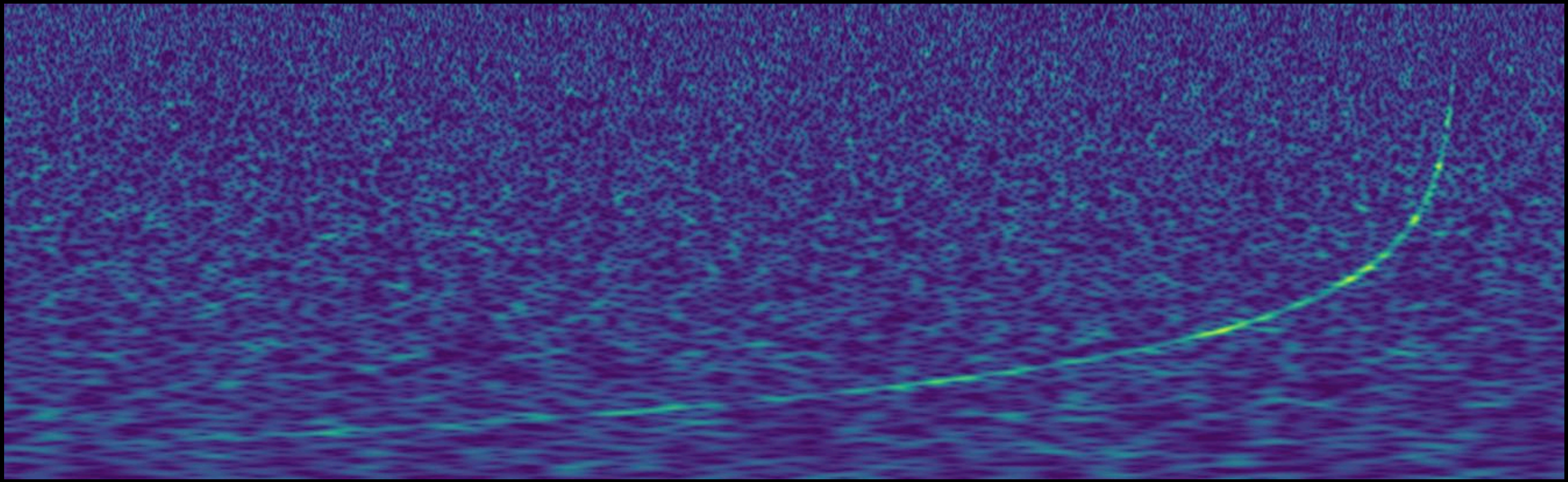


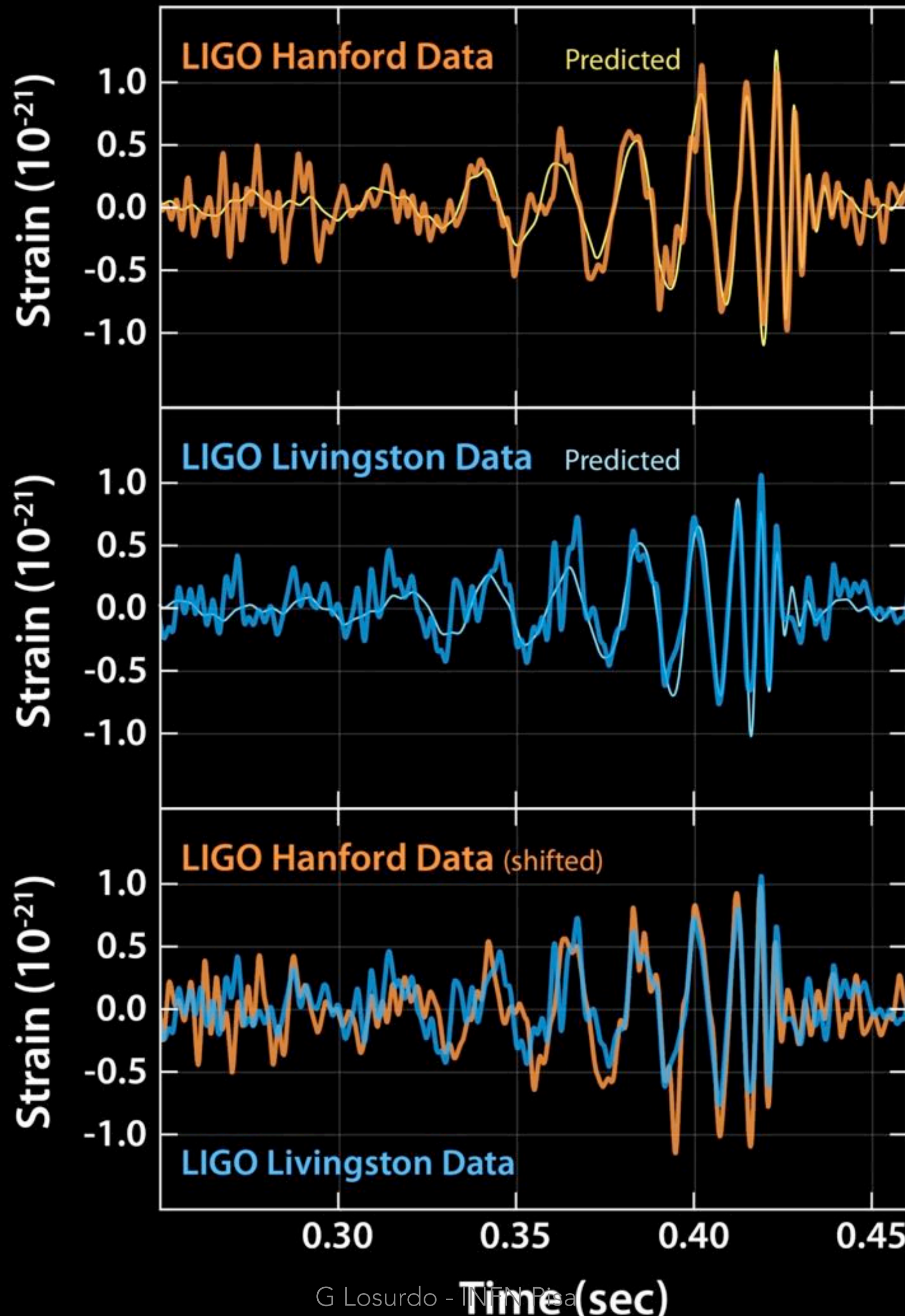
# GW170817: THE DAY AFTER

Giovanni Losurdo – INFN Pisa
presenting results of the
LSC and VIRGO Coll.

*"Rivelare le onde gravitazionali…
nessuna idea era più folle di questa"*

ADALBERTO GIAZOTTO

GW150914


LIGO Hanford Data
Predicted
Strain (10$^{-21}$)
1.0
0.5
0.0
-0.5
-1.0
LIGO Livingston Data
Predicted
Strain (10$^{-21}$)
1.0
0.5
0.0
-0.5
-1.0
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10$^{-21}$)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)

# GW150914: LESSONS

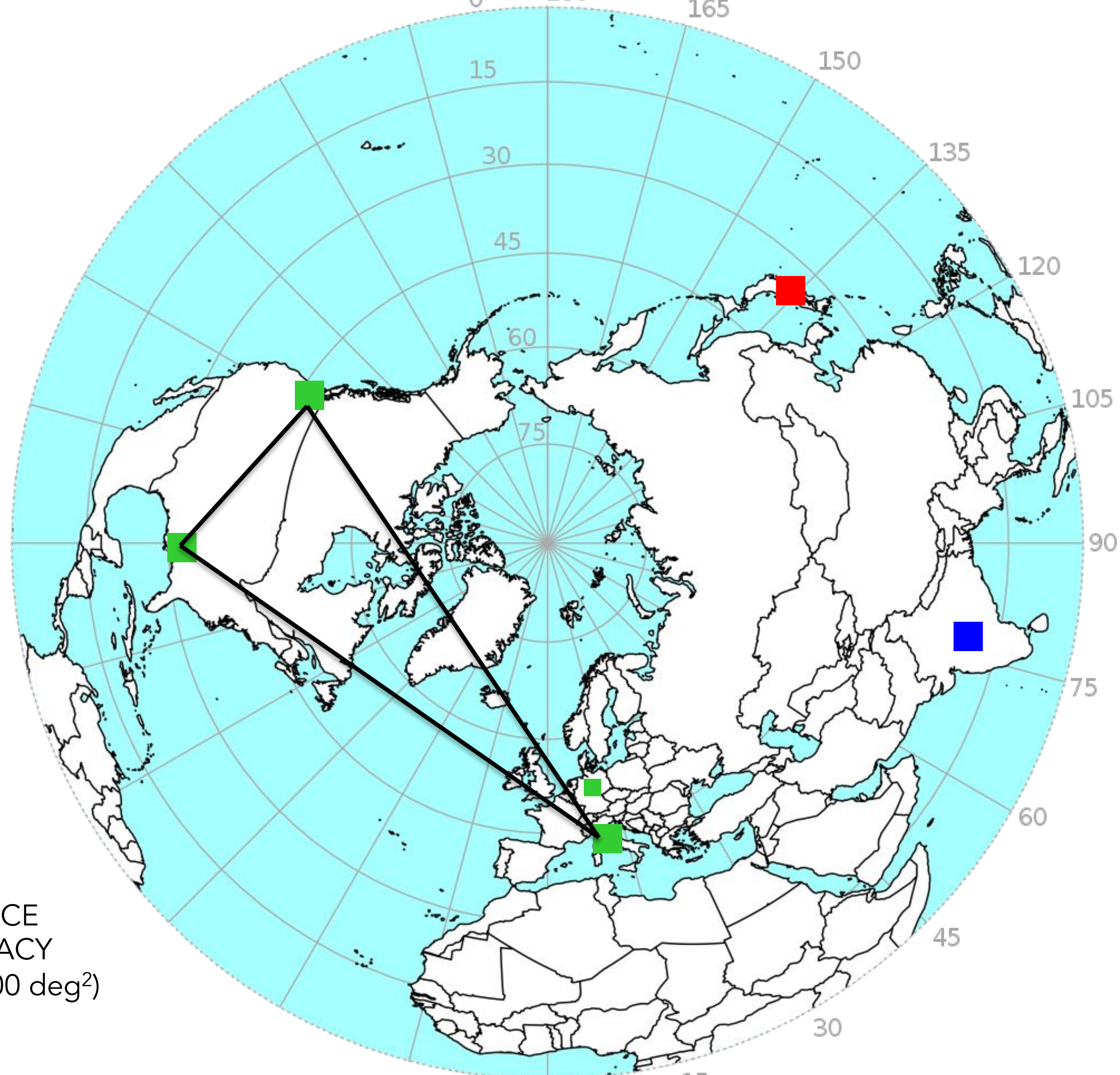
- First direct detection of gravitational waves (100 years after Einstein's prediction)
- First direct observation of black holes,
- First observation of the largest known stellar mass BH (>25 $M_{\odot}$)
- First observation of a binary black hole (BBH) system,
- First observation of a BBH merger
- First tests of general relativity in strong field (extreme) conditions: *"In conclusion, within our statistical uncertainties, we find no evidence for violations of general relativity in the genuinely strong-field regime of gravity."*

- ONE MORE LESSON: the ground based interferometers are the right instruments!

# August 1st, 2017

VIRGO JOINS LIGO IN THE OBSERVATION RUN O2

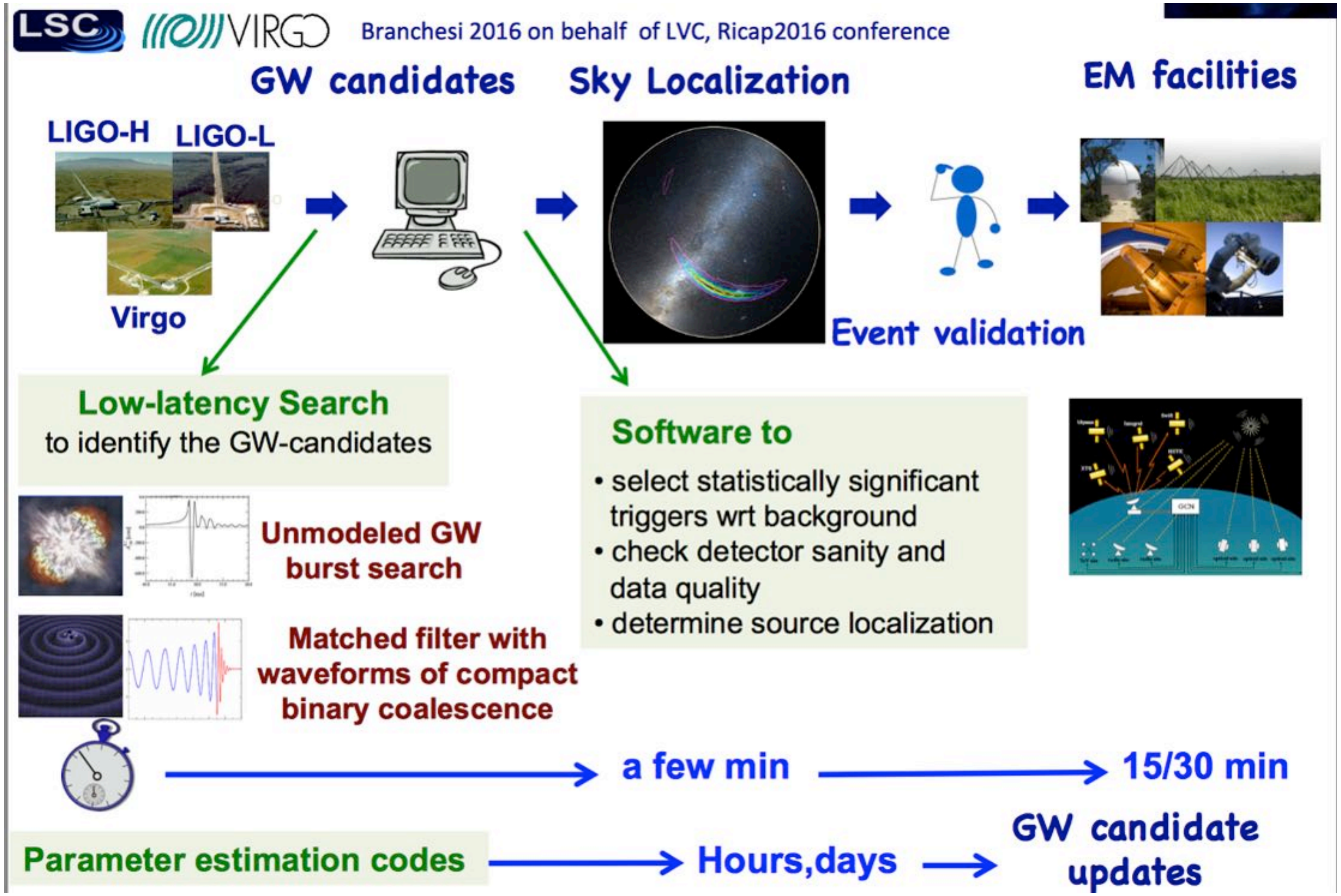
THREE 2G DETECTORS ACTING AS A “SINGLE MACHINE”




- OPERATION
- COMMISSIONING
- CONSTRUCTION
- APPROVED

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

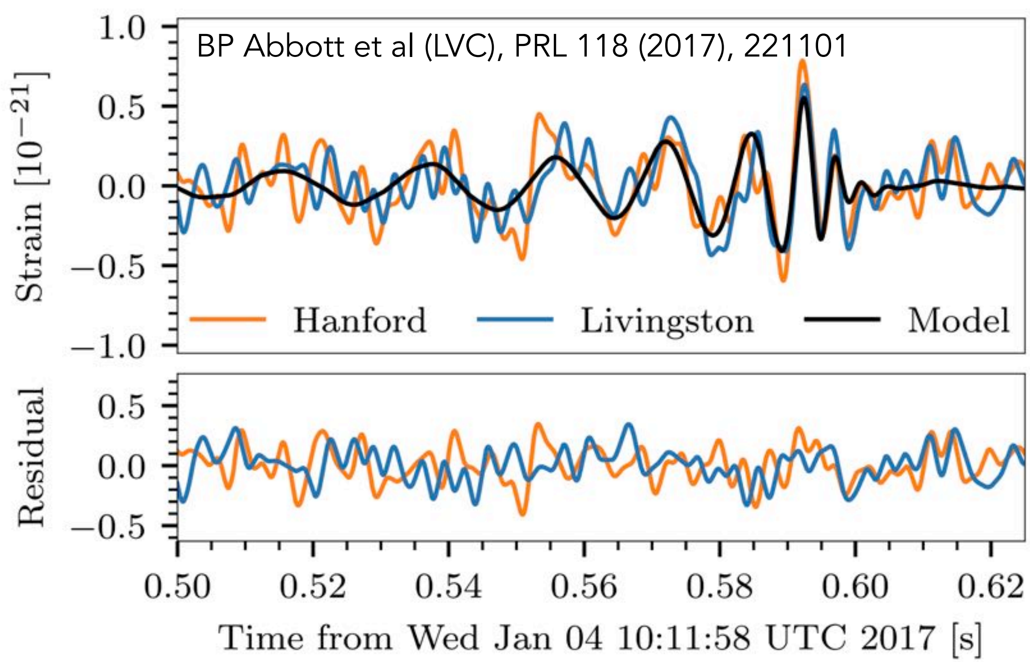
# E.M. FOLLOW-UP



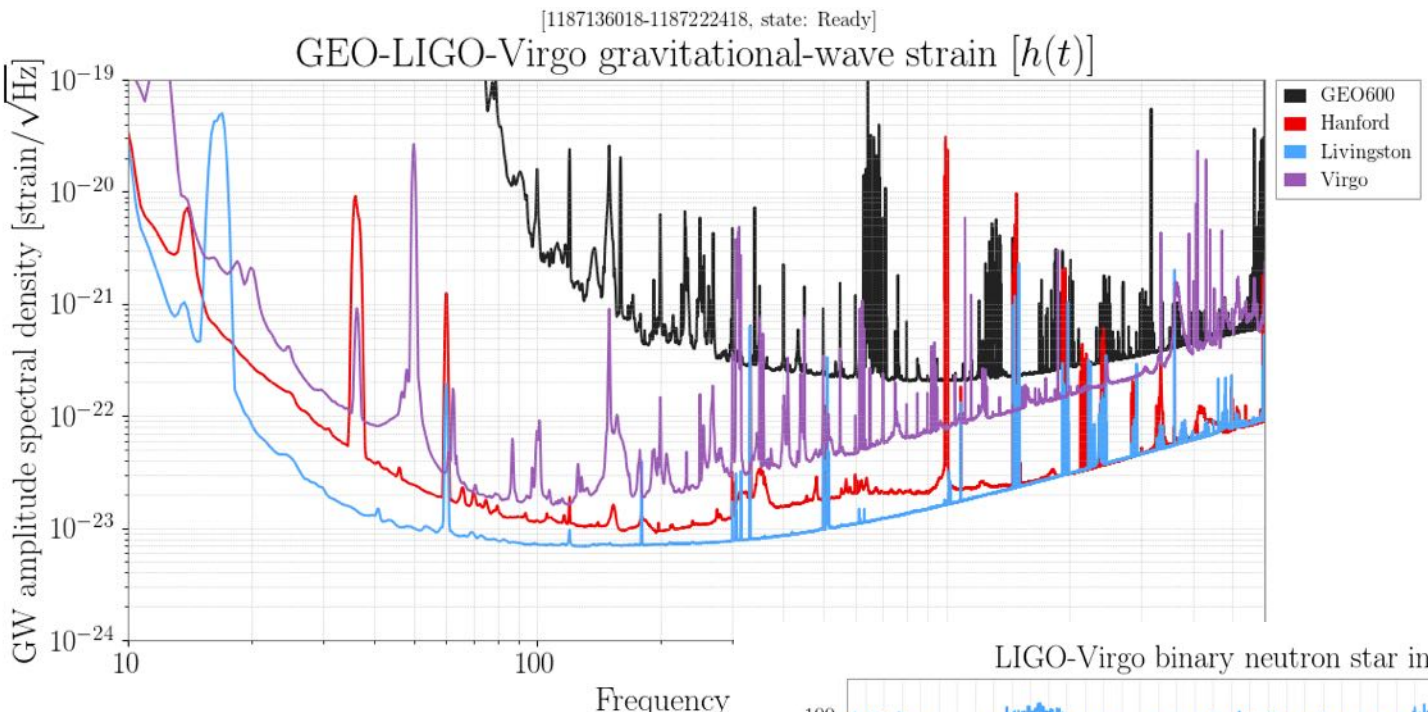

93 groups (>200 instruments) have signed the MoU with the LVC

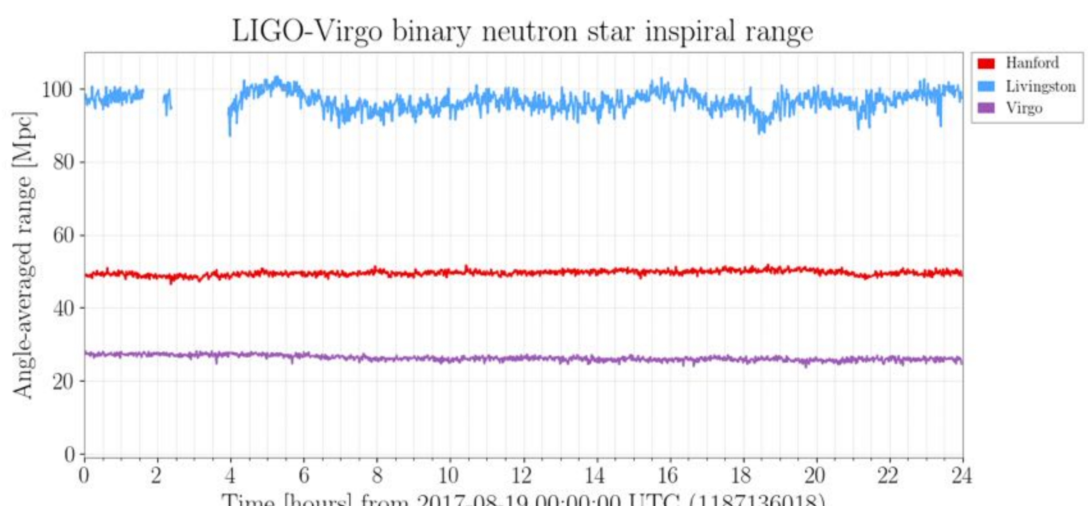
# THE O2 RUN - FACTS

- Started on November 30, 2016
- VIRGO joined on August 1st, 2017
- The run was stopped on Aug 25th, as previously planned by LIGO
- From Aug 1st to 25th: 14.9 days of triple coincidence observation
- One event published before Aug 1st (GW170104)

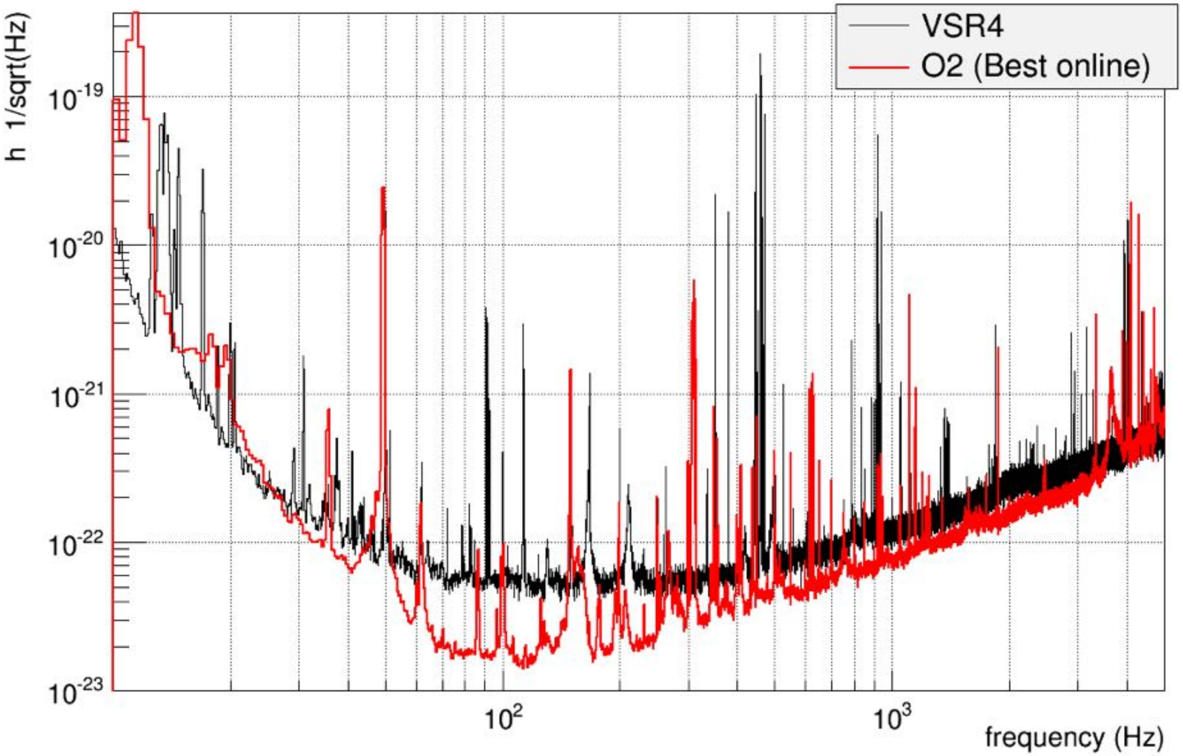


# NETWORK


[1187136018-1187222418, state: Ready]
GEO-LIGO-Virgo gravitational-wave strain [h(t)]
GW amplitude spectral density [strain/√Hz]
Frequency
GEO600
Hanford
Livingston
Virgo


LIGO-Virgo binary neutron star inspiral range
Angle-averaged range [Mpc]
Time [hours] from 2017-08-19 00:00:00 UTC (1187136018)
Hanford
Livingston
Virgo

# VIRGO SENSITIVITY



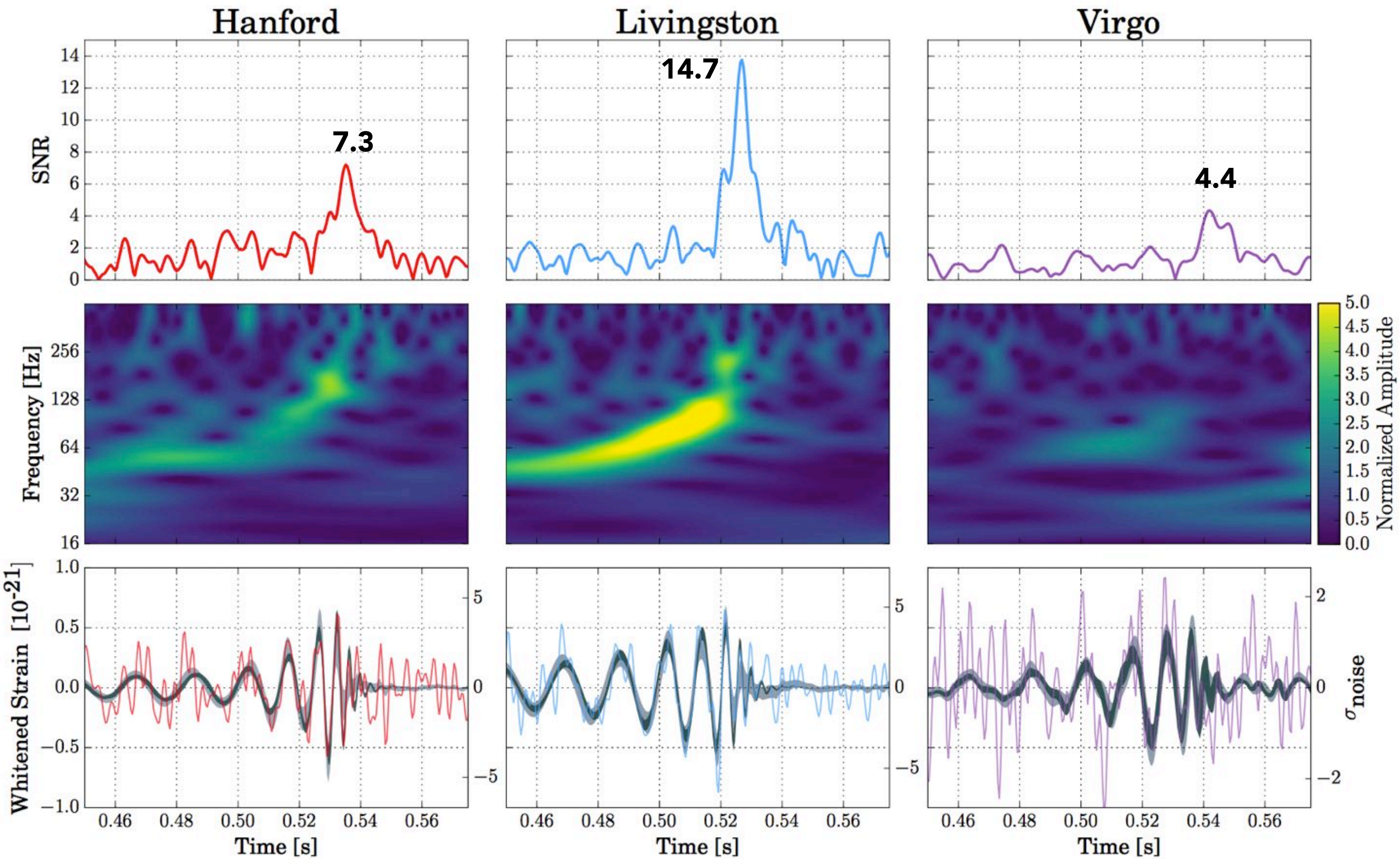

- VIRGO+ (2011): BNS range of 12 Mpc
- AdV (O2): 28 Mpc, ~12x larger volume of universe reached
  - now further improved: >30 Mpc

# O2 – SCIENCE

# August 14th, 2017

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

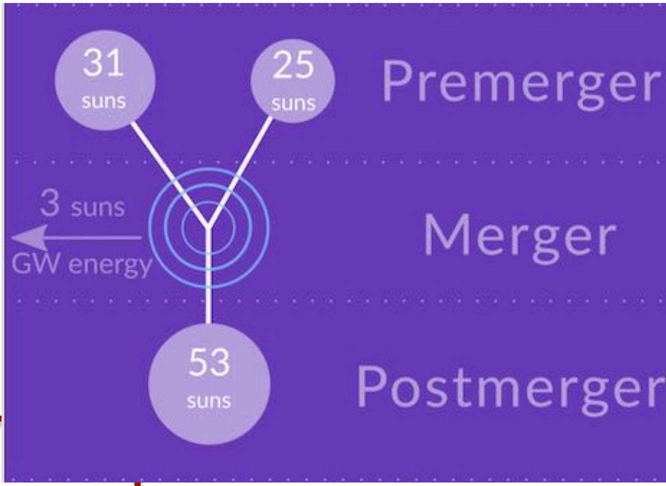
The GW hit Earth first at lat. 44.95° S, long. 72,97° W, Puerto Aysen, Chile. The signal was recorded at L1 first, then at H1 and Virgo with delays of ~8 and ~14 ms respectively




3-detector network SNR: 18.3

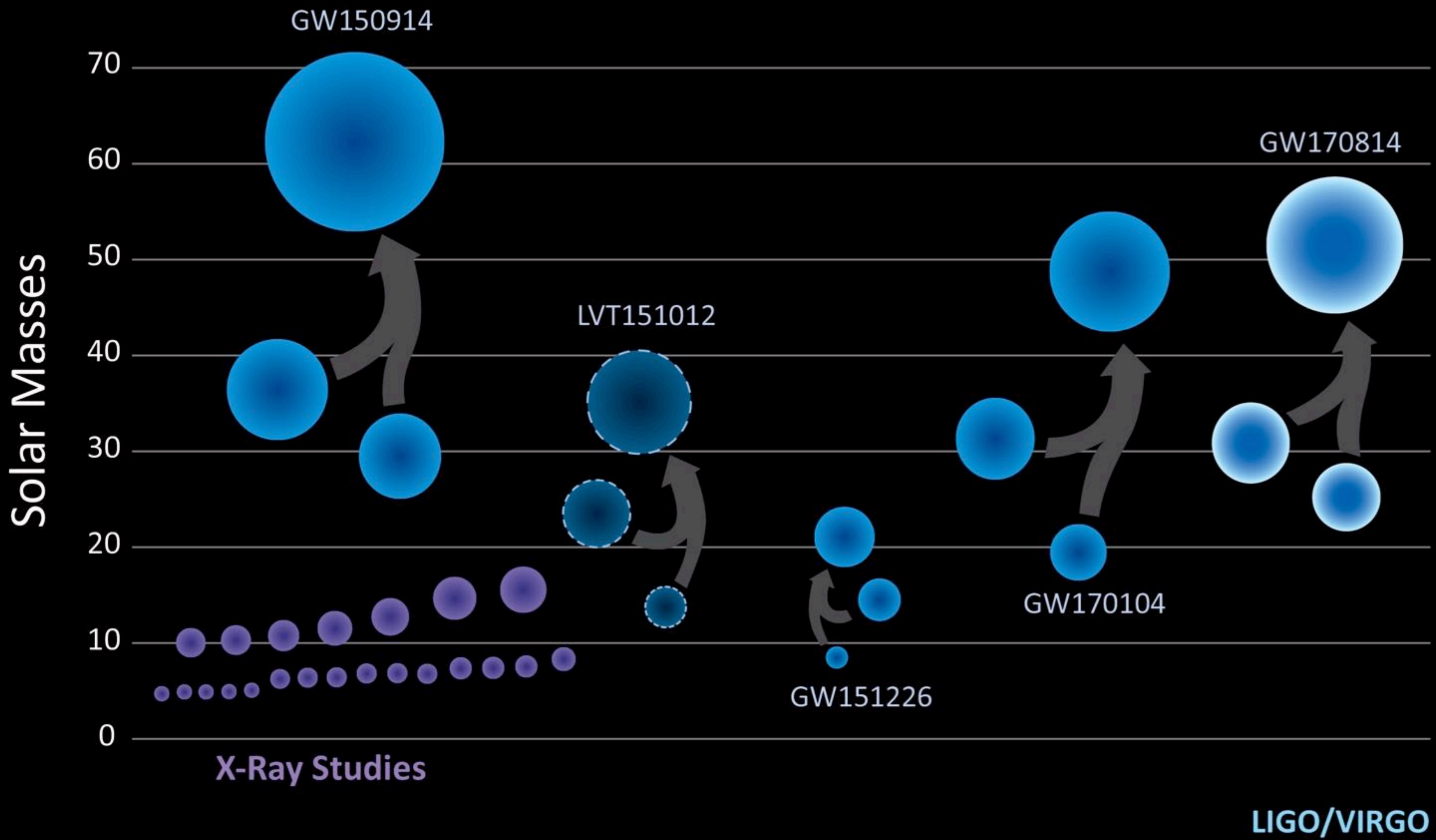
PRL, 119, 141101 (2017)

| | |
|---|---|
| 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 $M_\mathrm{f}$ | $53.2^{+3.2}_{-2.5}\ \mathrm{M}_\odot$ |
| Radiated energy $E_\mathrm{rad}$ | $2.7^{+0.4}_{-0.3}\ \mathrm{M}_\odot \mathrm{c}^2$ |
| Peak luminosity $\ell_\mathrm{peak}$ | $3.7^{+0.5}_{-0.5} \times 10^{56}\ \mathrm{erg\,s^{-1}}$ |
| Effective inspiral spin parameter $\chi_\mathrm{eff}$ | $0.06^{+0.12}_{-0.12}$ |
| Final black hole spin $a_\mathrm{f}$ | $0.70^{+0.07}_{-0.05}$ |
| Luminosity distance $D_\mathrm{L}$ | $540^{+130}_{-210}\ \mathrm{Mpc}$ |
| Source redshift $z$ | $0.11^{+0.03}_{-0.04}$ |

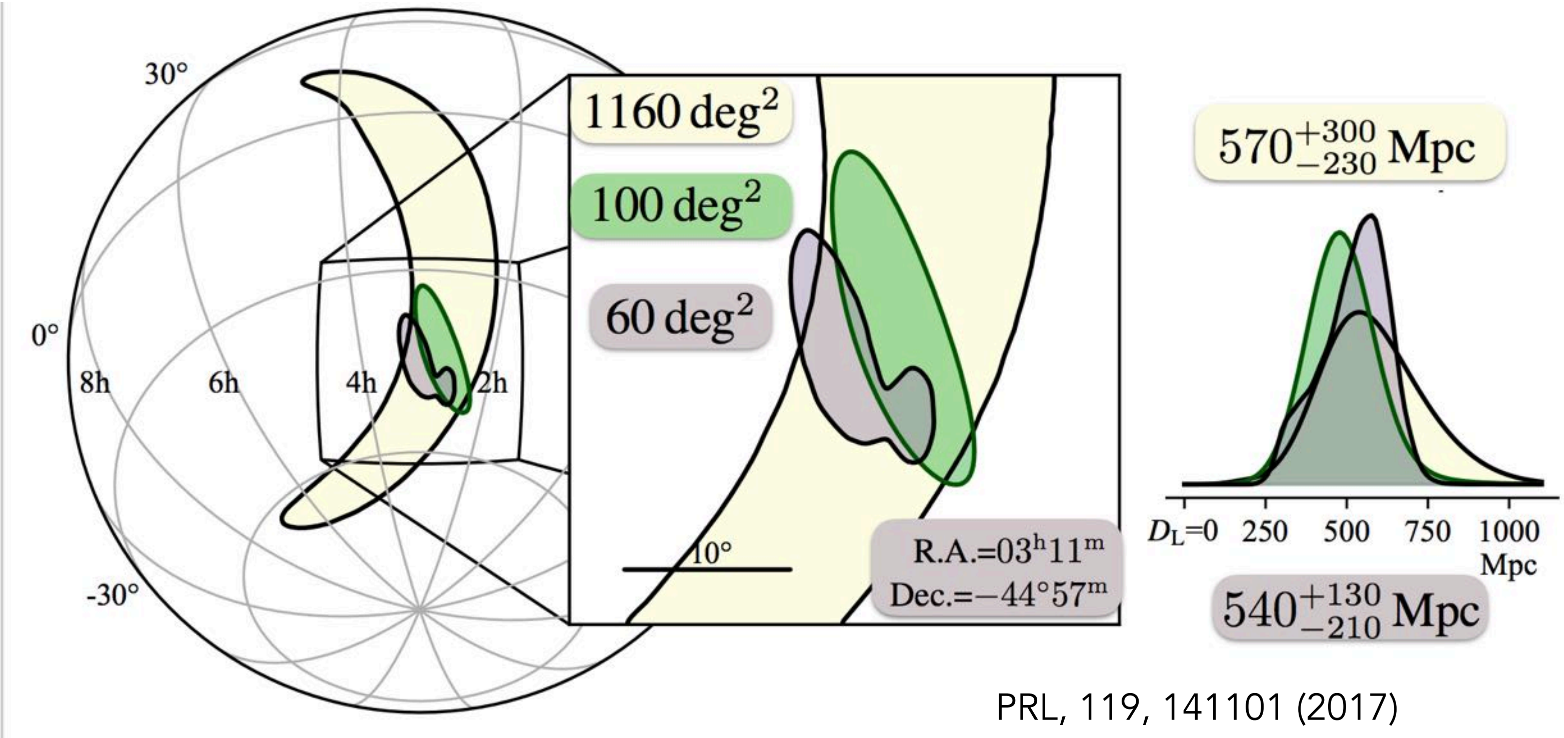



PRL, 119, 141101 (2017)

# Black Holes of Known Mass



# LOCALIZATION




PRL, 119, 141101 (2017)

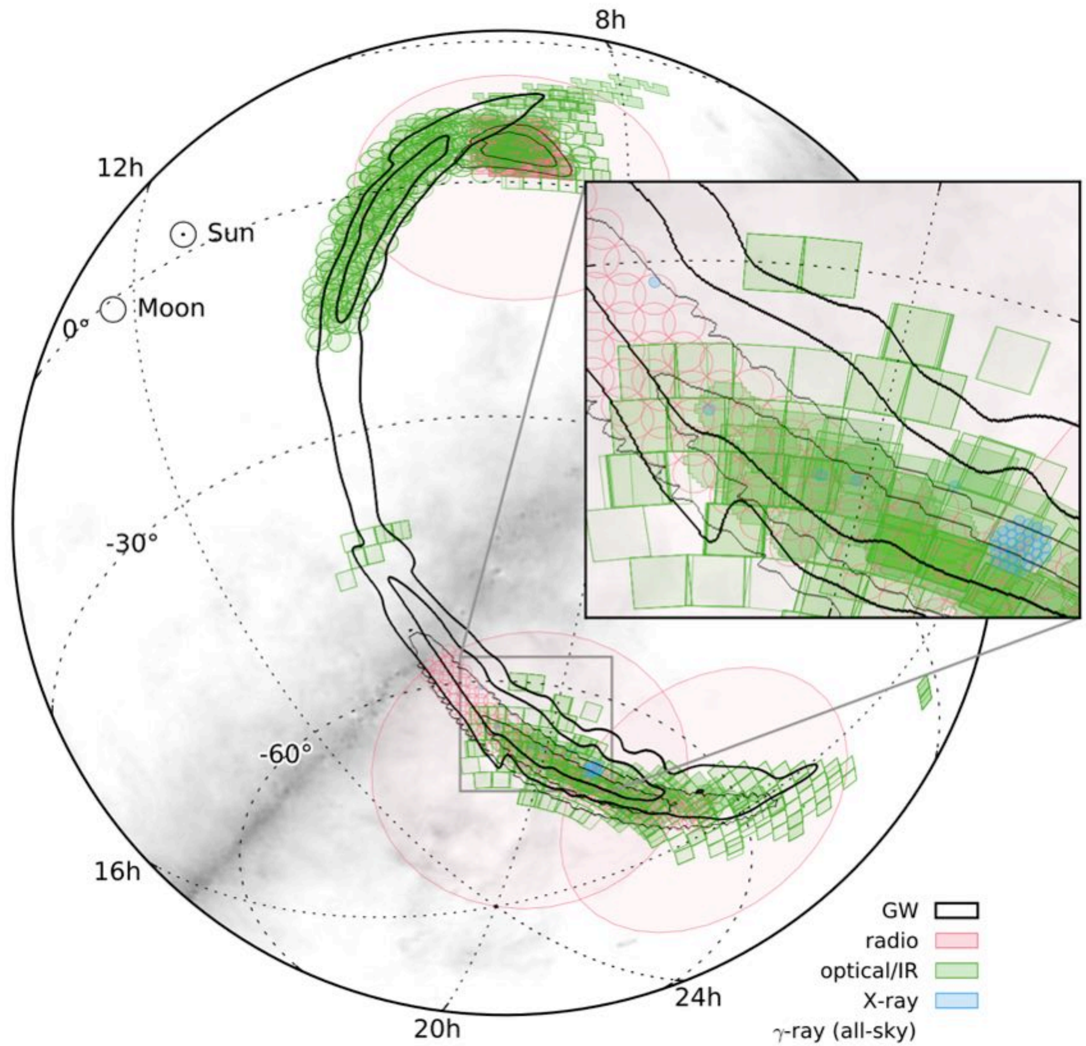
**VIRGO HELPS REDUCING:**

| | |
|---|---|
| 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 AND FOLLOW UP FOR GW150914

Abbott et al. (LIGO/VIRGO), APJL, 826:L13 (2016)

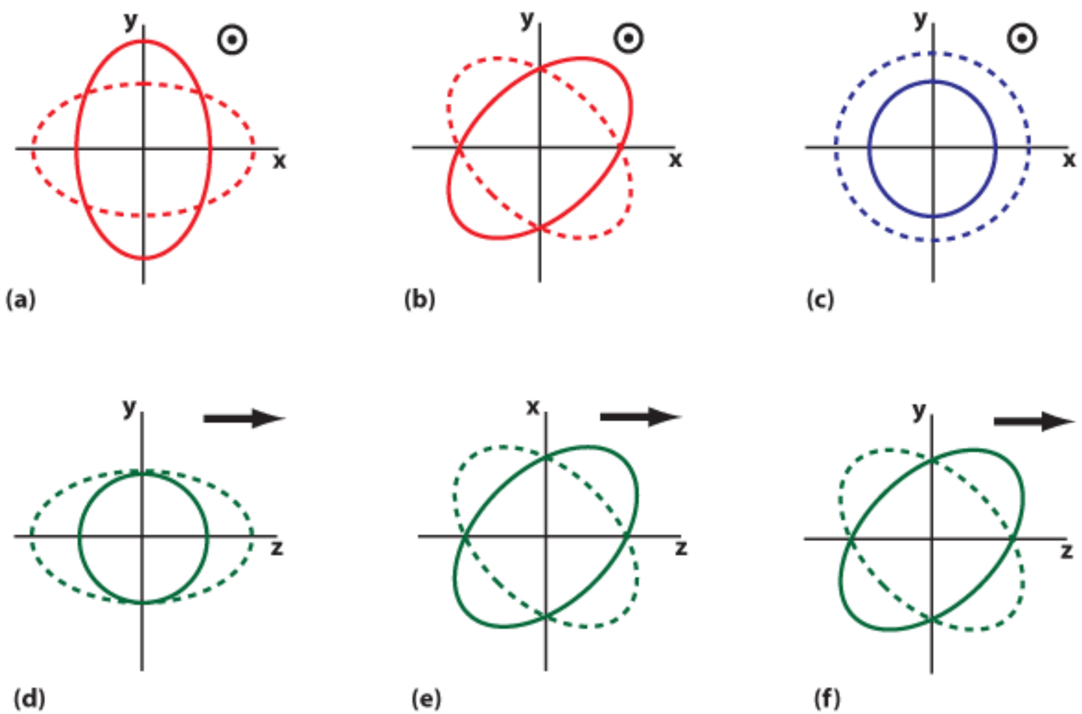


# POLARIZATION

GENERAL METRIC THEORIES OF GRAVITY ALLOW UP TO 6 POLARIZATION STATES

**TENSOR (SPIN 2)**
**GENERAL RELATIVITY**

**SCALAR (SPIN 0)**




**VECTOR (SPIN 1)**

# 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
  - only models with "pure" polarization states (tensor, vector or scalar) have been considered
  - a study with "mixed" states is underway
- RESULT: GR (purely tensor) is 200 and 1000 times more likely than purely vector/scalar respectively

# GW170814 - SUMMARY

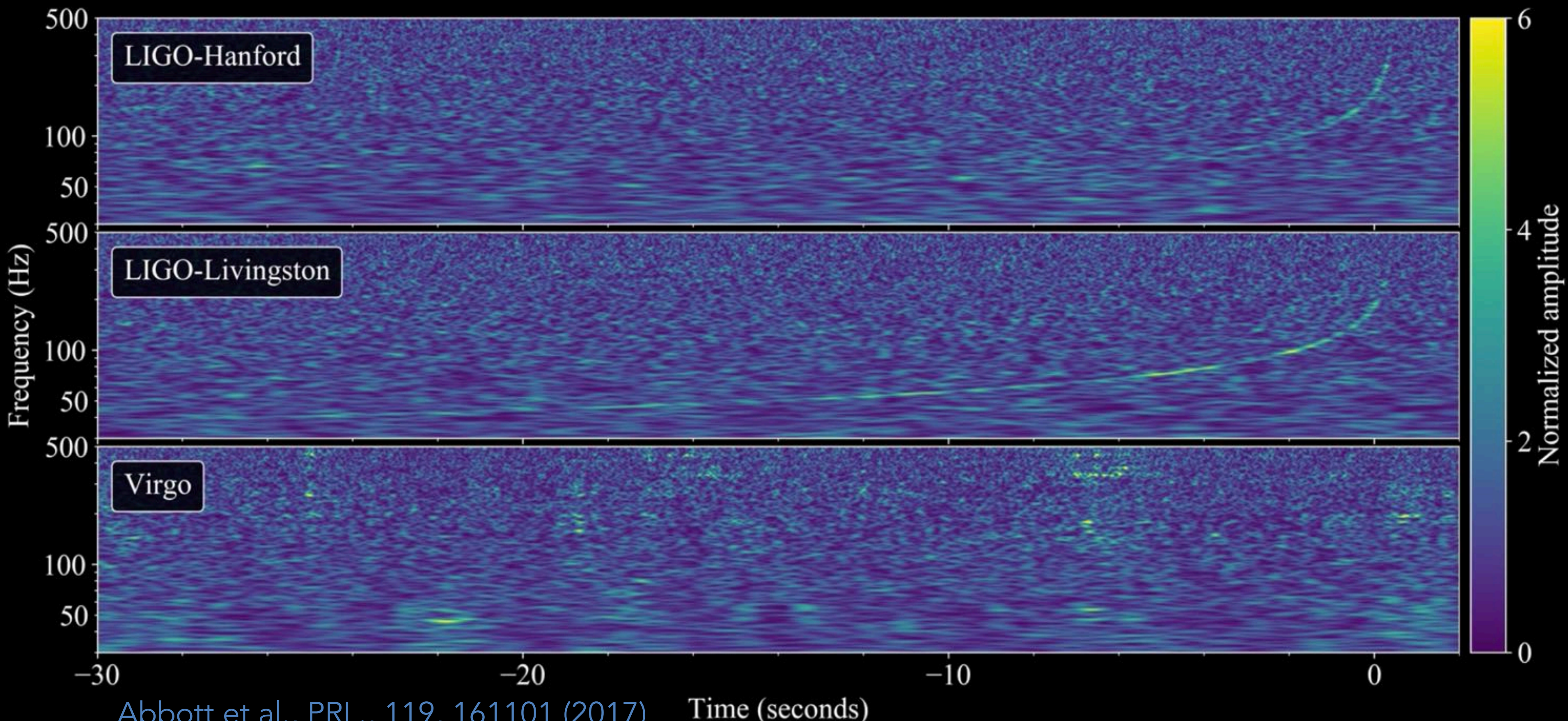
- FIRST EVENT SEEN BY VIRGO (4th overall)
- FIRST EVENT WITH SMALL SKY LOCALIZATION AREA, ENABLING EFFICIENT MULTI-MESSENGER OBSERVATIONS
- FIRST EVENT ALLOWING GW POLARIZATION STUDIES

# AUGUST 17th, 2017

IT…

# IT…

Aug 17th 2017 at 12:41 UTC Advanced LIGO-Virgo detected a binary neutron star inspiral

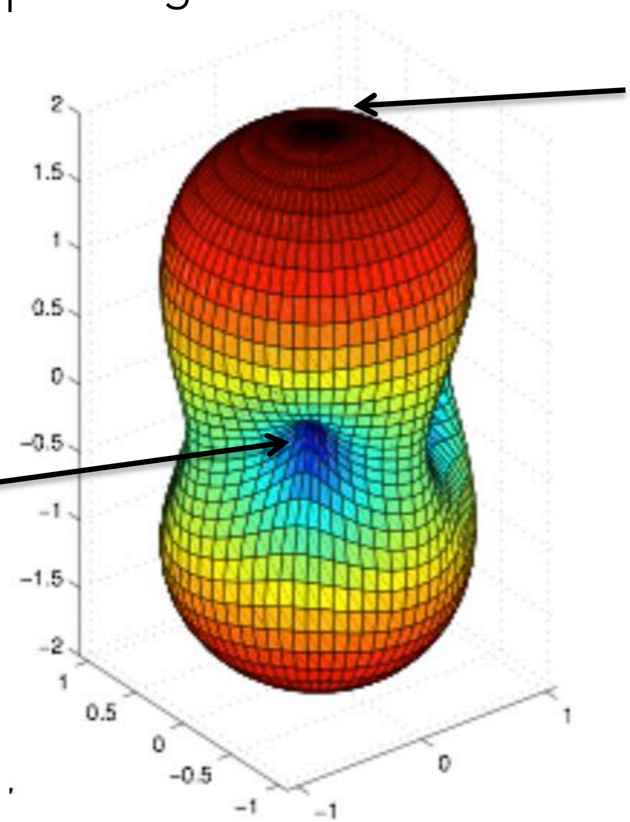



Abbott et al., PRL., 119, 161101 (2017)

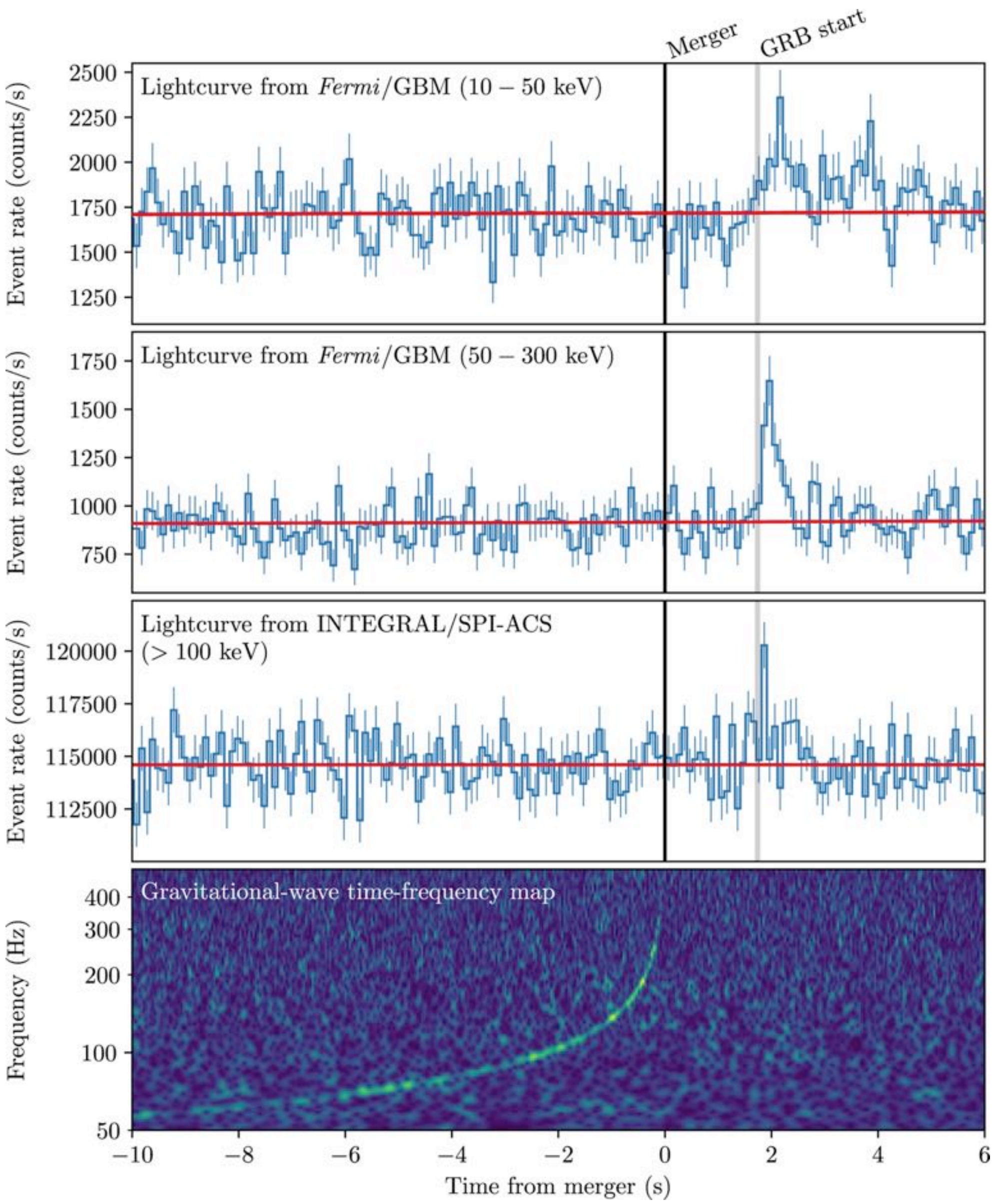
# ANTENNA PATTERN

The "INSPIRAL RANGE" is averaged over the antenna response to source direction and polarization
BNS RANGE = 28 Mpc → sight distance between 0 and ~ 63 Mpc
$BBH_{30}$ RANGE = 314 Mpc → sight distance between 0 and ~ 700 Mpc

314 x 2.24 ~ 700 Mpc



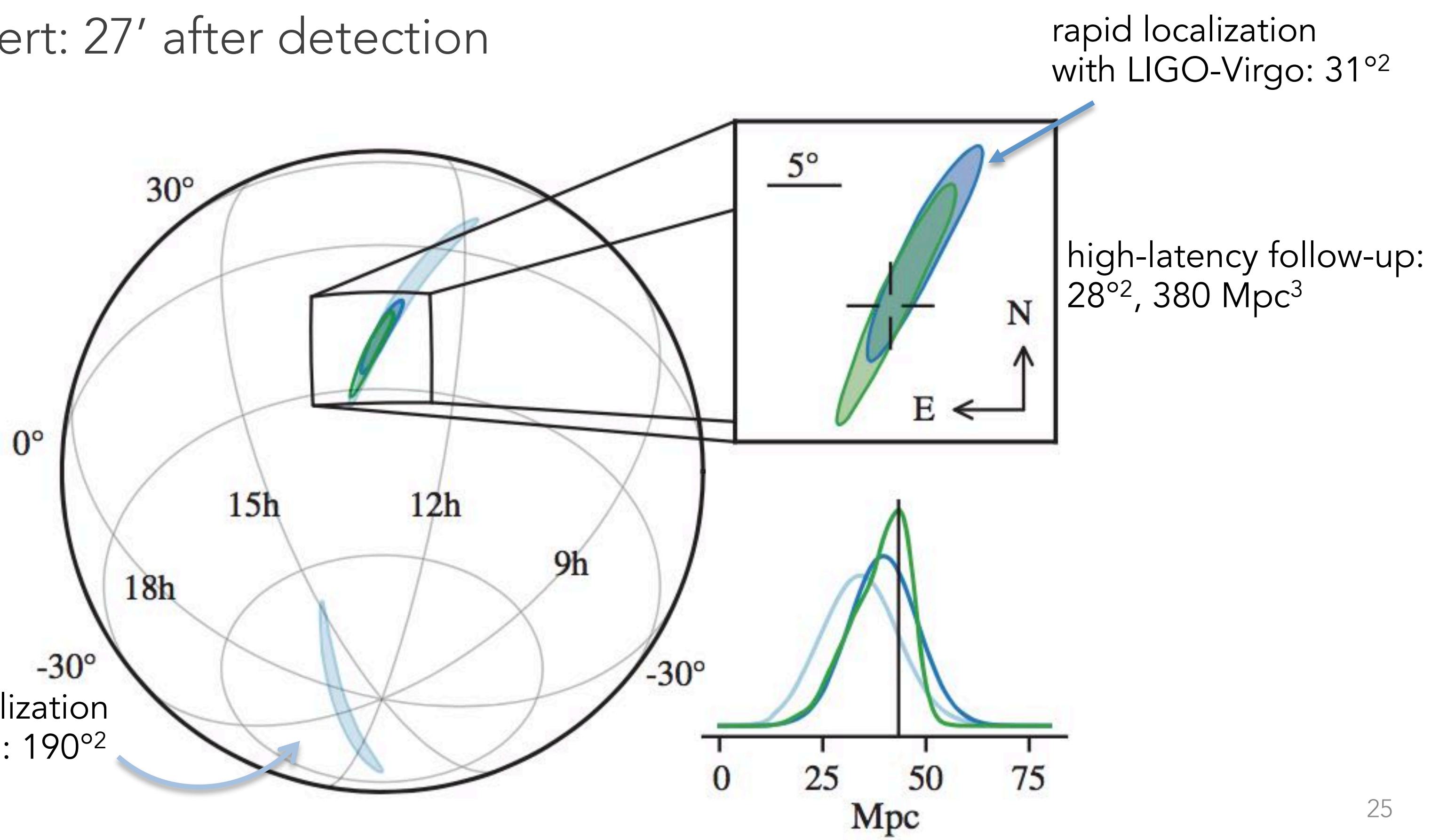

~0 Mpc




Abbott et al., ApJL., 848:L13 (2017)

A GRB event, 1.7 sec after…

- Early sky maps accurate to ~31°²
- Final sky maps: localization within 28°² (90% probability): vital for subsequent EM follow-up
- Initial alert: 27′ after detection

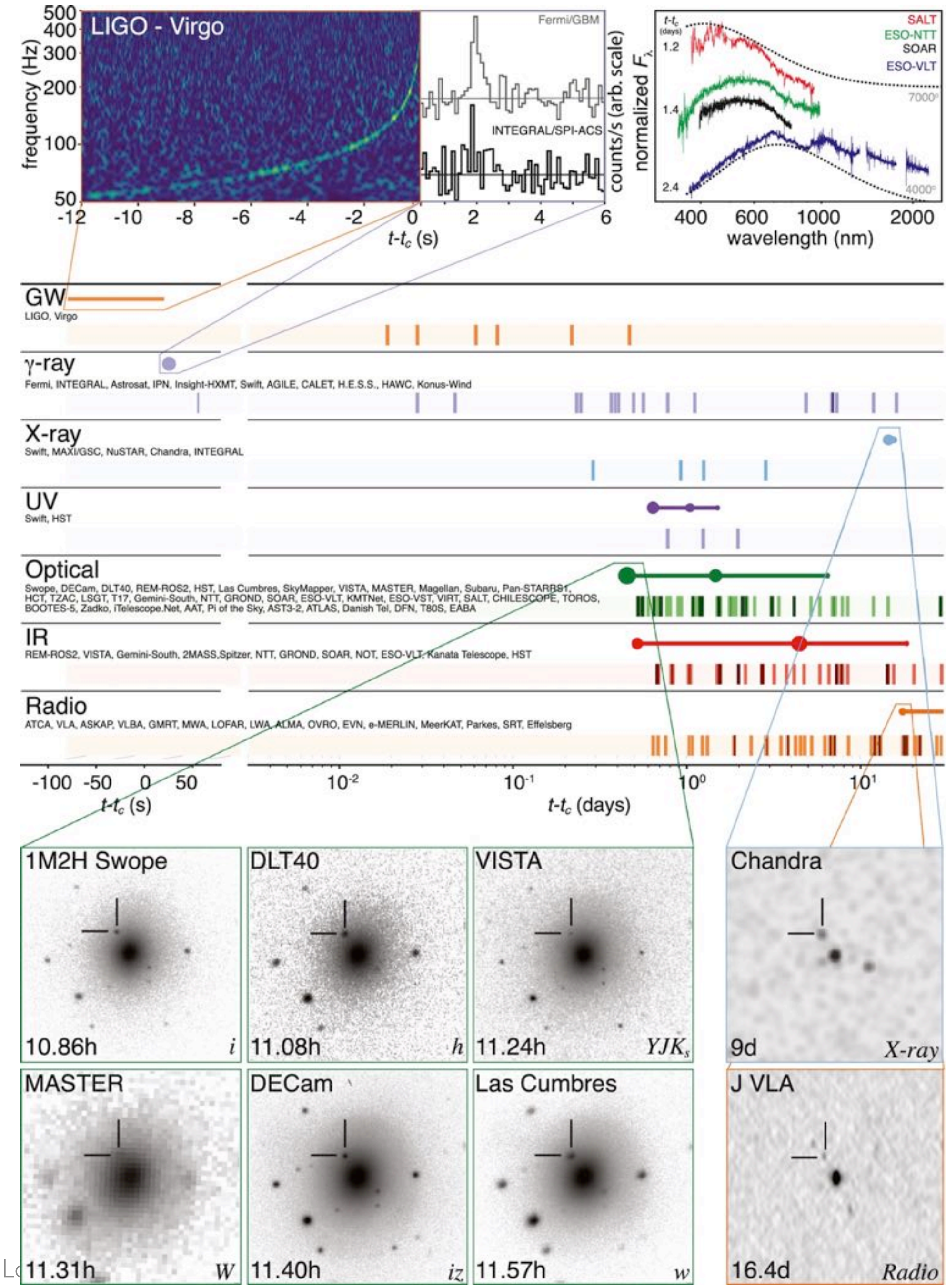


# …and the optical counterpart

SUMMARY

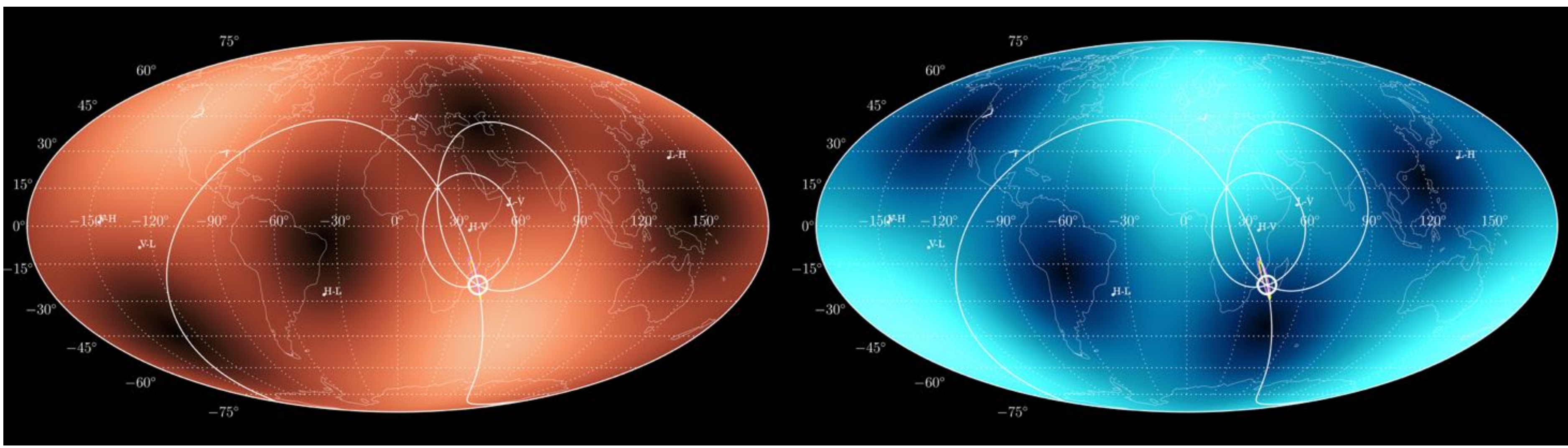
- BNS inspiral and merge
- Collision speed ~c/3, leading to a GRB
- Ejected neutron-rich material decays to heavy elements - observed as kilonova
- X-ray and radio afterglows formed by bubble of ejected material expanding into surrounding interstellar medium

Abbott et al., ApJL., 848:L12 (2017)



# GW170817

- Network SNR: 32.4: loudest signal so far
- FAR < 1/80000 yr : highly significant event
- Duration ~100 s: longest signal so far
- Small signal in Virgo: source close to blind spot. Quite important for localization



# GW179817

- Chirp mass measured over ~3000 cycles $\mathcal{M}_c = (m_1 m_2)^{3/5} (m_1 + m_2)^{-1/5}$

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

- Total mass (union of 90% credible region from different waveform models)

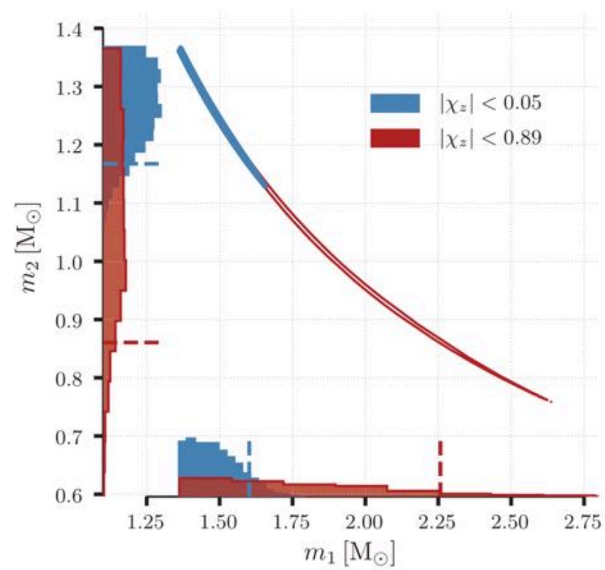
$$2.73 < M_{\text{Total}} < 3.29\ \mathrm{M}_\odot$$

- Constraint on the two masses (broad range due to mass-spin degeneracy)

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

- Luminosity distance:

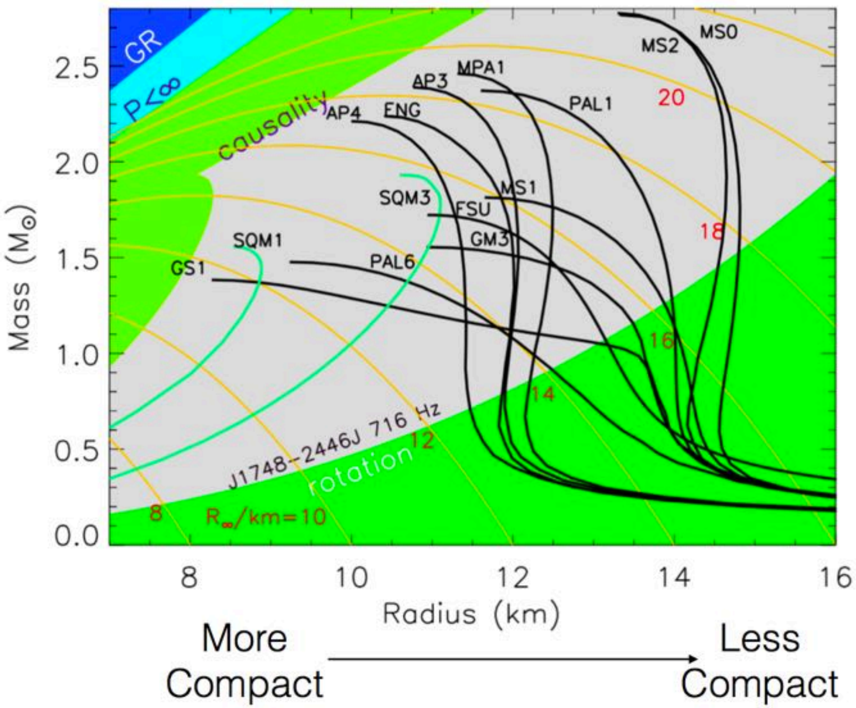
$$D_L = 40^{+8}_{-14}\ \text{Mpc}$$



# NEUTRON STARS

- EOS of nuclear matter
  - relation between density and pressure
  - relation between mass and radius

- NS respond to perturbations by deforming and oscillating
- Response determined by internal properties (density, pressure…)




Lattimer, arXiv:1305.3510

# BINARY NEUTRON STARS

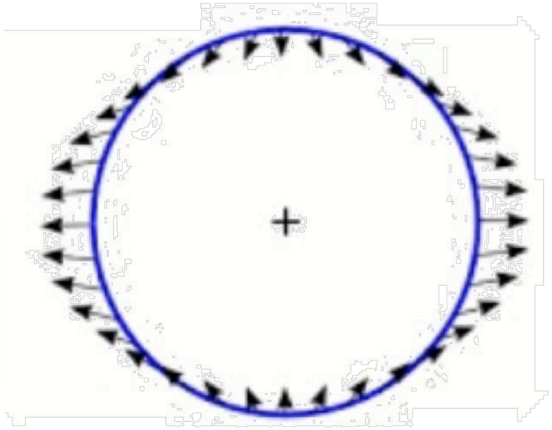
- Each NS is perturbed by the tidal field of the companion
- Tidal effects enter through "deformability"

$$Q_{ij} = -\lambda(\mathrm{EOS}; m)\tau_{ij}$$

quadrupole moment — tidal field of companion star

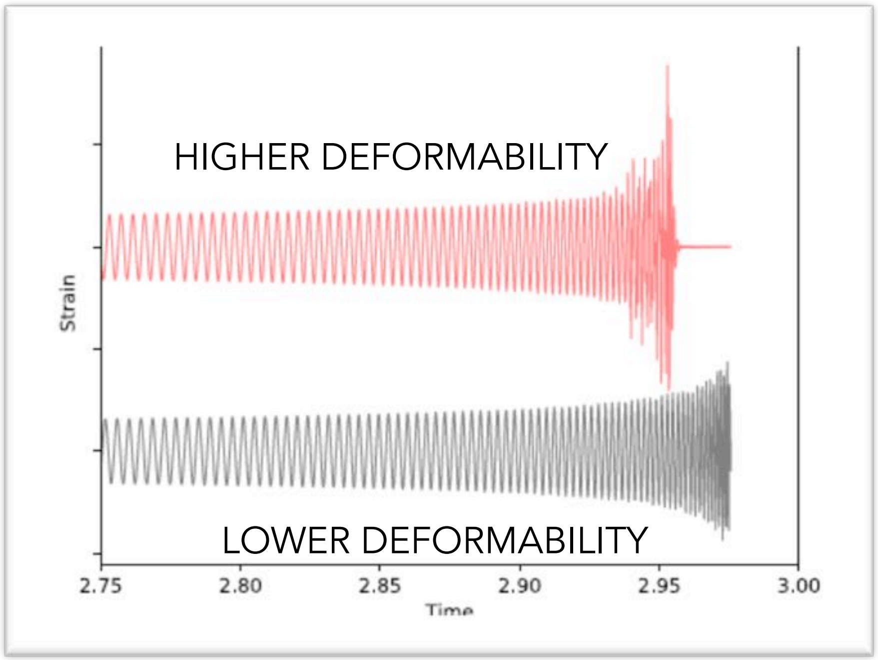
$$\lambda(m) = \frac{2}{3} k_2 R^5(m)$$

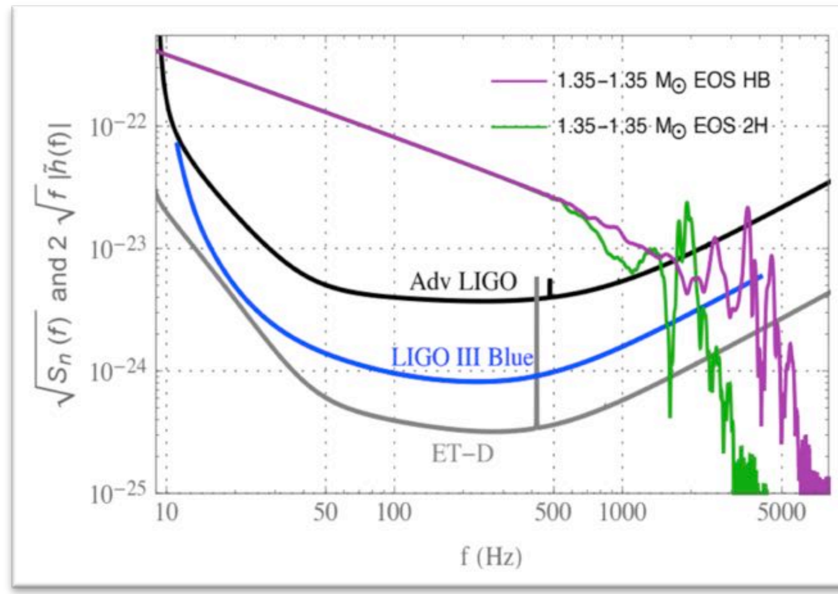
second Love number — NS radius

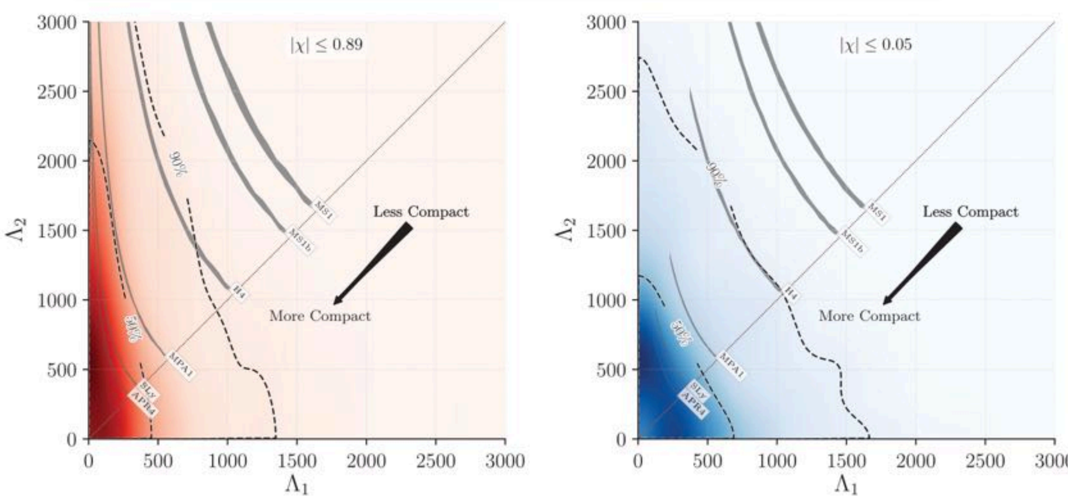


- Time-varying quadrupole moment → emission of GW

# BINARY NEUTRON STARS



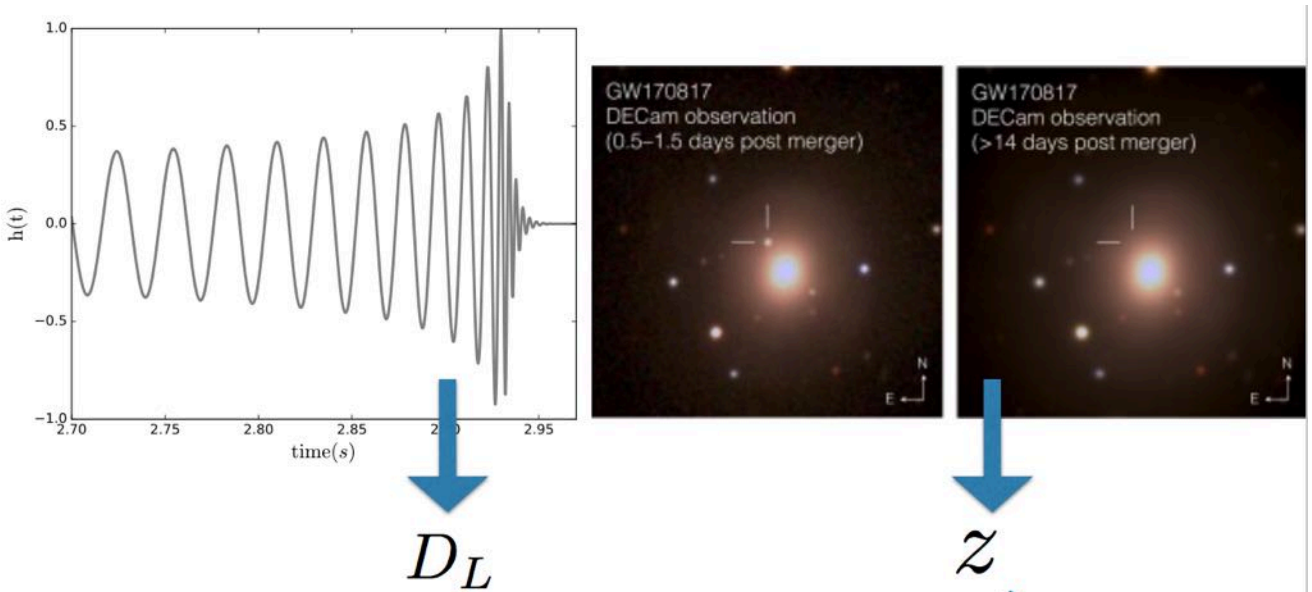



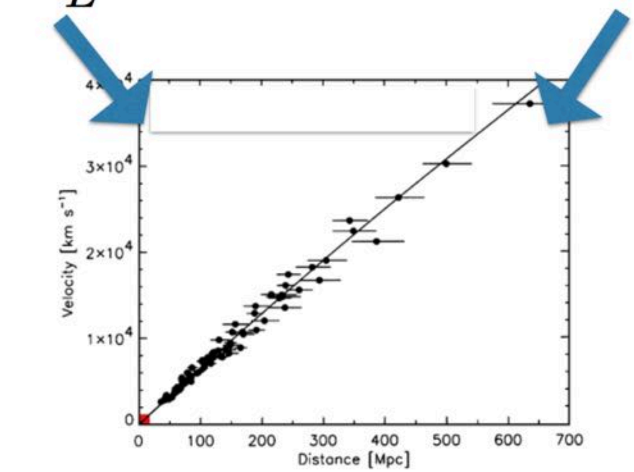




GW170817 data disfavor less compact stars

Waiting for HF sensitivity improvements…

# A STANDARD SIREN




Credit: W Del Pozzo

# A STANDARD SIREN

- Standard siren proposal (Schutz, 1986)

$$\Psi(f) \propto 2\pi f t_c - \Phi_c - \frac{\pi}{4} + \frac{3}{128}(\pi \mathcal{M}_z f)^{-5/3}[1 + \ldots]$$

Phase proportional to redshifted chirp mass!

$\propto \mathcal{M}(1+z)$

$$\tilde{h}_+(f) \propto A_0 \frac{\mathcal{M}_z^{5/6}}{D_L}[1+\cos^2 \iota]\, f^{-7/6} e^{i\Psi(f)}$$

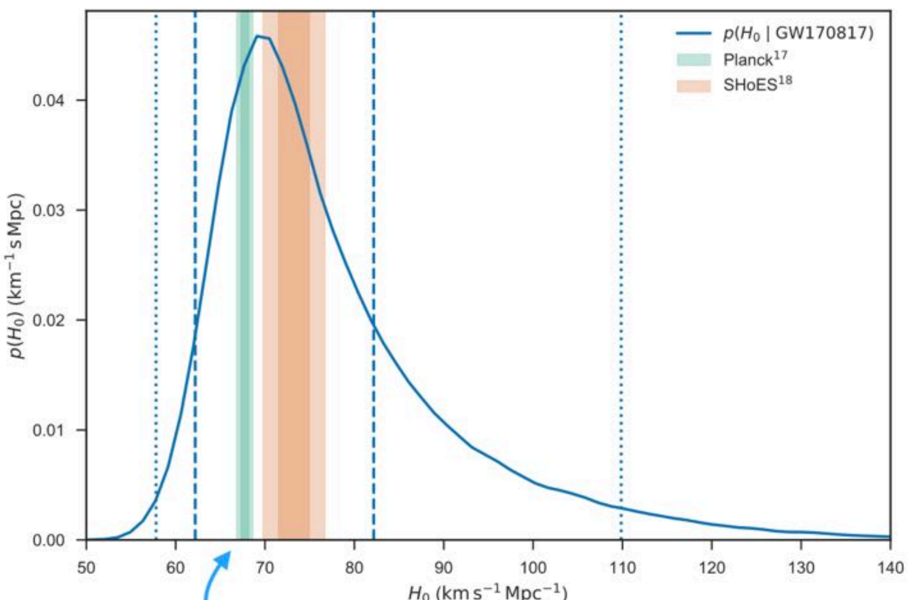
Amplitude proportional to redshifted chirp mass and luminosity distance

Inclination angle introduces an additional degeneracy

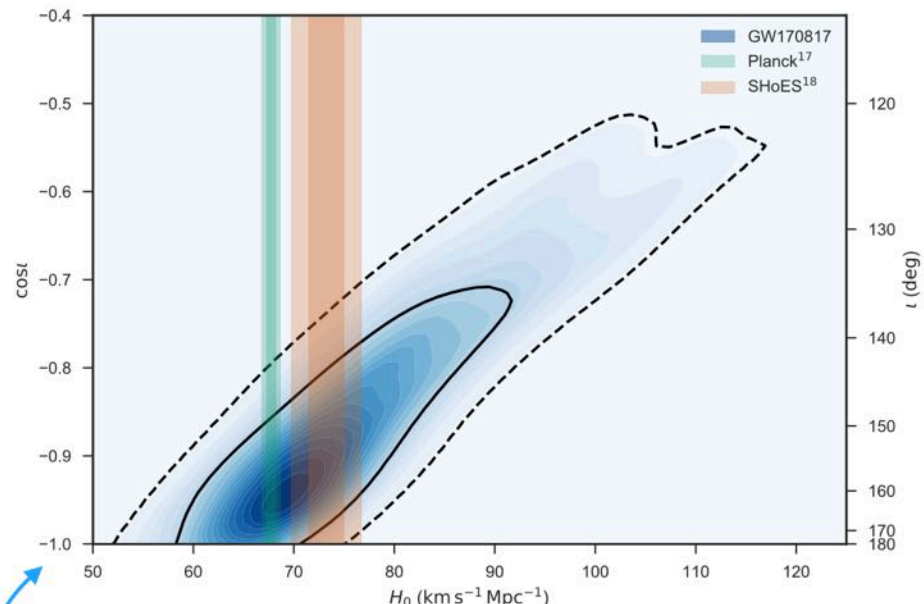
- From GW signal we obtain: redshifted chirp mass and luminosity distance
- If we have an EM counterpart we can measure the redshift and relate to distance!

# A STANDARD SIREN

Identification of GW170817 with host galaxy allows redshift measurement




Results in broad consistency with Planck and SHoES




Orbital angular momentum of binary anti-parallel to detector

Abbott et al.,Nature, 24471 (2017)

# SPEED OF GRAVITY

- 1.7 seconds over ~130 Myrs: WOW!

$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\mathrm{EM}}} \leqslant +7 \times 10^{-16}$$

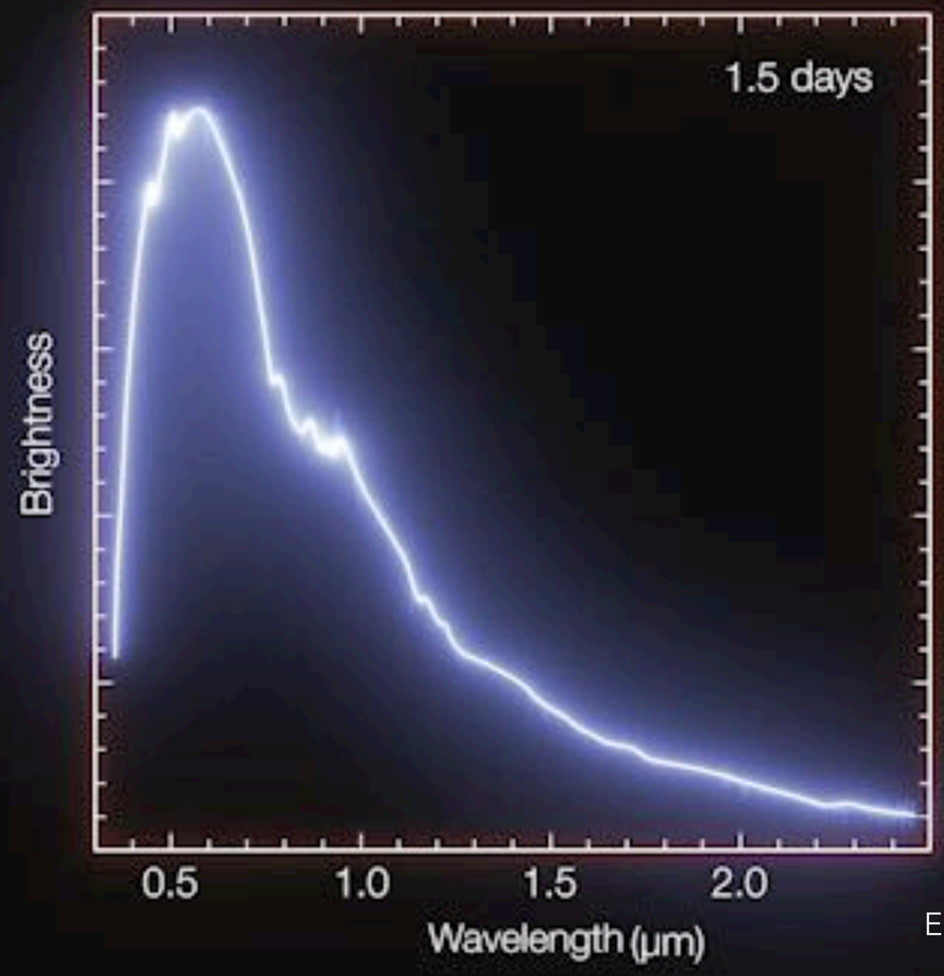
$\Delta v = v_{GW} - v_{EM}$

Assuming D=26 Mpc

Assuming sGRB emitted 10 s after GW

Abbott et al., ApJL., 848:L13 (2017)

# AND THEN…

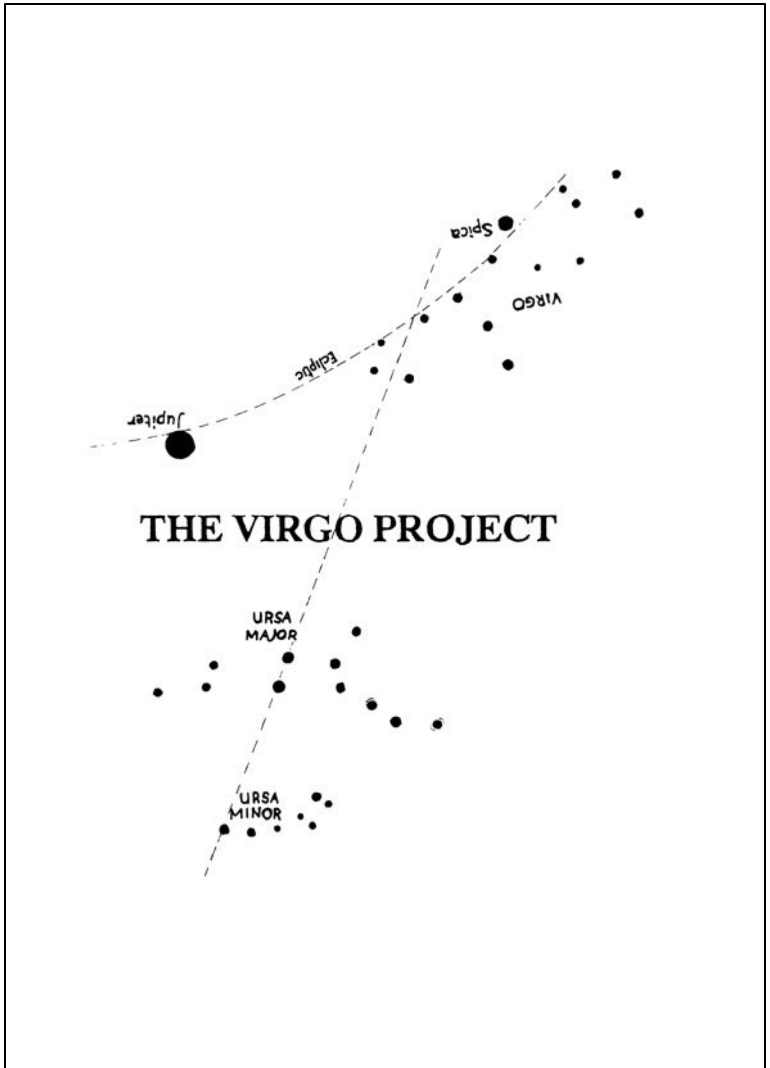



ESO-VLT/X-Shooter

# THE DAY AFTER GW170817

- GW170817 is another spectacular discovery in the new era of astronomy (astrophysics, cosmology, nuclear physics, fundamental physics, …)
- Likely to be just a preview of the science to come from the world-wide network of gravitational wave observatories

# THE 1989 VIRGO PROPOSAL




VIRGO must be considered both as an experiment and as a step towards a future observatory. The immediate goal of the VIRGO experiment is to realize, or to participate in, the first detection of gravitational radiation, but it also has the long term goal of being one component of the gravitational wave detectors network which will involve other detectors in other countries, and provide data of astrophysical interest. These goals imply a collaboration with the other groups having similar projects, without excluding some competition.

The group leaders from Italy, France, Germany, Scotland, and the USA have agreed to exchange all information and to collaborate on all the aspects of the construction of large interferometers in order to generate the international effort required by the birth of gravitational astronomy.

A BRILLET & A GIAZOTTO

# AN IMPORTANT LESSON

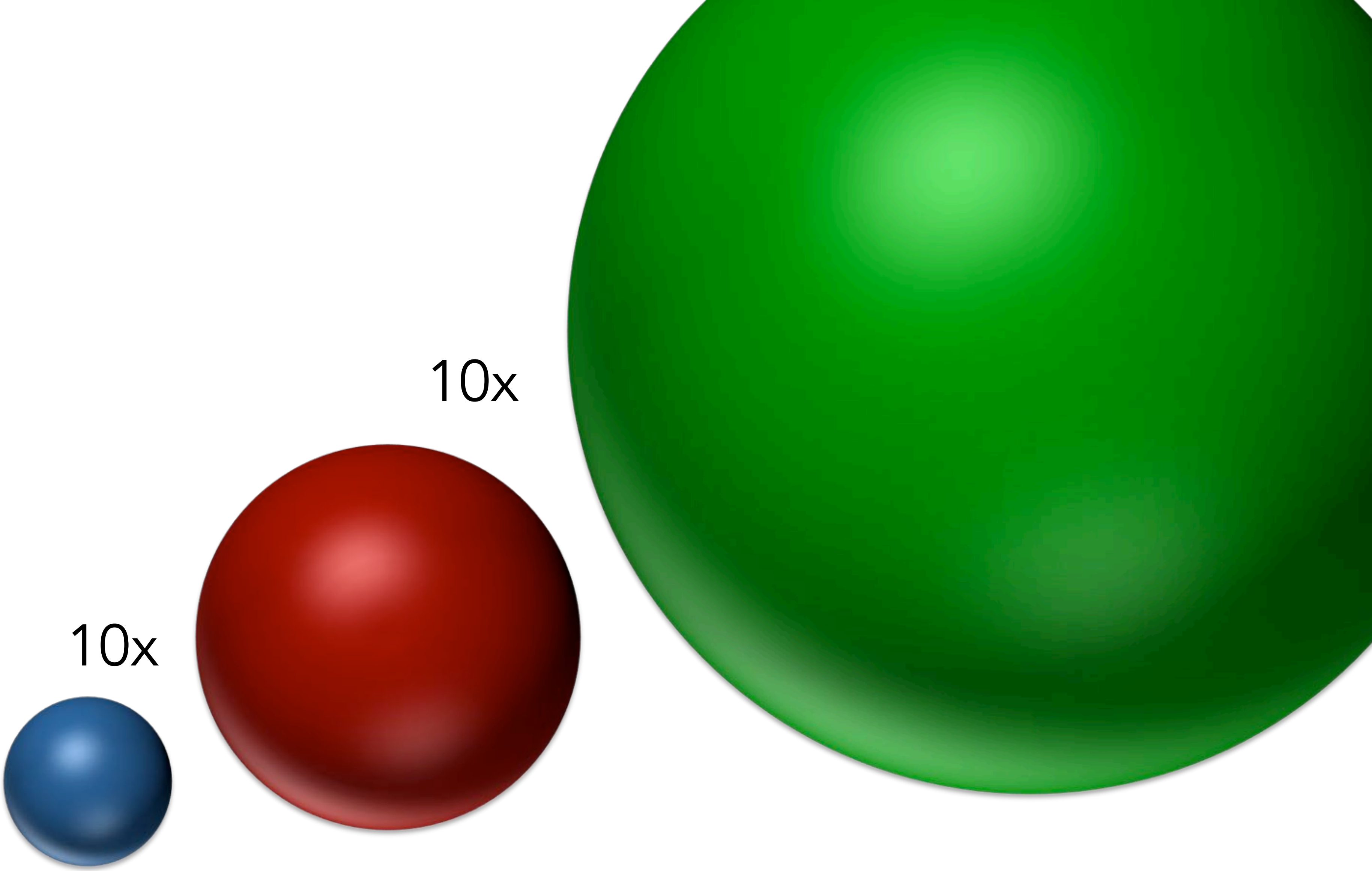
$$\# \text{ EVENTS} \propto d^3 \, T$$

1 day of data at a range of 80 Mpc is equivalent to 64 days at 20 Mpc
1 day of data at a range of 100 Mpc is equivalent to 2 days at 80 Mpc

it's good to observe for a long time,
it's even better to improve the sensitivity further

for this observation is stopped and time is dedicated
to commissioning/upgrading in order to further
increase the volume of observable universe ($d^3$)
and improve the machine stability (T)

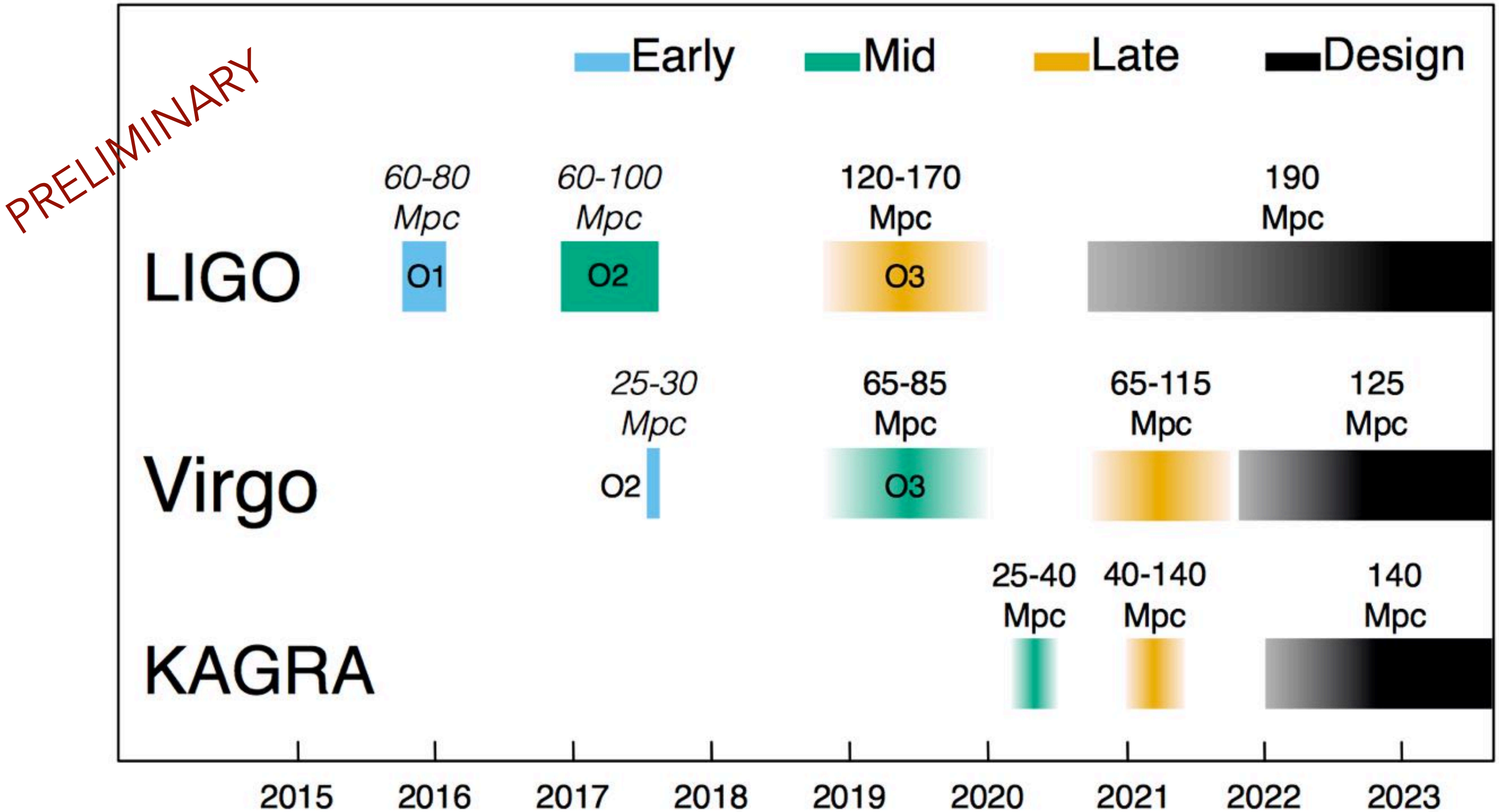
# PERSPECTIVES




VIRGO BEST
(12 Mpc)

AdV O2
(26 Mpc)

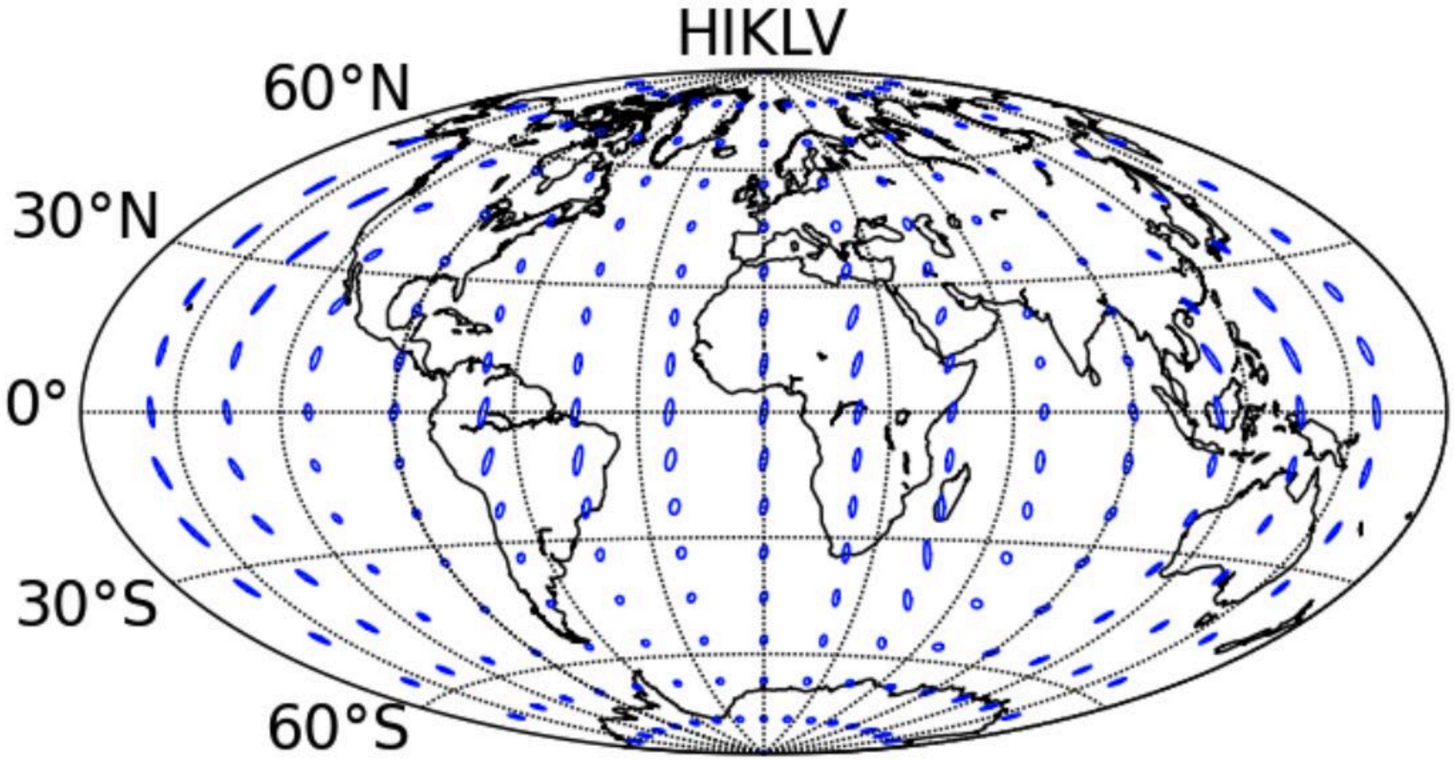
AdV O3 (goal)
(>65 Mpc)




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

B.P. Abbott et al. "Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA" (in preparation)

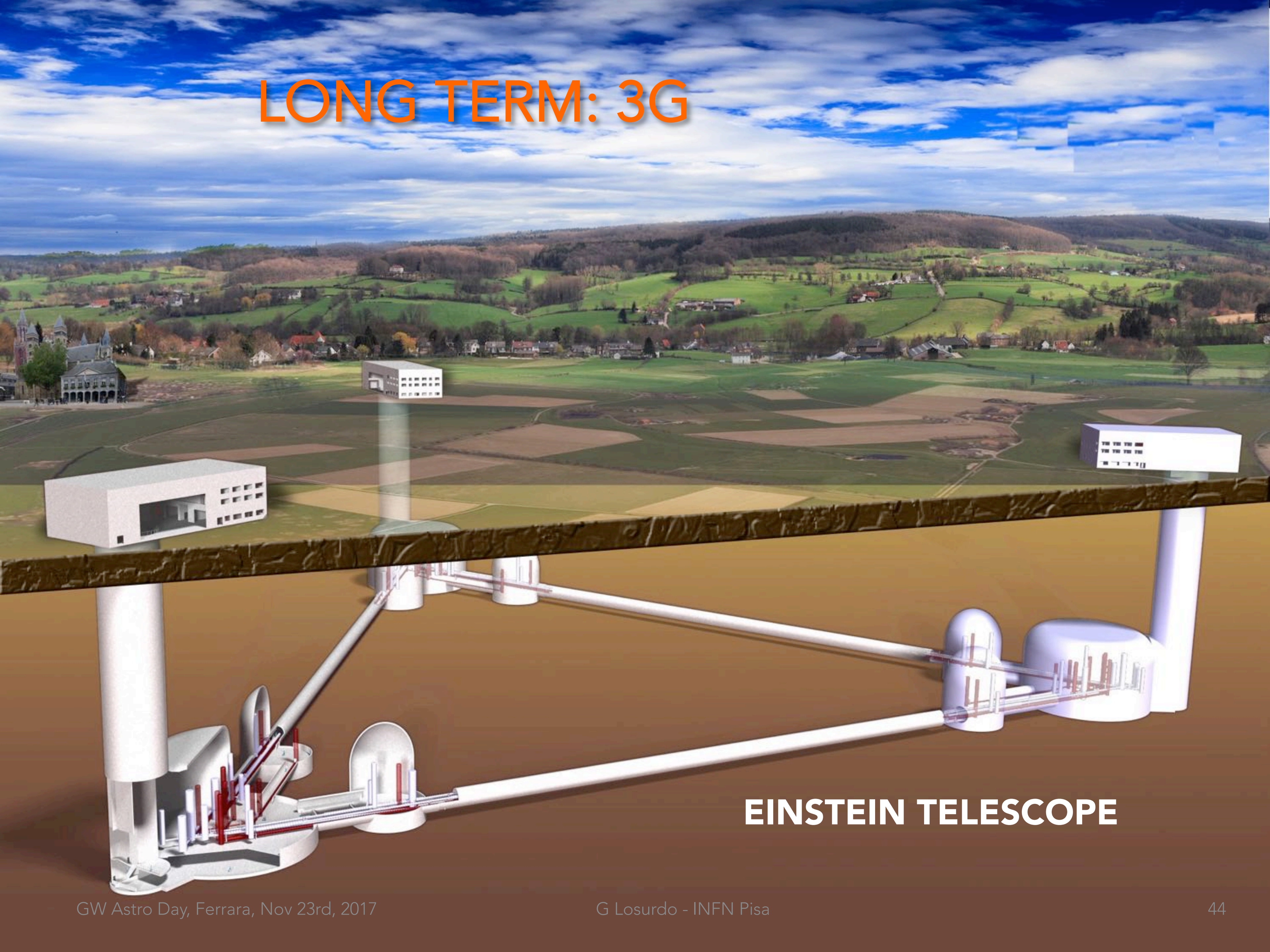
# THE MID-TERM GOAL




S Fairhurst, CQG 28, 2001

Localization capabilities of the 2G network at mid 2020s:
>60% of the sources localized within 10 $deg^2$

# LONG TERM: 3G



*Grandi invero sono le cose che in questo breve trattato io propongo alla visione e alla contemplazione degli studiosi della natura.*

*Grandi, dico, sia per l'eccellenza della materia per se stessa, sia per la novità loro non mai udita in tutti i tempi trascorsi, sia anche per lo strumento, in virtù del quale quelle cose medesime si sono rese manifeste al senso nostro.*

Galileo Galilei, *Sidereus Nuncius*, 1610