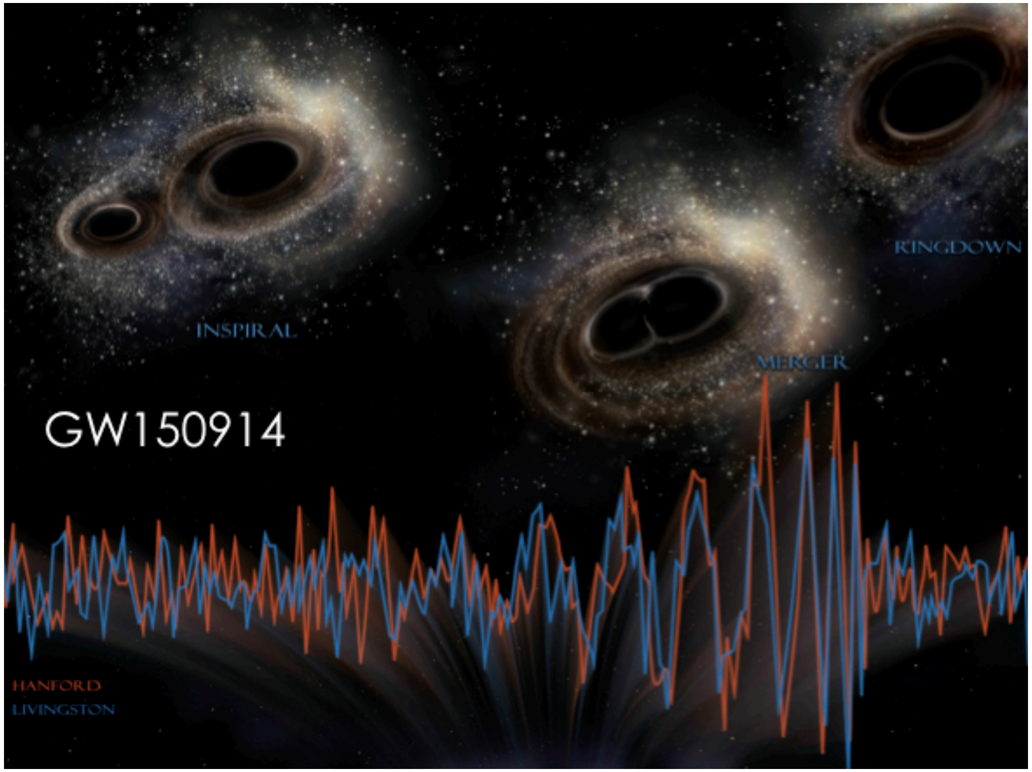
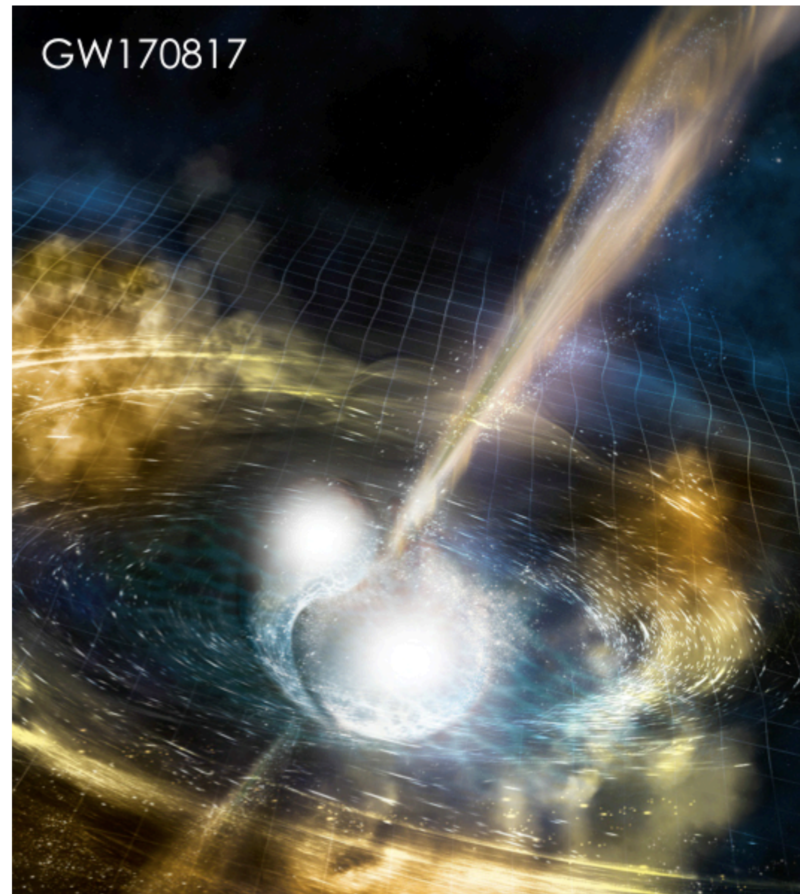
THE DAWN (and perspectives) of GRAVITATIONAL WAVE ASTRONOMY

Viviana Fafone
Tor Vergata University - INFN

THE BEGINNING OF A NEW ERA





PRESS RELEASE

3 October 2017

The Nobel Prize in Physics 2017

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2017

with one half to

Rainer Weiss
LIGO/VIRGO Collaboration

and the other half jointly to

Barry C. Barish
LIGO/VIRGO Collaboration

and

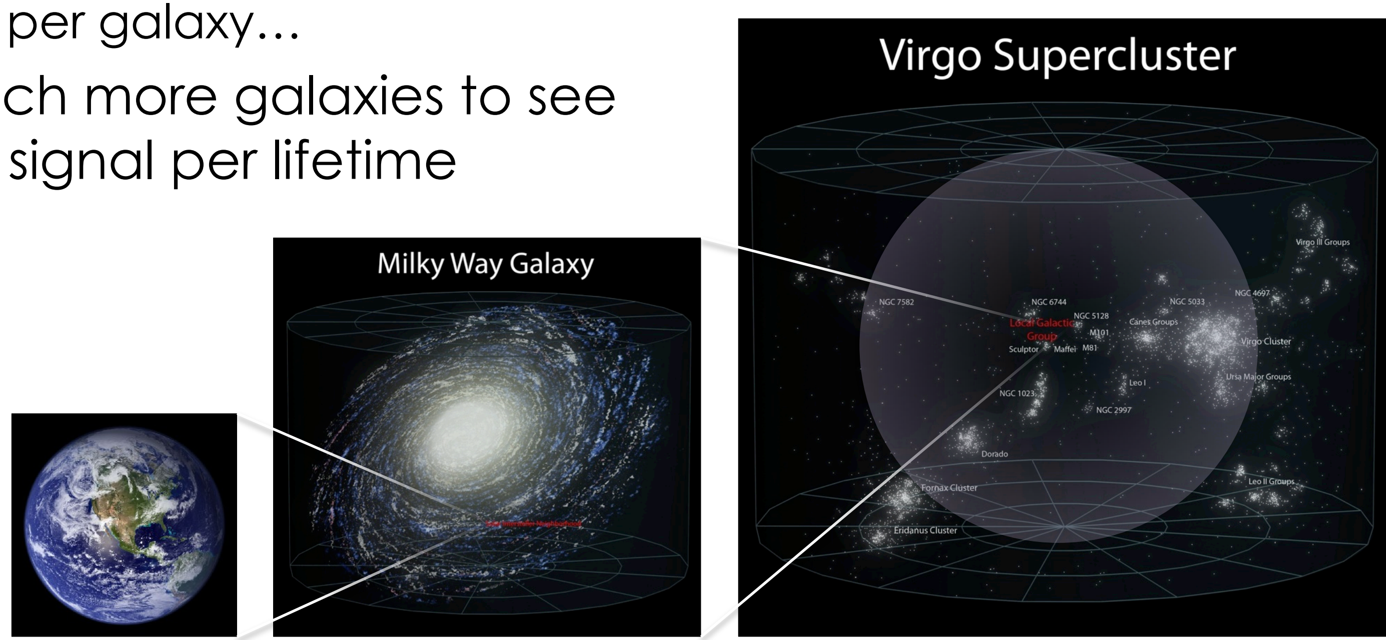
Kip S. Thorne
LIGO/VIRGO Collaboration

"for decisive contributions to the LIGO detector and the observation of gravitational waves"

HOW DID WE GET HERE: FROM 1ST TO 2ND GENERATION DETECTORS

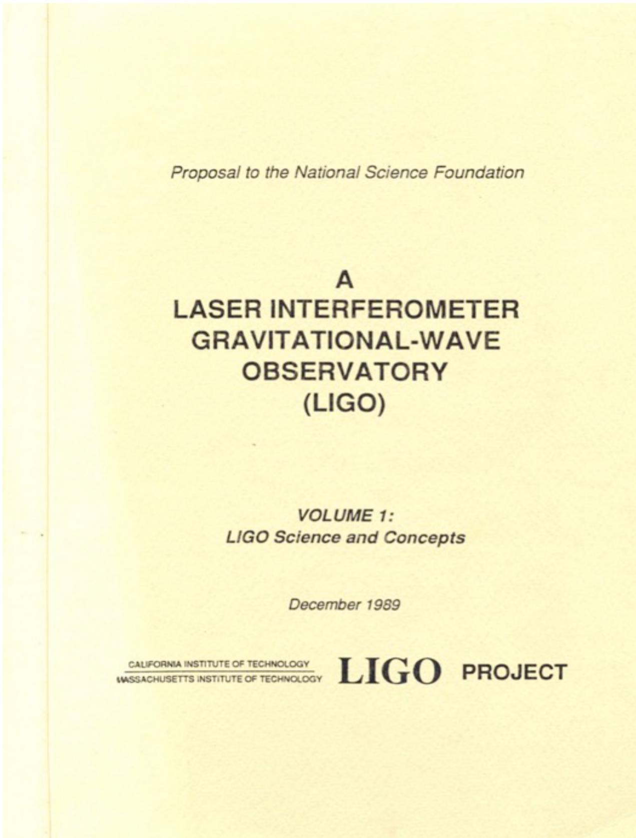
1G NETWORK

- First generation detectors and infrastructure built from mid-'90s to mid-2000; commissioned to design sensitivity and observed for several years
- In case of BNS merger:
  - Sensitivity sufficient to reach about 100 galaxies; however…
  - Expected rate is low: events happen once every 10,000 years per galaxy…
- Need to reach more galaxies to see at least one signal per lifetime



Credits: D. Shoemaker

1989

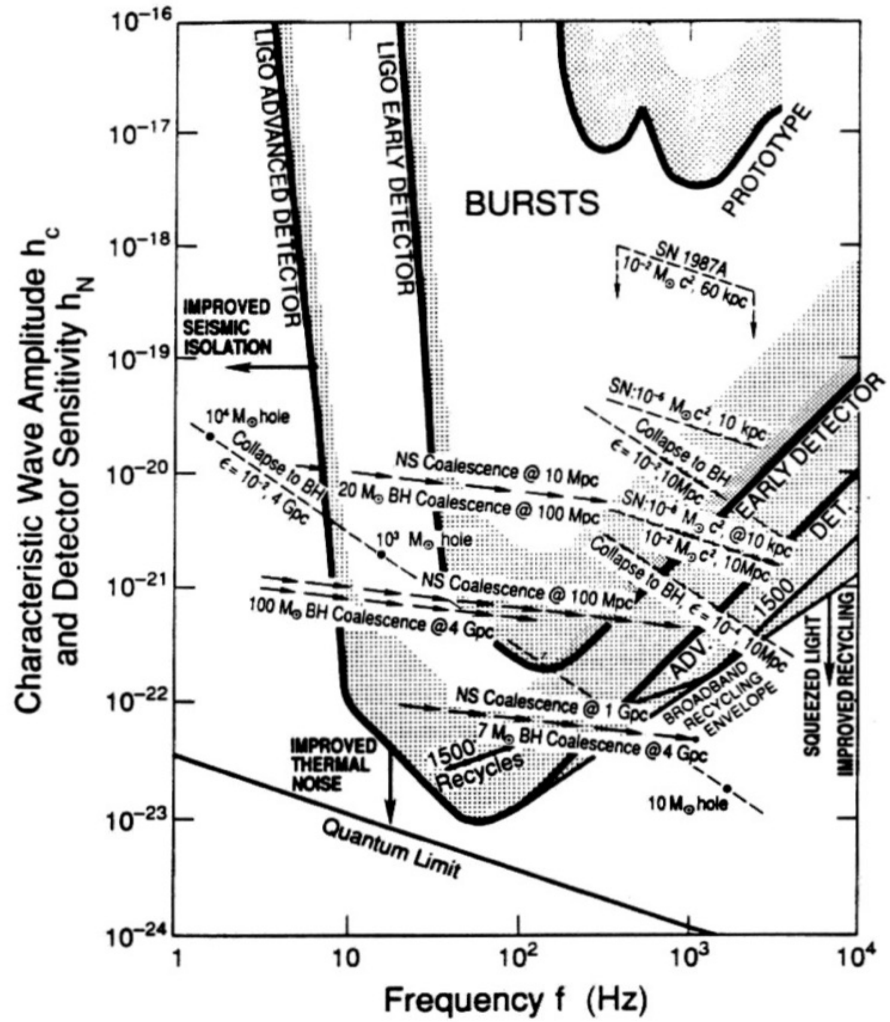

Proposal to the National Science Foundation

A
LASER INTERFEROMETER
GRAVITATIONAL-WAVE
OBSERVATORY
(LIGO)

VOLUME 1:
LIGO Science and Concepts

December 1989

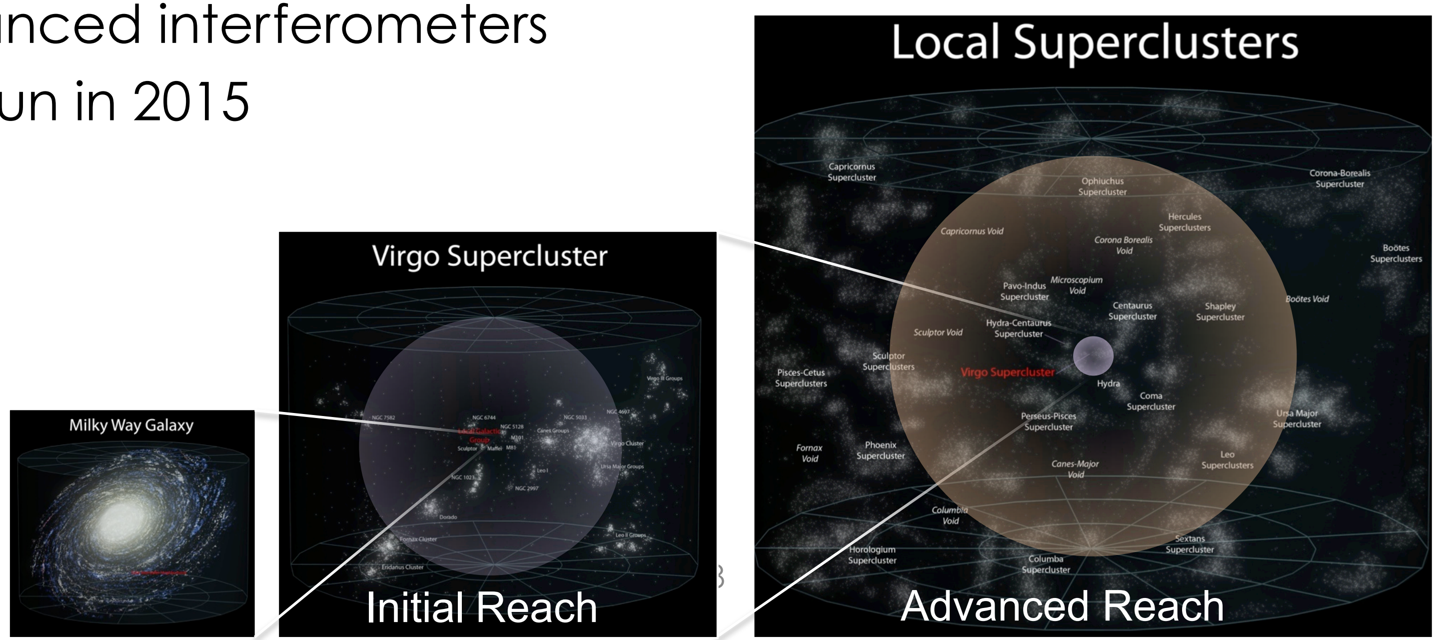
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LIGO PROJECT



THE CONCEPT OF AN "ADVANCED" DETECTOR WAS ALREADY IN THE LIGO PROPOSAL TO NSF

ADVANCED DETECTORS

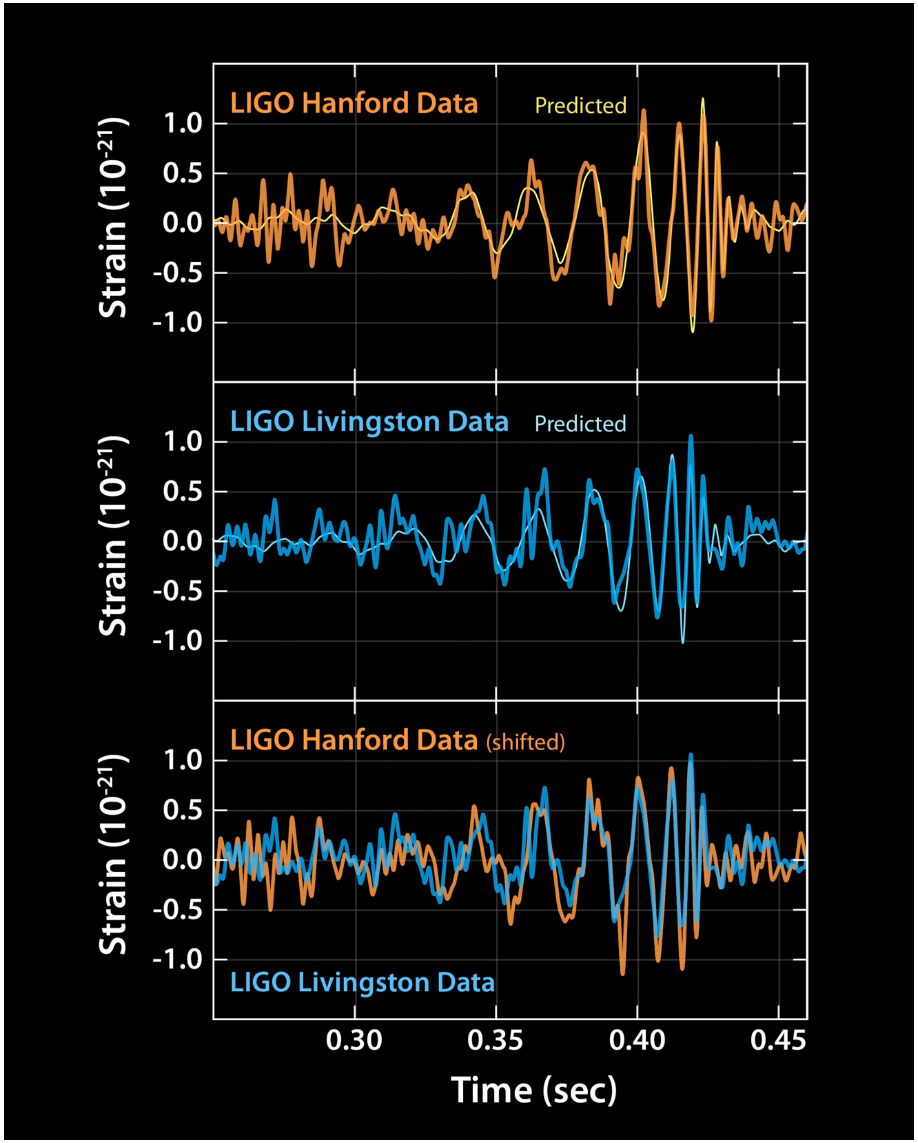
- While observing with initial detectors, parallel R&D led to better concepts
- ‘Advanced detectors’ are ~10x more sensitive → detection rate 10^3 larger
- NS-NS detection rate at design sensitivity order of 1 per month (will reach about 100,000 galaxies)
- Integration began in: 2011 (LIGO) and 2013 (Virgo)
- First advanced interferometers science run in 2015



Credits: D. Shoemaker

THE OBSERVATIONS

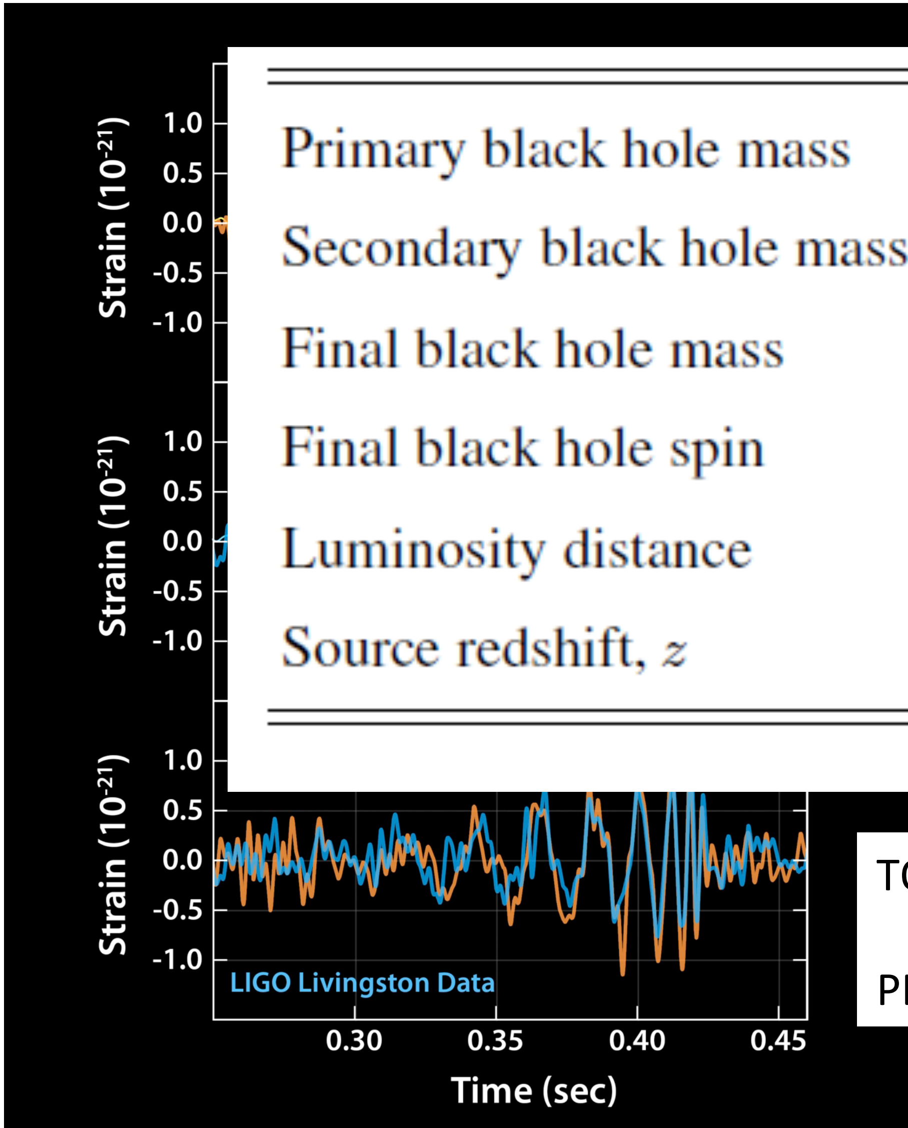
IN WITH A BANG: GW150914



Binary BH merger

Abbott et al., PRL, 116, 061102 (2016)

IN WITH A BANG: GW150914



Primary black hole mass	$36^{+5}_{-4}\ \mathrm{M}_\odot$
Secondary black hole mass	$29^{+4}_{-4}\ \mathrm{M}_\odot$
Final black hole mass	$62^{+4}_{-4}\ \mathrm{M}_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift, z	$0.09^{+0.03}_{-0.04}$

TOTAL ENERGY RADIATED IN GW: $3.0^{+0.5}_{-0.5} M_\odot c^2$

PEAK GW LUMINOSITY: $3.6^{+0.5}_{-0.4} \times 10^{56}$ erg/s

The most luminous event ever observed

Abbott et al., PRL, 116, 061102 (2016)

GW150914: MANY "firsts"

- First direct detection of gravitational waves (100 years after Einstein's prediction)
- First direct observation of black holes
- First observation of the largest known stellar mass BH (>25 solar masses)
- First observation of a binary black hole (BBH) system,
- First observation of a BBH merger
- First tests of general relativity in strong field (extreme) conditions

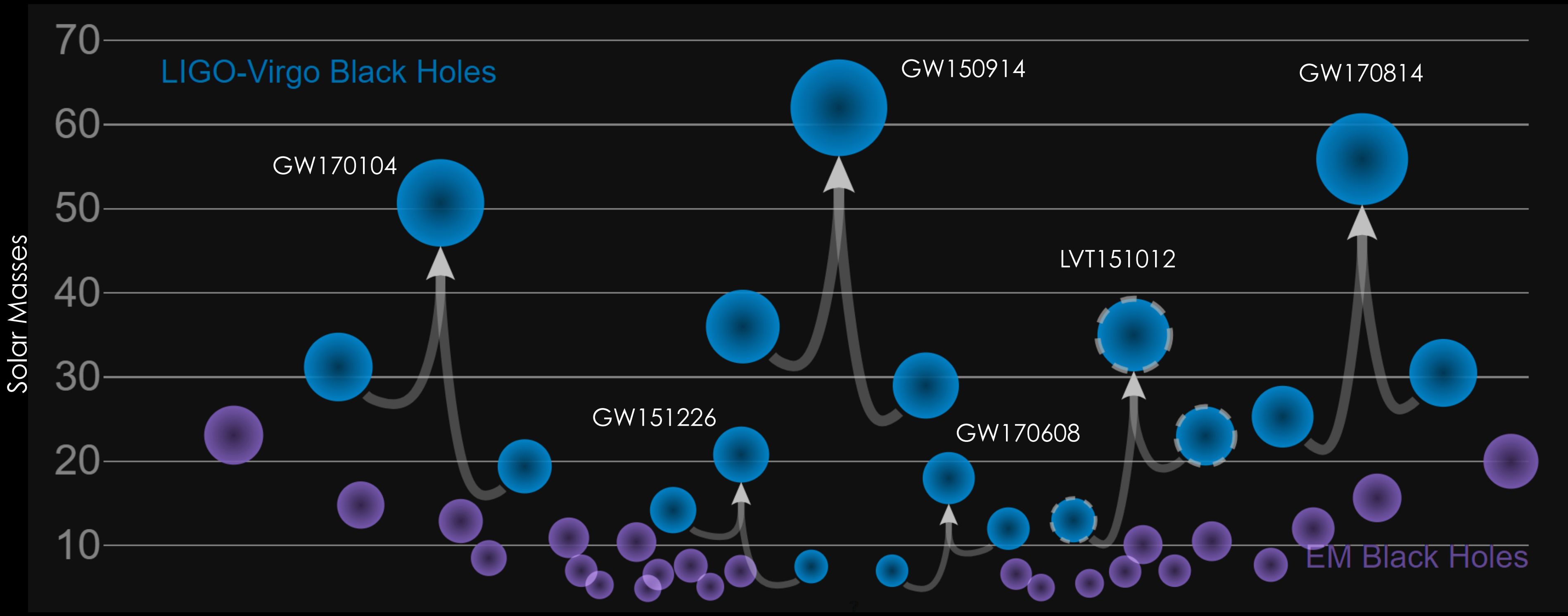
- AND: the ground based interferometers proved to be the right instruments!

ADVANCED DETECTORS SCIENCE FACTS

- First Observing Run (O1) from Sept 2015 to Jan 2016 – LIGO only
  - About 50 days of double coincidence time;
  - Two BBH mergers confirmed detections;
- O2 started on Nov 2016 and ended on Aug 25th, 2017
  - 117 days of double (LIGO) coincidence time;
  - Virgo joined from Aug 1st;
  - 15 days of triple coincidence data;
  - 3 BBH mergers detected;
  - First BNS coalescence.

Black Holes of Known Mass

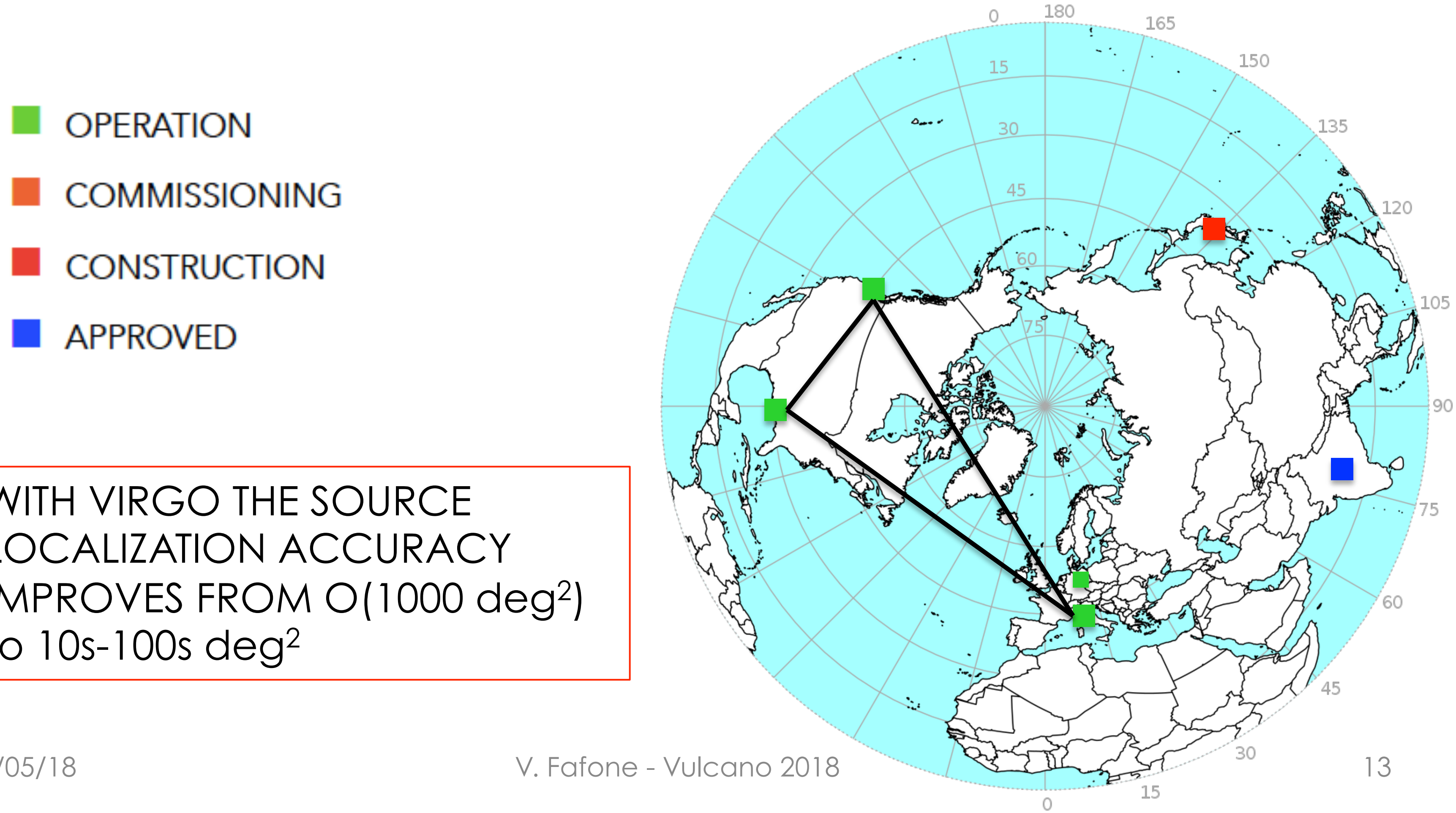
4 (+1) MORE BBH DETECTED AFTER GW150914:
A DIFFERENT POPULATION IS SHOWING UP



LIGO-Virgo | Frank Elavsky | Northwestern

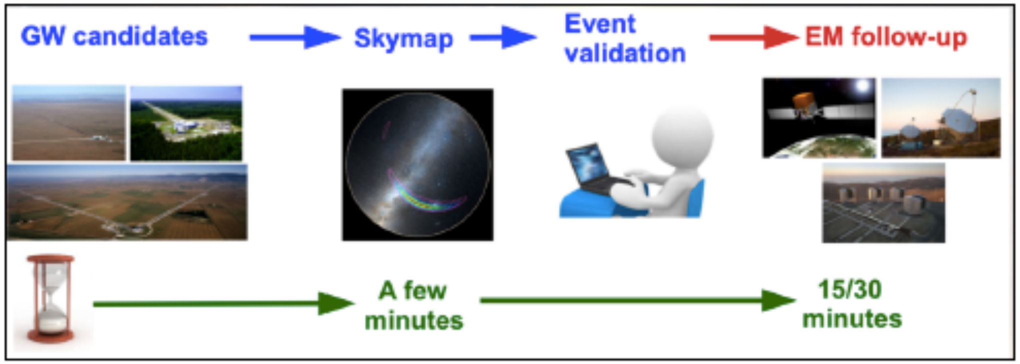
GW NETWORK IN O2

- Virgo joins LIGO in the observation run O2
- Three 2G detectors acting as a "single machine"

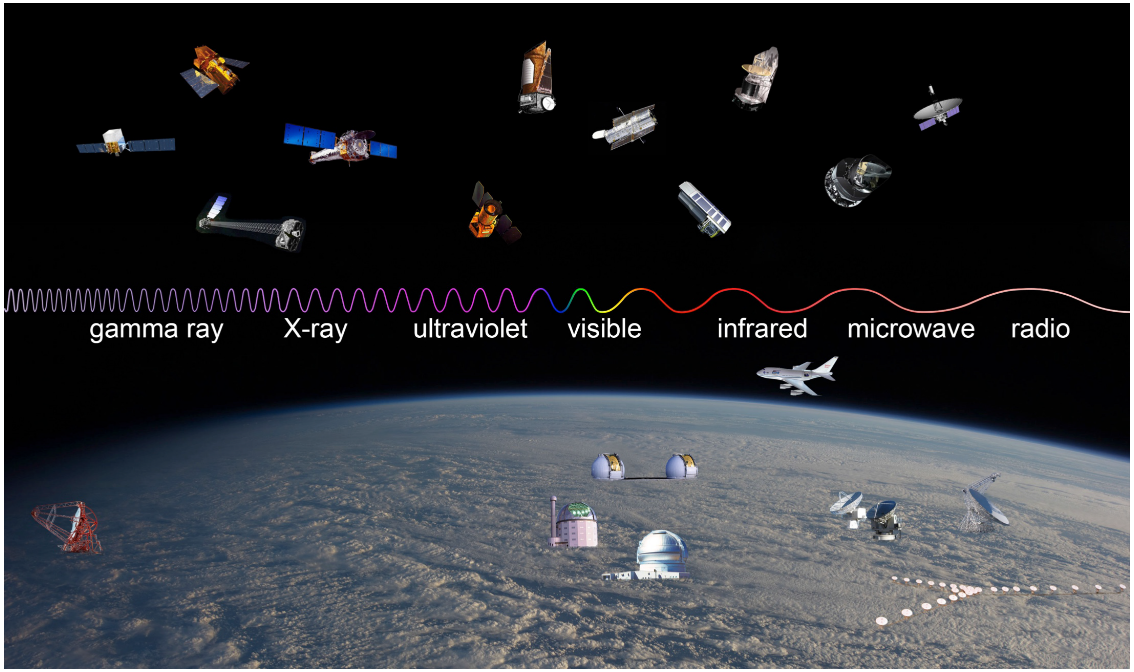


WITH VIRGO THE SOURCE LOCALIZATION ACCURACY IMPROVES FROM O(1000 deg^2) to 10s-100s deg^2

MULTI-MESSENGER NETWORK

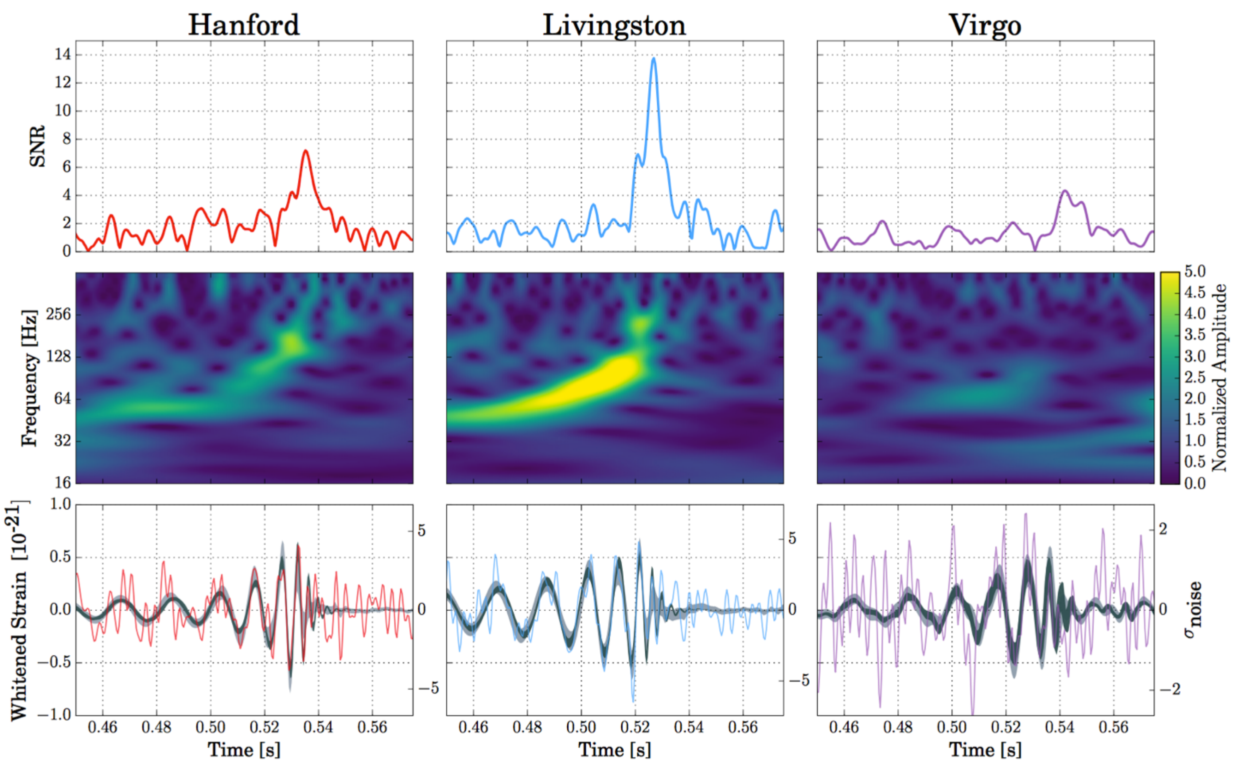


93 groups (>200 instruments) have signed the MoU with the LVC



August 14th, 2017

- At 10:30:43 UTC, Advanced Virgo and the two Advanced LIGO detectors coherently observed a transient GW signal produced by the coalescence of two stellar mass BH, with a false-alarm-rate of <~ 1 in 27 000 years

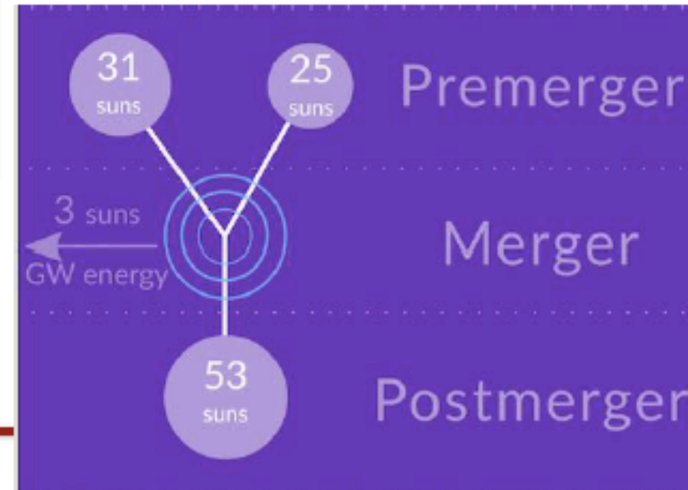


3-detector network SNR: 18.3

PRL, 119, 141101 (2017)

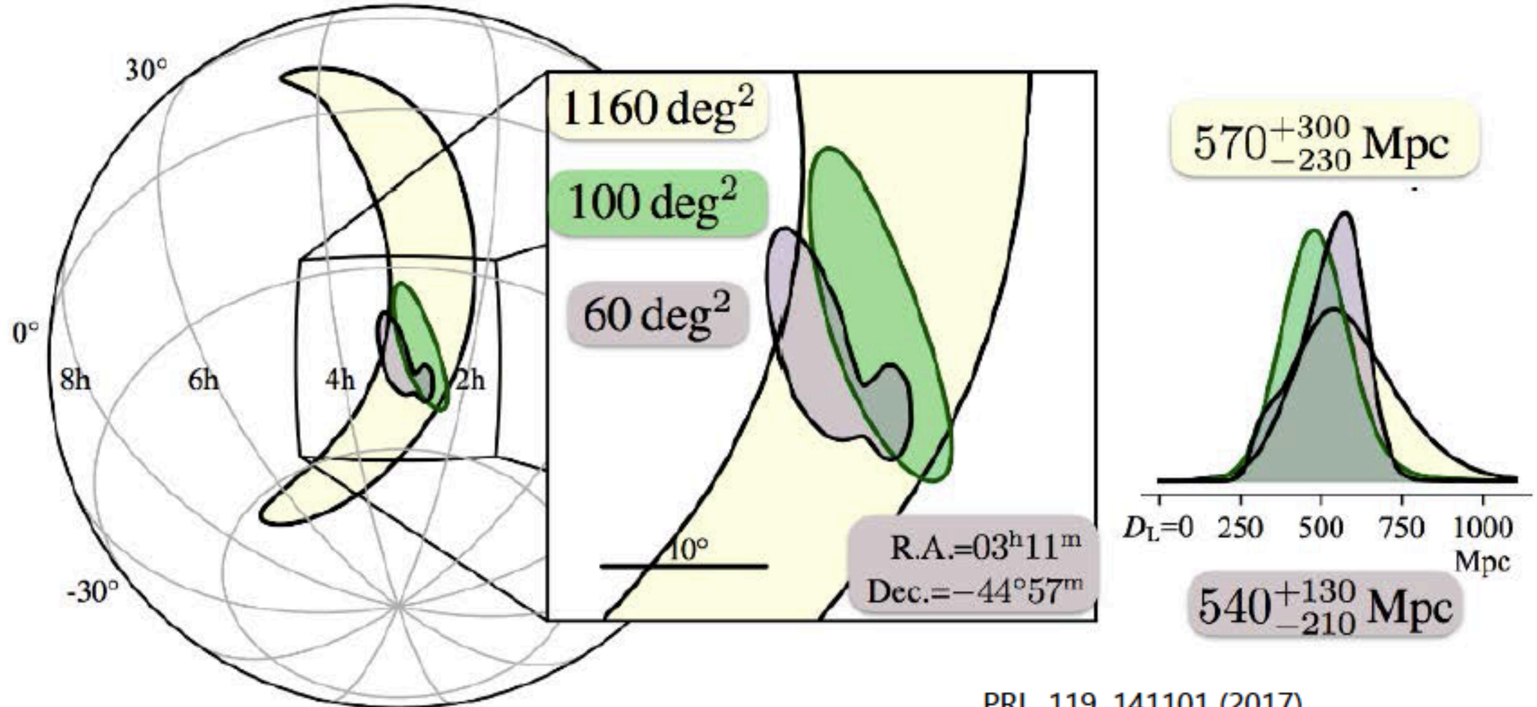
GW170814

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	$2.7^{+0.4}_{-0.3}\ \mathrm{M}_\odot c^2$
Peak luminosity ℓ_peak	$3.7^{+0.5}_{-0.5} \times 10^{56}\ \mathrm{erg\,s^{-1}}$
Effective inspiral spin parameter χ_eff	$0.06^{+0.12}_{-0.12}$
Final black hole spin a_f	$0.70^{+0.07}_{-0.05}$
Luminosity distance D_L	$540^{+130}_{-210}\ \mathrm{Mpc}$
Source redshift z	$0.11^{+0.03}_{-0.04}$



PRL, 119, 141101 (2017)

SKY LOCALIZATION



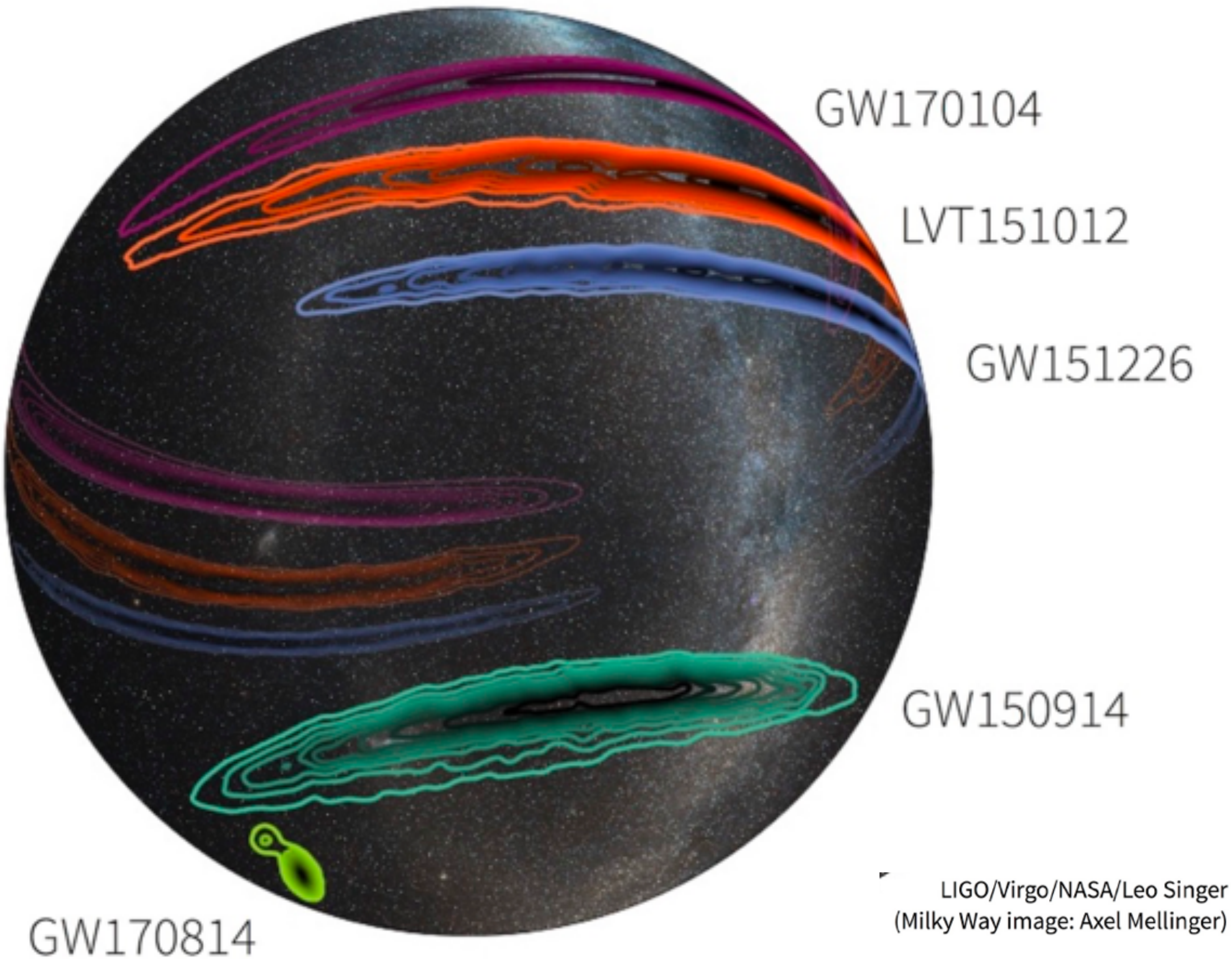
PRL, 119, 141101 (2017)

VIRGO HELPS REDUCING:

ERROR IN SKY AREA: 20x
ERROR IN DISTANCE: 1.5x
ERROR BOX ON THE SKY: 30x
(from 70 to 2 Mpc^3)

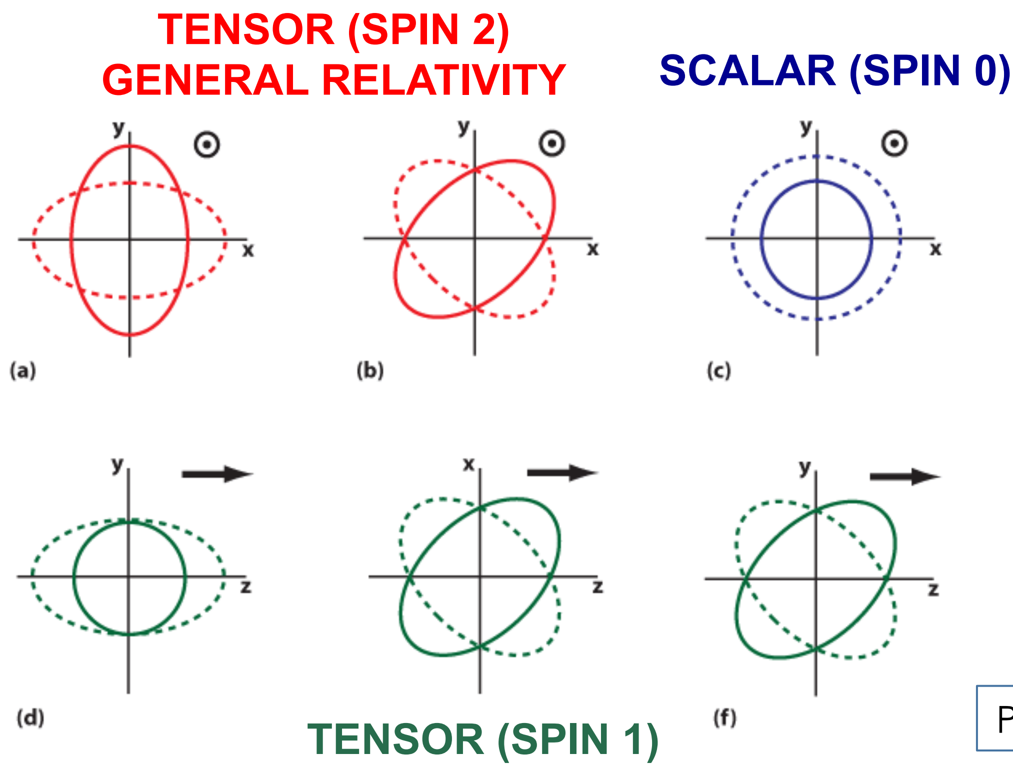
THE ERA OF GW ASTRONOMY HAS FINALLY STARTED

SKY LOCALIZATION



GW POLARIZATION

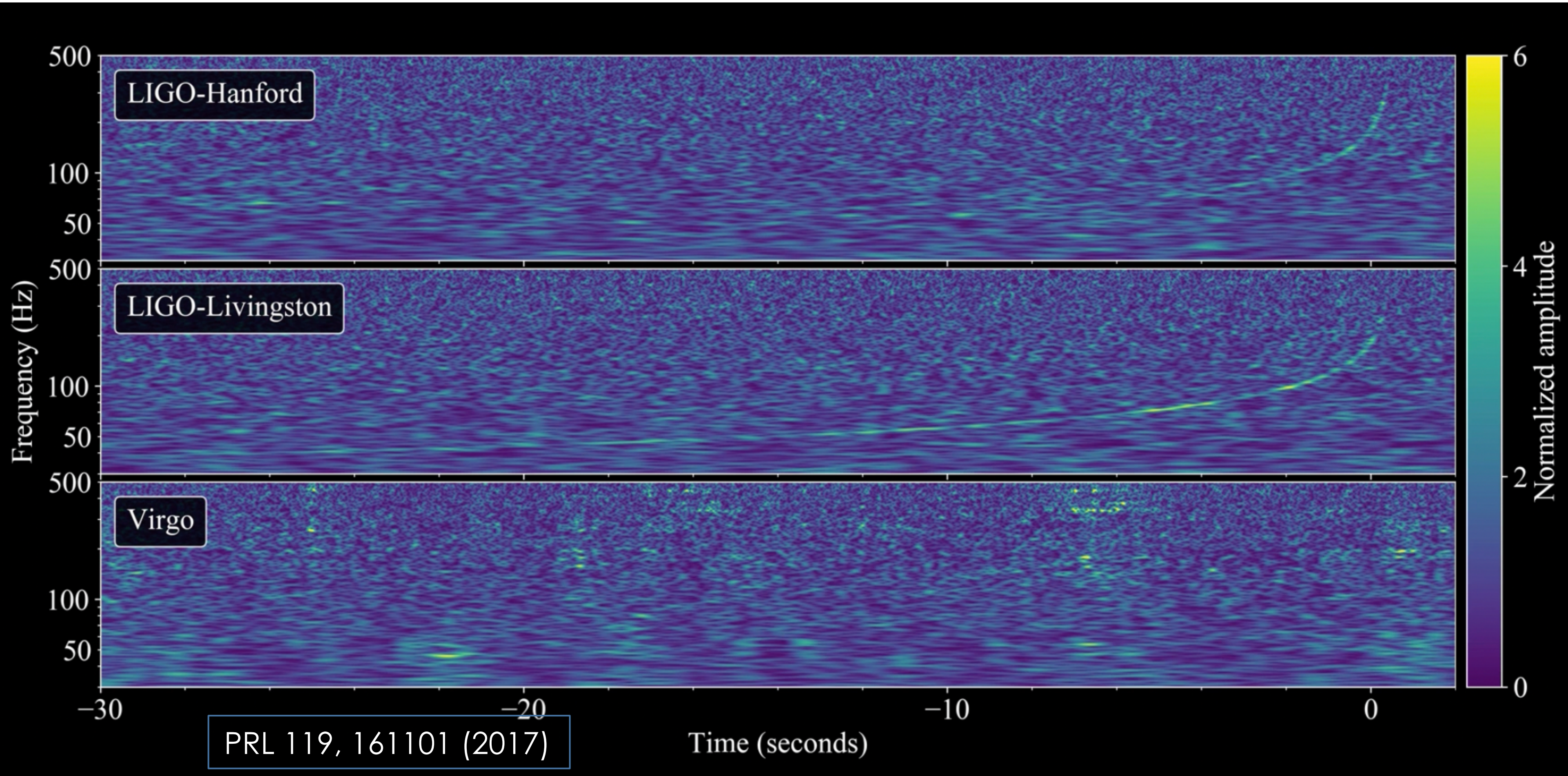
- For the first time, thanks to the the addition of a 3rd detector, one can probe the nature of the polarization states
- So far a preliminary and simplified investigation has been carried out, to illustrate the potential power of this new phenomenological test of gravity. GR (purely tensor) is 200 and 1000 times more likely than purely vector/scalar respectively



PRL, 119, 141101 (2017)

August 17th, 2017

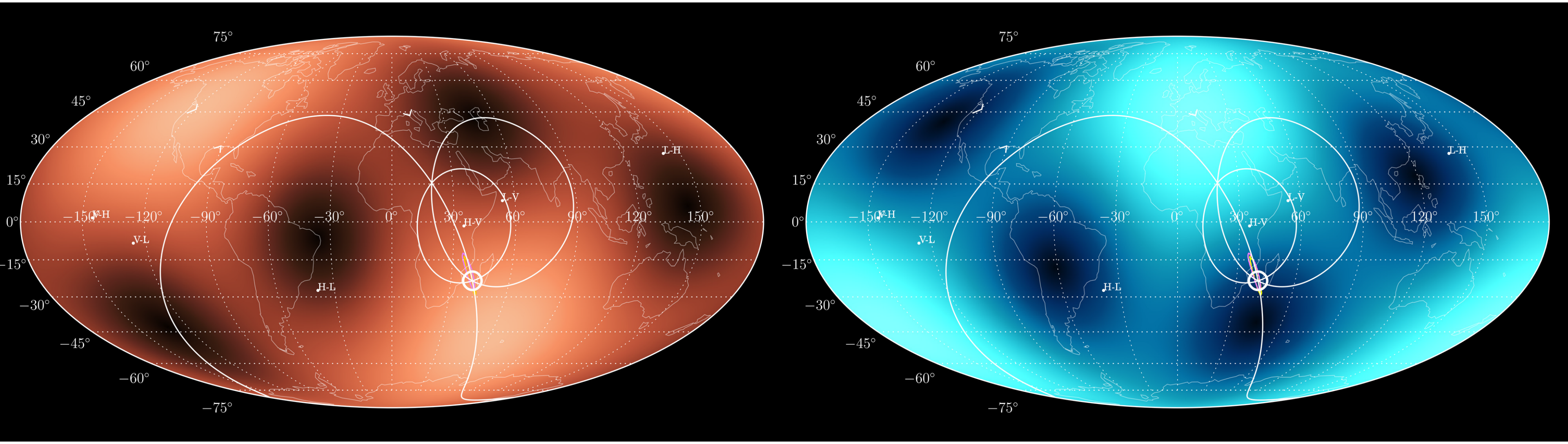
- At 12:41 UTC Advanced LIGO-Virgo detected a binary neutron star inspiral



PRL 119, 161101 (2017)

GW170817

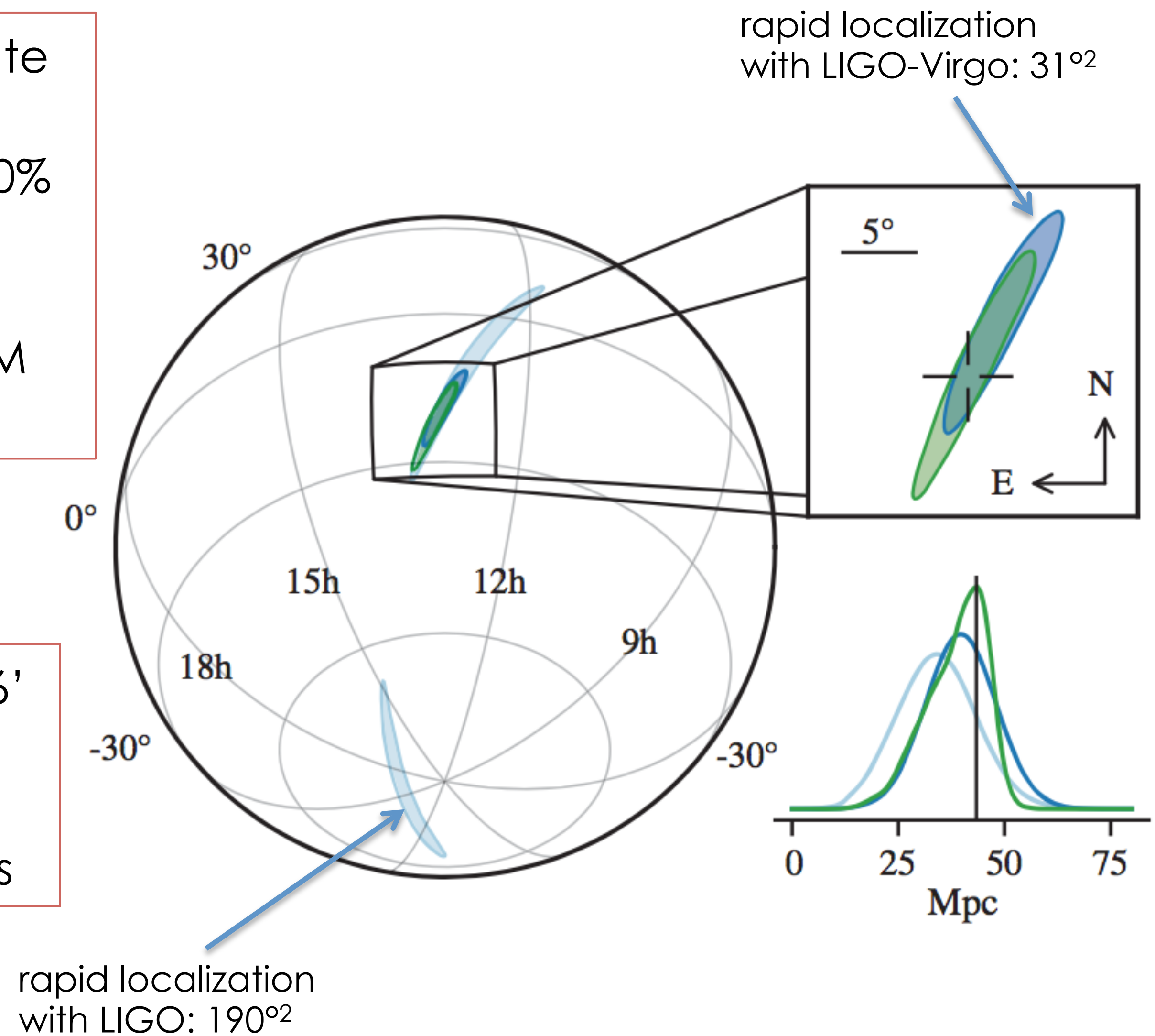
- Duration ~100 s: longest signal so far (3000 cycles in band)
- Network SNR: 32.4 → loudest signal so far
- SNR:
  - LIGO-Livingston: 26.4; LIGO-Hanford: 18.8; Virgo: 2.0
  - Small signal in Virgo: source close to blind spot. Quite important for localization



GW170817 localization

- Early sky maps accurate to ~31°^{2}
- Final sky maps: 28°^{2} (90% probability)
- 380 Mpc^3 in volume
- Vital for subsequent EM follow-up

- Trigger identification: 6'
- Initial alert: 27' after detection
- HLV final sky map: 5 hrs



GW170817 PROPERTIES

- Chirp mass measured over ~3000 cycles:

$$\mathcal{M}_c = (m_1 m_2)^{3/5} (m_1 + m_2)^{-1/5}$$

$$\mathcal{M}_c^{\rm det} = 1.1977^{+0.0008}_{-0.0003}\ M_\odot$$

- Total mass:

$$2.73 < M_{\rm Total} < 3.29\ {\rm M}_\odot$$

- Constraint on the two masses:

$$0.86 < m_i < 2.26\ {\rm M}_\odot$$

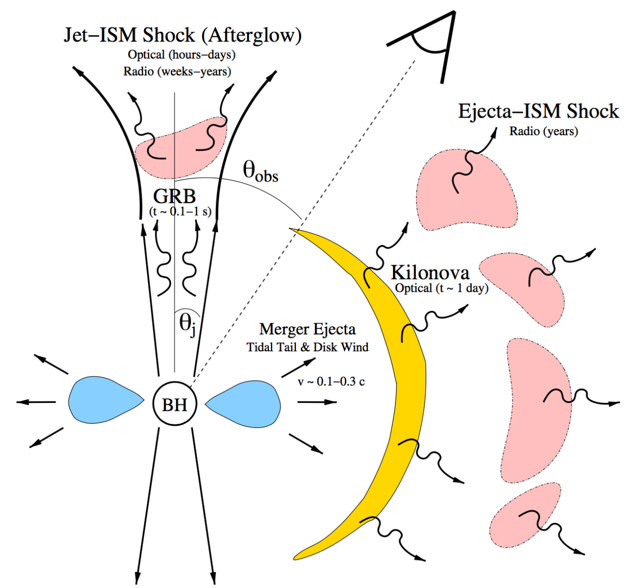
- Luminosity distance:

$$D_L = 40^{+8}_{-14}\ {\rm Mpc}$$

Closest ever observed GW source

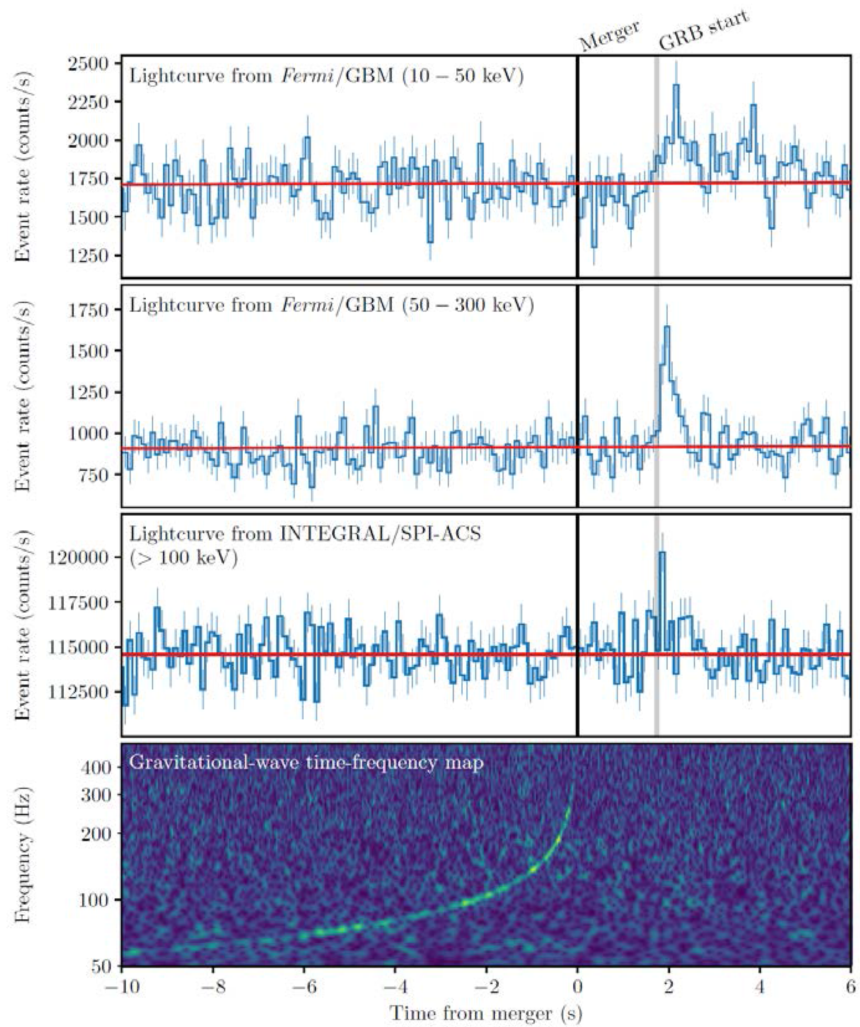
EXPECTED COUNTERPARTS

- Short GRB
  - prompt γ-ray emission (t>2 s)
  - multi-wavelength afterglow (X, optical, radio. Timescale: mins to months)
- Kilonova
  - Isotropic thermal emission produced by radioactive decay of rapid nucleon capture elements (r-process) synthesized in the merger ejecta
  - Term first introduced by Metzger et al (2010), but mechanism known since 1998 (Li & Paczynski)



GW170817 - GRB 170817A

- Fermi and INTEGRAL independently detected a gamma-ray burst with a time delay of 1.734±0.054 s with respect to the merger time
- The probability of a chance temporal and spatial association of GW170817 and GRB 170817A is 5.0 x 10^{-8}.



Binary neutron star (BNS) mergers are progenitors of (at least some) SGRBs

Astrophys. J. Lett. 848, L13 (2017)

FUNDAMENTAL PHYSICS

- Test of GW speed: GW170817 provides a stringent test of the speed of GWs through the measurement of the difference on the arrival times of GW and EM wave

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

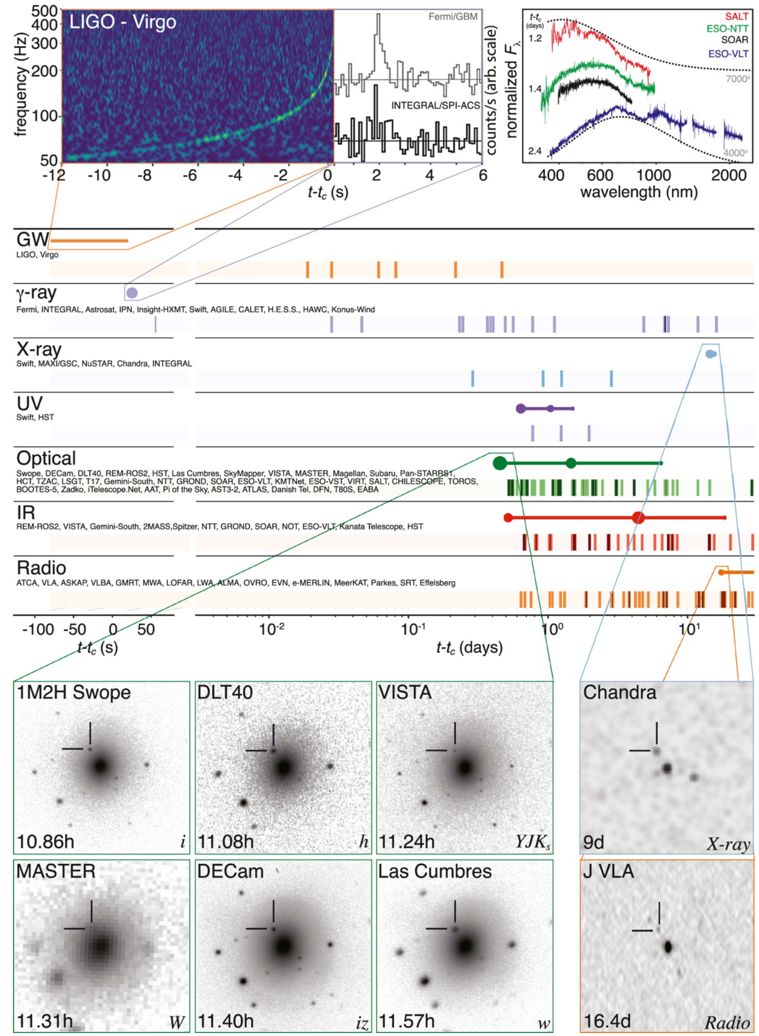
- → **GWs and light propagation speeds** are identical to about 1 part in 10^{15}

- **Test of the equivalence principle**: according to GR, GW and EM waves are deflected and delayed by the curvature of spacetime produced by any mass (i.e. background gravitational potential). Shapiro delay affects both waves in the same manner
- → Milky Way potential gives same effect to within about 1 part in a million

ApJL., 848:L13 (2017)

GW170817 - KILONOVA

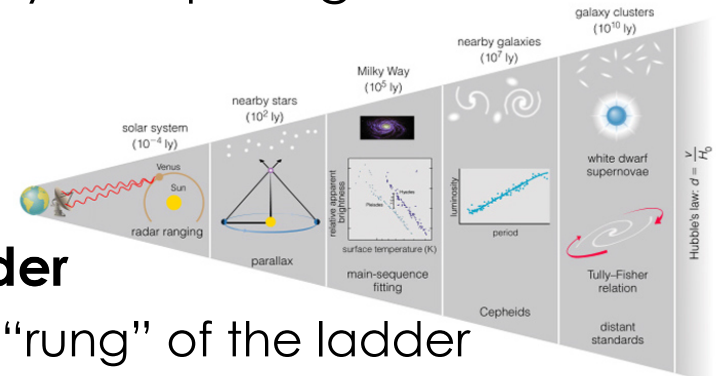
- Optical counterpart found in host galaxy NGC4993
- Optical/infrared/UV counterpart has been detected
  - first spectroscopic identification of a kilonova
- X-ray and a radio counterparts have been identified
  - off-axis afterglow? cocoon emission?



Astrophys. J. Lett. 848, L12 (2017)

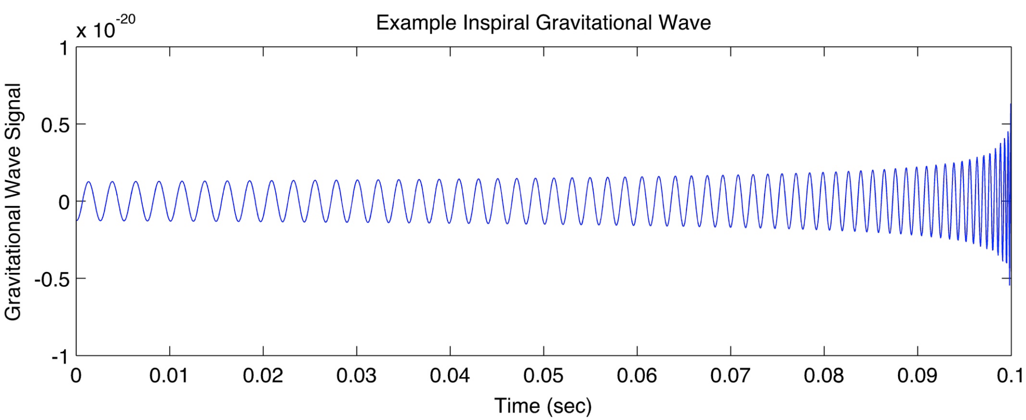
GW170817 - COSMOLOGY

- BNSs allow a new way of mapping out the large-scale structure and evolution of spacetimeby comparing distance and redshift



- **Current measurements depend on distance ladder cosmic distance ladder**
  - Possibility of systematic errors at every "rung" of the ladder

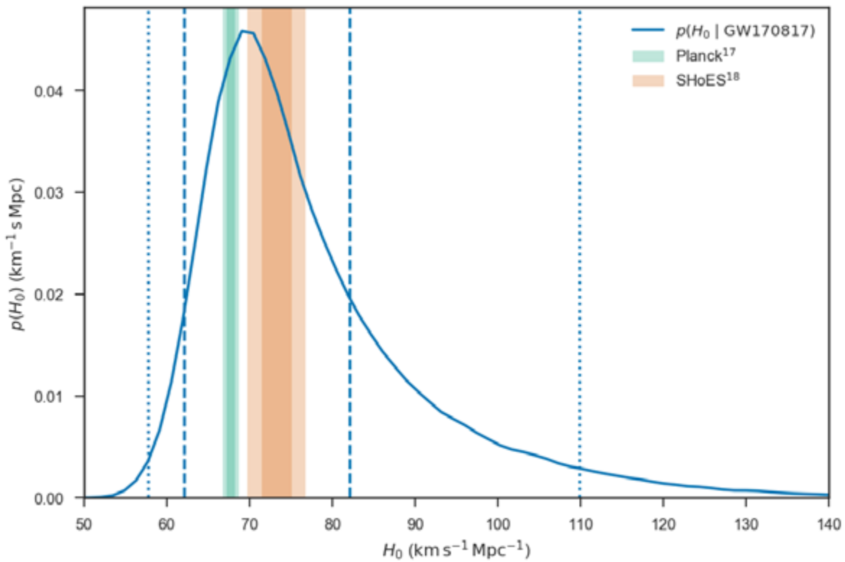
- **BNS are standard candles**
  - Distance can be measured directly from the GW signal



$$H_0 d_L = c z$$

2018

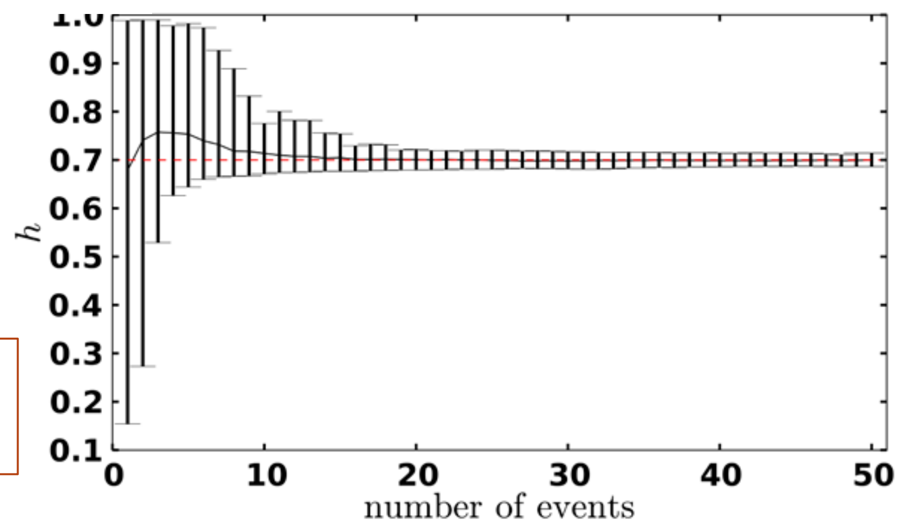
GW170817 - COSMOLOGY



$H_0 = 70\ (+12, -8)$ km/s/Mpc

LVC, Nature 551, 85 (2017)

Few tens of detections of BNS mergers with LIGO-Virgo will allow determining the Hubble parameters to about 1% accuracy

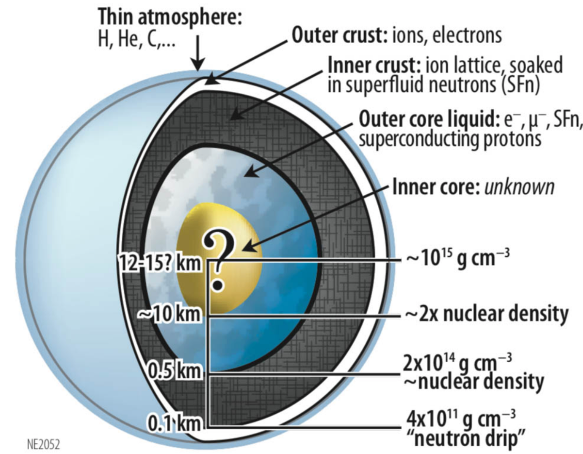


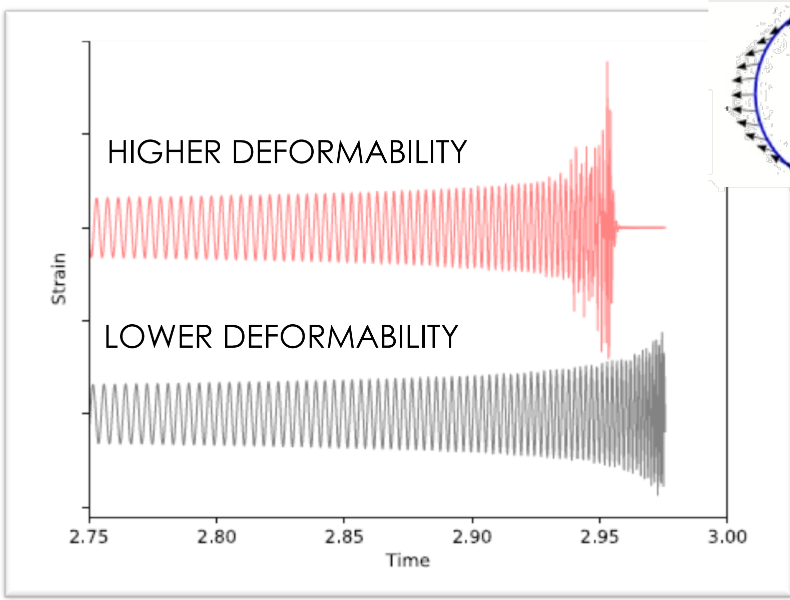
Third generation observatories allow studies of the Dark Energy equation of state parameter

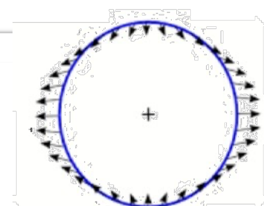
Del Pozzo, PRD 86, 043011 (2012)

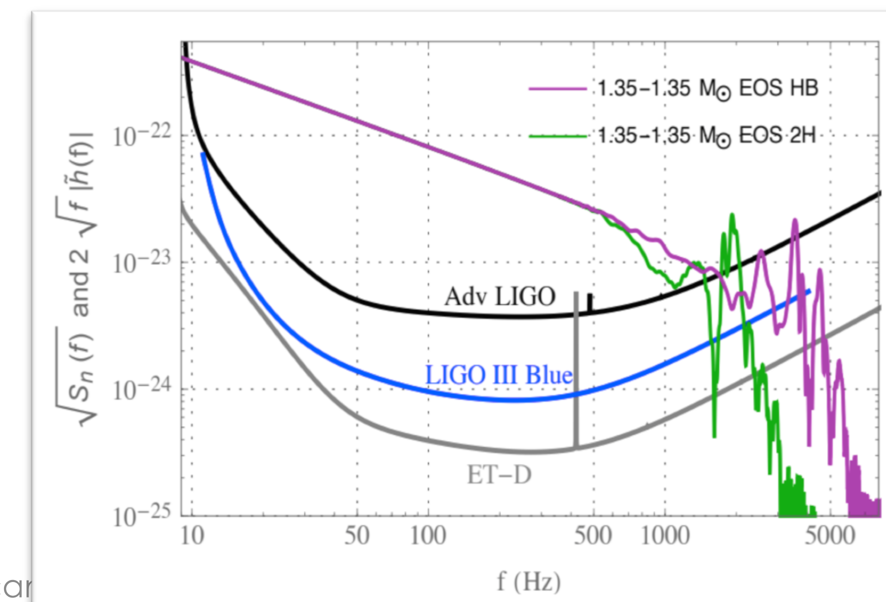
GW170817 – NS EOS

- Internal structure and composition (largely unknown) is encoded in the equation of state.
- Each NS is deformed by the tidal field of the companion
- Deformations leave an imprint on the GW emission









WHAT NEXT?

$\# \text{ EVENTS} \sim d^3 T$

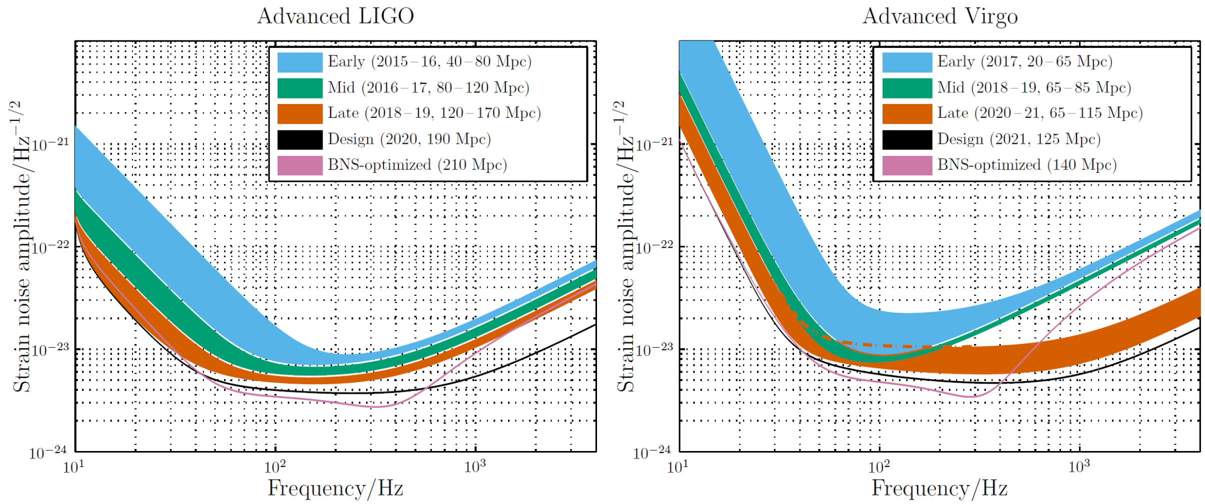
1 day of data at a range of 80 Mpc (Advanced LIGO in O1) is equivalent to 64 days at 20 Mpc (LIGO, 2009)

Observing for a long time is good, improving the sensitivity further is better.

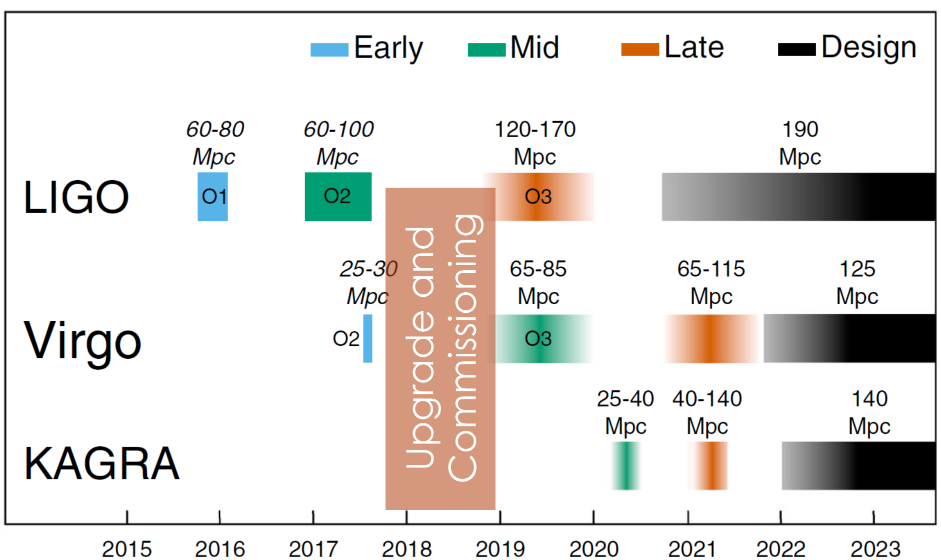
NEAR-TERM OBSERVING SCENARIO

Expected rates in O3
With LIGO @ 120 Mpc and
Virgo @ 65 Mpc

NS-NS	NS-BH	BH-BH
9^{+19}_{-7}	1^{+28}_{-1}	35^{+78}_{-26}

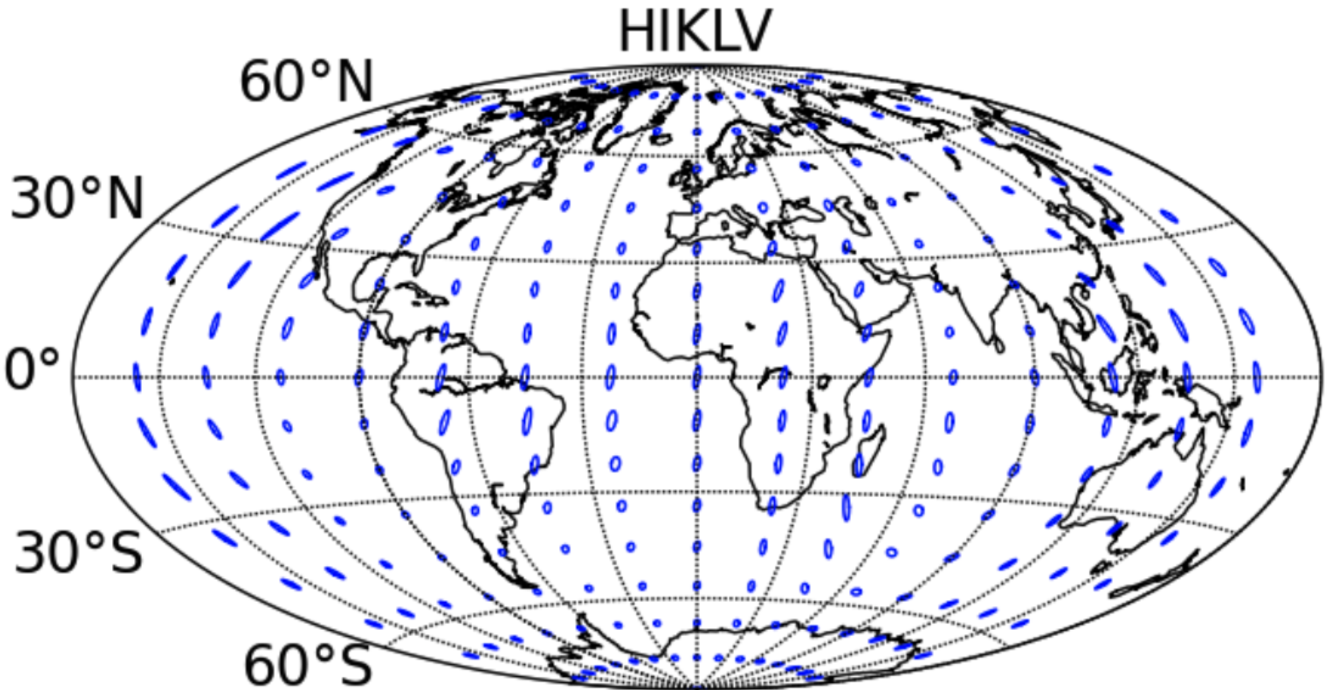


Living Rev Relativ (2018) 21:3



- …and LIGO India plans to come on line with Advanced LIGO sensitivity – with any upgrades incorporated – in 2024

NEAR-TERM OBSERVING SCENARIO



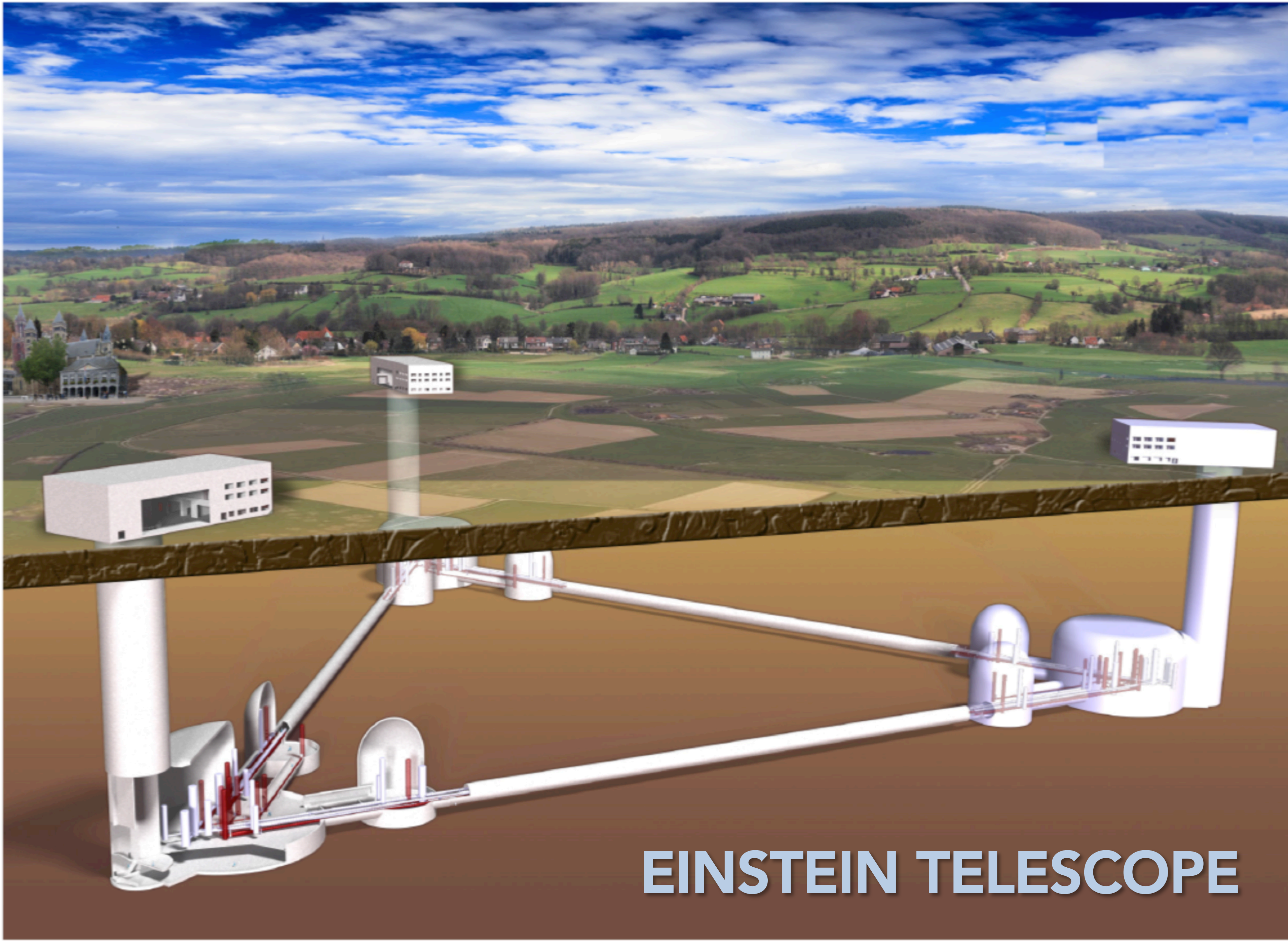
S Fairhurst, CQG 28, 2001

- KAGRA (2019) and LIGO-India (2024) will expand the network
- Localization capabilities of the 2G network at mid 2020s: >60% of the sources localized within 10 deg^2

LONGER TERM SCENARIO

- 2.5 G: Exploit the existing infrastructures at best of their capabilities through upgrades of the advanced detectors (event rate 5-10x)
  - Timeline:~2023
  - A+ at LIGO, AdV+ at Virgo
- 3 G: new infrastructures/detectors capable of reaching the early universe. One order of magnitude gained in sensitivity wrt 2G
  - Timeline: ~2030
  - Cost > 1 Geuros

1. Einstein Telescope: European project for a nested assembly of 6 co-located interferometers, 10 km long
   - underground
   - bandwidth extended to 1 Hz
   - cryogenics
2. Cosmic Explorer: US project for a 40 km interferometer


EINSTEIN TELESCOPE

CONCLUDING REMARKS

- GW detectors are finally making science after many decades of detector development: a new window on the universe has been opened
- GW170817 has offered a spectacular preview of the science to come from the world-wide, multi-messenger network of observatories
- O3 perspectives look very good, the era of OPA will start
- GW network will be enhanced with the addition of new detectors (KAGRA 2020, LIGO India 2024)and improvement of the existing ones (A+ and AdV+)
- 3G detectors being planned, targeting the early universe