Ground-based Gravitational-wave detectors: Results and Plans

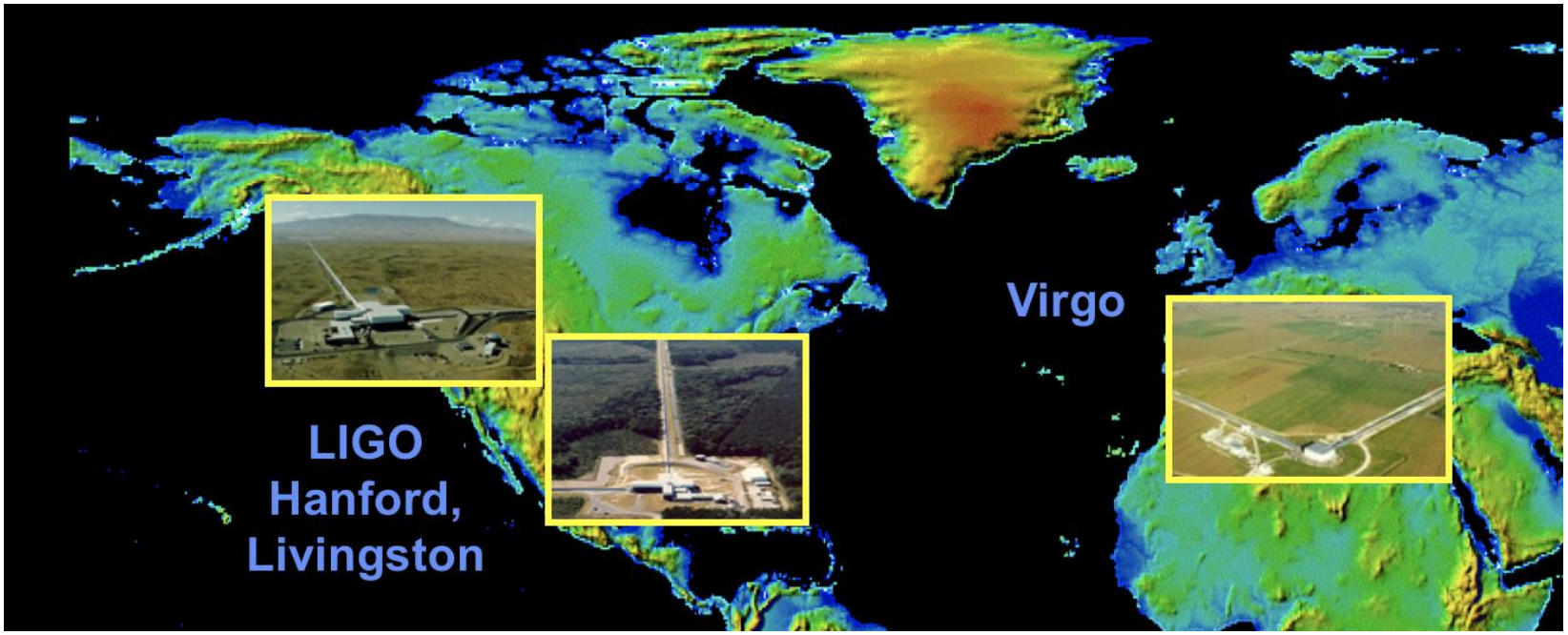
Aspen 2018 - The Particle Frontier

Aspen 26 March 2018

David Shoemaker

For the LIGO and Virgo Scientific Collaborations

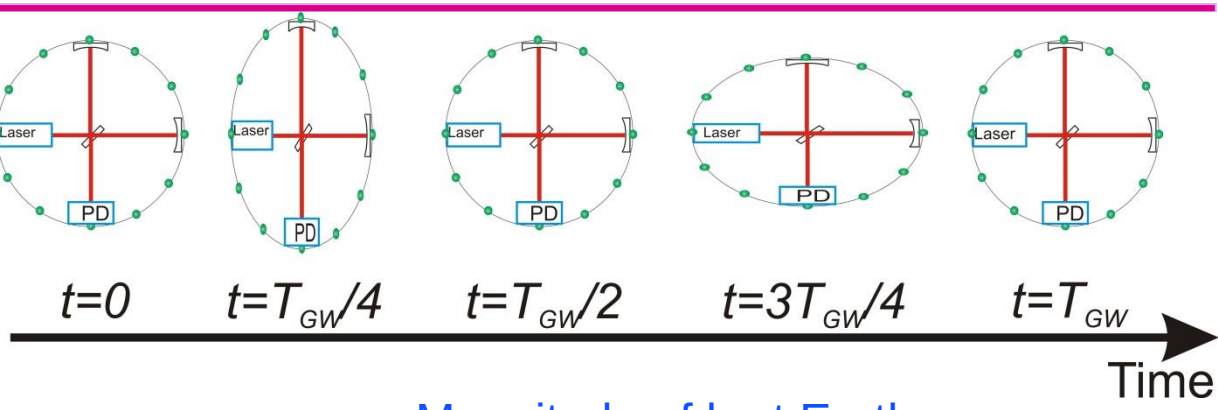
Ground based detectors



- Initial observatories, and instruments, constructed starting in mid-90's
  - **NSF Physics** for LIGO; Virgo's support from CNRS and INFN
- Observed, setting upper limits until 2011
- Both Virgo and LIGO undertook a complete rework of the instruments
- Advanced LIGO came on line in 2015 – First discovery 15 Sept 2015
- Advanced Virgo came on line in 2017 – First signal 14 August 2017

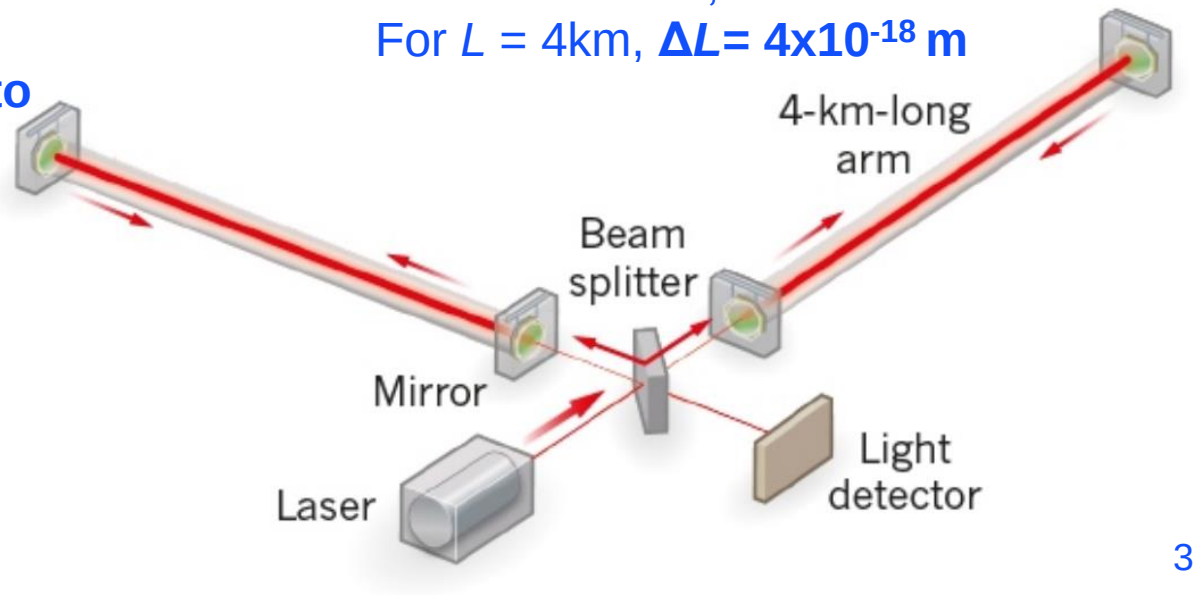
Measurement technique

- Enhanced **Michelson interferometers**
- 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….



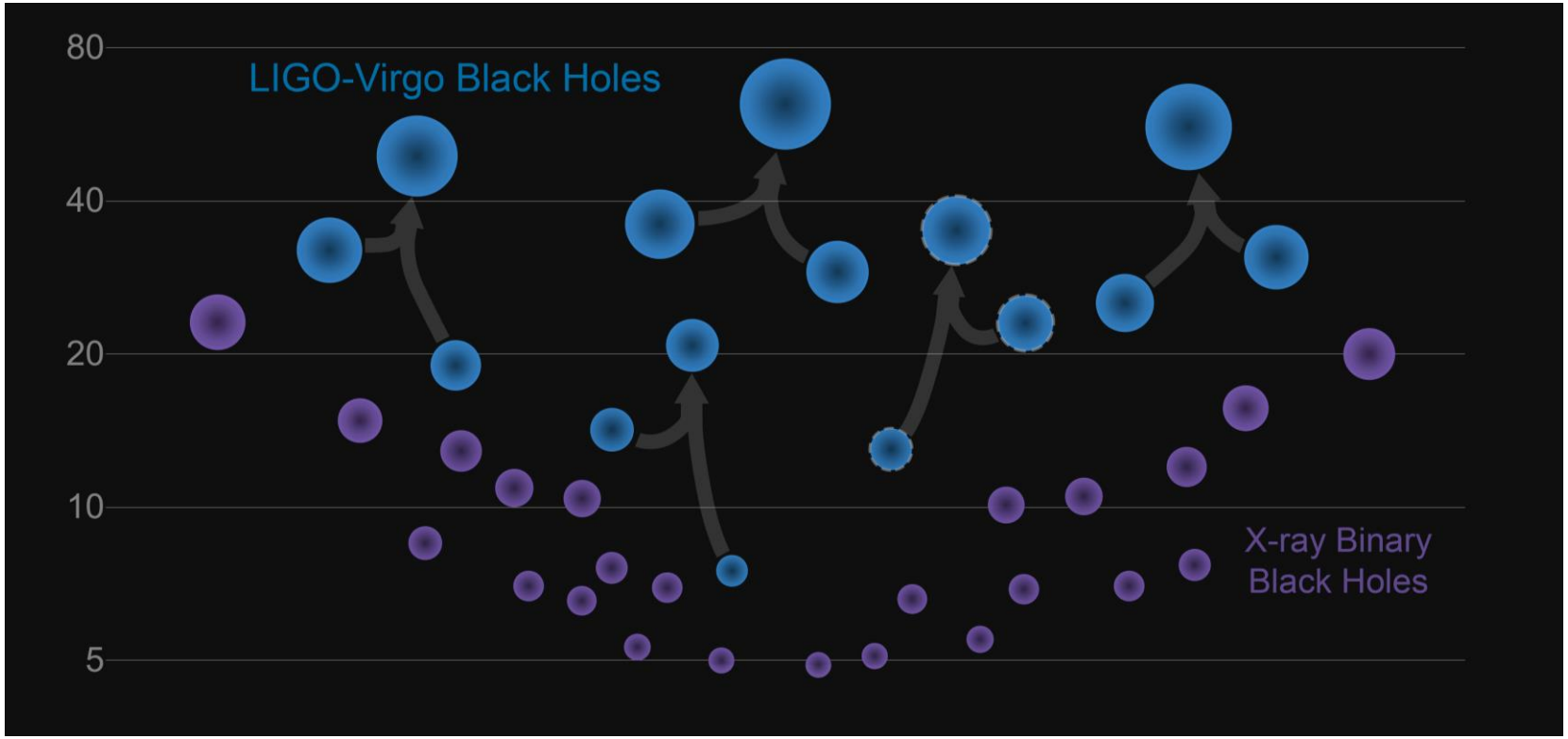
$$h \approx \frac{\Delta L}{L}$$

Magnitude of h at Earth:
Detectable signals h ~ 10^{-21}
(1 hair / Alpha Centauri)
For L = 1 m, $\Delta L = 10^{-21}$ m
For L = 4km, $\mathbf{\Delta L = 4x10^{-18}\ m}$

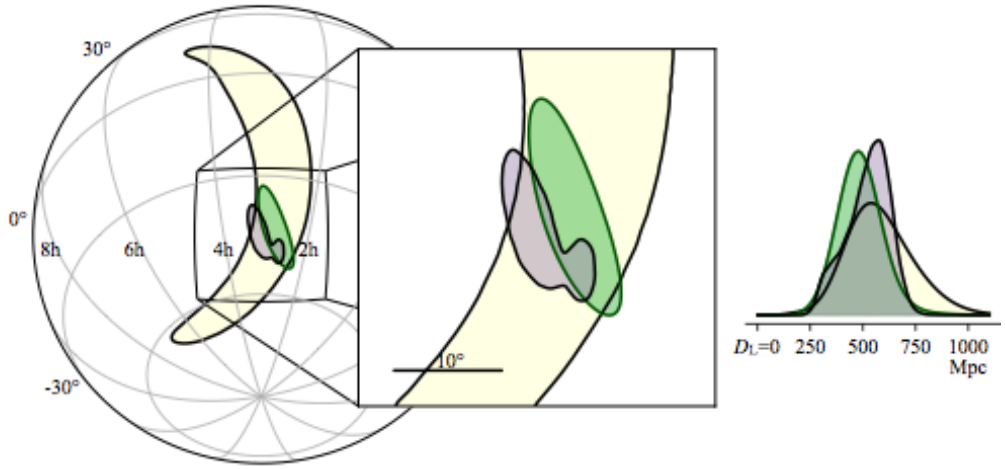


Stellar-mass Binary Black Holes

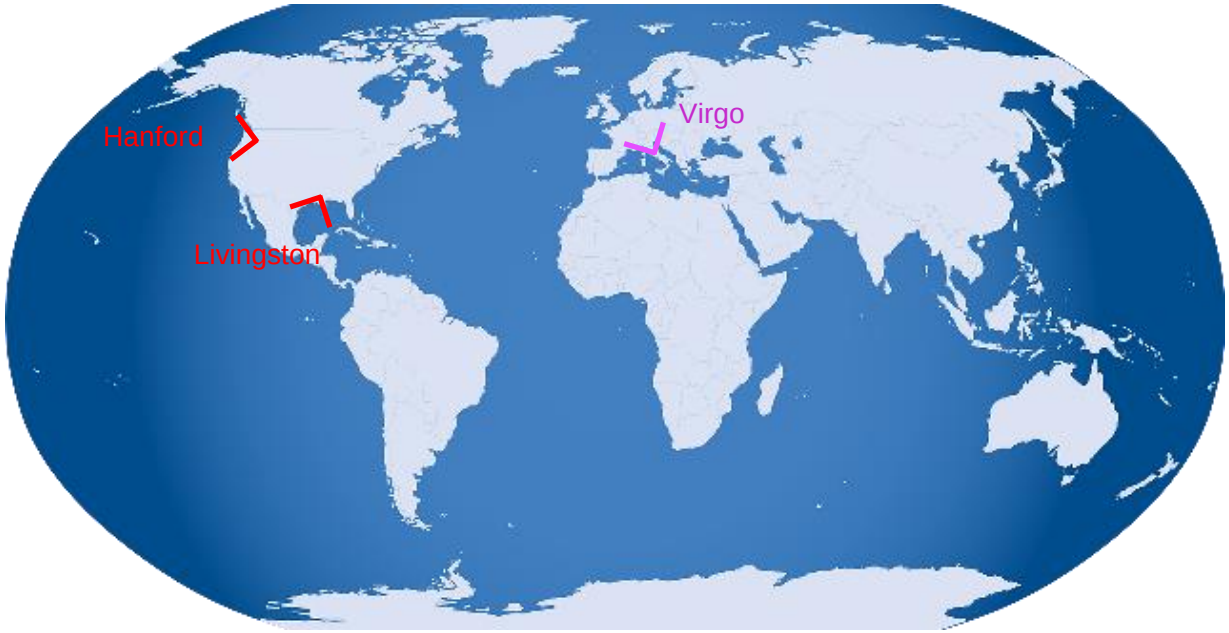
- 5 events published to date; 1 with both LIGO and Virgo detectors
- Consistency with GR in extremes of compactness and v/c ~0.6
- Revealed an unexpected class of heavier Stellar-mass BH



GW170814: Virgo **and** LIGO detectors, enabling triangulation, polarization sensing



Sky localization improves ~20x; Uncertainty in volume reduced ~34x

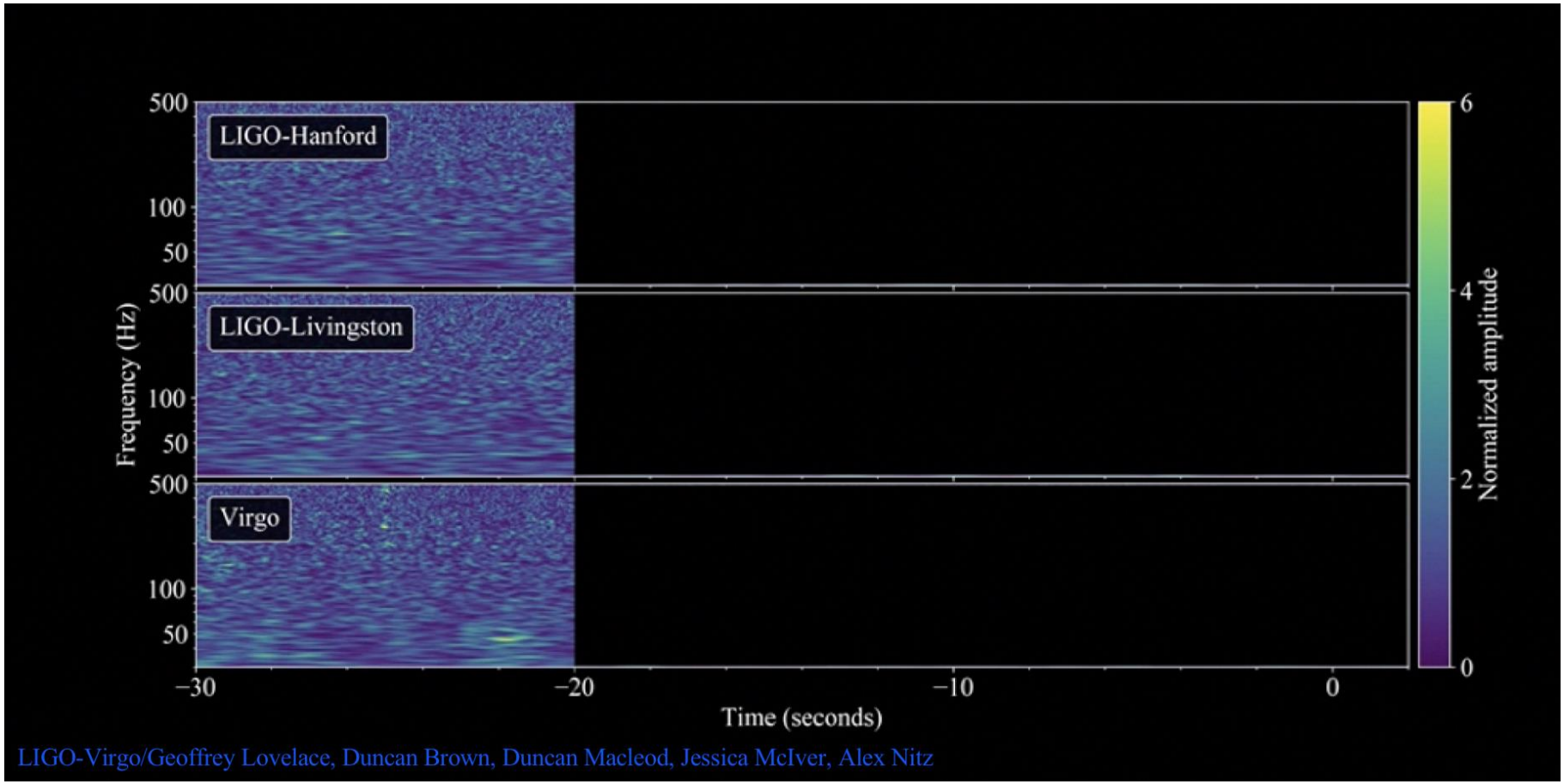


LIGO-Hanford and Livingston have similar orientations -> little information about GW polarizations

Virgo is not aligned with LIGO – giving polarization information

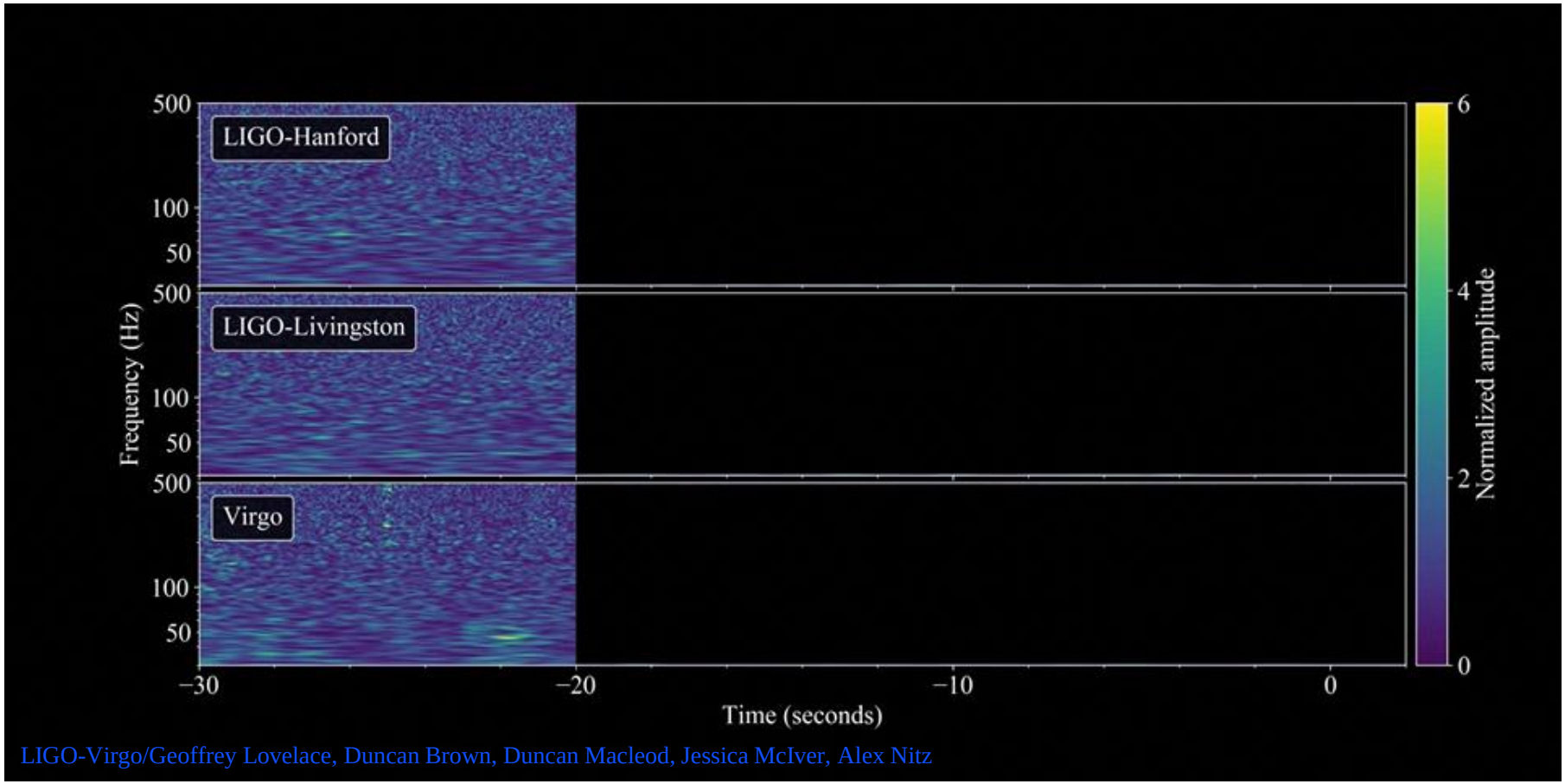
Three days later…

GW170817: Binary Neutron Star Coalescence



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

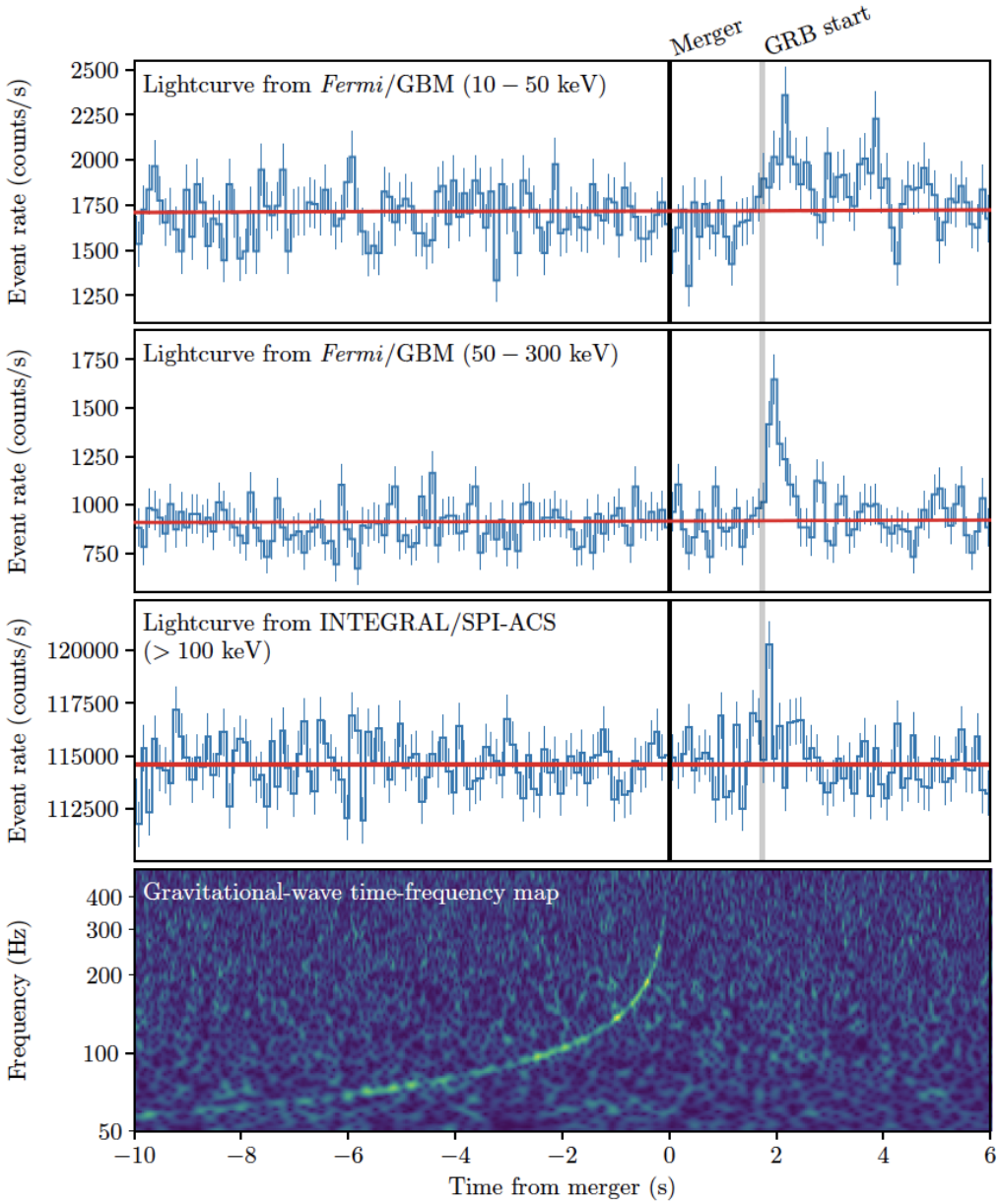
GW170817:
Binary Neutron Star Coalescence



LIGO-Virgo/Geoffrey Lovelace, Duncan Brown, Duncan Macleod, Jessica McIver, Alex Nitz

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

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

Multimessenger Observations

Approximate timeline:

GW170817 - August 17, 2017 12:41:04 UTC = t_0

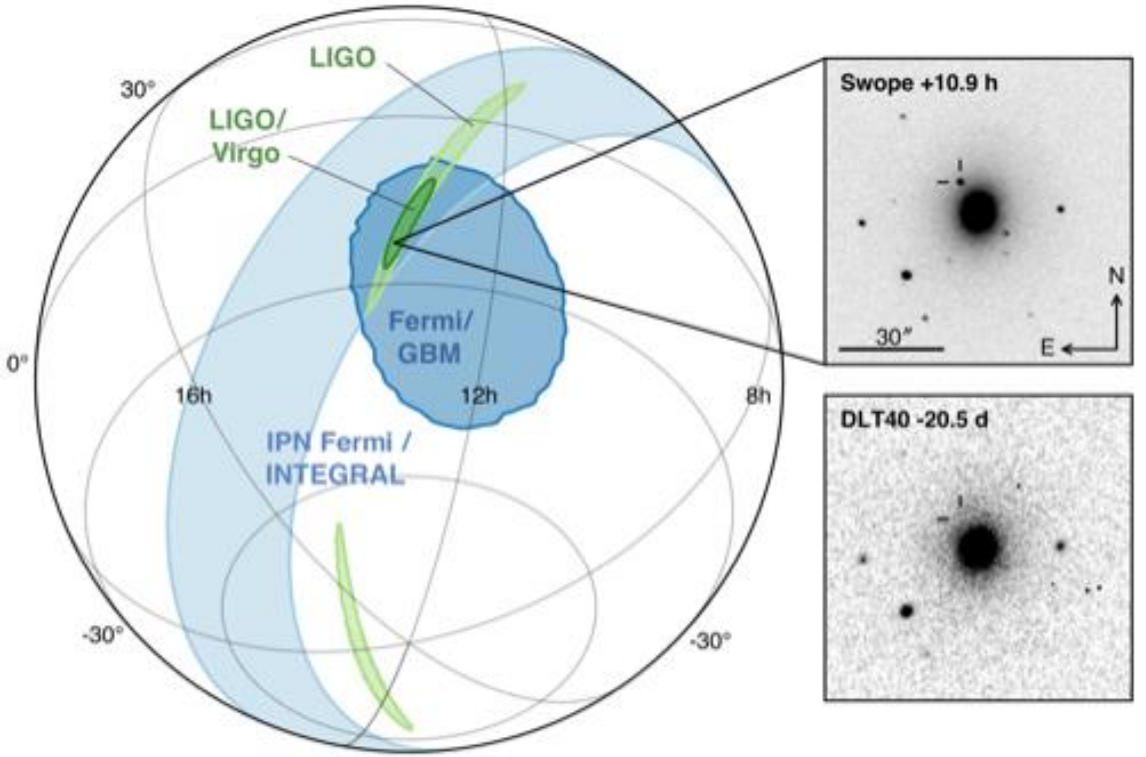
GRB 170817A
t_0 + 2 sec

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

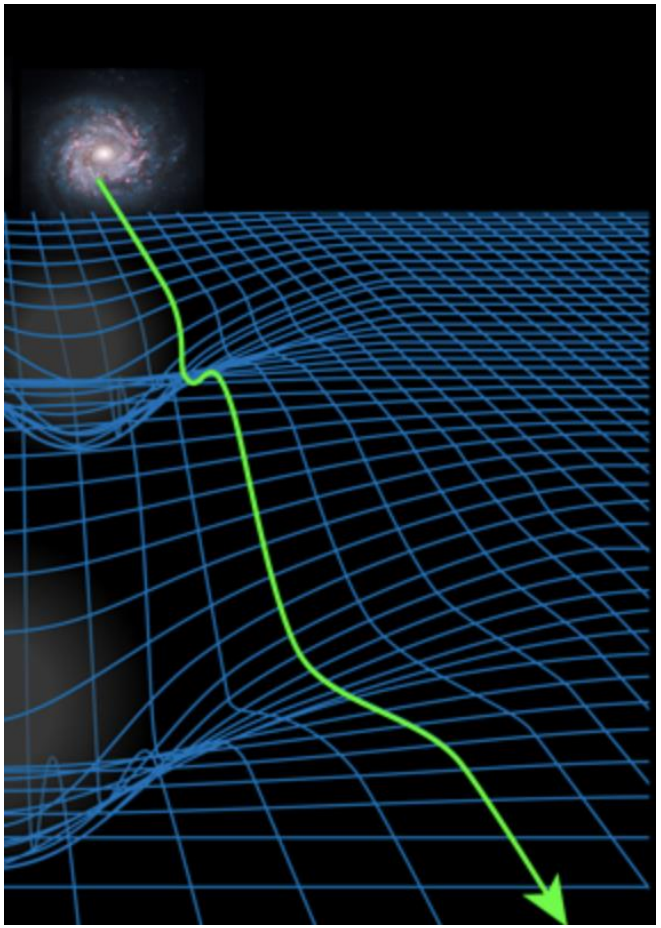


- The localisation region became observable to telescopes in Chile 10 hours after the event time (wait for nightfall!)
- Approximately 70 ground- and space- based observatories followed-up on this event
- **And…: transmutation of common elements (pure neutron matter) into gold!**

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

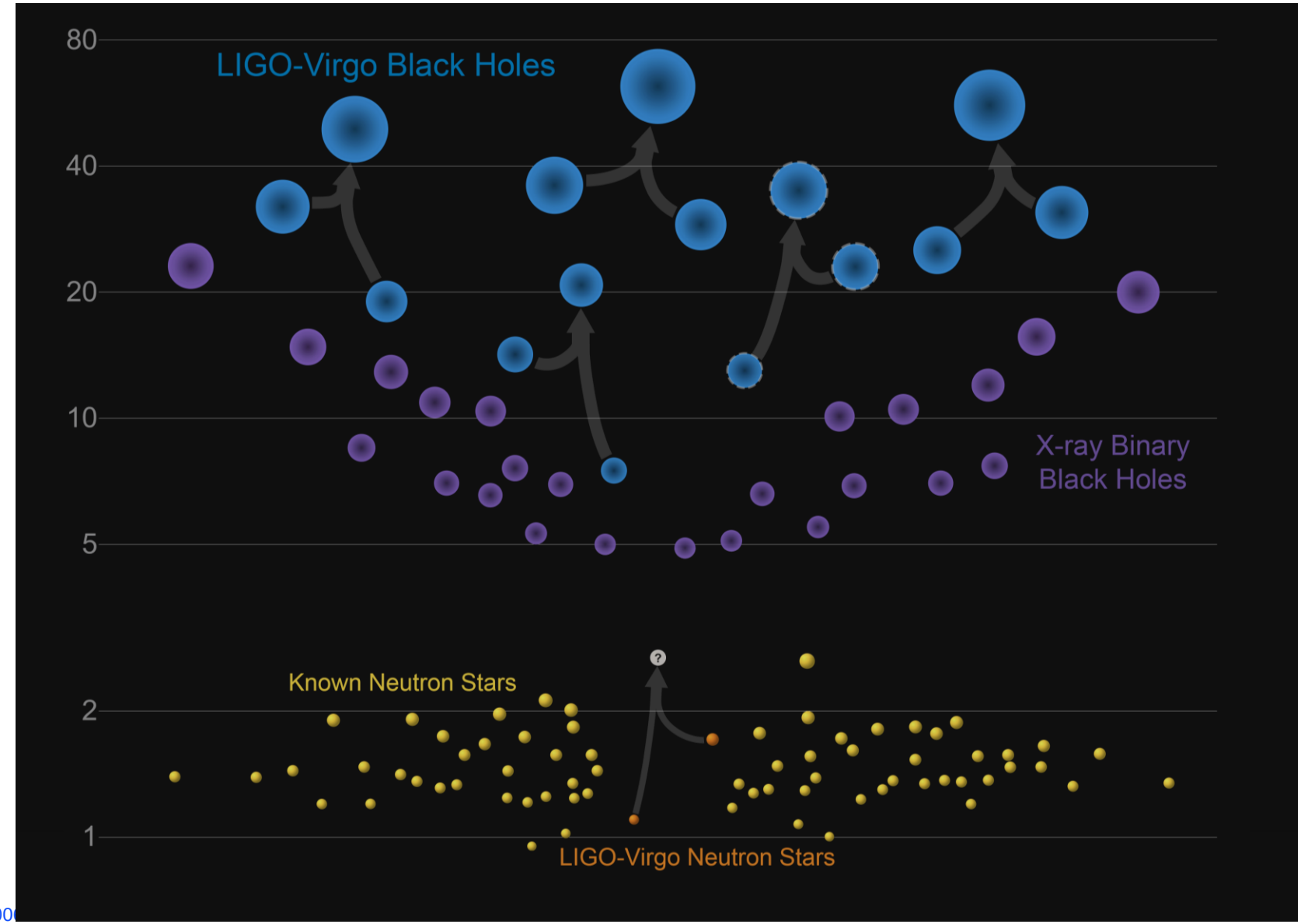
GW Physics with BNS

- Tight constraints on total mass (2.74 $M_\odot$), individual masses likely 1.2 and 1.5
- Equation of State/tidal deformability informed by deviations from point-mass waveform at end of coalescence
- Hubble constant calculated using new independent GW distance measurement to source
- Speed of GWs the same as Photons to one part in 10^{15} ; and Shapiro delay also the same
- …and a wealth of knowledge on the post-merger evolution, from EM observations



APS/Alan Stonebraker

Visual summary of signals to date



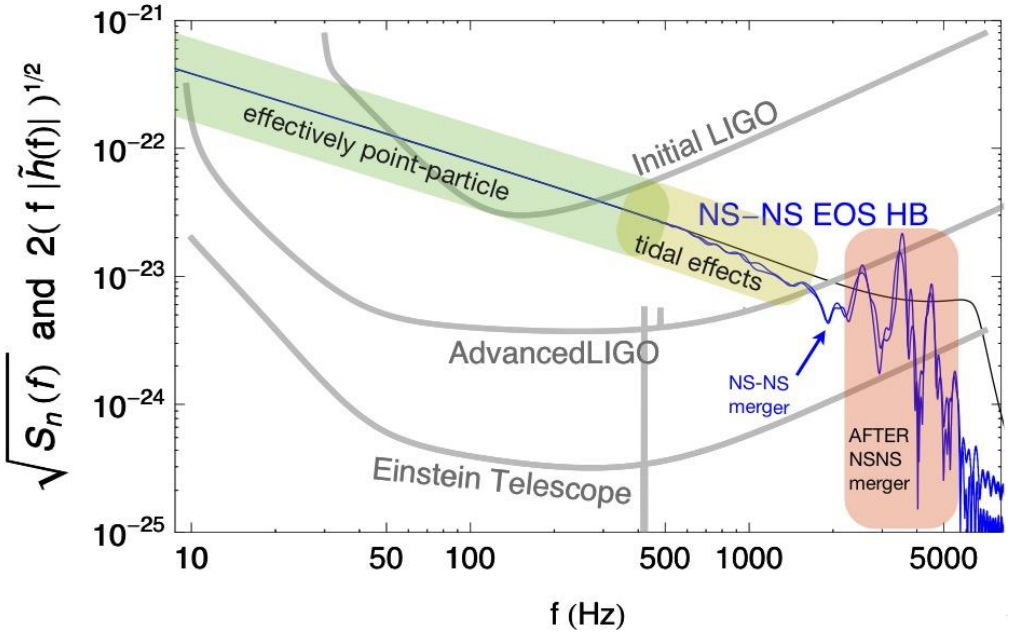
Near Future: 2019-20

- O2 – The Second Advanced detector Observing Run – was undertaken at 1/3-1/2 of the design sensitivity of the LIGO and Virgo instruments
- Currently both LIGO and Virgo improving sensitivity of instruments
- Next: ~1 year long O3 run
  - » Start in Winter (late 2018/early 2019)
  - » LIGO with a NS-NS 'reach' of ~120 Mpc, Virgo ~65 Mpc

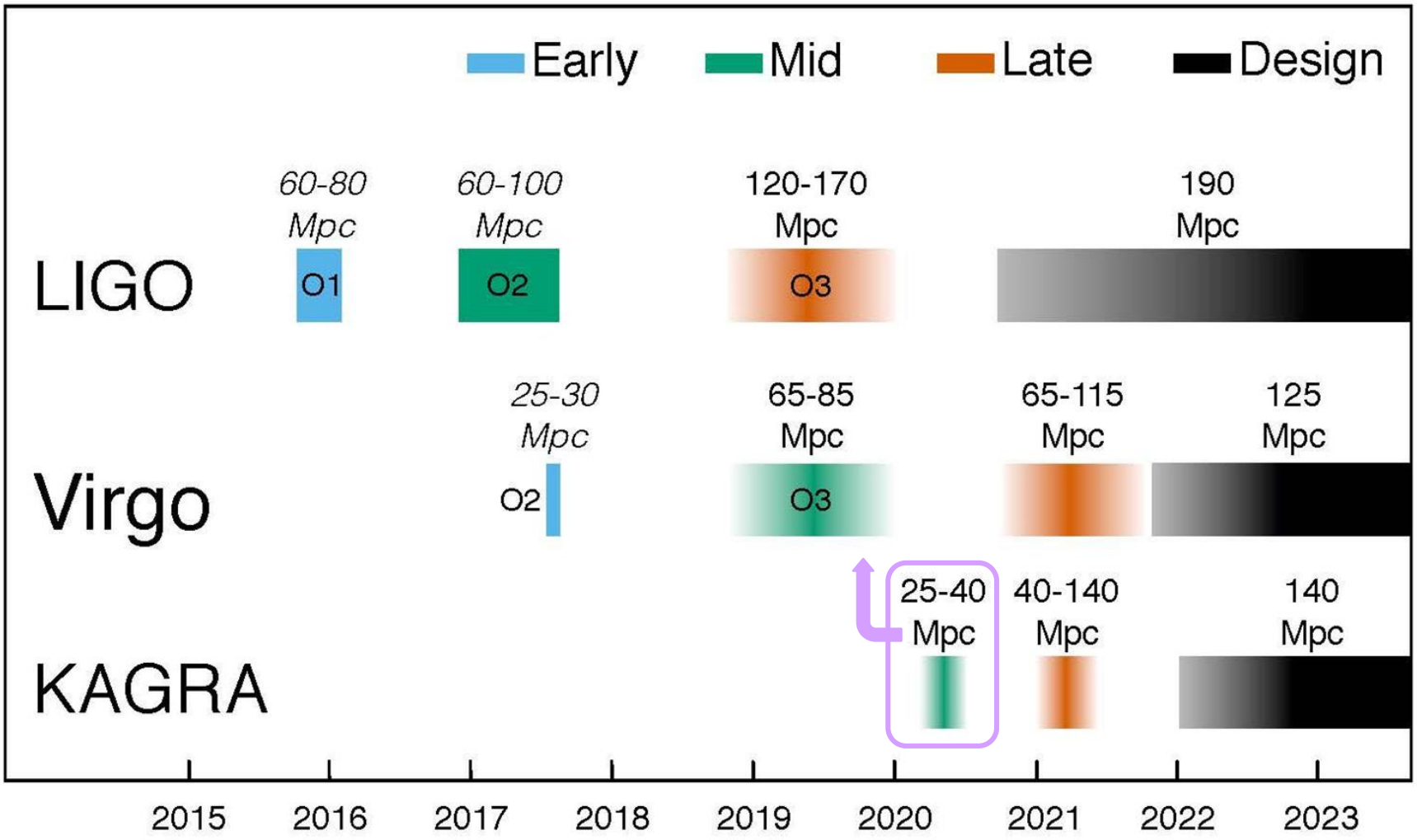
Best guesses for O3:

- **BBH: Several per month to several per week**
- **BNS: 1 to 10 in the year-long run**
- **NSBH: N=0 not ruled out in any scenario, most give ~50% N>0**

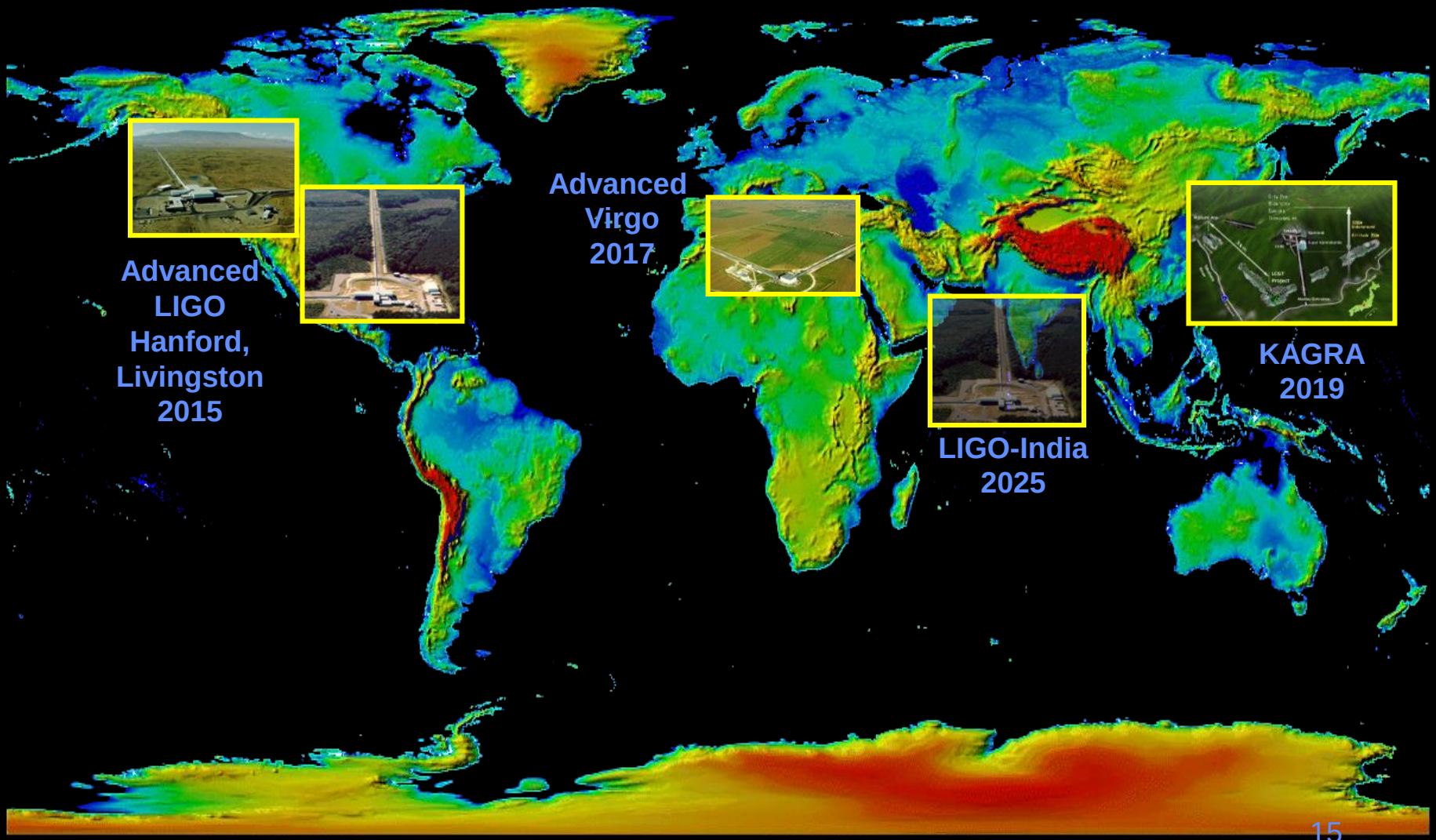
- **…and: better sensitivity offers more physics**



5-year plan


Early
Mid
Late
Design
LIGO
60-80 Mpc
O1
60-100 Mpc
O2
120-170 Mpc
O3
190 Mpc
Virgo
25-30 Mpc
O2
65-85 Mpc
O3
65-115 Mpc
125 Mpc
KAGRA
25-40 Mpc
40-140 Mpc
140 Mpc
2015
2016
2017
2018
2019
2020
2021
2022
2023

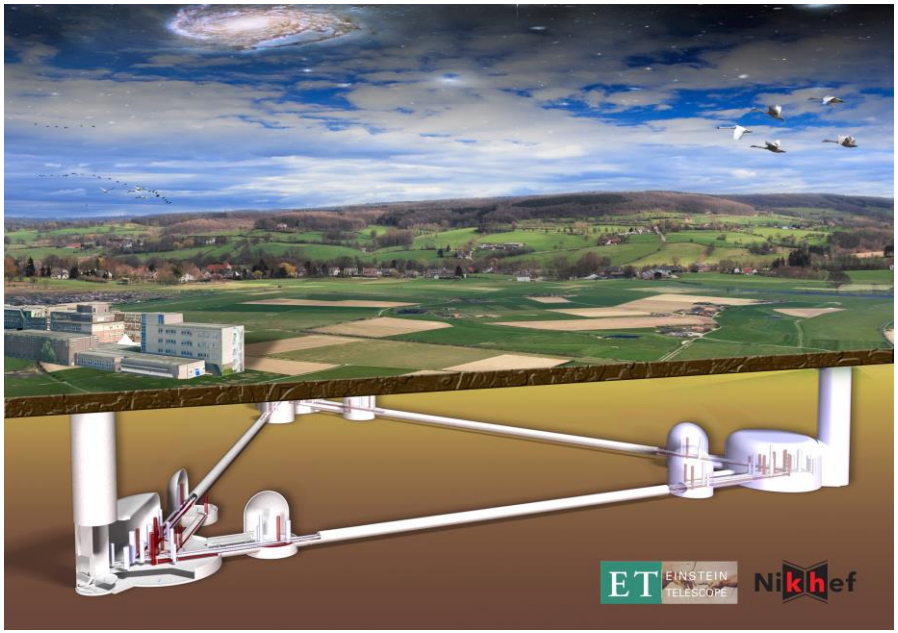
The advanced GW detector network



Longer Future

Signal grows with length – ***not*** most noise sources

- Thermal noise, radiation pressure, seismic, Newtonian unchanged
- Coating thermal noise improves *faster* than linearly with length
- 40km surface Observatory ‘toy’ baseline
  - can still find sites, earthmoving feasible; costs another limit…
- Concept offers sensitivity without new measurement challenges; could start at room temperature, modest laser power, etc.



- US and (figure) European visions
- Surface or underground
- ‘L’ or Δ geometry
- Cryogenics, multiple instruments

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 (ref. Sesana)
- 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