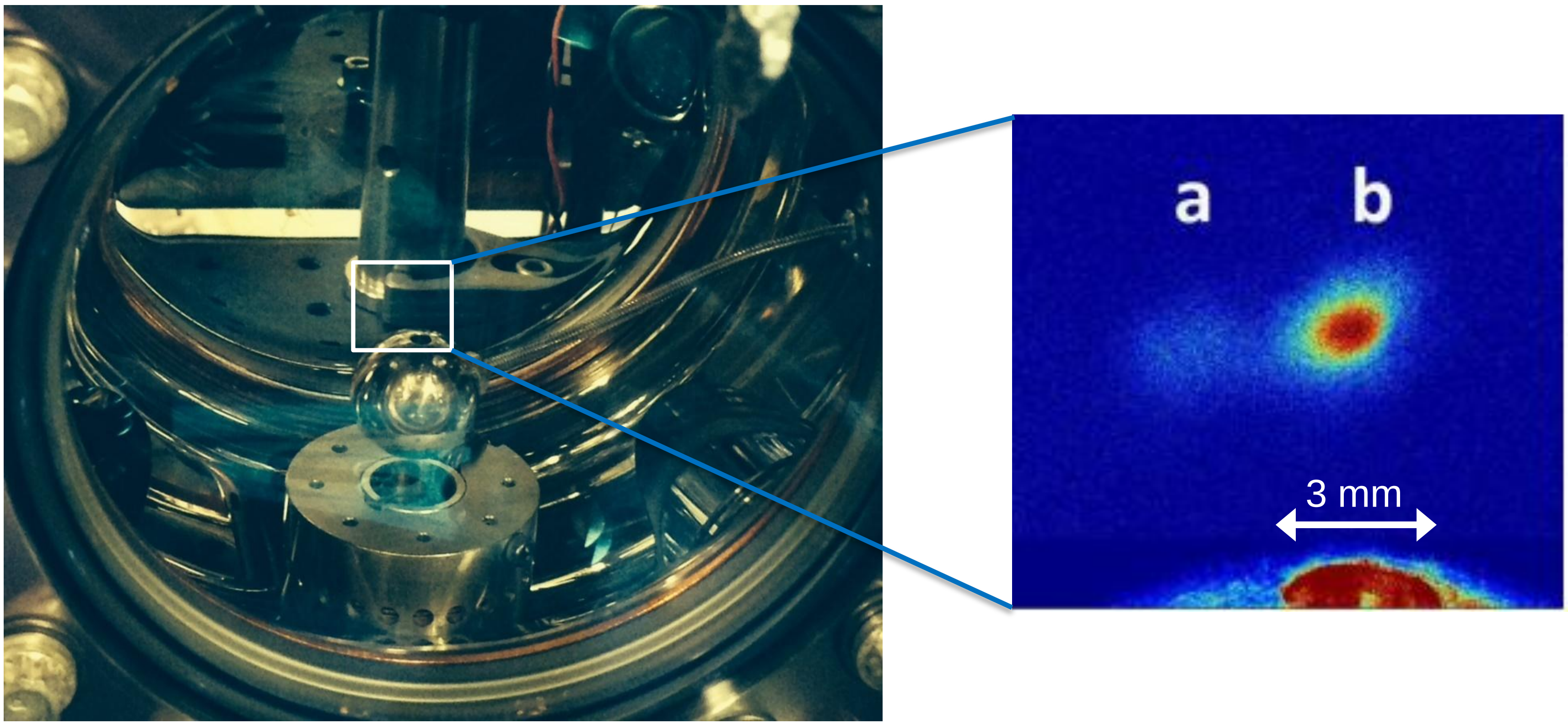
Atom-interferometers constraints on dark energy



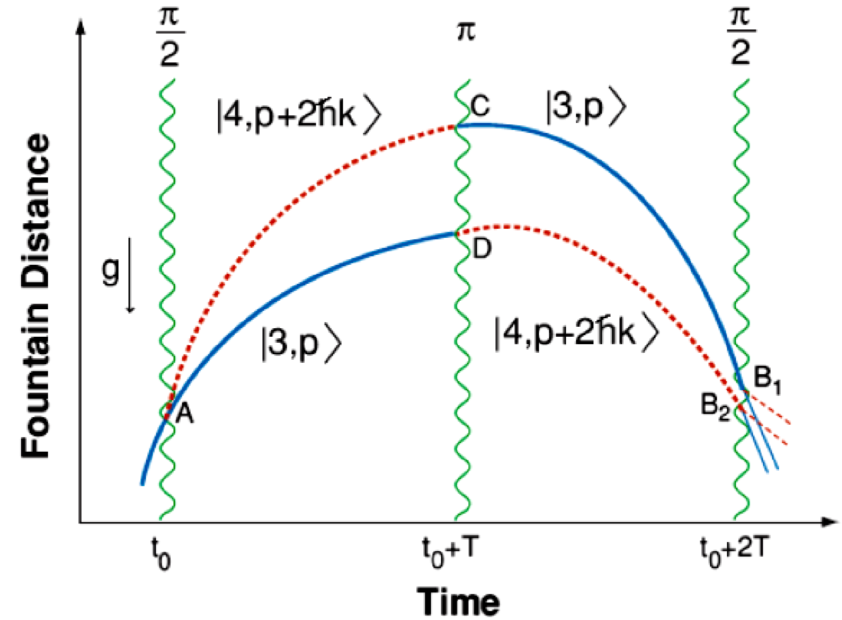
Galiano Island, 8/19/2015

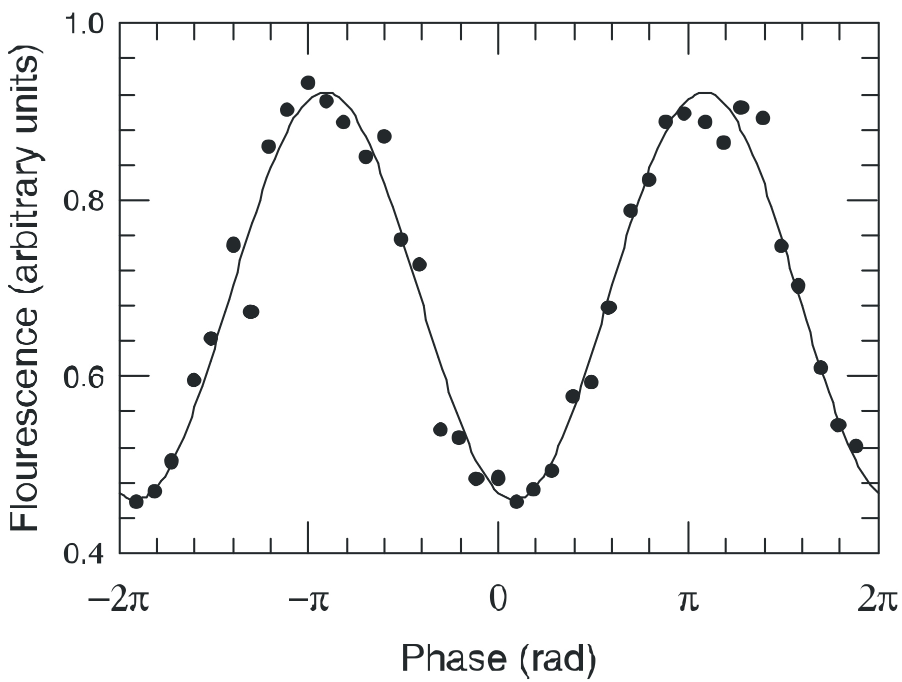
Contents

Basics

Light pulse atom interferometer

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



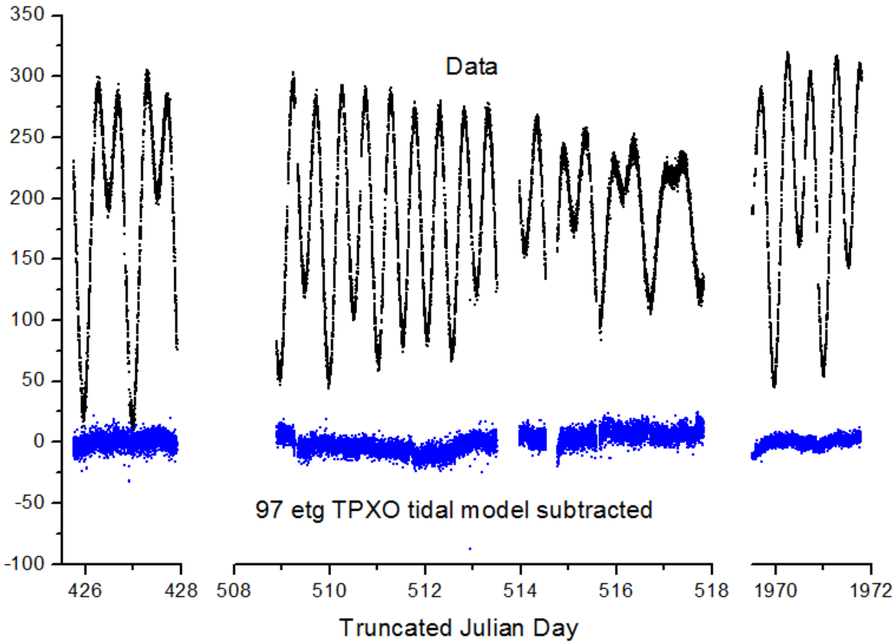


Each data point is from a single launch, determines g to 1.3ng =>11ng/sqrt(Hz)

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

Testing gravity

Isotropy of gravity



Comp.	result	result
$C_{2\omega}$	-0.48(14)	$\bar{s}^{XX} - \bar{s}^{YY} = 6.1(1.8)$
$D_{2\omega}$	-0.24(16)	$\bar{s}^{XY} = 0.98(68)$
C_{ω}	-3.36(7.60)	$s^{XZ} = 14(32)$
D_{ω}	7.88(7.96)	$s^{YZ} = -33(33)$
$C_{2\omega+\Omega}$	-0.81(55)	$s^{TY} = 125(86)$
$D_{2\omega+\Omega}$	-0.46(58)	$s^{TX} = -71(90)$
$C_{2\omega-\Omega}$	-1.02(56)	$s^{TY} = -6.7(3.8)$
$D_{2\omega-\Omega}$	0.98(57)	$s^{TX} = -6.5(3.8)$
$C_{\omega+\Omega}$	-4.6(5.4)	$s^{TX} = 96(112)$
$D_{\omega+\Omega}$	-4.7(5.4)	
$C_{\omega-\Omega}$	5.4(5.5)	$s^{TX} = -113(115)$
$D_{\omega-\Omega}$	1.3(5.2)	

- GR valid at 10^{-9} level!
- Complemented by lunar laser ranging (Battat *et al.*, PRL2007)

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

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

Equivalence Principle and Bound Kinetic Energy

Michael A. Hohensee* and Holger Müller
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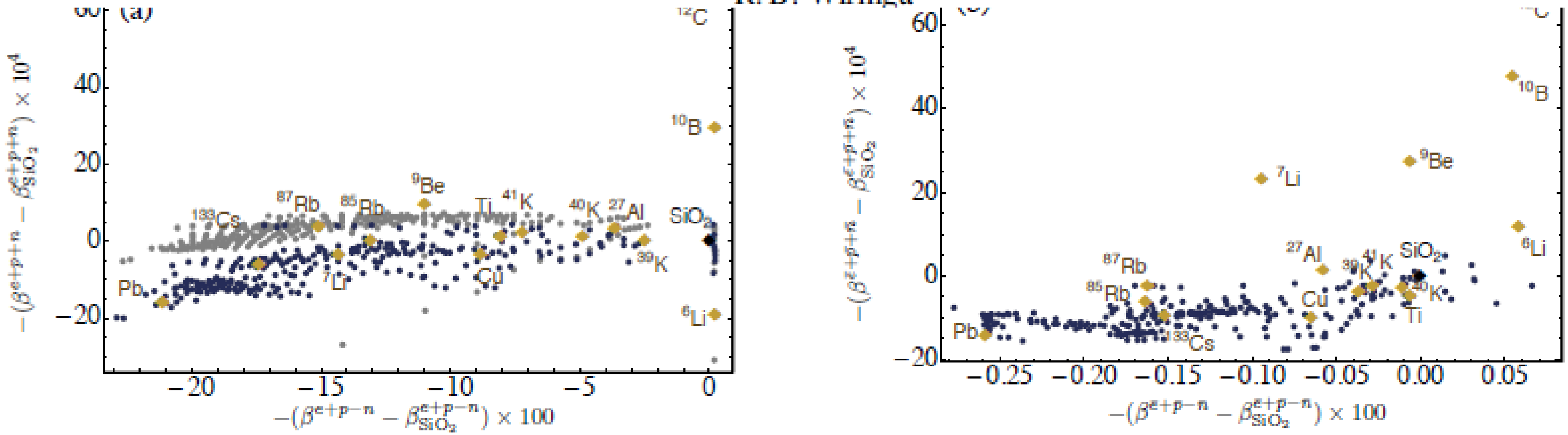
R. B. Wiringa

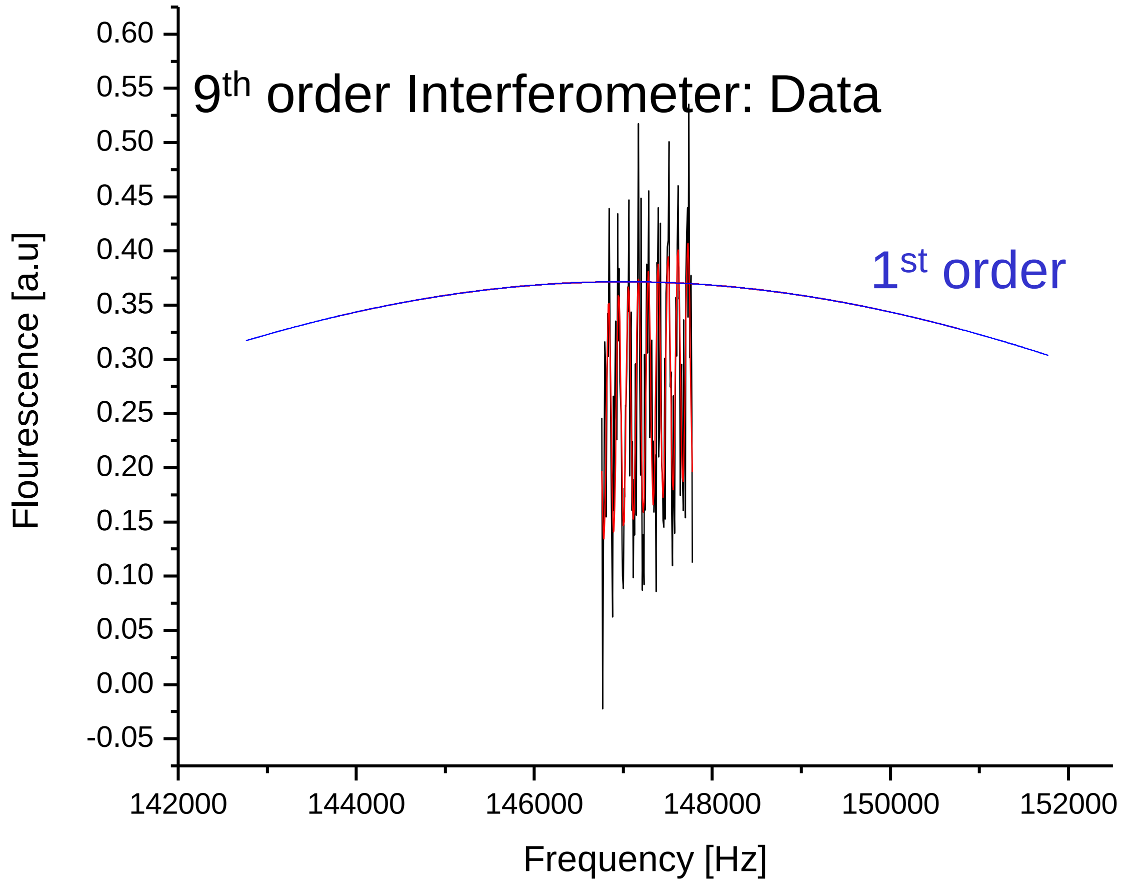


Limits x10^{-7}	$(a^{n}_{eff})_0$	$(a^{p}_{eff})_0 + (a^{n}_{eff})_0$	$(c^{n}_{eff})_{00}$	$(c^{p}_{eff})_{00}$	$(c^{e}_{eff})_{00}$
Clocks+UFF (2011)	-30±530	-10±110	-50±940	21±400	-10±400
	80	40	67	133	1400
Al+clocks+UFF	5.1±6.4	2.2±2.8	11±14	2.4±3.0	0.14±0.28

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

Improving the technology

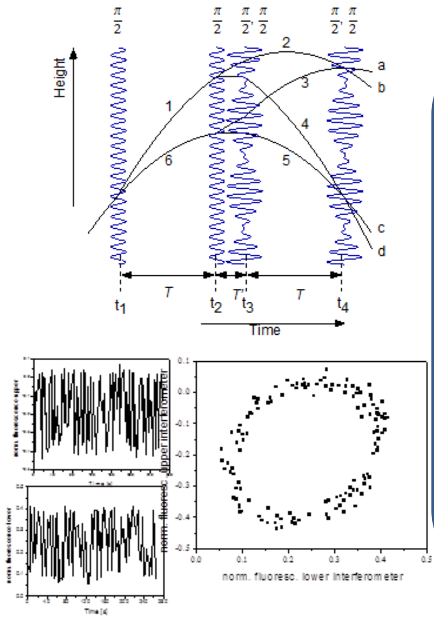
Large momentum transfer



=> Talk by Guglielmo Tino

H. M. *et al.*, PRL 100 (2009): Chiow *et al*, PRL 2009

Atom-optics technology development

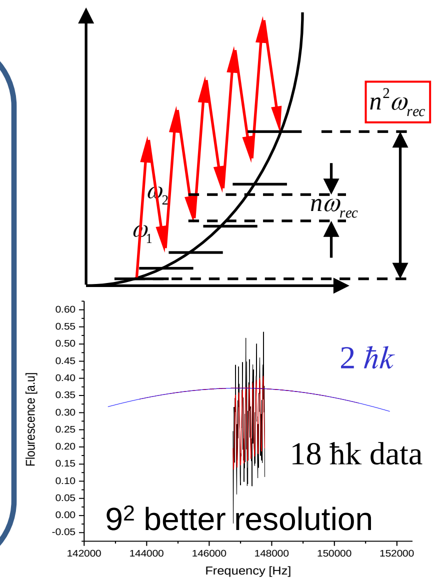


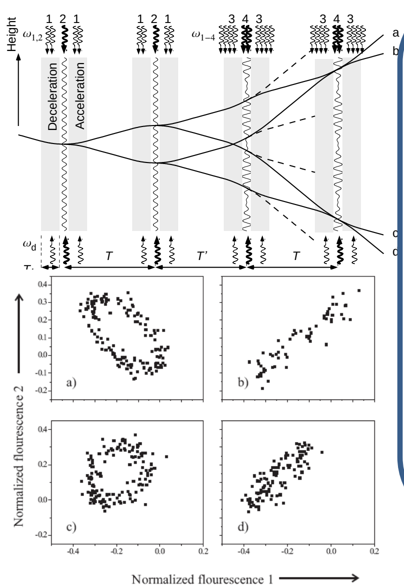
Simultaenous Conjugate Interferometers

- 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)



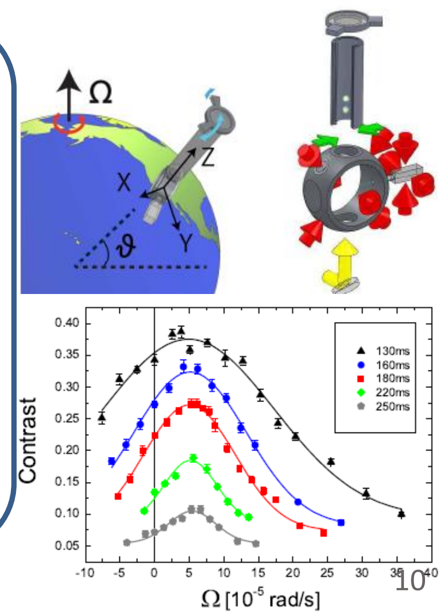


Optical lattice beam splitter

- 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)

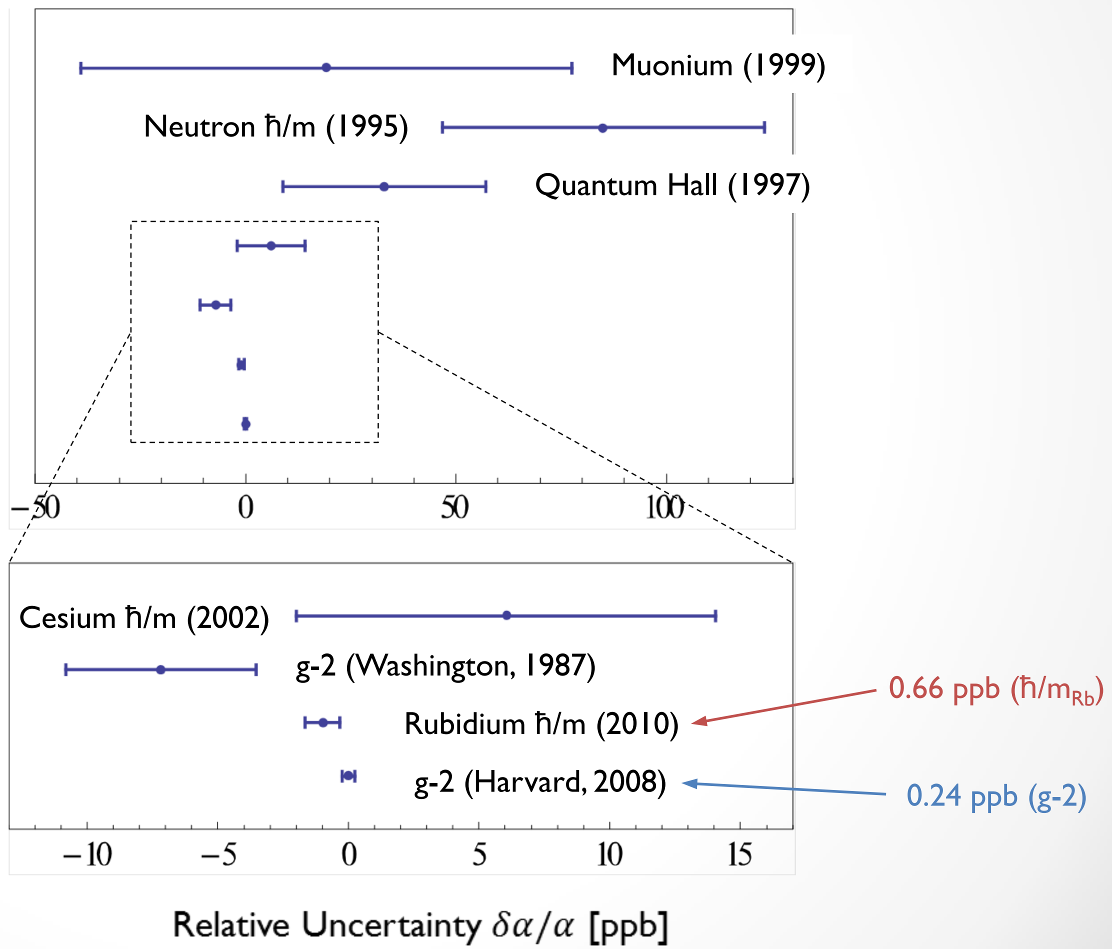


The fine structure constant: pushing to the 10^{-10} level of accuracy

Fine Structure Constant α

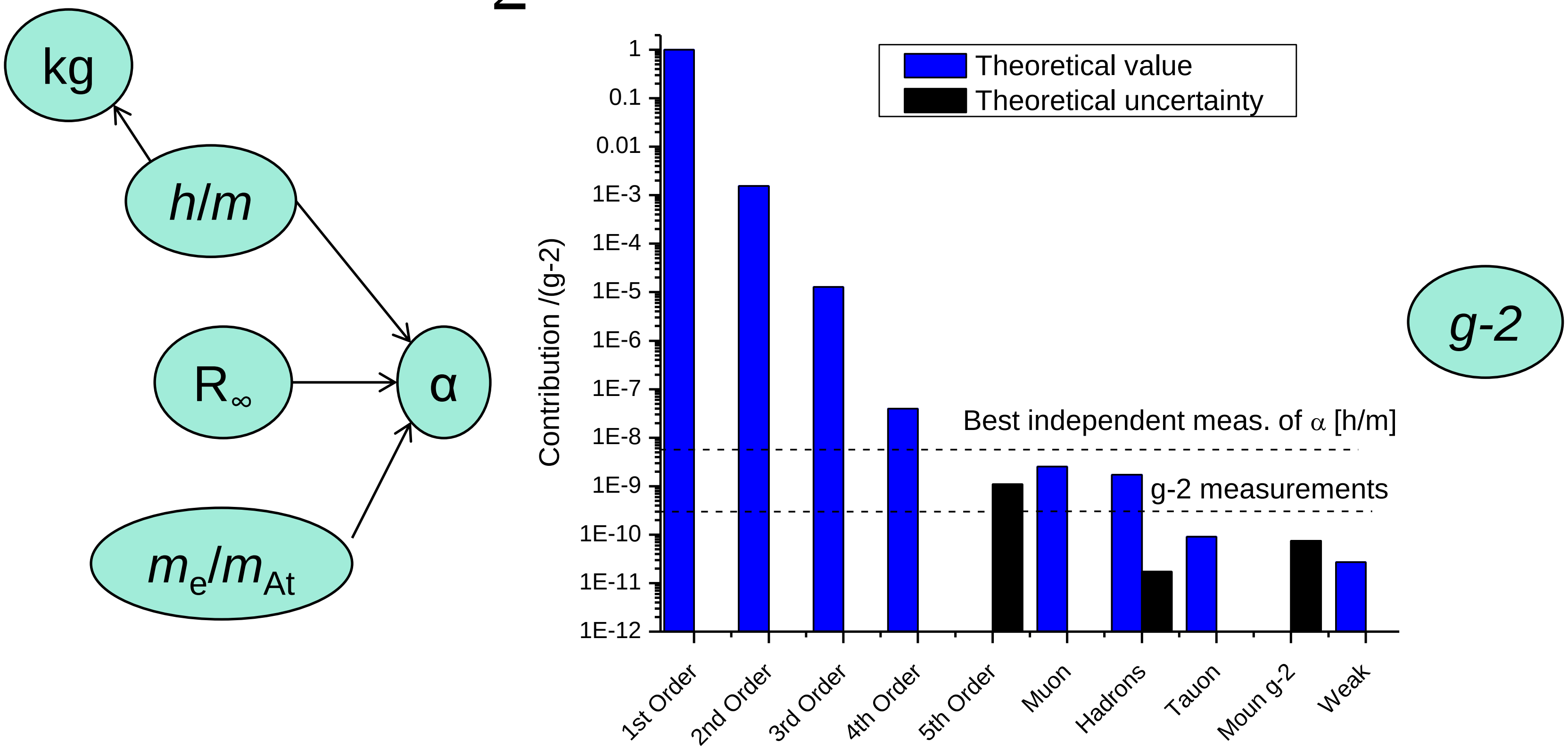
- $hcR_\infty = \frac{1}{2}\alpha^2 m_e c^2$

Select Alpha Measurements



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

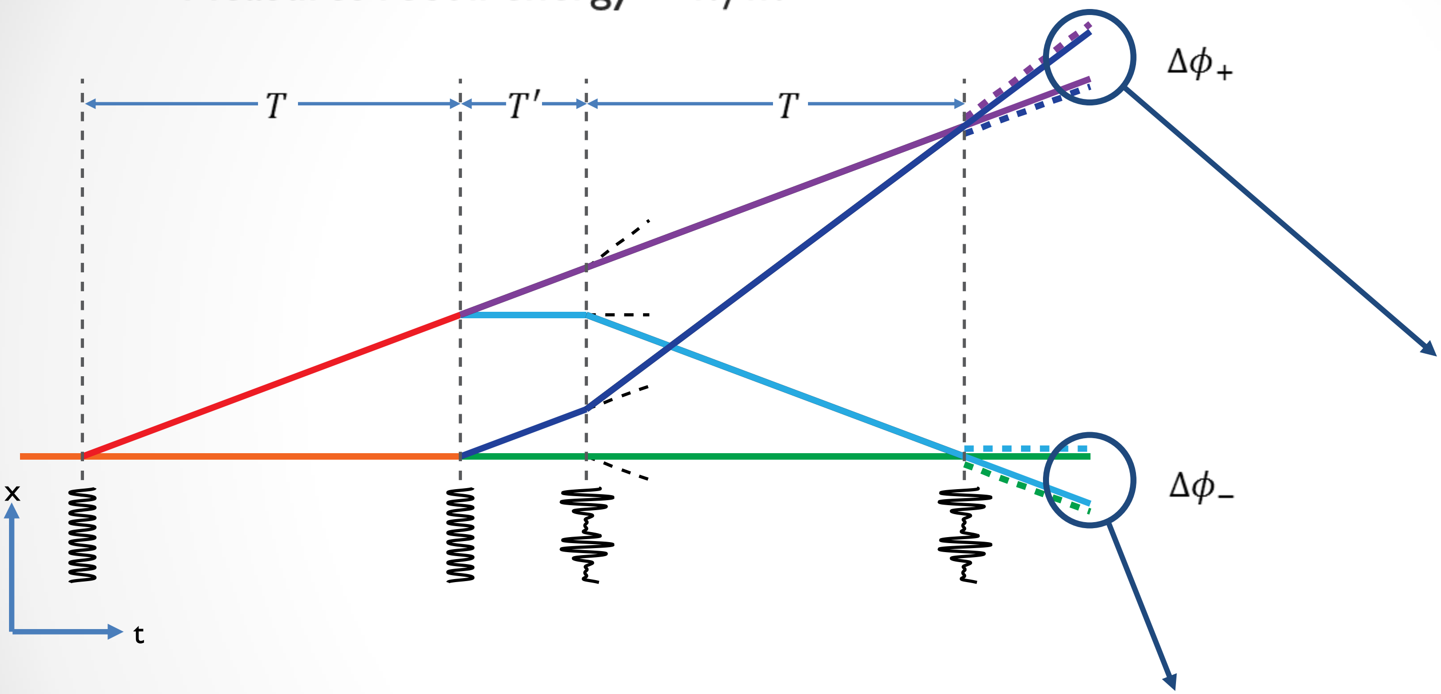
$$\frac{1}{2} m_e c^2 \alpha^2 \equiv R_\infty \hbar c$$

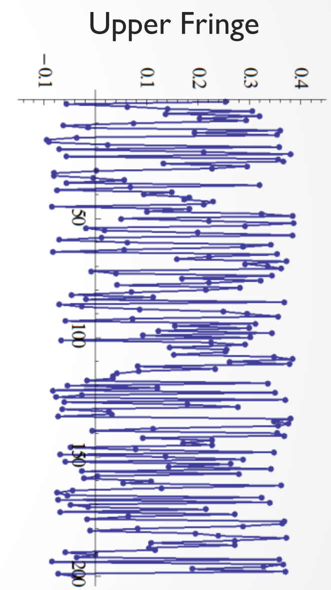


- All experiments and all theories have ppb accuracy
- Substantial parts of the Standard Model have to be right to yield α and g-2 at that level

Ramsey-Bordé Interferometer

- Measures recoil energy $\propto \hbar/m$

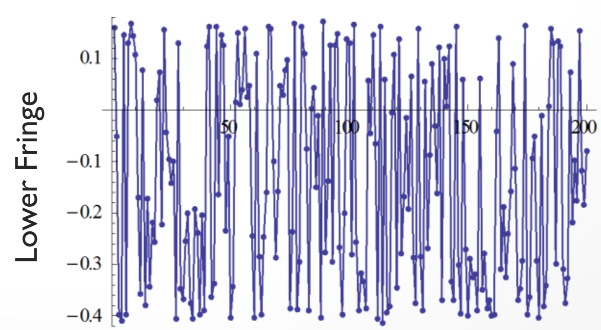


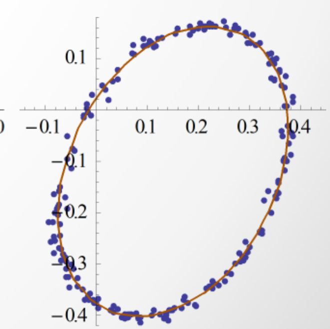


$$\Delta\phi_{\pm} = 8n^2\omega_r T \pm 2n\bar{k}aT(T+T')$$

Kinetic Energy

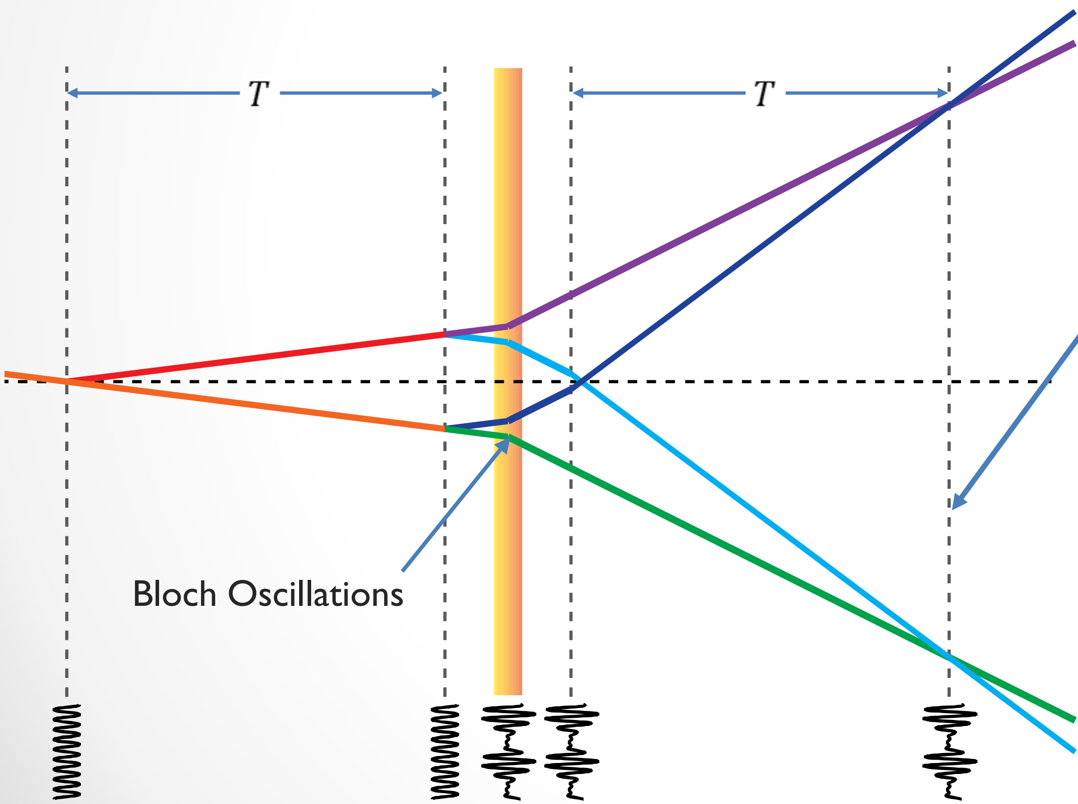
$$\omega_r = \frac{\bar{k}^2}{2}\frac{\hbar}{m}$$

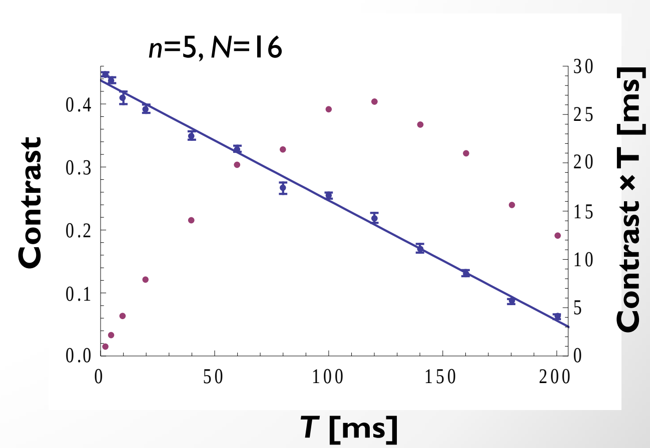




Common-mode Bloch Oscillations

- Increases total phase of interferometer $\Delta\phi = 16n(n+N)\omega_r T$
- Increases frequency splitting of last two pulse

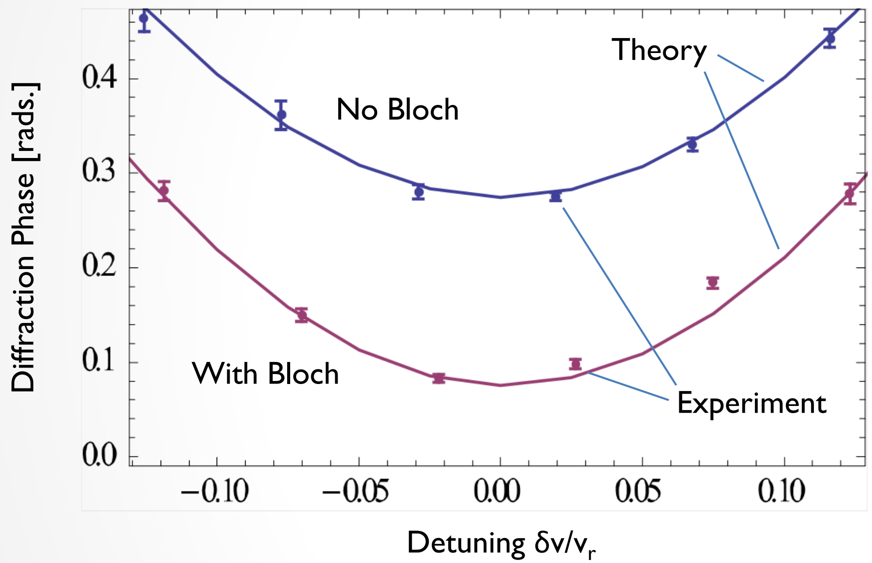




Diffrcation phase

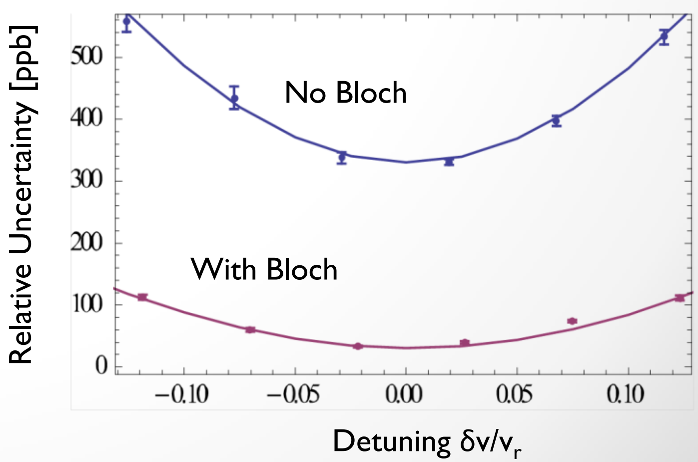
- Good agreement between theory and experiment

Dependence on Detuning



- Three parameters:
  - Amplitude of first two pulses,
  - Amplitude of last two pulses
  - Detuning

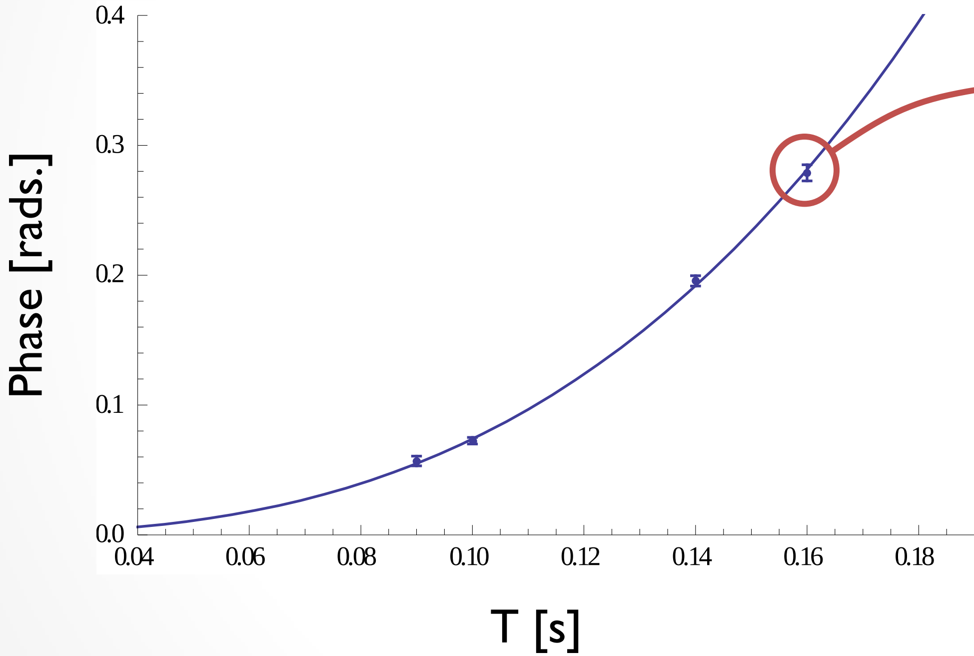
Contribution to Total Phase

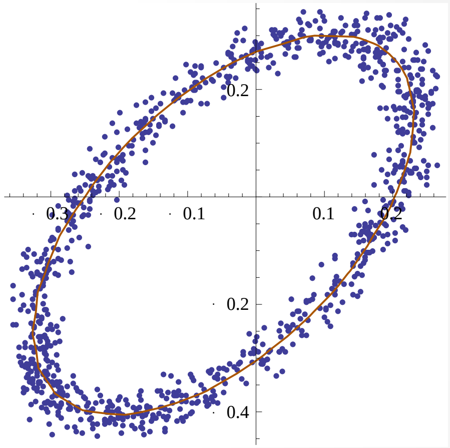


- Diffraction phase contribution to total signal is reduced with Bloch oscillations

Gradiometer Data

$$\Delta\phi = 2\gamma n\omega_r T^2 \frac{\hbar}{m}\left(2N(2T + T_2') + n(2T + T_1' + T_2')\right)$$

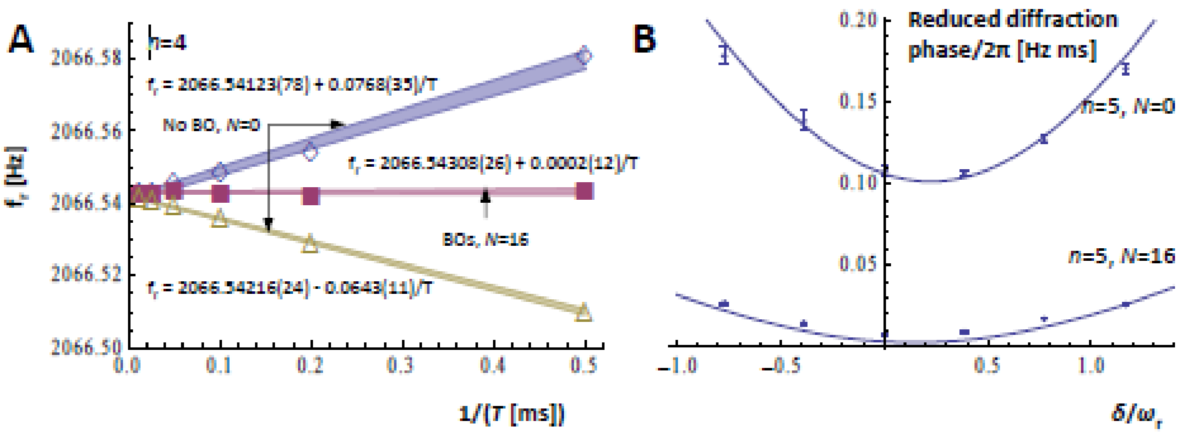


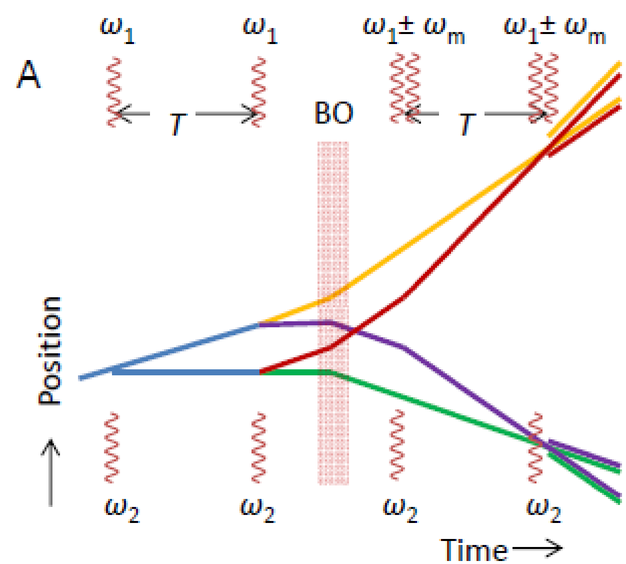


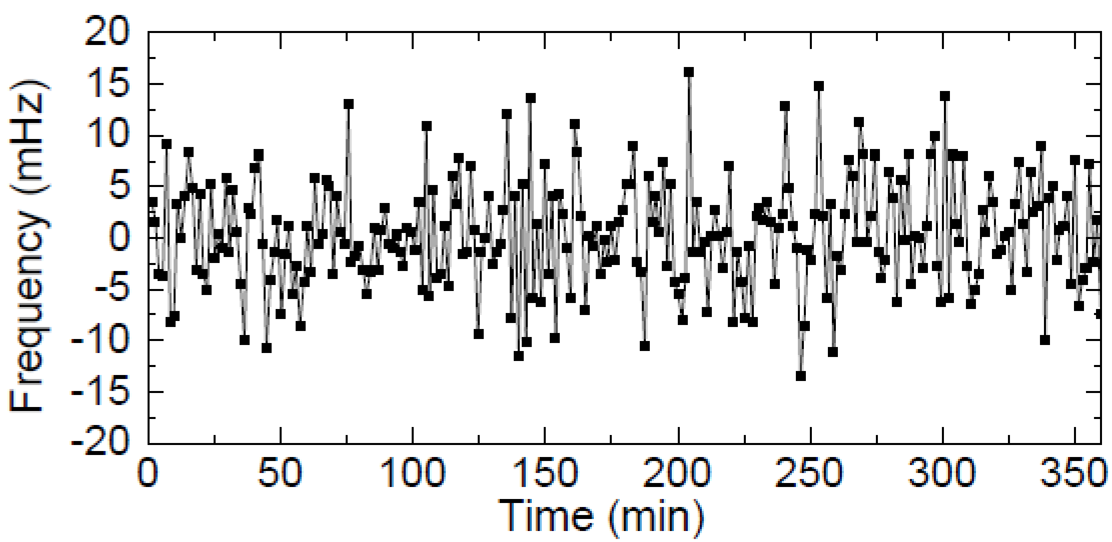
T=160ms
T_1'=5ms
T_2'=45ms

$$\gamma = 1.295(32) \times 10^{-6} \frac{m}{s^2}\frac{1}{m}$$

Atom interferometers at 10^{-10} accuracy







- Bloch oscillations
- Active feedback
- Diffraction phase reduced >1000 fold
- 0.25 ppb/(12 h)$^{1/2}$

Estey et al, arXiv:1410:8486

Systematics (2015)

- All uncertainties in parts-per-billion

n=4,

n=5, N=0,T=160ms

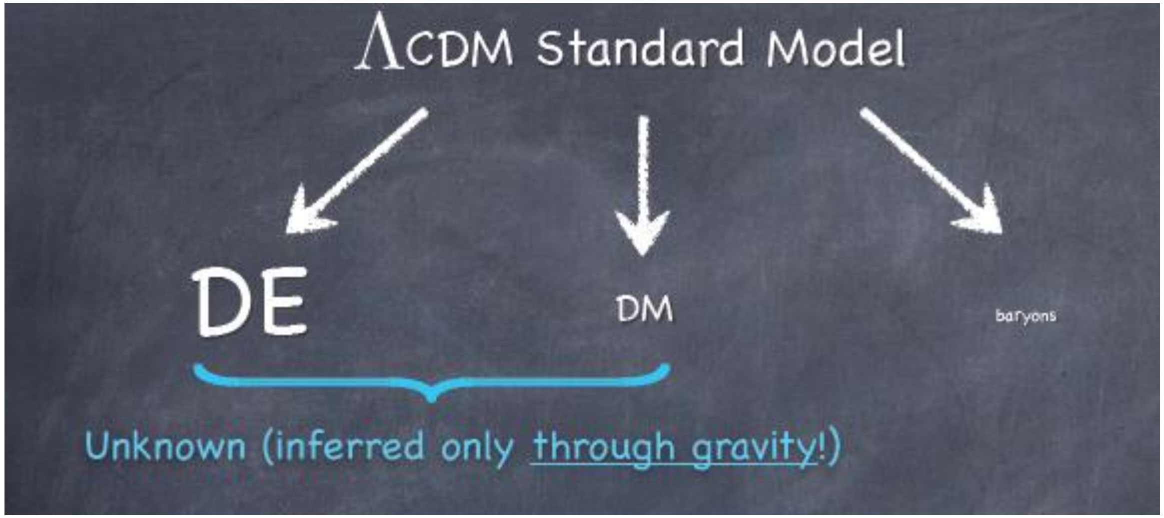
	Correction	Uncertainty	2012
Diffraction Phase	~0	(*)	340(3*)
Wavefront Curvature	0.05-0.4	(*)	
Laser Frequency	0.6	0.056	
Beam Alignment	-0.085	0.049	-1.5(1.1)
Gouy Phase	-1.945	0.042	-1.9(1)
Zeeman Shift	-0.015	0.014	0(0.2)
Gravity Gradient	-1.66	0.04	-15(1)
Frequency Difference	4.20	0.03	
Statistics		$0.5/(25h)^{1/2}$	$1.8/(6h)^{1/2}$
Total ($\hbar/m$)		0.52*	3.9

0.26 ppb in α

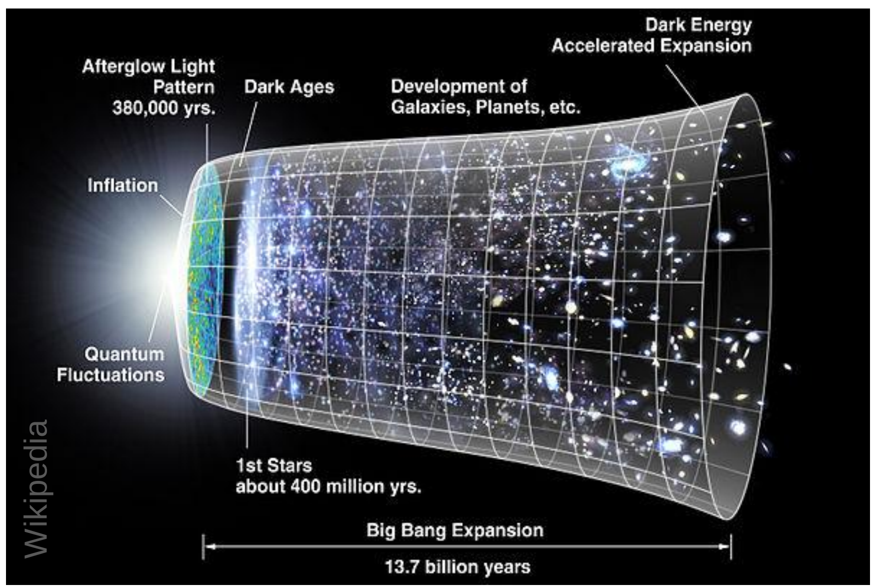
* Depends on atom sample characterization

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

Dark energy

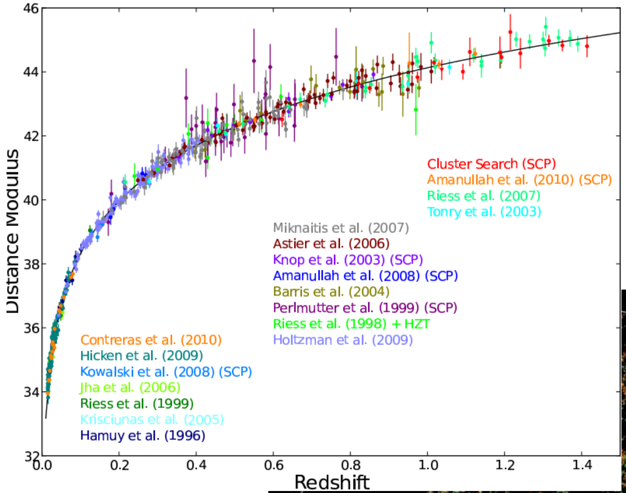


ΛCDM Standard Model
DE
DM
baryons
Unknown (inferred only through gravity!)



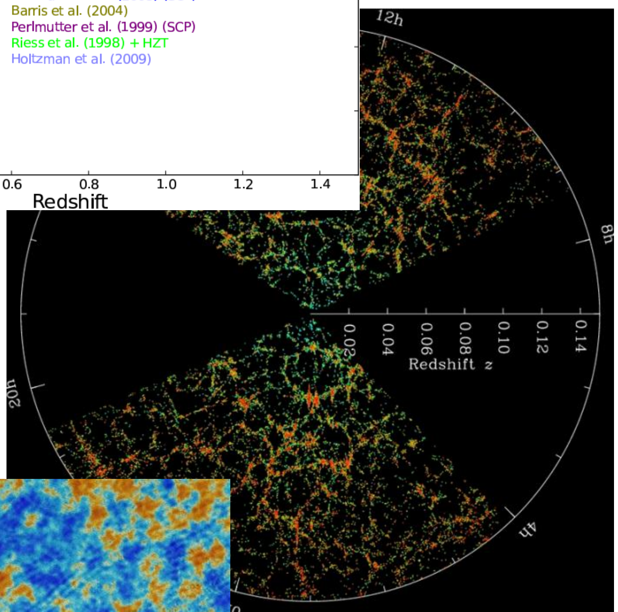
Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
Wikipedia

Evidence



Supernova Cosmology Project

+



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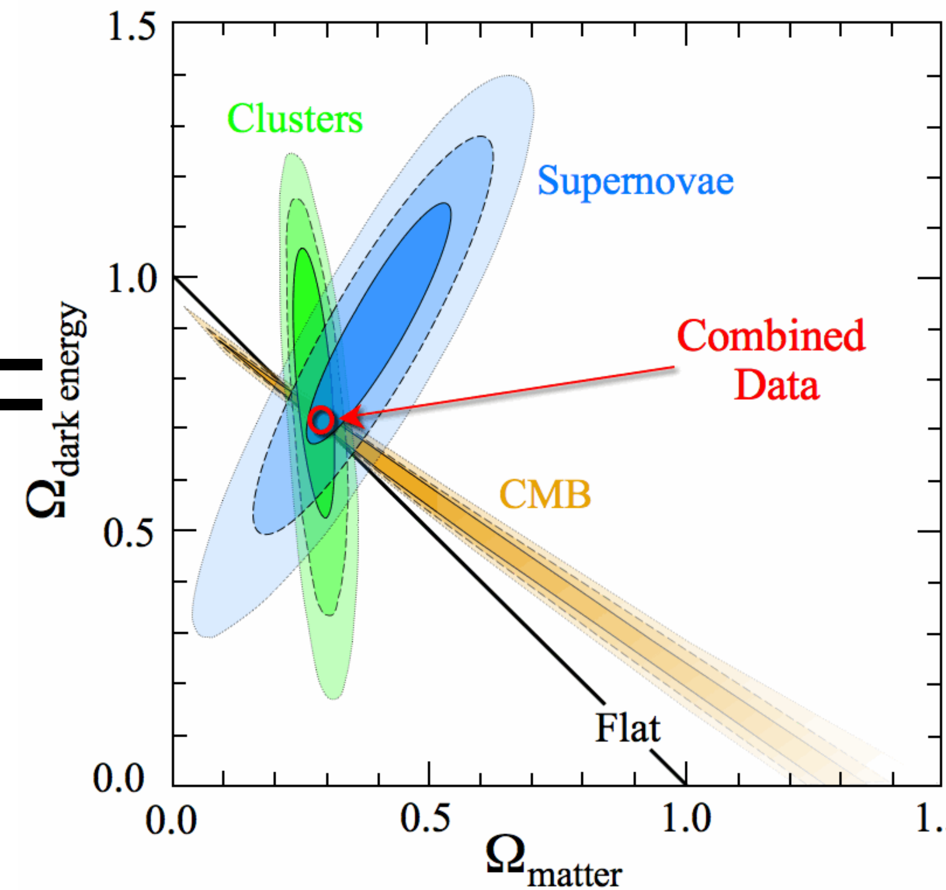
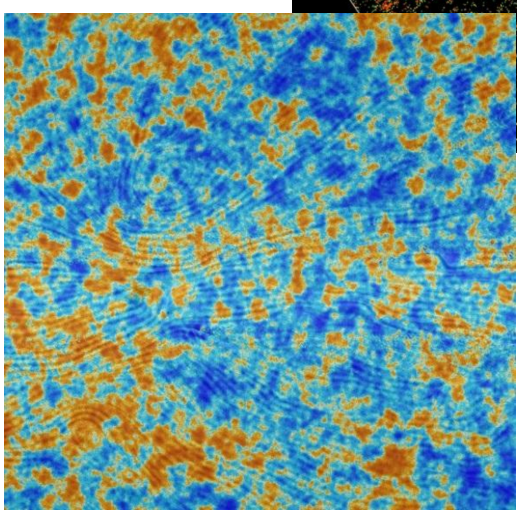




Sloan Digital Sky Survery

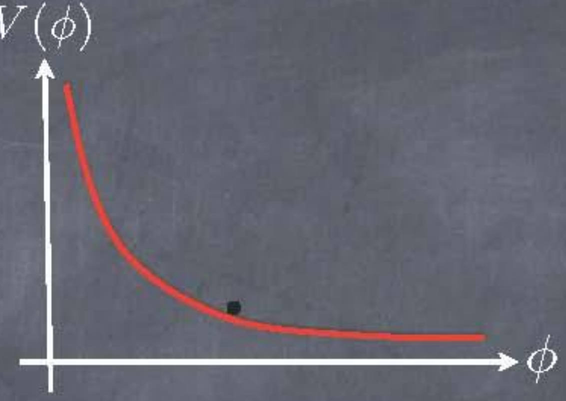
ESA/Planck

A Richer Dark Sector

- Dark energy candidates:

  Λ , quintessence...

  Ratra & Peebles (1988); Wetterich (1988); Caldwell, Dave & Steinhardt (1998)



In anticipation of potential surprises, prudent to explore a broader scope of microphysics and associated phenomena.

Axions...

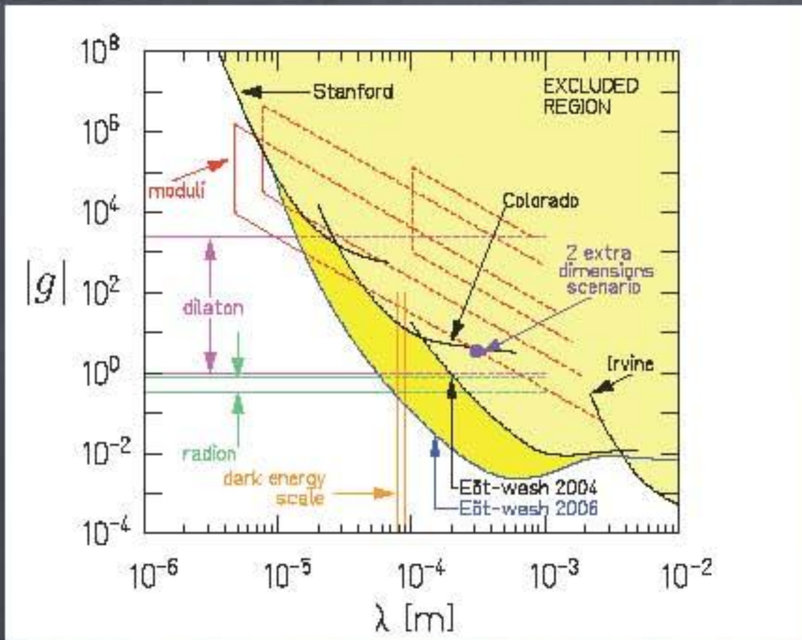
- Tantalizing prospect: dark sector includes new light fields (e.g. quintessence) that couple to both dark <u>and</u> baryonic matter.

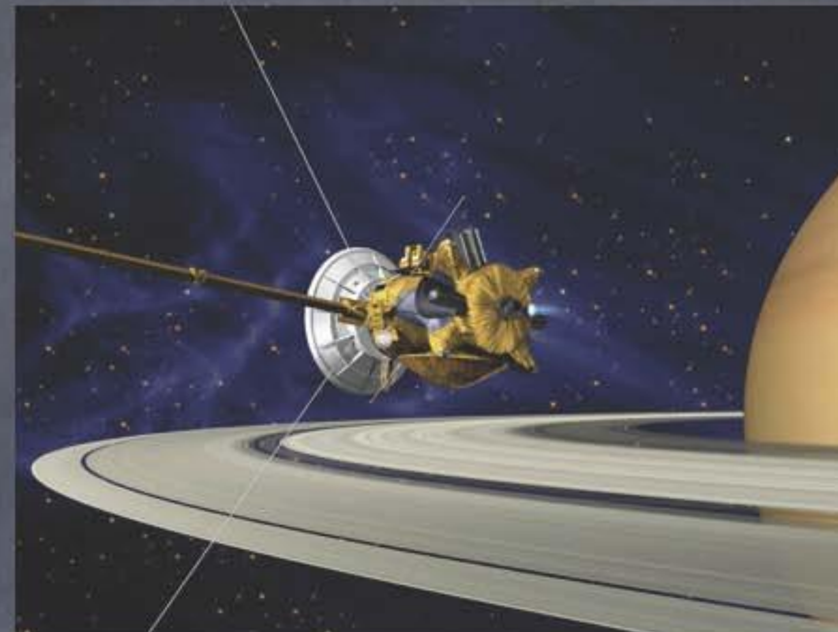
$\Longrightarrow$ ruled out?

Not so fast. Scalar fields can "hide" themselves from local exp'ts through screening mechanisms

$$\rho_{\rm here} \sim 10^{30} \rho_{\rm cosmos}$$

Experimental Program





Screening mechanisms have rich phenomenology for tests of GR:

- Forced us to rethink implications of existing data
- Inspired design of novel experimental tests

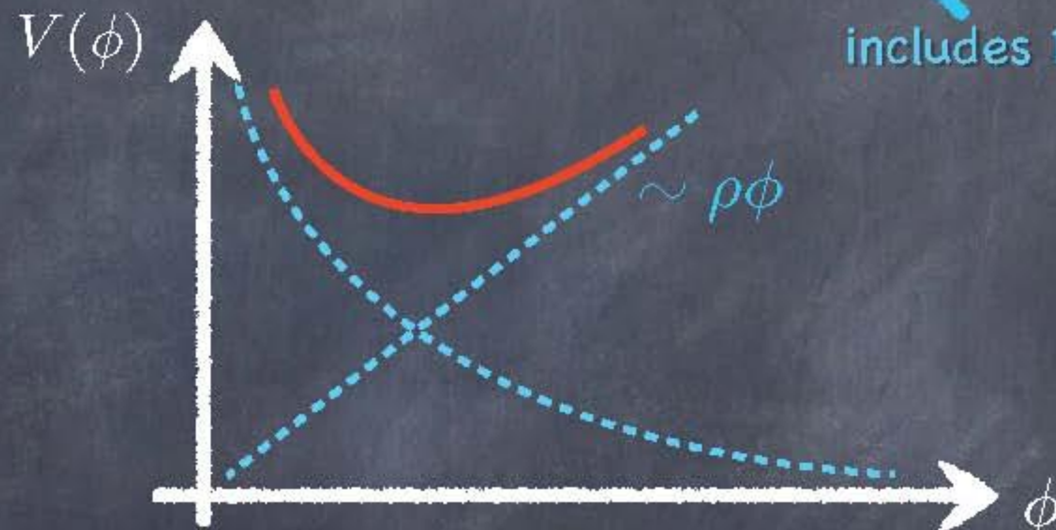
Chameleon Mechanism

Khoury & Weltman (2003); Gubser & Khoury (2004); Brax, van de Bruck, Davis, Khoury and Weltman (2004)

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) + \frac{g\phi}{M_{\rm Pl}} T^\mu_\mu$$

includes DM, baryons...

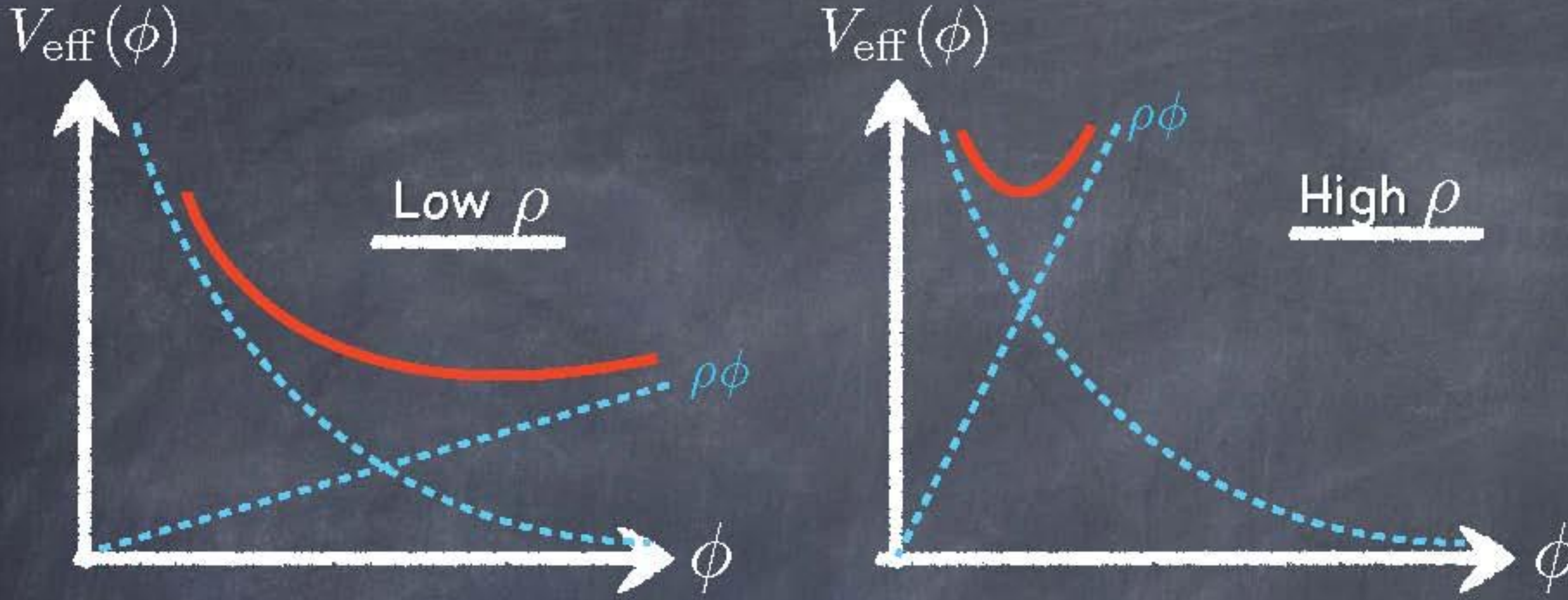
Fiducial pot.



Non-relativistic matter: $T^\mu_\mu = -\rho$

$$\Longrightarrow \quad V_{\rm eff}(\phi) = V(\phi) + \frac{g\phi}{M_{\rm Pl}}\rho$$

Depends on matter density



$\Longrightarrow$ $m^2 = V_{,\phi\phi}$ is increasing function of ρ

Lab. constraint: $m^{-1}(\rho_{\rm local}) \lesssim {\rm mm}$

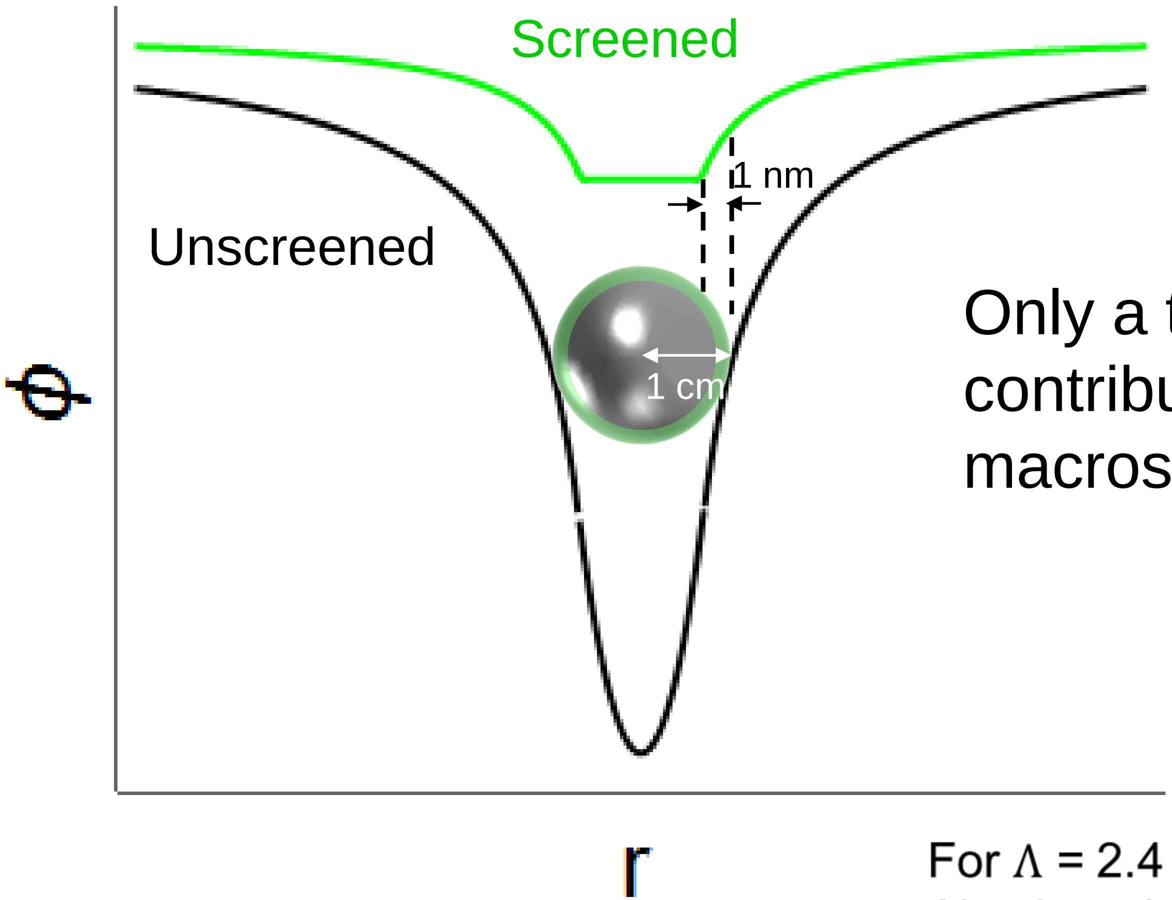
$\longrightarrow$ $m^{-1}(\rho_{\rm cosmos}) \lesssim {\rm Mpc}$

Factor of 10^{26} !

$\longrightarrow$ $m^{-1}(\rho_{\rm solar\ system}) \lesssim 10^6\ {\rm AU}$

$\therefore$ Long-range force in solar system $\longrightarrow$ ruled out???

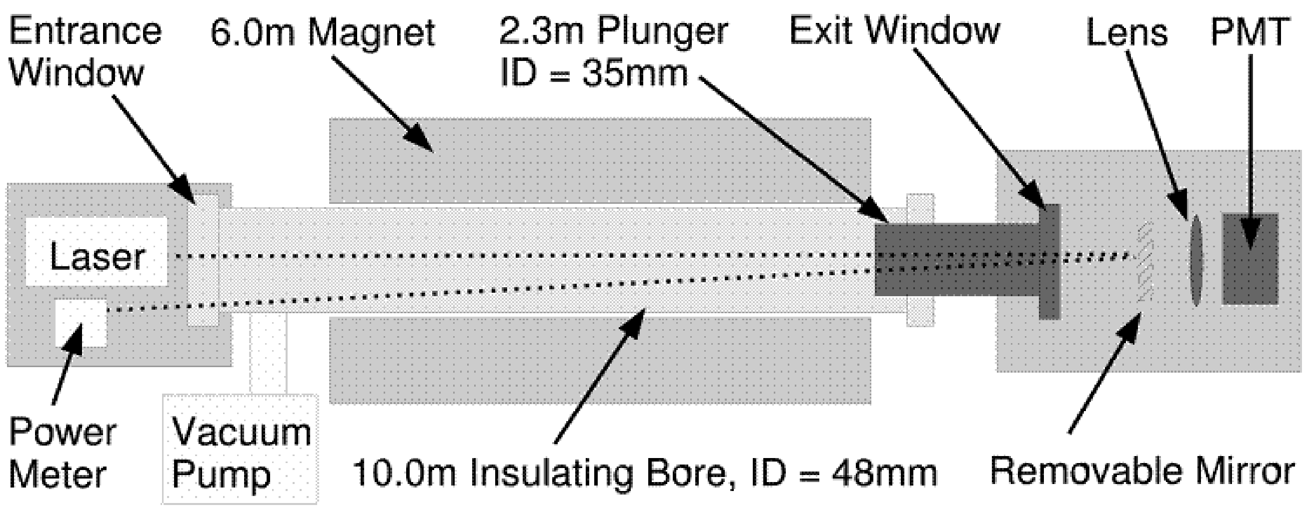
Chameleon screening



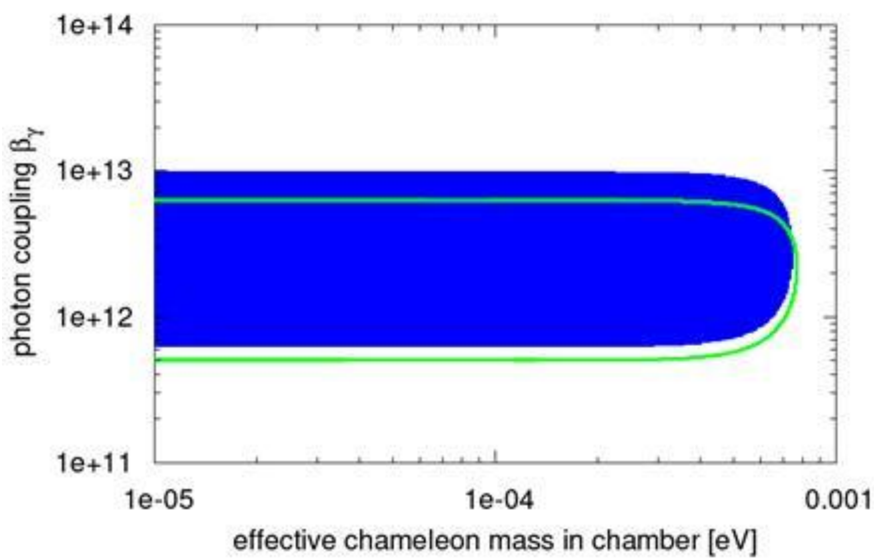
Only a thin shell contributes in macroscopic objects

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

GammeV Chameleon afterglow search

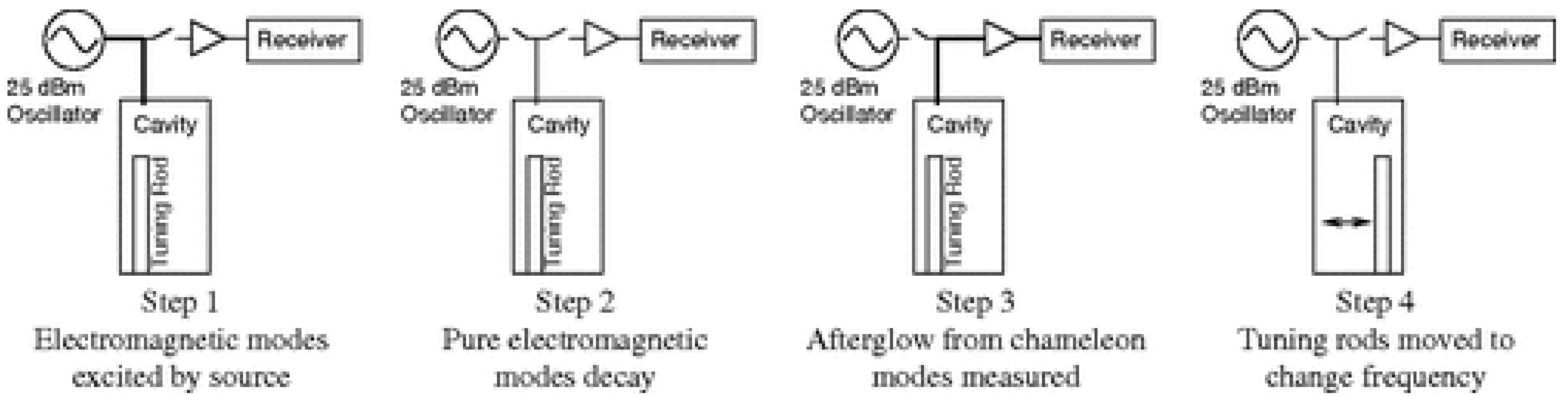


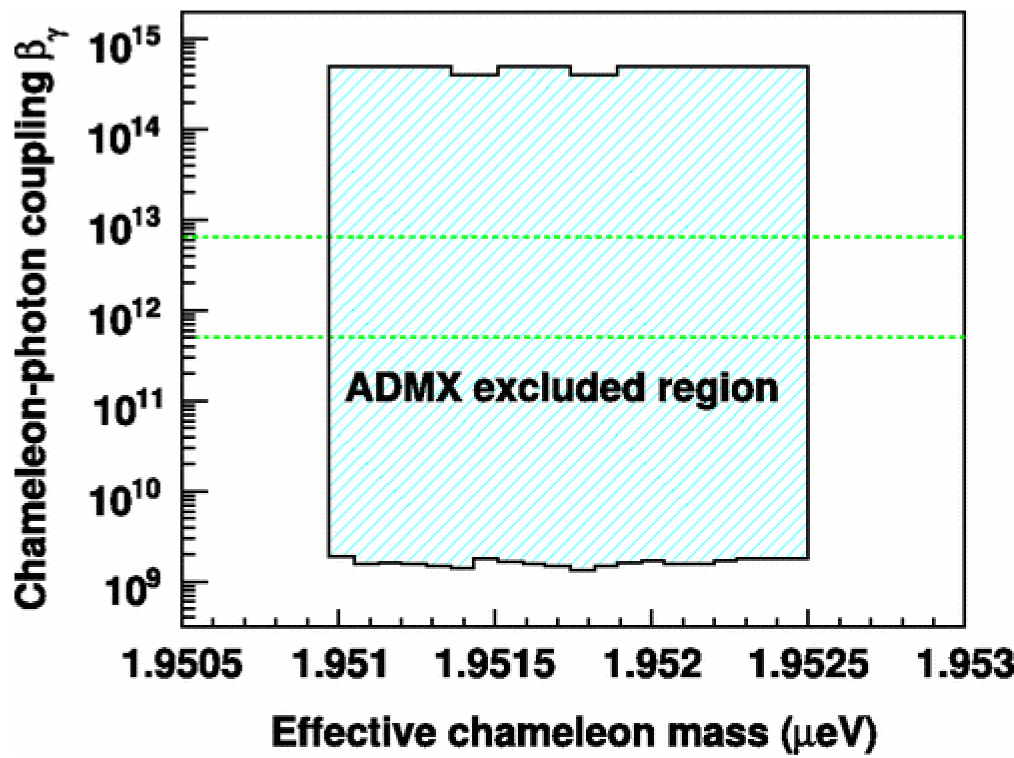
- Assumes coupling of photons and chameleons
- Laser beam on for ~1 hour
- Chameleons accumulate in bore
- Laser turned off
- Chameleons convert into photons => afterglow



GammeV Collaboration, PRL **105,** 261803 (2010).

ADMX Chameleon afterglow search





ADMX Collaboration, PRL **105,** 051801 (2010).

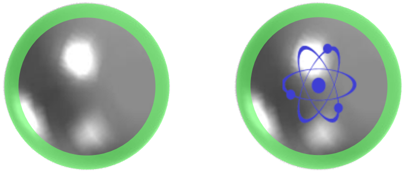
The idea

Probing Dark Energy with Atom Interferometry
C. Burrage, E. J. Copeland, E. A. Hinds
JCAP 1503 (2015) 03, 042

Realization:
Single atom's small size in ultra high vacuum makes it ideal test mass which evades screening

Unscreened force for atoms

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



$$\lambda = \frac{Shell\ mass}{Test\ mass}$$

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

$$\lambda_{atom} = 1$$

For most of parameter space

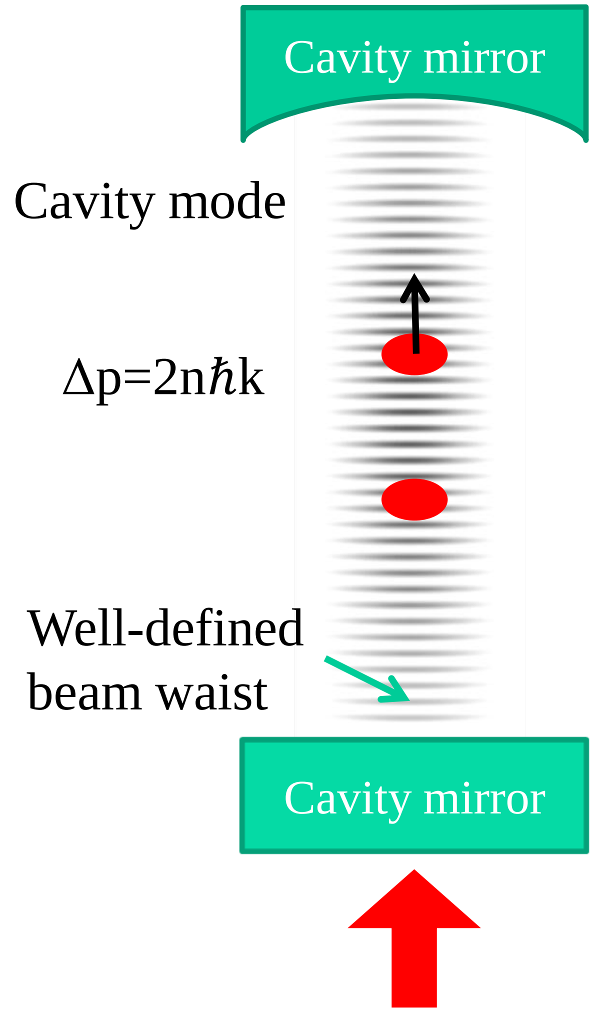
$$M < M_{Pl}$$

Unscreened force can be much stronger than gravity

Cavity-based atom interferometer

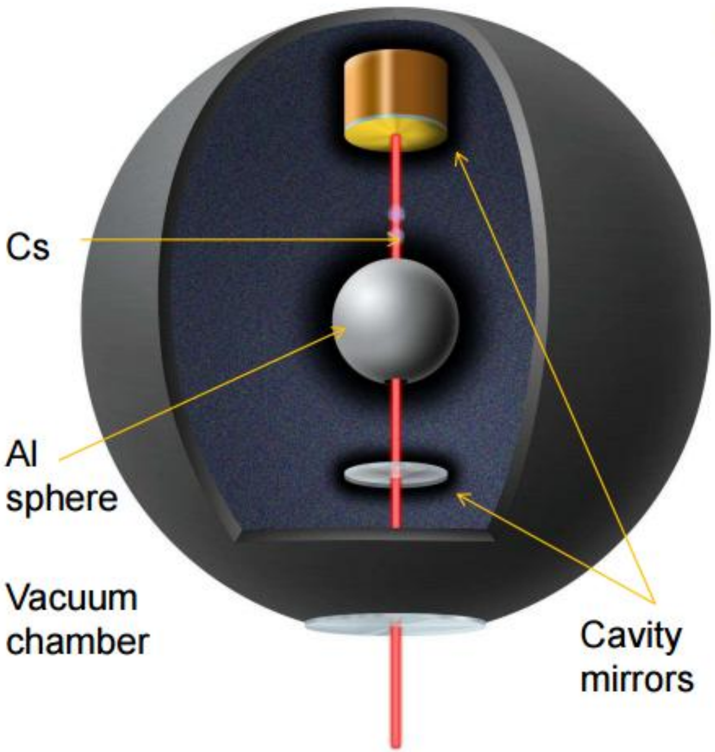
Features

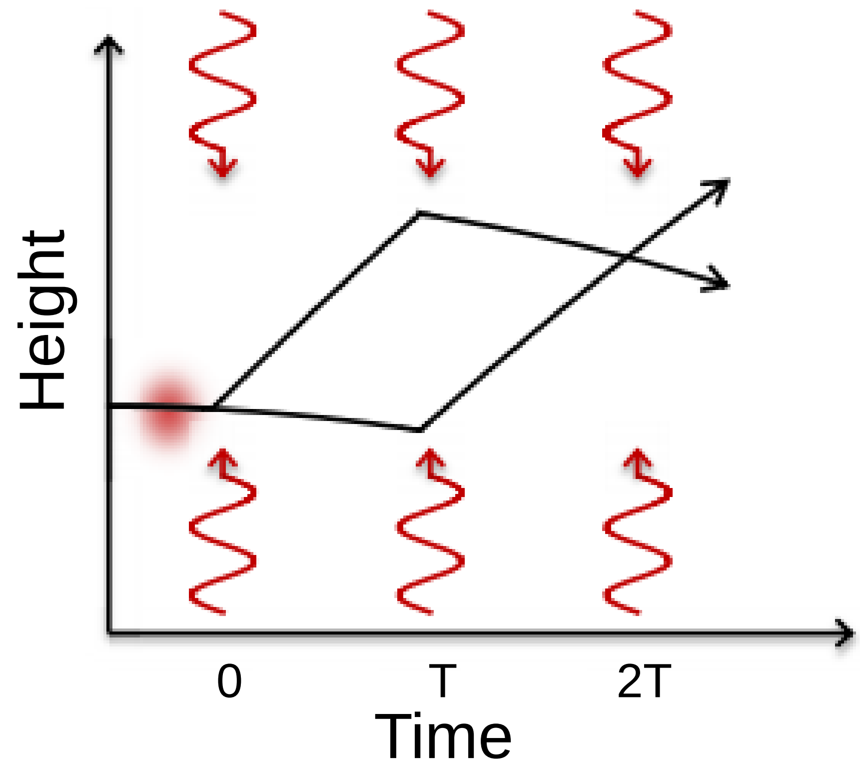
- Intensity enhancement
- Well-defined optical mode
- High accuracy and resolution
- Goal: $\Delta p = 100\hbar k$



P. Hamilton *et al.*, PRL (2015)

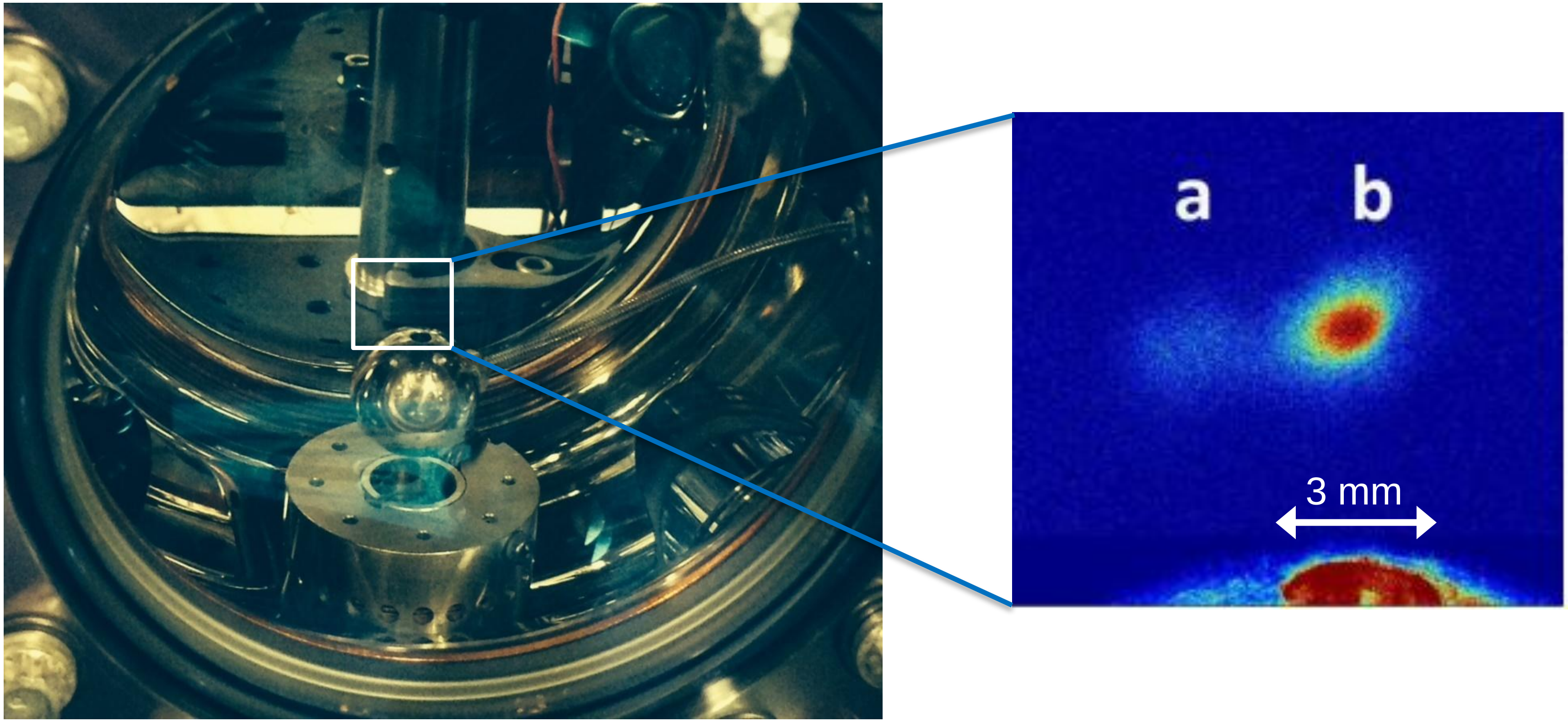
Atom interferometry





- Aluminum sphere source mass for scalar field
- Atoms act as test masses for force sensing
- Final state probability $\propto \vec{k} \cdot \vec{a}\, T^2$

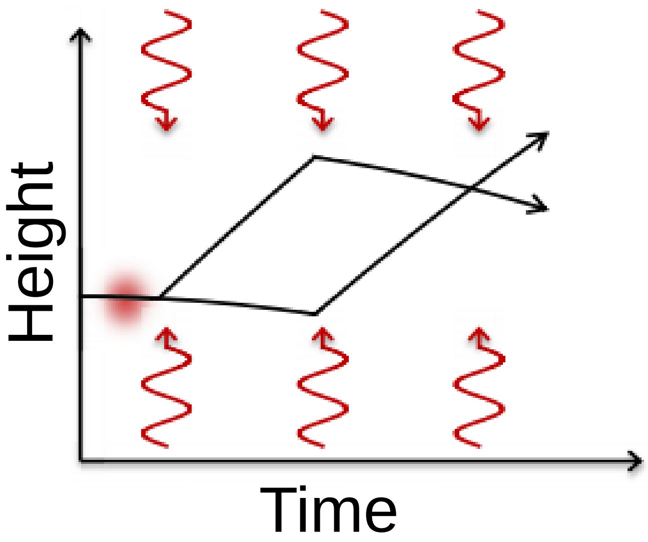
Detection

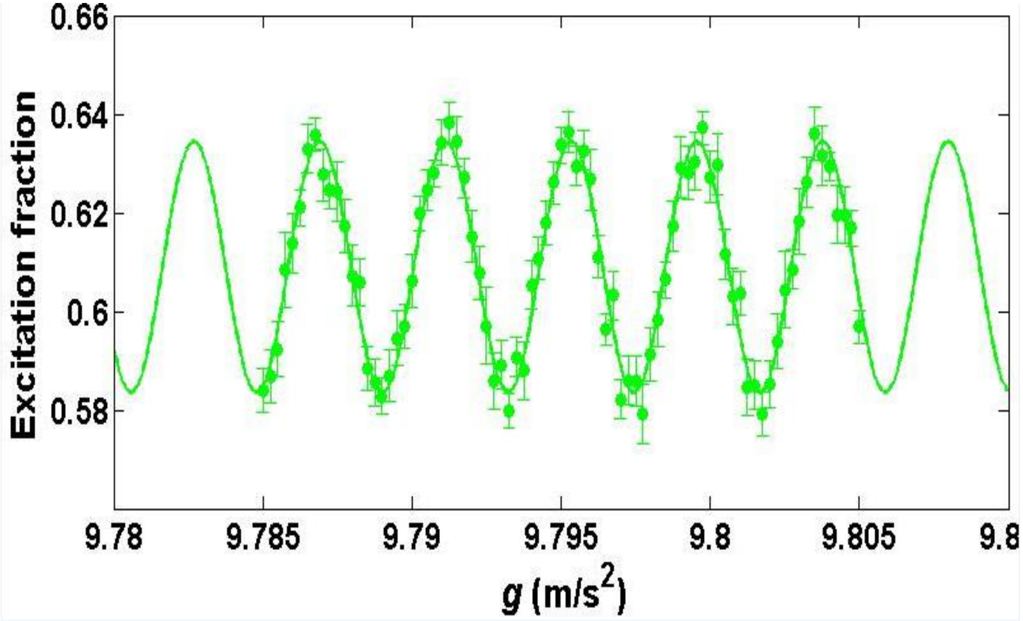


- Optically push one state to side before imaging
- Fluorescence detection of two output states
- Sphere moved in and out with translation stage

Gravimetry fringes

Interferometer phase depends on acceleration $\vec{a}$ and photon momentum $\vec{k}$

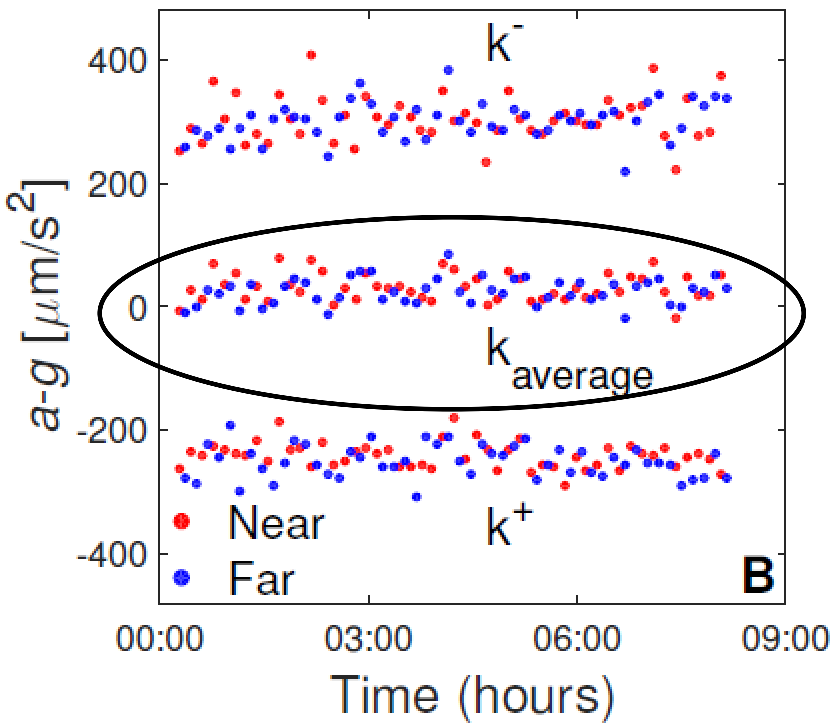




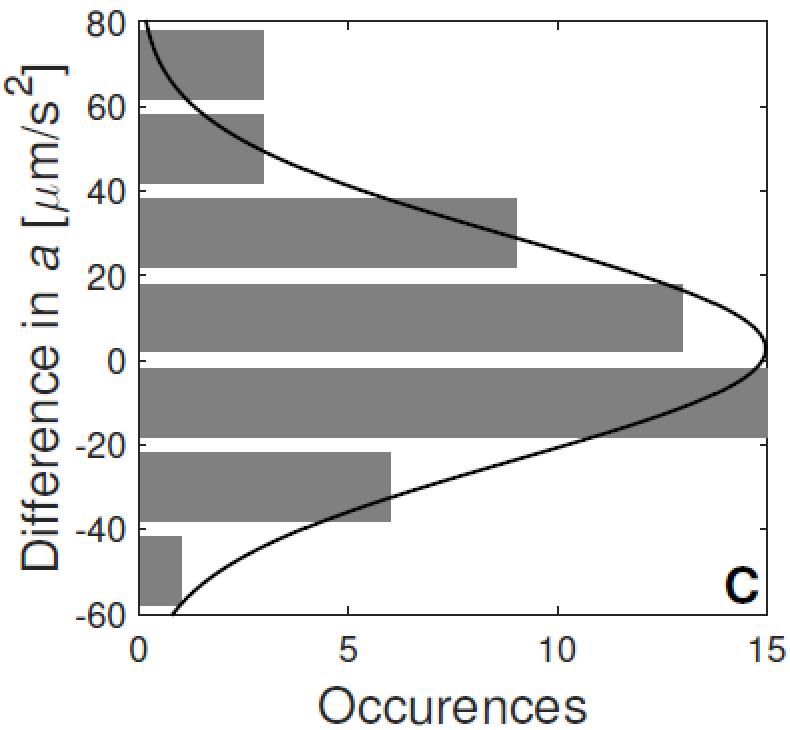
Lower state probability $\propto \mathrm{Cos}^2(\vec{k} \cdot \vec{a}\, T^2)$

Results

Red = sphere near
Blue = sphere far



Difference between
sphere near/far



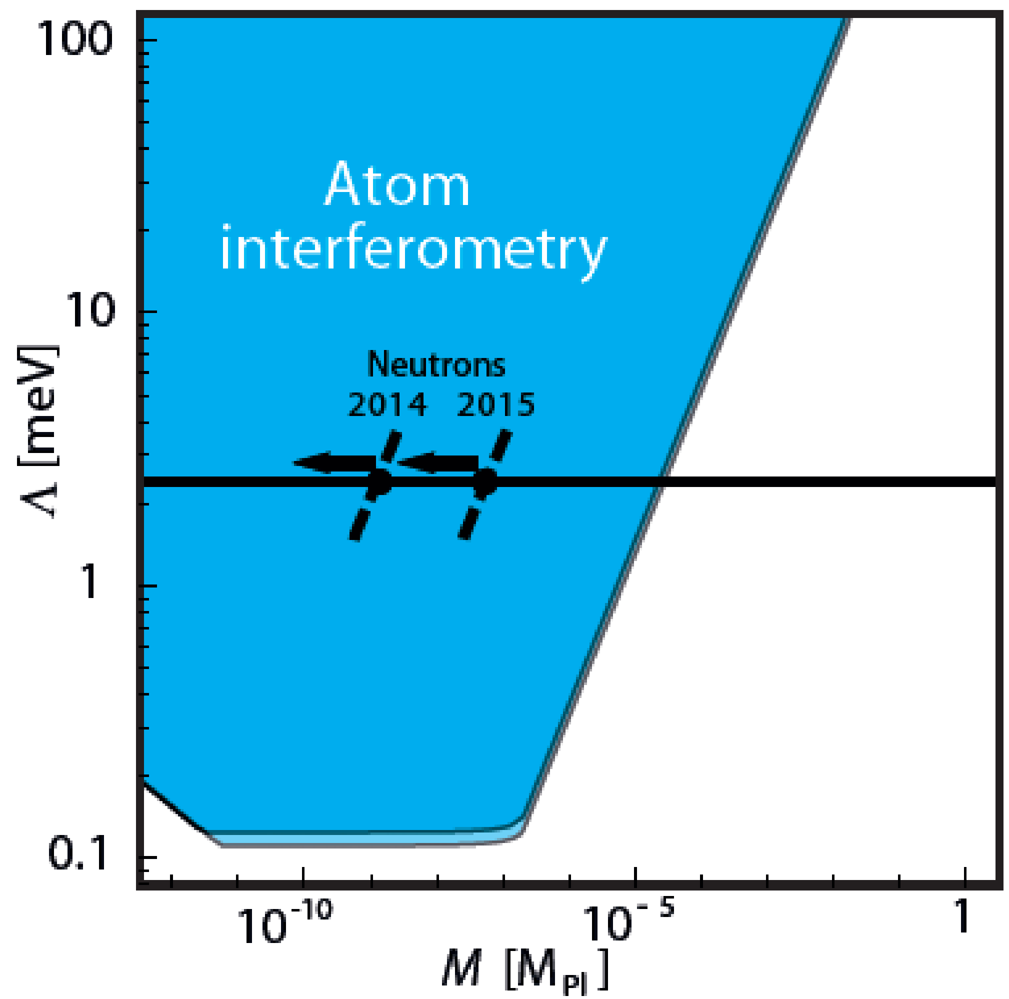
$$\Delta a = 2.3 \pm 3.3\ \mu\text{m/s}^2$$

P. Hamilton, M. Jaffe, P. Haslinger, Q. Simmons, H. Müller, J. Khoury
arXiv:1502.03888

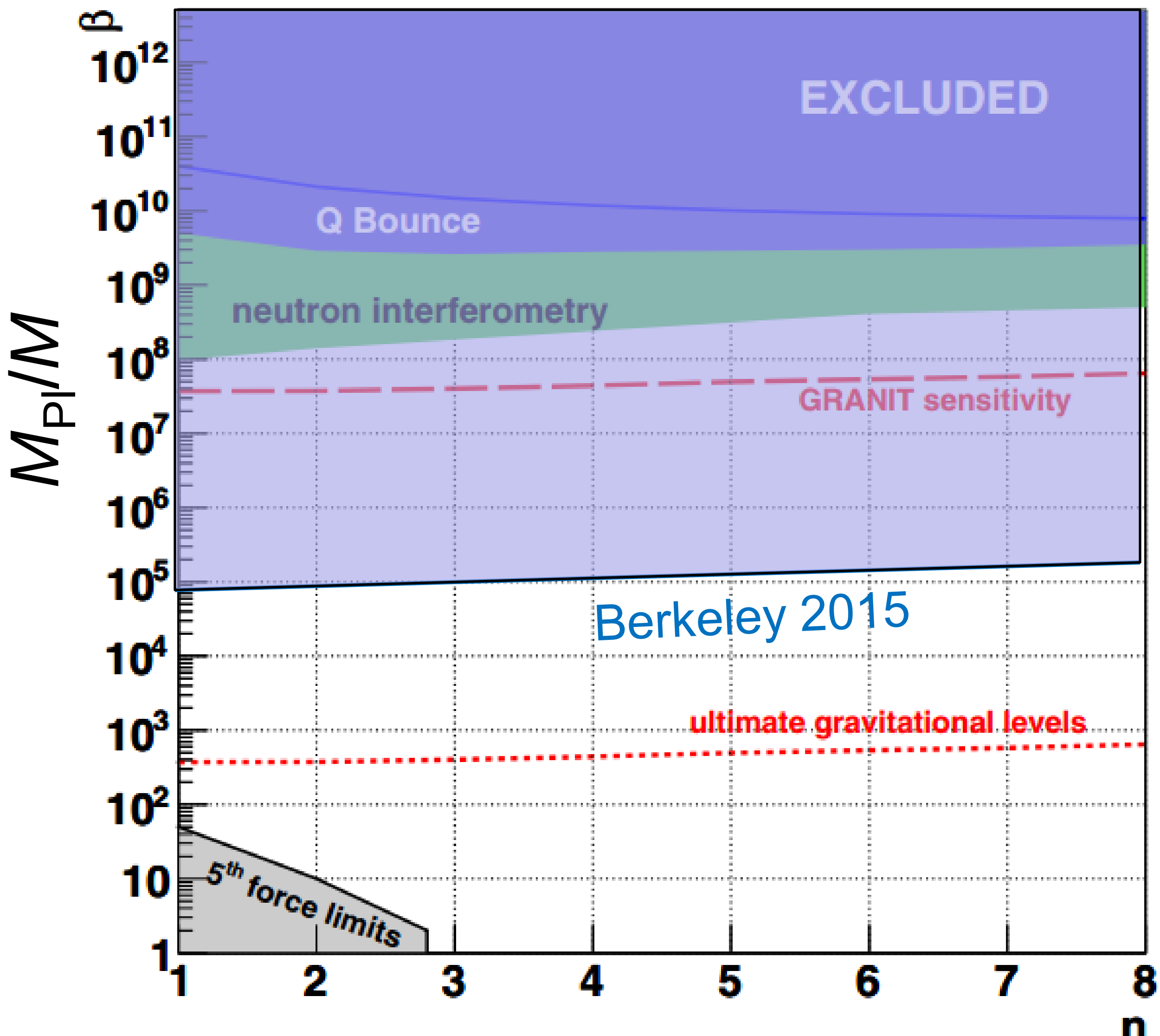
Results

	Average [µm/s²]	Error [µm/s²]
Statistics	2.7	3.3
Magnetic fields	-4.5	1.7
AC Stark effect	1.1	0.5
Surface Voltage	-	0.08
Total	**-0.7**	**3.7**

$a < 5.5$ µm/s² at 95% confidence level

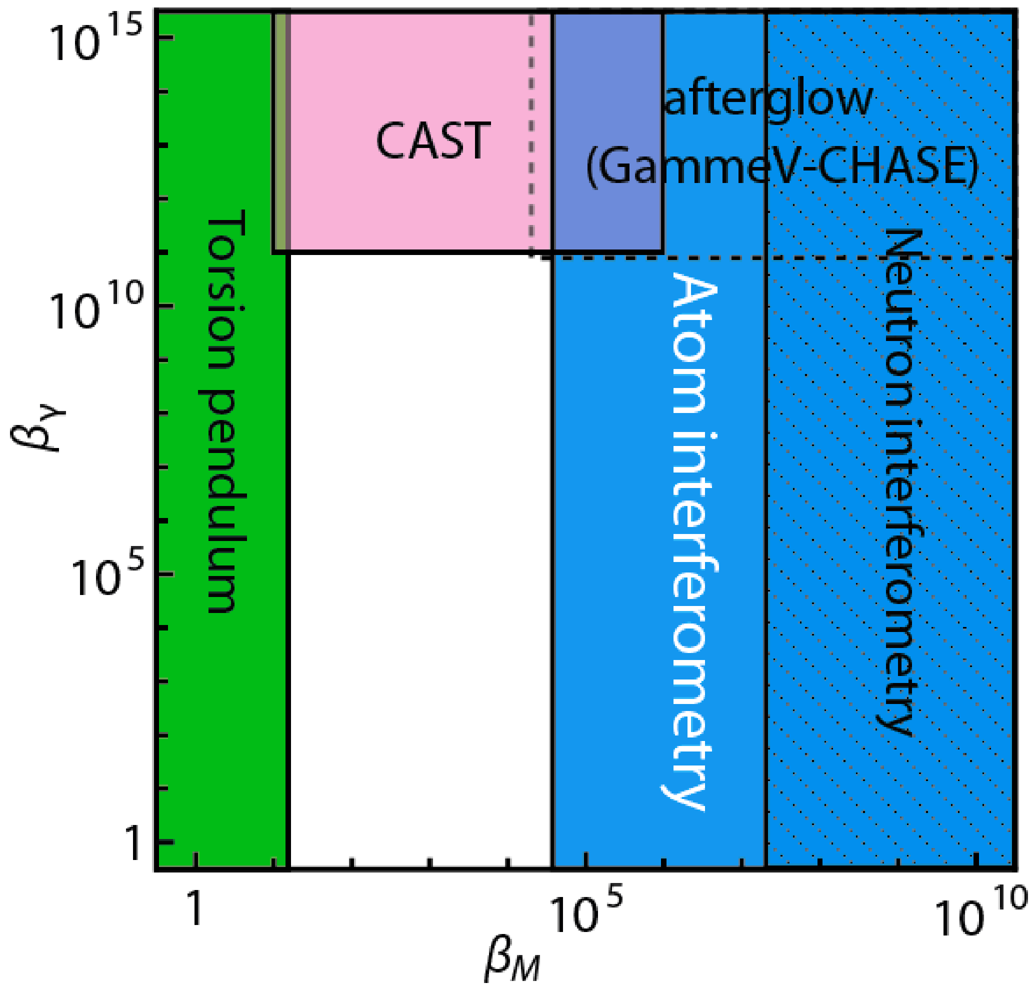


Results



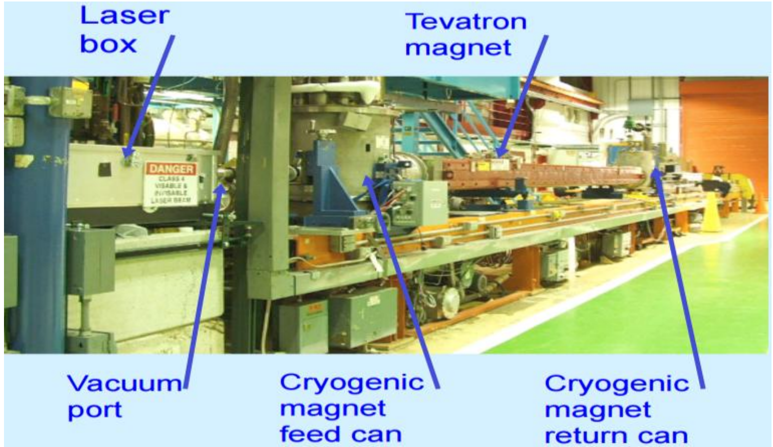
P. Brax, Physics Procedia **51,** 73 (2014)

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)

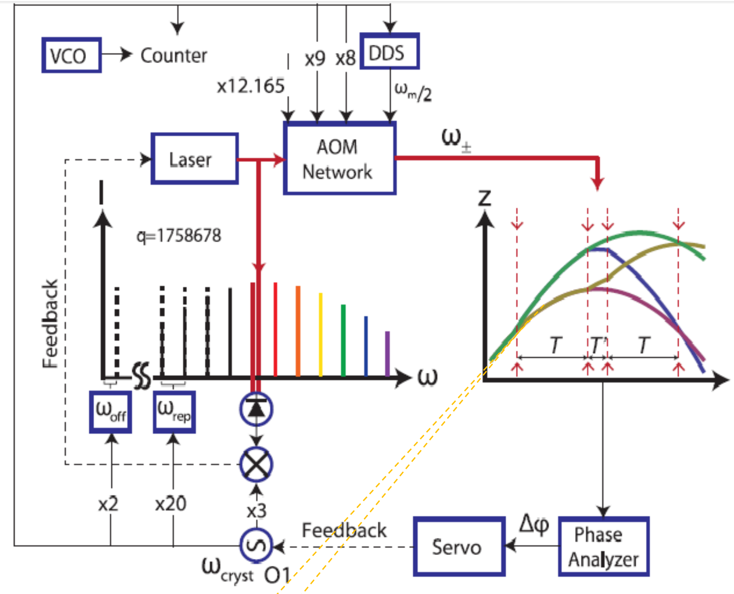
Limits including experiments using an additional coupling to the photon

Atom interferometry does not need photon coupling

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= $(mc^2/\hbar)/(2nN^2)$, 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

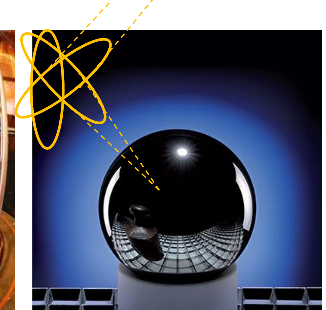
Application

- 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



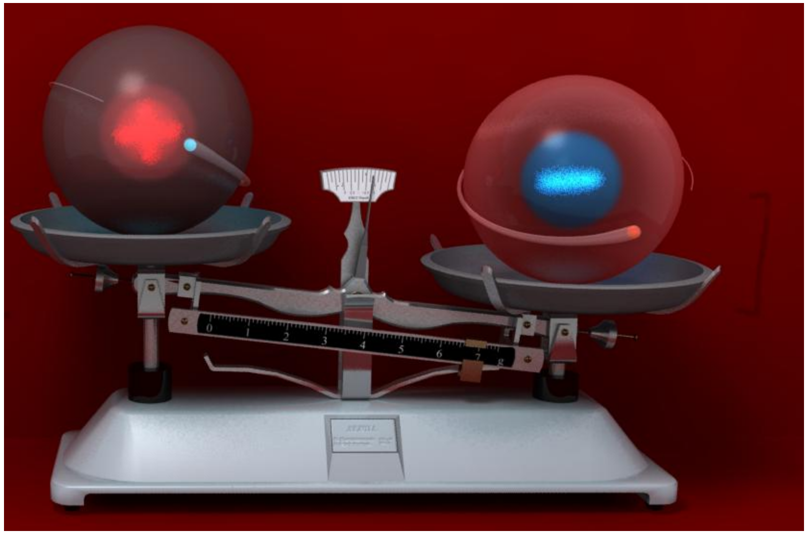
- 4 ppb for amu
- 30 ppb for kg
- No moving parts, gravity, standard resistors…
- Agrees with European versions
- <1 ppb in the future

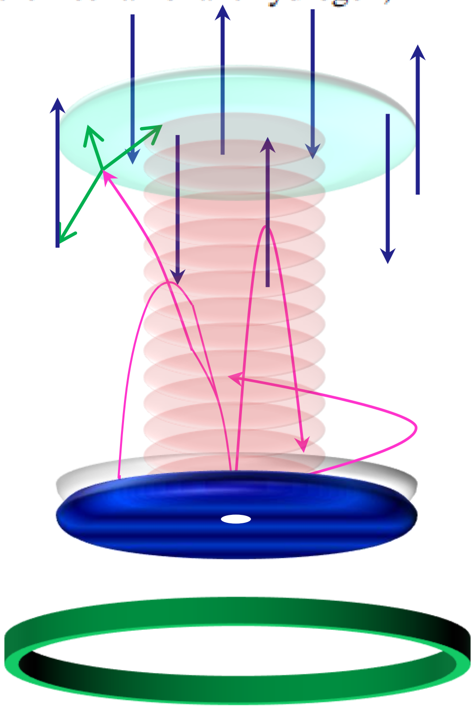
Independent methods realize the same definition ☺

Antimatter Interferometry for Gravity Measurements

Paul Hamilton,[1] Andrey Zhmoginov,[1] Francis Robicheaux,[2,‡] Joel Fajans,[1,†]
Jonathan S. Wurtele,[1,†] and Holger Müller[1,*,†]
[1]*Physics Department, University of California, Berkeley, California 94720, USA*
[2]*Department of Physics, Auburn University, Auburn, Alabama 36849, USA*
(Received 12 August 2013; published 25 March 2014)

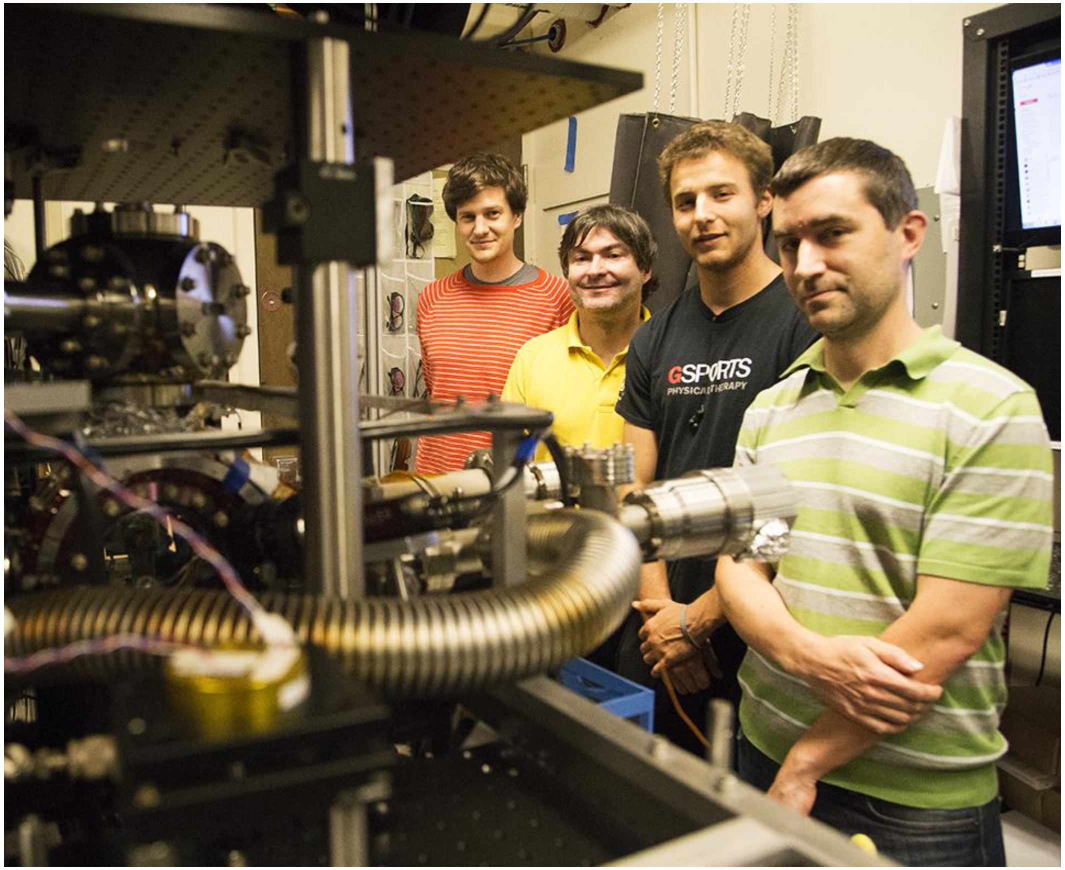
We describe a light-pulse atom interferometer that is suitable for any species of atom and even for electrons and protons as well as their antiparticles, in particular, for testing the Einstein equivalence principle with antihydrogen. The design obviates the need for resonant lasers through far-off resonant Bragg beam splitters and makes efficient use of scarce atoms by magnetic confinement and atom recycling. We expect to reach an initial accuracy of better than 1% for the acceleration of the free fall of antihydrogen, which can be improved to the part-per million level.





Thanks

Justin Khoury (U Penn)



Philipp Haslinger, HM, Matt Jaffe, Paul Hamilton

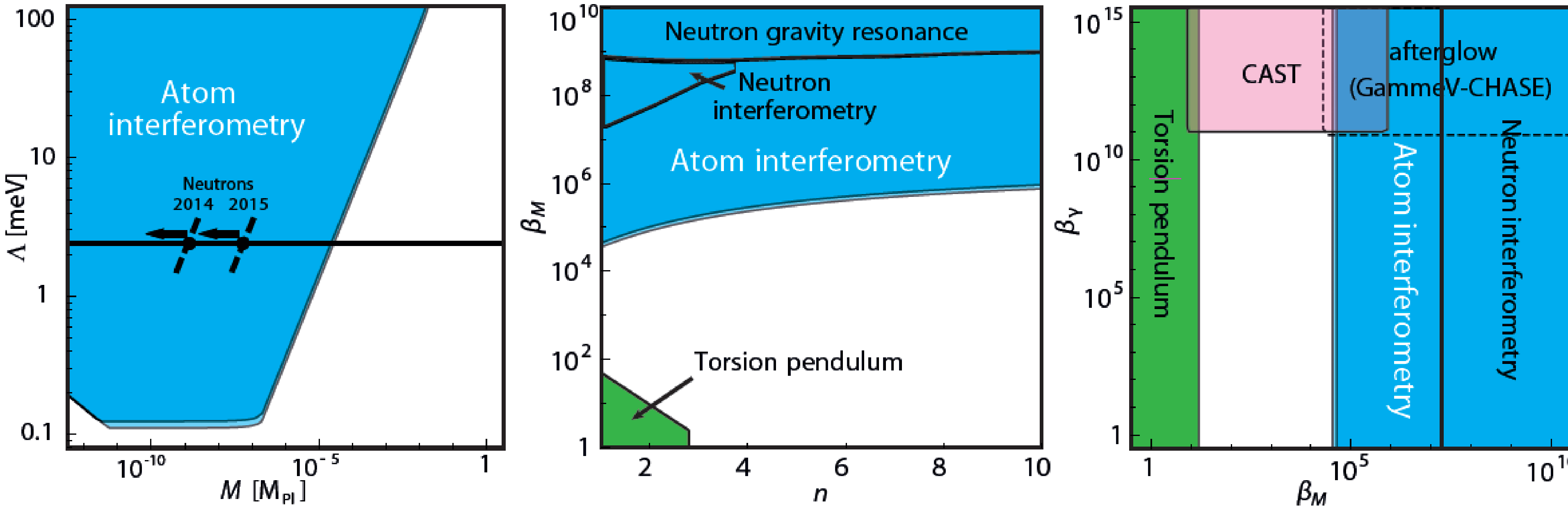
the David & Lucile Packard FOUNDATION

NSF

NASA

DARPA

Summary/ Outlook

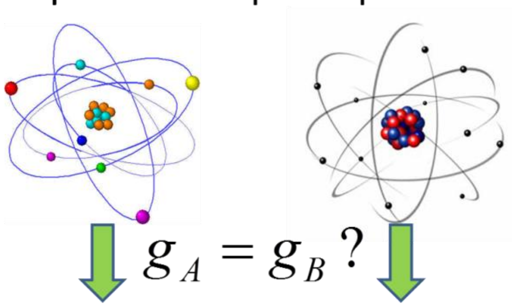


- Symmetrons
- *f*(*R*) gravity
- Varying dilatons…

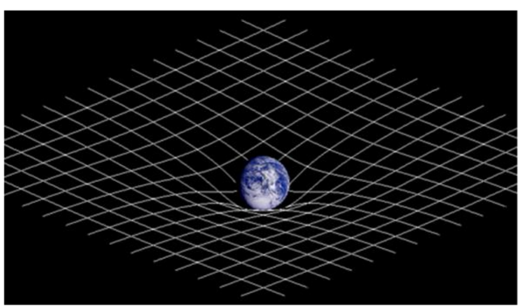
Please color the white area blue

Atom interferometry in space

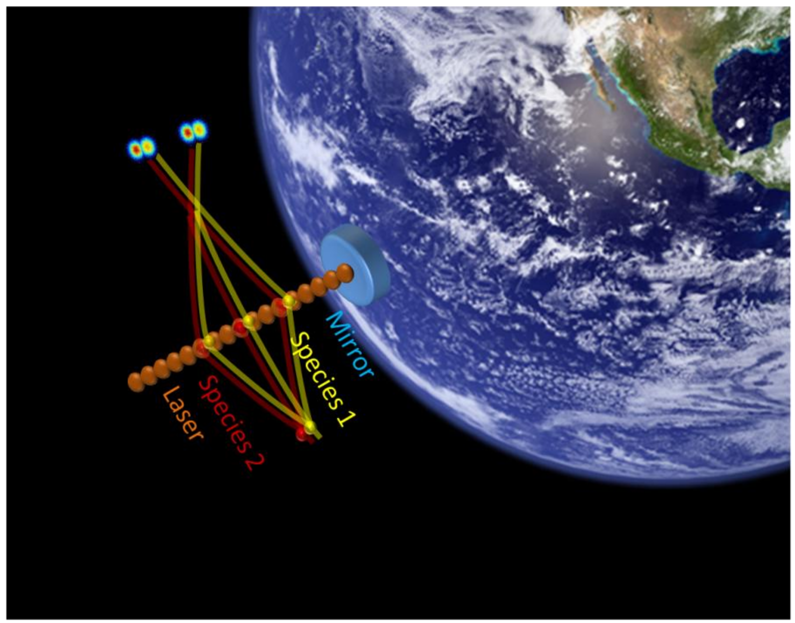
Equivalence principle



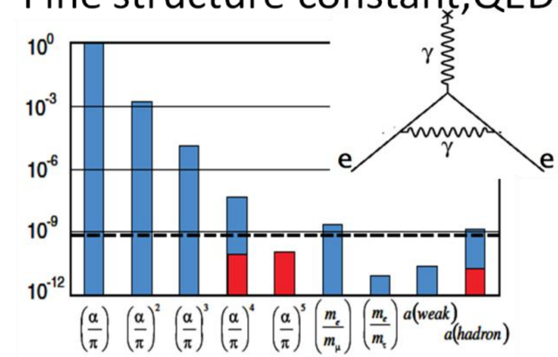
Post-Newtonian gravity



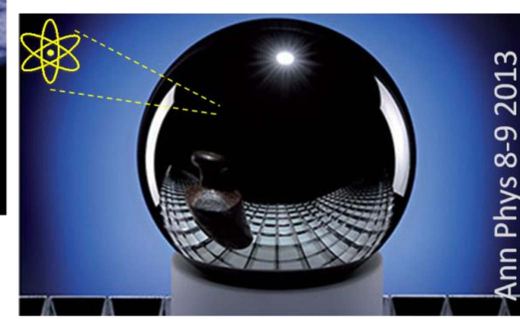
Light pulse atom interferometer in space



Fine structure constant,QED



Quantum mass standard



=> Talk by Jason Williams, Sheng-wey Chiow and Nan Yu