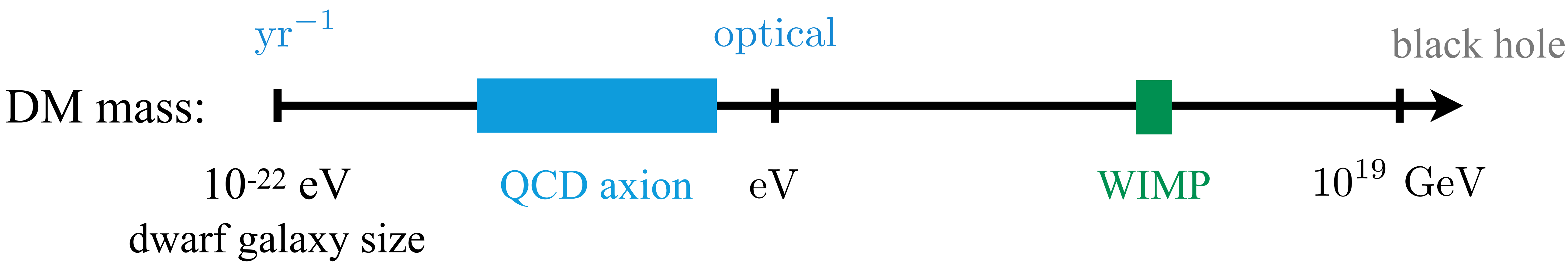
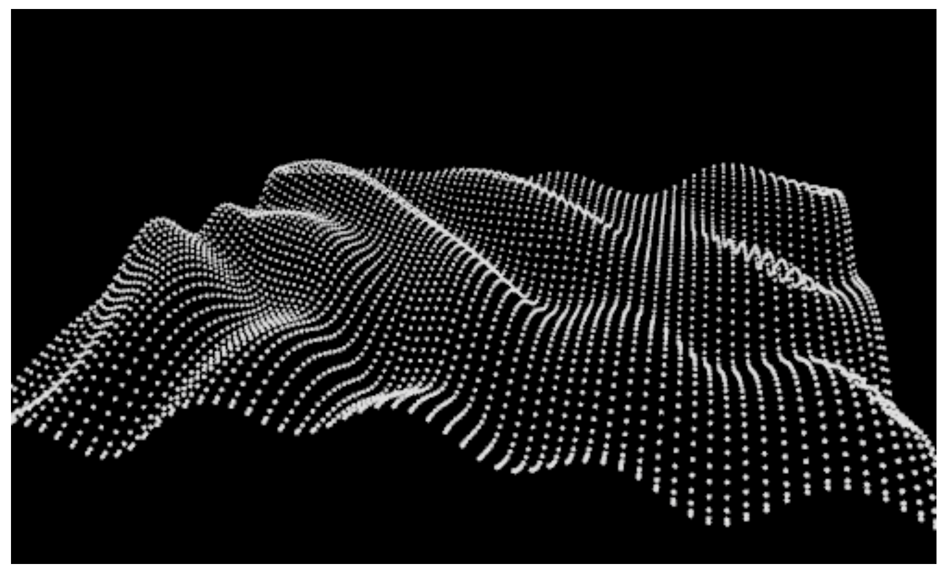
Ultralight Dark Matter and Gravitational Wave Detection

Peter Graham

Stanford

Dark Matter Direct Detection



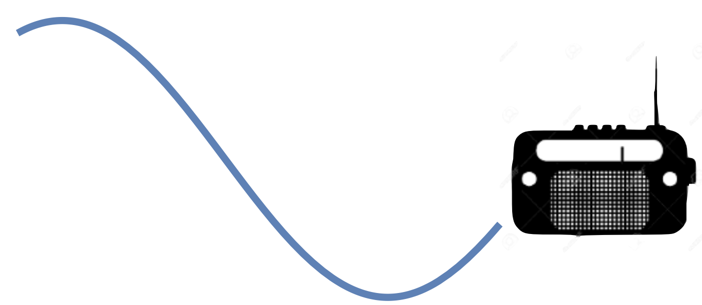


at long deBroglie wavelength
a "coherent" field

signal is line at
frequency = DM mass
and width 10^{-6}

new, precision detectors required

Detect coherent effects of entire field
(like gravitational wave detector)



Frequency range accessible!

DM Radio

with

Kent Irwin
Saptarshi Chaudhuri
Jeremy Mardon
Surjeet Rajendran
Yue Zhao

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SLAC

KIPAC

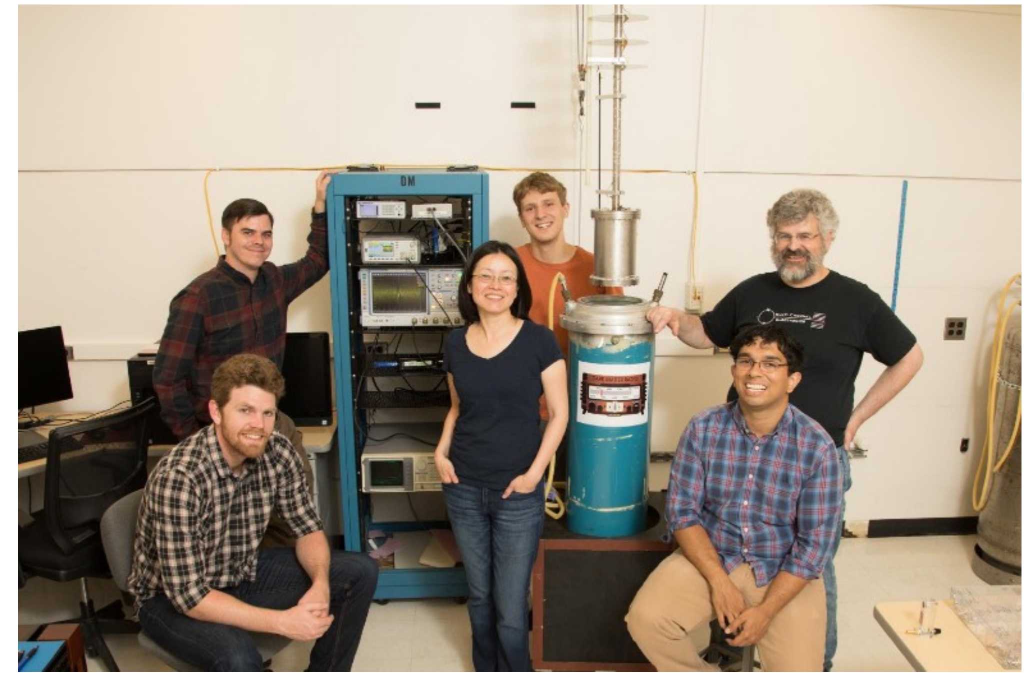
PRD **92** (2015) arXiv:1411.7382

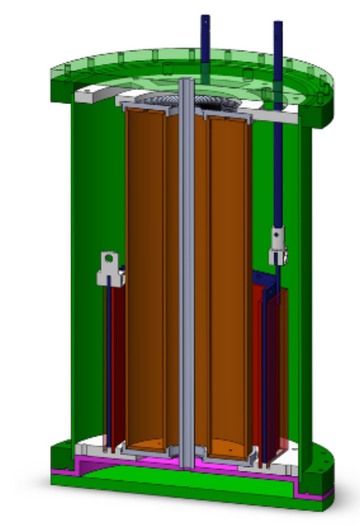
DM Radio Experiment

Widely tunable, lumped element EM resonator

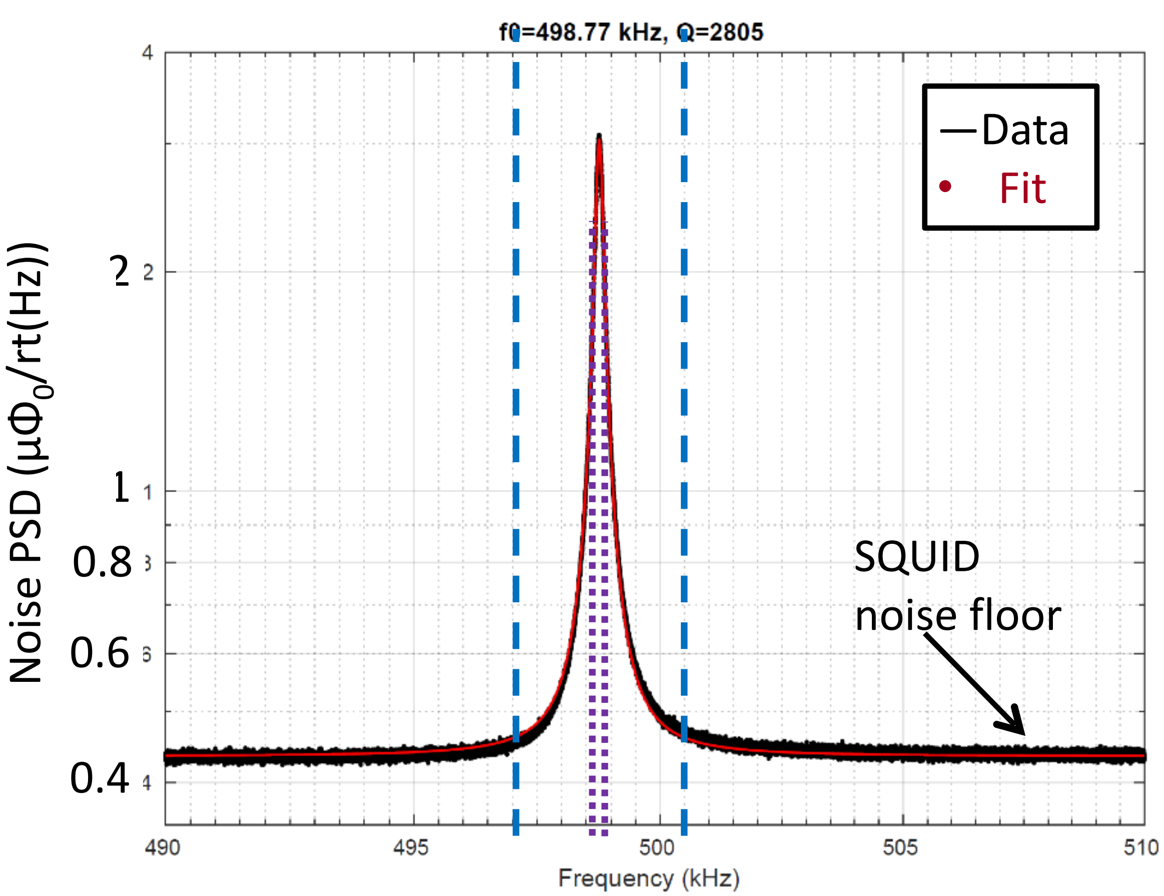
- low dissipation/low noise resonator Q ~ 10^6
- high precision magnetometry/amplifiers (SQUIDs)

start with hidden photon detection,
later add B field for axion detection





Pathfinder: 4 K 300 cm^3
under construction, initial results ~ 2018



Stanford: Arran Phipps, Dale Li, Saptarshi Chaudhuri, Peter Graham, Jeremy Mardon, Hsiao-Mei Cho, Stephen Kuenstner, Carl Dawson, Richard Mule, Max Silva-Feaver, Zach Steffen, Betty Young, Sarah Church, Kent Irwin
Berkeley: Surjeet Rajendran
Collaborators on DM Radio extensions:
Tony Tyson, UC Davis, Lyman Page, Princeton

see also Lindley Winslow's talk

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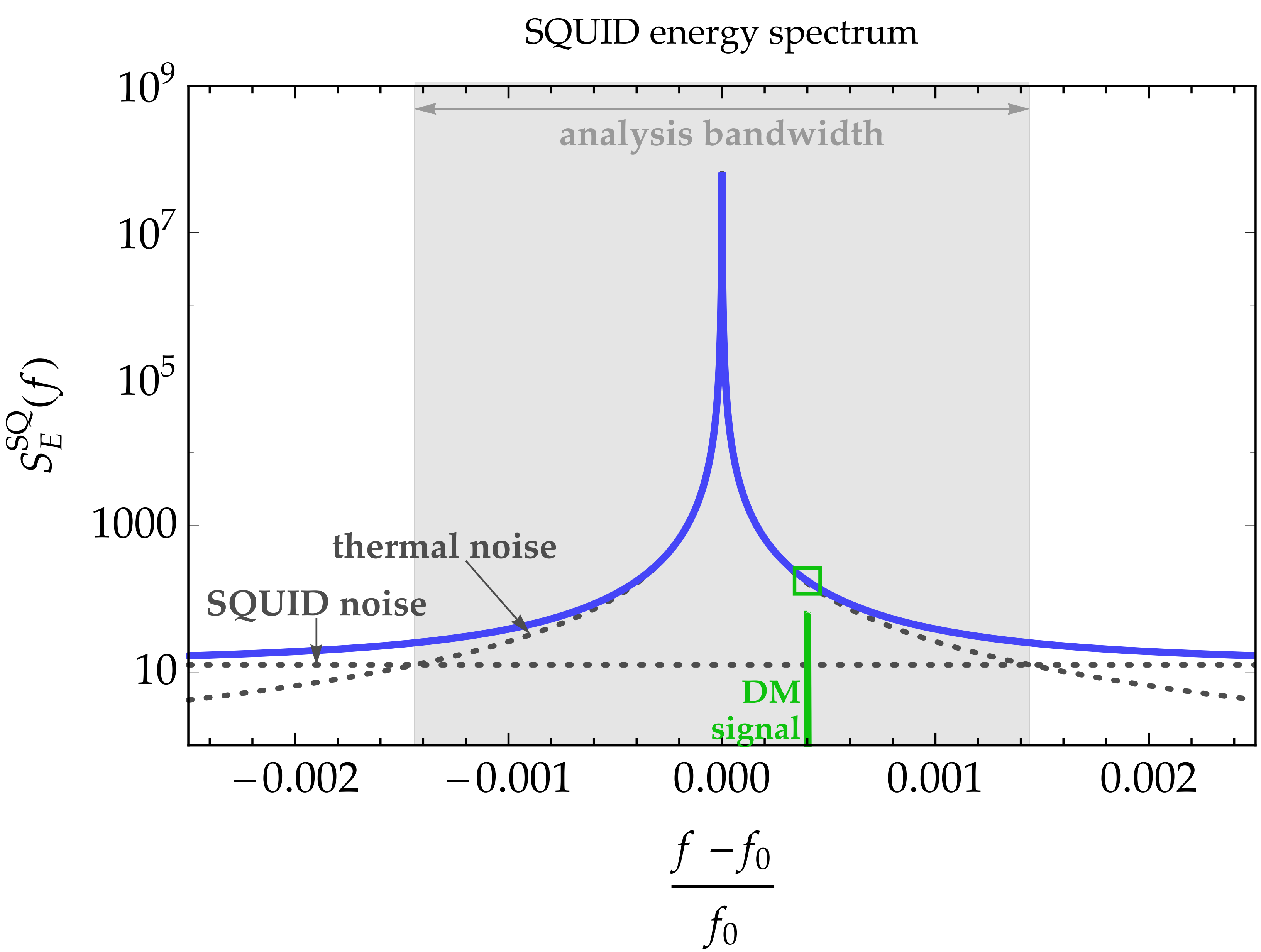
Optimizing Electromagnetic Axion Detectors

Chaudhuri, Irwin, PWG, Mardon arXiv:1803.01627

optimal experiment:

- make highest resonator Q possible, even above 10^6
- "out of band": take analysis bandwidth (step size) much broader than resonator and dark matter bandwidth

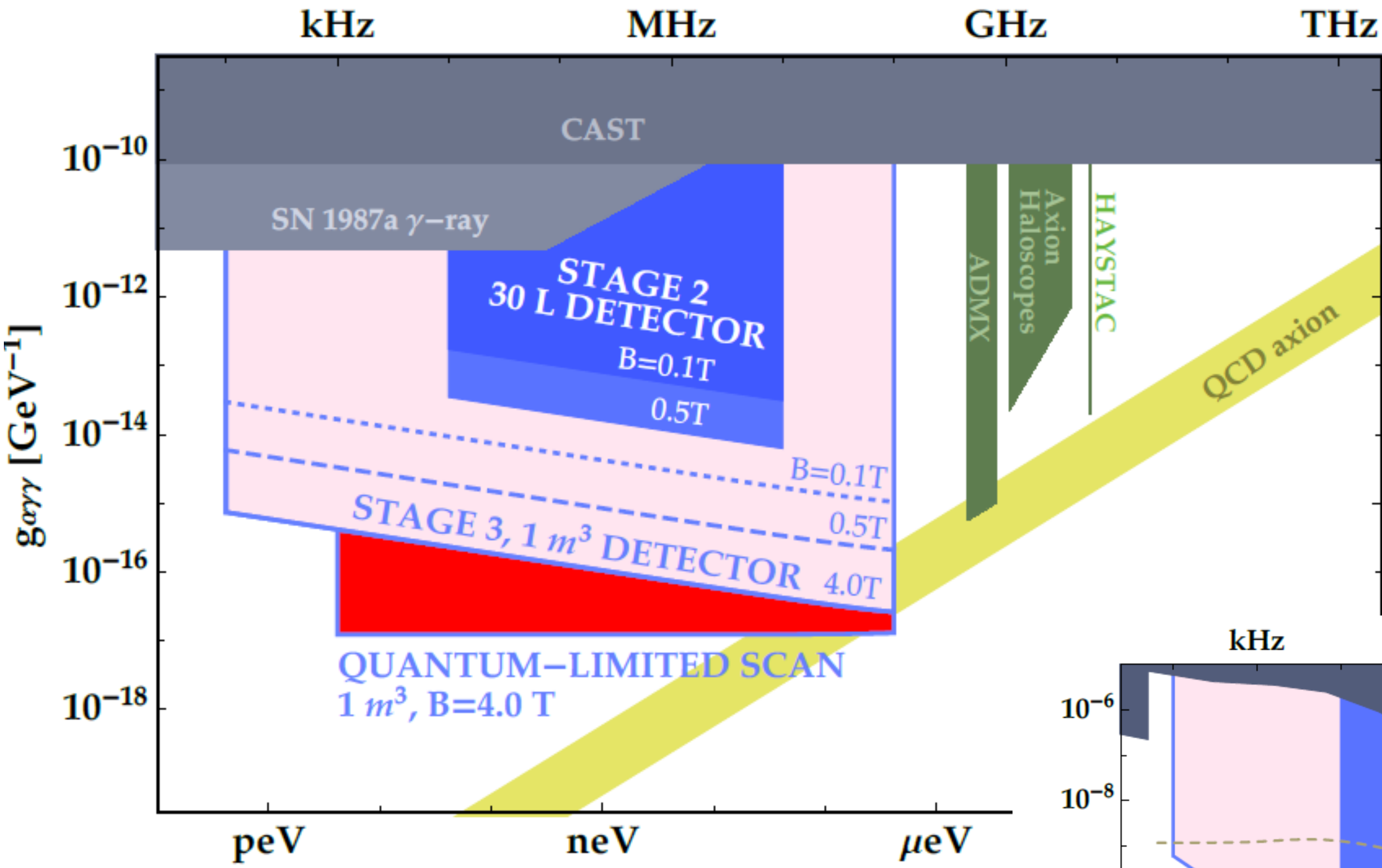


single resonator essentially reaches ultimate Bode-Fano limit

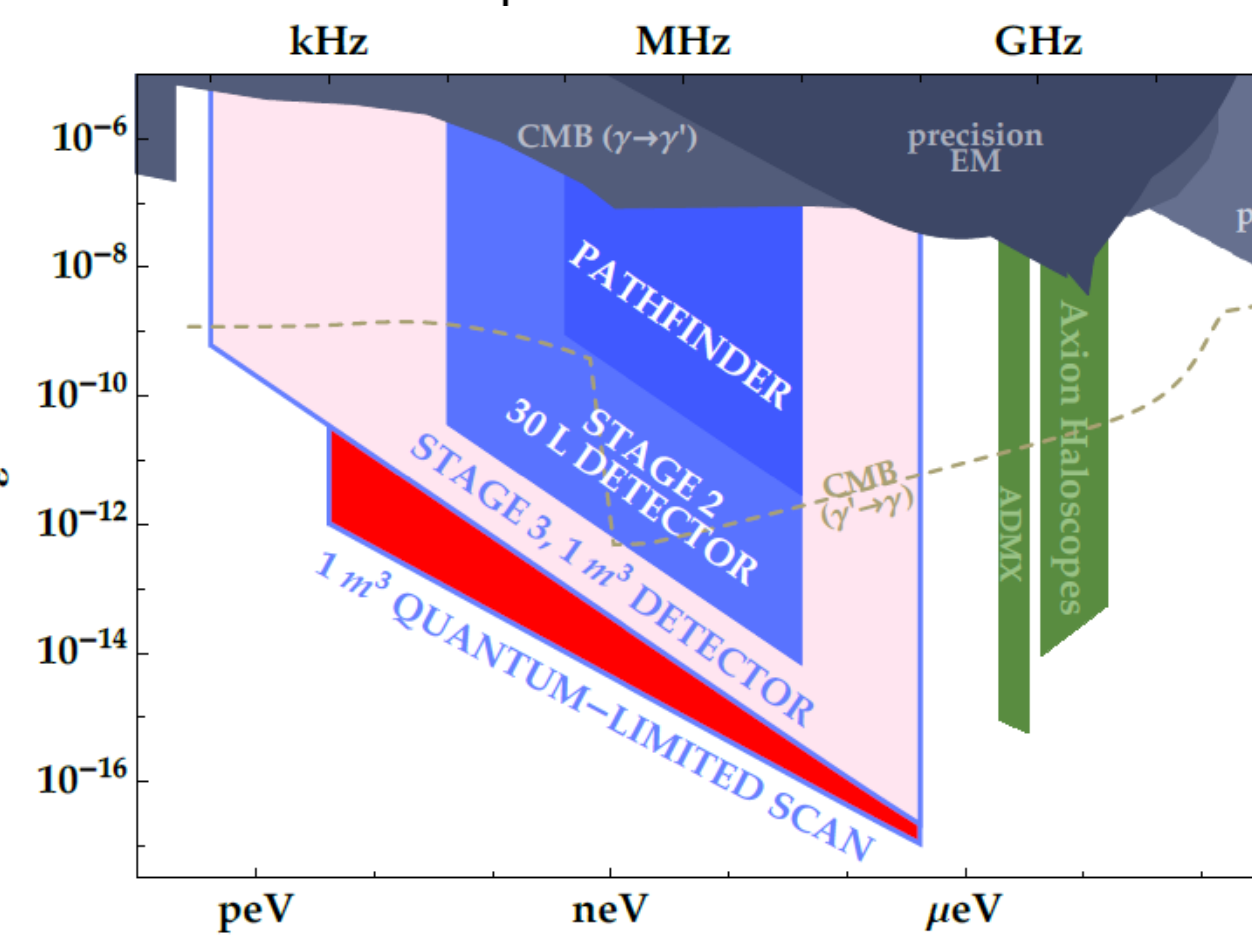
must also include quantum noise

can enhance sensitivity by orders of magnitude

DM Radio Sensitivities

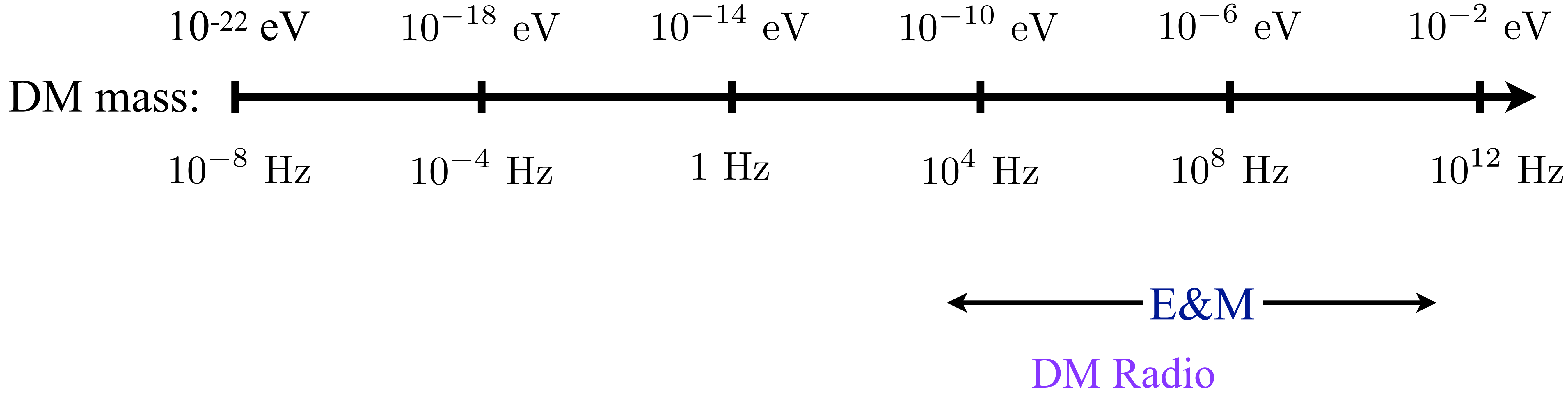


axion sensitivity



hidden photon sensitivity

Ultralight DM Direct Detection



Cosmic Axion Spin Precession Experiment (CASPEr)

with

Dmitry Budker
Micah Ledbetter
Surjeet Rajendran
Alex Sushkov

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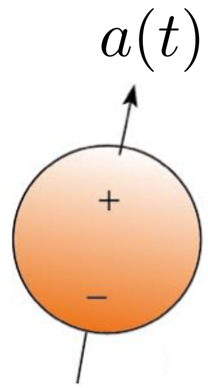
SIMONS FOUNDATION

DFG Deutsche Forschungsgemeinschaft

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

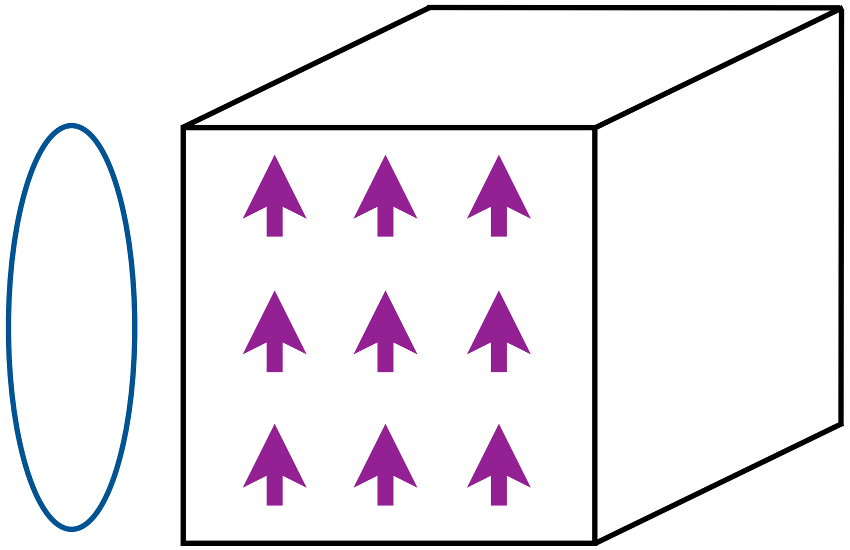
Cosmic Axion Spin Precession Experiment (CASPEr)

search for oscillating nuclear EDM
(not derivative suppressed)



and axion "wind" (spin precession)

SQUID
pickup



Applied EM fields cause NMR-style resonance

SQUID measures resulting transverse magnetization

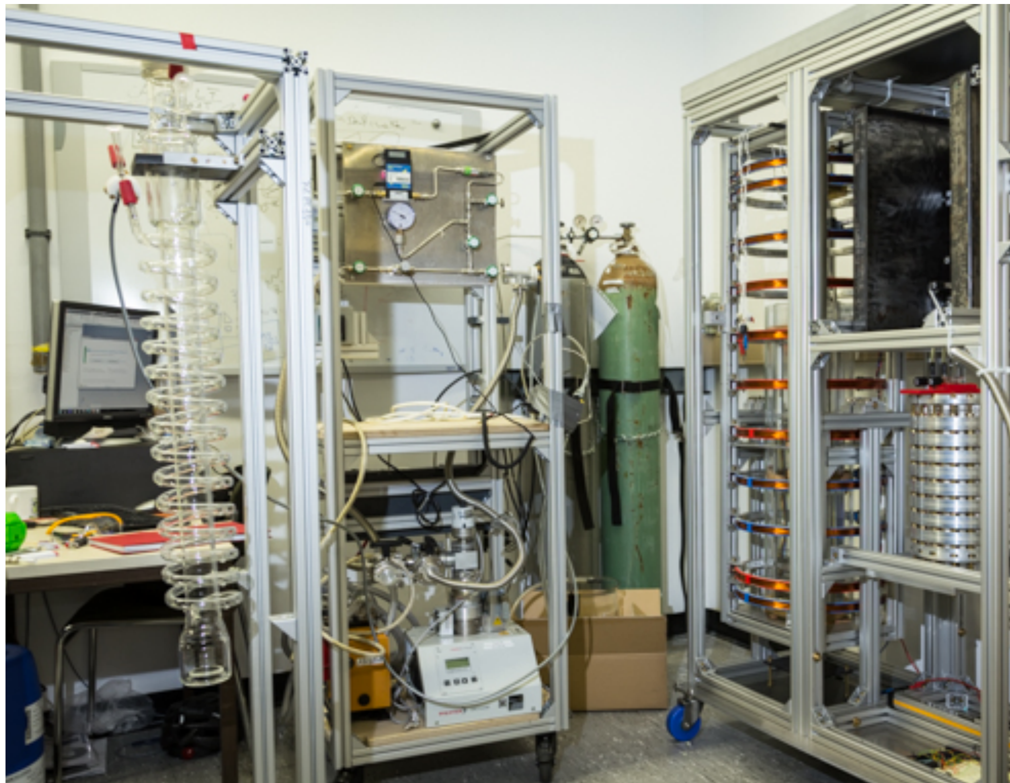
Only known way to reach QCD axion at lowest masses ~ kHz - MHz

Sensitivity comes from:

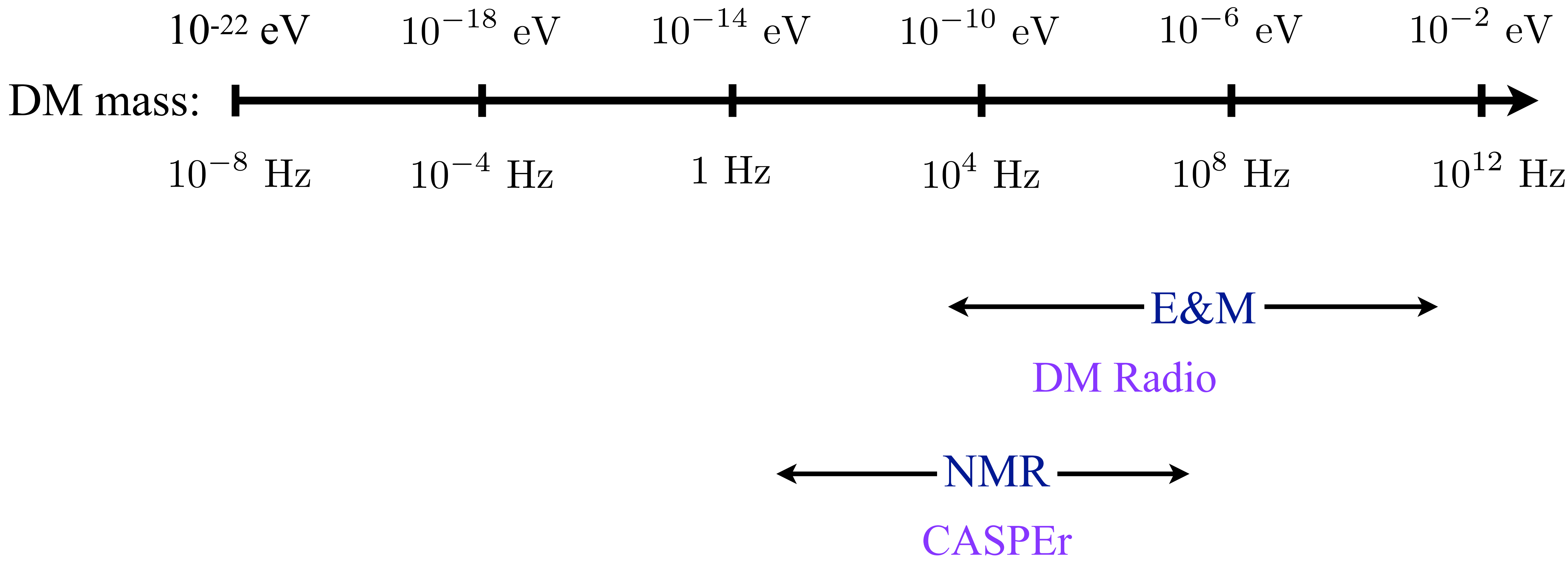
- NMR technology
- high precision magnetometry

first results out very soon!

under construction at Mainz and BU

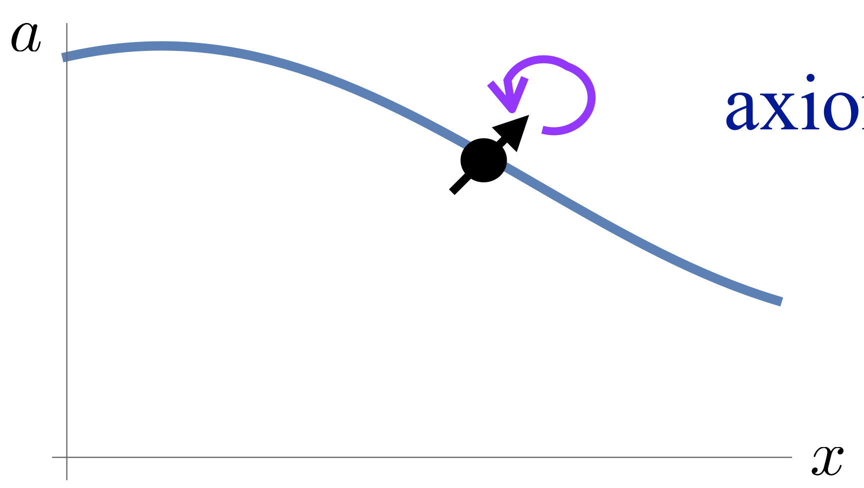


Ultralight DM Direct Detection



Ultralight DM Effects

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

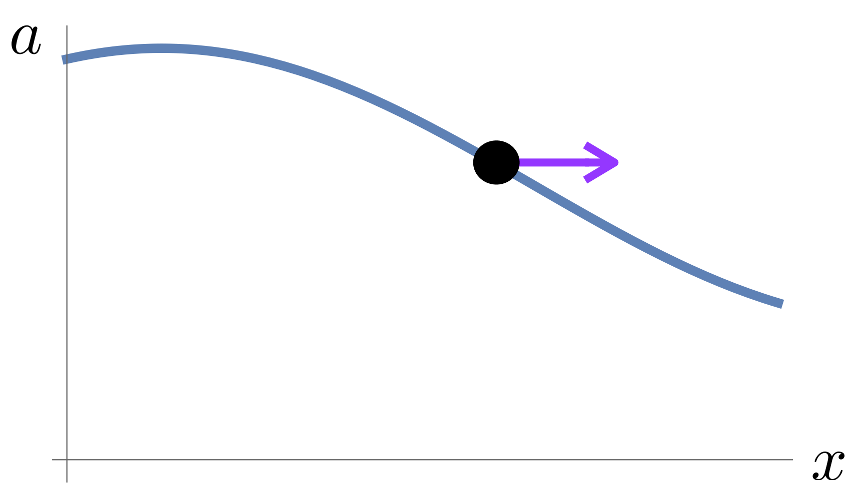


axion DM field gradient torques electron and nucleon spins

oscillates with axion frequency

proportional to axion momentum ("wind")

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



DM field gradient can exert a force

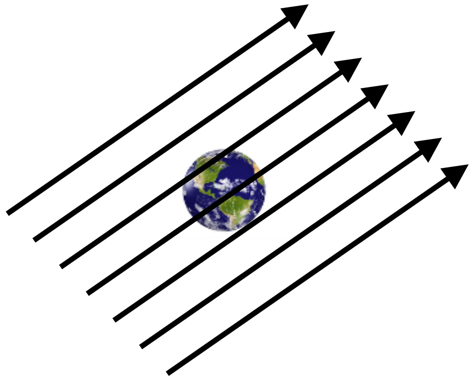
oscillatory and violates equivalence principle

same effects allow searches for hidden photons

Force/Torque from Ultralight Dark Matter

arXiv:1709.07852
arXiv:1512.06165

New oscillatory force/torque from dark matter



New Direct Detection Experiments:

Torsion Balances

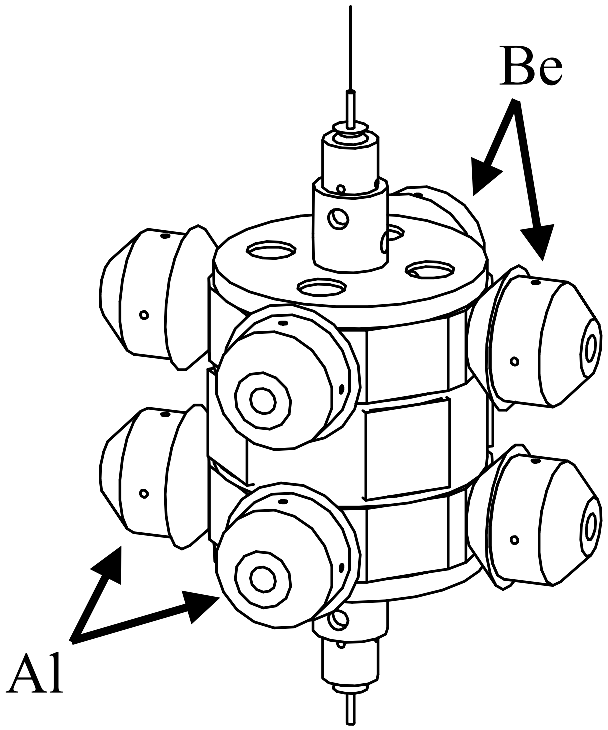
scalar balance for force
spin-polarized for torque

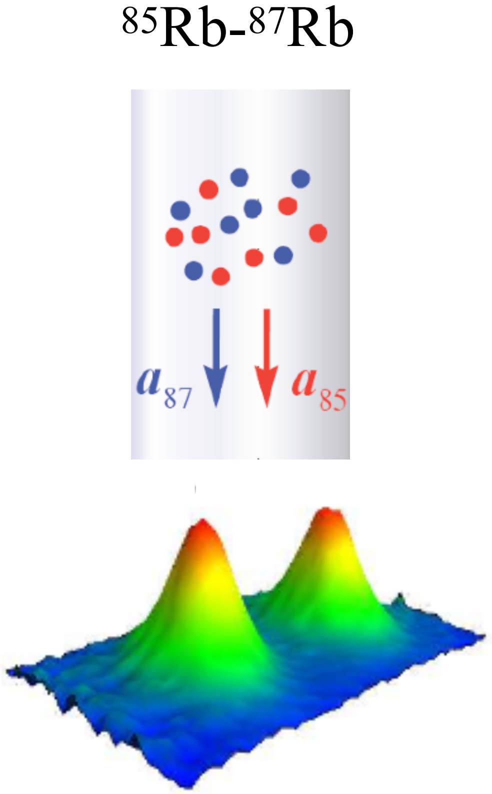
Atomic Interferometers (Clocks)

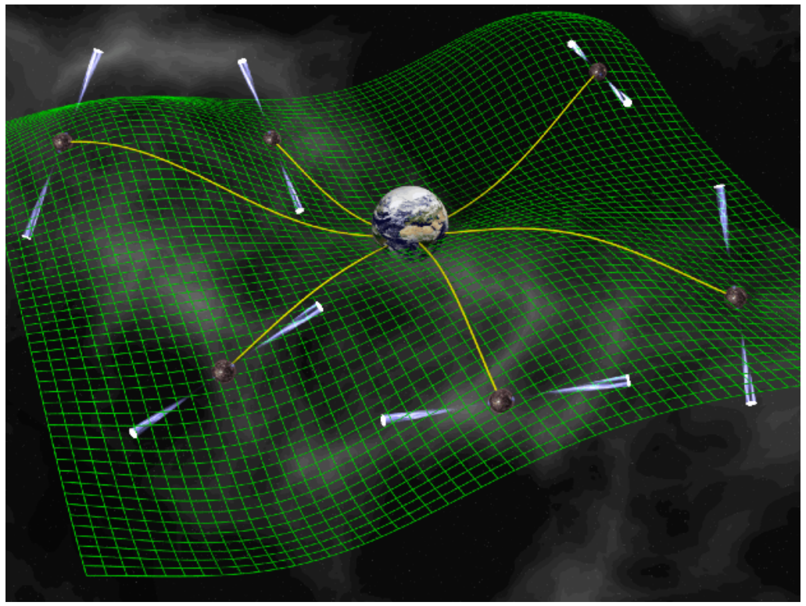
split + recombine atom wavefunction
measure atom spin and acceleration

Pulsar Timing Arrays

measure relative acceleration
of earth and pulsar







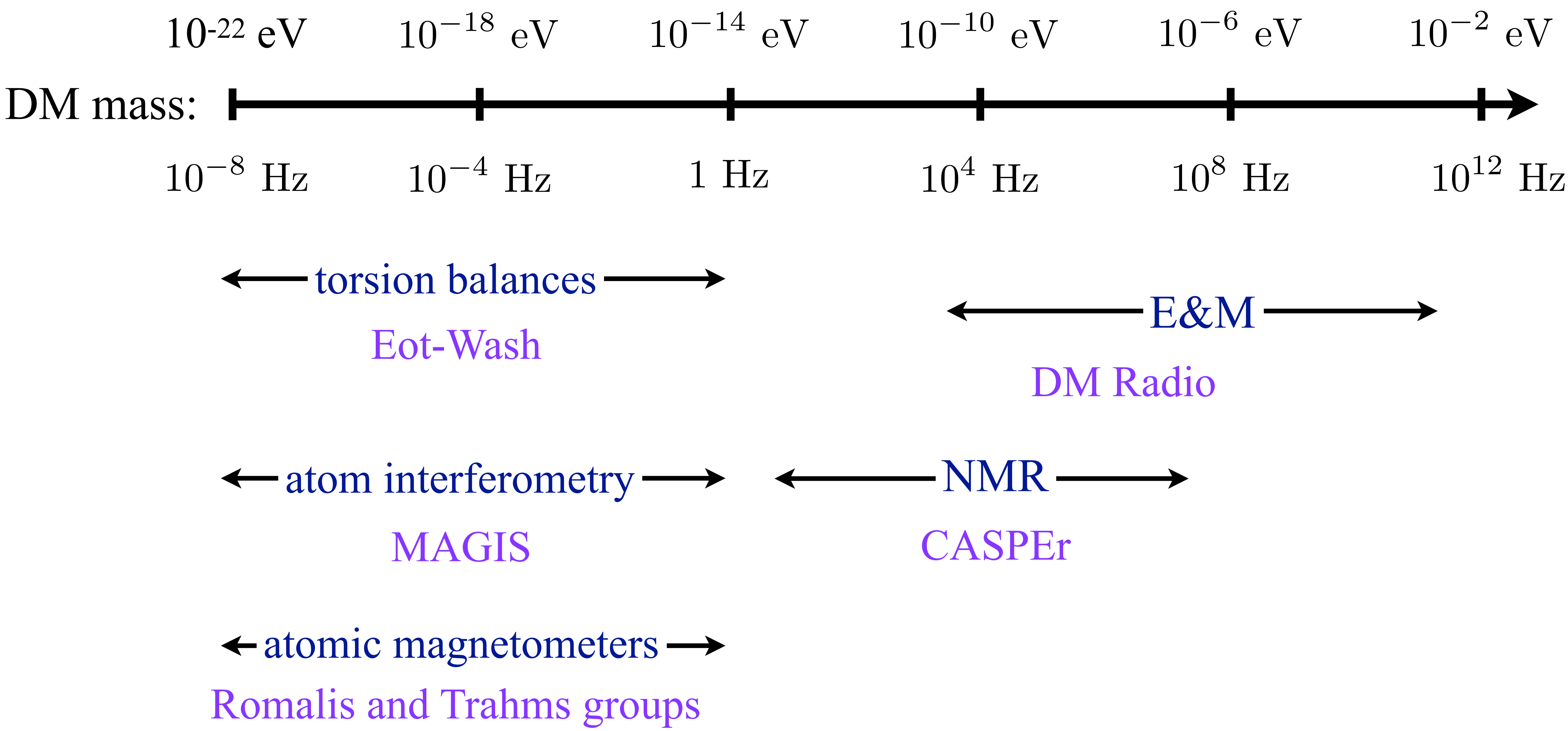
Eot-Wash analysis underway

In construction Kasevich/Hogan groups

See Mina Arvanitaki's talk

ultralight DM and gravitational wave detection similar!

Ultralight DM Direct Detection



these + many more new experiments (and ideas) will hopefully cover entire mass range for ultralight DM!

Gravitational Wave Detection with Atom Interferometry

PRD **97** (2018) arXiv:1710.03269

PRD **94** (2016) arXiv:1606.01860

PRL **110** (2013) arXiv:1206.0818

GRG **43** (2011) arXiv:1009.2702

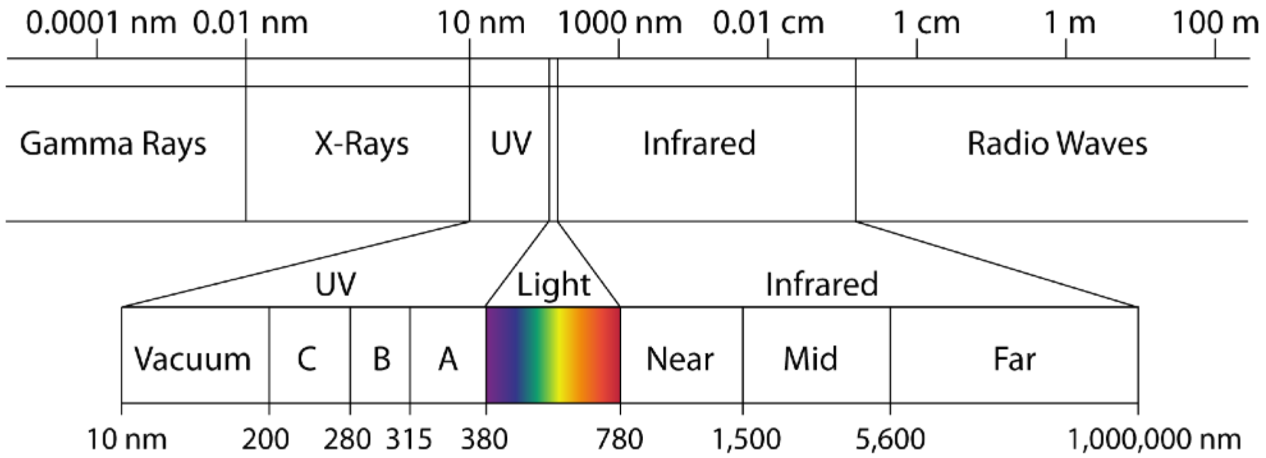
PLB **678** (2009) arXiv:0712.1250

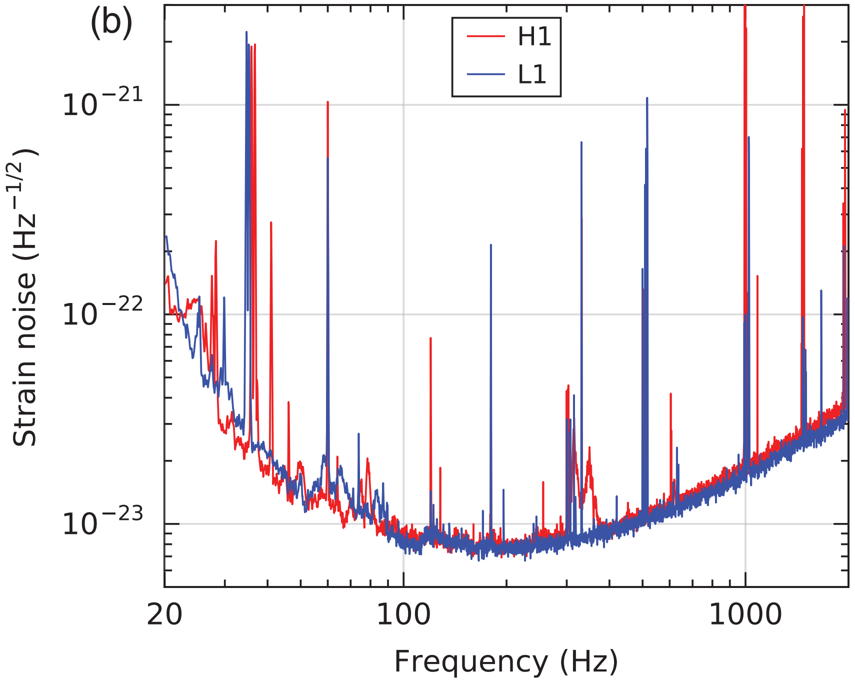
PRD **78** (2008) arXiv:0806.2125

Gravitational Spectrum

Gravitational waves open a new window to the universe

Every new EM band opened has revealed unexpected discoveries,

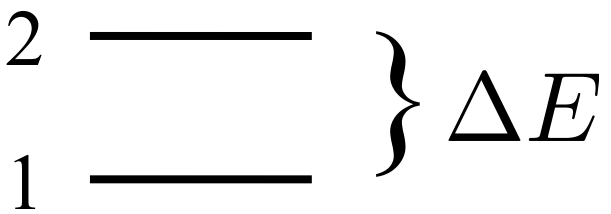




Advanced LIGO can only detect GW's > 10 Hz ➜ How look at lower spectrum?

New detectors?

Atomic Clock



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

beamsplitter
(laser pulse)

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

wait time t

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

beamsplitter

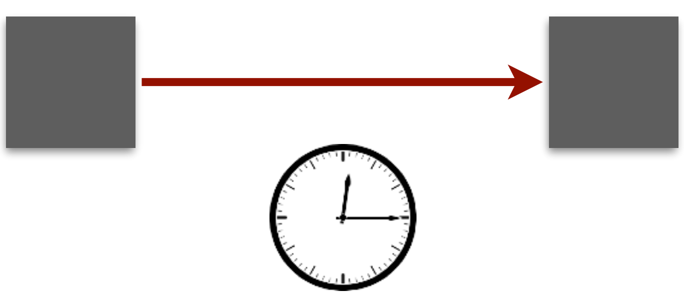
$$\frac{1}{2}\left[\left(\underbrace{1 - e^{i(\Delta E)t}}_{N_1}\right)|1\rangle + \left(\underbrace{1 + e^{i(\Delta E)t}}_{N_2}\right)|2\rangle\right]$$

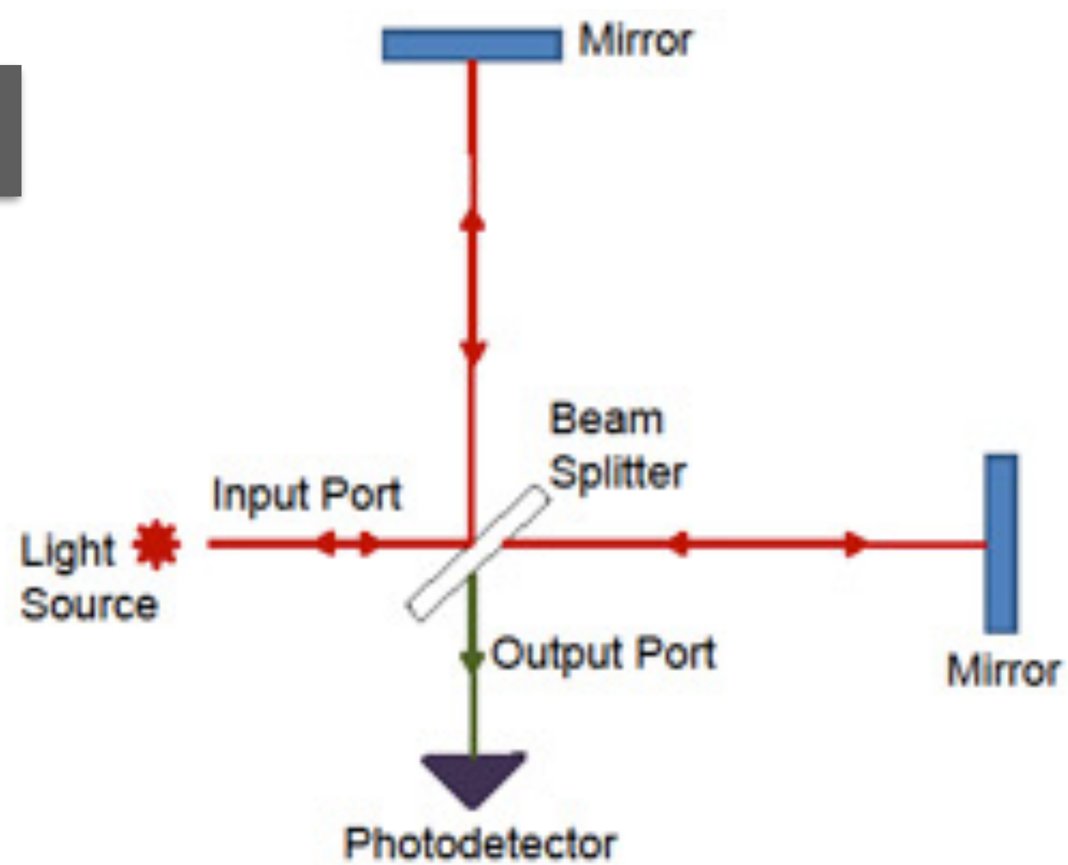
output ports

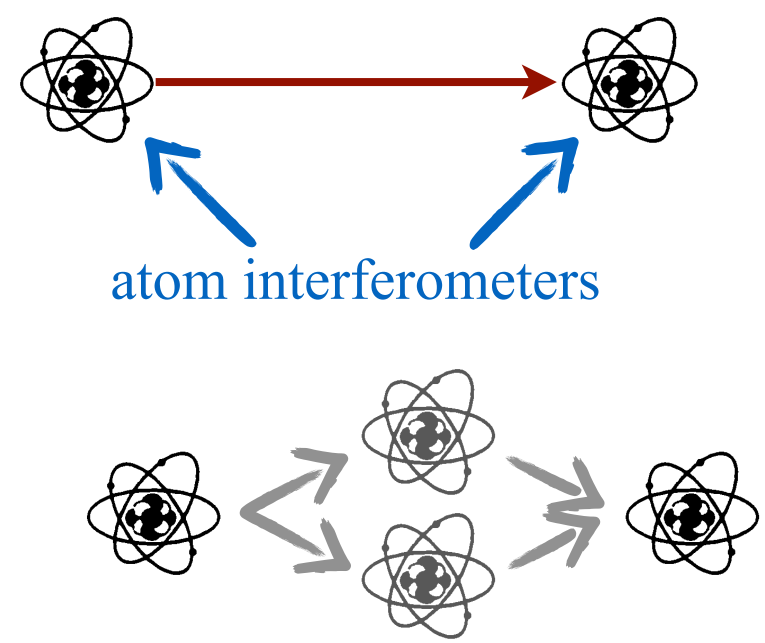
can measure times $t \sim \frac{1}{\Delta E} \sim 10^{-10}\,\text{s}$

Gravitational Wave Detection

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



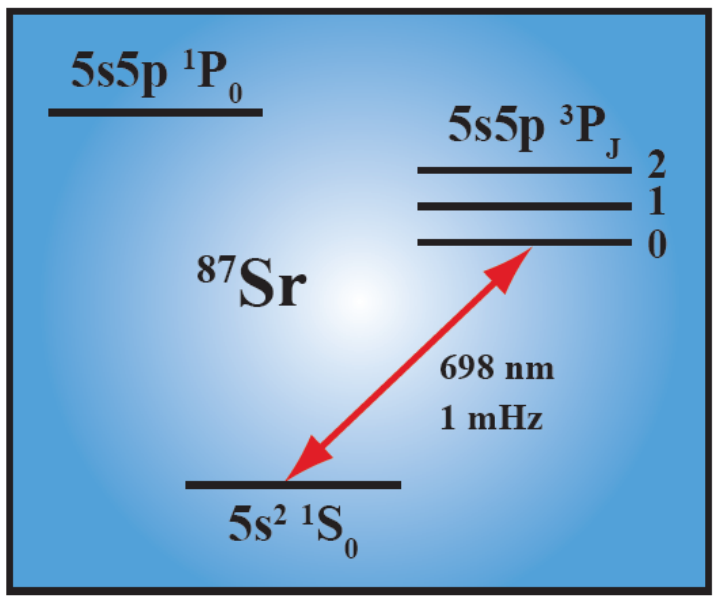




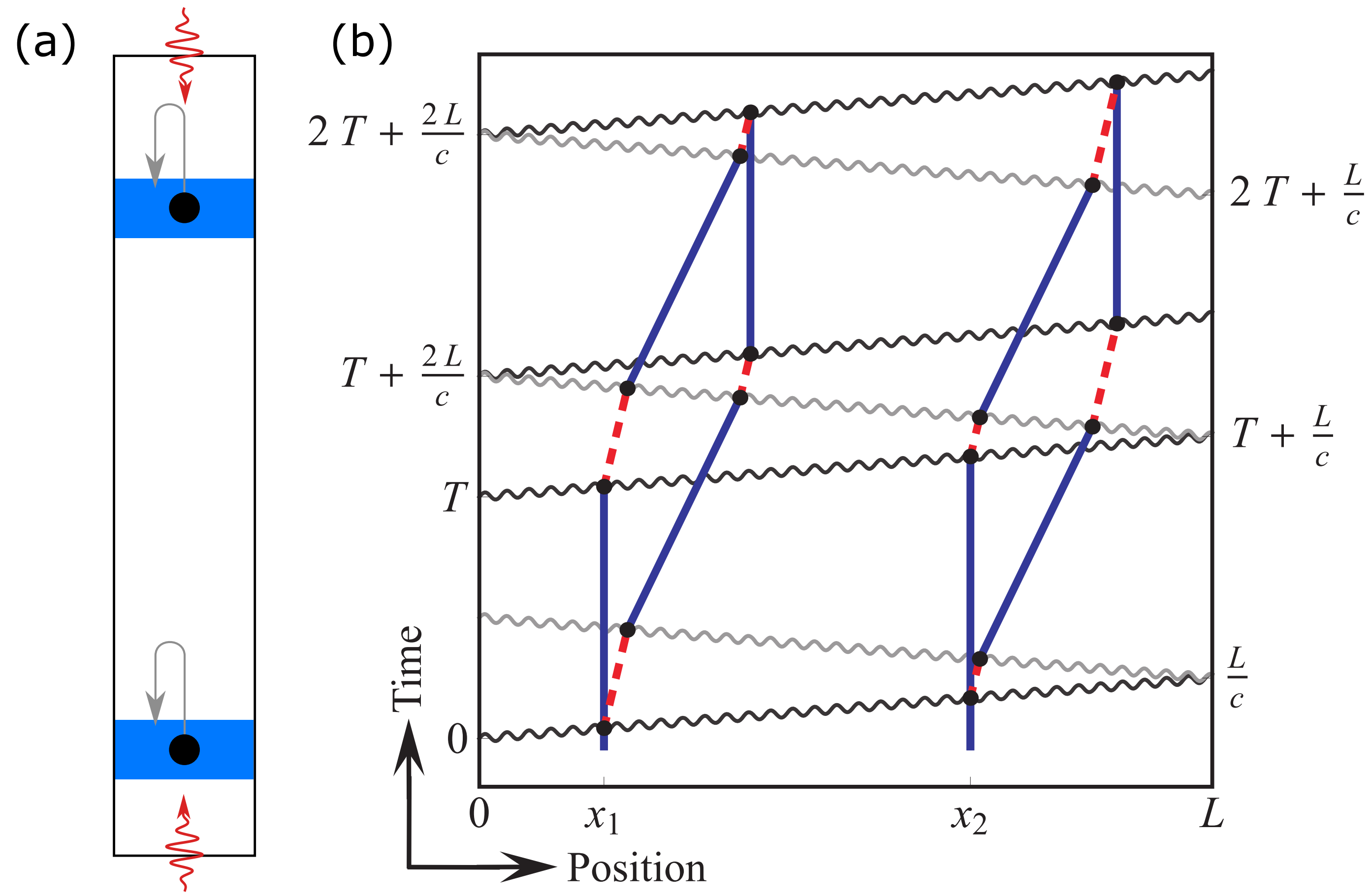
A Different Kind of Atom Interferometer

run atom interferometer as hybrid clock/accelerometer

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



Clock transition in candidate atom ^{87}Sr

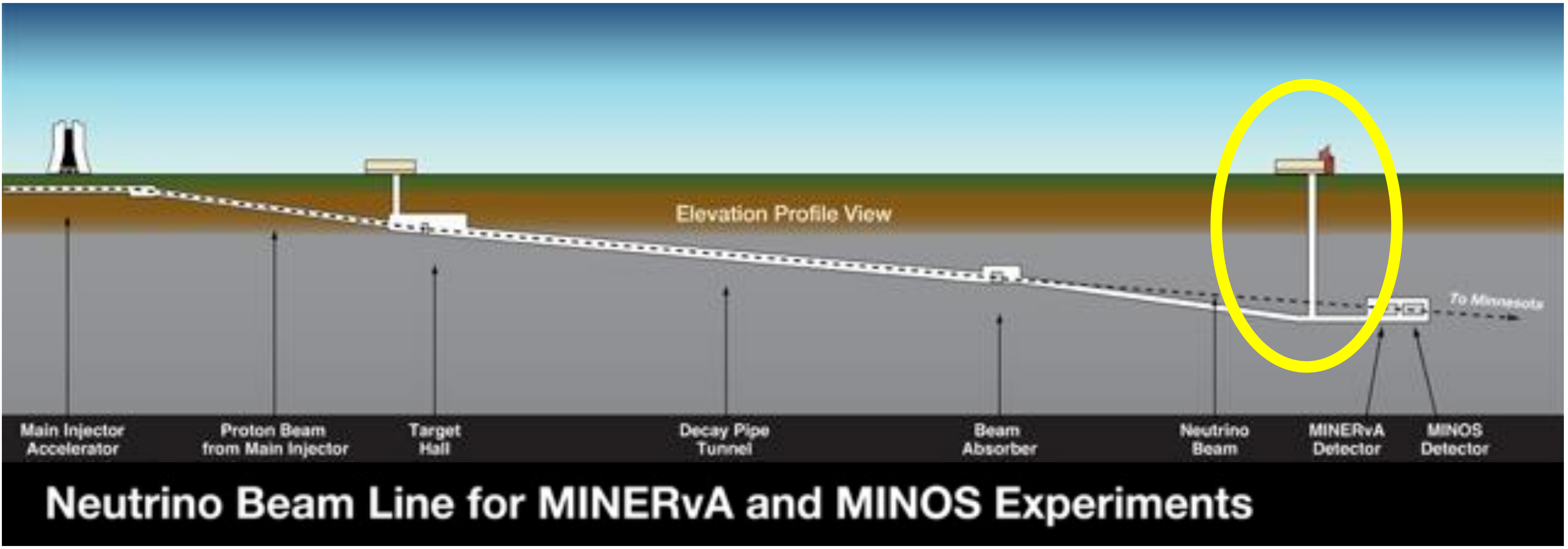


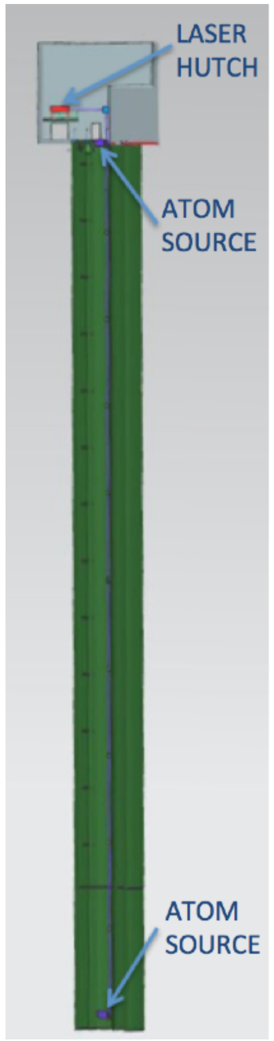
as a clock, measure light travel time ➜ remove laser noise with single baseline

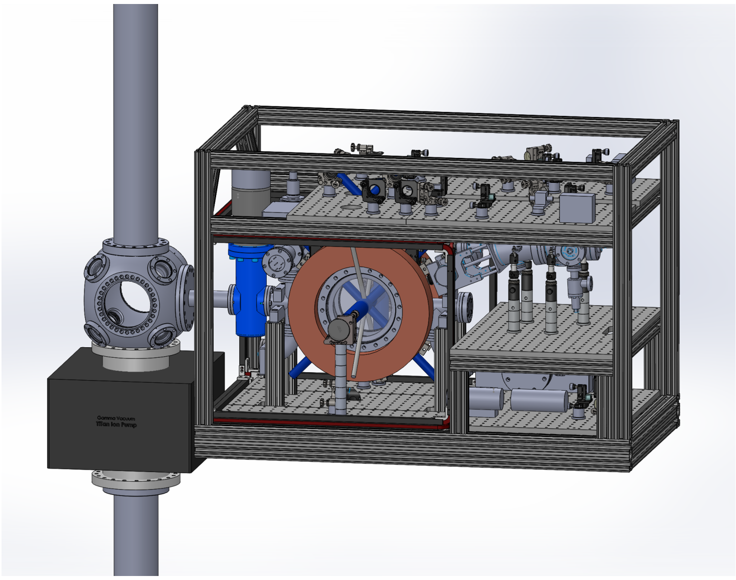
as an accelerometer ➜ atoms excellent inertial test masses

e.g. no seismic noise, no thermal noise, no gas collision noise, don’t charge

MAGIS-100 Proposal at Fermilab



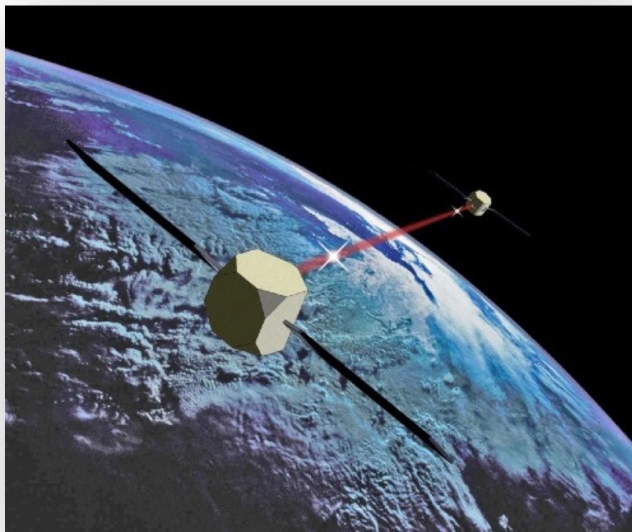


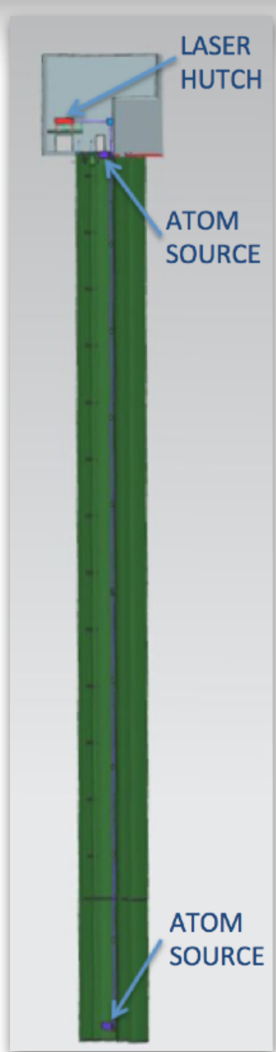


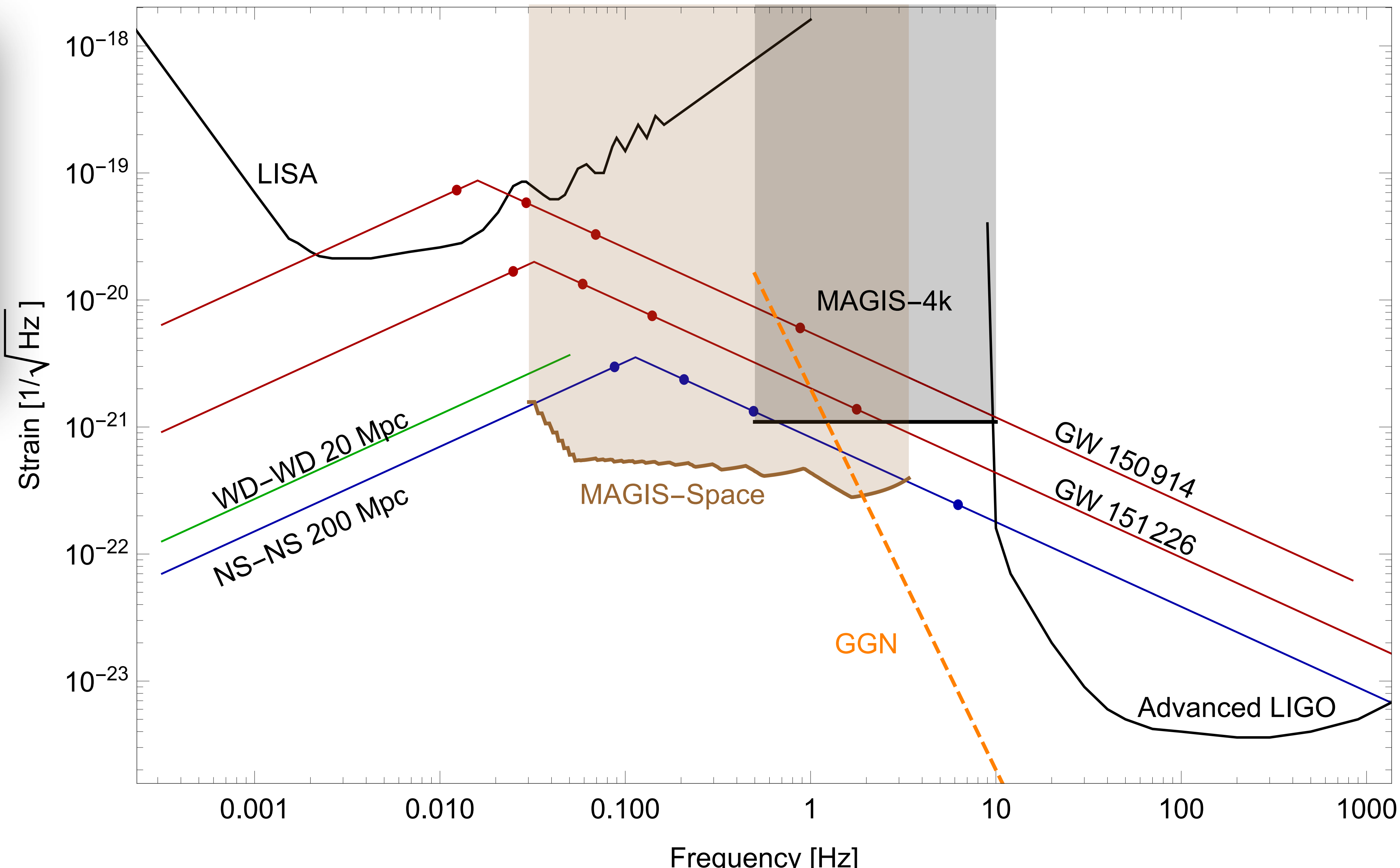
- 100 m atom interferometer drop tower
- Detect dark matter (see Mina Arvanitaki's talk)
- Equivalence Principle test
- Demonstrator for future gravitational wave detectors (~ km-scale terrestrial and satellite detectors)

Atom Interferometry for Gravitational Waves

Future detectors (terrestrial + satellite) could access mid-frequency band:







for example this band allows:

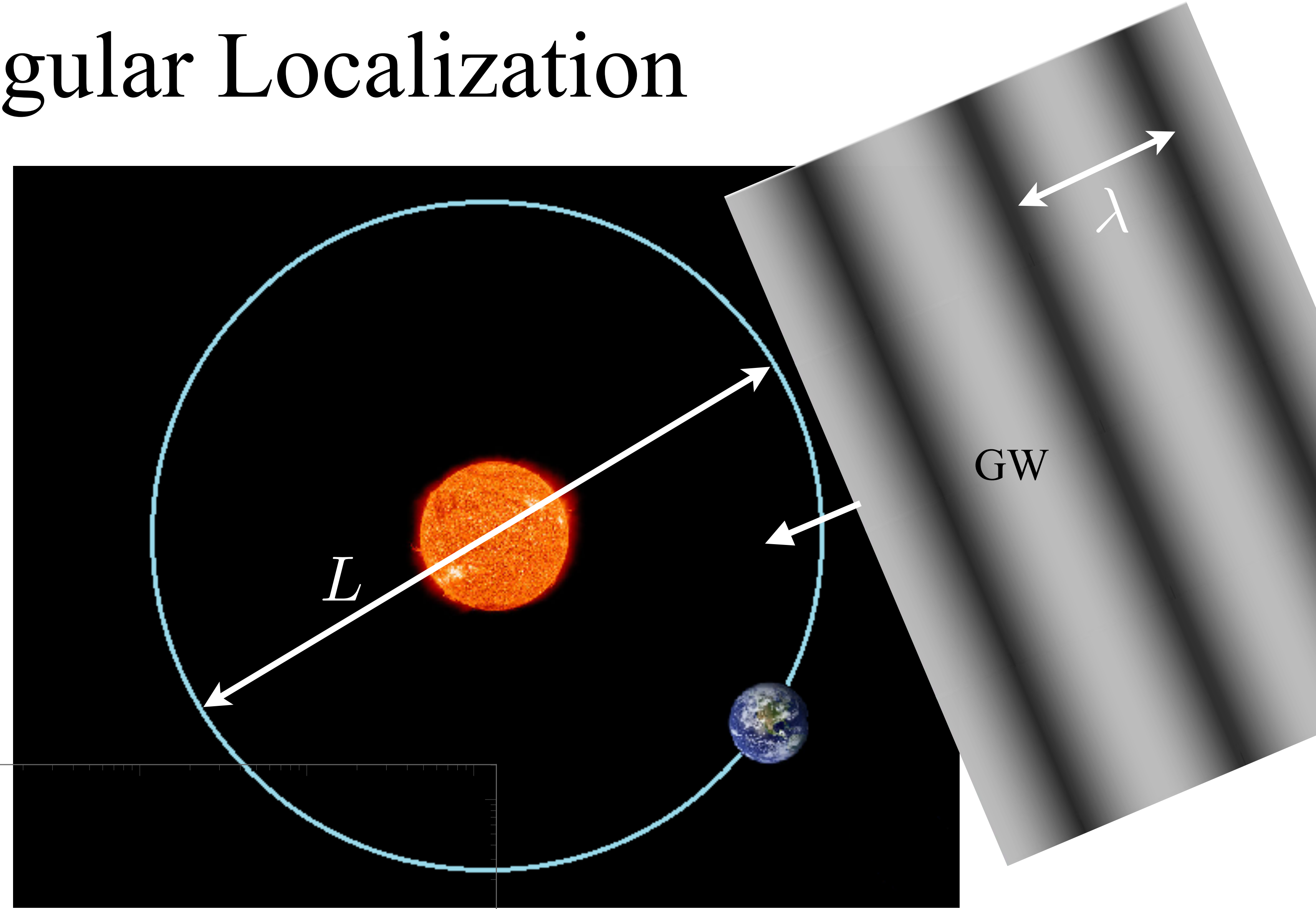
- observe new sources
- localize and predict BH and NS binary mergers for EM telescopes to observe
- good measurement of BH spins

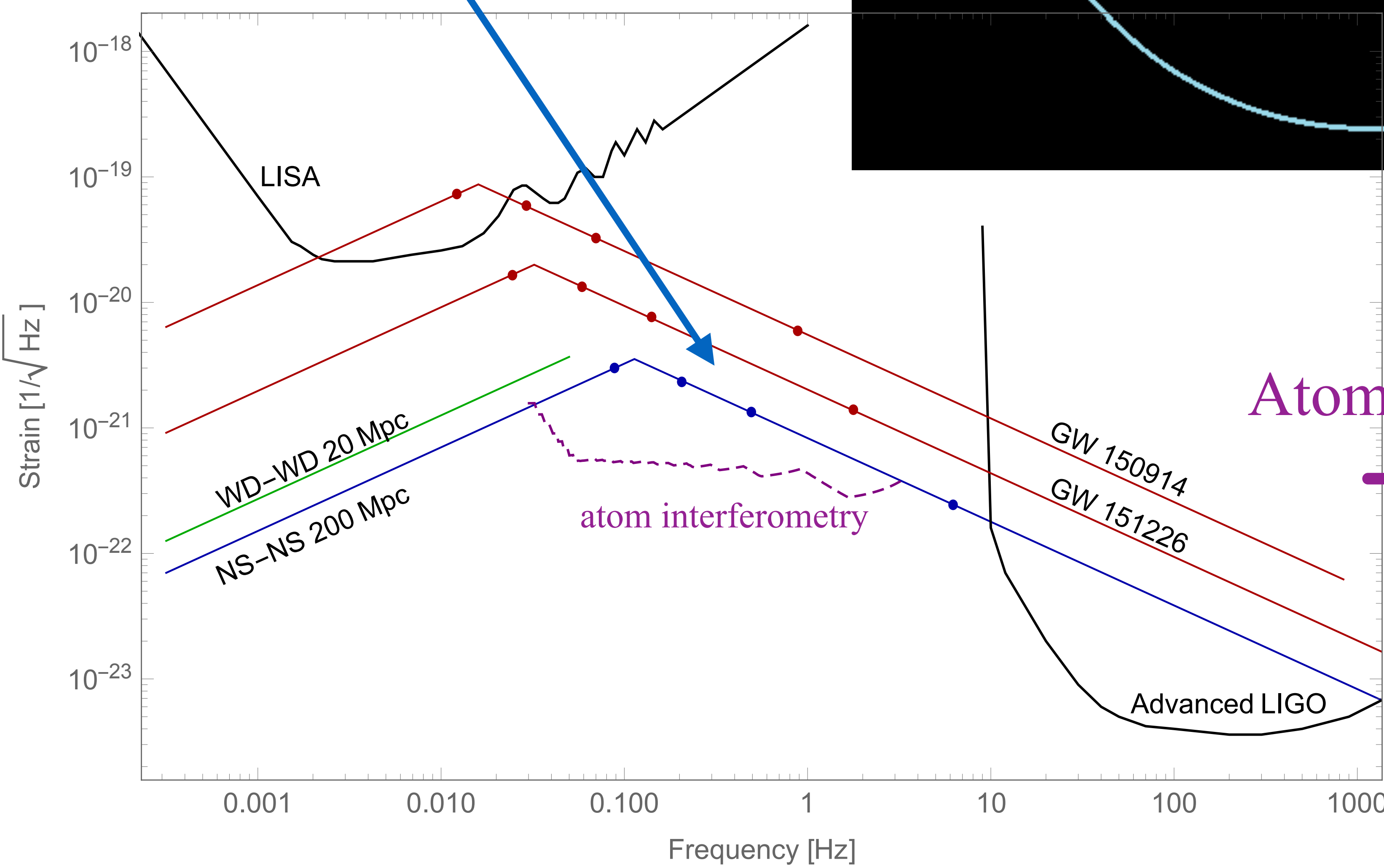
Angular Localization

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

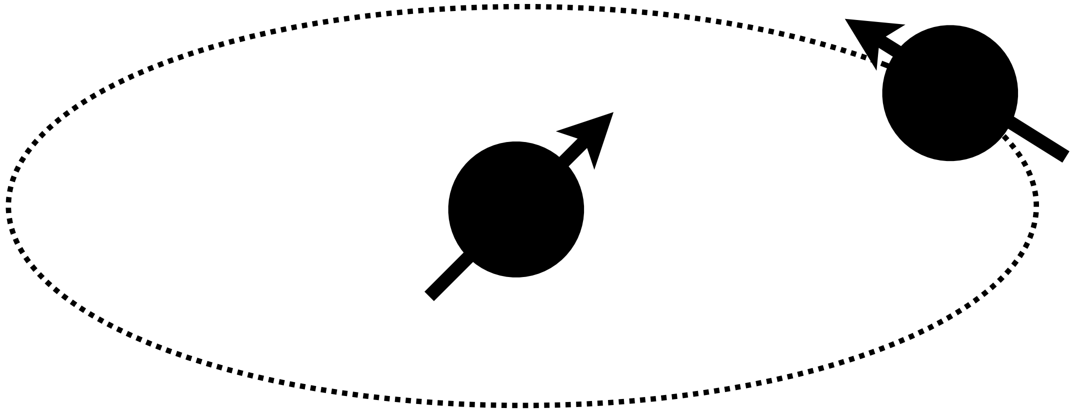




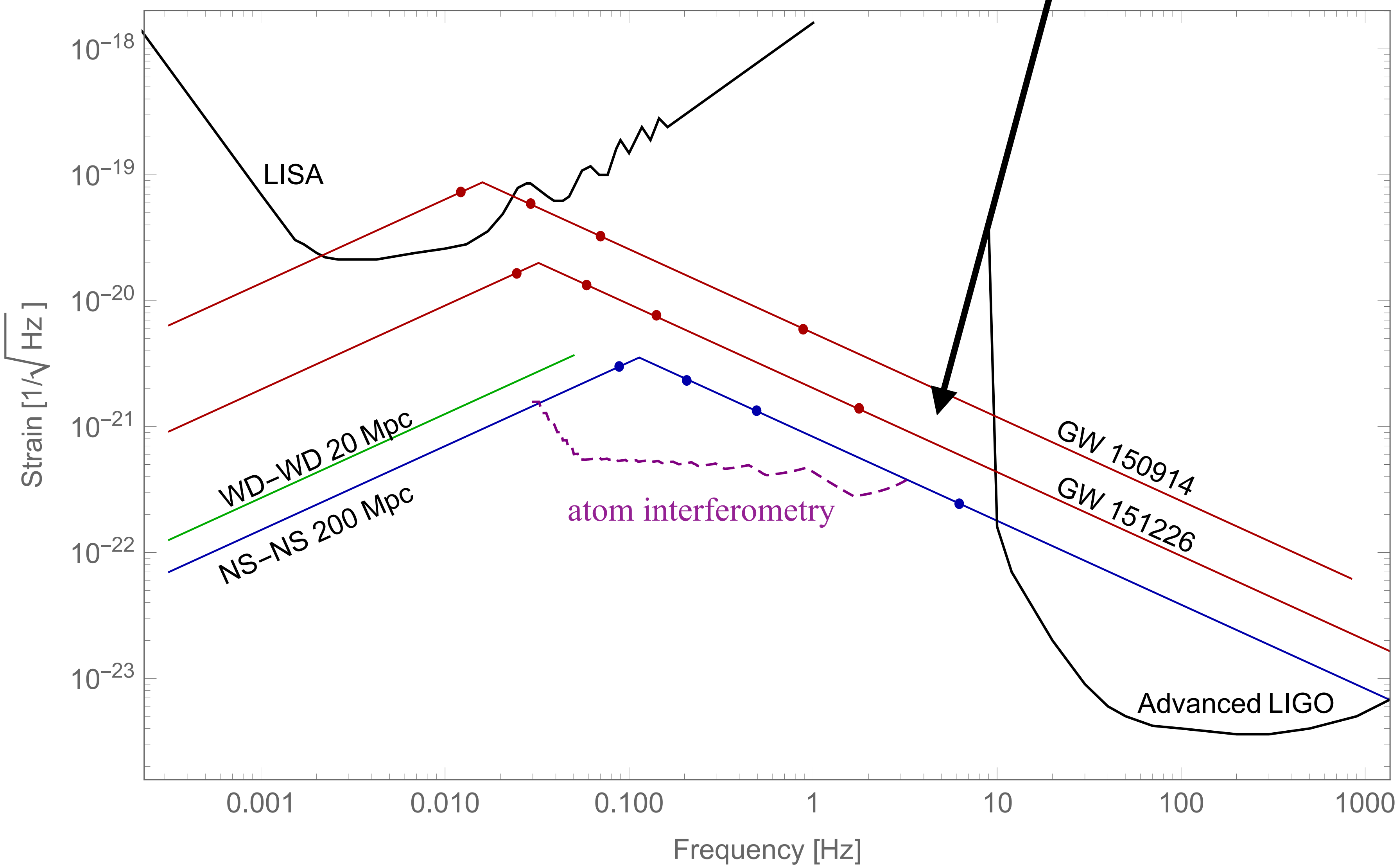
Atoms could access mid-frequency band ➜ ideal for angular localization

PWG + Sunghoon Jung PRD **97** (2018)

Initial Black Hole Spins Preliminary



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



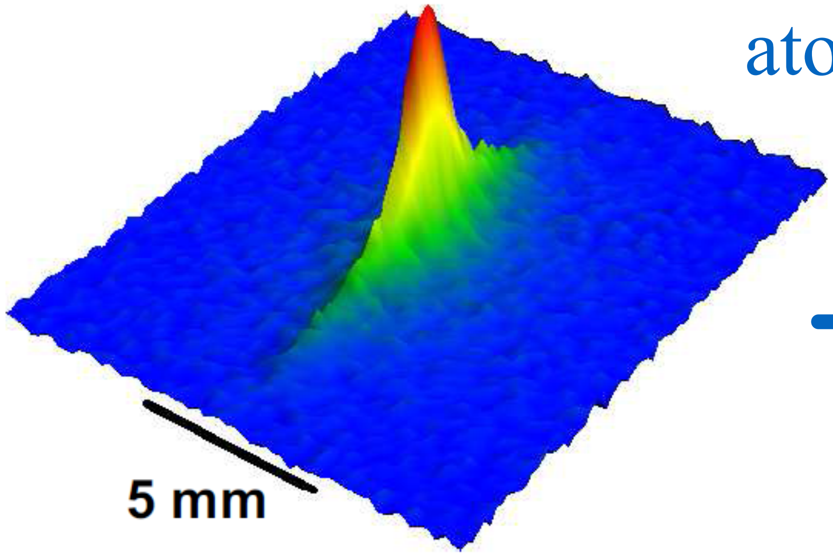
LIGO can't measure well, needs lower frequencies ➜ atoms (terrestrial or satellite) could measure?
gives info on formation history, etc. of BH's

Recent Experimental Results

(Kasevich and Hogan groups)

Stanford Test Facility

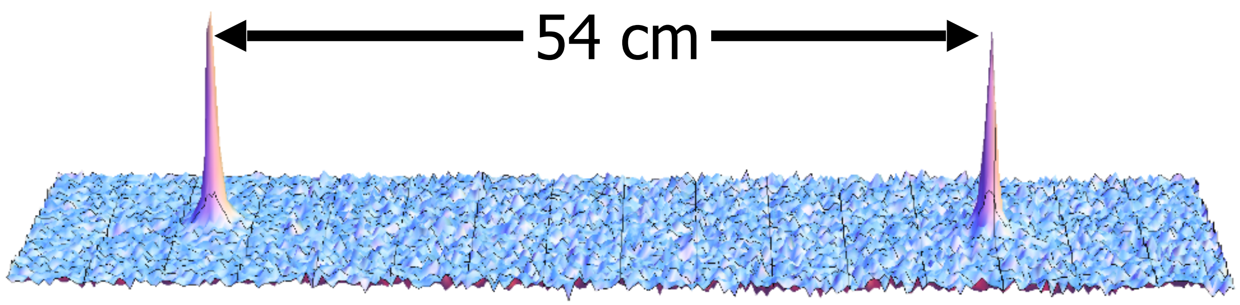
demonstrate necessary technologies:



atom cooling

➜ 50 pK

Macroscopic splitting of atomic wavefunction:



Kovachy et. al, *Nature* (2015)

Some Thoughts

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

detect coherent effects of entire field, not single particles

Combination of several experiments will cover QCD axion dark matter fully

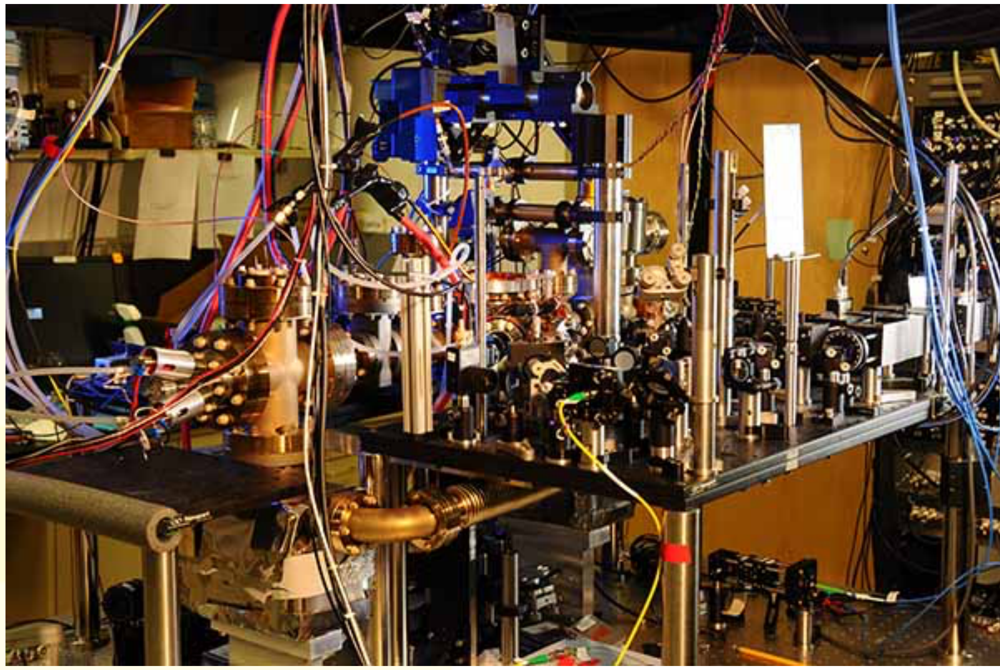
Many new experimental techniques!

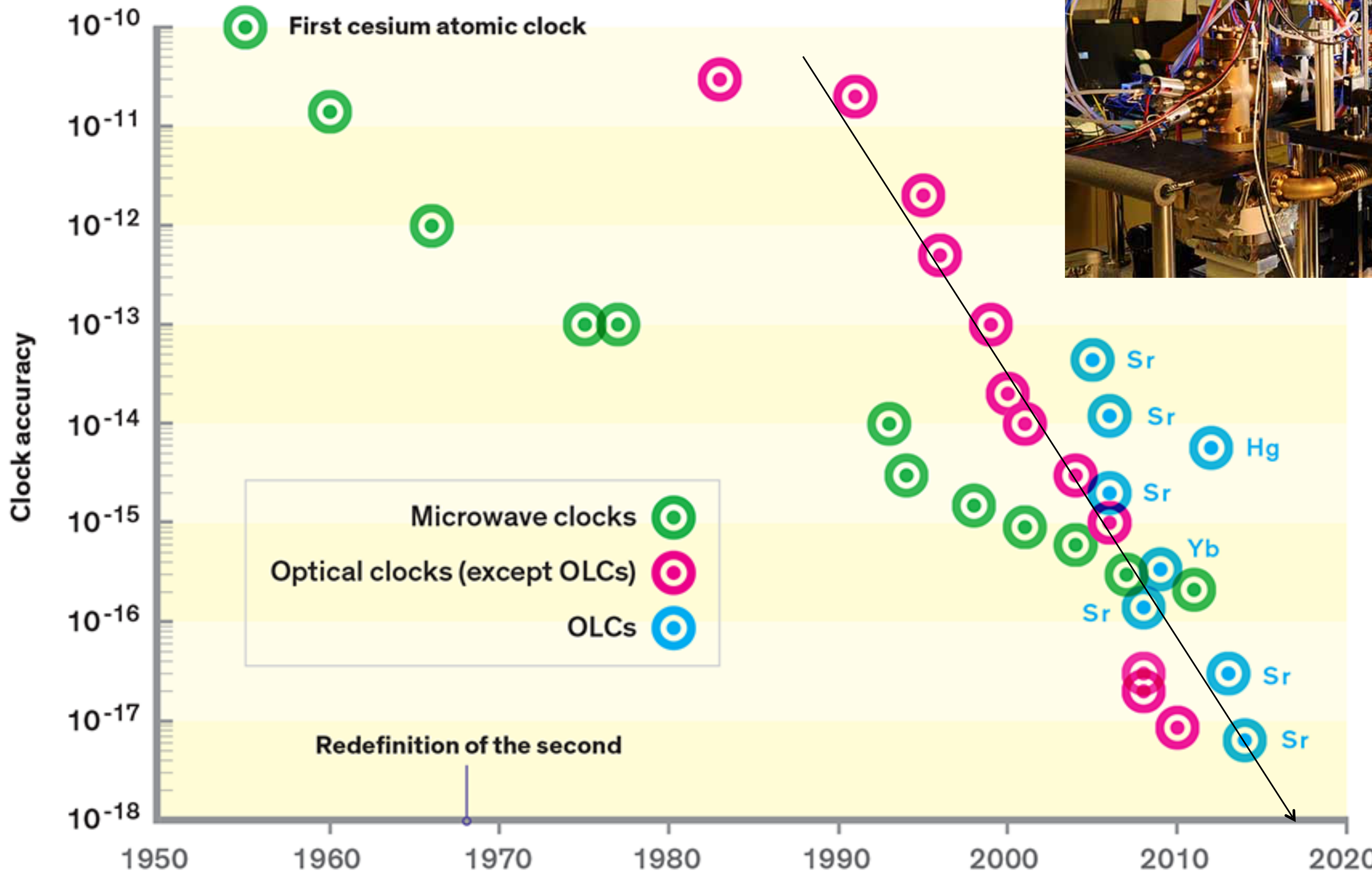
- EM resonators
- laser interferometry
- atom interferometry/clocks
- molecules
- NMR
- high-precision magnetometry (SQUIDs, atomic systems)
- torsion pendulums
- optically-levitated dielectric spheres
- …

Many more possibilities we haven't thought of yet…

Backup Slides

Atomic Clock Sensitivity





current technology already allows many new searches, and will improve by orders of magnitude

Possibilities for Light Dark Matter

Effective field theory ➜ only a few possible couplings to us
either scalar or vector, four types of experiments:

light DM

- E&M - drive currents
  $a\,F\tilde{F}$
- QCD - change nuclear properties
  $a\,G\tilde{G}$
- spin - cause precession
  $(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$
- scalar - new force/SM properties
  $aH^\dagger H$

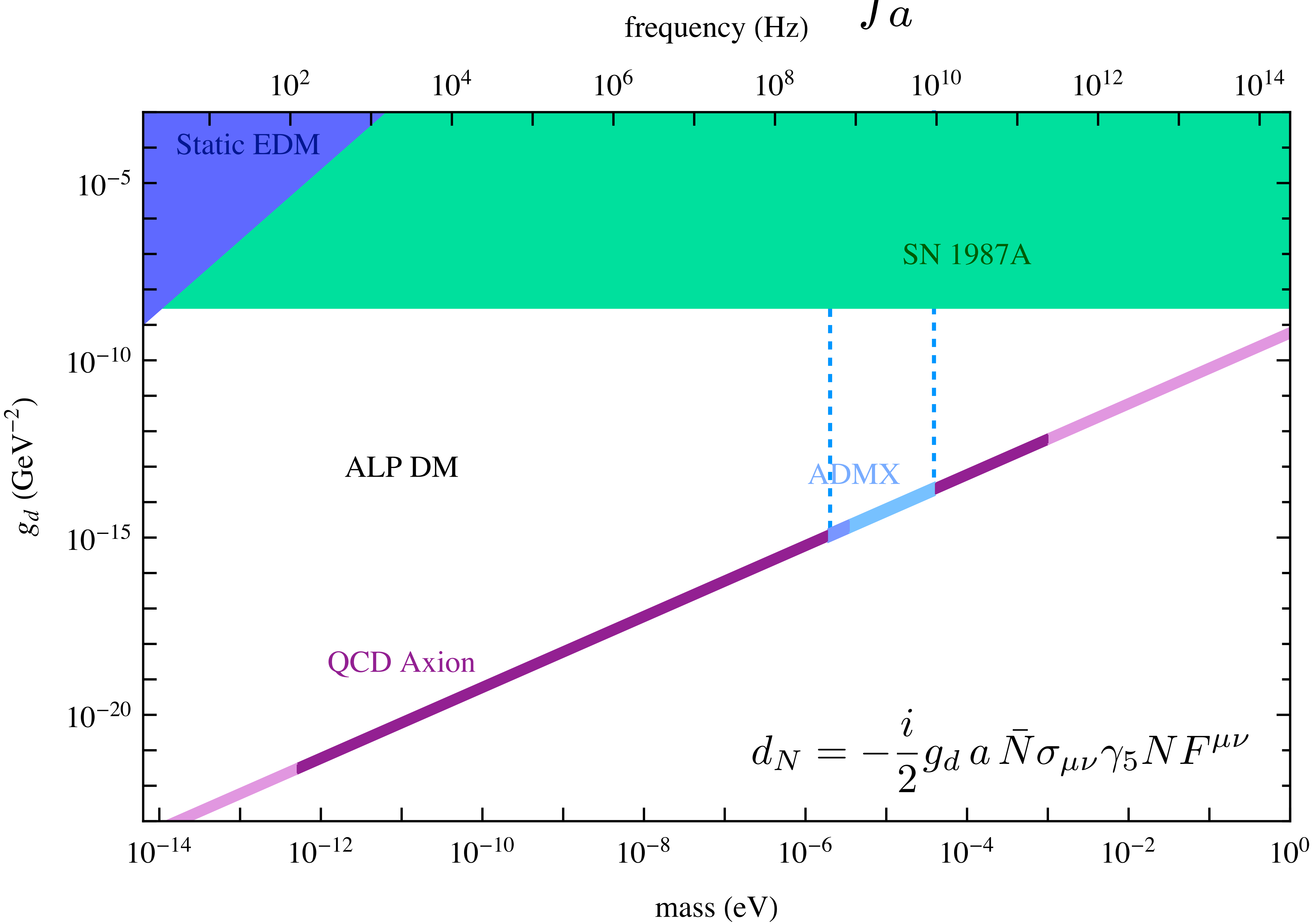
current axion searches
e.g. ADMX

e.g. aids axion detection

Can cover all these possibilities

with D.E.Kaplan, J.Mardon, S.Rajendran, & W.A.Terrano arXiv:1512.06165

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



CASPEr Sensitivity