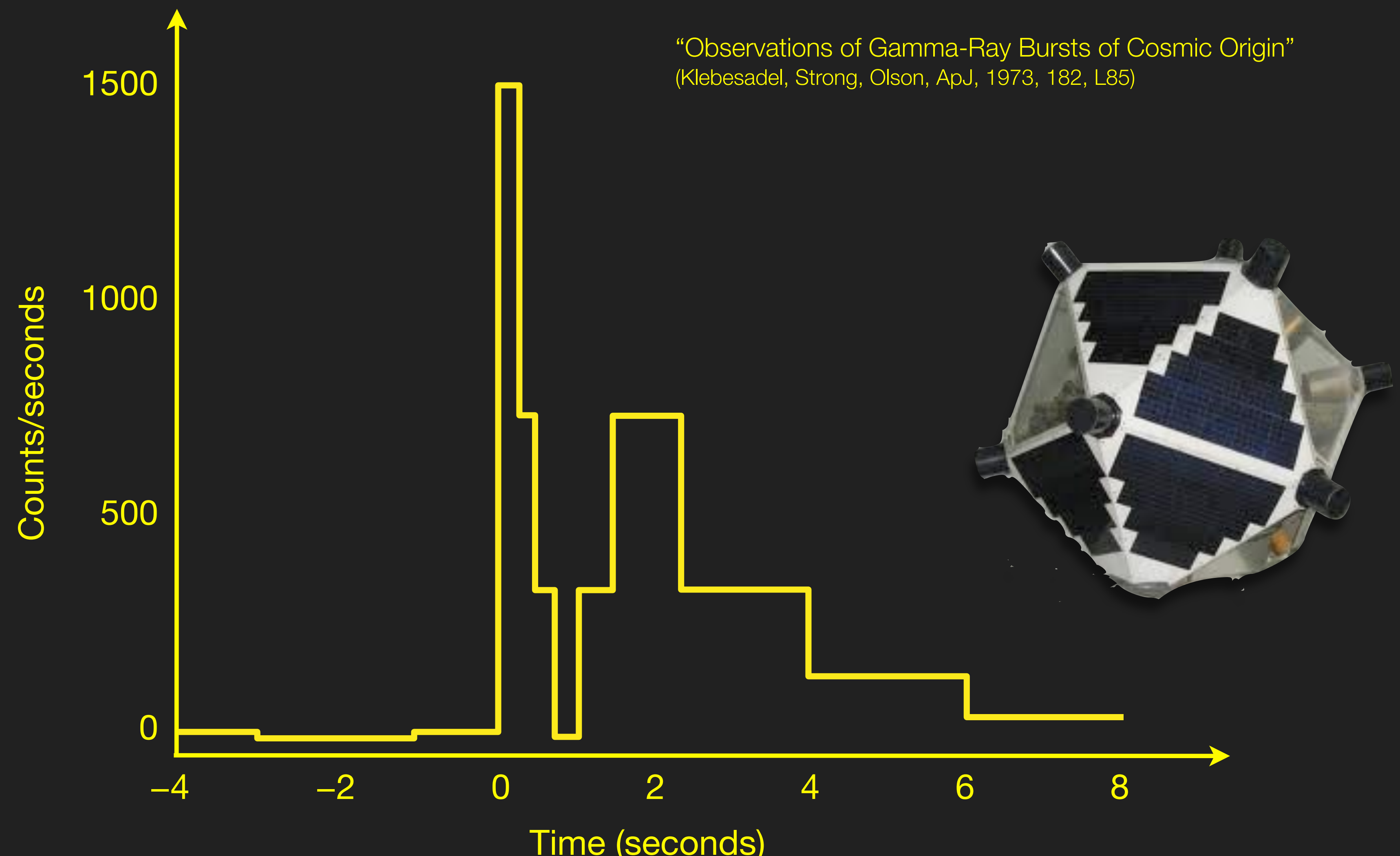
The most energetic explosions in the universe after the Big Bang: ***gamma-ray bursts***

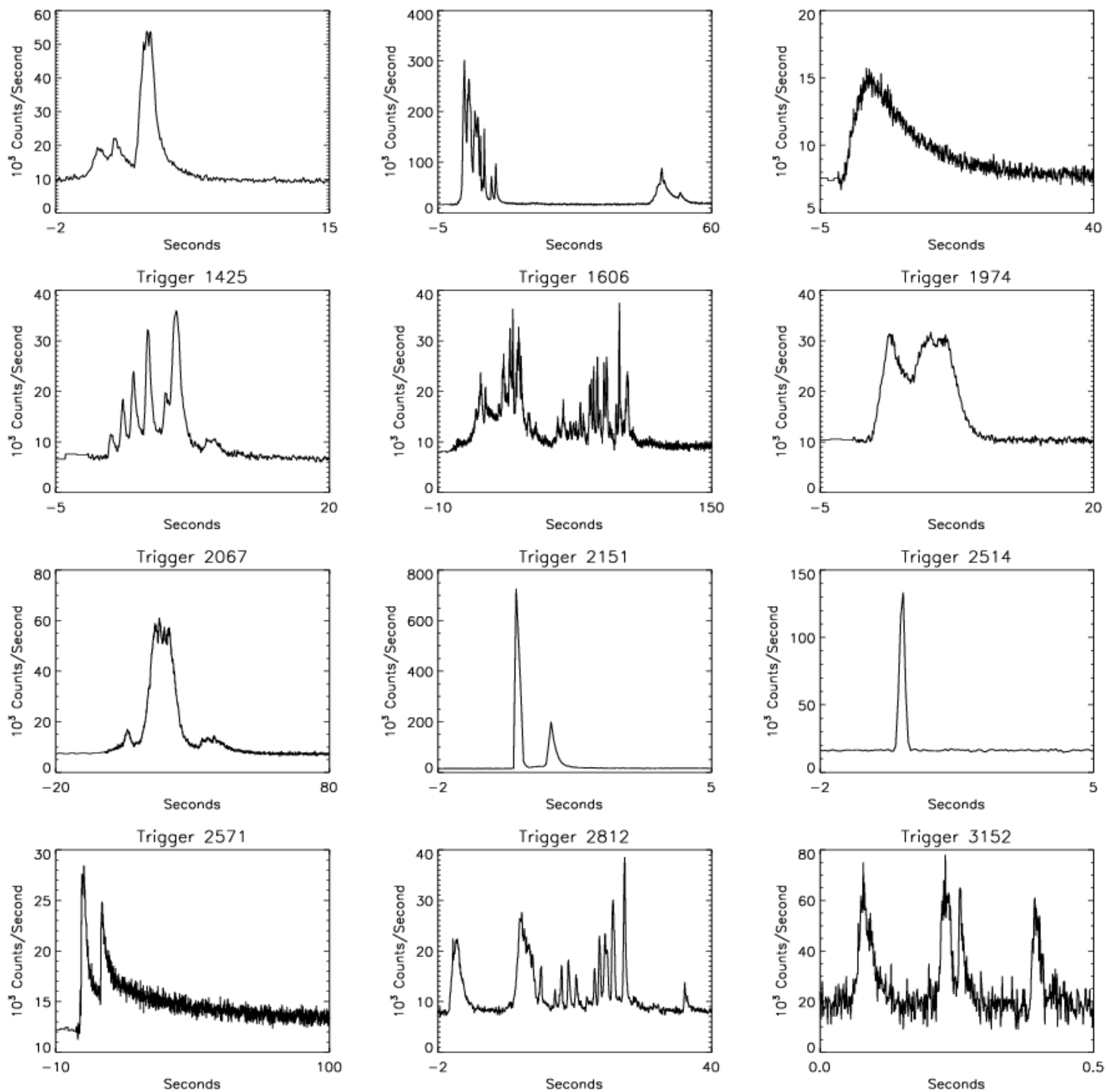
The **very first** gamma-ray burst

Detected on July 2 1967 (called: GRB 670702) by American satellite *Vela 4*



"Observations of Gamma-Ray Bursts of Cosmic Origin"
(Klebesadel, Strong, Olson, ApJ, 1973, 182, L85)

Duration of **prompt emission** of several gamma-ray bursts

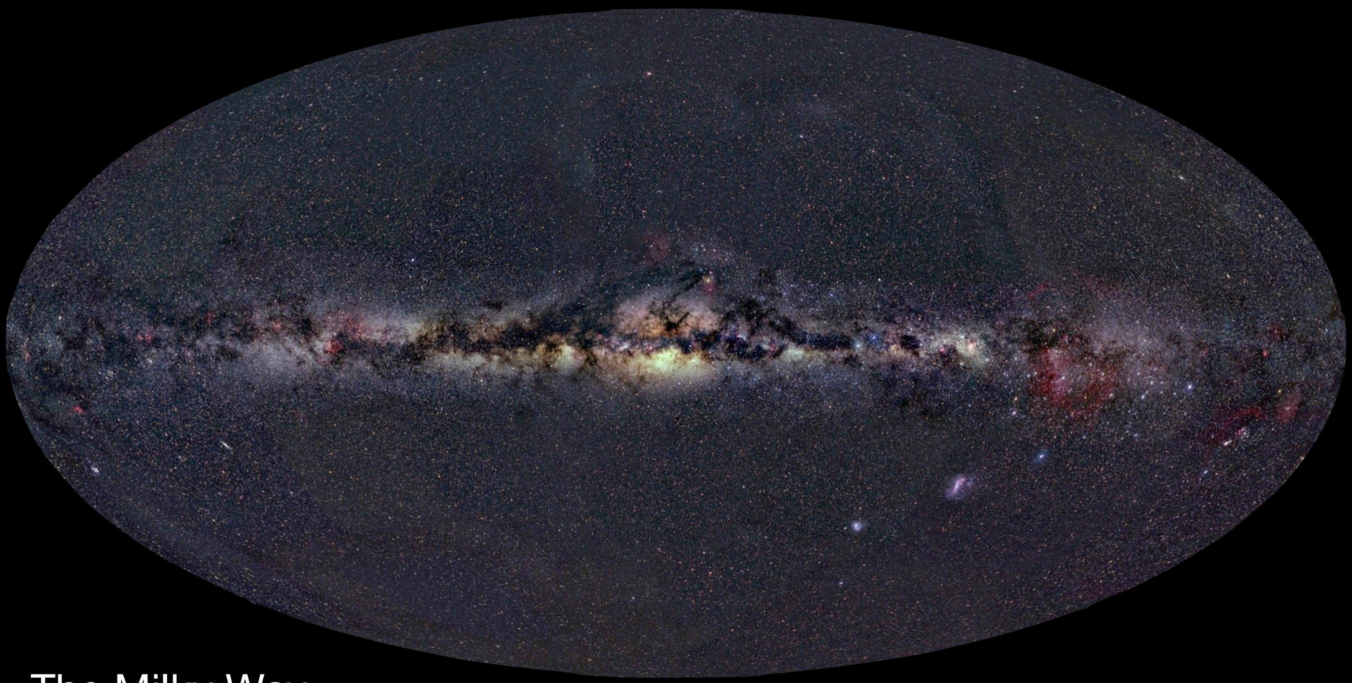


Photon counts per seconds

Duration of γ-ray emission (seconds)

Isotropically distributed in the sky

Thus GRBs can only be originating outside the Milky Way

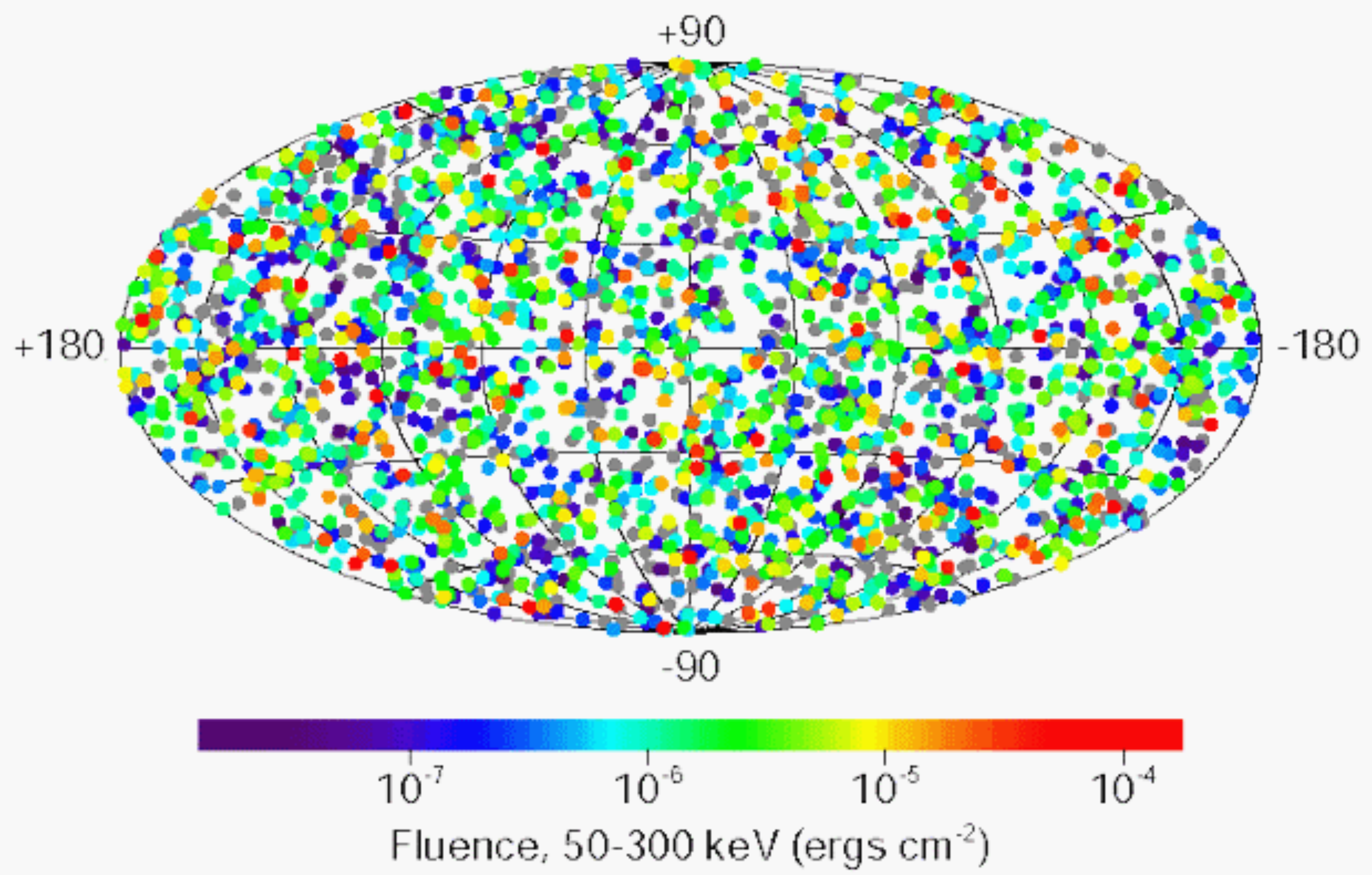


The Milky Way

Isotropically distributed in the sky

Thus GRBs can only be originating outside the Milky Way

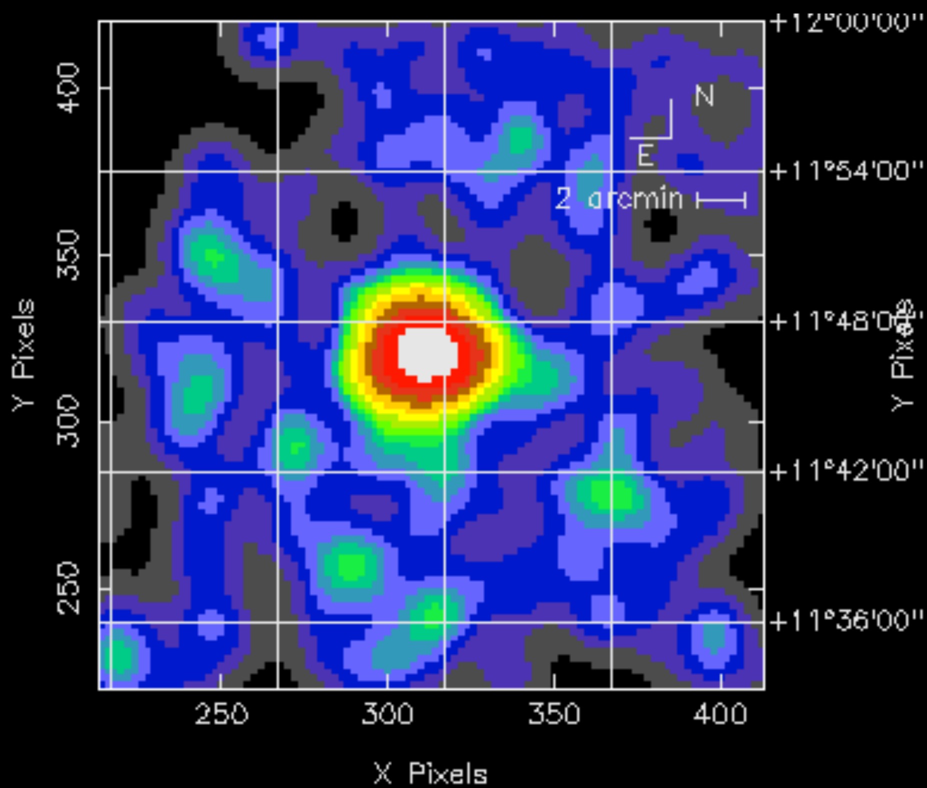
2704 gamma-ray bursts detected by space telescope *Compton Gamma Ray Observatory*
(years 1991-2000)



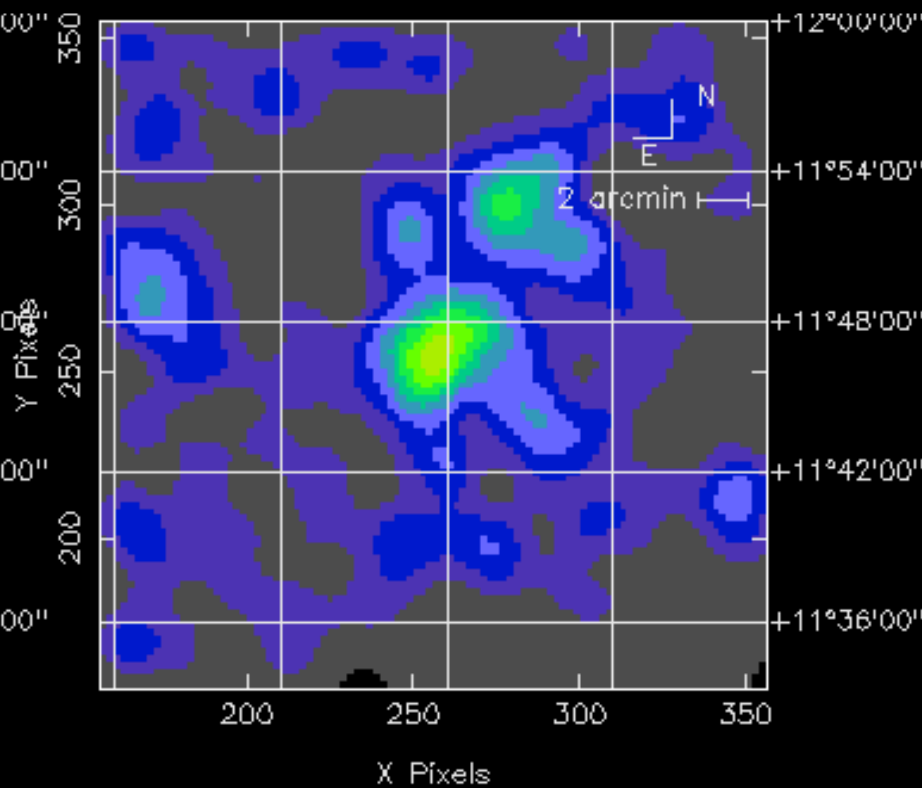
February 1997: the **first precise localisation**

(with arc-second precision)

X-ray emission of GRB 970228



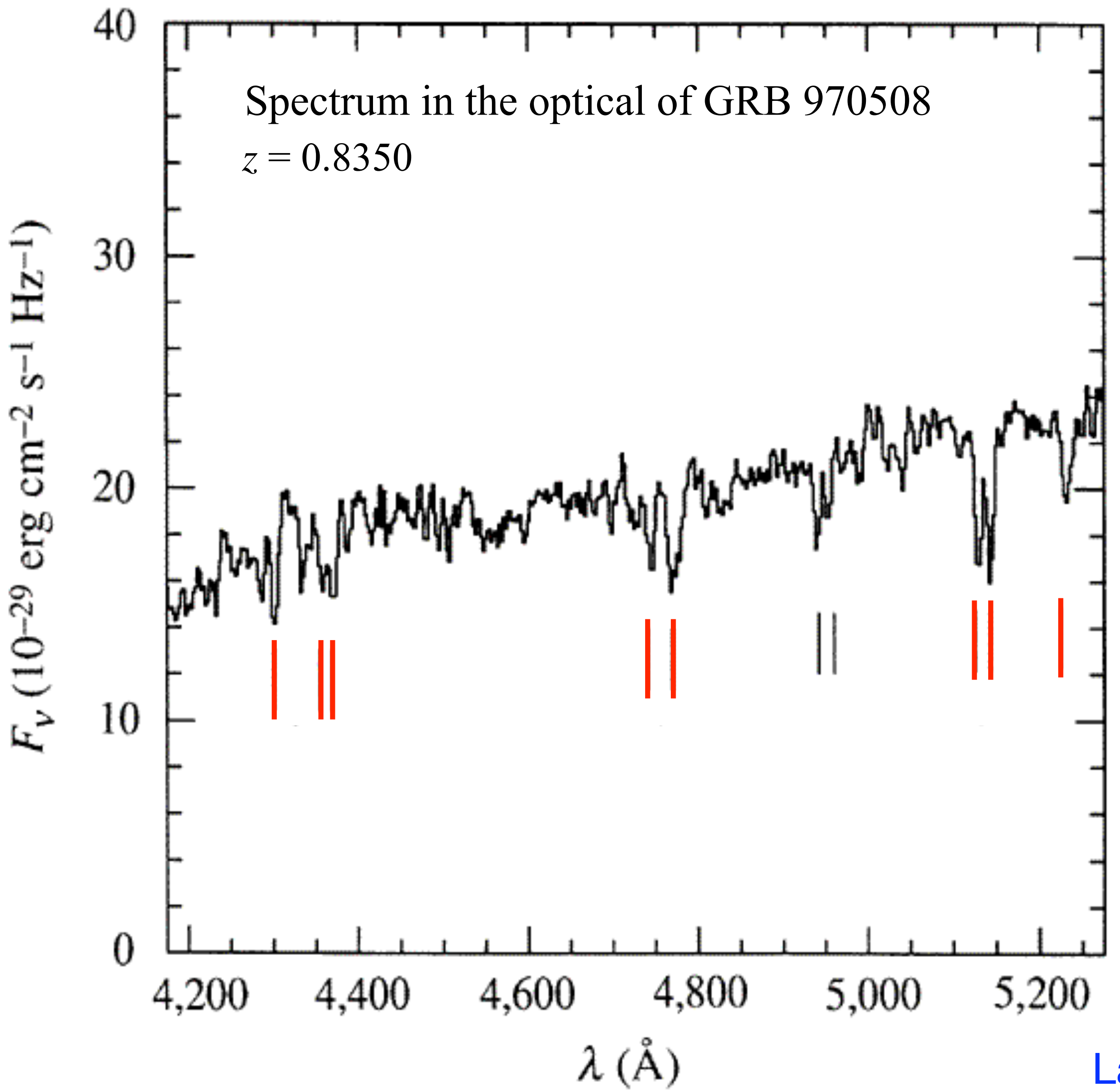
8 hours after γ-ray emission



3 days after γ-ray emission

May 1997: **first distance** determined for a gamma-ray burst

Measured from Doppler shift of wavelength (redshift: z)



Ion	λ_r(Å)	λ_o(Å)
FeII-2344	2344.21	4301.63
FeII-2374	2374.46	4357.14
FeII-2382	2382.76	4372.37
MnII-2576	2576.88	4728.57
FeII-2586	2586.65	4746.50
MnII-2594	2594.50	4760.91
FeII-2600	2600.17	4771.32
MnII-2606	2606.46	4782.86
MgII-2796	2796.35	5131.31
MgII-2803	2803.53	5144.48
MgI-2852	2852.96	5235.19

λ_r: rest-frame wavelength

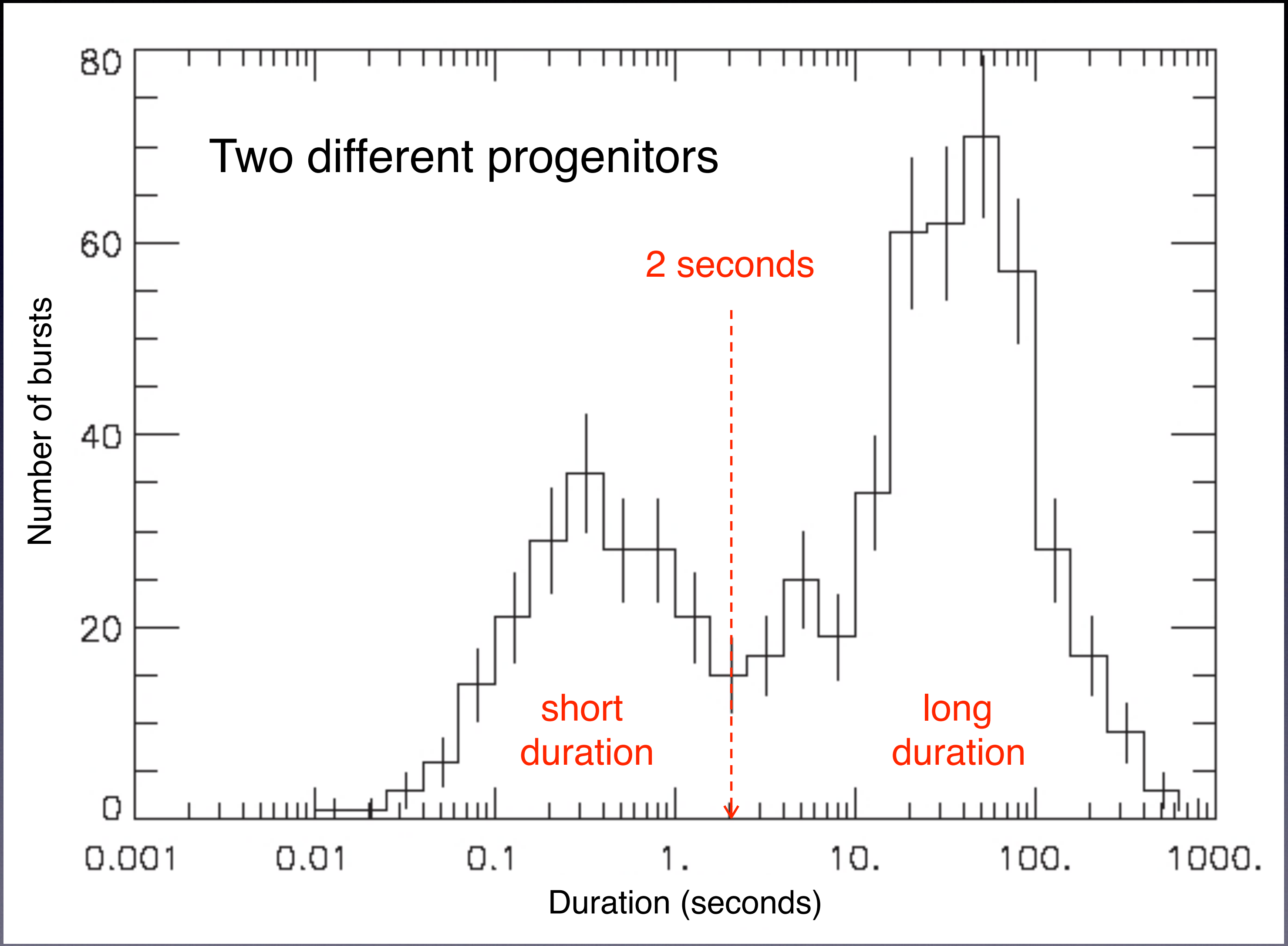
λ_o: observed wavelength

Redshift: $z = \dfrac{\lambda_o - \lambda_r}{\lambda_r}$

Larger $z \Longrightarrow$ more distant objects


Gamma-ray burst GRB 011121
Detection on Earth on November 21 2001
Redshift: z = 0.362
Explosion occurred 3.98 billion years ago

Bi-modal distribution of duration of GRBs



shortest 6 ms
GRB 910711

longest > 7 hours
GRB 111209A

Gamma-ray Bursts (GRBs): the most energetic explosions in the universe after the Big Bang

Definition:

- Brief and intense flashes of γ-rays (photon energies $E = 0.01–1$ MeV)
- Associated with explosion of stars at large distances
- Total energy emitted equivalent to that emitted by the Sun over its entire life

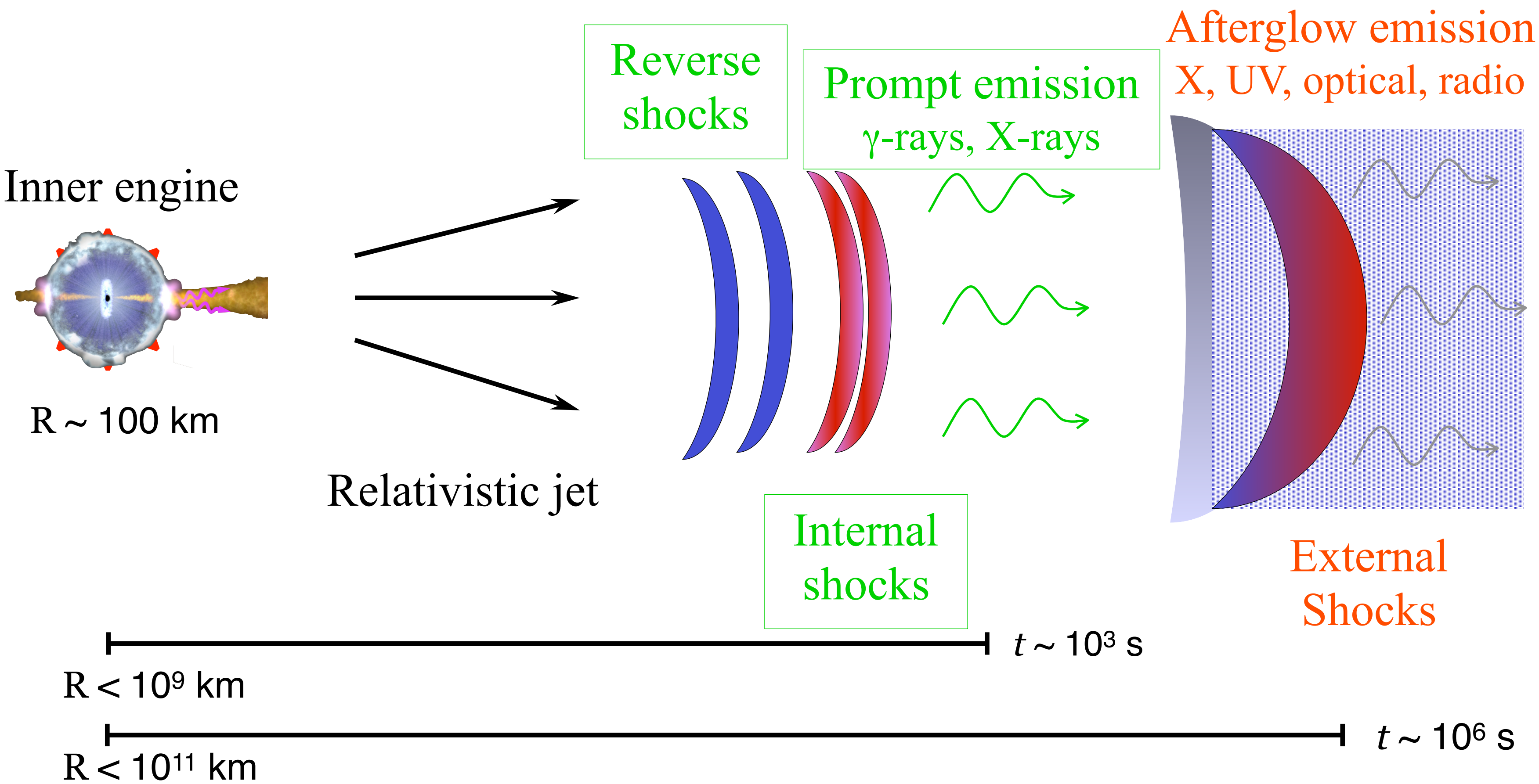
- Two types of GRBs: **short** ($t < 2$ sec) & **long** ($t > 2$ sec)
- For both, γ-ray photons originating in **collimated jets** emitted by compact and distant objects of stellar origin
- Final faith after explosion: **black hole**

Short-duration GRB ($t < 2$ s):

Long-duration GRB ($t > 2$ s):

Very-massive ($M > 30\ M_\odot$) fast-rotating star ⟶ gravitation collapse of core (core-collapse supernova) with energetic jet emission

Internal-external *fireball model*: physical mechanisms & scales



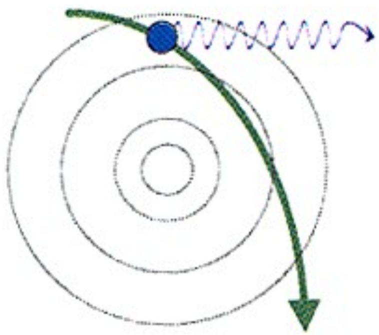
- No direct observations of inner engine
- γ-rays light curve: best evidence on inner engine
- Afterglow observations: surrounding of progenitor

Lorentz factor:

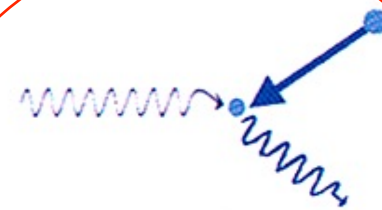
$$\Gamma = \frac{1}{\sqrt{1 - v^2/c^2}} = \frac{1}{\sqrt{1-\beta^2}} = \frac{dt}{d\tau}$$

$$\Gamma \sim 10^3 \Longrightarrow v / c \sim 0.999999$$

Basic radiation mechanisms for production of
high-energy photons in the universe

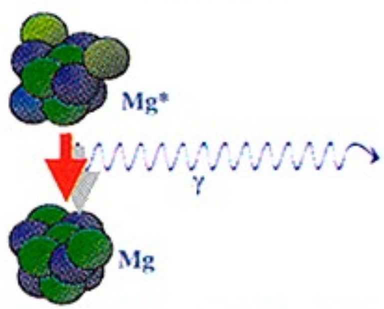


Accelerated Charged Particles

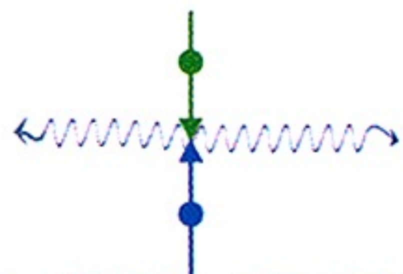


Inverse Compton Scattering

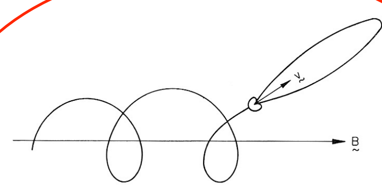
GRB
prompt emission



De-Excitation of Atomic Nuclei

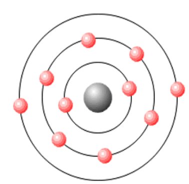


Annihilation of Particle-Antiparticle Pairs



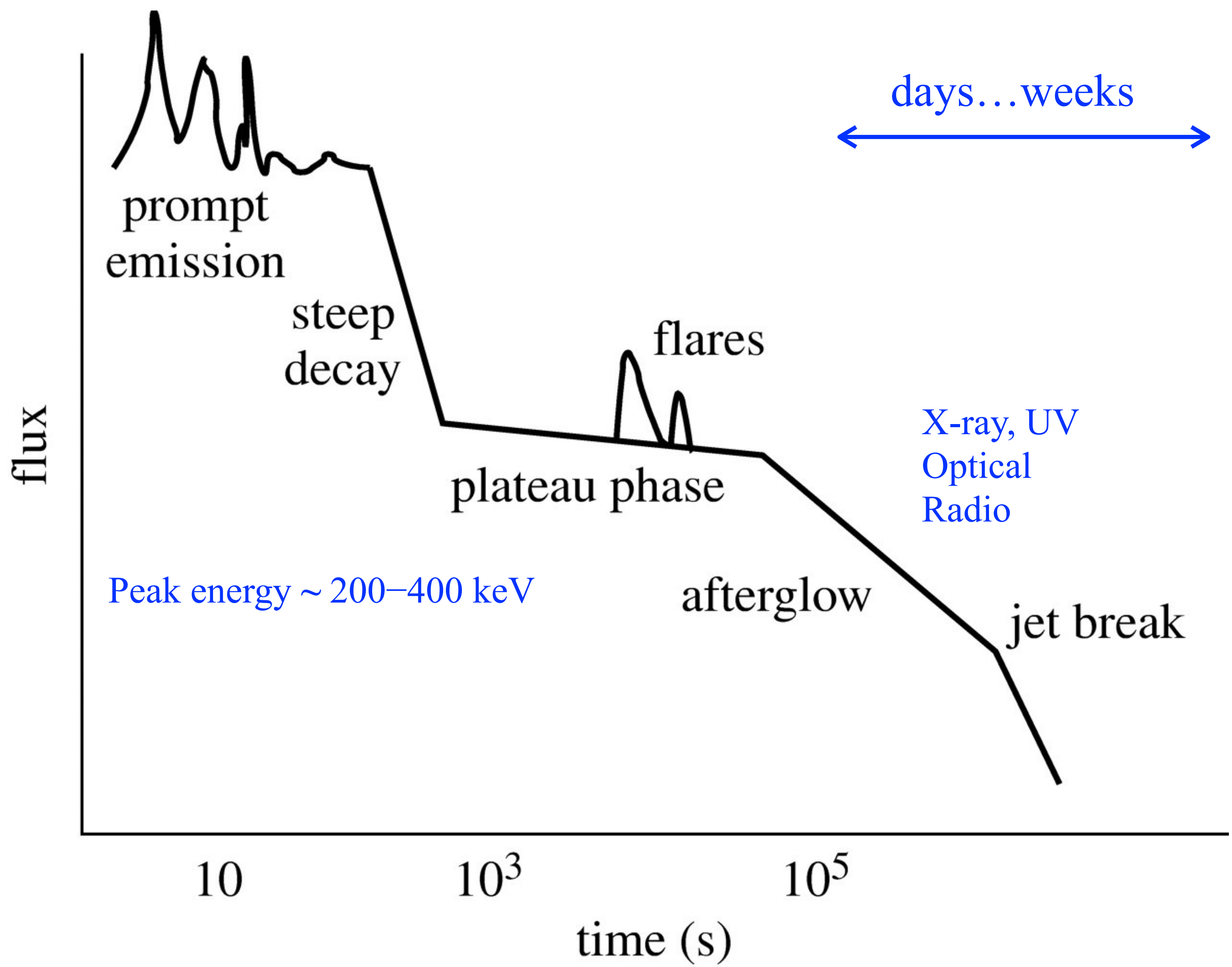
Synchrotron

GRB
prompt emission



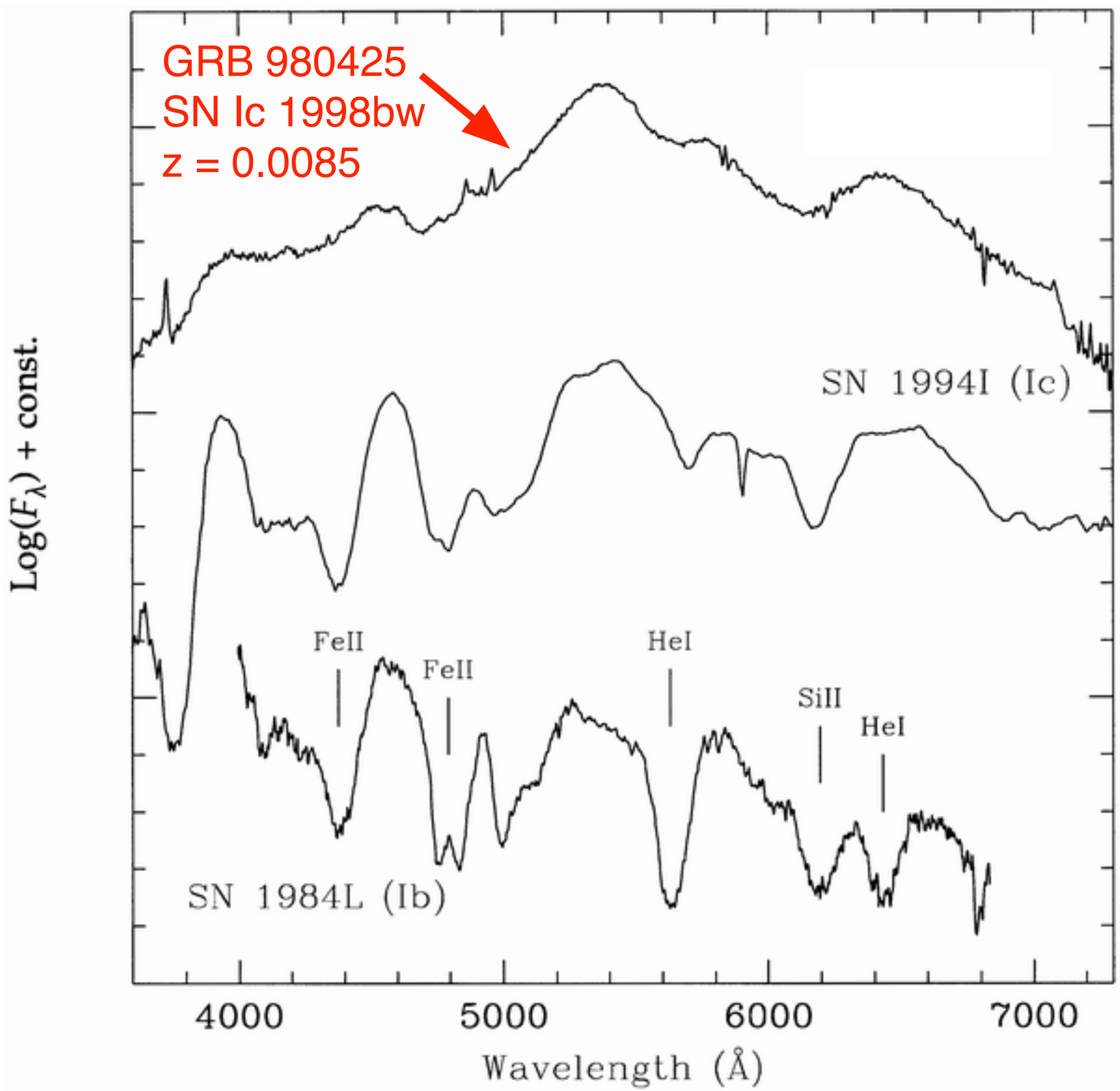
Characteristic X-rays

Light curve of a gamma-ray burst

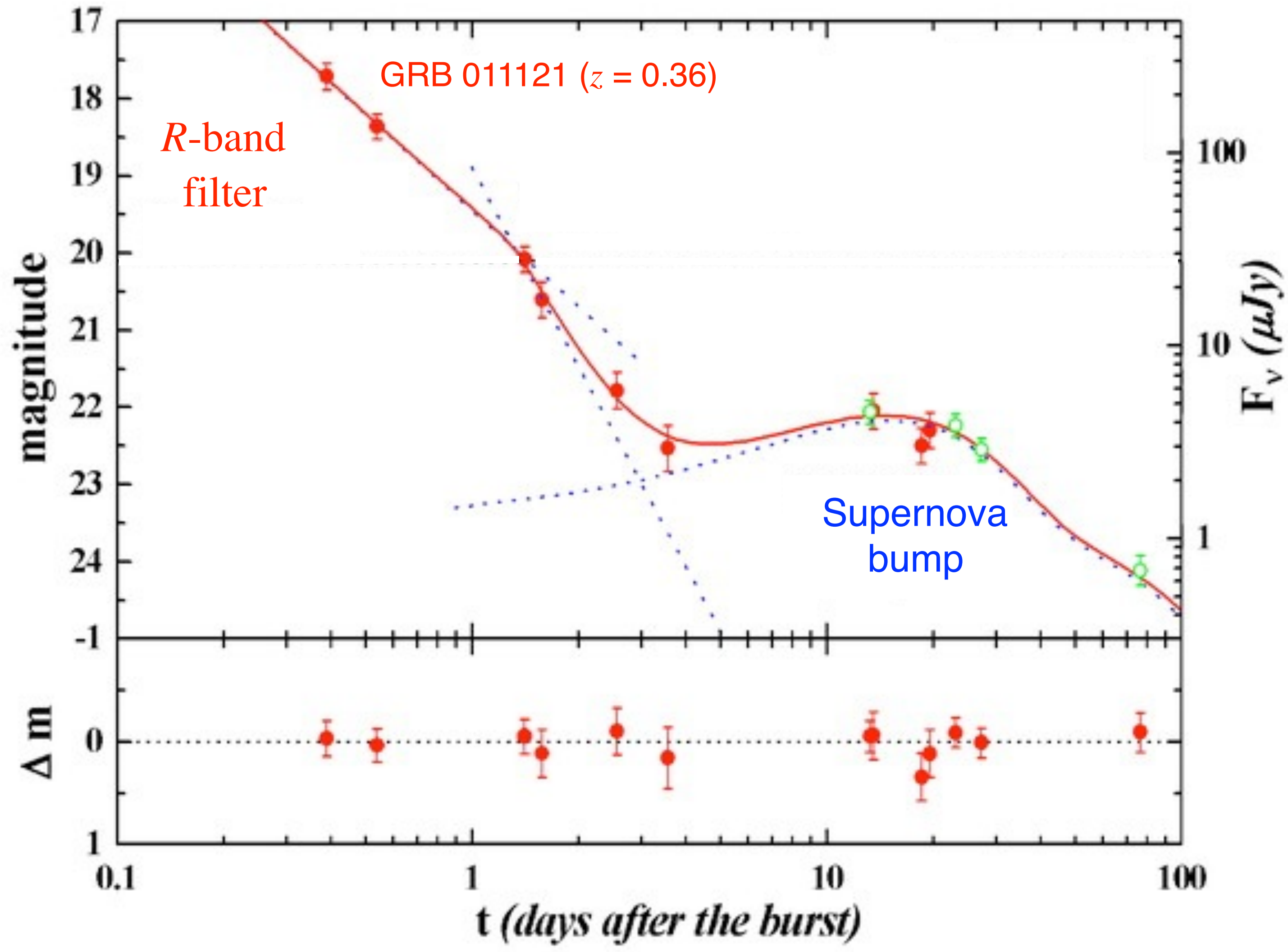


Long gamma-ray burst: **supernova connection**

Associated with SN Ic ($M > 30\ M_\odot$)



Long gamma-ray burst light curve with **supernova bump**



Gamma-ray burst statistics

Explosion of fast-rotating stellar system discovered in γ-ray

~ 1876 GRB detected since 1997

~ 1300 localized

447 with measured redshift (distance)

NS-NS or NS-BH merger

(short GRB $t \lesssim 2$ sec)

~ 28 with redshift

Core-collapse supernova

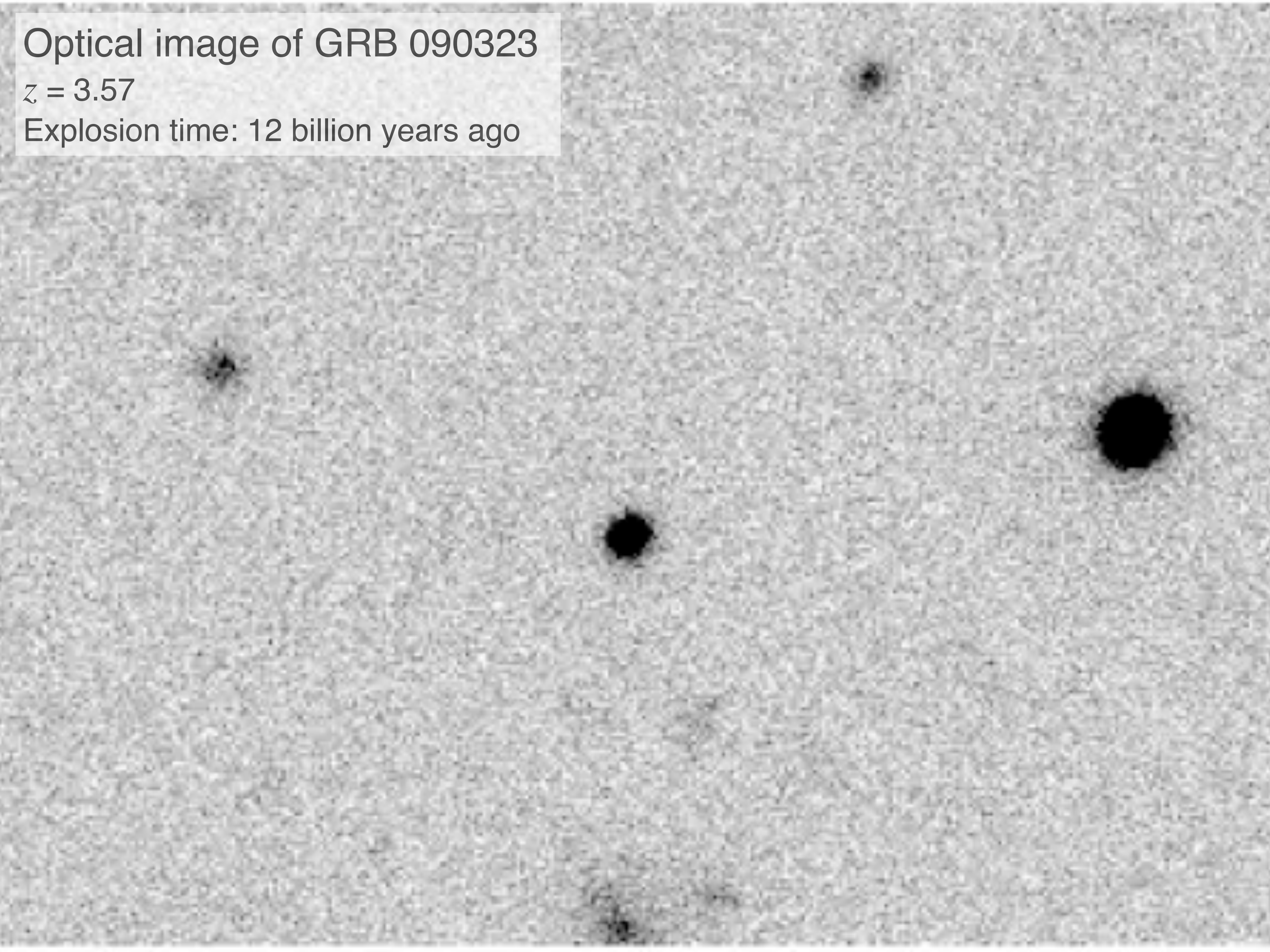
(long GRB $t \gtrsim 2$ sec)

~ 429 with redshift

Rates for long GRBs (very uncertain):

GRB/CC–SN…………………………………….. $1/10^3 – 1/10^5$
Rate in a galaxy……………………………..……….. $1/10^5\ yr^{-1}$
Detectable in full sky from Earth…………….…. several a day

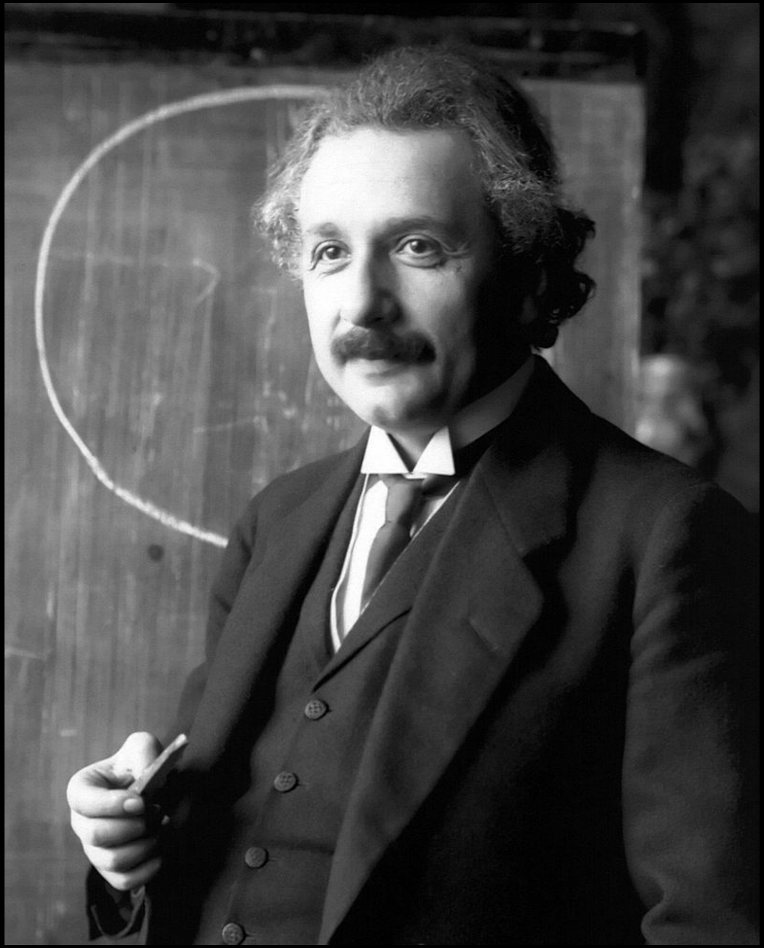
Intrinsically rare events, but universe full of stars!


Optical image of GRB 090323
z = 3.57
Explosion time: 12 billion years ago

Origin and detection of gravitational waves

Brief history

1915: Albert Einstein publishes the theory of General Relativity

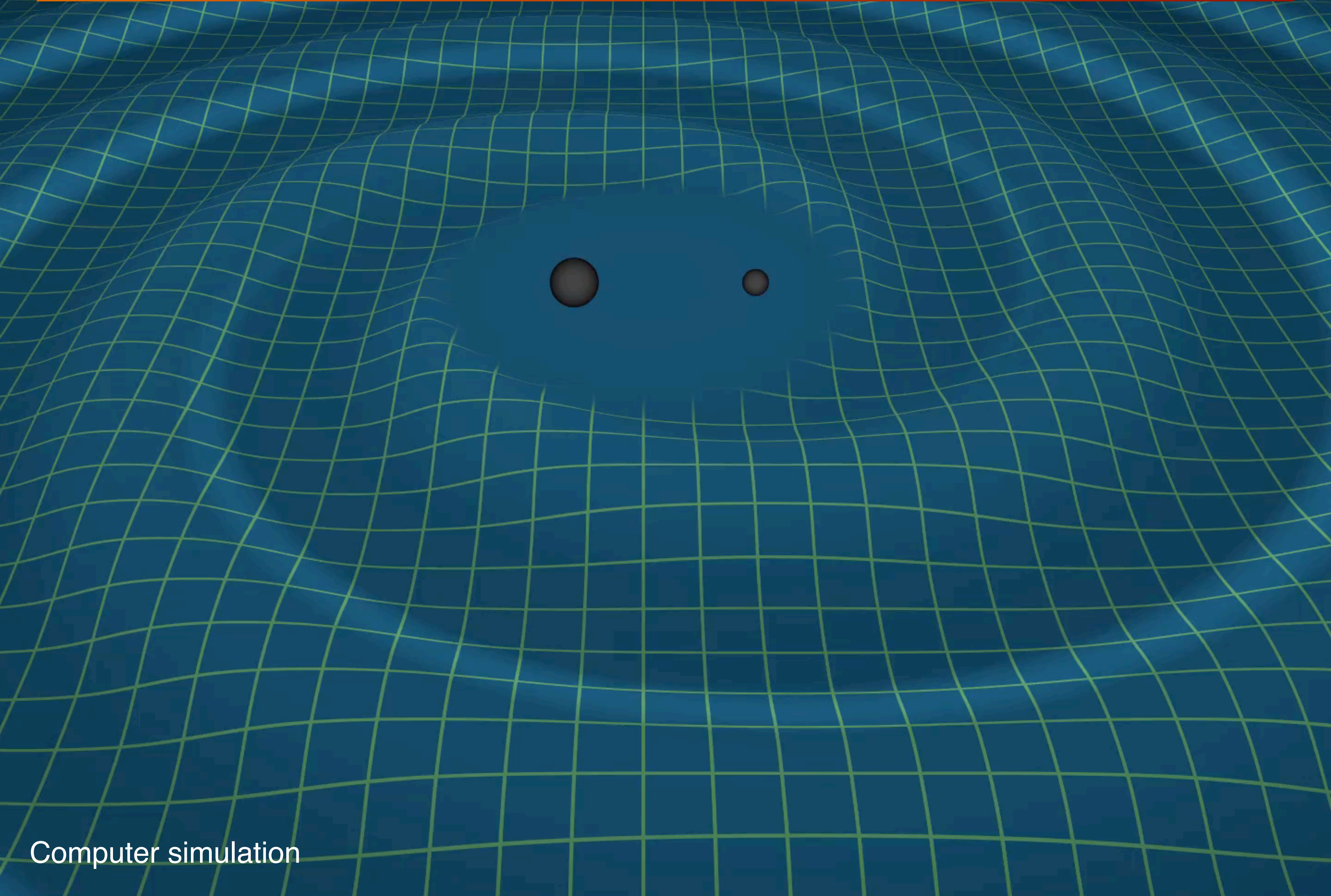


1916: existence of the gravitational waves as a consequence of General Relativity

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

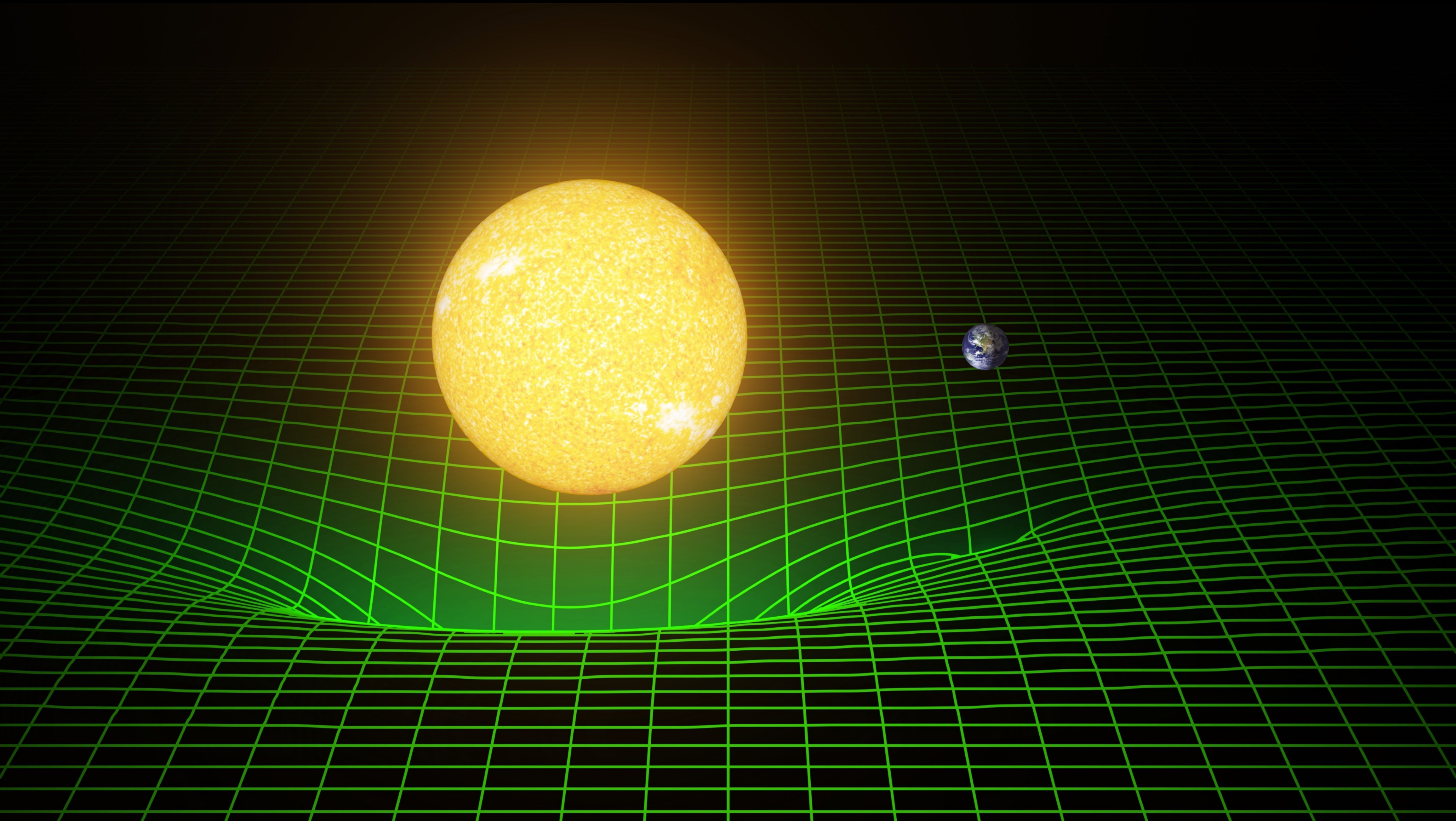


Computer simulation

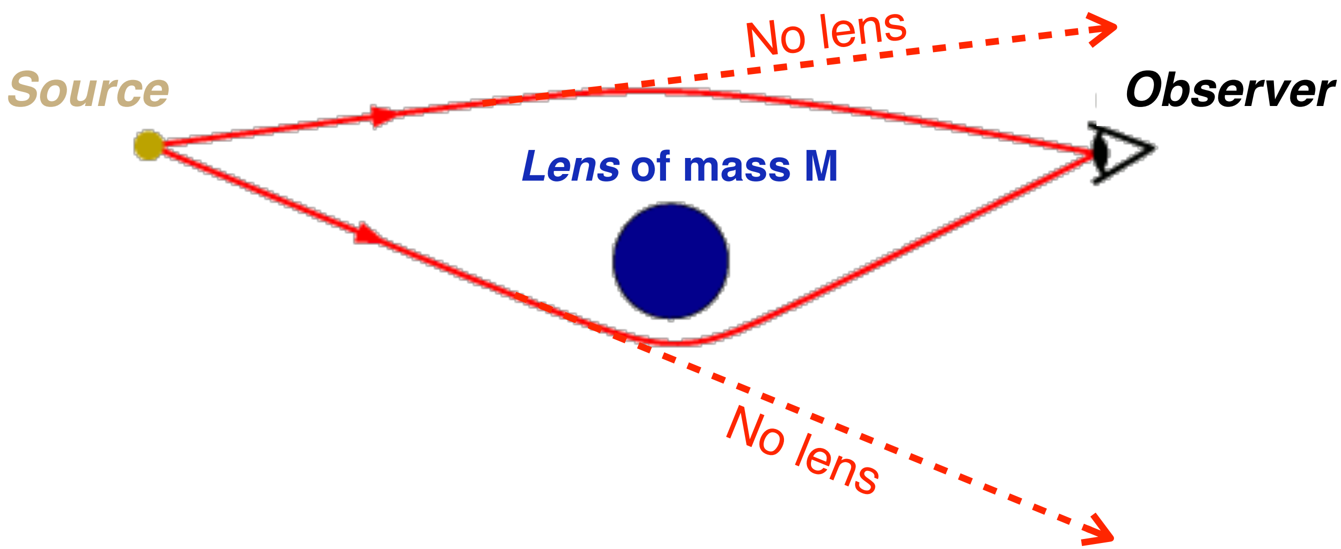
General Relativity predicts:

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

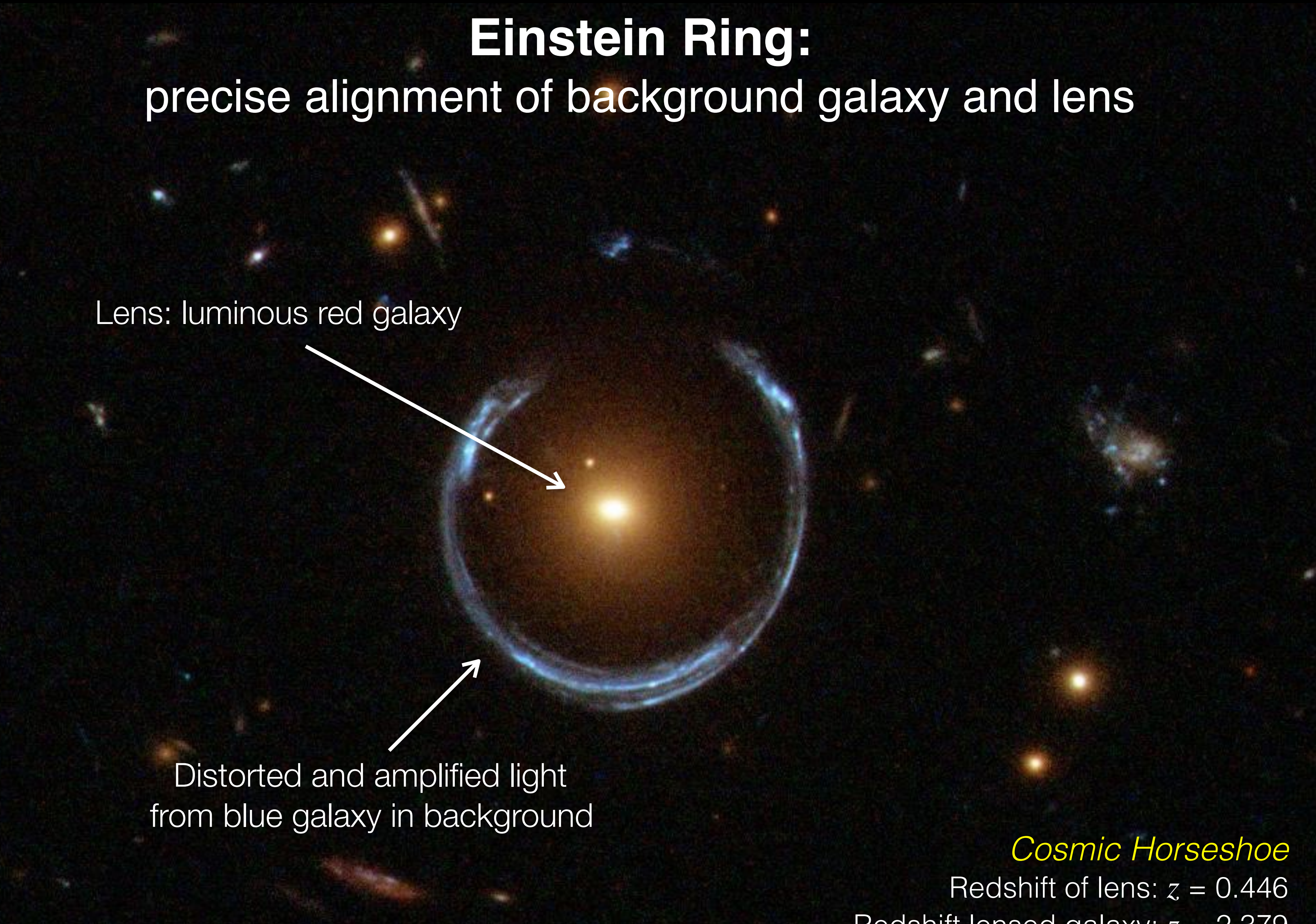
Effect of **deformation of space-time**: gravitational lensing

www.eso.org

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

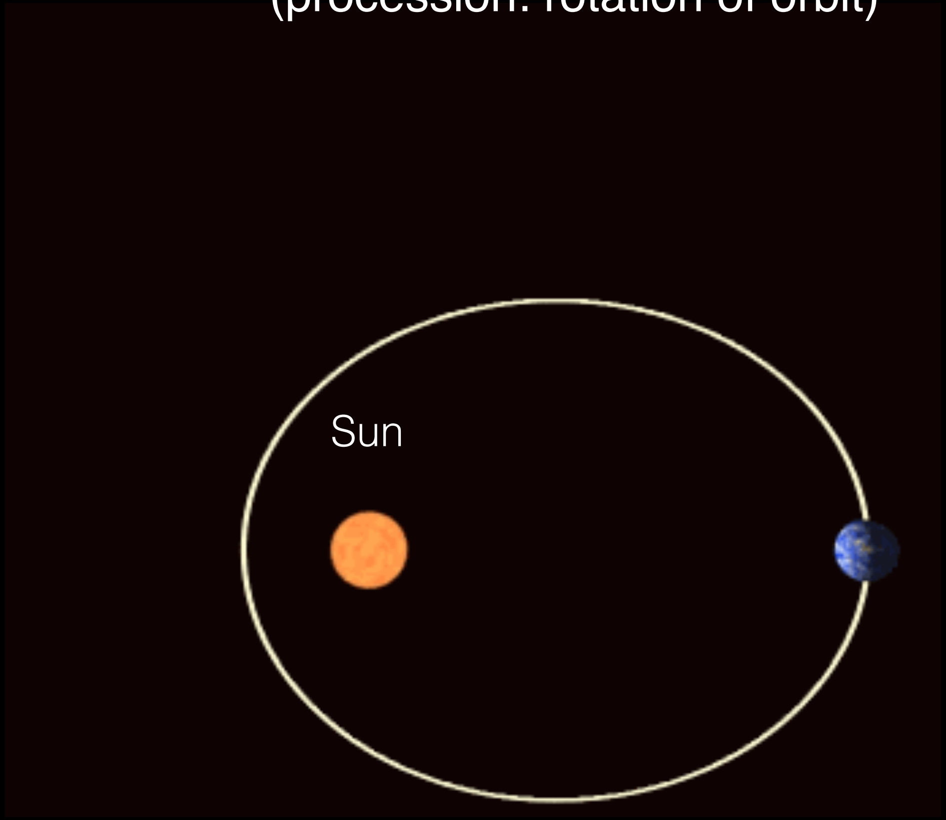
Einstein Ring:

precise alignment of background galaxy and lens



Precession of the perihelion of Mercury

(procession: rotation of orbit)



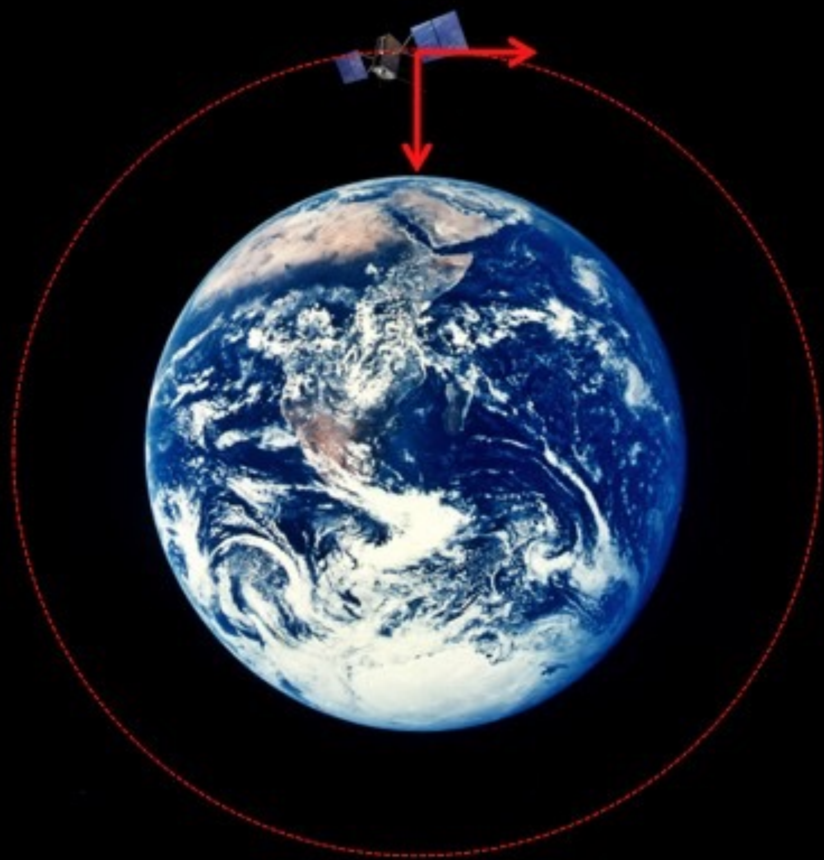
Mercury orbit without General Relativity

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:

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

G : gravitational constant

c : light speed

Energy emitted by gravitazione waves larger for more compact objects

Compactness:

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

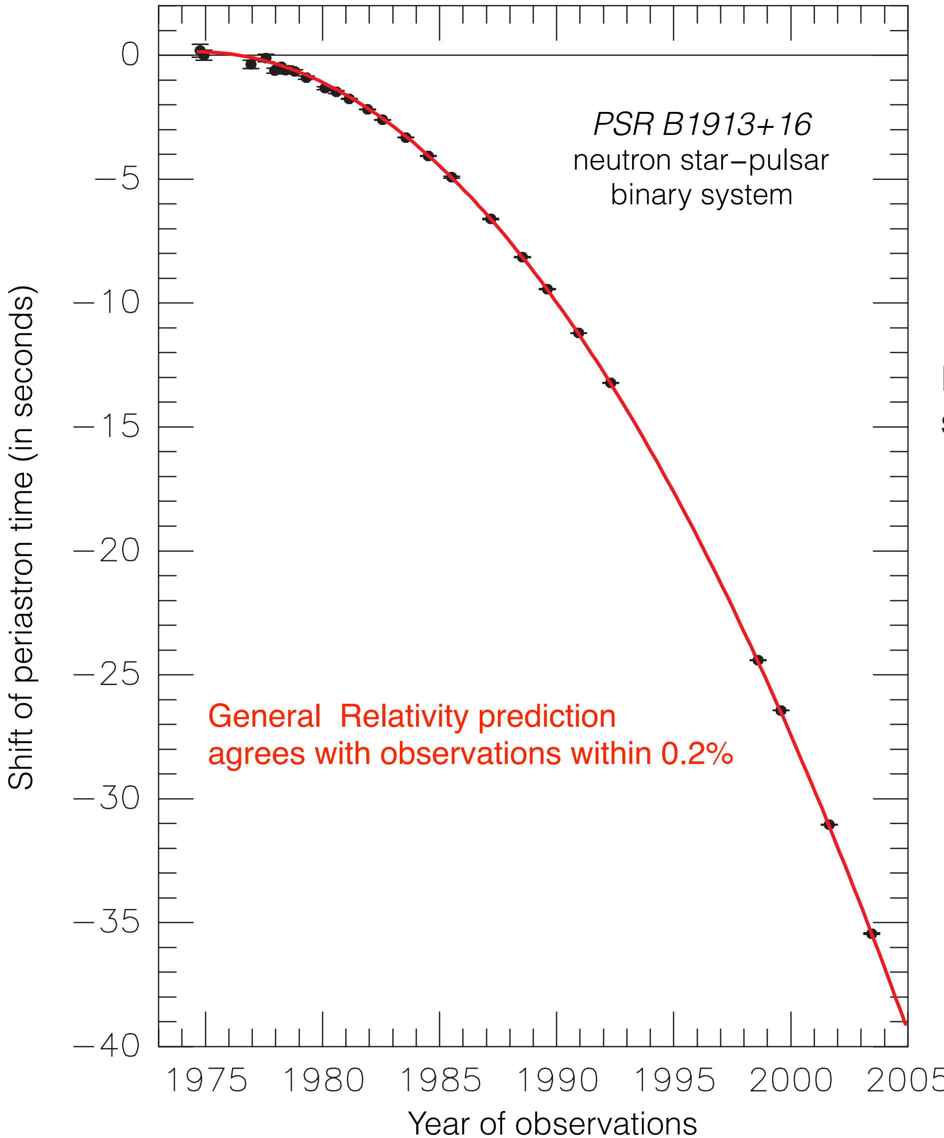
M: mass of object
R: radius of object

(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 $\Longrightarrow$ objects get closer



Precession of perihelion in binary system with 2 neutron stars

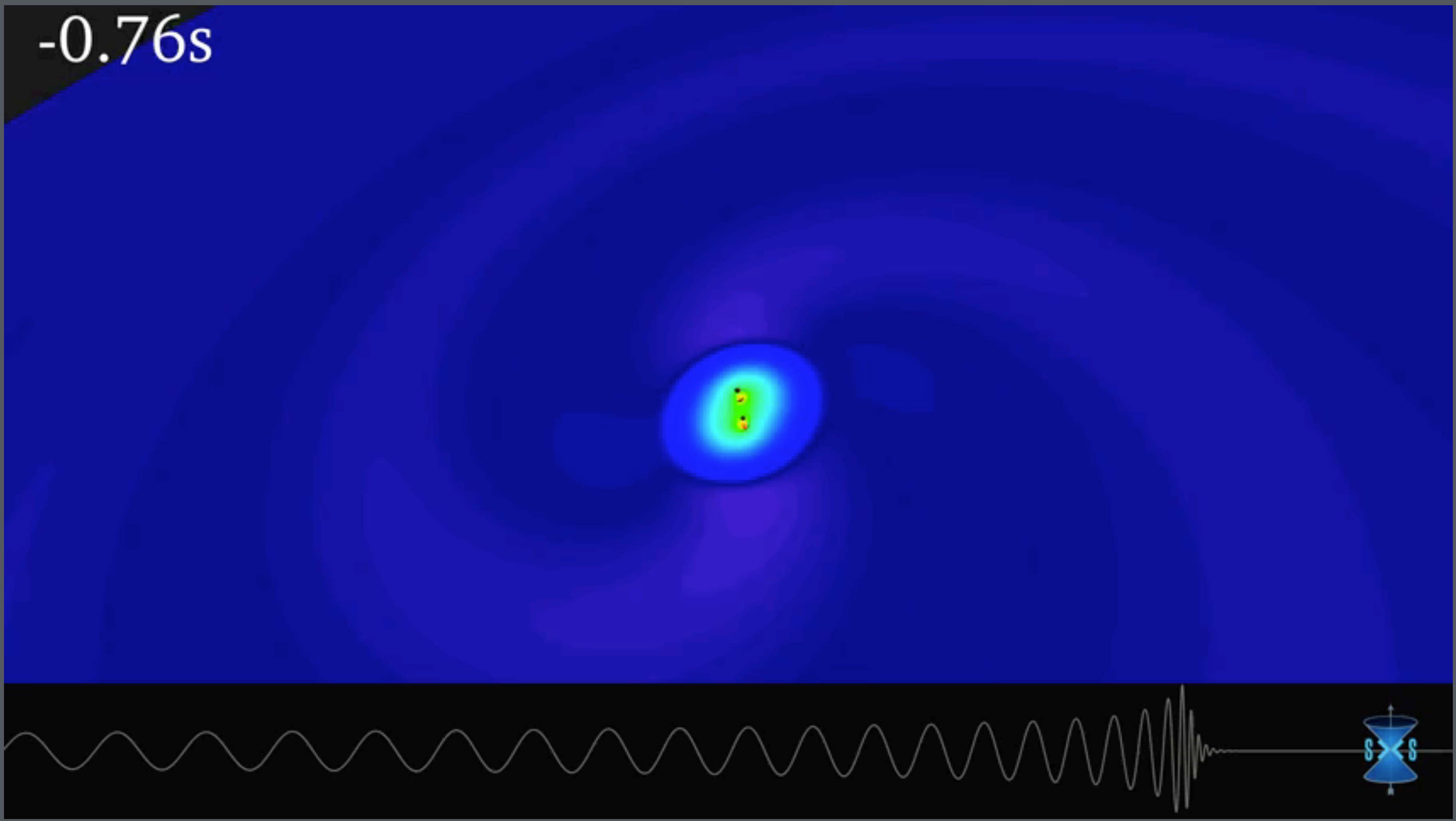
1975, first evidence of existence of GW:

- 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

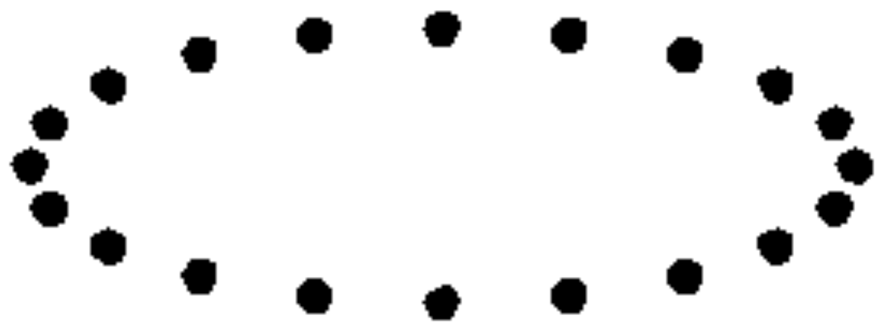
Source: GW150914



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

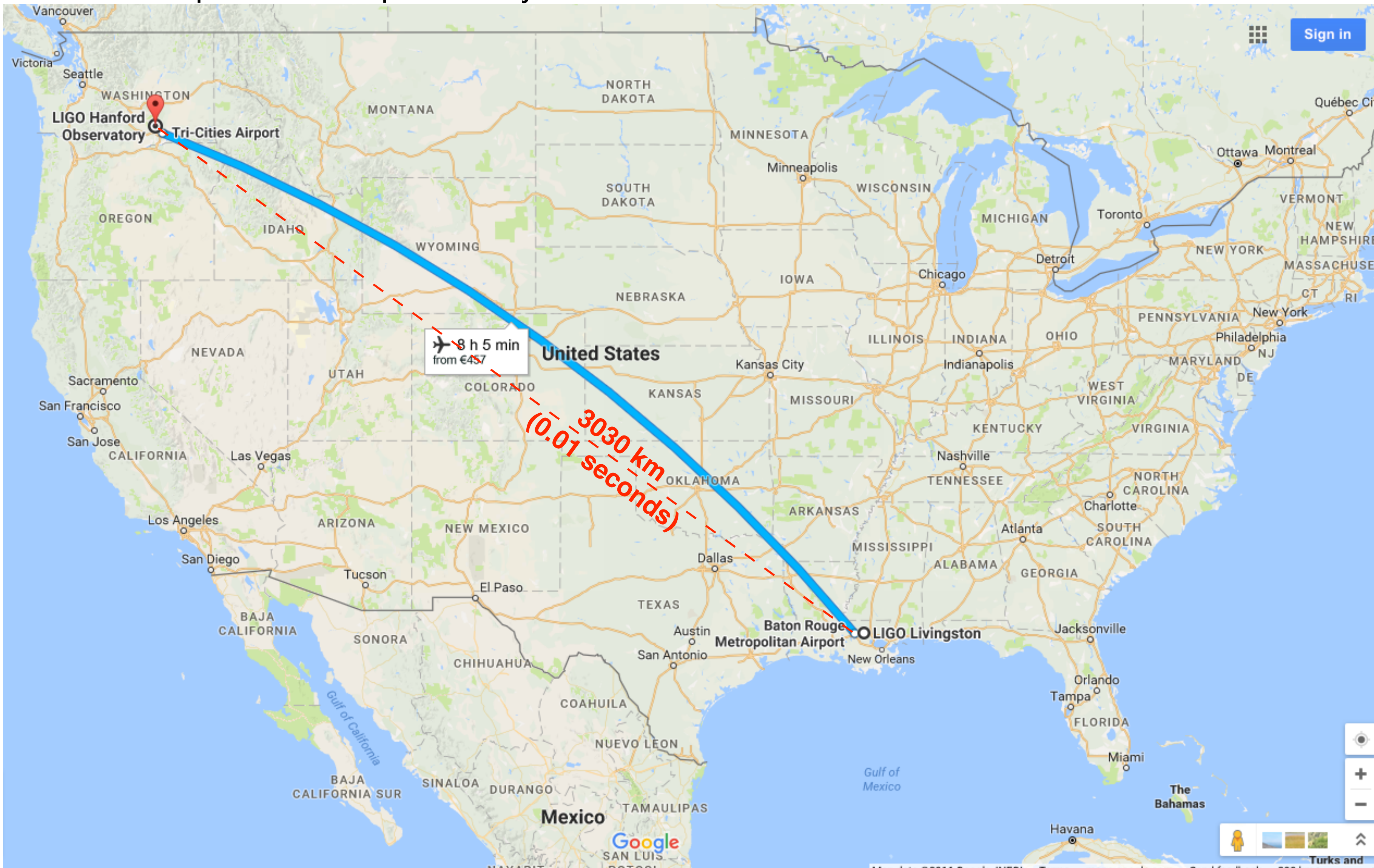
Computer simulation

The effect of passage of gravitational waves on a ring of particles
(wave oscillation of space-time)



LIGO: Laser Interferometer Gravitational-Wave Observatory

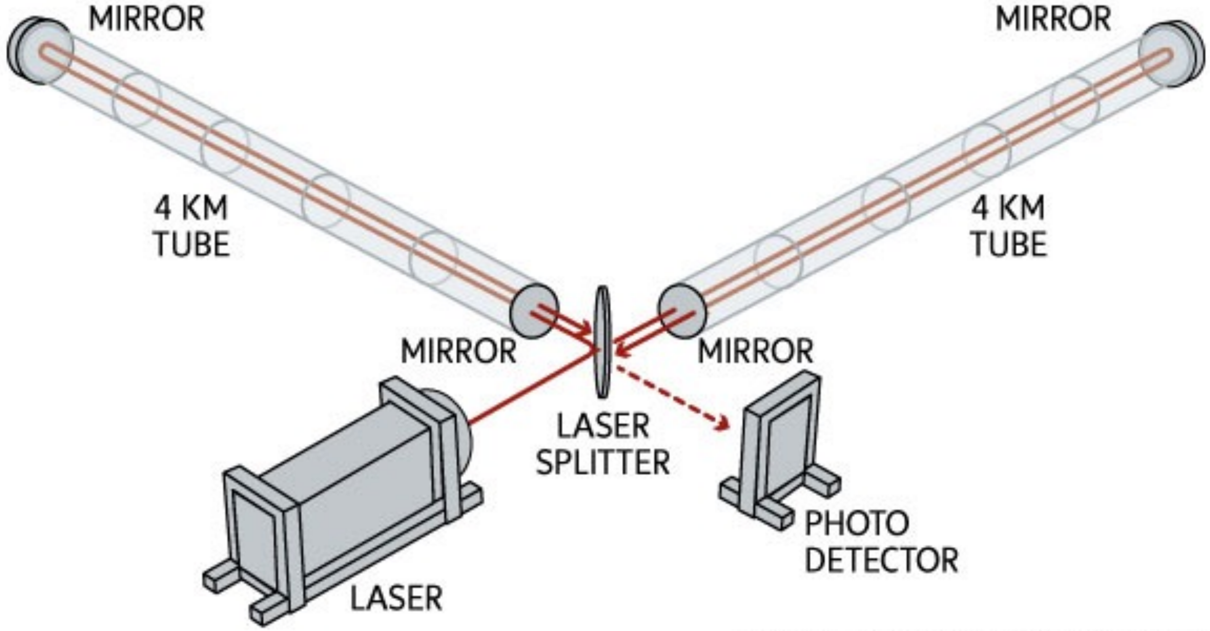
Two LIGO experiments separated by 3000 km



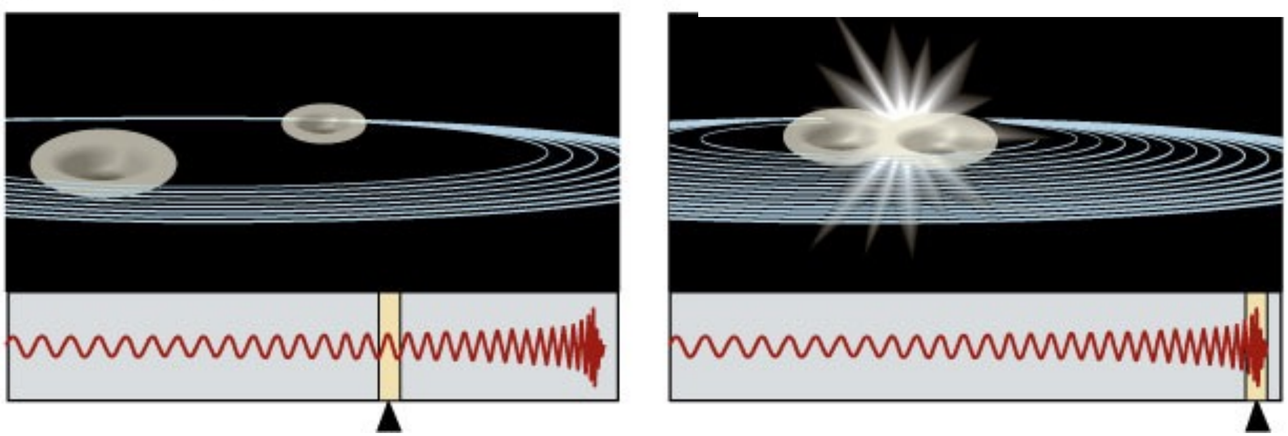
Any signal with delay longer than t = 10 ms is not due to GWs

LIGO: Laser Interferometer Gravitational-Wave Observatory

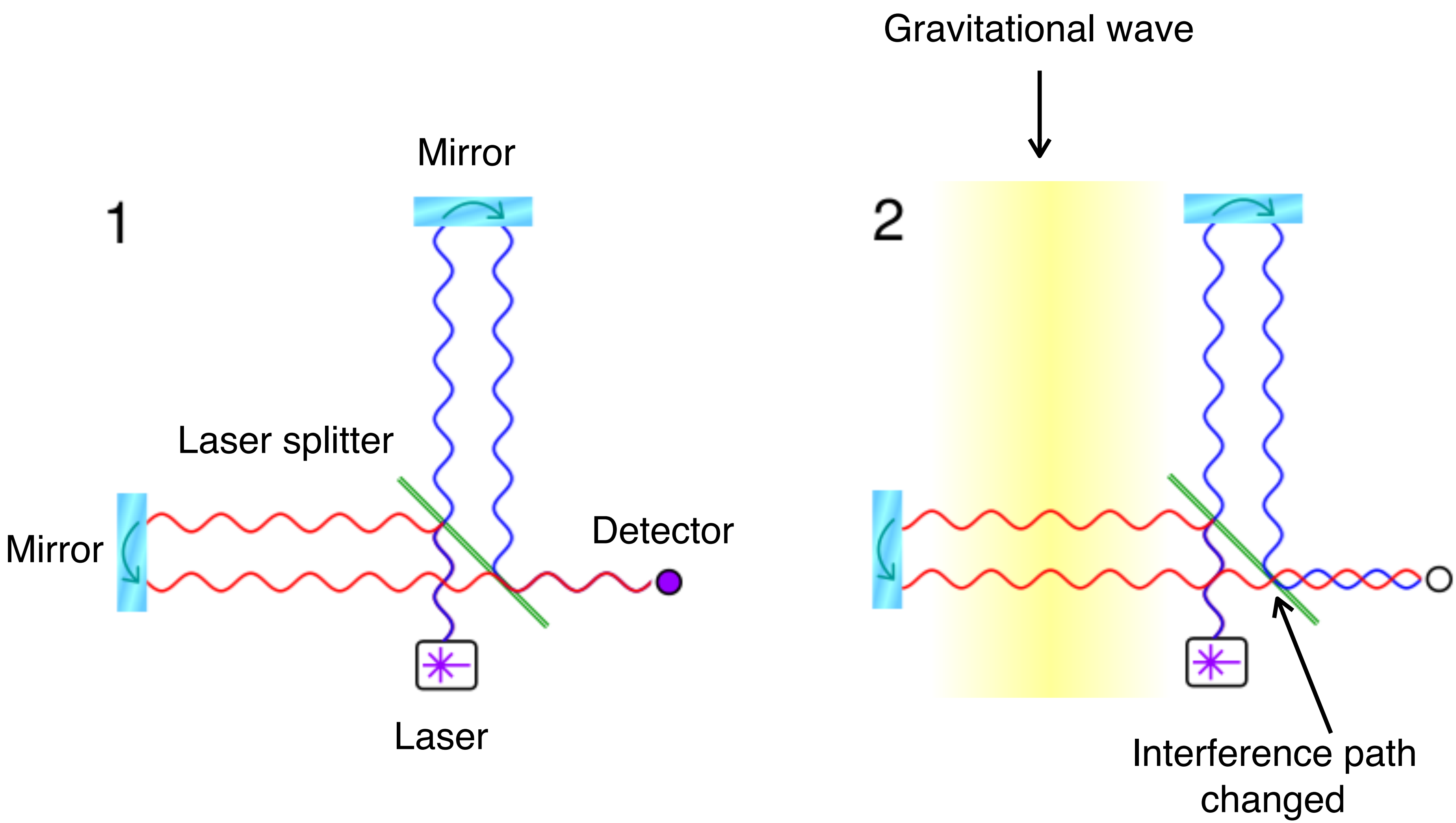
LIGO: Laser Interferometer Gravitational Wave Observatory



Black holes collide



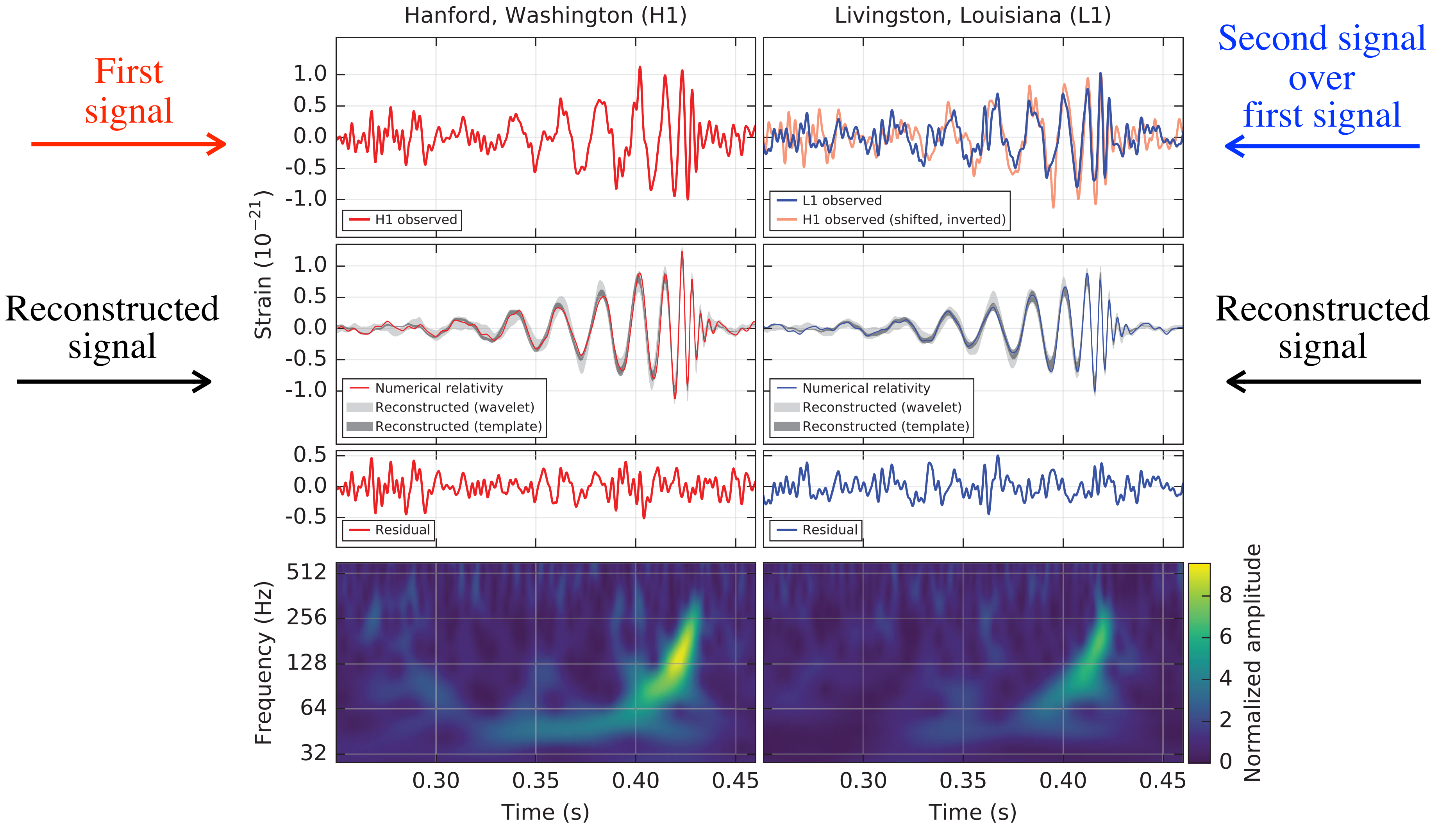
LIGO: Laser Interferometer Gravitational Wave Observatory



September 2015: gravitational waves are detected for the first time

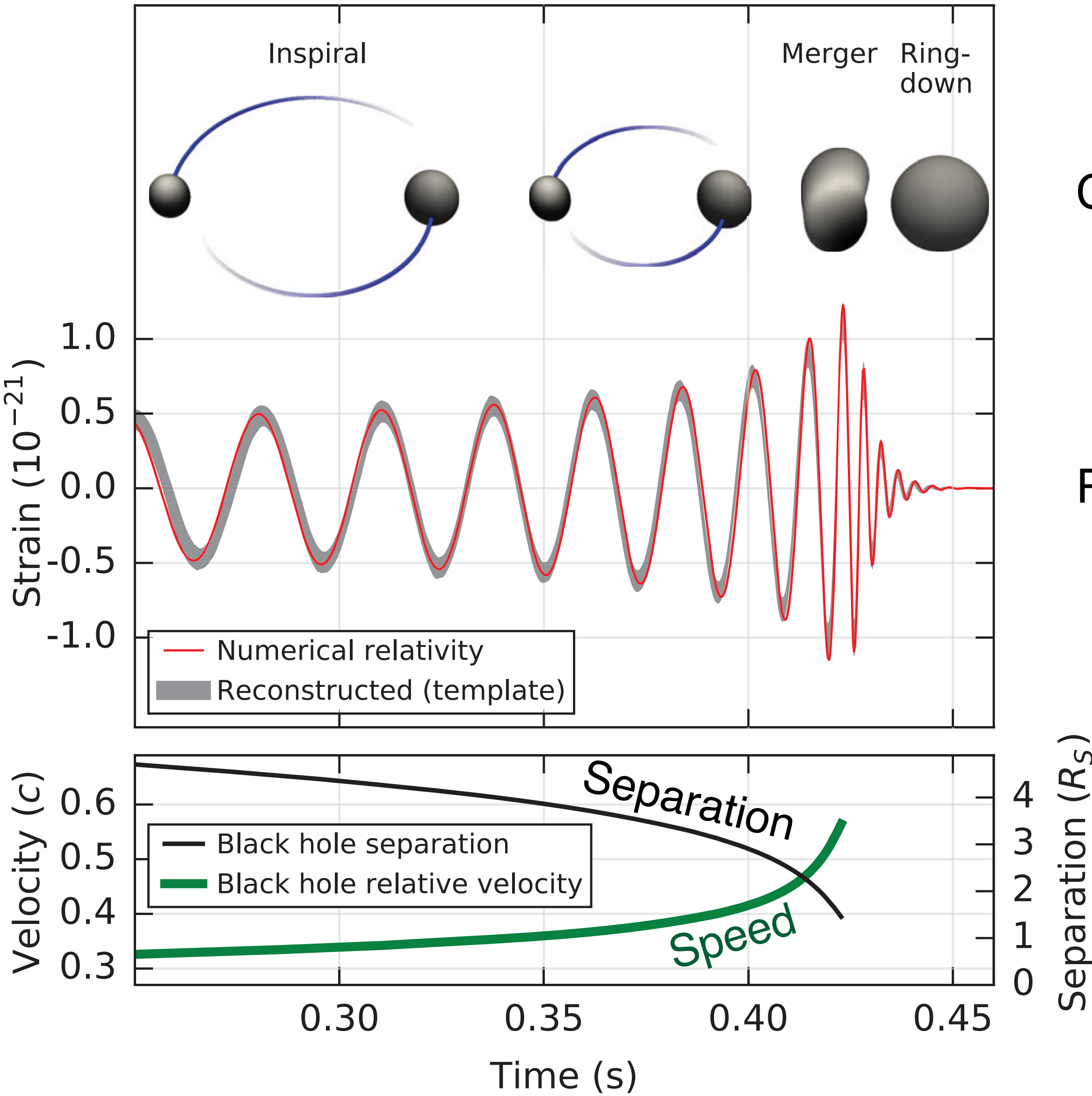
Strain $h = \Delta L/L$: deformation of space-time from a reference configuration (L: arm length)

Name of the source: **GW150914**



Measured final 5 orbits between to black holes before merger

Gravitational-wave strain amplitude in **GW150914**

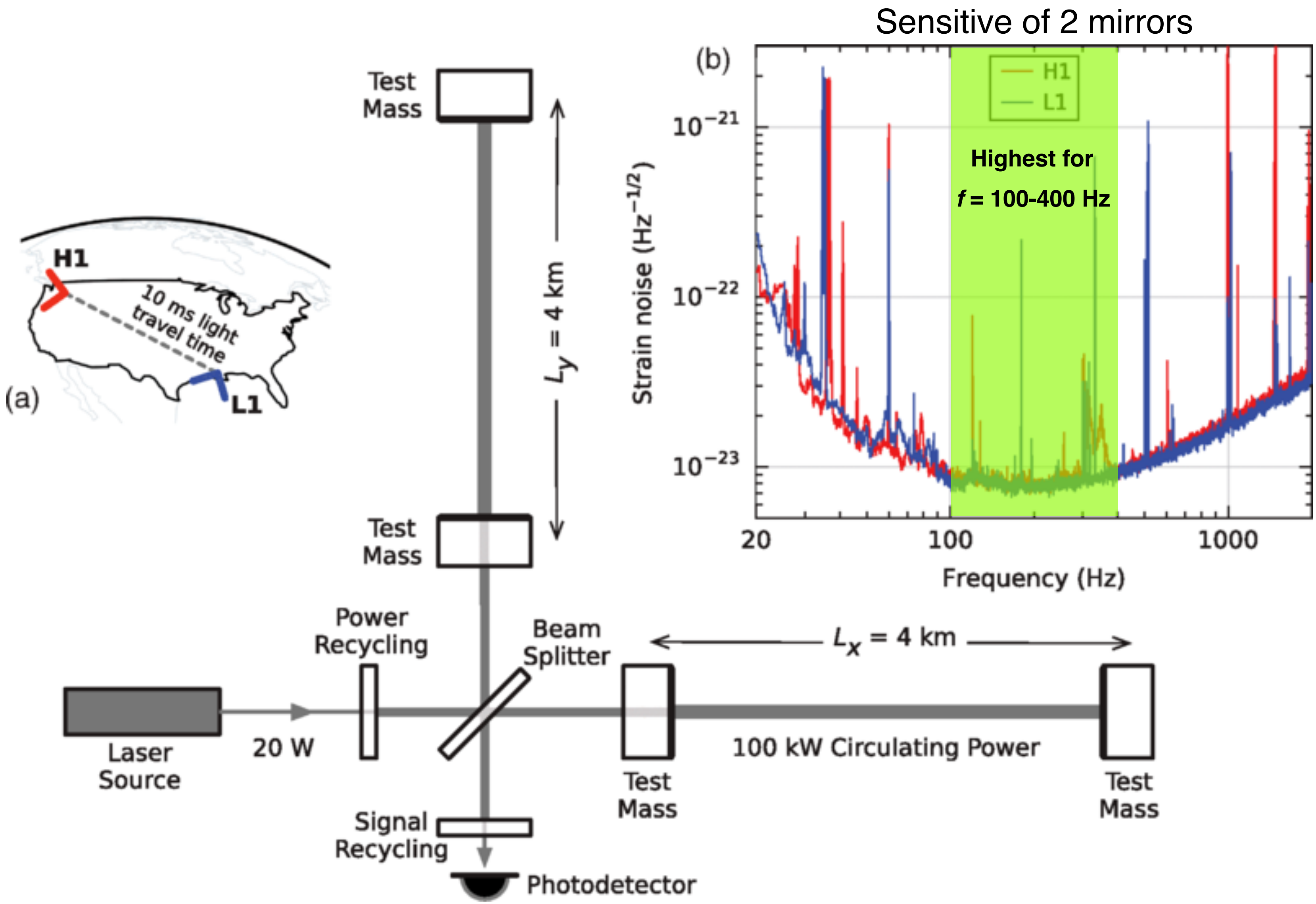


Coalescing of 2 black holes

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**

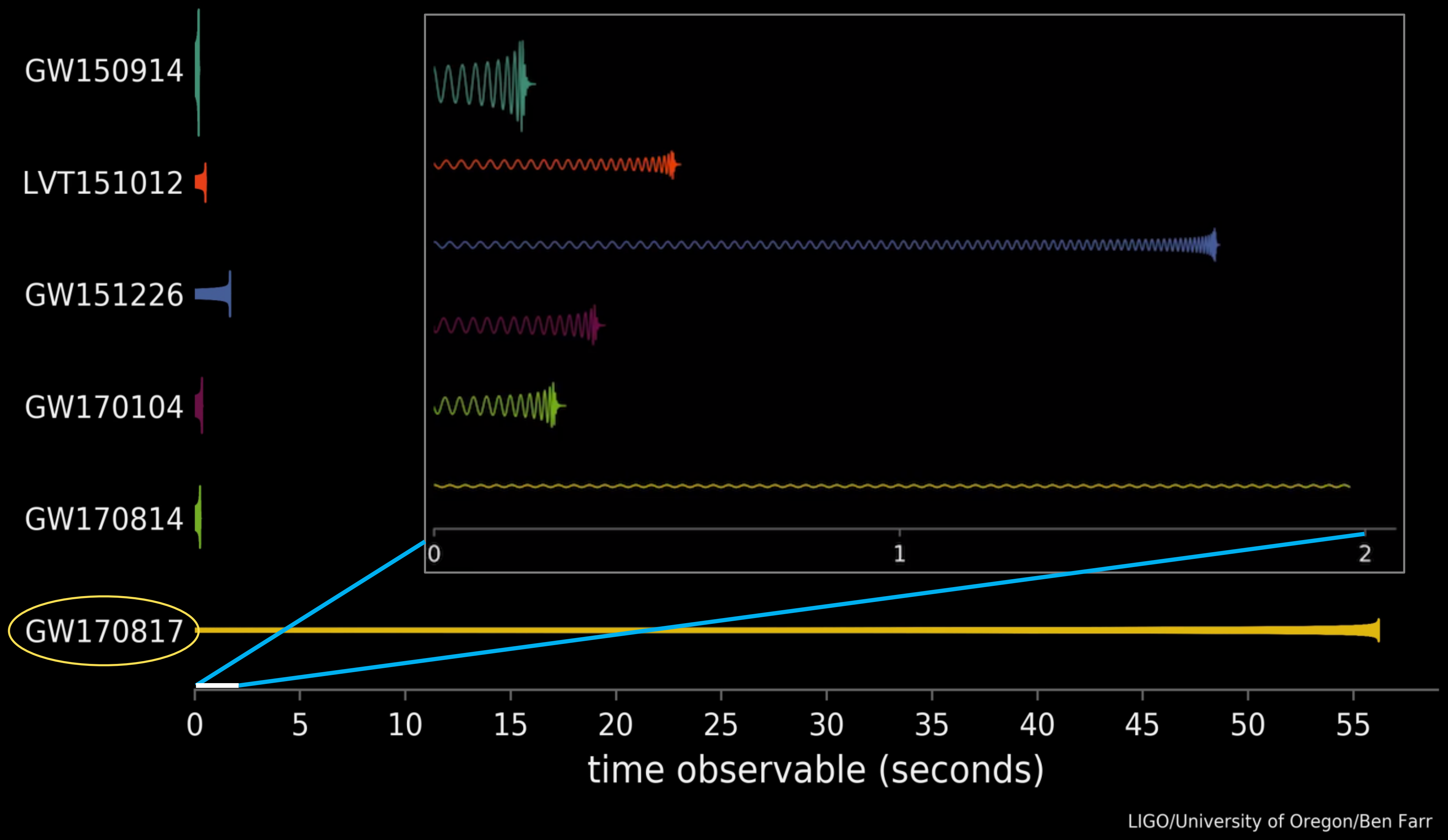
- Measured strain on Earth: $h = 10^{-21}$
- Over 4 km of arm size, this is 0.001 size of proton
- Corresponding to the ability to measure distance to closest star (Proxima Centauri, 4.2 light years = 4.02×10^{16} m) with precision of 40 μm (size of human hair)
- Strain at source: $h = 0.1$
- Signal 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: $E = mc^2 = 3.6 \times 10^{56}$ 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

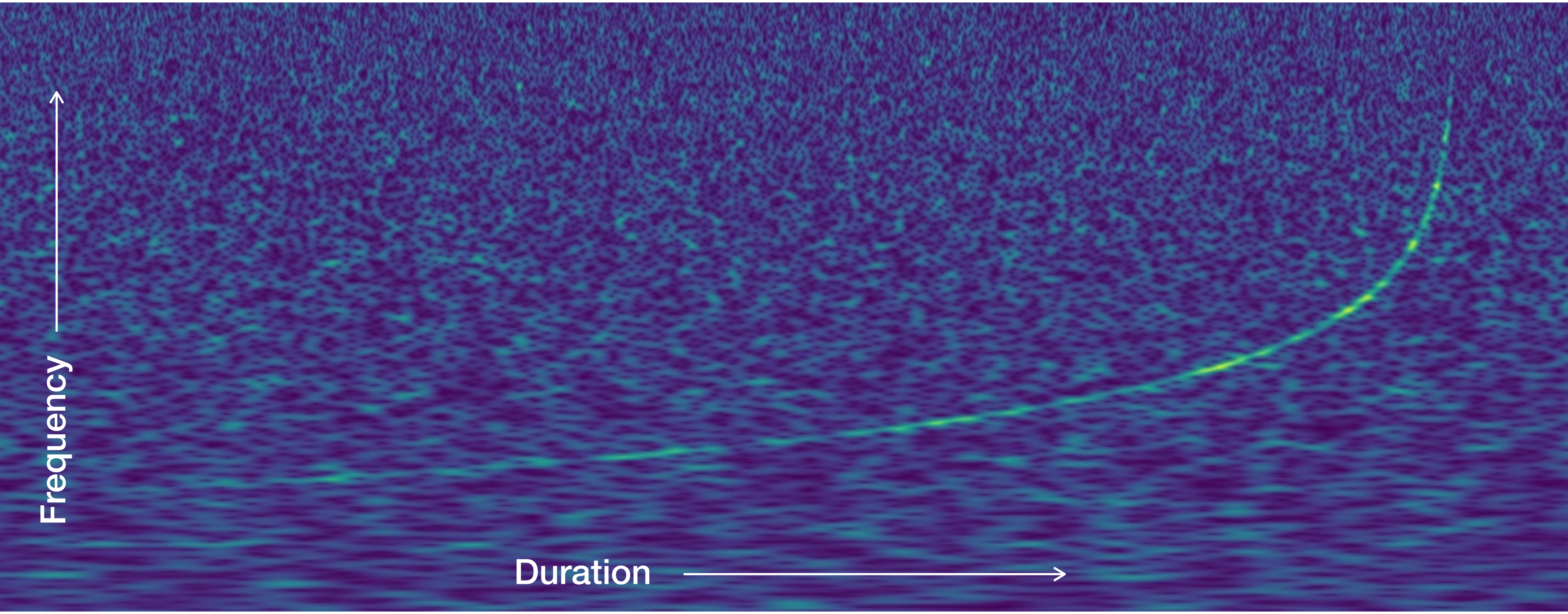
&

identification of the galaxy hosting the event

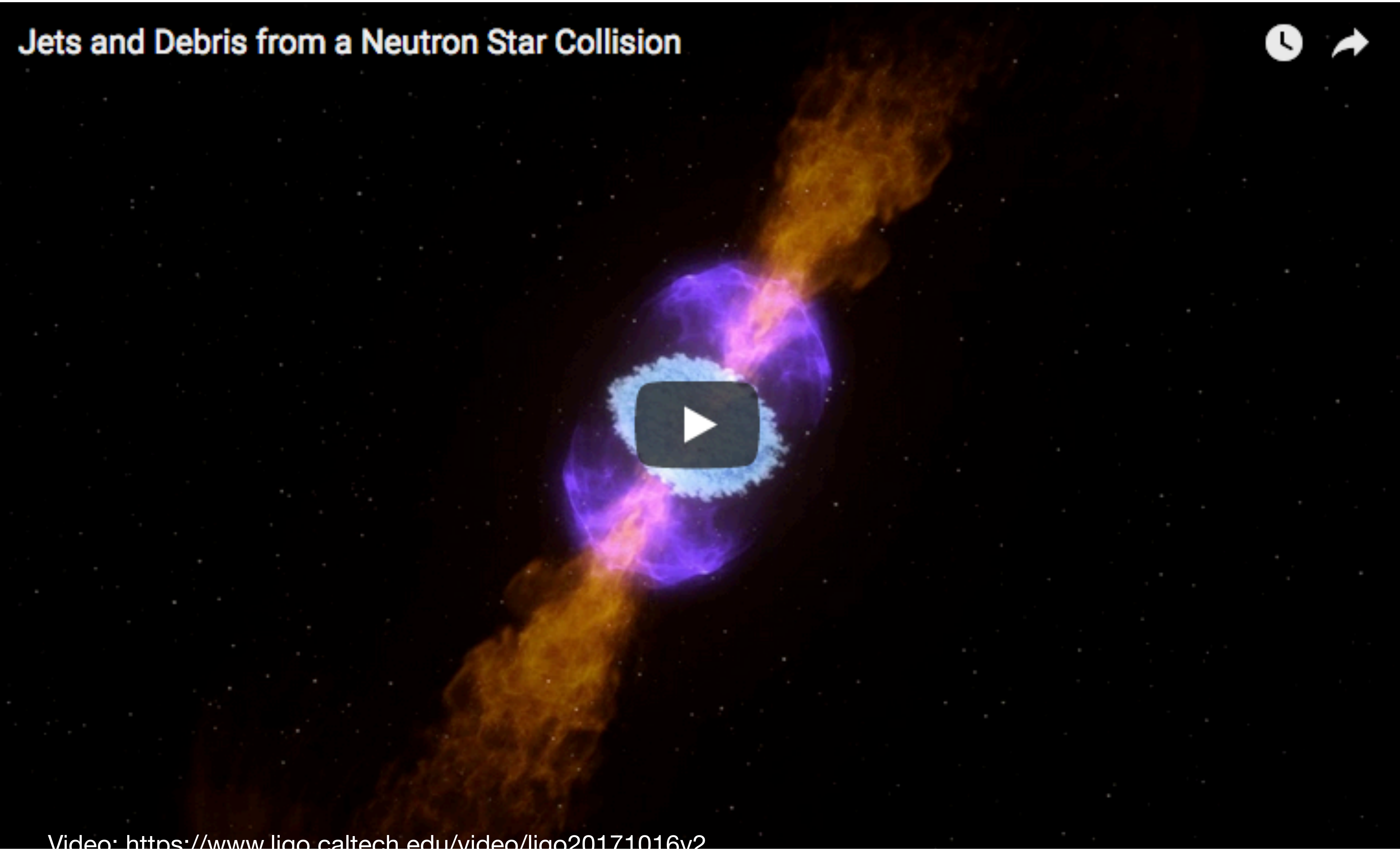
Duration of first 6 events observed



New GW event detected in August 17 2017



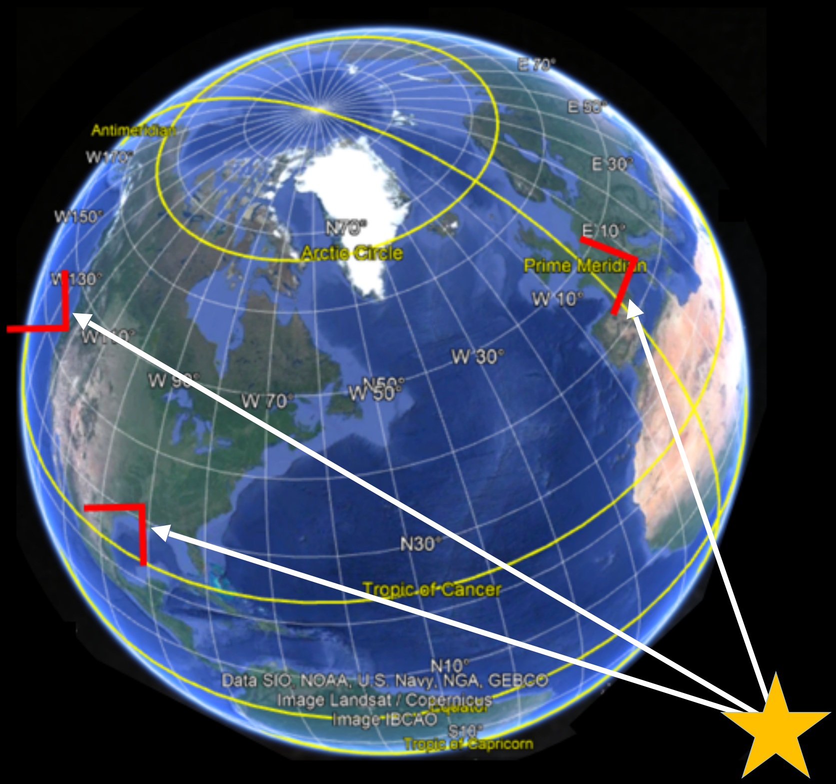
What perhaps happened: *Binary Neutron Star* (BNS) merger



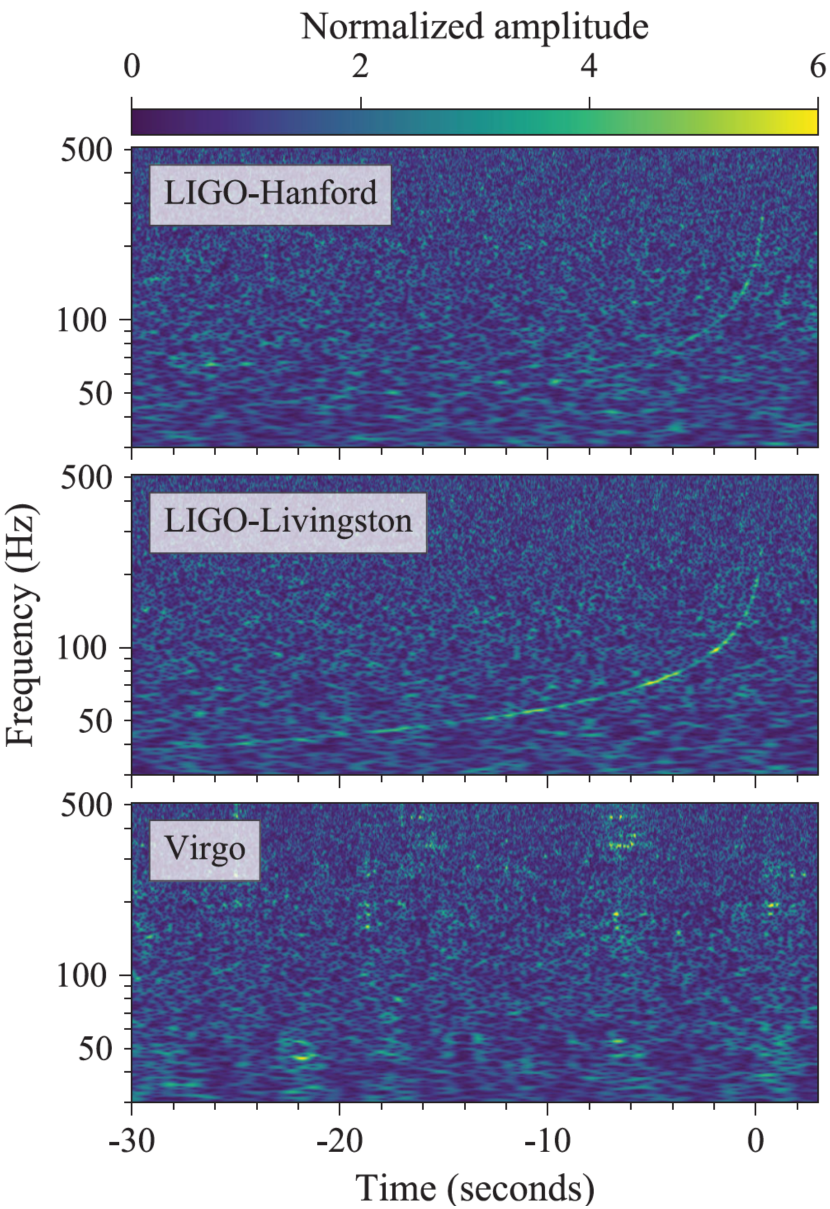
Video: https://www.ligo.caltech.edu/video/ligo20171016v2

What probably happened: *Binary Neutron Star* (BNS) merger

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



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

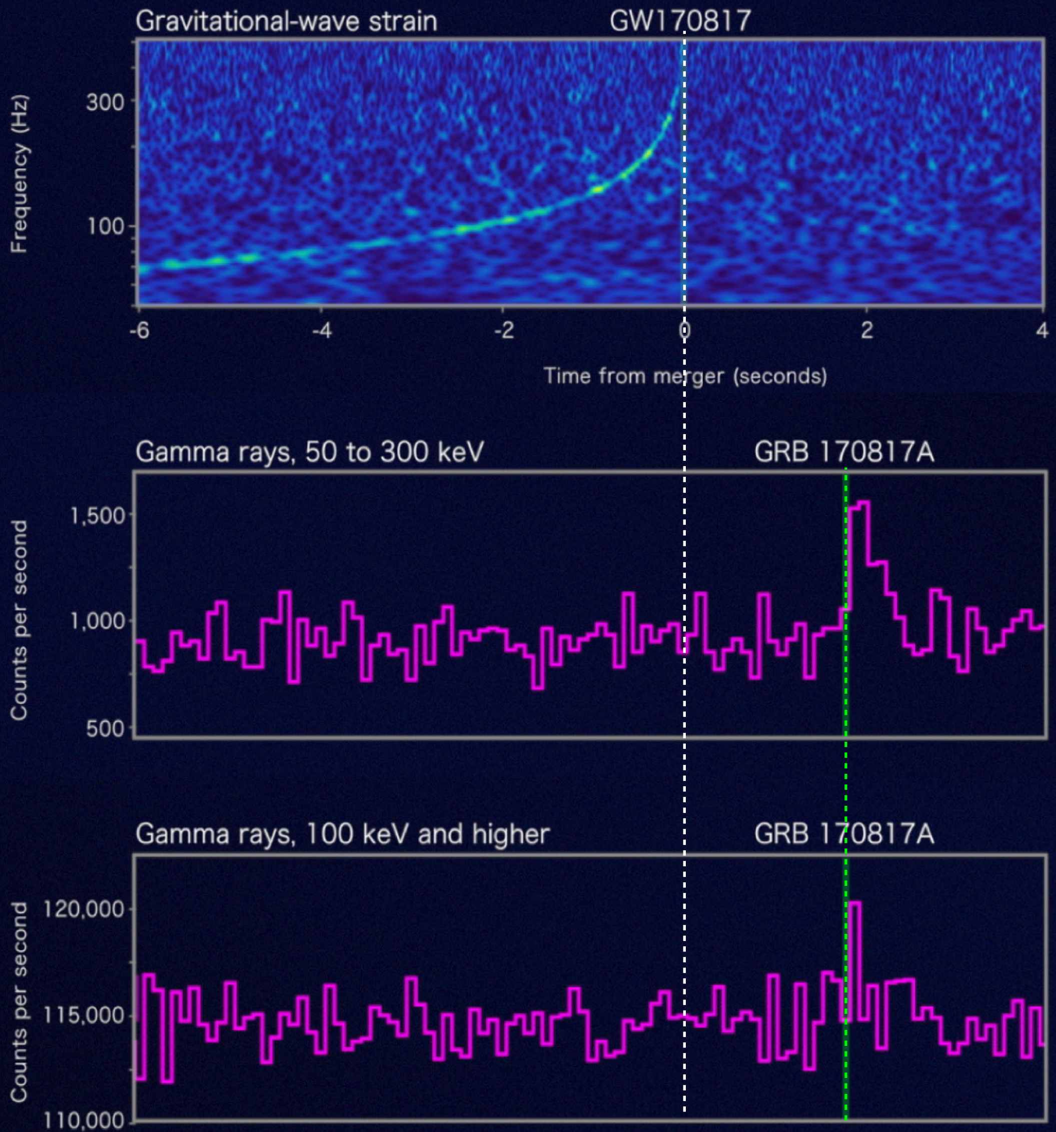


Source of gravitational waves:
GW170817

- 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)

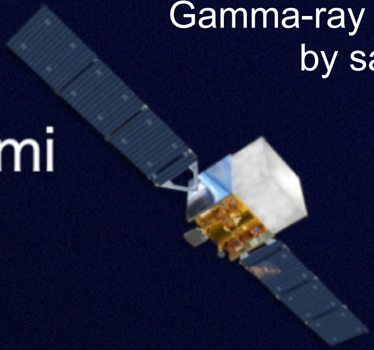
First detection of electromagnetic counterpart as a short GRB

LIGO-Virgo



Gamma-ray signal detected by satellites

Fermi



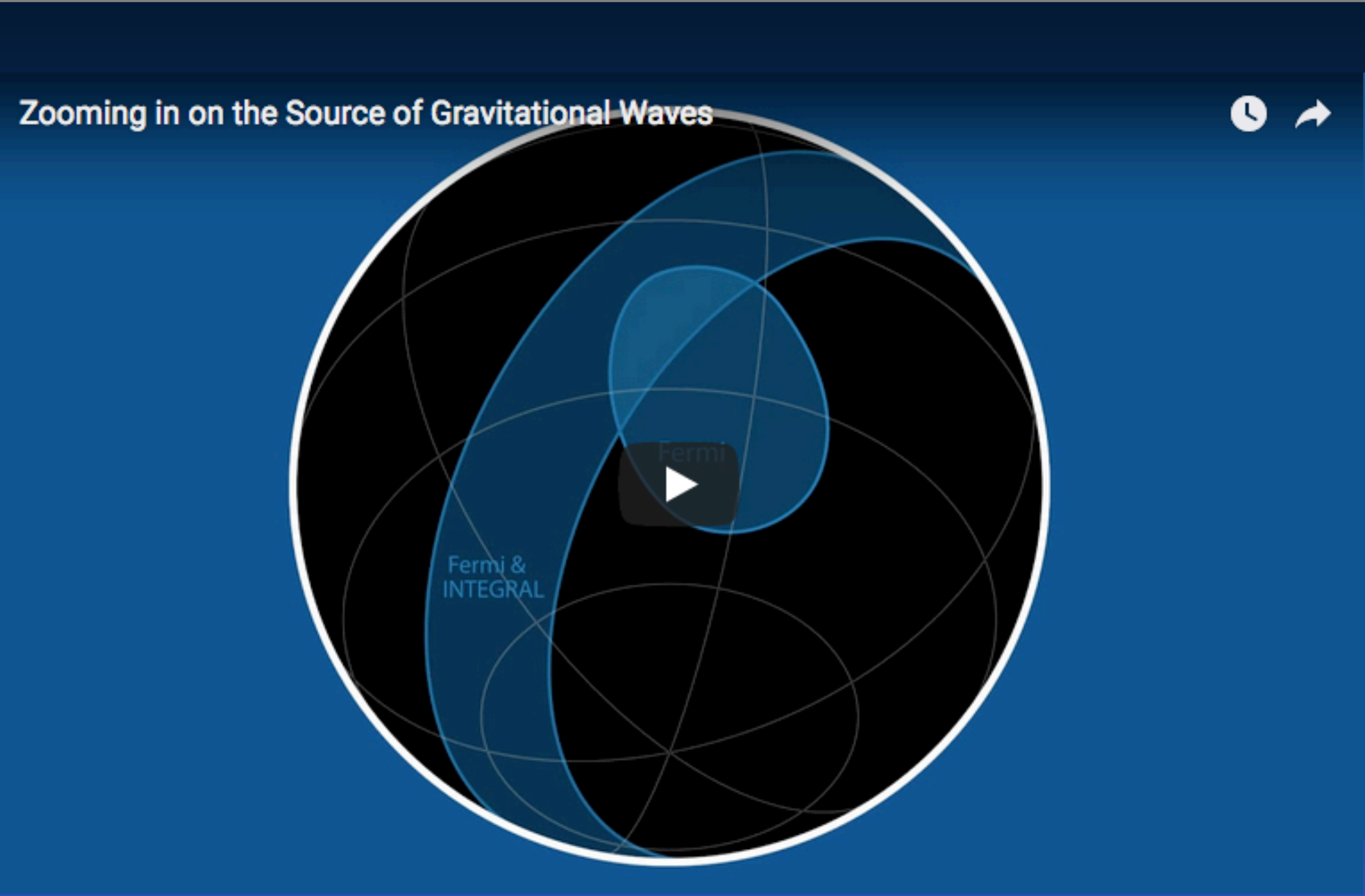
INTEGRAL

Time delay: 1.7 seconds

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

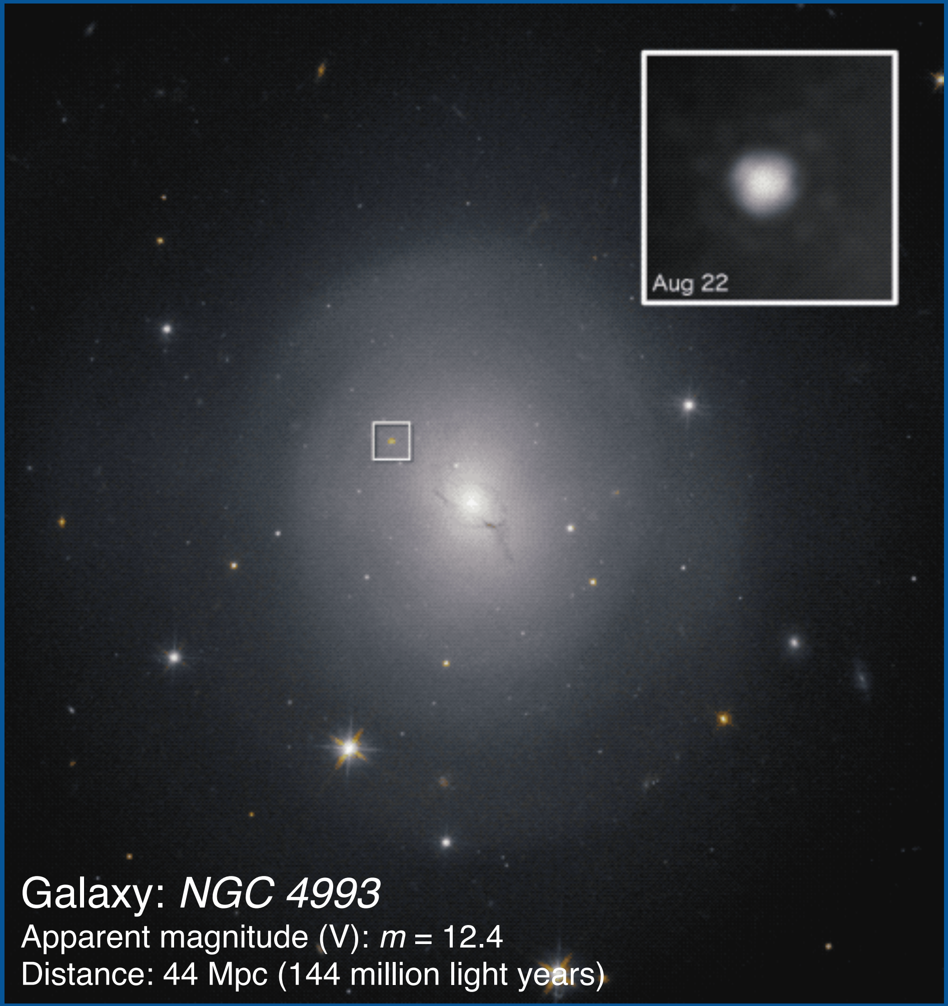
- More than 70 teams observed the field at time of GW detection with optical/IR telescopes

Optical/IR identification of galaxy that hosted BNS merger

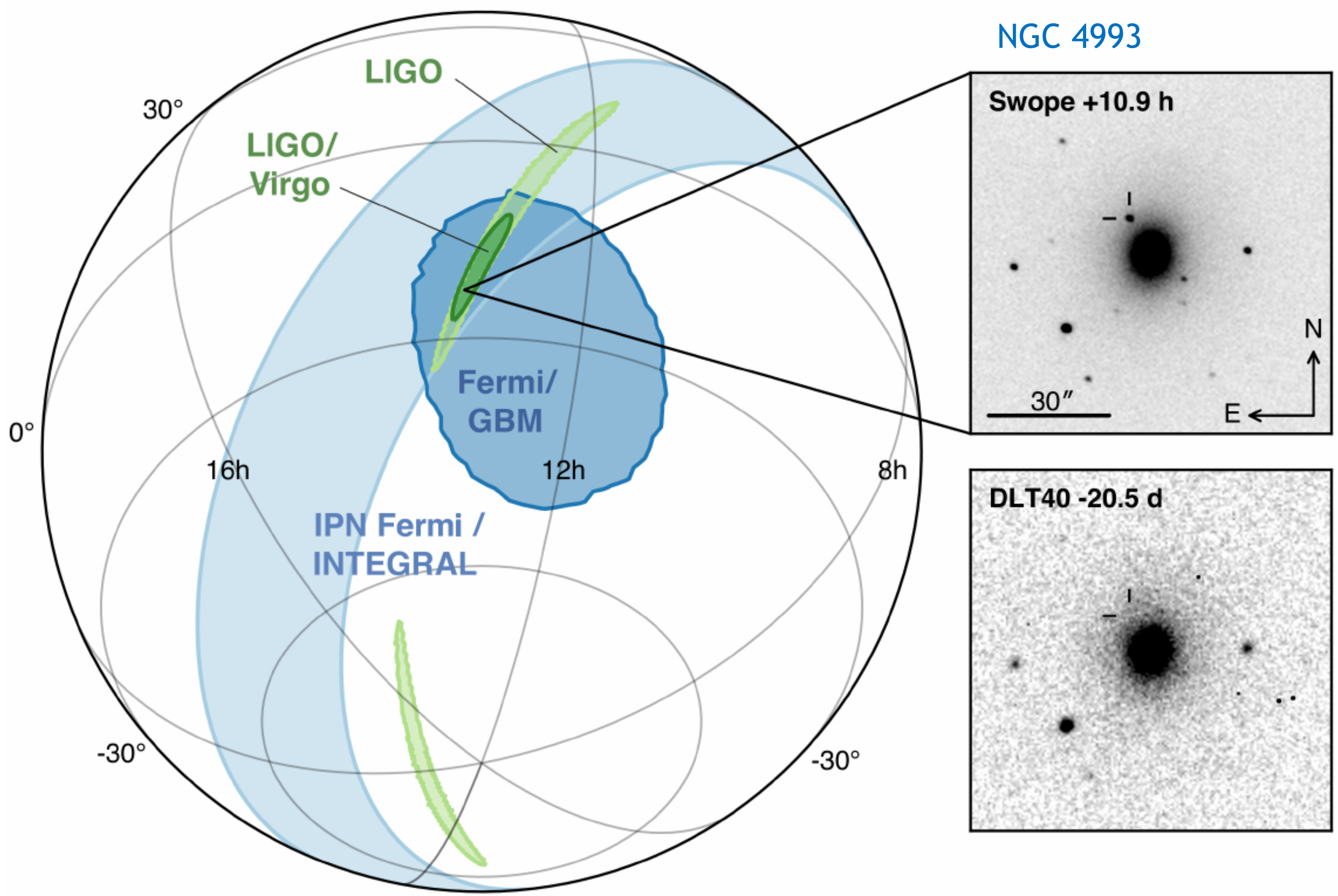


Video: https://www.ligo.caltech.edu/video/ligo20171016v7

Optical/IR identification of galaxy that hosted BNS merger

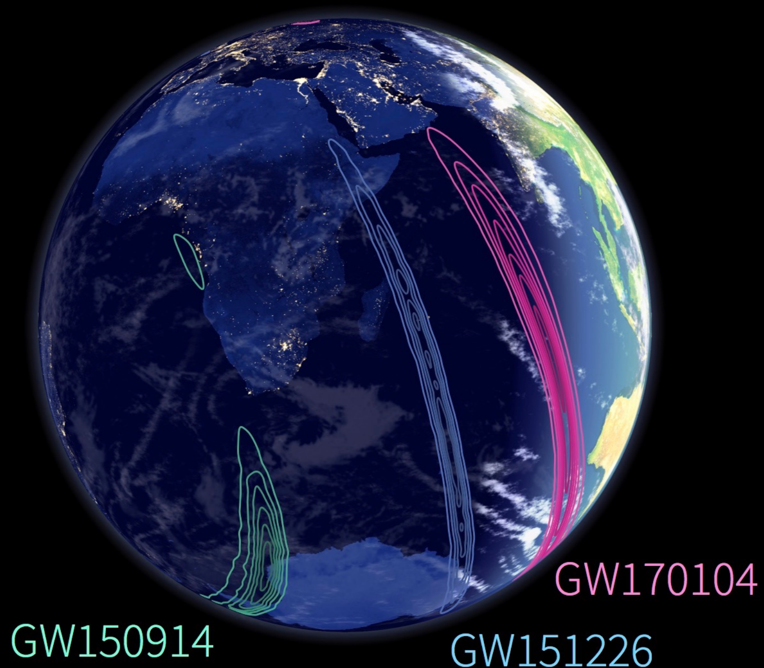


OPTICAL counterpart detection ~ 11 hours after GW trigger



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

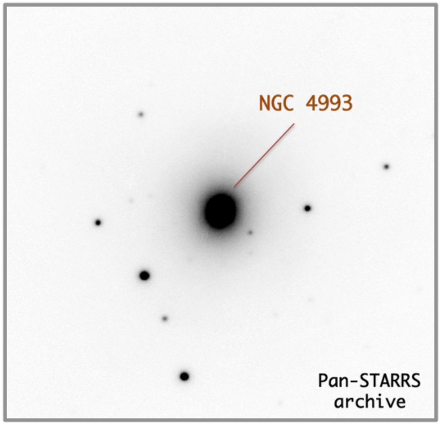
Localisation areas projected over the Earth surface

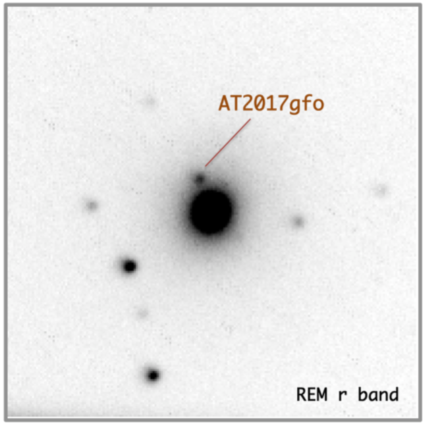


Previous sources detected with LIGO only

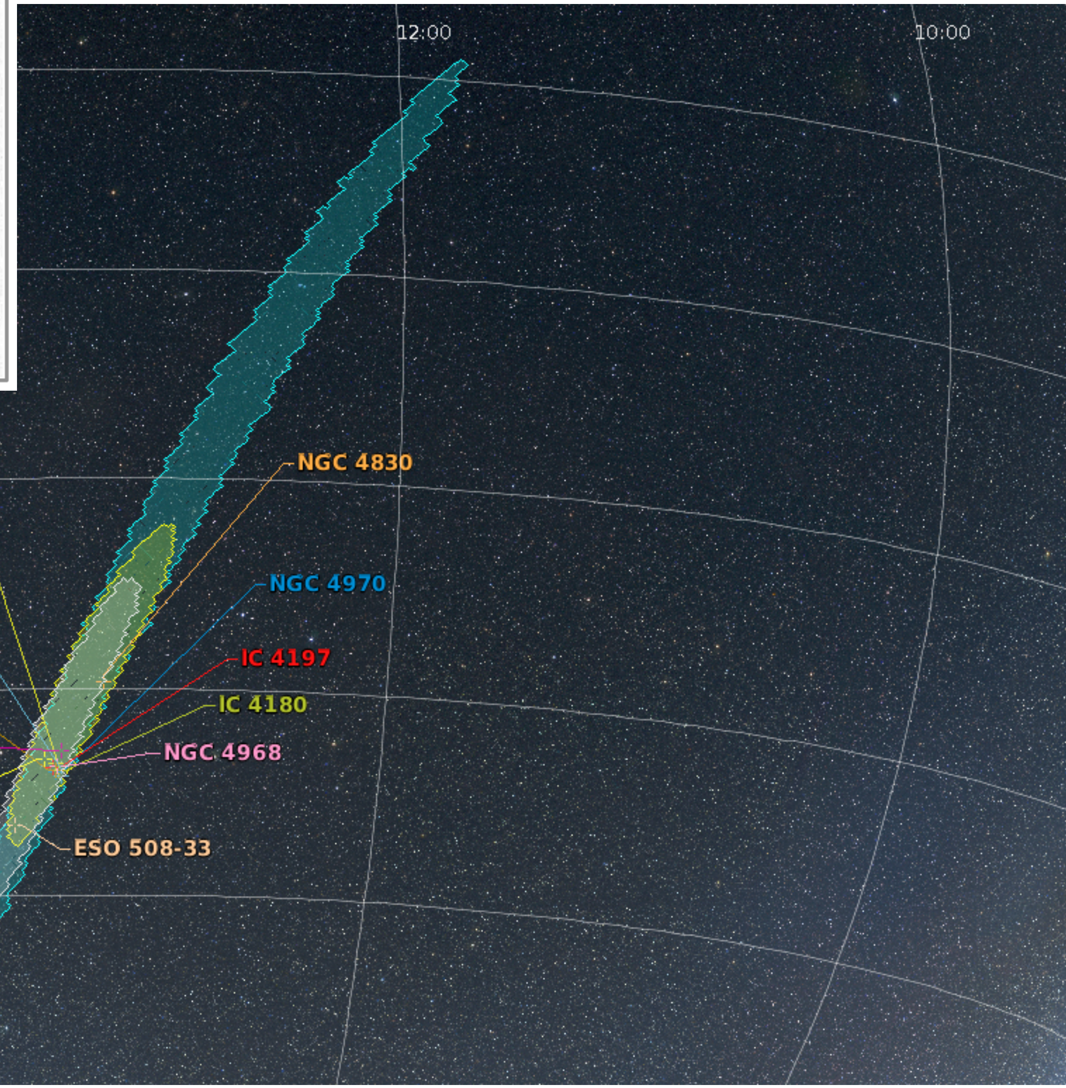
LIGO + Virgo
More precise localisation (28 square degrees) in Earth southern hemisphere

Optical/IR identification of galaxy that hosted BNS merger





GRAWITA: REM observations
~ 13 hours after GW trigger



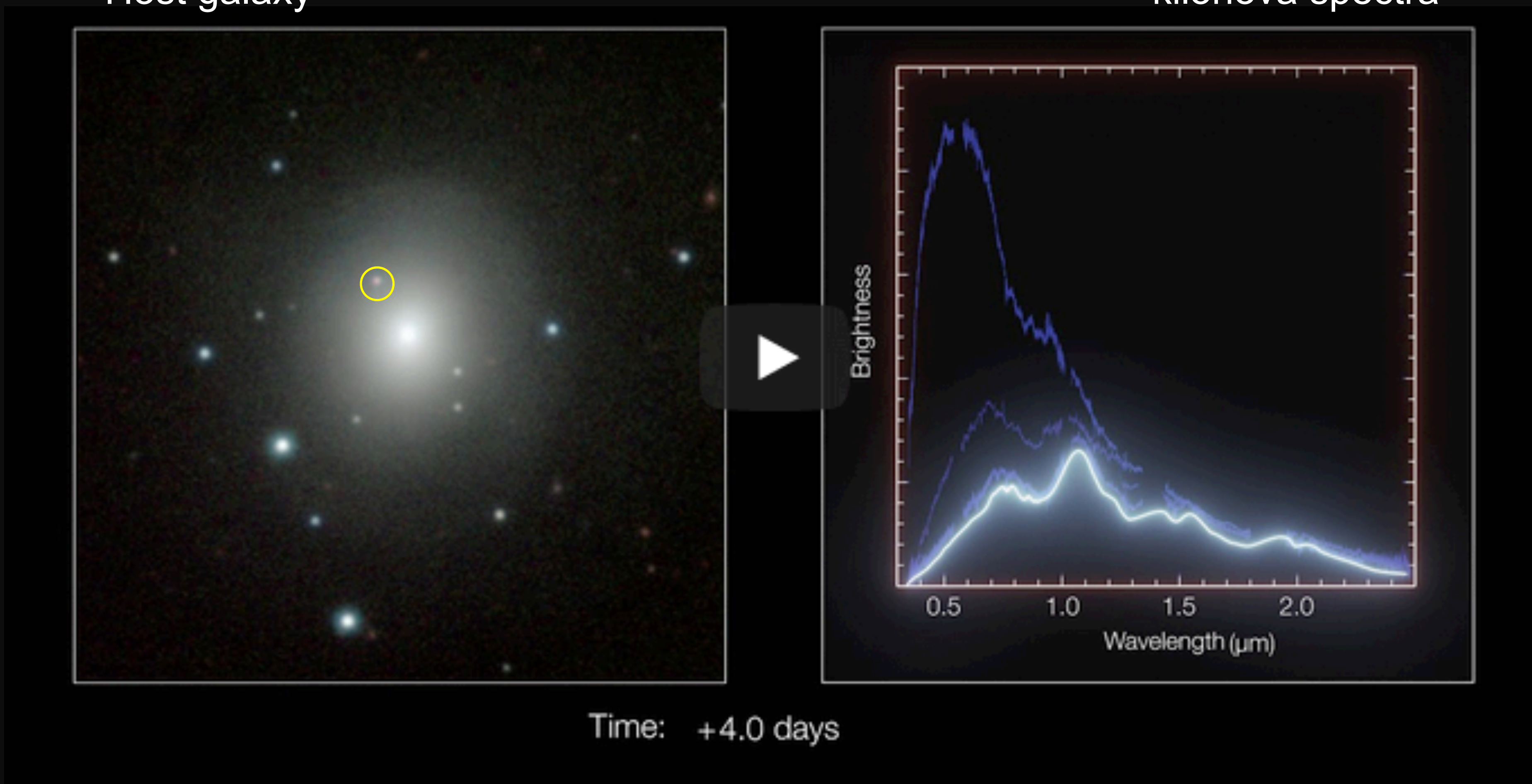
Rapid Eye Mount (REM) @ ESO La Silla (altitude: 2375 m)
Primary mirror: 60 cm
Secondary mirror: 23 cm

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

Time evolution of images and spectra

Host galaxy

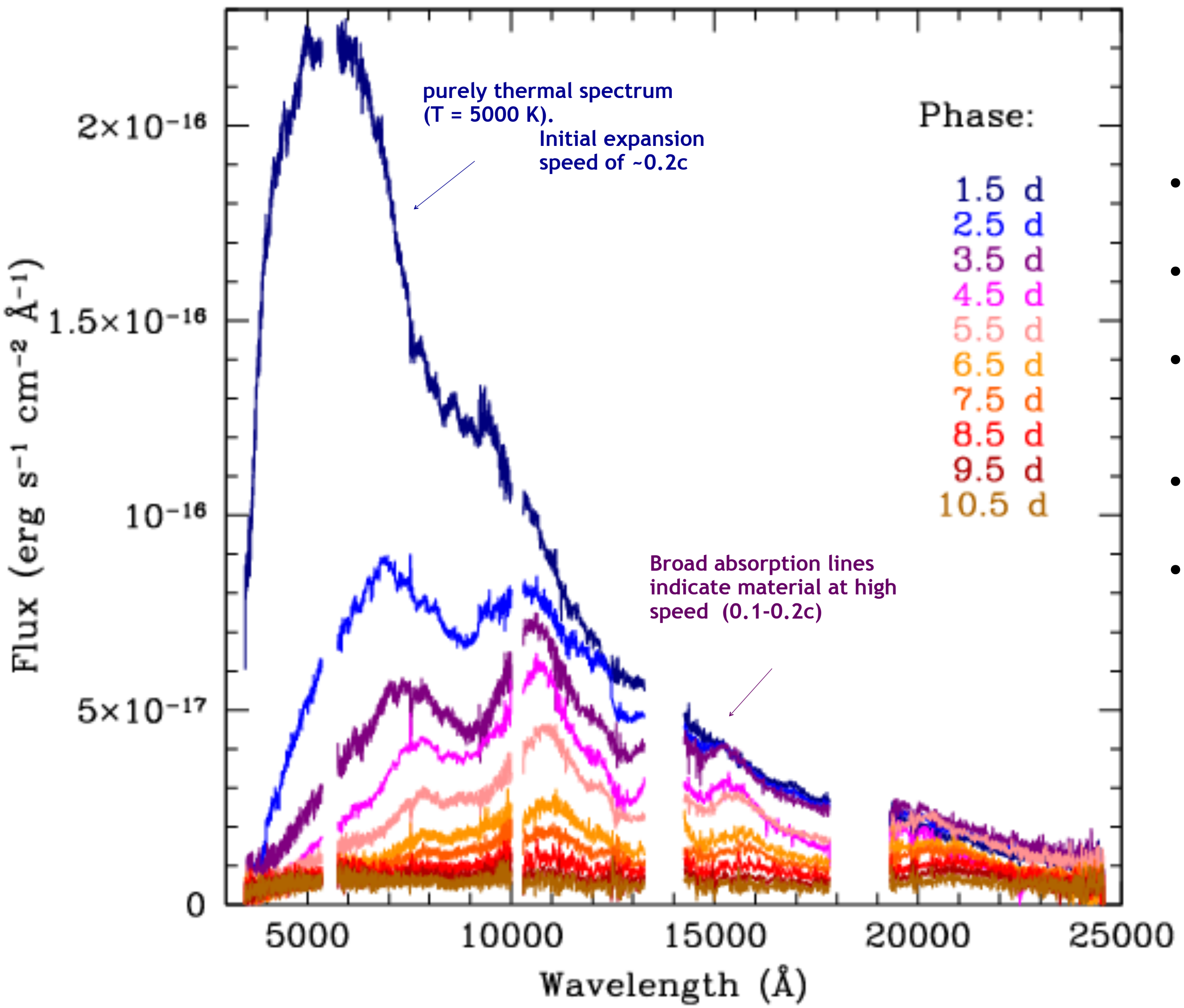
kilonova spectra



Video: https://www.eso.org/public/videos/eso1733e/

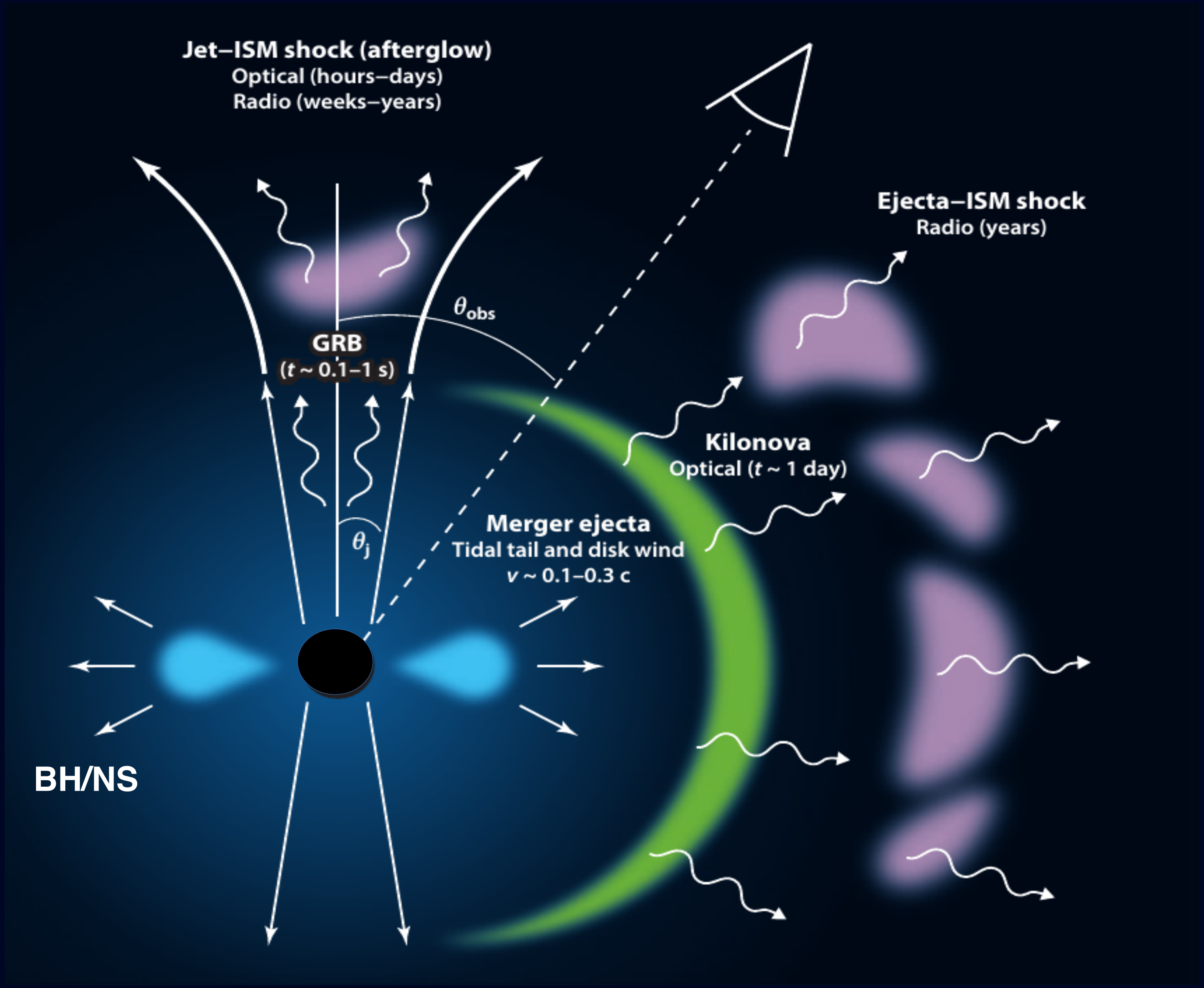
First evidence of *kilonova* & *r-process nucleosynthesis* in BNS

ESO VLT X-Shooter spectral sequence of AT2017gfo

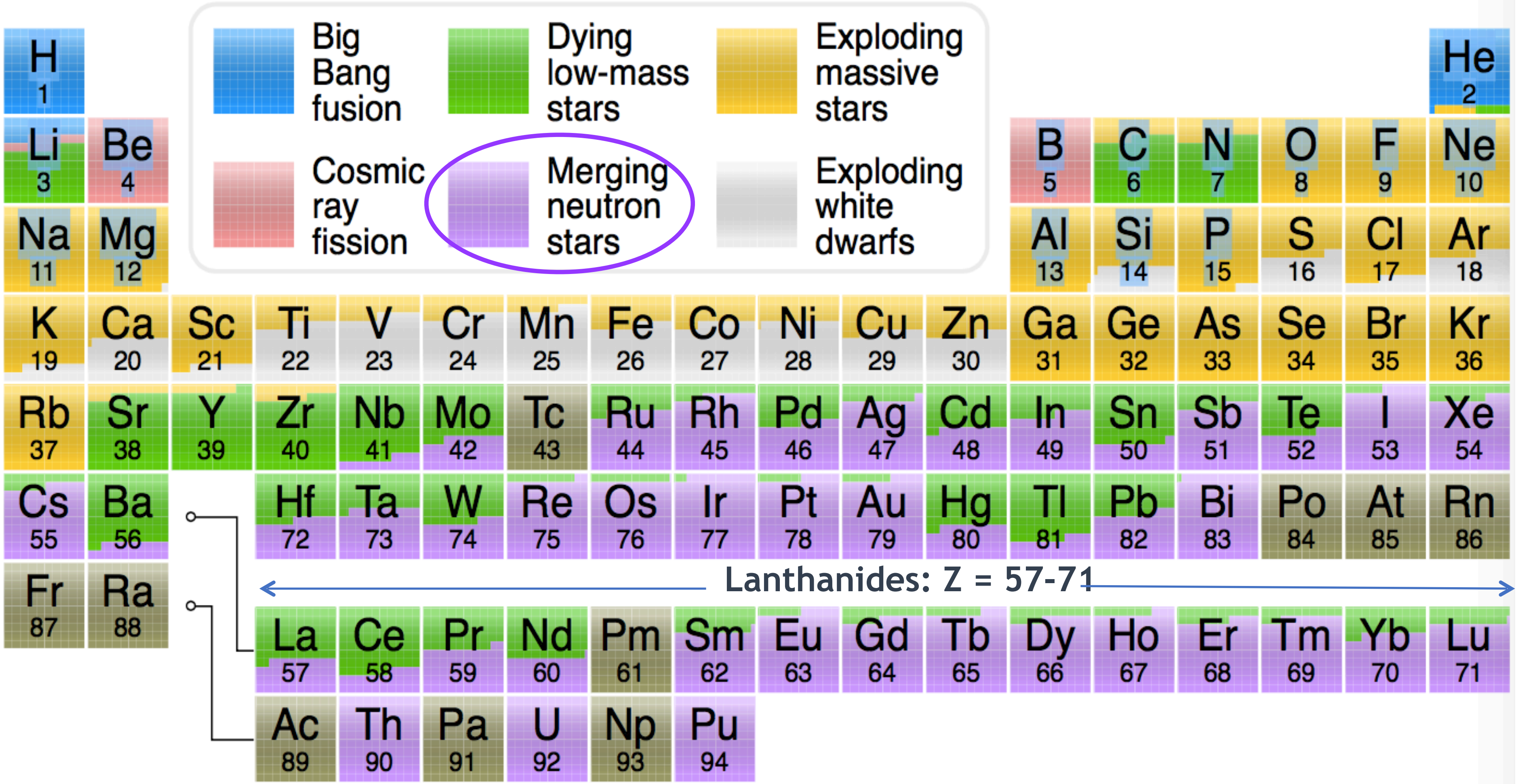


- In a couple of days, peak shifts to near infrared
- Broad spectral features appear
- These are completely different from those known for all SN types
- First confirmation of *kilonova* model
- Also supported by sGRB detection

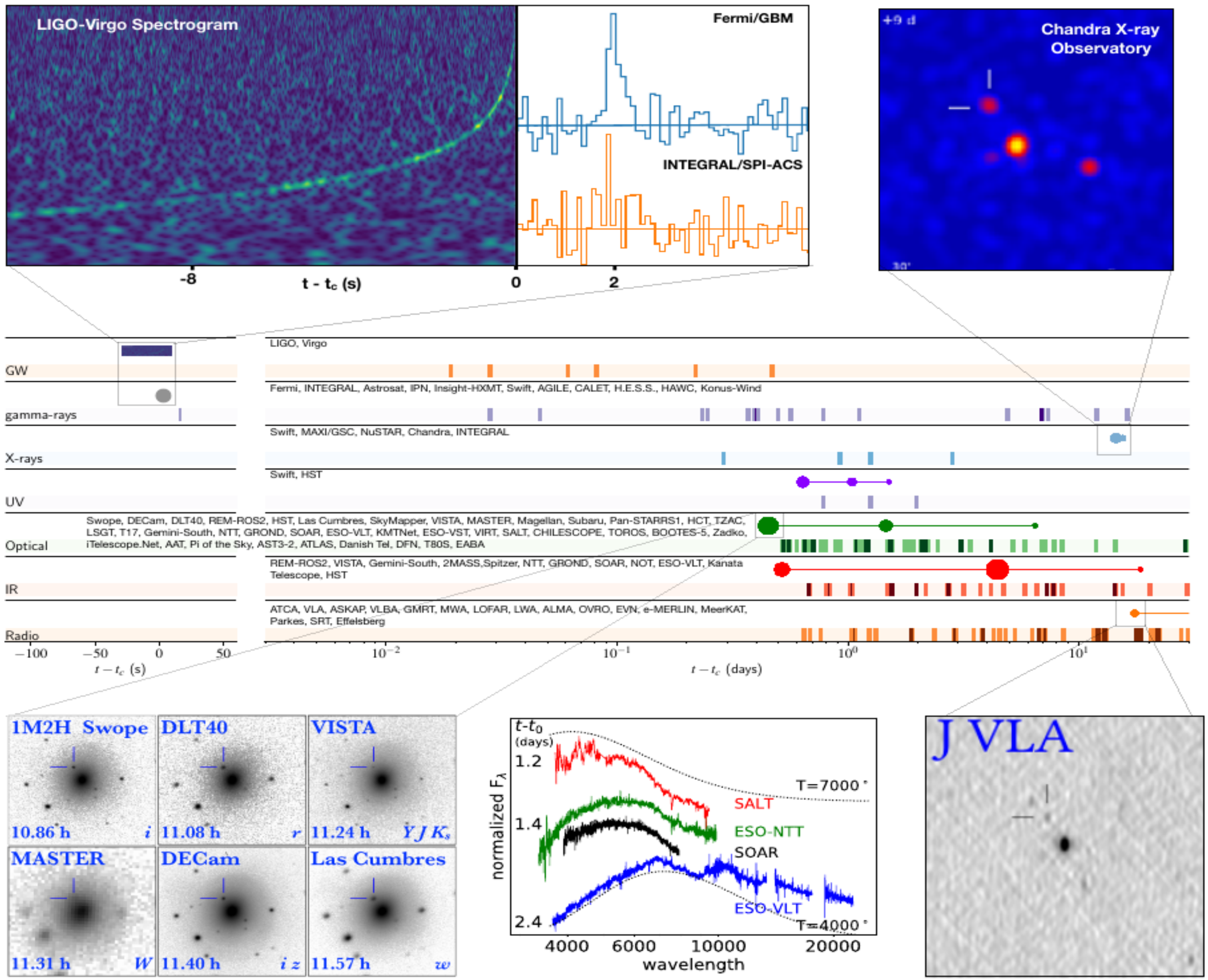
BNS merger: the expected facts



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



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



Abbott et al. 2017