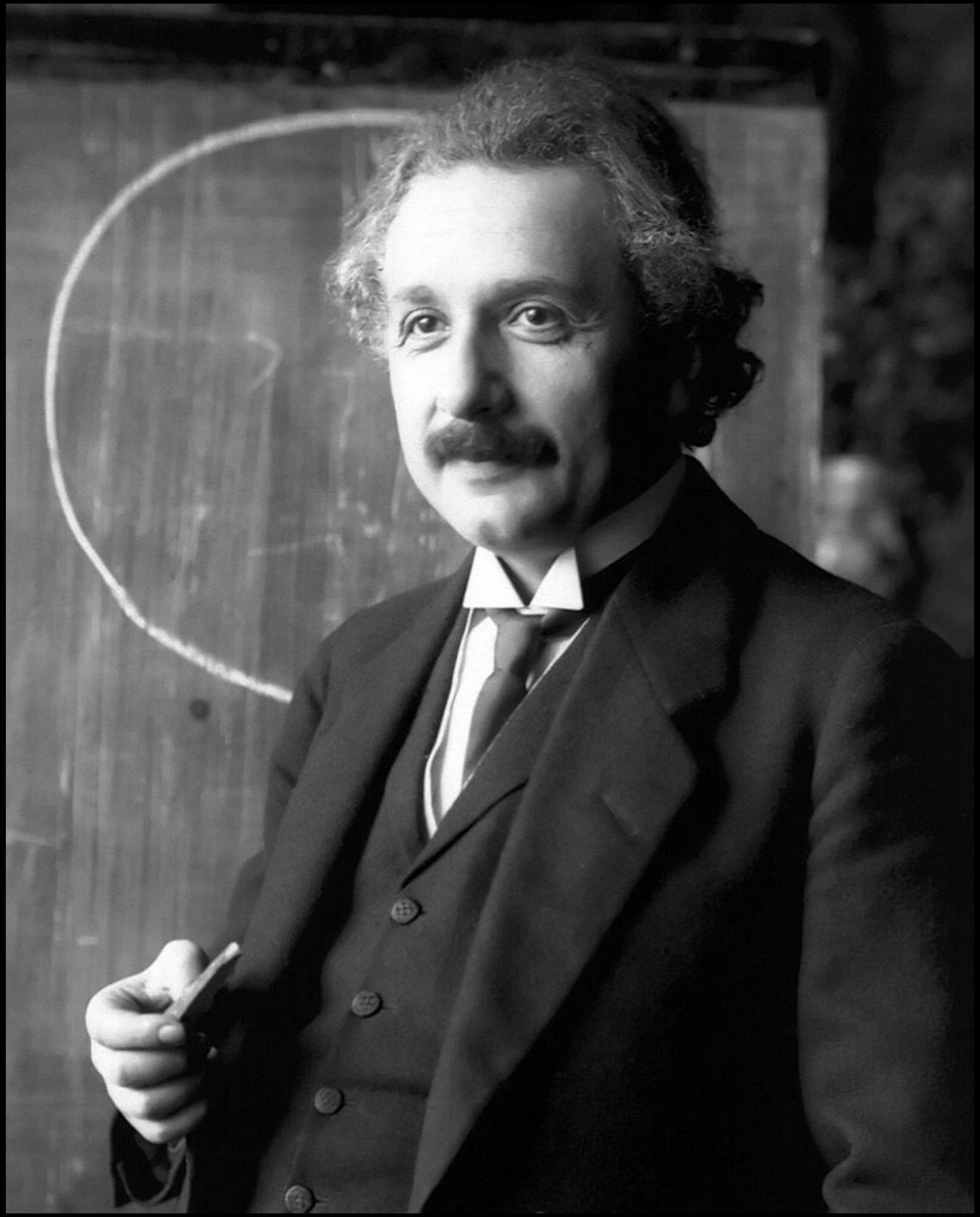
Brief history

1915: Albert Einstein publishes the theory of General Relativity

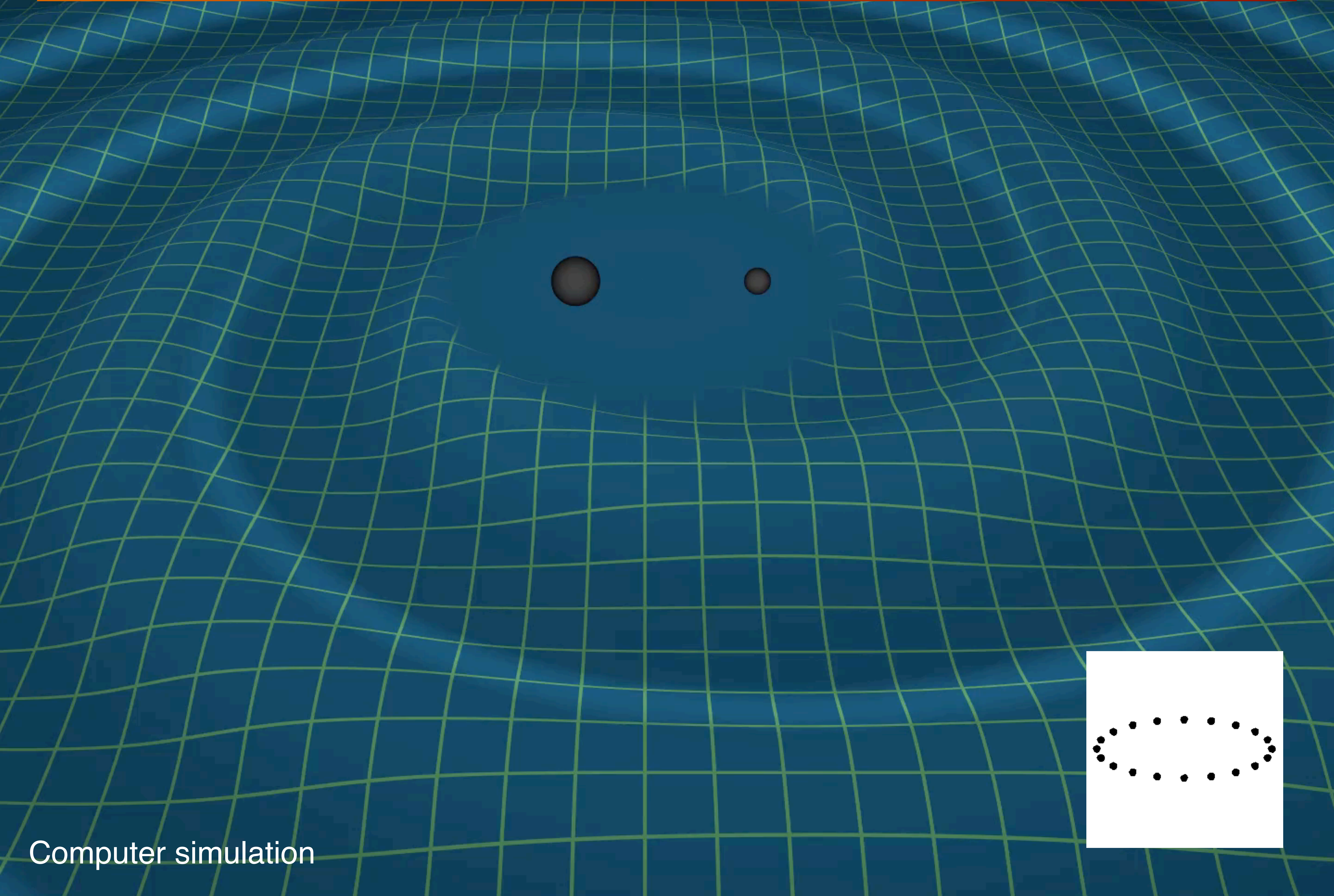


1916: existence of the gravitational waves as a consequence of General Relativity

Definition: objects with mass and moving generate changes in curvature of space-time, which propagate outwards at the speed of light in a wave-like manner

1916: Karl Schwarzschild finds the first exact solution of the Einstein's field equations $\Longrightarrow$ black hole concept

Fusion of black holes: strongest source of gravitational waves

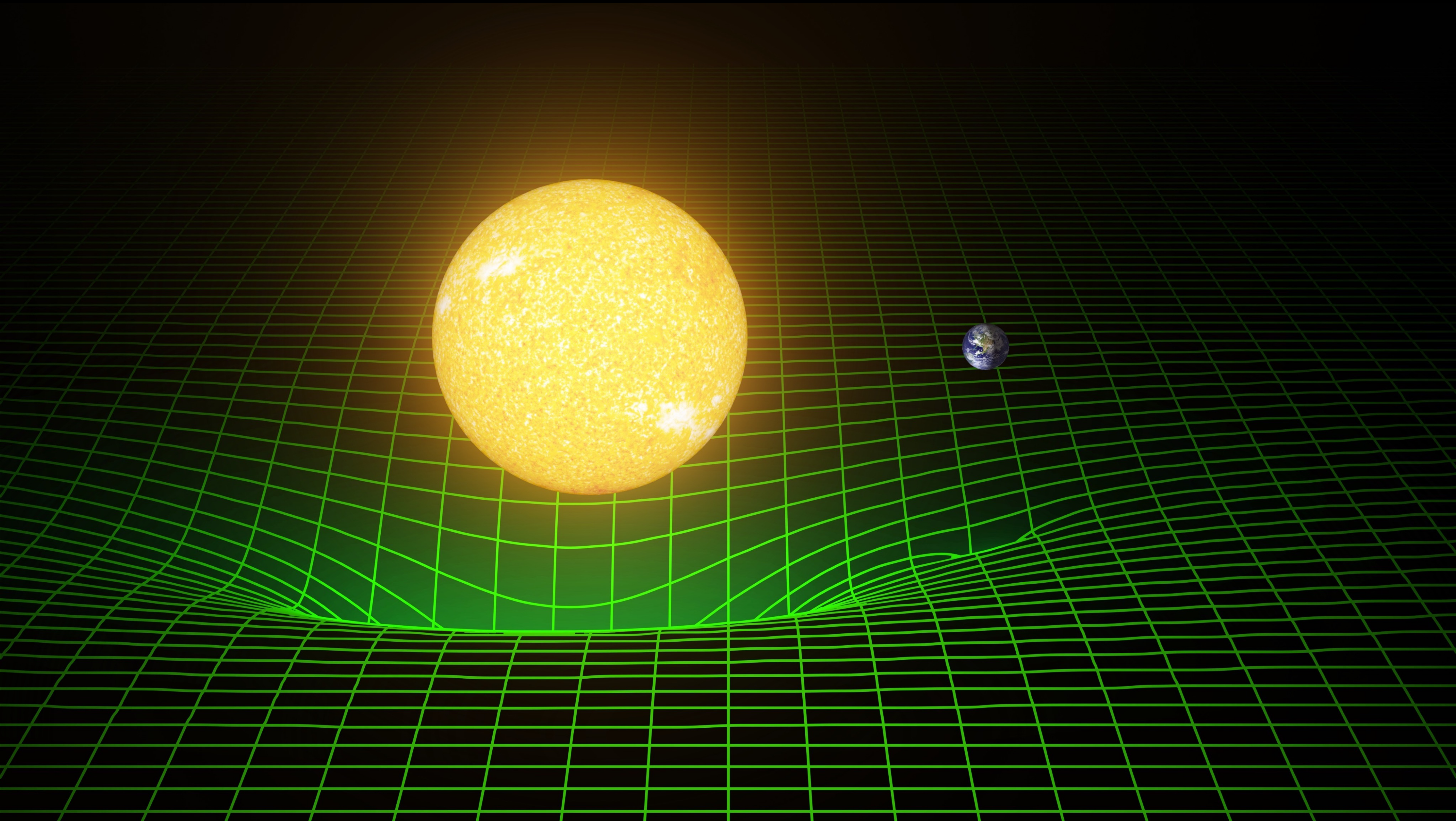


Computer simulation

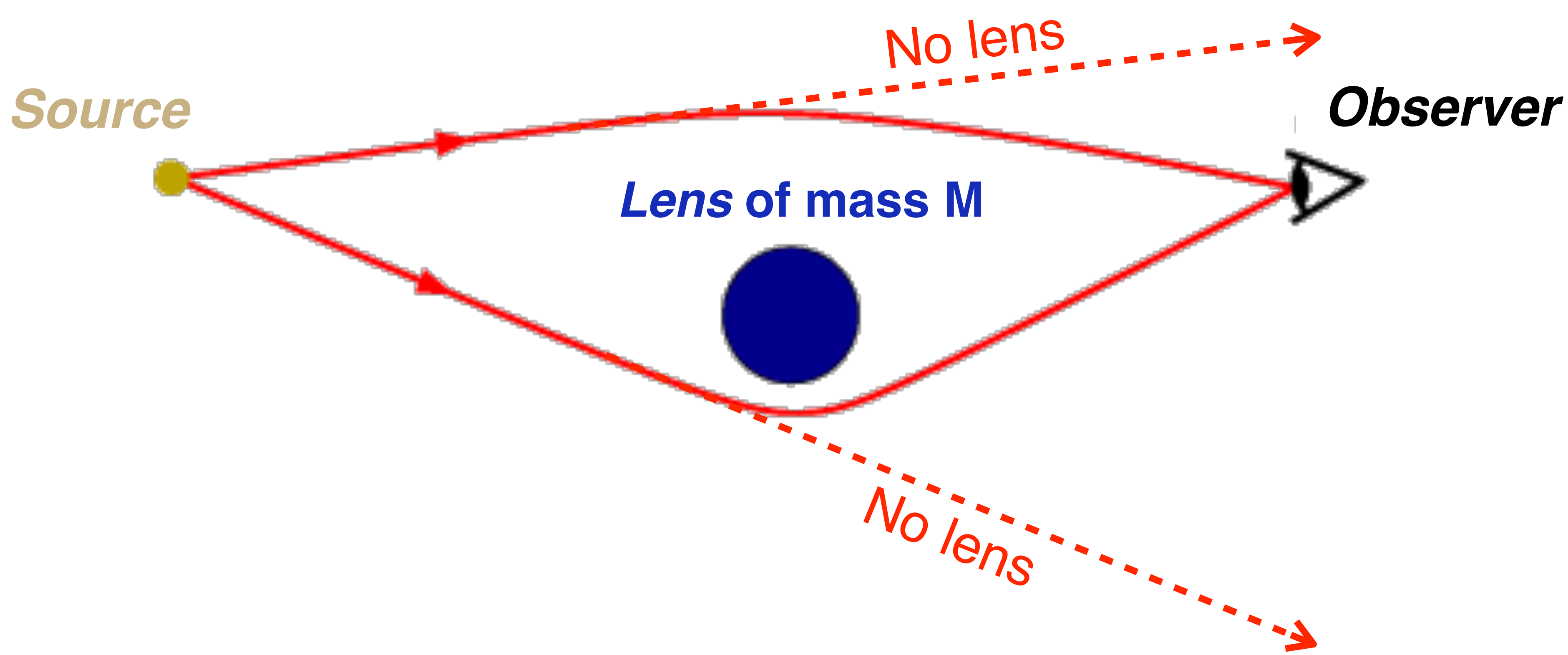
General Relativity predicts:

1. Gravitational lenses 🙂
2. Precession of the perihelion of planets 🙂
3. Gravitational redshift 🙂
4. **Gravitational waves** 😃

Any object with mass deforms geometry of ***space-time***



Gravitational lensing



Bending of light by object with mass due to **curvature of spacetime**

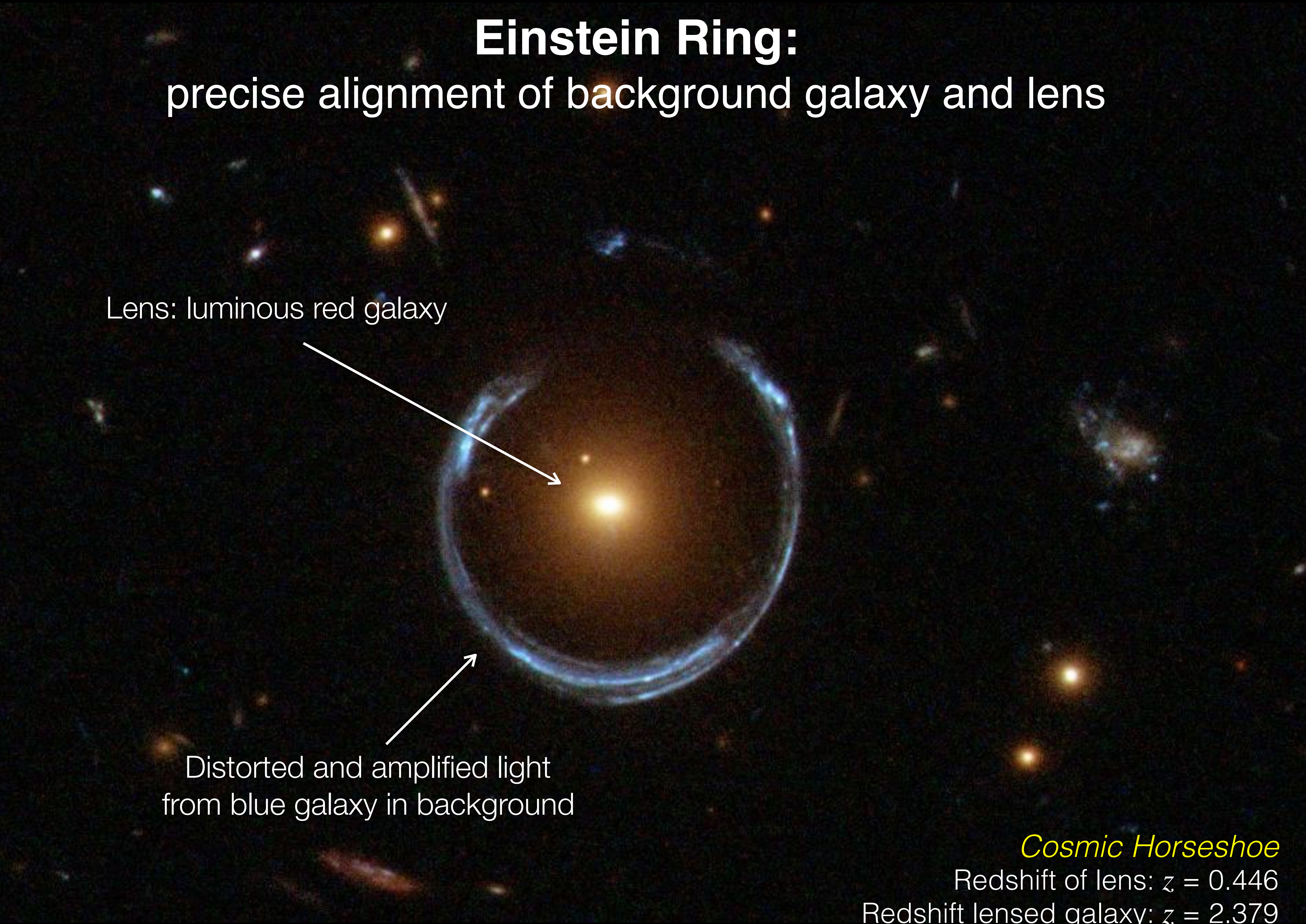
Gravitational lensing detected for the **first time in 1919** during a **solar eclipse** in South America

Effect of **deformation of space-time**: gravitational lensing

www.eso.org

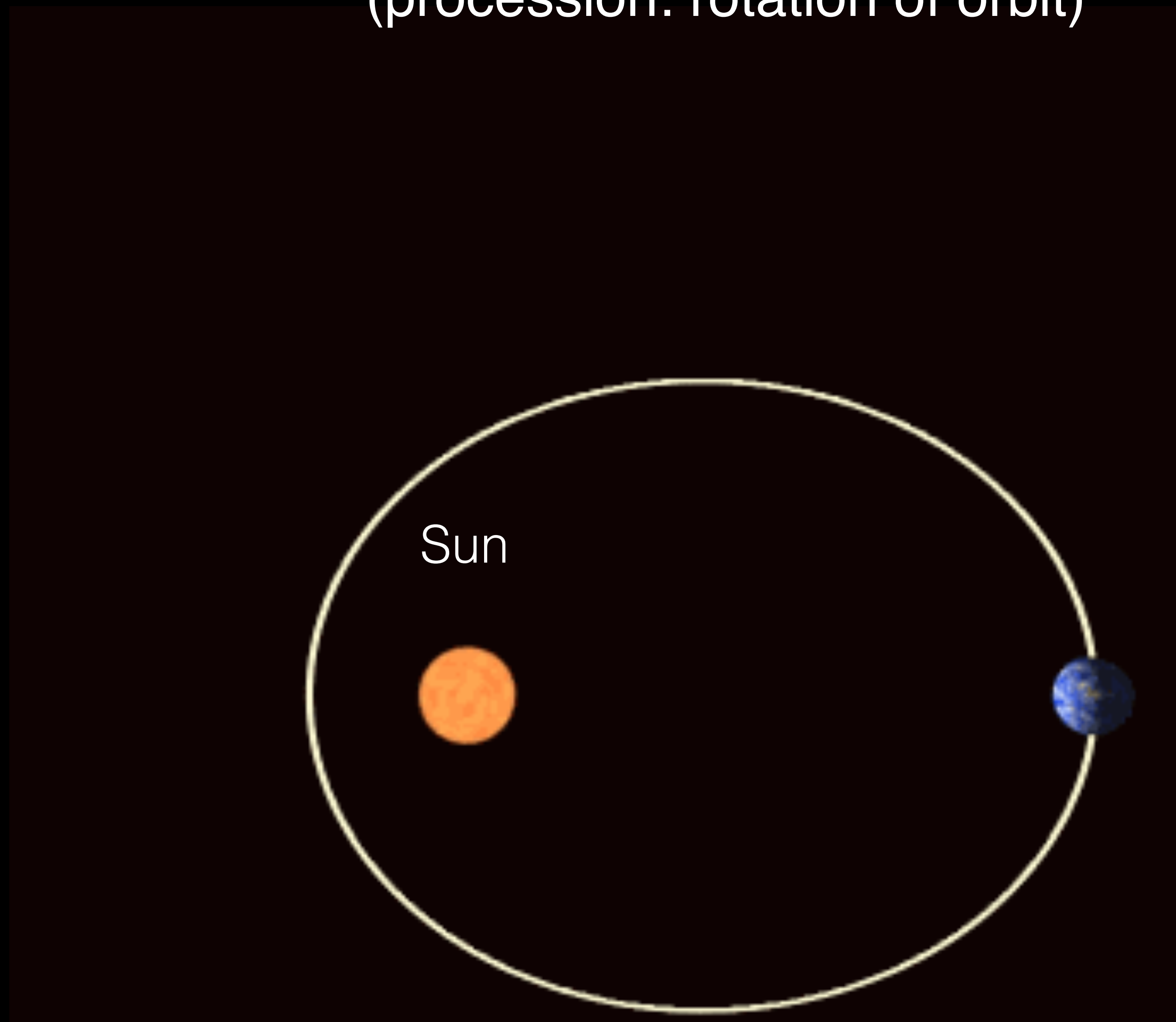
Video: www.eso.org/public/archives/videos/large_qt/eso1426b.mov

Einstein Ring:
precise alignment of background galaxy and lens



Precession of the perihelion of Mercury

(procession: rotation of orbit)



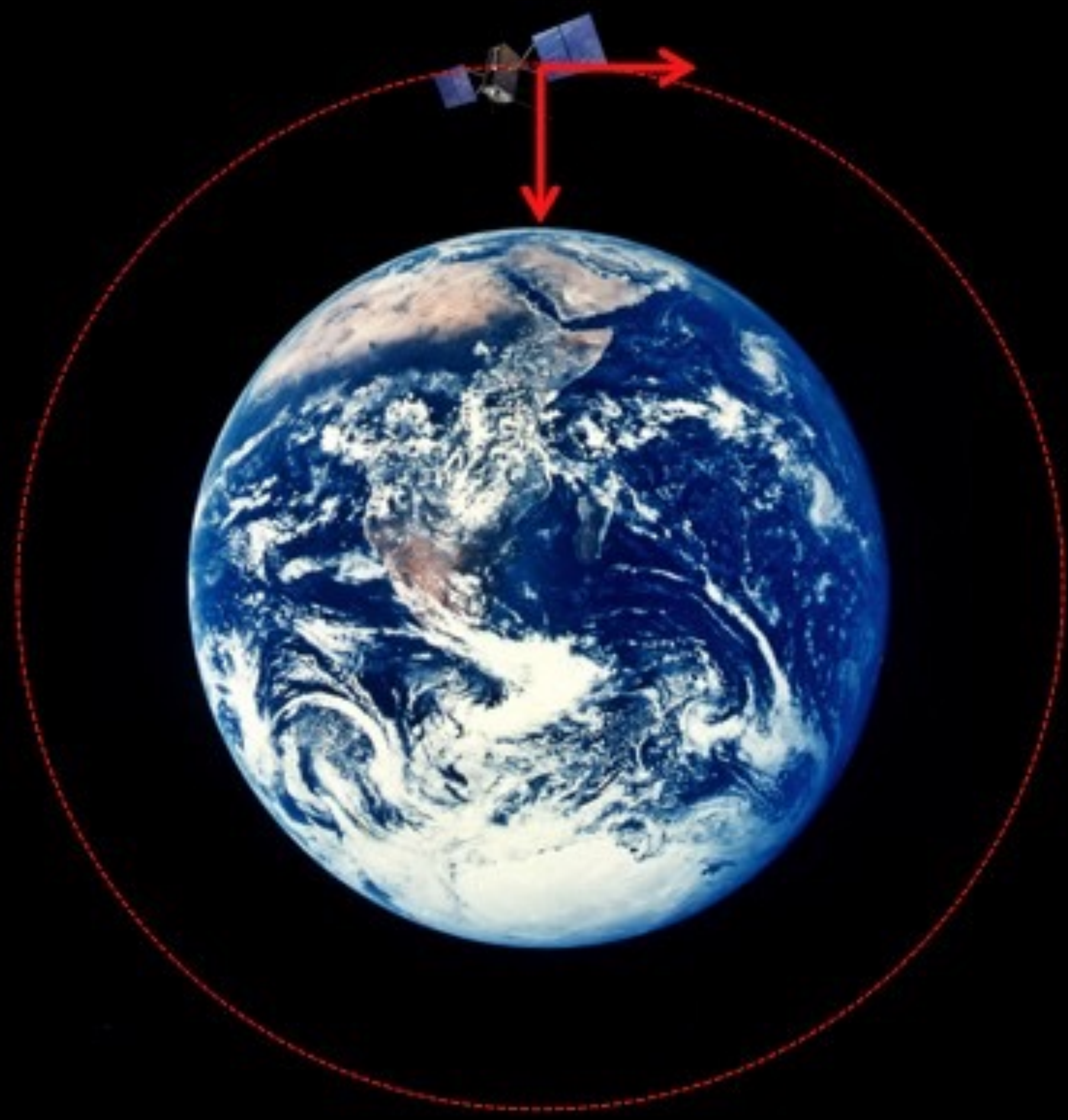
Mercury orbit without
General Relativity

Delay of Mercury perihelion (as seen from Earth): 43″ every 100 years (one degree every 8000 years)

Effect discovered by French mathematician and astronomer Urbain Le Verrier in 1859 and explained by A. Einstein in 1915

GPS uses General Relativity to calculate positions

GPS: Global Positioning System, with nanosecond precision clock
Satellites at 20 thousands km from Earth's surface give position with typical accuracy of 3 meters



Two relativistic effects (in opposite directions):

1. satellites are moving with respect to us, their clock slower by 7 μs/day
2. satellites feel different curvature of space-time with respect to us, their clock faster by 45 μs/day

Our total delay with respect to satellites: 45–7 = 38 μs/day (if ignored, positions off by 11.4 km/day)

General Relativity predicts the existence of gravitational waves

Why so difficult to detect?

All complicated by weakness of signal because:

1. Dipole moment is zero
2. Emitted power is quadruple, proportional to:

$$\frac{G}{5c^5} = 5\times10^{-61}\ \mathrm{s}^3\ \mathrm{cm}^{-2}\ \mathrm{g}^{-1}$$

G : gravitational constant

c : light speed

Energy emitted by gravitazione waves larger for more compact objects

Compactness:

$z = 2GM/(Rc^2)$

M: mass of object
R: radius of object

(dimensionless number, different from density)

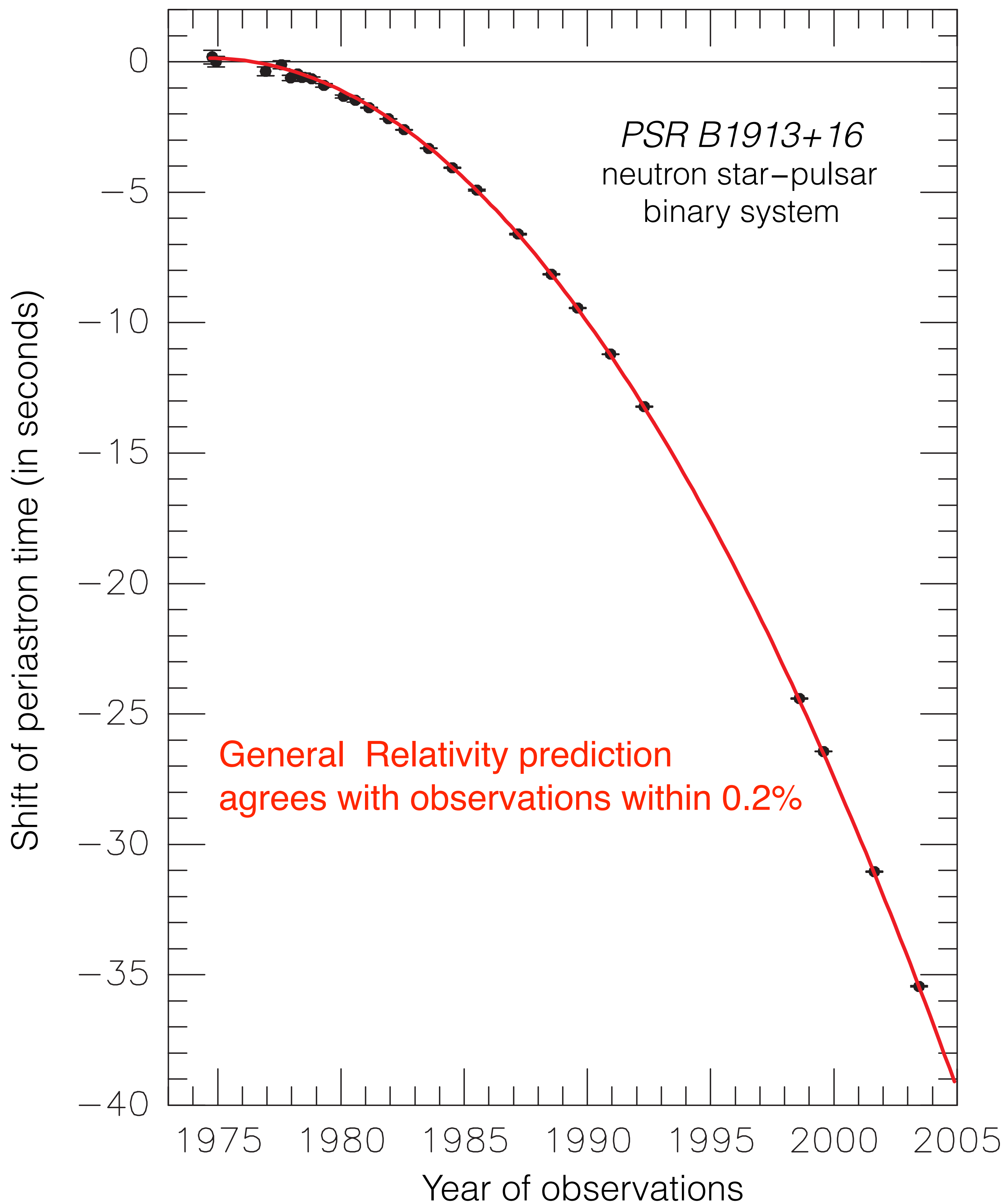
Object	Compactness
Earth	10^{-10}
Sun	10^{-6}
White Dwarf	$10^{-4} - 10^{-3}$
Neutron star	$0.2 - 0.4$
Black Hole	1

1975, first evidence of existence of GW:

Orbiting objects loose energy in gravitational waves

Precession of periastron in binary system of with neutron stars

Shit of periastron because two stars get closer



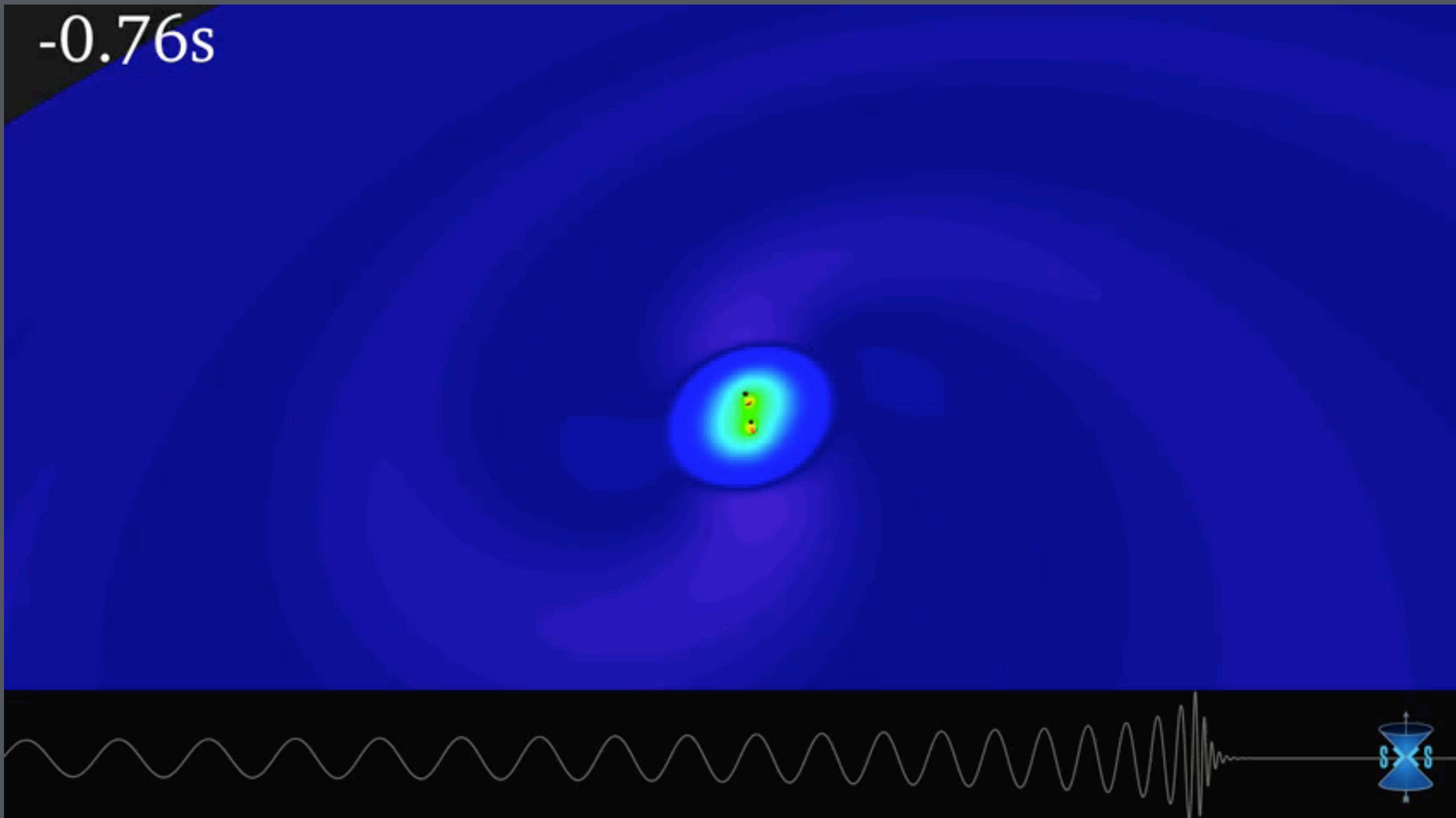
1975, first evidence of existence of GW:

- Einstein's equations predict that 2 orbing objects get faster and closer (inspiralization)
- Energy loss is due to emission of gravitational waves
- In one year the two stars PSR B1913+16 get closer by 3.5 meters
- At a distance of 6 kpc, this corresponds to 76.5 μ-arcsec / year
- This is called *Taylor & Weisberg Effect*

September 2015: first gravitazionale waves detected by experiment ***LIGO***

LIGO: Laser Interferometer Gravitational-Wave Observatory

Source: GW150914

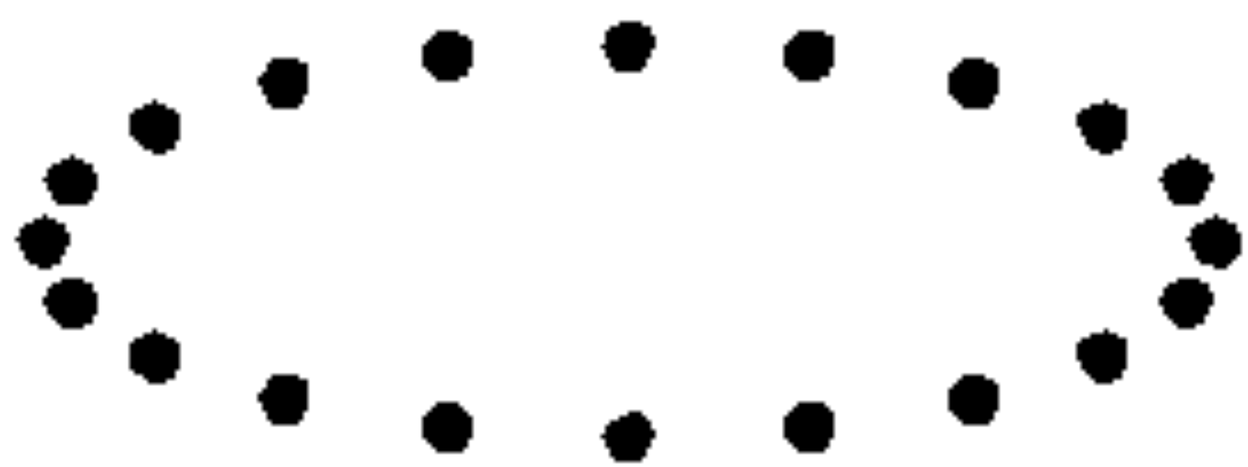


See video: https://www.ligo.caltech.edu/video/ligo20160211v10

Computer simulation

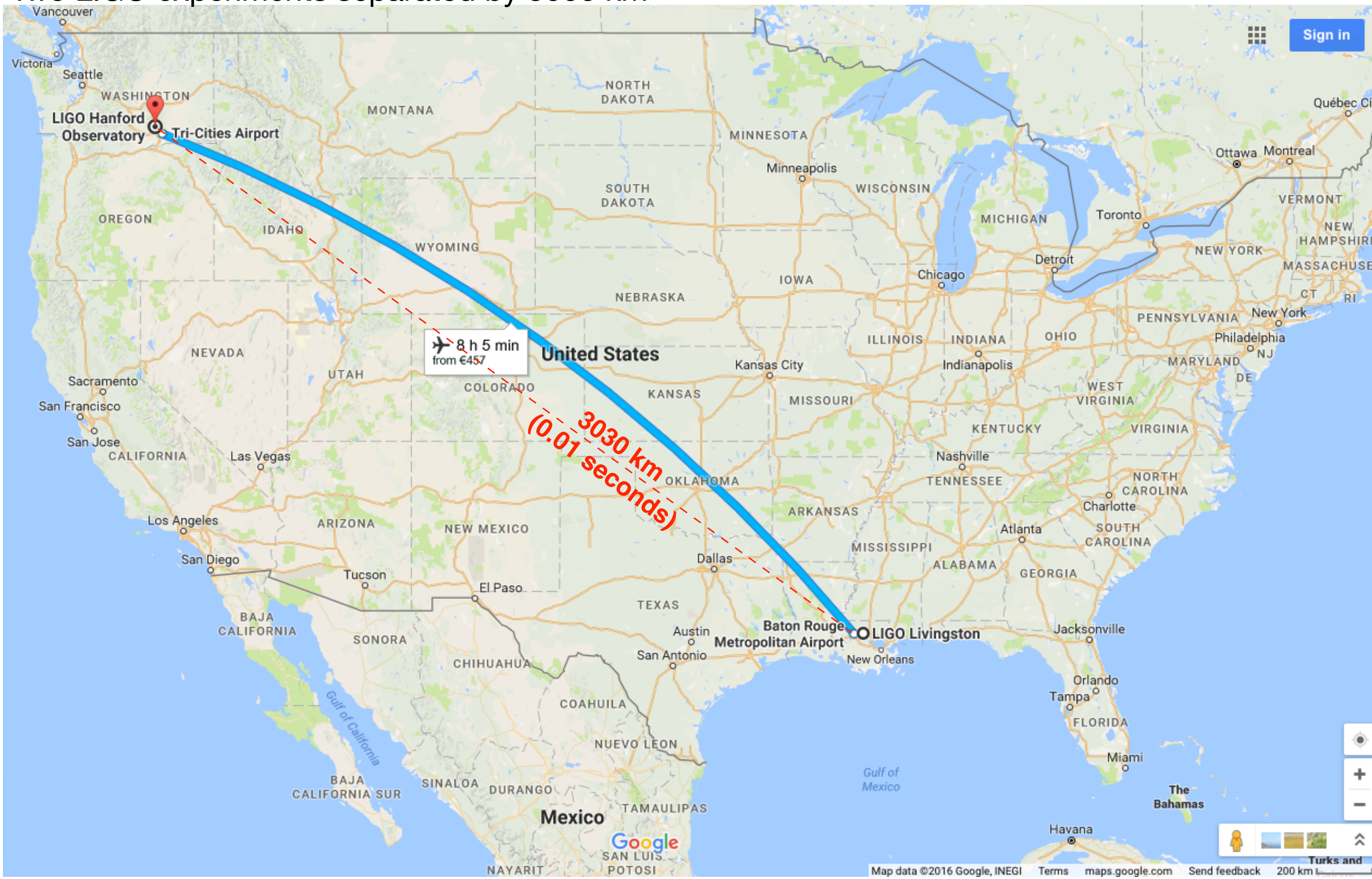
The effect of gravitational waves on a ring of particles

(wave oscillation of space-time)



LIGO: Laser Interferometer Gravitational-Wave Observatory

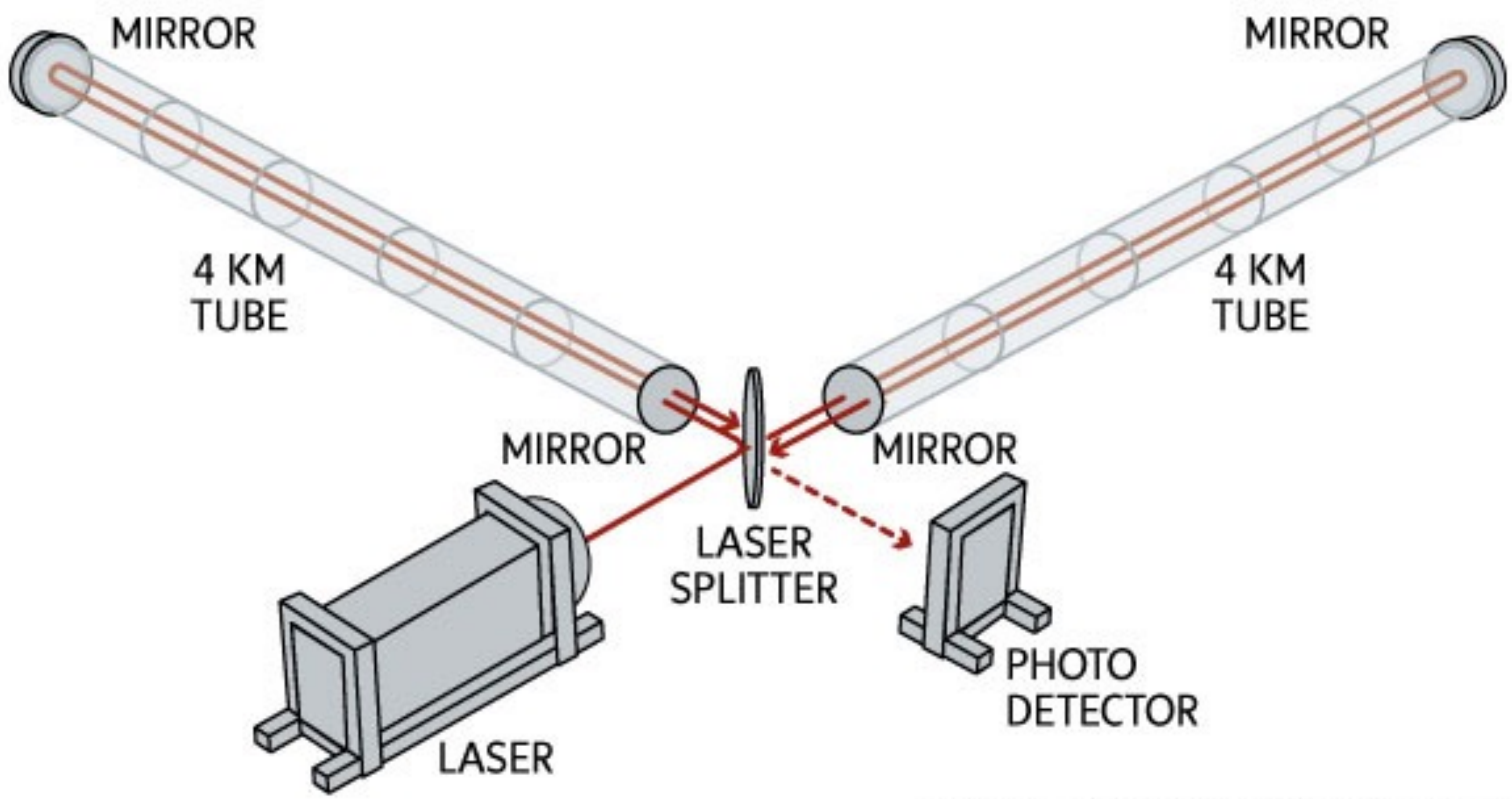
Two LIGO experiments separated by 3000 km



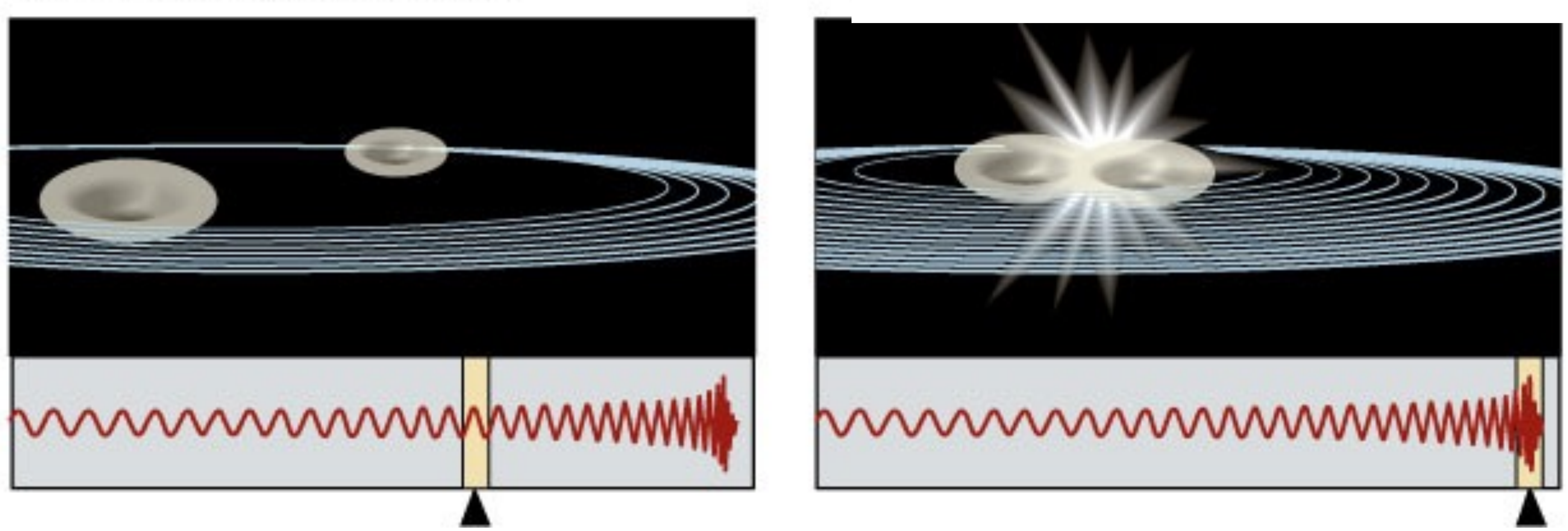
Any signal with delay longer than t = 10 ms is not due to GWs

LIGO: Laser Interferometer Gravitational-Wave Observatory

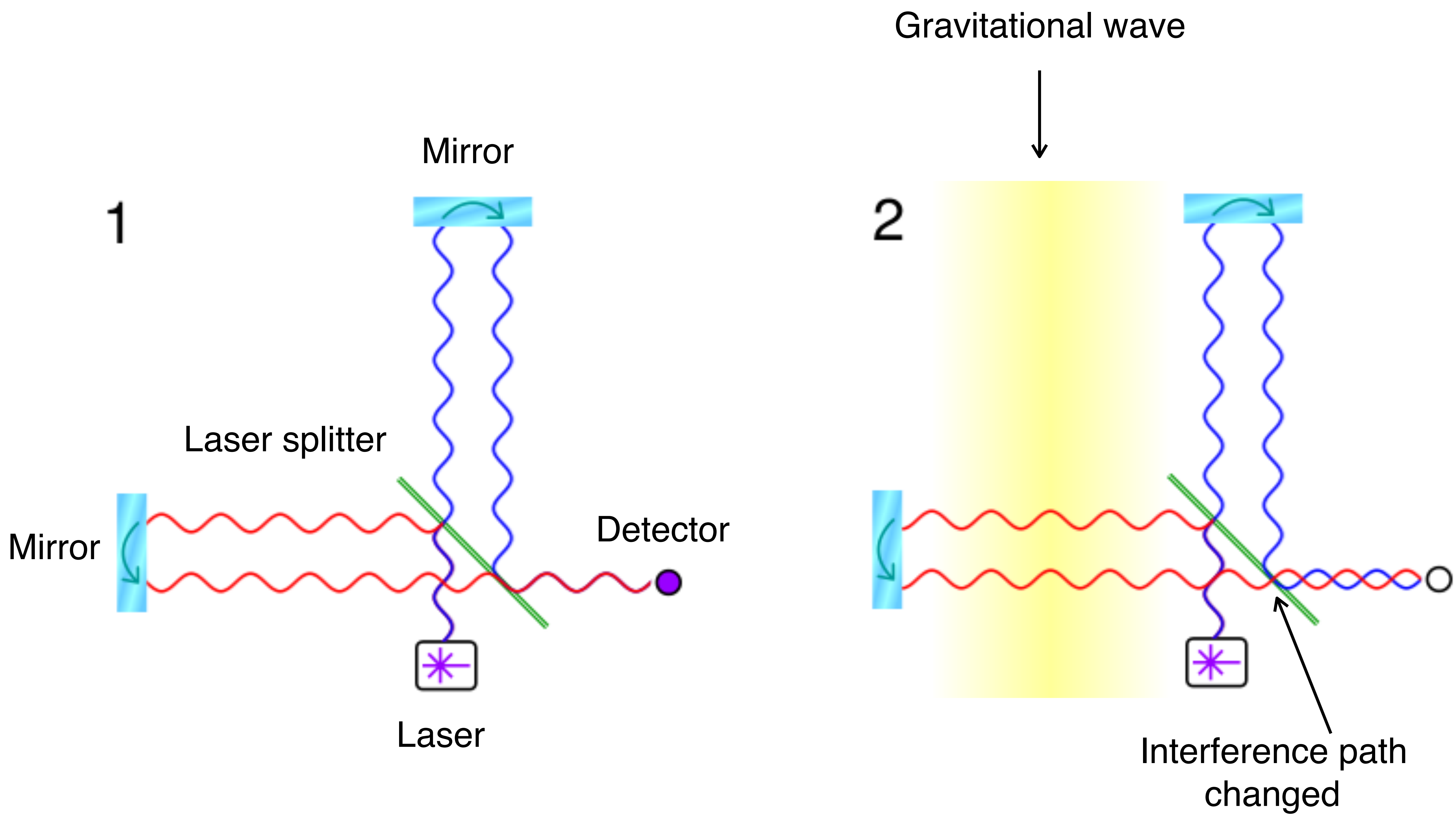
LIGO: Laser Interferometer Gravitational Wave Observatory



Black holes collide



LIGO: Laser Interferometer Gravitational Wave Observatory



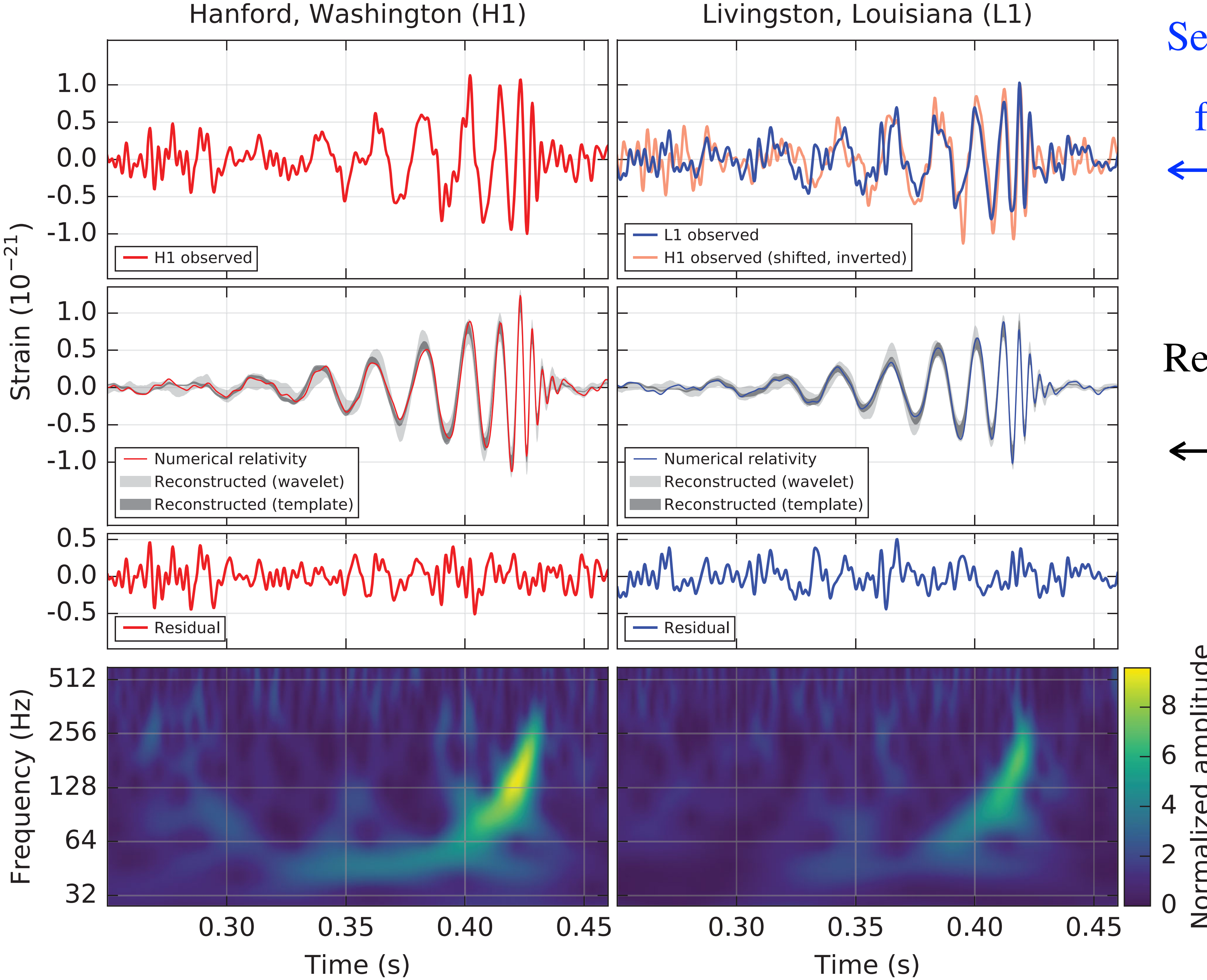
September 2015: gravitational waves are detected for the first time

Strain $h = \Delta L/L$: deformation of space-time from a reference configuration (L: arm length)

Name of the source: **GW150914**

First signal

Reconstructed signal

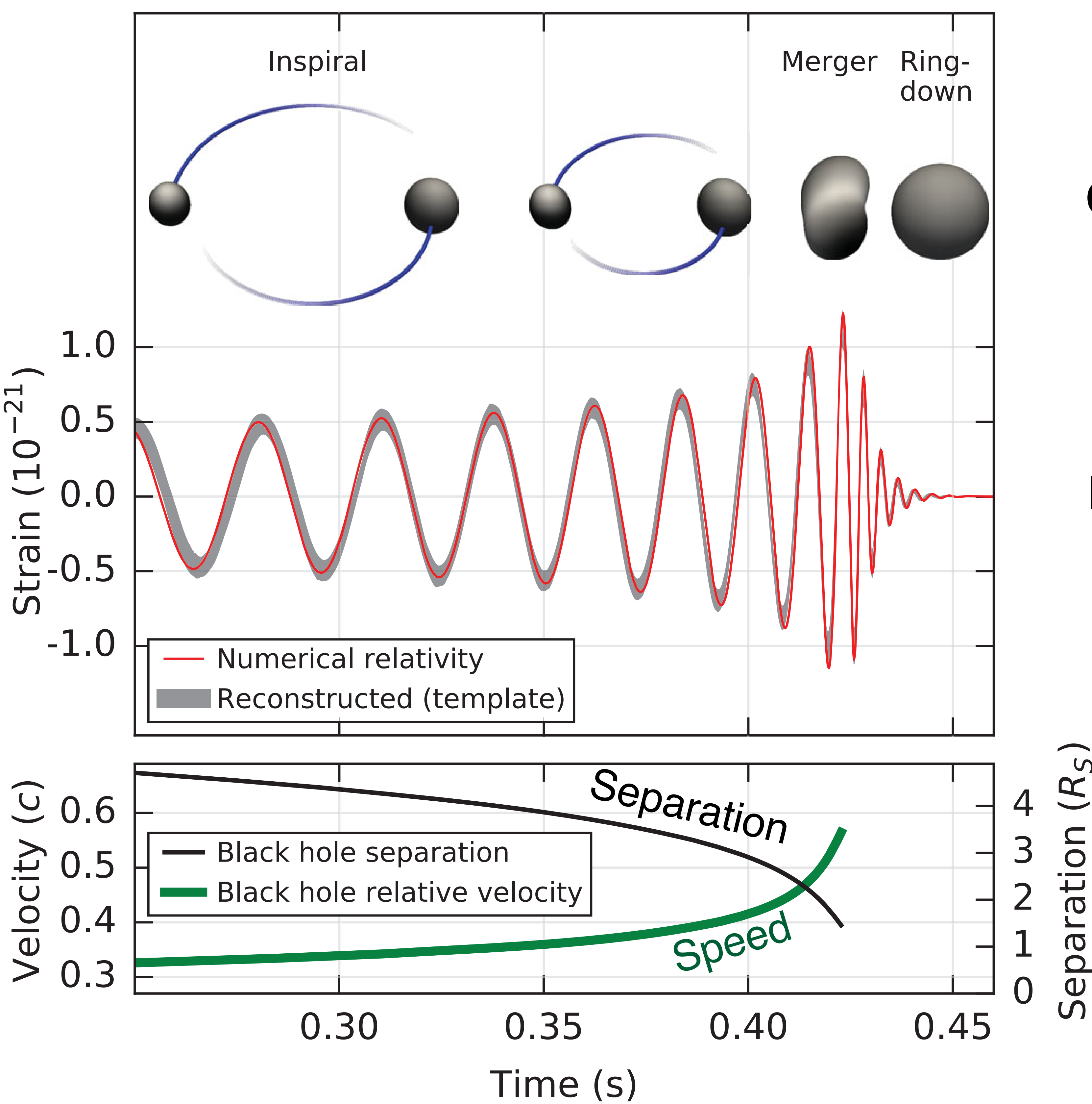


Second signal over first signal

Reconstructed signal

Measured final 5 orbits between to black holes before merger

Gravitational-wave strain amplitude in **GW150914**

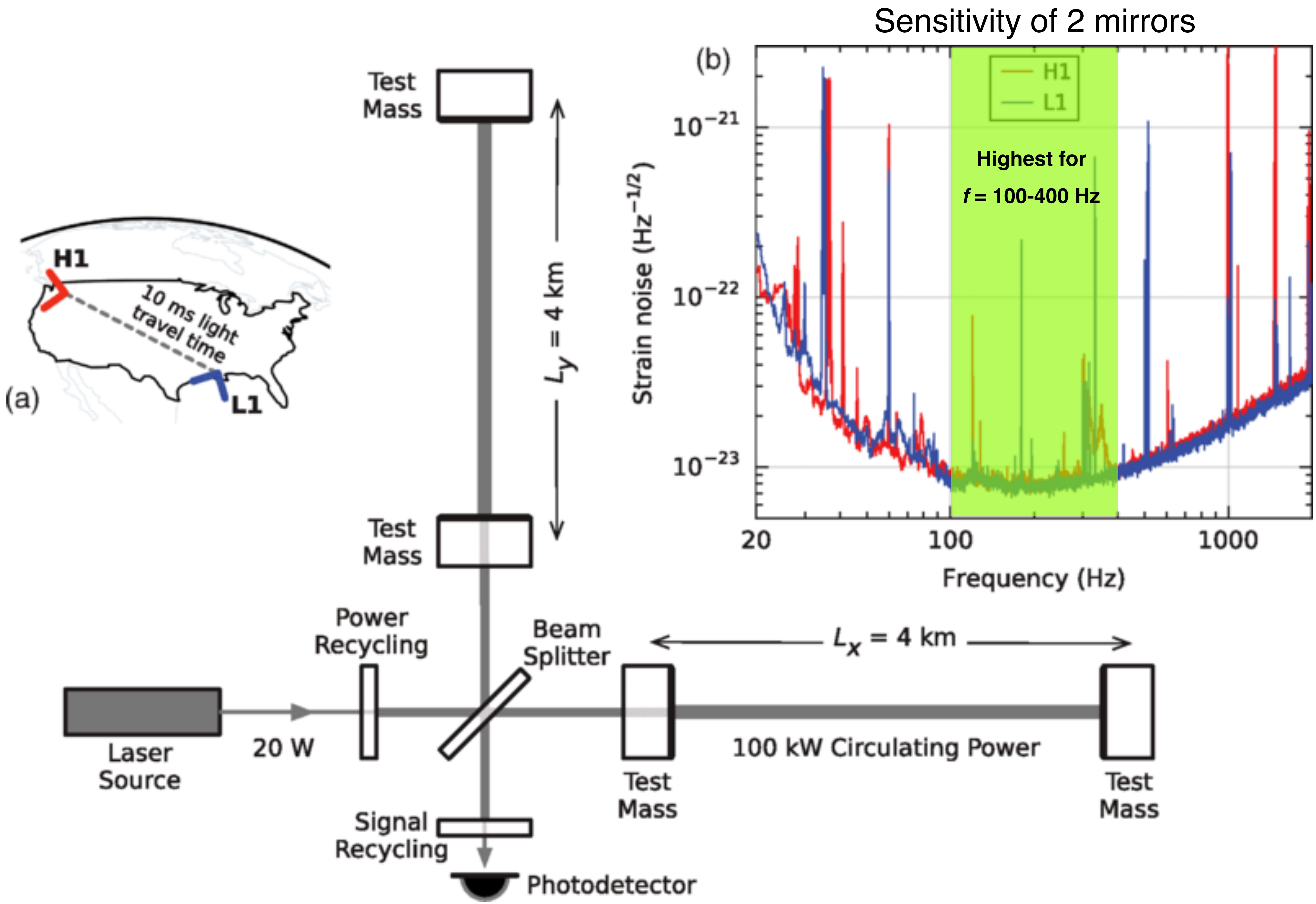


Coalescing of 2 black holes

Reconstructed waveform

Speed and separation between the two objects

LIGO: Laser Interferometer Gravitational-Wave Observatory



LIGO: Laser Interferometer Gravitational-Wave Observatory

First detection *GW150914* - **Summary**

- Measured strain on Earth: $h = 10^{-21}$
- Over 4 km of arm size, this is 0.001 size of proton
- Corresponding to the ability to measure distance to closest star (Proxima Centauri, 4.2 light years = 4.02×10^{16} m) with precision of 40 μm (size of human hair)
- Strain at source: $h = 0.1$
- Signal from two merging black holes of stellar origin, observed frequency gives masses of 2 bodies: $M \approx 30$–$35\ M_\odot$ (relatively low error 10–15%)
- Emitted energy: $E = mc^2 = 3.6\times10^{56}$ erg, or $m = 3\ M_\odot$ into gravitational waves
- This corresponds to energy emitted by radiation of all stars in galaxies in same time interval in entire universe
- Frequency proportional to orbital period, for $f = 75$ Hz (measured before coalescent) separation between two bodies larger than $R_s = 200$ km
- Distance of source not precisely known (40% uncertainty): $D = 0.1/h \times R_s \approx 410$ Mpc
- Speed of two bodies at time of merging: 70% of c

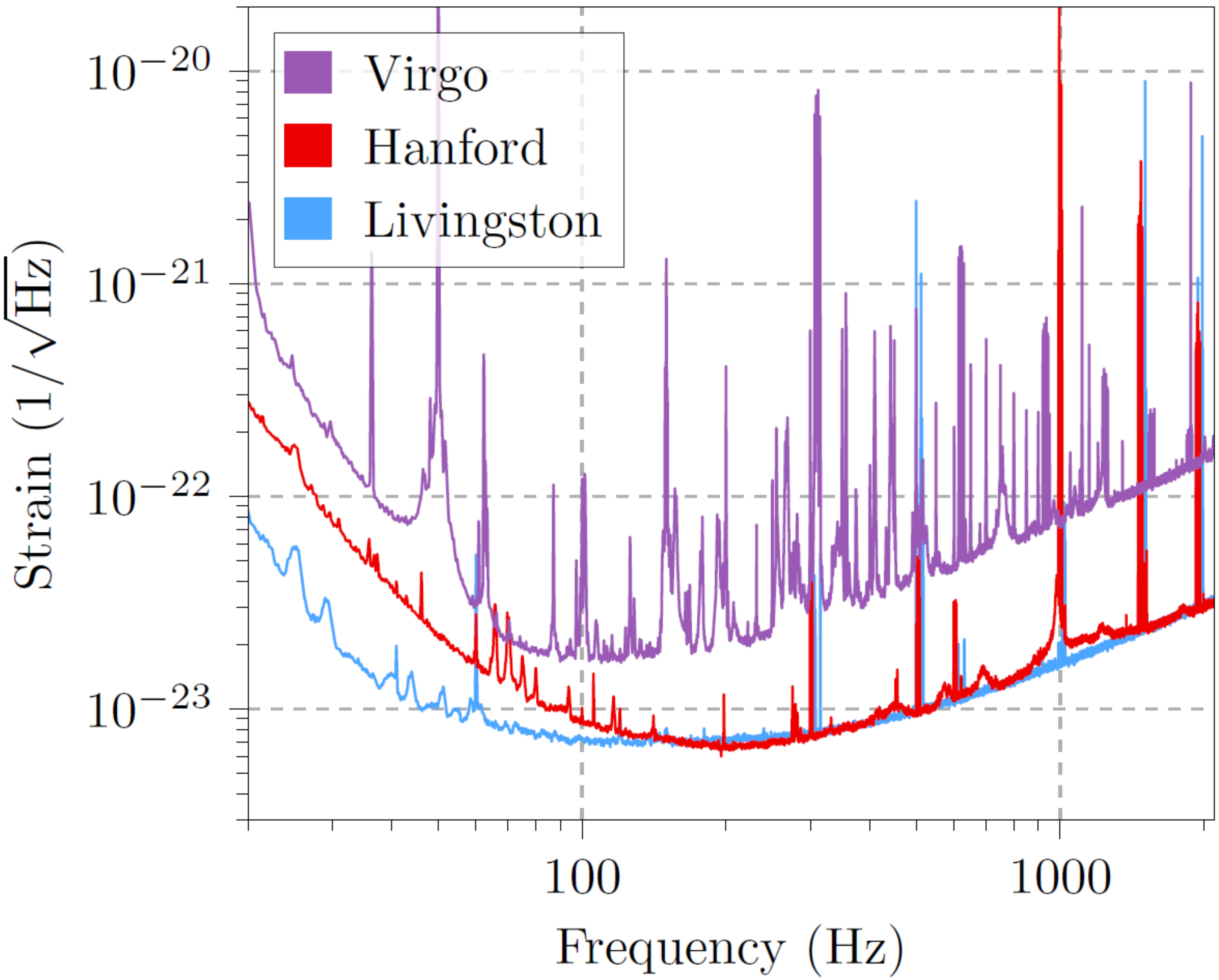
August 2017: detection of merging of 2 neutron stars

&

identification of the galaxy hosting the event

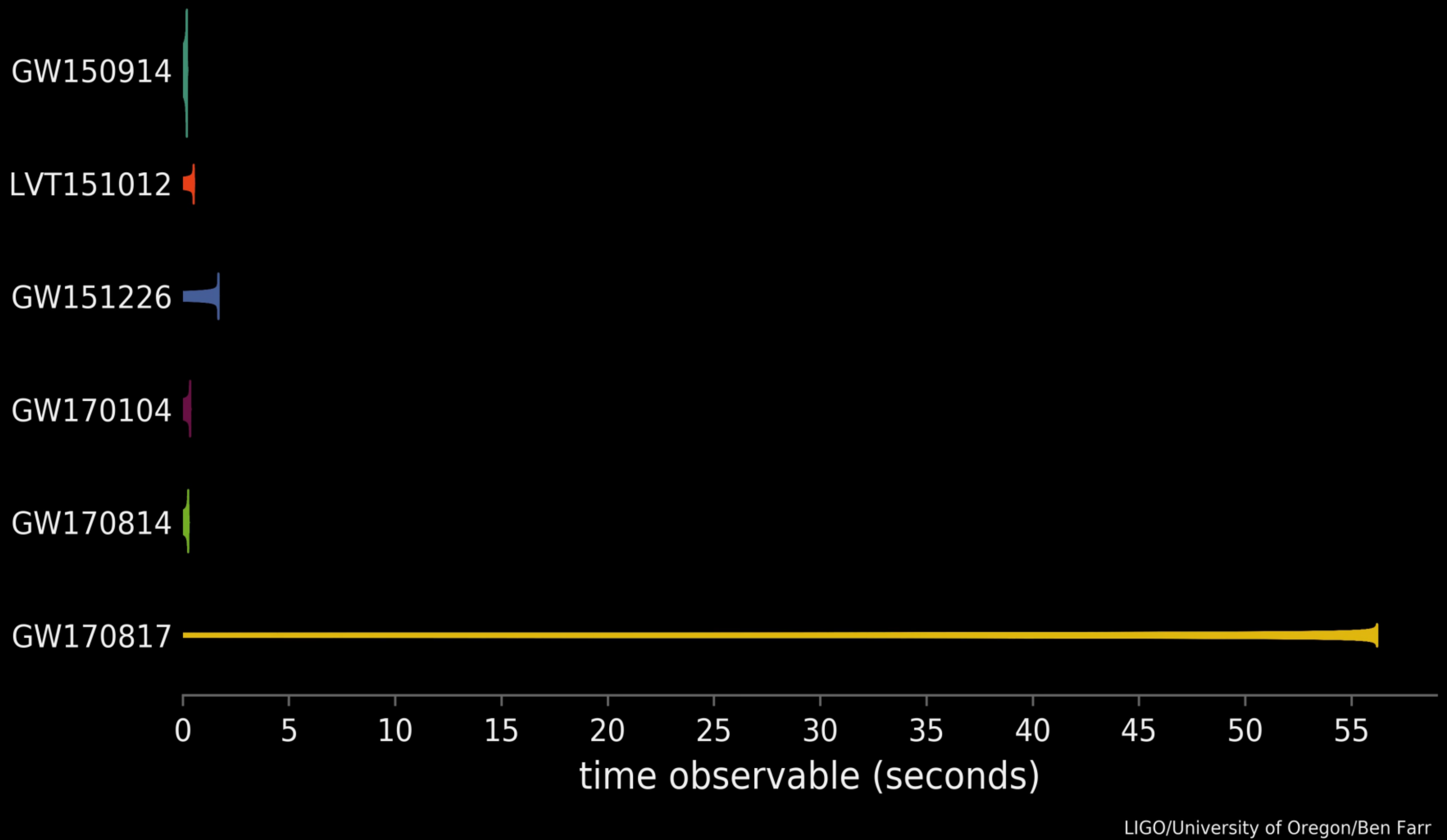
Advanced Virgo joined LIGO on 1– 25 August 2017

Sensitive vs. frequency for the 3 laboratories

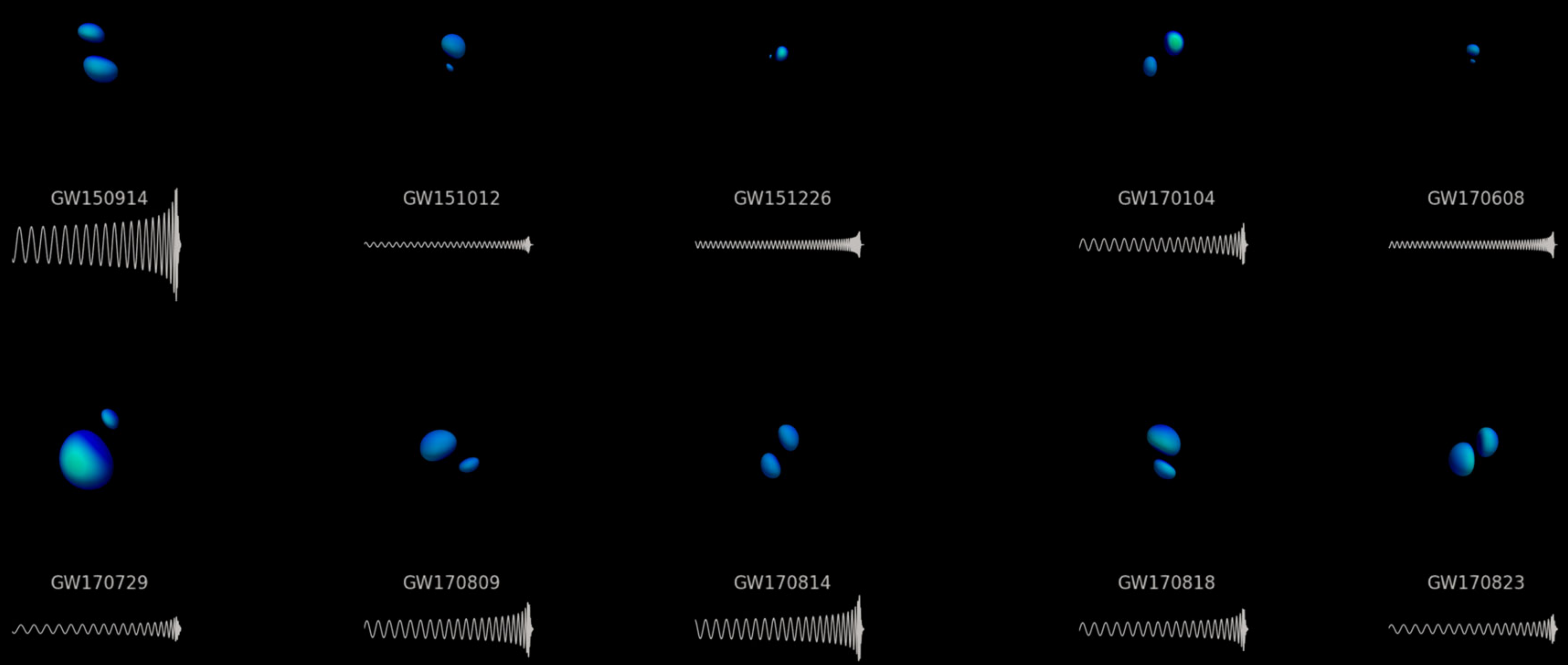


15 days of simultaneous observations by 3 laboratories

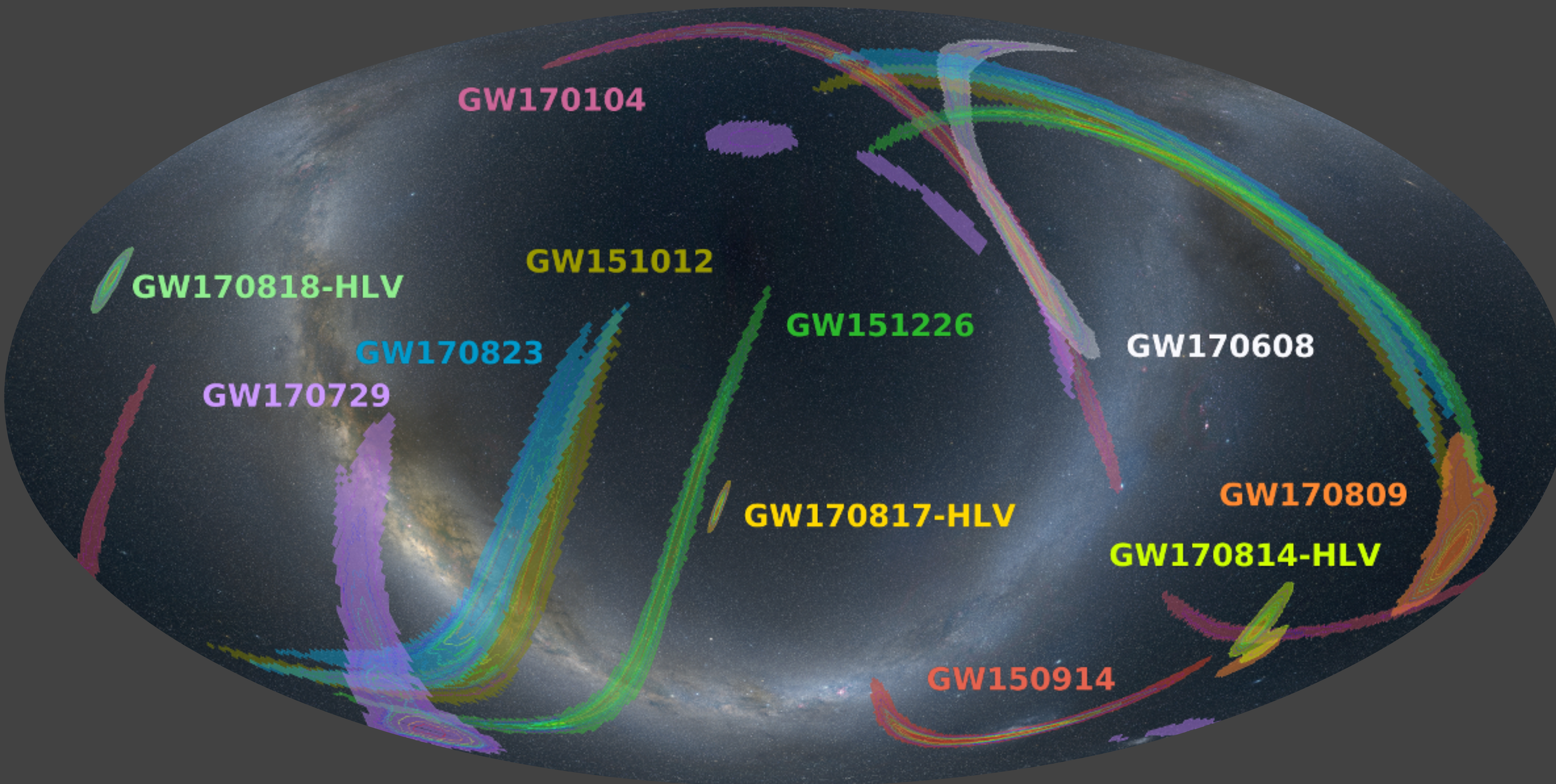
Duration of first 6 events in the runs O1 & O2



Total of 10 BH-BH mergers in O1 & O2



Total events with total 10 BH mergers & **1 NS/NS merger** in O1 & O2



The Milky Way (not centred)

Detection of gravitational waves

September 2015: first announcement of GW detection

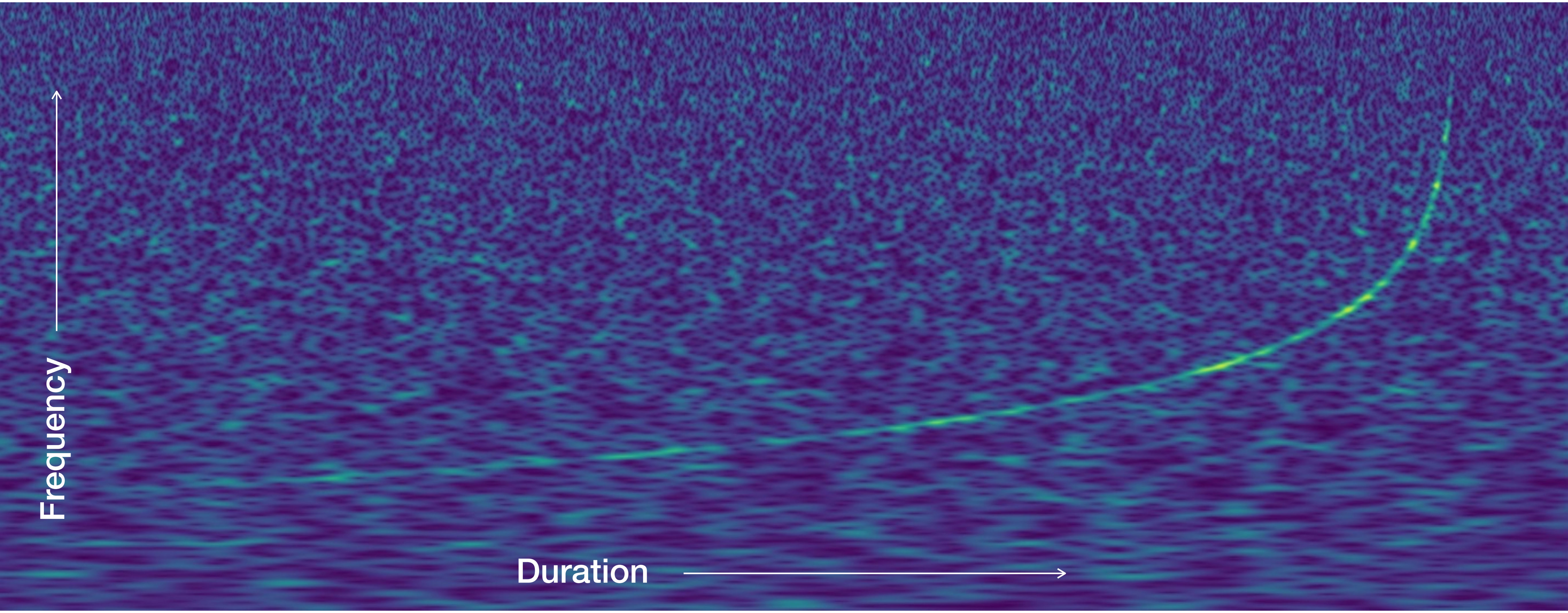
Total number of sources today from first 3 runs:

- **O1 & O2**: 10 BH-BH mergers & 1 NS-NS (or BH-NS?) merger
- **O3**: 45 events, of which: 23 BH-BH, 4 BH-NS, 4 NS-NS
- **O3 is over, NEXT: O4**

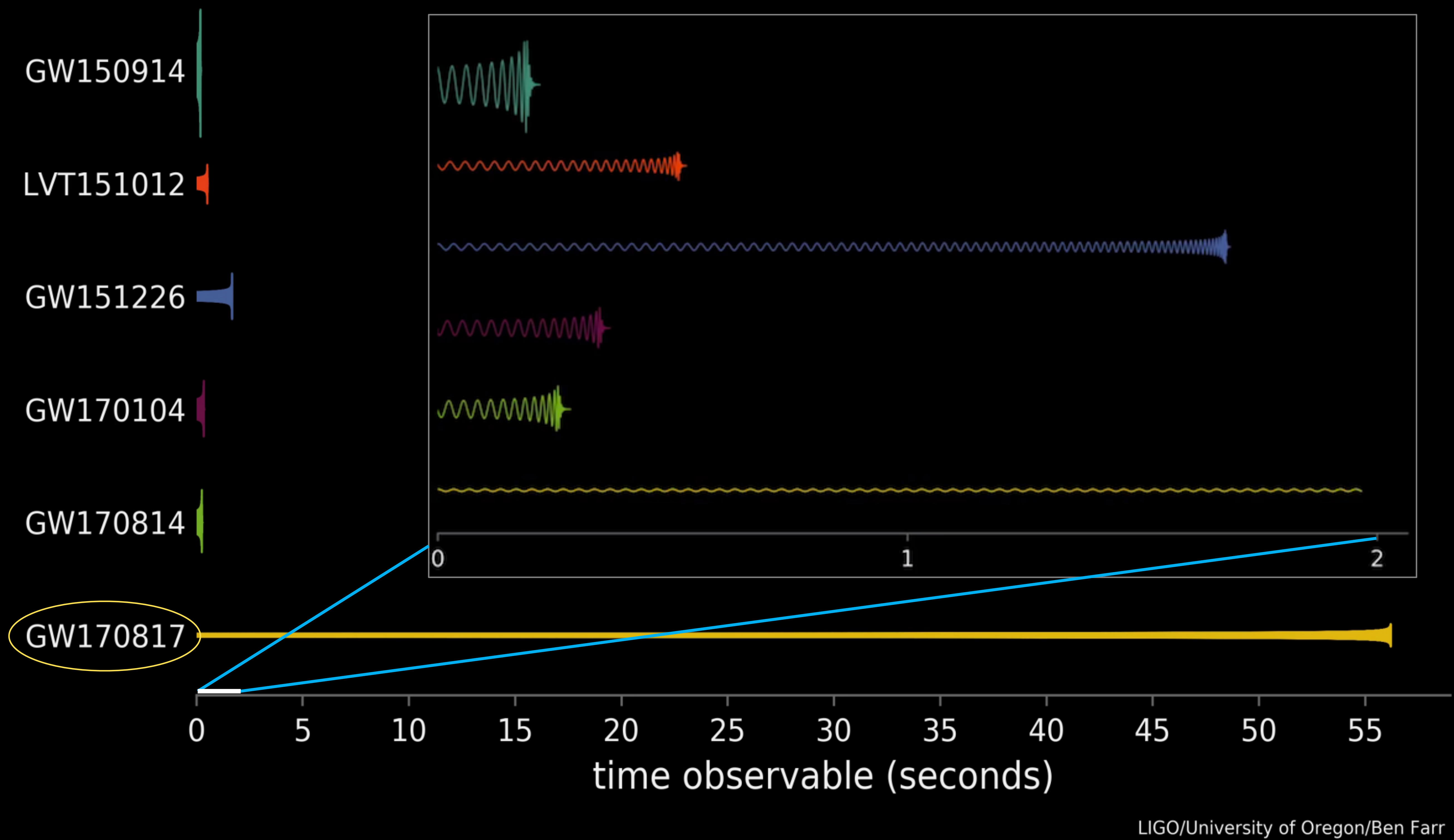
Sensitivity in distances:

- **BH-BH mergers:** ~ 500 Mpc
- **NS-NS mergers:** ~ 50 Mpc

NS/NS merger: most interesting GW event detected on August 17 2017

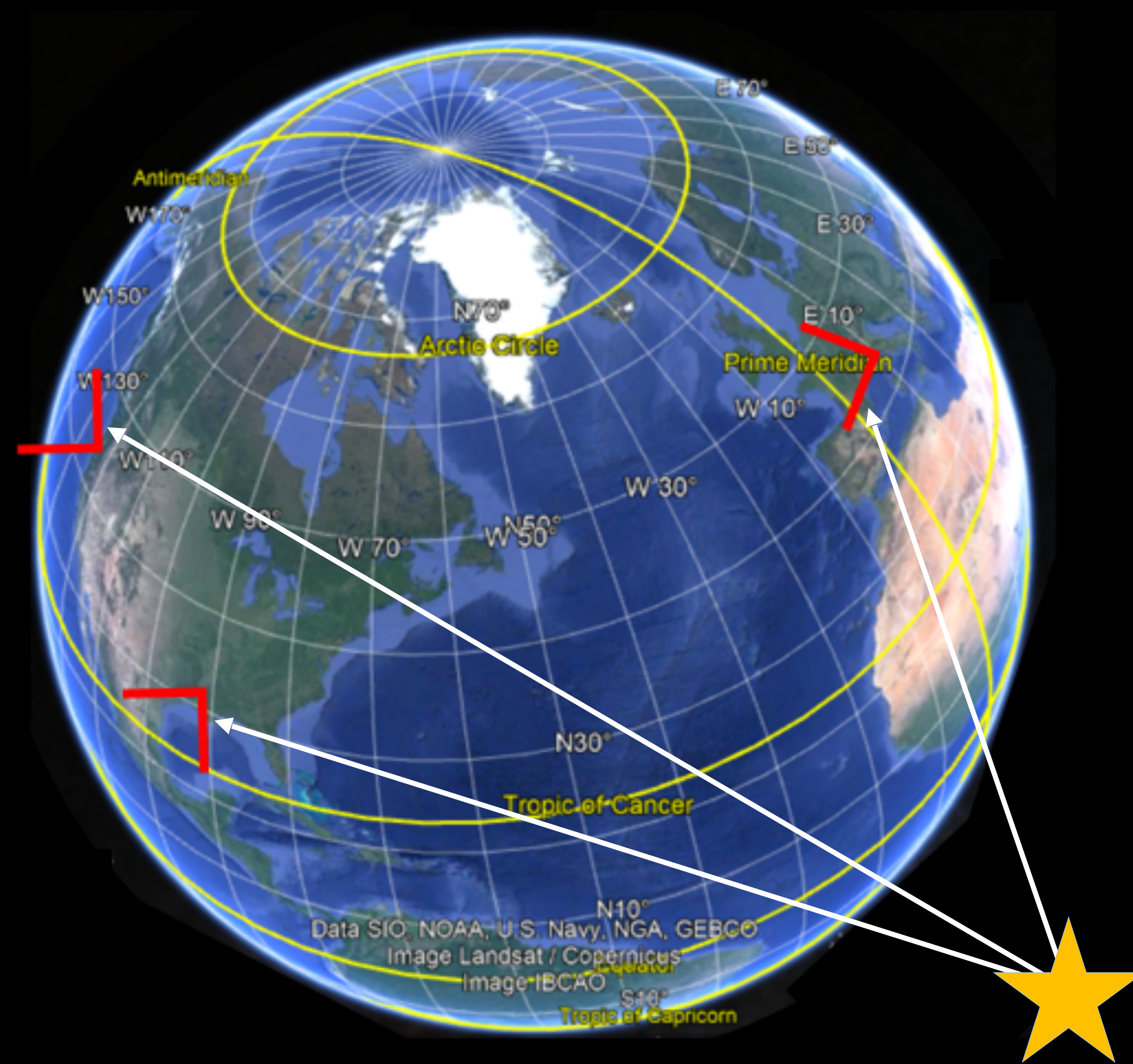


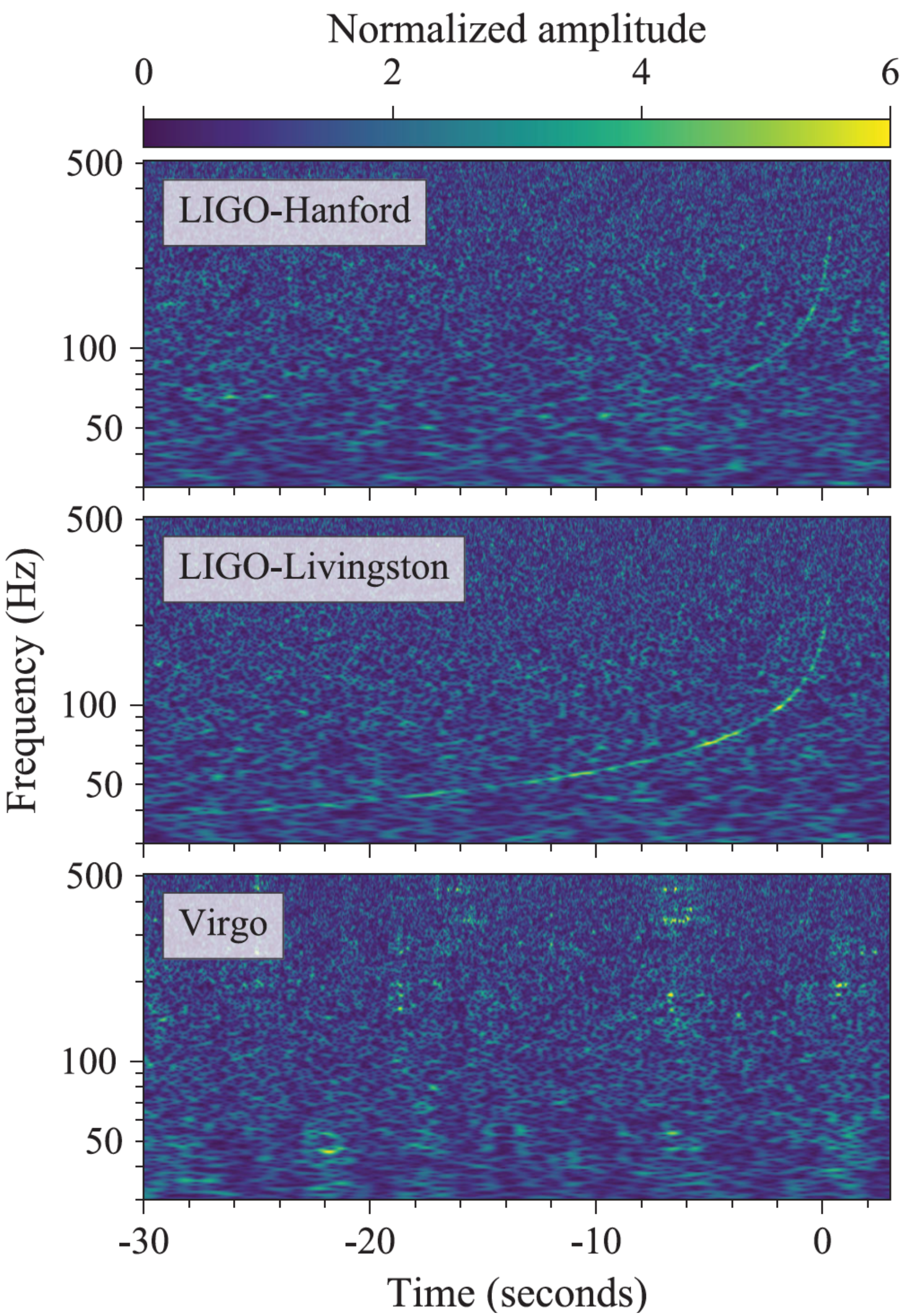
NS/NS merger: most interesting GW event detected on August 17 2017



Longest duration among all: 100 seconds, indicating lower masses

3-detector network: *LIGO* (2 in USA) & *Virgo* (1 in Cascina, Pisa)

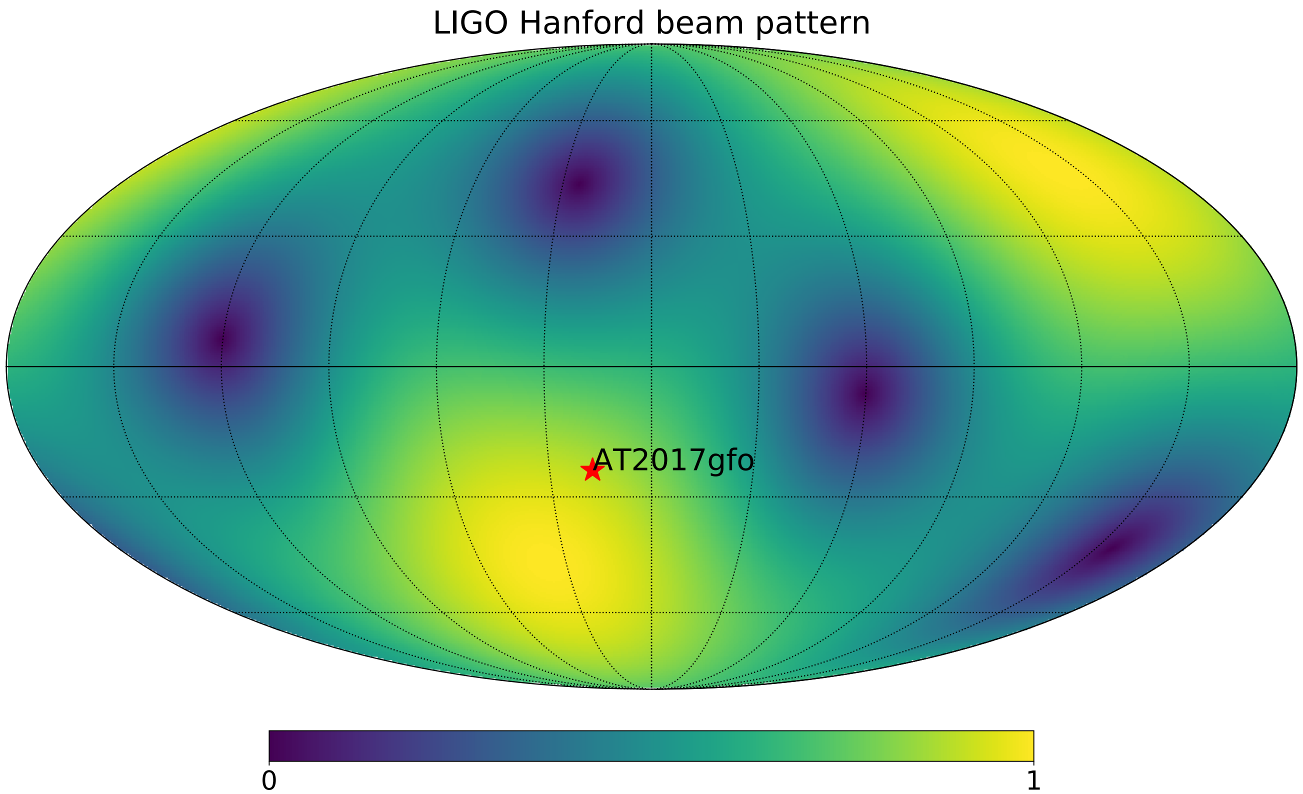


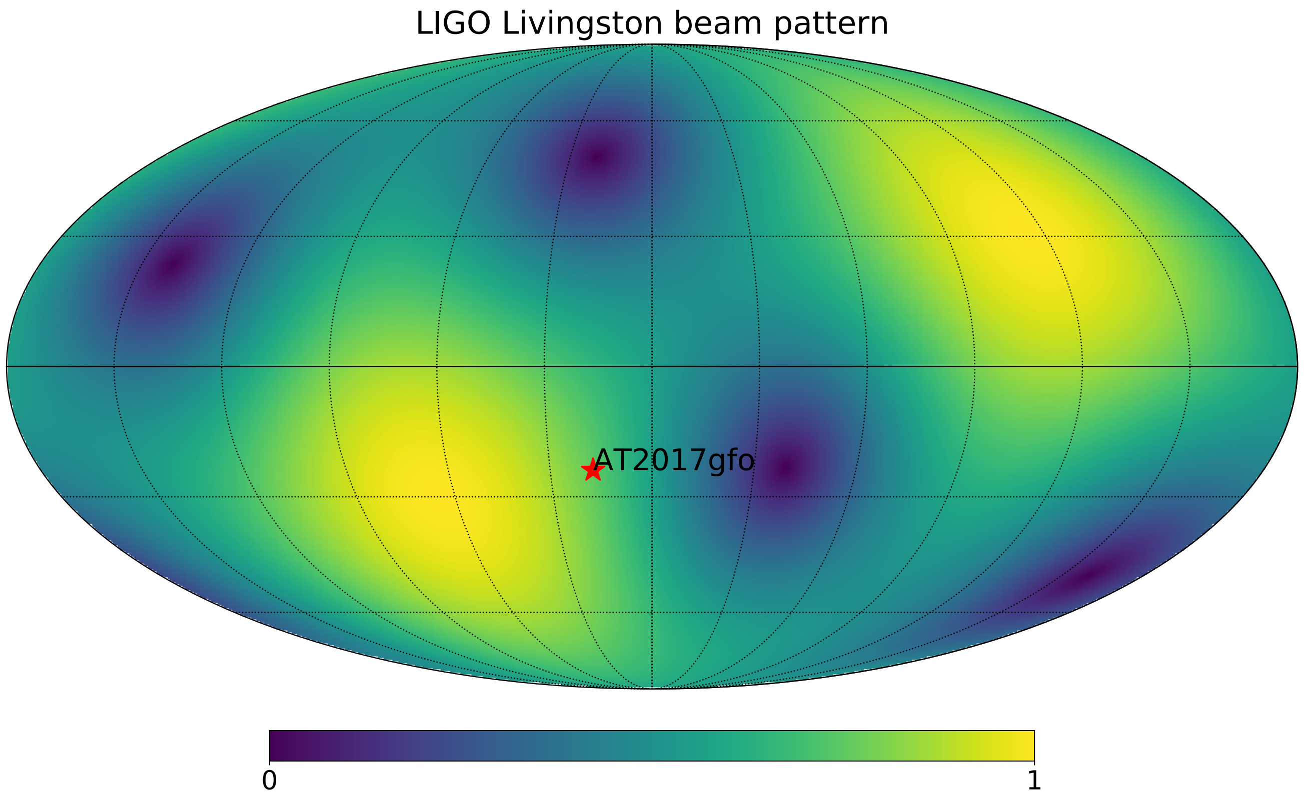


Source of gravitational waves: **GW170817**

- Event duration: 100 seconds
- Distance of source (derived from GW signal): 40 ± 8 Mpc (130 million light years)
- Final mass after coalition: $M = 2.7\ M_\odot$
- Masses of two objects very uncertain: $1.17\ M_\odot$ & $1.60\ M_\odot$
- Merger of 2 neutron stars (binary neutron stars - BNS) or perhaps a neutron star with black hole (NS-BH)

LIGO & Virgo sky sensitivity





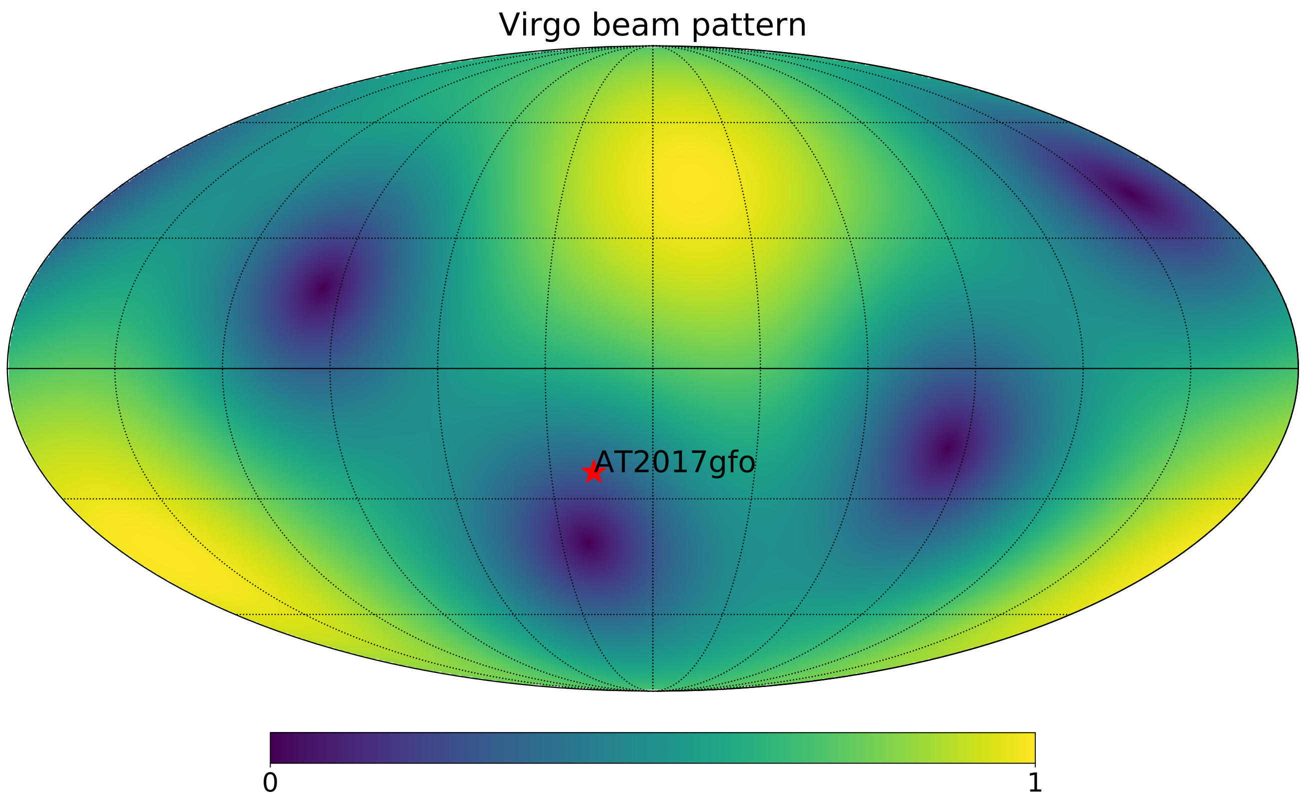
Names of event detected on August 17 2017:

GW170817 : gravitational wave source

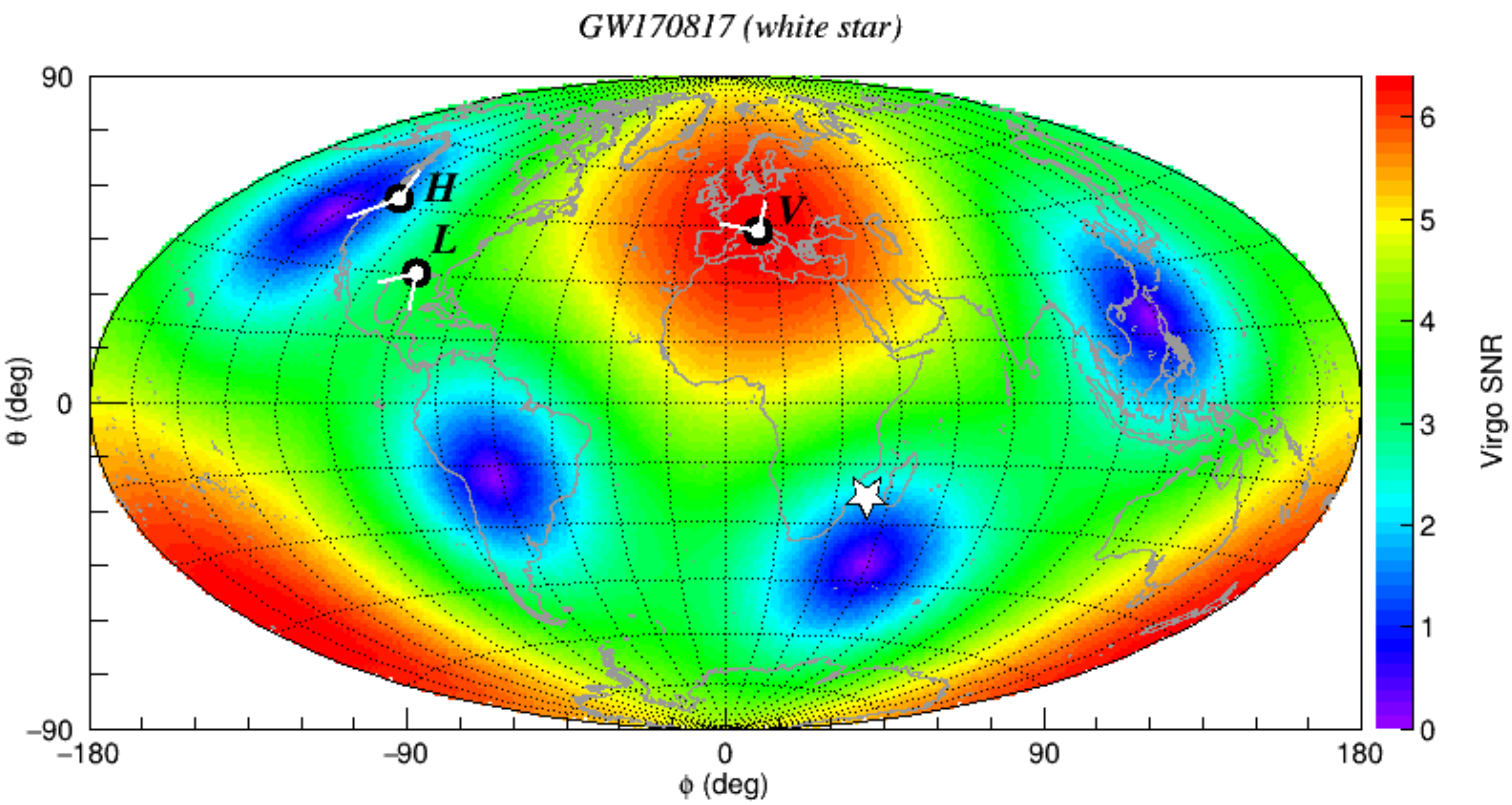
GRB170817A : short gamma-ray burst

AT 2017gfo : optical transient

KN170817 : kilonova

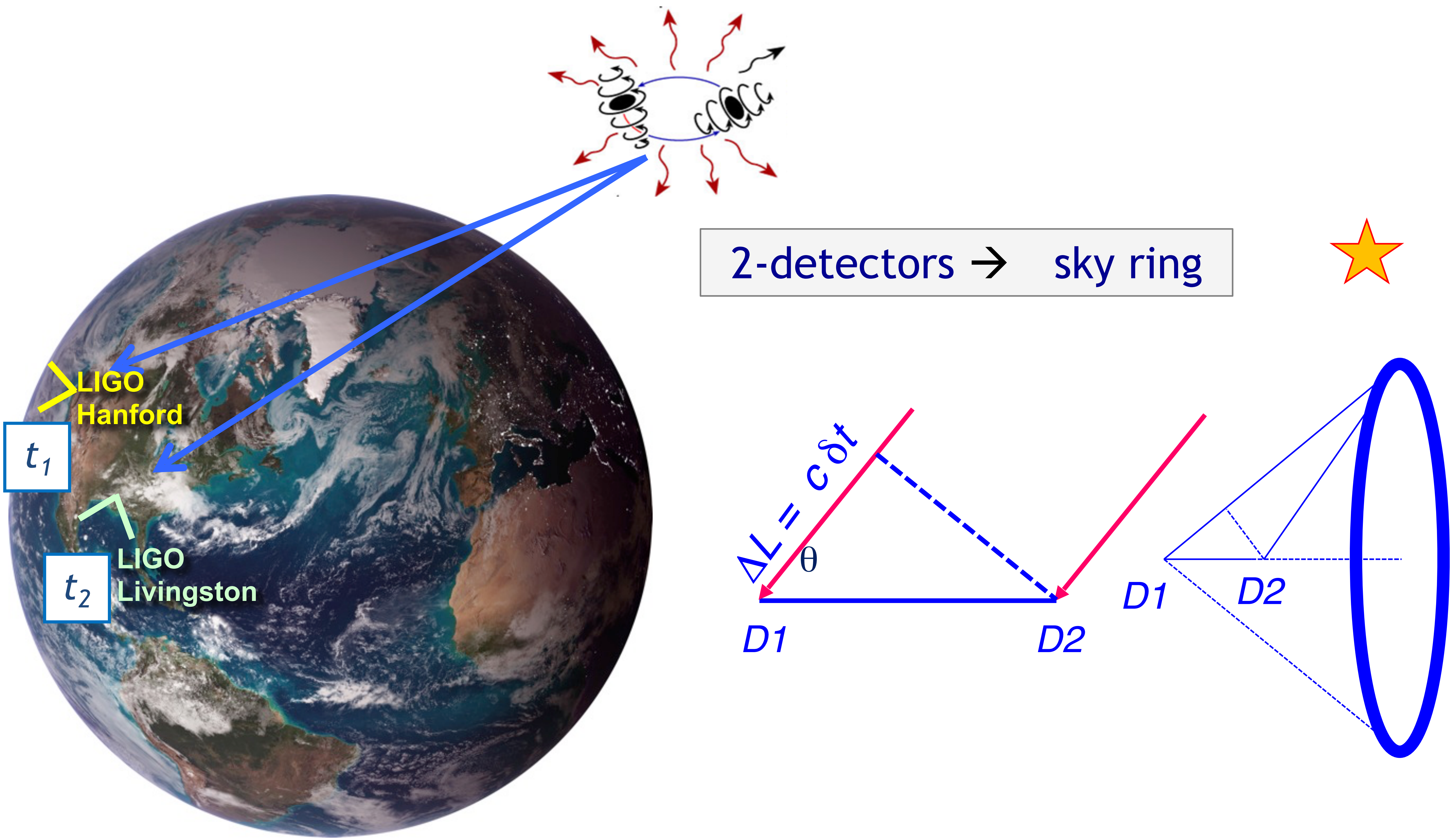


Virgo only sky sensitivity



Source localization by 2 gravitational waves detectors

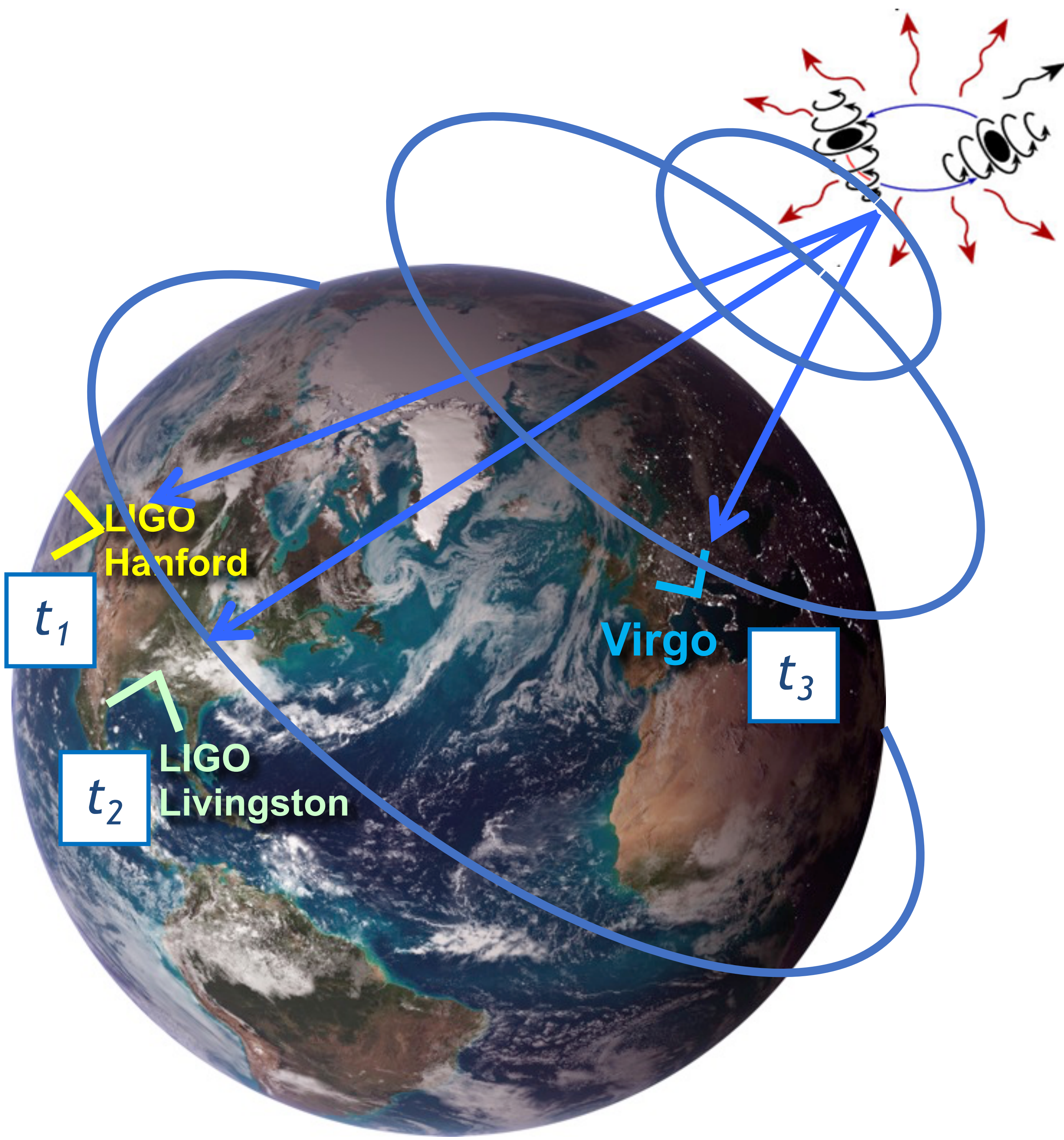
A single detector is unable to localize the source sky position.



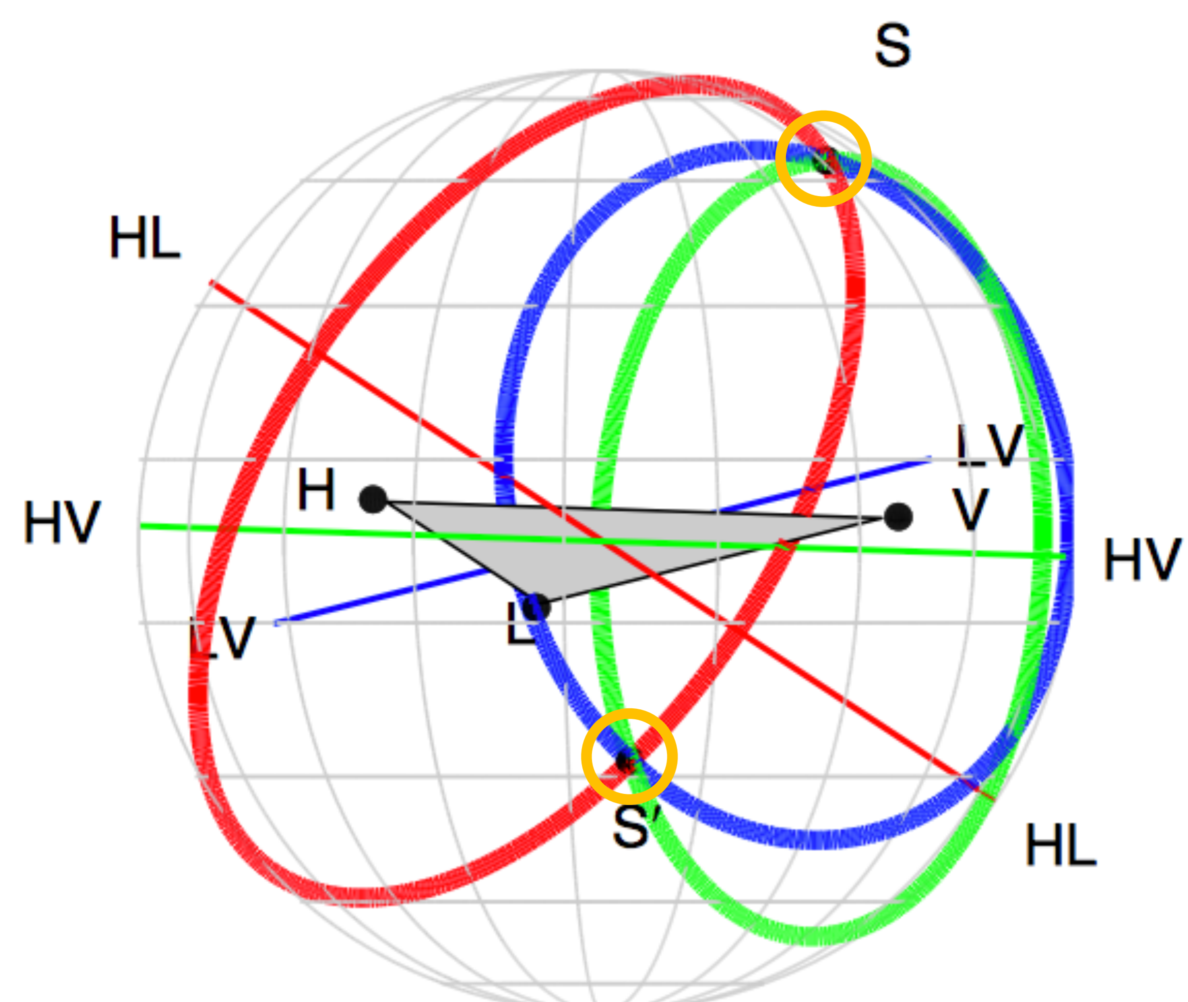
Source **sky localization** using two interferometers **is not effective**
Uncertainties account to **hundreds of square degrees**

Source localization by 3 gravitational waves detectors

*With **VIRGO** ON-LINE …*



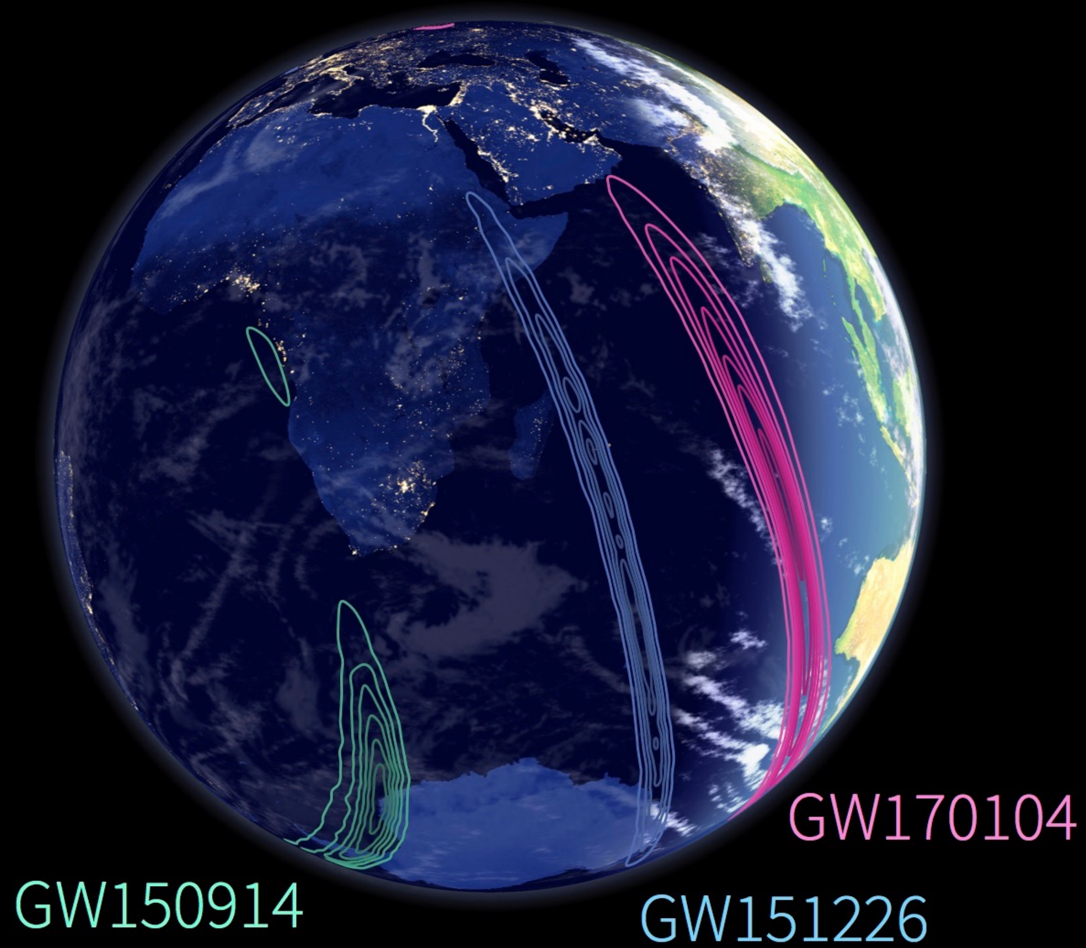
Coherent Detector Network



Uncertainties account to **tens of square degrees**

3-detector network: *LIGO* (2 in USA) & *Virgo* (1 in Cascina, Pisa)

Localisation areas projected over the Earth surface



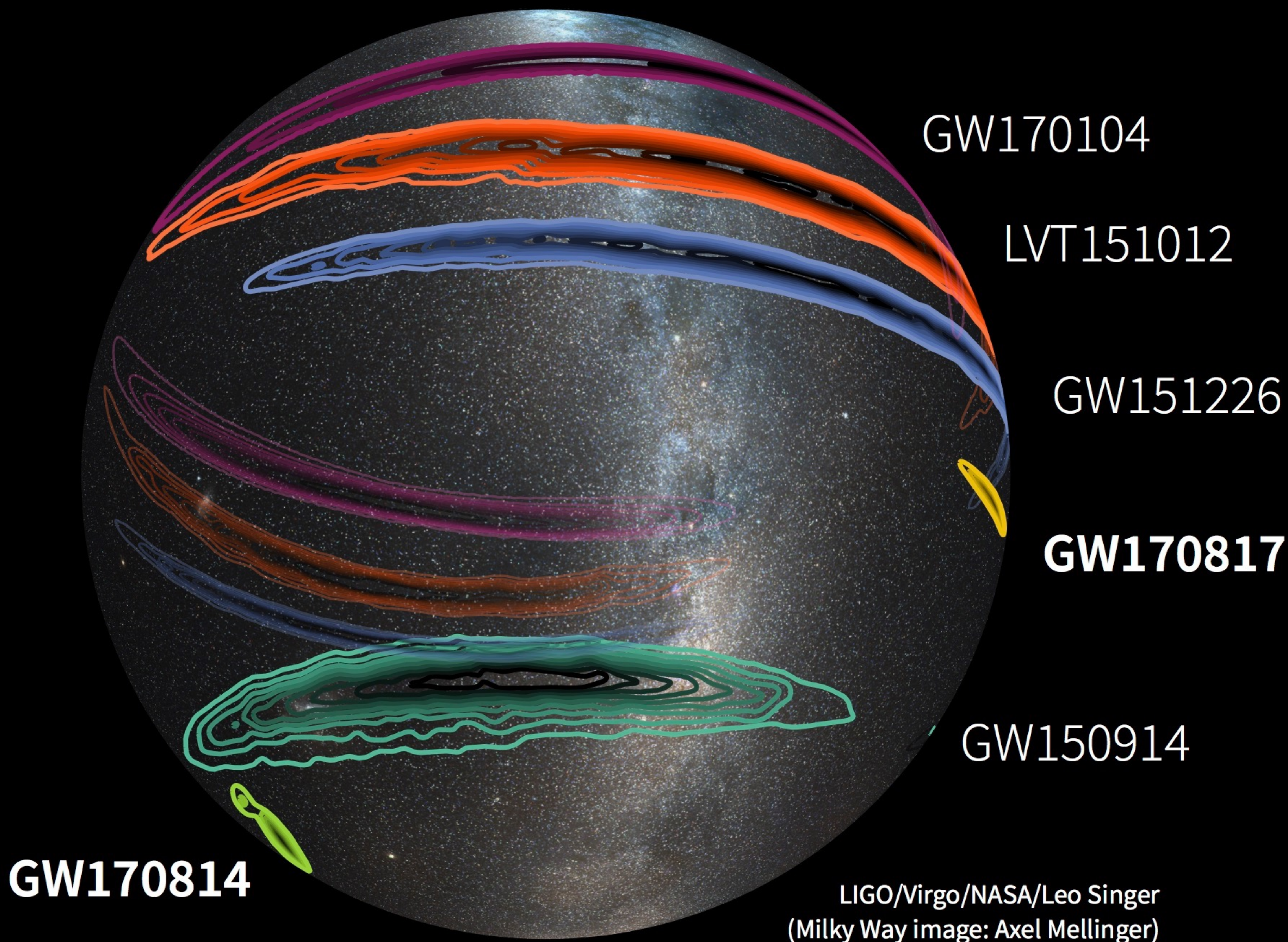
Previous sources detected with LIGO only

LIGO + Virgo

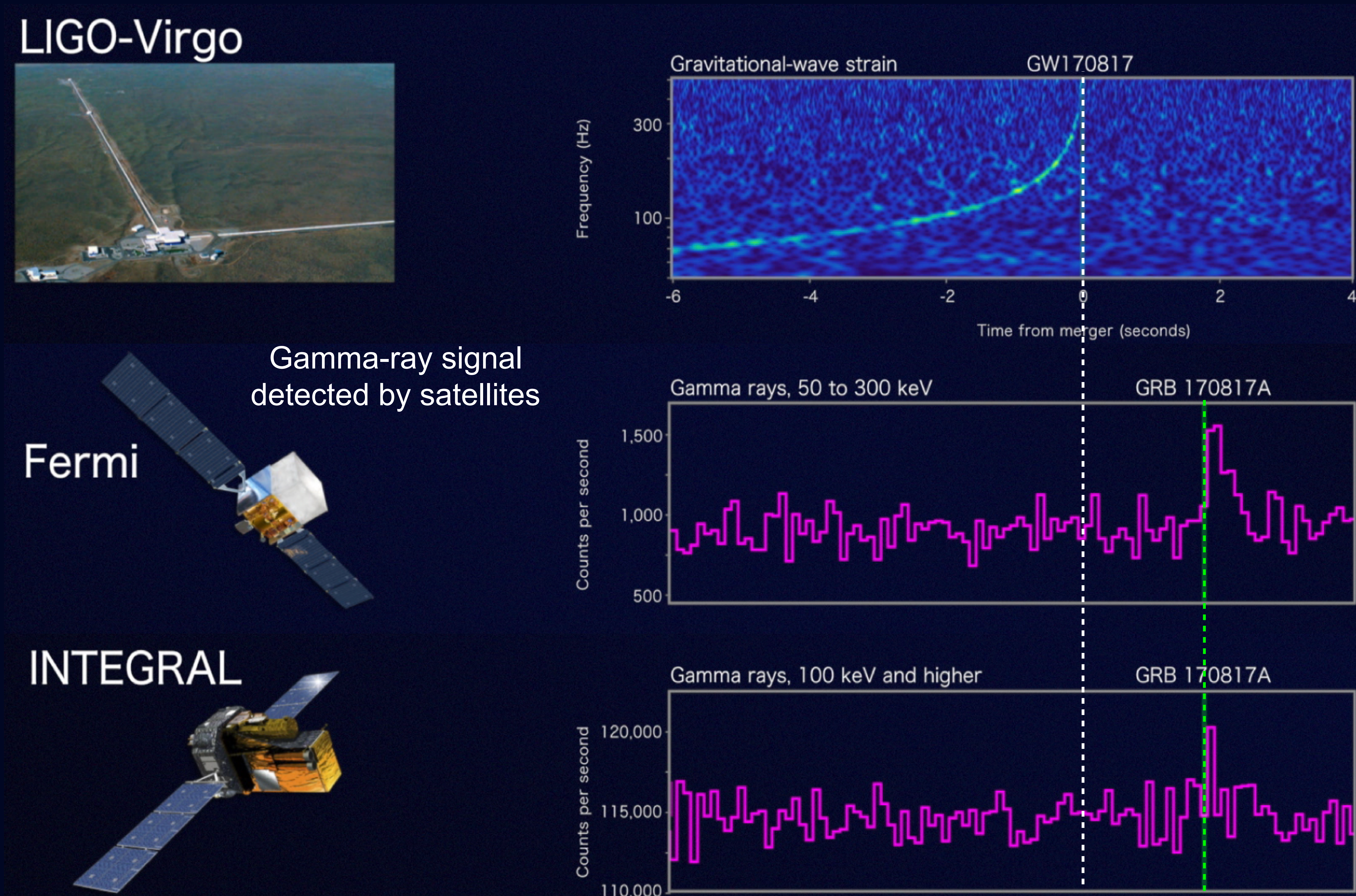
More precise localisation (28 square degrees) in Earth southern hemisphere

Today, best localised event: **S190814bv** (August 14 2019) in 5 deg^2 at 50% & in 23 deg^2 at 90%

3-detector network: *LIGO* (2 in USA) & *Virgo* (1 in Cascina, Pisa)



First detection of electromagnetic counterpart as a short GRB



Time delay: 1.7 seconds

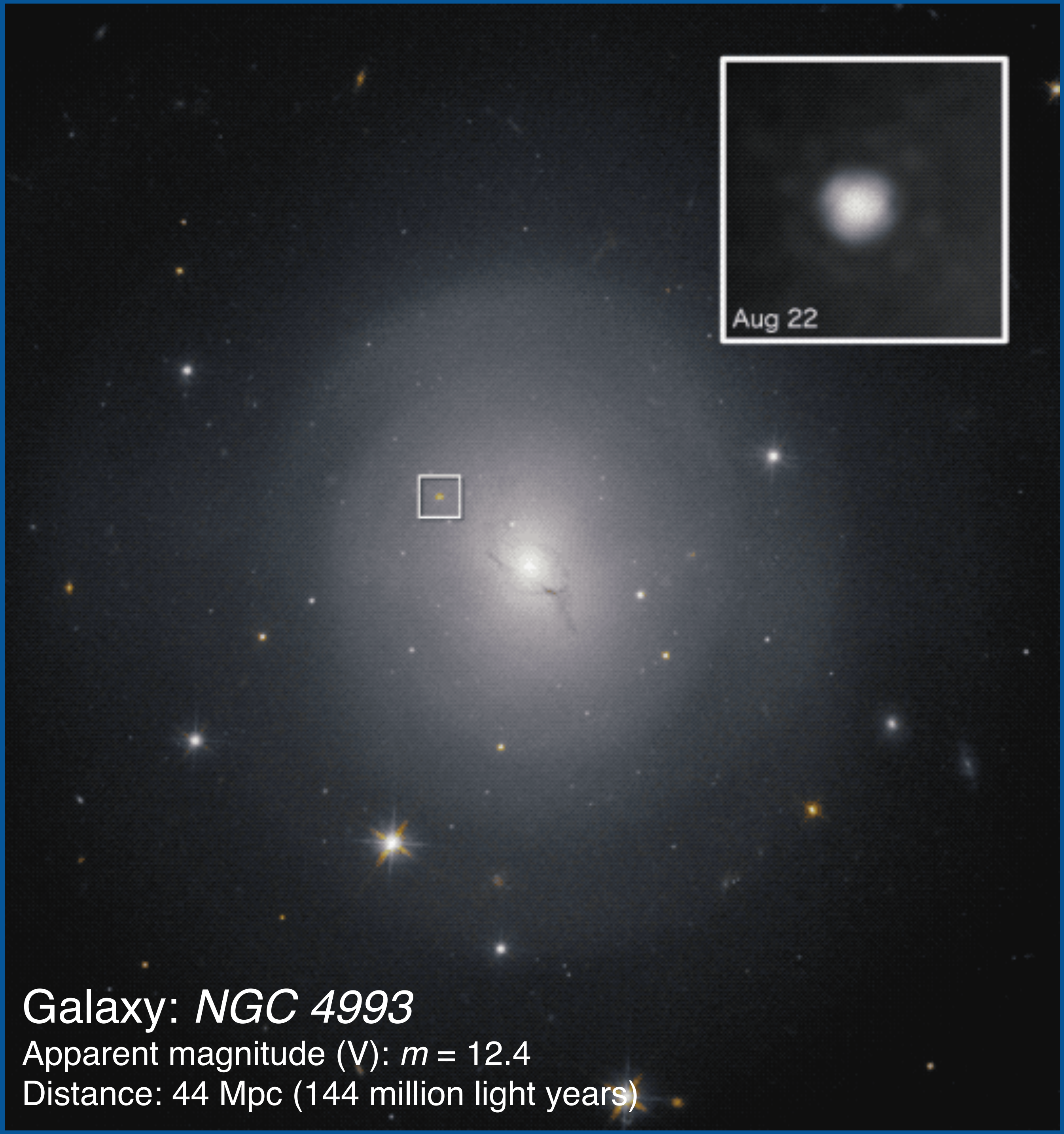
Detection & localisation of optical/IR transient & identification of host galaxy

- More than 70 groups observed the field with optical/IR telescopes

Optical/IR identification of galaxy that hosted BNS merger

See video: https://www.ligo.caltech.edu/video/ligo20171016v7

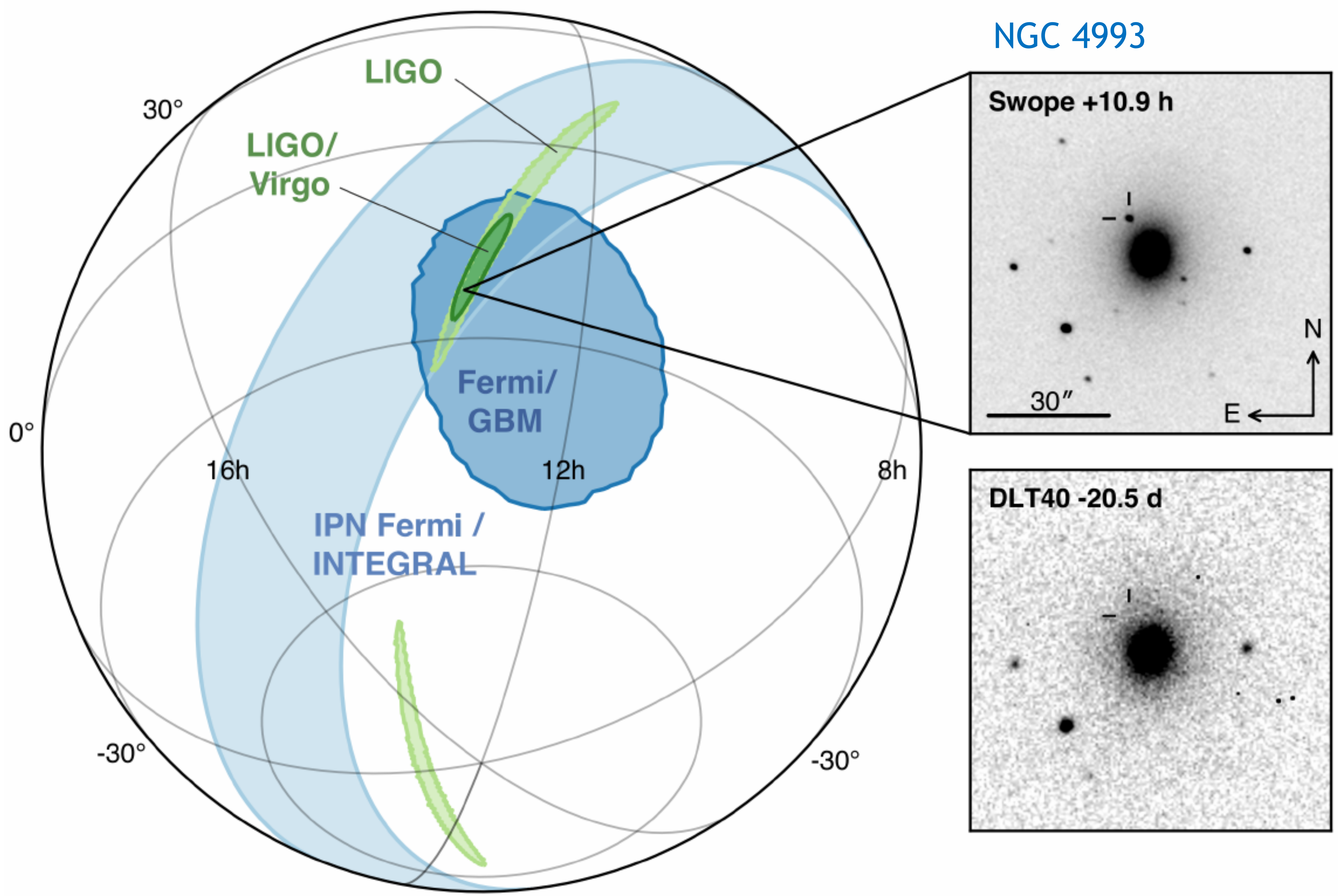
Optical/IR identification of galaxy that hosted BNS merger



Galaxy: *NGC 4993*
Apparent magnitude (V): $m = 12.4$
Distance: 44 Mpc (144 million light years)

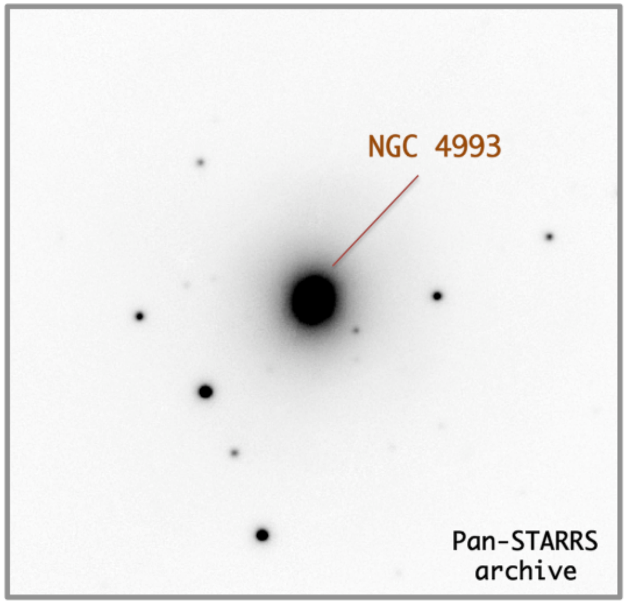
Optical/IR identification of galaxy that hosted BNS merger

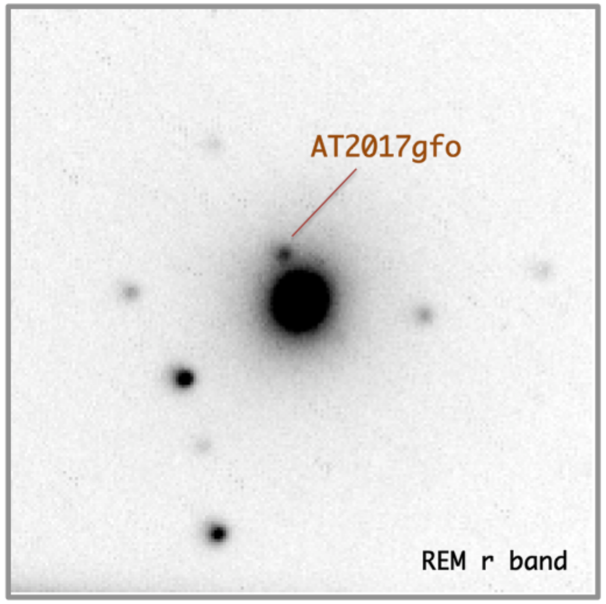
OPTICAL counterpart detection ~ 11 hours after GW trigger

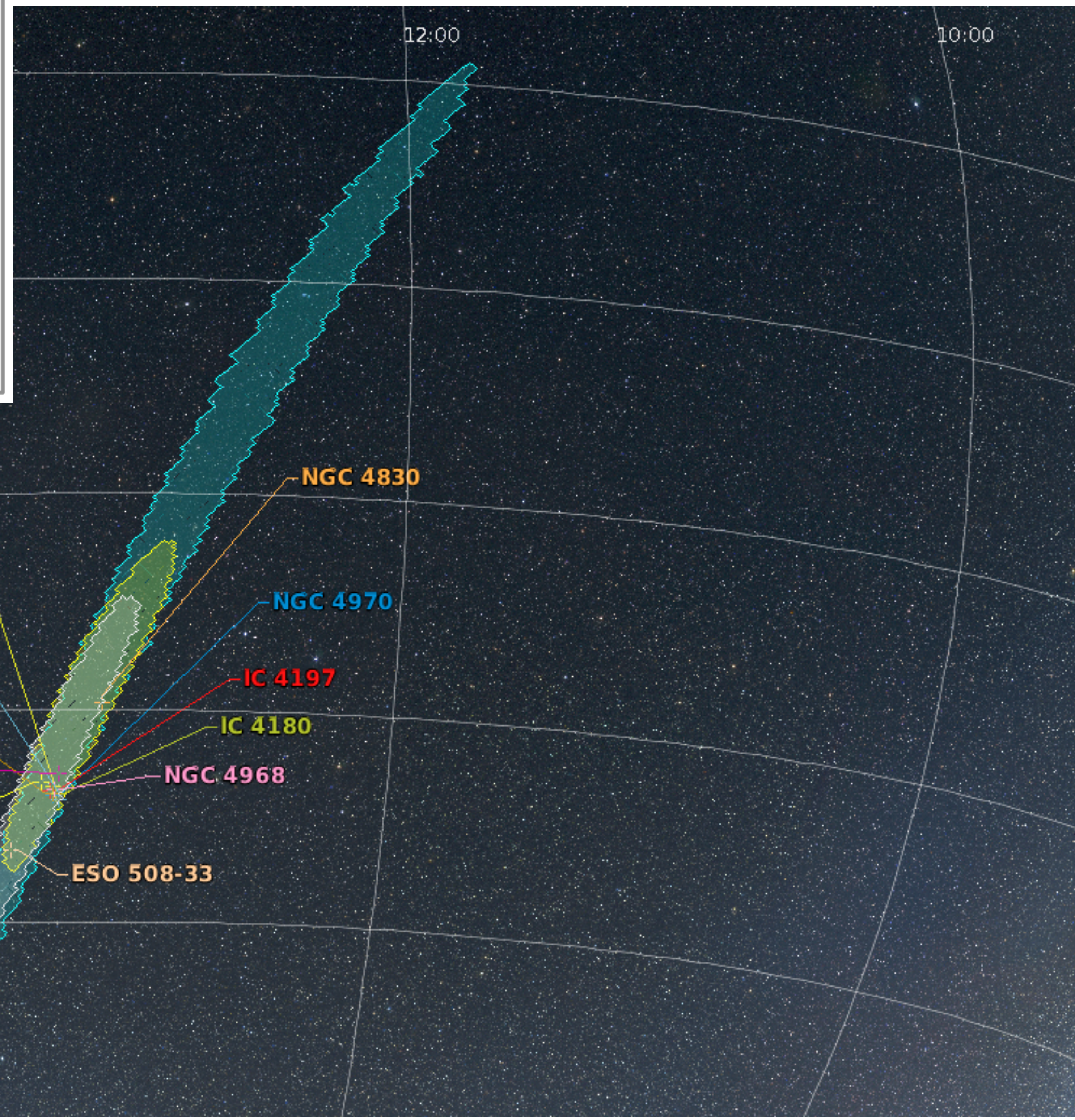


GRAWITA: GRAvitational Wave Inaf TeAm

Optical/IR identification of galaxy that hosted BNS merger







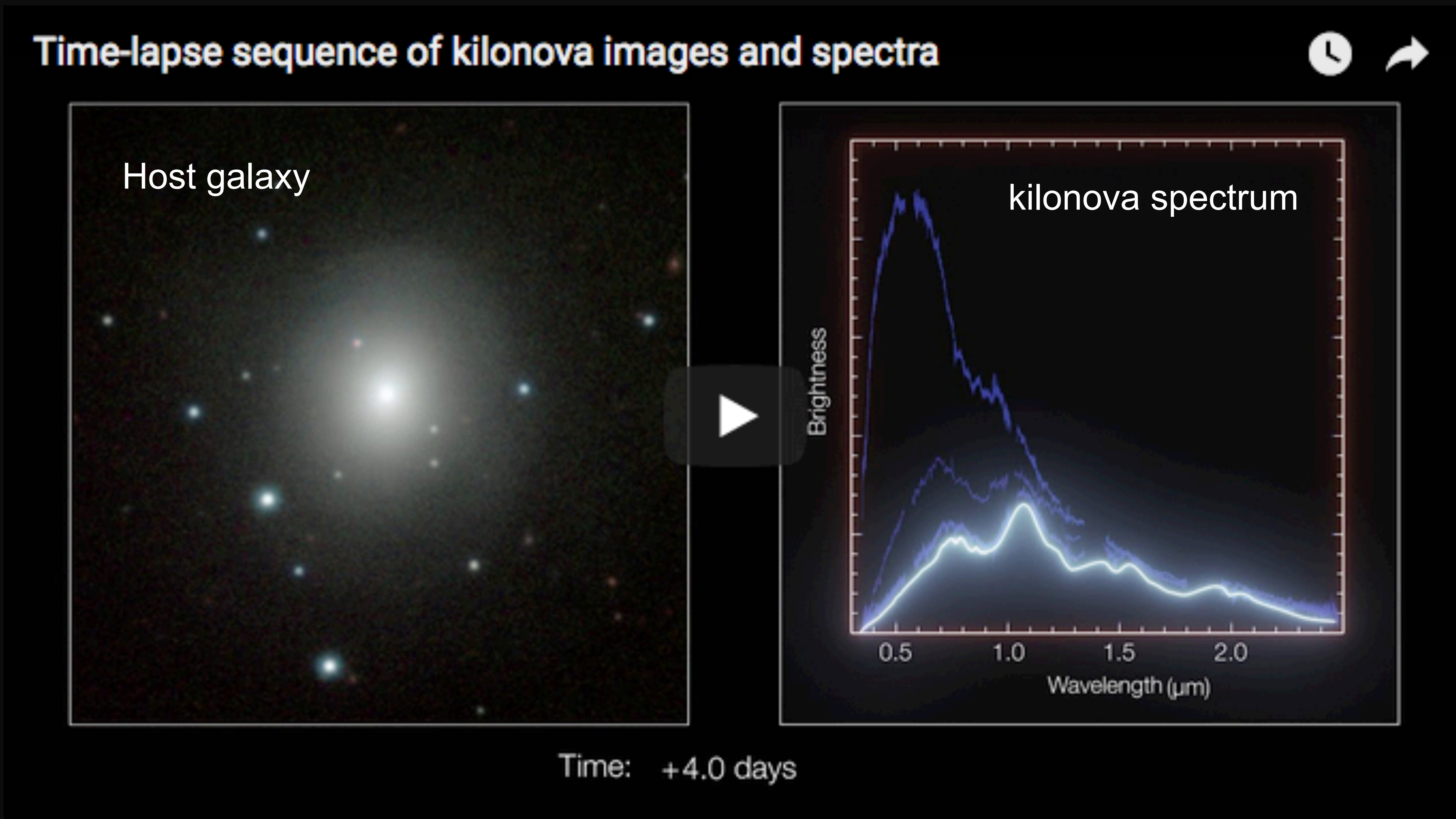
GRAWITA: REM observations
~ 13 hours after GW trigger

Rapid Eye Mount (REM) @ ESO La Silla (altitude: 2375 m)
Primary mirror: 60 cm
Secondary mirror: 23 cm

GraWITA

First evidence of *kilonova* & *r-process nucleosynthesis* in BNS

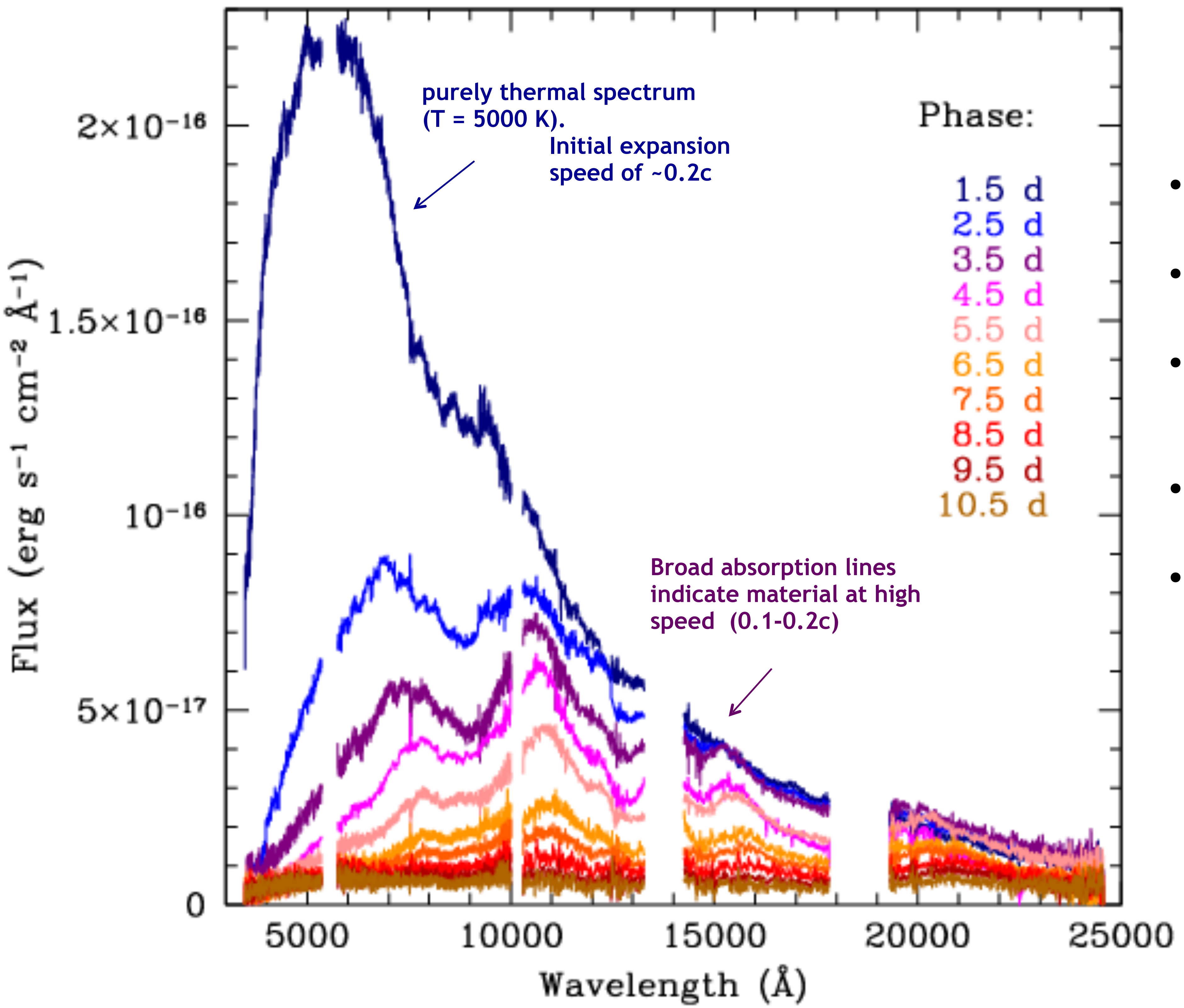
Time evolution of images and spectra



See video: https://www.eso.org/public/videos/eso1733e/

First evidence of *kilonova* & *r-process nucleosynthesis* in BNS

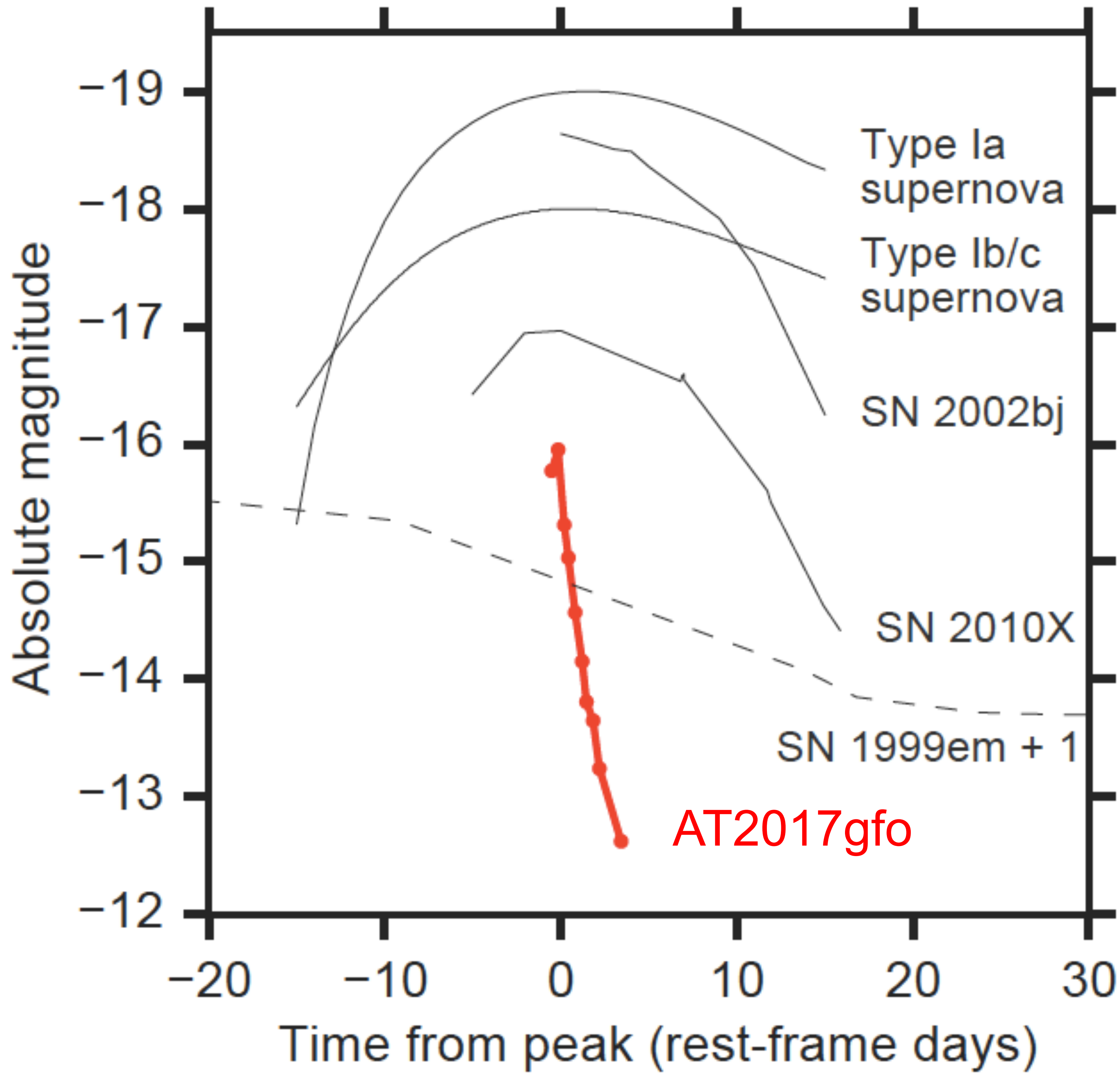
ESO VLT X-Shooter spectral sequence of AT2017gfo



- In a couple of days, peak shifts to near infrared
- Broad spectral features appear
- These are completely different from those known for all SN types
- First confirmation of *kilonova* model
- Also supported by sGRB detection

Light curve very fast, different from supernovae

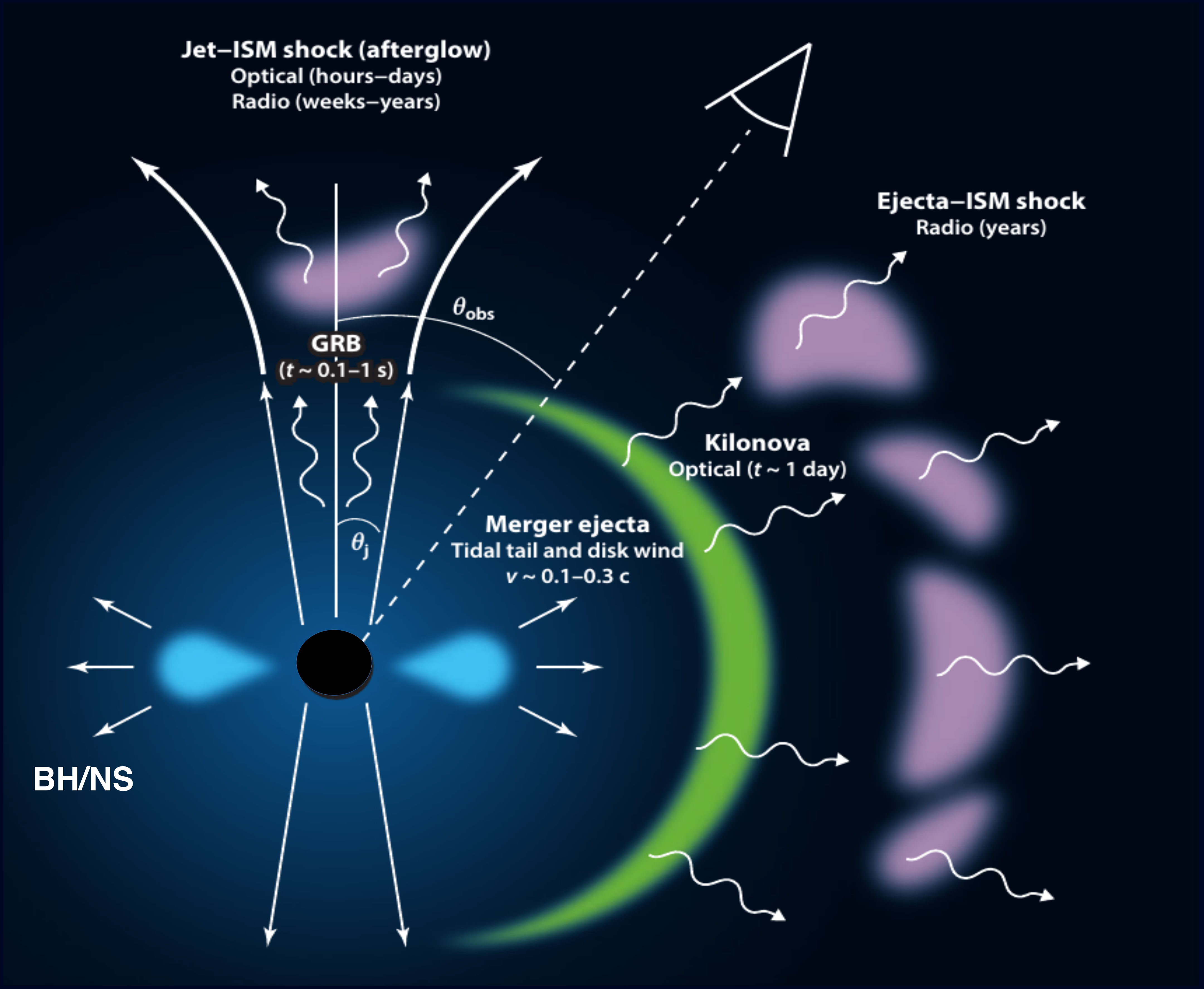
AT2017gfo evolves much more rapidly than any supernova



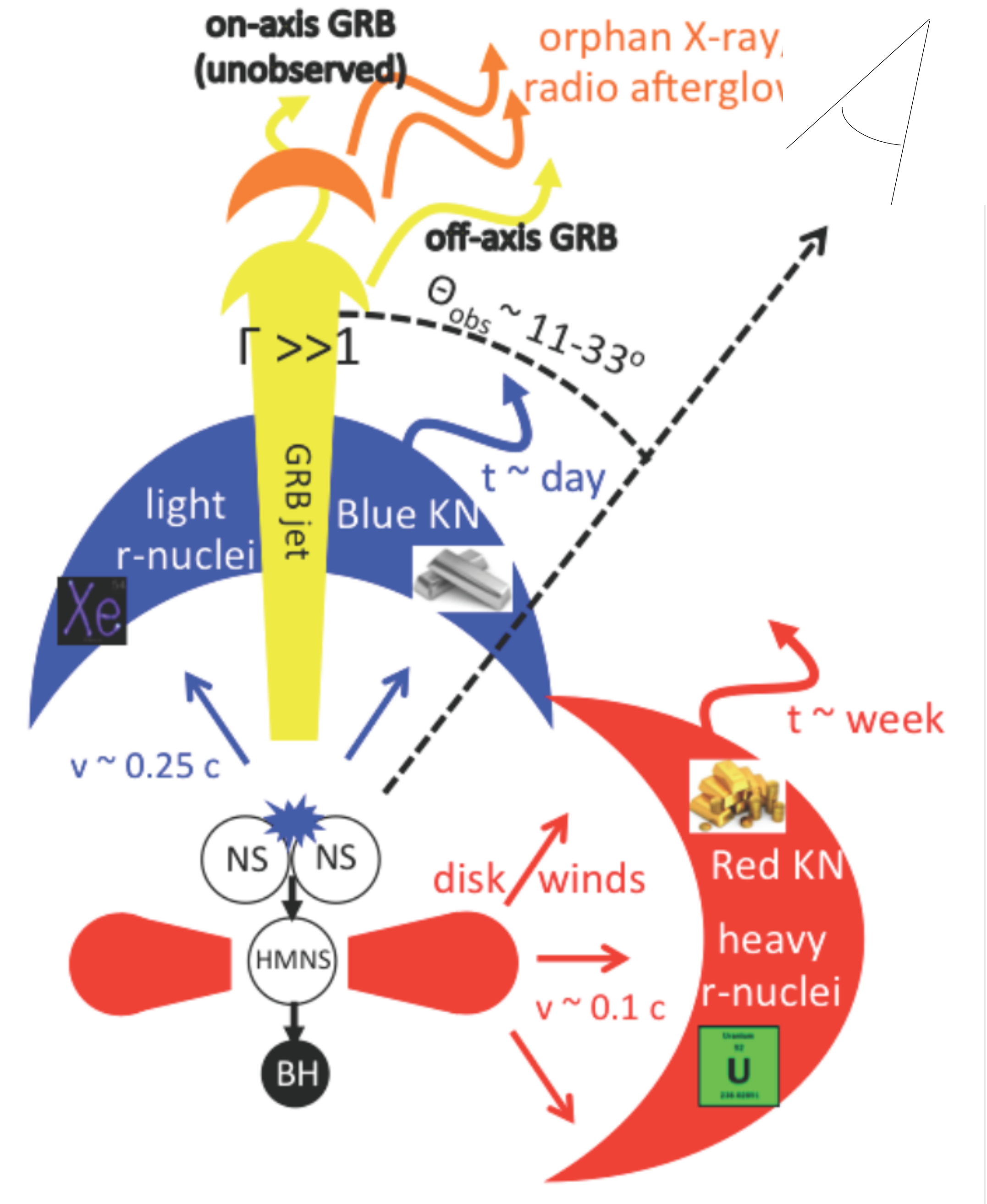
Model of what happened: *Binary Neutron Star* (BNS) merger

See video: https://www.ligo.caltech.edu/video/ligo20171016v2

BNS merger: the expected facts



The kilonova components



Blue

Dynamical ejecta

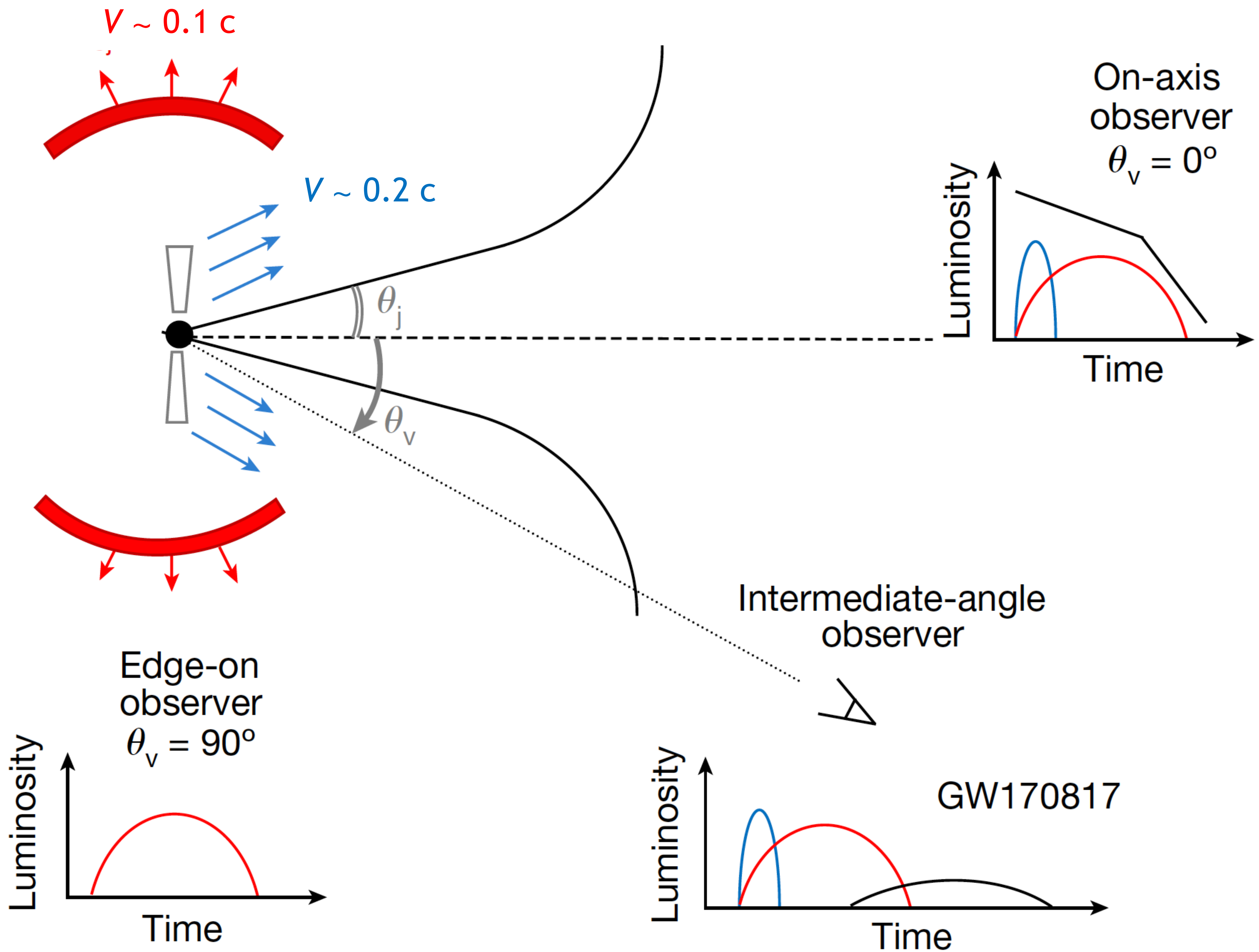
- ➢ Peaks at ~ 1 day after the merger
- ➢ Factory of light elements
- ➢ $v \sim 0.2 - 0.3\, c$

Red

Disk Winds

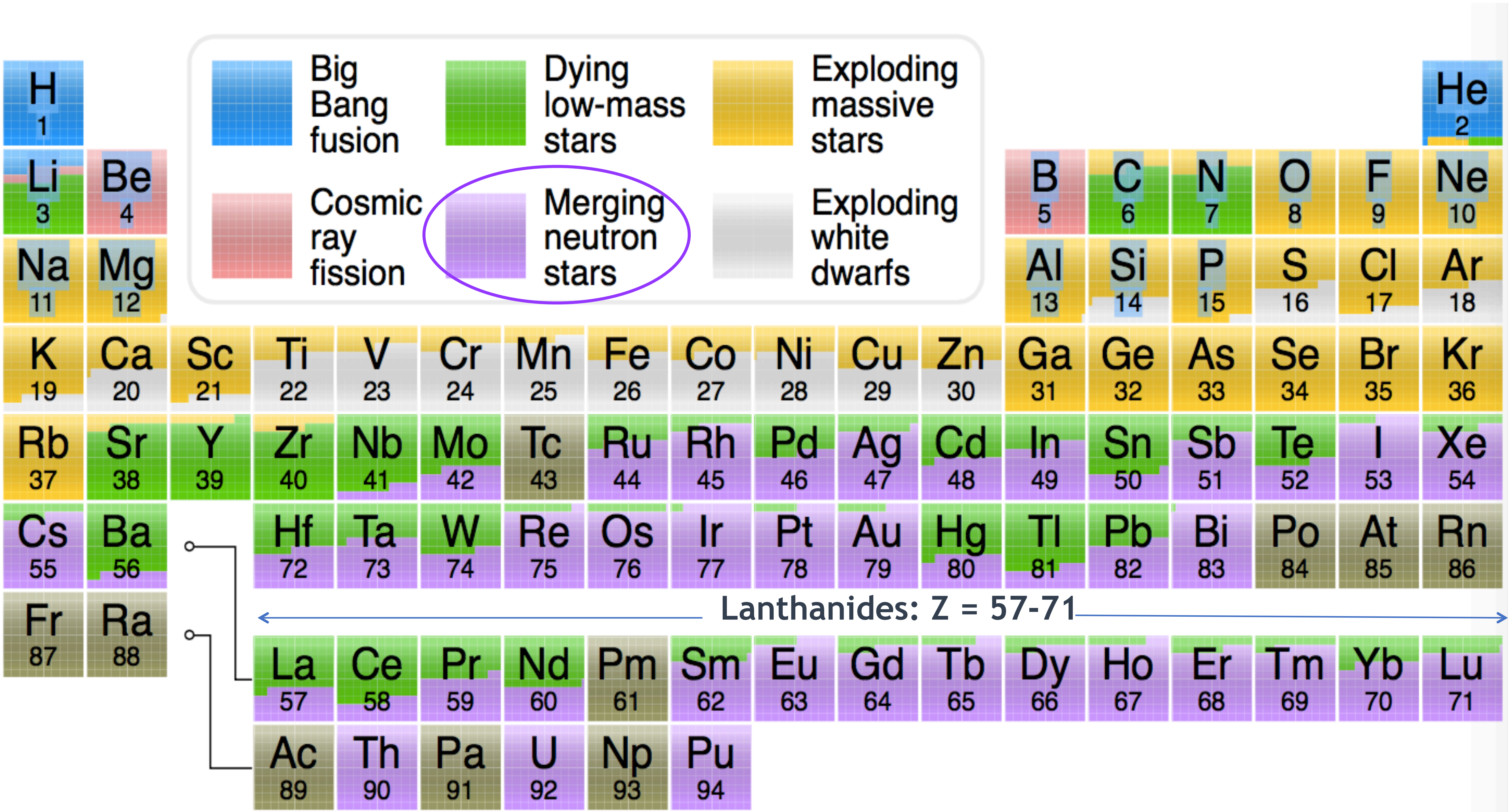
- ➢ Peaks at ~ 1 week after the merger
- ➢ Factory of heavy elements
- ➢ $v \sim 0.1\, c$

Geometry of GRB – kilonova system



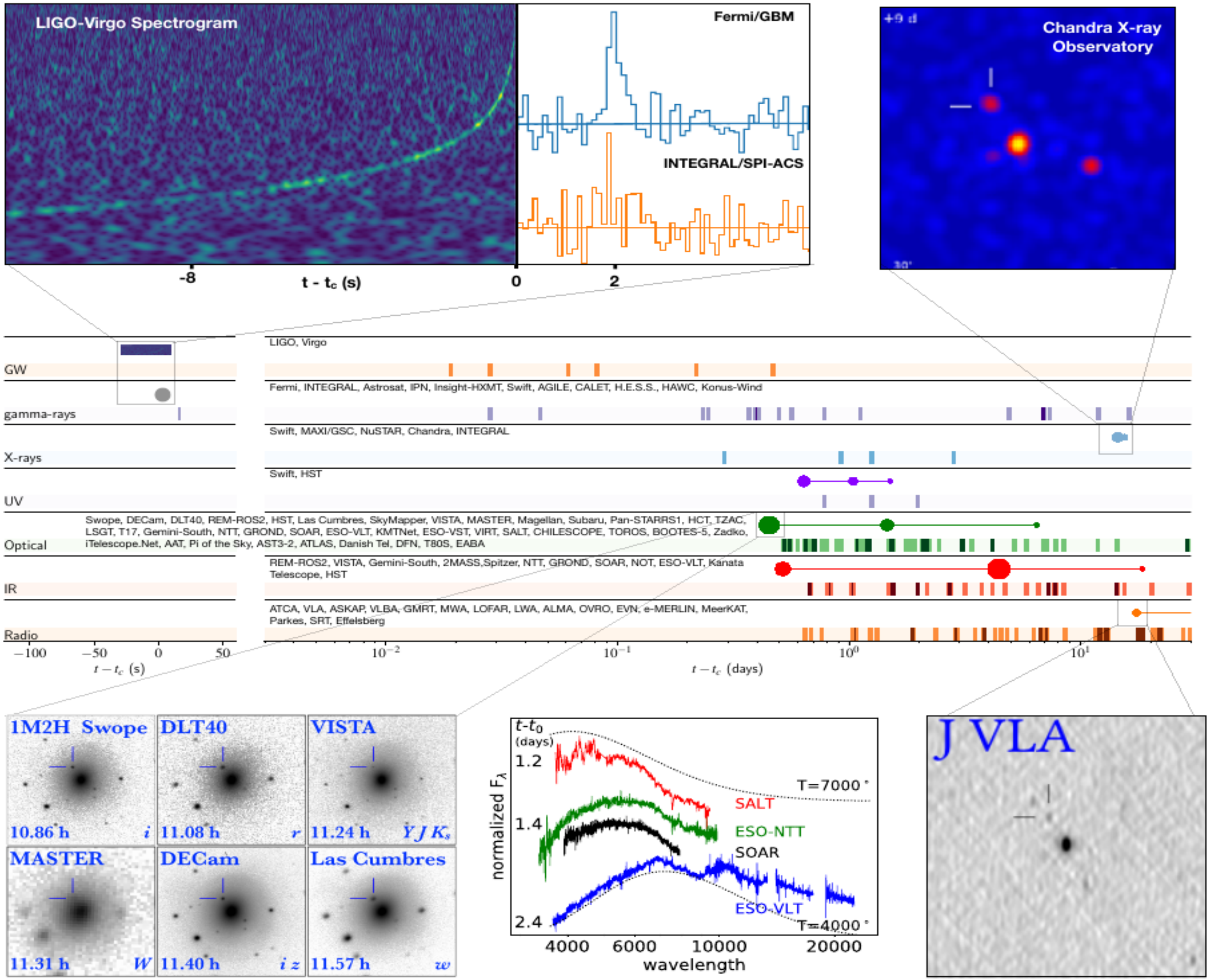
Summary: *Binary Neutron Star* (BNS) or NS-BH merger

Production of chemical elements in the universe & by *kilonova*



- More realistic atomic models and opacities to use with radiative transport codes
- Future work on identifying atomic species and measuring abundances

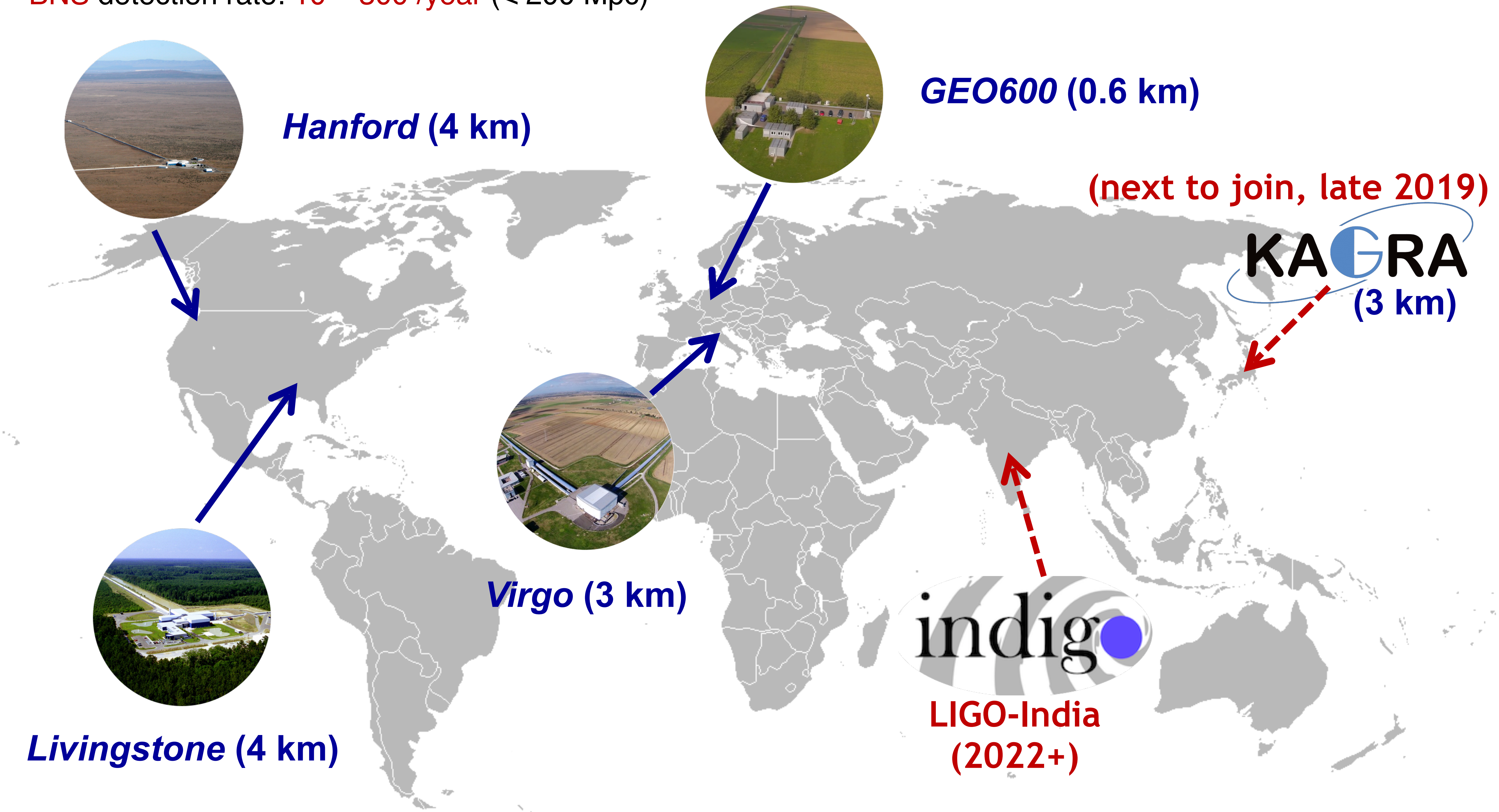
Summery: multi-messenger observations (but neutrinos have not been detected)



Abbott et al. 2017

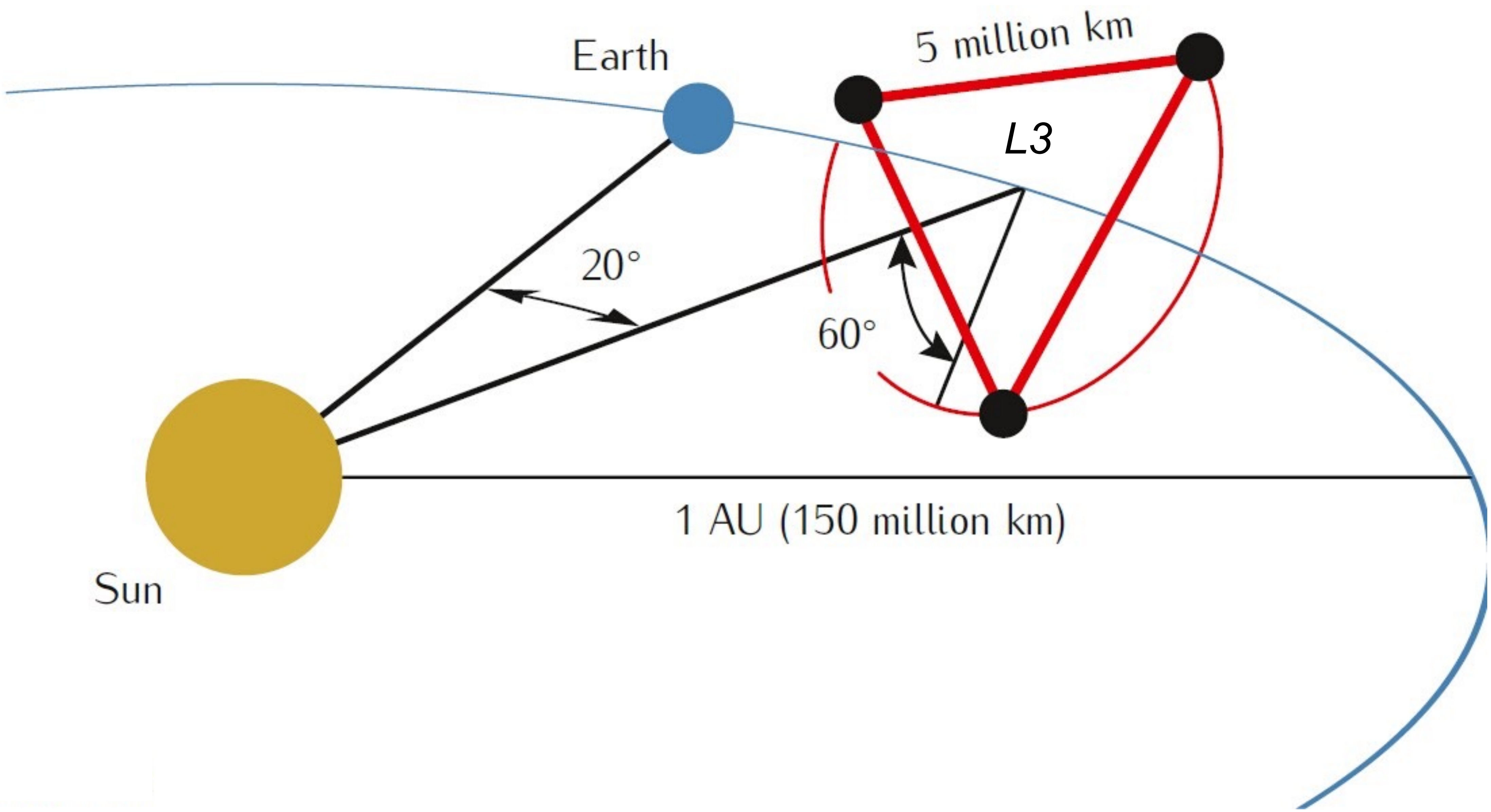
Detectors present and future

- BBH detection rate: 50 – 500 /year (< 400 Mpc)
- BNS detection rate: 10 – 300 /year (< 200 Mpc)



Gravitational wave physics has large implications in our effort to unify *gravity* with *quantum physics*

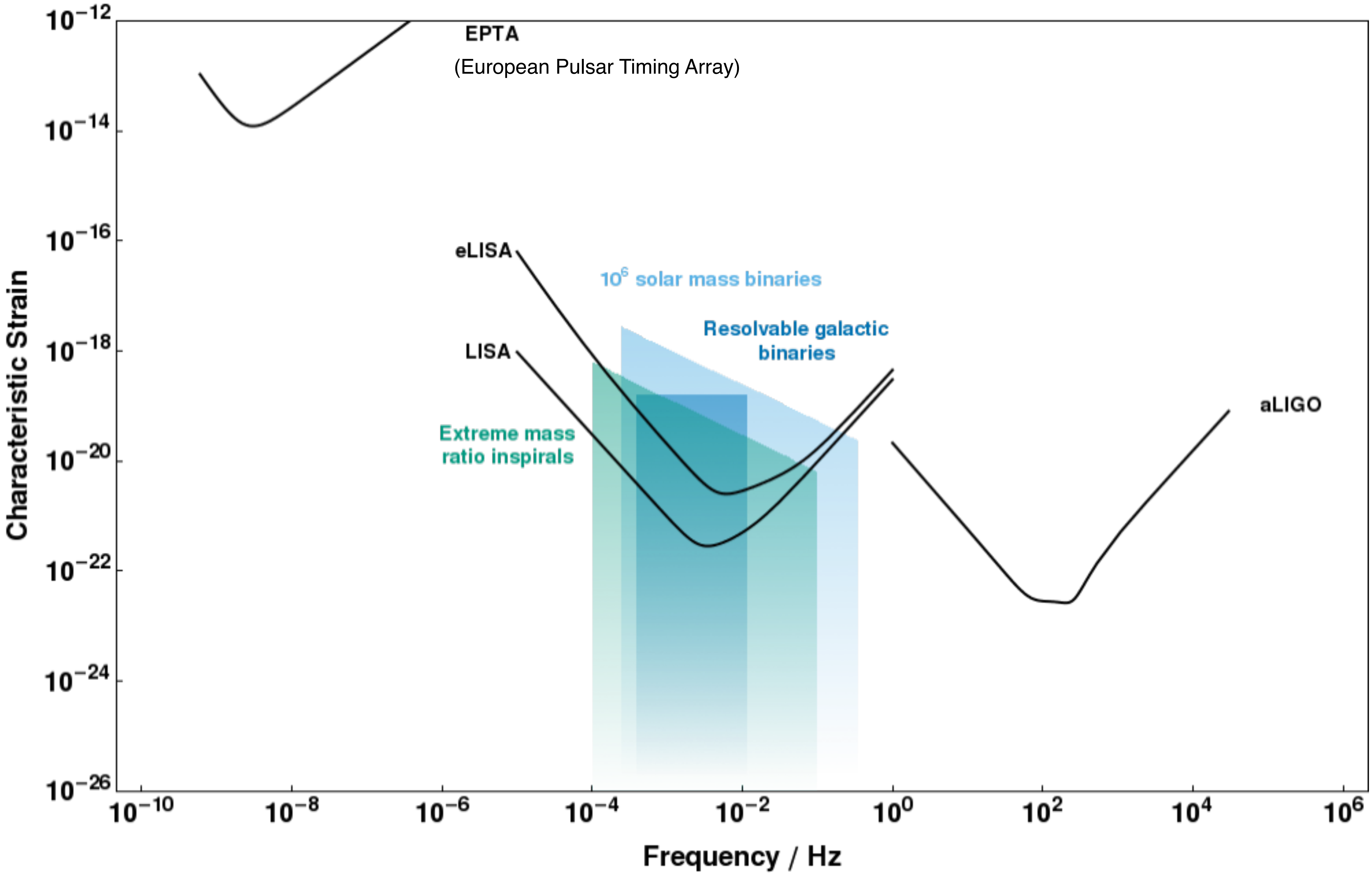
Future laboratories for gravitational waves from space: ESA mission in *L3* — Expected launch in 2034



https://www.elisascience.org

Future laboratories for gravitational waves from space:

evolved Laser Interferometer Space Antenna (eLISA)
Laser Interferometer Space Antenna (LISA)



Future observations of gravitational waves

The Gravitational Wave Spectrum