Atom interferometry and constraints on dark energy

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09/23/16

Outline

- Scalar fields and dark energy
- Atom interferometers
- Our experiment

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- Scalar fields and dark energy
- Atom interferometers
- Our experiment

The standard model is incomplete

Dark **Matter**

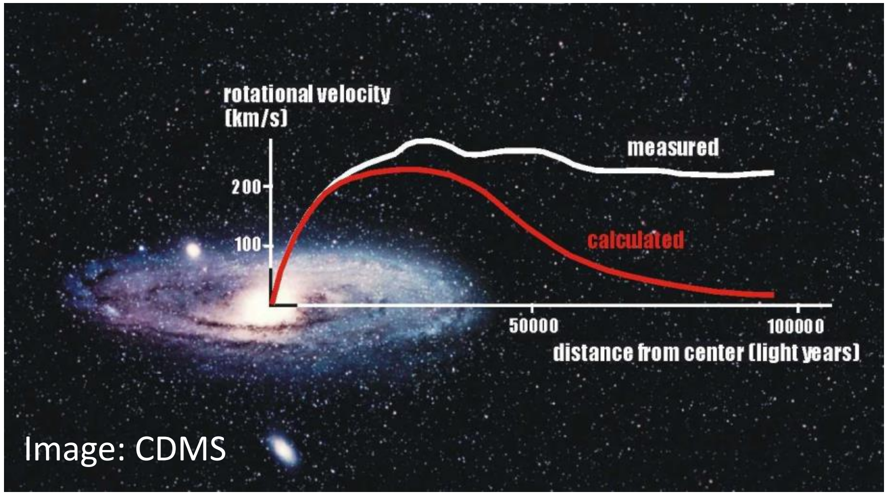
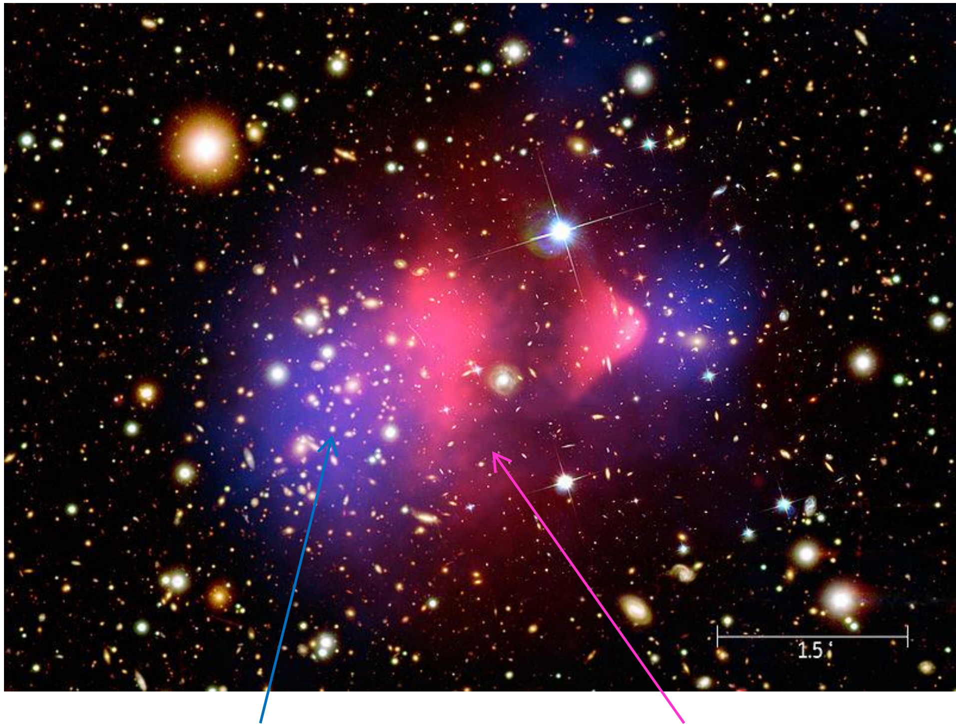


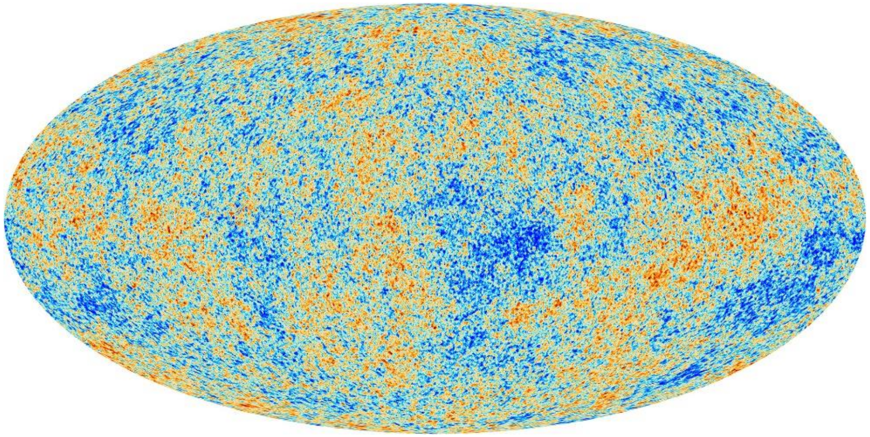
Image: CDMS



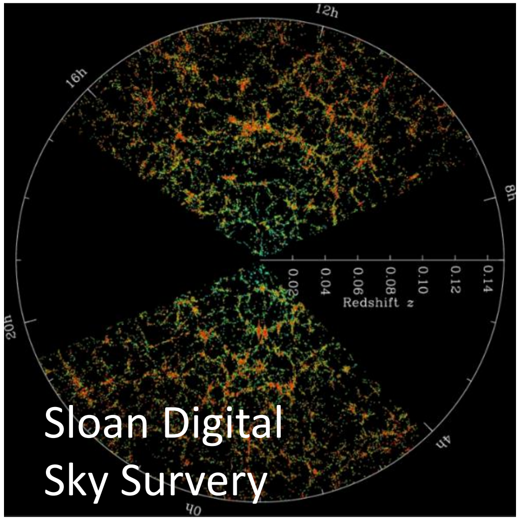
Reconstructed mass distribution (lensing)

Observed matter (Chandra x-ray observations)

The standard model is incomplete

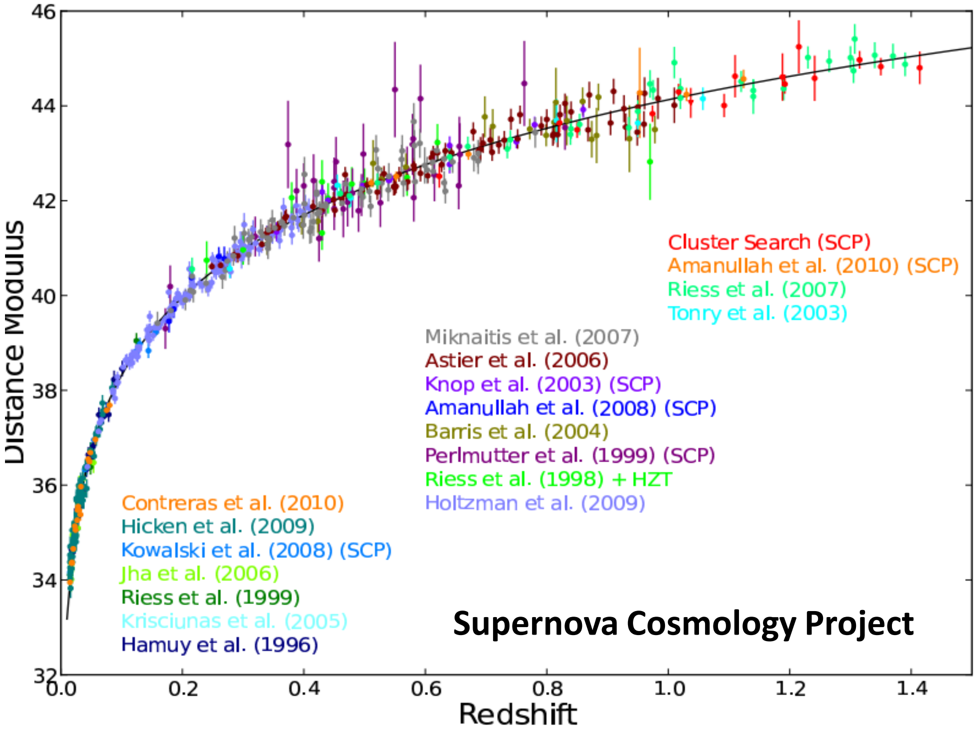


CMB (Planck)



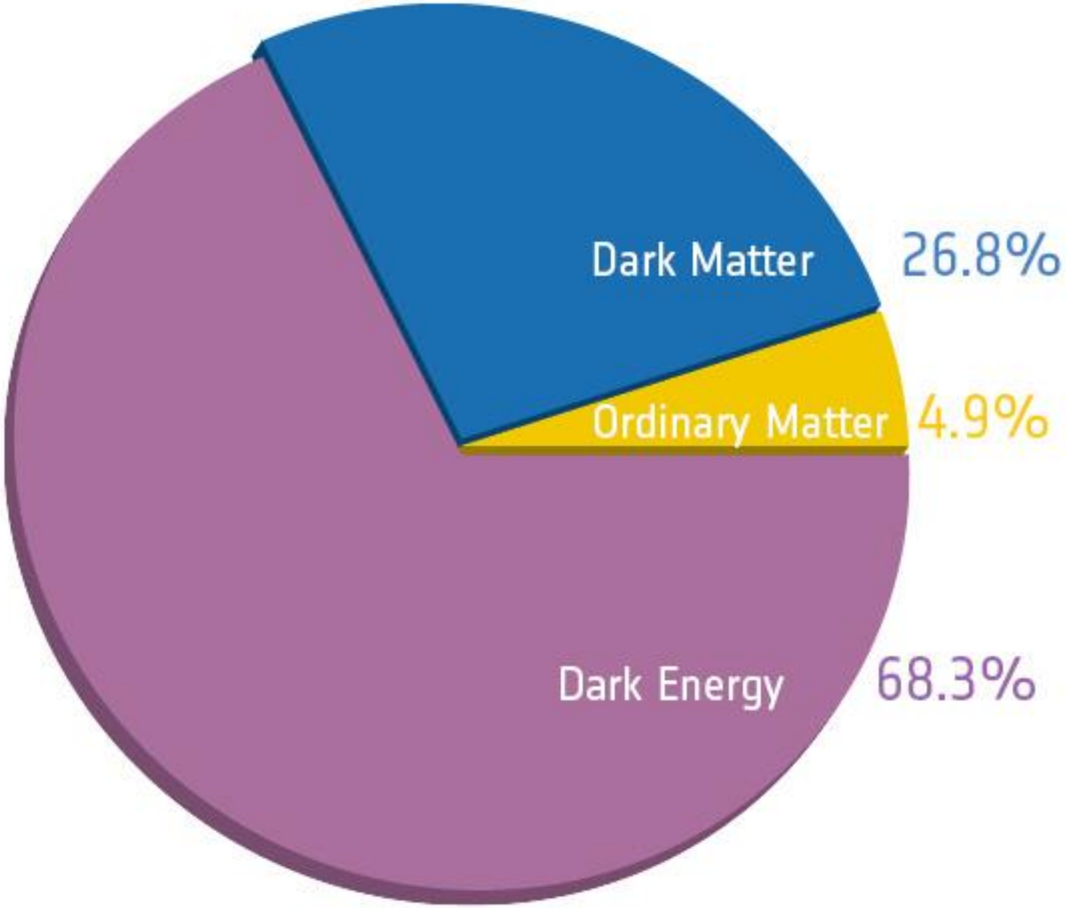
Sloan Digital
Sky Survery

Dark **Energy**



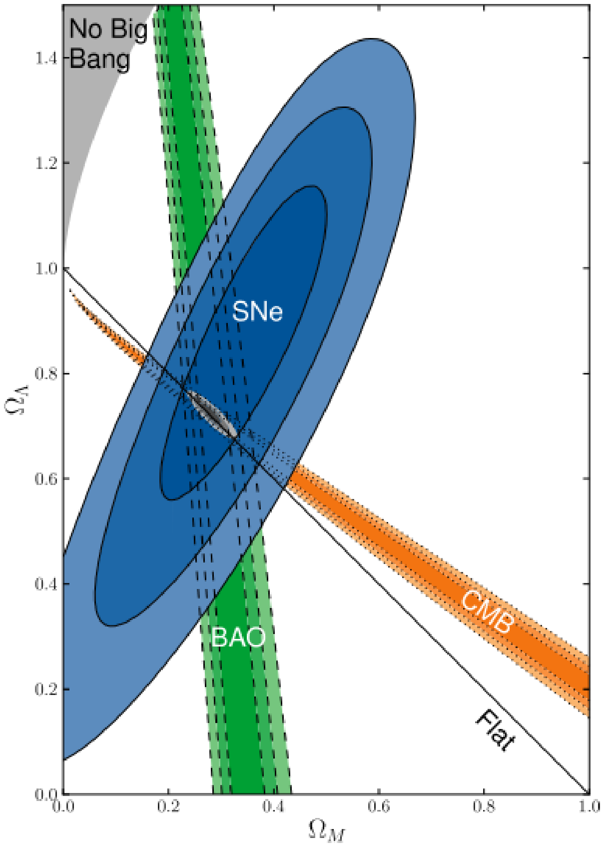
Supernova Cosmology Project

The standard model is incomplete



(Planck)

Dark energy



The Supernova Cosmology Project

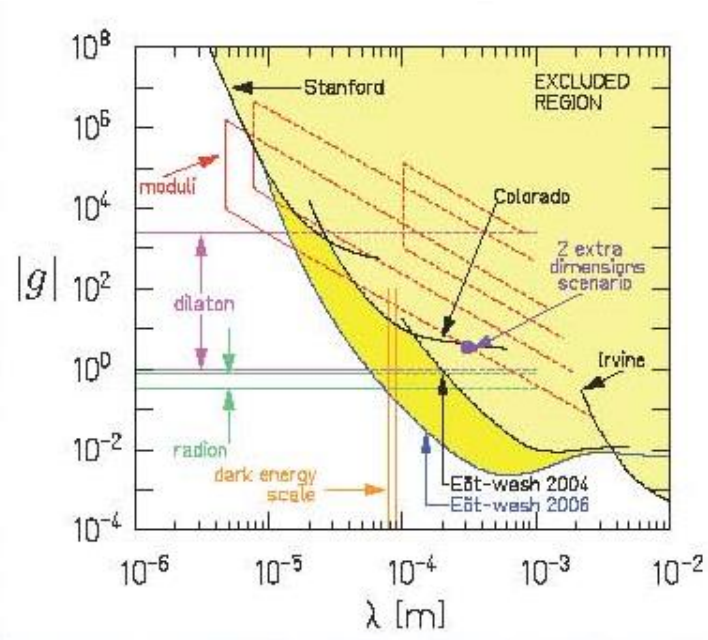
1. ~68% of energy density in the Universe
2. Energy scale (**2.4meV**)^4
    - ~4 hydrogen atoms / m^3
    - New energy scale = **new field**?
3. Composition unclear
    - Cosmological constant?
        - "Cosmological constant problem," "fine tuning", etc
    - **Dynamical field**?
        - **New scalar**?

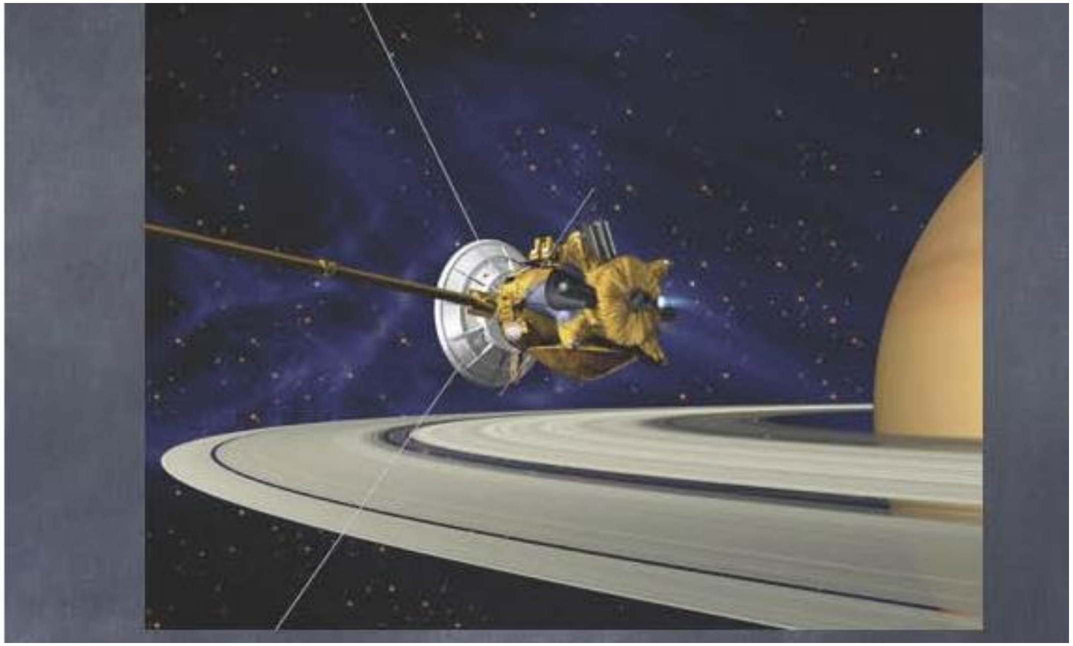
Scalar dark energy

Suppose a **simple scalar boson field**

- To explain dark energy, needs mass H_0 (Hubble scale) ≈ 10^{-33}eV
  - Required to explain timescale of dark energy density evolution
    - Evolution of a scalar field in an expanding universe $\ddot{\phi} + 3H\dot{\phi} + m^2\phi + \ldots = 0.$
  - Essentially massless on solar system scales
- $V_{Yukawa} \sim \frac{e^{-m\,r}}{r}$
  - Low mass → long range force

Scalar dark energy





Such low mass conflicts with fifth force / Equivalence Principle tests

Scalar dark energy

Not so fast. Generic **coupling to matter** can lead to **screening** in a laboratory environment.

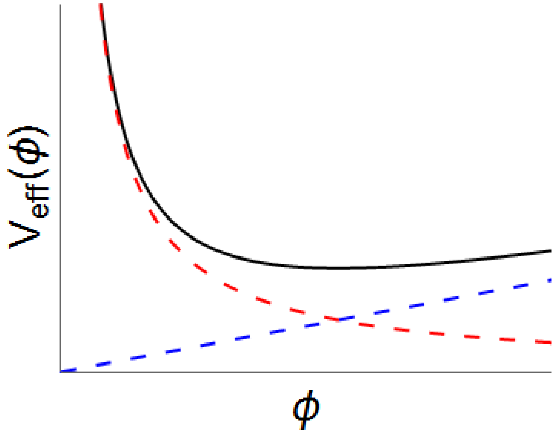
$$V_{\text{eff}} = \Lambda^4 + \frac{\Lambda^{4+n}}{\phi^n} + \frac{\phi}{M}\rho$$

Self-potential

Coupling to local density

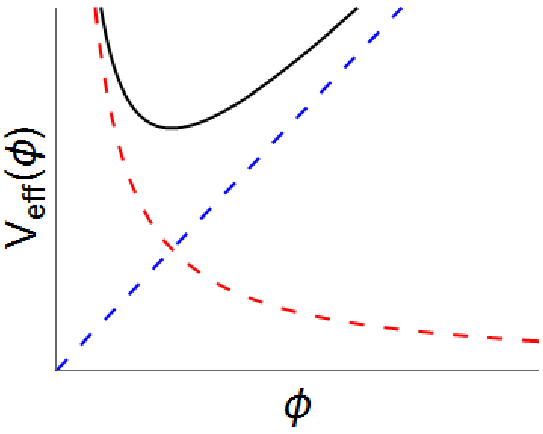
Low density ρ

vacuum



High density ρ

normal matter



Chameleon Mechanism

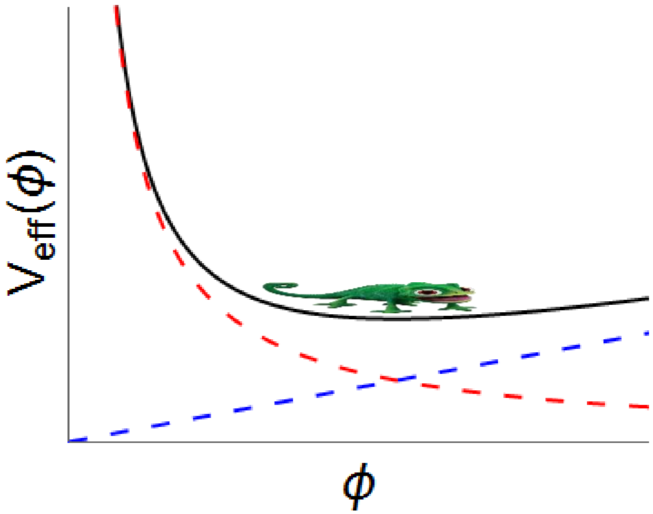
Khoury, Weltman
Phys. Rev. D **69**, 044026

Mass of chameleon is equal to the curvature of the potential:

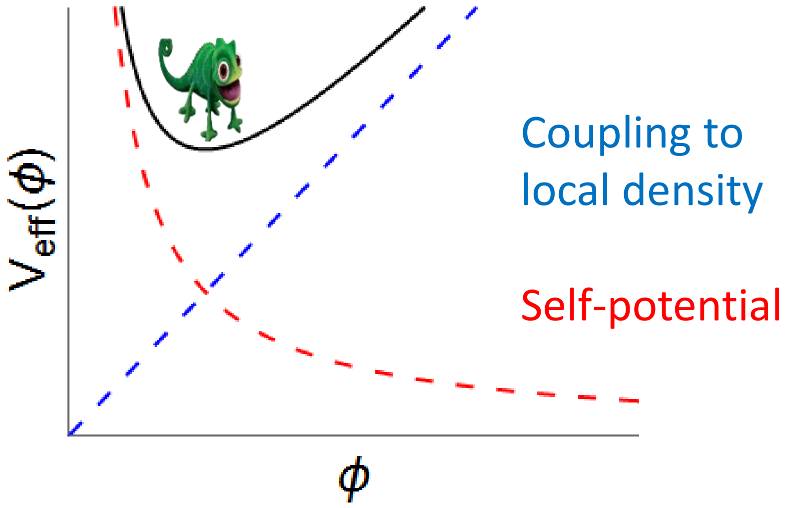
$$M_{chameleon} = \frac{\partial^2 V}{\partial \phi^2}$$

Low mass ⇒ Long range

High mass ⇒ Short range ⇒ screened



In vacuum



Normal matter

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

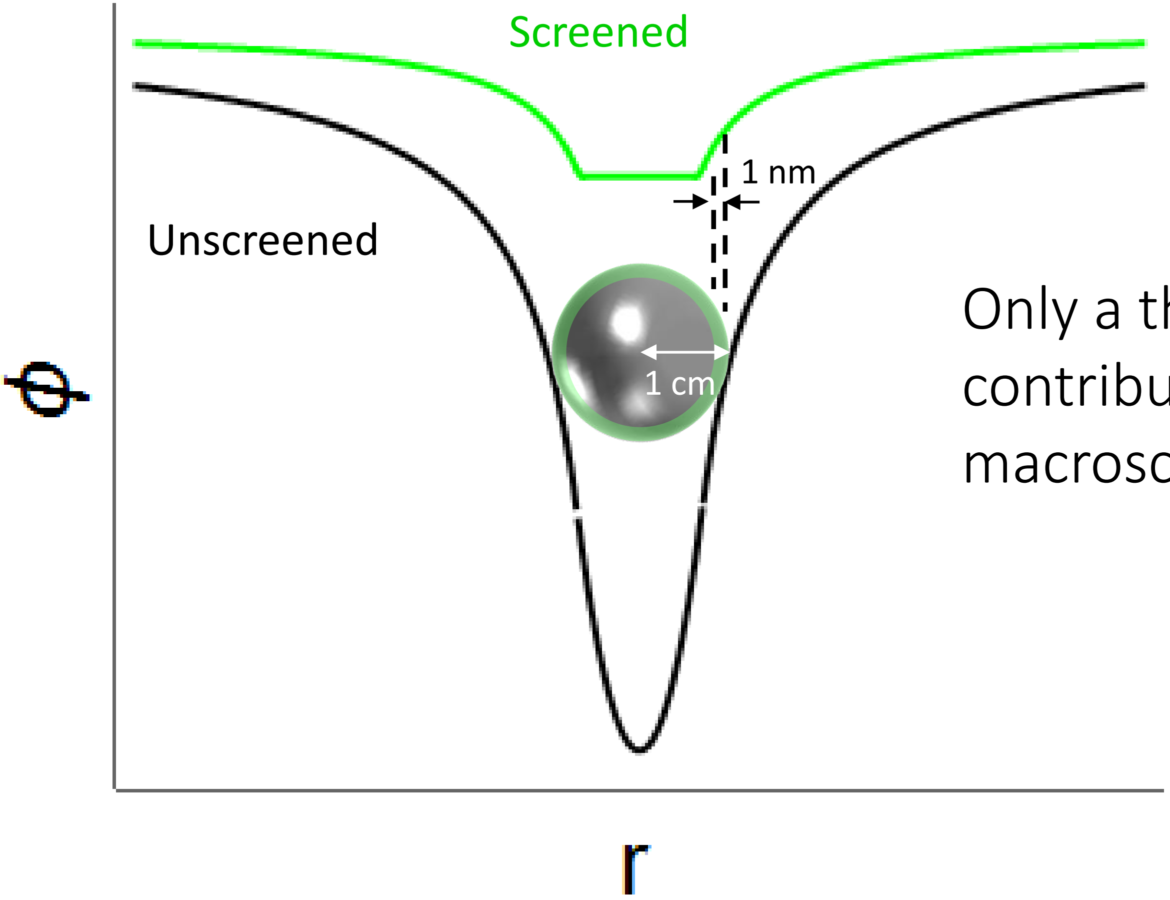
- Local screening
- Chameleons,
- Peebles-Ratra

Coupling

- Similar to chameleon
- Symmetrons
- Damour-Polyakov

Joyce, Jain, Khoury and Trodden, arXiv:1407.0059

Chameleon Screening



Only a thin shell contributes in macroscopic objects

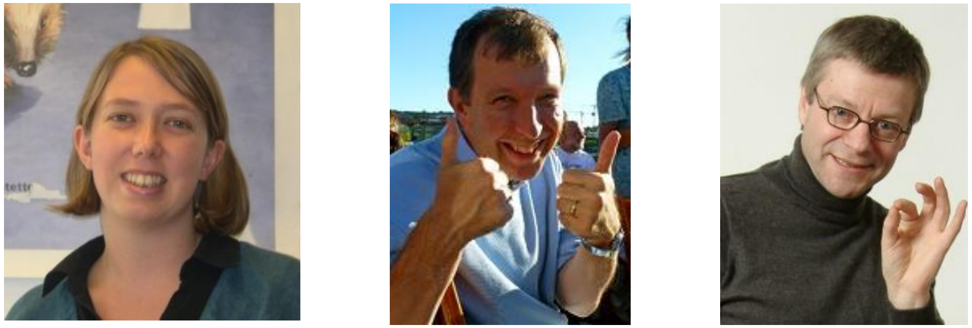
Chameleon field acts as a potential for objects

Atoms evade screening

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

Atom acts as nearly ideal test particle!

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



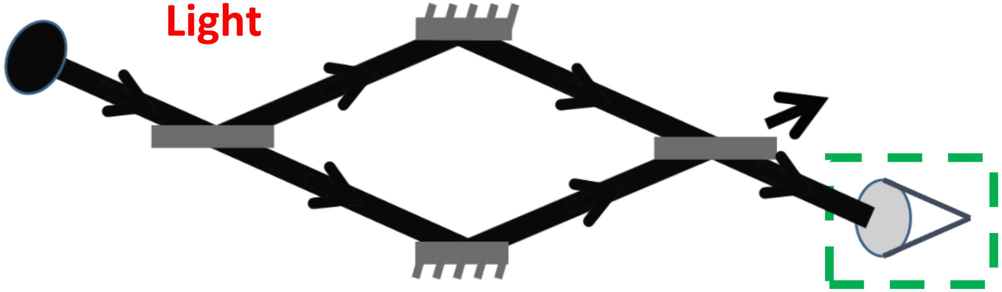
Burrage, Copeland, Hinds ***JCAP03****(2015)042*

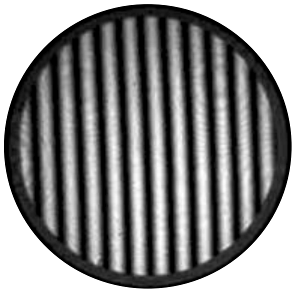
Outline

- Scalar fields and dark energy
- **Atom interferometers**
- Our experiment

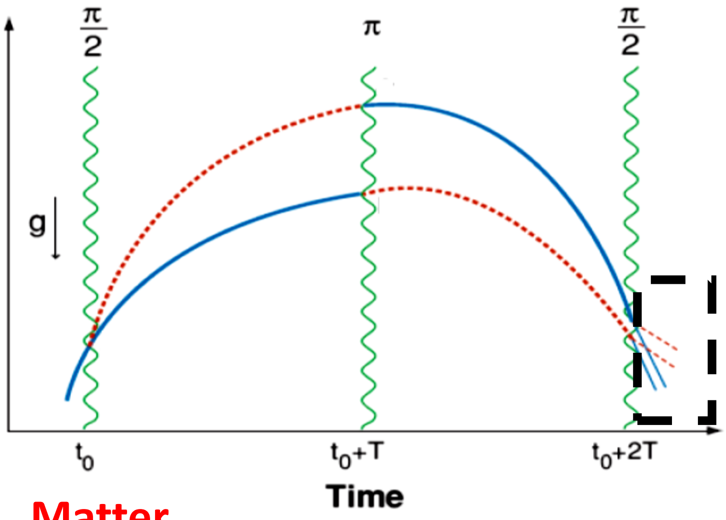
Interferometry

Light



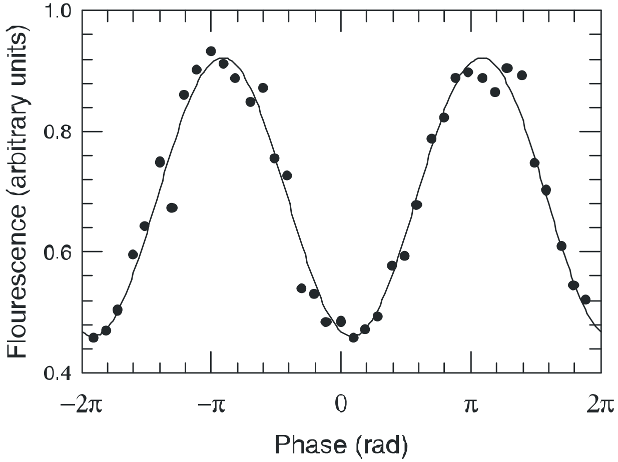


Beamsplitter *Mirror* *Beamsplitter*

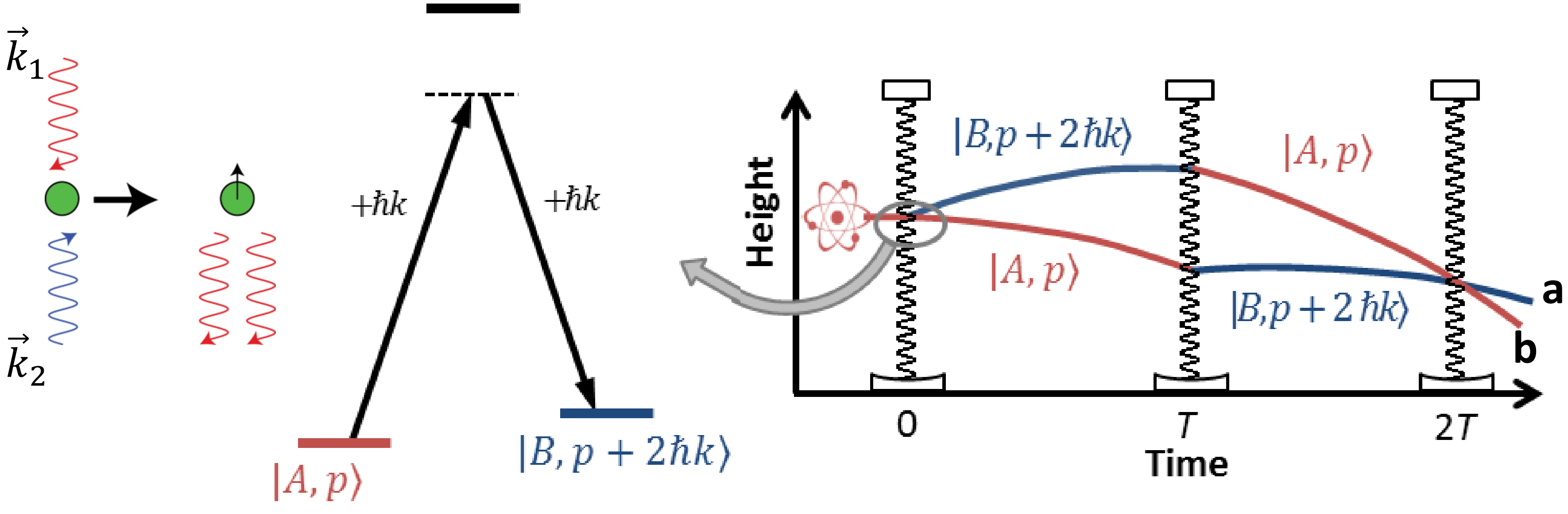


Matter

KY Chung et al. ***PRD 80****, 016002*



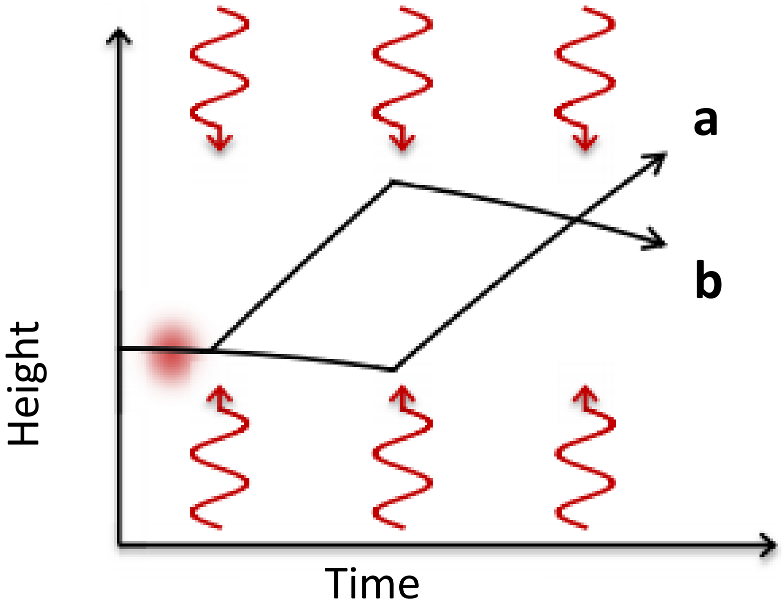
Light Pulse Atom Interferometry

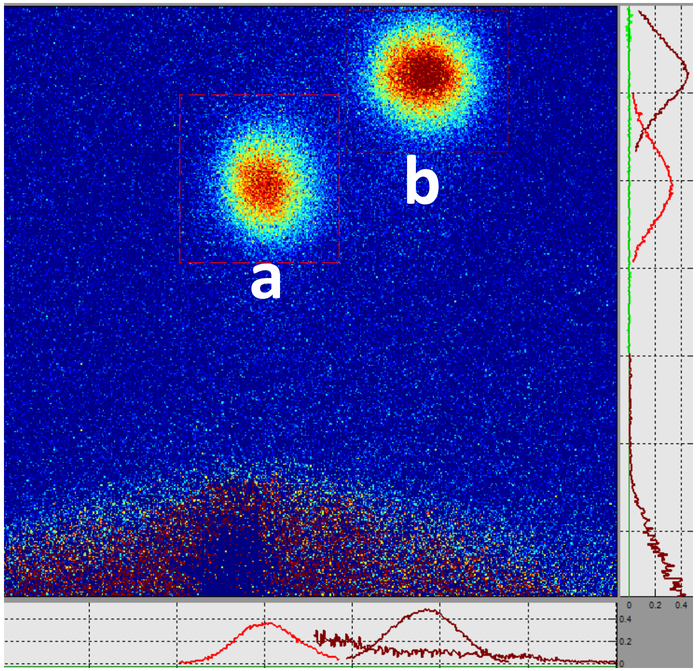


$$\Delta\varphi = -\frac{1}{\hbar}\oint L\,d\tau + \Delta\varphi_{\text{laser}}$$

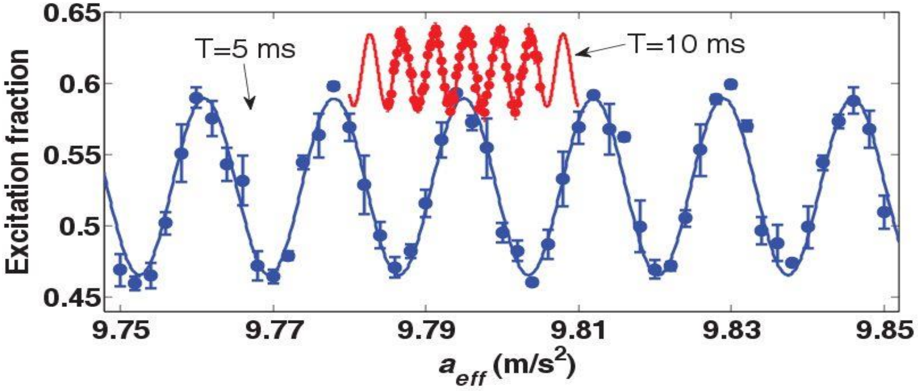
$$\boxed{= \vec{k}\cdot\vec{g}T^{2}}$$

Measurement



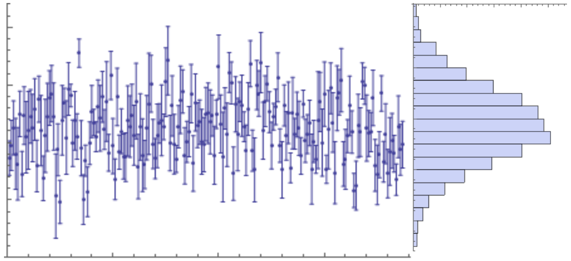


$$P_a \propto \mathrm{Cos}^2\left(\frac{1}{2}\vec{k}\cdot\vec{a}\,T^2\right) \Longrightarrow$$

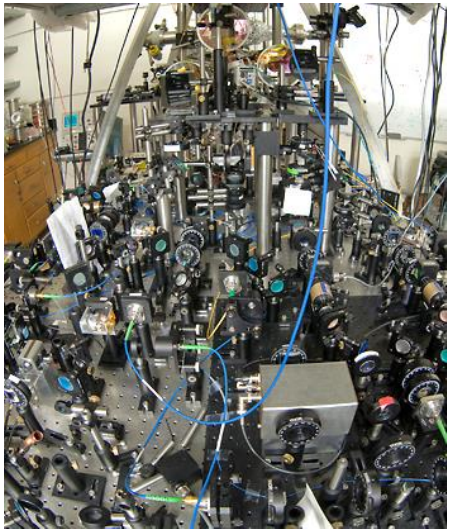


Precision interferometry

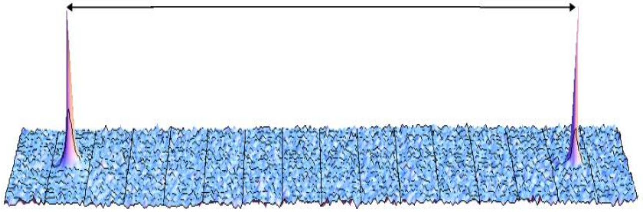
Brian Estey



Measuring the fine structure constant α at Berkeley

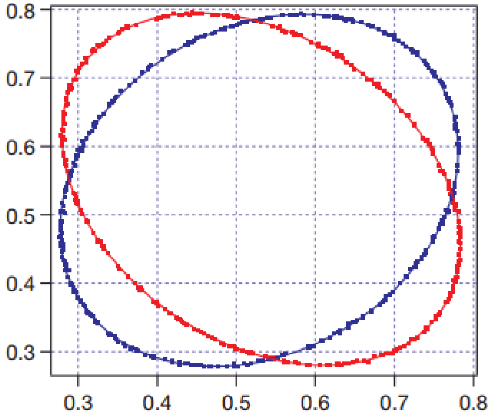


Tests of GR & QM
Stanford 10 meter atomic fountain



Jason Hogan

Nature 510



Measurement of Newton's gravitational constant "big G"

Outline

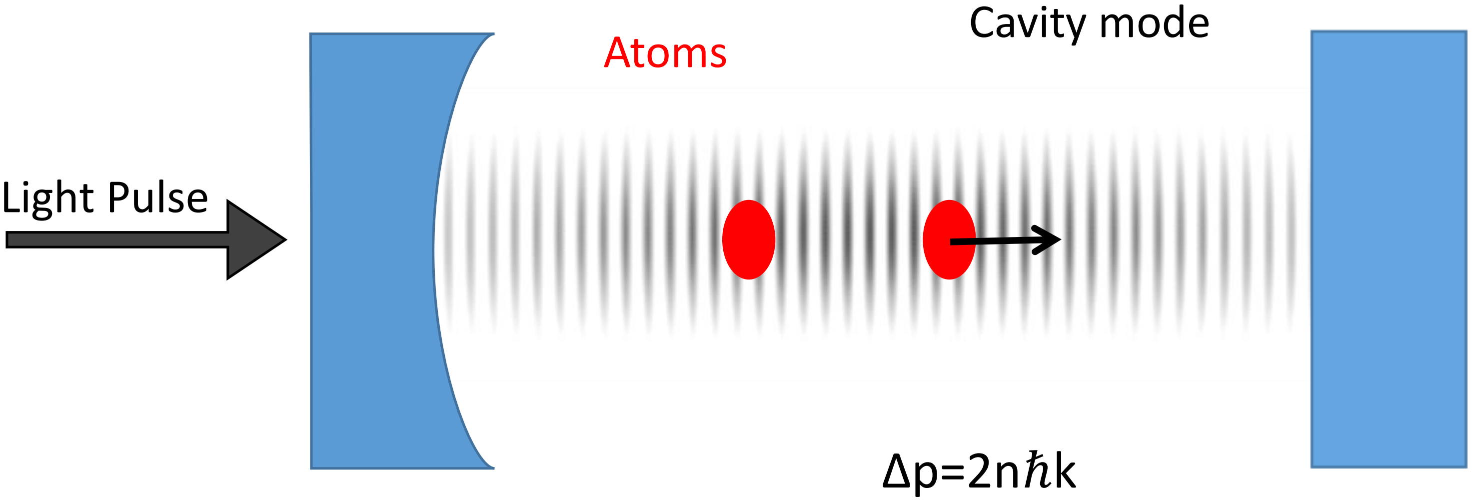
- Scalar fields and dark energy
- Atom interferometers
- Our experiment
    - First measurement
    - v2.0

Interferometry in a cavity

Higher Laser Intensity

Smooth Wavefronts

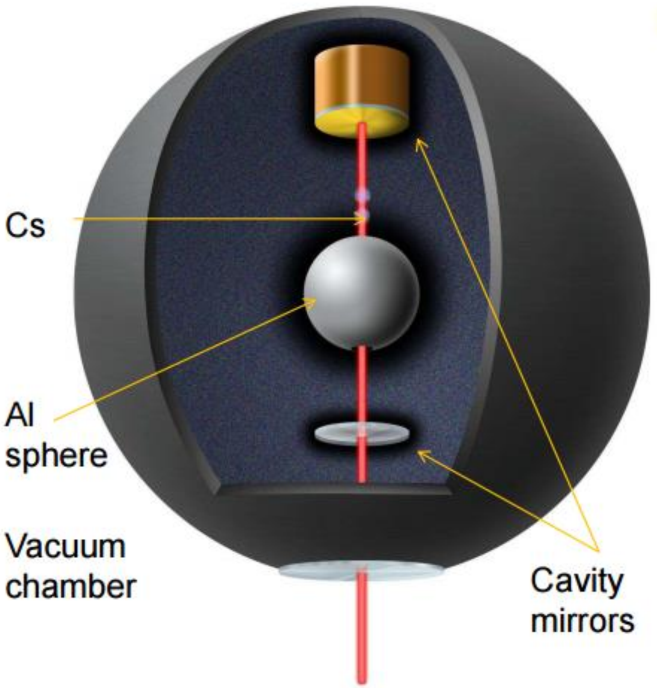
Well-defined beam parameters

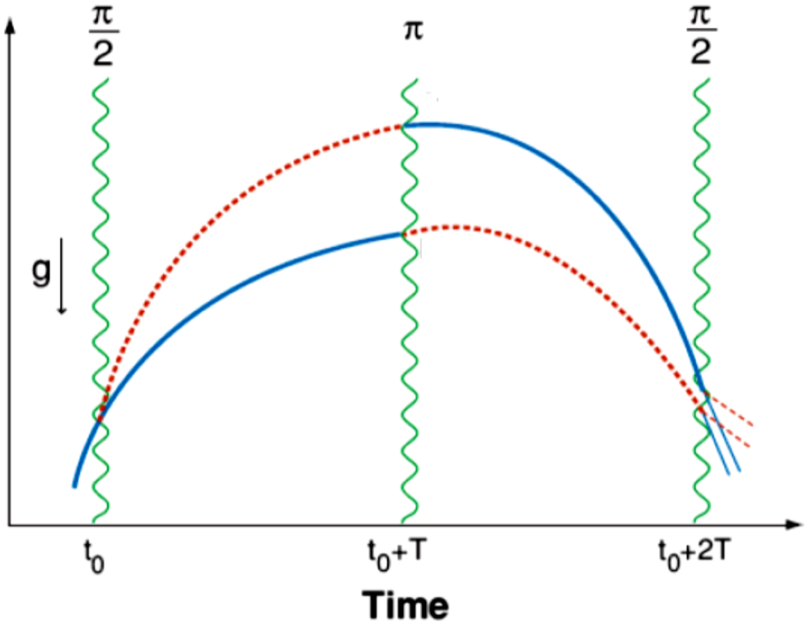


Advantages

Hamilton, MJ et al., **PRL** *114, 100405 (2015)*

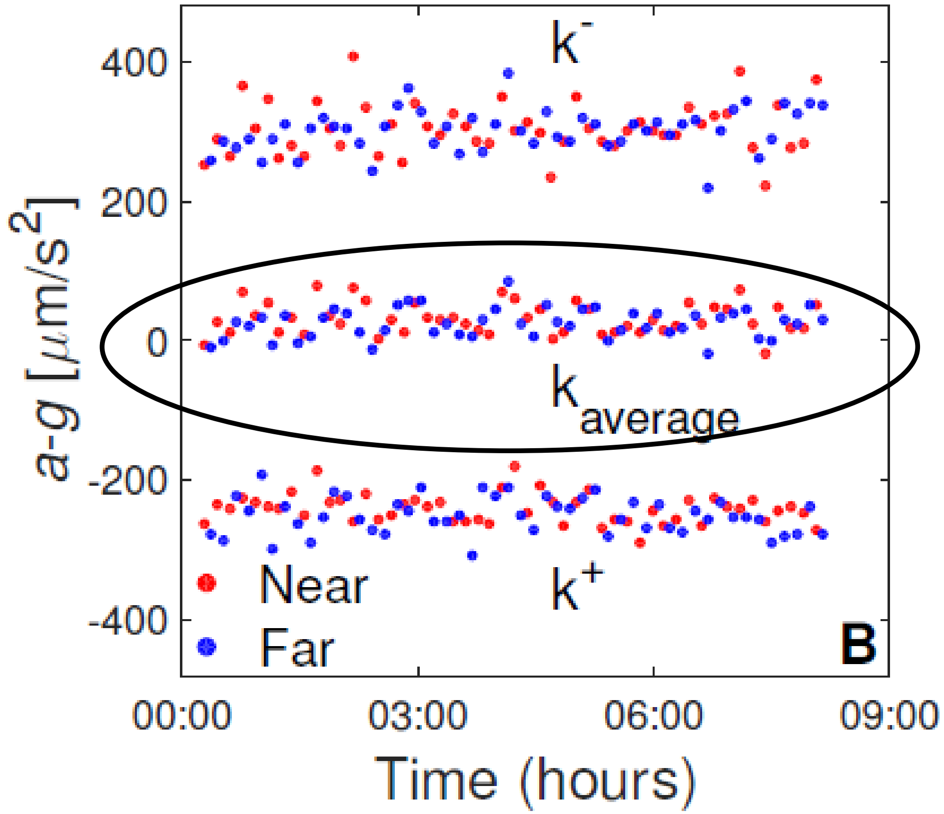
Chameleon search

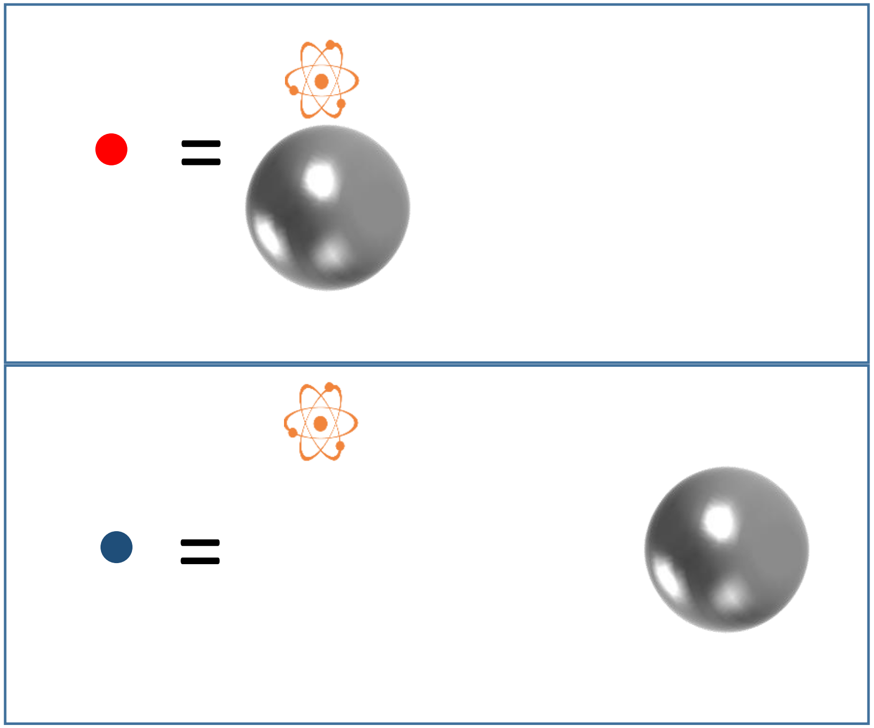




- Source mass provides scalar field gradient
- Atoms act as test masses for force sensing
- Final state probability $\propto \cos\left(\vec{k} \cdot \vec{a}\, T^2\right)$

First measurement

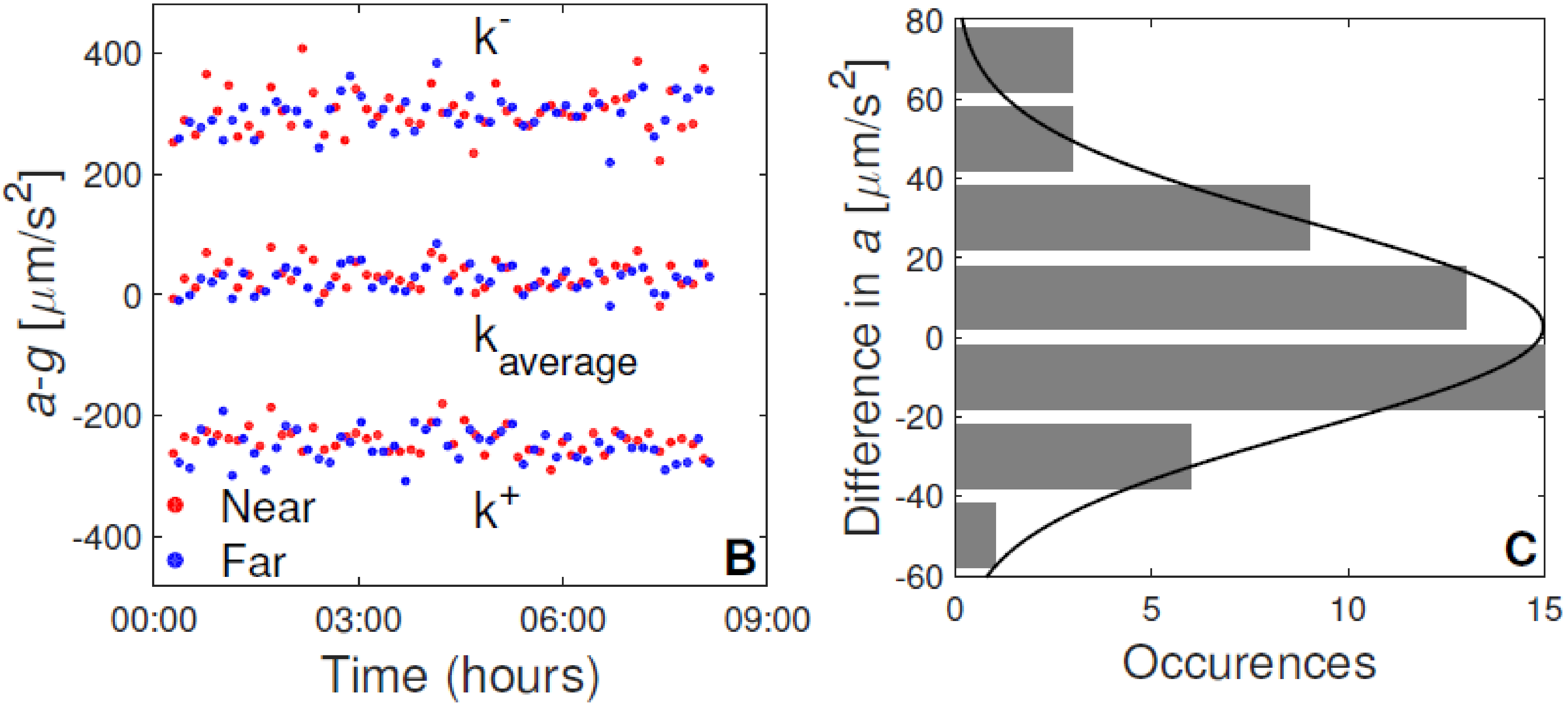




Look for an anomalous acceleration
when the atoms are near the sphere

First measurement

Difference between sphere near/far



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

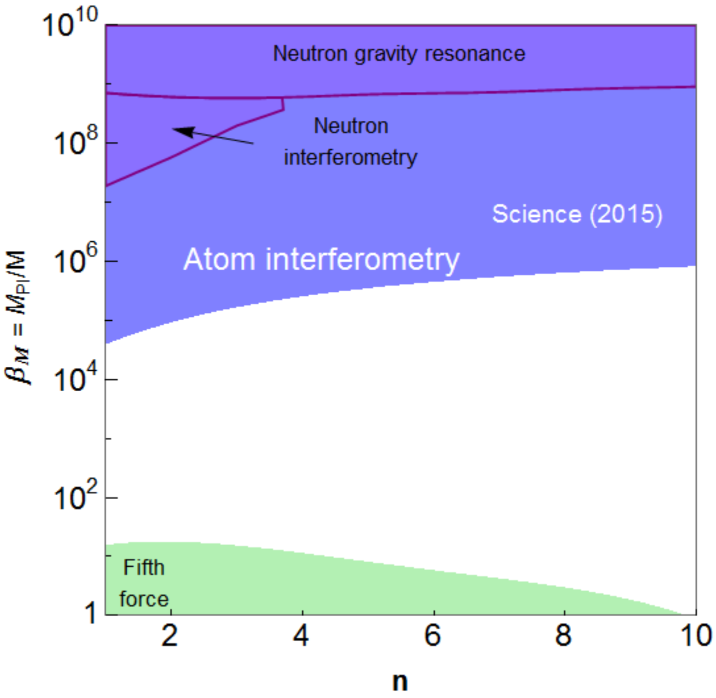
Hamilton, MJ et al., **Science** *21, 849-851 (2015)*

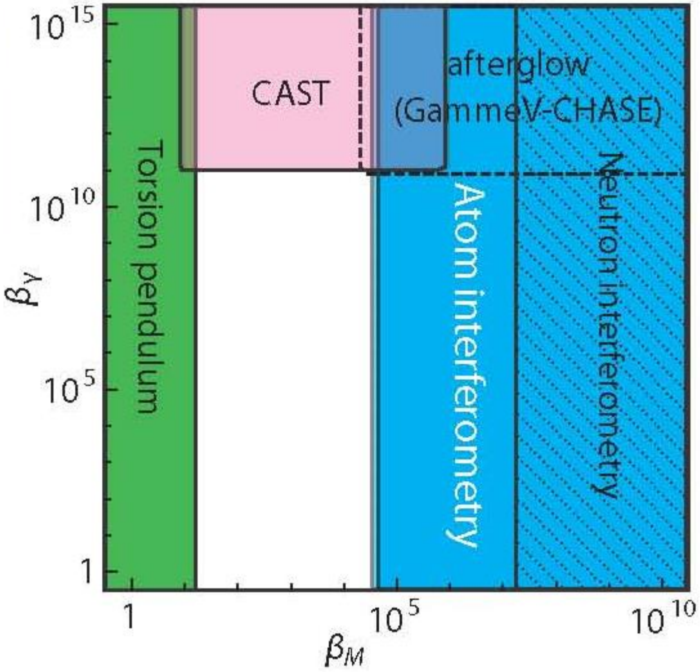
Chameleon limits

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

Self-potential

Coupling to local density





- **3-4 orders of magnitude** improvement
- Limits at cosmological dark energy Λ
- Independent of photon coupling β_γ

Outline

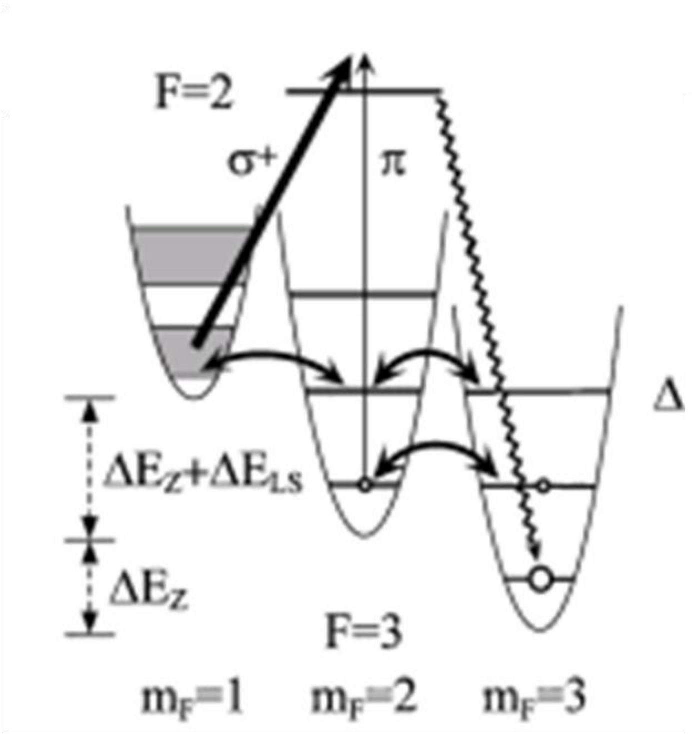
- Scalar fields and dark energy
- Atom interferometers
- Our experiment
  - First measurement
  - v2.0 – Major improvements

Overcome limitations?

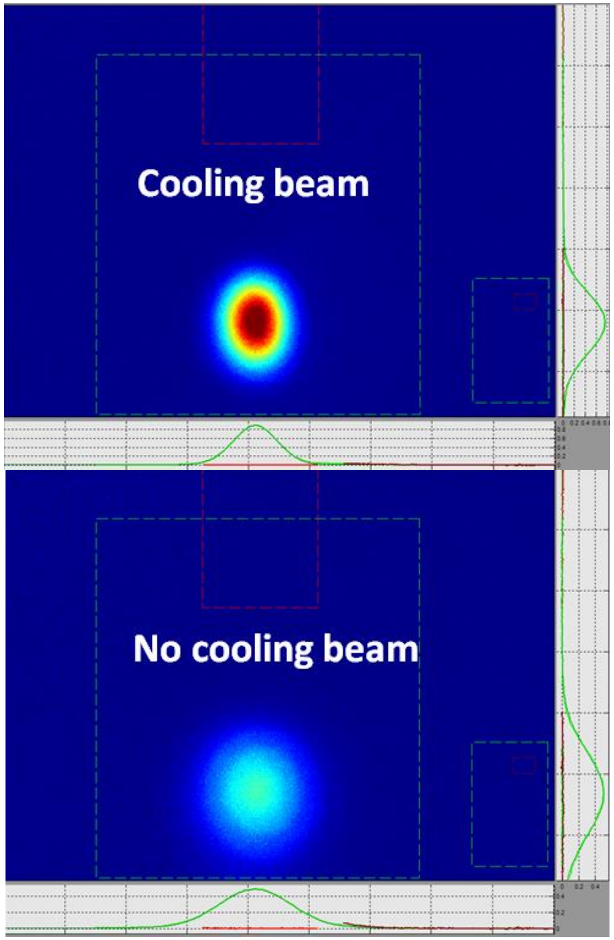
1. Colder atoms
2. Atom Launch
    - Longer pulse separation time T
    - More time close to source mass
3. New source mass
4. Vibration stabilization
    - Indistinguishable from desired signal, dominant noise source
5. Tilt Stabilization

Colder atoms

Raman Sideband Cooling



Kerman et al., PRL 84 3 (1999)

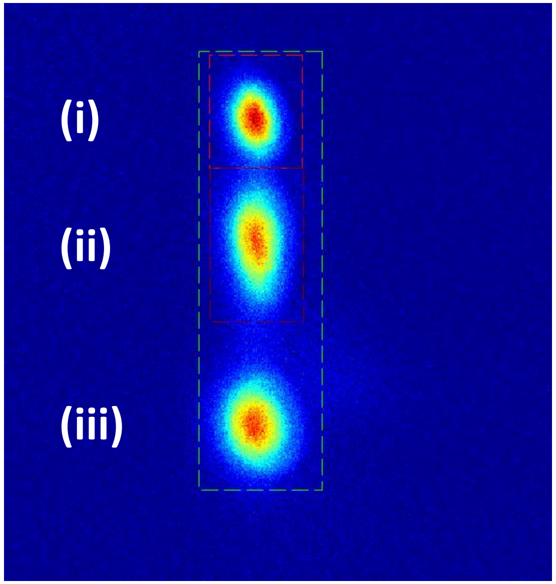


Atom launch

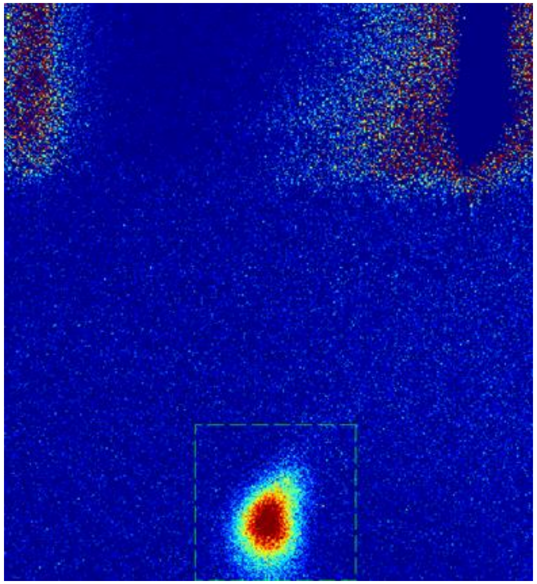
- Apply a standing light wave of two frequencies

Generates:
(i) Upward running lattice
(ii) Downward running lattice
(iii) Stationary lattice

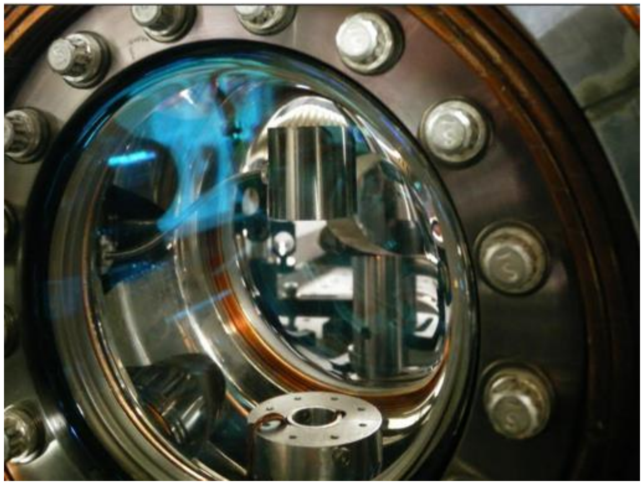
- Ramp frequency difference to change lattice velocities

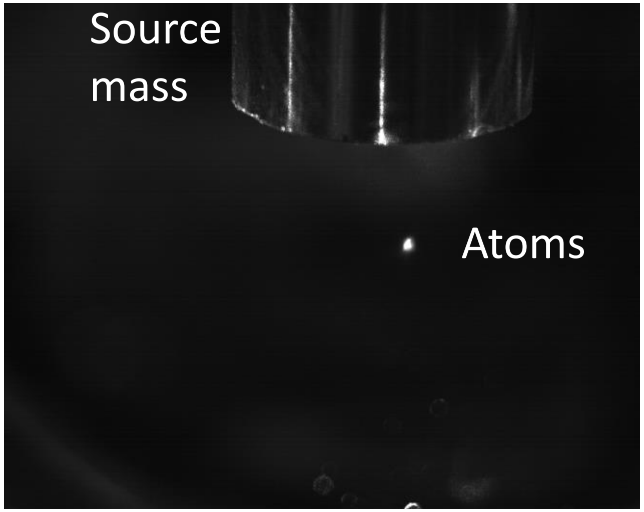


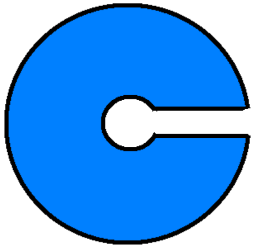
Upward-launched atoms moving towards the source mass



New source mass





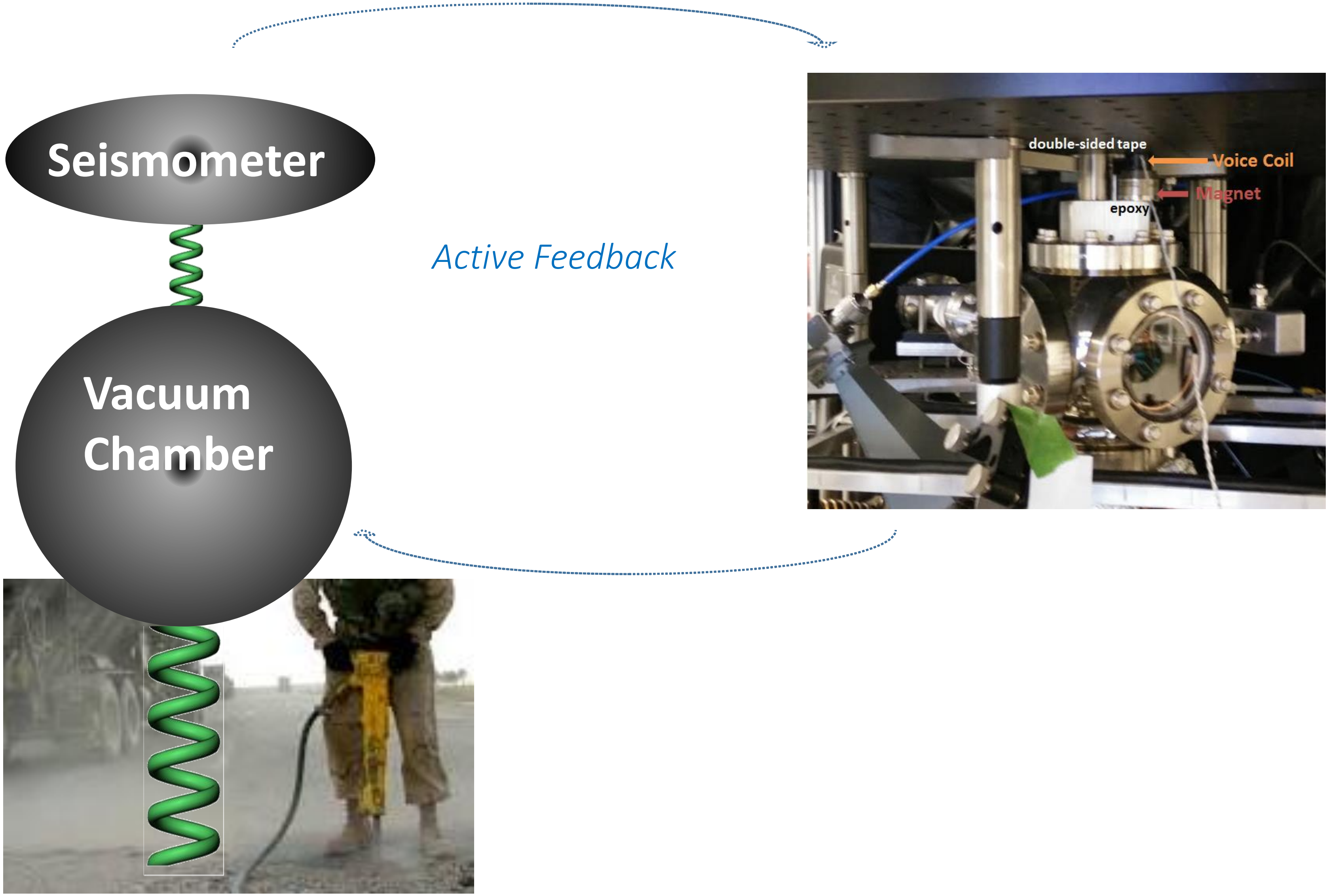


Cross-section

1. Above interferometer
   - Longer interrogation time
2. Tungsten → dense!
   - Measure gravitational attraction?
3. Larger thru-hole, slot
   - Lower systematics (ac Stark, etc)
4. Numerical Modeling
   - Collaboration with theory:

Elder, Khoury, Haslinger, MJ, Müller, Hamilton. **PRD** *94, 044051 (2016)*

Vibration stabilization

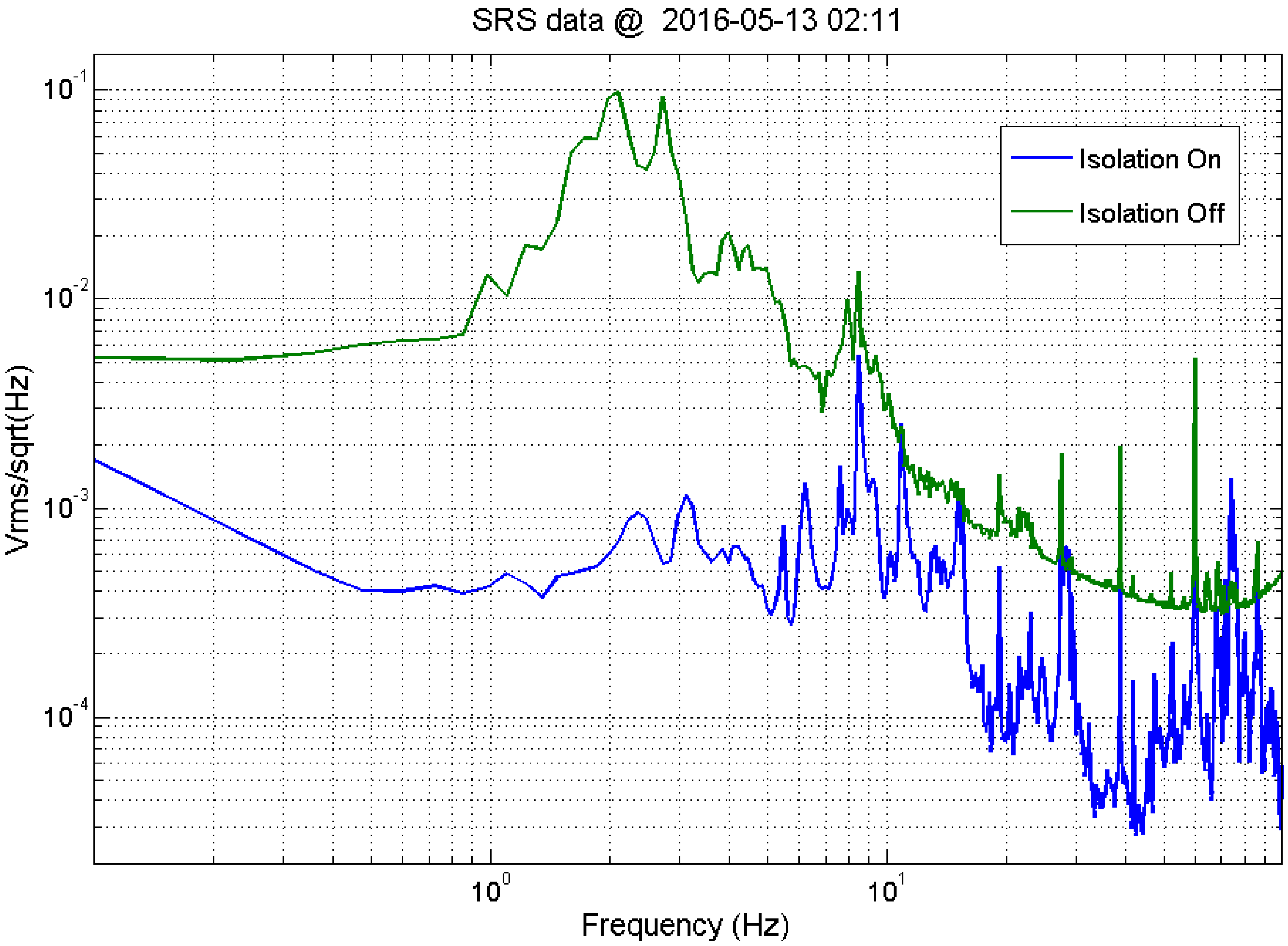


Seismometer

Vacuum Chamber

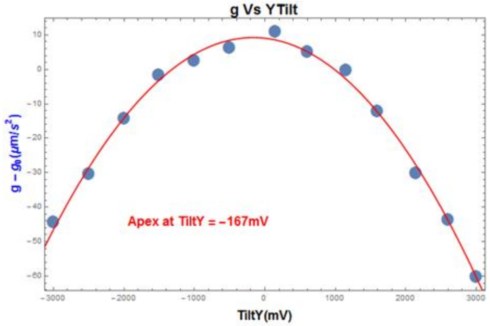
Active Feedback

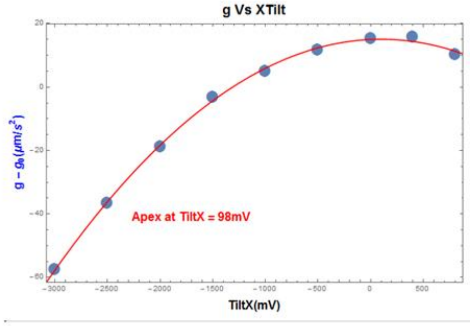
Vibration stabilization

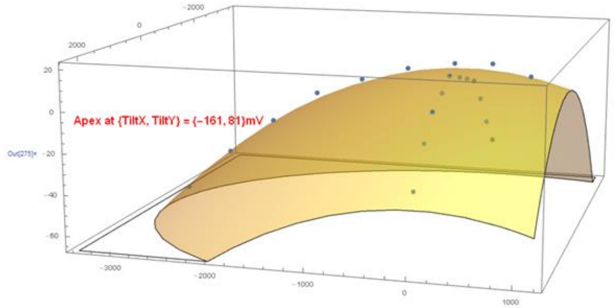


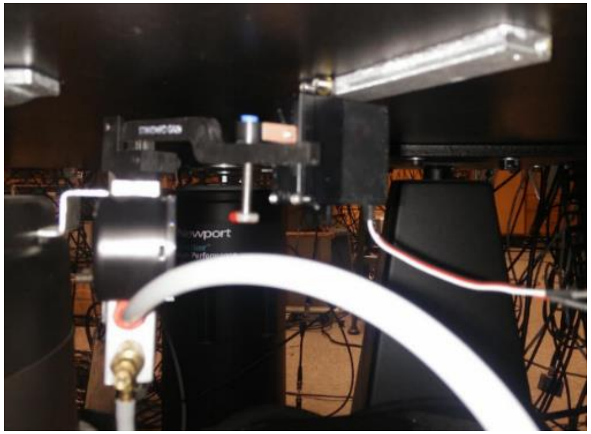
Tilt stabilization

- Measure tilt with electronic bubble level mounted on vacuum chamber
- Set points found by measuring g vs tilt and maximizing
- Feed back to servo motor controlling position of needle valve on table legs.

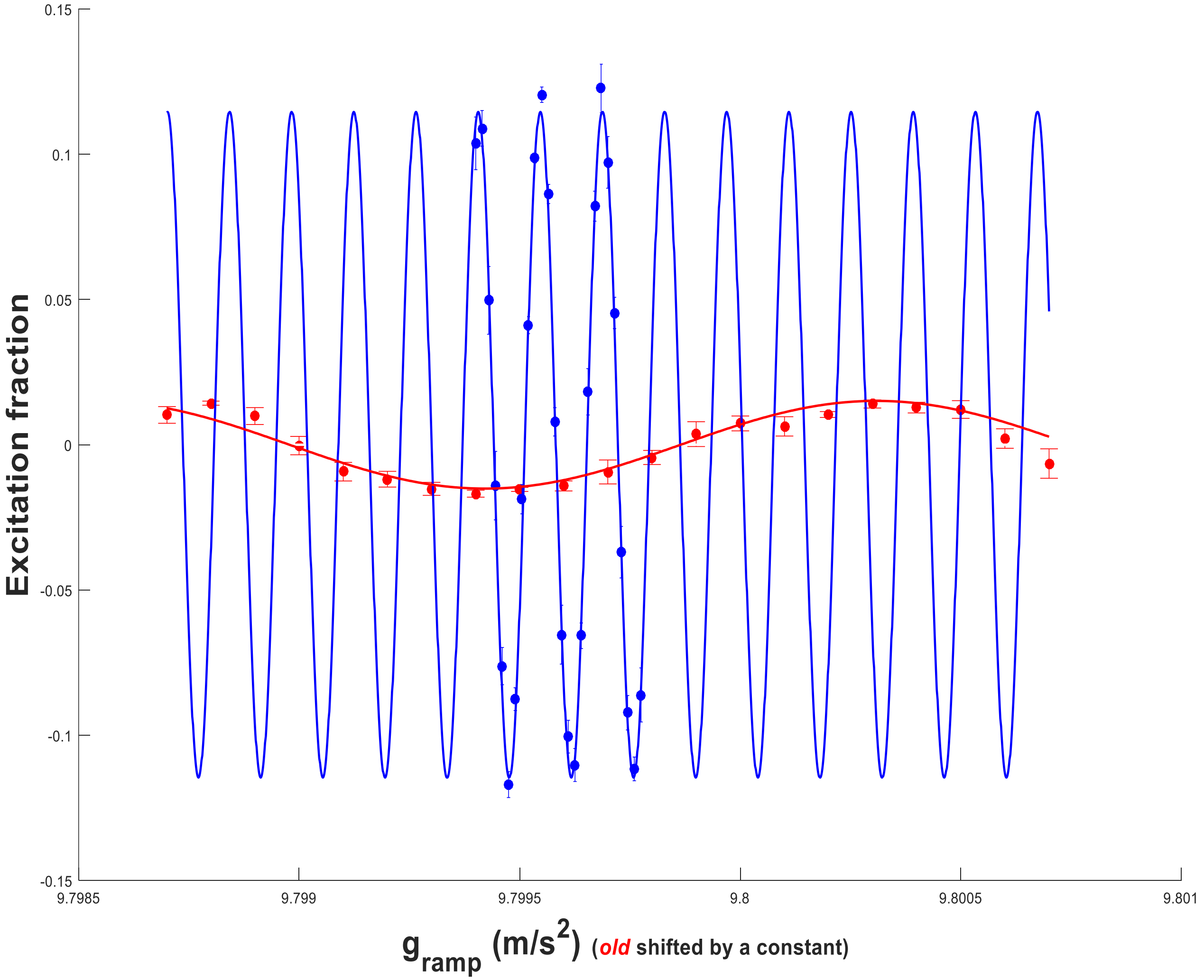






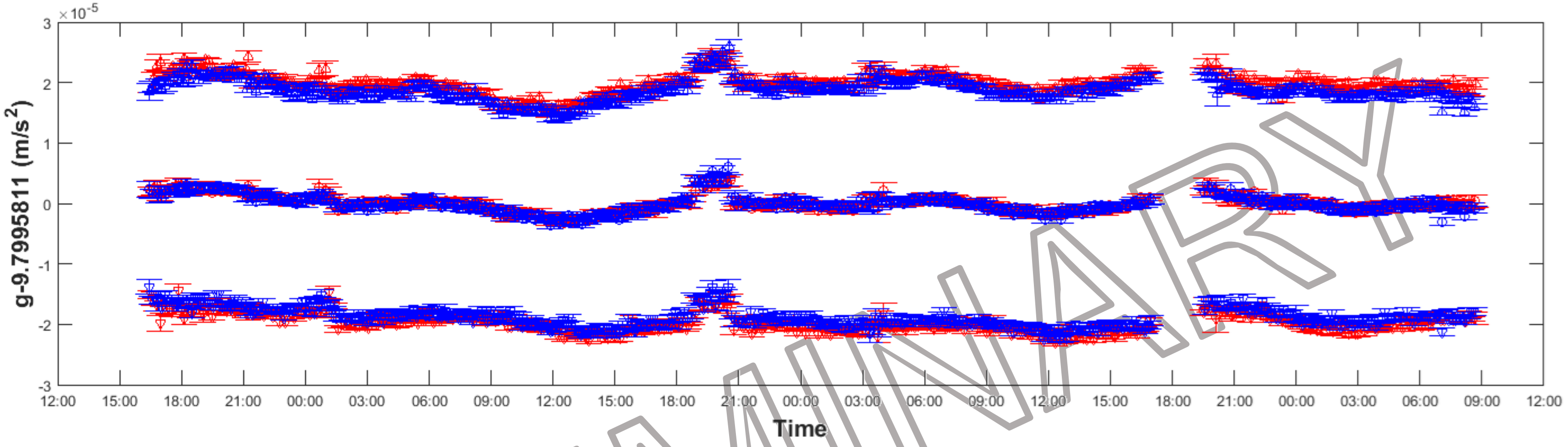


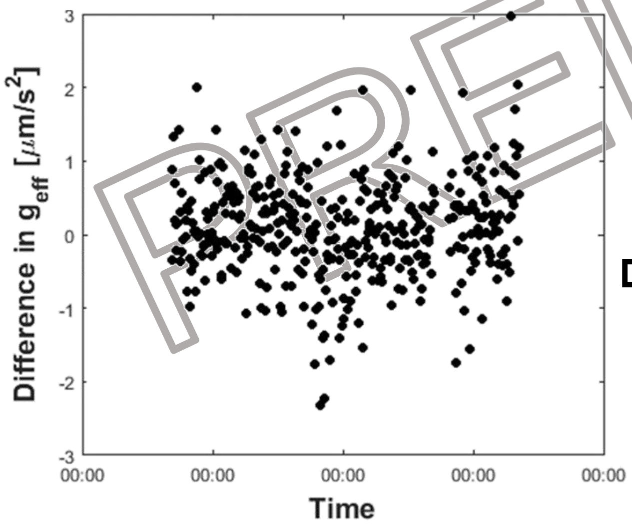
Progress

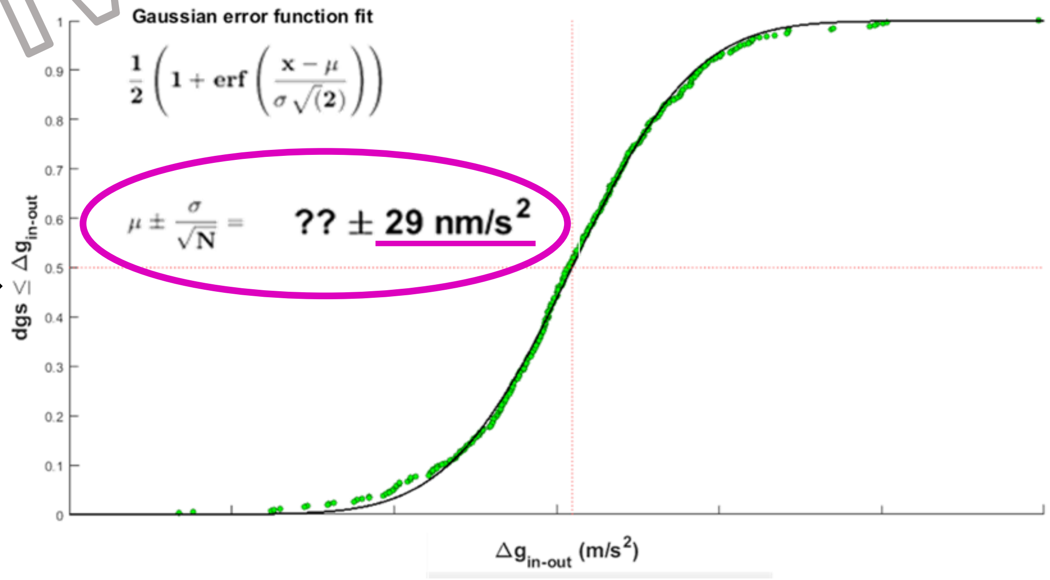

Excitation fraction
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
9.7985
9.799
9.7995
9.8
9.8005
9.801
g_{ramp} (m/s^2) (*old* shifted by a constant)

New statistical sensitivity

Data from **last weekend!**







Gaussian error function fit

$$\frac{1}{2}\left(1+\mathrm{erf}\left(\frac{x-\mu}{\sigma\sqrt{(2)}}\right)\right)$$

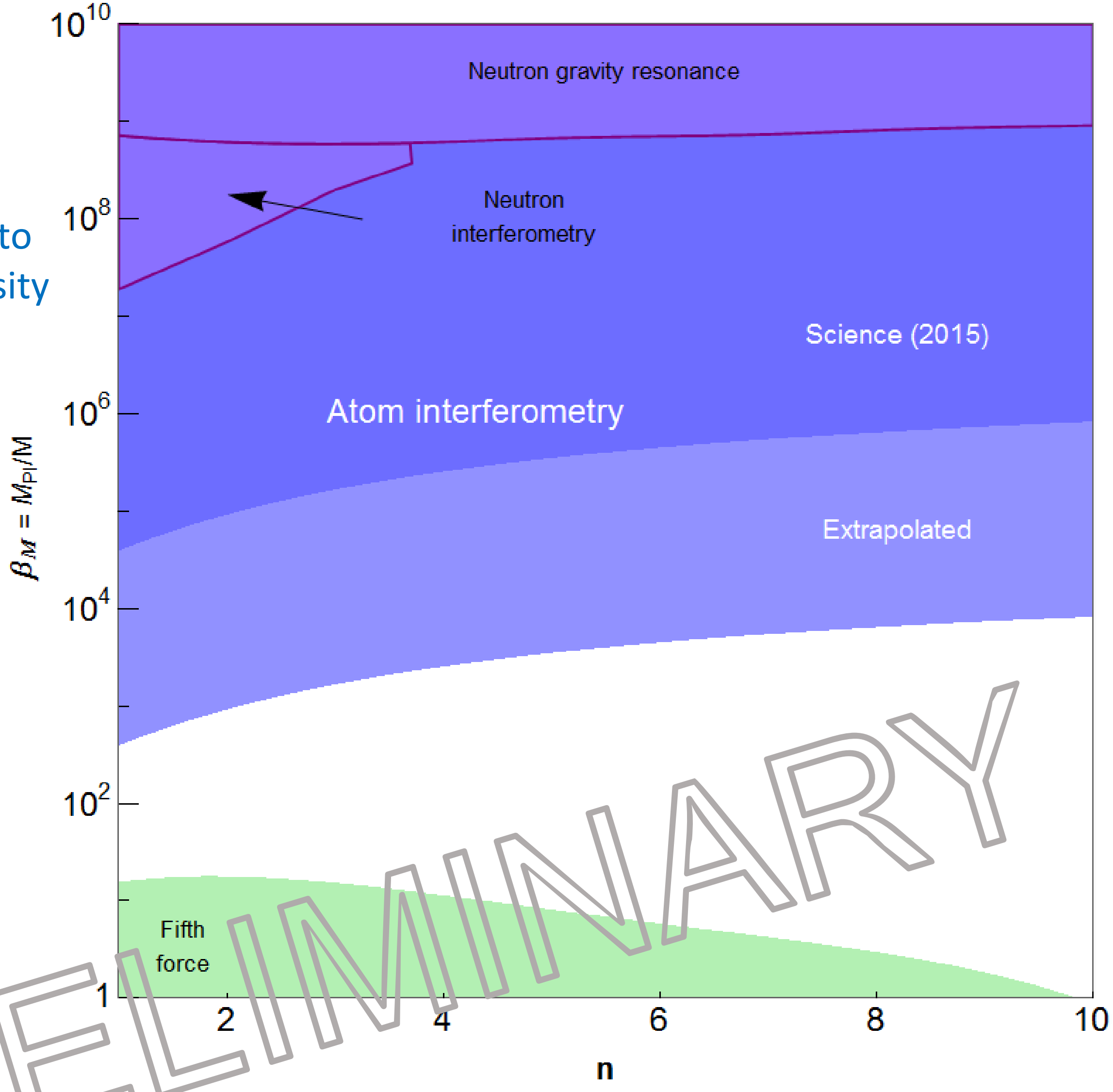
$\mu \pm \frac{\sigma}{\sqrt{N}} =$?? ± 29 nm/s^2

Projected chameleon coverage

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

Self-potential

Coupling to local density



Thank you!!

Chameleon Search
Paul Hamilton
Philipp Haslinger
Holger Müller
Victoria Xu
Justin Khoury
Ben Elder

Optical cavity interferometer development
Brian Estey
Justin Brown
Lothar Maisenbacher
Holger Müller