

# Multimessenger view of the Universe

*Perspectives and new approaches*

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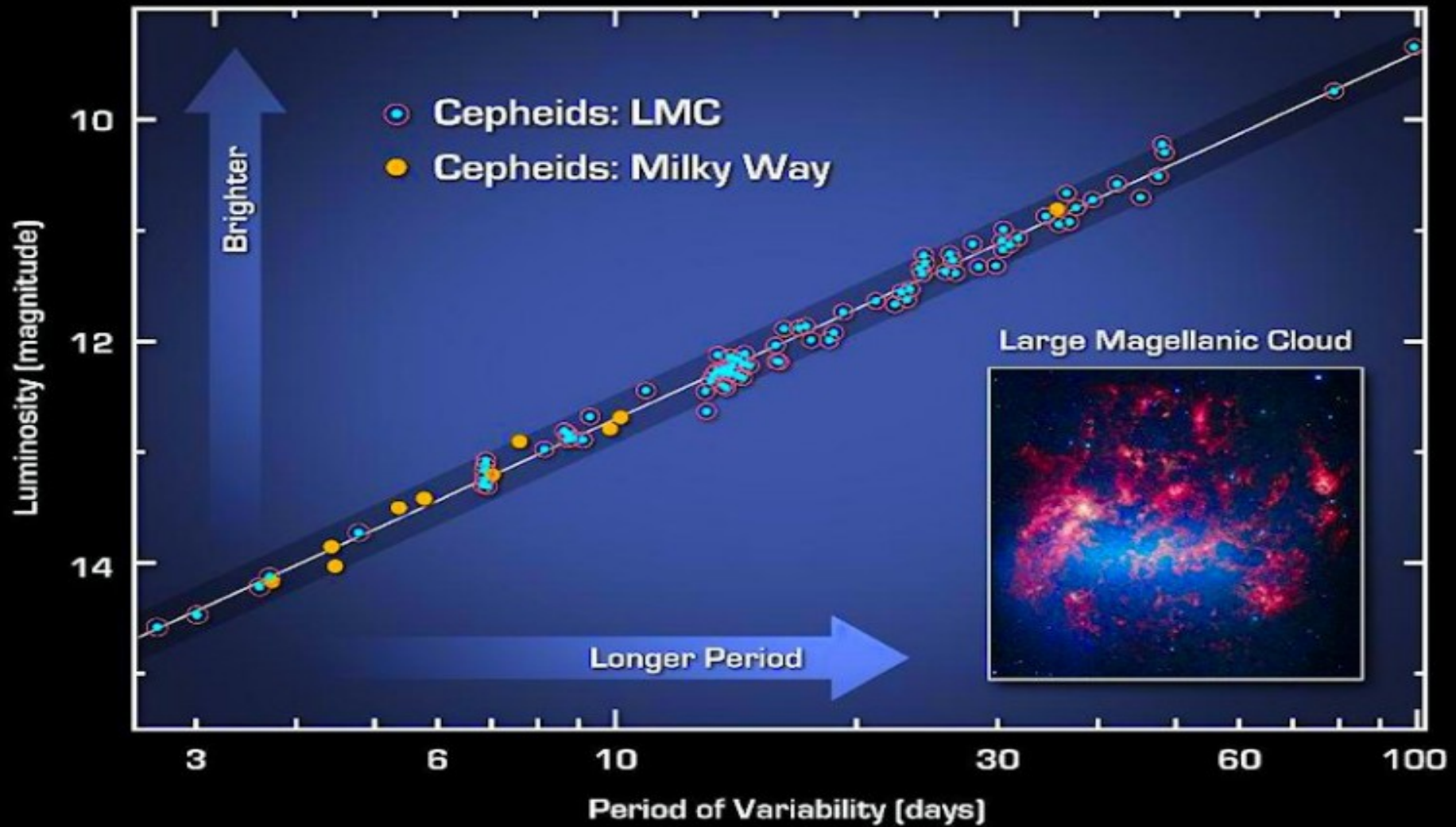


Equinox, IIT Guwahati, 26 January 2019



# 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 redshift rather than a blueshift.
- Edwin Hubble drew a line through the redshift vs. luminosity distance plot.







Scanned at the American  
Institute of Physics

Henrietta Leavitt



Edwin Hubble

... and his plot

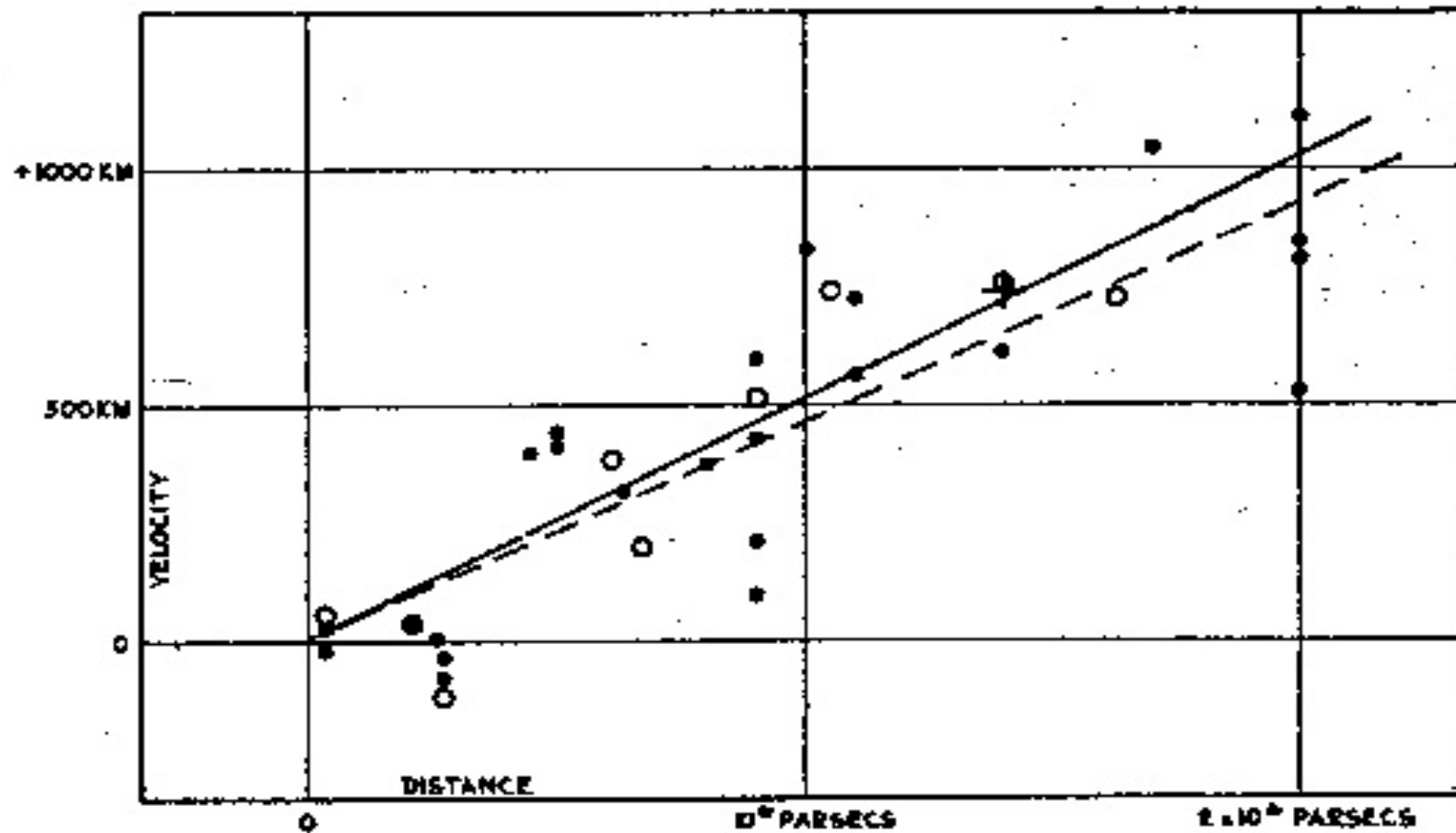
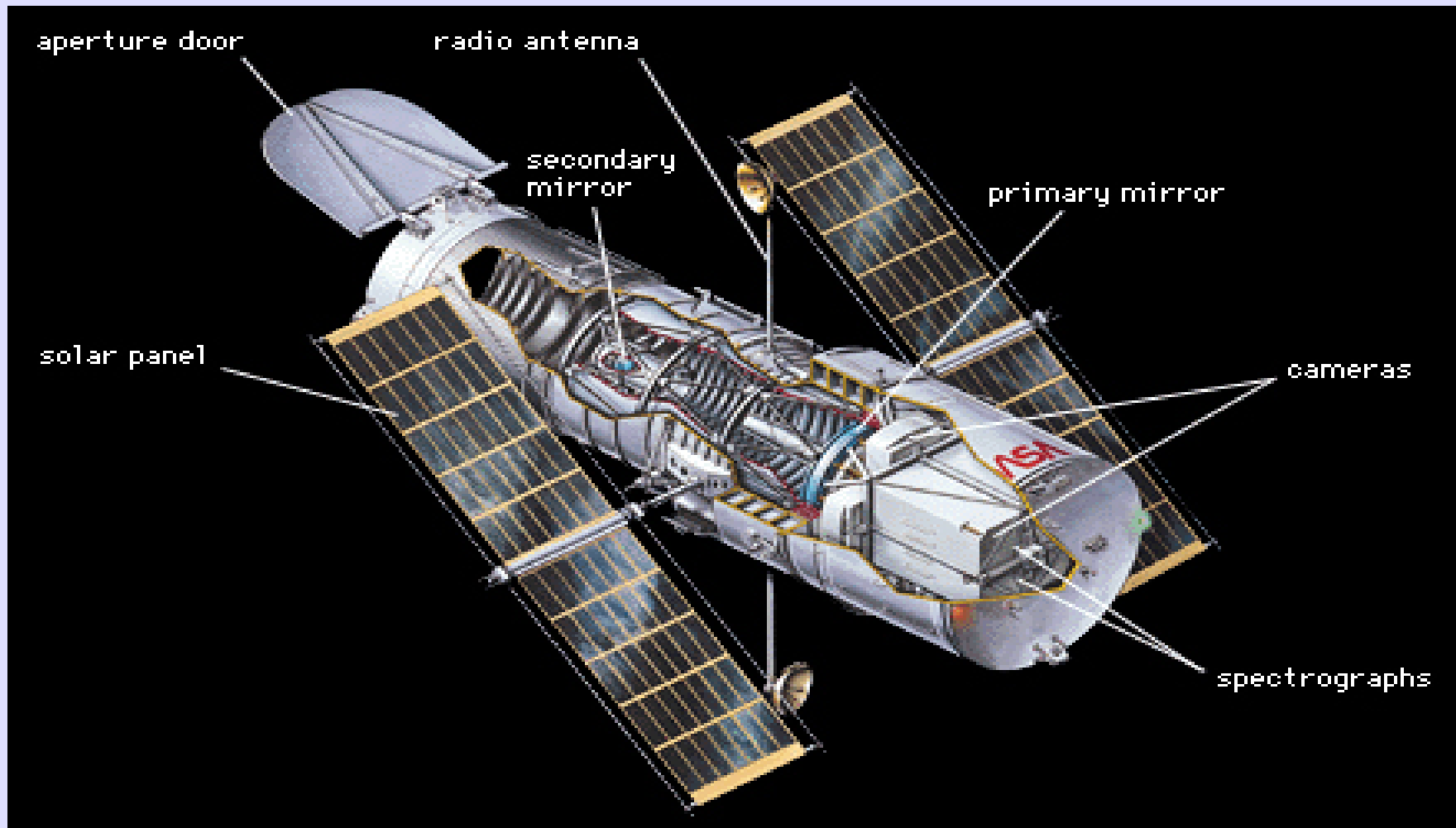


FIGURE 1

## 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.

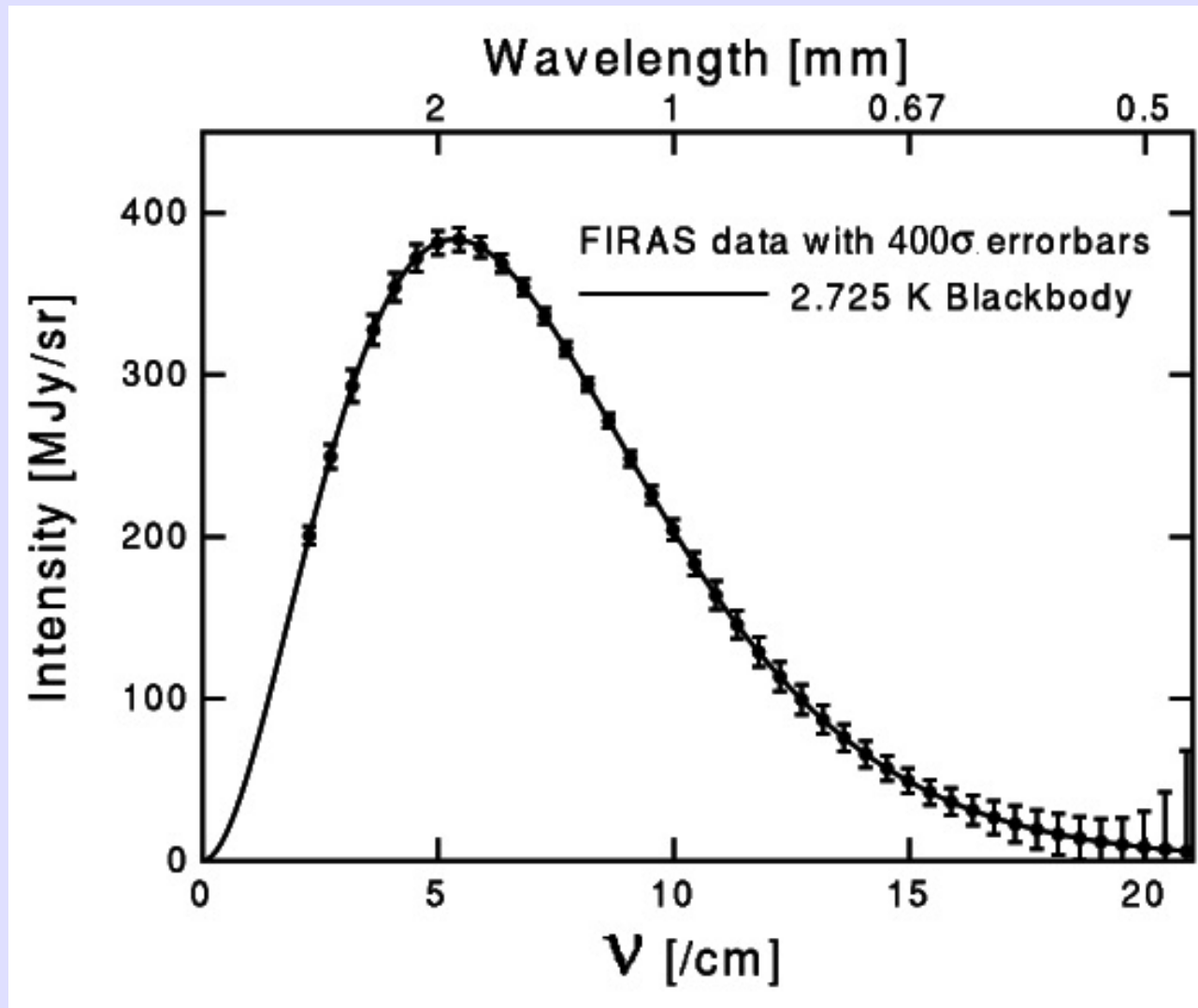
- Rapidly-rotating Pulsars in our galaxy. Timing studies should reveal departure from Keplerian motion of pulsar binaries and confirm General relativity.

## 3.2 IR, Microwaves

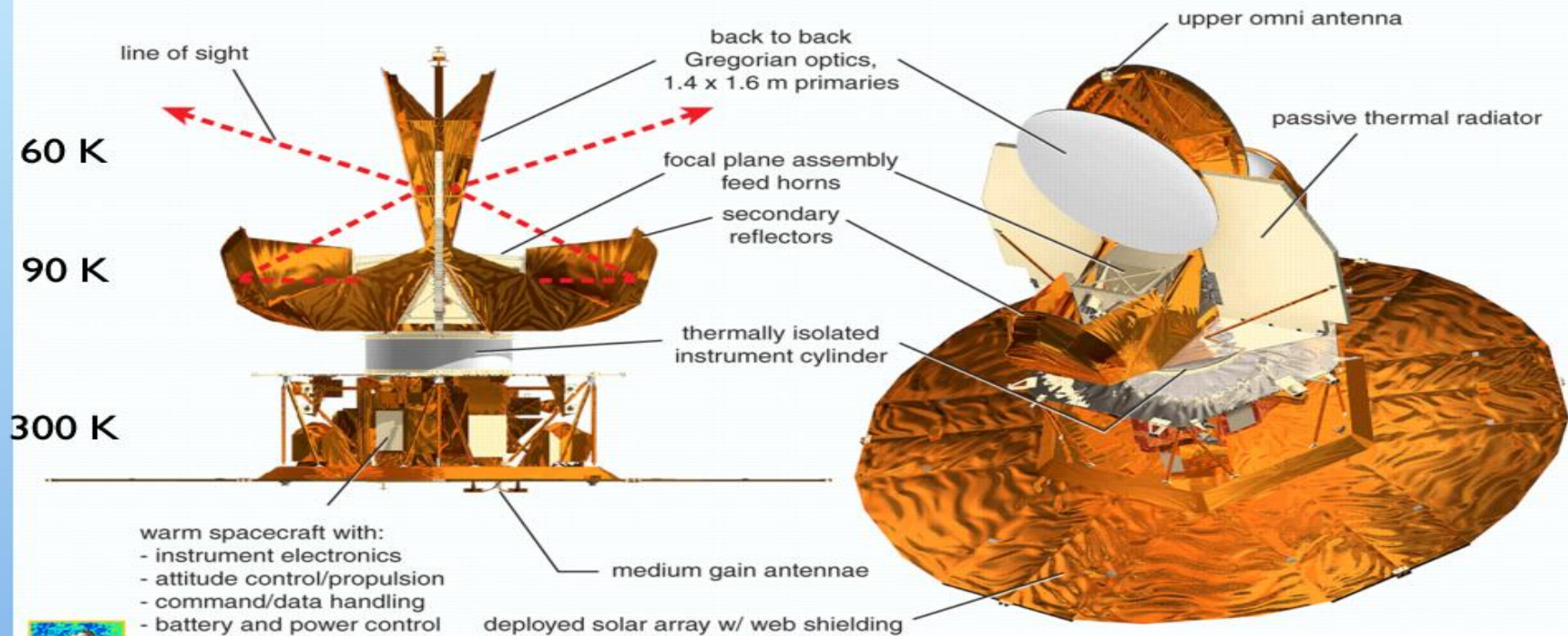
### Cosmic Microwave Background Radiation



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

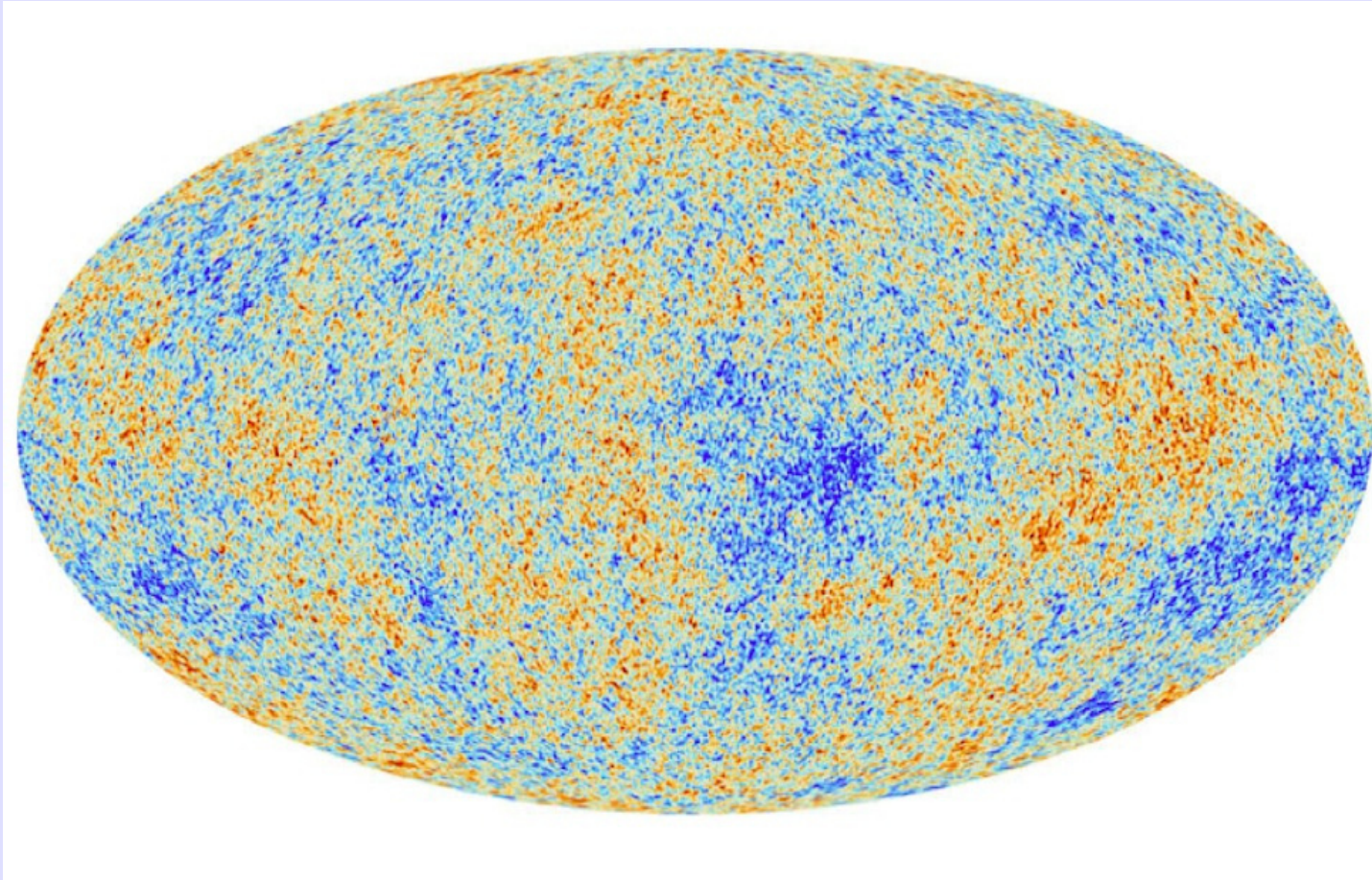


# WMAP Spacecraft and Instrument





Follow up : Planck satellite,  
Microwave fingerprinting of the creation of neutral Hydrogen

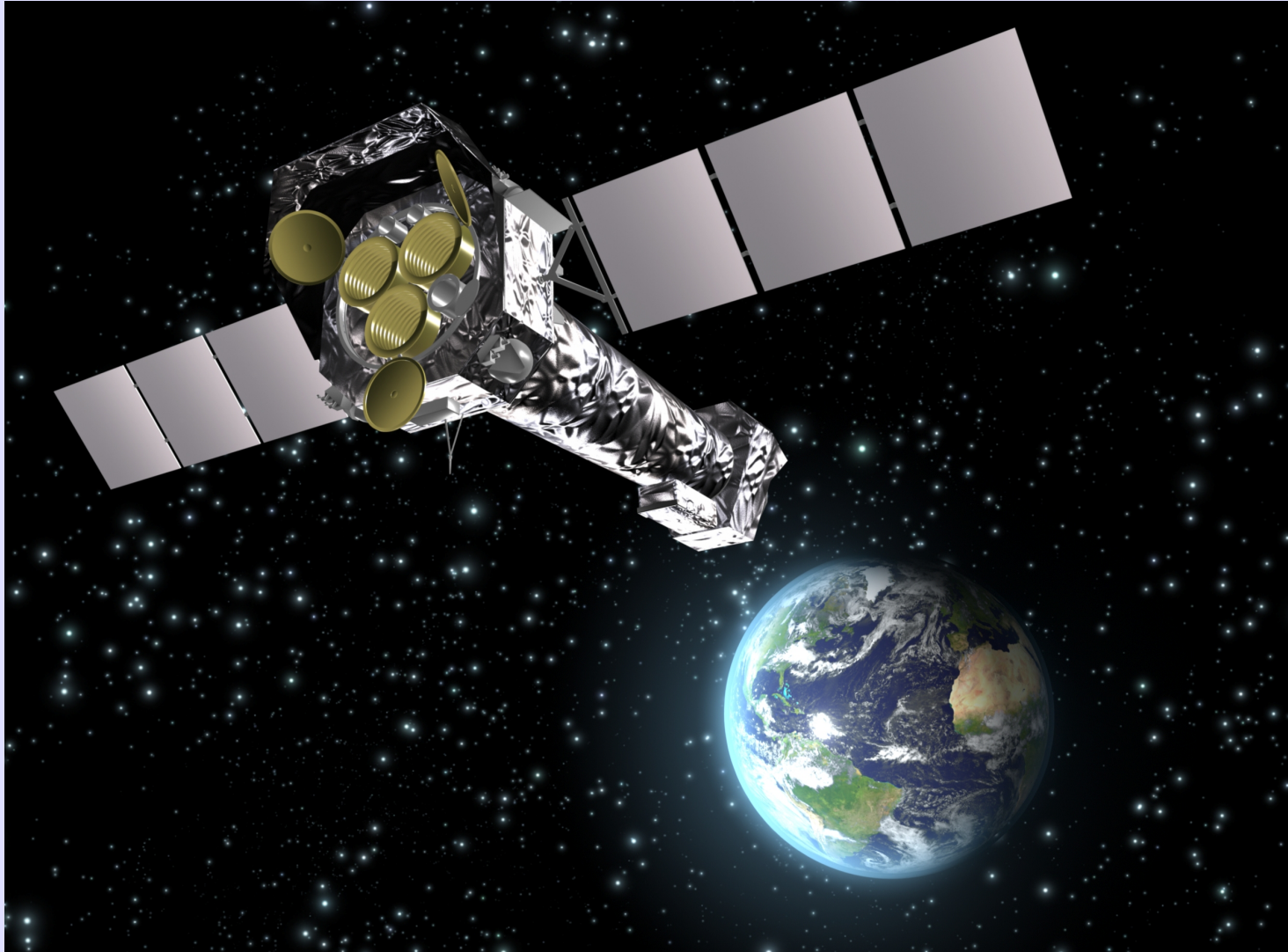


microwave map of the Universe. Largest variations milli-Kelvin.

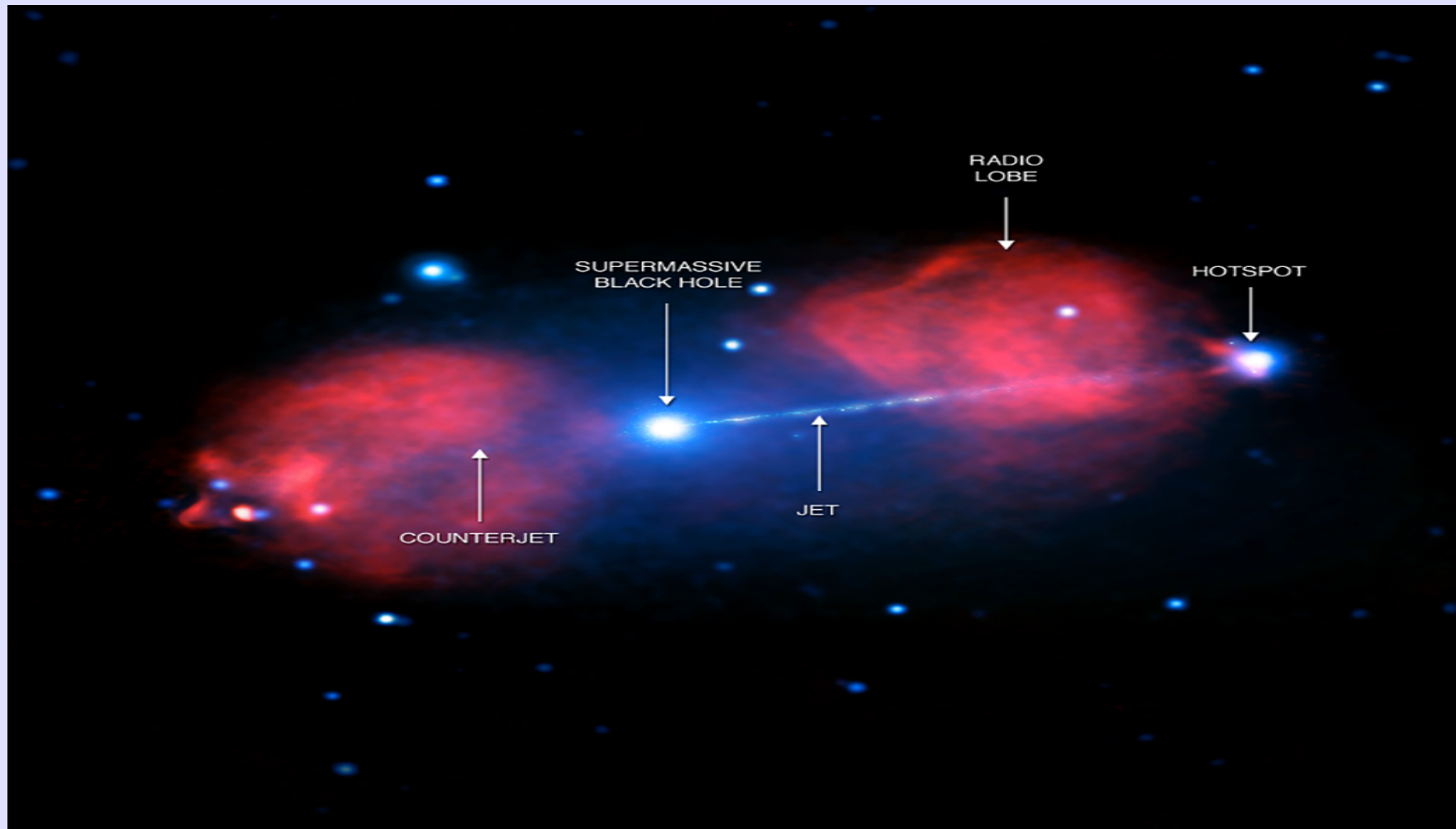


### 3.3 X-ray maps

Synchrotron radiation from very hot plasmas



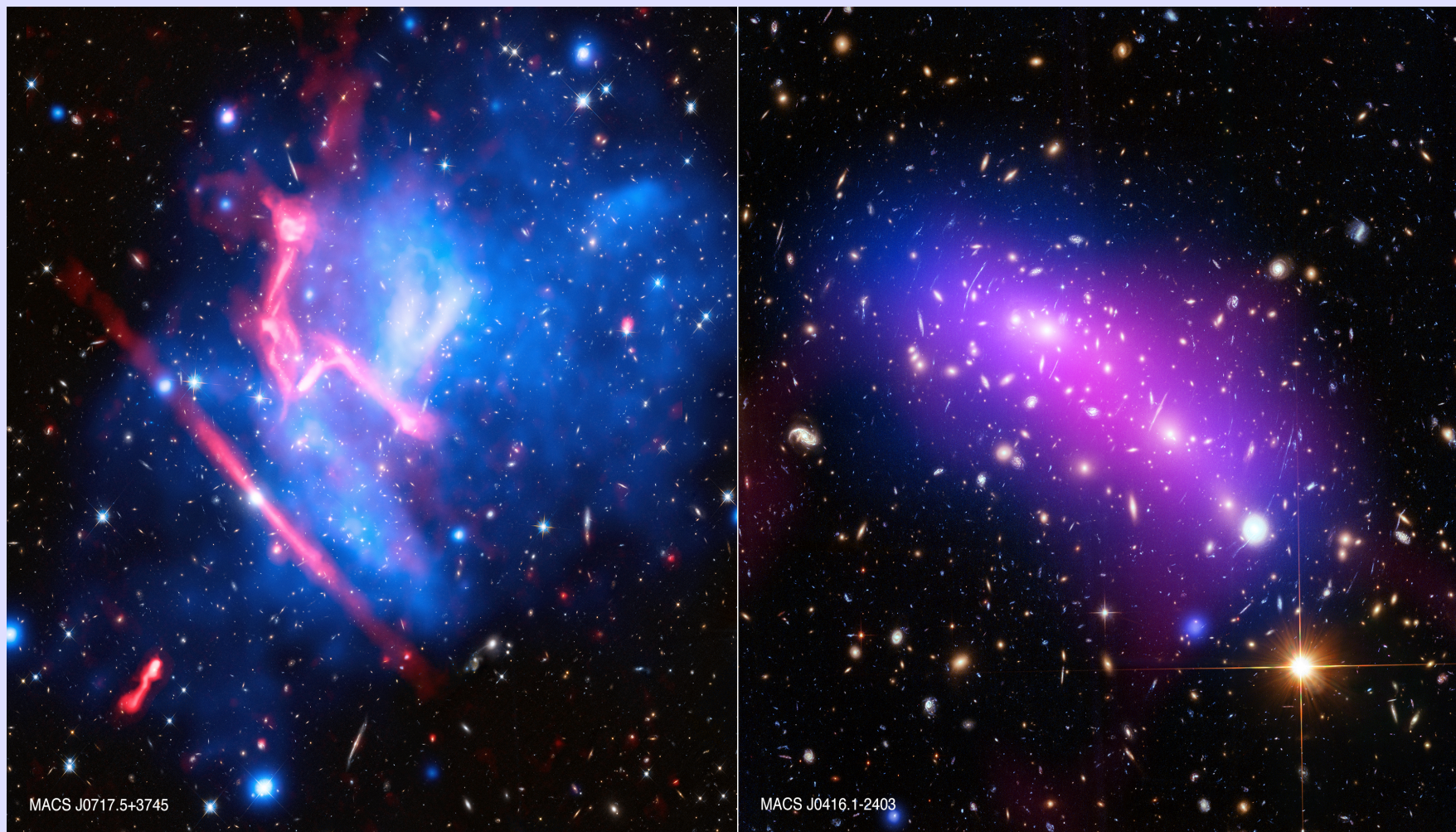
## XMM-Newton European Space Agency



“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



## 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.

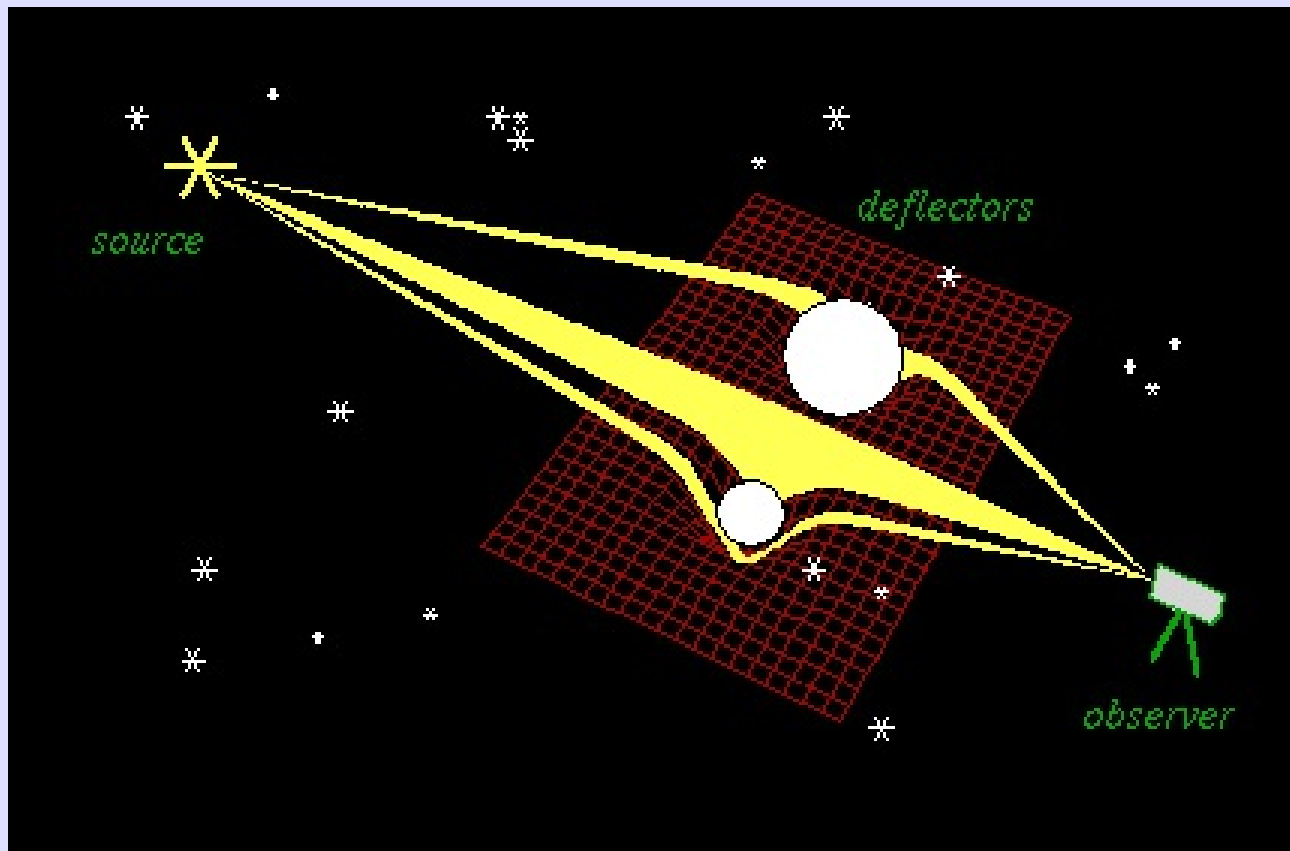
These new images of MACS J0416 and MACS J0717 contain data from three different telescopes:

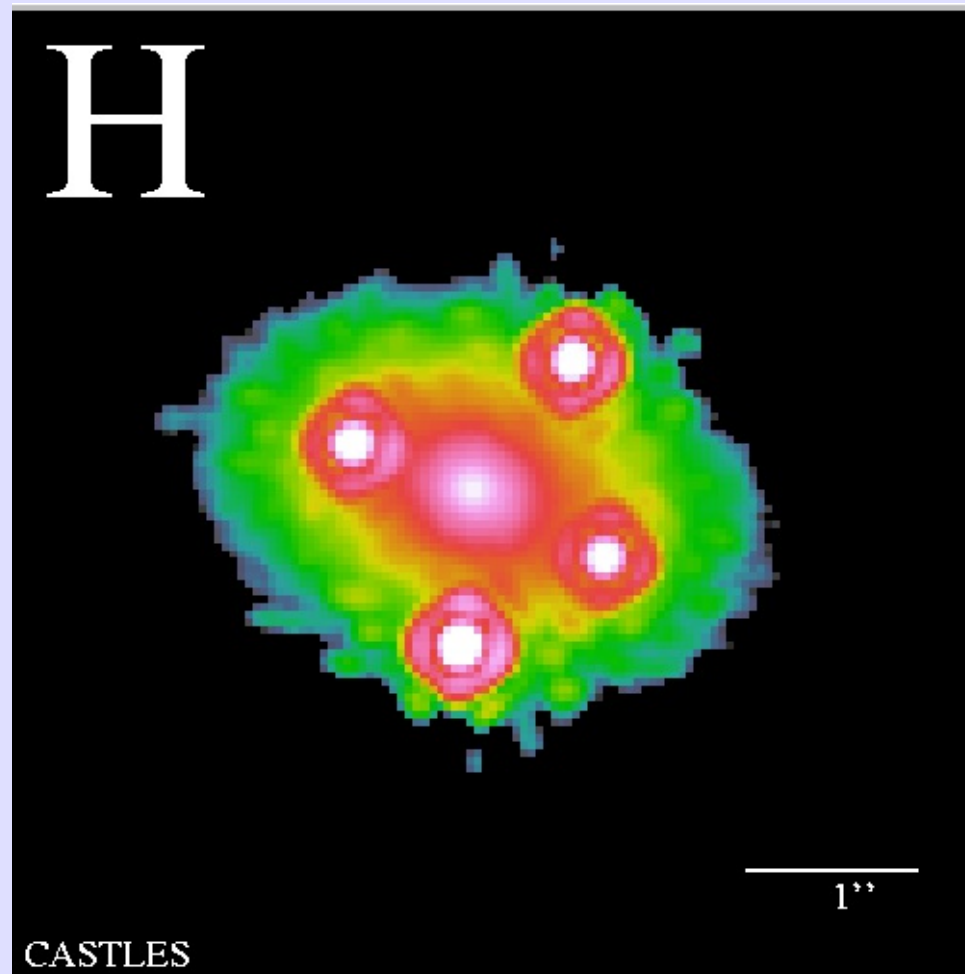
- NASA's Chandra X-ray Observatory (diffuse emission in blue),



- 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 Gravitational lensing





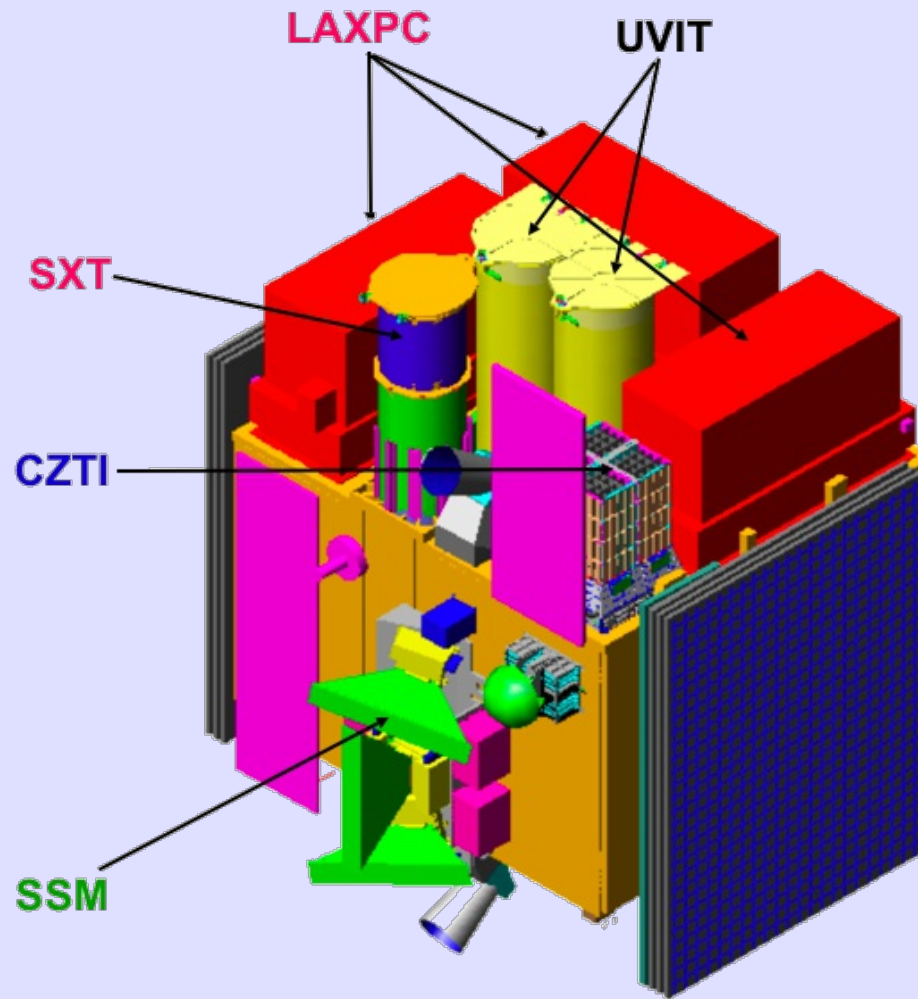
## 4 Putting together : optical, X-ray, G-lense



The pink is from X-ray and the blue from gravitational lensing

## 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

IIT Bombay G-Wave Group :

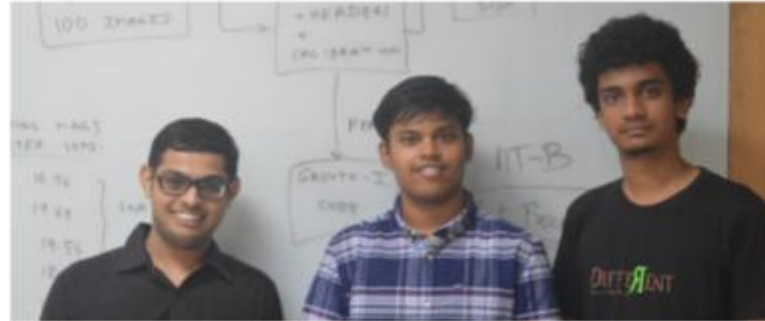




Dr. Archana Pai



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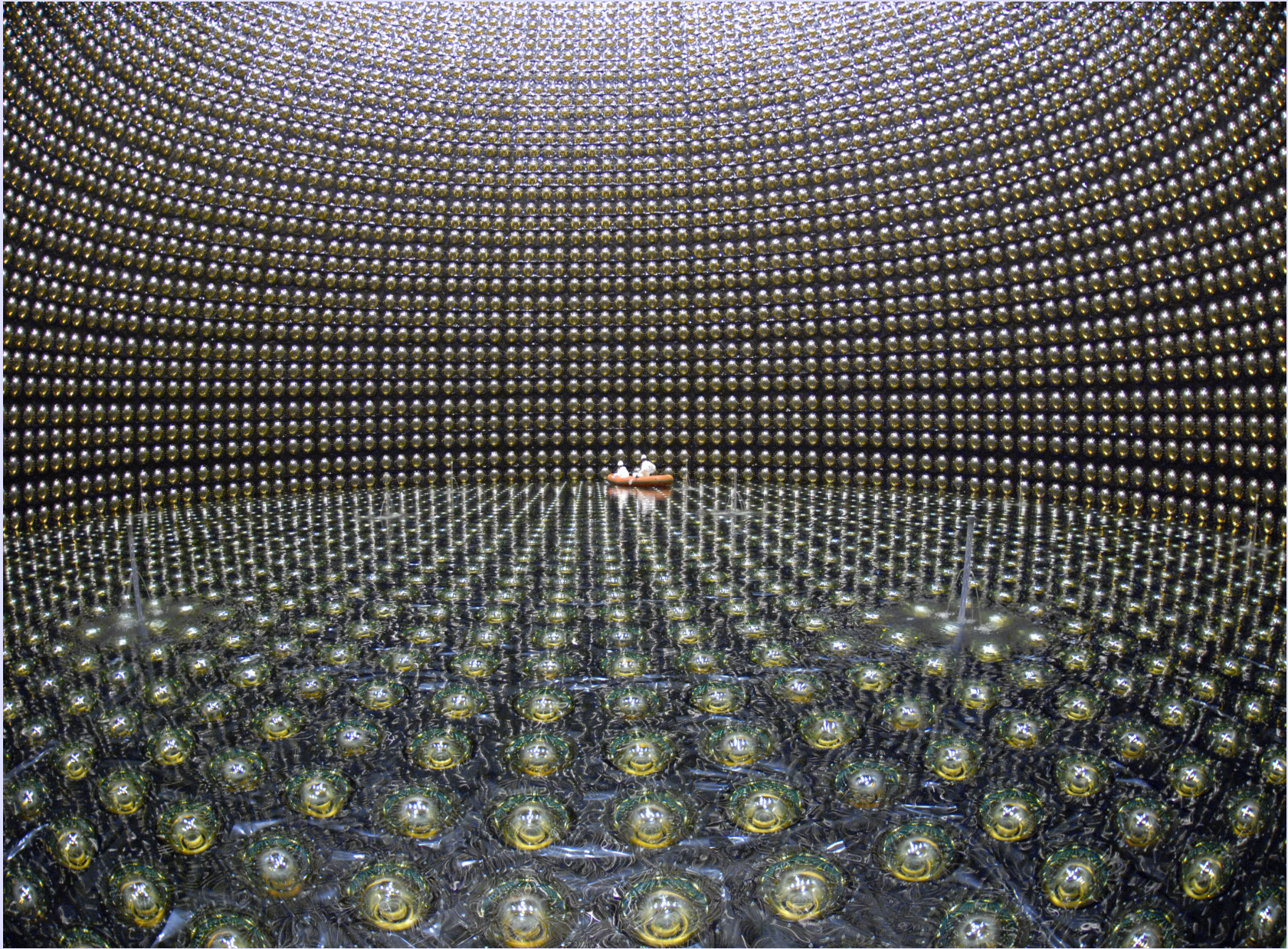


## 5 Looking beyond light

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

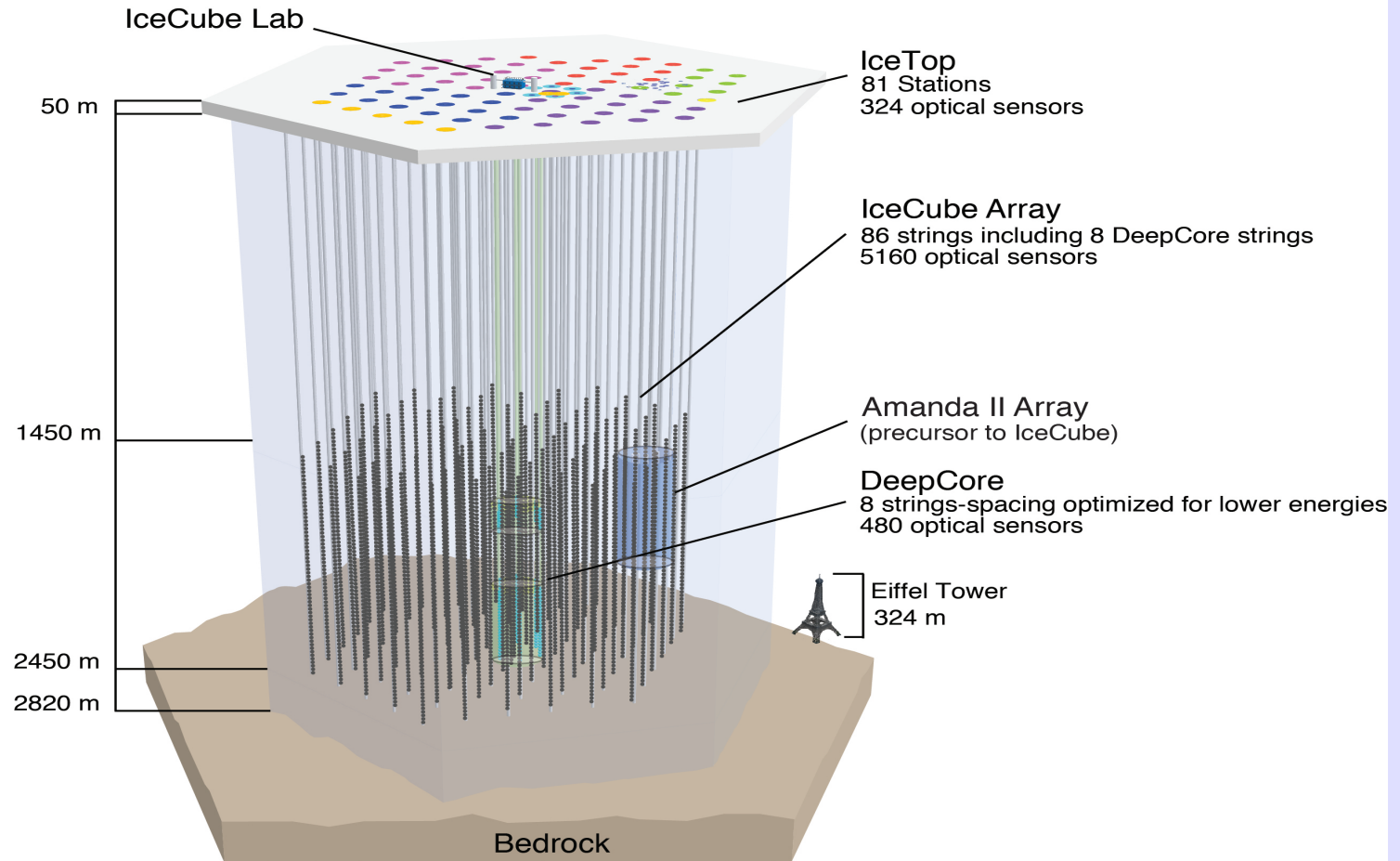
- SuperKamiokande







# - IceCube

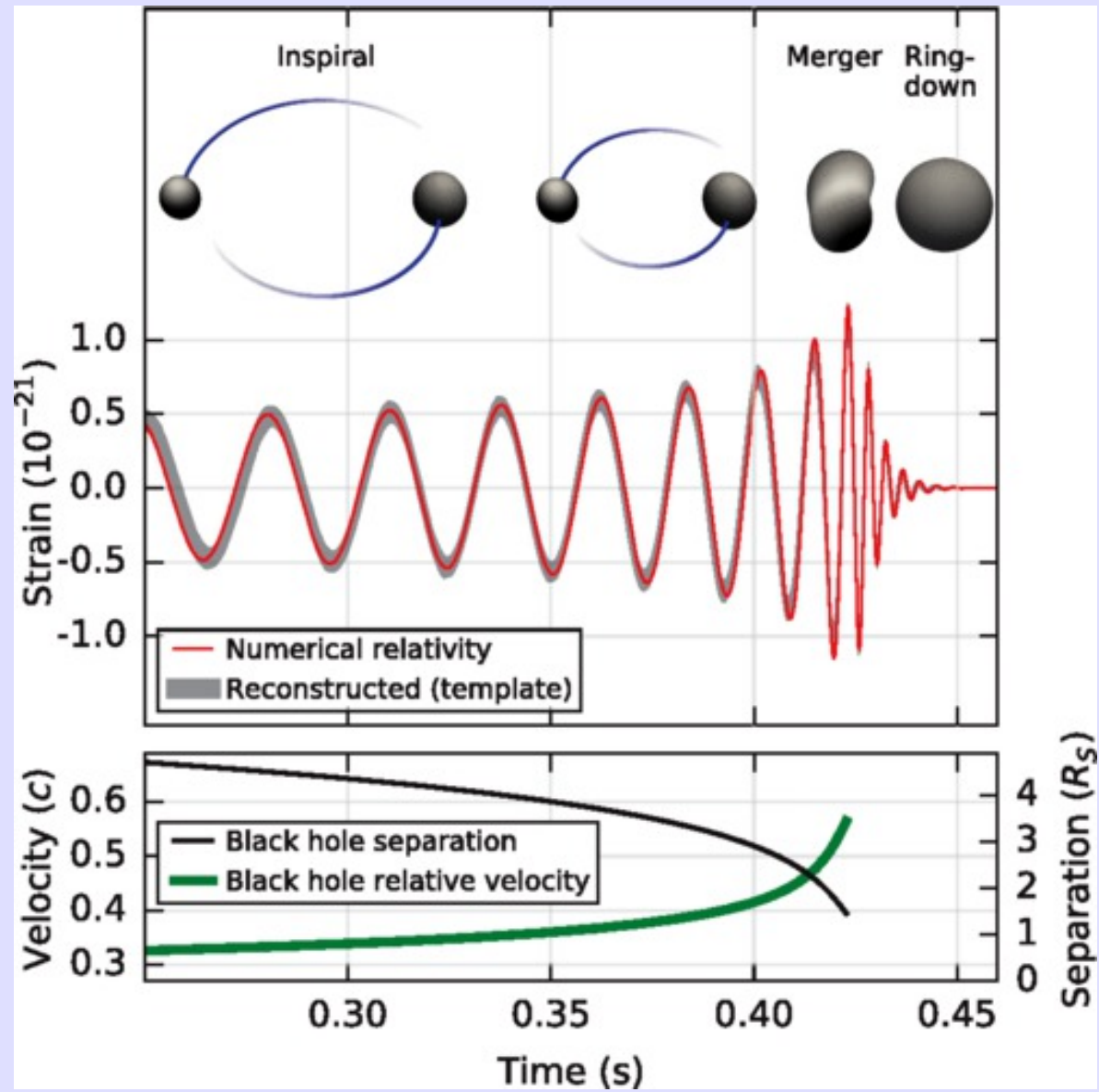


... and now

## 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,  $m_1$  and  $m_2$ , due to gravitational-wave emission.”



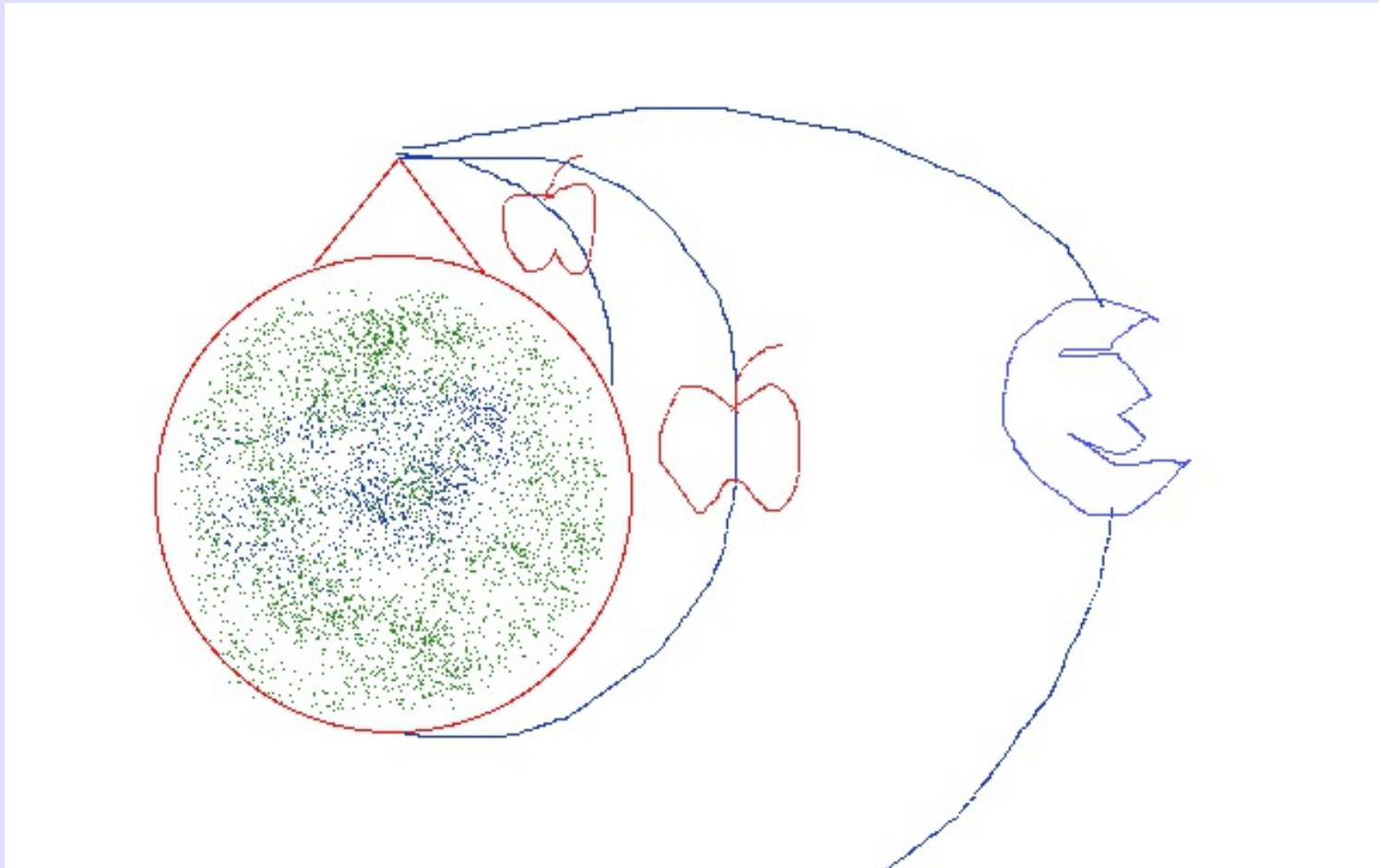
## Physical parameters

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

# 7 Relativity, General Relativity

Gravity  $\equiv$  Curved space-time

## 7.1 The apple and the Moon



The apple and the moon attracted the same way to the earth



## 7.2 In praise of Gravitation

- Universality – embraces everything, terrestrial as well as “heavenly” objects
- The beauty of the  $1 / r^2$  law – conservation of gravitational flux
- Earth, Moon and apple all act like point particles outside their physical extent ! ( what held up Newton 15 years)

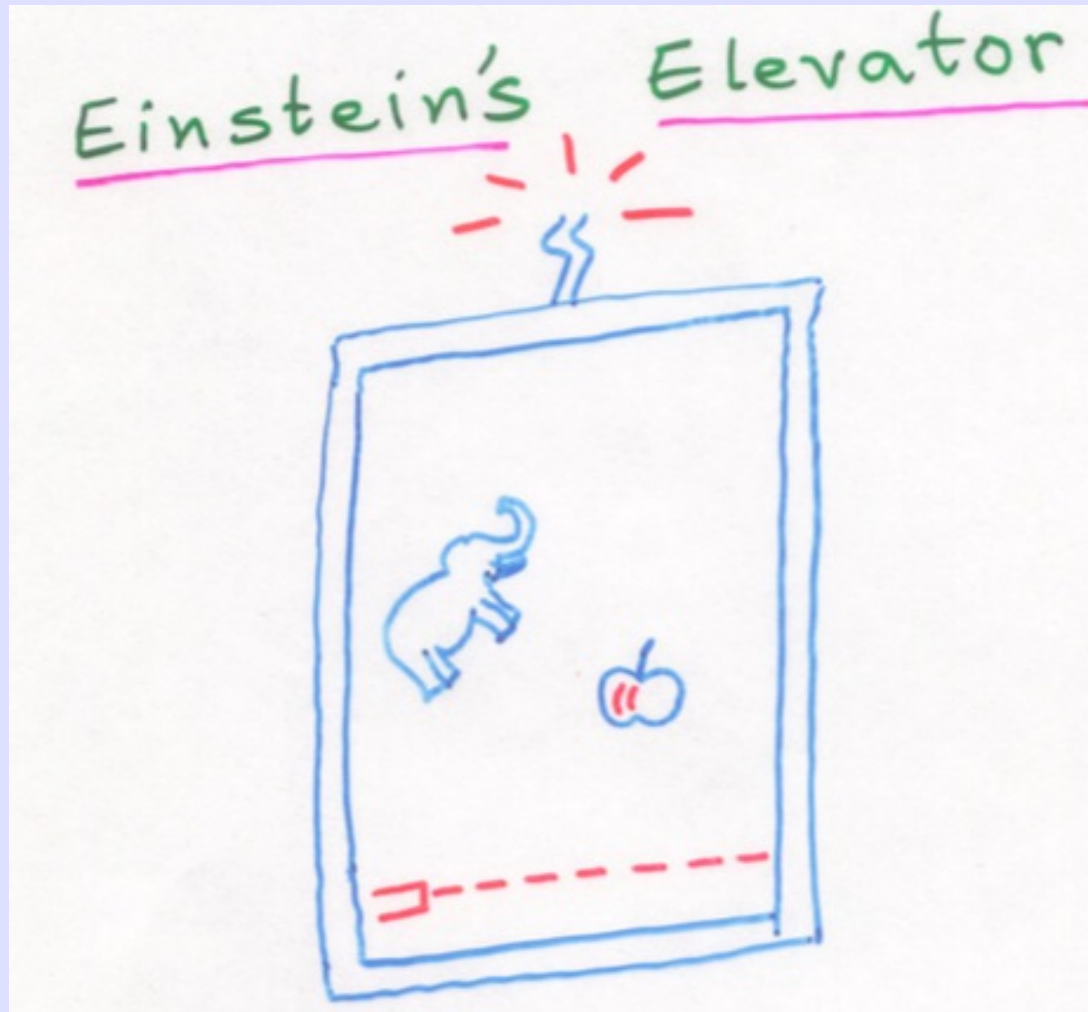
## 7.3 The simplest profoundest hint

### Principle of Equivalence

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

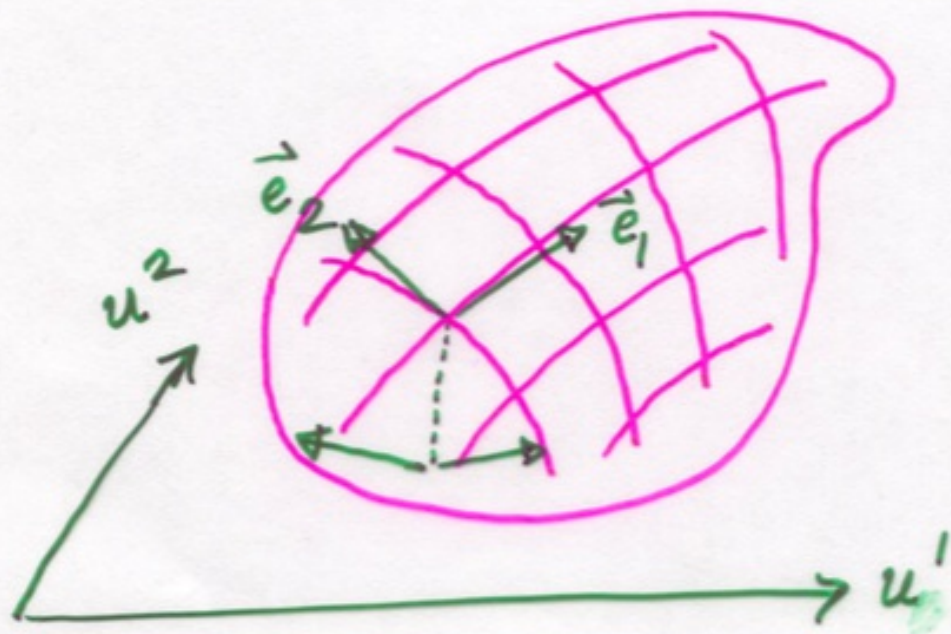
the test particle

$$m_1 a = G \frac{m_1 m_2 \hat{r}}{r^2}$$



- **Property of Gravity** : Same acceleration  $\leftrightarrow$  analogy to pseudoforce  $\leftrightarrow$  non-cartesian coordinates
- **Gravity in special frames** : Freely Falling Frame of Reference  $\leftrightarrow$  disappearance of Gravity  $\leftrightarrow$  Locally equivalent to inertial frame of reference  $\leftrightarrow$  Locally, Special Relativity
- **Same initial velocity**  $\leftrightarrow$  same trajectory ( regardless of mass)  $\leftrightarrow$  trajectory intrinsic property of space-time  $\leftrightarrow$  curved space-time.

## 7.4 Space-time metric



$$\vec{e}_1 \cdot \vec{e}_2 \text{ (Pythag.)}$$

$$= e_1^x e_2^x + e_1^y e_2^y + e_1^z e_2^z$$

$$\vec{e}_1 \cdot \vec{e}_2 \text{ (Gauss)}$$

$$= g_{xx} e_1^x e_2^x + g_{yy} e_1^y e_2^y$$

$$+ g_{zz} e_1^z e_2^z$$

$$+ 2g_{xy} e_1^x e_2^y + 2g_{yz} e_1^y e_2^z$$

$$+ 2g_{zx} e_1^z e_2^x$$

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

## 8 Quadrupole source

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

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

### 8.1 Electromagnetism and Gravity

#### Comparison and contrast

Nettlesome issues :

- Gauge artefacts / covariance / Equivalence Principle

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

- 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

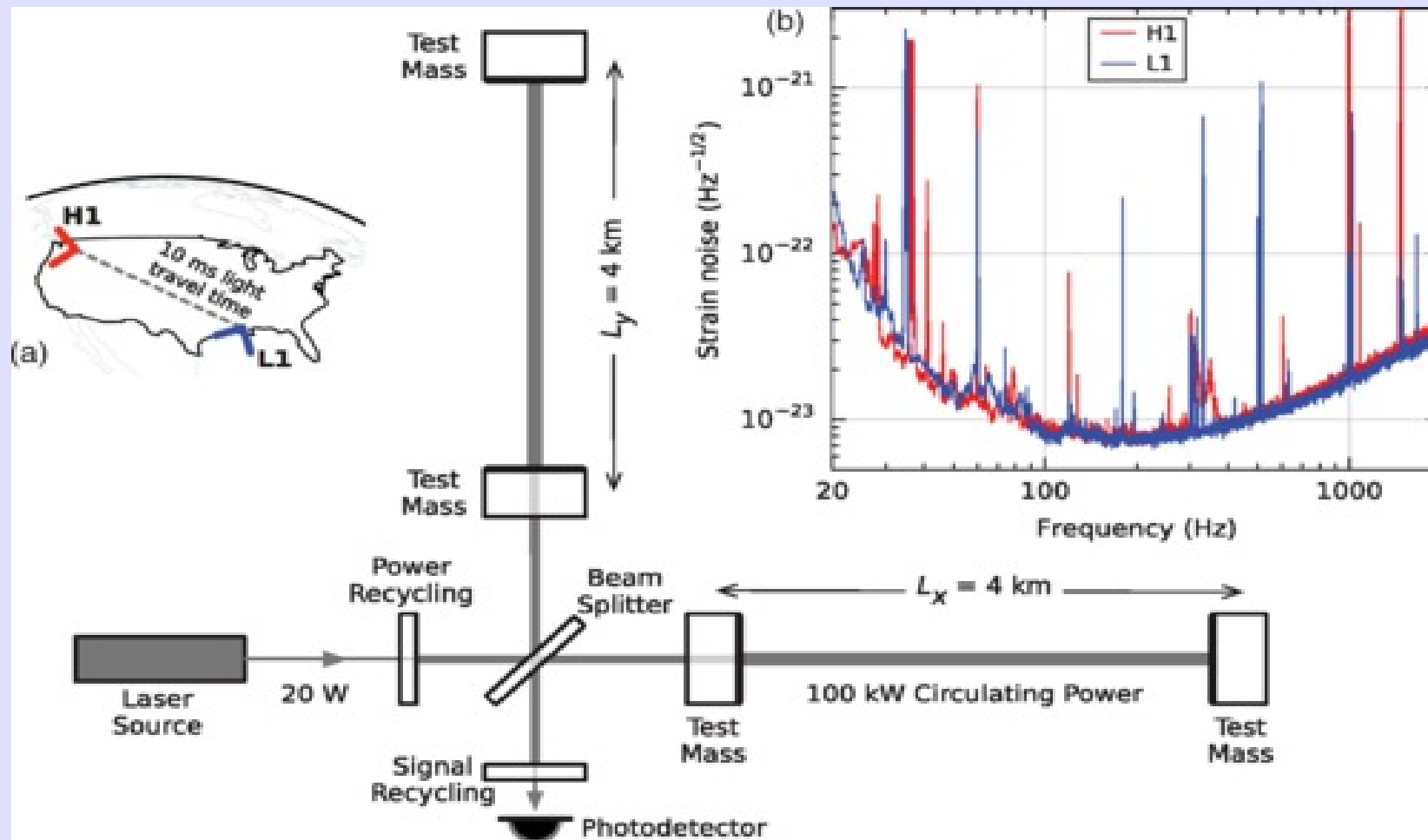
$$P = \frac{dE}{dt} = -\frac{32}{5} \frac{G^4}{c^5} \frac{(m_1 m_2)^2 (m_1 + m_2)}{r^5}$$

$$\frac{dr}{dt} = -\frac{64}{5} \frac{G^3}{c^5} \frac{(m_1 m_2) (m_1 + m_2)}{r^3}$$

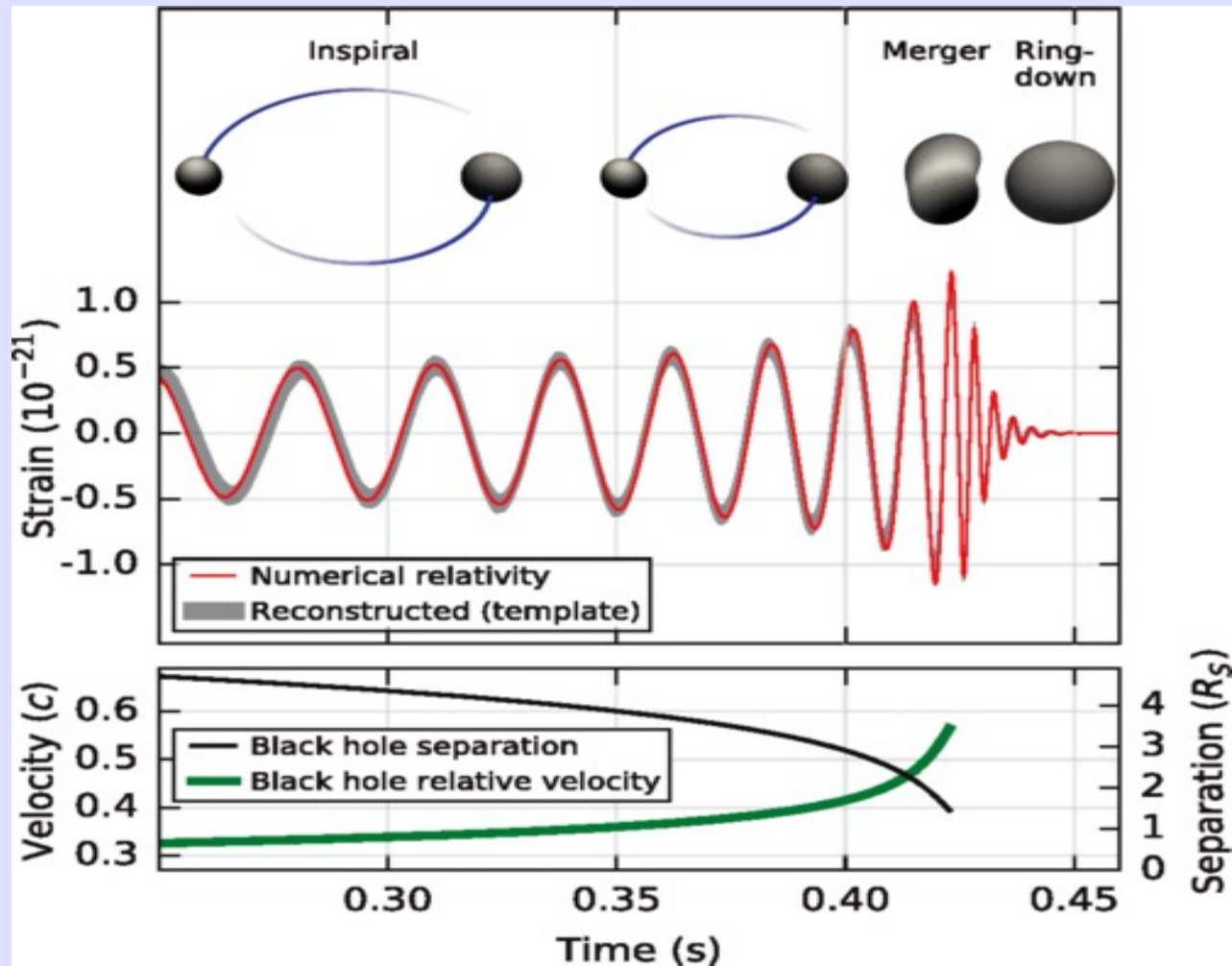
## 10.3 New technologies

Amazingly, LIGO project and the computational capabilities reach comparable levels of precision within a decade of each other, and in

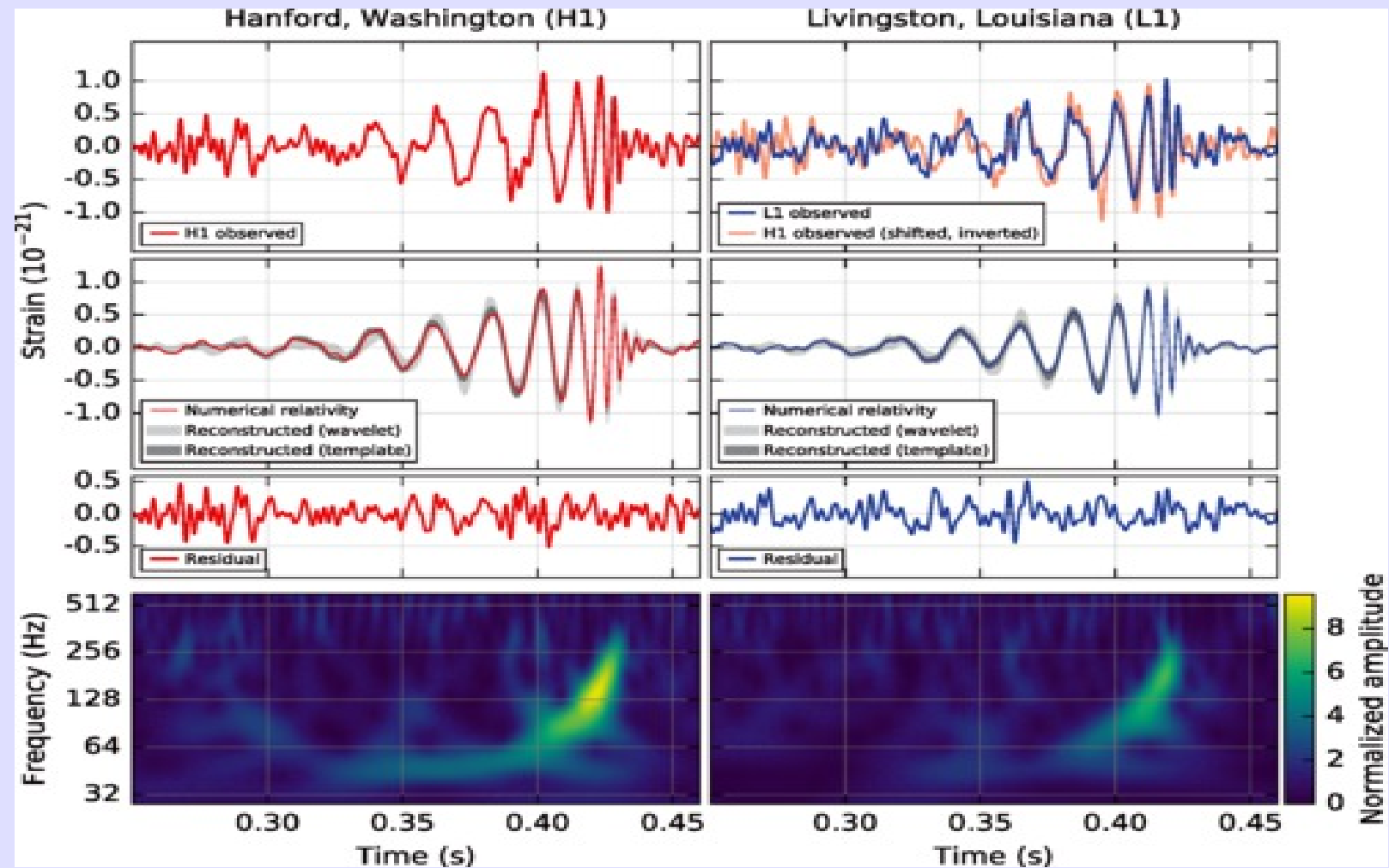
time for the discovery.



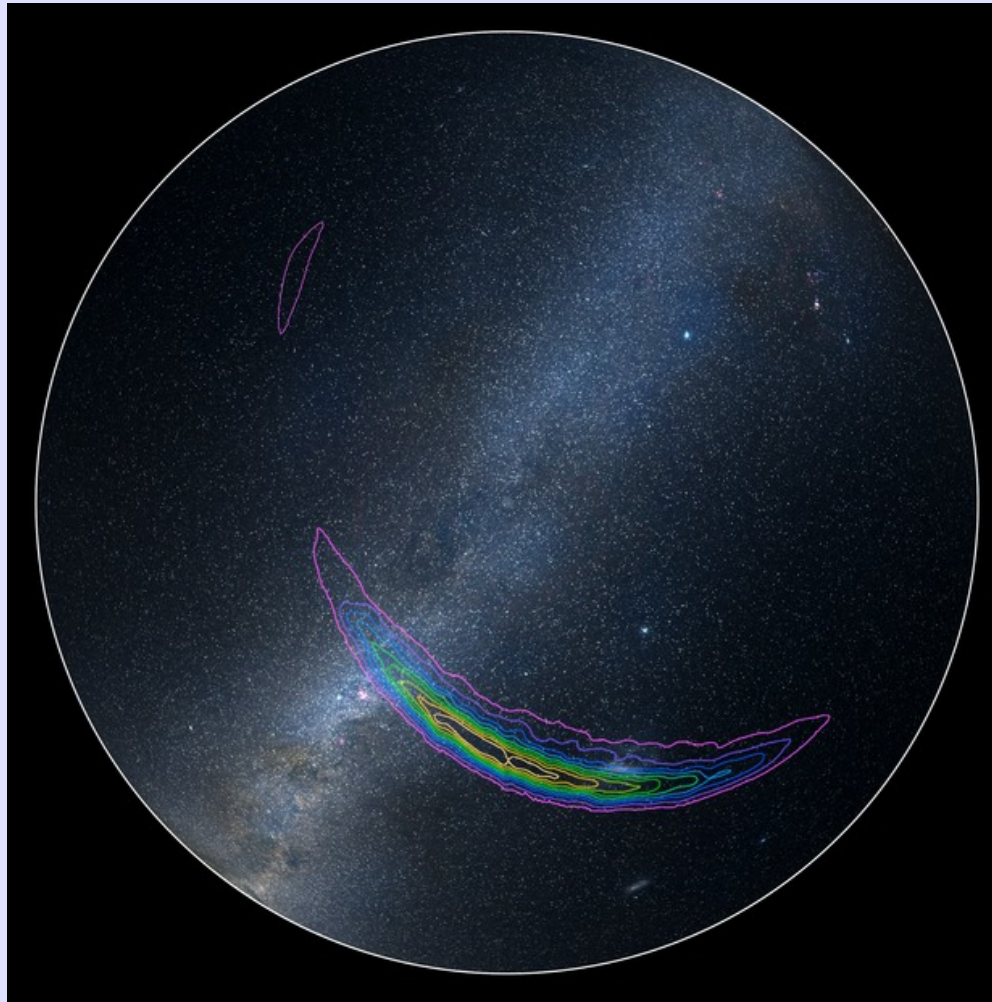
# 11 The merger and the “ring down”



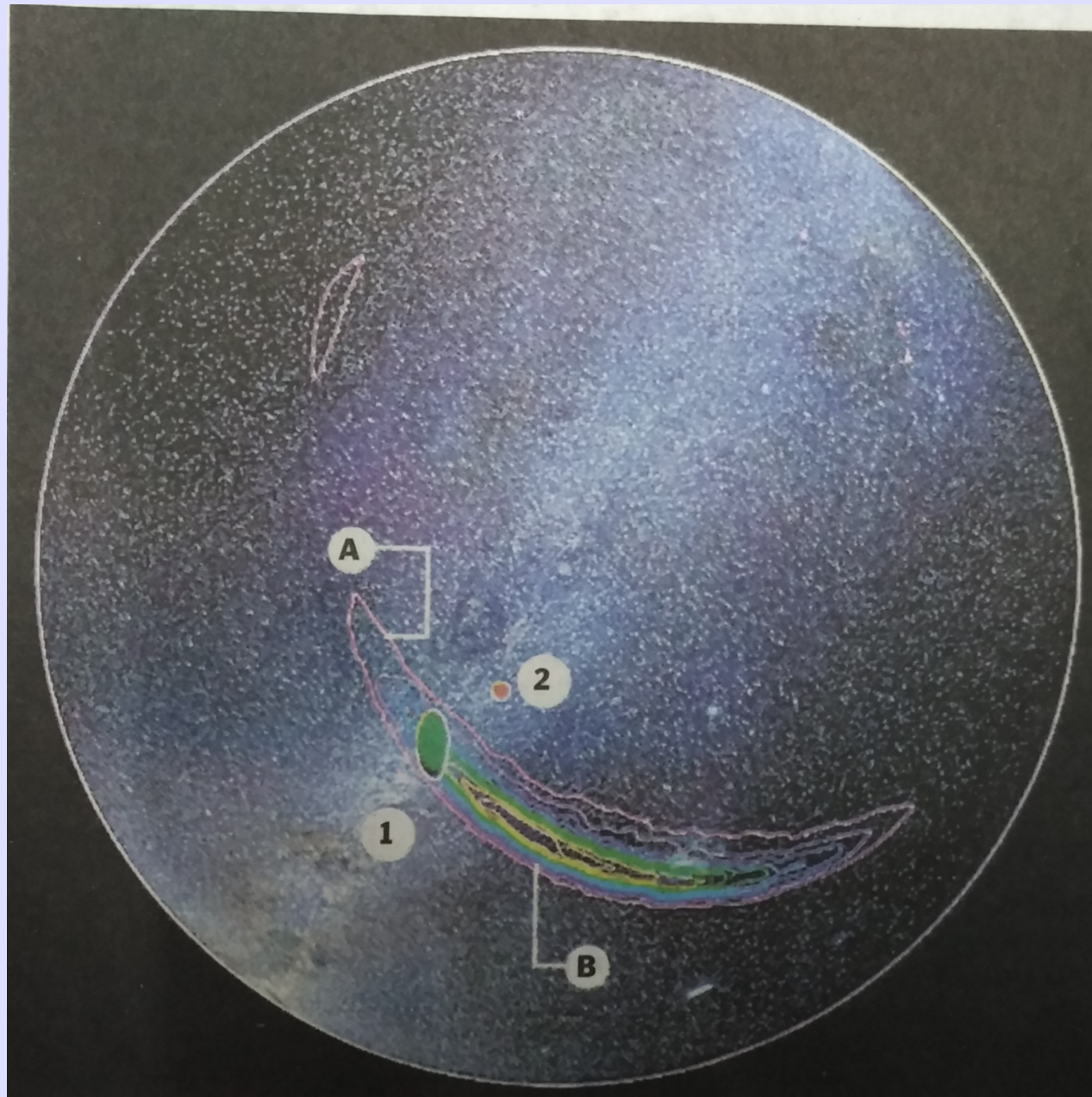
# 12 Details



## 13 LIGO - India









# 14 Conclusion

## Widest spectrum electromagnetic telescopey

- 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!
- Equation of state of supermassive objects

....Last page

Real time tracking using multimessenger probes.

Thank you!

*Typeset using TeXmacs!!*