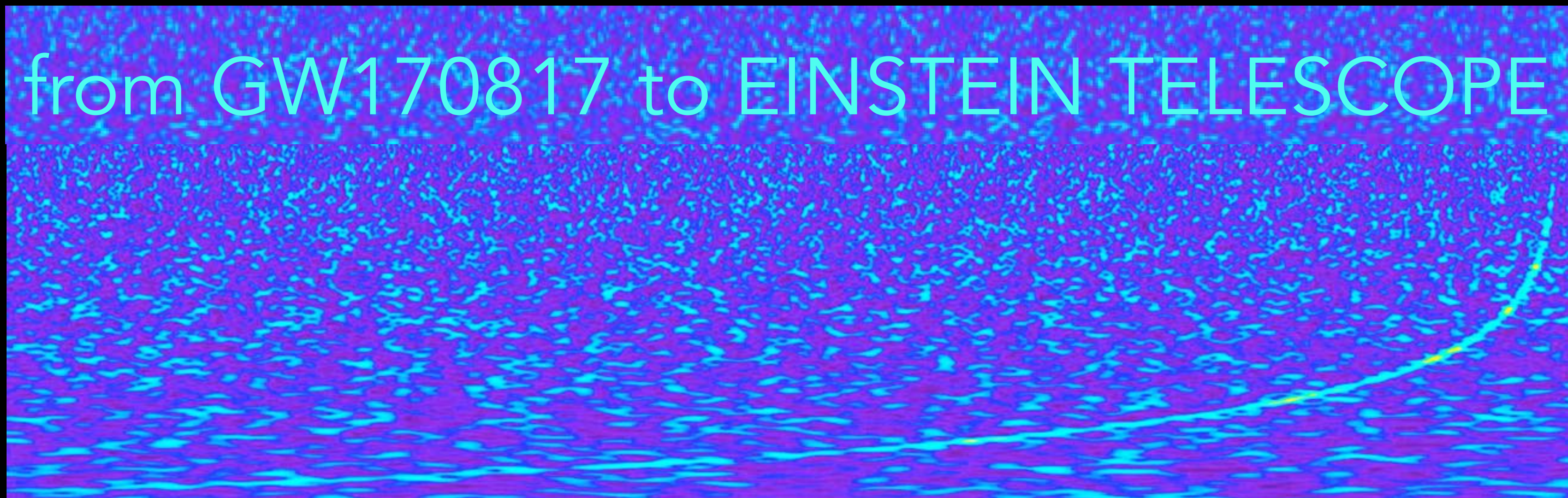
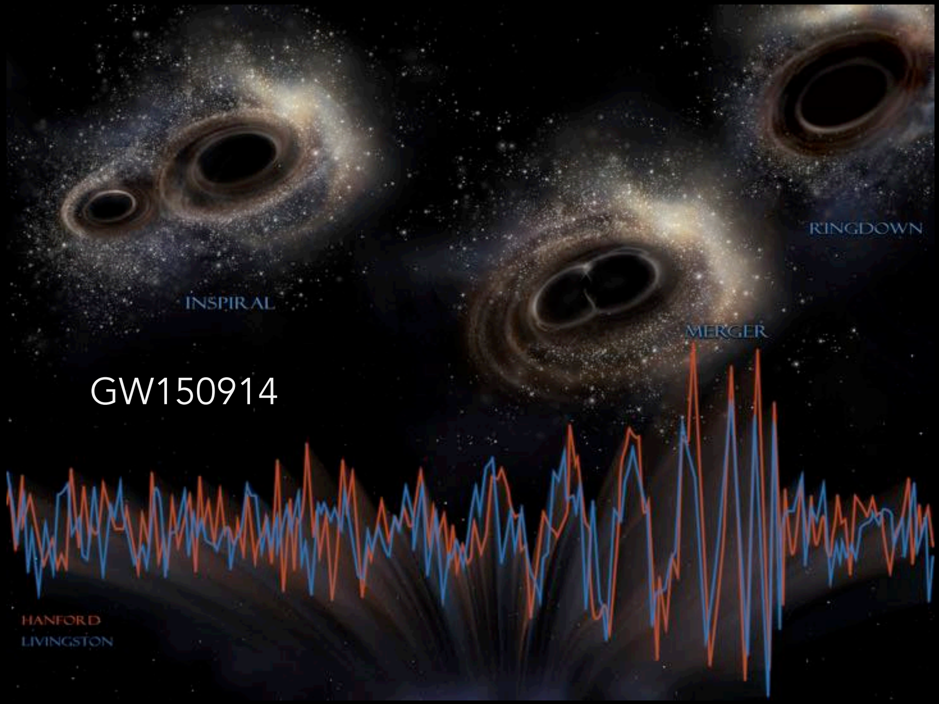
from GW170817 to EINSTEIN TELESCOPE

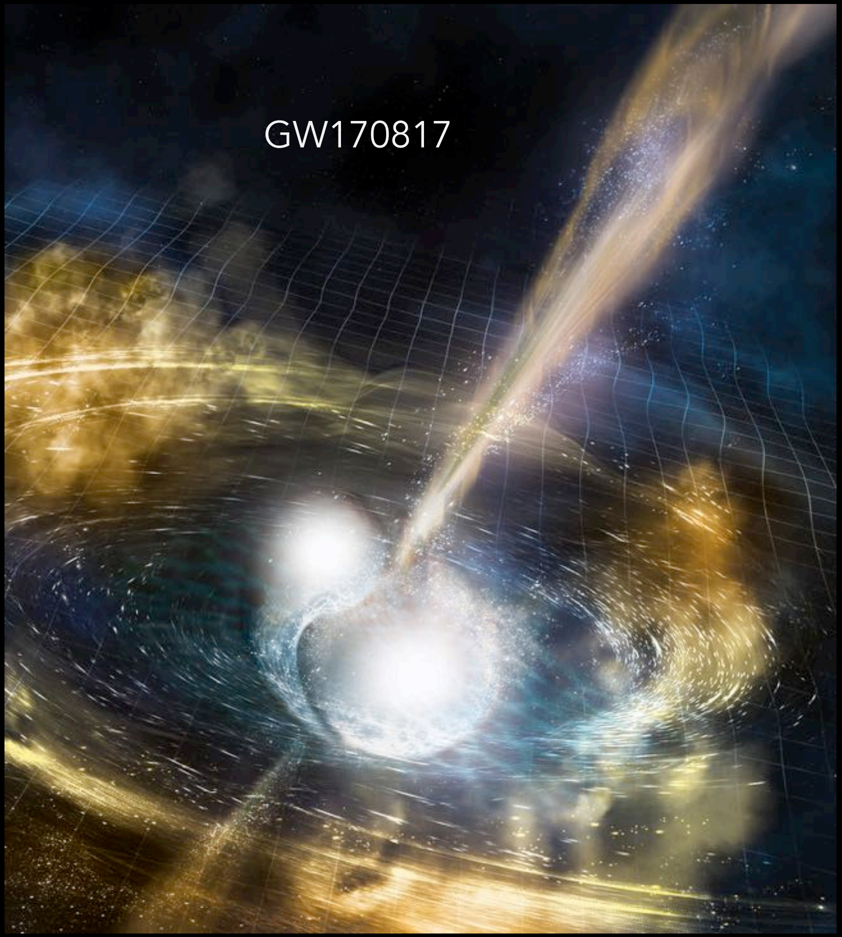


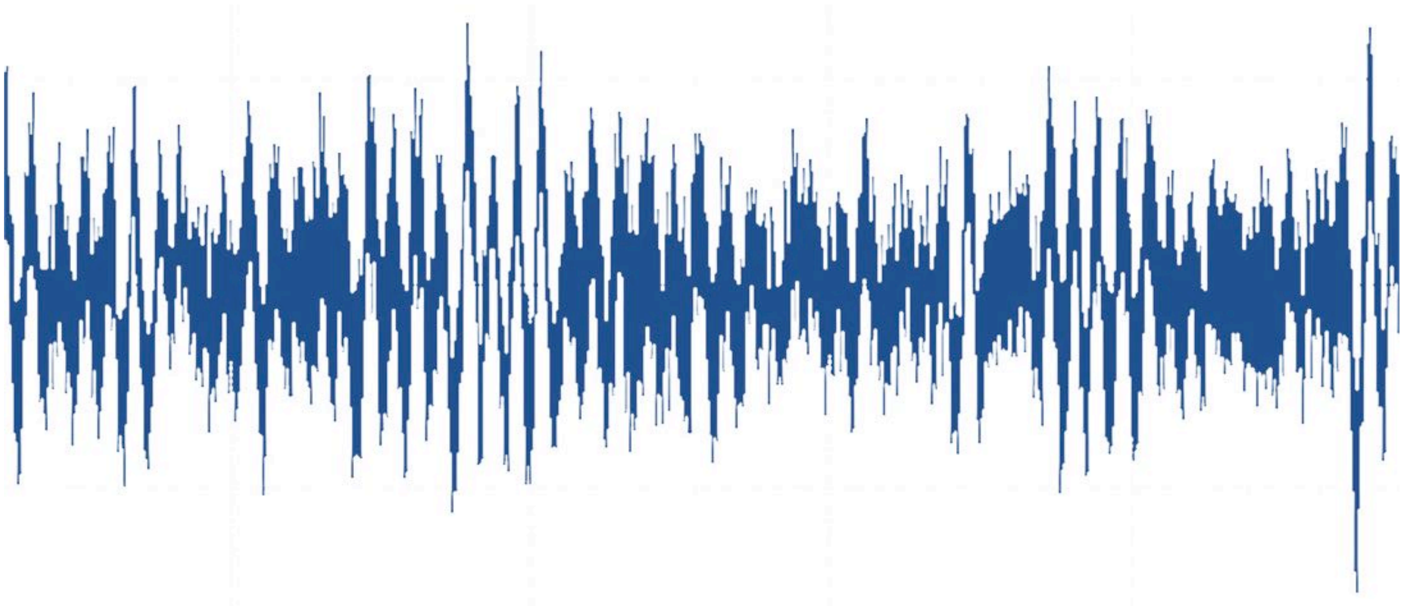
Giovanni Losurdo – INFN Pisa
presenting results of the
LSC and VIRGO Coll.

THE GREAT GIG IN THE SKY

TWO GROUND-BREAKING DISCOVERIES
A NEW ERA IN THE OBSERVATION OF THE UNIVERSE

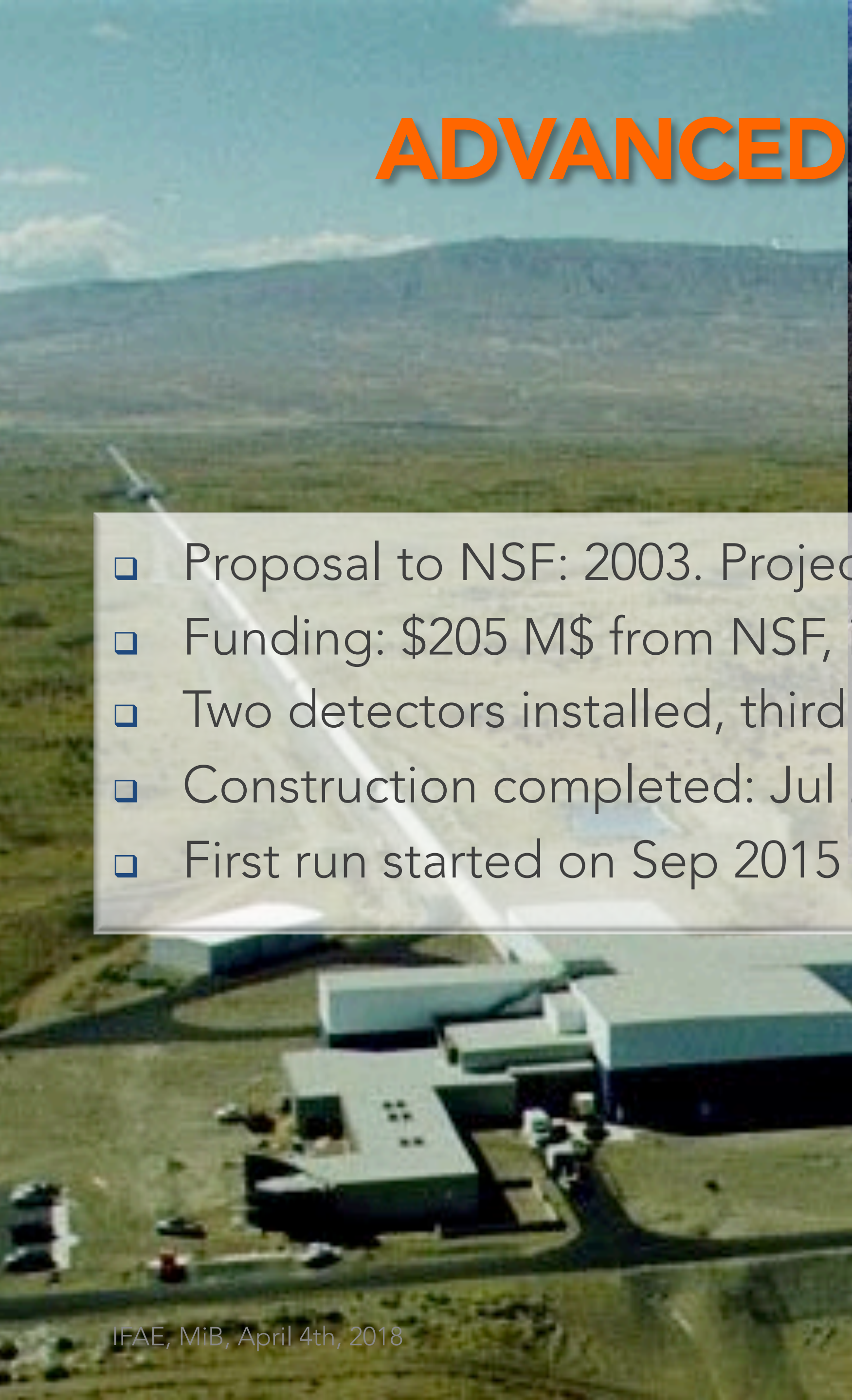






DETECTORS

ADVANCED LIGO



- Proposal to NSF: 2003. Project start: April 2008
- Funding: $205 M$ from NSF, in-kind contribution from D/UK/AUS
- Two detectors installed, third interferometer to be shipped to India
- Construction completed: Jul 2014
- First run started on Sep 2015

ADVANCED VIRGO

6 European countries
21 labs, ~280 authors

- Advanced Virgo (AdV): upgrade of the Virgo interferometric detector
- Partecipated by France and Italy (former founders of Virgo), The Netherlands, Poland, Hungary, Spain
- Funding approved in Dec 2009 (21.8 ME + Nikhef in kind contribution)
- Project formally completed with the start of the O2 run (Aug 1st, 2017)

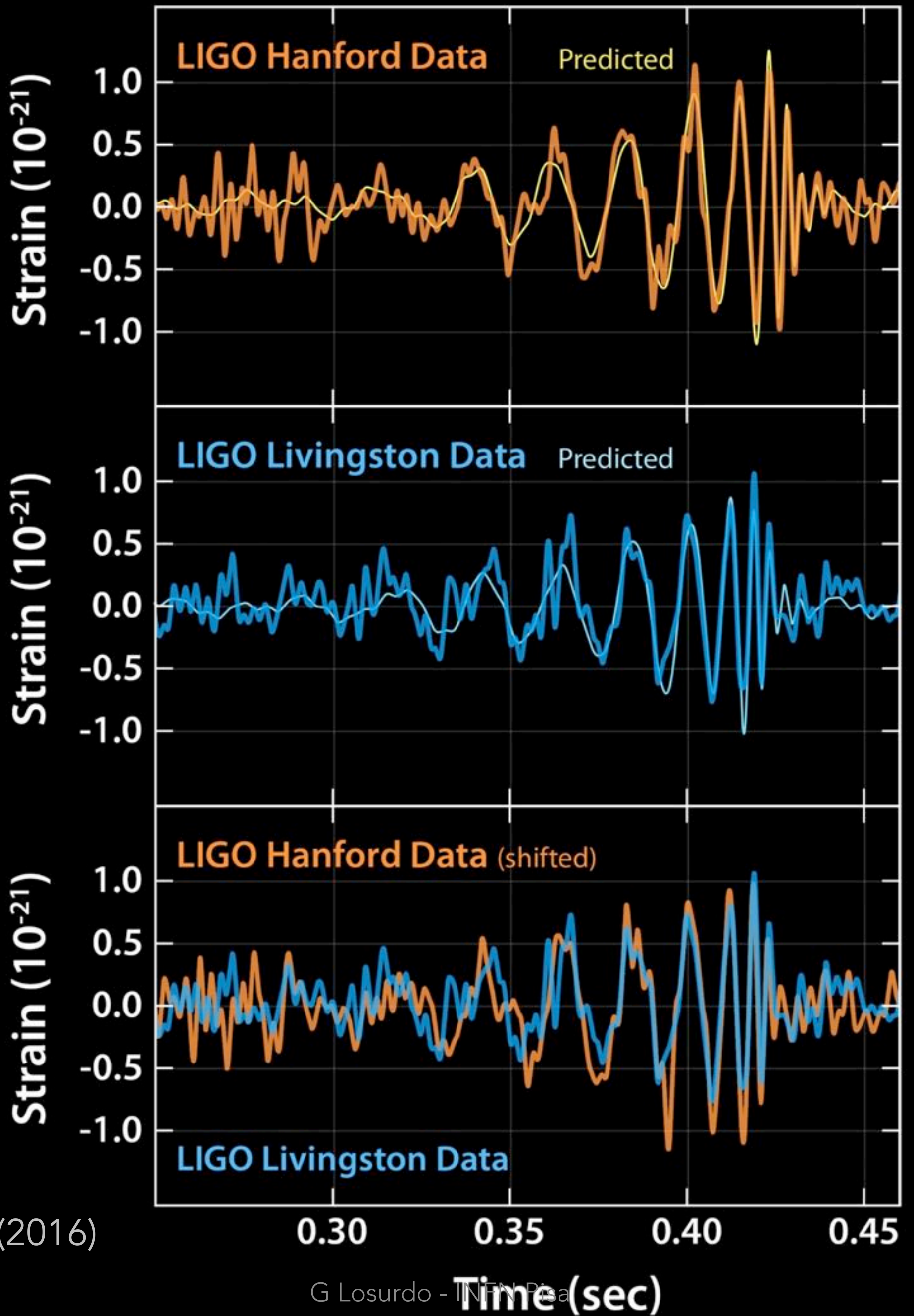
APC Paris
ARTEMIS Nice
EGO Cascina
INFN Firenze-Urbino
INFN Genova
INFN Napoli
INFN Perugia
INFN Pisa
INFN Roma La Sapienza
INFN Roma Tor Vergata
INFN Padova
INFN TIFPA Trento
LAL Orsay – ESPCI Paris
LAPP Annecy
LKB Paris
LMA Lyon
NIKHEF Amsterdam
POLGRAW
RADBOUD Uni. Nijmegen
RMKI Budapest
University of Valencia

…and more have just joined: GSSI, Milano Bicocca, Torino, UniSalerno

Credit: I. Nardecchia

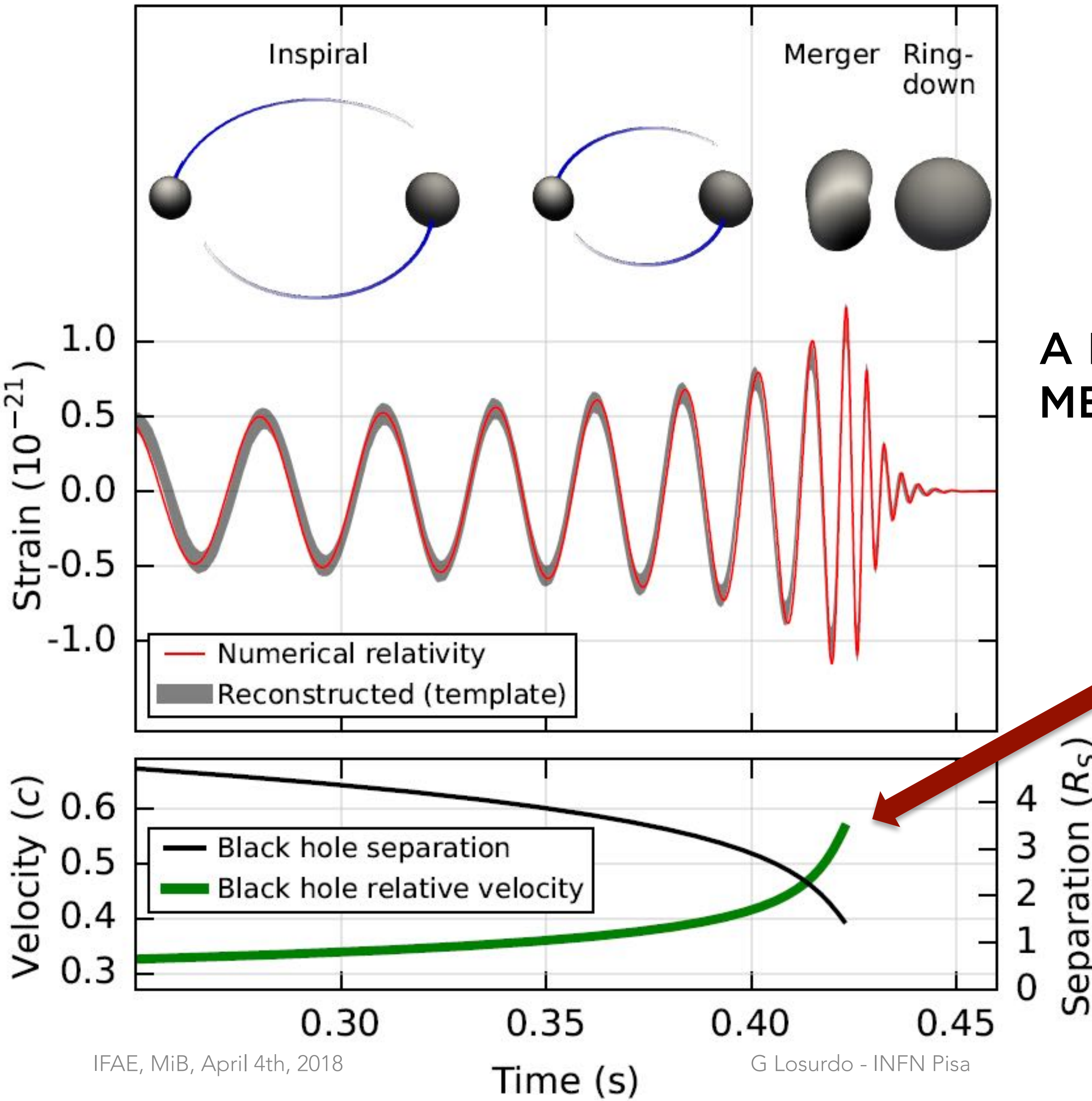
OBSERVATIONS

GW150914



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

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



A BINARY BLACK HOLE MERGER

v ~ 0.6 c

PARAMETERS

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

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	$410^{+160}_{-180}\ \mathrm{Mpc}$
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: $3.6^{+0.5}_{-0.4} \times 10^{56}\ \mathrm{erg/s}$

The most luminous event ever observed

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 $M_{\odot}$)
- 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

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

Black Holes of Known Mass

MORE BBH DETECTED AFTER GW150914:
A DIFFERENT POPULATION IS SHOWING UP

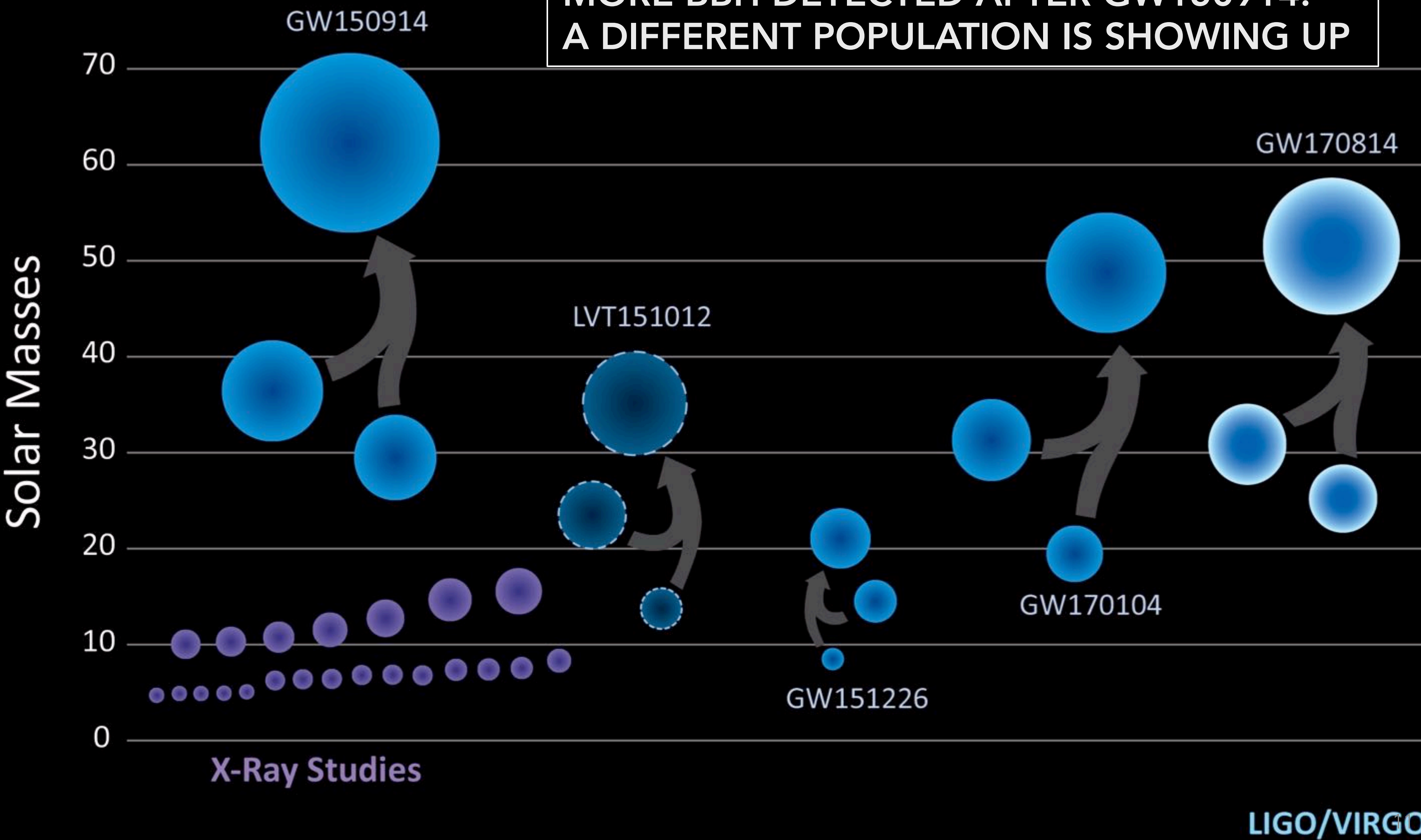


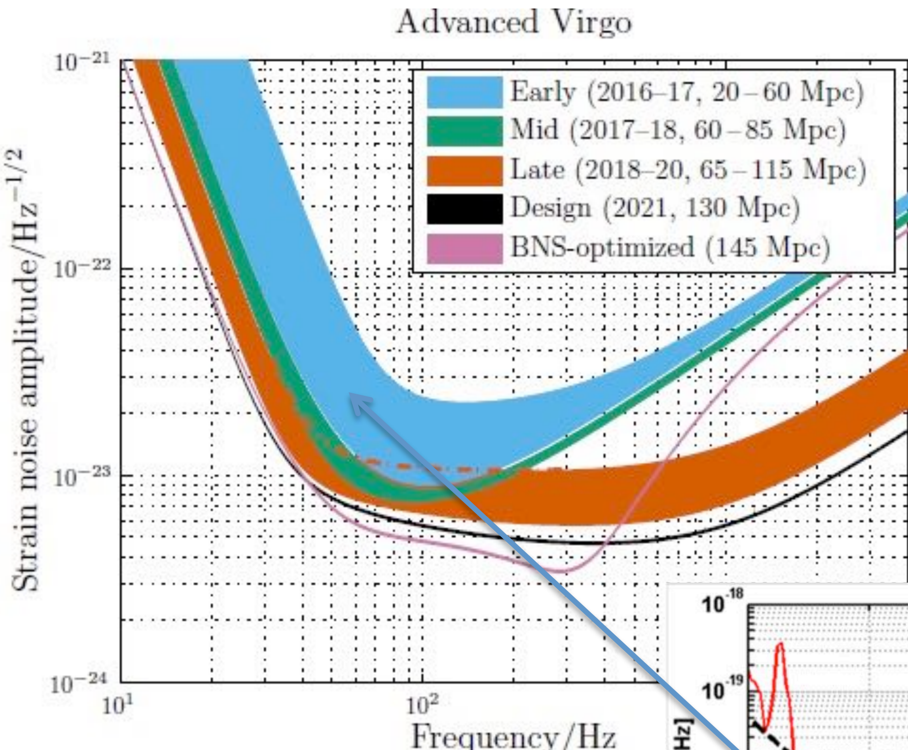
Image credit: LIGO/Caltech/Sonoma State (Aurore Simonnet)

August 1st, 2017

VIRGO JOINS LIGO IN THE OBSERVATION RUN O2

THREE 2G DETECTORS ACTING AS A “SINGLE MACHINE”

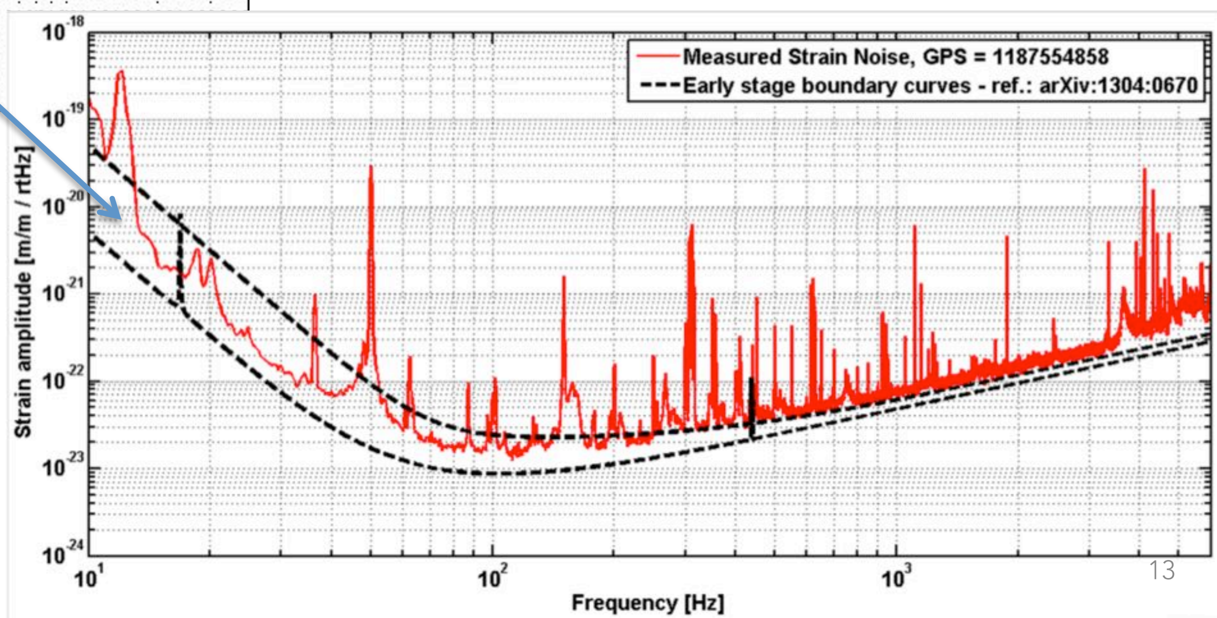
SENSITIVITY



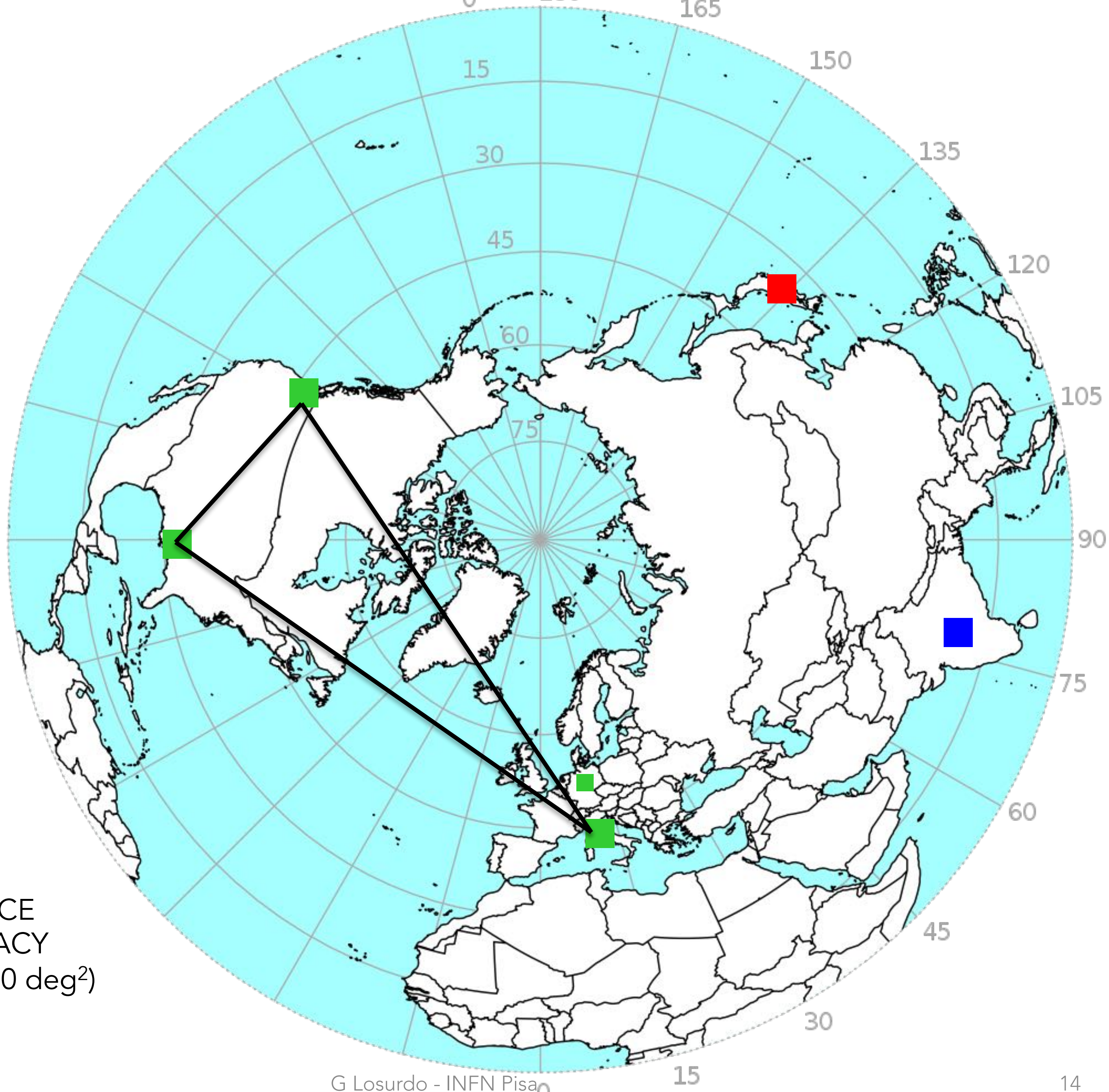
FROM THE 2013 "OBSERVING SCENARIO"

Abbott BP et al. (LSC-Virgo), arXiv:1304:0670

THE EARLY SENSITIVITY TARGET HAS BEEN MET

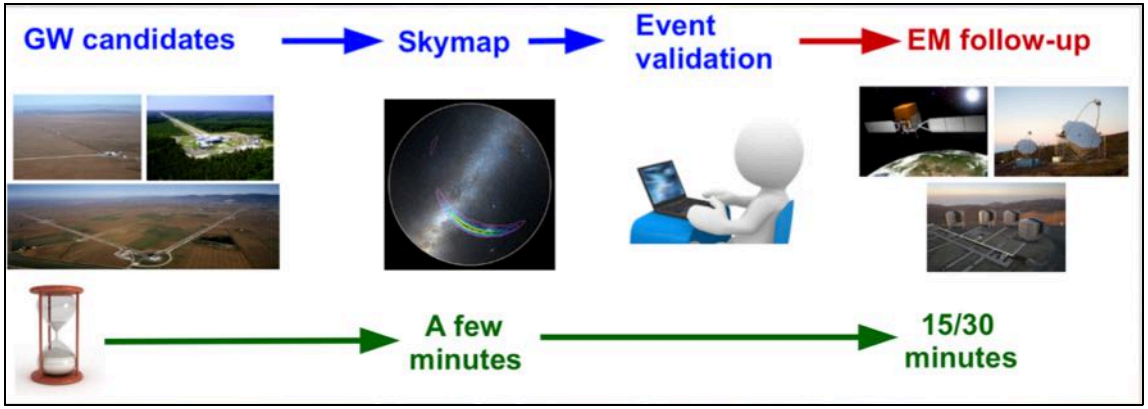


- OPERATION
- COMMISSIONING
- CONSTRUCTION
- APPROVED

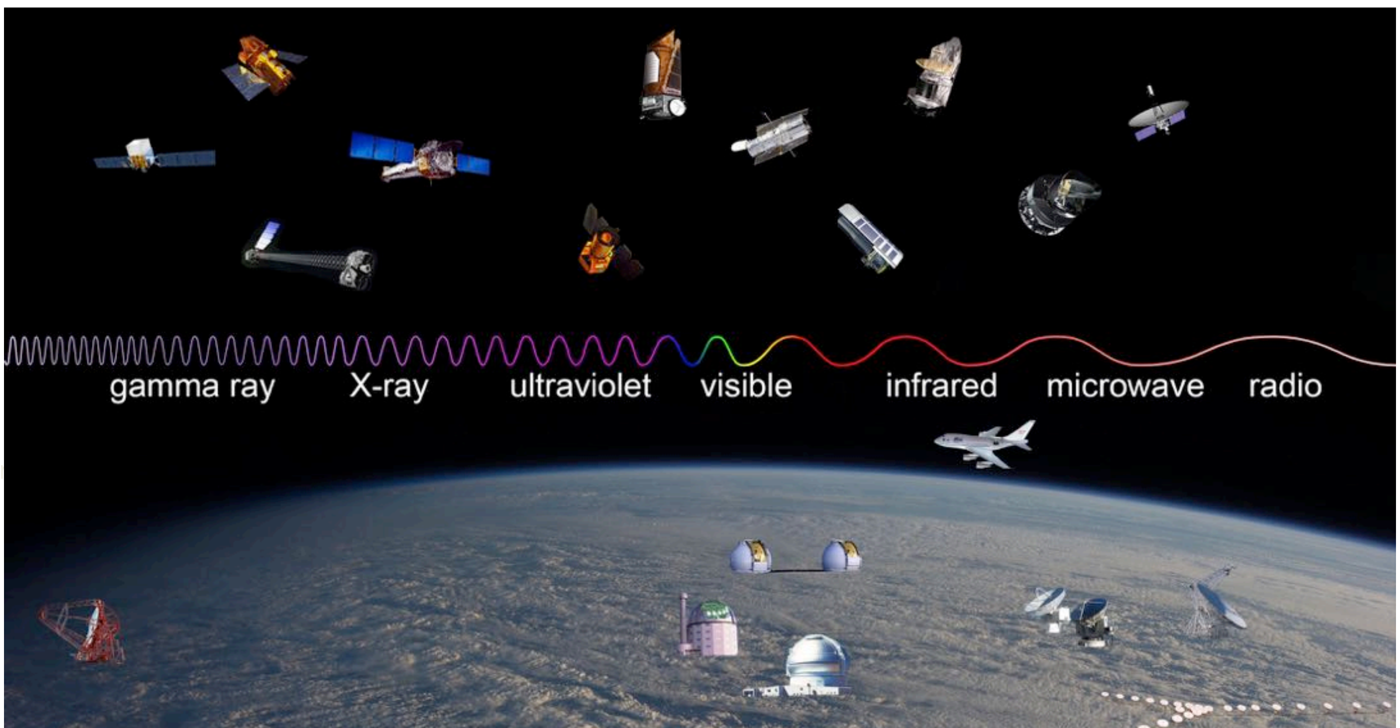


WITH VIRGO THE SOURCE LOCALIZATION ACCURACY IMPROVES FROM O(1000 deg^2) to 10s-100s deg^2

MULTI-MESSENGER NETWORK



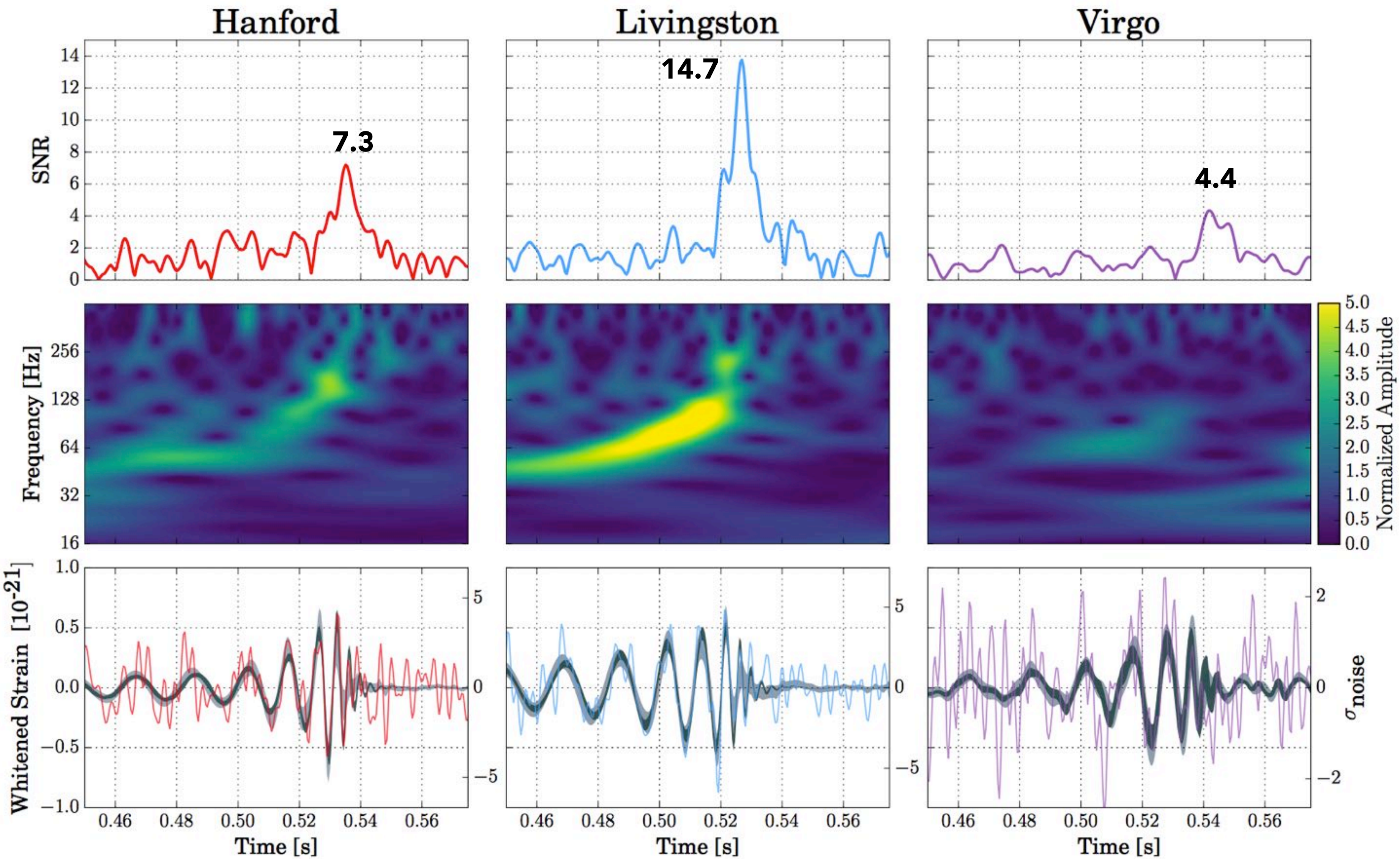
93 groups (>200 instruments) have signed the MoU with the LVC



August 14th, 2017

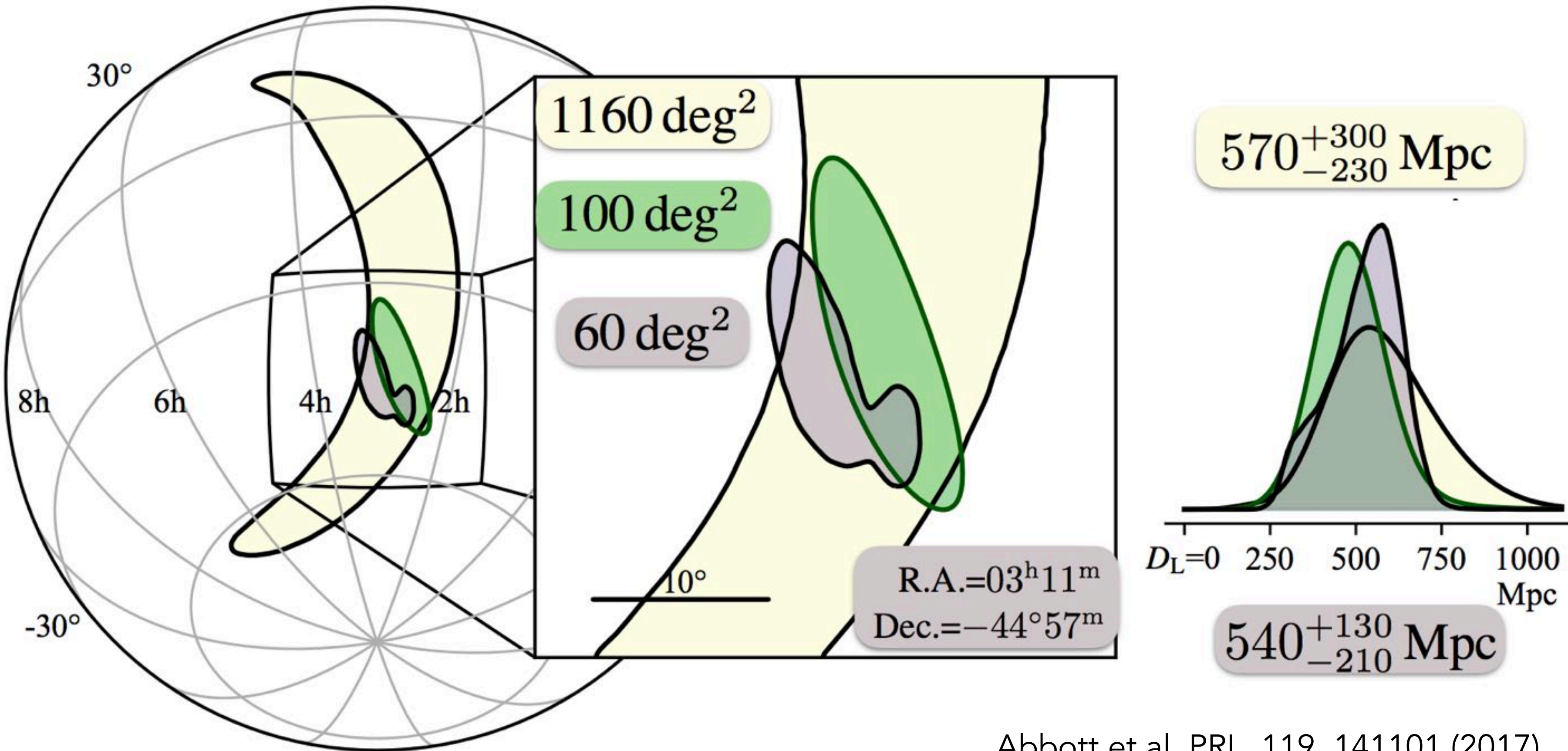
At 10:30:43 UTC, the Advanced Virgo detector and the two Advanced LIGO detectors coherently observed a transient gravitational-wave signal produced by the coalescence of two stellar mass black holes, with a false-alarm-rate of <~ 1 in 27 000 years

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)



Abbott et al, PRL, 119, 141101 (2017)

VIRGO HELPS REDUCING:

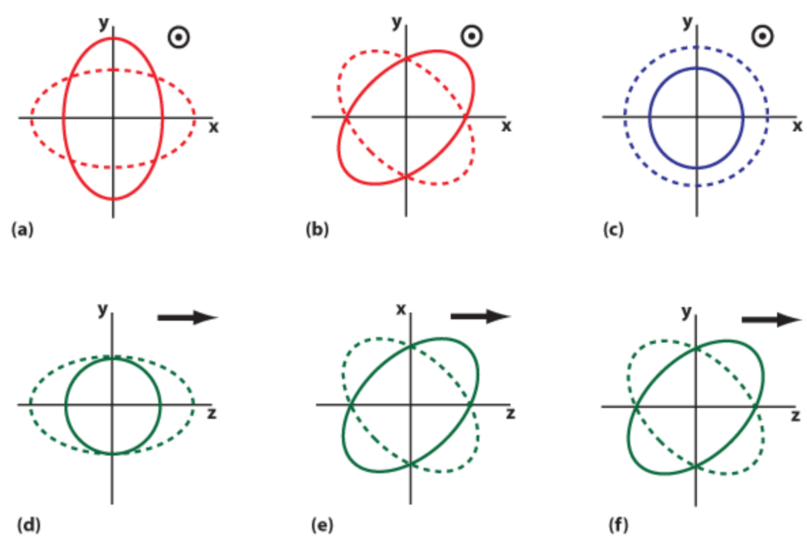
ERROR IN SKY AREA:	20x
ERROR IN DISTANCE:	1.5x
ERROR BOX ON THE SKY:	30x
(from 70 to 2 Mpc^3)	

POLARIZATION

- **For the first time**, thanks to the the addition of a 3rd detector, one can probe the nature of the polarization states
- PRELIMINARY ANALYSIS: GR (purely tensor) is 200 and 1000 times more likely than purely vector/scalar respectively

TENSOR (SPIN 2)
GENERAL RELATIVITY

SCALAR (SPIN 0)



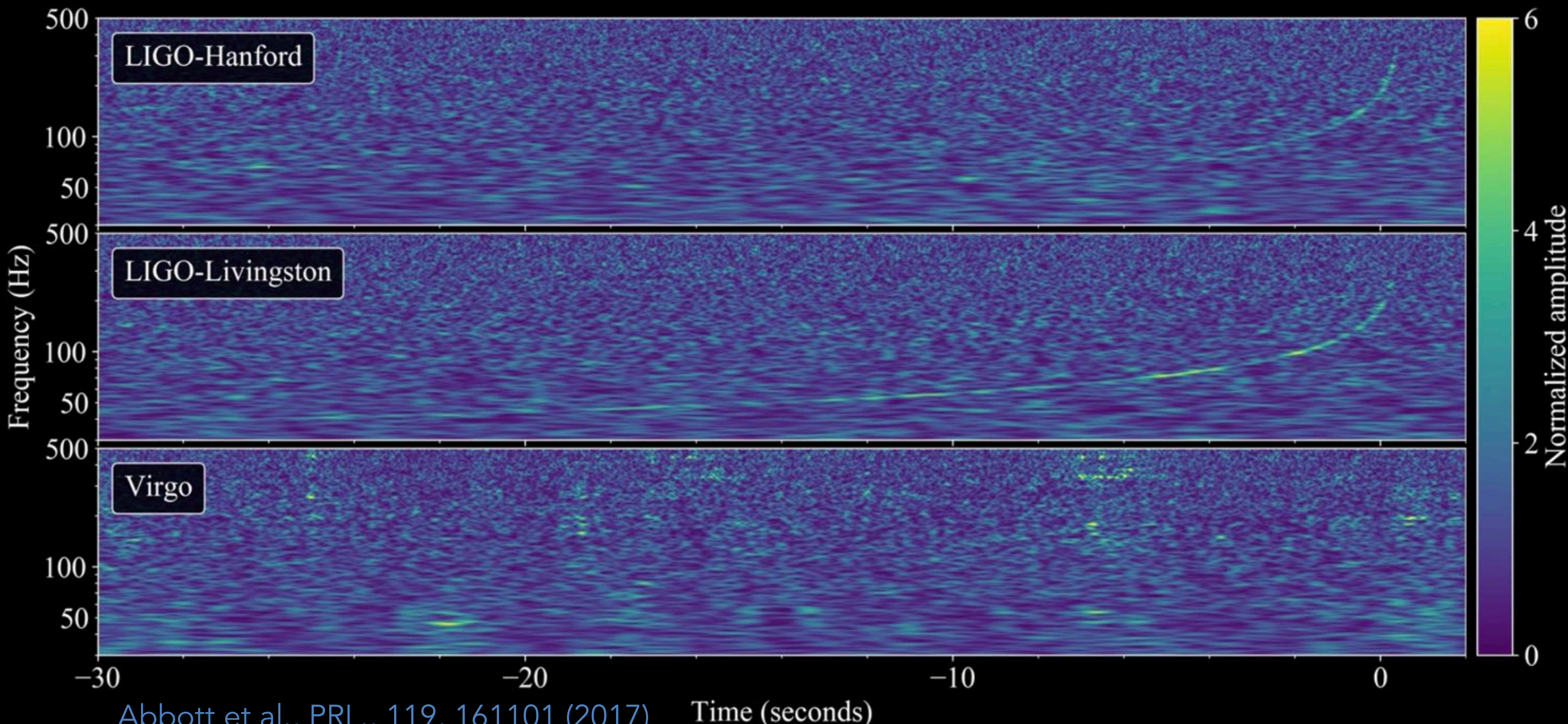
VECTOR (SPIN 1)

Abbott et al., PRL, 119, 141101 (2017)

AUGUST 17th, 2017

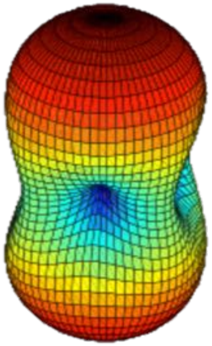
IT…

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

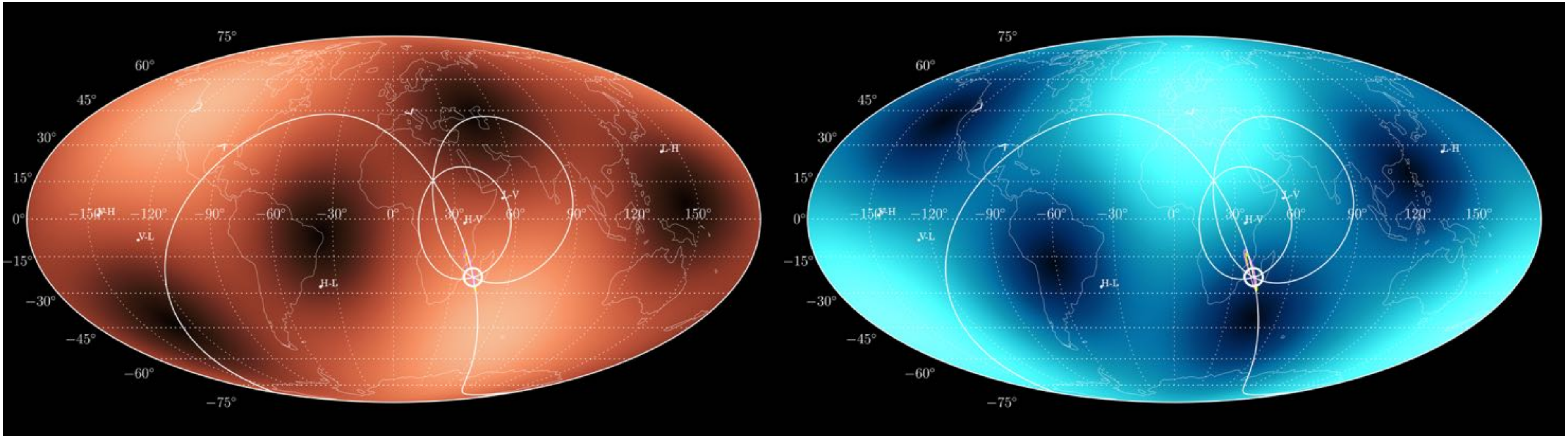


Abbott et al., PRL., 119, 161101 (2017)

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

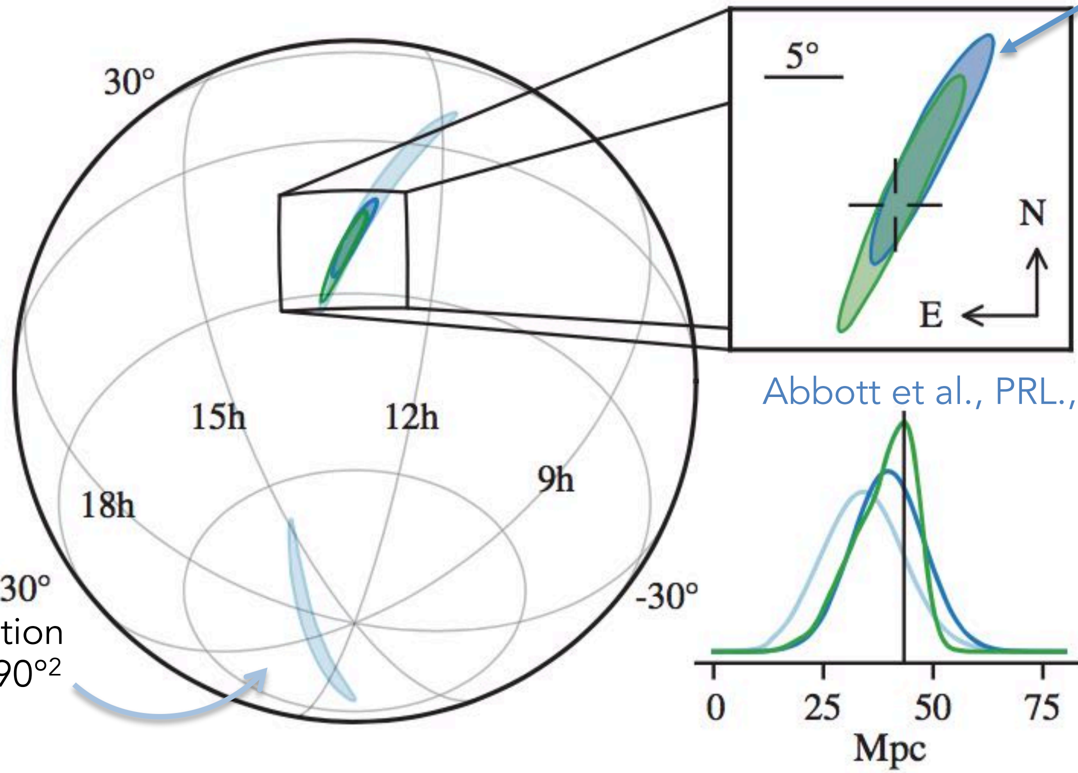


GW170817

- 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

rapid localization
with LIGO-Virgo: 31°^{2}

high-latency follow-up:
28°^{2}, 380 Mpc^3



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

rapid localization
with LIGO: 190°^{2}

GW170817

- 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:

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

- Constraint on the two masses:

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

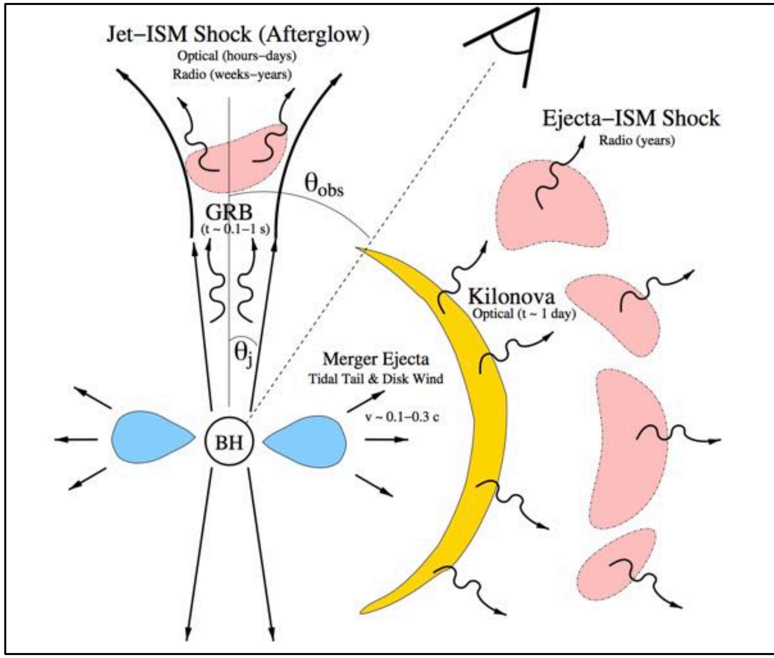
- Luminosity distance:

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

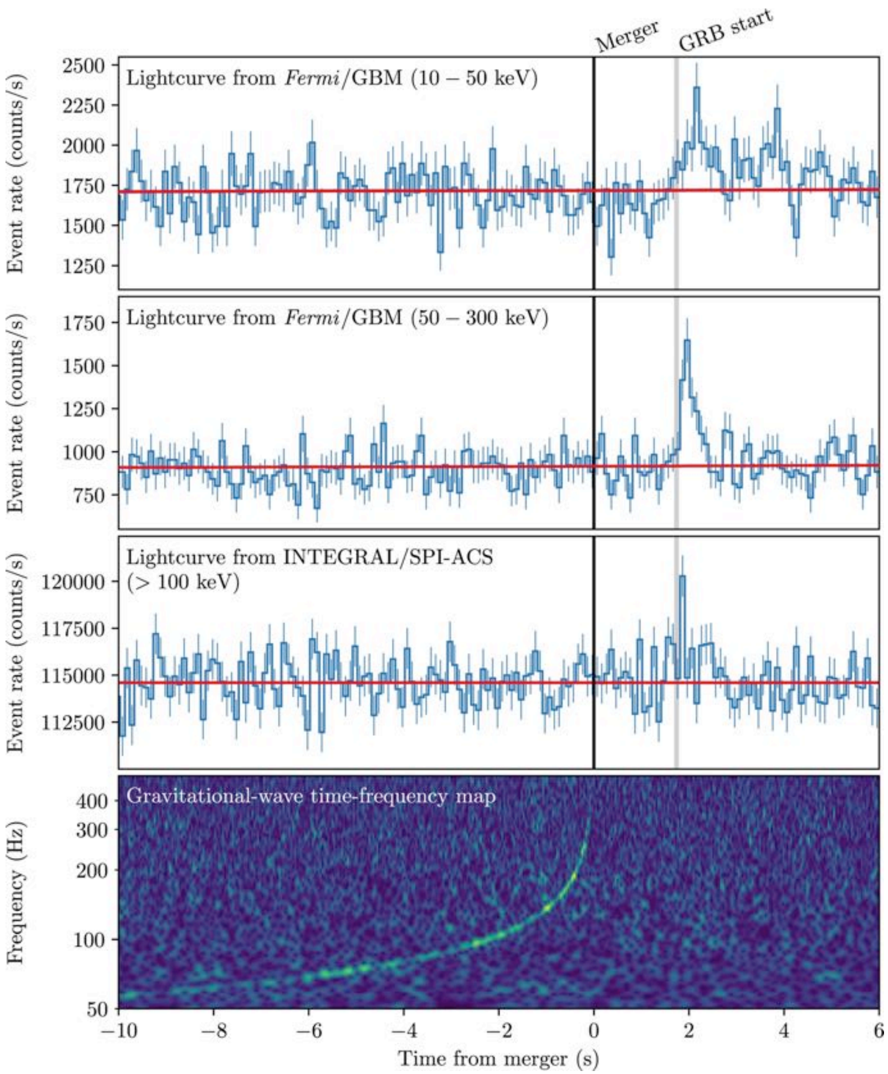
EXPECTED COUNTERPARTS

- 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)

Metzger & Berger, 2012



OBSERVATIONS



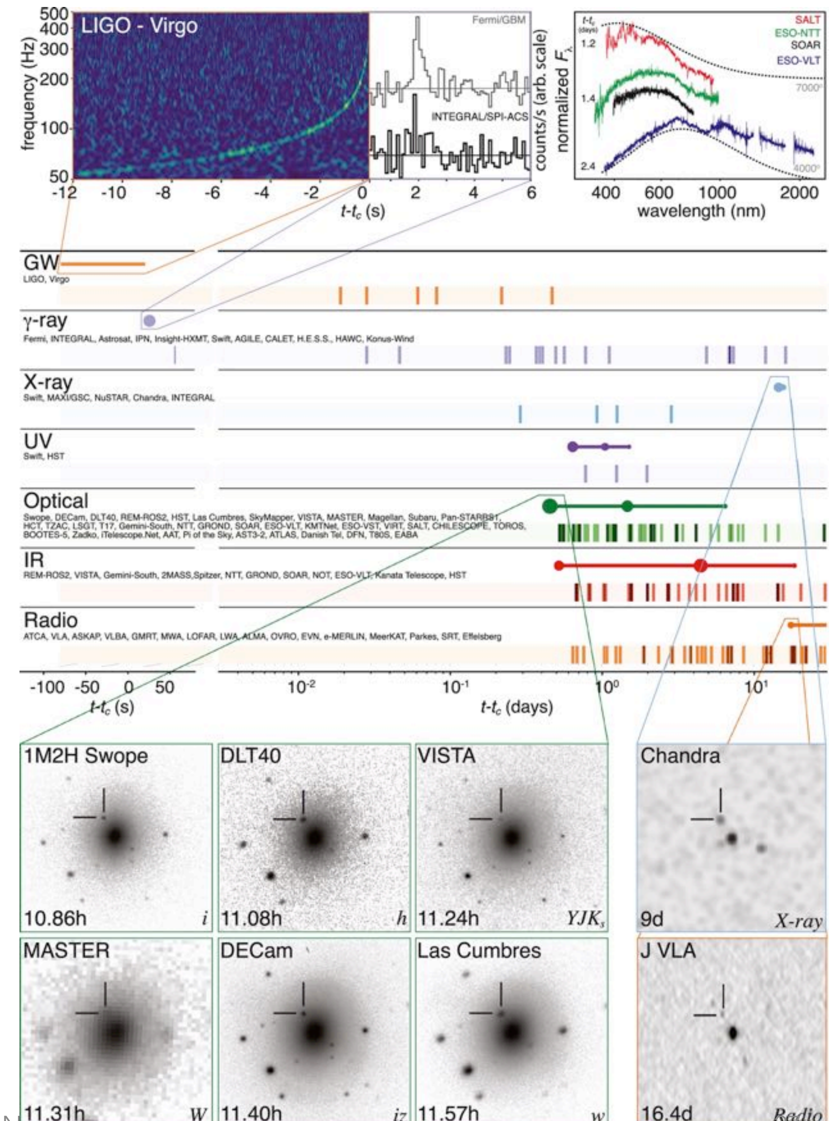
Abbott et al., ApJL., 848:L13 (2017)

A GRB event, 1.7 sec after…

First direct evidence that BNS mergers are progenitors of sGRB

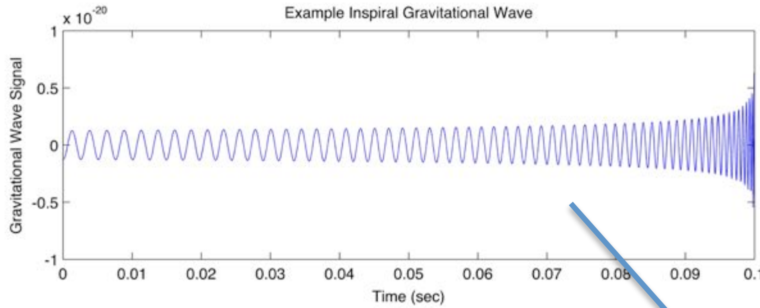
OBSERVATIONS

- 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?



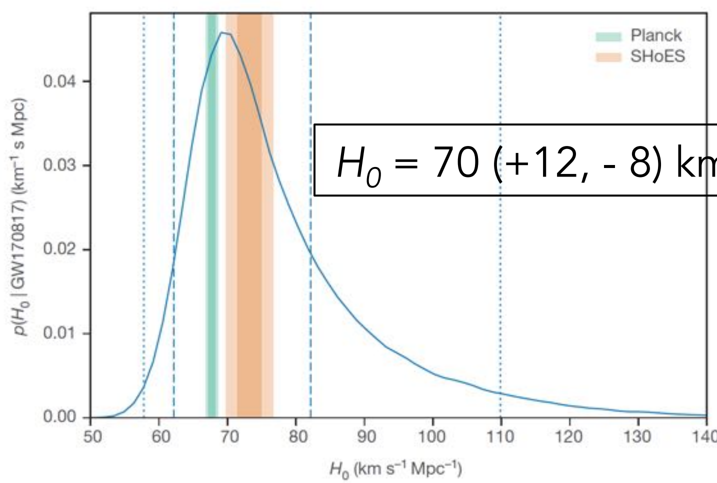
Abbott et al., ApJL., 848:L12 (2017)

MEASURING H_0

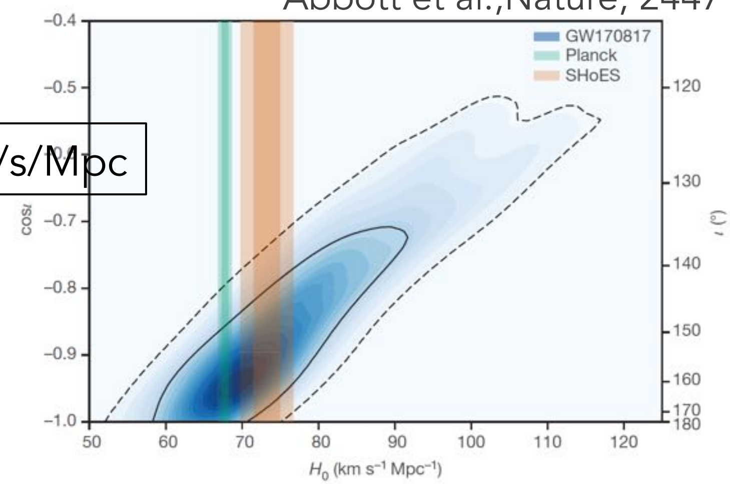


$$H_0 \, d_L = c \, z$$

Abbott et al.,Nature, 24471 (2017)



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



With a few tens of events a measurement with 1% accuracy will be possible (Del Pozzo, PRD, 2012)

THE SPEED OF GRAVITY

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

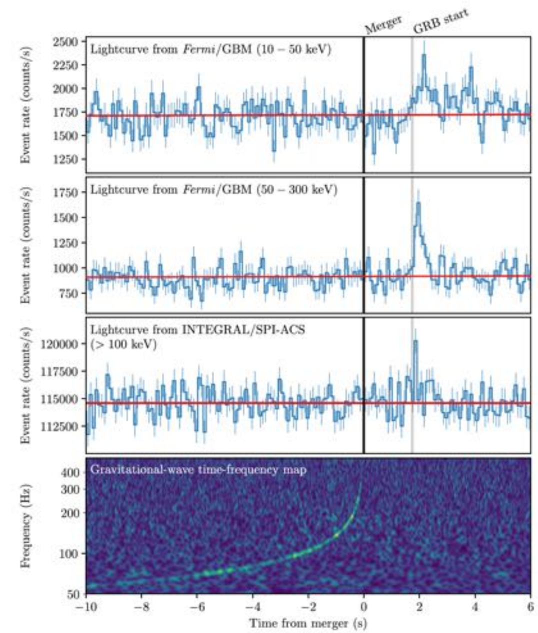
$$\frac{v_{GW} - c}{c} \approx \frac{c\Delta t}{D}$$

- $\Delta t = 1.7 \pm 0.5$ s over ~130 Myrs

$$-3 \cdot 10^{-15} \leq \frac{v_{GW} - c}{c} \leq 7 \cdot 10^{-16}$$

Assuming D=26 Mpc

Assuming sGRB emitted
10 s after GW

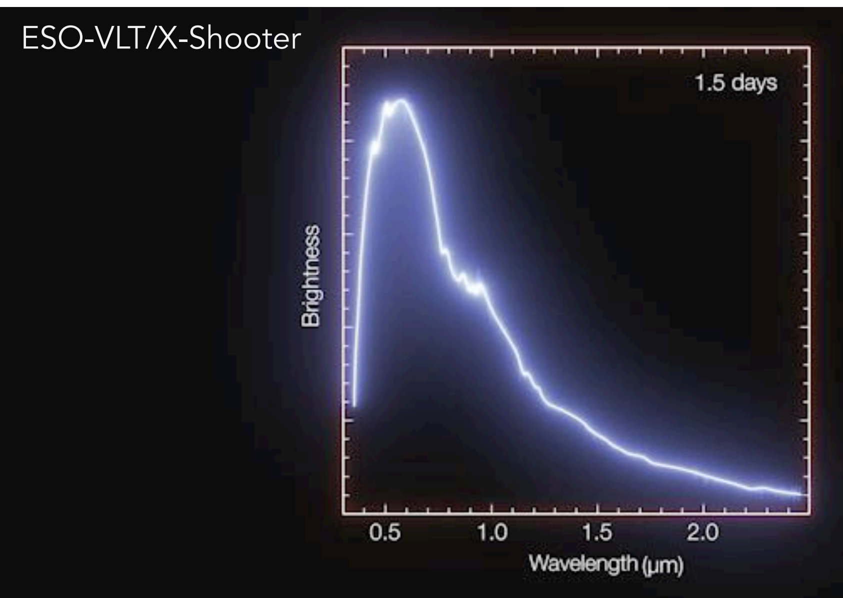


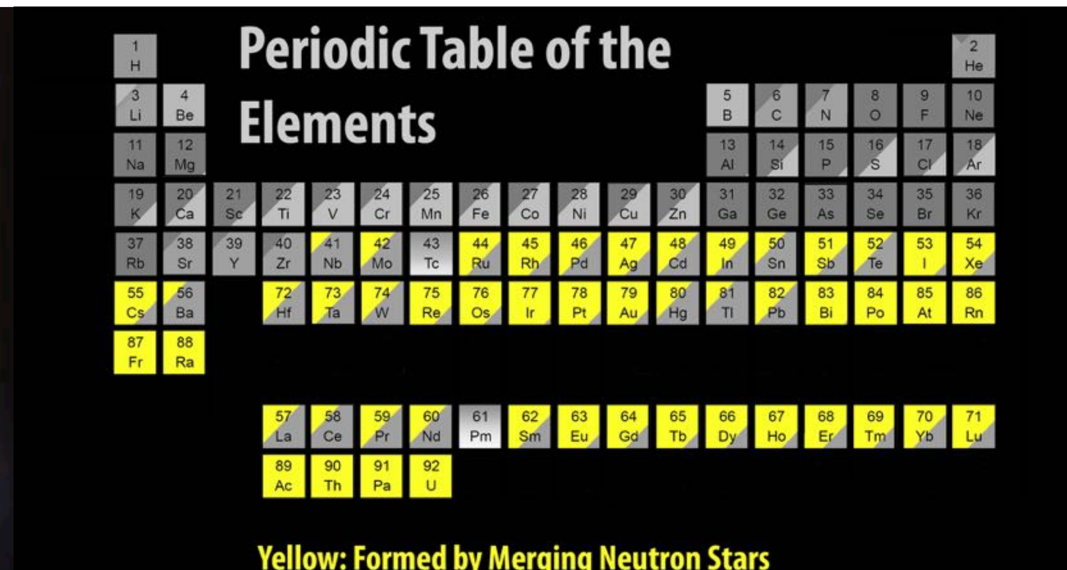
Abbott et al., ApJL., 848:L13 (2017)

KILONOVA

- Electromagnetic follow-up of GW170817 provides strong evidence for kilonova model
- Spectra taken over 2 week period across all electromagnetic bands consistent with kilonova models

e.g. Pian et al, Nature, 2017

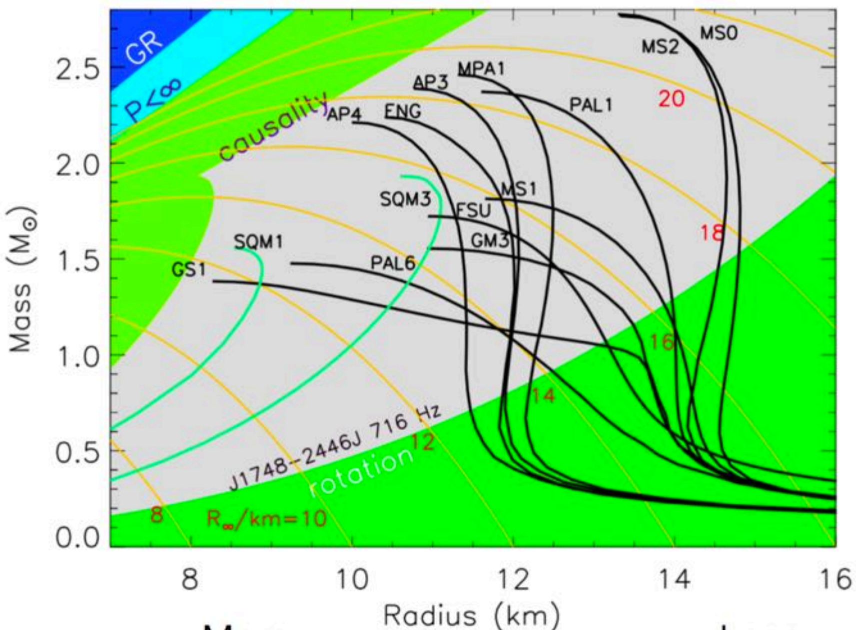




Credit: J Johnson (OSU)

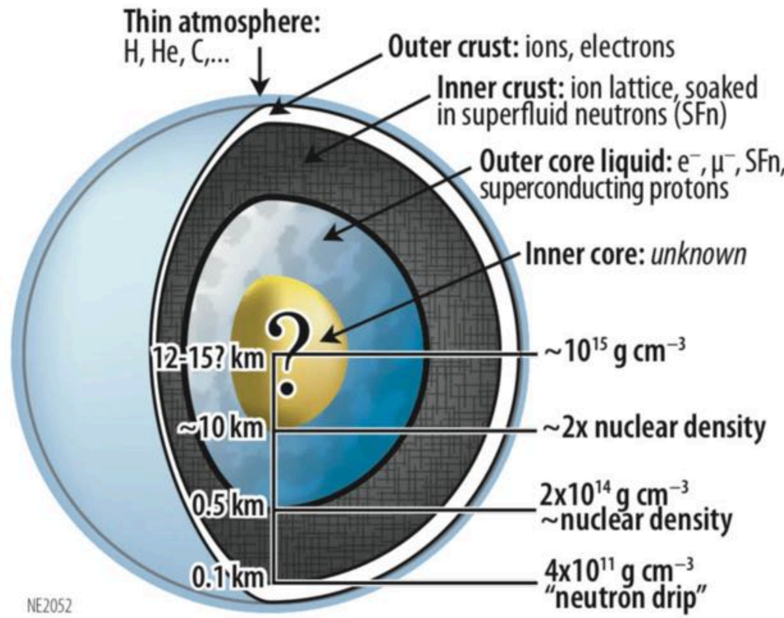
NEUTRON STARS

Image credit: NASA/NICER



More Compact → Less Compact

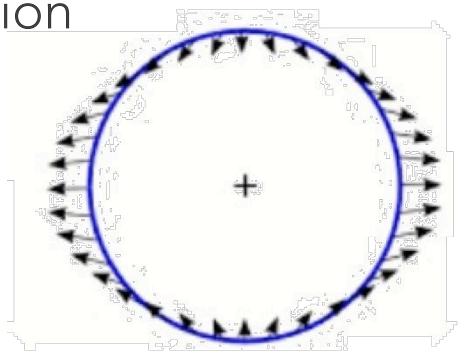
Lattimer, arXiv:1305.3510

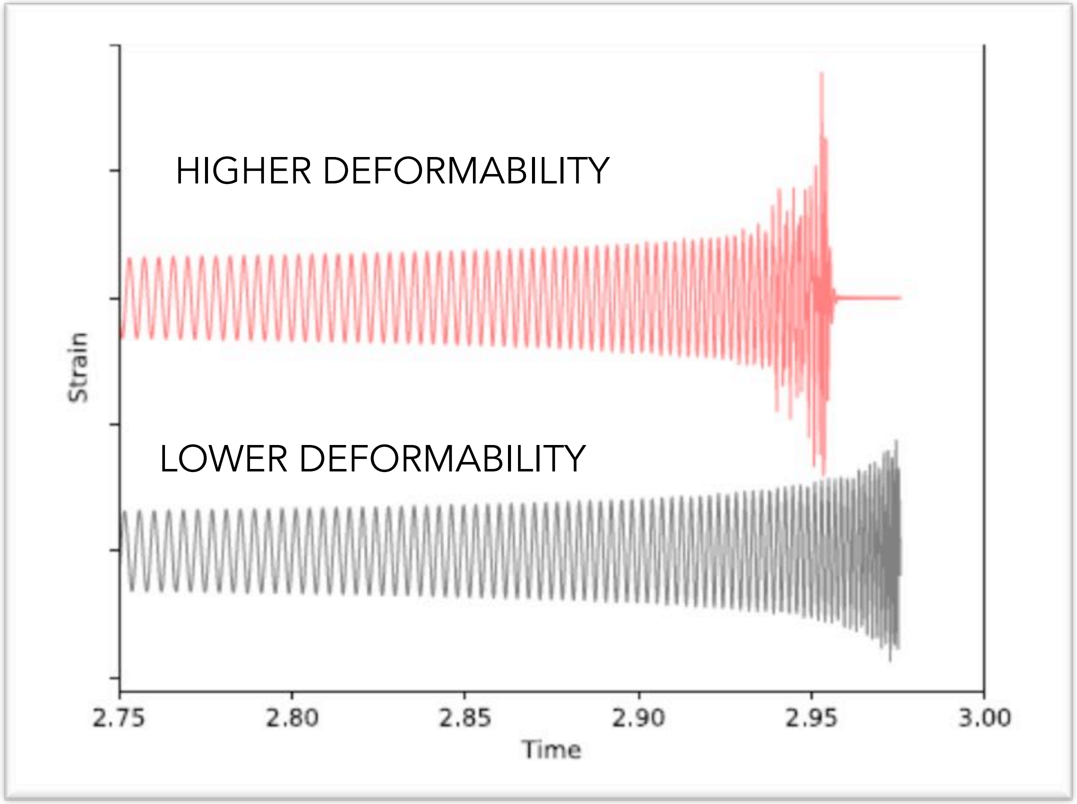


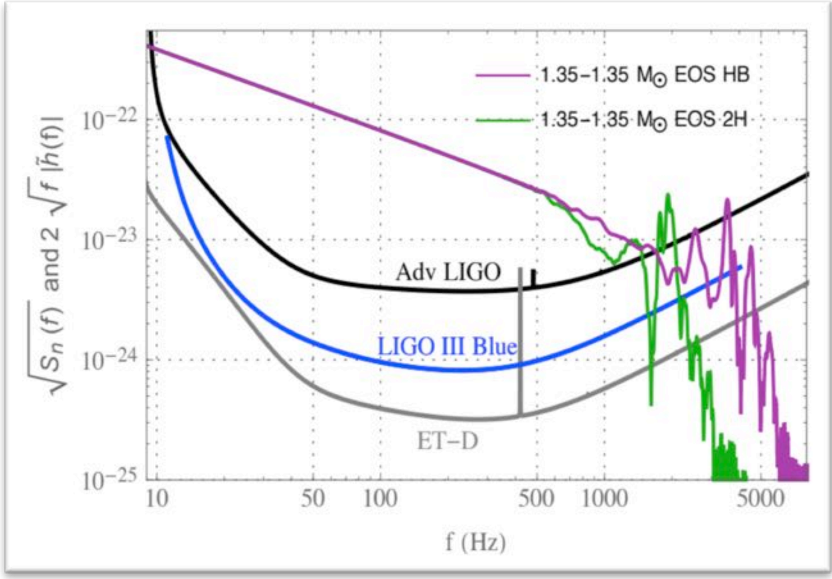
INTERNAL STRUCTURE AND COMPOSITION (LARGELY UNKNOWN) ENCODED IN THE EQUATION OF STATE

BINARY NEUTRON STARS

- Each NS is deformed by the tidal field of the companion
- Deformations leave an imprint on the GW emission



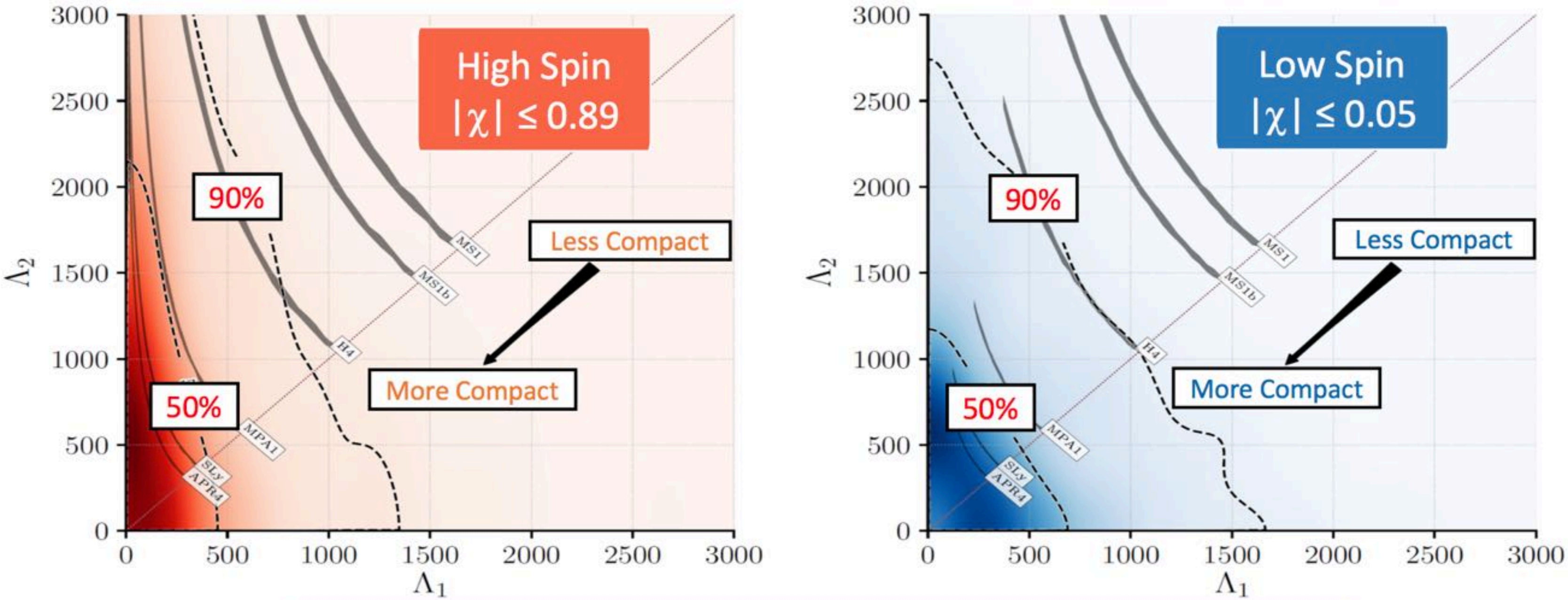




BINARY NEUTRON STARS

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

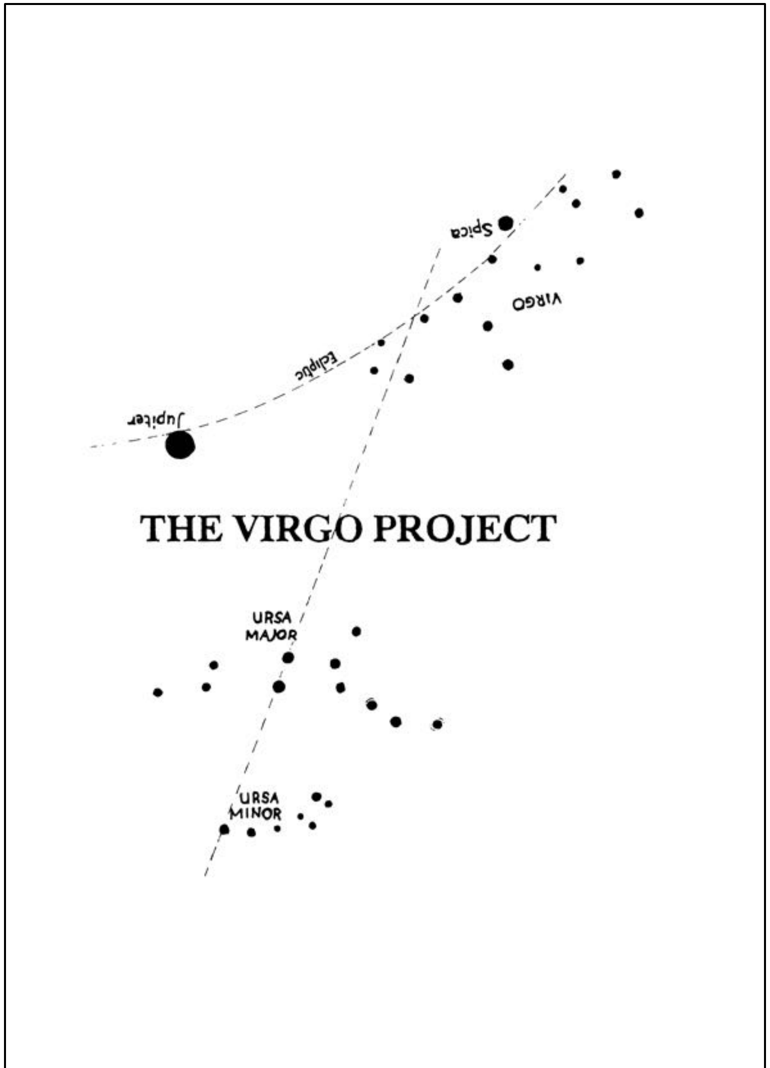
Probability density for the tidal deformability parameters



GW170817 data consistent with more compact NS

Waiting for HF sensitivity improvements…

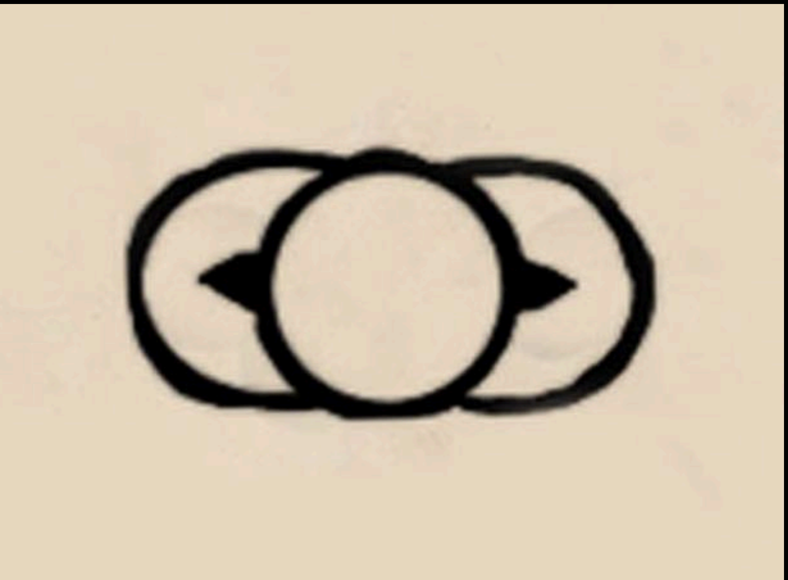
1989



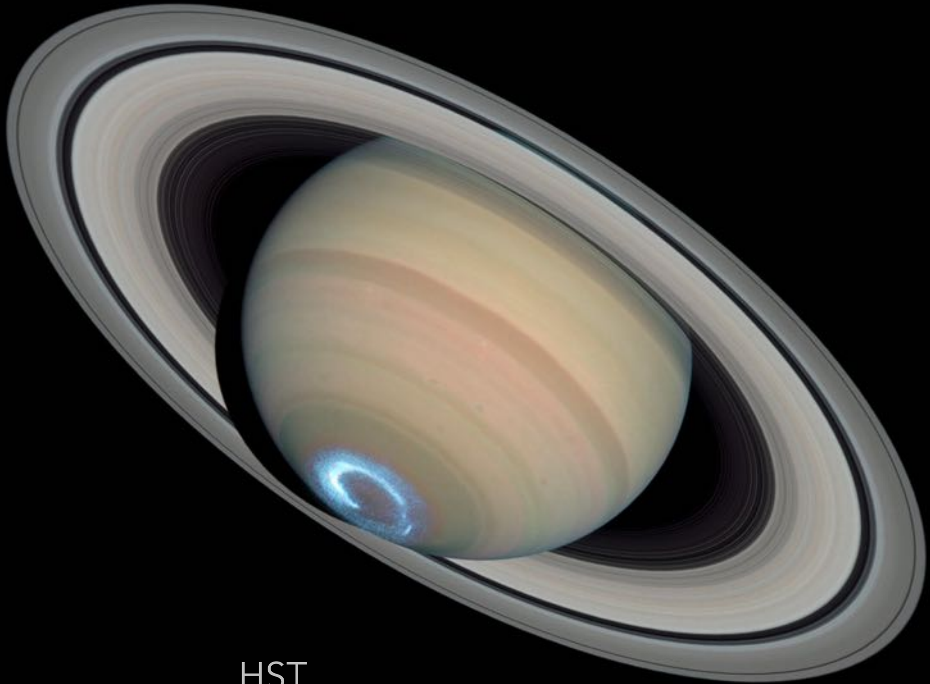
VIRGO must be considered both as an experiment and as a step towards a future observatory. The immediate goal of the VIRGO experiment is to realize, or to participate in, the first detection of gravitational radiation, but it also has the long term goal of being one component of the gravitational wave 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.

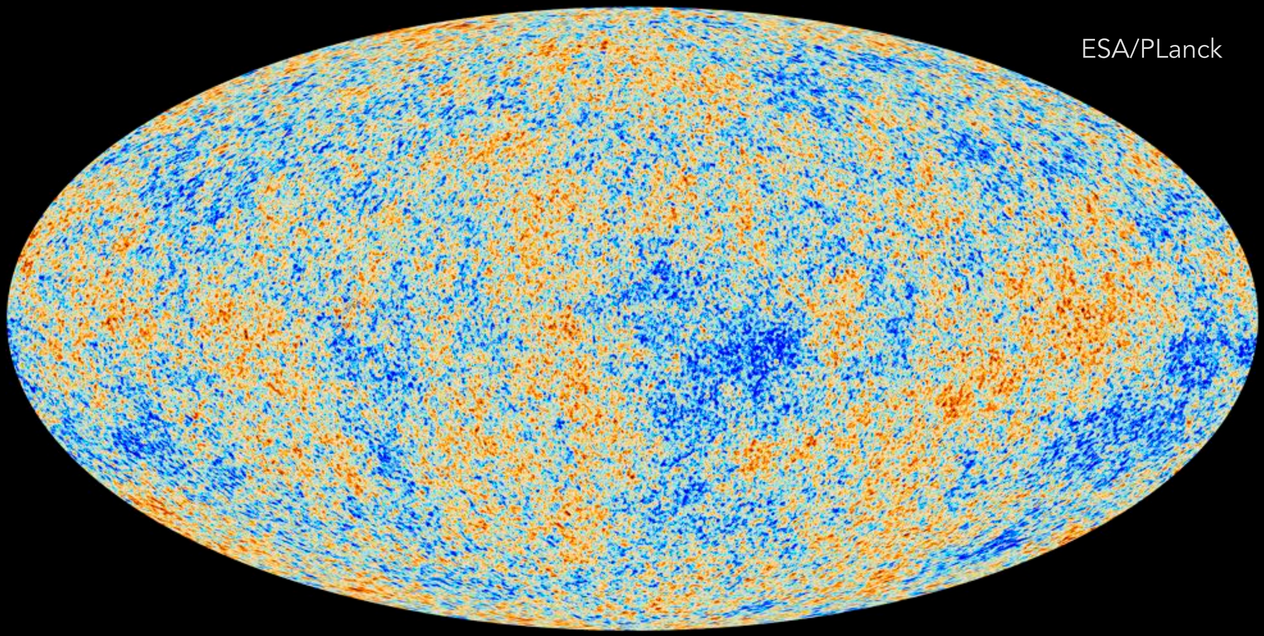
A BRILLET & A GIAZOTTO



Galileo's



HST



ESA/PLanck

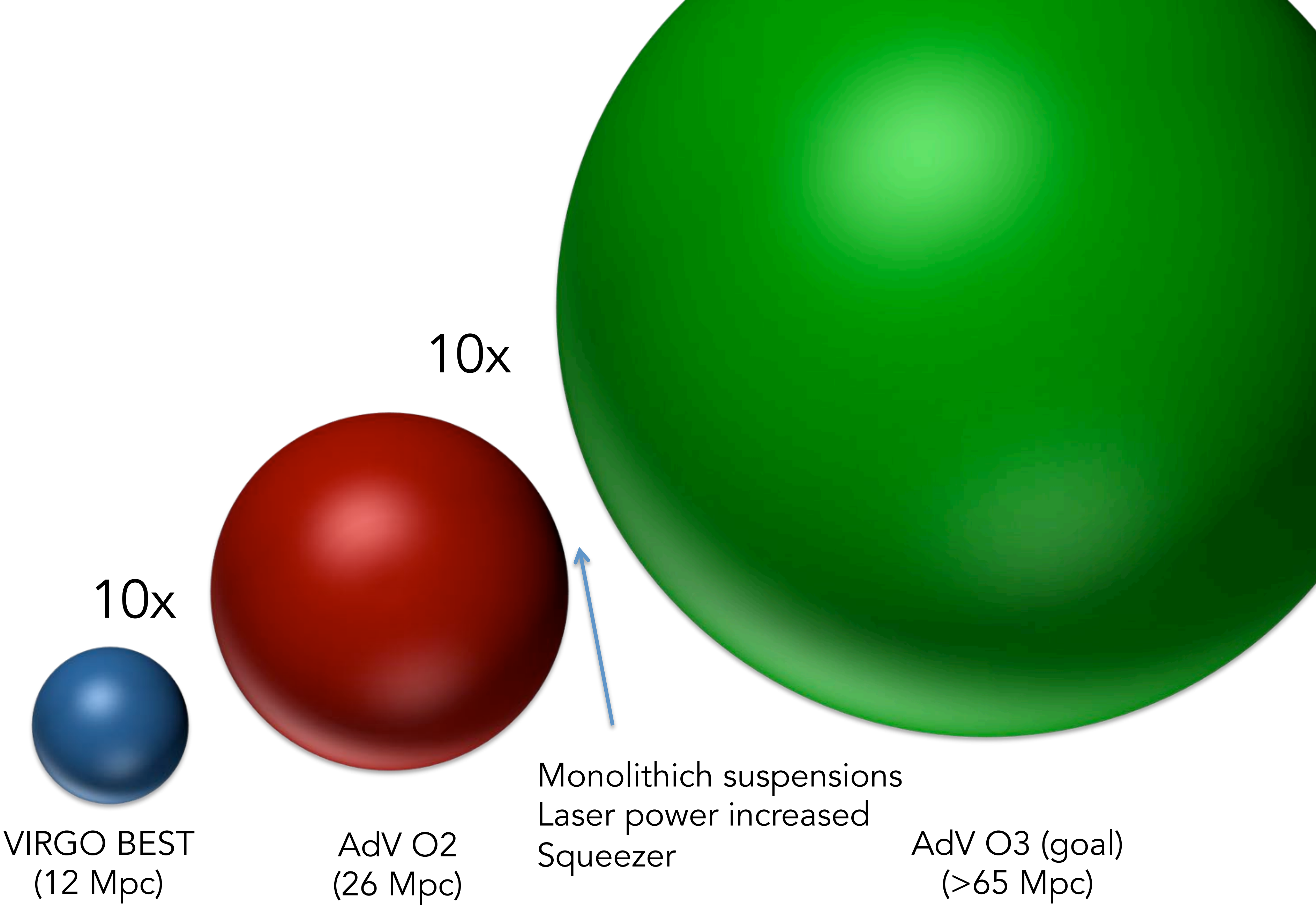
PERSPECTIVES

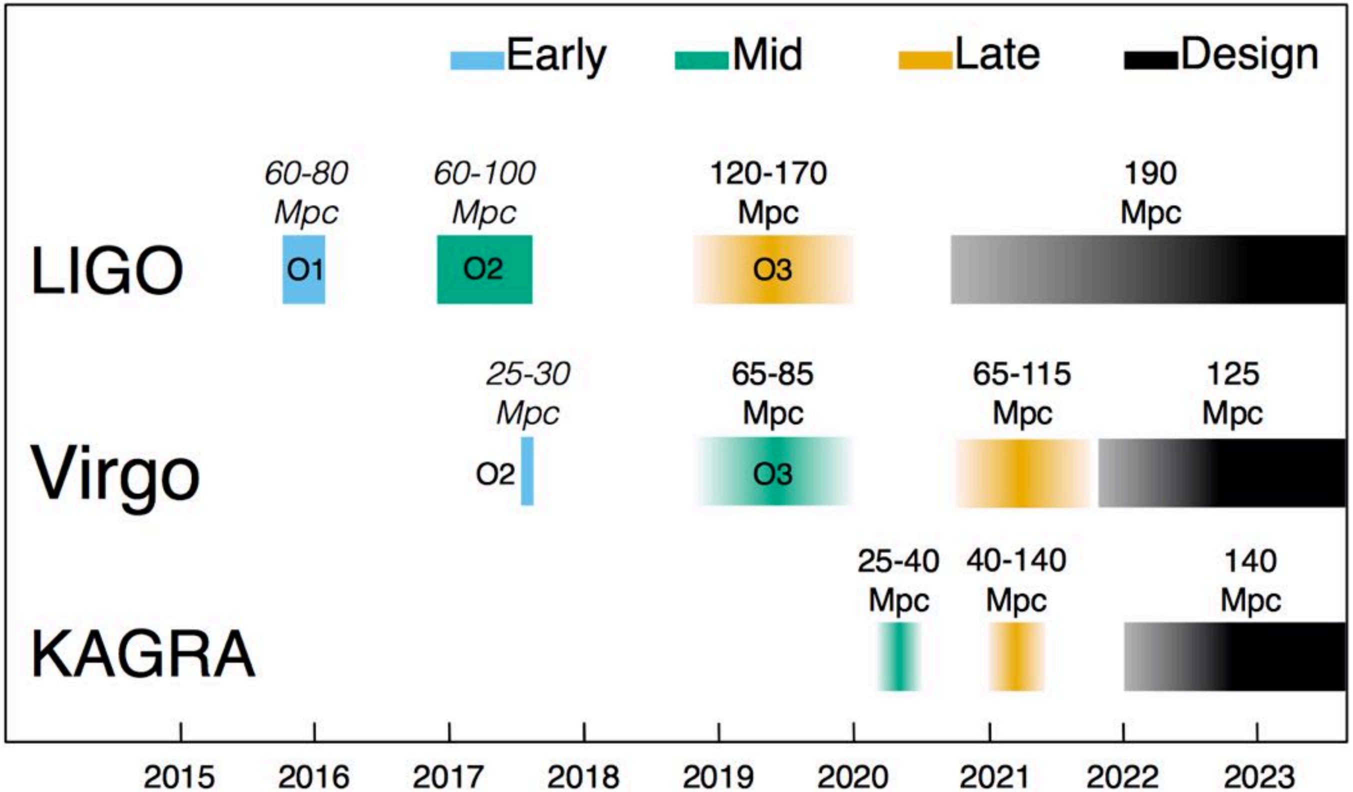
THE CASE FOR BETTER DETECTORS

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

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.

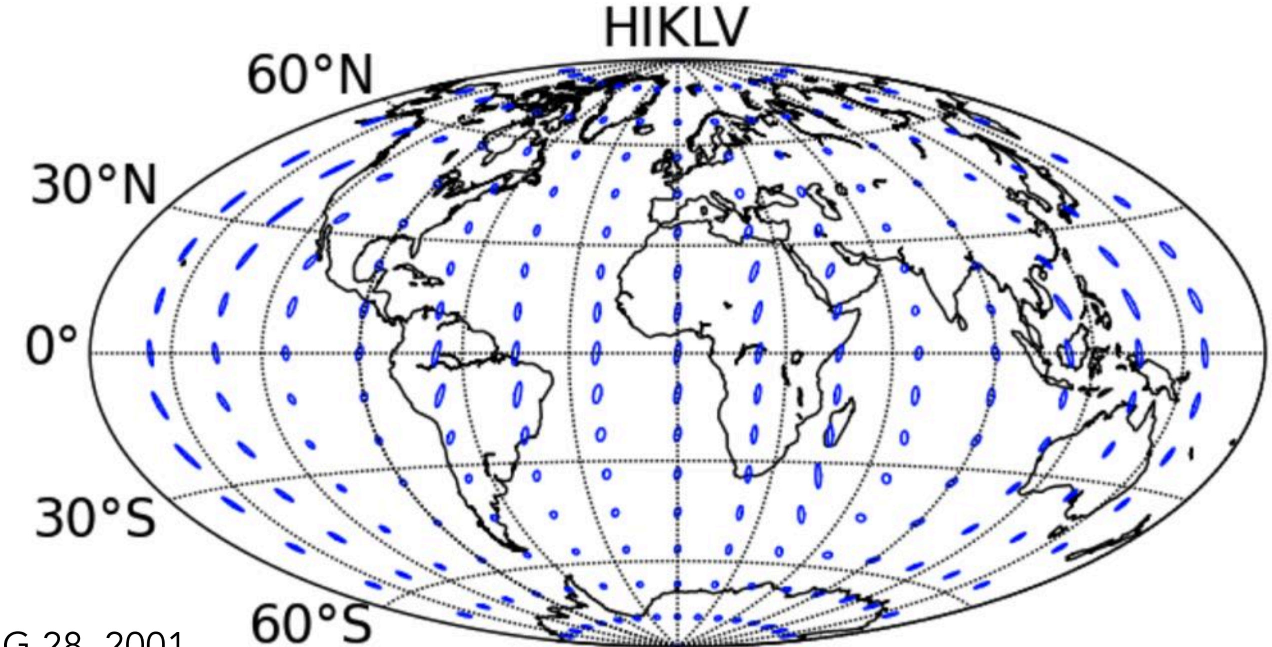

10x
10x
VIRGO BEST
(12 Mpc)
AdV O2
(26 Mpc)
Monolithich suspensions
Laser power increased
Squeezer
AdV O3 (goal)
(>65 Mpc)



…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" – ArXiv 1304.0670 (2017)

THE MID-TERM GOAL



S Fairhurst, CQG 28, 2001

KAGRA (2019) and LIGO-India (2024) will expand the network.
LIGO and Virgo expected to be upgraded to 2.5G (2023)

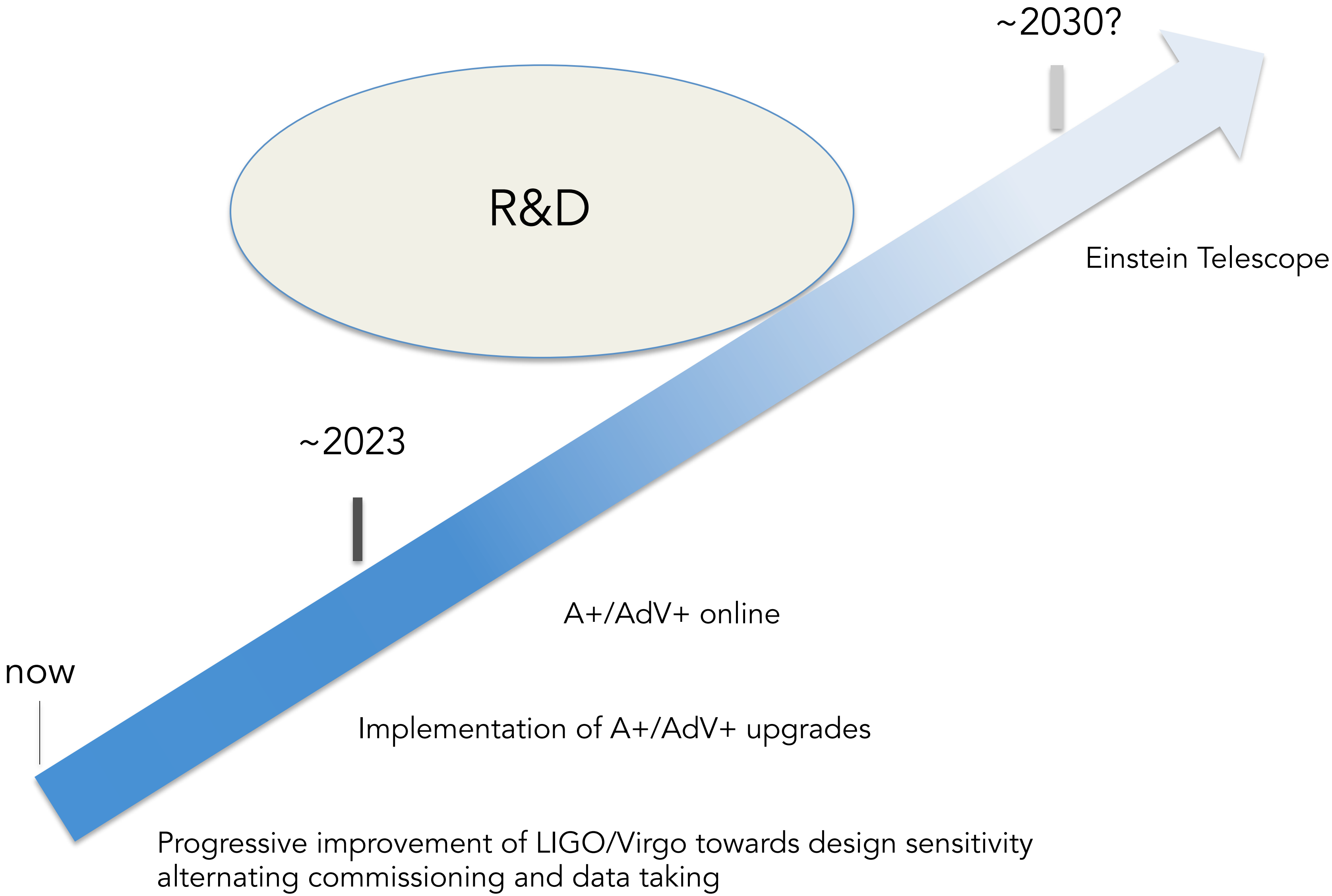
Localization capabilities of the 2G network at mid 2020s:
>60% of the sources localized within 10 deg^2

WHAT NEXT?

- **2.5 G:** a set of upgrades capable of enhancing the sensitivities of the current 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

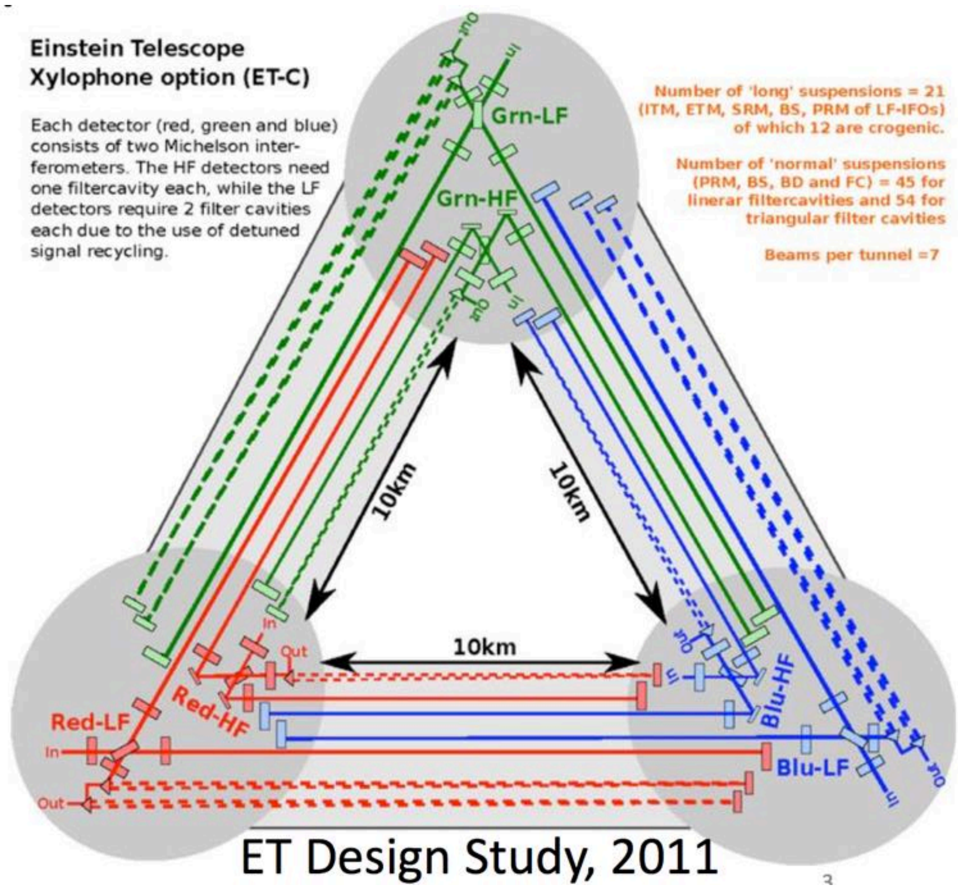
WHAT NEXT?

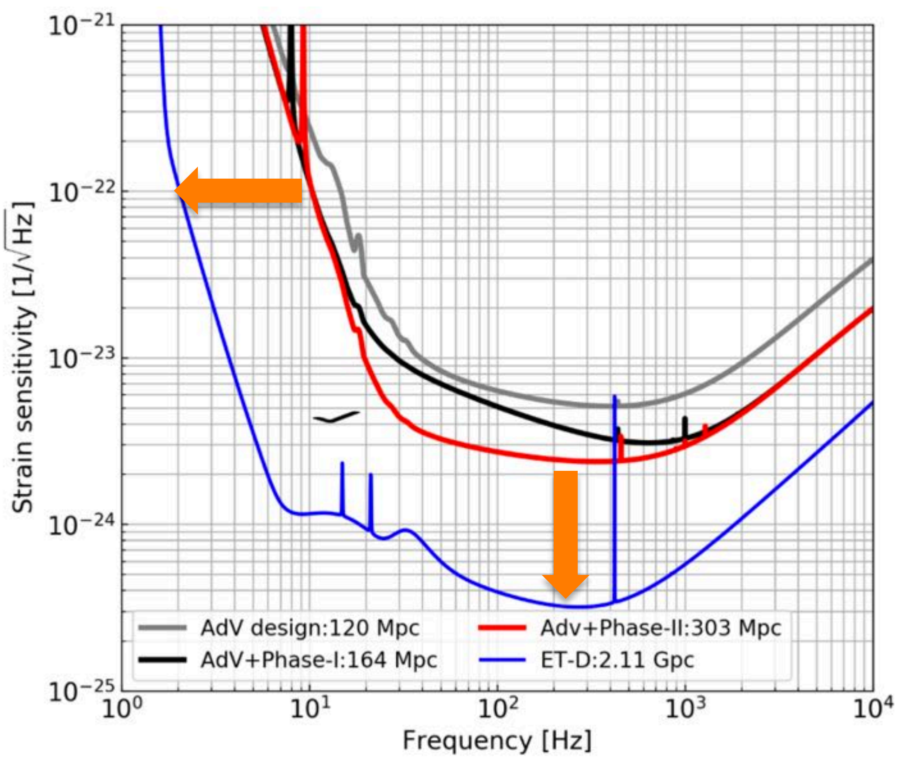

~2030?
R&D
Einstein Telescope
~2023
A+/AdV+ online
now
Implementation of A+/AdV+ upgrades
Progressive improvement of LIGO/Virgo towards design sensitivity
alternating commissioning and data taking

AdV+

- Set of upgrades for AdV, aimed to approach the "infrastructure limit", split in two phases
- Phase 1: BNS range up to 160 Mpc
  - frequency dependent squeezing
  - newtonian noise cancellation
- Phase 2: BNS range up to 260 (300) Mpc
  - new, larger mirrors
  - factor 3 of coating thermal noise reduction

EINSTEIN TELESCOPE





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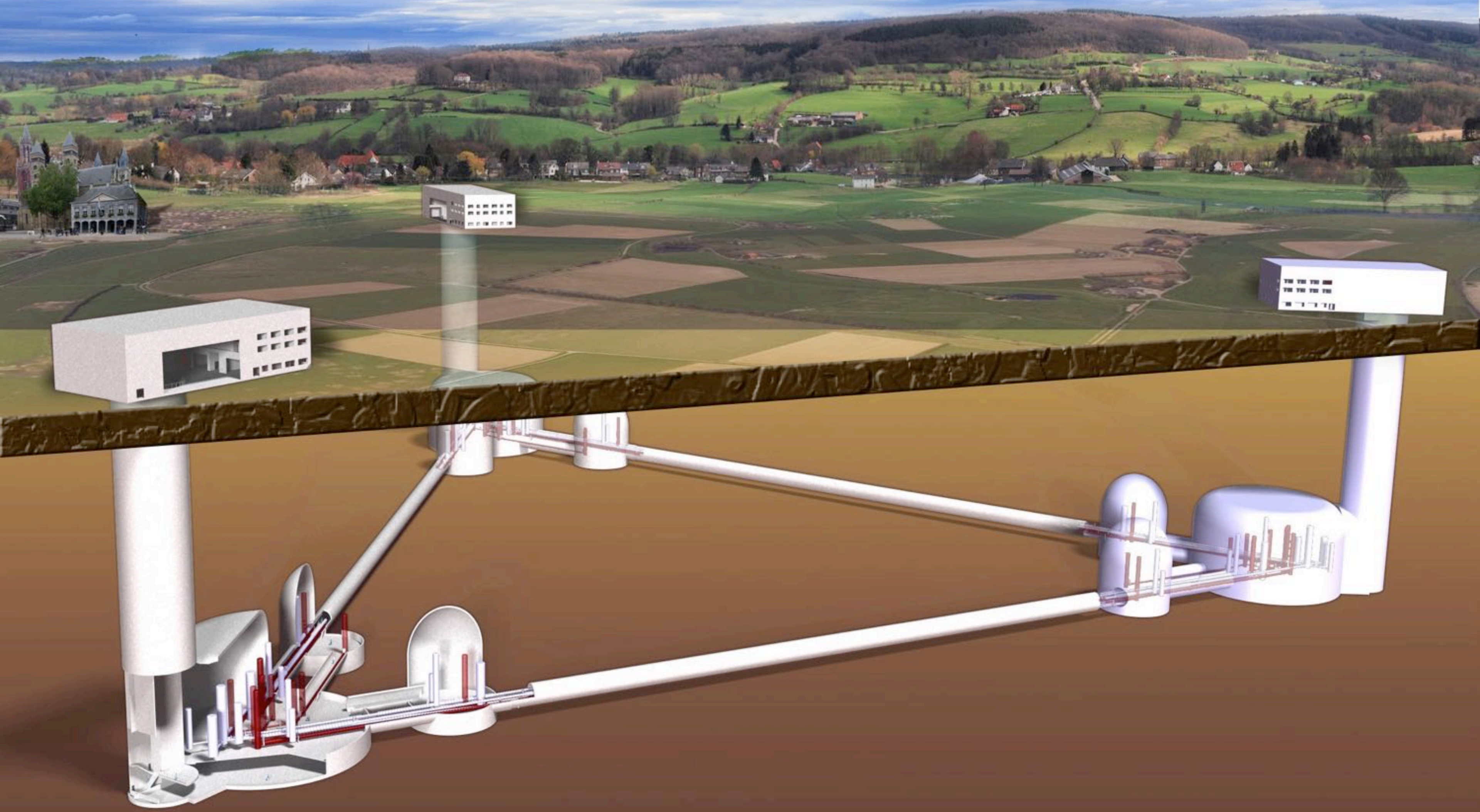
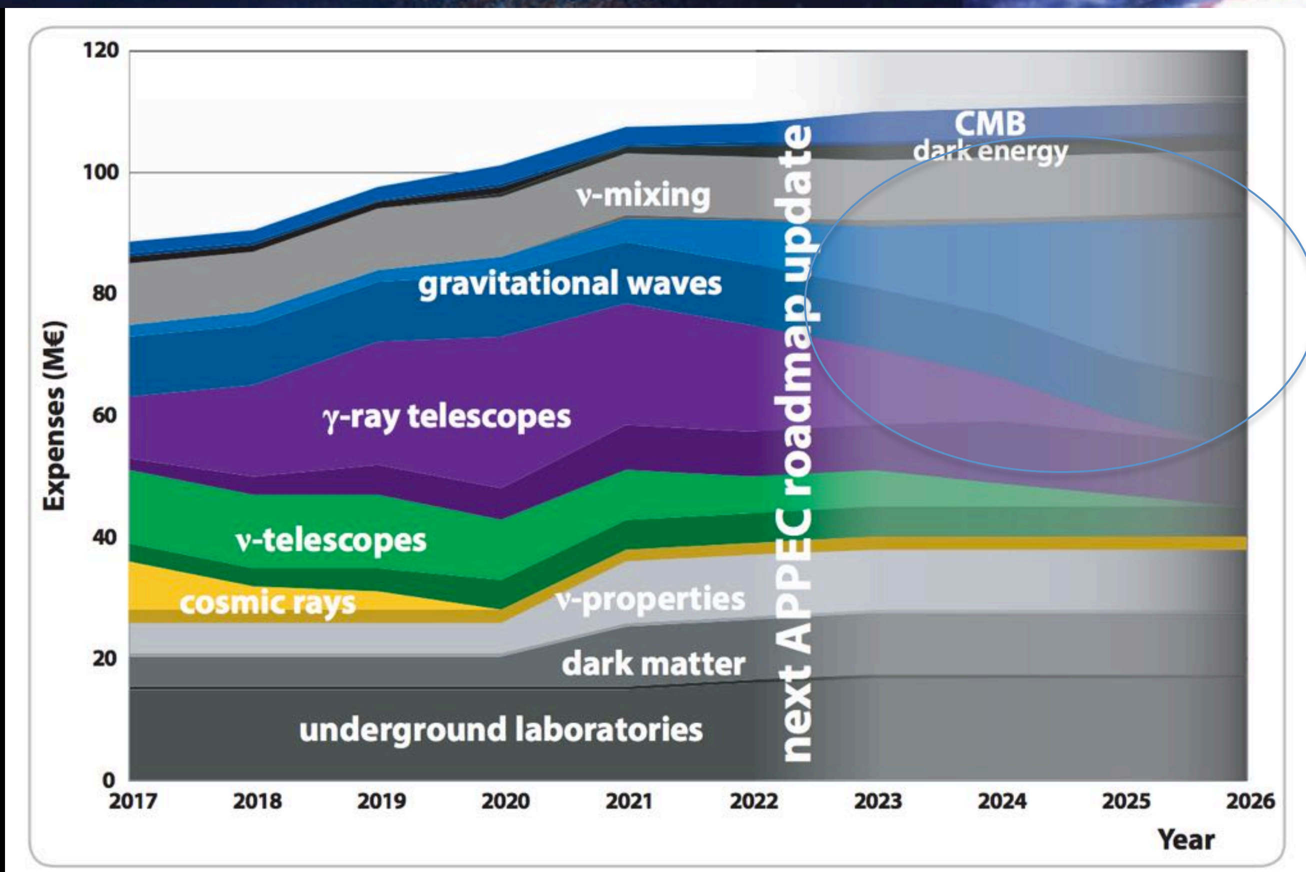
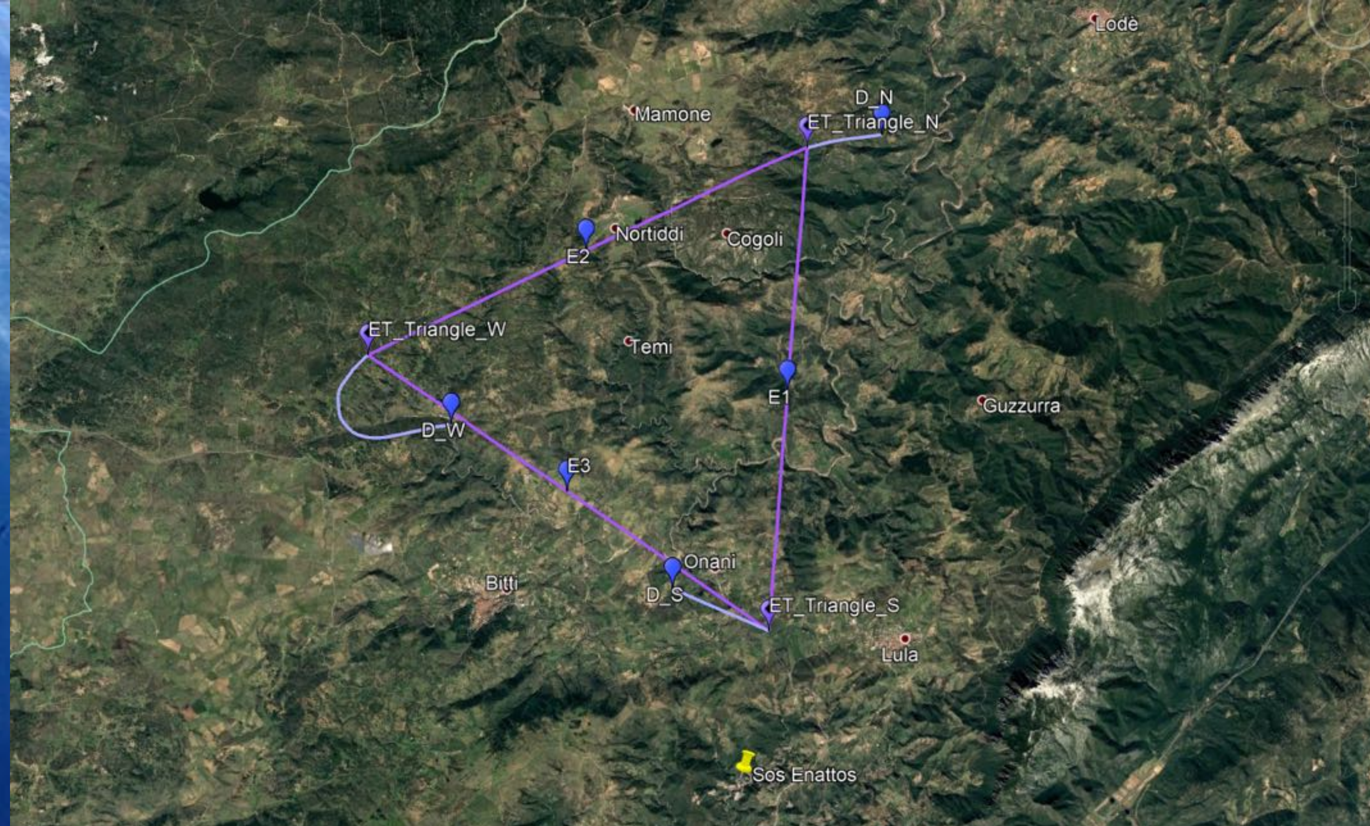


APPEC European Astroparticle Physics Strategy 2017-2026



ET: the big investment for the next decade



More at the ET Symposium, EGO, April 19-20

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
- GW network will be enhanced with the addition of new detectors and improvement of the existing ones
- 3G detectors being planned, targeting the early universe

RIVELARE LE ONDE GRAVITAZIONALI;
NESSUNA IDEA ERA PIU' FOLLE DI QUESTA.

A GIAZOTTO