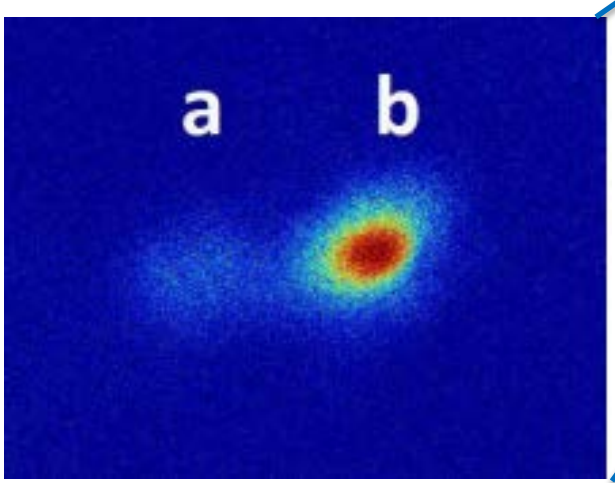
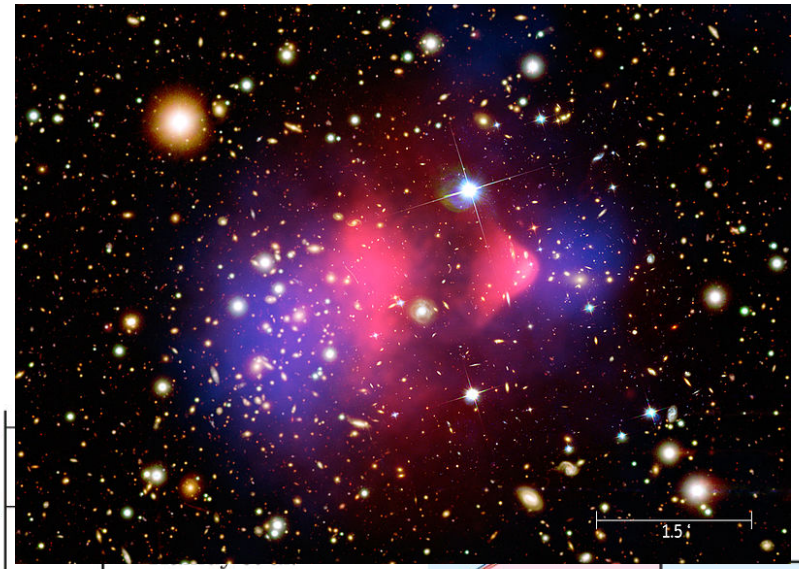
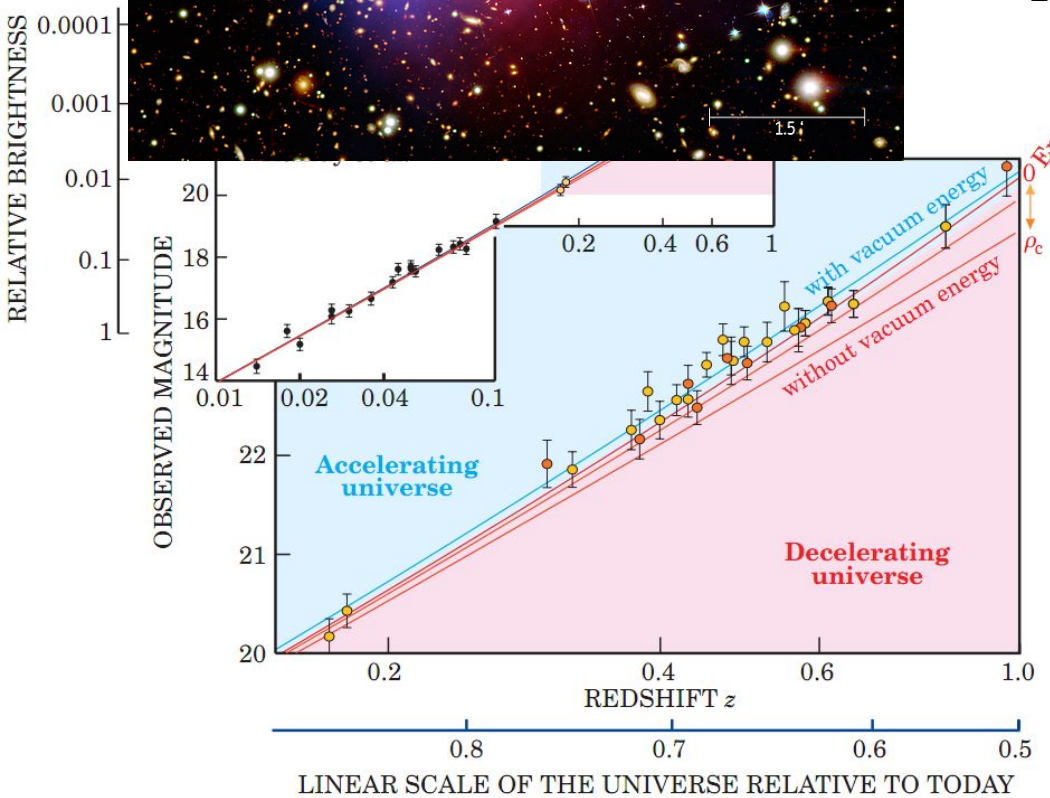
Shining light on dark matter and dark energy with lasers and atoms

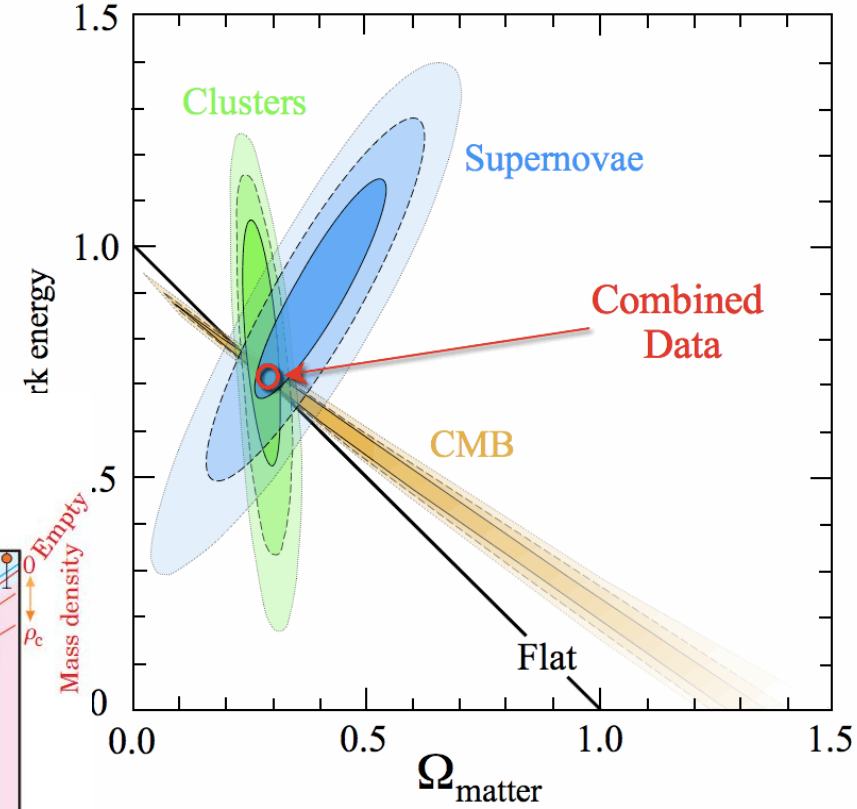


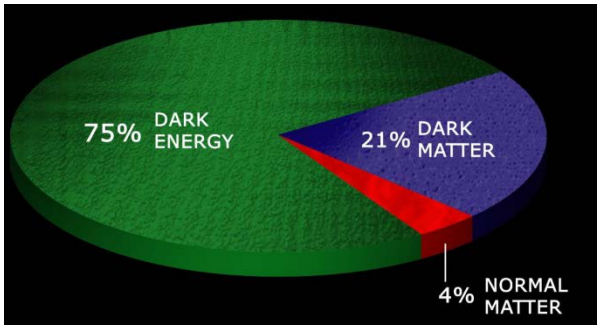
Holger Müller

The standard model is incomplete

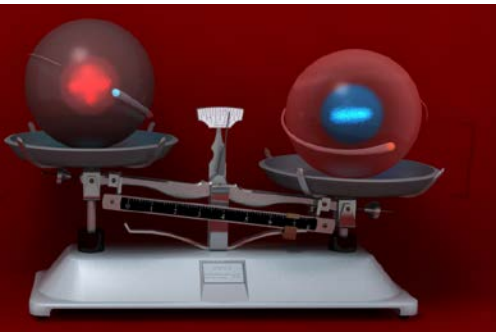




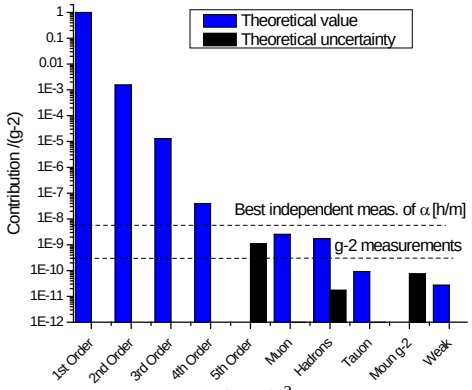




Signals for AI

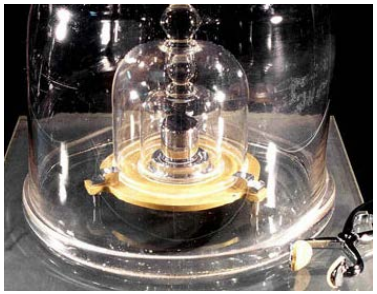


PRL **100,**031101 (2008); PRD 80, 016002 (2009); PRL **106** (2011); **111,** 151102 (2013); **112,** 121102 (2014).



$$3\times10^{-6}\times\left(\frac{m_e}{m_\mu}\right)^2 = 0.07\text{ppb}$$

Muon anomaly electron anomaly



Science **339,** 554 (2013)

Tests of gravity

- Isotropy as accurate as lunar laser ranging
- Equivalence principle: 100-fold improvement across the board.
- Kostelecky & Russell, RMP **83,** 11 (2011). 1/3 of all limits therein are atom interferometers
- Antimatter
- Potential for improvement => Mark Kasevich

Precision tests of the standard model

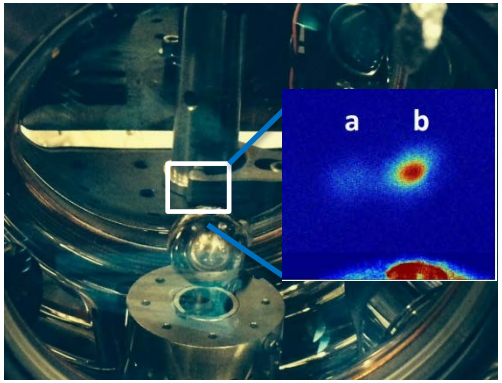
- Measuring the fine structure constant to 10^{-10}
- Broad test of standard model (like EDM, but no need for symmetry breaking)
- PRL **115,** 083002 (2015)
- Dark photons, interferometers
- Unit of mass

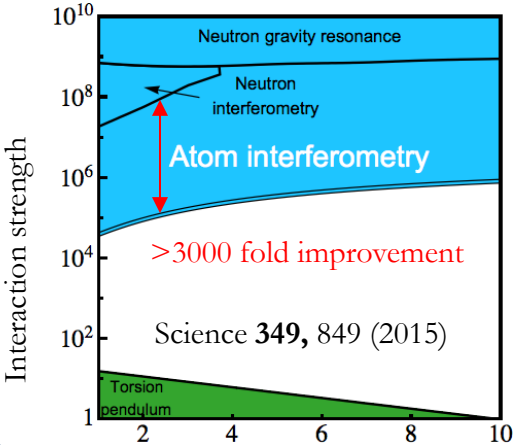
Screened forces

- Laboratory constraints on dark energy
- Tests, e.g., chameleon, *f*(*R*) gravity, symmetrons,…, that gathered 25,000+ citations in last 10 years
- 10^3 –fold improvement relative to neutrons, ADMX, GammeV, CAST,...
- additional 10^4 times realistic

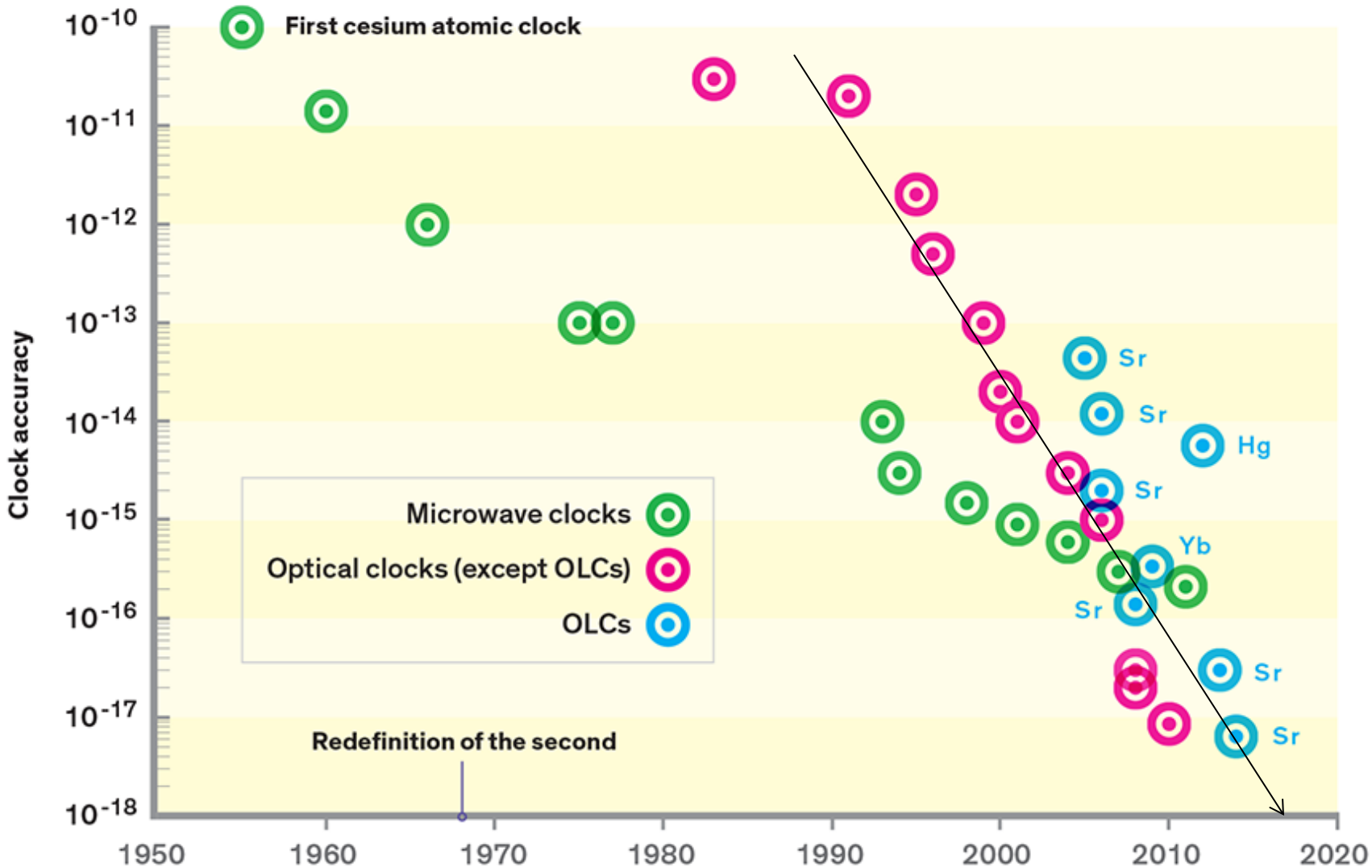
Dark matter wind

- AC force on mirror
- Axions, relaxions, B-L, …
- No dedicated experiments so far…





Moore's law in atomic physics

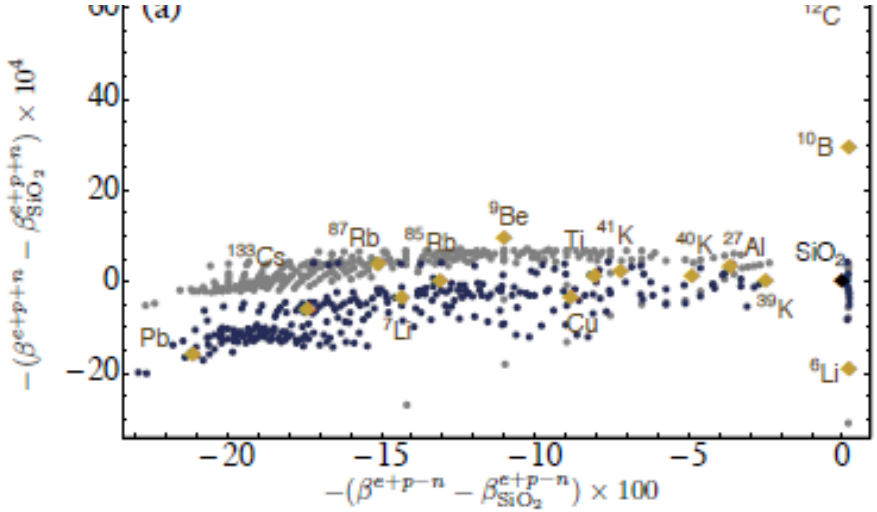


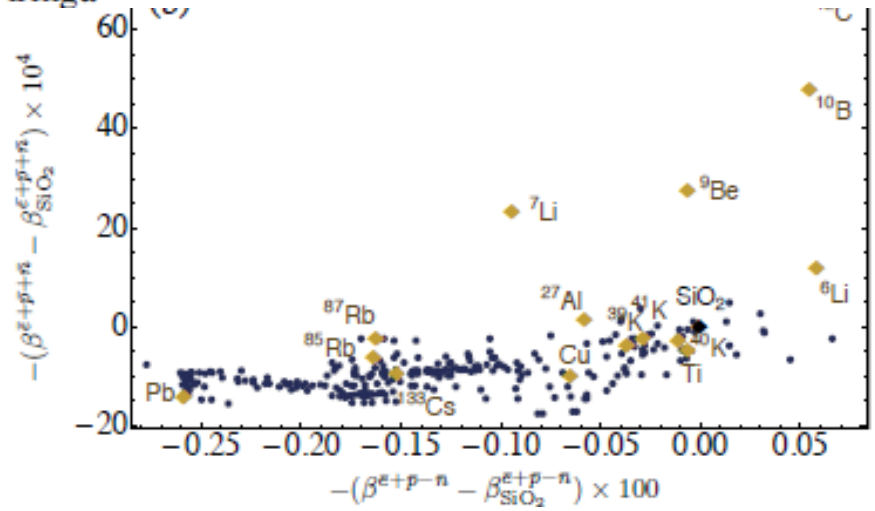
PRL 111, 151102 (2013) PHYSICAL REVIEW LETTERS week ending 11 OCTOBER 2013

Equivalence Principle and Bound Kinetic Energy

Michael A. Hohensee* and Holger Müller
Department of Physics, University of California, Berkeley, California 94720, USA

R. B. Wiringa

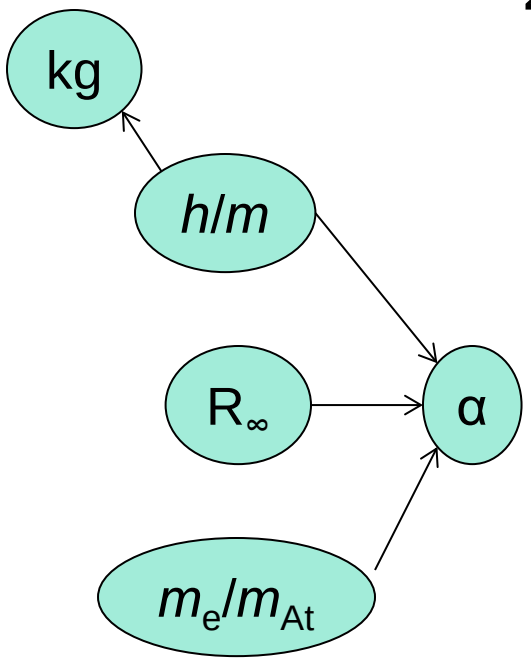


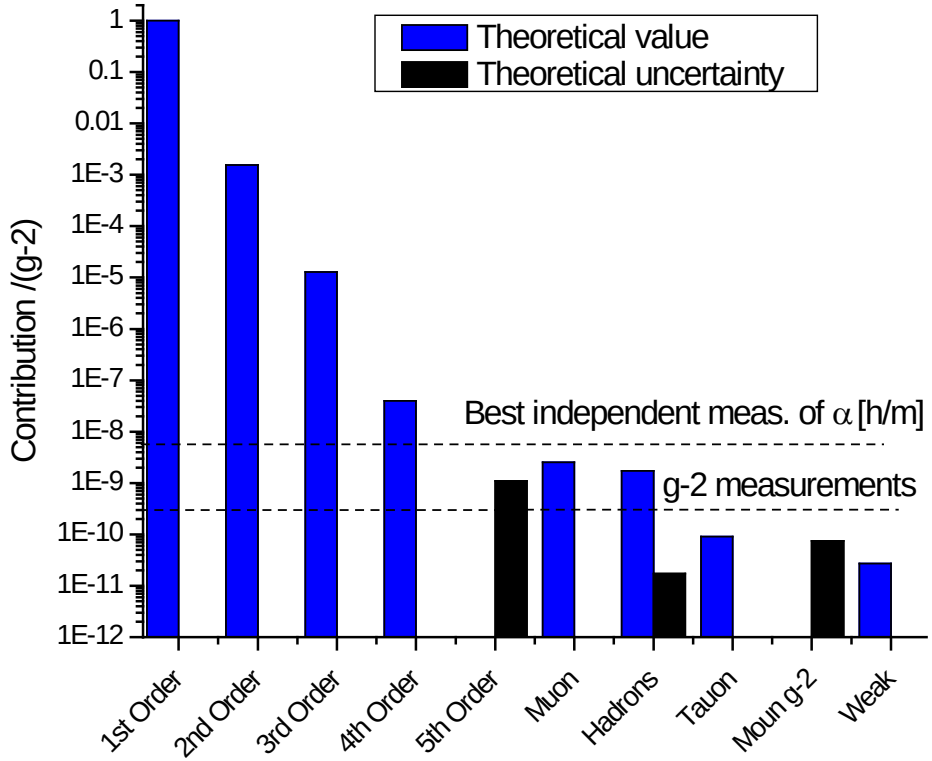


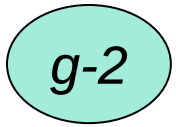
Limits x10^{-7}	$(a^n_{eff})_0$	$(a^p_{eff})_0 + (a^n_{eff})_0$	$(c^n_{eff})_{00}$	$(c^p_{eff})_{00}$	$(c^e_{eff})_{00}$
Clocks+UFF (2011)	-30±530	-10±110	-50±940	21±400	-10±400
	80	40	67	133	1400
Al+clocks+UFF	5.1±6.4	2.2±2.8	11±14	2.4±3.0	0.14±0.28

Kostelecky & Russell, RMP (2011), arXiv:0801.0287. Millionfold improvement feasible

$$\frac{1}{2} m_e c^2 \alpha^2 \equiv R_\infty \hbar c$$

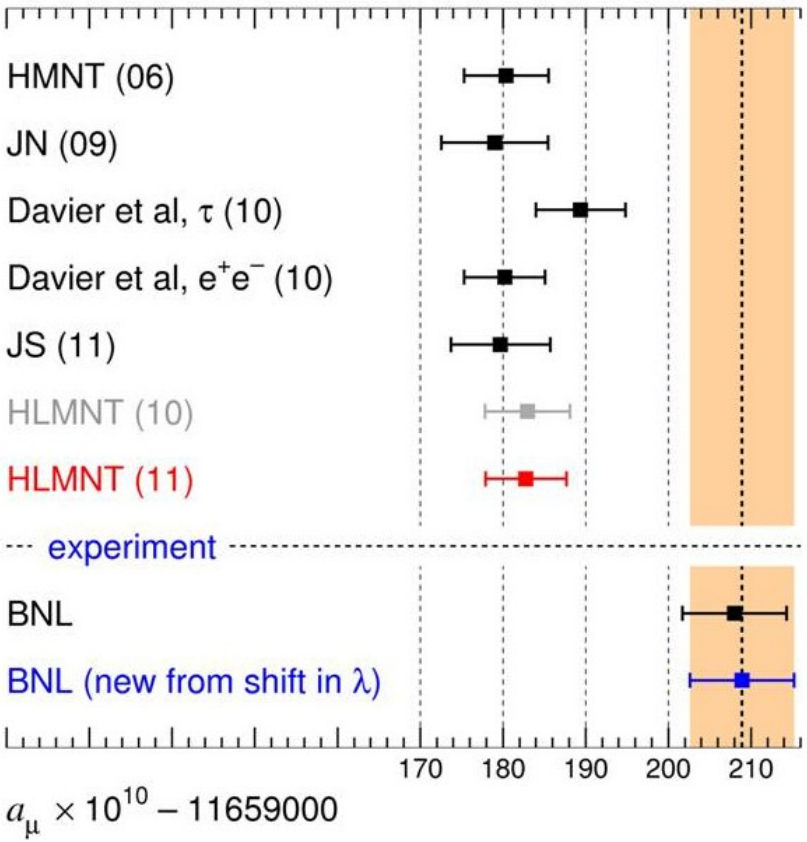






- All experiments and all theories have ppb accuracy
- Substantial parts of the Standard Model have to be right to yield α and g-2 at that level

Muon *g*-2



Muon g-2 campus at Fermilab

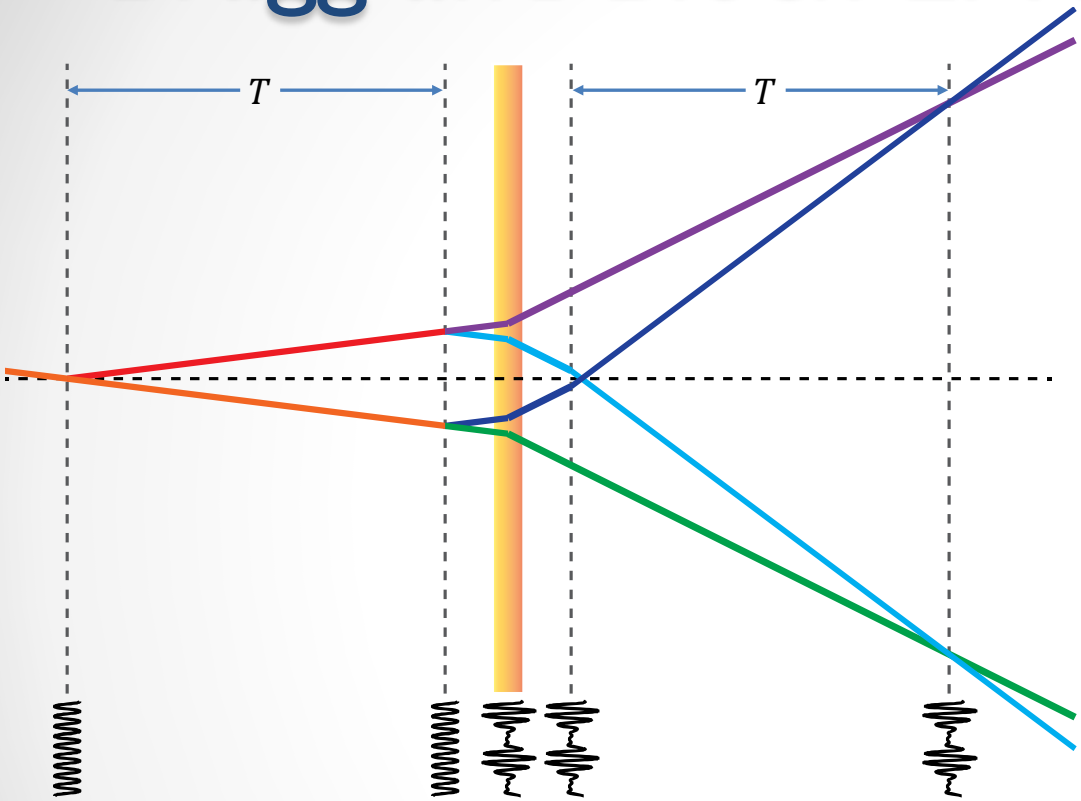
$$3\times10^{-6}\times\left(\frac{m_e}{m_\mu}\right)^2 = 0.07\text{ppb}$$

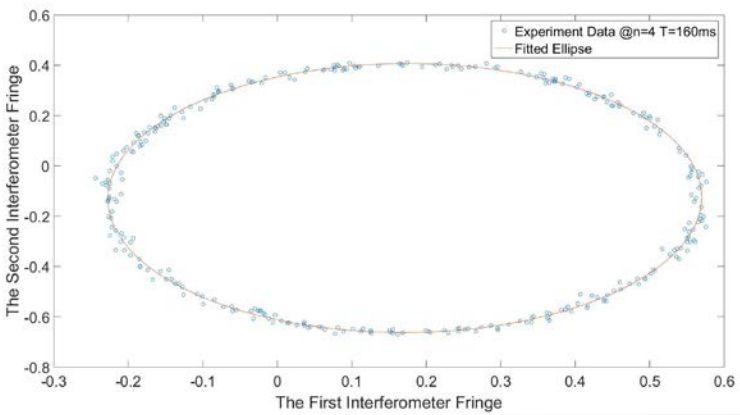
Can be tested in atomic measurement of α and g_e-2

Dark matter candidatess such as dark photons

Sensitive up to energy scales $m \sim [m_e/(10^{-12})]^{1/2} \sim 1$ TeV

Bragg and Bloch LMT methods





Largest matter-wave phase difference ever measured

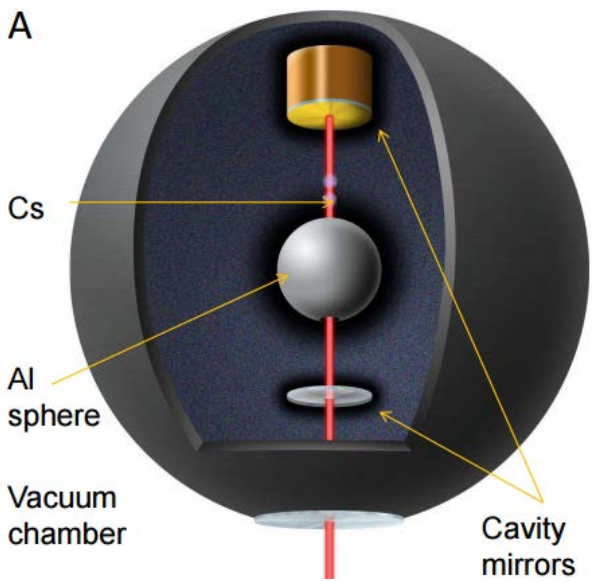
BraggBloch Oscillations

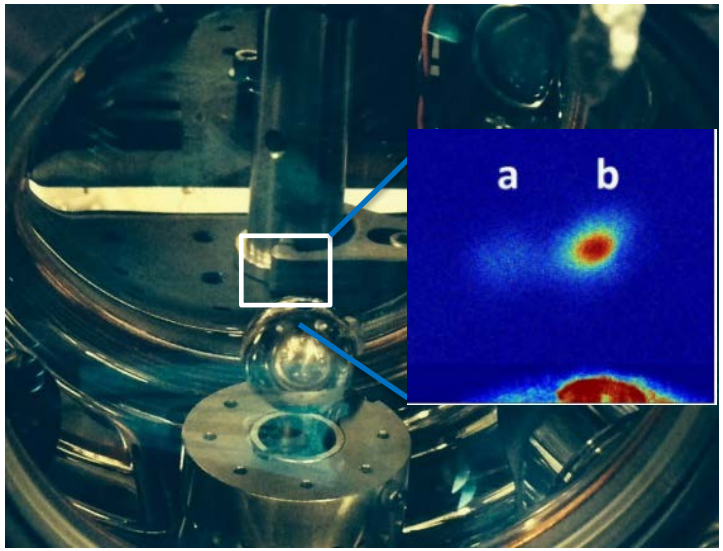
- PRL **100,** 180405 (2009)
- Kasevich/Stanford
- Tino/Florence
- Close/Australia
- Honeywell/Gyroscopes

Bloch

- PRL **102,** 140202 (2009) ; **115,** 083002 (2015)
- Biraben/Paris
- Honeywell/Gyroscopes
- …

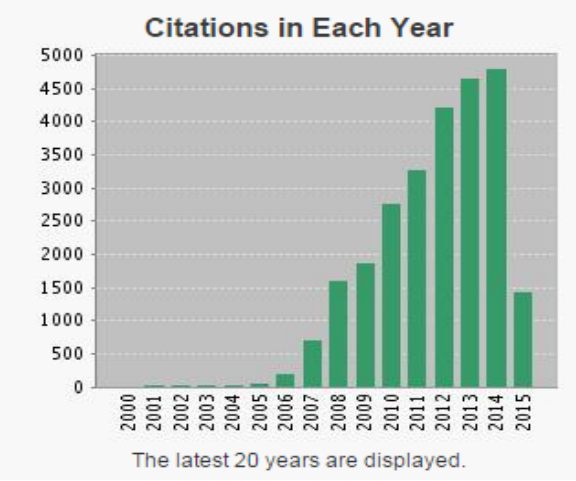
Quintessence constraints



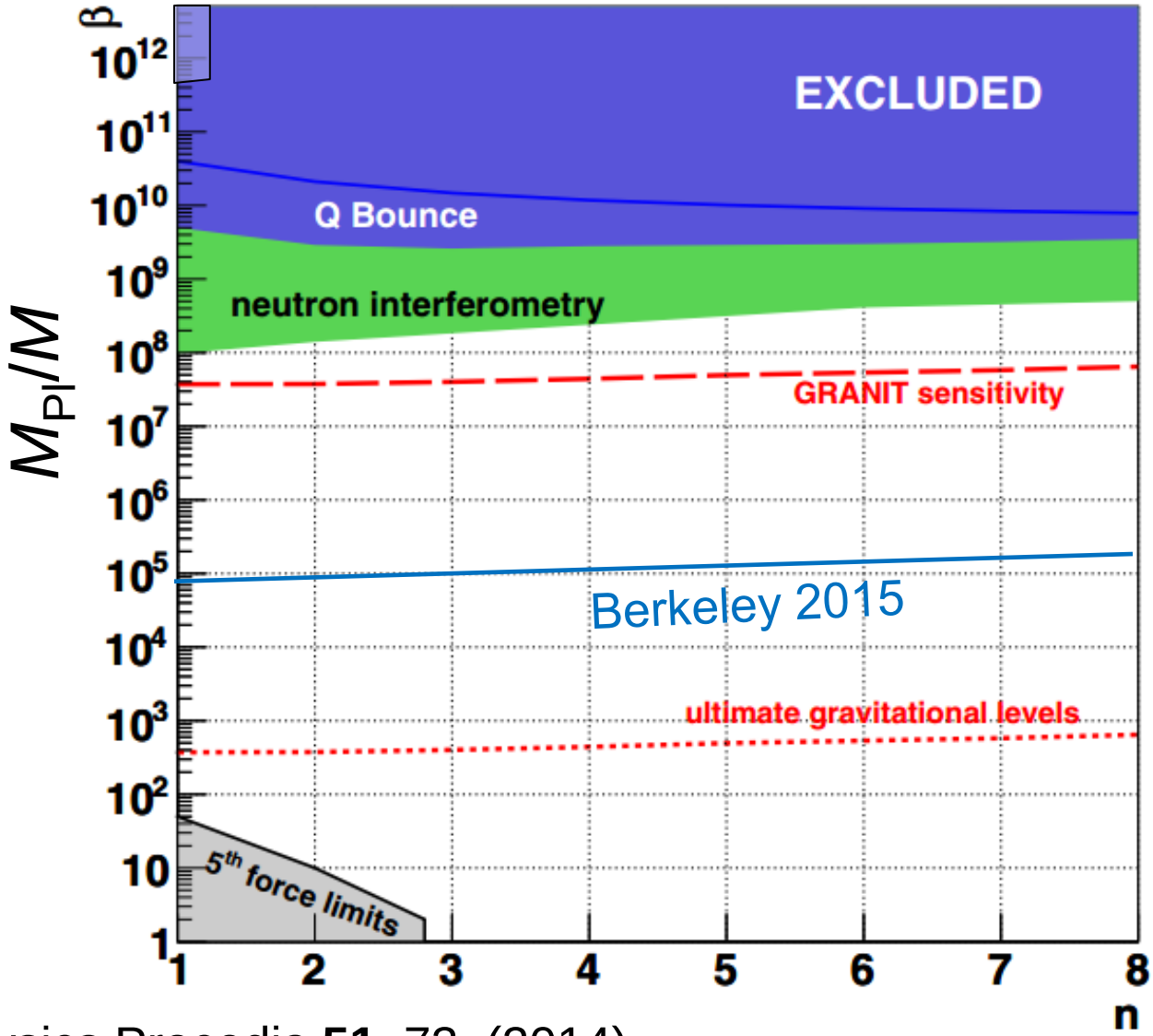


- Couples to skin of objects only
- Suppression aeviated in atomic experiments
- Plethora of candidates: moduli, extra dimensions, string theory…chameleons, symmetrons, $P(X)$, $f(R)$, Vainshtein…

oCern Axion Solar Telescope CAST
oGammeV collab
o Axion dark Matter Experiment ADMX
o Neutron Interferometers

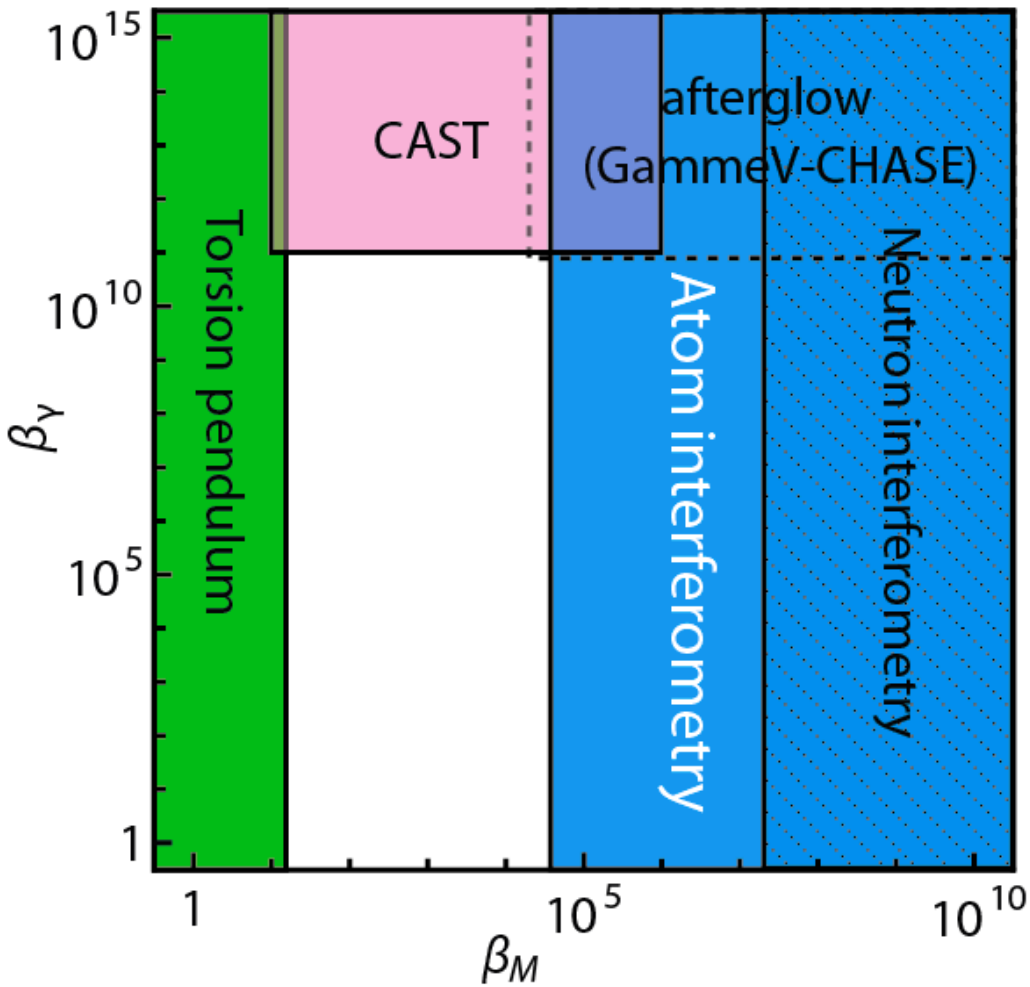


Results



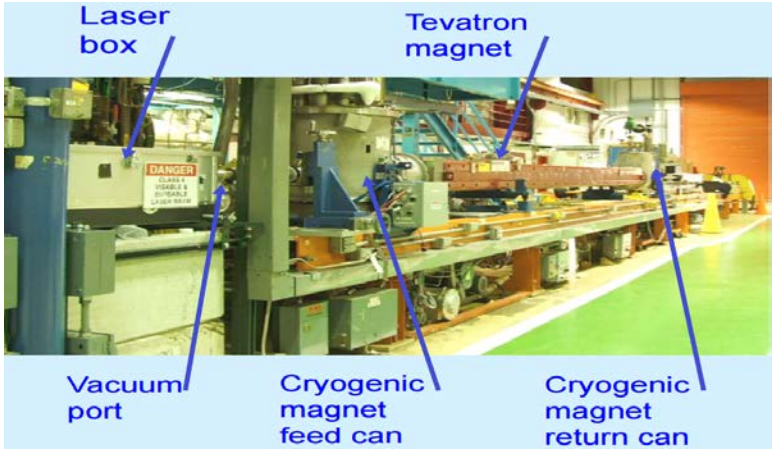
P. Brax, Physics Procedia **51,** 73 (2014)

Photon coupling comparison



View of the CAST experiment at CERN (Credit: CERN).

CAST- arxiv:1503.04561

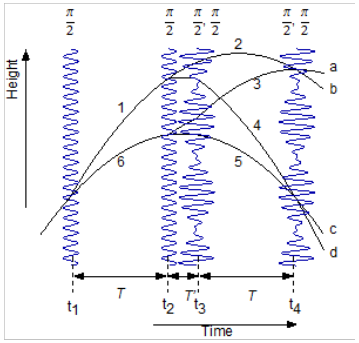


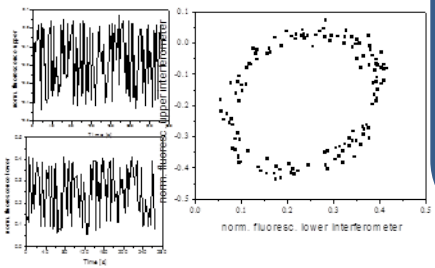
GammeV collaboration
J. Steffen et al. PRL 105, 261803 (2010)

Limits including experiments using an additional coupling to the photon

Atom interferometry does not need photon coupling

Atom-optics technology development



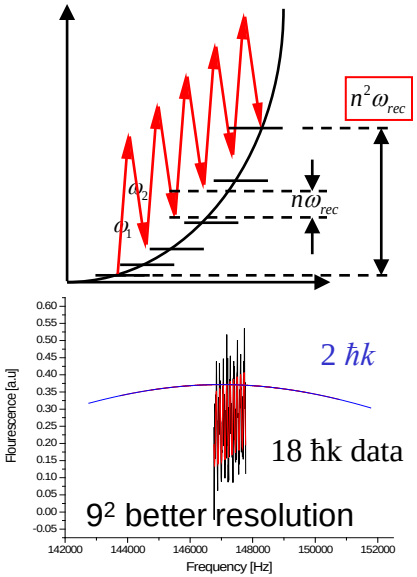


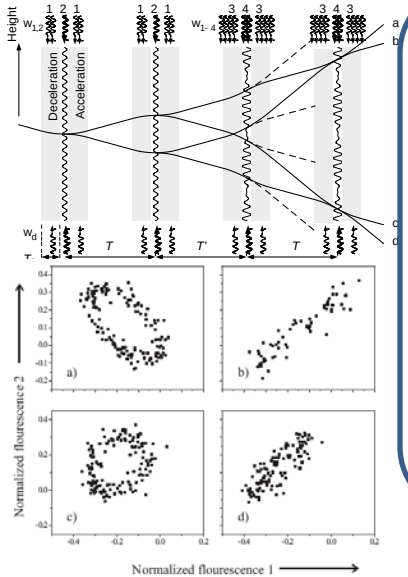
Simultaenous Conjugate Interferometers

- Fringes recovered from >>2 pi common-mode noise
- 2,500 fold gain in sensitivity
- Now being set up by the Biraben group, LKB Paris
- S.-W. Chiow et al., PRL 103, 050402 (2009)

Multiphoton Bragg diffraction

- Up to 24 photon kicks
- Increses signal
- Now used by, e.g., Mark Kasevich
- H.M. et al, PRL 100, 180405 (2008)



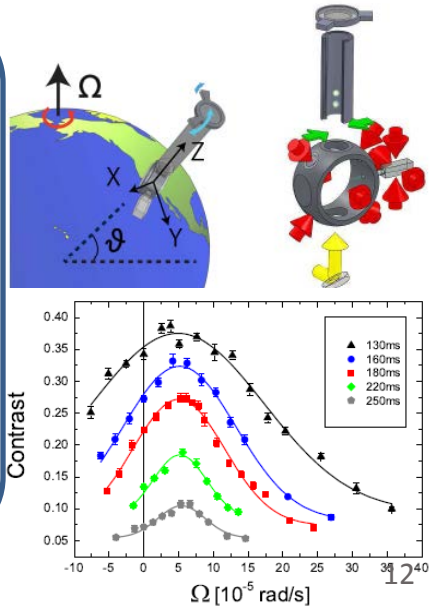


Optical lattice beam splitter

- Accelerated optical lattices to transfer momentum
- Scalable method to build larger interferometers
- Promising for gravity wave detection
- H.M. et al., PRL 102, 240403 (2009)

Coriolis compensation

- Earth's rotation compensated for by tip-tilt mirror
- Allowed us to build world's most sensitive interferometer
- Now used, e.g., at Stanford
- Lan et al., PRL 108, 0904902 (2012)



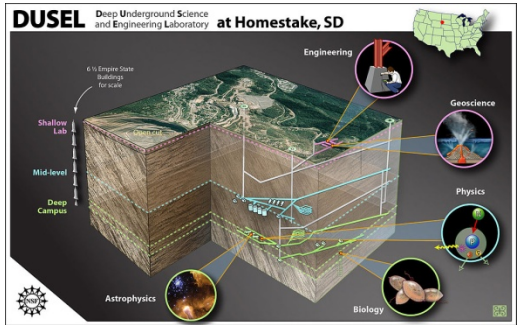
Enabling technologies

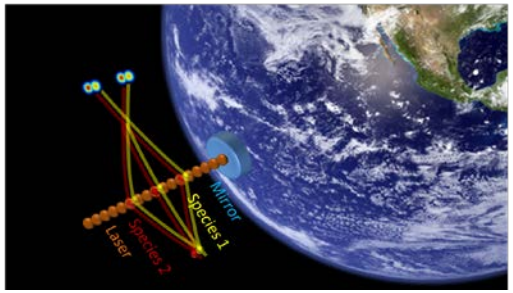
Lasers

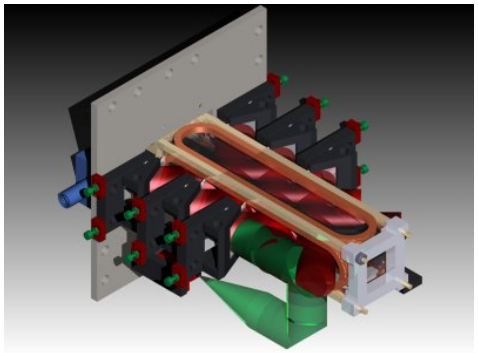
- Systematics scale with beam area and thus power
- CW lasers: watts
- Pulsed lasers: 10s of kW
- 10,000 suppression of leading systematics

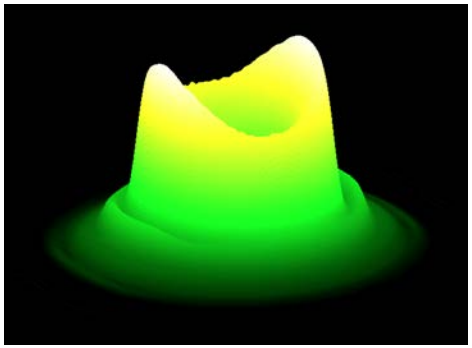
Environments

- Tall mineshafts or drop towers
- low-vibration labs







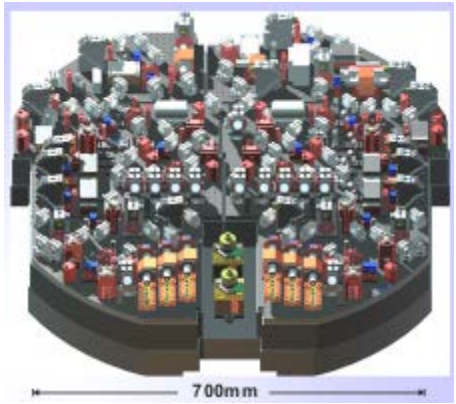


Sources

- High atom number
- efficient BEC production
- atom lasers
- 10-100-fold improvement in SNR and systematics

Optics

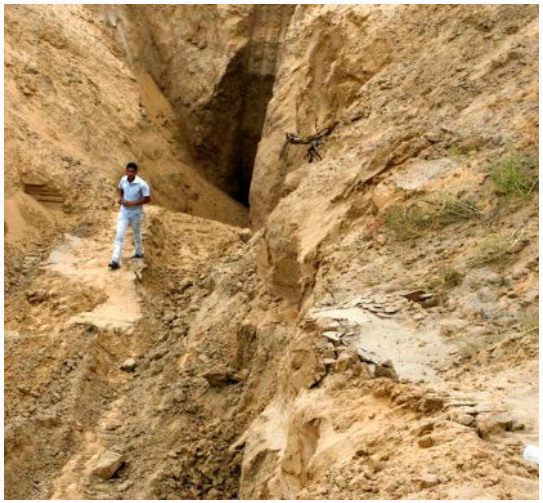
- stable
- compact
- Mobile
- increased uptime, repeatabiity

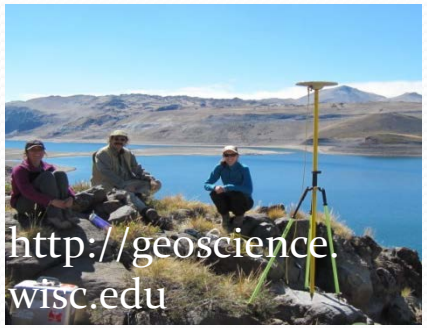


HU Berlin

Applications

- Prospecting for tunnels at Kerem Shalom, Israel
- Water table monitoring
  - Requires low drift, deployability
- Inertial navigation
  - Requires multiaxis operation



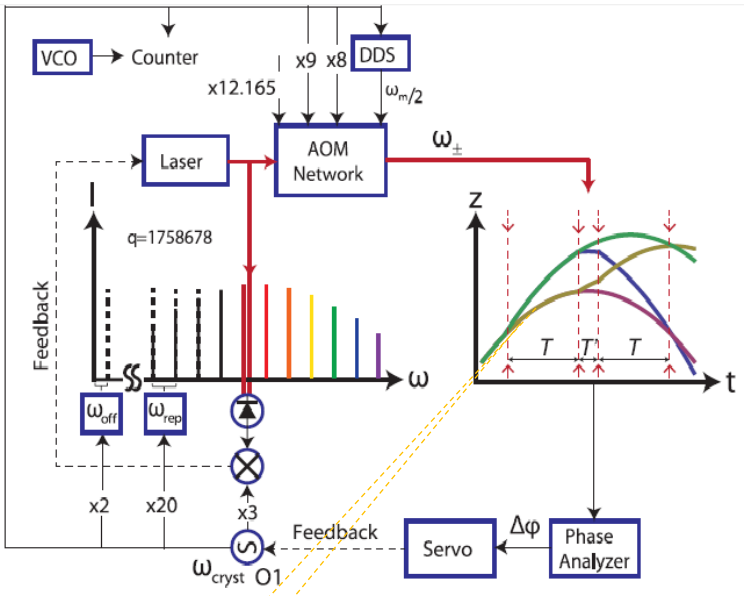


Honeywell

Science AAAS

A Clock Directly Linking Time to a Particle's Mass

Lan et al., Science **339,** 554 (2013)



$$\omega = \frac{1}{2nN^2}\frac{mc^2}{\hbar}$$

Key insight / innovation

- Feedback over atom interferometer using frequency comb
- Comb multiplies by N
- n-photon momentum transfer
- Clock frequency ~100 kHz= $(mc^2/h)/(2nN^2)$, exactly

Technology impact

- A single particle is useful as a time/frequency reference
- Cesium atom used as approximation of a point mass
- 4 ppb accuracy demonstrated, < 1 ppb feasible

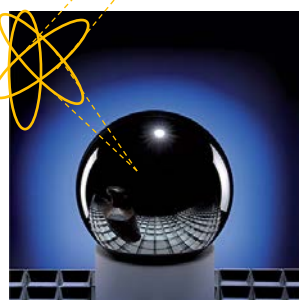
Application

- Mass standard in new SI where h and c are defined, kg measured
- With elementary (anti-) particles => equivalence principle with antimatter
- Light nanomechanical objects => mesoscopic mass standard

Watt balance

- 33 ppb for amu
- 33 ppb for kg
- Moving parts, gravity, standard resistors…
- Americans and Europeans disagree

Atom interferometer+counting



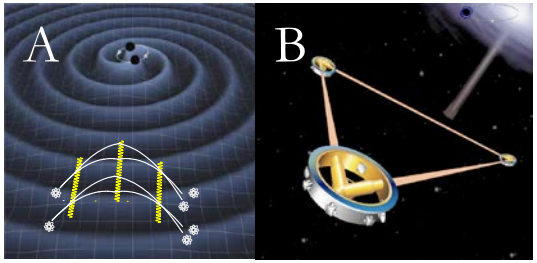
- 4 ppb for amu
- 30 ppb for kg
- No moving parts, gravity, standard resistors…
- Agrees with European versions
- <1 ppb in the future

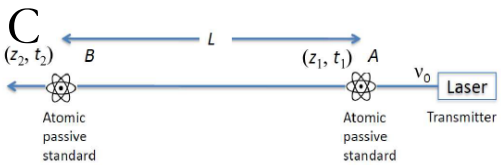
Independent methods realize the same definition ☺

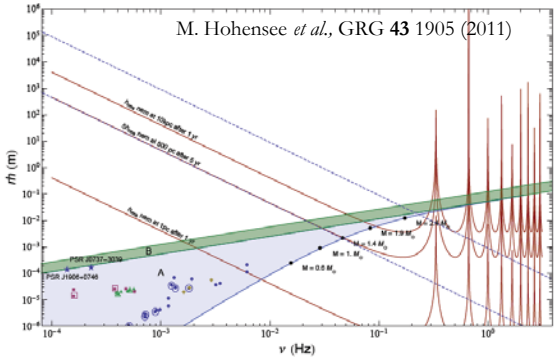
Atomic gravitational wave detection

Approaches

A. "AGIS," atoms as poof-masses
B. Single-laser interferometer using atoms as clock -- Nan Yu · Massimo Tinto GRG 2010
C. Light interferometry using atoms as drag-free proof masses







Key challenges

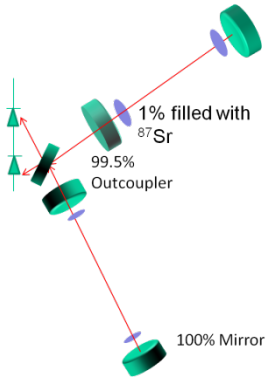
- Low atom number, high shot noise => Not competitive at high frequencies
- Atom temperature
- Technology maturity
- Novelty means that best approach may be unknown as yet

Key advantages

- No macroscopic proof masses
- No vibration isolation required
- Atoms have few internal degrees of freedom
  ⇒No thermal noise
  ⇒No radiation pressure noise

Current research

- Very large momentum transfer (Bloch oscillations)
- Noise sources, optimization
- Alternative schemes, e.g., superradiance
- Technology maturation
- Atom interferometers vs. other approaches

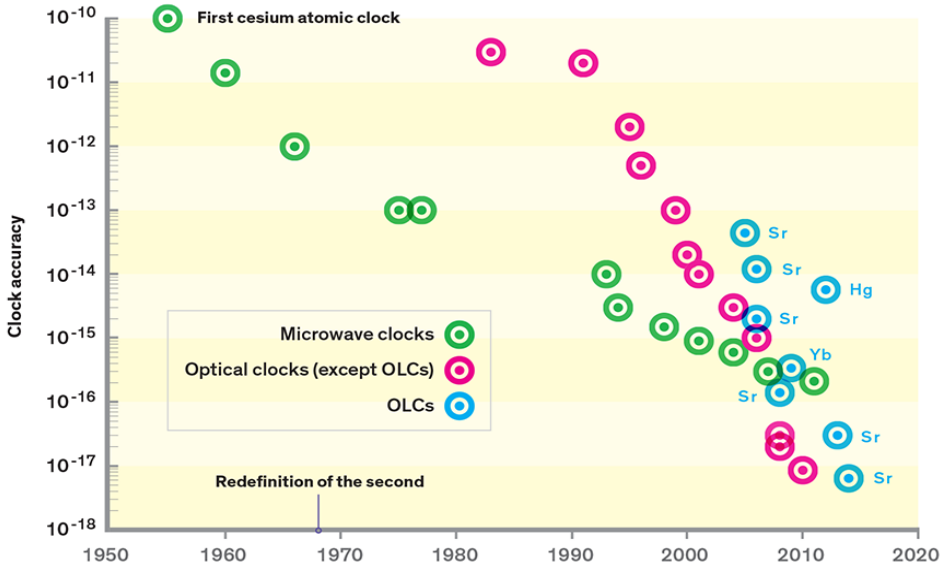


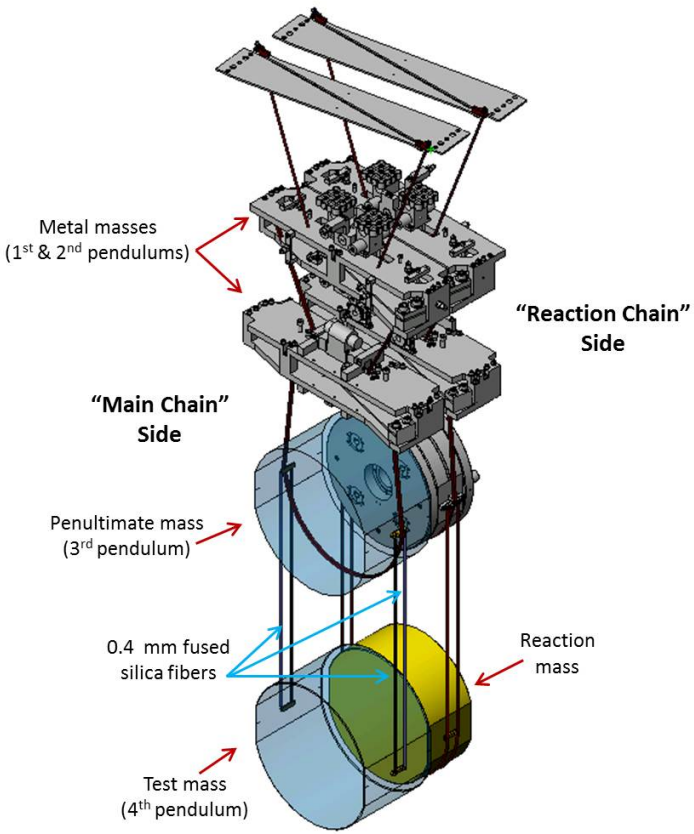
J. Harms, B.J.J. Slagmolen, R.X. Adhikari, M.C. Miller, M. Evans, Y. Chen, H. Müller, M. Ando, Phys. Rev. D **88,** 122003 (2013).
[M. Hohensee, S.-Y. Lan, R. Houtz, C. Chan, B. Estey, G. Kim, P.-C. Kuan, and H. Müller. Gen. Relativity Gravitat. **43,** 1905 (2013).

Building community

- Precision experiments are long-term experiments

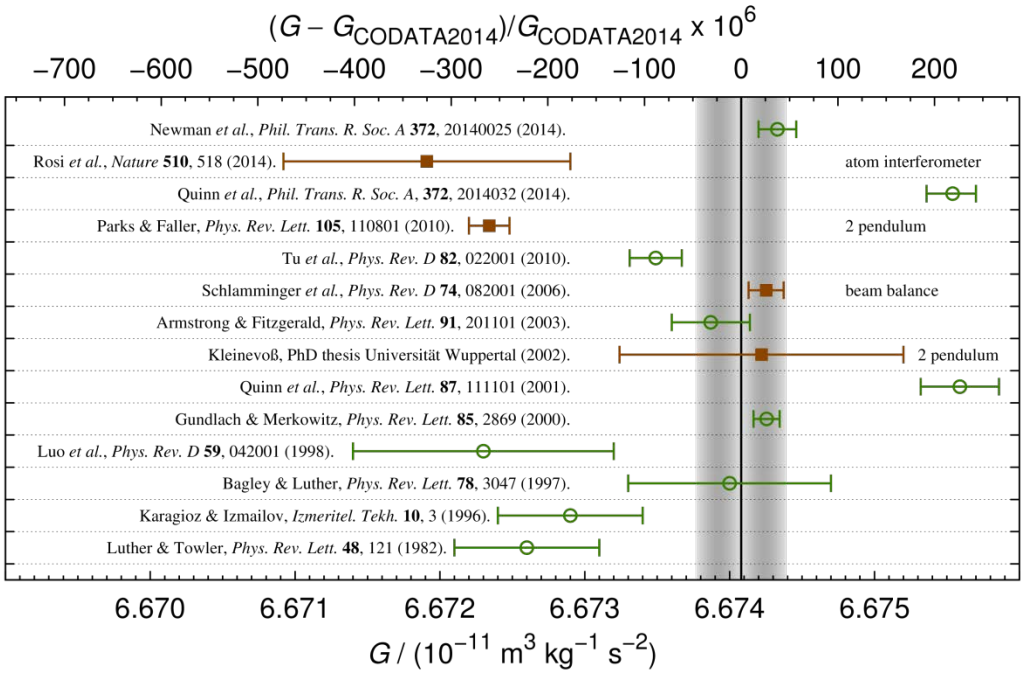
- Expertise needs to be maintained, cf. NIST, JILA

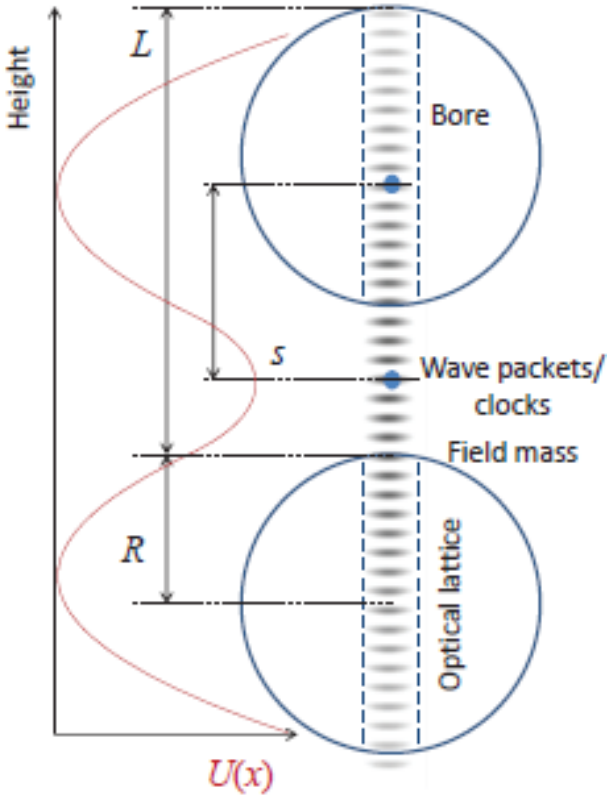




- Technology buildup
- It takes a village

G and Aharonov-Bohm of gravity





- AI measures potential
- allows measuring where u=const
- Verification of fundamental physics
- Force-free effect of gravity
- Atom position as systematic effect removed

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