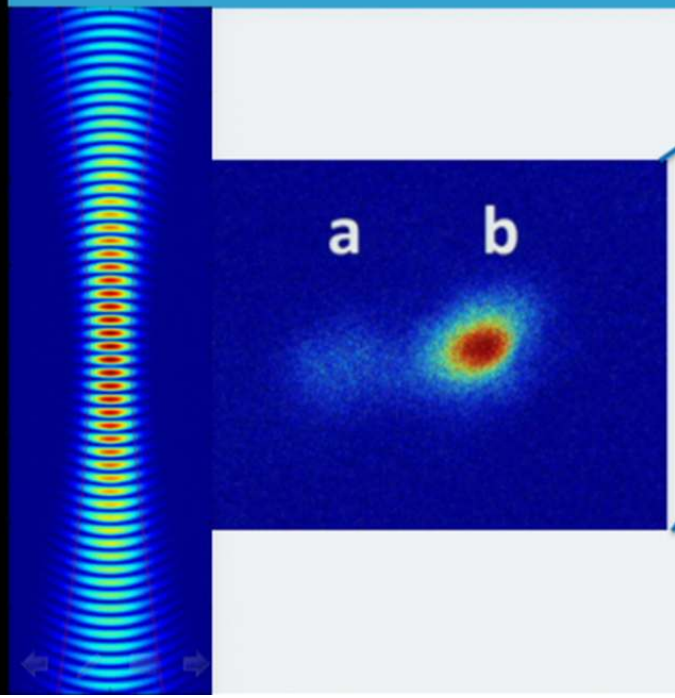
Title: Atomic-Physics Searches for Dark Energy

Date: Sep 14, 2016 02:00 PM

URL: http://pirsa.org/16090042

Abstract: Dark energy, the driver of the accelerated expansion of the universe, remains a conundrum. New physics may well be needed to explain it; from Lorentz invariance, this new physics should contain scalar fields, which should be straightforward to detect â€” so where are they? Physicists have now realized that scalar fields can hide from detection by three distinct screening mechanisms, which respectively rely on nonlinear features in the scalarâ€™s kinetic energy, potential energy, or coupling to normal matter. These fields go by names such as galileons, chameleons, f(R) gravity, or symmetrons and range from theoretically well-motivated and natural to speculative. We will present new techniques to detect these particles, relying on interferometry with cold atoms in vacuum. The low density of such atoms compared to bulk matter avoids triggering some screening mechanisms, while the high sensitivity of the interferometer overcomes other screening mechanisms by brute force. We will show limits ruling out substantial regions of parameter space for chameleons and symmetrons [Science 349, 849 (2015)] and argue that an interferometer with 10,000 fold improved sensitivity will be able to search the gamut of screened scalar fields. A positive identification would revolutionize particle physics and cosmology, but even a null result would have important implications for our understanding of the dark sector.

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



Holger Müller

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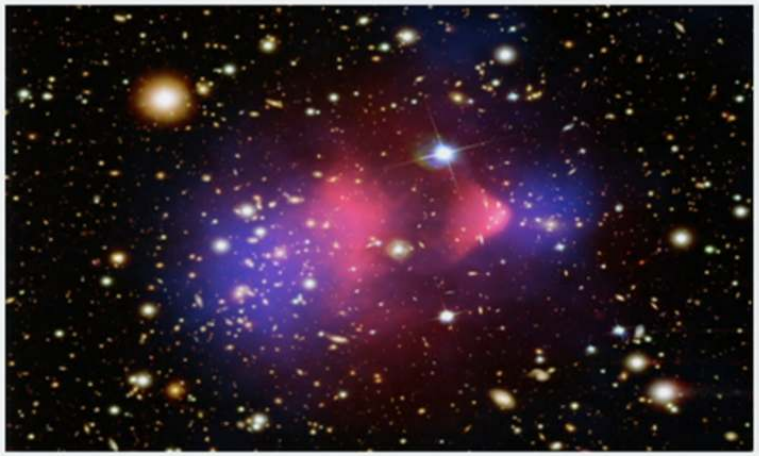
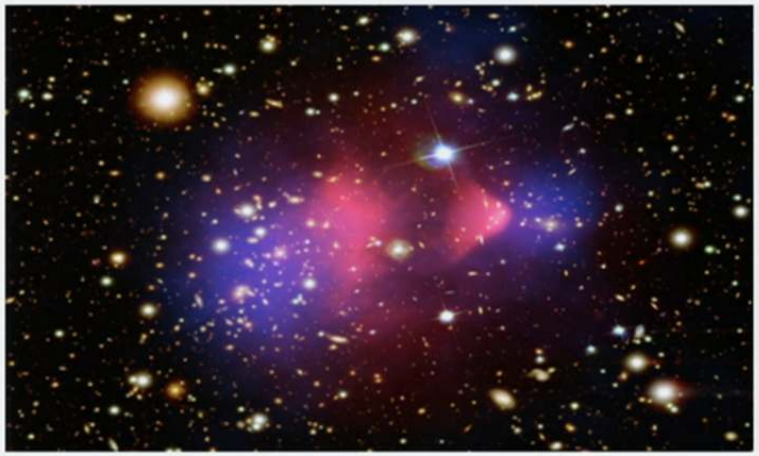
1. Introduction
2. Dark matter through the fine structure constant
3. Dark energy through screened-boson mediated forces
4. Outlook: galileons, symmetrons, and the next few orders of magnitude



Richard Parker, Brian Estey, Chenghui Yu, Weicheng Zhong, Shau-Yu Lan, Pei-Chen Kuan, H.M.

Dark matter



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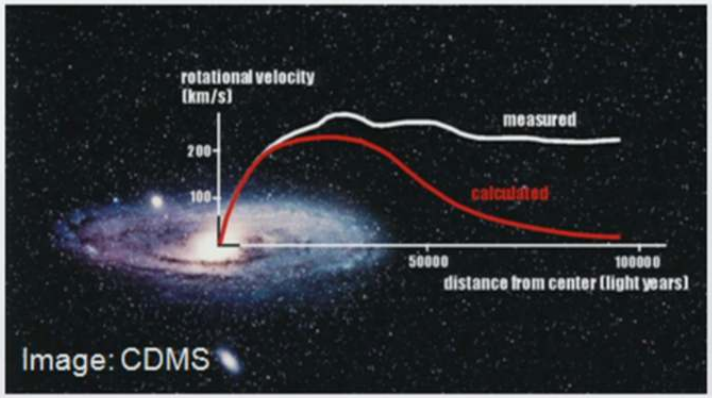
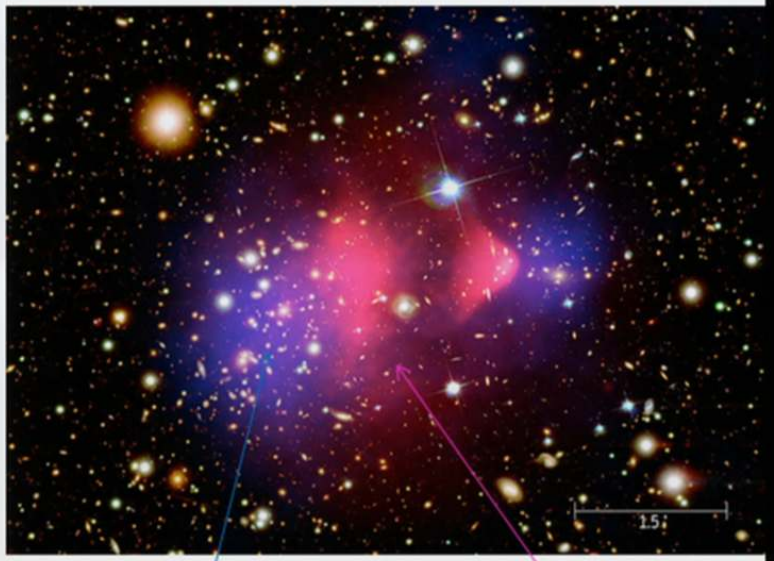
Dark matter

The standard model is incomplete

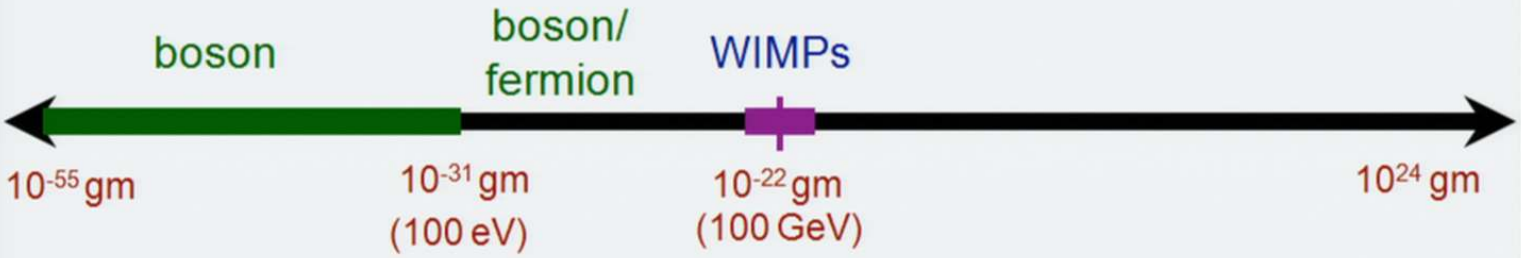




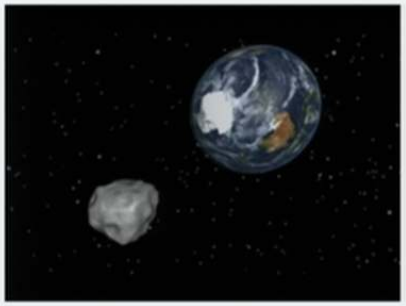
Reconstructed mass distribution (lensing)

Observed matter (Chandra x-ray observations)

The Dark Matter Landscape



Ultra-light	Moderately Heavy	Super Heavy
Large number density	Reasonable density	Ultra low density
Dark Wind	Dark Rocks	Dark Asteroids



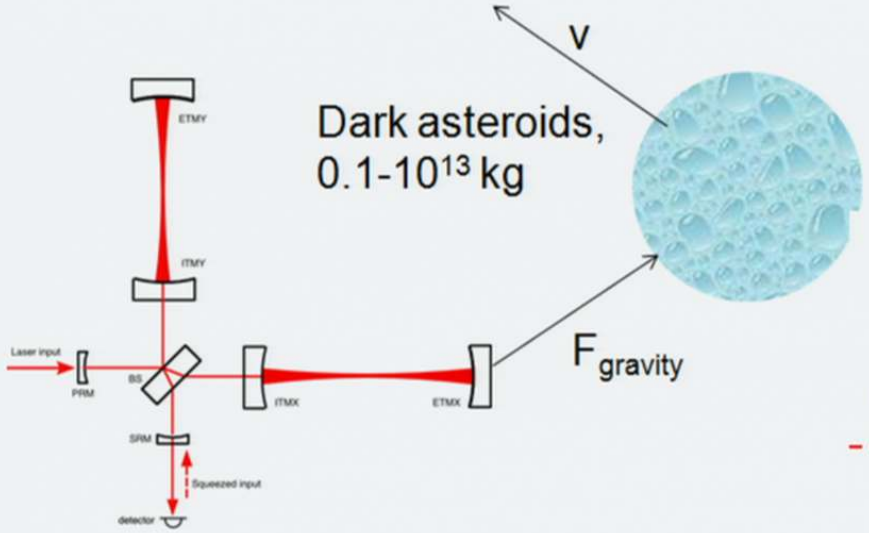
Surjeet Rajendran

Exploitable features?

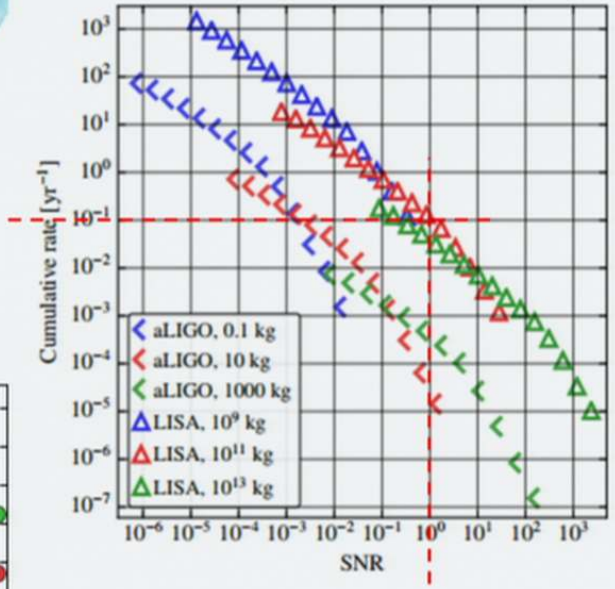
Input: DVI - 1280x720p@60Hz
Output: SDI - 1920x1080i@60Hz

LIGO as a dark matter detector

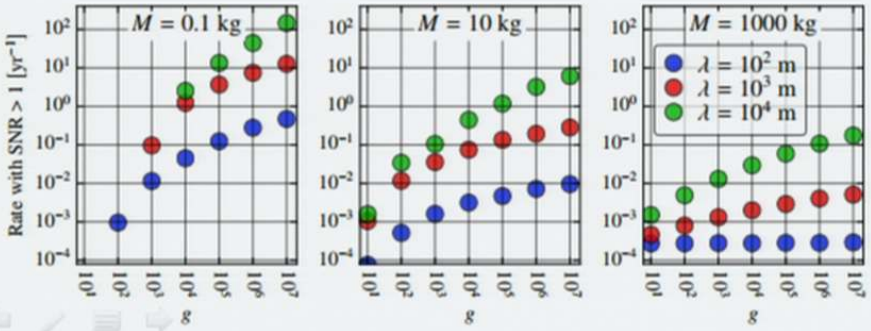
E. D. Hall, Th. Callister, V. V. Frolov, H. Müller, M. Pospelov, and R. X. Adhikari



One event every 10 years assuming only gravity

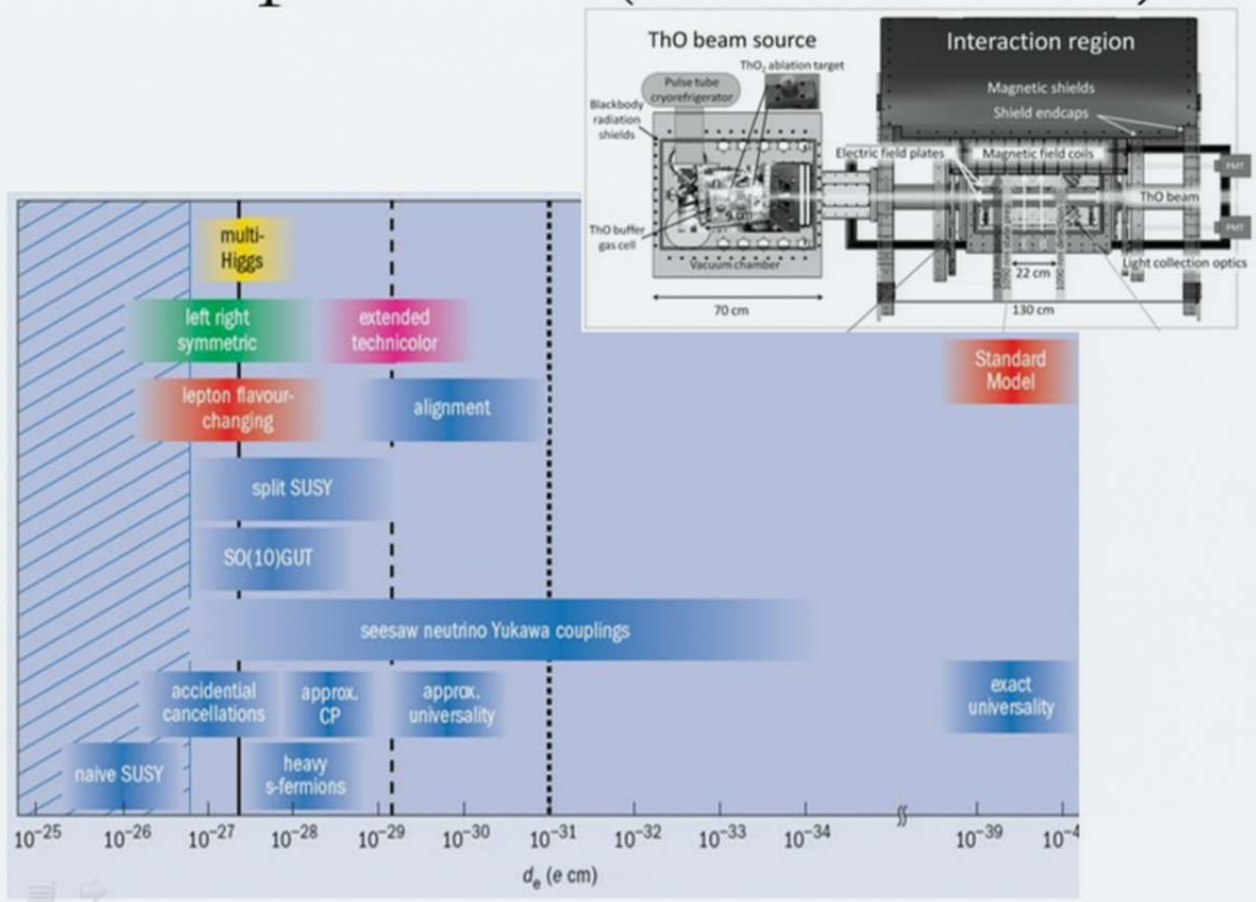


Multiple events/year with Yukawa coupling

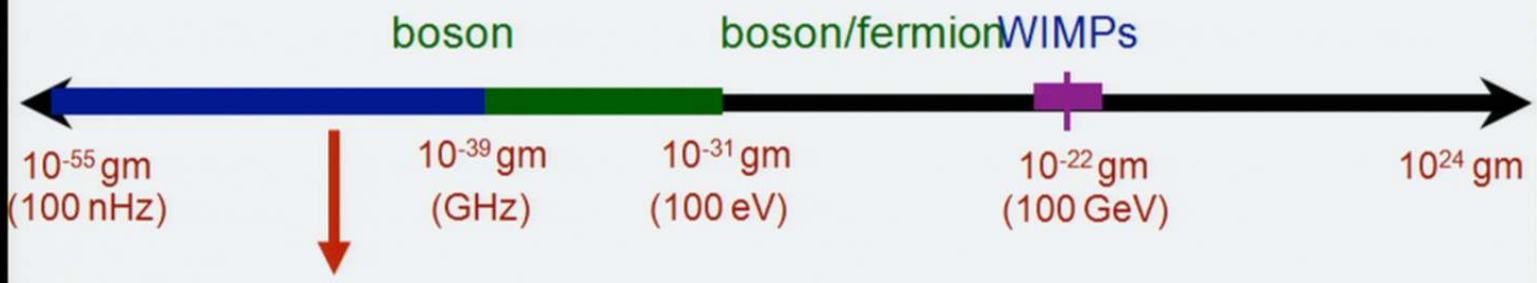


arXiv:1605.01103

Advanced Cold Molecule Edm experiment (Yale, Harvard)



Axion Dark Matter



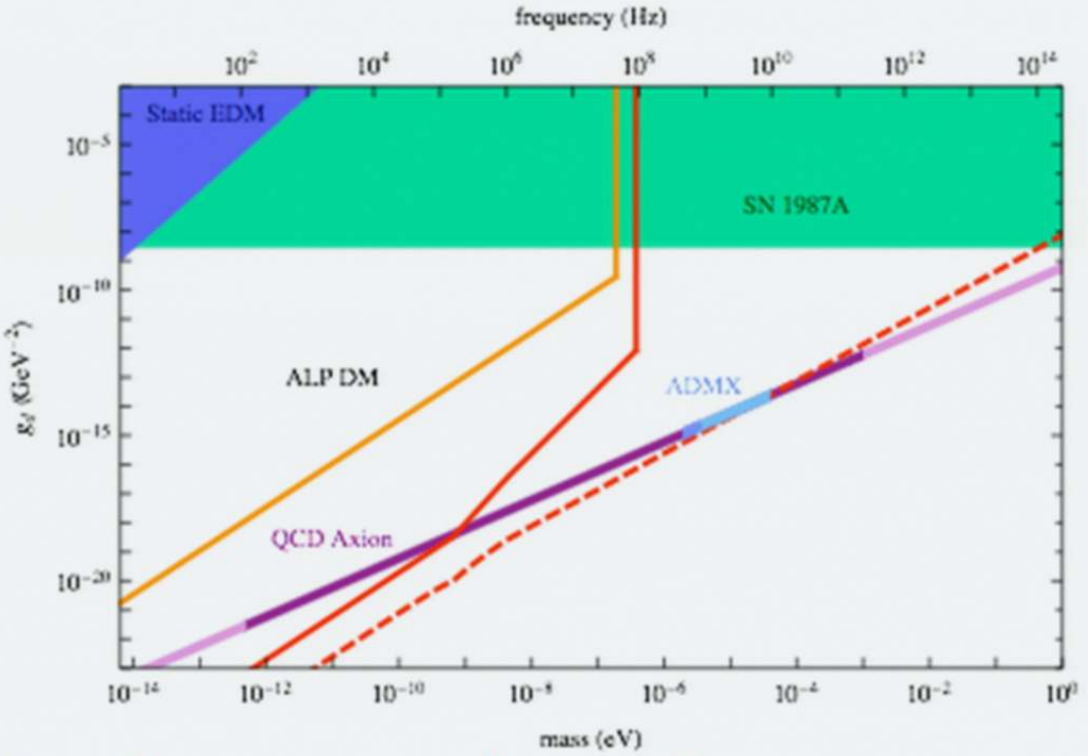
Cosmic Axion Spin Precession Experiment

D. Budker, P. Graham, M. Ledbetter, S. Rajendran, A. Sushkov

SIMONS FOUNDATION

HEISING - SIMONS FOUNDATION

DFG Deutsche Forschungsgemeinschaft



Larmor frequency = axion mass → resonant enhancement

SQUID measures resulting transverse magnetization

NMR well established technology, noise understood, similar setup to previous experiments

Example materials: LXe, ferroelectric $PbTiO_3$, many others

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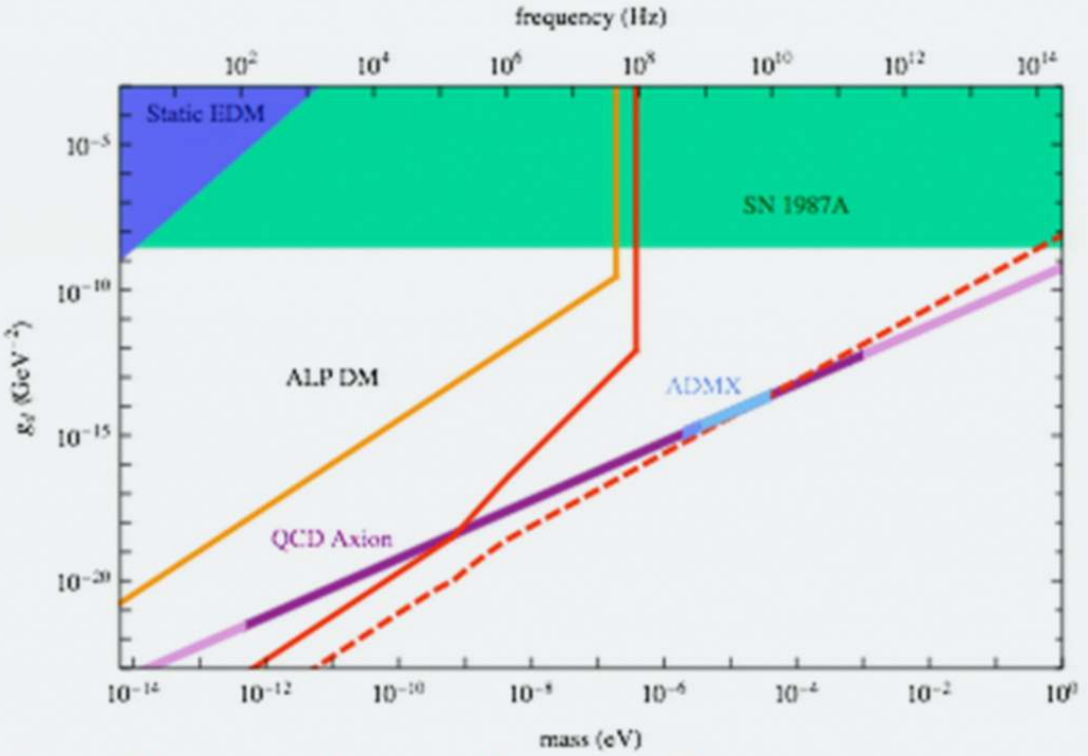

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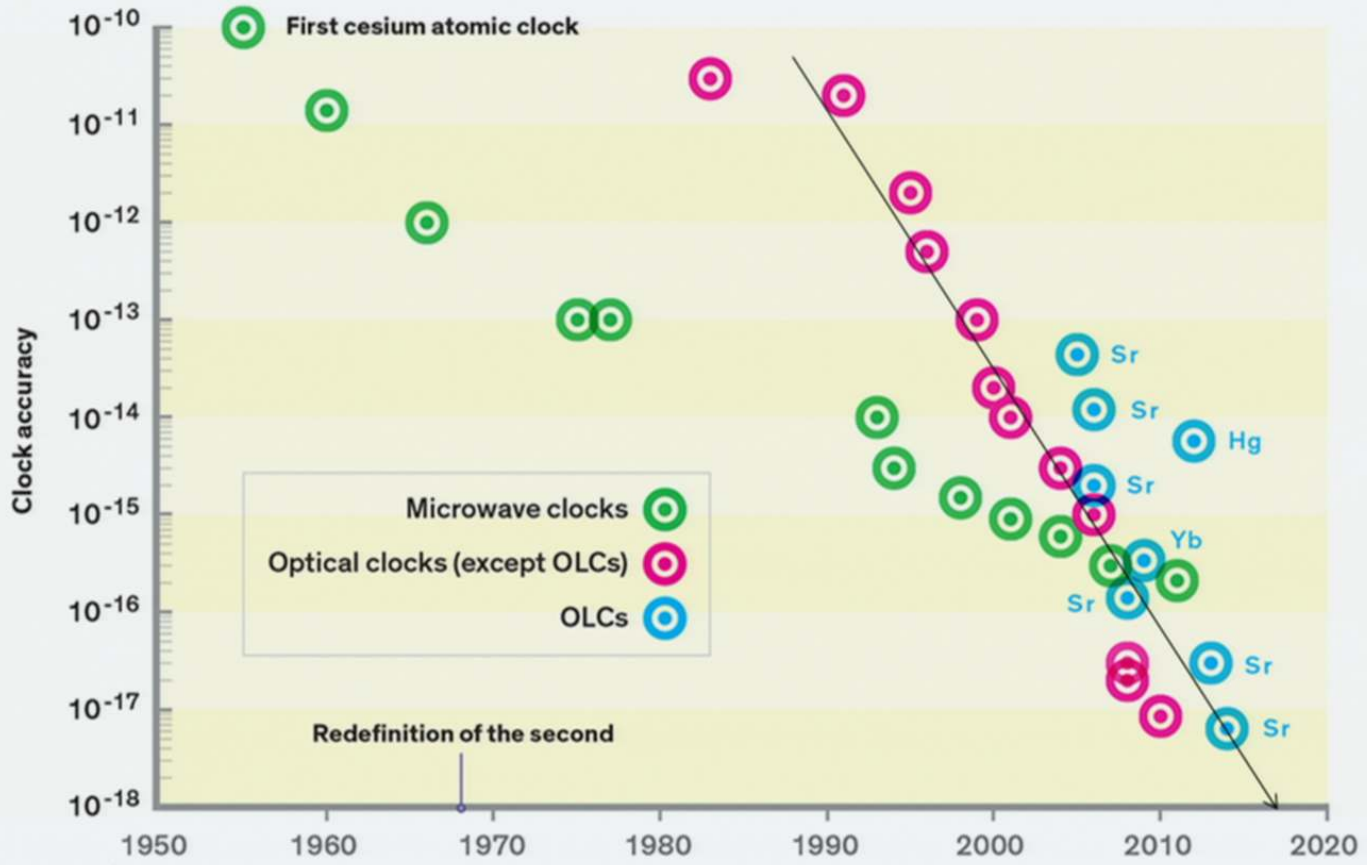
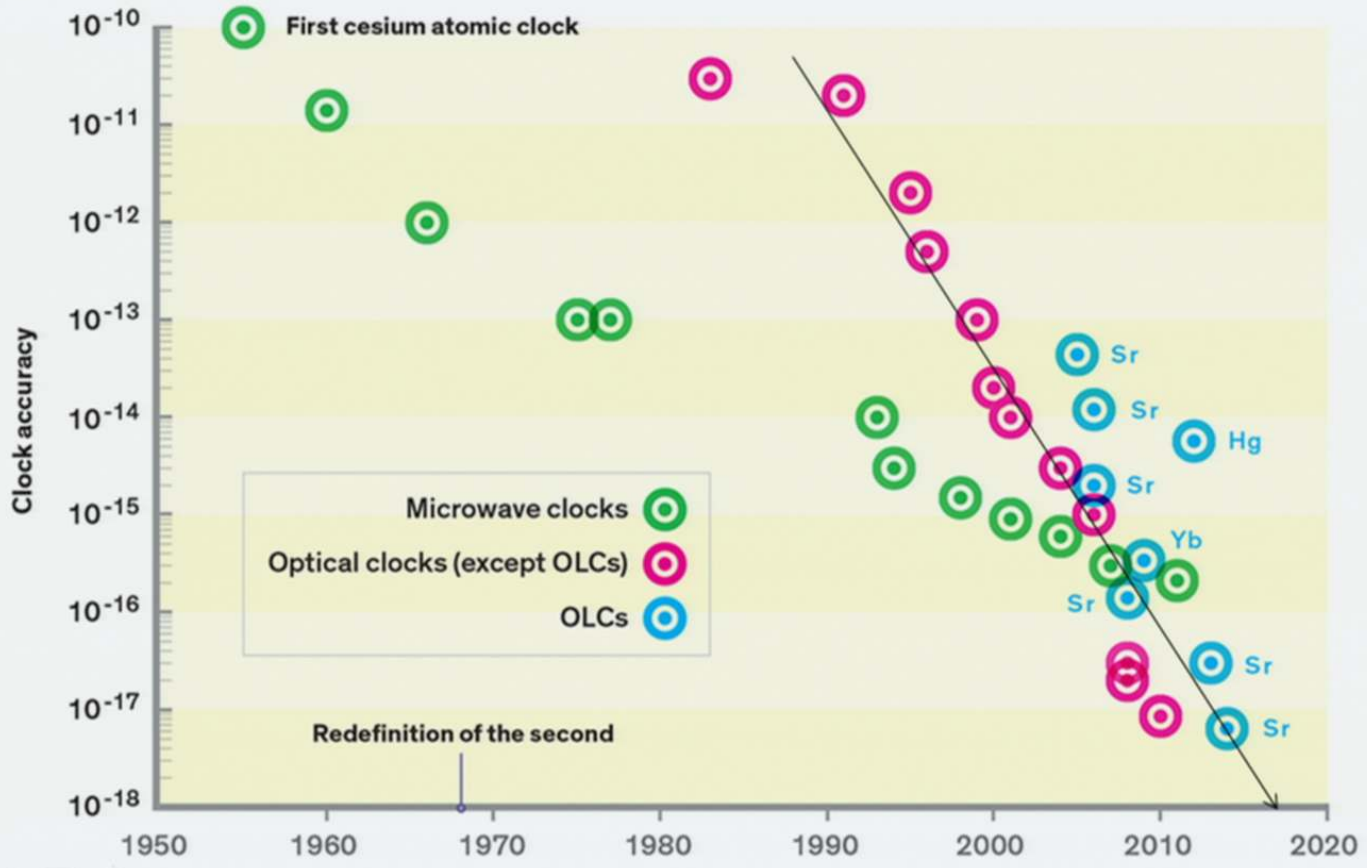
Moore's law in atomic physics

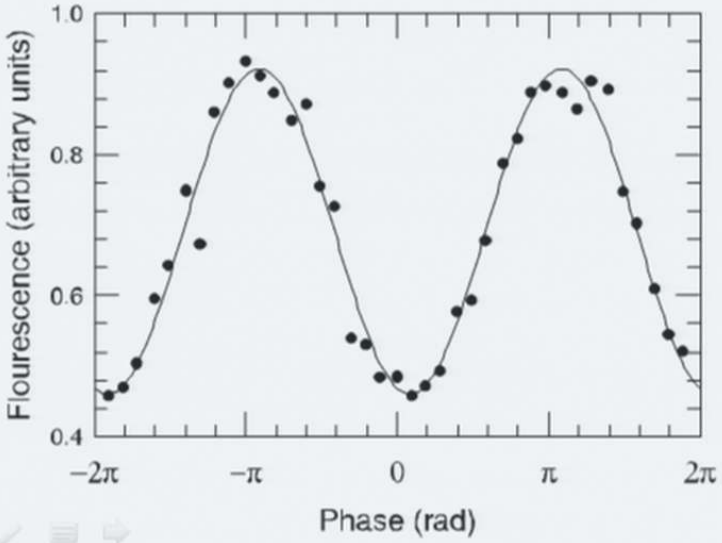


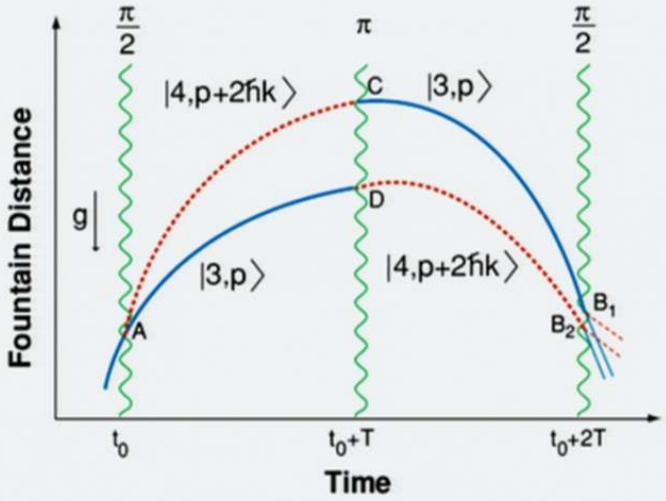
Moore's law in atomic physics



Light pulse atom interferometer

$$\Delta\varphi = -\frac{1}{\hbar}\oint L dt + \Delta\varphi_{\text{laser}}$$
$$= 2T^2\vec{\Omega}\cdot[\vec{k}\times(\vec{v}_0 + \vec{a}T)] + \vec{k}\vec{a}T^2$$
$$+ O(1/c^4)$$

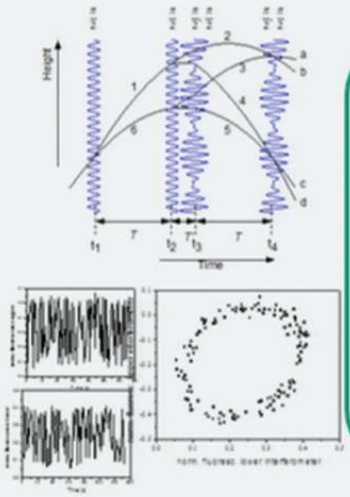




Each data point is from a single launch, determines g to 1.3ng =>11ng/sqrt(Hz)

HM *et al.*, PRL **100,** 031101 (2008); PRD **80,** 016002 (2009)

Atom-optics technology development

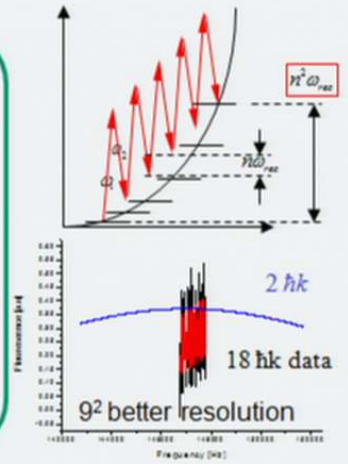


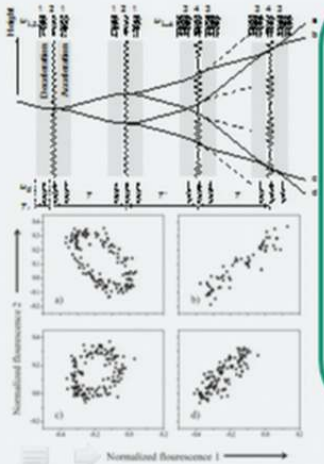
Simultaenous Conjugate Interferometers

- 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)



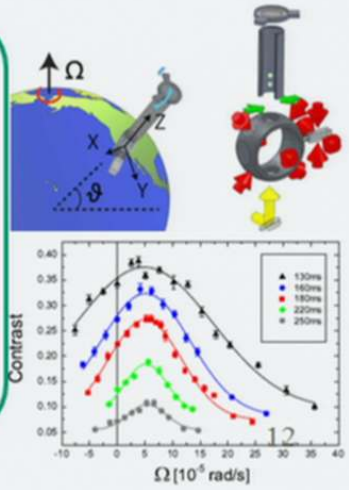


Optical lattice beam splitter

- 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)

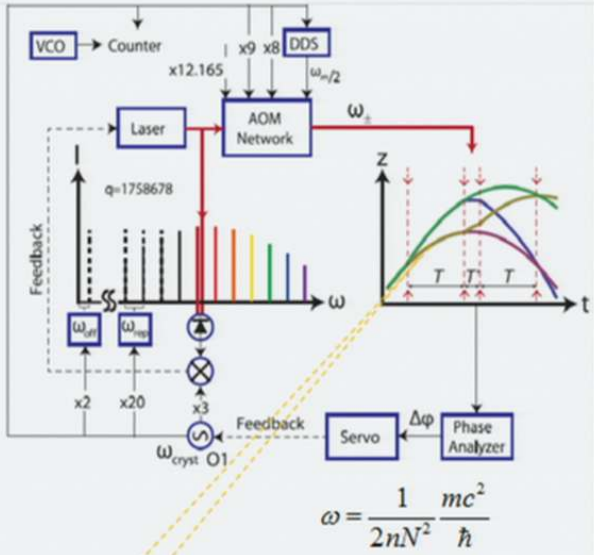


REPORTS

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

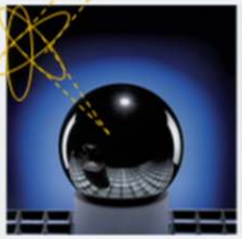
Application

- 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

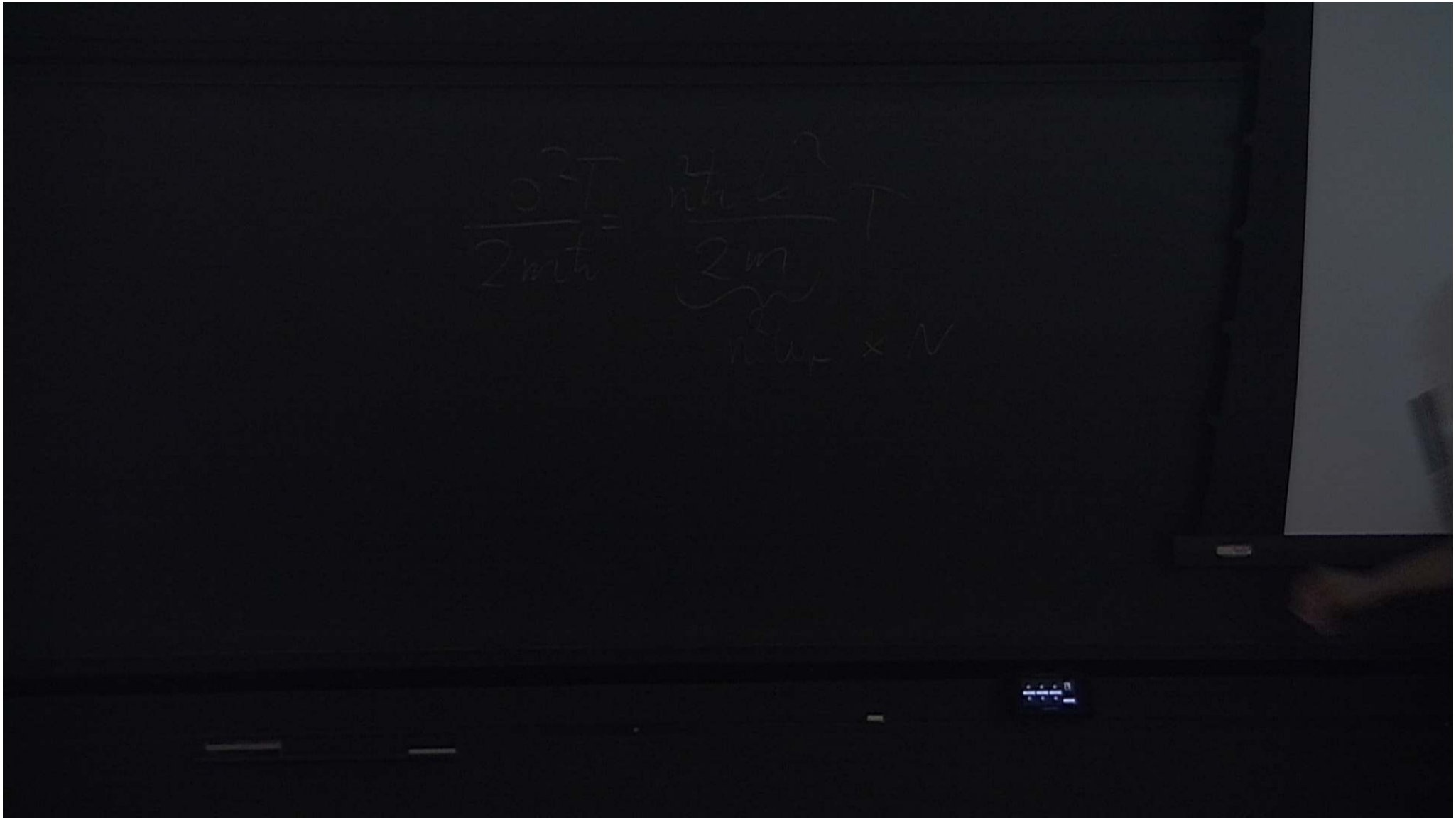
Atom interferometer+counting

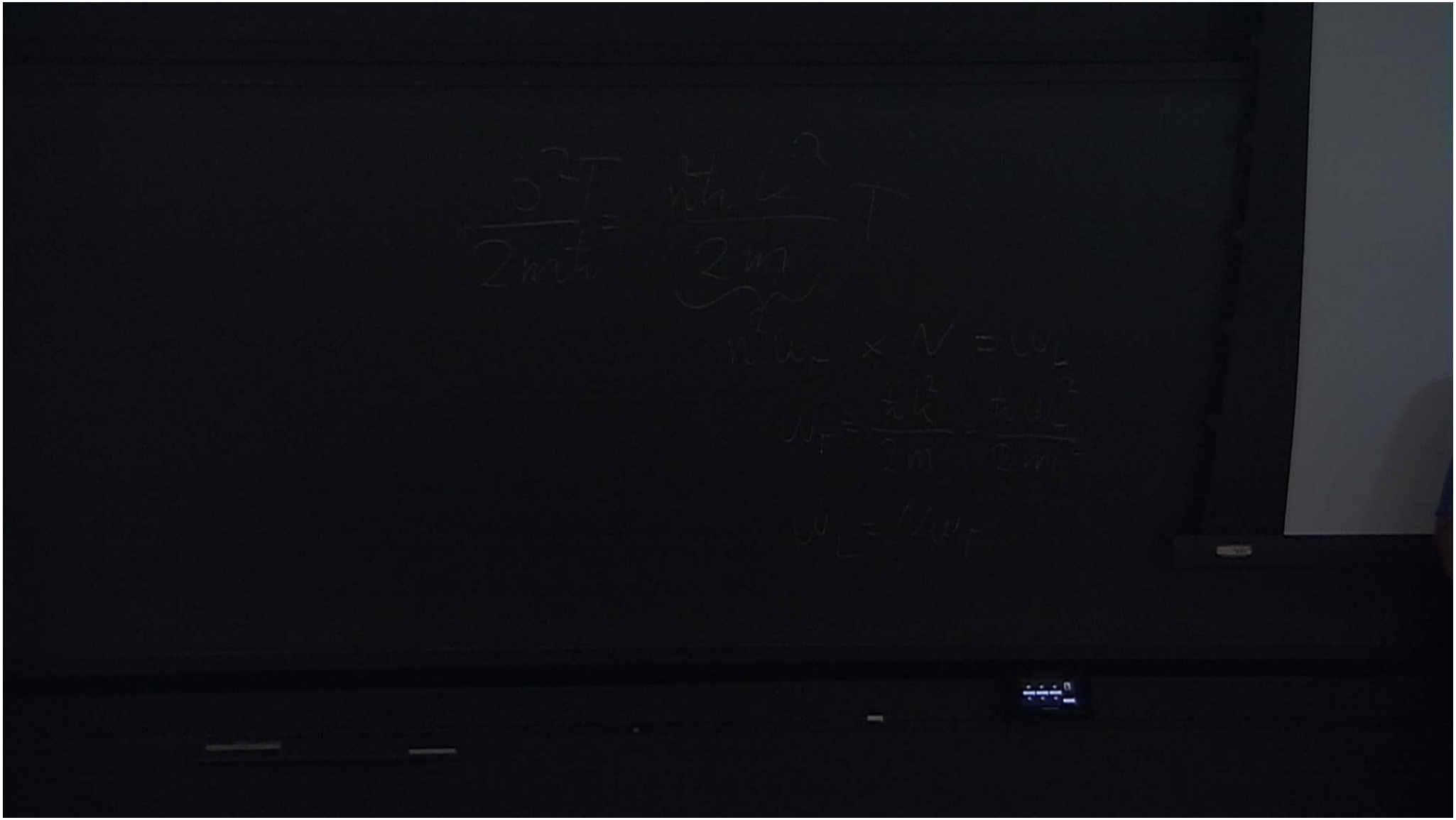


- 4 ppb for amu
- 30 ppb for kg
- No moving parts, gravity, standard resistors…
- Agrees with European versions
- <1 ppb in the future

Independent methods realize the same definition ☺

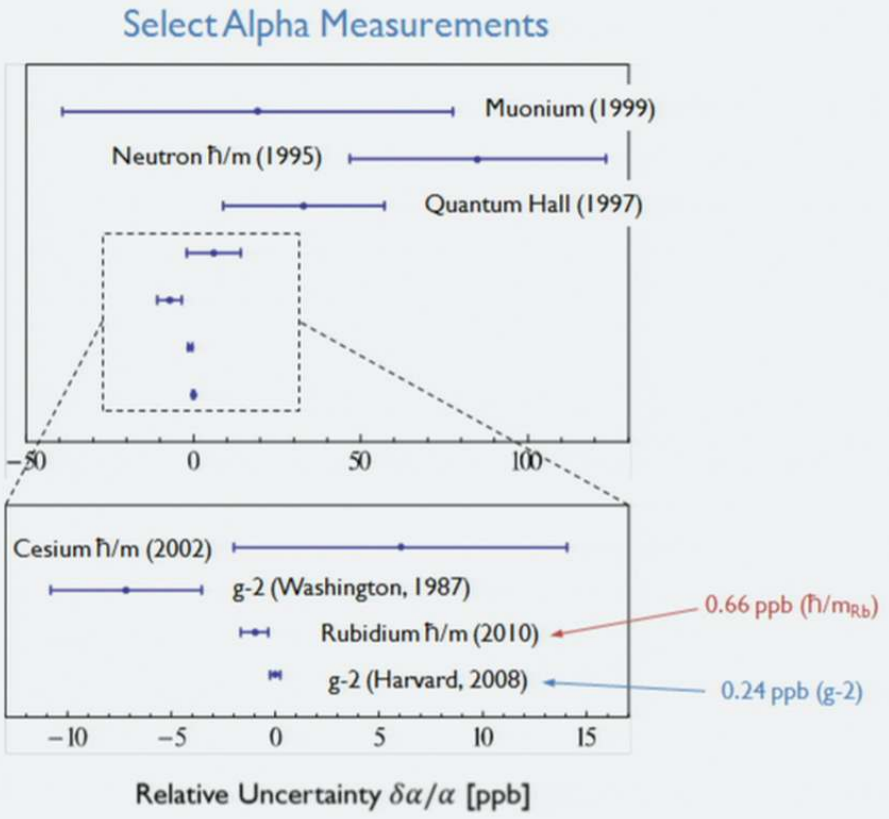
13





Fine Structure Constant α

- $hcR_\infty = \frac{1}{2}\alpha^2 m_e c^2$



Rev. Mod. Phys. 84, 1527 (**2012**)

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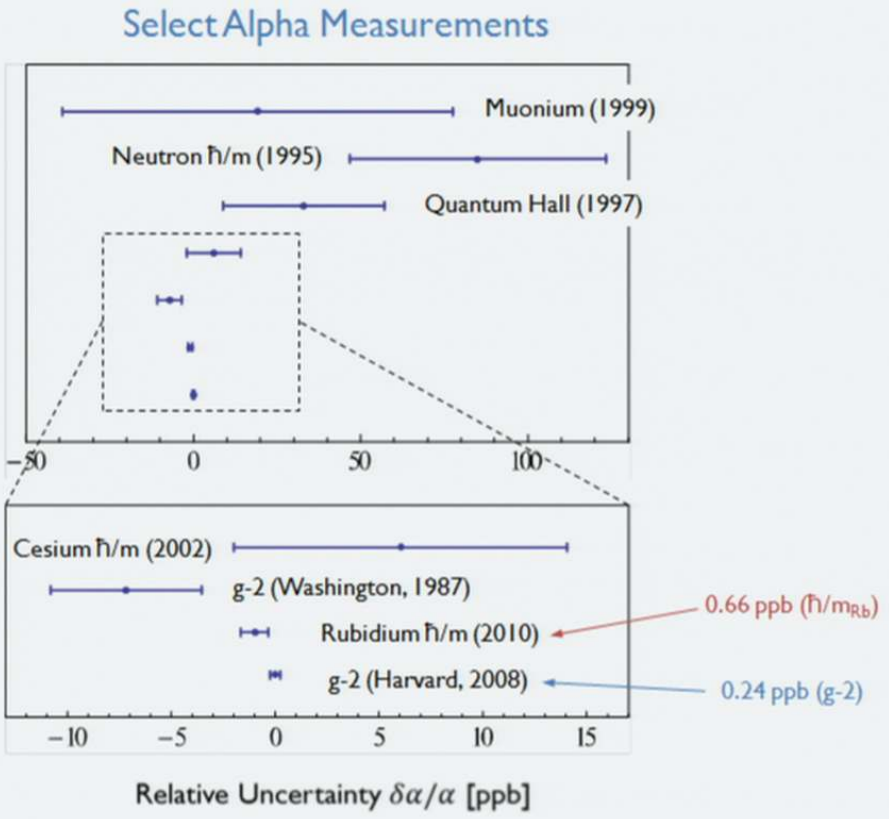
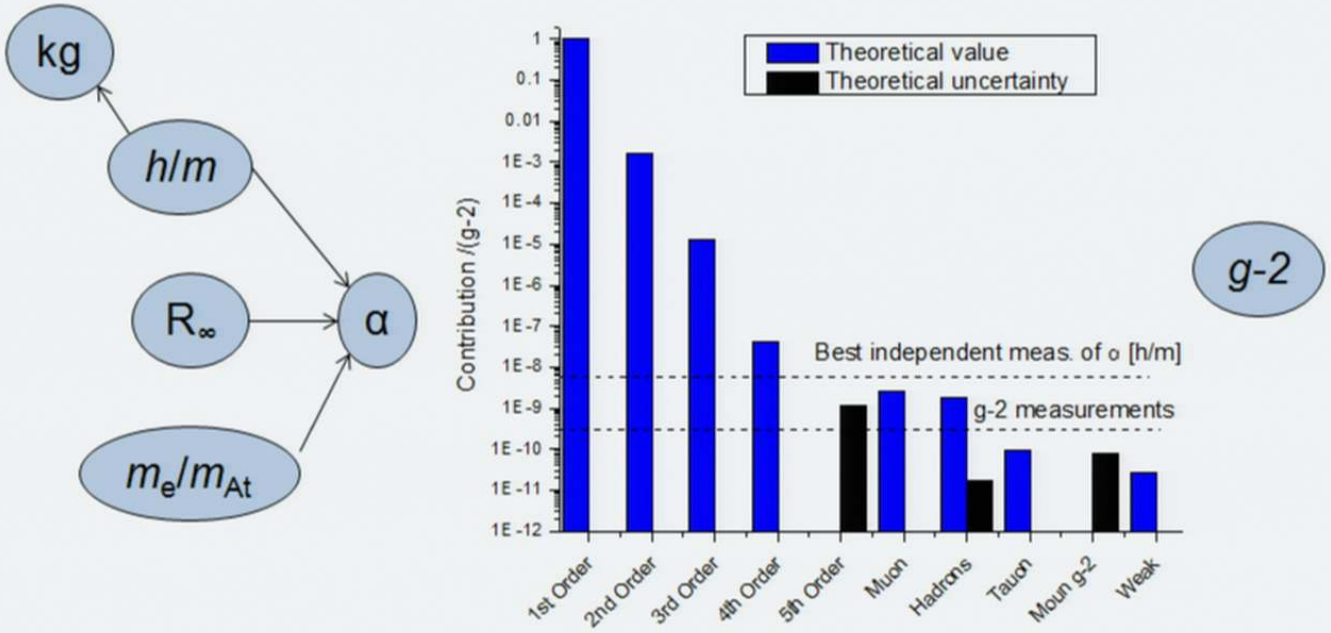


Rev. Mod. Phys. 84, 1527 (**2012**)

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

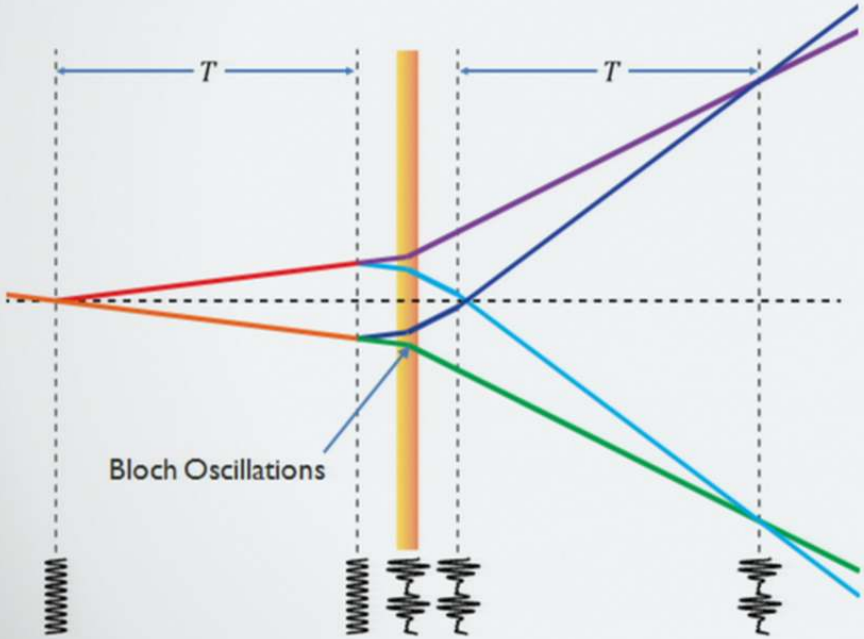


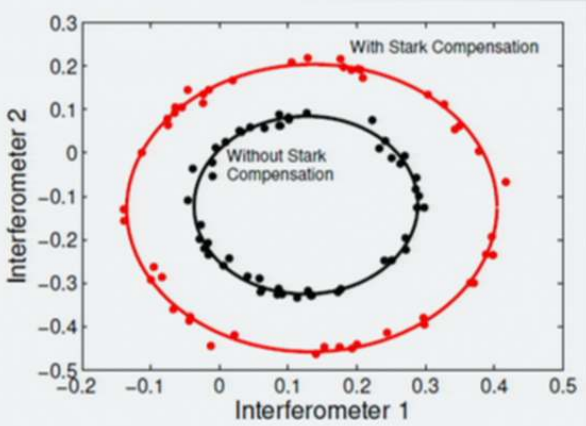
- All experiments and all theories have ppb accuracy
- Substantial parts of the Standard Model have to be right to yield α and g-2 at that level

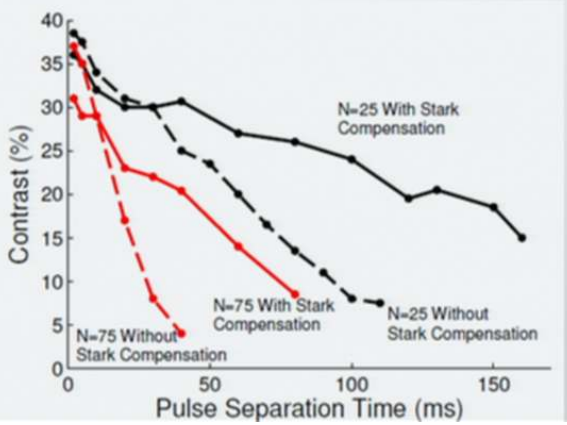
Common-mode Bloch Oscillations

- Increases total phase of interferometer
- Increases frequency splitting of last two pulse
- 6,000,000 rad matter-wave phase difference

$$\Delta\phi = 16n(n+N)\omega_r T$$

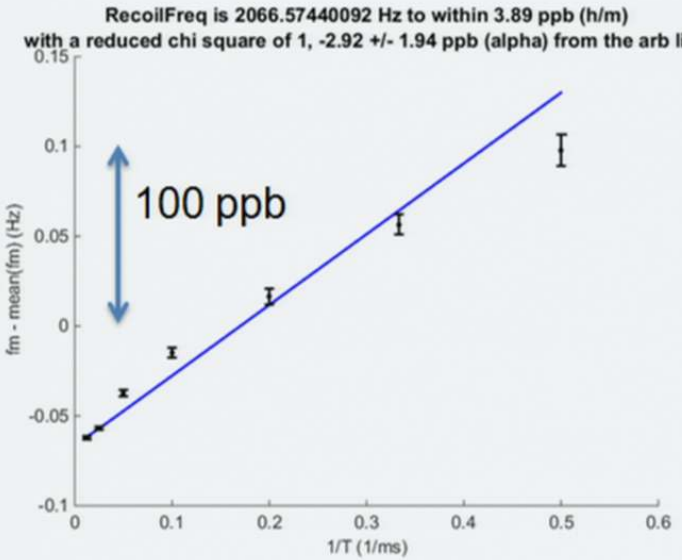




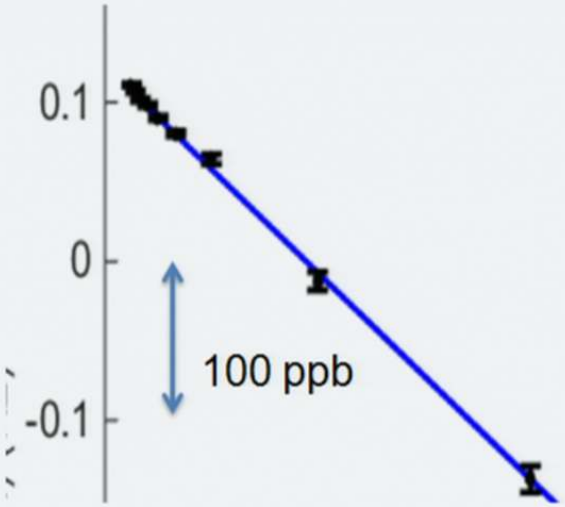


Understanding diffraction phases atom interferometers at 10^{-10}

Before filtering



With spatial filtering

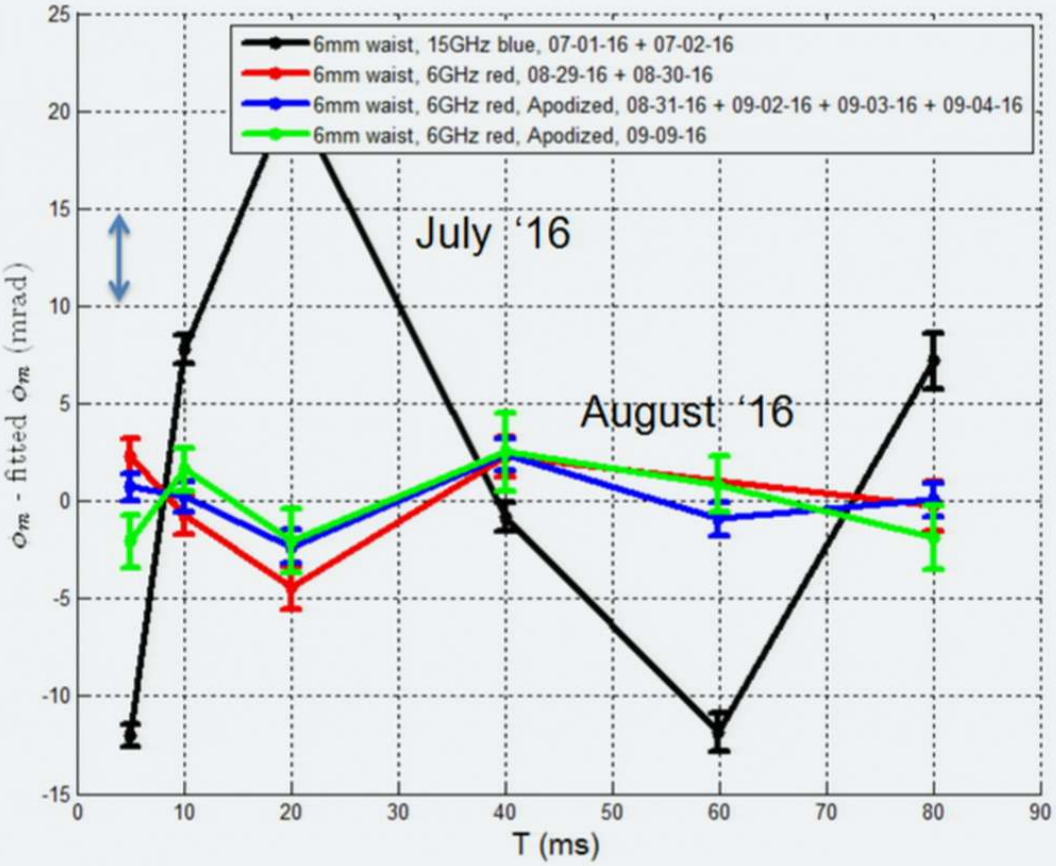


Spatial Filtering Beam

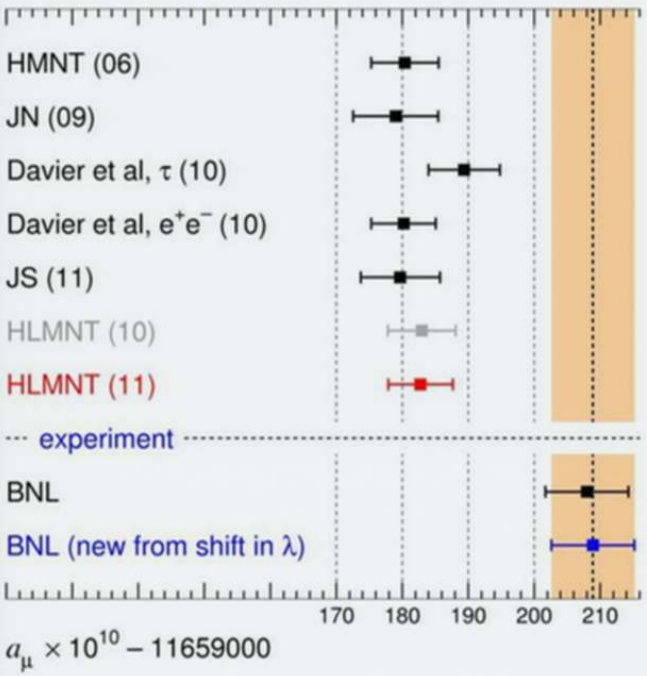
Estey et al, PRL (2015)

Anomalous Phases

1 ppb



g-2 and α



Muon g-2 campus at Fermilab

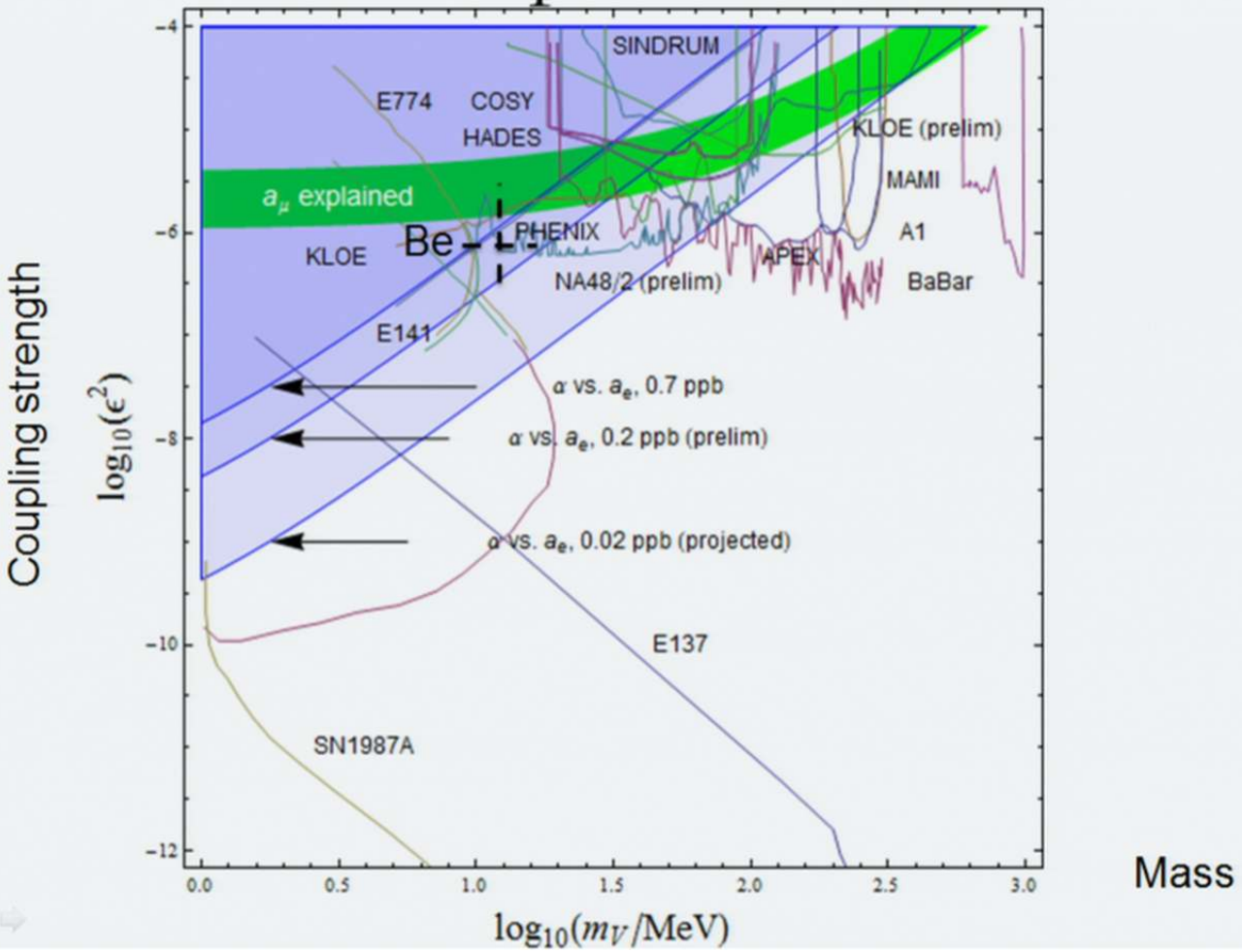
$$3\times10^{-6}\times\left(\frac{m_e}{m_\mu}\right)^2 = 0.07\text{ppb}$$

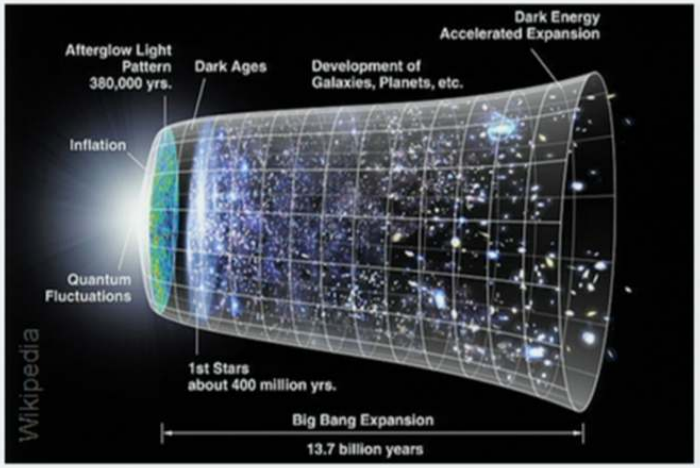
Can be tested in next-generation measurement of α and g_e-2

Dark matter candidatess such as dark photons

Sensitive up to energy scales $m \sim [m_e/(10^{-10})]^{1/2} \sim 100$ GeV

Dark photons

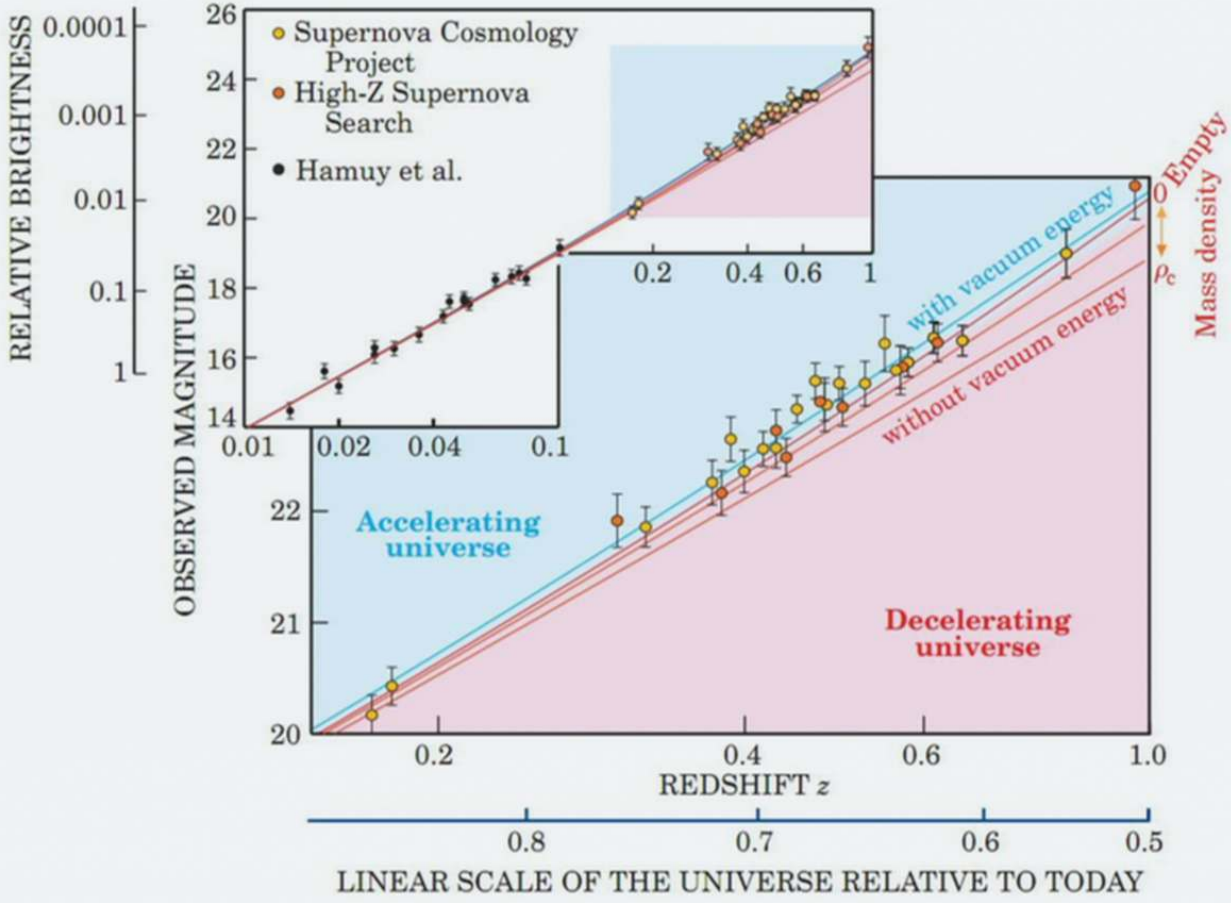




Paul Hamilton, Philipp Haslinger, Matt Jaffe, Brian Estey, Justin Khoury
H.M.

Dark energy

The standard model is incomplete



Saul Perlmutter

Dark Energy: Models?

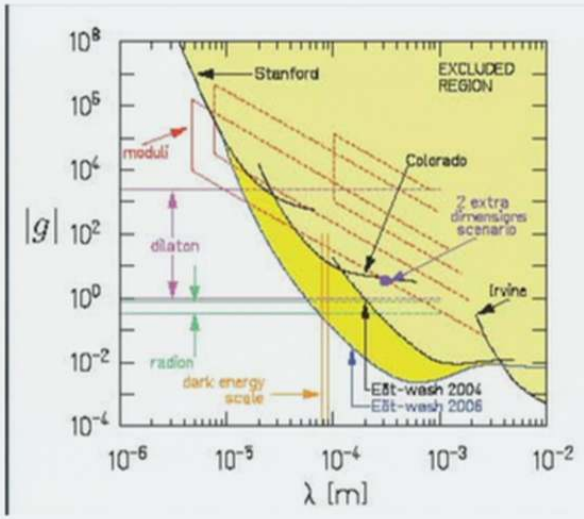
Vacuum fluctuations ~ Λ_{uv}^4 (Pauli, circa 1920) — 123 orders of magnitude off

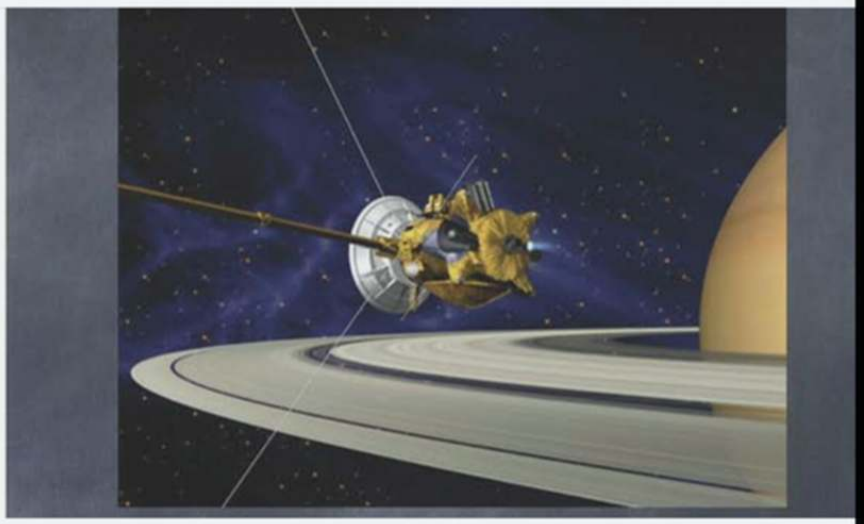
Cancellations cutting Λ_{uv}^4 and Λ_{uv}^2 — $m^4 \log(\Lambda_{uv}/m)$ still 33 orders off

$\Rightarrow$ New physics needed

- Typically new bosons
- To solve problem, must couple to normal matter
- ~Gravitational strength
- Must be compatible with existing experiments

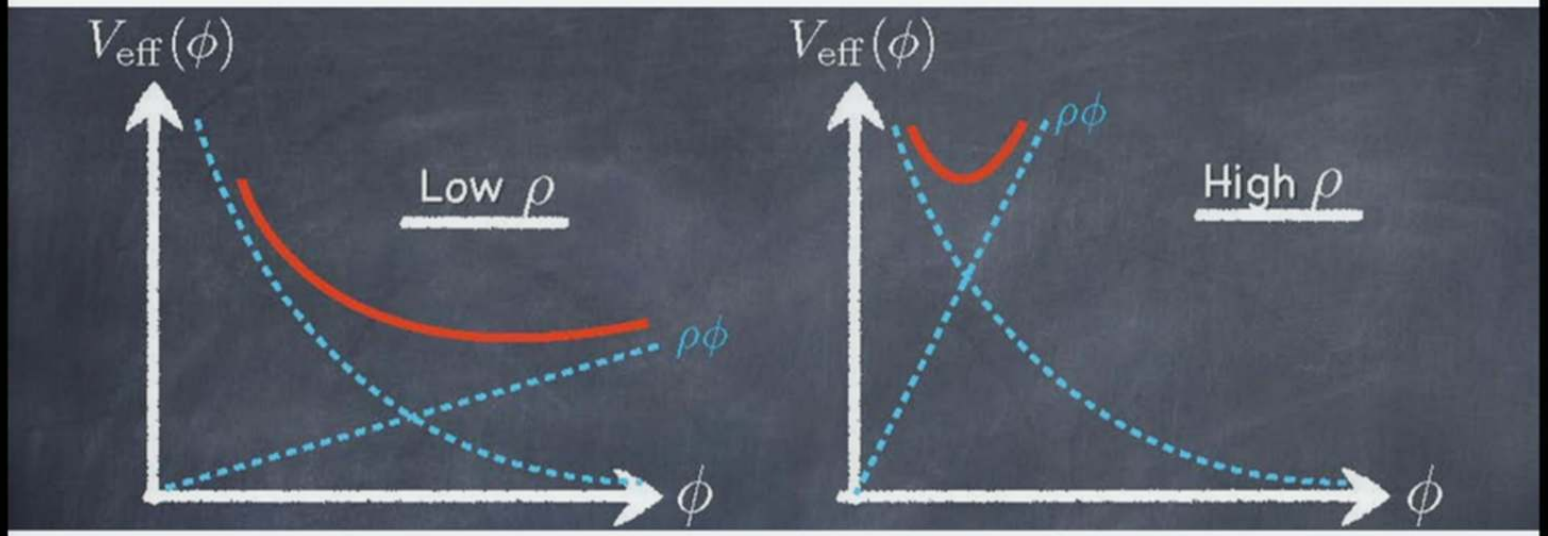
Direct interactions: ruled out?



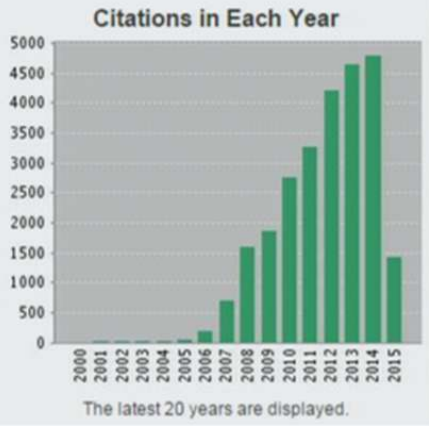


Not so fast….

DE-matter-coupling is screened

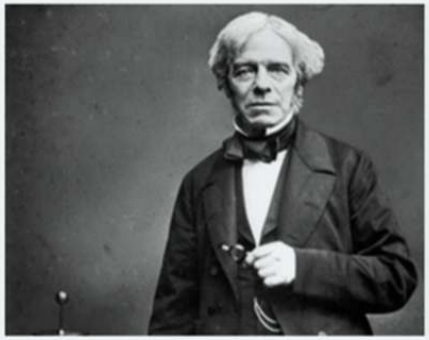


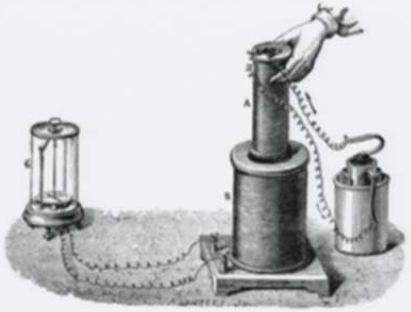
- M, extra dimensions, string theory…
- "$P(X)$, $f(R)$, Vainshtein…"
- **Experiments**
  - Cern Axion Solar Telescope CAST
  - GammeV collab
  - Axion dark Matter Experiment ADMX
  - Neutron Interferometers
  - Torsion balances



Faraday's law and Maxwell's equations

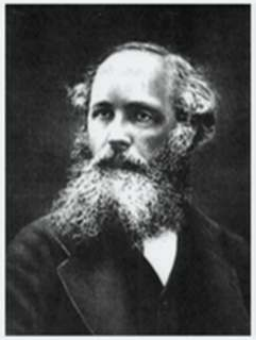
1831





$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

1861-65



$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

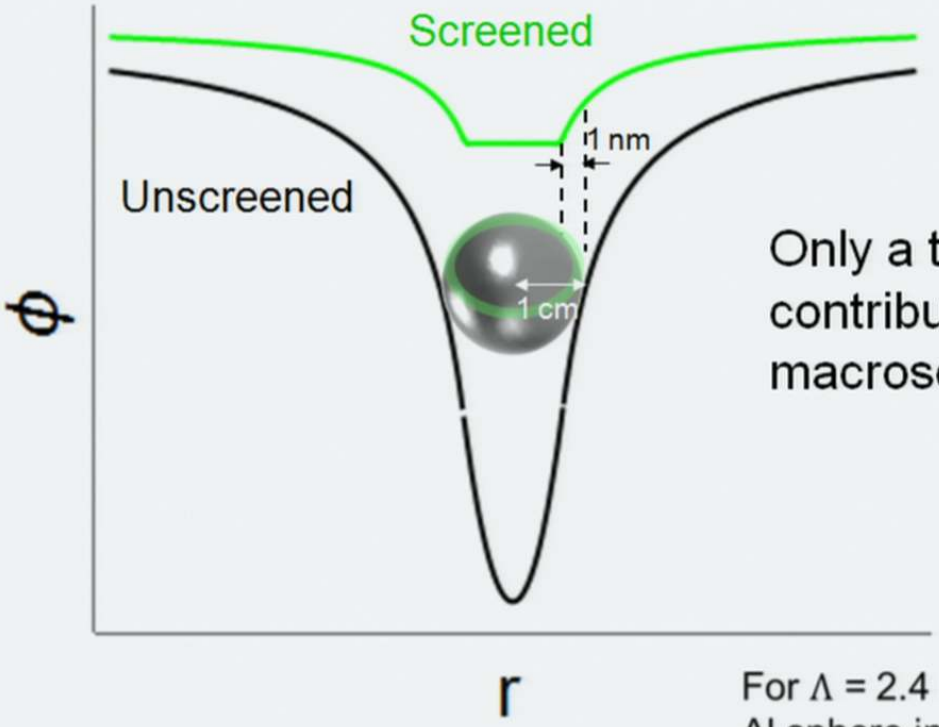
$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

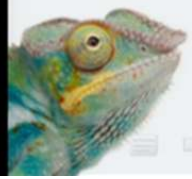
1886-89

Chameleon screening

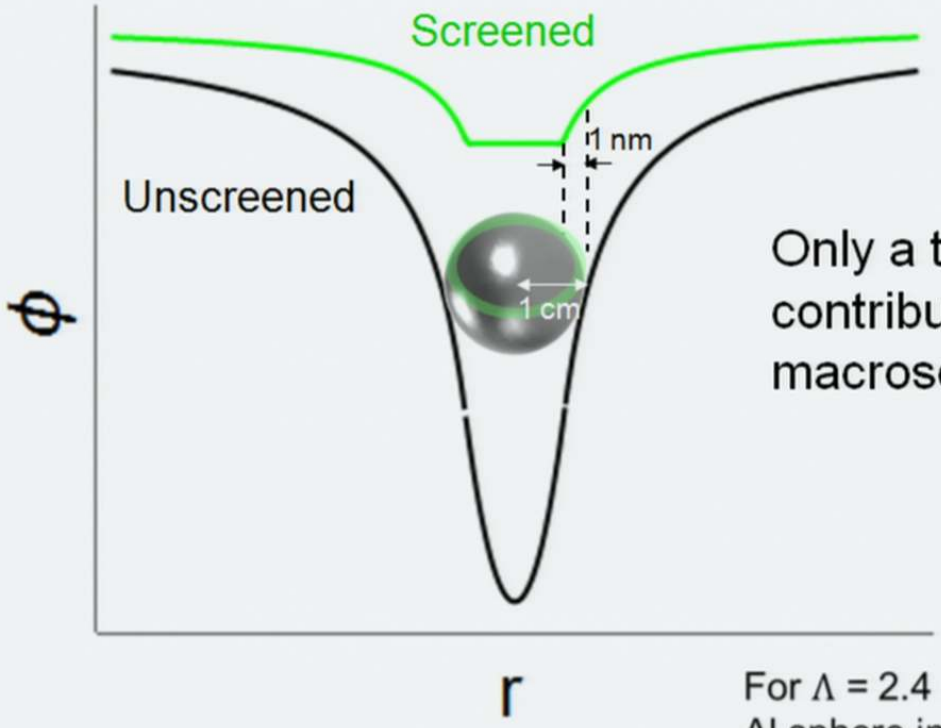


Only a thin shell contributes in macroscopic objects

For $\Lambda = 2.4$ meV, $M = 10^{-5}\ M_{Pl}$
Al sphere in 10^{-10} Torr vacuum



Chameleon screening



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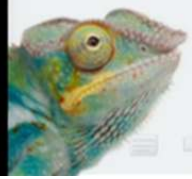


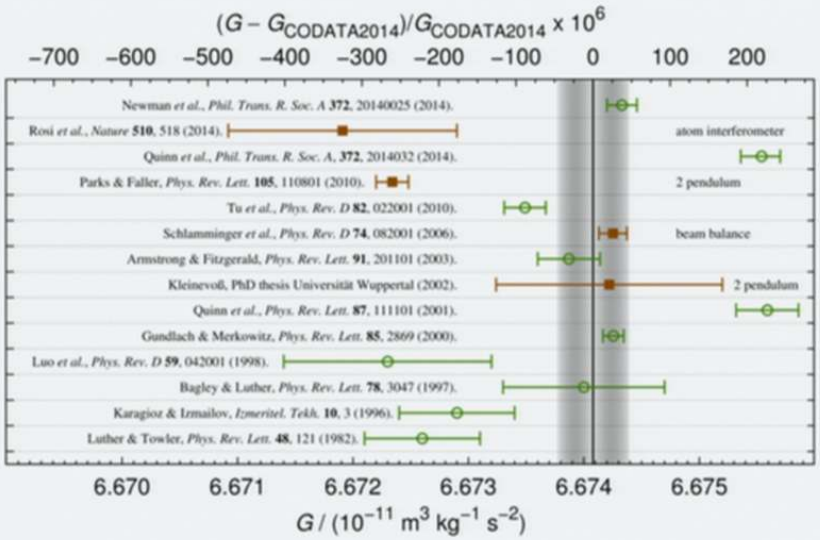
Unscreened force for atoms

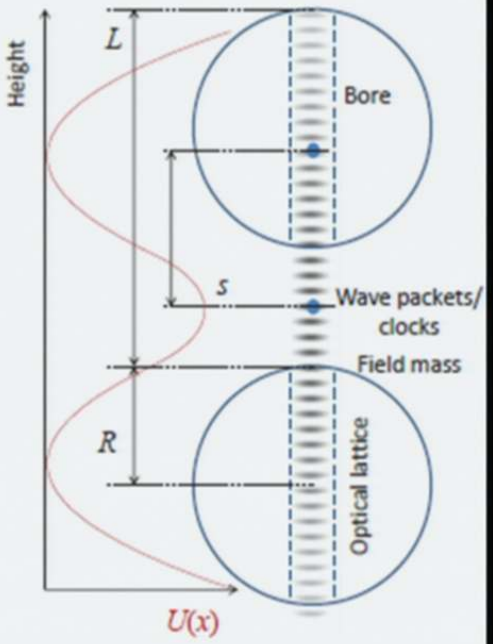
$$F_{chameleon} = \frac{GM_AM_B}{r^2}\left[1 + 2\,\lambda_A\cancel{\lambda_B}\left(\frac{M_{Pl}}{M}\right)^2\right]$$

$\lambda_{atom} = 1$

For most of parameter space

G and Aharonov-Bohm of gravity

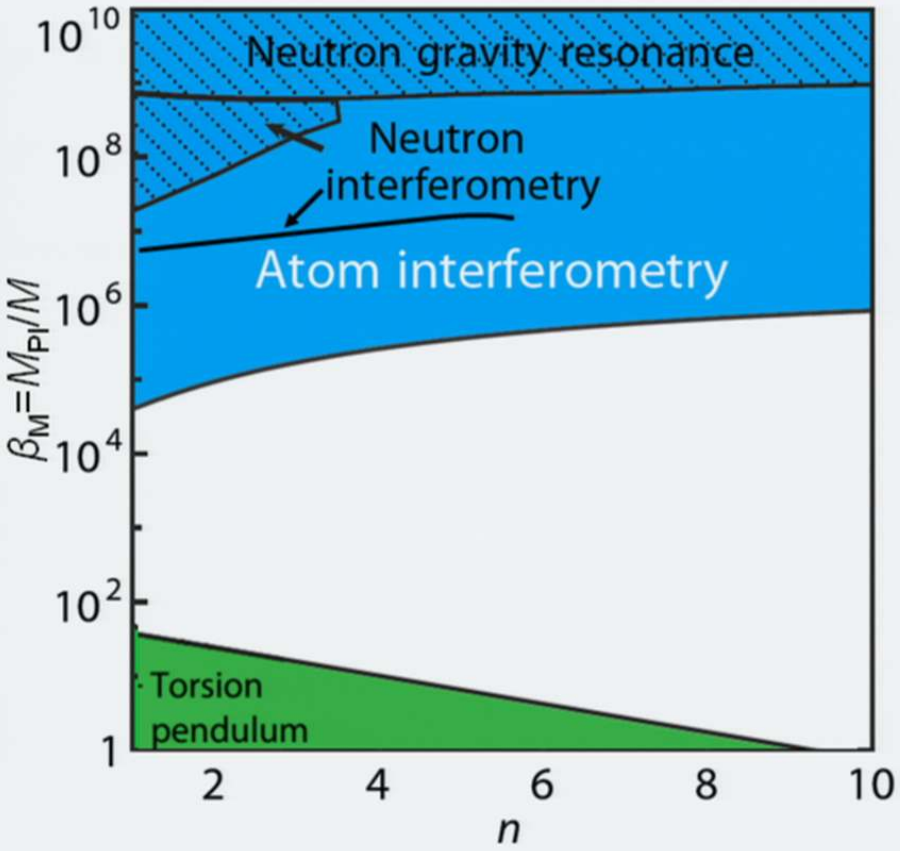




- New fundamental physics effect:
- Force-free effect of gravity
- Atom position as systematic effect removed

PRL **108,** 230404 (2013)

Dark energy limits



Limits at $\Lambda = 2.4\ \mathrm{meV}$ versus power law exponent n, of the chameleon potential

T. Jenke et al. PRL 112, 151105 (2014)

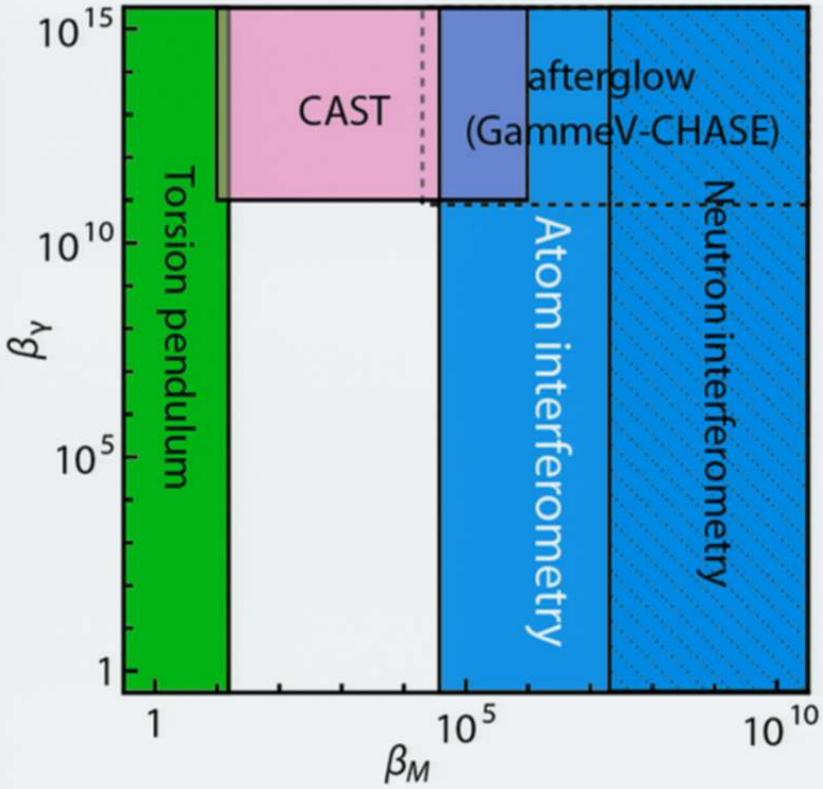
H. Lemmel et al. Phys. Lett. B 743 (2015) 310-314

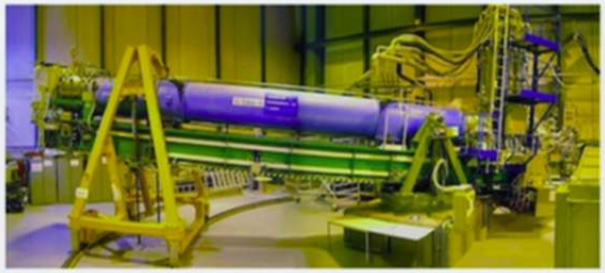
Amol Upadhye Phys. Rev. D **86**, 102003 (2012)

K. Li et al. arXiv:1601.06897 (2016)

P. Hamilton, M. Jaffe, P. Haslinger, Q. Simmons, H. Müller, J. Khoury Science 349, 849 (2015).

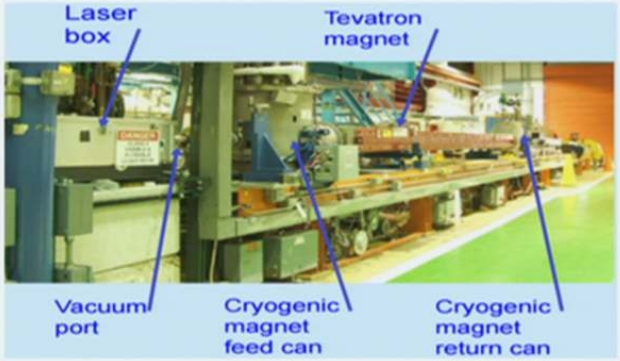
Photon coupling comparison





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

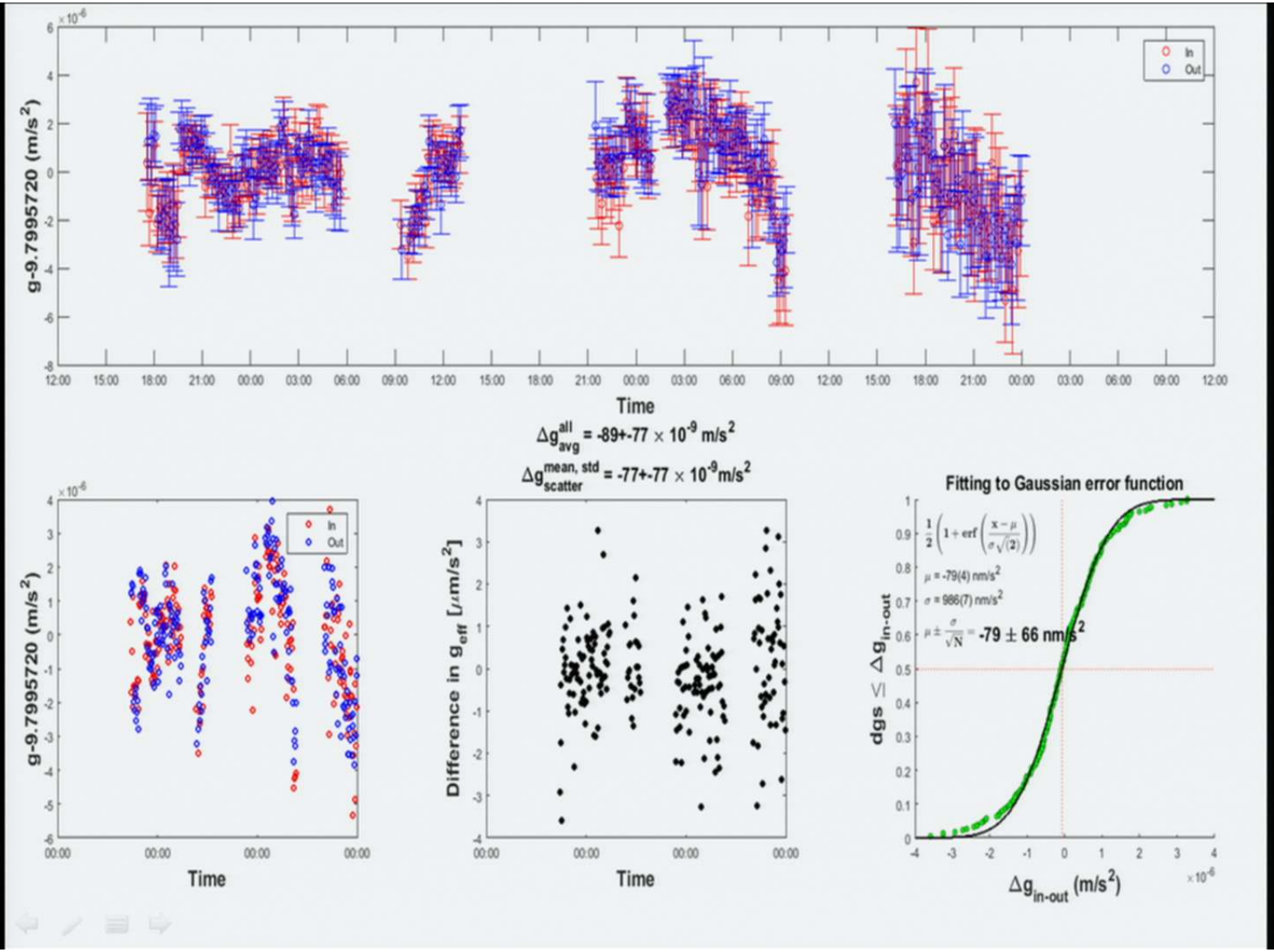
CAST- arxiv:1503.04561



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


g-9.7995720 (m/s^2)
Time
In
Out
Δg^{all}_{avg} = -89+-77 × 10^{-9} m/s^2
$\Delta g^{mean, std}_{scatter}$ = -77+-77 × 10^{-9}m/s^2
Difference in g_{eff} [μm/s^2]
Fitting to Gaussian error function
μ = -79(4) nm/s^2
σ = 986(7) nm/s^2
$\mu \pm \frac{\sigma}{\sqrt{N}}$ = -79 ± 66 nm/s^2
dgs V| Δg_{in-out}
Δg_{in-out} (m/s^2)

General dark energy models

$$L = -\frac{1}{2} Z^{\mu\nu}(\phi, \partial\phi, \ldots)\partial_\mu\phi\partial_\nu\phi - V(\phi) + g(\phi)T^\mu_\mu$$

Kinetic term
- Long-ranged screening
- "Vainshtein" mechanism
- P(X)
- Gallileon

Potential
- Local screening
- Chameleons,
- Peebles-Ratra

Coupling
- Similar to chameleon
- Symmetrons
- Damour-Polyakov

Joyce, Jain, Khoury and Trodden, arXiv:1407.0059

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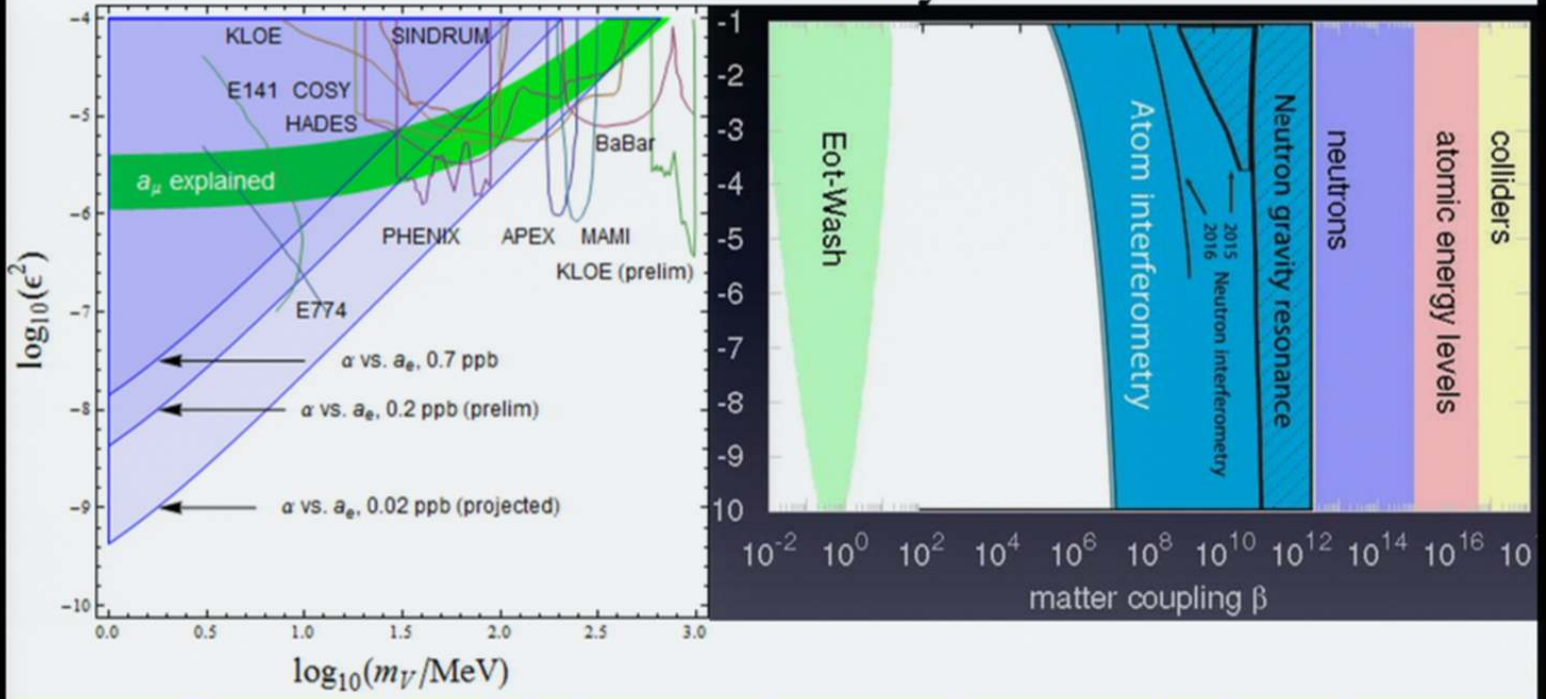
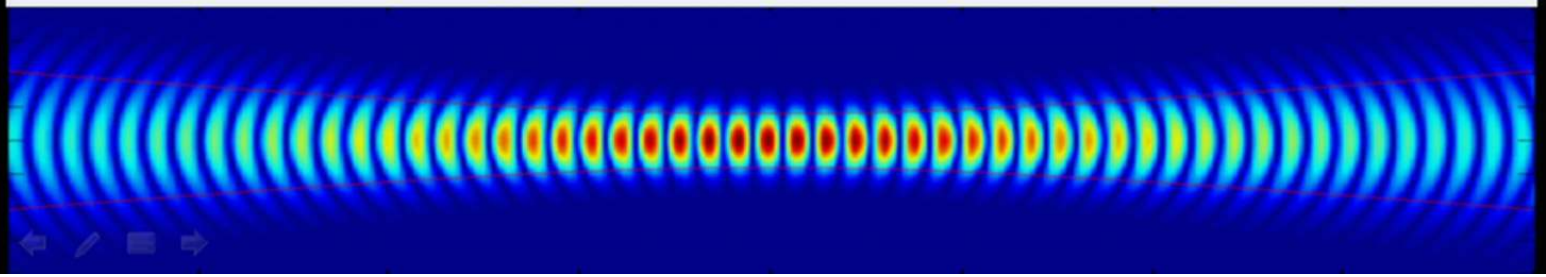
Summary


KLOE
SINDRUM
E141
COSY
HADES
BaBar
a_μ explained
PHENIX
APEX
MAMI
KLOE (prelim)
E774
α vs. a_e, 0.7 ppb
α vs. a_e, 0.2 ppb (prelim)
α vs. a_e, 0.02 ppb (projected)
$\log_{10}(\epsilon^2)$
$\log_{10}(m_V/\mathrm{MeV})$
Eot-Wash
Atom interferometry
2015
2016
Neutron interferometry
Neutron gravity resonance
neutrons
atomic energy levels
colliders
matter coupling β