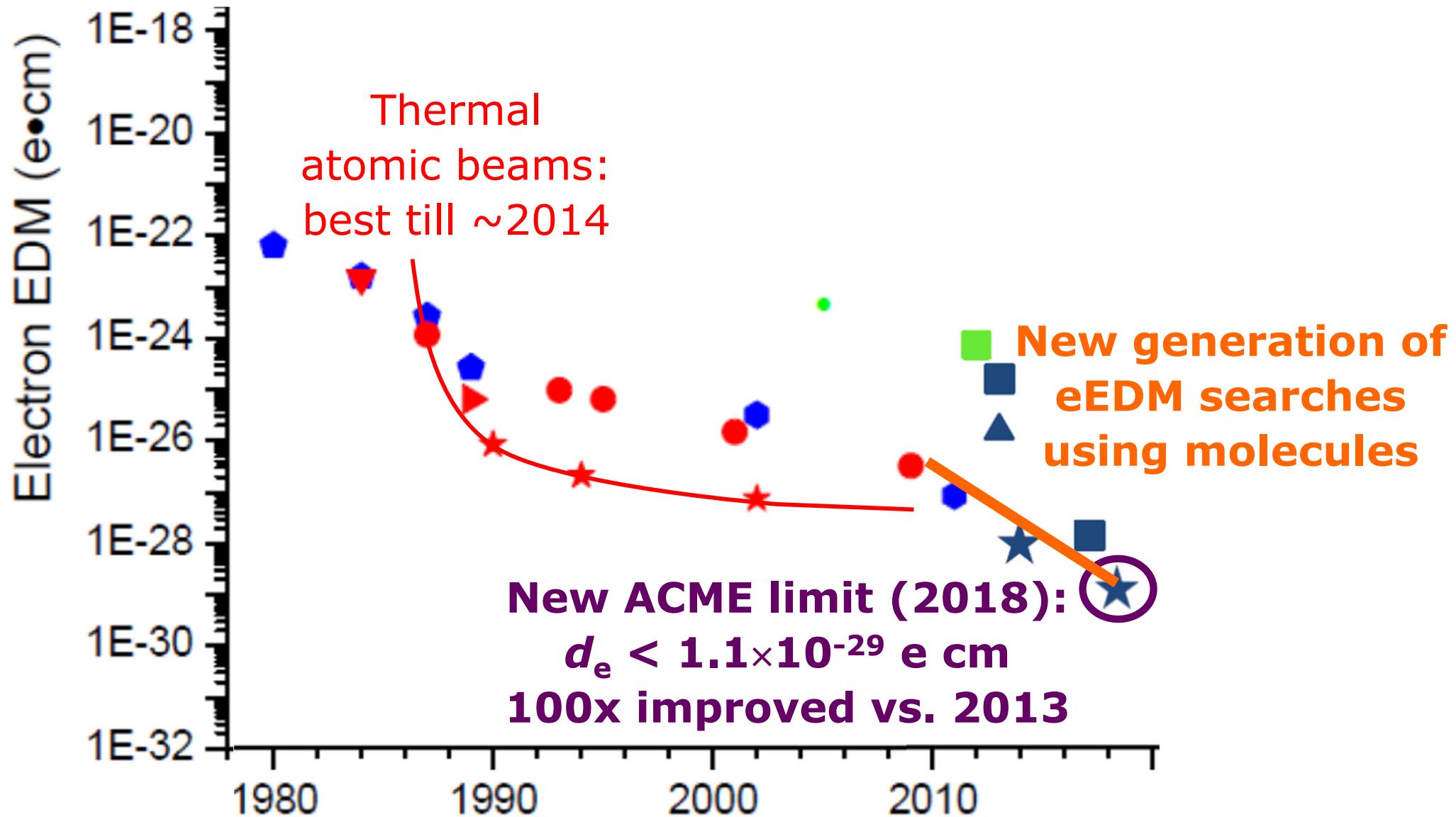
Example:
 $\mathcal{E}_{\text{eff}} \approx 78 \text{ GV/cm}$ for
electron in ThO*

Meyer & Bohn (2008);
Skripnikov, Petrov & Titov (2013, 2015);
Fleig & Nayak (2014),
Denis & Fleig (2016);
Skripnikov (2016)

Rapid recent progress
enabled by new methods for
cooling & measuring molecules

Similar enhancement in molecules for nuclear Schiff moments

Electron EDM limit vs. time

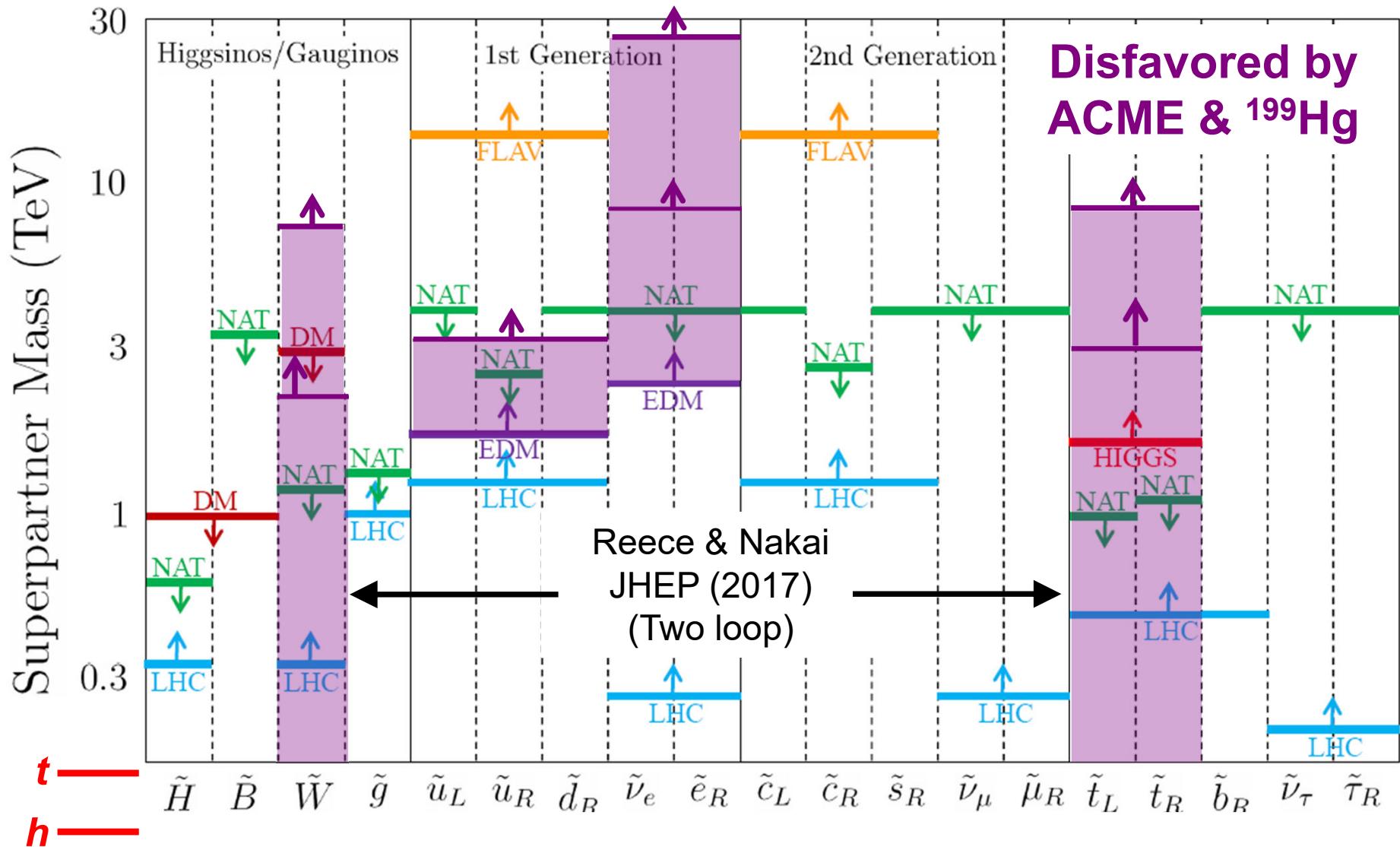


“electron EDM” experiments also probe tree-level CPV electron-nucleon couplings

EDMs in particle physics: supersymmetry

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

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

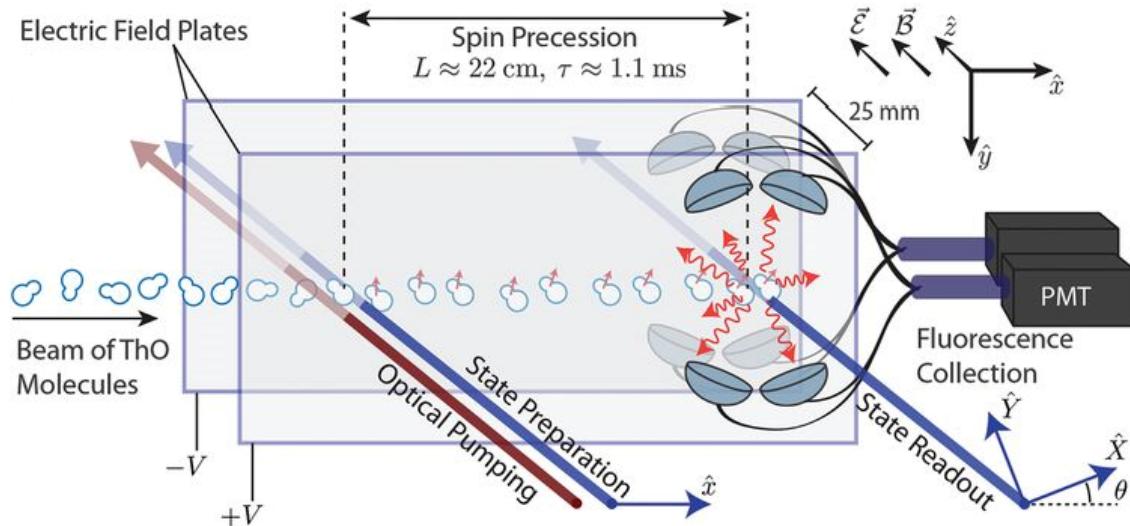


**Atomic EDM results push SUSY scale
to well above direct LHC limits**

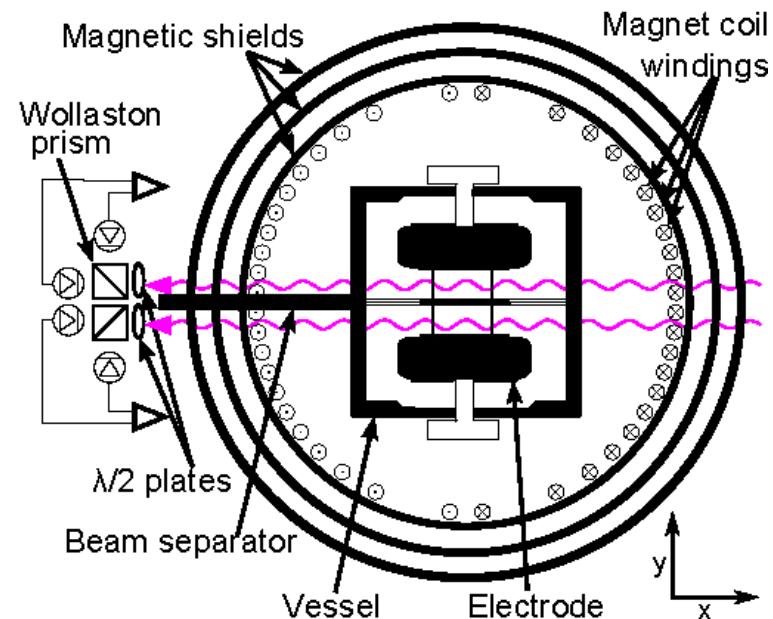
Electron & nuclear spin systems: state of the art

ACME (2014+18) ThO cryogenic beam:

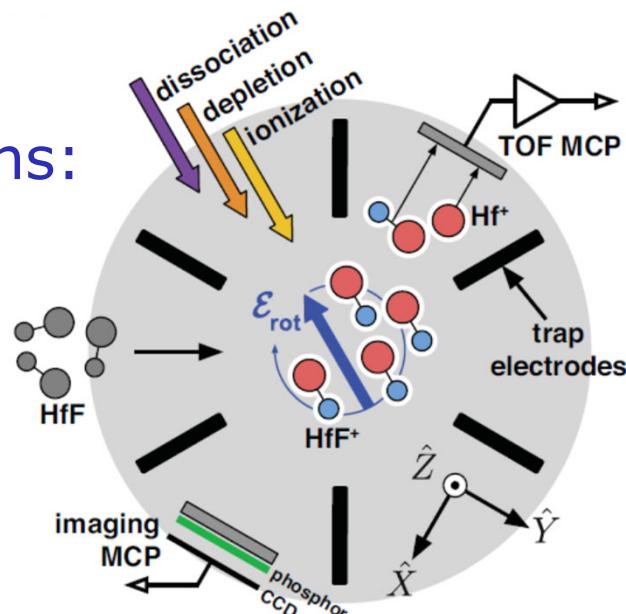
$$N\uparrow, \tau\downarrow, \varepsilon\uparrow\uparrow$$



Seattle ^{199}Hg (2016)
vapor cells: $N\uparrow\uparrow\uparrow, \tau\uparrow\uparrow\uparrow, \varepsilon\downarrow\downarrow$



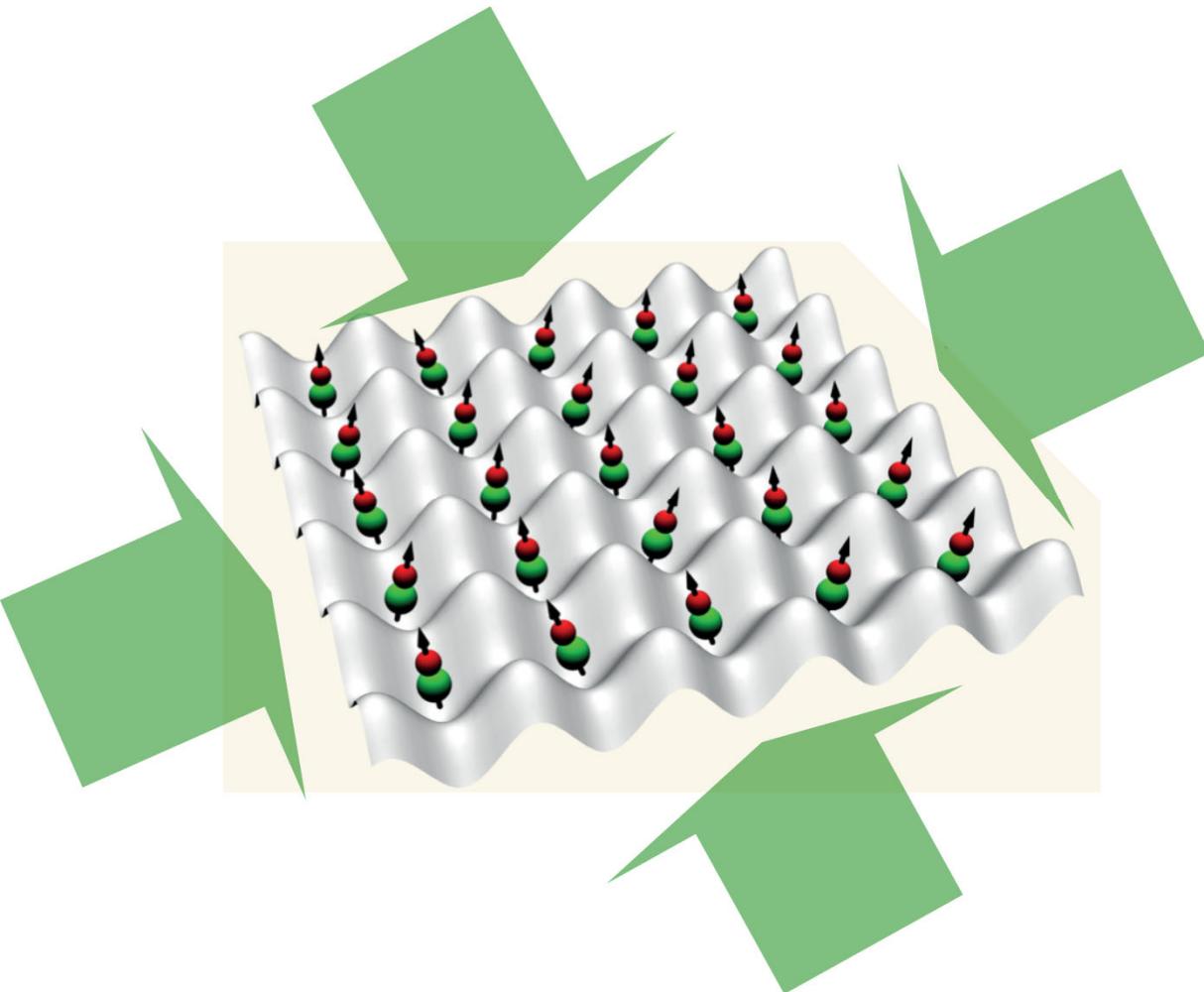
JILA (2017)
trapped HfF^+ ions:
 $N\downarrow, \tau\uparrow, \varepsilon\uparrow$



- All three:**
- underway $\gtrsim 10$ yrs
- upgrades ongoing
- **NOTHING ULTRACOLD!**
- **Complementary sensitivity to new underlying physics**

Towards “best case” EDM experiments

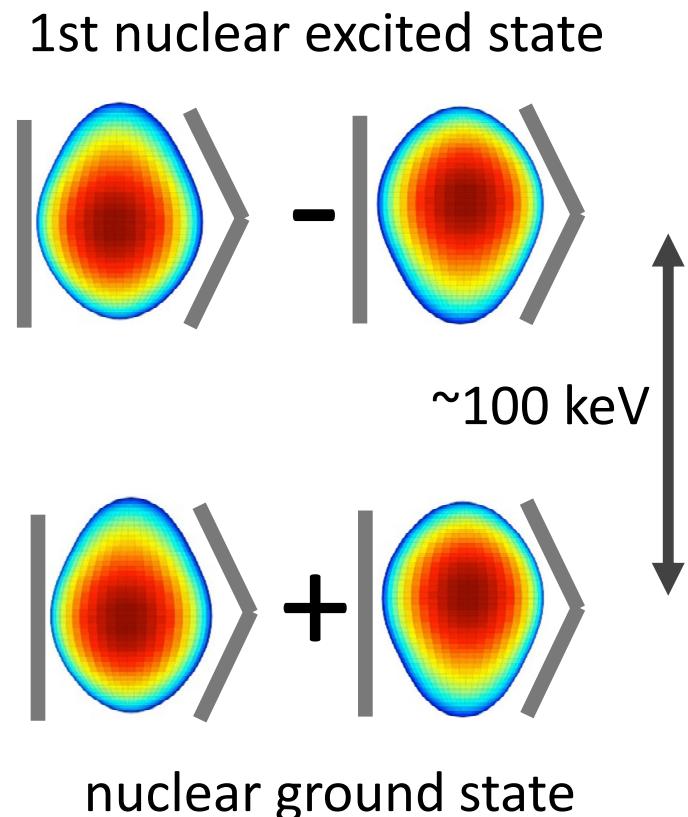
- Rapid advances in *ultracold* molecule production & trapping
⇒ molecular analogue of optical lattice clock on horizon



- Example for electron EDM:
with $\mathcal{E}_{\text{eff}} \sim 75 \text{ GV/cm}$
+ coherence time $\tau = 10 \text{ s}$
+ 100% detection
+ 10^6 molecules
- ⇒ **~1000x ACME sensitivity**
⇒ **~30x ACME mass reach**

Analogous advances with trapped molecular ions also feasible

"new" big enhancement for nuclear Schiff moments



Octupole deformation
 ^{225}Ra , ^{223}Fr , ^{227}Ac

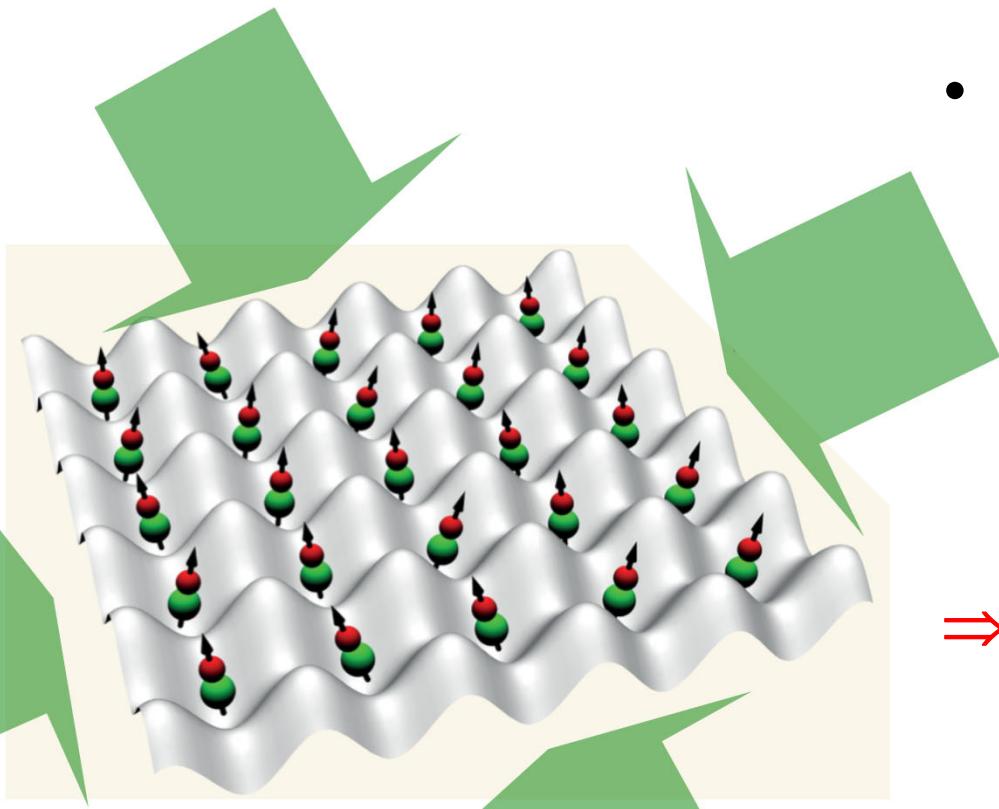
T-violating forces
mix the states

Enhancement:
 $\sim 300\text{-}1000\times$

From:
Andrew Jayich (UCSB)

- Biggest enhancement in actinide region → radioactive species
- Experiments already underway w/laser cooled/trapped ^{225}Ra atoms
 - New ideas to use in polar molecules → enhancement²

Next-gen Schiff moment search w/radioactive molecules



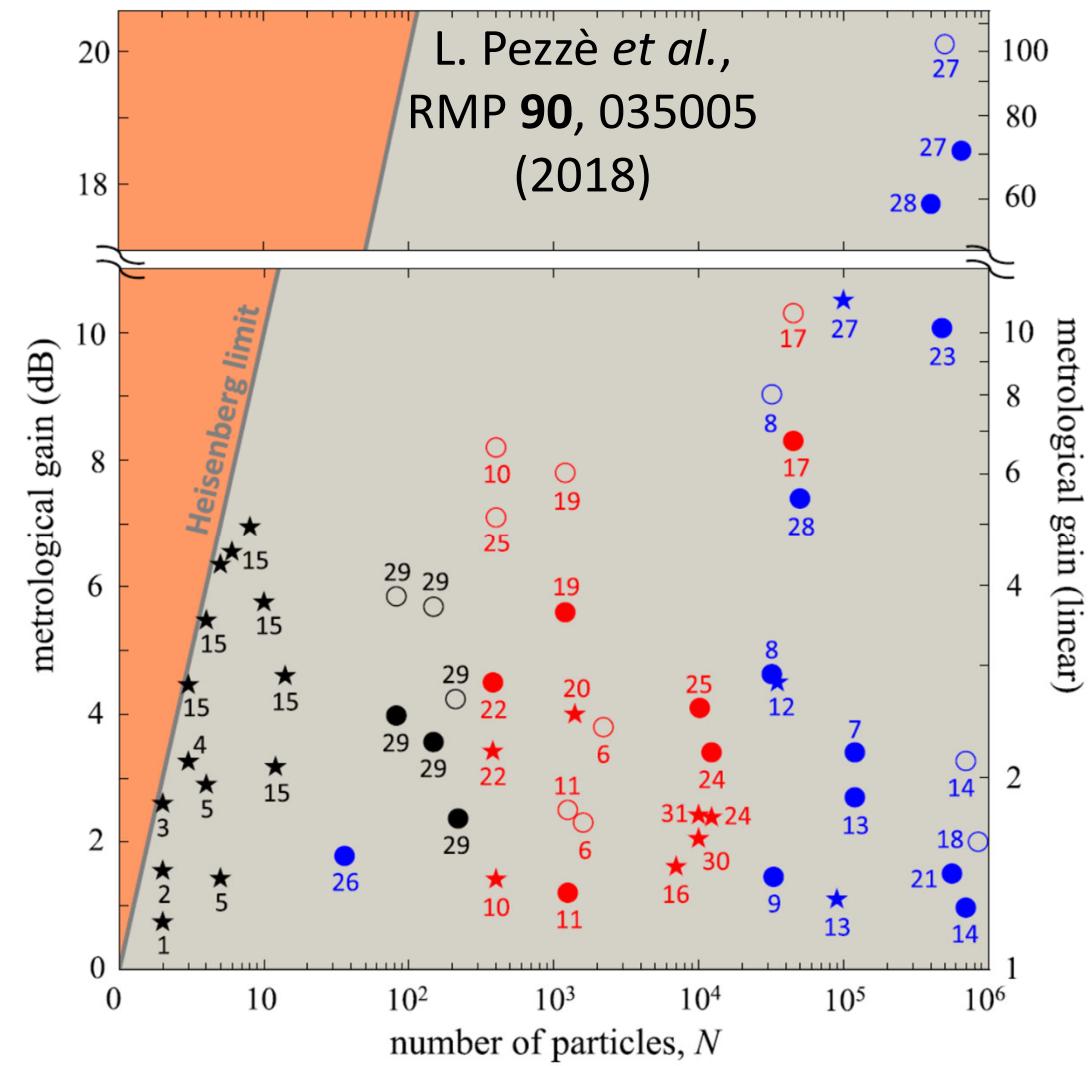
- **Sensitivity Estimate:**
 - 300x SM enhancement
 - near-ideal molecular structure
 - $\tau_{coh} \sim 10$ s [Cornish, Zwierlein, etc.]
 - ~100% detection efficiency
 - $n = 10^4$ molecules
- $\Rightarrow \sim 1000$ x improvement
vs. ^{199}Hg state of the art

Analogous advances
with trapped molecular
ions also feasible

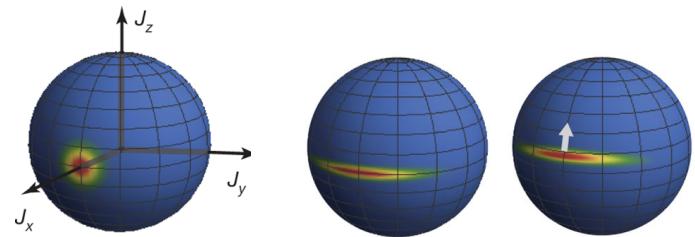
All these parameters
ALREADY DEMONSTRATED
with stable bi-alkali molecules

+Long-term potential for dramatic further improvements:
Longer τ_{coh} , larger n , ...

On the horizon: beyond standard quantum limit for clocks, EDMs, interferometers,...



Multi-particle spin squeezing
(a type of quantum entanglement)



O Hosten et al. *Nature* 1-4 (2016)

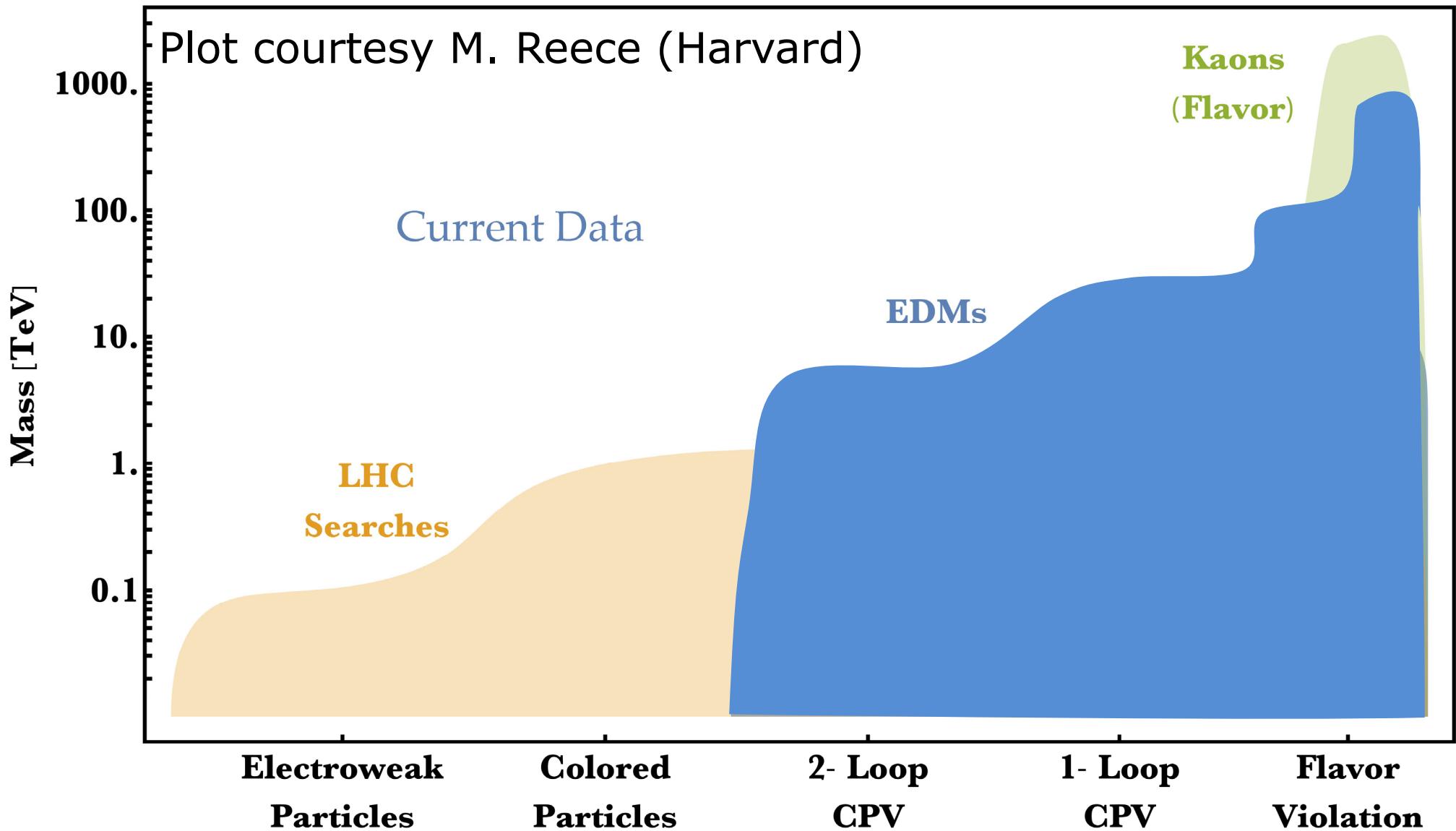
enables measurements of N -particle systems with sensitivity up to $N^{1/2}$ times better than fundamental limit for unentangled particles

Recent demonstrations: 10-100x actual gain in realistic test systems
Requires carefully engineered, strong interparticle interactions

Generic discovery potential of EDMs (assuming near-maximal CP violation)

Breadth of new physics versus depth of mass reach

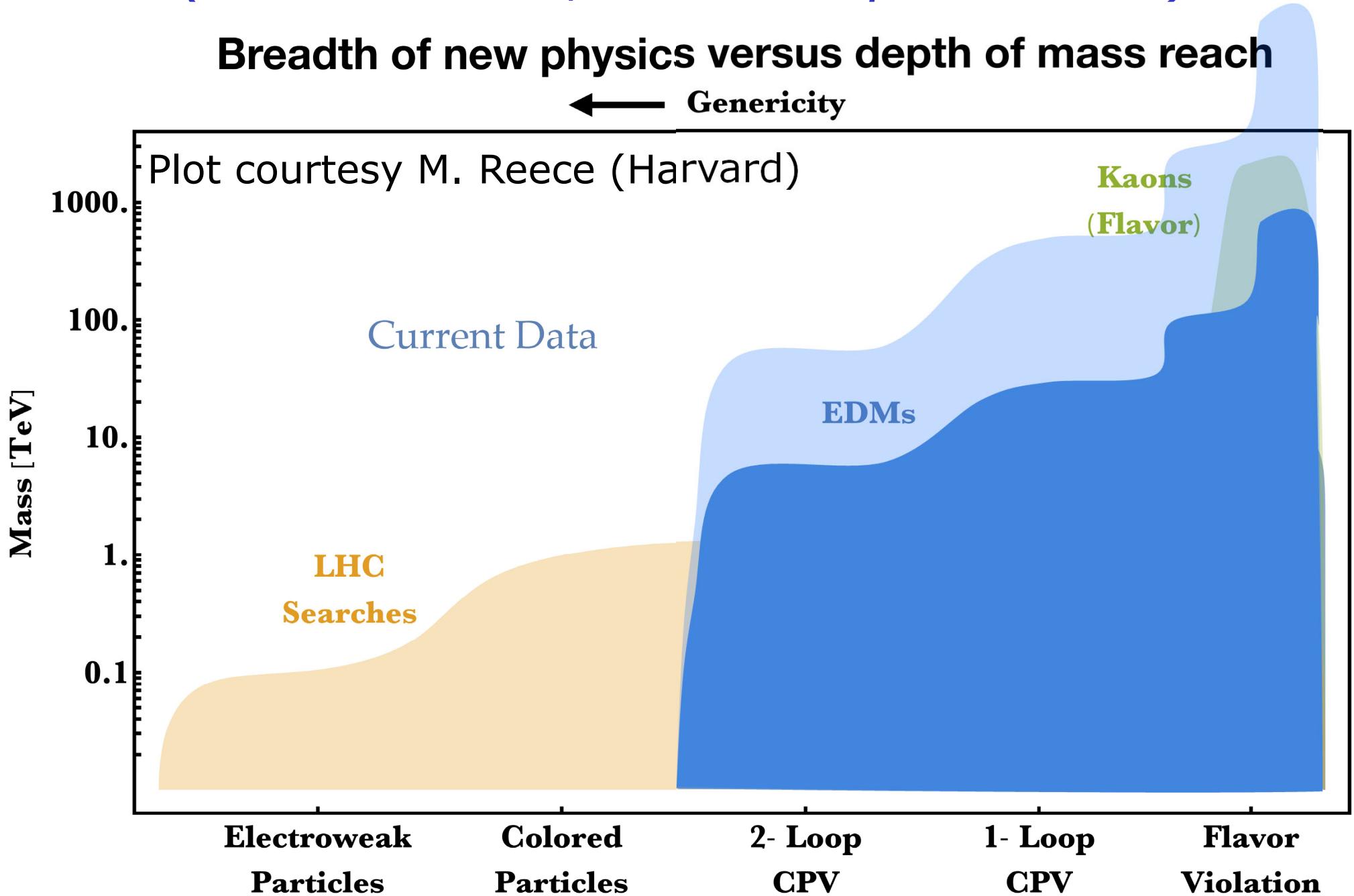
← Genericity



Generic discovery potential of EDMs (maximal CPV, 1000x improvement)

Breadth of new physics versus depth of mass reach

← Genericity



Some primary takeaways:

AMO-based EDM searches

probe well-motivated new physics at $>>$ TeV scale

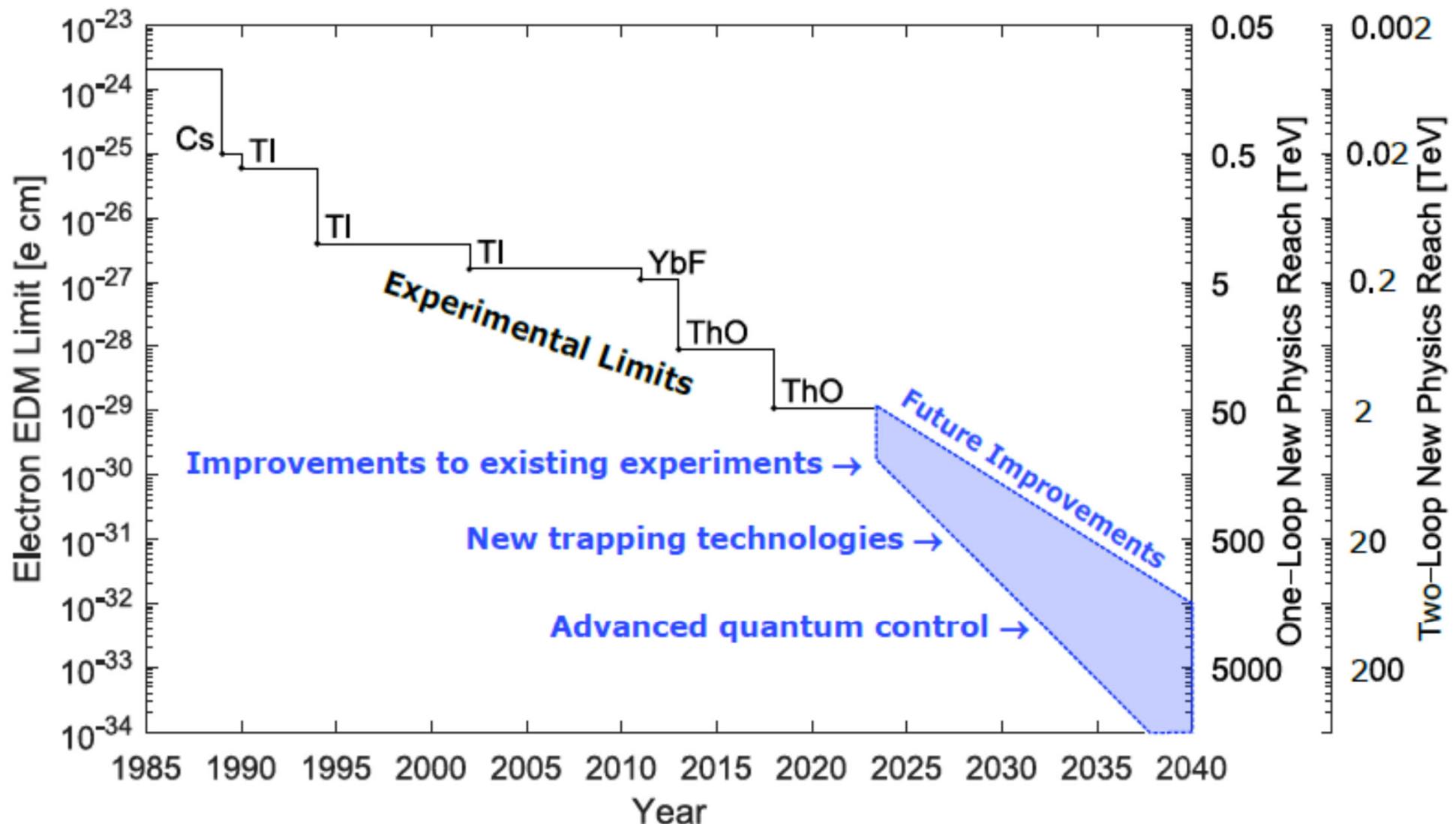
- recent rapid progress, anticipated to continue based on new methods to make ultracold/trapped molecules + deformed nuclei
- plausible projections for 1000x improvement in ~10 years, projected 10x improvement in ~2 years (electron EDM)
- complementary to neutron EDM, storage ring EDM experiments
- Development of squeezing methods likely to advance even further in future
- New era of experiments with larger collaborations outside usual AMO paradigm
- exciting window for BSM physics discovery: probe up to PeV scale in ~10 years**

Other AMO-based techniques

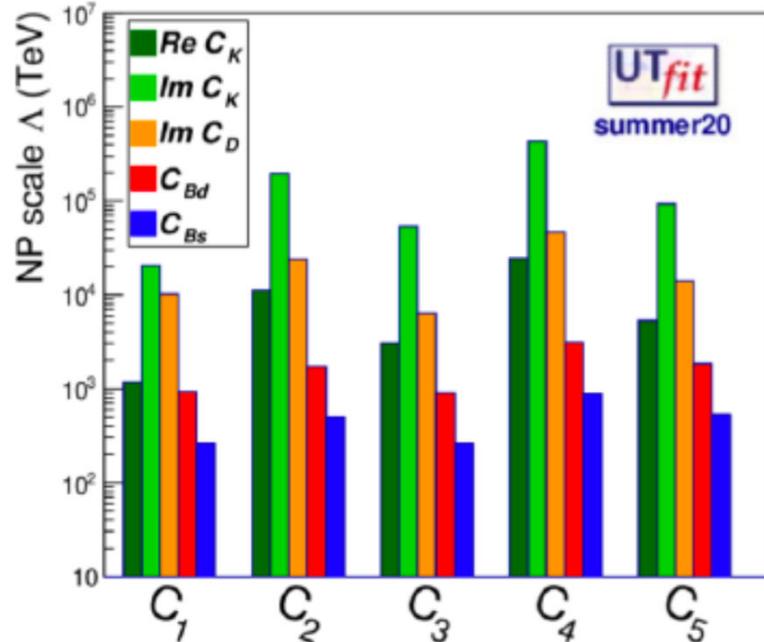
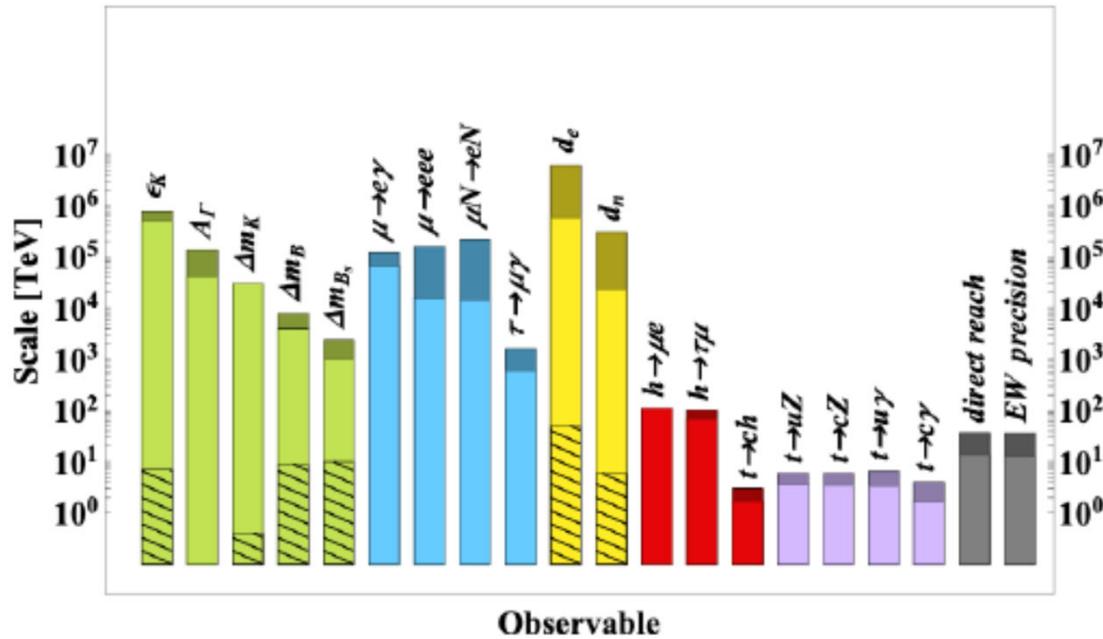
probe gravity in new ways + fifth forces + dark matter

- rapid progress in clocks, interferometers, optomechanical force sensors, ...
- explosion of new ideas to use AMO methods to probe particle physics

EXTRA SLIDES



Plot courtesy N. Hutzler (Caltech)



- assuming NP is heavy \Rightarrow SMEFT
- flavor observables probe very high scales
 - decoupling
 - Minimal Flavor Violation
 - hierarchical new physics flavor couplings

Some points relevant to Snowmass:

- Increasingly complex experiments (gravitational wave detectors, EDMs, etc) driving formation of **larger collaborations**: 3-10(?) PIs
BUT
 - collaborative funding mechanisms not solidified in AMO community
 - scaling (parallel systems, long integration times) not pursued
 - access to engineers, stable base funding NOT typical
 - **Clocks** central to all precision measurement
space clock array = distributed spacetime sensor
many applications: gravitational waves, space navigation, etc.
 - **Interferometers** for gravity waves & many other applications
 - **EDMs** provide probe of new physics at >> TeV scale
 - rapid progress anticipated, based on molecule cooling/trapping + deformed nuclei
 - New motivations to search for **light, weakly-coupled particles**...BUT with little theory guidance:
perfect match for AMO methods (nimble, sensitive, inexpensive)
 - Development of **squeezing** methods:
likely to advance many primary frontiers BUT needs R&D for specific systems

Summary

- Several precision quantum sensing techniques well suited for future advances in HEP science (Interferometers, Mechanics, Traps, Clocks)
- Mid-scale efforts already launching at DOE labs (e.g. MAGIS)
- Many existing and developing small-scale experiments (precision torsion balance experiments, opto-mechanics, levitated sensors, optical interferometers, clocks, trapped atoms and molecules)
- Technical limiting factors in many (opto)-mechanical experiments (external vibration, gravity gradient noise) could be addressed by a development of a suitable underground facility that was open to outside users (cavity experiments, torsion balances, matter wave interferometers)