Gravitational waves: A new astronomy

Prof Sheila Rowan

For the LIGO Scientific Collaboration

Public Lecture

14th September 2016

Fundamentals

- In nature there are 4 fundamental forces

	Relative strength
Gravitation (our very existence)	1
Weak (radioactive decay)	$\sim 10^{25}$
Electromagnetic (holds matter together)	$\sim 10^{37}$
Strong (nuclear force)	$\sim 10^{39}$

Gravity – by far the weakest – yet very important

because

all particles of mass exert the same sign of gravitational pull – so the forces from all particles add up

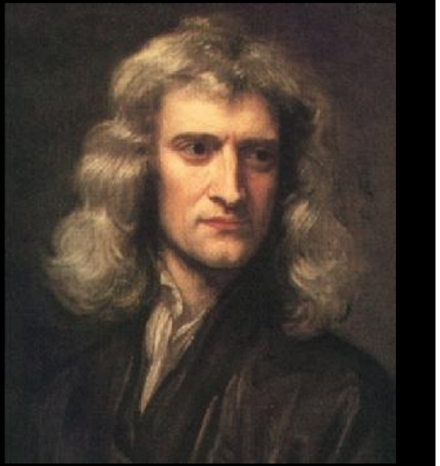
Gravity

… causes the birth and death of stars

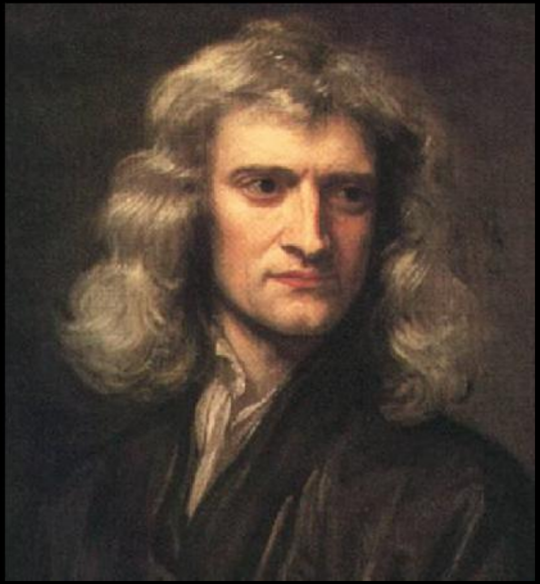
The fact we exist at all..

- clouds of dust pulled together to form the galaxies, the stars and hence the planets.

Described by Newton in his ‘Law of Gravitation’

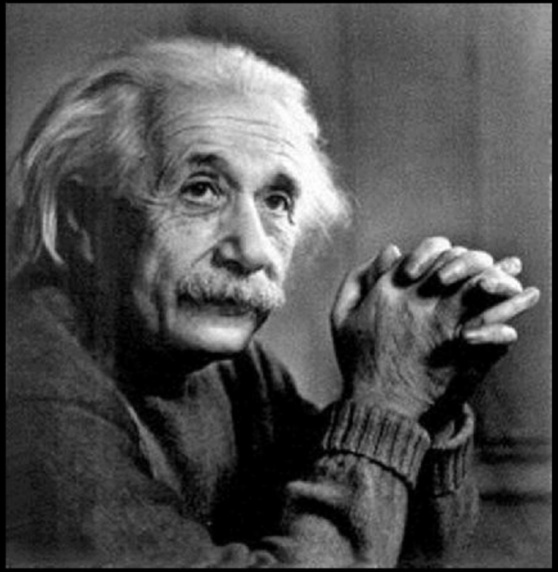


Gravitation



Newton's Theory

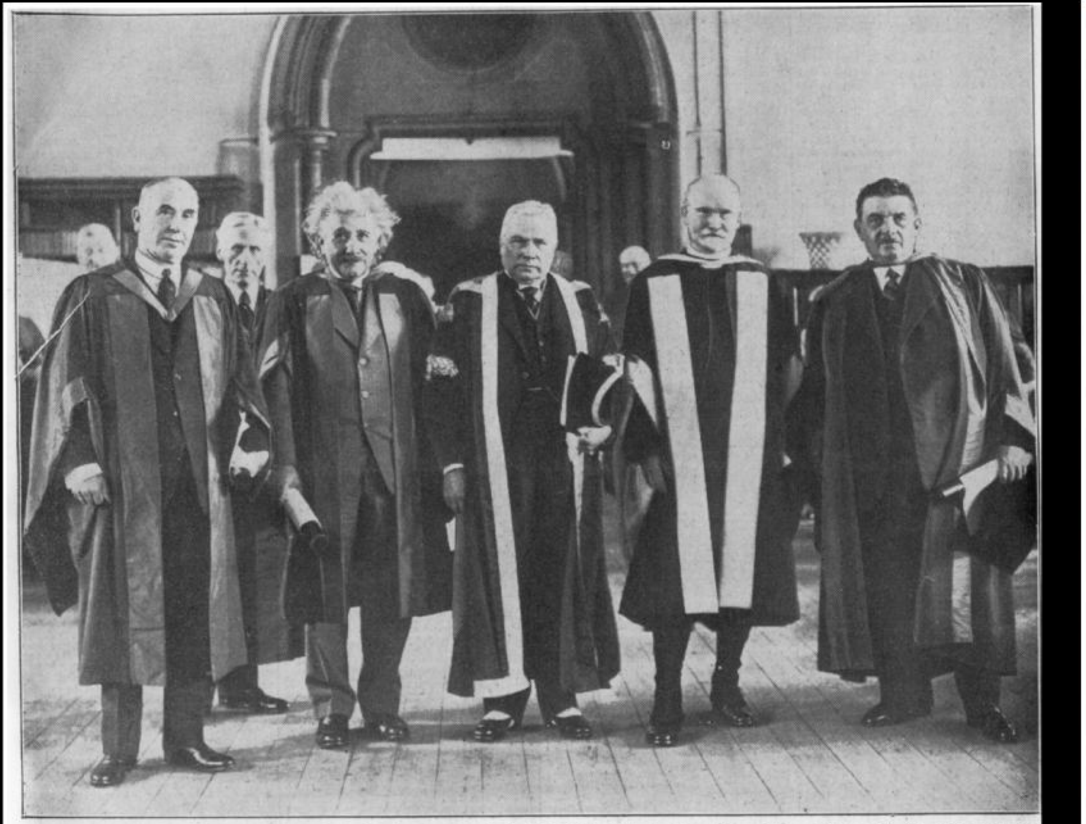
"instantaneous action at a distance"



Einstein's Theory

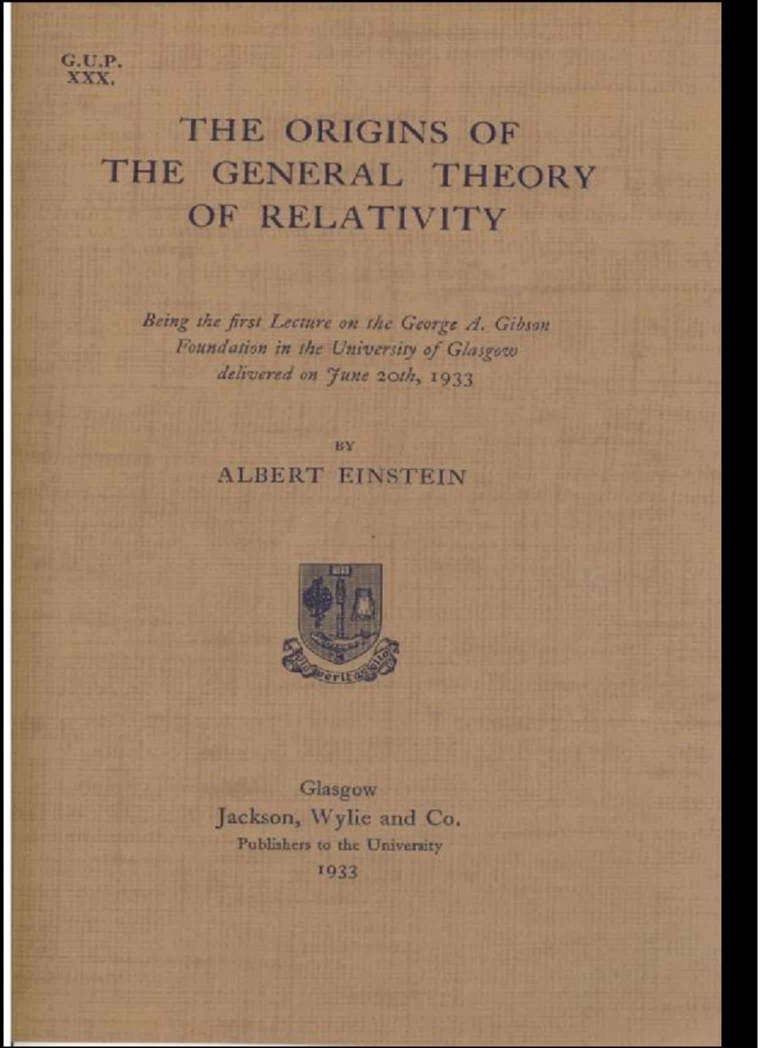
information cannot be carried faster than speed of light – there must be gravitational 'radiation'

Gravitational waves - a prediction of General Relativity (1916)



A group of some of the honorary graduates taken after the ceremony in the Bute Hall of Glasgow University yesterday. Left to right—The Right Hon. Sir Robert S. Horne; Emeritus Professor William Blair-Bell, University of Liverpool; Professor Albert Einstein; Principal Sir Robert S. Rait; the Archbishop of Armagh and Primate of All Ireland; and M. Edouard Herriot, former Prime Minister of France.

Einstein in Glasgow 1933



G.U.P.
XXX.

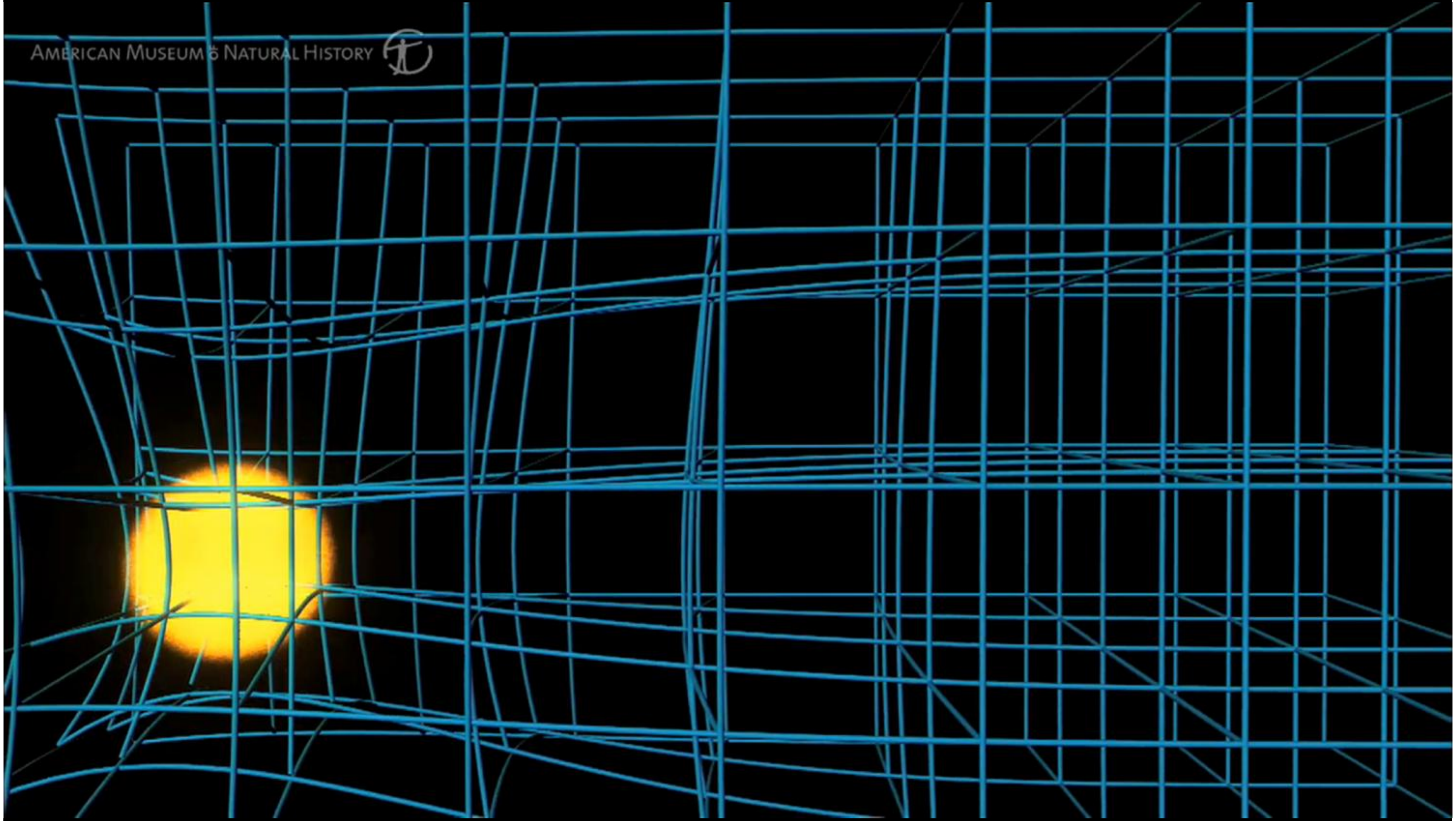
THE ORIGINS OF
THE GENERAL THEORY
OF RELATIVITY

Being the first Lecture on the George A. Gibson
Foundation in the University of Glasgow
delivered on June 20th, 1933

BY
ALBERT EINSTEIN

Glasgow
Jackson, Wylie and Co.
Publishers to the University
1933

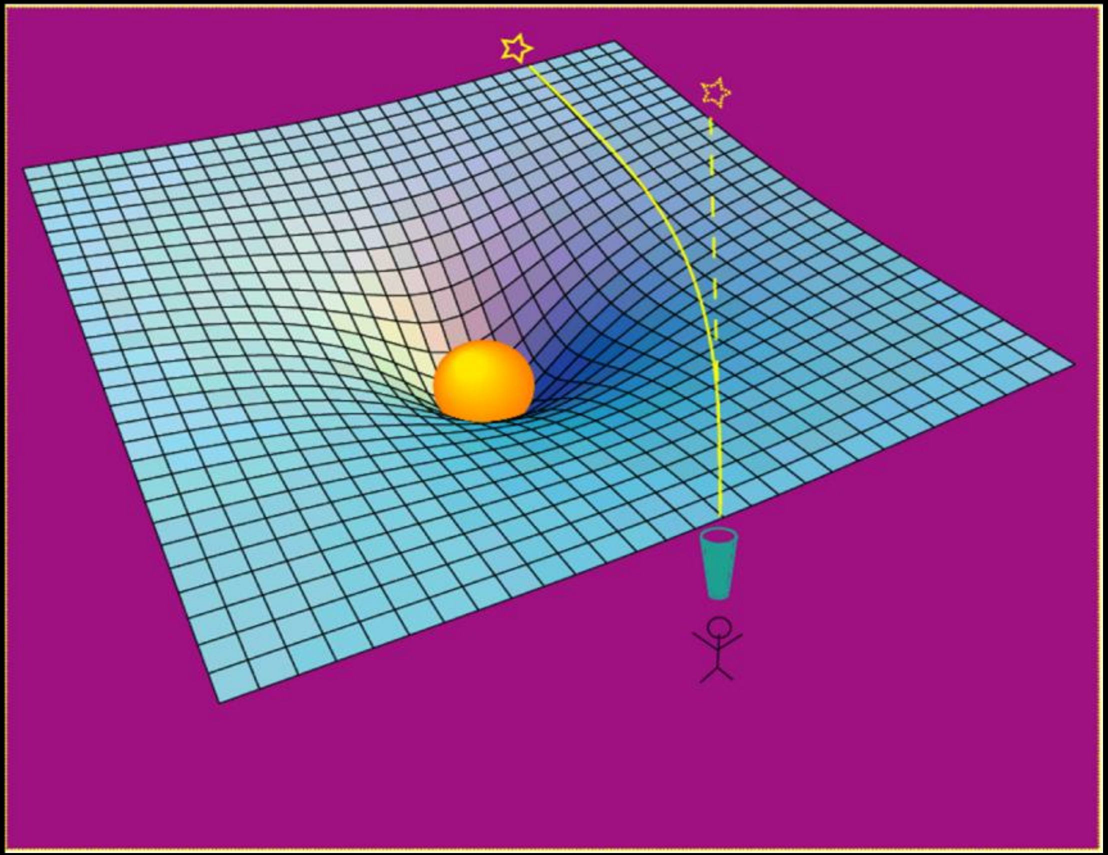
Matter curves space-time.
Space-time guides motion of matter.



‘Gravitational Waves – the experimentalist’s view’

- **Gravitational waves**

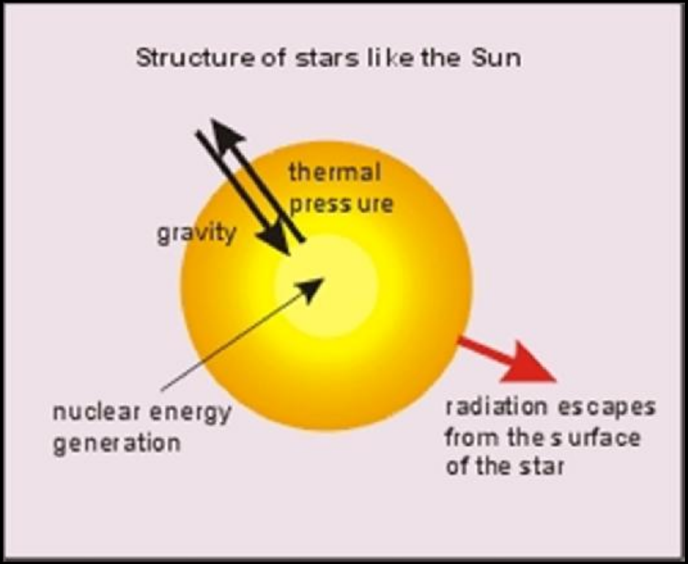
  ‘ripples in the curvature of spacetime’ – or fluctuating strains in space - that carry information about changing gravitational fields



Gravity : the death of stars

- In a star like our sun the gravitational force is balanced by the 'radiation pressure' of the heat coming out from hydrogen fusing into helium

  What happens when the 'fuel' runs out?



- Larger stars - the core collapse is catastrophic and the gravity so strong that the protons and electrons in the core get forced together to form neutrons – 'neutron stars'.

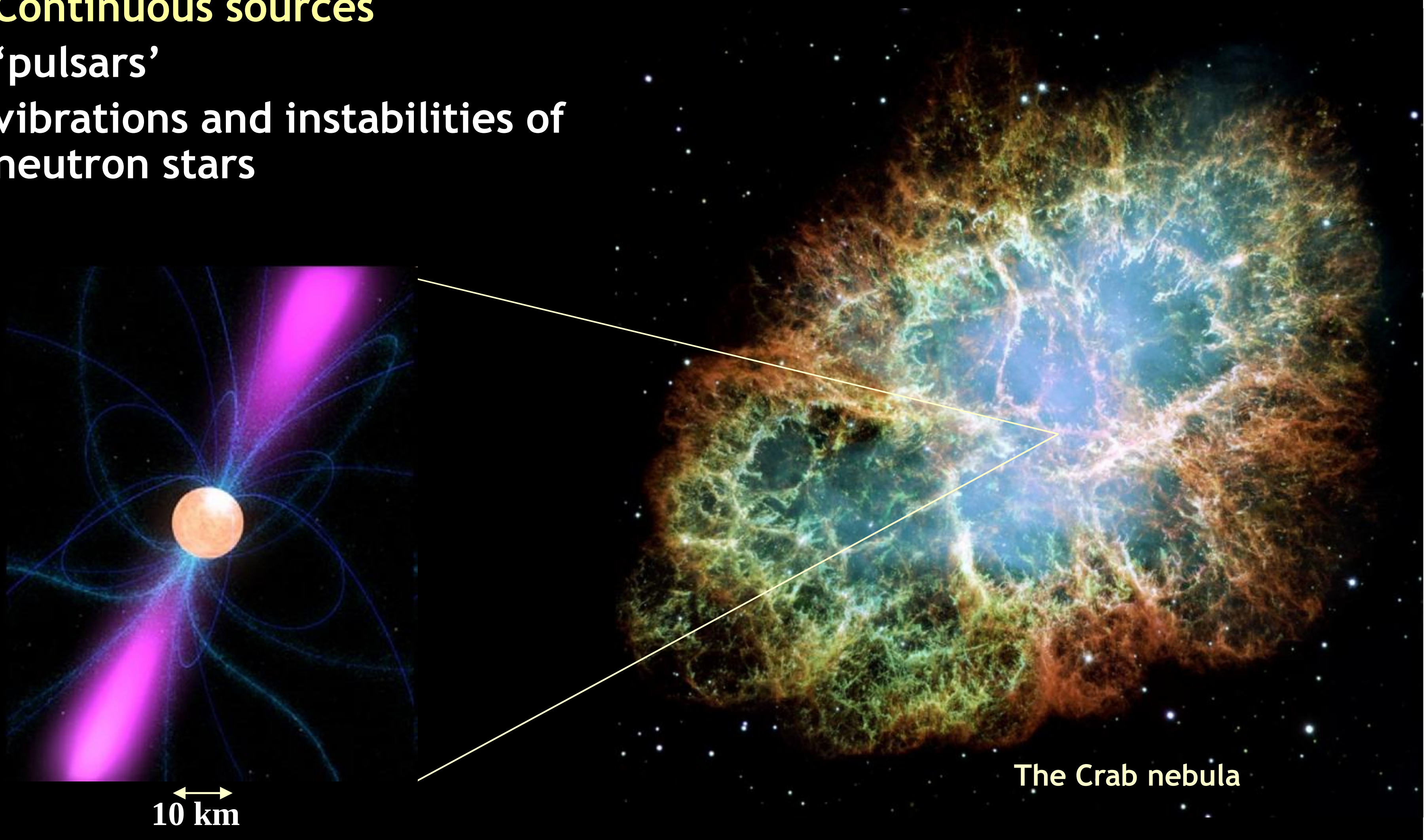
- Huge energy given off and outer layers blasted away –

  Supernova Explosion

- May even form a 'Black Hole'

‘Gravitational Waves’- possible sources

- Continuous sources
  ‘pulsars’
  vibrations and instabilities of neutron stars

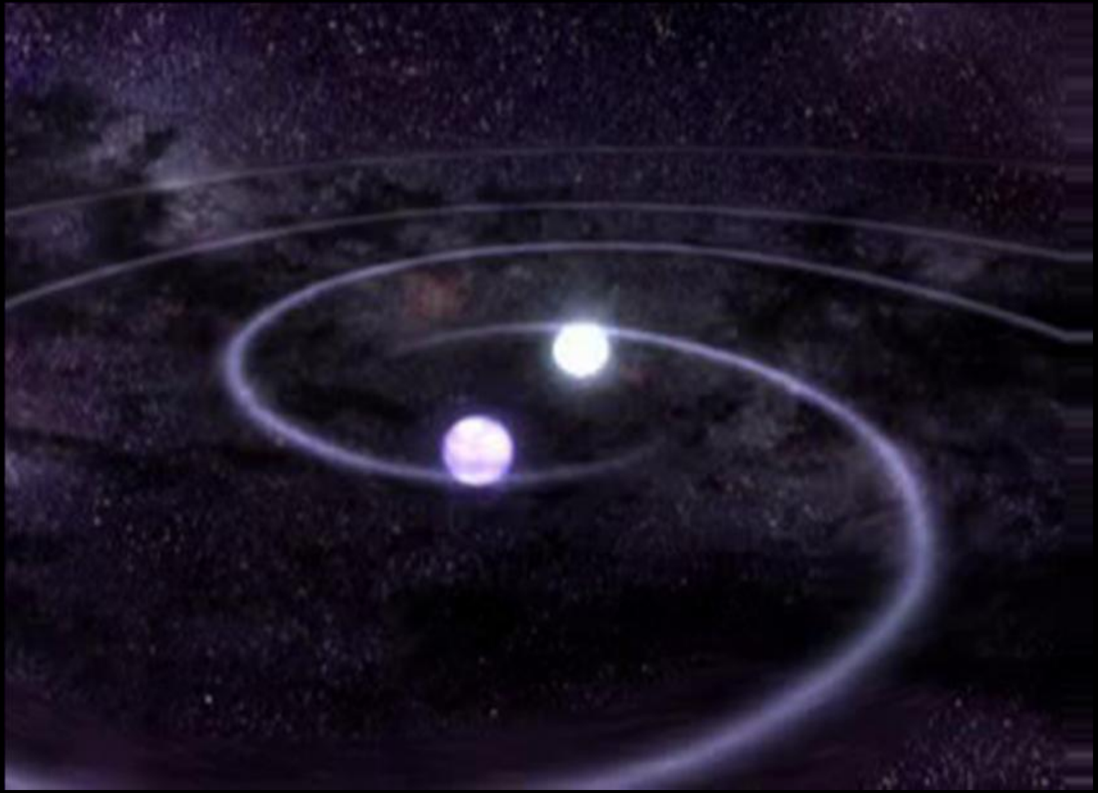


The Crab nebula

‘Gravitational Waves’- possible sources

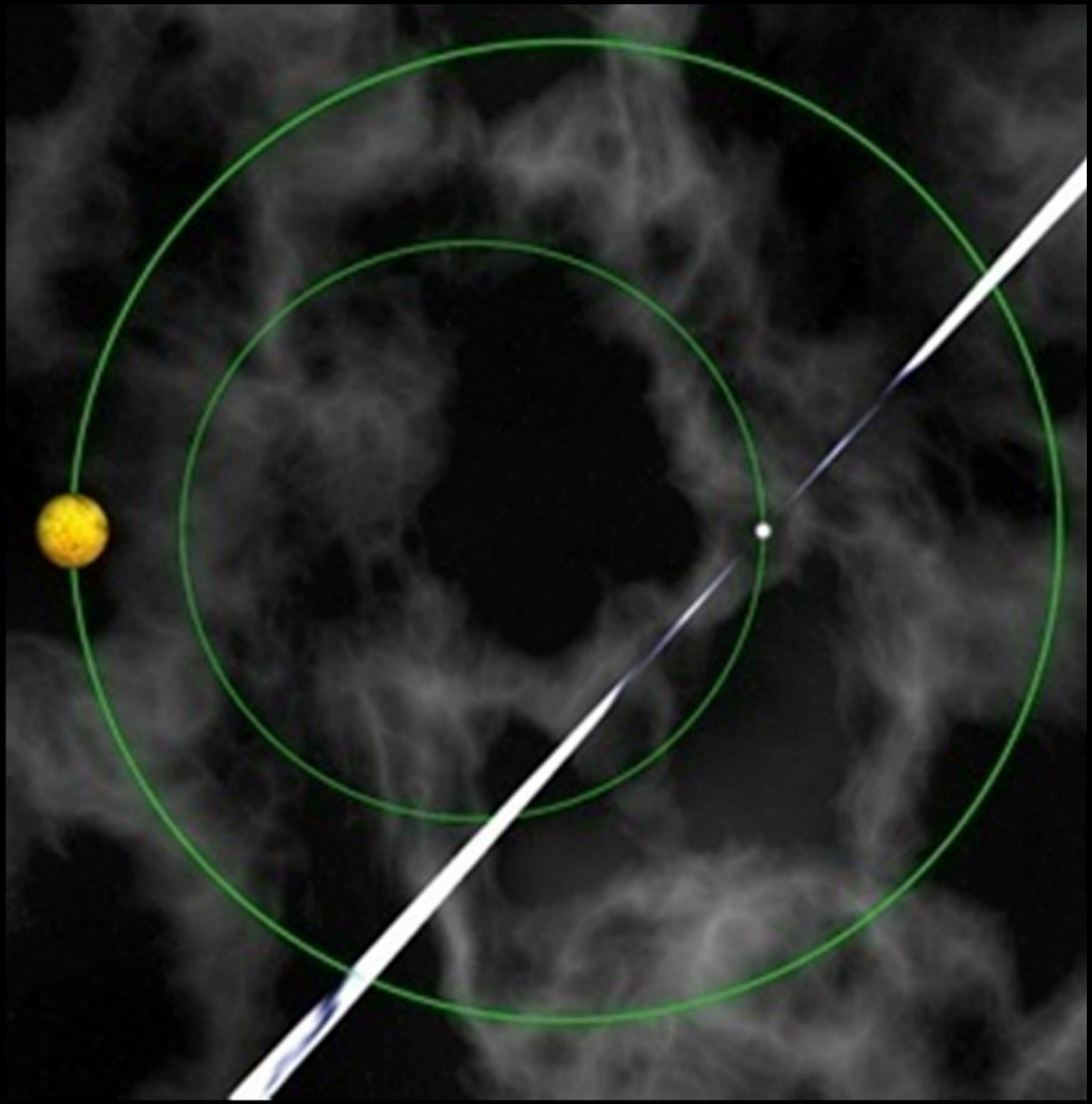
- **Pulsed or burst sources**

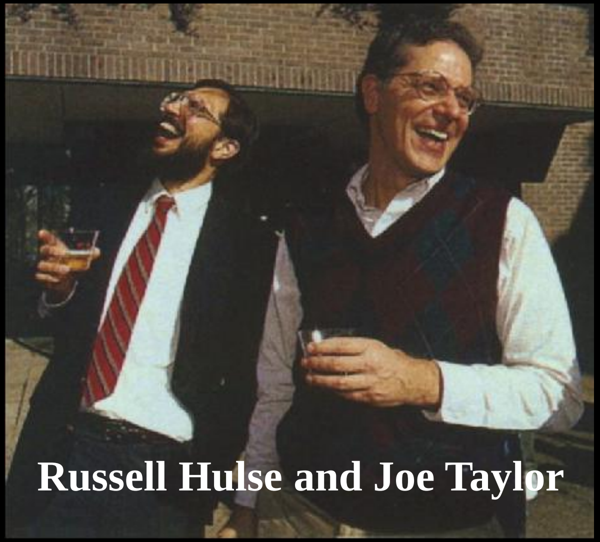
  Orbits and collisions of pairs of neutron stars or black holes..



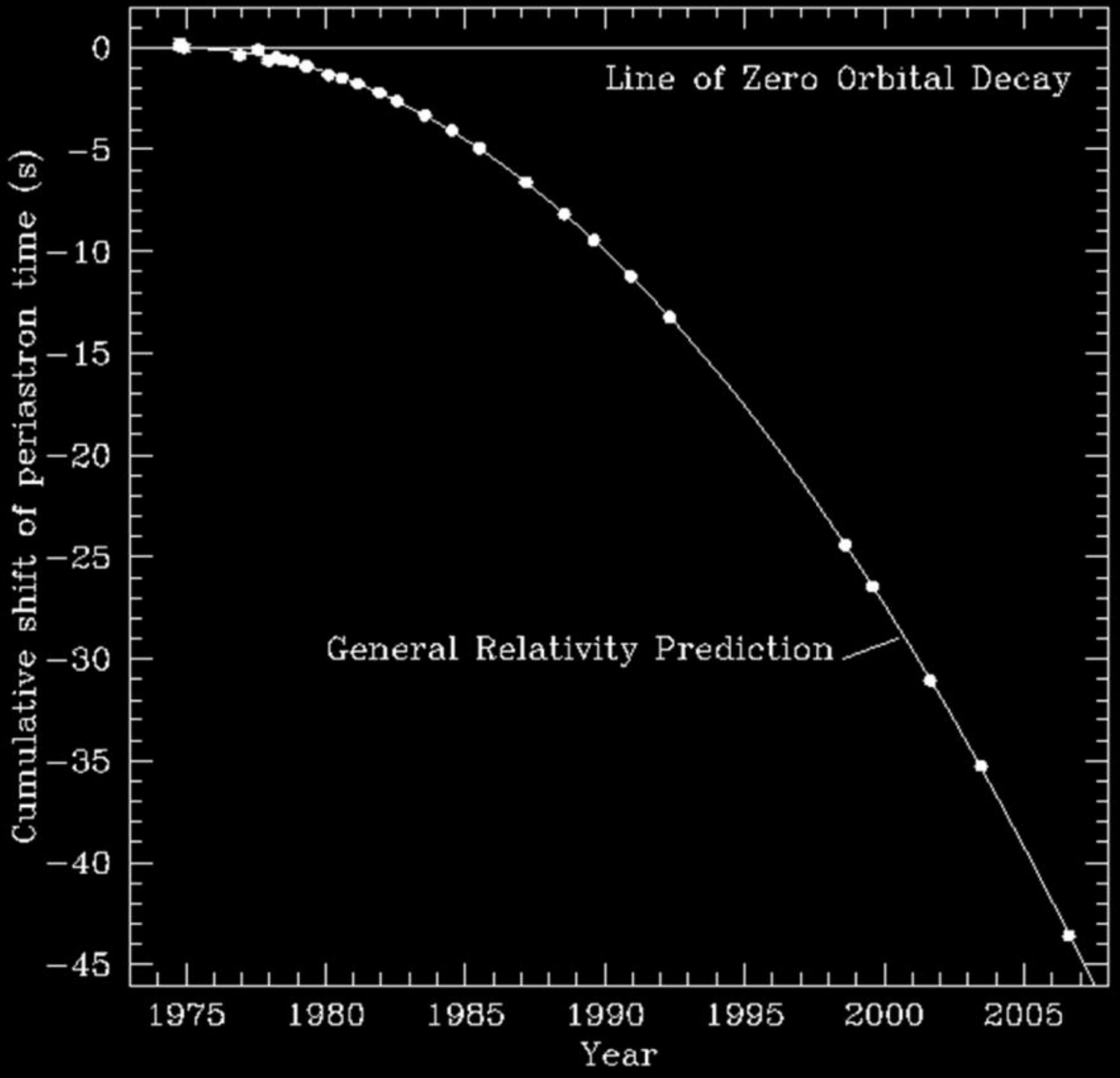
Credit :NASA/Goddard Space Flight Center

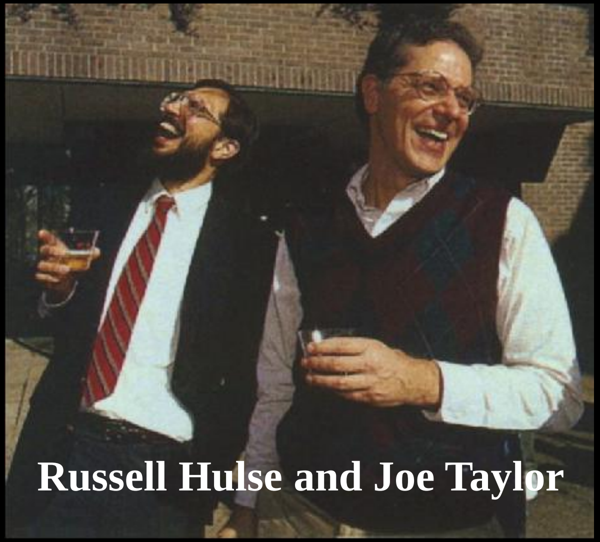
Binary stars spiralling in to collide



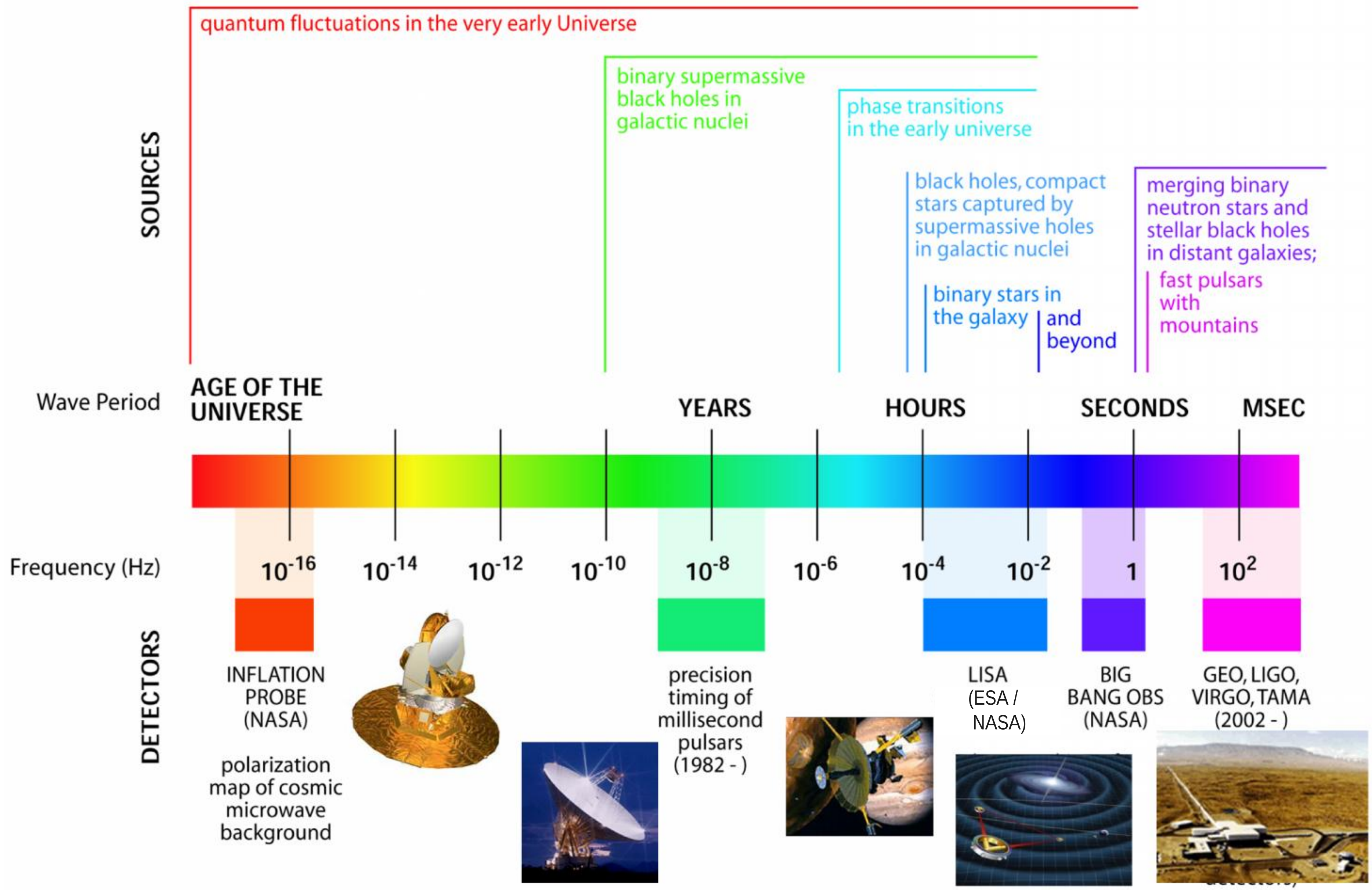


Russell Hulse and Joe Taylor


Line of Zero Orbital Decay
General Relativity Prediction
Cumulative shift of periastron time (s)
0
−5
−10
−15
−20
−25
−30
−35
−40
−45
1975
1980
1985
1990
1995
2000
2005
Year


Russell Hulse and Joe Taylor

THE GRAVITATIONAL WAVE SPECTRUM



SOURCES

quantum fluctuations in the very early Universe

binary supermassive black holes in galactic nuclei

phase transitions in the early universe

black holes, compact stars captured by supermassive holes in galactic nuclei

binary stars in the galaxy

and beyond

merging binary neutron stars and stellar black holes in distant galaxies;

fast pulsars with mountains

Wave Period	AGE OF THE UNIVERSE				YEARS		HOURS		SECONDS	MSEC
Frequency (Hz)	10^{-16}	10^{-14}	10^{-12}	10^{-10}	10^{-8}	10^{-6}	10^{-4}	10^{-2}	1	10^{2}

DETECTORS

INFLATION PROBE (NASA)

polarization map of cosmic microwave background

precision timing of millisecond pulsars (1982 -)

LISA (ESA / NASA)

BIG BANG OBS (NASA)

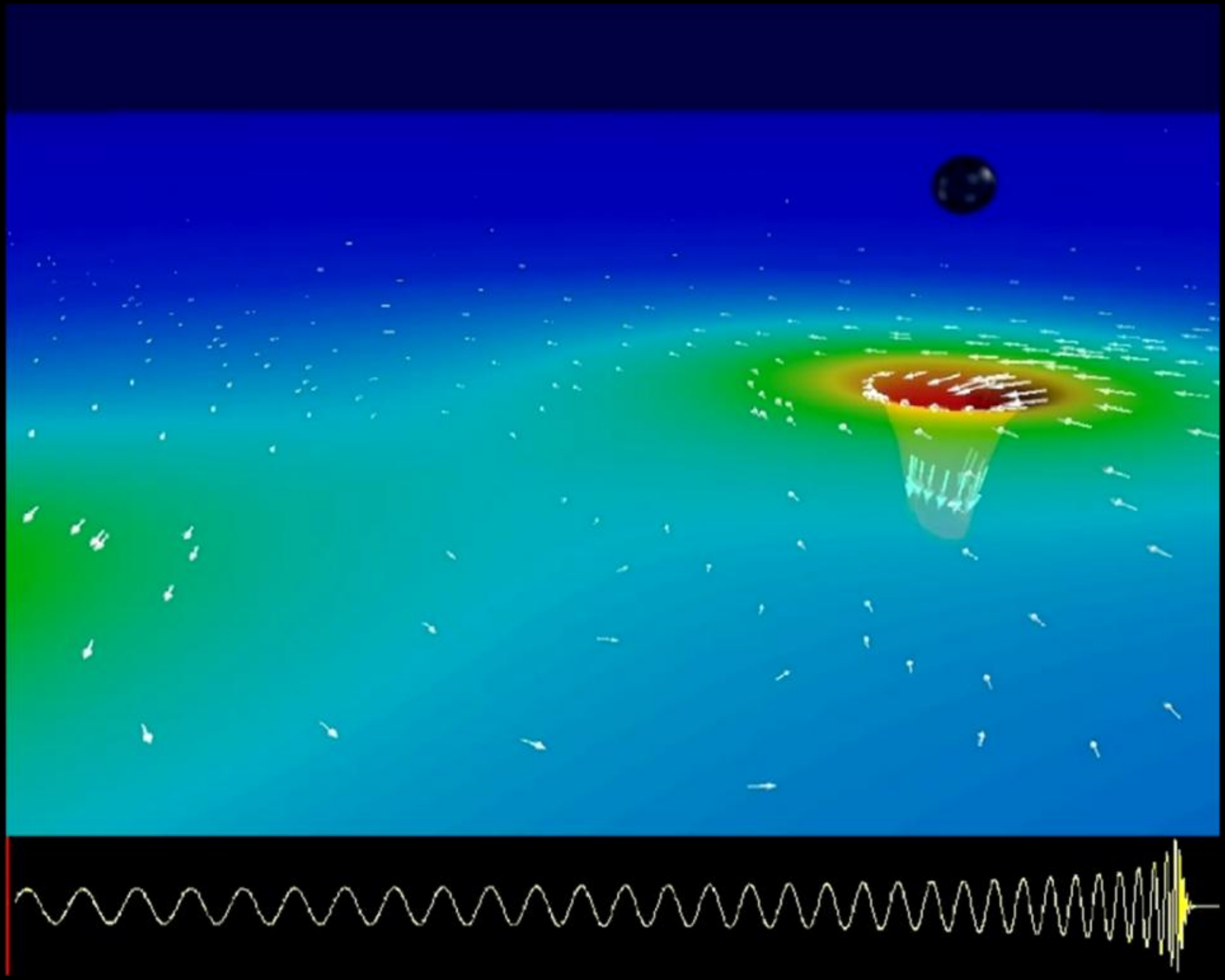
GEO, LIGO, VIRGO, TAMA (2002 -)

Listening for Merging Binary Black Holes

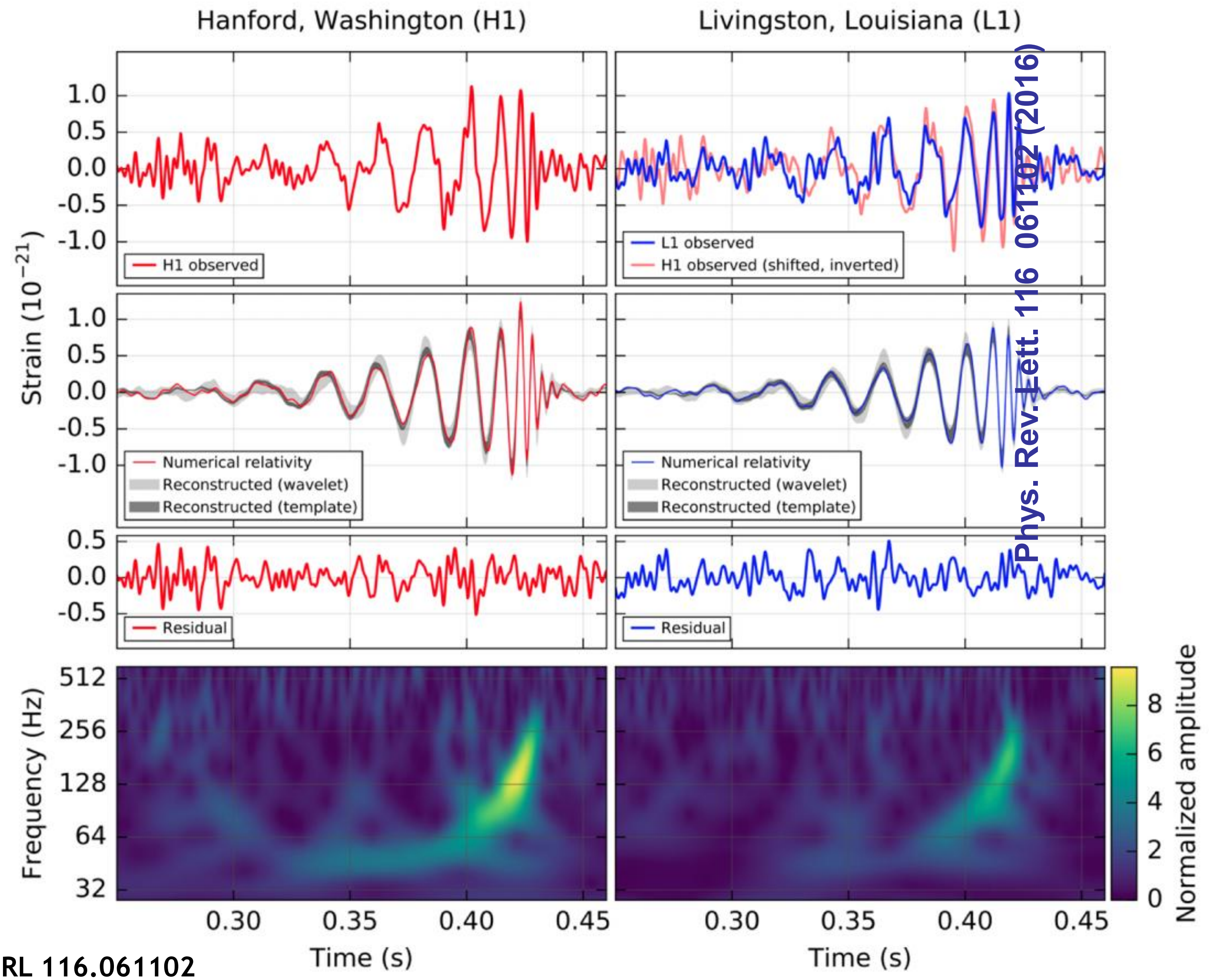
http://www.black-holes.org/explore/movies

Caltech/Cornell "Simulating Extreme Spacetime" (SXS) Collaboration

Movie simulation credit:
Harald Pfeiffer (CITA)



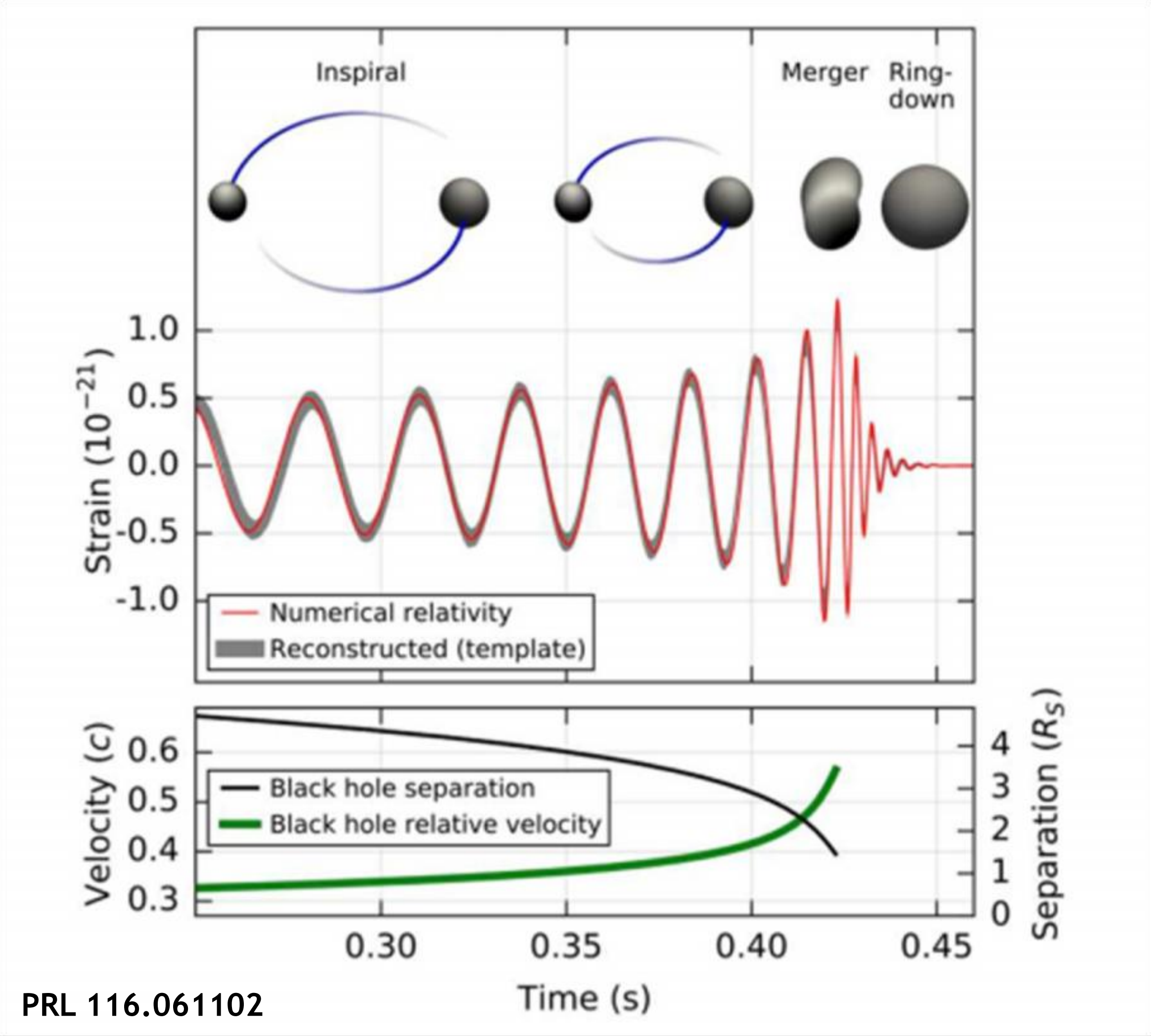
With two ‘detectors’ the LIGO and Virgo collaborations found such a signal a year ago today! – reported in Feb 2016



Phys. Rev. Lett. 116 061102 (2016)

PRL 116.061102

What was it we saw ?



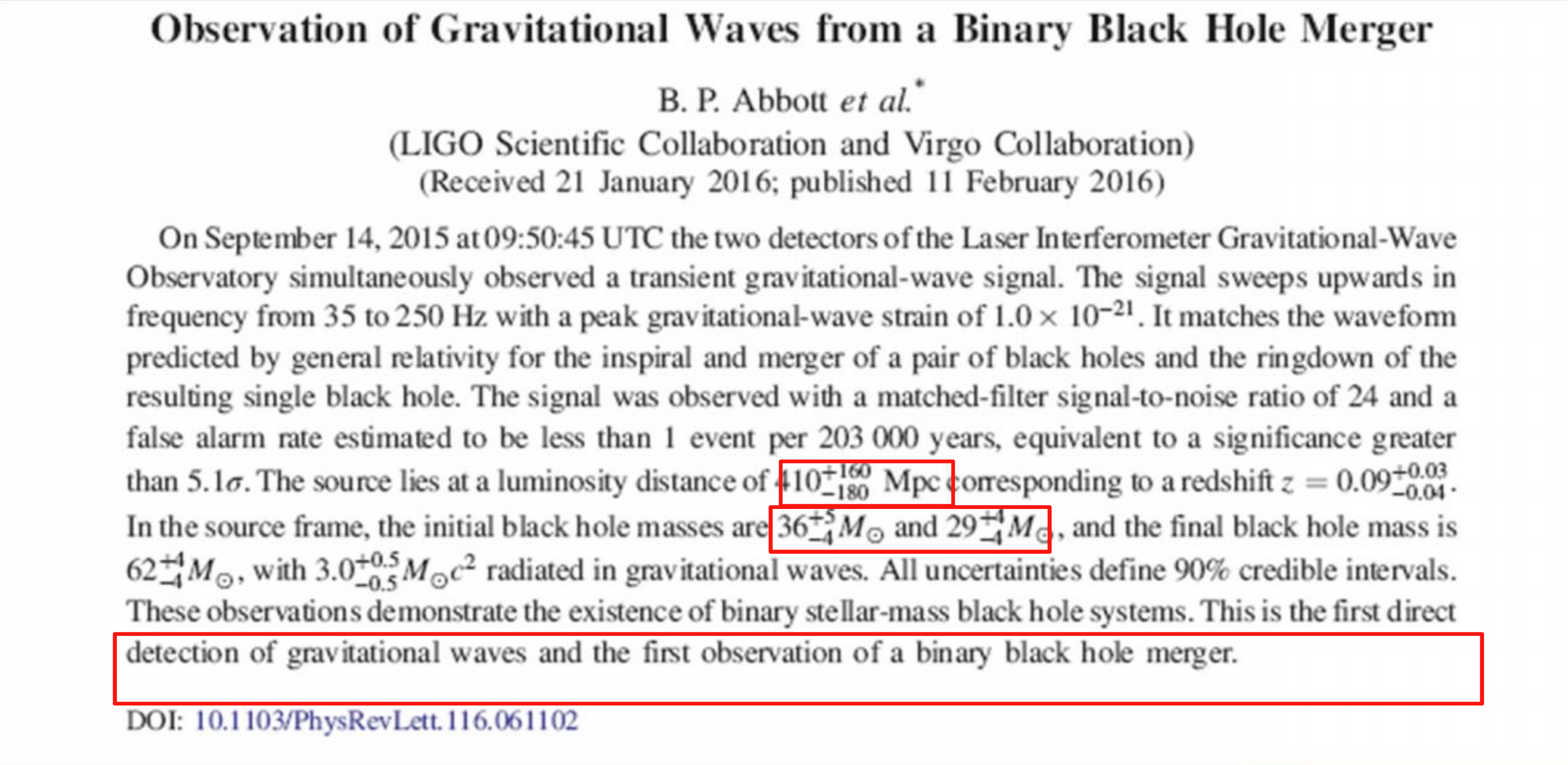
PRL 116.061102

Really exciting discovery – verifies Einstein, Schwarzschild by making first true gravitational observation of two black holes colliding

Detected in the 100th anniversary year of General Relativity

Announced in the 100th anniversary year of the prediction of the existence of gravitational waves

The paper - published Thursday Feb 11th in Physical Review Letters



Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

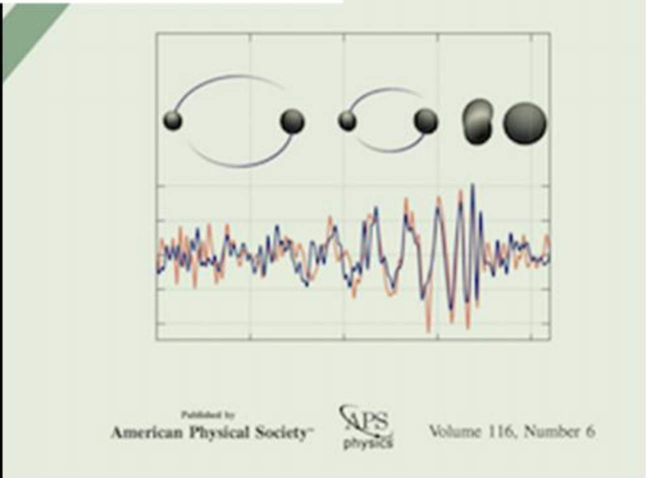
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

From exact signal shape we get masses of the individual black holes

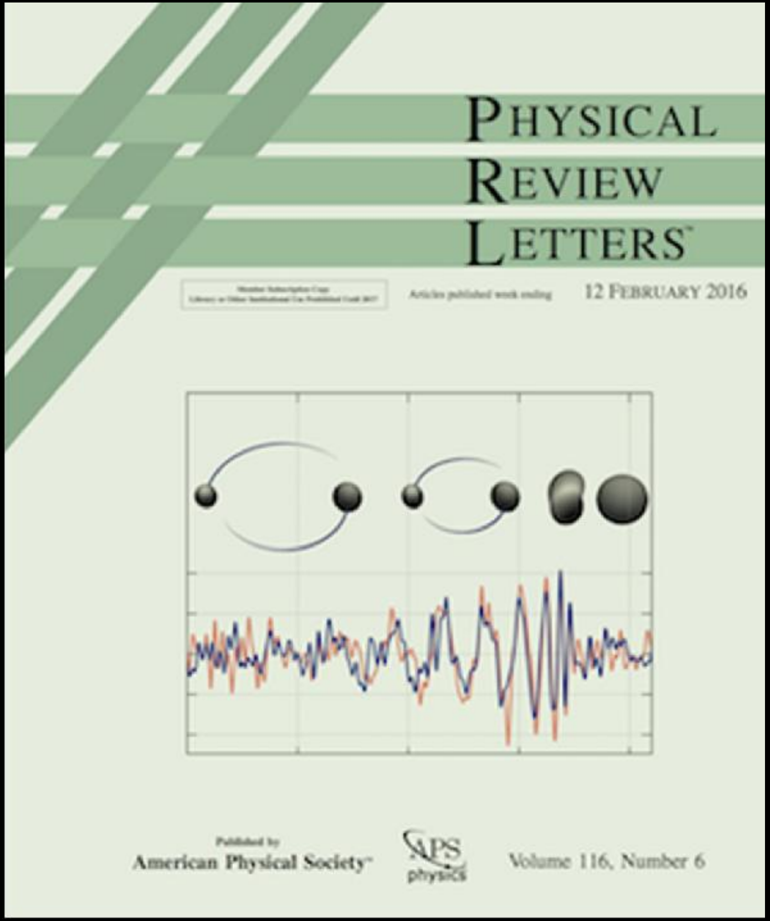
From the signal size we get the distance to the coalescence :
~ 1.3 Billion Light Years

From precise evolution of the frequency of the signal we get the black hole spins



Properties of the final black hole

- Mass: 62 times the mass of the sun (~ 20 million Earths)
- Event horizon: Schwarzschild radius: ~183 km (diameter ~366 km, so about the size of Iceland)
- Spinning ~100 times a second
- Horizon equatorial velocity: ~0.4 times the speed of light



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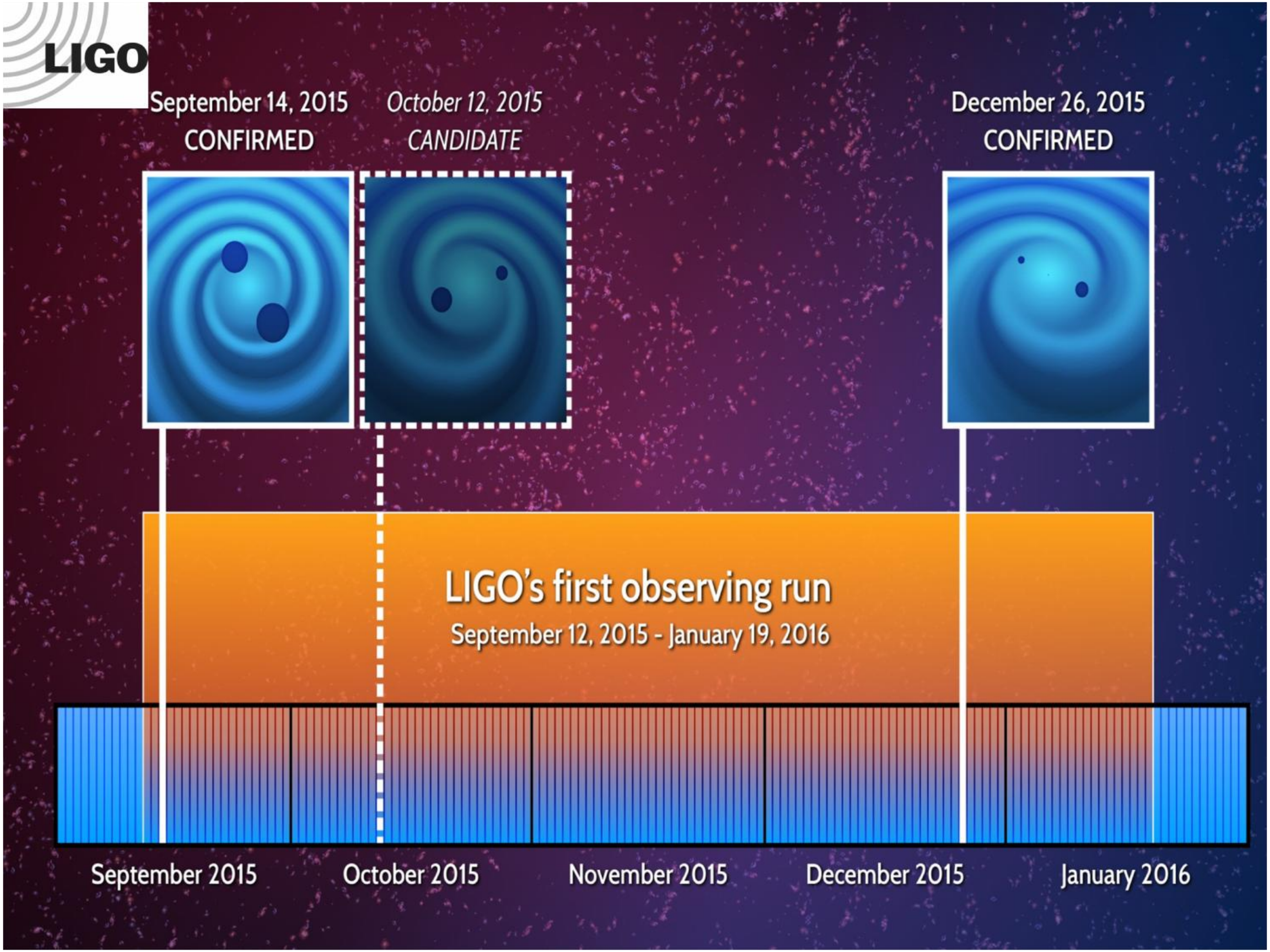


September 14, 2015
CONFIRMED

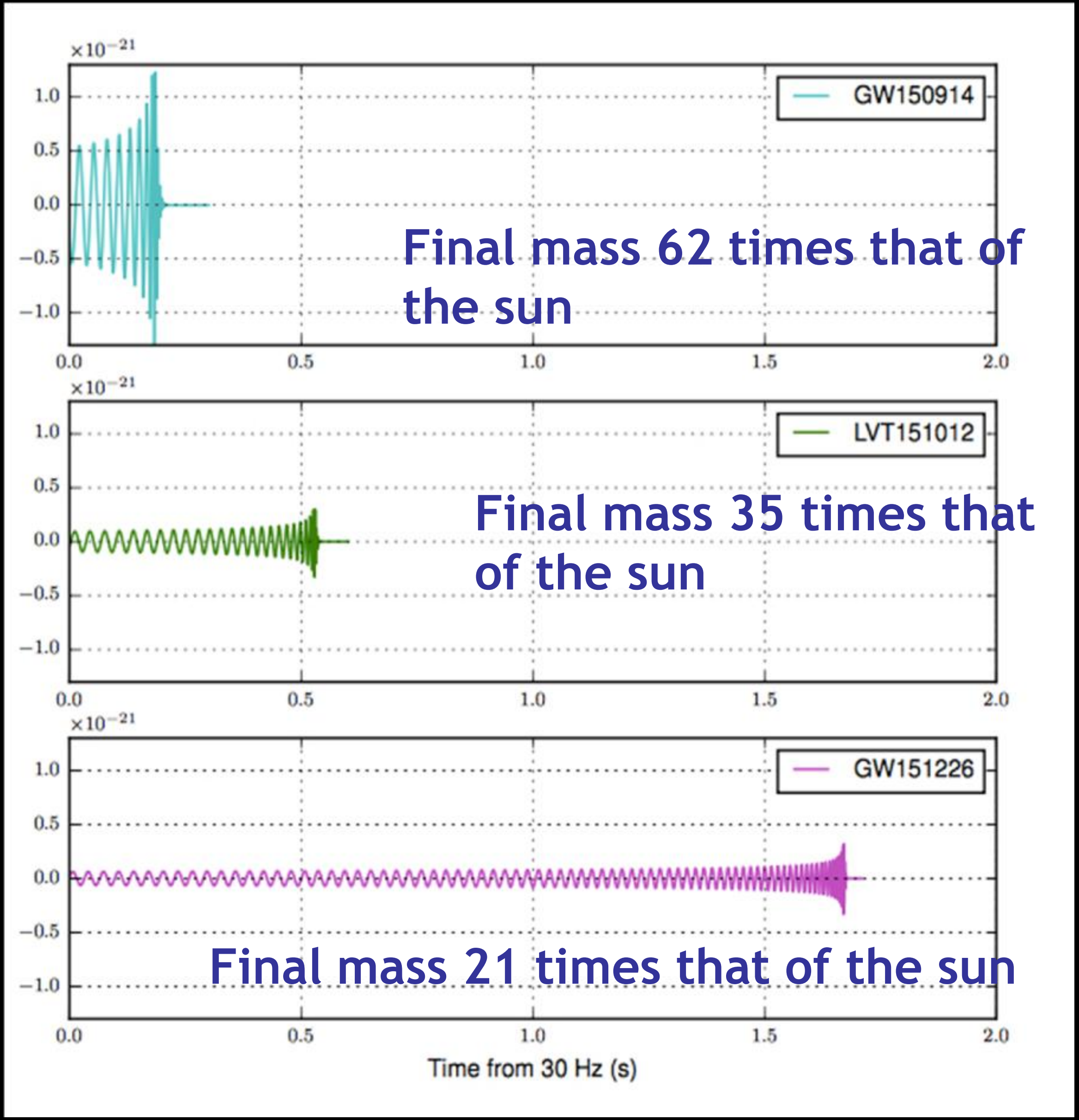
October 12, 2015
CANDIDATE

December 26, 2015
CONFIRMED

LIGO's first observing run

September 12, 2015 - January 19, 2016

Comparison of the three signals



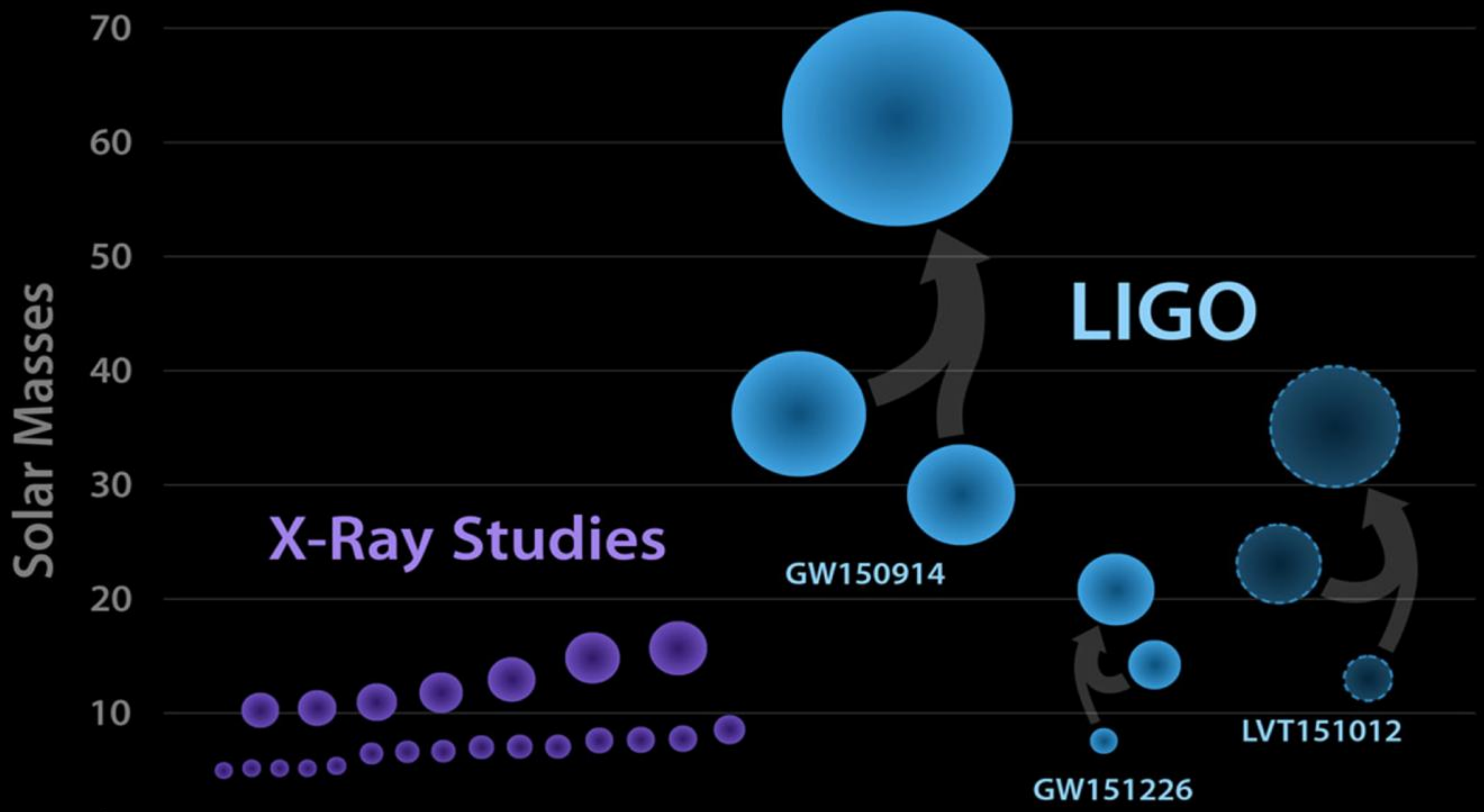
Final mass 62 times that of the sun

Final mass 35 times that of the sun

Final mass 21 times that of the sun

arxiv.org/abs/1606.04856

Black Holes of Known Mass



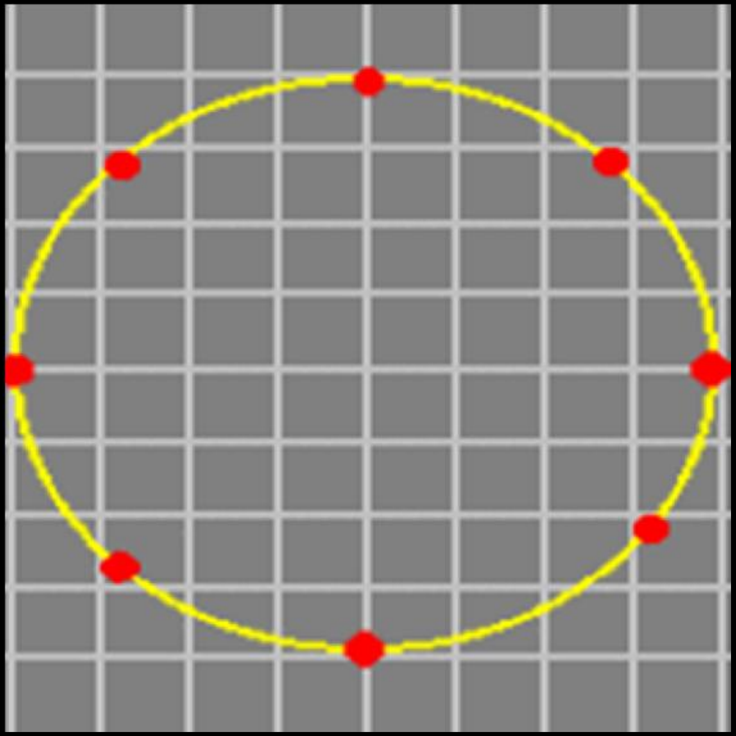
Caltech Press Office

Gravitational Waves : A Strain in Space

- Gravitational waves cause a tiny strain in space
- They are like ripples on the surface of a pond
- Why are we interested?
  - A new window on the Universe – a new astronomy
- We can study objects that don’t emit light or electromagnetic signals

- How can we ‘see’ them on Earth?

The Effect of Gravitational Waves



Looking at a fixed place in space while time moves forward, the waves alternately *stretch* and shrink the space

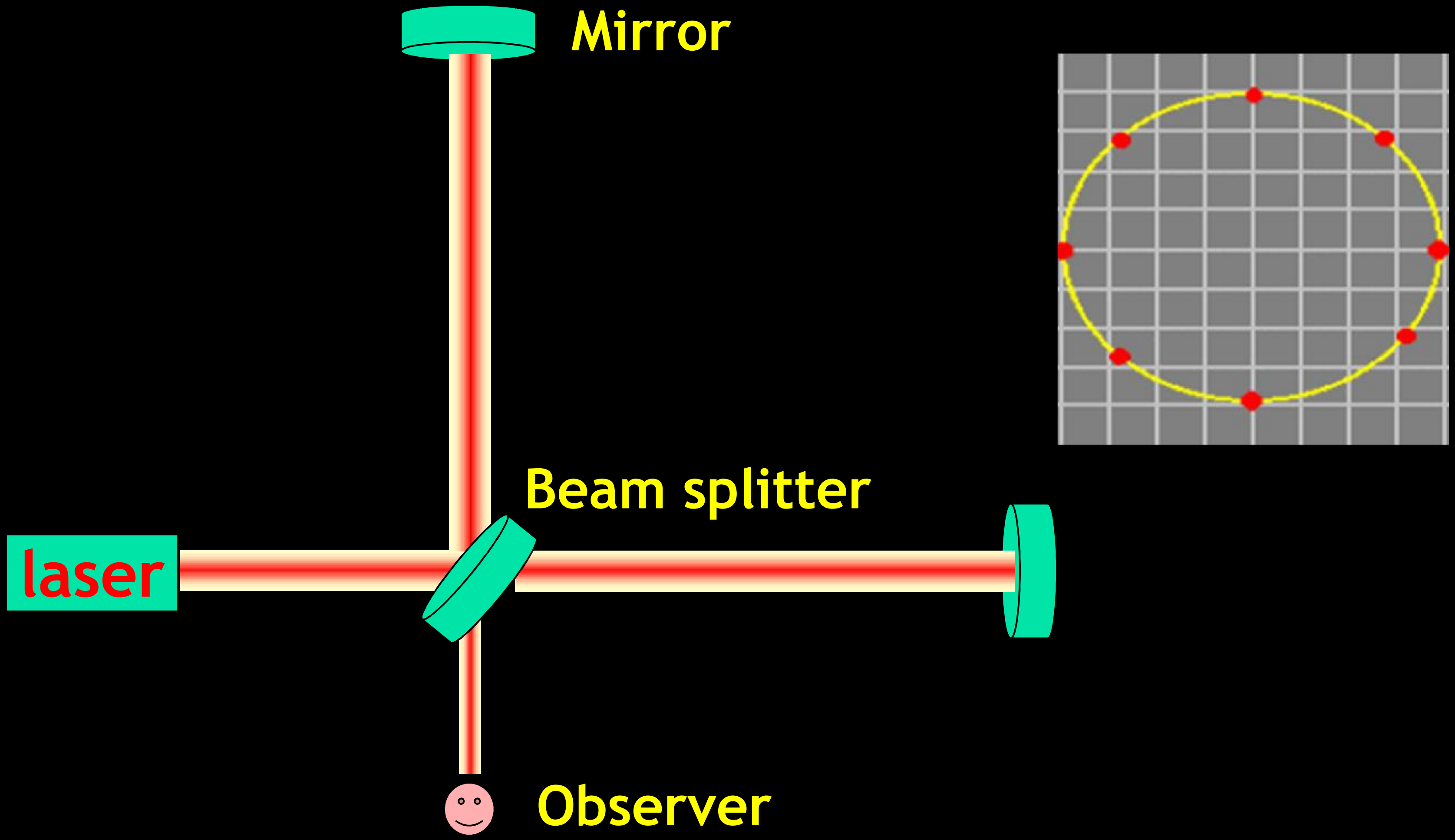
How can we detect them?

- Extremely challenging experiments
  - – for masses separated by 1 m expected change in separation caused by a typical gravitational wave is ~10^{-22}m or less

- Width of a human hair is ~50 microns (50 x 10^{-6}metres)
- Size of a typical atom is ~10^{-10} metres…..

- Need a very good ‘ruler’
  - – use the wavelength of light

Michelson Interferometer



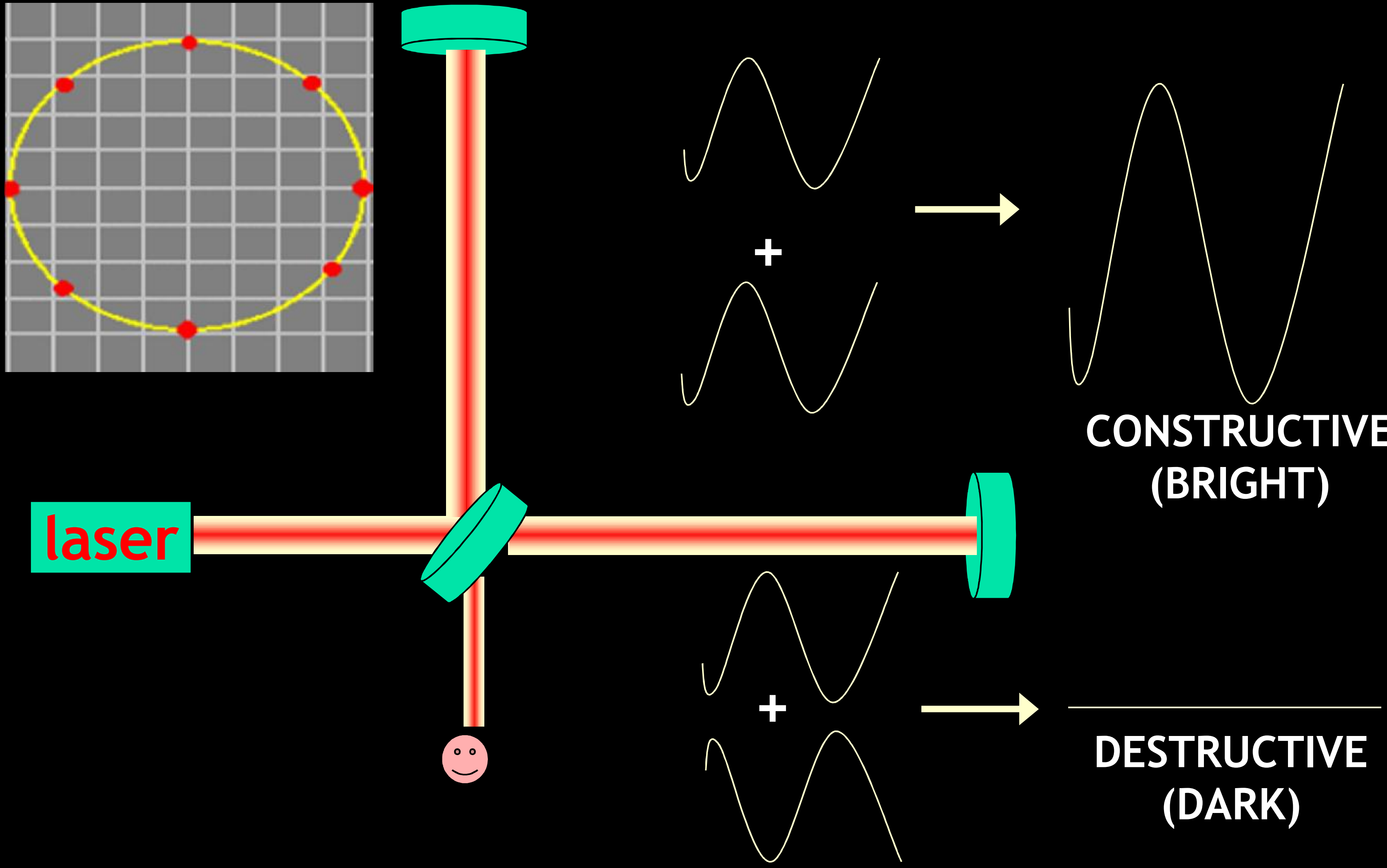
Mirror

Beam splitter

laser

Observer

Addition of Light Waves (Interference)



CONSTRUCTIVE
(BRIGHT)

DESTRUCTIVE
(DARK)

Main limitations to sensitivity

- Photon shot noise (improves with increasing laser power) and
- radiation pressure (becomes worse with increasing laser power)

There is an optimum light power which gives the same limitation expected by application of the Heisenberg Uncertainty Principle - the ‘Standard Quantum limit’

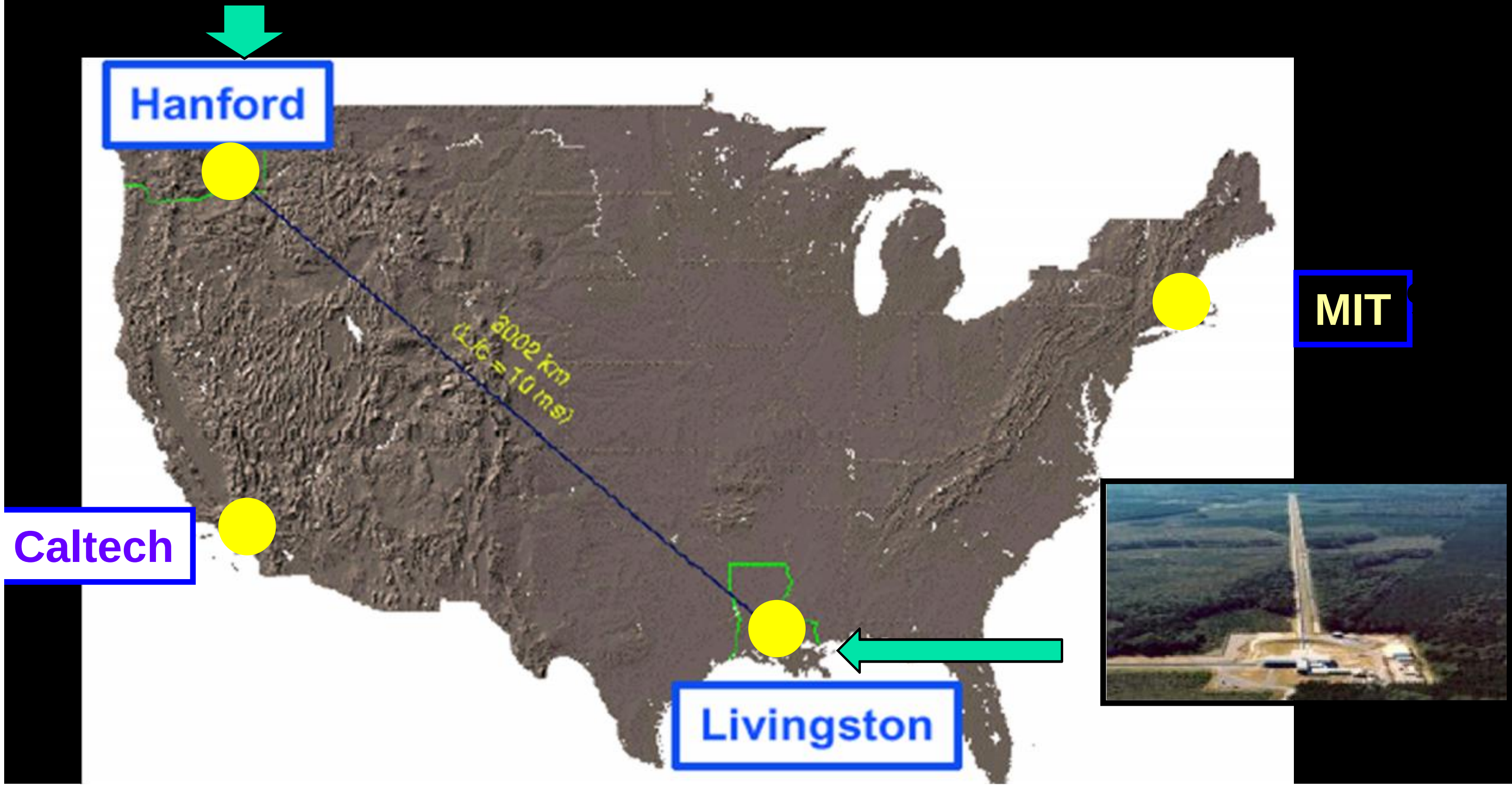
- Seismic noise (relatively easy to isolate against – use suspended mirrors
- Gravitational gradient noise – particularly important at frequencies below ~10 Hz
- Thermal noise – (Brownian motion of test masses and suspensions)

All point to long arm lengths being desirable

- **Global network of interferometers developed**

LIGO Observatories

- Mission: to develop gravitational-wave detectors, and to operate them as astrophysical observatories
- Jointly managed by Caltech and MIT; responsible for operating LIGO Hanford and Livingston Observatories
- Requires instrument science at the frontiers of physics fundamental limits



LSC LIGO Scientific Collaboration

ttps://www.zeemaps.com/map?group=245330

The LIGO Scientific Collaboration: a group of 900+ scientists worldwide who have joined together in the search for gravitational waves.

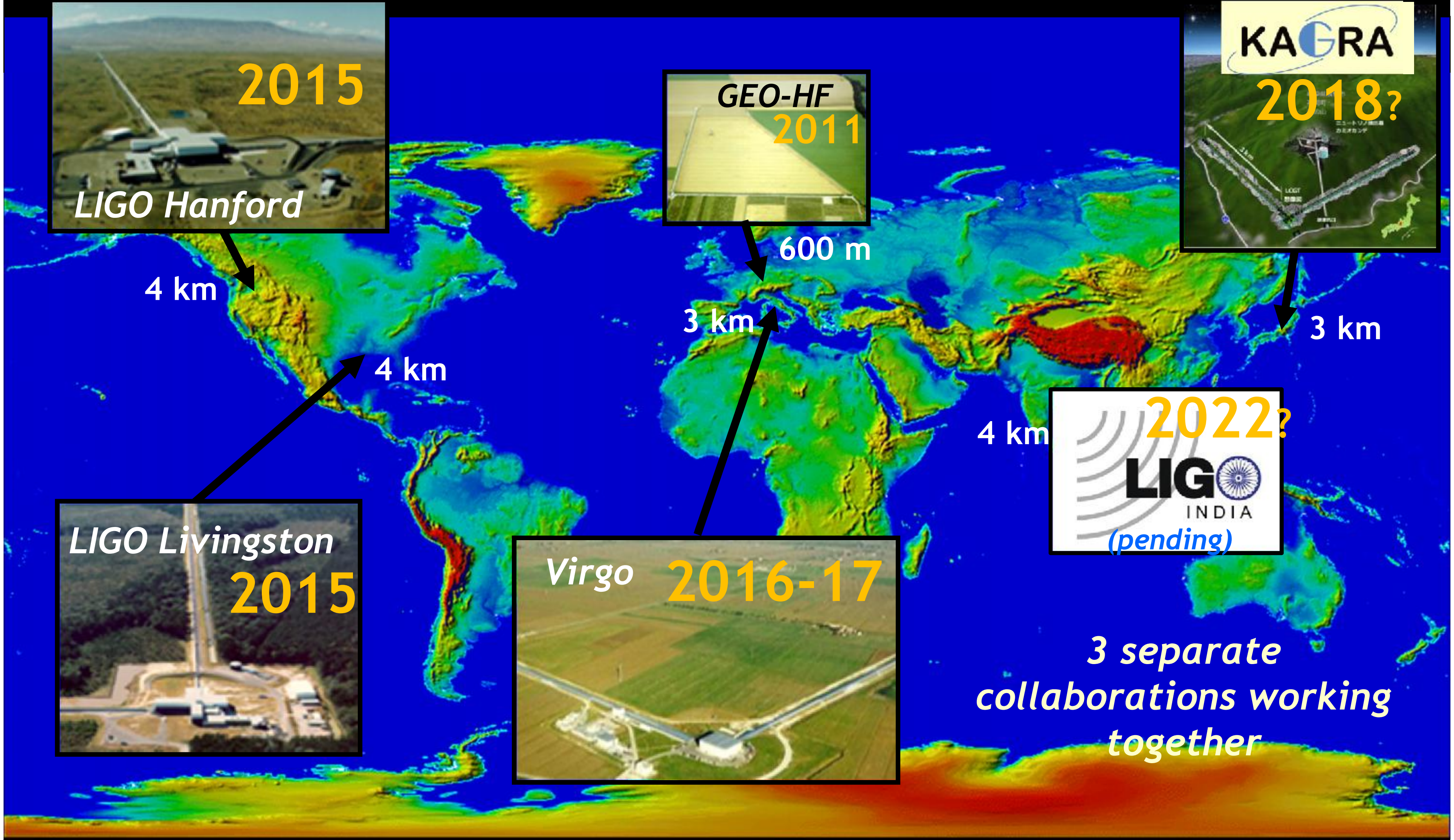
Initial LIGO detectors

LIGO project (USA)

- 2 detectors of 4km arm length (+ originally 1 detector of 2km arm length)
- Washington State and Louisiana

Additional challenges…

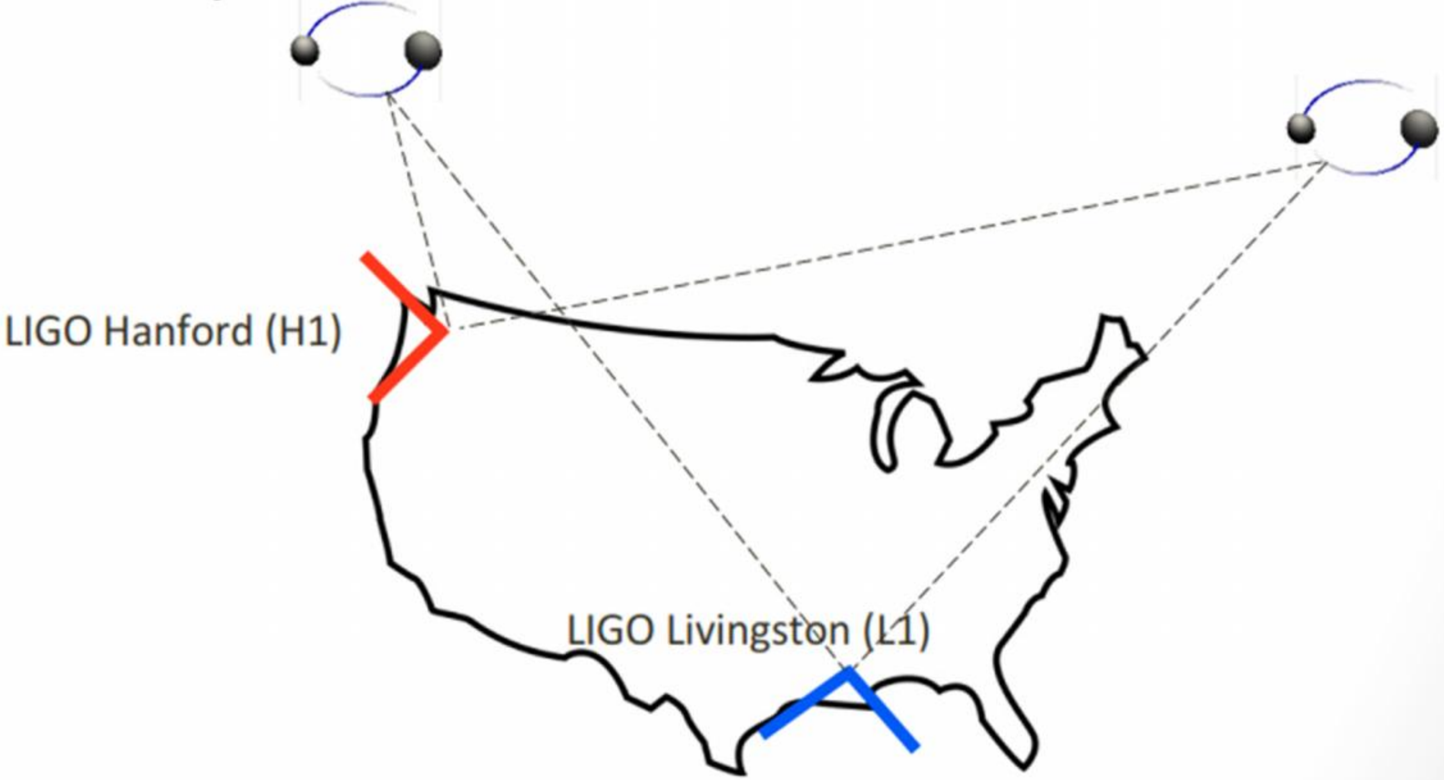
Advanced GW Detector Network: Under Construction → Operating



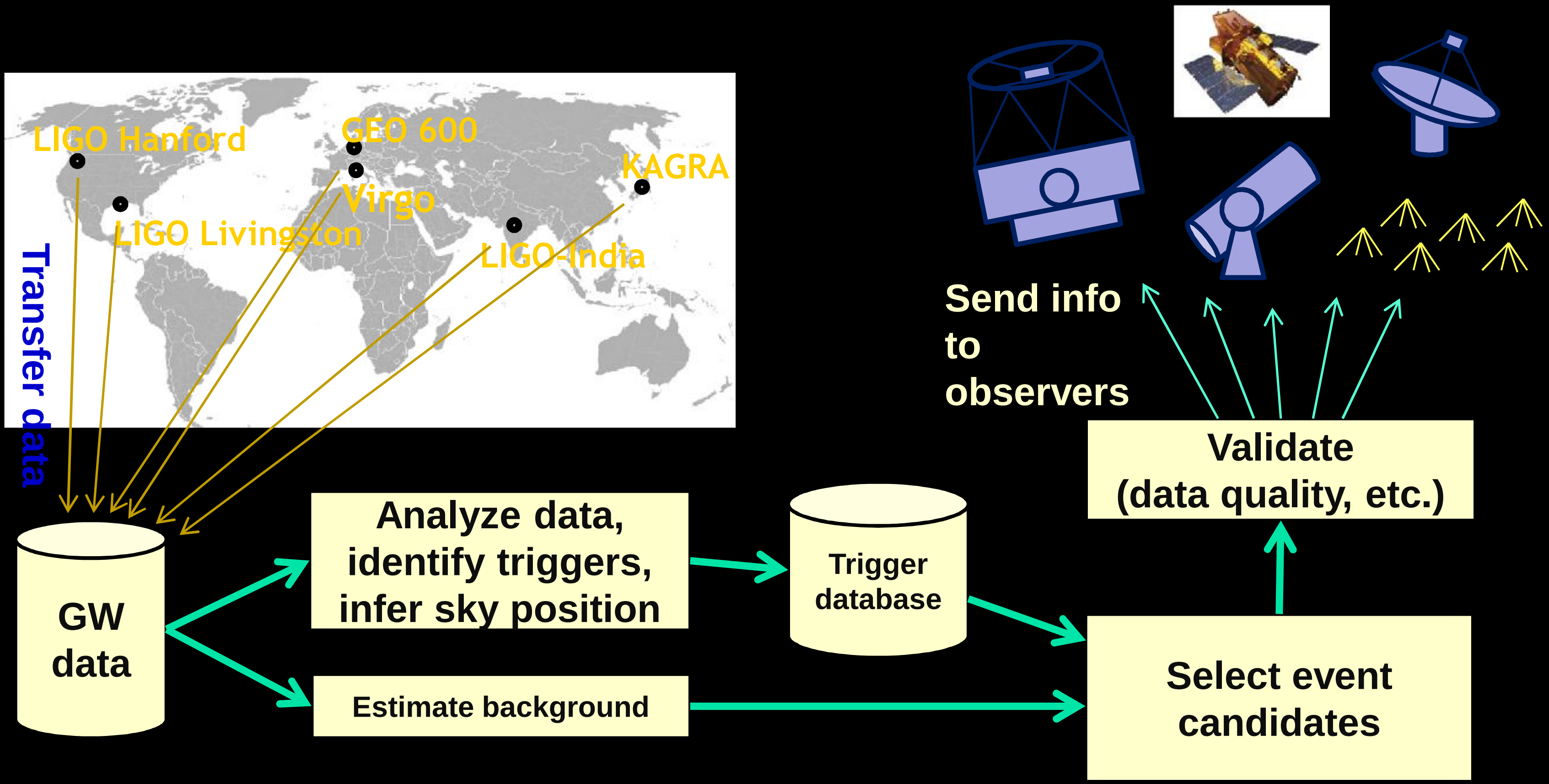
3 separate collaborations working together

Rapid Source sky-localisation

- The sky location of the gravitational wave source can be estimated through the event arrival time at each detector
  - gravitational waves travel at the speed of light
- Rapid sky localisation allows search for counterpart transient signals by optical, X-ray, GRB, ... observatories



Generating and Distributing Prompt Alerts



GW data

Analyze data, identify triggers, infer sky position

Estimate background

Trigger database

Select event candidates

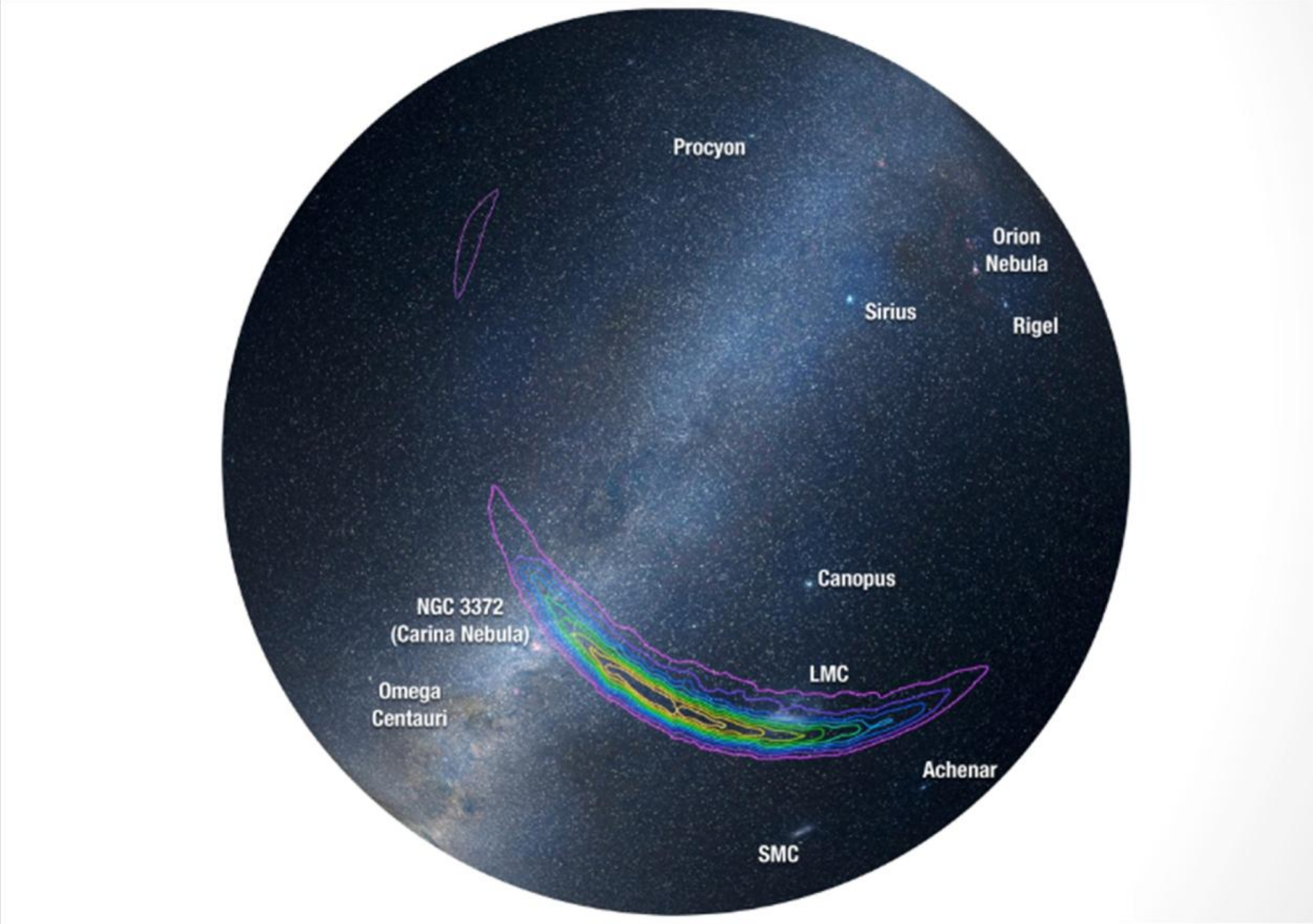
Validate (data quality, etc.)

Send info to observers

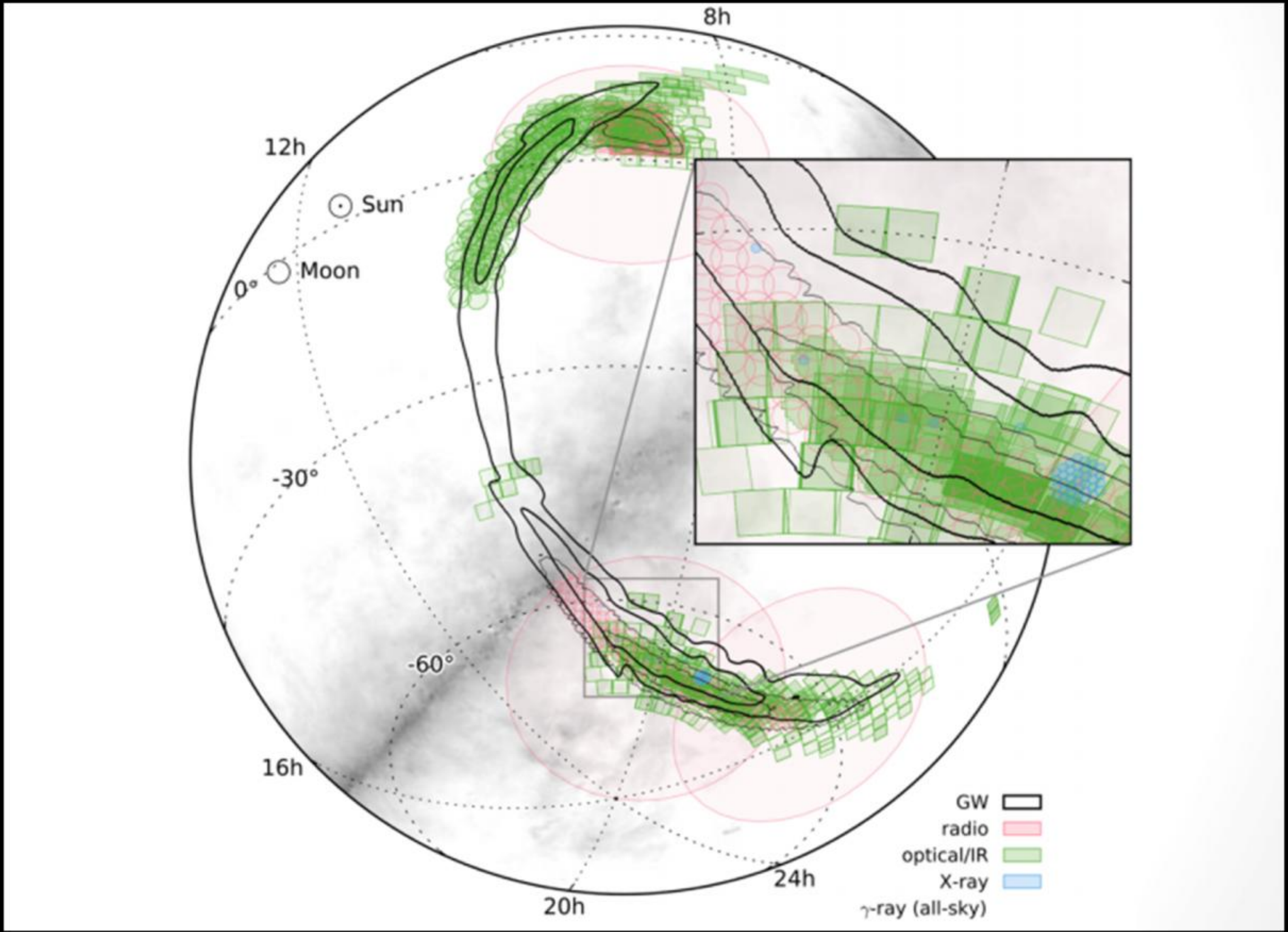
- Challenge: GW reconstructed sky regions are large !
- With just the two LIGO detectors: typically a few hundred square degrees
- LIGO+Virgo: typically several tens of square degrees
- Will improve with KAGRA and LIGO-India

Swift: NASA E/PO, Sonoma State U., Aurore Simonnet

GW150914 Sky Location estimate

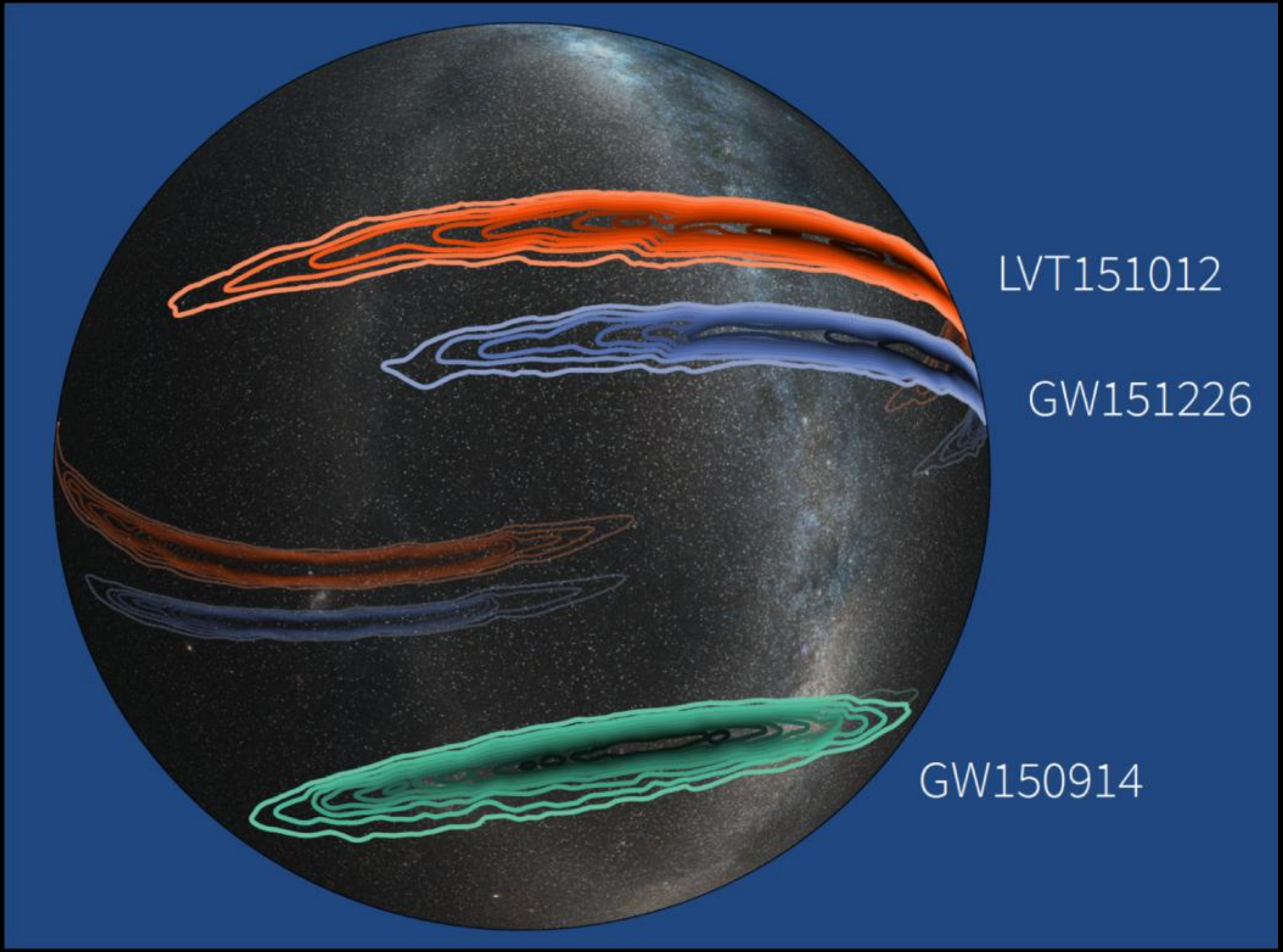


Credit: Shane Larson, Northwestern University; Roy Williams, Caltech; Thomas Boch, CDS Strasbourg



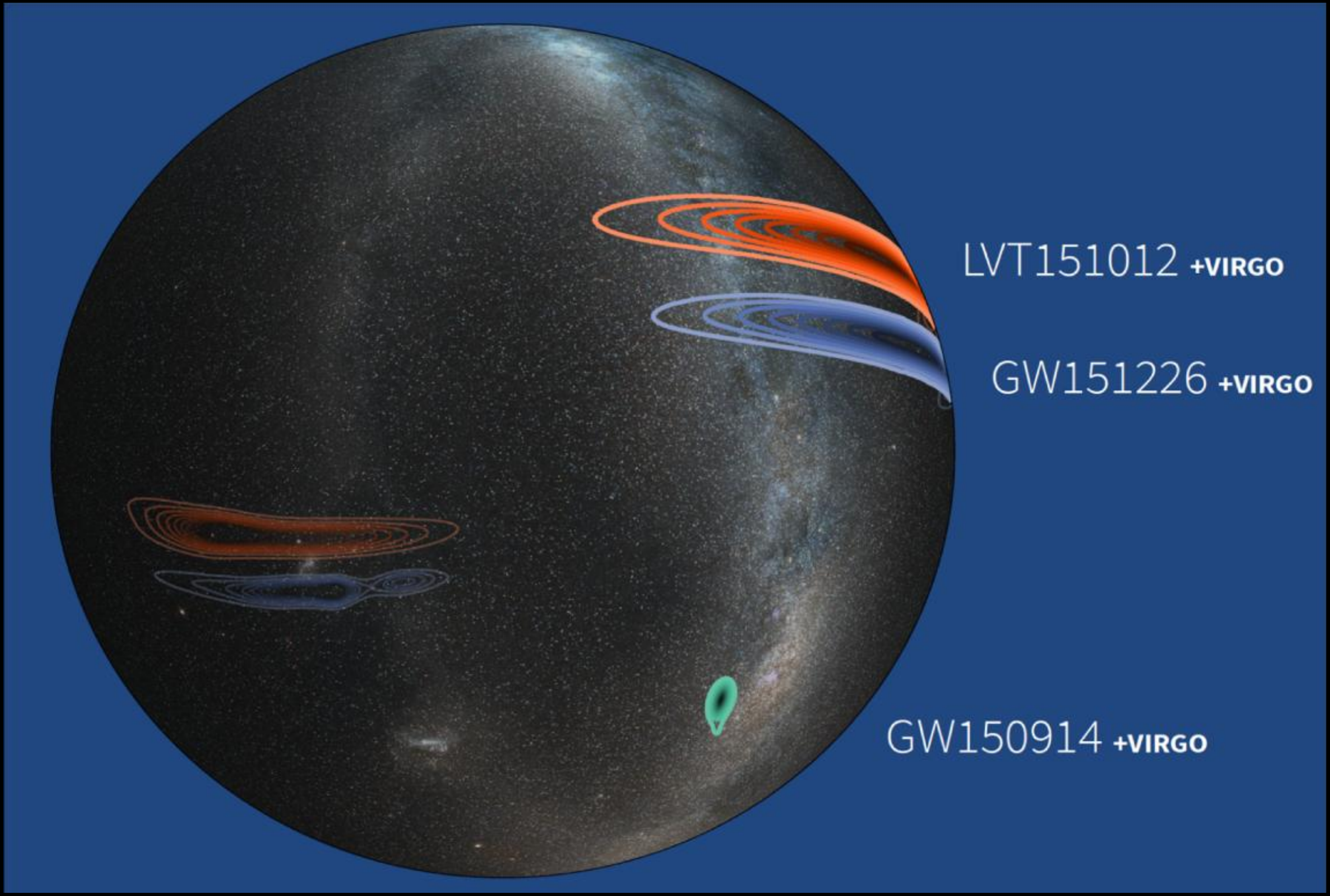
arXiv:1602.08492v2 [astro-ph.HE]

Sky Locations of Gravitational-wave Events GW150914, GW151226 and Candidate LVT151012 (our signals so far)



Credit: Leo Singer

Simulated Sky Locations of O1 Events and Candidate Including the Virgo Interferometer



Credit: Leo Singer

Next steps

- Improve the sensitivity of the Advanced LIGO detectors and operate for longer (2nd scientific run starts in early summer with ‘Advanced Virgo’ detector located in Italy expected to be operating also)
- Observe along with other similar detectors - KAGRA in Japan when they become operational and potentially one in India
- Look for other signals – from neutron star binary coalescences, pulsars, exploding stars etc – ***new Astronomy!!***

Take forward research for upgrades to the Advanced detectors and new generation detectors in Europe, the USA and elsewhere..

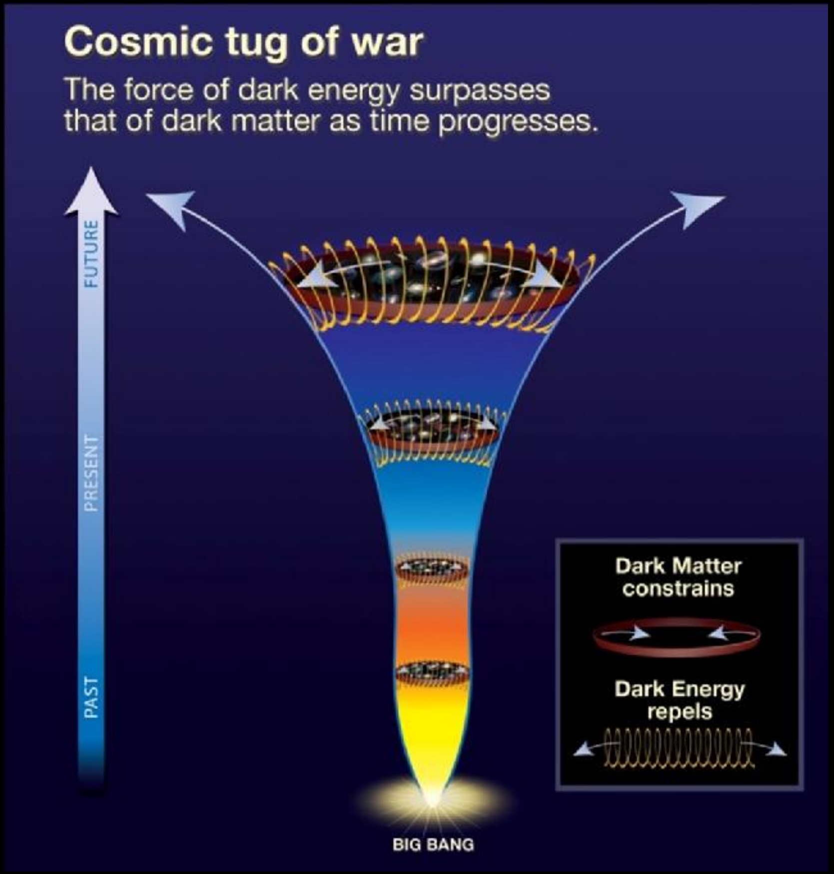
Science questions to be answered

Fundamental physics and general relativity

- *What are the properties of gravitational waves?*
- *Is general relativity the correct theory of gravity?*
- *Is general relativity still valid under strong-gravity conditions?*
- *Are Nature's black holes the black holes of general relativity?*
- *How does matter behave under extremes of density and pressure?*

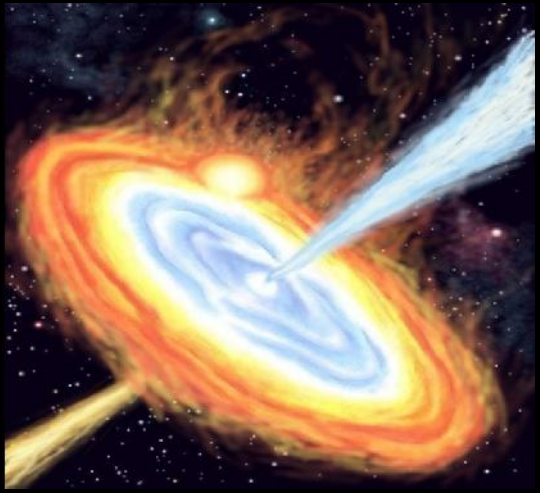
Cosmology

- *What is the history of the accelerating expansion of the Universe?*



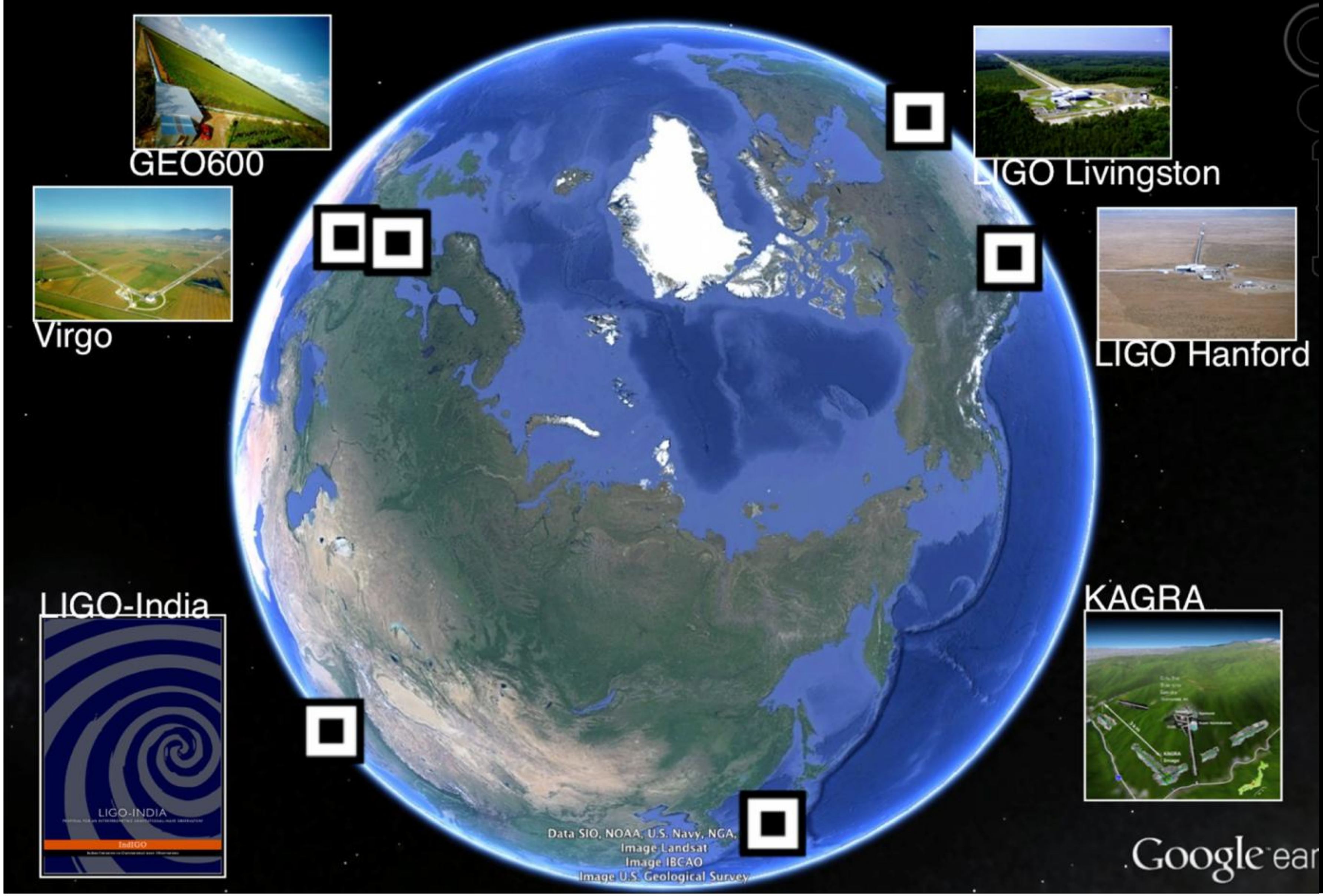
Science questions to be answered

Astronomy and astrophysics



- *Where and when do massive black holes form and how are they connected to the formation of galaxies?*
- *What happens when a massive star collapses?*
- *How massive can a neutron star be?*
- *How abundant are stellar-mass black holes?*
- *Do intermediate mass black holes exist?*
- *What is the central engine behind gamma-ray bursts?*
- *Do spinning neutron stars emit gravitational waves?*
- *What is the distribution of white dwarf and neutron star binaries in the galaxy?*

Gravitational wave detector network ~2020

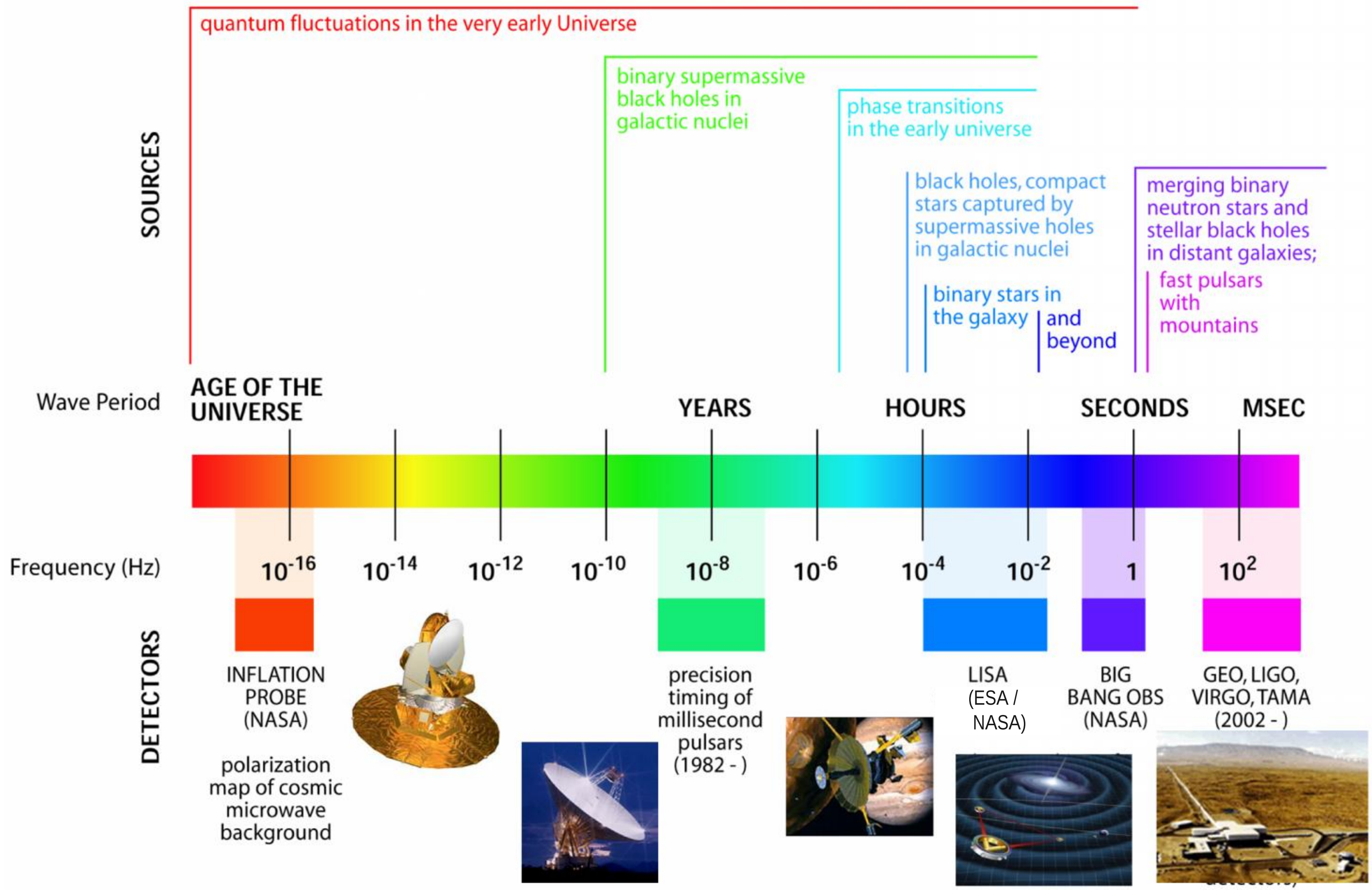


The era of gravitational wave astronomy is here!

- We expect soon to be making regular detections...
- When we do, it is inevitable we will want to see further into the Universe.....see new sources......with better signal-to-noise .....driven by maximising the astronomy and astrophysics we can do

- In addition to the need for better detectors on the ground there is additional science we can do with detectors in space....

THE GRAVITATIONAL WAVE SPECTRUM



SOURCES

quantum fluctuations in the very early Universe

binary supermassive black holes in galactic nuclei

phase transitions in the early universe

black holes, compact stars captured by supermassive holes in galactic nuclei

binary stars in the galaxy

and beyond

merging binary neutron stars and stellar black holes in distant galaxies;

fast pulsars with mountains

Wave Period

AGE OF THE UNIVERSE

YEARS

HOURS

SECONDS

MSEC

Frequency (Hz)

10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2}

DETECTORS

INFLATION
PROBE
(NASA)

polarization
map of cosmic
microwave
background

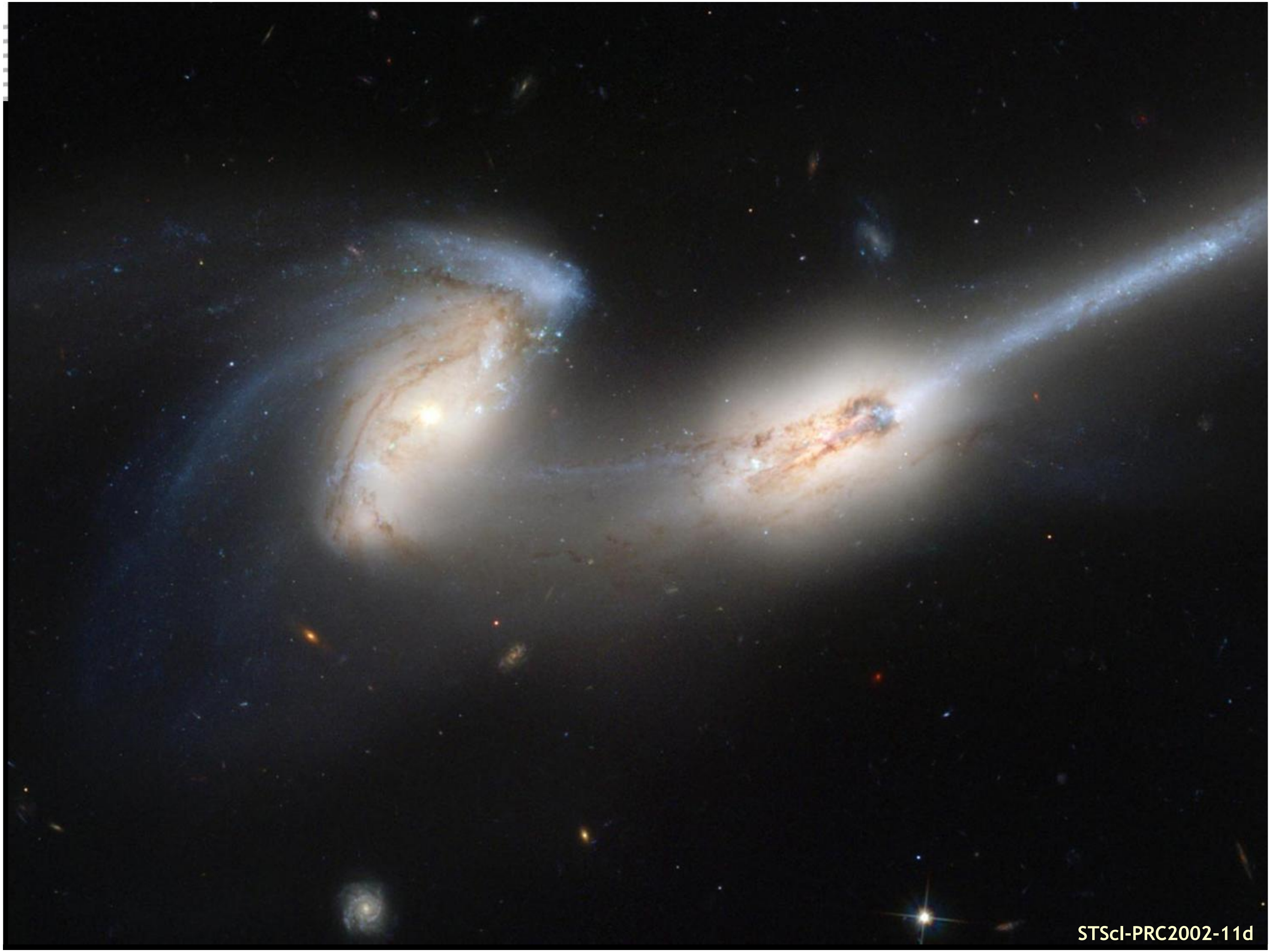
precision
timing of
millisecond
pulsars
(1982 -)

LISA
(ESA /
NASA)

BIG
BANG OBS
(NASA)

GEO, LIGO,
VIRGO, TAMA
(2002 -)

Credit:÷ 2002 R. Gendler, Photo by R. Gendler



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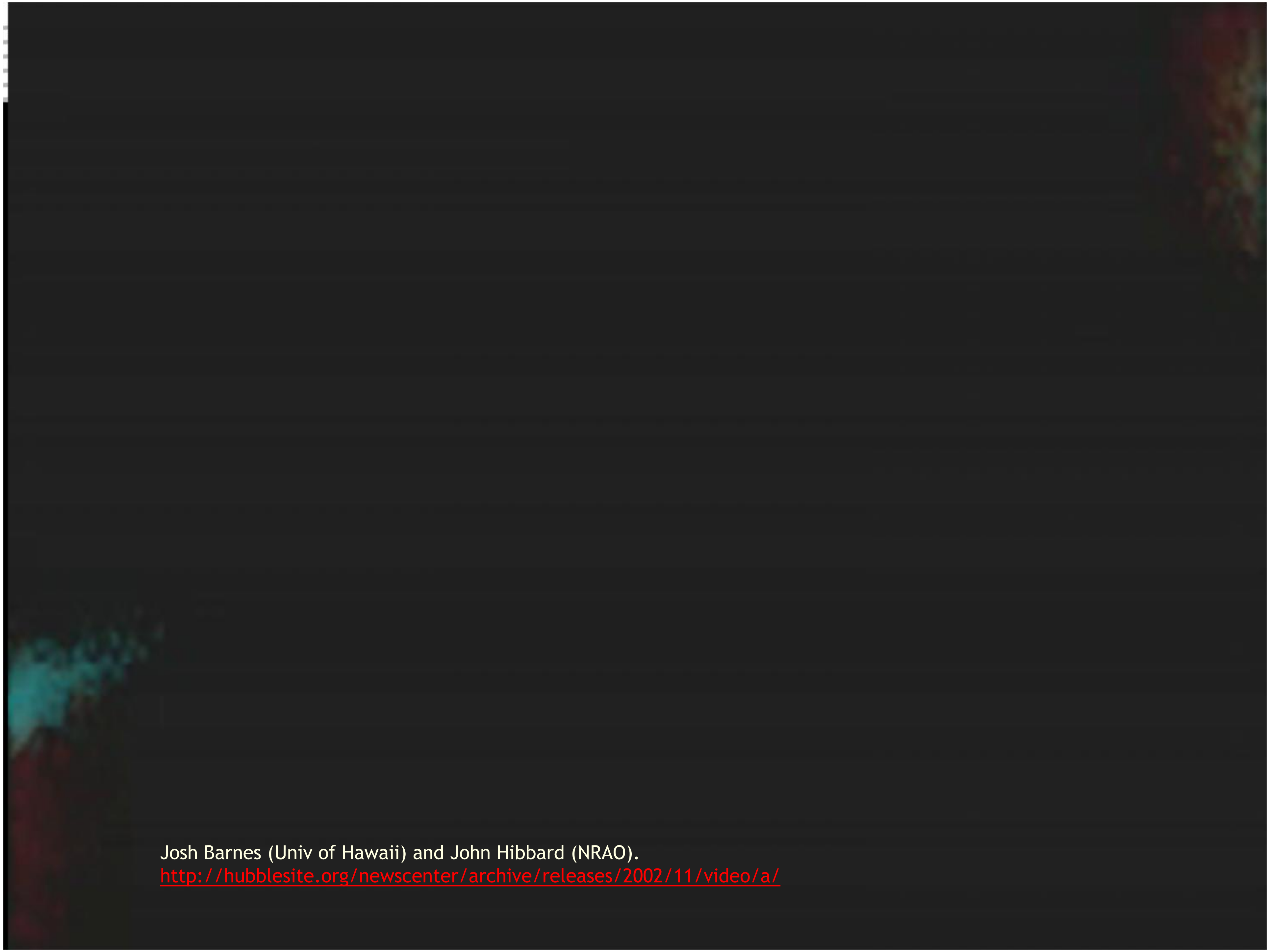
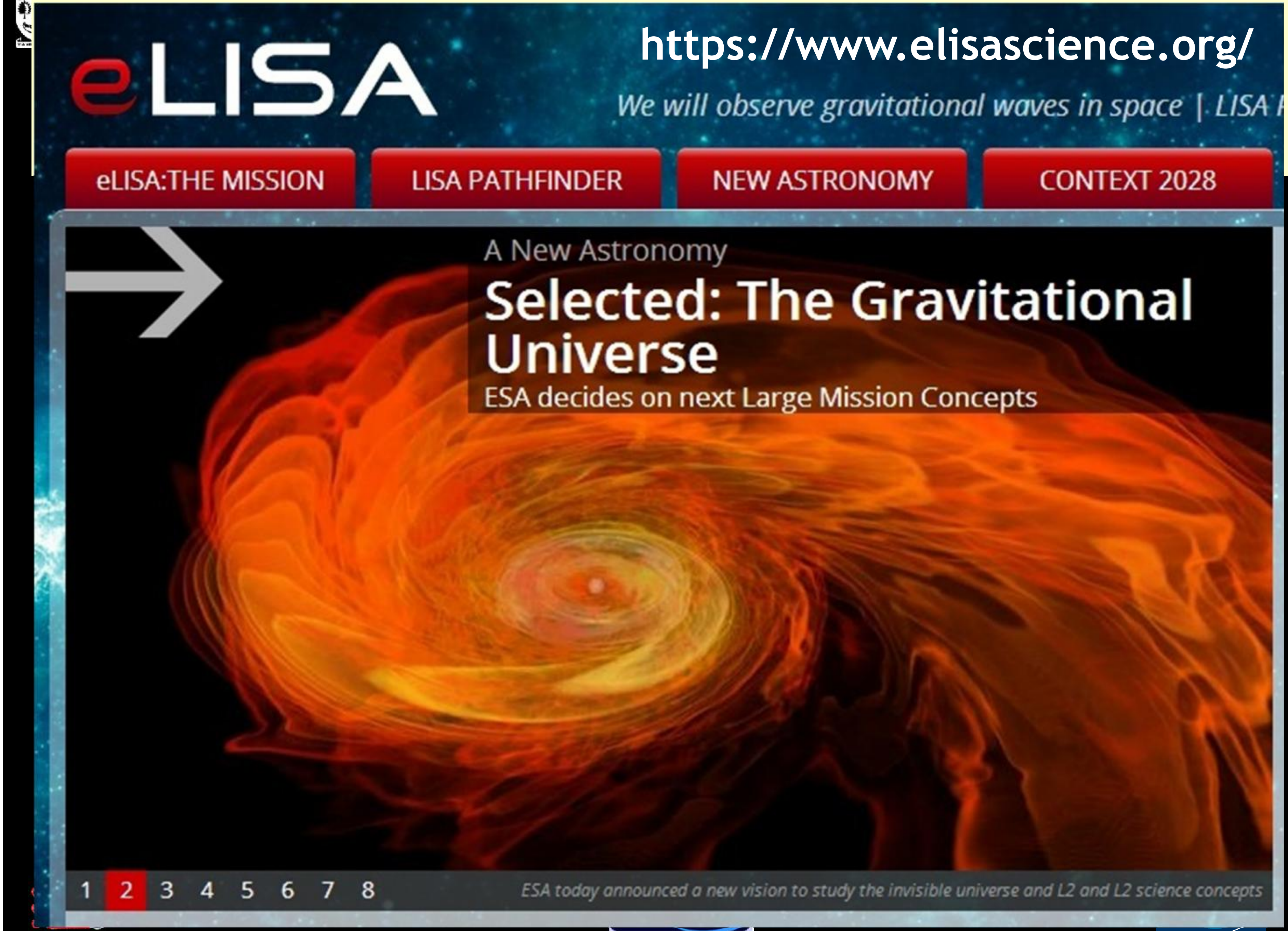


Josh Barnes (Univ of Hawaii) and John Hibbard (NRAO).
http://hubblesite.org/newscenter/archive/releases/2002/11/video/a/

Josh Barnes (Univ of Hawaii) and John Hibbard (NRAO).
http://hubblesite.org/newscenter/archive/releases/2002/11/video/a/



https://www.elisascience.org/

A New Astronomy

Selected: The Gravitational Universe

ESA decides on next Large Mission Concepts

ESA today announced a new vision to study the invisible universe and L2 and L2 science concepts

The Network of Gravitational Wave Facilities

- Advanced Detectors have made first detections! – network data to follow
    - Advanced LIGO (USA/International)
    - Advanced VIRGO (Italy/France/Netherlands)
    - KAGRA (Japan)
    - GEO-HF (UK/Germany)

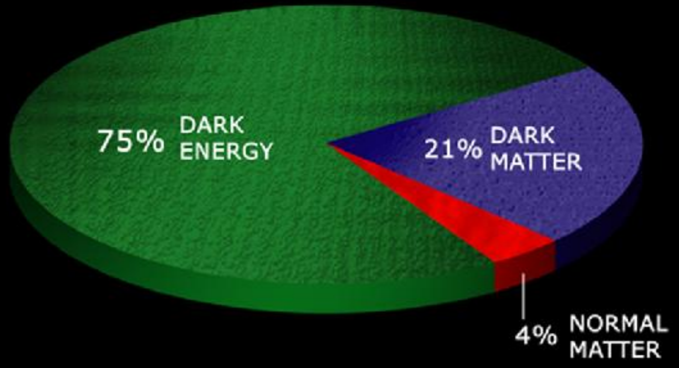
- 3rd generation
    - Lab research underway around the globe
    - 3rd generation detector in Europe? – The Einstein Telescope
    - Future upgrades in the US?

- Spaced based detector
    - Demonstrator launched 2015
    - Mission launch 2034?

How much of the Universe is made of matter we understand?

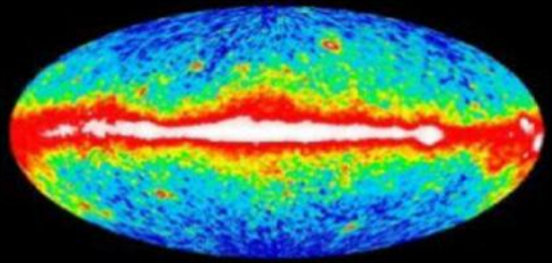
Approximately 4-5%

- There is also
  - "Dark matter"
    which we only see through its gravitational effects.
  - "Dark energy",
    which is causing the expansion of the Universe to *accelerate* and no-one knows why.



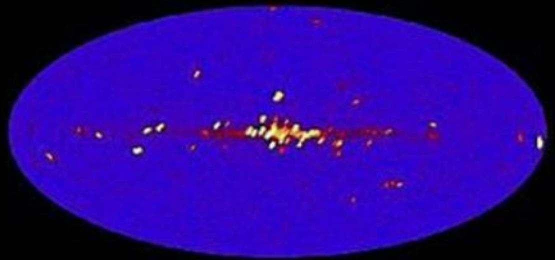
To help us understand we need new physics ideas, particularly for gravity

As each new window on the universe has opened, it has led to completely unexpected discoveries.

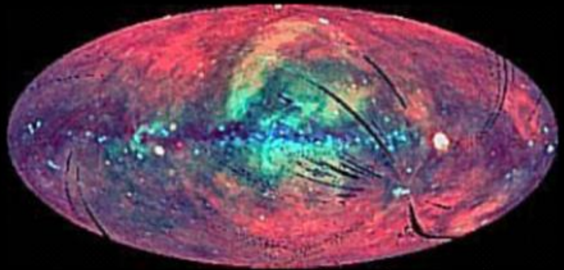


Gamma-Ray >100MeV (CGRO, NASA)

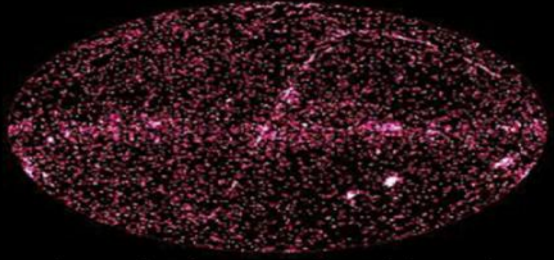
Gamma-Ray (N. Gehrels et.al. GSFC, EGRET, NASA)



X-Ray 2-10keV (HEAO-1, NASA)



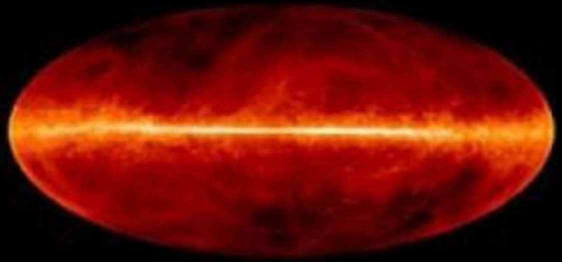
X-Ray 0.25, 0.75, 1.5 keV (S. Digel et. al. GSFC, ROSAT, NASA)



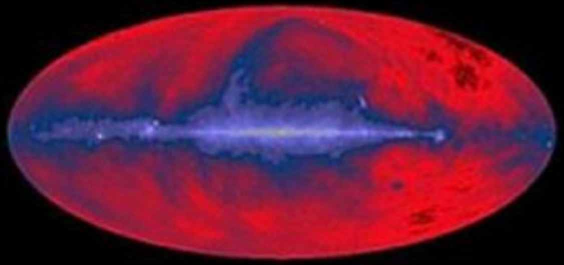
Ultraviolet (J. Bonnell et.al.(GSFC), NASA)

Visible (Axel Mellinger)

Infrared (DIRBE Team, COBE, NASA)

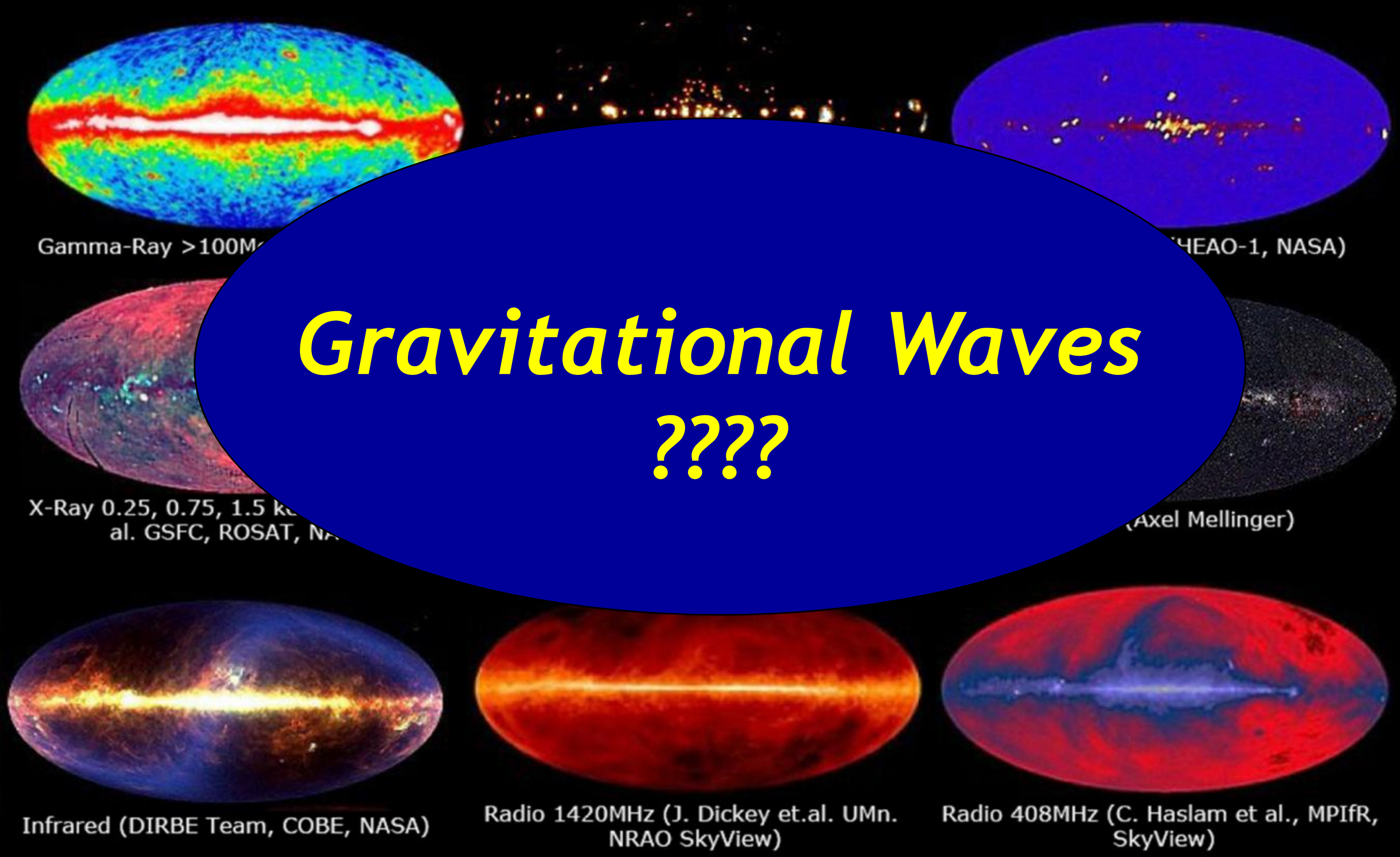


Radio 1420MHz (J. Dickey et.al. UMn. NRAO SkyView)



Radio 408MHz (C. Haslam et al., MPIfR, SkyView)

What more discoveries will Gravitational Waves reveal?



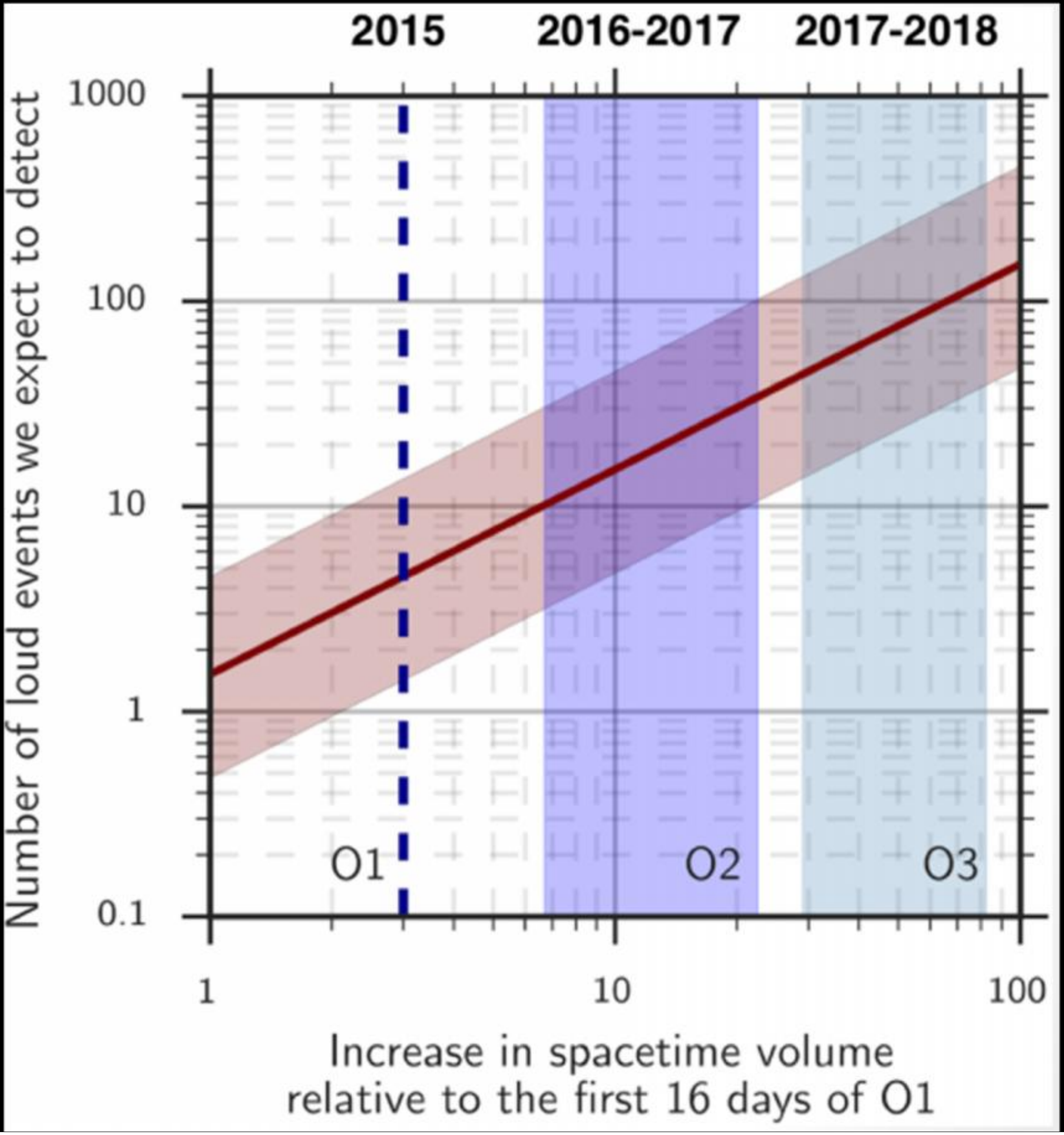
Gravitational Waves

????

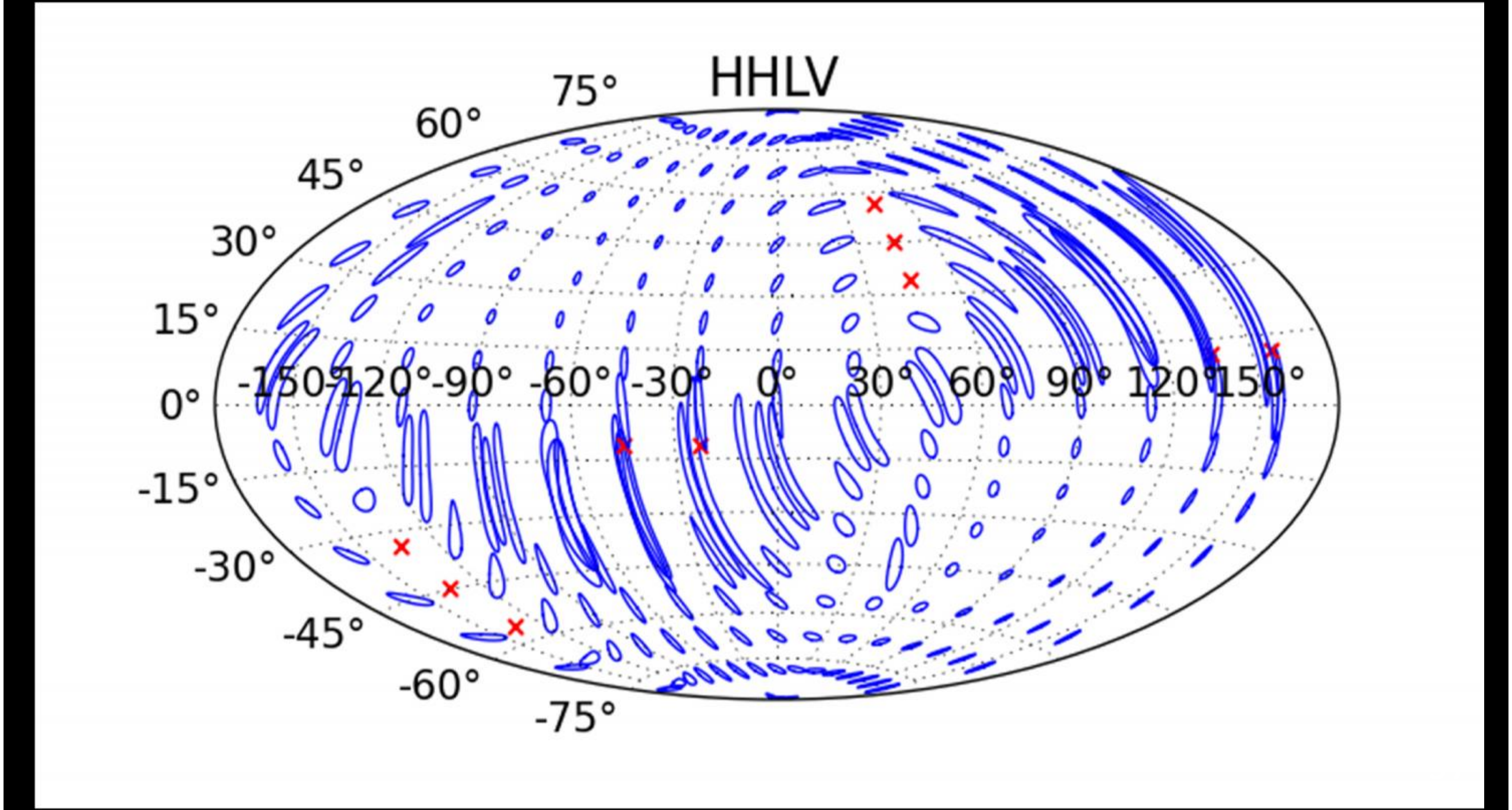
Prospects for next observing runs

- The next observing runs target improved sensitivities and longer runs
- Further black hole systems clearly represent a key target
- We will also be searching for signals from neutron star collisions, stochastic background, rotating neutron stars, unmodelled transients, …

http://arxiv.org/pdf/1602.03842v1.pdf

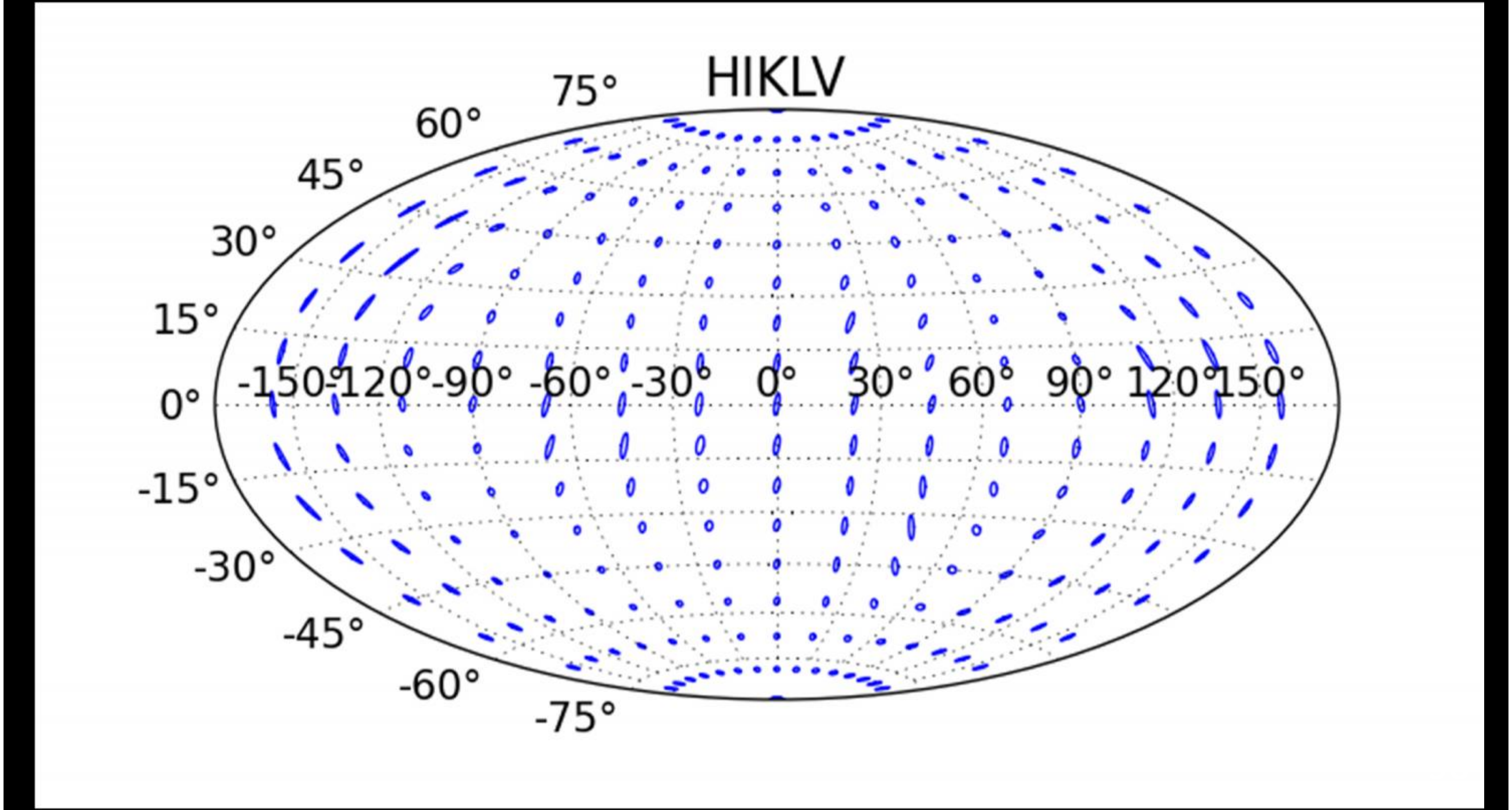


Sky localisation with 3 detector sites



S. Fairhurst, "*Improved source localization with LIGO India*", arXiv:1205.6611v1

Sky localisation with 5 detector sites



S. Fairhurst, "*Improved source localization with LIGO India*", arXiv:1205.6611v1