Experiments Big and Small

Savas Dimopoulos
Stanford University

Why Small?

- Theoretical

Why Small?

- Theoretical
- Experimental

  Precision Frontier

Why Small?

- Theoretical
- Experimental

  Precision Frontier
- Sociological

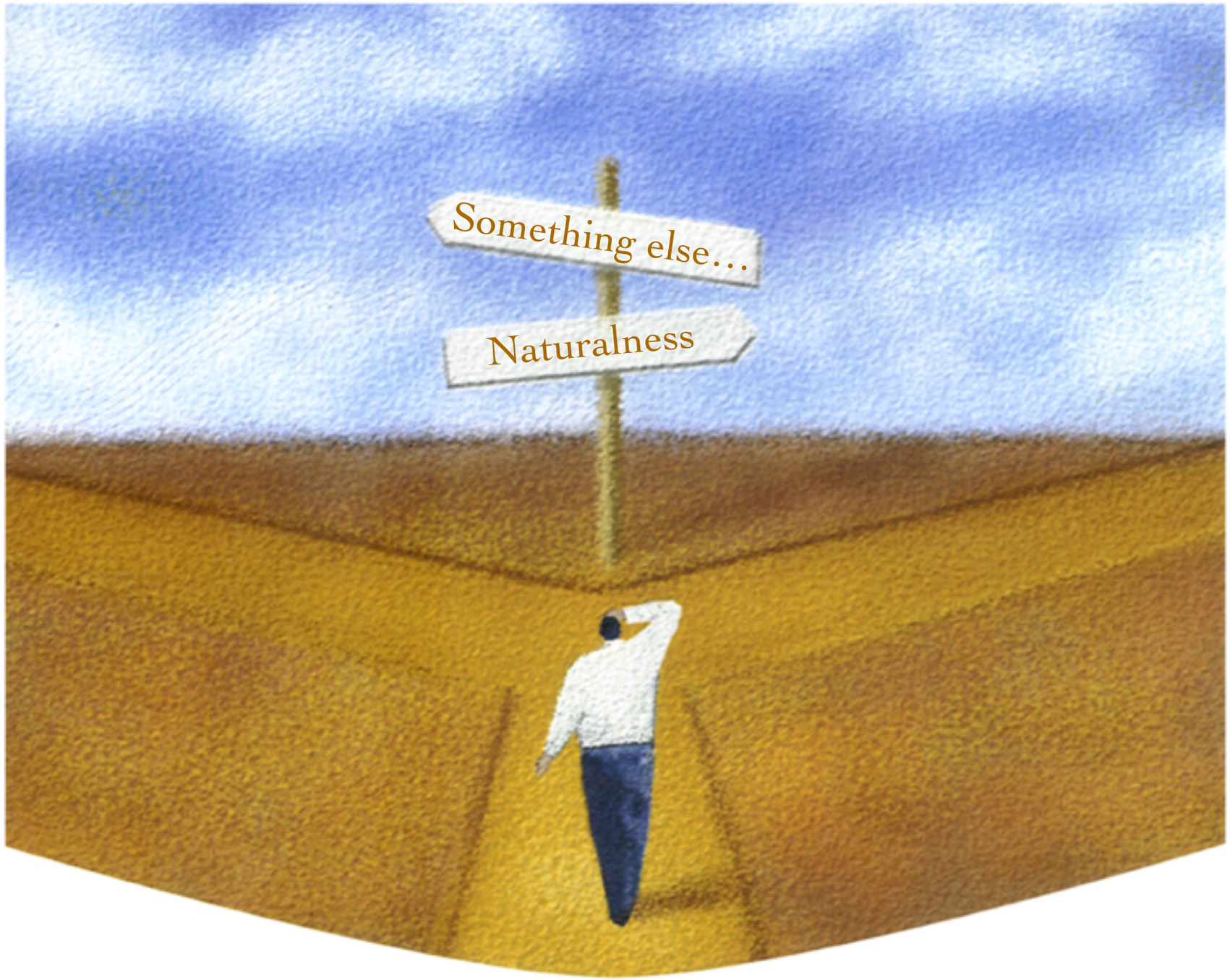
  Time and Money

Outline

- Small Numbers and Big Experiments

- Big Answers from Small Experiments

Probing Small Numbers with Large Machines



Small Numbers and Coincidences

Naturalness - Dynamics

Problem	Solution
Hydrogen Binding Energy	$E_b = \frac{1}{2}\frac{e^4}{(4\pi)^2} m_e$
Deuteron Binding Energy Nuclear Binding Energy	$E_b \approx \frac{1}{2}\frac{1}{(4\pi)^2}\frac{m_N}{2}$
π^+ - π^o mass difference	Symmetry/Dynamics
$K - \bar{K}$ mixing	Flavor Symmetry
Electron Mass	Chiral Symmetry

Small Numbers and Coincidences

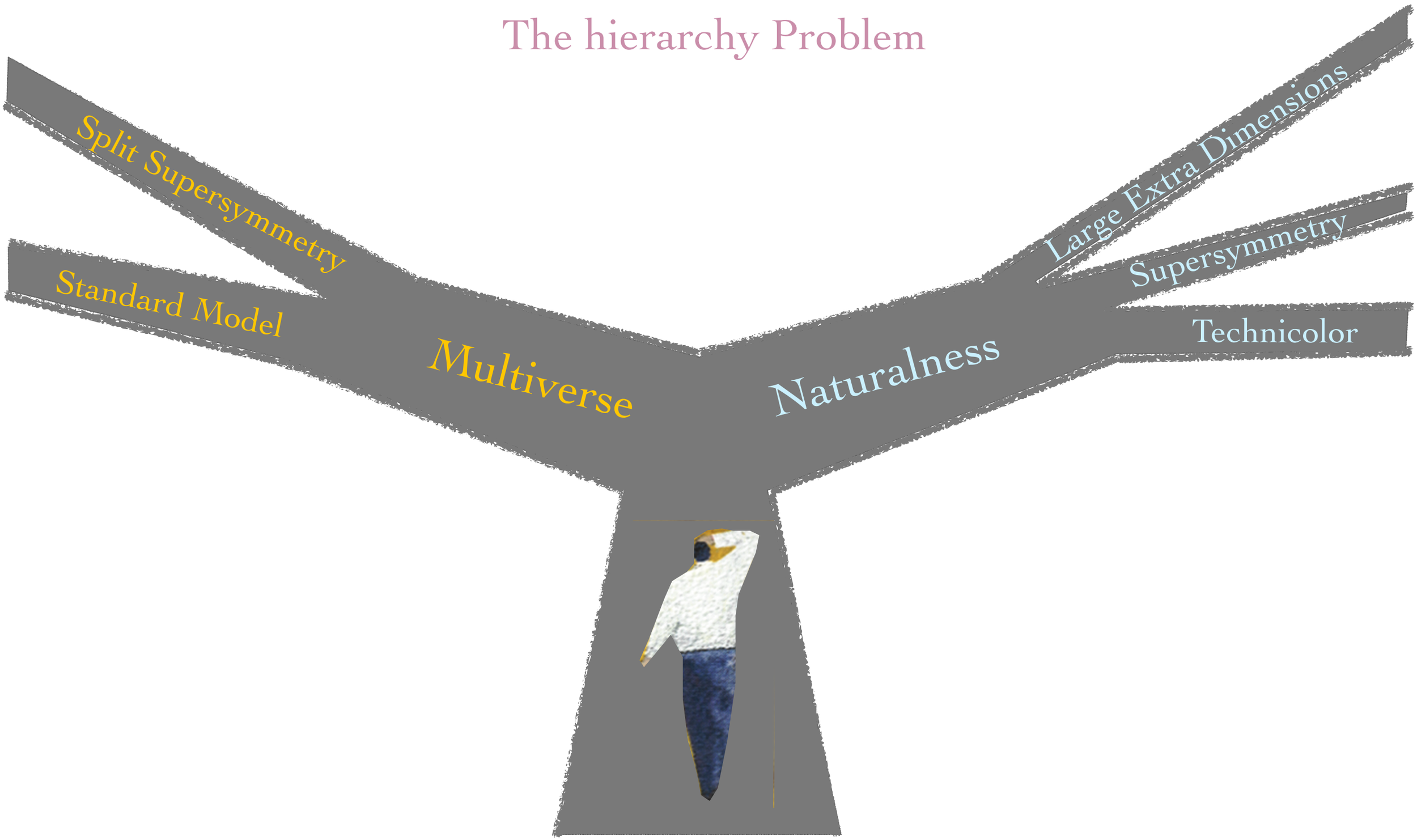
Something else…

Problem	Solution
Earth-Sun Distance	Environmental Selection 10^{22} suns
Cosmological Constant	Environmental Selection? 10^{500} universes!
7 eV line of ^{229}Th nucleus	"Look-elsewhere" effect
Solar-Lunar Eclipse	Plain Luck!

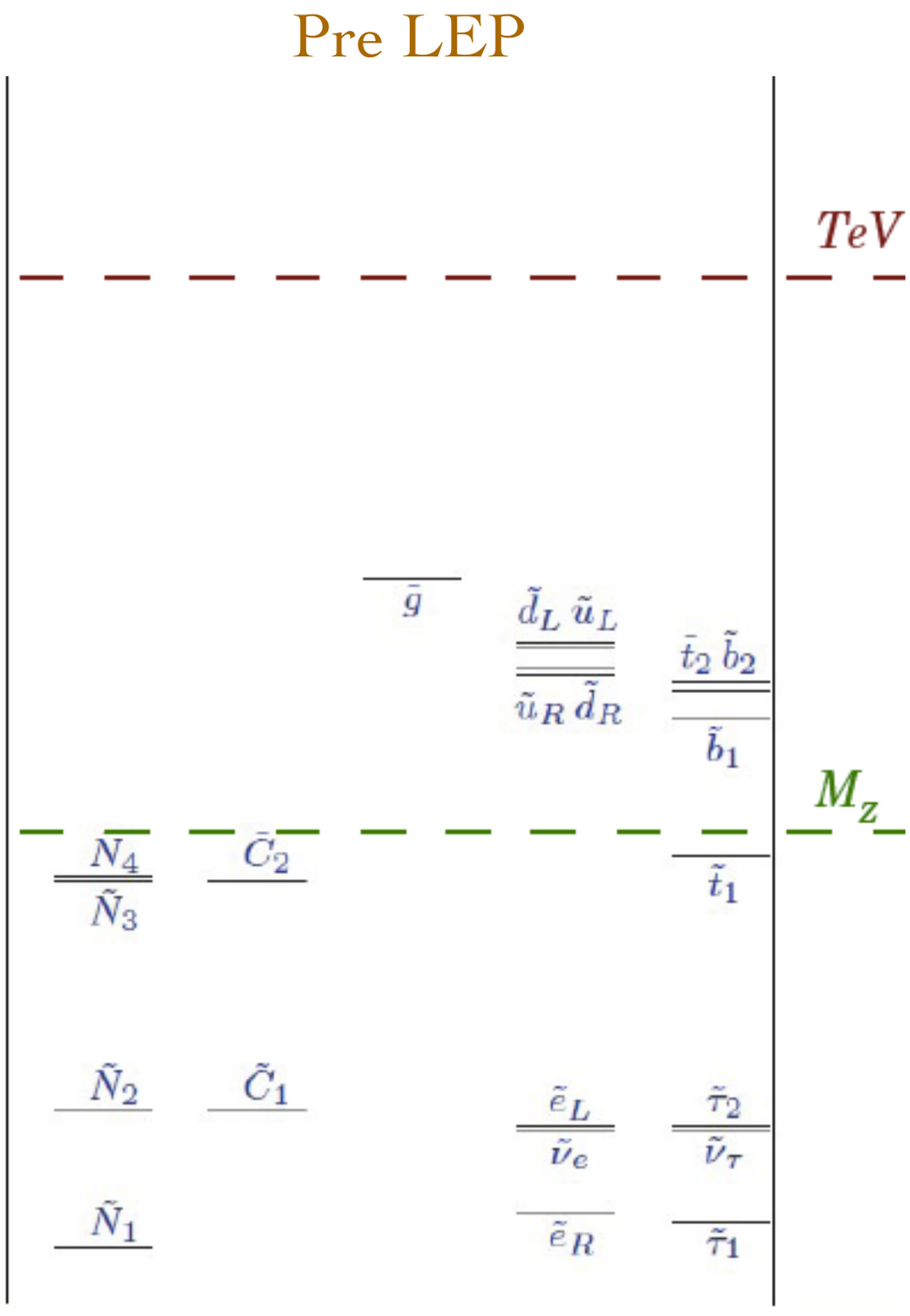
Small Numbers and Coincidences

What about the Electroweak Scale?

The hierarchy Problem



The Hard Facts



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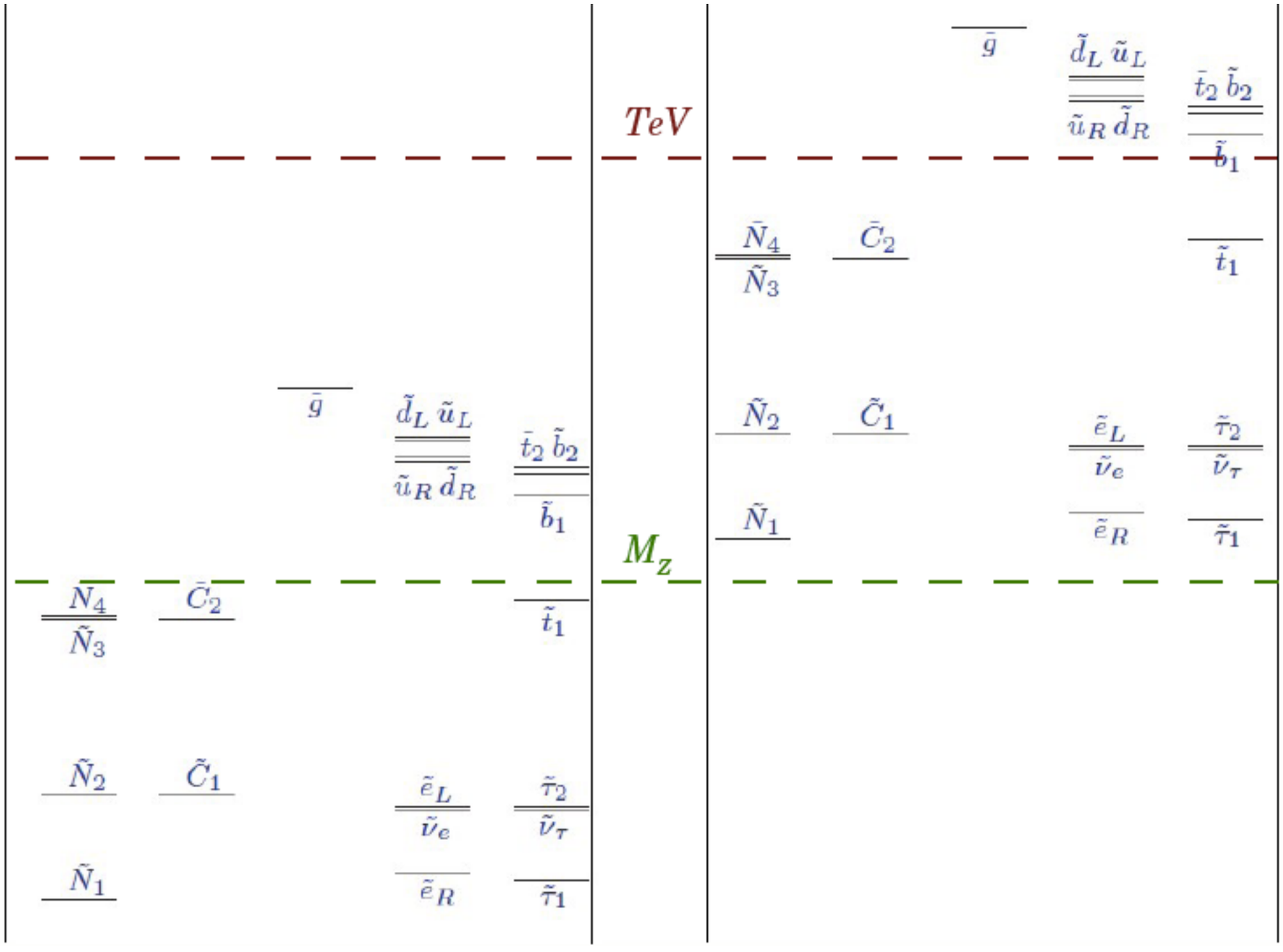
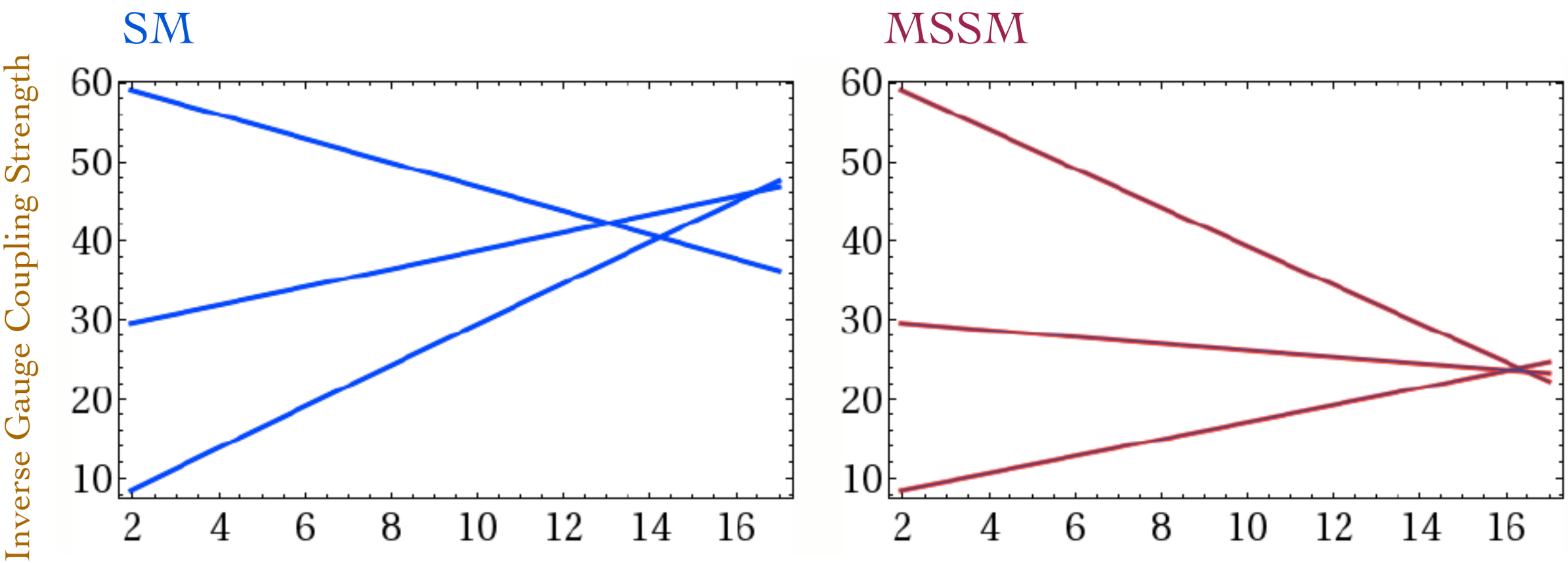


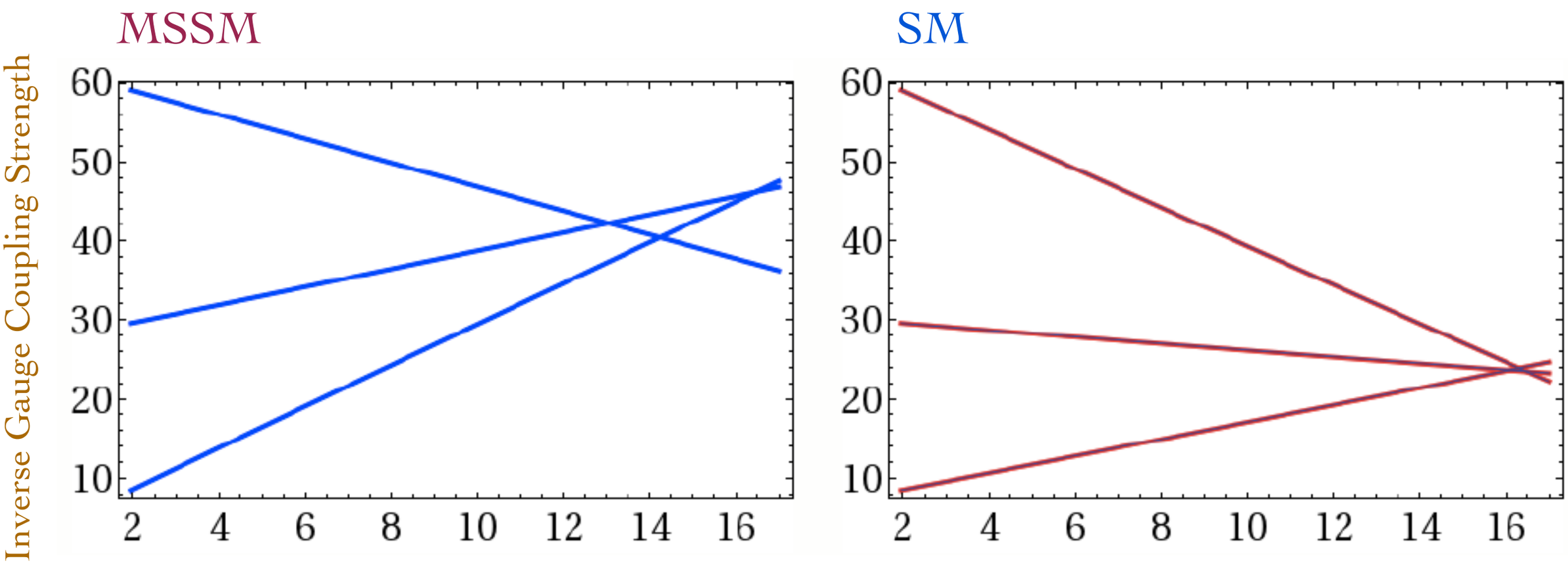
The connection with the hierarchy problem is diminished

Why Supersymmetry?



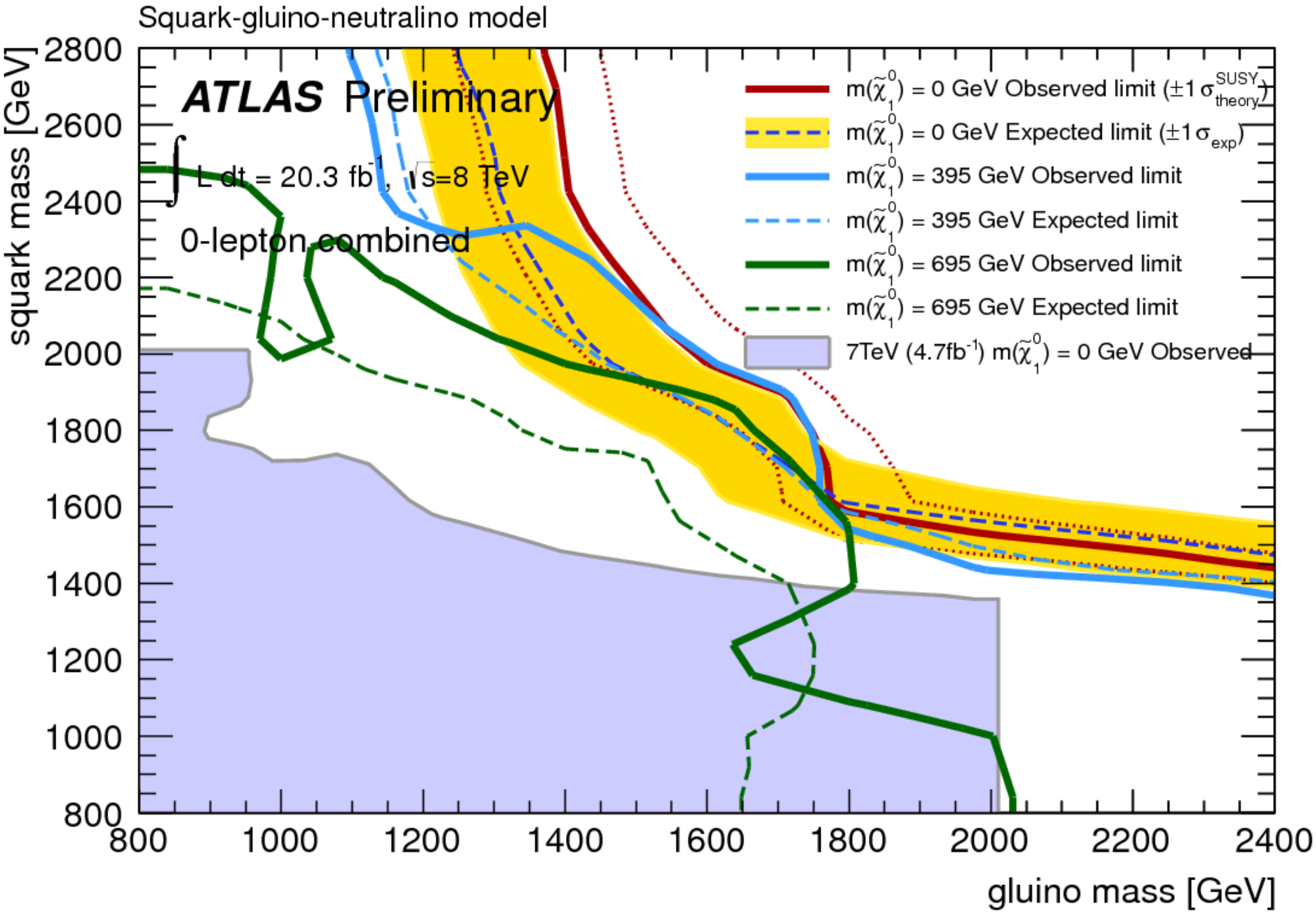
Gauge Coupling running at two loops

Why Supersymmetry?



Gauge Coupling running at two loops

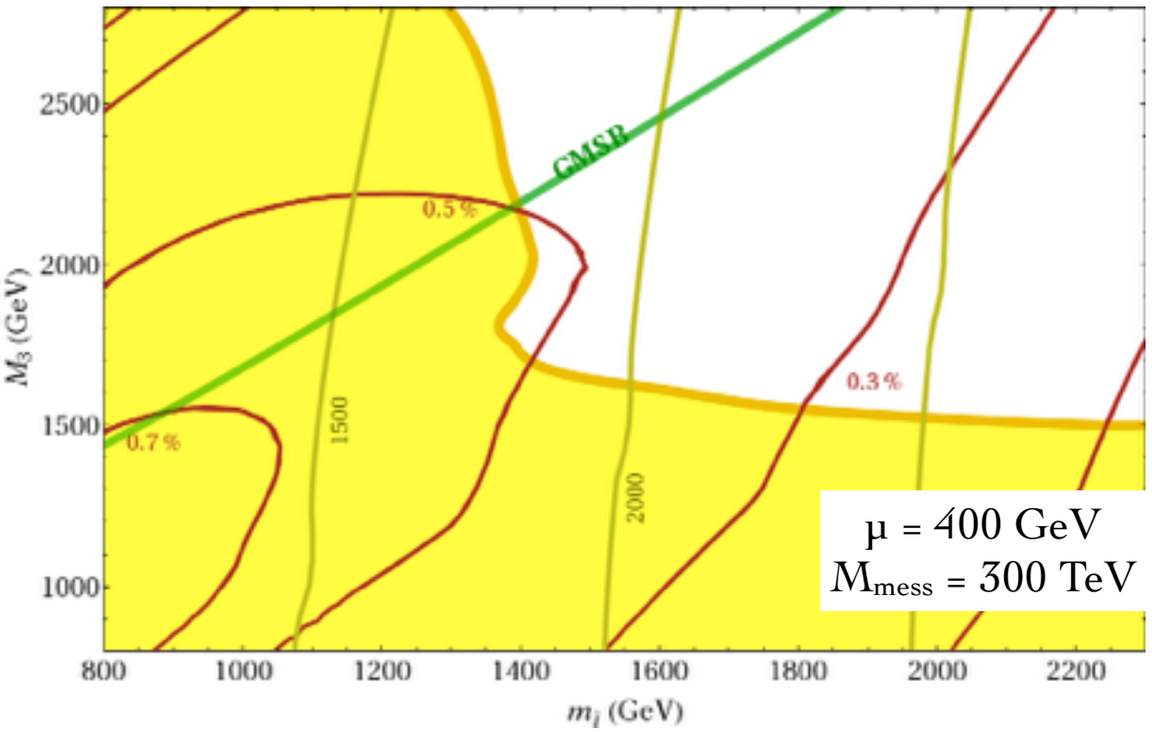
The Missing Superpartner Problem



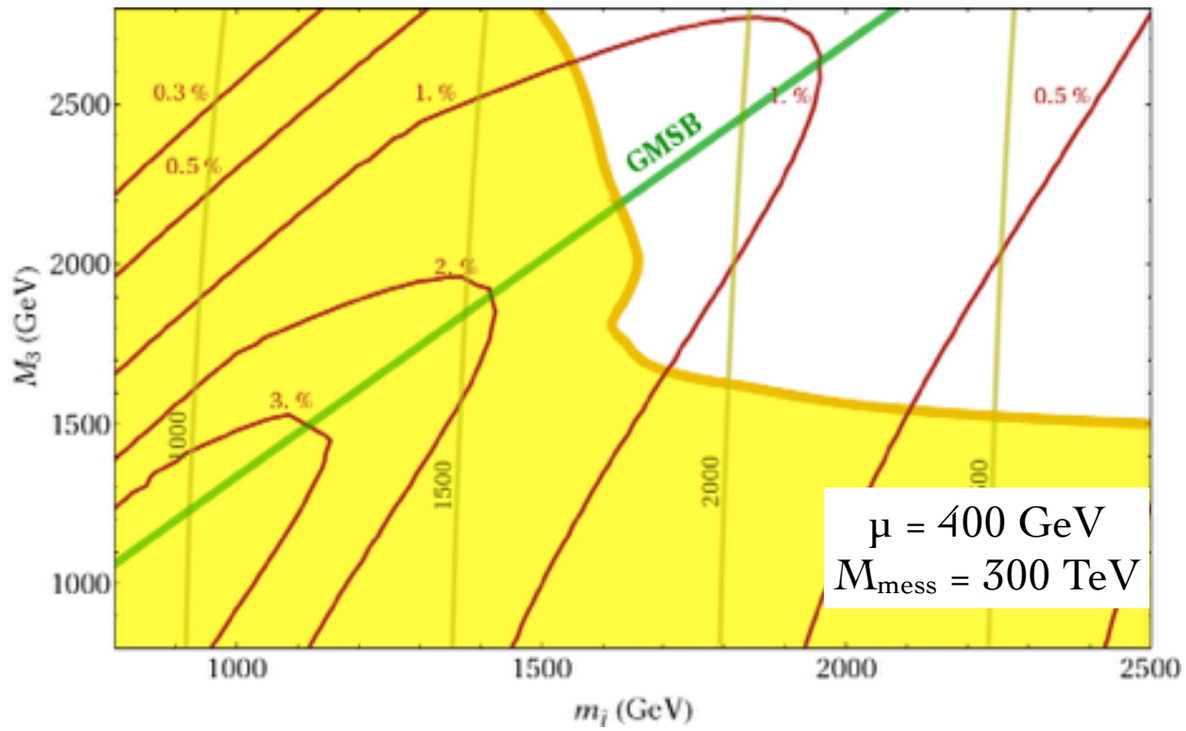
The Status of Naturalness in SUSY

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

MSSM with A-terms



NMSSM
or any model that "fixes" the Higgs mass



- In the MSSM: Tuning more than 1%

- Natural SUSY and RPV: Gluino bounds above a TeV imply significant tuning

Maximally Natural Theory

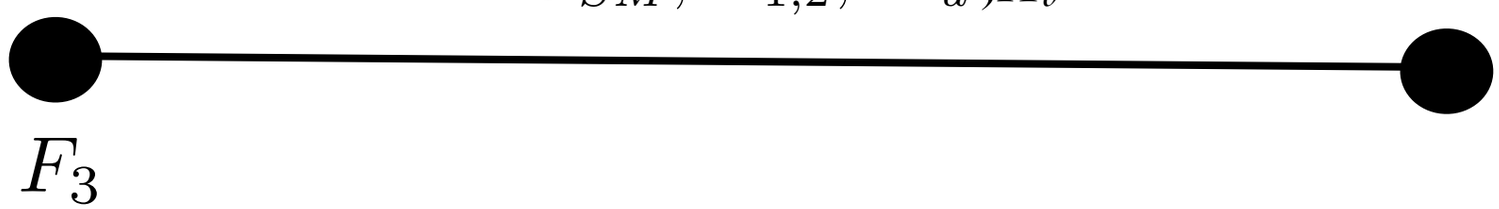
S.D., K. Howe, J. March-Russell 2014

Antoniadis, S.D., Pomarol, Quirros 1998

$4D\ N=1$ SUSY
orbifold brane

$5D$ SUSY
$G_{SM},\ F_{1,2},\ H_u\ ,H_\partial$

$4D\ N=1$ SUSY
orbifold brane



F_3

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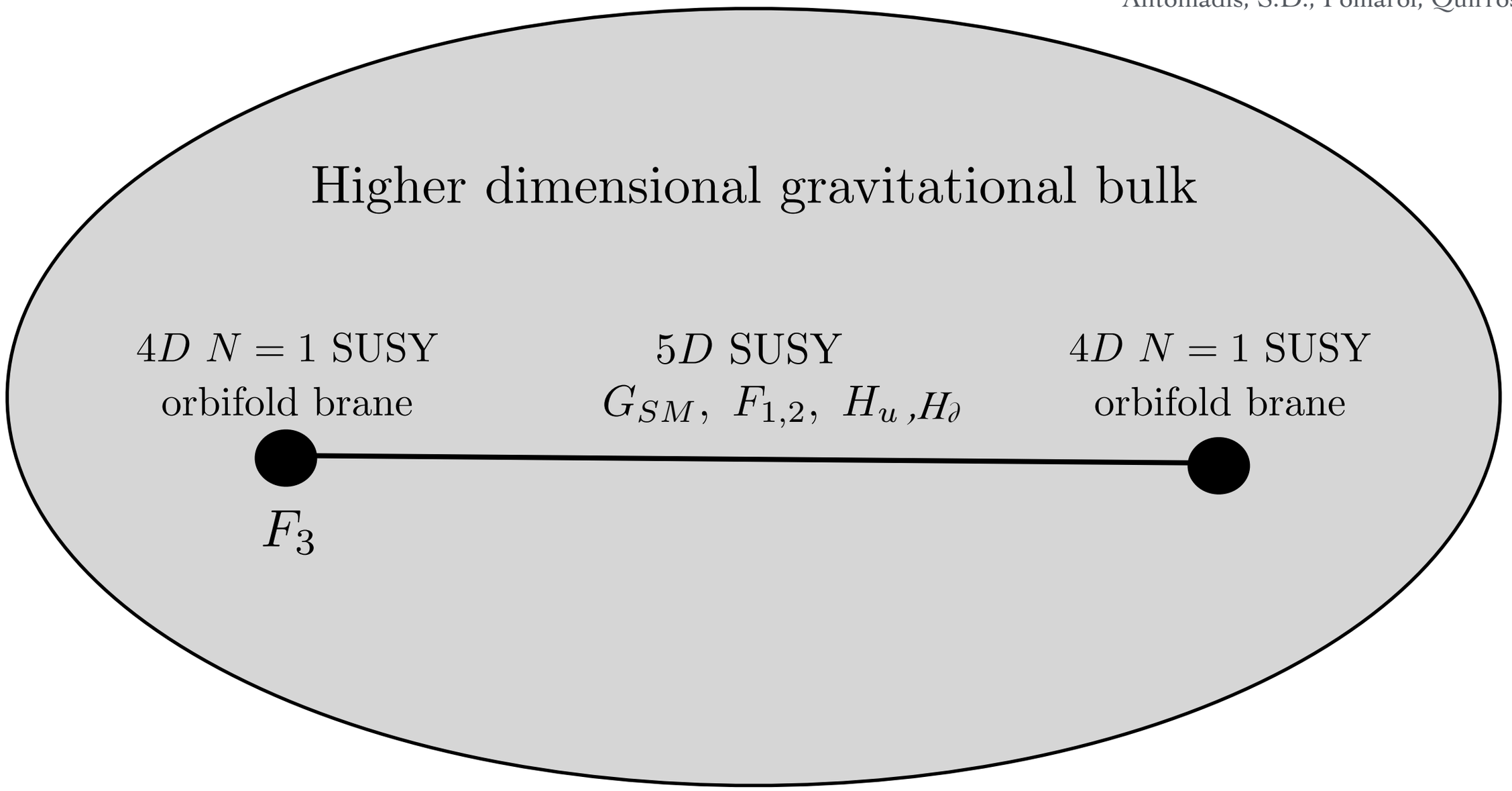
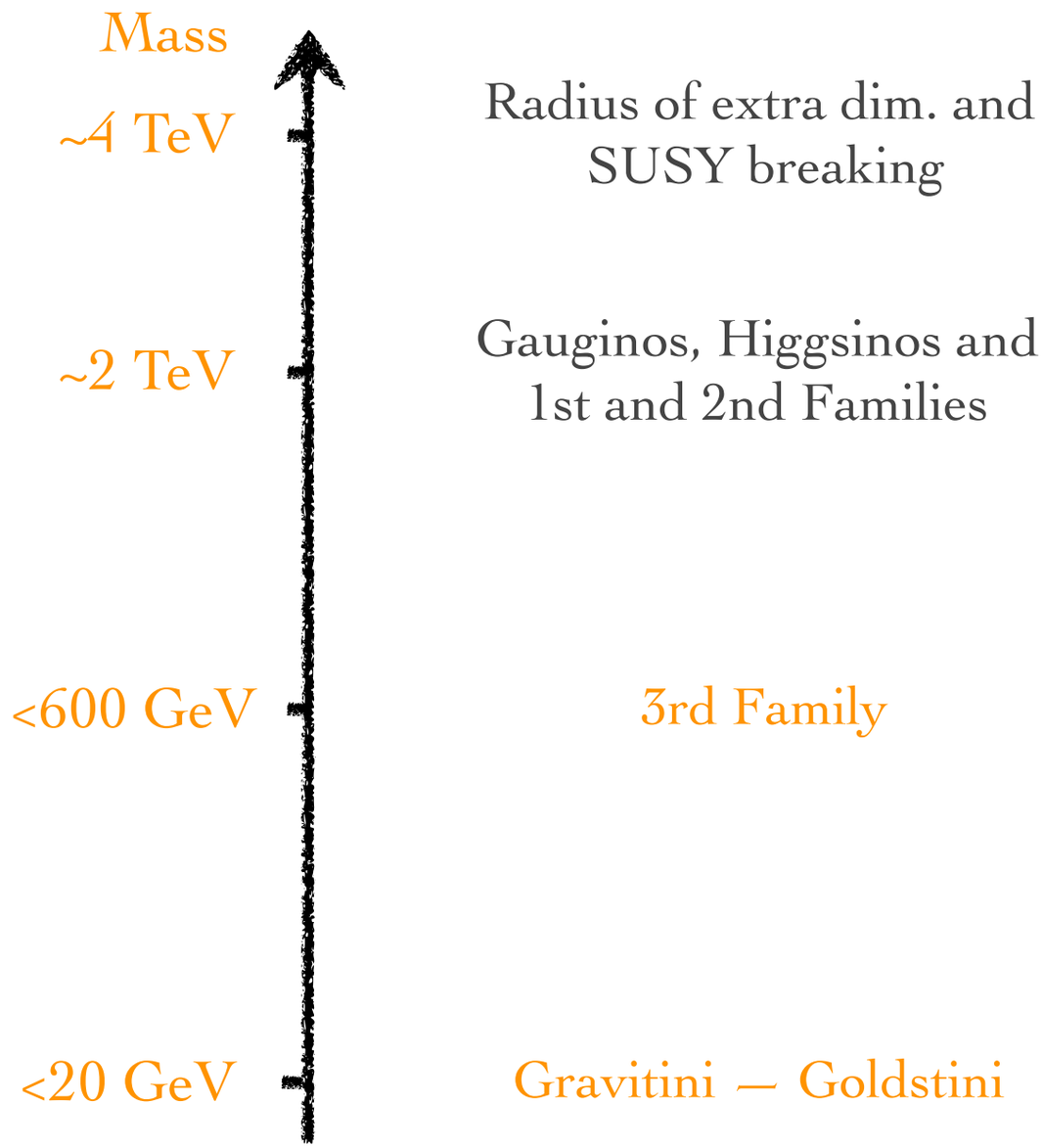


Multiple Protection

- SUSY
- TeV dimensions: Locality
- Natural SUSY (Split Families)
- Non-Local SUSY breaking: No Logs
- Dirac Gauginos and Higgsinos: No μ term

Bottom Line: Can be as 50% tuned!
Unification sacrificed for Naturalness

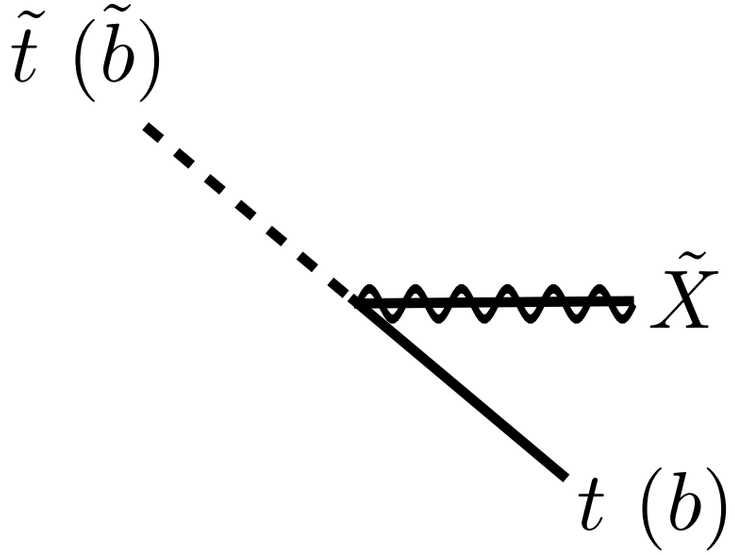
SS SUSY Breaking Spectrum



Experimental Signatures

- ‘Vanilla’ signature

  Stop decay to Goldstino



$$\tilde{t} \to t + \text{ MET}$$
$$m_{\tilde{t}} \gtrsim 700 \text{ GeV}$$

CMS SUS-13-004,-011
ATLAS-CONF-2013-024,-037

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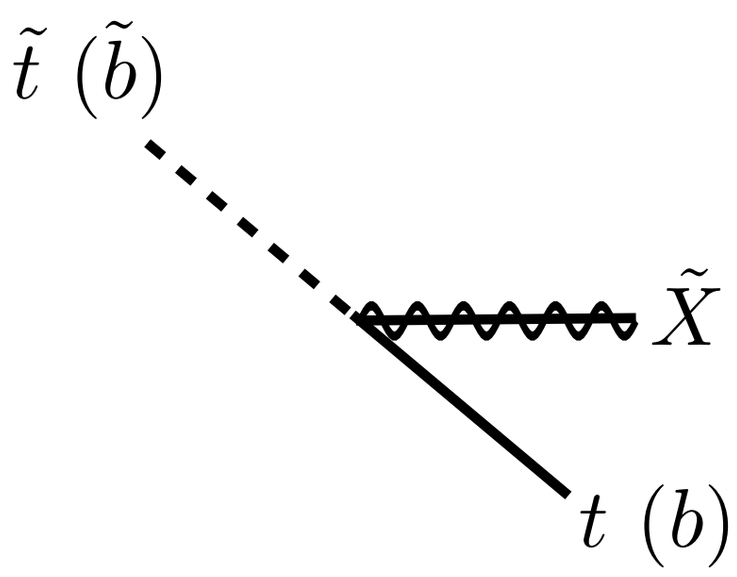
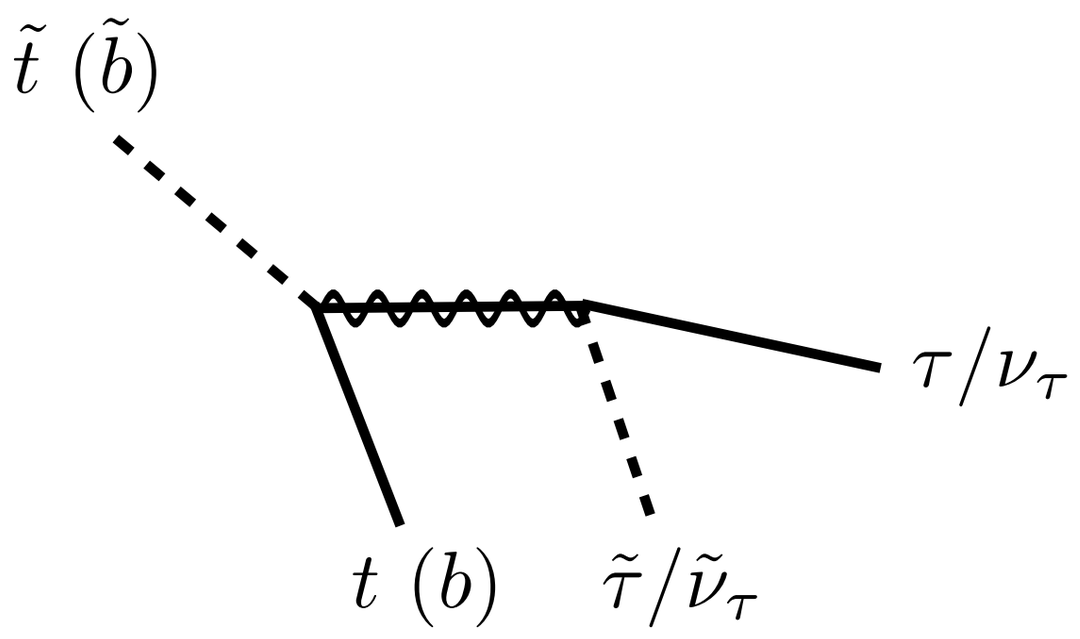


$\tilde{t} \to t +$ MET
$m_{\tilde{t}} \gtrsim 700$ GeV ✓

CMS SUS-13-004,-011
ATLAS-CONF-2013-024,-037

- 3-body off-shell

  Stop decay to
  possibly long-lived stau NLSP

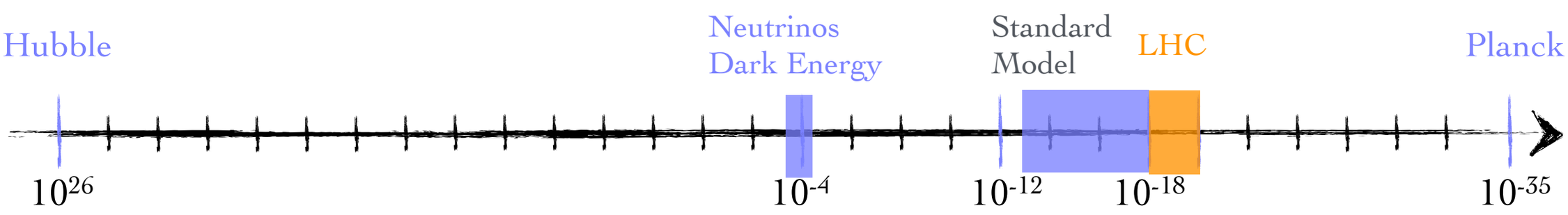


$\tilde{t}(\tilde{b}) \to b + (1\tau, 2\tau) +$ MET
$m_{\tilde{t}} \gtrsim 450$ GeV ✓

(gmsb motivated ATLAS-CONF-2014-014)

$\tilde{t}(\tilde{b}) \to t + (1\tau, 2\tau) +$ MET ✗

Big Answers From Small Experiments



80% of the energy scale left to explore

Dark Matter, Strong CP, String theory suggests there is more

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 $\epsilon F^{EM}_{\mu\nu} F^{\mu\nu'}$
  - Dilaton, moduli, new dimensions

How Do You Probe The Low Energy Frontier?

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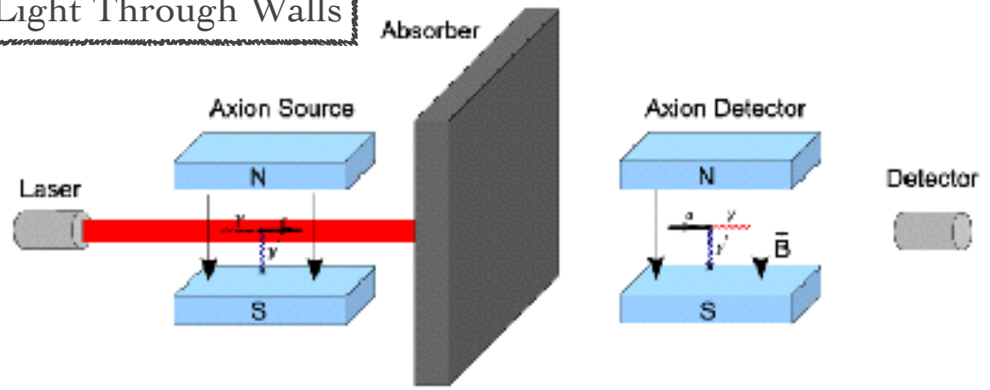
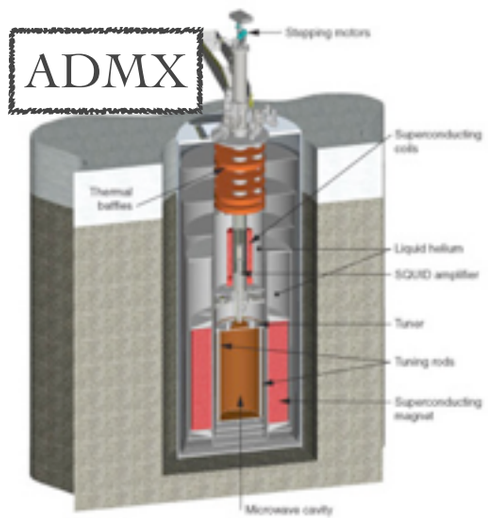
Light Through Walls



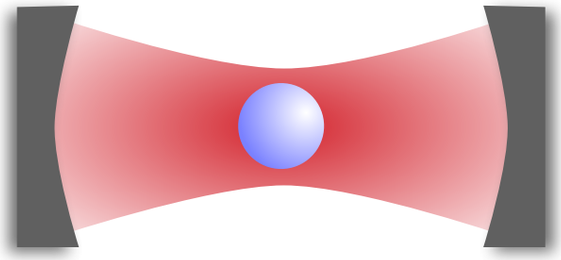
LIGO

ADMX



How Do You Probe The Low Energy Frontier?

Optically Levitated Objects



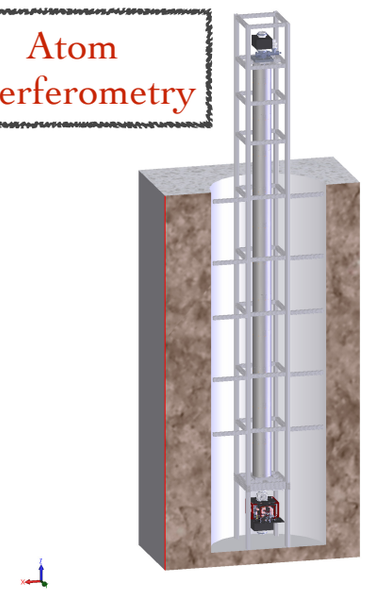
- Short Range Forces
- Gravitational Wave detection at high frequencies
- Tests of Quantum Mechanics

NMR

- Axion Field Detection

LIGO

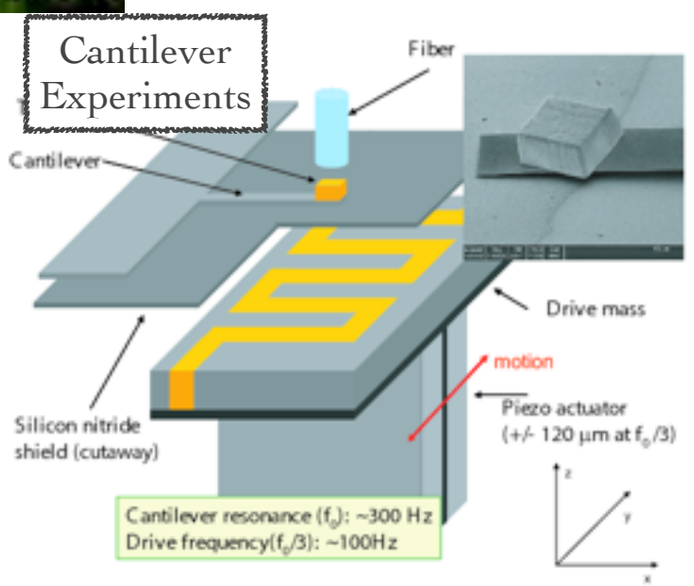
Atom Interferometry



- 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



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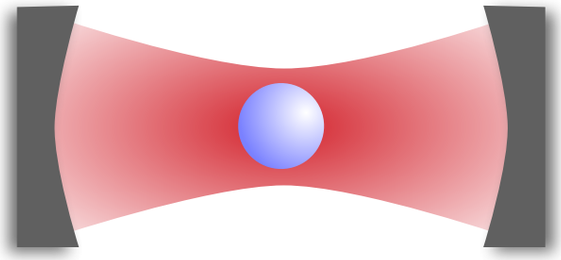

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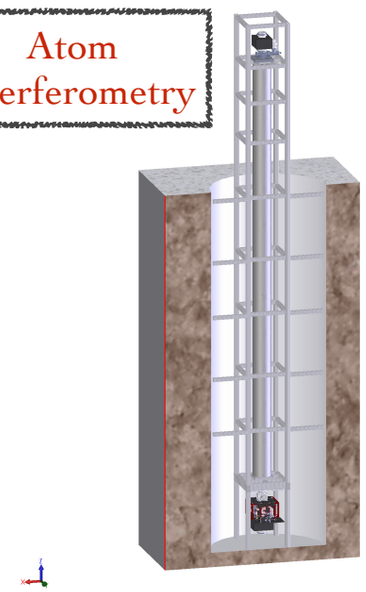

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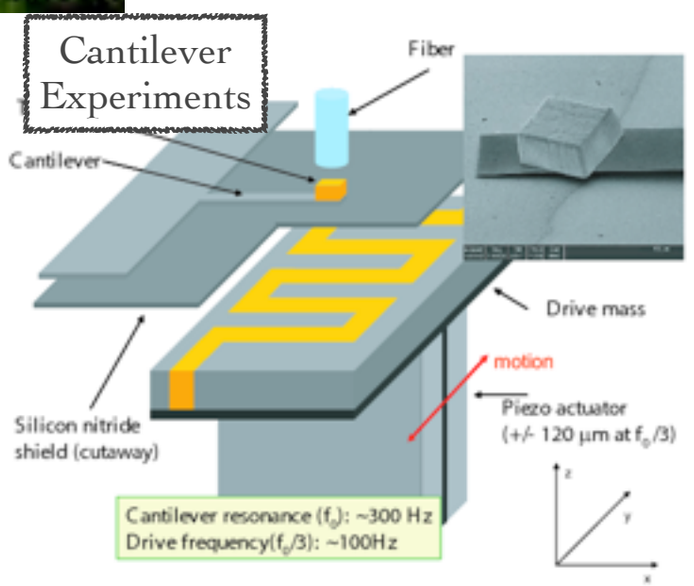
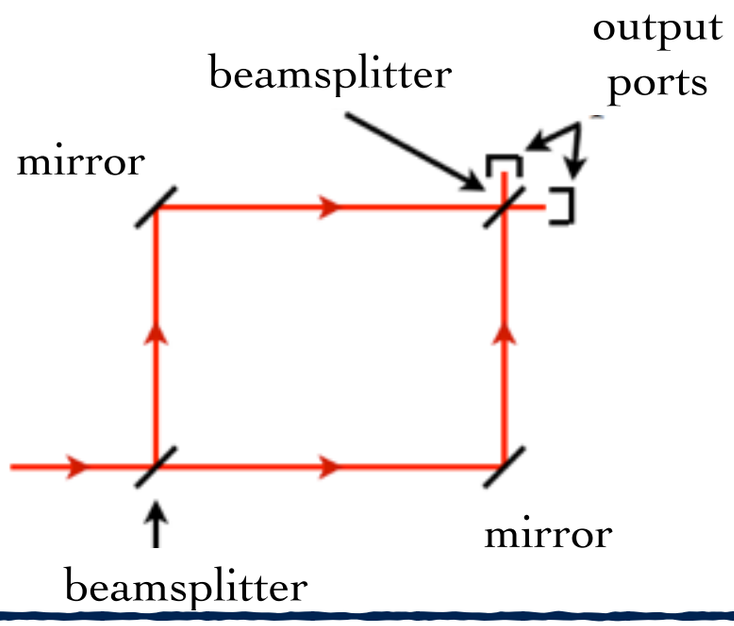


Light vs Atom Interferometry

Light



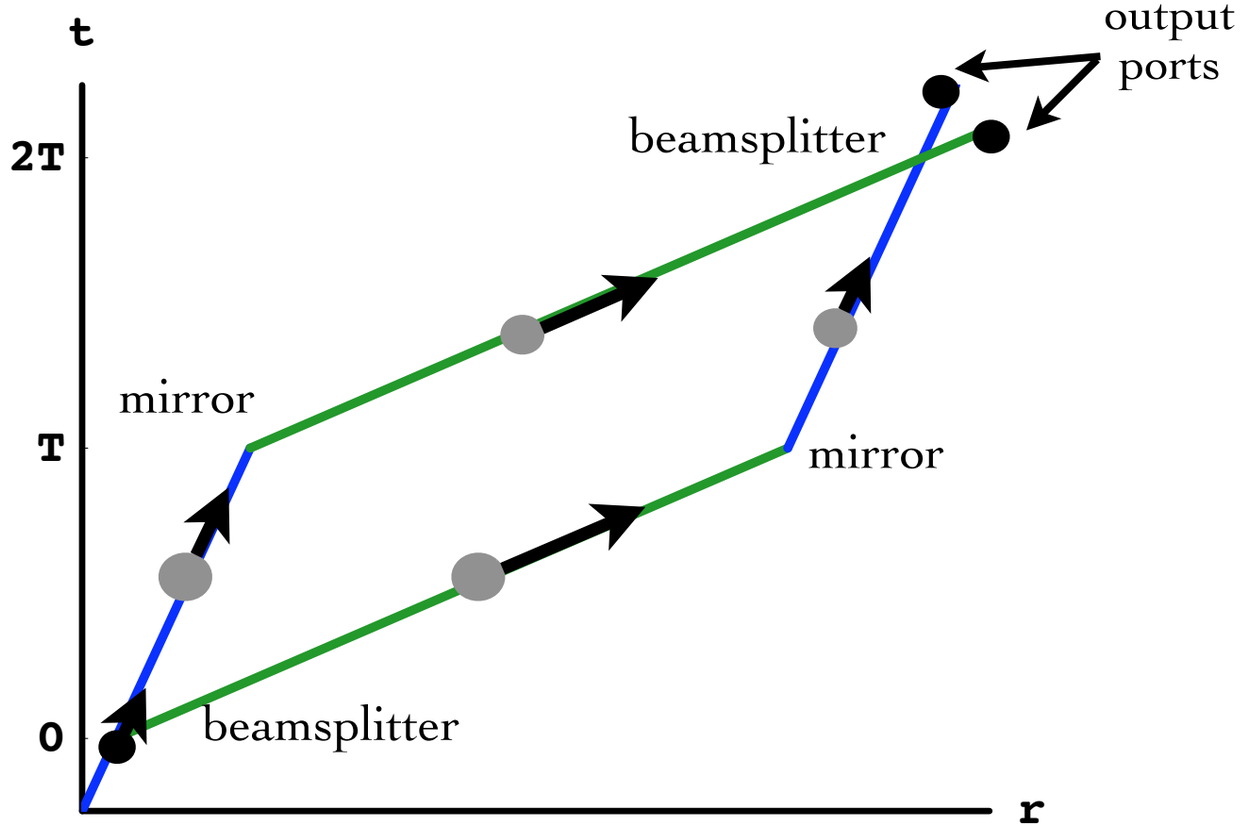
accuracy of measurement

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

Atoms

For atoms T~ 1 sec

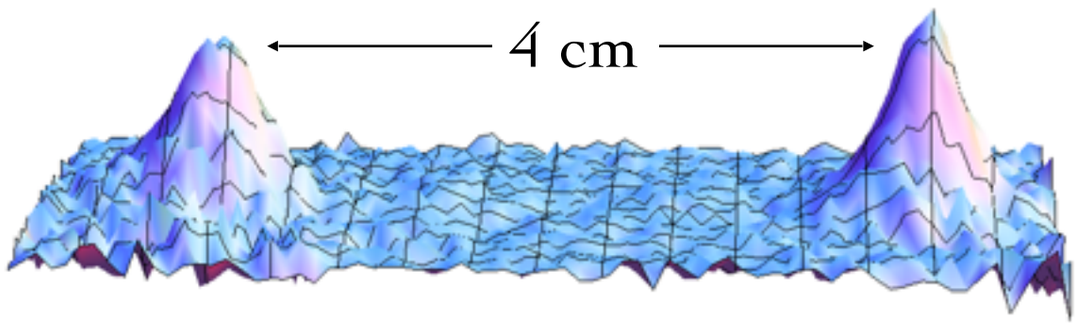
$\Rightarrow$ L= cT ~ Earth-Moon distance!

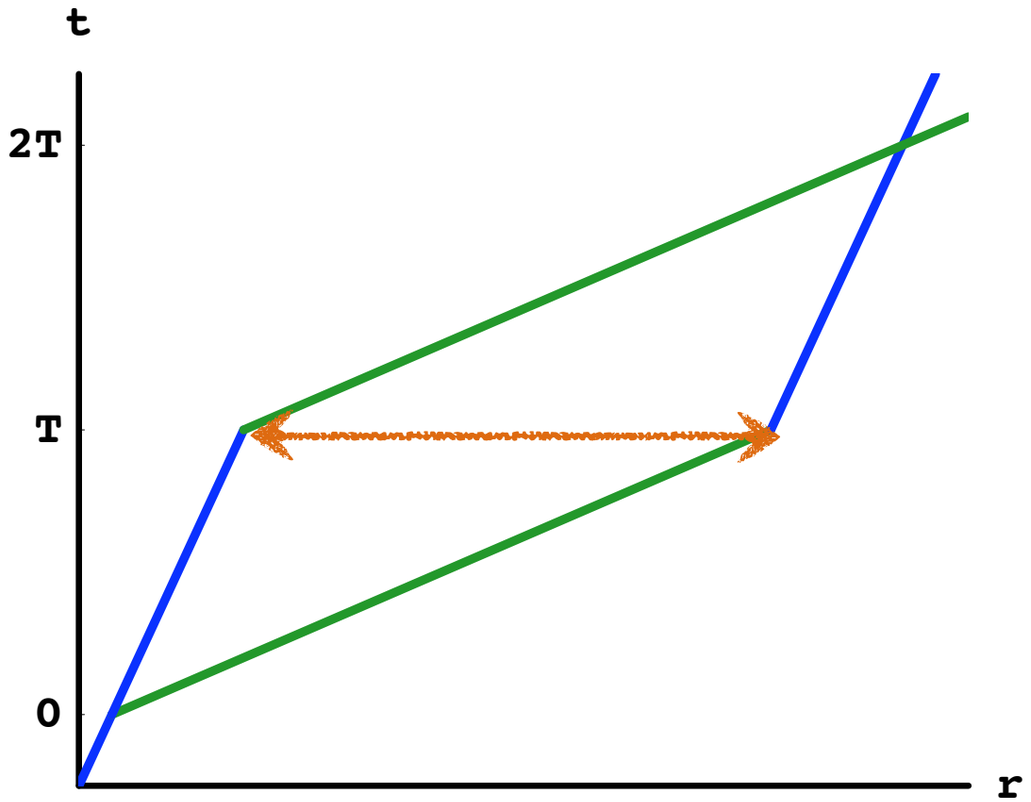


10 m Atom Interferometer (2013)

Hogan, Kasevich et. al.

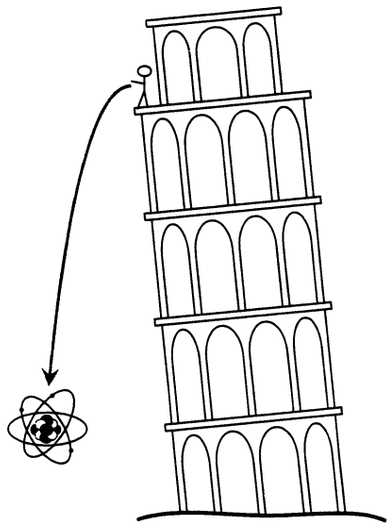
Maximum Wavepacket Separation





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

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

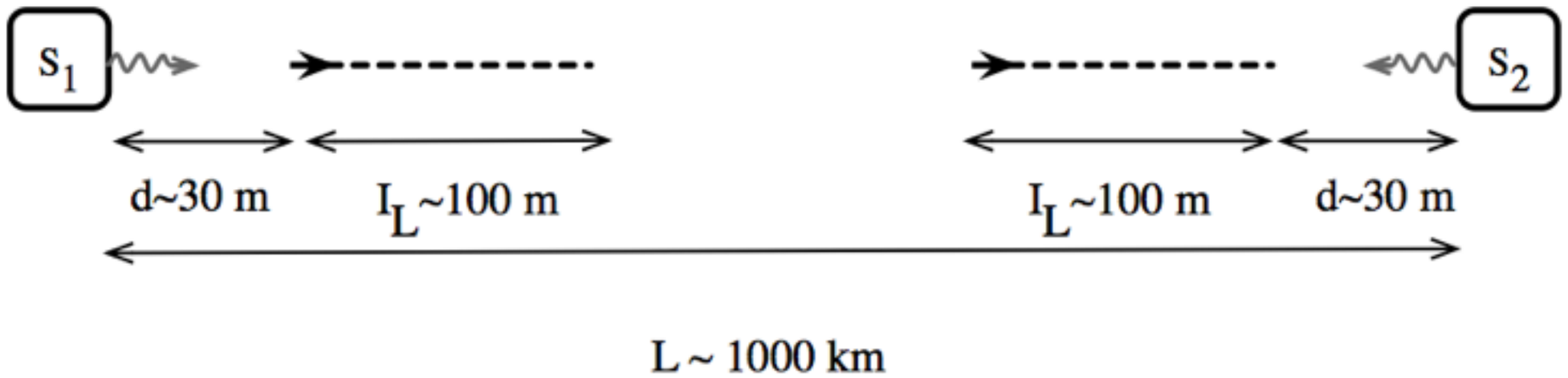
Newton's Gravity

Gravity Gravitates

Kinetic Energy Gravitates

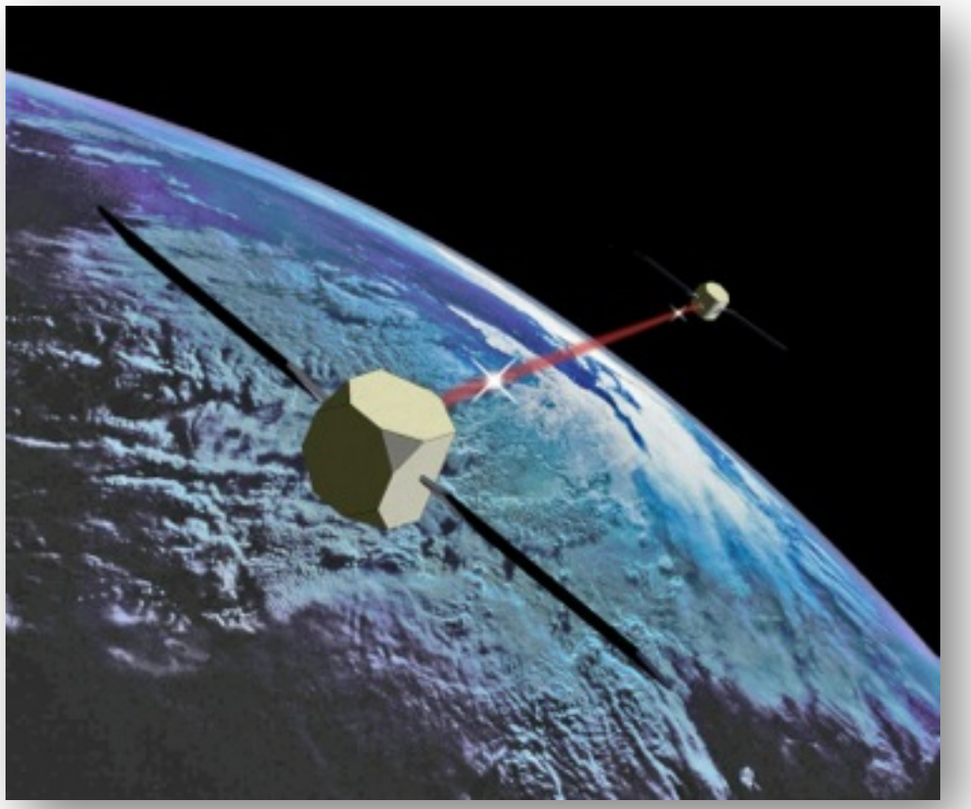
Gravitational Wave Detection with Atom Interferometry

SD, Graham, Hogan, Kasevich, Rajendran 2008



Physical Distances between atoms oscillate with the GW amplitude:

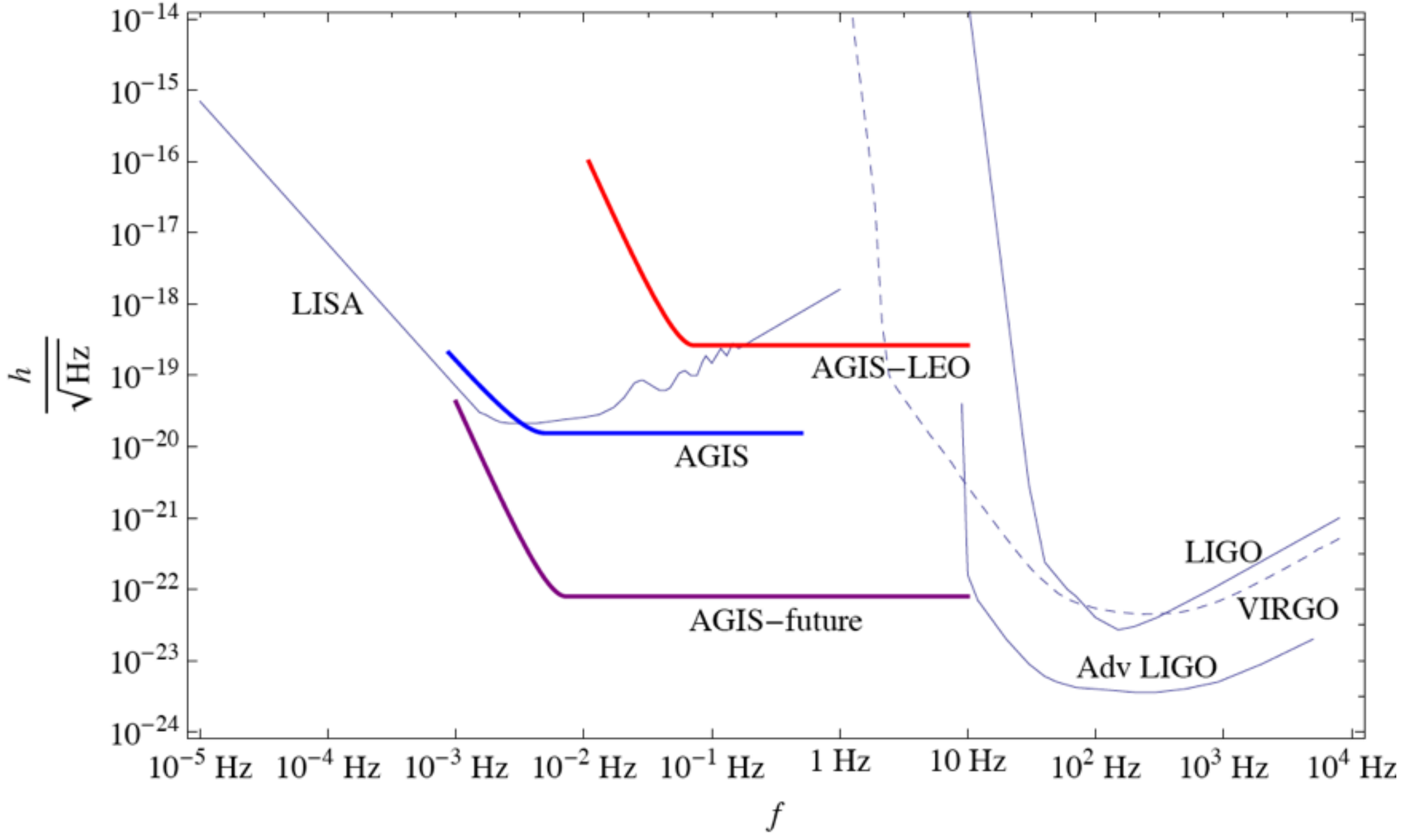
$L = L_o(1 + h \cos(\omega t))$



- Currently funded by NASA NIAC grant (NASA Innovative Advanced Concepts)

- MIGA - Philip Bouyer: Ground based GW detector in Bordeaux

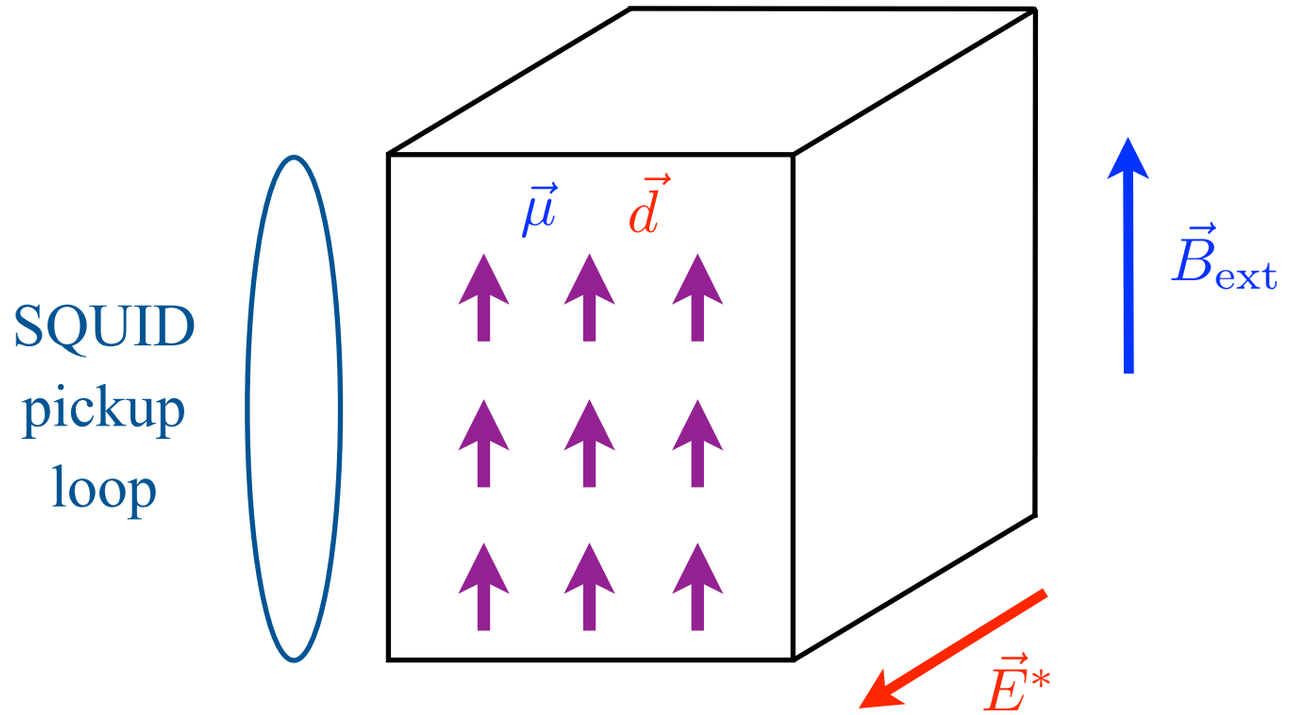
Projected Sensitivity in Space



AGIS: 1000 km
LISA: 5000000 km

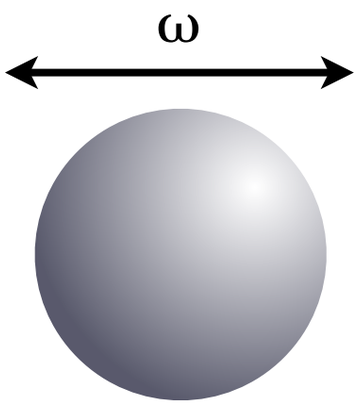
Precision Magnetometry

Nuclear Magnetic Resonance

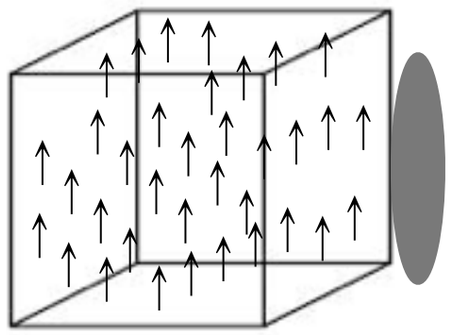


Cosmic Axion Detection

Budker, Graham, Rajendran, et. al.



Oscillating Source Mass



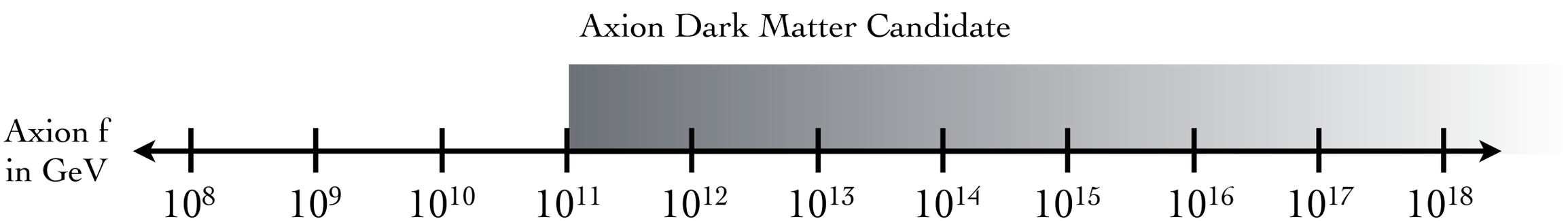
NMR

SQUID

Short-range axion exchange

Arvanitaki and Geraci

Reach of New QCD Axion Detection Ideas



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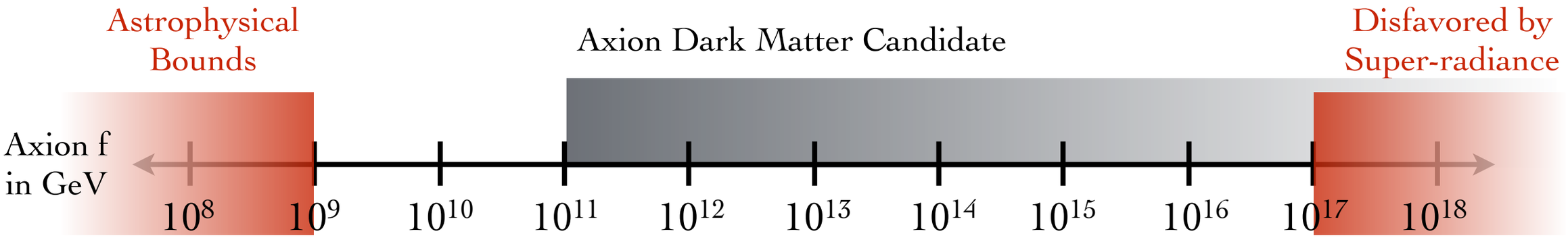

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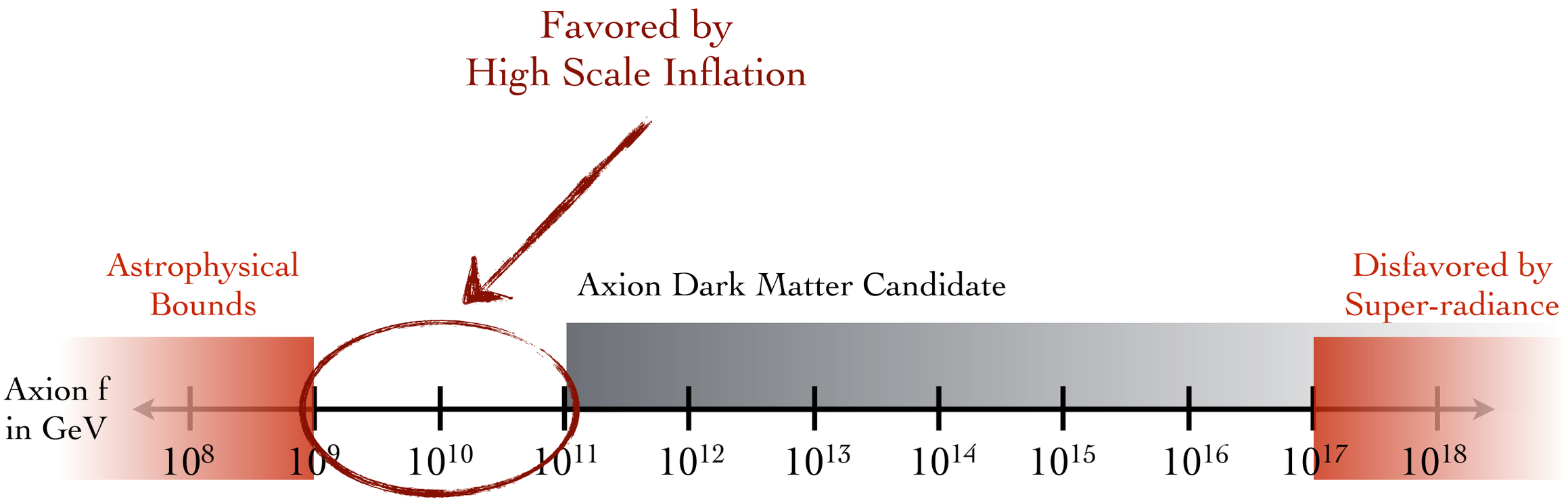

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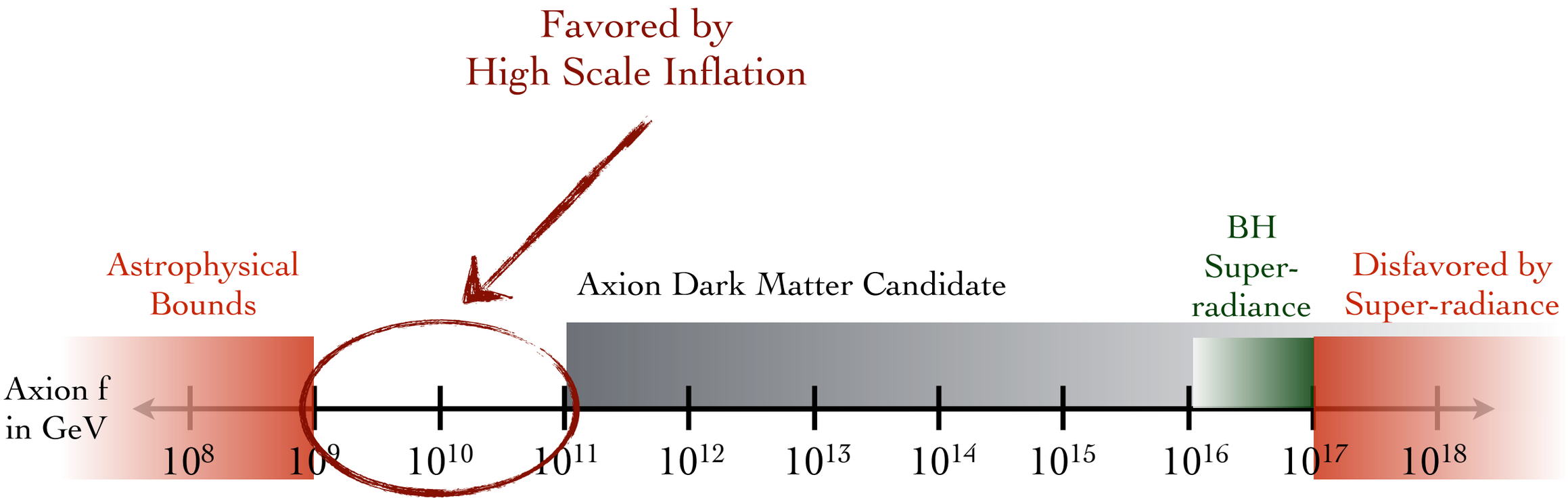

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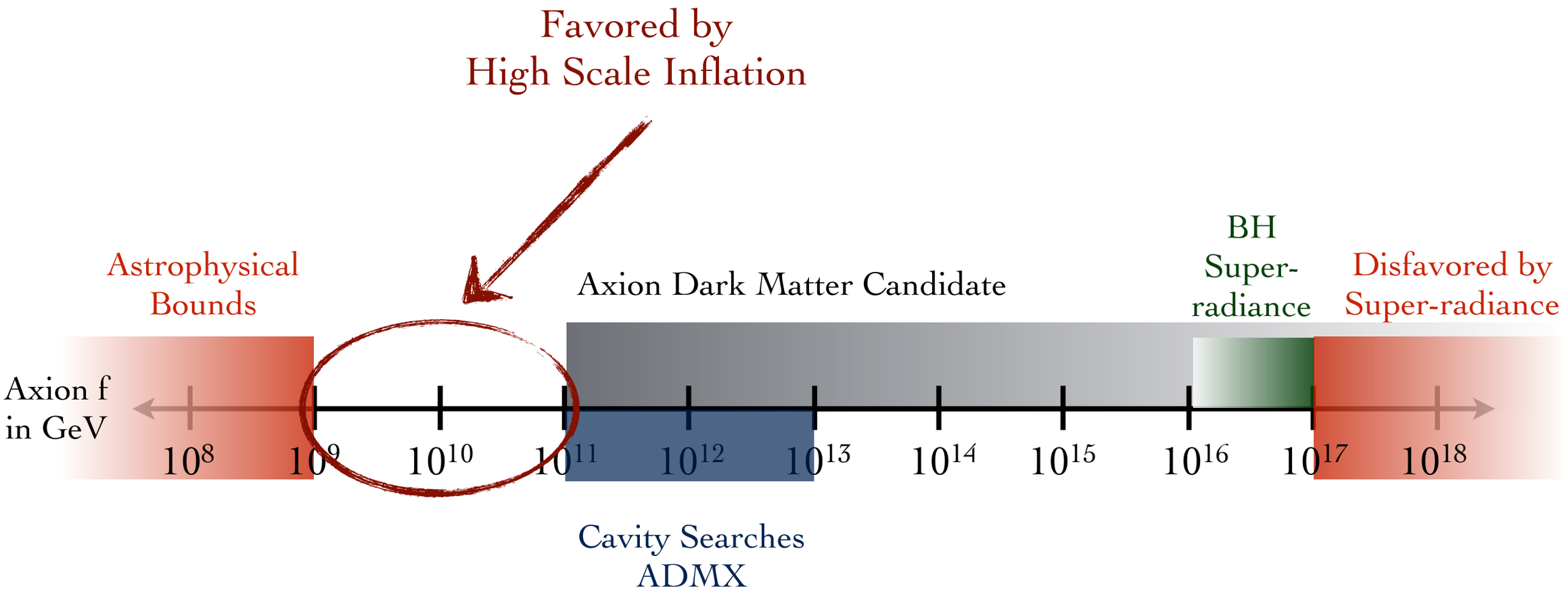

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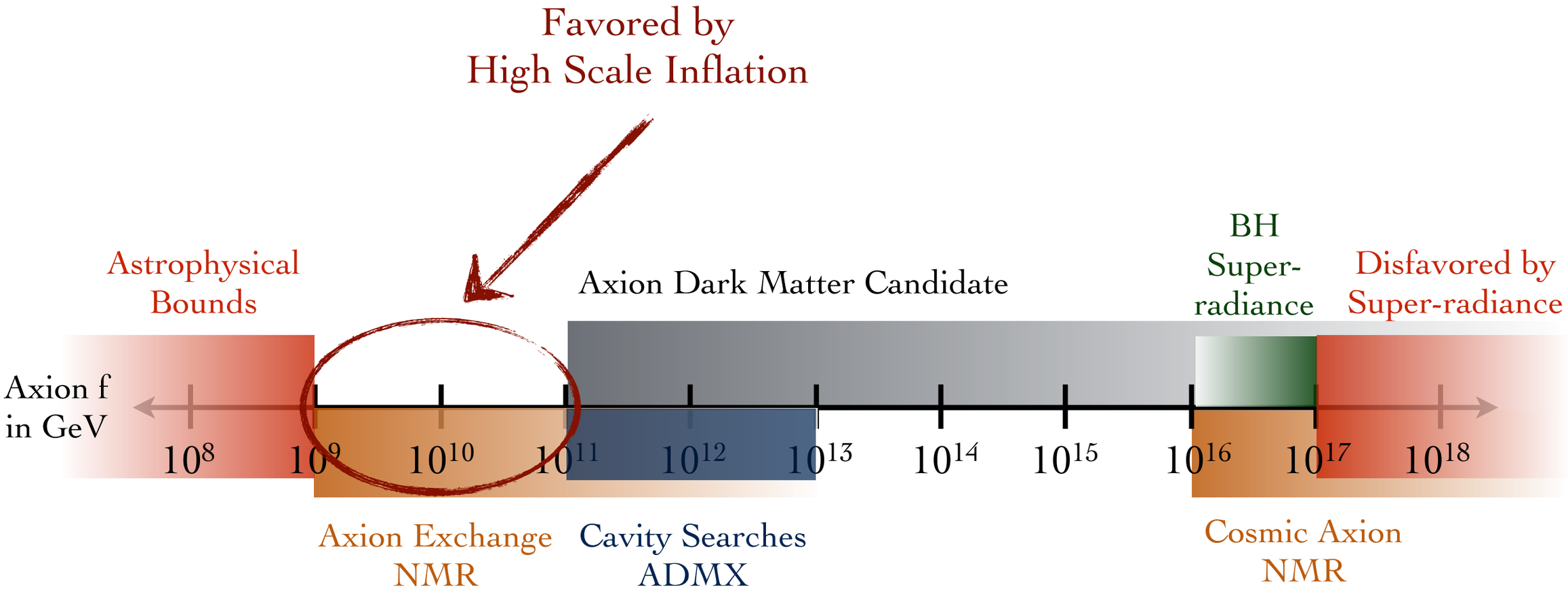
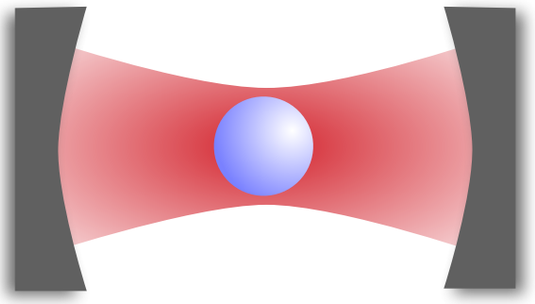
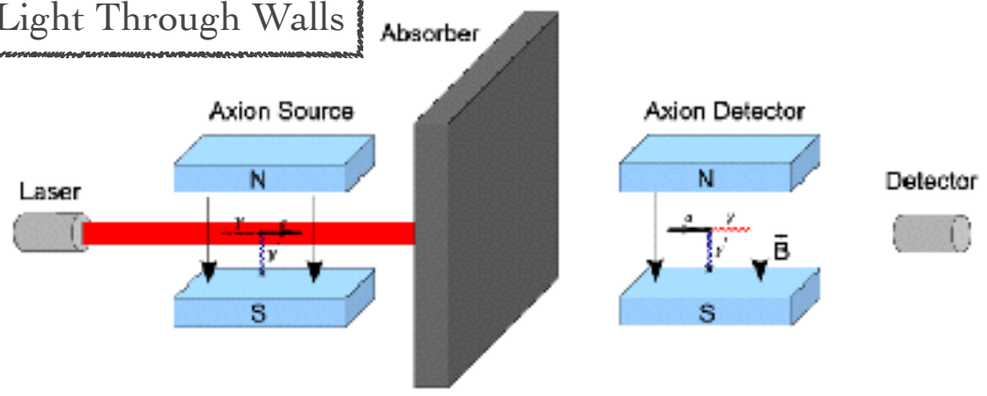


Scattered Experiments

Optically Levitated Objects

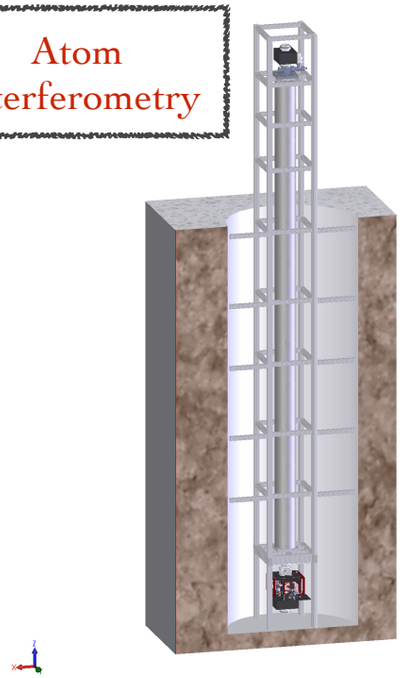


Light Through Walls

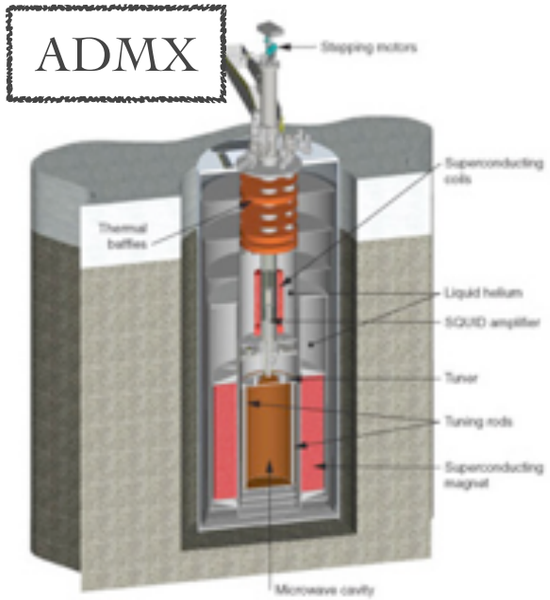


NMR

Atom Interferometry



ADMX



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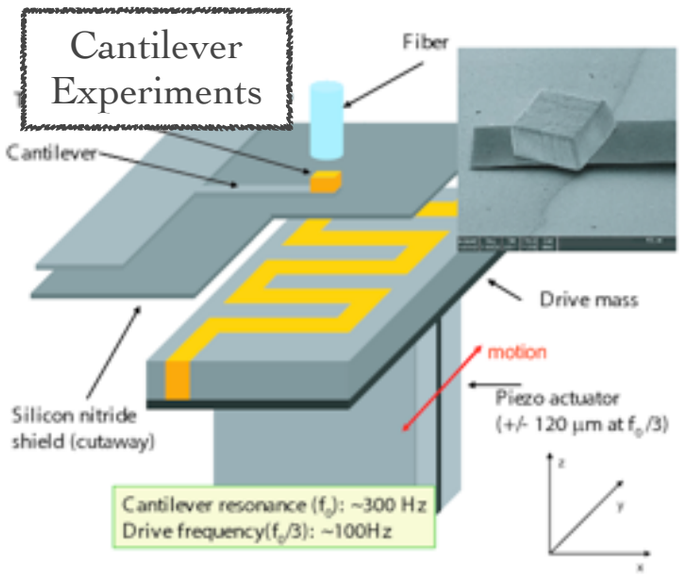

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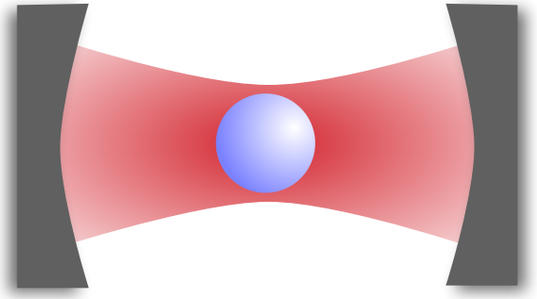

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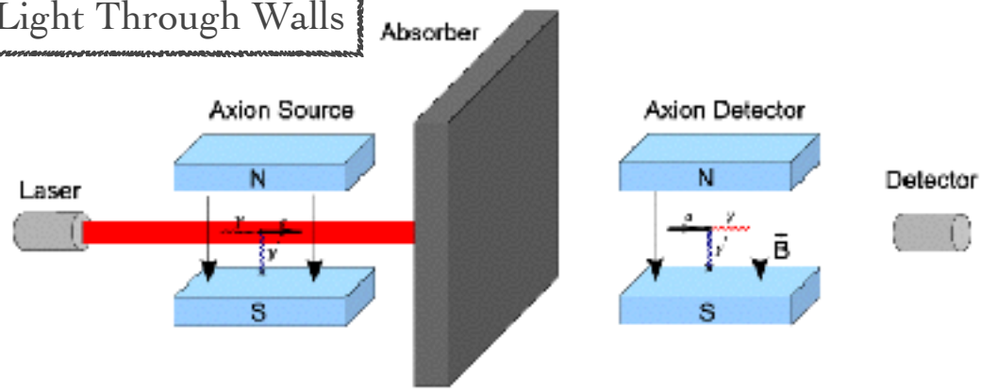
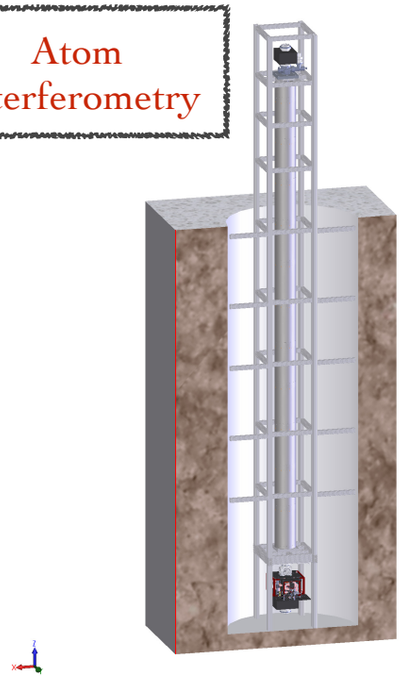
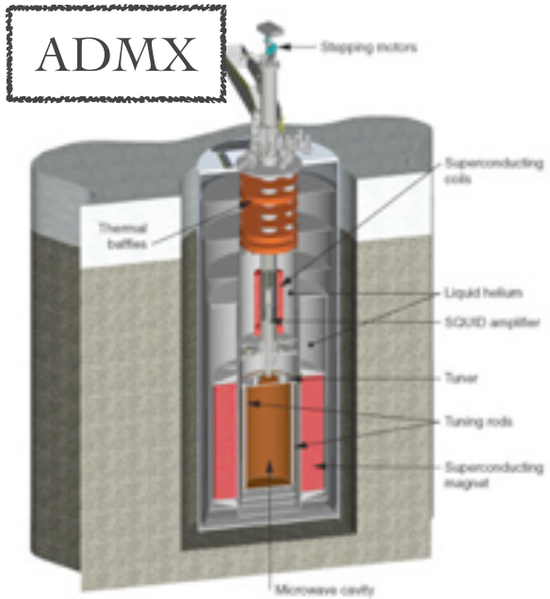


NMR

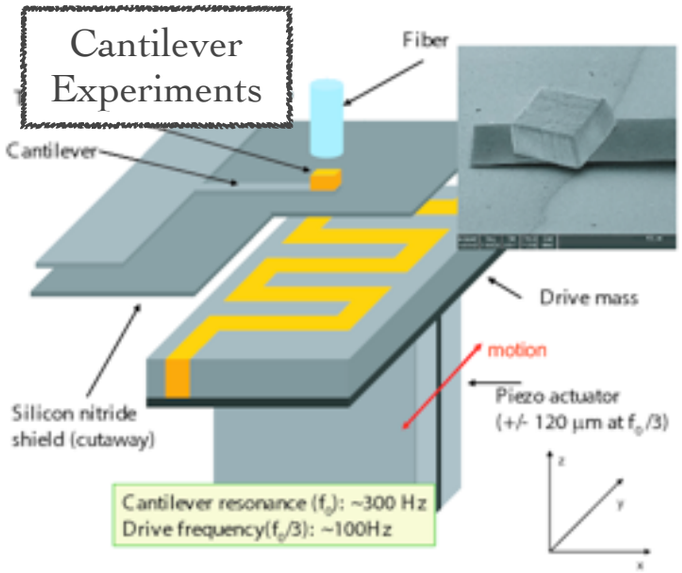
Atom Interferometry



ADMX



Cantilever Experiments



Scattered Experiments

Do They Need a Home?

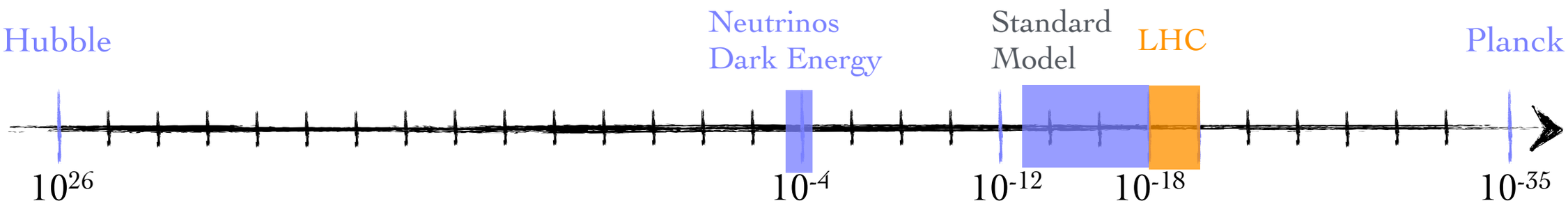
Super-Lab for Fundamental Physics?

- Super-Lab: 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

Super-Lab for Fundamental Physics?

- Opportunity for Physics
  - Ideas' Incubator
  - Shared Lab Resources
- Sociological Opportunities
  - Private funding can have big impact
  - New vision for investing public resources

Length Scales in the Universe



Scale in m

There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy.
- Hamlet