Class 22 : Gravitational Waves

ASTR350 Black Holes (Spring 2022)

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Recap

- Event Horizon Telescope
- Direct constraints on size and shape of event horizon for M87
  - allows measurement of mass and inclination
  - determination of physical mechanism of radiation emission
  - future may allow constraints on
    - no hair theorem
    - physics of jet creation
    - tests of GR

...but at the moment we haven't learned anything new

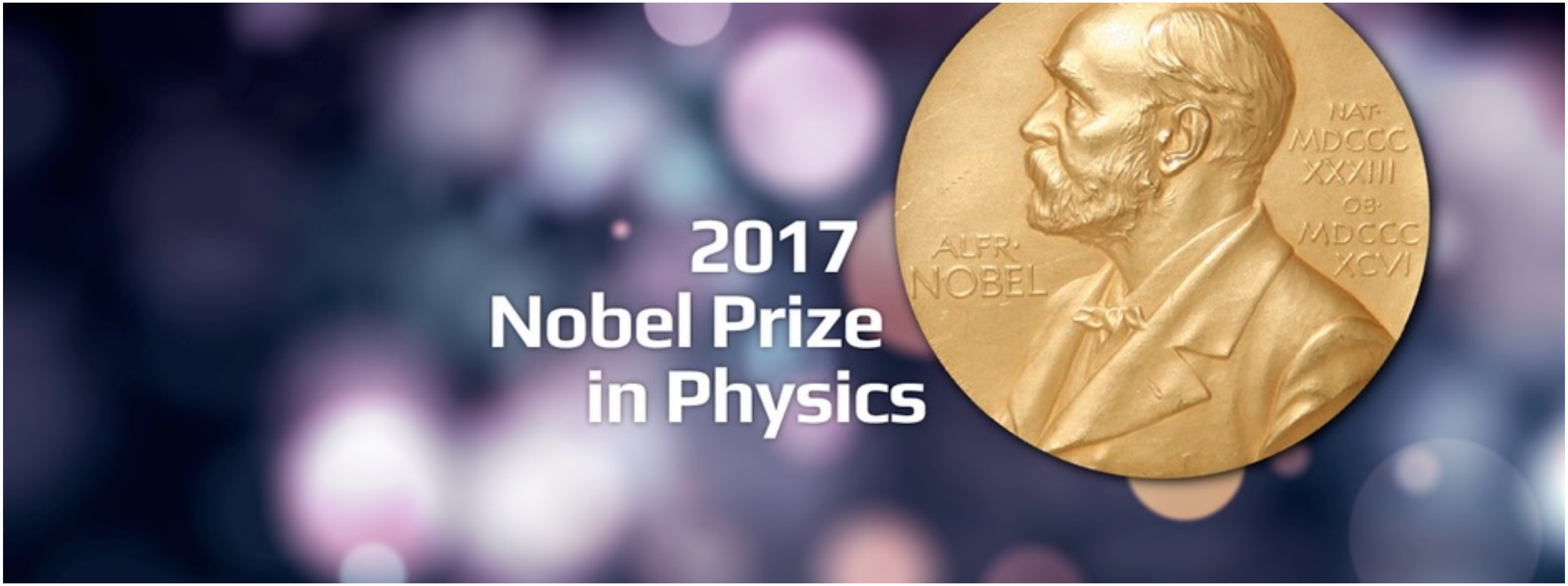
This Class

- A new window that ***has*** given us tremendous new info
  - Basics of gravitational waves… ripples of curvature in spacetime, traveling at the speed of light
  - The binary pulsar… first time that effect of gravitational waves had been observed (through decay of orbit of two neutron stars)

Basics of Gravitational Waves

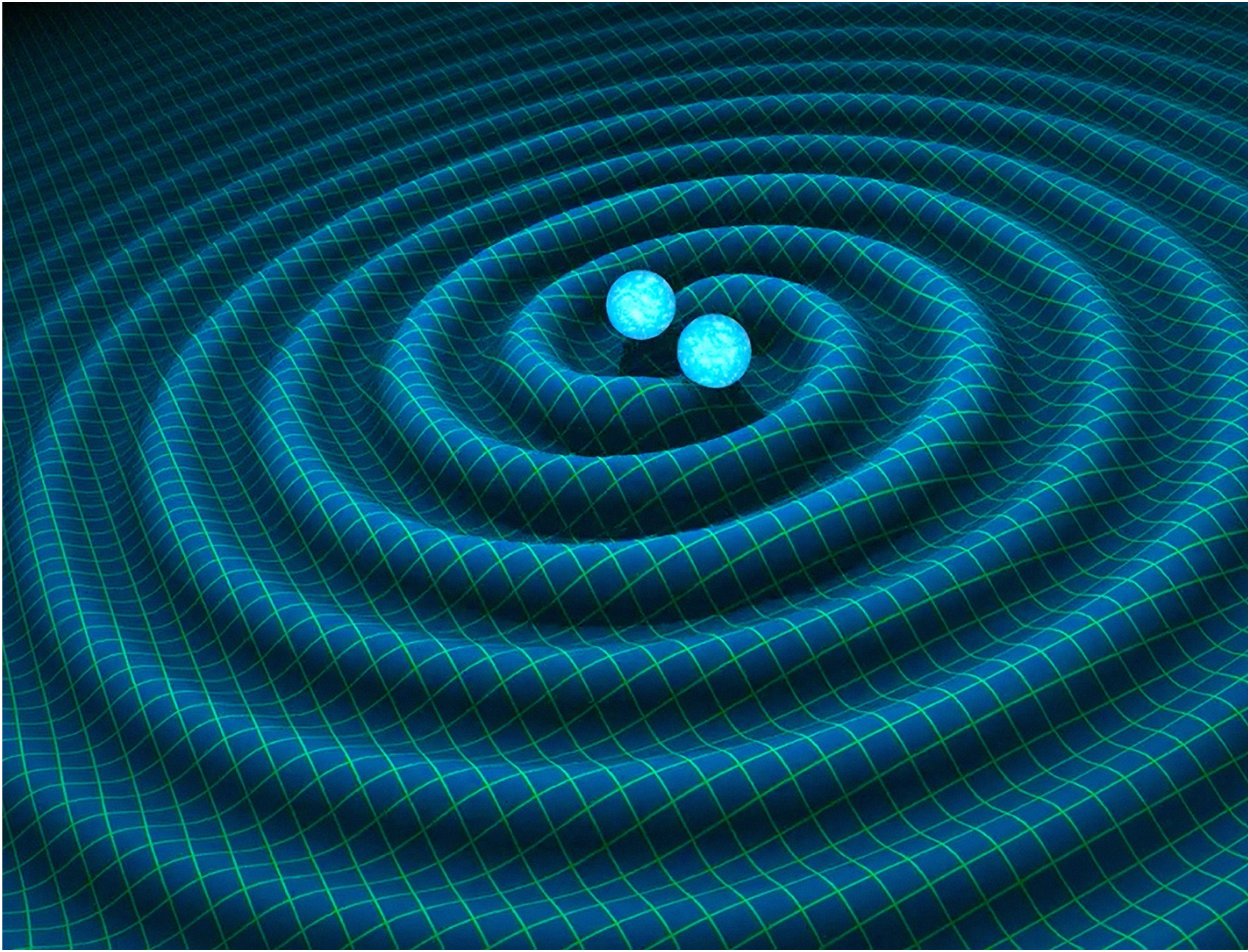
- **Fundamental prediction of GR**: there is no Newtonian equivalent
  - Accelerating masses create ripples in the curvature of space-time
  - Ripples propagate at the speed of light
  - Carry information about changing gravitational fields
  - Interesting history… Einstein predicted them in 1916, was shown to have made some mistakes, then disavowed them, then finally accepted them, but died ~20 yrs before evidence
- Features of gravitational waves…
  - Usually extremely weak!
  - Only become strong when massive objects are orbiting very close to each other.
  - Gravitational waves carry energy away from orbiting objects… lets objects spiral together.

Gravitational Waves Explained: Minute Physics



The 2017 Nobel Prize in Physics was awarded to three key players in the development and ultimate success of the Laser Interferometer Gravitational-wave Observatory (LIGO). Barry C. Barish, Kip S. Thorne and Rainer Weiss

https://www.ligo.caltech.edu/page/press-release-2017-nobel-prize#cit



What can emit gravitational waves?

- Not anything static
- Waves fundamentally come from Einstein's insight that gravity travels at the speed of light. If the mass configuration is unmoving, there are no changes to propagate and thus no waves
- As a result, we need to think about what can change the gravitational field, and what cannot
- And we need to think about a lot of mass moving quickly; remember, gravity is weak, so to get ***detectable*** gravitational waves requires special circumstances!

Not spherical collapse or explosion

- What about something like a supernova that produces a collapse to a black hole? That's a lot of mass moving rapidly.
- But if the explosion or collapse is completely spherically symmetric, we get ***no*** gravitational radiation!
- We can understand this by remembering that in Newtonian theory (also in GR) the gravitational field outside a spherical mass is identical to the field outside a point at the center with the same total mass
- Thus a "gravity meter" couldn't tell there is an explosion or collapse... even to a black hole!

Not axisymmetric rotation

- Not as easy, but something that is axisymmetric and rotating around that axis, also doesn't emit gravitational waves
- Thus even my favorite neutron stars, rotating hundreds of times per second, don't emit GW if they rotate axisymmetrically!
- More generally, a term you might see is that for GW to be emitted you need a time-changing ***quadrupole***
- So what are examples of such sources?

Source category 1: binaries

- Two stars orbiting around each other naturally have a time-varying quadrupole
- To get substantial GW strength, need these to be massive objects moving fast
- For binaries to appear in the tens of Hz to thousands of Hz frequency range detectable with LIGO, only neutron stars and stellar-mass black holes are possible
- And that's what's been seen; nearly 100, almost all double black holes (more in the next lecture). Two NS-NS, two possible NS-BH. No other source categories
- But let's talk about them anyway; who knows what the future might bring!

Source category 2: bursts

- Consider a core-collapse supernova
- Wait, didn't we say that those won't emit GW?
- No, we said that they won't emit GW ***if the collapse and explosion is spherically symmetric***
- In reality, there is a lot of turbulence, so SN aren't completely symmetric and they do emit some GW
- But not much: maybe a fraction 10^{-9} of the total energy in a supernova goes into GW (most into neutrinos)
- Could see them using current GW detectors if they happened in our Galaxy; occurs ~once/century
- But maybe we'll get lucky!

Source category 3: continuous

- A binary spirals inward and thus (in LIGO) lasts a short time and changes its frequency a lot
- But consider, say, a mountain on a neutron star
- That's nonaxisymmetric, so it does emit GW
- But the mountain has to be small, because given the strong gravity of NS, bumps are smashed almost flat
- So it's a weak signal related to the rotational frequency of the star. It also lasts a very long time
- Weak signal, very long time -> maybe we could see it eventually?

Source category 4: stochastic

- Here "stochastic" means "the sum total of a lot of sources that we can't detect individually"
- This could be a lot of binaries with individually weak signals; for example, very distant binaries
- Or it could be something amazing; it is expected that in the very early ($<10^{-34}$ seconds after BB!) universe, the inflationary epoch could produce stochastic GW
- These have a broad signal across a wide range of frequencies
- So now let's think about some more general characteristics of GW

Change in Frequency of GW with time during merger

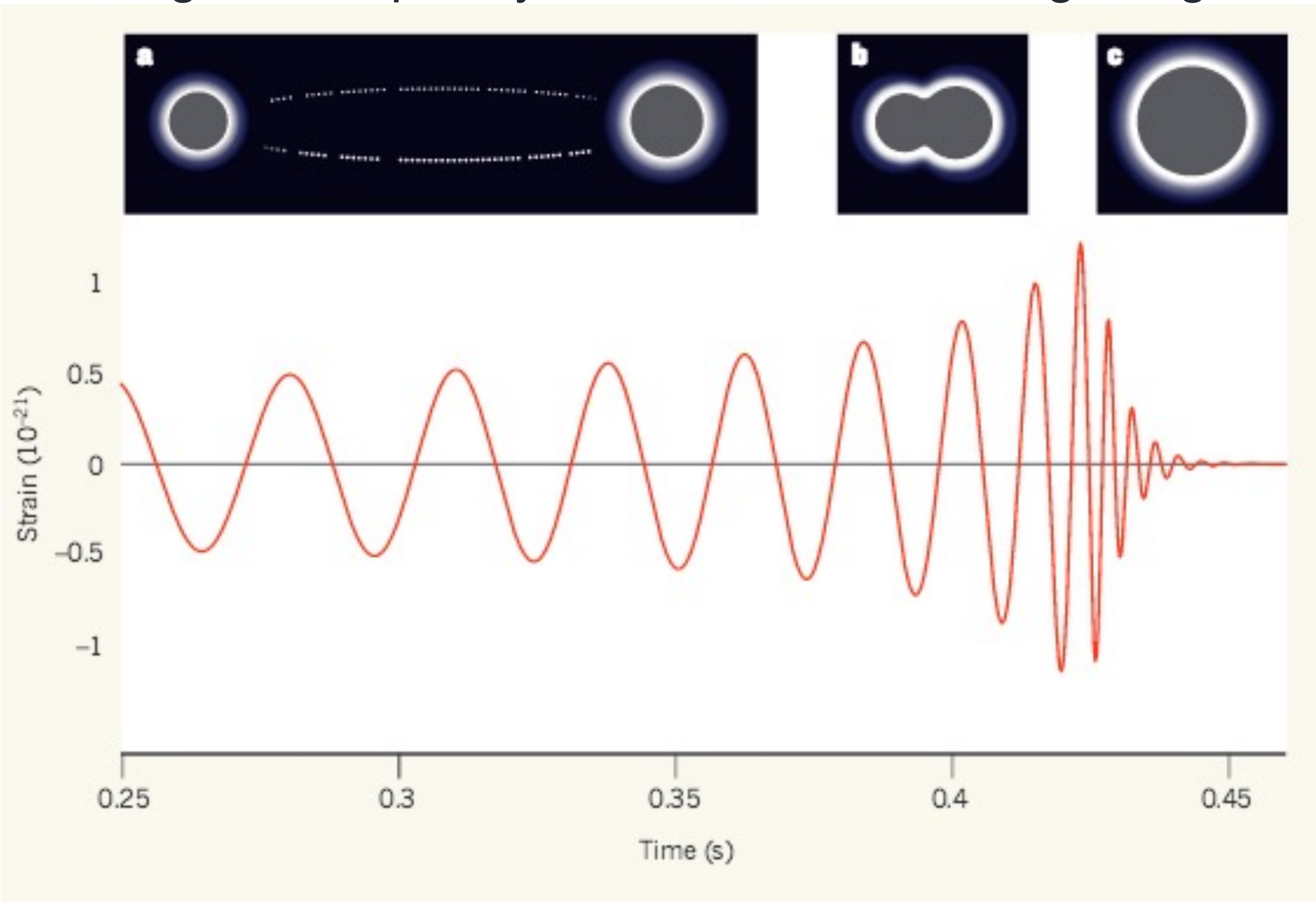
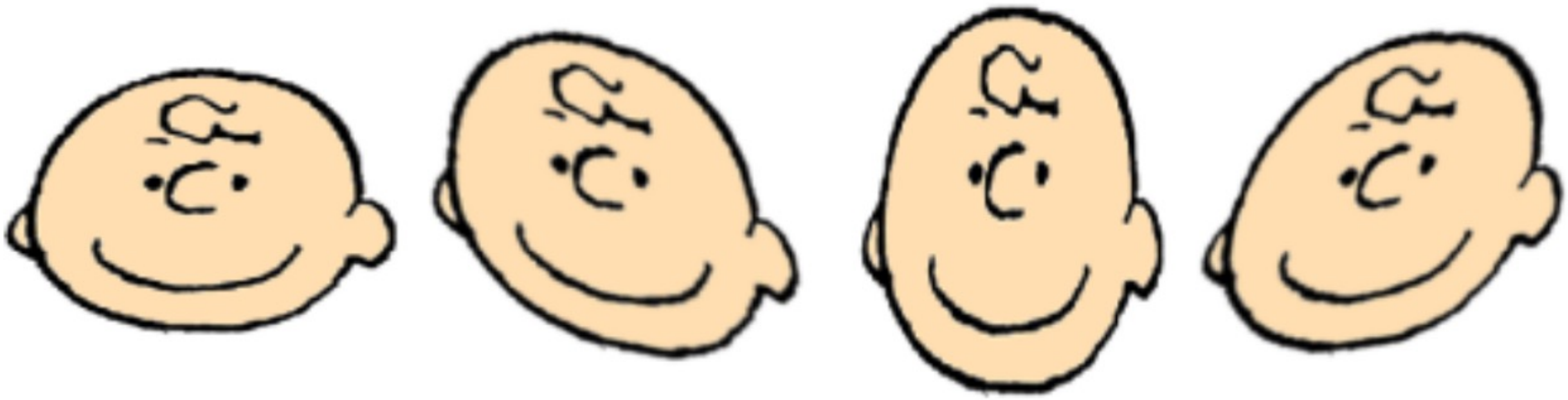


Figure 1 | A gravitational wave from merging black holes. Abbott *et al.*[3] report the detection of a

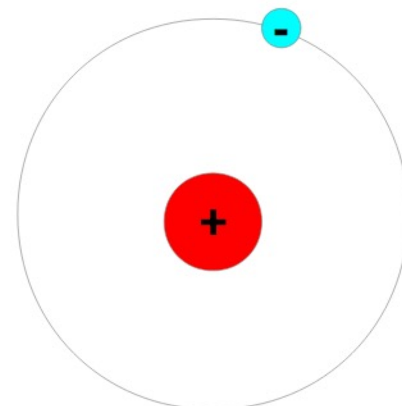
When GW passes through space deforms it

Michela Mapelli



But deformations are very small:

h= strain=relative deformation

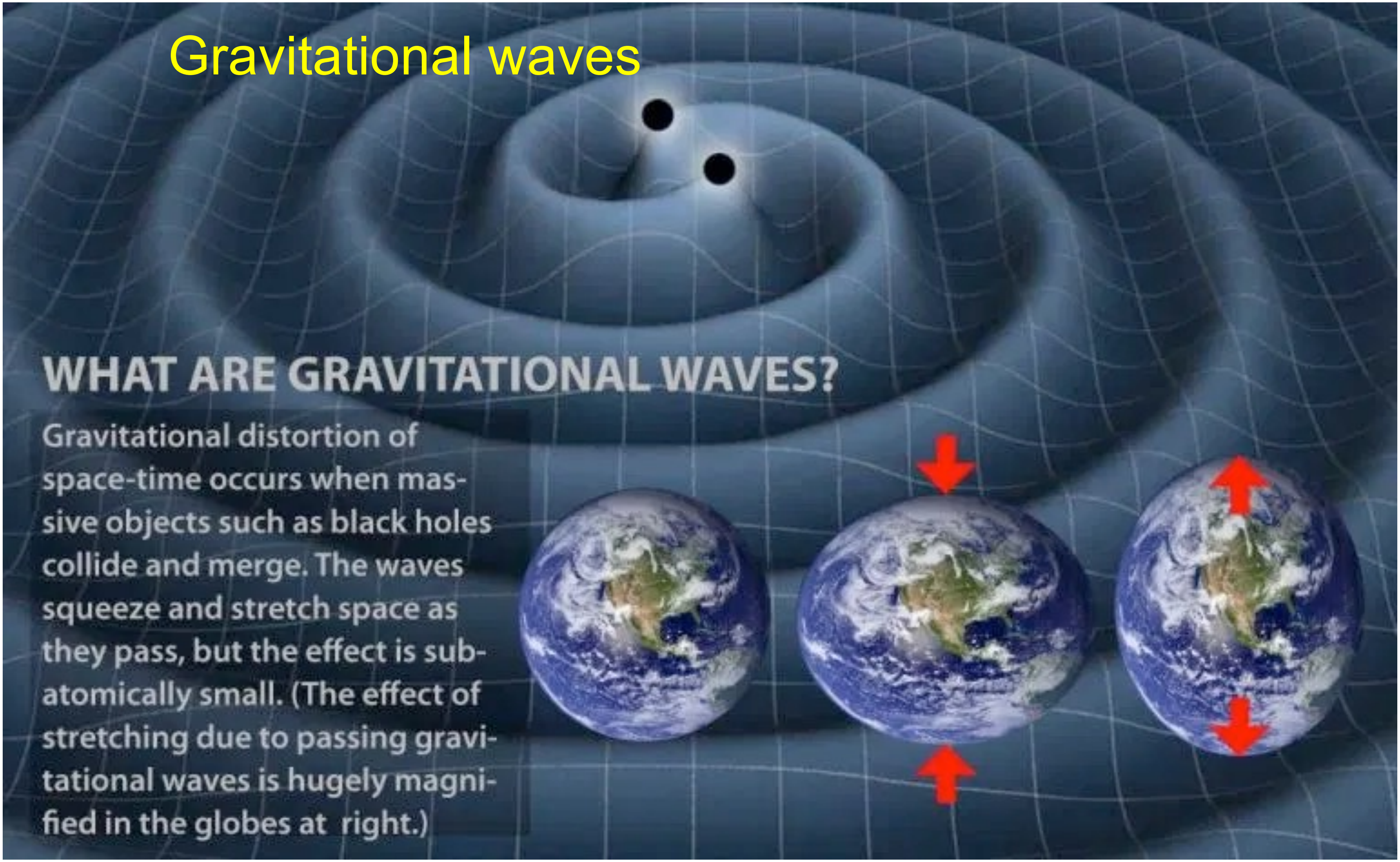


$$h = \Delta L/L \sim 10^{-21}$$

Over the sun-earth distance of 1.5×10^{13}cm,

$hL = \Delta L/L \sim 1.5 \times 10^{-8}$ cm

strain is change in length/length ($\Delta L/L$)


Gravitational waves
WHAT ARE GRAVITATIONAL WAVES?
Gravitational distortion of space-time occurs when massive objects such as black holes collide and merge. The waves squeeze and stretch space as they pass, but the effect is subatomically small. (The effect of stretching due to passing gravitational waves is hugely magnified in the globes at right.)

GRAVITATIONAL WAVES

General Relativity states that any masses with changing quadrupole will produce gravitational waves.
But for us to detect the waves the objects have to be extremely massive, and moving very quickly.

Since the two stars revolving around each other in a bound orbit are accelerated, gravitational radiation is generated.

Gravitational waves carry away energy and momentum at the expense of the orbital decay of two stars, thereby causing the stars to gradually spiral towards each other and giving rise to shorter and shorter periods.

GRAVITATIONAL WAVES

Think of gravitational waves as “ripples on space-time.” Imagine dropping a bowling ball on a trampoline–ripples will travel outward in all directions.

Similarly, large masses in the universe can create gravitational waves when they rotate around each other, collide with each other, or explode.

GRAVITATIONAL WAVES

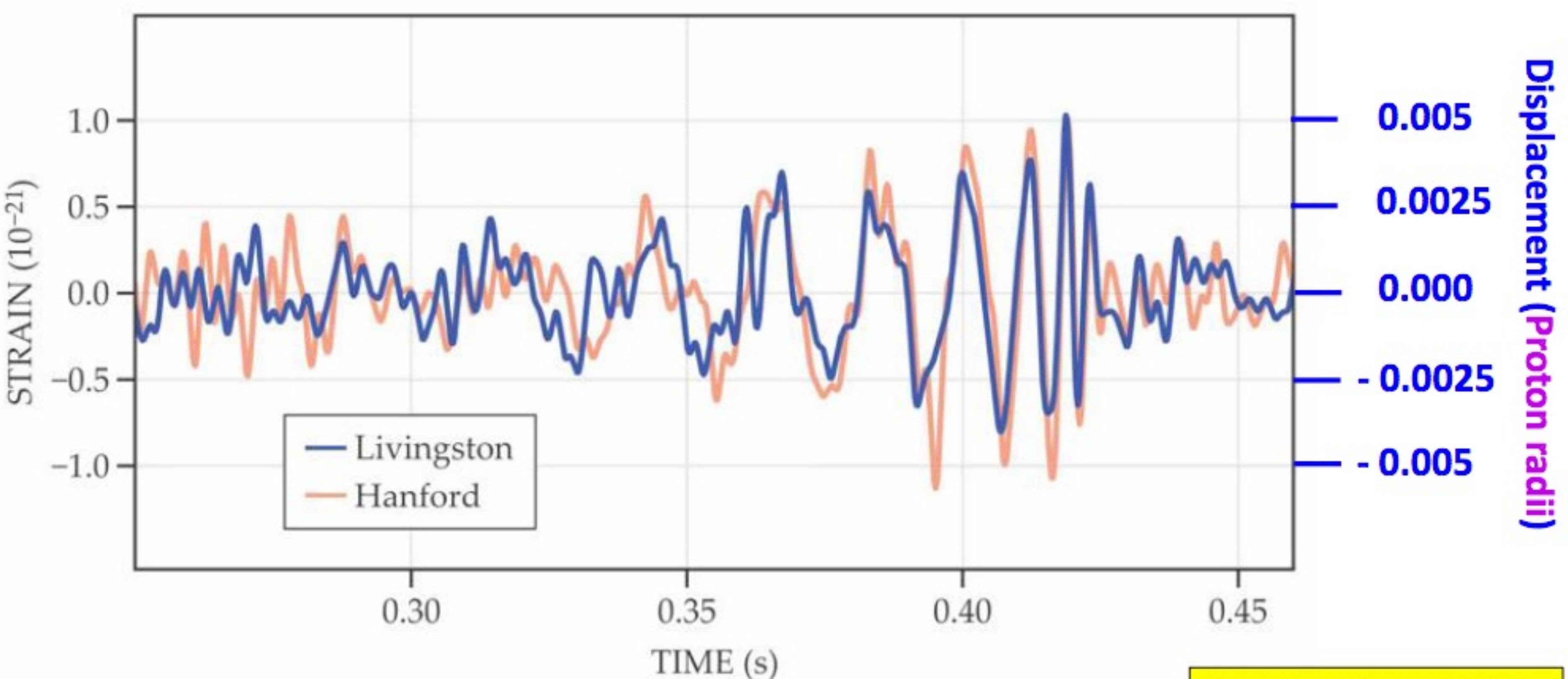
- As a gravitational wave passes an observer, the observer will find spacetime distorted by the effects of strain*.
  - Distances between objects increase and decrease rhythmically as the wave passes, at a frequency equal to that of the wave. The magnitude of this effect decreases in proportion to the **inverse** distance from the source.[

LIGO sources have strain h~dL/L ~ 10^{-21} to 10^{-22}
This is .001 the diameter of a proton over the length of the LIGO arms
The wavelengths of **gravitational waves** are ~ dimension of the system near the merger of two black holes. For black holes with masses 10 -100 $M_{\odot}$, **wavelengths** are ~ hundred to thousand km

*strain is change in length/length ($\Delta L/L$)

Event GW150914

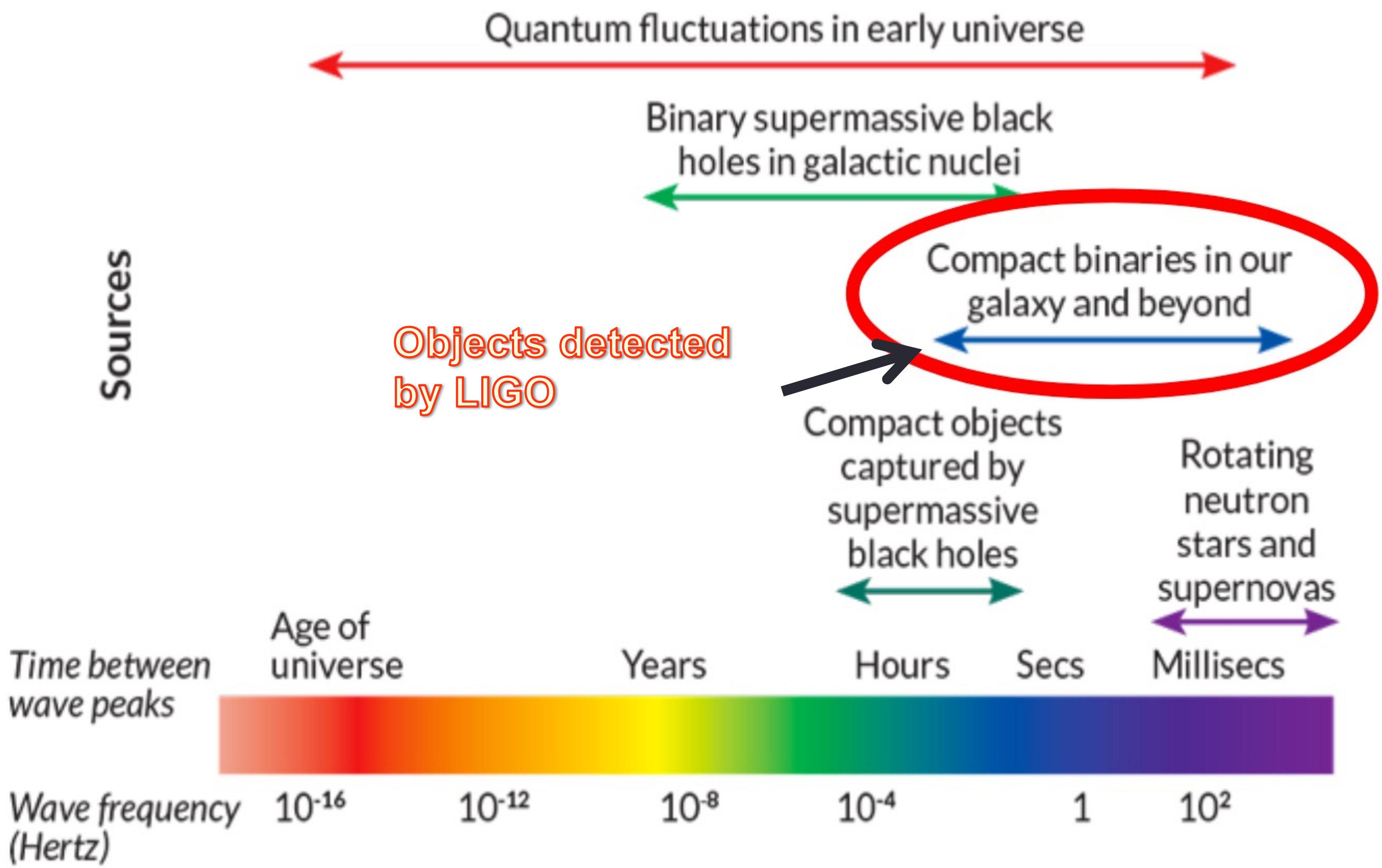
On September 14th 2015 the gravitational waves generated by a binary black hole merger, located about 1.4 Gly from Earth, crossed the two LIGO detectors displacing their test masses by a small fraction of the radius of a proton



Proton radius=0.87 fm

Measuring intervals must be smaller than 0.01 seconds

What are the astrophysical objects with non-zero quadrupole?



Michela Mapelli

– EMISSION of GWs implies LOSS of ORBITAL ENERGY:

a= radius of orbit
m_1 and m_2 are the masses of the 2 objects

$$E_{orb} = -\frac{G\, m_1\, m_2}{2\, a}$$

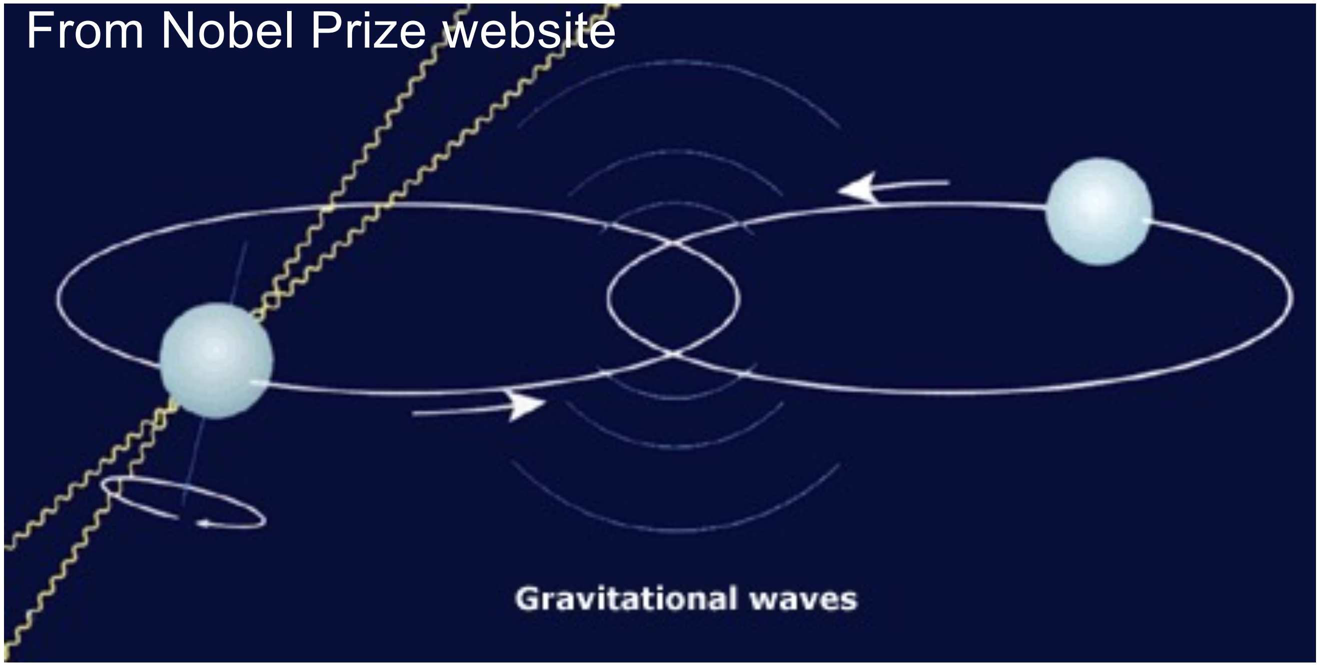
THE BINARY SHRINKS WHILE EMITTING GWs TILL IT MERGES

and the frequency increases

https://www.youtube.com/watch?v=g8s81MzzJ5c

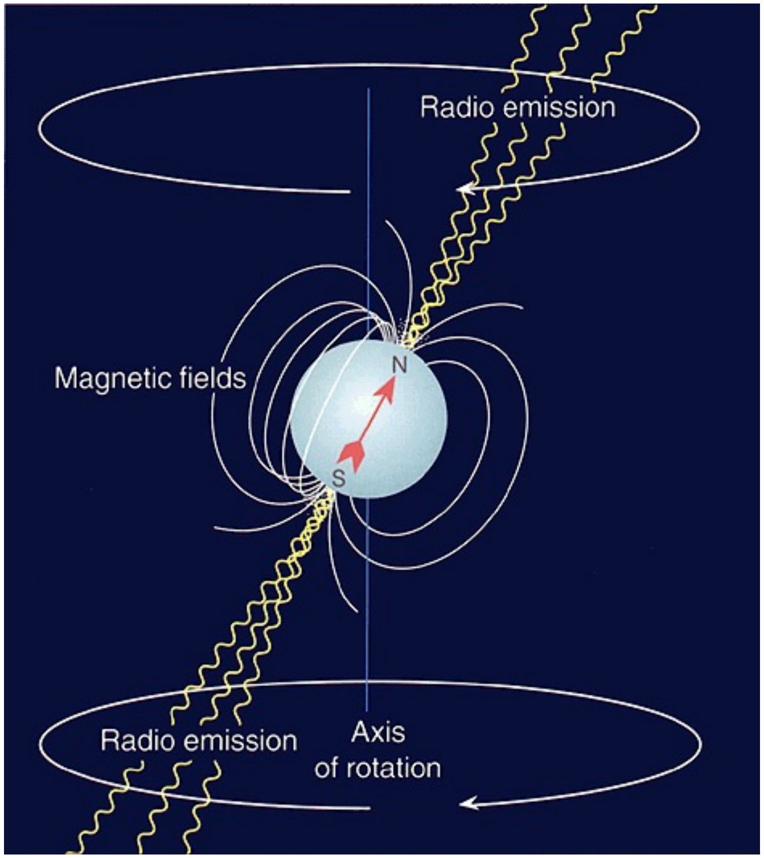
II : The first binary pulsar (PSR 1913+16)

- Russell Hulse & Joseph Taylor (1974)
  - Discovered remarkable binary system (2 Neutron stars orbiting very close to each other)
  - Nobel prize in 1993



Hulse-Taylor system

- Two **neutron stars** orbiting each other- v~300km/sec~0.1%c, 7.75 hr period, separation is 7.5×10^5km ~twice size of our sun
- One neutron star is a pulsar –
  - Neutron star is spinning on its axis (period of 59ms)
  - Emits pulse of radio towards Earth with each revolution
  - Acts as a very accurate clock!
- Strong gravity- good place to test GR
  - Orbit precesses 4 deg/year!
  - Orbit is shrinking due to gravitational waves
  - Why?

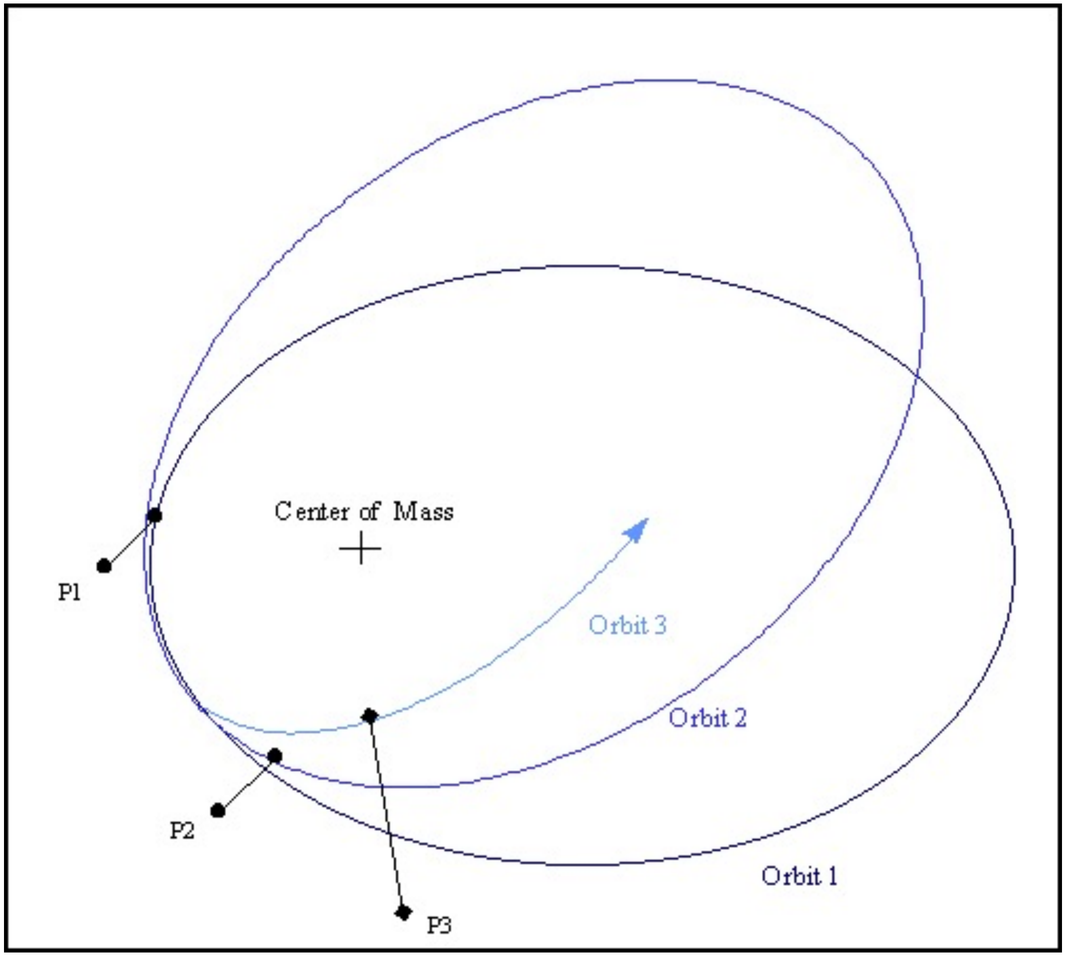


Binary Pulsar

The binary pulsar PSR 1913+16 precession is 4.2 degrees per year (compared to **43 arc-seconds per century for Mercury)**

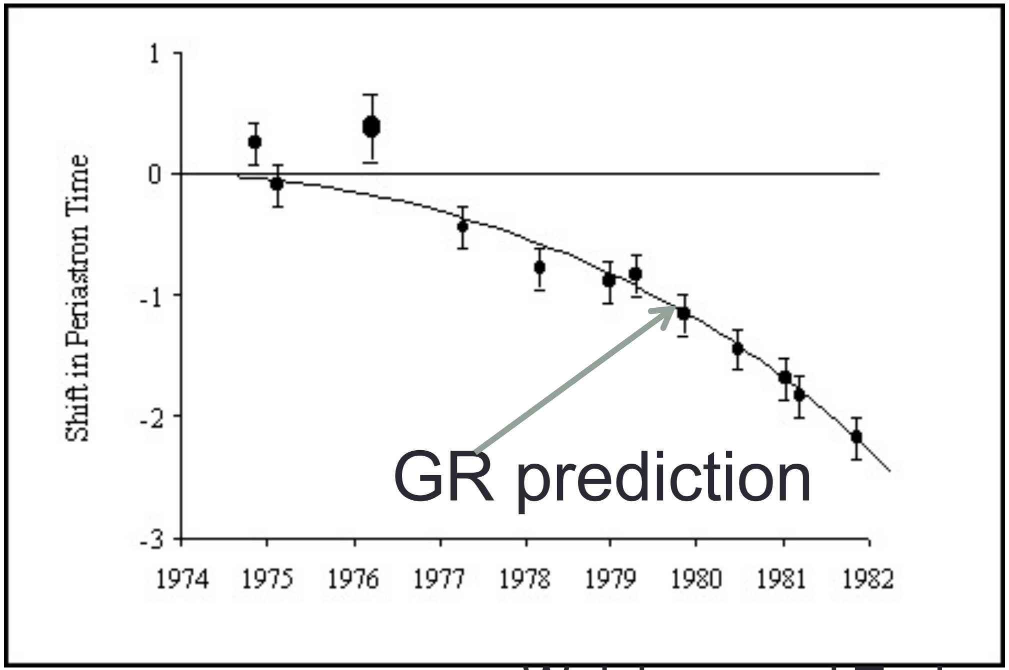
A measure of "how relativistic you are" is ($2\phi/c^2$) where ϕ is the Newtonian potential (GM/r)
At the surface of the sun $2\phi/c^2$ is $2x10^{-6}$ while close to a neutron star it is 0.2

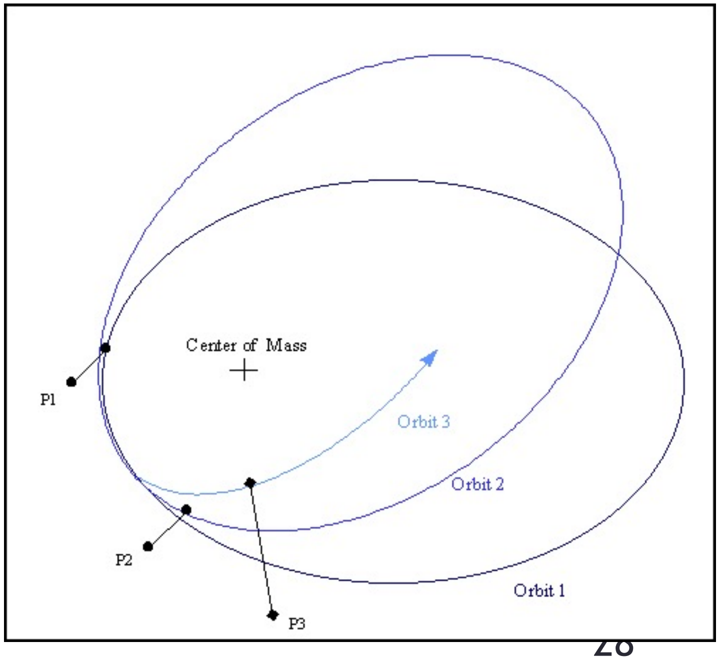
Precession of Orbit- Also seen in S2 around SgrA*



Precise test of certain aspects of GR

- When pulsar is approaching Earth, pulse frequency increases (Doppler shift); when pulsar is receding, pulse frequency decreases -- orbit of pulsar can therefore be "mapped"
- Orbit seen to be precessing (same physics as for Mercury) and shrinking (loss of energy due to gravitational waves) at the rate predicted by Einstein's theory to ~part in 1000





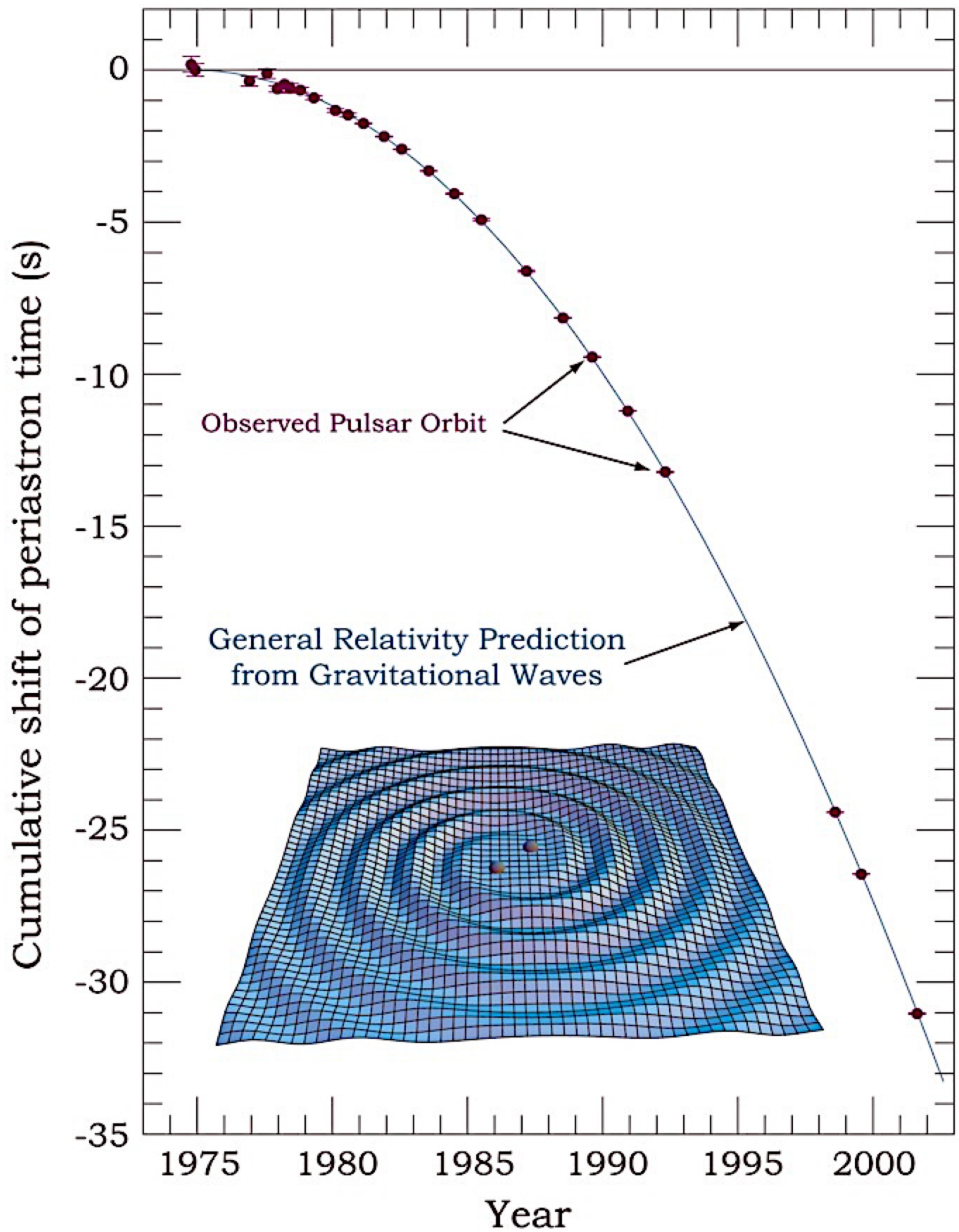
Weisberg and Taylor (2004)

As data have gotten better the agreement with General Relativity is more and more precise

A strong theory survives stronger and stronger tests

Binary pulsars were the first unambiguous detection of the effects of gravitational radiation

Merger in about 300 Million years



Binary Pulsar Tests of GR

The rate of orbit decrease (which is a reflection of the energy loss to gravitational radiation)

and

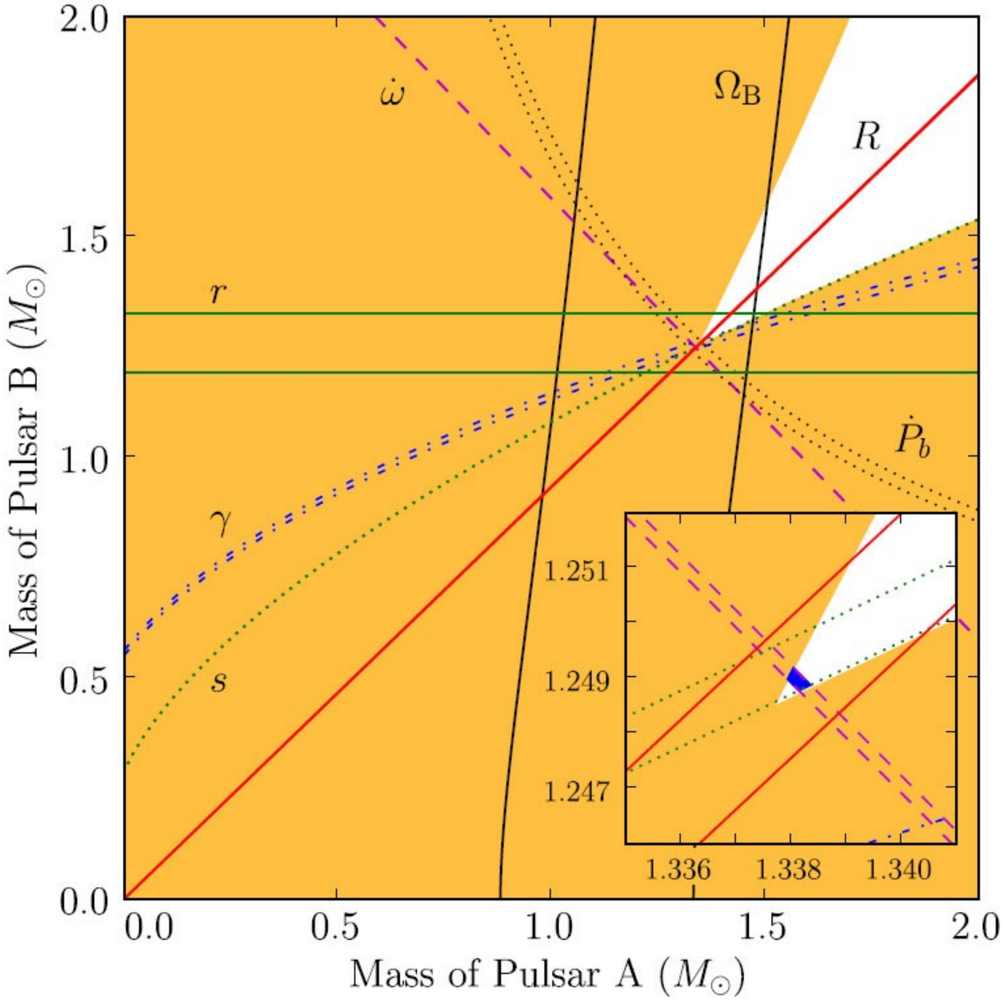
the Shapiro delay-the light emitted from the pulsar must travel through the intense gravitational field of the pulsar when exiting the system and thus there is time dilation

and

can test the Strong Equivalence Principle (SEP), Lorentz invariance and conservation of momentum.

Best pulsar test of GR: The Double Pulsar J0737-3039 (2 pulsars in orbit around each other) GR is verified with an uncertainty of 0.05%

Testing Einstein!



Double pulsar: Kramer et al.


Arecibo Radio Telescope in Puerto Rico

Collapse of Arecibo Telescope

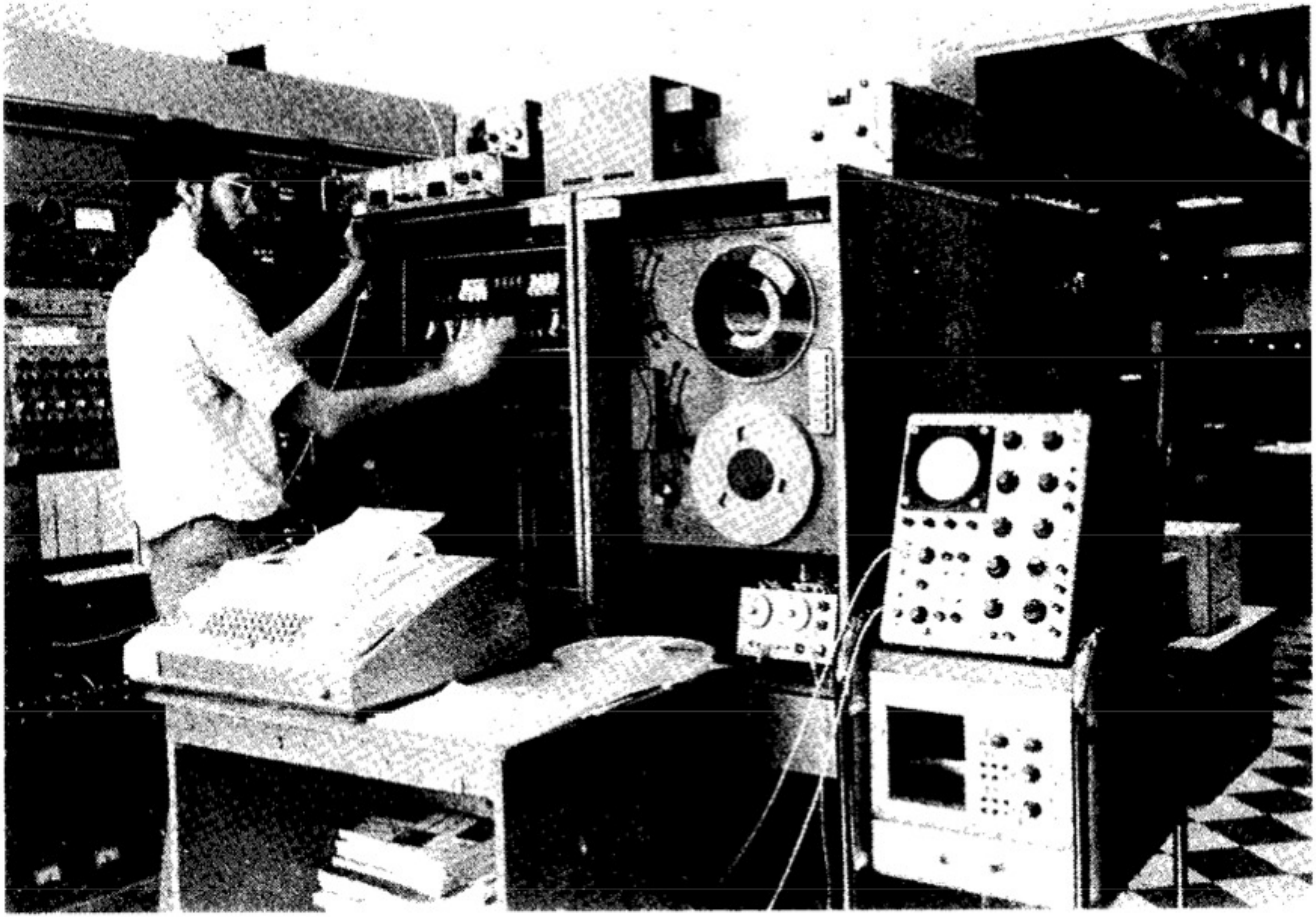


Fig. 5: A picture of myself with the Modcomp II/25 minicomputer used for the pulsar search at Arecibo, taken in the Arecibo control room shortly after the discovery of the binary pulsar.