# Windows into deep space

*from telescopes to Gravitational wave detection*

Urjit Yajnik, IIT Bombay

SVNIT Surat, April 1, 2016

# 1 Reaching out to galaxies

- Begin in the 1920's ...

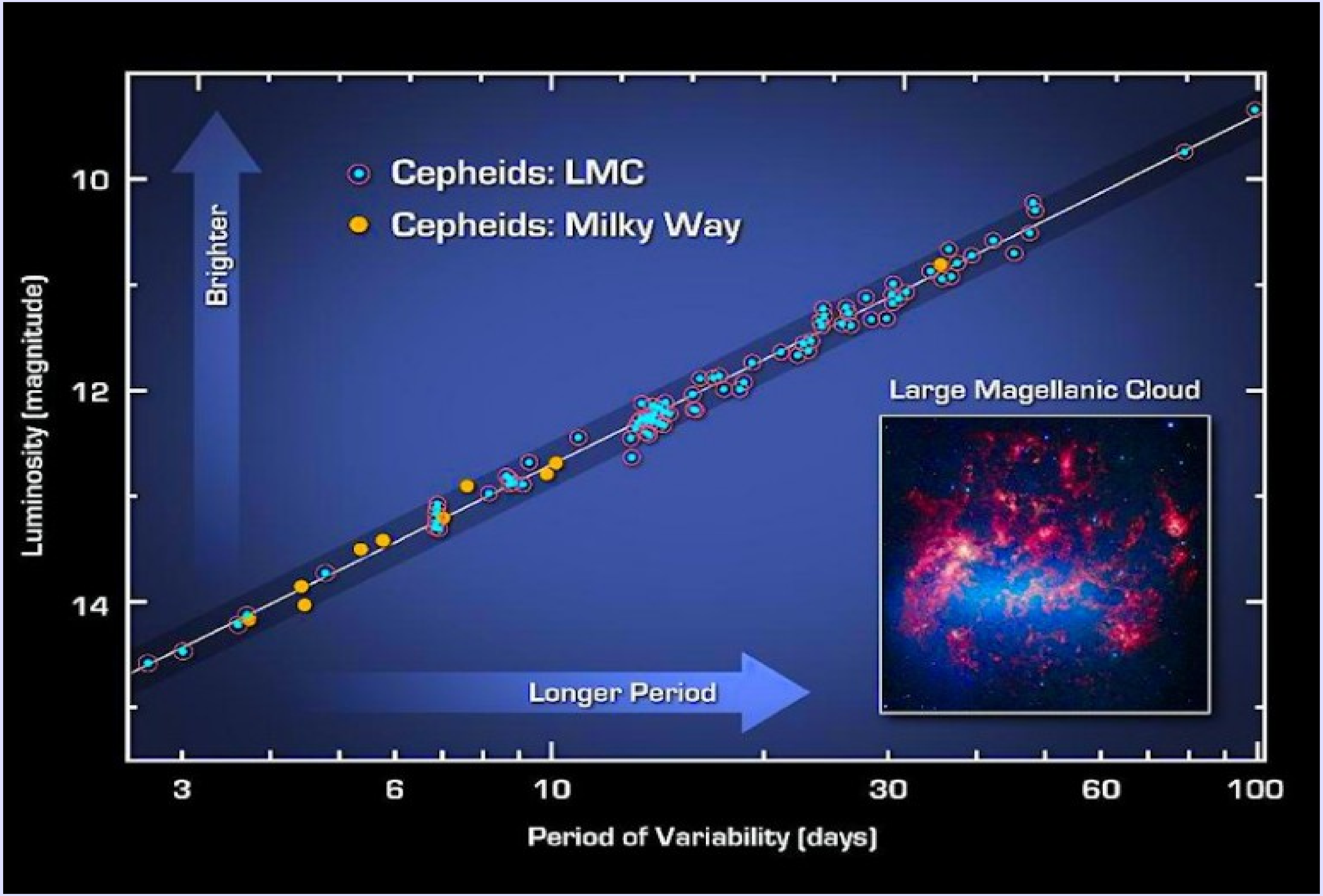
- New telescopes like Hale observatory and Mt. Palomar 200 in. telescope

  for the first time made galaxies visible in detail to human beings

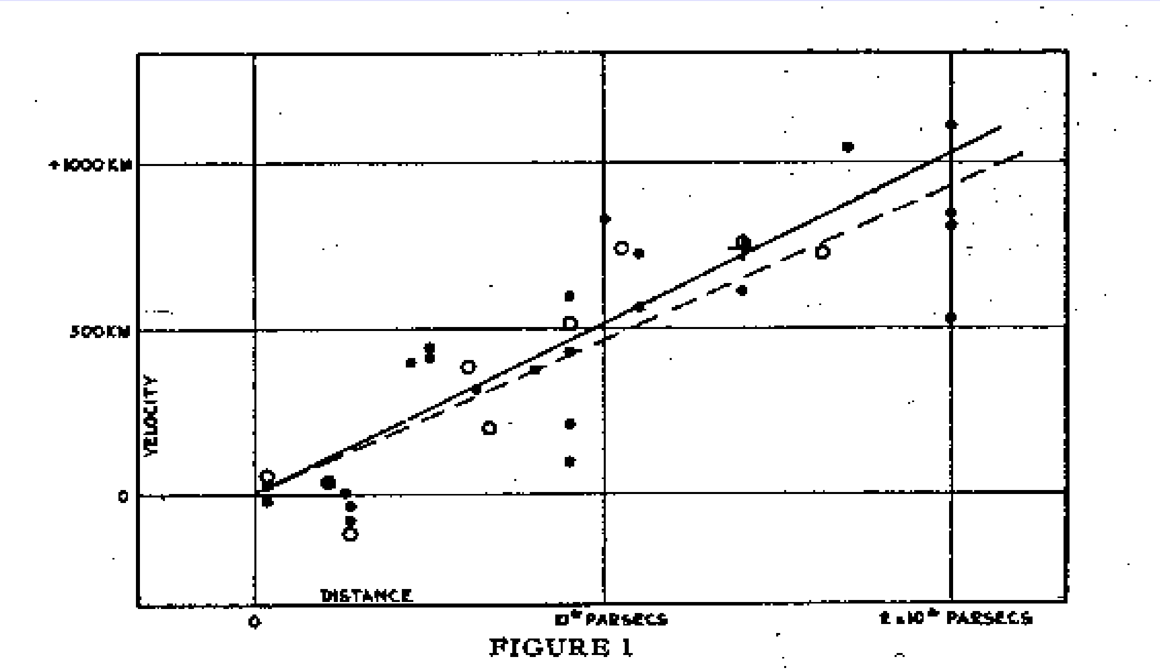
- Henrietta Leavitt calibrates the Cepheid variables

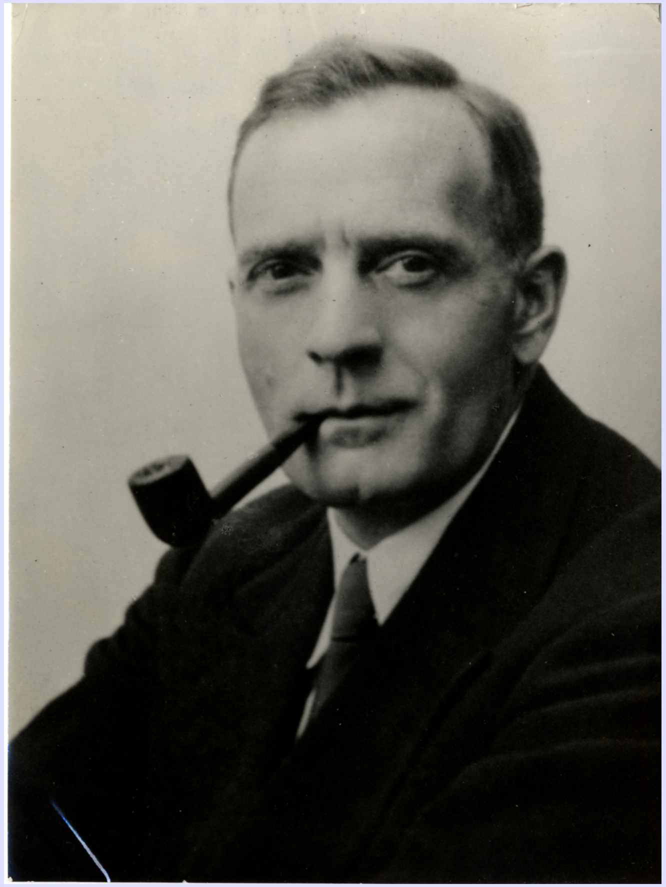
- Hydrogen spectra of most of the 20+ galaxies showed a red-shift rather than a blueshift.

- Edwin Hubble drew a line through the redshift vs. luminosity distance plot.


Cepheids: LMC
Cepheids: Milky Way
Brighter
Luminosity (magnitude)
10
12
14
Large Magellanic Cloud
Longer Period
3
6
10
30
60
100
Period of Variability (days)

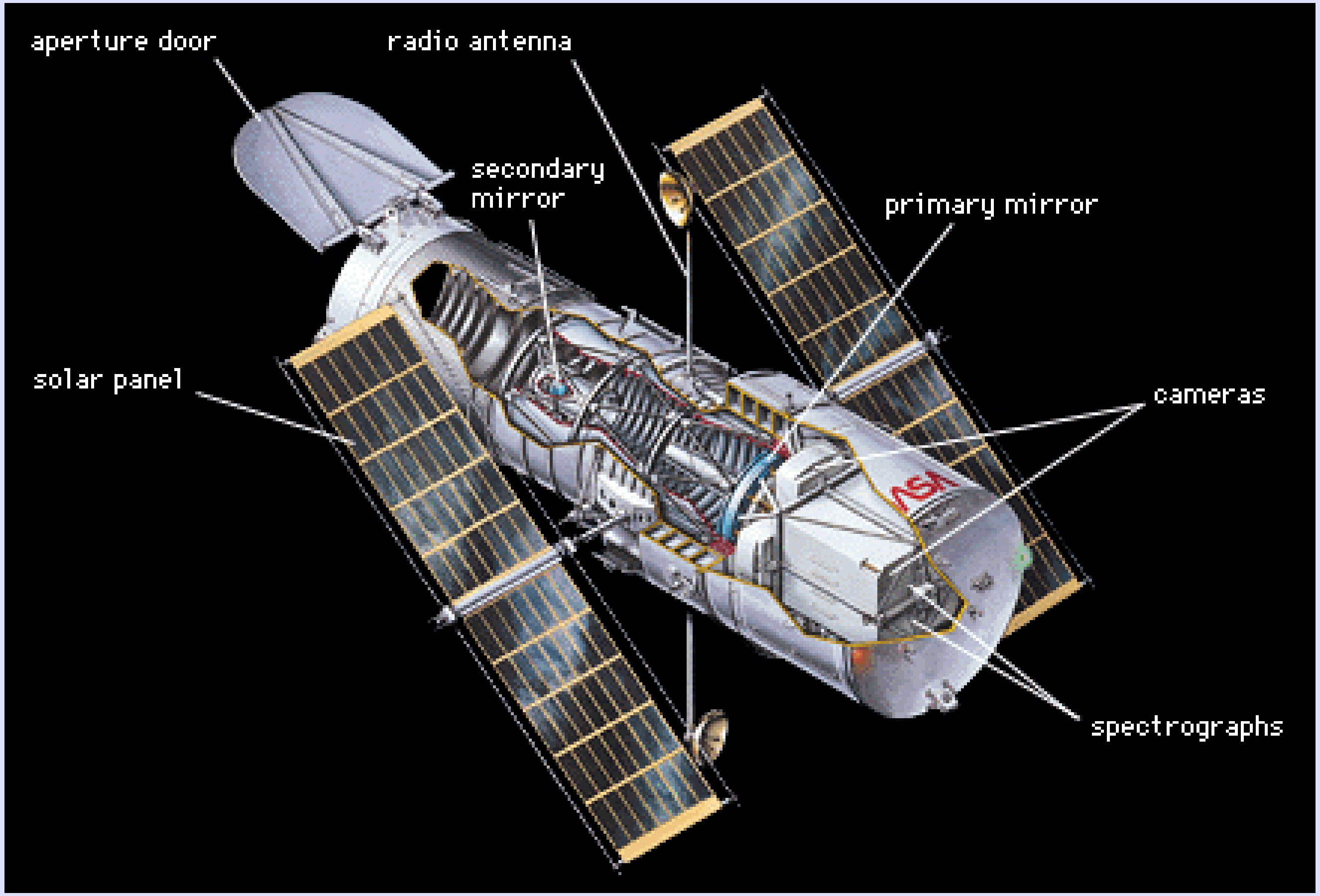

Henrietta Leavitt



Edwin Hubble and his plot

# 2 Going beyond the earth



Hubble Space Telescope

# 3 Spreading the spectrum

## 3.1 Radio astronomy

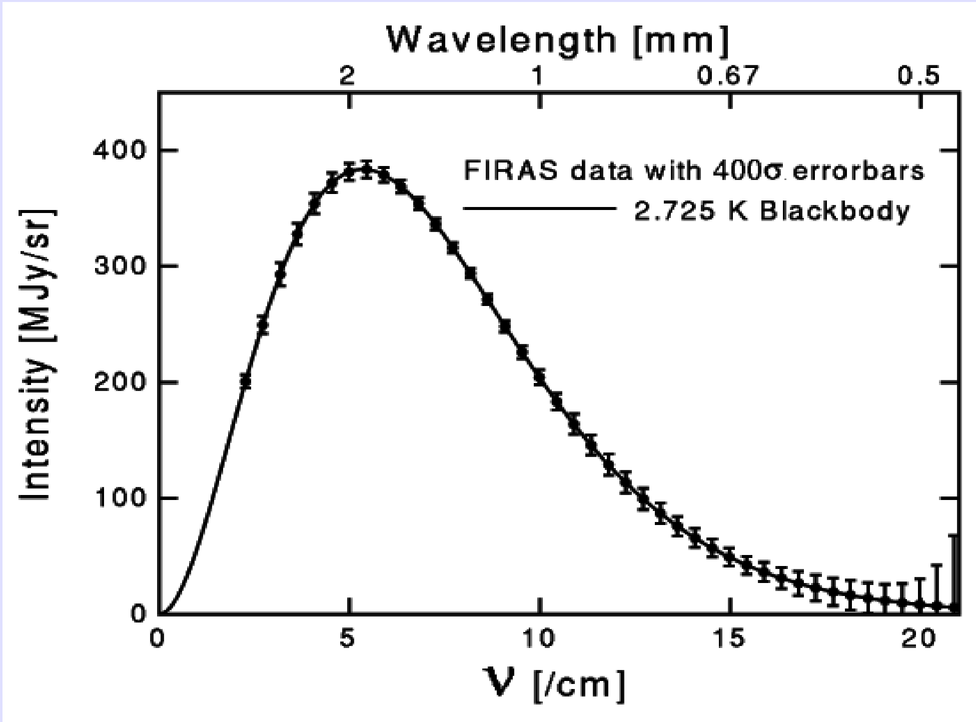
Giant Meter Wave Radio Telescope

30 fully steerable gigantic parabolic dishes of 45m diameter each spread over distances of upto 25 km.

- Protogalaxies and protoclusters yet in formation. Observe neutral Hydrogen line at 1420 MHz redshifted by factors of 3 to 10, at frequencies of about 350 and 130 MHz.

- Rapidly-rotating Pulsars in our galaxy. Timing studies should reveal departure from Keplerian motion of pulsar binaries and confirm General relativity.

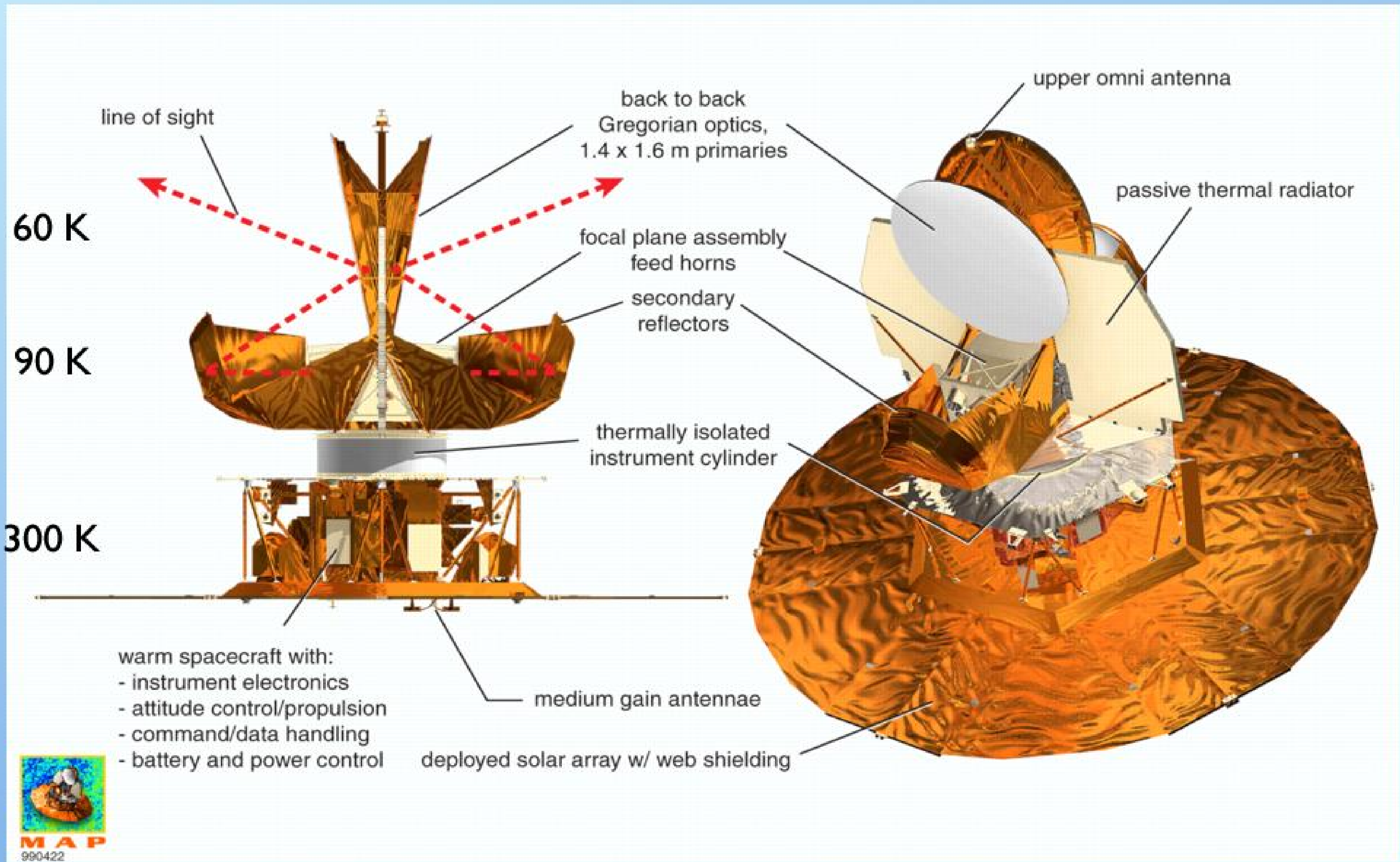
# 3.2 IR, Microwaves




Cosmic Microwave Background Radiation

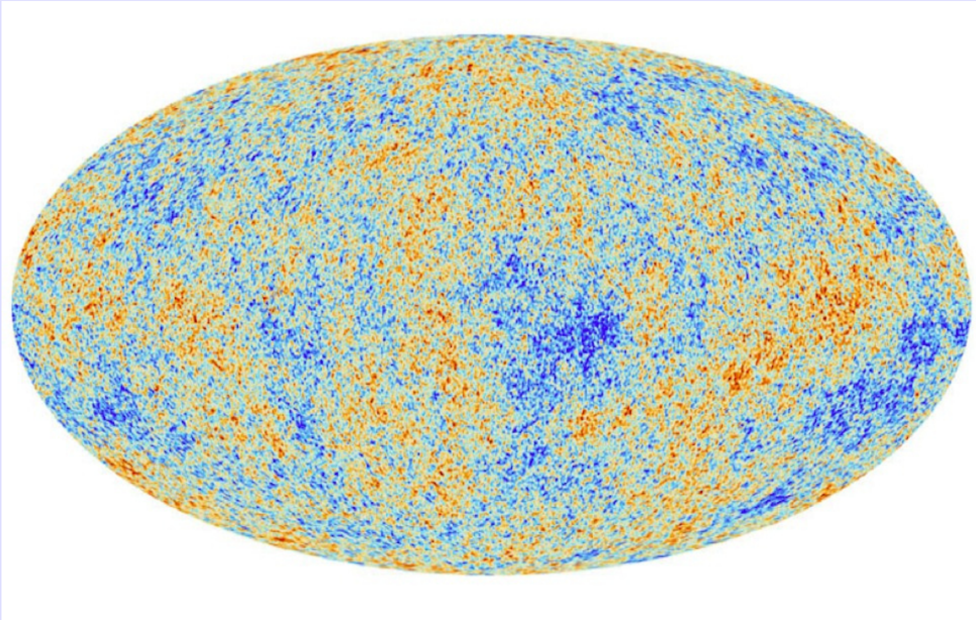
Predicted 1940’s, discovered 1964, confirmed 1992, Nobel 2006

# *WMAP* Spacecraft and Instrument



Follow up : Planck satellite,

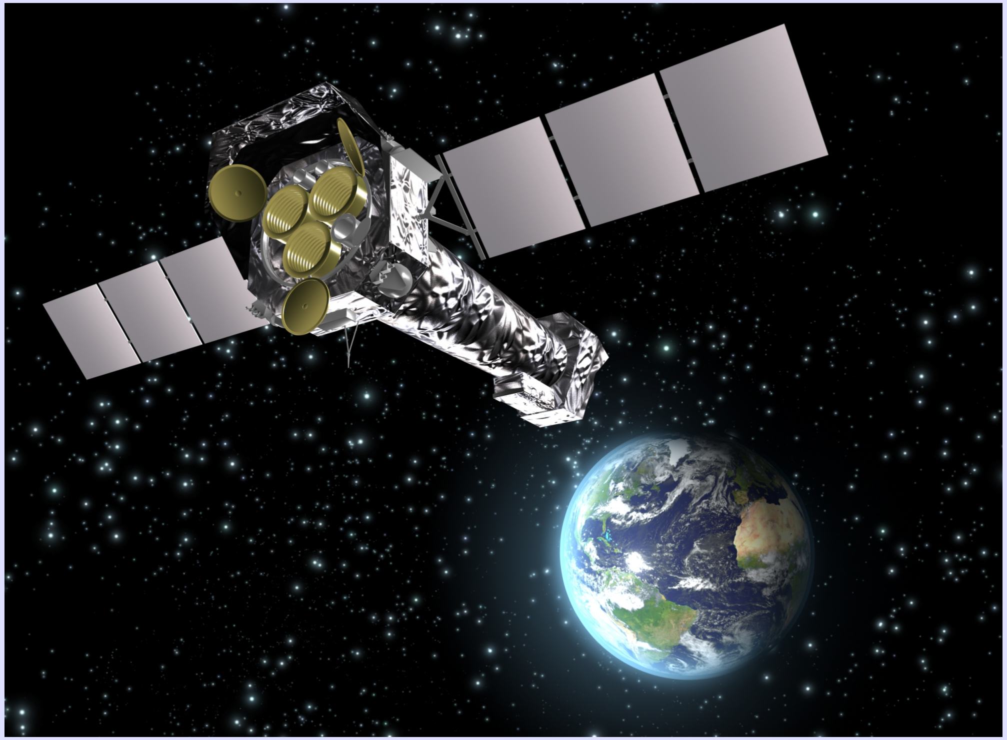
Microwave fingerprinting of the creation of neutral Hydrogen



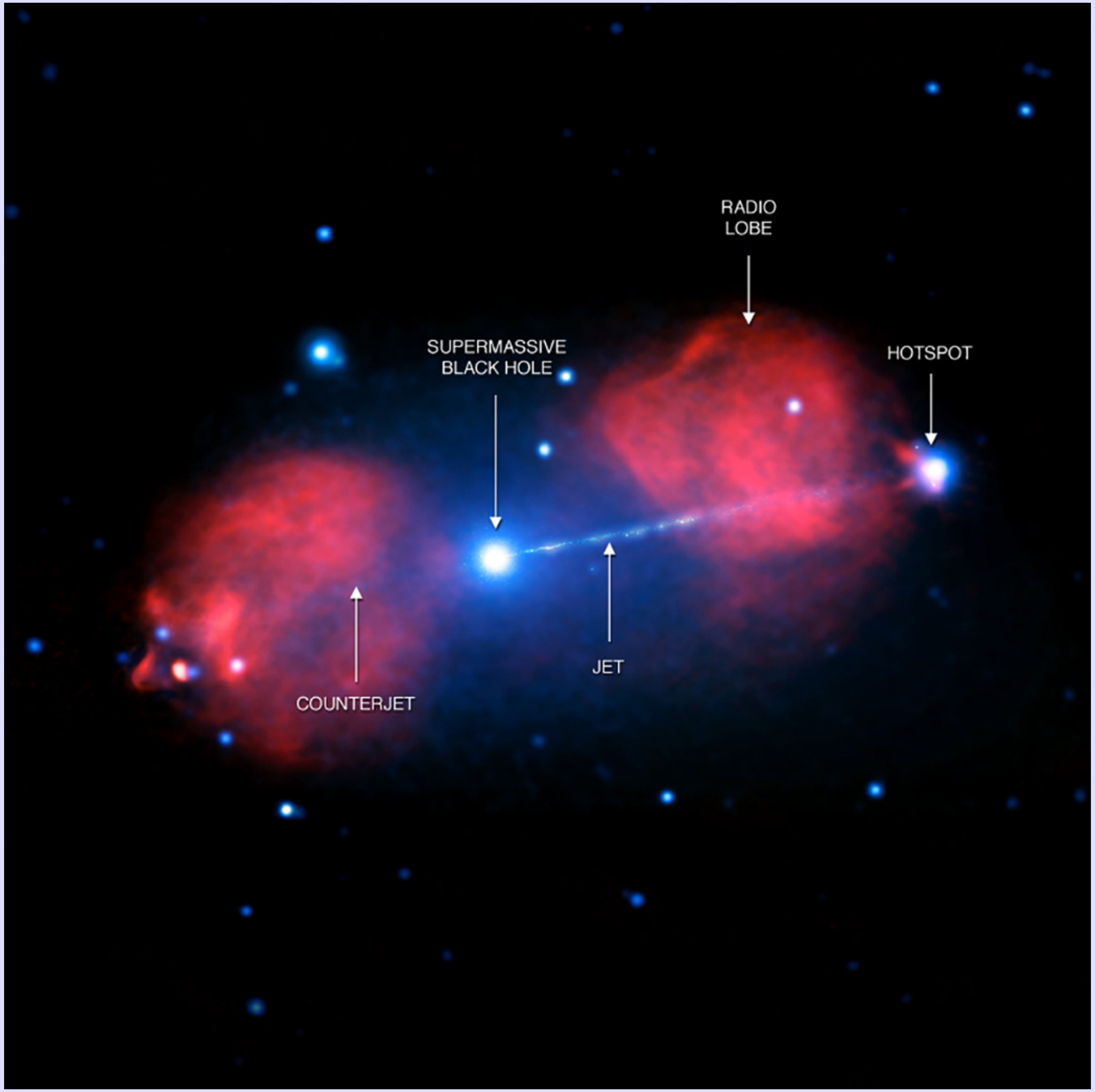
microwave map of the Universe. Largest variations milli-Kelvin.

## 3.3 X-ray maps

Synchrotorn radiation from very hot plasmas



XMM-Newton European Space Agency

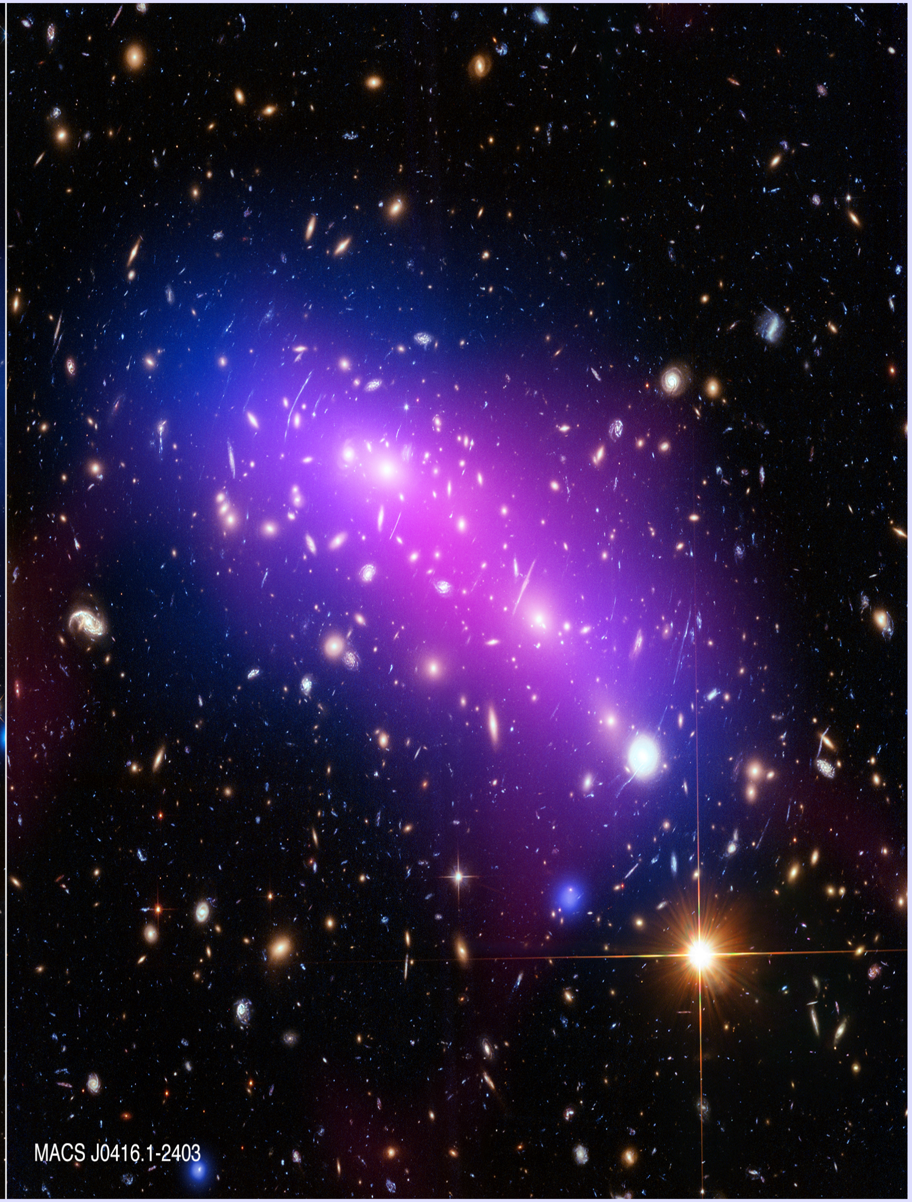

RADIO
LOBE
SUPERMASSIVE
BLACK HOLE
HOTSPOT
COUNTERJET
JET

“Pictor A” emitting a 300000 light year long X-ray jet.

Our whole galaxy size is 100000 light years.

Image from Chandra X-ray telescope, NASA

# 3.4 Putting them together : optical, X-ray, (G-lense )

## MACS J0416

→ is a pair of colliding galaxy clusters

→ Distance from Earth - about 4.3 Billion l.yr.s

→ They are combining to form an even bigger cluster.

## MACS J0717

→ Complex and highly distorted of galaxy clusters known

→ Site of a collision between four clusters.

→ Distance from Earth about 5.4 billion light years.

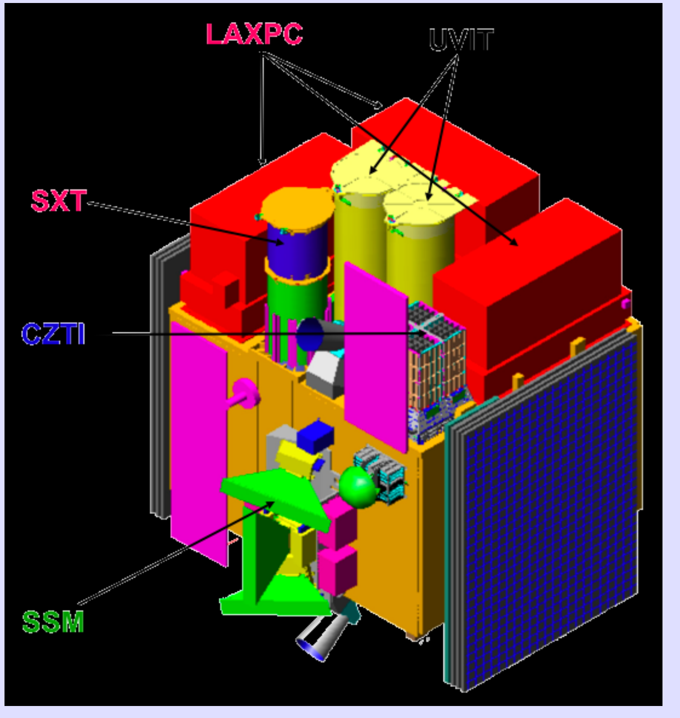
These new images of MACS J0416 and MACS J0717 contain data from three different telescopes:

– NASA's Chandra X-ray Observatory (diffuse emission in blue),

- Hubble Space Telescope (red, green, and blue),
- NSF’s Jansky Very Large Array (diffuse emission in pink)
- Also data from Giant Metrewave Radio Telescope in India

### 3.4.1 Our own Astrosat

A multi-wavelength astronomy mission




launched September 2015

Observing from a near-Earth, equatorial orbit.
Five instruments

a) Visible (320–530 nm),

b) Near UV (180–300 nm),

c) Far UV (130–180 nm),

d) Soft X-ray (0.3–8 keV and 2–10 keV),

e) Hard X-ray (3–80 keV and 10–150 keV).

Studies of objects ranging from

a) nearby solar system objects

b) distant stars

c) objects at cosmological distances

Timing studies ranging from milliseconds to days

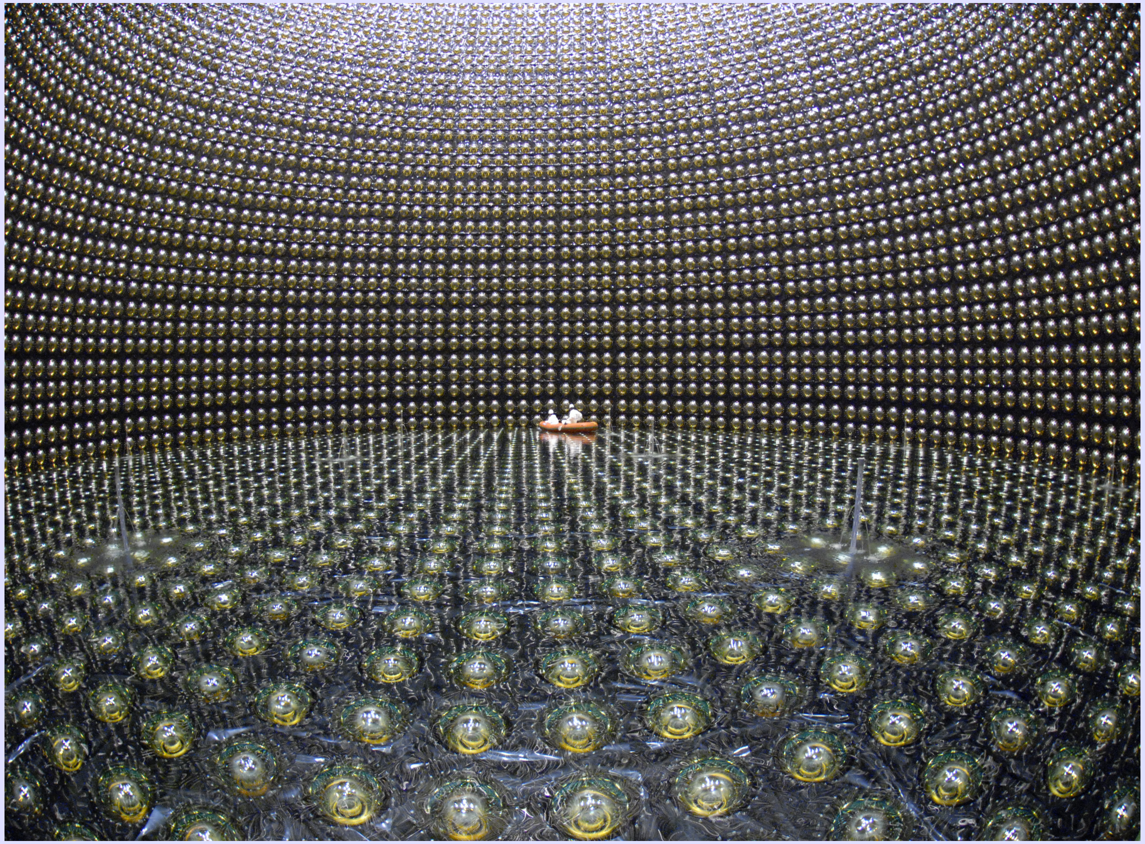
a) Pulsations of hot white dwarfs

b) Active galactic nuclei

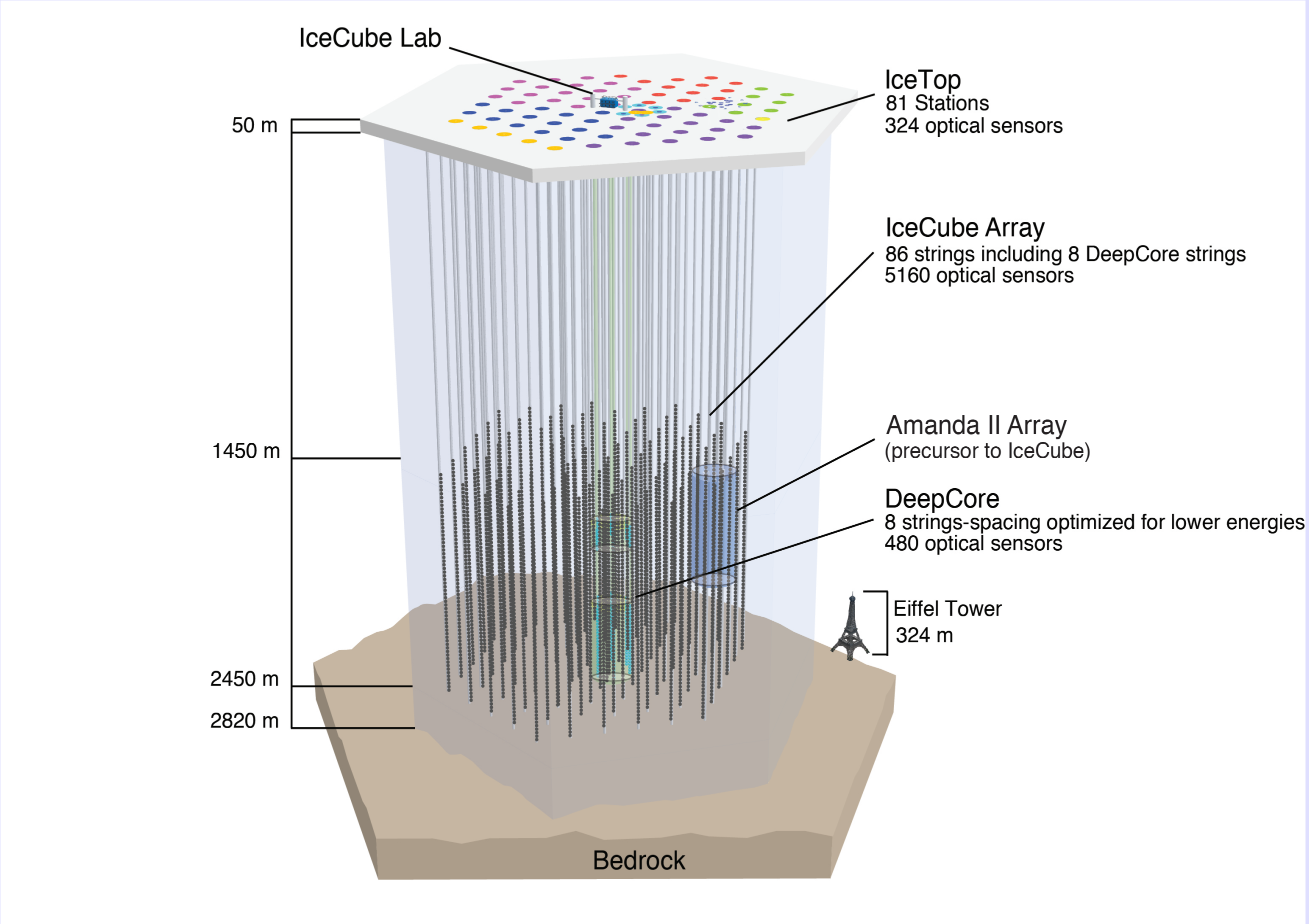
# 4 Looking beyond light

Neutrinos! Technique born in 1987 by accidental observation of Supernova neutrinos in a cavern meant to observe proton decay.

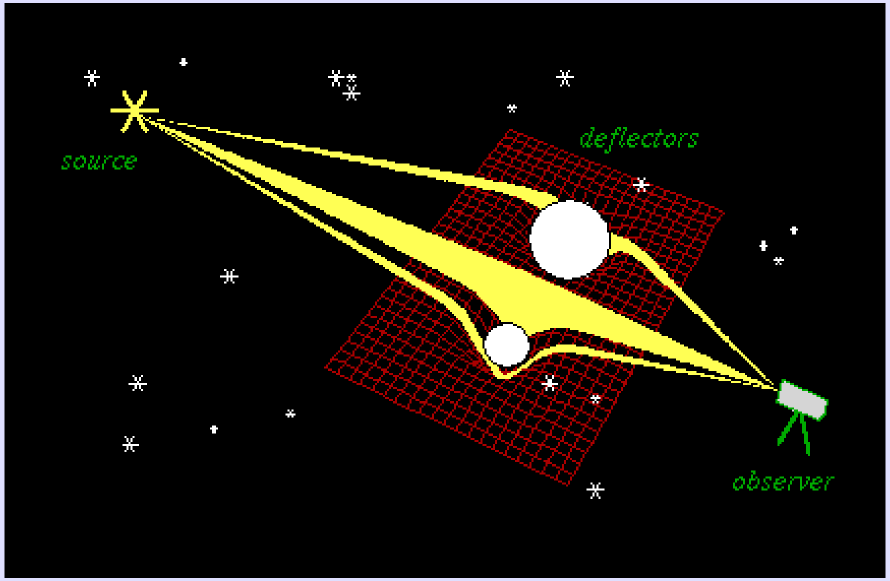
- SuperK

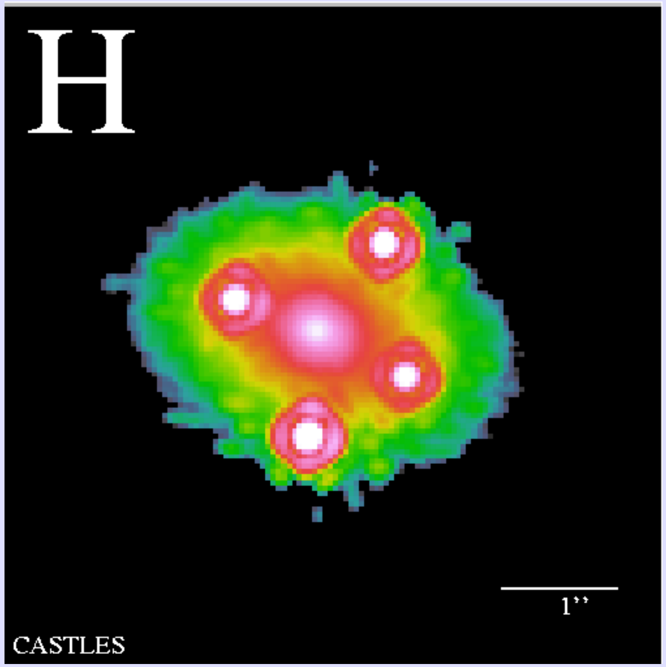


- IceCube


IceCube Lab
IceTop
81 Stations
324 optical sensors
50 m
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
Amanda II Array
(precursor to IceCube)
1450 m
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
Bedrock

# 5 Gravitational lensing




... and now

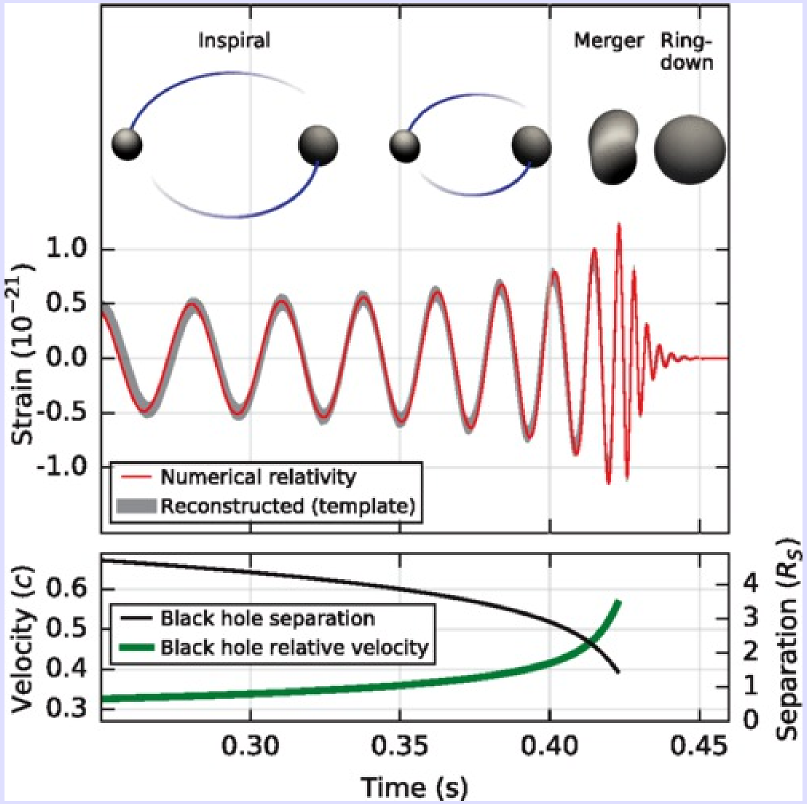
# 6 Gravitational Waves

From Physical Review Letters, Feb 2016, B. P. Abbot et al, LIGO and VIRGO collaborations :

“The basic features of GW150914 point to it being

produced by the coalescence of two black holes — i.e., their orbital inspiral and merger, and subsequent final black hole ringdown. Over

0.2 s, the signal increases in frequency and amplitude in about 8 cycles from 35 to 150 Hz, where the amplitude reaches a maximum. The most plausible explanation for this evolution is the inspiral of two orbiting masses, m1 and m2, due to gravitational-wave emission."



# Physical parameters

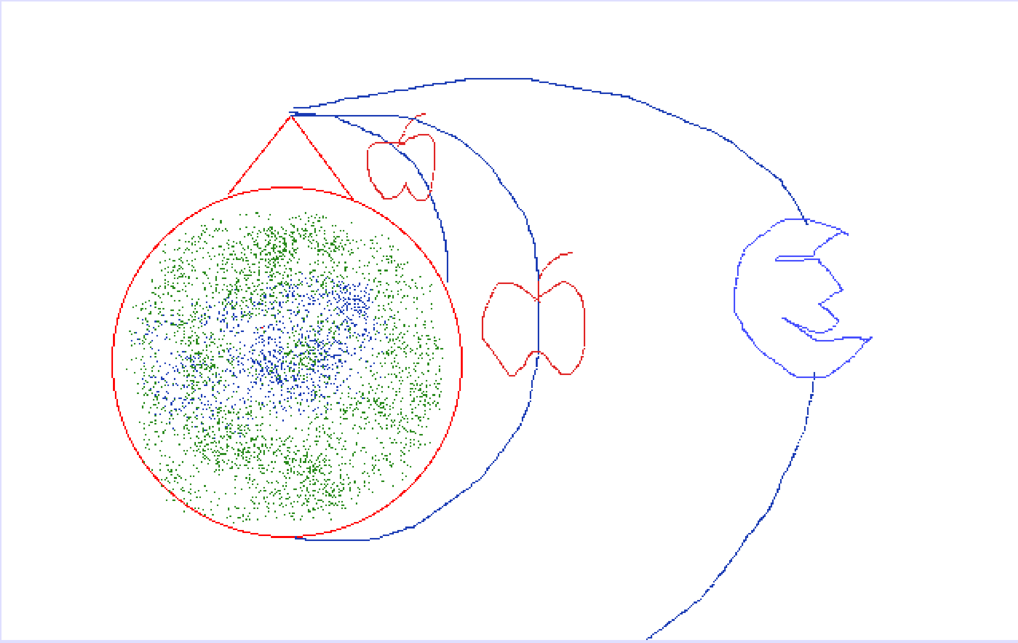
| | |
|---|---|
| Primary black hole mass | $36^{+5}_{-4} M_\odot$ |
| Secondary black hole mass | $29^{+4}_{-4} M_\odot$ |
| Final black hole mass | $62^{+4}_{-4} M_\odot$ |
| Final black hole spin | $0.67^{+0.05}_{-0.07}$ |
| Luminosity distance | $410^{+160}_{-180}$ Mpc |
| Source redshift $z$ | $0.09^{+0.03}_{-0.04}$ |

# 7 Relativity, General Relativity

**Gravity ≡ Curved space-time**

## 7.1 The apple and the Moon

### Universal Gravitation



### The beauty of the $1/r^2$ law.

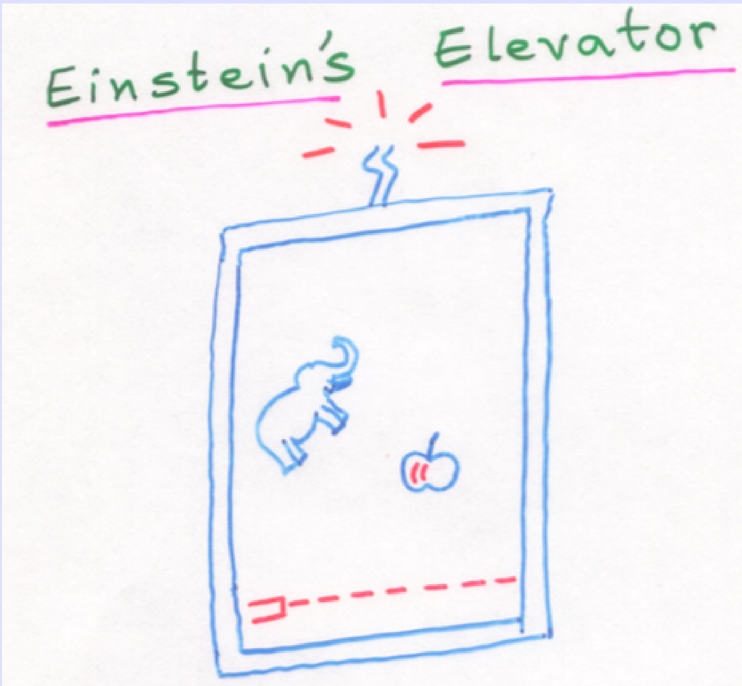
The Earth and the Moon act like point particles, making similarity to the apple apparent.

## 7.2 The simplest profoundest hint

### Principle of Equivalence

In the second law, the “inertia” cancels out against the “charge” of the test particle

$$\cancel{m}_1 \boldsymbol{a} = G\frac{\cancel{m}_1 m_2 \hat{\boldsymbol{r}}}{r^2}$$

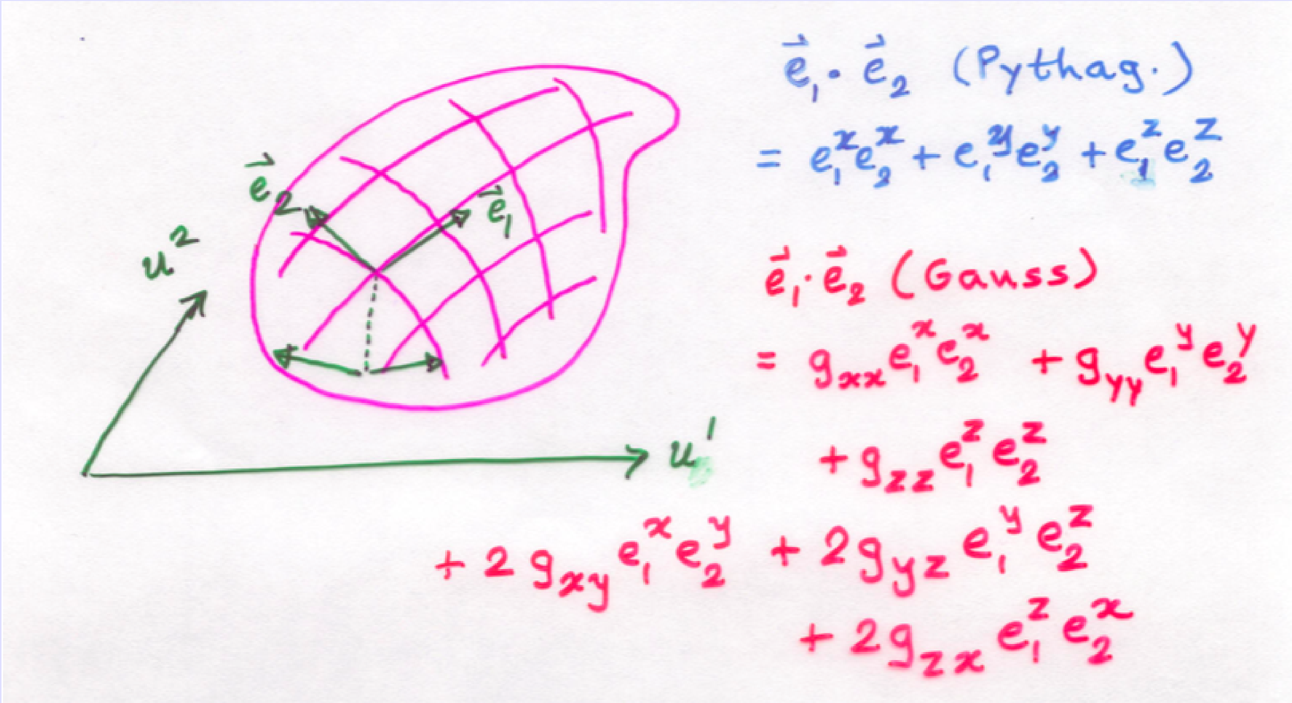


- → Property of Gravity : Same acceleration <–> analogy to pseudoforce <-> non-cartesian coordinates

- → Gravity in special frames : Freely Falling Frame of Reference <-> disappearance of Gravity <-> Locally equivalent to inertial frame of reference <-> Locally, Special Relativity

- → Same initial velocity <-> same trajectory ( regardless of mass) <-> trajectory intrinsic property of space-time <-> curved space-time.

## 7.3 Space-time metric




$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}$$

# 8 Quadrupole source

$$g_{\mu\nu} \cong \eta_{\mu\nu} + h_{\mu\nu}$$

$$\bar{h}_{ij}(t,r) = \frac{2G}{c^4 r} \ddot{I}_{ij}(t-r),$$

## 8.1 Electromagnetism and Gravity

Comparison and contrast

Nettlesome issues :

- Gauge artefacts / covariance / Equivalence Principle

$$t^{\mu\nu}_{LL} = -\frac{c^4}{8\pi G} G^{\mu\nu} + \frac{c^4}{16\pi G(-g)} ((-g)(g^{\mu\nu} g^{\alpha\beta} - g^{\mu\alpha} g^{\nu\beta}))_{,\alpha\beta}$$

- Initial value problem!!

# 9 Optimism, error and retraction

[ ... 1913 ... ]

Born: "I should like to put to Herr Einstein a question, namely, how quickly the action of gravitation is propagated in your theory. That it happens with the speed of light does not elucidate it to me. There must be a very complicated connection between these ideas."

Einstein: "It is extremely simple to write down the equations for the case when the perturbations that one introduces in the field are infinitely small. Then the g's differ only infinitesimally from those that would be present without the perturbation. The perturbations then propagate with the same velocity as light. —

Born: "But for great perturbations things are surely very complicated?"

Einstein: "Yes, it is a mathematically complicated problem. It is especially difficult to find exact solutions of the equations, as the equations are nonlinear." Excerpts from discussion after Einstein's Fall 1913 lecture in Vienna on The present position of the problem of gravitation," already two years before he had the final field equations [in the textbook "Gravitation" (1973), by Misner Thorne and Wheeler]

[... 23 years later ...]

Nevertheless, in 1936 Einstein wrote to his friend Max Born:

Together with a young collaborator, I arrived at the interesting result that gravitational waves do not exist, though they had been assumed a certainty to the first approximation. This shows that the non-linear general relativistic field equations can tell us more or, rather, limit us more than we have believed up to now. [ "Einstein versus the Physical Review" Daniel Kennefick, Physics Today 2005 ]

[ ... One year later ... ]

Einstein and Rosen published a corrected version in Journal of Franklin Institute, Philadelphia, 1937.

# 10 The discovery

## 10.1 Antecedents

Weber's cylinders
Univ. of Maryland 1970's

## 10.2 The Hulse-Taylor pulsar

Discovery 1989

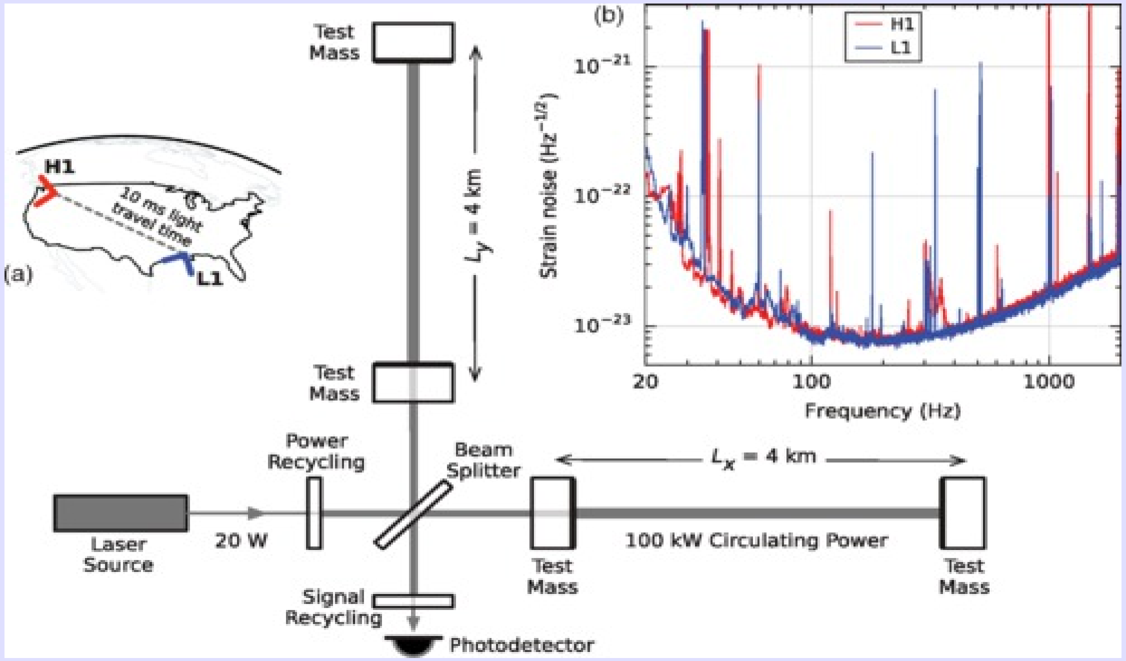
Nobel Prize 1993

$$P = \frac{\mathrm{d}E}{\mathrm{d}t} = -\frac{32}{5}\frac{G^4}{c^5}\frac{(m_1 m_2)^2(m_1+m_2)}{r^5}$$

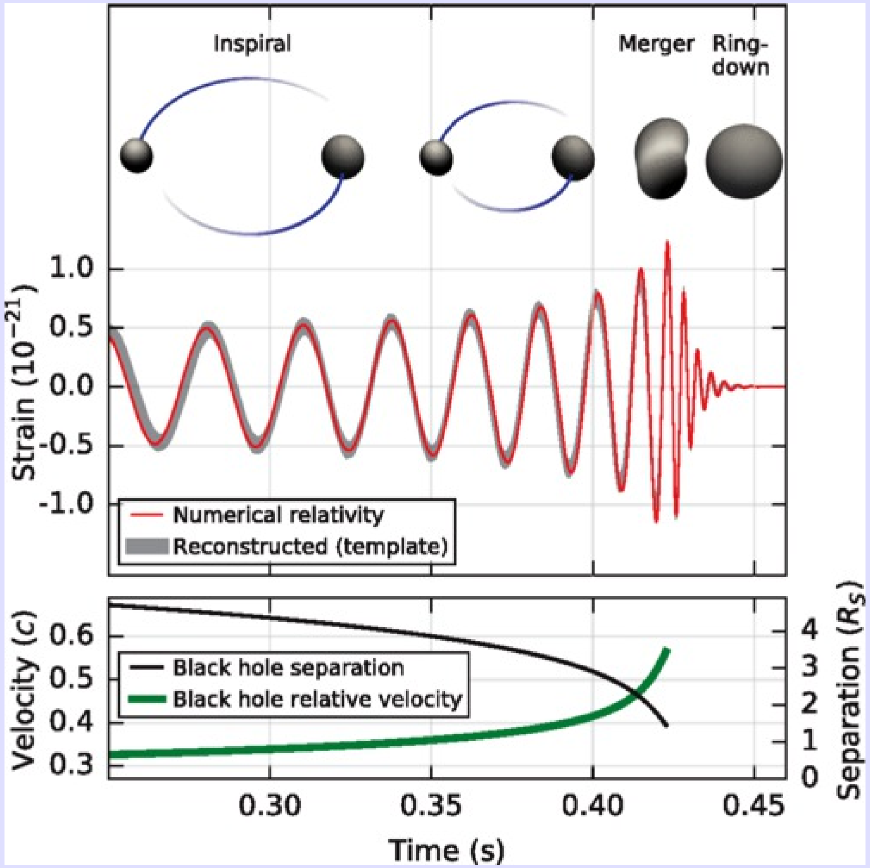
$$\frac{\mathrm{d}r}{\mathrm{d}t} = -\frac{64}{5}\frac{G^3}{c^5}\frac{(m_1 m_2)(m_1+m_2)}{r^3}$$

## 10.3 New technologies

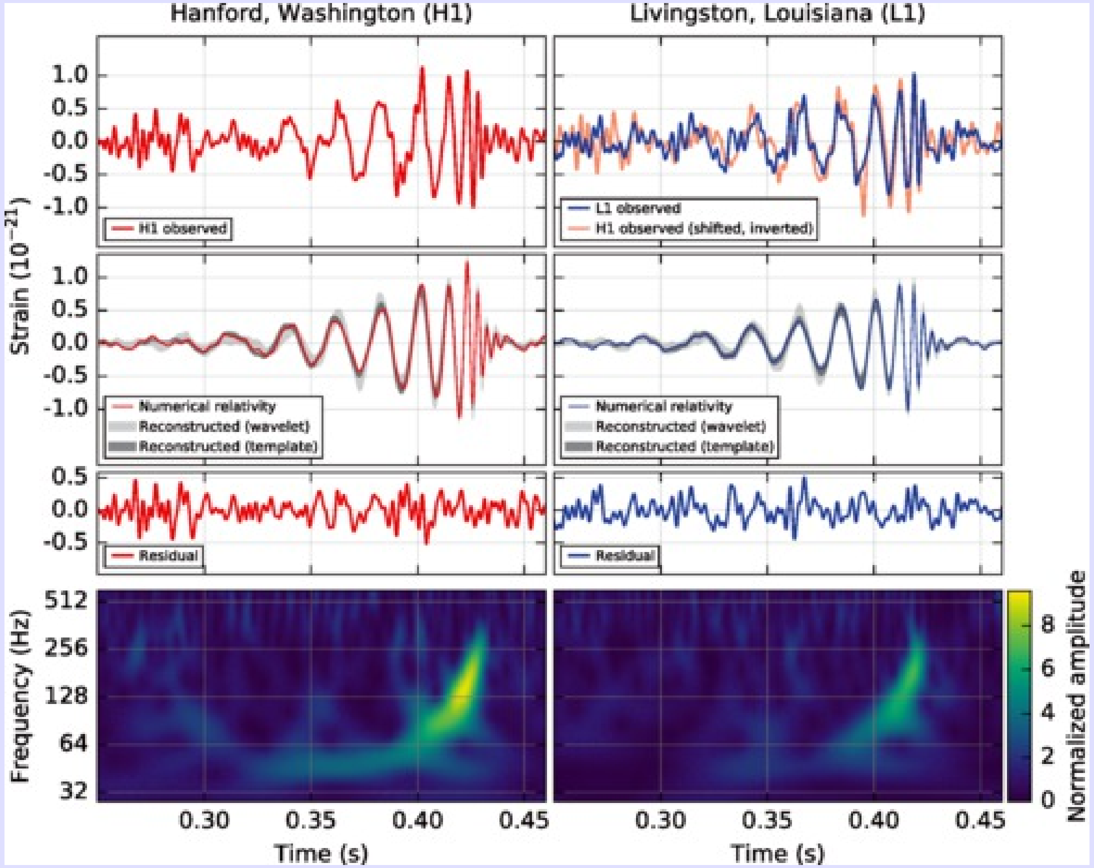
Amazingly, LIGO project and the computational capabilites reach comparable levels of precision within a decade of each other, and in time for the discovery.



# 11 The merger and the "ring down"

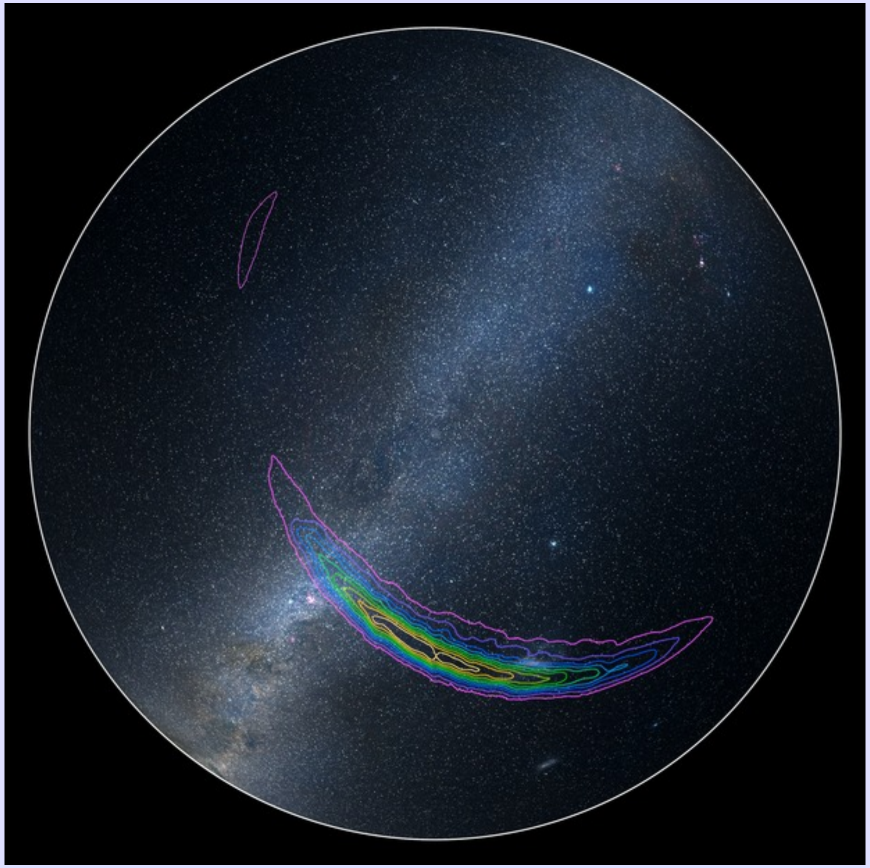


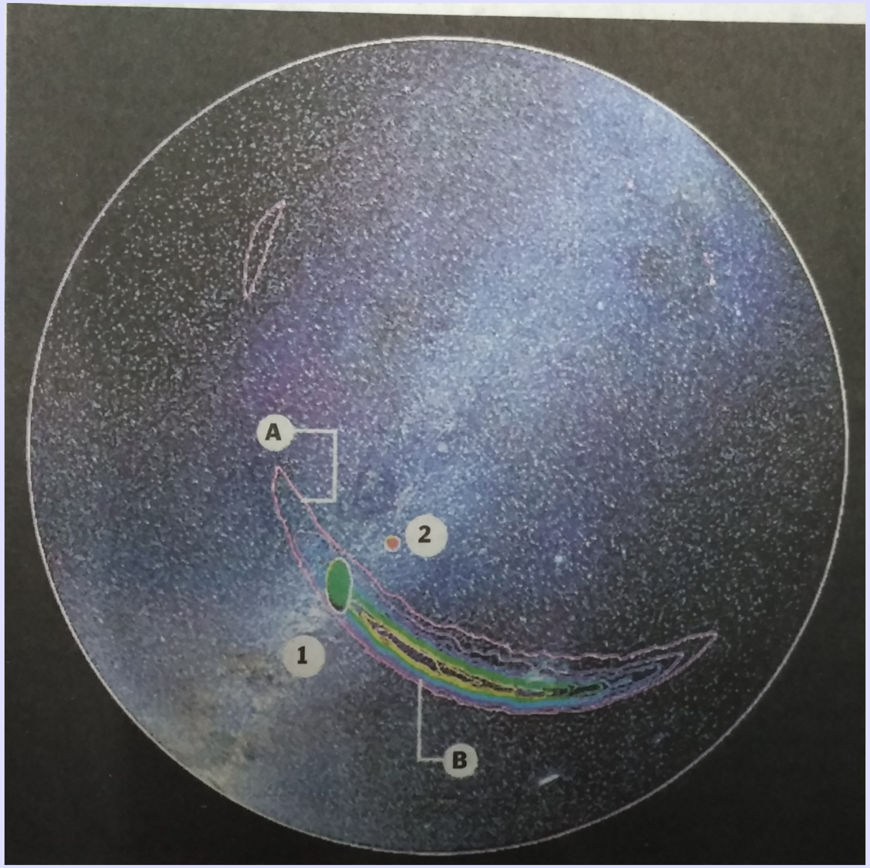
# 12 Details



Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain ($10^{-21}$)
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
Normalized amplitude
Time (s)

# 13 LIGO - India




A
2
1
B

# 14 Conclusion

Widest spectrum electromagnetic telescopy

- From creation of primordial Hydrogen
- To supermassive blackholes at centers of galaxies

Neutrino Astrophysics

- The puzzle of neutrino mass
- The inner structure and unfolding of a supernova

Towards a new astronomy - Gravitational Waves

- Go where photons (Radio, Microwave, IR, optical, UV, Gamma, UHE-> PeV) and neutrinos can not go!
- Otherwise unseen objects and their systems
- Equation of state of supermassive objects