Title: Experiments Big and Small

Date: Oct 31, 2014 02:30 PM

URL: http://pirsa.org/14100116

Abstract: I will talk about the implications of the current LHC results and the Higgs discovery on the principle of Naturalness, that has been guiding particle physics for the last forty years. Then I will discuss the role that low energy experiments can play for the future of particle physics.

Why Small?

- Theoretical


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Why Small?

- Theoretical

- Experimental

  Precision Frontier

Why Small?

- Theoretical
- Experimental
  - Precision Frontier
- Sociological
  - Time and Money

Outline

- Small Numbers and Big Experiments
- Big Answers from Small Experiments

The Hierarchy Problem

Small numbers give the biggest hints

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Small numbers give the biggest hints

proton   electron

$$\frac{\text{Gravitational Force}}{\text{Electric Force}} =$$

0.0000000000000000000000000000000000000001

The Hierarchy Problem

Small numbers give the biggest hints

proton

electron

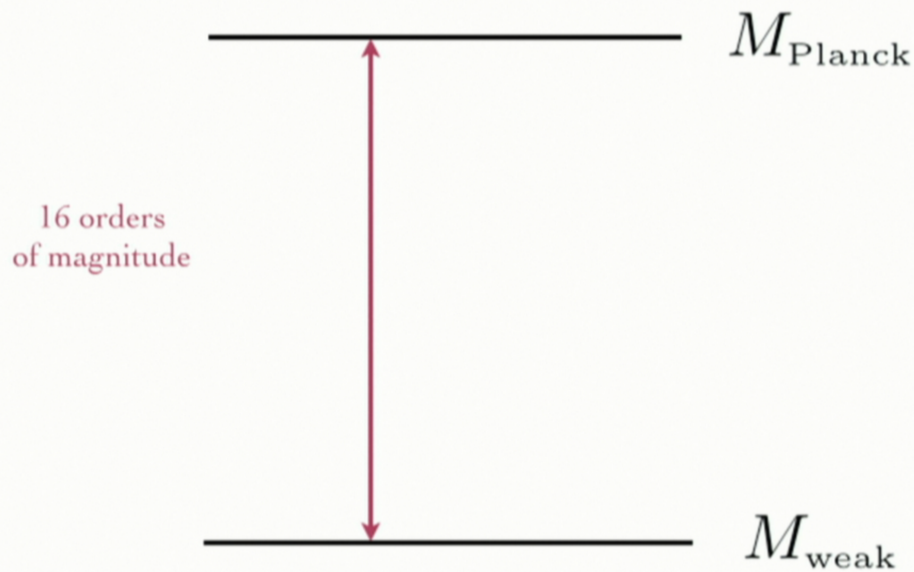
$$\frac{\text{Gravitational Force}}{\text{Electric Force}} =$$

0.0000000000000000000000000000000000000001

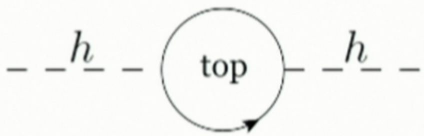
The hierarchy problem

$$M_{\text{Planck}} = G_{\text{Newton}}^{-\frac{1}{2}} = 10^{19}\ \text{GeV}$$

$$M_{\text{weak}} = G_{\text{Fermi}}^{-\frac{1}{2}} = 10^{3}\ \text{GeV}$$



Quantum Corrections in the Standard Model



$$m^2_{\text{higgs}} \propto M^2{}_{\text{Planck}}$$

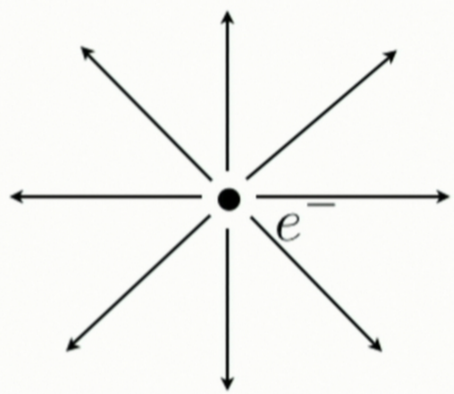
Theory is not Natural, requires a fine tuning

or

Need new symmetry to protect the Higgs in the Standard Model

A Historic Precedent for a New Symmetry

Non-relativistic electron self-energy

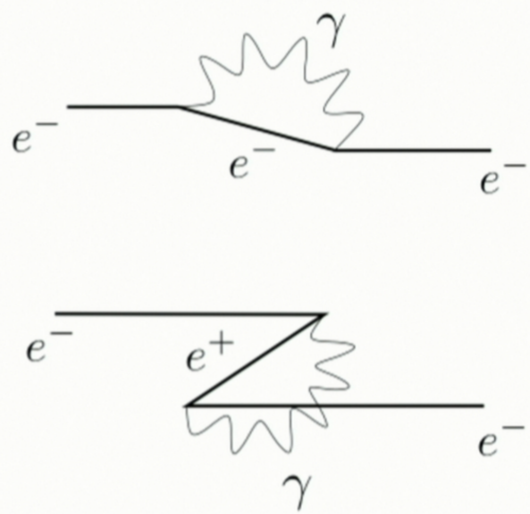


Classically

$$E = \frac{\alpha}{r_{\rm min}} = \alpha M_{\rm Planck}$$

No understanding of why $m_{\rm electron} \ll M_{\rm Planck}$

The Positron and Quantum Corrections



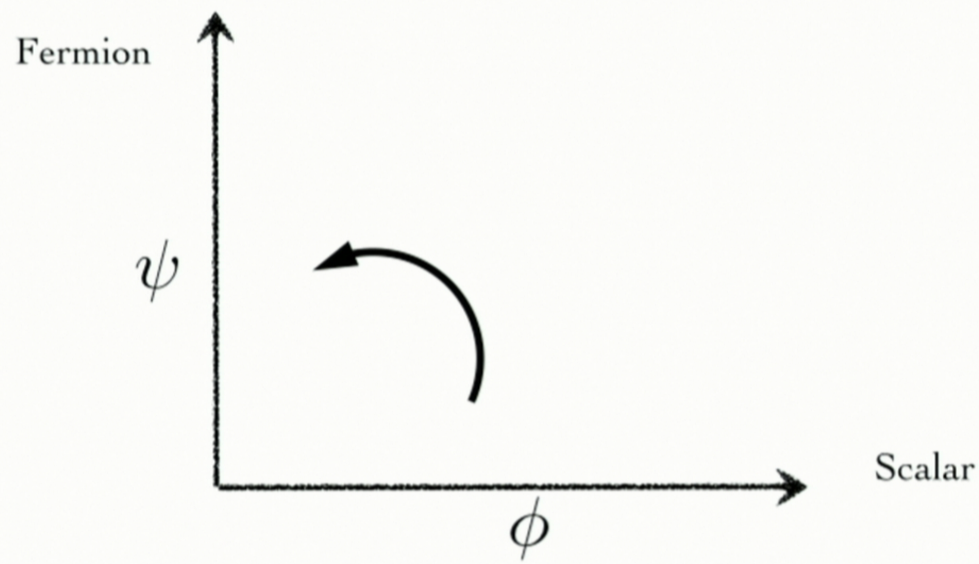
$$\alpha\left(M_{\rm Planck} + m_e \log\frac{M_{\rm Planck}}{m_e}\right)$$

$$\alpha\left(-M_{\rm Planck} + m_e \log\frac{M_{\rm Planck}}{m_e}\right)$$

$$\boxed{\alpha\, m_e\, \log\frac{M_{\rm Planck}^2}{m_e^2}}$$

No explanation why $m_e \ll M_{\rm Planck}$ but once set, it's stable

A New Symmetry for the SM Higgs



$m_\psi{}^2 = m_\phi{}^2$

Supersymmetric Standard Model

The Supersymmetric Standard Model

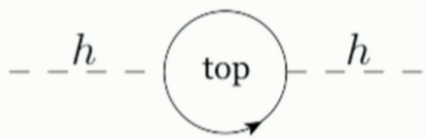
- New Symmetry: Supersymmetry
- New Particles: Superparticles
- Every particle has a superpartner:

lepton → slepton quark → squark	}	matter
photon → photino gluon, W → gluino, Wino	}	force
Higgs → Higggsino		

Supersymmetry not exact in nature:

$$m_{spartner}^2 = m_{sm}^2 + m_{susy}^2$$

Superparticles and Quantum Corrections



$\propto M^2{}_{\text{Planck}}$

$\propto -M^2{}_{\text{Planck}} + M^2{}_{\text{SUSY}}$

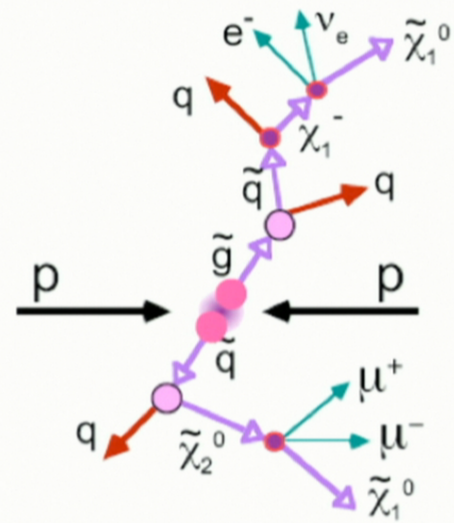
$\propto M^2{}_{\text{SUSY}}$

If sparticles are at the weak scale so must be the higgs

$m_{weak}{}^2 = m_{susy}{}^2$

Supersymmetry

- Super-particles produced at the LHC



- The lightest sparticle stable: Dark Matter Candidate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2400
[GeV]
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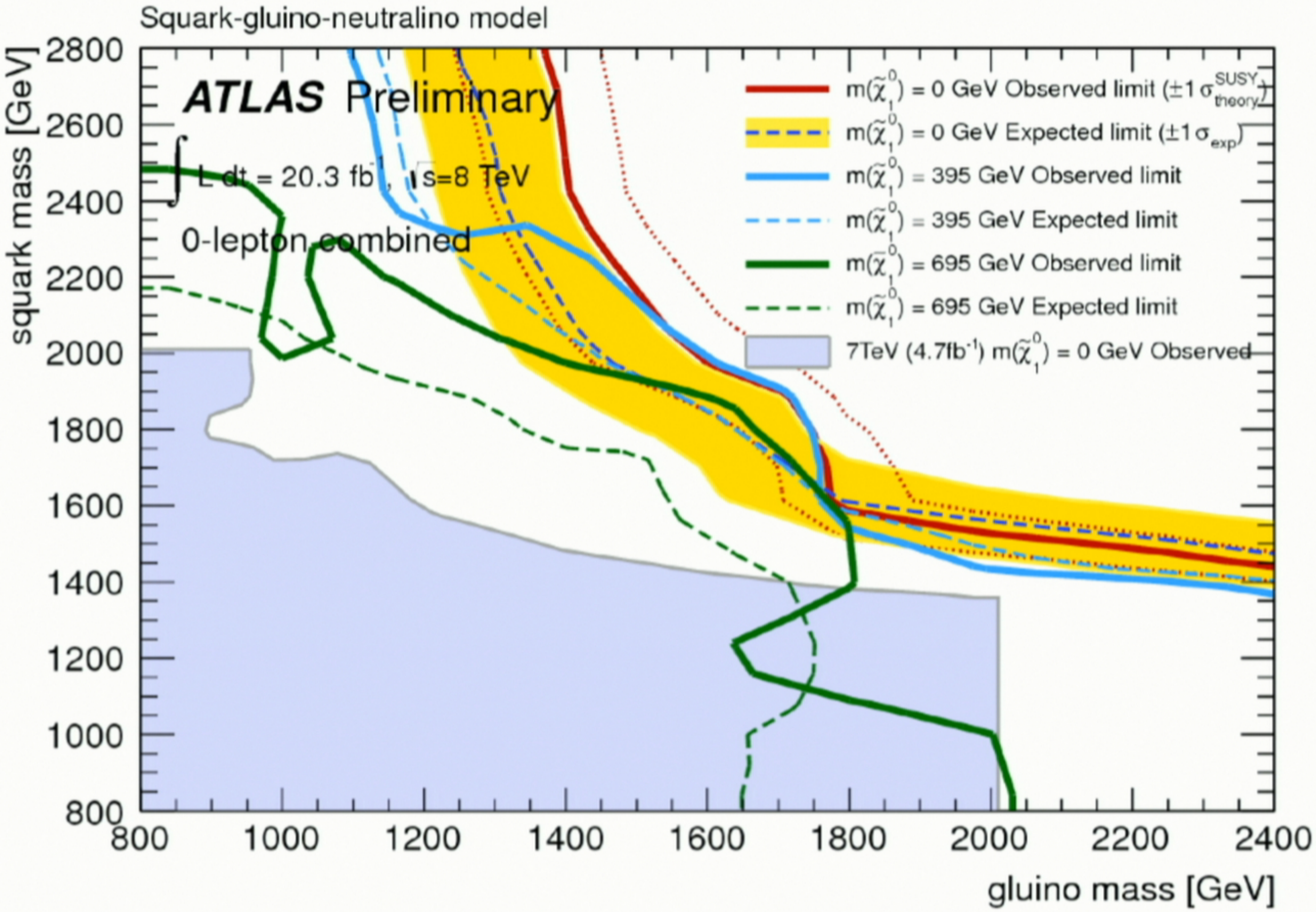
The Missing Superpartner Problem



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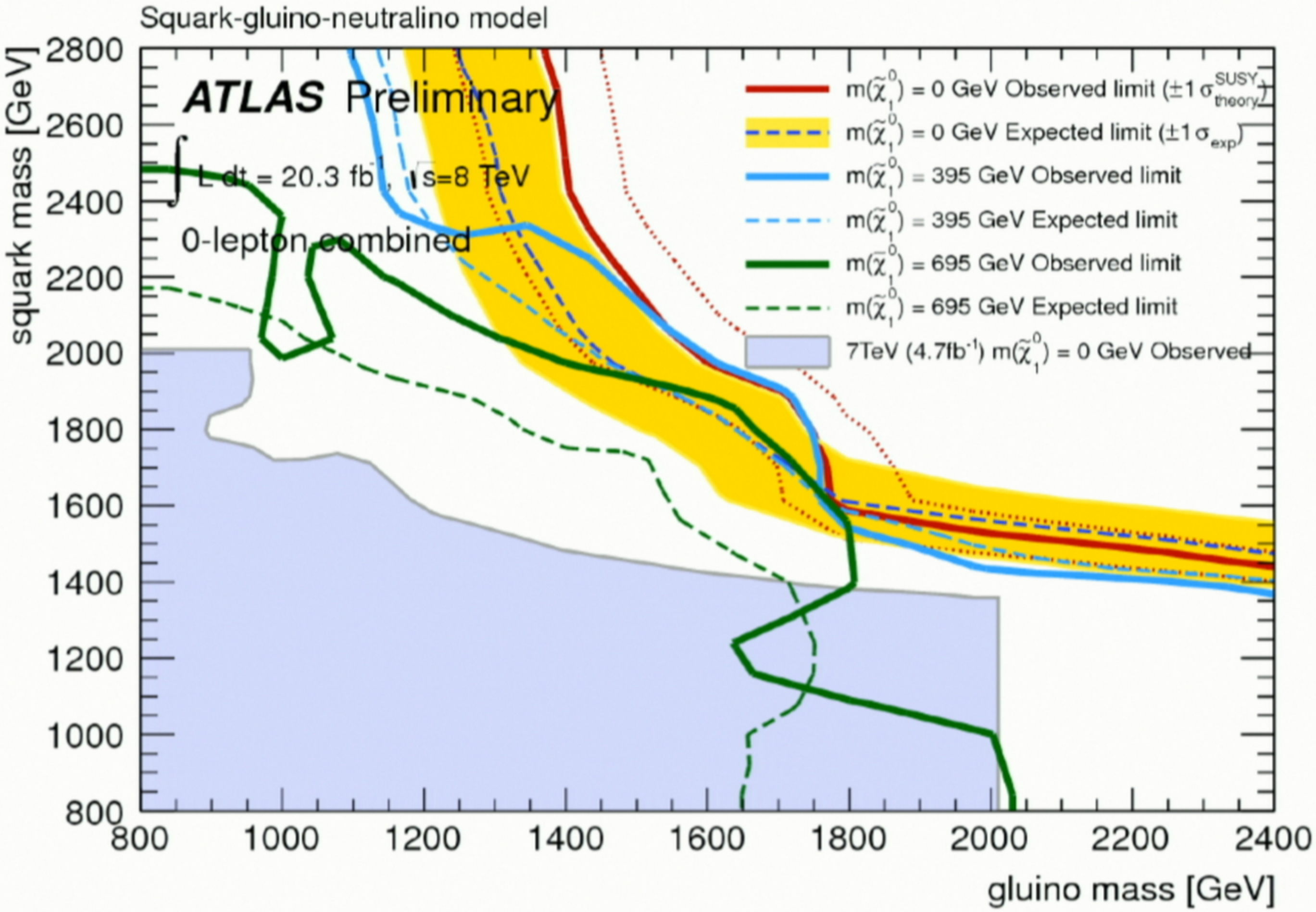
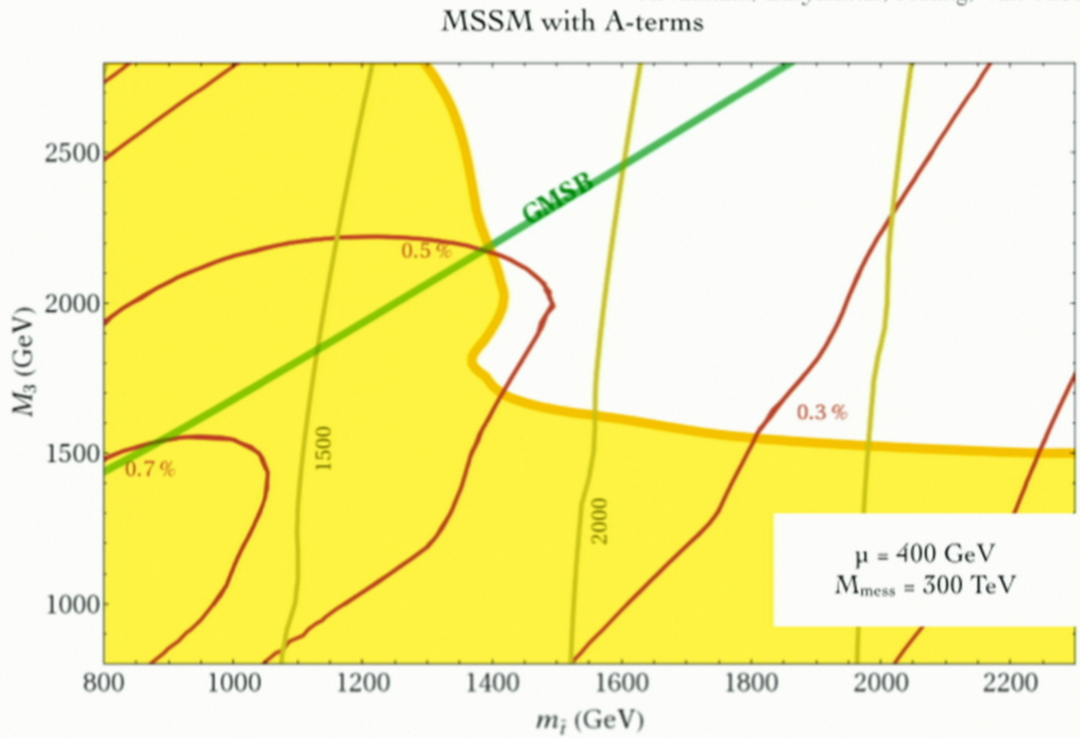


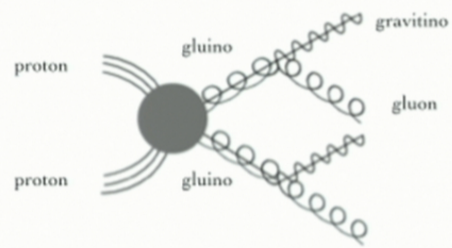
The Status of Naturalness in SUSY

Arvanitaki, Baryakhtar, Huang, Van Tilburg, Villadoro (2013)



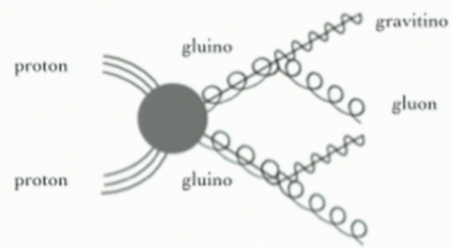
- Minimal Supersymmetric Standard Model appears more than 1% tuned

Supersymmetry searches at the LHC



Main Supersymmetric signature at the LHC:
Missing Energy (from the gravitino)
+
Large Transverse Momentum (energy from the visible particles)

Supersymmetry searches at the LHC



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Missing Energy (from the gravitino)
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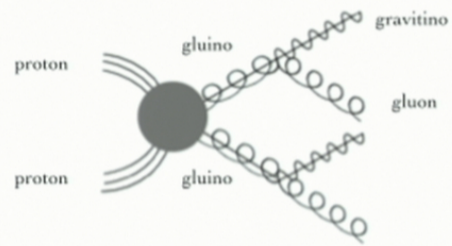
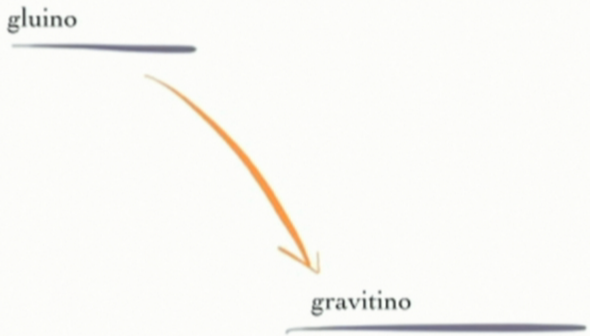
Supersymmetry searches at the LHC

- Supersymmetric Decays in 4d
- Supersymmetric Decays in Extra Dimensions





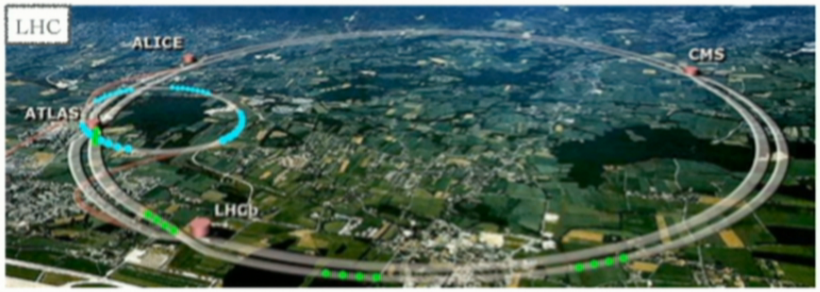
Gluon $p_T \sim (1/2) M_{gluino}$

LHC potential: ✓

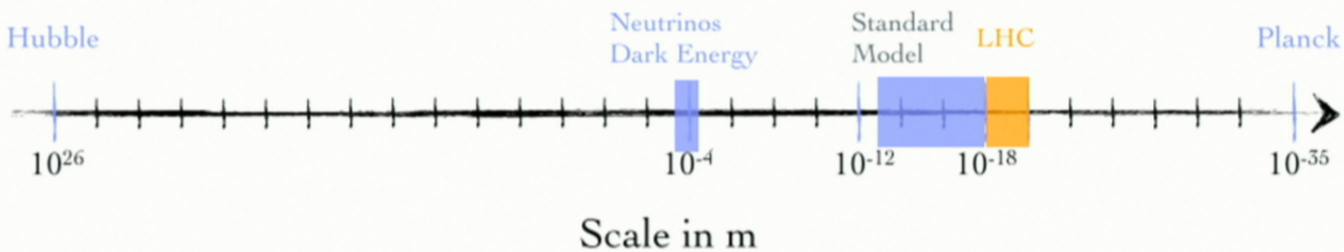
Gluon $p_T << (1/2) M_{gluino}$

LHC potential: ✗

Stay Tuned!



Big Answers From Small Experiments

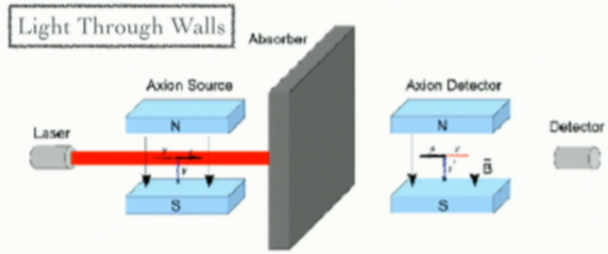


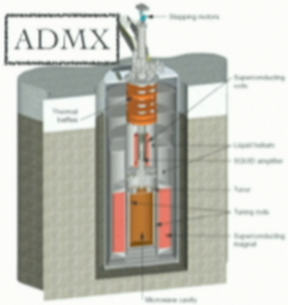
80% of the energy scale left to explore

The Low Energy Frontier

- In the Standard Model
  - Gravitons
  - Cosmic Neutrinos
- In String Theory
  - Axion(s) Also DM and Strong CP!
  - Photons kinetically mixing with our photon $\epsilon\, F^{EM}_{\mu\nu} F^{\mu\nu\prime}$
  - Dilaton, moduli, new dimensions

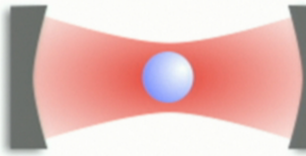
How Do You Probe The Low Energy Frontier?





How Do You Probe The Low Energy Frontier?

Optically Levitated Objects



- Short Range Forces
- Gravitational Wave detection at high frequencies
- Tests of Quantum Mechanics

- Axion Field Detection

NMR

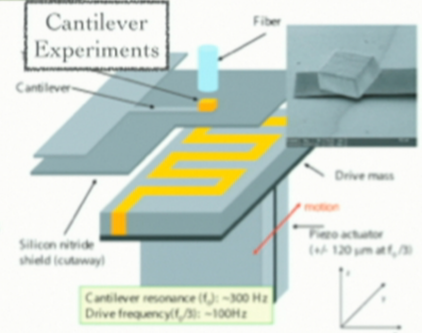
LIGO

Atom Interferometry

- Equivalence principle at 15 decimals
- Gravitational Wave detection at low frequencies
- EDM searches
- Tests of Atom Neutrality at 30 decimals

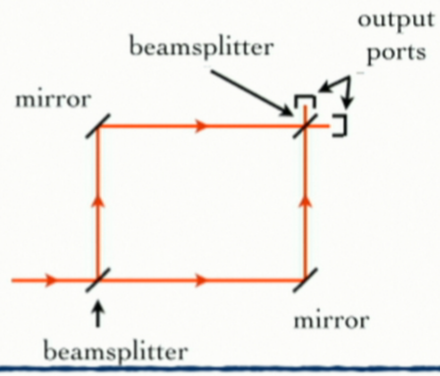
- Short Distance Tests of Gravity
- Extra Dimensions

Cantilever Experiments



Light vs Atom Interferometry

Light



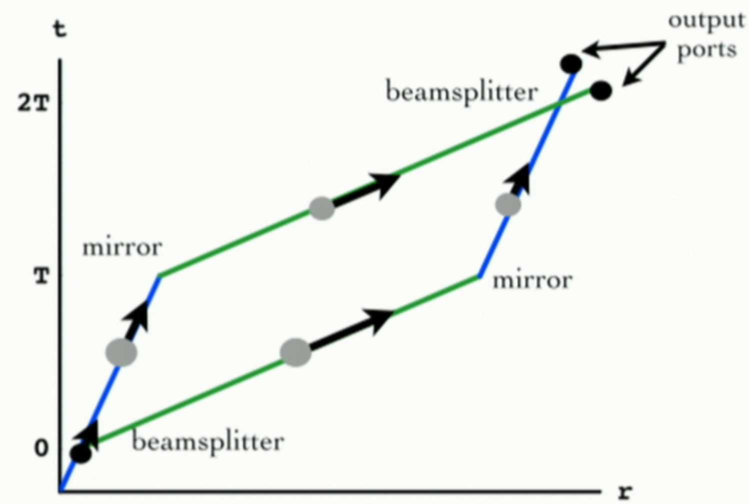
accuracy of measurement

$$\frac{\delta L}{L} \approx \frac{\lambda}{L} \times \text{phase resolution}$$

Atoms

For atoms T~ 1 sec

⇒ L= cT ~ Earth-Moon distance!



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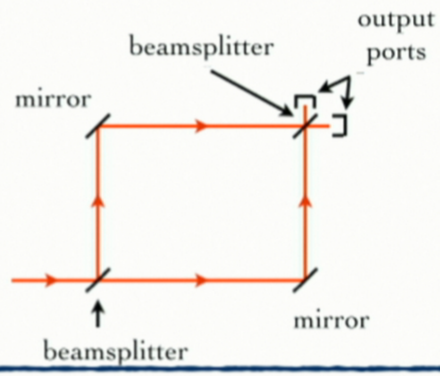

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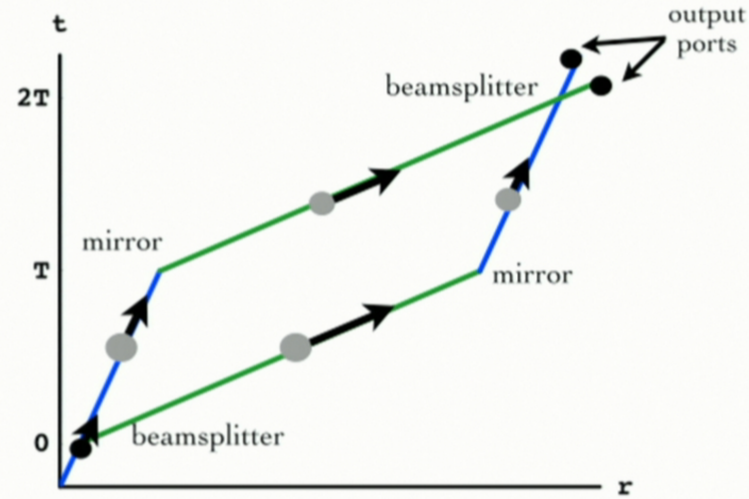
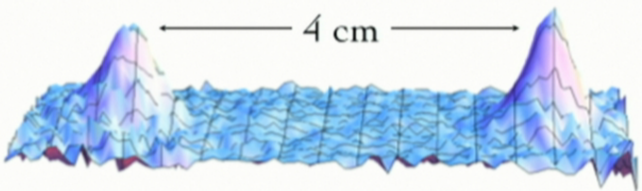
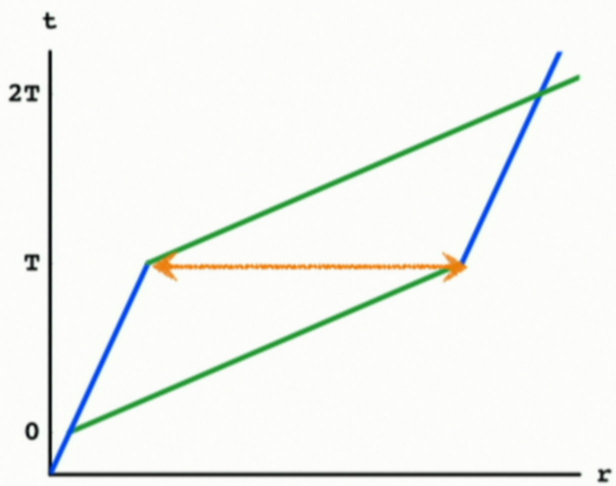


10 m Atom Interferometer (2013)

Hogan, Kasevich et. al.

Maximum Wavepacket Separation





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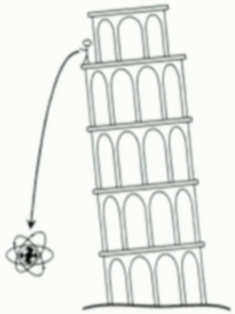
Testing Gravity at Large Distances

SD, Graham, Hogan, Kasevich
2006



An atom interferometer is a precision accelerometer

- Tests of the equivalence principle

Galileo $\sim g$

Future $\sim 10^{-17} g$

- Tests of General Relativity

$$\frac{d\vec{v}}{dt} = -\nabla\phi \qquad -\nabla\phi^2 \qquad -\vec{v}^2\nabla\phi$$

Newton's Gravity | Gravity Gravitates | Kinetic Energy Gravitates

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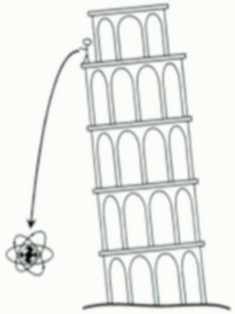

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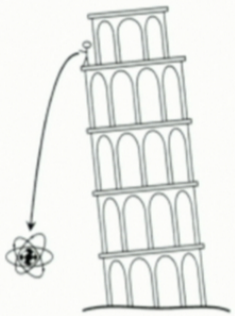

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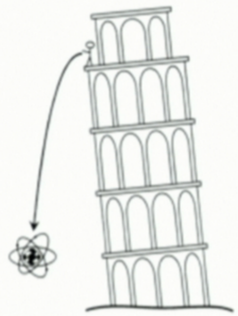
Testing Gravity at Large Distances

SD, Graham, Hogan, Kasevich 2006



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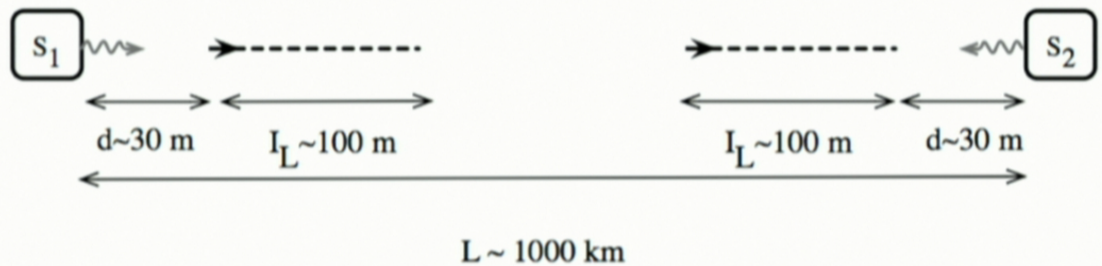
Newton's Gravity	Gravity Gravitates	Kinetic Energy Gravitates

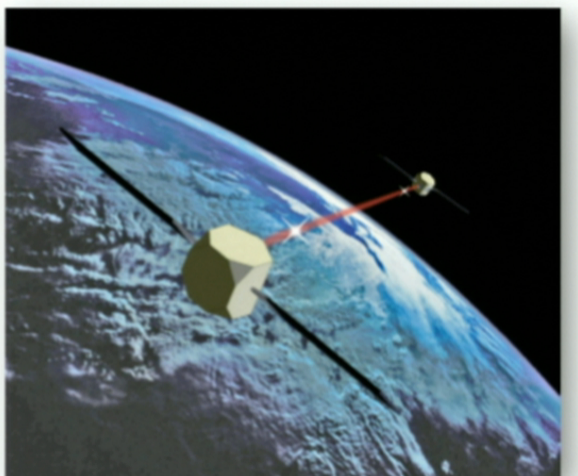
Gravitational Wave Detection with Atom Interferometry

SD, Graham, Hogan, Kasevich, Rajendran
2008



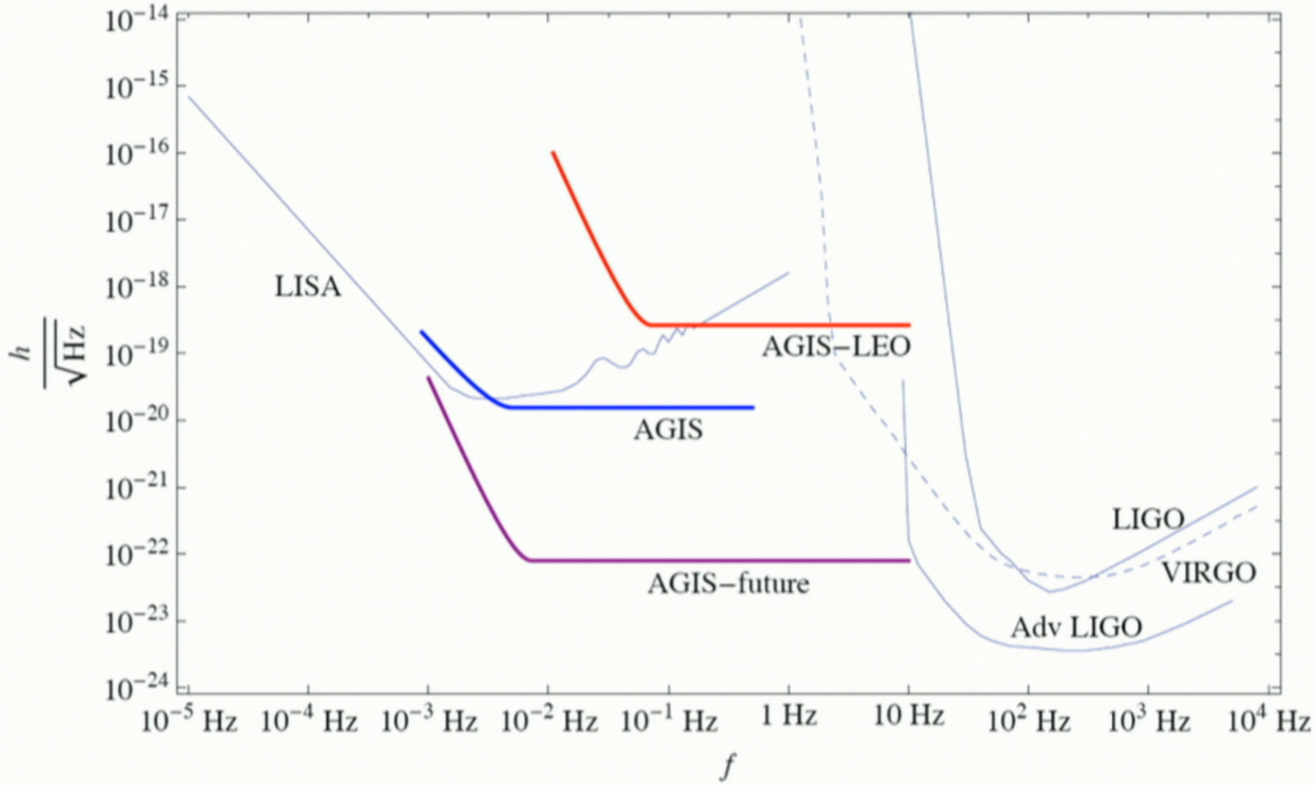
Physical Distances between atoms oscillate with the GW amplitude:

$L = L_o(1 + h\cos(\omega t))$



- Currently funded by NASA NIAC grant (NASA Innovative Advanced Concepts)
- MIGA - Philip Bouyer: Ground based GW detector in Bordeaux

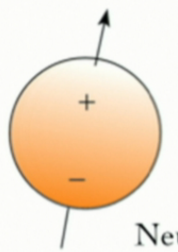
Projected Sensitivity in Space



AGIS: 1000 km
LISA: 5000000 km

Why is the Electric Dipole Moment of the Neutron Small?

The Strong CP Problem and the QCD axion



Neutron
EDM

EDM ~ e fm θ_{QCD}

$$L_{\rm SM} \supset \frac{g_s^2}{32\pi^2}\theta_{\rm QCD} G^a \tilde{G}^a$$

Experimental bound: $\theta_{QCD} < 10^{-10}$

Solution:
θ_{QCD} is a dynamical field, an axion

Axion mass from QCD:

$$\mu_a \sim 6\times 10^{-11}\ \text{eV}\ \frac{10^{17}\ \text{GeV}}{f_a} \sim (3\ \text{km})^{-1}\ \frac{10^{17}\ \text{GeV}}{\text{f}_\text{a}}$$

f_a : axion decay constant

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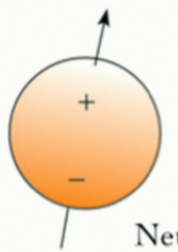

Neutron EDM

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f_a : axion decay constant


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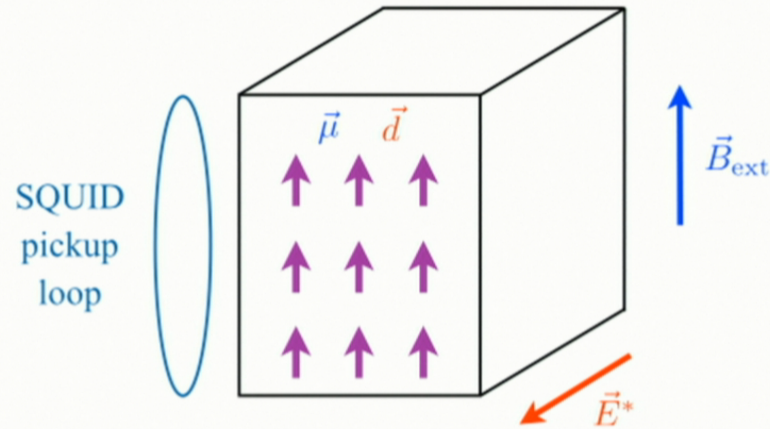
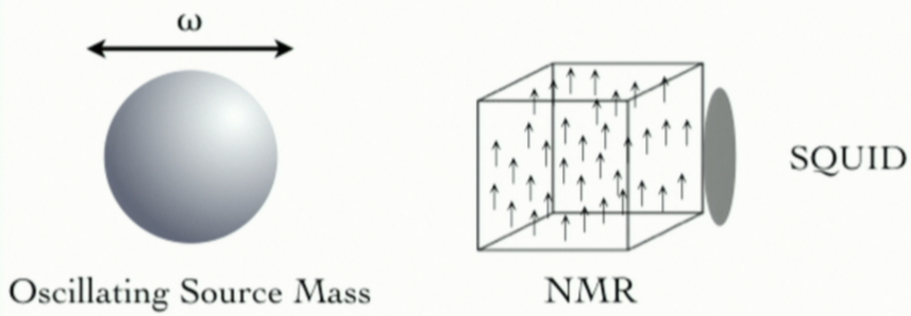
Precision Magnetometry

Nuclear Magnetic Resonance

Cosmic Axion Detection

Budker, Graham, Rajendran, et. al.

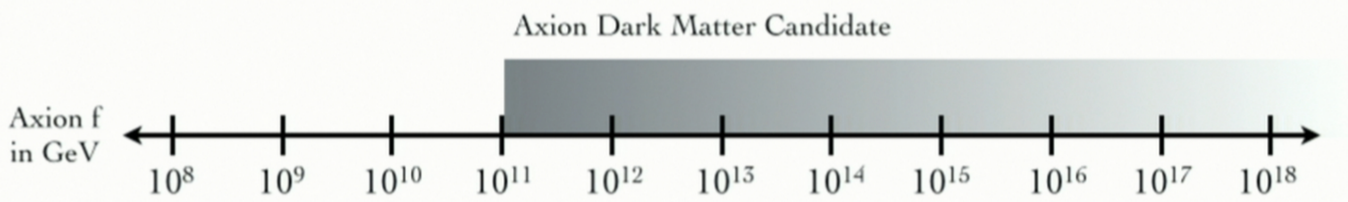




Short-range axion exchange

Arvanitaki and Geraci

Reach of New QCD Axion Detection Ideas



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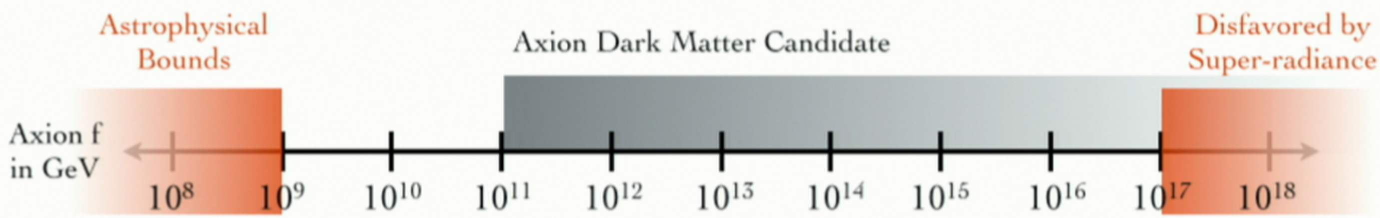
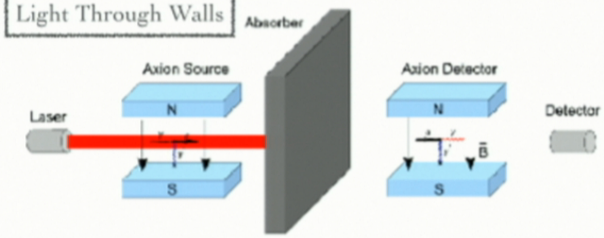
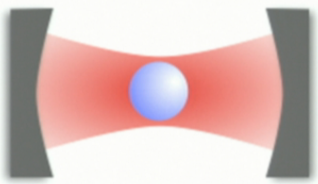


Scattered Experiments

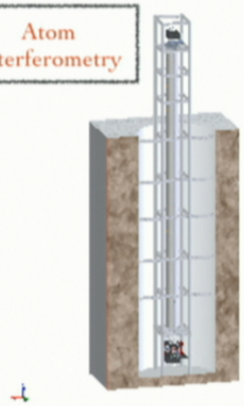
Light Through Walls



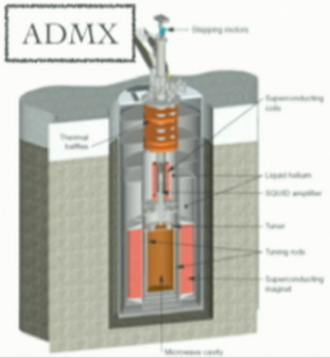
Optically Levitated Objects



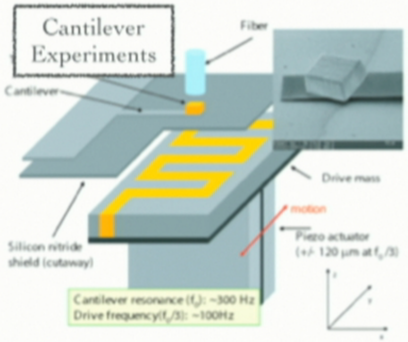
Atom Interferometry



ADMX



Cantilever Experiments



Scattered Experiments

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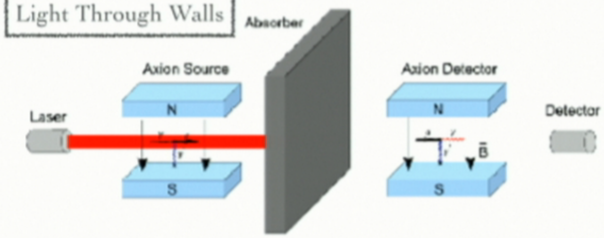

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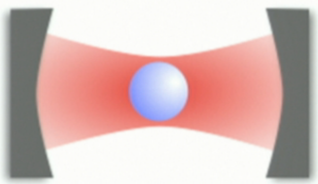
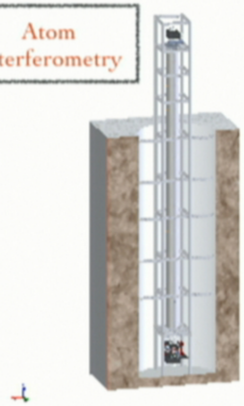


NMR

Atom Interferometry



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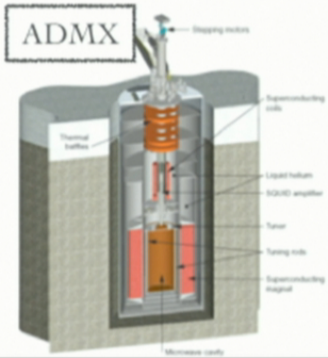

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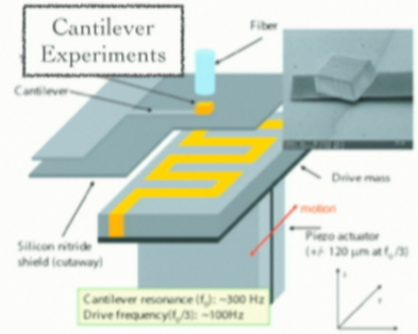

Scattered Experiments

Do They Need a Home?

Super-Lab for Fundamental Physics?

- A Laboratory housing ≳ 20 small scale experiments on fundamental physics
- Fundamental Physics: New Forces, New Particles, New Dimensions, New phenomena…
- ANY Experimental Technique
- HEP Model of a Users Facility plus Local Personnel


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