Catching the (Gravity) Waves

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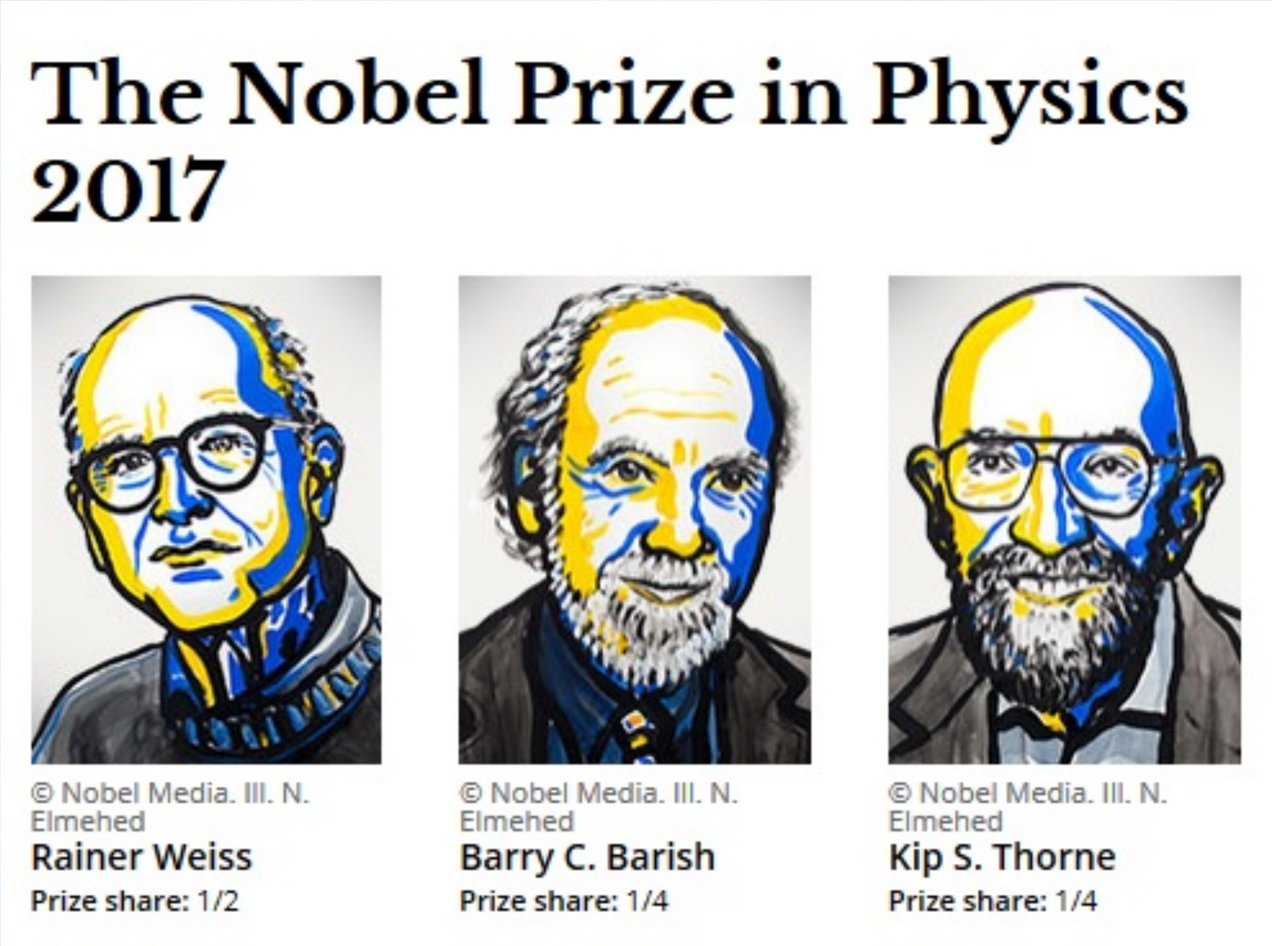
The Quest for…

unlikely,

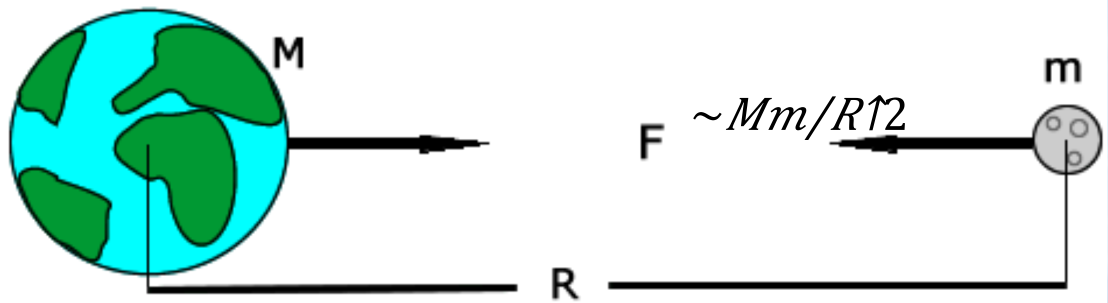
unmeasurable

…that changed everything!



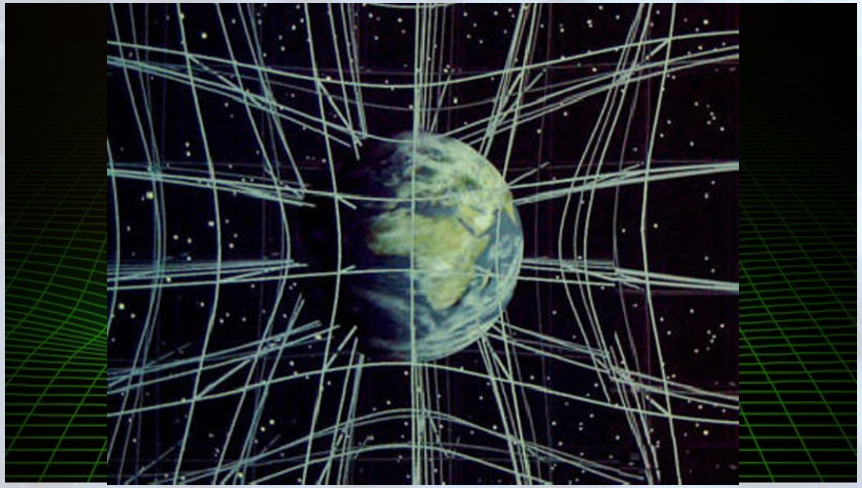
Year 1687….Gravity

- Isaac Newton
- Attractive force between massive bodies



November 1915 … Relativity

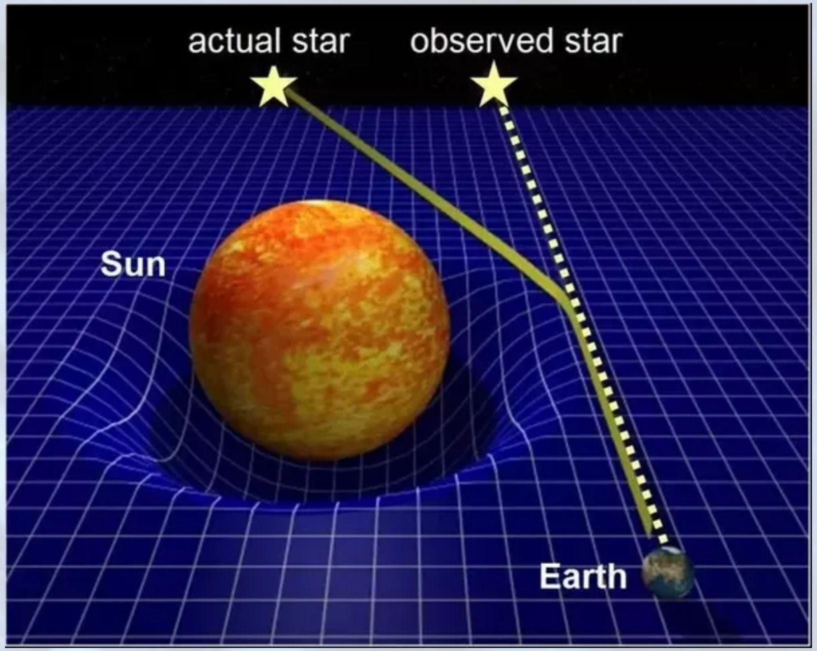
- Albert Einstein and General Theory of Relativity
- Revolution in our understanding of gravity
- Gravity is the bending of space due to mass

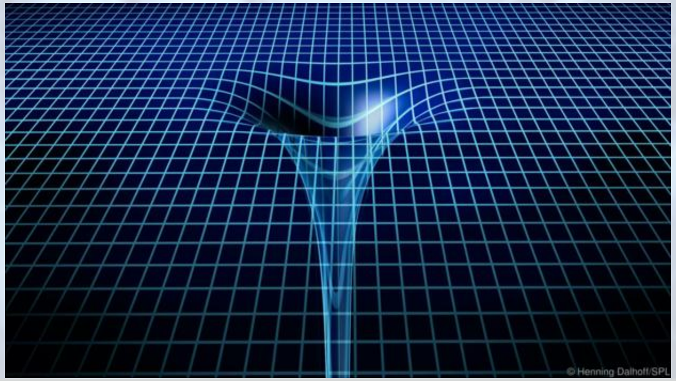


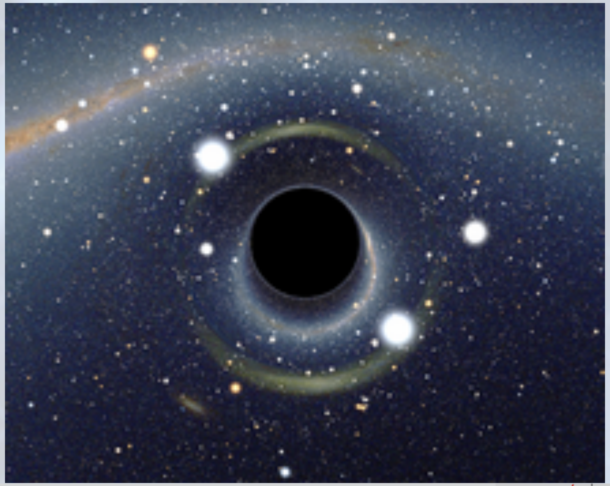
Mass tells space how to bend and space tells mass how to move.

New Concepts

- Light bending in the vicinity of matter
  - Light moves in curved space
  - Light follows curved paths
- Existence of black holes
  - Objects that not even light can escape
  - Space too curved







Gravitationa
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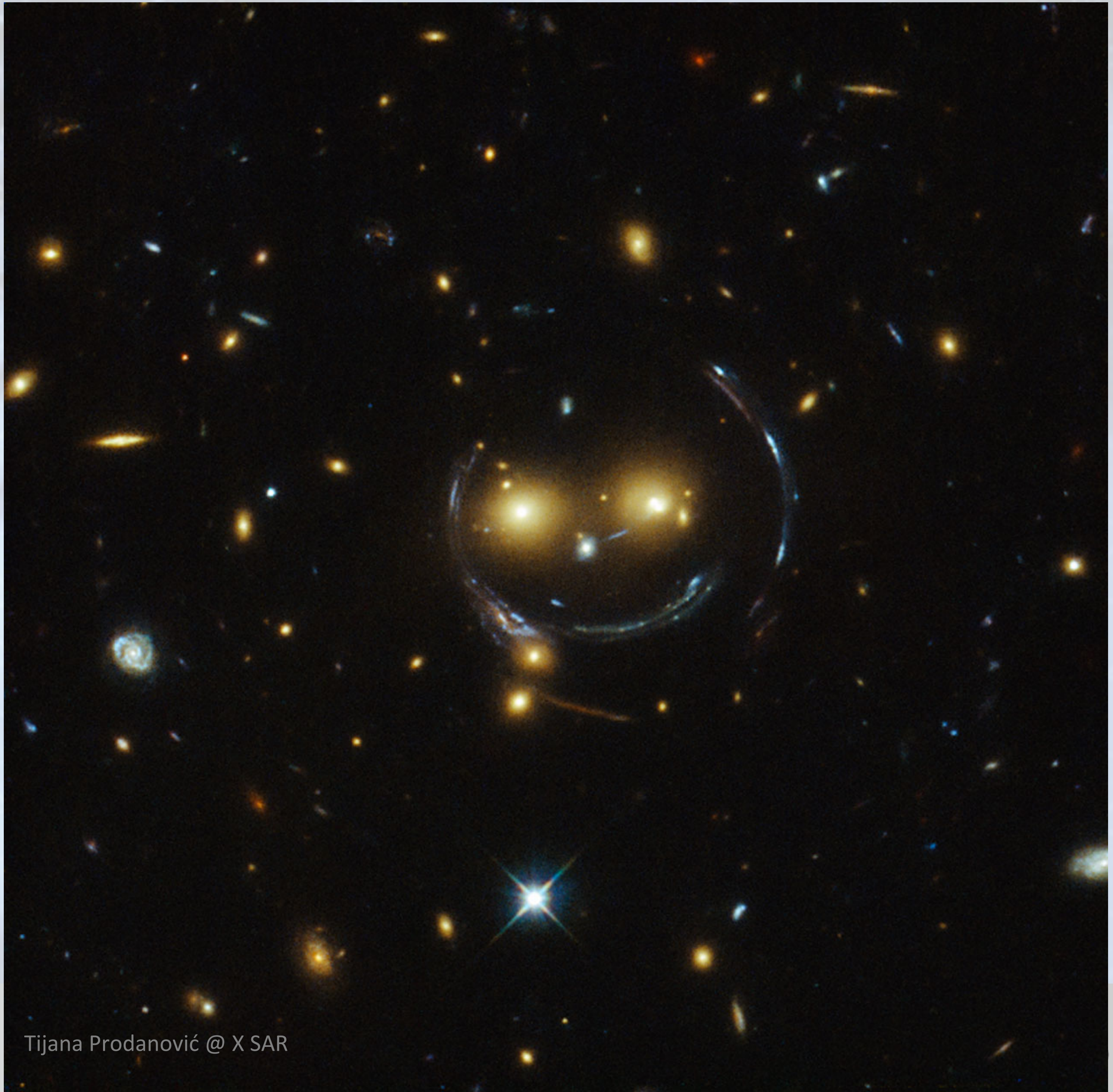
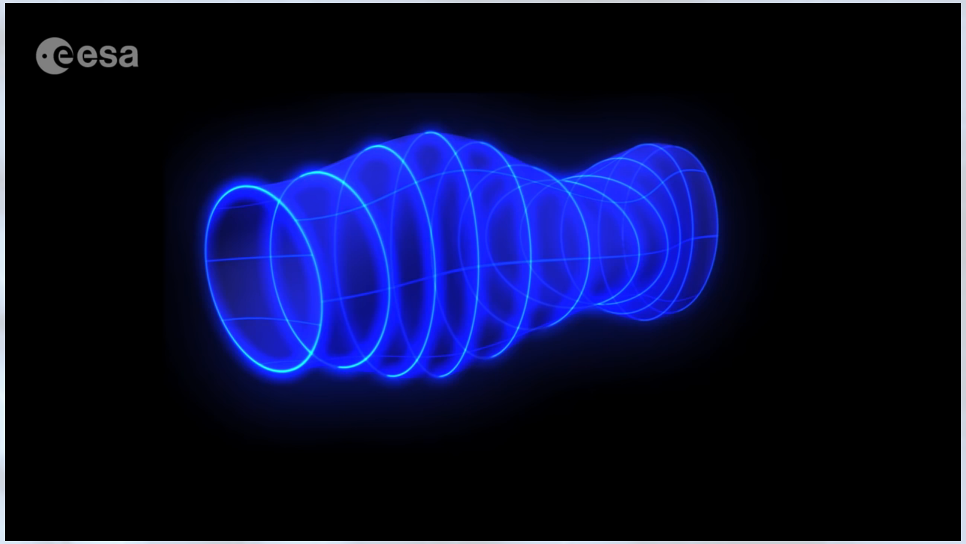


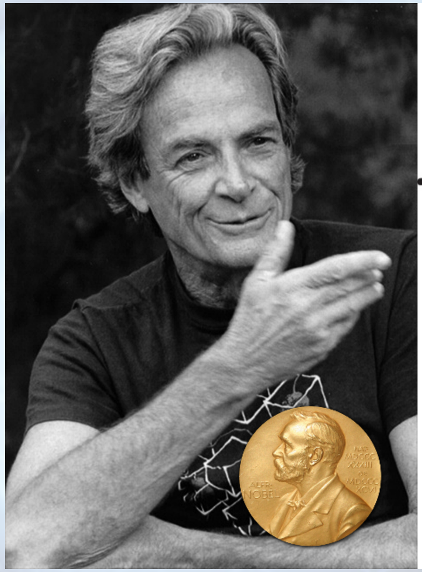
New Concepts

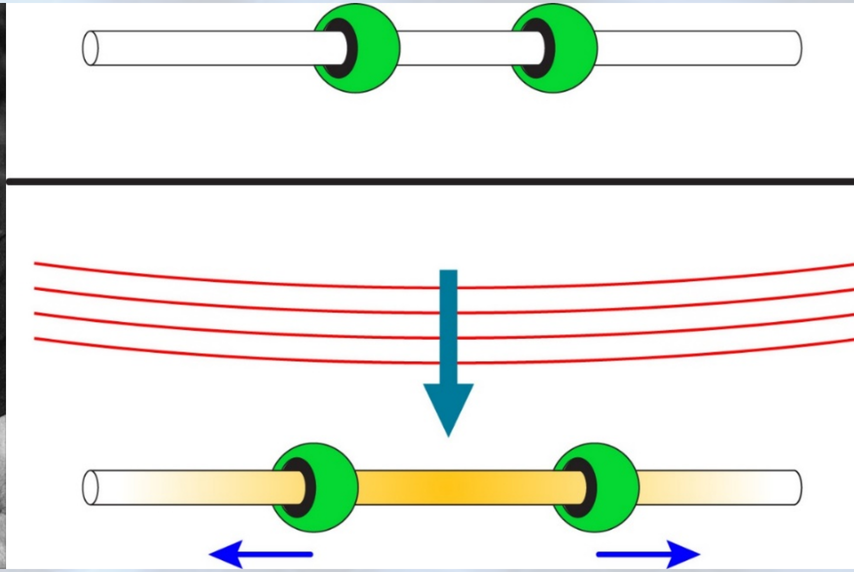
- Existence of gravitational waves
  - Accelerating matter
  - Disturbance of space-time
  - Waves in space-time itself
  - Similar to emission of EM waves when accelerated charges make disturbances in EM fields which we see as light
- But, just a mathematical artefact or physical?
- Can it be observed? Do the carry energy?



January 1957… Gravitational Waves

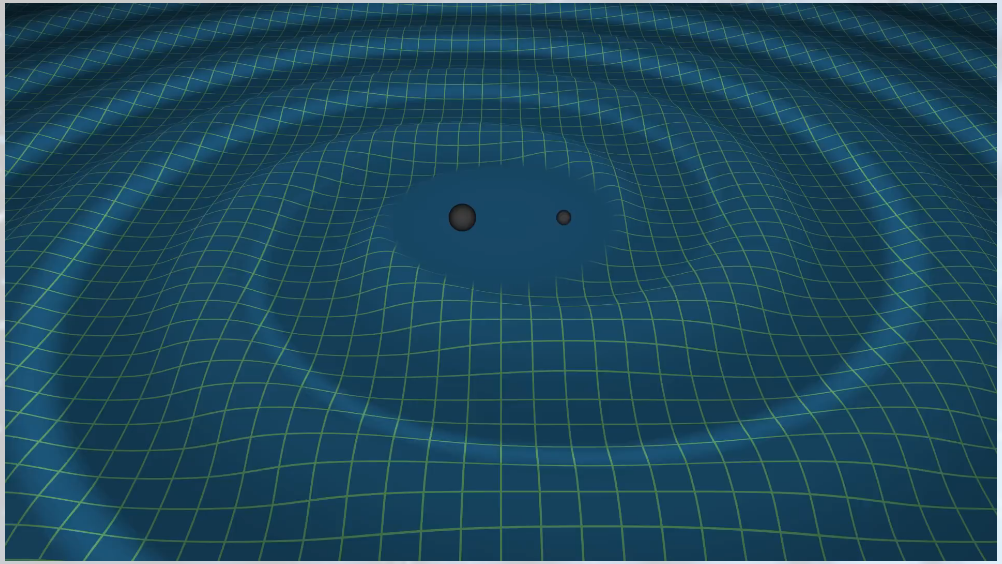
- Chapel Hill general relativity conference at University of South Carolina
- Do gravitational waves carry energy?
- “Sticky Bead Argument”
  - Richard Feyman
  - Analogy – gravitational wave moves beads along the stick and due to friction stick heats up

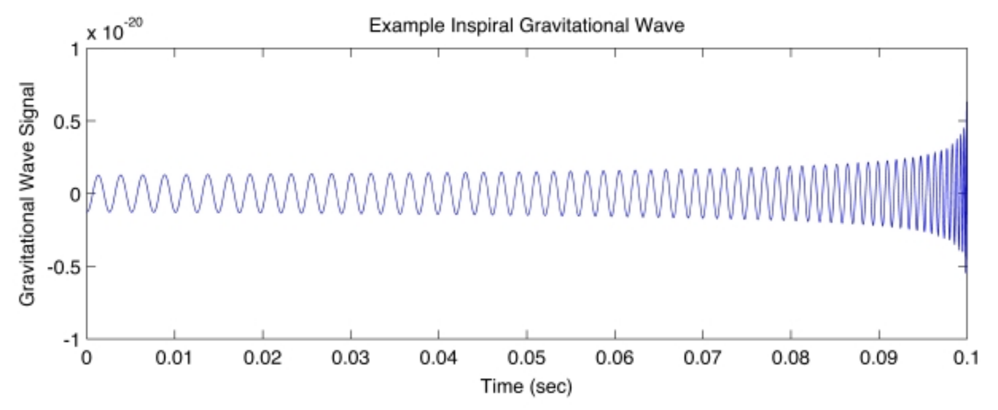




Systems lose energy when emitting gravitational waves!

Sources of Gravitational Waves: Mergers

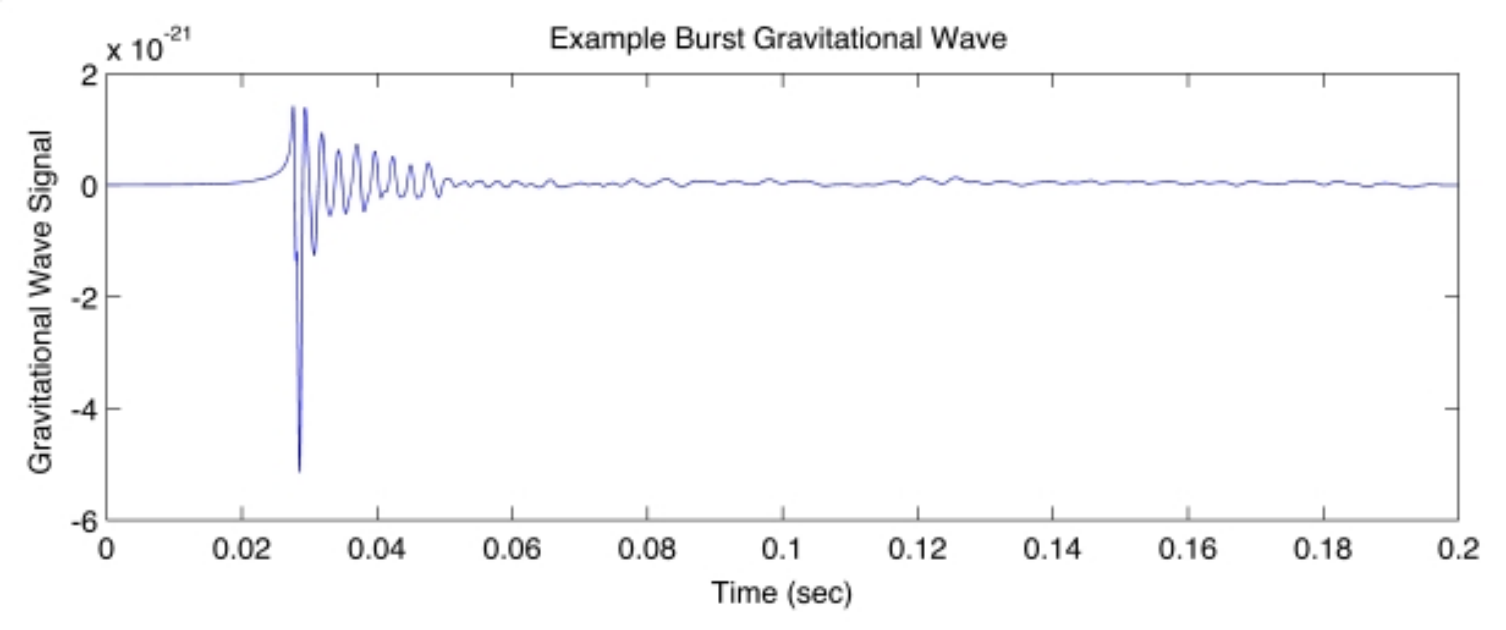




- Binary systems
- System loses energy by emitting gravitational waves
- Orbit decays (bodies move closer(
- Merger
- High amplitude waves emitted in the final stages

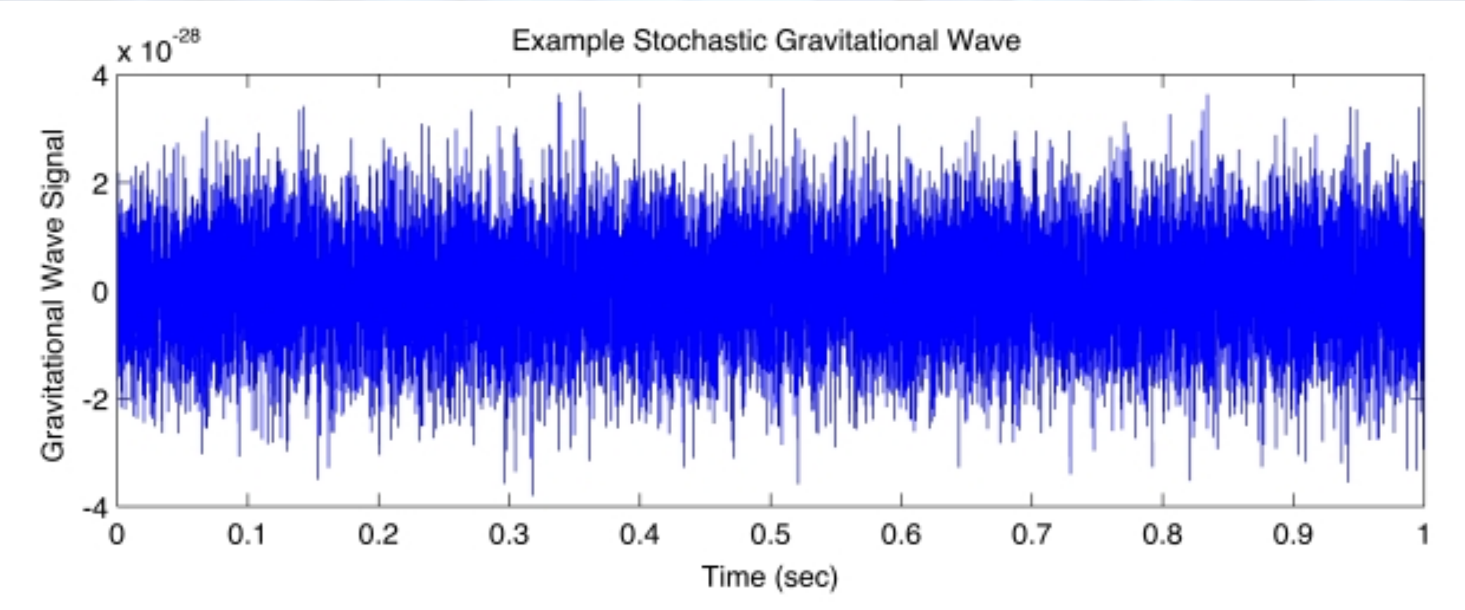
Sources of Gravitational Waves : Bursts

- Supernovae
- Black hole or neutron star birth
- Sudden collapse of massive body



Sources of Gravitational Waves : Early Universe

- Stochastic gravitational waves
- Echo of the big bang
- Cosmic gravitational background

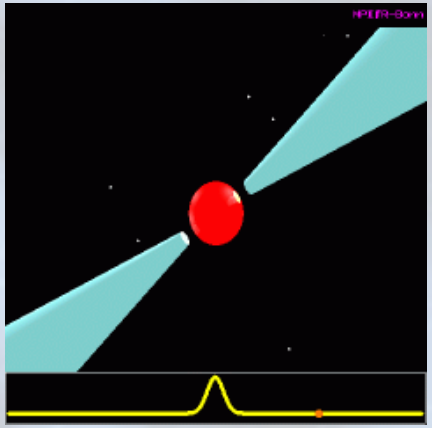


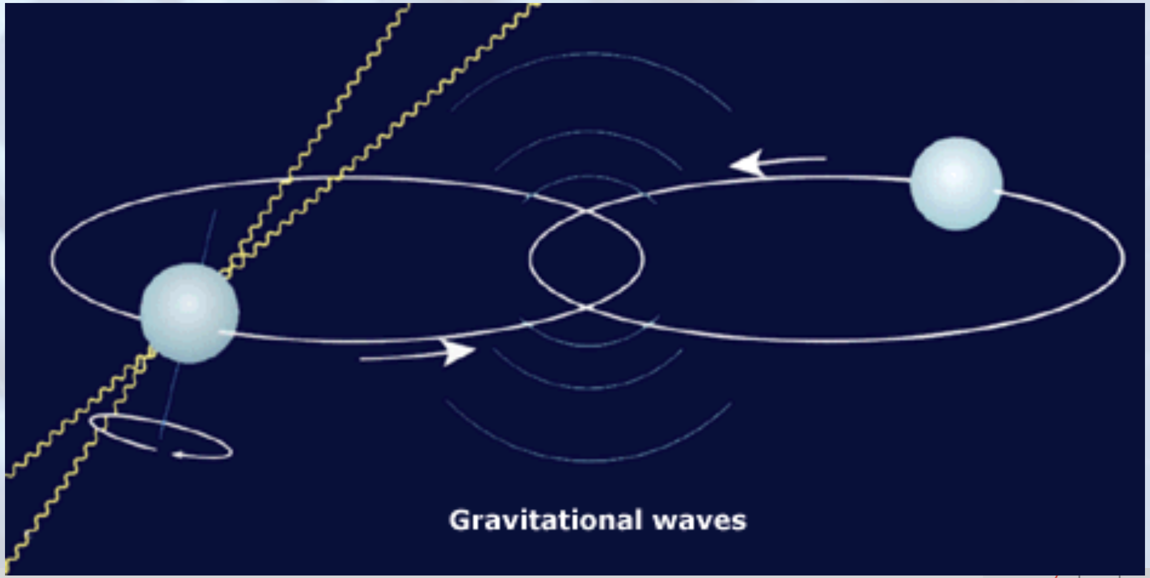
Unmeasurable?

- Energy of gravitational waves very small
- Wave amplitude decreases with distance (~1/r)
- Possibility to catch maybe only gravitational waves from mergers of most massive objects!
- Only mergers where merger timescale is shorter than Hubble time
- Hopeless?
- Not even Einstein believed that they will ever be detected

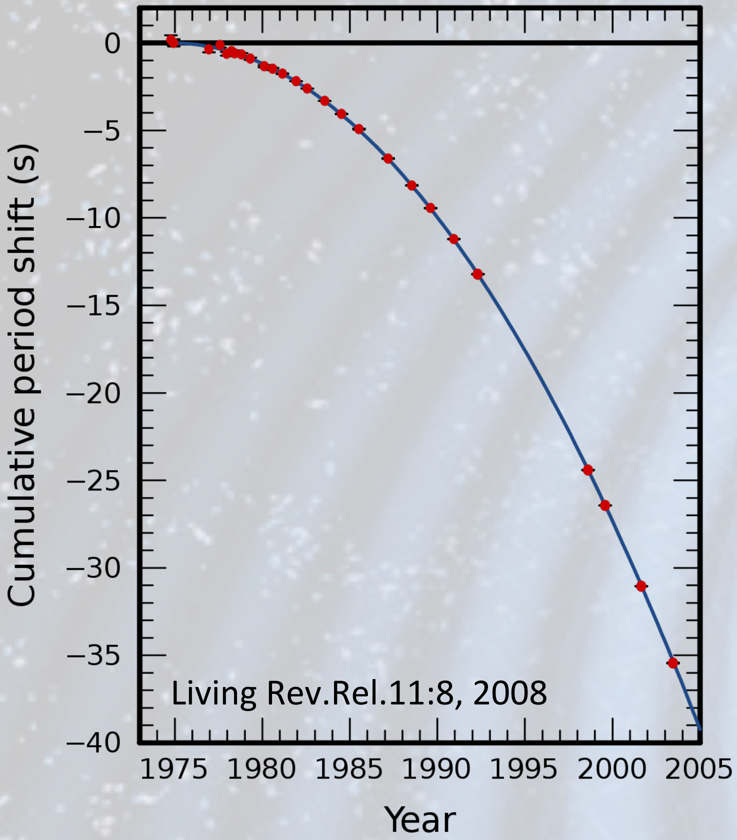
Year 1974 … Indirect Detection

- Joseph Taylor & Alan Russel Hulse
  - Detected a pulsar PSR1913+16
  - Signal is periodically running late or running fast
  - Pulsar in a binary system with a neutron star!





Hulse-Taylor pulsar



- Separation less than Earth-Moon orbit
- Period approx. 8h
- Accelerated motion – emission of gravitational waves
- System loses energy
- Orbit decays
- Period shortens (Taylor et al 1979)
- Measured! 40 sec over 30 years
- Will merge in ~ 300 Myr

Direct consequence of emission of gravitational waves detected!

The Nobel Prize in Physics 1993
Russell A. Hulse, Joseph H. Taylor Jr.

Share this: 32

The Nobel Prize in Physics 1993

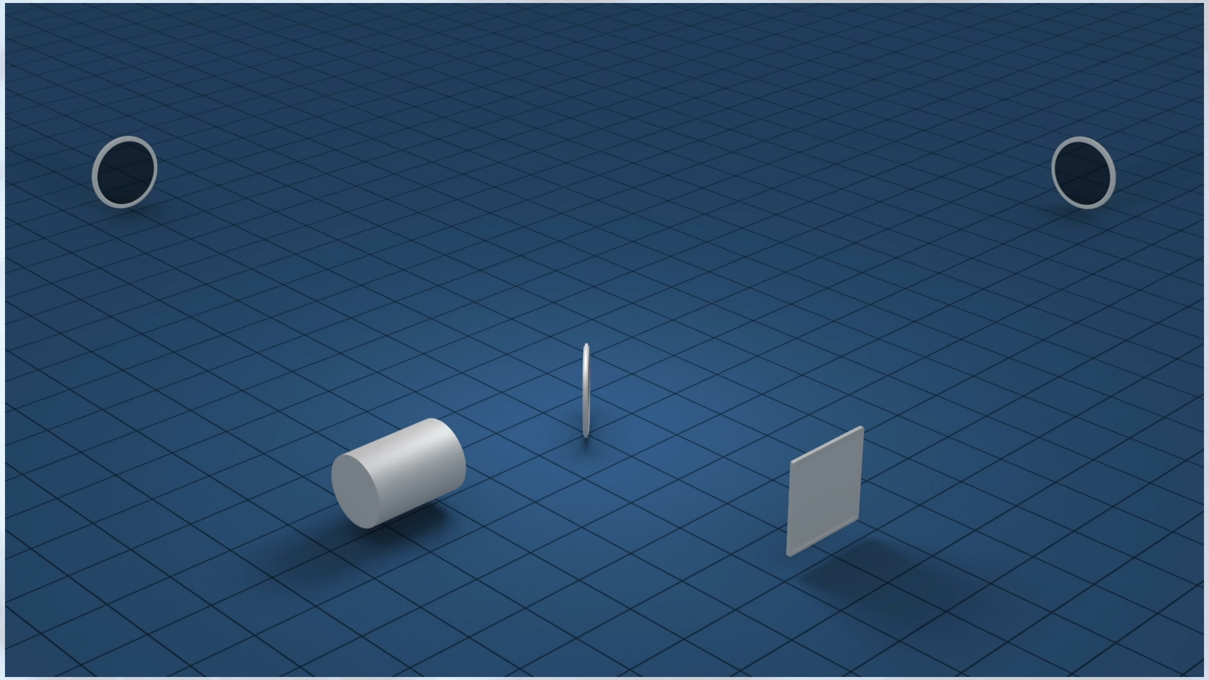
Russell A. Hulse
Prize share: 1/2

Joseph H. Taylor Jr.
Prize share: 1/2

The Nobel Prize in Physics 1993 was awarded jointly to Russell A. Hulse and Joseph H. Taylor Jr. *"for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"*

Detecting Gravitational Waves

- Laser interferometry
- Split laser beam into two orthogonal beams
- Light bounces off mirrors and interferes
- Gravitational waves – transverse waves from some direction
- Spacetime oscillates – shrinks in one and stretches in other direction
- Laser interference pattern changes



Laser Interferometer Gravitational-Wave Observatory (LIGO)

- Caltech-MIT joint effort
- Project leaders: Kip Thorne, Rainer Weiss, Ronald Drever (died in March 2017) & Barry Barish
- Started in 70s with smaller models (1.5 and 40m)
- Idea about 2 large detectors submitted in 1983
- Construction 1994-1999

Year 2002 …Detector

- Two large detectors in USA separated 3000km

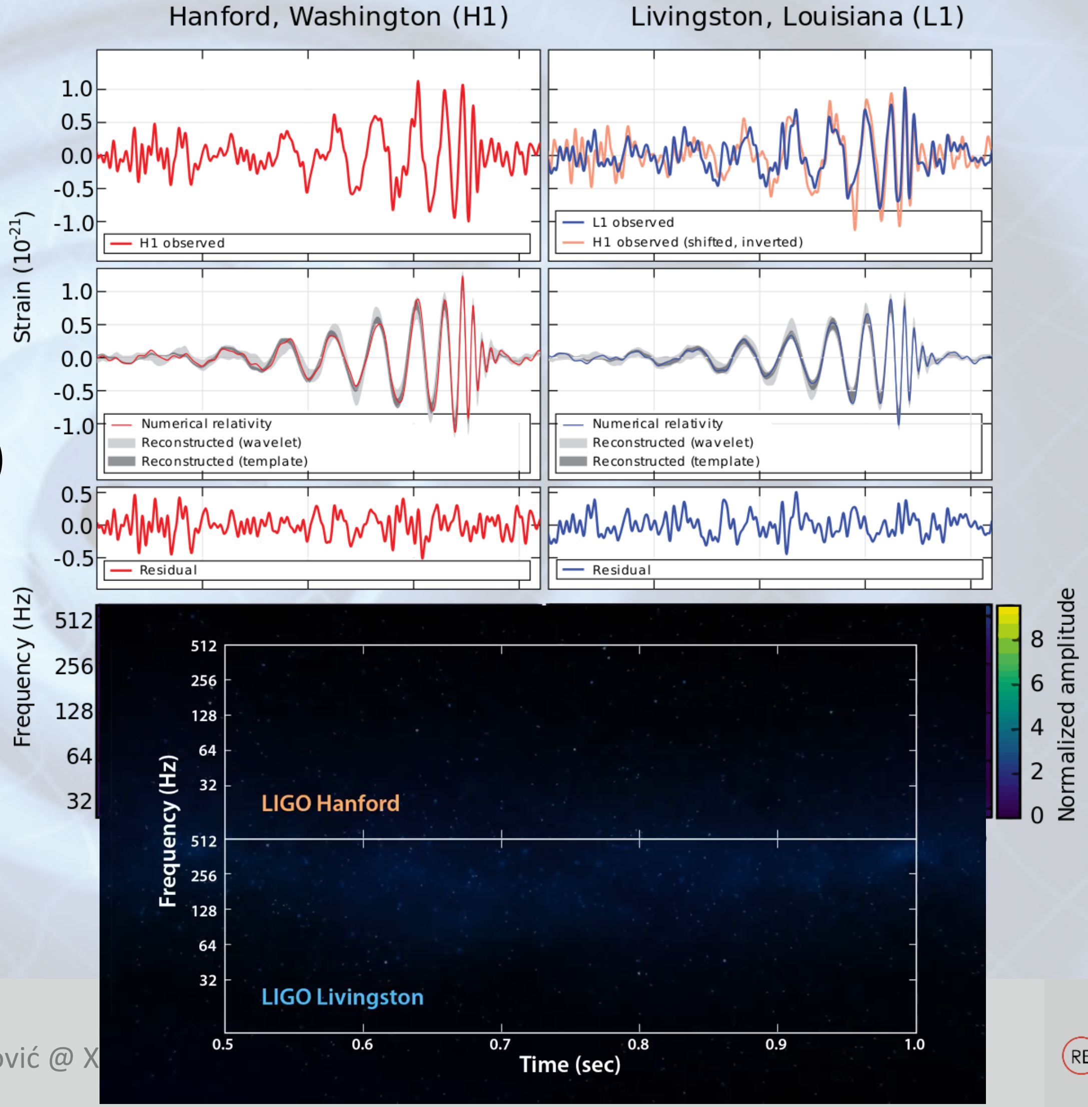
- Beam arms (vacuum) of length 4km
- Look for simultaneous signal in both detectors (noise: earthquakes and other disturbances)

Year 2010-2016 … LIGO

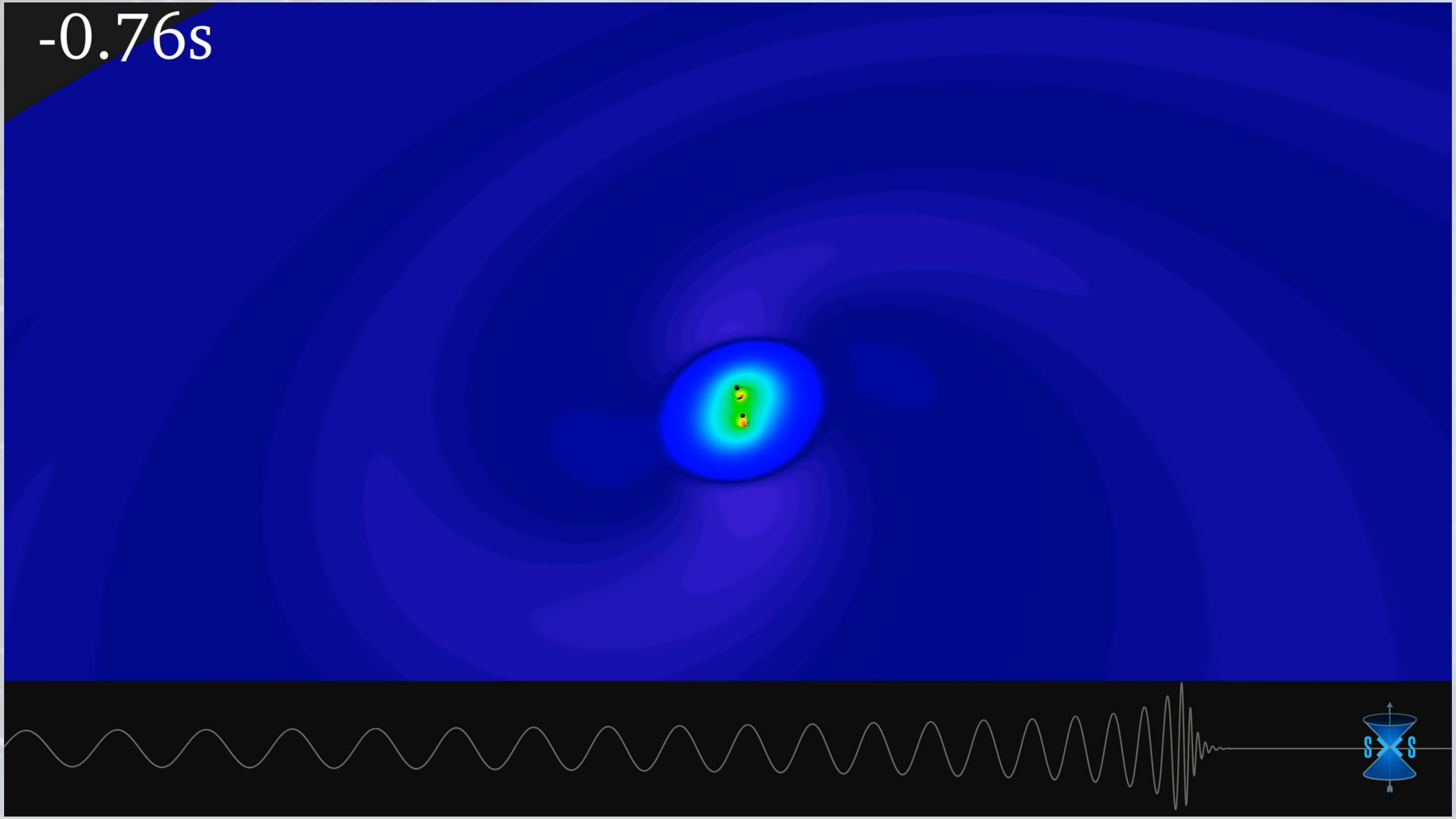
- Running from 2002-2010 LIGO did not make any detections
- Closed for improvements
- aLIGO – advanced LIGO (Davide 2015)
- Can detect shifts of 1000x smaller than proton scale (~10^{-18}m)
- Testing phase
- First run scheduled for September 18th 2015

September 14th 2015 … First waves!

- 4:50 am
- Unexpected, identical, simultaneous signal recorded by both detectors!
- More tests?
- Real signal! GW150914 (Abbot et al 2016)
- Merger of 2 black holes of 36 M_{sun} and 29 M_{sun}
- At 410 Mpc
- 3M_{sun} of energy released in gravitational waves!



First Detection- Merger of 2 Black Holes

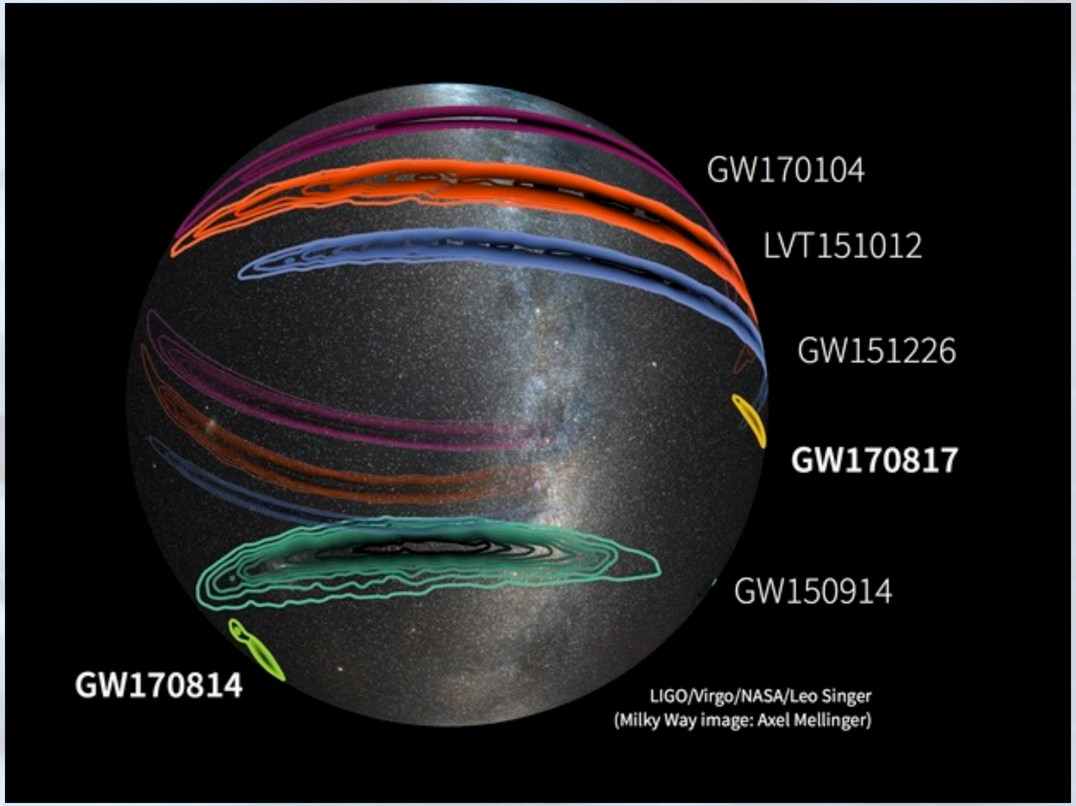


August 2017 … Backup!

- Advanced VIRGO starts with operations in Italy close to Pisa
- European gravitational wave detector (France, Italy, Nederland, Poland, Spain, Hungary)
- Arms of length 3km

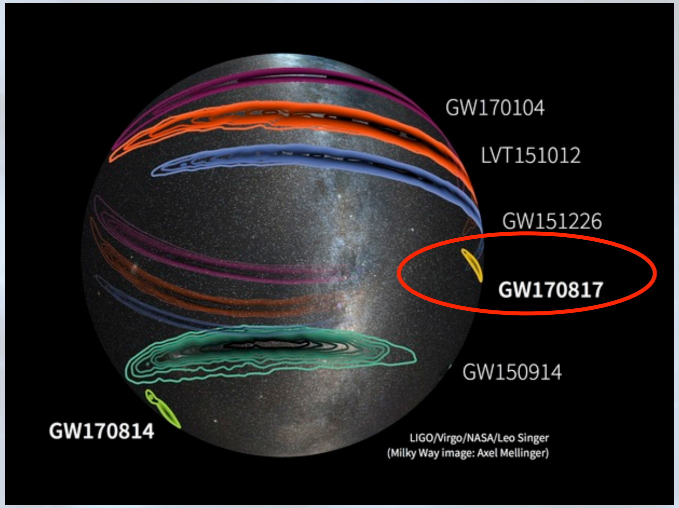
Waves Keep Coming…

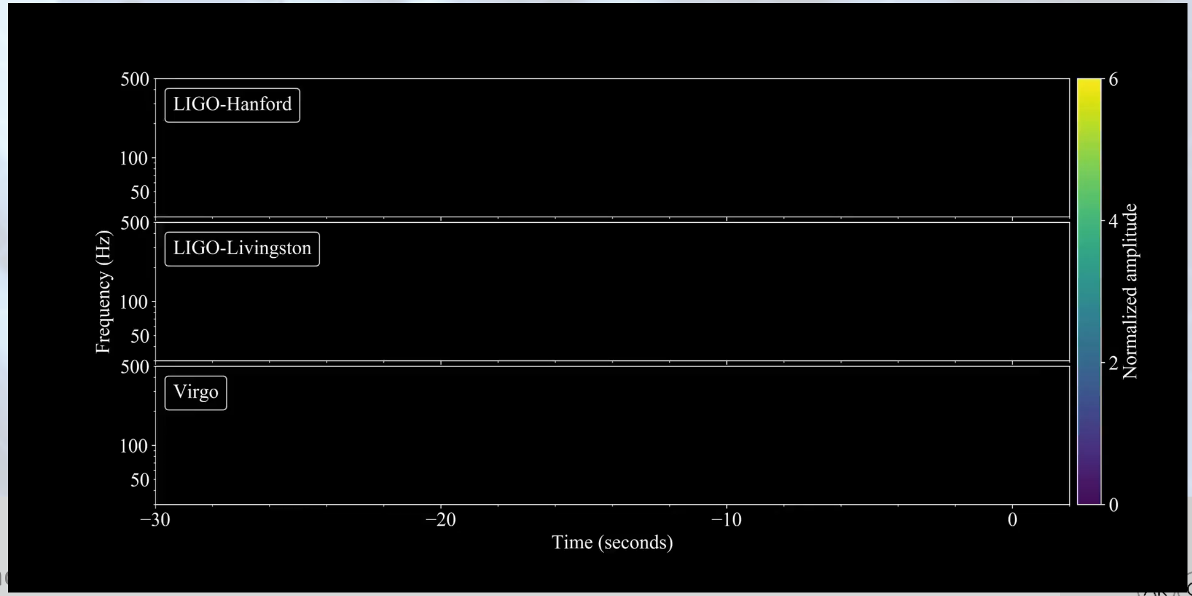
- Dec. 26th 2015 – merger of 2 BHs
  - 14 and 8 solar masses at ~ 440 Mpc
- Jan. 4th 2017 – merger of 2 BHs
  - 32 and 19 solar masses at ~ 1Gpc
- August 14th 2017 – merger of 2 BHs detected by both LIGO and VIRGO
  - 31 and 25 solar masses at ~ 0.3 Gpc
- June 7th 2017, announced on Nov. 15th
  - 7 and 12 solar masses at ~ 0.3 Gpc



August 17th 2017 … Waves from the Neighborhood

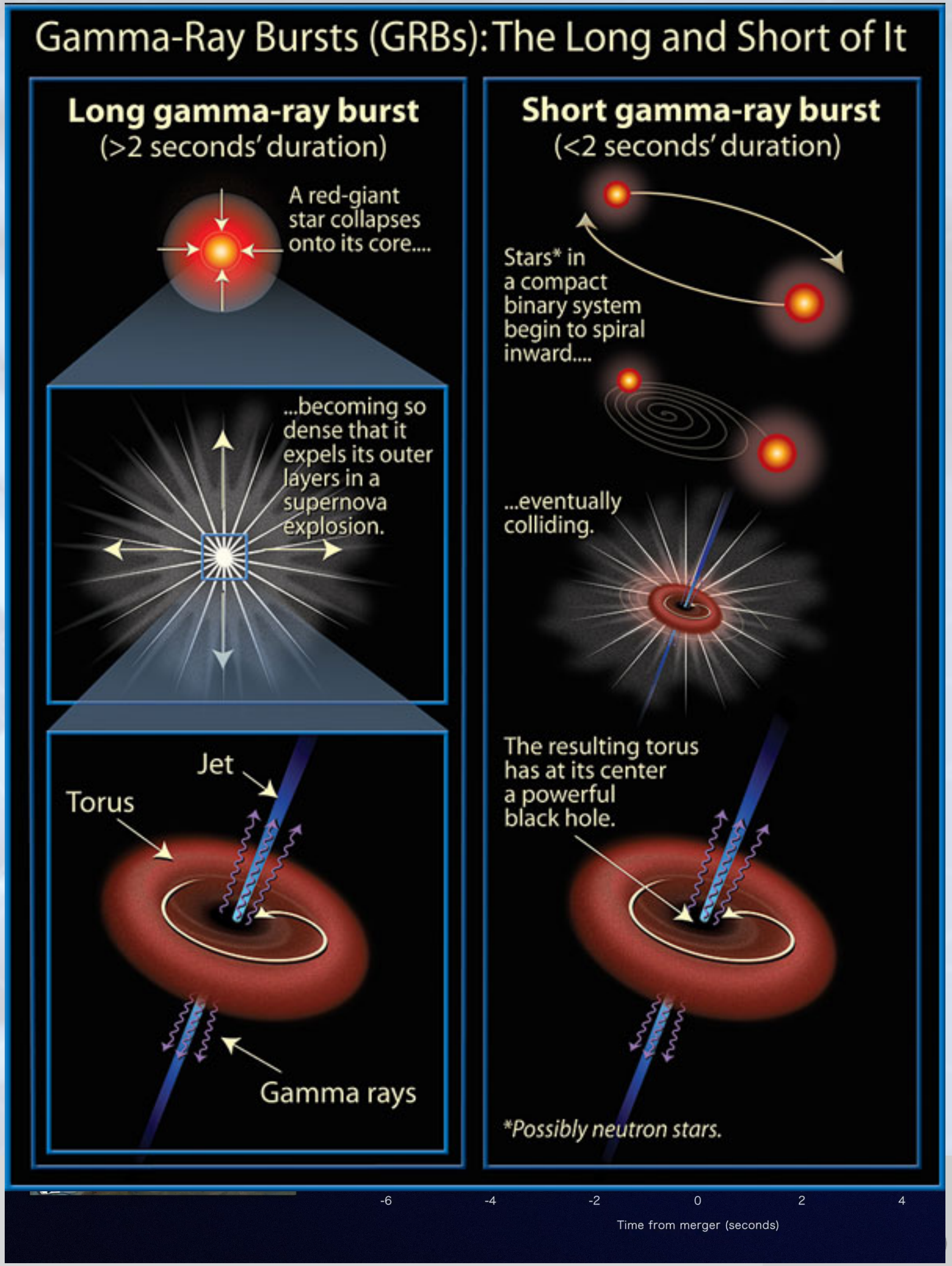
- Signal lasted 100 sec!
- Detected by LIGO but not VIRGO– location!
- Merger at only ~ 40 Mpc
- Merging bodies of much smaller masses
  - 1.1 - 1.6 solar masses
- Neutron stars!
- Abbott et al. 2017, PRL 119, 161101





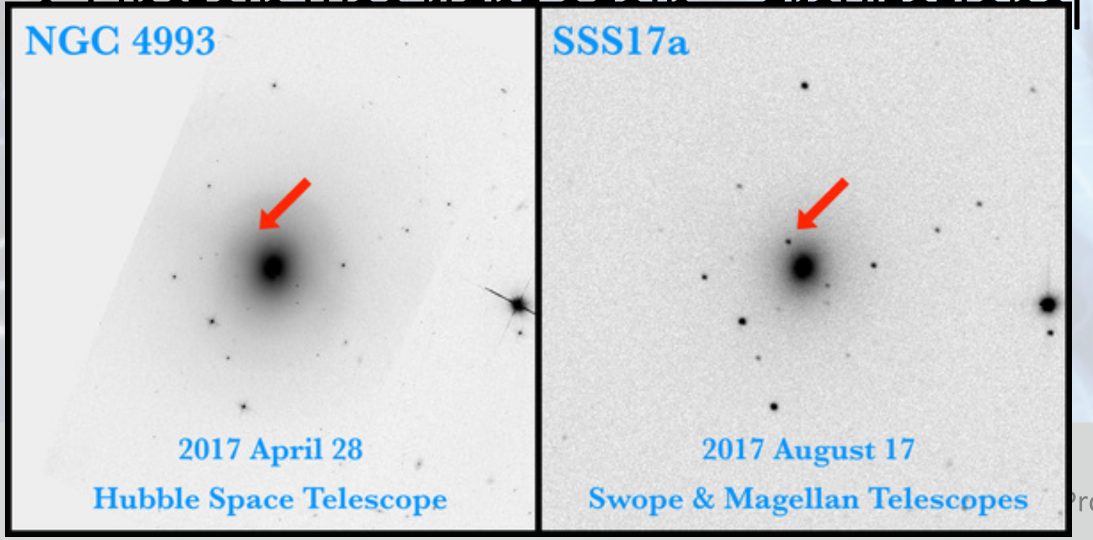
Gamma Ray Burst!

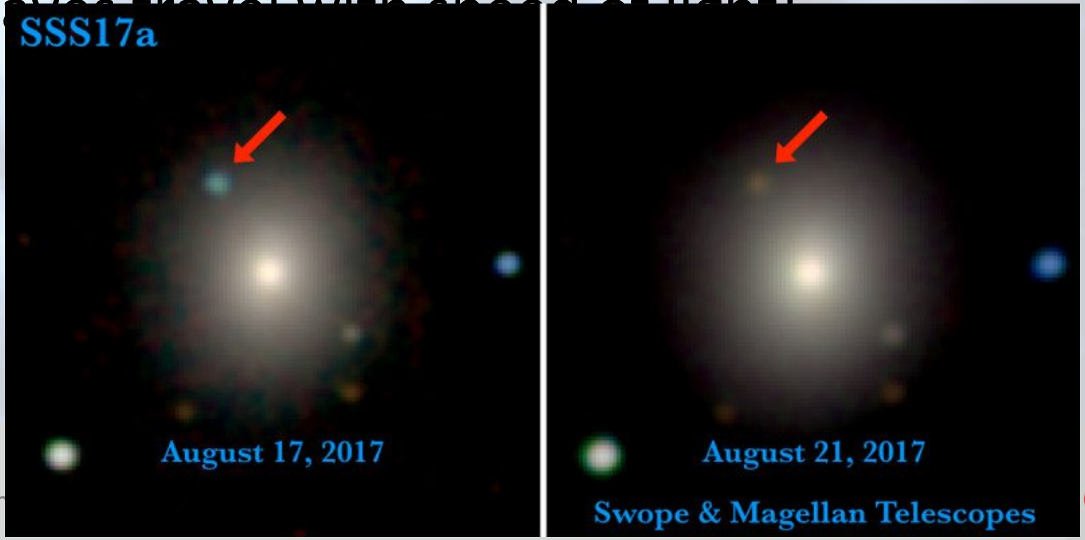
- Short GRB detected 2 sec after gravitational wave detection from same direction
- Origin of GRBs still a mystery
  - Short – neutron star mergers?
  - Long – supernovae?
- Now we know that at least some short GRBs are from neutron star mergers!



Location, location, location!

- Serendipitous pinpointing of location by LIGO detection and VIRGO non-detection
- Immediate multi-wavelength observation campaign (Abbott et al. 2017, ApJL 848, L12)
- A fading source detected in all bands from radio to X ray
- Visible for few days
- Kilonova! Explosion due to collisions of neutron stars (ejecta <10%M_{sun})
- Einstein was right again – gravitational waves travel with speed of light!

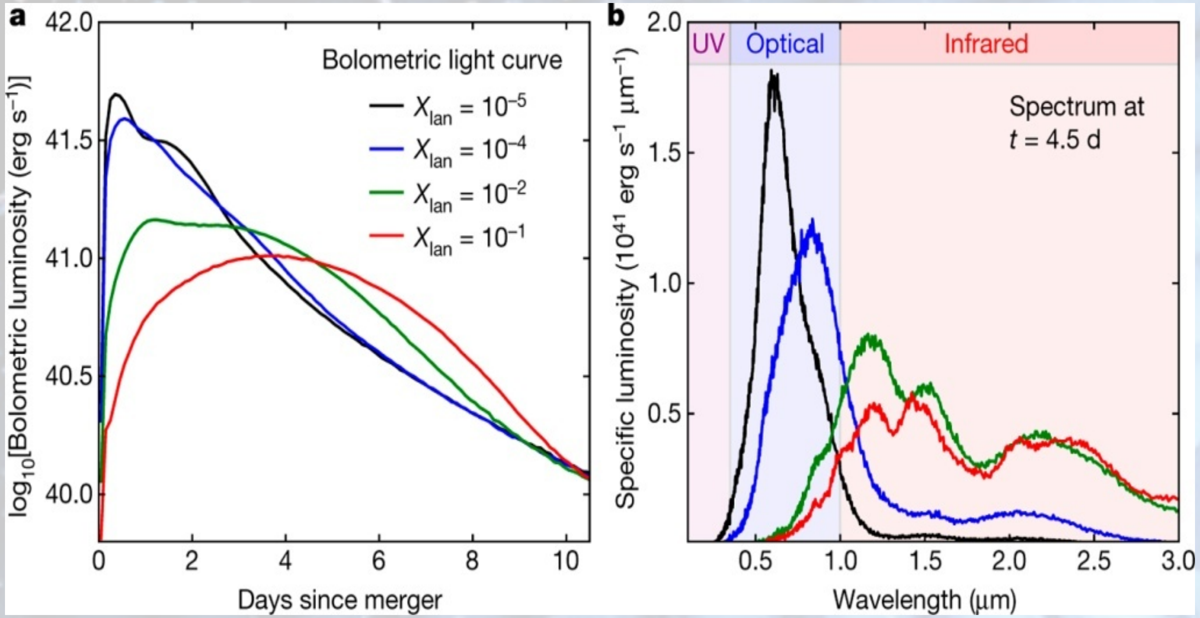


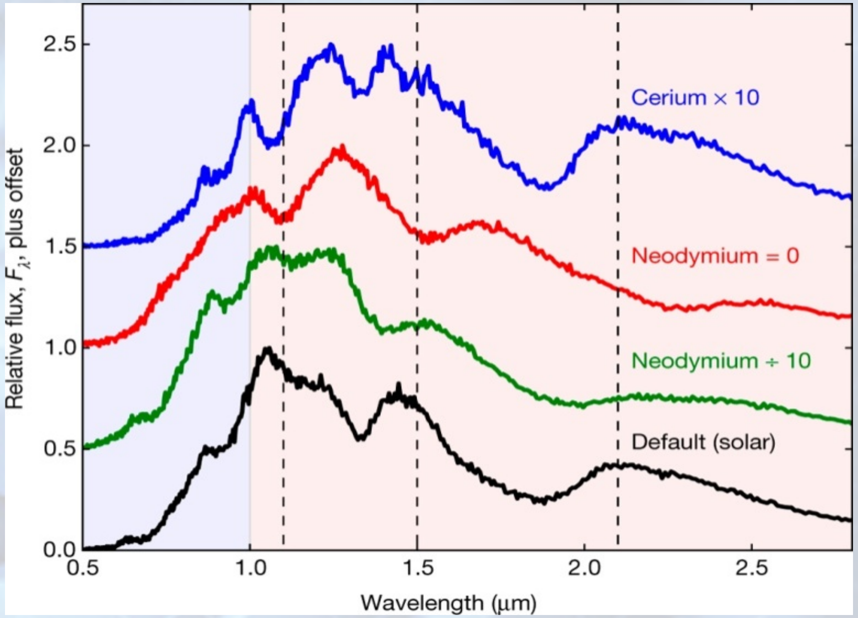


Cosmic Gold Factories!

- Origin of heaviest elements (z> 28) still unknown
- R-process (rapid neutron capture)
- Best guess: neutron star mergers (Lattimer & Schramm 1974) and supernovae
- Radiation from freshly synthetized radioactive material ejected powers kilonova!
- Yield of gold and platinum of this kilonova was estimated to be ~ Earth mass! (Kasen et al. 2017, Nature, 551, 80)

Models of kilonovae demonstrating the observable signatures of r-process abundances





D Kasen *et al.* *Nature* **551,** 80–84 (2017) doi:10.1038/nature24453

Ejecta with Fe-group elements (A<140), kilonova peaks at optical at 1-day timescale – “blue KN”
Ejecta with lanthanides (A>140), kilonova peaks at near IR at 1-week timescale – “red” KN

The Astrophysical Journal Letters, 848:L17 (10pp), 2017 October 20 Cowperthwaite et al.

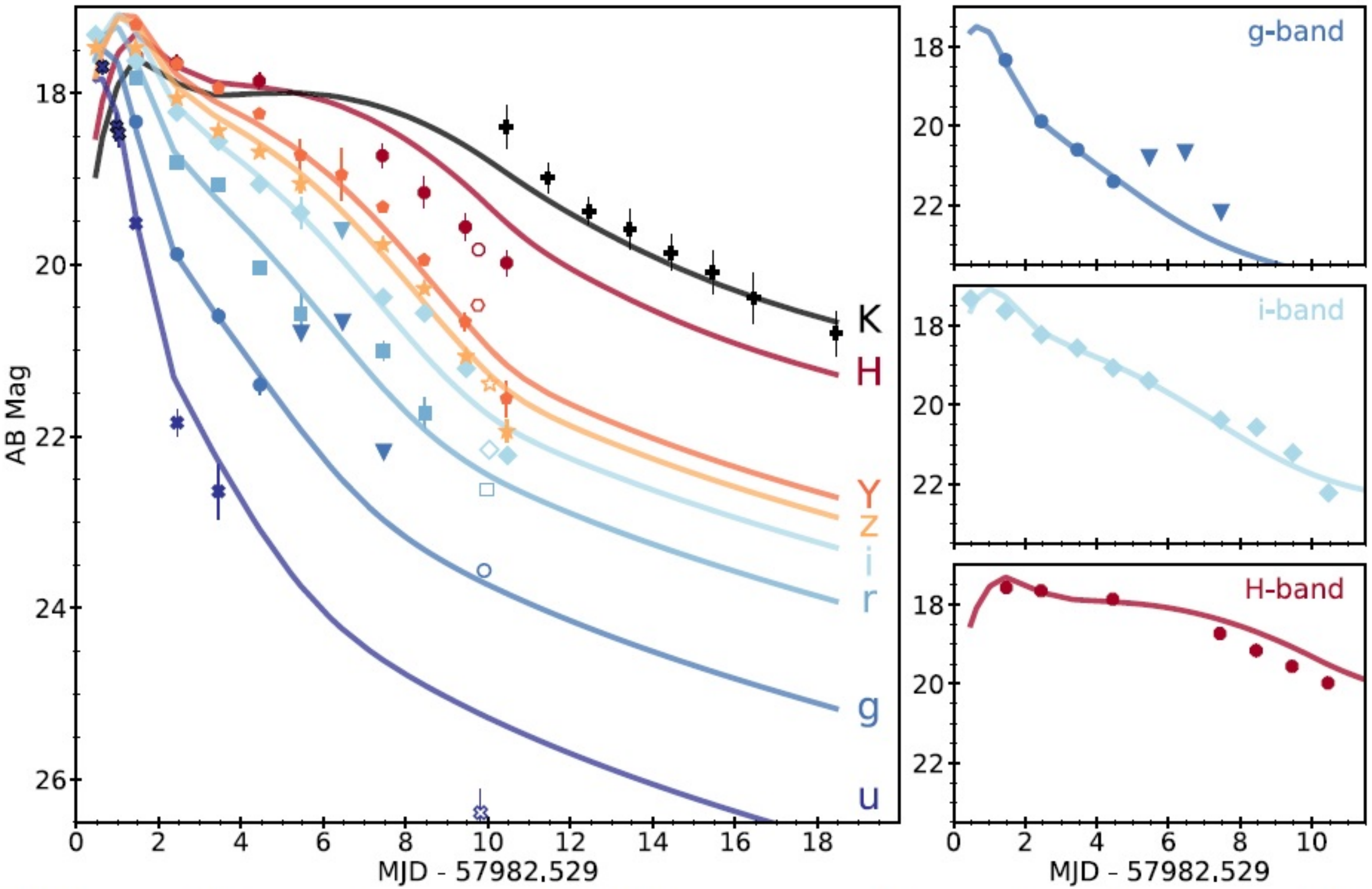
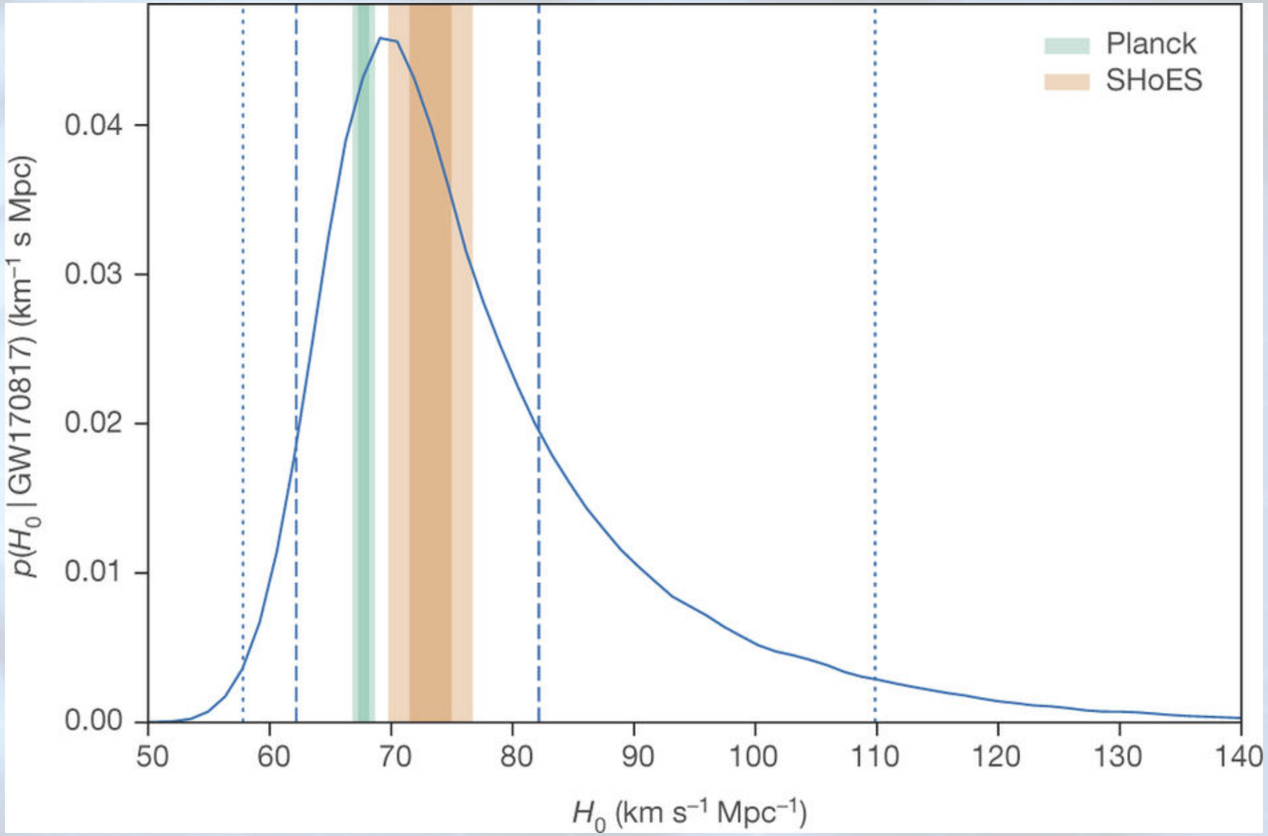


Figure 1. UV, optical, and NIR light curves of the counterpart of GW170817. The two-component model for *r*-process heating and opacities (Section 4) is shown as solid lines. The right panels focus on the *g* (top), *i* (middle), and *H*-band photometry (bottom) over the first 10 nights. Triangles represent 3σ upper limits. Error bars are given at the 1σ level in all panels, but may be smaller than the points.

Standard Sirens!

- Independent measurement of Hubble constant
- Need GW source and its optical counterpart (kilonova event)
  - From GW get luminosity distance but not redshift

LIGO collaboration 2017, Nature, 551, 85



$$H_0 = 70.0^{+12}_{-8} \ km/s/Mpc$$

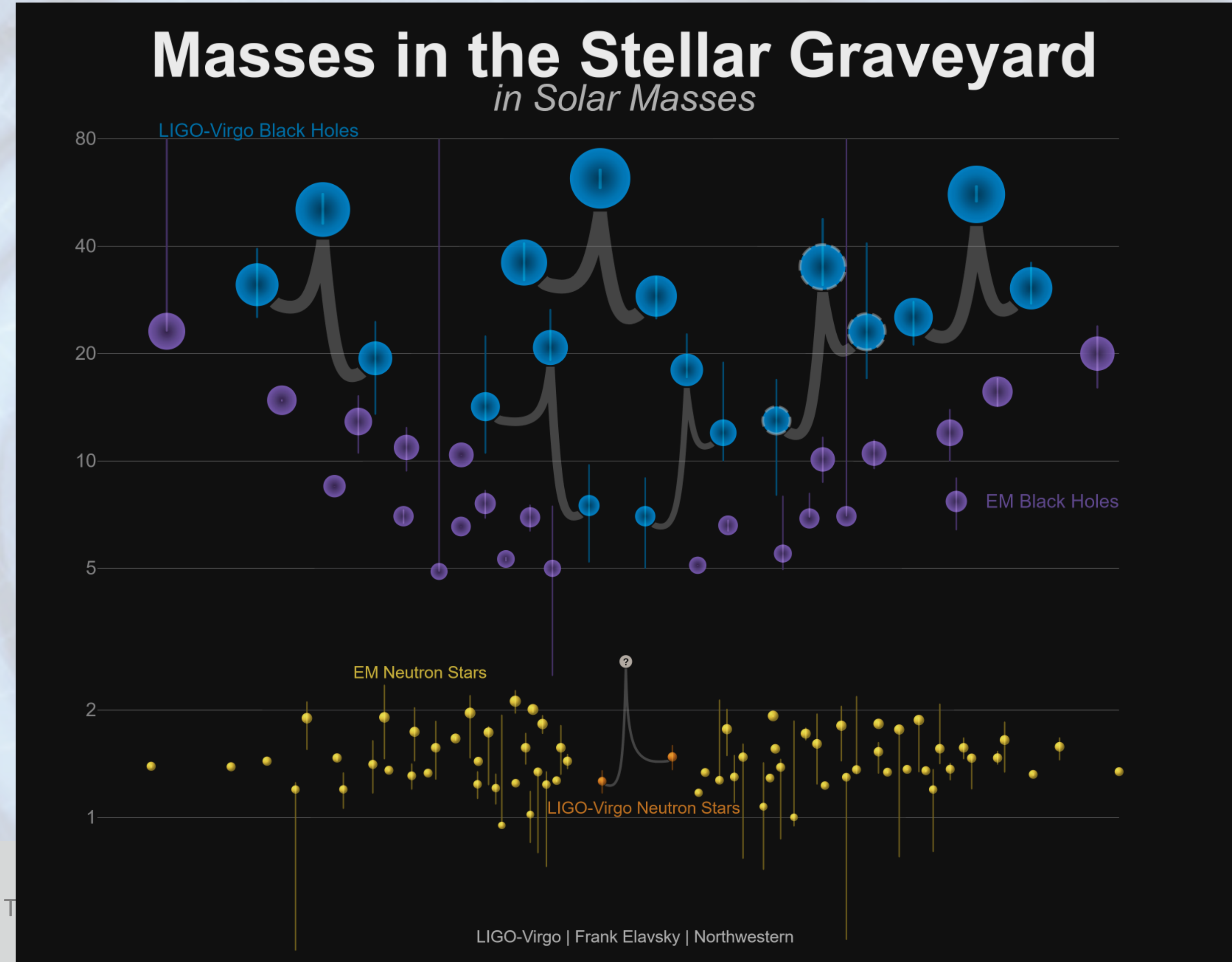
What Have we Learned?

- Neutron star mergers sources of
  - Some GRBs
  - Some fraction of r-process elements
- Gravitational waves move with speed of light
- First observations of binary BHs and their mergers
- Massive BHs are common and so are BH binaries

What Have we Learned?

- Black holes are massive!
- Have to revise our stellar evolution models – observed BHs are much larger than we thought possible
    - Standard thinking was that more massive stars have strong winds and lose material so BHs should not be larger than $\sim 10 M_{sun}$

(LIGO-Virgo/Frank Elavsky/Northwestern)



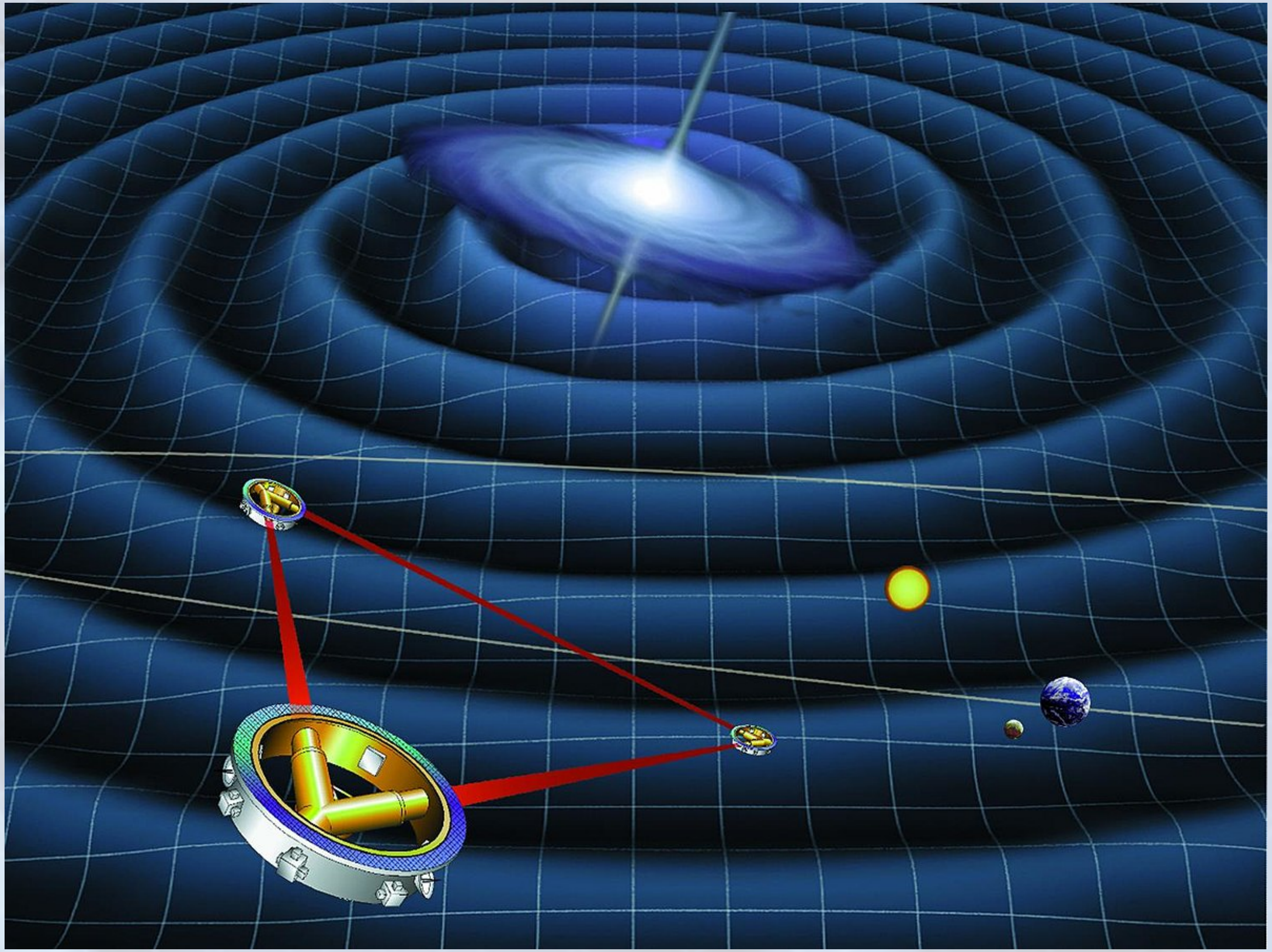
What do We Hope to Learn?

- See supernovae explosions
- See binary BH-NS mergers
- Early universe (stochastic waves? Planck scale?)
- Dark matter
- About gravity

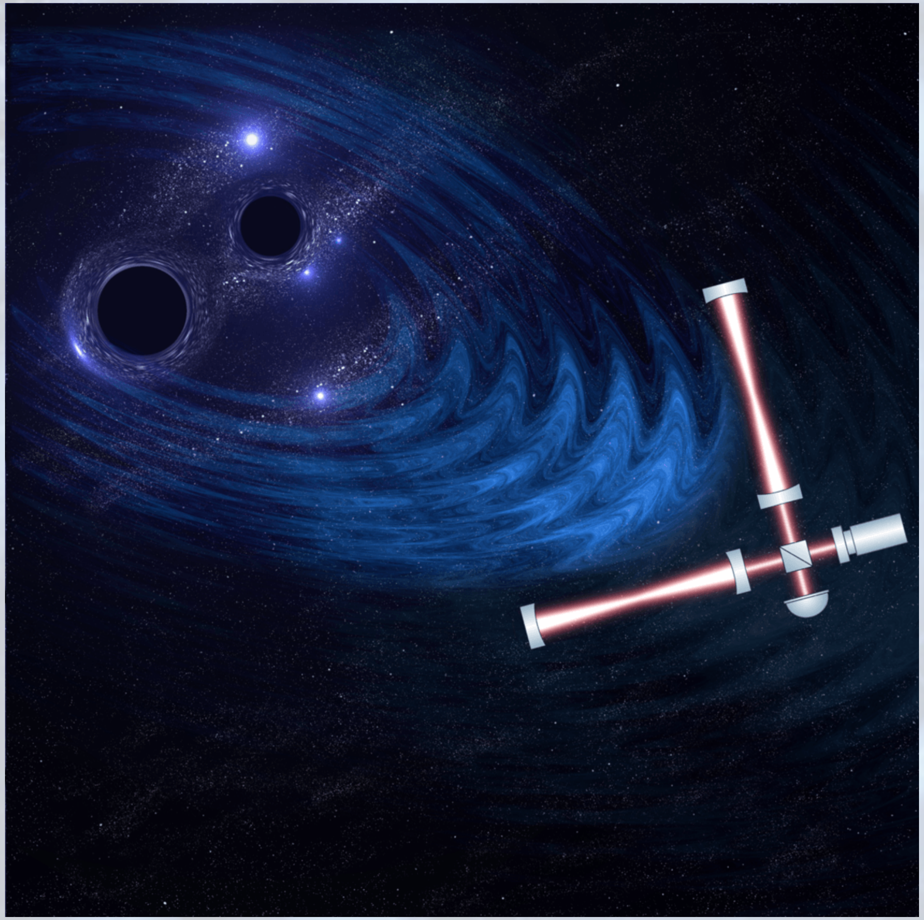
- More of the unexpected and undetected

More to Come!

- eLISA – evolved Laser Interferometer Space Antenna

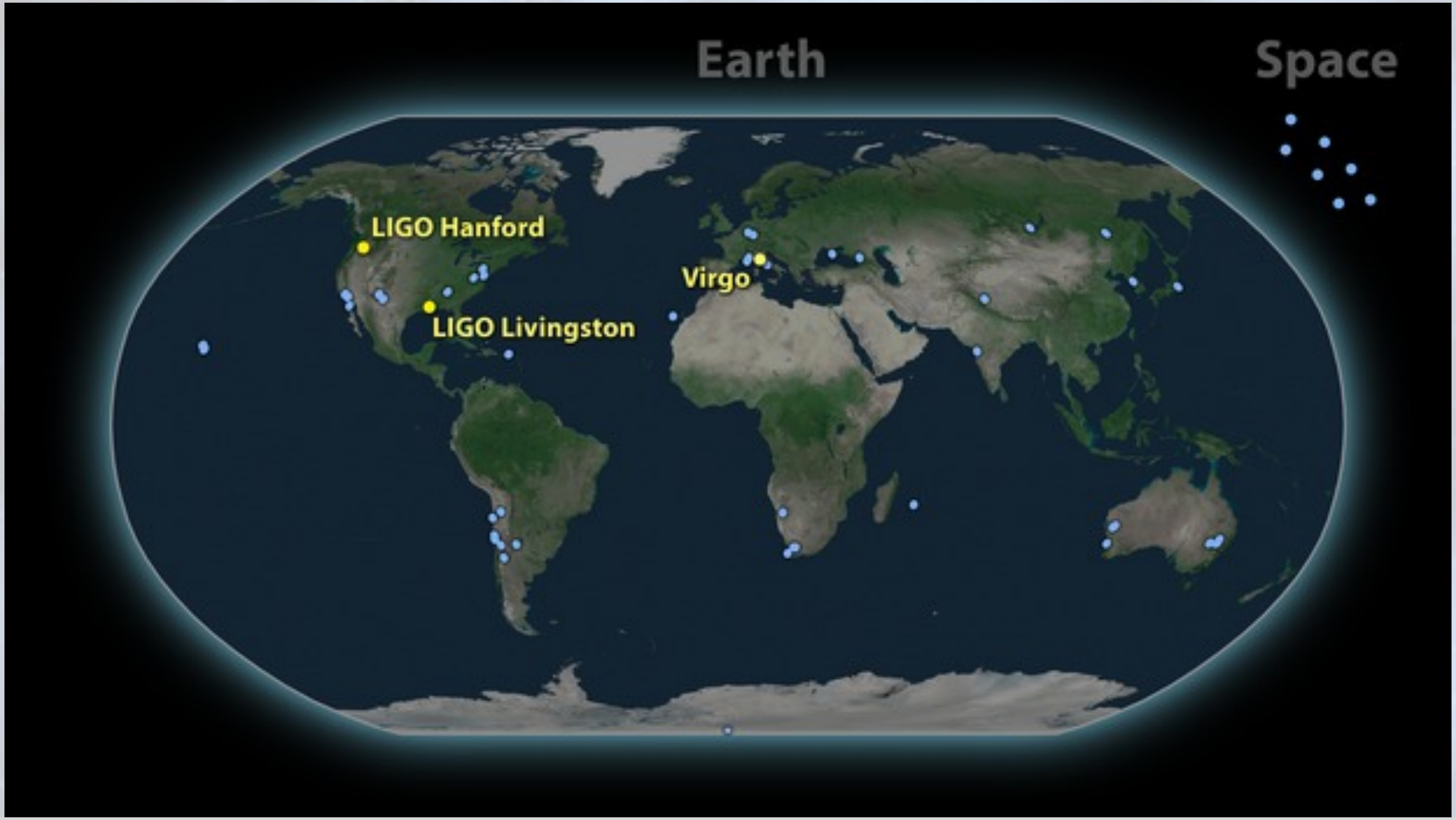


New Era of Astronomy has Begun!



Thank you!

Detekcija sudara neutronskih zvezda



Gravitacioni talasi i “propadanje” orbite

- Ukupna gravitaciona masa sistema
  - Nije prost zbir masa
  - Zbir masa mirovanja i kinetičkih energija, umanjen za energiju gravitacione veze Sistema $M = M_1 + M_2 - M_1 M_2 / 2a$

- Sistem gubi energiju emitovanjem gravitacionih talasa
- Kao posledica, smanjuje se rastojanje među članovima Sistema
- Vreme potrebno da se tela konačno spoje zbog emitovanaj gravitacionih talasa $t = 3\times 10^{17}\, god. \, a_{AU}^4 / M_1 M_2 (M_1 + M_2)/M_s^3$
  - Za Zemlju $t \sim 10^{23}\, god.$
  - Za neutronske zvezde mase Sunca, da bi ovo vreme bilo jednako starosti svemira, rastojanje im mora biti $a < 0.016 AU$

Neutron Star Merger