Precision Measurement for Particle Physics

Peter Graham

Stanford

Motivation

Precision measurement offers a powerful new approach for particle physics

- New technologies rapidly pushing precision measurement
  - e.g. atomic clocks have 18 digit precision

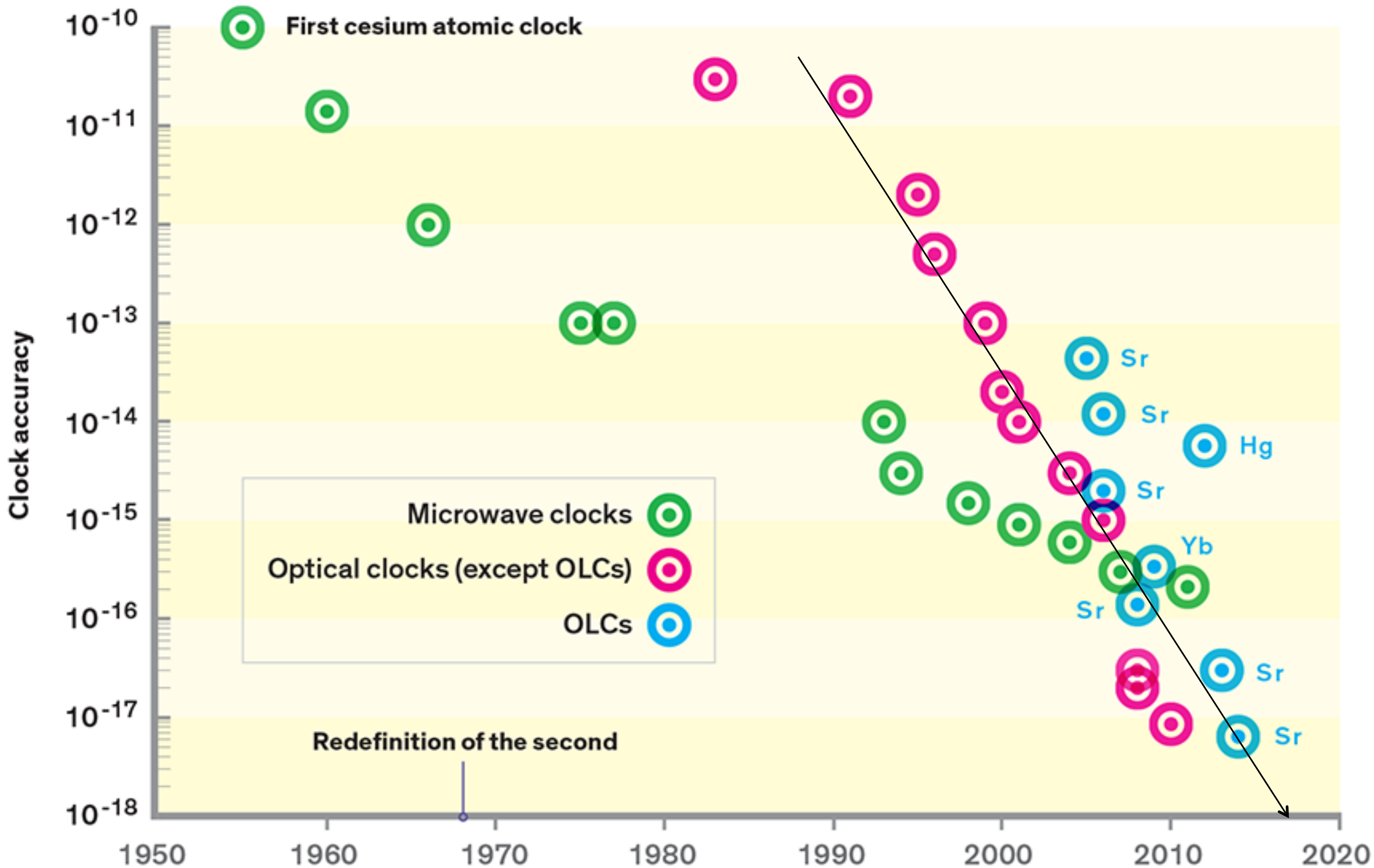
Motivation

Precision measurement offers a powerful new approach for particle physics

- New technologies rapidly pushing precision measurement
  - e.g. atomic clocks have 18 digit precision
- Much well-motivated new physics requires precision measurement, invisible to conventional particle colliders/detectors
  - axions, gravitational waves…
  - critical questions such as hierarchy problem or nature of dark matter may not be answered at weak scale

Many promising, unexplored directions

Rapid Sensitivity Advance



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

New Physics

We know there is new physics out there (e.g. dark matter, baryogenesis)

Where is it? Many hints (e.g. fine-tuning problems)

New Physics

We know there is new physics out there (e.g. dark matter, baryogenesis)

Where is it? Many hints (e.g. fine-tuning problems)

Light ($\ll$ weak scale)

<u>Very weak coupling</u>

high precision sensors

Heavy (weak scale)

<u>High coupling (EM, weak, strong)</u>

high energy accelerators

Outline

1. Theory motivation: dynamical relaxation for the hierarchy problem
2. Axions with NMR and EM Resonators
    1. Cosmic Axion Spin Precession Experiment (CASPEr)
    2. DM Radio
3. Atom interferometry for dark matter and gravitational waves

Dynamical Relaxation for the Hierarchy Problem

with

David E. Kaplan
Surjeet Rajendran

PRL **115** (2015) arXiv:1504.07551

Hierarchy Problem

Why is Higgs so light? Significant motivation for exploring weak scale

Previous solutions (supersymmetry, technicolor, extra dimensions, etc.)

- new physics at weak scale, cuts off loops
- motivates WIMPs
- tension with LHC results

Hierarchy Problem

Why is Higgs so light? Significant motivation for exploring weak scale

Previous solutions (supersymmetry, technicolor, extra dimensions, etc.)

- new physics at weak scale, cuts off loops
- motivates WIMPs
- tension with LHC results

New class of solutions to hierarchy problem

- dynamical relaxation in early universe (“relaxion”)
- minimal model has no new physics at weak scale
- motivates light (axion-like) DM

Dynamical Relaxation

- make fundamental constant (Higgs mass) a dynamical variable
- accept large, untuned initial value
- driven to small value in early universe (similar to axion for strong CP)

Dynamical Relaxation

- make fundamental constant (Higgs mass) a dynamical variable
- accept large, untuned initial value
- driven to small value in early universe (similar to axion for strong CP)

dynamical Higgs mass is a field: the axion

minimal model solves hierarchy problem:

Standard Model + QCD axion (softly-broken shift symmetry) + inflaton

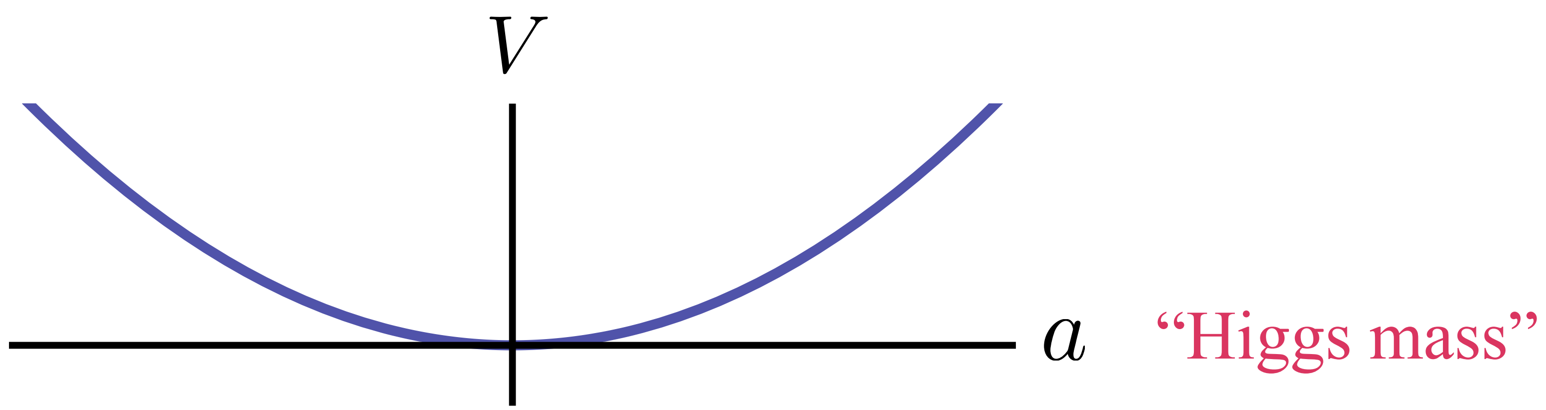
Dynamical Relaxation

- make fundamental constant (Higgs mass) a dynamical variable
- accept large, untuned initial value
- driven to small value in early universe (similar to axion for strong CP)

dynamical Higgs mass is a field: the axion

minimal model solves hierarchy problem:

Standard Model + QCD axion (softly-broken shift symmetry) + inflaton



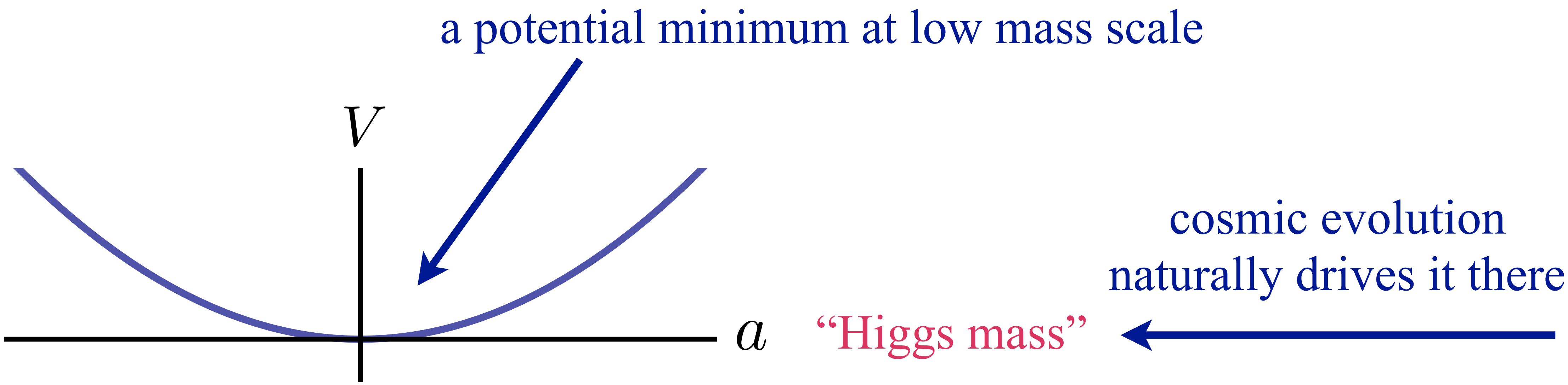
Dynamical Relaxation

- make fundamental constant (Higgs mass) a dynamical variable
- accept large, untuned initial value
- driven to small value in early universe (similar to axion for strong CP)

dynamical Higgs mass is a field: the axion

minimal model solves hierarchy problem:

Standard Model + QCD axion (softly-broken shift symmetry) + inflaton



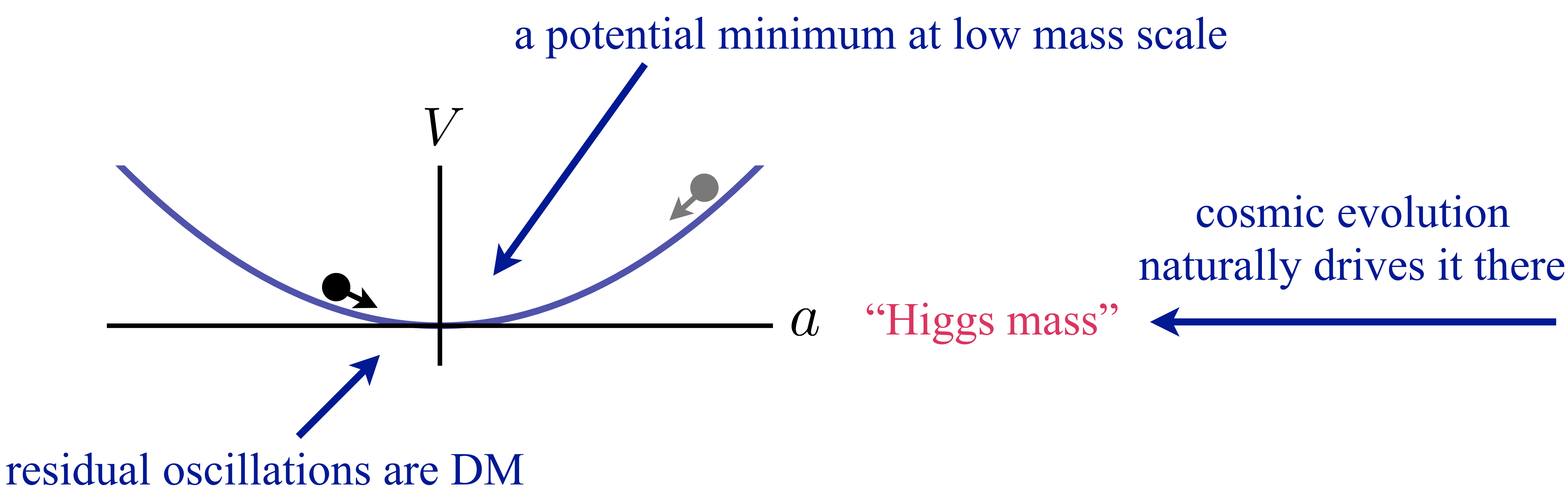
Dynamical Relaxation

- make fundamental constant (Higgs mass) a dynamical variable
- accept large, untuned initial value
- driven to small value in early universe (similar to axion for strong CP)

dynamical Higgs mass is a field: the axion

minimal model solves hierarchy problem:

Standard Model + QCD axion (softly-broken shift symmetry) + inflaton



predicts light field DM coupled to Higgs

Predictions

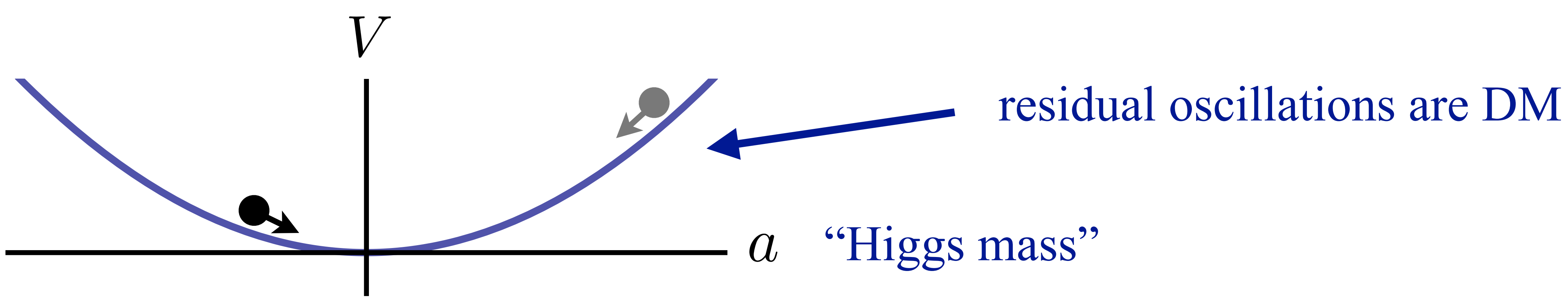
Dynamics (SUSY, extra dimensions…) ➜ weak-scale particles (e.g. WIMP)

Dynamical Relaxation ➜ light particles (e.g. axion)

Predictions

Dynamics (SUSY, extra dimensions…) ➜ weak-scale particles (e.g. WIMP)

Dynamical Relaxation ➜ light particles (e.g. axion)



Axion DM fluctuates Higgs VEV ➜ oscillates all scales (electron mass…)

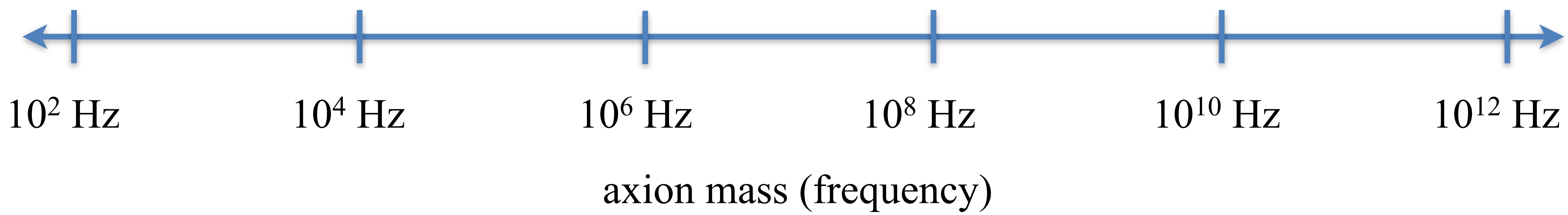
observation would be proof of mechanism

Need high precision experiments to detect axion (and to see this effect)

Precision measurement for axions and other light dark matter

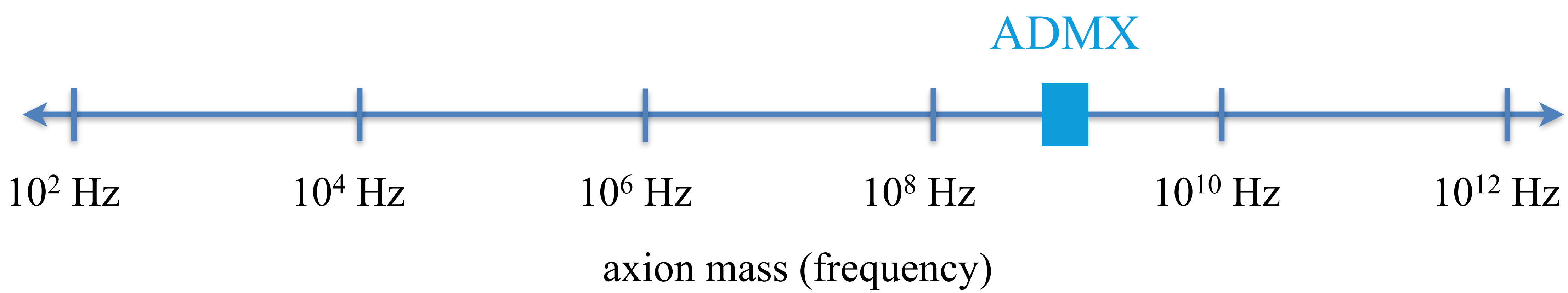
Example: Axion Dark Matter

Most axion dark matter space currently unexplored:



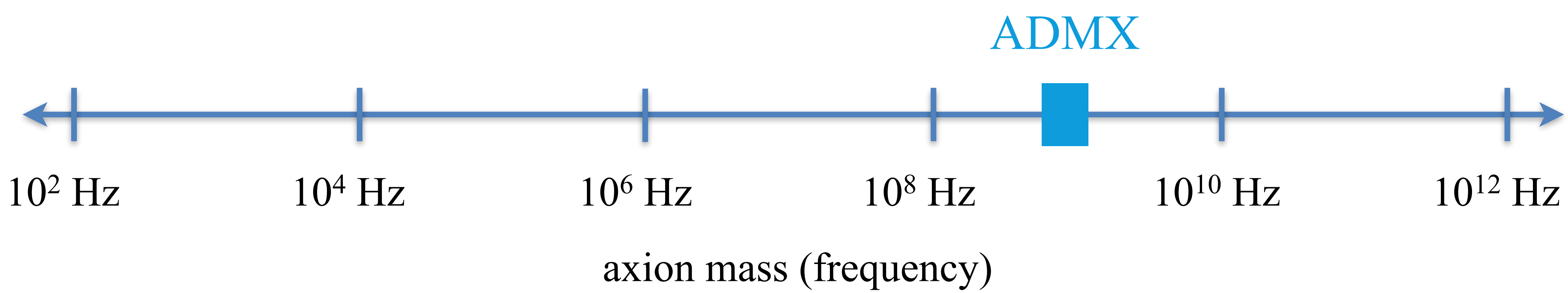
Example: Axion Dark Matter

Most axion dark matter space currently unexplored:



Example: Axion Dark Matter

Most axion dark matter space currently unexplored:

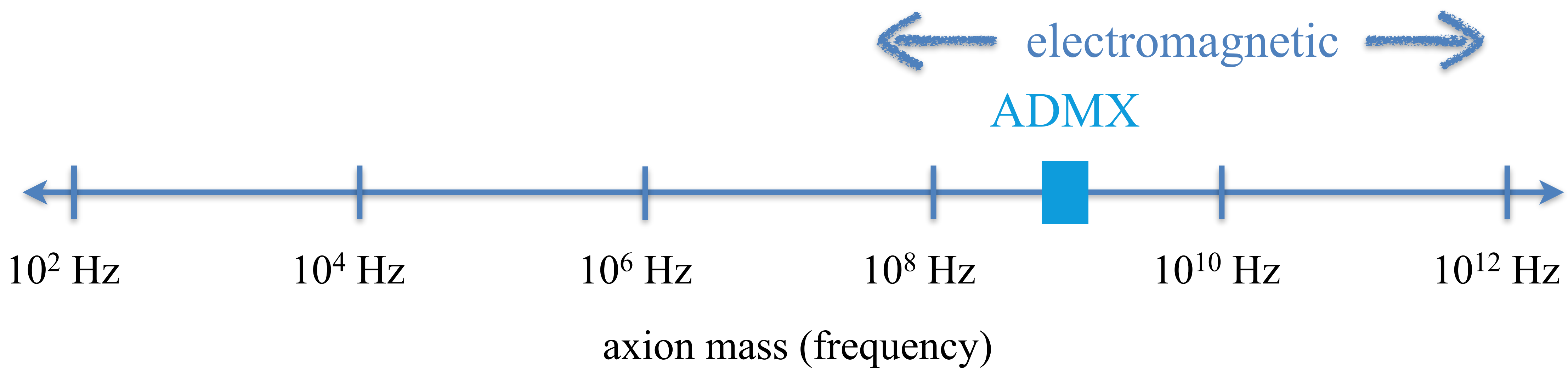


Axion couplings

$a\,F\tilde{F}$	E&M
$a\,G\tilde{G}$	QCD
$(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$	matter (spin)

Example: Axion Dark Matter

Most axion dark matter space currently unexplored:

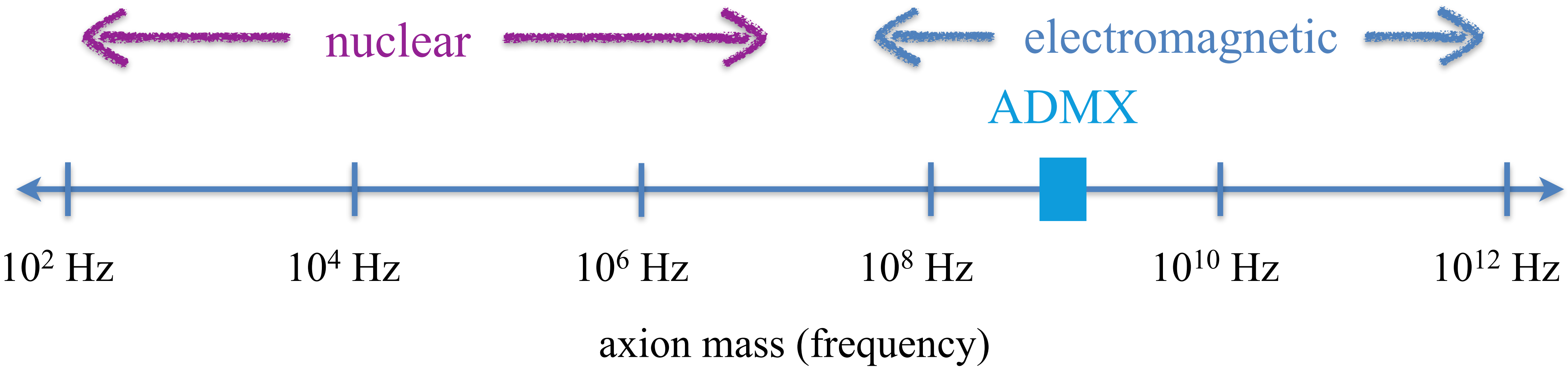


Axion couplings:

$a\,F\tilde{F}$	E&M	current searches
$a\,G\tilde{G}$	QCD	
$(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$	matter (spin)	

Example: Axion Dark Matter

Most axion dark matter space currently unexplored:



Axion couplings:

- $a\,F\tilde{F}$ — E&M — current searches
- $a\,G\tilde{G}$ — QCD
- $(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$ — matter (spin)

other couplings can reach axion parameter space previously impossible

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

The Axion

Strong CP problem:

$\mathcal{L} \supset \theta\, G\widetilde{G}$ creates nucleon EDM $d \sim 3 \times 10^{-16}\, \theta\, e\, \mathrm{cm}$ measurements ➜ $\theta \lesssim 10^{-9}$

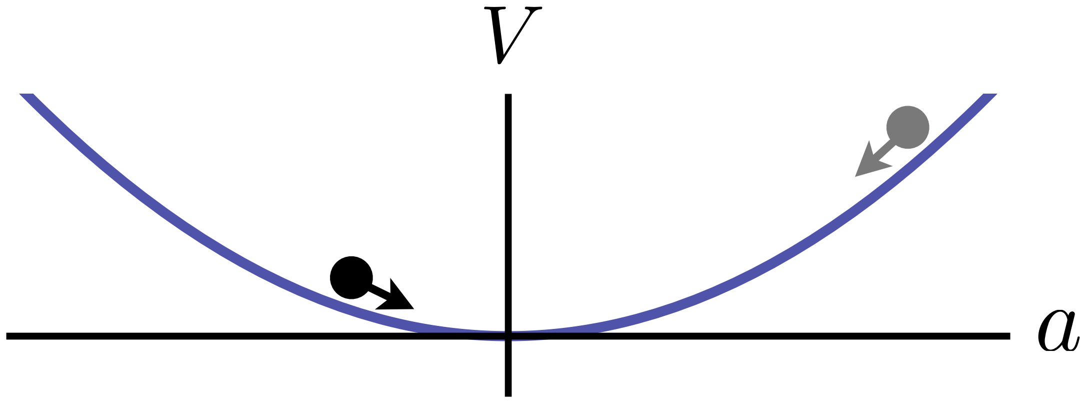
The Axion

Strong CP problem:

$\mathcal{L} \supset \theta \, G\widetilde{G}$ creates nucleon EDM $d \sim 3 \times 10^{-16} \, \theta \, e \, \text{cm}$ measurements ➜ $\theta \lesssim 10^{-9}$

Axion solution:

make it dynamical $\mathcal{L} \supset \frac{a}{f_a} G\widetilde{G}$ so damps down towards zero



$$a(t) \sim a_0 \cos\left(m_a t\right)$$

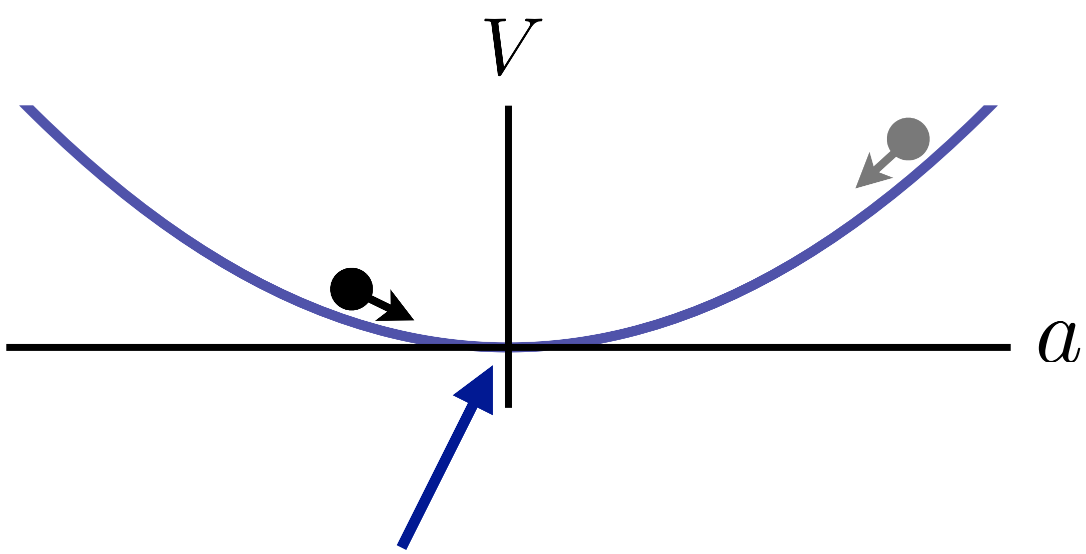
The Axion

Strong CP problem:

$\mathcal{L} \supset \theta\, G\widetilde{G}$ creates nucleon EDM $d \sim 3 \times 10^{-16}\, \theta\, e\, \mathrm{cm}$ measurements ➜ $\theta \lesssim 10^{-9}$

Axion solution:

make it dynamical $\mathcal{L} \supset \frac{a}{f_a} G\widetilde{G}$ so damps down towards zero



$$a(t) \sim a_0 \cos\left(m_a t\right)$$

still has small residual oscillations today ➜ Axion is a natural dark matter candidate

Preskill, Wise & Wilczek, Abott & Sikivie, Dine & Fischler (1983)

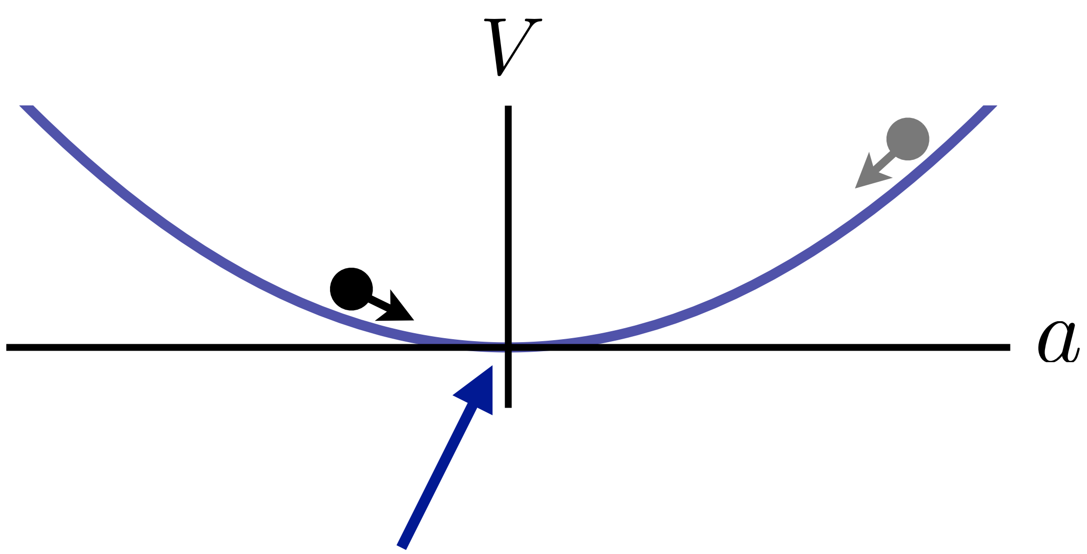
The Axion

Strong CP problem:

$\mathcal{L} \supset \theta \, G\widetilde{G}$ creates nucleon EDM $d \sim 3 \times 10^{-16} \, \theta \, e \, \text{cm}$ measurements ➜ $\theta \lesssim 10^{-9}$

Axion solution:

make it dynamical $\mathcal{L} \supset \frac{a}{f_a} G\widetilde{G}$ so damps down towards zero



$$a(t) \sim a_0 \cos\left(m_a t\right)$$

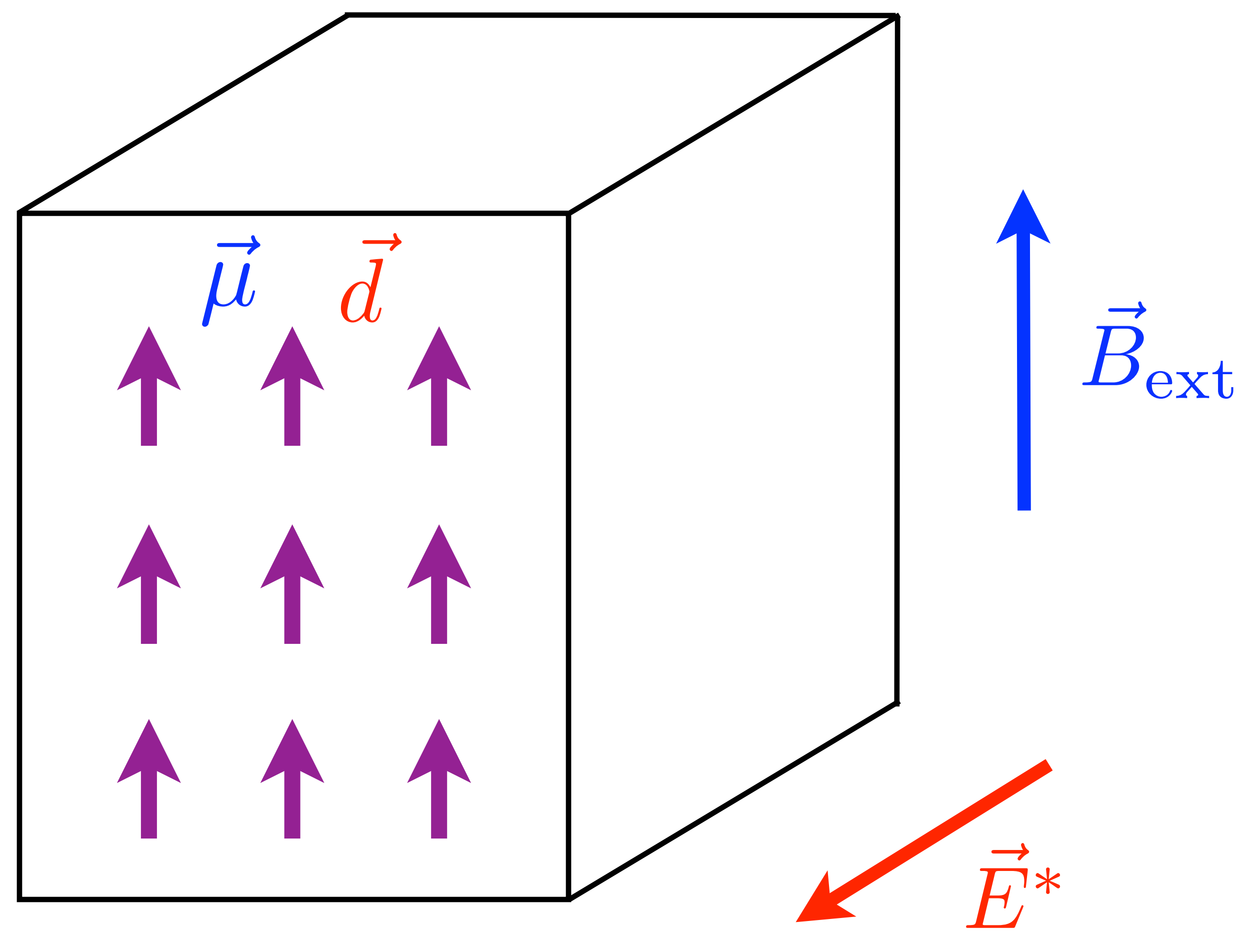
still has small residual oscillations today ➜ Axion is a natural dark matter candidate

Preskill, Wise & Wilczek, Abott & Sikivie, Dine & Fischler (1983)

Axion DM causes oscillating nucleon EDM today

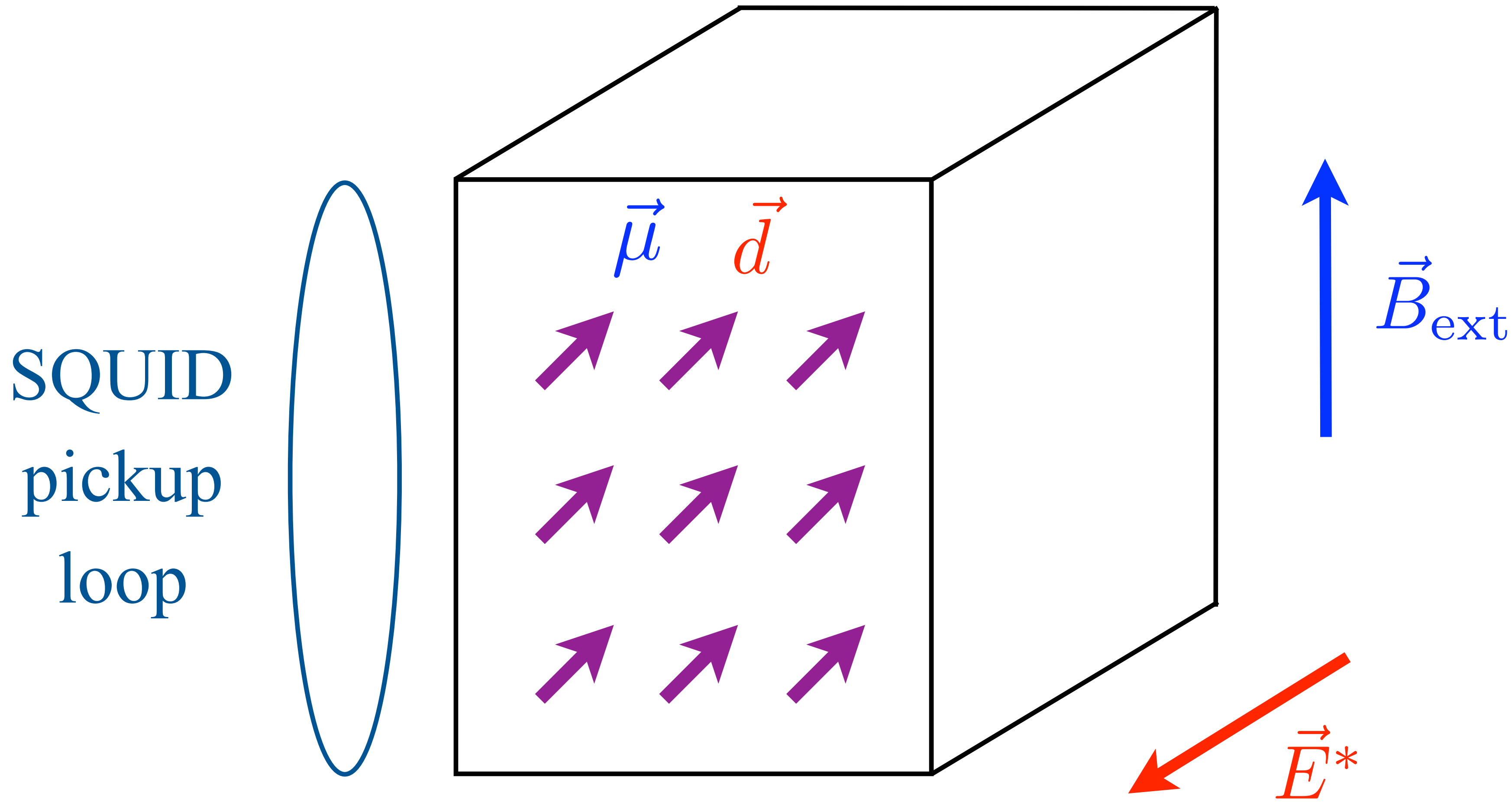
generally light bosonic DM causes oscillating fundamental "constants"

Cosmic Axion Spin Precession Experiment (CASPEr)



Larmor frequency = axion mass ➔ resonant enhancement

Cosmic Axion Spin Precession Experiment (CASPEr)



Larmor frequency = axion mass ➔ resonant enhancement

SQUID measures resulting transverse magnetization

ferroelectric (e.g. $PbTiO_3$), NMR pulse sequences (spin-echo,…),…
quantum spin projection (magnetization) noise small enough

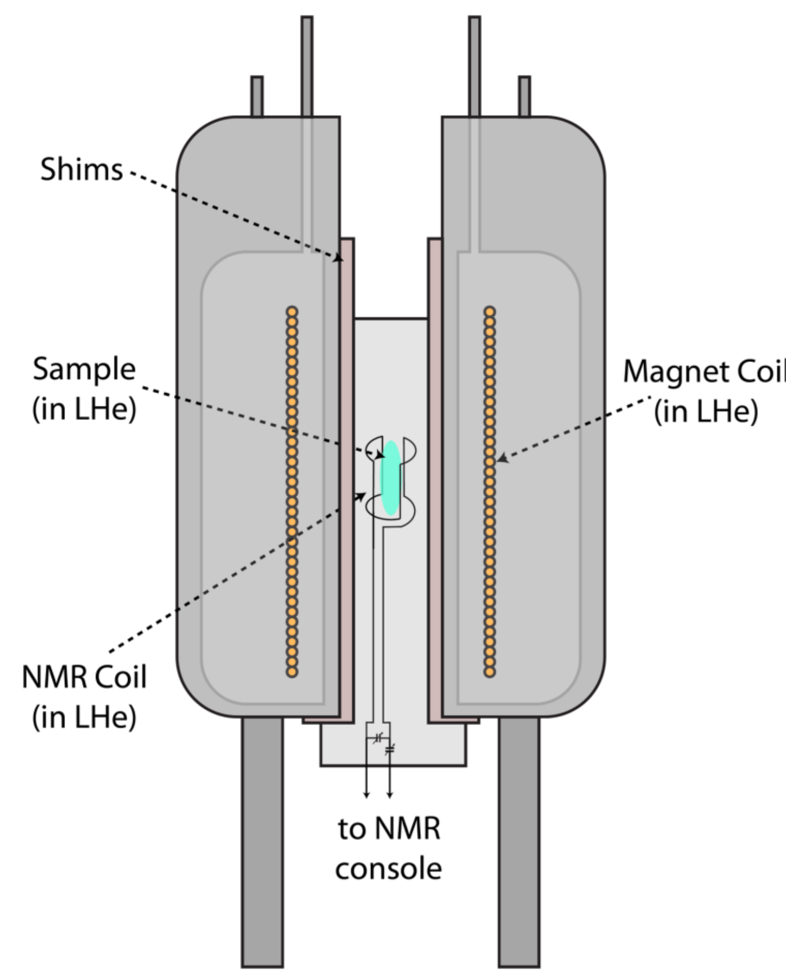
Cosmic Axion Spin Precession Experiment (CASPEr)

NMR techniques and high precision magnetometry

No other way to search for light axions

Would be the discovery of dark matter and glimpse into physics at high energies

Under construction at Mainz and BU



Boston University
Alexander Sushkov

Cal State
Derek J. Kimball

JGU Mainz
Dmitry Budker
Peter Blümler
Arne Wickenbrock

Helmholtz Institute Mainz
John Blanchard
Nathan Leefer

Stanford
Peter W. Graham

UC Berkeley
Dmitry Budker
Surjeet Rajendran

SIMONS FOUNDATION

HEISING - SIMONS
FOUNDATION

DFG Deutsche Forschungsgemeinschaft

DM Radio

with

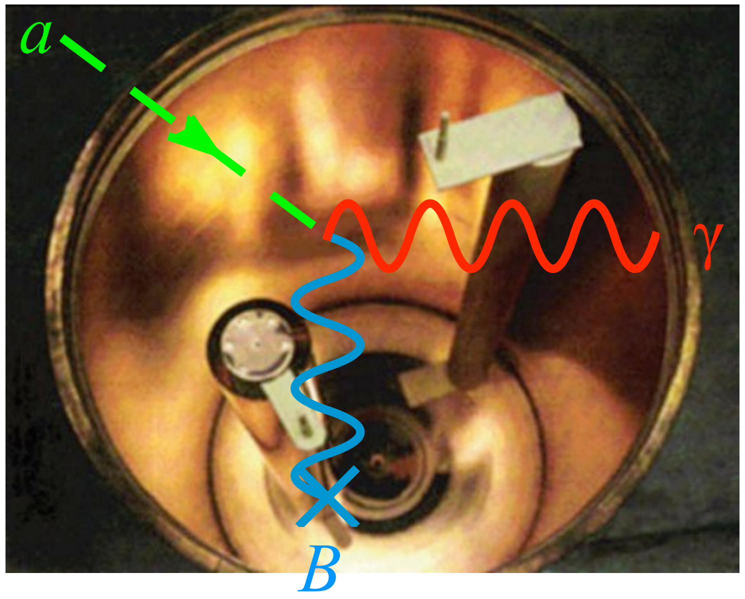
Kent Irwin
Saptarshi Chaudhuri
Jeremy Mardon
Surjeet Rajendran
Yue Zhao

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

Electromagnetic Detectors

ADMX focuses on axions ~ 0.5 - 10 GHz

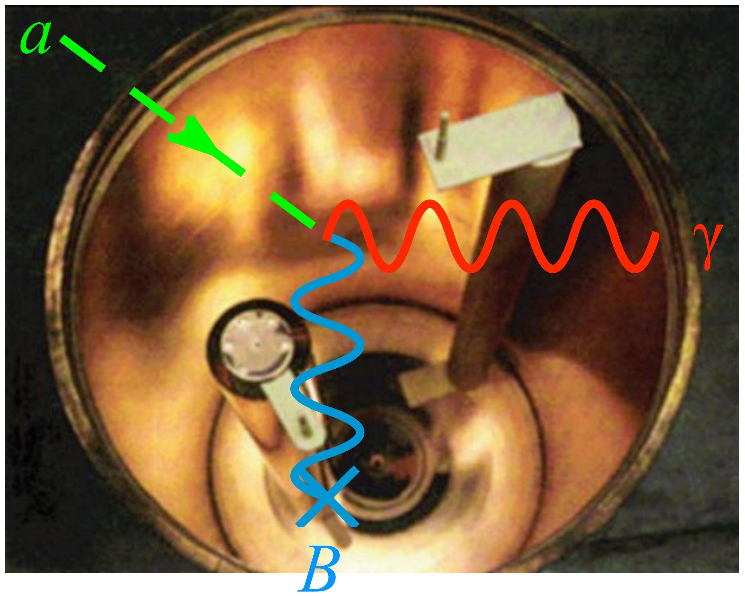
cavity limit: axion wavelength ~ size of cavity



Electromagnetic Detectors

ADMX focuses on axions ~ 0.5 - 10 GHz

cavity limit: axion wavelength ~ size of cavity



Would like to see both scalars and vectors over broad mass range

new effects for axion wavelength > experiment size

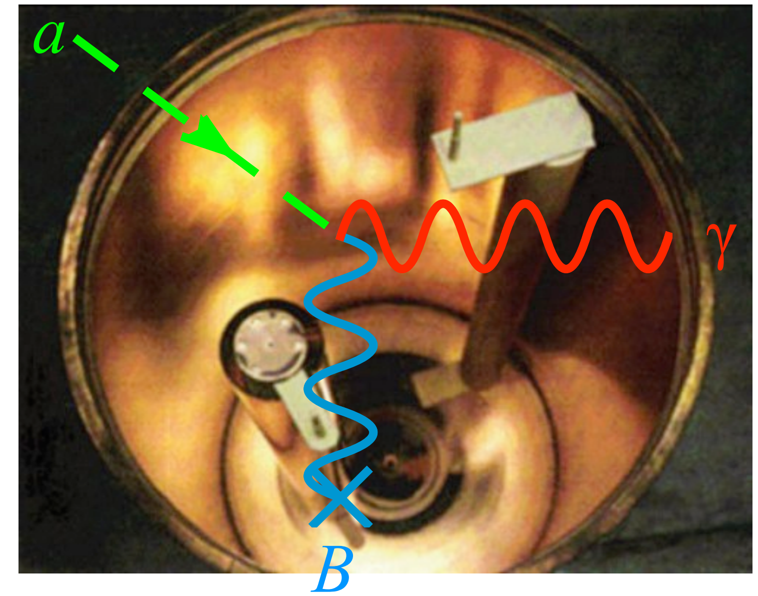
still want EM resonator (LC circuit not cavity)

S. Thomas, P. Sikivie

Electromagnetic Detectors

ADMX focuses on axions ~ 0.5 - 10 GHz

cavity limit: axion wavelength ~ size of cavity



Would like to see both scalars and vectors over broad mass range

new effects for axion wavelength > experiment size

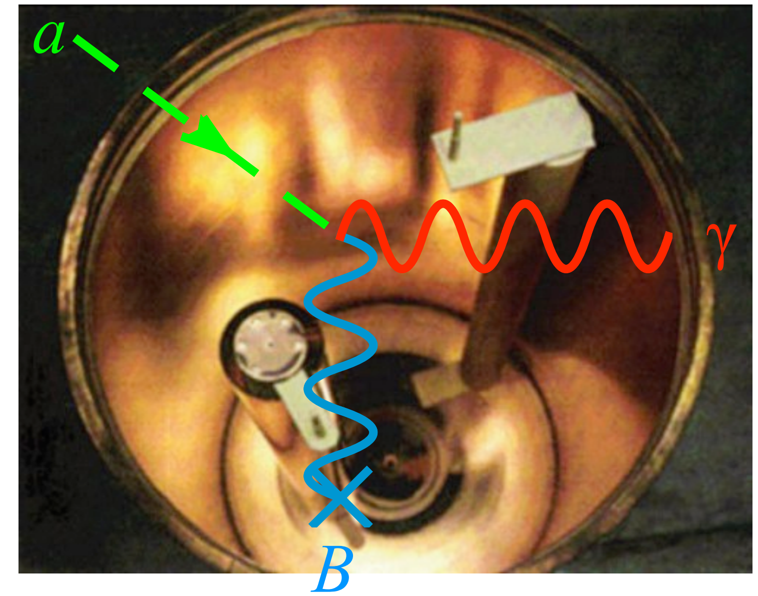
still want EM resonator (LC circuit not cavity) S. Thomas, P. Sikivie

DM Radio:

Electromagnetic Detectors

ADMX focuses on axions ~ 0.5 - 10 GHz

cavity limit: axion wavelength ~ size of cavity



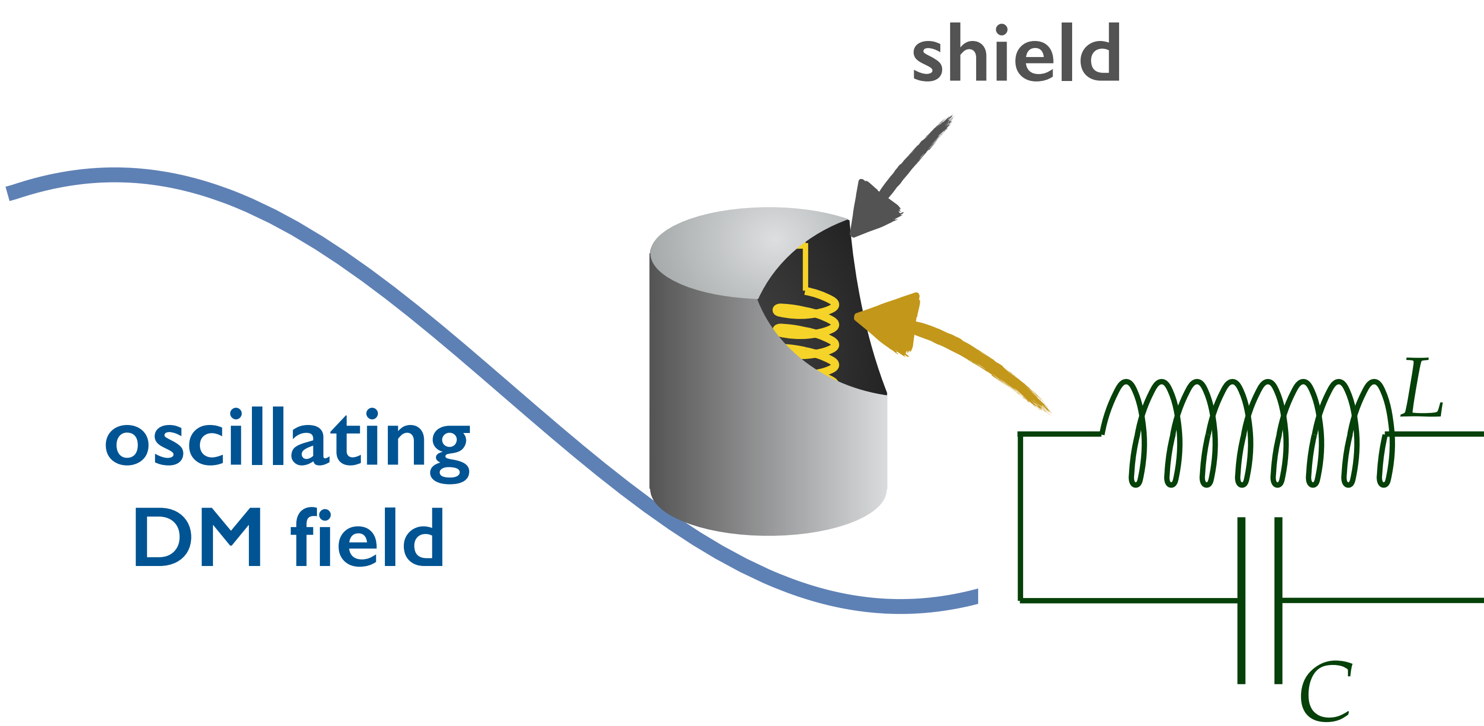
Would like to see both scalars and vectors over broad mass range

new effects for axion wavelength > experiment size

still want EM resonator (LC circuit not cavity)

S. Thomas, P. Sikivie

DM Radio:

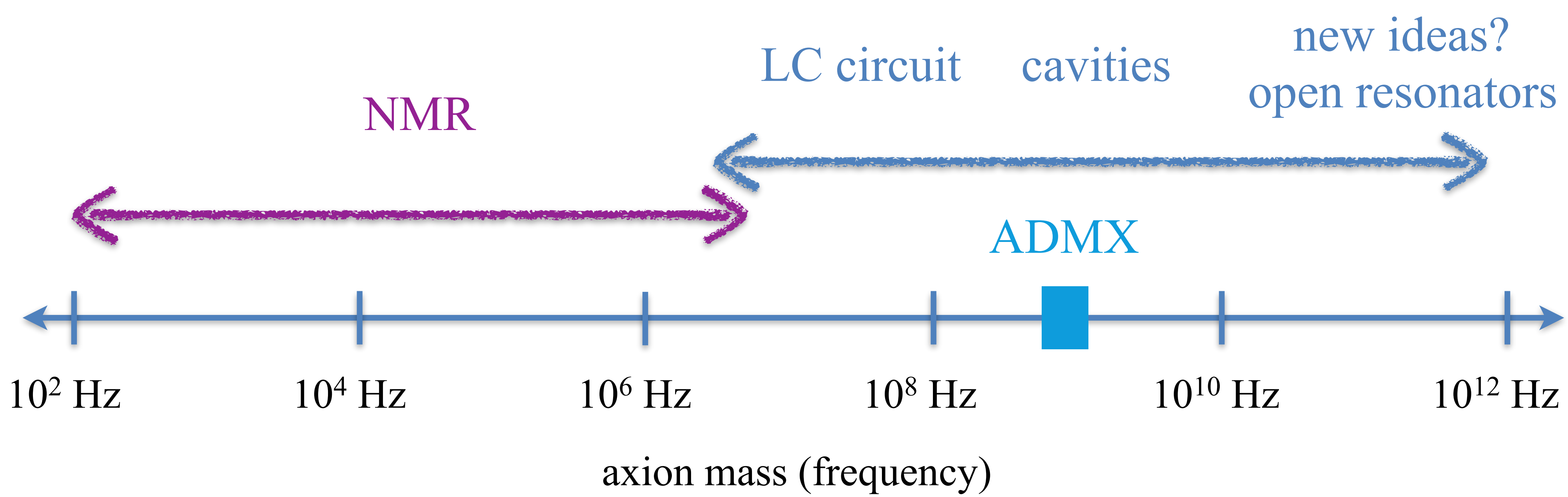


Tunable EM resonator Q ~10^6 (a radio)

SQUID readout

Axion Dark Matter

May be able to cover all of axion dark matter:



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

Atom Interferometry and Accelerometers

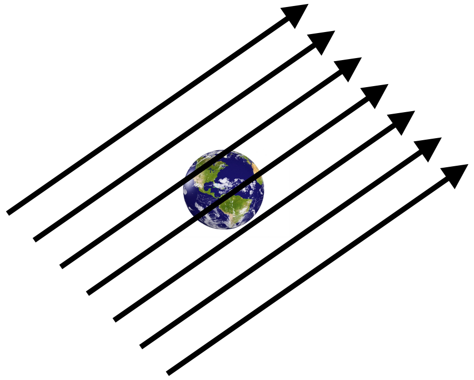
with

Jason Hogan
Mark Kasevich
Surjeet Rajendran

Force from Dark Matter

for many DM models (e.g. relaxion)

DM exerts force on matter: $F \propto g\sqrt{\rho_{\rm DM}}\cos(m_{\rm DM}t)$

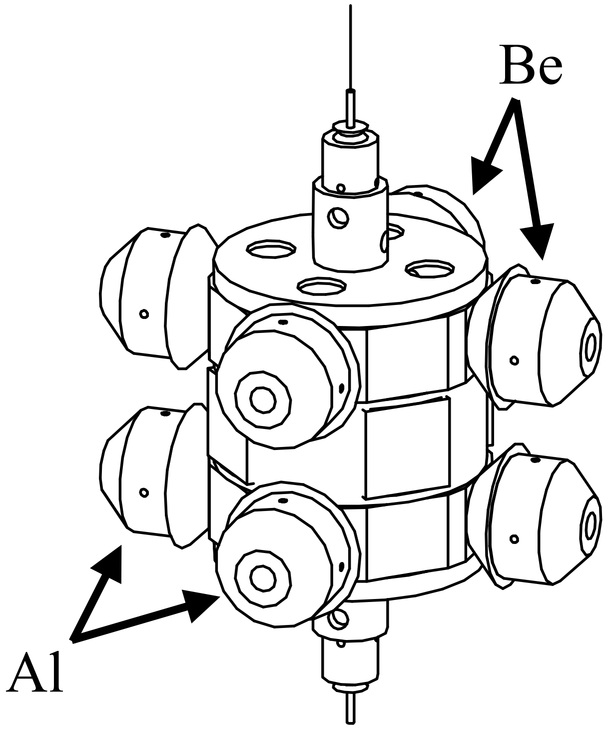


Force is oscillatory and equivalence-principle violating

scalar DM would also cause oscillation of "constants" e.g. electron mass

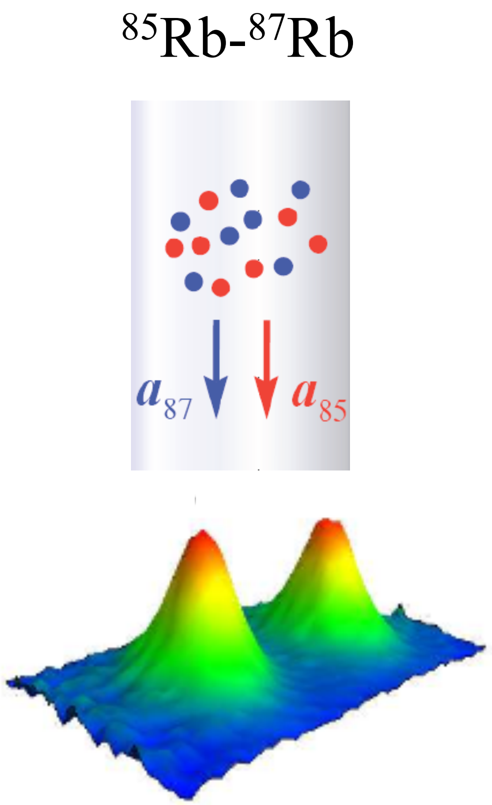
New Direct Detection Experiments:

Torsion Balances



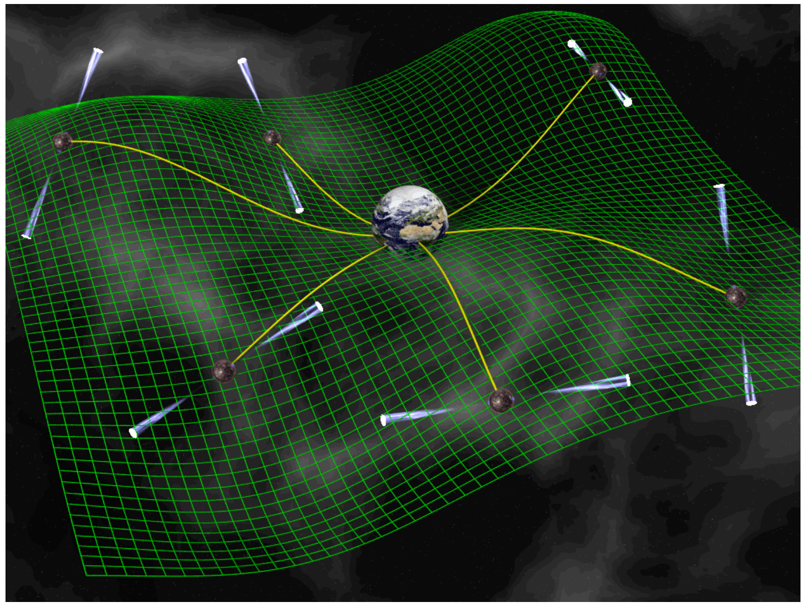
Eot-Wash analysis underway

Atom Interferometers



In construction Kasevich/Hogan groups

Pulsar Timing Arrays



Can probe orders of magnitude past current limits

arXiv:1512.06165

Gravitational Wave Detection with Atom Interferometry

with

Savas Dimopoulos
Jason Hogan
Mark Kasevich
Surjeet Rajendran

W.M. KECK FOUNDATION

PRL **110** (2013) arXiv: 1206.0818
PLB **678** (2009) arXiv: 0712.1250
PRD **78** (2008) arXiv: 0806.2125

Gravitational Wave Motivation

Gravitational waves open a new window to the universe

Unique astrophysical information (WD's, NS's, BH's)

- probe near horizon geometry of BH

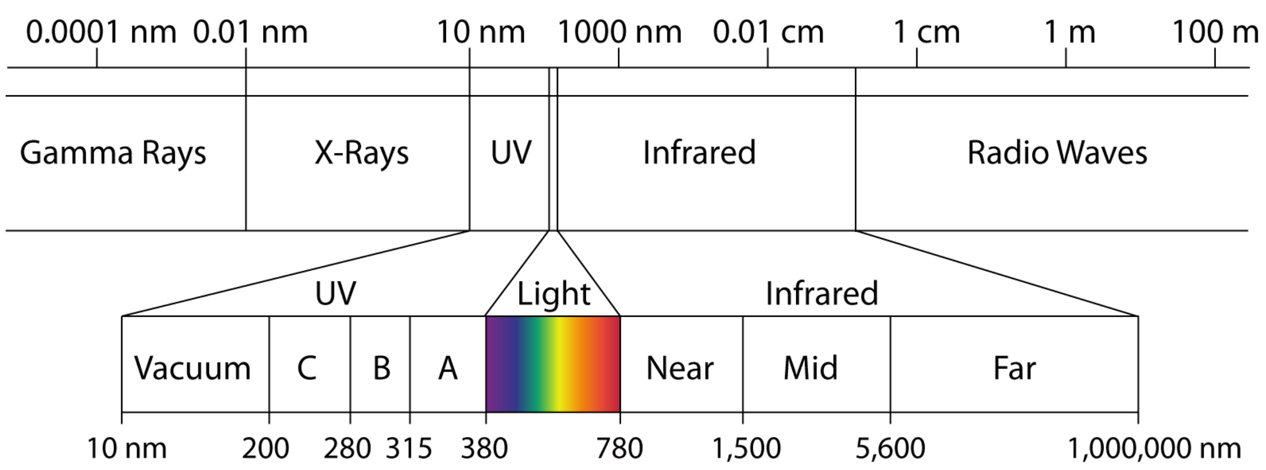
Directly observe universe before CMB formed

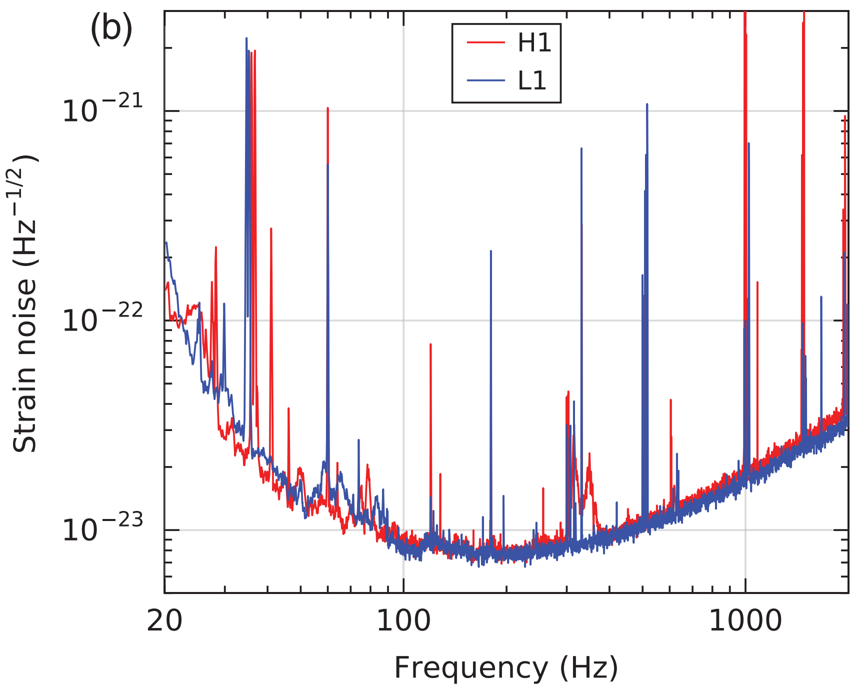
- signals from inflation, reheating, phase transitions…

Gravitational waves will be major part of future of astronomy, astrophysics and cosmology

Gravitational Spectrum

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





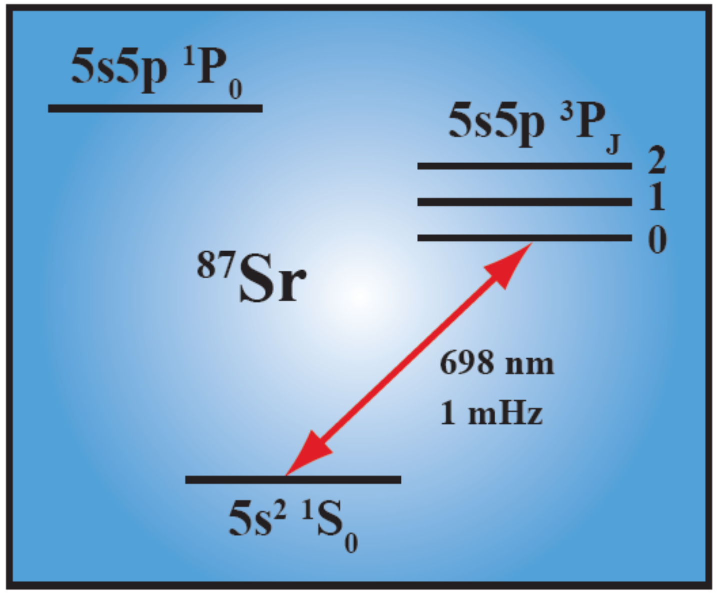
Advanced LIGO can only detect GW's > 10 Hz ➜ How look at lower spectrum?

New detectors?

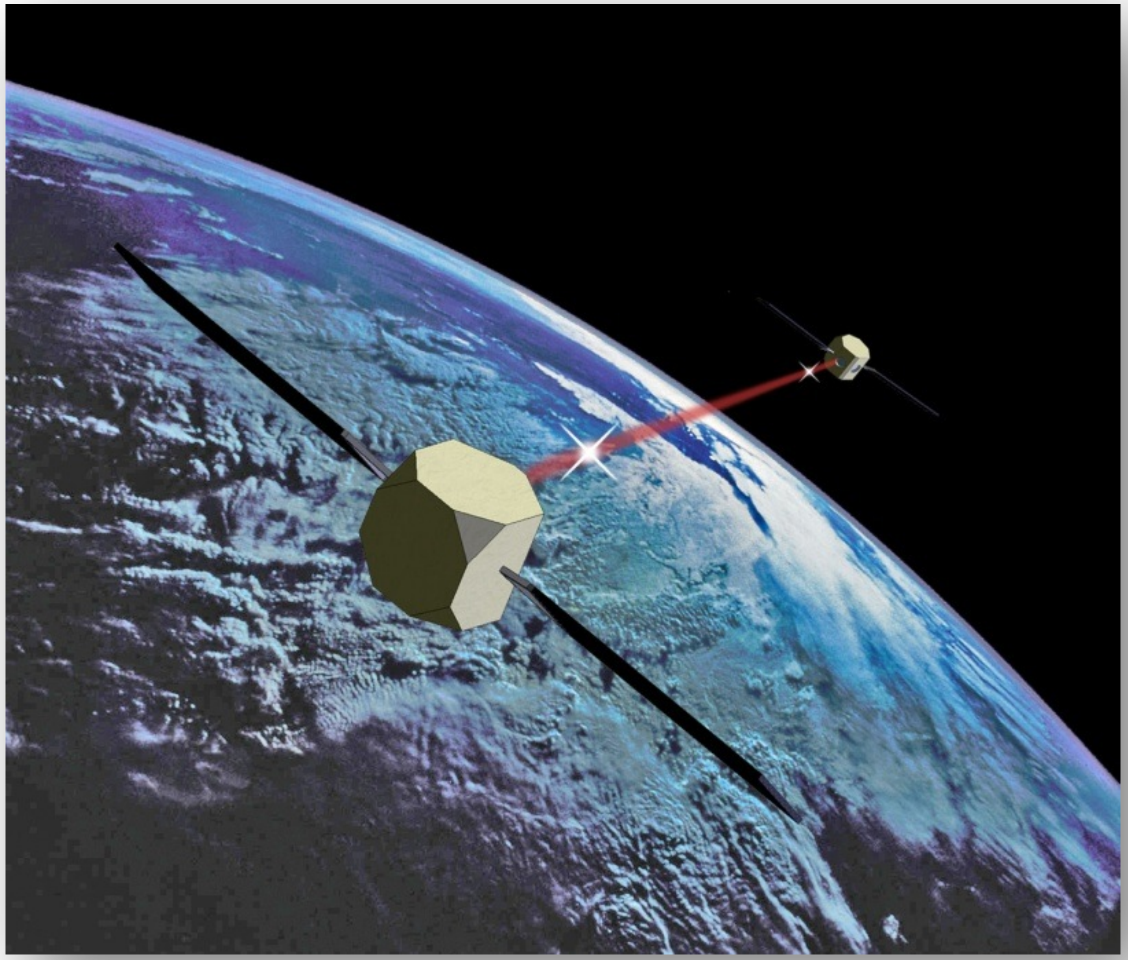
Atom Interferometry for Gravitational Waves

long laser baseline, atoms are excellent inertial proof masses

atoms act as clocks, measure light travel time



Clock transition in candidate atom ^{87}Sr

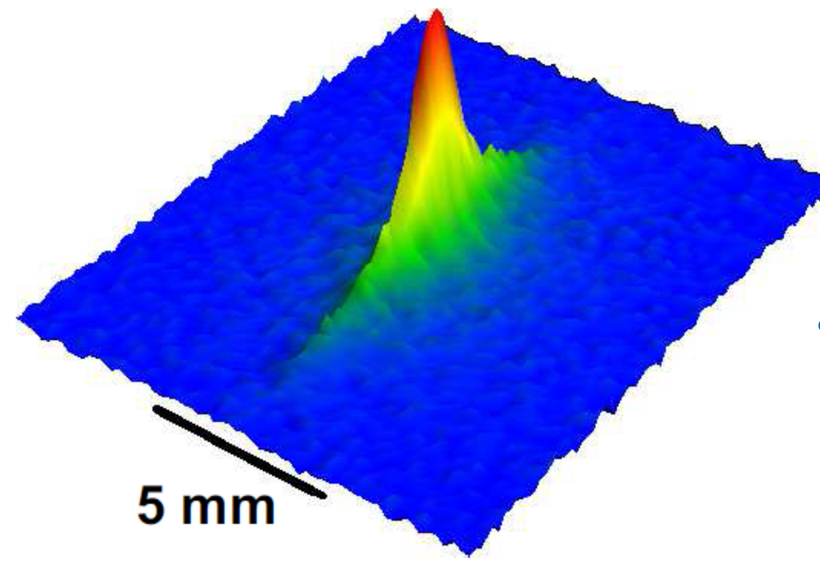


opens new bands in gravitational spectrum

Recent Experimental Results

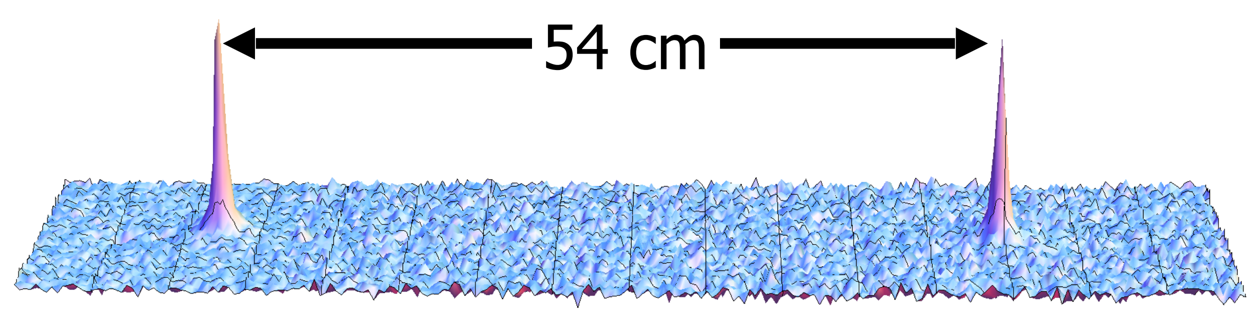
(Kasevich and Hogan groups)

Stanford Test Facility



➜ 50 pK

Macroscopic splitting of atomic wavefunction:



much of the technology needed for GW's now demonstrated

Summary

If the new physics is not at weak scale, we will need new approaches

Precision measurement is a powerful tool for particle physics and cosmology

e.g. axions, gravitational waves…

new techniques beyond traditional particle colliders/detectors:

atomic interferometry, precision magnetometry, NMR, EM resonators, torsion balances…

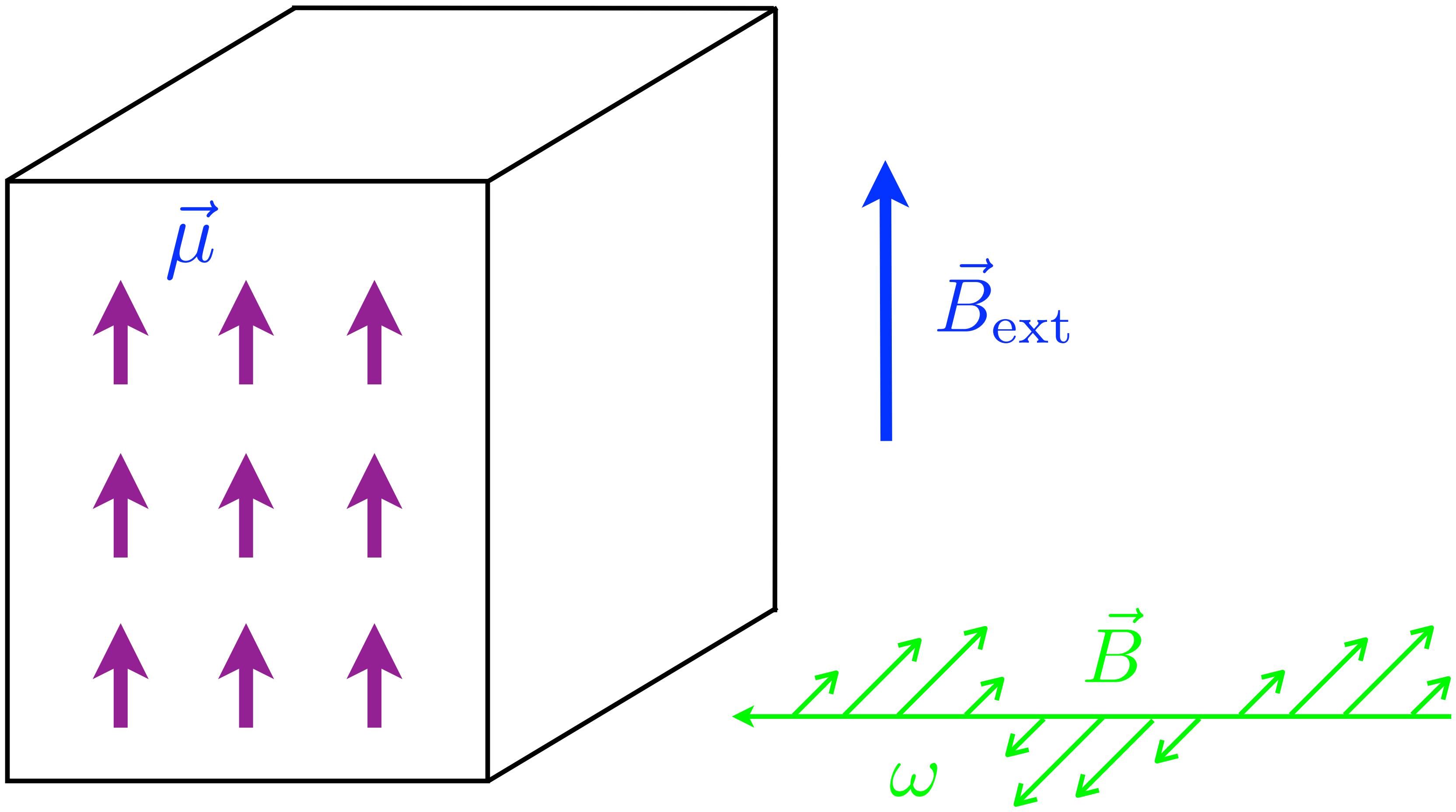
Examples:

1. Cosmic Axion Spin Precession Experiment (CASPEr) - in construction at BU and Mainz
2. DM Radio - in construction at SLAC/Stanford
3. Atom Interferometry for DM and gravitational wave detection - demonstrator at Stanford

Many more possibilities…

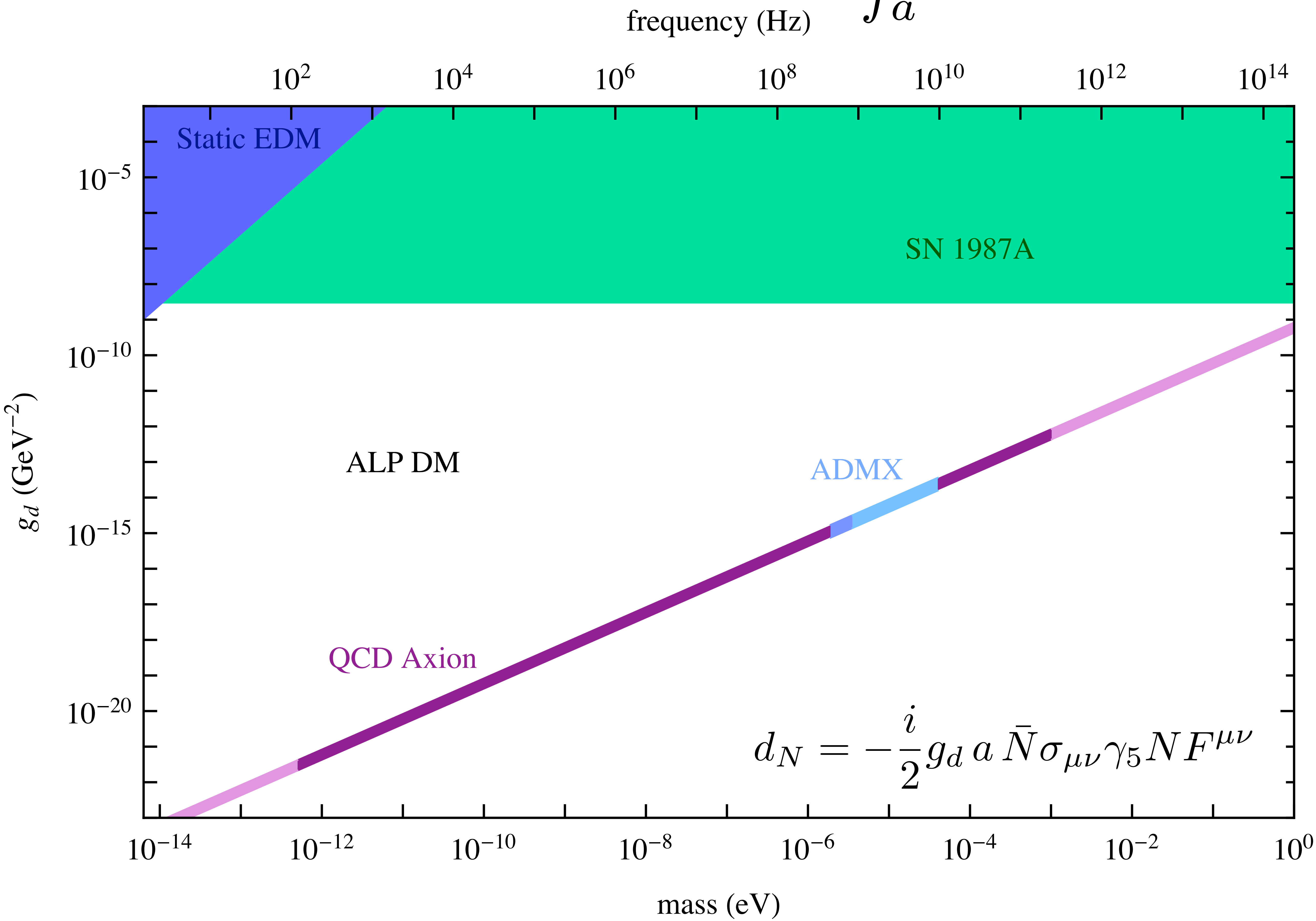
Backup

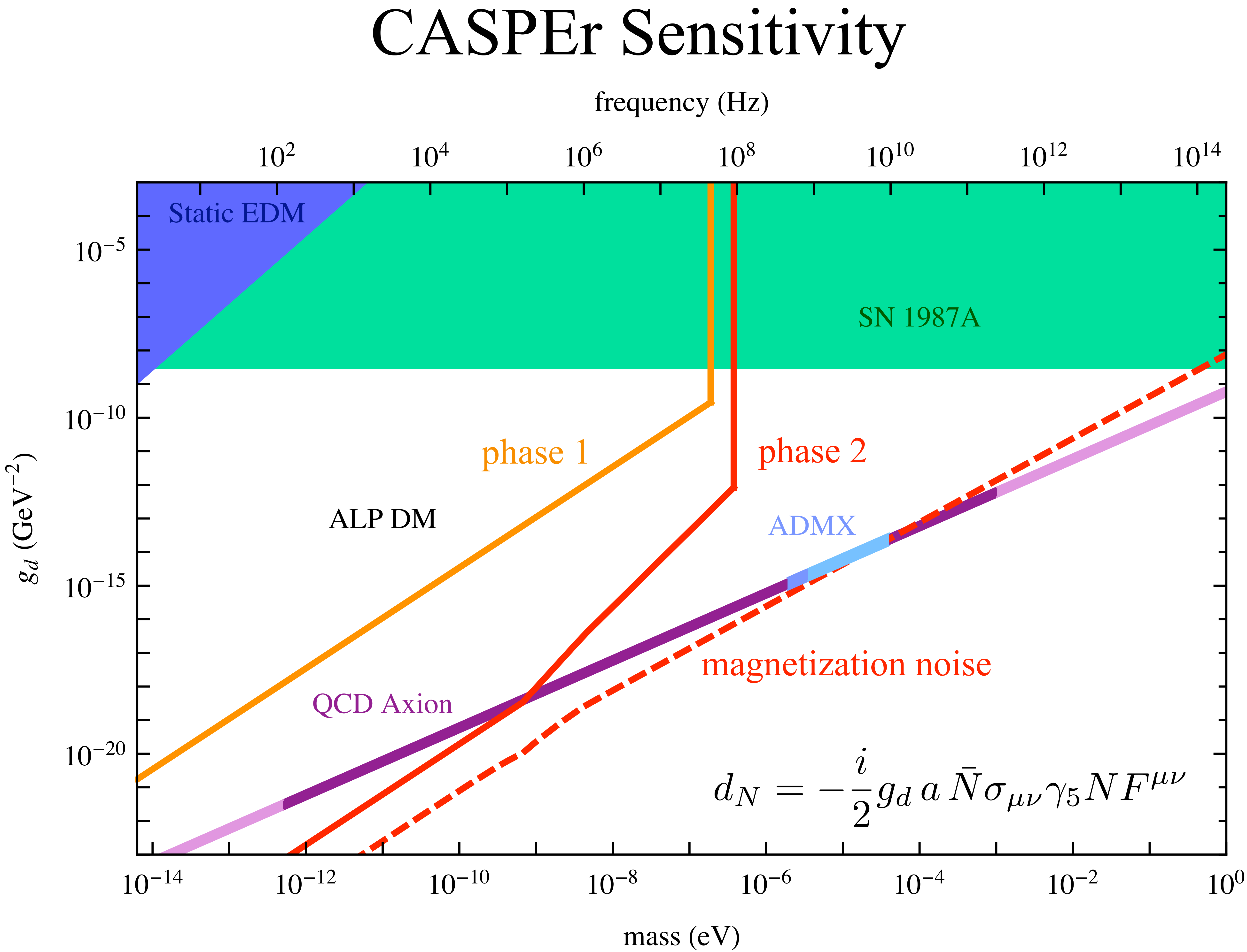
Axions with NMR



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

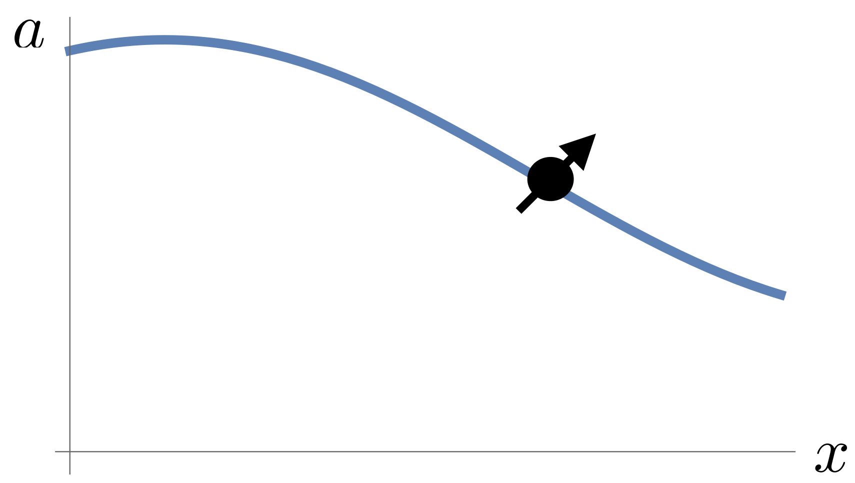
Axion Limits on $\frac{a}{f_a} G\widetilde{G}$




CASPEr Sensitivity
frequency (Hz)
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
Static EDM
SN 1987A
phase 1
phase 2
ALP DM
ADMX
magnetization noise
QCD Axion
$d_N = -\frac{i}{2} g_d \, a \, \bar{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu}$
g_d (GeV^{-2})
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^0
mass (eV)

CASPEr-Wind

can also use direct coupling of axion to nucleons: $(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$ ➜ $H \ni \nabla a \cdot \vec{\sigma}_N$

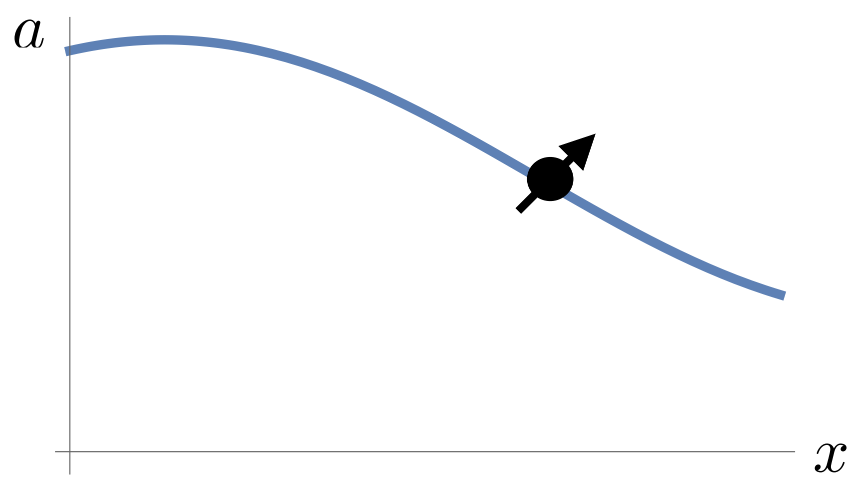


nuclear spins precess in DM axion field

proportional to axion momentum (“wind”)

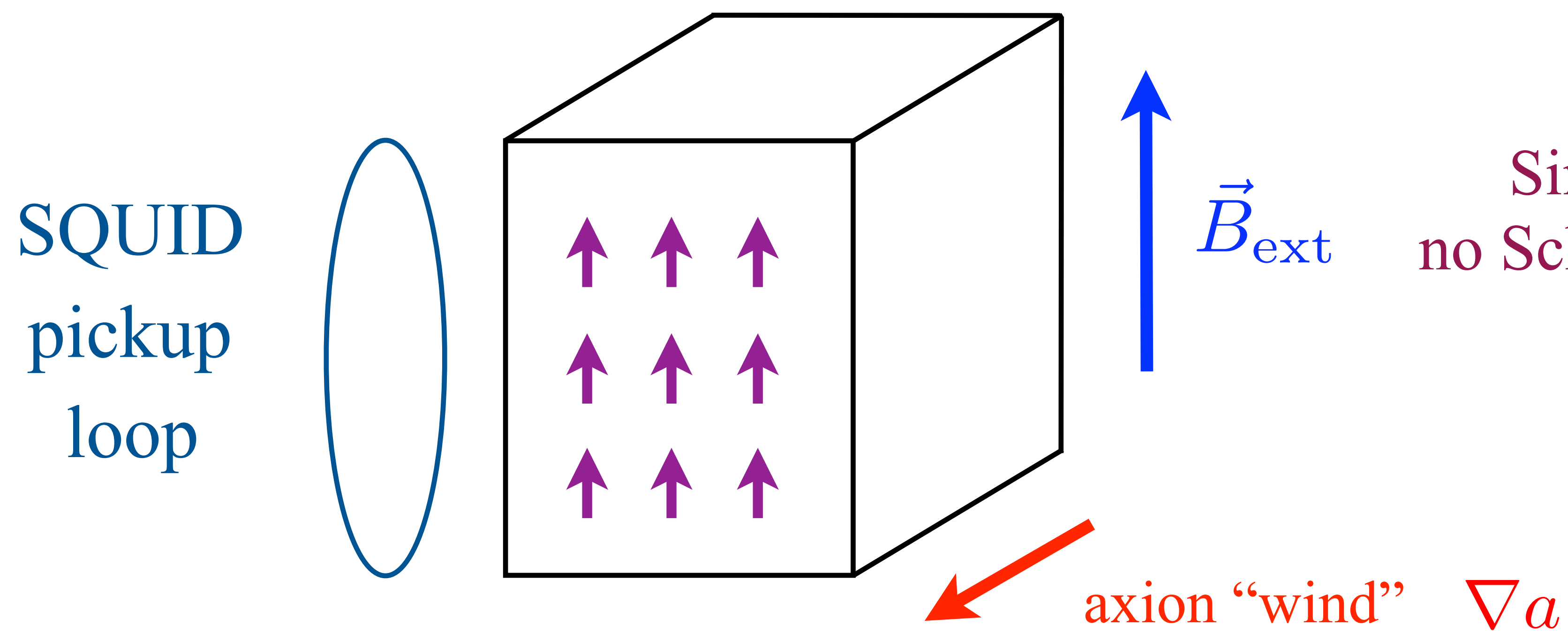
CASPEr-Wind

can also use direct coupling of axion to nucleons: $(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$ ➜ $H \ni \nabla a \cdot \vec{\sigma}_N$



nuclear spins precess in DM axion field

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)

Possibilities for Light Dark Matter

All UV theories summarized by only a few possibilities
(symmetry, effective field theory):

scalar	pseudo-scalar (axion)	$a\,F\tilde{F}$	E&M
		$a\,G\tilde{G}$	QCD
		$(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$	matter (spin)
	scalar	$\phi\,h^\dagger h,\ \phi\,\mathcal{O}_{\rm SM}$	SM properties (electron mass)
vector	vector	$A'_\mu\bar{\psi}\gamma^\mu\psi$	charged
		$F'_{\mu\nu}F^{\mu\nu}$	DM-photon mixing
		$F'_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$	dipole moment
	axial-vector	$A'_\mu\bar{\psi}\gamma^\mu\gamma^5\psi$	spin

Can cover all these possibilities!

arXiv:1512.06165

Possibilities for Light Dark Matter

All UV theories summarized by only a few possibilities
(symmetry, effective field theory):

scalar

- pseudo-scalar (axion)
  - $a\, F\tilde{F}$ — E&M
  - $a\, G\tilde{G}$ — QCD — CASPEr
  - $(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$ — matter (spin) — CASPEr
- scalar
  - $\phi\, h^\dagger h,\ \phi\, \mathcal{O}_{\rm SM}$ — SM properties (electron mass)

vector

- vector
  - $A'_\mu\bar{\psi}\gamma^\mu\psi$ — charged
  - $F'_{\mu\nu}F^{\mu\nu}$ — DM-photon mixing
  - $F'_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$ — dipole moment — CASPEr
- axial-vector
  - $A'_\mu\bar{\psi}\gamma^\mu\gamma^5\psi$ — spin — CASPEr

Can cover all these possibilities!

arXiv:1512.06165

Possibilities for Light Dark Matter

All UV theories summarized by only a few possibilities
(symmetry, effective field theory):

scalar

	Operator	Coupling	Experiment
pseudo-scalar (axion)	$a\,F\tilde{F}$	E&M	DM Radio + ADMX
	$a\,G\tilde{G}$	QCD	CASPEr
	$(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$	matter (spin)	CASPEr
scalar	$\phi\,h^\dagger h,\ \phi\,\mathcal{O}_{\rm SM}$	SM properties (electron mass)	

vector

	Operator	Coupling	Experiment
vector	$A'_\mu\bar{\psi}\gamma^\mu\psi$	charged	
	$F'_{\mu\nu}F^{\mu\nu}$	DM-photon mixing	DM Radio + ADMX
	$F'_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$	dipole moment	CASPEr
axial-vector	$A'_\mu\bar{\psi}\gamma^\mu\gamma^5\psi$	spin	CASPEr

Can cover all these possibilities!

arXiv:1512.06165

Possibilities for Light Dark Matter

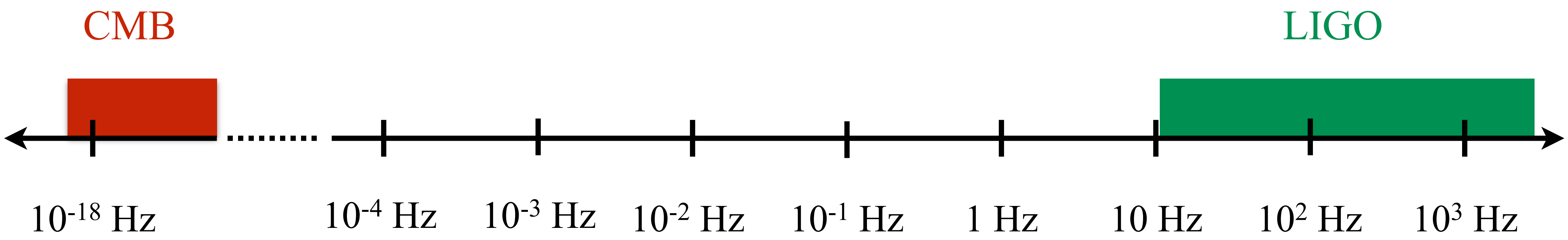
All UV theories summarized by only a few possibilities
(symmetry, effective field theory):

		Operator	Coupling	Experiment
scalar	pseudo-scalar (axion)	$a\,F\tilde{F}$	E&M	DM Radio + ADMX
		$a\,G\tilde{G}$	QCD	CASPEr
		$(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$	matter (spin)	CASPEr
	scalar	$\phi\, h^\dagger h,\ \phi\,\mathcal{O}_{\rm SM}$	SM properties (electron mass)	accelerometers
vector	vector	$A'_\mu\bar{\psi}\gamma^\mu\psi$	charged	accelerometers
		$F'_{\mu\nu}F^{\mu\nu}$	DM-photon mixing	DM Radio + ADMX
		$F'_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$	dipole moment	CASPEr
	axial-vector	$A'_\mu\bar{\psi}\gamma^\mu\gamma^5\psi$	spin	CASPEr

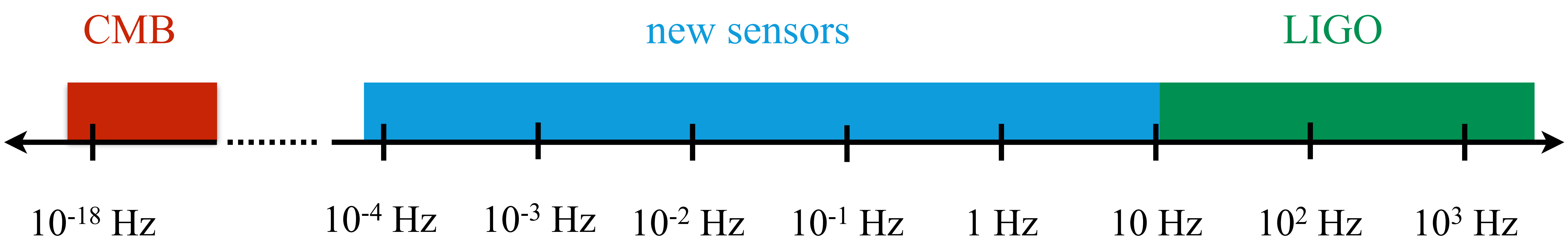
Can cover all these possibilities!

arXiv:1512.06165

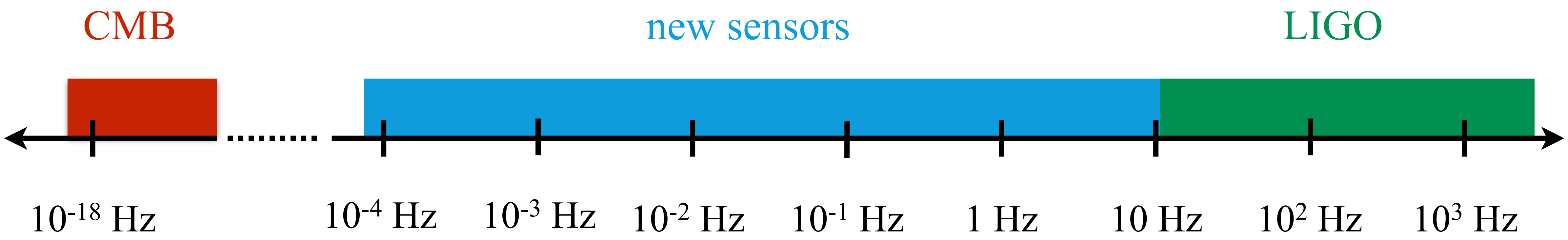
Gravitational Wave Spectrum



Gravitational Wave Spectrum



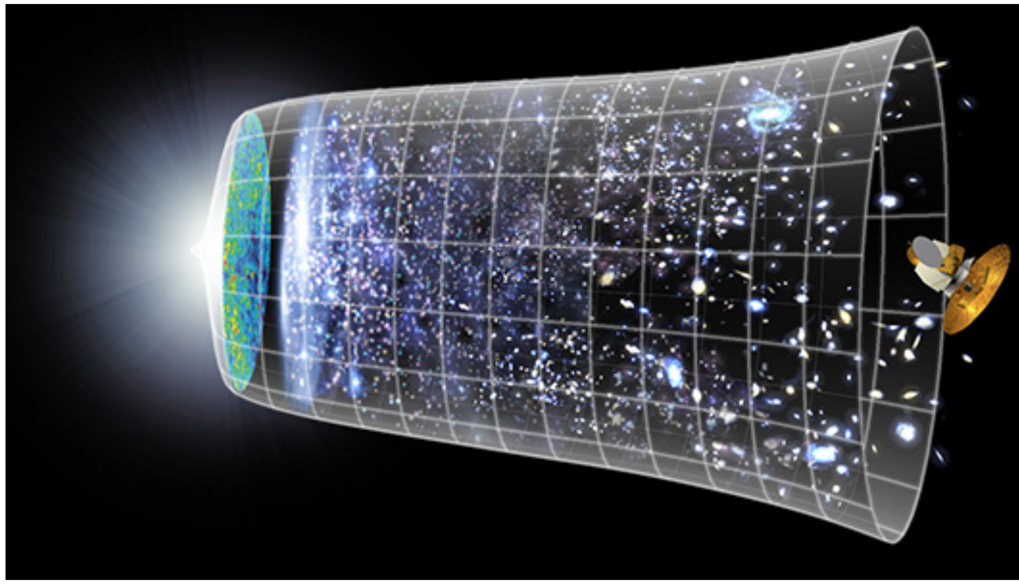
Gravitational Wave Spectrum



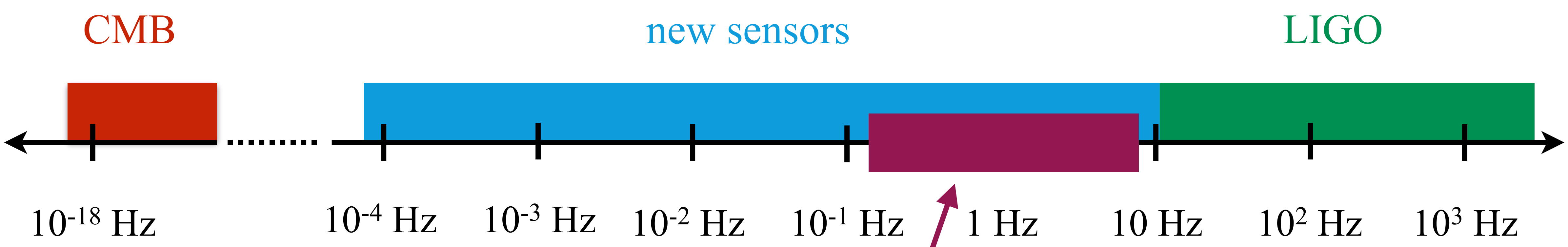
Early universe is transparent to gravitational waves

Rare opportunity to study cosmology before last scattering

CMB: $z \sim 10^3$ but nucleosynthesis: $z \sim 10^{10}$



Gravitational Wave Spectrum

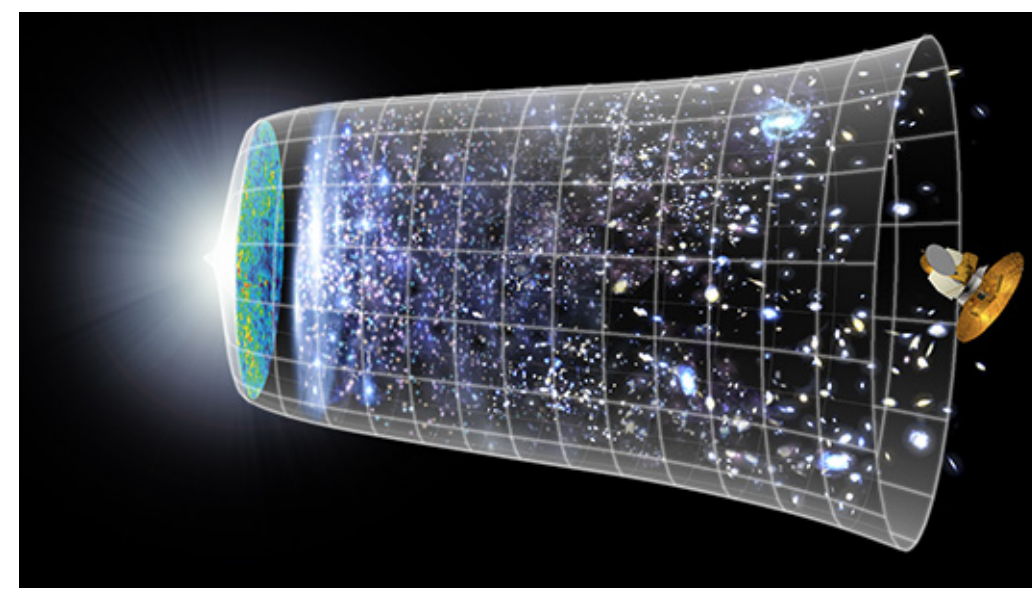


Early universe is transparent to gravitational waves

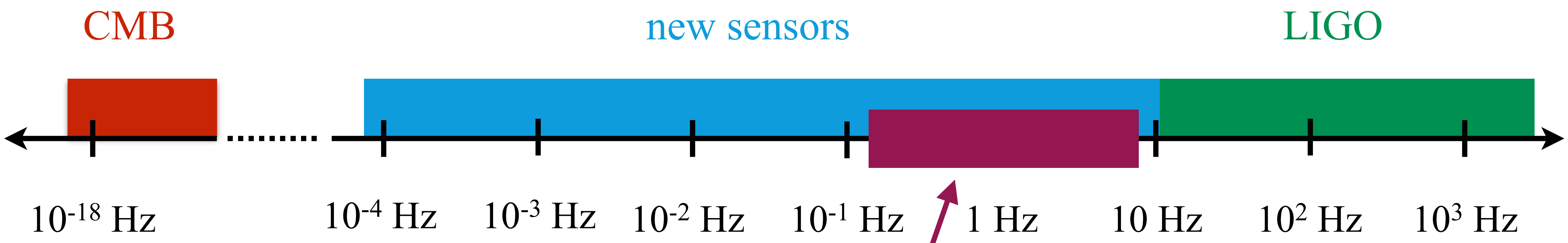
Rare opportunity to study cosmology before last scattering
CMB: $z \sim 10^3$ but nucleosynthesis: $z \sim 10^{10}$

e.g. inflation may be observable in ~ 1 Hz band

cosmology best probed at frequencies ~ 1 Hz and below:
e.g. phase transitions, reheating, dark energy (redshifts), etc.



Gravitational Wave Spectrum

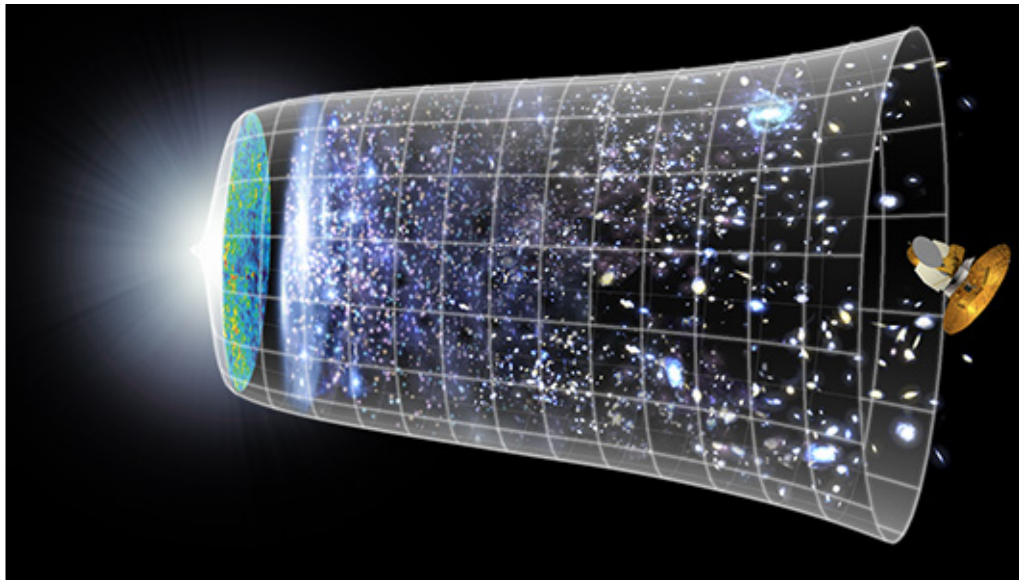


Early universe is transparent to gravitational waves

Rare opportunity to study cosmology before last scattering

CMB: $z \sim 10^3$ but nucleosynthesis: $z \sim 10^{10}$

e.g. inflation may be observable in ~ 1 Hz band



cosmology best probed at frequencies ~ 1 Hz and below:

e.g. phase transitions, reheating, dark energy (redshifts), etc.

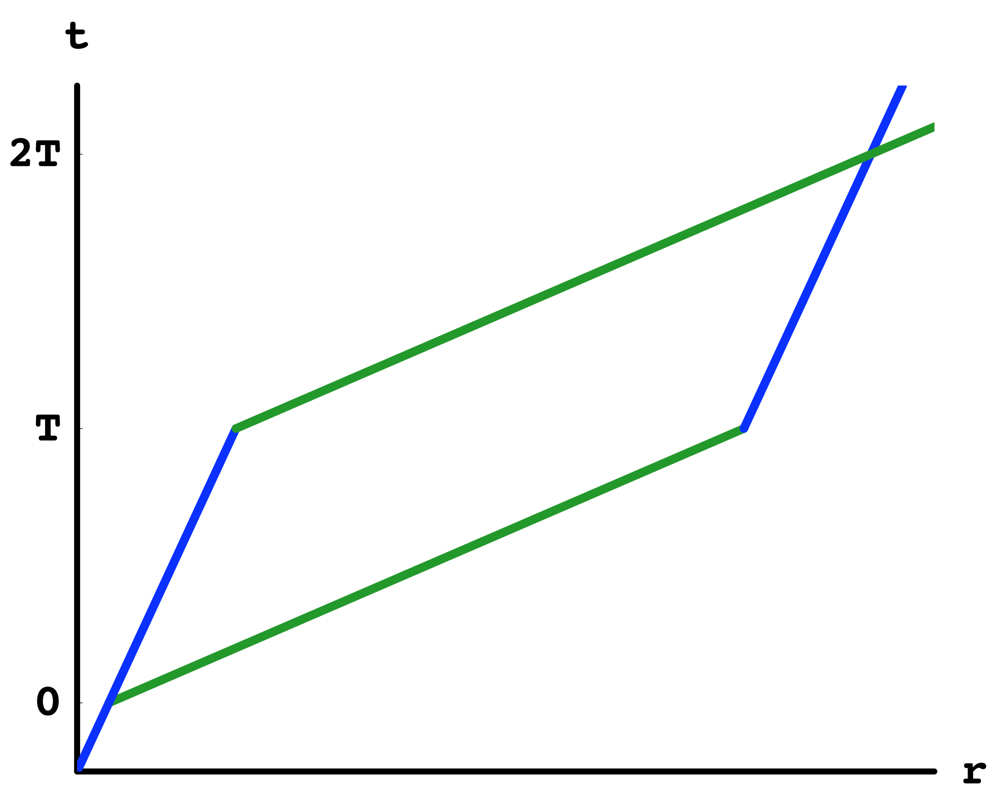
many astrophysical signals at lower frequencies:

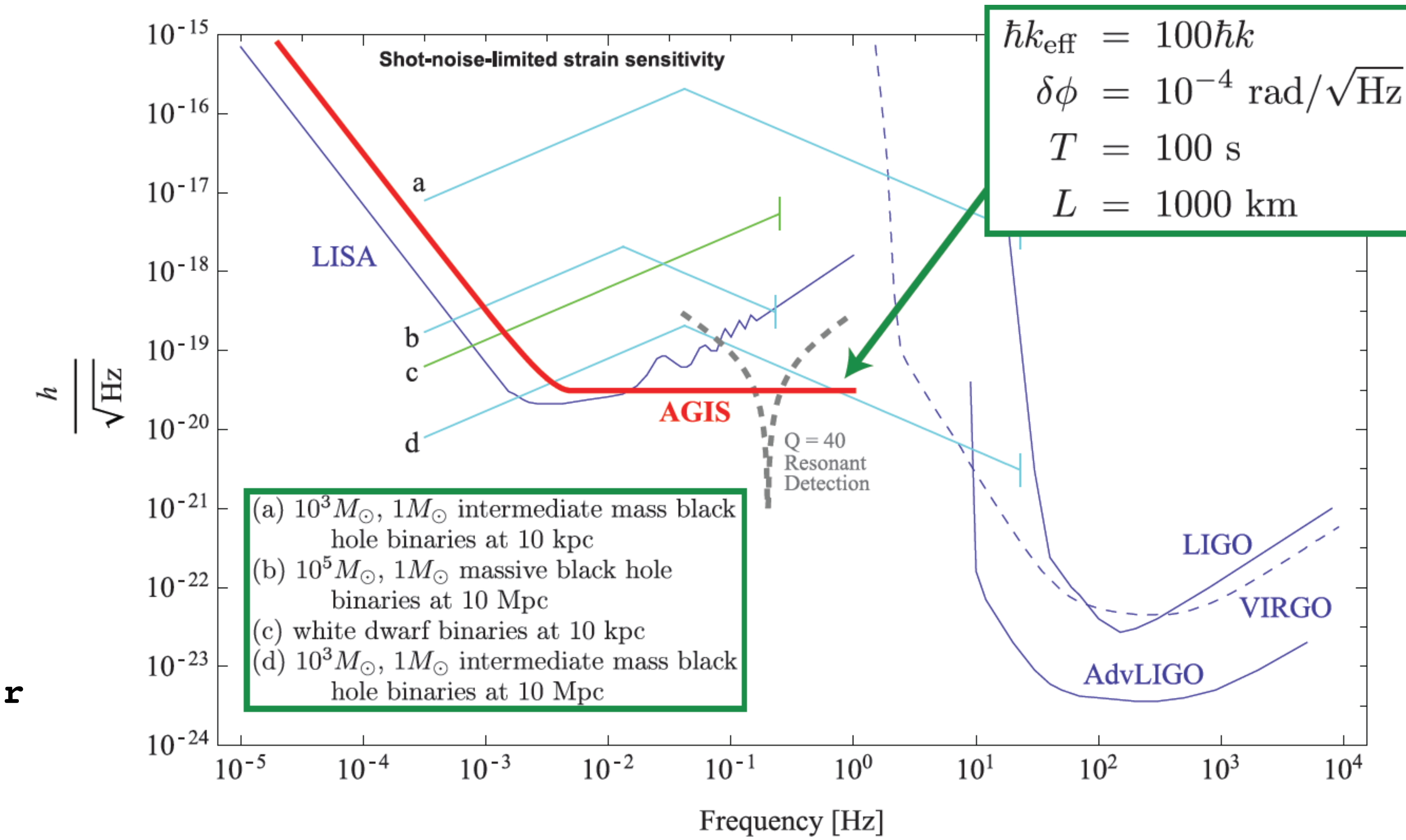
black holes (strong field gravity), neutron stars, white dwarfs

could give only probe of energies far above colliders

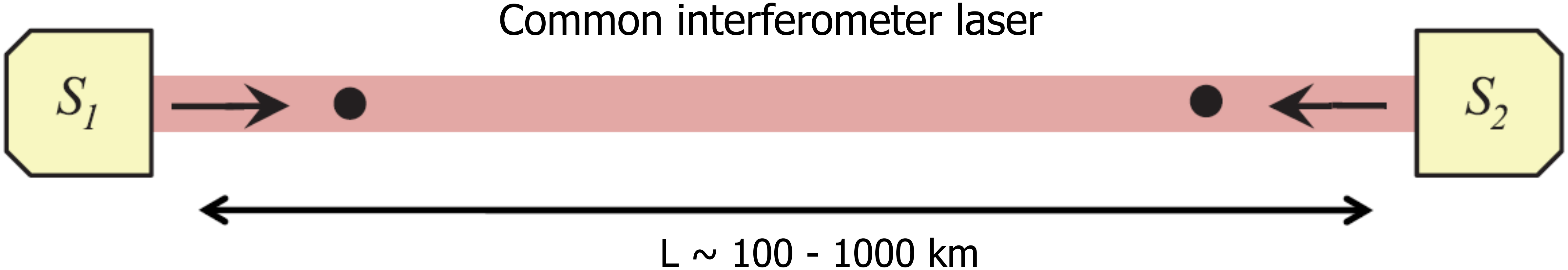
Atomic Gravitational Wave Interferometric Sensor (AGIS)

Atom in accelerometer sequence, GW modulates interferometer phase



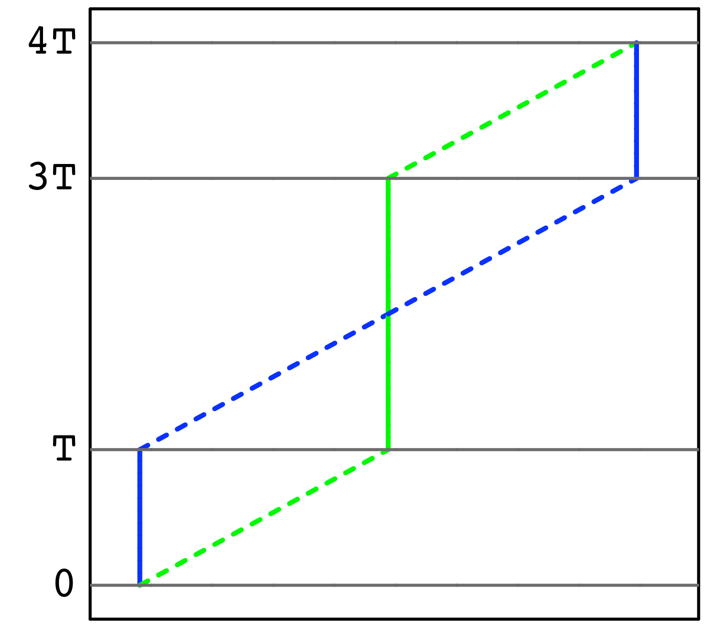


Common interferometer laser

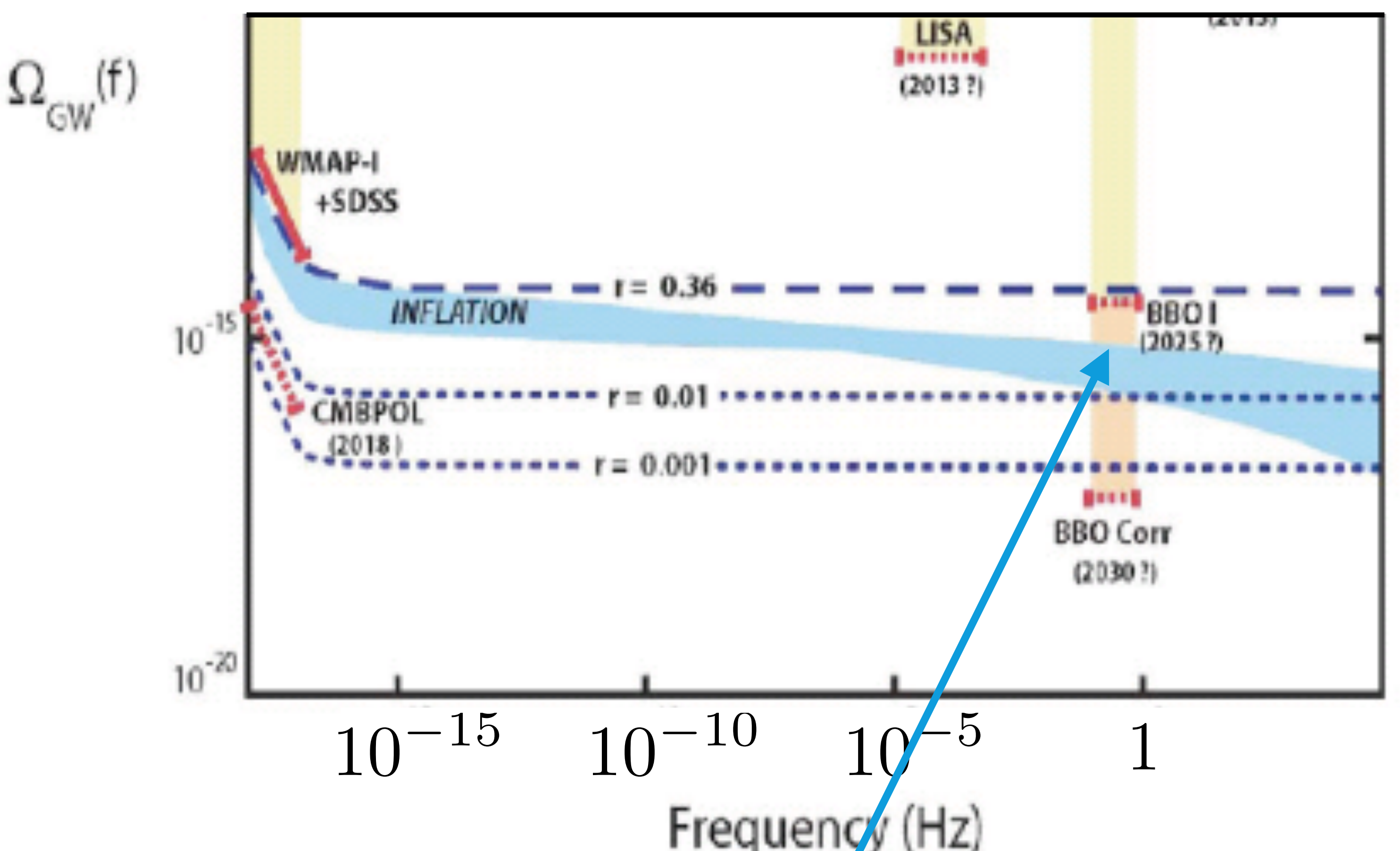


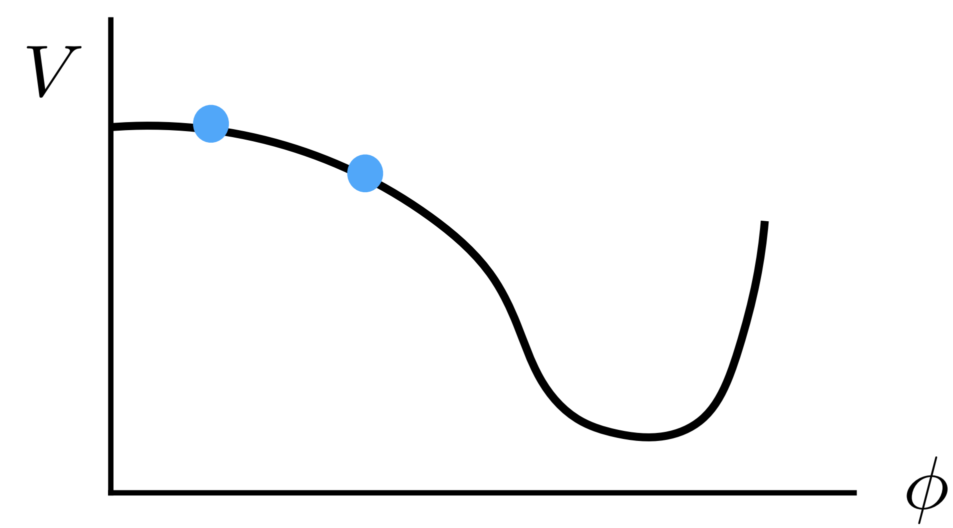
Resonant Detection and Inflation

(Preliminary!)



Atomic detector can run in resonant mode,
may be able to reach highest level of GW's from inflation





observe many e-folds in to inflation

detect at ~1 Hz

probe inflaton potential