LIGO-Virgo Status Report

In between the Observation Runs 2 and 3

ICHEP, Seoul – July 5, 2018

Nicolas Arnaud (narnaud@lal.in2p3.fr)

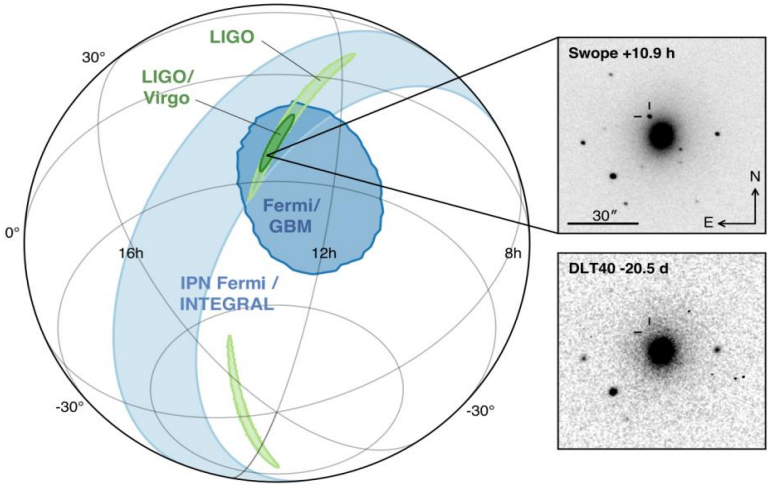
Laboratoire de l'Accélérateur Linéaire (CNRS/IN2P3 & Université Paris-Sud)

European Gravitational Observatory (Consortium, CNRS & INFN)

On behalf of the Virgo Collaboration and the LIGO Scientific Collaboration

VIR-0437A-18

DCC G1800297



EGO EUROPEAN GRAVITATIONAL OBSERVATORY

cnrs

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

UNIVERSITÉ PARIS SUD

université PARIS-SACLAY

Outline

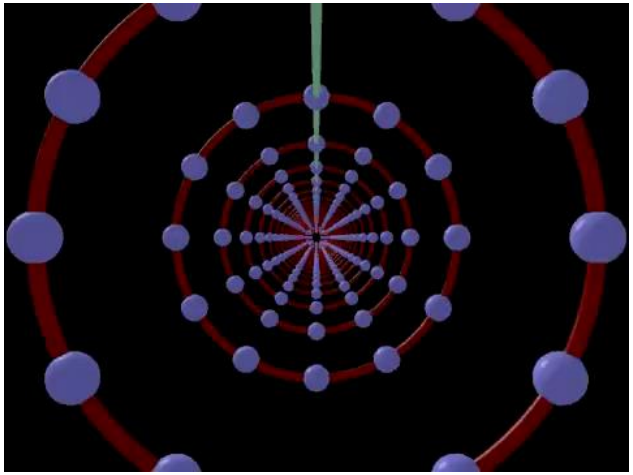
- Gravitational waves in a nutshell
  - Properties
  - Sources
- The LIGO-Virgo global network
  - Giant suspended interferometric detectors
  - Multi-messenger astronomy

See plenary talk
by Peter Shawhan
on Monday morning
(11:30-12:00)
Multi-messenger Astrophysics

- The August 2017 detections
  - LIGO-Virgo joint data taking period at the end of the Observation Run 2 (O2)
  - GW170814: the first 3-detector observation
  - GW170817: the first binary neutron star coalescence and the following kilonova
- 18 months break between O2 and O3: September 2017 → early 2019
  - LIGO-Virgo upgrades and sensitivity improvements
  - Current status
- Towards O3
  - Open public alerts
  - Expected sensitivities and rates

Gravitational waves (GW)

- One of the first predictions of general relativity (GR, 1916)
  - Accelerated masses induce perturbations of the fabric of the spacetime, propagating at the speed of light – 'speed of gravity'



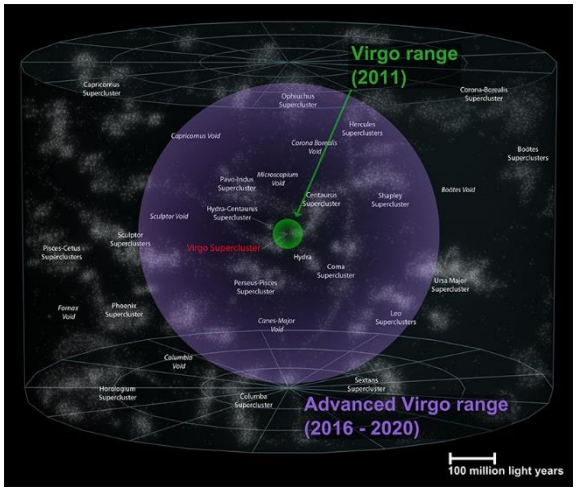
- Traceless and transverse (tensor) waves
  - 2 polarizations in GR: « + » and « × »

- Quadrupolar radiation
  - Deviation from axisymmetry to emit GW
  - No dipolar radiation

- GW strain h
  - Dimensionless
  - Scales like 1/distance

- Detectors directly sensitive to h

  → Small sensitivity gains can lead to large improvements in even rate



Gravitational waves (GW)

- One of the first predictions of general relativity (GR, 1916)
  - Accelerated masses induce perturbations of the fabric of the spacetime, propagating at the speed of light – ‘speed of gravity’

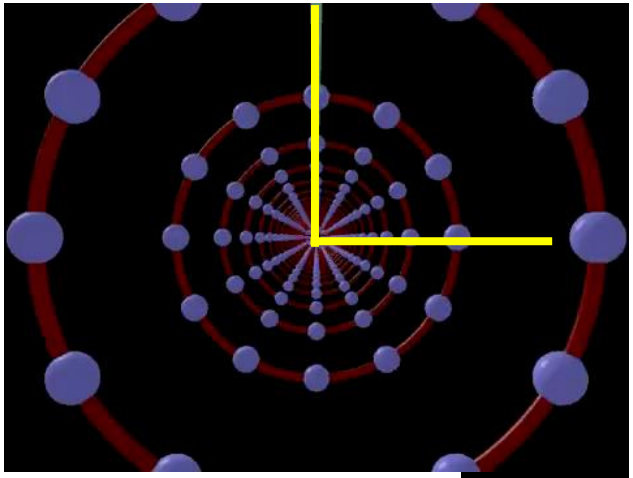
- Traceless and transverse (tensor) waves
  - 2 polarizations in GR: « + » and « × »

- Quadrupolar radiation
  - Deviation from axisymmetry to emit GW
  - No dipolar radiation

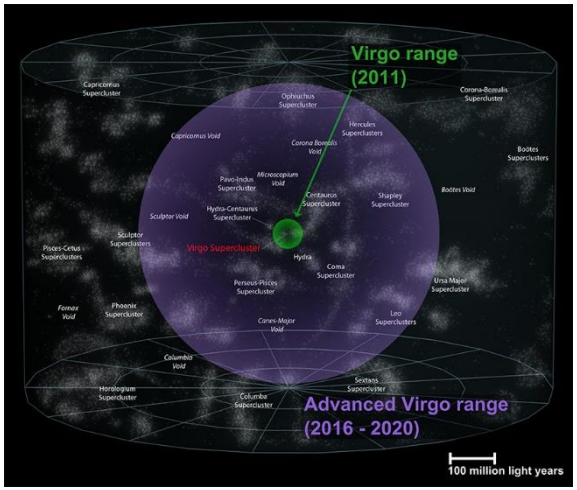
- GW strain h
  - Dimensionless
  - Scales like 1/distance

- Detectors directly sensitive to h

  → Small sensitivity gains can lead to large improvements in even rate

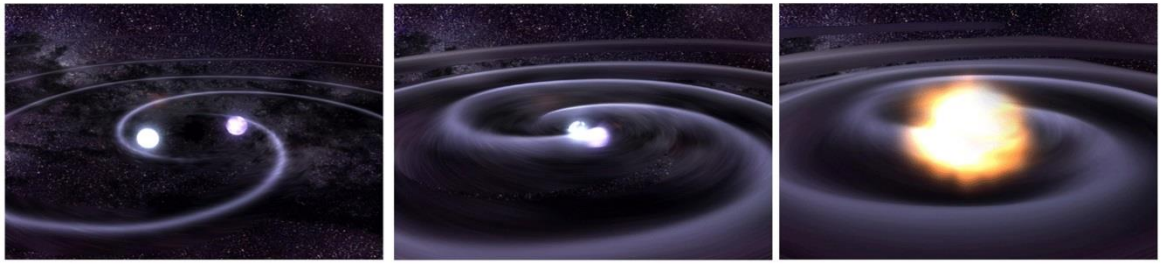


Virgo
LIGO



A diversity of sources

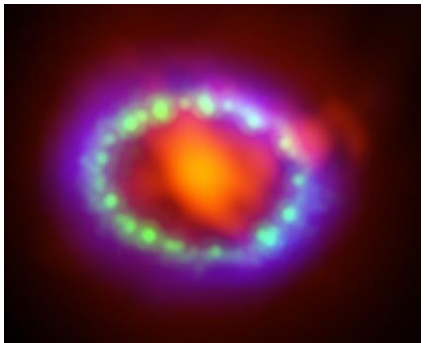
- Rough classification
  - Signal duration
  - Frequency range
  - Known/unknown waveform
  - Any counterpart (E.M., neutrinos, etc.) expected?



- Compact binary coalescence
  - Last stages of the evolution of a system like PSRB 1913+16
    → Compact stars get closer and closer while loosing energy through GW
  - Three phases: inspiral, merger and ringdown
    → Modeled via analytical computation and numerical simulations

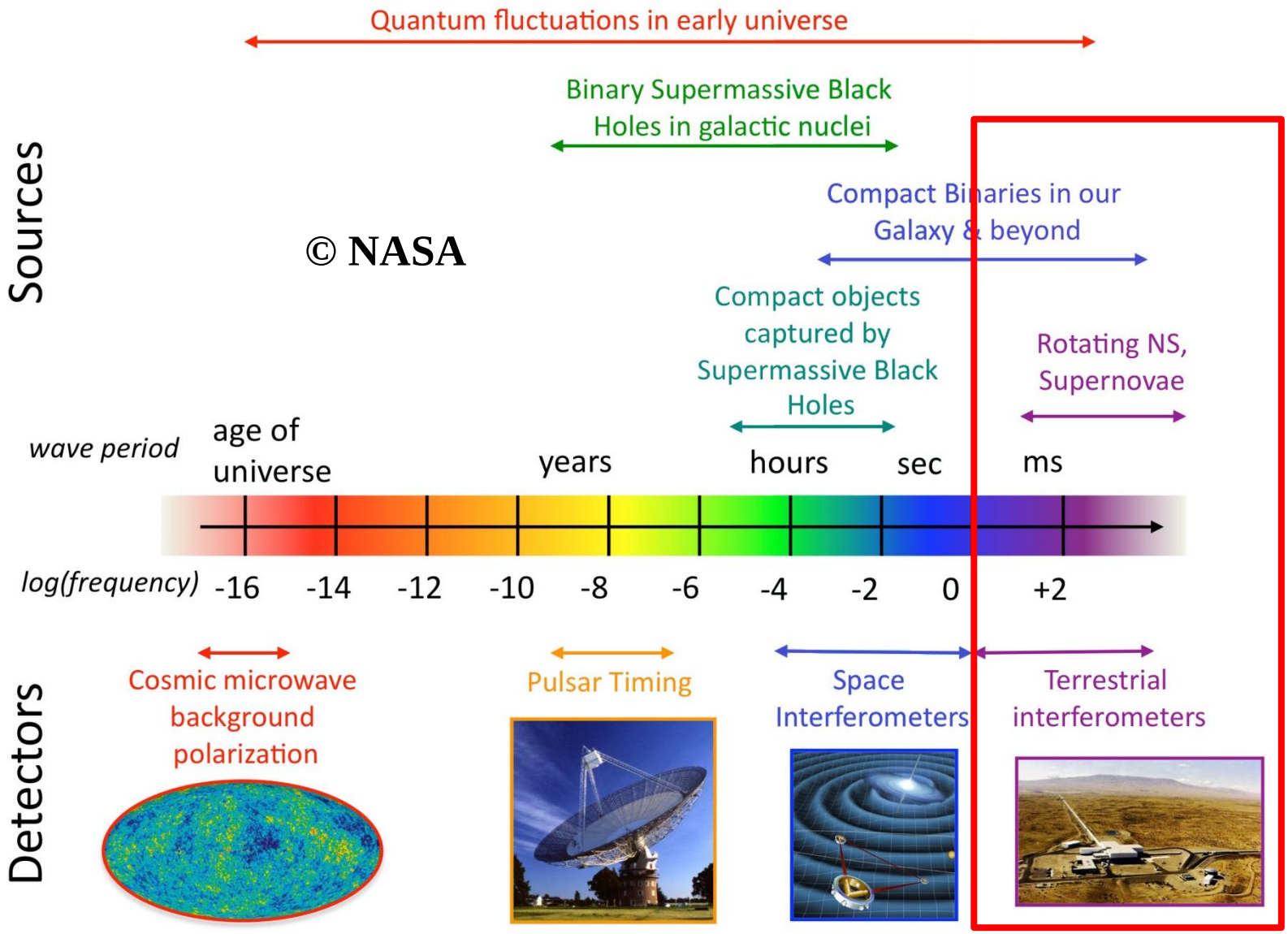
- Transient sources (« bursts »)
  - Example: type II supernovae

- Permanent sources
  - Pulsars, Stochastic backgrounds

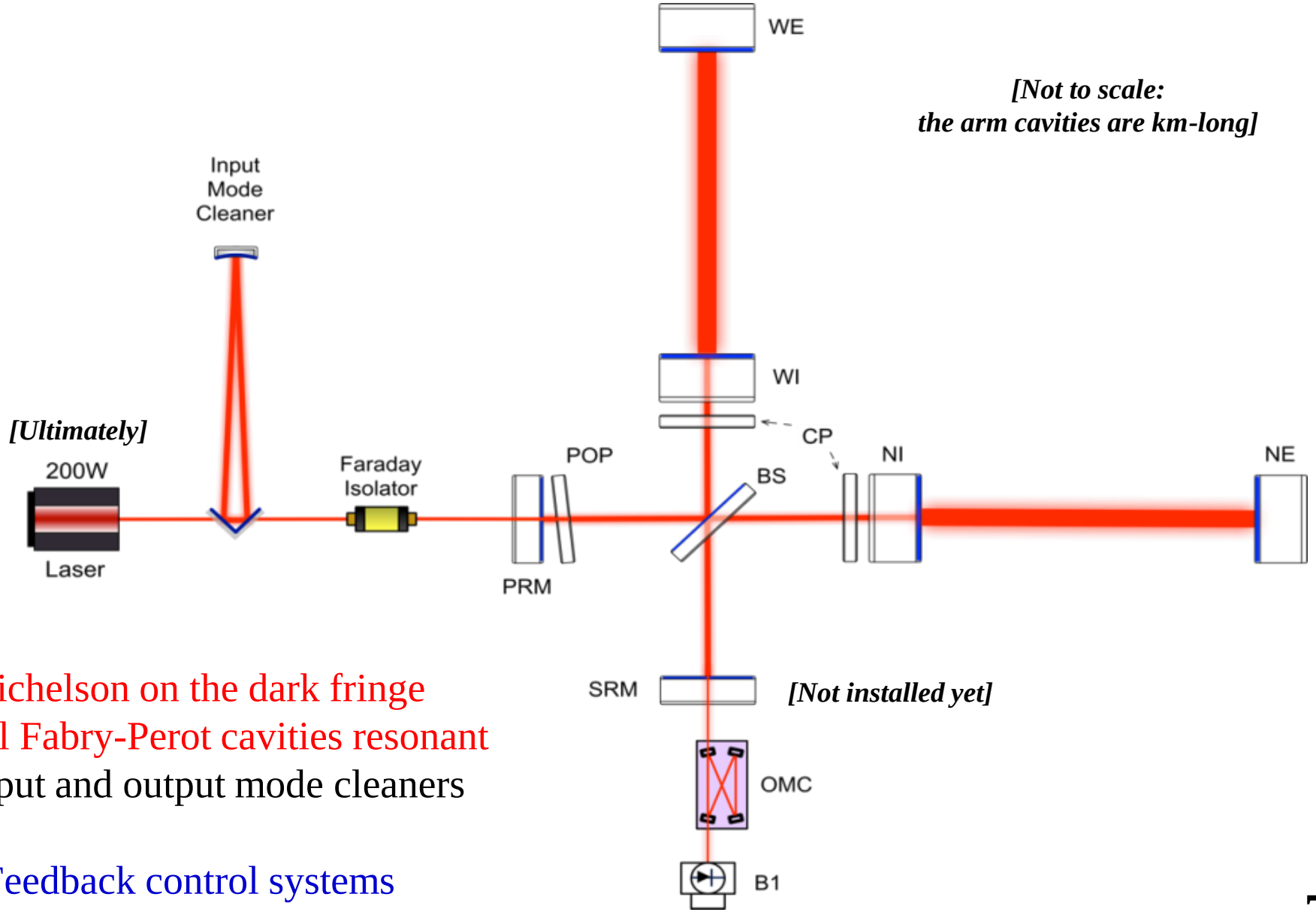


SN 1987A
Alma
Hubble
Chandra

Gravitational wave spectrum



The Advanced Virgo detector scheme

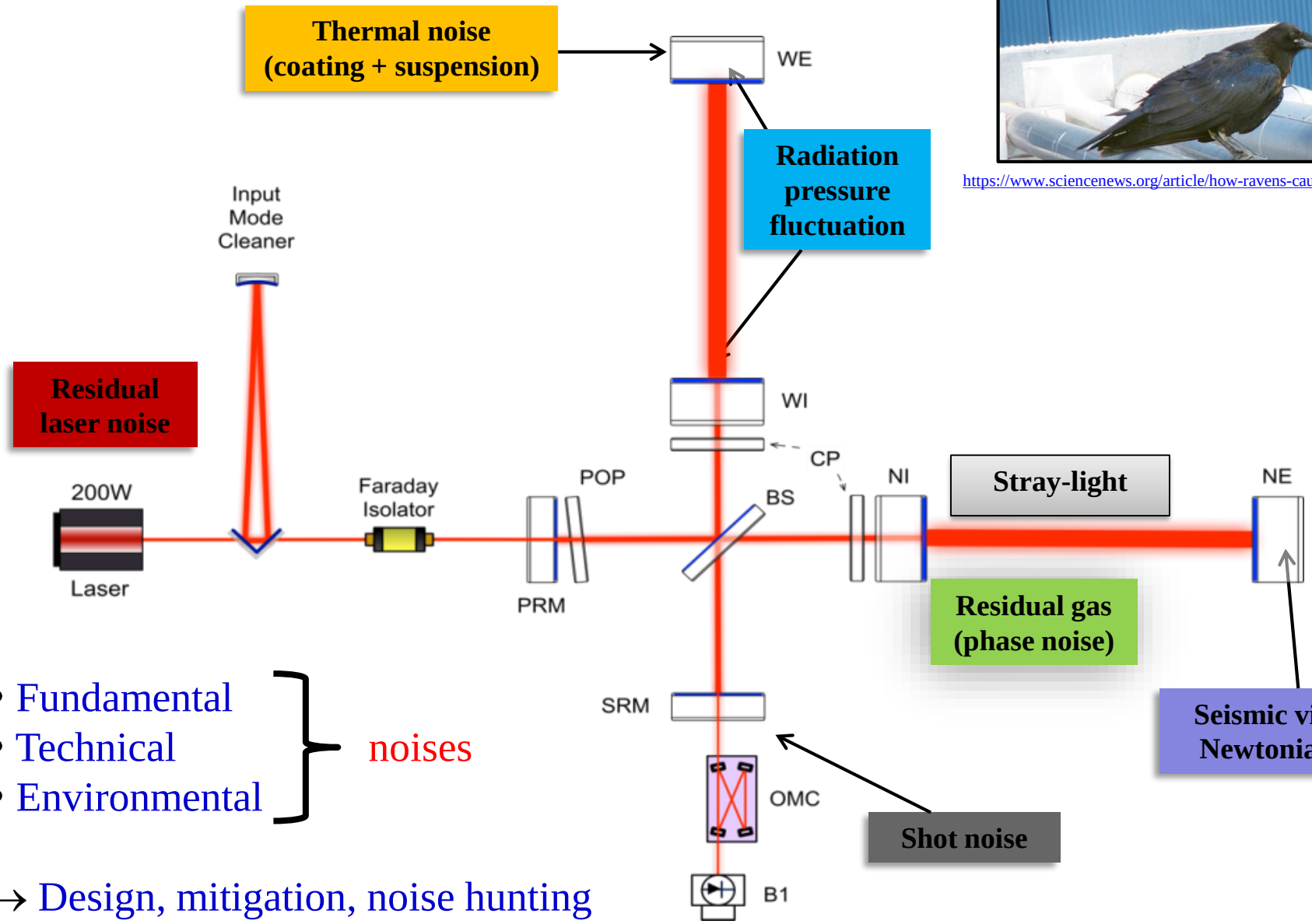


- Michelson on the dark fringe
- All Fabry-Perot cavities resonant
- Input and output mode cleaners

→ Feedback control systems

Main interferometer noises

https://www.sciencenews.org/article/how-ravens-caused-ligo-data-glitch



- Fundamental
- Technical
- Environmental

} noises

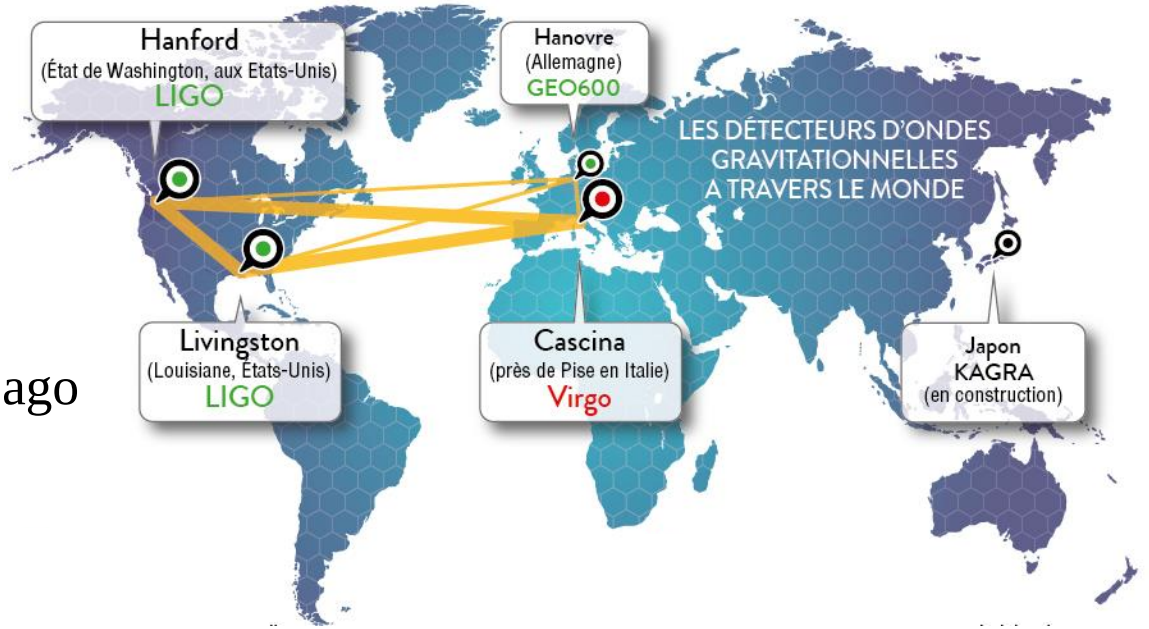
→ Design, mitigation, noise hunting

A network of interferometric detectors

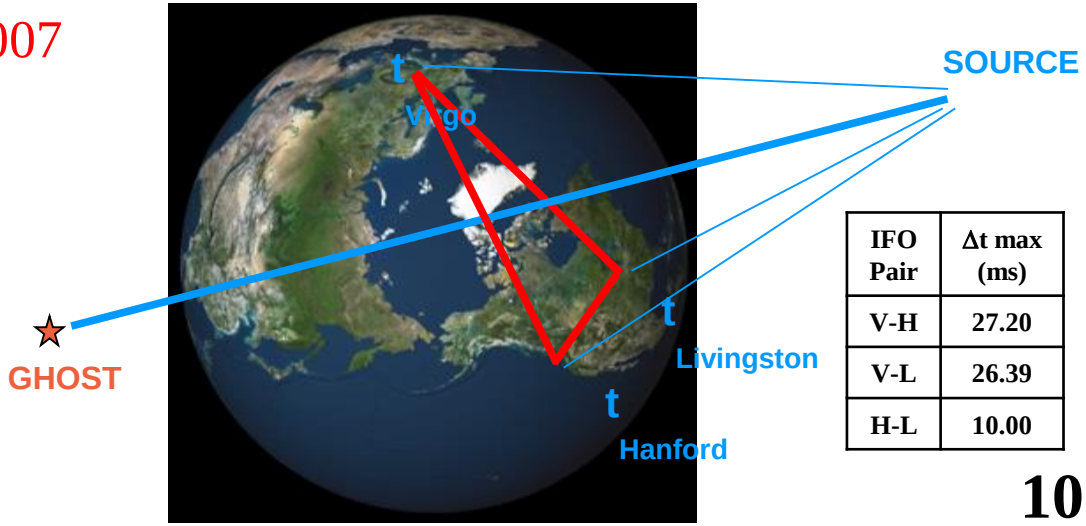
A network of interferometric detectors

- A single interferometer is not enough to detect GW
  - Difficult to separate a signal from noise confidently
  - There have been unconfirmed claims of GW detection years ago

→ Need to use a network of interferometers



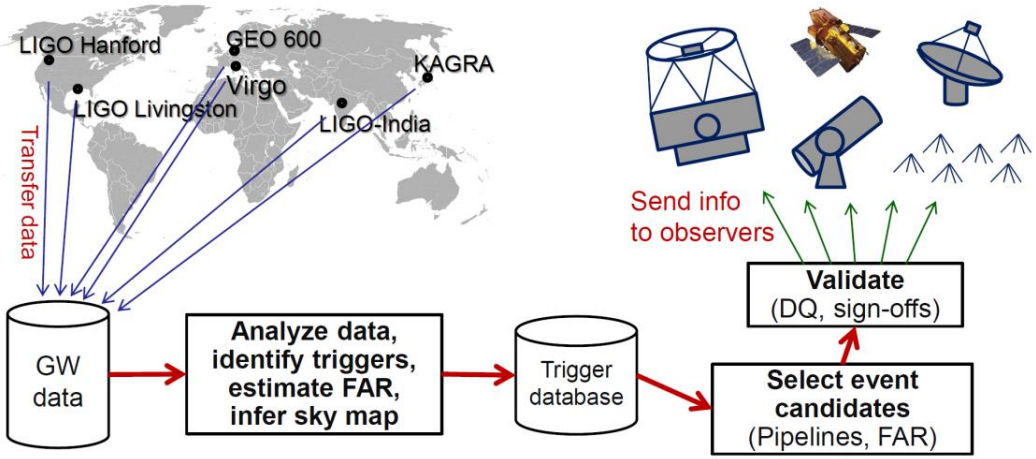
- Agreements (MOUs) between the different projects – Virgo/LIGO: 2007
  - Share data, common analysis, publish together
- IFO: non-directional detectors; non-uniform response in the sky
- Threefold detection: reconstruct source location in the sky



IFO Pair	Δt max (ms)
V-H	27.20
V-L	26.39
H-L	10.00

Exploiting multi-messenger information

- Transient GW events are energetic
  - Only (a small) part of the released energy is converted into GW
    → Other types of radiation released: electromagnetic waves and neutrinos
- Astrophysical alerts ⇒ tailored GW searches
  - Time and source location known ; possibly the waveform
    → Examples: gamma-ray burst, type-II supernova
- GW detectors are also releasing alerts to a worldwide network of telescopes
  - Agreements signed with ~90 groups – 150+ instruments, 10 space observatories



- Low latency h-reconstruction and data transfer between sites
  - Online GW searches for burst and compact binary coalescences

LIGO and Virgo data taking periods

- 2010-2016: Pluriannual upgrade program of the LIGO and Virgo detectors
  - Ultimate goal: to increase the instrument sensitivity by one order of magnitude
    → Increase the volume of Universe probed by a factor 1,000

- Observation Run 1 (« O1 »): September 2015 → January 2016
  - LIGO detectors only

  → First two detections of gravitational-wave (GW) signals
    - GW150914 (detected on 2015/09/14) and GW151226
    - In both cases the coalescence of two stellar-mass black holes

- Observation Run 2 (« O2 »): November 30, 2016 – August 25, 2017
  - Maintenance and upgrade in between O1 and O2 for the LIGO detectors
  - First the two LIGO detectors, then LIGO and Virgo from August 1st
  - More binary black hole mergers: GW170104, GW170608, GW170814
  - First binary neutron star merger: GW170817

- Then, one year of upgrade before starting the Observation Run 3 (« O3 »)
  - Early 2019, for about one year

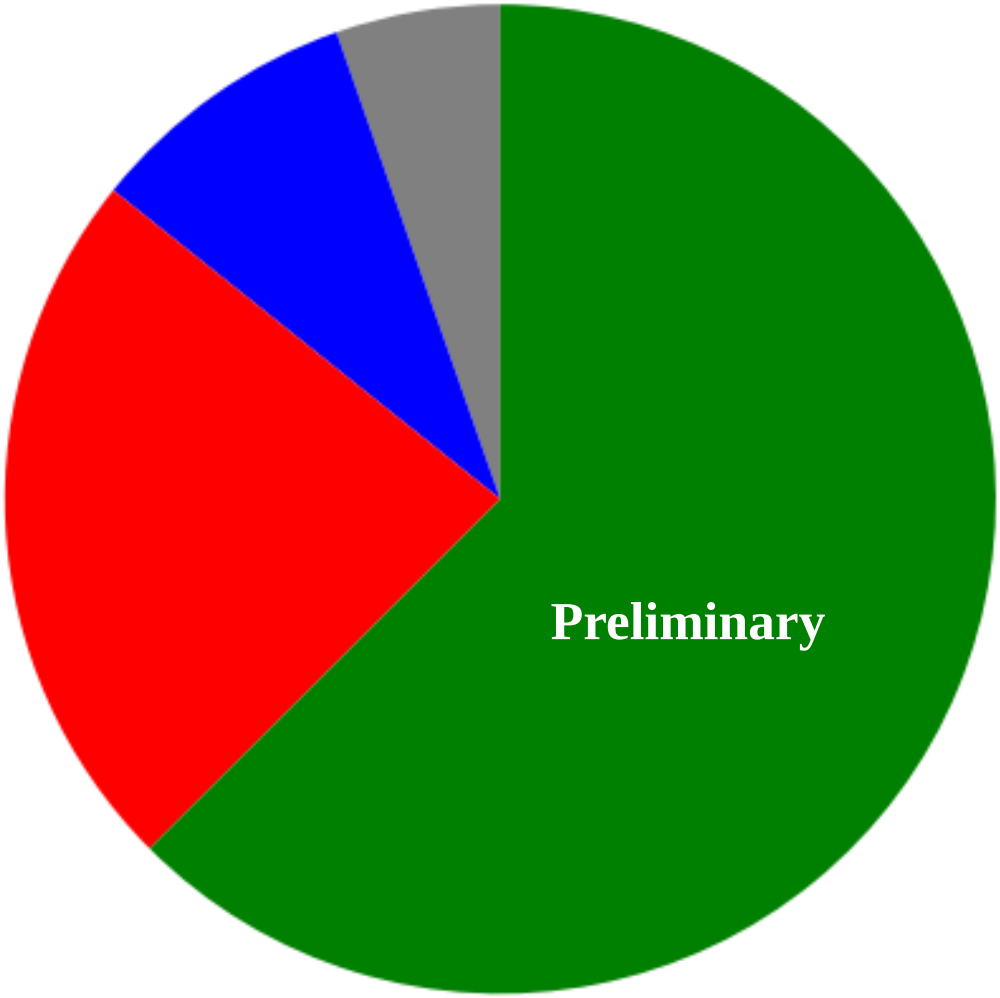
Global network data taking: August 2017

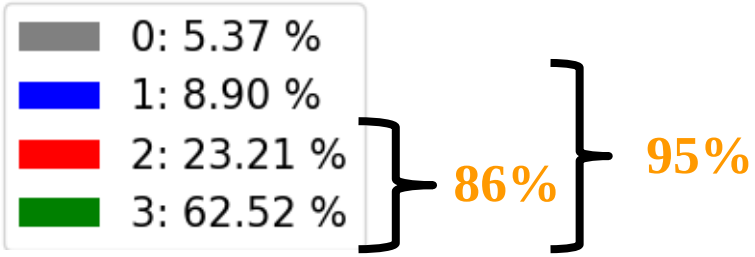
- Network duty cycle
  - Single detectors:
    Green ↔ Good science data
  - Network:

- Synchronized maintenance periods clearly visible

Global network data taking: August 2017

- Number of instruments online simultaneously for the LIGO-Virgo network

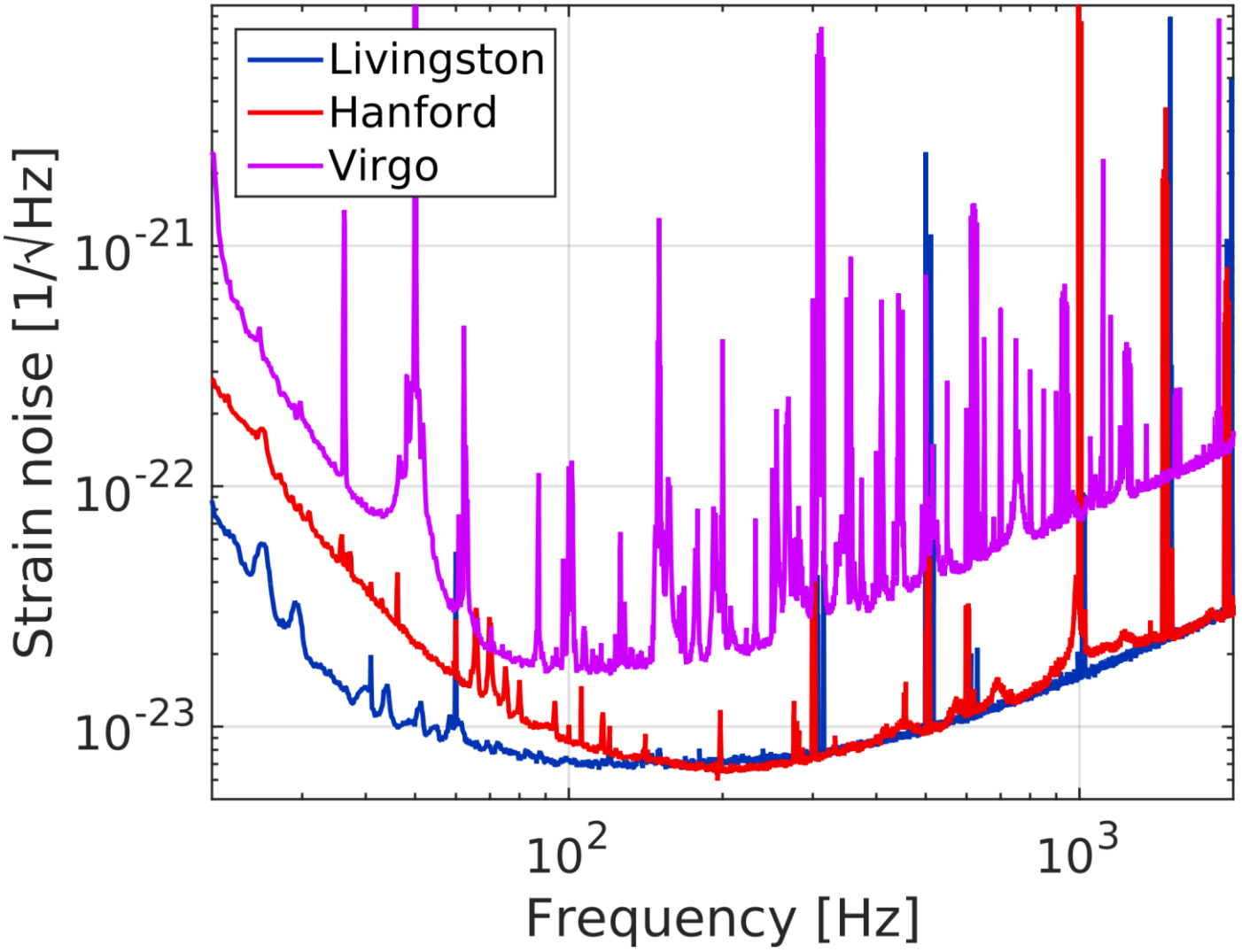




→ Plan is to improve these performances next year

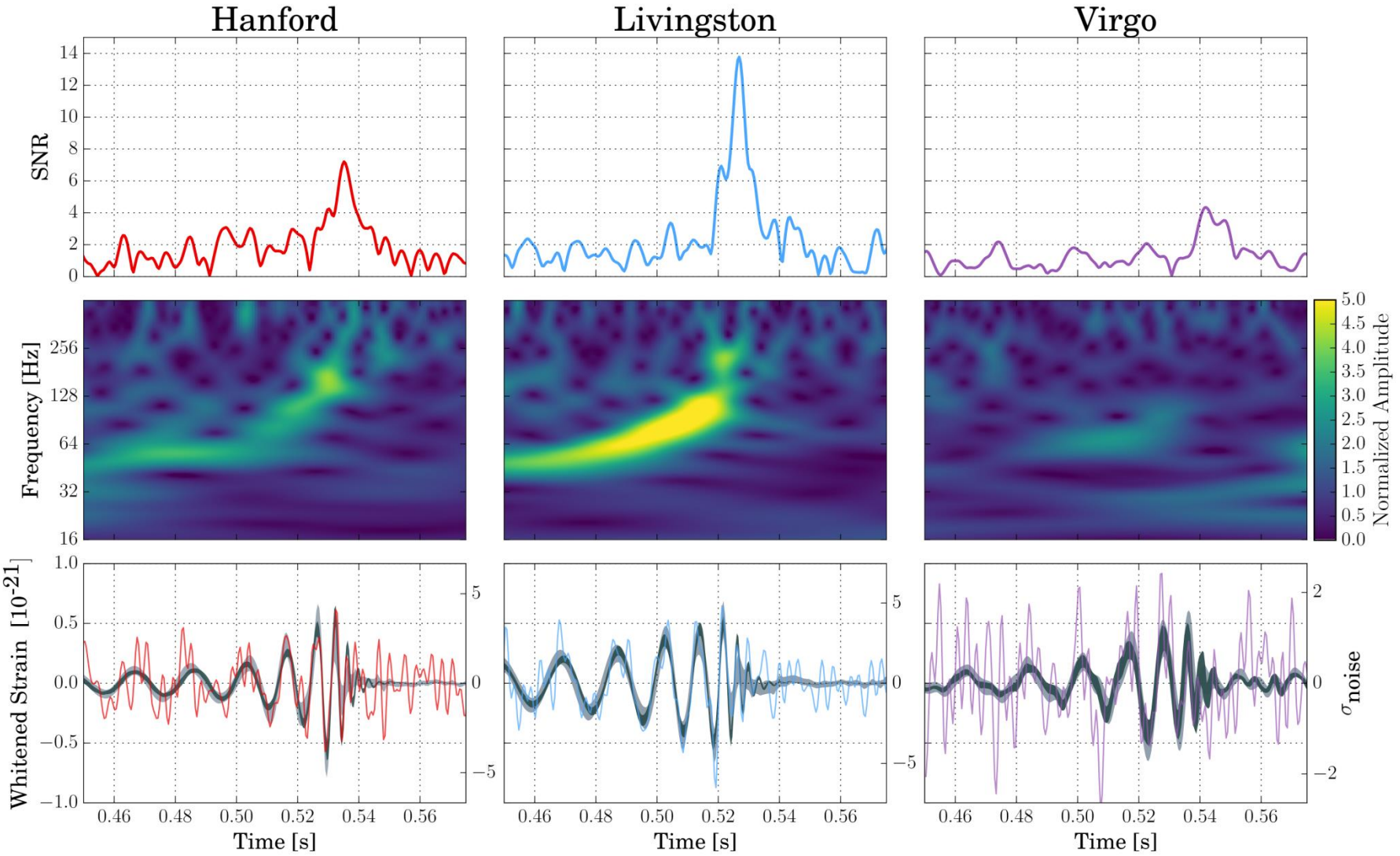
Global network data taking

- Typical August 2017 sensitivities



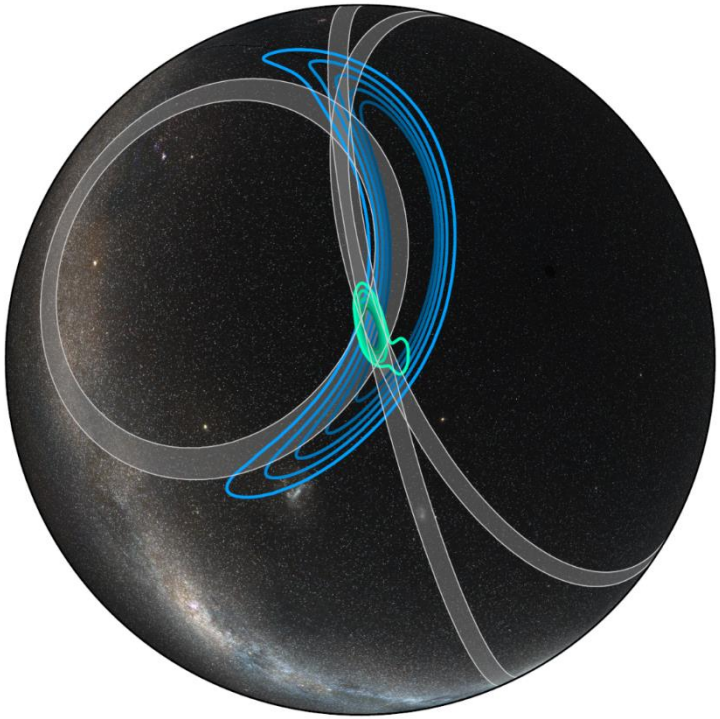
GW170814: first three-detector observation

- Another binary black hole merger



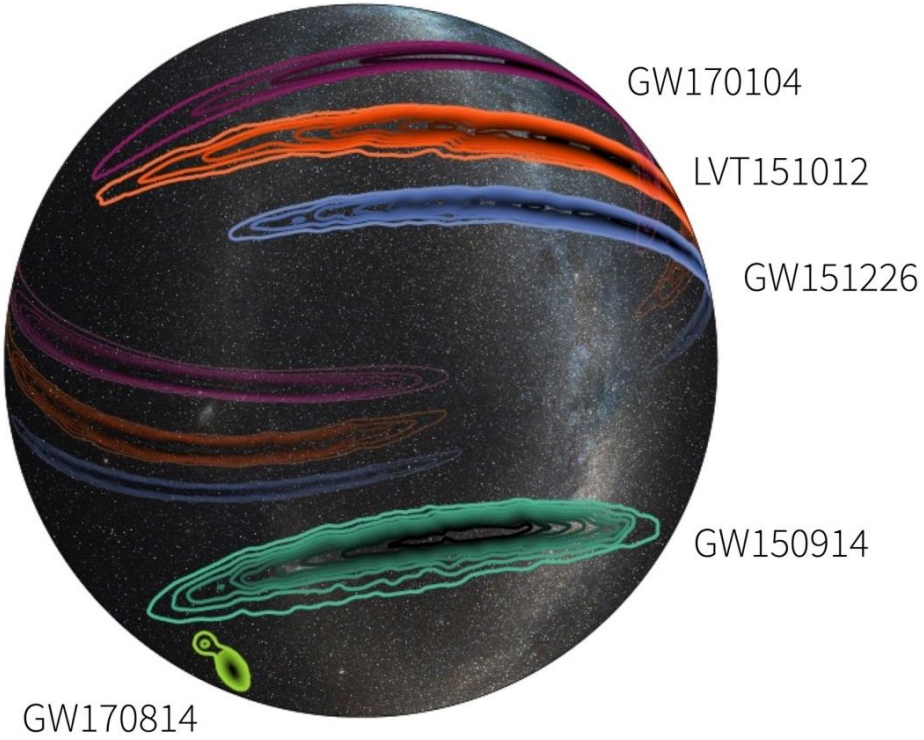
GW170814 LIGO-Virgo sky localization

- Triangulation
  - Delays in the signal arrival time between detectors
  - Difference in shape and amplitude for the detected signals



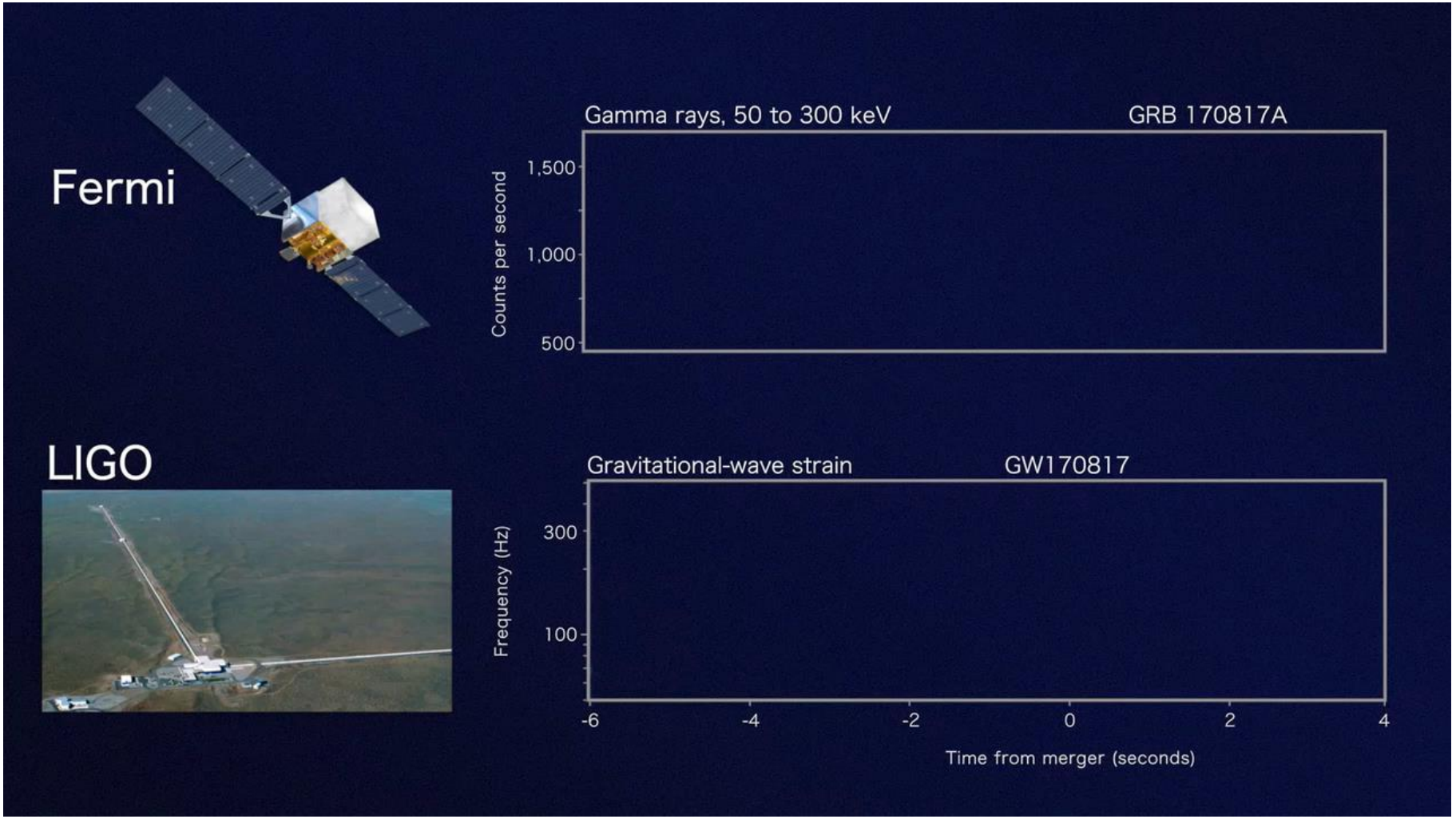
- Much-improved sky localization
  - Three detectors vs. two

  → One order of magnitude gain



GW170817: first binary neutron star merger

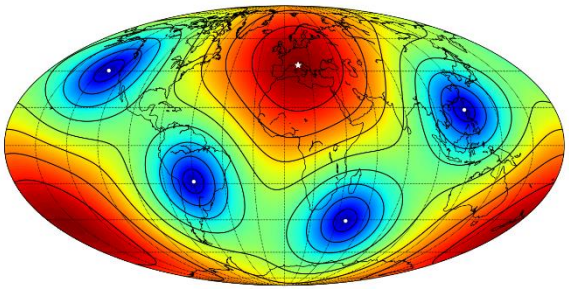
- Gravitational waves + gamma ray burst + kilonova (after source localized)

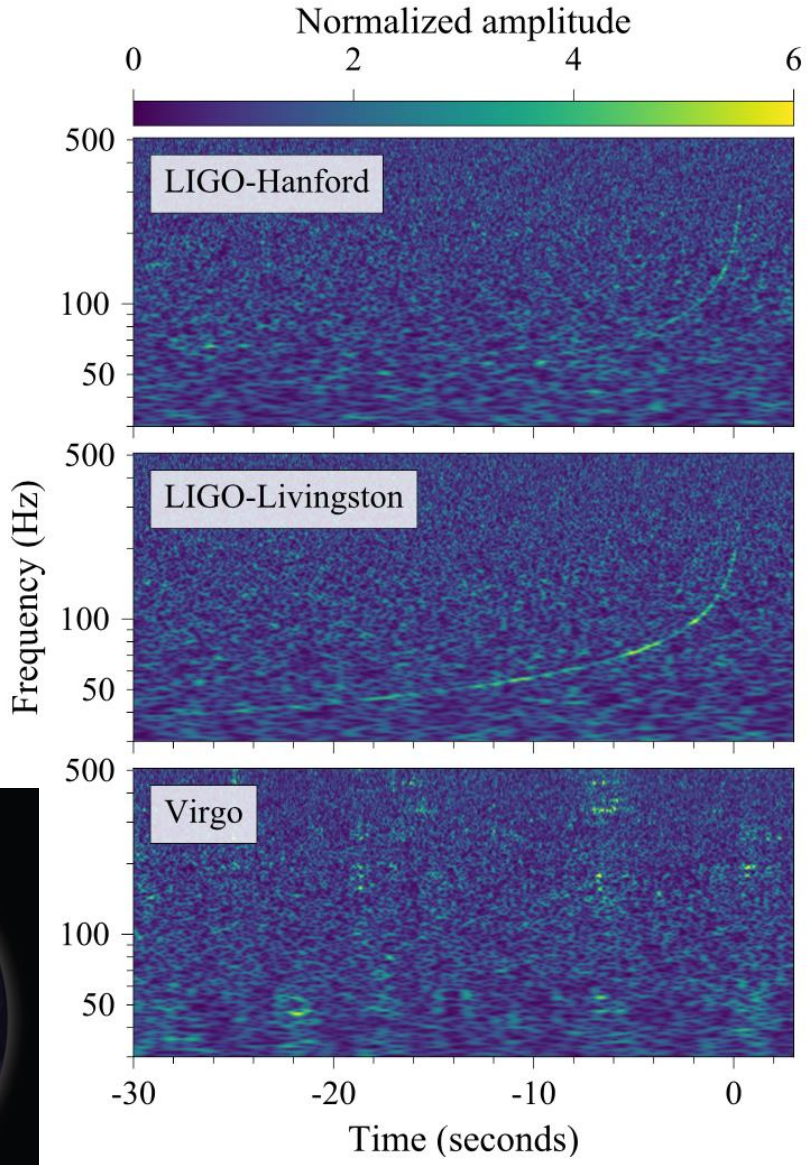


GW170817: first binary neutron star merger

- Strong signal in both LIGO detectors
- No signal in Virgo
  - Worse sensitivity
  - Source location close to a blind spot
    → Antenna pattern effect

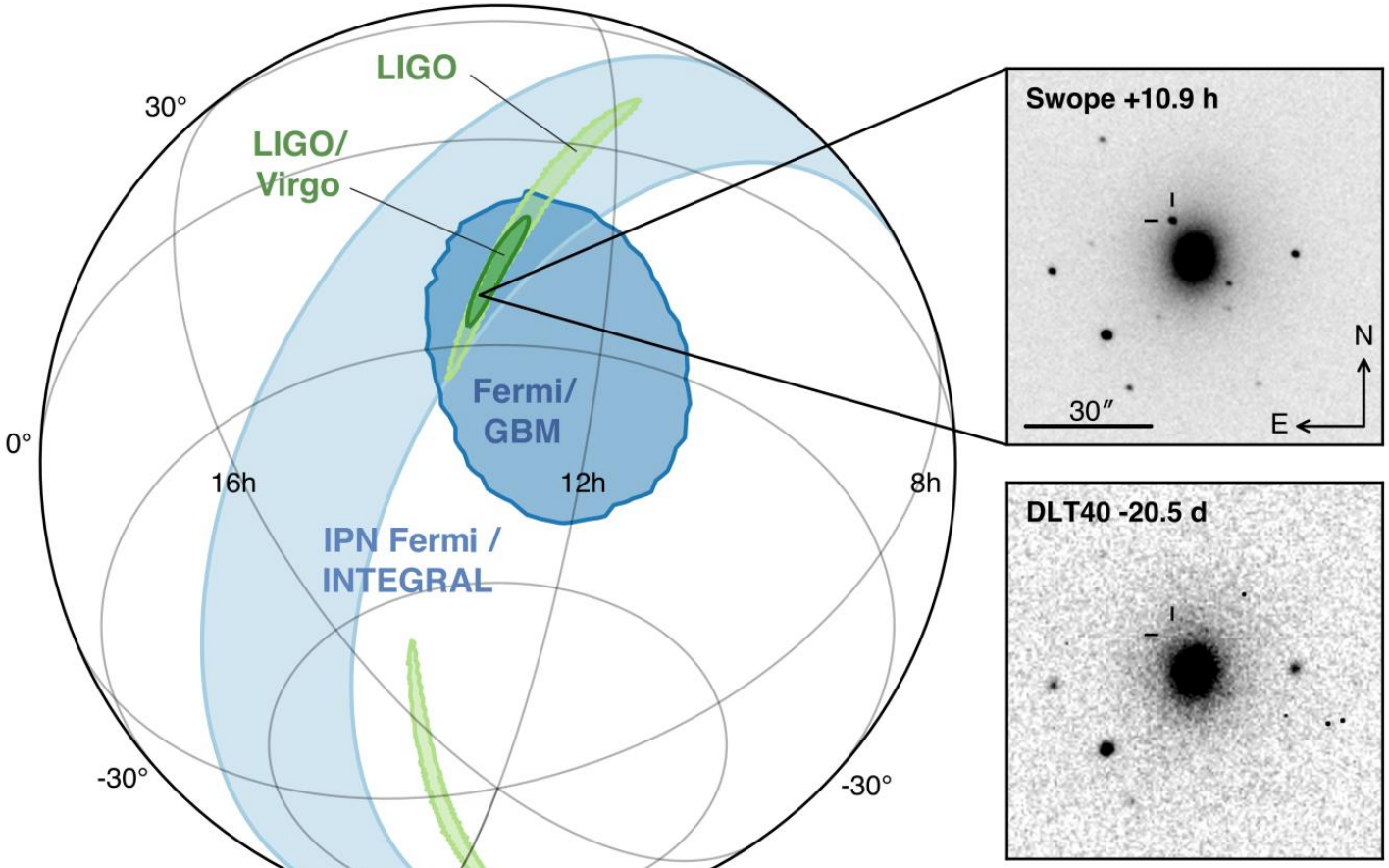
→ Accurate sky localization (30 square deg.)
  - Latency of about 5 hours
  - Consistent with Fermi and Fermi-Integral localizations





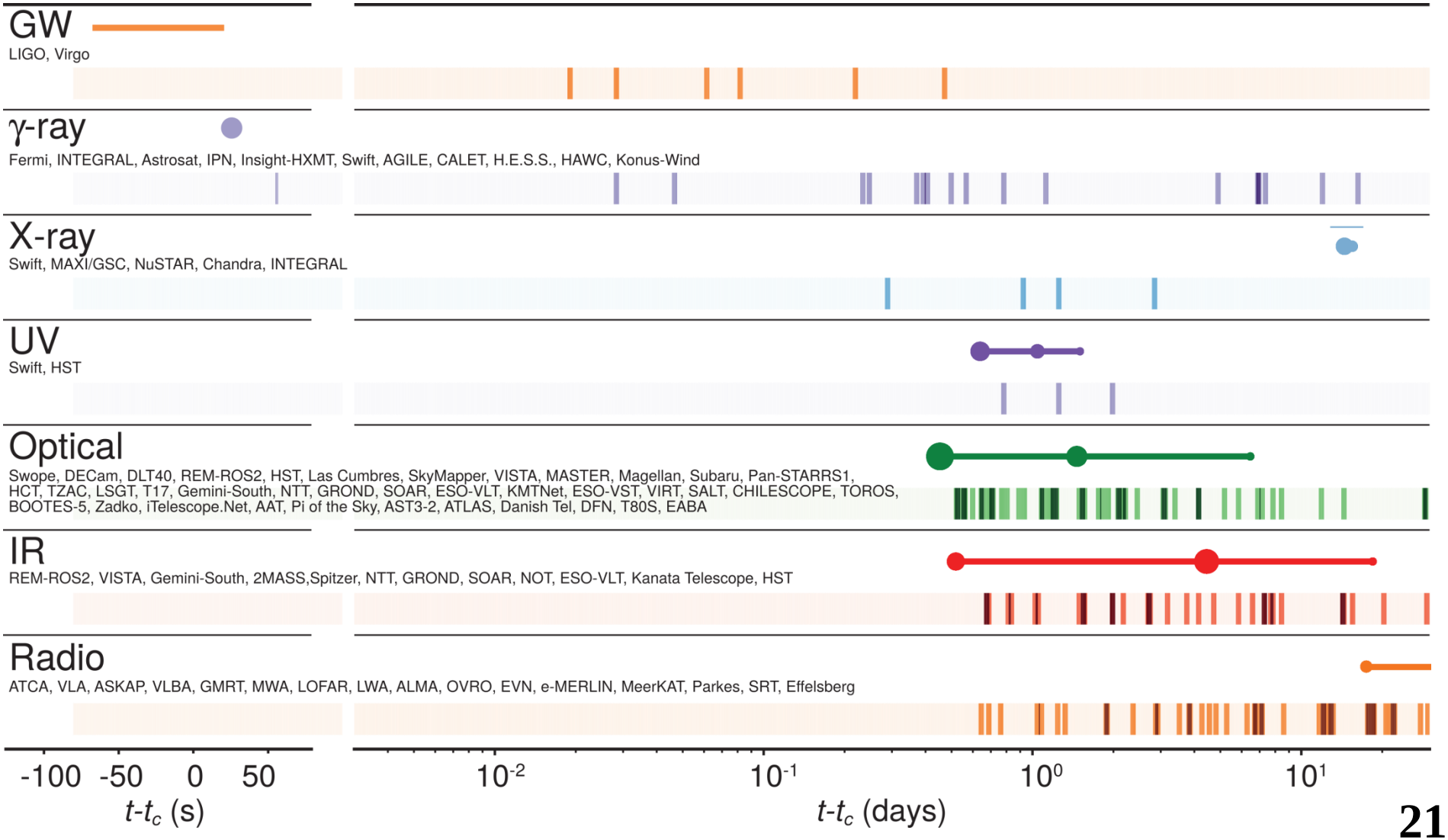
GW170817 sky localizations & source position

- Green: LIGO and LIGO + Virgo
- Blue : information from gamma ray burst satellites
- Optical discovery
  - Telescope Swope



GW170817 multi-messenger astronomy

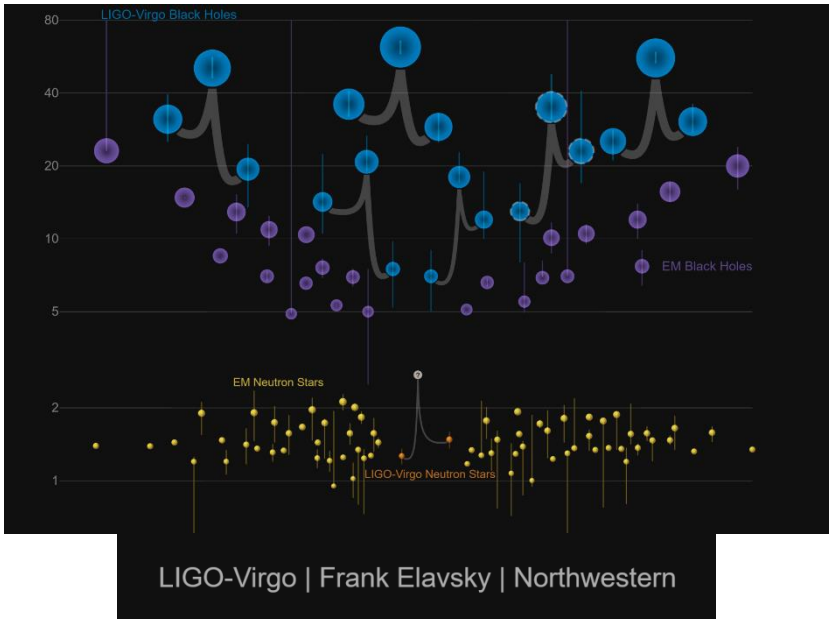
- Gravitational waves + gamma ray burst + whole electromagnetic spectrum

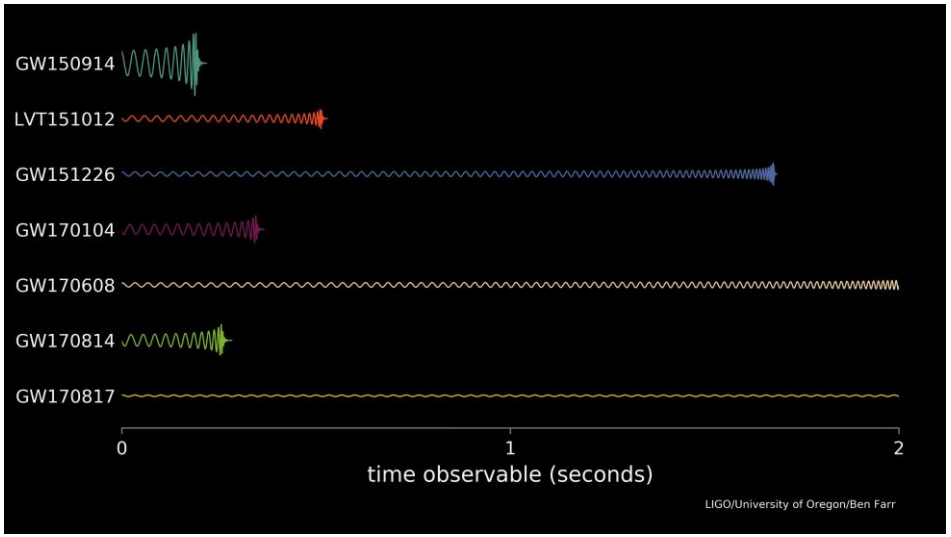


Summary of LIGO-Virgo published detections

- Observation Runs 1 and 2

- Five binary black hole coalescences
  - GW150914, GW151226, GW170104, GW170814, GW170608
- One neutron star coalescence: GW170817



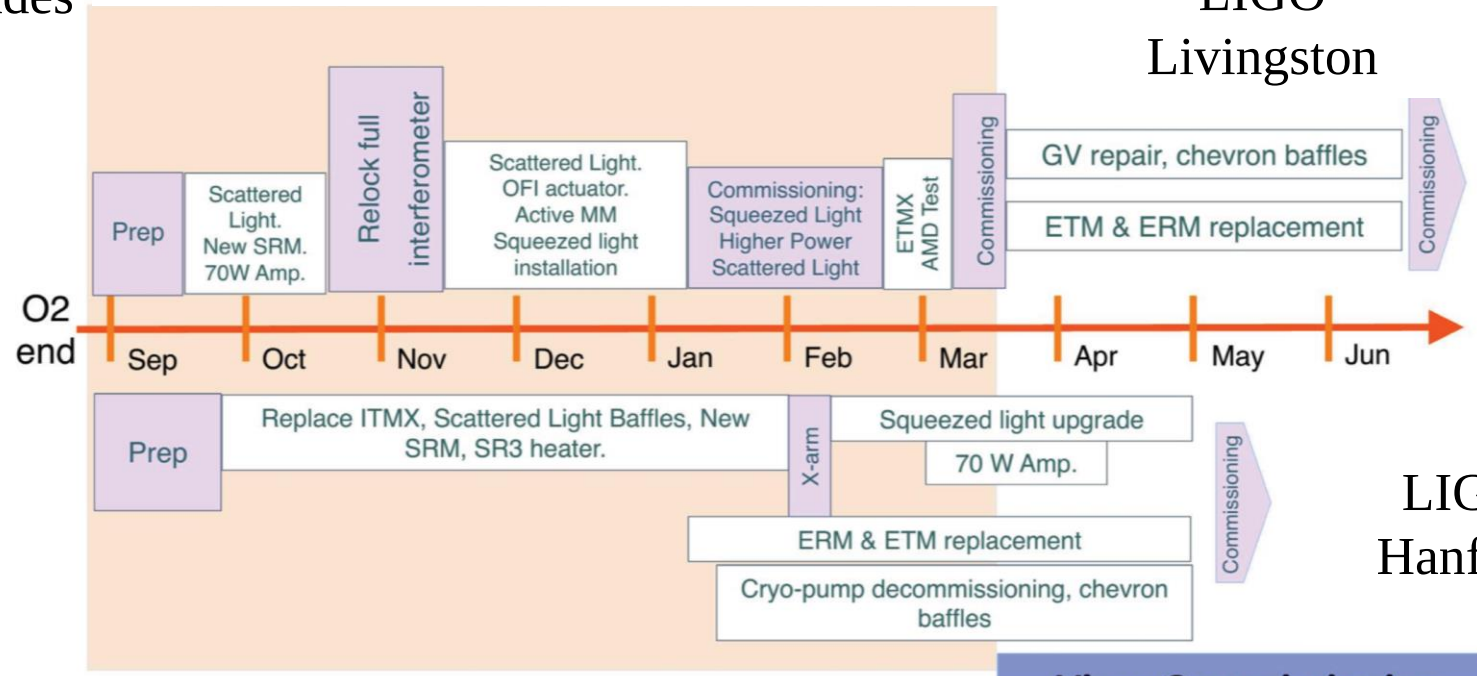


- O2 catalog paper in preparation
  → Should be released after the Summer

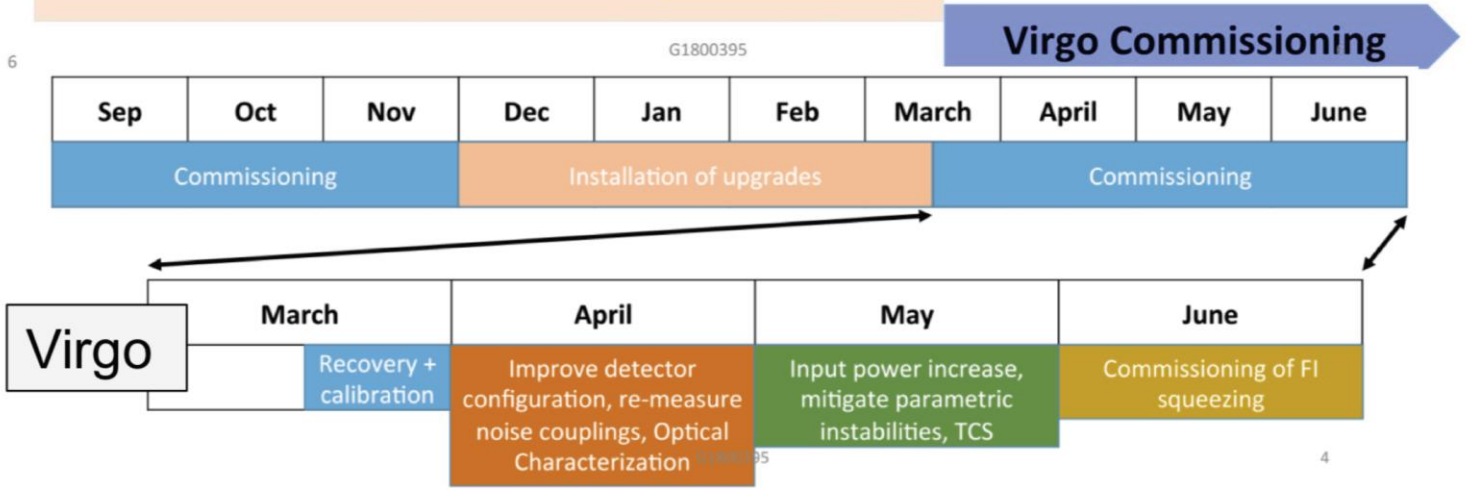
One year-long LIGO-Virgo shutdown

- Upgrades

LIGO Livingston



LIGO Hanford



Virgo upgrades and commissioning

- Hardware upgrades
  - High-power laser (up to 50W delivered)
  - Monolithic suspensions
  - Vacuum system
  - Frequency-independent squeezing
  - Installation of an array of seismic sensors to measure the Newtonian noise

- Technical and environmental noise hunting
  - Use experience gained during the commissioning and O2 data taking phases
  - Improve/tighten detector control

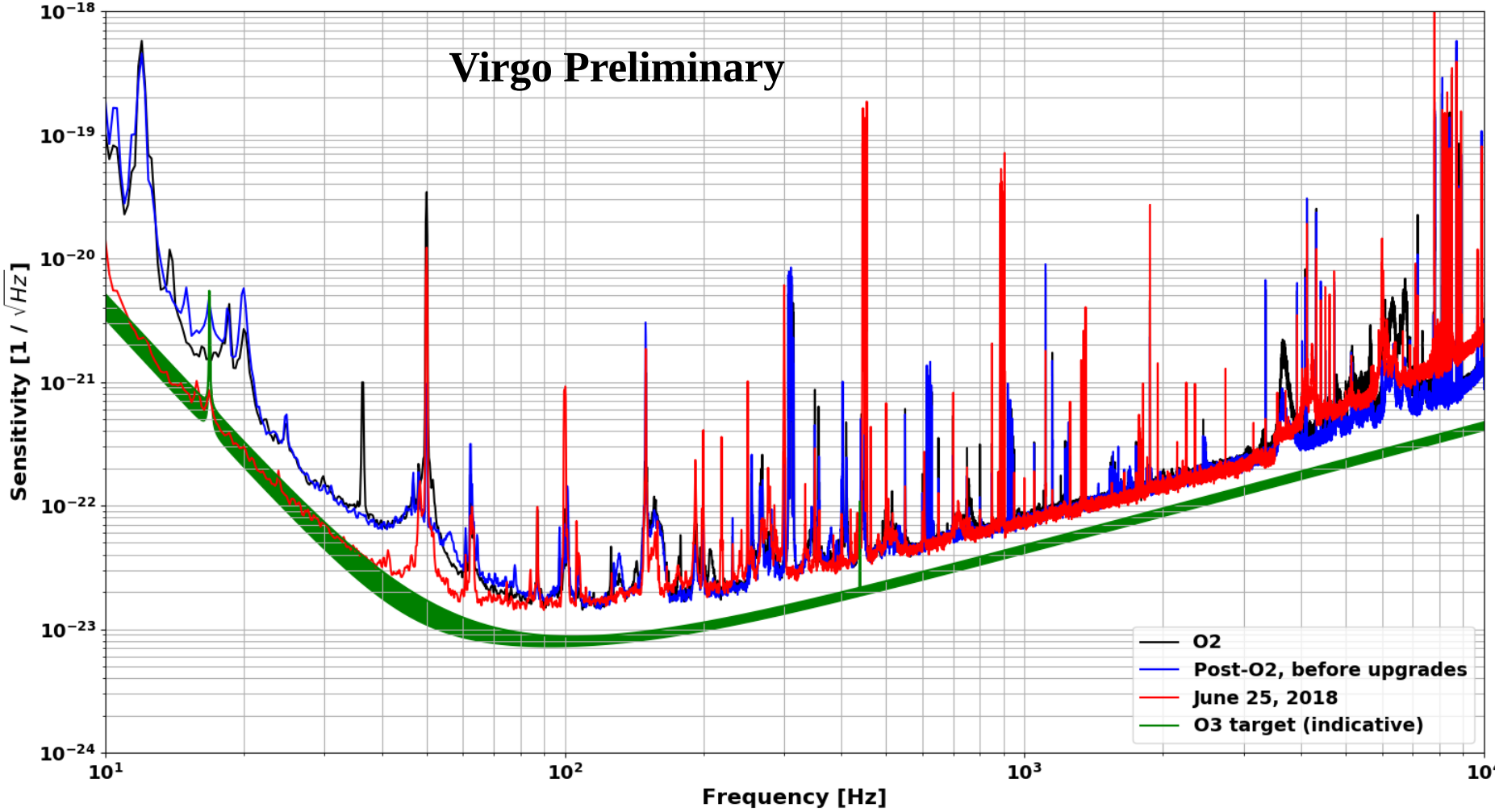
→ Planning
  - Post-O2 commissioning phase until early December 2017
  - Hardware upgrades until mid-March 2018
  - Then back to commissioning until end of the year
    - Sensitivity already improved with respect to the O2 data taking period

} Planning on track

- Reminder: O3 run will start in early 2019 with all detectors (Virgo + LIGO) online

Current Virgo performance

- End of June
- O2
- Post-O2, before upgrades
- Indicative O3 target



→ Improvement already significant for binary black-hole coalescences

Virgo improvements and plans

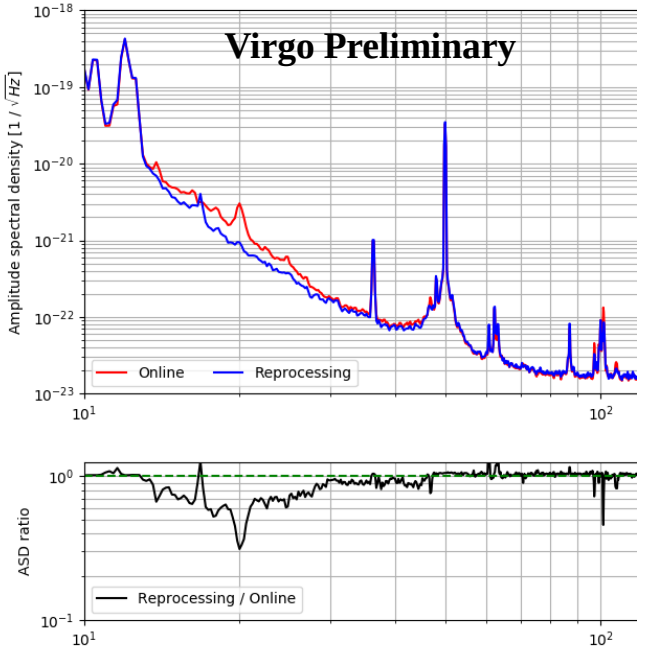
- Improved steering of the new monolithic suspensions

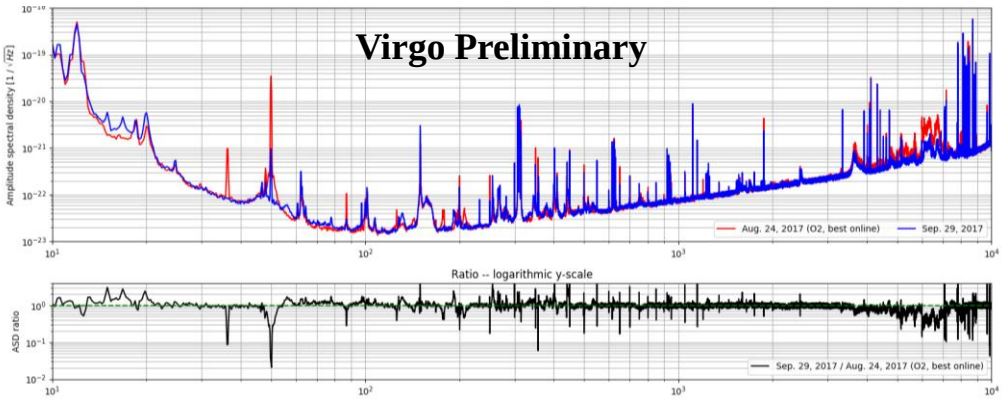
- Online subtraction of noise contributions
  - Offline as well
    → Reprocessing

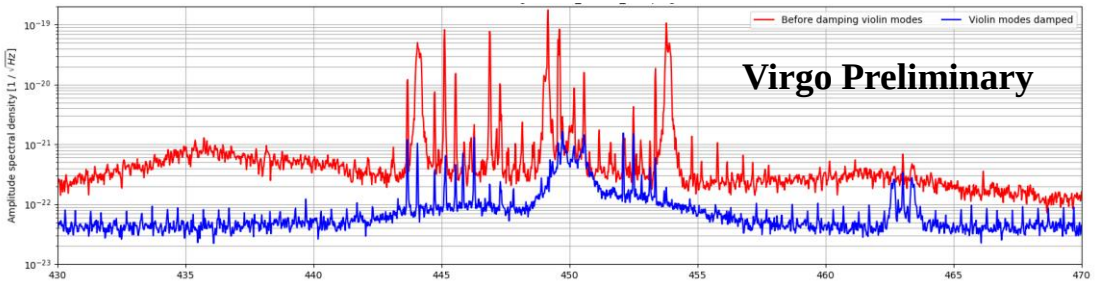
- Noise hunting

- Violin mode damping
  - Suspension wire resonances

- Next steps
  - Laser input power increase
    → Thermal effects, etc. to be mitigated
  - More noise hunting

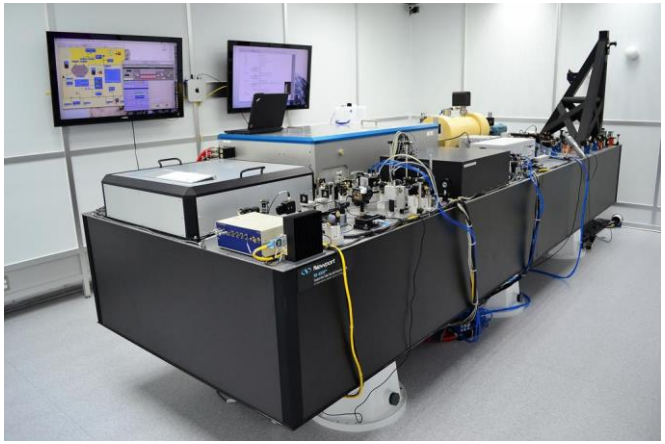






LIGO upgrades and commissioning

- Major hardware upgrade at both sides
  - Stray light control
  - Mirror replacement
  - Environment sensors
  - Increasing laser power
  - Decreasing laser noise
  - Squeezed light source



- Lessons learned from past commissioning periods
  - LIGO Hanford: attempted high power operation
  - LIGO Livingston: concentrated on low-frequency noise mitigation

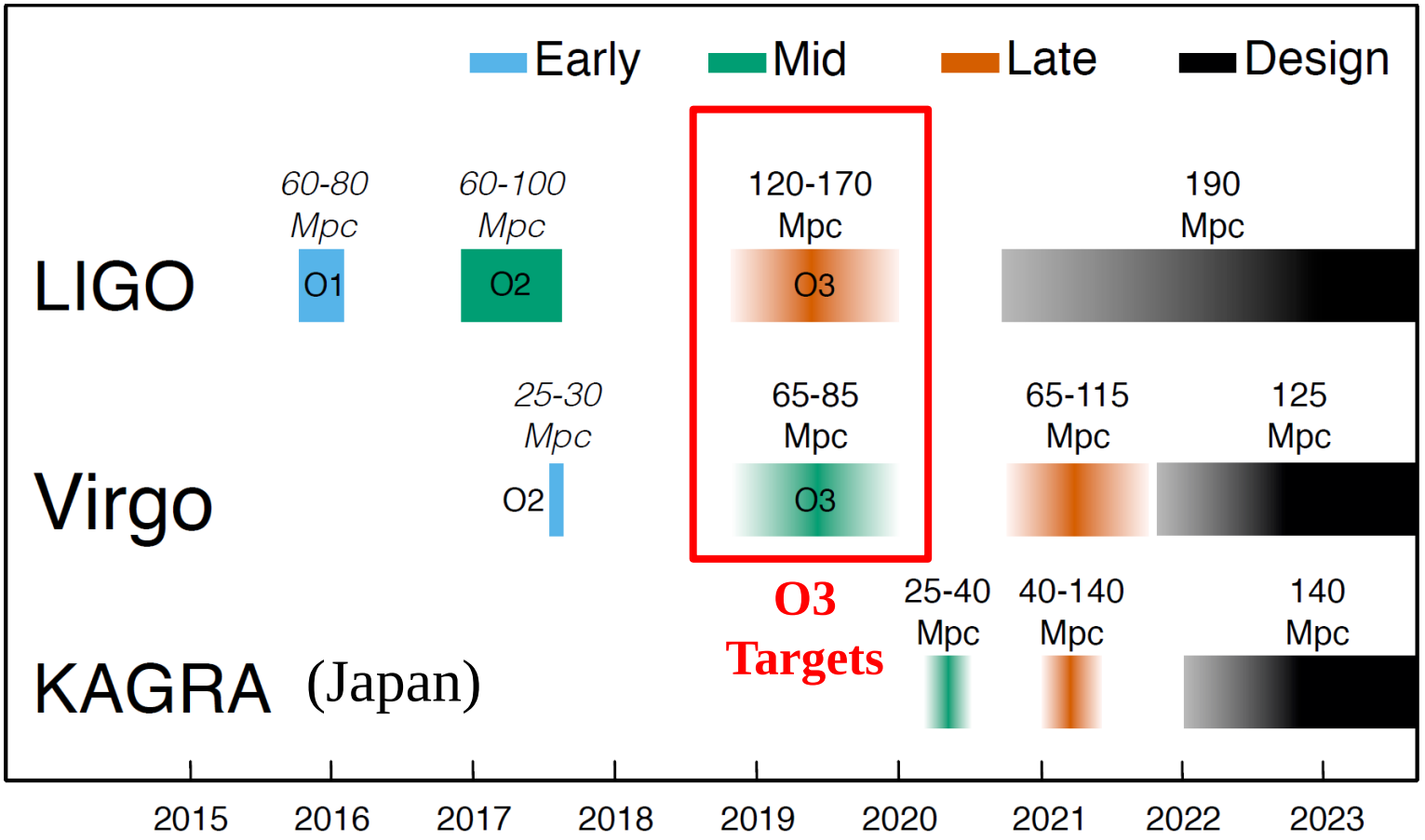
- In-vacuum work to be done in the coming weeks
  - Limited delay due to the breaking of some monolithic suspension wires
  - Then back to commissioning / sensitivy improvement / noise hunting

→ LIGO Livingston: clear path from the O2 sensitivity to the O3 goal
LIGO Hanford: low-frequency noise reduction needed to achieve this goal

Observing scenario

https://doi.org/10.1007/s41114-018-0012-9

- Sensitivity improvement over time
  - Expressed in terms of « Binary Neutron Star (BNS) range »
    → Sky- and orientation-averaged distance up to which
    one can detect a BNS merger with a signal-to-noise ratio of 8



Possibly online before end of O3

O3: GW alerts and telescope follow-up

- https://gw-astronomy.org/wiki/OpenLVEM/TownHallMeetings2018, Amsterdam

- LIGO-Virgo alerts during O3 will all be public
  - False alarm rate ⇔ Purity
  - Compact binary coalescence candidates / bursts

- Information provided through GCN(*) notices and circulars
  - Lowest possible latency – O(10 minutes), maybe less!?
  - Automated checks (detector status, data quality, environment) followed by human vetting
    → Possible retraction notices after a few hours at most

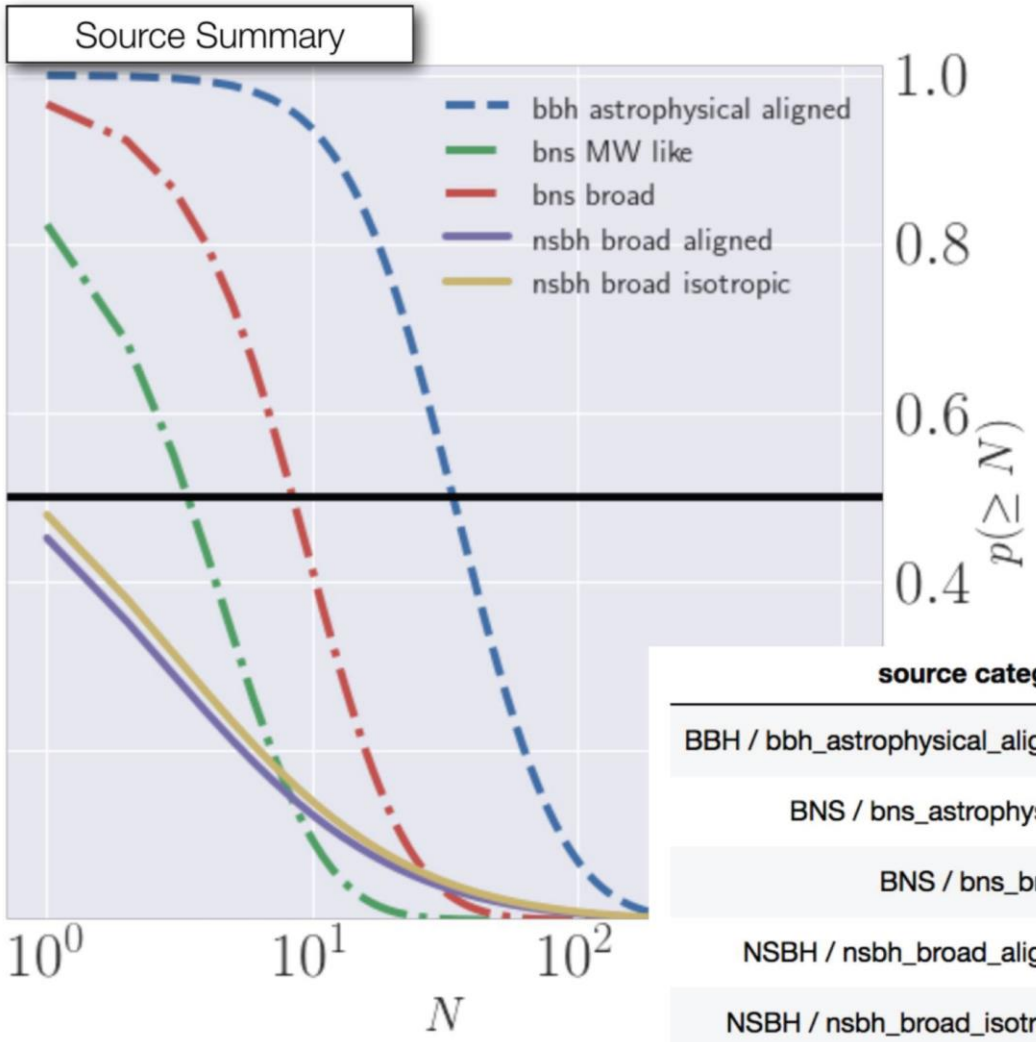
- Data public after 18 months
  - Work in progress to define the LIGO-Virgo core science program
  - 1 hour of data already public around the event when discovery published

→ Communication expected both ways: LIGO-Virgo ⇔ Astronomers

(*) **GCN: gamma-ray burst coordinates network**

O3: Expected rates

- https://gw-astronomy.org/wiki/OpenLVEM/TownHallMeetings2018, Amsterdam



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}

On the longer term

- Post-O3 Virgo upgrades
  - Newtonian noise cancellation
  - Frequency-dependent squeezing
  - Signal recycling
  - Full-power laser (up to 200 W)

  → Virgo sensitivity goal: ~160 Mpc [BNS range]
- After O4 (mid-2022): « Advanced Virgo + »

  → Make the best possible use of the existing infrastructure
  - Larger mirrors
  - Improved coating

  → Reduce thermal noise

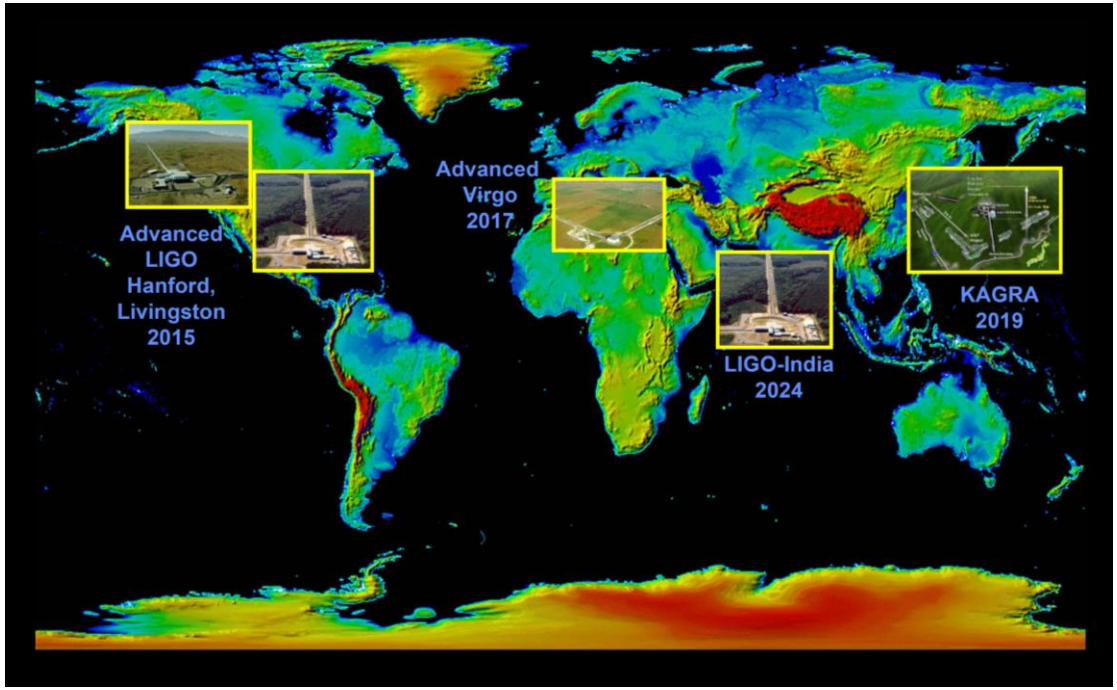
  → Sensitivity goal: ~300 Mpc [BNS range]

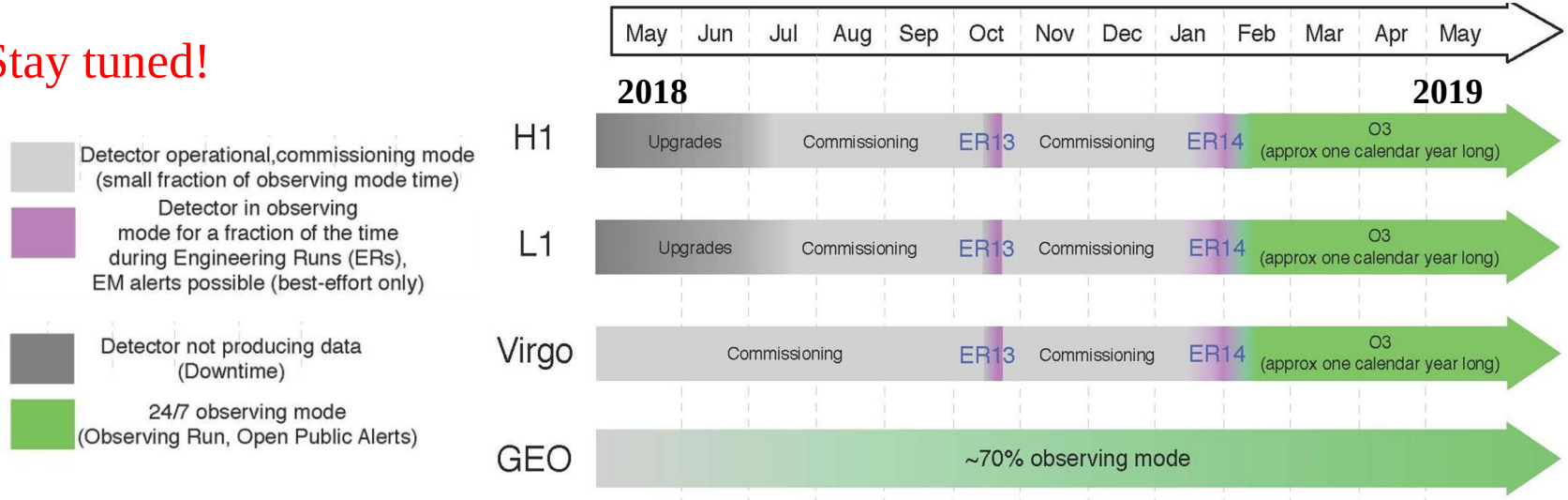
Similar plans for LIGO

- Launch of the LISA space mission scheduled for 2034

  → Space detector complementary with ground-based observatories
- Projects of third-generation detectors
  - Einstein telescope: continental Europe
  - Cosmic explorer: US + UK

Outlook



- The global network of advanced gravitational-wave detectors is now a reality
- Sensitivity already good enough to detect gravitational waves
  - Improvements expected in the near future
    → Upgrade program until end of 2018 for both LIGO and Virgo
  - Roadmap document being written about the update of the Advanced detectors
  - R&D activities already ongoing for 3rd generation instruments

→ Stay tuned!