DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

GORDON AND BETTY MOORE FOUNDATION

Fermilab

Gravitational Wave Astronomy

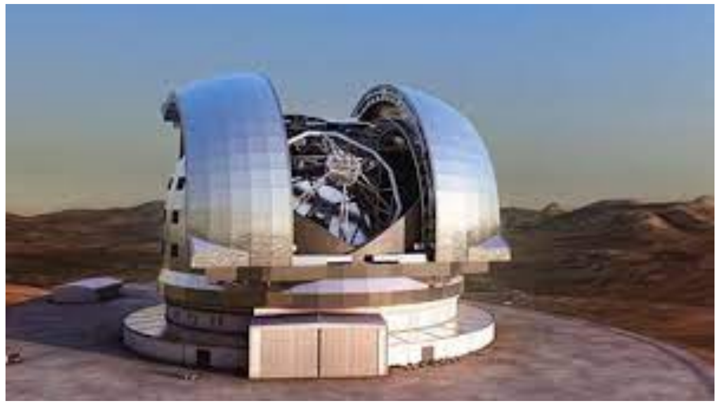
New Eyes into the Universe

Surjeet Rajendran,
The Johns Hopkins University

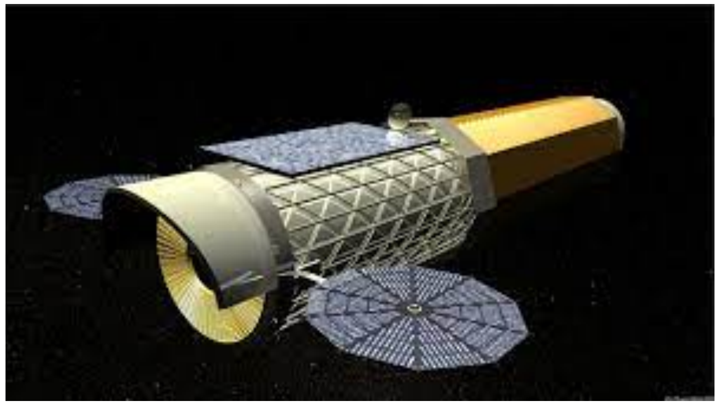
The Universe

Observed Universe Only Through Light.

Pulsar



Supernova

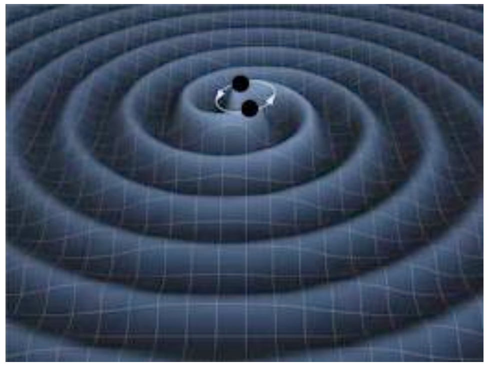


Black Holes

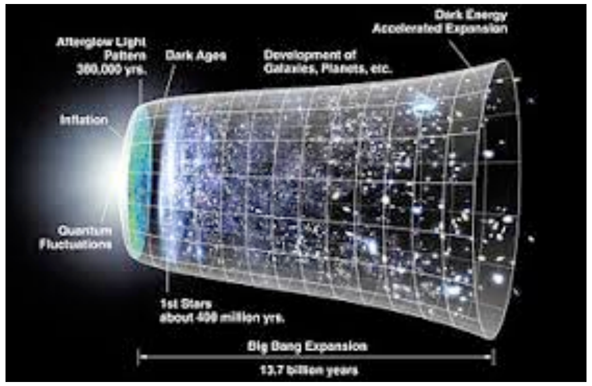
Gamma Ray
Burst

Discovered new phenomena in every part of electromagnetic spectrum

Are there objects in the universe that do not emit light?



How can we study them?



Black Holes

Gravity!

Big Bang

Objects are too far away for direct gravitational effect - need a wave tied to gravity

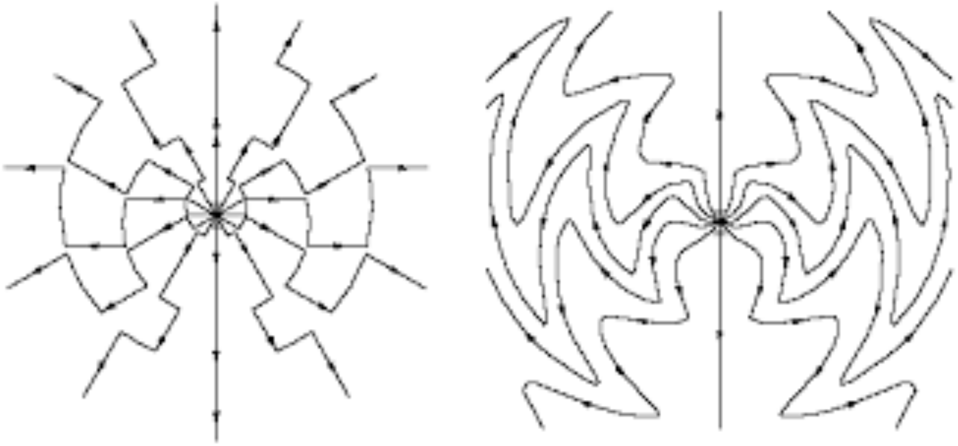
Waves

Why do they exist?

Throw a stone in a pool of water.

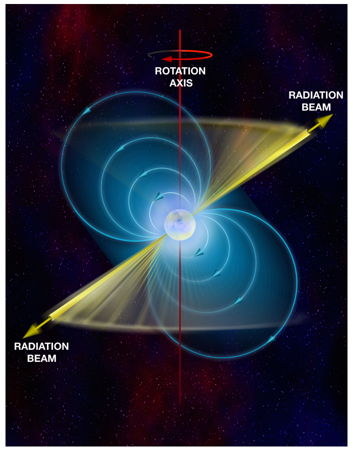
Waves emerge, propagating the disturbance.

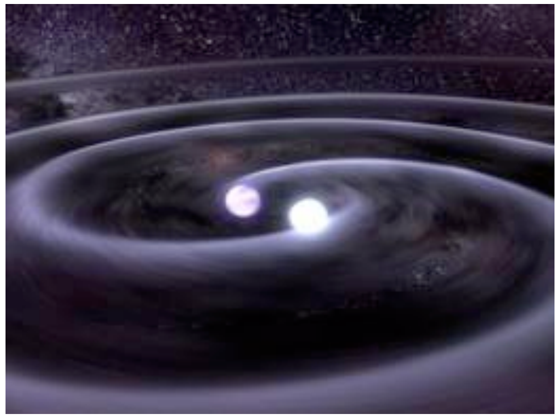
How do we detect them?



Accelerating charges.
Electric field is disturbed.

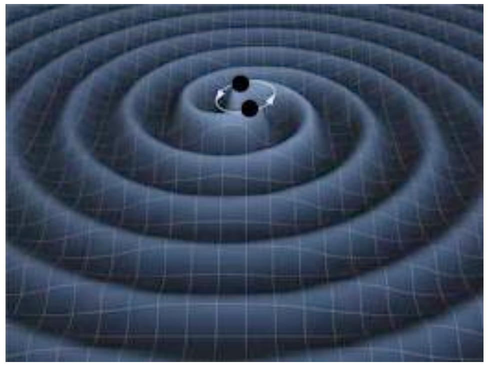
Waves propagate - this is light!





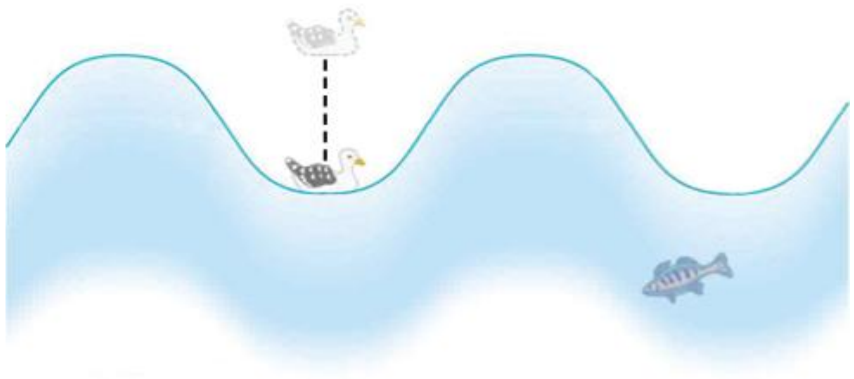
Stars move around.
Disturbs gravity.

Gravitational Waves.



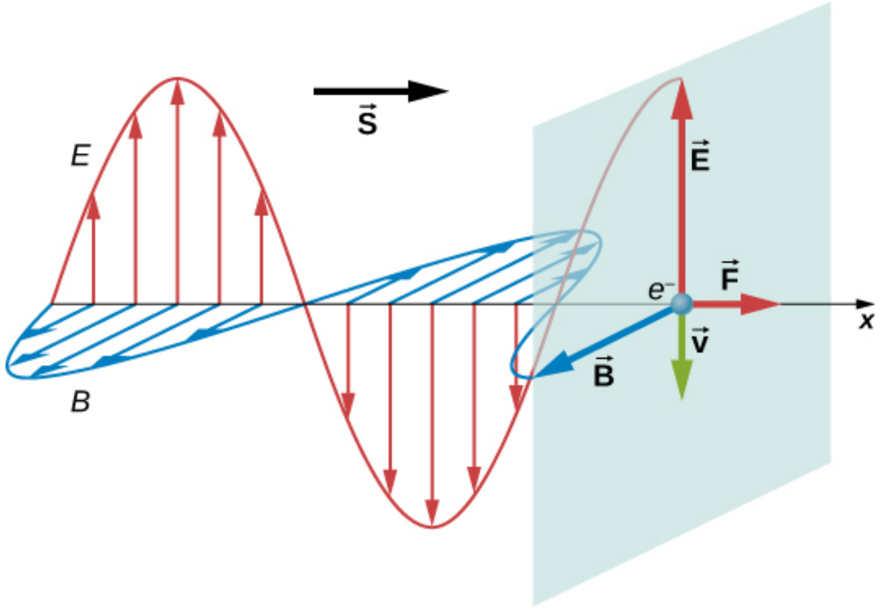
Detection

What do the waves do?



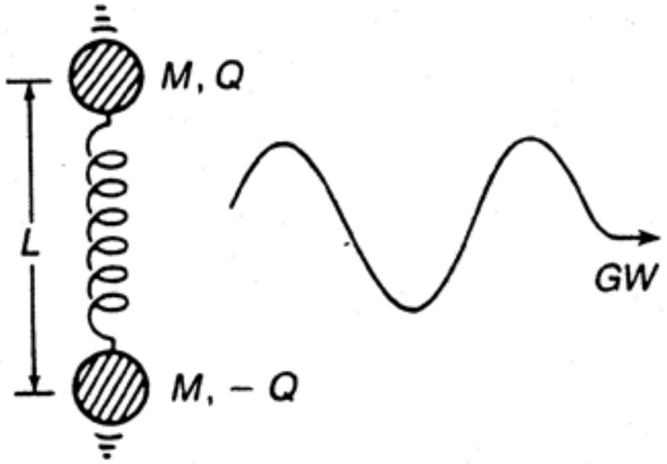
Objects move up and down.

Detect this motion



Electrons accelerate along electric field

Detect Current

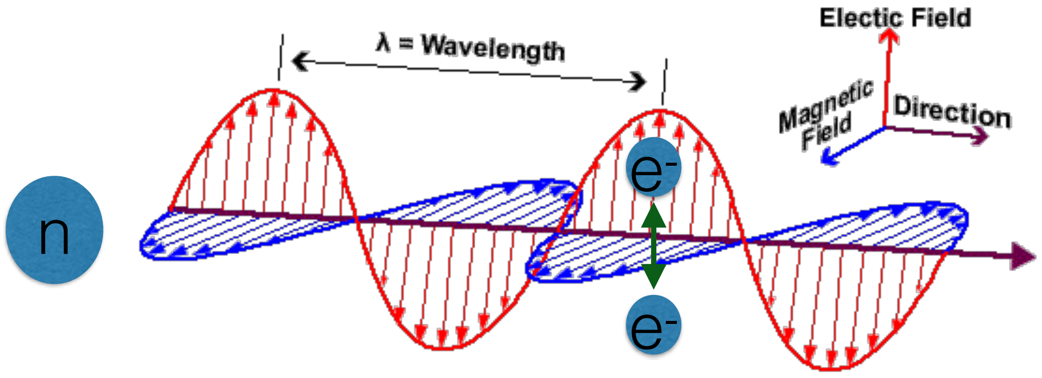


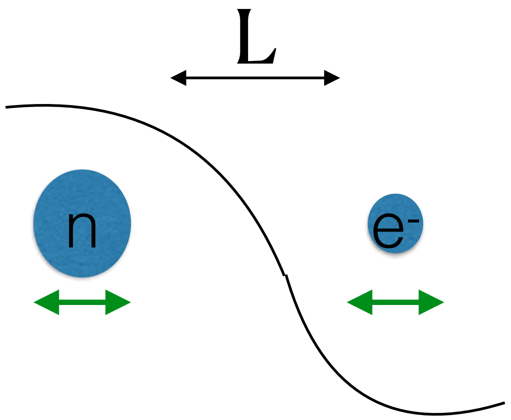
Objects move due to gravity?

Is this motion immediately visible?

Universal Gravitation

What can we physically observe?





Electromagnetic wave moves electron.
But not neutron.

Gravity causes both neutron and electron to move the same way

Detect relative motion between neutron and electron.

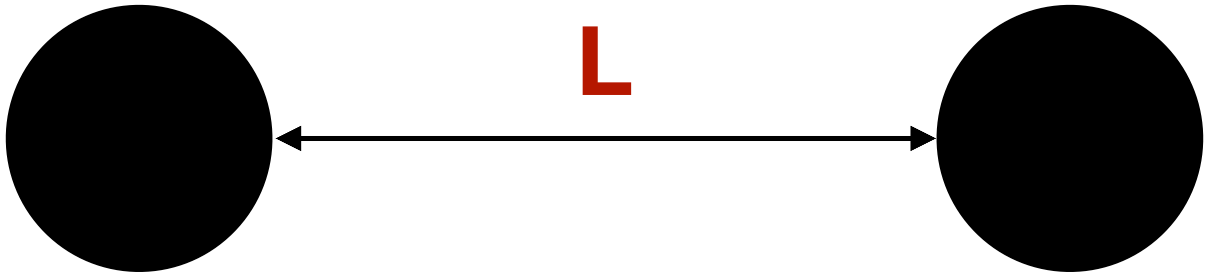
At leading order, no change in relative distance.

A wave will have different amplitude at neutron vs electron
Relative acceleration proportional to separation L

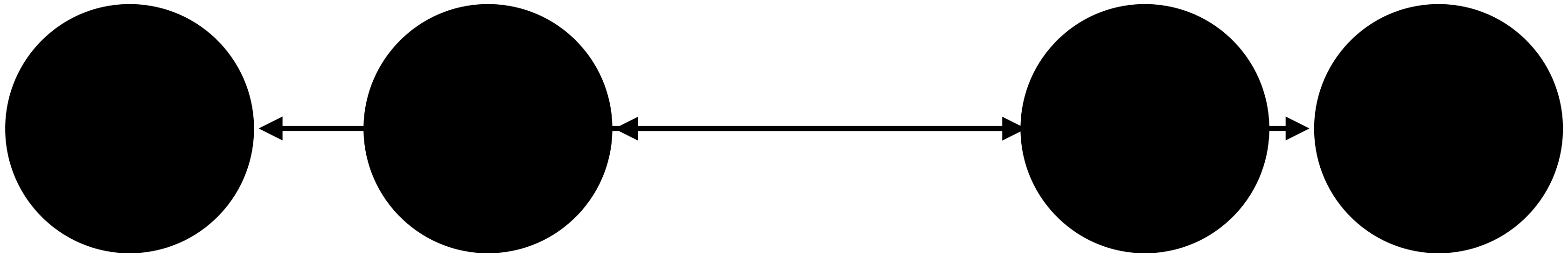
$$\delta L \sim hL$$

Gravitational Wave Detection

Two objects separated by L



Gravitational Wave causes distances to modulate



Detect Tiny Length Change

Need: Precision Sensing + Vibration Isolation

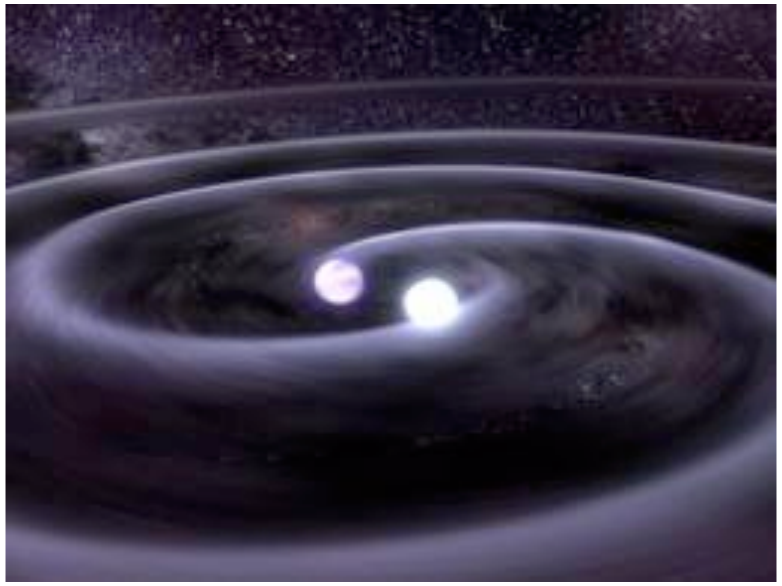
How tiny? How isolated?

Gravitational Wave Sources

How big are these waves?

$$\delta L \sim hL$$

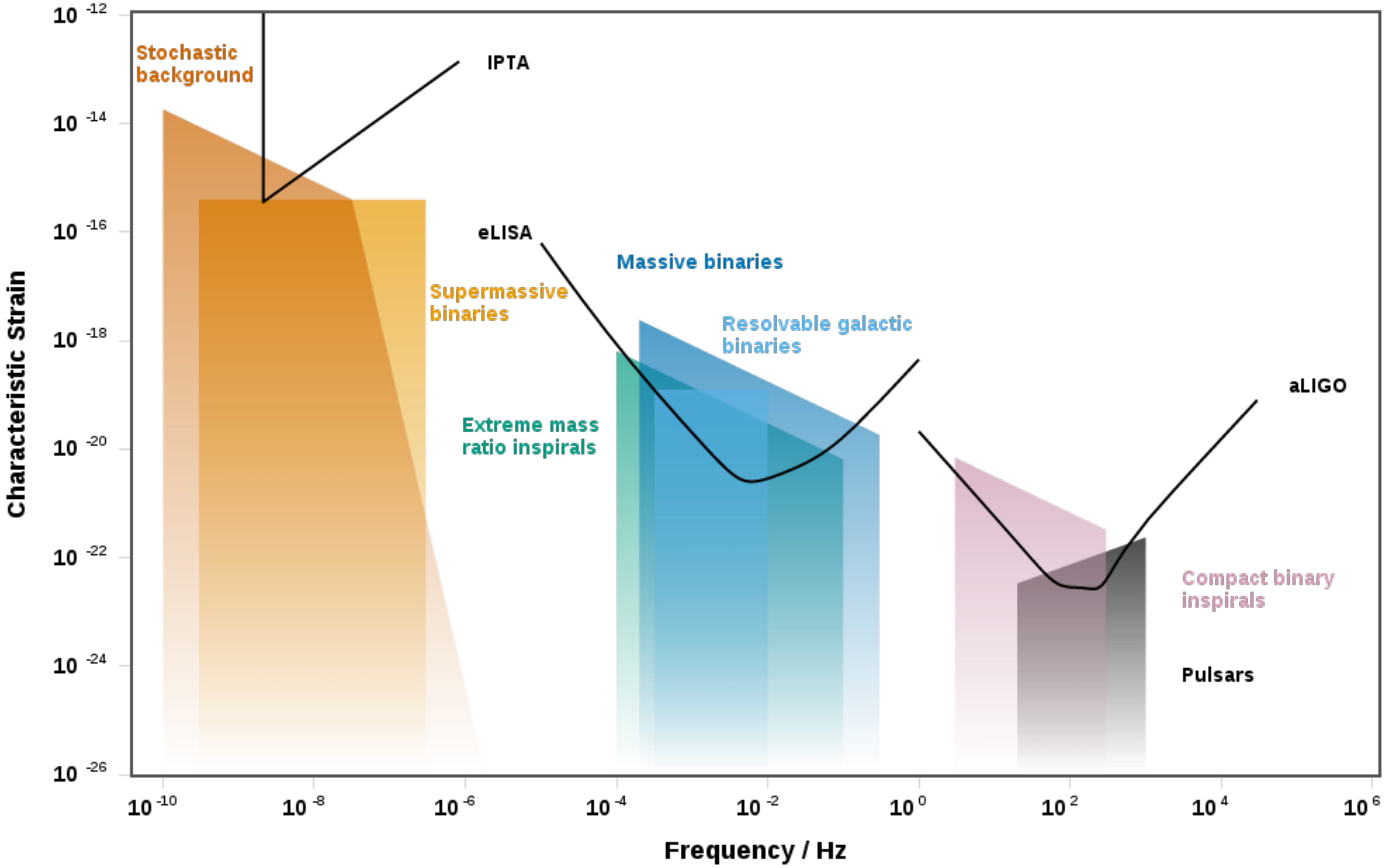
Too weak to be seen.



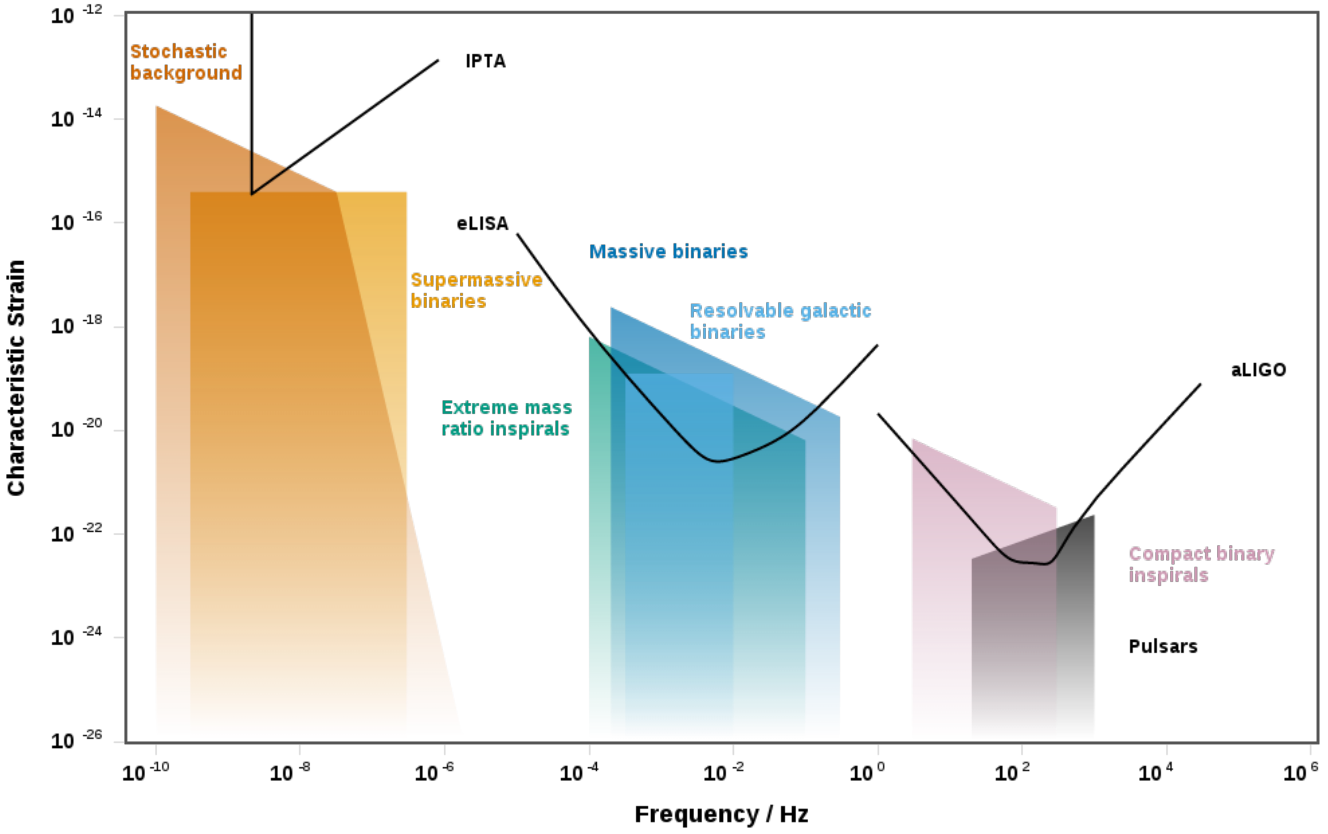
Amplitude strong function of frequency

Heavier black holes give brighter gravitational wave but at lower frequency

Gravitational Wave Sources



Challenges



$h \sim 10^{-23}$ @ 100 Hz **Metrology**

Two objects, separated by $L \sim 1000$ km, $\boxed{h L \sim 10^{-17}\ \mathrm{m}}$

Acceleration Noise $< 10^{-17}\ \mathrm{m}/(10^{-2}\ \mathrm{s})^2 \sim 10^{-13}\ \mathrm{m/s^2}$

$h \sim 10^{-15}$ @ 1 nHz

Two objects, separated by $L \sim 1000$ km, $h L \sim 10^{-9}$ m

Acceleration Noise $< 10^{-9}\ \mathrm{m}/(10^{9}\ \mathrm{s})^2 \sim \boxed{10^{-27}\ \mathrm{m/s^2}}$

Stability

Outline

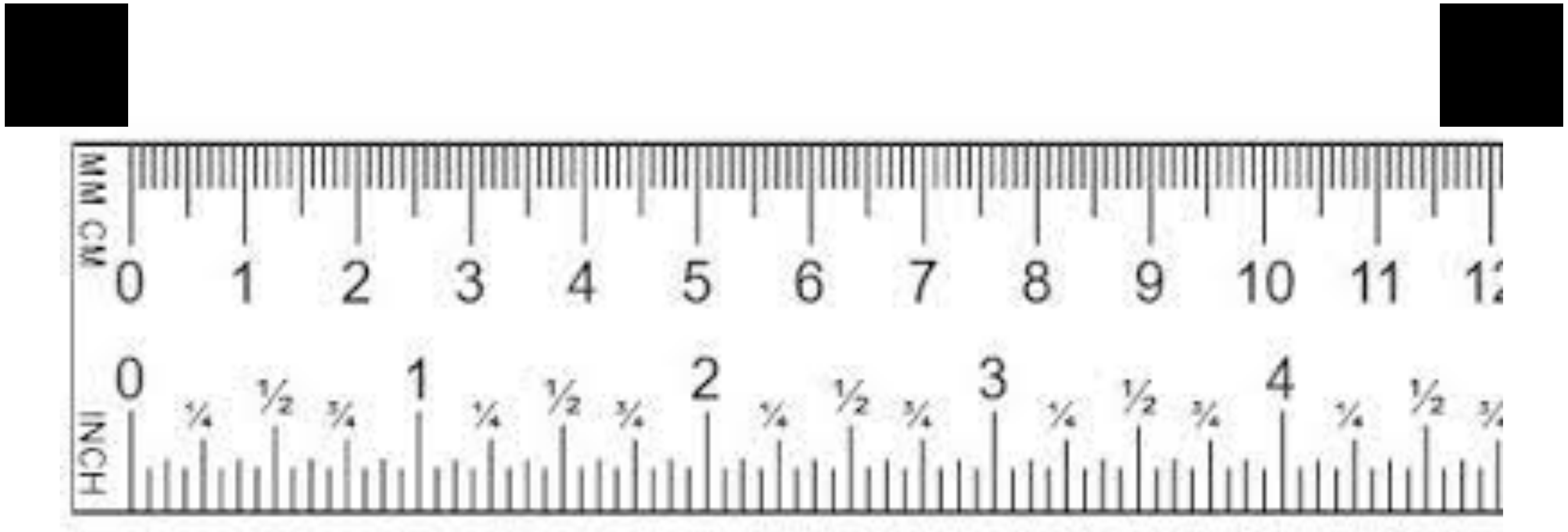
1. Quantum Sensors
2. LIGO (10 Hz)
3. MAGIS (Hz)
4. LISA (mHz)
5. Asteroids (μHz)
6. Astrometry? (nHz - μHz)
7. Pulsar Timing Array (nHz)
8. Conclusions

Quantum Sensors

Length Measurement

How can we measure distance ~ 10^{-17} m?

Can we use a conventional ruler?



Ruler can’t have a marking that is finer than the size of an atom (~ 10^{-10} m) let alone the atomic nucleus (~ 10^{-15} m)

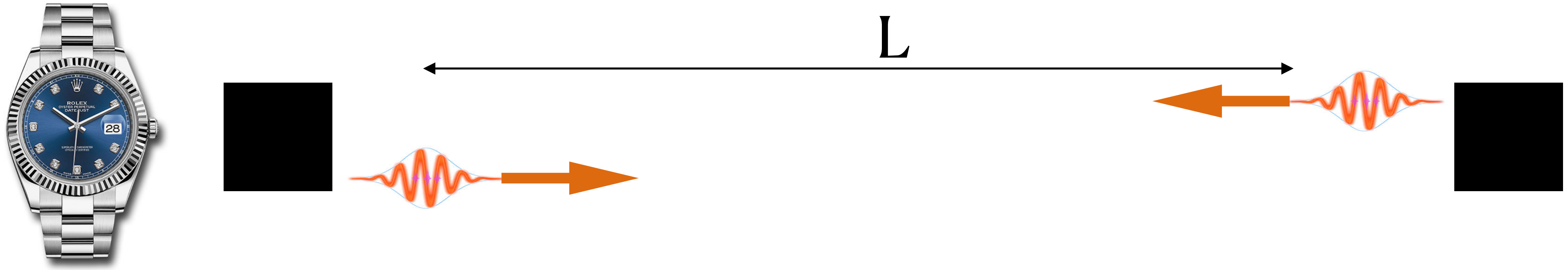
Ruler length will change with temperature variations

Can one even make a ~ 1000 km ruler?

Length Measurement

How can we measure distance ~ 10^{-17} m?

Fact: Speed of light = c = 3×10^{8} m/s is a constant



Send light at time T_1, Measure Time T_2 when the pulse arrives back

$$L = \frac{c}{2}\left(T_2 - T_1\right)$$

If time can be measured to ~ 10^{-25} s, distance can be measured to ~ 10^{-17} m

Still Hard - but light can travel over long distances, so at least possible to cover ~ 1000 km

Quantum Sensors

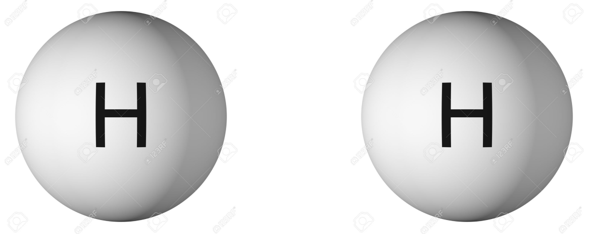
How can we measure time ~ 10^{-25} s?

Use Conventional Clock?

Degrade due to Friction

Comparison?

Use Quantum Mechanics



10^{80} H atoms in the universe, exactly identical

No Friction!

How??

Frequency and Time

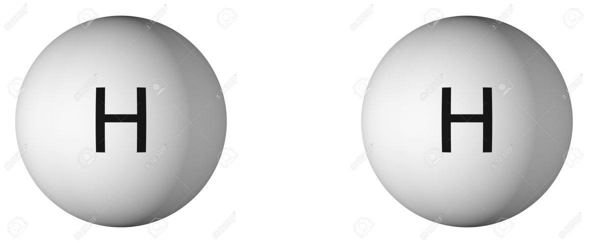
How can we measure time ~ 10^{-25} s?

Clock is an oscillator at frequency f
Measure time by counting number of complete oscillations

$$f\,T = N$$

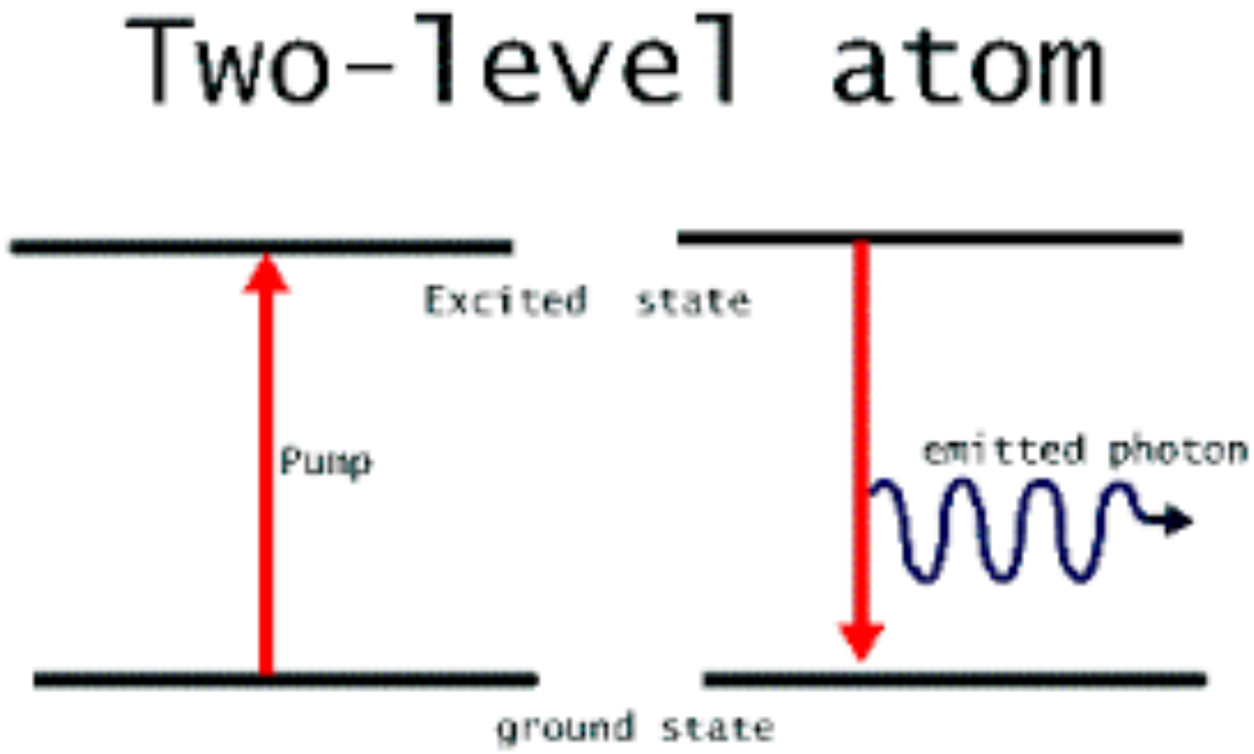
$$\text{Or, } T = N/f$$

With stable frequency, get good clock!



Energy levels of H atoms are exactly identical!

Lasers

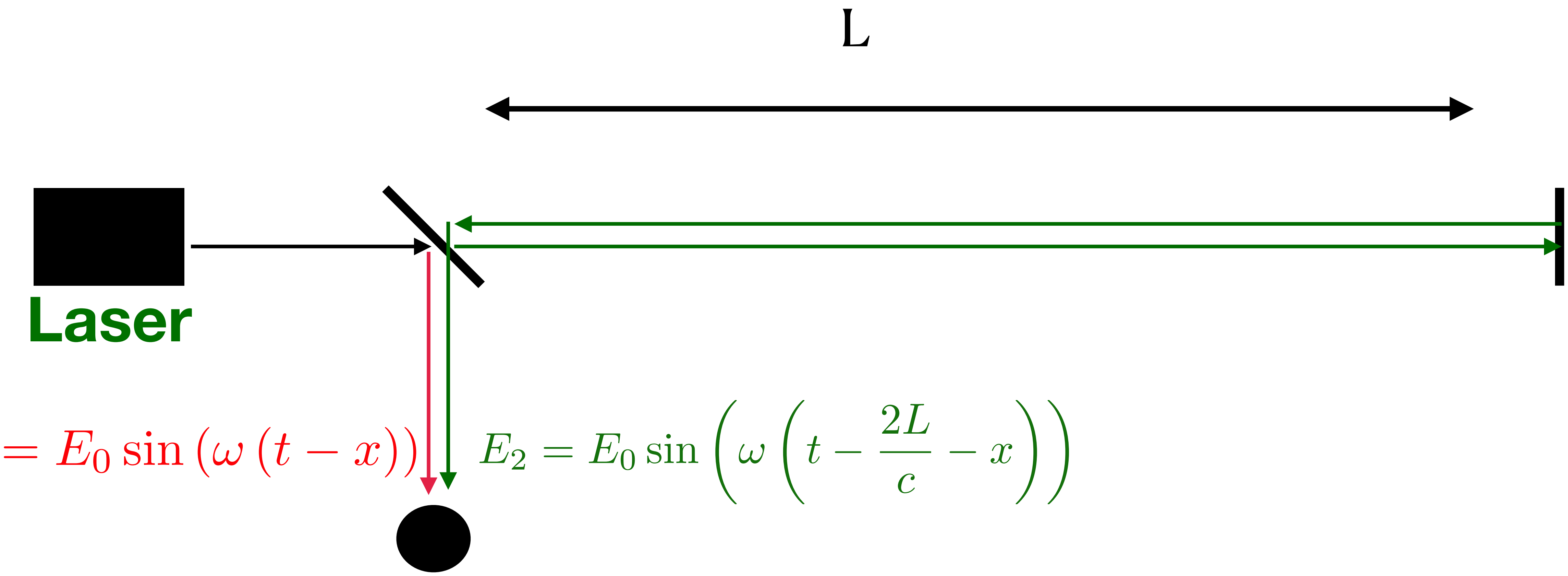


Key Idea: Repeated excitation of same atomic levels.
Emitted photon always at same energy.

Thus stable frequency!

Fabry Perot Cavity

Use stable laser frequency to measure length



$$E_1 = E_0 \sin\left(\omega\left(t - x\right)\right)$$

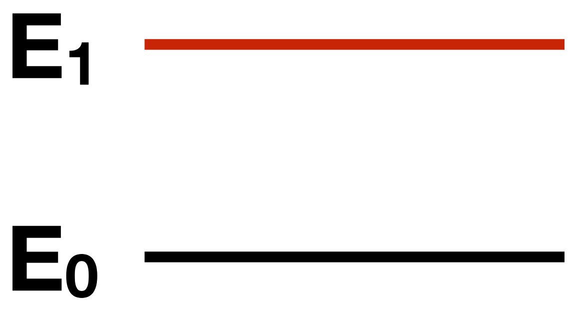
$$E_2 = E_0 \sin\left(\omega\left(t - \frac{2L}{c} - x\right)\right)$$

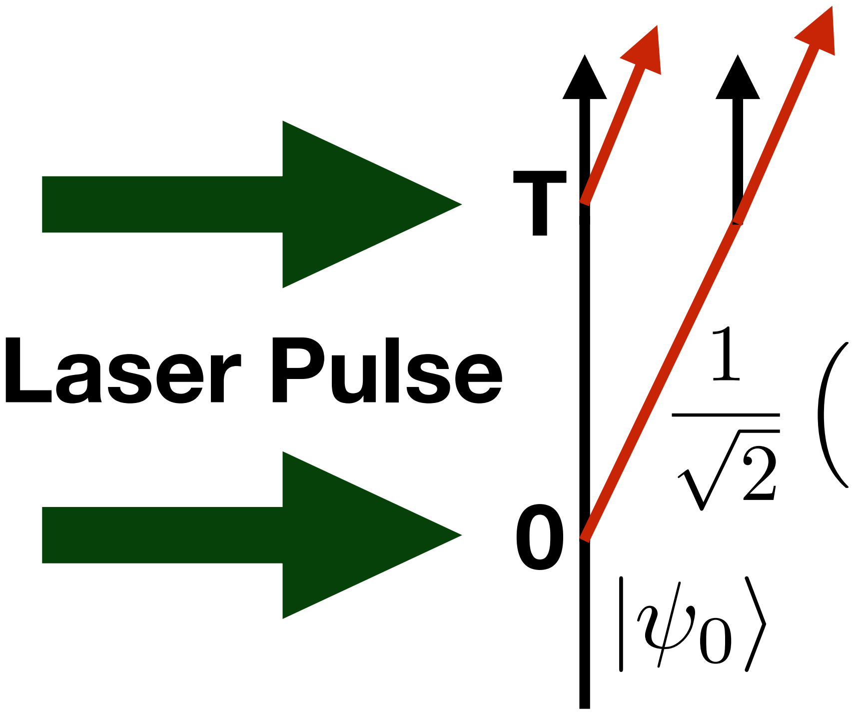
Photo Detector
Measure Intensity of Light

$$I_T = \left(E_1 + E_2\right)^2$$

Intensity depends on L!

Atomic Clock





$$\frac{1}{2}\left(|\psi_0\rangle + |\psi_1\rangle + e^{i(E_0-E_1)T}\left(-|\psi_0\rangle + |\psi_1\rangle\right)\right)$$

$$\frac{1}{\sqrt{2}}\left(|\psi_0\rangle + e^{i(E_0-E_1)t}|\psi_1\rangle\right)$$

$$|\psi_0\rangle$$

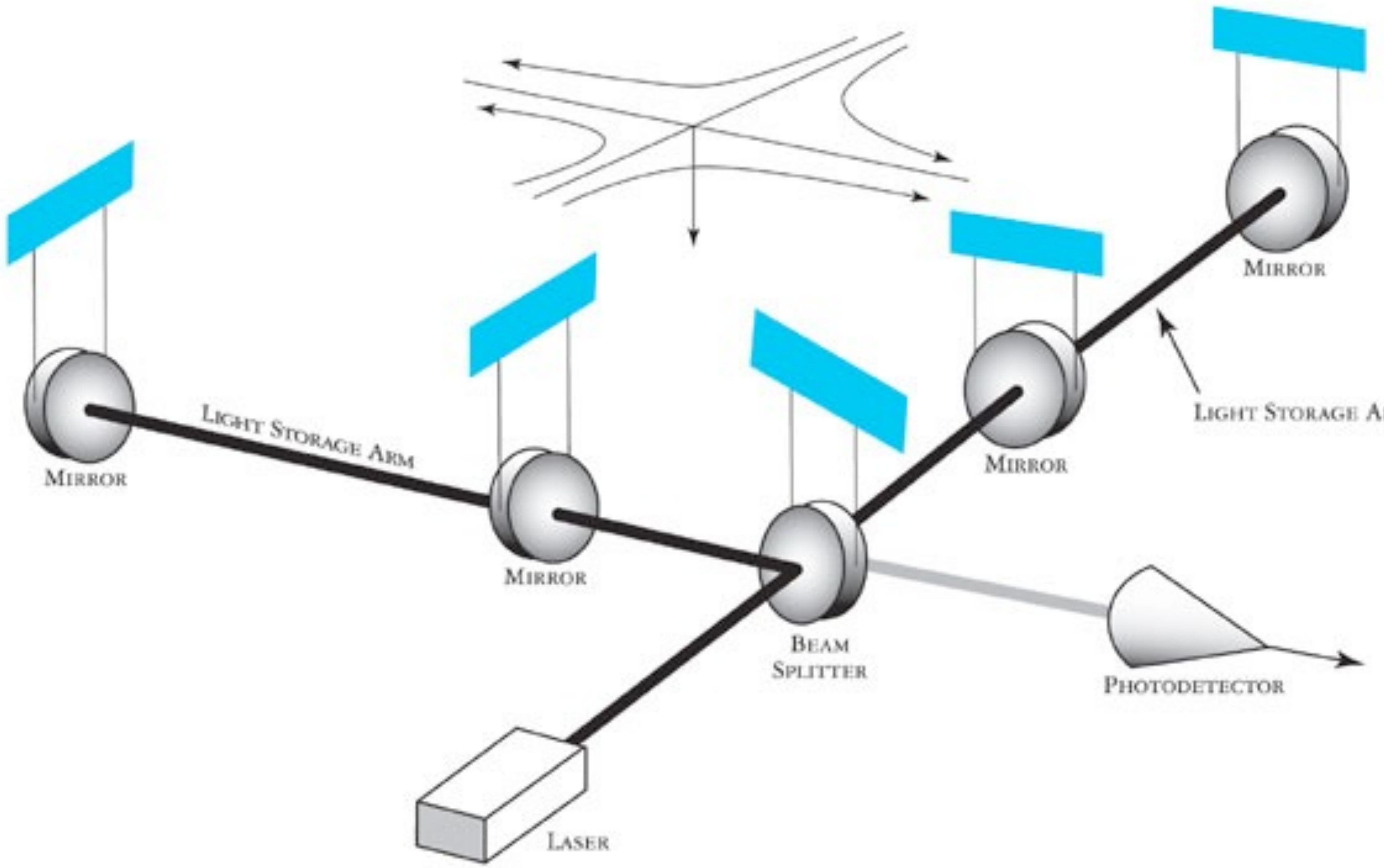
$$\text{Final State: } \frac{1}{2}\left(\left(1 - e^{i(E_0-E_1)T}\right)|\psi_0\rangle + \left(1 + e^{i(E_0-E_1)T}\right)|\psi_1\rangle\right)$$

$$\text{Count Atoms in } |\psi_0\rangle \propto \sin^2\left((E_0 - E_1)\,T\right)$$

Stable energy difference used to measure time

LIGO

LIGO

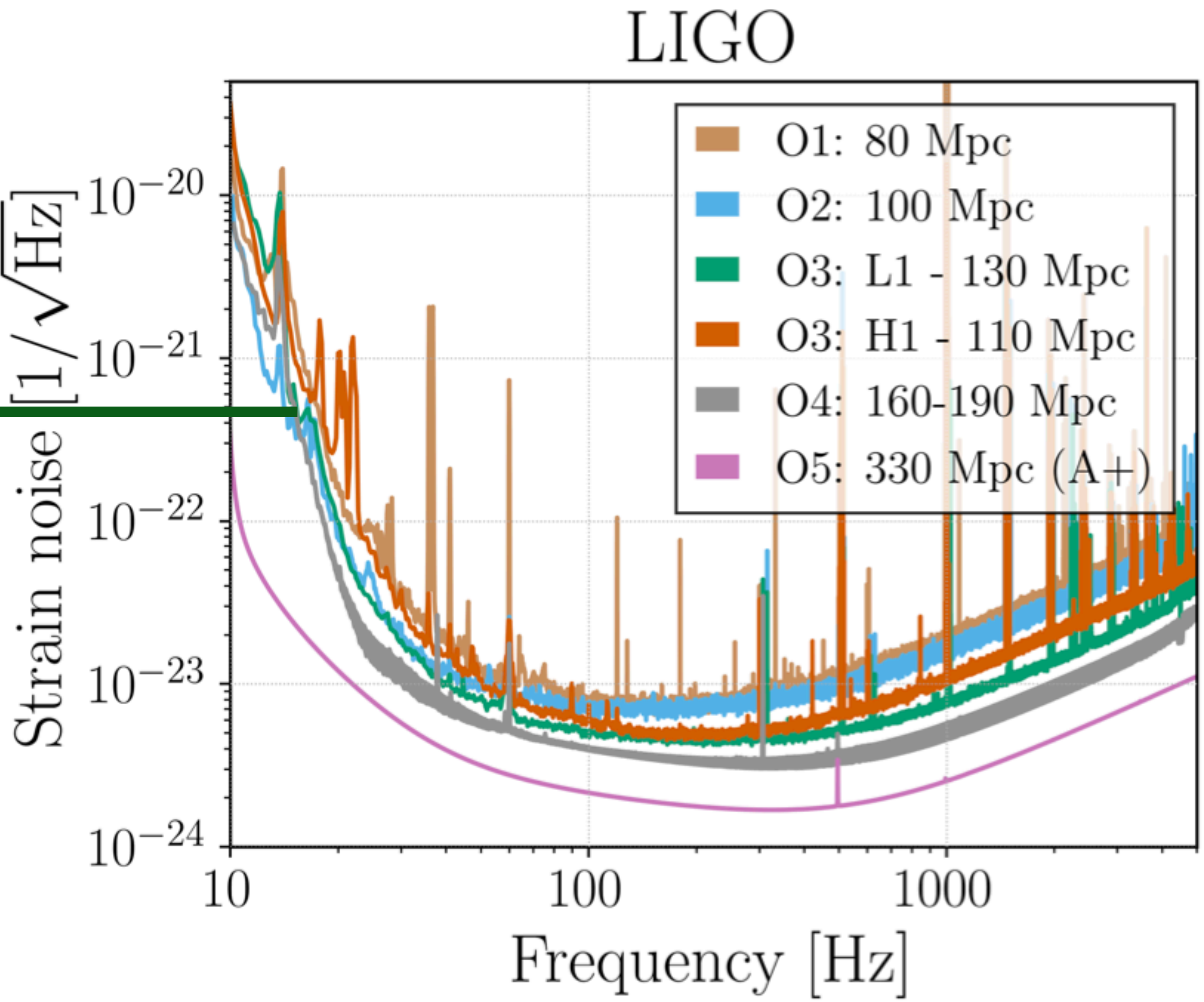


2 mirrors, separate by ~ 4 km
Bounce ~ 200x. Effective Arm length ~ 1000 km

Use optical interferometer to measure

Use vibration isolation

Gravitational Waves Detected!

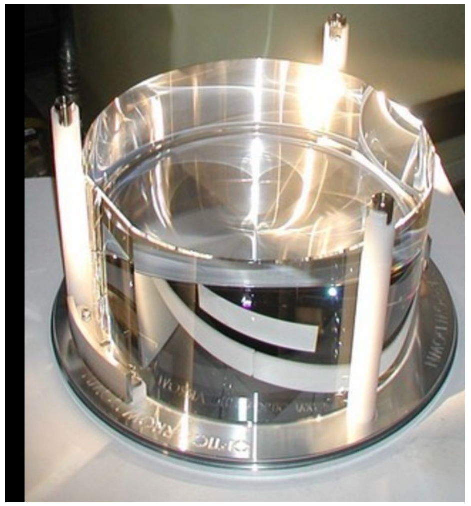


Seismic Noise

Successful Detection in 2015
Nobel Prize in Physics in 2017

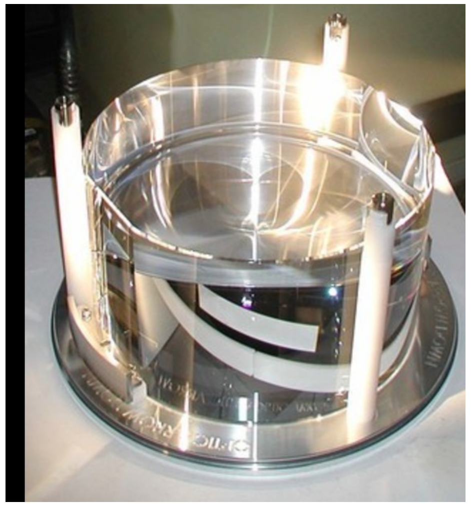
MAGIS

MAGIS



Take LIGO's mirrors

Drop them



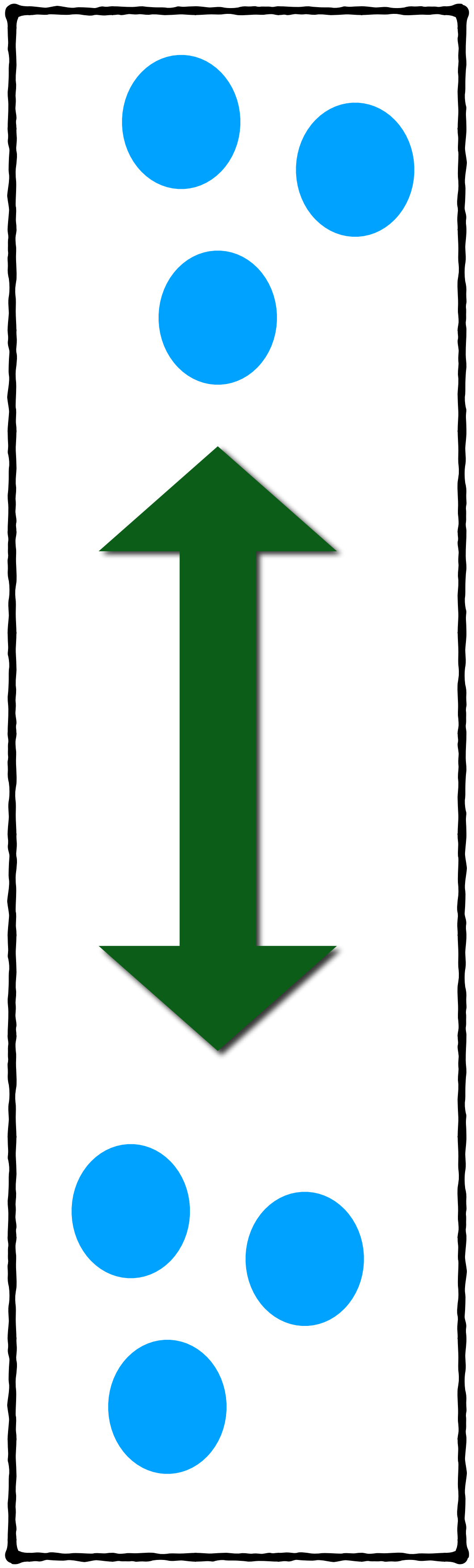
Measure distance between them as they are falling

Gravitational wave still causes modulation
But, system completely vibration isolated!

Problem: Cannot drop 40 kg sapphire mirror.
Can we drop something cheap, yet precise?

Atoms!

Atom Interferometers



Drop a cold cloud of atoms at the top and bottom of a ~ km long vertical mine shaft

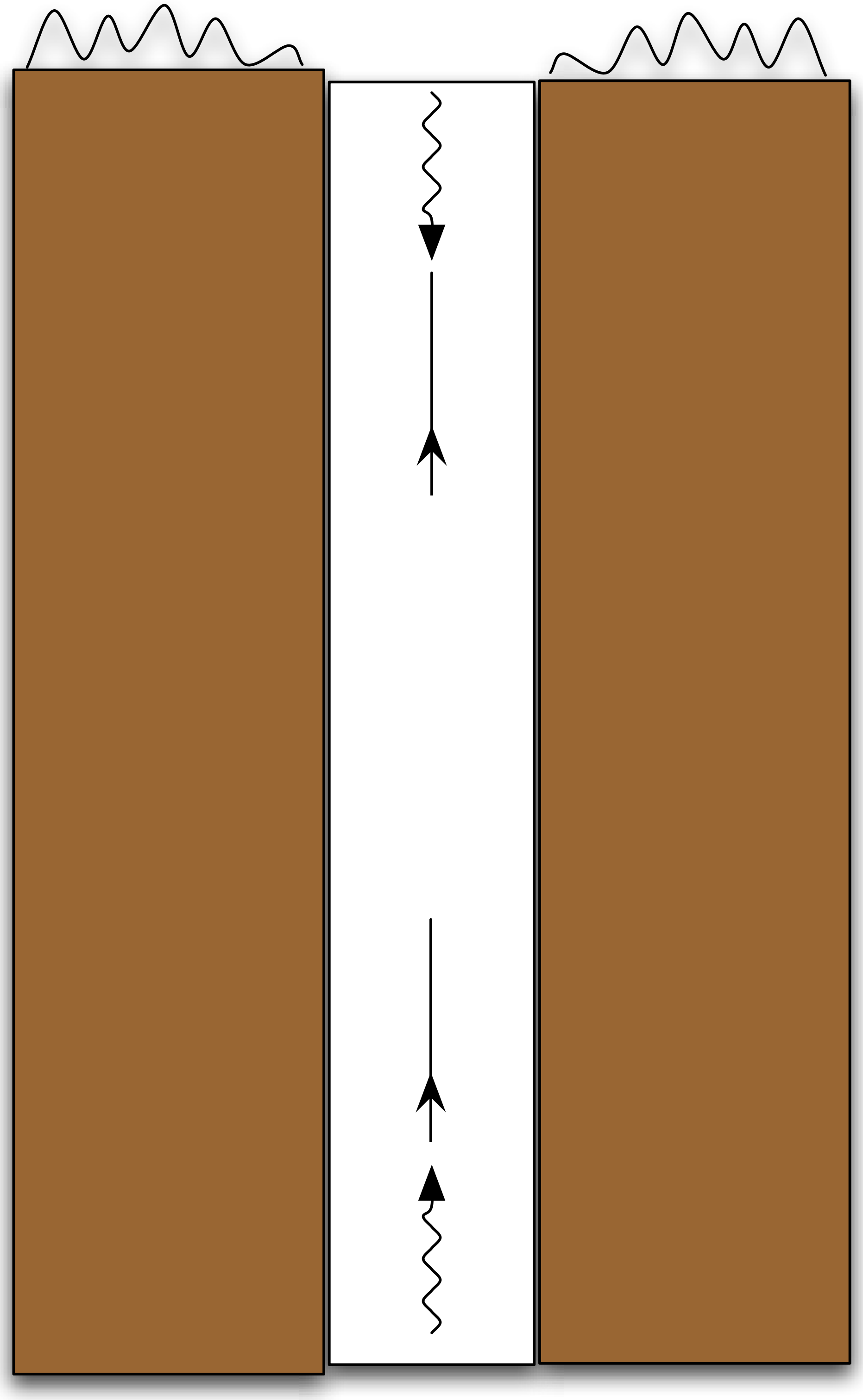
Atom’s own clock serves as a way to measure distance

Measure the relative acceleration between them the clouds when they are in free fall

Observe gravitational wave, no direct seismic noise

Under Development at Fermilab

Ultimate Background for Terrestrial Gravitational Wave Detection



Seismic vibrations gravitationally couple to the free falling atoms.

Cannot be shielded.

Allows for gravitational wave detection down to

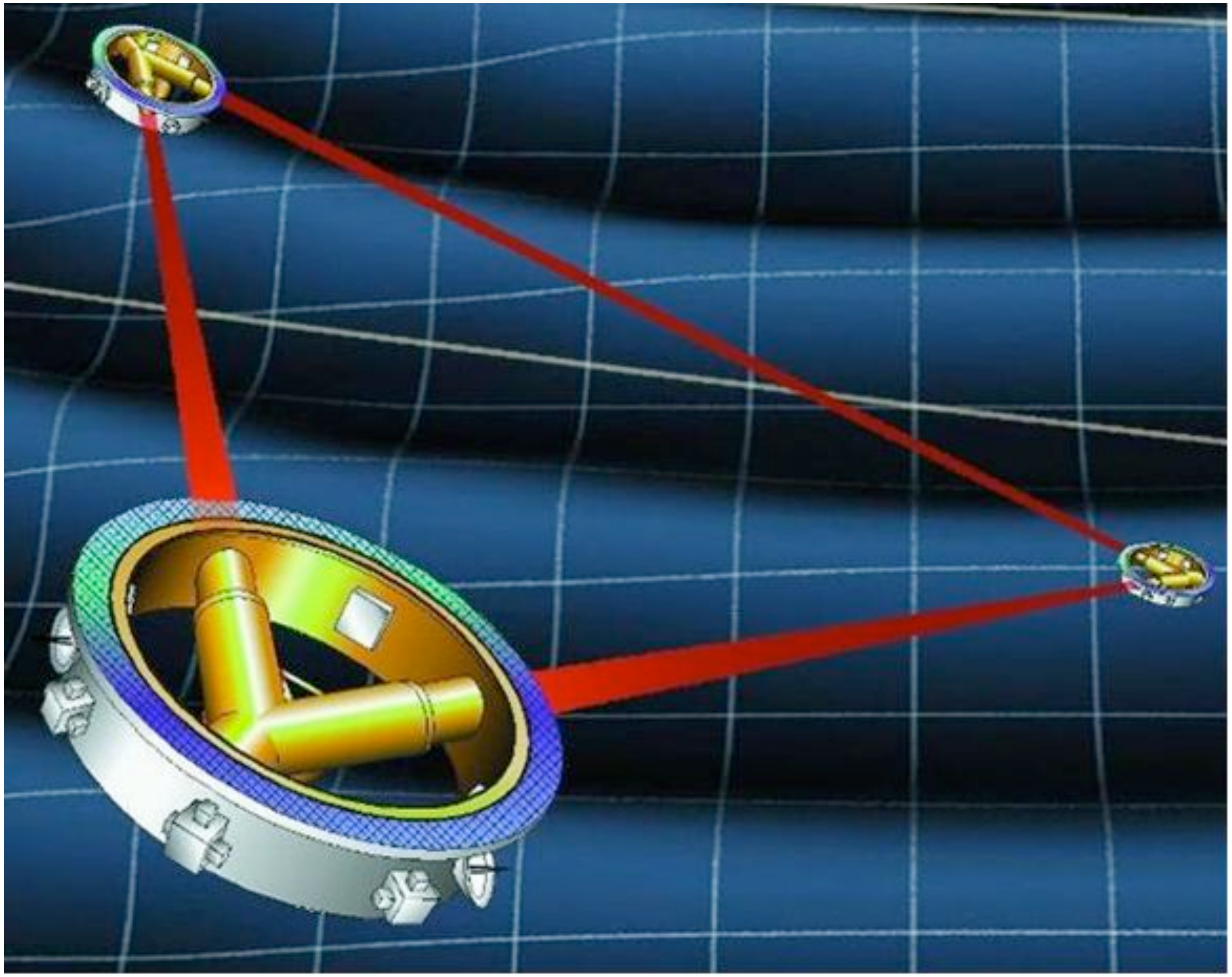
$$\omega \sim 0.3\ \mathrm{Hz}$$

(Thorne and Hughes)

LISA

Satellite based Gravitational Wave Detection

LISA



Technical Details

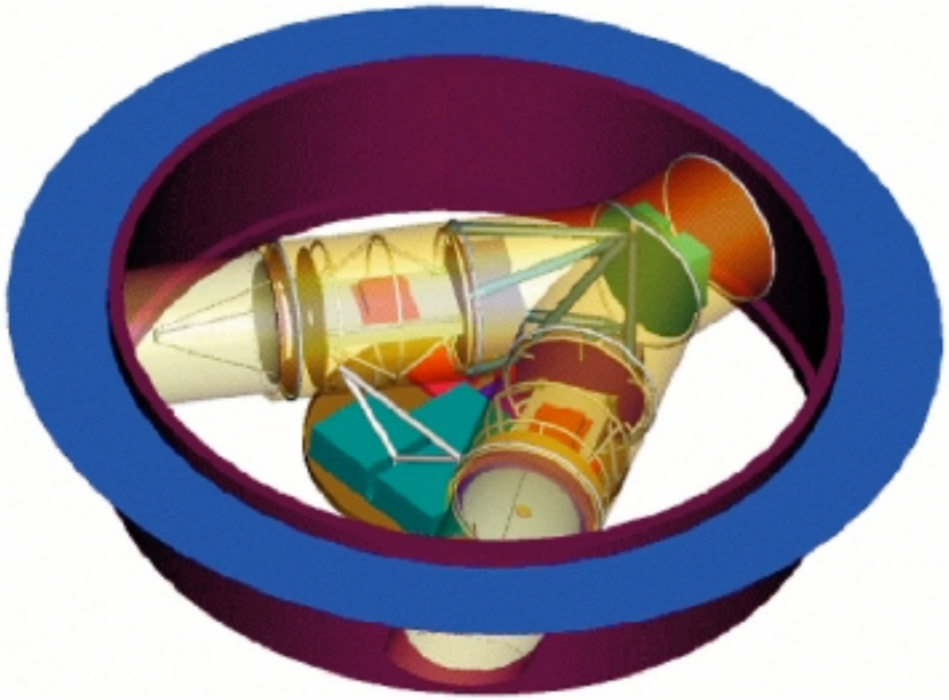
Arm length L ~ 5 million km.

Measure length changes between free floating mirrors due to gravitational wave.

A gravity wave of amplitude $h \sim 10^{-20}$ causes a length change $hL \sim 10^{-10}$ m.

The LISA Challenge

LISA Satellite



Mirror Position should fluctuate by < 0.1 nm in the frequency band of interest.

Mirror is inside a satellite of mass of a few hundred kg.

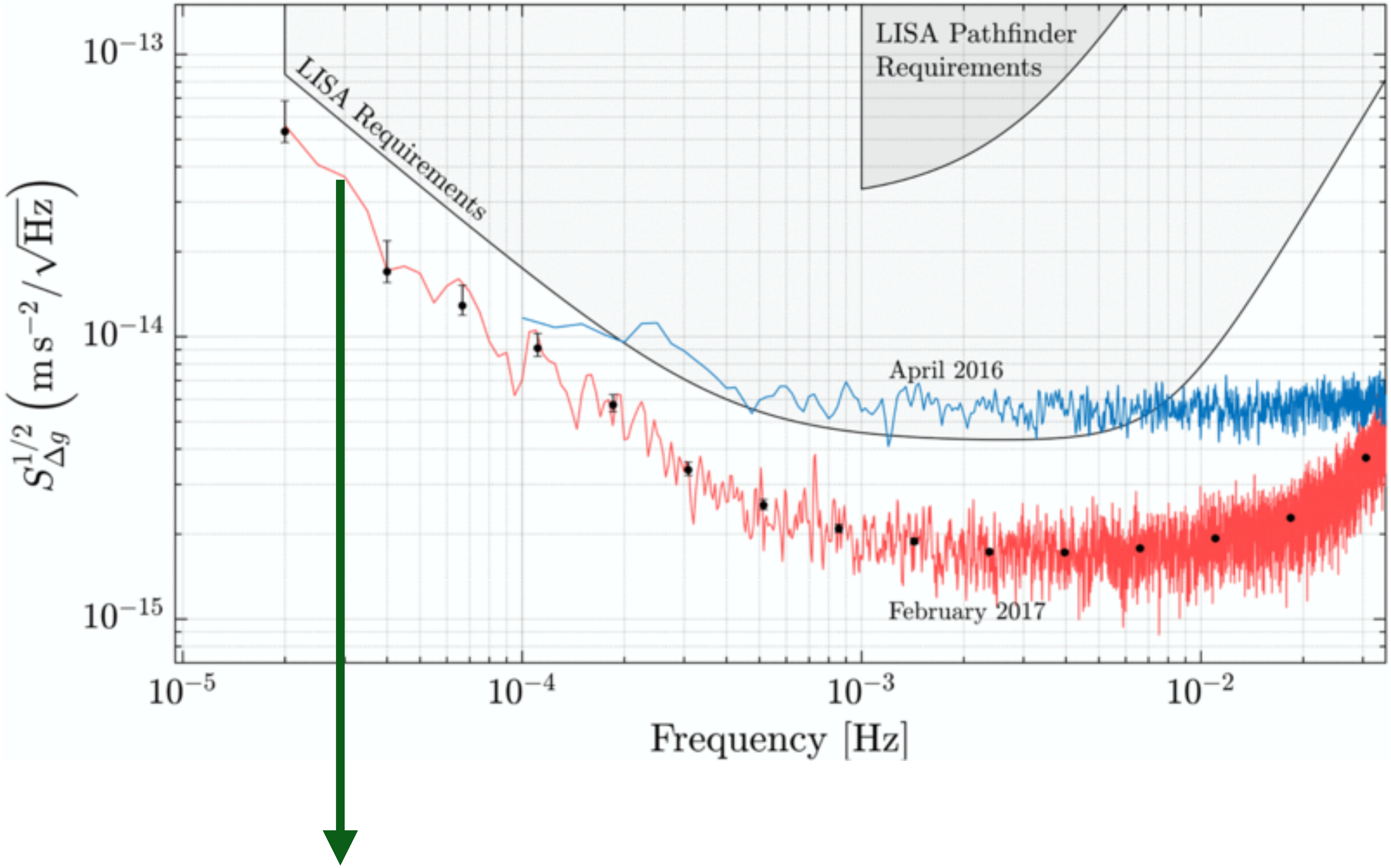
Free floating mirror gravitationally coupled to vibrations of the satellite.

Requires position control of the satellite ~ $1 \ \frac{\mathrm{nm}}{\sqrt{\mathrm{Hz}}} \text{ at } 10^{-2} \ \mathrm{Hz}$

(LISA Pre Phase A Report)

Major hurdle for LISA - Successfully demonstrated by LISA Pathfinder!

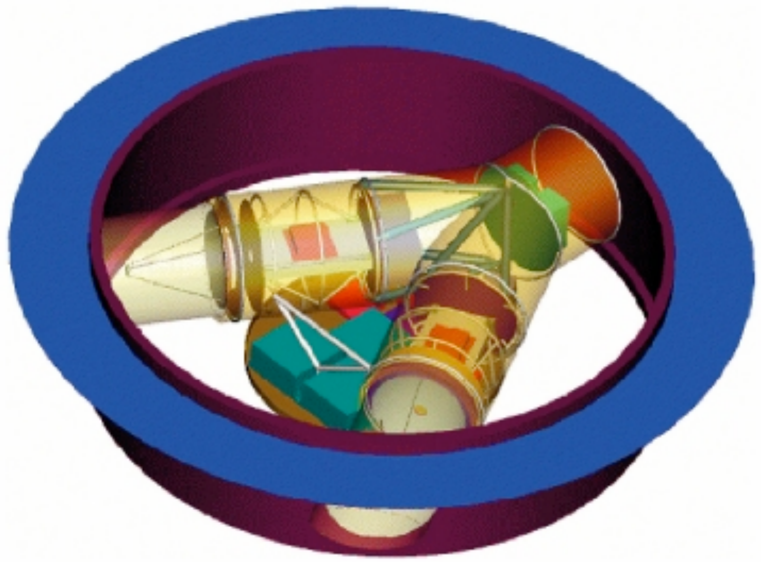
LISA Pathfinder Results



Hard to remove low frequency noise

Asteroids

Asteroids



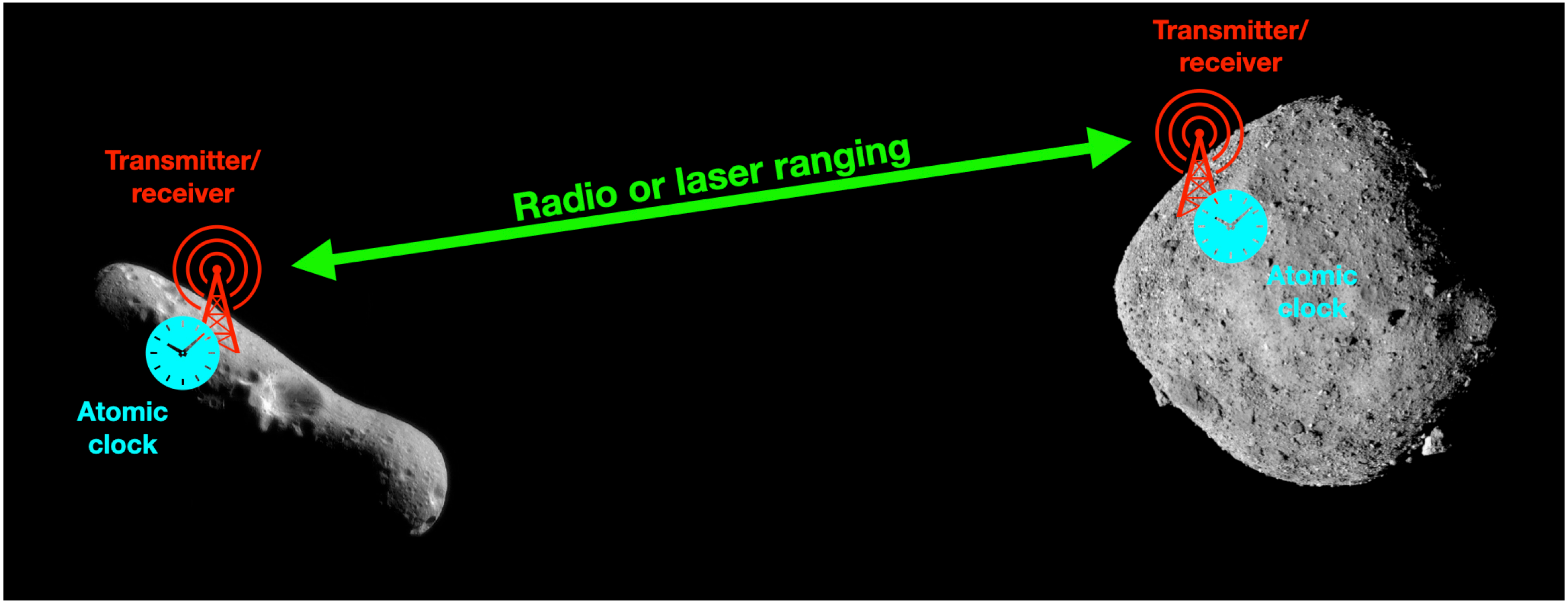
~ 1000 kg satellite gets pushed around by various solar system effects (solar intensity fluctuations, cosmic ray charging etc.)

Combat using large mass - but cannot launch heavier than ~ 1000 kg

Center of mass of planets is stable
But seismic and atmospheric activity!

~ 10 km rocky asteroid
Sufficiently stable center of mass, low seismic activity!

Asteroids

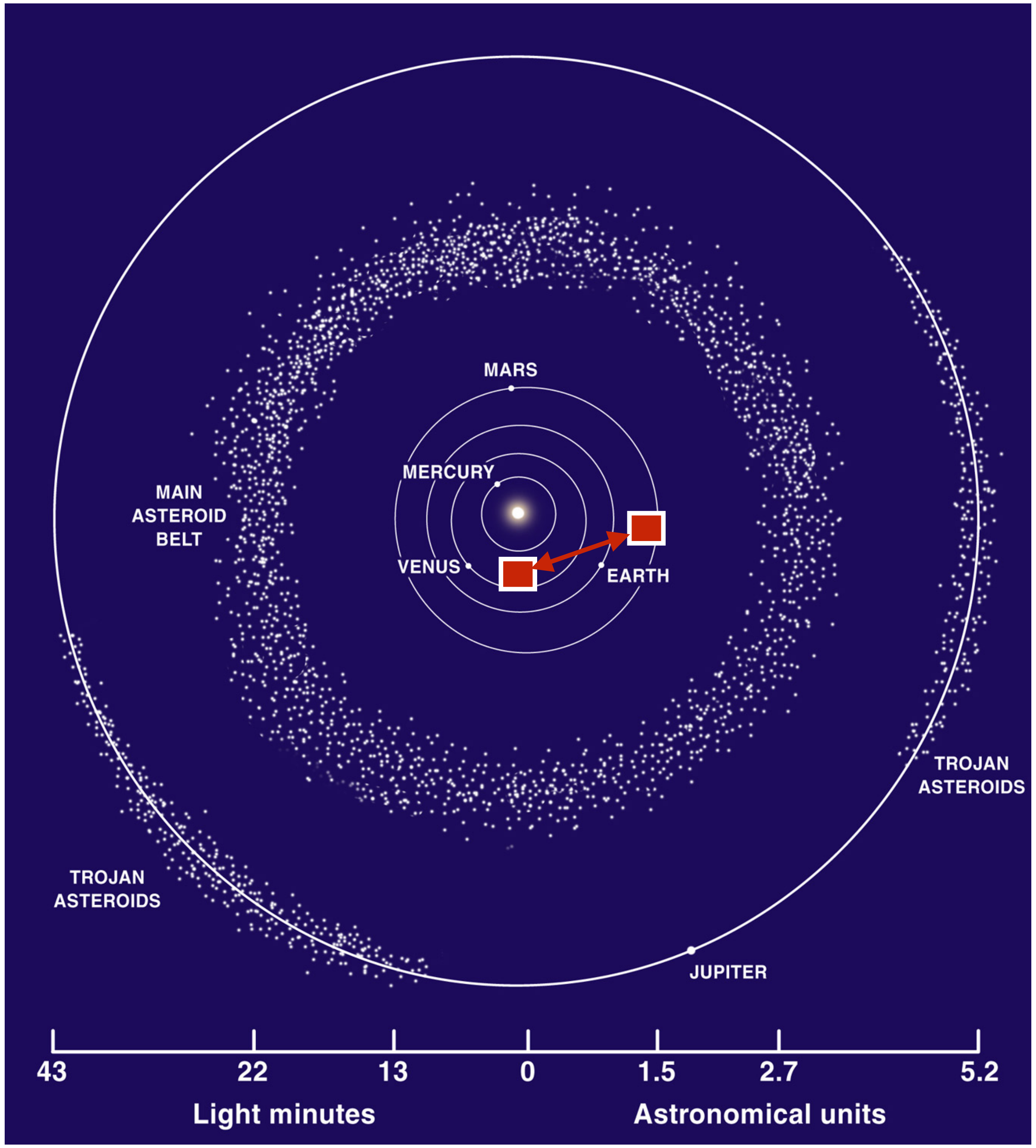


Robotic craft have landed on asteroids since ~ 2000 (JHU APL/Japan)

Seismic measurements on Moon/Mars indicate asteroids are stable enough

Required atomic clocks exist terrestrially

Ultimate Background for Inner Solar System Gravitational Wave Detection



Measure distance between two objects in the inner solar system

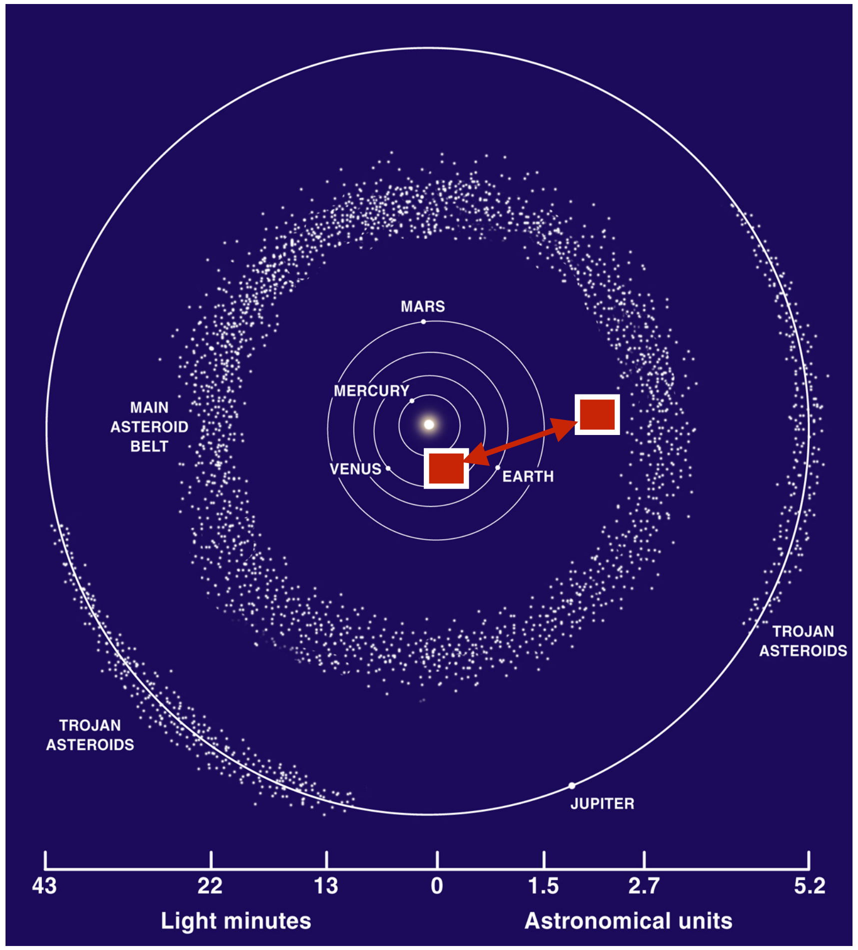
~ 100s of asteroids in asteroid belt also exert gravitational accelerations on the objects

Cannot be shielded

Blocks gravitational wave detection below μHz with proof masses inside the inner solar system

Astrometry?

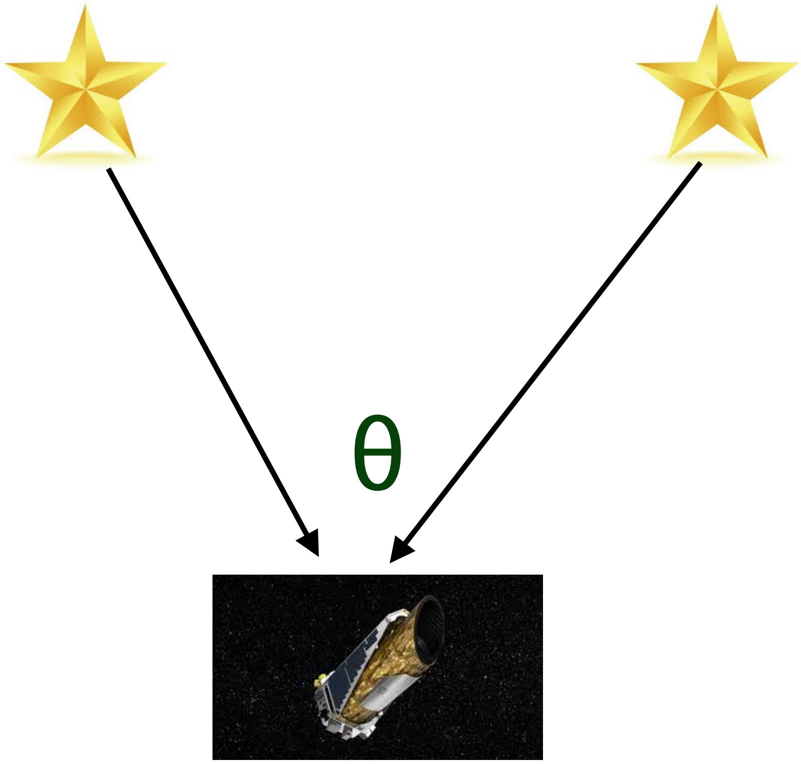
Combatting Asteroid Noise



Asteroids cause unacceptable fluctuations in the distance between objects inside the inner solar system

Could go to outer solar system - around Neptune?

Other options?

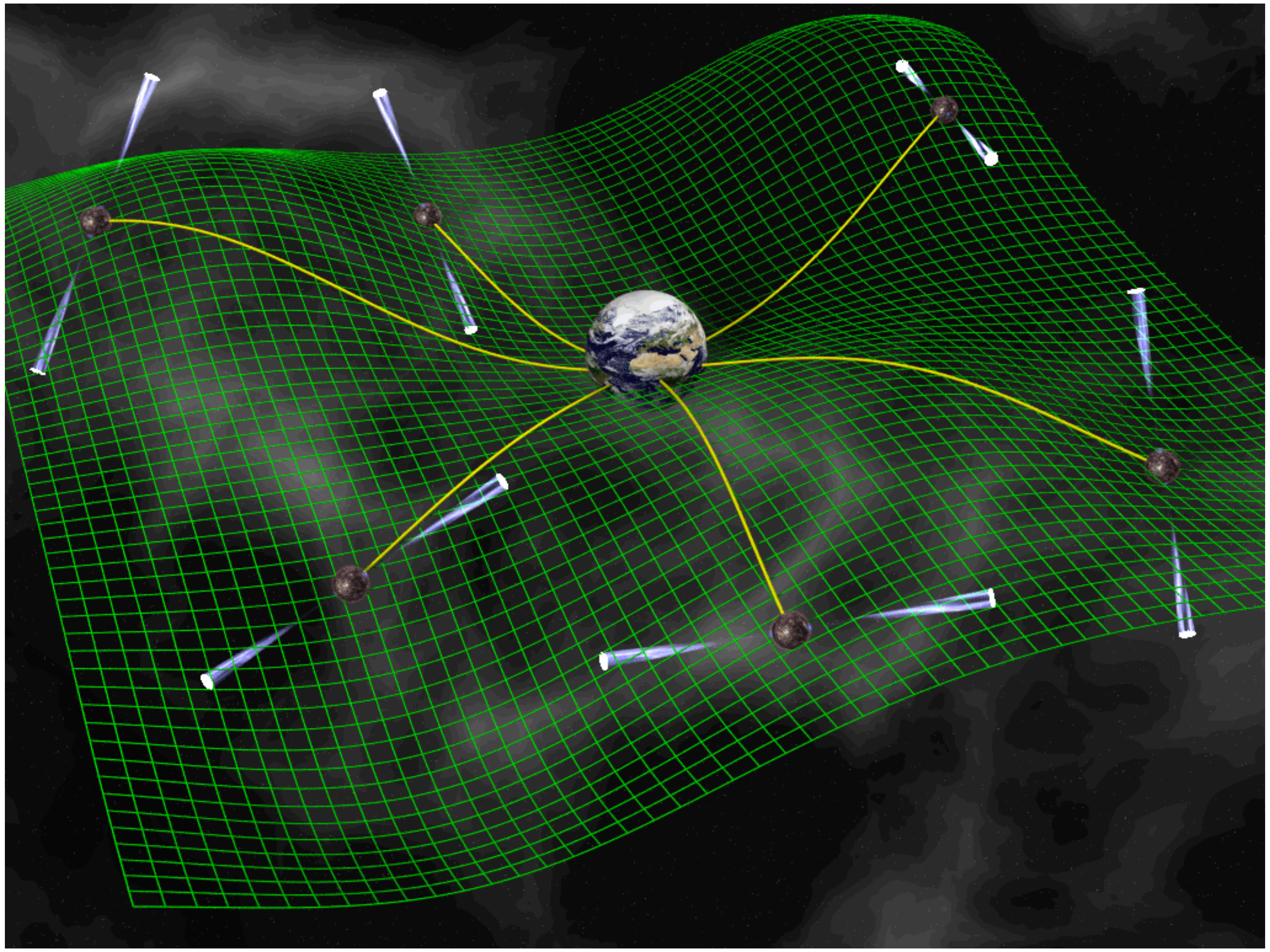


Measure relative angle between distant stars

Cancels common Position fluctuations of satellite due to asteroid noise

Pulsar Timing Array

Pulsar Timing Array



Millisecond Pulsars have very stable rotations

Known to be good clocks

Measure time of arrival of pulses using radio telescope + atomic clock

Gravitational wave modulates arrival time

Array approaching sensitivity necessary for certain estimated gravitational wave backgrounds

May detect gravitational waves soon!

Conclusions

Conclusions

- Gravitational Waves provide new eyes into the universe
- With LIGO, already beginning to directly probe the space-time around black holes
- Lower frequency instruments offer unique probes of supermassive black hole geometries, early universe cosmology as well as white dwarf and neutron star physics
- Discoveries have already upended conventional theories of stellar formation and evolution. Likely to lead more surprises in terms of black hole physics.