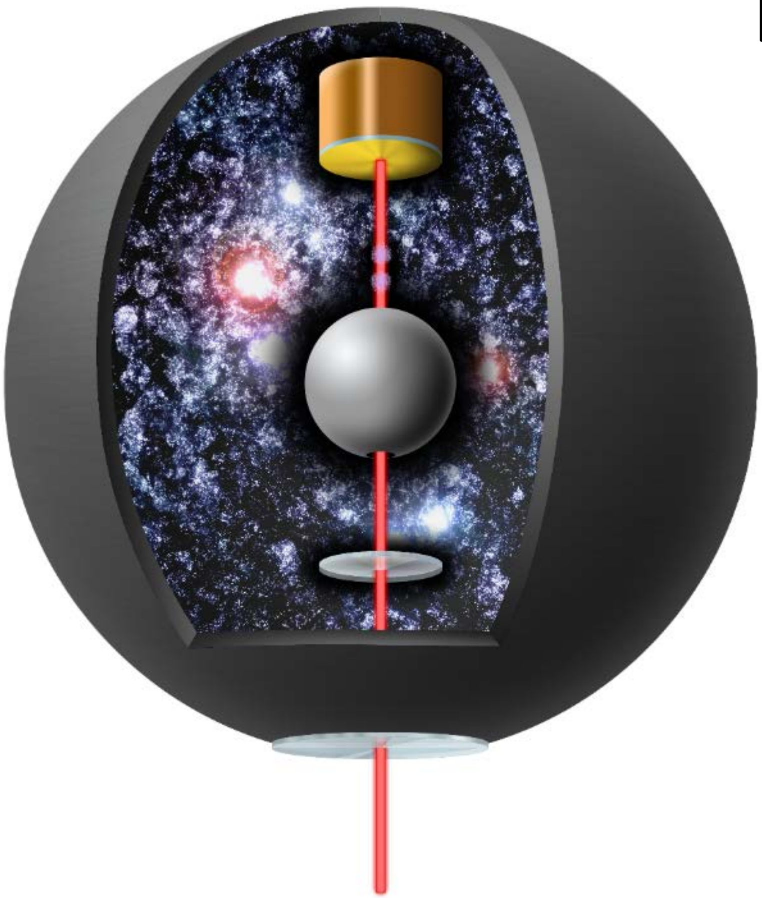
UCLA



Fundamental physics with matter wave interferometry*

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W. M. KECK FOUNDATION

Office of Naval Research Science & Technology ONR

UNIVERSITY OF CALIFORNIA Office of the President

Outline

1. Introduction to matter wave interferometry
2. Berkeley dark energy search
3. UCLA Bloch oscillation accelerometer
4. HUNTER – sterile neutrino search

de Broglie waves

It all starts with a Ph.D. thesis!
(de Broglie, 1924)

$$E = mc^2 = \hbar\omega_C$$

Lorentz invariance requires

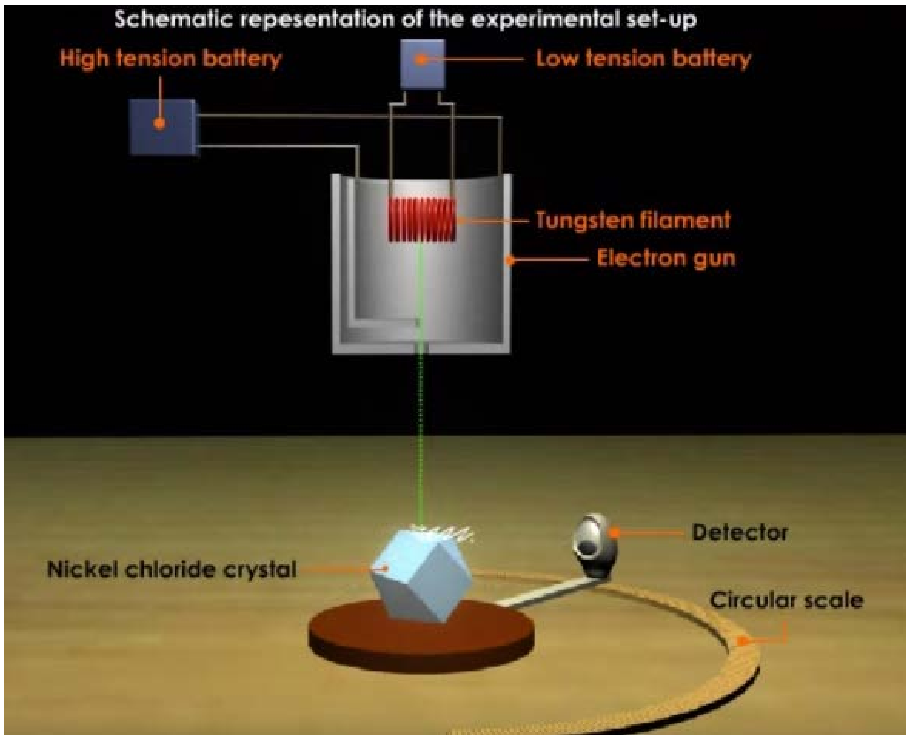
$$\Psi \sim \exp\left(-i\omega_C\tau\right)$$

- Holds in all of QM and QFT

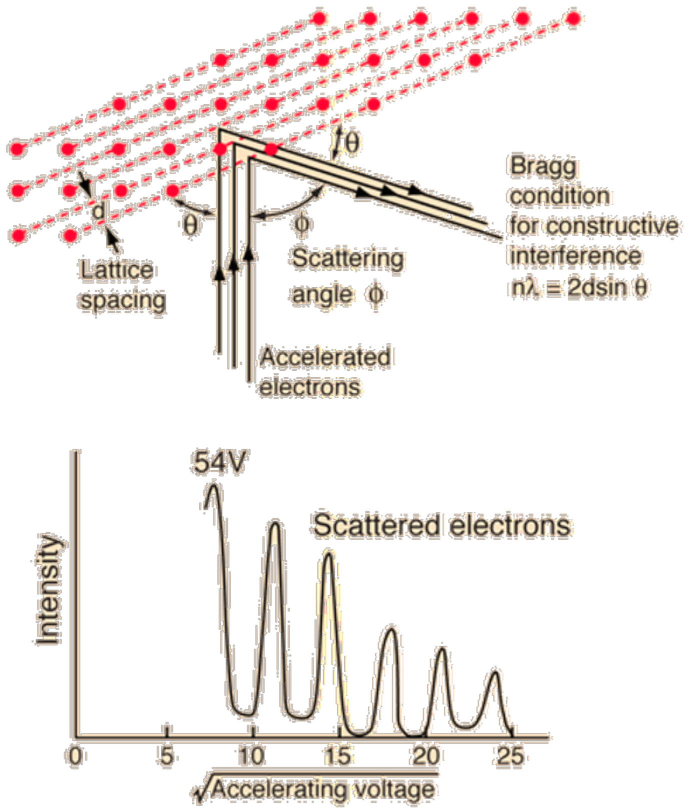
$$\lambda_{dB} = \frac{h}{mv}$$

From electrons...

1927 Davisson Germer experiment

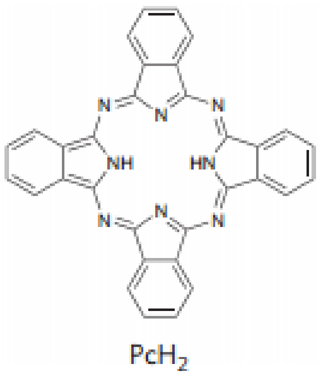


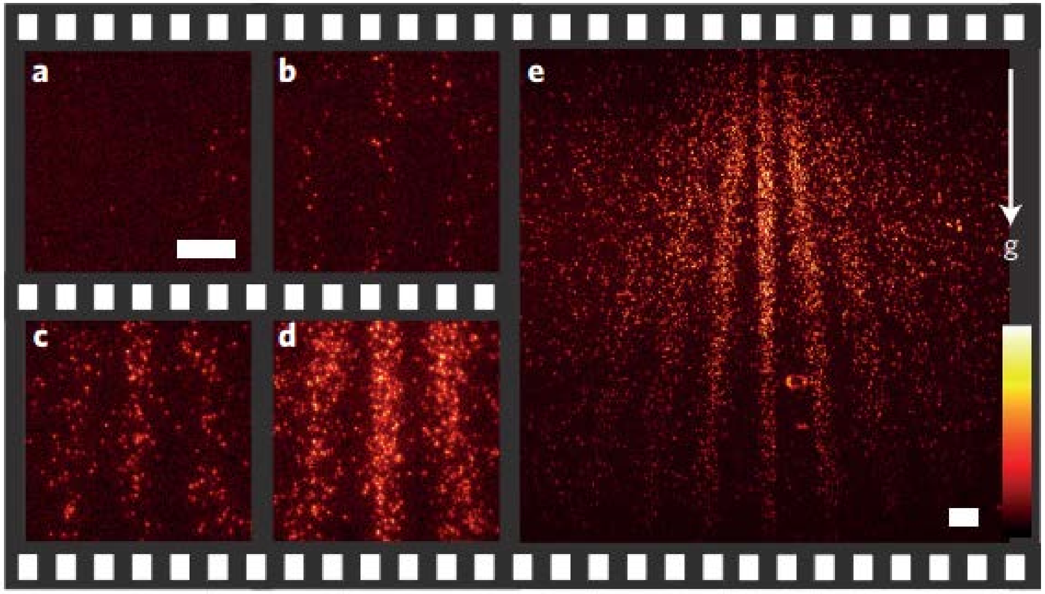
Credit: Tutorvista.com

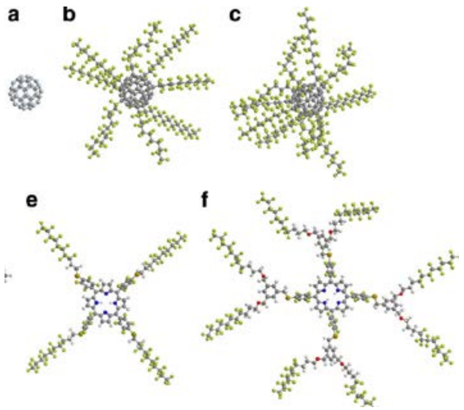


Davisson, C. J., "Are Electrons Waves?," Franklin Institute Journal 205, 597 (1928)

...to large molecules





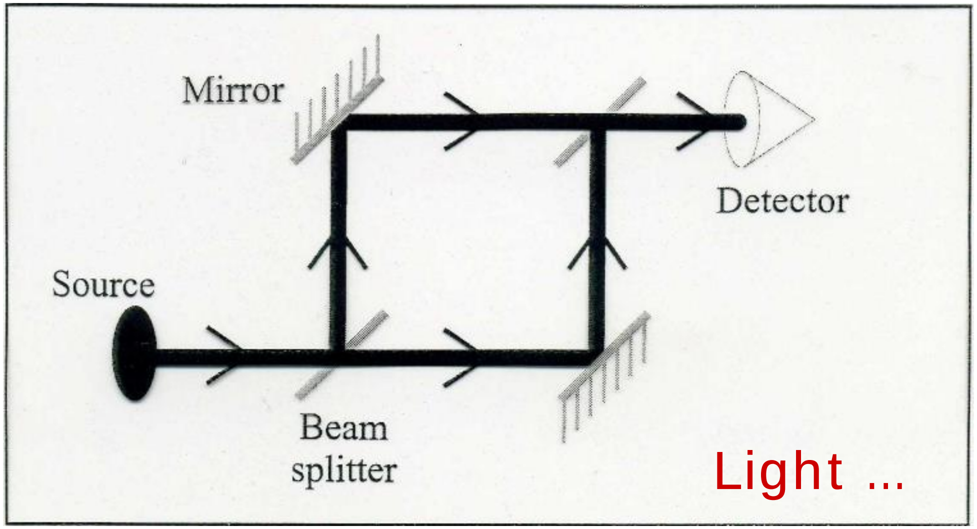


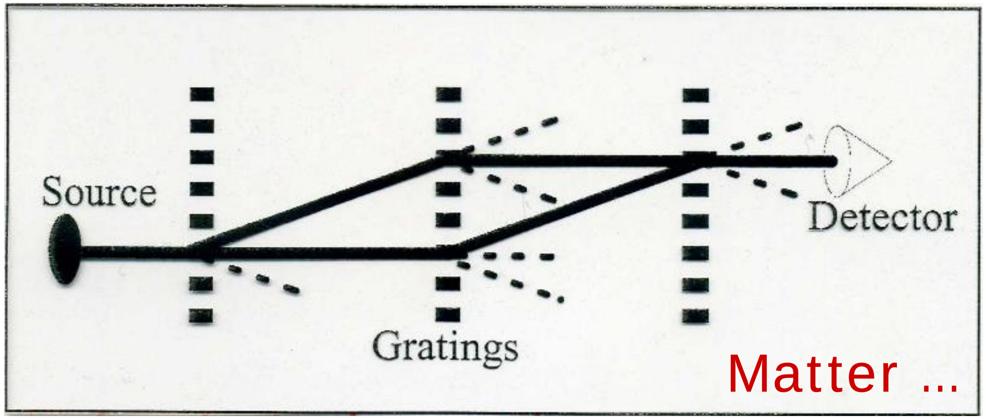
Gerlich et al., *Nat.Comm.* **2**, 263 (2011)

Buckyballs and molecules with thousands of atoms interfered by Zeilinger & Arndt groups in Vienna

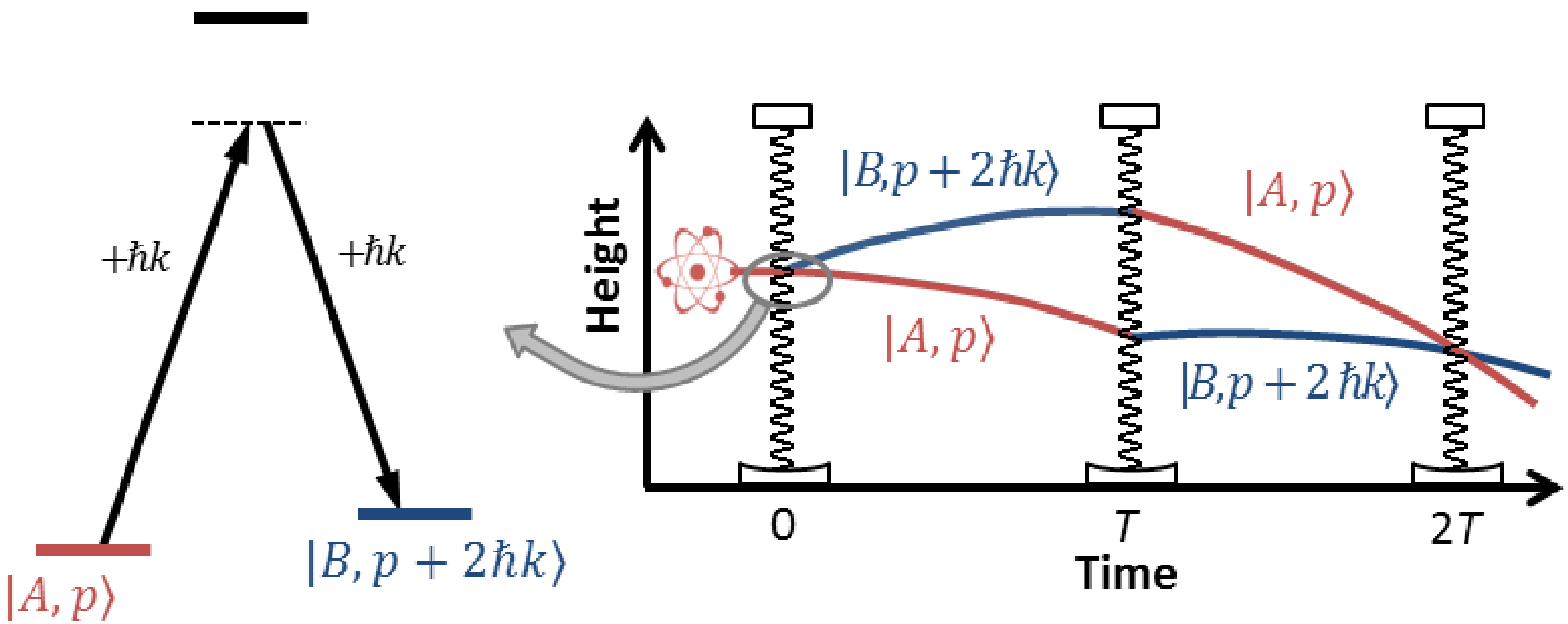
Working towards viruses and bacteria

Modern matter interferometry





Light pulse atom interferometer



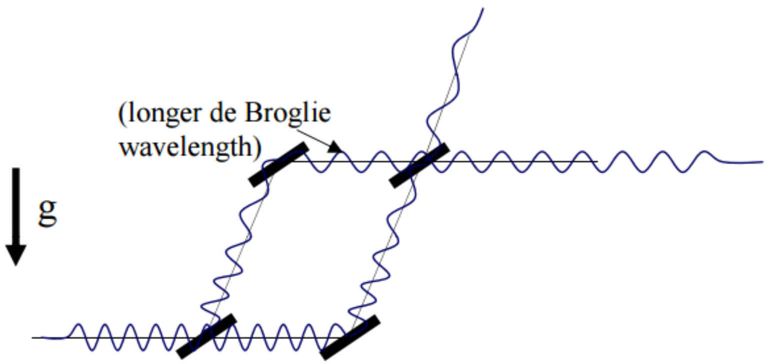
$$\Delta\varphi = -\frac{1}{\hbar}\oint L\, d\tau + \Delta\varphi_{\text{laser}}$$

$$= \vec{k} \cdot \vec{g} T^2$$

Measuring all accelerations

Gravity/Accelerations

As atom climbs gravitational potential, velocity decreases and wavelength increases



Rotations

Sagnac effect for de Broglie waves

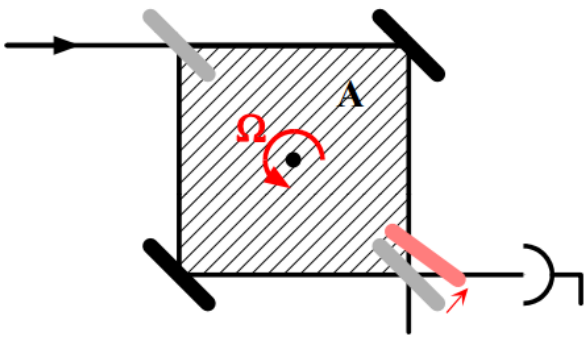


Figure credit: Kasevich

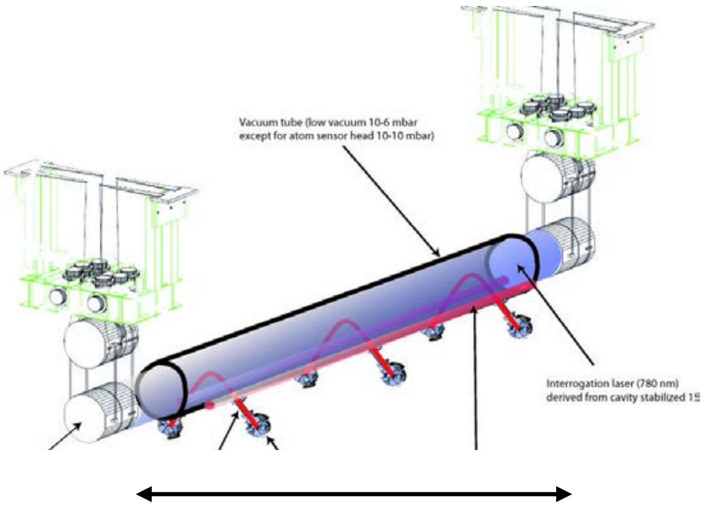
Demonstrated sensitivity of atom interferometers

- Accelerations: <ppb of g!
- Rotations: <nrad/s !

Field uses:

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

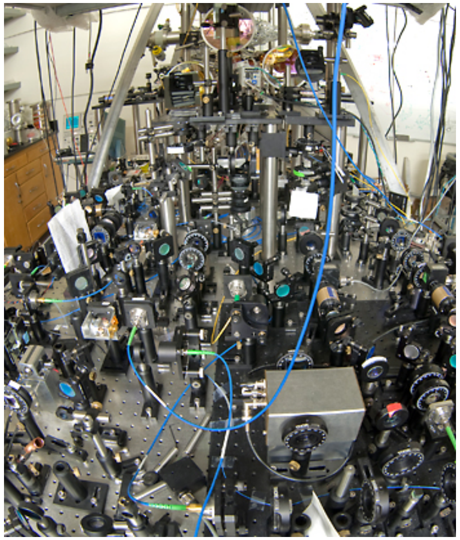
Applications



300 m

Gravity wave detection
MIGA collaboration

Tests of general relativity
Stanford 10 meter atomic fountain



Fine structure constant
Measurement
3m atomic fountain
Berkeley

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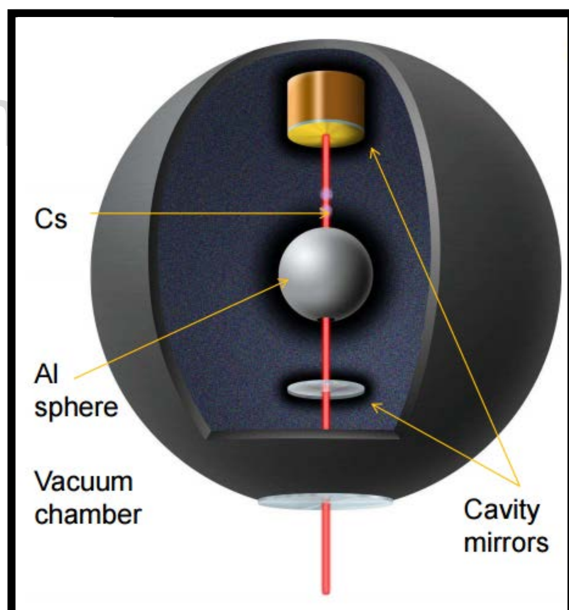
2. **Berkeley dark energy search**

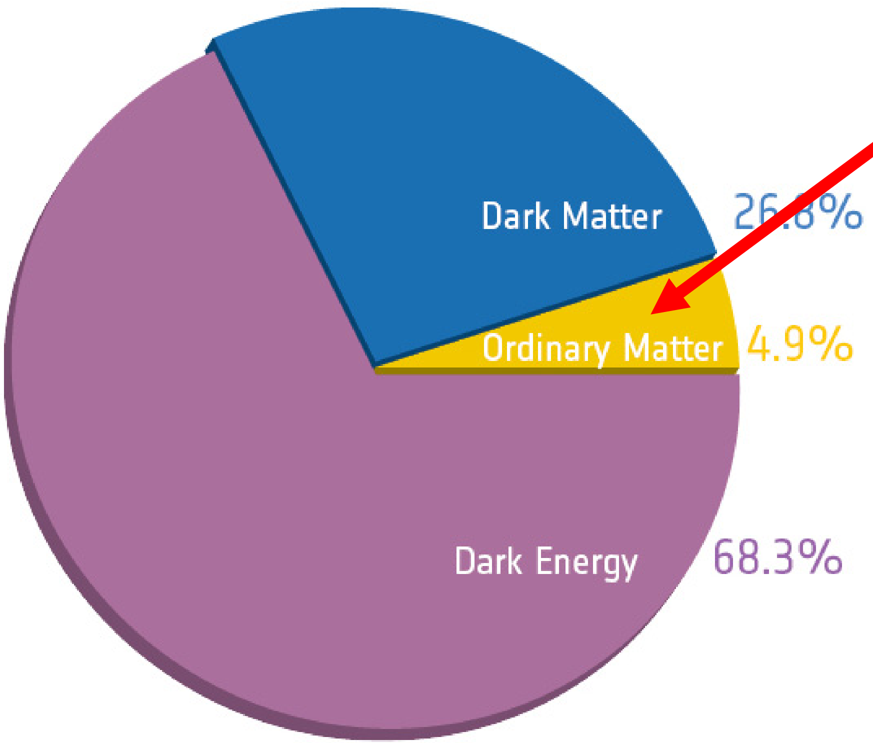
3. UCLA Bloch elerometer

4. HUNTER – search



Standard Model is incomplete

Contents of the Universe



ESA/Planck

We know this part very well!!
Decades of testing and no definitive violations of SM.

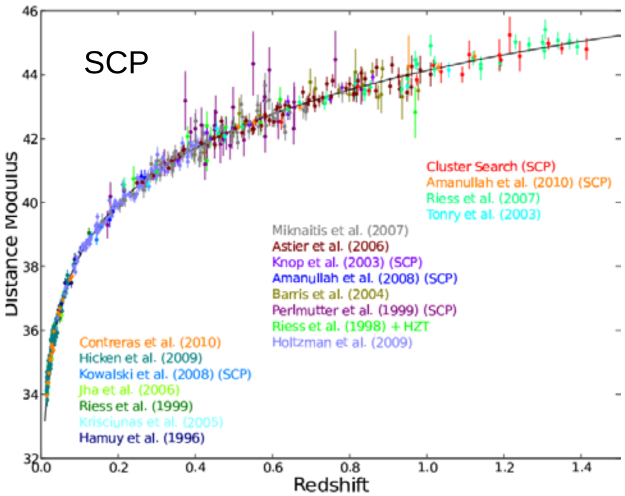
But what is the rest?

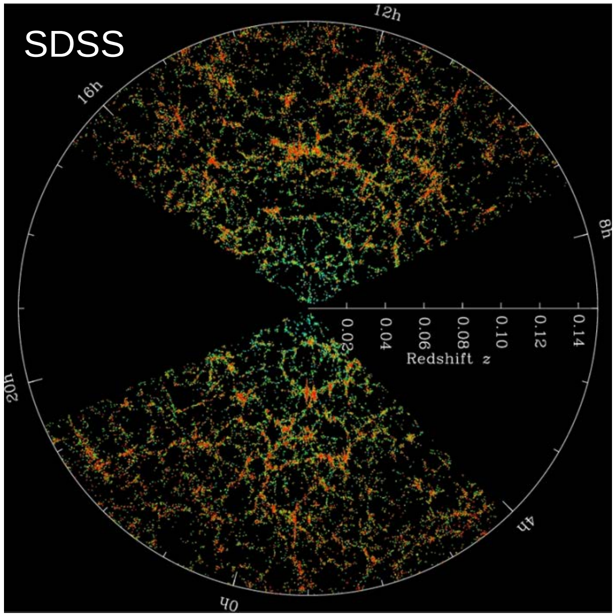
What is dark energy?

What is dark matter?

Why matter and not antimatter?

What can astronomers learn?



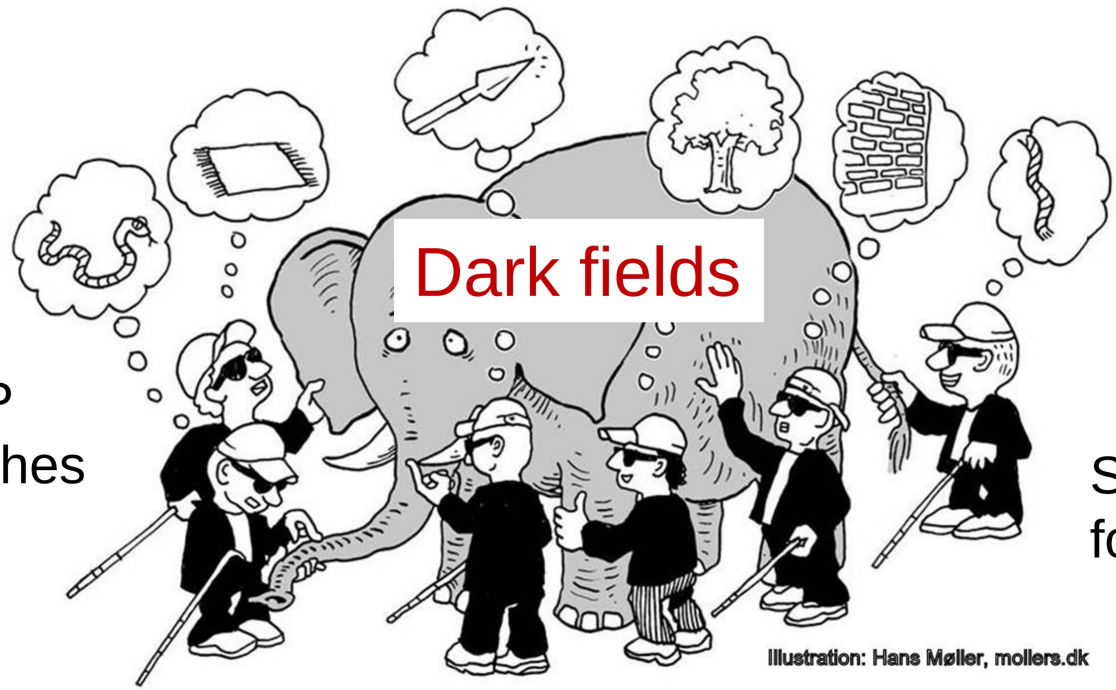


- Dark energy density, 4 hydrogen / m^3 or an energy scale of 2.4 meV
- Equation of state for dark energy
- Time evolution of dark energy?

Very large-scale experiments for measuring single properties of dark energy.

In the dark…

AMO observations can help test complementary properties



WIMP searches

Structure formation

Accelerators

AMO

CMB

Supernova

Scalar dark energy

How can we detect scalar fields in the laboratory?

Measuring local expansion of the universe is beyond reach.

…but **new fields** can lead to **new forces** between objects.

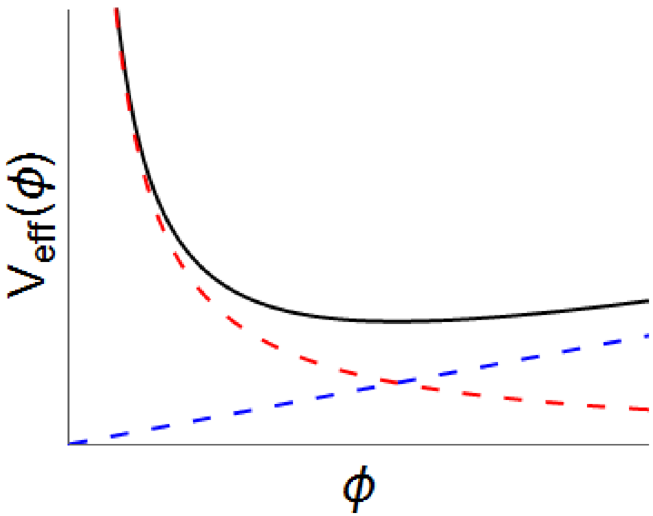
Quintessence + coupling

Quintessence: dark energy = scalar field (Ratra, Peebles 1988!)

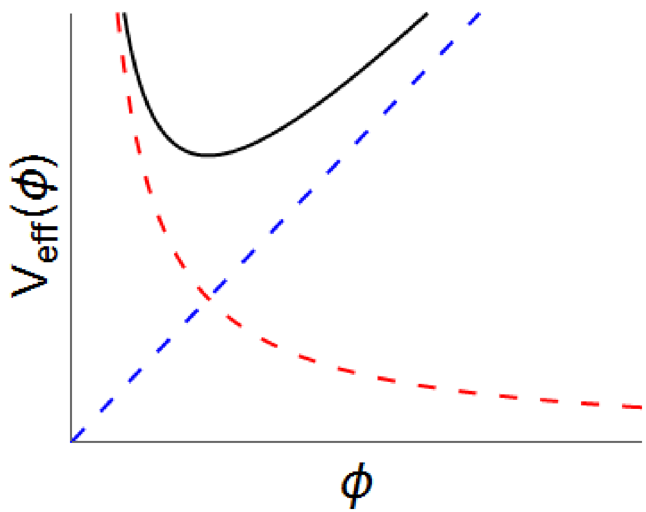
$$V_{\mathrm{eff}} = \Lambda^4 + \frac{\Lambda^{4+n}}{\phi^n} + \frac{\phi}{M}\rho$$

“Textbook” quintessence

Coupling to local density



Low density ρ
vacuum



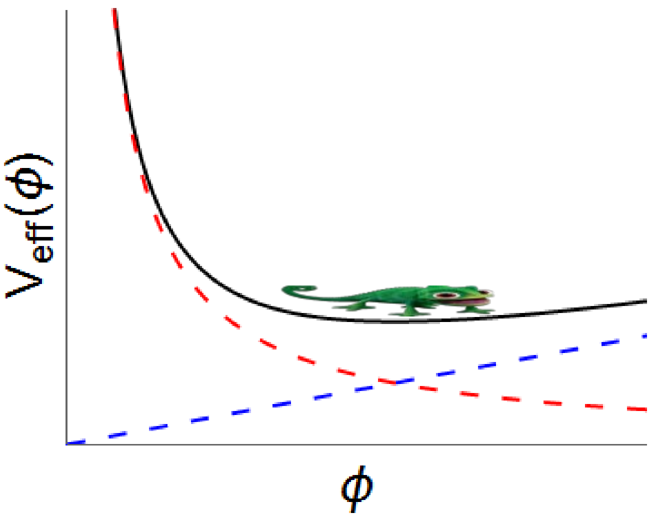
High density ρ
normal matter

2 parameters:
Λ and M

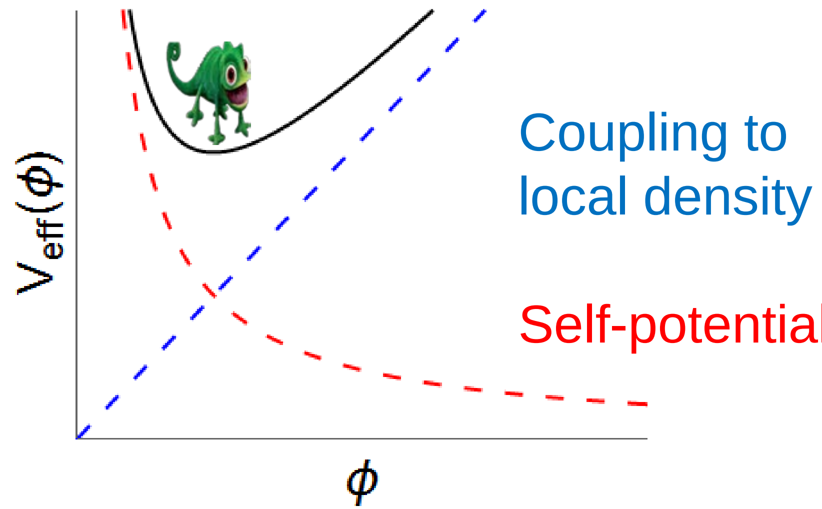
Chameleon mechanism

Khoury, Weltman
Phys. Rev. D **69**, 044026

Curvature ⇒ Mass ⇒ 1 / range



In vacuum ⇒ long range



Near normal matter ⇒ short range

Screened force

Newtonian force

New chameleon force

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

$$\lambda_i(\Lambda, M, \rho_i, r_i) = \frac{Shell\ mass}{Test\ mass}$$

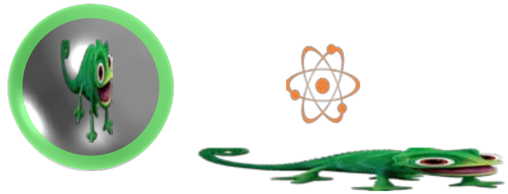
Can be extremely small ($\ll 10^{-20}$) for macroscopic objects

$$M < M_{Pl}$$

Unscreened force can be much stronger than gravity

Atoms evade screening

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



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

Burrage, Copeland, Hinds JCAP03(2015)042

Generic predictions of forces

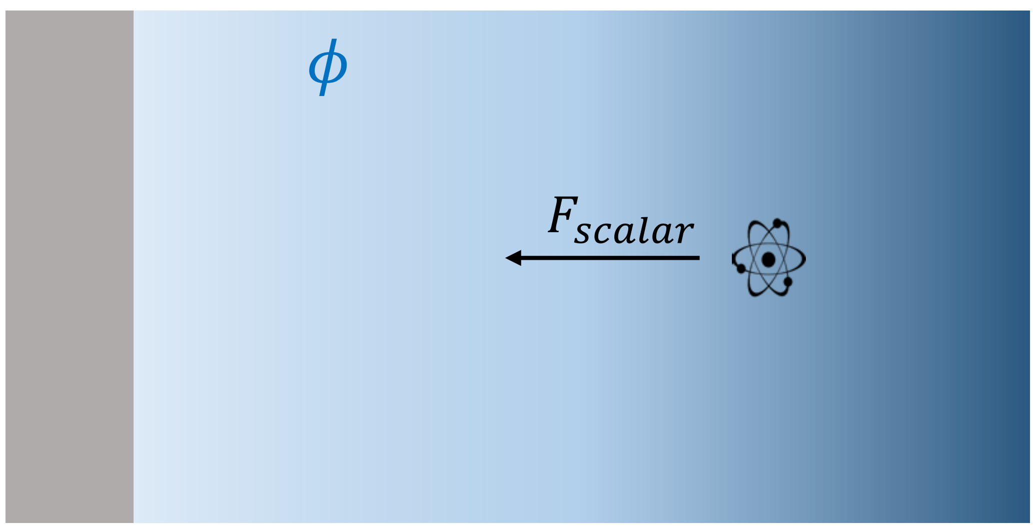
Chameleons are one example, but in general scalar fields with couplings to matter can create screened forces:

Coupling

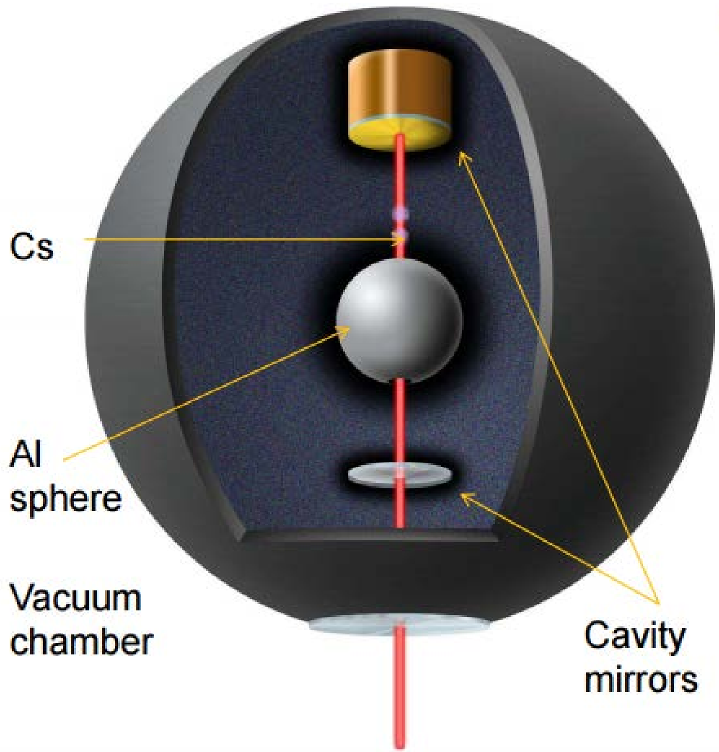
Scalar gradient

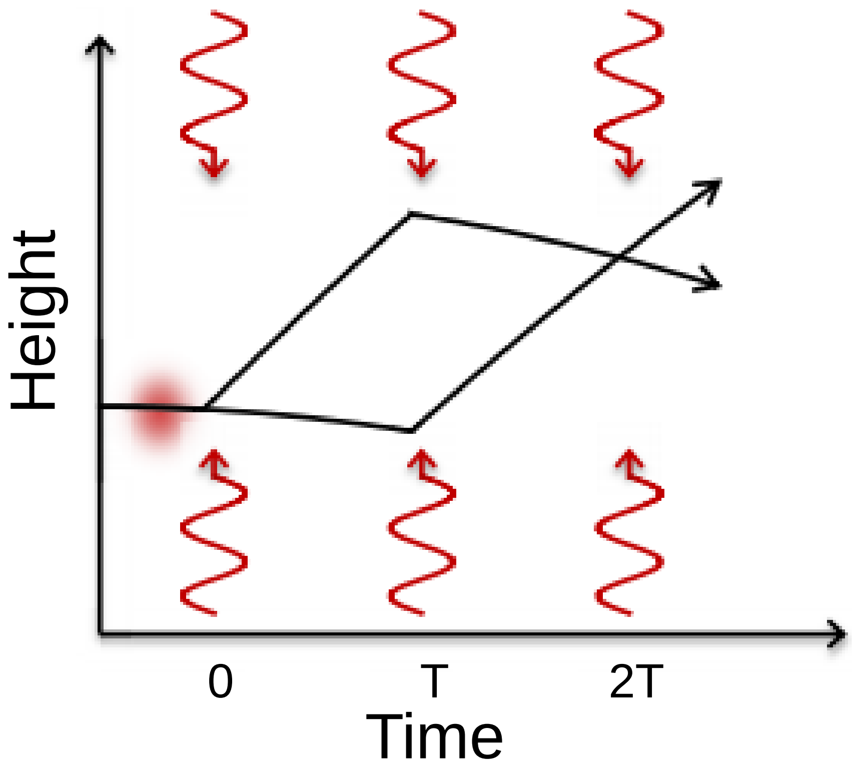
$$a_{scalar} = \frac{GM}{r^2} - \frac{\beta(\phi)}{M_{pl}} \lambda_a \nabla\phi$$

Screening



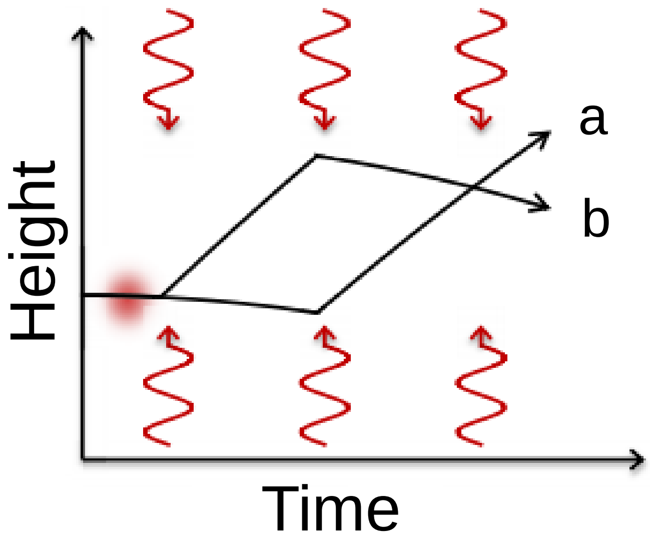
Berkeley dark energy search

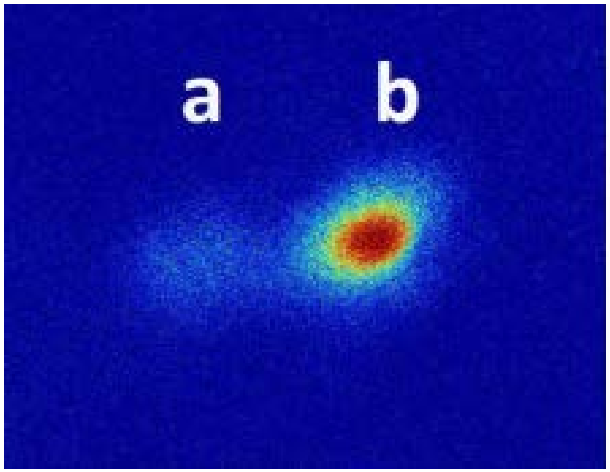




- Metal sphere creates gradient in scalar field
- Atoms act as test masses for force sensing

Detection



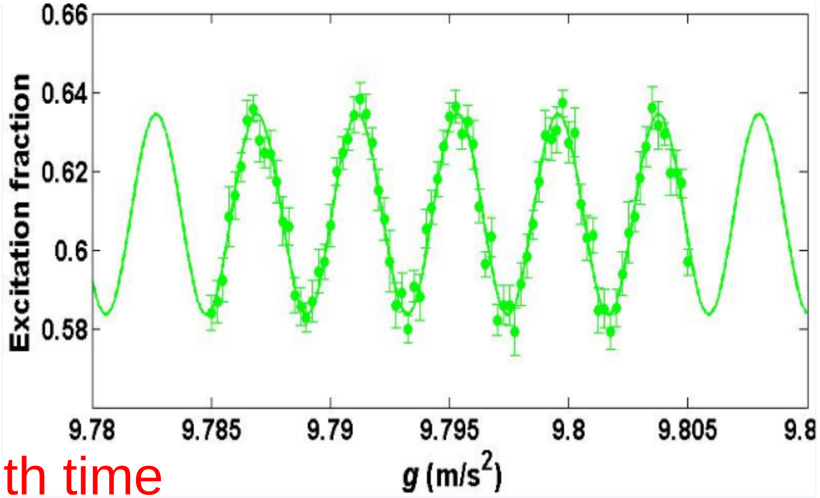


Probability

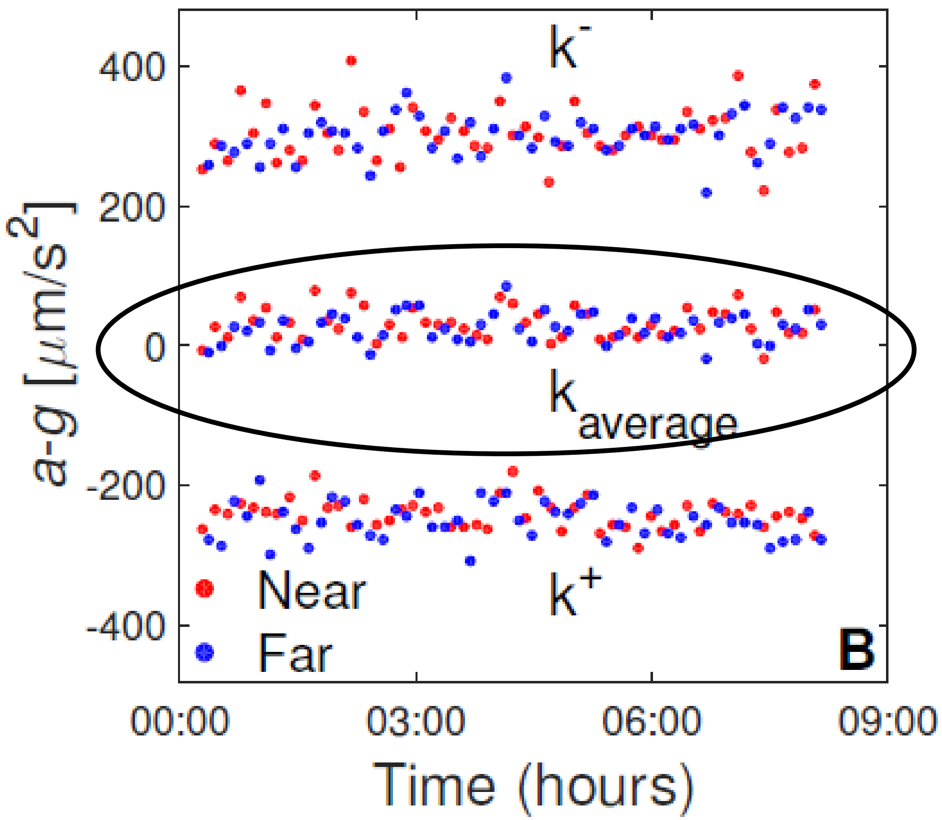
$$\propto \mathrm{Cos}^2(\vec{k}\cdot\vec{a}\,T^2)$$

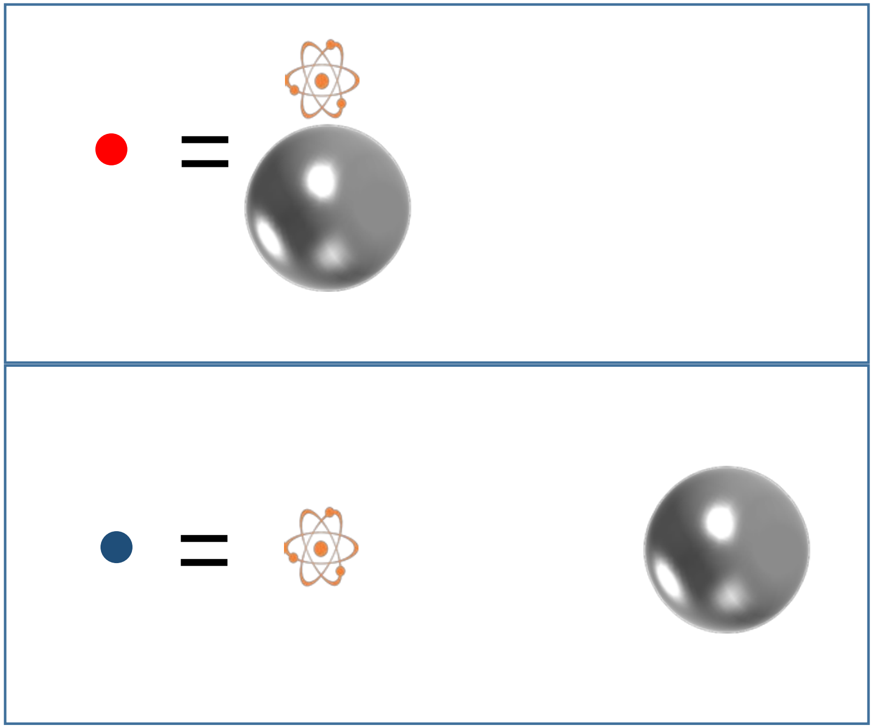
Sensitive to accelerations → force sensor

Scales with time near source mass



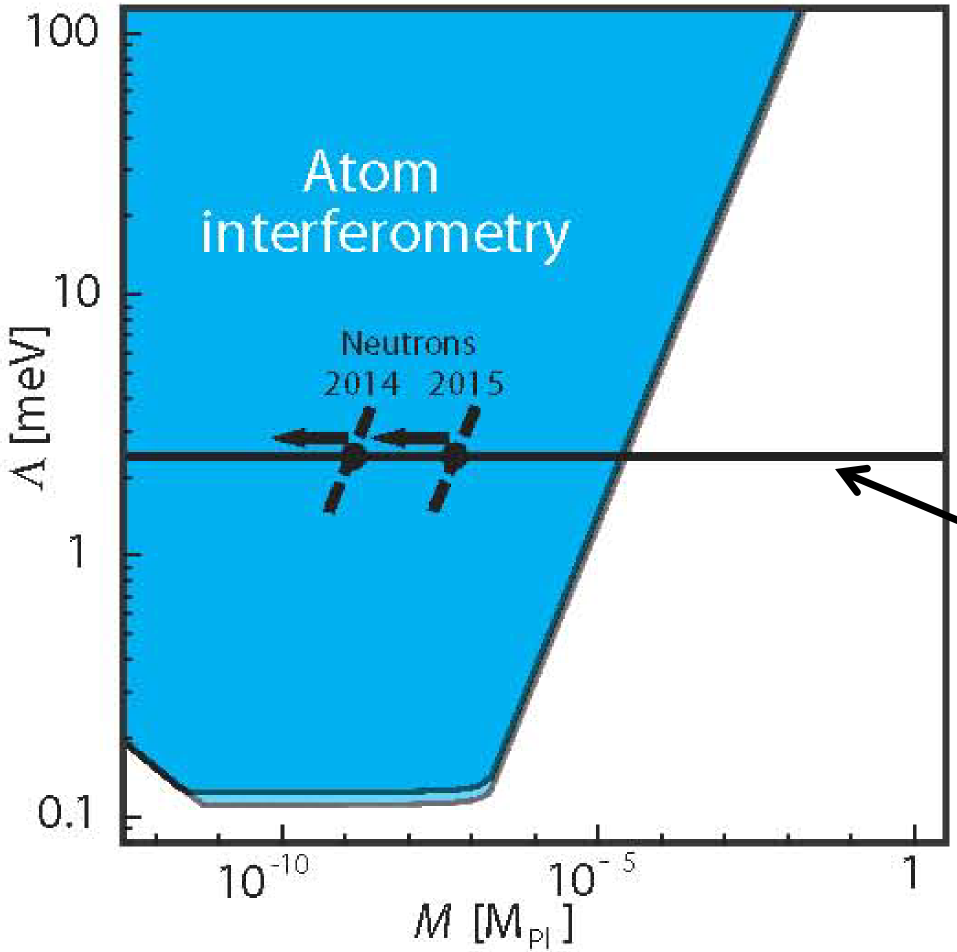
Results





Search for an anomalous acceleration when atoms are near the source

Dark energy limits



$$V_{\text{eff}} = \Lambda^4 + \frac{\Lambda^{4+n}}{\phi^n} + \frac{\phi}{M}\rho$$

Quintessence potential

Coupling to local density

Cosmological dark energy
$\Lambda = 2.4$ meV

$$M > 2.3 \times 10^{-5} M_{Pl}$$

$$\Delta a = 2.3 \pm 3.3\ \mu\text{m/s}^2$$

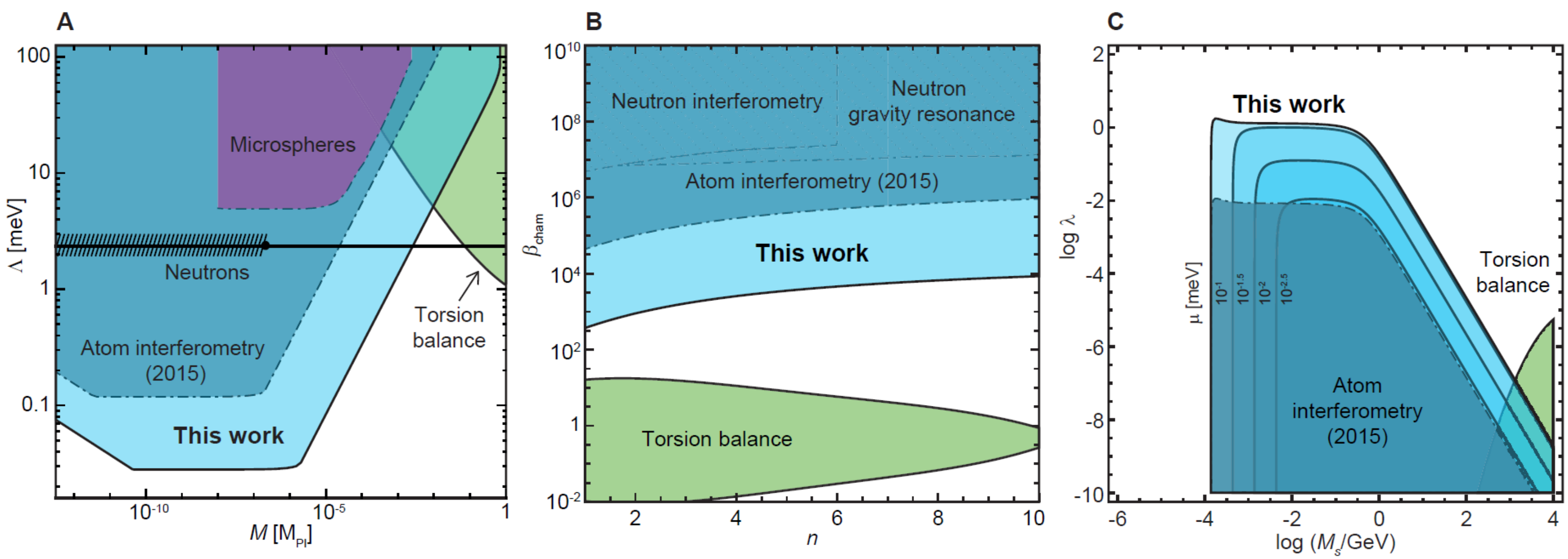
Hamilton et al., Science 21, 849-851 (2015)

Latest results

After a year of hard work and improvements

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

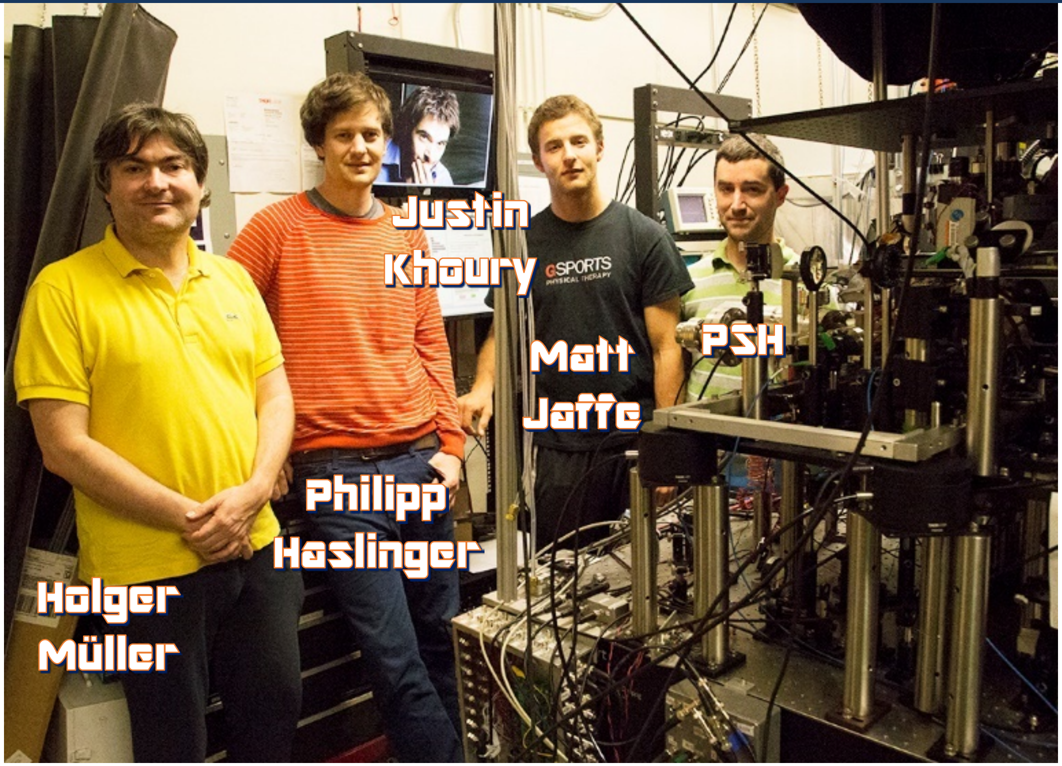
100x improvement on chameleon and symmetron bounds



Jaffe et al., Nature Physics (2017)

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

Acknowledgements



Dark energy search

Matt Jaffe Philipp Haslinger Victoria Xu

Benjamin Elder Justin Khoury Amol Upadhye

PI : Holger Müller

How do we go further?

The small size of the Berkeley experiment limits its absolute sensitivity:

Berkeley ~10^{-6} g / √Hz

Gravimeters ~10^{-9} g / √Hz

Stanford 10m fountain ~10^{-12} g

…other experiments take advantage of free fall distances at the meter scale.

Two possibilities:
- Trapped atom interferometry
- Microgravity such as CAL / BEC CAL

Outline

1. Intro to matter wave interferometry

2. Berkeley dark energy search

3. **UCLA Bloch oscillation accelerometer**

4. HUNTER – sterile neutrino search

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.

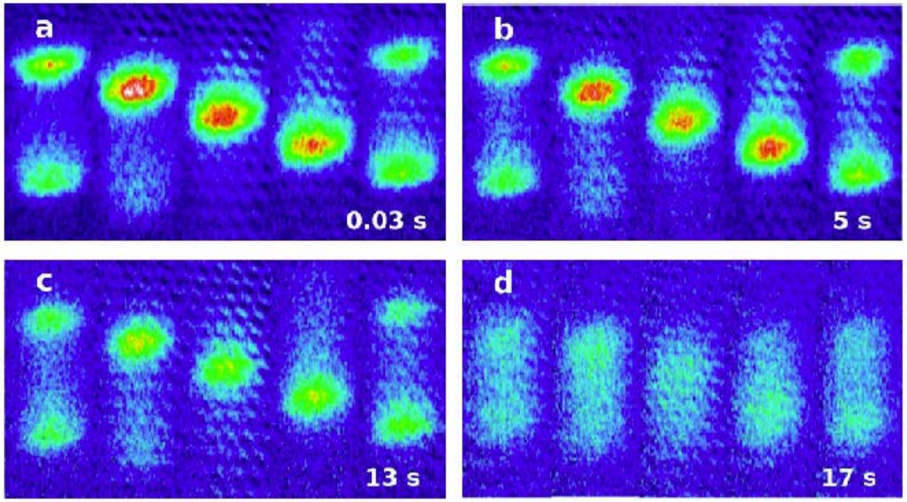
Enable measurement of AC signals

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

Bloch oscillations

In quantum mechanics a force on a particle in a periodic potential leads to changes in momentum called Bloch oscillations.

$$\omega_{Bloch} = \left(F \times \frac{\lambda}{2}\right)/\hbar \quad \text{(~kHz scale)}$$



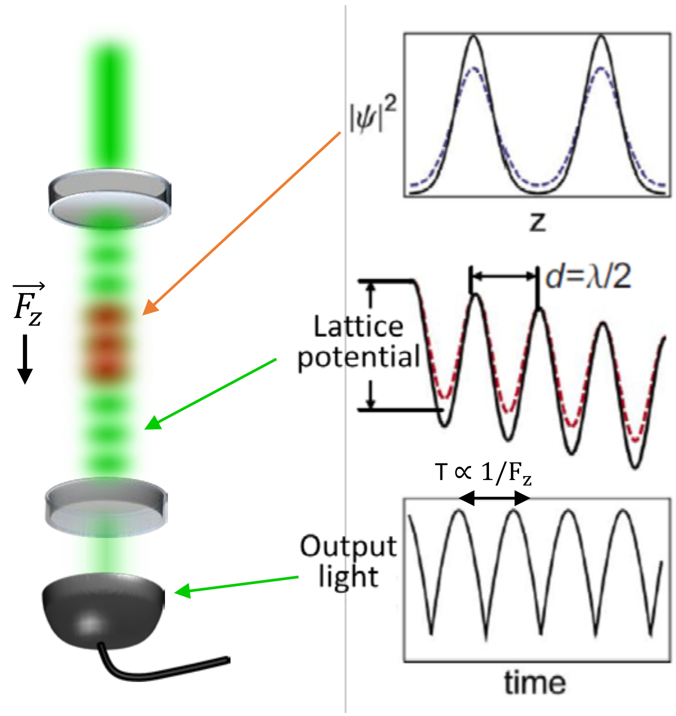
Tino PRL 106, 038501 (2011)

Usual method:

1. Bloch oscillations in lattice
2. Release atoms
3. Destructively image

Continuous trapped accelerometer

Collectively couple atoms to the optical cavity.



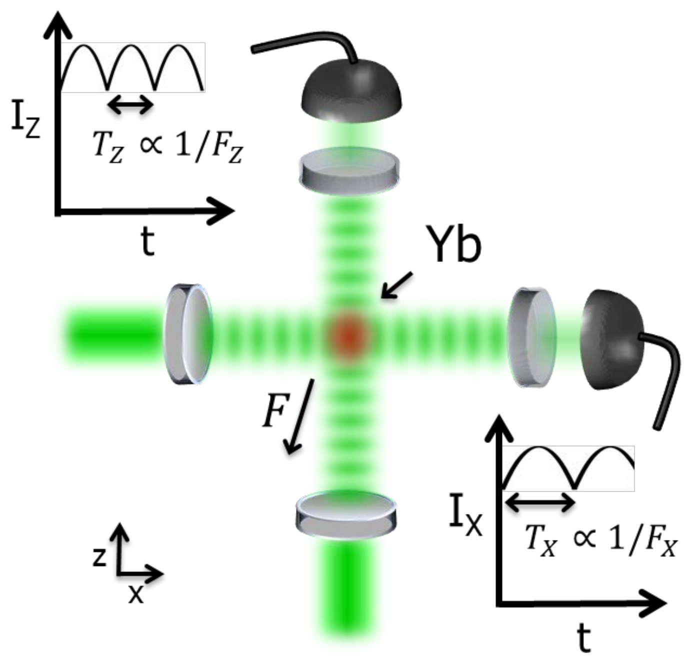
Adapted from Peden et al.

Atomic wavefunction modulates at Bloch frequency…

which couples to the intracavity lattice…

leading to modulation of the output light field.

Continuous trapped accelerometer



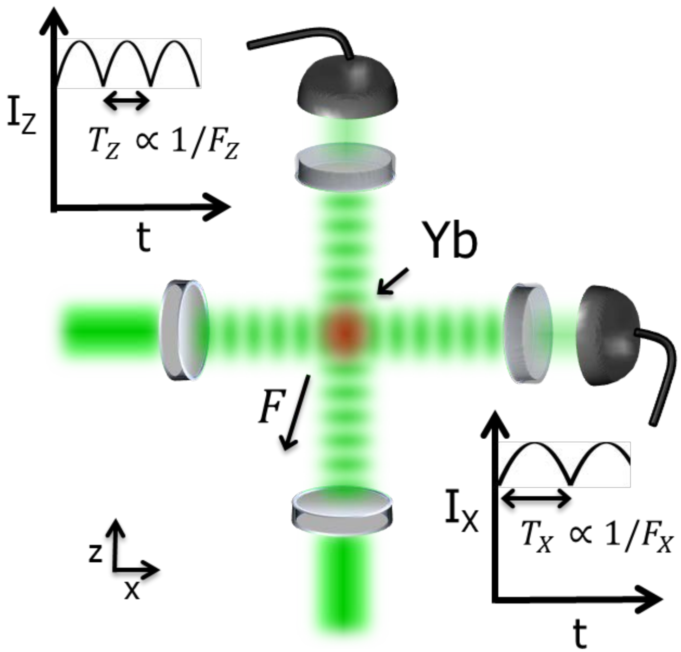
The output light of an optical cavity used to generate the optical lattice will modulate at the Bloch frequency

$$\omega_{Bloch} = \left(F \times \frac{\lambda}{2}\right)/\hbar$$

Advantages:

- Long coherence time
- Continuous readout
- Reduced vibration sensitivity
- Efficient detection

Applications

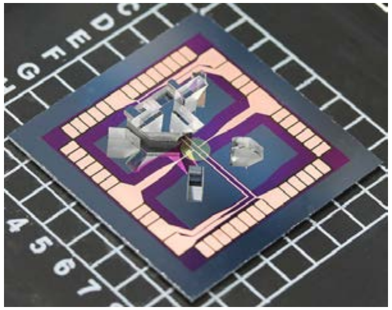


Inertial sensing:

- 10^6 trapped Yb atoms
- 5 s coherence

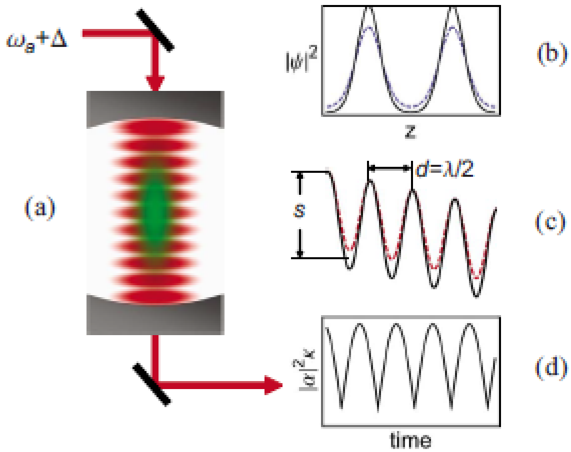
$\Rightarrow \frac{10^{-8} g}{\sqrt{\mathrm{Hz}}}$ shot-noise sensitivity

Dream sensor: integrated optical cavity/atom chip



Dana Anderson, JILA

Cavity Bloch theory



Peden et al. PRA 80, 043803 (2009)

Simplified Hamiltonian

$$H = \frac{\hat{p}^2}{2M} + Mgz + \frac{\hbar g_0^2 \cos^2(k_c z)\hat{a}^\dagger \hat{a}}{\delta} - \mathrm{i}\hbar\eta\left(\hat{a} - \hat{a}^\dagger\right) - \mathrm{i}\hbar\kappa \hat{a}^\dagger \hat{a}\ .$$

Equations of motion

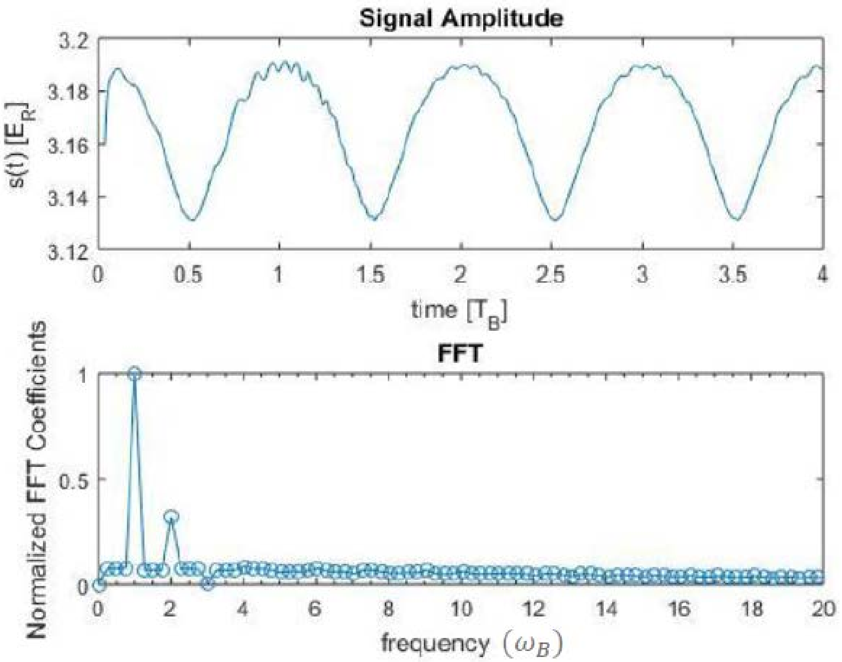
$$\mathrm{i}\hbar\,\dot{\Psi} = \left(-\frac{\hbar^2}{2M}\partial_z^2 + \frac{\hbar g_0^2\,\alpha^*\alpha}{\delta}\cos^2(k_c z) + Fz\right)\Psi$$

$$\dot{\alpha} = -\mathrm{i}\frac{\alpha}{\delta}g^2(t) + \eta - \kappa\alpha\ ,$$

α = field amplitude
g = coupling (essentially vacuum Rabi frequency)
δ = detuning from cavity resonance
η = pumping rate
κ = cavity loss

Cavity Bloch theory

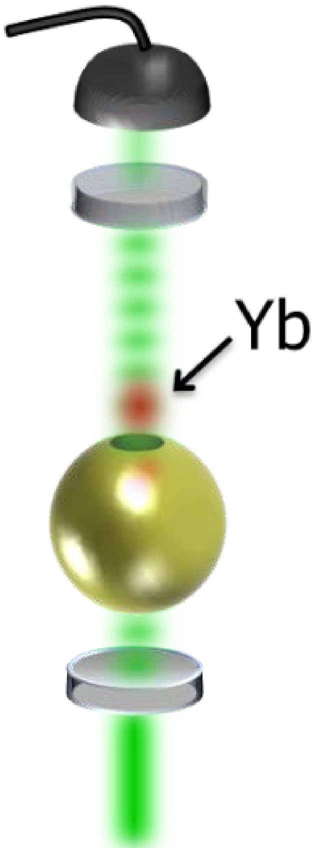
Numerical simulations



- **10^6** Yb atoms
- Bloch frequency **7.4 kHz**
- Cavity – **5 cm** long, **99.9%** reflectivity, **1 MHz** linewidth
- Lattice depth **3 E_R**
- Collective cooperativity >**10,000**

→ **10^{-7} g / √Hz**

Testing dark energy



Dark energy

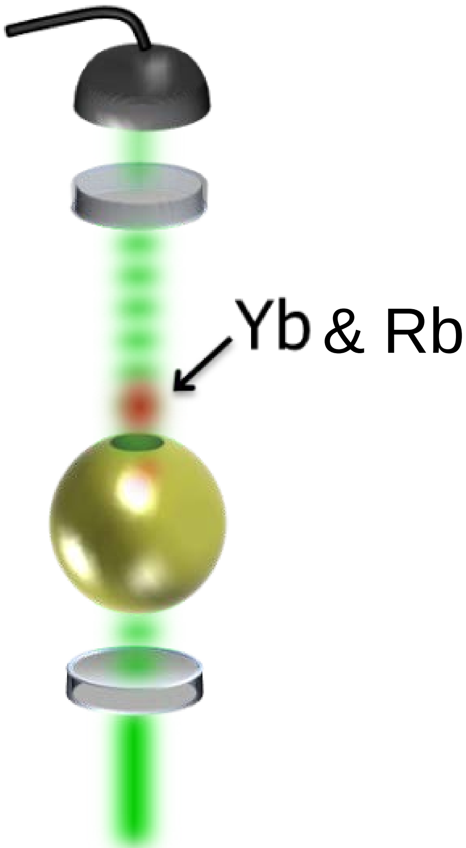
Projected $10^{-9}g$ sensitivity in one day of integration

$\Rightarrow$ 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

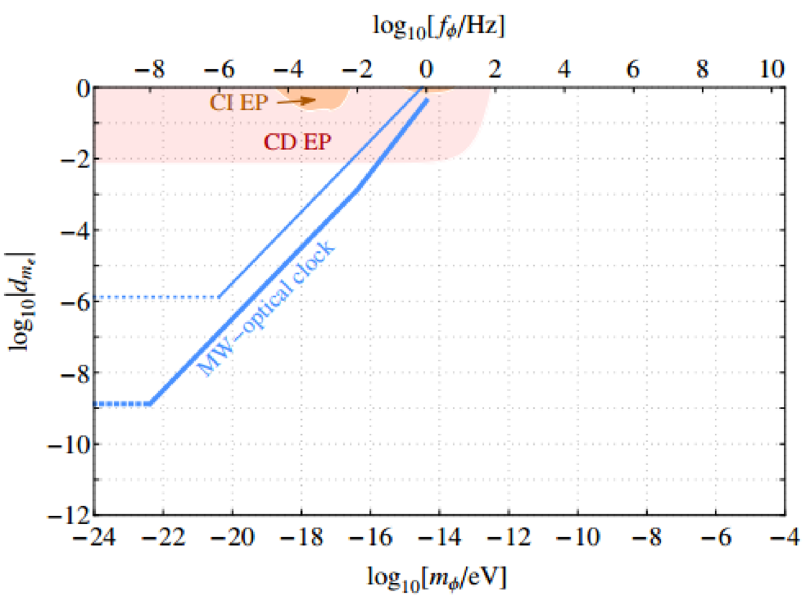
Testing dark energy / dark matter



Dark matter

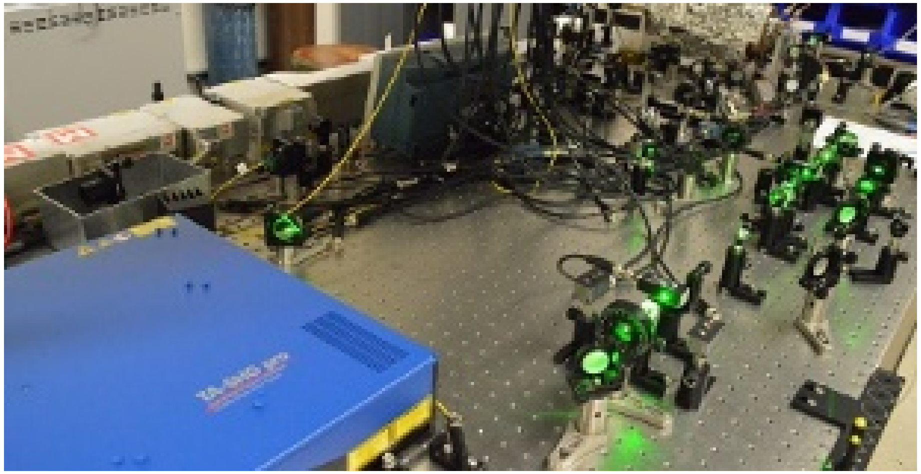
Time varying dilatons oscillate at Compton frequency.

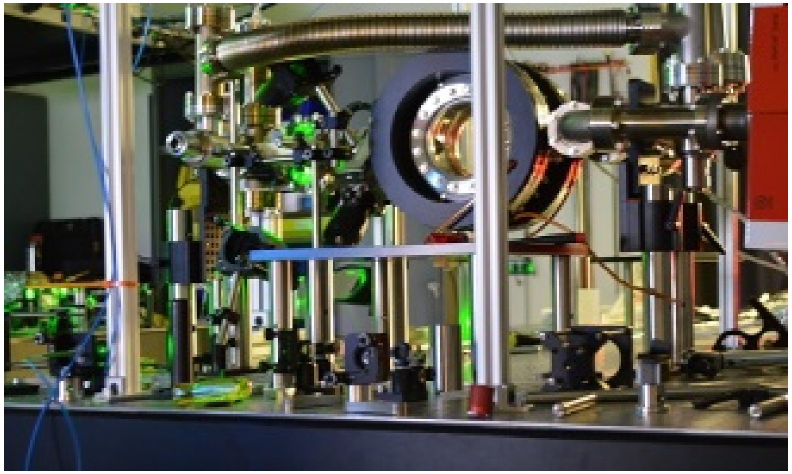
10 kHz detection bandwidth for an EP test could improve constraints



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

Current status





Two stage cooling at 399 nm and 556 nm

Permanent magnet 2D MOT will be loaded from dispensers into 3D MOT

Zerodur cavity testing on benchtop

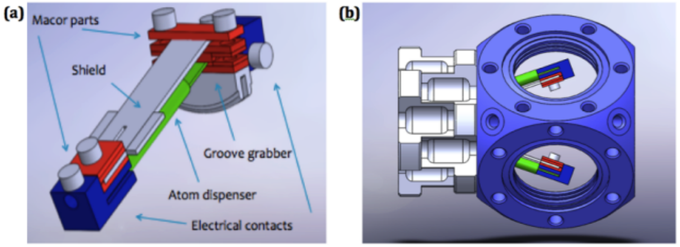
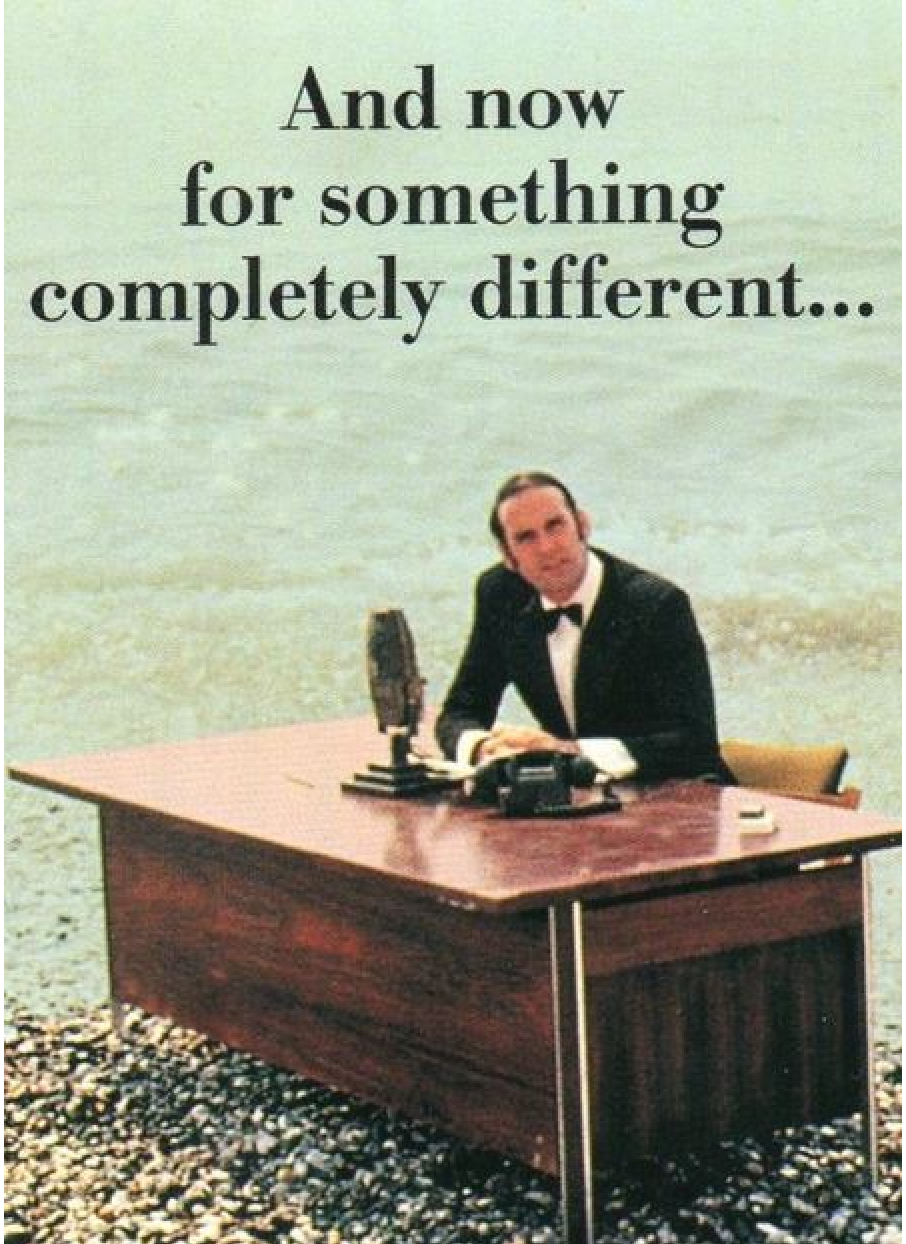


FIG. 3: (a) Atom dispenser assembly. For clarity, the atom dispenser is shaded green, the electrical contacts are blue, and the Macor insulating parts are red. (b) Atom dispensers mounted inside the 2D MOT chamber.

HUNTER - sterile neutrino search



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HUNTER - Heavy Unseen Neutrinos by Total Energy-momentum Reconstruction

- Identifying the galactic dark matter is one of the key problems of modern physics.
- Many large scale experiments are searching for heavy “supersymmetric WIMPs” and will soon either find them or run into backgrounds.
- HUNTER will seek an entirely different dark matter candidate, the “sterile neutrino”, which would also fill a gaping hole in the Standard Model.

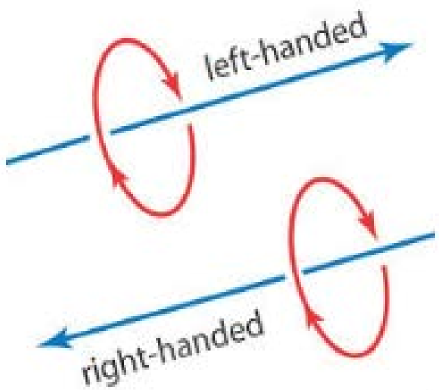
Jeff Martoff (Temple)
Eric Hudson (UCLA)
Paul Hamilton (UCLA)
Peter F. Smith (UCLA)
Andrew Renshaw (Houston)
Hanguo Wang (UCLA)

Funding from W.M. Keck Foundation

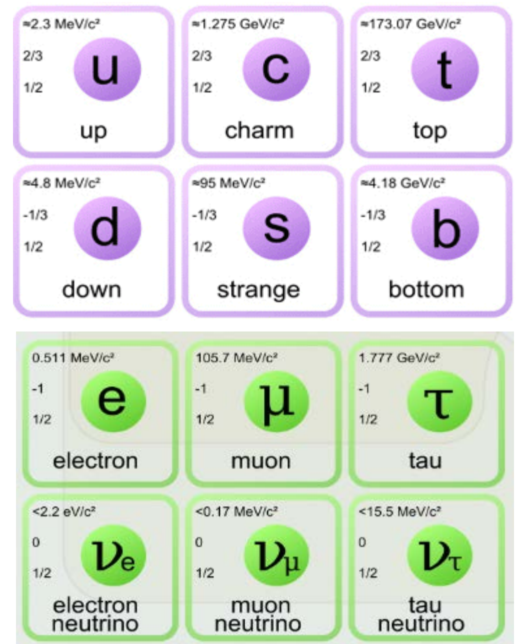
Missing right-handed neutrino states

Quarks and Leptons have an
elementary unit of spin

L H or R H relative to motion



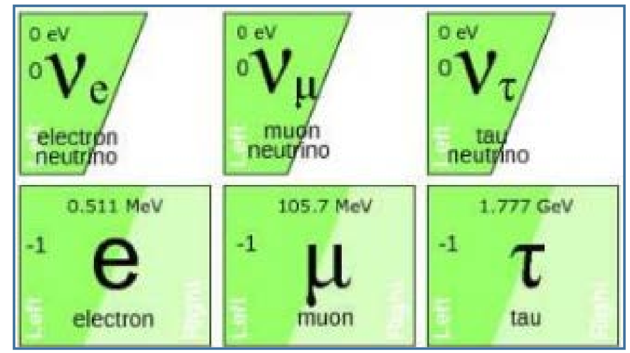
Left handed	right handed
✓	✓
✓	✓
✓	✓
✓	**MISSING**



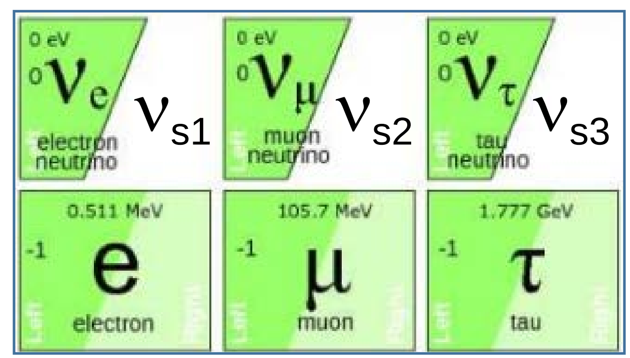
Unseen in existing neutrino interactions

Addition of sterile neutrino states

- Pre-1980: neutrinos thought zero mass with only LH states (& anti-neutrinos RH)
- Post-1980: Neutrinos confirmed to have have small but non-zero masses
- Non-zero mass indicates both LH and RH states should exist, but not yet seen



- Thus the missing neutrinos must have either high mass or Interaction strength much weaker than known neutrinos
- Hence named ‘sterile’ (= ‘quasi sterile’)
- No clear prediction of mass



Mass range of the known 'elementary' particles

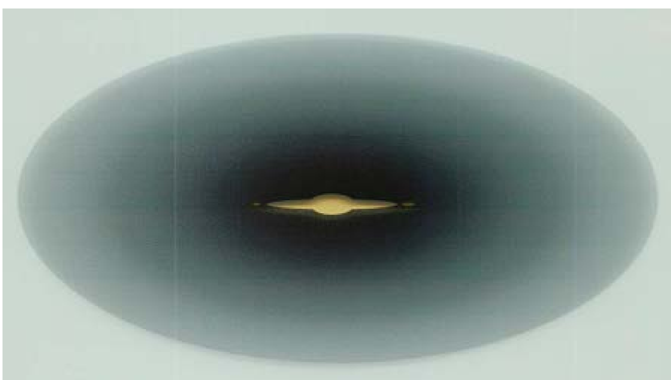
1meV 10meV 100meV 1 eV 10eV 100eV 1 keV 10keV 100keV 1 MeV 10MeV 100MeV 1GeV 10GeV 100GeV 1TeV

Neutrinos ν1 ν2 ν3 electron muon tau

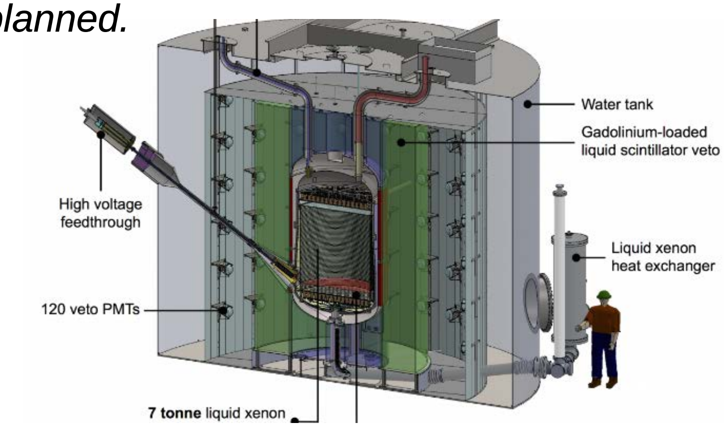
Bound Quarks D,U, S, C, B, T

New stable particle for dark matter ?

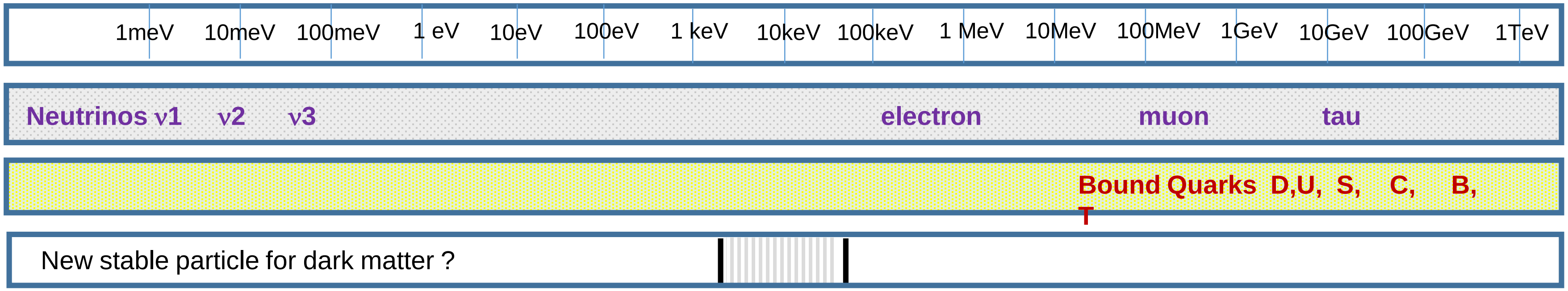
Galactic dark matter Problem

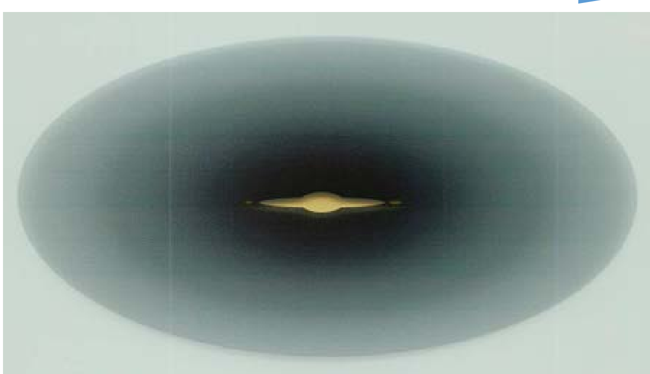


No heavy particle dark matter signals seen in underground ton-scale detectors or at Large Hadron Collider. Multi-ton detectors planned.



Galactic Dark Matter - keV-mass sterile neutrinos can provide the answer

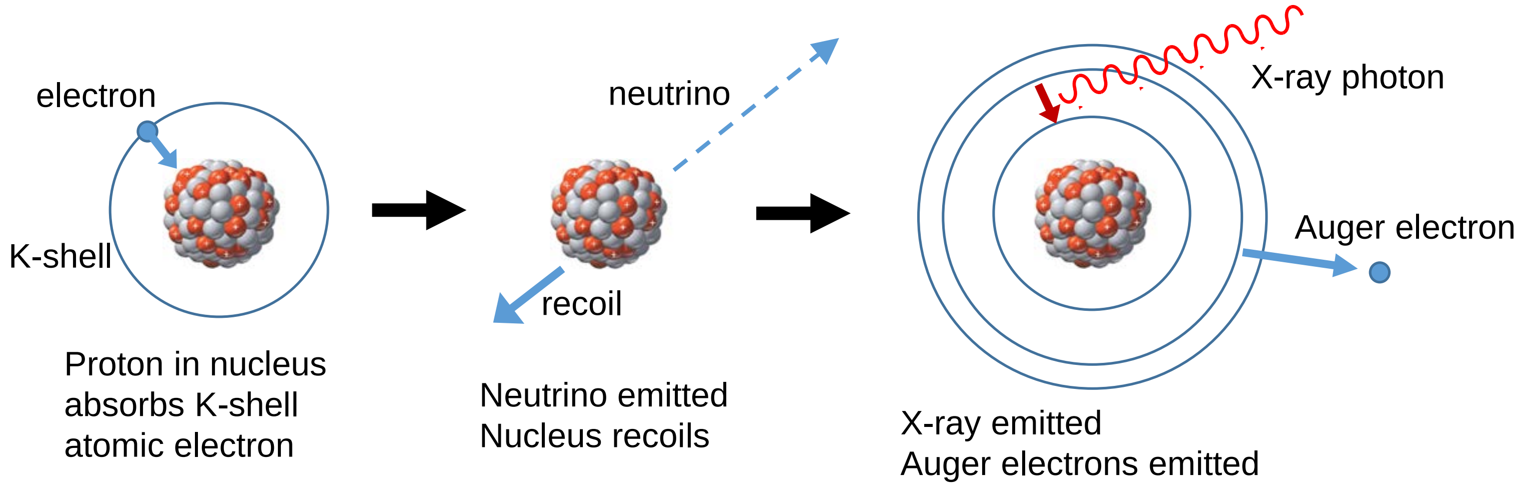




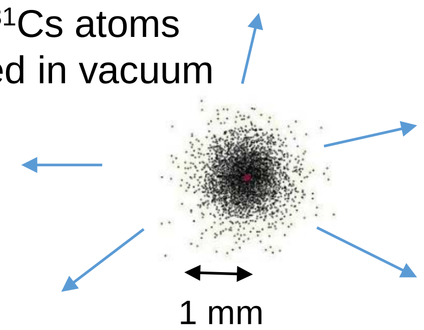
Theoretical calculations show

- ~ 10 keV sterile neutrino mass range fits known galactic dark matter density.
- Weak relative coupling < 10^{-4} gives stability for universe lifetime.
- Direct detection not feasible in the foreseeable future

Proposed K-capture experiment: measuring the mass of an unseen neutrino



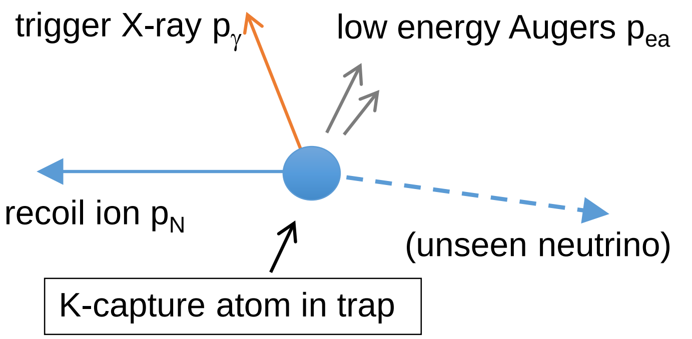
- Cloud of ^{131}Cs atoms suspended in vacuum



- measure momentum of ion, X-ray , e, to calculate neutrino momentum and mass
- **This will find rare keV-mass sterile neutrinos up to Q value of decay (350 keV for ^{131}Cs)**
- **Fraction of signal events gives relative coupling**

Summary of HUNTER principle
(**H**eavy **U**nseen **N**eutrinos by **T**otal **E**nergy-momentum **R**econstruction)

Measurements required:

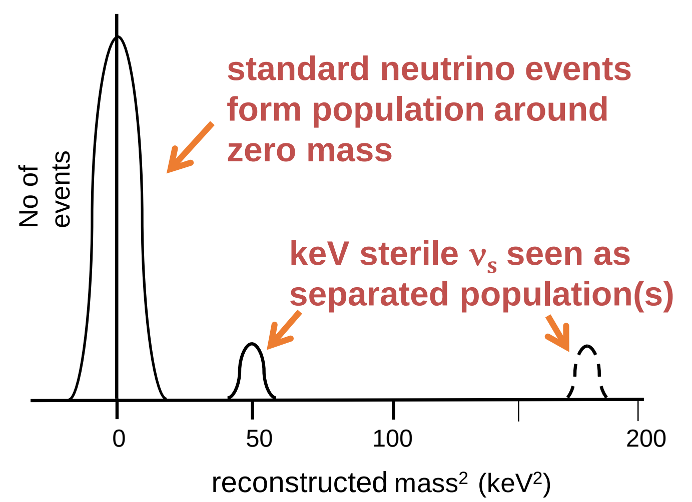


Mass reconstruction formula:

$$m_\nu^2 = [Q - E_a - E_\gamma - E_N]^2 \quad - \quad [\mathbf{p_\gamma + p_{ea} + p_N}]^2$$

missing energy   missing momentum

Reconstructed mass spectra:



- This is the 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

see Peter F. Smith, arxiv:1607.06876 for details

How can the electron neutrino from K-capture become a sterile neutrino ?

neutrino flavors (ν_e , ν_μ , ν_τ , ν_{s1} ν_{s2} ν_{s3}) ⟷ mixtures of definite mass (ν_1 , ν_2 , ν_3 , ν_4, ν_5, ν_6)

$$\begin{vmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_{s1} \\ \nu_{s2} \\ \nu_{s3} \end{vmatrix} = \begin{vmatrix} c_{11} & c_{12} & c_{13} & c_{14} & c_{15} & c_{16} \\ c_{21} & c_{22} & c_{23} & \cdot & \cdot & \cdot \\ c_{31} & c_{43} & c_{33} & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{vmatrix} \begin{vmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \\ \nu_6 \end{vmatrix}$$

mass eigenstates

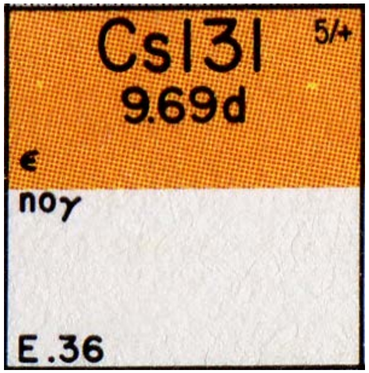
$$\nu_e = c_{11}\nu_1 + c_{12}\nu_2 + c_{13}\nu_3 + c_{14}\nu_4 + c_{15}\nu_5 + c_{16}\nu_6$$

standard neutrino mass states

admixture of 'sterile' neutrinos

Lower probability but will be seen as rare events

131-Cs Decay



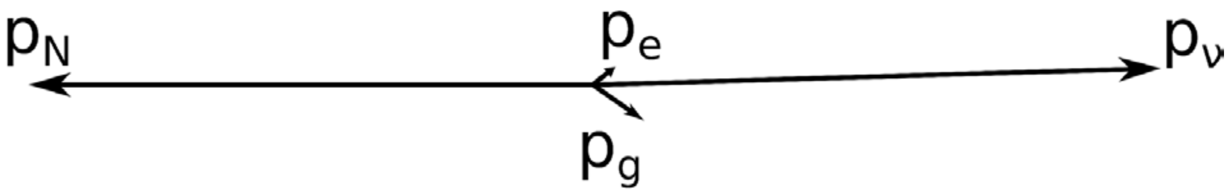
$t_{1/2}$=9.7 da, EC 100%,
Q_{EC}=355 keV

131-Cs -> 131-Xe (stable)
+ν
+ x-rays (4-35 keV)
+ Auger e^{-}'s (3-150 eV)

No penetrating radiation, no radioactive daughter.

Commercially available
(IsoRay brachytherapy seeds)
$10K/order + $1K/Ci

Basic Kinematics



p_N , p_ν ~ .35 MeV/c $\quad$ 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 !

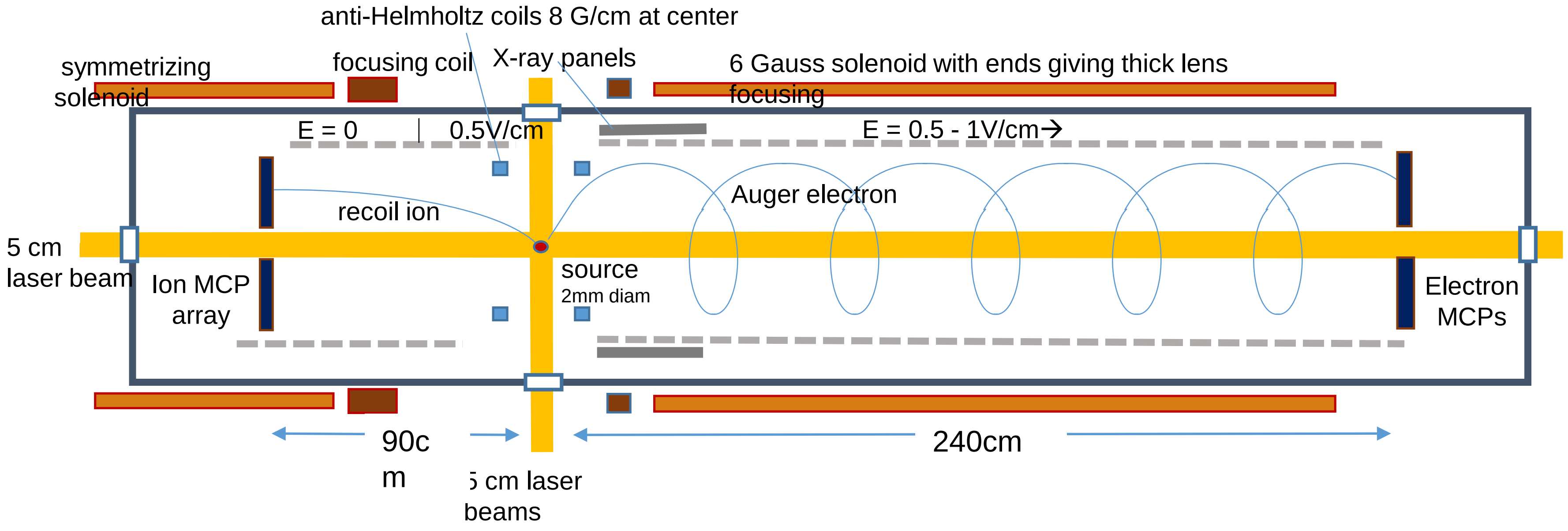
This sets the scale of measurement accuracy needed.

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

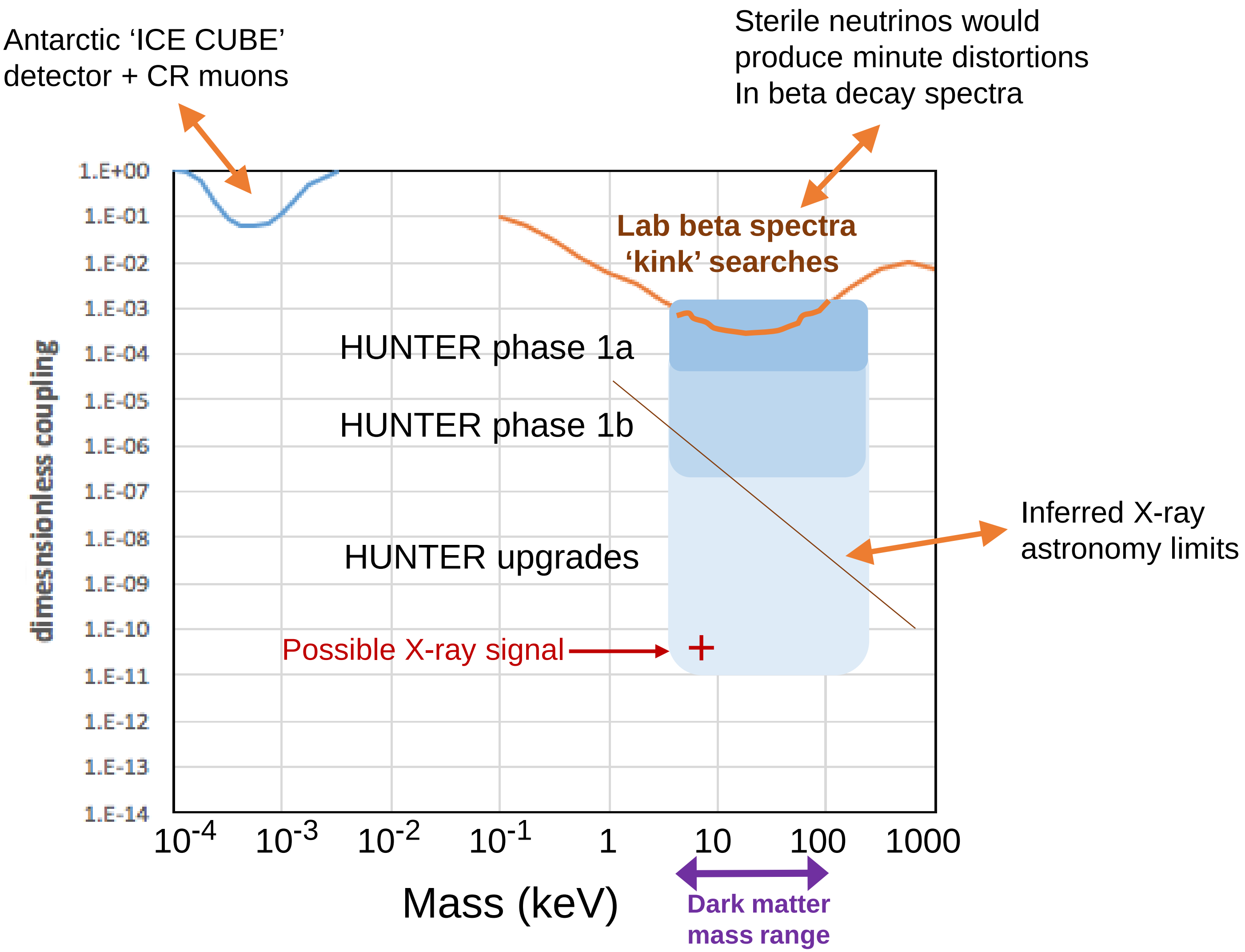
Trapped atoms must be colder than this by factor 3 or more.

Practical configuration

- 4m long vacuum vessel
- Source trapped in intersecting laser beams
- X-ray photon detected by scintillator + multi-anode SiPM array
- Recoil ion and Auger electrons directed by electric fields to MCP arrays
- Longer electron path length confined by magnetic spiraling



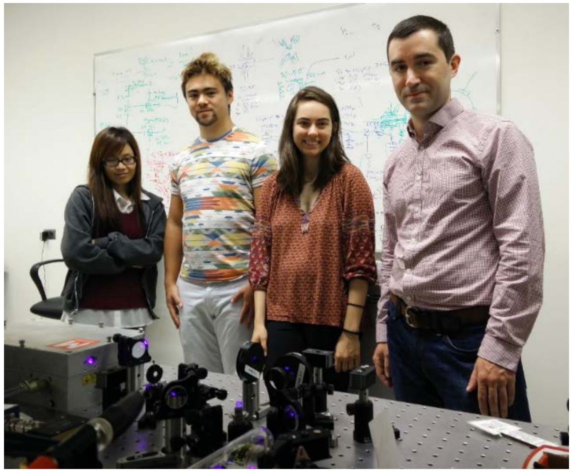
Existing limits and future coverage of HUNTER experiment



Summary

- **Matter wave interferometry**
- **Test of dark energy at Berkeley**
  - 100x improvement on first limits of screened scalar fields
- **Experiments in development at UCLA**
  - Cavity detection of Bloch oscillations for continuous force sensing
  - HUNTER – sterile neutrino search
  - Precision ion interferometry

Thanks



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