Small Scale experiments for fundamental physics

ICTP Summer School on Particle Physics, June 12-15

Part 2

A. Geraci, University of Nevada, Reno

Syllabus

- Introduction
- New (scalar) forces
- Gravitational Waves and Ultralight Dark Matter
- New (spin-dependent) forces

(relation to axions, EDMS, Cosmic DM experiments)

Outline for Lectures

- Lecture 2 –

-Gravitational waves

New Techniques:

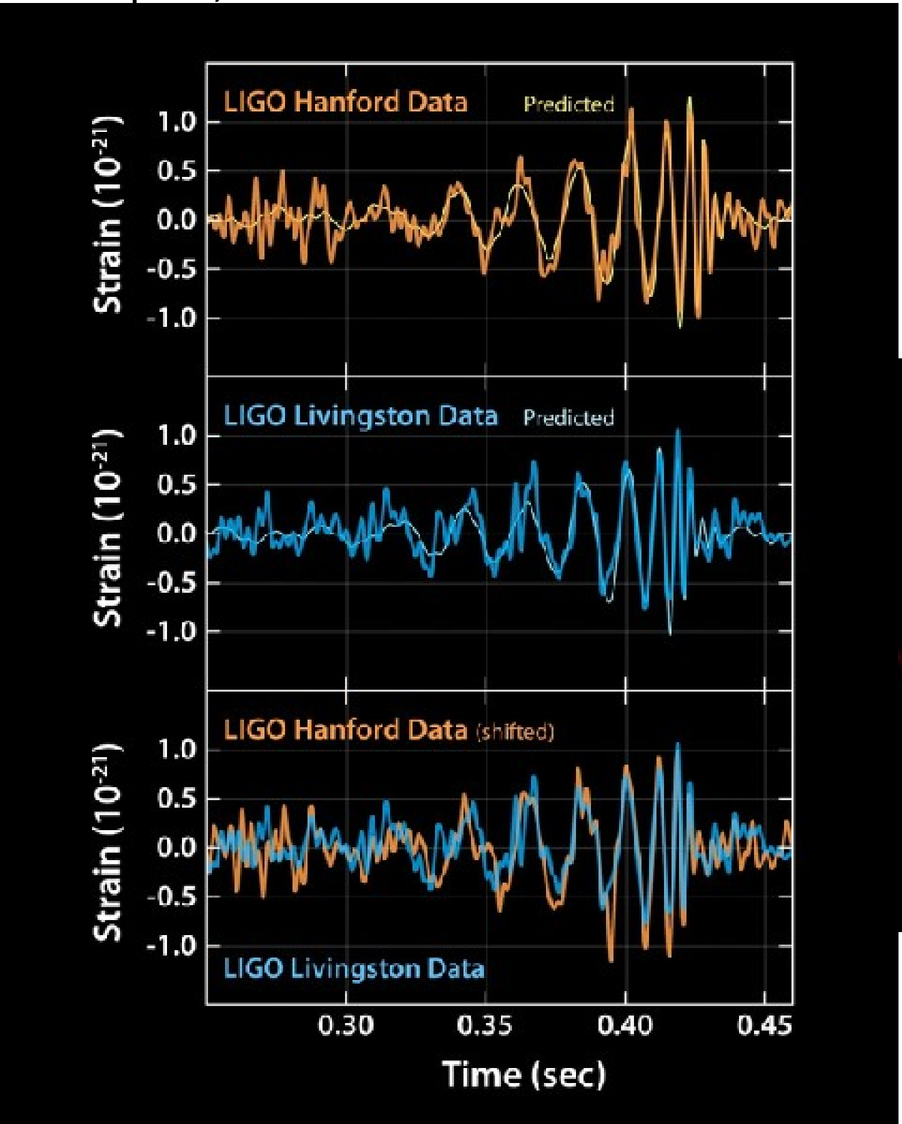
→ Levitated sensors

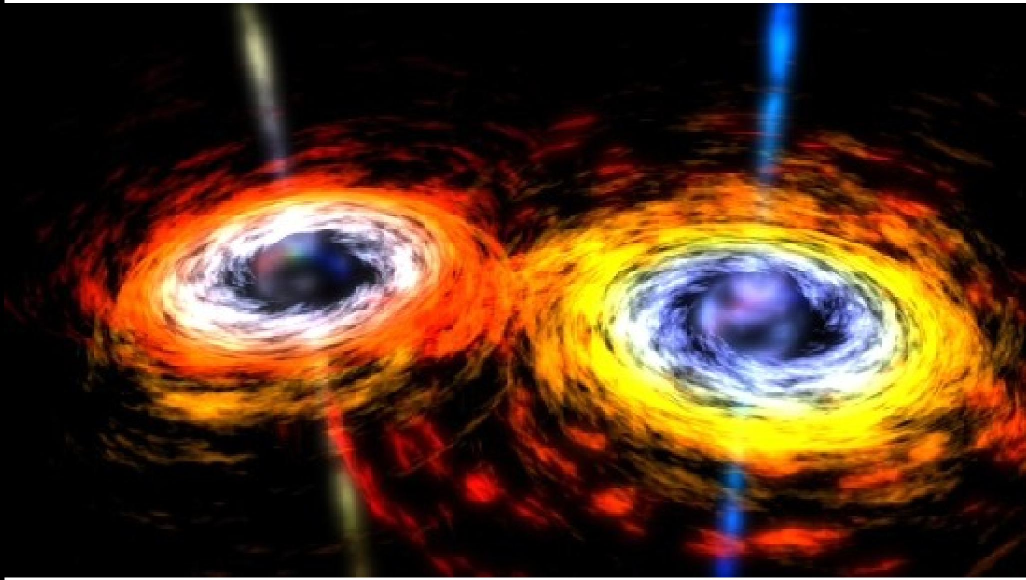
→ Atom interferometry

-Ultralight scalar field dark matter

Gravitational Waves

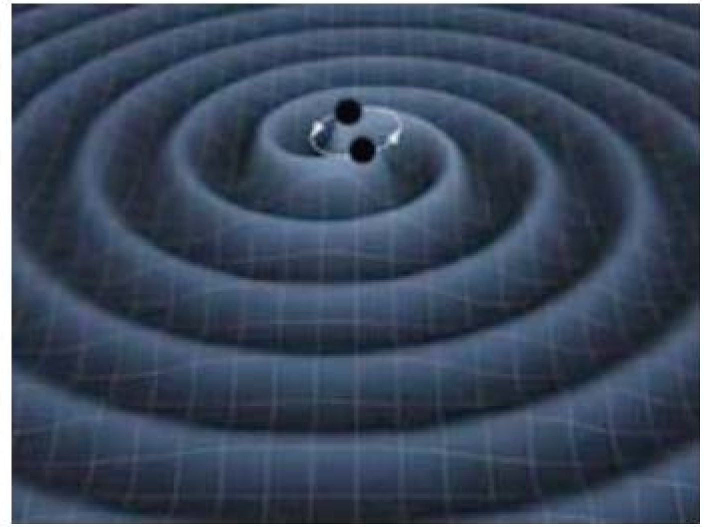
Sep 14, 2015





B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) Phys. Rev. Lett. **116**, 061102 (2016).

Gravitational waves



- Several BH events now discovered by Advanced LIGO!
- Sources:
  - Inspirals of astrophysical objects
  - Inflation, Phase transitions, etc.

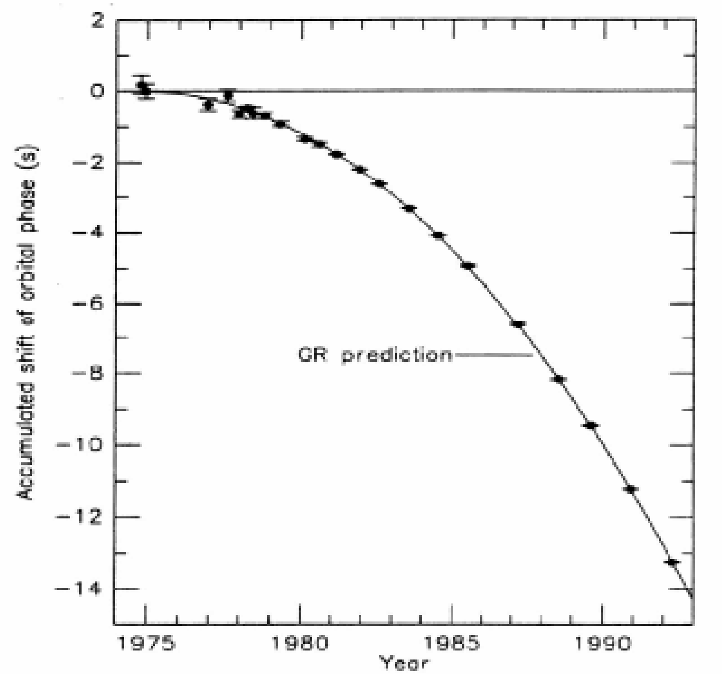
Indirect evidence: Hulse Taylor Binary

- Binary system of neutron stars emits gravitational waves

Rapidly spinning pulsar (17Hz)
orbits around another star with 8h period

Period speeds up ~14s over 1975-1993

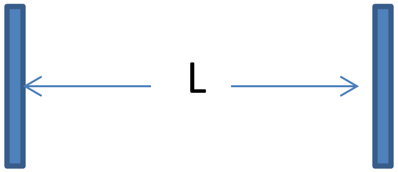
Nobel Prize 1993 (Hulse, Taylor)



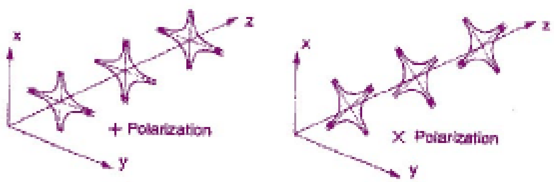
J. H. Taylor, L. A. Fowler & P. M. McCulloch
Nature277, 437-440 doi:10.1038/277437a0

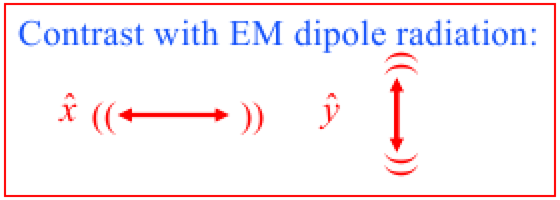
Gravitational Waves

- Stretch and squeeze the space between test masses



- Strain h = ΔL/L
- 2 polarizations (+ and x)





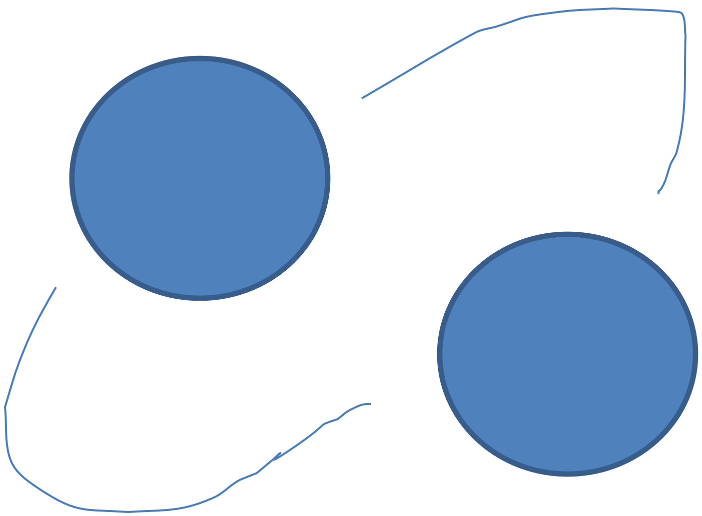
A. Weinstein, notes
caltech.edu/laac/undergraduate_resources.shtml

Sources of Gravitational Radiation

- Example: Neutron star binary

Accelerating charge – EM radiation (dipole)
Accelerating mass – Gravitational radiation (quadrupole)

e.g. rotating dumbells



e.g. $h \sim 10^{-21}$

$f \sim 400$ Hz

Resonant bar detectors

Bar driven into resonant oscillation by passing GW

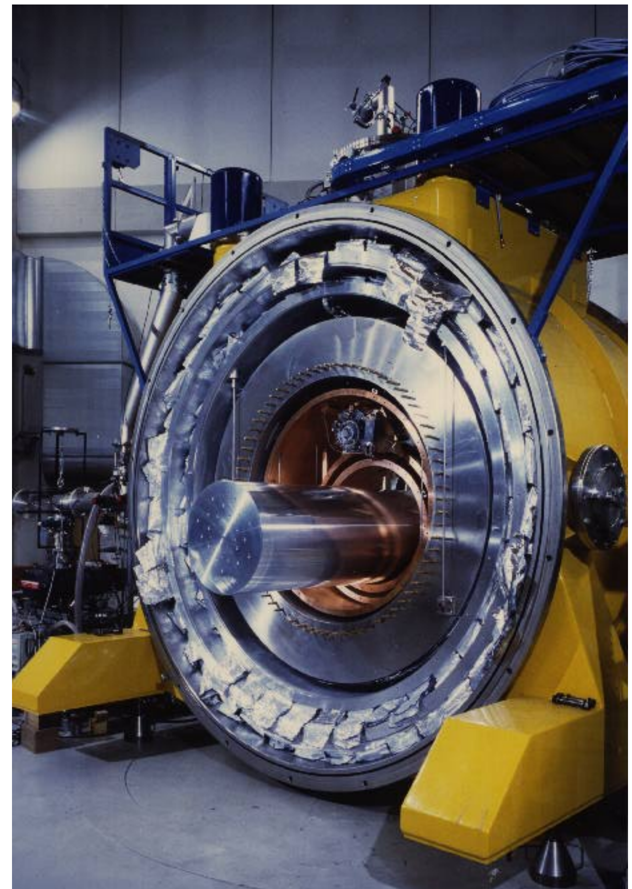
J. Weber (1969)

$$\omega_0 = 2\pi(1.6\,\mathrm{kHz})$$

Aluminum bar

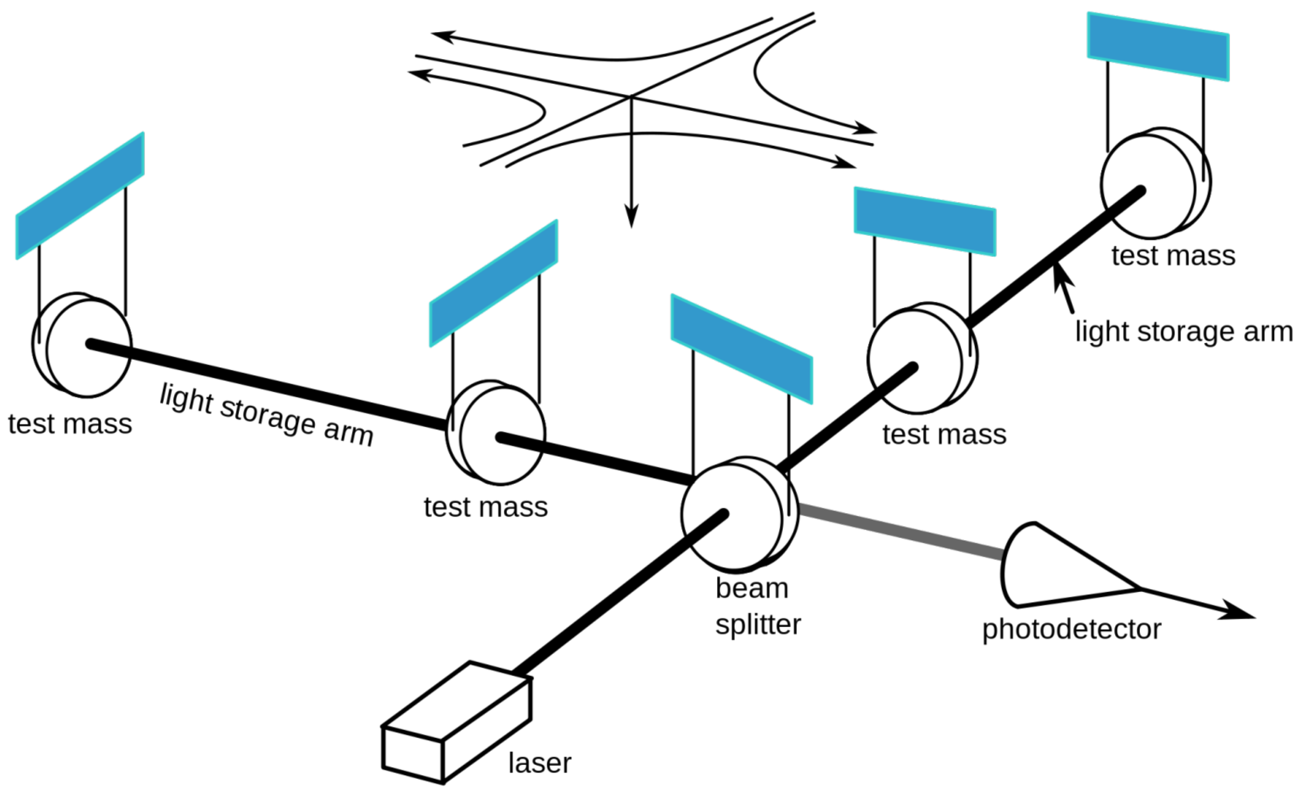
Resonant bar detectors

AURIGA experiment (Padova,Italy)



- 2.3 tons of Aluminum, 3 m long
- 0.1 K dilution fridge
- $Q=4 \times 10^6$
- Resonant frequency 900 Hz
- Capacitive measurement
- $h \sim 10^{-21} /(Hz)^{1/2}$

Interferometer detectors

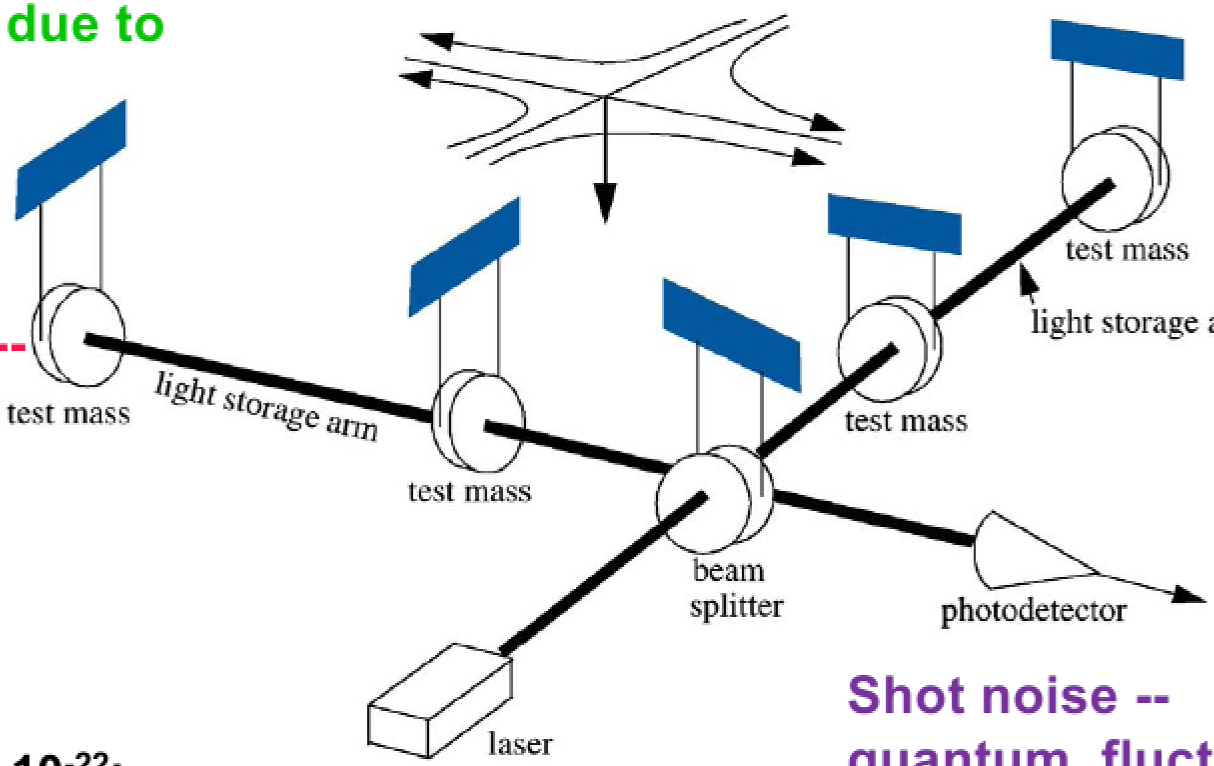


Global network of GW detectors

Interferometer detectors

Seismic motion -- ground motion due to natural and anthropogenic sources

Thermal noise -- vibrations due to finite temperature



$$h = \Delta L / L$$

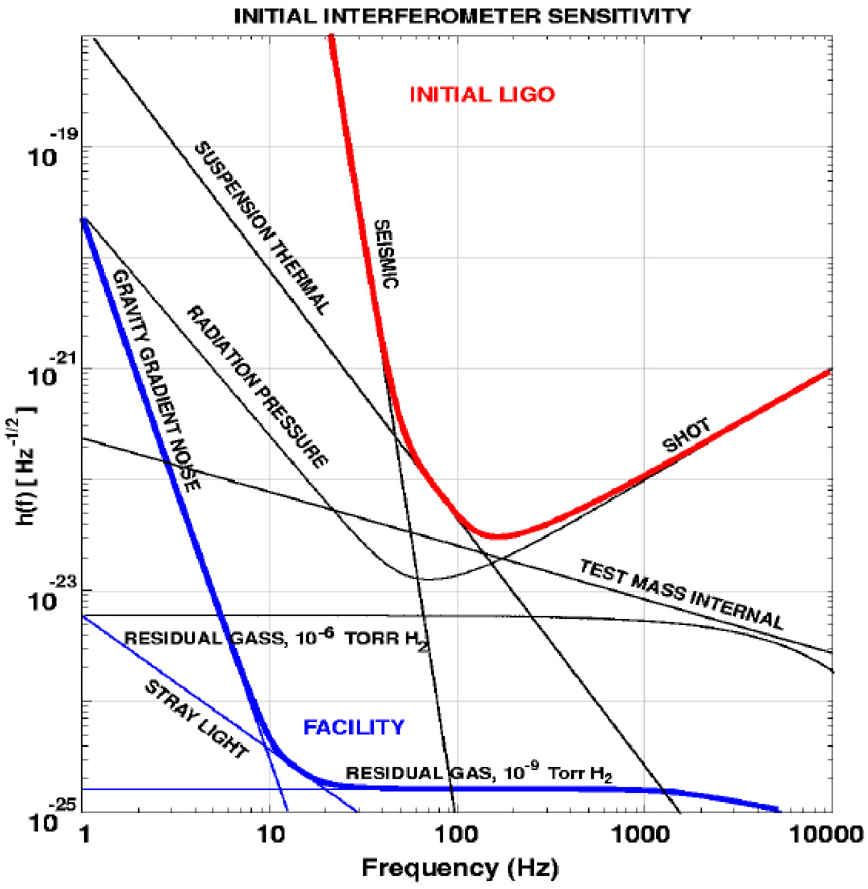
want to get $h \leq 10^{-22}$;
can build L = 4 km;
must measure
$\Delta L = h L \leq 4\times10^{-19}$ m

Shot noise -- quantum fluctuations in the number of photons detected

AJW, LIGO SURF, 6/16/06

A. Weinstein, notes caltech.edu/laac/undergraduate_resources.shtml

Sensitivity of LIGO



Alan Weinstein, notes
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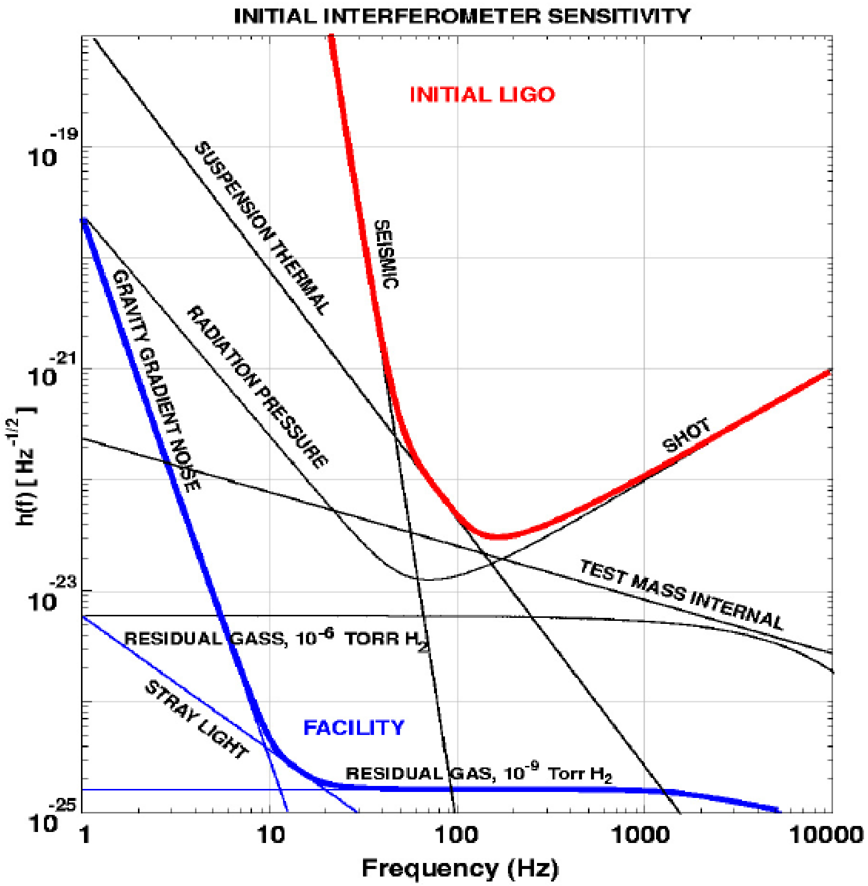
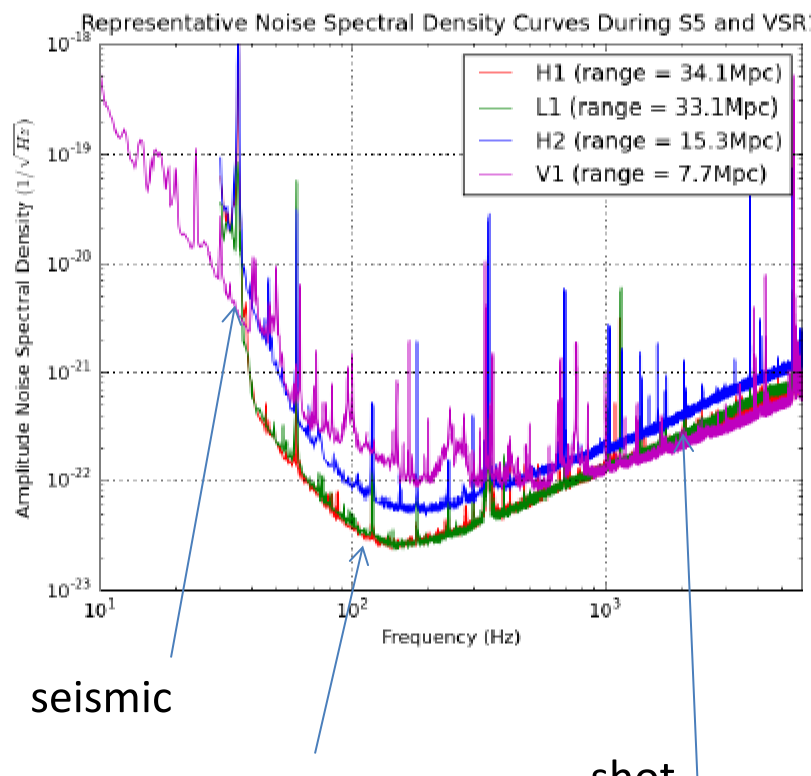
Sensitivity of LIGO





seismic

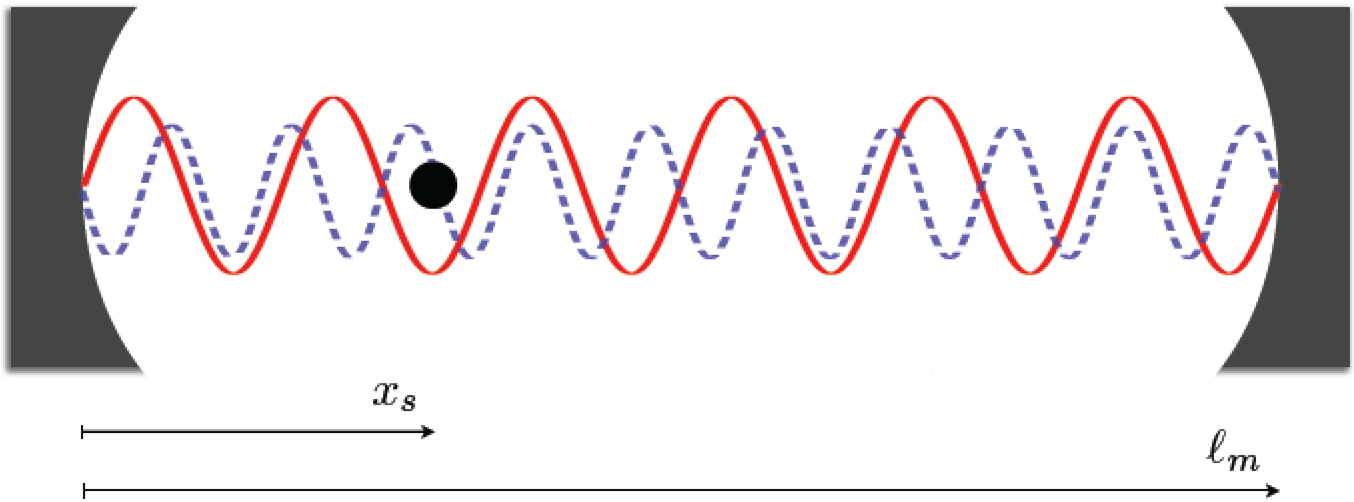
shot

thermal

Alan Weinstein, notes
caltech.edu/laac/undergraduate_resources.shtml

LIGO-T0900499

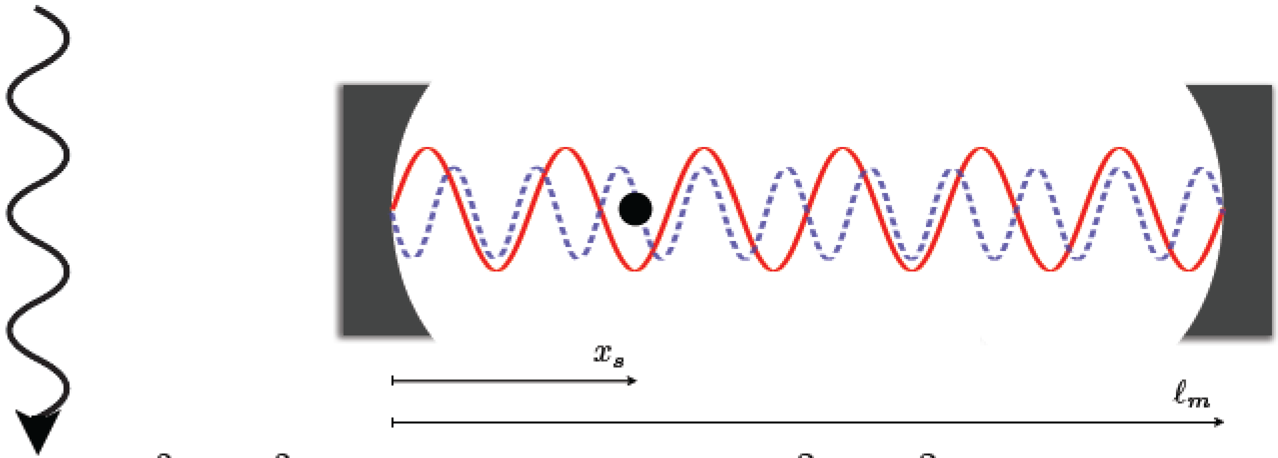
Gravitational Wave Detection with levitated optomechanics



- Fused silica sphere (r = 150nm) or disc (t = 500nm, r = 75 μm)
  In an optical cavity of size 10-100 m
- One laser to trap, one to cool and measure sensor position

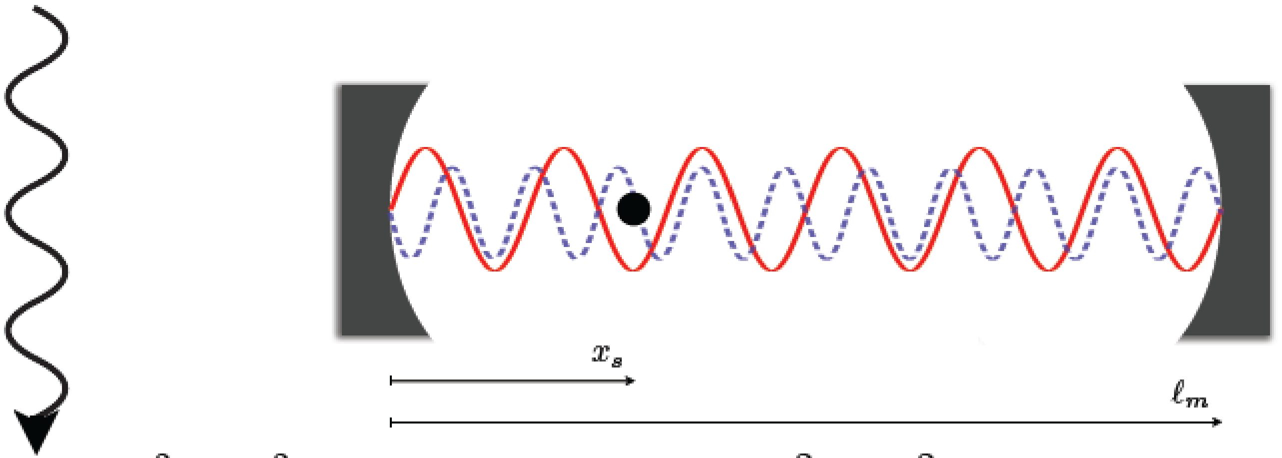
A. Arvanitaki and AG, arxiv: 1207.5320 (2012)

Gravitational Wave Detection



$$ds^2 = dt^2 - (1 + h\cos(\omega(t - y)))dx^2 - dy^2 - (1 - h\cos(\omega(t - y)))dz^2$$

Gravitational Wave Detection

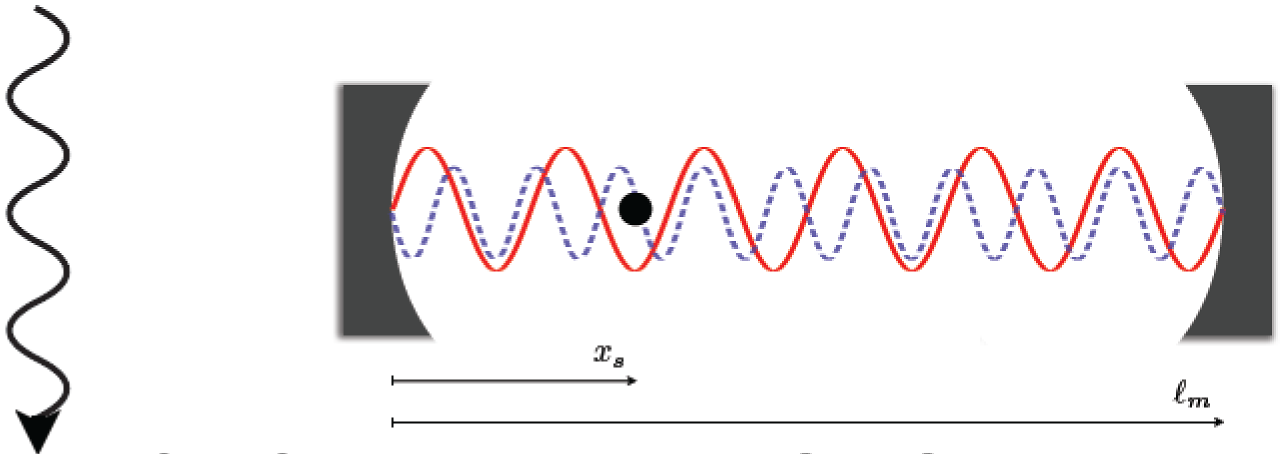


$$ds^2 = dt^2 - (1 + h\cos(\omega(t-y)))dx^2 - dy^2 - (1 - h\cos(\omega(t-y)))dz^2$$

Gravitational wave changes the physical distance between the end mirrors:

$$L = \ell_m[1 + \frac{1}{2}h\cos(\omega t)]$$

Gravitational Wave Detection



$$ds^2 = dt^2 - (1 + h\cos(\omega(t-y)))dx^2 - dy^2 - (1 - h\cos(\omega(t-y)))dz^2$$

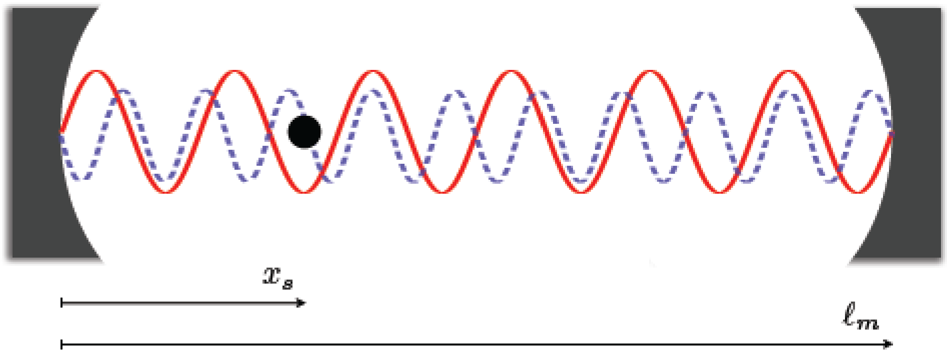
Gravitational wave changes the physical distance between the end mirrors:

$$L = \ell_m[1 + \frac{1}{2}h\cos(\omega t)]$$

and the distance from the input mirror to the sensor

$$X_S = x_s[1 + \frac{1}{2}h\cos(\omega t)]$$

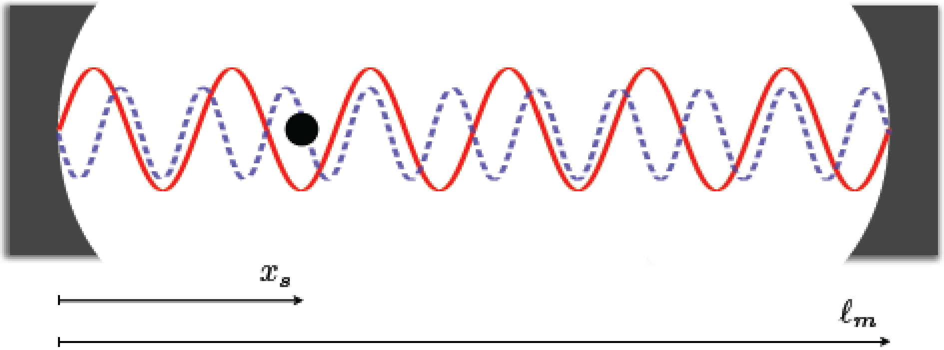
Gravitational Wave Detection



- Moving end mirror displaces physical position of anti-node relative to sensor

Anti-node shift (LL gauge) : $$\delta X_{anti-node} = \frac{1}{2}\ell_m h$$

Gravitational Wave Detection



- Moving end mirror displaces physical position of anti-node relative to sensor

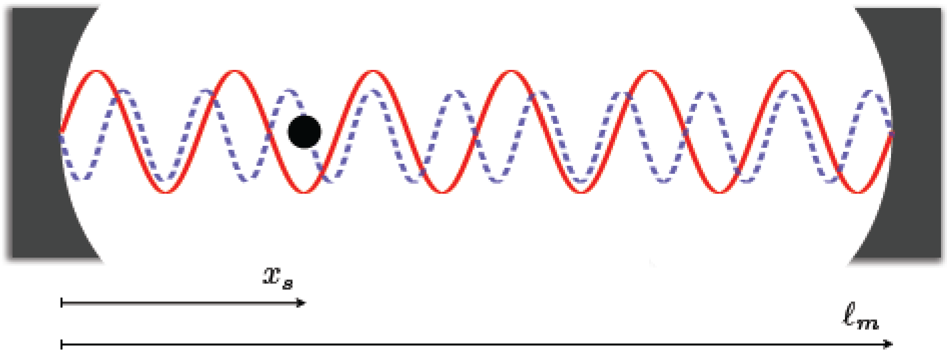
Anti-node shift (LL gauge) : $\delta X_{anti-node} = \frac{1}{2} \ell_m h$

Sphere shift (LL gauge) : $\delta X_S = \frac{1}{2} x_s h$

- Sensor position changes with respect to trap minimum:

$$\Delta X = \frac{1}{2}(x_s - \ell_m)h + O(h^2)$$

Gravitational Wave Detection



$$\Delta X = \frac{1}{2}(x_s - \ell_m)h + O(h^2)$$

$$\boxed{F_{gw} = -\frac{m\omega_{gw}^2}{2}(x_s - \ell_m)h_0 \cos(\omega_{gw}t + \phi)}$$

- Laser intensity changed to match trap frequency to GW frequency
- For a 100m cavity, $h \sim 10^{-22}$ Hz $^{-1/2}$ at high frequency
- Limited by thermal noise in sensor (not laser shot noise)

Tunable resonant detector

- Like Weber bar detectors with wide tunability

J. Weber (1969)

Aluminum bar

$$\omega_0 = 2\pi(1.6\,\text{kHz})$$

Thermal-noise limited strain sensitivity

Gas damping

$$h_{\min} = \frac{4}{\omega_0{}^2 l_m}\sqrt{\frac{k_B T_{eff}\gamma_g b}{m}}$$

Thermal-noise limited strain sensitivity

Photon-recoil heating

Gas damping

Limit from laser cooling

$$h_{\min} = \frac{4}{\omega_0{}^2 l_m} \sqrt{\frac{k_B T_{eff} \gamma_g b}{m} \left(1 + \frac{\gamma_{sc} + R_+}{n_i \gamma_g}\right)}$$

Thermal-noise limited strain sensitivity

Photon-recoil heating

Gas damping

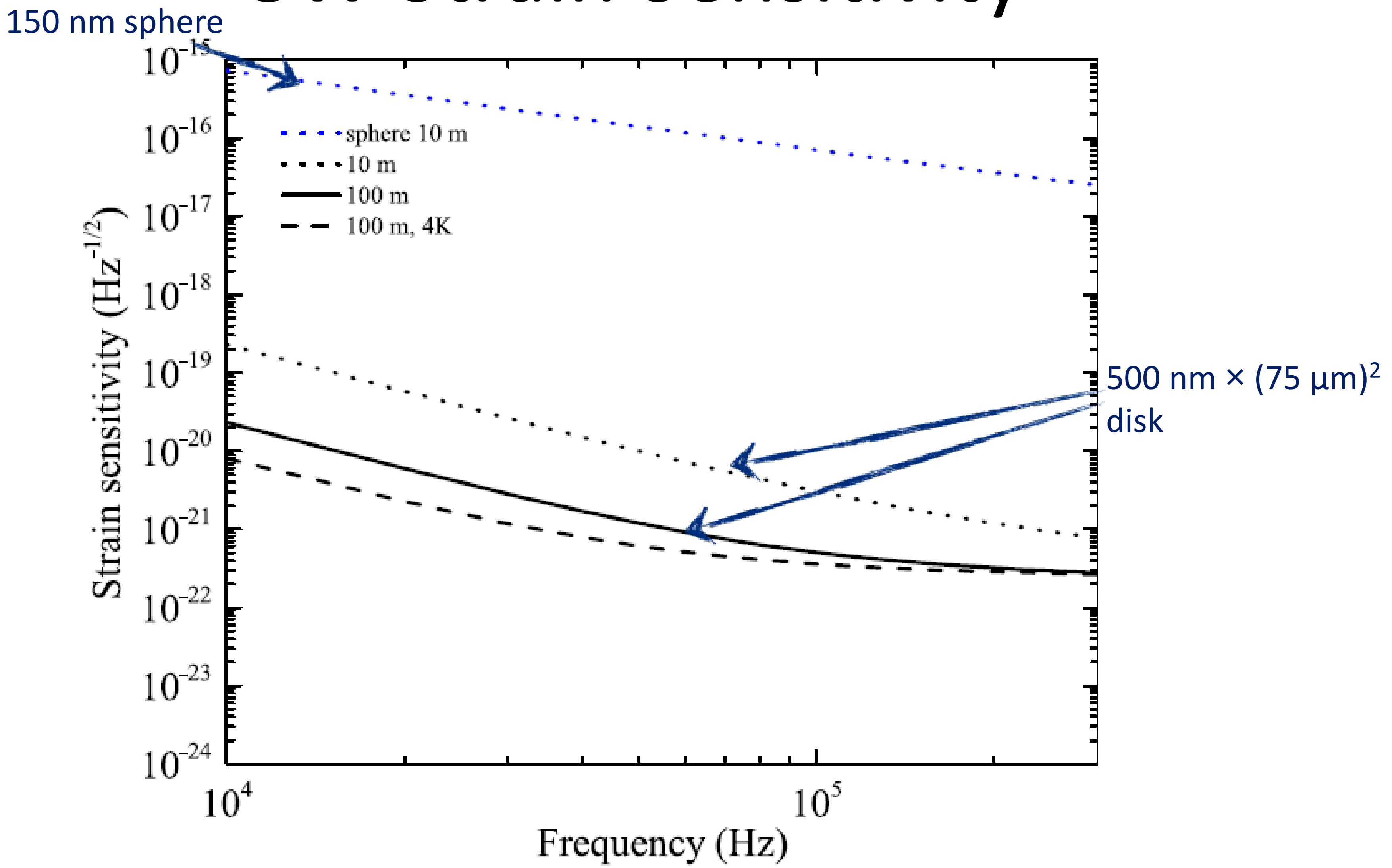
Limit from laser cooling

$$h_{\min} = \frac{4}{\omega_0{}^2 l_m} \sqrt{\frac{k_B T_{eff} \gamma_g b}{m} \left(1 + \frac{\gamma_{sc} + R_+}{n_i \gamma_g} \right)} H(\omega_0)$$

$$H(\omega_0) = \sqrt{1 + \left(\frac{2F}{\pi} \right)^2 \sin^2(\omega_0 l_m / c)}$$

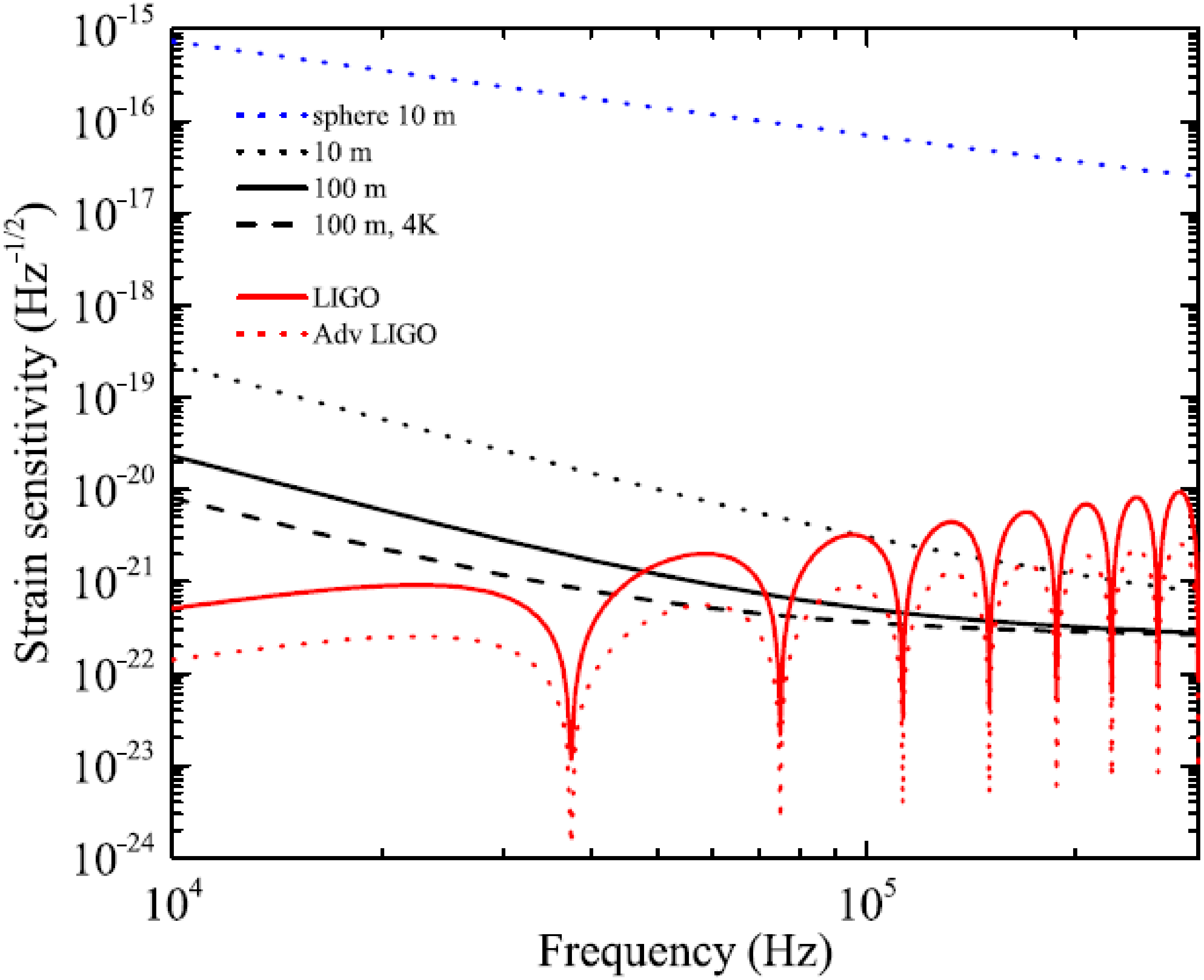
Cavity suppresses response above pole

GW Strain Sensitivity



Differing sensitivity between the two geometries
due to difference in mass and in light scattering properties

GW Strain Sensitivity



100 m

Size scale:

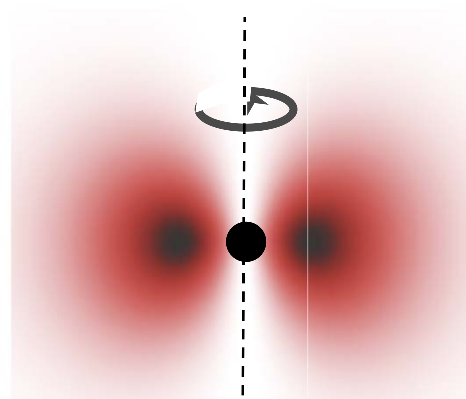
LIGO

GW sources at high-frequency

- Astrophysical Sources
  Natural upper bound on GW frequency
  inverse BH size ~ 30 kHz

- Beyond standard model physics
  - QCD Axion → Annihilation to gravitons in cloud around Black holes

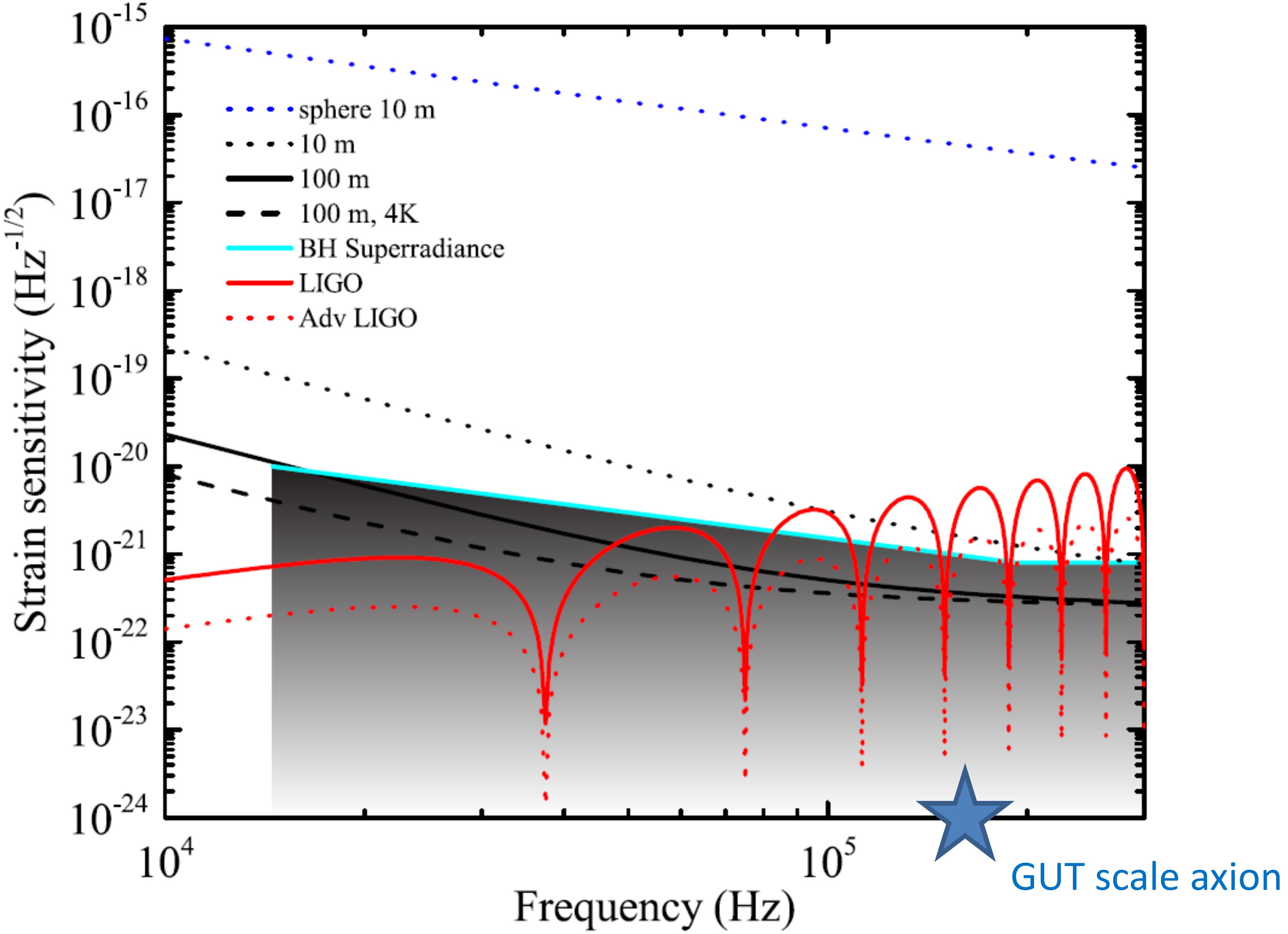
A. Arvanitaki et. al, PRD, 81, 123530 (2010)



Black hole superradiance

  - String cosmology R. Brustein et. al. Phys. Lett. B, 361, 45 (1995)
  - The unknown?

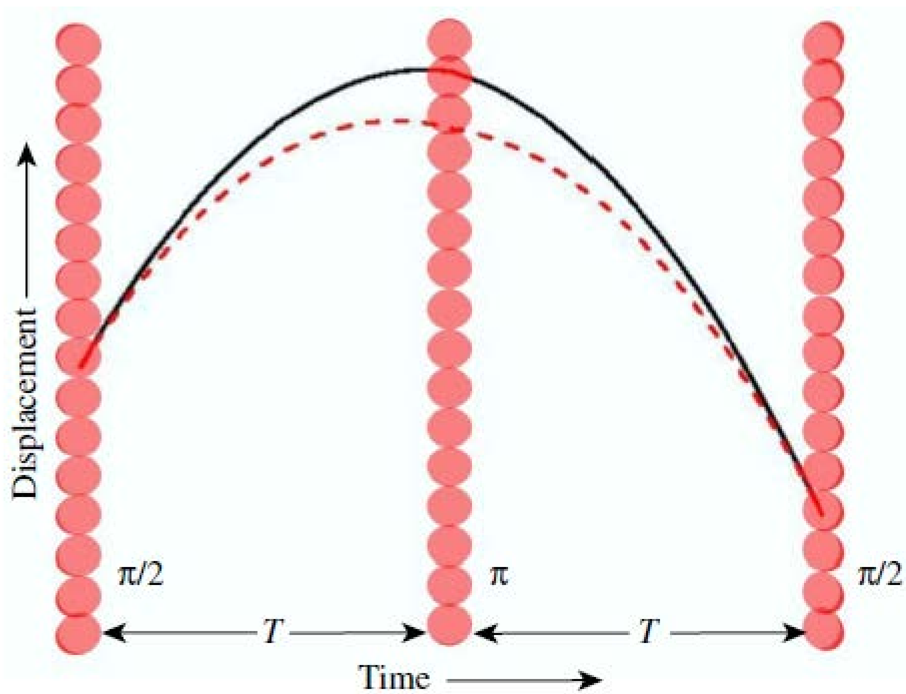
GW Strain Sensitivity



Distance to source 10 kpc

Matter-wave interferometers

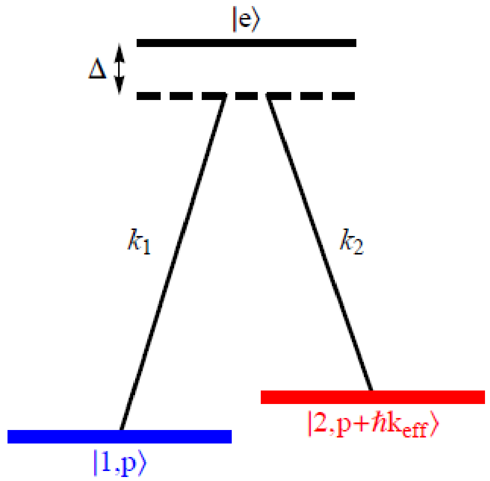
- Excellent for accelerometers, gyroscopes
- Example: atom interferometer

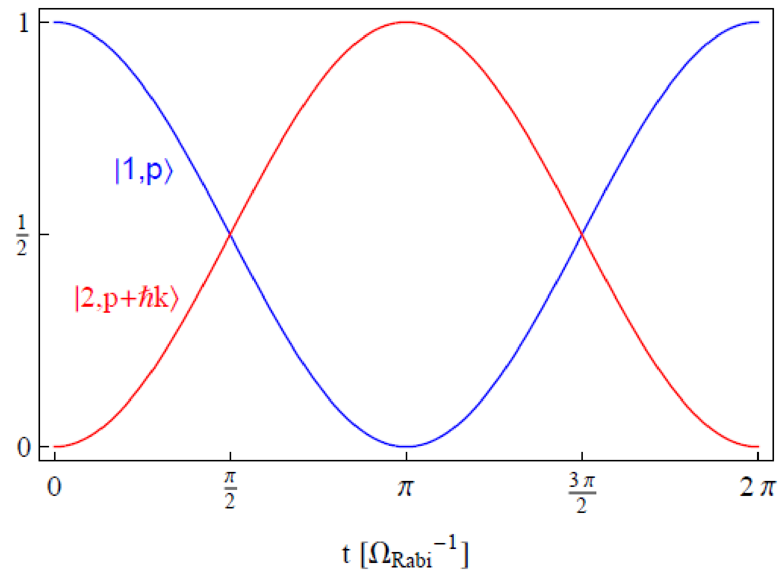


Signal: $\phi = kaT^2$

Sensitivity: $ng/\sqrt{Hz}$ or better

Atom interferometry with Raman transitions





Dimopoulos et.al., Arxiv:0806.2125

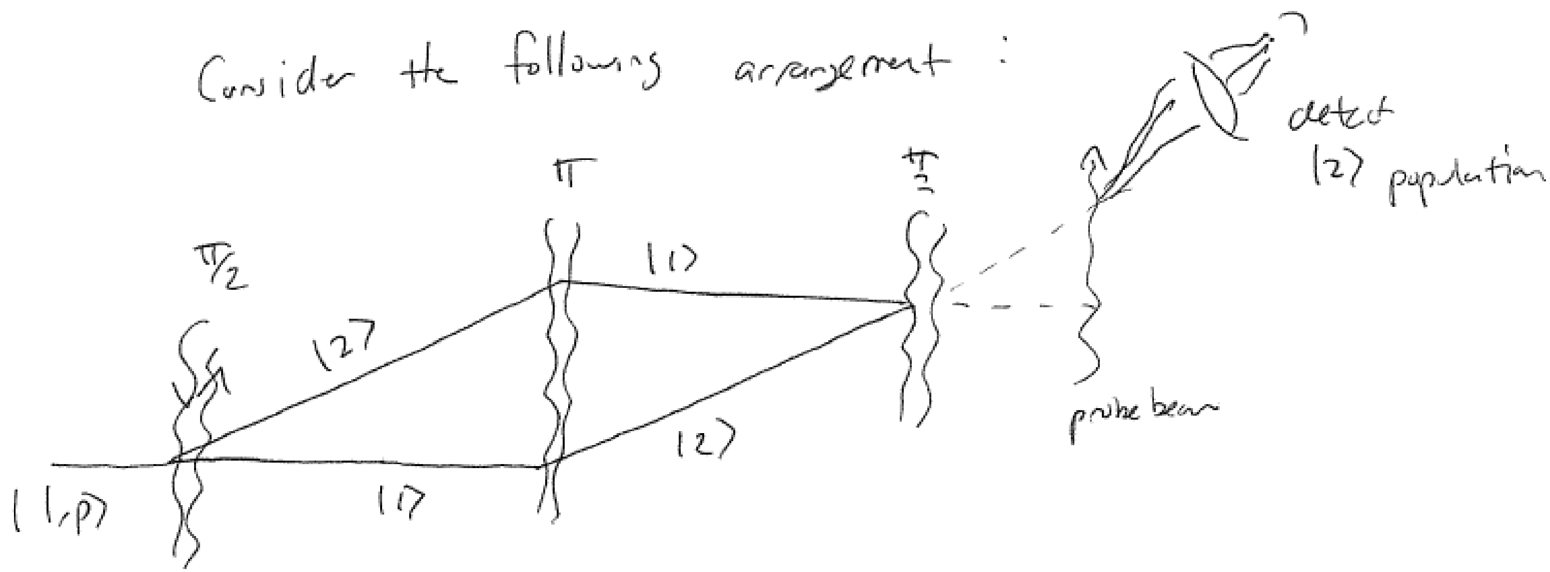
Beamspitters and Mirrors

e.g. a $\frac{\pi}{2}$ pulse will create equal superposition of $|1\rangle$ & $|2\rangle$ from initial state $|1\rangle$.

$$|\psi_0\rangle = |1, p\rangle$$

$$|\psi\rangle = \{|1, p\rangle + e^{i\phi_1}|2, p + 2\hbar k\rangle\}$$

Consider the following arrangement:



beamsplitter mirror beamsplitter

Phase shifts in Atom Inteferometry

Probability to be in state 1 after 2nd beamsplitter pulse: $[1+\cos(\Delta\phi)]/2$

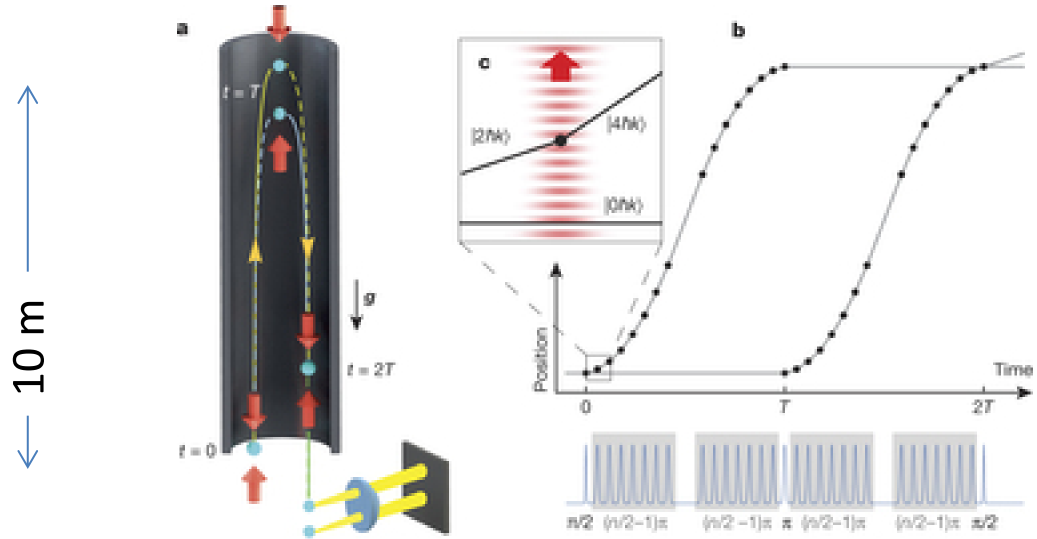
$$\Delta\phi = \Delta\phi_{\text{prop}} + \Delta\phi_{\text{laser}} + \Delta\phi_{\text{sep}}.$$

$$\Delta\phi_{prop} = \frac{1}{\hbar}\int (S_u - S_l) = \frac{1}{\hbar}\int (\frac{1}{2}mv_u^2 - mgz_u)dt - \frac{1}{\hbar}\int (\frac{1}{2}mv_l^2 - mgz_l)dt$$

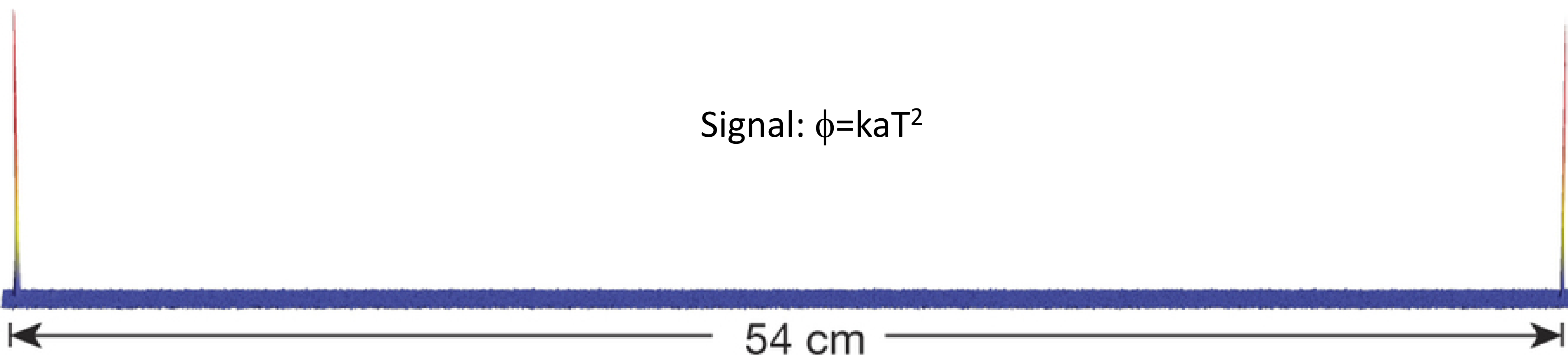
$$\Delta\phi_{laser} = k_{eff}(z_i - z_{1l} - z_{1u} + z_{2l})$$

$$\Delta\phi_{sep} = \frac{m}{2\hbar}(v_{2u} - v_R + v_{2l})(z_{2l} - z_{2u})$$

Quantum superpositions at half-meter scale!

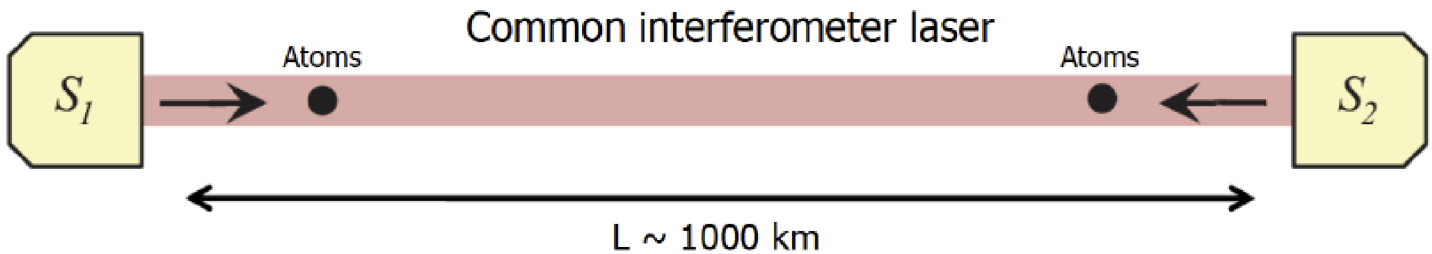


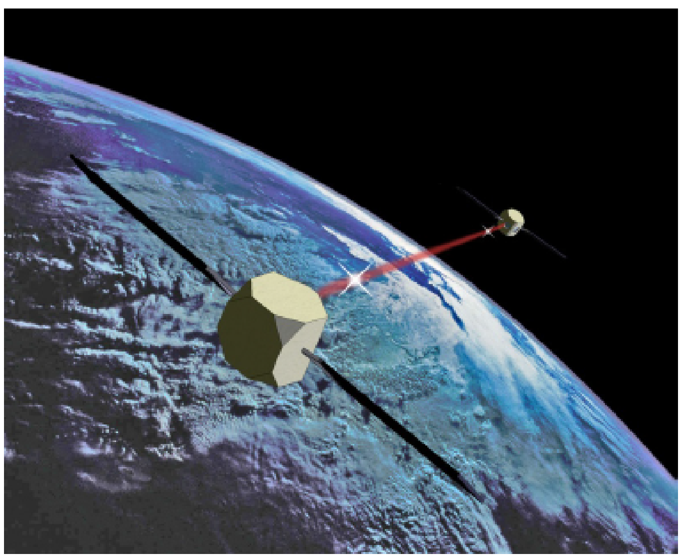
Signal: ϕ=kaT^2



T. Kovachy et.al, Nature 528, 530–533 (24 December 2015)

- Atom interferometers for gravitational wave detection

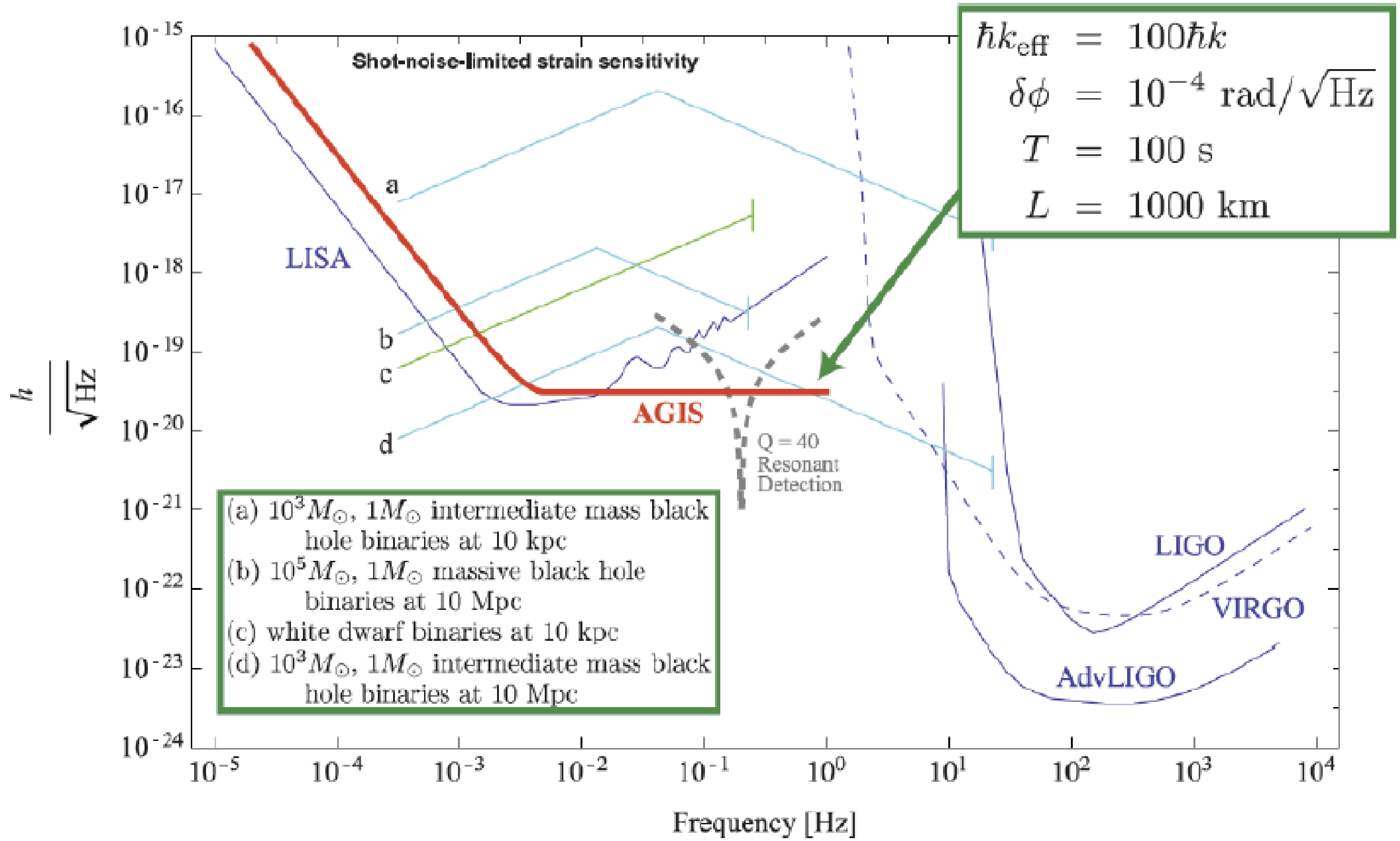




- Atoms are test masses
- Atom is **inertially decoupled** (freely falling); insensitive to vibration
- *However*: Lasers vibrate, are noisy
- **Differential measurement** with common laser helps suppress noise

https://www.nasa.gov/pdf/740776main_SaifSpringSymposium2013-1.pdf

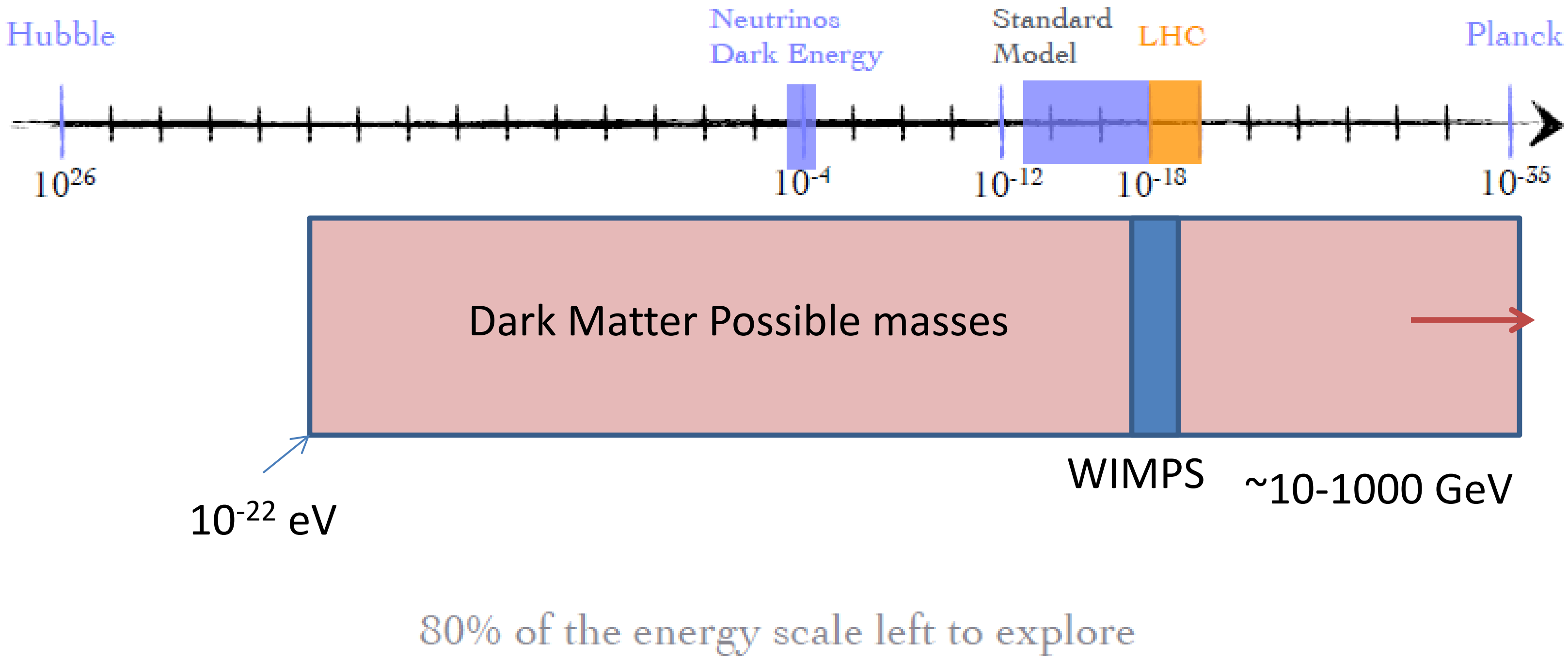
- Atom interferometers for gravitational wave detection



- Space-based atom GW detector could have science potential comparable to LISA

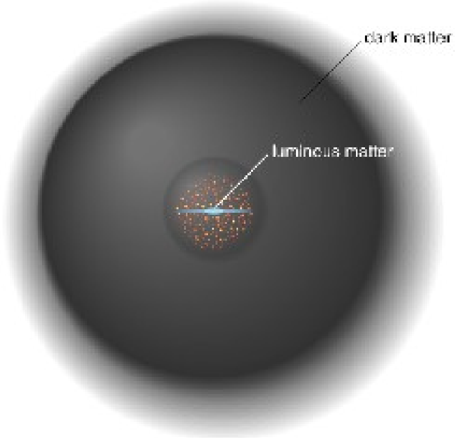
https://www.nasa.gov/pdf/740776main_SaifSpringSymposium2013-1.pdf

The length scales of the Universe

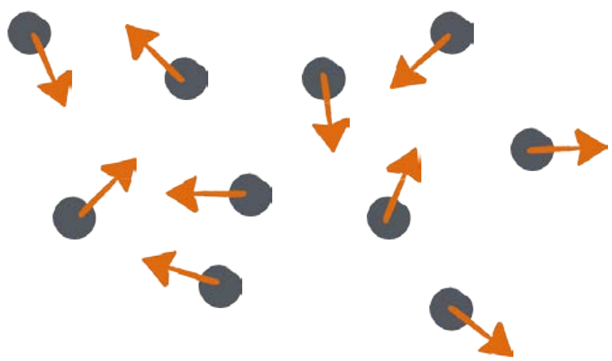


What If DM Is a Boson and Very Light?

Dark Matter Particles in the Galaxy



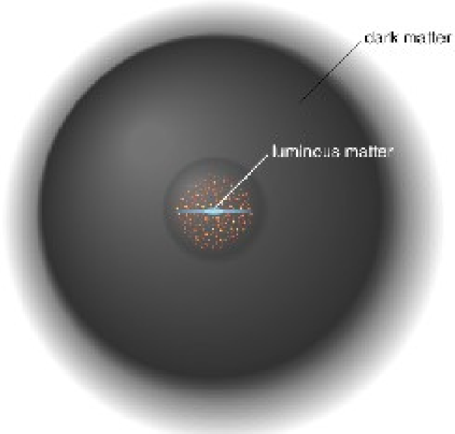
Usually we think of …



like a WIMP

What If DM Is a Boson and Very Light?

Dark Matter Particles in the Galaxy



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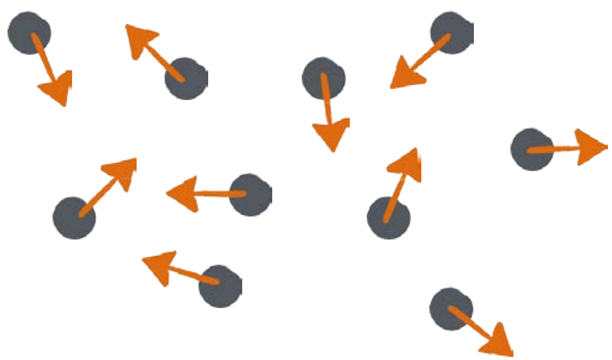
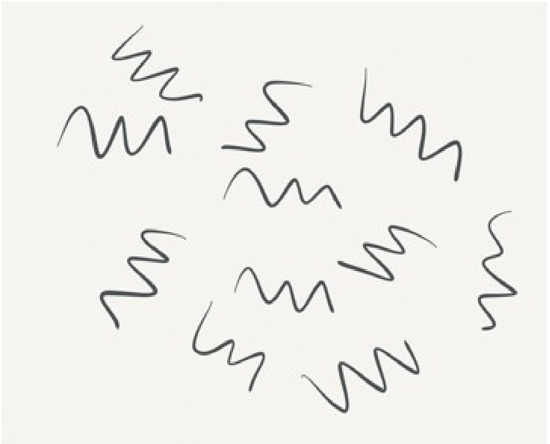


like a WIMP

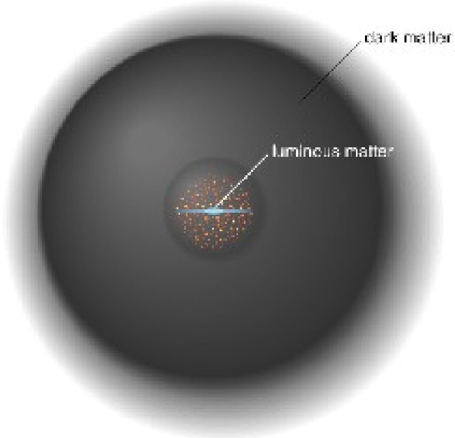
instead of…

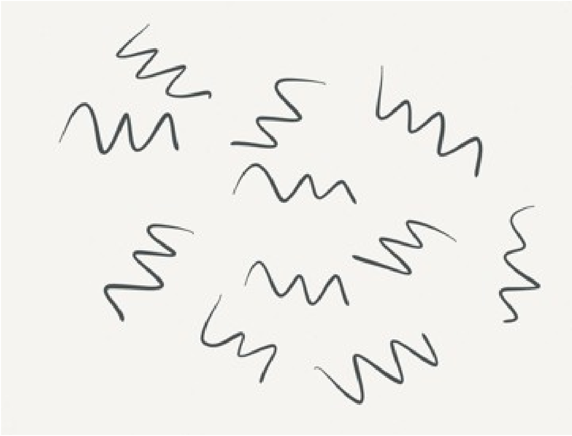


$$\lambda_{DM} = \frac{\hbar}{m_{DM} v}$$

What If DM Is a Boson and Very Light?

Dark Matter Particles in the Galaxy

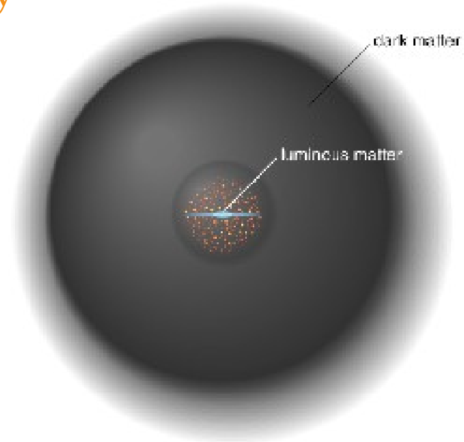


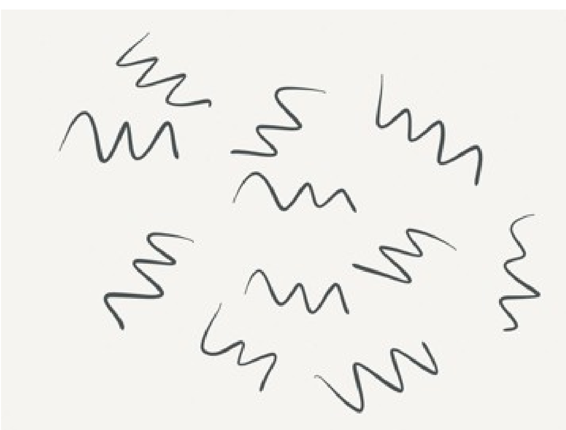


Decreasing DM Mass

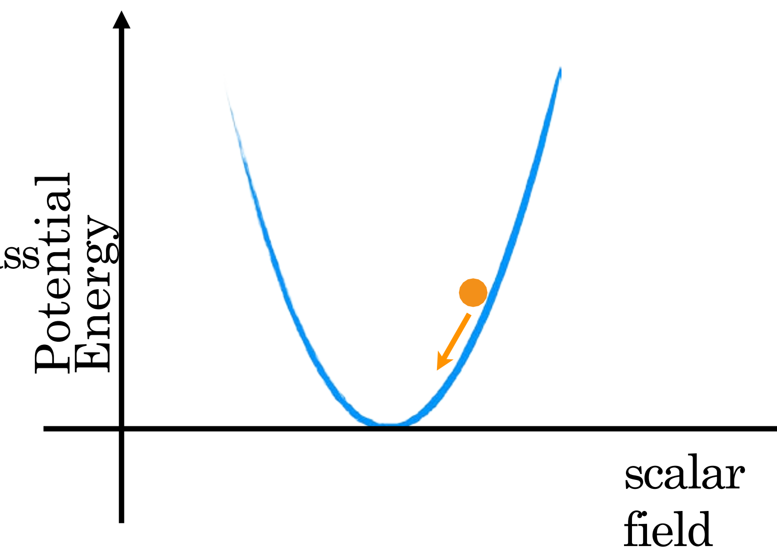
What If DM Is a Boson and Very Light?

Dark Matter Particles in the Galaxy





Decreasing DM Mass



Equivalent to a Scalar Wave

Going from DM particles to a DM "wave"

When $n_{DM} > \frac{1}{\lambda_{DM}^3}$

In our galaxy this happens when $m_{DM} < 1$ eV/c^2

we can talk about DM $\phi(x,t)$ and locally

$$\phi(t) \approx \phi_0 \cos \omega_{DM} t$$

with amplitude

$$\phi_0 \propto \frac{\sqrt{\text{DM density}}}{\text{DM mass}}$$

with frequency

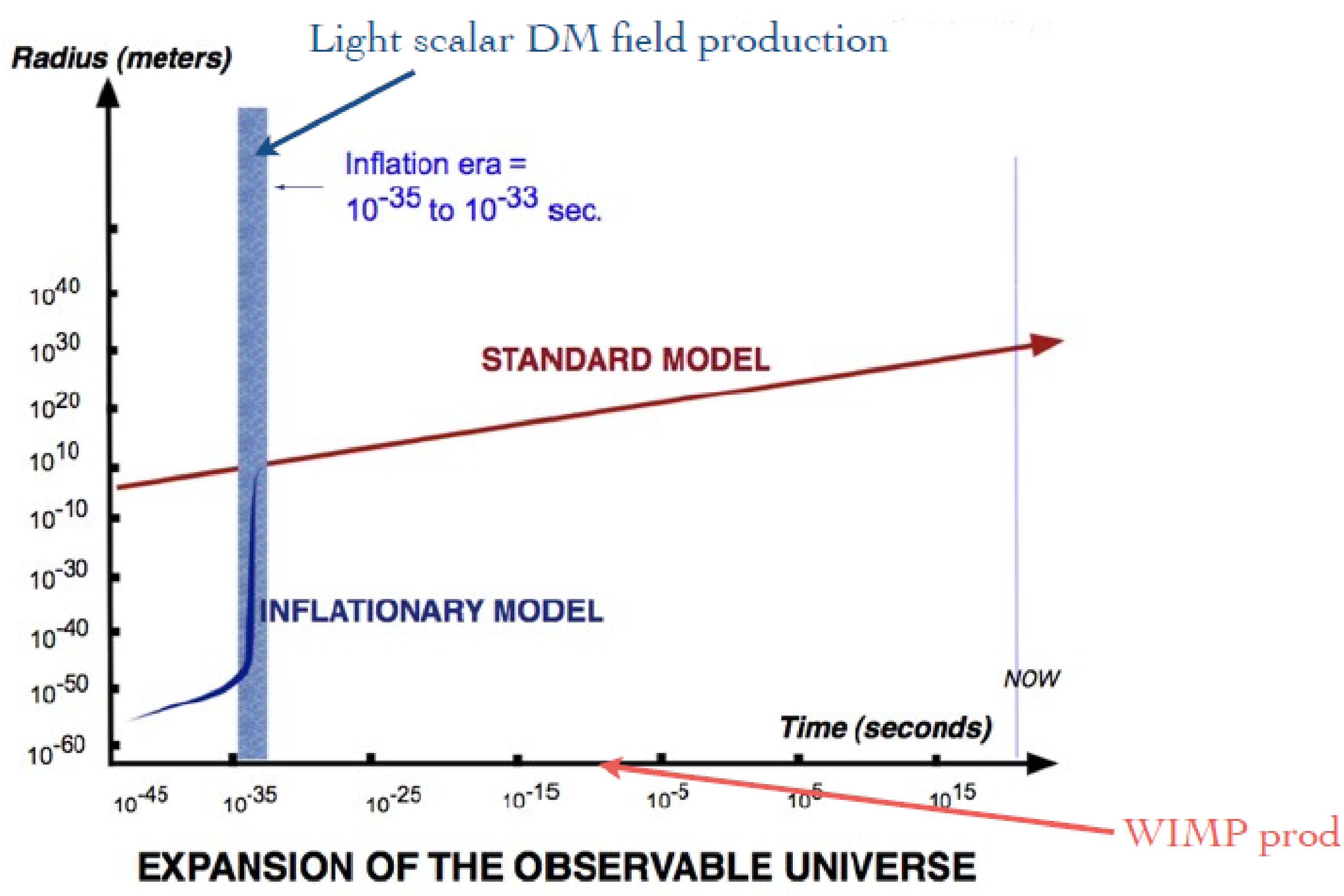
$$\omega_{DM} \approx \frac{m_{DM} c^2}{\hbar}$$

and finite coherence

$$\delta\omega_{DM} \approx \frac{m_{DM} v^2}{\hbar} = 10^{-6} \omega_{DM}$$

Scalar DM field production

- The "misalignment mechanism" during inflation

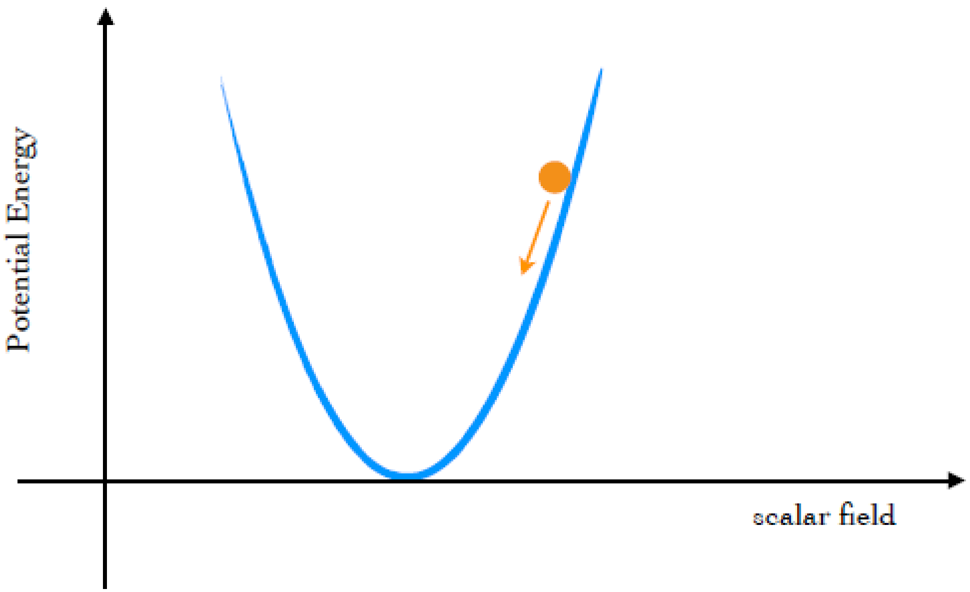


Light scalar Dark Matter

- Just like a harmonic oscillator

$$\ddot{\phi} + 3\ H\ \dot{\phi} + m_\phi^2 \phi = 0$$

$$\ddot{x} + \gamma\ \dot{x} + \omega^2 x = 0$$



Frozen when:
Hubble > m_ϕ

Oscillates when:
Hubble < m_ϕ

ρ_ϕ scales as a^{-3}
just like Dark Matter

Initial conditions set by inflation

Light scalar Dark Matter

- Dark Matter can exist at a variety of mass scales:

  $>10^{-22}$ eV (size of dwarf galaxies)

➢ Ultralight DM looks like coherent field rather than particle

$$\phi(\boldsymbol{r}, t) = \phi_0 \cos\left(\omega_\phi t - \boldsymbol{k}_\phi \cdot \boldsymbol{r} + \ldots\right).$$

$$\phi_0 = \hbar\sqrt{2\rho_{\mathrm{DM}}}/(m_\phi c)$$

Spatial and time variations of masses and fundamental constants

$$-\mathcal{L}_n^{\text{int}} = (\sqrt{\hbar c}\phi)^n \times \left(\frac{m_e \bar{\psi}_e \psi_e}{\Lambda_{n,e}^n} + \frac{m_p \bar{\psi}_p \psi_p}{\Lambda_{n,p}^n} - \frac{1}{4\Lambda_{n,\gamma}^n} F_{\mu\nu}^2 + \dots \right).$$

$$\frac{m_f^{\text{eff}}}{m_f} = 1 + \frac{(\sqrt{\hbar c}\phi(\mathbf{r},t))^n}{\Lambda_{n,f}^n},$$

$$\frac{\alpha^{\text{eff}}}{\alpha} \approx 1 + \frac{(\sqrt{\hbar c}\phi(\mathbf{r},t))^n}{\Lambda_{n,\gamma}^n}.$$

$$\phi(\boldsymbol{r},t) = \phi_0 \cos(\omega_\phi t - \boldsymbol{k}_\phi \cdot \boldsymbol{r} + \dots).$$

$$\phi_0 = \hbar\sqrt{2\rho_{\text{DM}}}/(m_\phi c)$$

Other properties of ultralight scalars

- Mediates new interactions in matter

  - Generates a fifth force in matter

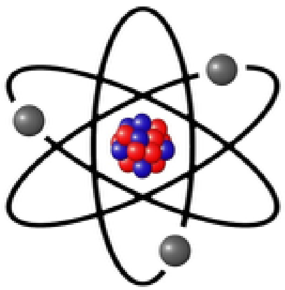
$$F \sim \frac{(d_i Q_i)^2}{4\pi M_{Pl}^2} \frac{M_1 M_2}{r^2} e^{-m_\phi r}$$

  - Generates Equivalence Principle violation

Techniques for sensing oscillating scalar DM

- Atomic clocks
- Bar detectors
- Torsion Balances
- Atom Interferometers

Oscillating Atomic and Nuclear Energy Splittings



- Optical Splittings

$$\Delta E_{\text{optical}} \propto \alpha_{EM}^2 m_e \sim \text{eV}$$

- Hyperfine Splittings

$$\Delta E_{\text{hyperfine}} \propto \Delta E_{\text{optical}} \alpha_{EM}^2 \left(\frac{m_e}{m_p}\right) \sim 10^{-6}\ \text{eV}$$

- Nuclear Splittings $\Delta E\ (m_p, \alpha_s, \alpha_{EM}) \sim 1\ \text{MeV}$

DM appears as a signature in atomic (or nuclear) clocks

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DM appears as a signature in atomic (or nuclear) clocks

Atomic Clocks

- Kept tuned to an atomic energy level splitting

Current definition of a second:
the duration of 9192631770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom

- Have shown stability of 1 part in 10^{18}

Compared to 1 part in 10^{13} expected by DM

- Have won several Nobel prizes in the past 20 years

How does and Atomic Clock Work?

Keep a laser tuned to a long-lived (> minutes) atomic transition

How well can I measure the frequency of the laser when tuned to the atom?

$$\frac{\delta f}{f} \sim \frac{\Gamma_{\mathrm{atom}}}{f} \frac{1}{\sqrt{N_{\mathrm{atoms}}}} \sqrt{\frac{\tau_{\mathrm{cycling}}}{t_{\mathrm{experiment}}}}$$

How do you take the measurements?

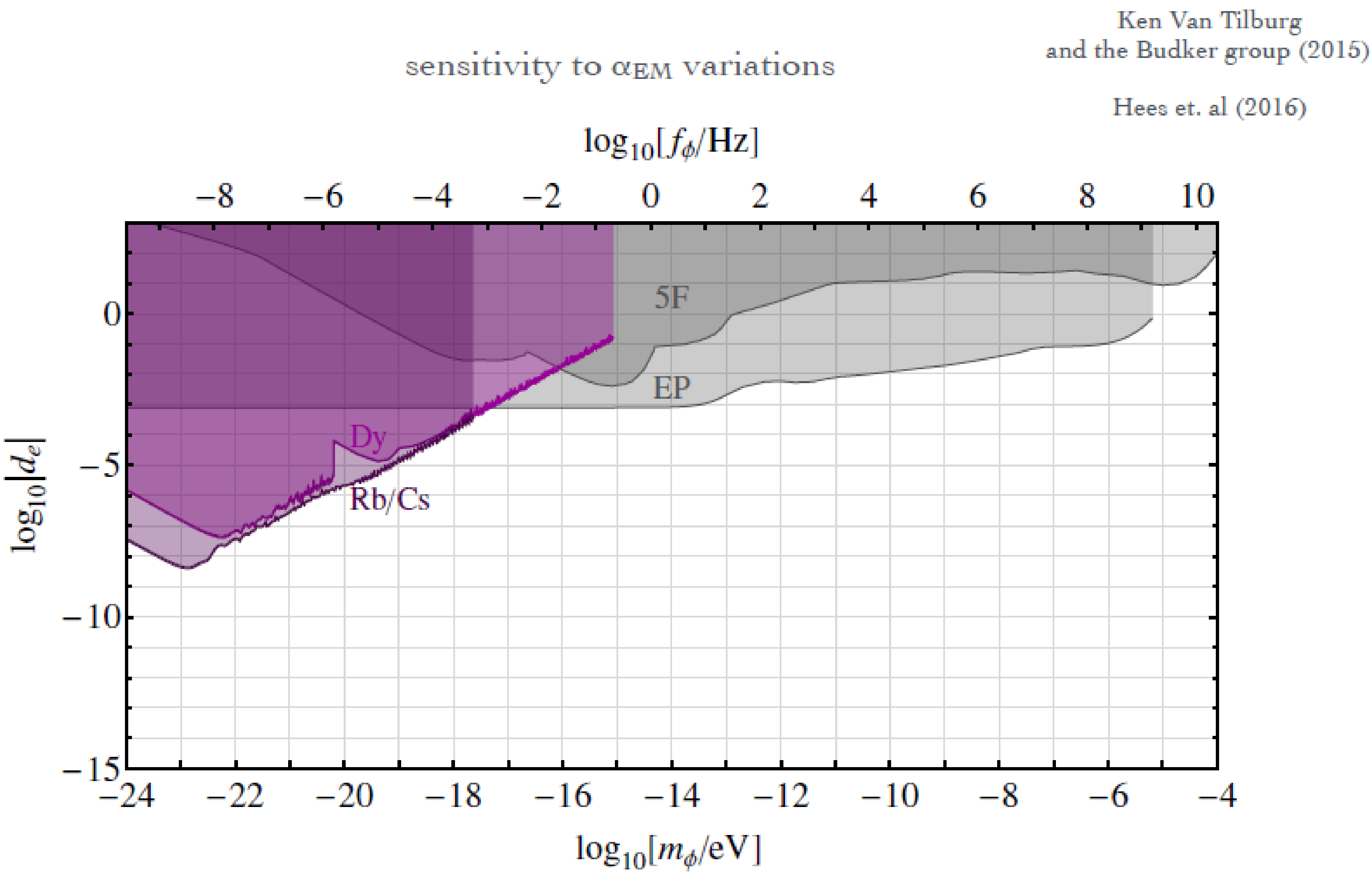
- Observe two clocks every $\tau_{cycling}$ to remove systematics
- Calculate ratio of frequencies which depends on Dark Matter
- Take Fourier transform to look for oscillations with period longer than $\tau_{cycling}$

Atomic Clock DM searches are broadband searches

What type of comparisons can we do?

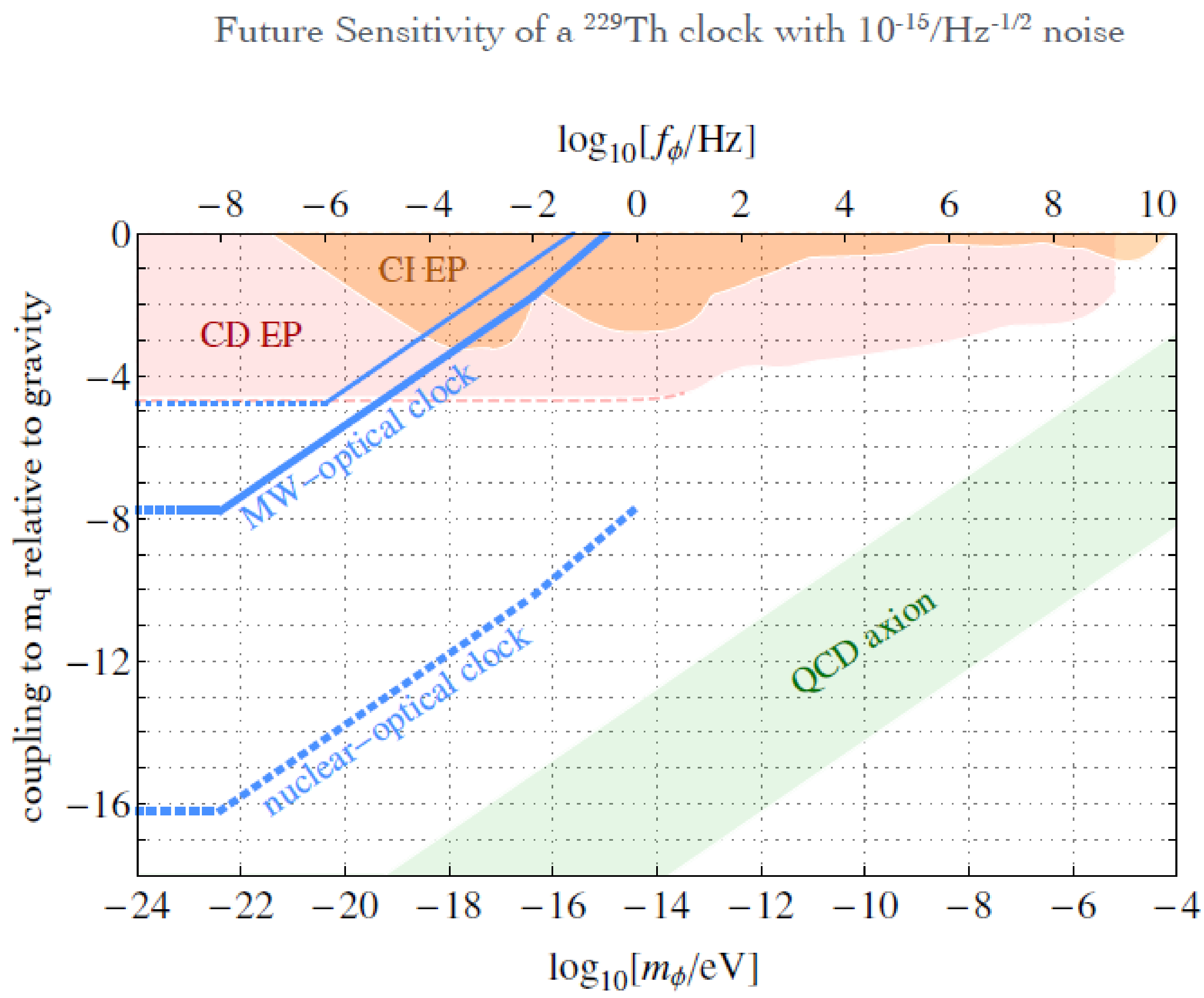
- Hyperfine to Optical transitions
  - Sensitive to m_e, m_q, and α_s (less to α_{EM})
- Optical to Optical transitions
  - Sensitive to α_{EM}
- Nuclear to Optical transitions
  - Sensitive to m_e, α_{EM}, m_q, and α_s

The Dy isotope and Rb/Cs Clock Comparison



Analysis performed with existing data

Projected - Future Clock Comparisons



Detecting oscillating interatomic distances

- The Bohr radius changes with DM
  - $r_B \sim (\alpha\, m_e)^{-1}$

$$\frac{\delta r_B}{r_B} = -\left(\frac{\delta\alpha_{EM}}{\alpha_{EM}} + \frac{\delta m_e}{m_e}\right)$$

- The size of solids changes with DM
  - $L \sim N\, (\alpha\, m_e)^{-1}$

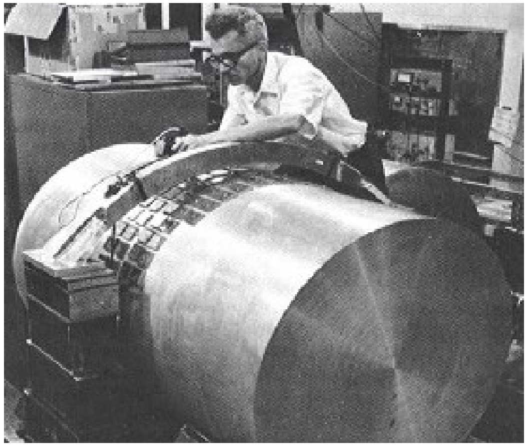
$$\frac{\delta L}{L} = -\left(\frac{\delta\alpha_{EM}}{\alpha_{EM}} + \frac{\delta m_e}{m_e}\right)$$

Need macroscopic objects to get a detectable signal

A. Arvanitaki, K. Van Tilburg, S. Dimopoulos (2015)

Resonant-Mass Detectors

- In the 1960's: The Weber Bar

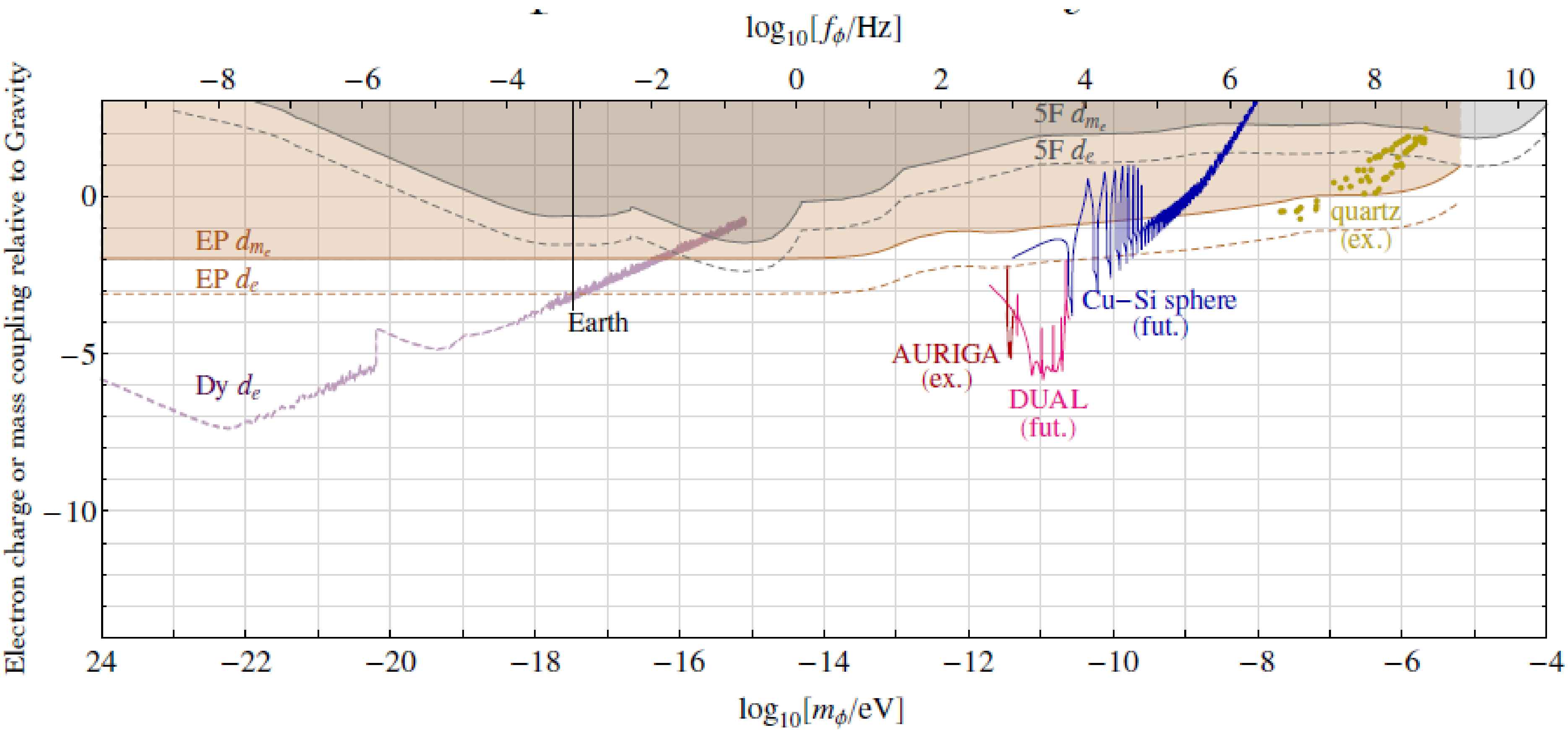


Strain sensitivity h~10^{-17}

- Today: AURIGA, NAUTILUS, MiniGrail

Strain sensitivity h~10^{-23}

Experimental Sensitivity



A. Arvanitaki, K. Van Tilburg, S. Dimopoulos (2015)

Ultralight DM with accelerometers

Dark Matter Direct Detection with Accelerometers

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Spin	Type	Operator	Interaction	Oscillating DM Effects	Searches
0	scalar	$\phi\, h^\dagger h$, $\phi\, \mathcal{O}_{\rm SM}$	Higgs portal / dilaton	m_e, m_p, α variation	Atomic clocks [51]
				acceleration	⋆
	pseudo-scalar	$a\, G^{\mu\nu} \tilde{G}_{\mu\nu}$	axion-QCD	nucleon EDM	CASPEr [18]
		$a\, F^{\mu\nu} \tilde{F}_{\mu\nu}$	axion-E&M	EMF along B field	ADMX [13]
		$(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$	axion-fermion	spin torque	CASPEr [18]
1	vector	$A'_\mu \bar{\psi}\gamma^\mu\psi$	minimally coupled	acceleration	⋆
		$F'_{\mu\nu} F^{\mu\nu}$	vector–photon mixing	EMF in vacuum	DM Radio [32], ADMX
		$F'_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$	dipole operator	spin torque	CASPEr [18]
	axial-vector	$A'_\mu \bar{\psi}\gamma^\mu\gamma^5\psi$	minimally coupled	spin torque	CASPEr [18]
2 (?)	tensor	$h'_{\mu\nu} T^{\mu\nu}$ (?)	gravity-like	grav. wave-like	grav. wave detectors?

Arxiv: 1512.06165(2015)

Dark Matter induced acceleration

Consider Higgs portal DM:

$$\mathcal{L} \supset \frac{b\phi}{m_h^2}\langle h\rangle g_{h\psi\psi}\bar{\psi}\psi$$

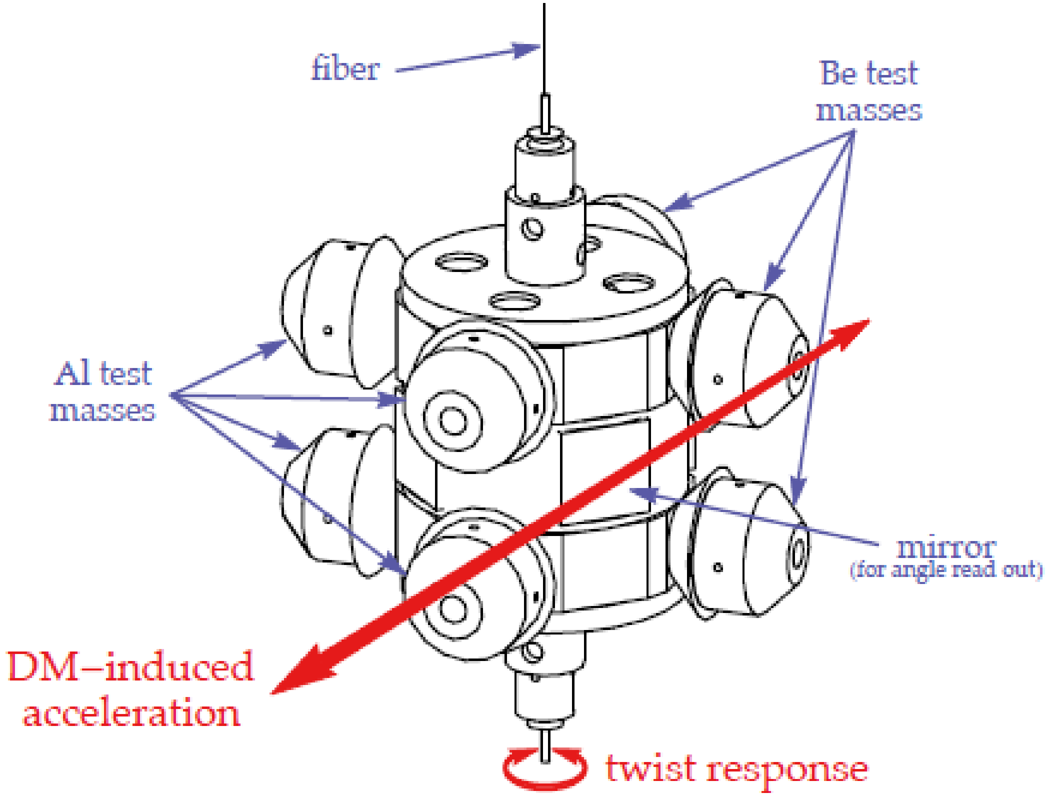
Force on matter due to: $\nabla\phi$

-Different materials with different composition, different binding energies etc. experience relative accelerations due to DM field
-Violates EP
-In direction of grad phi (changes over times longer than coherence time)

Arxiv: 1512.06165(2015)

Torsion balance tests

- Tests of Equivalence principle

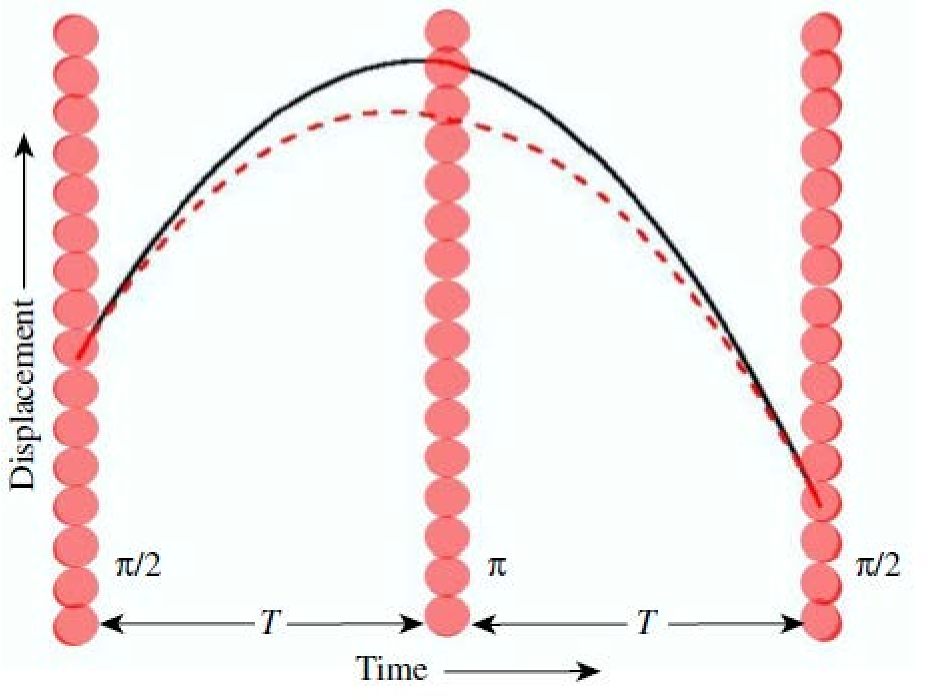


Arxiv: 1512.06165(2015)

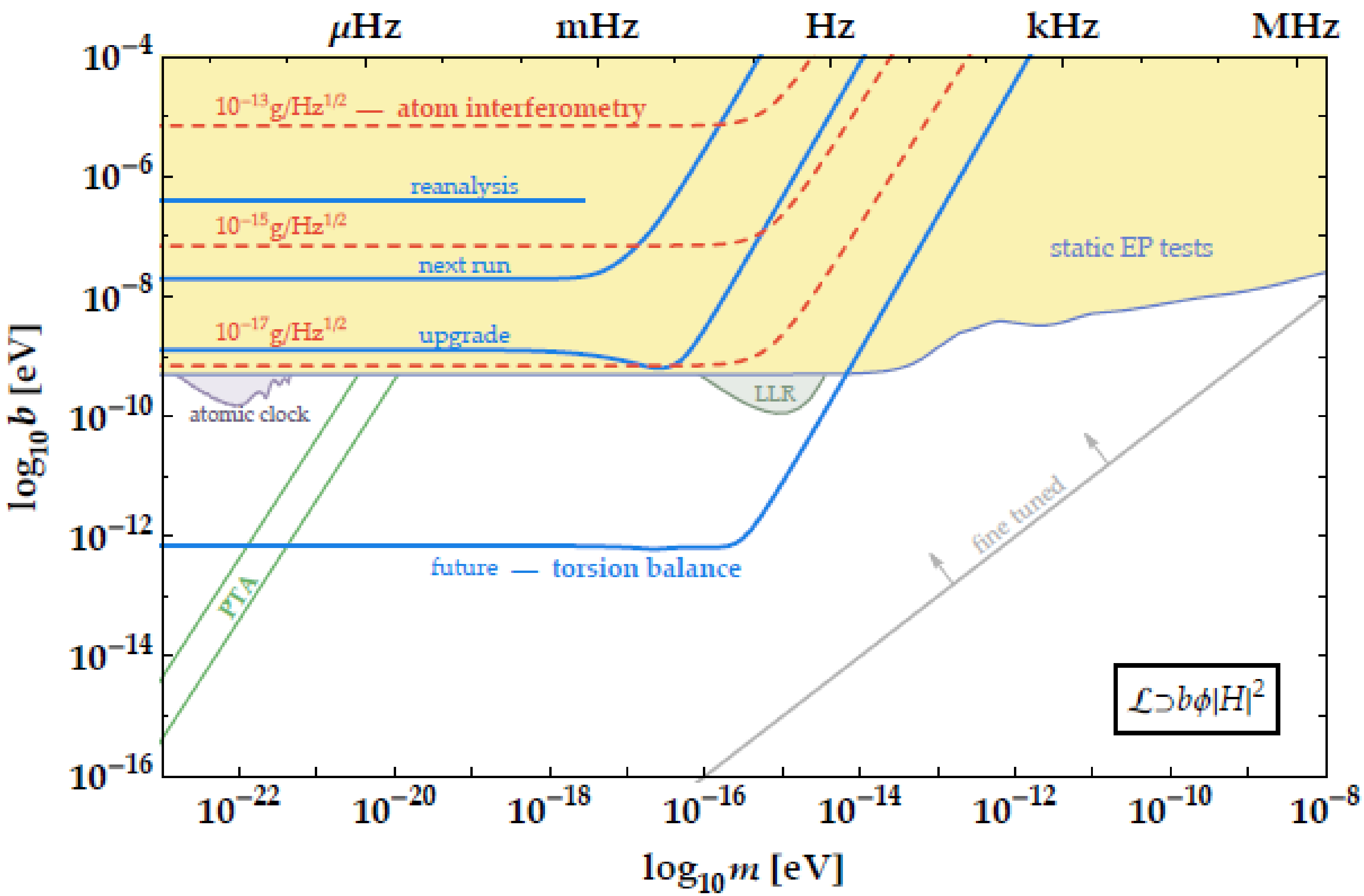
Atomic Interferometers

- Also can measure force due to $\nabla\phi$

  e.g. for different atomic isotopes

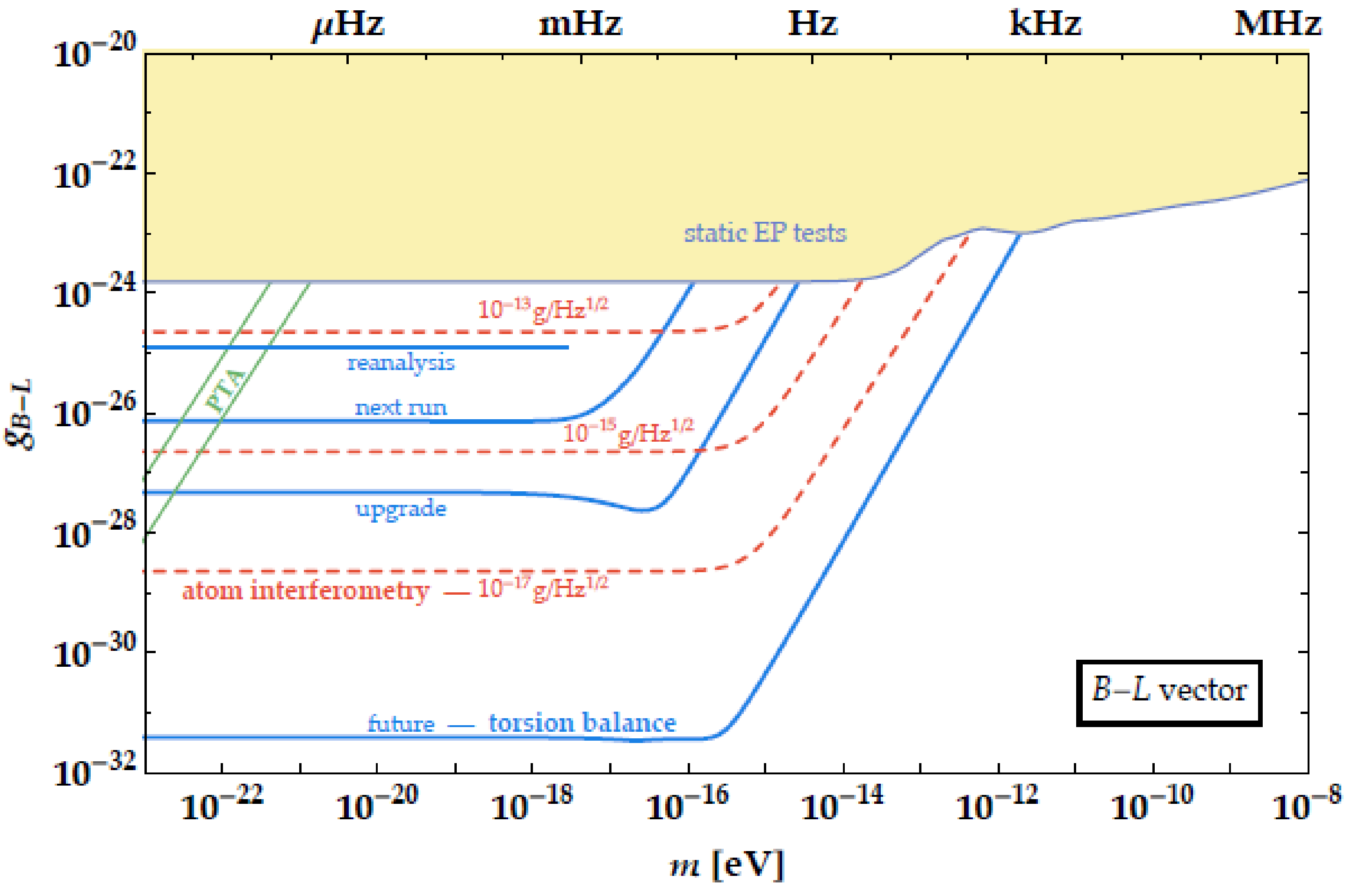


Higgs portal



Arxiv: 1512.06165(2015)

Vector (B-L) portal



Arxiv: 1512.06165(2015)

Time-varying acceleration of earth and masses of atoms

$$\frac{\Delta g_n}{g} = \frac{\Delta M_\oplus}{M_\oplus}$$
$$= \left(\frac{2\rho_{\mathrm{DM}}\hbar^3}{m_\phi^2 c \Lambda_n^2}\right)^{n/2} \times \frac{1}{2^{(n-1)}} \cos(n\omega_\phi t - n\boldsymbol{k}_\phi \cdot \boldsymbol{r} + \ldots)$$

$$g(t) = g_0[1 + \delta_g \cos(\omega t + \theta_0)],$$

$$m(t) = m_0[1 + \delta_m \cos(\omega t + \theta_0)]$$

Mach-Zehnder Atom interferometer

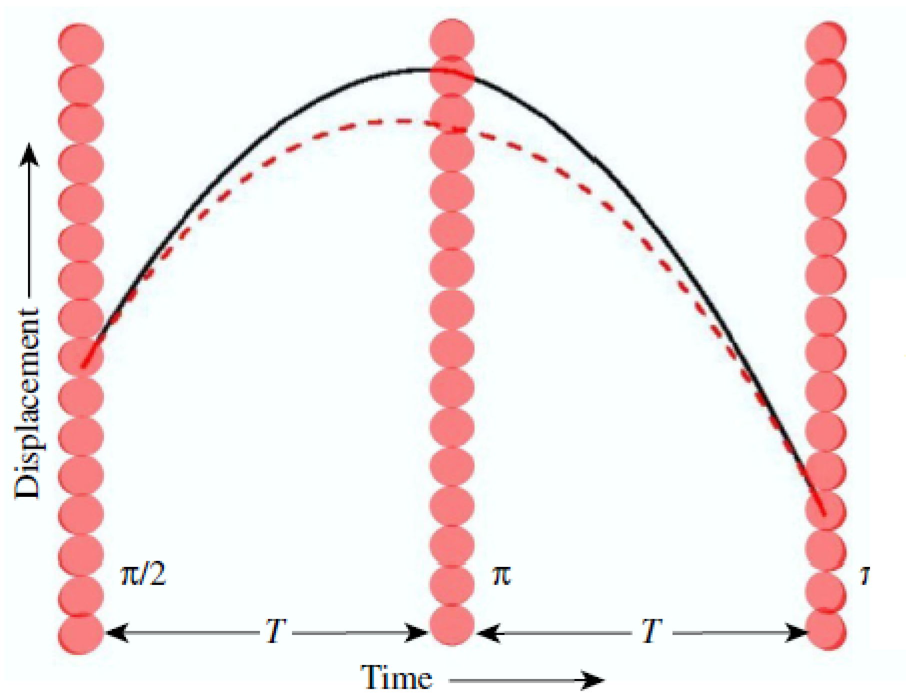
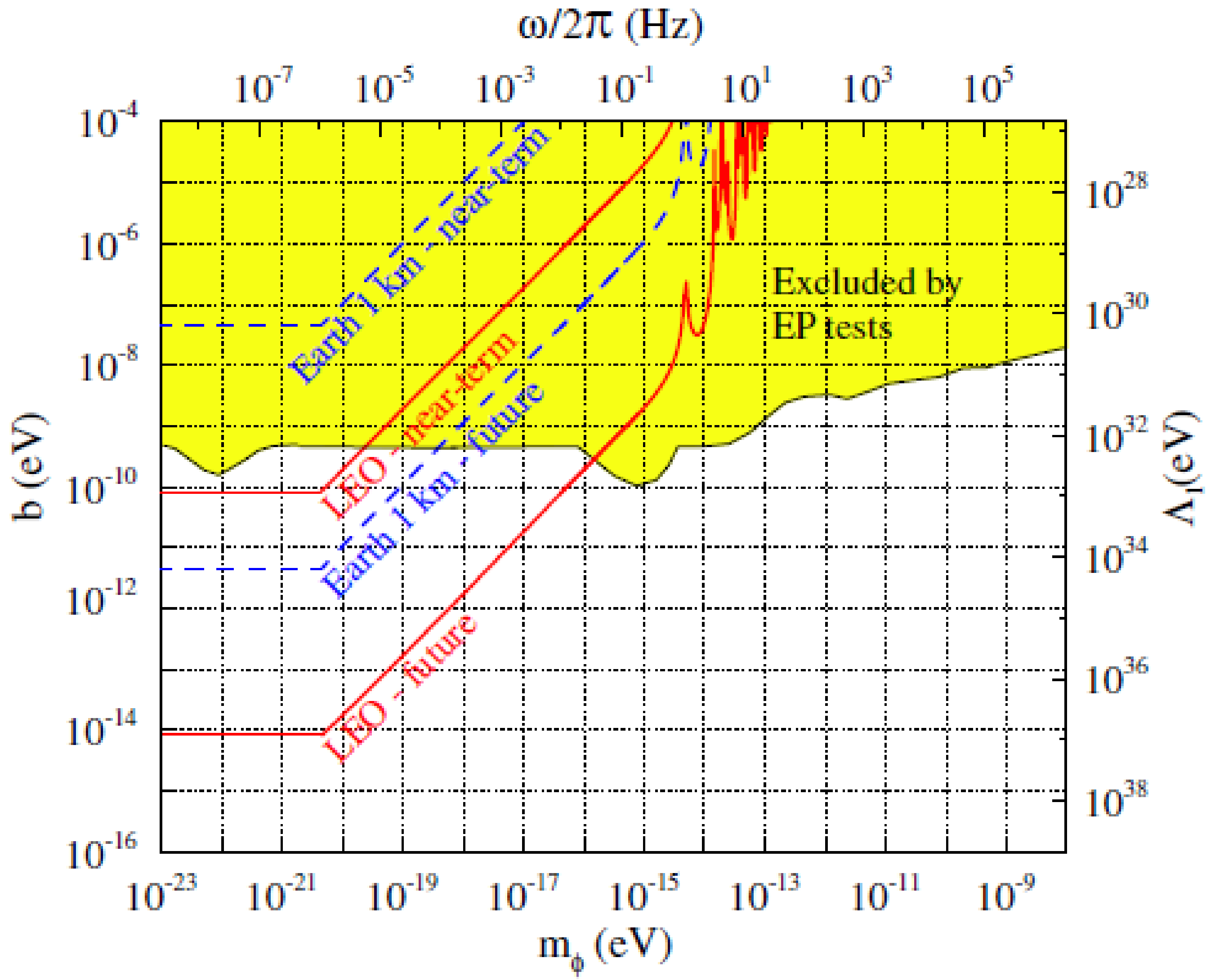


FIG. 1. Spacetime diagram for the Mach-Zehnder atom interferometer. Atomic wave packets are split into a superposition state with differing momenta, reflected with a mirror (π) pulse, and recombined with a final beam splitter pulse. The final population in state $|1>$ is given by $[1+\cos(\Delta\phi)]/2$.

$$v_R(t) = \hbar k_{\mathrm{eff}}/m(t) \approx \frac{\hbar k_{\mathrm{eff}}}{m_0}[1 - \delta_m \cos(\omega t + \theta_0)].$$

$$\begin{aligned}\Delta\phi = &-k_{\mathrm{eff}} g_0 T^2 - \delta_m \frac{2 g_0 k_{\mathrm{eff}} T}{\omega}(\sin \omega T - \sin 2\omega T) \\ &+ [\delta_g + 2\delta_m] \frac{g_0 k_{\mathrm{eff}}}{\omega^2}(1 - 2\cos \omega T + \cos 2\omega T) \\ &+ \delta_m \left(\frac{k_{\mathrm{eff}}(v_L + v_R/2)}{\omega}\right)(2 \sin \omega T - \sin 2\omega T)\end{aligned}$$

Higgs portal search



AG and Andrei Derevianko, *Phys. Rev. Lett. 117, 261301 (2016).*

Summary

- New AMO techniques (levitated particles, atom interferometers) could enable search for GWs at higher (and lower) frequency
- Variety of methods to search for oscillating ultralight dark matter

-time variation of constants (clocks)

-length changes in materials (resonant bars)

-accelerometers (torsion balances, atomic interferometers)

(next lectures) Axions, spin-dependent new forces