EGO/Virgo Visit

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EGO EUROPEAN GRAVITATIONAL OBSERVATORY

cnrs dépasser les frontières

IJCLab Irène Joliot-Curie

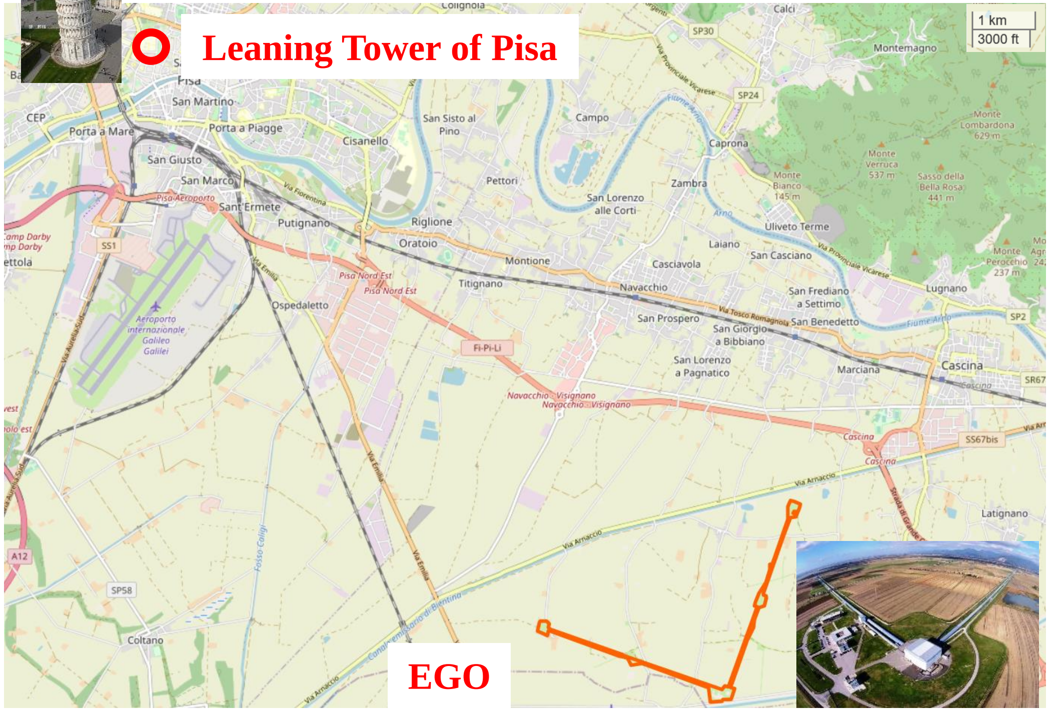
UNIVERSITÉ PARIS SUD

université PARIS-SACLAY

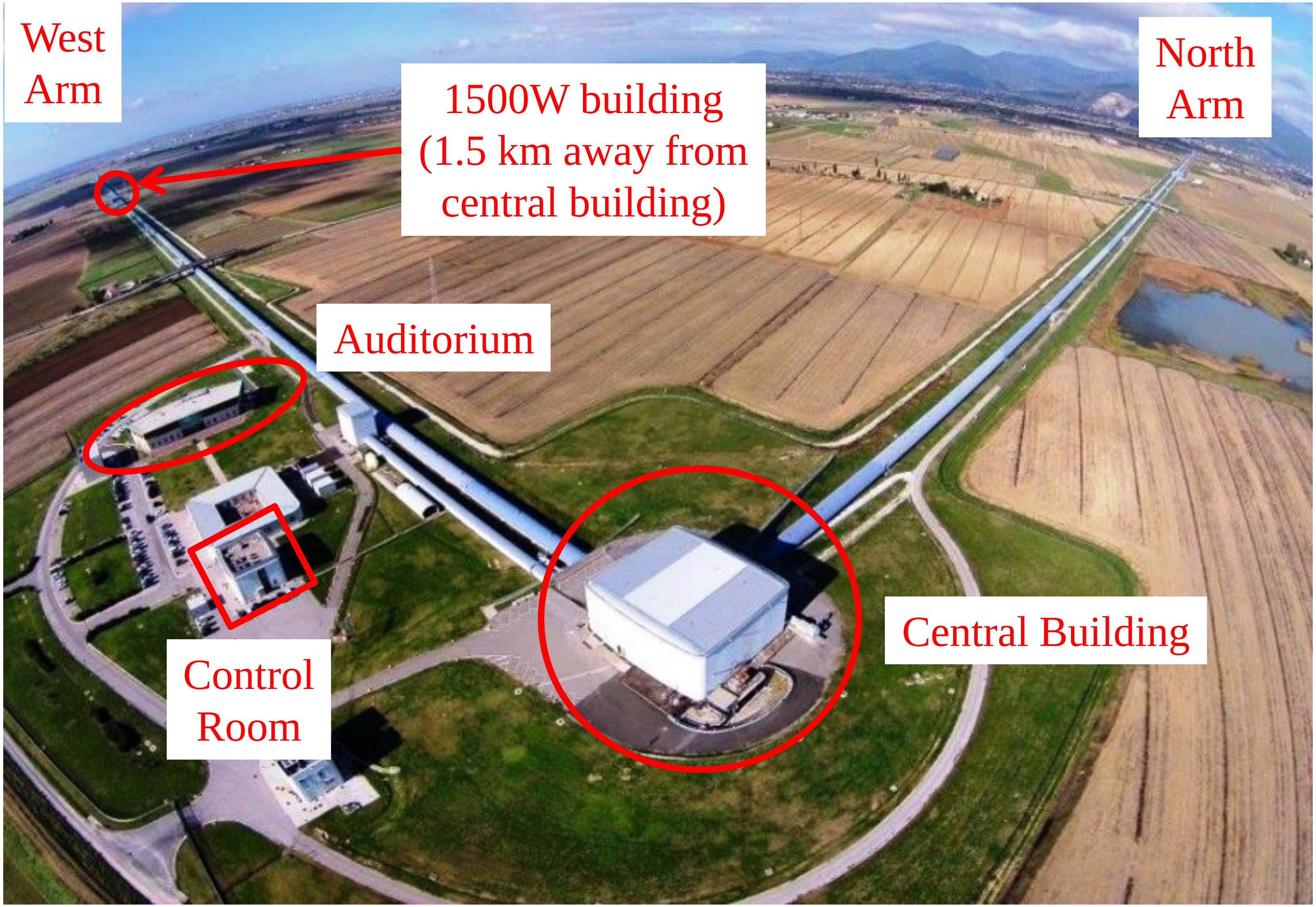
Thanks to the many colleagues from the LAL (now IJCLab) Virgo group, Virgo and LIGO, from wich I borrowed ideas and material for this talk

Virgo @ EGO

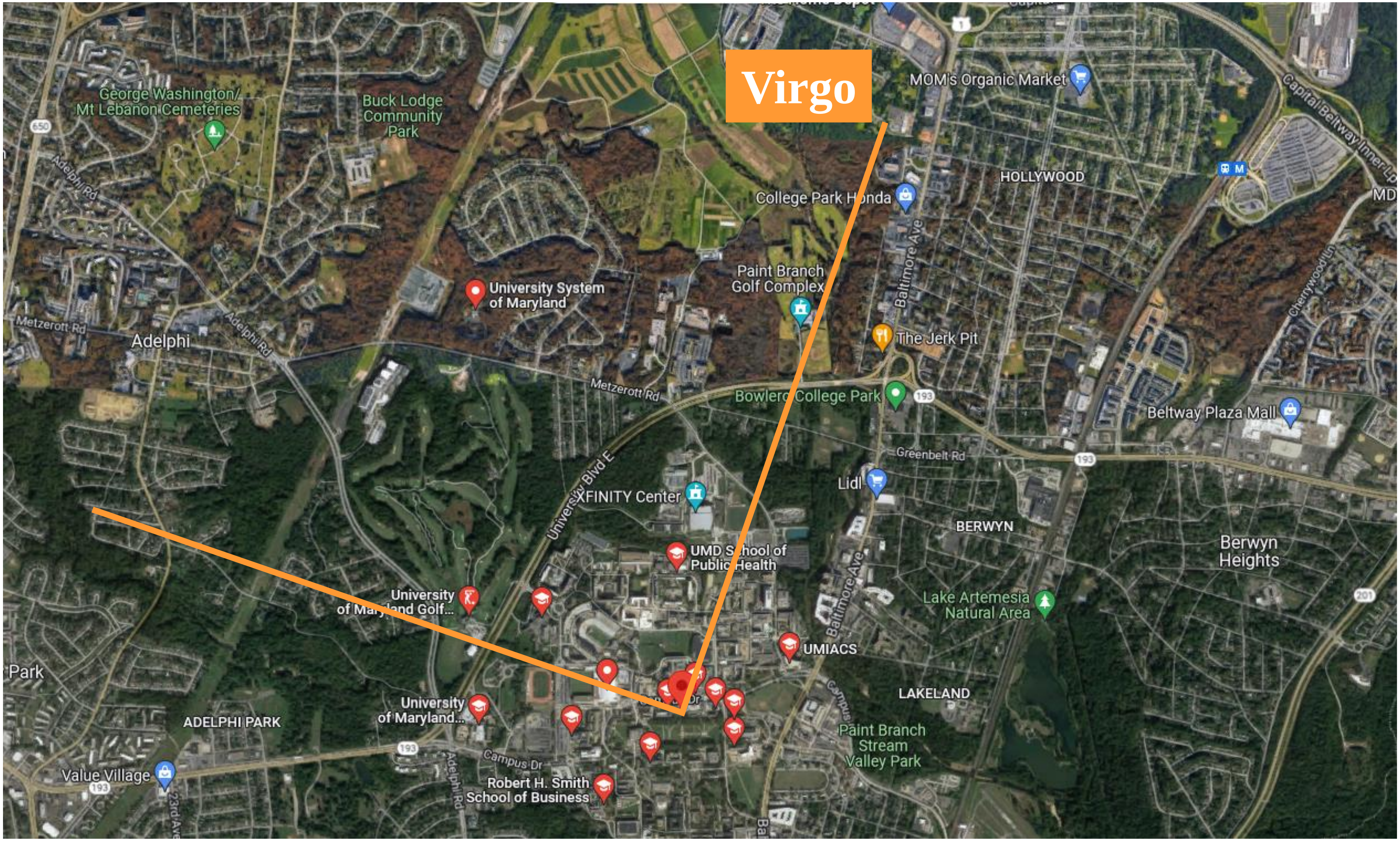
- European Gravitational Observatory (EGO): the lab hosting the Virgo detector
- Recent snapshot: ~800 members / ~530 authors
- ~140 participating institutions from 15 countries
  - Gathered in ~35 groups from 9 countries



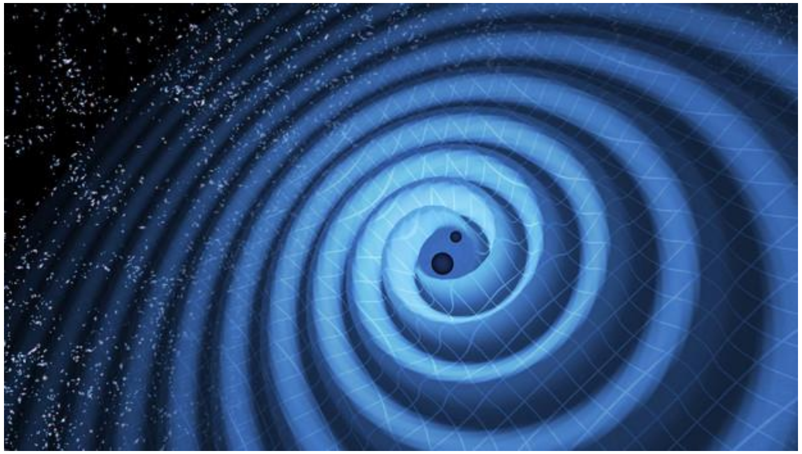
Virgo from the sky



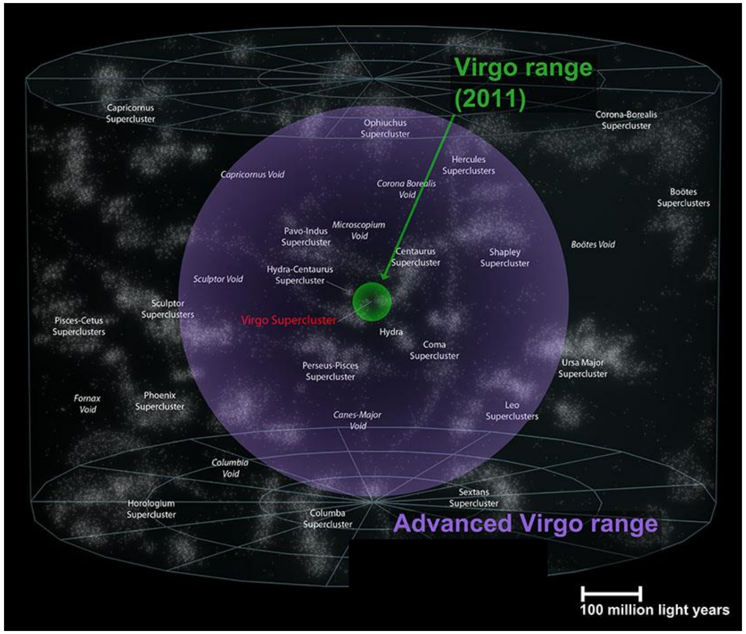
If Virgo were located in University of Maryland, College Park



Gravitational waves



- One of the first predictions (1916) of general relativity (1915)
  - Accelerated masses induce perturbations of the spacetime that propagate at the speed of light
- No gravitational wave (GW) emission if the source is axisymmetrical
  - A « good » source must have an asymmetrical mass distribution

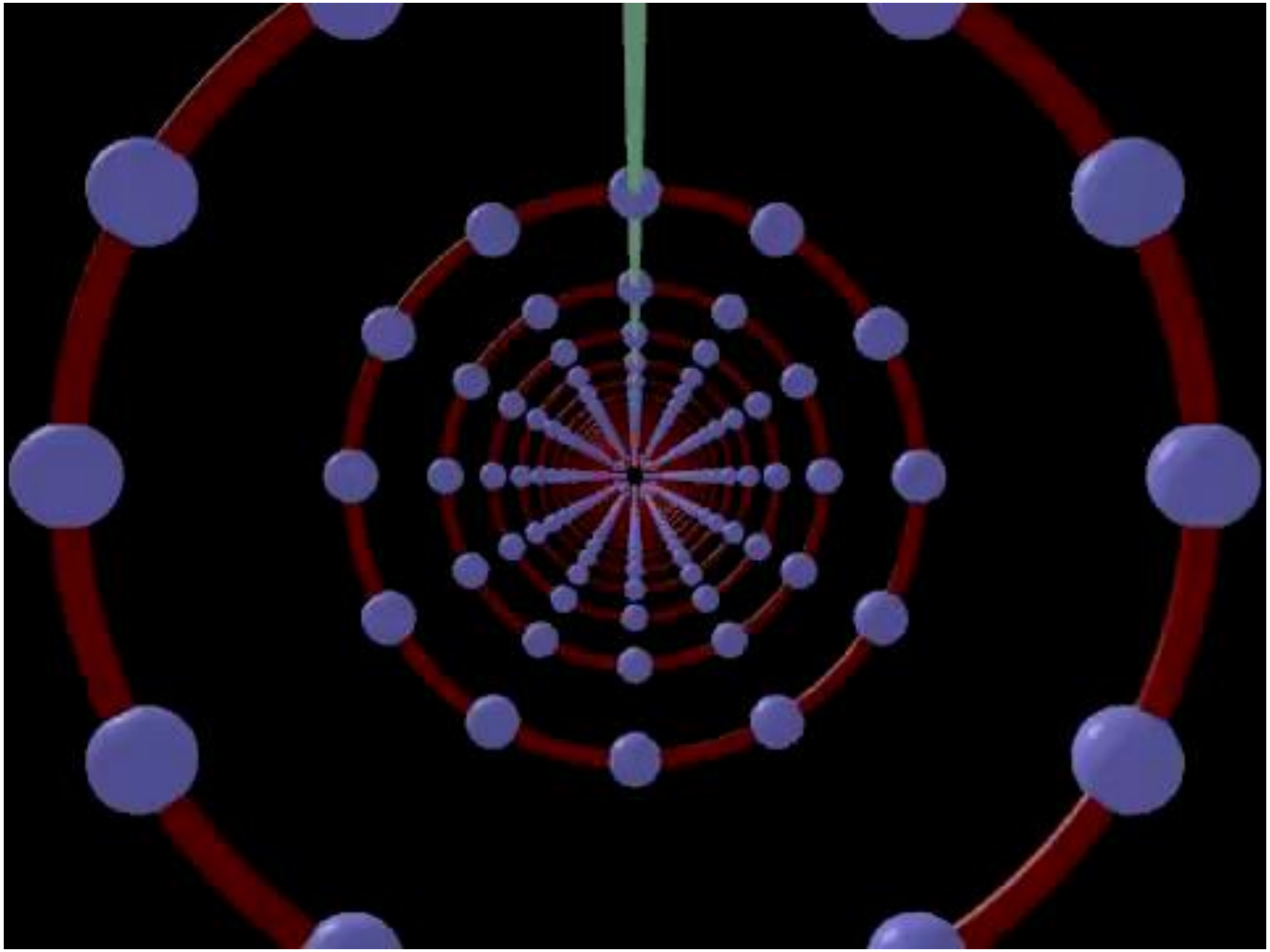


- GW amplitude h
  - Dimensionless
  - Scales down like 1/(distance to source)
- Detectors are directly sensitive to h

→ Factor 2 (10) gain in sensitivity
⇔ Gain of a factor 2 (10) in distance
⇔ Observable Universe volume scales by a factor 8 (1000)

Effect of gravitational waves on test masses

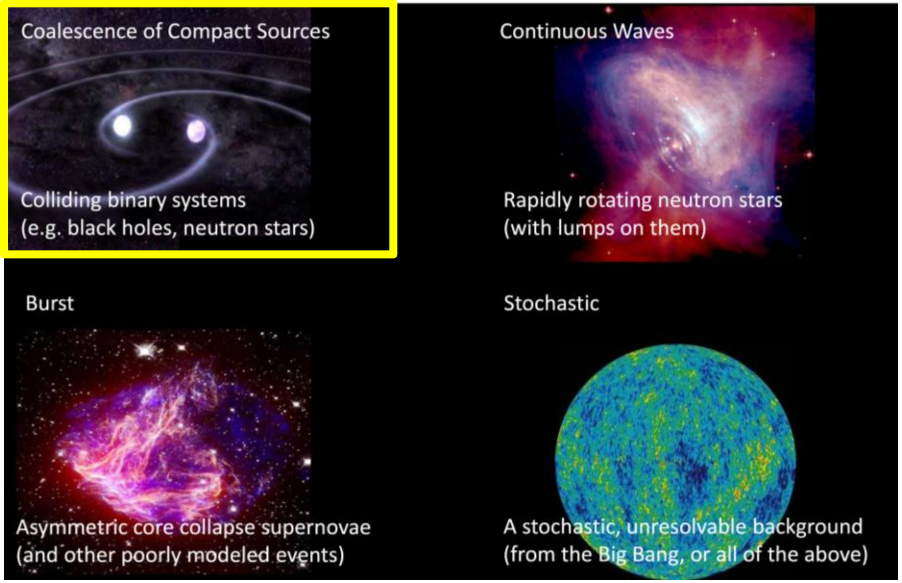
- In 3D

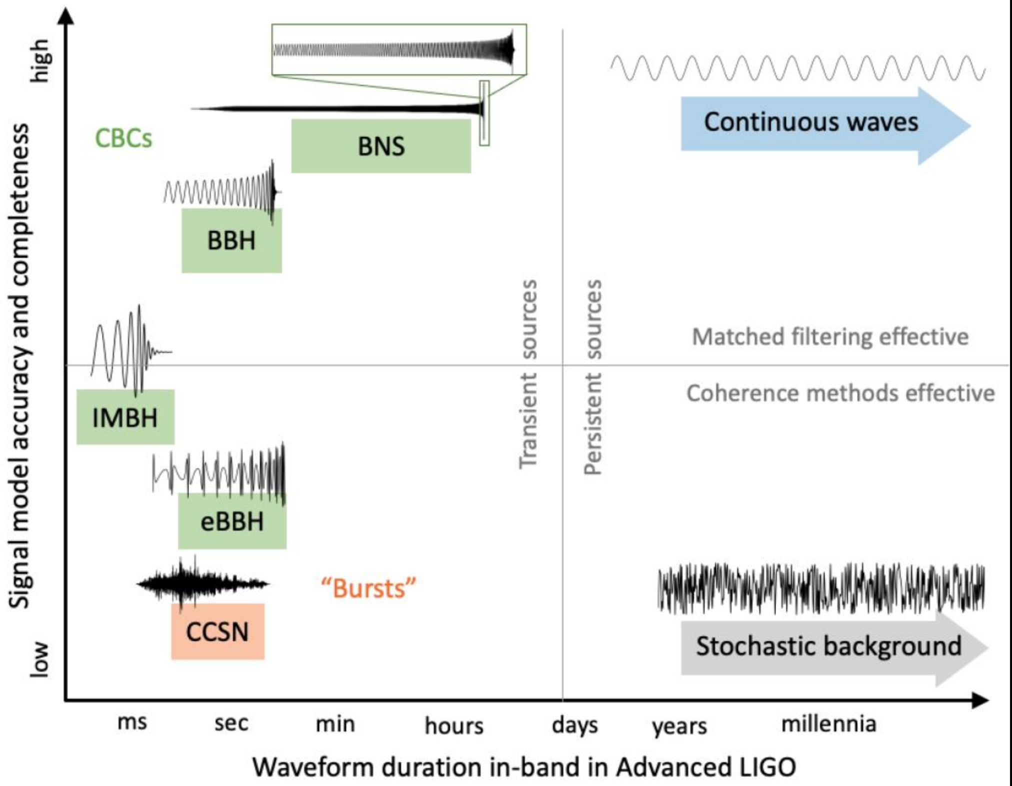


GW sources

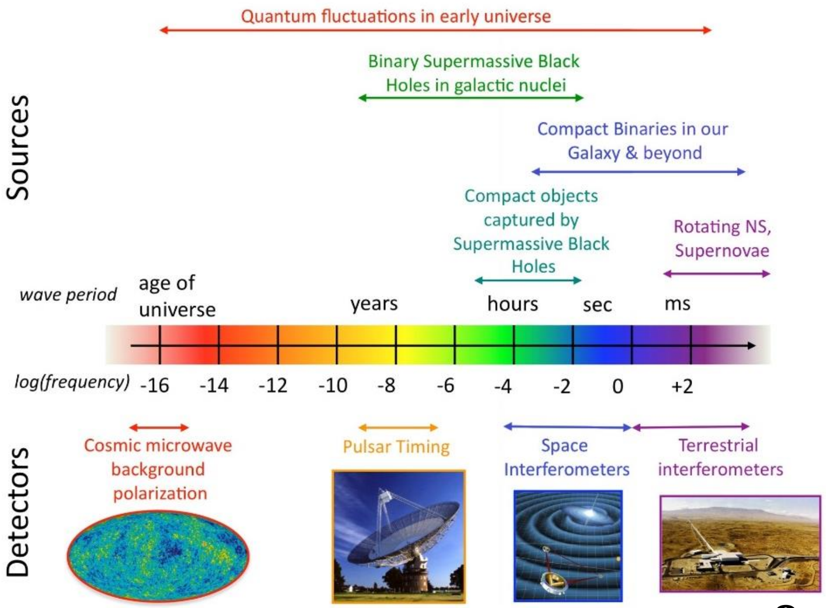
- Classification
  - Transient / Continuous
  - Modeled / Unmodeled

→ Drives the choice of the data analysis methods



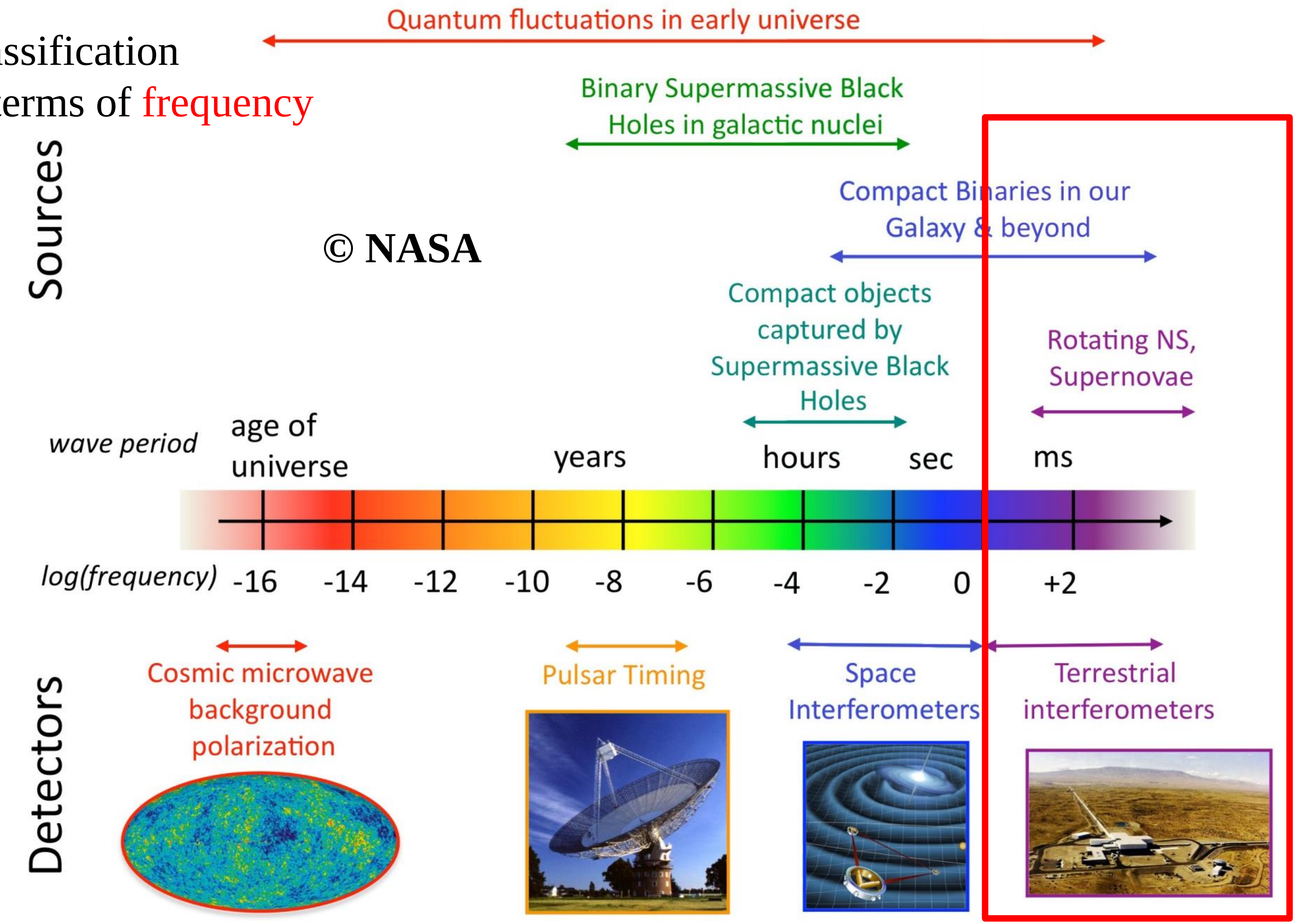


- GW frequency contents / evolution
- Detector bandwidth



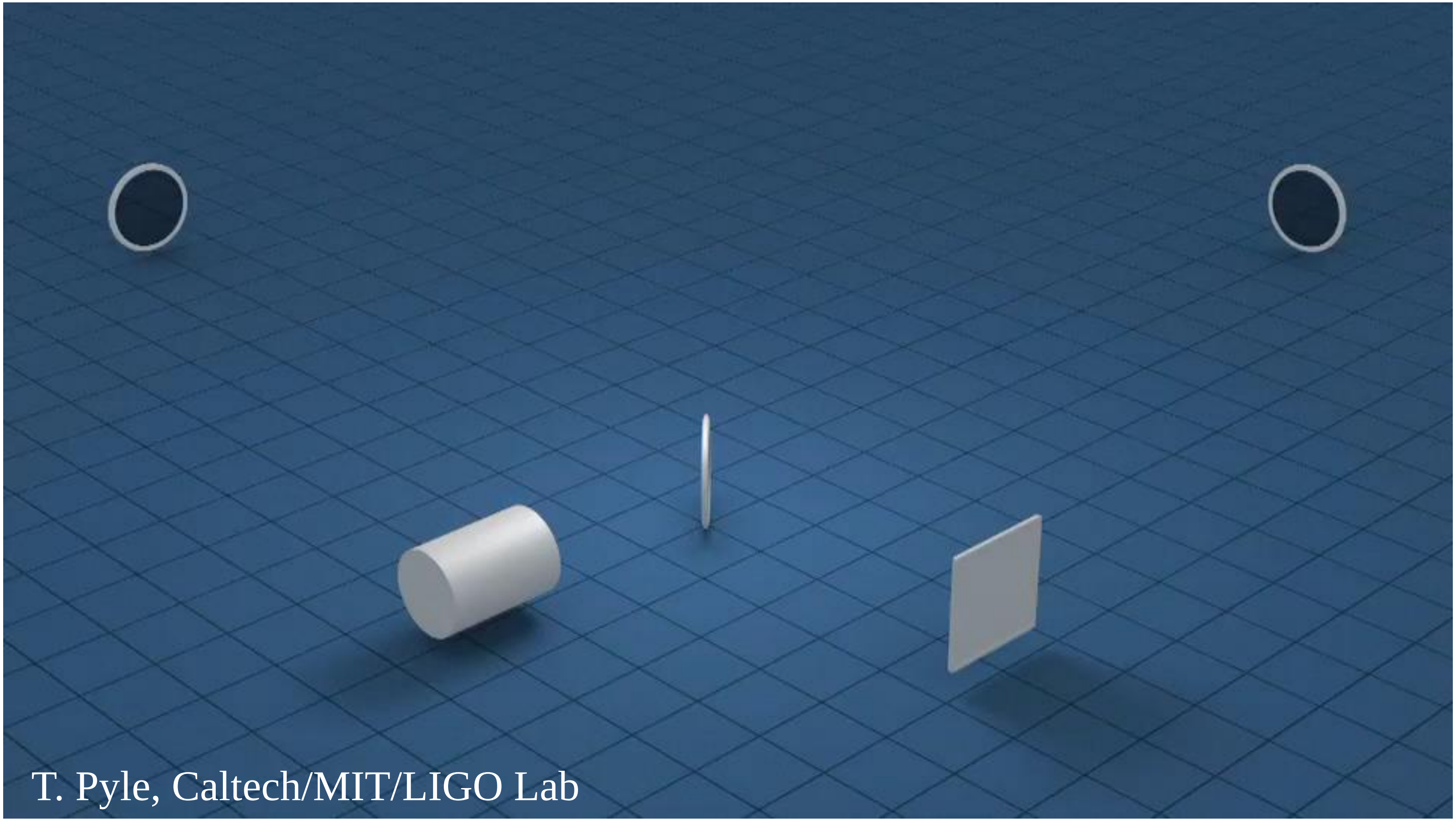
Gravitational wave spectrum

- Classification in terms of frequency



LIGO, Virgo, etc.

An interferometer in a nutshell

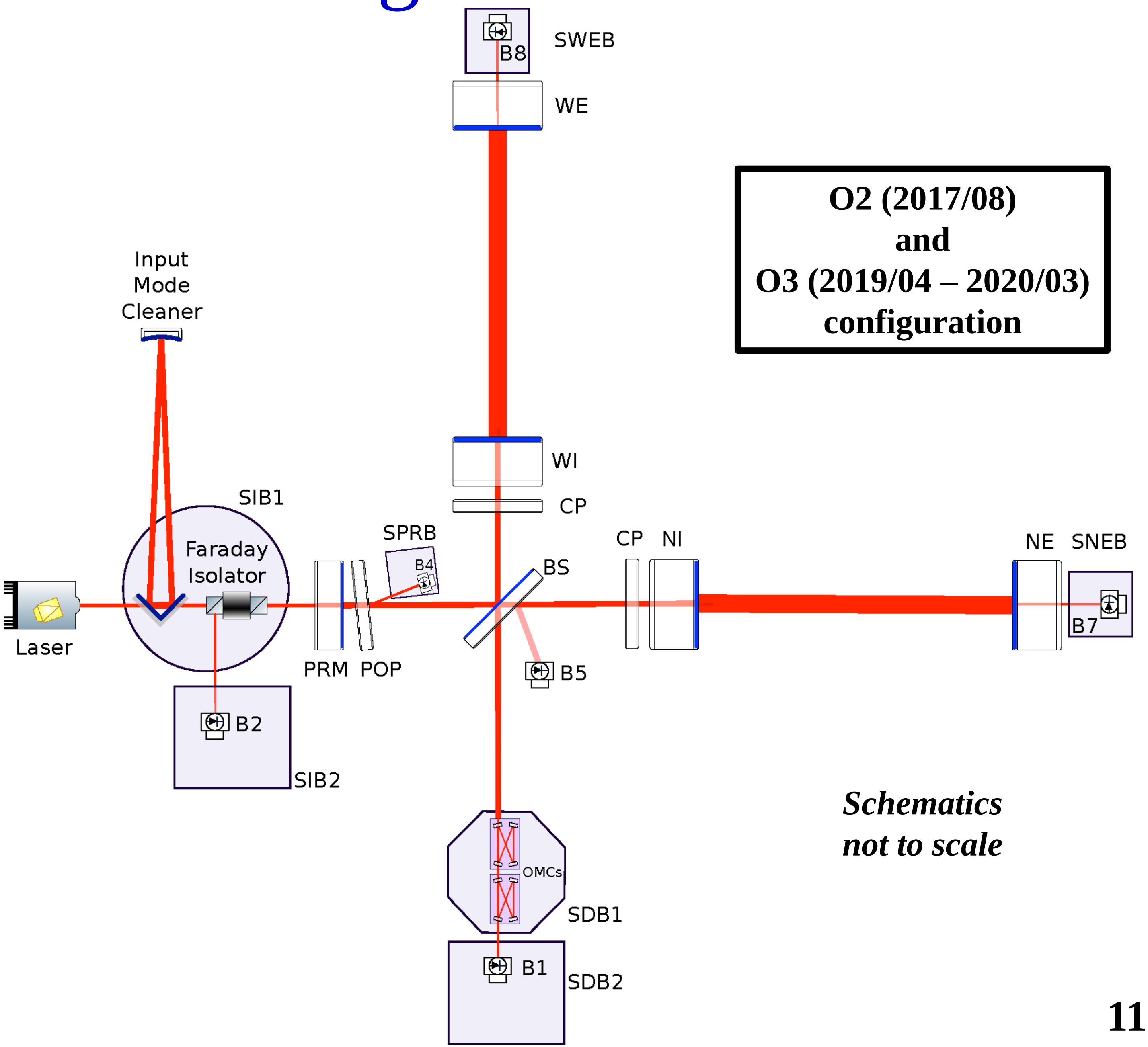


Sensitivity $\propto$ 1 / (arm length) / √(laser power)

As small as possible

The Advanced Virgo detector scheme

- Suspended, power-recycled, Michelson interferometer, with Fabry-Perot cavities in the kilometric arms



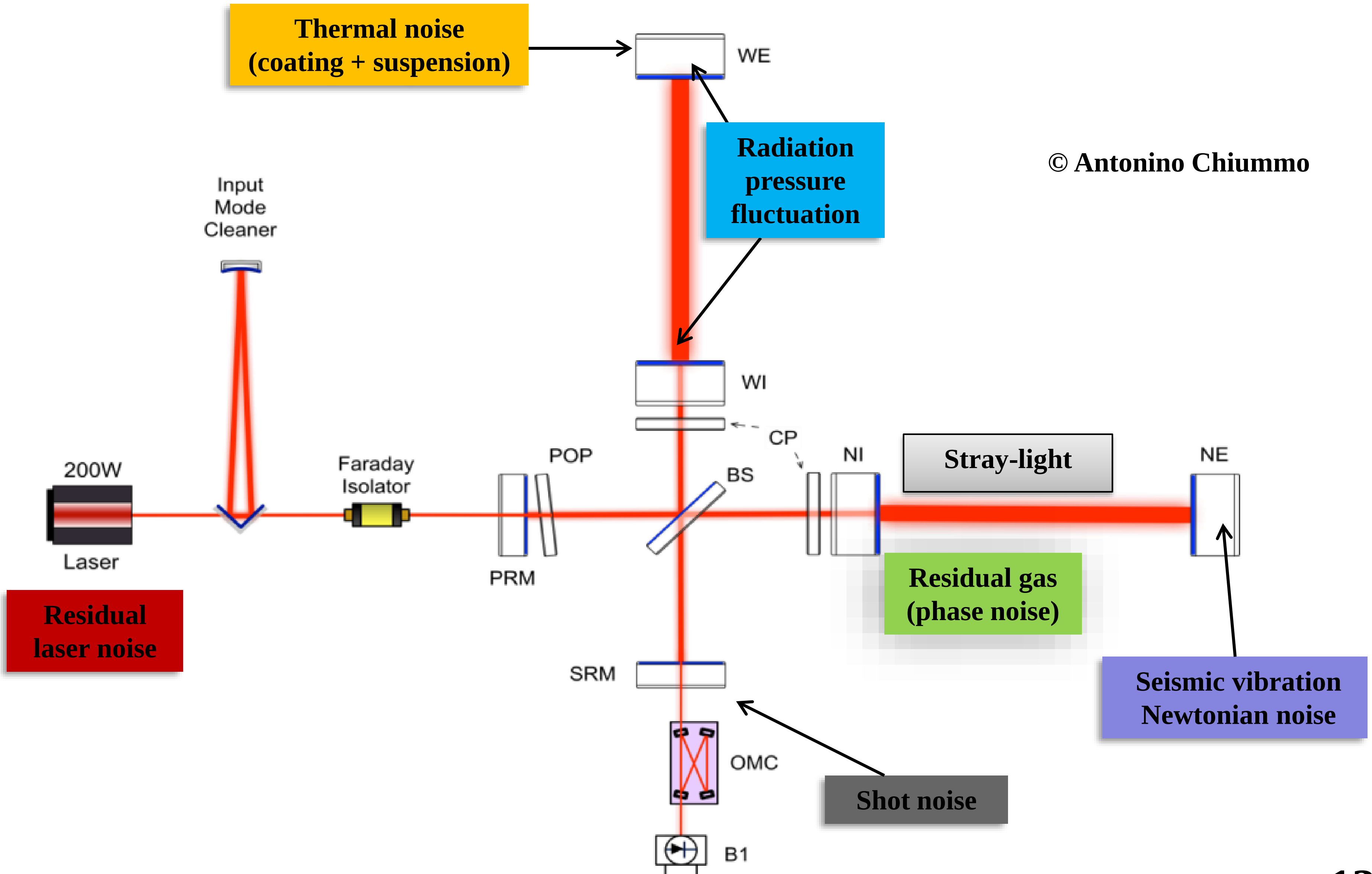
O2 (2017/08)
and
O3 (2019/04 – 2020/03)
configuration

Schematics not to scale

Noise & sensitivity

- Noise: any kind of disturbance which pollutes the dark fringe output signal
- Detecting a GW of frequency f ↔ amplitude h « larger » than noise at that frequency
- Interferometers are wide-band detectors
  - GW can span a wide frequency range
  - Frequency evolution with time is a key feature of some GW signals
    → Compact binary coalescences for instance
- Numerous sources of noise
  - Fundamental
    → Cannot be avoided; optimize design to minimize these contributions
  - Instrumental
    → For each noise, identify the source; then fix or mitigate
    → Then move to the next dominant noise; iterate…
  - Environmental
    → Isolate the instrument as much as possible; monitor external noises
- IFO sensitivity characterized by its amplitude spectrum density (ASD, unit: 1/√Hz)
  - Noise RMS in the frequency band $[f_{min};f_{max}] = \sqrt{\int_{f_{min}}^{f_{fmax}} \mathbf{ASD^2(f)\,df}}$

Main interferometer noises



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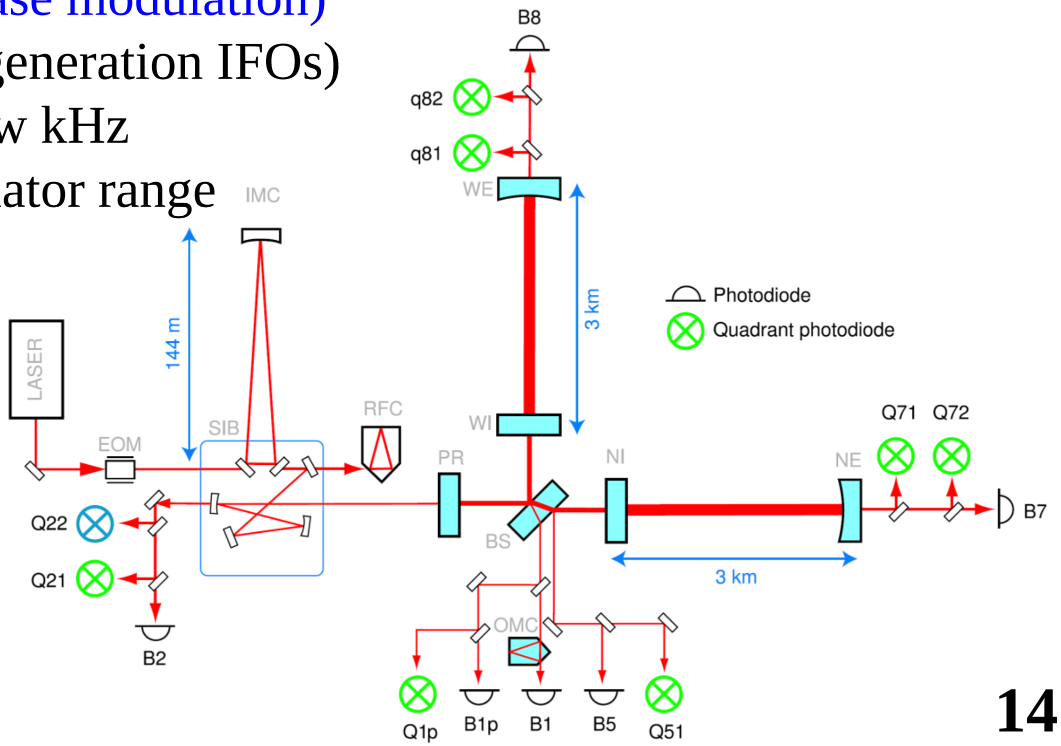
Interferometer control

- A complex working point
  - Resonant Fabry-Perot and recycling cavities + IFO on the dark fringe
  - Arm length difference controled with an accuracy better than 10^{-15} m
  - The better the optical configuration, the narrower the working point
- « Locking » the IFO is a non-trivial engineering problem
  - Use several error signals to apply corrections on mirror positions and angles
    - → Pound-Drever-Hall signals (phase modulation)
    - → Auxiliary green lasers (for 2nd generation IFOs)
  - Feedback loops from few Hz to few kHz
  - Cope with filter bandwith and actuator range
- Multi-step lock acquisition procedure

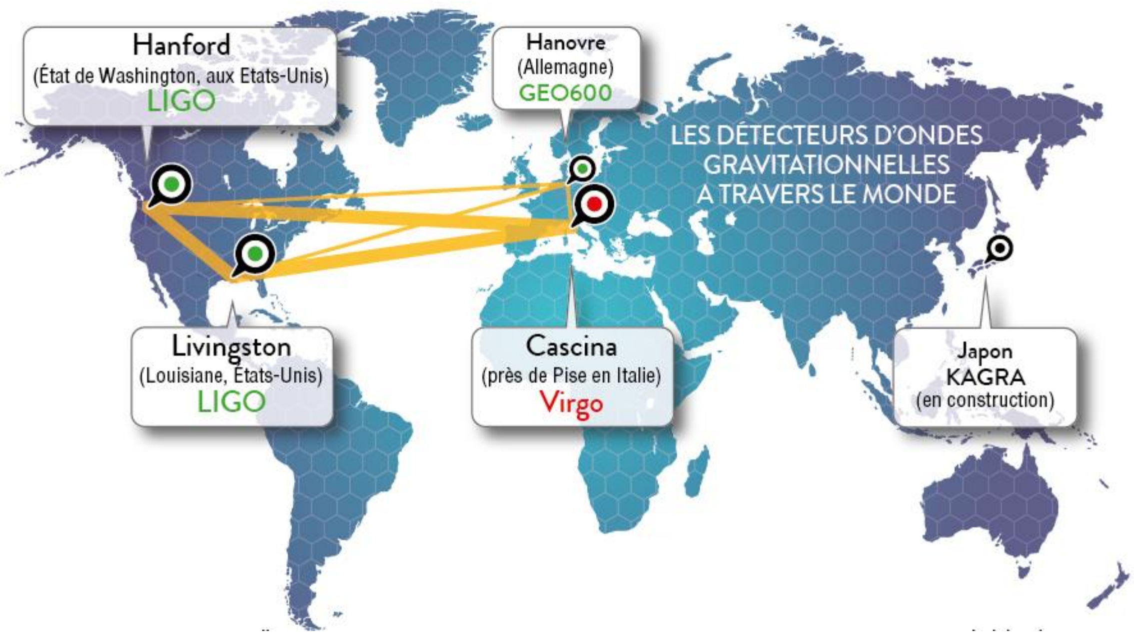
Free mirrors
↓
Local control
↓
Global control



A network of interferometric detectors

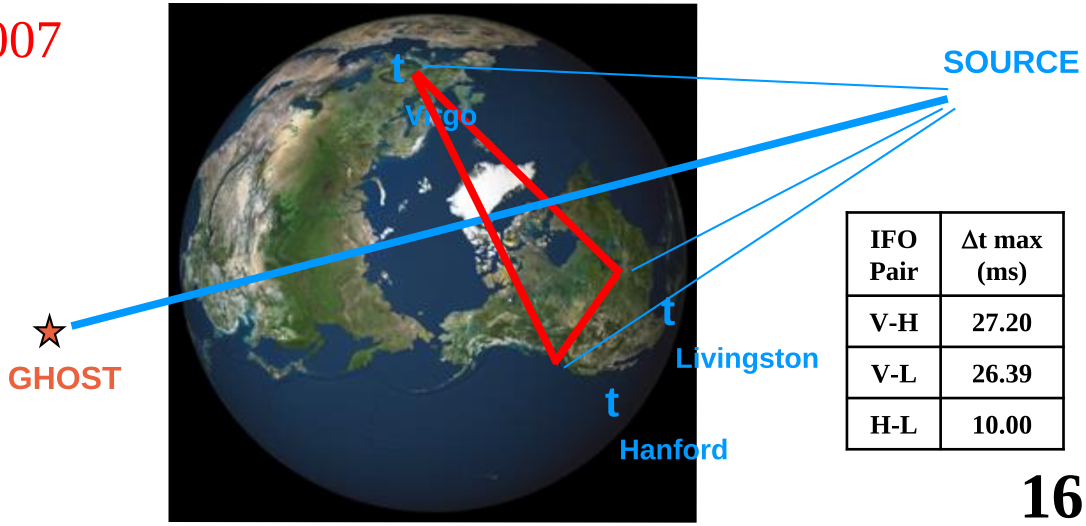
A network of interferometric detectors

- 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



$\rightarrow$ 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

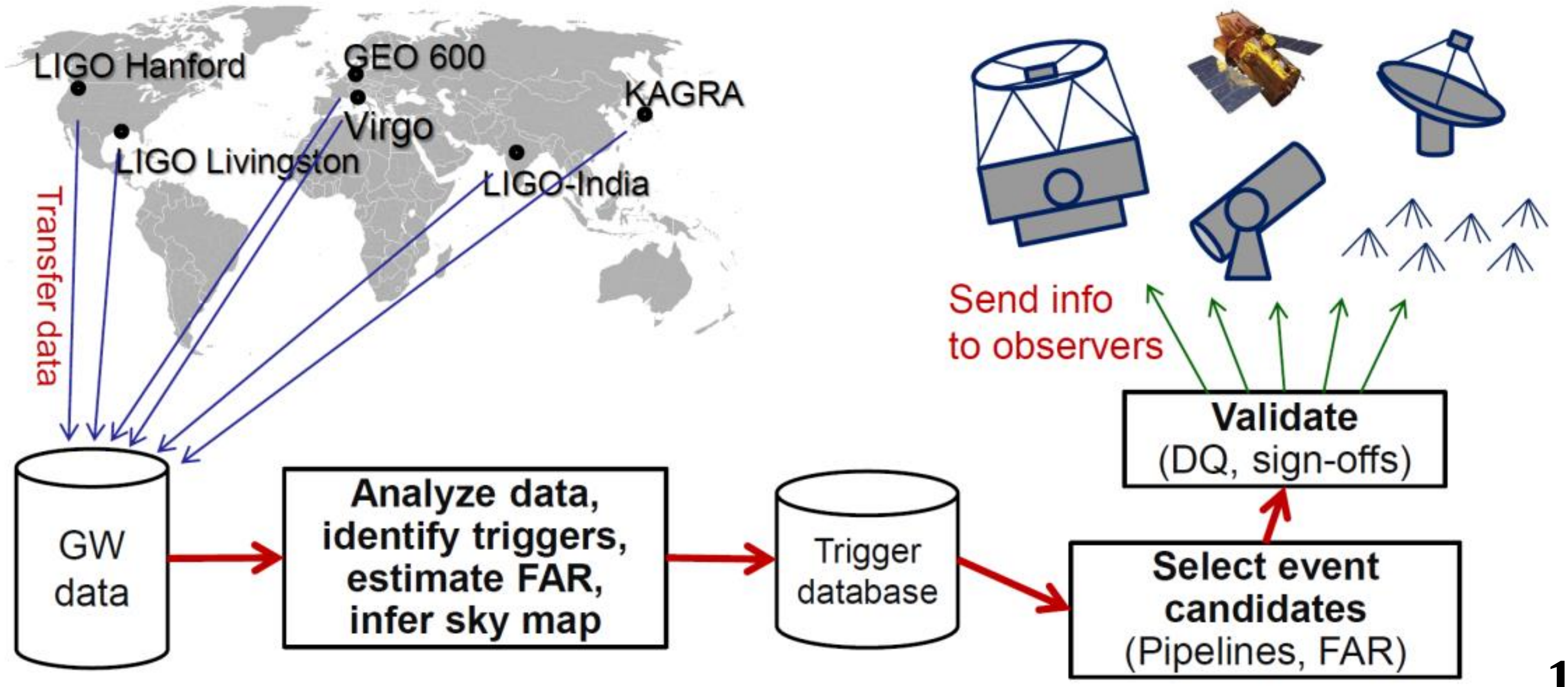


IFO Pair	Δt max (ms)
V-H	27.20
V-L	26.39
H-L	10.00

A network of partners

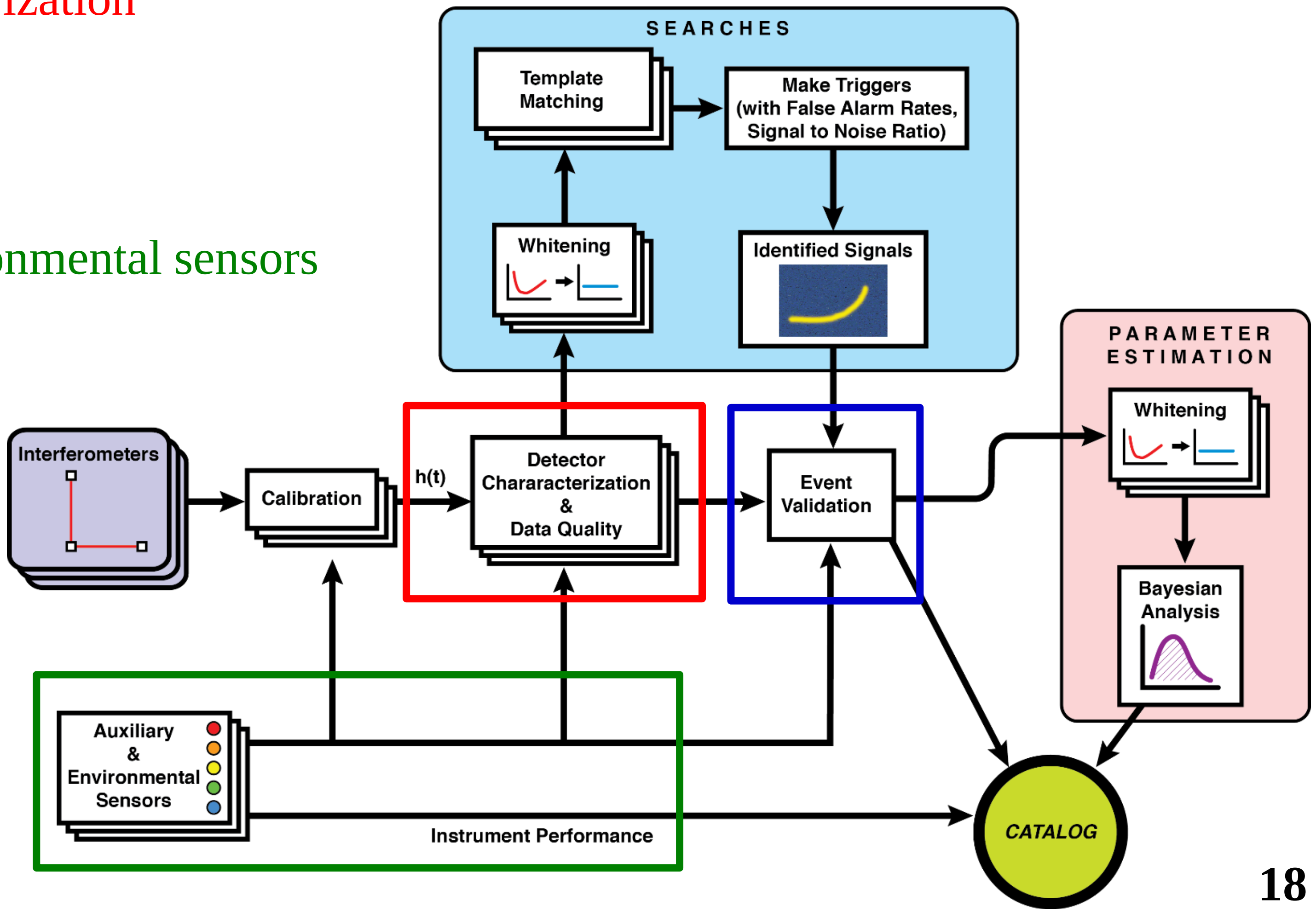
- Search for counterparts of the gravitational wave signal
  - Electromagnetism
  - Neutrinos
  - Particles

Tens of partner telescopes



LVK dataflow

- From: **A guide to LIGO-Virgo detector noise and extraction of transient gravitational-wave signals**
  - B. P. Abbott *et al.*, 2020 *Class. Quantum Grav.* **37** 055002
- Detector Characterization & Data Quality
- Event validation
- Auxiliary & environmental sensors
- Different latencies
  - Online
  - Offline
  - On-demand
- Many monitoring levels
  - Detector
  - Network
  - Analyses



1916-2022: a century of progress

Theory

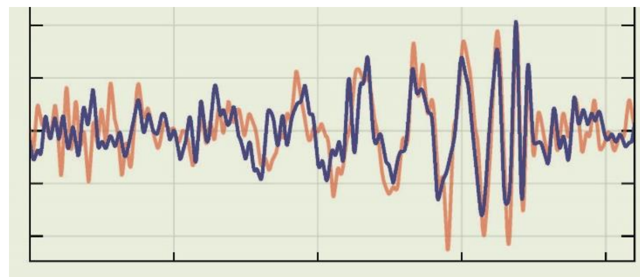
- **1916: GW prediction (Einstein)**
- **1957: Chapel Hill Conference (Bondi, Feynman, Pirani, etc.)**
- **1963: rotating BH solution (Kerr)**
- **1990's: CBC PN expansion (Blanchet, Damour, Deruelle, Iyer, Will, Wiseman, etc.)**
- **2000: BBH effective one-body approach (Buonanno, Damour)**
- **2006: BBH merger simulation (Baker, Lousto, Pretorius, etc.)**

Experiment

- **1960's: first Weber bars**
- **1970: first IFO prototype (Forward)**
- **1972: IFO design studies (Weiss)**
- **1974: PSRB 1913+16 (Hulse & Taylor)**
- **1980's: IFO prototypes (10m-long) (Caltech, Garching, Glasgow, Orsay)**
  → End of 1980's: Virgo (Brillet, Giazotto) and LIGO proposals
- **1990's: LIGO and Virgo funded**
- **2005-2011: initial IFO « science » » runs**
- **2007: LIGO-Virgo MoU**
- **First half of the 2010's: Upgrades**
- **2015: First Advanced LIGO run** } **First GW Detections**
- **2017: First Advanced Virgo run** }
- **…**

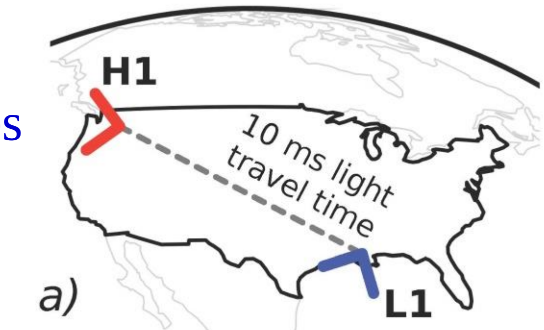
September 14, 2015, 11:51 CEST

- Signal observed in the two LIGO detectors with a 7 ms delay
  - Extremely short (< 1 s)
  - Very strong
    - With respect to the instrumental noise
    - Very weak in absolute terms

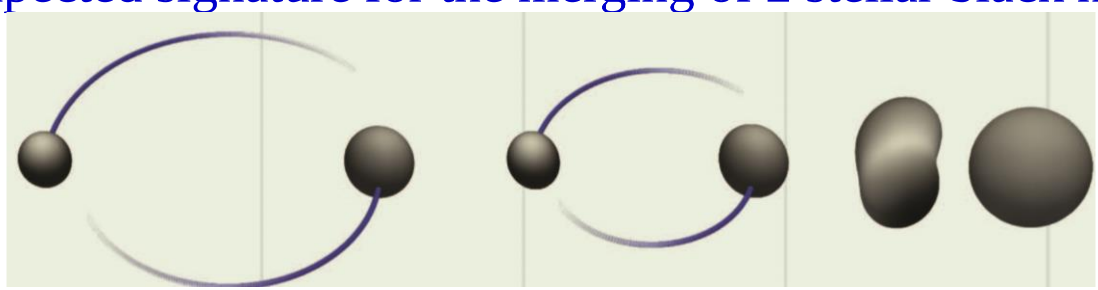


Event called GW150914:

- **Gravitational wave**
- **2015**
- **September**
- **14**

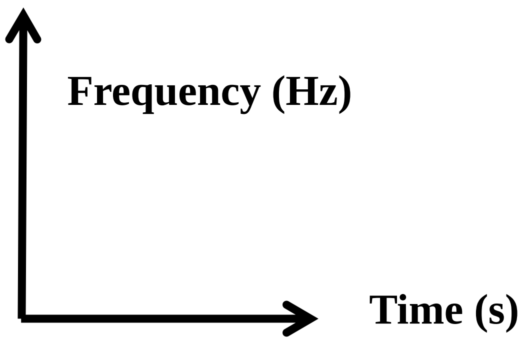


- Expected signature for the merging of 2 stellar black holes

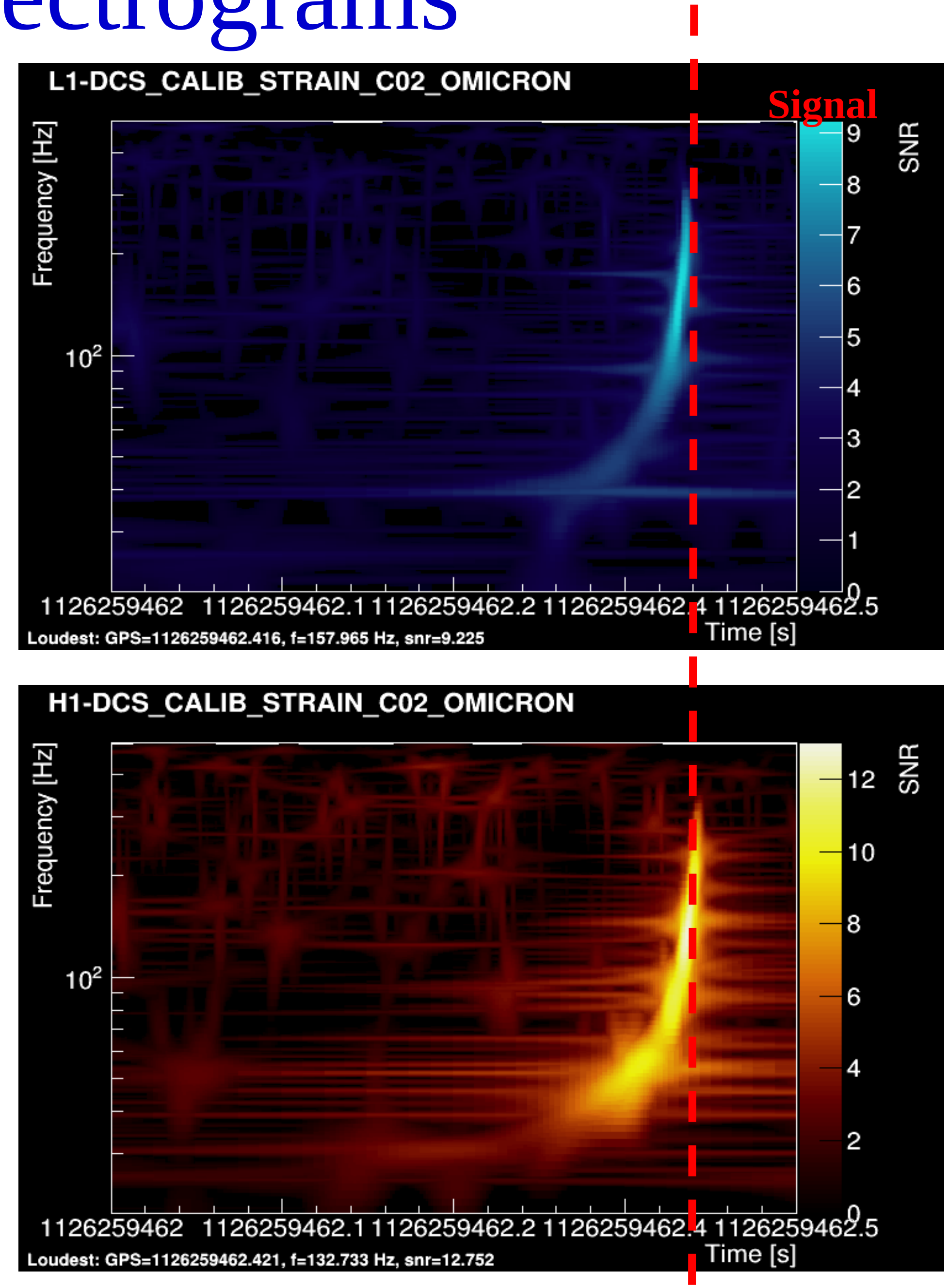


GW150914: spectrograms

- Time-frequency maps



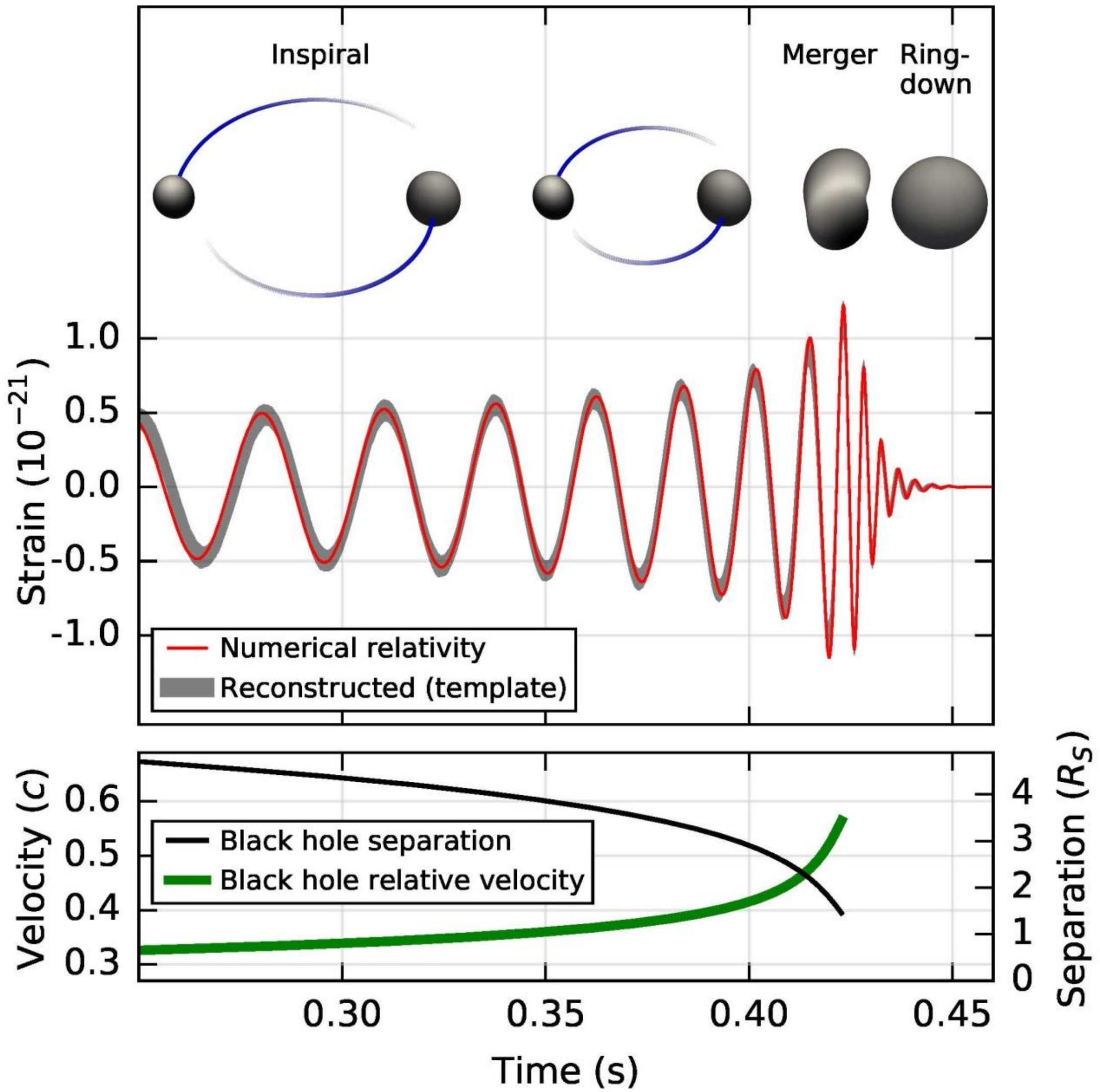
- Search for an excess of energy with respect to the noise
  - Using wavelets
- The excess must be coherent (and coincident in time) in between the two detectors
- Real time analysis during O1!
- GW150914 is strong enough to be visible « by eyes »



Why two black holes?

- Result of matched filtering!
  - Excellent match between the best template and the measured signal
- Two massive compact objects orbiting around each other at 75 Hz (half the GW frequency), hence at relativistic speed, and getting very close before the merging: only a few R_S away!

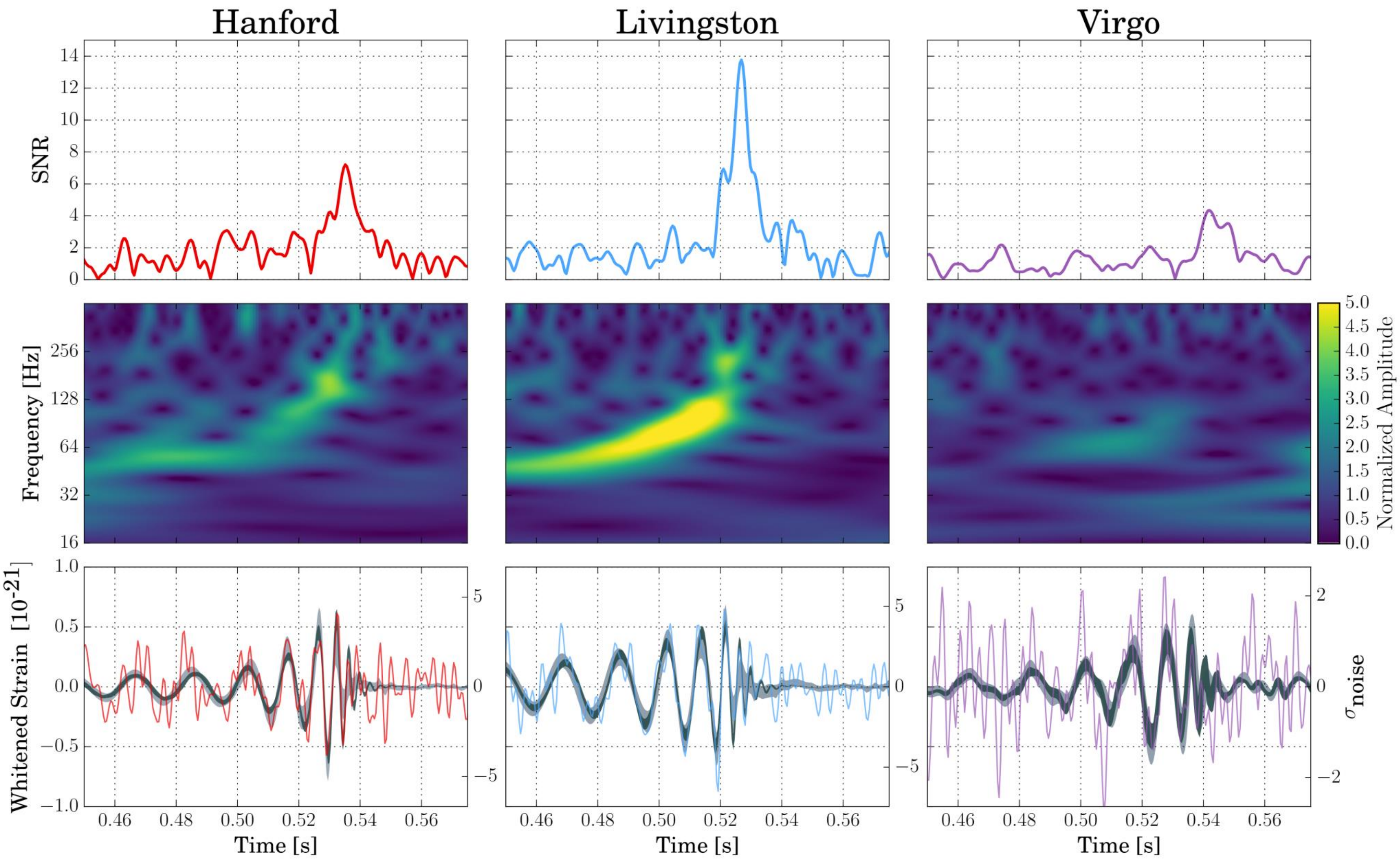
→ Black holes are the only known objects which can fit this picture



- About 3 M_{Sun} radiated in GW
- The « brighest » event ever seen
  - More powerful than any gamma-ray burst detected so far
  - Peak power larger than 10 times the power emitted by the visible Universe

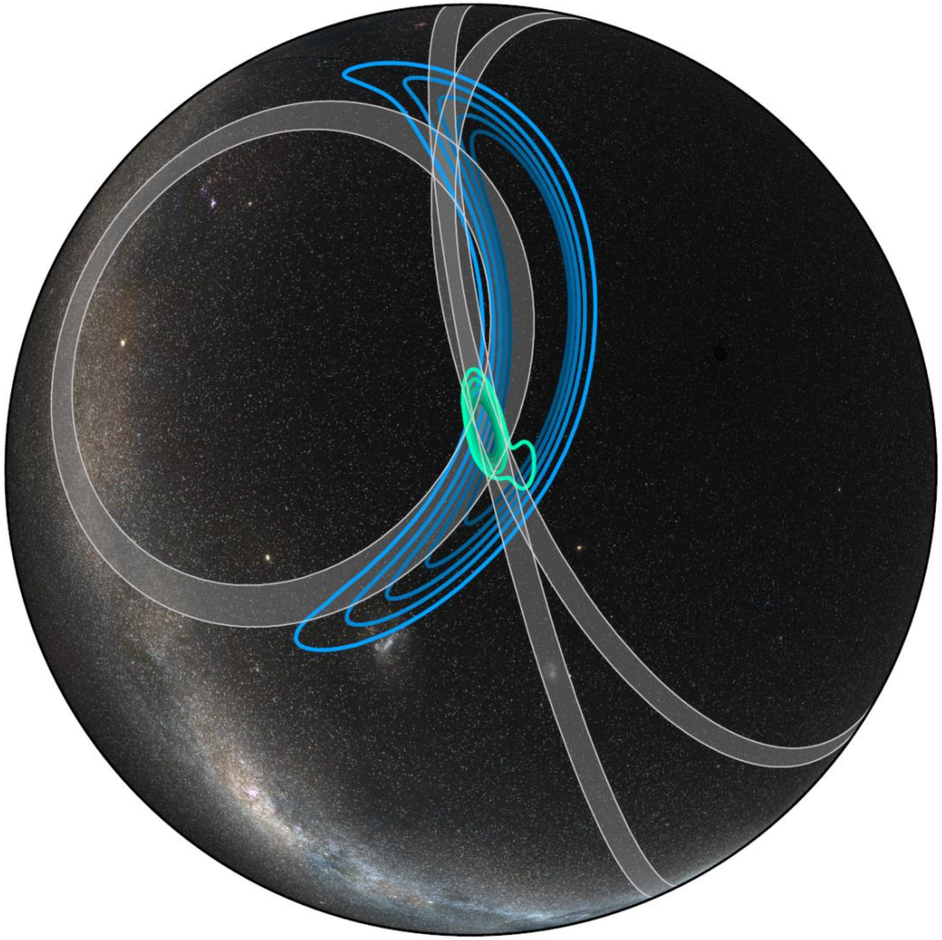
GW170814: first 3-detector signal

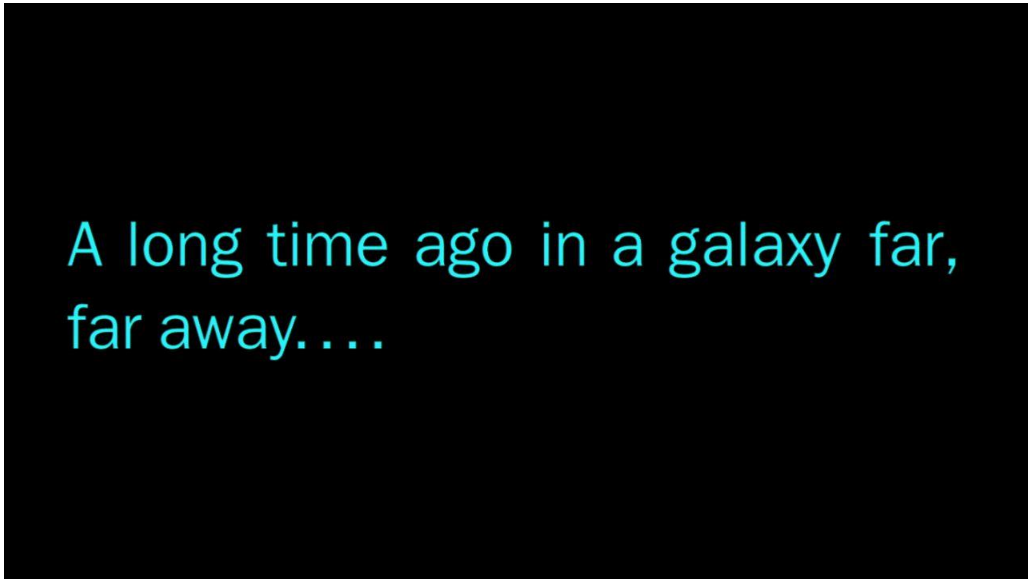
- Detailled studies confirm evidence of a signal in the Virgo detector



GW170814: LIGO-Virgo sky localization

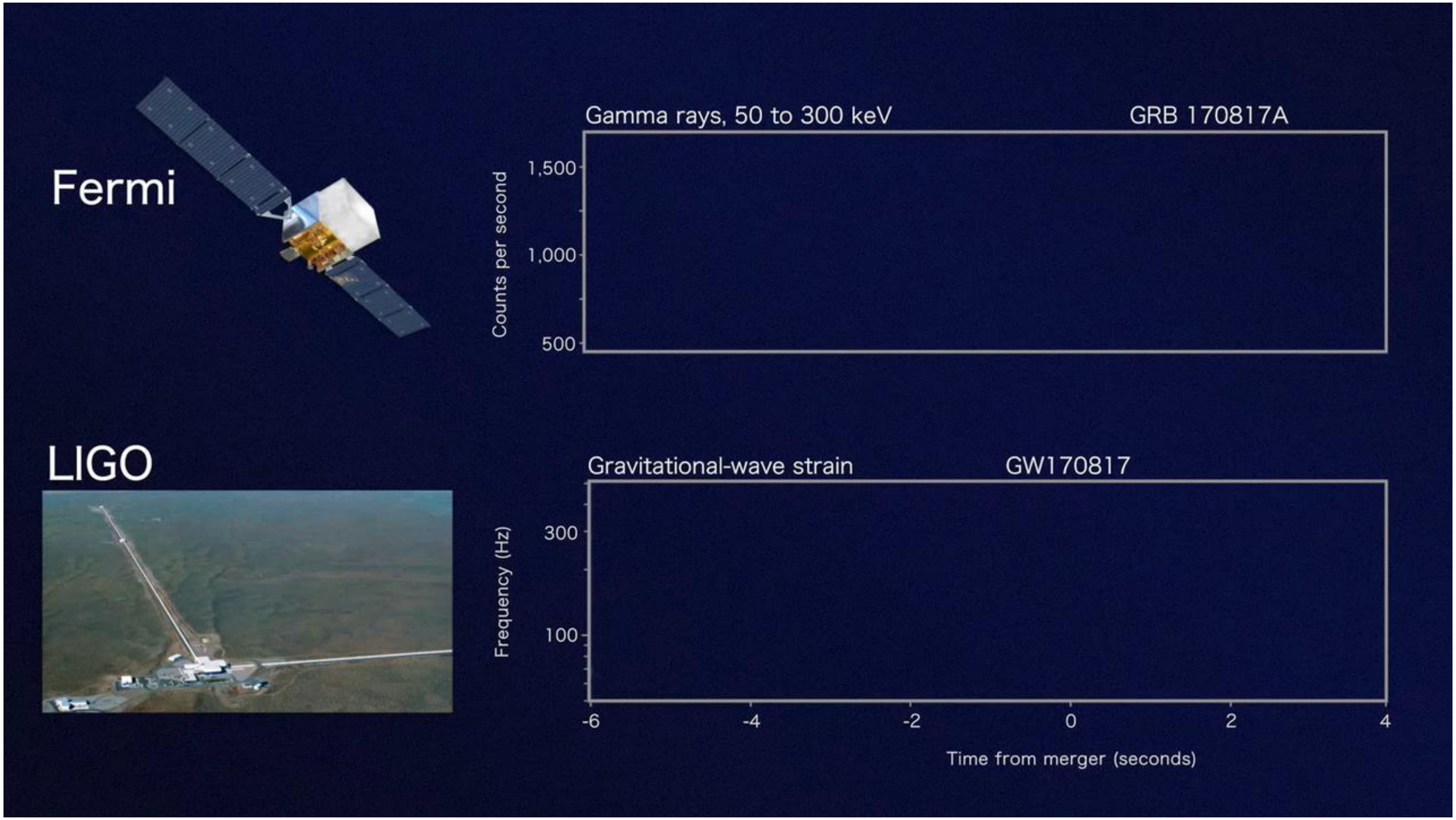
- Triangulation
  - Delays in the signal arrival time between detectors
  - Difference in shape and amplitude for the detected signals




A long time ago in a galaxy far,
far away....

Thursday August 17, 2017 – 14:41 CEST

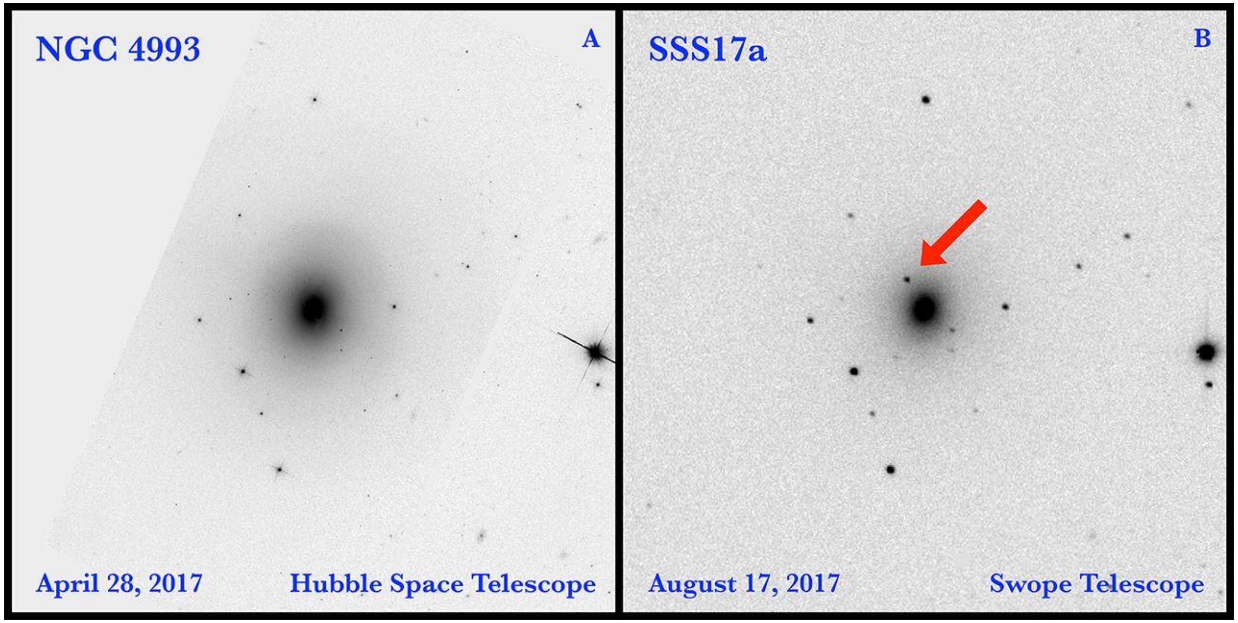
- Signals recorded within 1.7 second
  - LIGO (gravitational waves) first
  - Then the GBM instrument (gamma ray burst) on board the Fermi satellite

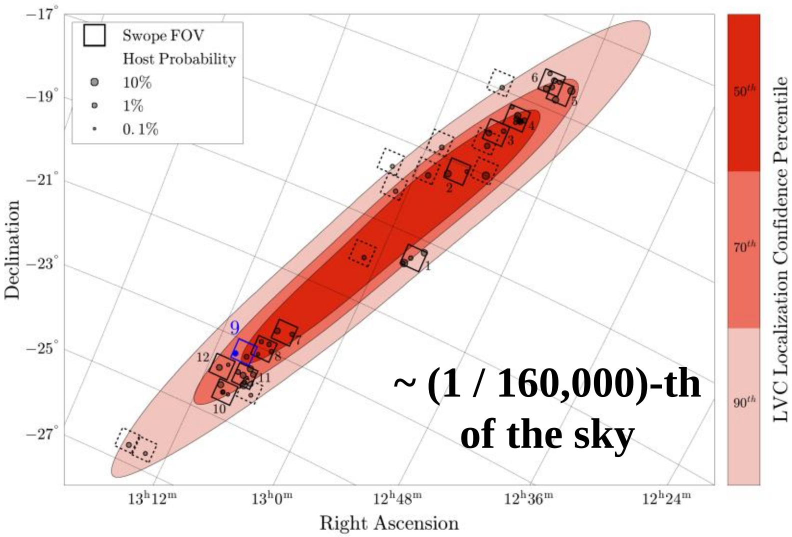


The following night…

- 2017/08/18
  01:33 CEST

→ Discovery of the optical counterpart by the SWOPE telescope in Chile



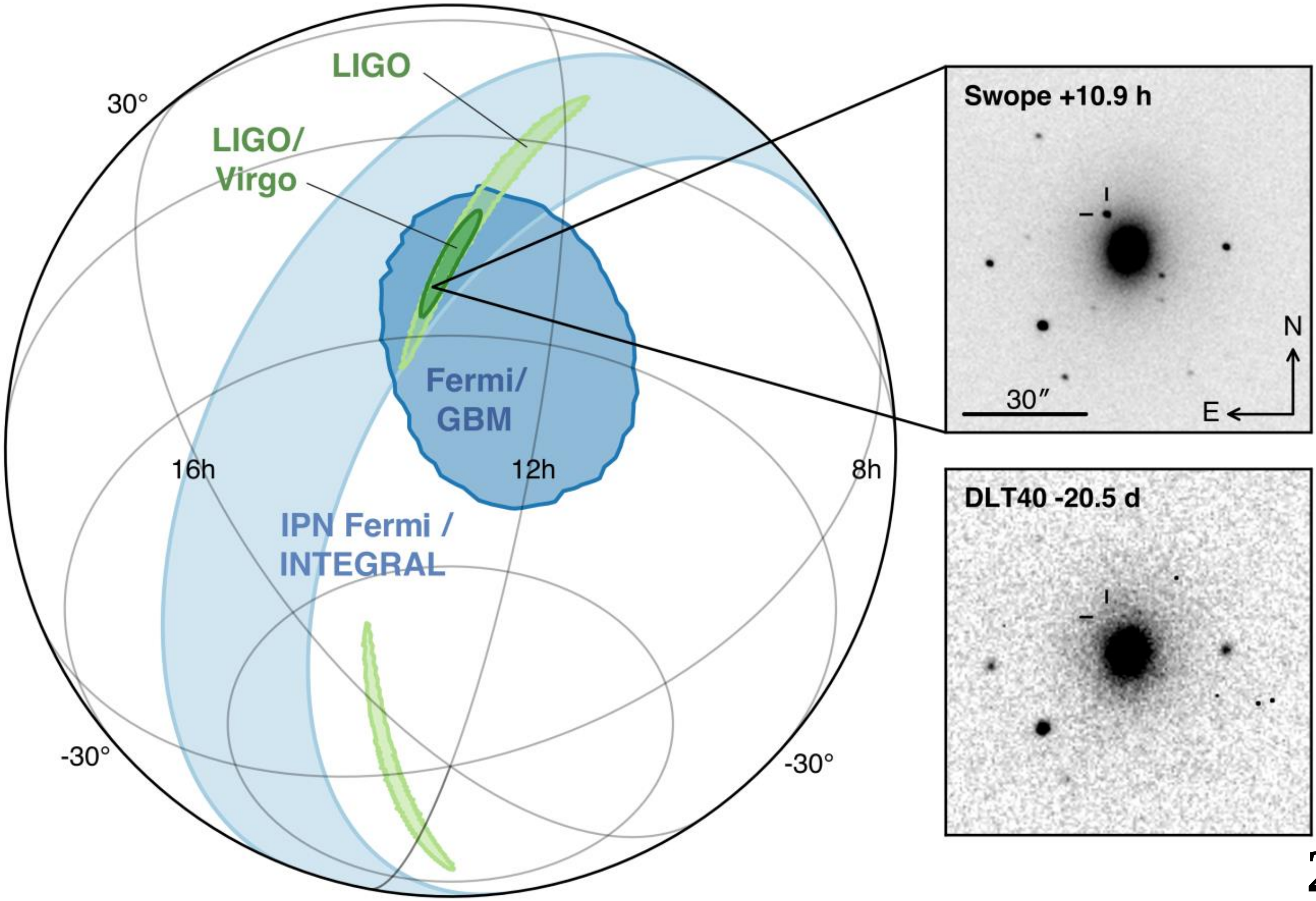


Sky localizations & source position

- Combined Signal / Noise Ratio of 32.4
- Source close to one of the Virgo blind spots

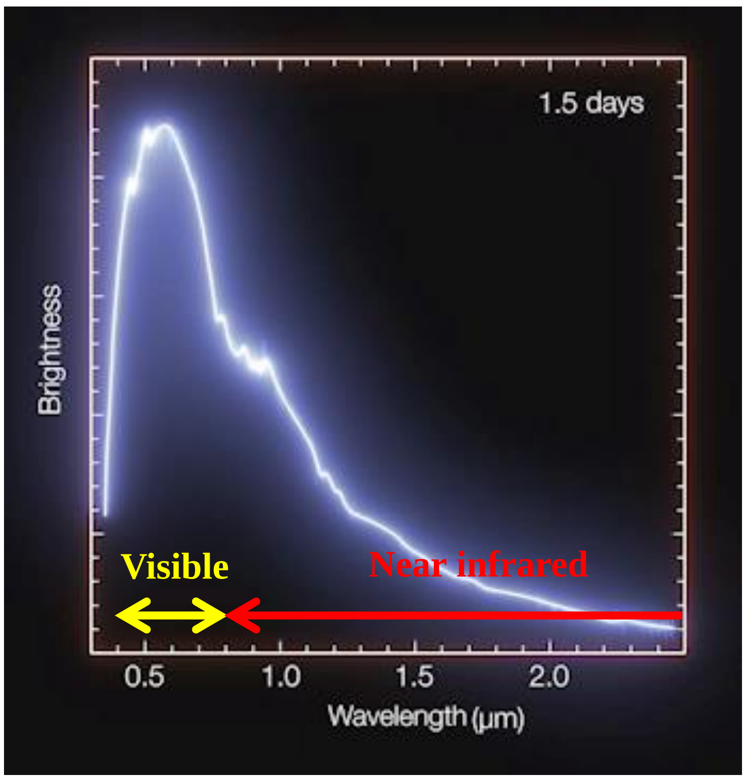
→ Accurate sky localization sent at 19:55 CEST (+ 05:14 after GW was recorded)

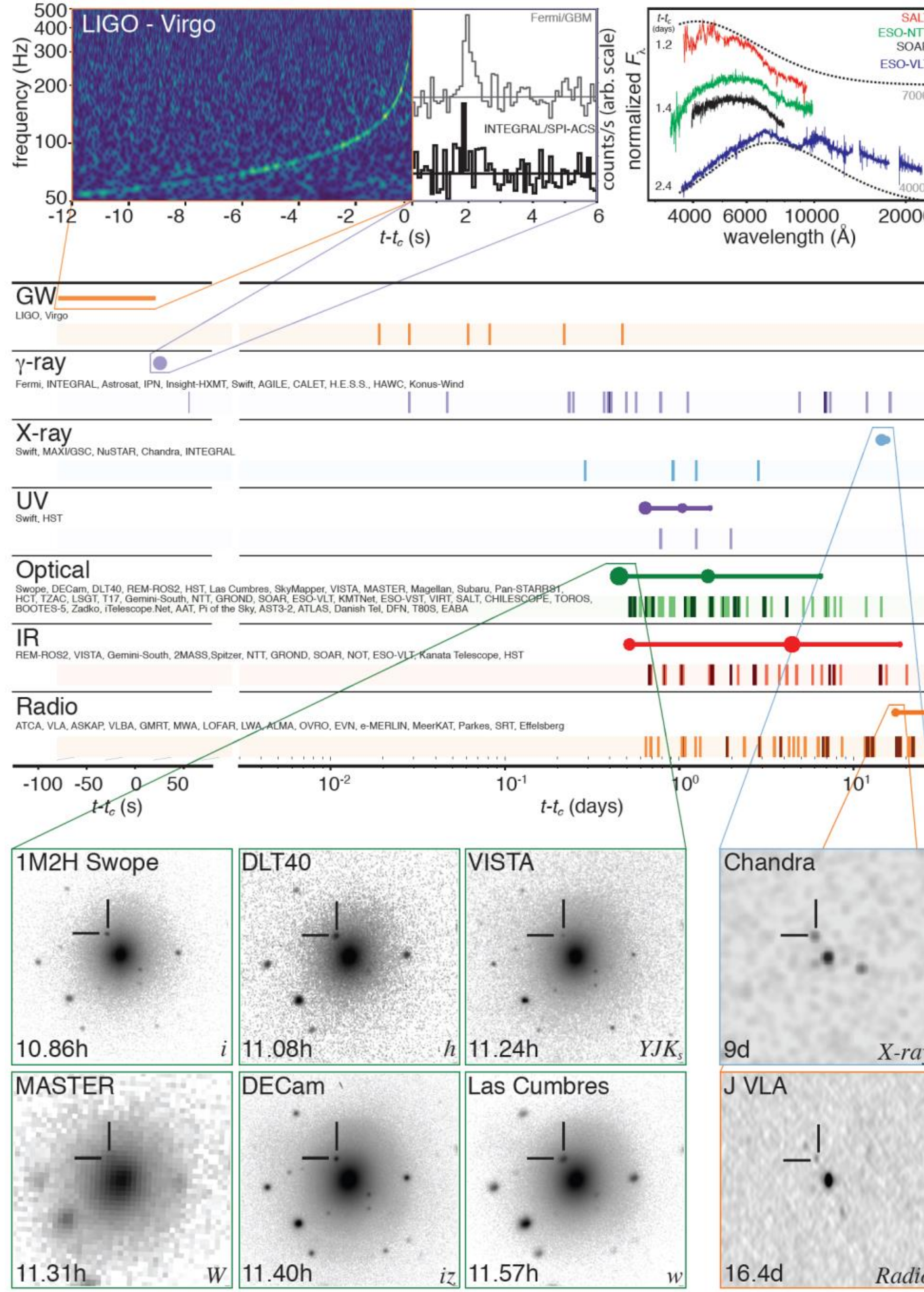
- Green: LIGO and LIGO + Virgo
- Blue : information from gamma ray burst satellites
- Optical discovery (Swope)



Multi-messenger Astronomy

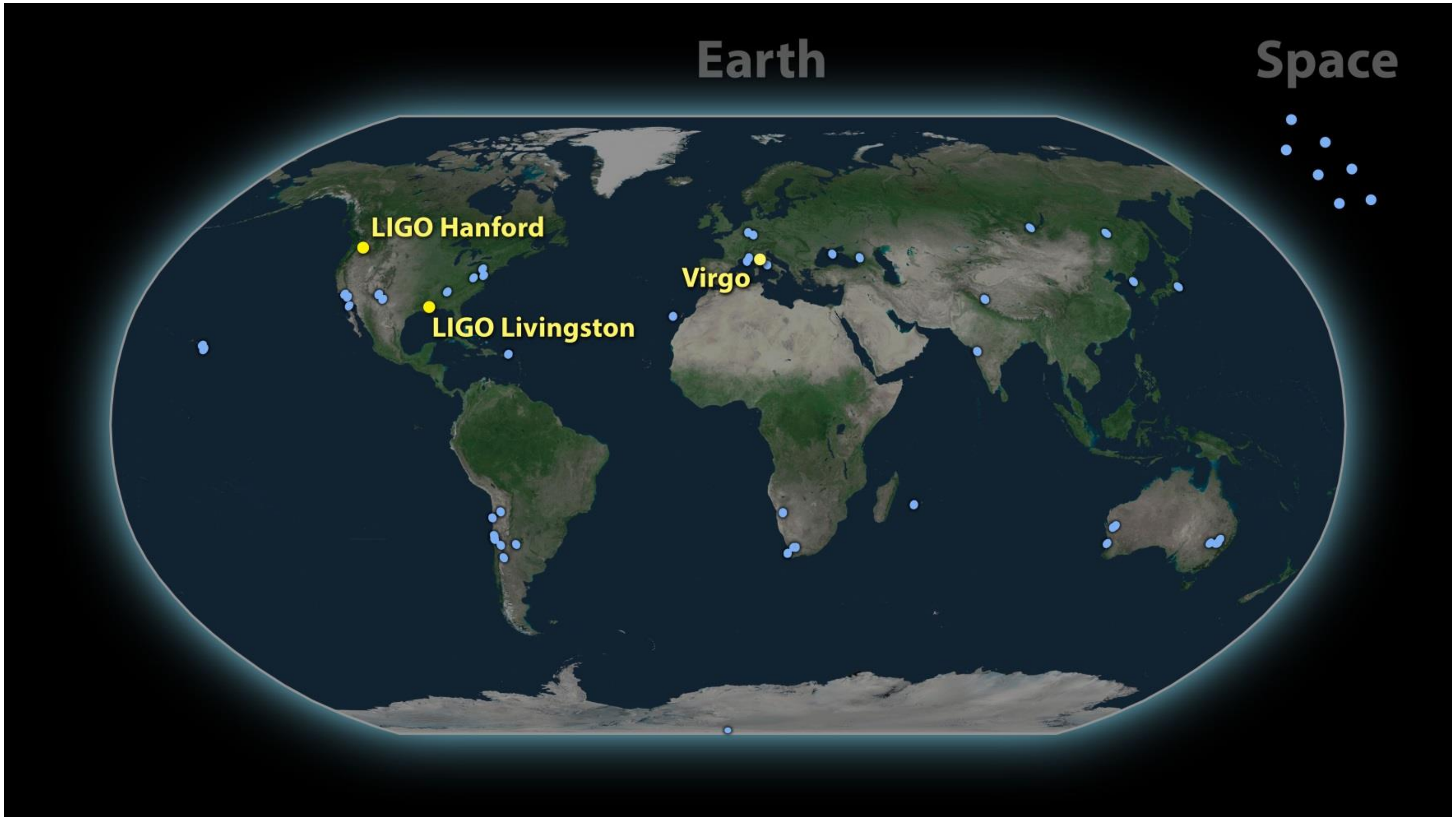
- Gravitational waves, gamma-ray burst, the whole electromagnetic spectrum





Worldwide astronomy

- Three gravitational-wave detectors
- Tens of partner observatories

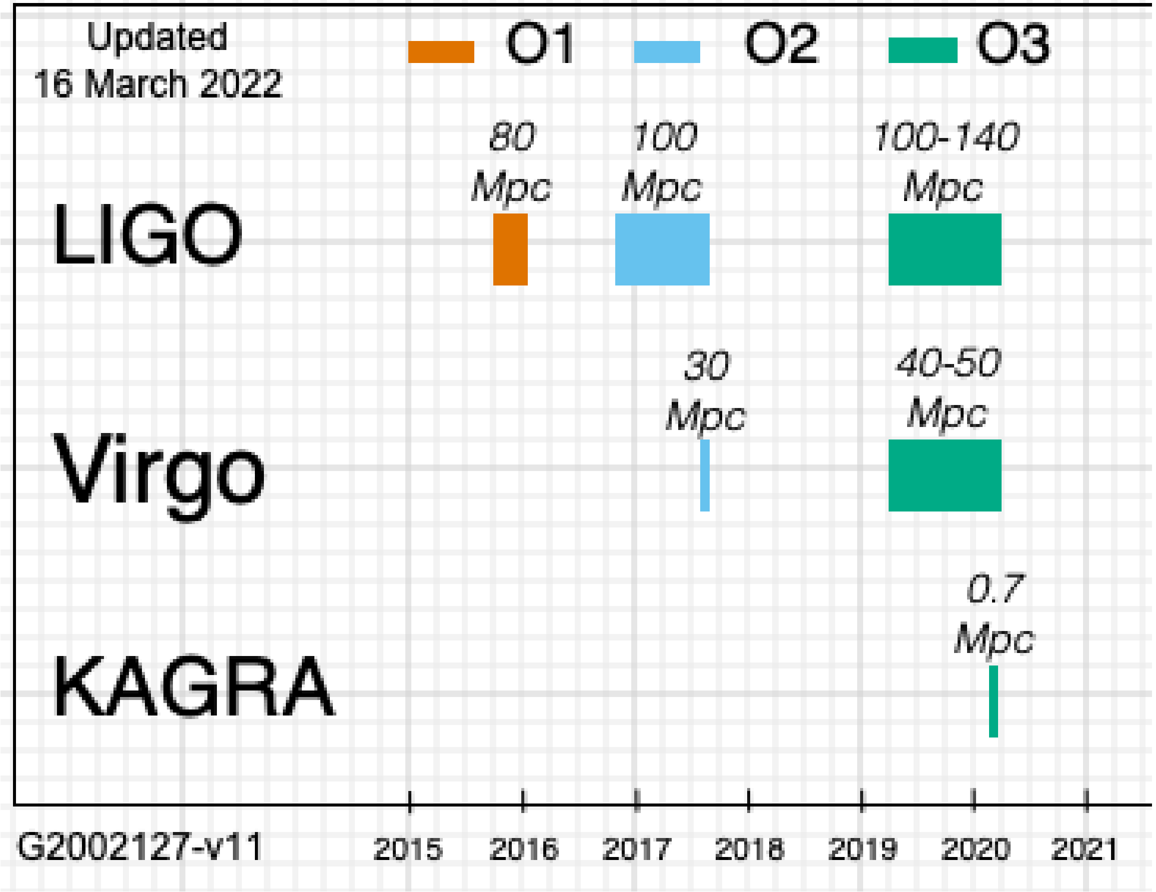


The LIGO-Virgo O3 run

- 01 April 2019 → 27 March 2020
  - 1 month commissioning break: October 2019

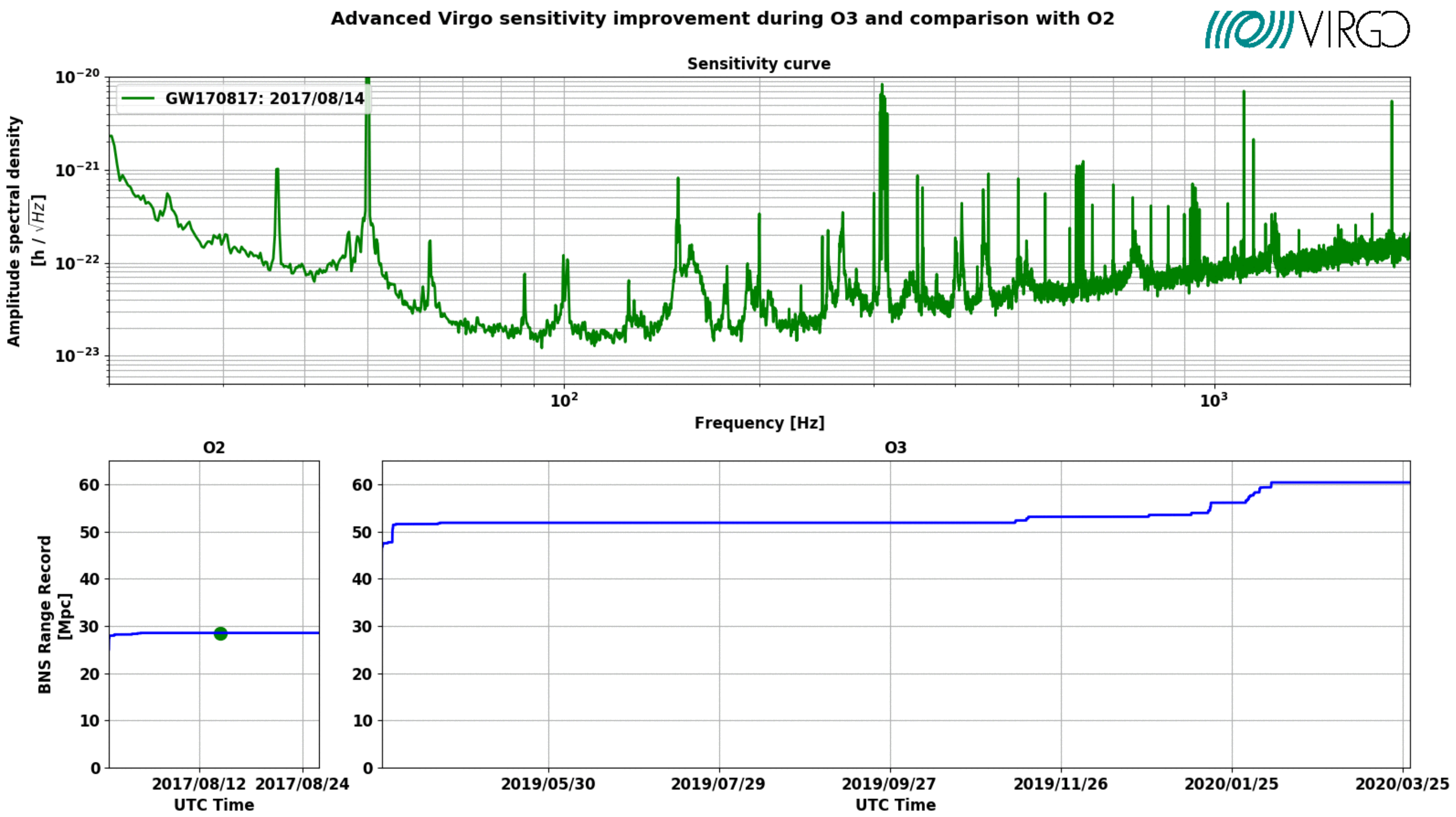
  → Ended 1 month earlier than anticipated due to the covid-19 pandemic

- Ox: Observing Run x
  - O1: LIGO detectors
  - O2: Mostly LIGO, Virgo in August'17
  - O3: LIGO-Virgo



The LIGO-Virgo O3 run

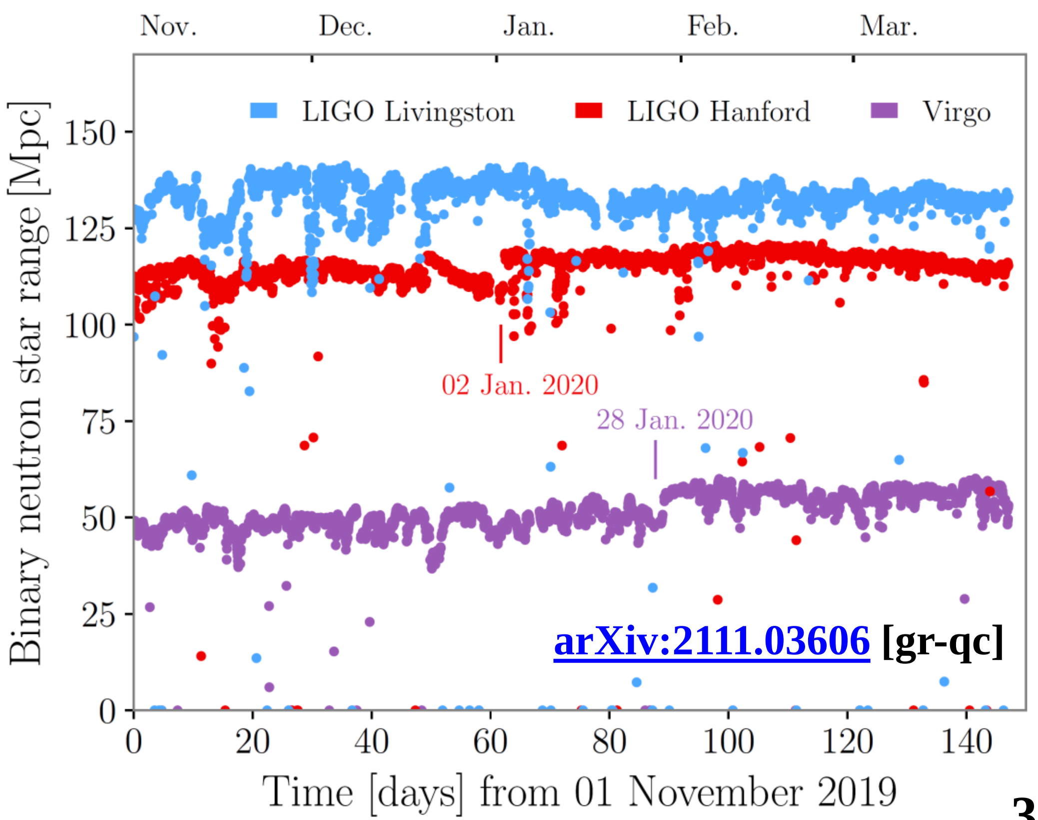
- O2-O3 improvements in the Virgo sensitivity
  - BNS range: average detection distance assuming an SNR threshold of 8



Sensitivity curve and range

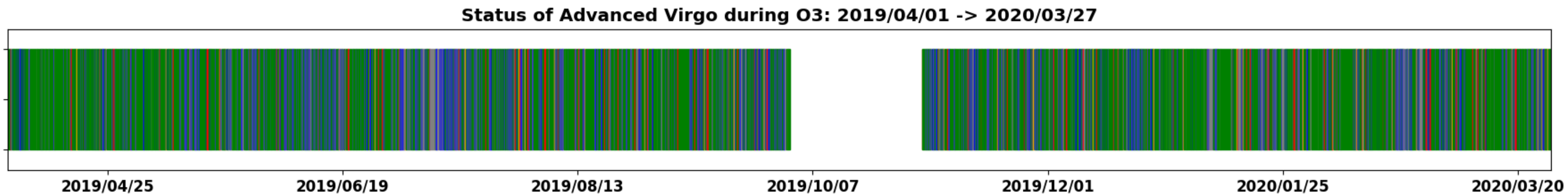
- Select a particular type of GW sources: binary neutron star (BNS) mergers
- Average source location over the whole sky
- Average the binary system inclination as well
- Convention: detection ↔ SNR = 8
  - Signal-to-Noise Ratio
- Reminder: $h(t) \propto 1 / \text{distance}$

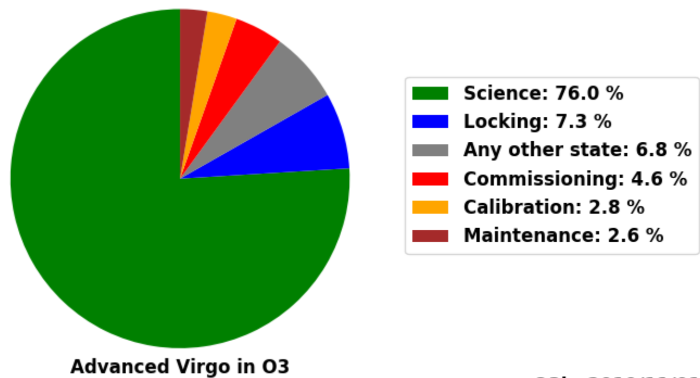
→ Sensitivity curve ↔ BNS range
  - Typical unit: Megaparsec [Mpc]

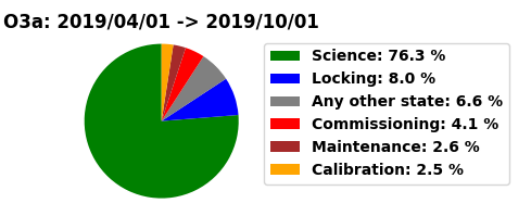


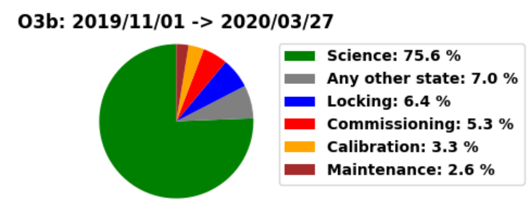
The LIGO-Virgo O3 run

- Virgo duty cycle over O3



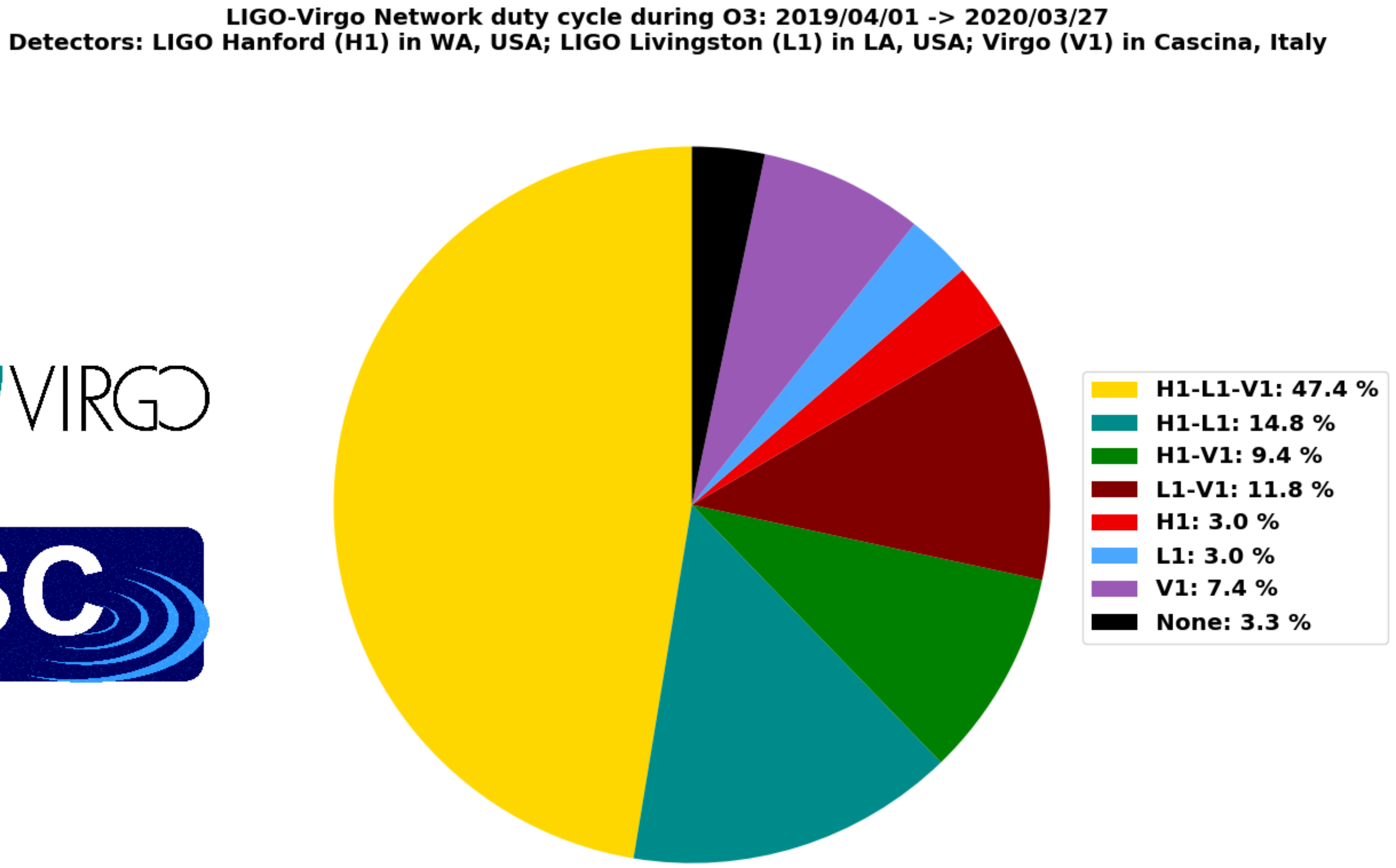






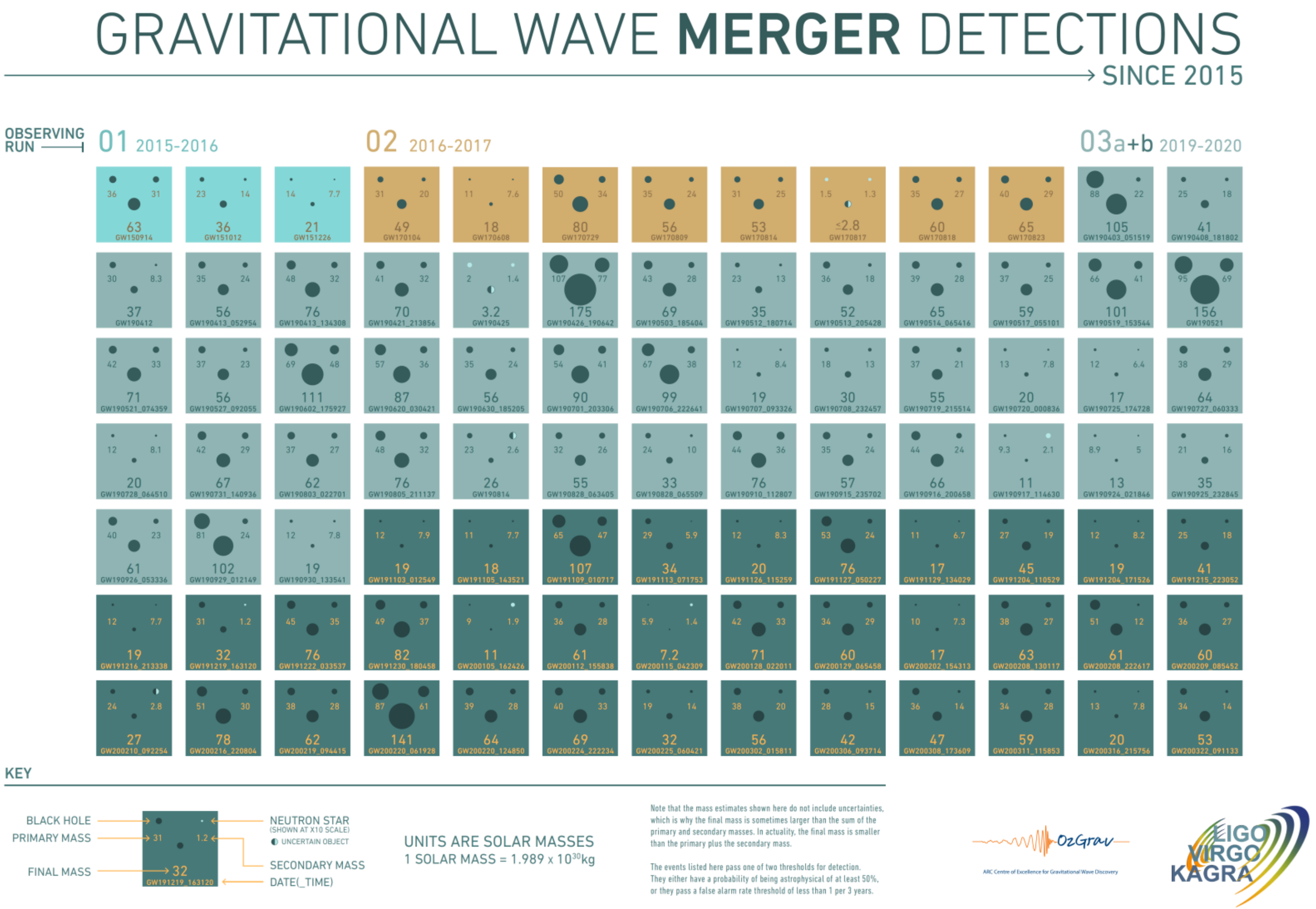
The LIGO-Virgo O3 run

- Global 3-detector network duty cycle during O3



A harvest of detections

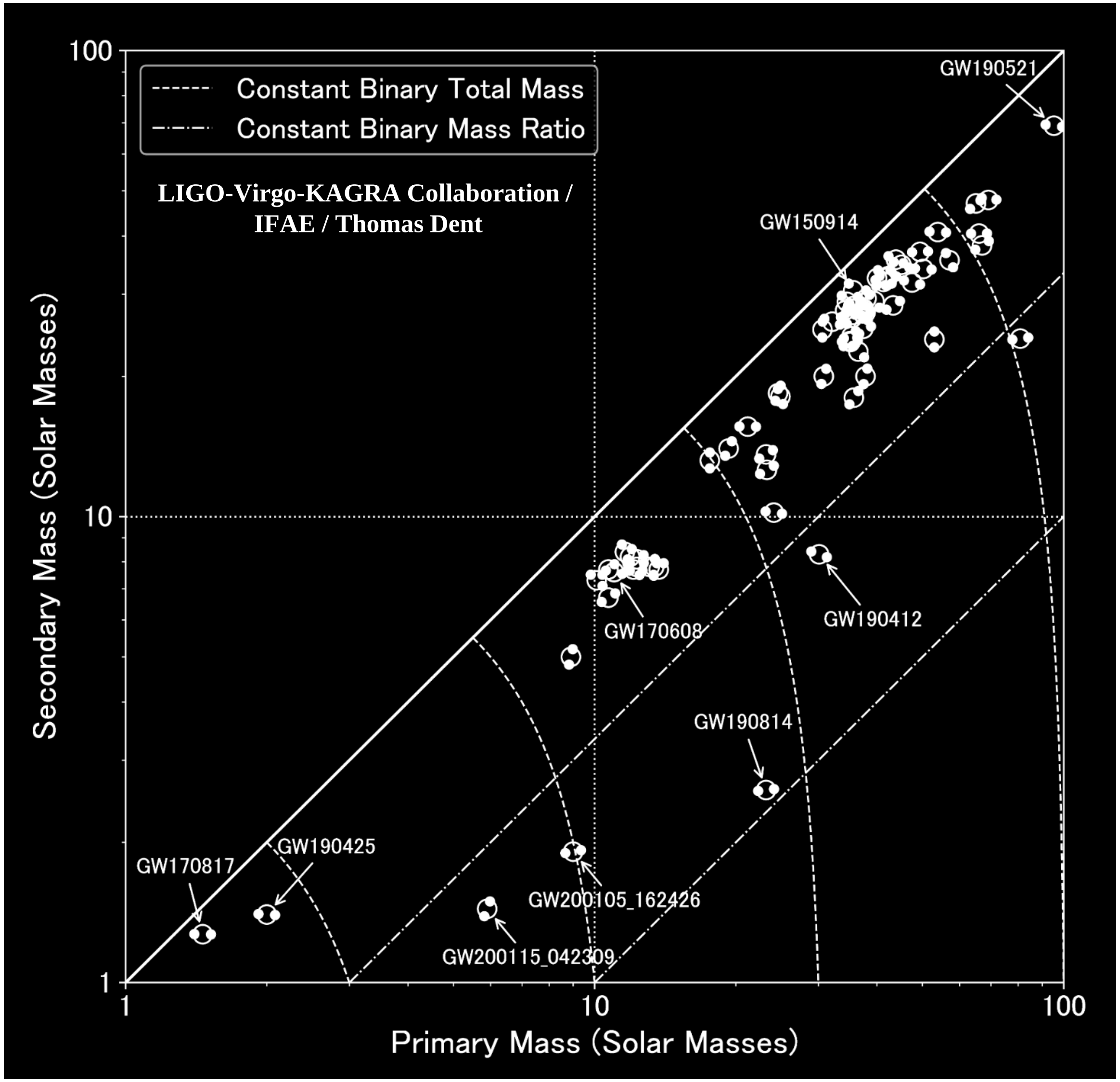
- 90 signals in the latest edition of the LIGO-Virgo-KAGRA catalog: GWTC-3



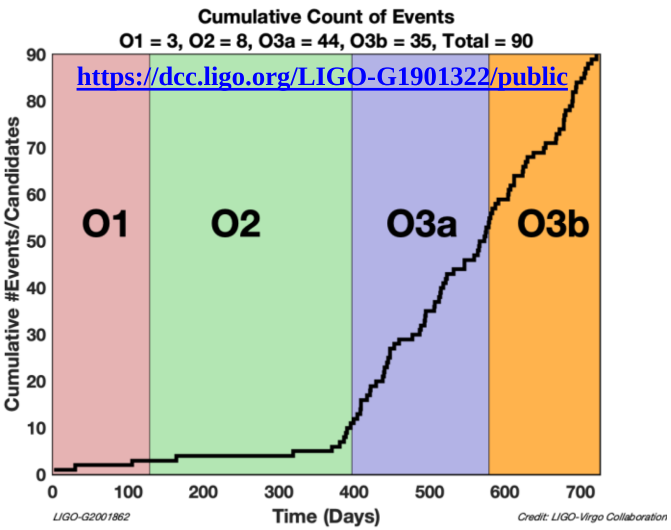
LVK transient GW detections

- All compact binary mergers
  - The three expected types have been detected
    - BBH: Binary black hole
    - BNS: Binary neutron star
    - NSBH: Neutron star – black hole

- Classified by the masses of the compact objects which have merged
  - x-axis: primary mass → Heavier object
  - y-axis: secondary mass → Lighter object



An increasing detection rate

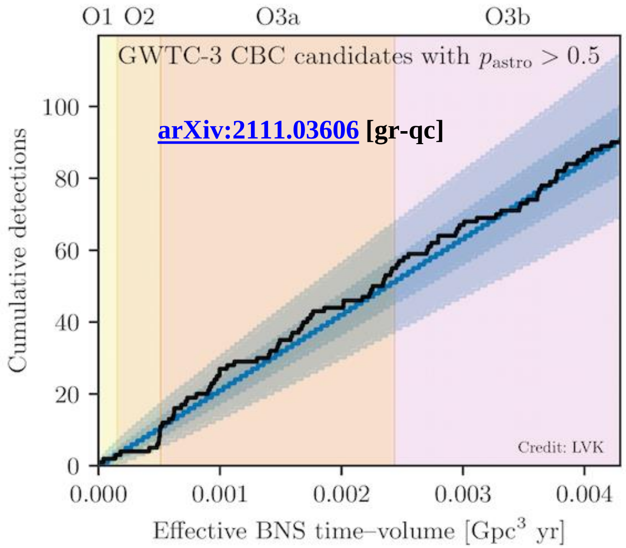


- Cumulative number of detections
  → Sharp increase of the rate
  comparing O1-O2 with O3

- A direct consequence of the detector improved sensitivities over time

→ Quantity "equivalent" to a collider integrated luminosity:
(Volume of the Universe probed) × (Time of observation)

- The cumulative number of detections scales linearly versus it



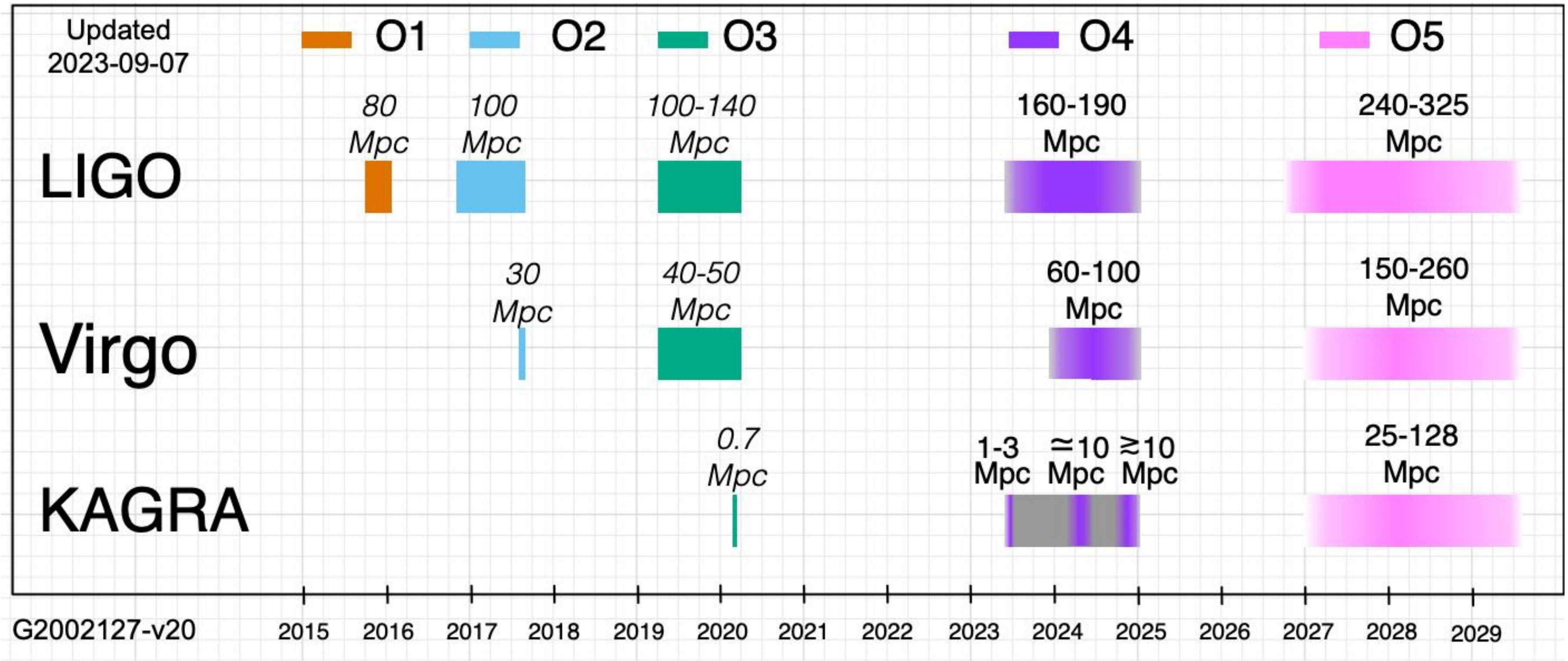
Of data taking periods and upgrades

- LVK is a meta-collaboration aiming at optimizing the global yield of the network
  - Joint strategy

    → Data taking periods:

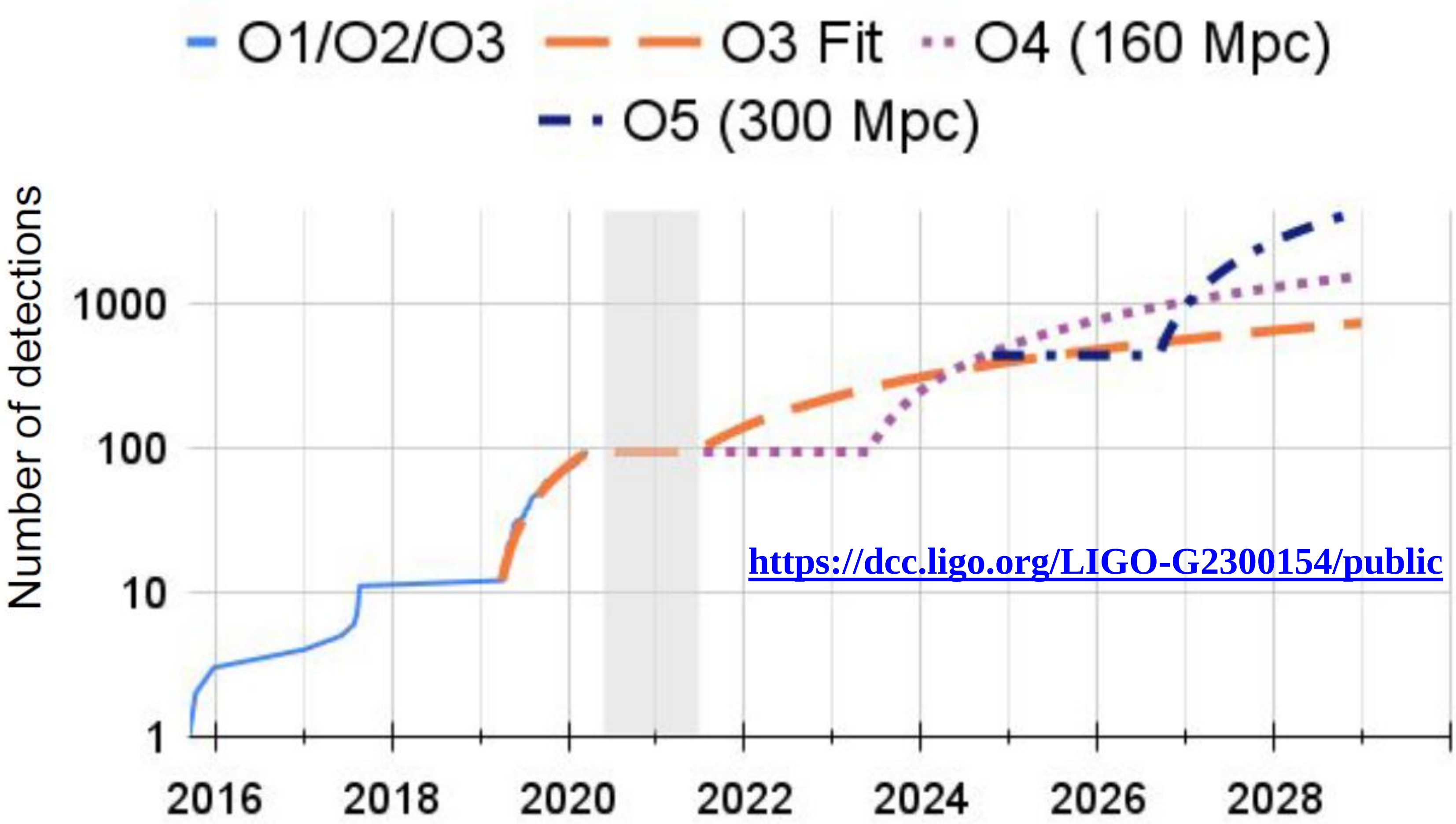
    Observing Runs (O*n*) Past: *n=1,2,3* Current: *n=4* Future: *n=5,etc.*

    → Upgrades



Of data taking periods and upgrades

- Alternating data taking and upgrade periods should lead to more events in the end



https://dcc.ligo.org/LIGO-G2300154/public

→ Extrapolation to O4 and O5 assuming BNS range of second most sensitive detector and duty cycle similar to O3

From O3 to O4

- Ambitious program of upgrades for all detectors in the network
  - Slowed down (at best) by covid-19

    → According to pre-pandemic plans, O4 should have ended in early 2023! ☹

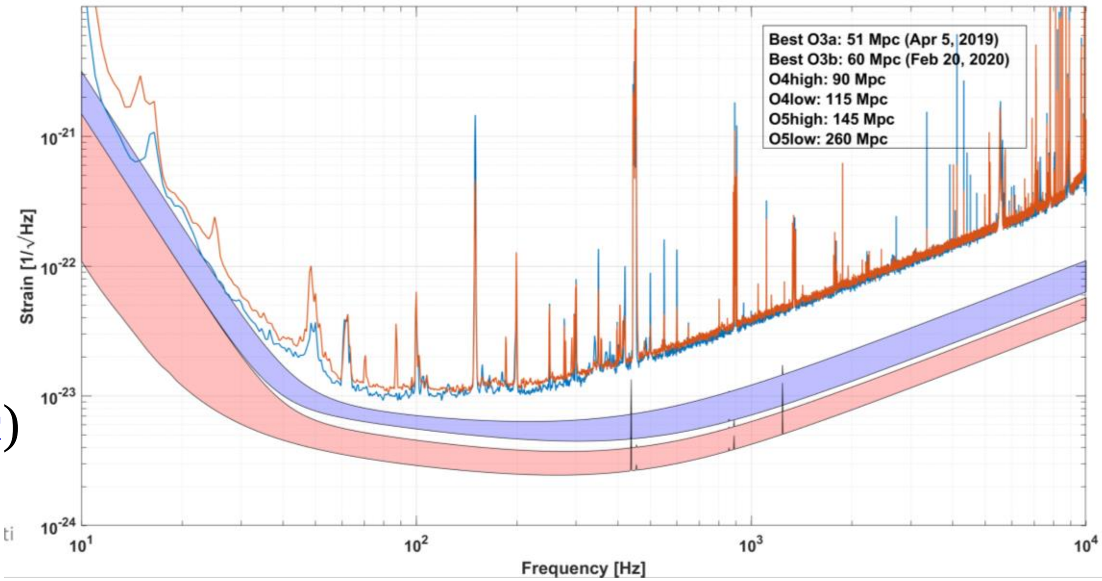
- Manifold goals
  - Increase binary merger detection rate from ~1/5 days to ~1/2 days
  - Improve public alerts
    - Latency
    - Localization
    - Classification
  - Improve SNR of detected GWs
    - Can only help searches and signal analyses

    → Possibly discover new sources!?

- LVK public plans regularly updated at https://observing.docs.ligo.org/plan

- Public wiki and mailing list: bookmark and subscribe to if interested
  - https://wiki.gw-astronomy.org/OpenLVEM

Upgrading Virgo: Advanced Virgo+



- Project proposed in 2017
- Two phases
  - Phase I: O3/O4 (2023-2024)
    - Main target: quantum noise
    - Reduction of technical noises

    → BNS range goal: O(100 Mpc)
  - Phase II: O4/O5 (2026-2027)
    - Main target: thermal noise

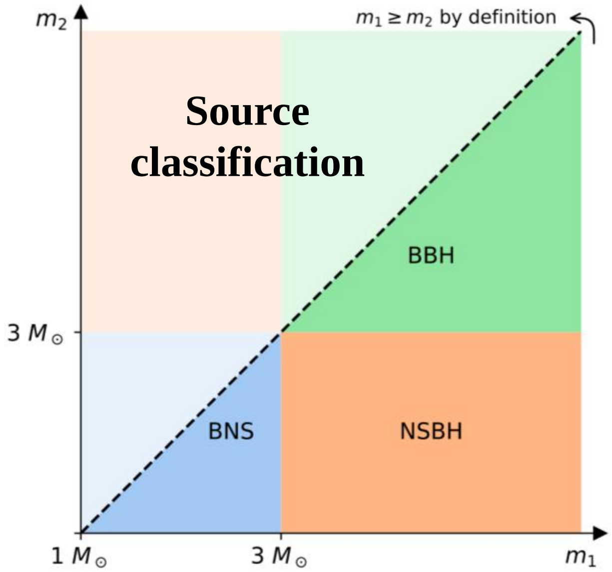
      → More invasive upgrade: mirrors to be changed

    → BNS range goal: O(200 Mpc)
- But…
  - Problems to properly control the upgraded Virgo detector
  - Excess of noise – of unknown origin – which strongly limits the sensitivity

  → Virgo has not joined the O4 run yet
- Work will continue to improve the sensitivity until next March at the latest
  - Then, Virgo will join the second part of O4 regardless of its performance at the time

Public alerts in O4

- Two types of public alerts based on false alarm rate (FAR)
  - Significant alerts
    - Compact binary mergers: FAR < 1/month
    - Bursts: FAR < 1/year
    - Passing automated and human-vetted data quality checks
  - Low significance alerts
    - FAR up to 2/day)
    - Only automated data quality checks



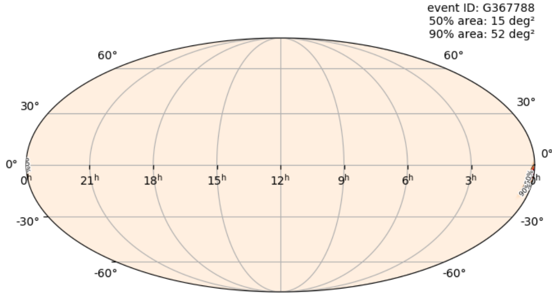
https://emfollow.docs.ligo.org/userguide

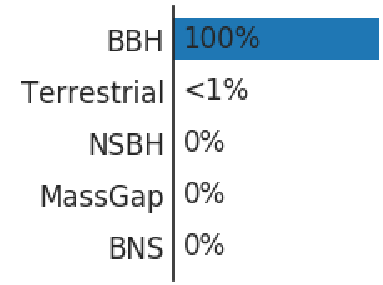
- New early warning alert stream
  - Goal: send alert *before* merger time

    → "Negative" latency: up to tens of seconds

- Public alert sequence
  - Preliminary alerts
    - First fully automated with a latency < 30 s (typically ~20s)
    - Updates as needed, final one < 5 minutes after online search completed
  - Significant triggers: rapid response team involved
    - Initial circular or retraction
    - Updates as needed – in particular improved parameter estimation

Vetting alerts in low latency



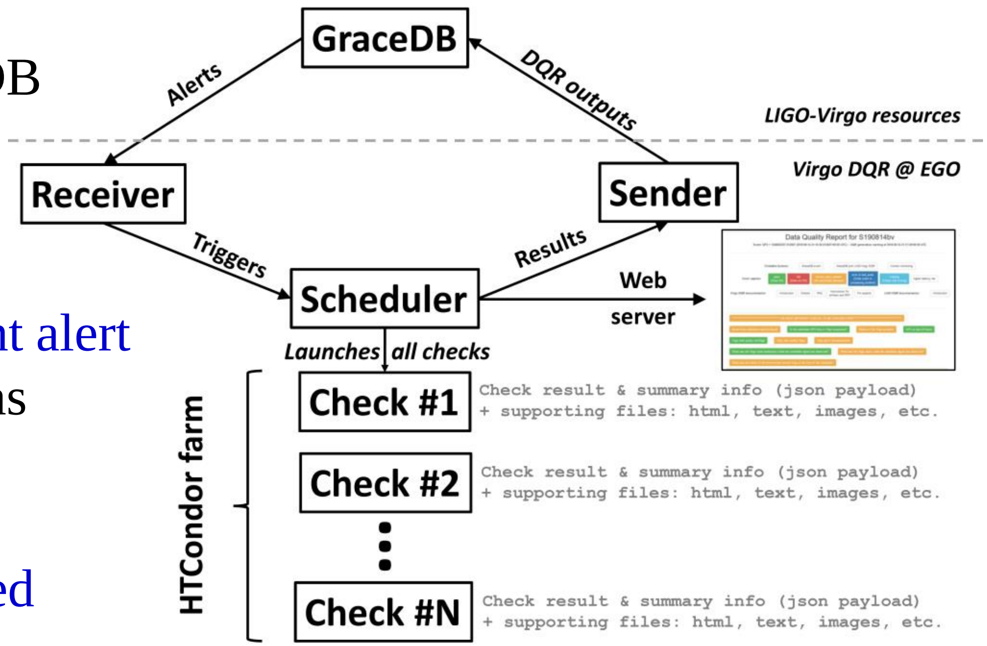


https://gracedb.ligo.org/superevents/S200311bg/view

- Goals: confirm/retract public alerts in O(few minutes)
  - Dedicated database with a public-facing interface: GraceDB https://gracedb.ligo.org/superevents/public/O3
  - Public information: GPS time, type of event, skymap
  - Use of the Gamma-ray Coordination Network (GCN)

- Key tool: the Data Quality Reports
  → Set of automated checks triggered upon receiving an alert from GraceDB
    - Example: the Virgo O3 DQR

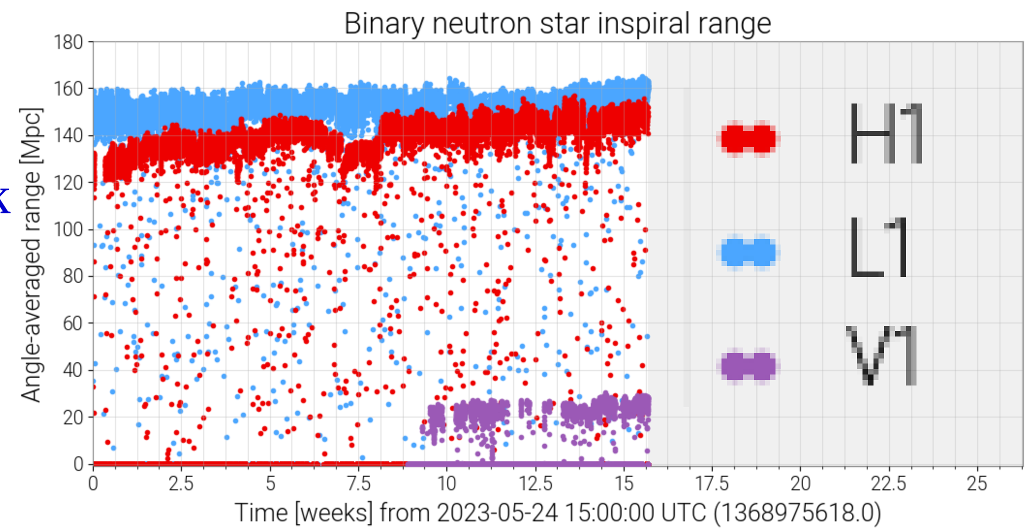
- Rapid Response Team meeting at short notice immediately after each significant alert
  - On-duty experts from all relevant areas
    - Including DetChar
  → Deciding the fate of the alert
    - O3: 80 alerts, of which 24 retracted



[2210.15634] Virgo Detector Characterization and Data Quality: tools

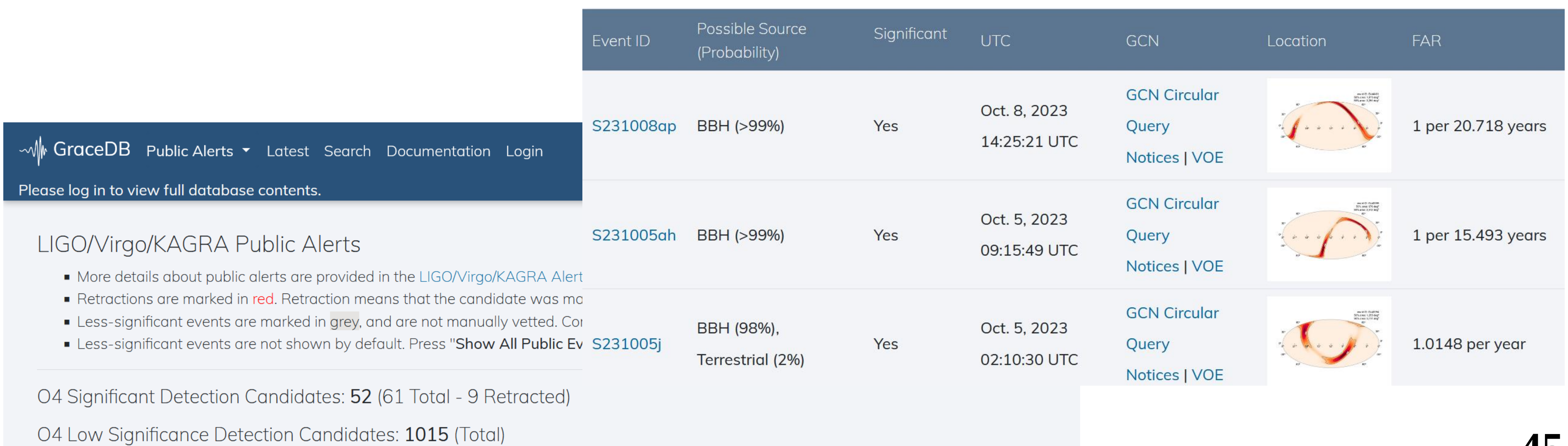
The O4 run

- Started on May 24, 2023
  - 20 months in total, with up to two months of commissioning break
    → Should end in January 2025



- LIGO detectors close to (if not at) target sensitivity

- Public alerts
  - https://gracedb.ligo.org/superevents/public/O4



GraceDB Public Alerts Latest Search Documentation Login

Please log in to view full database contents.

LIGO/Virgo/KAGRA Public Alerts

- More details about public alerts are provided in the LIGO/Virgo/KAGRA Alert
- Retractions are marked in red. Retraction means that the candidate was mo
- Less-significant events are marked in grey, and are not manually vetted. Co
- Less-significant events are not shown by default. Press "Show All Public Ev

O4 Significant Detection Candidates: 52 (61 Total - 9 Retracted)

O4 Low Significance Detection Candidates: 1015 (Total)

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR
S231008ap	BBH (>99%)	Yes	Oct. 8, 2023 14:25:21 UTC	GCN Circular Query Notices | VOE		1 per 20.718 years
S231005ah	BBH (>99%)	Yes	Oct. 5, 2023 09:15:49 UTC	GCN Circular Query Notices | VOE		1 per 15.493 years
S231005j	BBH (98%), Terrestrial (2%)	Yes	Oct. 5, 2023 02:10:30 UTC	GCN Circular Query Notices | VOE		1.0148 per year

Beyond O4: O5 and more

- Clear (approved and funded) plans until O5 for Virgo and LIGO: ~2028
  - <u>Example:</u> Advanced Virgo plus, phase II

- Ongoing developments for third-generation ("3G") detectors
  - Not ready before 2035 – earliest / (very) optimistic schedule

→ About a decade to bridge
  - Push existing infrastructures to their limits – Virgo_nEXT project
    - Possible overlap between advanced detectors and 3rd generation
  - Pave the way to future detectors
    - Common R&D and developments
      → Use existing instruments as testbeds
  - Keep vivid technical knowledge and skills
    - Train new generation of scientists

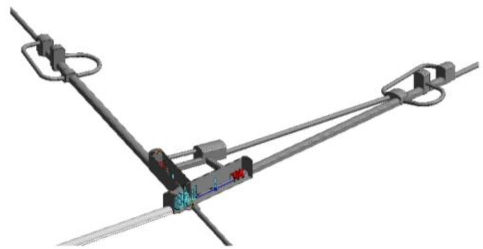
→ Current Virgo problems may lead to a strong change of plans
  - Making the recycling cavities more stable would require infrastructure work
    → Decision in the coming months

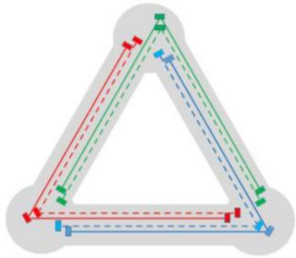
On the even longer term: Einstein Telescope

- Einstein telescope in a nutshell

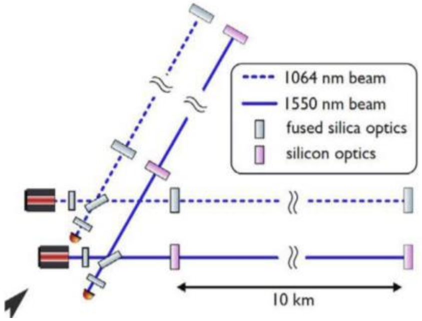
Credit: Alessio Rocchi

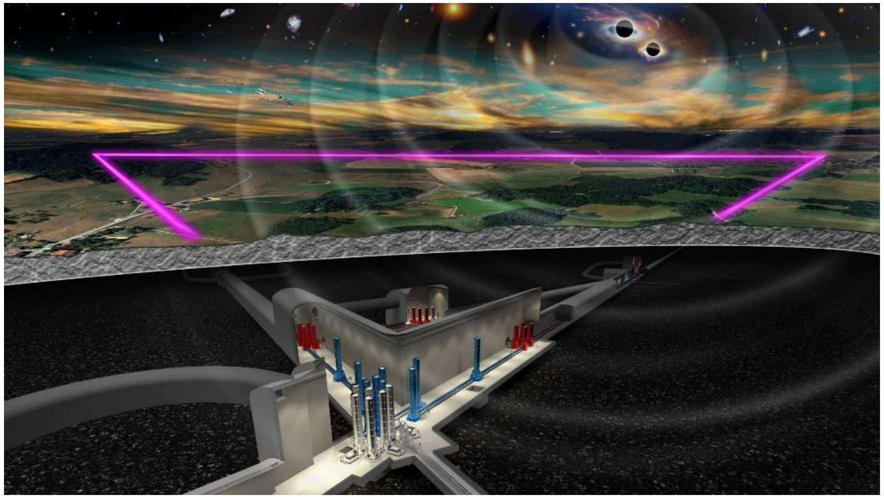
- Xylophone (multi-interferometer) Design
- **Underground**
- **Cryogenic**
- Triangular shape
- Multi-detector design
- Longer arms

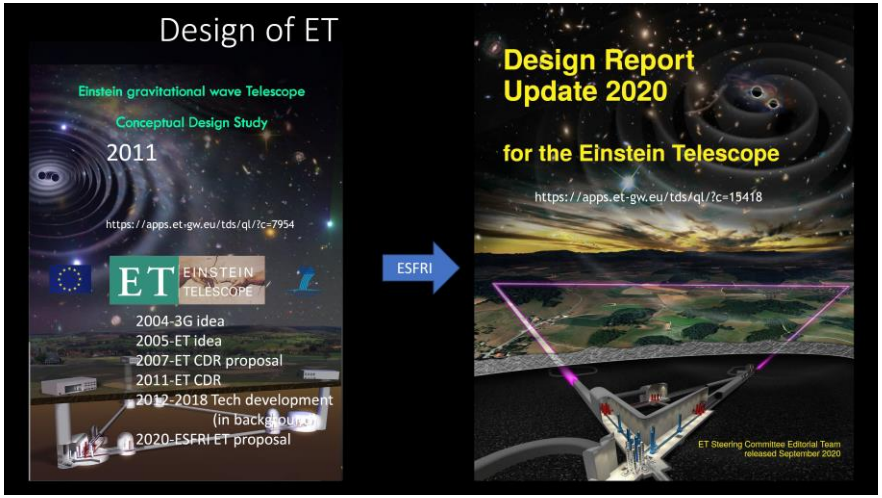




- Wide frequency range
- Massive black holes (LF focus)
- Localization capability
- (more) Uniform sky coverage
- Polarization disentanglement
- High Reliability (high duty cycle)
- High SNR







On the even longer term: Cosmic Explorer

- Two 20÷40 km-long detectors above ground, located in the US
  - Using mature technology from current interferometers

- Reference: A Horizon Study for Cosmic Explorer
  - https://arxiv.org/abs/2109.09882