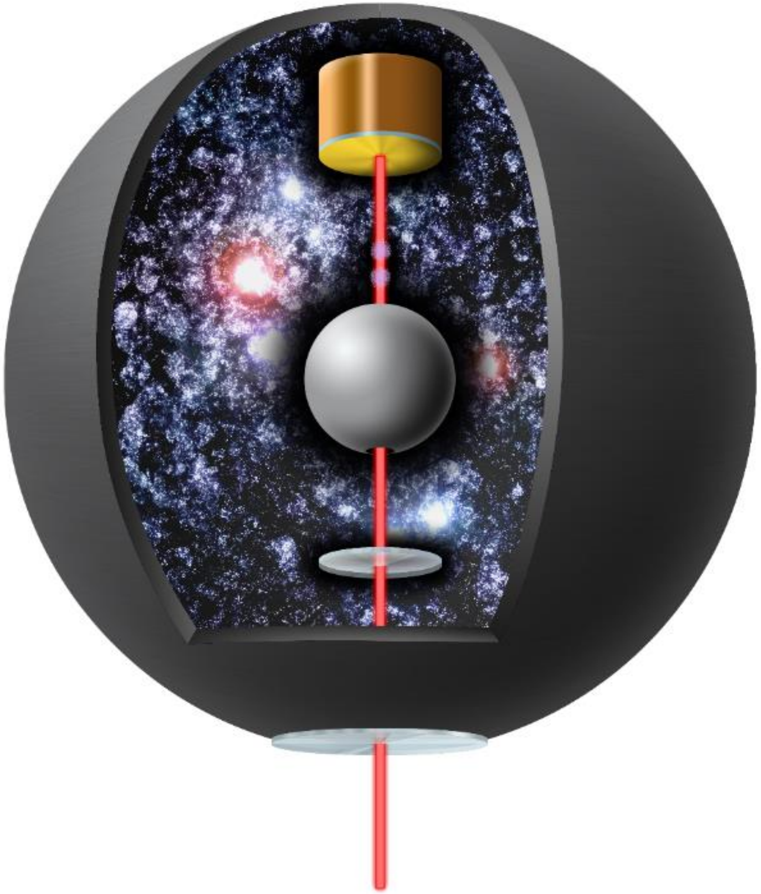
UCLA



Atomic physics tests of dark matter and energy

Paul Hamilton

PPC 2018

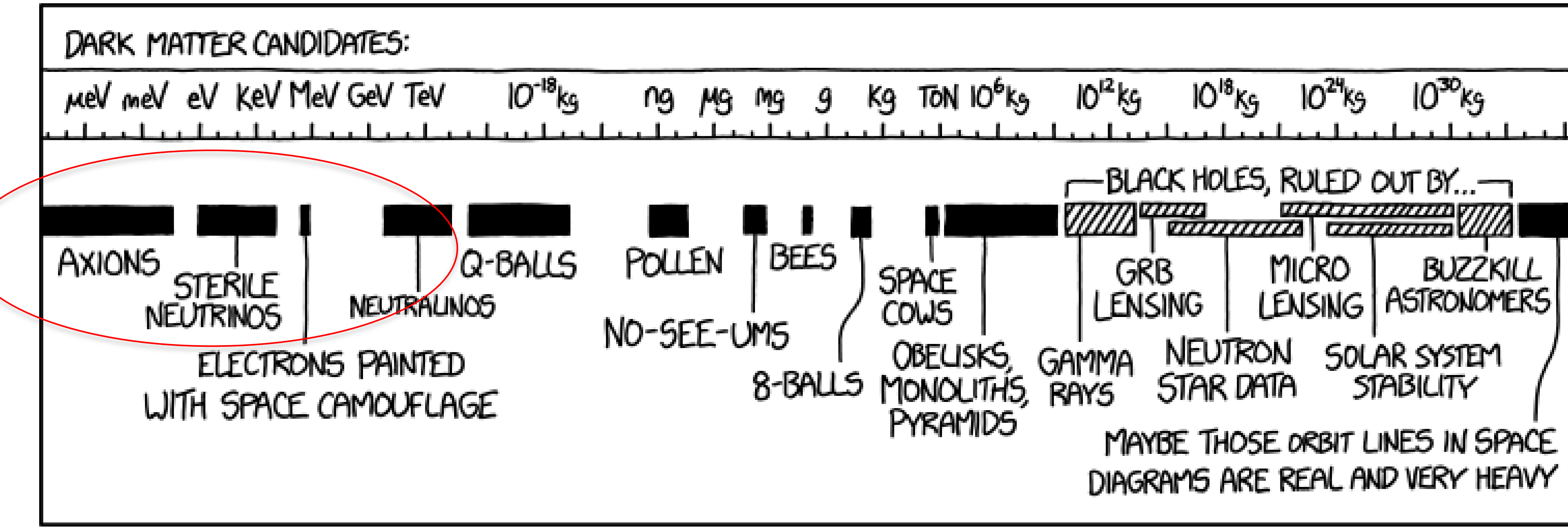
Outline

1. **Introduction to precision AMO**

2. Matter wave force sensors

3. HUNTER – sterile neutrino search

Outline



XKCD

Why precision AMO?

Control of single quantum states

+

Universal and well understood properties of atoms

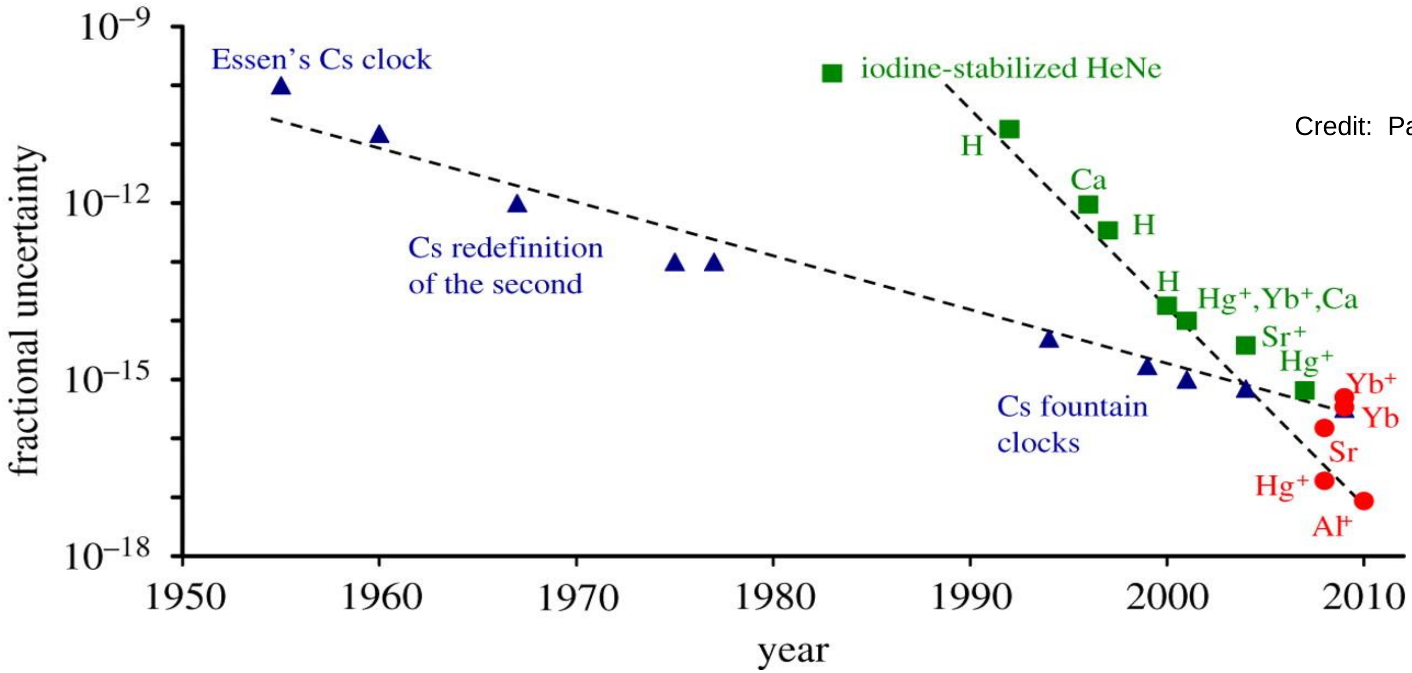
+

Unrivalled precision

=

Testbed for theories

Moore's law for precision?



Credit: Patrick Gill

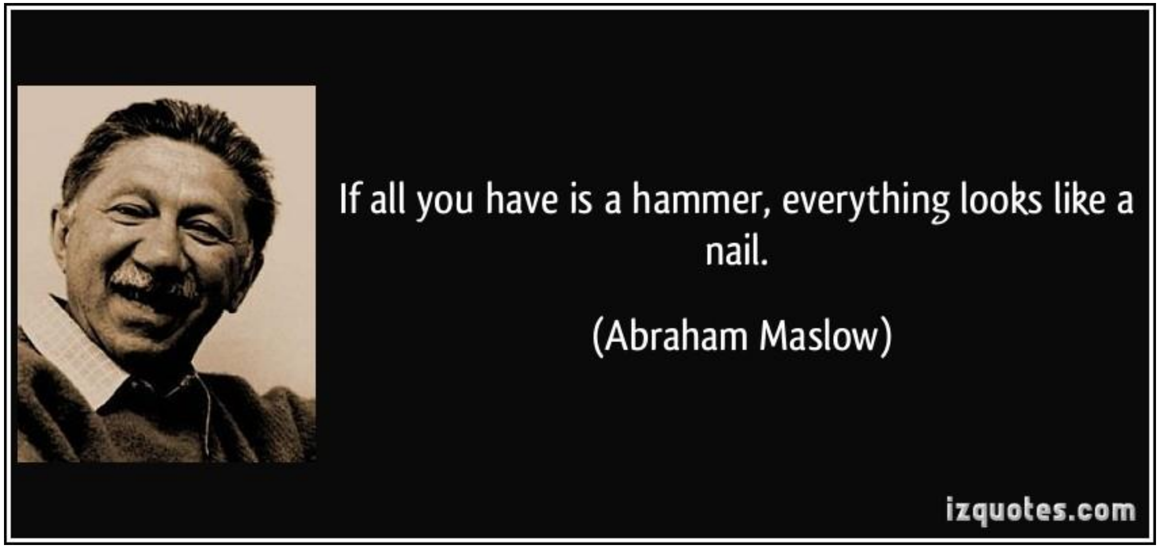
Typical precision 100 mHz on 10^{15} Hz = 10^{-16} in one second.

…10^{-18} now, 10^{-20} and beyond seem feasible.

- Doppler shift from continental drift, GR redshift for 1 cm

Many technological breakthroughs in AMO driven by improving clocks.
…what else can we apply it to?

Maslow's hammer



Development of better tools has often driven progress in physics.

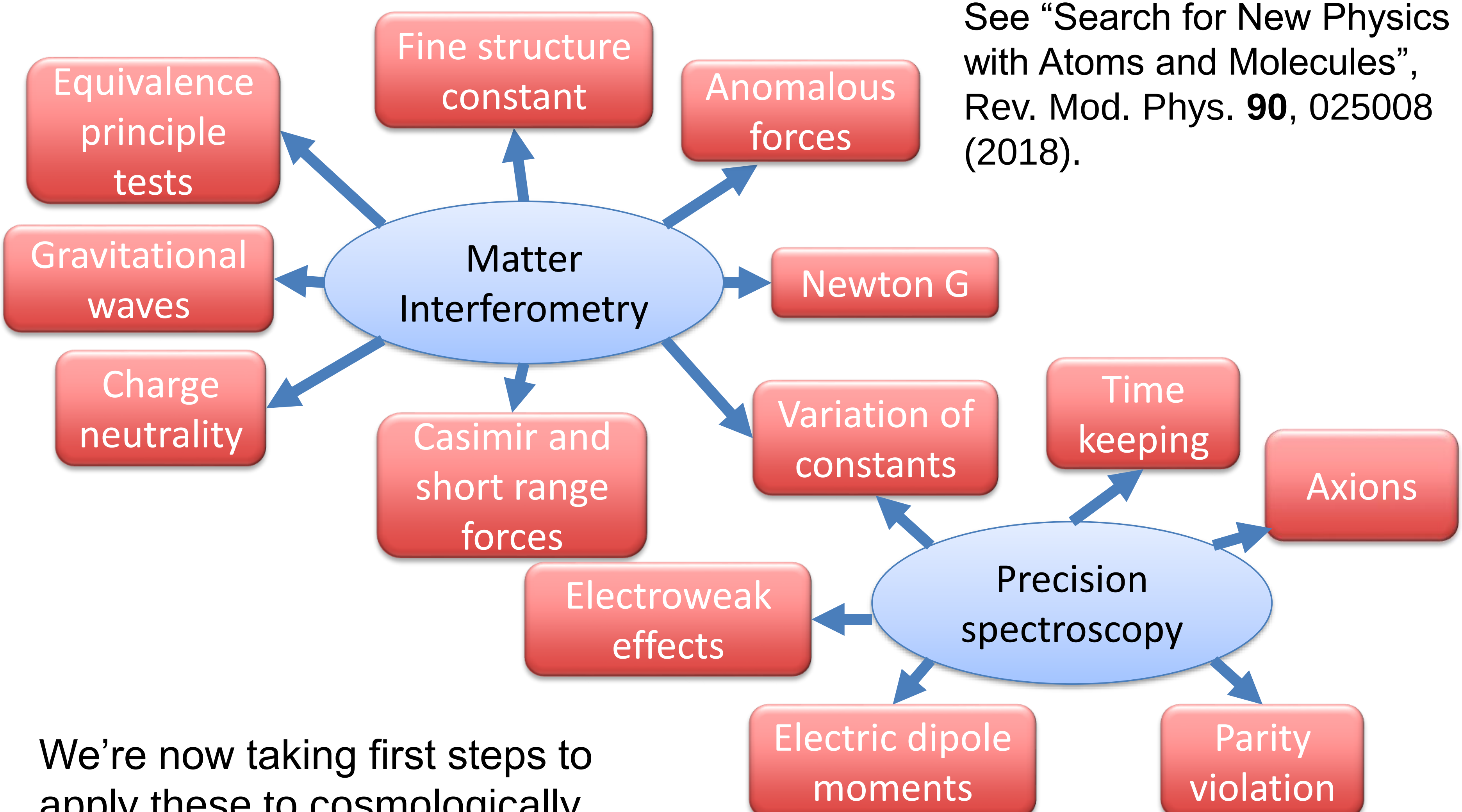
So - if you have a really good clock, try to make everything a frequency measurement.

HEP: Hammer = high energy collisions to produce new particles

AMO: Hammer = precision frequency measurements to look for small energy shifts

AMO physics adds tools

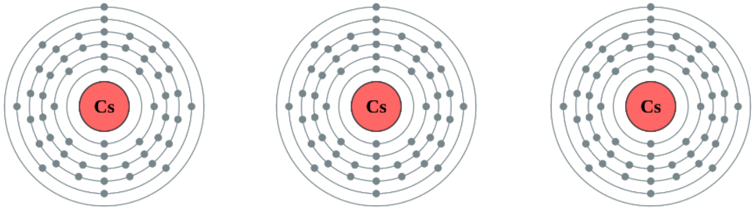
See “Search for New Physics with Atoms and Molecules”, Rev. Mod. Phys. **90**, 025008 (2018).



We’re now taking first steps to apply these to cosmologically interesting physics…

Keys to high precision

- Universal properties of atoms in single quantum states



Every atom is the same so we can average over ensembles and many experimental runs to increase precision.

Keys to high precision

- Use of atomic properties and symmetries to isolate small effects
  - Relies on perturbation theory – **don't need matching precision in the atomic theory**

No new effect:

$$\langle\psi|H'|\psi\rangle = 0$$

New effect:

$$\langle\psi|H'|\psi\rangle = \text{small energy shift}$$

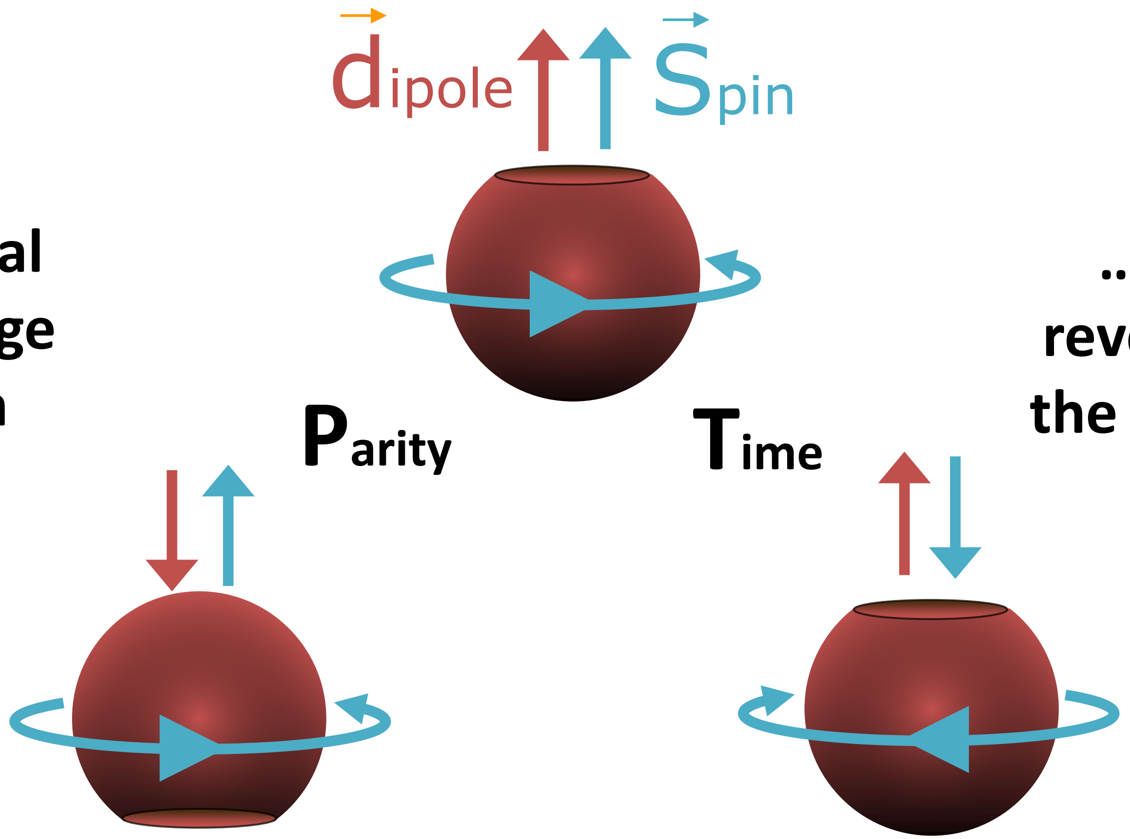
Atomic wavefunction of modest accuracy

Limited only by experimental precision

Example: EDMs

Consider a particle with an electric dipole moment (EDM):

Parity reversal flips the charge distribution



...while time reversal changes the spin direction

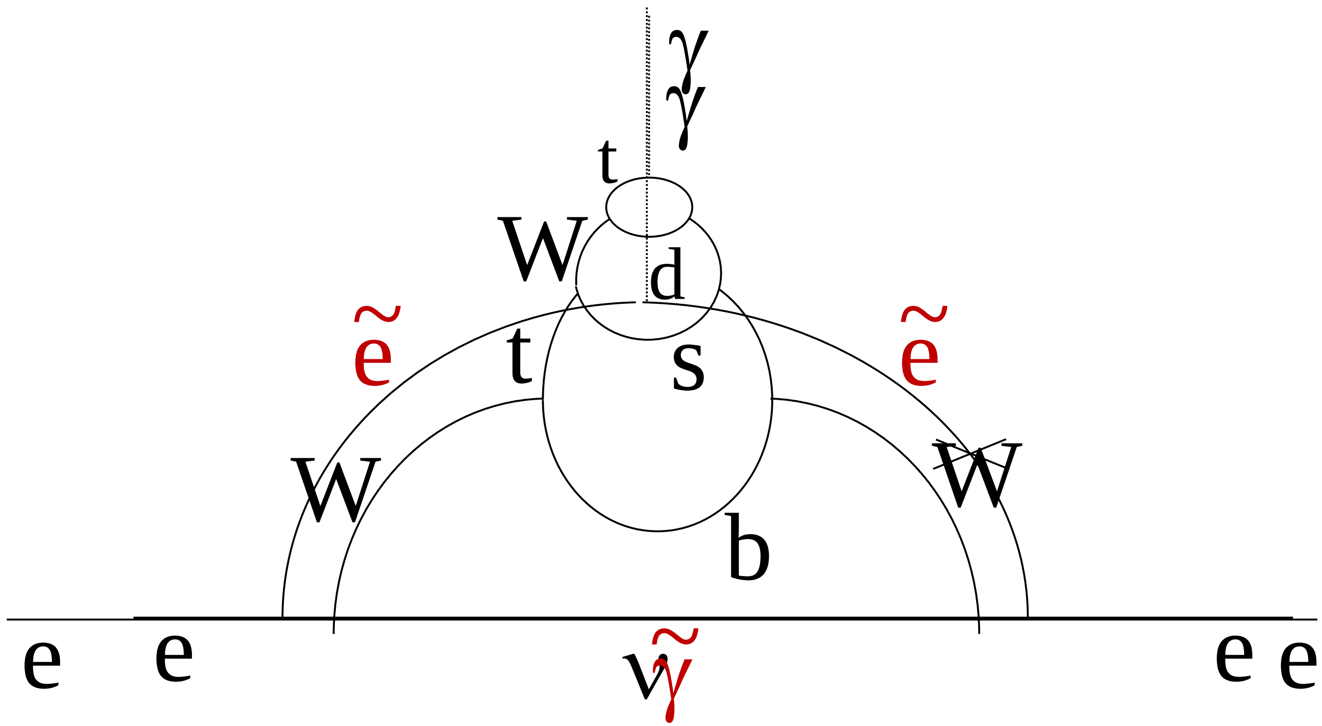
CPT Theorem ⇒

T violation **=** **CP** violation

Where do EDMs come from?

Standard Model

Supersymmetry



4 loops ⇒ heavily suppressed

1 loop ⇒ no cancellations

Note: Feynman diagrams = perturbation theory
Acts very much like electron with small new effect.

Electron EDM to atomic EDM

Keys: small change in property of electron + new properties

EDM interaction with electric field given by

$$H = -\vec{d} \cdot \vec{E}$$

But the EDM must be along the spin of the electron so

$$\vec{d} = d_e \vec{S}$$

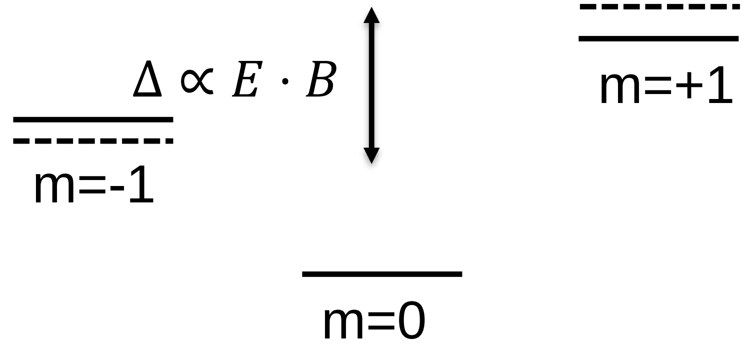
In a magnetic field then we have $H_{EDM} \propto \vec{B} \cdot \vec{E}$

$\rightarrow$ Look for an effect that flips sign with both $\vec{B}$ and $\vec{E}$
(CP-violating - very hard to mimic with "normal" physics)

Electron EDM to atomic EDM

With EDM

$$H_{EB+EDM} \propto |mE| + mB + m\,E\cdot B$$



Energy shift = $\langle \psi | d_e S \cdot E | \psi \rangle$

Limits on EDM don’t require high accuracy electronic wavefunctions.

0.2 mHz shift $\rightarrow d_e \approx 10^{-29} e \cdot \mathrm{cm}$ (ACME,2018)

Incredibly small!

Blow up classical electron to size of solar system

→bump ~cm

Constraints on new particles >10 TeV!

Electron EDM summary

Keys:

- Control of quantum state
  - typically lasers / laser cooling
- New properties from coupling to new field
  - P and T odd effect
- Precision
  - <1 mHz spectroscopy

What else can we do?

Axion-like particles

Coupling to nucleons creates oscillating EDM   (Rajendran, Graham)

Axion searches look for coupling to electromagnetic field

$$L \propto g_{a\gamma} \frac{a}{f_a} F\tilde{F} \propto E \cdot B$$

Gluon coupling leads to oscillating EDM

$$L \propto \frac{a}{f_a} trG\tilde{G}$$

Use NMR techniques but with electric field to look for spin precession.

Modern atomic magnetometers ~ 1 fT / √Hz

11 orders of magnitude smaller than Earth's field!

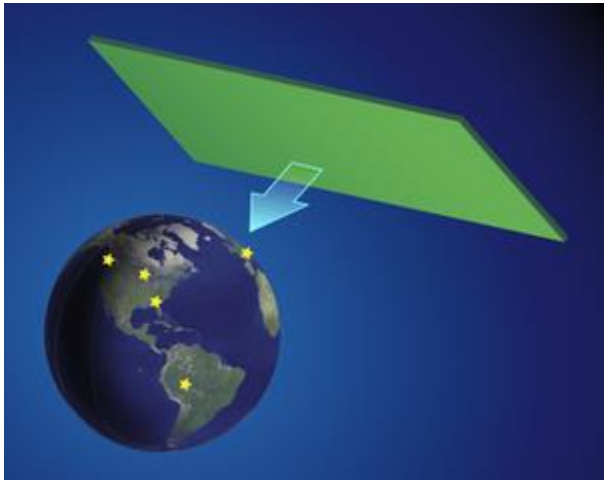
Ref: CASPER, Budker et al., Phys. Rev. X **4**, 021030 (2014)

GNOME/NOSE

Dark matter

Domains of dark matter could cause anomalous magnetic fields and accelerations as we pass through them. **Pustelny et al., Annalen Phys. 525, 659-670 (2013)**

→ Look for correlated signals across Earth.



APS/[Alan Stonebraker]

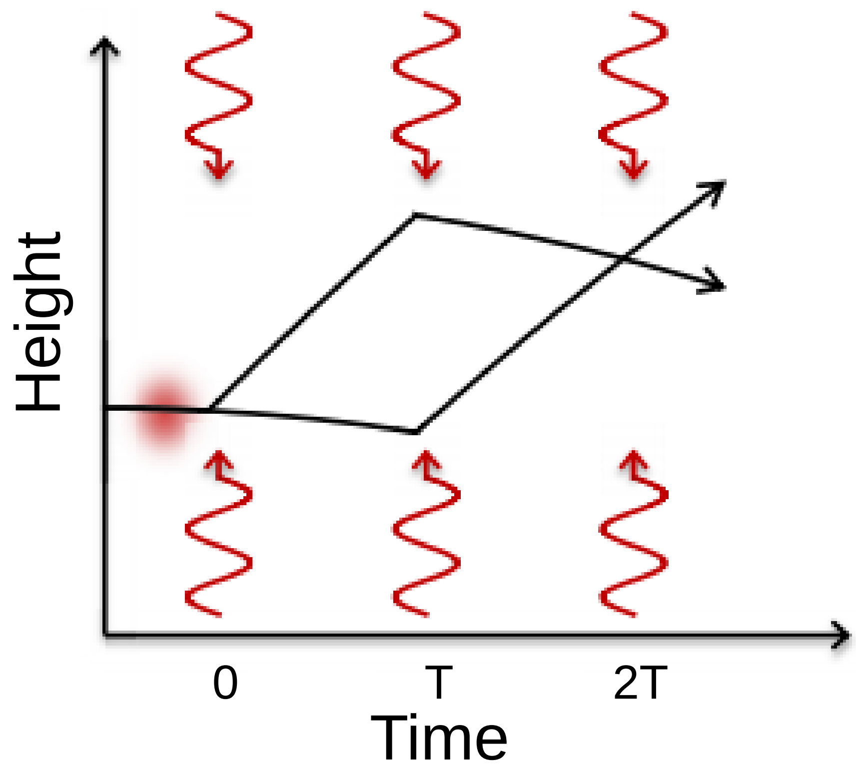
Rubidium magnetometers in GNOME (Global Network Of Magnetometers for Exotic physics).

Atom interferometers will be part of NOSE (Network of Sensors for Exotic physics).

Outline

1. Introduction to precision AMO
2. **Matter wave force sensors**
3. HUNTER – sterile neutrino search

Atomic force sensors

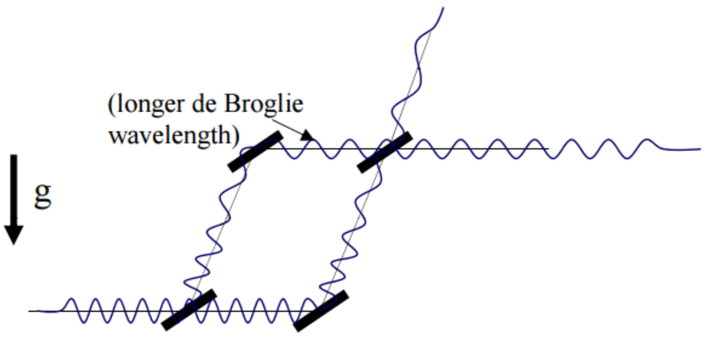


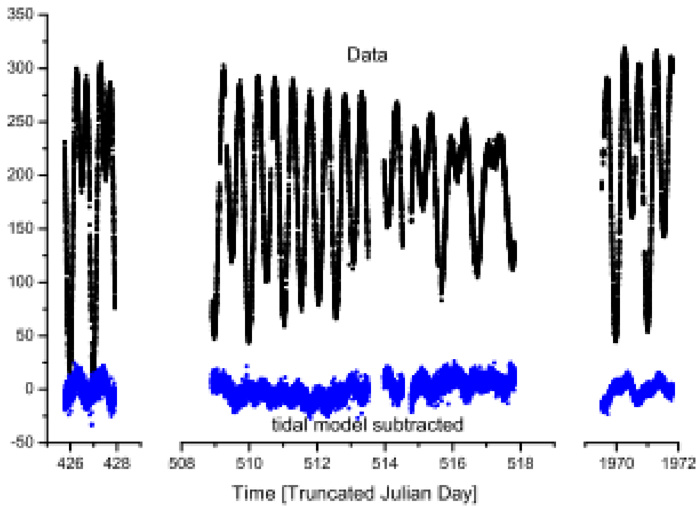
- Matter wave interferometers: atoms act as test masses for force sensing.
- Roughly think about a potential difference across the arms leads to a phase shift.

Measuring all accelerations

Gravity/Accelerations

As atom climbs gravitational potential, velocity decreases and wavelength increases





Rotations

Sagnac effect for de Broglie waves

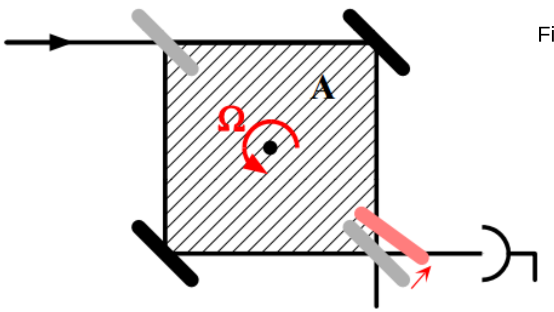


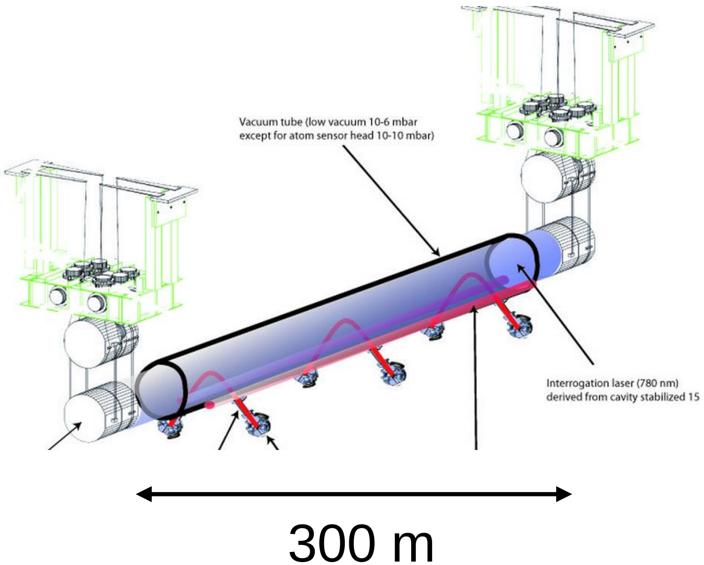
Figure credit: Kasevich

Field uses:

- Inertial navigation
- Mineral and oil searches
- Hydrology
- Proposed for geodesy

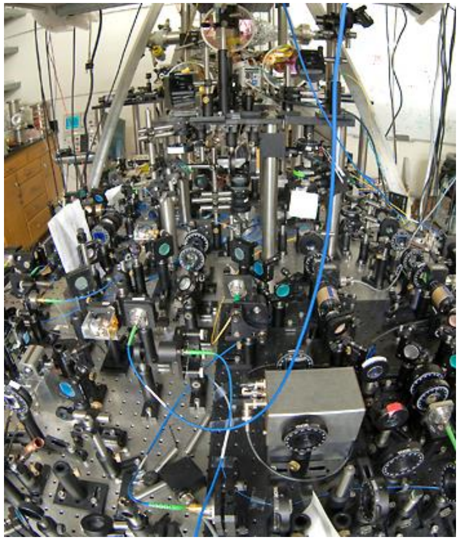
- Accelerations: ~ppb !
- Rotations: <nrad/s !

Applications



Gravity wave detection
MIGA collaboration

Tests of general relativity
Stanford 10 meter atomic fountain



Fine structure constant measurement
3m atomic fountain
Berkeley

Ex: Scalar field forces

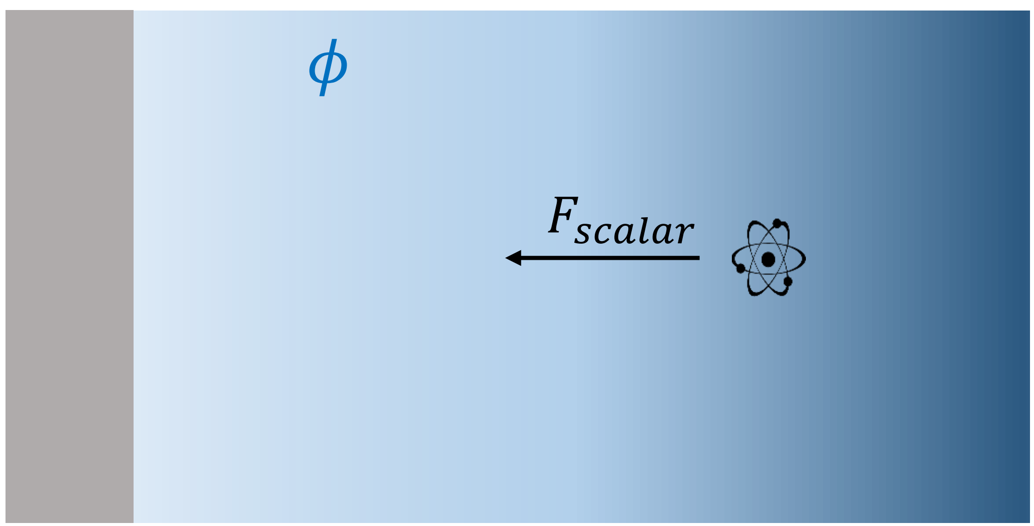
Chameleons are one example, but in general scalar fields with couplings to matter can create screened forces:

Coupling

Scalar gradient

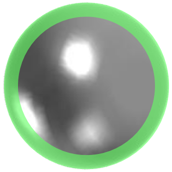
$$F_{scalar} = \frac{GM_AM_B}{r^2} - \frac{\beta(\phi)}{M_{pl}} \lambda_a \nabla\phi$$

Screening



Atoms evade screening

$$F_{chameleon} = \frac{GM_A M_B}{r^2}\left[1 + 2\,\lambda_A \cancel{\lambda_B} \left(\frac{M_{Pl}}{M}\right)^2\right]$$



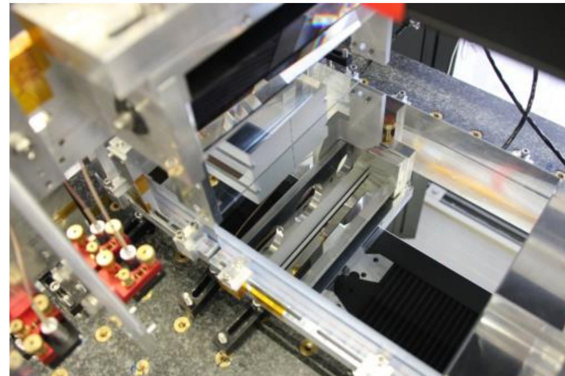
$\lambda \ll 1$ as small as 10^{-20}!

$\lambda_{atom} = 1$ For most of parameter space

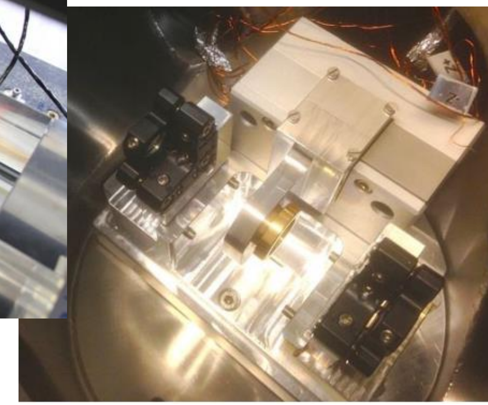
Burrage, Copeland, Hinds JCAP03(2015)042

Other detection methods

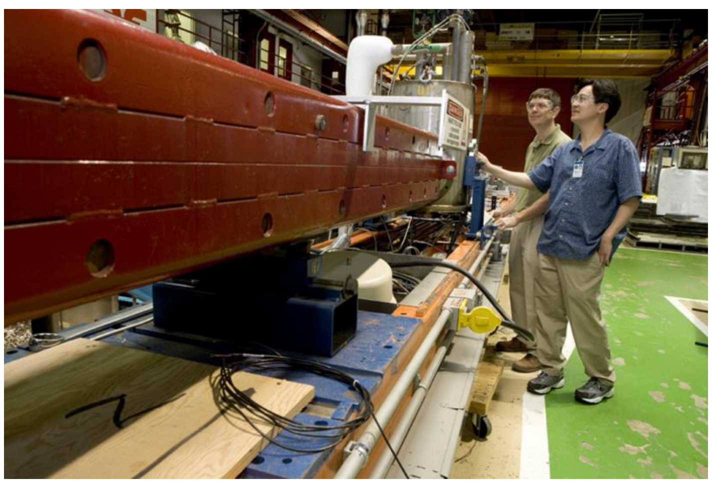
CAST search for solar axions at CERN



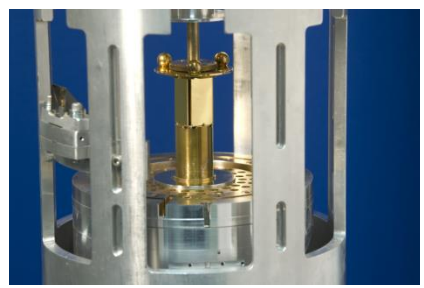
Neutron interferometry



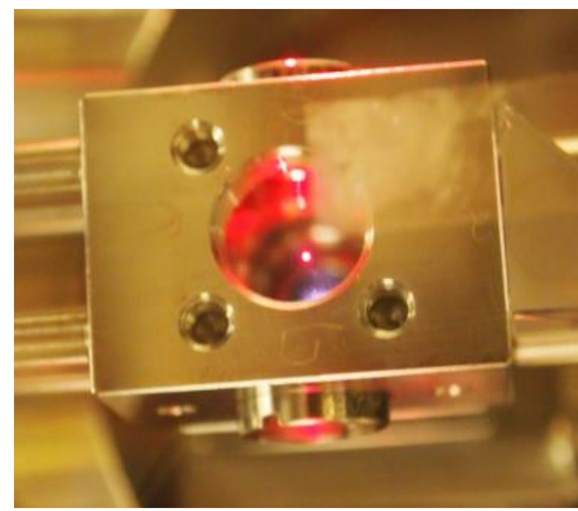
Optomechanical recoil KWISP proposal



GammeV light shining through wall at Fermilab



Eotwash torsion pendulum

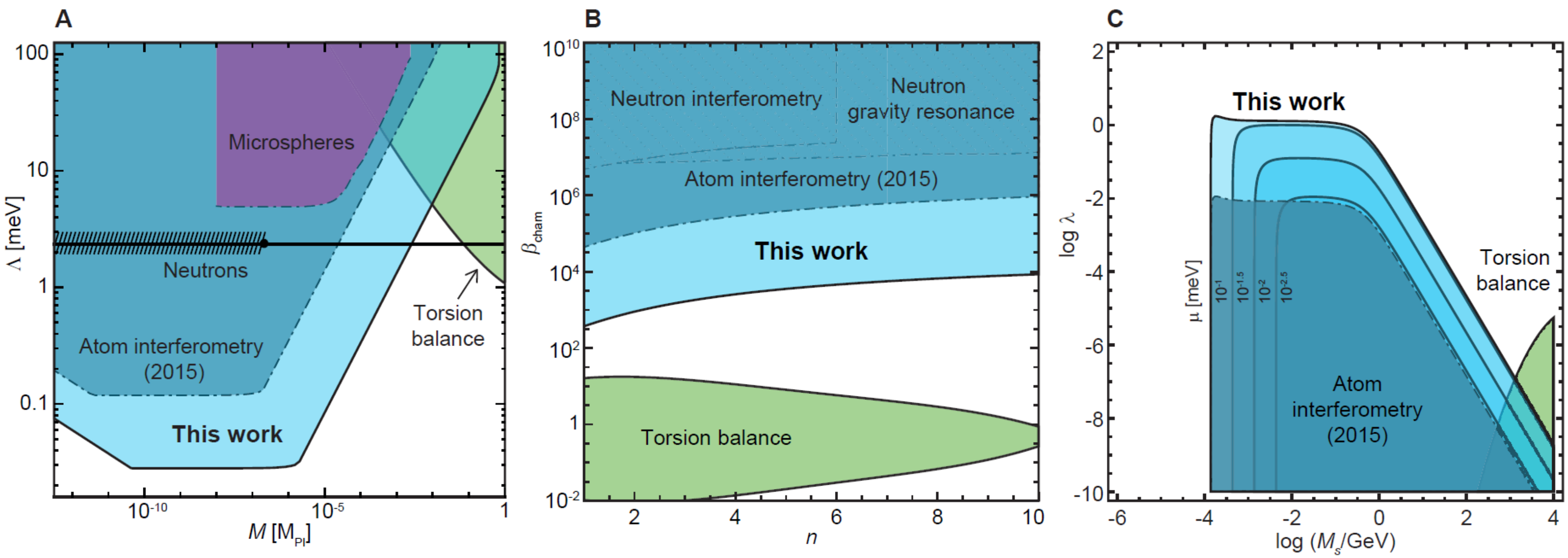


Stanford microsphere

Limits on anomalous forces

100x improvement on chameleon and symmetron bounds

→ $a_{anomaly} < 45\ \mathrm{nm/s^2}$ (95% confidence)



Take home message: a few orders of magnitude more will either discover or rule out these theories

Simple CW atom interferometer

"Ideal" atom interferometer:

- Simple
- Compact
- High sensitivity
- Continuous measurement

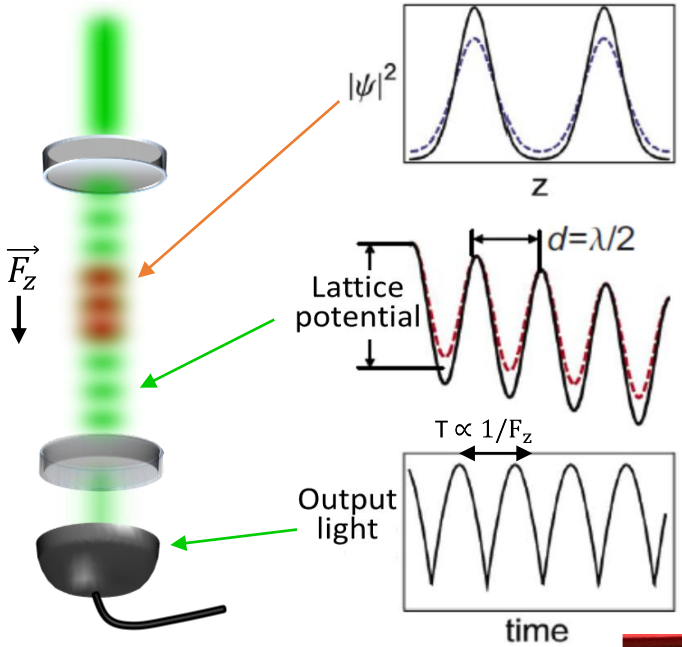
Goal: Turn on a laser and plug the output of a detector into an oscilloscope.

Enable measurement of AC signals

Principle: **Monitor atoms effect on a standing wave in an optical cavity**

Continuous trapped accelerometer

Collectively couple atomic “wave” to the optical cavity.

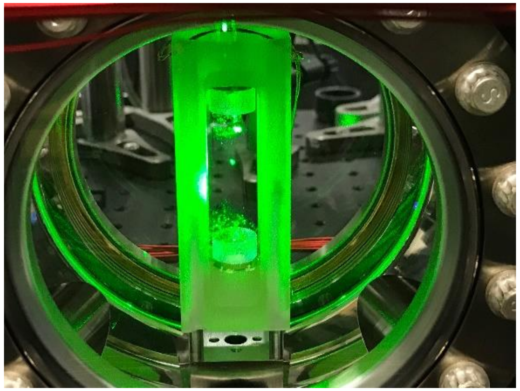


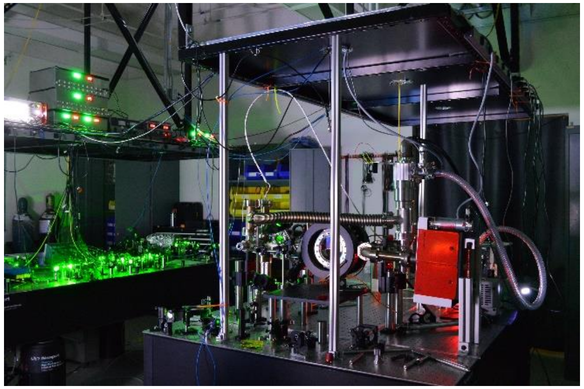
Atomic wavefunction modulates at Bloch frequency…

which couples to the intracavity lattice…

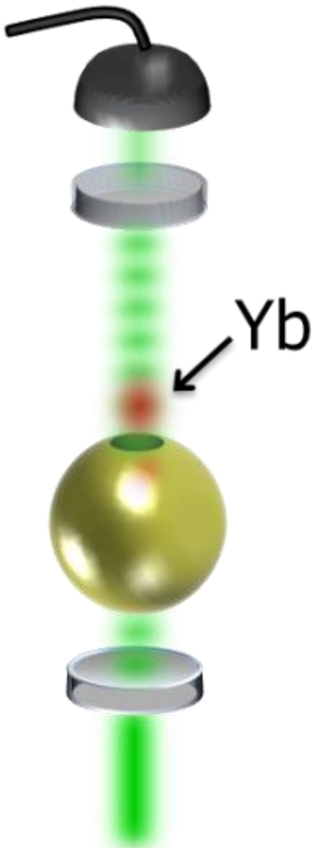
leading to modulation of the output light field.

Adapted from Peden et al.





Testing dark energy



Dark energy

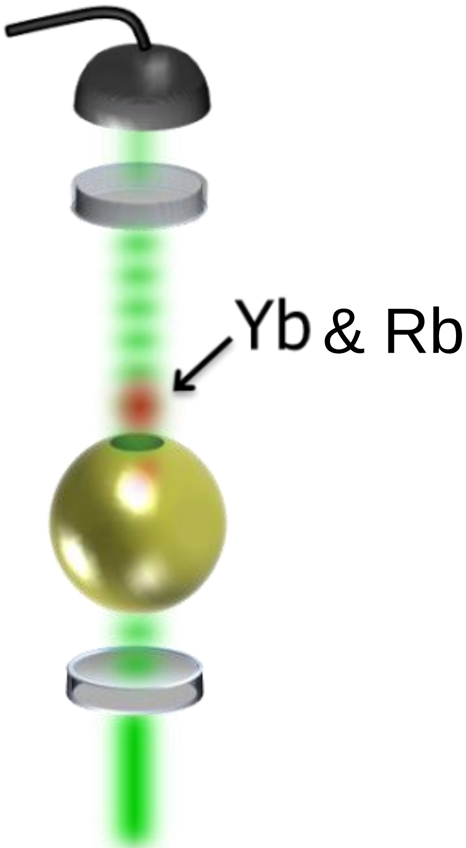
Projected $10^{-9}g$ sensitivity in one day of integration

$\Rightarrow$ Rule out chameleons and constrain other scalar theories

Model	Description
Chameleon	Mass couples to matter density
Symmetron	Coupling depends on matter density
f(R) gravity	Equivalent to chameleon theory
Preferred scale	Maps to chameleon theory

- Reduced vibration sensitivity / easier isolation
- Long coherence time

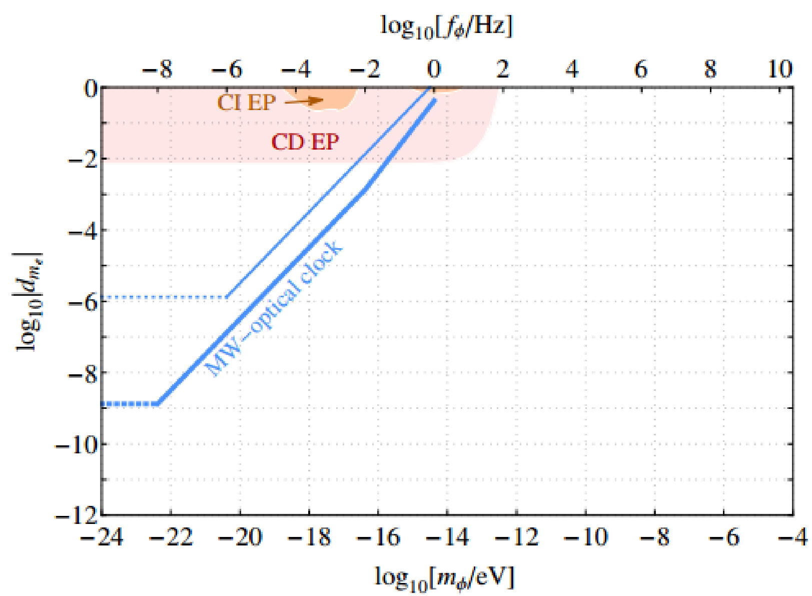
Testing dark energy / dark matter



Dark matter

Time varying dilatons oscillate at Compton frequency.

10 kHz detection bandwidth for an EP test could improve constraints



Tilburg Phys. Rev. D **91**, 015015

Outline

1. Introduction to precision AMO

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3. **HUNTER – sterile neutrino search**

Sterile neutrino

Strong scientific case for existence of ‘sterile’ neutrinos

- Particle physics: origin of mass of neutrinos not understood and little constraint on possible heavy masses

- Astrophysics: keV neutrinos attractive as a warm dark matter candidate

- Sensitive laboratory experiment = cost effective method for searching the relevant mass range (and also works even if not dark matter)

Exhaustive review on keV sterile neutrinos: arxiv:1602.04816

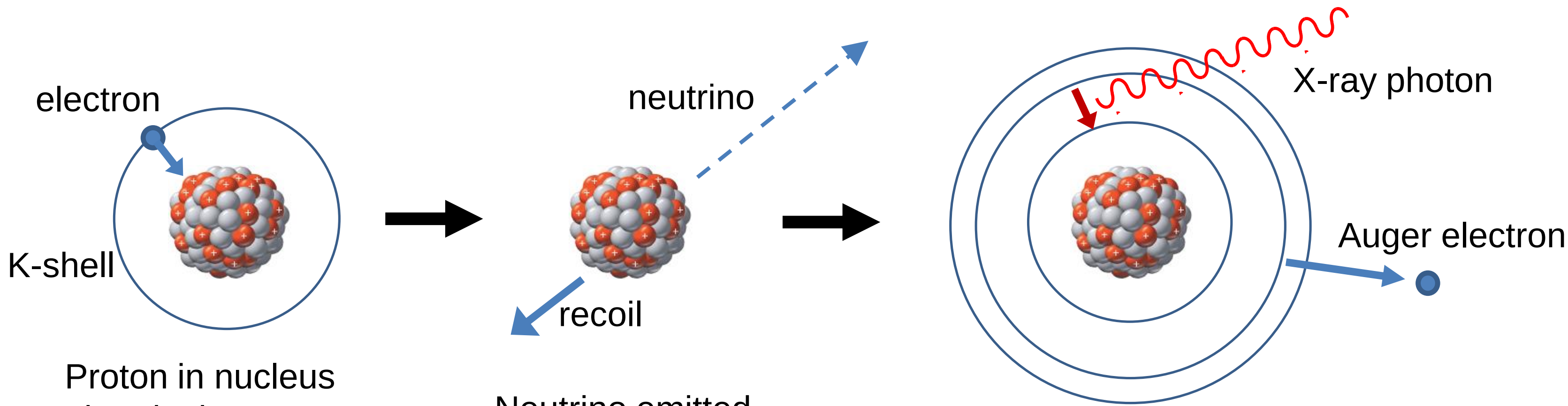
AMO Direct Detection

- Extremely rare processes difficult because # of atoms is small
  - Can't compete with WIMP detectors or colliders in event rate
  - But can detect rare isotopes with 10^{-16} precision
  - Rare decays also possible (e.g. sterile neutrinos with HUNTER)

- Typically sensitive to only a few parameters
  - No single device with range of an accelerator or telescope
  - But scale of experiments is much smaller in size and cost

HUNTER concept

<u>H</u>eavy **<u>U</u>**nseen **<u>N</u>**eutrino by **<u>T</u>**otal **<u>E</u>**nergy-momentum **<u>R</u>**econstruction

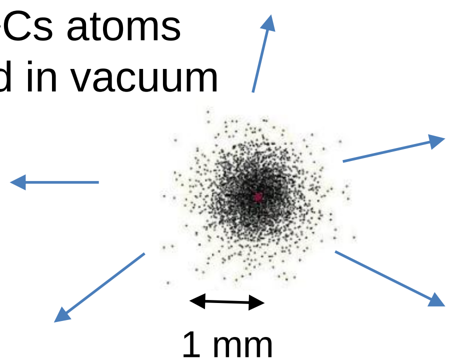


Proton in nucleus absorbs inner atomic electron

Neutrino emitted
Nucleus recoils

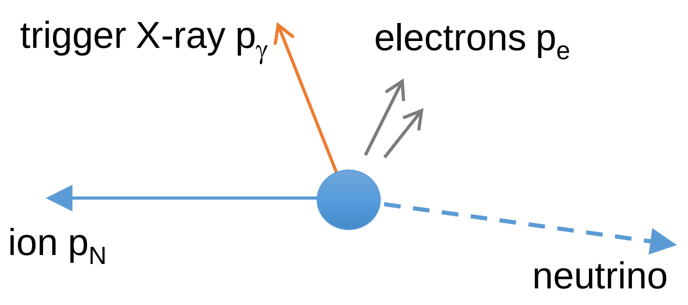
X-ray emitted
Auger electrons emitted

- Cloud of ^{131}Cs atoms suspended in vacuum



- Measure momentum of ion, X-ray, and electron to calculate neutrino momentum and mass
- **Detect rare keV-mass sterile neutrinos up to Q value of decay (350 keV for ^{131}Cs)**
- **Fraction of events gives relative coupling**

HUNTER concept

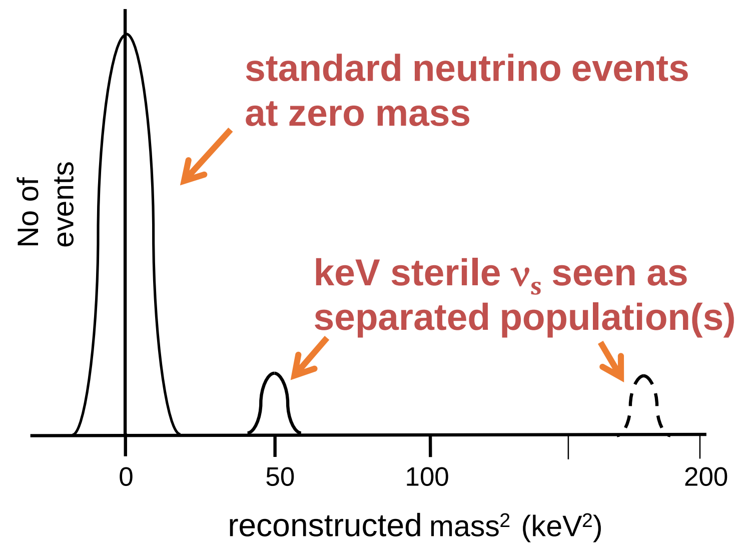


Mass reconstruction formula:

$$m_\nu^2 = [Q - E_e - E_\gamma - E_N]^2 \quad - \quad [\,\mathbf{p}_\gamma + \mathbf{p}_e + \mathbf{p}_N]^2$$

missing energy   missing momentum

Reconstructed mass spectra:



- Only known method of giving a separated population of sterile neutrino events
- Can find sterile neutrinos independently of whether they form all or part of the dark matter

Radioactive isotope choice

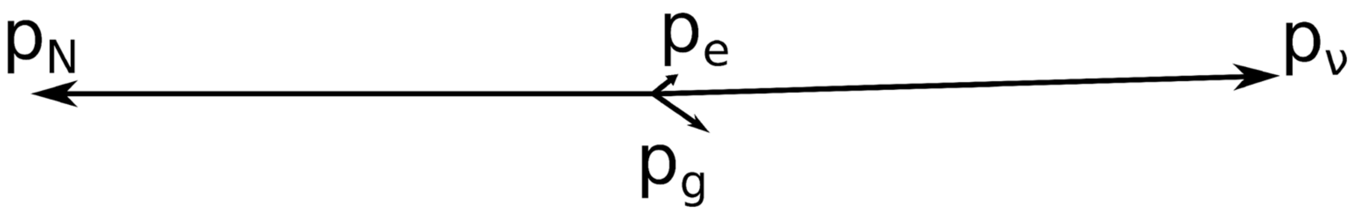
Desired properties of nuclear decay:

- Electron capture - low energy visible products and E,**p** by time-of-flight (TOF)
- Prefer alkali metal for laser trapping and cooling (need <100 uK to define initial momentum)
- $t_{1/2}$> 1 day (no accelerator beam)
- Isotope availability (medical)

From >60 possible nuclides to essentially only one meets requirements:

^{131}Cs

Kinematics



p_N , p_ν ~ .35 MeV/c v_N ~ 800 m/s

p_e ~ .01 MeV/c, p_g ~ .03 MeV/c

$m_\nu^2 = [Q - E_e - E_g - E_N]^2 - [\mathbf{p}_g + \mathbf{p}_e + \mathbf{p}_N]^2$

Ignore e and x-ray, calculate effect of m_ν on p_N:

$p^2/2m_N + (p^2+m_\nu^2)^{1/2} - m_\nu = Q$

Accurate first-order solution: $p= Q(1 - m_\nu^2/2Q^2)$

For m_ν =10 keV, effect is .04% of p !

This sets the scale of measurement accuracy needed.

Note: this δp is equal to the thermal momentum p_{th} at 150 μK.

Trapped atoms must be colder than this by factor 3 or more.

Reaction microscope

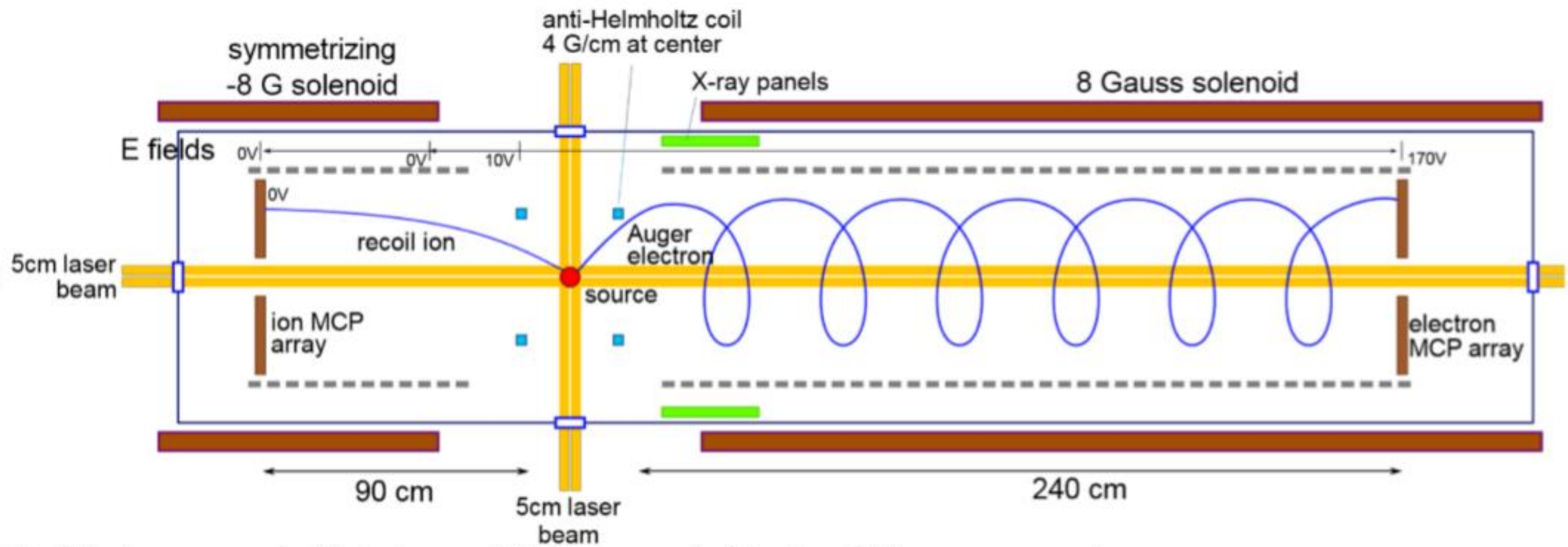
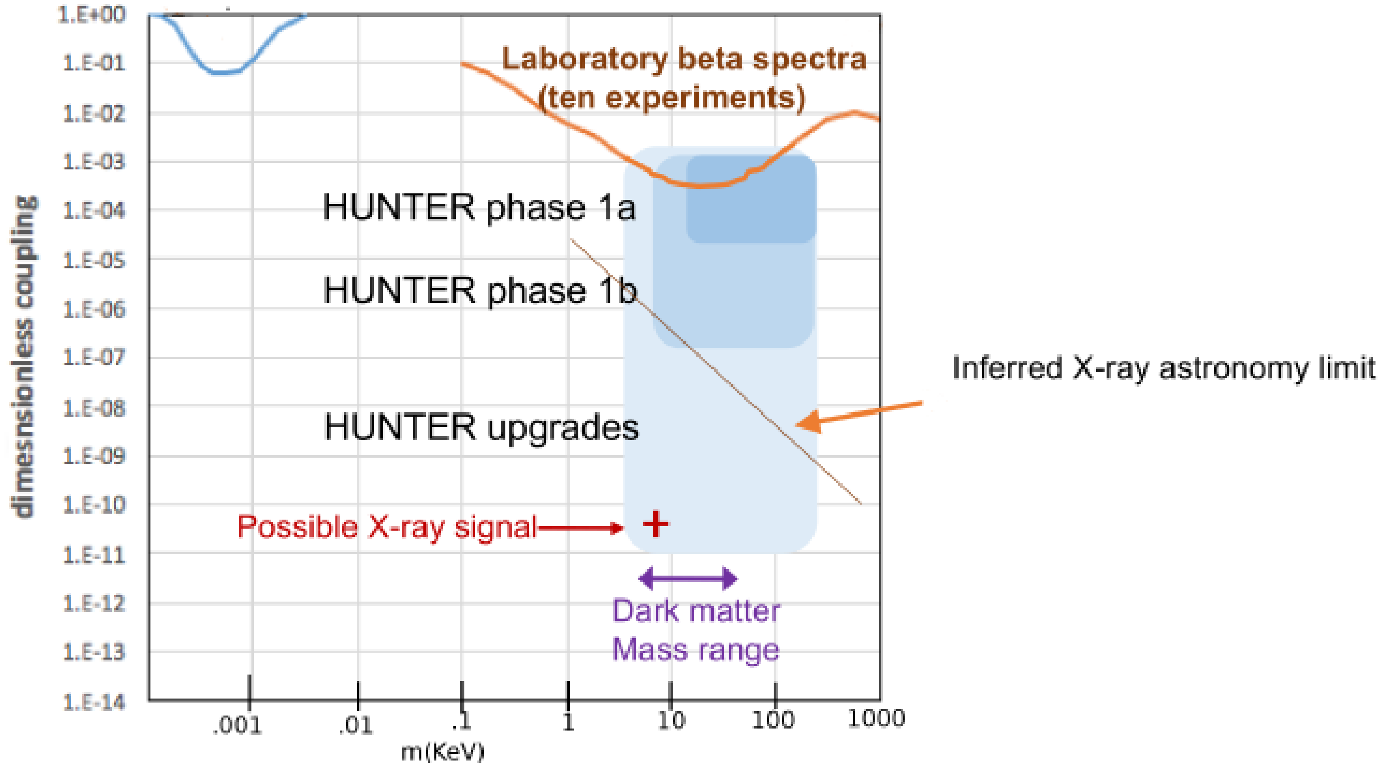


Fig 3.5: Arrangement of detectors and MOT source inside ultra-high vacuum vessel.

- Trigger time-of-flight (TOF) on x-ray detection
- Momenta from TOF and spatial resolution of MCP’s
- Spectrometer concept first developed for chemical reaction studies
- Recoil ions collected up to 4π and steered onto MCP's by axial electric field
- Electrons collected from 6% of 4π into confining axial magnetic field (solenoid)
- Momentum accuracy required is achieved by multiple atomic physics groups

Phasing and limits



Later phases would include acceptance and trap population upgrades to progressively improve limits.

Summary

Precision AMO physics can provide some complementary measurements in fundamental physics:

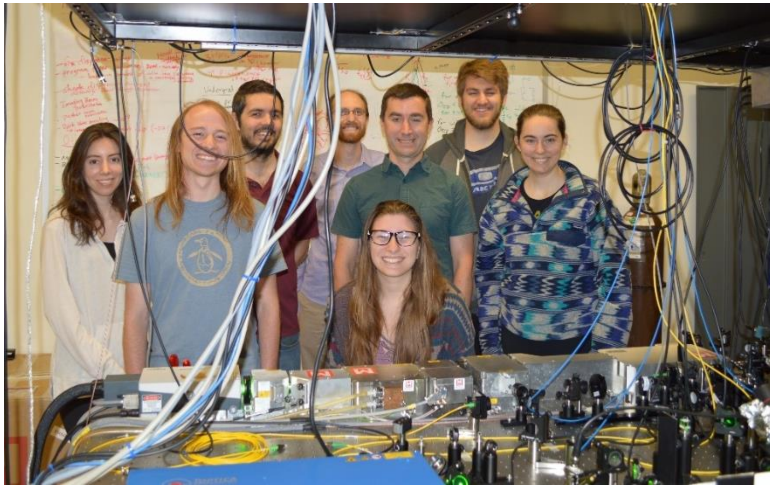
Keys:

- Clean control of quantum state
- Typically look for background free signal
  - New couplings lead to new properties
- High precision tools available

Very strong and increasing support from AMO community for precision measurement of physics beyond Standard Model.

Suggestions from theorists highly welcome!

Thanks



Collaborators

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Yvette de Sereville

Postdocs

Robert Niederriter
Adam West

The future

Physics	Model	Description	AMO method
Dark Energy	Chameleon	Mass couples to matter density	Interferometry
	Symmetron	Coupling depends on matter density	“”
	f(R) gravity	Equivalent to chameleon theory	“”
	Preferred scale	Maps to chameleon theory	“”
Dark Matter	Varying dilaton	Time varying EP	Interferometry
	Topological DM	Time dependent anomalous forces	Interferometry Magnetometry
	Axions	Spin dependent force	Magnetometry
Matter / Antimatter	EDMs	CP violating electric dipole moment	Atoms, molecules, particles
	Antihydrogen	Test of free fall	Various
Fundamental constants	Fine structure	Time variation	Ions, optical clocks, atoms
	m_e/m_p	Time variation	Molecules
Gravity	Charged particles	Test of free fall	Ions, electrons
	Grav. waves		Interferometry
	EP Tests		Interferometry

AMO is taking first steps to add new tools for testing theories of cosmological interest