Ultralight Dark Matter and the Precision Frontier

Peter Graham

Stanford

Direct Detection

Divide direct detection into two regimes:

black holes

DM mass:

10^{-22} eV

dwarf galaxy size

10^{19} GeV

Direct Detection

Divide direct detection into two regimes:

black holes

DM mass:

10^{-22} eV
dwarf galaxy size

$10\,\mathrm{eV}$

$10^{19}\ \mathrm{GeV}$

$\rho_{\mathrm{DM}} \approx 0.3\,\frac{\mathrm{GeV}}{\mathrm{cm}^3} \approx (0.04\,\mathrm{eV})^4$ ➔ high phase space density if $m \lesssim 10\,\mathrm{eV}$

Direct Detection

Divide direct detection into two regimes:

black holes

DM mass:

10^{-22} eV
dwarf galaxy size

axion

$10\,\mathrm{eV}$

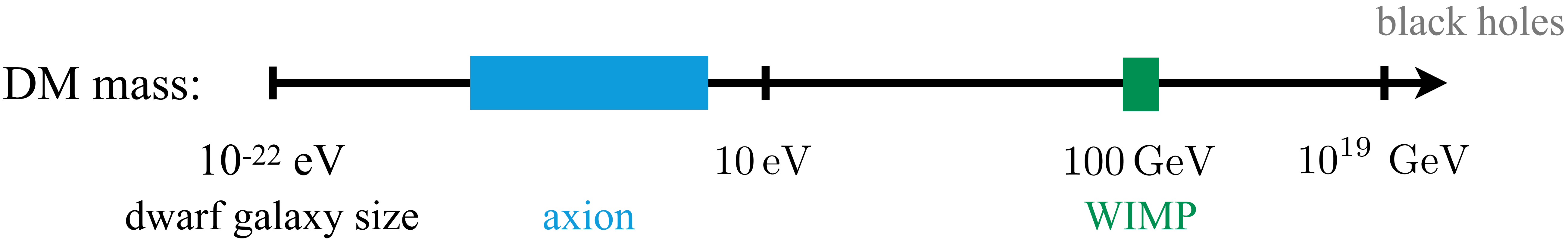
$100\,\mathrm{GeV}$
WIMP

$10^{19}\ \mathrm{GeV}$

$\rho_{\mathrm{DM}} \approx 0.3\,\frac{\mathrm{GeV}}{\mathrm{cm}^3} \approx (0.04\,\mathrm{eV})^4$ ➔ high phase space density if $m \lesssim 10\,\mathrm{eV}$

Direct Detection

Divide direct detection into two regimes:



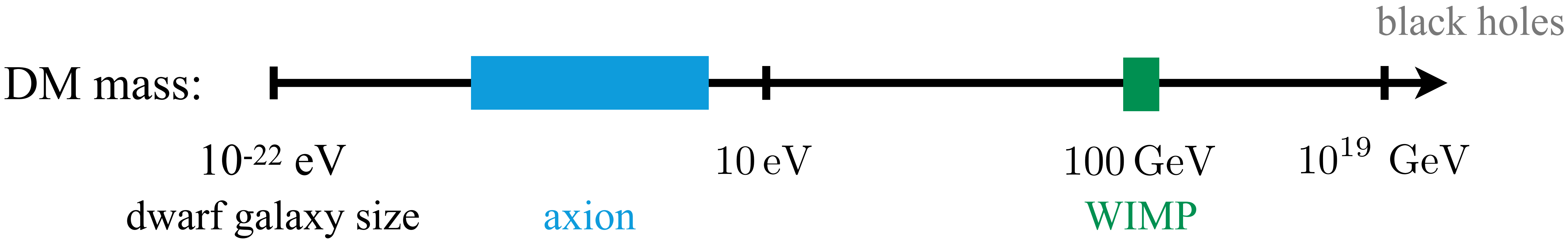
$\rho_{\rm DM} \approx 0.3\,\frac{\rm GeV}{\rm cm^3} \approx (0.04\,{\rm eV})^4$ ➔ high phase space density if $m \lesssim 10\,{\rm eV}$

field-like (e.g. axion)
new, precision detectors required

particle-like (e.g. WIMP)
particle detectors best

Direct Detection

Divide direct detection into two regimes:



black holes

DM mass:

10^{-22} eV
dwarf galaxy size

axion

10 eV

100 GeV
WIMP

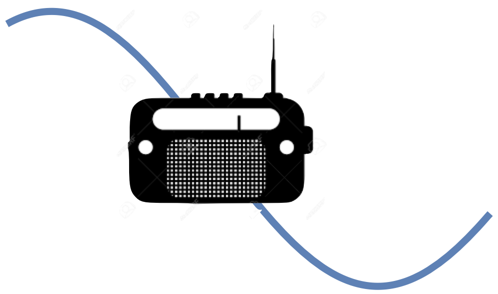
10^{19} GeV

$\rho_{\rm DM} \approx 0.3\,\frac{\rm GeV}{\rm cm^3} \approx (0.04\,{\rm eV})^4$ ➔ high phase space density if $m \lesssim 10\,{\rm eV}$

field-like (e.g. axion)

new, precision detectors required

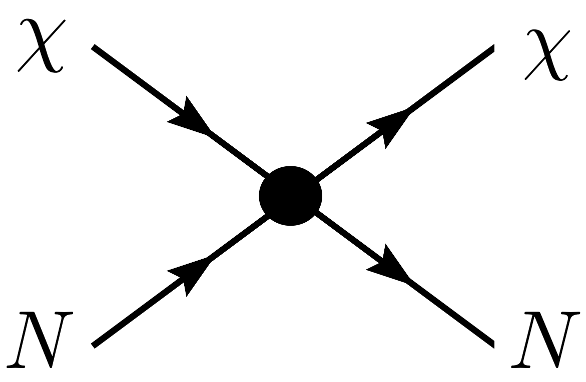
Detect coherent effects of entire field
(like gravitational wave detector)



particle-like (e.g. WIMP)

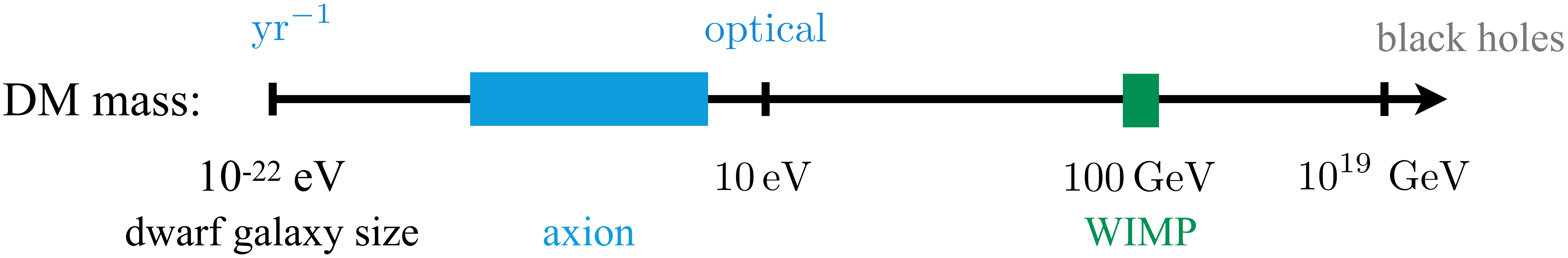
particle detectors best

Search for single, hard particle scattering



Direct Detection

Divide direct detection into two regimes:



yr^{-1} optical black holes

DM mass:

10^{-22} eV $10\,\text{eV}$ $100\,\text{GeV}$ 10^{19} GeV

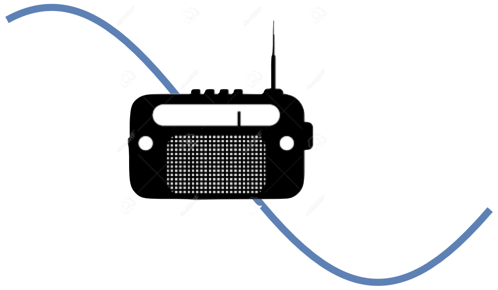
dwarf galaxy size axion WIMP

$$\rho_{\rm DM} \approx 0.3\,\frac{\rm GeV}{\rm cm^3} \approx (0.04\,{\rm eV})^4$$ ➔ high phase space density if $m \lesssim 10\,\text{eV}$

field-like (e.g. axion)

new, precision detectors required

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

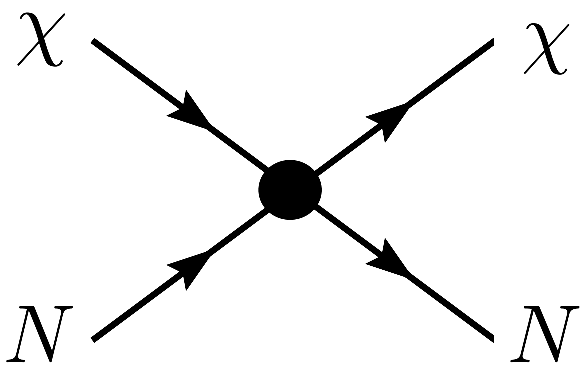


Frequency range accessible!

particle-like (e.g. WIMP)

particle detectors best

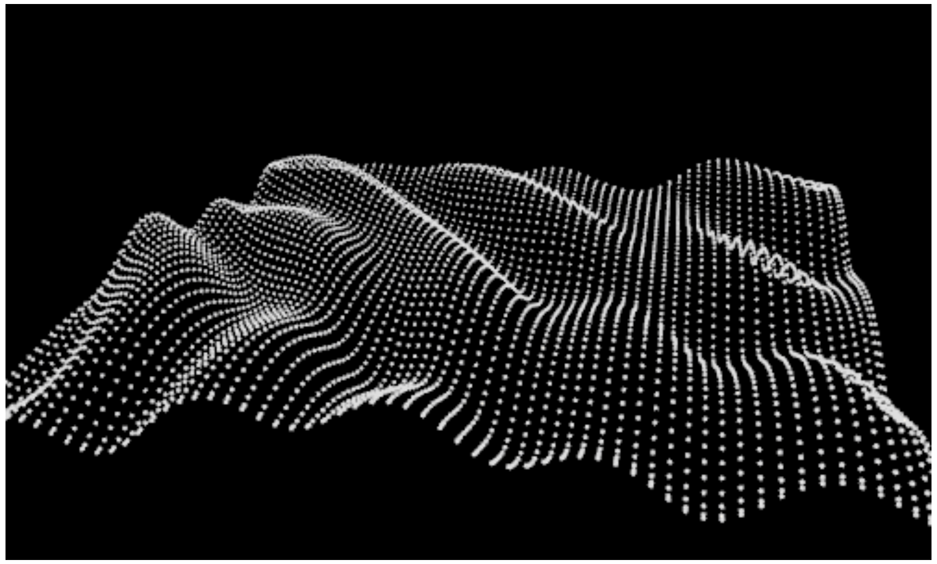
Search for single, hard particle scattering

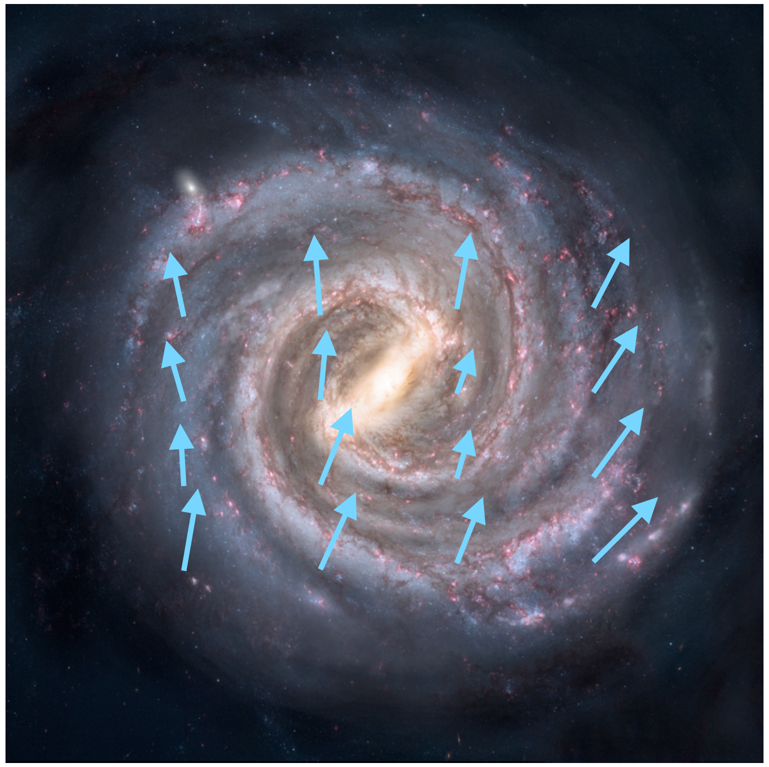


“Field” Dark Matter

particle DM

DM at long deBroglie wavelength
useful to picture as a “coherent” field:



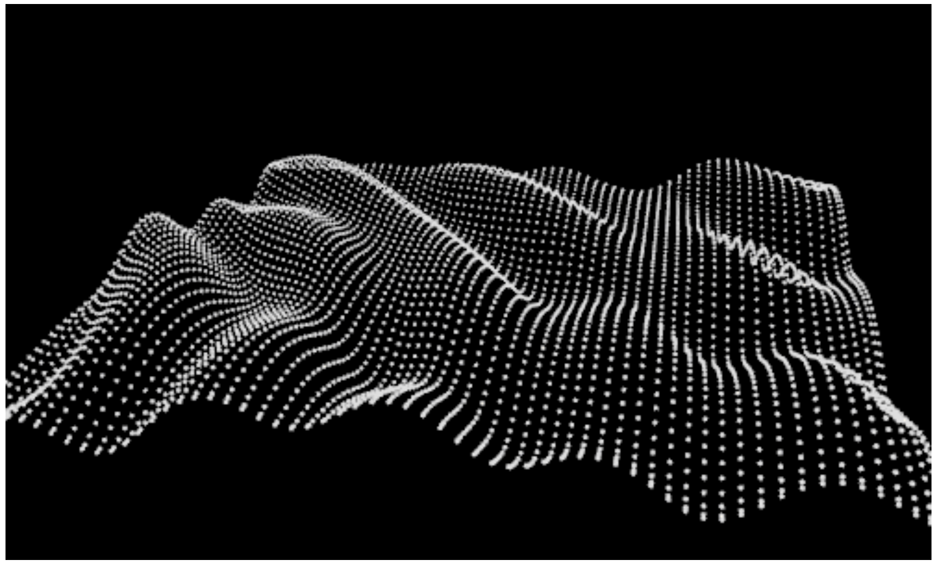


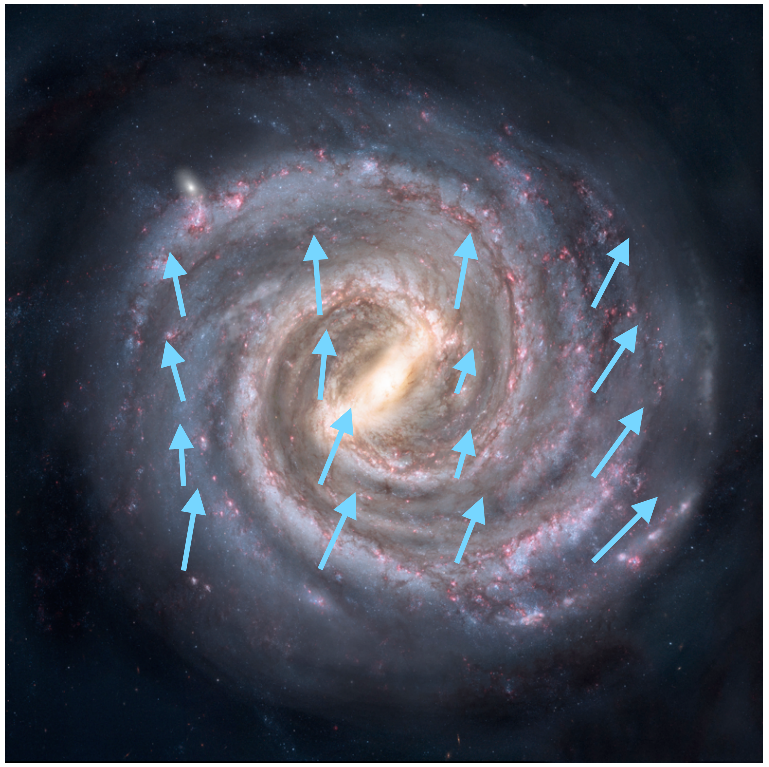
“Field” Dark Matter

particle DM

→

DM at long deBroglie wavelength useful to picture as a “coherent” field:

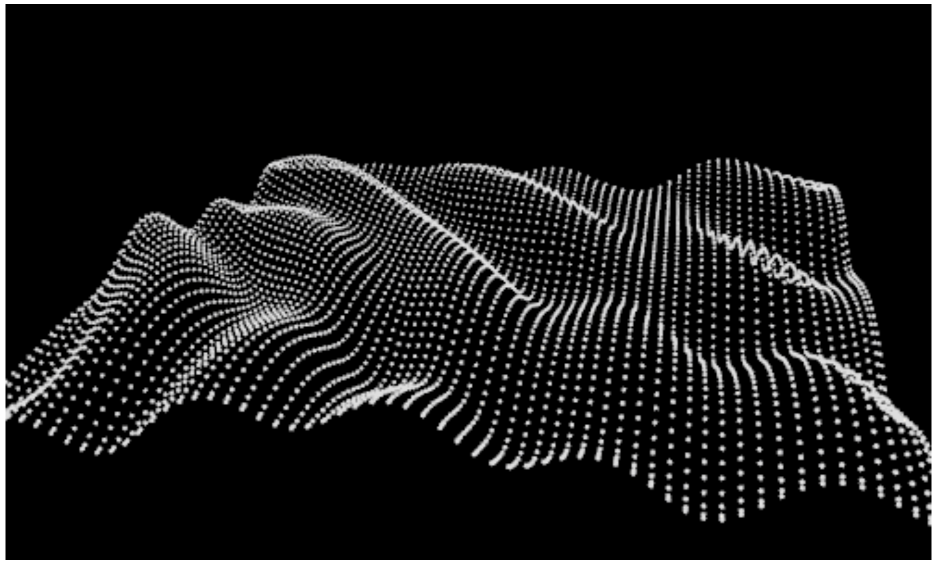


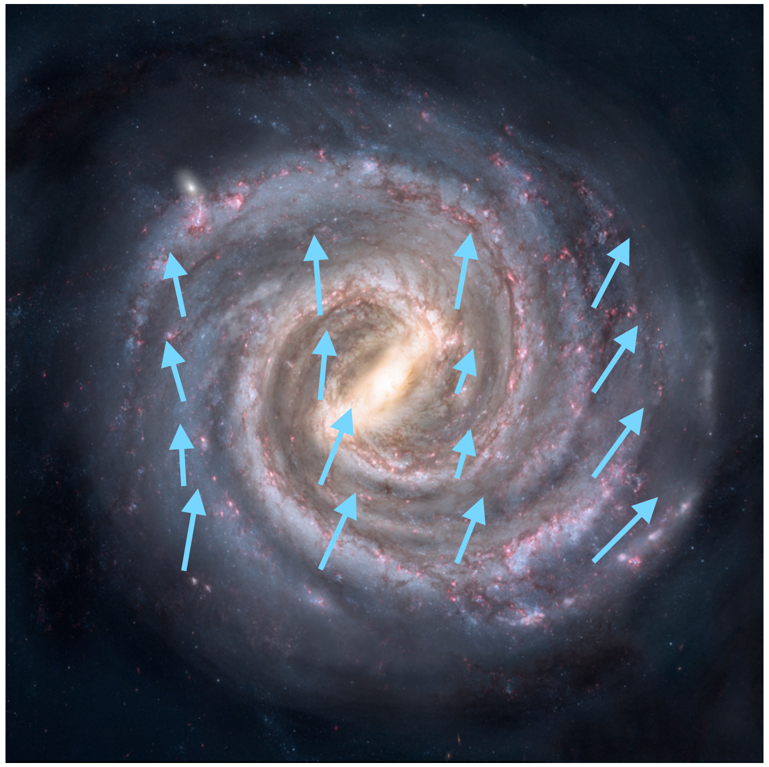


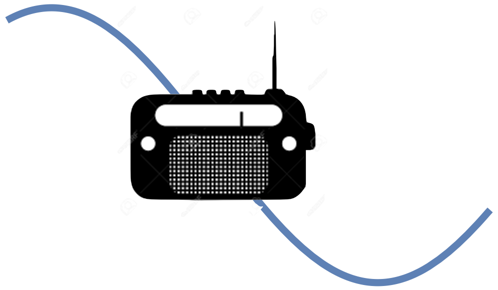
“Field” Dark Matter

particle DM

DM at long deBroglie wavelength
useful to picture as a “coherent” field:







signal frequency = DM mass = m

spread by DM kinetic energy $\sim mv^2$

galactic virial velocity $v \sim 10^{-3}$ ➜ line width $\sim 10^{-6} m$

➜ coherence time, $Q \sim 10^6$ periods

New High Precision Experiments for DM

Caveat: I will only describe a few ideas (that I've been involved in),
but there are many more new experiments,
this is a rapidly evolving area!

DM Radio

with

Kent Irwin
Saptarshi Chaudhuri
Jeremy Mardon
Surjeet Rajendran
Yue Zhao

+ collaborating with Tony Tyson + Mani Tripathi's groups (Davis)

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

DM Radio Experiment

Widely tunable, lumped element EM resonator

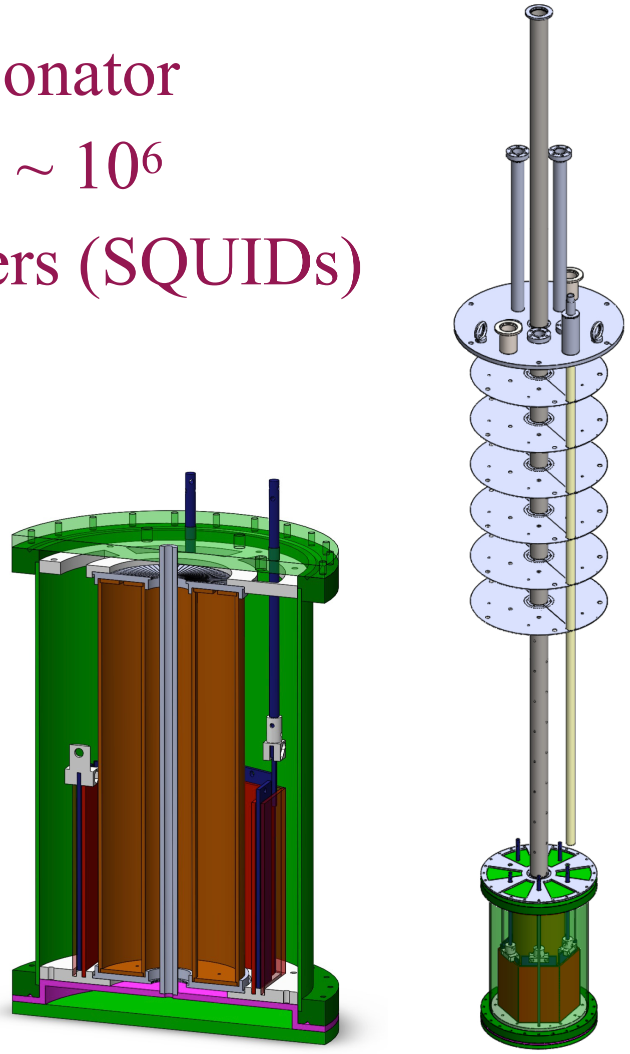
- low dissipation/low noise resonator $Q \sim 10^6$
- high precision magnetometry/amplifiers (SQUIDs)

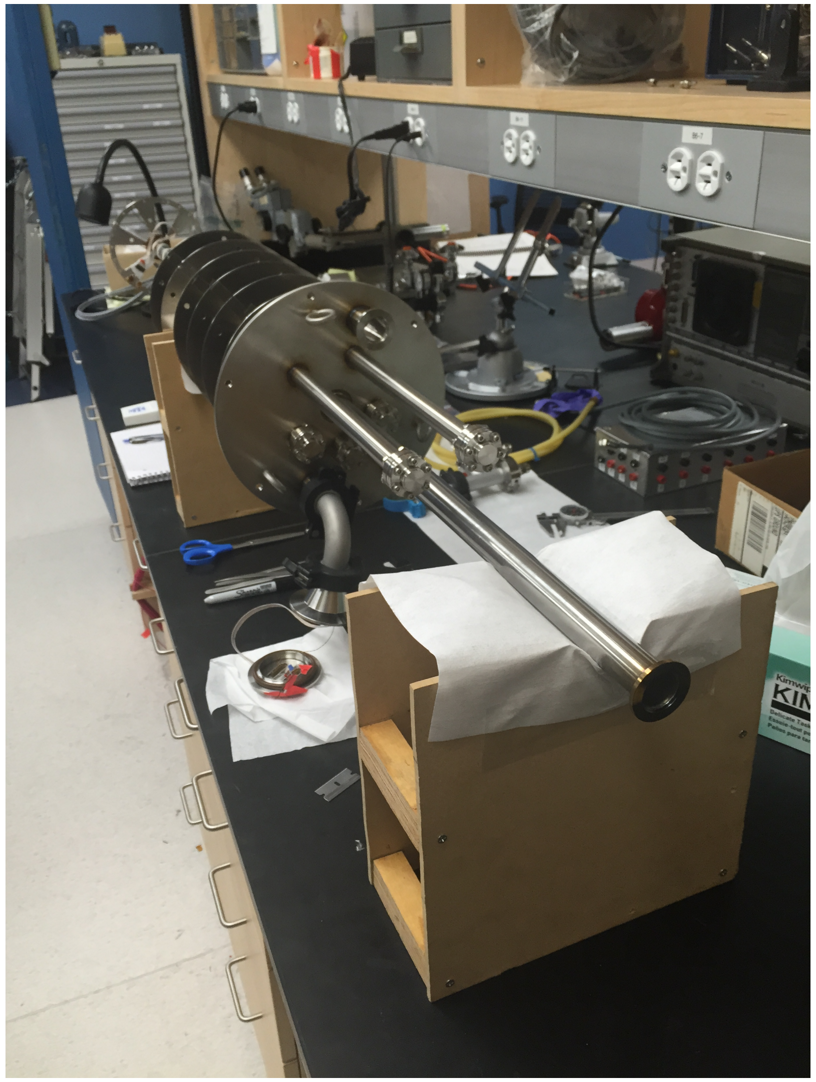
DM Radio Experiment

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

see Arran Phipps's talk here

DM Radio

galactic virial velocity ~ 10^{-3} ➜ dark matter signal width ~ $10^{-6} f$

must scan frequencies to find dark matter

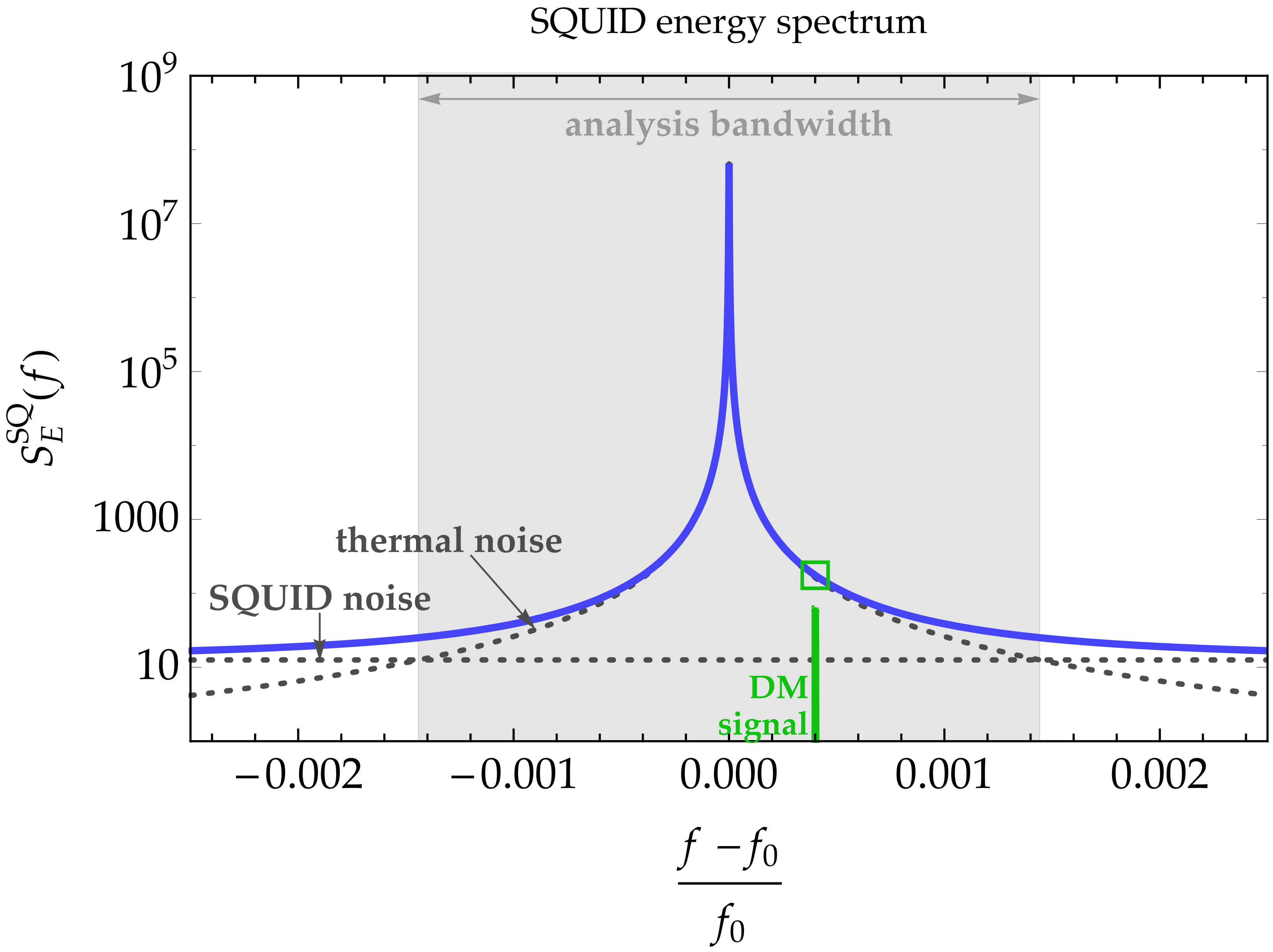
DM Radio

galactic virial velocity ~ 10^{-3} ➜ dark matter signal width ~ $10^{-6} f$

must scan frequencies to find dark matter

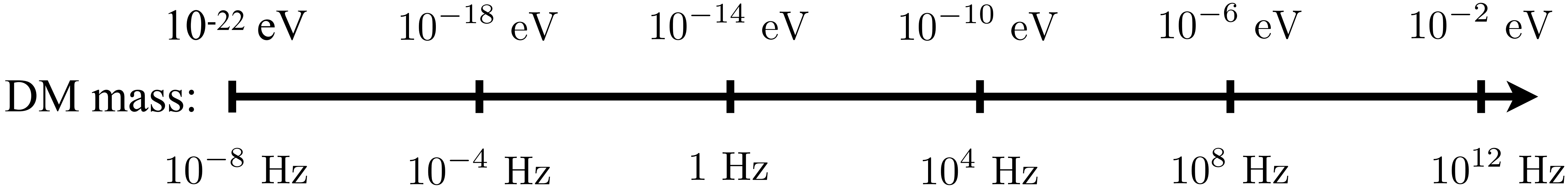
optimal experiment:

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



can enhance sensitivity by orders of magnitude

Ultralight DM Direct Detection

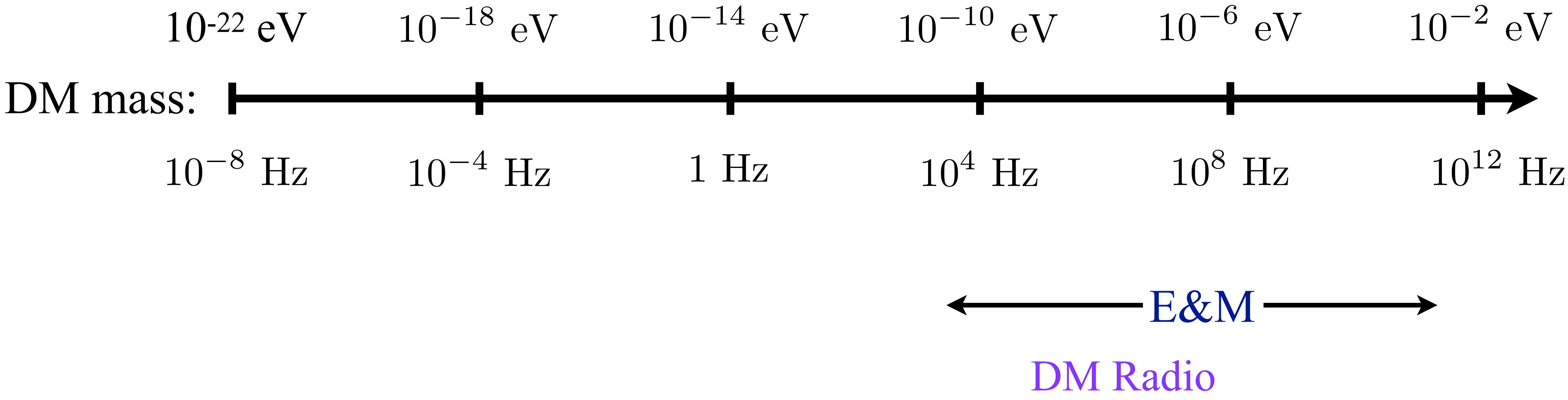


DM mass:

10^{-22} eV | 10^{-18} eV | 10^{-14} eV | 10^{-10} eV | 10^{-6} eV | 10^{-2} eV

10^{-8} Hz | 10^{-4} Hz | 1 Hz | 10^{4} Hz | 10^{8} Hz | 10^{12} Hz

Ultralight DM Direct Detection



10^{-22} eV 10^{-18} eV 10^{-14} eV 10^{-10} eV 10^{-6} eV 10^{-2} eV

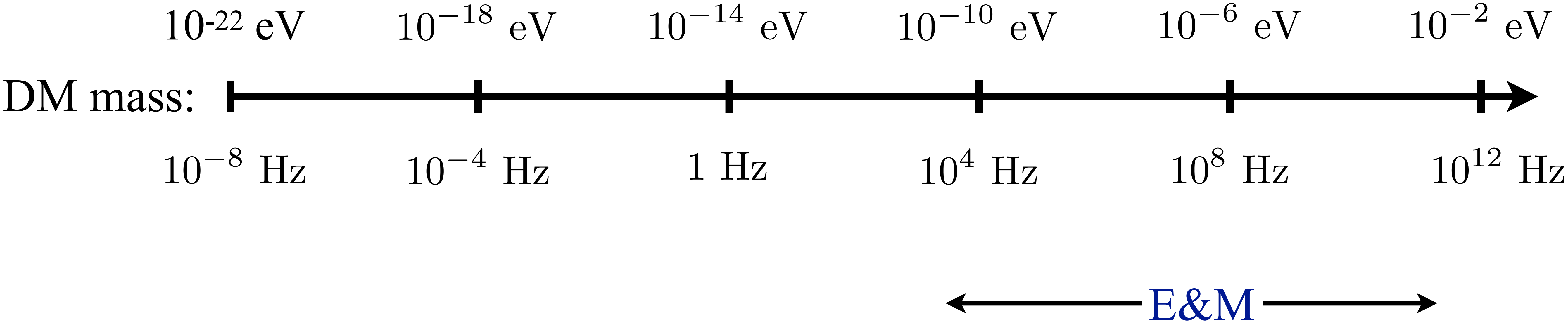
DM mass:

10^{-8} Hz 10^{-4} Hz 1 Hz 10^{4} Hz 10^{8} Hz 10^{12} Hz

E&M

DM Radio

Ultralight DM Direct Detection



10^{-22} eV 10^{-18} eV 10^{-14} eV 10^{-10} eV 10^{-6} eV 10^{-2} eV

DM mass:

10^{-8} Hz 10^{-4} Hz 1 Hz 10^{4} Hz 10^{8} Hz 10^{12} Hz

E&M

DM Radio

also: cavities, dielectrics…

see talks by C. Boutan,

J. Yoo, A. Millar

Cosmic Axion Spin Precession Experiment (CASPEr)

with

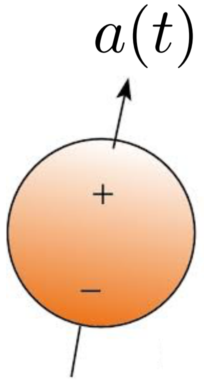
Dmitry Budker
Micah Ledbetter
Surjeet Rajendran
Alex Sushkov

HEISING - SIMONS FOUNDATION
SIMONS FOUNDATION
DFG Deutsche Forschungsgemeinschaft

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

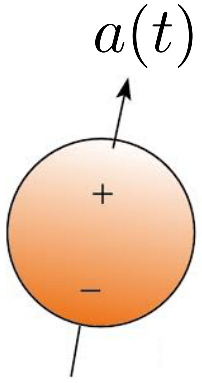
QCD Coupling

Axion solution to strong CP problem:
make nucleon EDM dynamical instead of a fundamental constant
dependent on background axion field



QCD Coupling

Axion solution to strong CP problem:
make nucleon EDM dynamical instead of a fundamental constant
dependent on background axion field



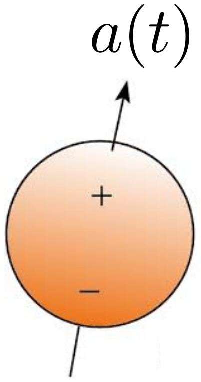
➜ axion DM causes oscillatory nuclear EDM

using this nuclear coupling completely changes axion detection
this QCD coupling is only axion coupling not derivative-suppressed at low mass

generally light bosonic DM causes oscillating fundamental "constants"

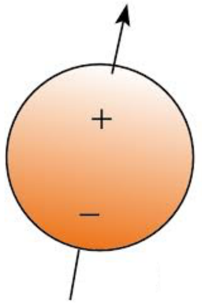
Cosmic Axion Spin Precession Experiment (CASPEr)

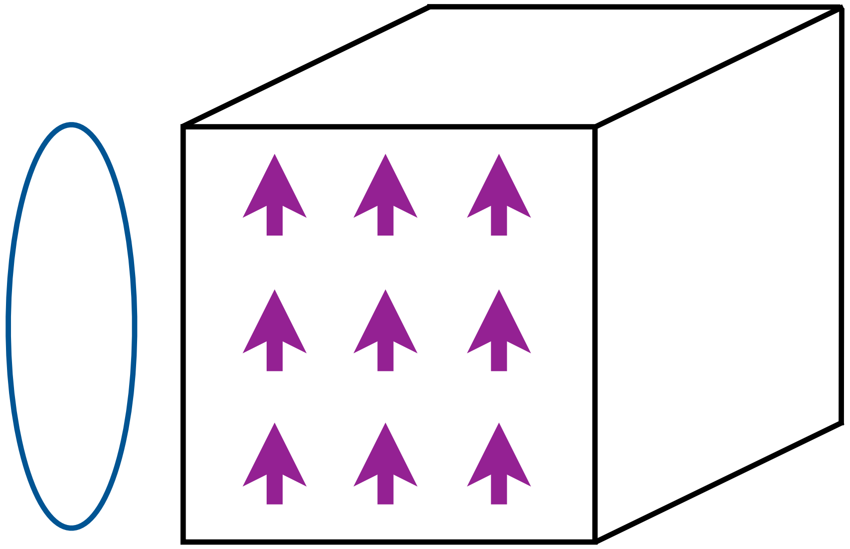
search for oscillating nuclear EDM



Cosmic Axion Spin Precession Experiment (CASPEr)

search for oscillating nuclear EDM



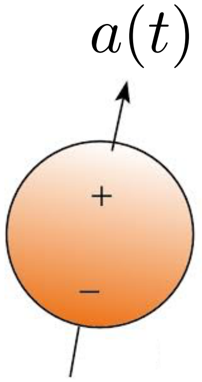


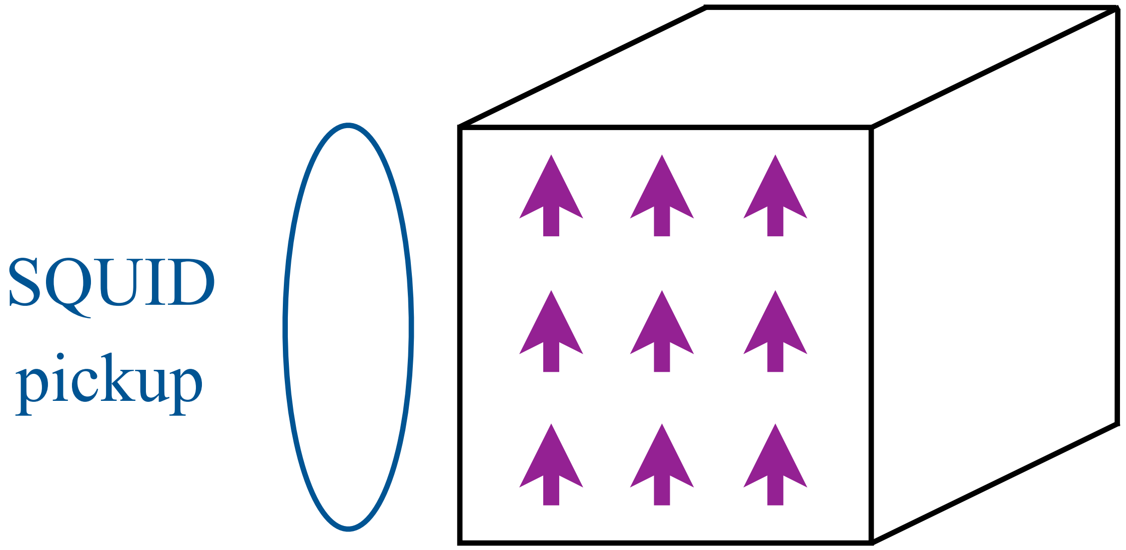
Applied EM fields cause NMR-style resonance

SQUID measures resulting transverse magnetization

Cosmic Axion Spin Precession Experiment (CASPEr)

search for oscillating nuclear EDM





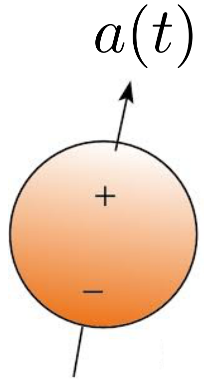
Applied EM fields cause NMR-style resonance

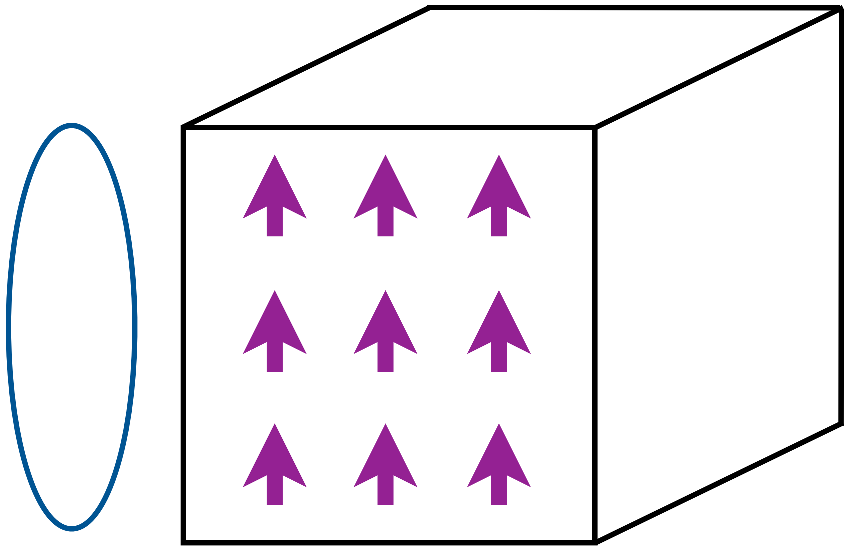
SQUID measures resulting transverse magnetization

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

Cosmic Axion Spin Precession Experiment (CASPEr)

search for oscillating nuclear EDM





SQUID pickup

Applied EM fields cause NMR-style resonance

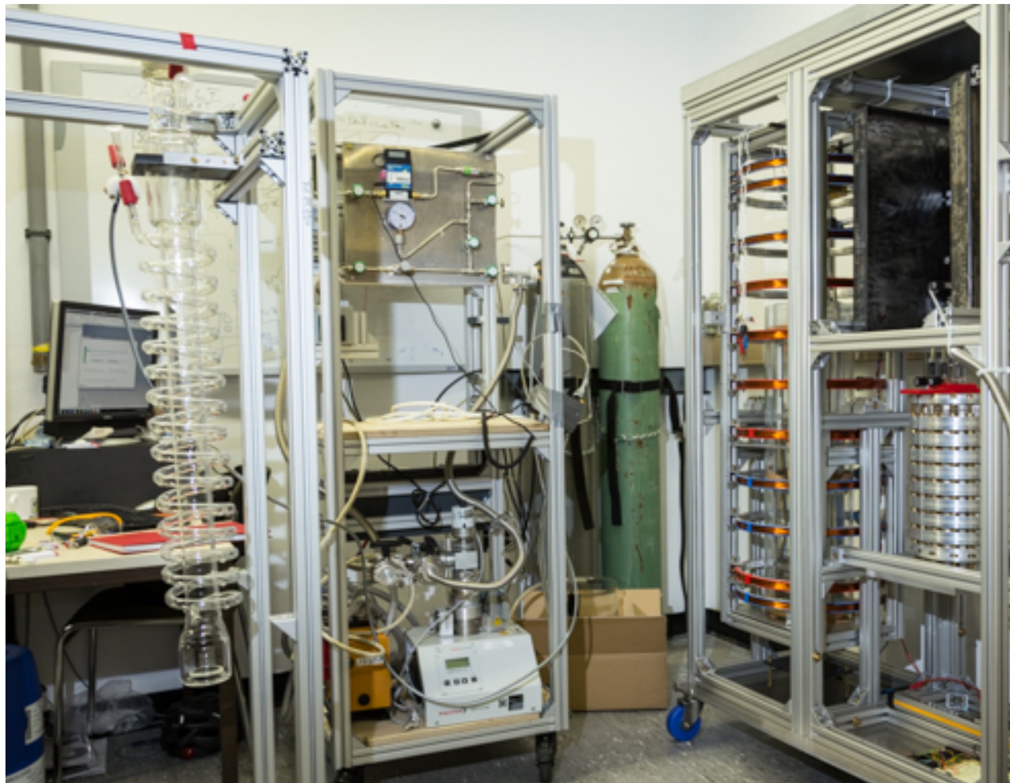
SQUID measures resulting transverse magnetization

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

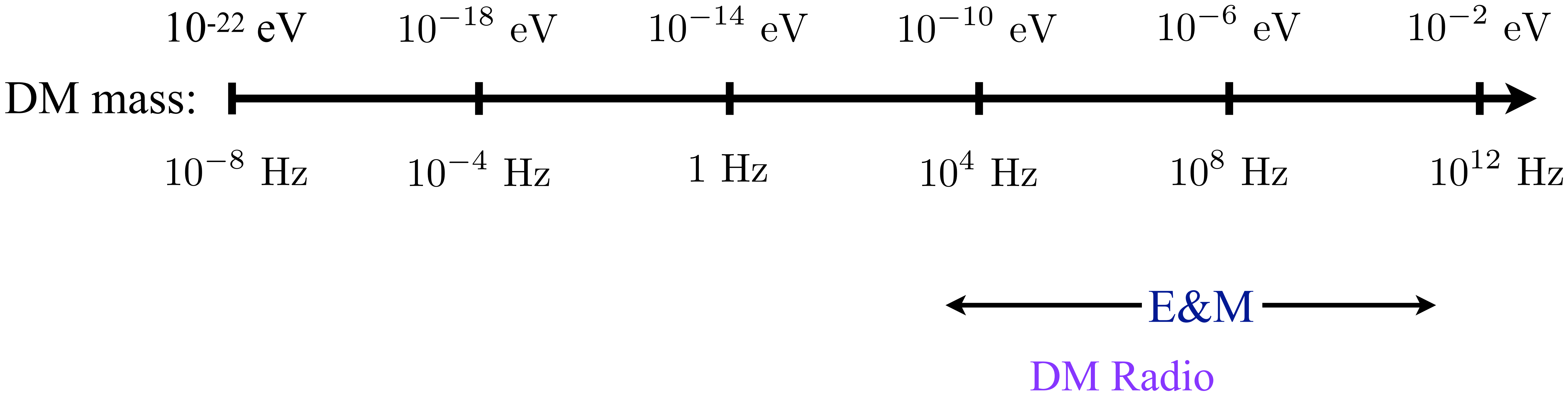
Sensitivity comes from:

- NMR technology
- high precision magnetometry

under construction at Mainz and BU



Ultralight DM Direct Detection



10^{-22} eV 10^{-18} eV 10^{-14} eV 10^{-10} eV 10^{-6} eV 10^{-2} eV

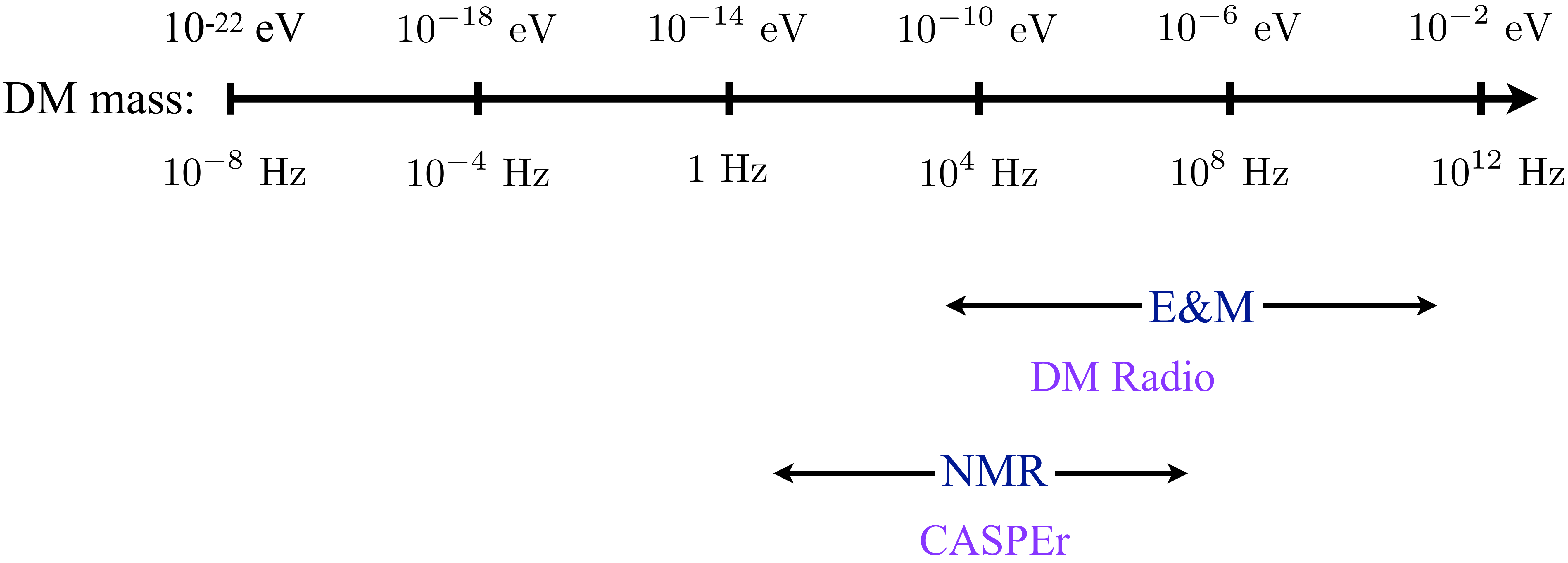
DM mass:

10^{-8} Hz 10^{-4} Hz 1 Hz 10^{4} Hz 10^{8} Hz 10^{12} Hz

E&M

DM Radio

Ultralight DM Direct Detection



10^{-22} eV 10^{-18} eV 10^{-14} eV 10^{-10} eV 10^{-6} eV 10^{-2} eV

DM mass:

10^{-8} Hz 10^{-4} Hz 1 Hz 10^{4} Hz 10^{8} Hz 10^{12} Hz

E&M

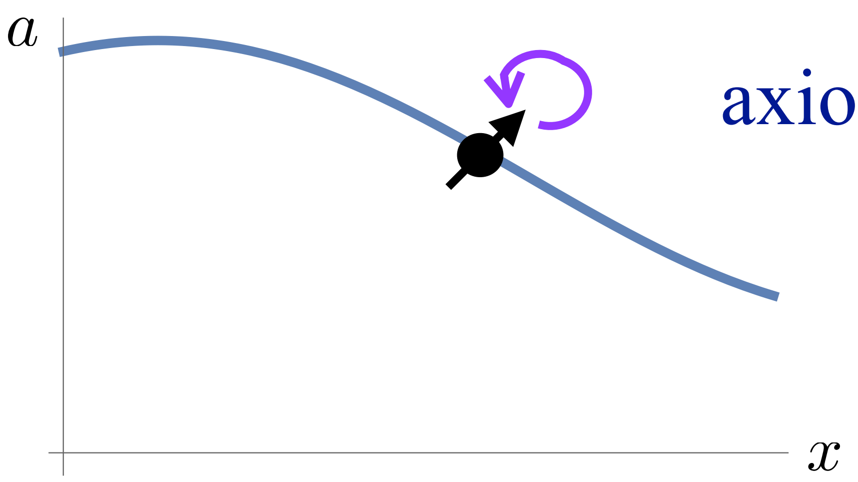
DM Radio

NMR

CASPEr

Axion DM Effects

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



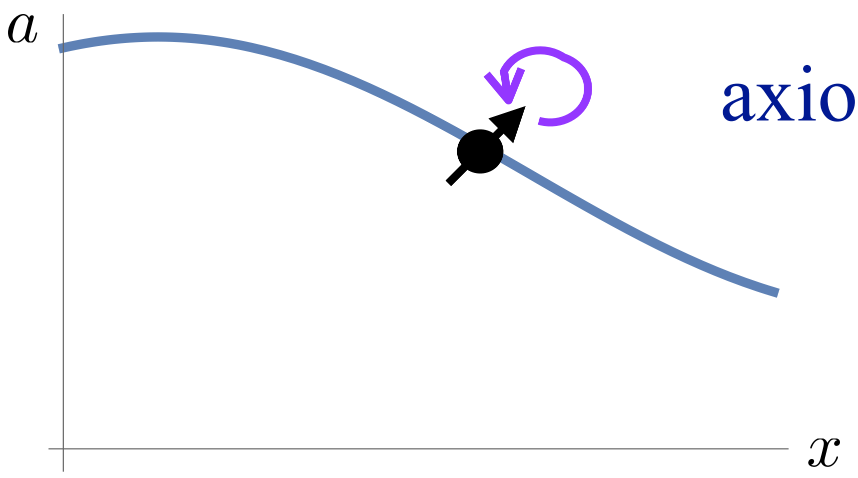
axion DM field gradient torques electron and nucleon spins

oscillates with axion frequency

proportional to axion momentum (“wind”)

Axion DM Effects

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

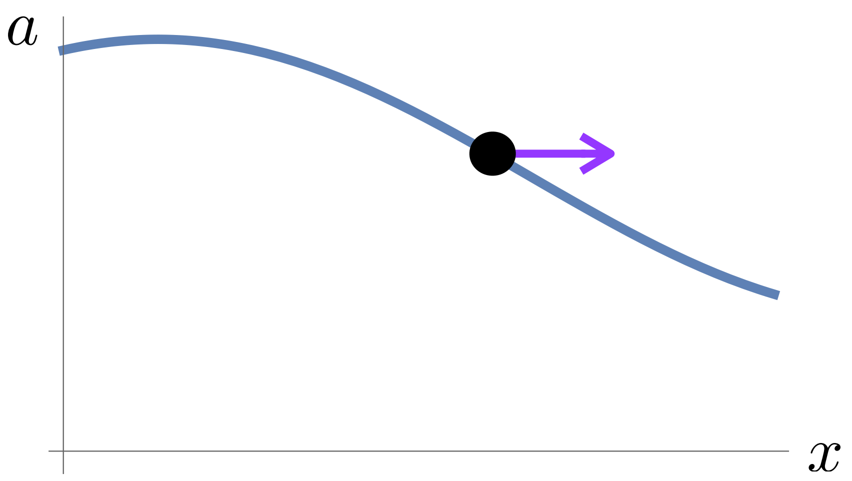


axion DM field gradient torques electron and nucleon spins

oscillates with axion frequency

proportional to axion momentum (“wind”)

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



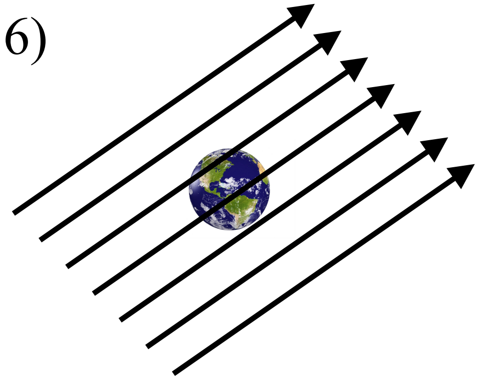
axion DM field gradient can exert a force

oscillatory and violates equivalence principle

same effects allow searches for hidden photons

Force/Torque from Dark Matter

with D.E.Kaplan, J.Mardon, S.Rajendran, & W.A.Terrano PRD **93** (2016)



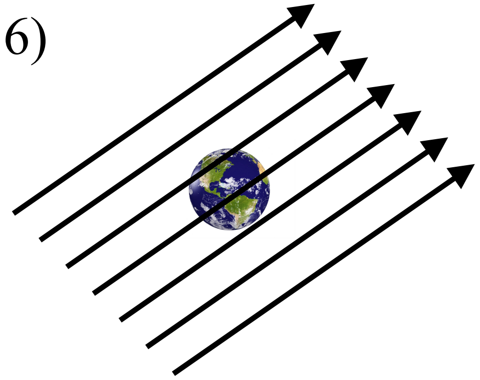
New oscillatory force/torque from dark matter

Equivalence principle violating

New Direct Detection Experiments:

Force/Torque from Dark Matter

with D.E.Kaplan, J.Mardon, S.Rajendran, & W.A.Terrano PRD **93** (2016)



New oscillatory force/torque from dark matter

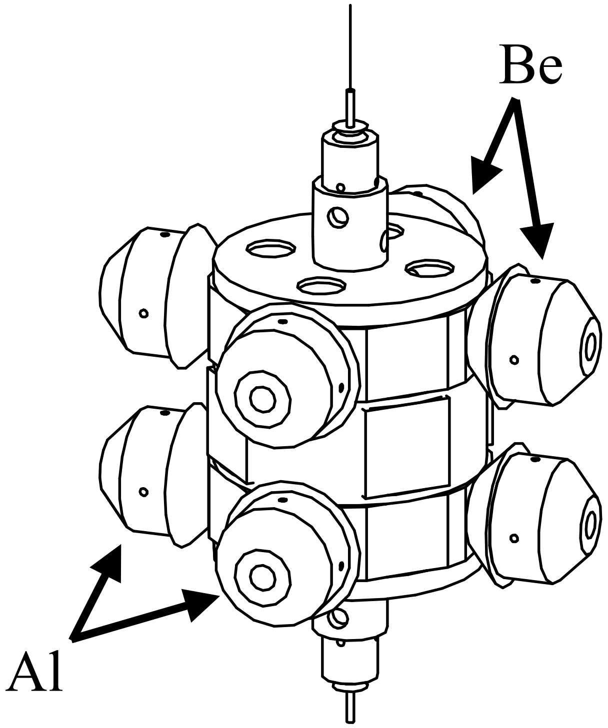
Equivalence principle violating

New Direct Detection Experiments:

Torsion Balances

scalar balance for force

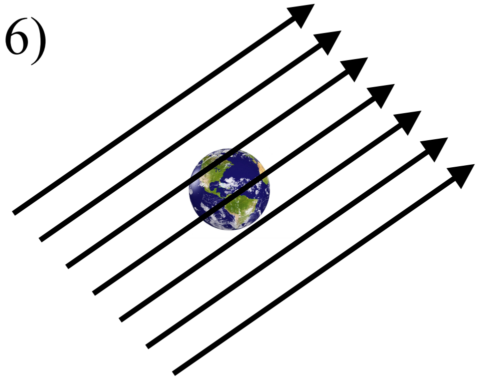
spin-polarized for torque



Eot-Wash analysis underway

Force/Torque from Dark Matter

with D.E.Kaplan, J.Mardon, S.Rajendran, & W.A.Terrano PRD **93** (2016)



New oscillatory force/torque from dark matter

Equivalence principle violating

New Direct Detection Experiments:

Torsion Balances

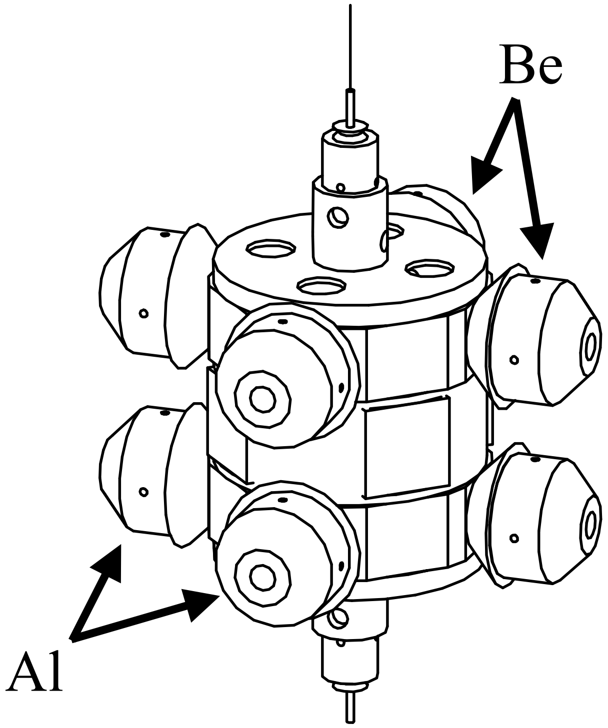
scalar balance for force

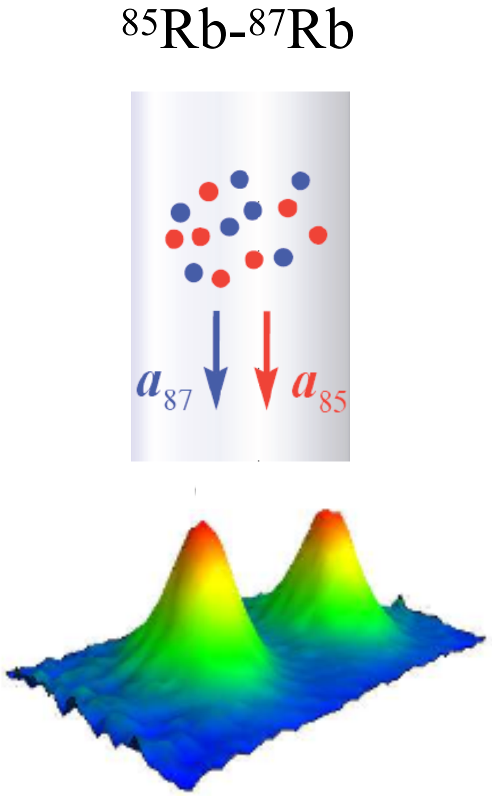
spin-polarized for torque

Atomic Interferometers (Clocks)

split + recombine atom wavefunction

measure atom spin and acceleration



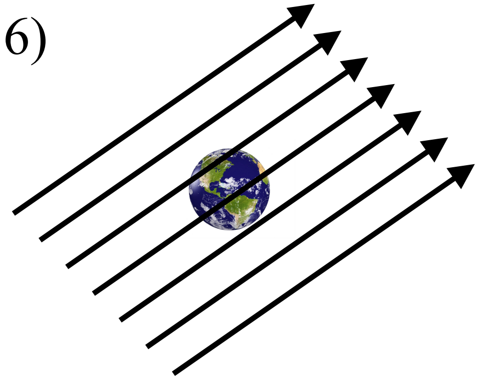


Eot-Wash analysis underway

In construction Kasevich/Hogan groups

Force/Torque from Dark Matter

with D.E.Kaplan, J.Mardon, S.Rajendran, & W.A.Terrano PRD **93** (2016)



New oscillatory force/torque from dark matter

Equivalence principle violating

New Direct Detection Experiments:

Torsion Balances

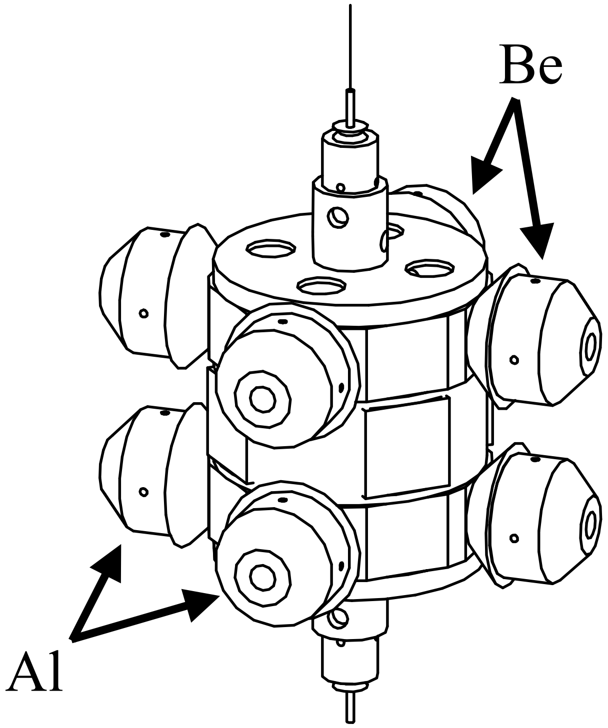
scalar balance for force
spin-polarized for torque

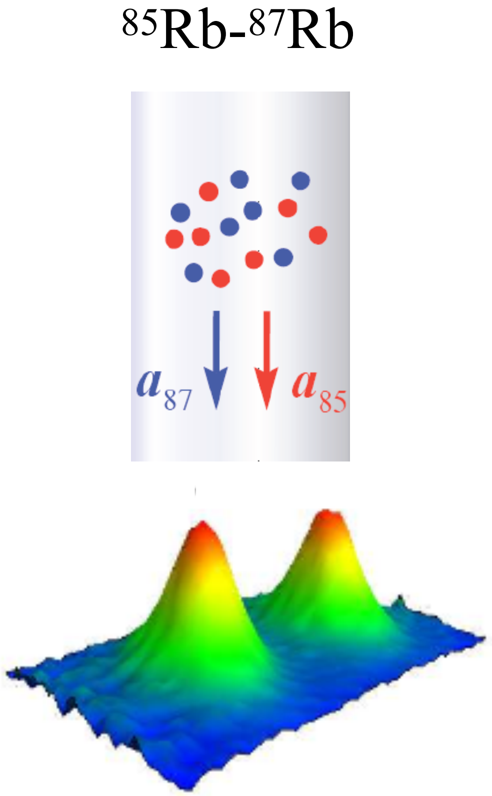
Atomic Interferometers (Clocks)

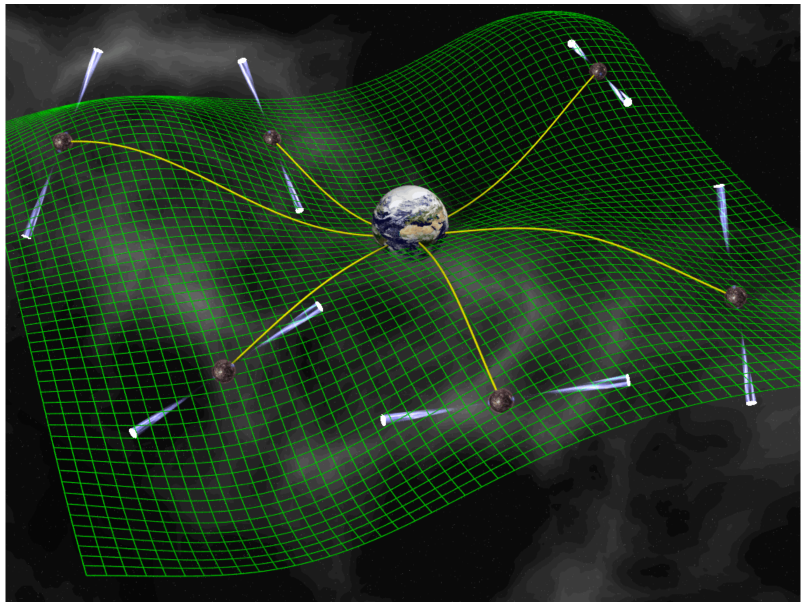
split + recombine atom wavefunction
measure atom spin and acceleration

Pulsar Timing Arrays

measure relative acceleration
of earth and pulsar





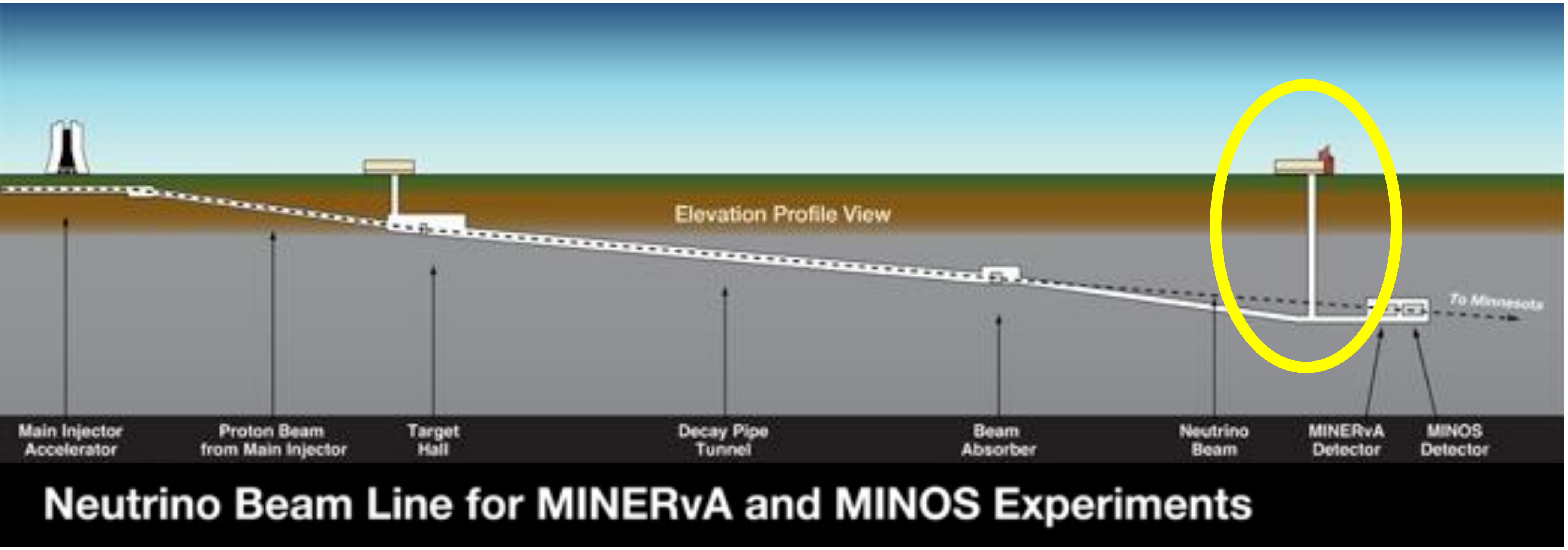


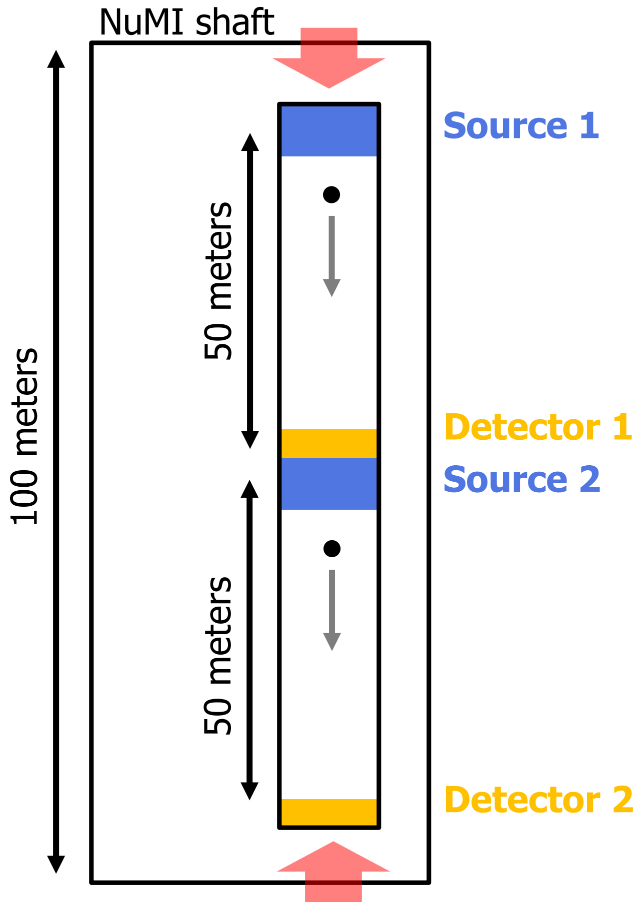
Eot-Wash analysis underway

In construction Kasevich/Hogan groups

ultralight DM and gravitational wave detection similar!

MAGIS-100 Proposal at Fermilab





- 100 m atom interferometer drop tower
- Detect dark matter through oscillatory force/torque
- Demonstrator for future gravitational wave detector

Gravitational Wave Detection with Atom Interferometry

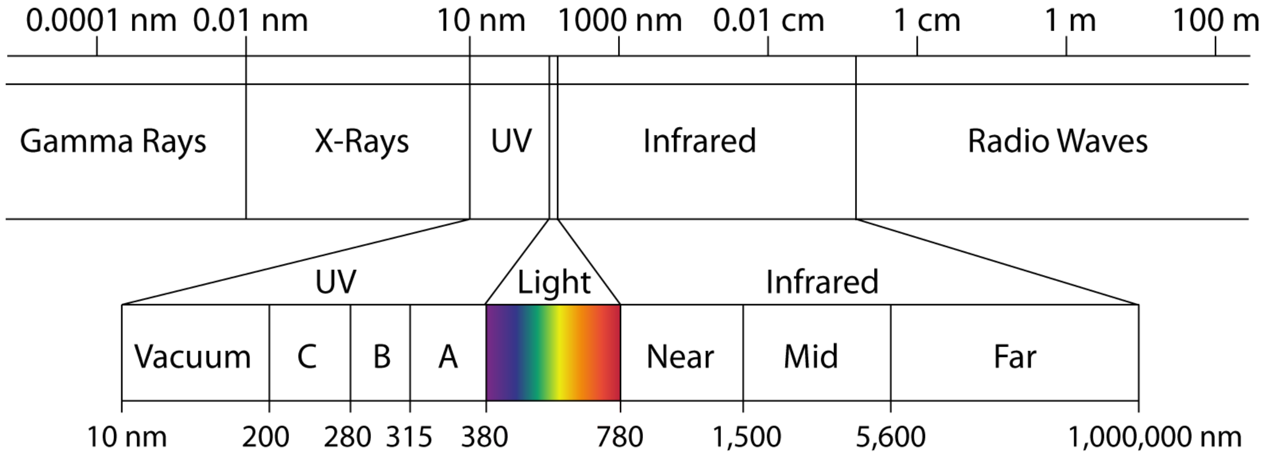
PRD **94** (2016) arXiv:1606.01860
PRL **110** (2013) arXiv:1206.0818
GRG **43** (2011) arXiv:1009.2702
PLB **678** (2009) arXiv:0712.1250
PRD **78** (2008) arXiv:0806.2125

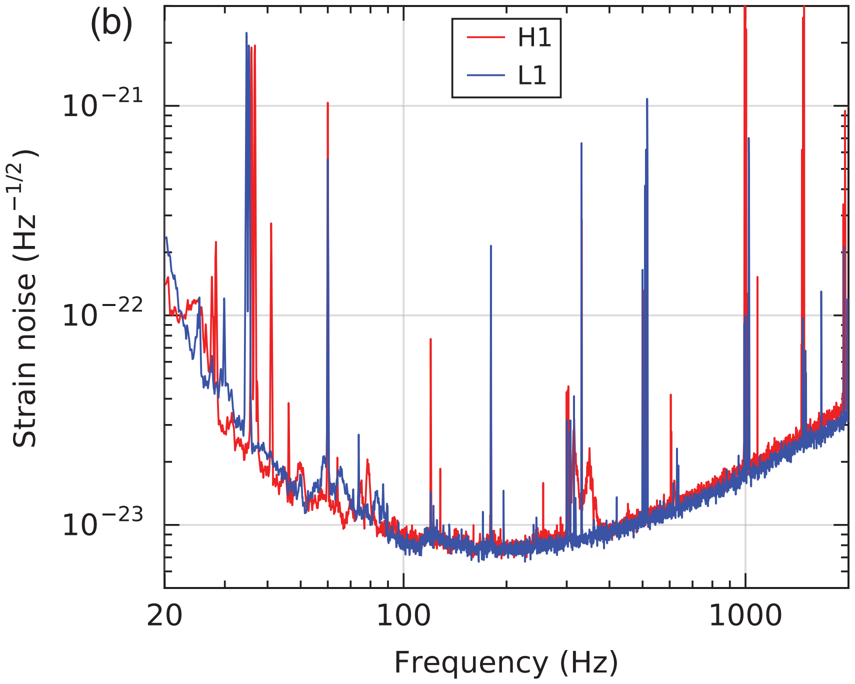
W.M. KECK
FOUNDATION

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?

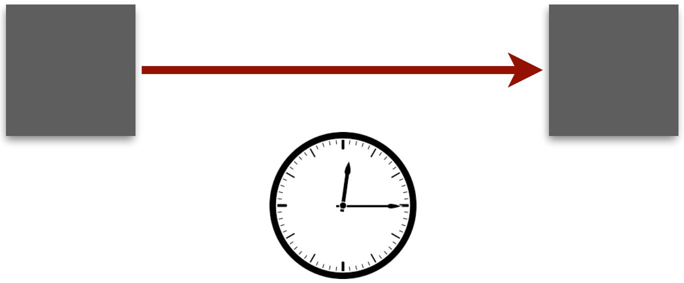
Gravitational Wave Detection

Gravitation Wave Detector

inertial test masses

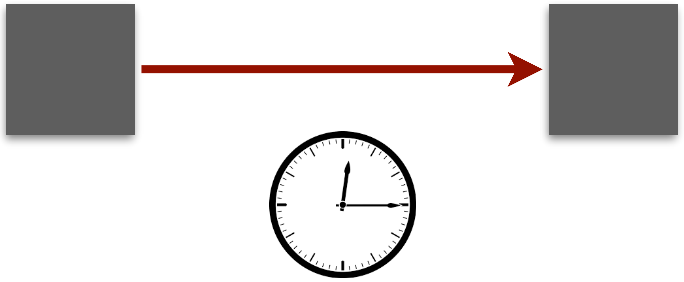
baseline

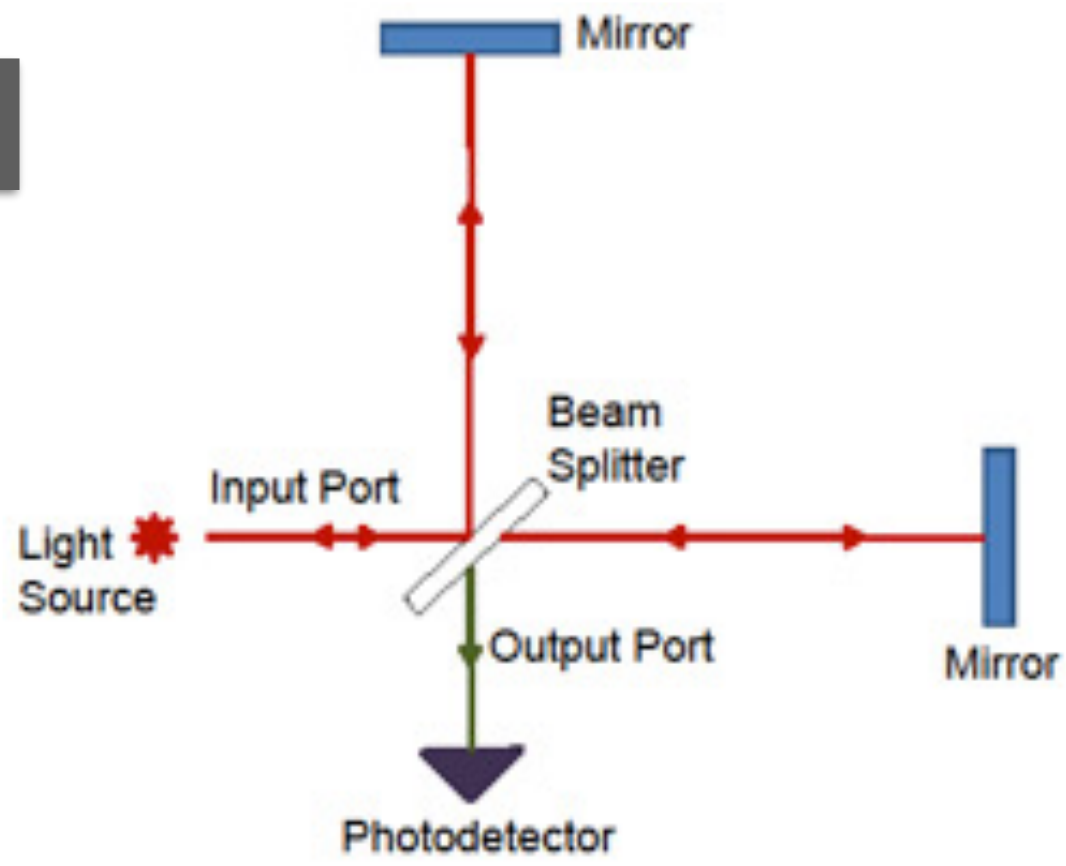
good clock



Gravitational Wave Detection

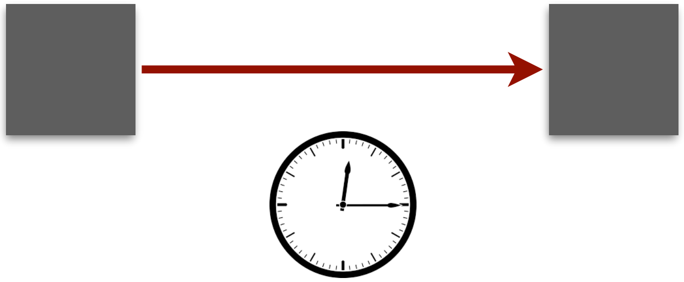
Gravitation Wave Detector	LIGO
inertial test masses	mirrors
baseline	laser
good clock	second arm

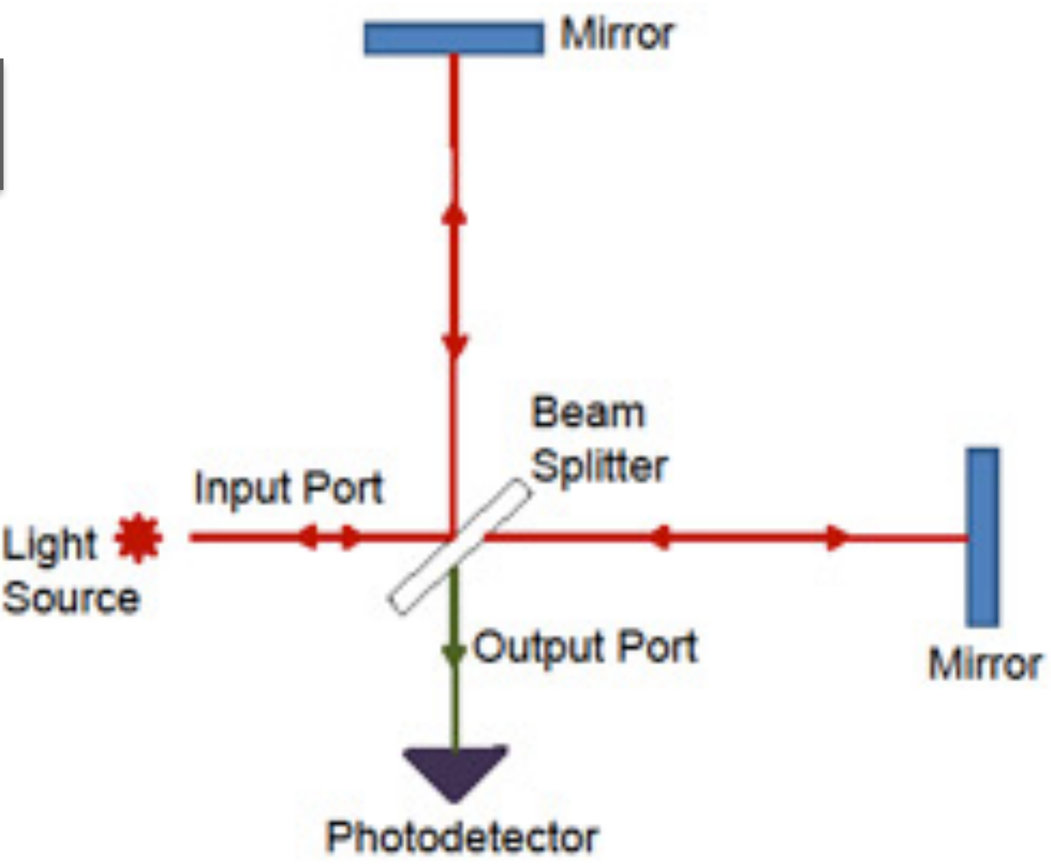




Gravitational Wave Detection

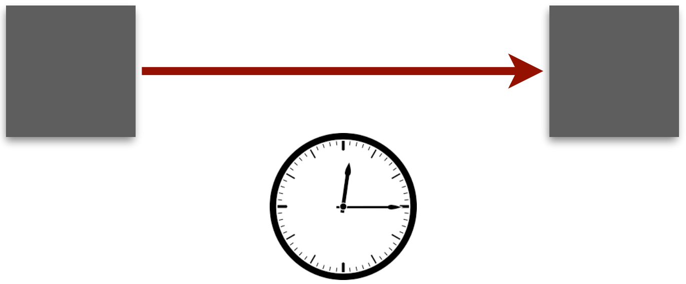
Gravitation Wave Detector	LIGO	Atom Interferometry
inertial test masses	mirrors	atoms
baseline	laser	laser
good clock	second arm	atoms

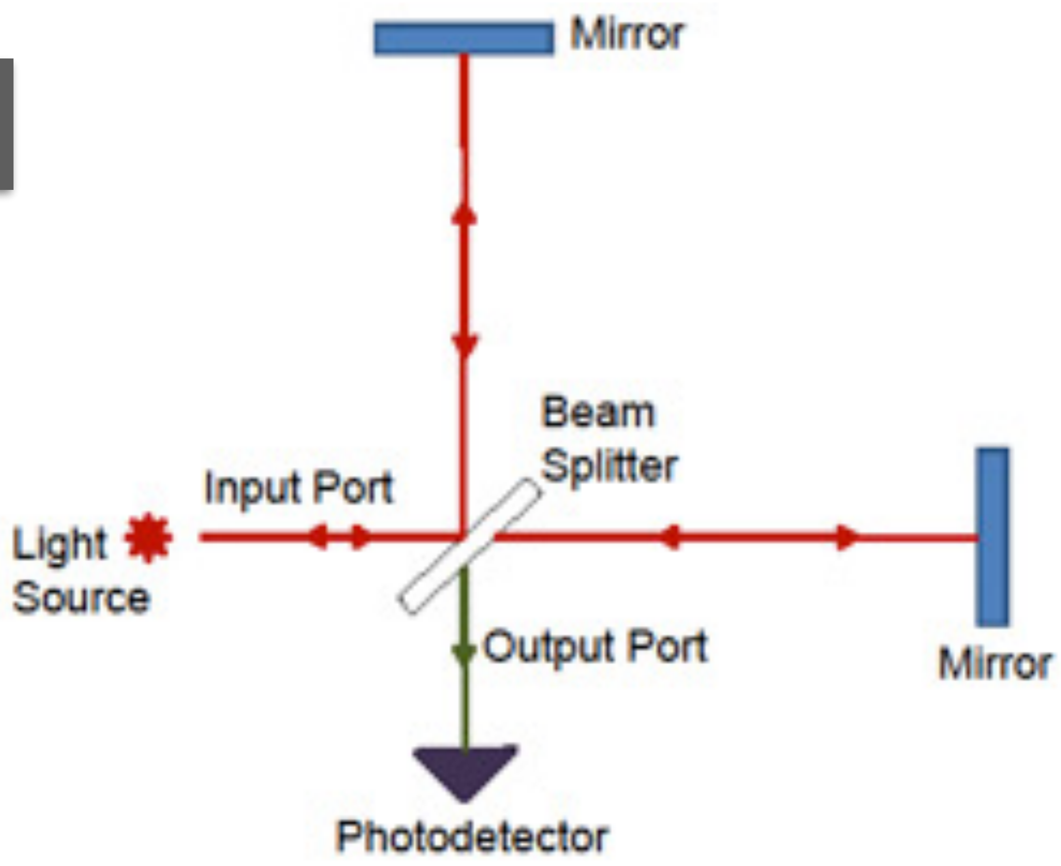


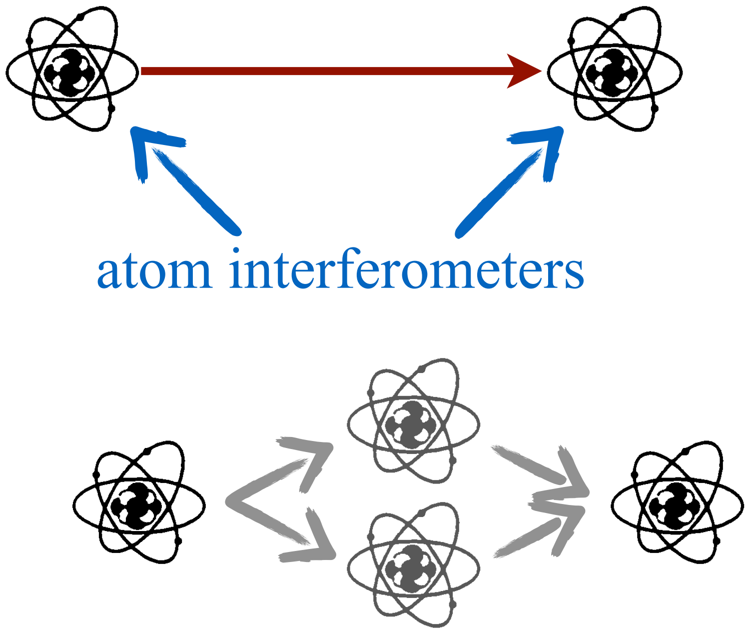


Gravitational Wave Detection

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

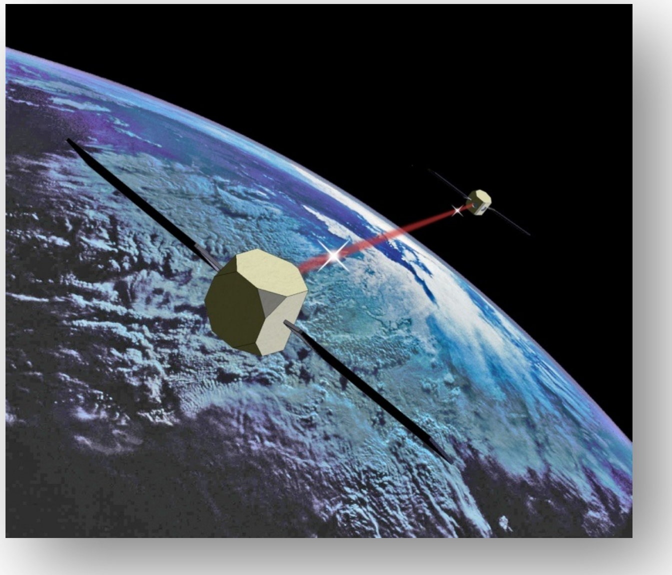


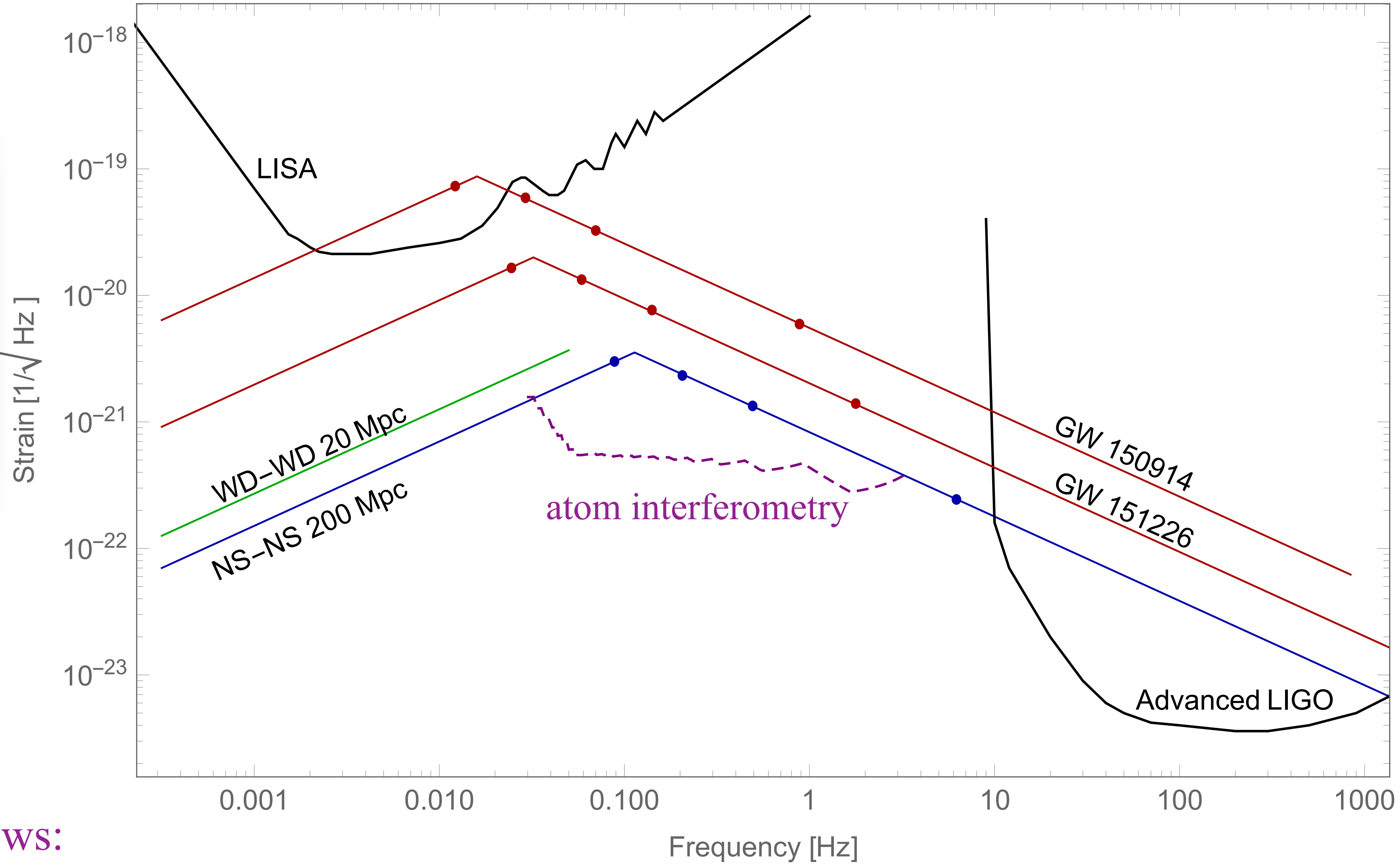



atom interferometers

Atom Interferometry for Gravitational Waves

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



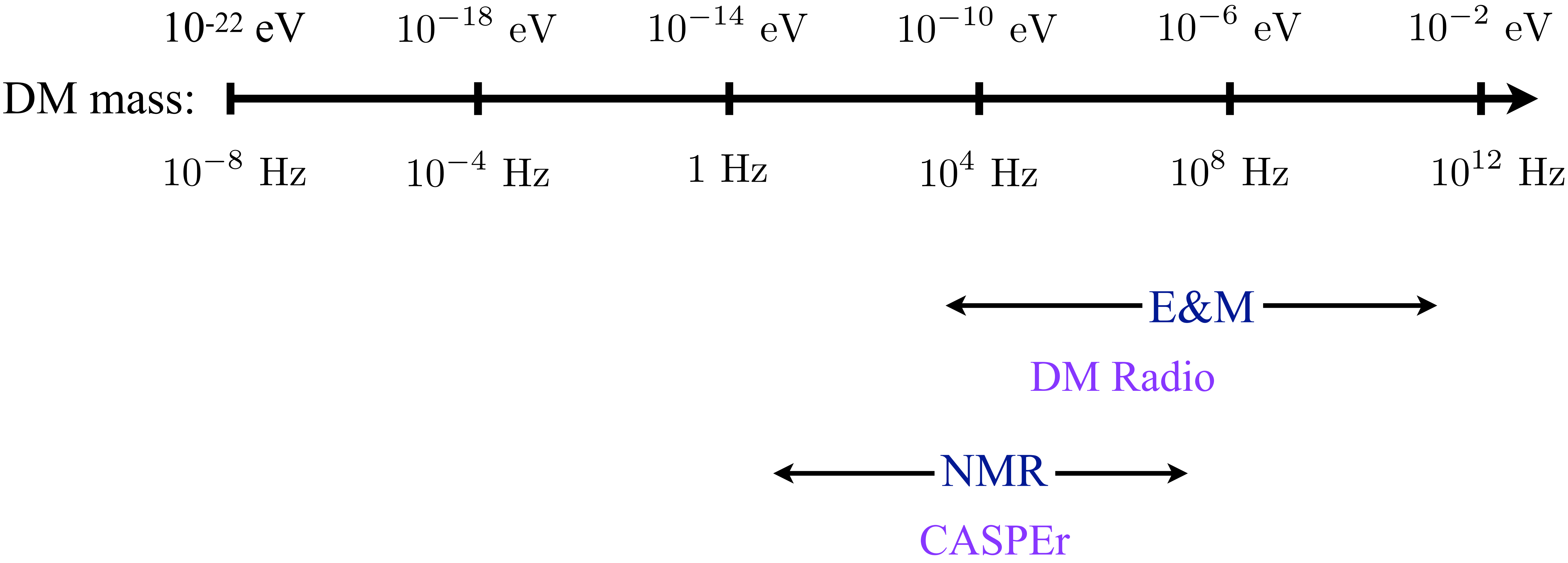


for example this band allows:

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

with Sunghoon Jung

Ultralight DM Direct Detection



DM mass:

10^{-22} eV
10^{-18} eV
10^{-14} eV
10^{-10} eV
10^{-6} eV
10^{-2} eV

10^{-8} Hz
10^{-4} Hz
1 Hz
10^{4} Hz
10^{8} Hz
10^{12} Hz

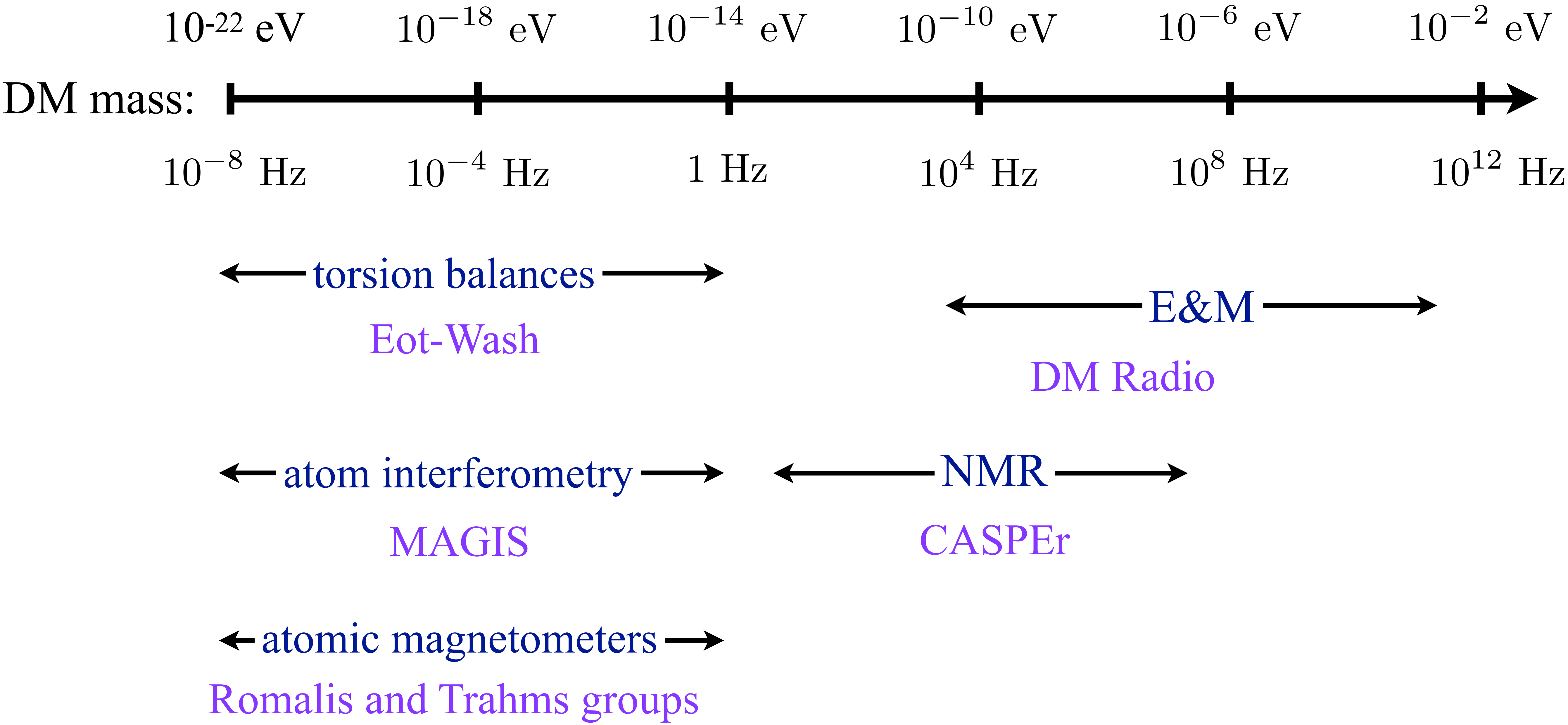
E&M

DM Radio

NMR

CASPEr

Ultralight DM Direct Detection



10^{-22} eV　10^{-18} eV　10^{-14} eV　10^{-10} eV　10^{-6} eV　10^{-2} eV

DM mass:

10^{-8} Hz　10^{-4} Hz　1 Hz　10^{4} Hz　10^{8} Hz　10^{12} Hz

torsion balances

Eot-Wash

E&M

DM Radio

atom interferometry

MAGIS

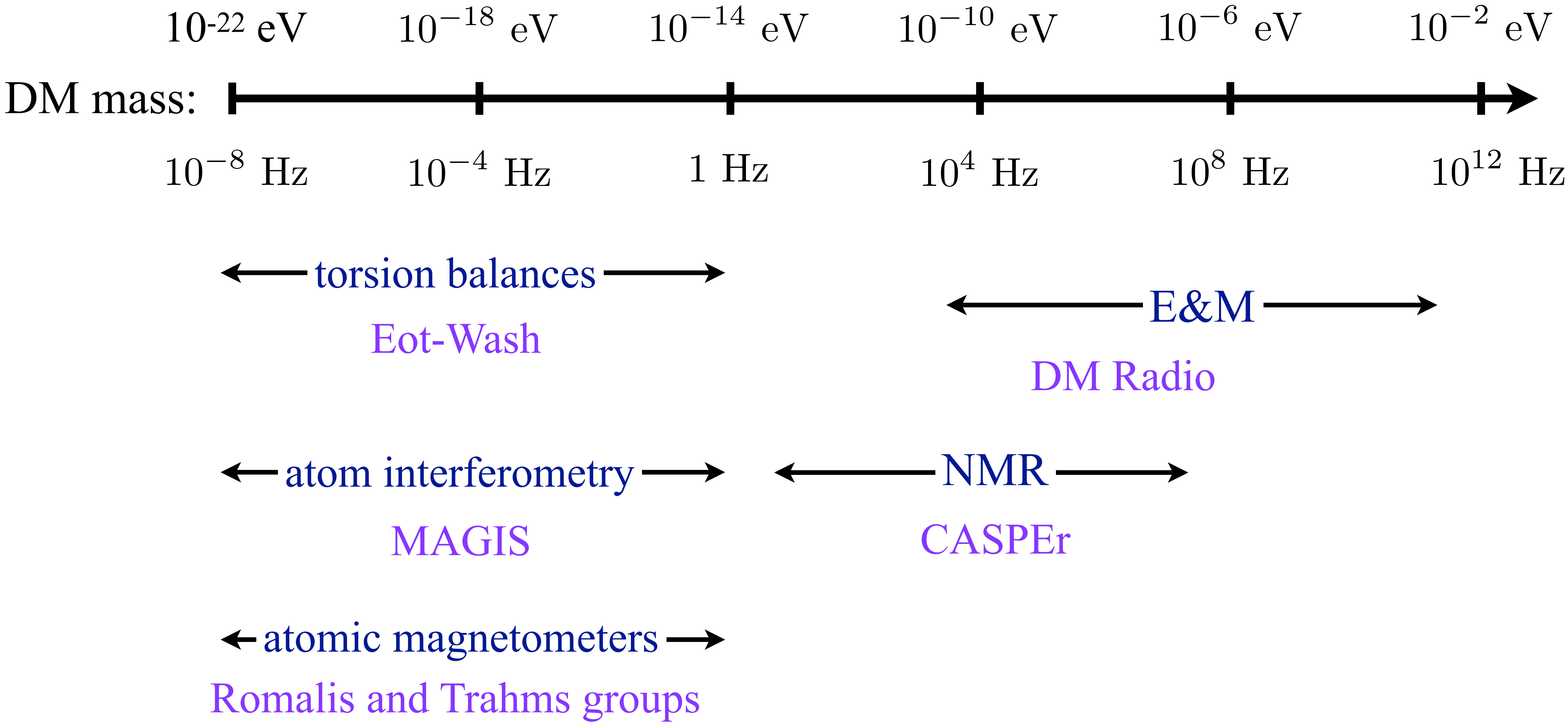
NMR

CASPEr

atomic magnetometers

Romalis and Trahms groups

Ultralight DM Direct Detection



10^{-22} eV 10^{-18} eV 10^{-14} eV 10^{-10} eV 10^{-6} eV 10^{-2} eV

DM mass:

10^{-8} Hz 10^{-4} Hz 1 Hz 10^{4} Hz 10^{8} Hz 10^{12} Hz

torsion balances

Eot-Wash

E&M

DM Radio

atom interferometry

MAGIS

NMR

CASPEr

atomic magnetometers

Romalis and Trahms groups

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

Summary

Precision measurement is a powerful tool for particle physics and cosmology

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

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

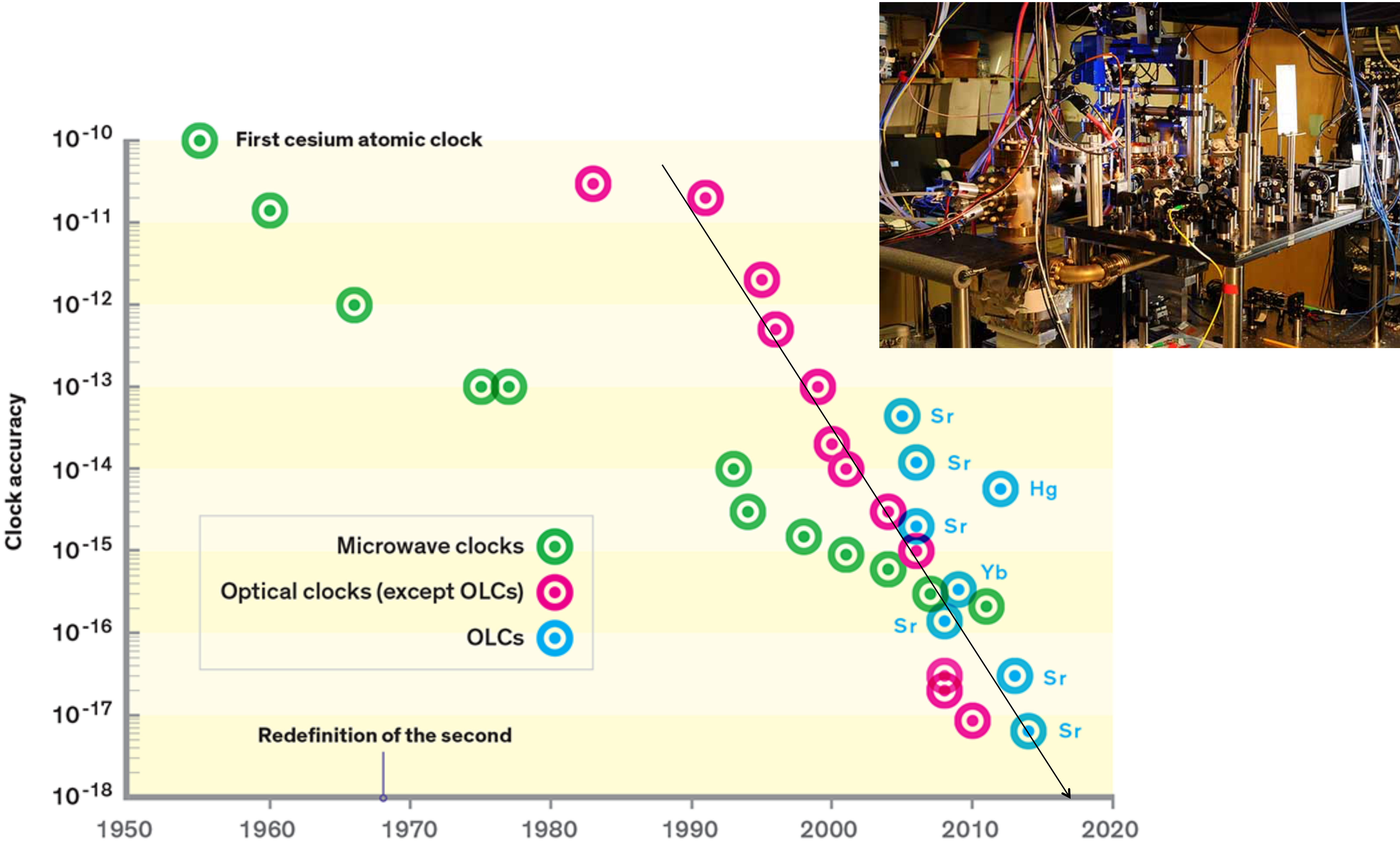
detect coherent effects of entire field, not single particles

- EM resonators
- laser interferometry
- atom interferometry (clocks)
- 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

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

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
  $aH^\dagger H$

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

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
$a\,F\tilde{F}$

current axion searches
e.g. ADMX

QCD - change nuclear properties
$a\,G\tilde{G}$

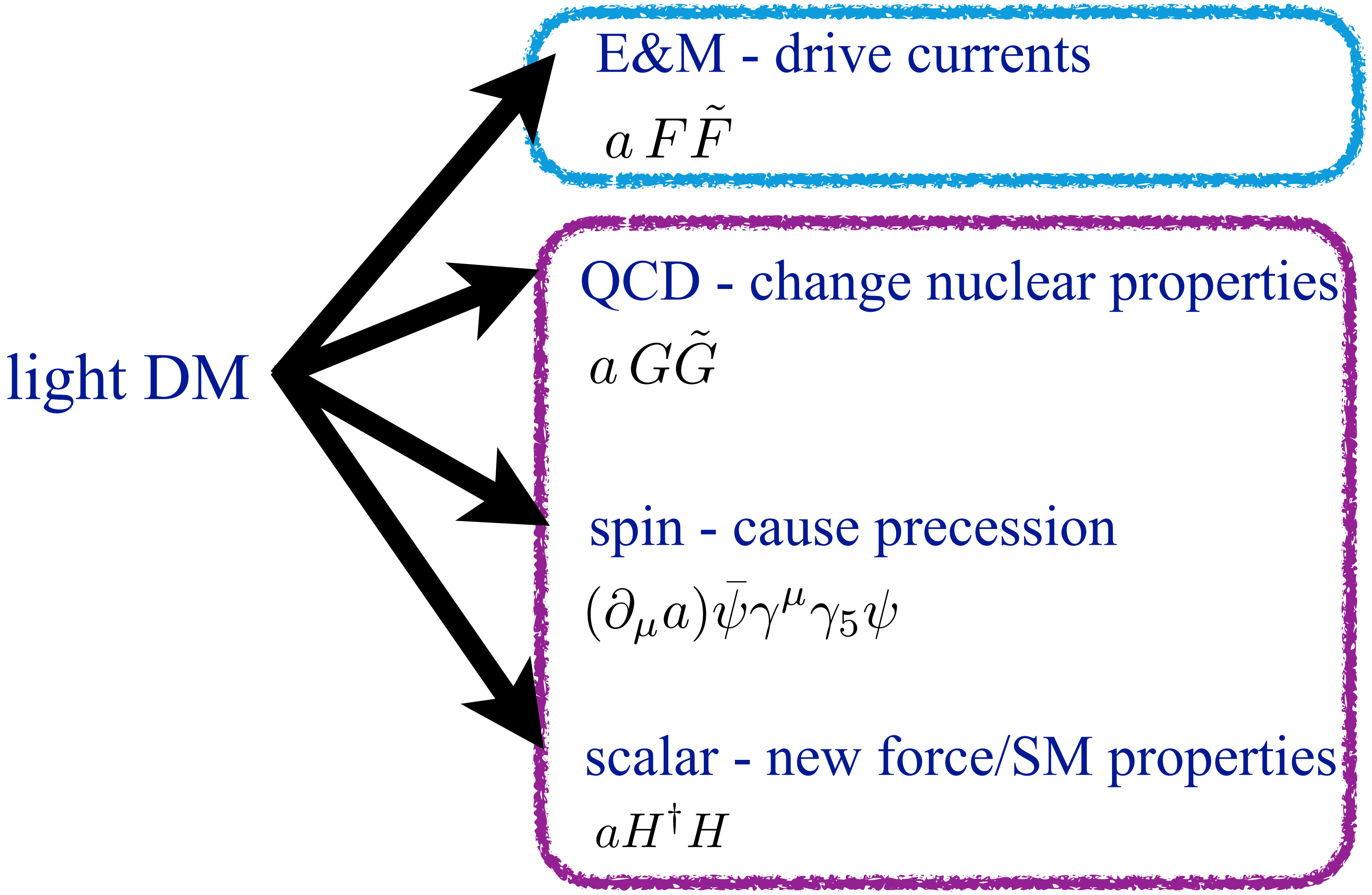
spin - cause precession
$(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$

scalar - new force/SM properties
$aH^\dagger H$

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

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
$a\,F\tilde{F}$

current axion searches
e.g. ADMX

QCD - change nuclear properties
$a\,G\tilde{G}$

spin - cause precession
$(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$

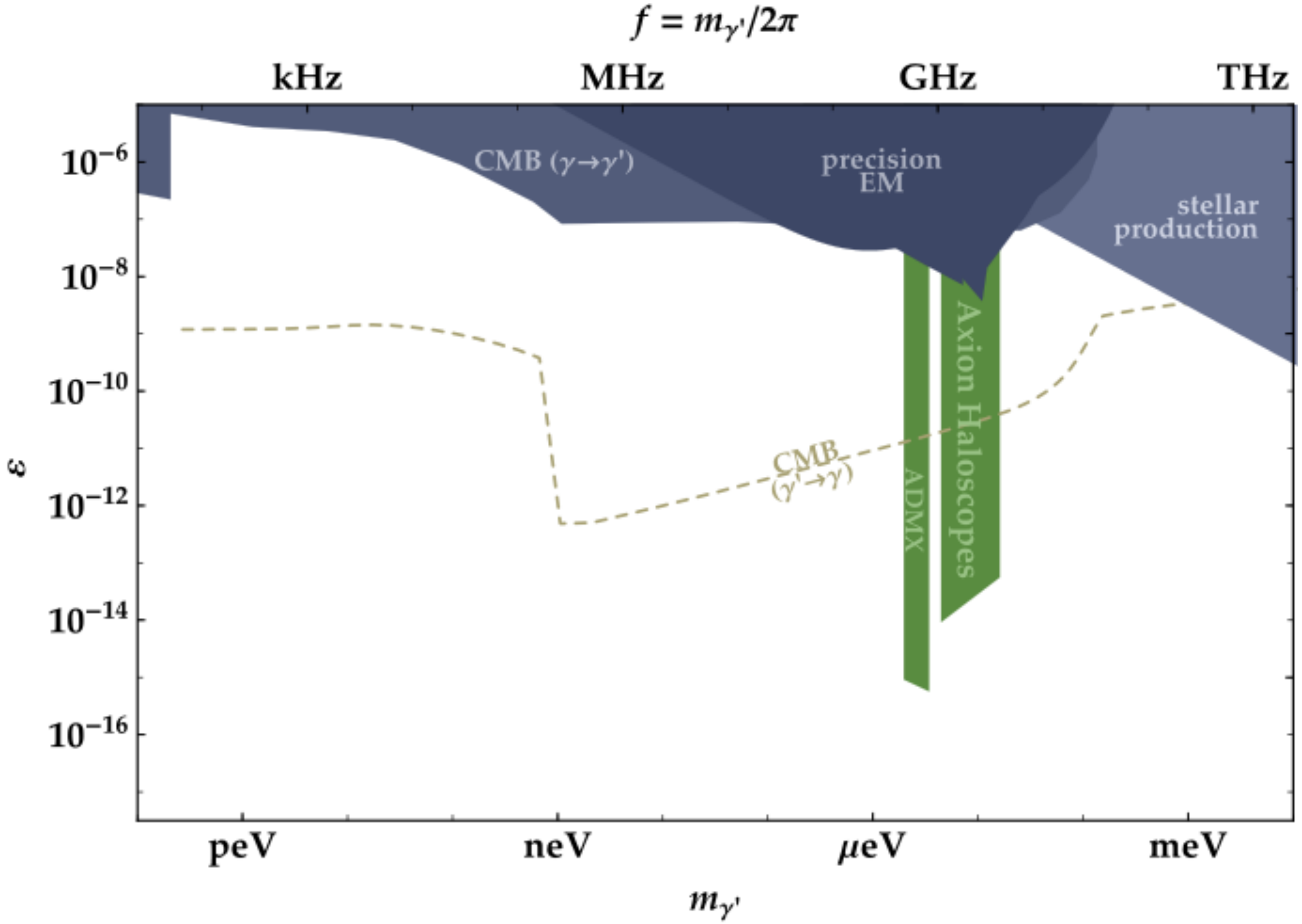
scalar - new force/SM properties
$aH^\dagger H$

e.g. aids axion detection

Can cover all these possibilities

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

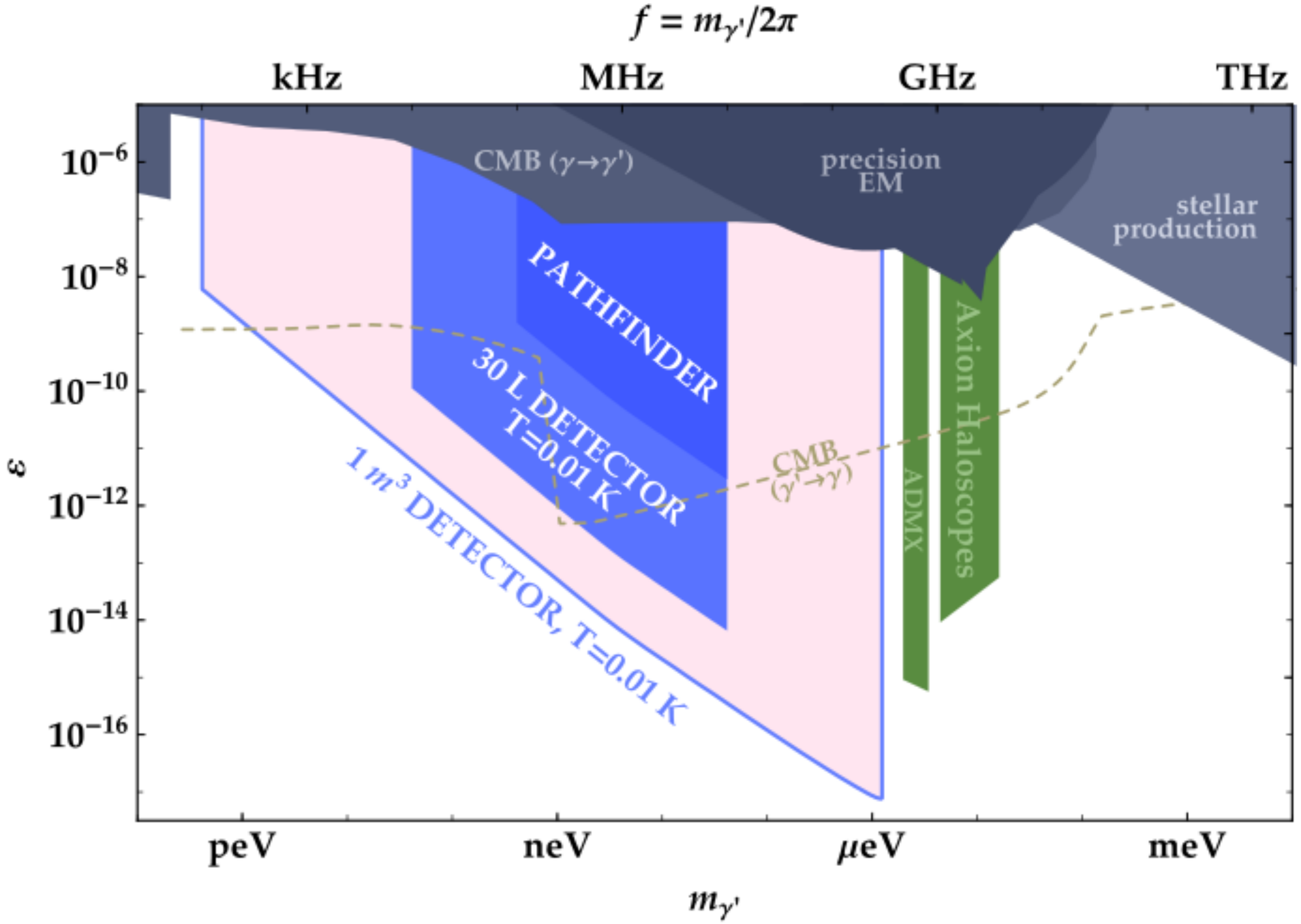
DM Radio Sensitivity to Hidden Photons



coupling
to E&M

DM Radio Sensitivity to Hidden Photons

coupling
to E&M

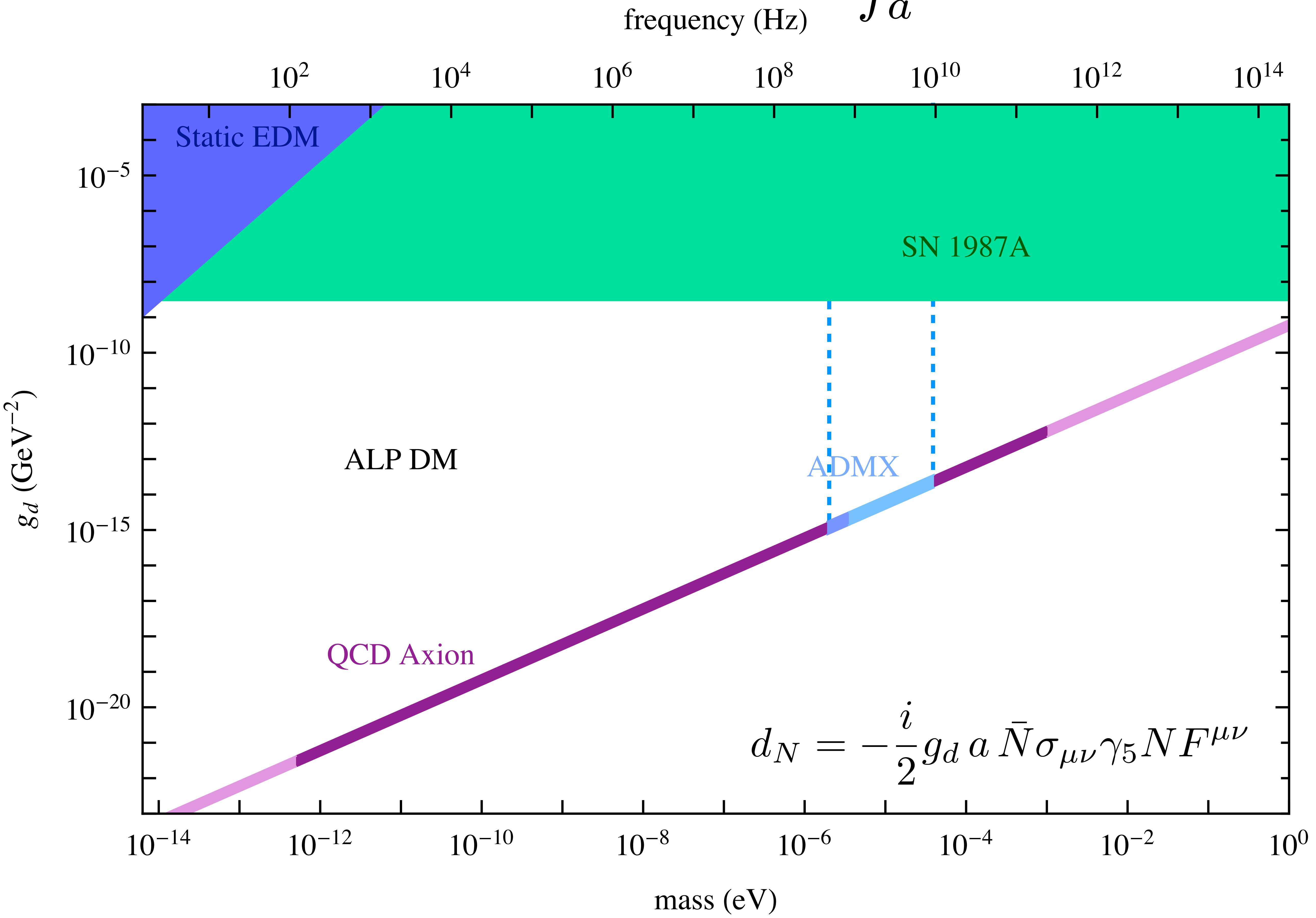


we found hidden photon DM is produced by inflation, and in this frequency range

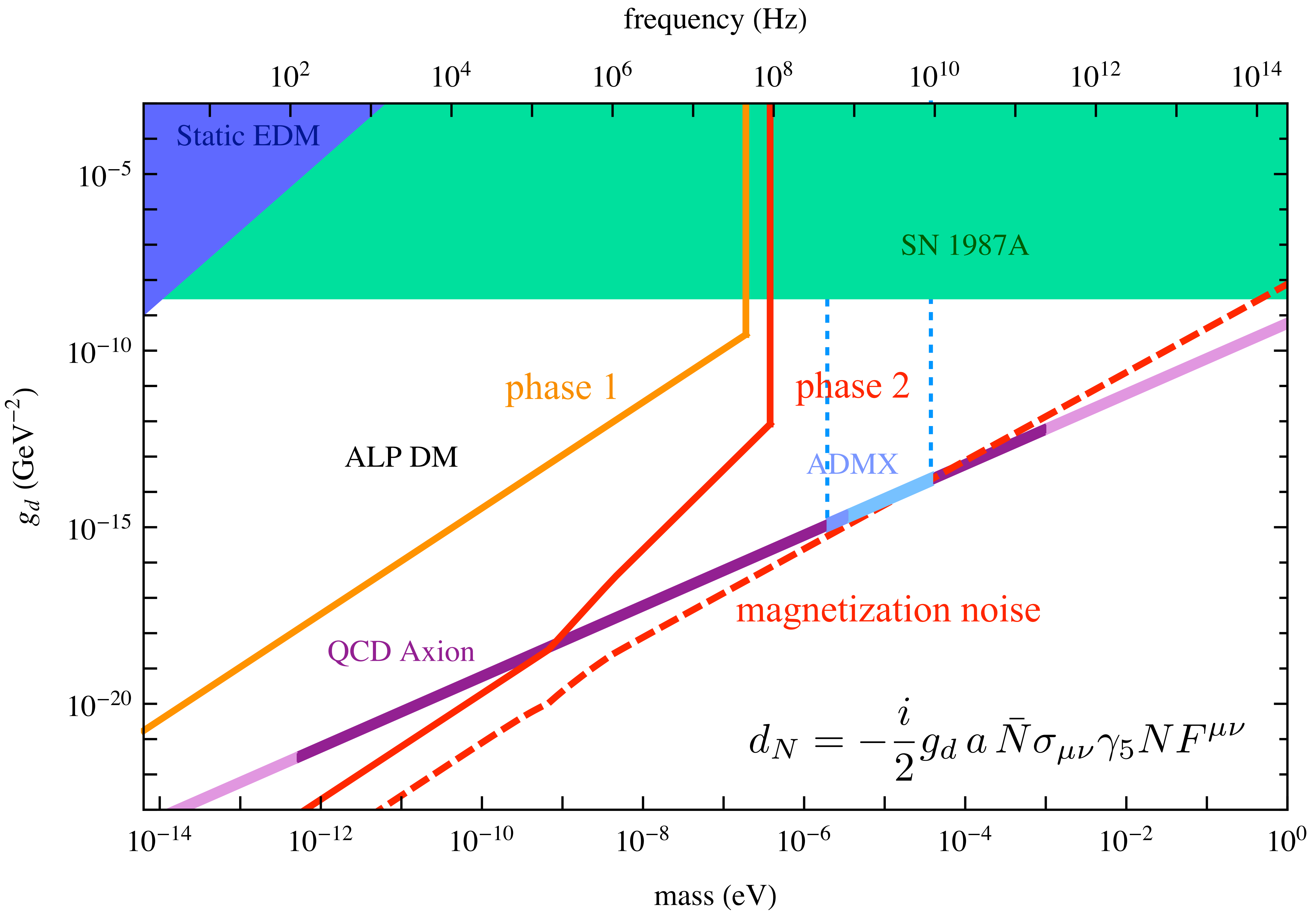
PWG, Mardon, Rajendran PRD **93** (2016)

a discovery allows measurement of DM power spectrum:
verify quantum fluctuation production
and measure scale of inflation

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



CASPEr Sensitivity



Gravitational Wave Detection with Atom Interferometry

with

Savas Dimopoulos
Jason Hogan
Mark Kasevich
Surjeet Rajendran

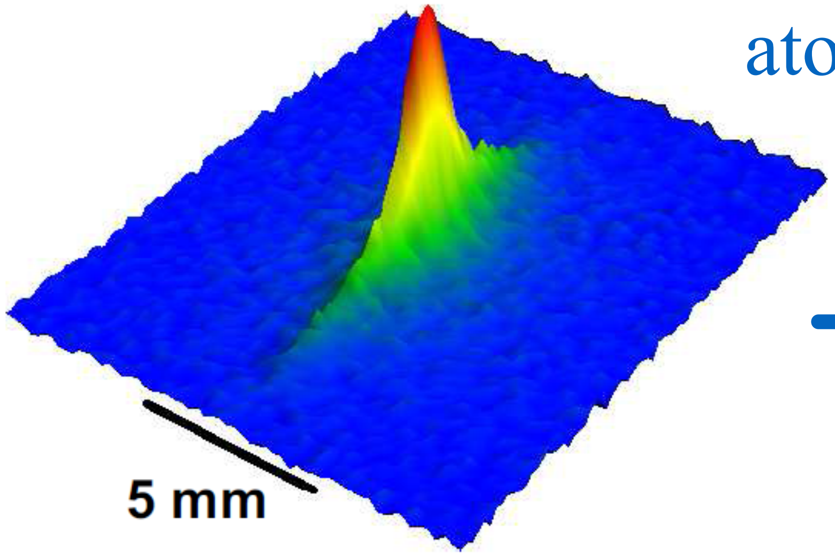
PRD **94** (2016) arXiv:1606.01860
PRL **110** (2013) arXiv:1206.0818
GRG **43** (2011) arXiv:1009.2702
PLB **678** (2009) arXiv:0712.1250
PRD **78** (2008) arXiv:0806.2125

Recent Experimental Results

(Kasevich and Hogan groups)

Stanford Test Facility

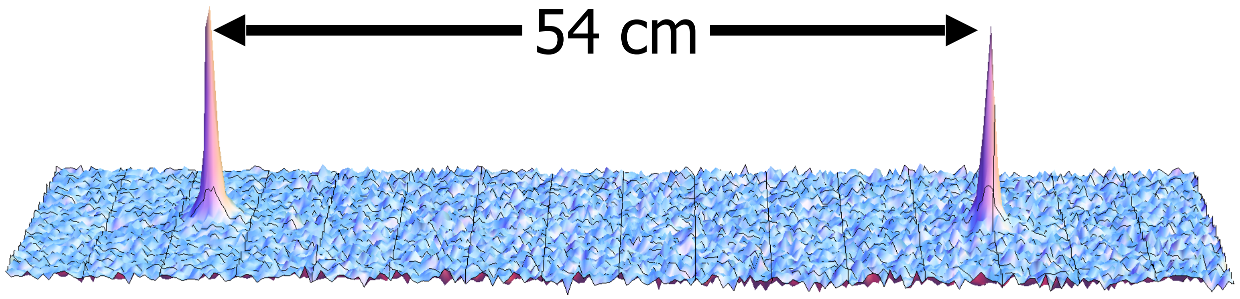
demonstrate necessary technologies:



atom cooling

➜ 50 pK

Macroscopic splitting of atomic wavefunction:



Kovachy et. al, *Nature* (2015)