# The Precision Frontier of Particle Physics

Peter Graham

Stanford

# Cosmic Axion Spin Precession Experiment (CASPEr)

with

Dmitry Budker
Micah Ledbetter
Surjeet Rajendran
Alex Sushkov

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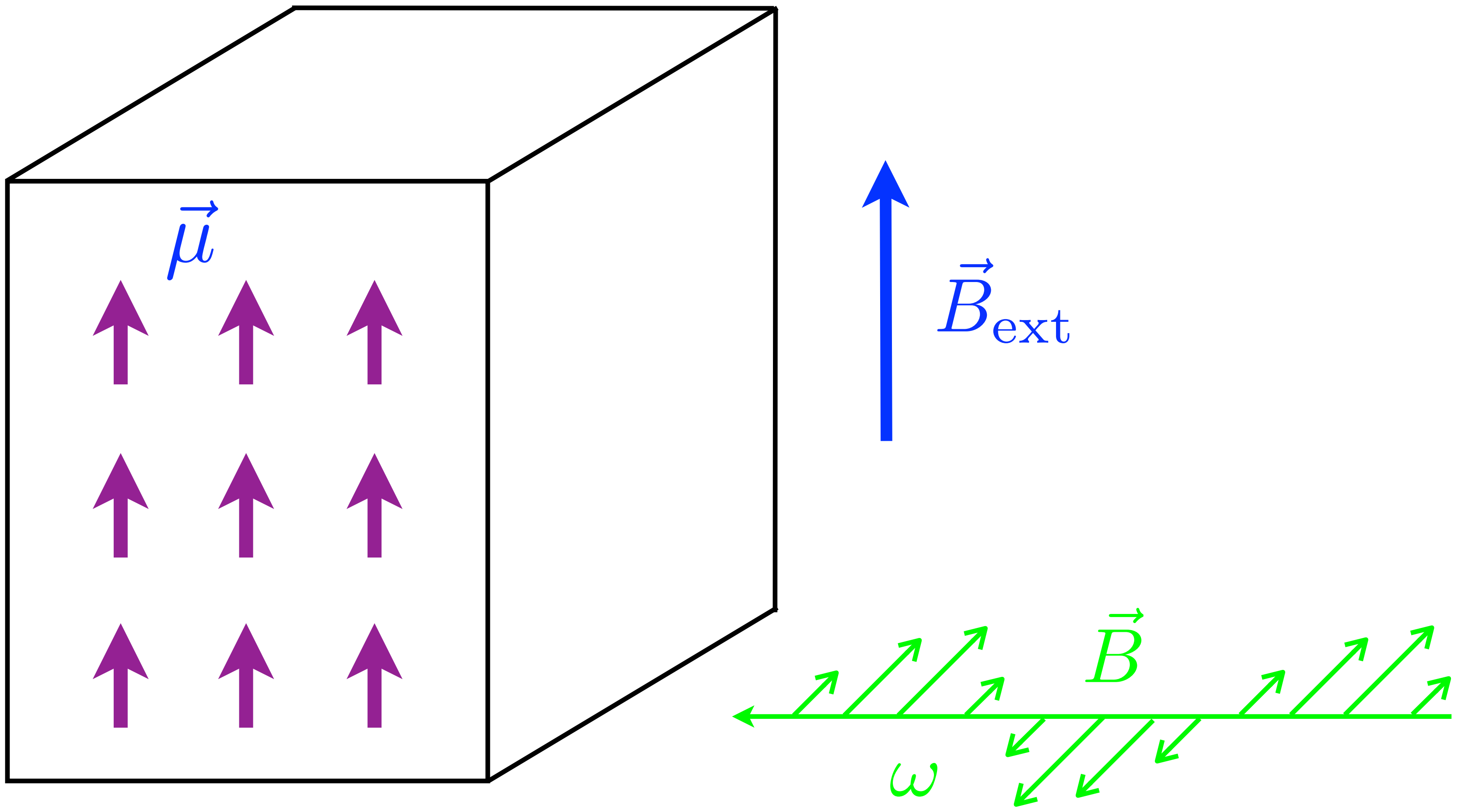
DFG Deutsche Forschungsgemeinschaft

PRX **4** (2014) arXiv:1306.6089
PRD **88** (2013) arXiv:1306.6088
PRD **84** (2011) arXiv:1101.2691

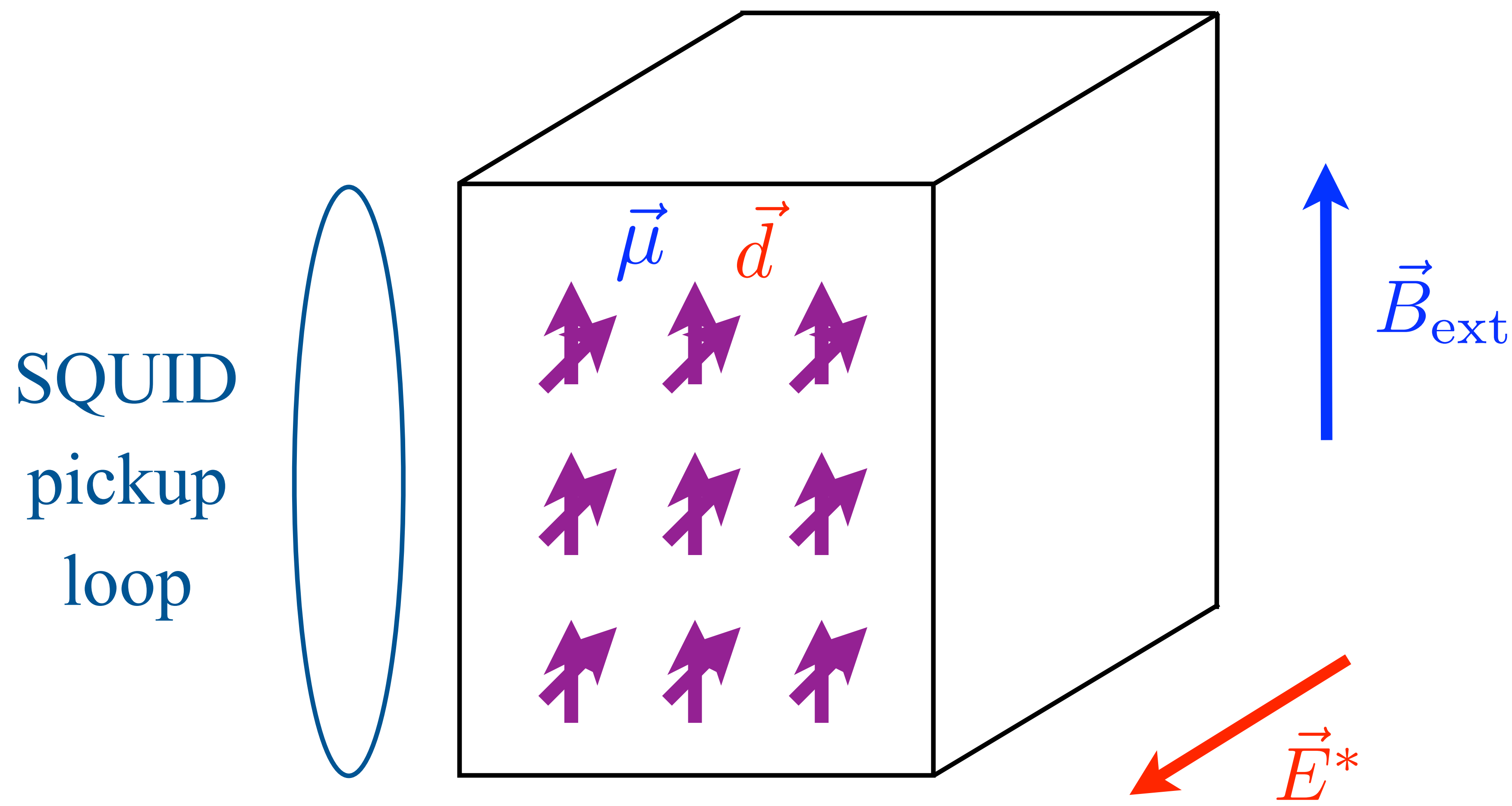
# Axions with NMR




NMR resonant spin flip when Larmor frequency $2\mu B_{\rm ext} = \omega$

# Cosmic Axion Spin Precession Experiment (CASPEr)

NMR techniques + high precision magnetometry




Larmor frequency = axion mass ➔ resonant enhancement

SQUID measures resulting transverse magnetization

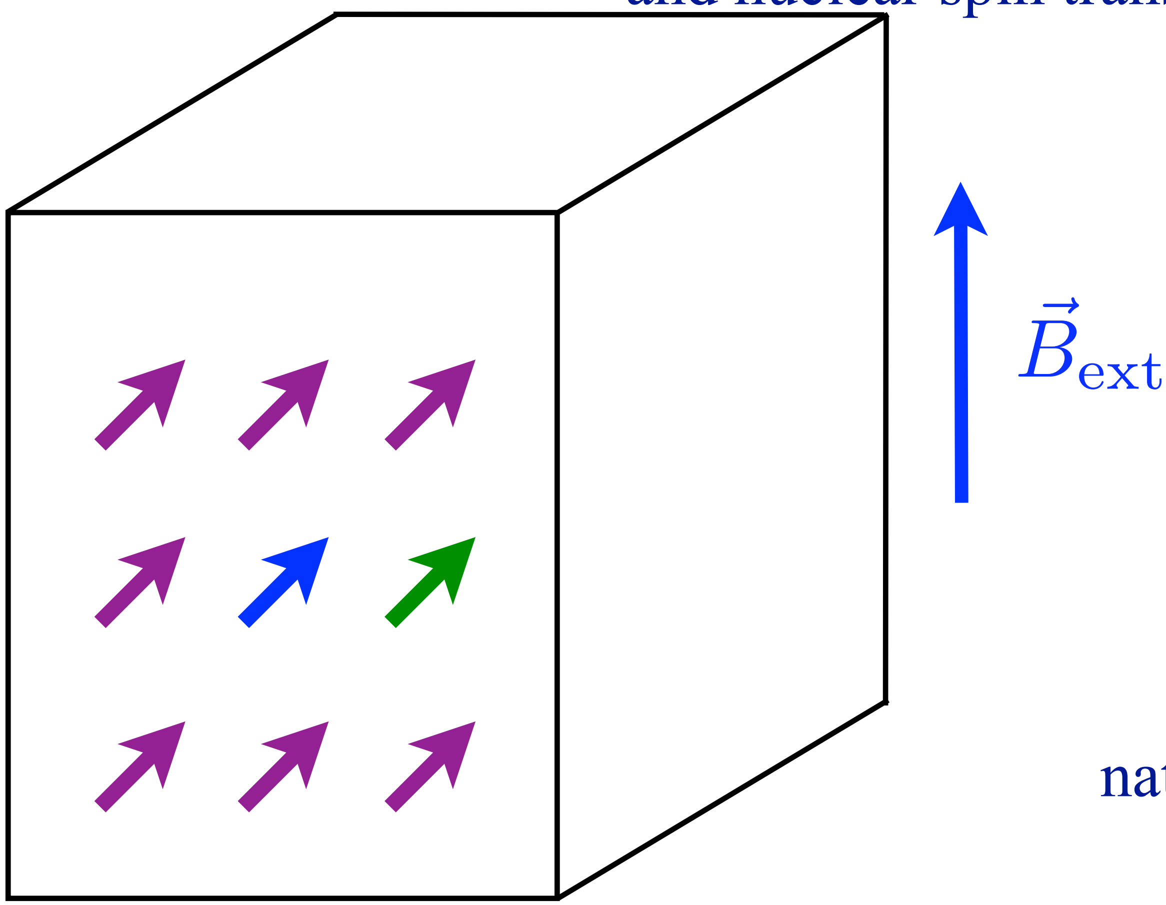
# Resonant Enhancement

resonance ➜ scan over axion masses by changing $B_{ext}$

magnetization signal increases linearly in time (axion periods)

resonant enhancement limited by axion coherence time $\tau_a \sim \frac{2\pi}{m_a v^2}$

and nuclear spin transverse relaxation time $T_2$




local B-field inhomogeneities:

$$\vec{B}(\vec{r_1}) \neq \vec{B}(\vec{r_2})$$

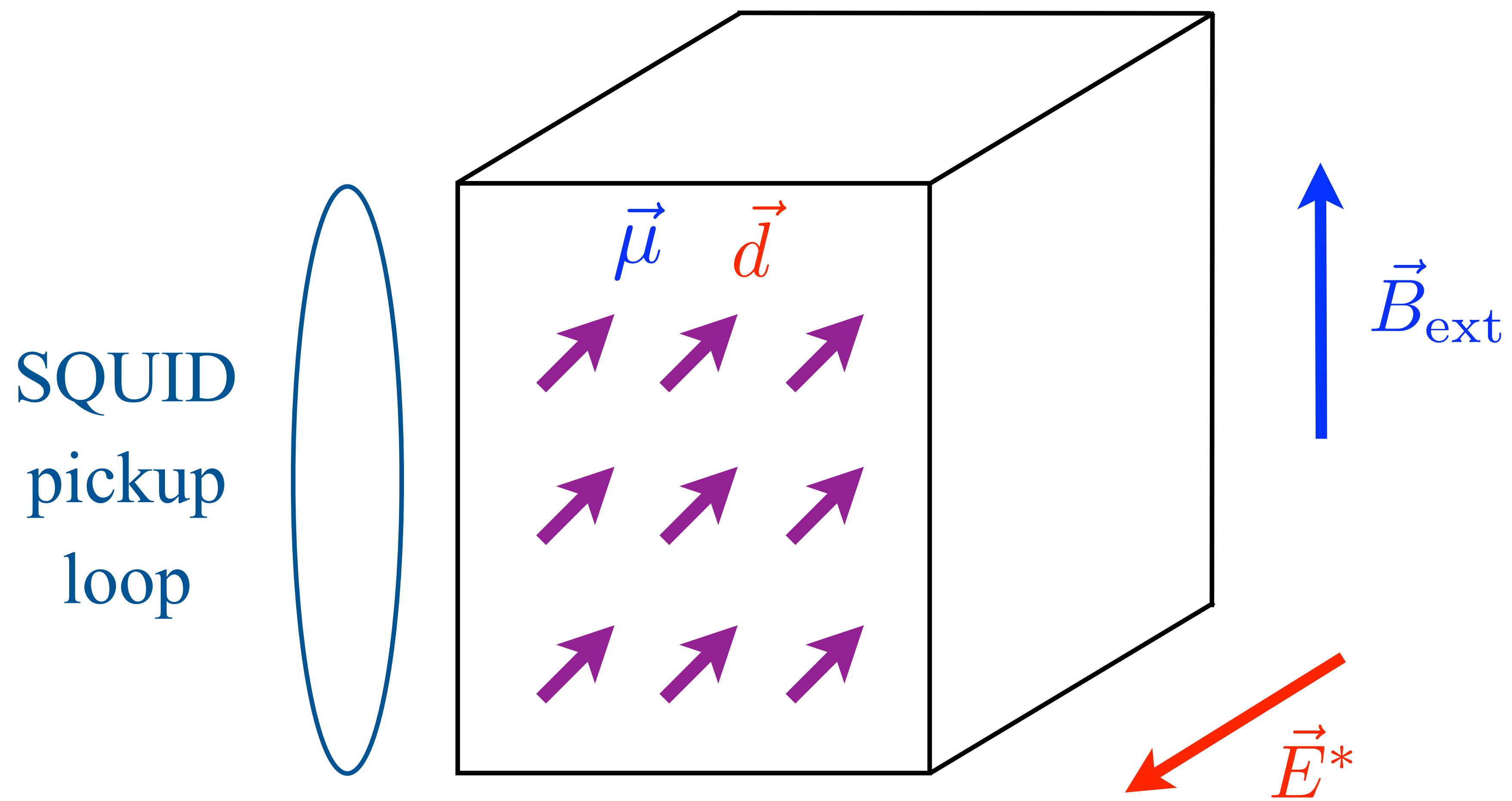
and spin-spin interactions source transverse spin dephasing

naturally: $T_2 \sim \left(\mu_N \left(\frac{\mu_N}{\mathring{A}^3}\right)\right)^{-1} \sim 1 \text{ ms}$

designed NMR pulse sequences can improve (dynamic decoupling)
demonstrated $T_2$ = 1300 s in Xe

# Cosmic Axion Spin Precession Experiment (CASPEr)

NMR techniques + high precision magnetometry



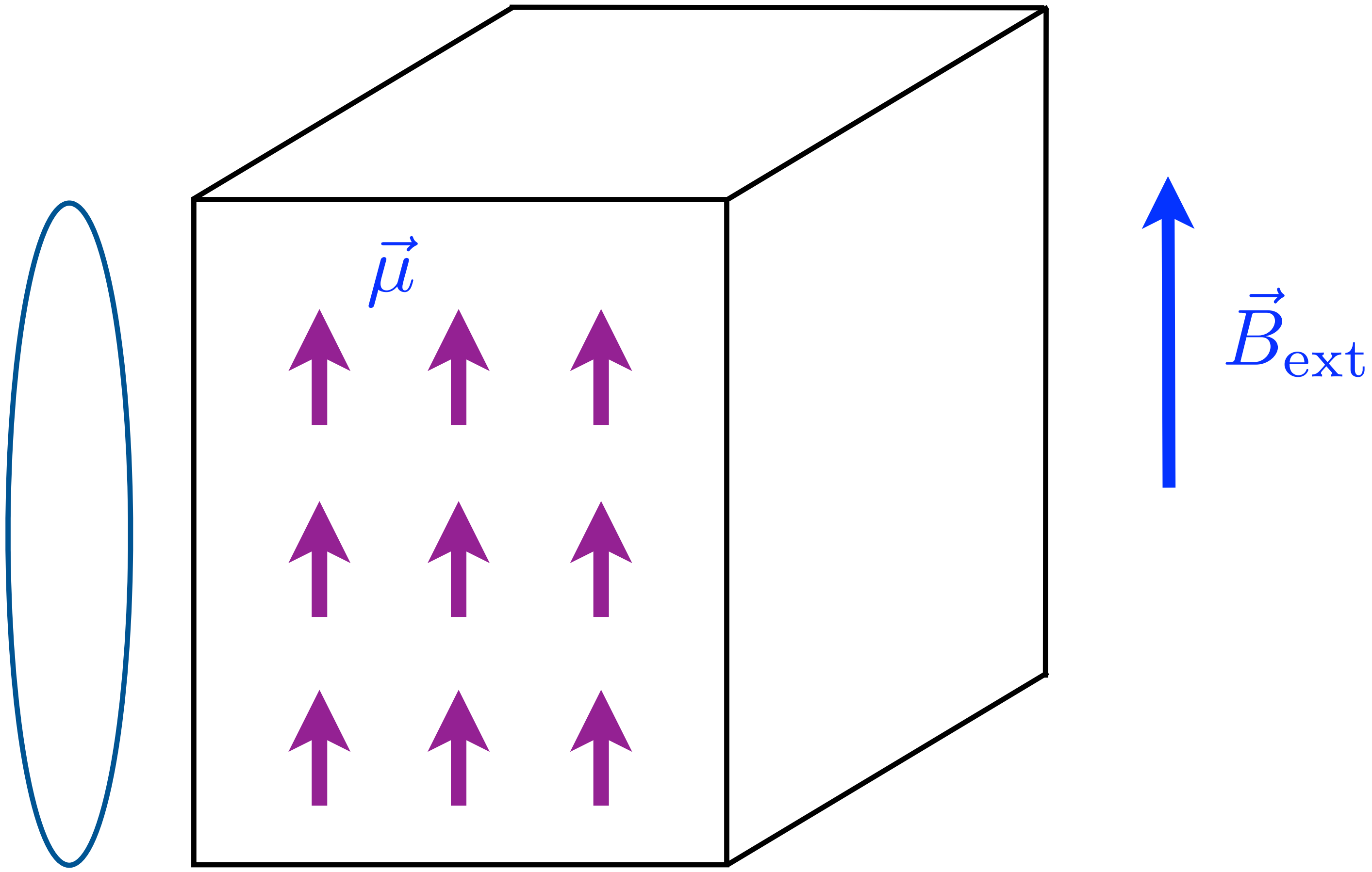

ferroelectric (e.g. $PbTiO_3$) for large E*

NMR pulse sequences (spin-echo,…) for longer $T_2$

NMR techniques for high polarization fraction

quantum spin projection (magnetization) noise small enough

# Magnetization Noise




a material sample has magnetization noise

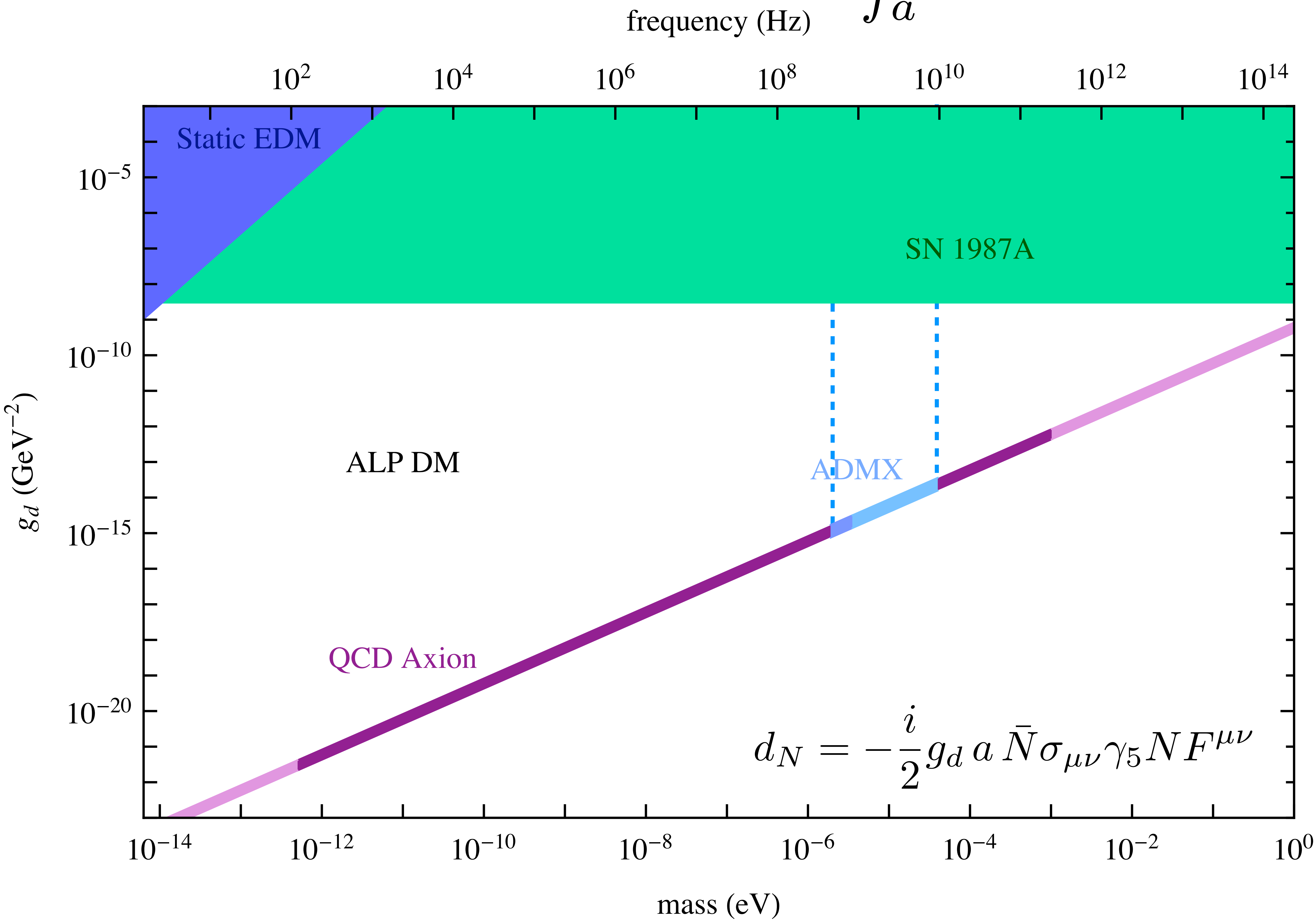
irreducible noise arises from quantum spin projection

every spin necessarily has random quantum projection onto transverse direction

Magnetization (quantum spin projection) noise: $$S(\omega) = \frac{1}{8}\left(\frac{T_2}{1 + T_2^2\left(\omega - 2\mu_N B\right)^2}\right)$$

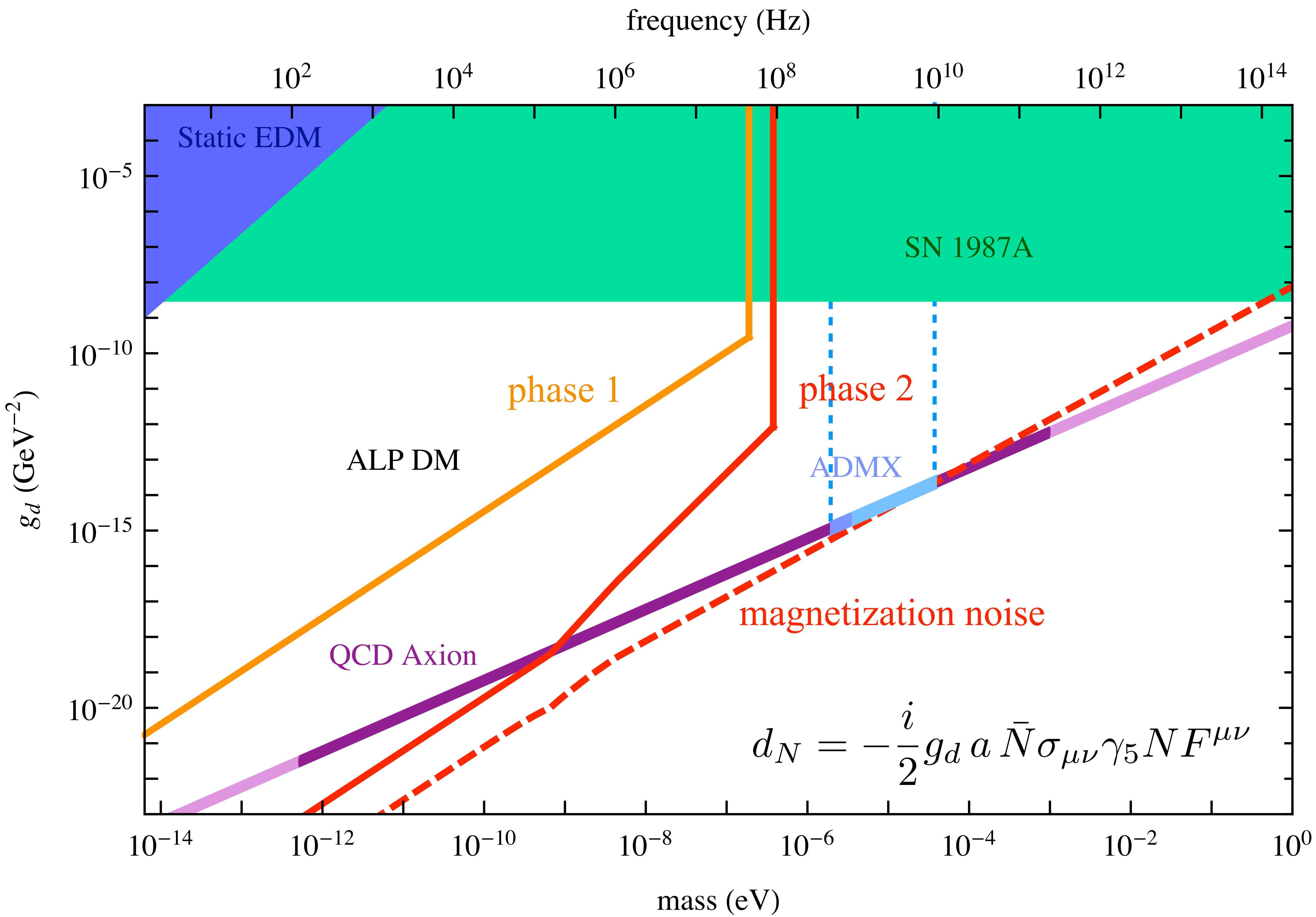
an approximate estimate, in a particular sample magnetization noise must be measured

# Axion Limits on $\frac{a}{f_a} G\widetilde{G}$



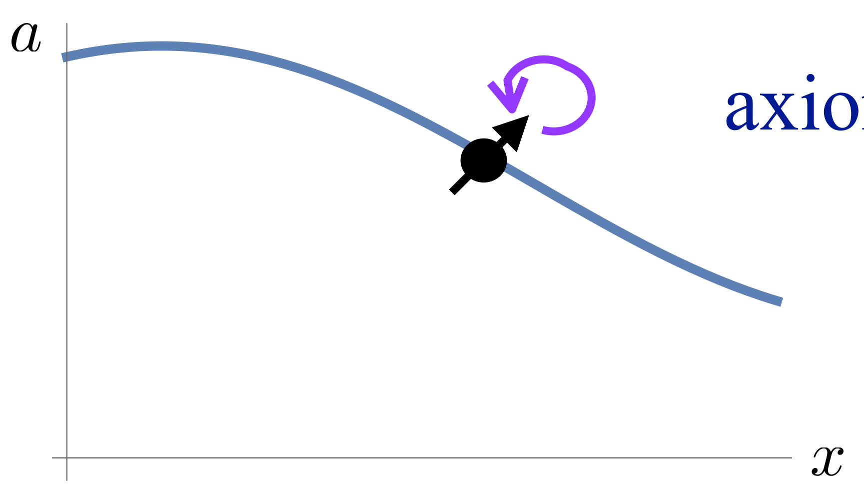

$$d_N = -\frac{i}{2} g_d \, a \, \bar{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu}$$

# CASPEr Sensitivity



# CASPEr-Wind

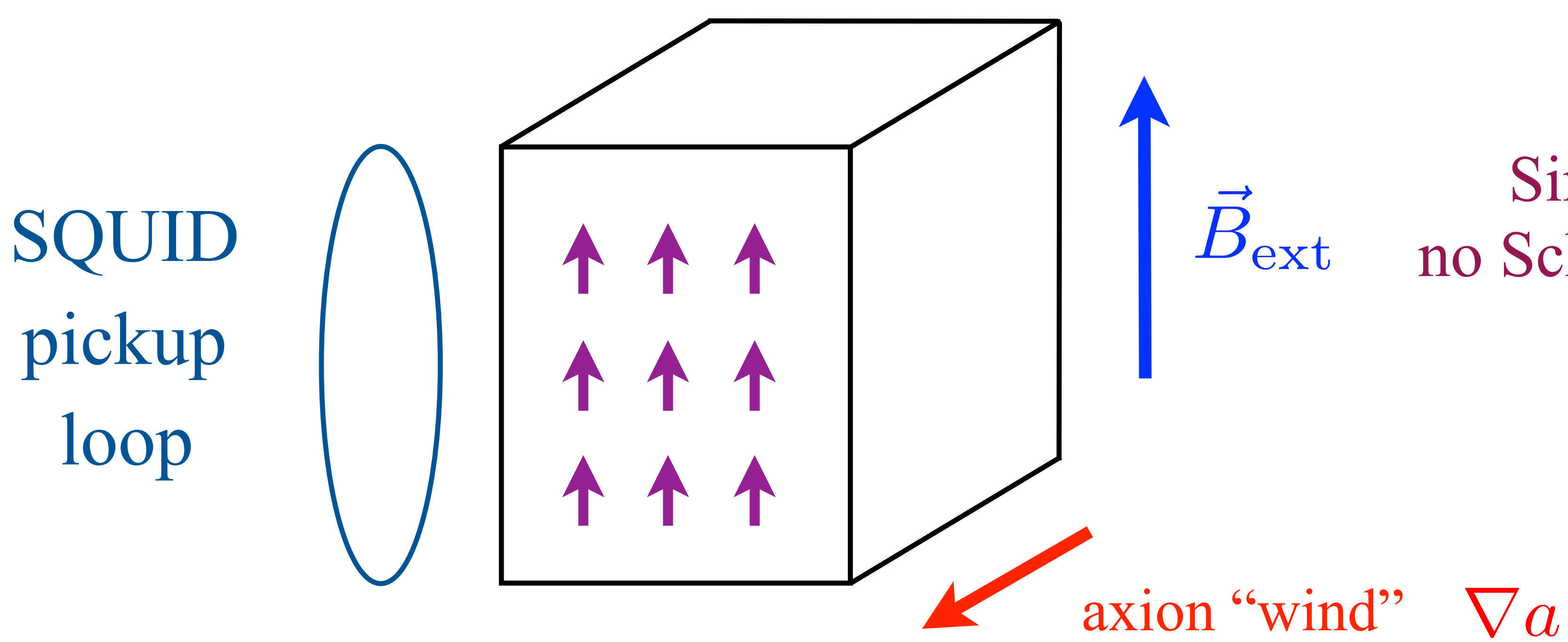
spin coupling: $(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$ ➜ $H \ni \nabla a \cdot \vec{\sigma}_N$




axion DM field gradient torques electron and nucleon spins

oscillates with axion frequency

proportional to axion momentum (“wind”)




Similar to CASPEr-Electric but
no Schiff suppression, no polar crystal
➜ can use LXe or $^3$He

makes a directional detector for axions (and gives annual modulation)

# Cosmic Axion Spin Precession Experiment (CASPEr)

New field of axion direct detection, similar to early stages of WIMP direct detection

No other way to search for light axions

Would be the discovery of dark matter and glimpse into physics at high energies ~ $10^{16}$ - $10^{19}$ GeV

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Berkeley UNIVERSITY OF CALIFORNIA
Stanford
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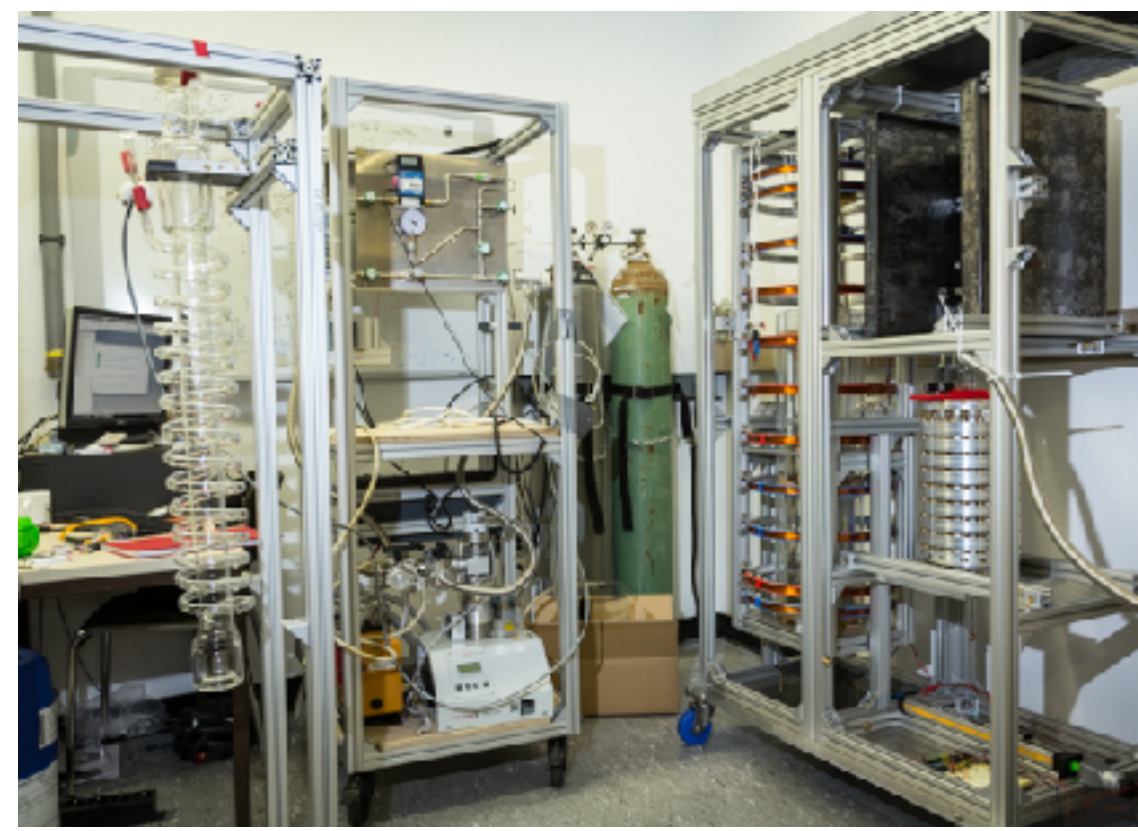
HELMHOLTZ GEMEINSCHAFT Helmholtz-Institut Mainz
JGU JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Dmitry Budker
Alexander Sushkov
Peter W. Graham
Surjeet Rajendran
Derek J. Kimball
Arne Wickenbrock
John Blanchard
Marina Gil Sendra
Gary Centers
Nataniel Figueroa
Deniz Aybas
Adam Pearson
Hannah Mekbib
Tao Wang

under construction at Mainz and BU



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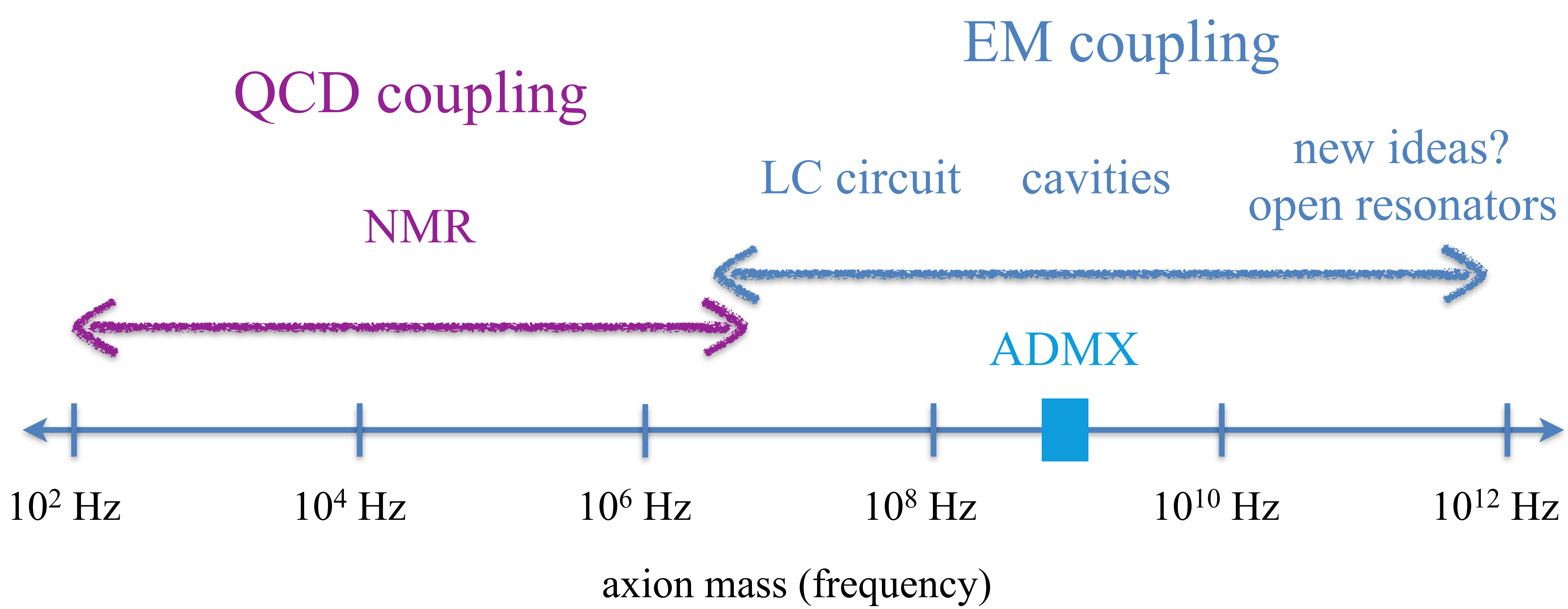
# QCD Axion Dark Matter

May be able to cover all of QCD axion dark matter:

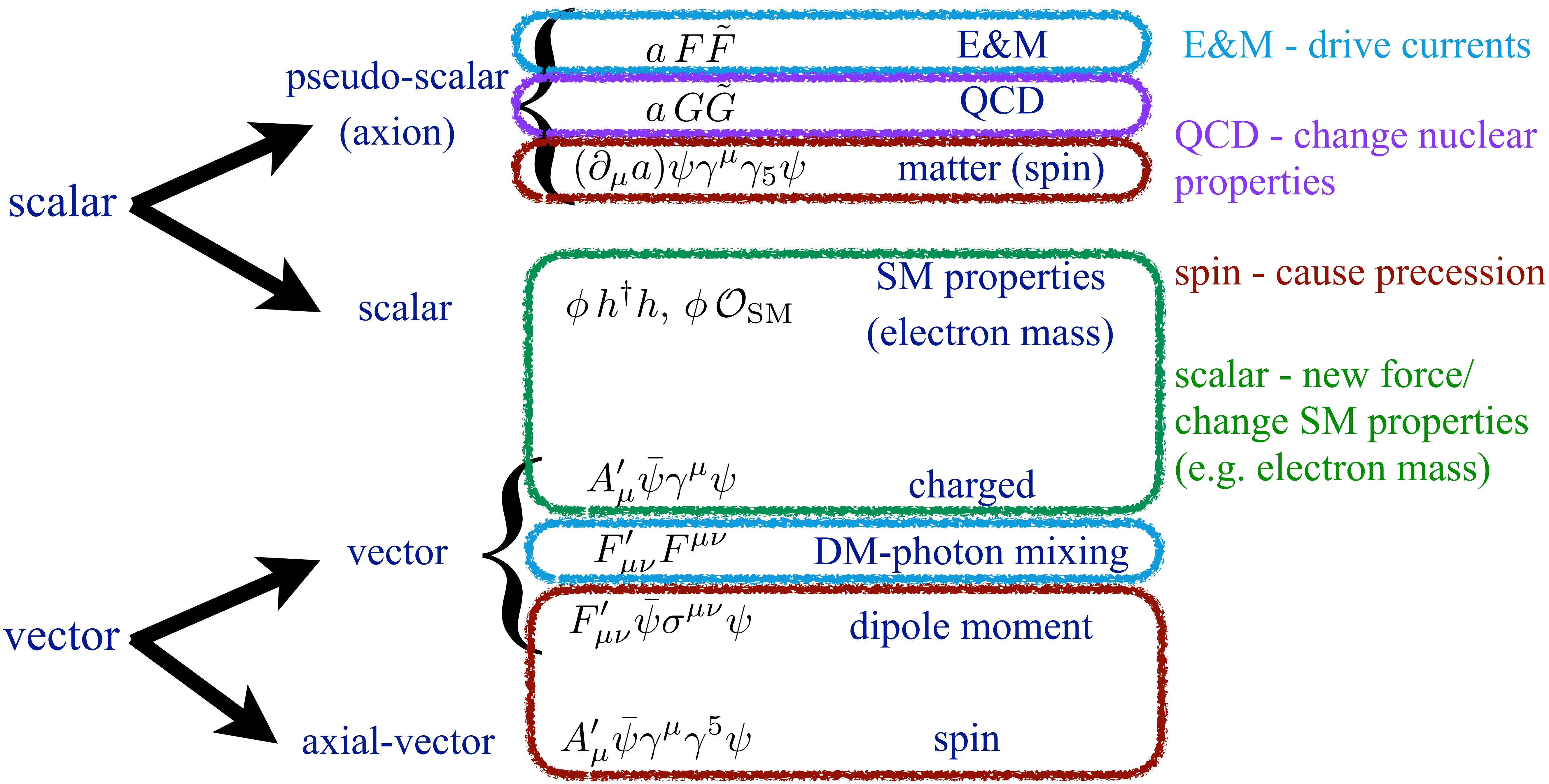



many more new ideas beyond these for axion detection in general!

# Other Couplings & Techniques

# Possibilities for Light Dark Matter

Only really 4 different types of effects, 4 types of experiments needed

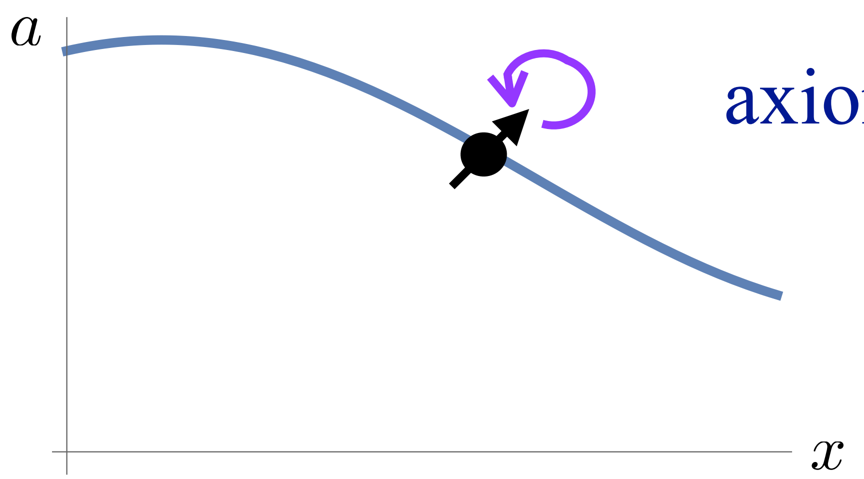



Can cover all these possibilities!

arXiv:1512.06165

# Axion DM Effects

spin coupling: $(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$ ➜ $H \ni \nabla a \cdot \vec{\sigma}_N$

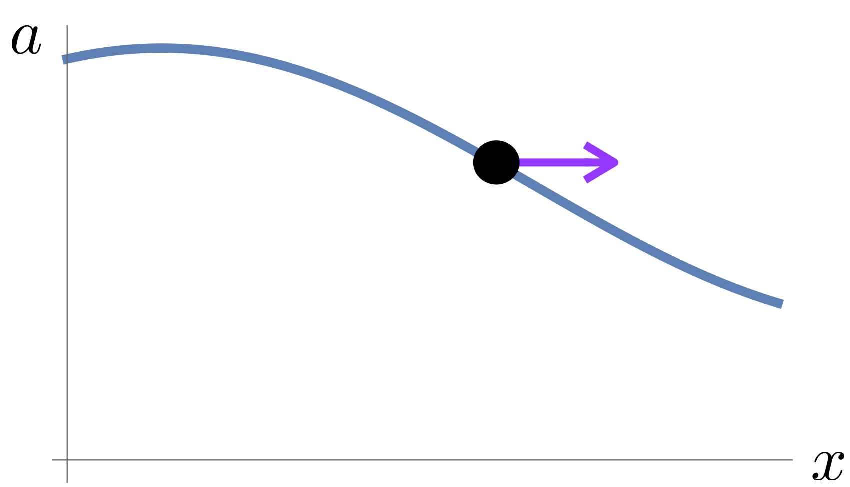



axion DM field gradient torques electron and nucleon spins

oscillates with axion frequency

proportional to axion momentum (“wind”)

scalar coupling: $aH^\dagger H$ e.g. change electron mass




axion DM field gradient can exert a force

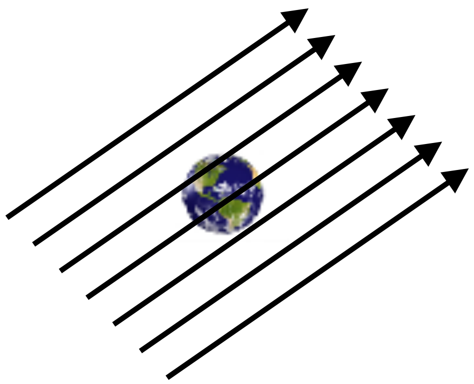
oscillatory and violates equivalence principle

same effects allow searches for hidden photons

# Force/Torque from Dark Matter

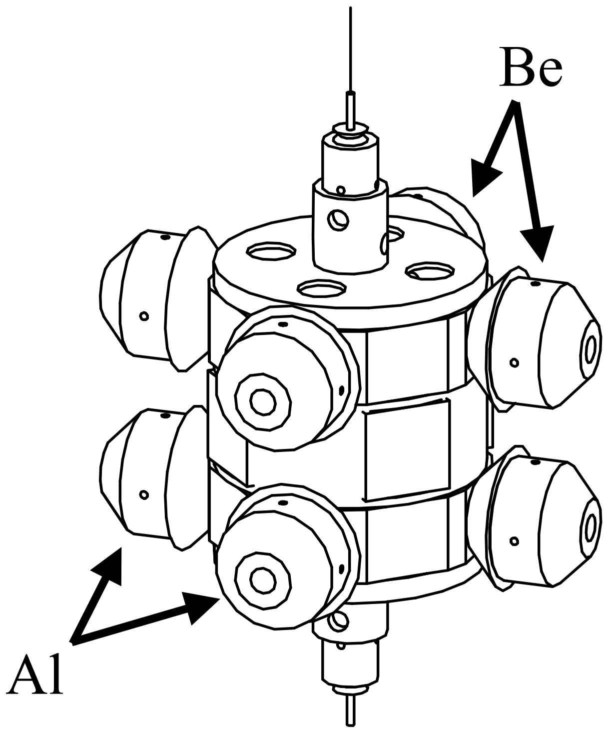
PRD **93** (2016) arXiv:1512.06165

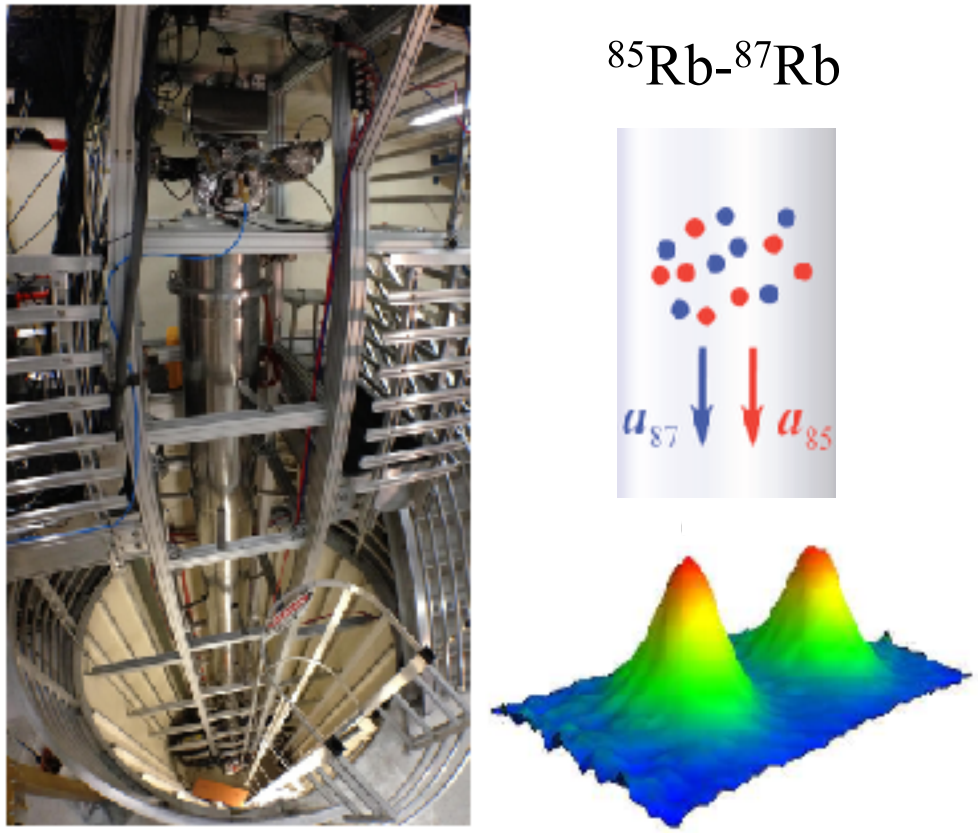
New oscillatory force/torque from dark matter

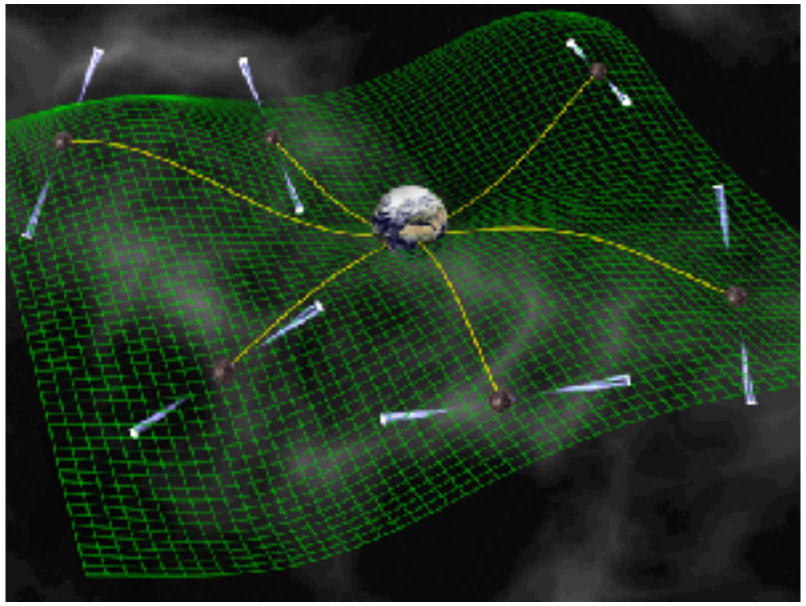


New Direct Detection Experiments:

| Torsion Balances | Atom Interferometers | Pulsar Timing Arrays |
| --- | --- | --- |
| scalar balance for force<br>spin-polarized for torque | split + recombine atom wavefunction<br>measure atom spin and acceleration | DM and gravitational wave<br>detection similar |



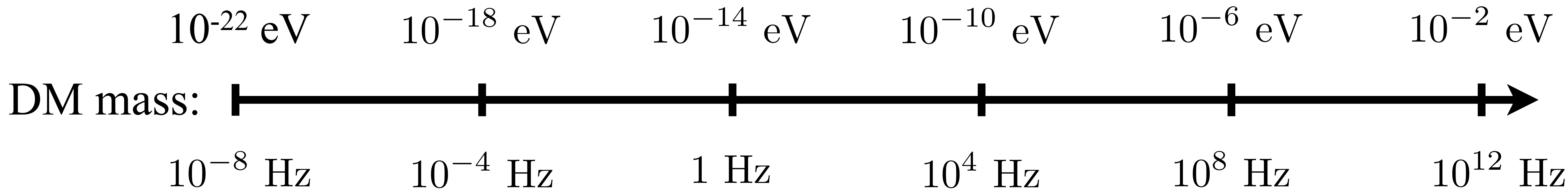
Eot-Wash analysis underway

with Will Terrano

In construction Kasevich/Hogan groups

covers frequency range ~10 Hz down to $yr^{-1}$

# DM Direct Detection




← torsion balances →

← atomic magnetometers →

← atomic clocks/ interferometry →

← E&M →

← NMR →

Coupling:

- E&M
- QCD
- Spin
- Scalar

Eot-Wash (spin)

Eot-Wash (scalar)

Atom Interferometry (spin)

Atom Interferometry (scalar)

CASPEr-Electric

CASPEr-Wind

ADMX

HAYSTAC

LC Circuit

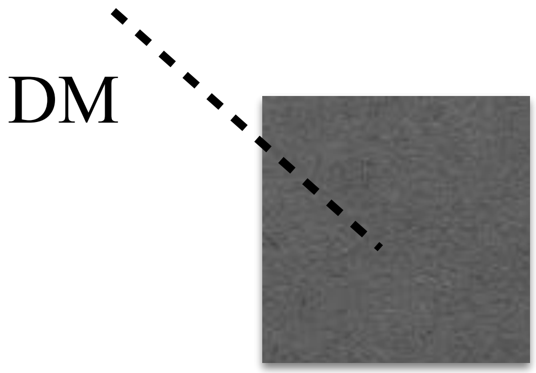
DM Radio

ABRACADABRA

+ many important new force/transmission experiments (e.g. ARIADNE)

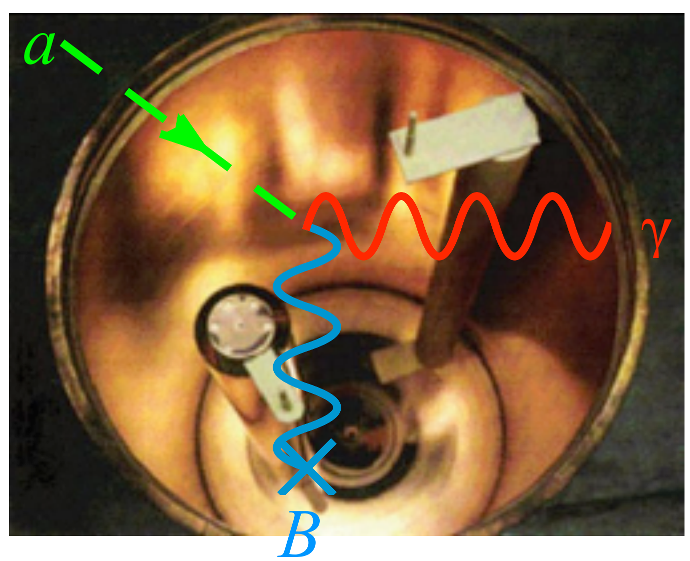
# New Force and Transmission Experiments

## DM expts:



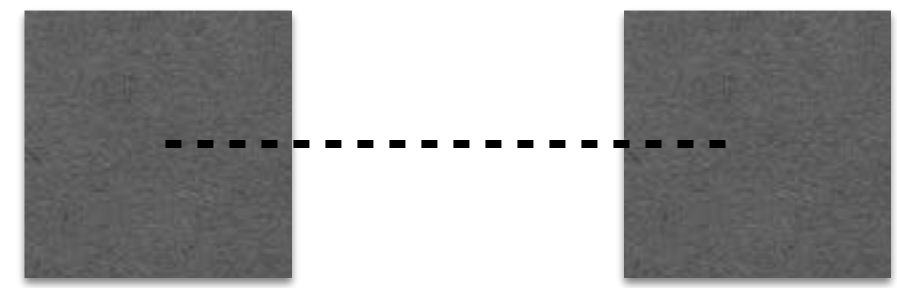

amplitude $\propto g$

microwave cavity (e.g ADMX)



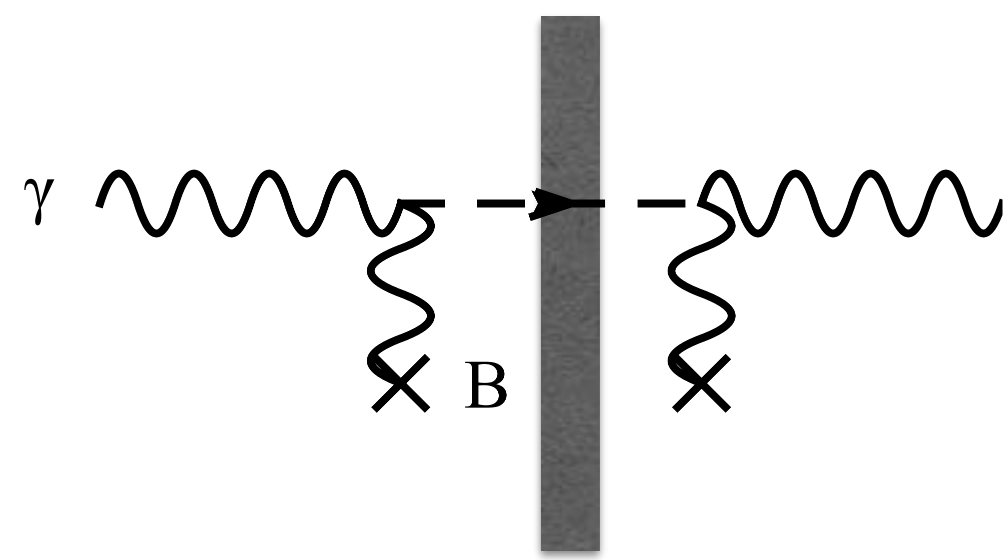

resonance optimal, need to scan frequencies
reach smaller couplings, limited mass range

## New force/transmission expts:



amplitude $\propto g^2$

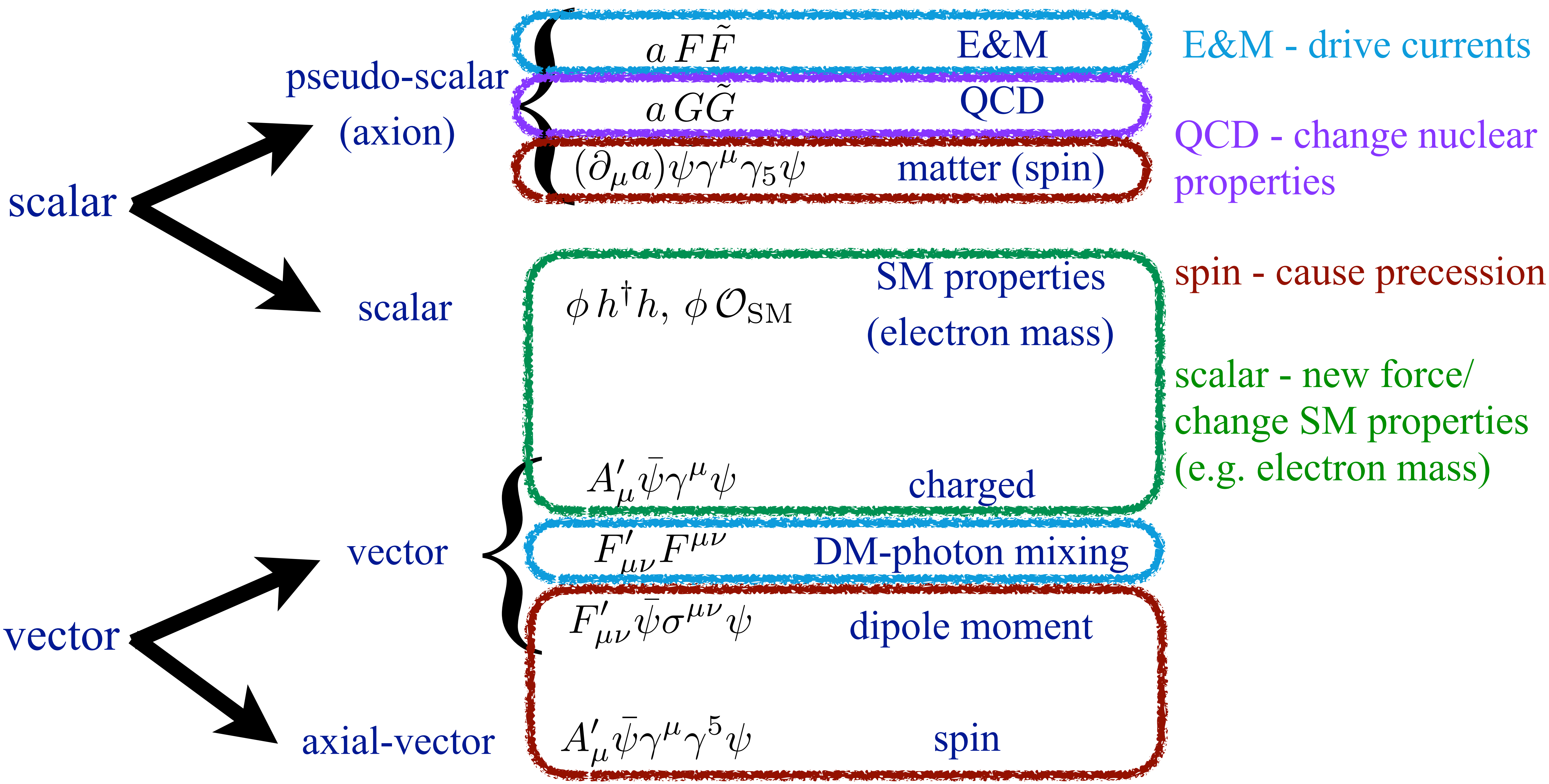
light-through-walls (e.g. ALPS)




covers all masses (below expt cutoff)
not as sensitive in coupling

# Possibilities for New Fields

4 types of couplings




arXiv:1512.06165

# Possible New Forces

Moody and Wilczek (PRD 1984)

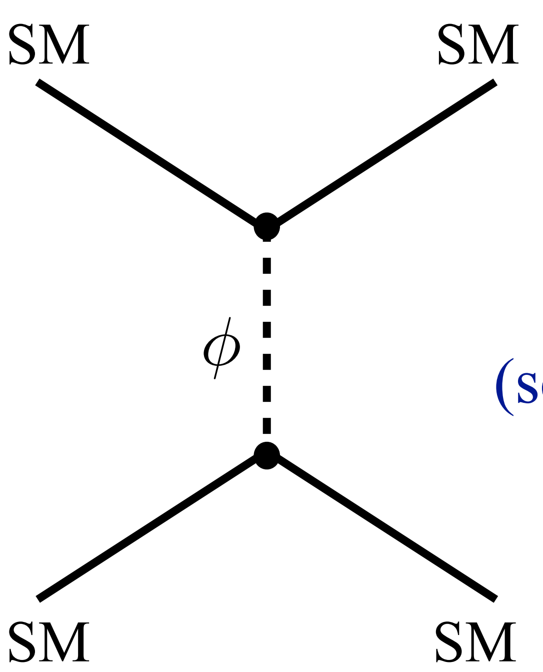
search for a new scalar with a few types of new forces:

Scalar (monopole field)

$\phi\, h^\dagger h,\ \phi\, \mathcal{O}_{\rm SM}$ SM properties (electron mass)

Pseudoscalar (dipole field)

$(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$ matter (spin)




monopole-monopole (scalar-scalar) $V \sim \frac{g_1 g_2}{r}\, e^{-mr}$

if $\phi$ has nonzero mass $m$

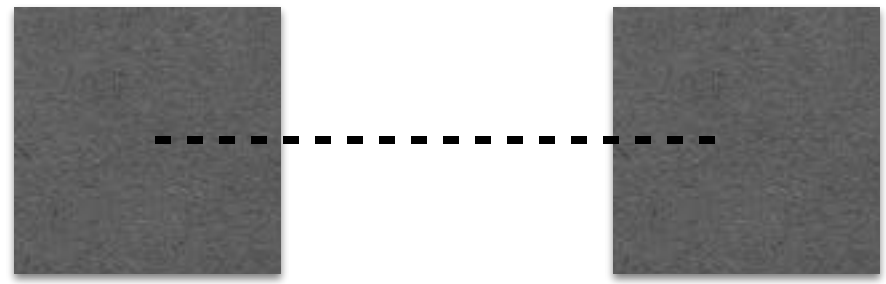
monopole-dipole (scalar-pseudoscalar) $V \sim \frac{g_1 g_2}{r^2}\vec{\sigma}\cdot\hat{r}\ (1+mr)\ e^{-mr}$

spin-dependent forces

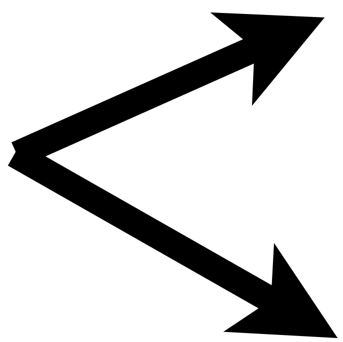
dipole-dipole (pseudo-pseudo) $V \sim \frac{g_1 g_2}{r^3}\left(\vec{\sigma}\cdot\vec{\sigma}+\vec{\sigma}\cdot\hat{r}\ \ \vec{\sigma}\cdot\hat{r}\right)\left(1+mr+m^2r^2\right)e^{-mr}$

effective field theory ➜ only a few possibilities

# Experimental Strategies for New Forces



scalar force



Equivalence principle violation: two different test masses

- will see infinite range (zero mass) force
- suppressed by composition difference (usually ~ $10^{-1}$ - $10^{-2}$)

deviations from $r^{-2}$ : move test mass around

- only sensitive at masses ~ distance scale of expt

spin-dependent force: control spins of source and test masses

- limited by shortest distance achievable ($V \sim r^{-2}$ or $r^{-3}$), bad backgrounds (EM) at short distances

# Motivations

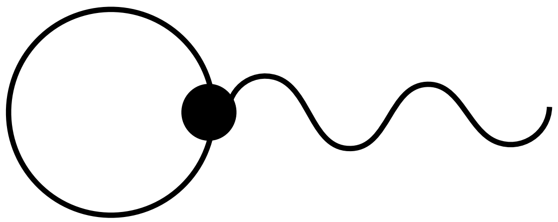
new light particles/deviations from gravity well motivated by many theories: axions, moduli (SUSY), extra dimensions…

e.g. twin Higgs has a new photon, will pick up some (small) kinetic mixing, but potentially testable by high precision experiments/astrophysics

Cosmological Constant Problem:

Raman Sundrum

great, vague, idea: turn off graviton coupling to loops (once far enough off-shell)

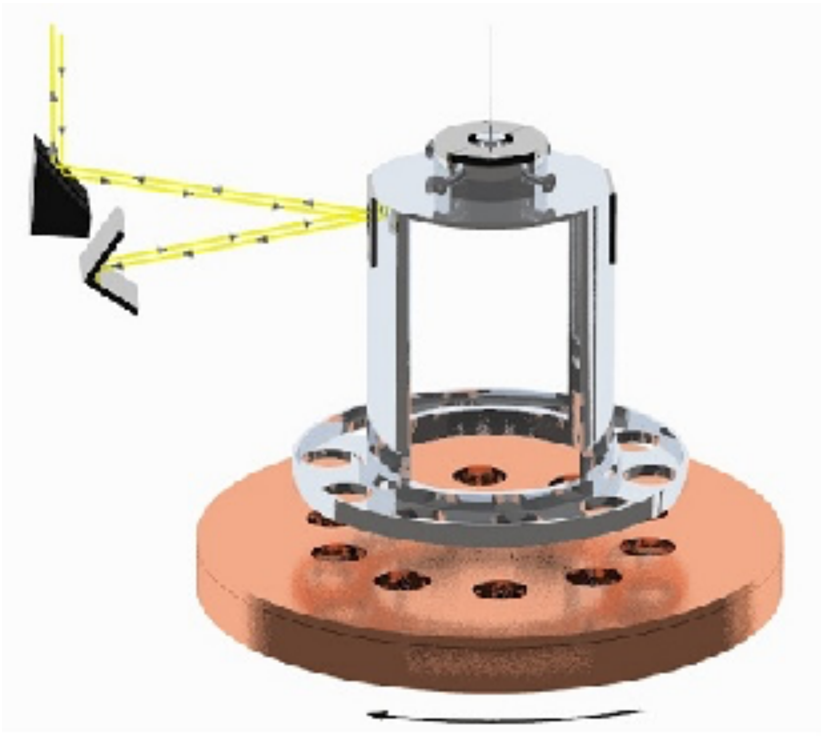


$\propto \Lambda^4$ ➜ require cutoff at momenta $\Lambda \sim \text{meV} \sim (100\,\mu\text{m})^{-1}$

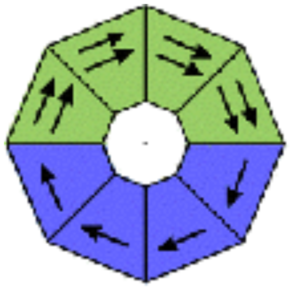
➜ Newtonian gravity $\frac{1}{r^2}$ will cut off below 100 μm

# Eot-Wash Torsion Pendulums

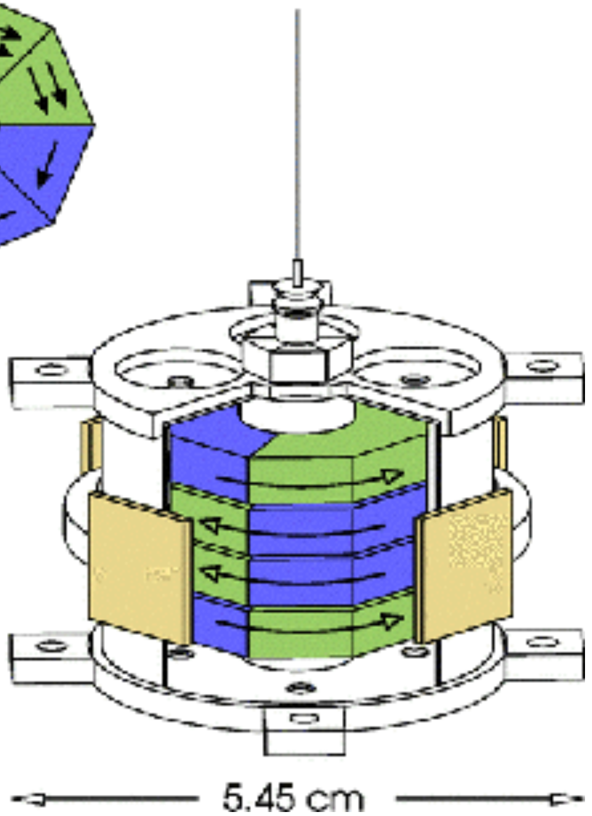
high sensitivity possible: use laser readout of angle



<u>backgrounds:</u>
fiber thermal noise,
laser readout noise,
EM forces (Casimir),
gravity gradients



spin-polarized pendulums:

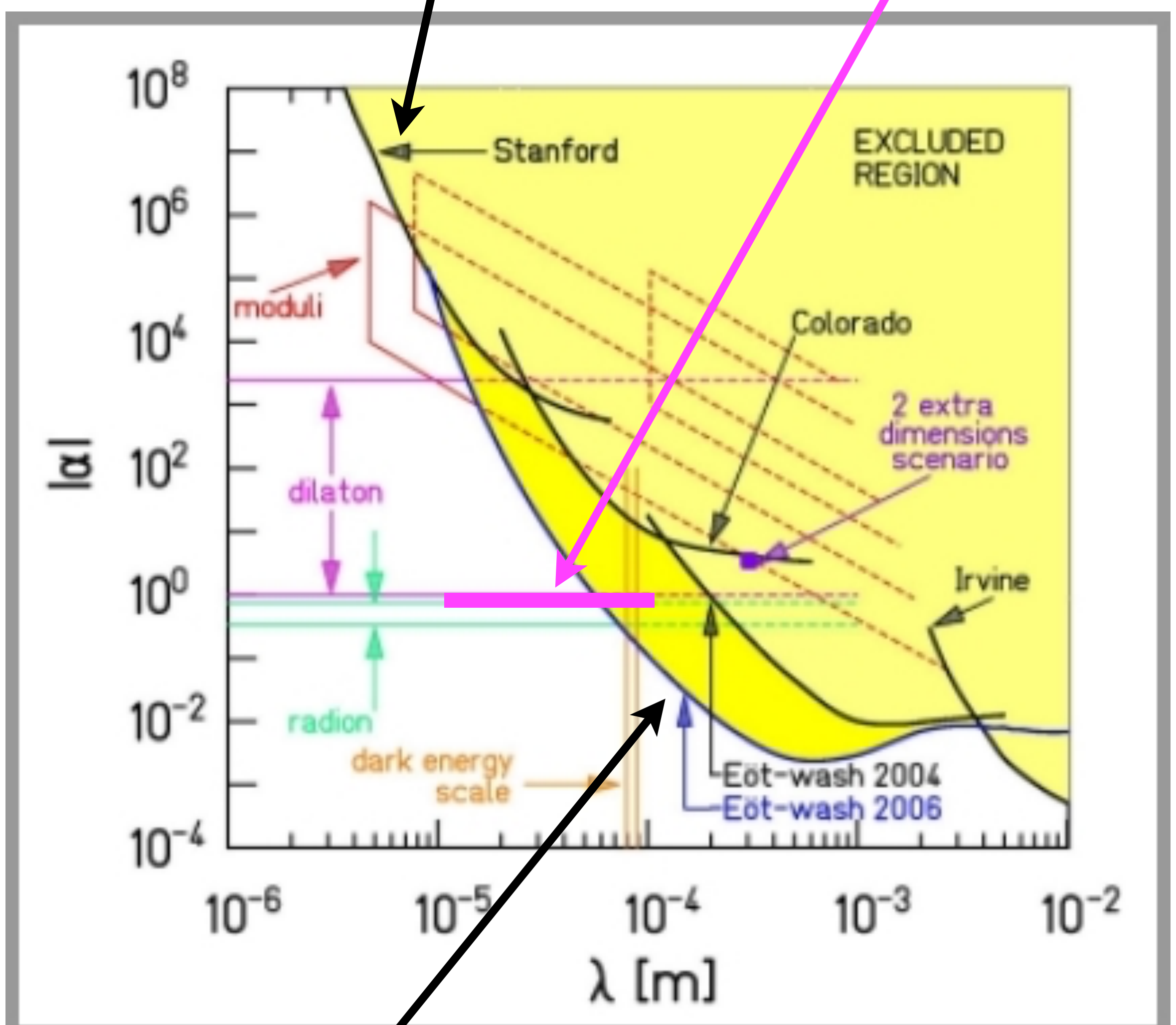


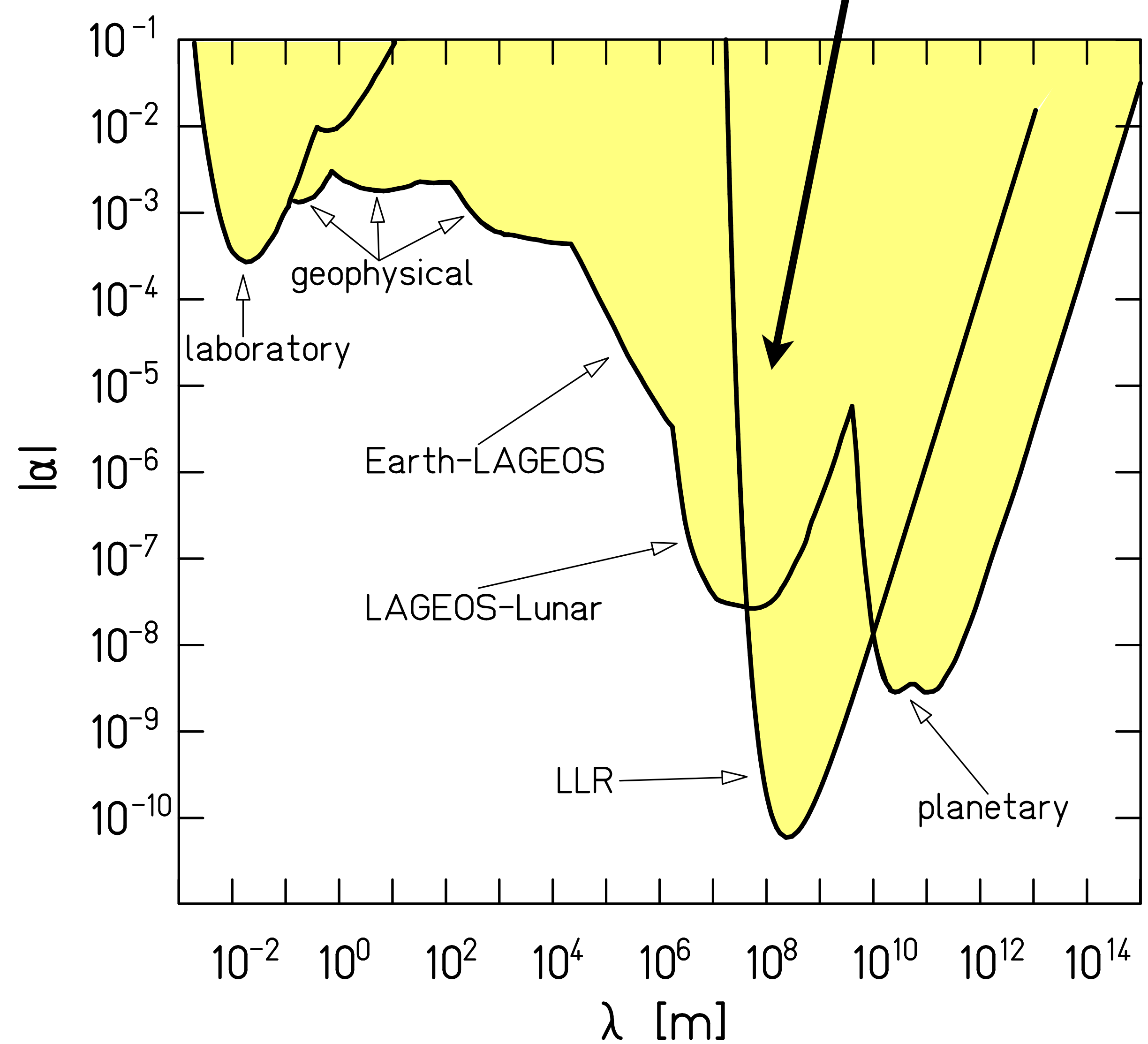
# Deviations from $1/r^2$

cantilever

cosmological constant problem

note shape




torsion pendulum

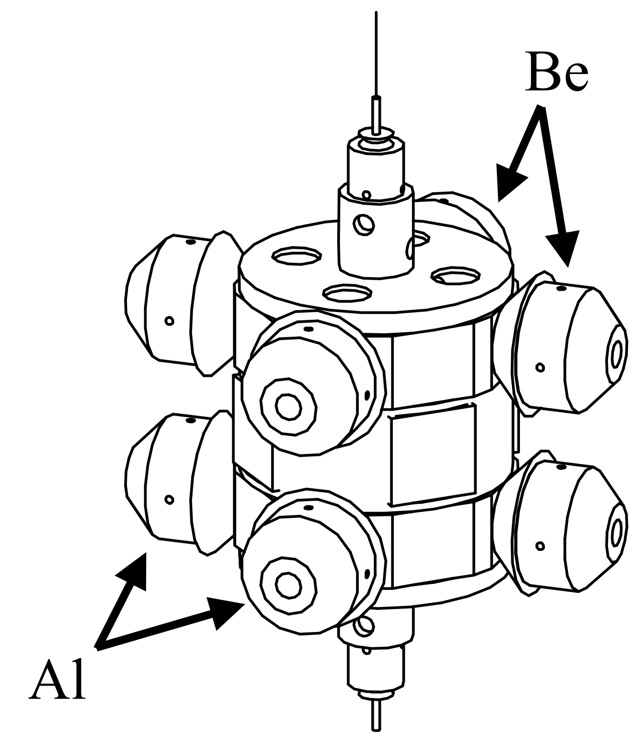
α = strength relative to gravity $\lambda \sim m^{-1}$

# Equivalence Principle

Best current limits ~ $10^{-13}$ and will likely improve from:

- Lunar Laser Ranging: earth - moon falling towards sun
- torsion balances: two masses (e.g. Al-Be) toward earth

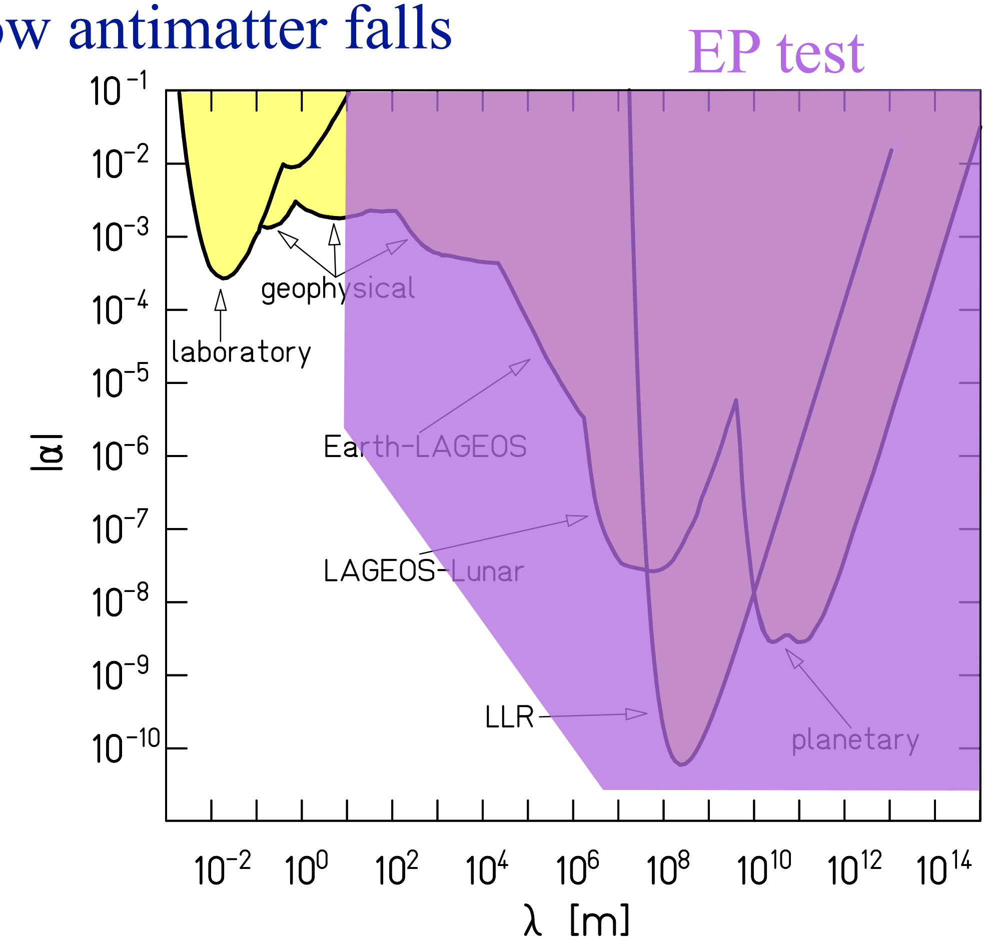
## Torsion Balances



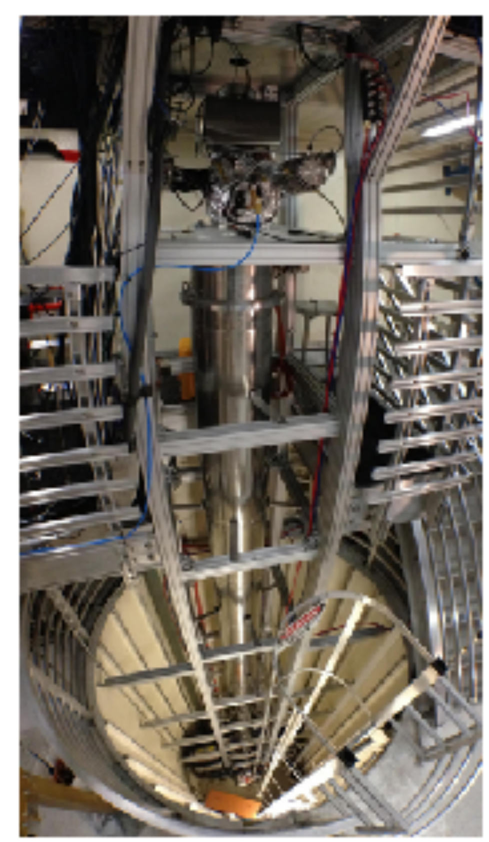

$10^{-13}$ so good it bounds how antimatter falls

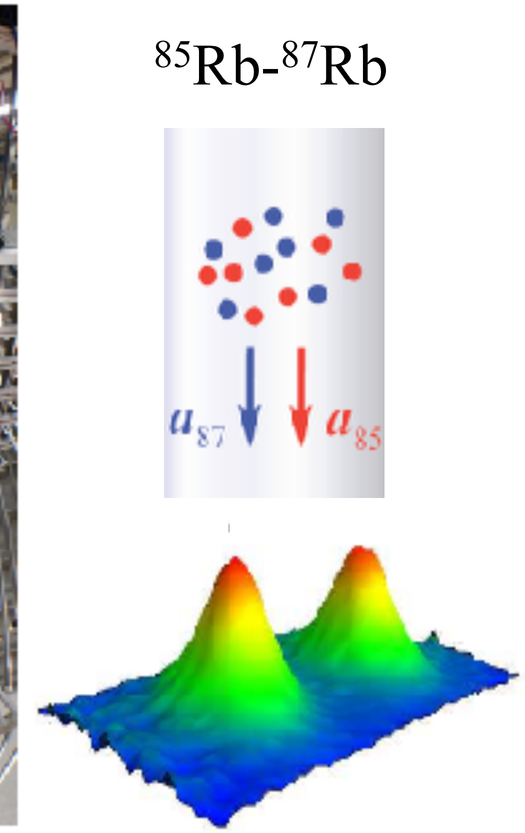
can only see forces ~6000 km or longer

HW: is a short-range EP test interesting?




## Atom Interferometers

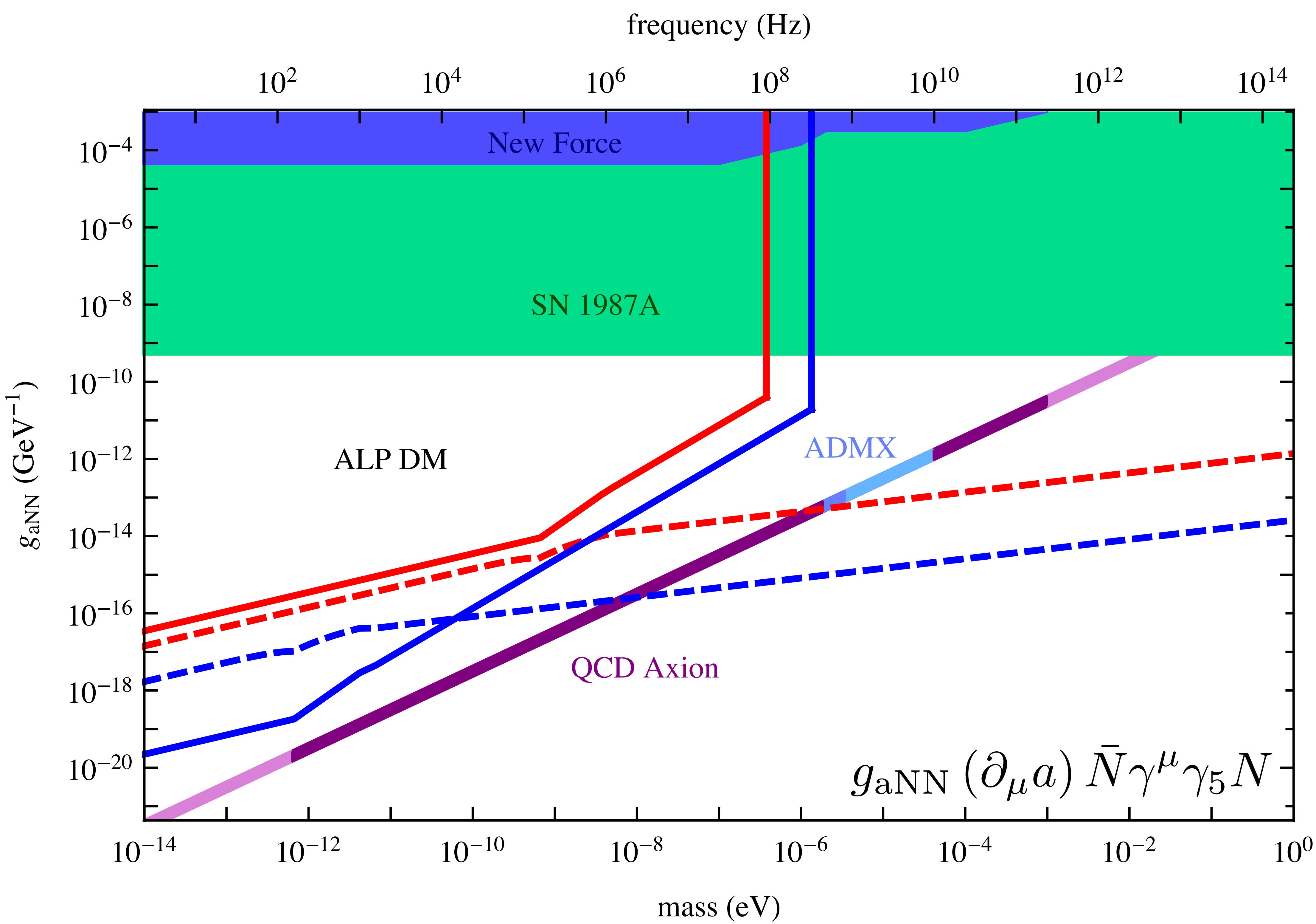





New techniques coming:

- Satellite Test of Equivalence Principle (STEP)
- Atom interferometry

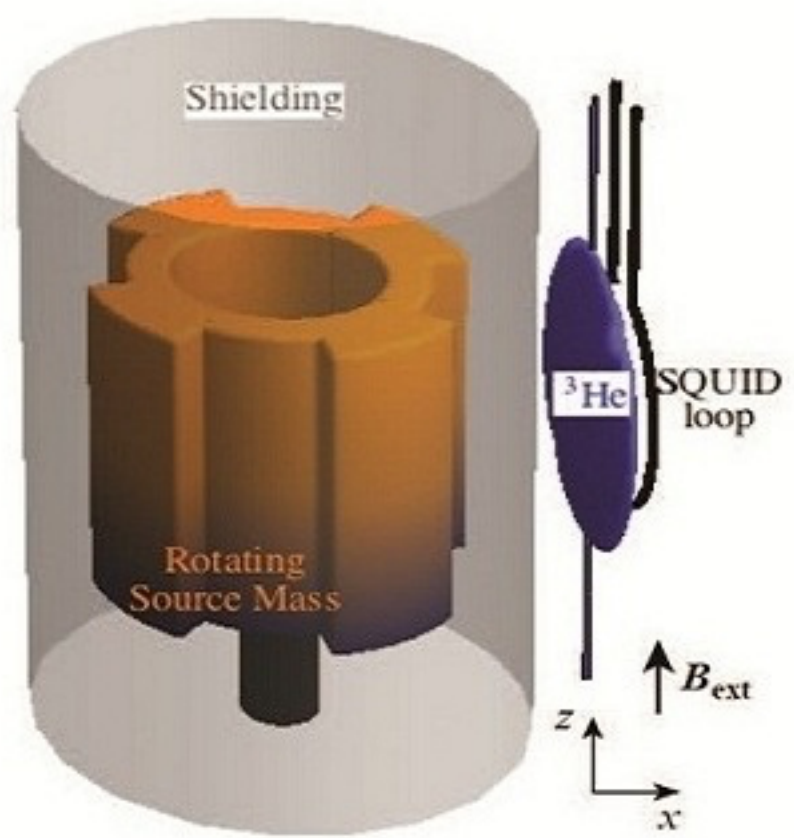
# Spin-Dependent Forces

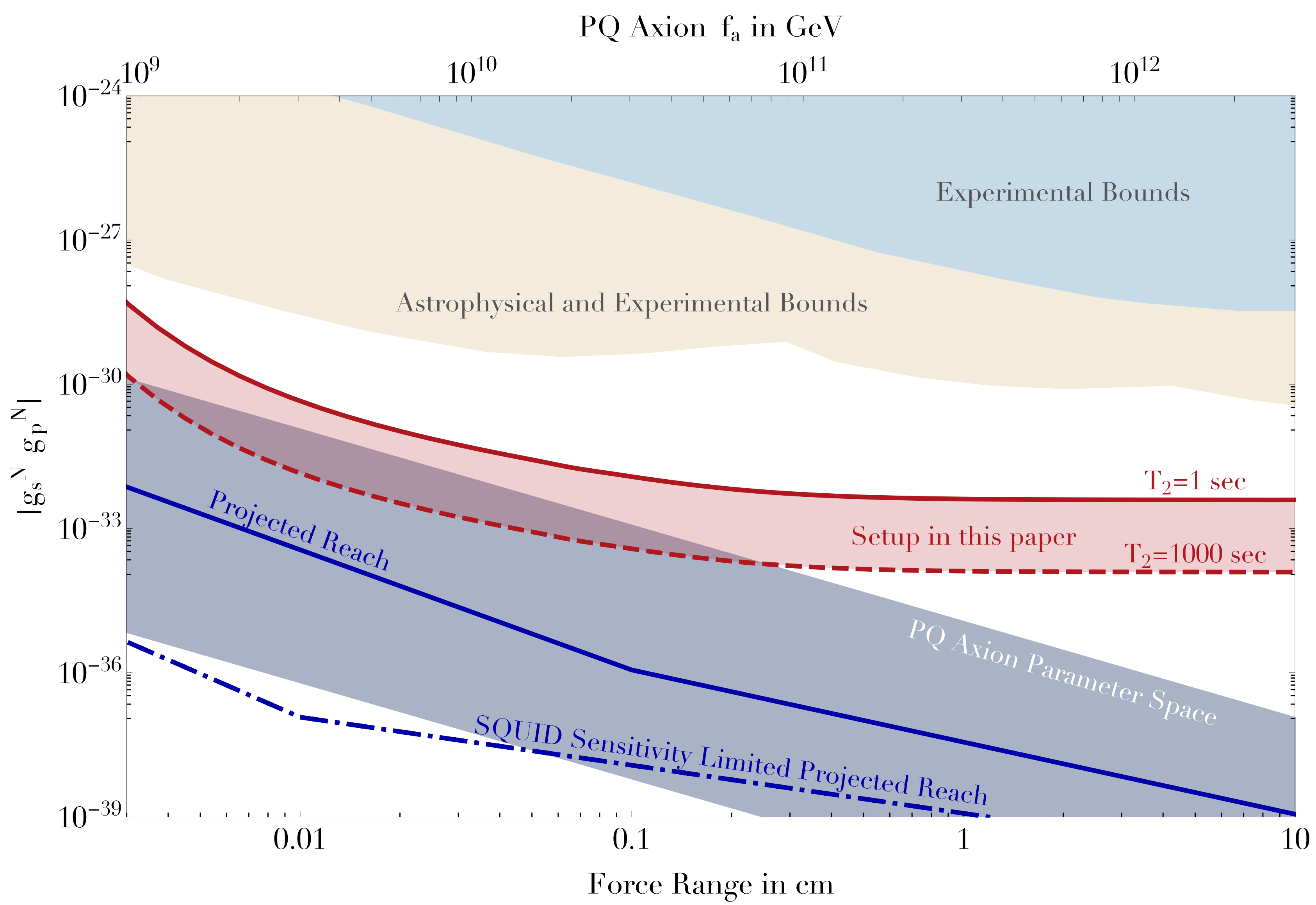



generally hard for lab measurements to beat astro bounds in spin-dependence

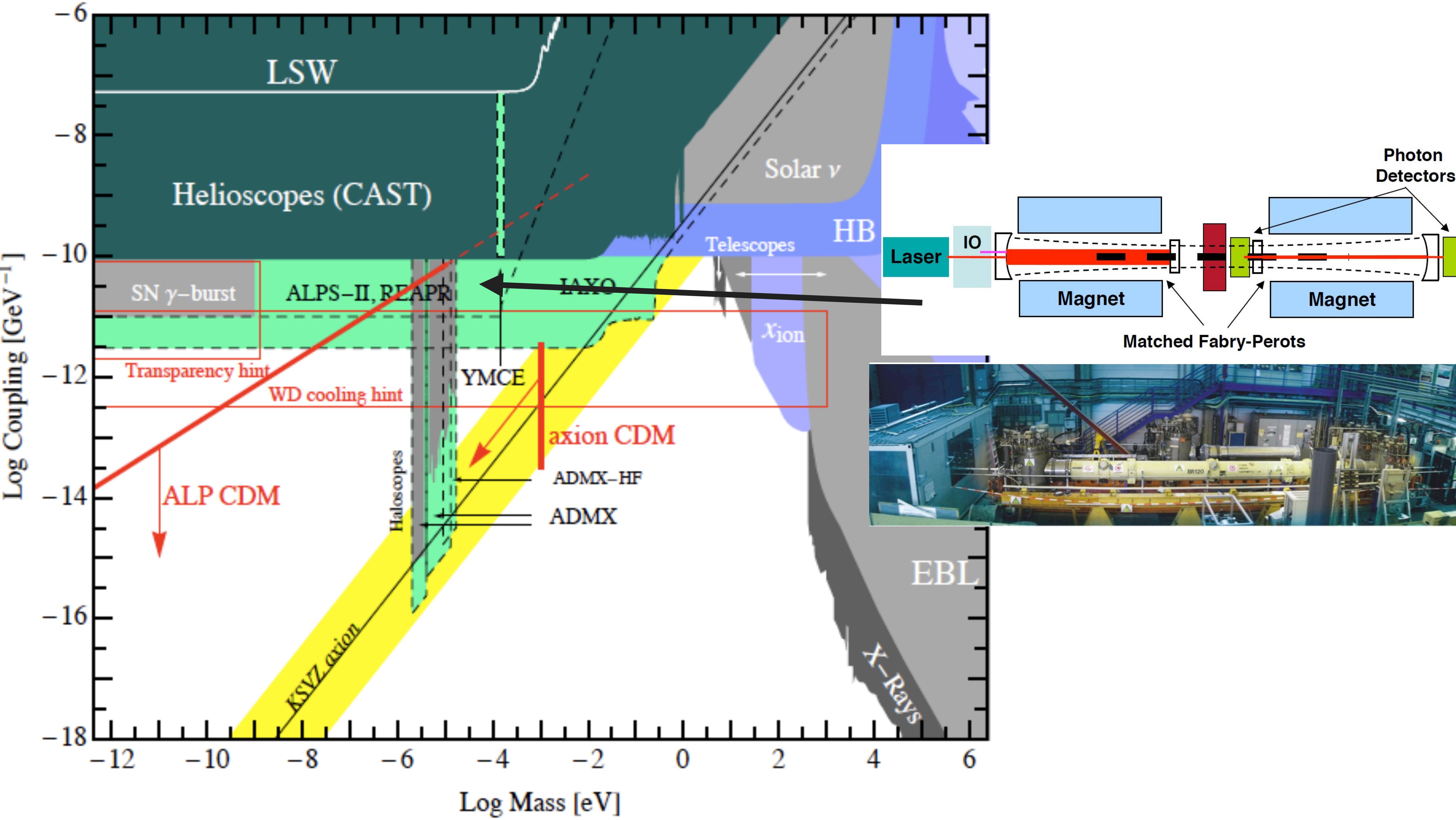
# ARIADNE

new experiment for axion detection though new force (monopole-dipole)
uses NMR as detection technology



# Light-Through-Walls



# Gravitational Wave Detection with Atom Interferometry

with

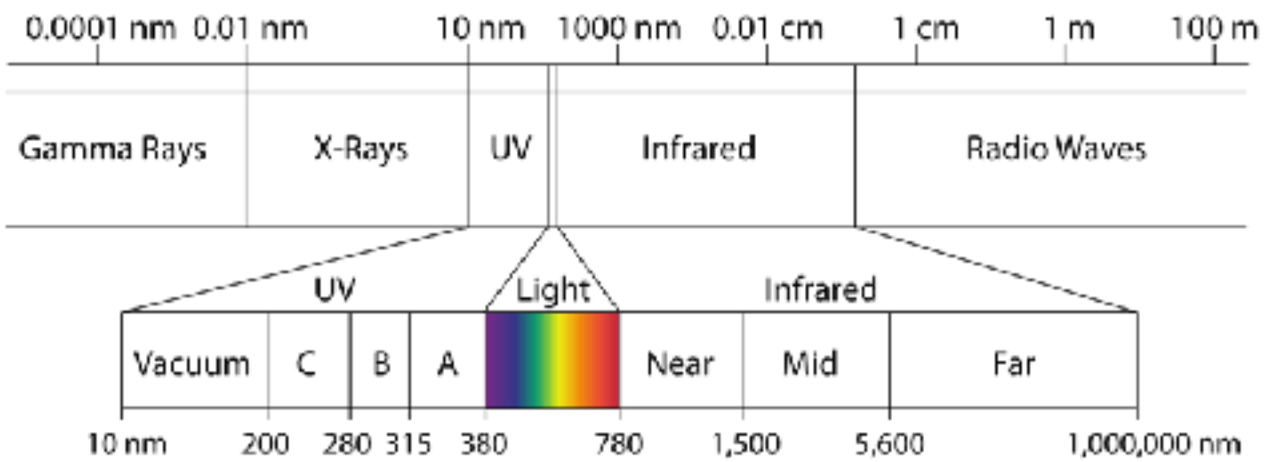
Savas Dimopoulos
Jason Hogan
Mark Kasevich
Surjeet Rajendran

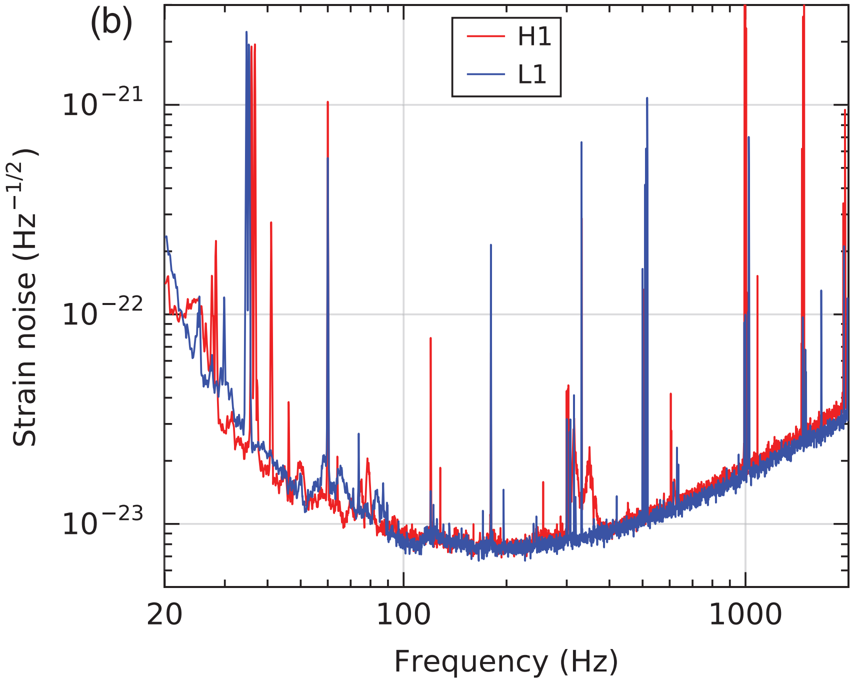
W.M. KECK FOUNDATION

PRD **94** (2016) arXiv:1606.01860
PRL **110** (2013) arXiv:1206.0818
GRG **43** (2011) arXiv:1009.2702
PLB **678** (2009) arXiv:0712.1250
PRD **78** (2008) arXiv:0806.2125

# Gravitational Spectrum

Every new EM band opened has revealed unexpected discoveries, gravitational waves give a new spectrum



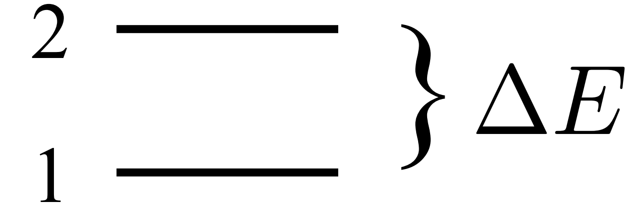

Advanced LIGO can only detect GW's > 10 Hz ➜ How look at lower spectrum?

New detectors?

# Atomic Clock

$$|\text{atom}\rangle = |1\rangle$$

beamsplitter




$$\frac{1}{\sqrt{2}}\left(|1\rangle + |2\rangle\right)$$

wait time t

$$\frac{1}{\sqrt{2}}\left(|1\rangle + e^{i(\Delta E)t}|2\rangle\right)$$

beamsplitter

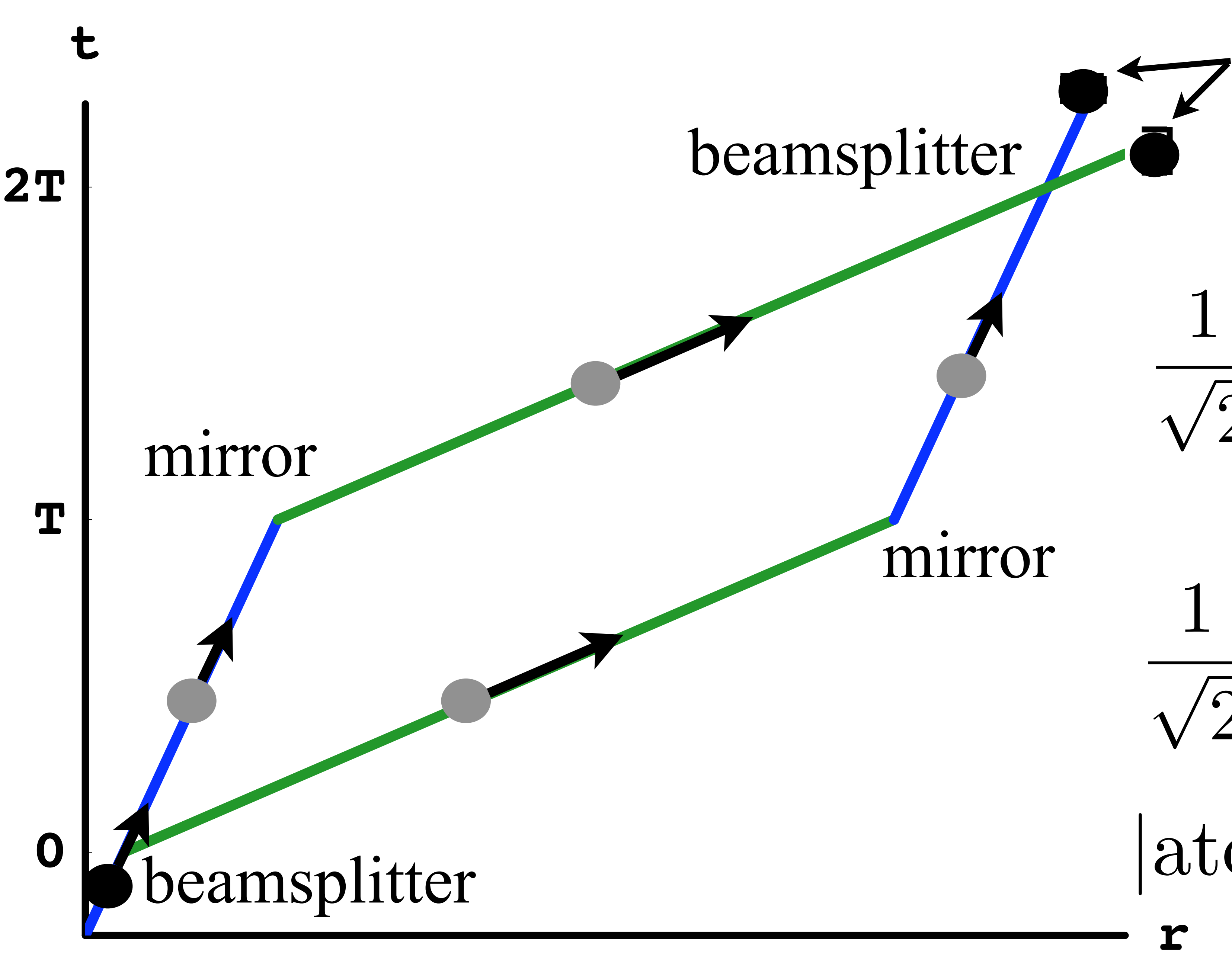
$$\frac{1}{2}\left[\underbrace{\left(1 - e^{i(\Delta E)t}\right)}_{N_1}|1\rangle + \underbrace{\left(1 + e^{i(\Delta E)t}\right)}_{N_2}|2\rangle\right]$$

output ports

can measure times $t \sim \frac{1}{\Delta E} \sim 10^{-10}\,\text{s}$

# Atom Interferometry

## Space-time Interferometry



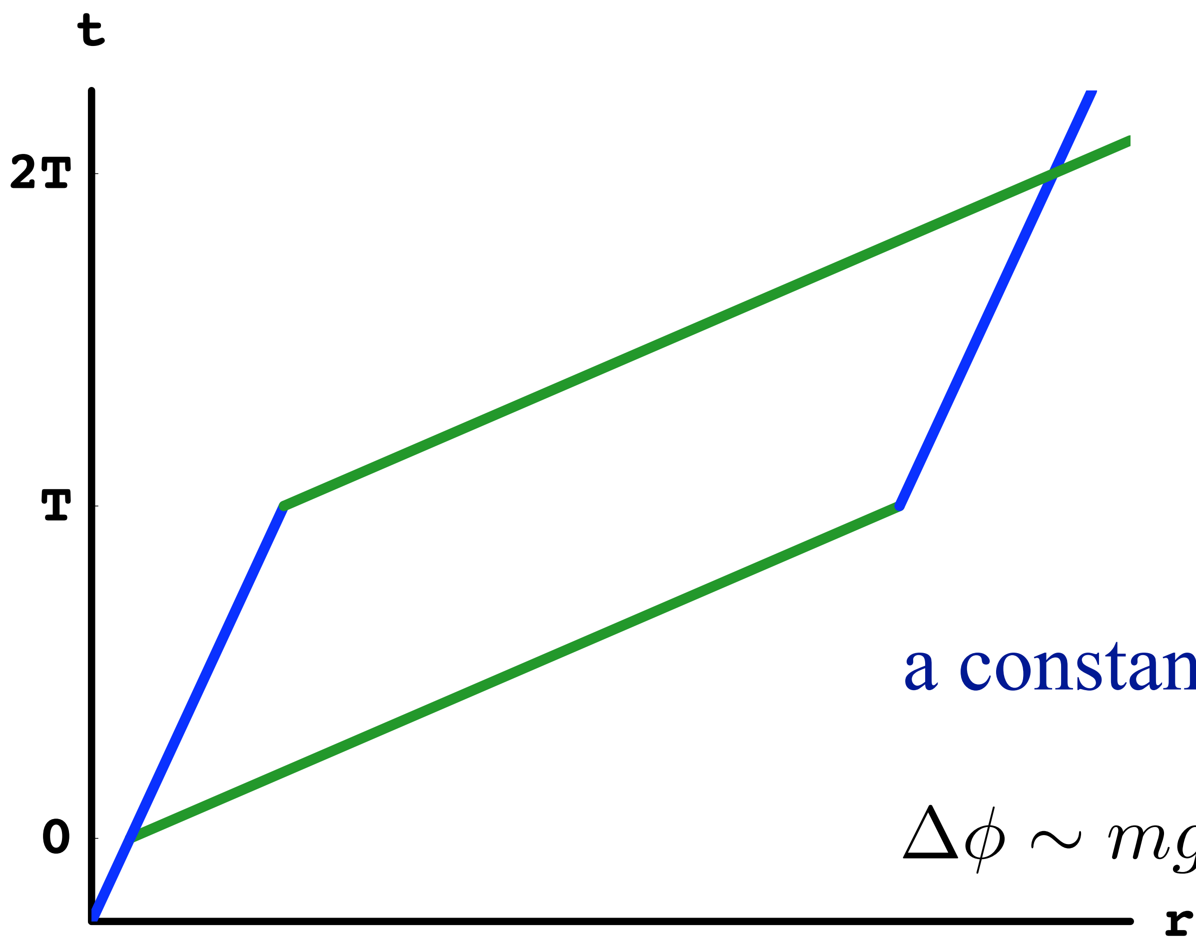

$$\frac{1}{\sqrt{2}}(|2, p+k\rangle + e^{i\Delta\phi}|1, p\rangle)$$

$$\frac{1}{\sqrt{2}}(|1, p\rangle + e^{i\Delta\phi}|2, p+k\rangle)$$

$$|\text{atom}\rangle = |1, p\rangle$$

cancels clock shift exactly, what is left?

# Sensitivity of Atom Interferometry




GR calculation PRD **78** (2008)

$$\Delta\phi = \int L dt = \int m d\tau = \int p_\mu dx^\mu$$

a constant gravitational field produces a phase shift:

$$\Delta\phi \sim mg(\Delta h)T \sim mg\left(\frac{k}{m}T\right)T = kgT^2 \sim 10^8 \text{ rad}$$

the interferometer can be as long as T ~ 1 sec ~ earth-moon distance!

$$\Delta\phi \sim \frac{1}{\sqrt{N_{\text{atoms}}}}\frac{1}{\sqrt{N_{\text{shots}}}}$$

each shot ~ 1s ➜ $N_{\text{shots}} \sim 10^7$

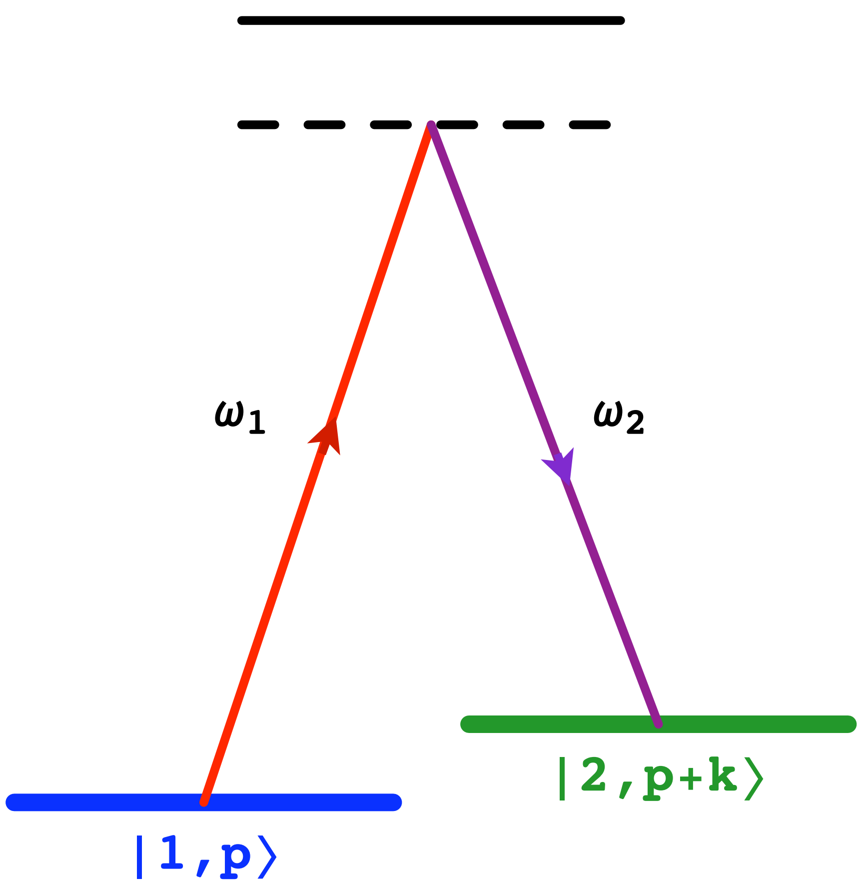
$N_{\text{atoms}} \sim 10^6$ per shot

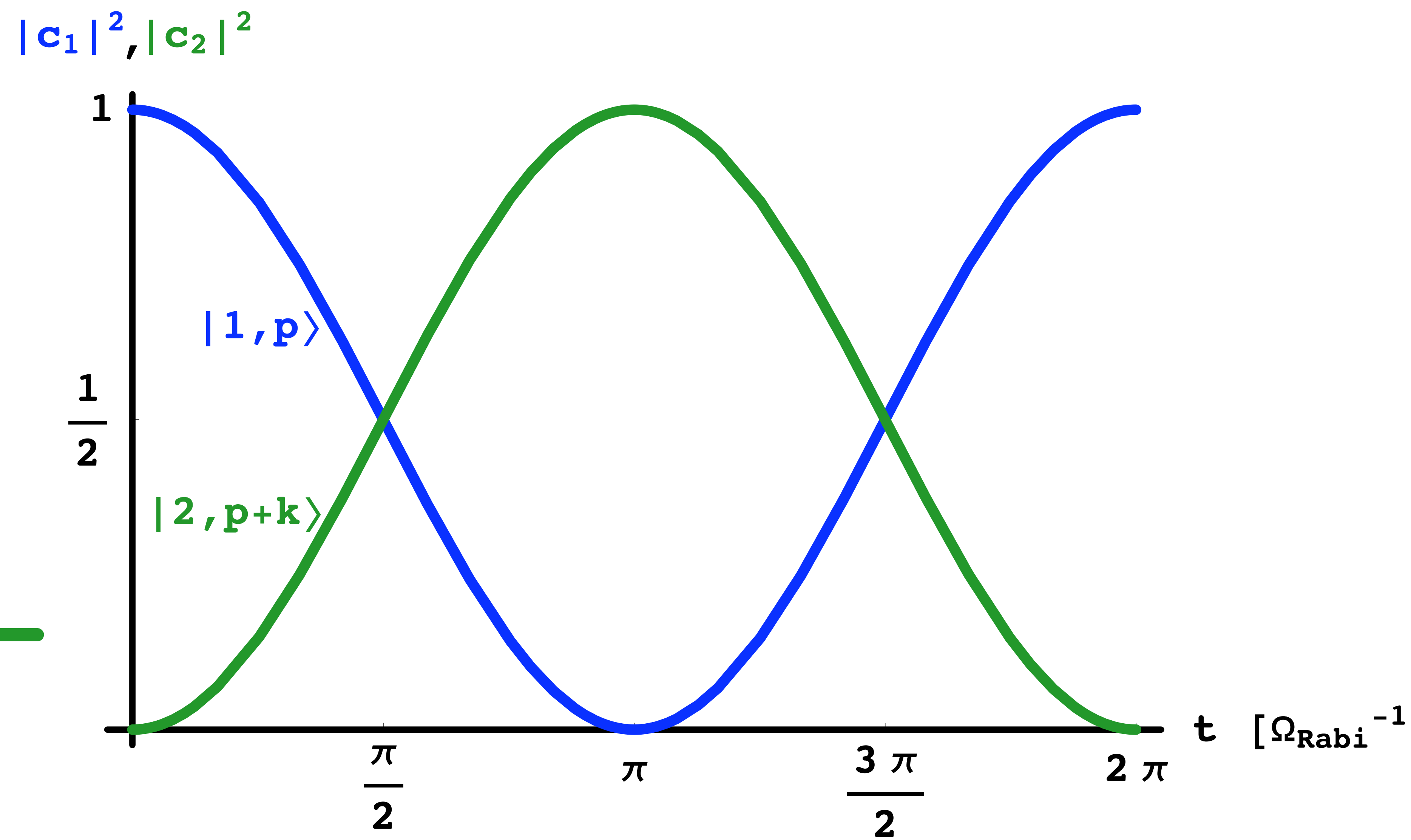
➜ sensitivity in one year ~ $10^{-7}$ rad

have sensitivity to forces as small as $\sim 10^{-15} g$

# Raman Transition

$$\psi = c_1|1,p\rangle + c_2|2,p+k\rangle$$

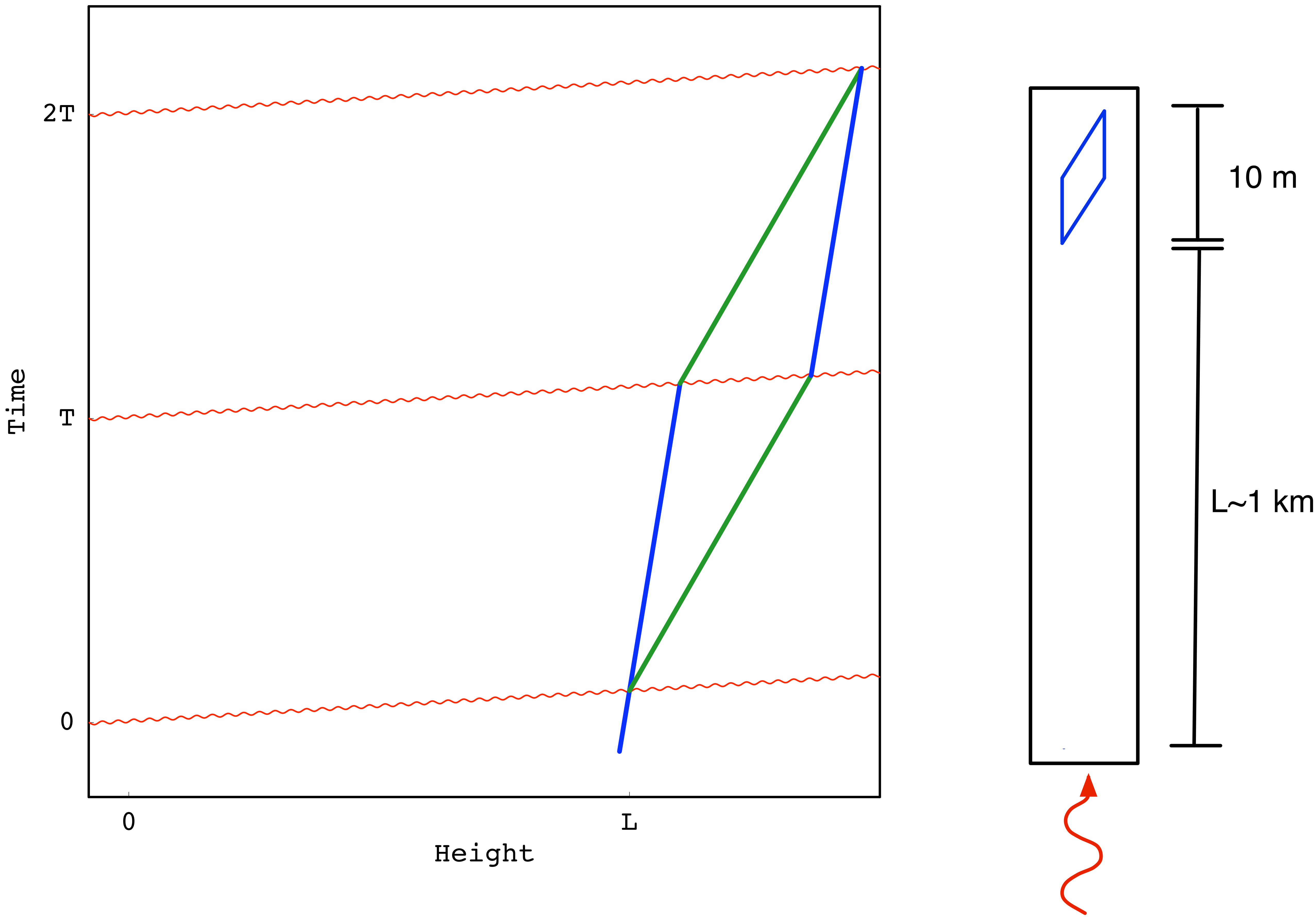


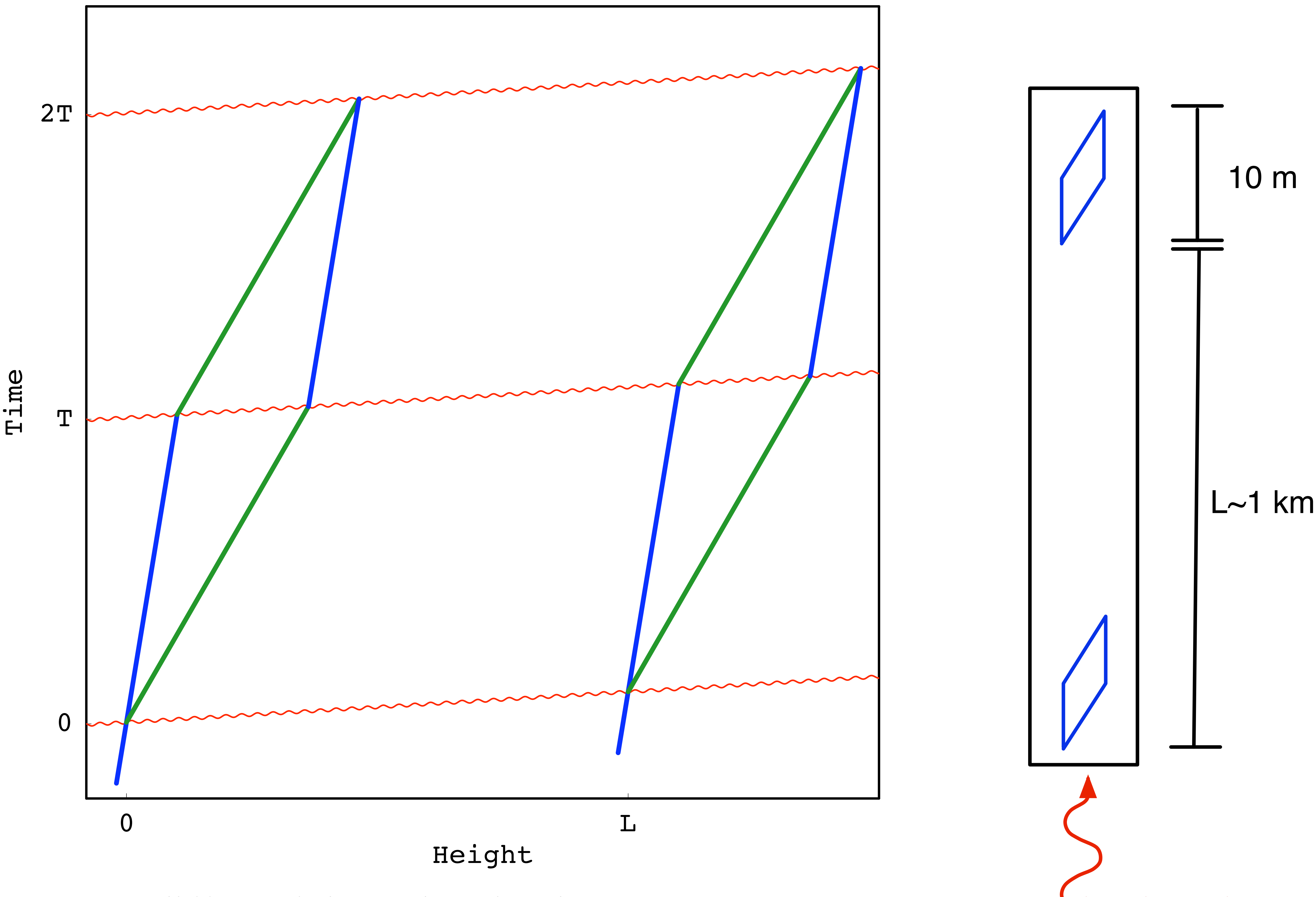

$\pi/2$ pulse is a beamsplitter

$\pi$ pulse is a mirror

# Gravity Wave Signal



# Differential Measurement




measures differential acceleration between two atoms: removes seismic noise

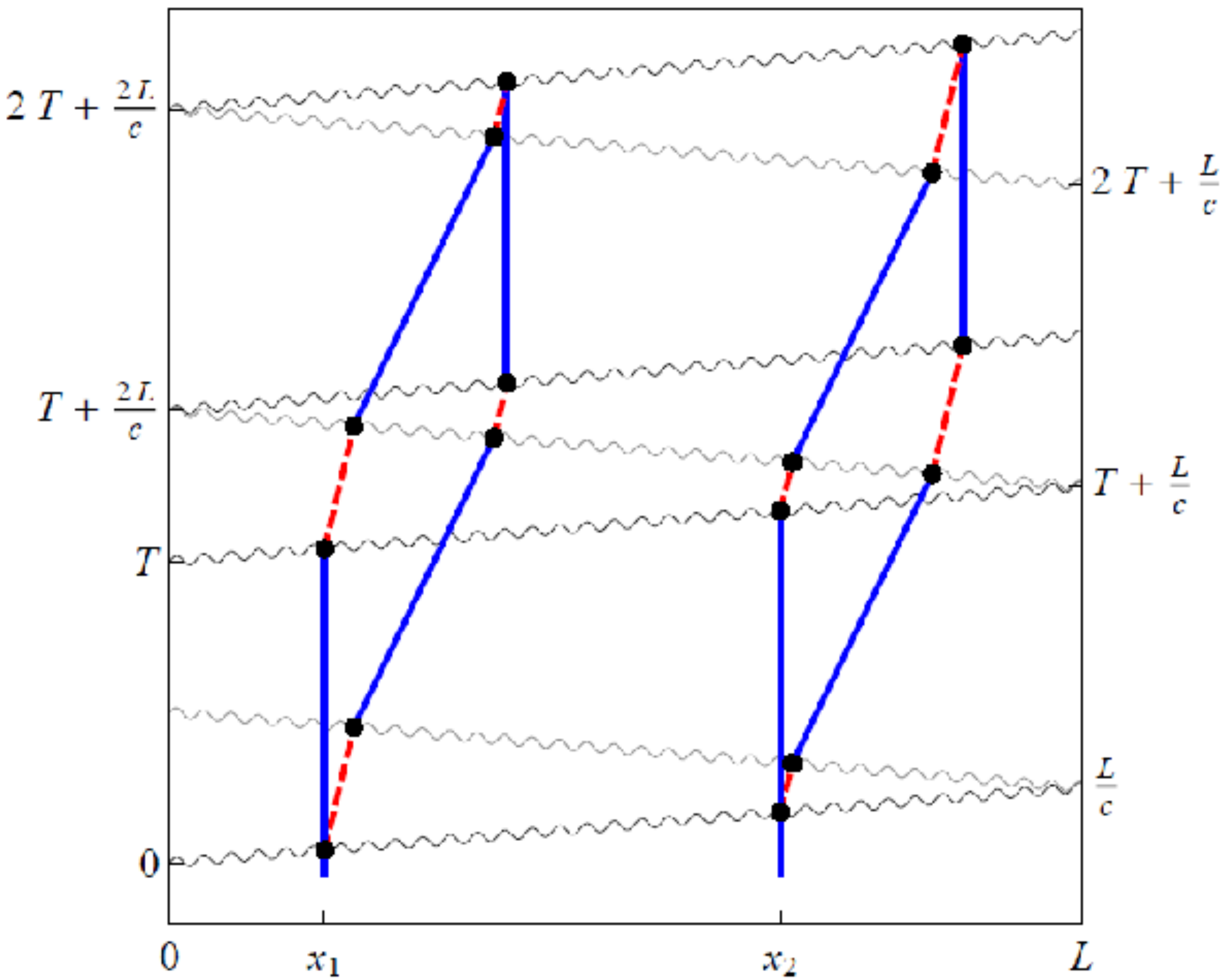
# Laser Phase Noise

remove laser noise using multiple baselines

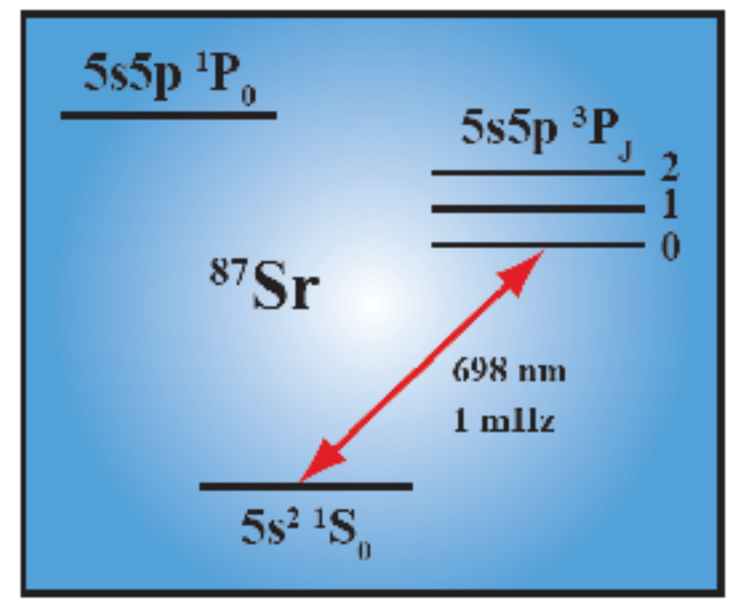
# Laser Phase Noise Insensitive Detector

run atom interferometer as hybrid clock/accelerometer

PWG, Hogan, Kasevich, Rajendran PRL **110** (2013)




atoms act as clocks, measure light travel time



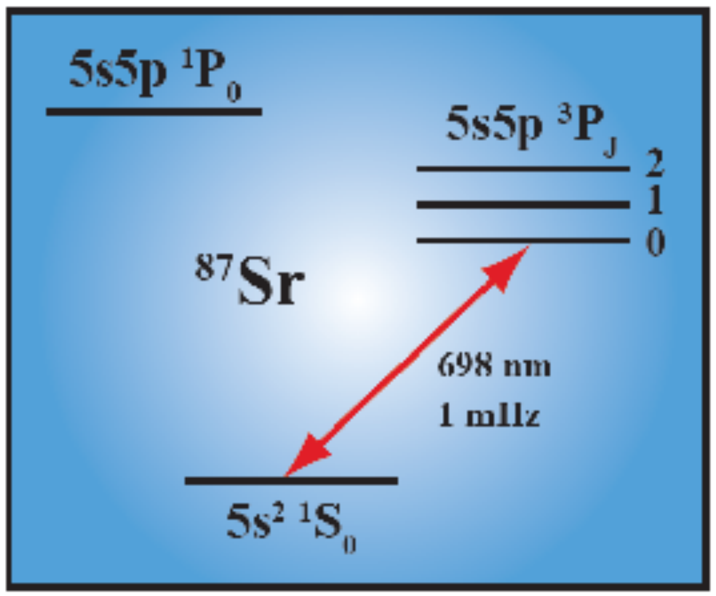

Clock transition in candidate atom $^{87}$Sr

Removes laser noise, allows single baseline detection

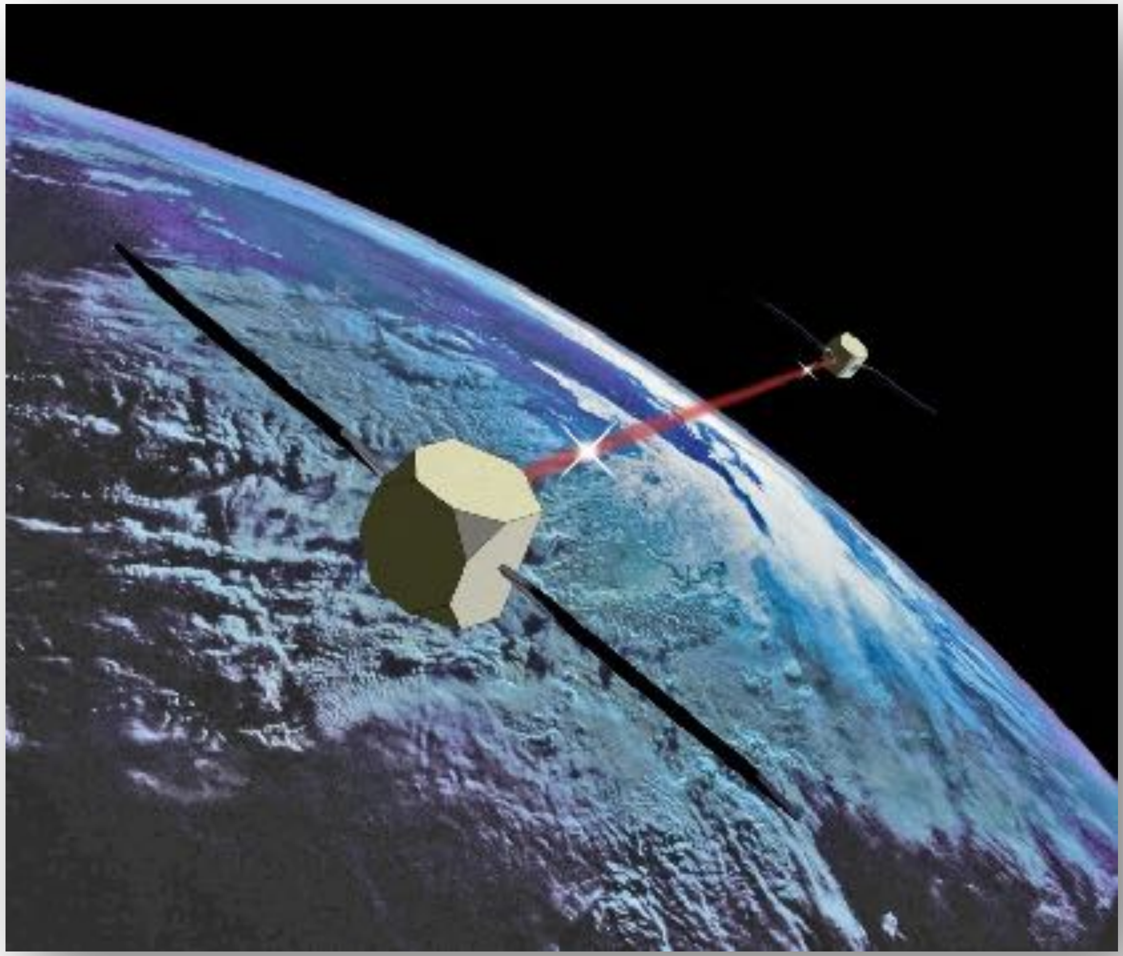
# Atom Interferometry for Gravitational Waves

run atom interferometer as hybrid clock/accelerometer

PWG, Hogan, Kasevich, Rajendran PRL **110** (2013)




Clock transition in candidate atom $^{87}$Sr

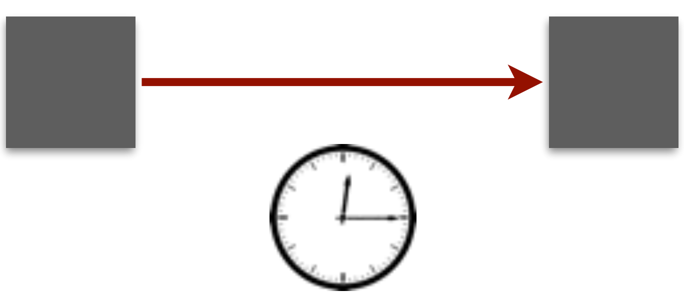


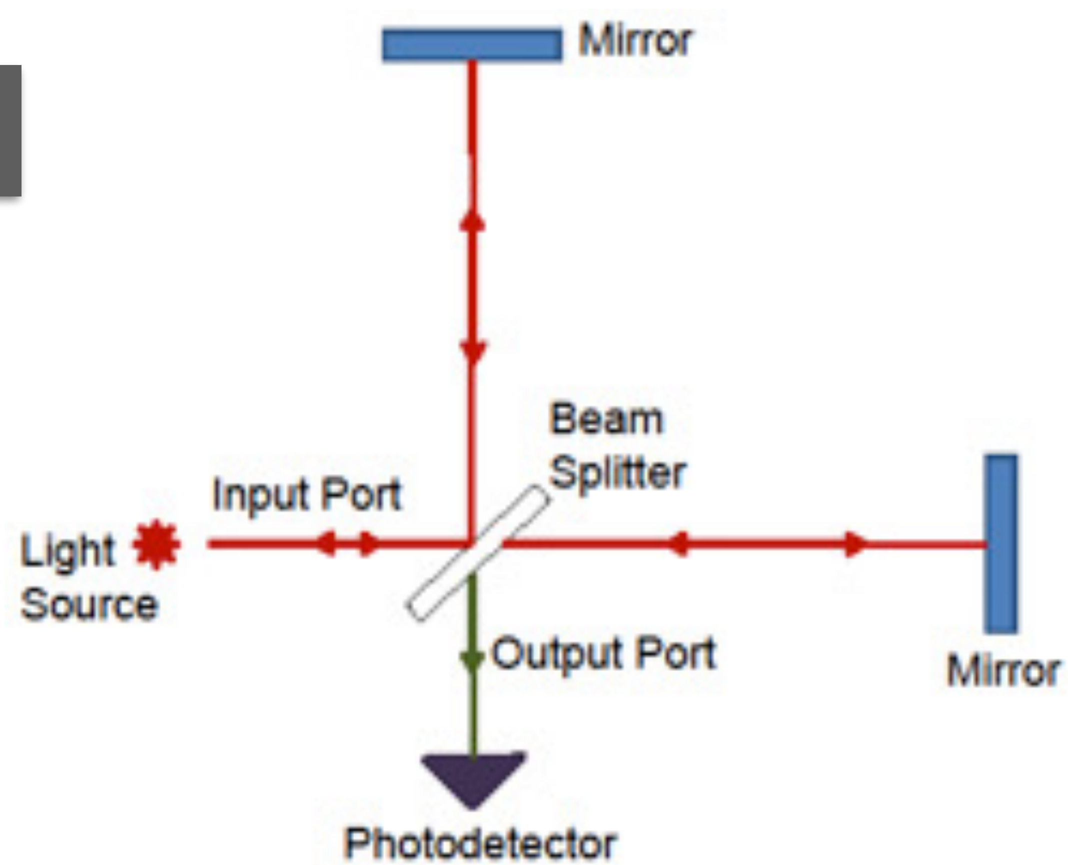
atoms act as clocks ➜ remove laser noise

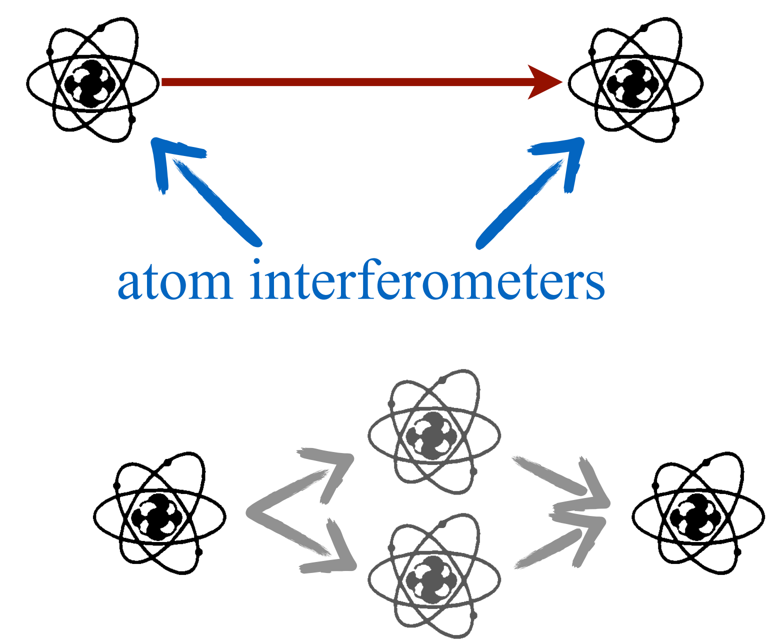
accelerometer ➜ atoms are good inertial test masses, removes many noise sources (seismic, thermal vibrations, vacuum gas collisions, charging…)

# Gravitational Wave Detection

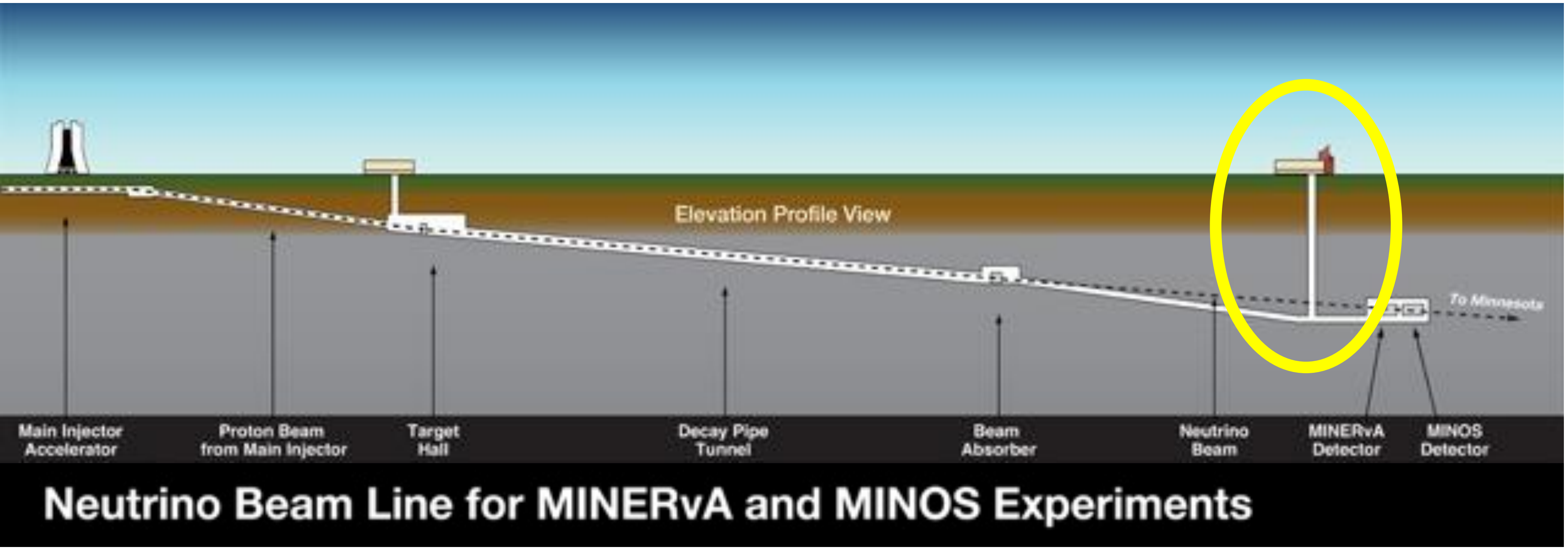
| Gravitation Wave Detector | LIGO | Atom Interferometry |
|---|---|---|
| inertial test masses | mirrors | atoms |
| baseline | laser | laser |
| good clock | second arm | atoms |

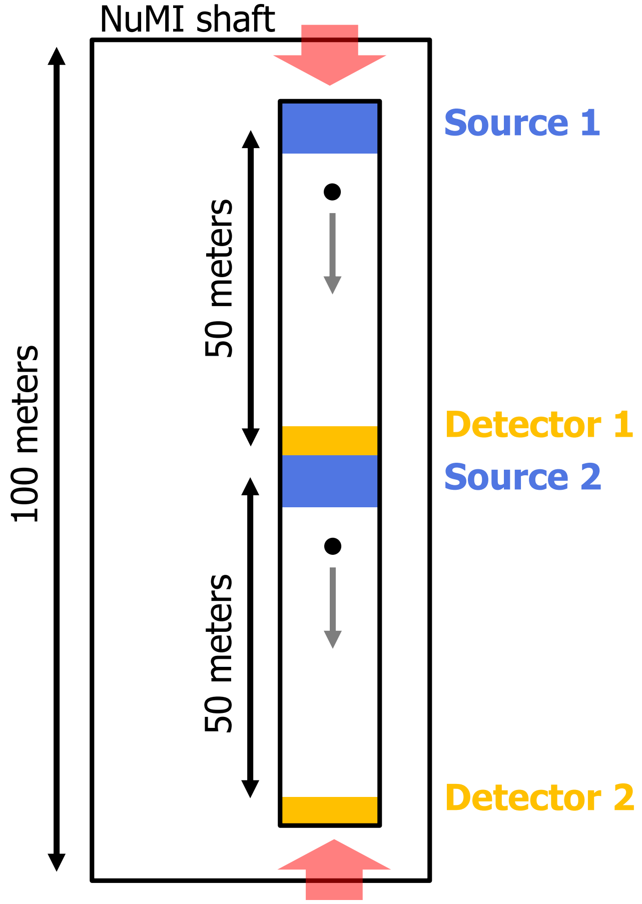




# 100 m Detector Proposal at Fermilab

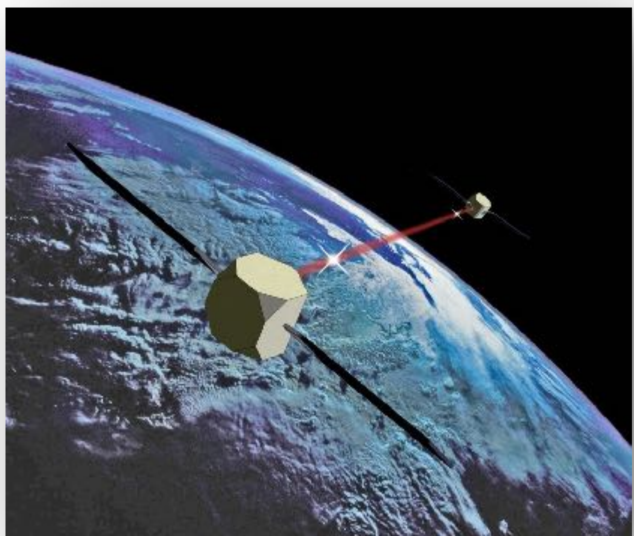


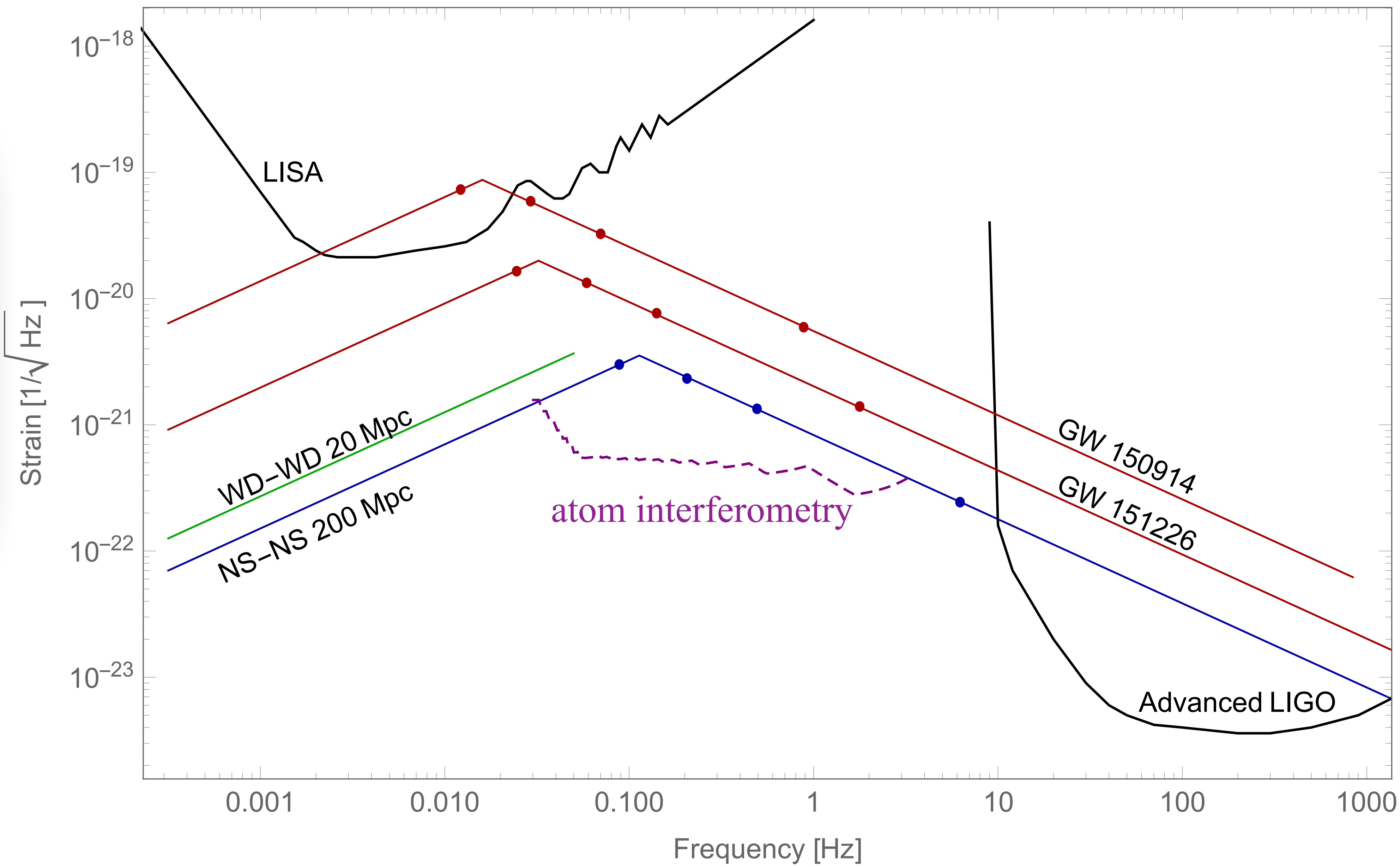

- 100 m atom interferometer (accelerometer) drop tower
- >3 s drop time to split and recombine atomic wavefunctions
- Detect dark matter through oscillatory force
- Also gravitational waves from unknown sources
- Lead to ~km scale detector for GW's (e.g. BH mergers) and DM, opens band below LIGO and above LISA (~ 0.1 - 10 Hz)

# Atom Interferometry for Gravitational Waves

Atoms could access mid-frequency band



earth orbit allows polarization measurement with single detector




for example this band allows:

localize sources on the sky (e.g. sub-degree accuracy) and predict BH and NS binary mergers for other telescopes to observe

with Sunghoon Jung

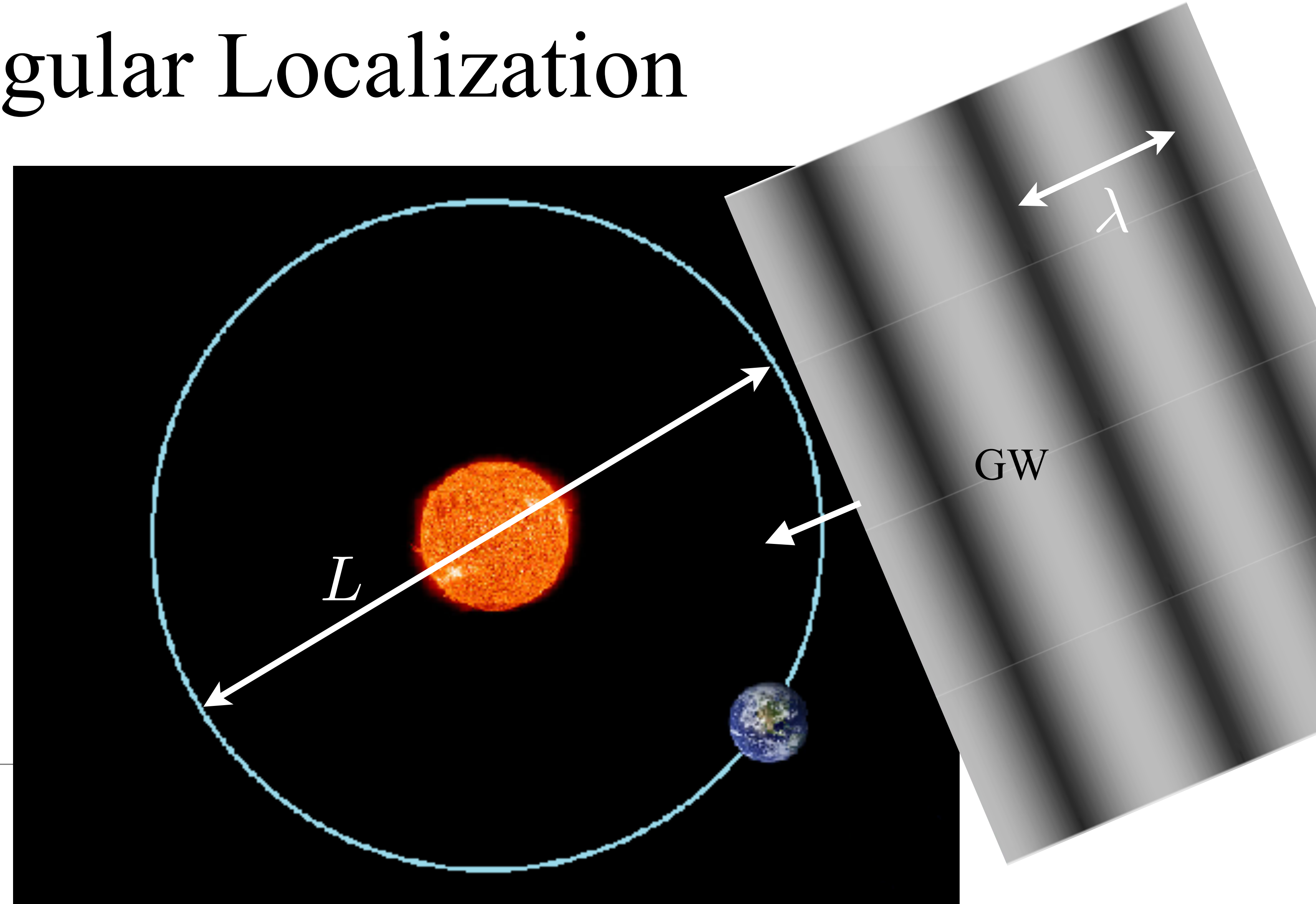
may measure initial BH spins and orbital eccentricity

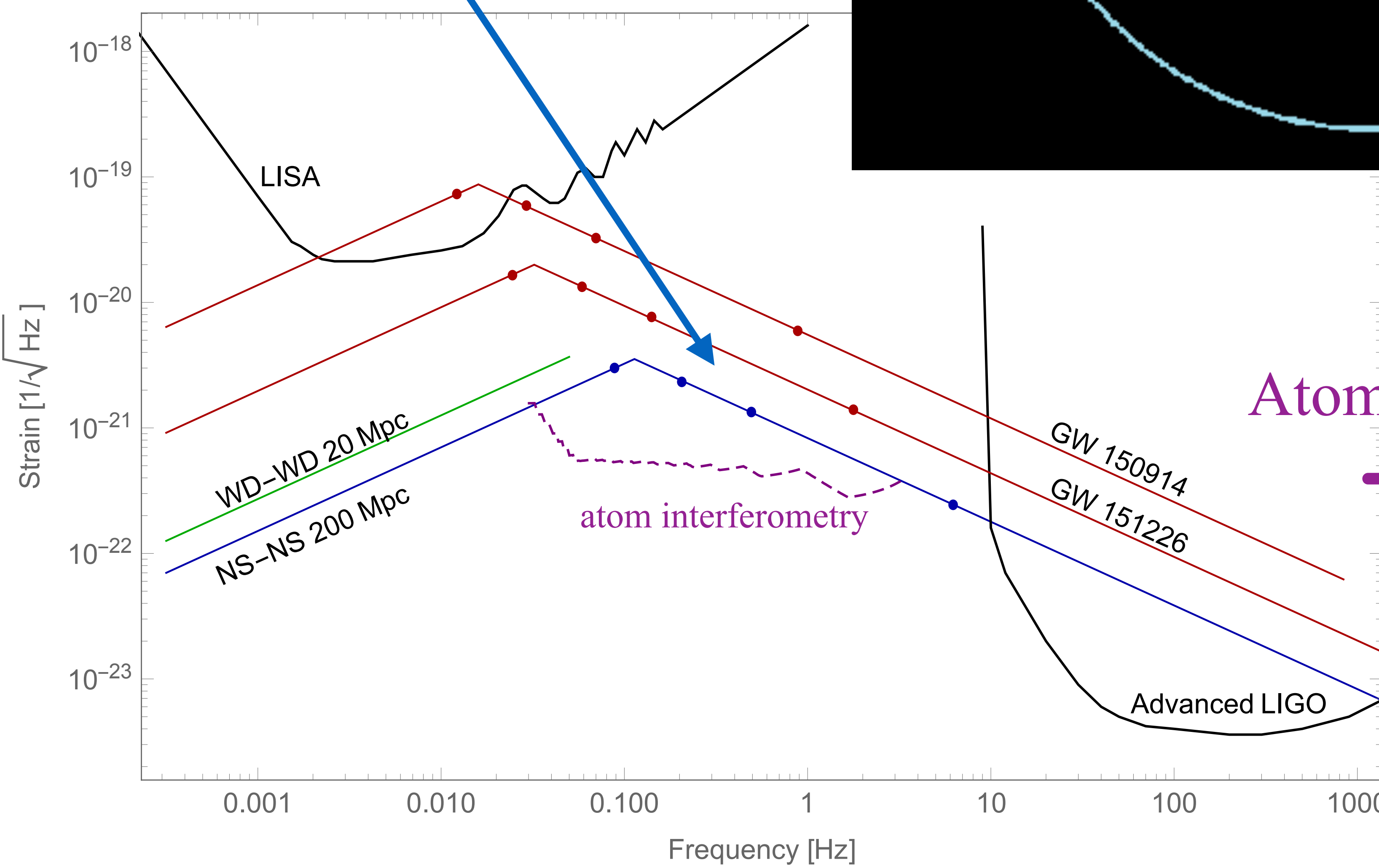
# Angular Localization

phase advance across orbit (between detectors) dominates angular resolution

$$\Delta\theta \sim \mathrm{SNR} \cdot \frac{L}{\lambda}$$

➜ highest frequencies where source lasts 6 months are best

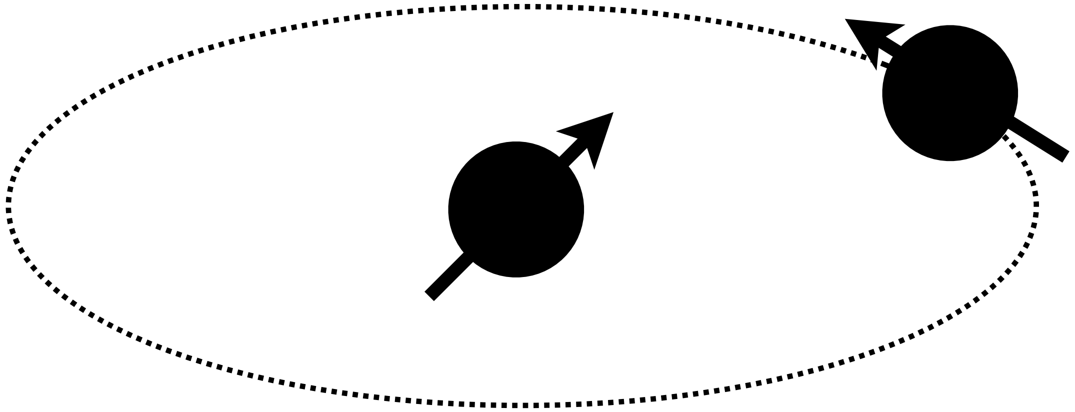


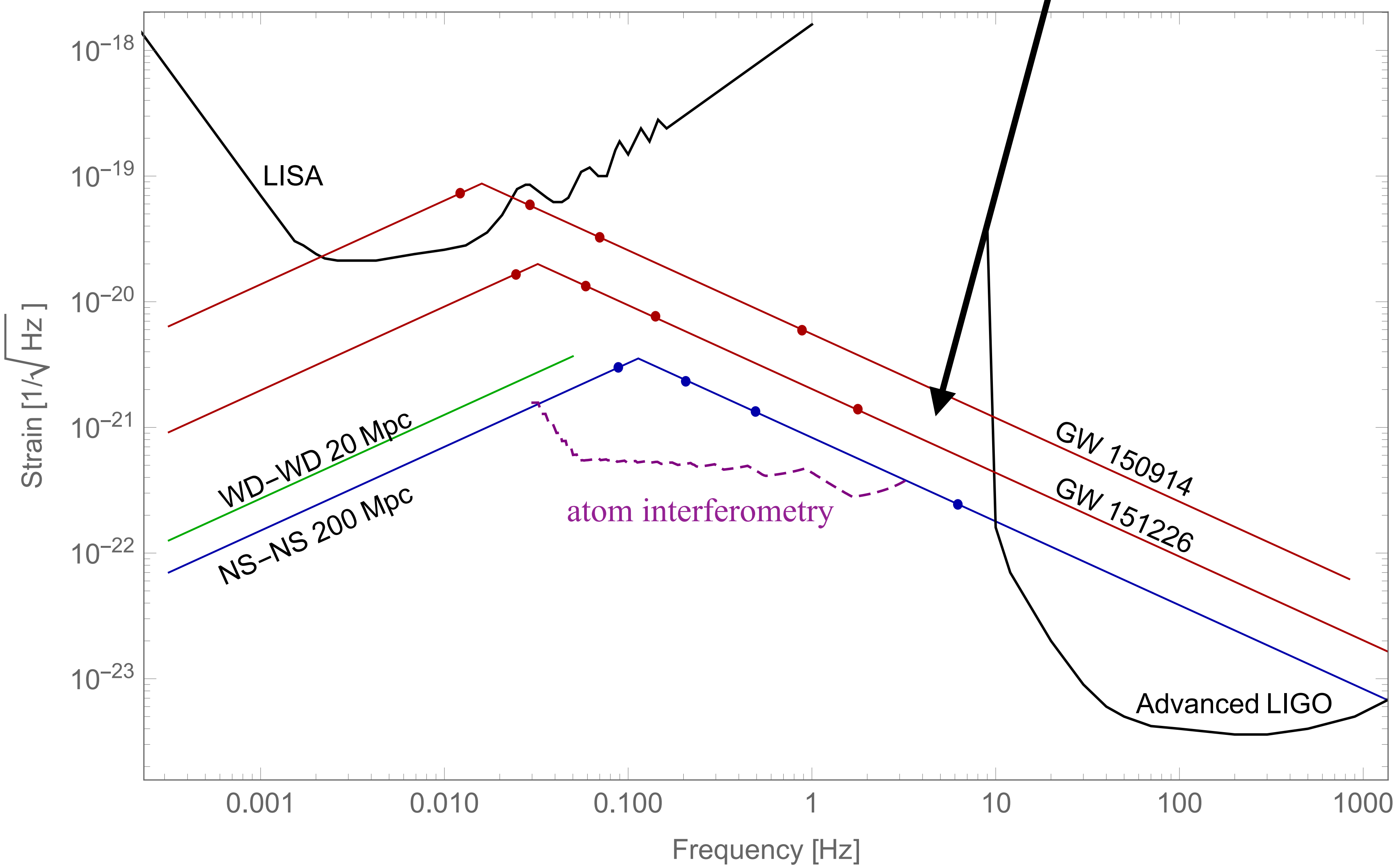

Atoms could access mid-frequency band
➜ ideal for angular localization

with Sunghoon Jung

# Initial Black Hole Spins



Gravitomagnetic BH binary spin-spin effects fall rapidly with distance, seen only in highest frequencies before merger



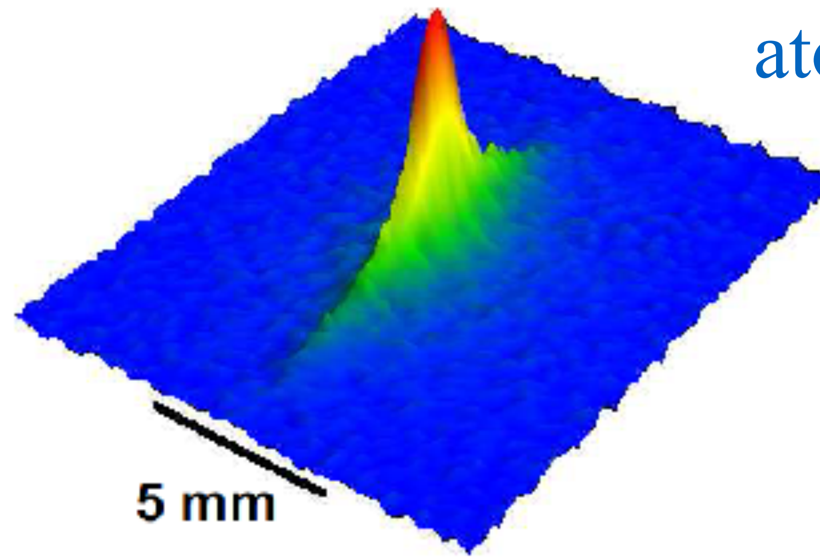

LIGO can't measure well, needs lower frequencies ➜ atoms (terrestrial or satellite) could measure?
gives info on formation history (primordial?), etc. of BH's

# Recent Experimental Results

(Kasevich and Hogan groups)

## Stanford Test Facility

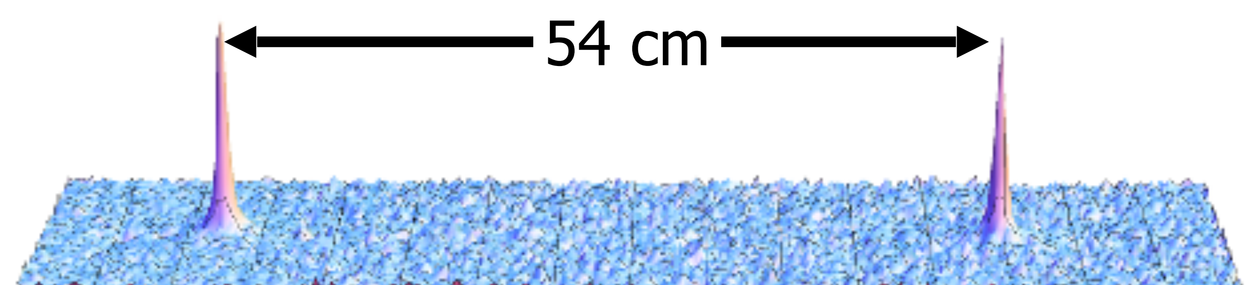
demonstrate necessary technologies:




atom cooling

→ 50 pK

Macroscopic splitting of atomic wavefunction:




Kovachy et. al, *Nature* (2015)

# Summary

Precision measurement is a powerful tool for particle physics and cosmology

new technologies beyond traditional particle detection

e.g. combination of several experiments will cover QCD axion dark matter fully

Light dark matter (axions) and gravitational wave detection similar:

detect coherent effects of entire field, not single particles

- laser interferometry
- atom interferometry (clocks)
- EM resonators (e.g. cavities)
- NMR
- high-precision magnetometry (SQUIDs, atomic systems)
- torsion pendulums
- optically-levitated dielectric spheres
- …

Many more possibilities we haven't thought of yet…