Gravitational-wave Observatories and First Detections: LIGO and Virgo

IAU

22 August 2018

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For the LIGO and Virgo Scientific Collaborations

Credits

Measurement results: LIGO/Virgo Collaborations,
PRL 116, 061102 (2016); Phys. Rev. Lett. 119, 161101 (2017);
Phys. Rev. Lett. 119, 141101 (2017); hys. Rev. Lett. 118, 221101 (2017);
Phys. Rev. Lett. 116, 241103 (2016)

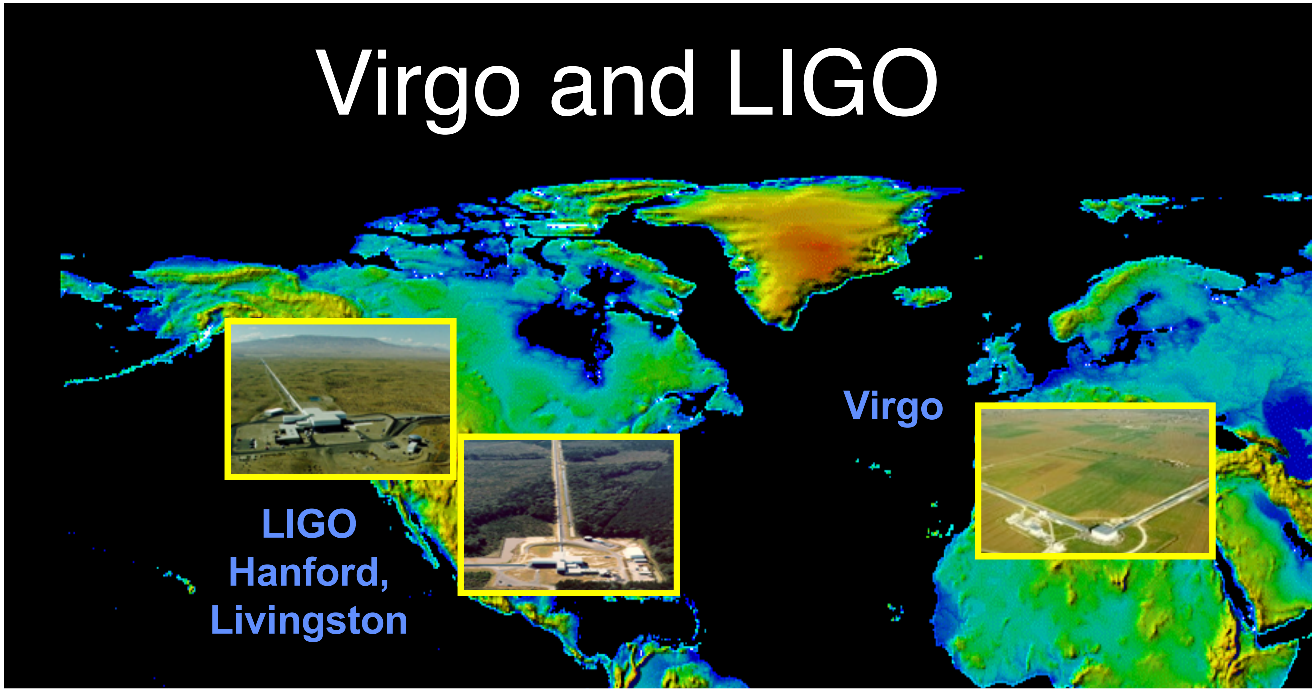
Simulations: SXS Collaboration; LIGO Laboratory

Localization: S. Fairhurst arXiv:1205.6611v1

Slides from (among others) L. Nuttal, P. Fritschel, L. Cadonati

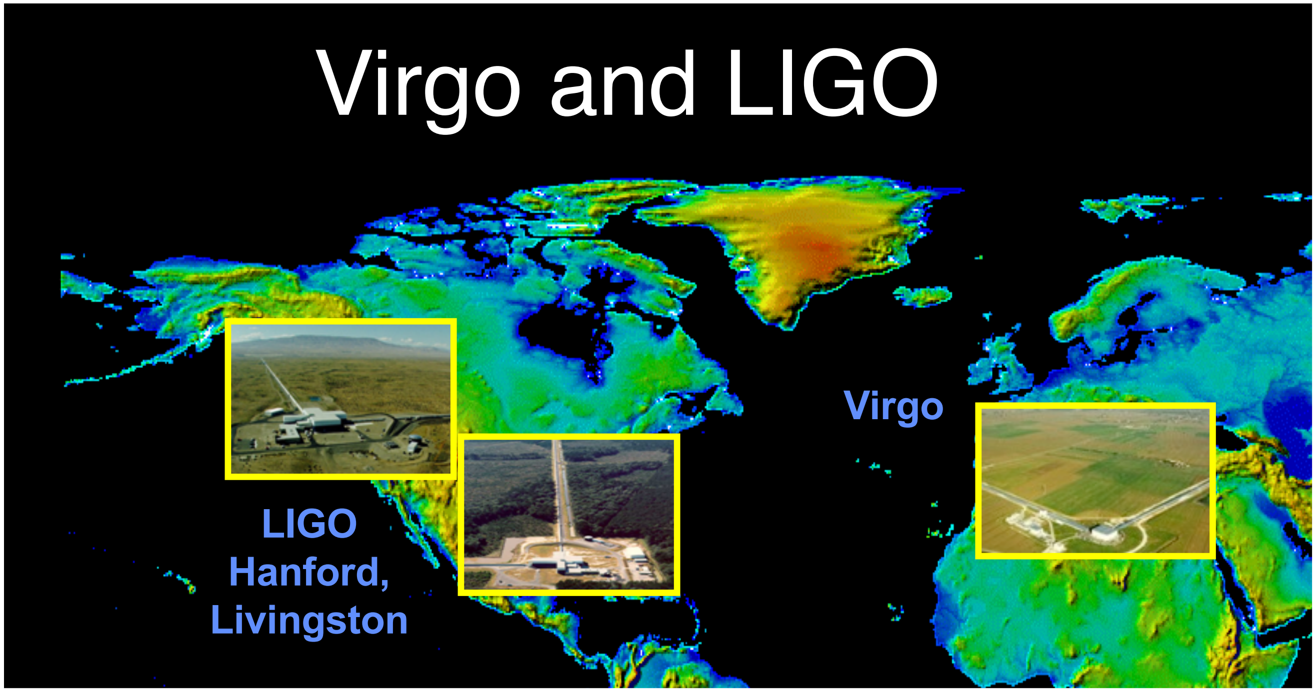
Photographs: LIGO Laboratory; MIT; Caltech; Virgo

LIGO-G1801613-v1



Virgo and LIGO built a brand new kind of observatory to detect gravitational waves in the 1990's

LIGO thanks the NSF for its vision and support!



Virgo and LIGO built new observatories in the 90's

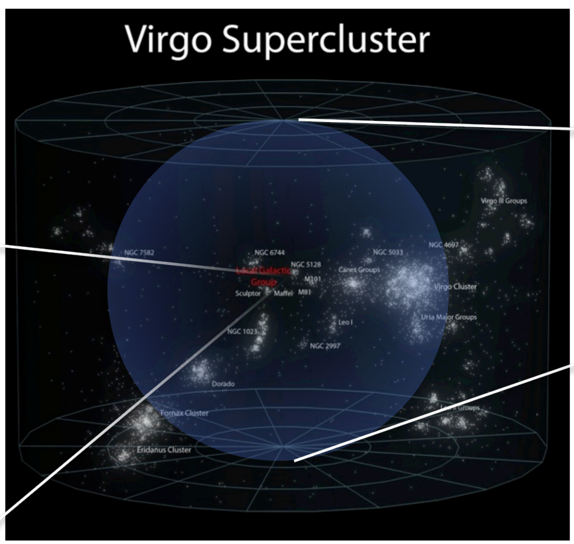
…and Observed with the initial detectors 2005-2011,
and saw **no signals**

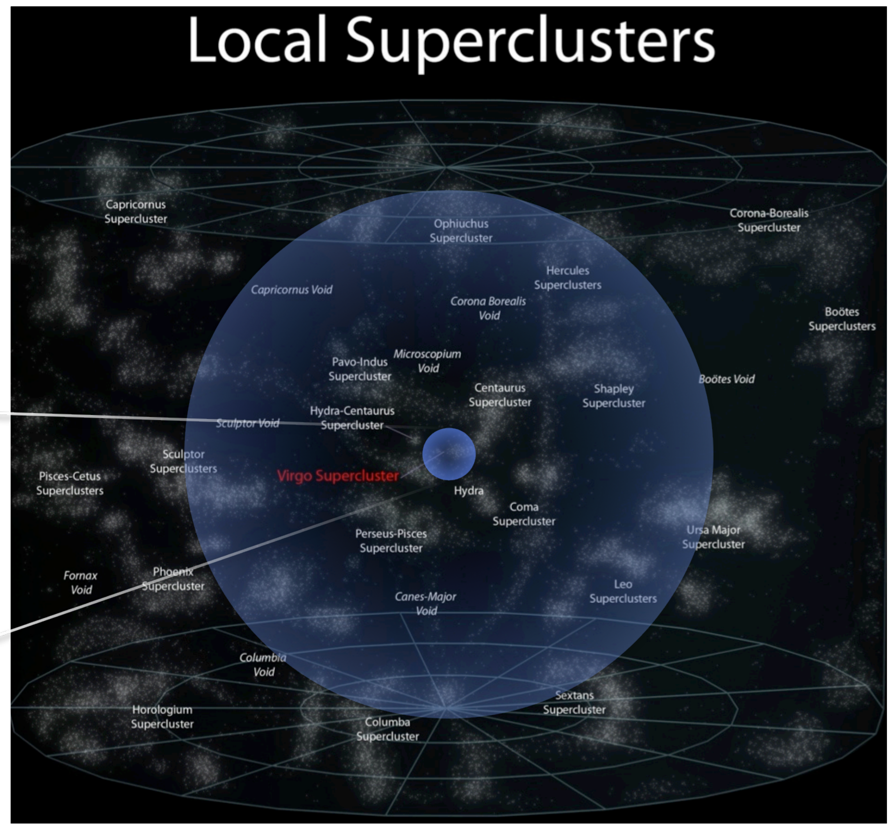
(with some interesting non-detections)

Advanced Detectors: a *qualitative* difference

- Foreseen in original 1989 proposal
- While observing with initial detectors, parallel R&D led to better concepts
- Design for **10x better sensitivity**

- We measure **amplitude**, so signal falls as **1/*r***
- **1000x more candidates**





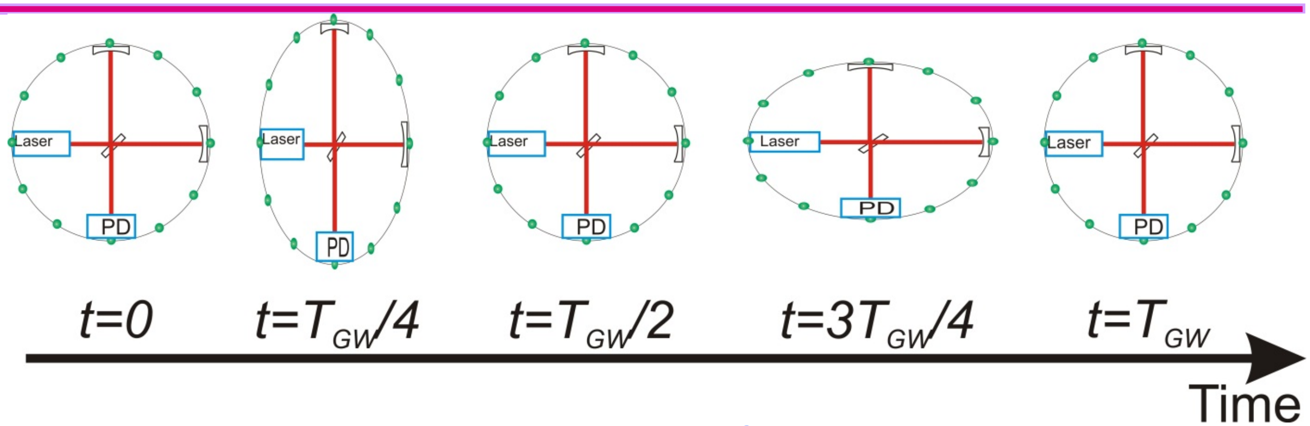
M. Evans

Initial Reach

Advanced Reach

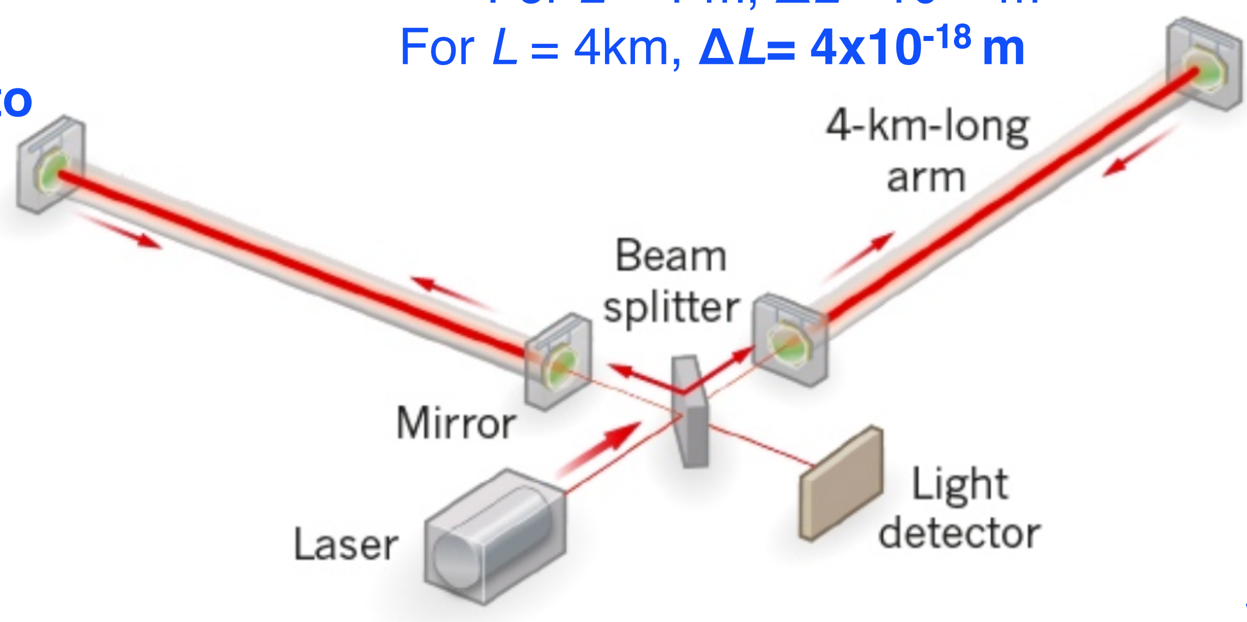
What is our measurement technique?

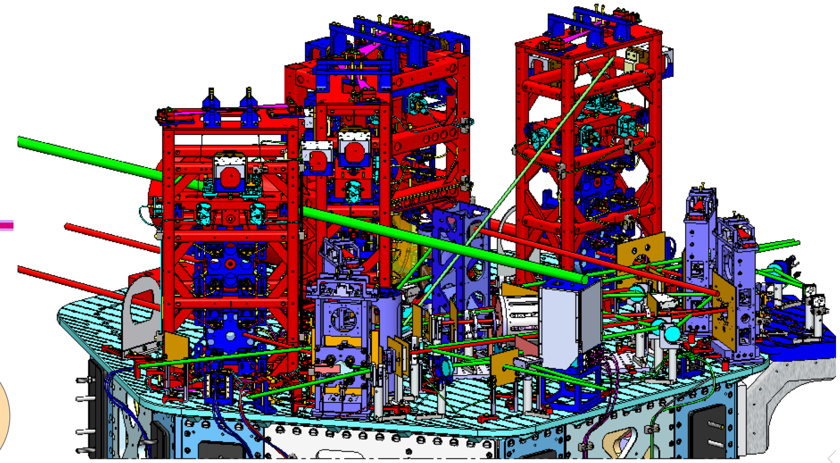
- Enhanced **Michelson interferometers**
- LIGO, Virgo use variations
- GWs modulate the distance between the end test mass and the beam splitter
- The interferometer acts as a transducer, turning GWs into photocurrent proportional to the strain amplitude
- **Arms are short compared to our GW wavelengths, so longer arms make bigger signals → multi-km installations**
- Arm length limited by taxpayer noise….

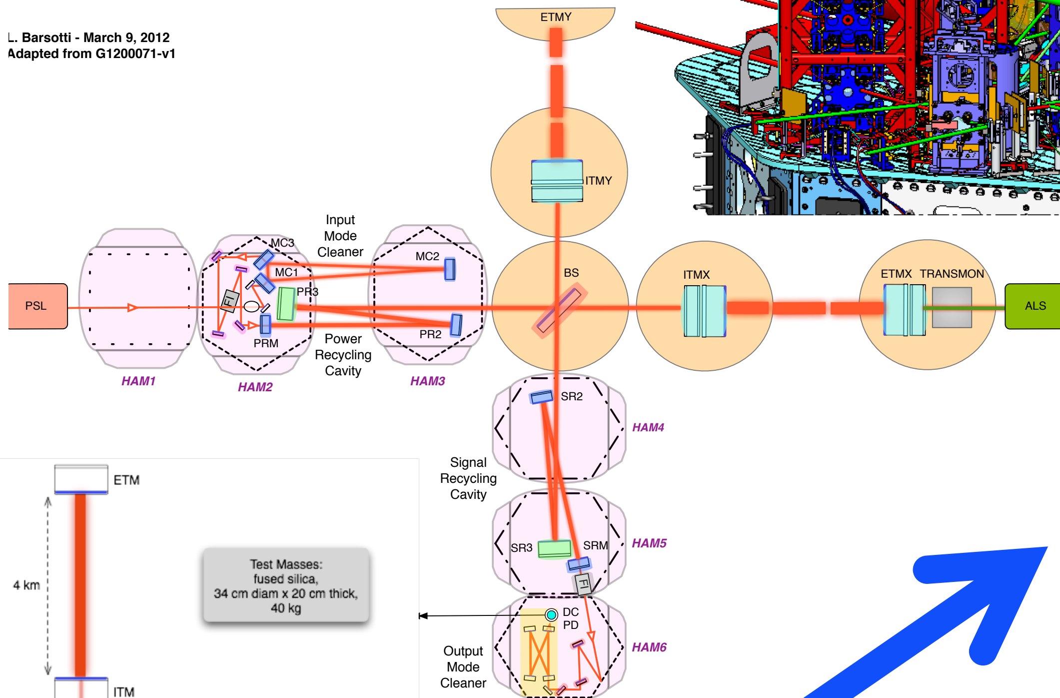


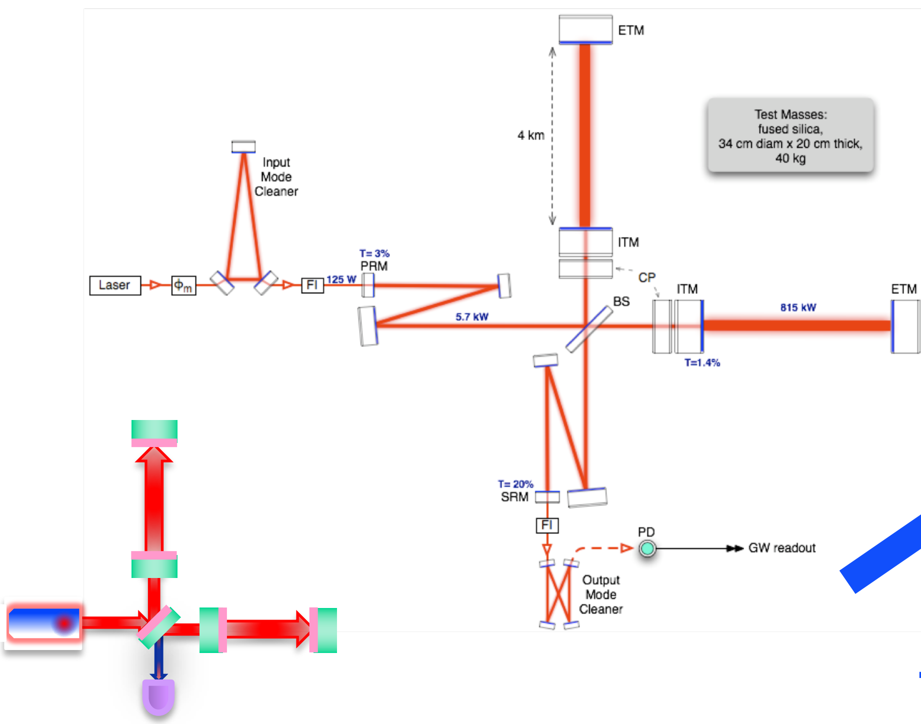
$$h \approx \frac{\Delta L}{L}$$

Magnitude of h at Earth:
Detectable signals h ~ 10^{-21}
(1 hair / Alpha Centauri)
For L = 1 m, ΔL= 10^{-21} m
For L = 4km, **ΔL= 4×10^{-18} m**









photodiode

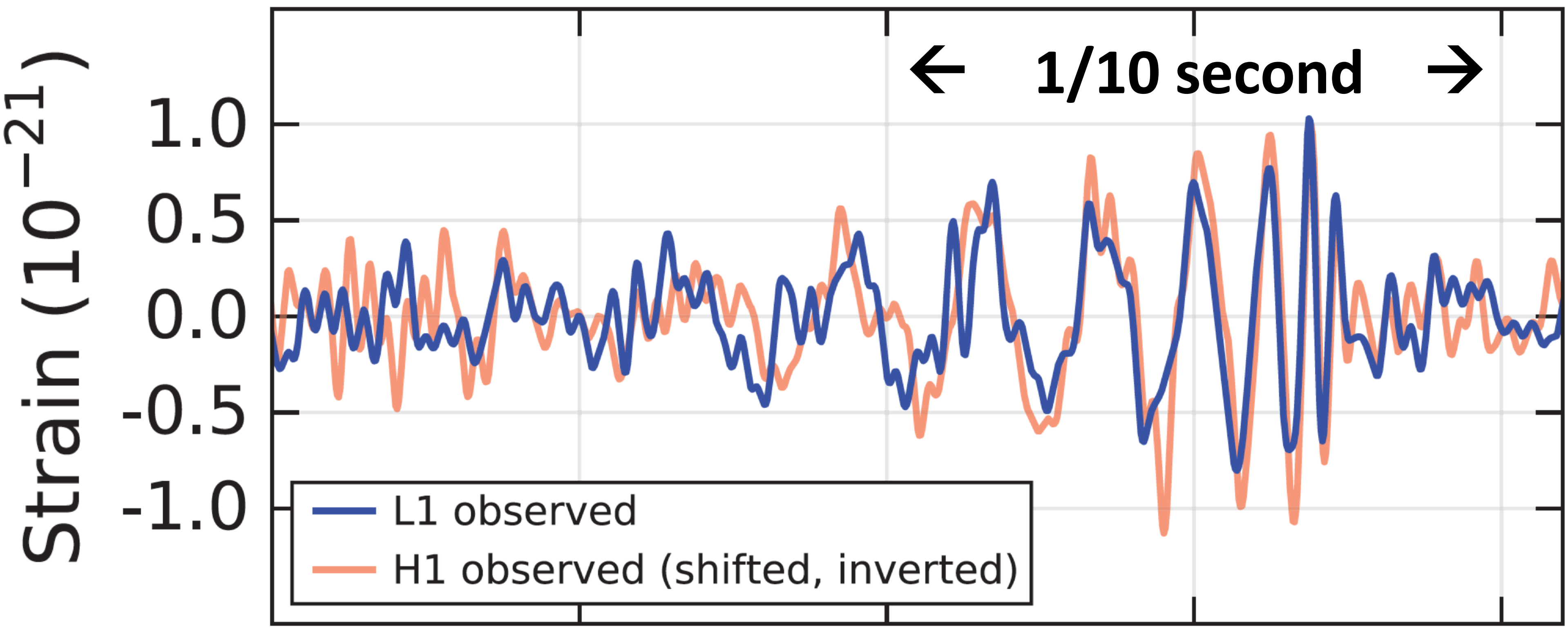
Reality axis

The real instrument is far more complex than a simple Michelson…


Virgo detector, EGO, Cascina Italy

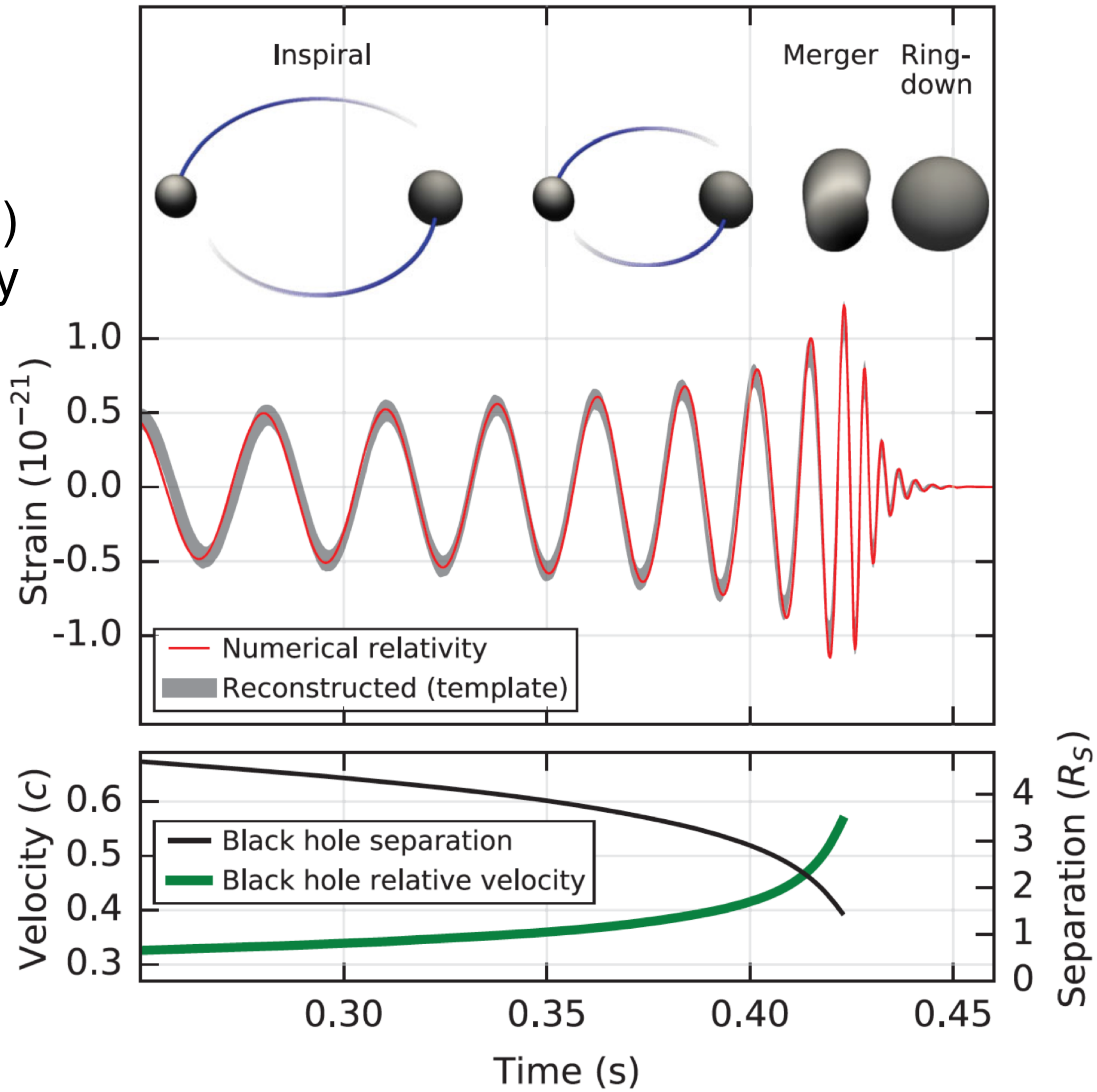
GW150914

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory caught the first gravitational-wave signal



We measure *h(t)* – think 'strip chart recorder'

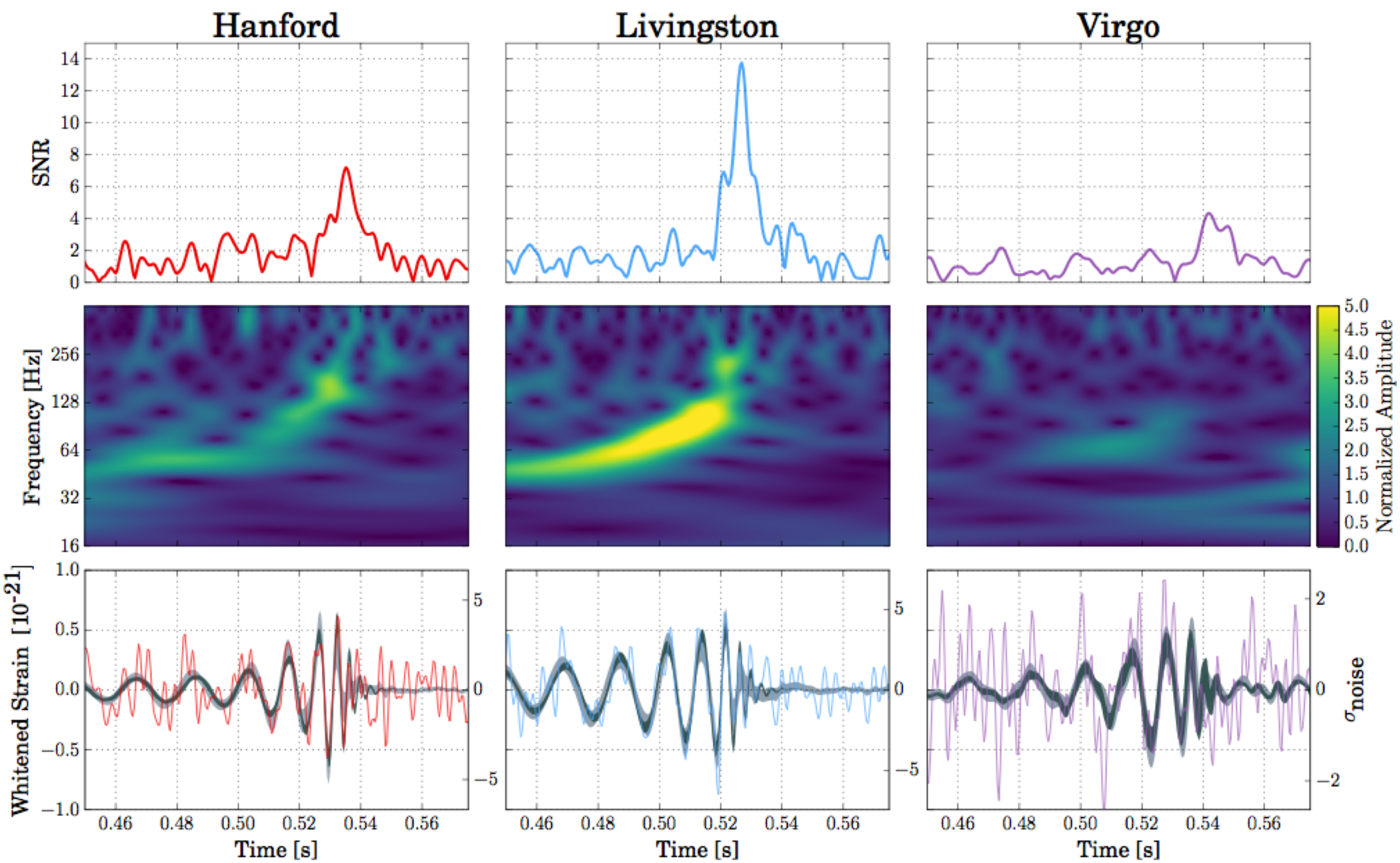
- The output of the detector is the (signed) strain as a function of time
- Earlier measurements of the pulsar period decay (Taylor/Hulse/Weisberg) measured energy loss from the binary system – a beautiful experiment
  - » radiation of gravitational waves confirmed to *remarkable* precision to lowest order
- **LIGO can actually measure the change in distance between our own test masses, due to a passing space-time ripple**
  - » Instantaneous amplitude rather than time-averaged power
  - » Much richer information!



GW170814

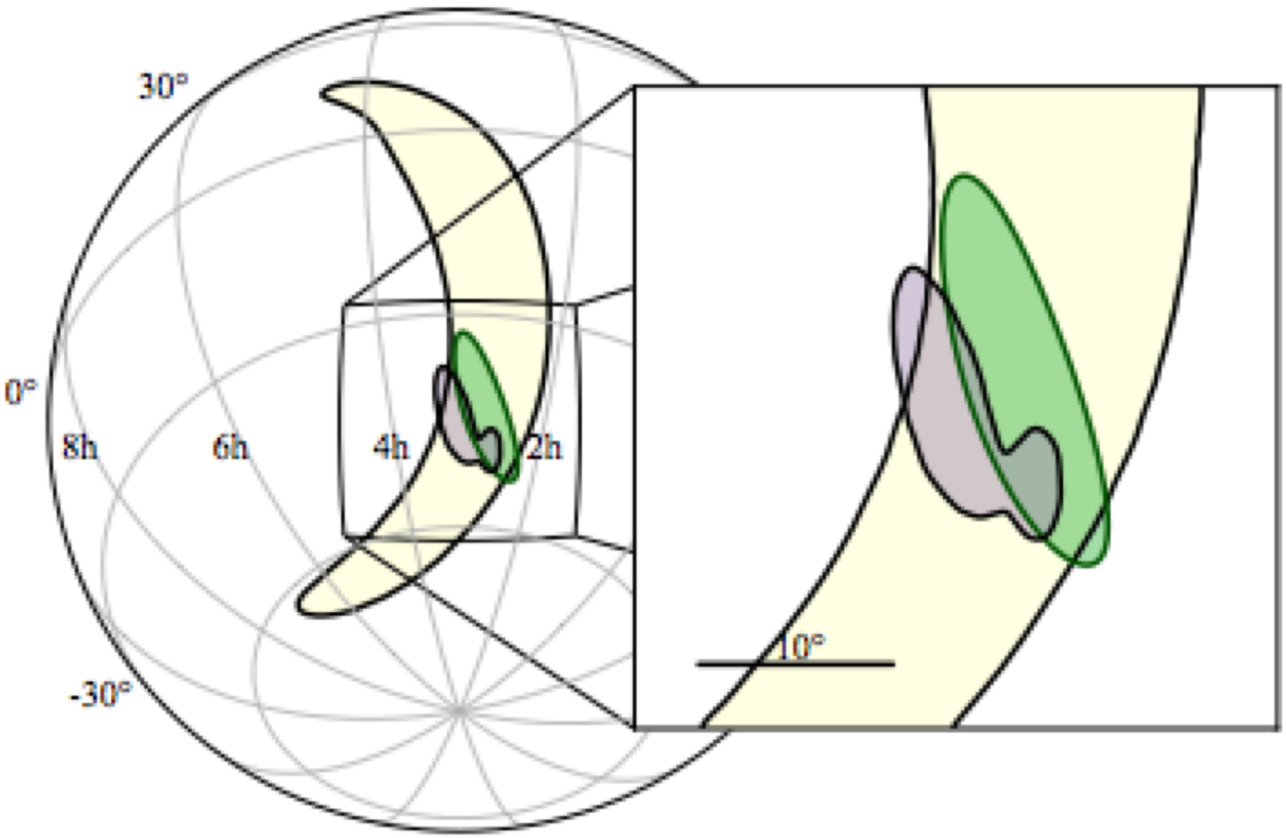
14 August 2017

The first GW signal observed by LIGO-Hanford, LIGO-Livingston and Virgo

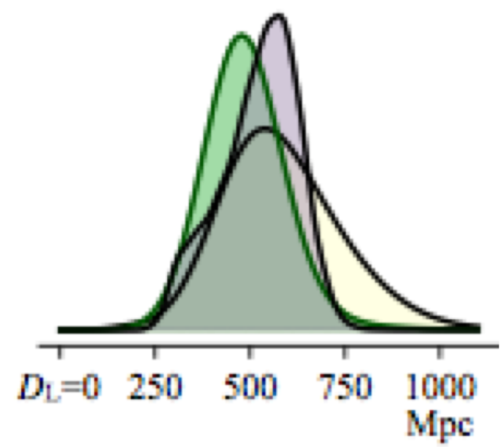


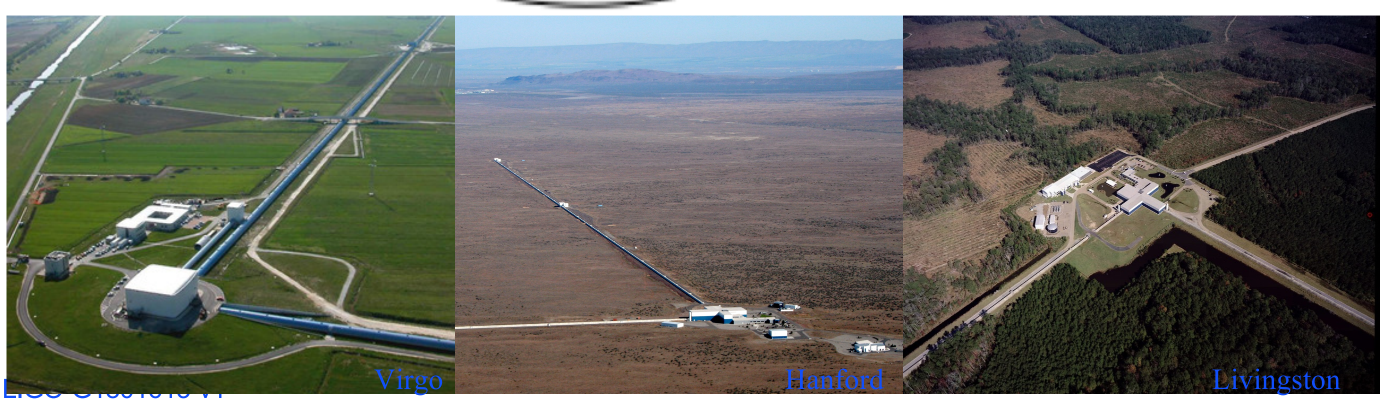
B. P. Abbott et al., *A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence*, 2017, Phys. Rev. Lett., 119, 141101

GW170814



Sky localization improves ~20x

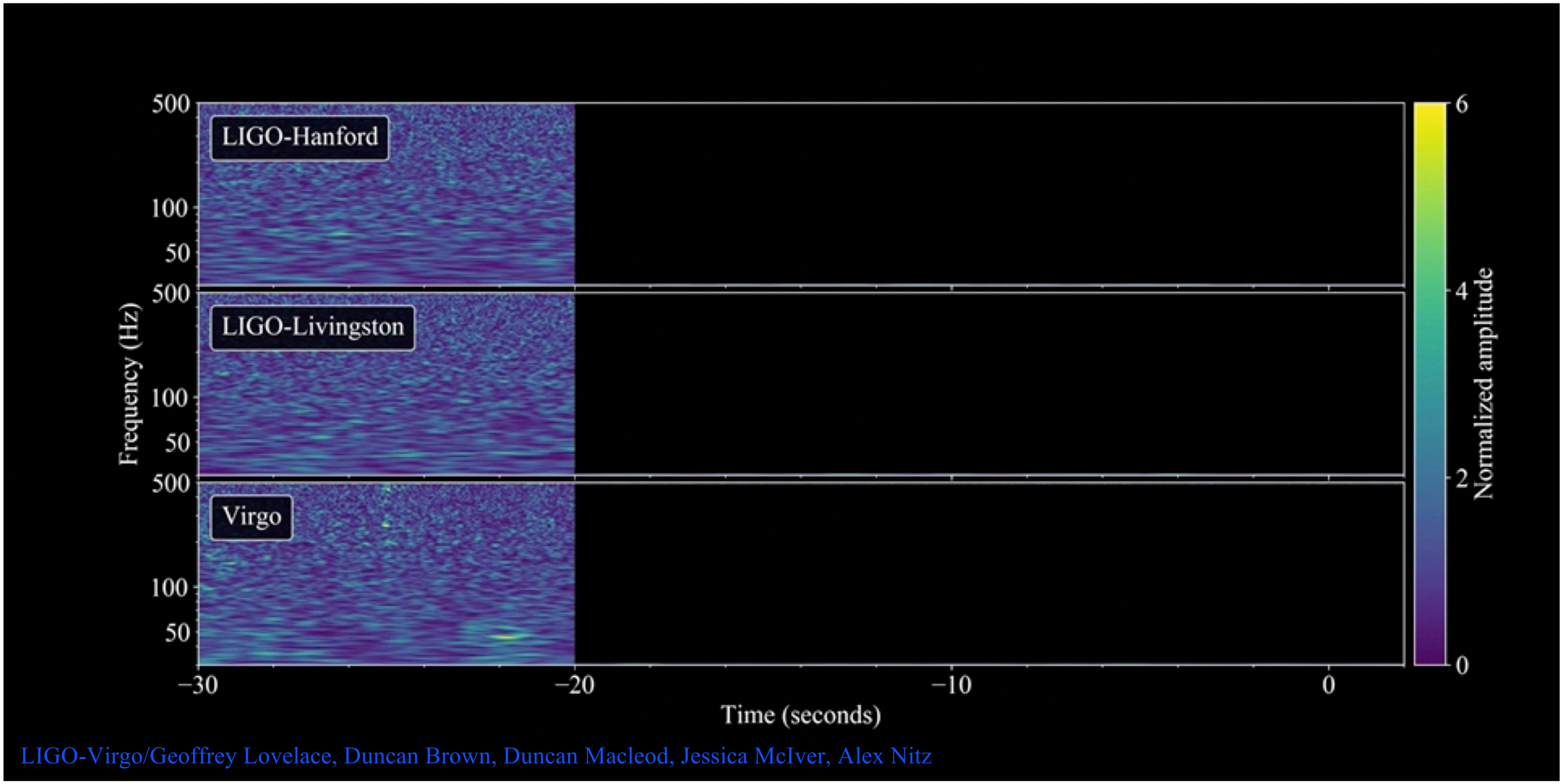




Uncertainty in volume reduced ~34x

GW170817

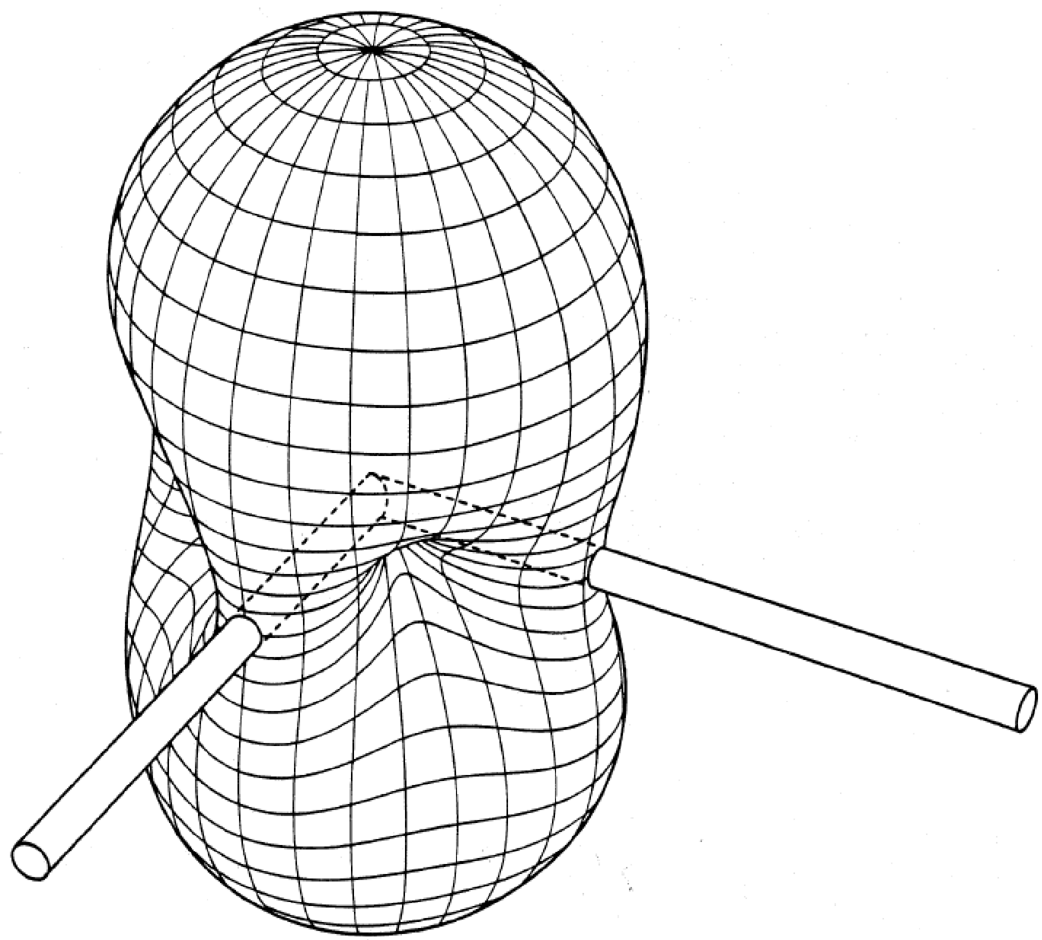
17 August 2017



https://doi.org/10.1103/PhysRevLett.119.161101

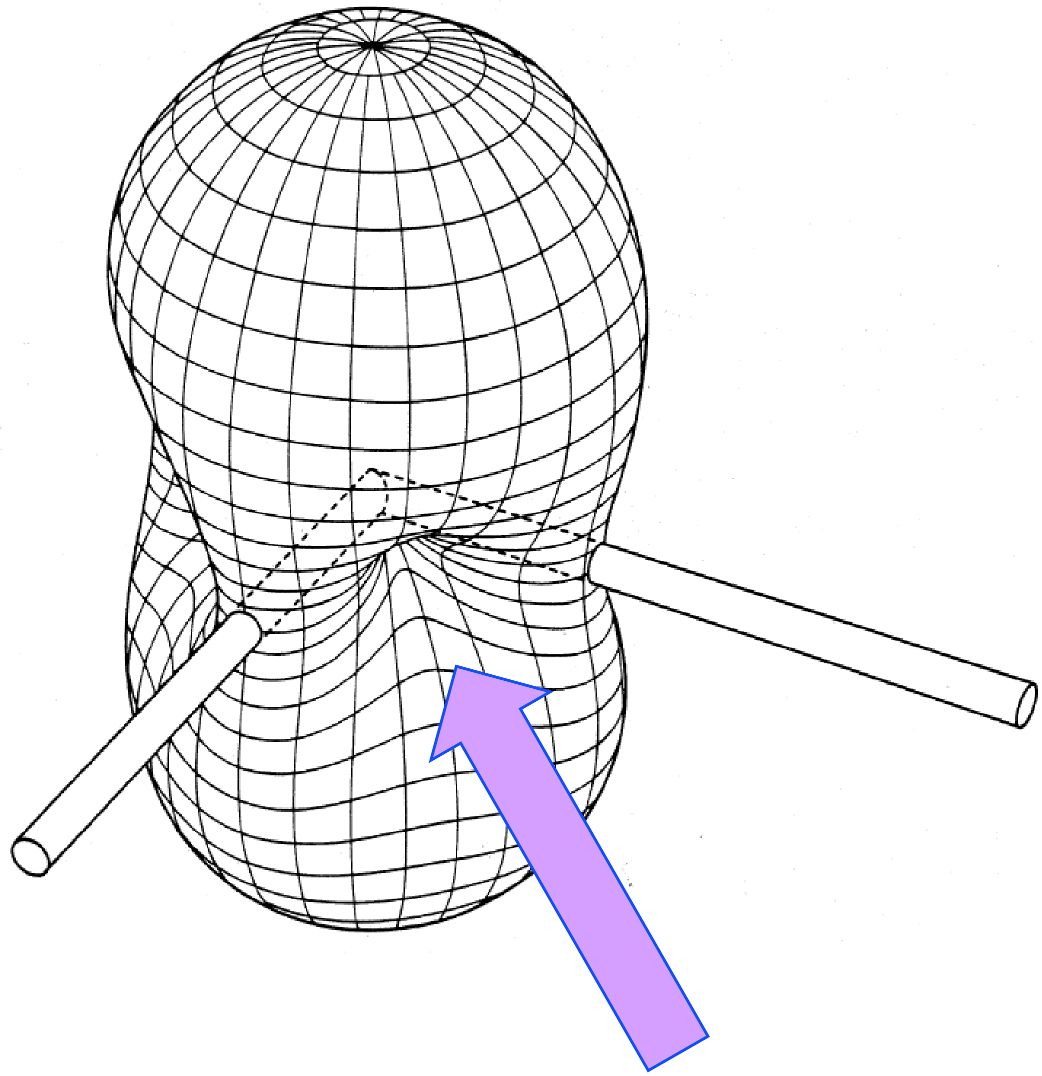
Antenna pattern for a single detector

- Maximal for overhead or underfoot source
- 1/2 for signals along one arm
- …and zero at 45 degrees

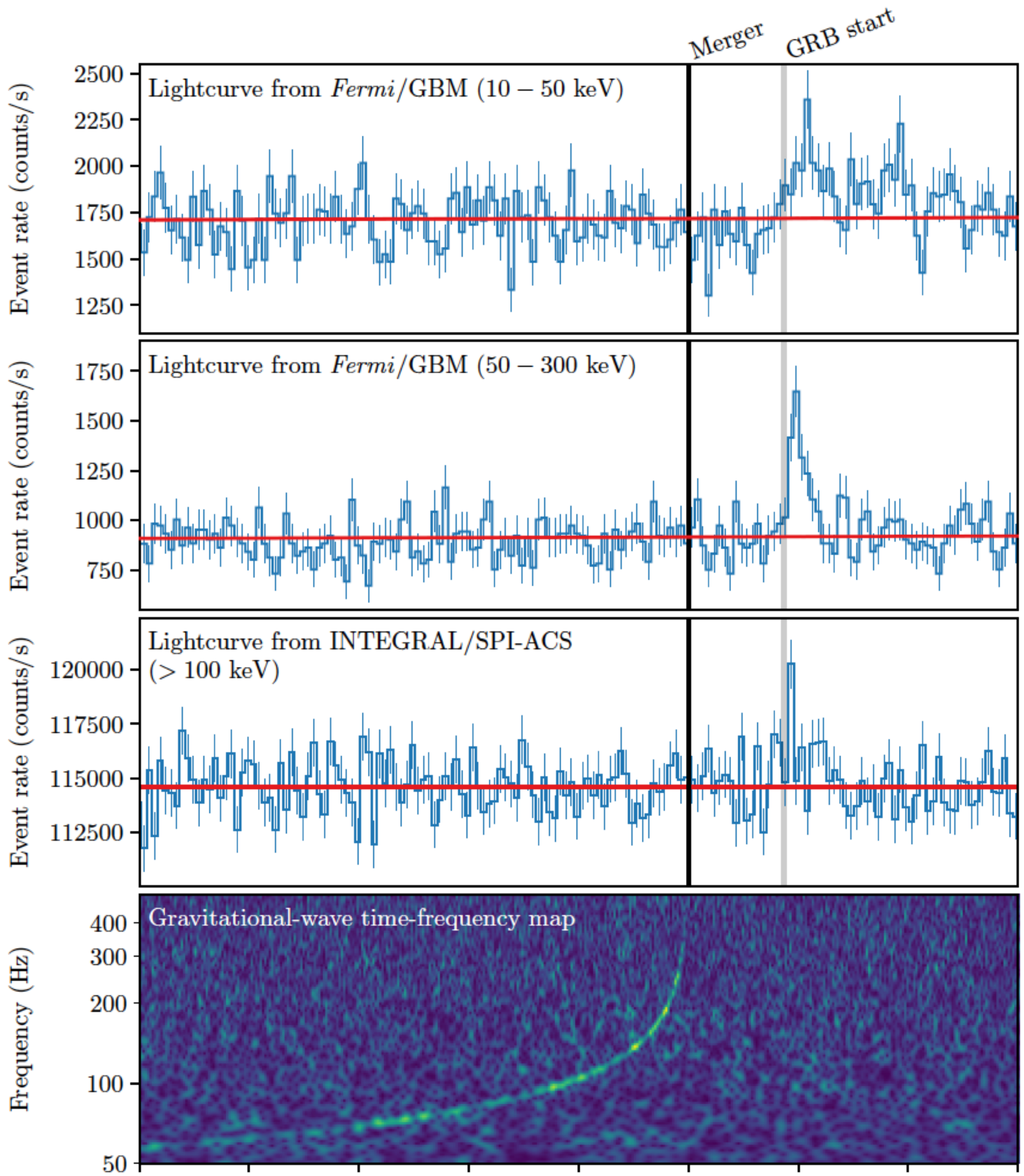


Antenna pattern for a single detector

- Maximal for overhead or underfoot source
- 1/2 for signals along one arm
- …and zero at 45 degrees
- GW170817 fell on Virgo close to 45 degrees!
- Did no harm for localization. (GW170814 proved the detector was working, happily)



GRB 170817A



GRB 170817A occurs (1.74 ± 0.05) seconds after GW170817

It was autonomously detected in-orbit by Fermi-GBM (GCN was issued 14s after GRB) and in the routine untargeted search for short transients by INTEGRAL SPI-ACS

Probability that GW170817 and GRB 170817A occurred this close in time and with location agreement by chance is 5.0×10^{-8} (Gaussian equivalent significance of 5.3σ)

BNS mergers are progenitors of (at least some) SGRBs

B. P. Abbott et al., *Gravitational Waves and Gamma Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A*, 2017, ApJL in press.
doi:10.3847/2041-8213/aa920c

Multimessenger Observations

Approximate timeline:

GW170817 - August 17, 2017 12:41:04 UTC = $\mathbf{t_0}$

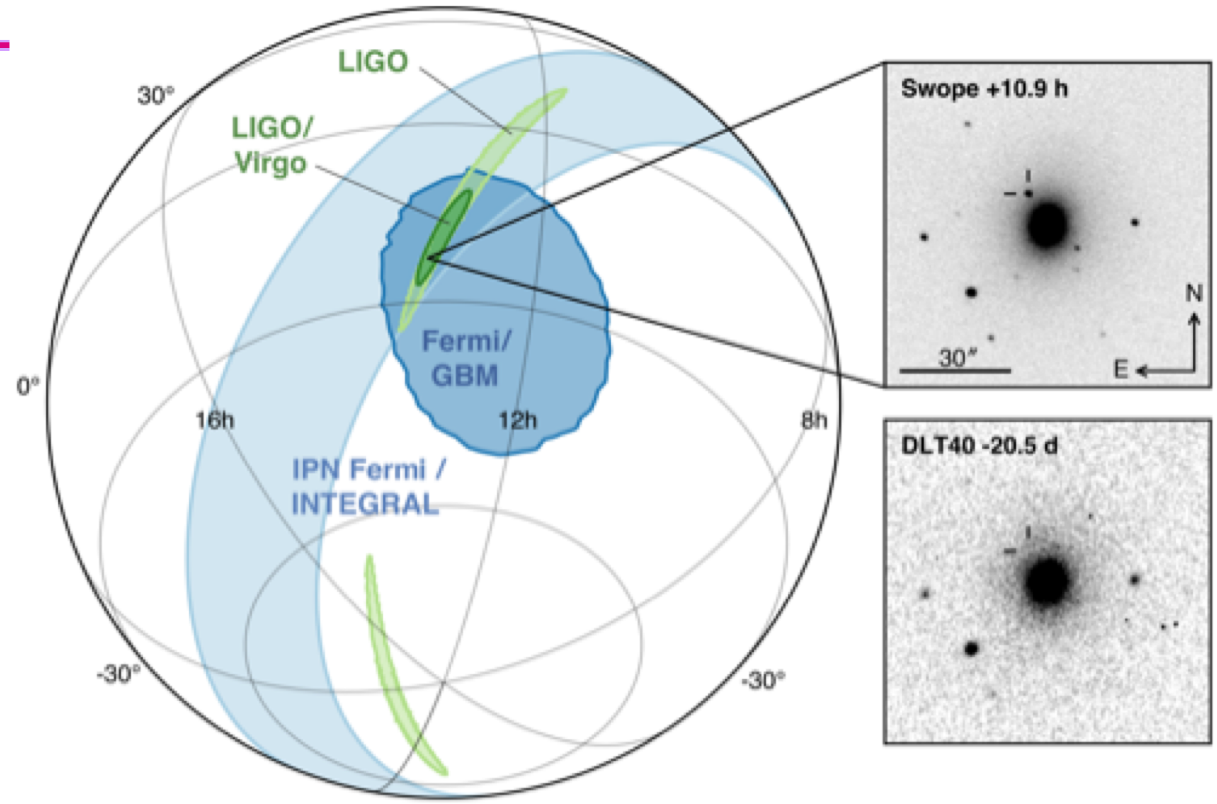
GRB 170817A
t_0 + 2 sec

LIGO signal found
t_0 +6 minutes

LIGO-Virgo GCN reporting BNS signal associated with the time of the GRB
t_0 +41 minutes

SkyMap from LIGO-Virgo
t_0 + 4 hours

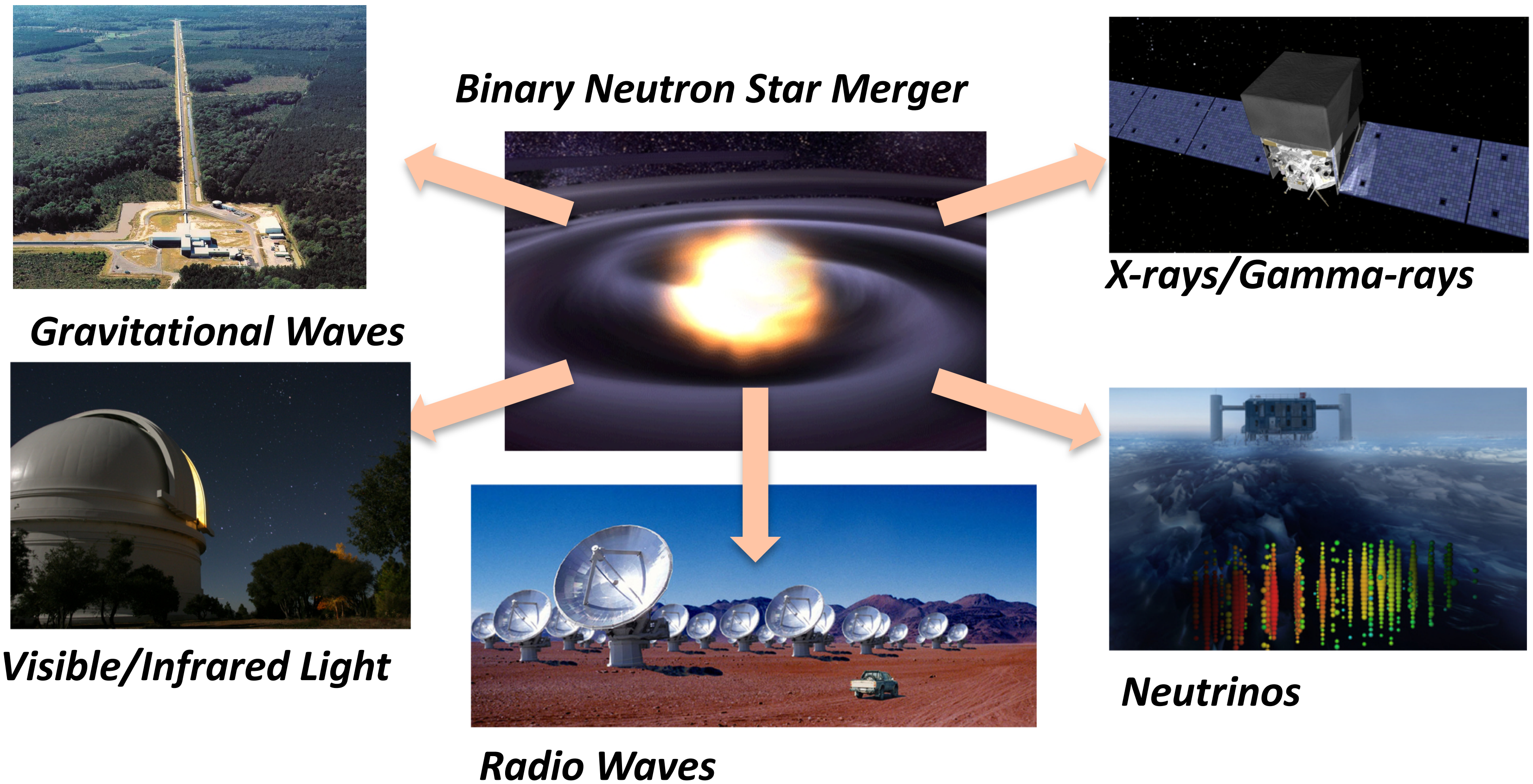
Optical counterpart found
t_0 + 11 hours



- The localisation region became observable to telescopes in Chile 10 hours after the event time (wait for nightfall!)
- Approximately 70 ground- and space- based observatories followed-up on this event

B. P. Abbott, *Multi-messenger Observations of a Binary Neutron Star Merger*, 2017, ApJL in press. doi:10.3847/2041-8213/aa91c9

Multi-messenger Astronomy

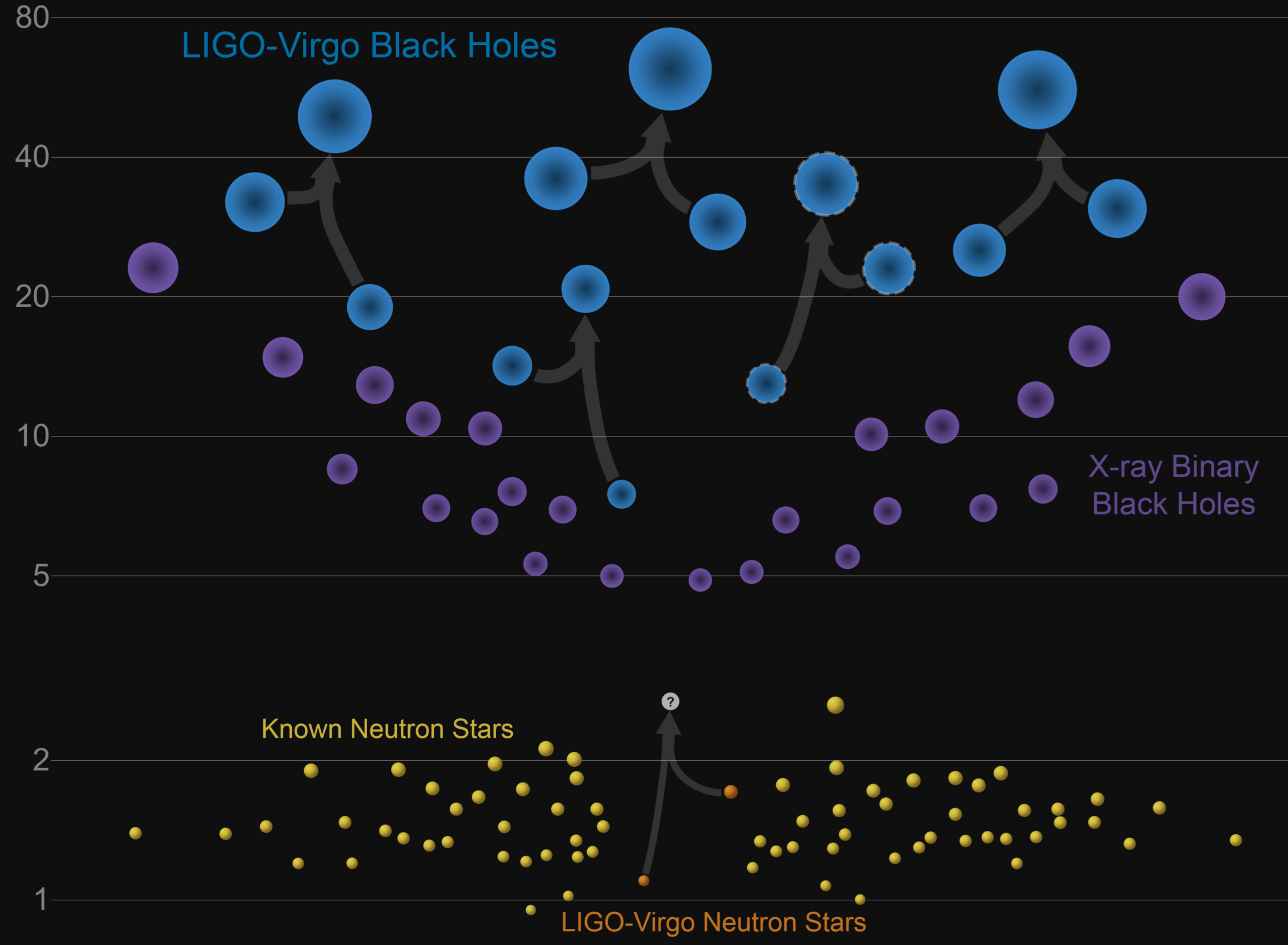


LIGO and Virgo signed agreements with 95 groups for EM/neutrino followup of GW events

- ~200 EM instruments - satellites and ground based telescopes covering the full spectrum from radio to very high-energy gamma-rays
- Worldwide astronomical institutions, agencies and large/small teams of astronomers

Masses in the Stellar Graveyard

in Solar Masses



LIGO-Virgo/Frank Elavsky/Northwestern

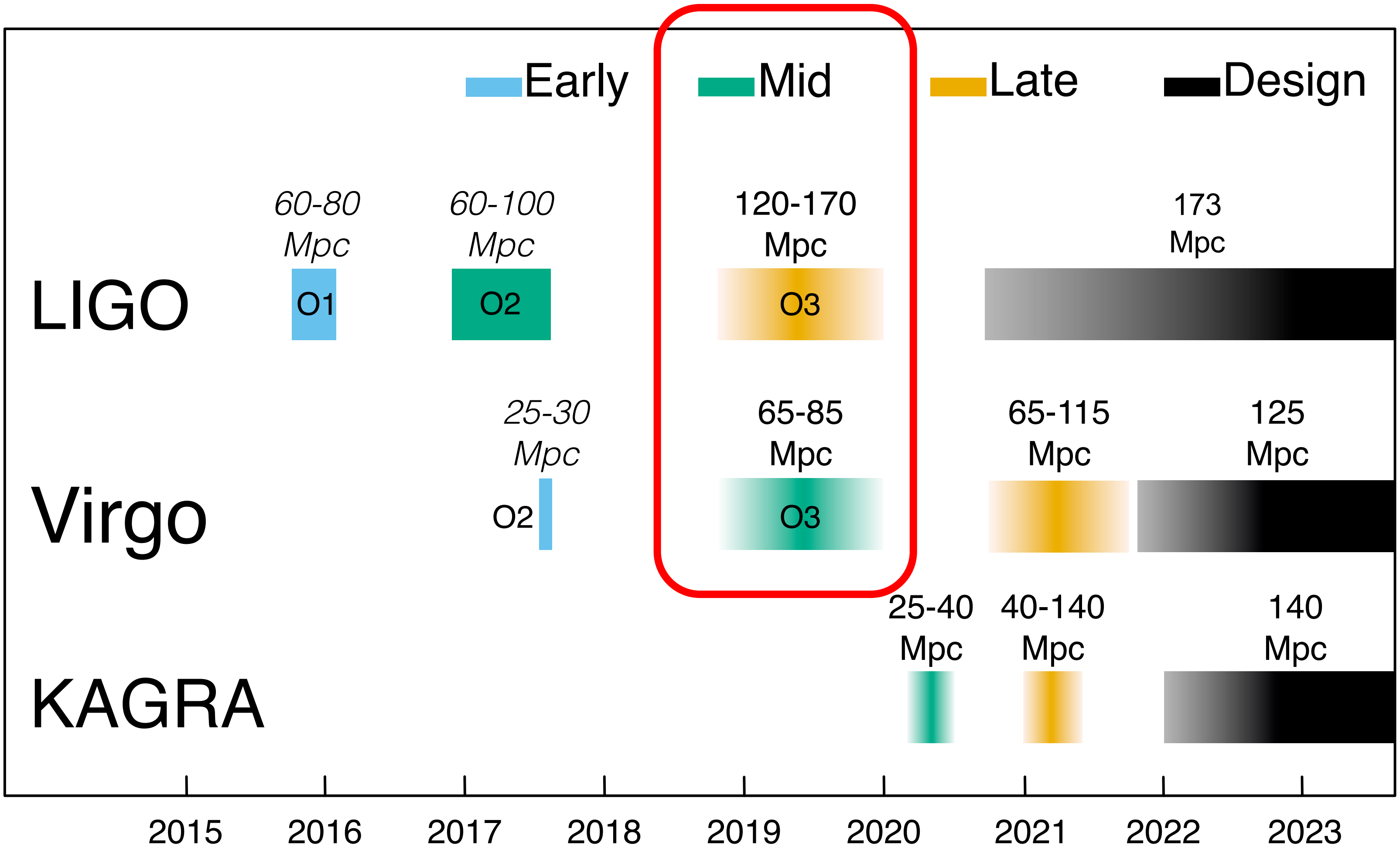
LIGO Scientific Collaboration and Virgo Collaboration

~1500 members, ~120 institutions, 21 countries

What does the future hold?

Observing Timeline

Binary Neutron Star Range



Adapted from B. P. Abbott et al., *Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA*, 2016, Living Rev. Relativity 19

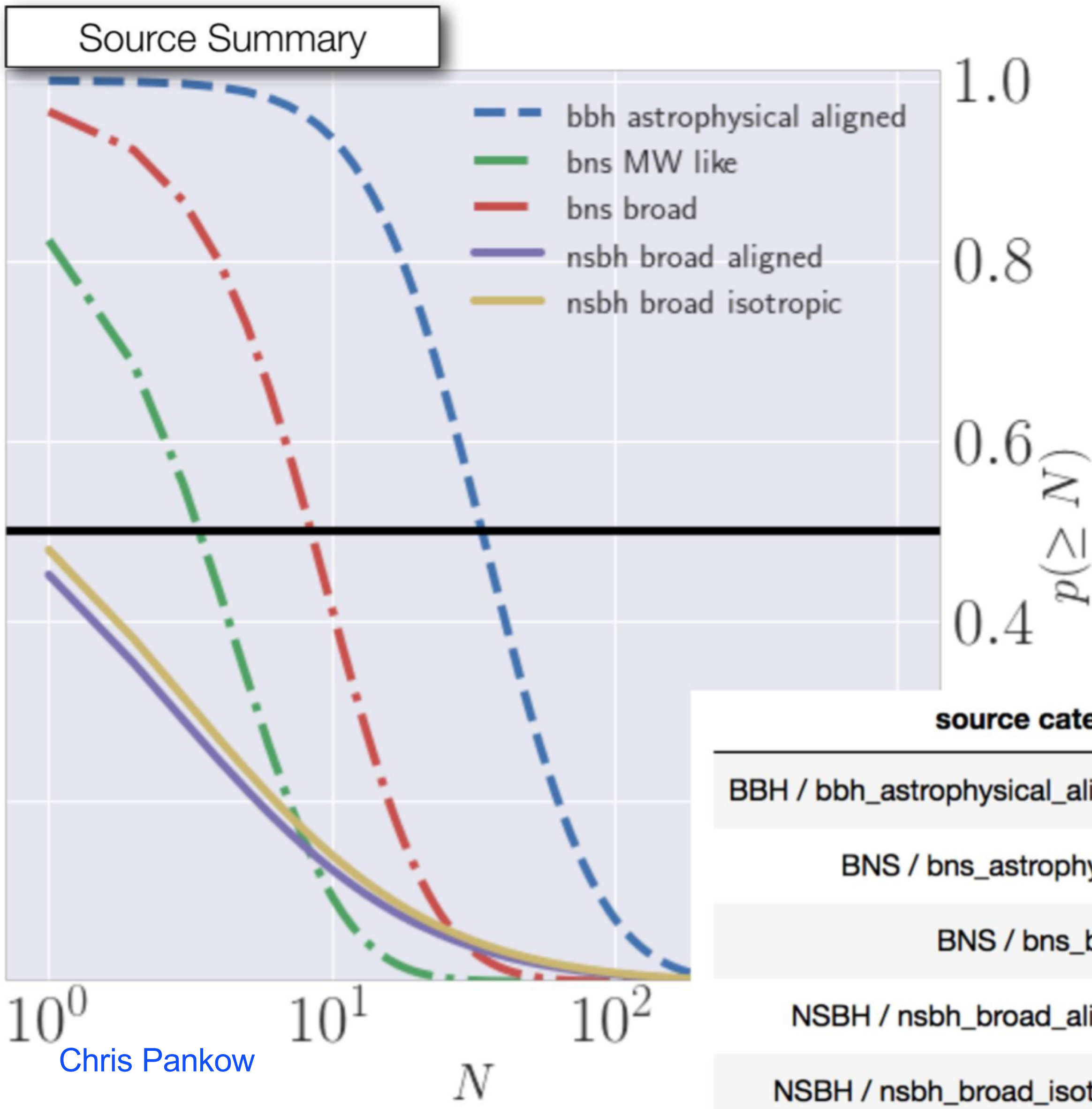
The O3 Observing Run

- Instruments now being upgraded/commissioned
- Current start date February 2019
- Duration roughly one calendar year
- Engineering runs in ~October and ~January
- LIGO and Virgo synchronized, sharing real-time data
  - » Joint alerts, MoUs, publications
- KAGRA may join toward end of O3
- LIGO instruments 120 Mpc (BNS, SNR 8, averaged)
- Virgo: 20 → 60 Mpc
- **→ Network ~x2 better**
- Better SNR for a given source; more detailed information, less ambiguity
- Greater reach, higher rates

GW Observatories for Multi-Messenger Astrophysics

- Nominally continuous operation
  - » Currently about 70% for each LIGO detector, higher for Virgo
  - » 50-60% network uptime; will improve with running/tuning
- The entire sky is visible all the time the instruments are up
  - » No pointing of instruments
  - » ‘phased array’ can be formed in any direction in the sky
- Striving for latencies of just a few minutes for alerts
- Open, public alerts with enough information to find hosts

Rates in O3



Chris Pankow

There are caveats, but the general picture is:

BBH: at least a few per month, maybe more

BNS: 1–10, possibly up to ~1 per month

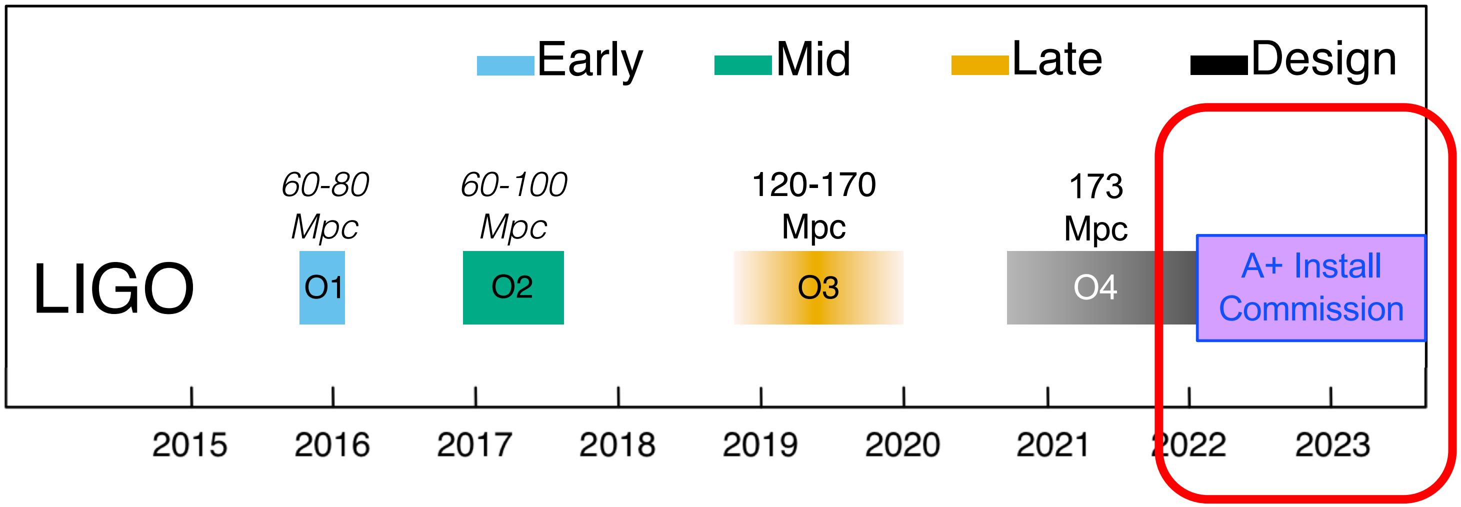
NSBH: Could detect one or more during O3, but uncertain. We'll see!

source category	full year VT	N_d
BBH / bbh_astrophysical_aligned	6.8×10^8 Mpc^3 yr	34^{+79}_{-25}
BNS / bns_astrophysical	3.2×10^6 Mpc^3 yr	4^{+9}_{-4}
BNS / bns_broad	7.3×10^6 Mpc^3 yr	9^{+19}_{-7}
NSBH / nsbh_broad_aligned	5.0×10^7 Mpc^3 yr	1^{+24}_{-1}
NSBH / nsbh_broad_isotropic	5.7×10^7 Mpc^3 yr	1^{+28}_{-1}

Once O3 is running, ~February 2019:

- Fundamental change for O3: Open Public Alerts for Triggers
  - » No more standard EM follow-up MOUs or private GCN alerts!
  - » LIGO/Virgo to release public alerts for **all event candidates for which we have reasonable confidence**
    - – For binary mergers: target 9 out of 10 valid
    - – More restrictive threshold for unmodeled GW burst candidates
    - – We can “promote” a weaker GW candidate if it is coincident with a GRB, core-collapse supernova, etc.
  - » We’ll provide basically the **same information as in O2**: significance, time, binary type classification, sky position and distance 3D map
    - – Source classifier; Remnant mass classifier
    - – Considering adding some more information to aid prioritization
  - » We’ll provide **automatic *preliminary* alerts** before human vetting – goal is to provid this within minutes
- See https://www.ligo.org/scientists/GWEMalerts.php for more info

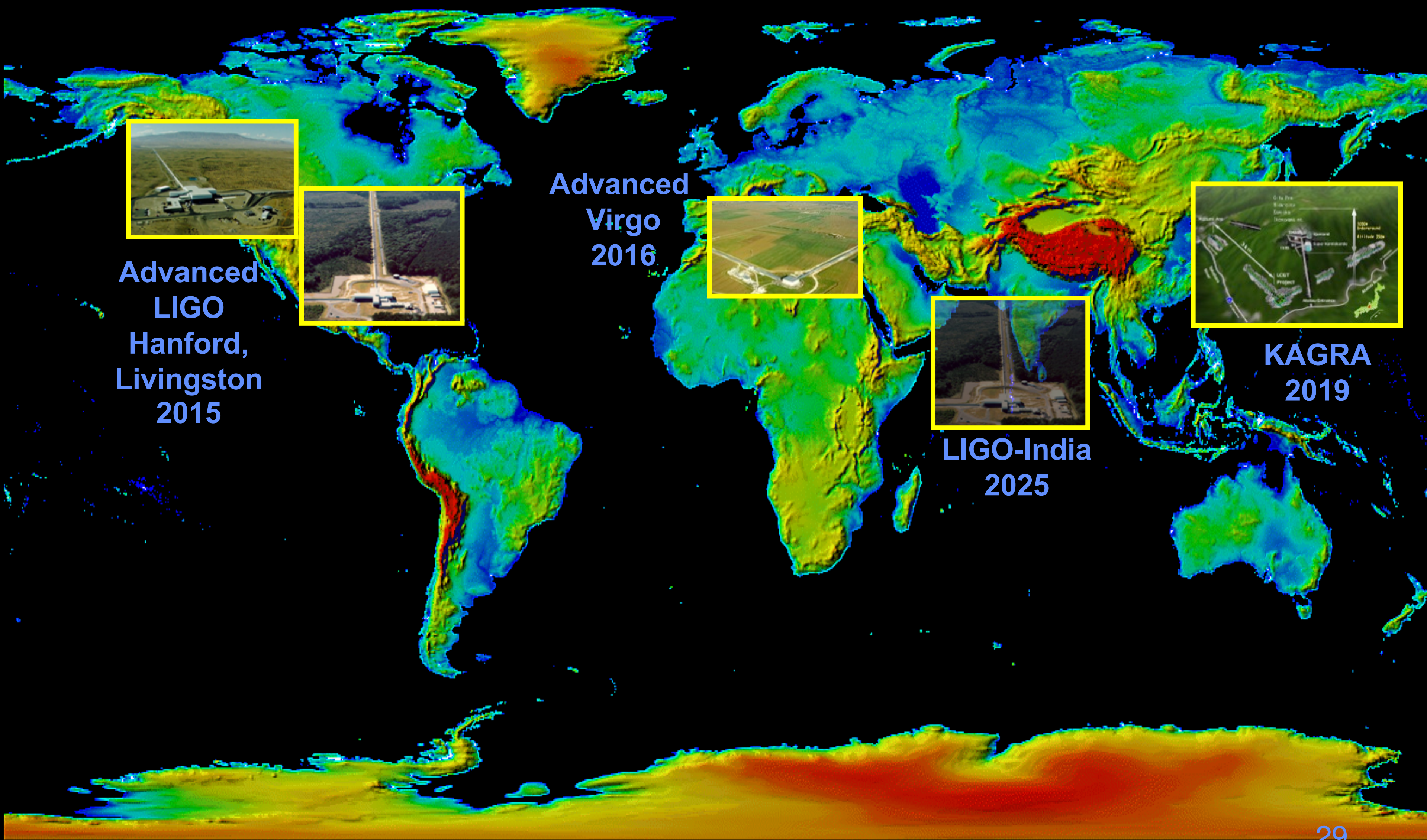
More Sensitivity: LIGO A+



- An incremental upgrade to aLIGO that leverages existing technology and infrastructure, with minimal new investment, and moderate risk
  - » Similar effort for Virgo: AdV+
- Target: factor of 1.7 increase in range over aLIGO

  ➔ **About a factor of 4-7 greater CBC event rate**
- Stepping stone to third-generation (3G) detector technology
- Bridge to future 3G GW astrophysics, cosmology, and nuclear physics
- Can be observing within 6 years (mid-2024)

The Network in mid-2020's



3rd Generation

- When could this new wave of ground instruments come into play?
- Appears 15 years from *t*=0 is a feasible baseline
  - » Initial LIGO: 1989 proposal, and at design sensitivity 2005
  - » Advanced LIGO: 1999 White Paper, GW150914 in 2015
- **Modulo funding, could envision 2030's**
- Should hope – and strive and plan – to have great instruments ready to 'catch' the end phase of binaries seen in LISA space-based detector
- Worldwide community working together on concepts and the best observatory configuration for the science targets

- **Crucial for all these endeavors: to expand the scientific community planning on exploiting these instruments far beyond the GR/GW enclave**
  - » Costs are like TMT/GMT/ELT – needs a comparable audience
  - » Events like GW170817 help!

Just the beginning of a new field – new instruments, new discoveries, new synergies

Milliseconds	Minutes to Hours	Years to Decades	Billions of Years
LIGO/Virgo	LISA	Pulsar Timing Array	Cosmology Probes