Регистрация гравитационных волн

Основано на презентации Gabriele Vedovato (INFN) 20/02/2018

Gravitational Waves

Einstein

1915

General Relativity

Einstein

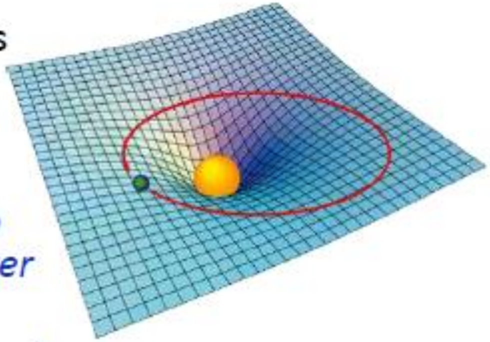
1916

Gravitational Waves

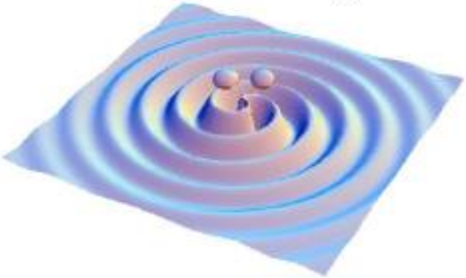
Gravity is not a force but it is related to the curvature of space-time

- *"Matter tells space how to curve and space tells matter how to move."*

(John Wheeler)



Are ripples of space-time metric generated by accelerated masses (predicted by GR)

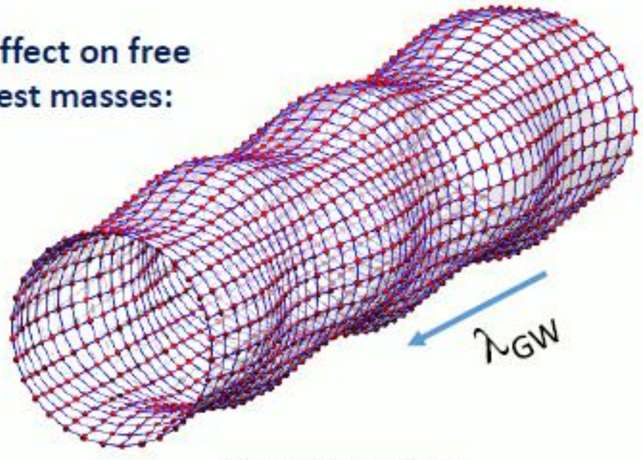


Gravitational Waves far away from sources

- gravitational waves are physical: carry curvature, energy, momentum, angular momentum (Pirani 1950's)
- weak-field linear approximation of General Relativity
  - analogies with electromagnetic waves:

light speed, transverse, 2 polarization components $\boldsymbol{h}_+, \boldsymbol{h}_\times$

Effect on free test masses:

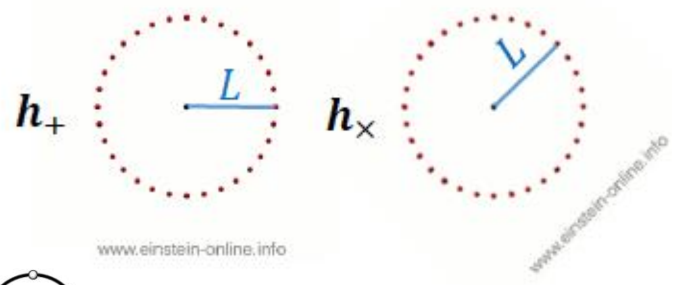


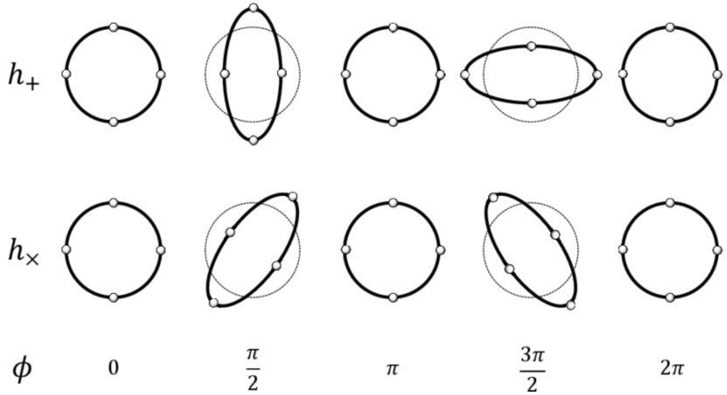
www.einstein-online.info

GW amplitude is strain: $$\boldsymbol{h} = \frac{2\Delta L}{L}$$

ΔL is the change in separation of two masses a distance L apart

tensor polarizations $\boldsymbol{h}_+$ and $\boldsymbol{h}_\times$ *rotated by* $\frac{\pi}{4}$ ***in the wavefront plane:***





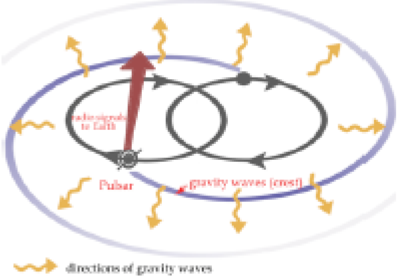
Gravitational Waves: The evidence

In 1974, Hulse and Taylor discover the binary system PSR 1913+16

Taylor and Weisberg measured the decrease of the orbital period along many years

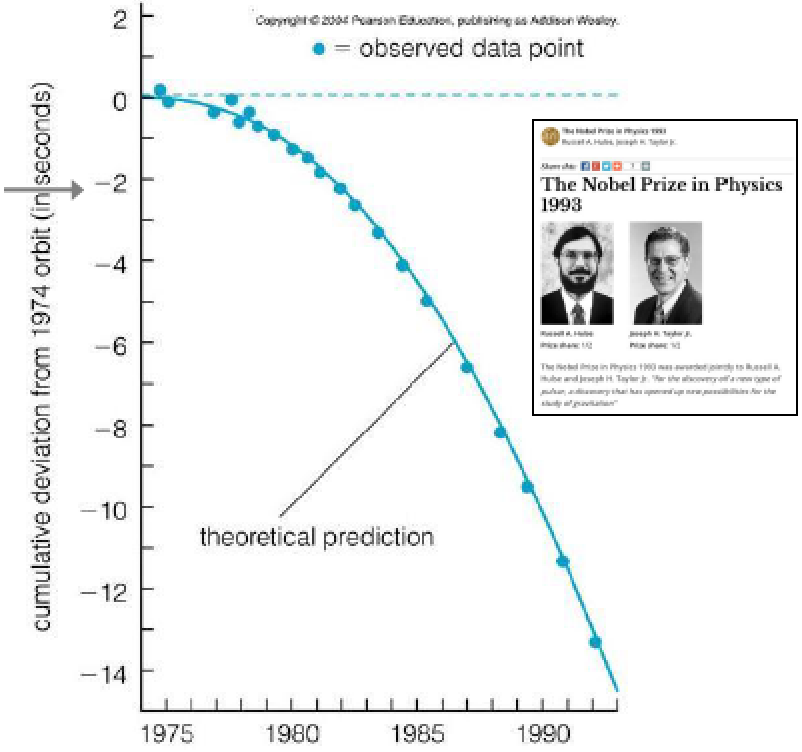
$m_1 = 1.4\ M_\odot$

$m_2 = 1.36\ M_\odot$



They discovered that the decay period is in precise agreement with the loss of energy due to gravitational waves described by Einstein's general theory of relativity

First indirect evidence of the gravitational waves



The Nobel Prize in Physics 1993

Russell A. Hulse

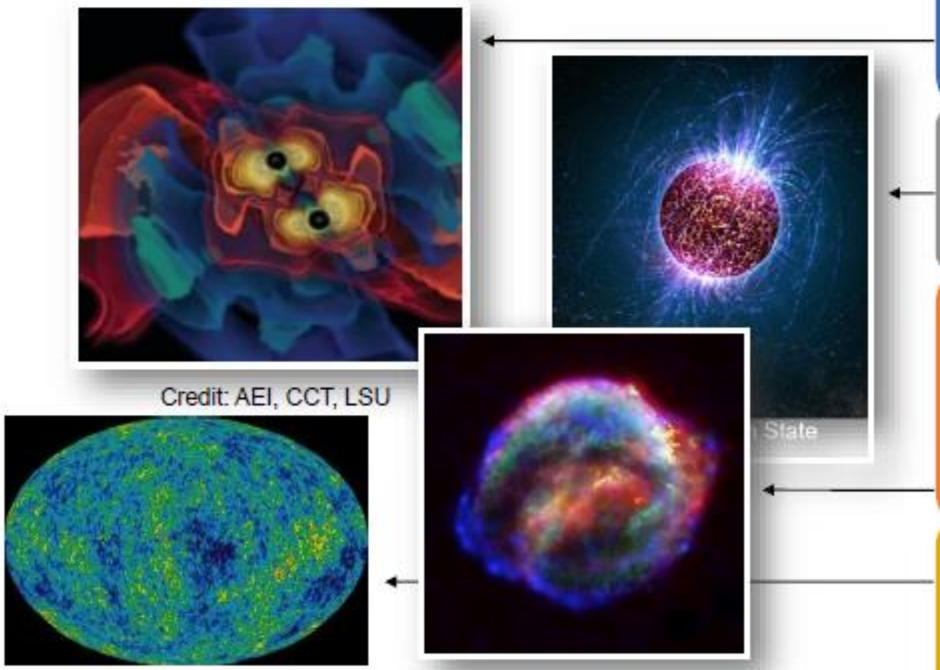
Joseph H. Taylor Jr.

Prediction from general relativity

- spiral in by 3 mm/orbit
- merge in 300 million years

Sources of Gravitational Waves

Since we can’t generate detectable gravitational waves on Earth, the only way to study them is to look to the places in the Universe where they are generated by nature.



Credit: AEI, CCT, LSU

NASA/WMAP Science Team

Credit: Chandra X-ray Observatory

Compact Binary Inspiral

Binary Neutron Star (BNS)
Binary Black Hole (BBH)
Neutron Star-Black Hole Binary (NSBH)

Continuos

Spinning Neutron Stars (Pulsars)

Burst

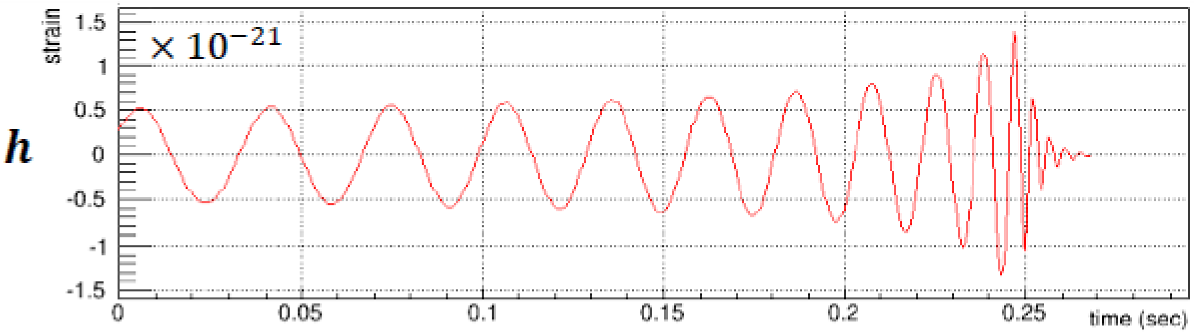
Asymmetric Core Collapse SN
Cosmic Strings
Unknown ???

Stochastic

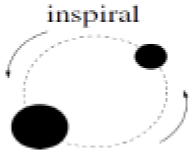
Incoherent background from primordial GWs or an ensemble of unphased sources

GWs from compact binary coalescences

- The most efficient emitters among expected GW sources
- Up to ~ 10% total mass converted in gravitational radiation



INSPIRAL
GW emission described by quadrupole formula. Analytical solution available



MERGER
Only numerical solution available

RINGDOWN
Perturbative and numerical solutions

GW can be used as a standard candle.

Last inspiraling cycles enter the bandwidth of earth-based detectors.

General Relativity in strong field highly non-linear regime

NS would bring more physics (Equation of State, ...)

The Gravitational Waves Hunting

1960s

Weber devised and constructed the first bar detector

1970s – 2000s

Room Temperature & Cryogenic Bar Detectors

Narrow Band Frequency detectors
(100 Hz @ 1KHz) & ($h \sim 10^{-21}$)

AURIGA – INFN/Padova

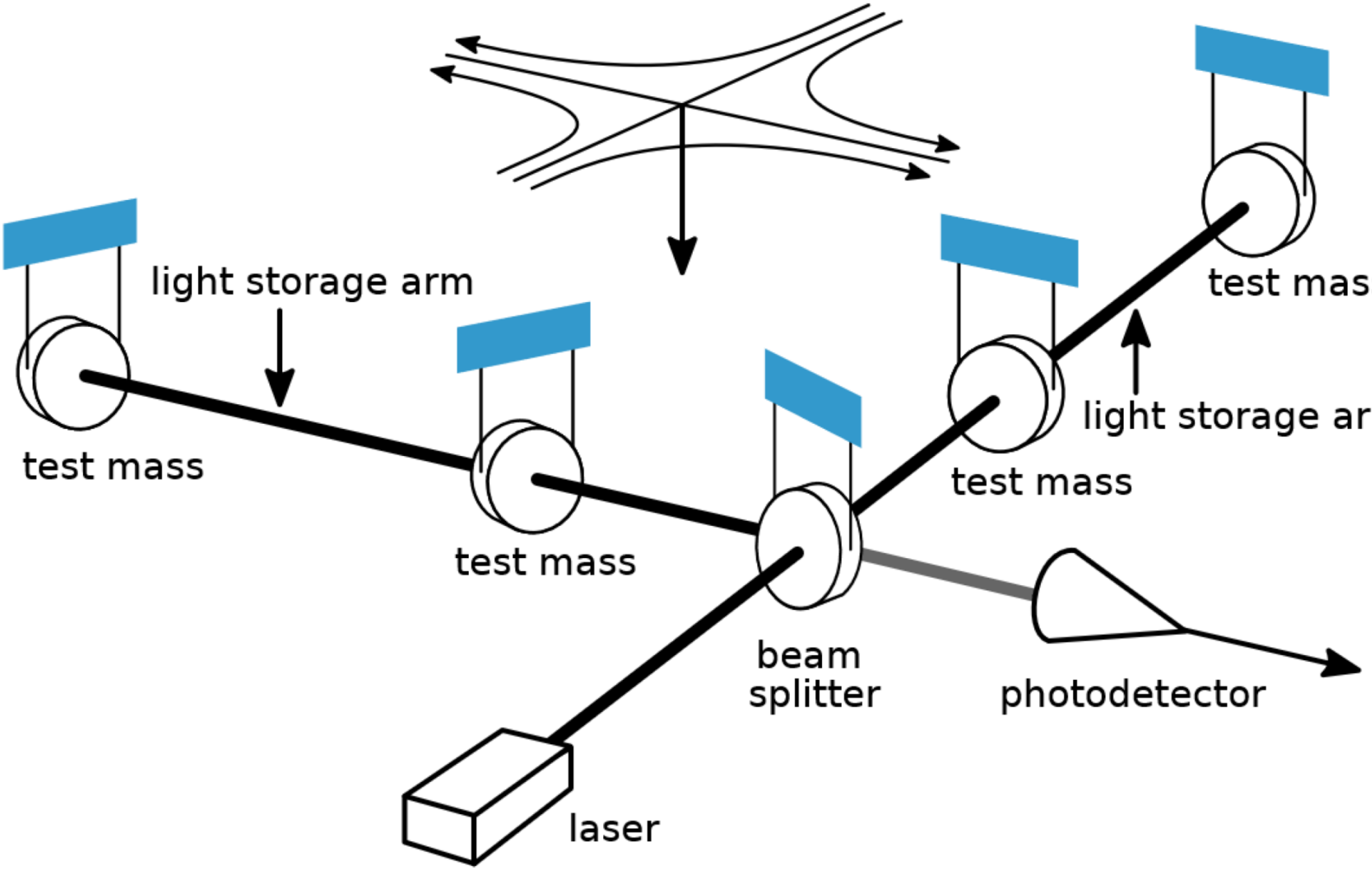
1970s – 2010s

Interferometers
Concept, Contruction & Operational

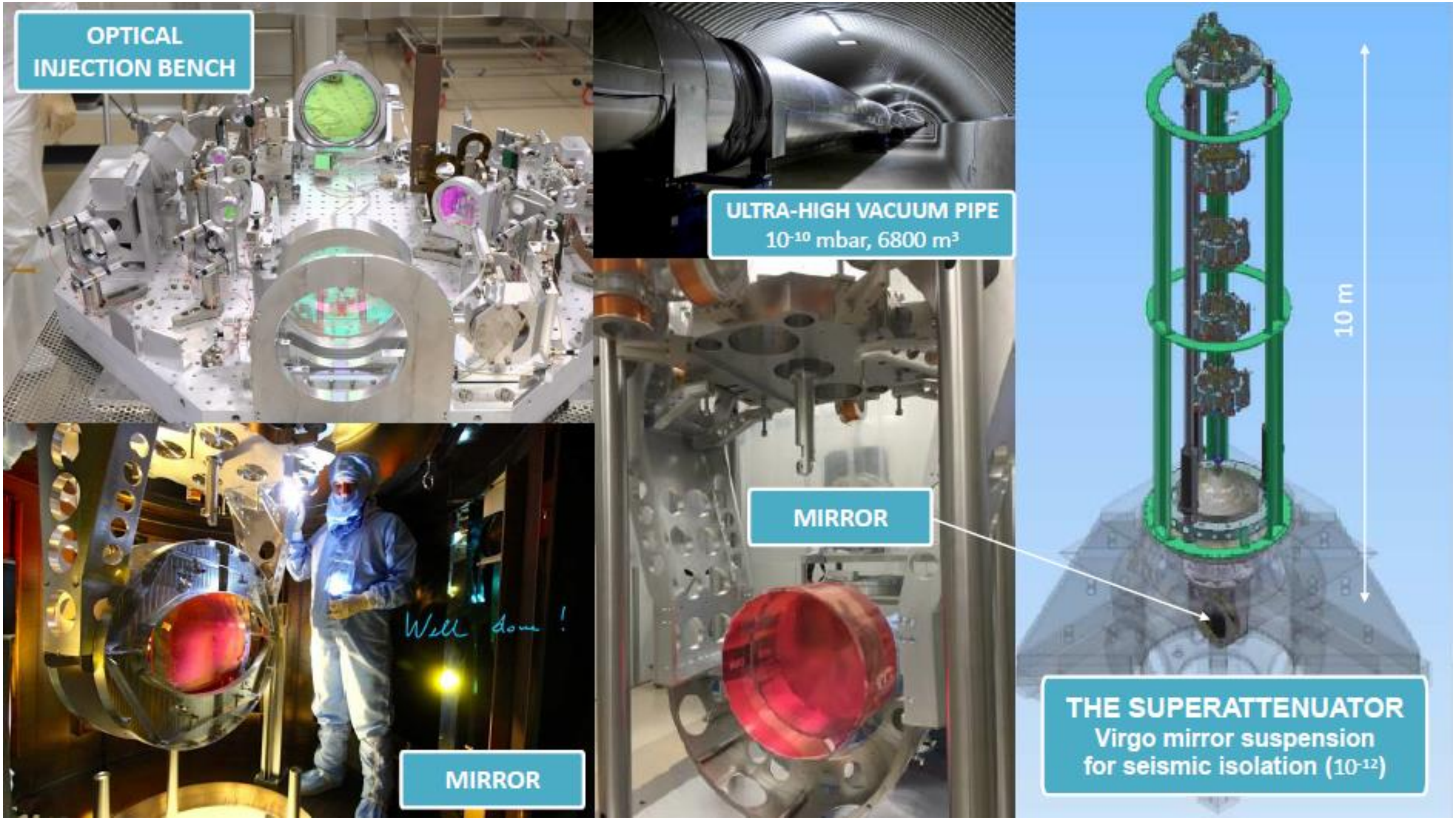
Broad Band Frequency detectors
(20 – 6000 Hz) & ($h \sim 10^{-23}$)

Virgo : Scientific Collaboration
Italy, *France*, Netherlands, Poland, Hungary and Spain

Principal scheme of an interferometer



How it looks

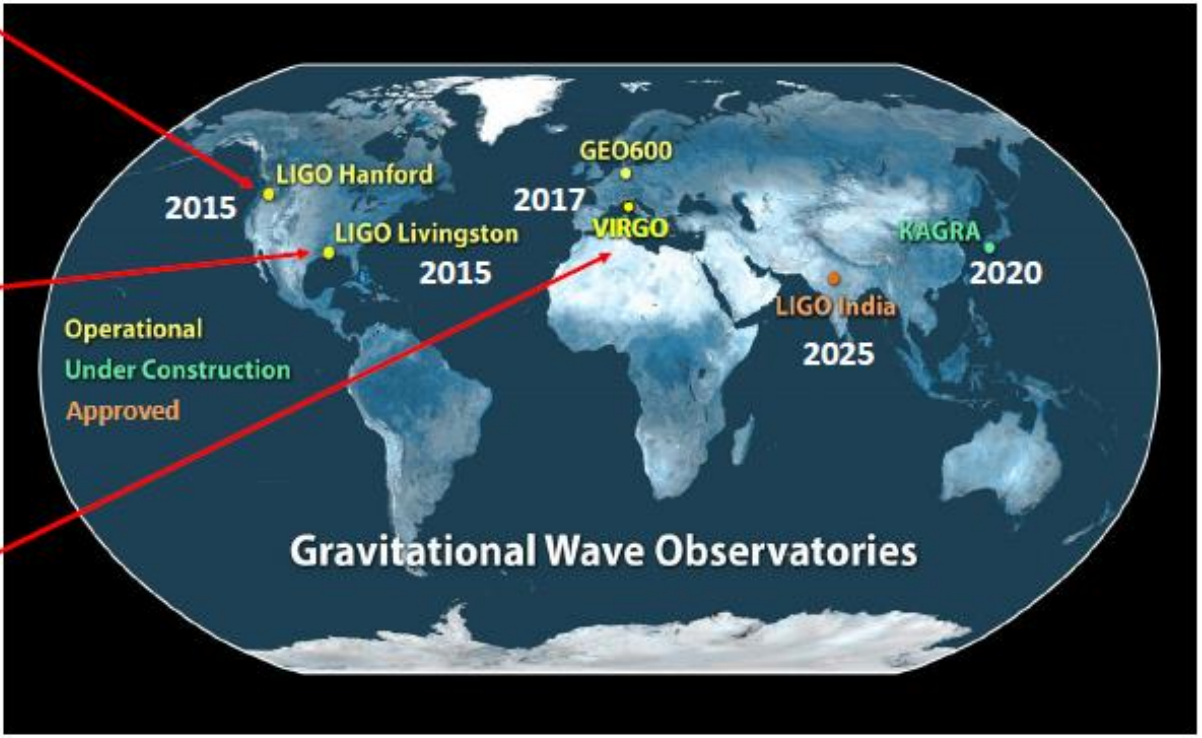

OPTICAL INJECTION BENCH
ULTRA-HIGH VACUUM PIPE
10-10 mbar, 6800 m³
MIRROR
Well done!
MIRROR
10 m
THE SUPERATTENUATOR
Virgo mirror suspension
for seismic isolation (10-12)

The Network of Gravitational Wave Detectors


LIGO Hanford


LIGO Livingston

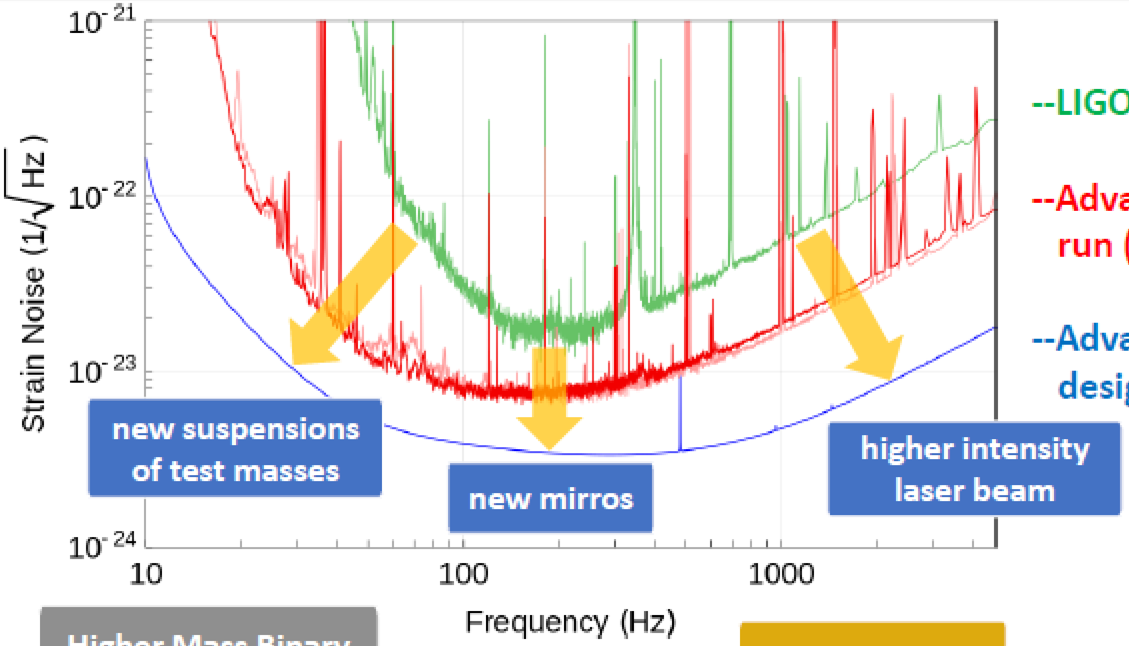

Virgo Cascina (Pisa)



Operational
Under Construction
Approved

Gravitational Wave Observatories

Spectral Sensitivity Enhancement



--LIGO S6 run (2010)

--Advanced LIGO O1 run (2015)

--Advanced LIGO design goal

new suspensions of test masses

new mirros

higher intensity laser beam

Higher Mass Binary BH Coalescences (Intermediate Mass)

BBH mergers BH ring-down

NS transients

and yet UNKNOWN SOURCES

Stochastic background

NS periodic emission

Supernove

sample target sources

Directional Sensitivity of Detectors

Each interferometer senses only one of the two GW polarizations:

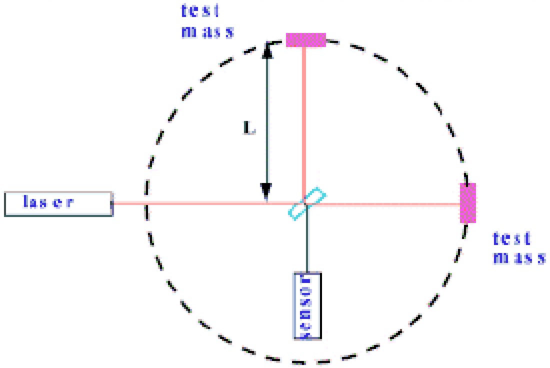
- measures the linear combination

$$h_{det} = F_{+}h_{+} + F_{\times}h_{\times}$$

$$F_{+,\times}(\text{sky direction})$$

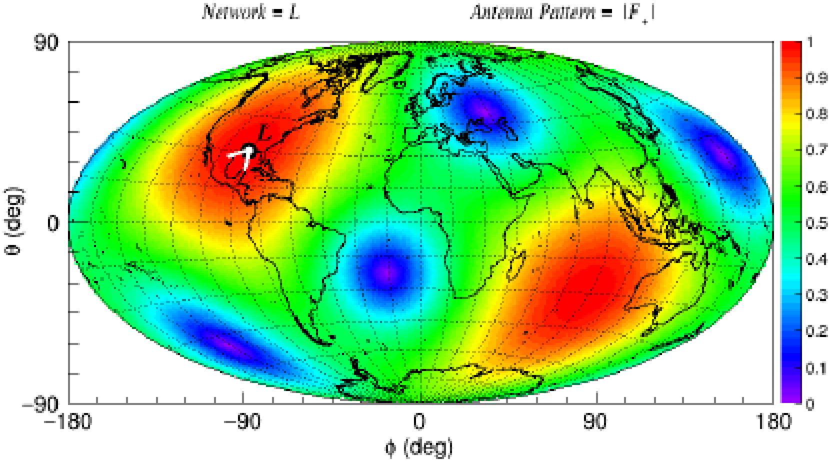
antenna patterns for + and x

- misses the orthogonal combination



Broad directional sensitivity:

LIGO Livingston

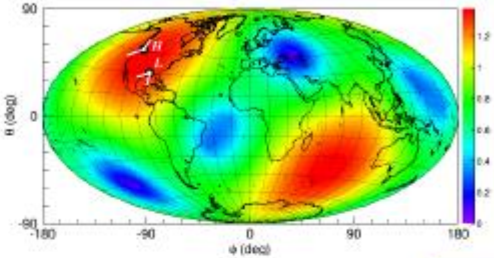


Benefit of adding Virgo detector

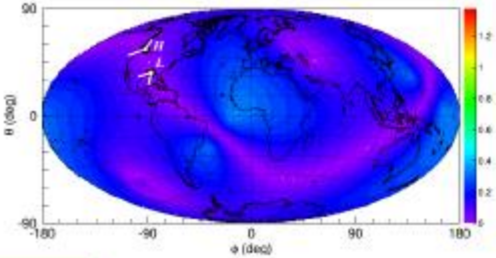
- **Detection confidence**: lower background and higher Signal-to-Noise Ratio
- Increased **time coverage of the survey** by detector pairs
- **coverage of sky and both GW polarizations**: better waveform reconstruction

LIGO Hanford + LIGO Livingston

$|\vec{F}_{+}|$

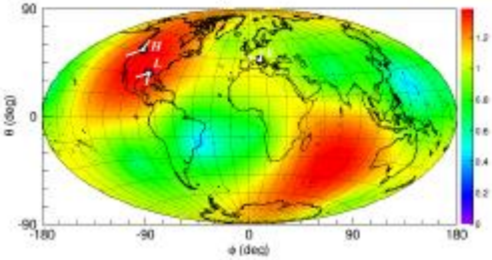


$|\vec{F}_{\times}|$



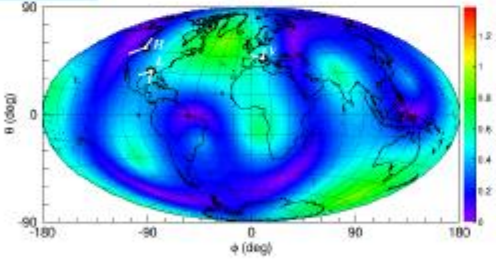
LIGO Hanford + LIGO Livingston and Virgo

$|\vec{F}_{+}|$



assuming same spectral sensitivity

$|\vec{F}_{\times}|$

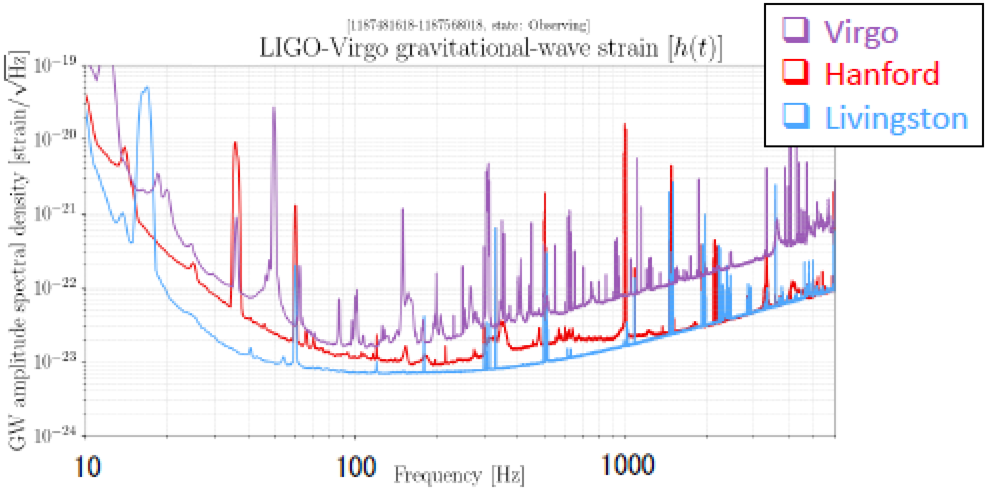


Recap of recent observational campaigns

- **«O1»** [Sept.2015, Jan. 2016]
  - **49 days** of coincident observations by LIGO Hanford and Livingston with science quality data
- **«O2»** [Nov. 2016, Aug. 25 2017]
  - **120 days** of coincident observations by LIGO, ~ **16 days with Virgo**
  - **10 GW alerts** sent to LIGO-Virgo partners for multimessenger followup

Virgo joined the science run from Aug. 1

online monitoring of detectors:
losc.ligo.org
www.virgo-gw.eu/status.html

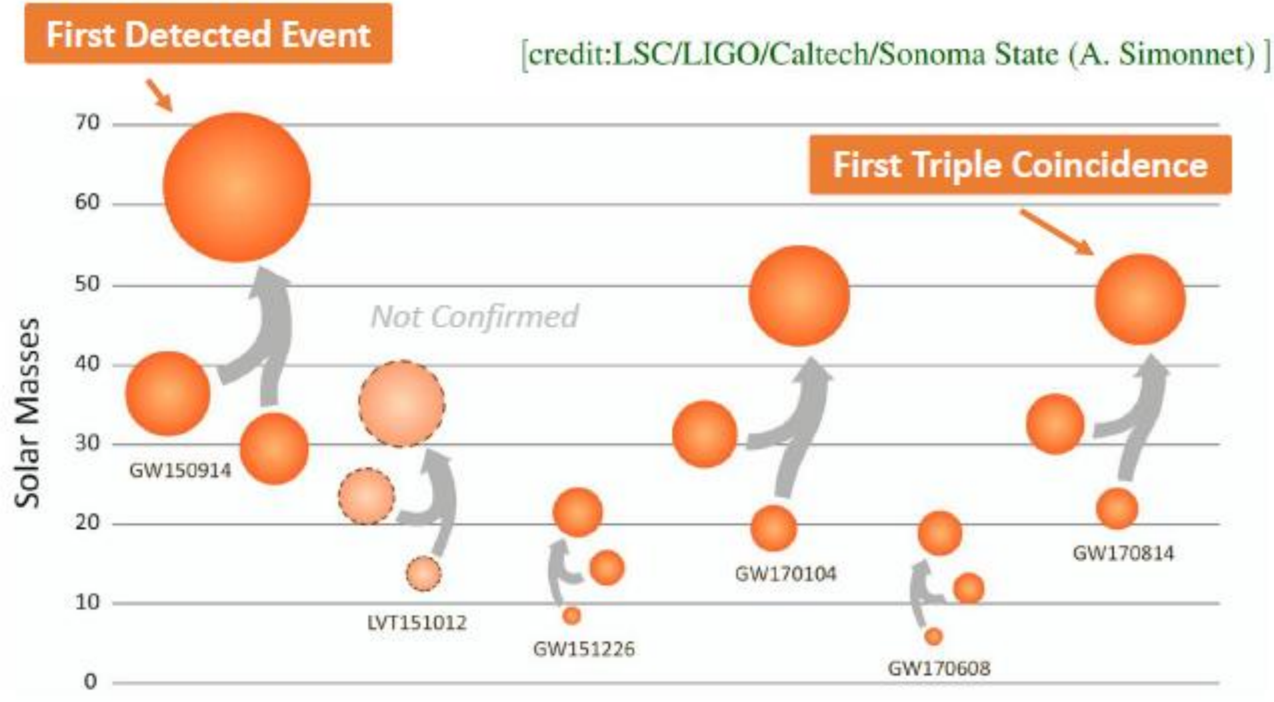


☐ observations 2015-17 vs 2010:

averaged observable volume of Universe : ~**100x** gain for **BBH** like GW150914
~**30x** gain for **BNS** coalescence events

Published Black Holes of Known Mass

Data Release: losc.ligo.org



First Detected Event

[credit:LSC/LIGO/Caltech/Sonoma State (A. Simonnet)]

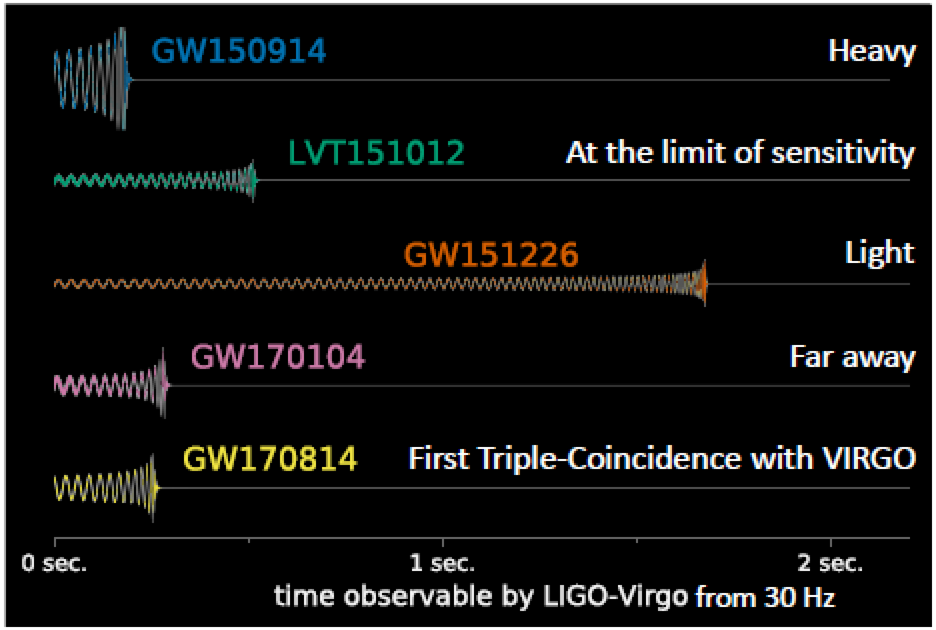
First Triple Coincidence

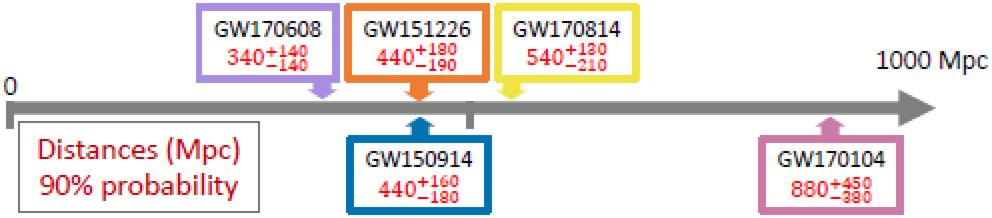
Unexpected Population of Binary Black Holes

- higher mass *x-ray binary BHs are lighter:* $< 15M_\odot$
- merger rate compatible with highest expectations *12-213 Gpc* $^{-3}$ *yr* $^{-1}$
- testbed for checking General Relativity
- no related electromagnetic emission found
- heavy mass BBH system most likely formed in a low-metallicity environment: $< ½$-$¼ \; Z_\odot$

LIGO-Virgo Black Holes : how diverse have they been?

Comparison of the Gravitational Waveforms





GW170608 340^{+140}_{-140}

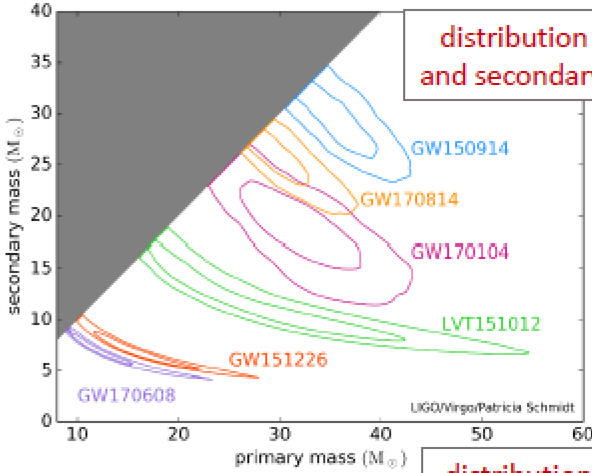
GW151226 440^{+180}_{-190}

GW170814 540^{+130}_{-210}

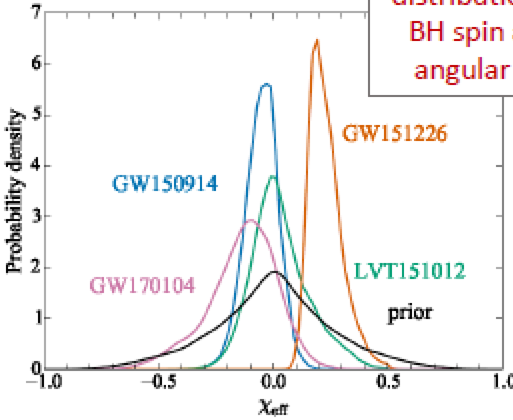
GW150914 440^{+160}_{-180}

GW170104 880^{+450}_{-380}

Distances (Mpc)
90% probability



distribution of primary and secondary BH masses

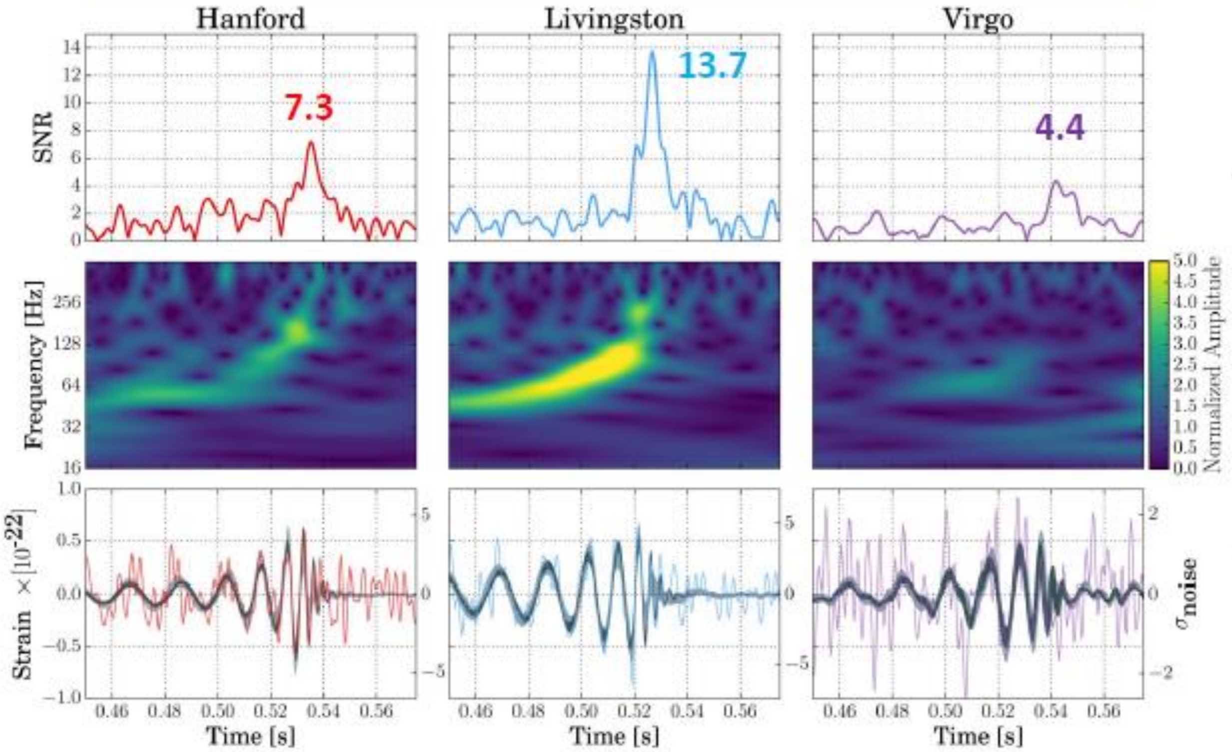


distribution of effective BH spin along orbital angular momentum

GW170814 : Virgo is in the game!

On August 14, 2017 at 10:30:43 UTC, Virgo & LIGO detected the first triple coincidence BBH event

Primary black hole mass m_1	$30.5^{+5.7}_{-3.0}\,\mathrm{M}_\odot$
Secondary black hole mass m_2	$25.3^{+2.8}_{-4.2}\,\mathrm{M}_\odot$
Chirp mass $\mathcal{M}$	$24.1^{+1.4}_{-1.1}\,\mathrm{M}_\odot$
Total mass M	$55.9^{+3.4}_{-2.7}\,\mathrm{M}_\odot$
Final black hole mass M_f	$53.2^{+3.2}_{-2.5}\,\mathrm{M}_\odot$
Radiated energy E_rad	$2.7^{+0.4}_{-0.3}\,\mathrm{M}_\odot c^2$



← **SNR time series** using the best matching template

← **Time-frequency** representation of the strain data around the time of GW170814

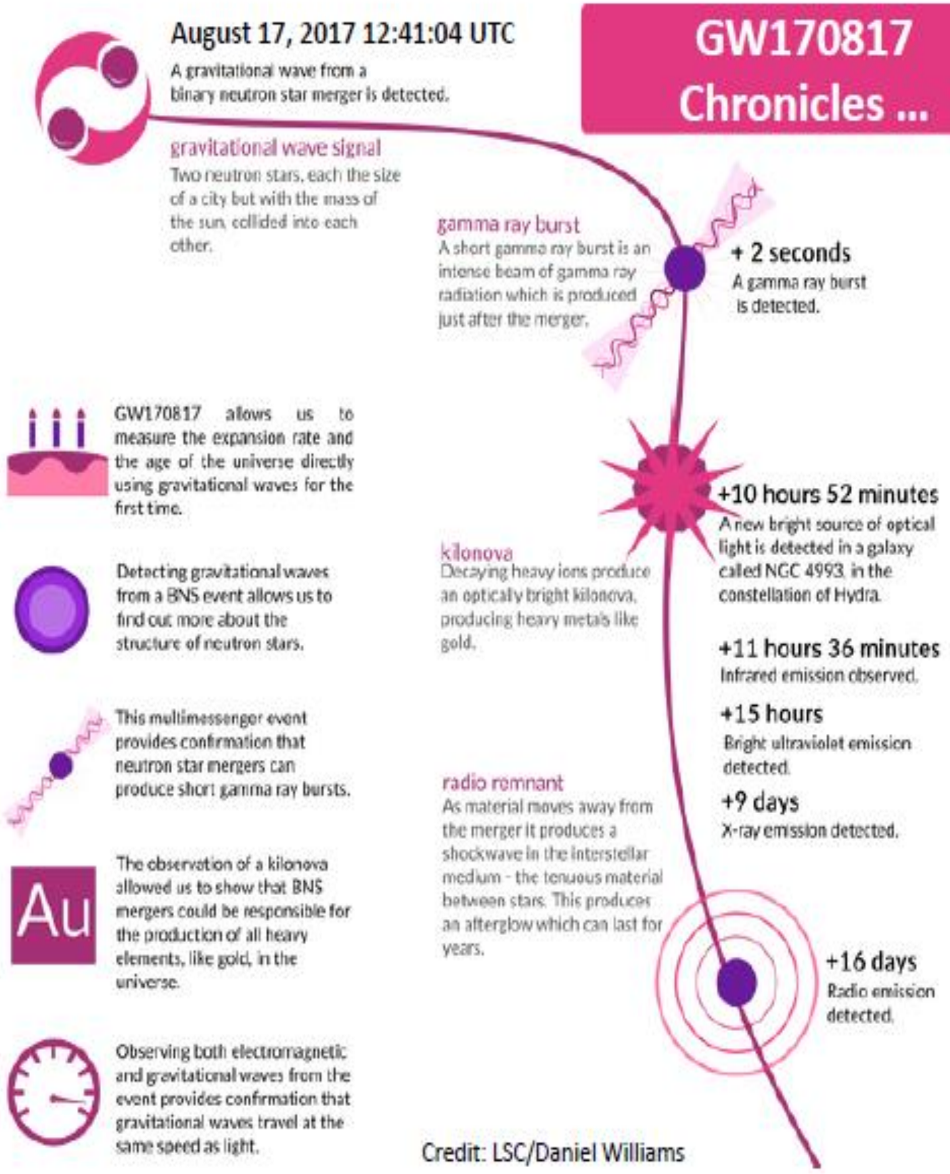
← **Reconstructes waveforms**

- BBH model (dark gray)
- Unmodel (light gray)
- Whitened data (color)

What did we learn ?

- Einstein was right!
- Stellar Binary black holes exist
- Binary black holes merge within he lifetime of the universe
- Largest stellar mass black hole to date ($M > 20\,M_\odot$)
- BBH merger rate: $103^{+110}_{-63}\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
- Test GR in strong field
  - No evidence for violation of General Relativity
  - $m_g < 7.7 \times 10^{-23}$ eV/c^2

GW170817 Chronicles ...



August 17, 2017 12:41:04 UTC

A gravitational wave from a binary neutron star merger is detected.

gravitational wave signal

Two neutron stars, each the size of a city but with the mass of the sun, collided into each other.

gamma ray burst

A short gamma ray burst is an intense beam of gamma ray radiation which is produced just after the merger.

+ 2 seconds

A gamma ray burst is detected.

+10 hours 52 minutes

A new bright source of optical light is detected in a galaxy called NGC 4993, in the constellation of Hydra.

kilonova

Decaying heavy ions produce an optically bright kilonova, producing heavy metals like gold.

+11 hours 36 minutes

Infrared emission observed.

+15 hours

Bright ultraviolet emission detected.

+9 days

X-ray emission detected.

radio remnant

As material moves away from the merger it produces a shockwave in the interstellar medium - the tenuous material between stars. This produces an afterglow which can last for years.

+16 days

Radio emission detected.

GW170817 allows us to measure the expansion rate and the age of the universe directly using gravitational waves for the first time.

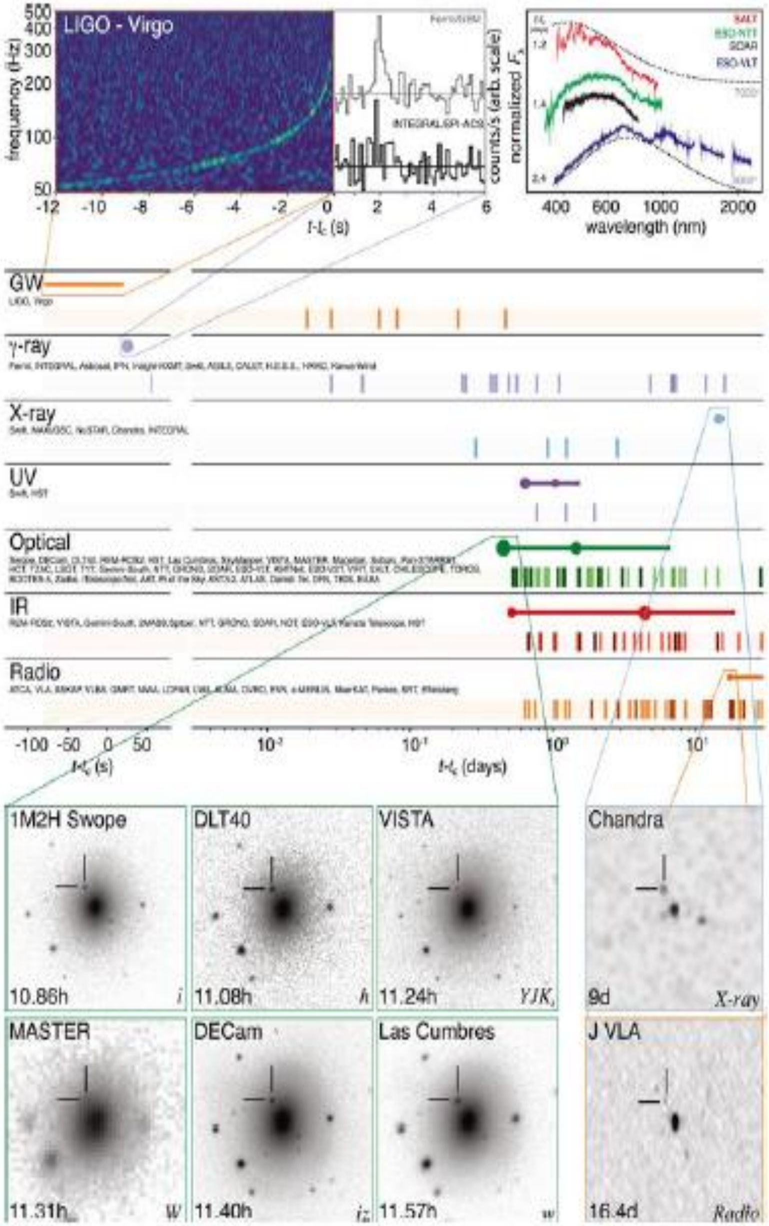
Detecting gravitational waves from a BNS event allows us to find out more about the structure of neutron stars.

This multimessenger event provides confirmation that neutron star mergers can produce short gamma ray bursts.

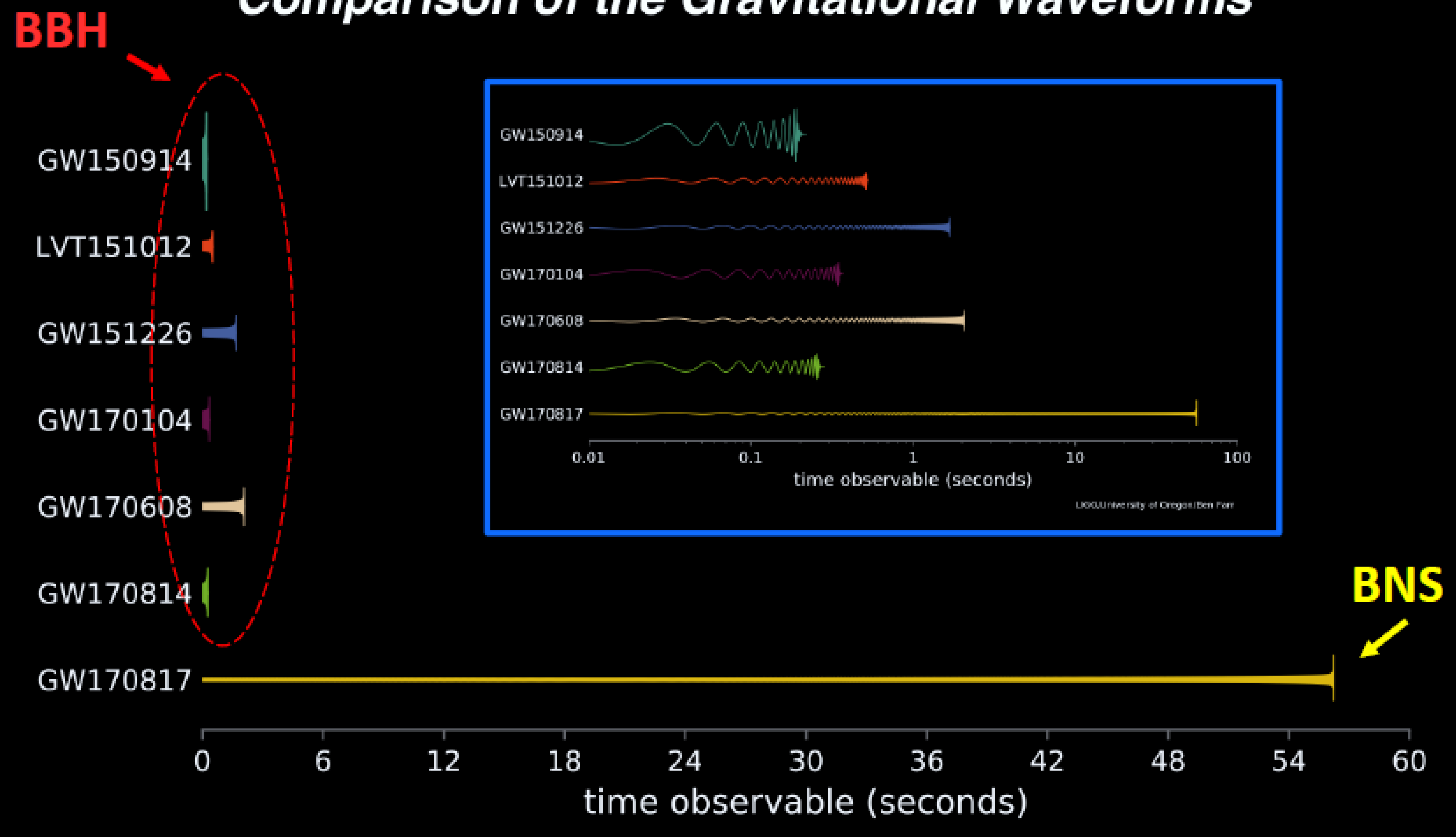
The observation of a kilonova allowed us to show that BNS mergers could be responsible for the production of all heavy elements, like gold, in the universe.

Observing both electromagnetic and gravitational waves from the event provides confirmation that gravitational waves travel at the same speed as light.

Credit: LSC/Daniel Williams



Comparison of the Gravitational Waveforms



LIGO/University of Oregon/Ben Farr

GW170817 : The sky localization

- **Rapid Localization** results 90% confidence (within hours)

  Only LIGO = 190 deg^2 (two islands along an arc of equal time delay)

  LIGO+Virgo = 31 deg^2

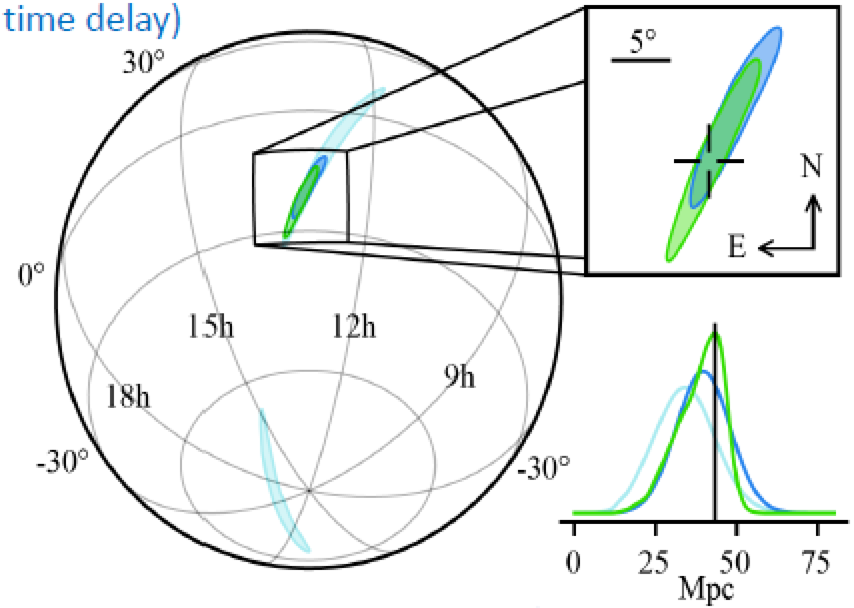
- **Refined localization** (days)

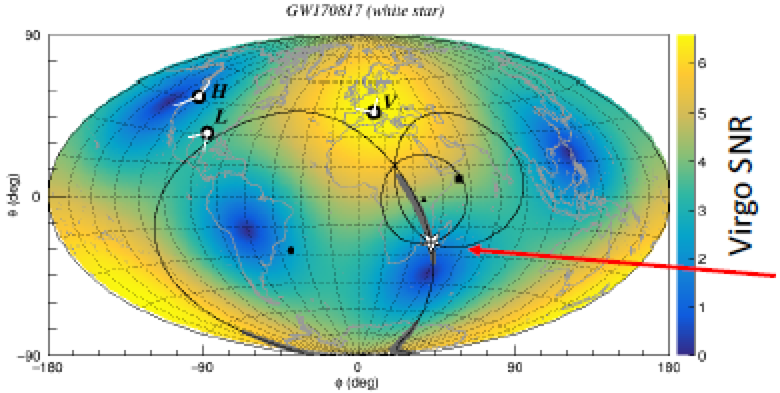
  LIGO+Virgo = 28 deg^2

- **Source distance** ≈ 40 Mpc

- **Localization volume** ≈ 380Mpc^3

  containing about 50 known galaxies

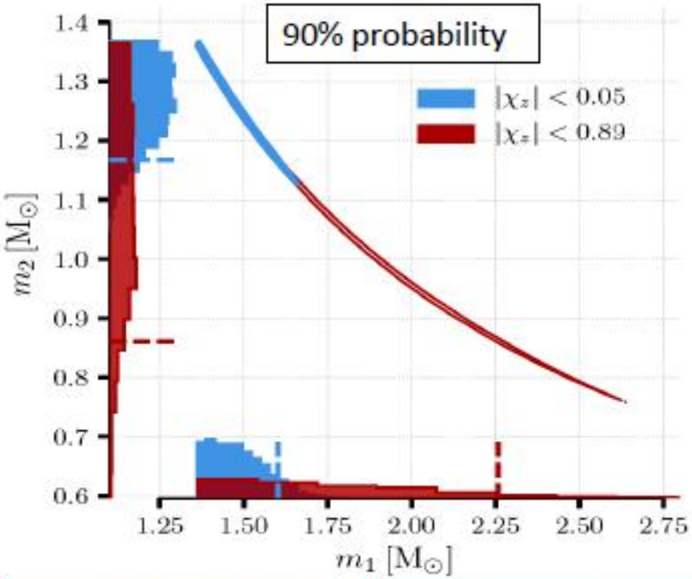




How Virgo Contribute ?

Amplitude consistency of measured signal

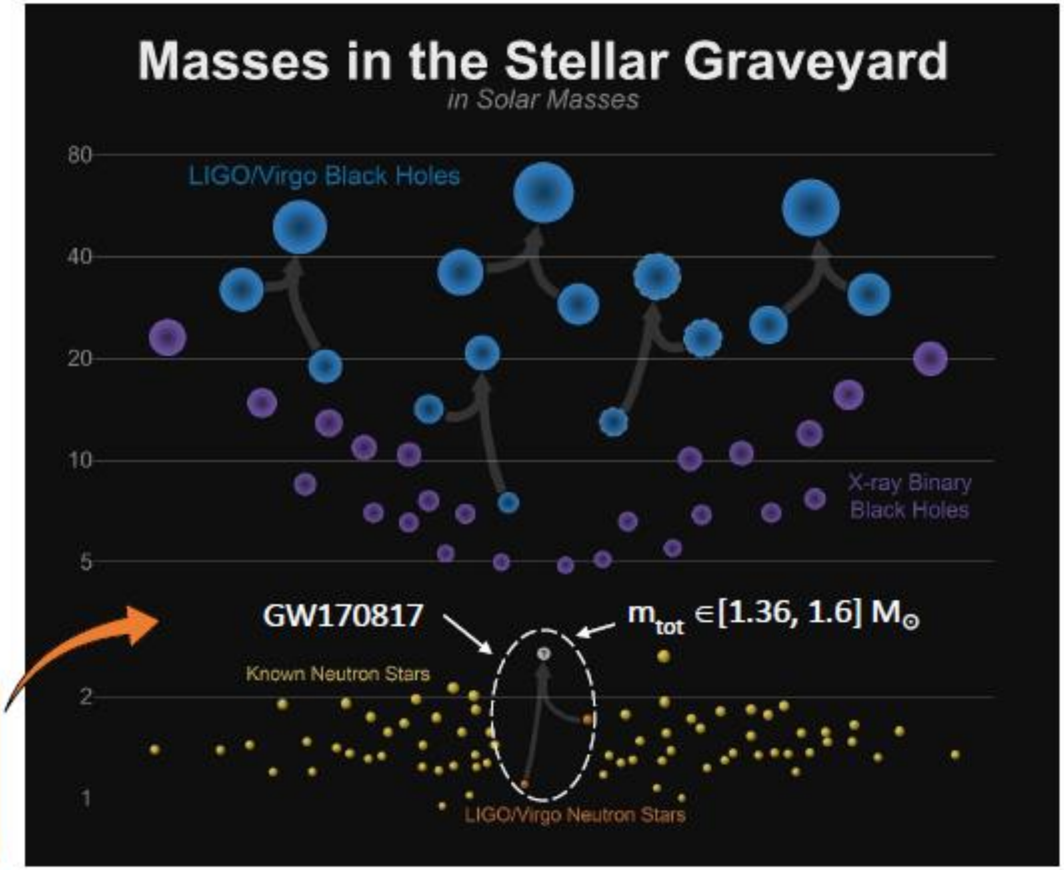
GW170817 : The masses



$m_1 \in [1.36, 1.6\ ]\ \mathrm{M}_\odot$
$m_2 \in [1.17, 1.36,]\ \mathrm{M}_\odot$

$m_1 \in [1.36, 2.26]\ \mathrm{M}_\odot$
$m_2 \in [0.86, 1.36]\ \mathrm{M}_\odot$

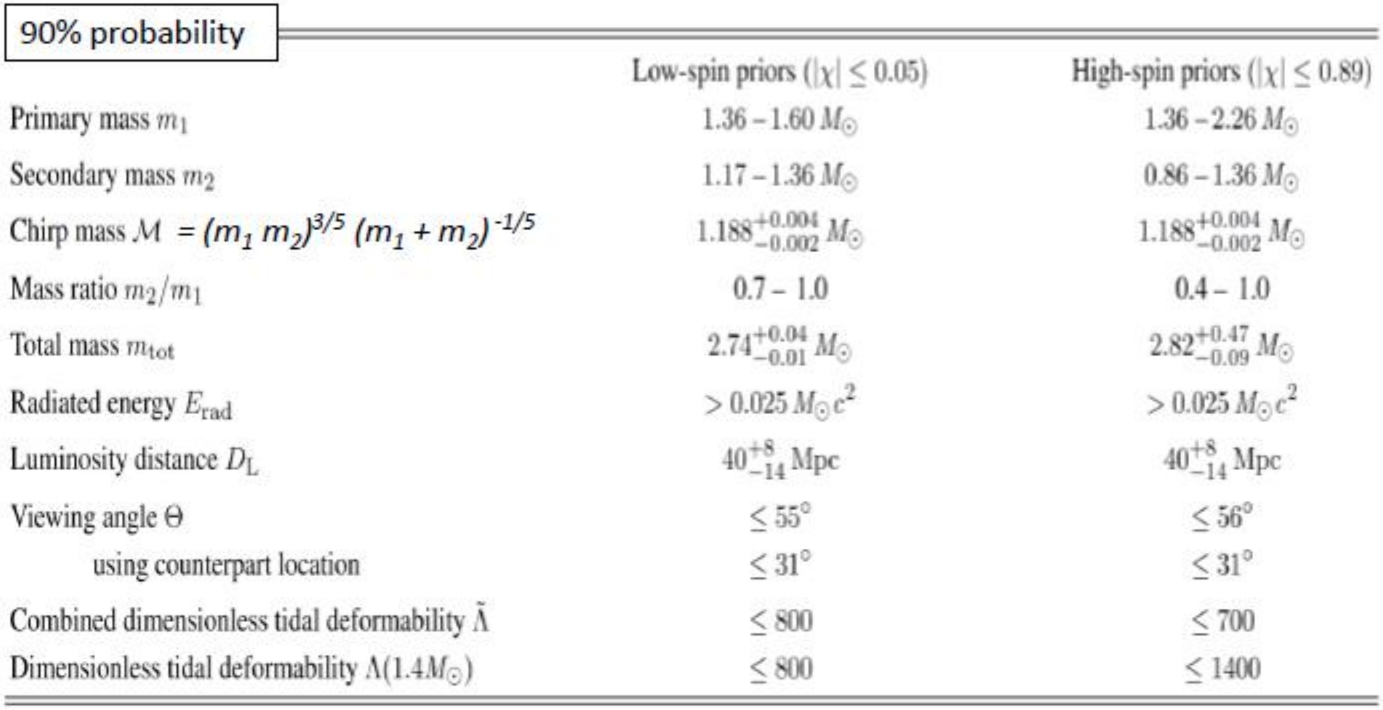
Consistent with mass distribution of known NS, inconsistent with that of known Black holes



GW170817

$m_{tot} \in [1.36, 1.6]\ \mathrm{M}_\odot$

GW170817 : Source properties, summary



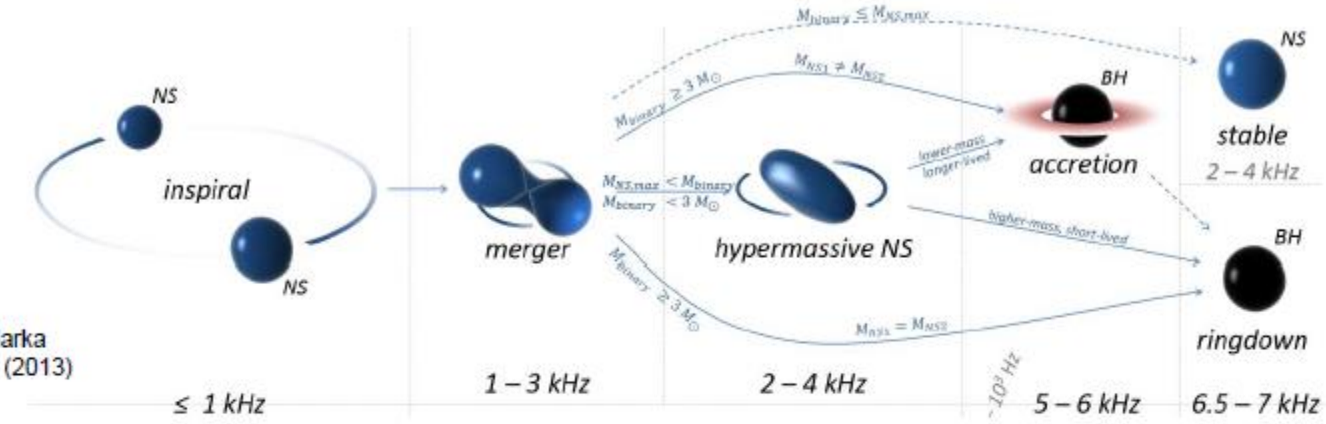
90% probability

		Low-spin priors ($|\chi| \leq 0.05$)	High-spin priors ($|\chi| \leq 0.89$)
	Primary mass m_1	$1.36 - 1.60\ M_\odot$	$1.36 - 2.26\ M_\odot$
	Secondary mass m_2	$1.17 - 1.36\ M_\odot$	$0.86 - 1.36\ M_\odot$
	Chirp mass $\mathcal{M} = (m_1\, m_2)^{3/5}\, (m_1 + m_2)^{-1/5}$	$1.188^{+0.004}_{-0.002}\ M_\odot$	$1.188^{+0.004}_{-0.002}\ M_\odot$
	Mass ratio m_2/m_1	$0.7 - 1.0$	$0.4 - 1.0$
	Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01}\ M_\odot$	$2.82^{+0.47}_{-0.09}\ M_\odot$
(1)	Radiated energy $E_{\rm rad}$	$> 0.025\ M_\odot c^2$	$> 0.025\ M_\odot c^2$
(2)	Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
(3)	Viewing angle Θ	$\leq 55°$	$\leq 56°$
	using counterpart location	$\leq 31°$	$\leq 31°$
	Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
	Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

1) *Radiated Energy: lower bound on the energy emitted before the onset of strong tidal effects at* $f_{\rm GW} \approx 600$ Hz

2) *Inspiral signals from coalescences are standard sirens … but distance is correlated with viewing angle* Θ (3)

GW170817 : The Fate of a Neutron Star Binary Merger

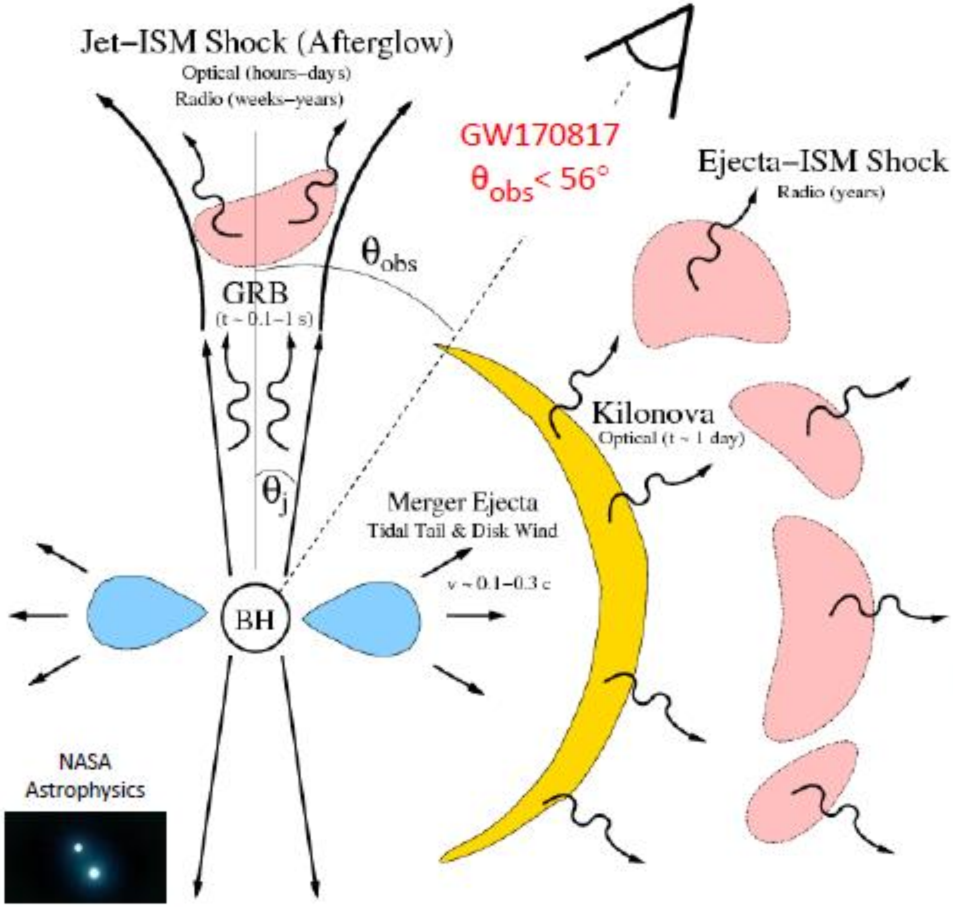


Bartos, Brady, Marka
CQG 30 123001 (2013)

Remnant - *Astrophysical Journal Letters*; **851**(1):L16(13); 2017

- BNS mergers may result in a short- or long-lived neutron star remnant that could emit gw following the merger.
- Searches have been made for short (tens of ms) and intermediate duration (≤ 500 s) gw signals from a NS remnant at frequencies up to 4 kHz.
- **There is no evidence of a post-merger signal of astrophysical origin**. However, upper limits placed on the strength of gw emission cannot definitively rule out the existence of a short- or long-lived post-merger neutron star.

GRB170817A, AT2017fgo : Electromagnetic Counterparts of BNS Mergers



1

The neutron stars inspiral

2

Produce a short gamma-ray burst

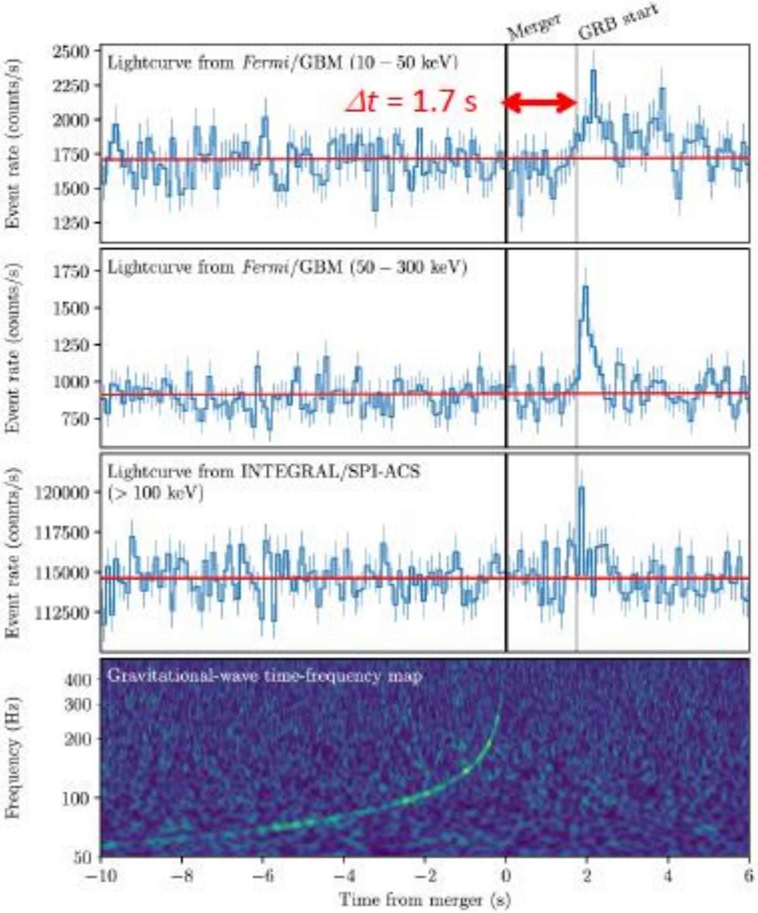
3

can fling out hot, radioactive material in the form of a "kilonova"

4

form a massive neutron star or black hole with a possible remnant debris disk around it

Association of **GW170817** and **GRB170817A** & Fundamental Physics



- **GW170817 provides a stringent test of the speed of gravitational waves**

$$\frac{v_{GW} - c}{c} \approx \frac{c\Delta t}{D}$$

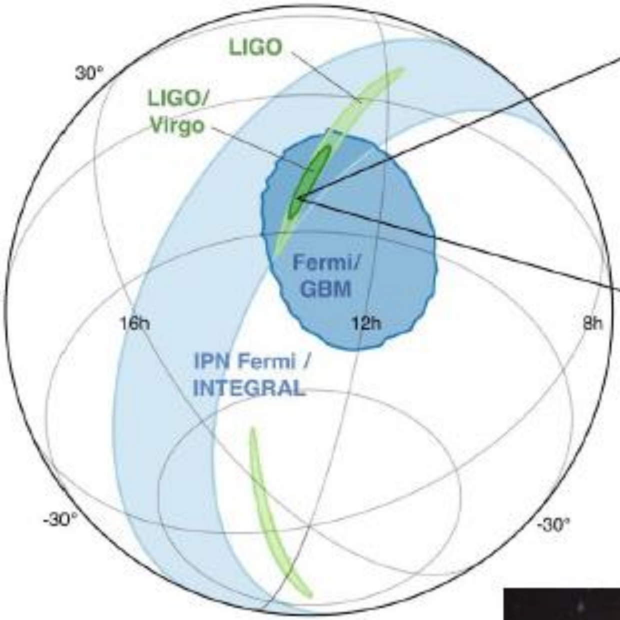
- Conservative assumptions
  - Δt = [-10, +1.74] sec
  - $D \approx$ 26 Mpc
    - Conservative limit – use 90% confidence level lower limit on GW source from parameter estimation

$$\boxed{-3 \times 10^{-16} \leq \frac{v_{GW} - c}{c} \leq +7 \times 10^{-16}}$$

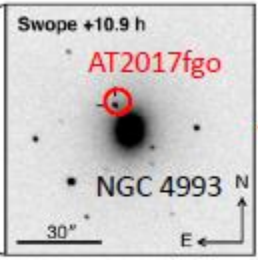
- **GW170817 also puts limits on violations of Lorentz Invariance and Equivalence Principle**

LIGO Scientific Collaboration and Virgo Collaboration, Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A" Astrophys. J. Lett., 848:L13, (2017)

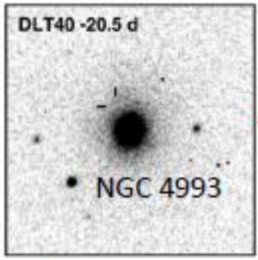
Discovery of Optical Counterpart **(AT2017fgo)** and Host Galaxy **(NGC 4993)**



Localization of the gravitational-wave, gamma-ray, and optical signals



The 1M2H team was the first to discover the optical counterpart AT2017fgo in the host galaxy NGC 4993 with the 1m Swope telescope 10.9 hr after the merger time



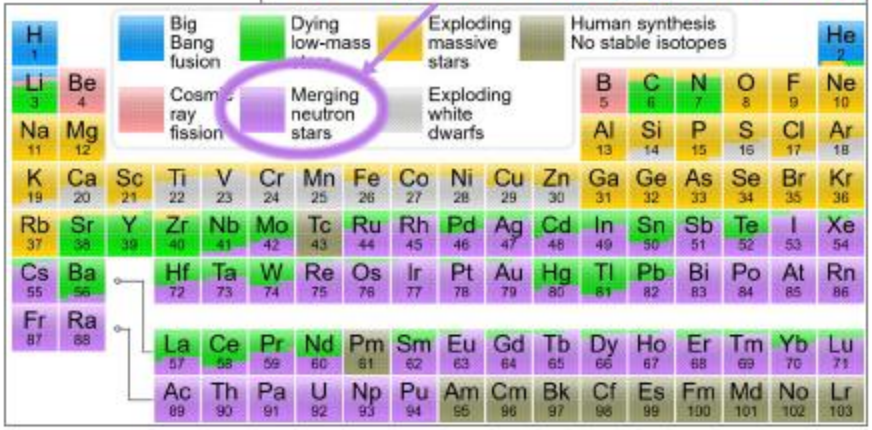
The DLT40 pre-discovery image from 20.5 days prior to merger

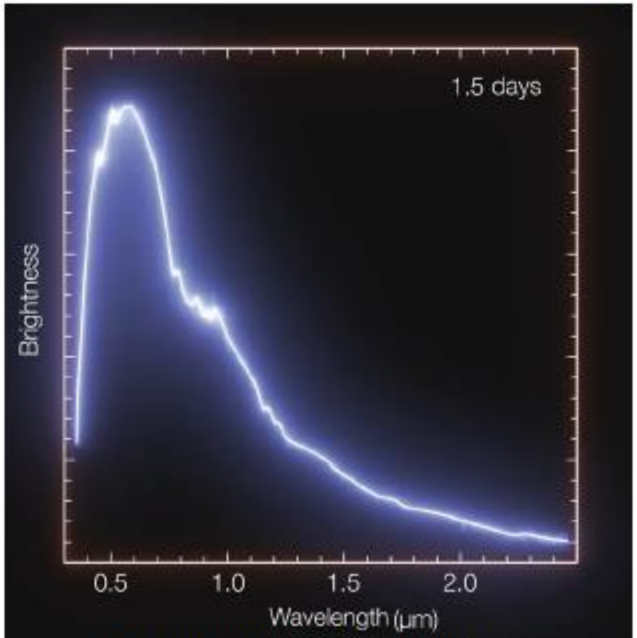
European Southern Observatory Very Large Telescope

Binary Neutron Star Mergers Produce Kilonovae

- **Electromagnetic follow-up of GW170817 provides strong evidence for kilonova model**
  - kilonova-isotropic thermal emission produced by radioactive decay of rapid neutron capture ('r-process') elements synthesized in the merger ejecta
- **Spectra taken over 2 weeks period across all electromagnetic bands consistent with kilonova models**
  - "Blue" early emission dominated by Fe-group and light r-process formation; later "red" emission dominated by heavy element (lanthanide) formation
- **Recent radio data prefers 'cocoon' model to classical short-hard GRB production!**

Elements produced in merging neutron stars





Credit: ESO/E. Pian et al./S. Smartt & ePESSTO/L. Calçada

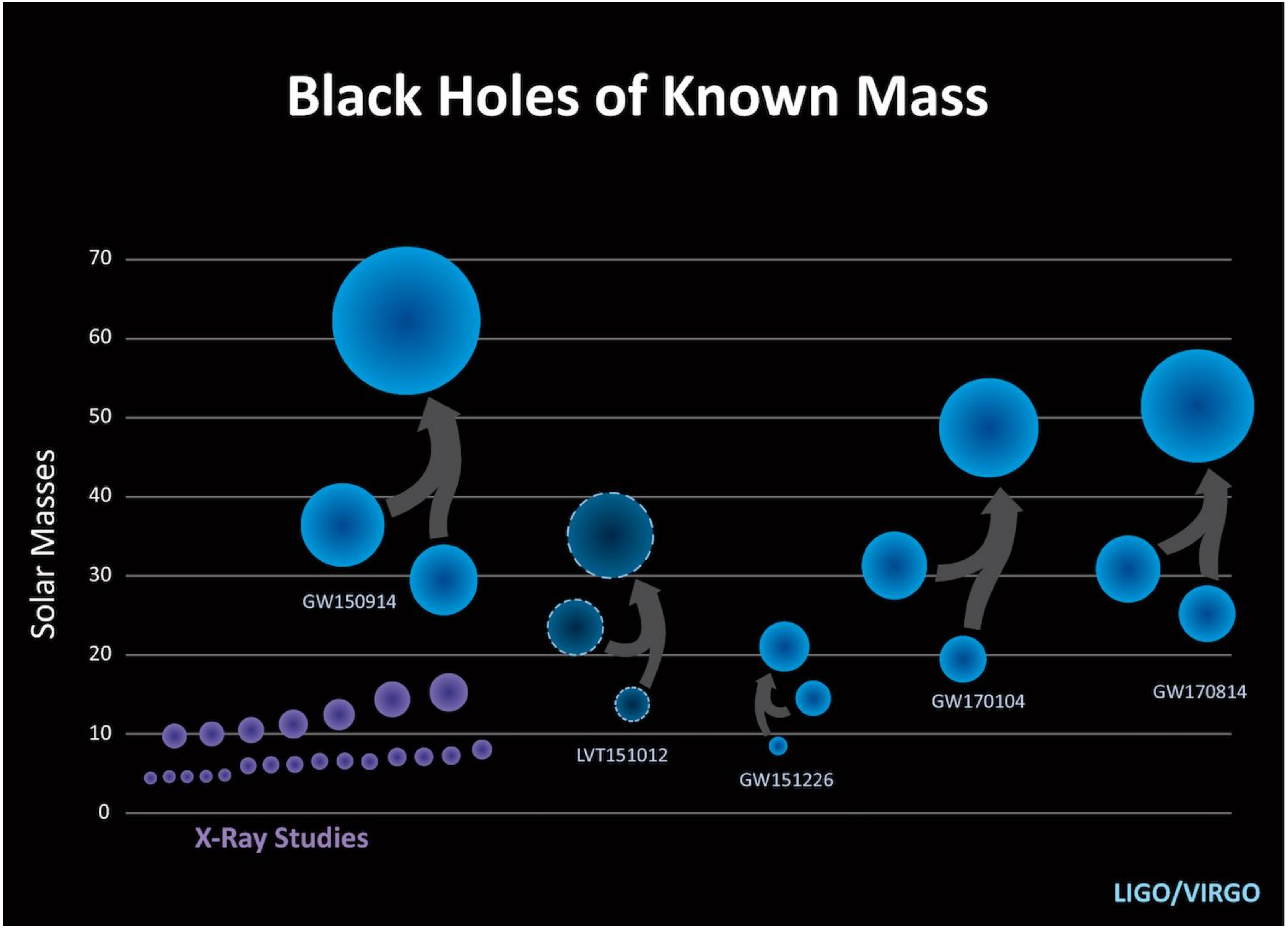
Animation is based on a series of spectra of the kilonova observed by the X-shooter instrument on ESO's Very Large Telescope in Chile.

What did we learn ?

- **BNS merger rate :** $1540^{+3200}_{-1220}\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ (BBH : $103^{+110}_{-63}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$)
- Confirmation of **association between short GRBs and BNS** mergers, and new insights into physics of GRB events
- Limits on dynamical ejecta in the associated **kilonova**
- BNS mergers as **producers of heavy elements** confirmed
- **Independent measurement of the Hubble constant** consistent with prior measurements
- Test of General Relativity
  - GW signal is **consistent with GR over thousands of cycles**
  - GW polarization is **consistent with tensorial**
  - Speed of gravity is **consistent with speed of light** to one part in 10^{-15}

THANK YOU

Что изменилось



Несколько цитат

- Обычные черные дыры образуются после коллапса отдельных звезд, и ученые полагали, что предельная масса примерно в 15 раз больше массы нашего Солнца. Сверхмассивные черные дыры, скрывающиеся в центре почти каждой галактики, поглощают миллиарды звезд. Однако астрофизики не видели, чтобы коллапсирующие звезды образовывали черные дыры промежуточных масс. Вот почему для всех стал неожиданностью тот факт, что с помощью LIGO в феврале 2016 года удалось засечь рябь в пространстве, вызванную слияние двух черных дыр, масса которых в 29 и 36 раз соответственно превосходит массу Солнца.
- Теоретики говорят, что существует возможность формирования таких тяжелых черных дыр еще до появления первых звезд: речь идет о прямом распаде вещества в кипящую плазму частиц, которые наполнили космос сразу после Большого Взрыва. Если открытие LIGO не было просто статистическим искажением, то пространство может просто кишеть такими «первичными» черными дырами, что будет исчерпывающим объяснением того, куда подевалось 85% вещества во Вселенной.

- Если взять за основу текущий порог LIGO и тот факт, что она находит сигнал раз в два месяца (в среднем), можно с уверенность сказать, что в каждой галактике размером с Млечный Путь, которую мы можем зондировать, есть как минимум с десяток таких систем.
- Более того, наши рентгеновские данные показывают, что есть много бинарных черных дыр с меньшей массой; возможно, значительно больше, чем массивных, которые может найти LIGO. И это даже не учитывая данные, указывающие на существование черных дыр, которые не включены в жесткие бинарные системы, а их должно быть большинство. Если в нашей галактике есть десятки черных дыр средней и высокой массы (в 10-100 солнечных масс), должны быть сотни (3-15 солнечных масс) бинарных черных дыр и тысячи изолированных (небинарных) черных дыр звездной массы.