The Precision Frontier of Particle Physics

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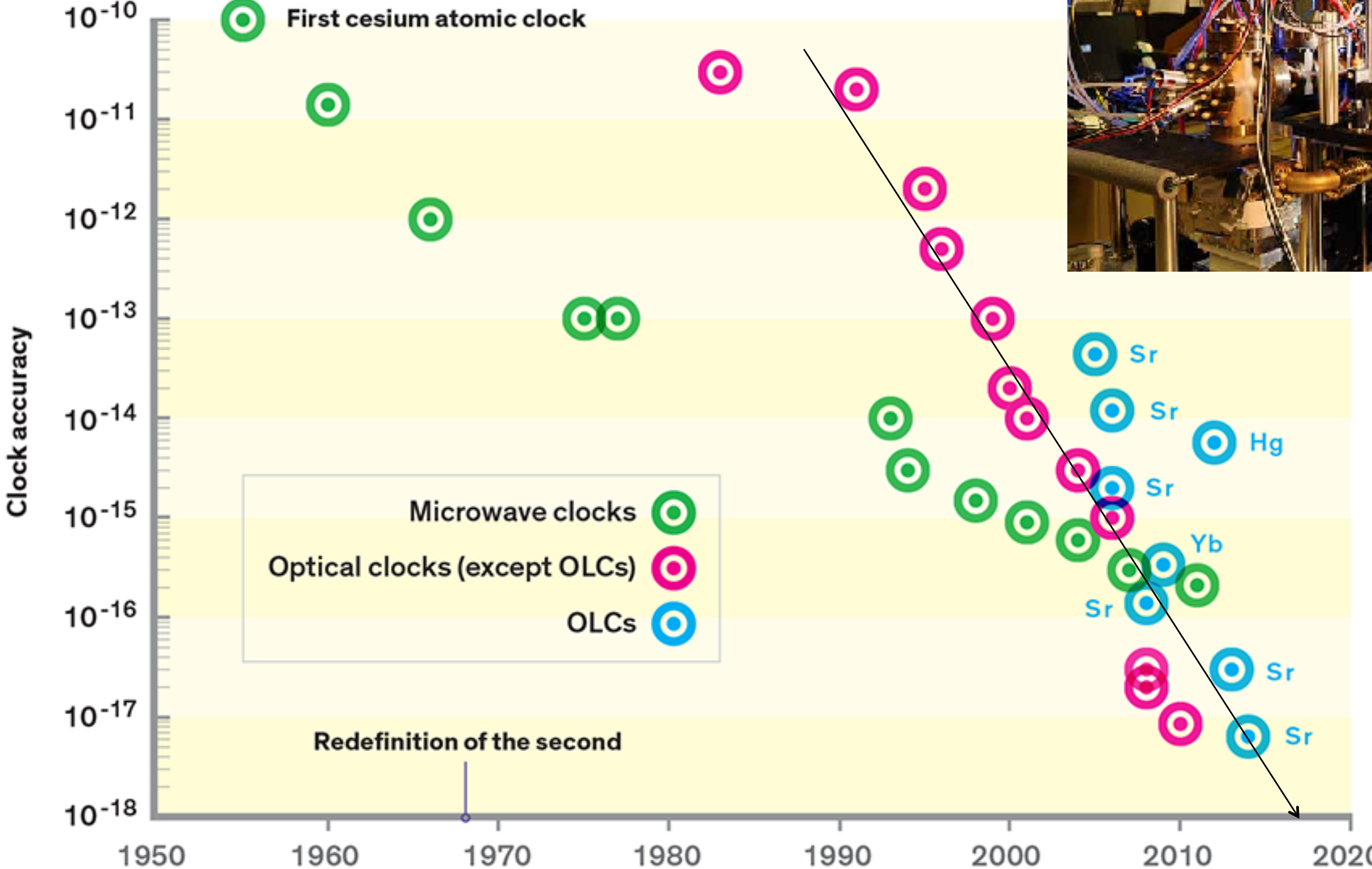
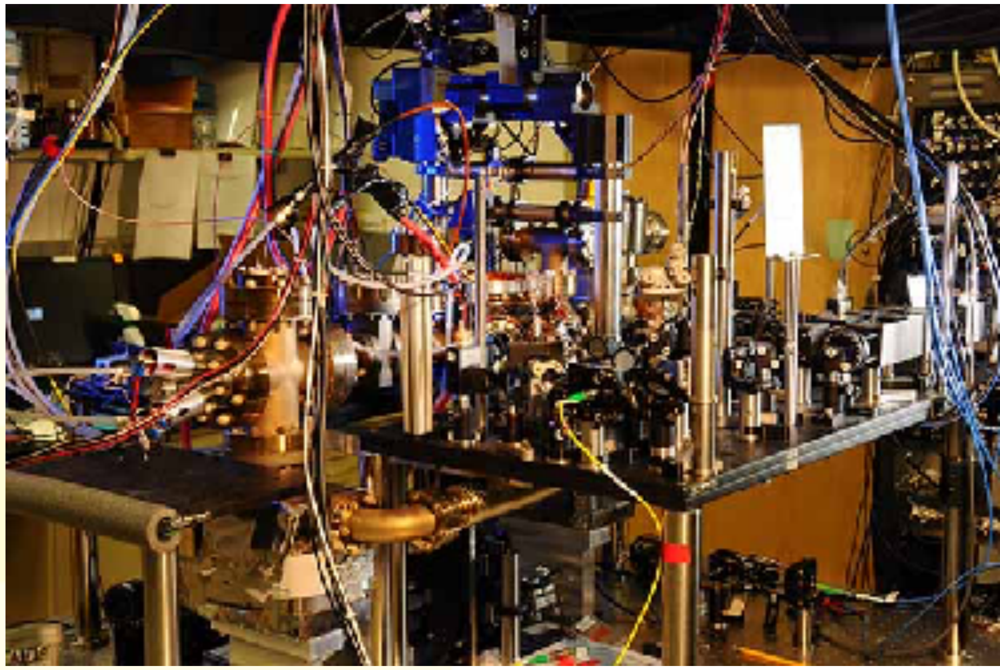
We've made amazing progress with colliders and conventional particle detectors (e.g. WIMP detectors), but some important things can't be seen this way:

- axions
  - critical questions such as hierarchy problem or nature of dark matter may not be answered at weak scale
- gravitational waves
  - from e.g. BH's, inflation, early universe,…
- new long-range forces
- etc.

to see these, we need a new approach

Atomic Clock Sensitivity





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

Precision Experiments

Precision measurement offers a powerful new approach for fundamental physics

not completely new (e.g. EDMs, new forces, etc.),
but small compared to traditional particle detection

- New technologies rapidly pushing precision measurement
  - e.g. atomic clocks have 18 digit precision
- Often small-scale, "table-top" experiments*
  - can do many <$10M experiments

*not for gravitational waves

Many exciting, unexplored directions

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)

Small coupling

high precision sensors

Heavy (weak scale)

Large coupling (EM, weak, strong)

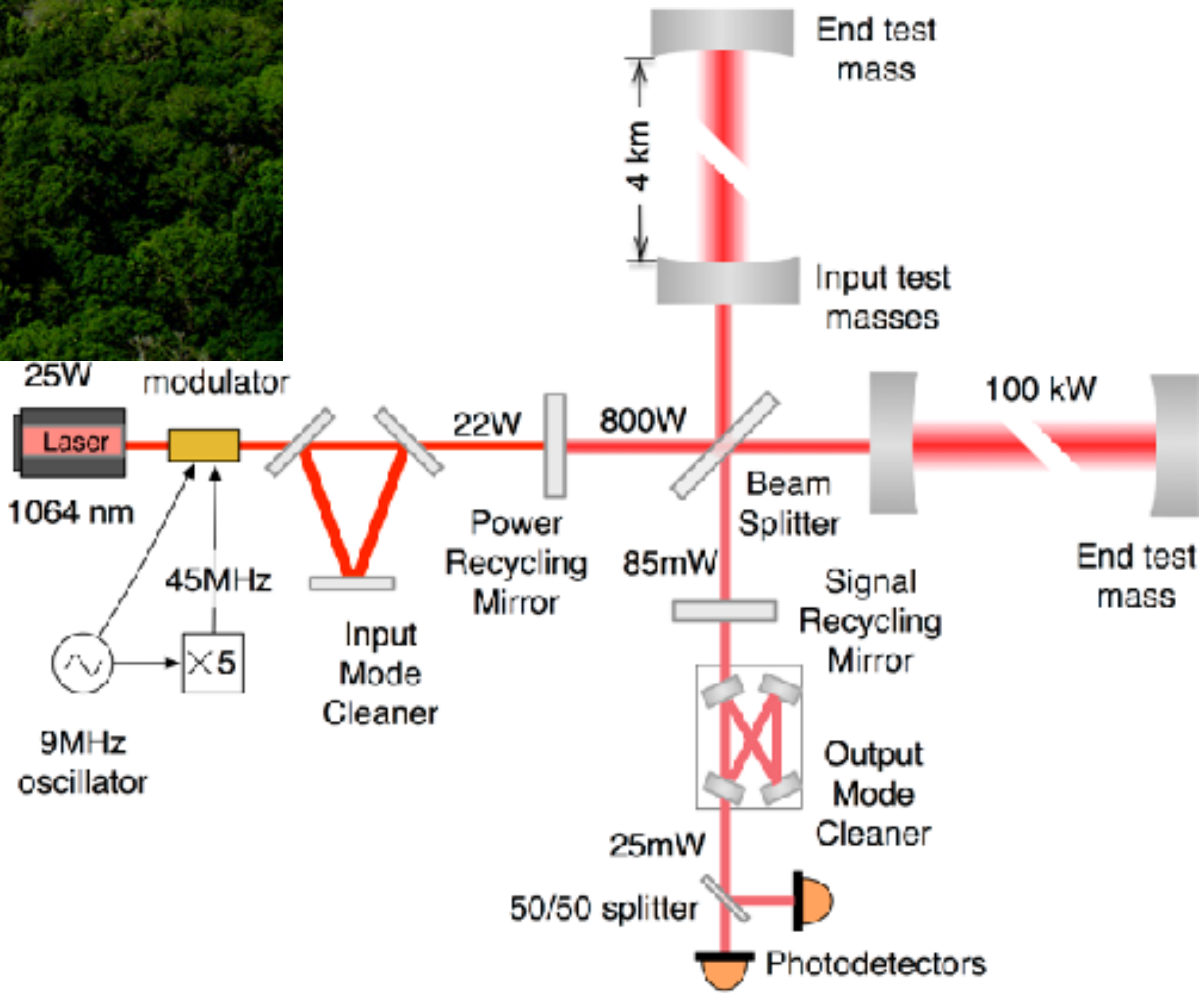
high energy accelerators

Outline

1. Motivation & Overview
2. LIGO example
3. Dark Matter Detection (axions, hidden photons, ultralight DM)
   - Cosmic Axion Spin Precession Experiment (CASPEr)
   - DM Radio
   - Other new techniques (e.g. accelerometers)
4. New Forces and Transmission Experiments
   - Eot-Wash torsion balances
   - light-through-walls
5. Gravitational wave detection with atom interferometry

LIGO

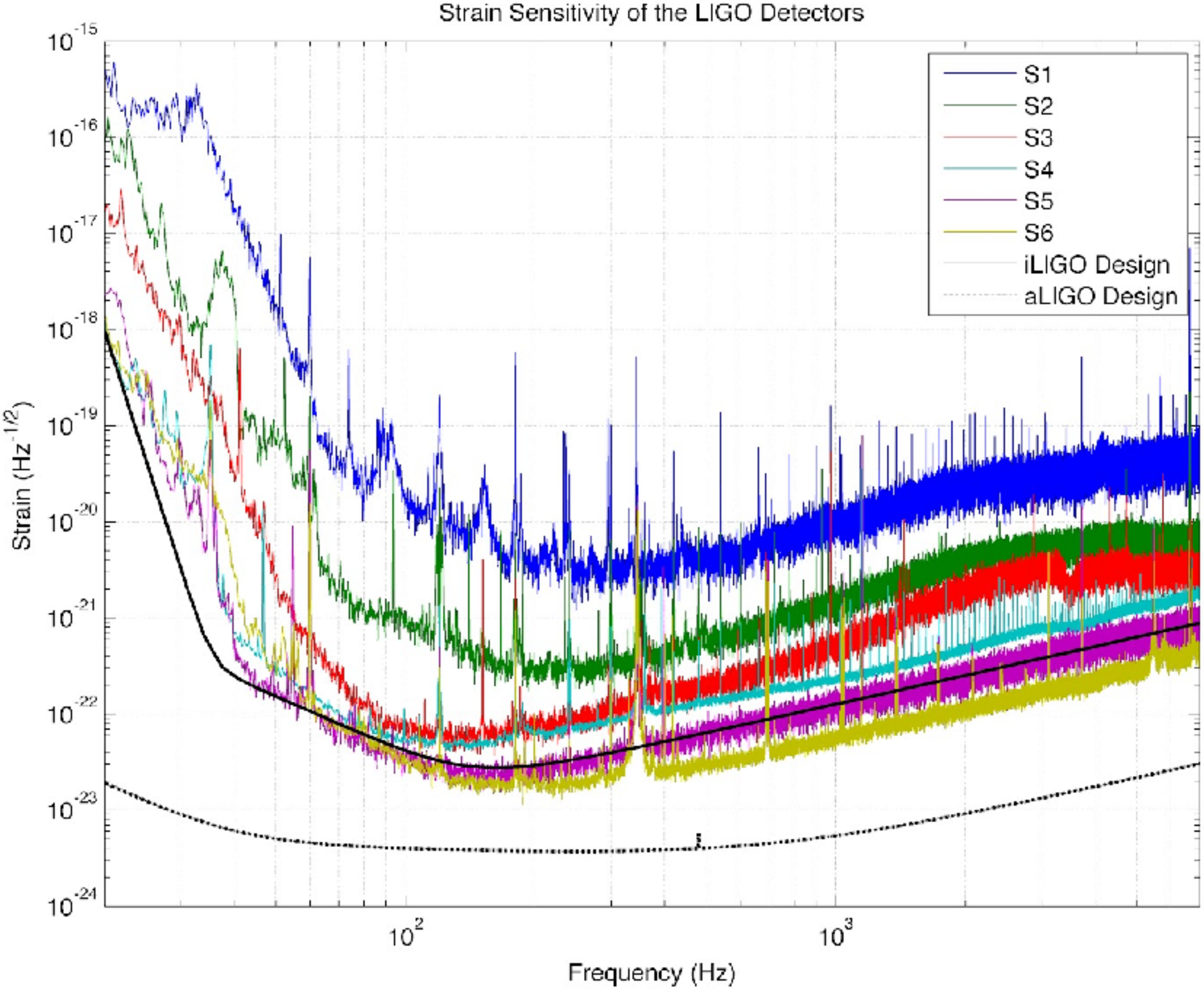
LIGO


End test mass
4 km
Input test masses
25W
modulator
Laser
1064 nm
45MHz
×5
9MHz oscillator
22W
Input Mode Cleaner
Power Recycling Mirror
800W
Beam Splitter
100 kW
End test mass
85mW
Signal Recycling Mirror
Output Mode Cleaner
25mW
50/50 splitter
Photodetectors

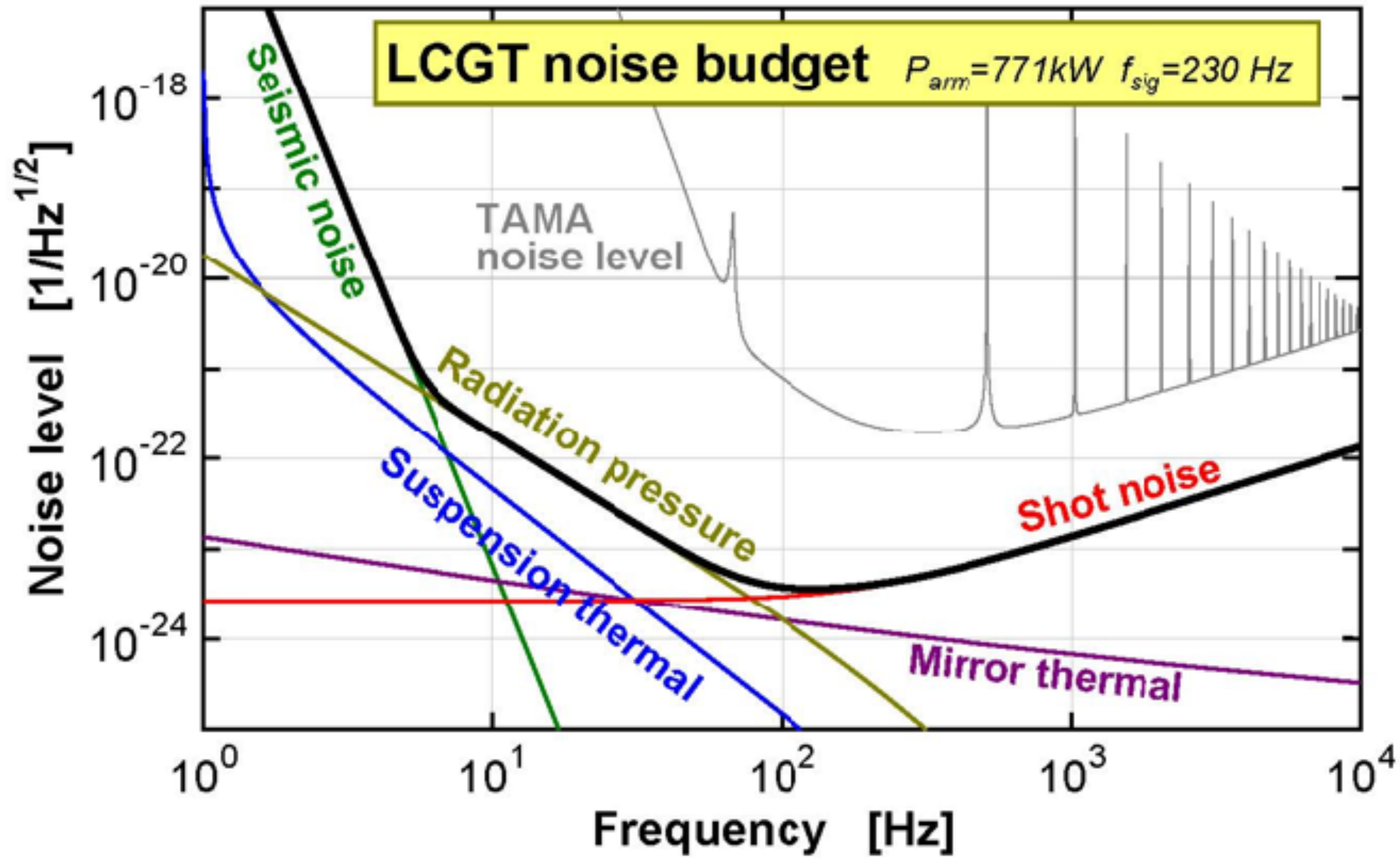
Estimate LIGO Sensitivity

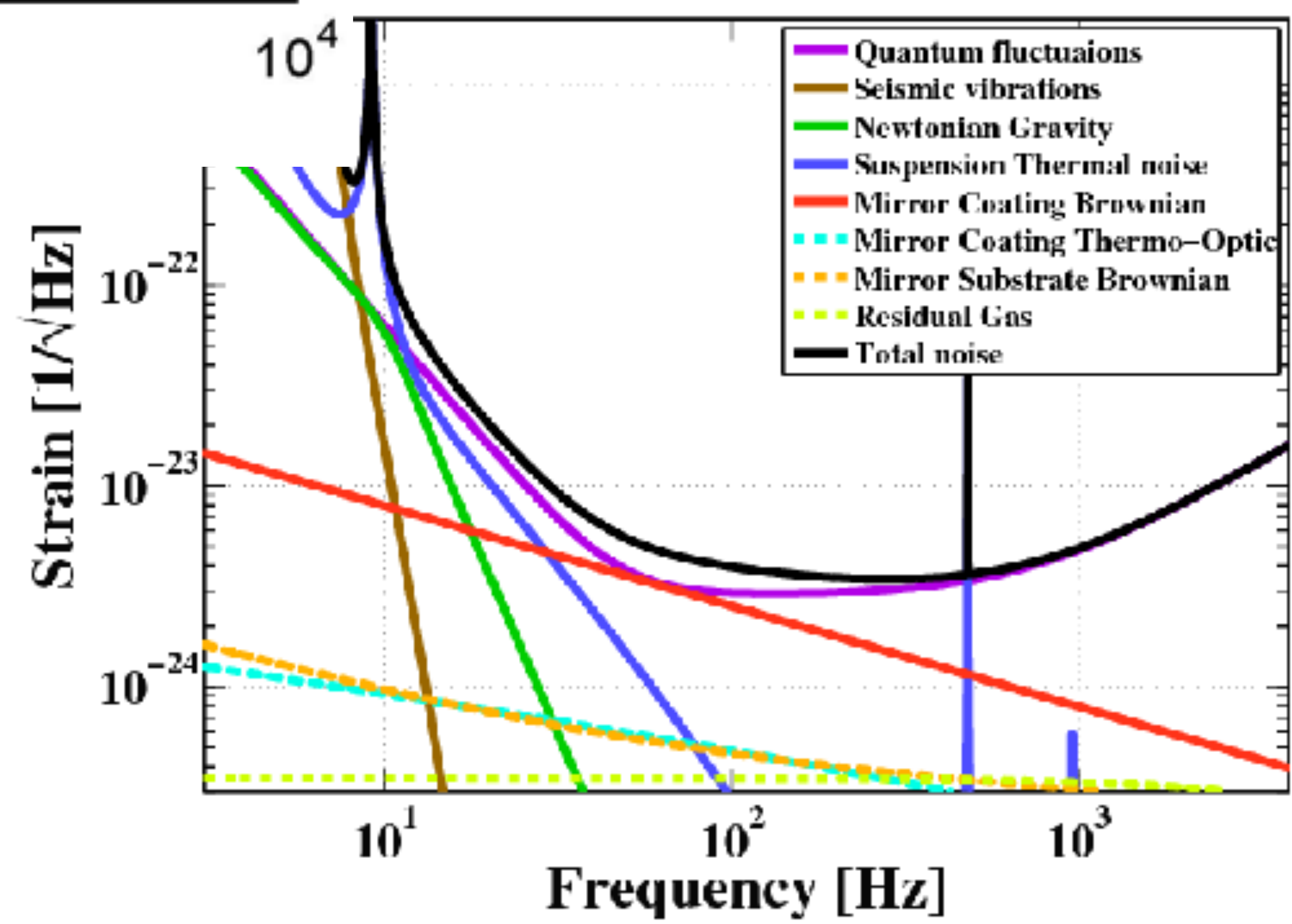
see notes

LIGO Sensitivity

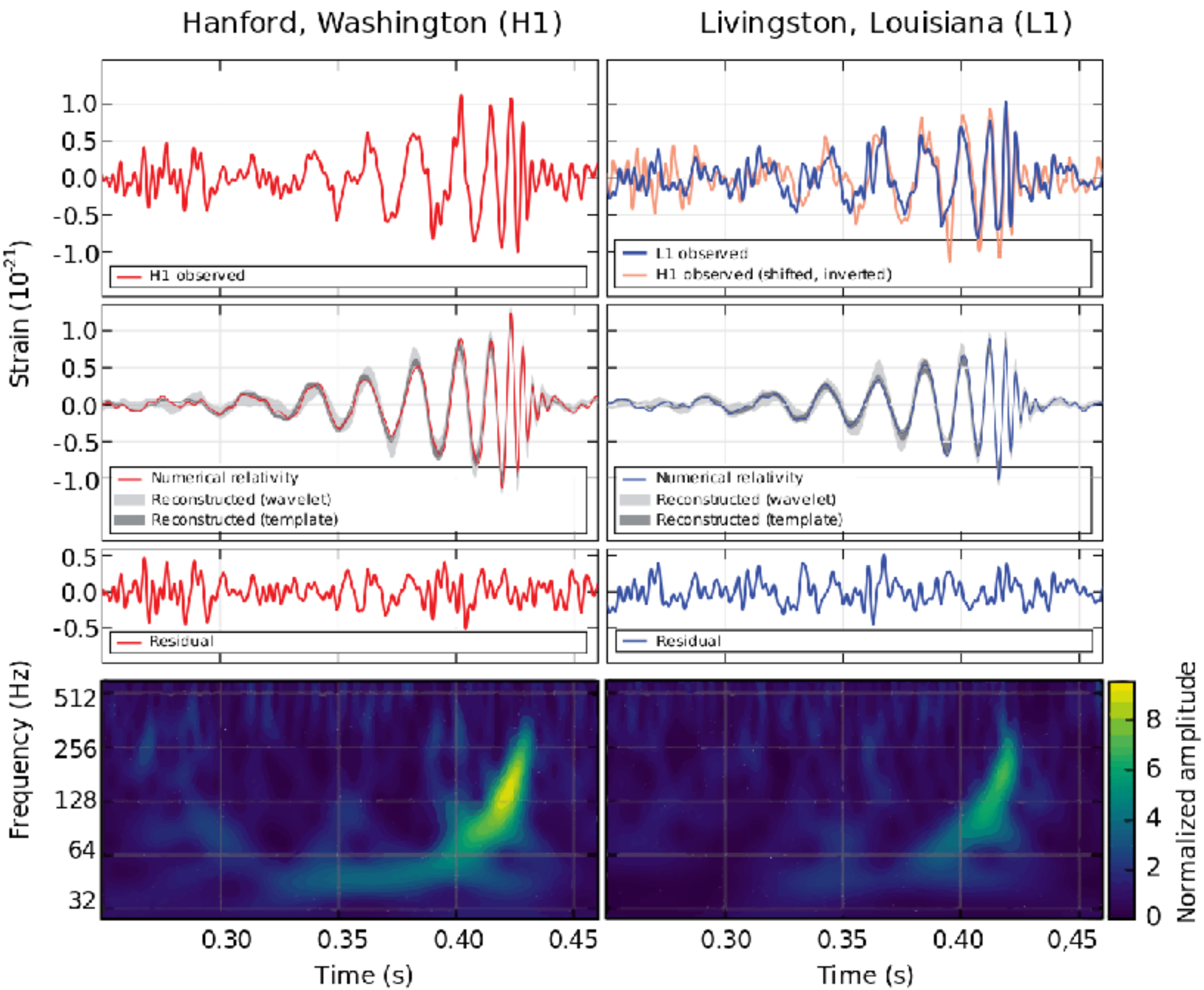


LIGO Sensitivity





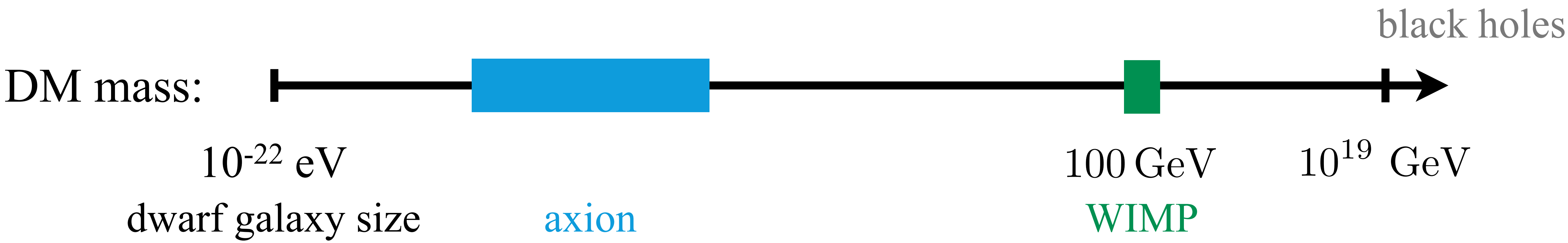
LIGO Event


Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
Normalized amplitude
0
2
4
6
8
0.30
0.35
0.40
0.45
Time (s)

Dark Matter Detection

Dark Matter Candidates

What do we know about dark matter?



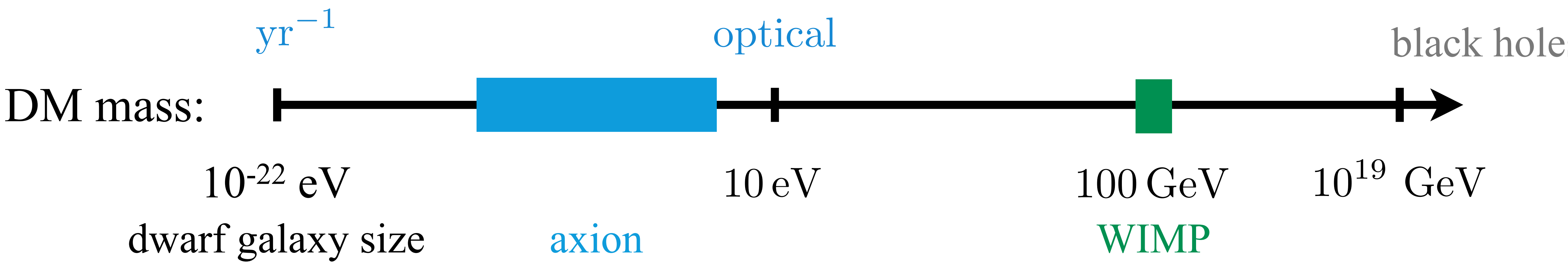
WIMP is well-motivated, significant direct detection effort focused on WIMPs

Axion is other best-motivated candidate, only a small fraction of parameter space covered

Huge DM parameter space currently unexplored!

Direct Detection

How can we detect DM?

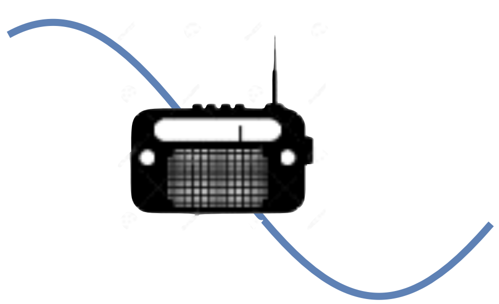


$\rho_{\mathrm{DM}} \approx 0.3\,\frac{\mathrm{GeV}}{\mathrm{cm}^3} \approx (0.04\,\mathrm{eV})^4$ ➔ high phase space density if $m \lesssim 10\,\mathrm{eV}$

field-like (e.g. axion)

new detectors required

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

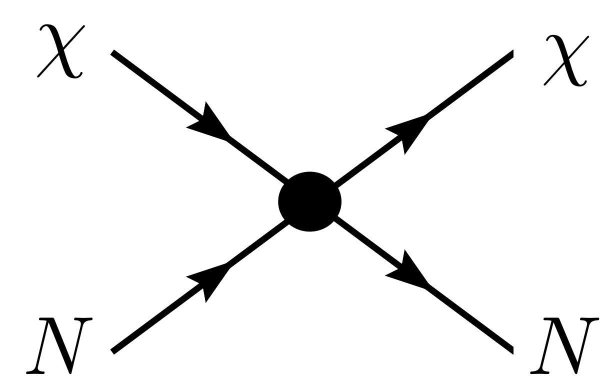


Frequency range accessible!

particle-like (e.g. WIMP)

particle detectors best

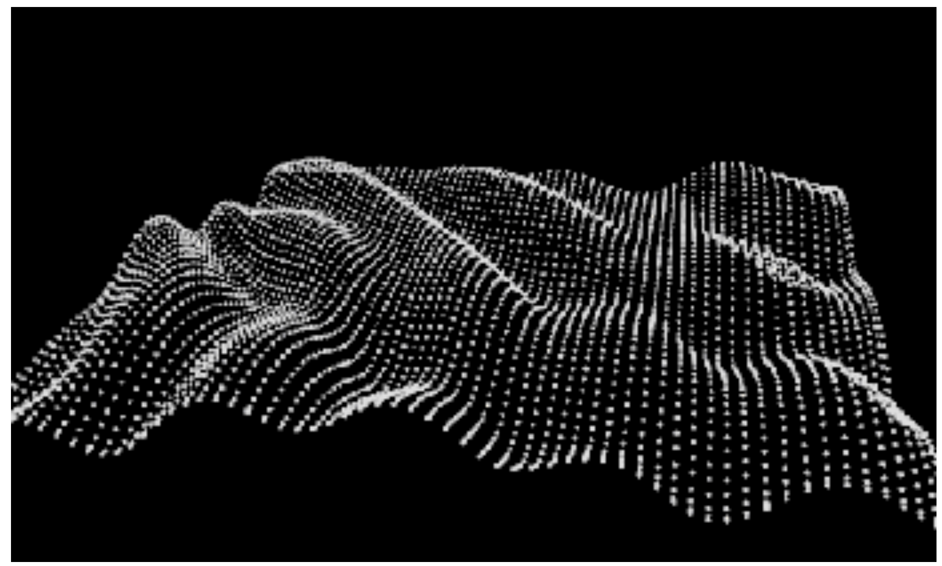
Search for single, hard particle scattering

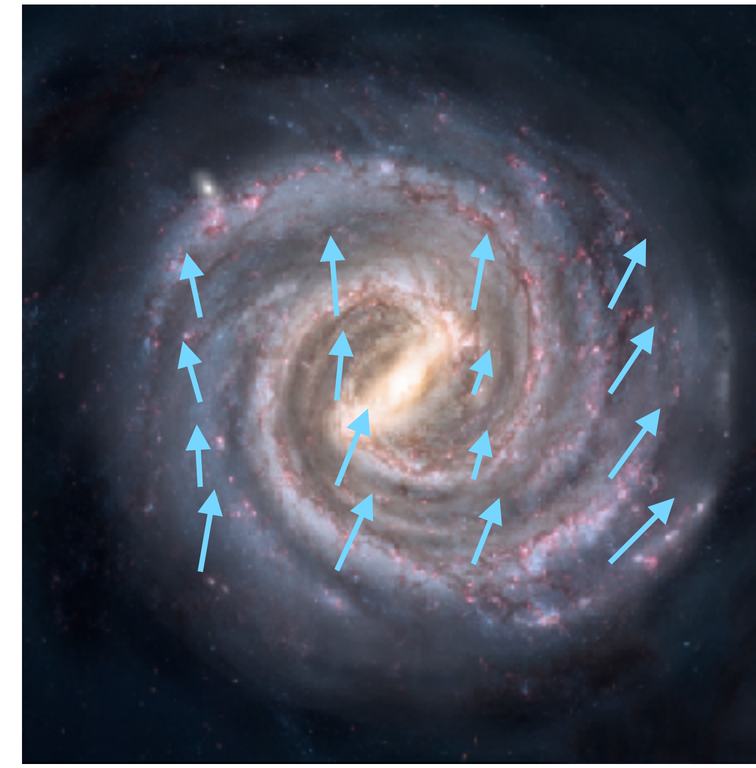


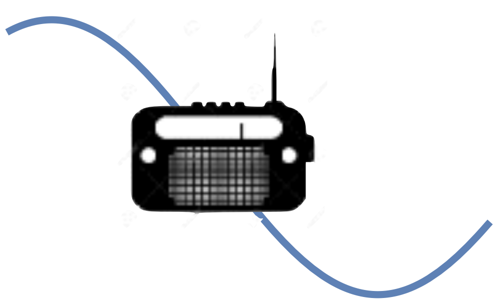
"Field" Dark Matter

particle DM

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







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

Possibilities for Light Dark Matter

Effective field theory: all UV theories summarized by only a few possibilities:

Spin	Type	Operator	Coupling
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

current searches (e.g ADMX)

use other couplings

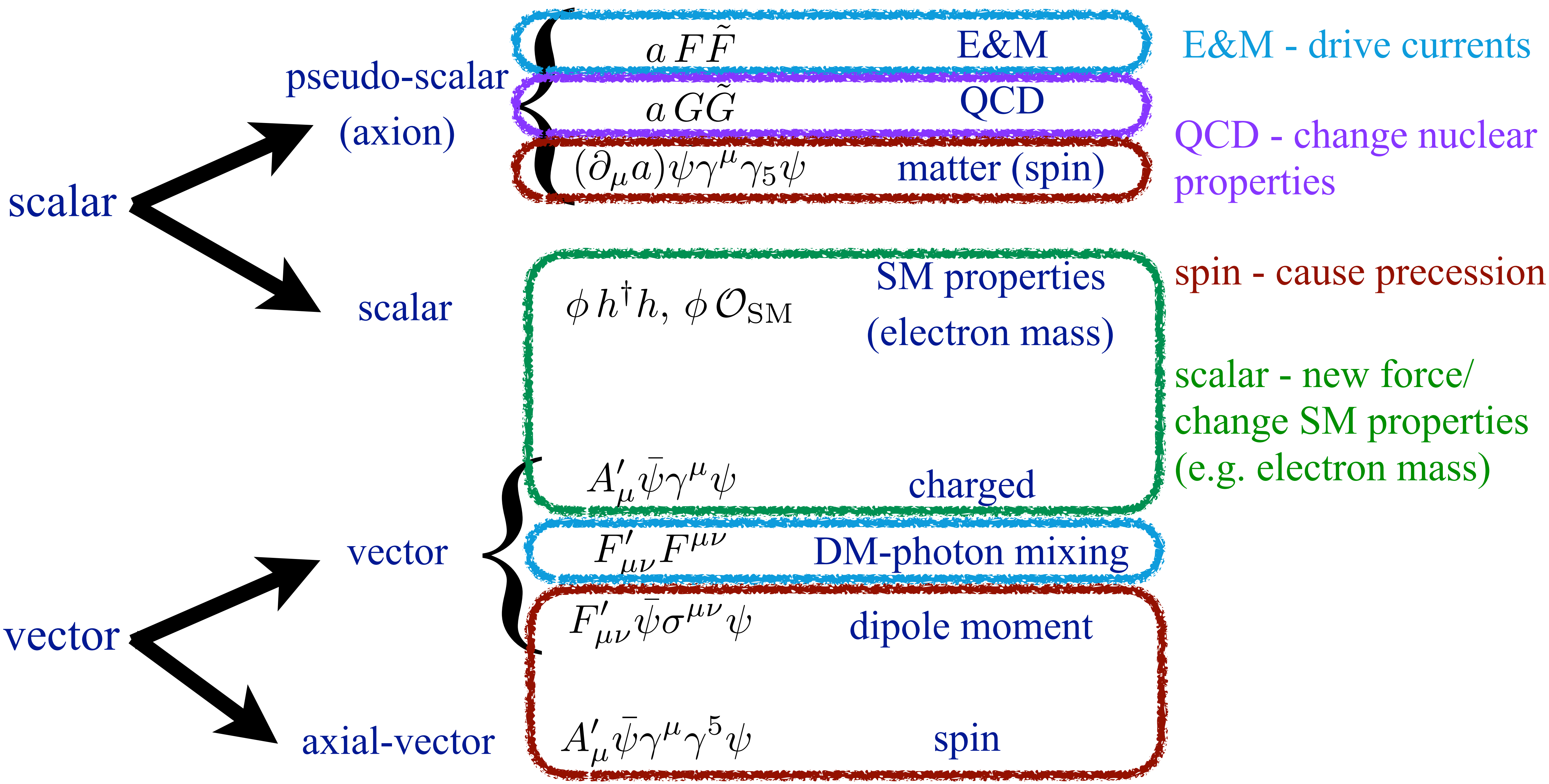
e.g. can reach axion parameter space considered impossible

Can cover all these possibilities!

arXiv:1512.06165

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 Detection

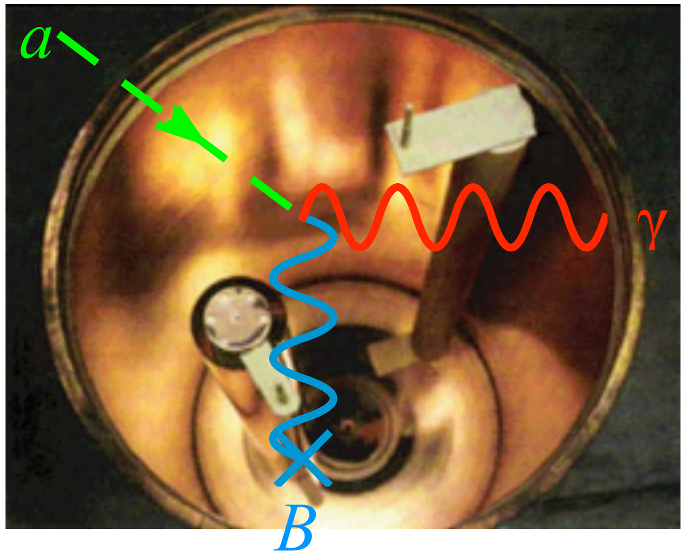
Existing Axion Searches

all existing experiments rely on axion coupling to E&M (photons): $\mathcal{L} \supset a\, F\tilde{F} = a\, \vec{E} \cdot \vec{B}$

drives cavity at frequency m_a

ADMX focuses on axions ~ 0.5 - 10 GHz

axion Compton wavelength ~ size of cavity



$a\, F\tilde{F} \sim a\, \partial\, (A\, \partial A)$ is a derivative operator

integrate by parts ➜ all effects depend on derivative of axion field

all effects suppressed by $\sim \dfrac{\text{experiment size}}{\text{axion wavelength}}$

at lower masses, axion wavelength ➜ 300 km

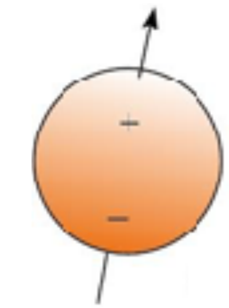
(axions from fundamental scales near Planck scale)

how cover the full axion mass range? a different operator

The Axion

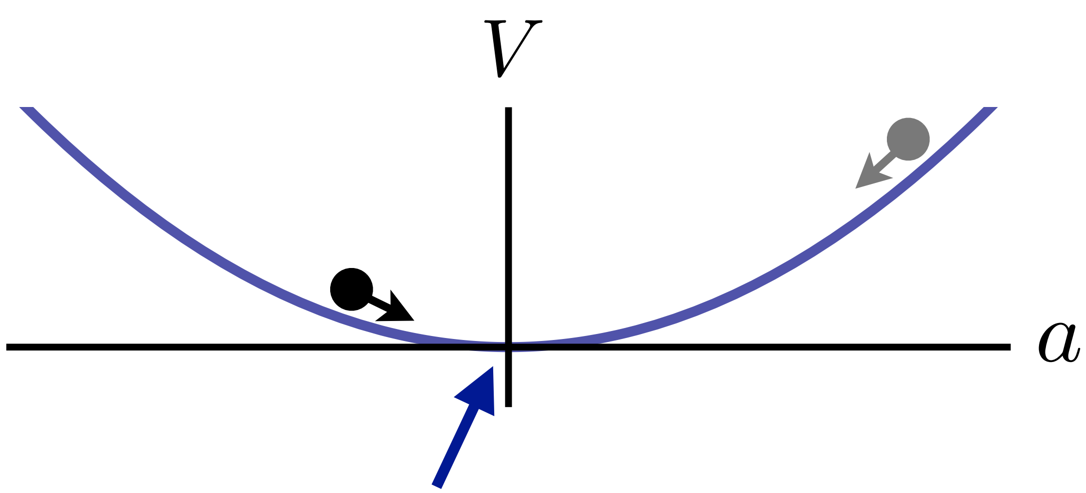
Strong CP problem:

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



Axion solution:

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



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

calculate a_0:

$$m_a^2\, a_0^2 \sim \rho_{\mathrm{DM}} \sim 0.3\, \frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

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

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

adiabatic approximation ➜ $d \sim 3 \times 10^{-16}\, \dfrac{a}{f_a}\, e\,\mathrm{cm}$

Axion DM causes oscillating nucleon EDM today, not a derivative effect!

completely changes axion detection

generally light bosonic DM causes oscillating fundamental “constants”

A Different Operator For Axion Detection

all (free) nucleons radiate: lab? stars?

standard EDM searches not sensitive to oscillating EDM,
we’ll use resonance to enhance signal

collective effect of EDM in condensed matter system enhances signal