Gravitational wave observations with ground-based interferometers: status and perspectives

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on behalf of the Virgo Collaboration

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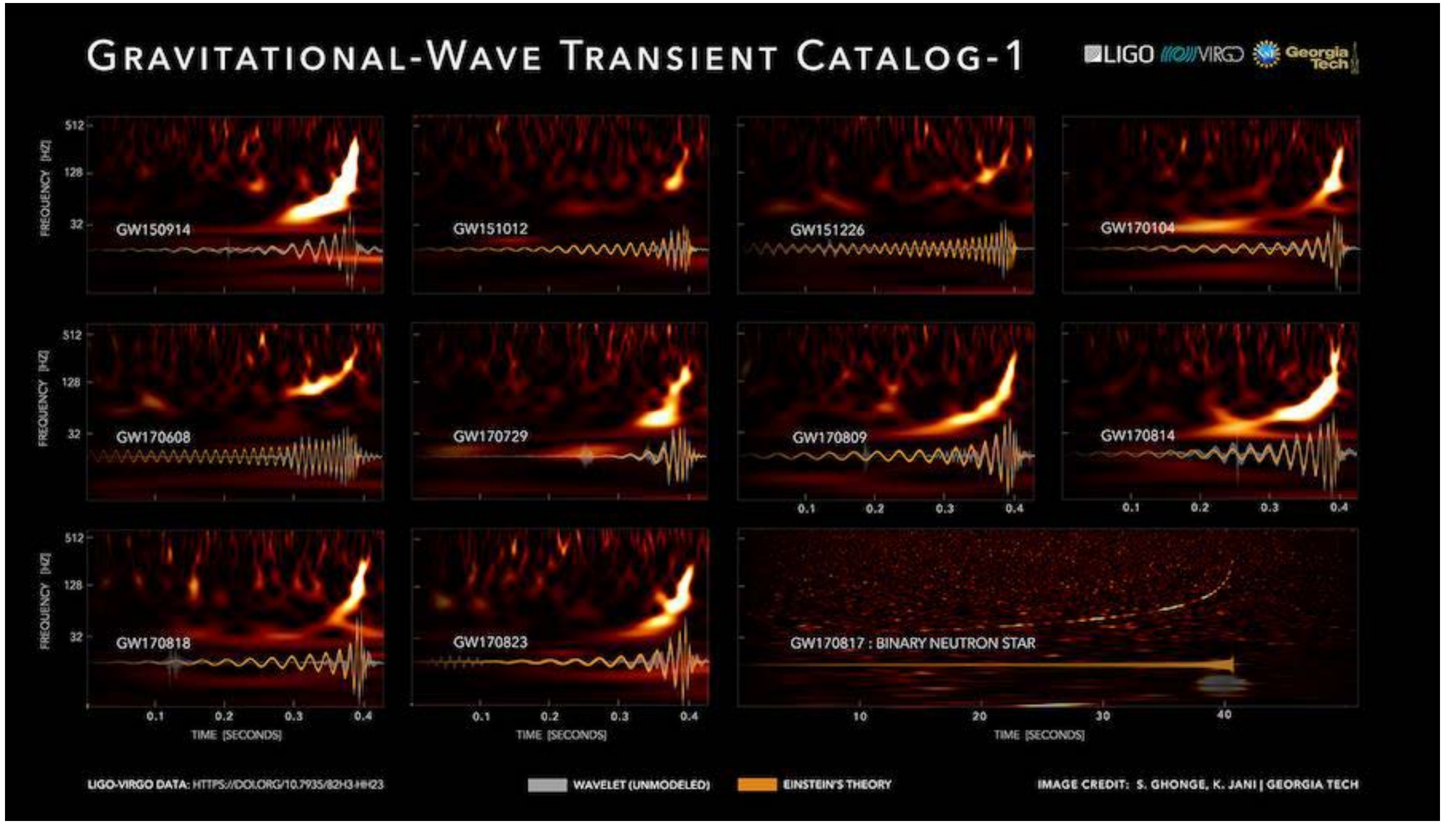
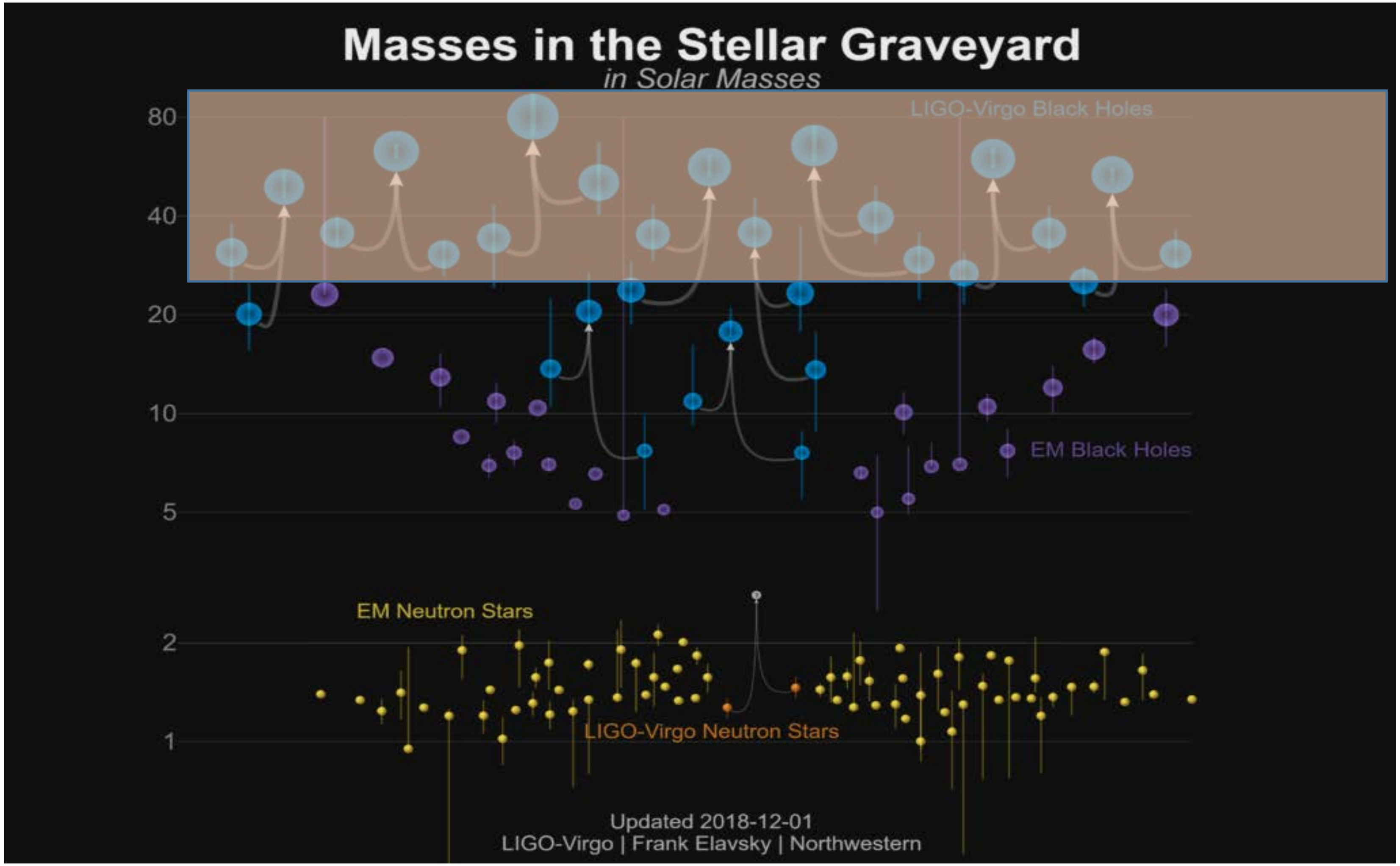
Scientific achievements from O1-O2

Binary systems detected: extract information on masses, spins, energy radiated, position, distance, inclination, polarization. Population distribution may shed light on formation mechanisms

GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. X 9, 031040 – Published on September 4, 2019



Scientific achievements from O1-O2

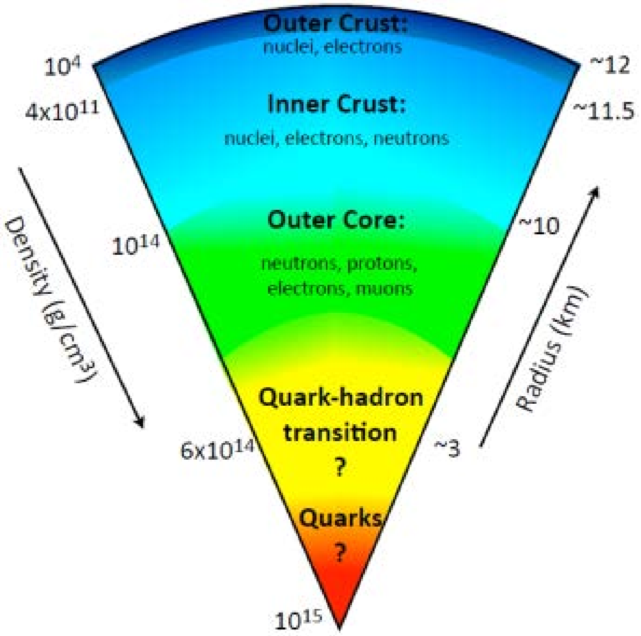


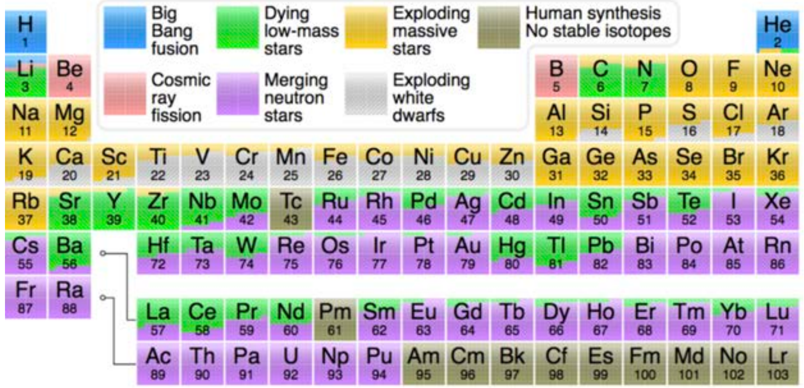
New family of BH?

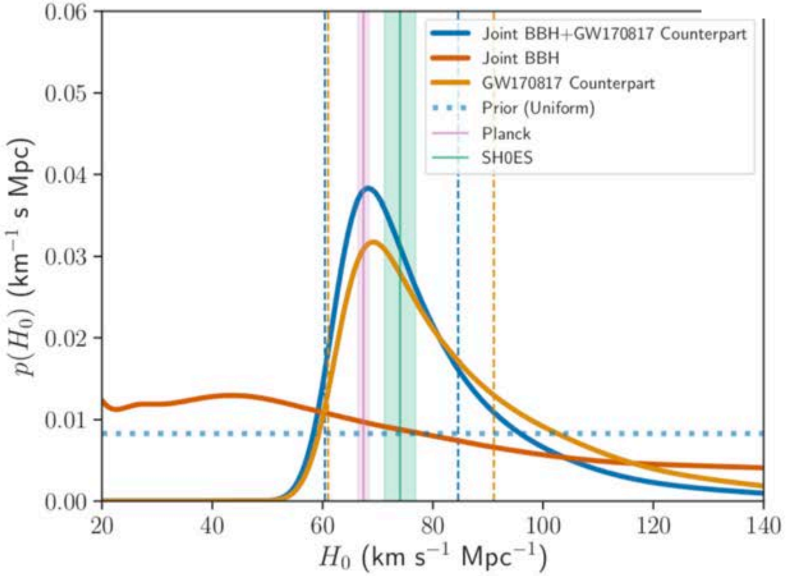
Scientific achievements from O1-O2

More:

- GR tests: probing GR in strong field conditions
- Multimessenger astronomy
- Nucleosynthesis and enrichment of the Universe
- Cosmology
- Nuclear matter physics







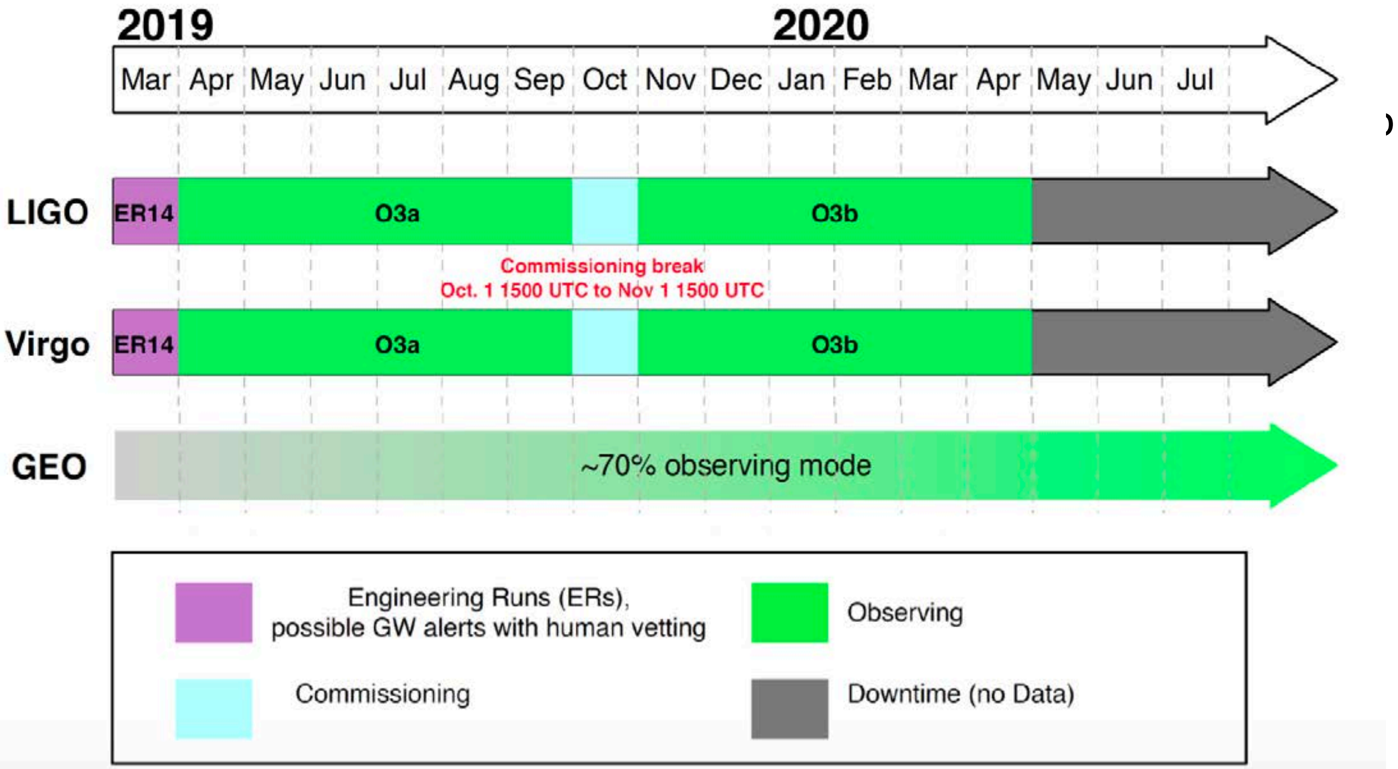
$$H_0 = 68^{+14}_{-7} \text{ km s}^{-1} \text{ Mpc}^{-1}$$

O3 run

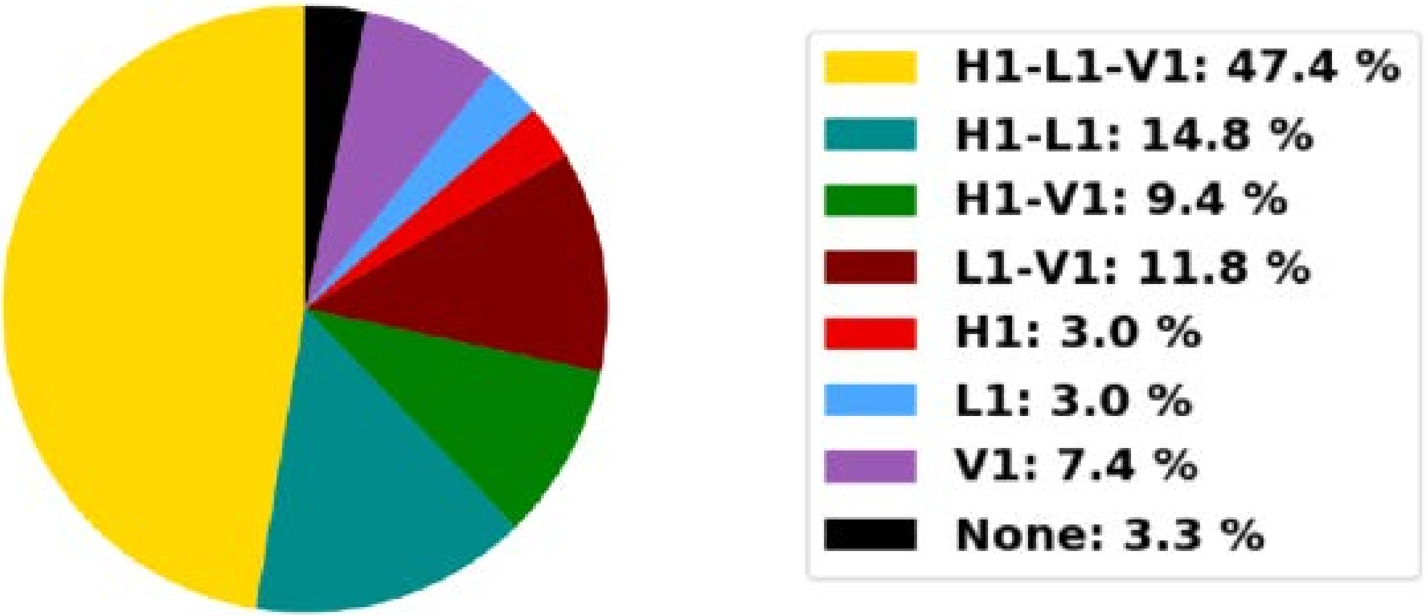
O3 started on April 2019

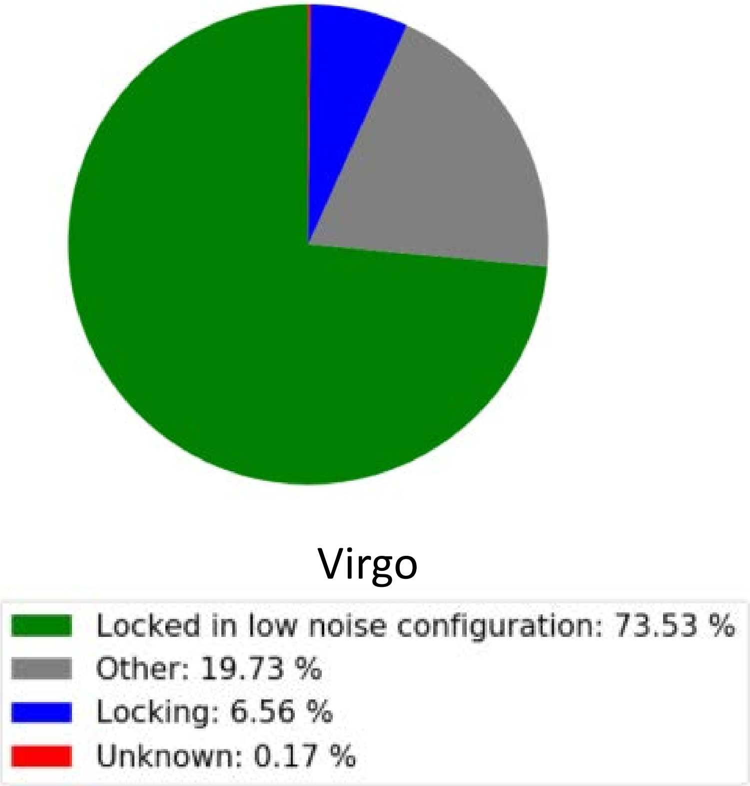
Due to the pandemic

- O3 run globally suspended on March 27 (about 1 month earlier than planned)
- All activities suspended → LIGO and Virgo decision to focus on upgrades planned for O4 when activities could restart



O3 run duty cycle



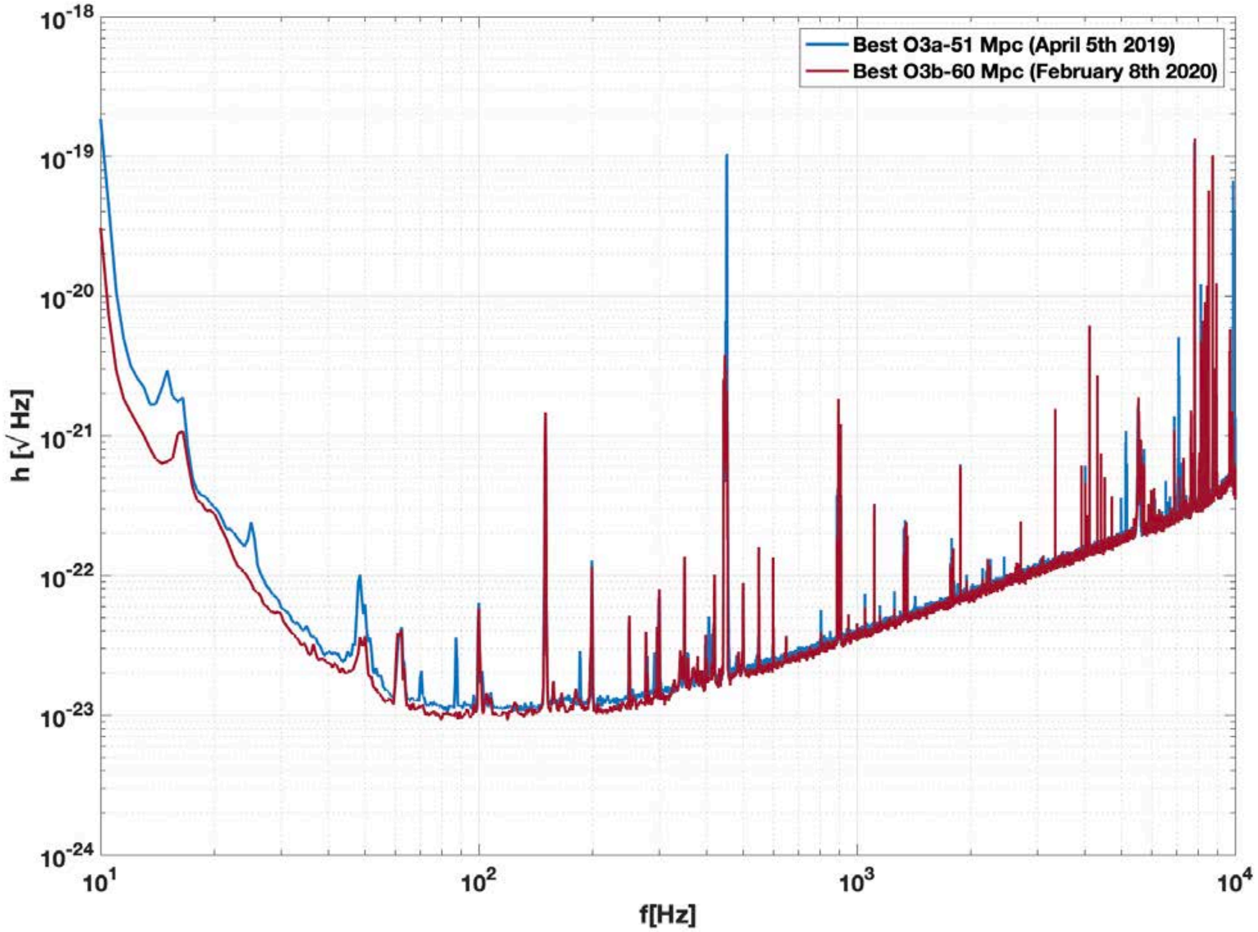


HLV Science segments: 83.4% = 47.4% triple + 36.0% double coincidences; 3.3% no detector on

Virgo duty cycle: 75.97%
Note that Virgo dedicated 2 shifts per week to commissioning (i.e. 9.5% calculated loss) in O3b

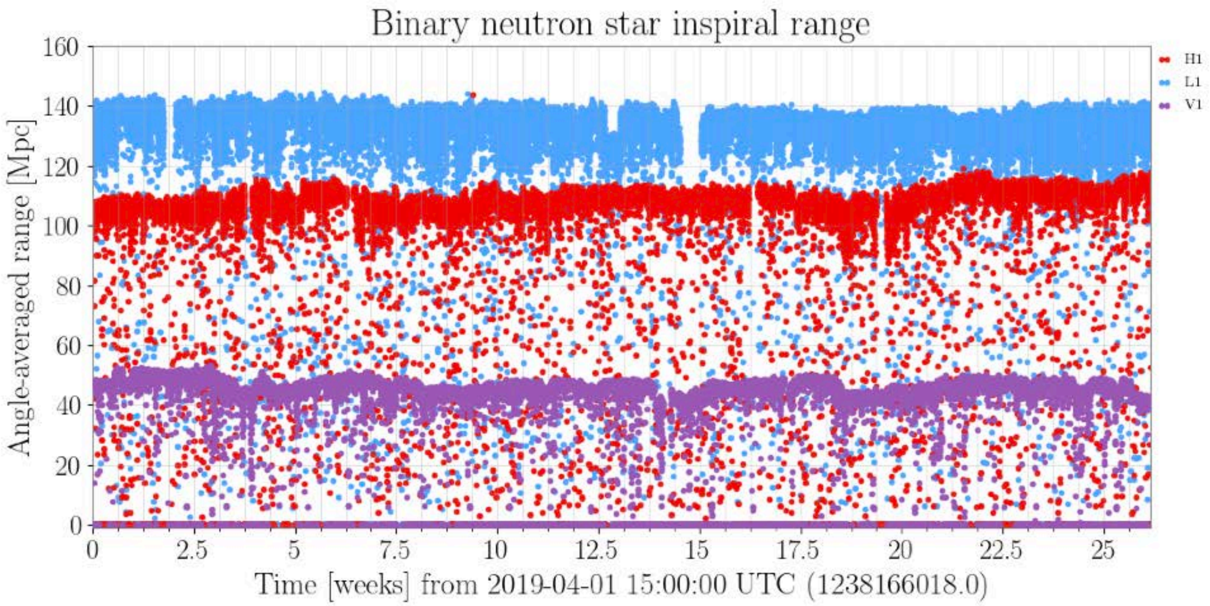
Credit: J.v.d.Brand

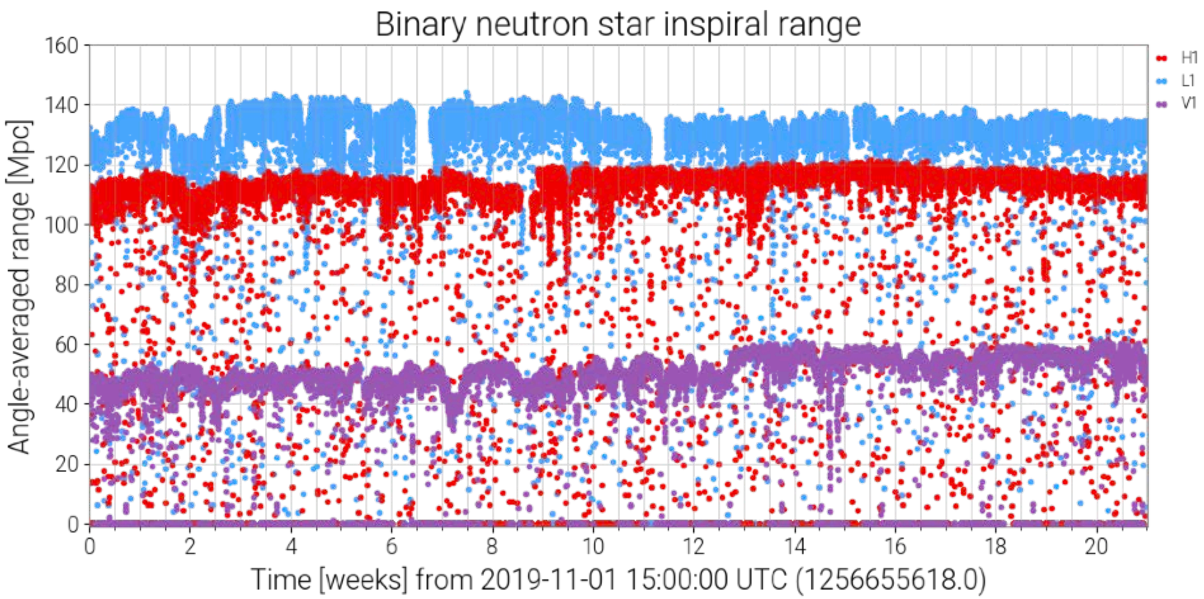
O3a-O3b performances



Wideband improvement from O3a to O3b

O3a-O3b performances: BNS





- H1: 100+ to 120 Mpc
- L1: 120+ to 140+ Mpc
- Virgo: 40 to 50+ Mpc

- H1: 110 to 120 Mpc
- L1: 120+ to 140+ Mpc
- Virgo: 50+ to 60 Mpc

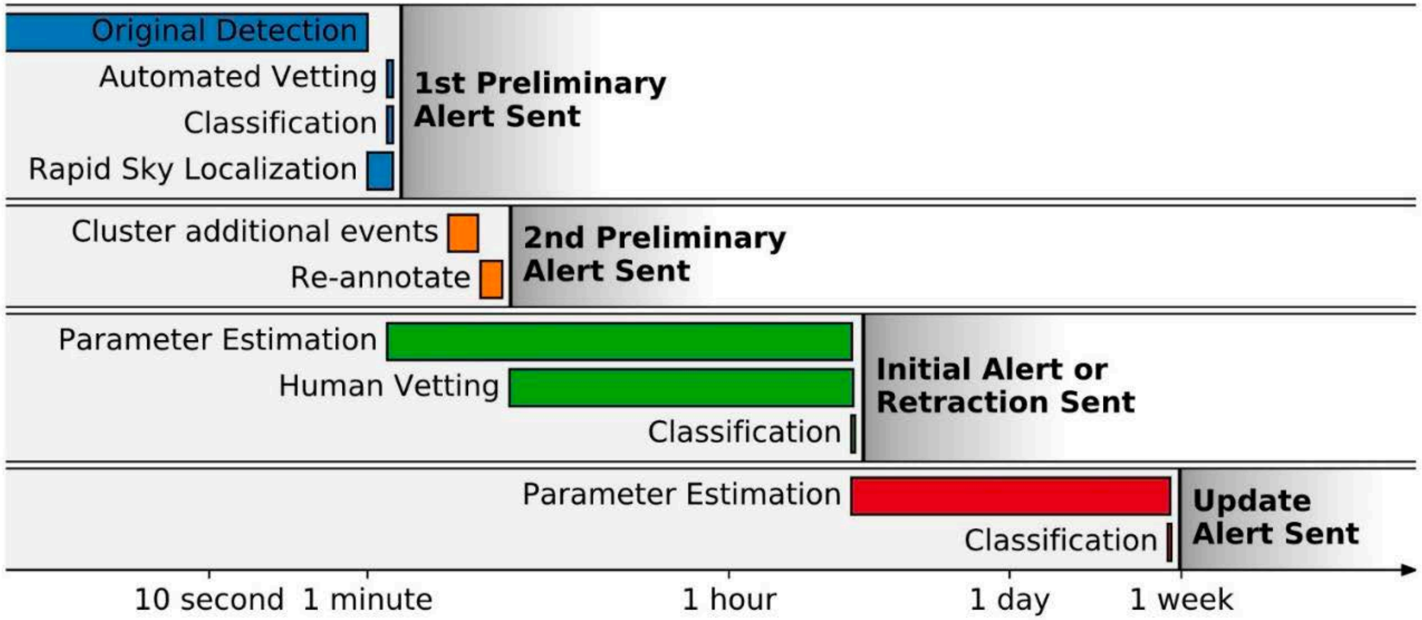
O3 alerts

LIGO-Virgo data are jointly analyzed in real-time

- Modelled (compact binary coalescences) and unmodelled searches («bursts»)
- ➢ Detect and localize potential transient GW signals

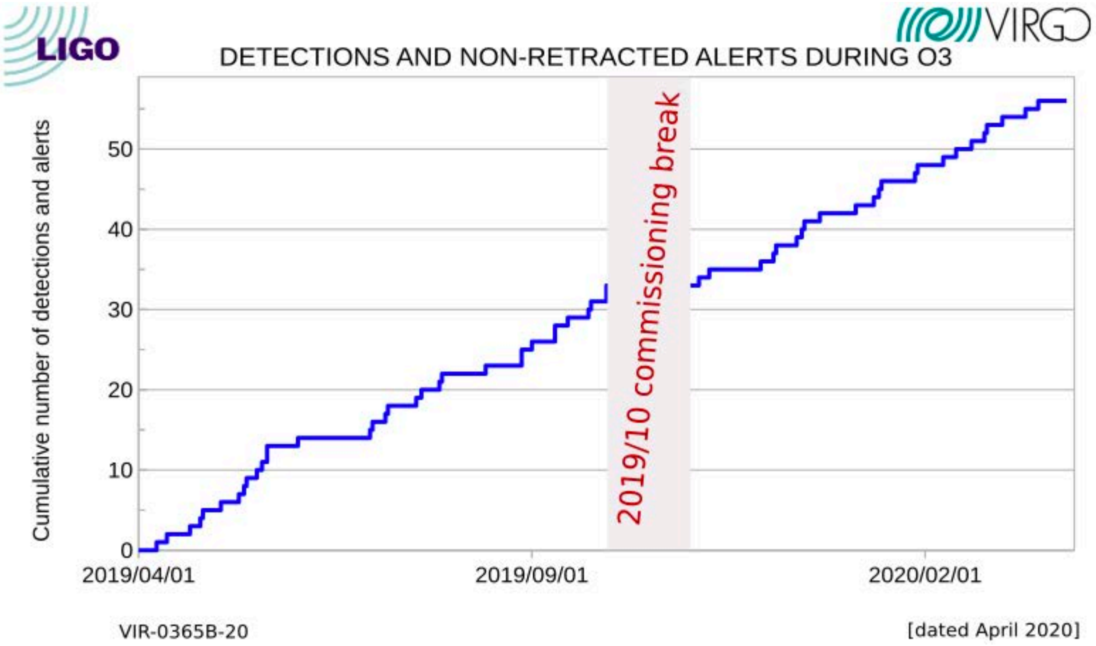
When a significant-enough candidate is found

- False-alarm rate lower than 1 / O(few months)
- ➢ Alert sent to astronomers in order to search for counterparts through NASA's Gamma-ray Coordinates Network (GCN)



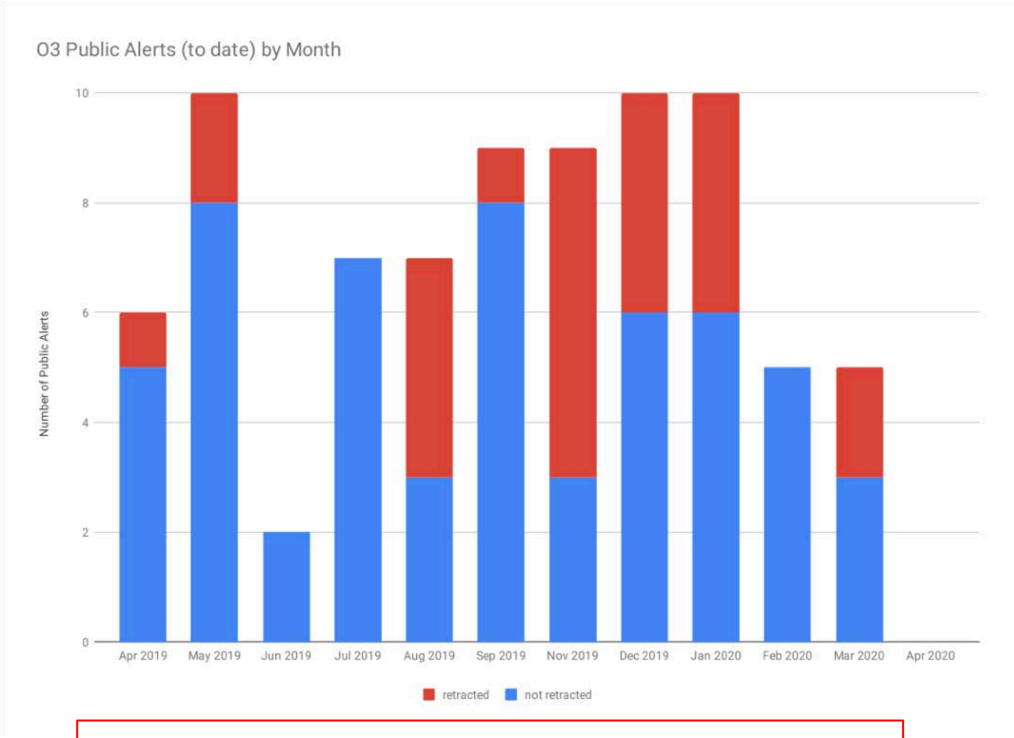
- Expert vetting
- ➢ Public alerts can be retracted

O3 GW candidates


DETECTIONS AND NON-RETRACTED ALERTS DURING O3

VIR-0365B-20

[dated April 2020]

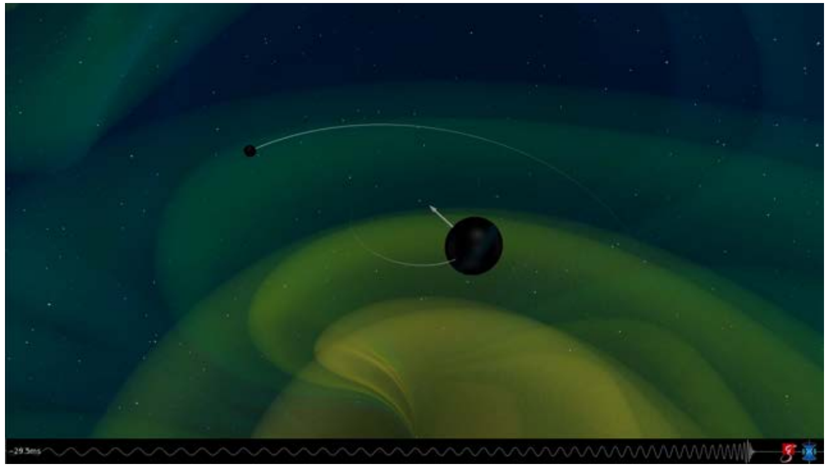

O3 Public Alerts (to date) by Month

See https://gracedb.ligo.org/latest/

- 80 GW-only candidates: 24 retractions, 56 after excluding retractions
- Offline analysis should confirm most of these candidates, and may uncover additional events
- 4 discovery papers already published, focused on «exceptional» events; dozens of papers in preparation

O3 first results

- **GW190412**: Observation of a binary-black-hole coalescence with asymmetric masses (PRD 102, 043015, 2020)
  - First observation of BBH merger with significantly different masses (30 & 8 $M_\odot$)
  - Mass ratio about 0.28
  - GR predicts the contribution of terms beyond the quadrupolar one
  - First observation of GW higher multipoles (l = m = 3)
    - new test of GR



$$h_+ - i h_\times = \sum_{\ell\geq 2}\sum_{-\ell\leq m\leq \ell} \frac{h_{\ell m}(t,\lambda)}{D_L}\, {}_{-2}Y_{\ell m}(\theta,\phi)$$

- If $q \approx 1$ h_{22} and even $\ell = m$ dominate, but in this case

  $\ell = m = 3$ and subsequent odd terms gain of relevance
  - $f_{\ell m} \approx m f_{orb}$ (far the merging)
  - Precessing of the spin and of the orbital plane

O3 first results

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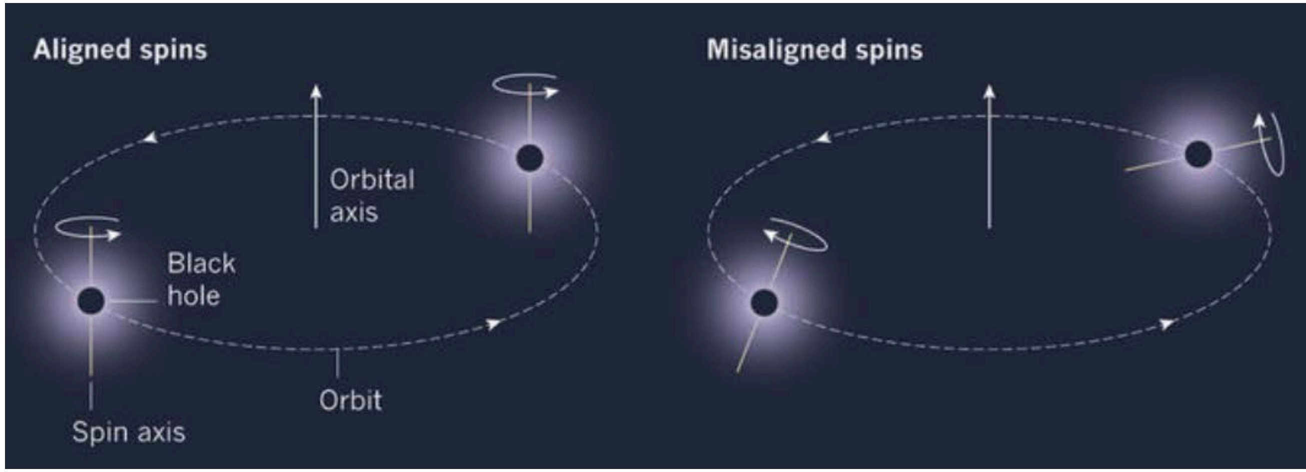
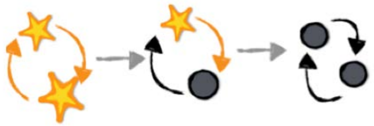
  - Mass ratio about 0.28
  - GR predicts the contribution of terms beyond the quadrupolar one
  - First observation of GW higher multipoles (l = m = 3)
    - new test of GR
  - Marginal hints of precession
    - Impact on BH population
    - Astrophysical formation channels

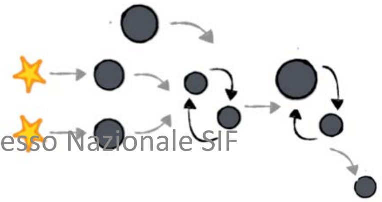


Isolated binary



→ spins preferentially aligned with the binary orbital angular momentum

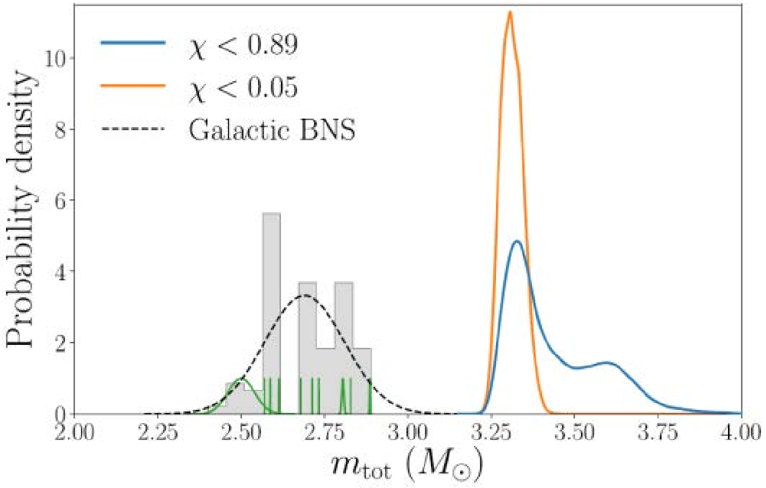
Cluster binary



→ isotropic spin orientations

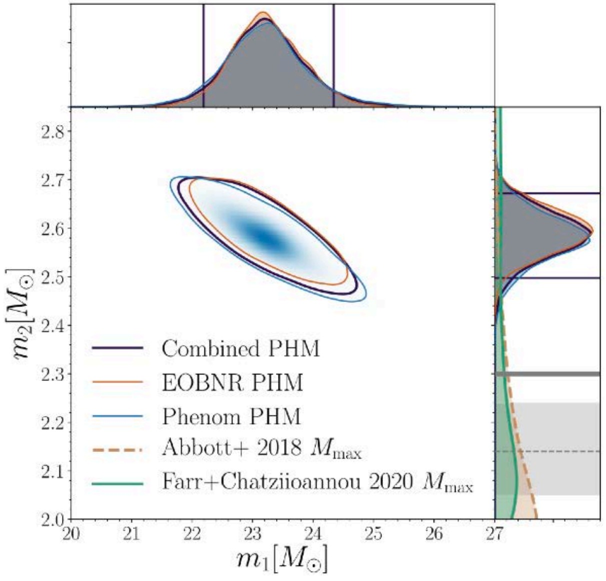
O3 first results

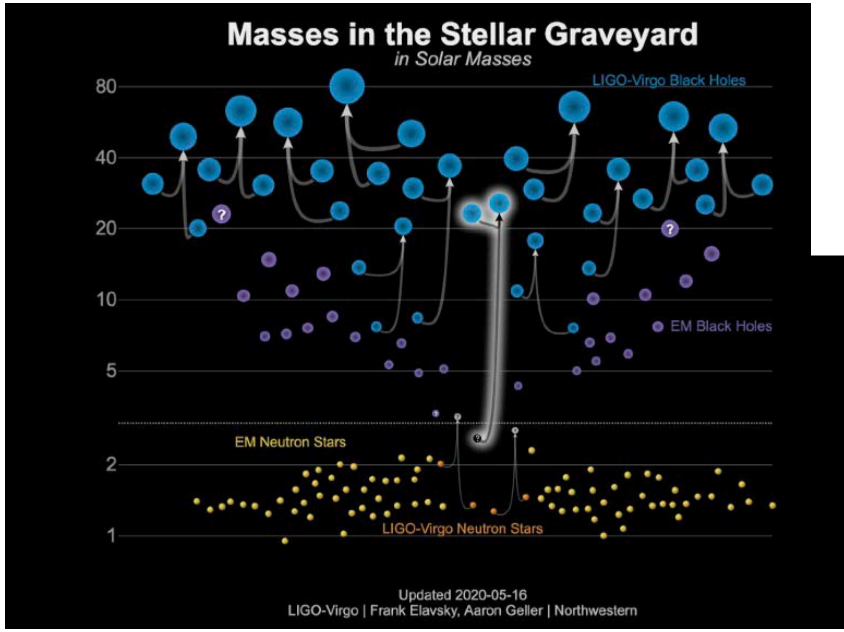
- **GW190425**: Observation of a compact binary coalescence with total mass ~ 3.4 $M_\odot$ (ApJL, 892:L3, 2020)
  - Most likely second BNS after GW170817 (BBH or NSBH cannot be ruled out)
  - No em counterpart (more distant and less well localized - 8284 deg^2 90% credible sky area)
  - Two interferometers detection (L1 + Virgo – $\mathrm{SNR}_{\mathrm{Virgo}}$ = 2.5 - below threshold 4)
  - Total mass larger than any known system so far. More than 5σ larger than the Galactic population mean (composed by 10 BNS expected to coalesce within the Hubble time among 17 known BNS)
  - Astrophysical Implications
    - (Small) Impact on the Astrophysical Rate
    - Hypothesis on the possible system origins
    - And if they are instead BHs?
      - Mass Gap BHs!
      - Primordial BHs!



O3 first results

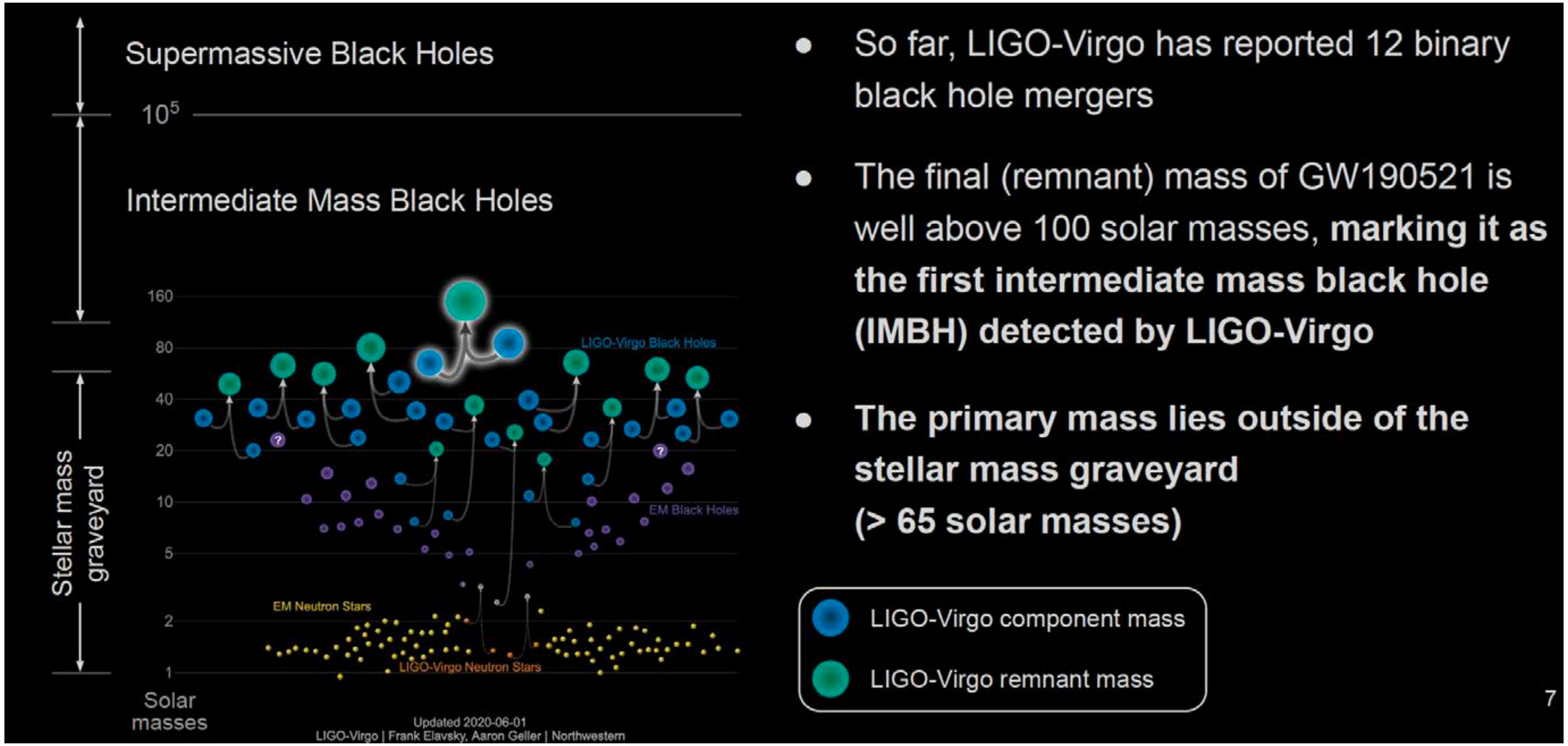
- **GW190814:** Gravitational waves from the coalescence of a 23 $M_\odot$ black hole with a 2.6 $M_\odot$ compact object (ApJL, 896:L44, 2020)
  - Uncertain nature of the second component: BH or NS?
    - either the lightest BH or heaviest NS ever observed
  - Mass ratio 9:1
  - Multipole emission observed
  - Clear evidence of inclination
  - Challenge for formation models





O3 first results

- **GW190521**: Gravitational waves from an extraordinarily massive merging binary system: two black holes of 66 and 85 $M_\odot$, which generated a final black hole of 142 $M_\odot$ (Discovery paper - Phys. Rev. Lett. 125, 101102 (2020) - Astrophysical implications - Astrophys. J. Lett. 900, L13 (2020))

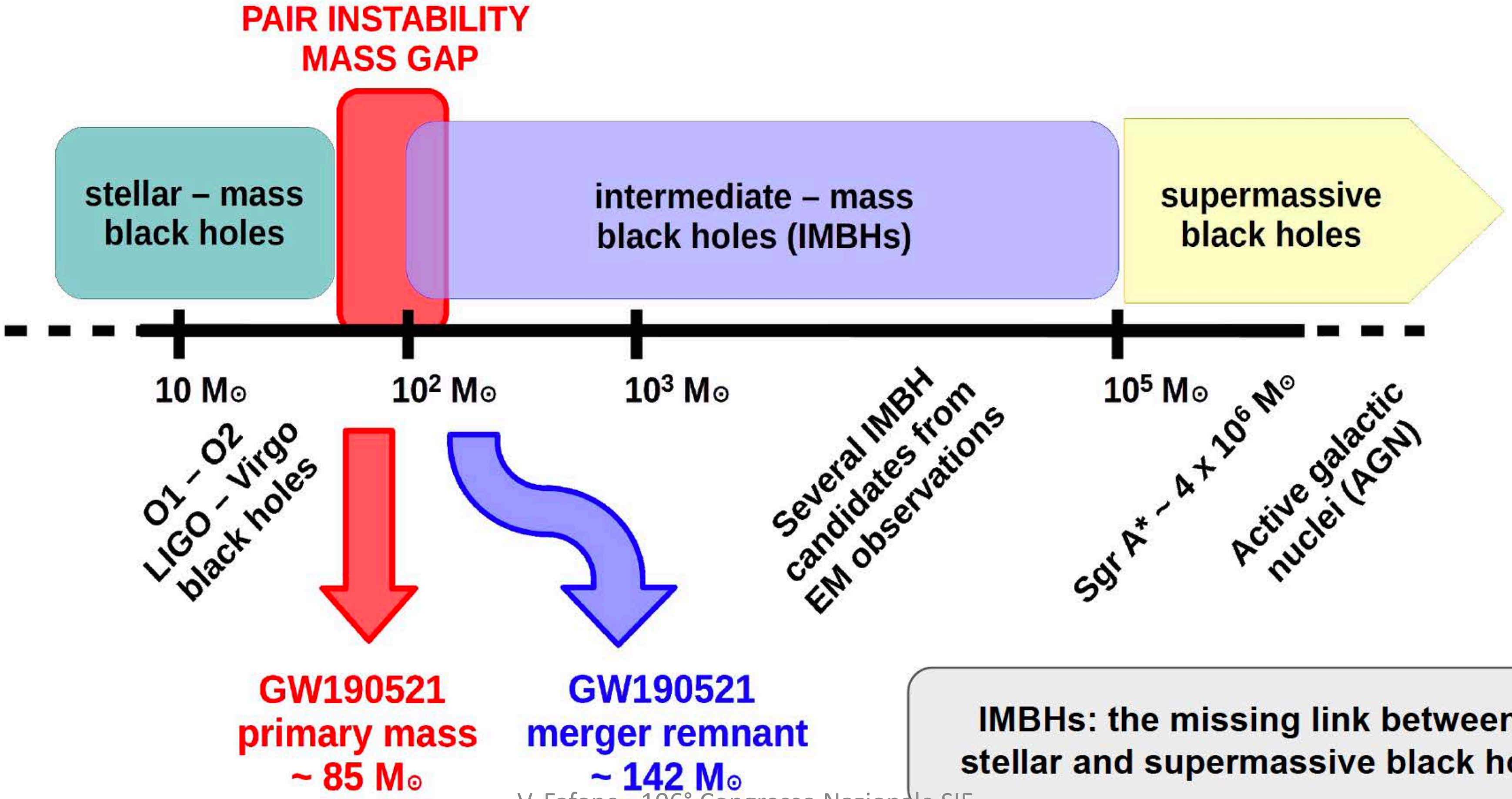


- So far, LIGO-Virgo has reported 12 binary black hole mergers
- The final (remnant) mass of GW190521 is well above 100 solar masses, **marking it as the first intermediate mass black hole (IMBH) detected by LIGO-Virgo**
- **The primary mass lies outside of the stellar mass graveyard (> 65 solar masses)**

● LIGO-Virgo component mass
● LIGO-Virgo remnant mass

GW190521

Astrophysical implications



PAIR INSTABILITY MASS GAP

stellar – mass black holes

intermediate – mass black holes (IMBHs)

supermassive black holes

10 M⊙

10^2 M⊙

10^3 M⊙

10^5 M⊙

O1 – O2 LIGO – Virgo black holes

Several IMBH candidates from EM observations

Sgr A* ~ 4 x 10^6 M⊙

Active galactic nuclei (AGN)

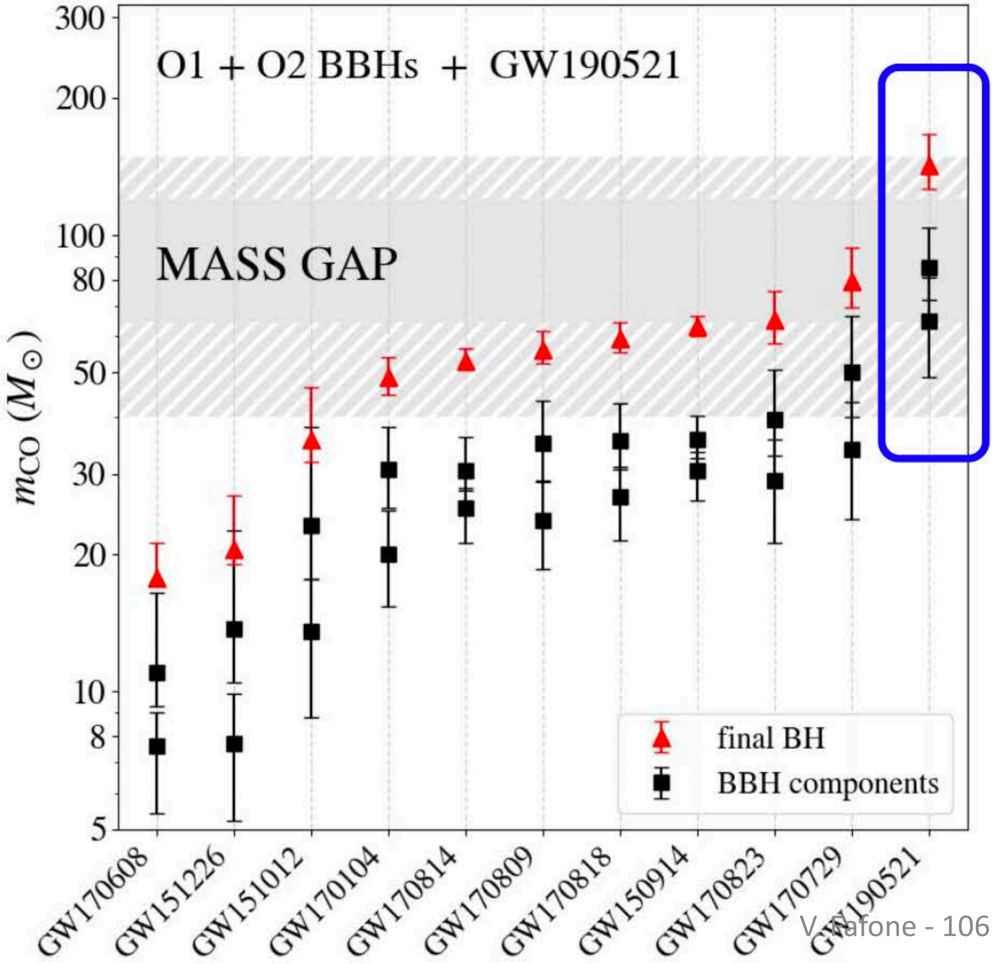
GW190521 primary mass ~ 85 M⊙

GW190521 merger remnant ~ 142 M⊙

IMBHs: the missing link between stellar and supermassive black holes

GW190521

Primary component in the pair-instability (PI) mass gap



Efficient pair production in massive stars drives (pulsational) pair instability:

opens a gap in ~ 65 - 120 $M_\odot$ range

Large uncertainties on mass gap boundaries:

- Nuclear reaction rates, e.g. ^{12}C(α,γ)^{16}O
- Collapse of hydrogen envelope
- Stellar rotation
- Convection model

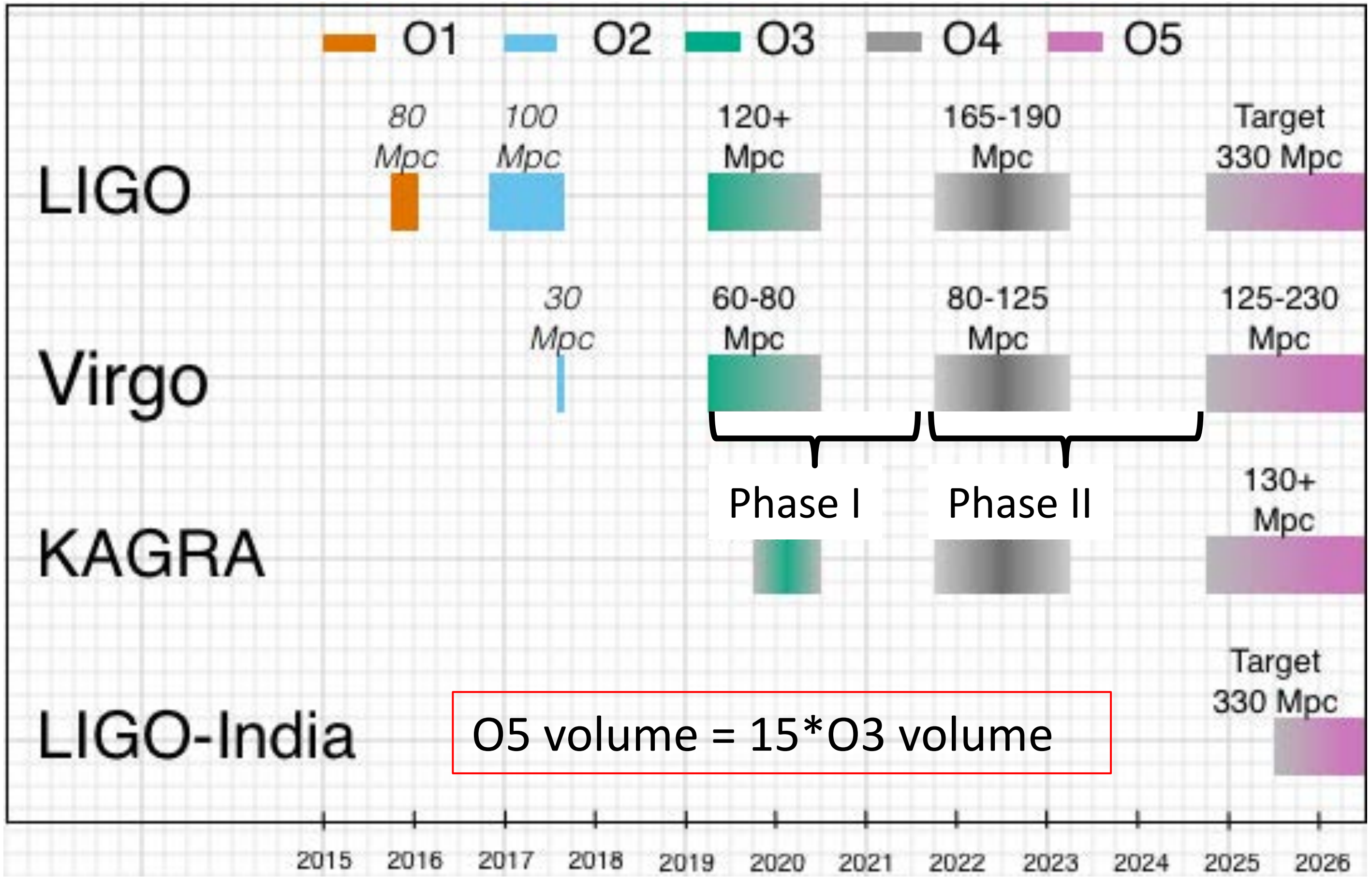
CHALLENGE FOR STELLAR EVOLUTION

O3 results: more to come

- New issues of the GW transient catalog
- Focus on “special” individual events
- New companion papers
- Search ongoing on the full O3 dataset
- LIGO-Virgo data become public after an initial proprietary period:
  - around an exceptional event after the publication of the associated paper;
  - chunks of 6 months, 18 months after the end of the data taking;
  - Gravitational Wave Open Science Center: https://www.gw-openscience.org/about/

The path towards O4 and O5

- Shutdown period between O3 and O4 to upgrade the current detectors → Advanced+ detectors
- Four detectors online in O4: 2 LIGOs, Virgo and KAGRA



O5 volume = 15*O3 volume

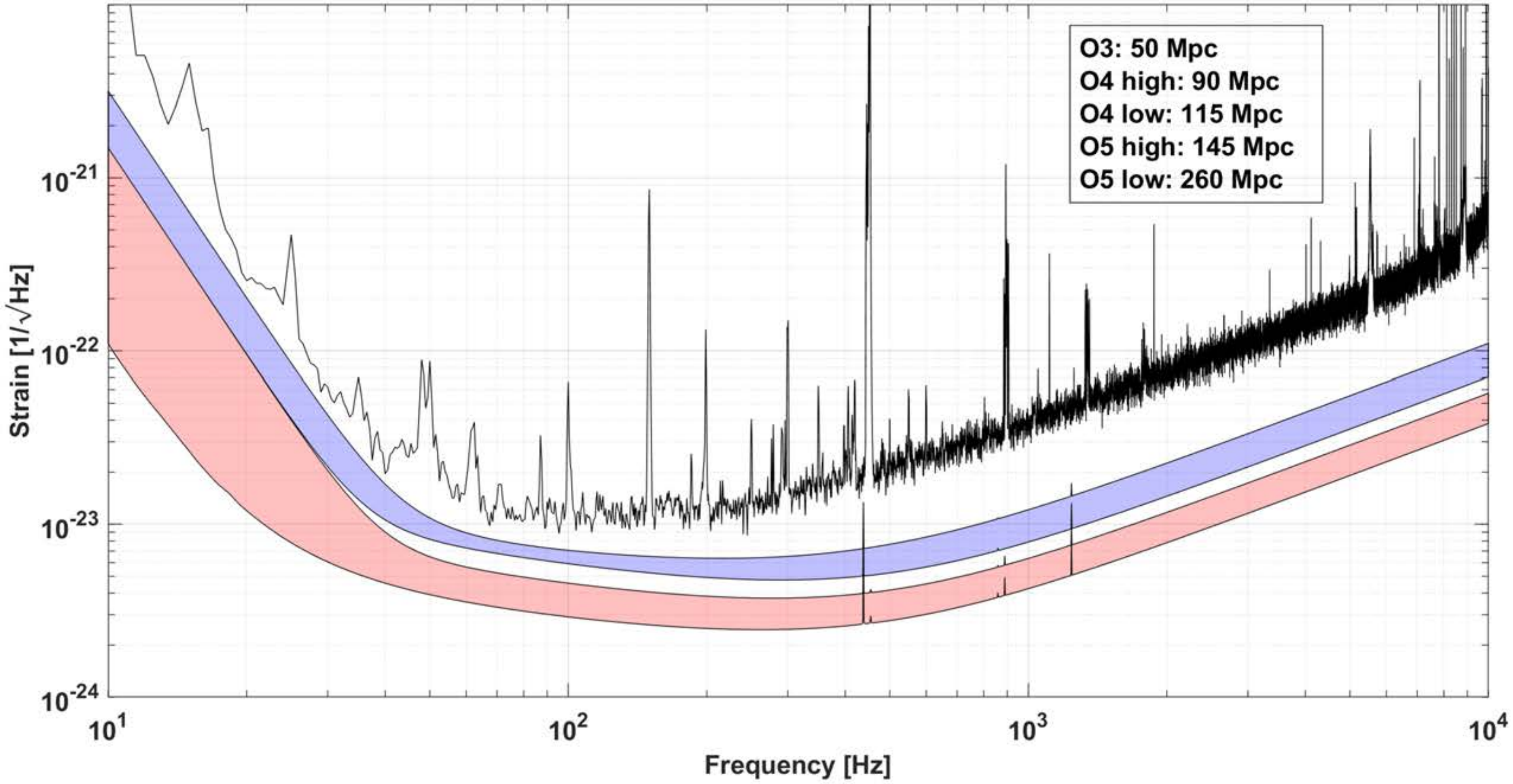
AdV+: content

- Phase I
  - Signal recycling (not done in AdV yet)
  - Higher laser power (40 W, AdV run with 26 W so far)
  - Frequency dependent squeezing (frequency independent squeezing already done in AdV)
  - Newtonian noise cancellation

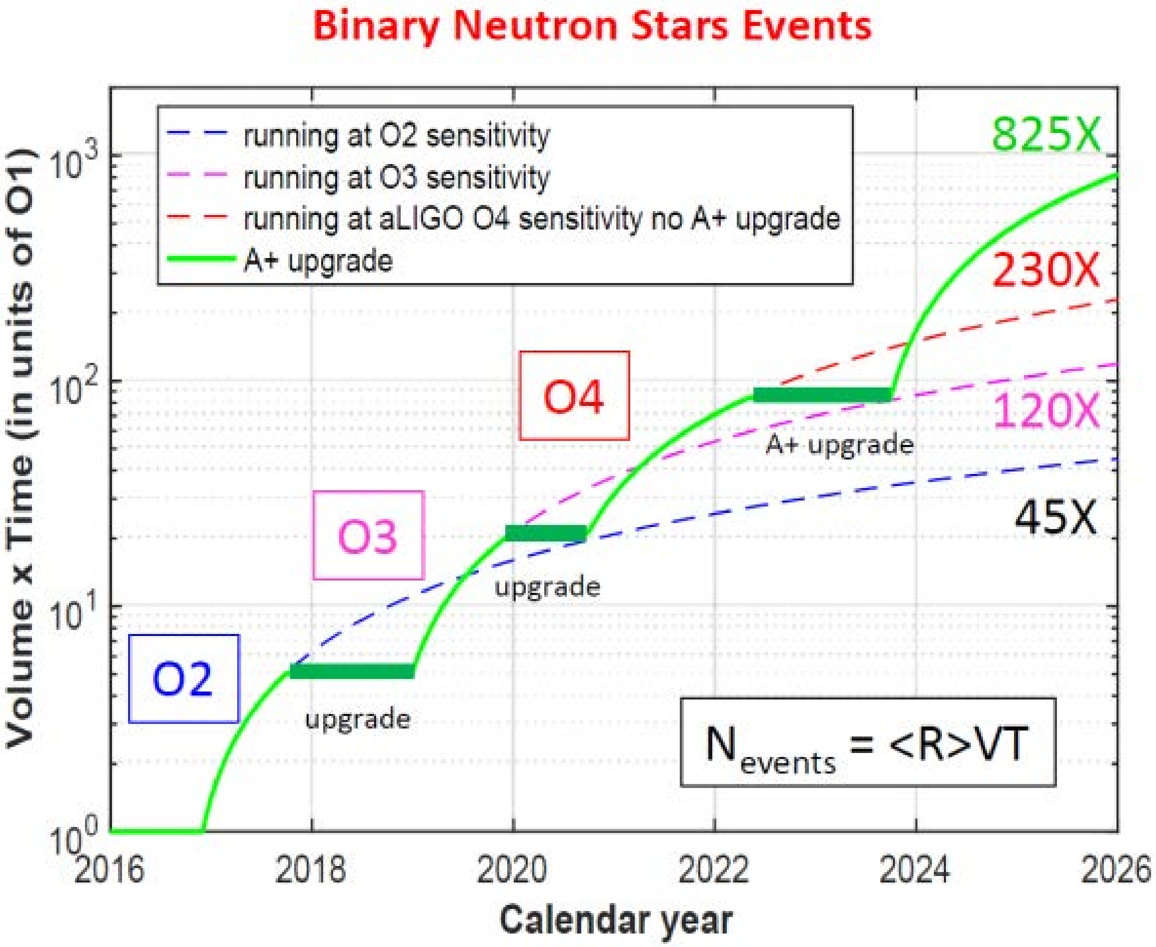
- Phase II
  - Further increase of laser power (60 W or more)
  - Larger beams on end test masses
    - ~10 cm radius
    - Larger end test masses (~ 100 kg)
  - Better coatings: lower mechanical losses, less point defects, better uniformity

AdV+: sensitivity goal

- **Phase I:** reduce quantum noise, hit against thermal noise
- **Phase II:** push down the thermal noise wall



AdV+: sensitivity goal



$N_{events} = \langle R \rangle VT$

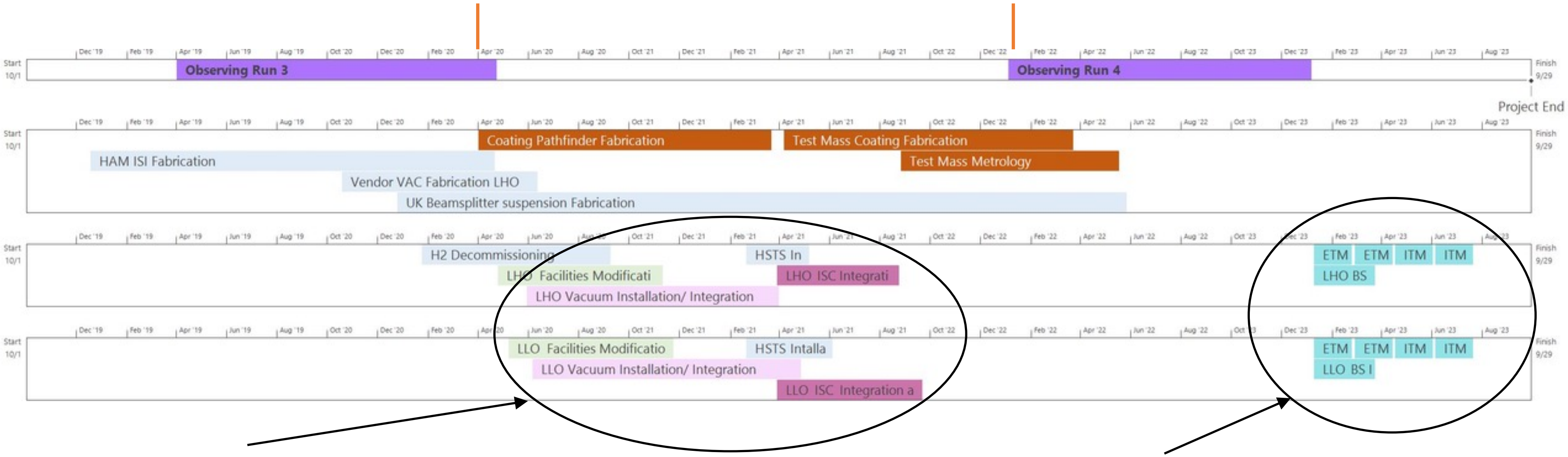
<R>	average astrophysical rate
V	volume of the universe probed → $(\text{Range})^3$
T	coincident observing time

Synchronization with LIGO A+

- A+ approved in 2018
  - 5 years plan
  - 2018 – 2023
  - Similarities among the two upgrade programs

Apr '20

Gen '22



Frequency dependent squeezing

Mirrors change

What next?

- 2nd generation GW detectors will explore local Universe, initiating the precision GW astronomy
- A factor of 10 improvement in terms detection distance is needed to have cosmological investigations
- ET (and Cosmic Explorer in the US) will extend the science potential of 2G/2G+ and will introduce new science targets

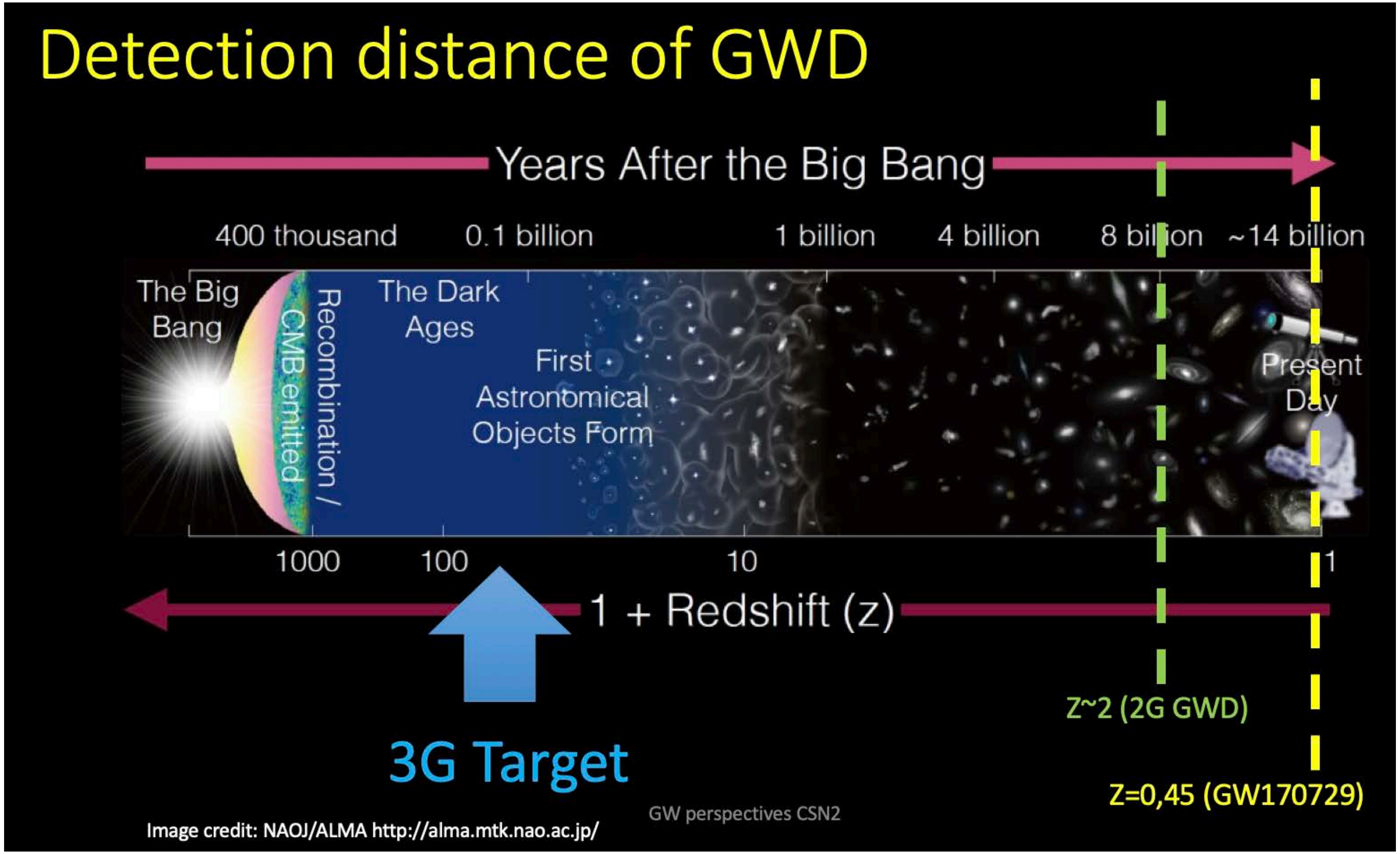
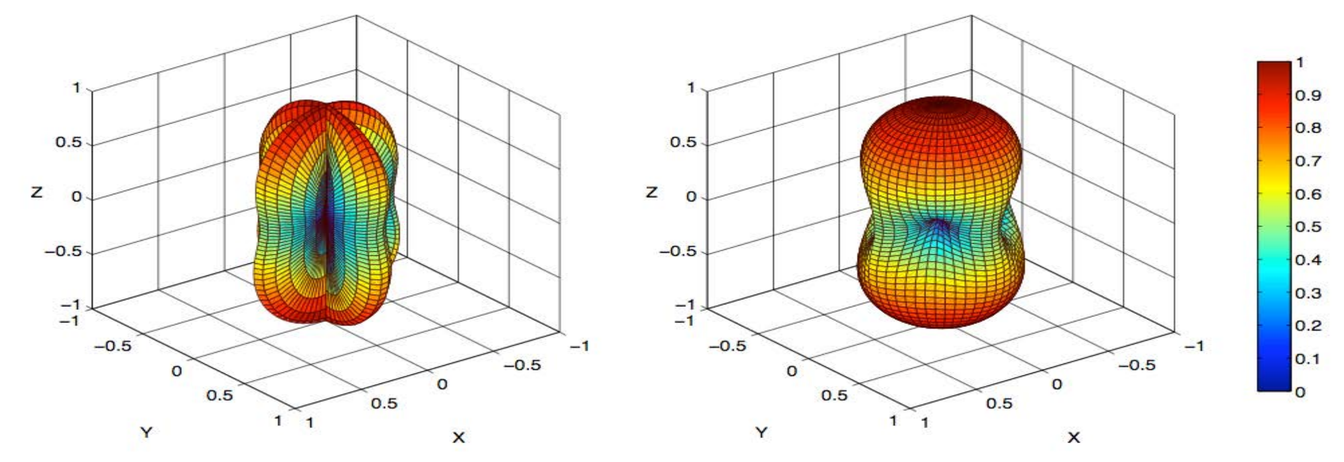


Image credit: NAOJ/ALMA http://alma.mtk.nao.ac.jp/

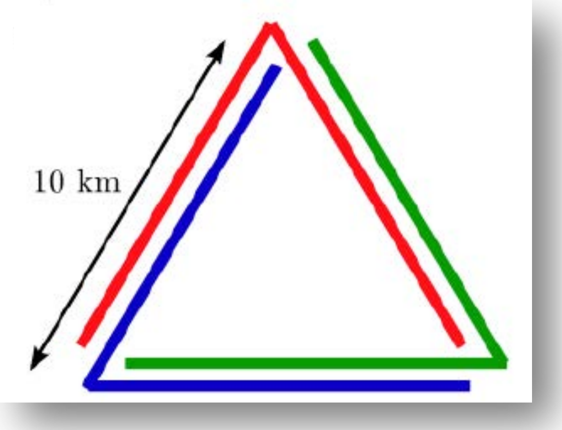
A step forward: Einstein Telescope –
the 3G concept in Europe

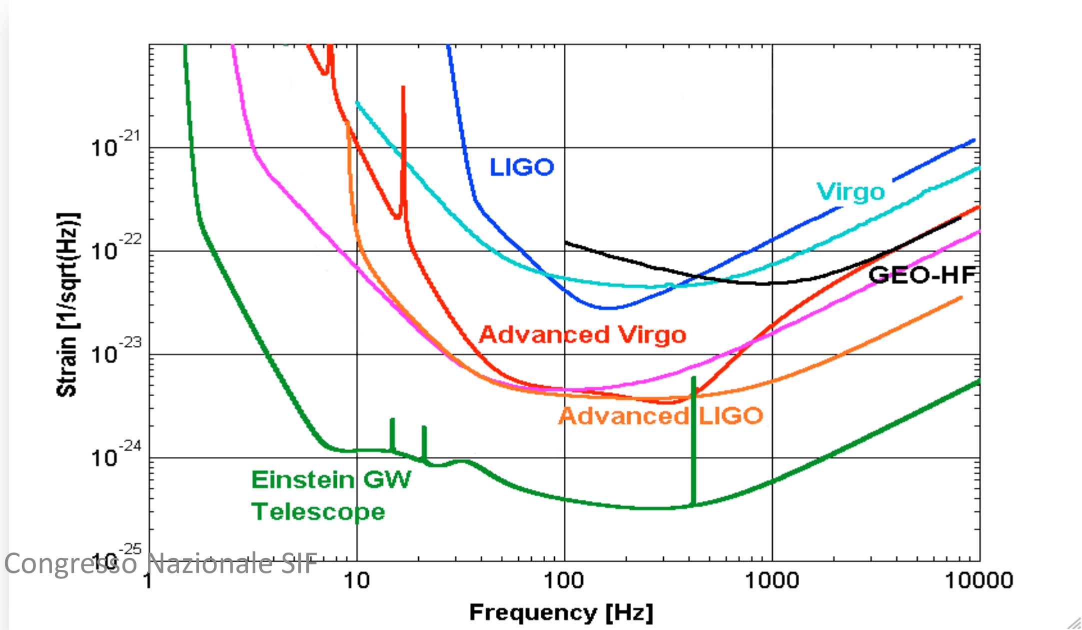
- New infrastructure
- 10 km arms, underground operation
- Mirrors cooled at low T
- Want to see the full sky, to resolve both polarizations, to have redundancy → **triangle.**
- Want to increase the bandwidth → **xylophone → 6 interferometers**



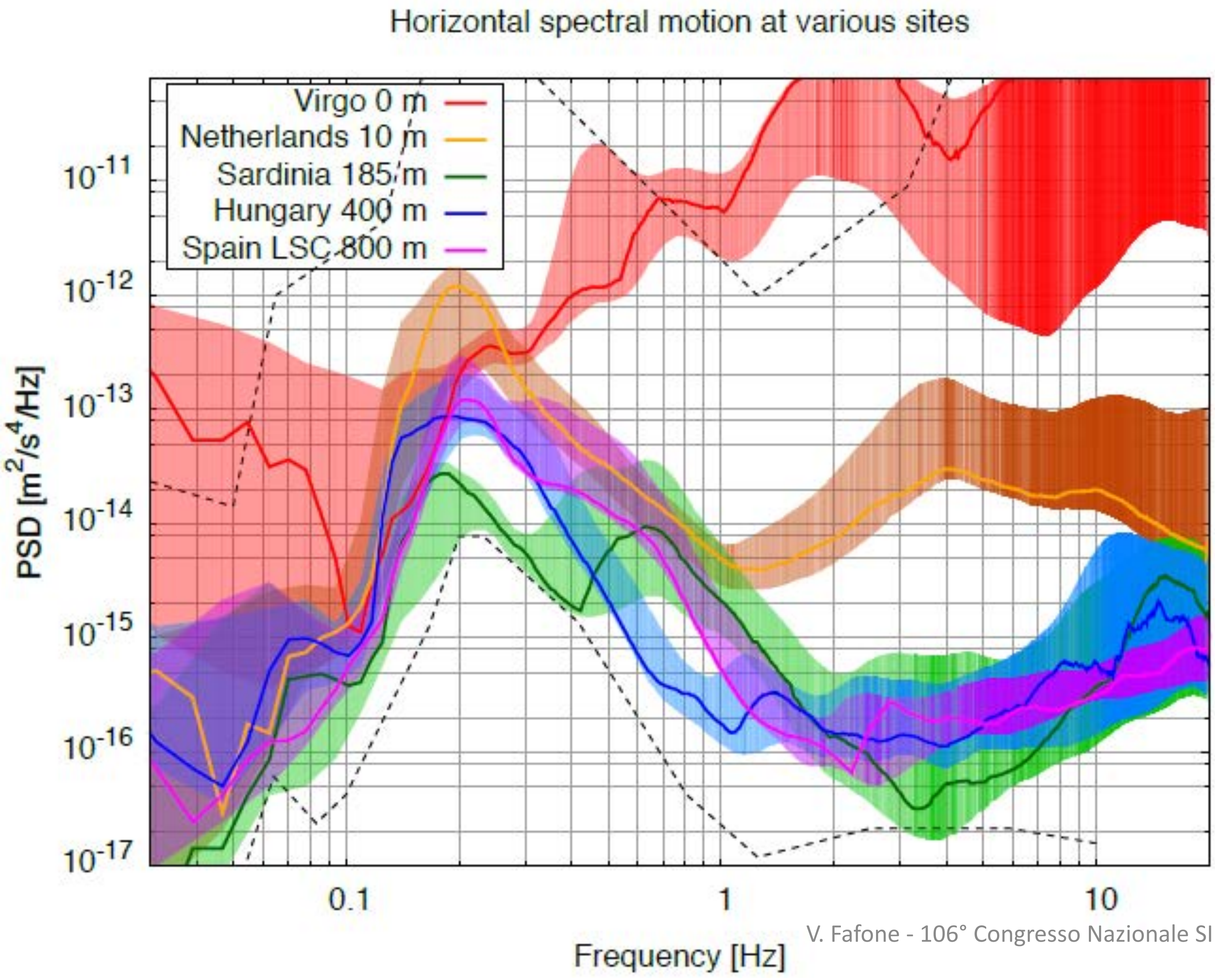
Single L-shaped ITF

Triangle of 3 ITFs

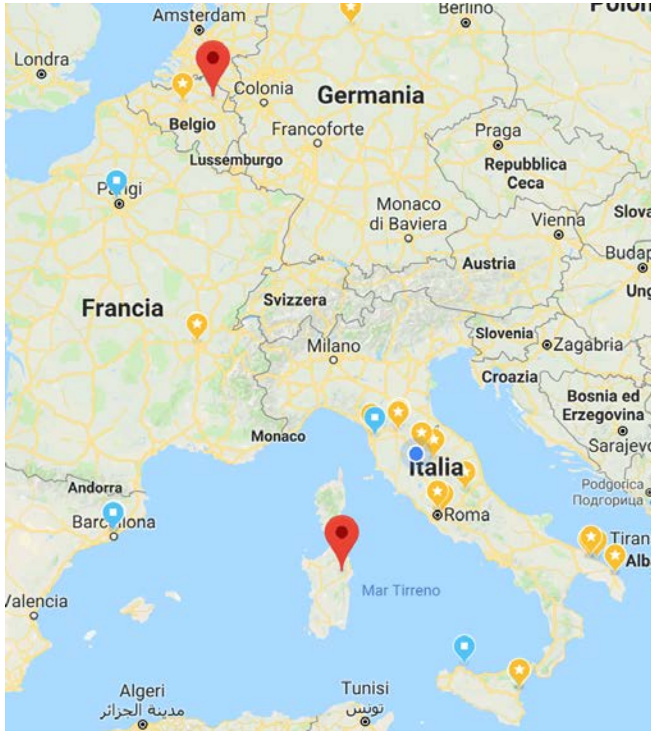




ET site: 2 candidates



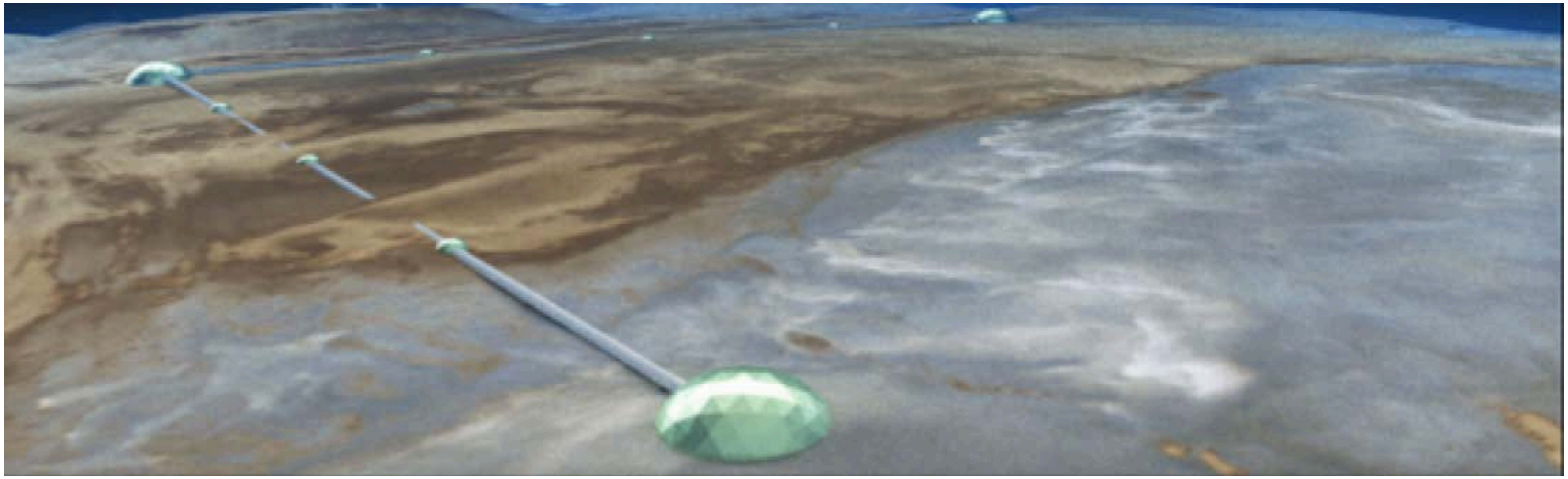
- 3 borders site (NL-B-DE)
- Sardinia site (IT)



Cosmic Explorer (US)

- Third-generation GW observatory
- Target sensitivity a factor of > 10 improvement in comparison to current advanced detectors
- Above ground, 40 km arm length, L configuration

Formal design study under way (M. Evans, MIT, lead PI)
cosmicexplorer.org



Credits: D. Reitze

+version ITFs/3G science case

- Fundamental questions in Gravity:
  - New/further tests of GR
  - Exploration of possible alternative theories of Gravity
  - How to disprove that Nature black holes are black holes in GR (e.g. non tensorial radiation, quasi normal modes inconsistency, absence of horizon, echoes, tidal deformability, spin-induced multipoles)

Fundamental interactions, Dark matter, dark energy

- Fundamental questions in particle physics
  - Axions and ultralight particle through the evaluation of the consequences of new interactions, their impact on two bodies mechanics, in population and characteris of BHs, NSs

Inflation, additional interactions, dark matter

- Probing the EOS of neutron stars (isolated NS and NS in binary systems)

Nuclear physics, quark-gluon plasma

- Exotic objects and phenomena (cosmic strings, exotic compact objects: boson stars, strange stars/gravastars, …)
- Cosmology and Cosmography with GWs
- Accurate Modelling of GW waveforms

Cosmology

- GW models in alternative theory of gravitation
- The population of compact objects discovered by GWs is the same measured by EM? Selection effects on BHs and NSs?

Cosmology

- What is the explosion mechanism in Supernovae?
- What is the history of SuperMassive black holes?
- GW Stochastic Background? Probing the big bang?

Nuclear physics

- Multimessenger Astronomy in 3G: If we are able cumulate enough SNR before the merging phase, we can trigger e.m. observations before the emission of photons

Cosmology, inflation

Astroparticle, GRB, Neutrino Physics

Credit: M. Punturo

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- Fundamental questions in Gravity:
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Fundamental interactions, Dark matter, dark energy

Inflation, additional interactions, dark matter

Nuclear physics, quark-gluon plasma

Cosmology

Cosmology

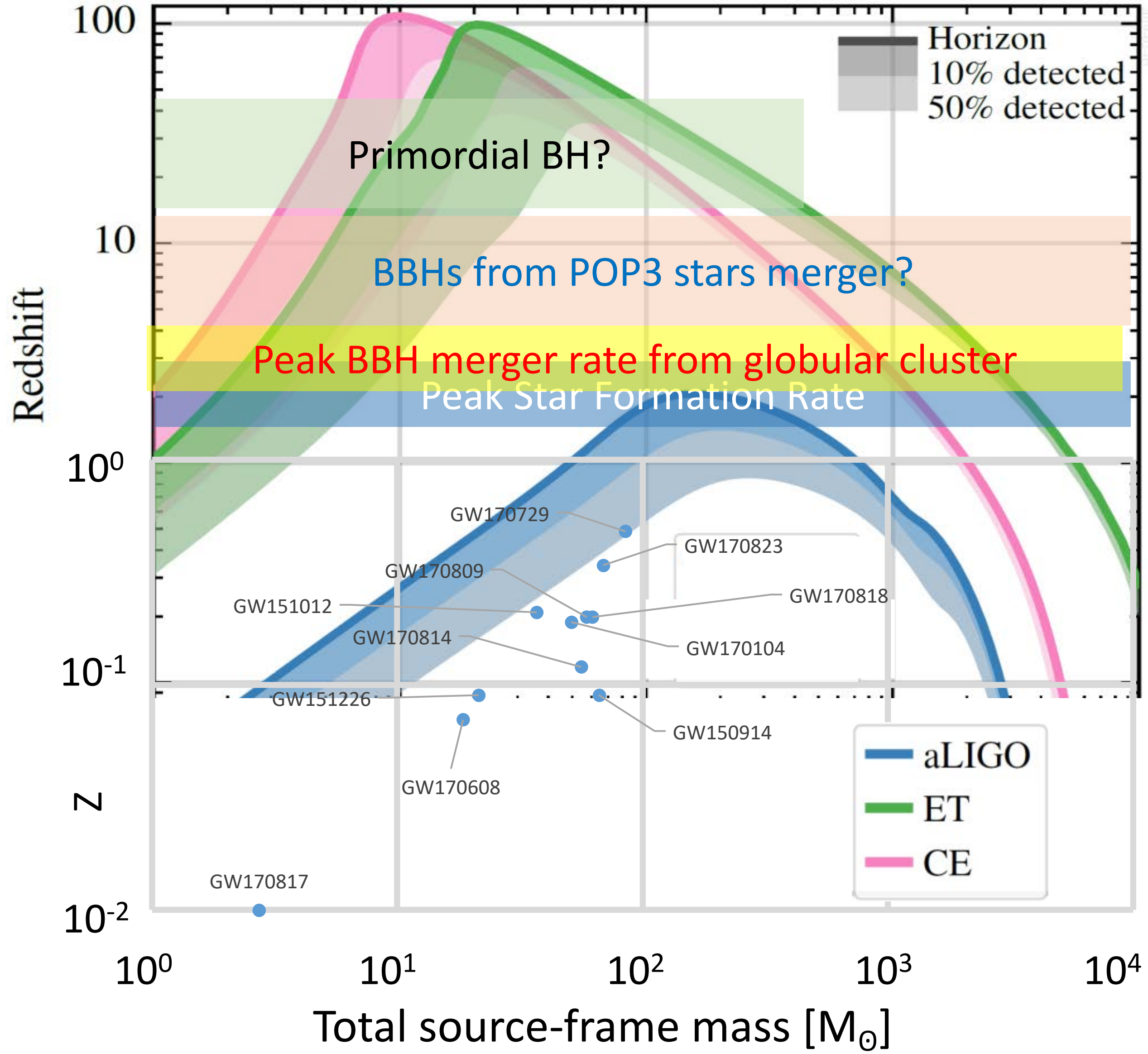
Nuclear physics

Cosmology, inflation

Astroparticle, GRB, Neutrino Physics

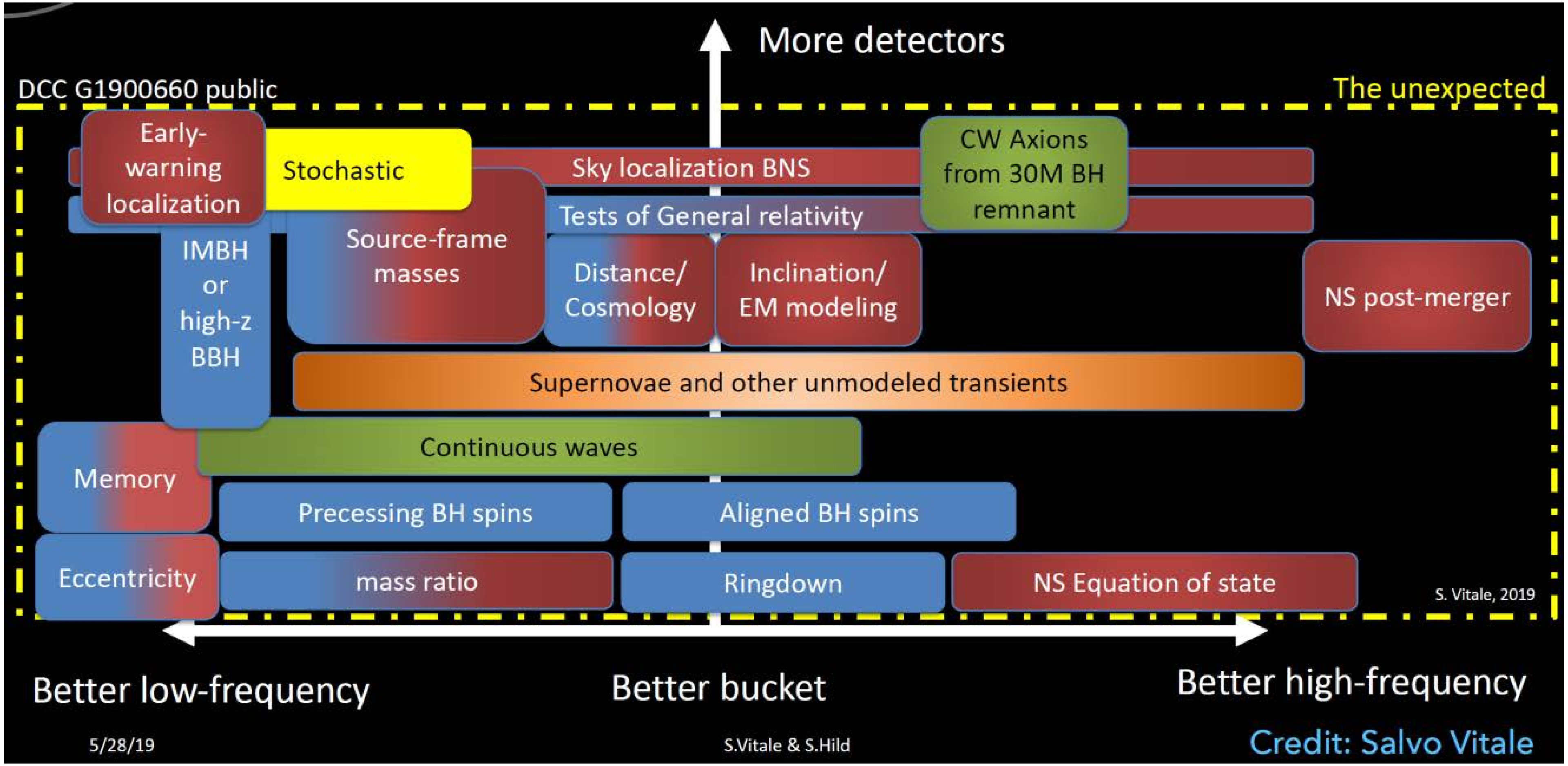
Science case for the Einstein Telescope:
https://arxiv.org/pdf/1912.02622.pdf

Observing earliest moments of formation of stars and structures



Where is the Physics?

- The design of the 3G observatory is driven by the physics objectives
  - At what frequency are they?

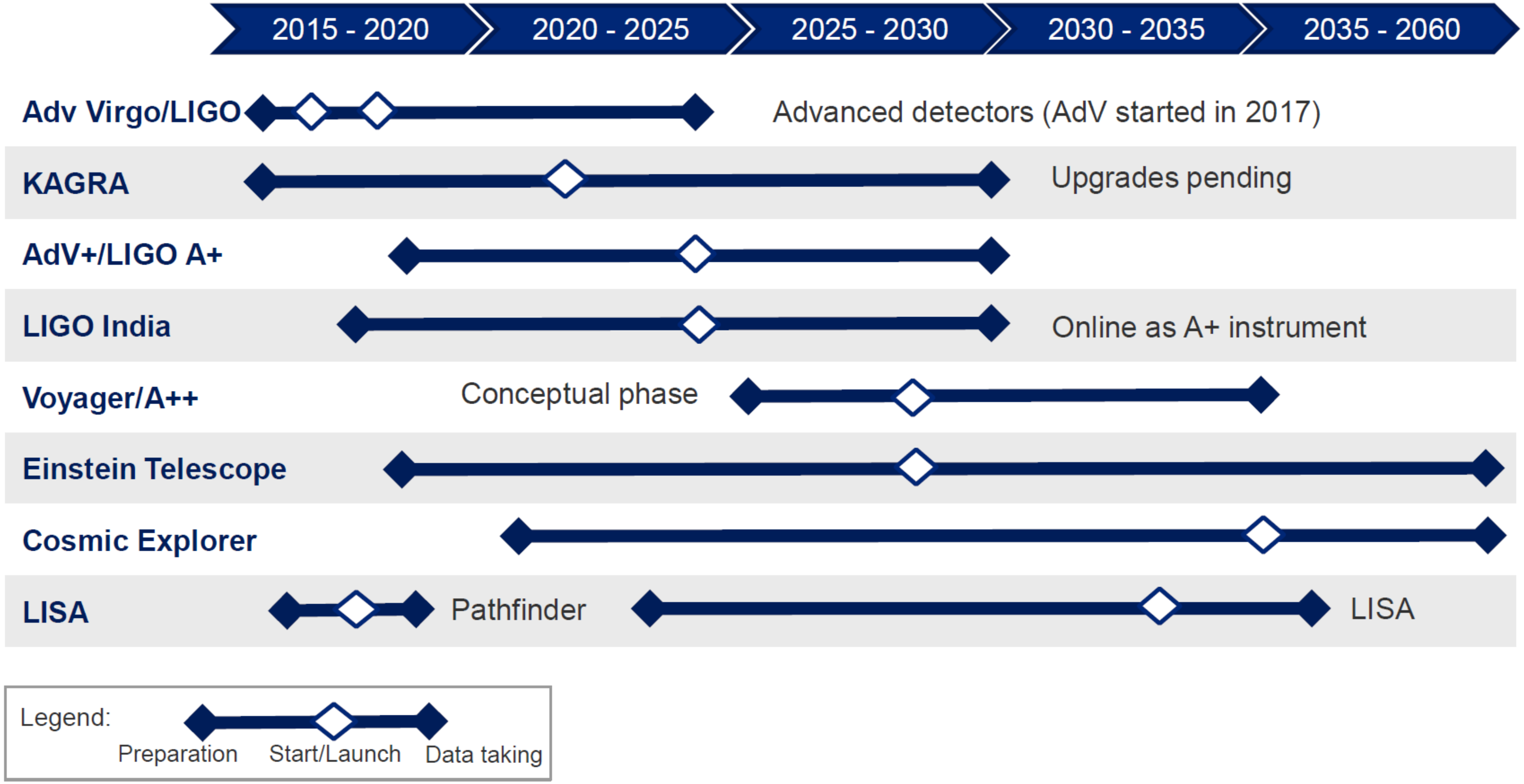


Credit: Salvo Vitale

Everywhere!

We need a wide band observatory

The Global Scenario



2015 - 2020
2020 - 2025
2025 - 2030
2030 - 2035
2035 - 2060

Adv Virgo/LIGO Advanced detectors (AdV started in 2017)

KAGRA Upgrades pending

AdV+/LIGO A+

LIGO India Online as A+ instrument

Voyager/A++ Conceptual phase

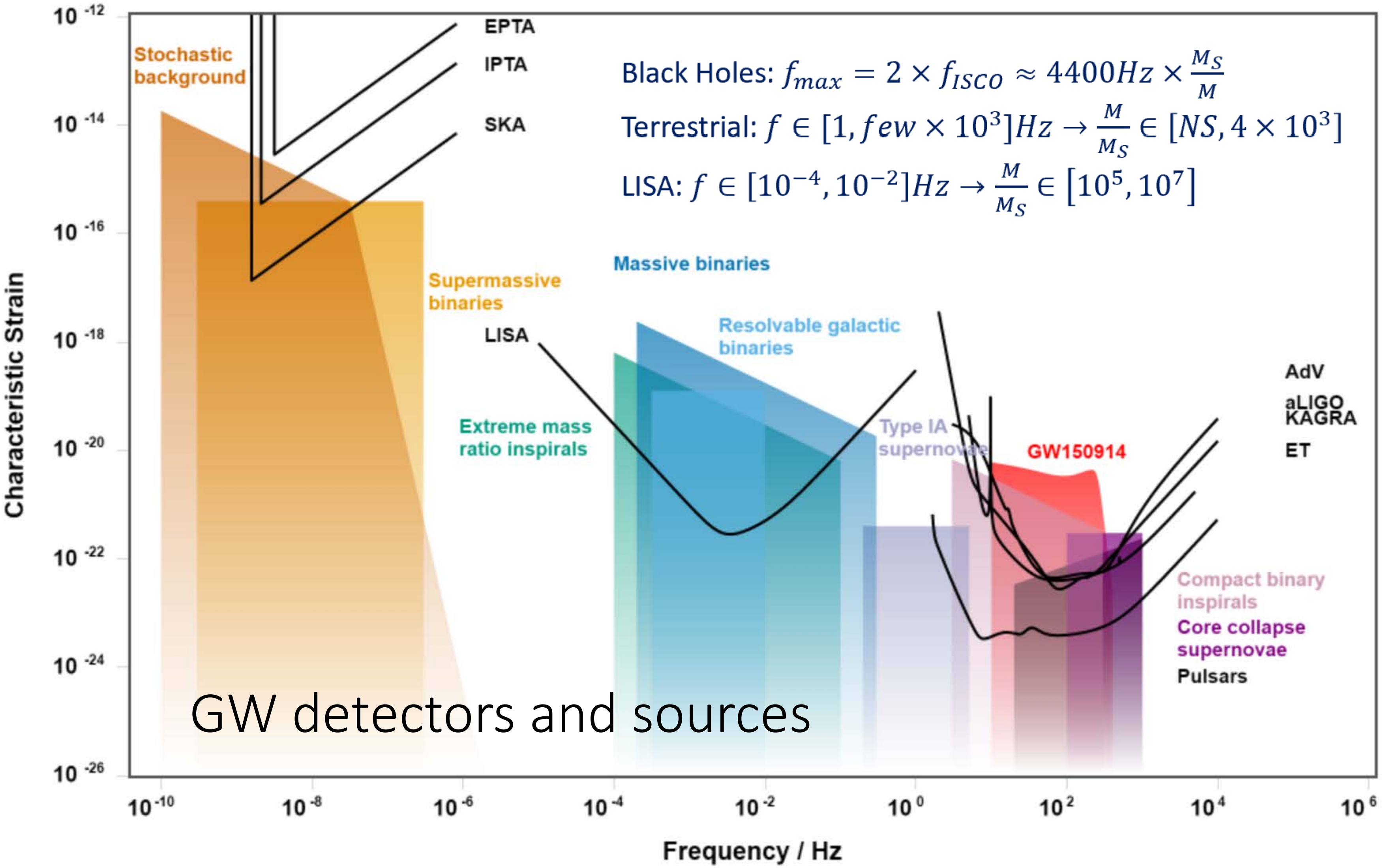
Einstein Telescope

Cosmic Explorer

LISA Pathfinder LISA

Legend:
Preparation
Start/Launch
Data taking

Multiwavelenght GW Astronomy



Black Holes: $f_{max} = 2 \times f_{ISCO} \approx 4400Hz \times \frac{M_S}{M}$

Terrestrial: $f \in [1, few \times 10^3]Hz \rightarrow \frac{M}{M_S} \in [NS, 4 \times 10^3]$

LISA: $f \in [10^{-4}, 10^{-2}]Hz \rightarrow \frac{M}{M_S} \in [10^5, 10^7]$

GW detectors and sources

http://gwplotter.com/

The future is bright