LIGO: An Observatory for Detection of Gravitational Wave

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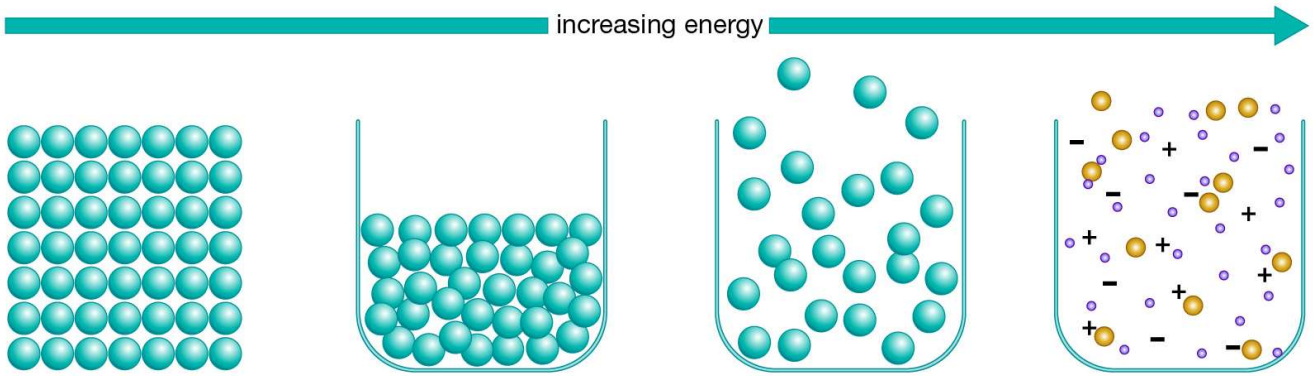
Azadi Ka Amrit Mahotsav

3rd September 2021

States of Matter



SOLID **LIQUID** **GAS** **PLASMA**

Institute for Plasma Research
Gandhinagar

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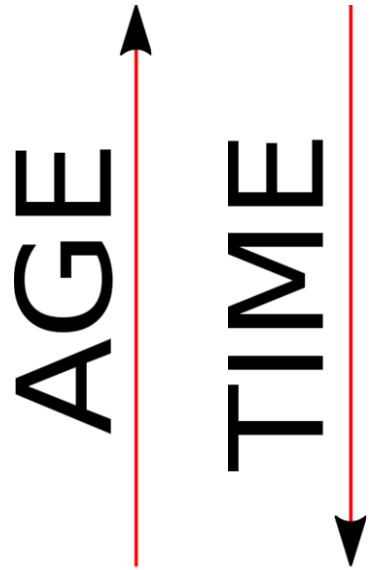
Source of matter

Form	Duration
Earth	4.5 billion years
Single celled	3.8 billion years
Plants	600 million years
Fish	420 million years
Reptiles	300 million years
Mammals	178 million years
Birds	65 million years
Primates	55 million years
Humans	Present



But time did not start when Earth was formed……..

And so did the states of matter

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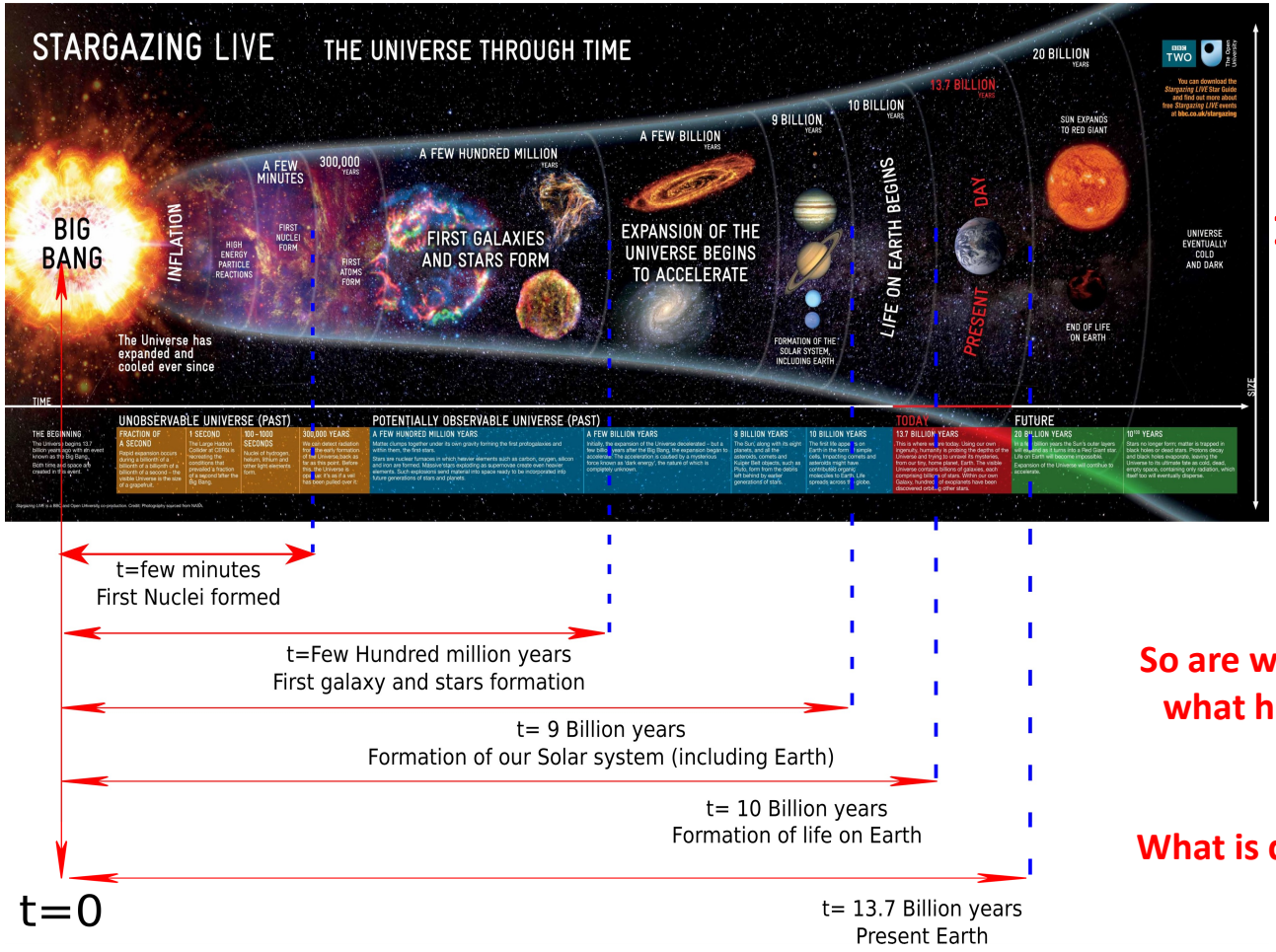
Age of Universe



t=few minutes
First Nuclei formed

t=Few Hundred million years
First galaxy and stars formation

t= 9 Billion years
Formation of our Solar system (including Earth)

t= 10 Billion years
Formation of life on Earth

t=0

t= 13.7 Billion years
Present Earth

TIME has already started 13.7 billion years ago in the vastness of SPACE

Question ??
So are we seeing the remnants of what had occurred 13.7 billion years ago….
&
What is destined for the future ??

Answer
It is embedded in the time capsule which has occurred 13.7 billion years back

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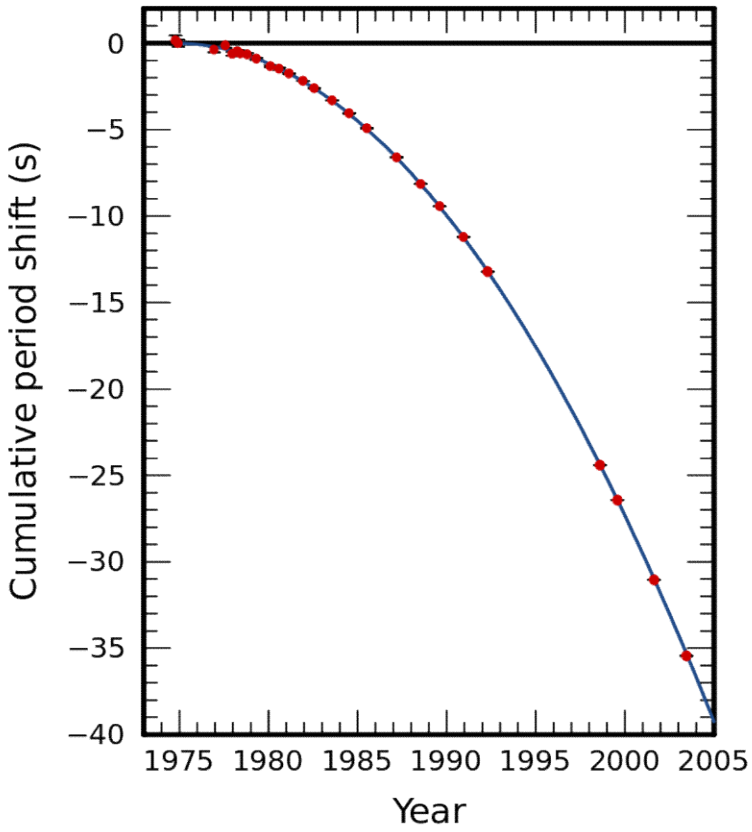
Deciphering the Answer

- Joseph Taylor and Russell Hulse from the discovery of binary pulsar 1913+16 in 1974 noticed some curious events
- Pulsar is a natural timing clock in the sky
- Pulsar rotated on its axis at 17 times per second (period = 59 ms) but, showed a variation in arrival time having a period of 7.75 hours
- Over an observation of 30 years, it was concluded that this pulsar had a binary pair and with time lost its energy.
- The loss in energy was in agreement with Einstein's general theory of relativity.
- 1993 Hulse and Taylor received the Nobel Prize in Physics

The question still remains how did the loss of energy happen and how it could be observed



Courtesy: https://en.wikipedia.org/wiki/Hulse%E2%80%93Taylor_binary

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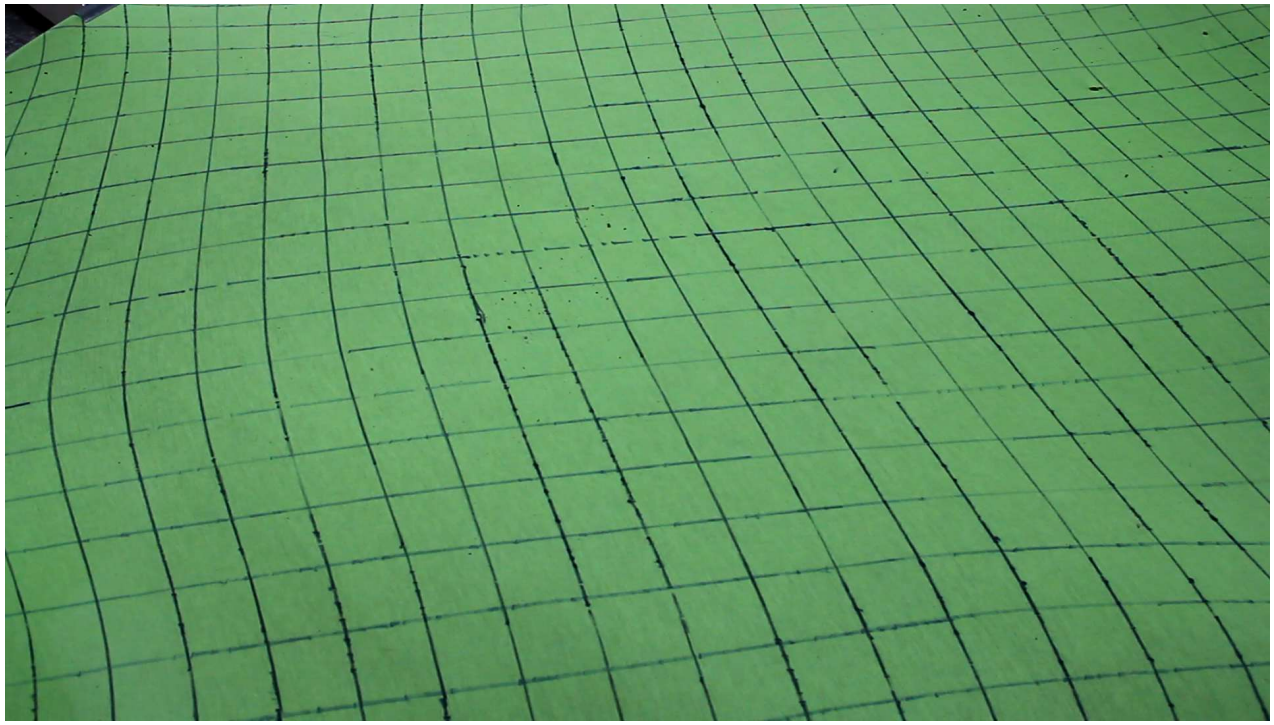
GR explained briefly



GR is essentially distortion of space by dense object predicted by Einstein

In comparison to Newton's laws of Gravity (in our world), Einstein's GR highlights warping of space by dense object and a less dense object moving towards the more denser object

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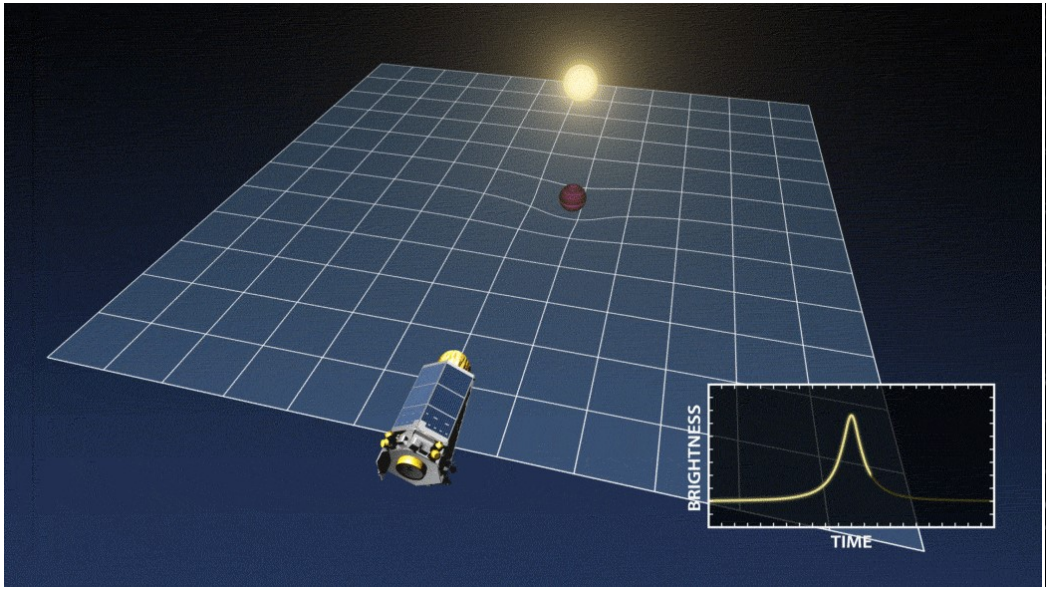
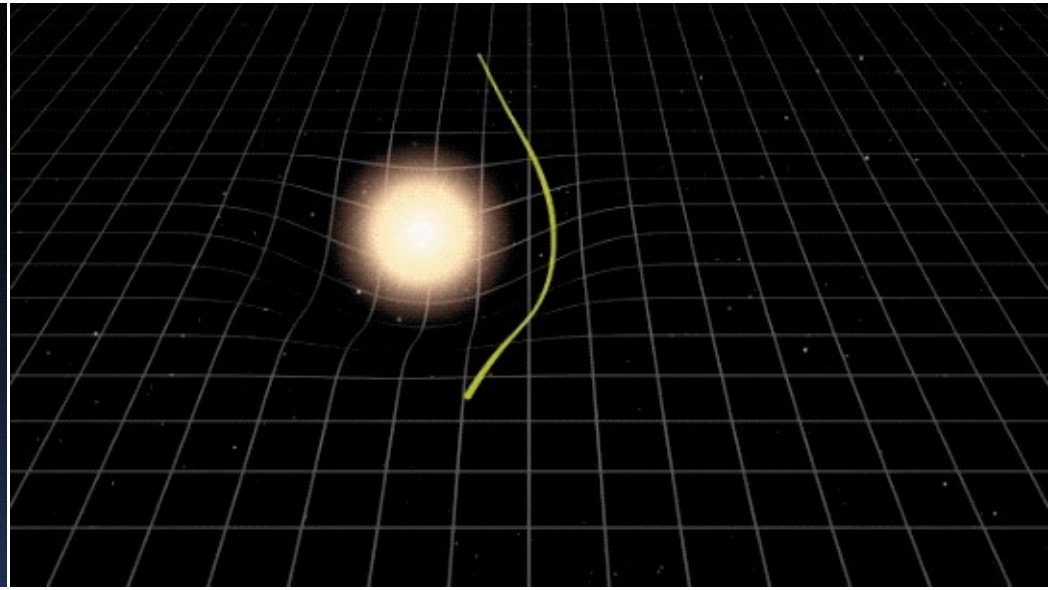
Examples of GR





Gravitational Lensing

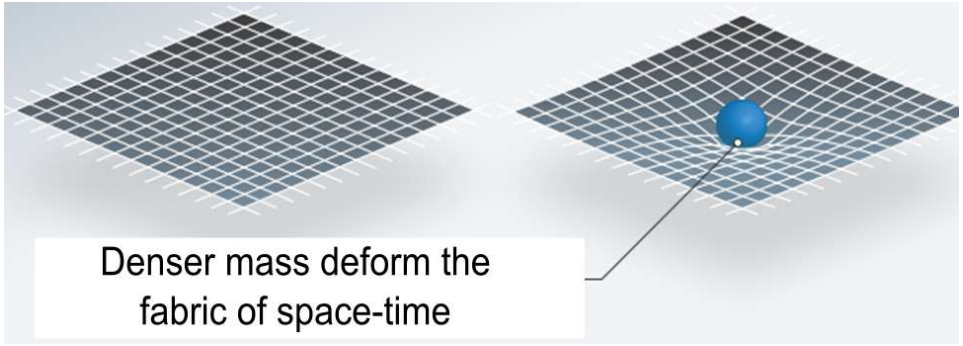
Gravitational time dilation

Courtesy (Gravitational lensing): https://www.jpl.nasa.gov/news/searching-for-far-out-and-wandering-worlds

Courtesy (Gravitational time dilation): https://nasa.tumblr.com/post/187009797389/how-gravity-warps-light

Elasticity of space

Newton's SPACE is RIGID
Einstein's GR consider SPACE has a finite stiffness, therefore the space is elastic



Einstein field equation is given by:

$$\mathbf{T} = \frac{c^4}{8\pi G}\mathbf{G}$$

T : Stress energy tensor
G : Einstein curvature tensor

A Good analogy is Hooke's Law on spring-mass system

$F = k\,x$

where F is the force creating deformation of x on spring

The value $k = \frac{c^4}{8\pi G}$ is 10^{43} N and the displacement is k^{-1} which is very small

Due to this extreme stiffness of space a dense matter is required to deform the SPACE

∴ Gravity is the curvature in space due to massive objects and is dynamical. From here the concept of spacetime arises

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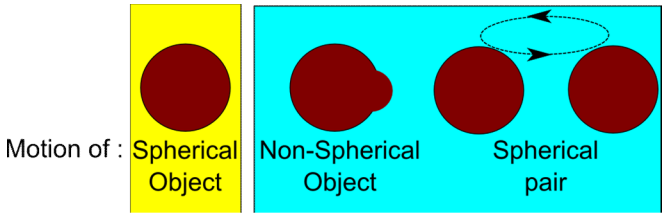
Loss of Energy

Why the pulsar 1913+16 showed a variation in arrival time of the pulses: was orbiting with another star

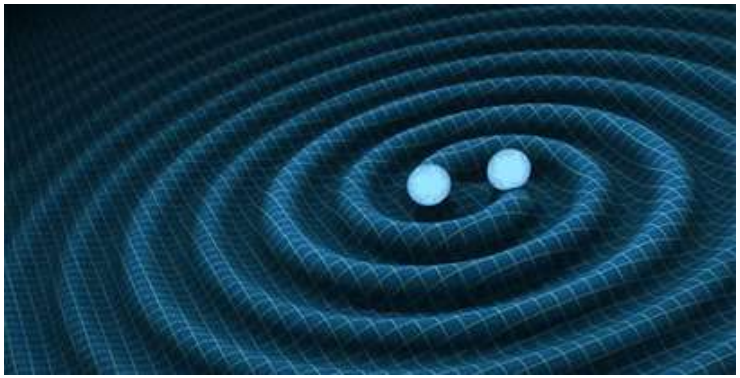
Observation: There was a variation in period of the orbital motion

Conclusion: Decay in orbit – Loss of energy



A perfect spherical object will not deform space

Deformation is created only by non-spherical motion of masses



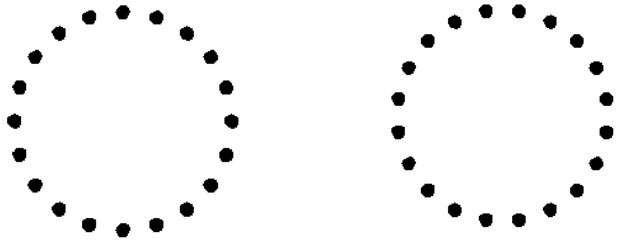
Binary object in orbital motion deforming the space

As loss of energy is periodic, it signifies a wave

As the loss in energy is in agreement with Einstein's prediction of gravitational waves, the energy dissipated by an orbiting binary is said to be the source of Gravitational Wave (GW)

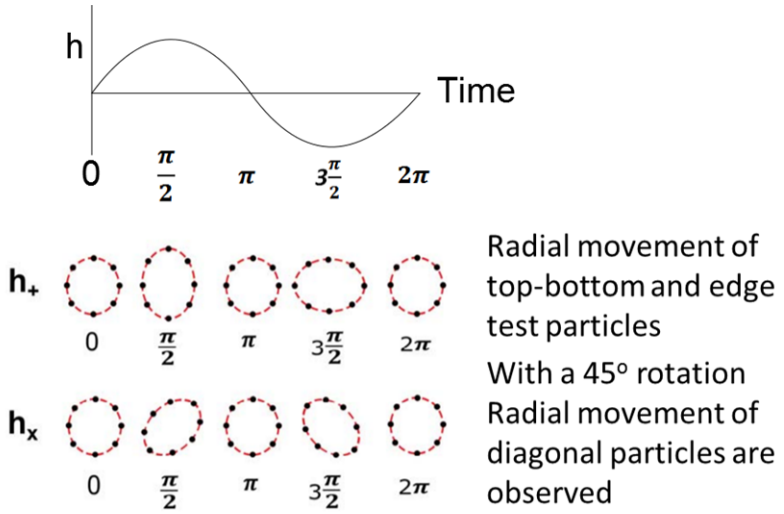
Gravitational Wave

GWs are transparent to matter and they set matter to oscillate
GWs propagate with speed of light



+ polarisation x polarisation

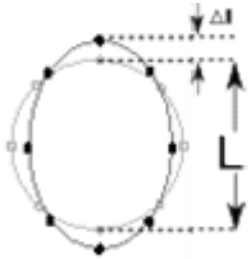
Test particles behaving in gravitational field



Radial movement of top-bottom and edge test particles

With a 45° rotation Radial movement of diagonal particles are observed

The simplest form of non-spherical deformation is the quadrupole moment,
Indicates that GW are quadrupole in nature



Relative change in spacing between the test masses '*h*' is $\frac{\Delta l}{L}$, which is the GW amplitude

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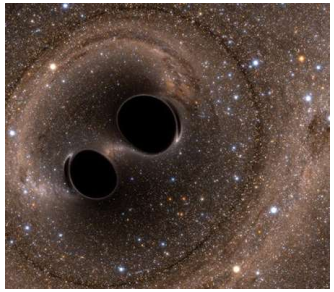
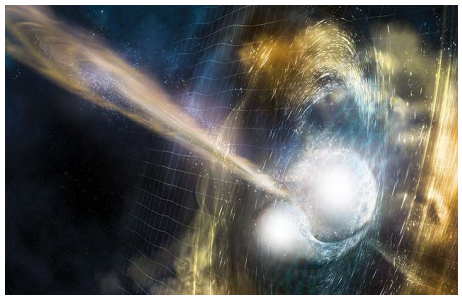
Sources of Gravitational waves



Black hole pairs

Courtesy: https://www.ligo.caltech.edu/news/ligo20160211

Courtesy: https://theconversation.com/at-last-weve-found-gravitational-waves-from-a-collapsing-pair-of-neutron-stars-85528



Neutron star pairs

Supernova

Courtesy: https://www.wikipedia.org/

1 solar mass = 1.9×10^{30} kg
1 MPc = 3×10^{22} m

An example:

Assume coalescing black holes have M=1 x solar mass,
At 10 MPc distance, the strain amplitude will be $h \sim \frac{r_s}{R} \epsilon^{0.5}$
r_s is the Schwarzchild radius ($r_s = 2\frac{GM}{c^2}$) and R (10MPc) is the distance of the observer
The value of h~3×10^{-22} which is small, and the displacement value $\Delta l = h.L \sim 1.2x10^{-18}m$

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Earlier GW Detectors

Joseph Weber-first resonant bar detector

Explorer detector

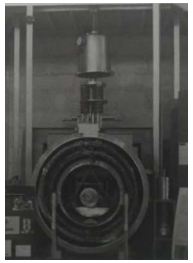
Detector at Stanford

Room temperature based detectors

Allegro

Nautilis

Auriga



Cryo based detectors

Network of bar detectors measured strain $h \sim 10^{-20}$ (which are rare events)

It was here that
Laser interferometers replaced bar detectors

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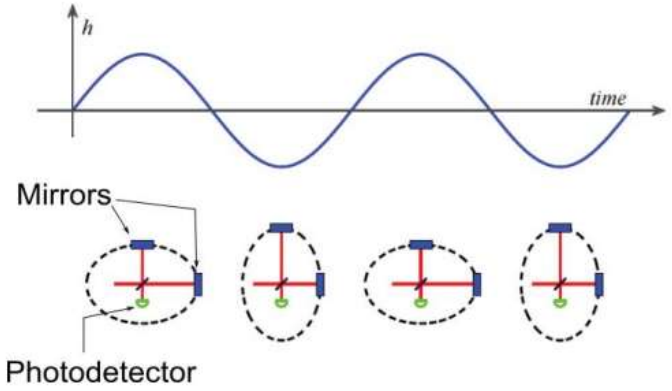
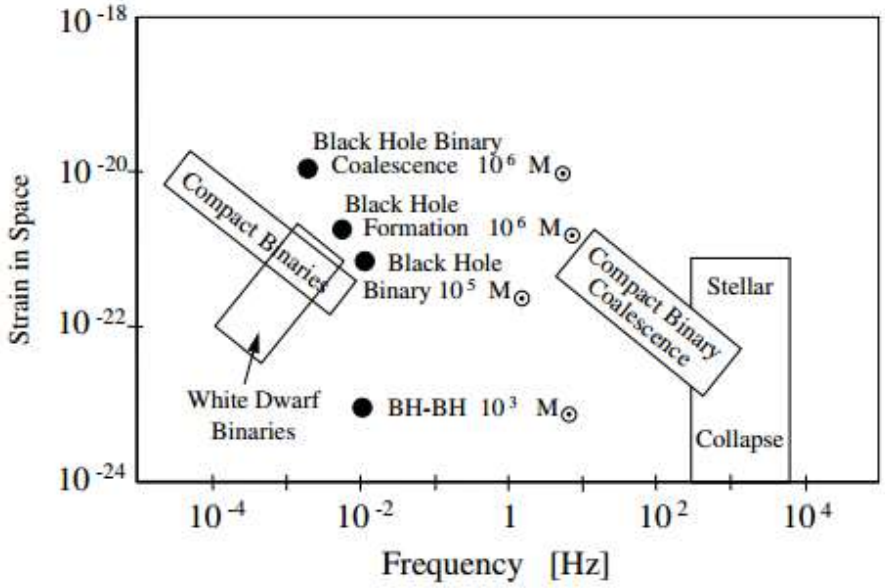
Laser Interferometer



Simple Michelson arrangement helps

GW frequencies ranges from ~10^{-17}Hz to ~10^{3} Hz



Frequency >10Hz - ground based detectors
Lower frequency – space based detectors

Advantages over Bar detector

- Work at wide range of frequencies
- Velocity of light compared instead of sound
- No length limitation due to resonant frequency
- Light can be reflected back and forth to increase path length

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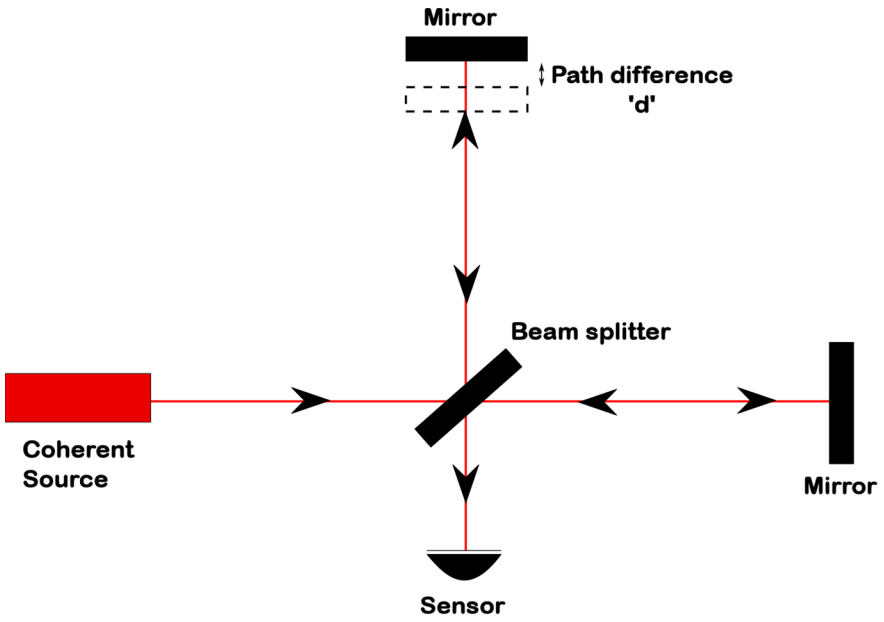
Basics of Michelson Interferometer



$$d = m\frac{\lambda}{2}$$ Constructive interference

$$d = (m + \frac{1}{2})\lambda$$ Destructive interference

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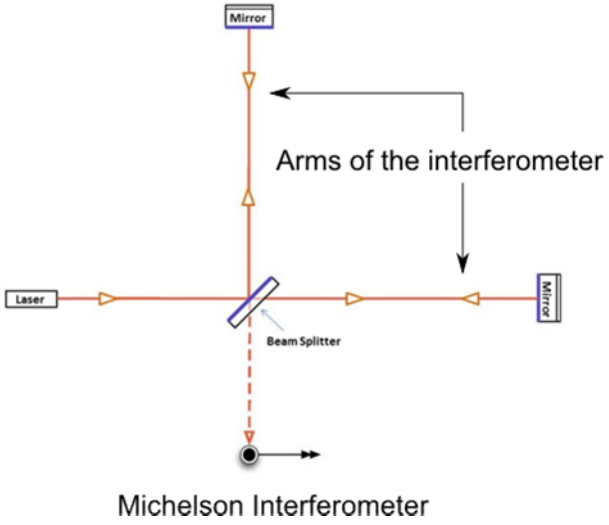
Modified interferometer



Michelson Interferometer

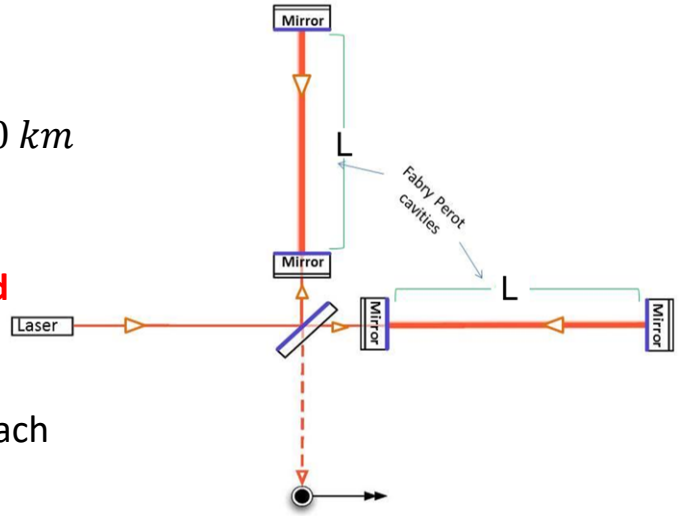
If GW $\lambda \sim 3000\ km$

Optimal value of $L = \frac{\lambda}{4} = \frac{3000\ km}{4} = 750\ km$

This is large

By inserting mirrors in each arm, **desired** path length can be achieved

Now a **Fabry-Perot cavity** is formed in each arm of the interferometer

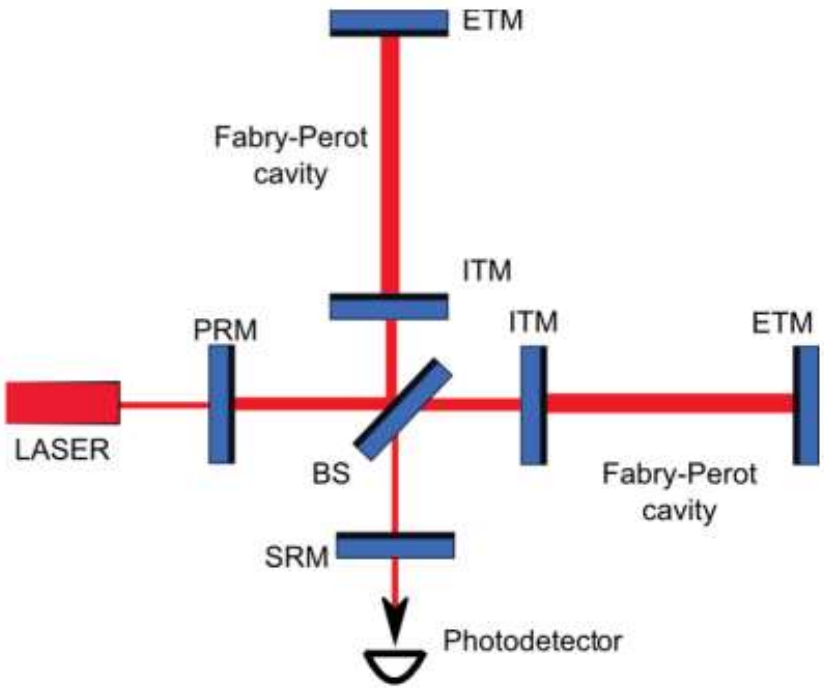


Modified Michelson Interferometer

To have a proper coupling between the GW and the detector:

- The storage time of light in the interferometer must match the GW period
- The power in the optical cavity should be high to see the effect

LIGO detector

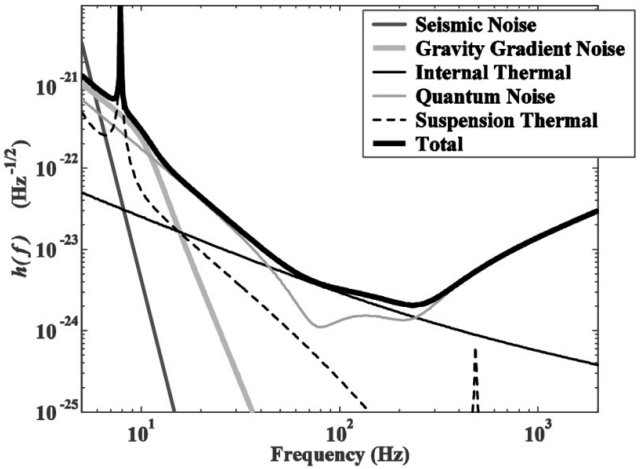


Two more mirrors are introduced in the detector:

- Power recycling mirror
- Signal recycling mirror

Other parameters which influence the detector:

i. **Seismic noise – Due to ground motion**
ii. **Newtonian noise – Gravity gradient**
iii. **Thermal noise – Mirrors and suspension**
iv. **Quantum noise - Photons**



Main task is to identify and then mitigate the noise

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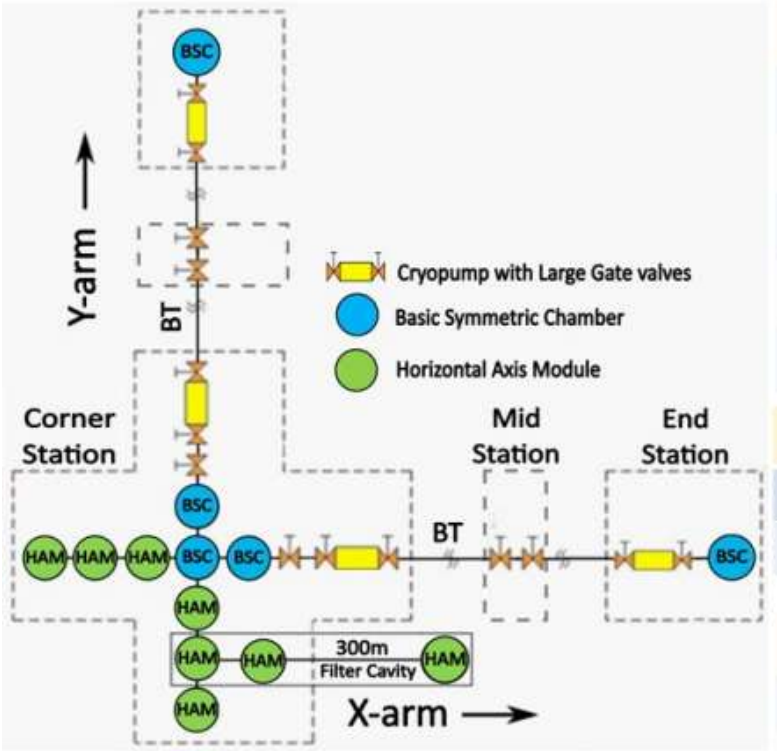
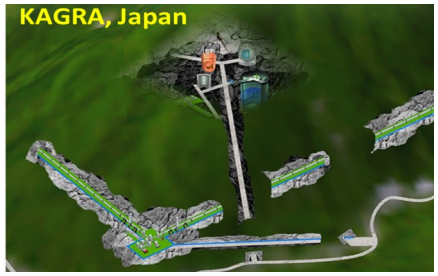
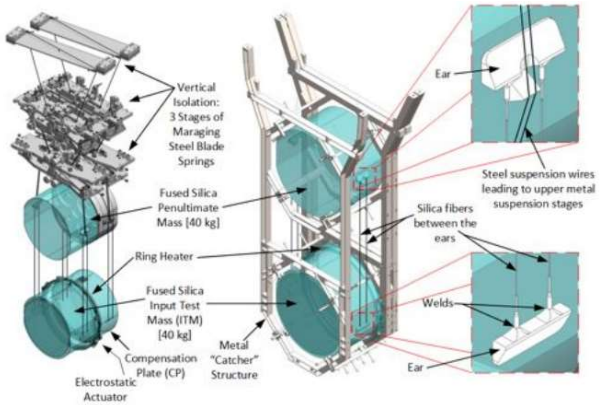
LIGO observatory







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LIGO-India

LIGO-India site: Aundha, Near Hingoli in Maharashtra state

DCSEM – Site acquisition, development and civil infrastructure

IPR – Vacuum facility setup, vacuum controls and monitoring, interferometer controls and data acquisition*

RRCAT – Interferometer detector, , 3rd generation & upgrades technology development and detector controls*

IUCAA – Site identification & characterization, GW science, Data handling, storage and analysis

4-Nodal institutes

LIGO-India when completed will add to the network of existing detectors and improve localization of the GW sources

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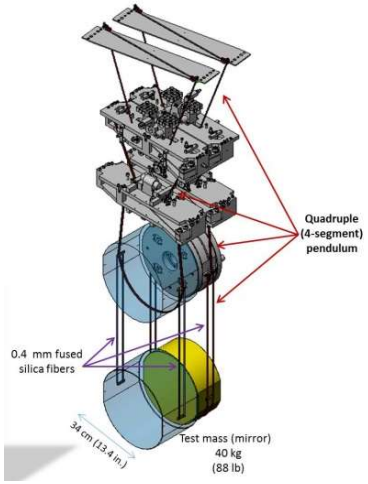
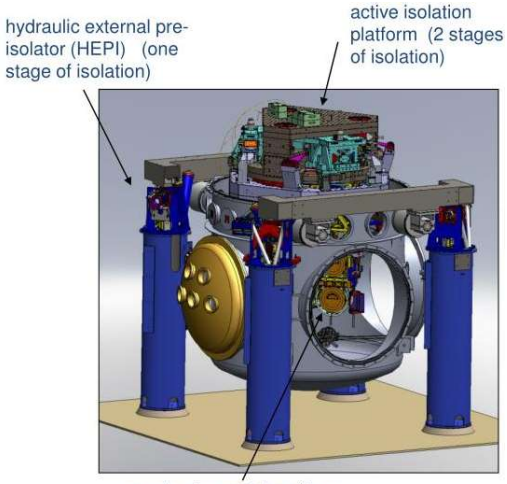
Installation and Setup Challenges in LIGO

Aligning 4 Km beam tube



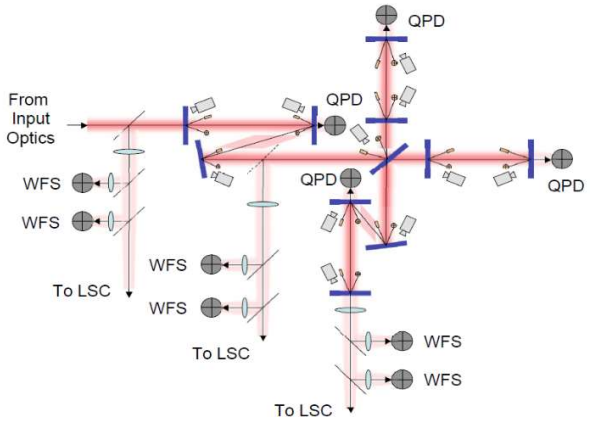
Suspended optics

40 Kg FS mirror



Vacuum enclosure with suspended optics

Courtesy: ligo.caltech.edu, LIGO-G1701594-v1



Sensing and control

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Challenges for IPR

Large volume chambers

Basic Symmetric Chamber (BSC)

Horizontal Access Module (HAM)

Beam tube

Cryopump and Large gate valves

Data acquisition and controls

- Selection of steel for fabrication of chambers and beam tube
- Integration of BSC and HAM with spools and adapters
- Fabrication and installation of 8 km beam tube
- Integration and efficient operation of cryopumps
- Alignment and integration of large size gate valves
- Total volume to be evacuated : 10,000 m^3
- Pressure to be maintained : < 10^{-9} mbar

Gases	Pressure (mbar)
N_2	$6x10^{-11}$
H_2O	$1x10^{-10}$
H_2	$1x10^{-10}$
CO_2	$2x10^{-11}$
CO	$5x10^{-11}$
CH_4	$3x10^{-11}$

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IPR's Effort towards LIGO-India project

Basic Symmetric Chamber (BSC)

Horizontal Access Module (HAM)

Parameters Achieved

Equipment	Unit	Basic Symmetric Chamber		Horizontal Access Module
Internal Diameter	m	2.6		2.1
Height	m	5.2		2.9
Wall Thickness	mm	12.7		12.7
Surface Area	Sq. m	52		27
Volume	Cu. m	27		11
Quantity	Numbers	1		1
Vacuum Requirement :	mbar			
Main Volume		Acceptance	1.0×10^{-7}	1.0×10^{-7}
		Demonstrated	8.9×10^{-8}	8.2×10^{-8}
Annulus volume		Acceptance	1.0×10^{-5}	1.0×10^{-5}
		Demonstrated	4.0×10^{-6}	8.8×10^{-6}
He leak rate:	mbar.l/s			
Local		Acceptance	1.0×10^{-9}	1.0×10^{-9}
		Demonstrated	5.2×10^{-10}	8.2×10^{-10}
Global		Acceptance	5.0×10^{-7}	5.0×10^{-7}
		Demonstrated	3.9×10^{-9}	4.6×10^{-9}

1:1 scale prototype fabrication of BSC and HAM chambers

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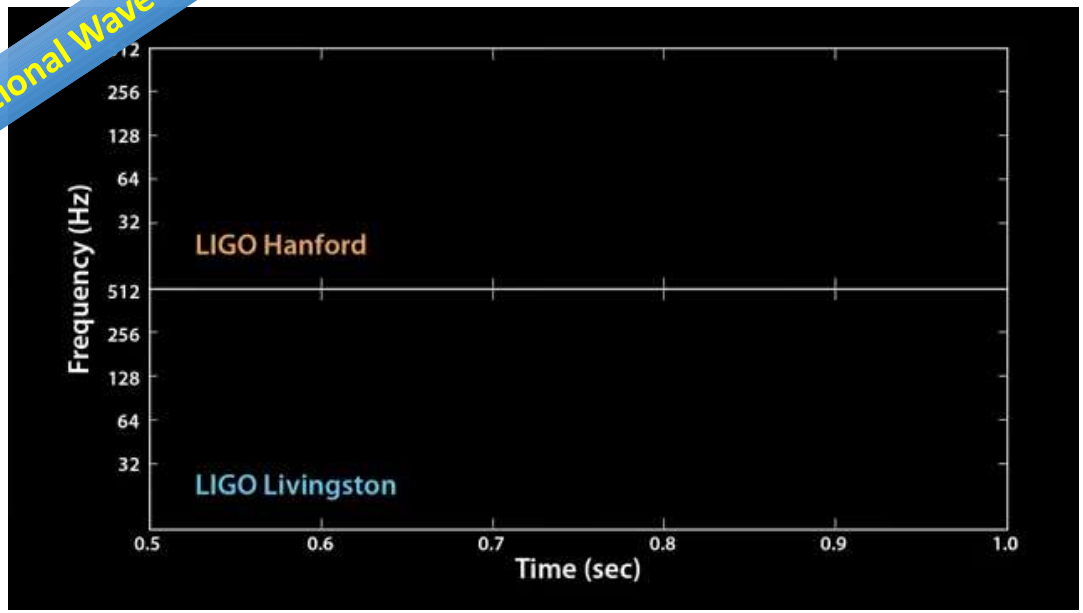
Discovery of GW

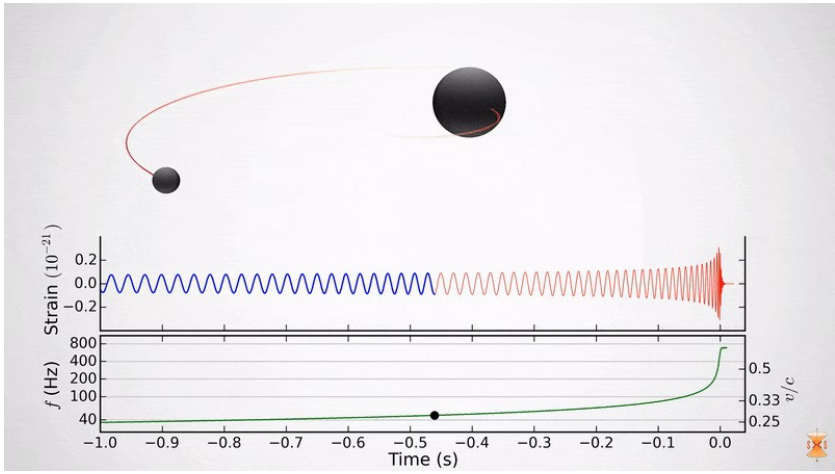
Gravitational Wave discovered



Inspiral, merger and ring-down of two Black-Holes of 36 and 29 solar masses.

Final black hole has a mass of 62 solar mass, rest 3 solar mass radiated as energy

Event occurred 410 Mpc from Earth



Animation of inspiral, merger and ring-down

1 solar mass = 1.9×10^{30} kg

1 MPc = 3×10^{22} m

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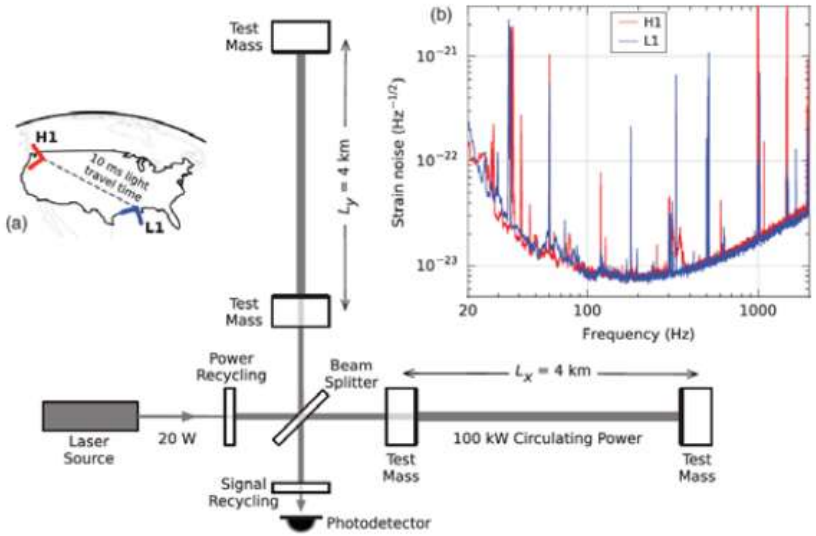
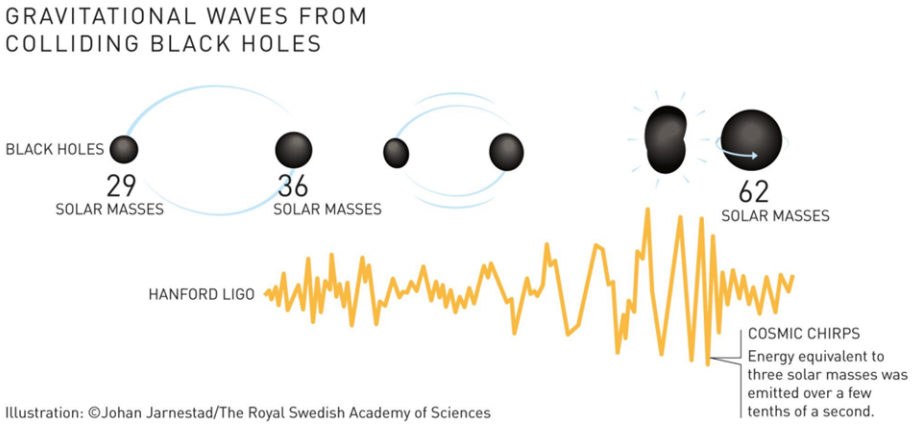
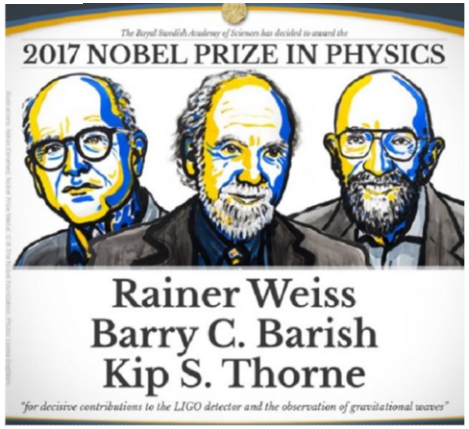
Achievement



September 14, 2015





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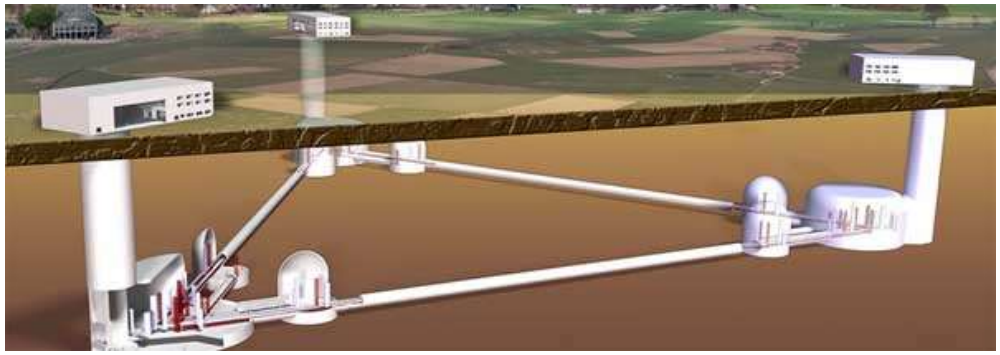
Importance of GW and GW Research

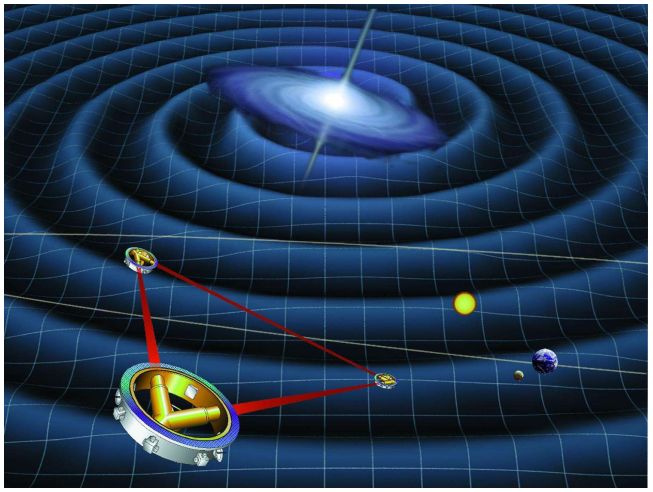
- GW study can address many key points which were either till date a prediction or confined in a mathematical calculation
- In the 100 years of Einstein's numerical calculations, phenomena like gravitational lensing and existence of black holes were actually seen
- GW research brings out a cutting edge technology in the field of science and engineering such that the least count of any scale can be improved many folds
- As a possibility (my thoughts) there might be other states of matter present around us which have low vibrational energy
- GW studies also gives out possibilities to reach those places where electromagnetic spectrum are masked

Other planned detectors



Einstein Telescope (ET)
Arm length: 10 km

Courtesy:
https://stfc.ukri.org/research/particle-physics-and-particle-astrophysics/particle-astrophysics/ground-based-gravitational-wave-detectors-current-generation/



Laser Interferometer Space Antenna (LISA)
Arm length: 2.5 million km

Courtesy:
https://www.lisamission.org/articles/lisa-mission/lisa-mission-gravitational-universe

Acknowledgement: LIGO-Division IPR

Thanks for listening