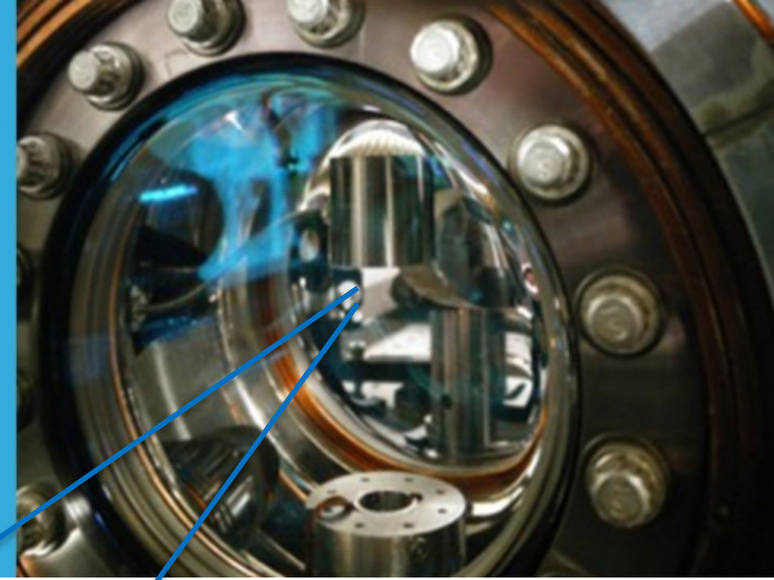
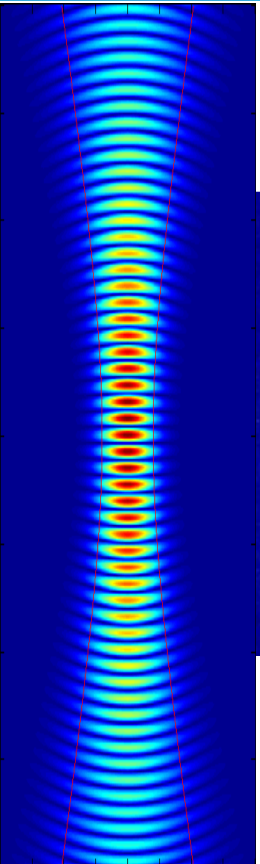
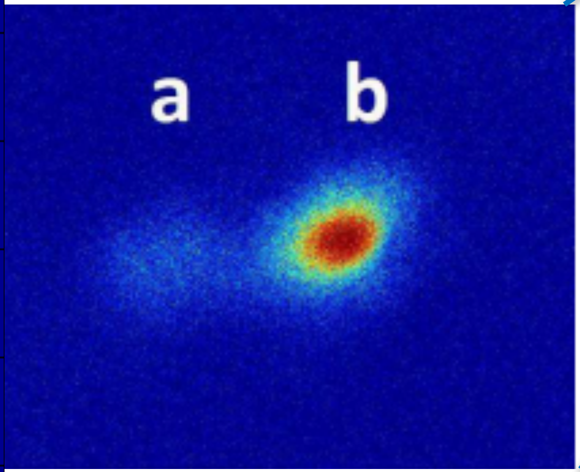
# Shining light on dark matter and dark energy with lasers and atoms

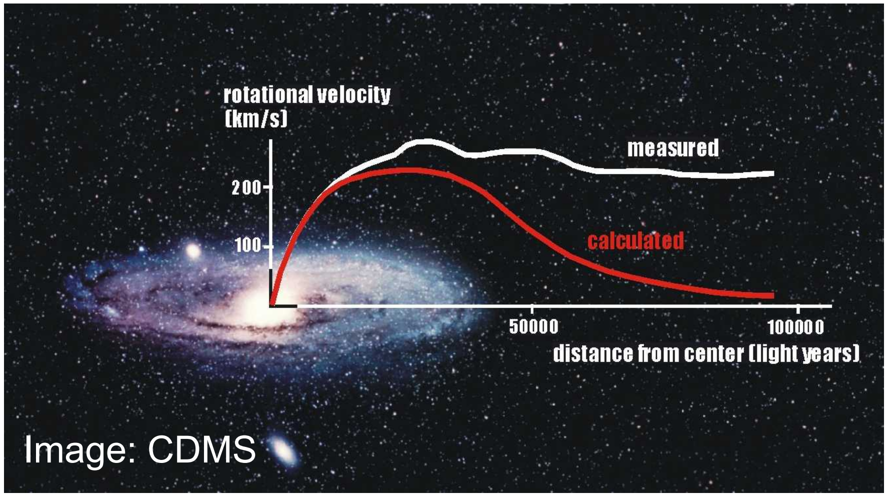


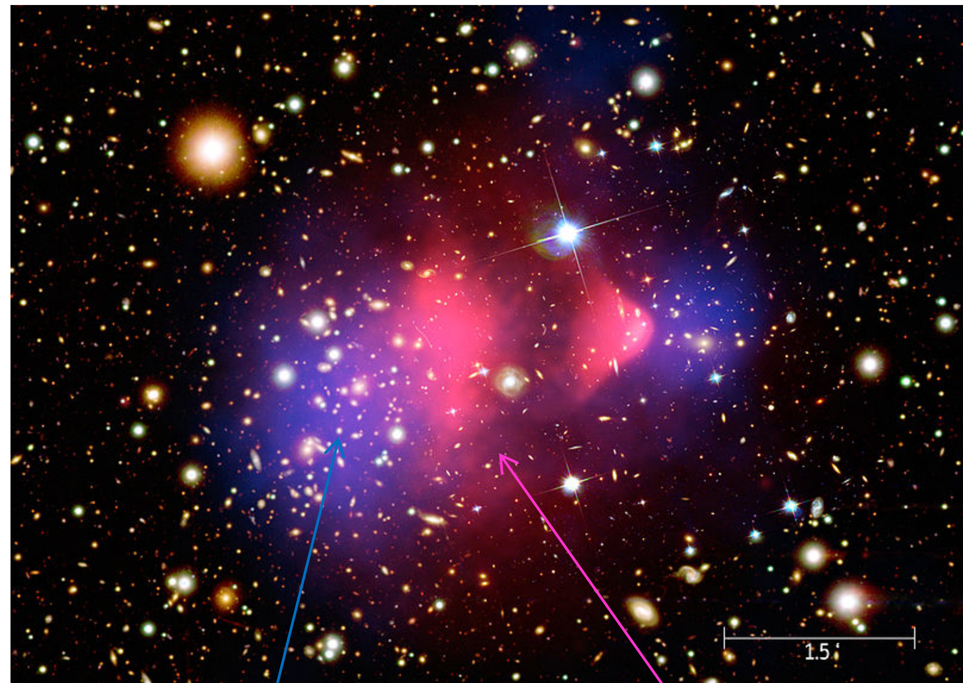


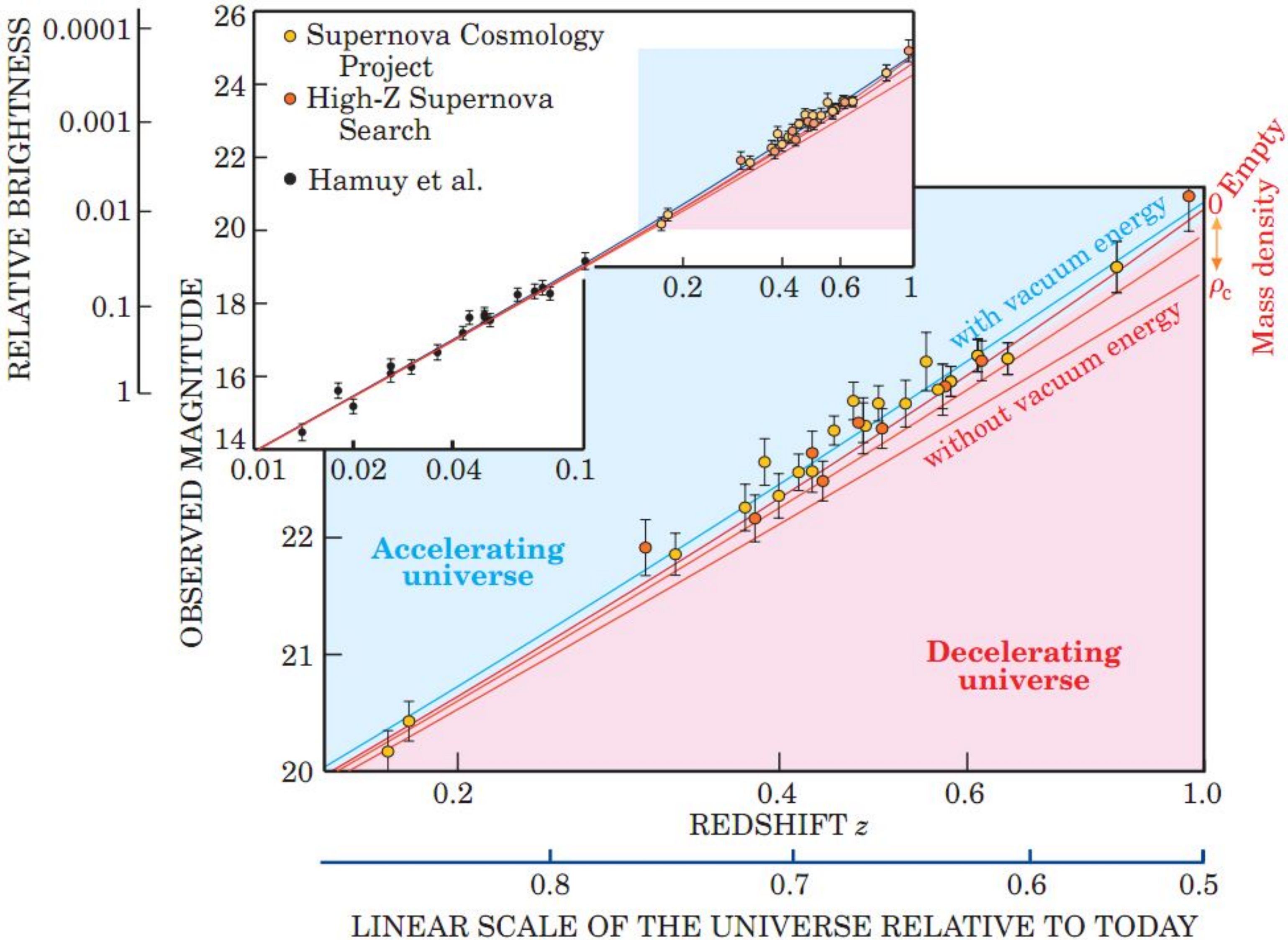



Holger Müller

# Contents

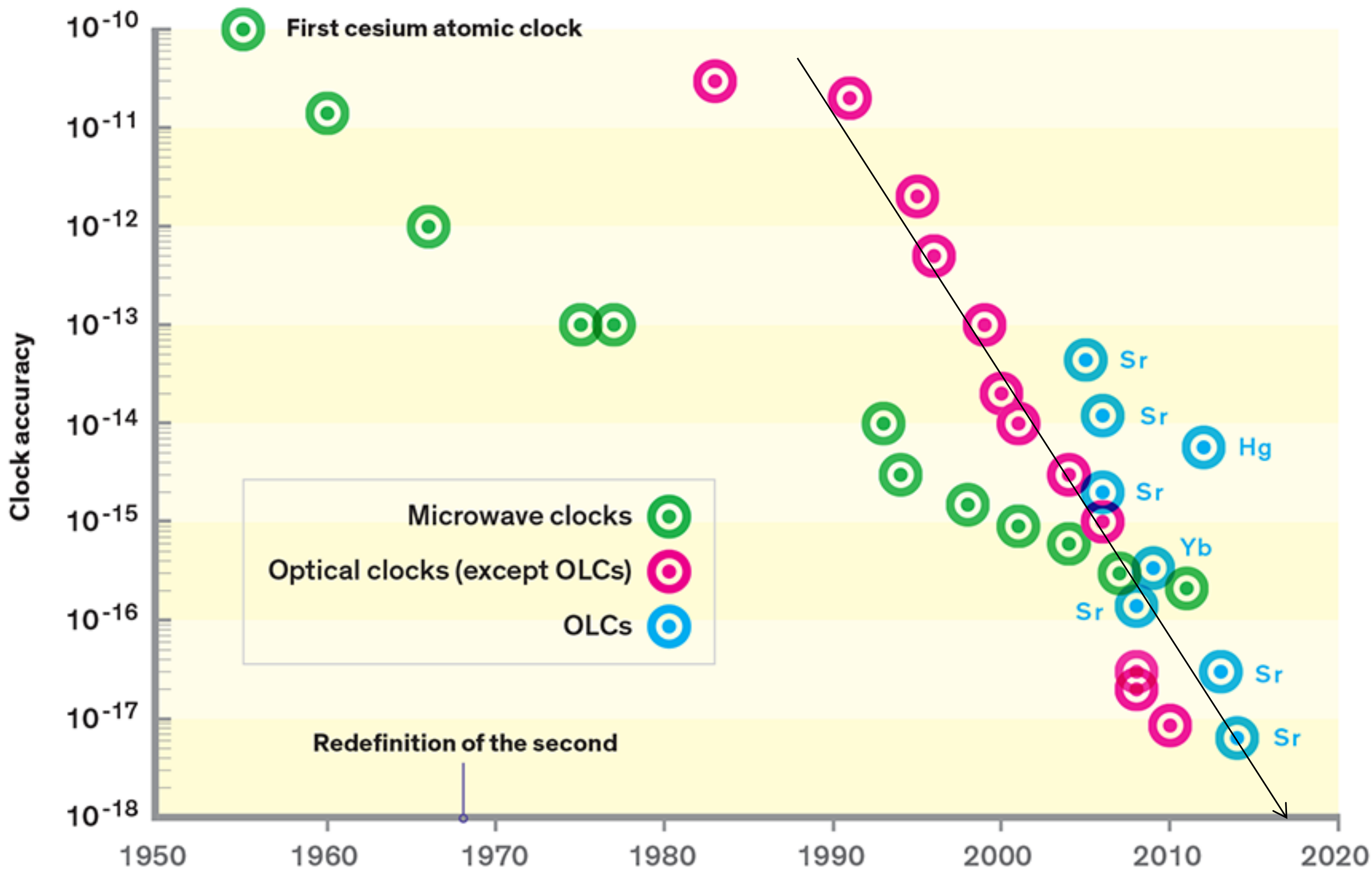

rotational velocity
(km/s)
200
100
measured
calculated
50000
100000
distance from center (light years)
Image: CDMS


1.5'
Reconstructed mass distribution (lensing)
Observed matter (Chandra x-ray observations)



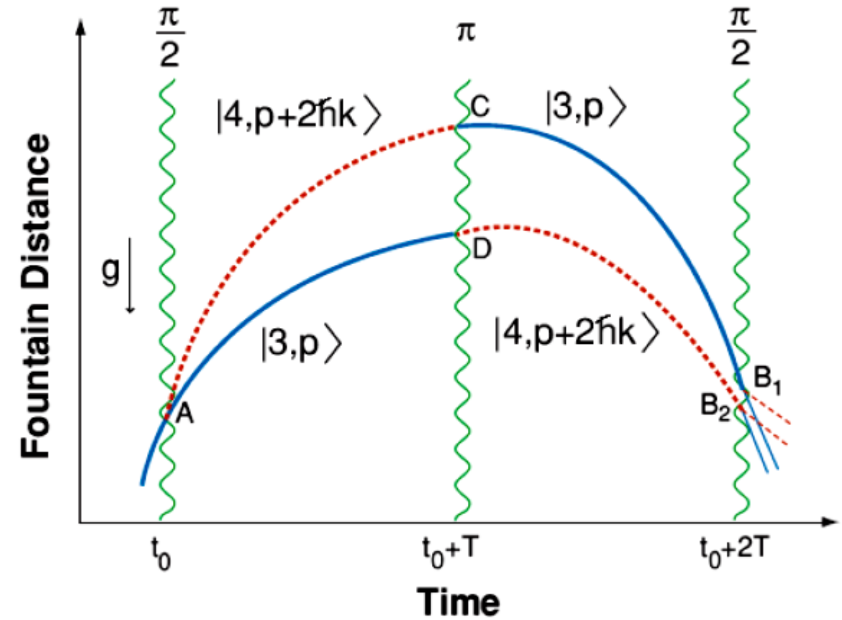

Saul Perlmutter

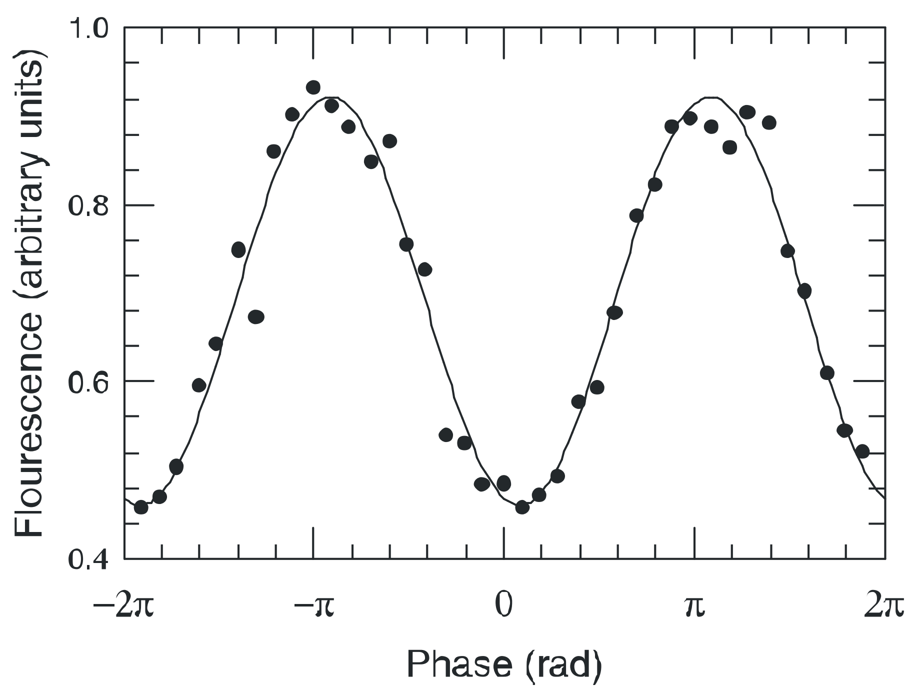
# Moore's law in atomic physics



# Light pulse atom interferometer

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



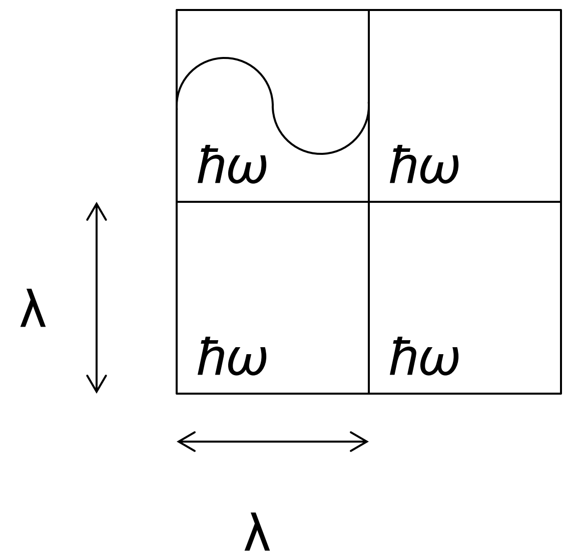

Each data point is from a single launch, determines g to 1.3ng =>11ng/sqrt(Hz)

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

# Dark Energy density

$\Lambda \qquad \approx 10^{-52}/m^2$

$\qquad \approx 1/(\text{present size of universe})^2$

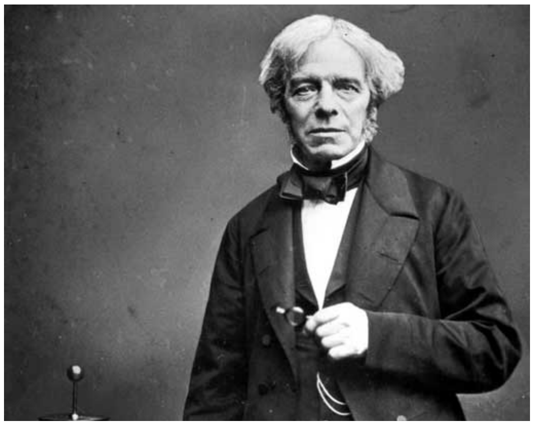


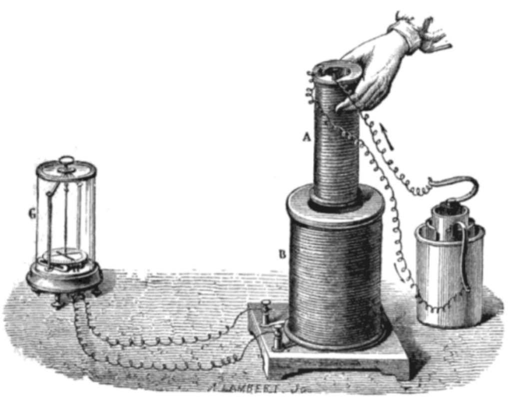

Energy density corresponding to that is more intuitive

- 7 Hydrogen rest masses/$m^3$
- E=14 V/m
- One photon of $\lambda \approx 100$ μm per $\lambda^3$

# Faraday's law and Maxwell's equations

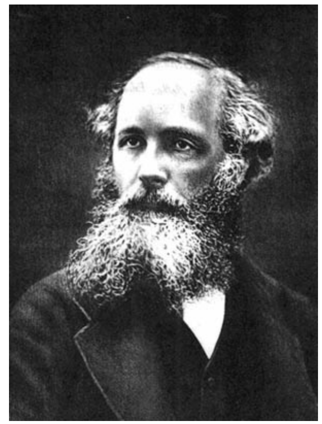
1831





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

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

# Dark Energy: Models?

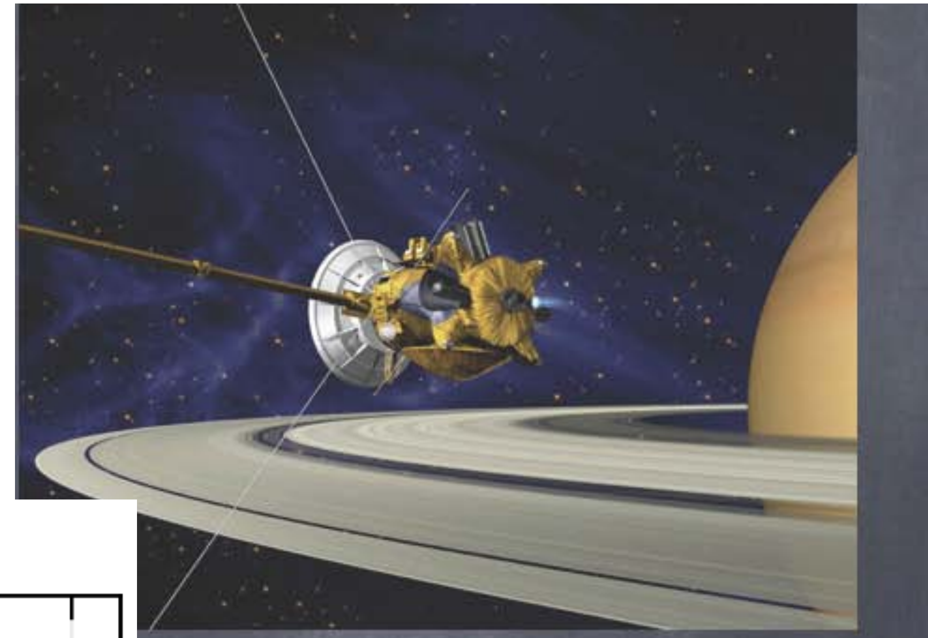
Vacuum fluctuations ~ $\Lambda_{uv}^4$ (Pauli, circa 1920) — 123 orders of magnitude off

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

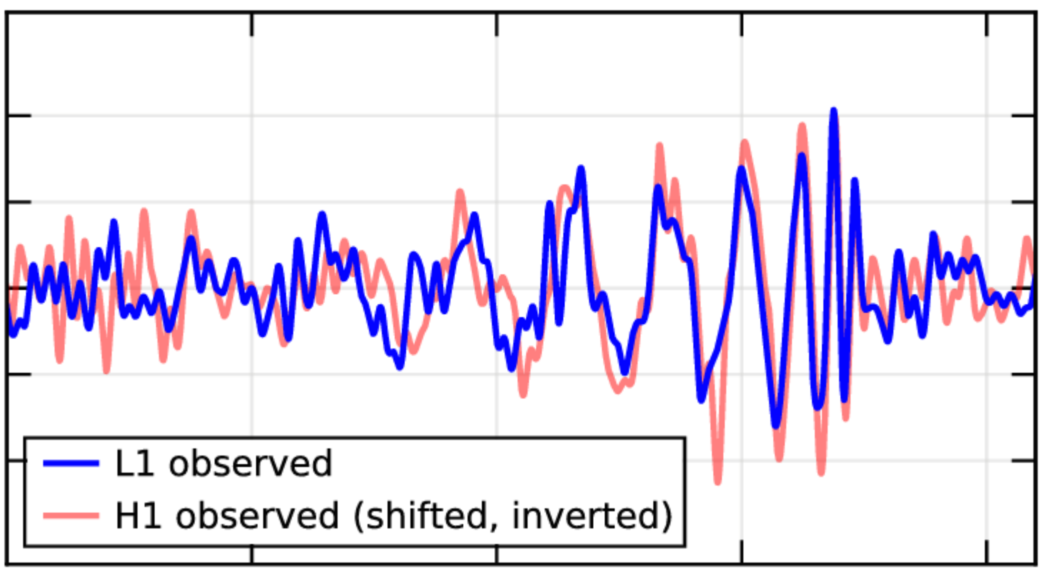
$\Rightarrow$ New physics needed

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

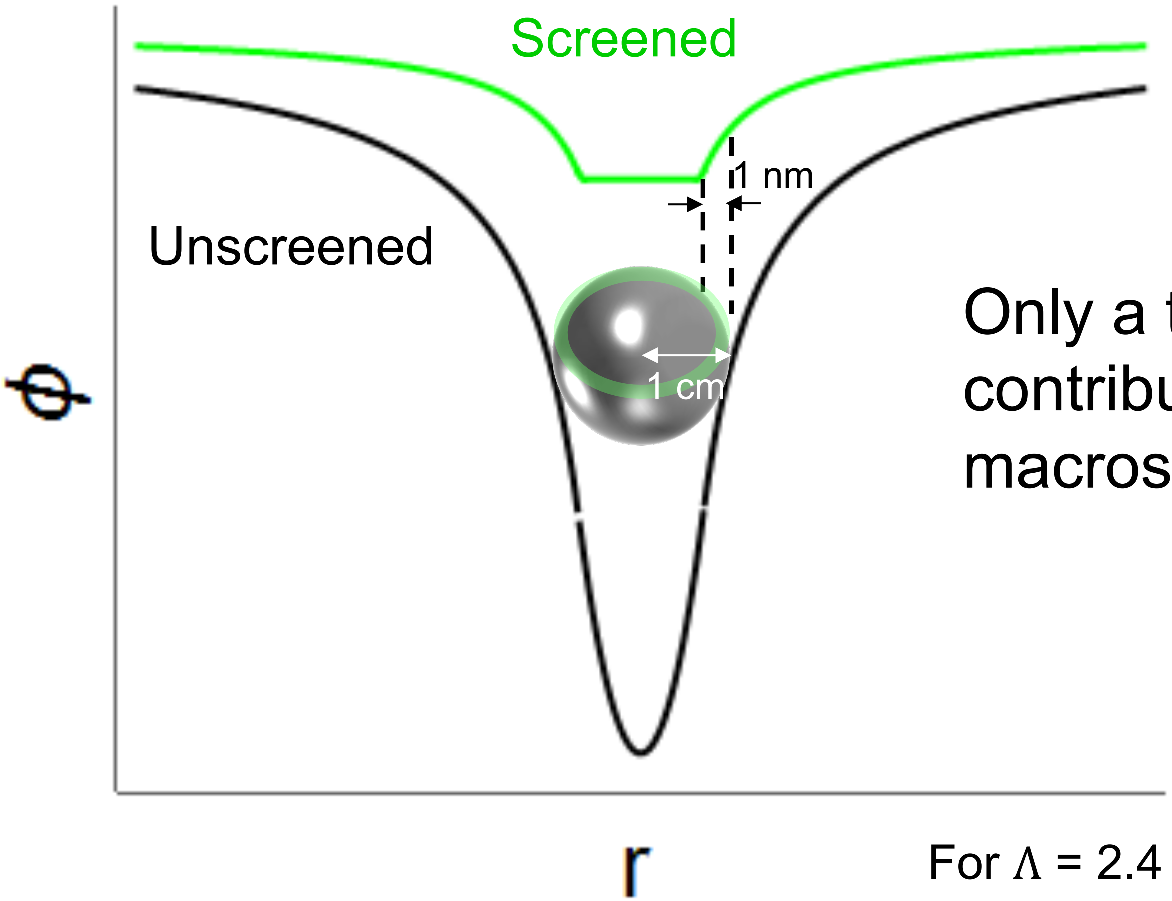
# Testing gravity



Livingston, Louisiana (L1)



# 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

# The idea

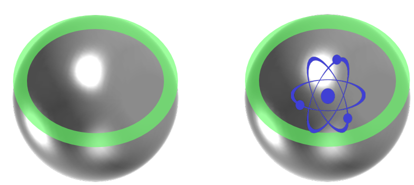


*Probing Dark Energy with Atom Interferometry*
C. Burrage, E. J. Copeland, E. A. Hinds
JCAP 1503 (2015) 03, 042

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

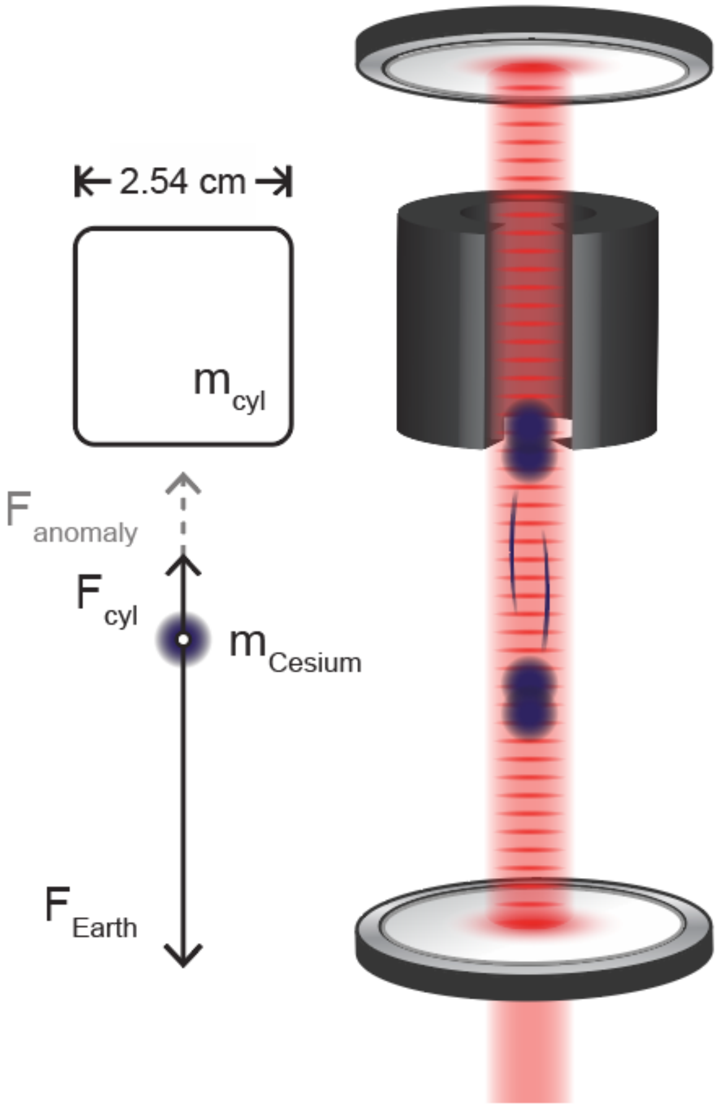
$$\lambda_{atom} = 1$$

For most of parameter space

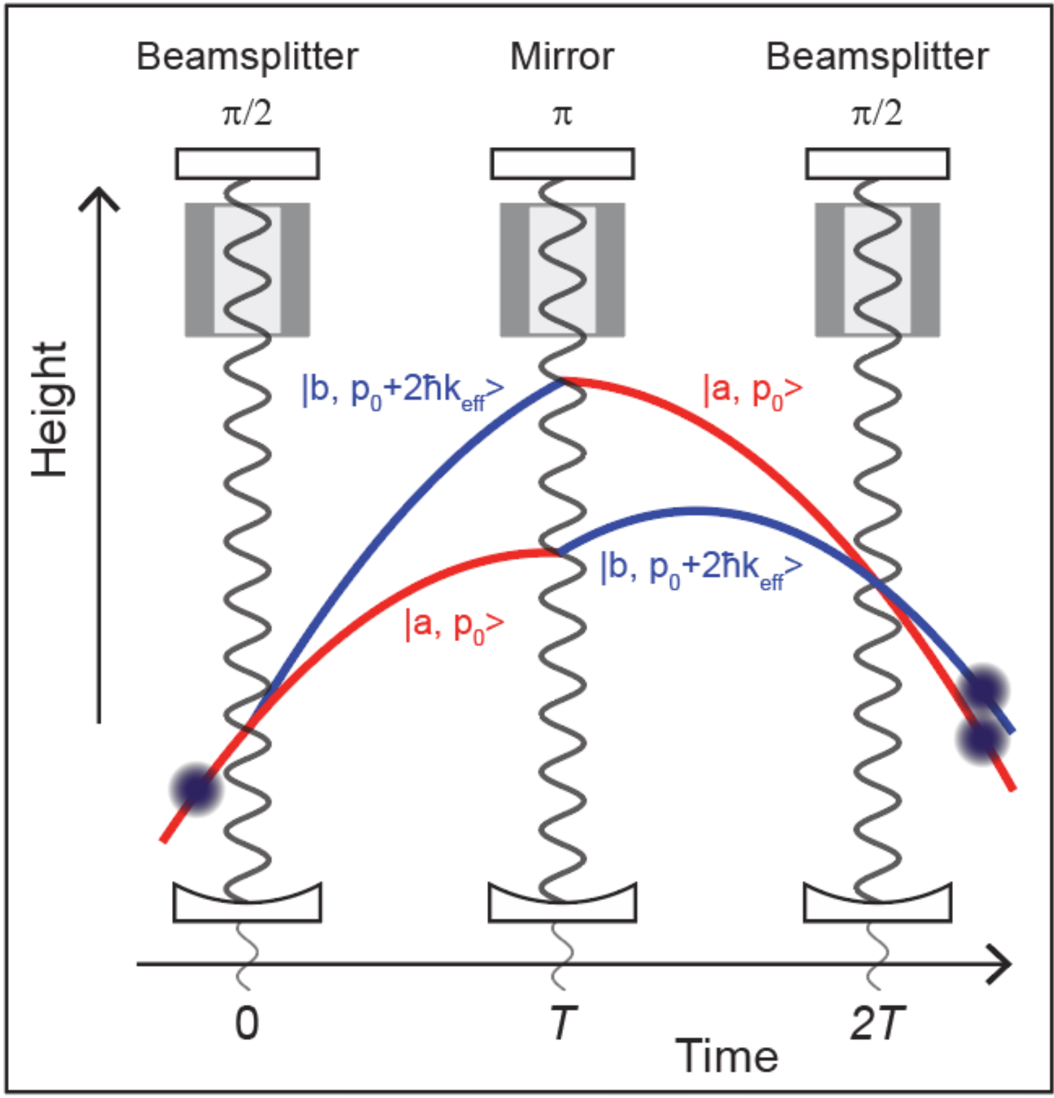
$$M < M_{Pl}$$

Unscreened force can be much stronger than gravity

# Setup

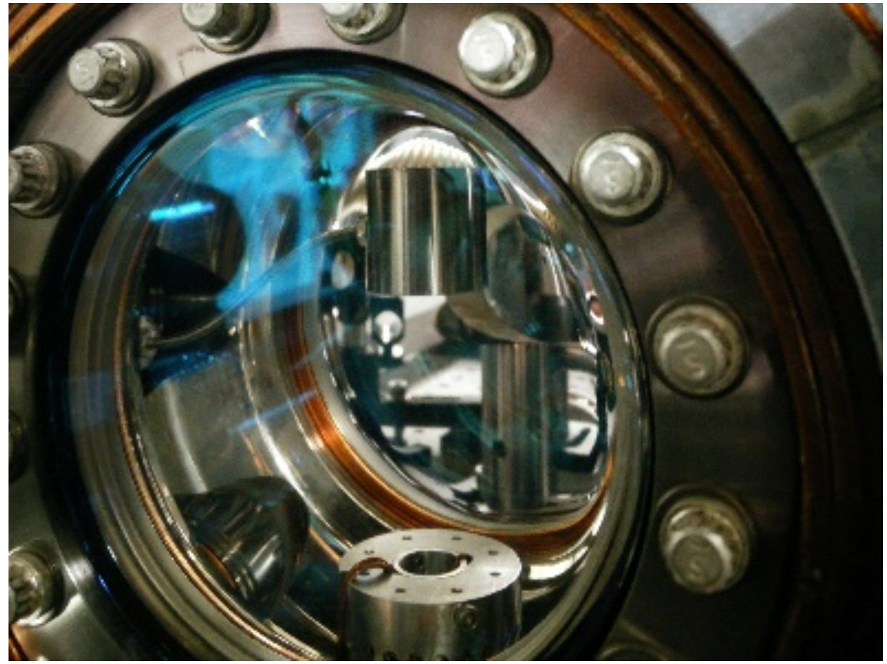


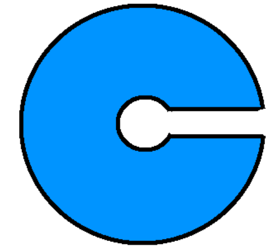
2.54 cm
$m_{cyl}$
$F_{anomaly}$
$F_{cyl}$
$m_{Cesium}$
$F_{Earth}$

Beamsplitter
π/2
Mirror
π
Beamsplitter
π/2
Height
|b, $p_0+2\hbar k_{eff}$>
|a, $p_0$>
|b, $p_0+2\hbar k_{eff}$>
|a, $p_0$>
0
T
2T
Time

# IMPROVED SETUP



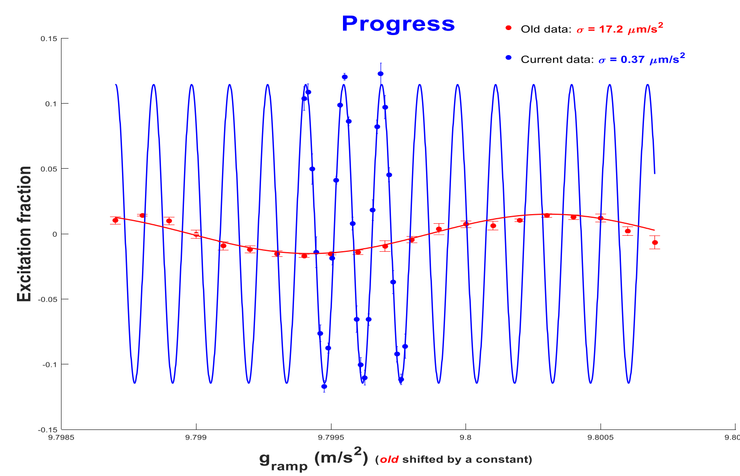


**Colder atoms**
- Raman sideband cooling
- 100s of nK

**Vibration isolation**
- dominant noise source
- $2^{nd}$ stack

**Launch**
- Longer T
- signal proportional $T^2$

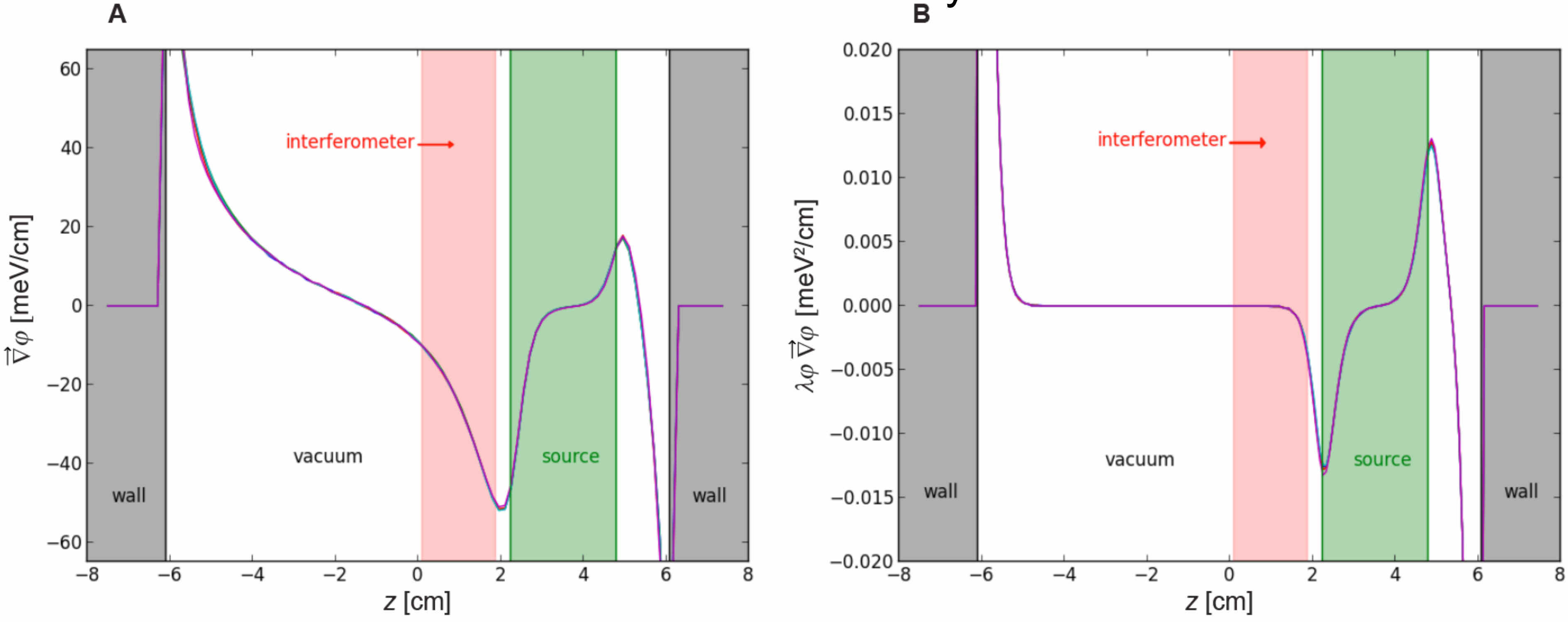
Tungsten test mass
- Slotted for systematics control
- Gravity 70 nm/$s^2$



# 3-D Field simulations

Chameleon

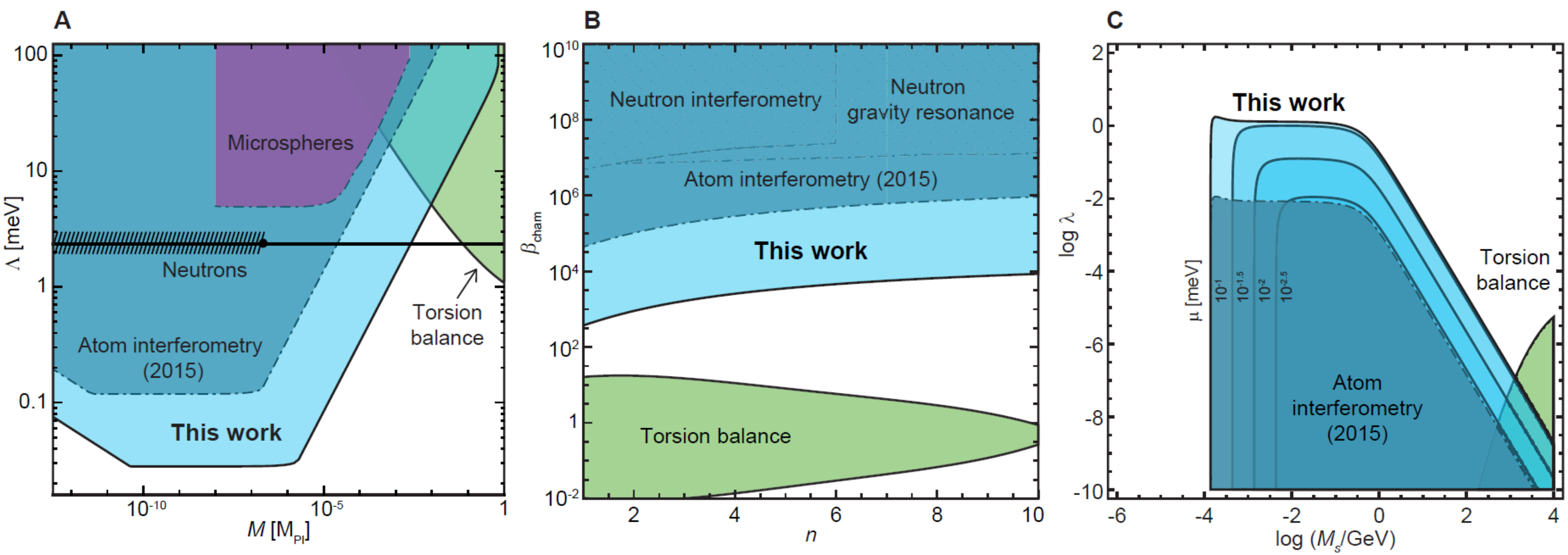
Symmetron



# Preliminary improved limits

Chameleons

Symmetrons




Interaction strength

# 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

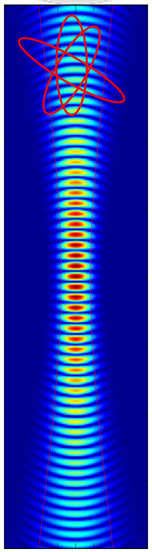
**Coupling**
- Similar to chameleon
- Symmetrons
- Damour-Polyakov

Joyce, Jain, Khoury and Trodden, arXiv:1407.0059

# Dreams

- Atoms in the free vacuum of space
    - Unlimited free evolution
    - Direct exposure to dark matter/dark energy candidates
    - Gravitational waves
- High-quality laser beams
    - Low systematics
    - High contrast
- Laser on the ground feasible?
- Wake field shield for $10^{-14}$-$10^{-8}$ Torr

Retroreflector,
Camera
Atom dispenser

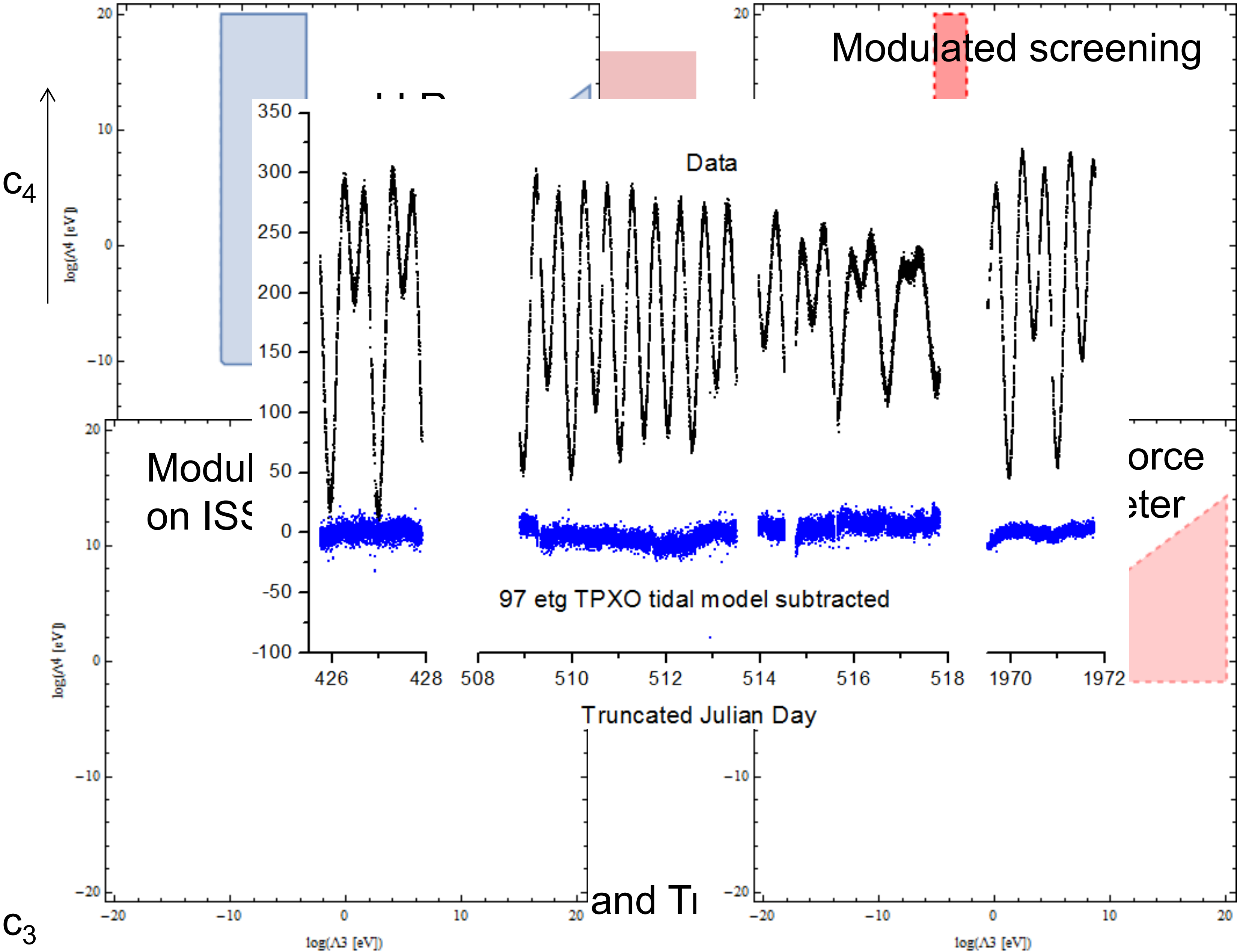


300 km

$w_0$=50 cm

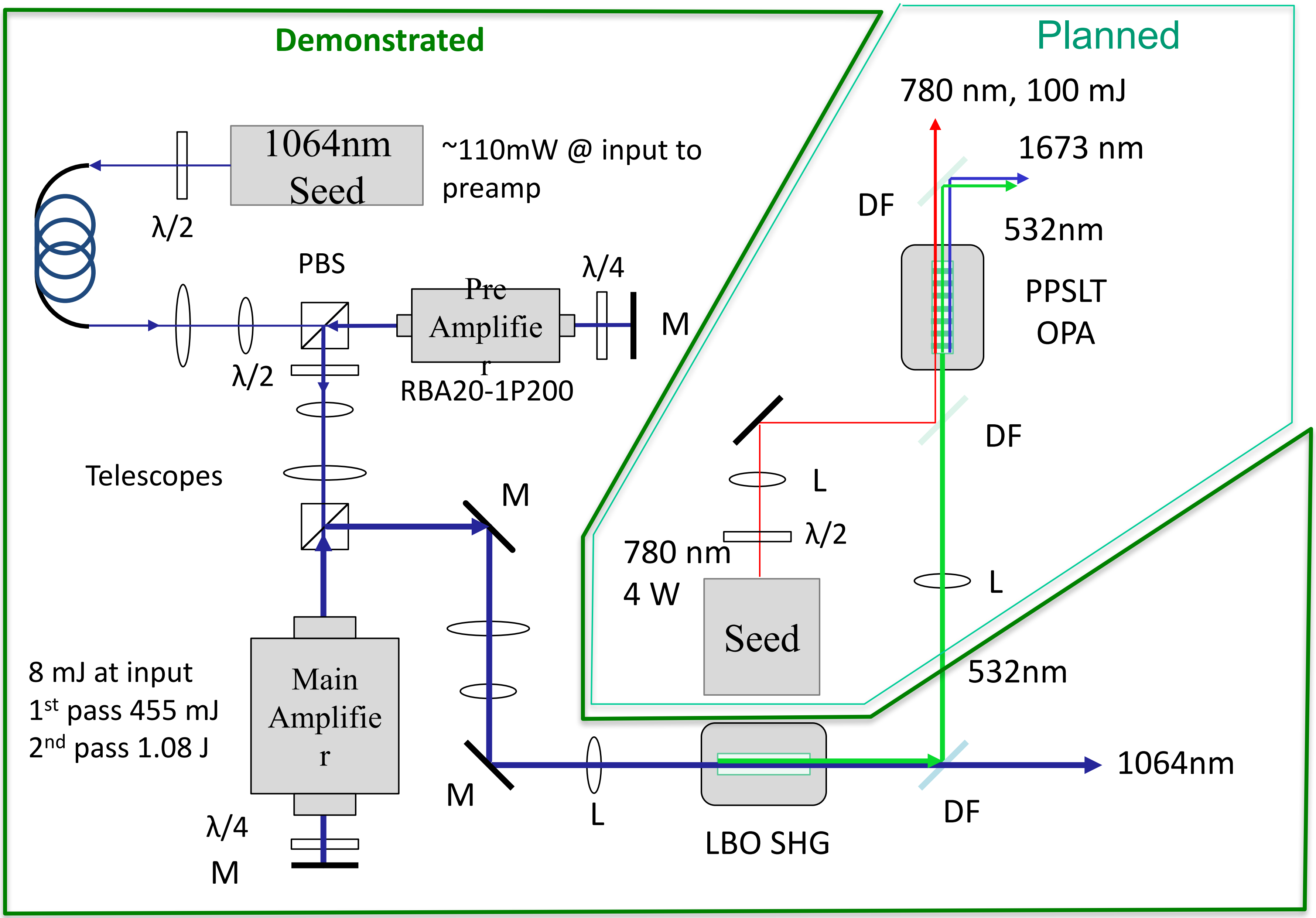

0.14 J

# Galileons

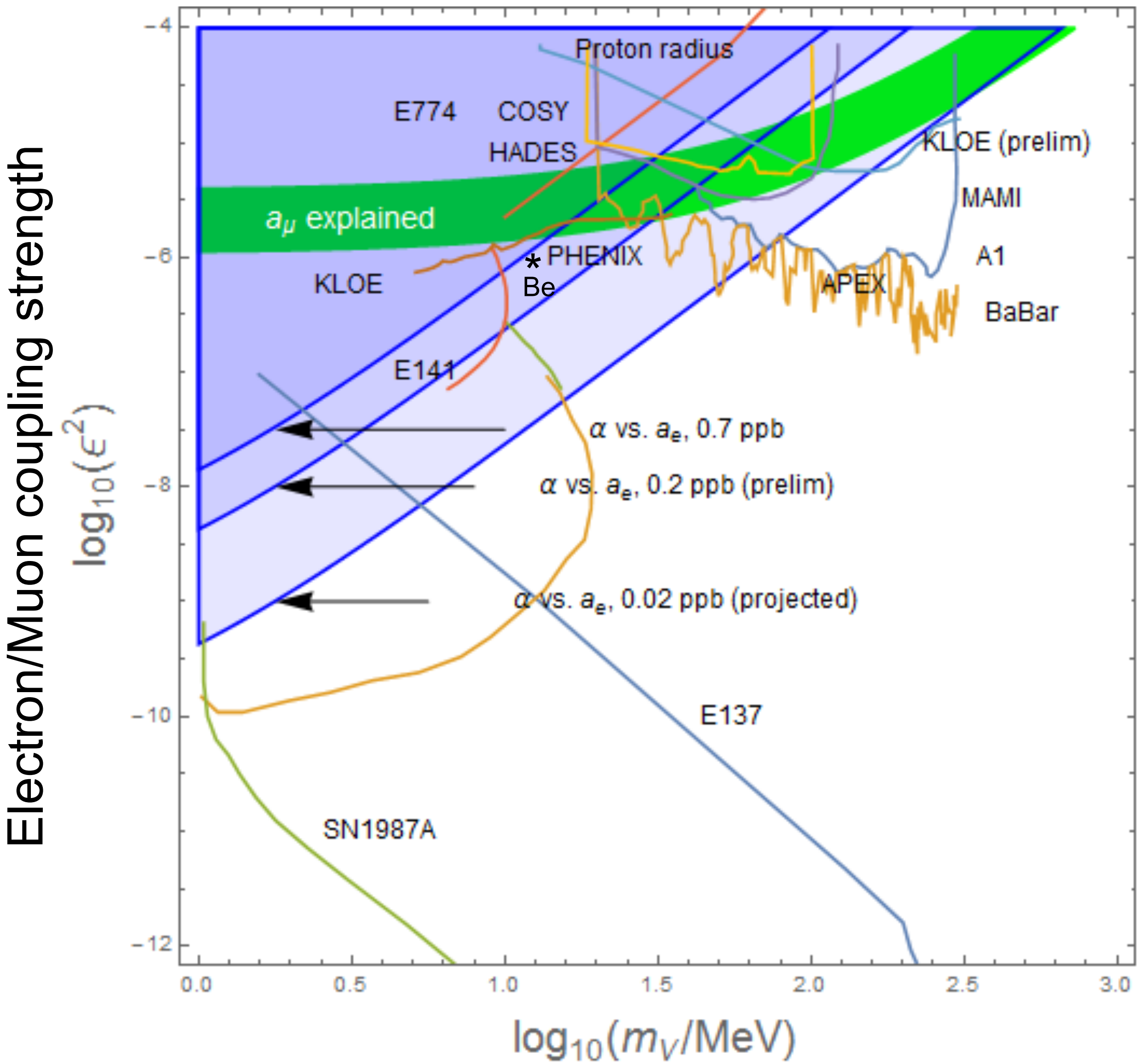


c4
c3
Modulated screening
Modul
on ISS
orce
eter
and Ti
log(Λ4 [eV])
log(Λ3 [eV])
Data
97 etg TPXO tidal model subtracted
Truncated Julian Day

# Long Pulse tunable 780 nm Laser Schematic



# Dark photons, hadrophobic

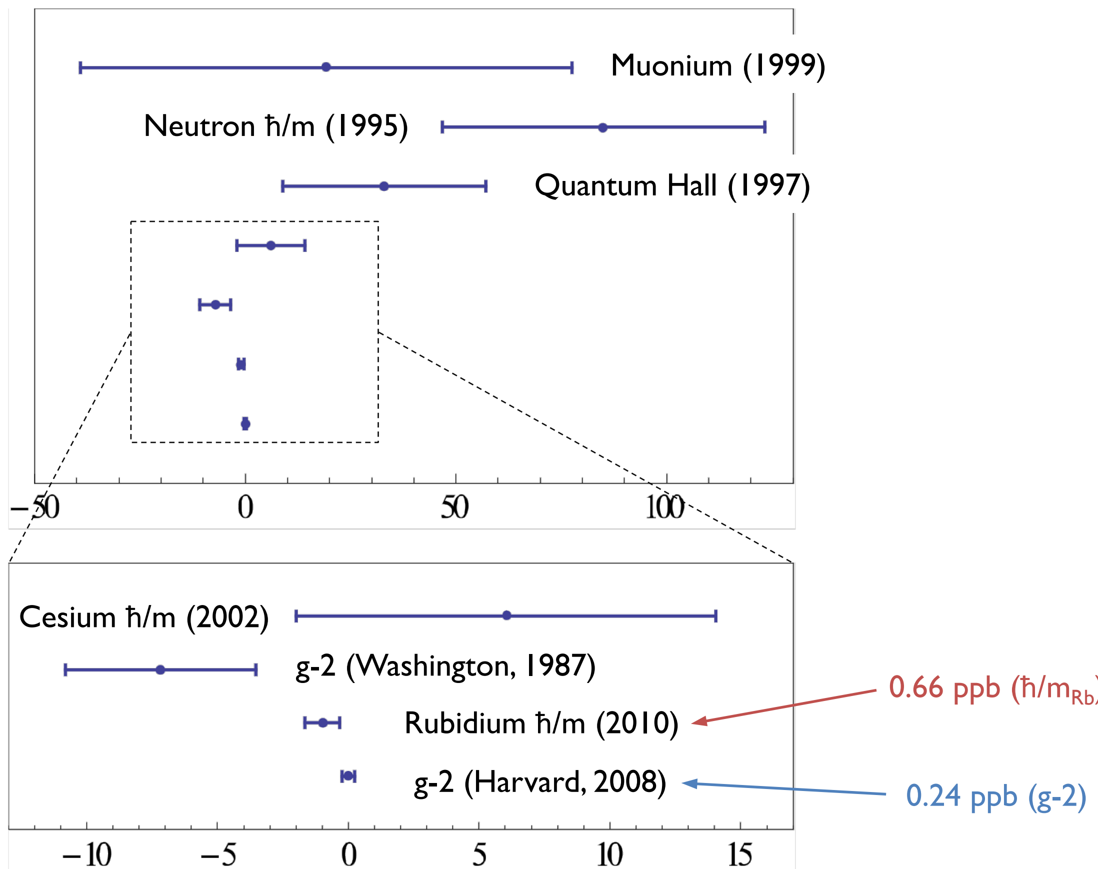



High energy limits assume 100% decay into e+ e- and become weaker if this is not the case.

# Fine Structure Constant α

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

Select Alpha Measurements



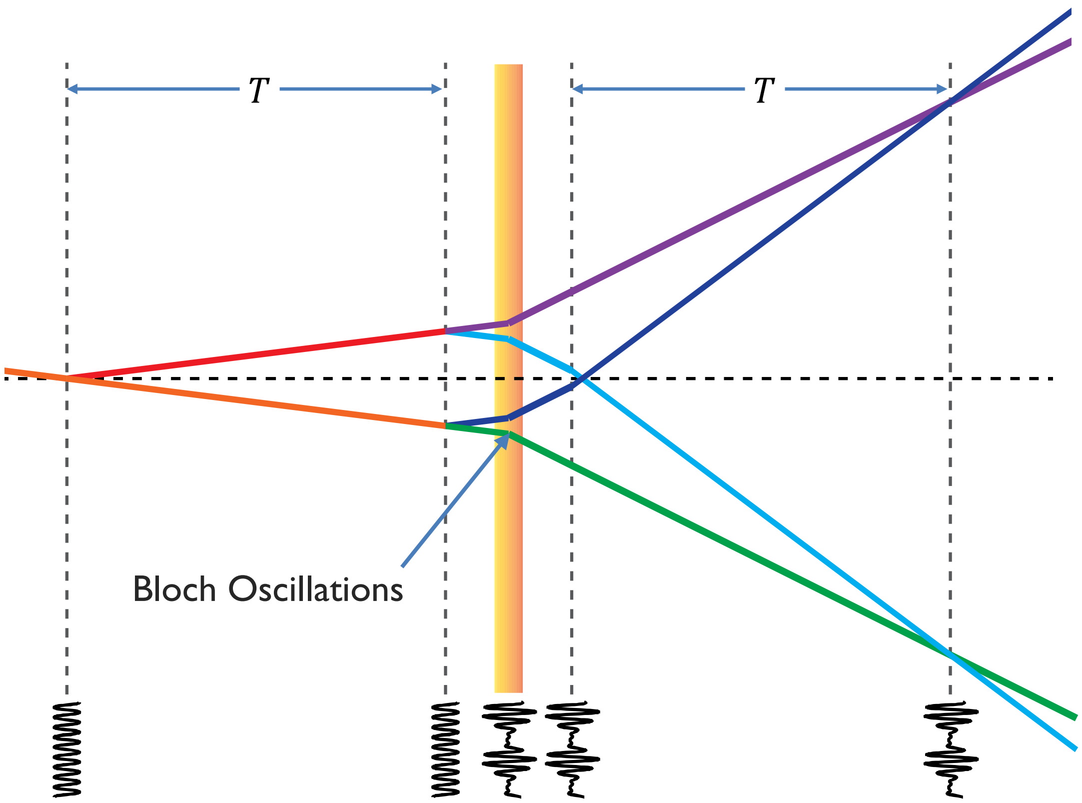

Relative Uncertainty $\delta\alpha/\alpha$ [ppb]

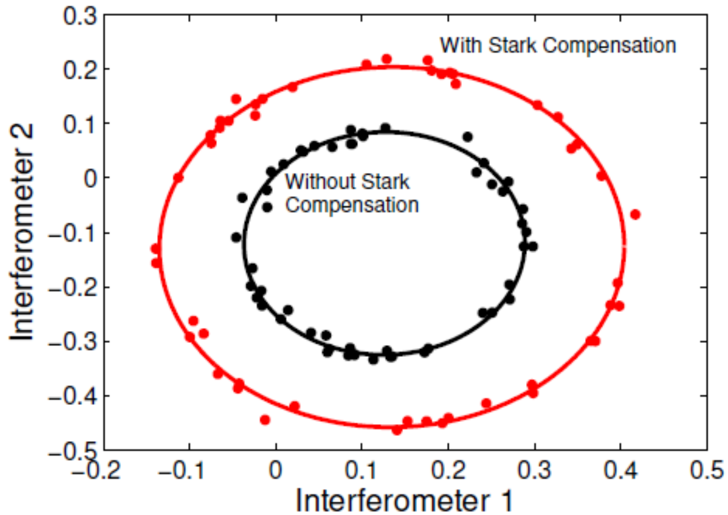
Rev. Mod. Phys. 84, 1527 (**2012**)

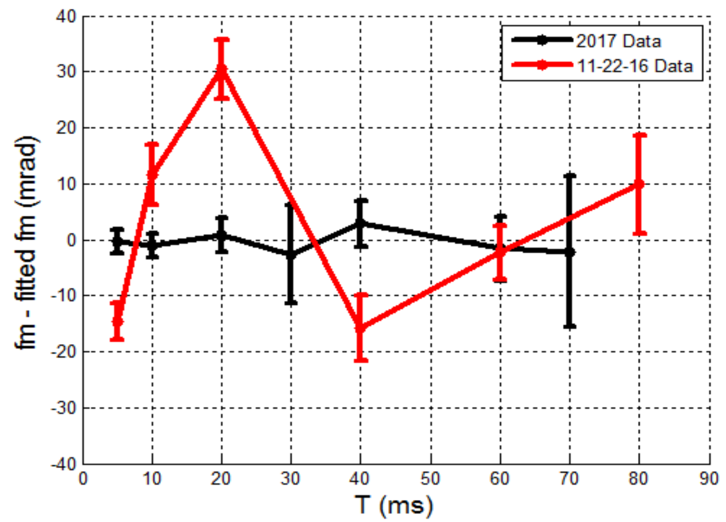
# Common-mode Bloch Oscillations

- Increases total phase of interferometer
- Increases frequency splitting of last two pulse
- $>10^7$ rad matter-wave phase difference

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

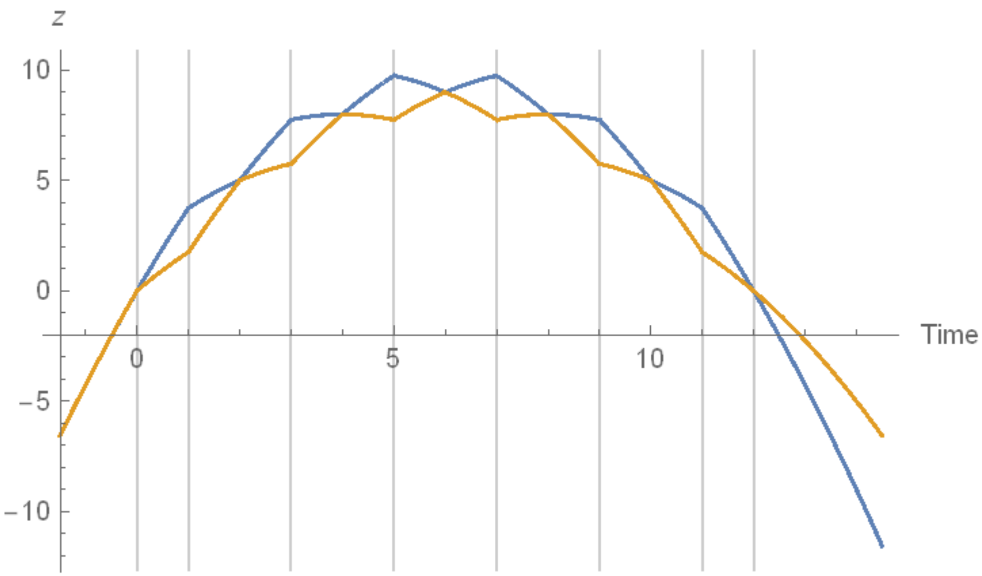


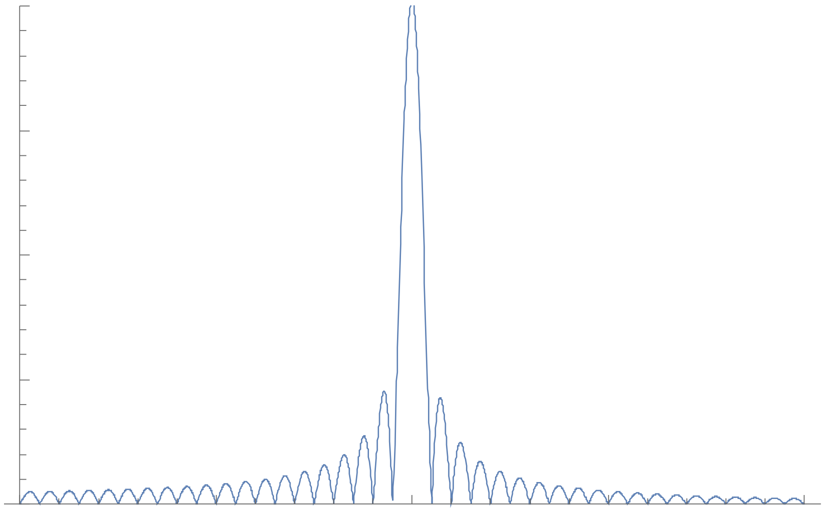



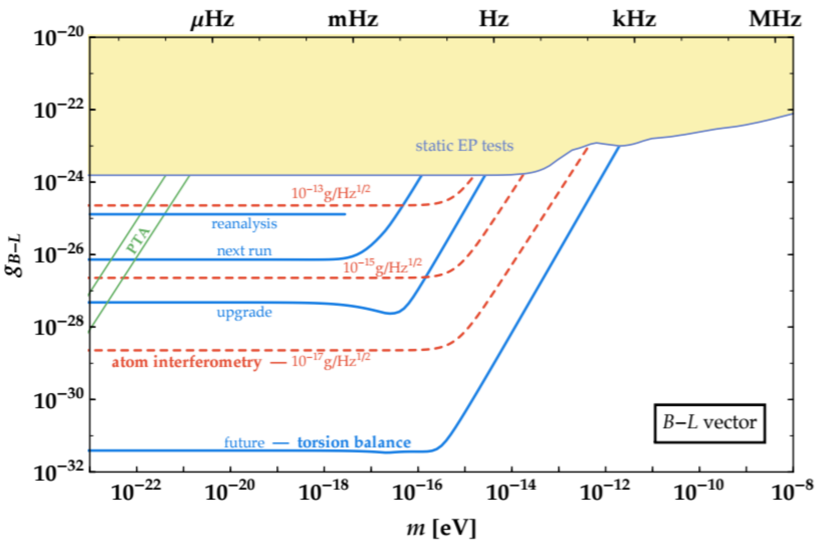




Now 2x200 BOs => 800 ħk

# Juggling interferometer



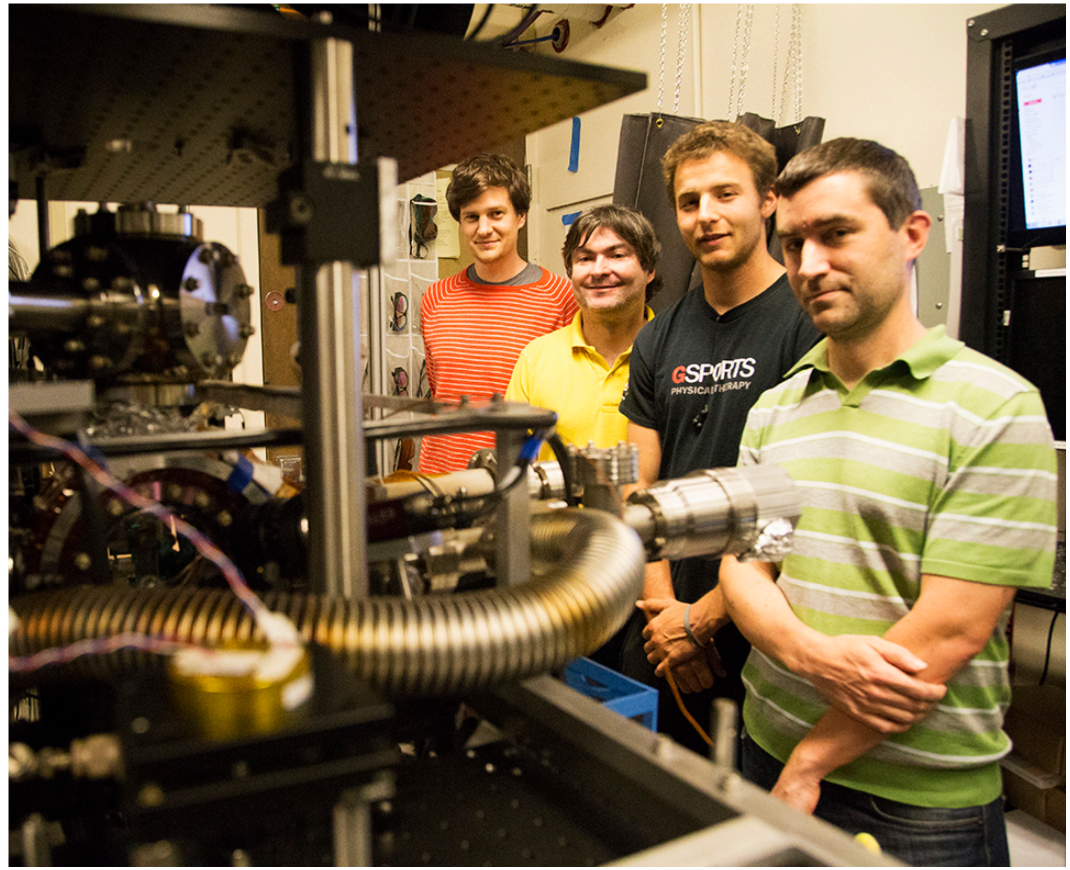



AC sensitivity for dark-matter detection

[P. W. Graham, J. M. Hogan, M. A. Kasevich, S. Rajendran, arXiv:1606.01860]

# Thanks

Justin Khoury (U Penn)




Philipp Haslinger, HM, Matt Jaffe, Paul Hamilton

the David & Lucile Packard FOUNDATION

NSF

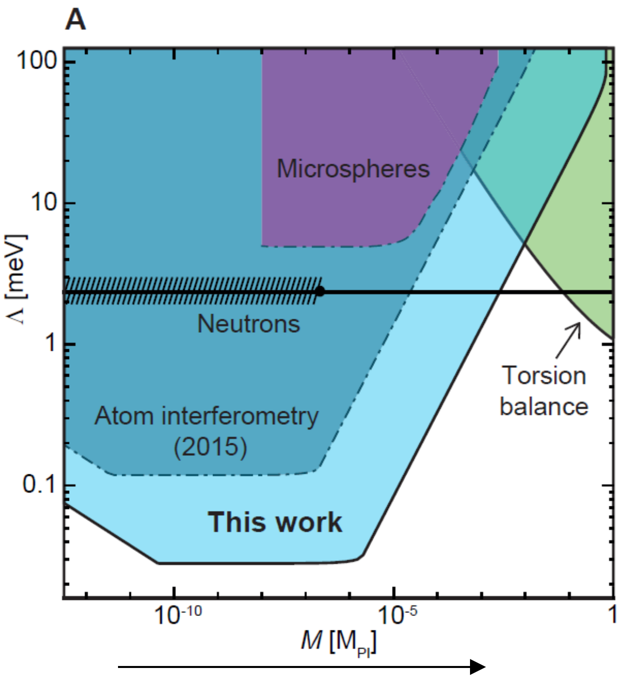
NASA

DARPA

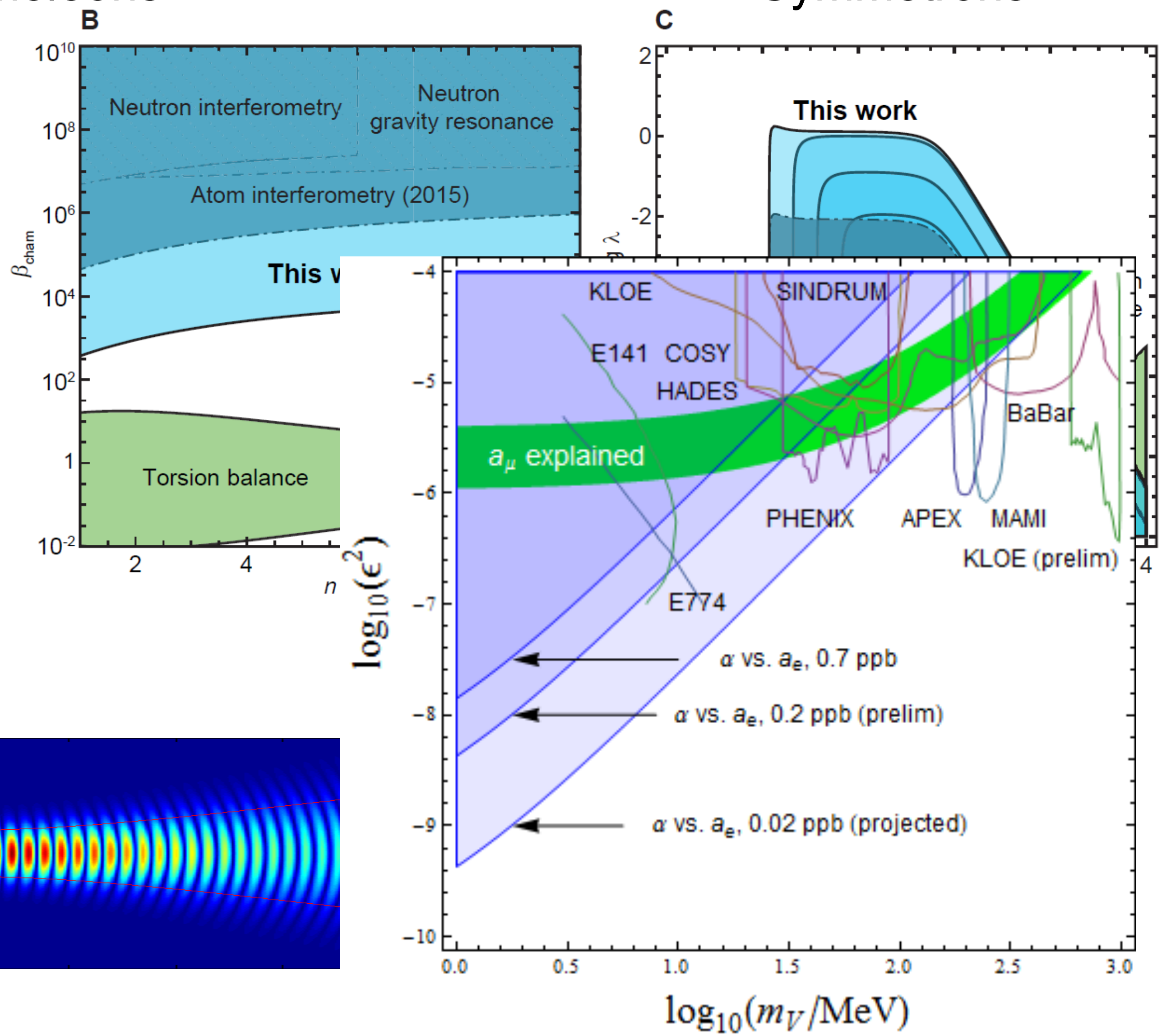
# Summary

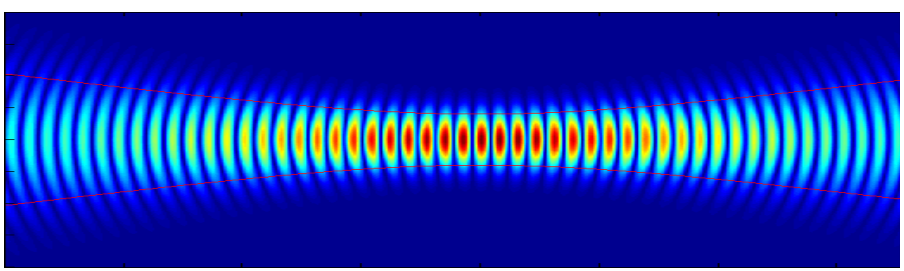
## Chameleons

## Symmetrons

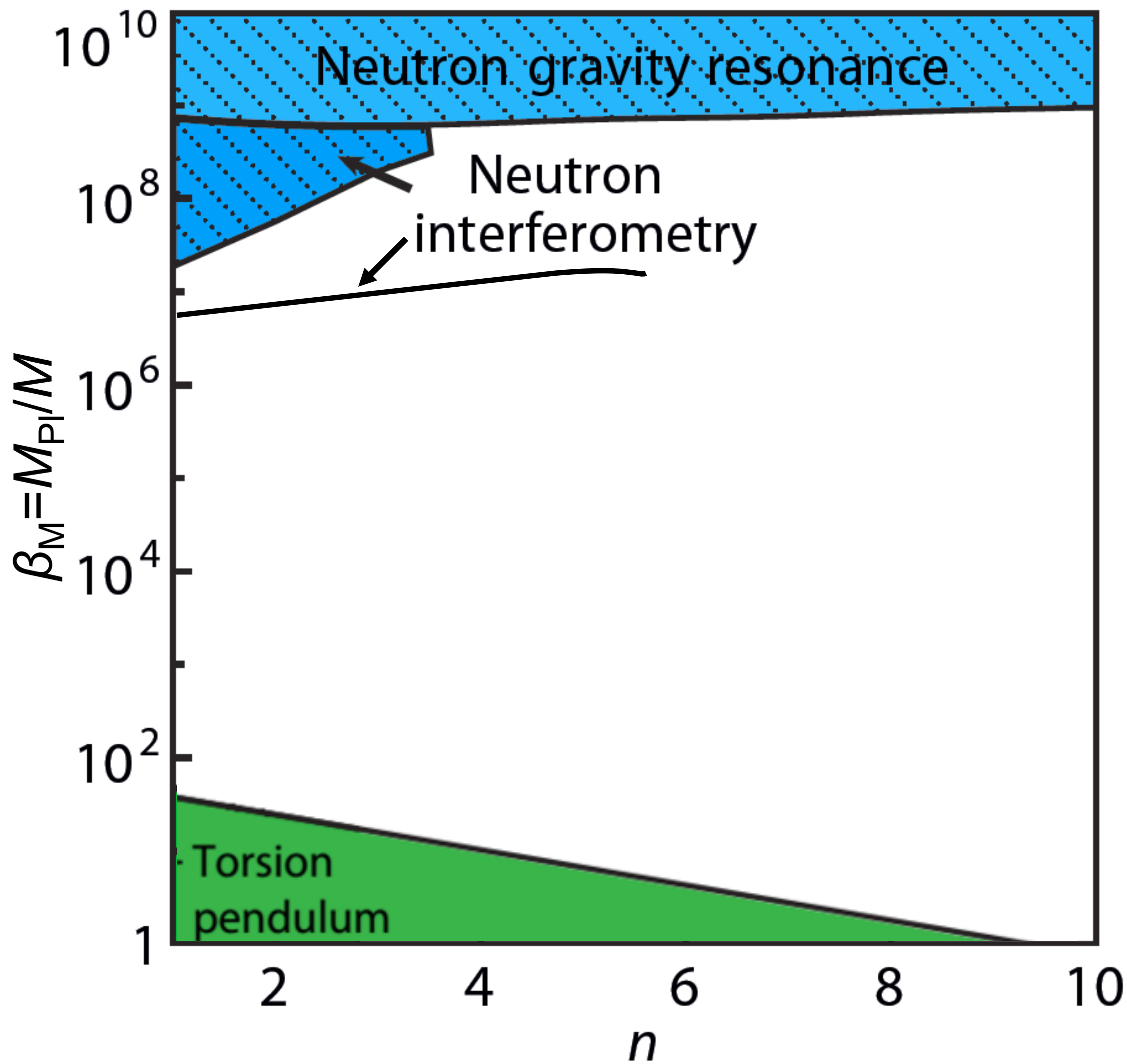



Interaction strength



# 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)

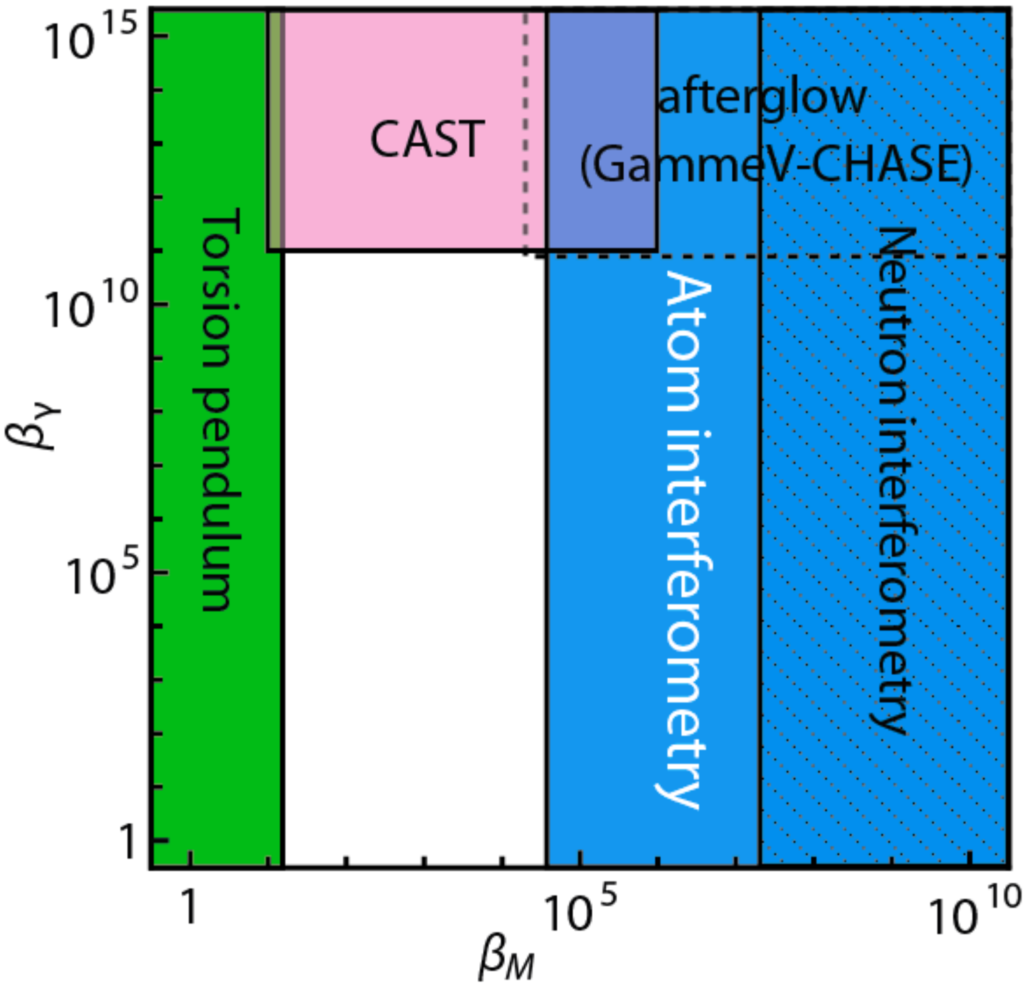
H. Lemmel et al. Phys. Lett. B 743 (2015) 310-314

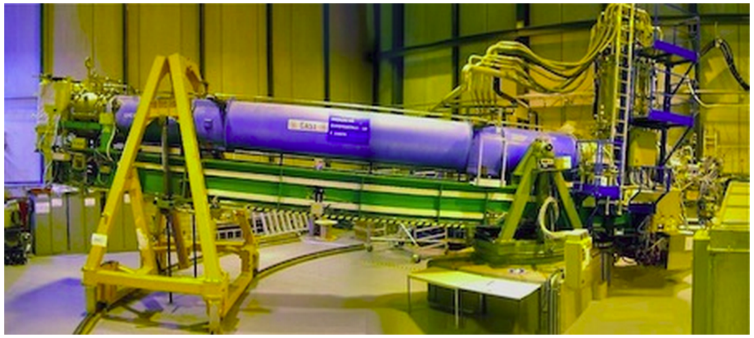
Amol Upadhye Phys. Rev. D **86**, 102003 (2012)

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

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

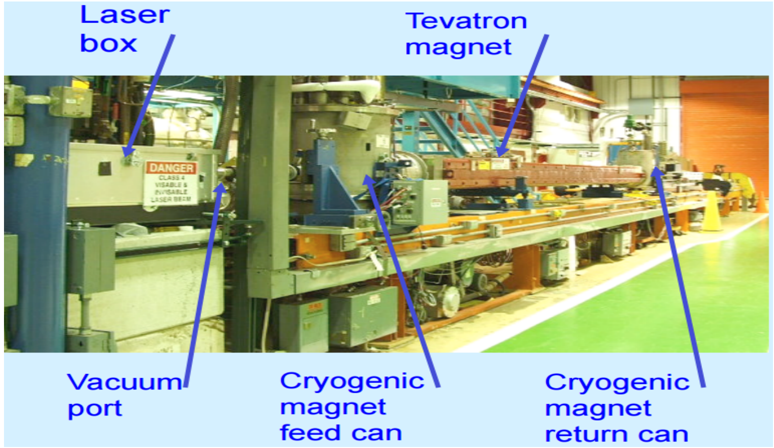
# Photon coupling comparison



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

CAST- arxiv:1503.04561




GammeV collaboration

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

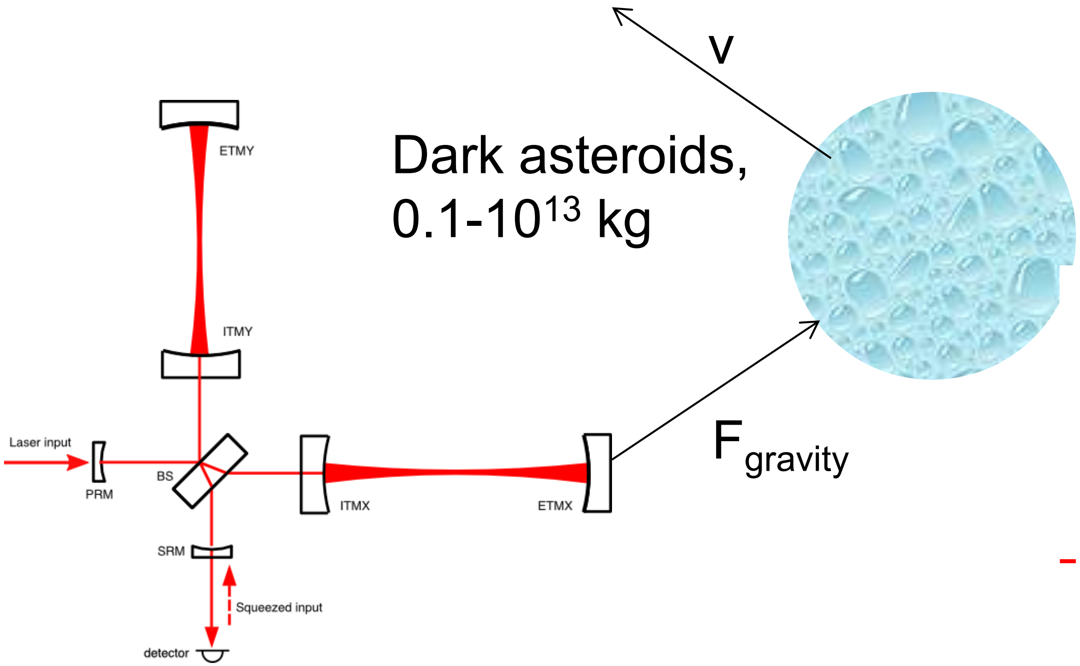
Limits including experiments using an additional coupling to the photon

Atom interferometry does not need photon coupling

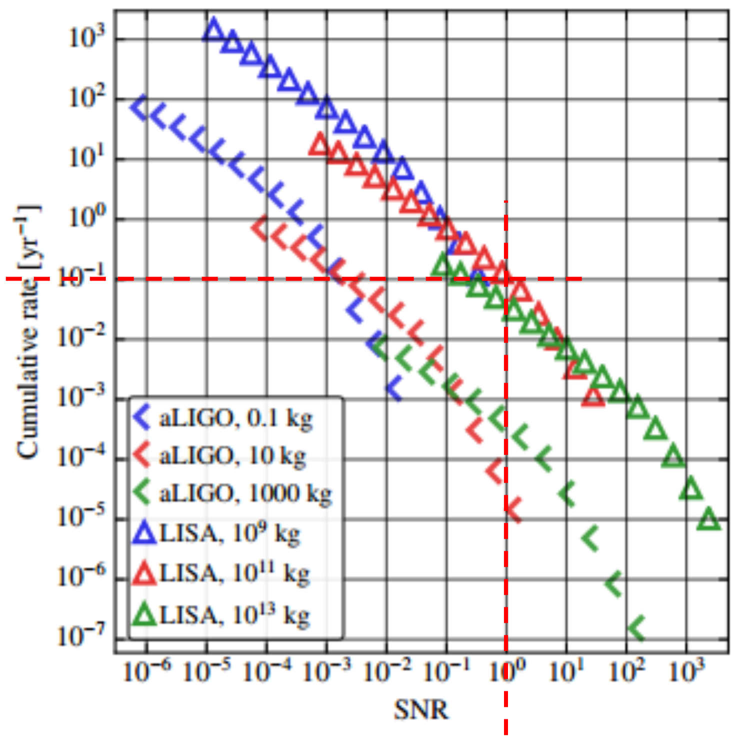
# LIGO as a dark matter detector

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

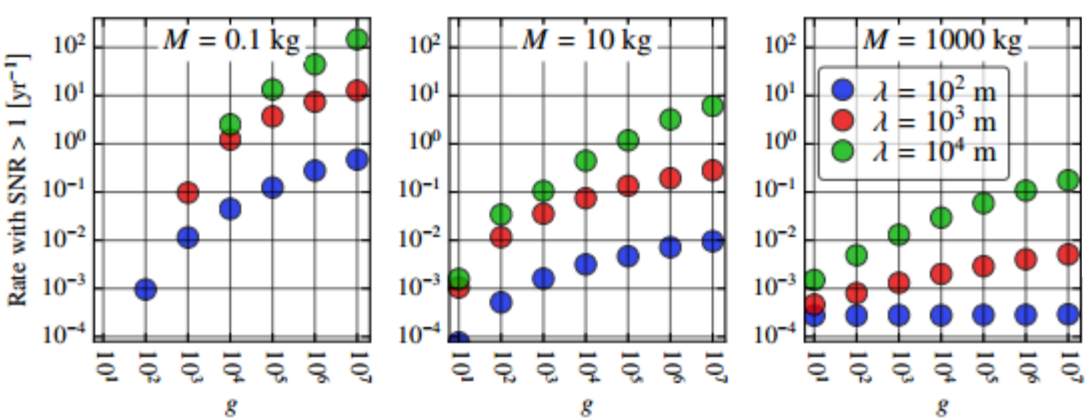
Dark asteroids, $0.1\text{-}10^{13}$ kg




One event every 10 years assuming only gravity




Multiple events/year with Yukawa coupling




arXiv:1605.01103