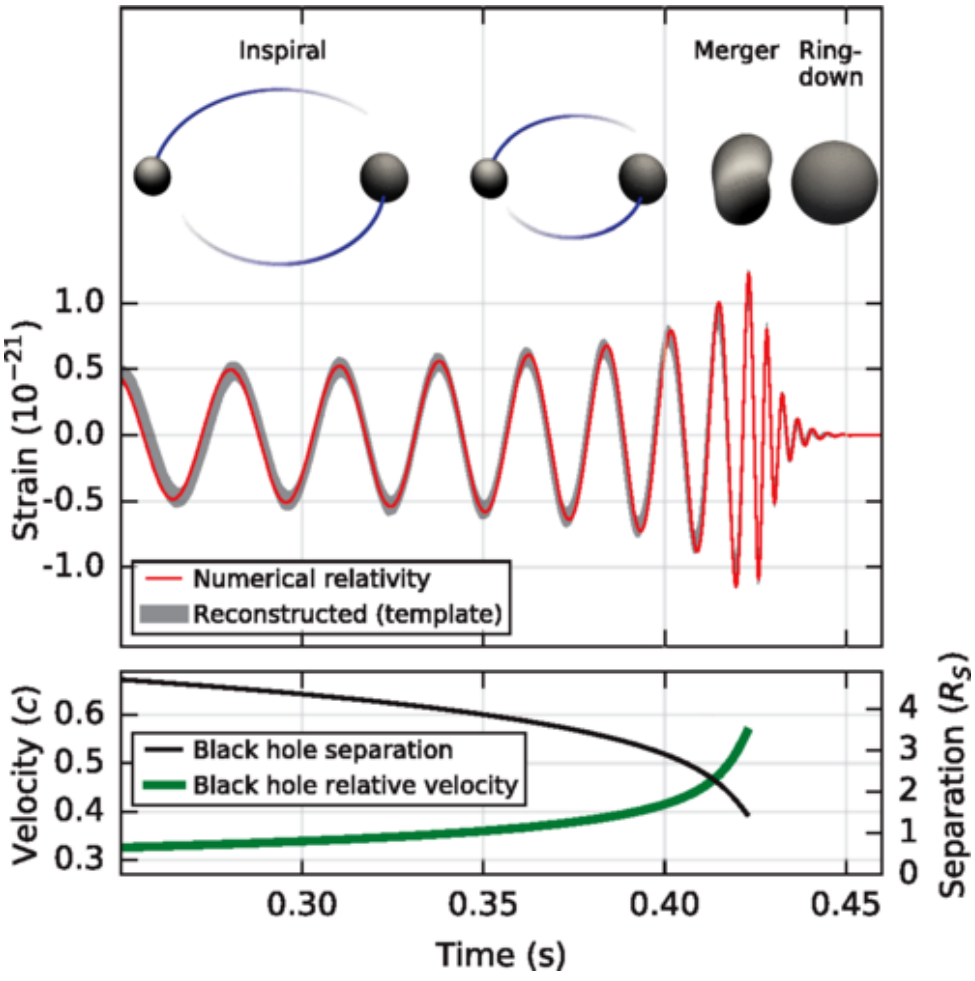
A HUNDRED YEARS LATER ...

February 11, 2016: *On September 14, 2015 the Earth suffered a small, transient deformation, lasting for about half a second. This was due to the merger of two black holes about 30 times more massive than our Sun, a billion years ago and about 400 mega parsecs in the Southern direction. . . .*

The Simulation & The Signal



Credits: DOI: http://dx.doi.org/10.1103/PhysRevLett.116.061102

https://losc.ligo.org/s/events/GW150914/audio/GW150914_NR_shifted.wav

What are Waves?

Waves are localized disturbances propagating at finite speeds.

A wave has a speed, an amplitude which is a measure of the size of the disturbance, and a wavelength which denotes its spatial extent (or a period which denotes its duration).

Examples: Water waves, sound, light, radio-waves, ...

What propagates is the ability to induce disturbance in the surroundings.

What are Gravitational Waves?

These are disturbances in the geometry of the space-time, travelling at the speed of light.

Here is a visualization*.

They induce transient deformations in the plane perpendicular to their direction of propagation.

Tidal deformations*.

An extreme exaggeration**.

* https://www.youtube.com/watch?v=psLuYxMetP0

** https://www.youtube.com/watch?v=WgE6lb_i78A

Discovery of Black Hole Binary: Observation Facts

Signal to noise	24
False Alarm probability	$< 2 \times 10^{-7}$
Duration from 30 Hz	~ 200 ms
cycles from 30 Hz	~ 10
Peak strain	1×10^{-21}
Peak displacement	$\pm$ 0.002 fm
frequency/wavelength at peak	150 Hz/ 2000 km
No. of offline analysis pipelines	5
CPU Hrs consumed	50 million
No. of researchers	$\sim$ 1000, 80 Inst., 15 countries

Credits: https://losc.ligo.org/s/events/GW150914/GW150914-FactSheet-BW.pdf

Discovery of Black Hole Binary: Inferred parameters:

Likely distance	230 – 570 Mpc
Initial mass/Remnant BH mass	60 – 70/ 58 – 67
Primary/secondary BH mass	32 – 41/ 25 – 33
Primary Spin/Secondary spin	$< 0.7/ < 0.9$
Remnant spin	$0.57 - -0.72$
Peak speed of BHs	$\sim 0.6c$
Ring down frequency	~ 250 Hz
Peak GW luminosity	3.6×10^{56}
Radiated Energy	$2.5 - -3.5 M_\odot$
Graviton mass bound	$< 1.2 \times 10^{-22}$ eV
Consistent with General Relativity	passes all tests performed

The Electromagnetic View . . .

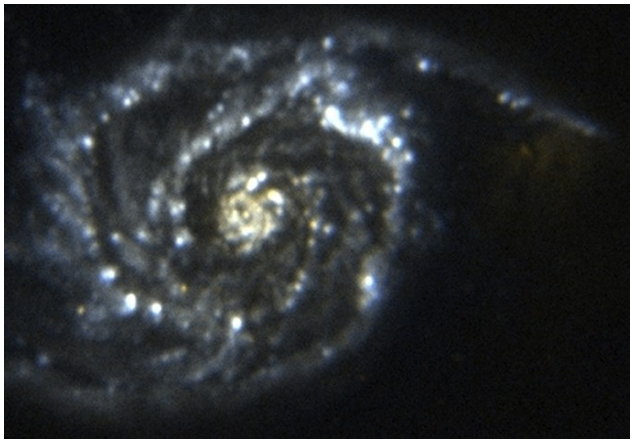
infrared

visible

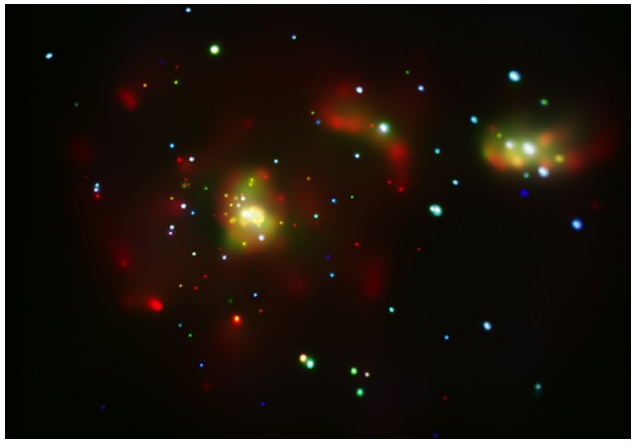
Credits:

http://www.physci.mc.maricopa.edu/Astronomy/astlabs/ast114/galaxy-lab/m51.htm
http://coolcosmos.ipac.caltech.edu/cosmic_classroom/multiwavelength_astronomy/multiwavelength_museum/m51.html

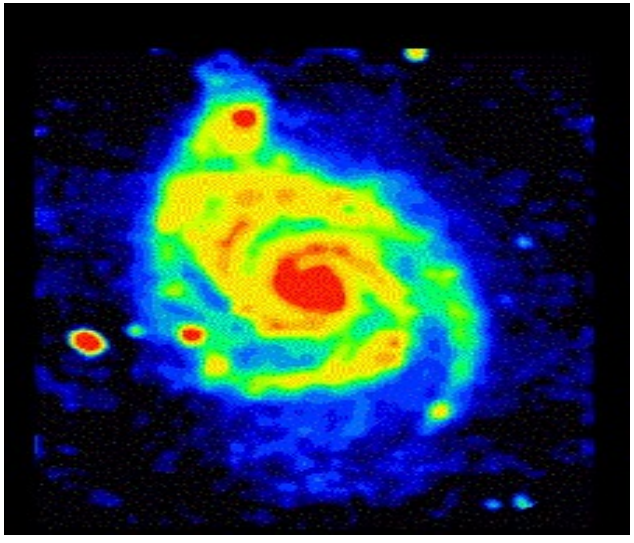
The Electromagnetic View



ultraviolet



x-ray



Radio

GWs ?

Sources of Gravitational Waves

Any matter distribution which is at least quadrupolar and has an accelerated time variation, produces gravitational waves.

However the amplitudes are usually very small and only somewhat extreme astrophysical processes produce significant gravitational waves. Here are the formulae -

$$\text{Ampl} \sim 10^{-44} \times \frac{\ddot{Q}}{\text{Dist}} \quad , \quad \text{Power} \sim 10^{-54} \times \dddot{Q}^2 \ \text{W}$$

$$\ddot{Q} \sim \text{Mass} \times \text{Len}^2 \times \text{Freqn}^2 \quad , \quad \dddot{Q} \sim \ddot{Q} \times \text{Freqn}$$

Sources of Gravitational Waves

Examples are: (a) violent events such as collapse leading to supernovae, (b) mergers of compact binaries, (c) primordial waves from the very early universe etc.

They have wide ranging spatial/temporal scales of variation eg:

Compact binaries have frequencies ranging over $10^{-4} - 10^{4}$ Hz (wavelengths of about $10 - 10^{9}$ kms) while primordial waves or those from mergers of super-massive black holes would have frequencies around nano-Hz (10^{14} km).

For current detectors, compact binaries of NS-NS, NS-BH, BH-BH are the most promising candidates.

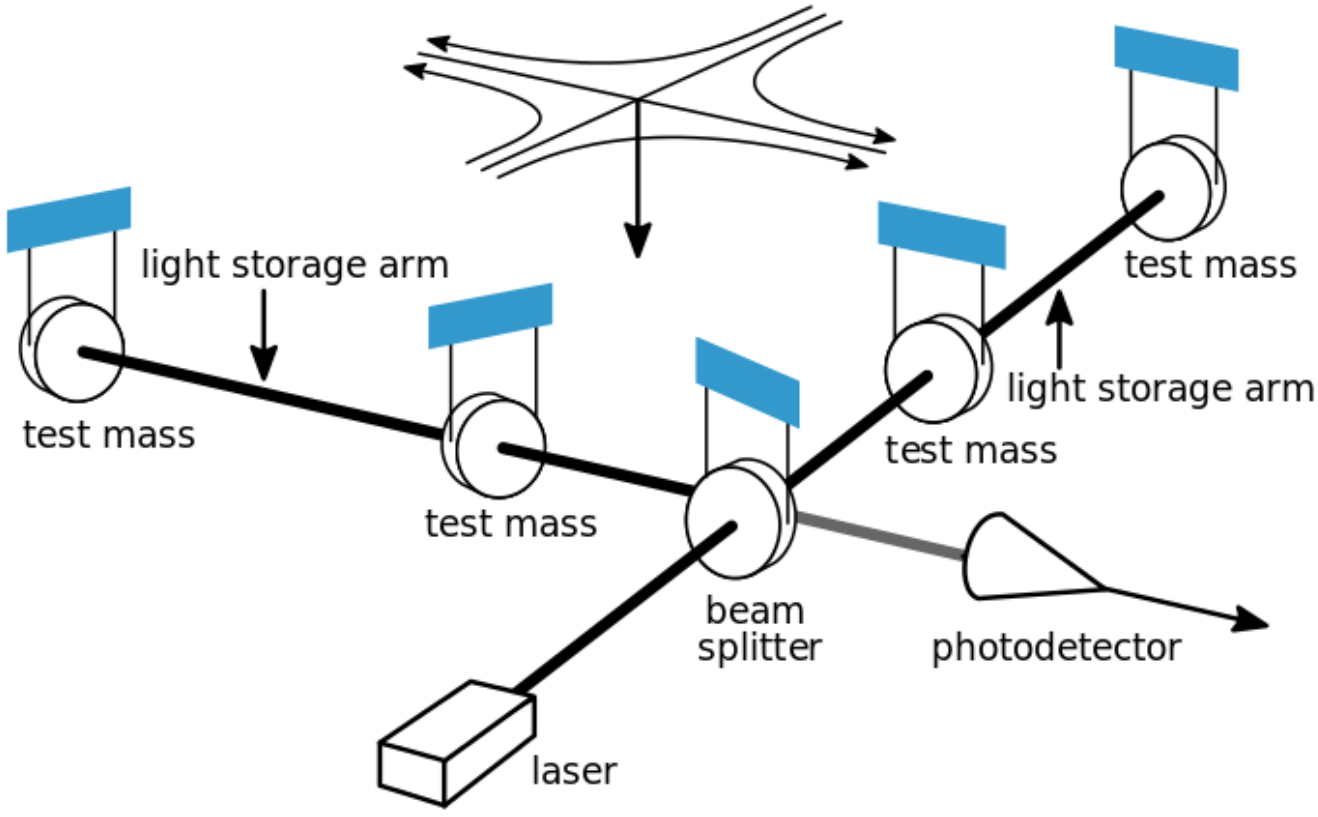
The Challenge

Source	Man made	Earth-Sun	NS mountain	NS-NS	BH-BH
Distance	10^6 m	Light Year	Kpc	Kpc	Mpc
Amplitude	10^{-44}	10^{-25}	10^{-24}	$10^{-23} - 10^{-19}$	10^{-16}
Power (W)	10^{-40}	10^{2}	10^{30}	$10^{18} - 10^{38}$	10^{48}

$$\text{Strain} := \delta L/L \sim \text{Amplitude}/2$$

Need to measure strain $\sim 10^{-23} - 10^{-21}$ for the most promising binaries in the range: $10 - 10^3$ Hz (wavelength $10^2 - 10^4$ kms).

The Interferometer



Schematic diagram of initial LIGO interferometer.

Credits: Wikipedia and
https://www.youtube.com/watch?v=psLuYxMetP0

The Sub-systems

Optics: Laser, beam splitters, Fabry-Perot cavities with vacuum, mirrors, photo-detectors, . . . ;

Suspension System: The optical assembly must be mounted so as to be mechanically isolated and yet must be 'free' to move in the plane parallel to the ground.

These have to be very elaborate in order to eliminate/minimize any real or spurious strain i.e. "noise" produced by non-GW processes.

The Noise

Thermal jitters, distortion of the mirrors – use cryogenics;

Radiation pressure on the mirrors – reduce the laser power;

Beam spread due to scattering, fluctuations and reflection defects – mirror material, coating and vacuum system;

Quantum mechanical fluctuations in the Laser and photo-detector (shot noise) – increase laser power, use squeezed light sources;

Some of the LIGO details

Specs	**aLIGO (iLIGO)**
Strain sensitivity	8×10^{-23} (10^{-21})
Optical power at input	125 W(6 W)
Optical power at mirrors	800 kW (30 kW)
Cavity beam size	6 cm (4 cm)
Test masses	40 kg (11 kg)
Mirror diameter	35 cm (25 cm)
Seismic isolation system	3 (0) stage active, 4 (5) stage passive

(Edited from https://dcc.ligo.org/public/0037/G080303/000/G080303-00.pdf)

What Next?

Earth based GW observatories are limited to the frequency range of a few Hz to kHz. To observe in lower frequency ranges one option is to go to space (eg eLISA). But even this leaves out many possible sources. One alternative being explored is that of Pulsar Timing Arrays.

Our own, Dr. Manjari Bagchi, is an expert on pulsars and is likely to be part of a project/group on PTA.

Since a new field of Gravitational Wave Astronomy is opened up, there is lot more work to be done and of course many opportunities for the younger generation.

Process of a Scientific Discovery

Establish a reliable theoretical prediction of a phenomenon; (took 4 decades)

Search for a viable verification system - any such system necessarily has noise; (interferometer development took over 2 decades)

Ensure that the predicted signature is unambiguously distinguished from the noise; (sophisticated data analysis)

Interpretation of data and augmentation of knowledge. (got a new tool to understand the universe).

Science, Technology, Management, Funding, Outreach

Science, pushing at the boundaries of the known, poses concrete challenges;

The challenges spur technology development;

Complex challenges need large scale deployment of efforts which brings in collaborations and requires public support and investment;

The spin-offs are newer technology, materials and skill developments in human resource which is the biggest and most invaluable spin-off since that has the capacity to take on future challenges.

LIGO Collaboration (and LHC) are good illustrations of the necessity and interplay of these five components.

THANK YOU !