Gravitational wave observations: achieved results, status and perspectives

V. Fafone

University of Roma Tor Vergata and INFN

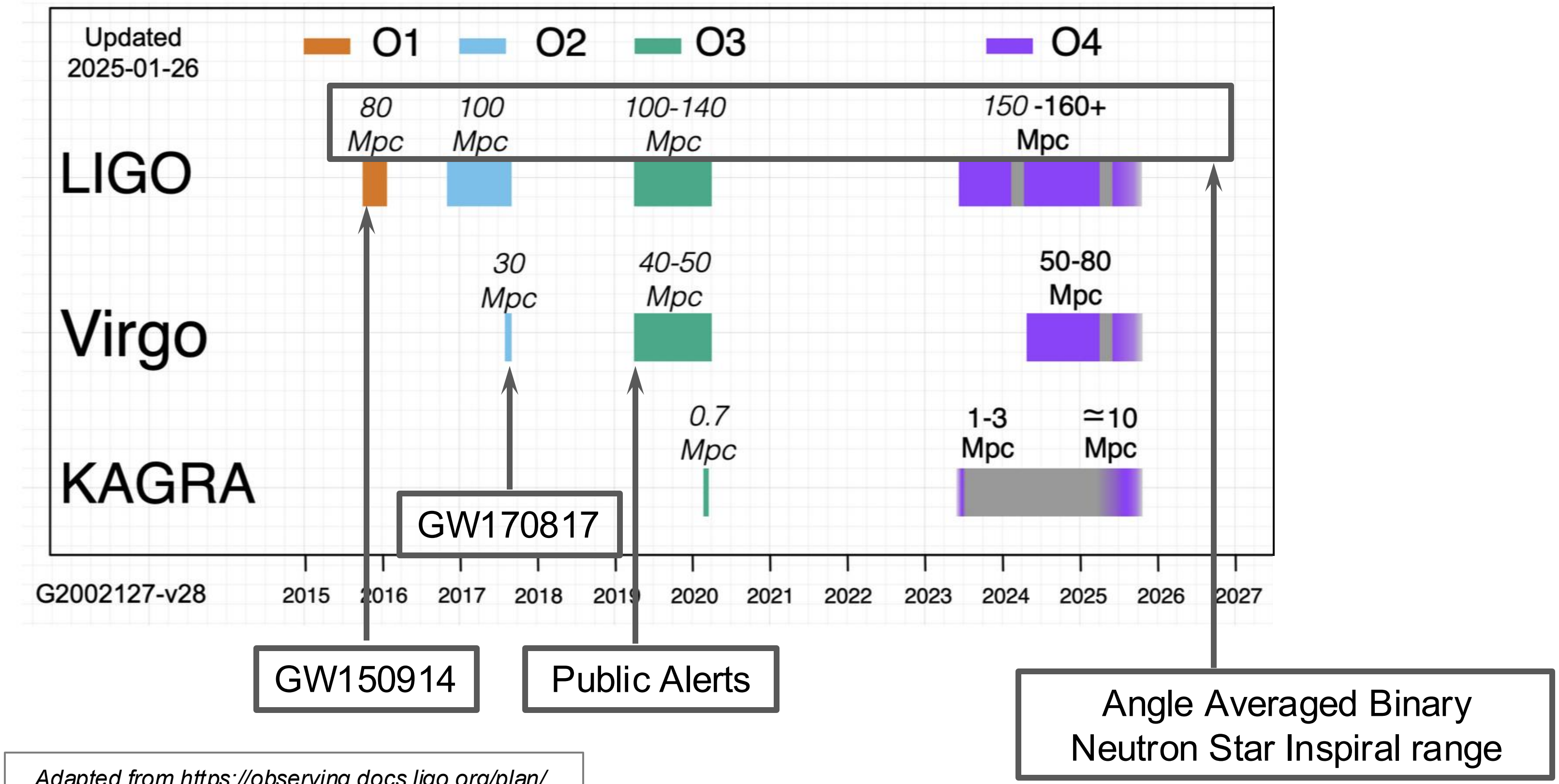
String Theory as a Bridge between Gauge Theory and Quantum Gravity

February 17-19, 2025

GW detectors network

- Increase the detection confidence.
- Source parameters inference (inc. sky location and GW polarization).
- Astrophysics of the source

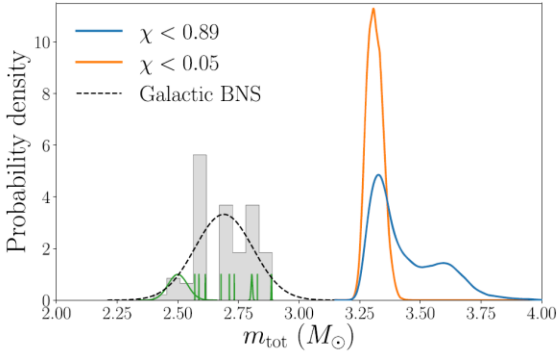
Observing runs



Adapted from https://observing.docs.ligo.org/plan/

O3 outstanding events

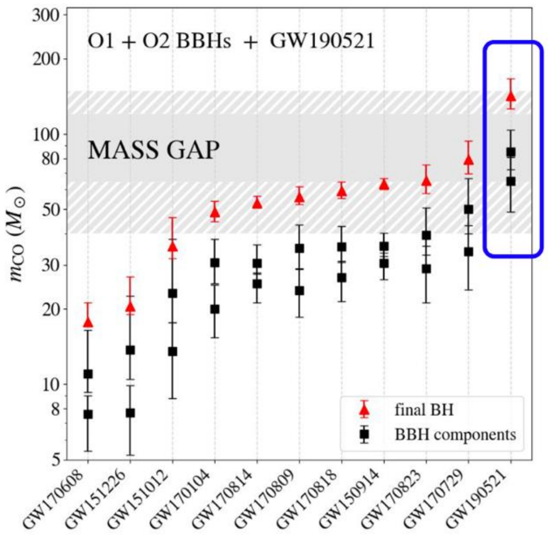
- **GW190412**: first observed BBH possessing unequal mass ratio
  - Masses: ~3, ~8 $M_\odot$
  - First observation of GW higher multipoles (l = m = 3)
  - [Abbott et al., Phys. Rev. D **102**, 043015 (2020)]
- **GW190425**: BNS merger of total mass of ~3.4 $M_\odot$
  - Significantly larger than any other known BNS system (5σ from mean of Galactic BNS)
  - [Abbott et al., *ApJL* **892**, L3 (2020)]



- **GW190814**: the most asymmetric mass ratio merger ever observed
  - (*m1*/*m2* = 9)
  - The secondary mass of 2.6 $M_\odot$ lies in the lower *'mass gap'* → either the lightest BH or the heaviest NS ever observed
  - [Abbott et al., *ApJL* **896**, L44 (2020)]

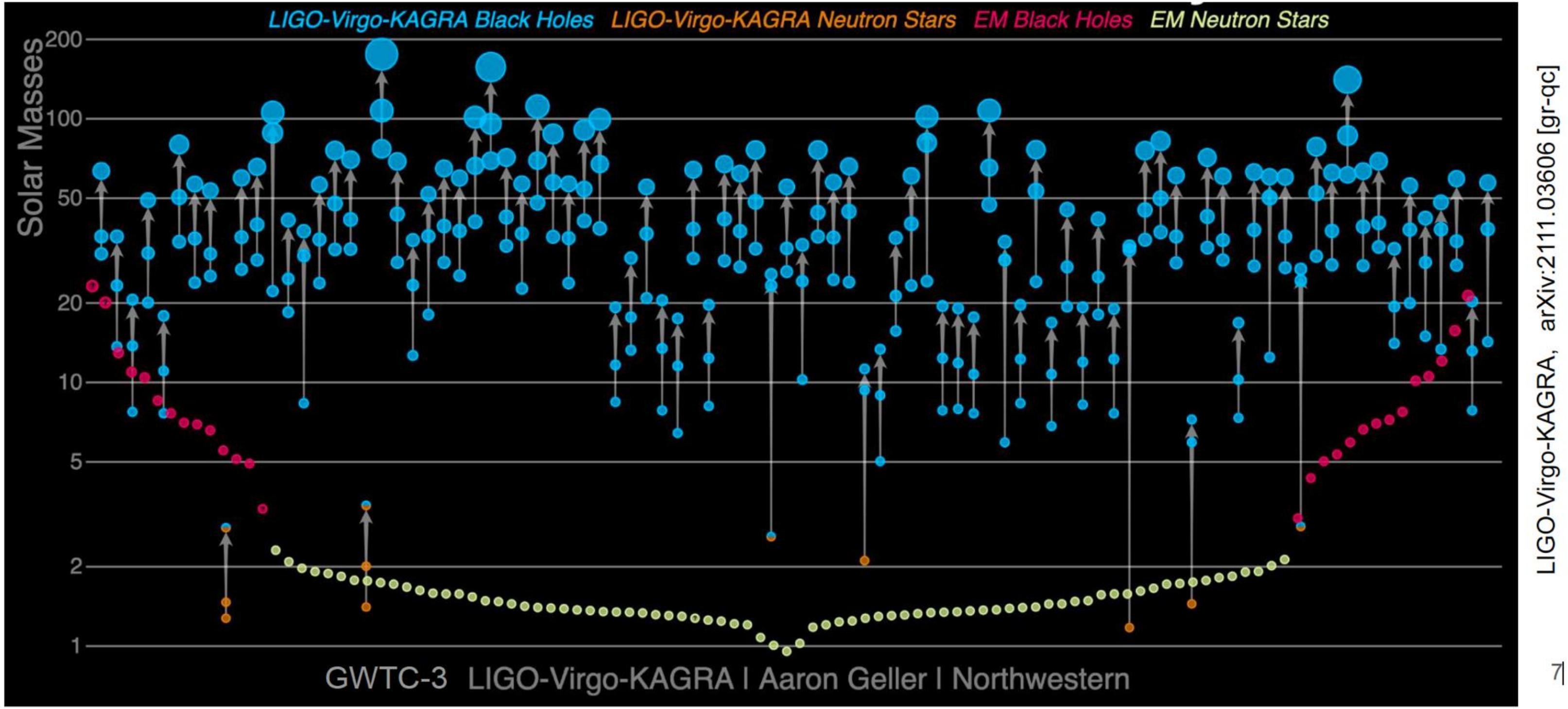
O3 outstanding events

- **GW190521**: BBH with component masses ~66 and 85 $M_\odot$ → final BH of 142 $M_\odot$
  - First observation of an intermediate mass BH ($M_f > 100\ M_\odot$).
  - First observation of a BH in the (pulsational) pair instability upper mass gap 65 - 120 $M_\odot$.
  - Farthest source so far (z ~ 0.8)
  - [Abbott et al., Phys. Rev. Lett. **125**, 101102 (2020)]
  - [Abbott et al., *ApJL* **900**, L13 (2020)]



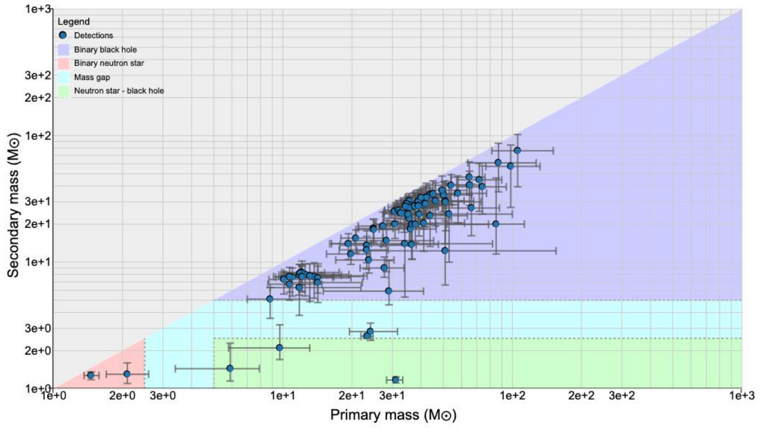
- **GW200105** & **GW200115**: 1st unambiguous detection of NSBH (2 event candidates)
  - [Abbott et al., *ApJL* **915**, L5 (2021)]

Gravitational-Wave Transient Catalog



- Binaries detected, so far → Astrophysics, cosmology, test of GR and fundamental physics

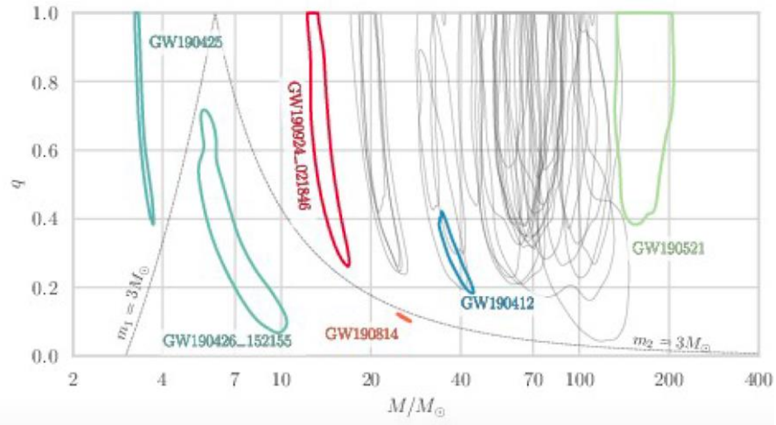
A glance at the detections



http://catalog.cardiffgravity.org/

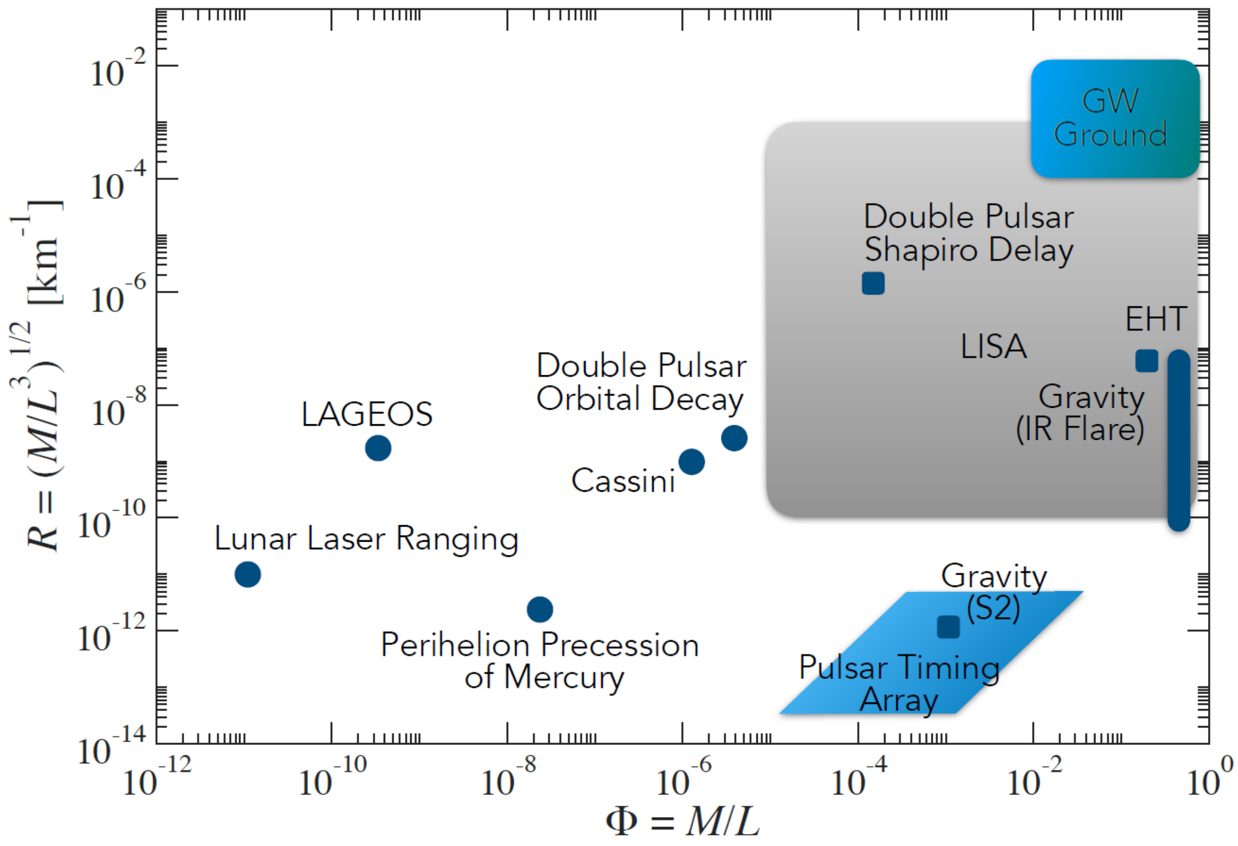
- Total masses of BBH systems from 14 $M_\odot$ for GW190924_021846 to 150 $M_\odot$ for GW190521
- This catalog includes binary systems with significantly asymmetric mass ratios

- Available events start shaping our understanding of population
- Statistical recovery of key information ($H0$, lensing, spin distribution, higher order corrections, eccentricity, …) is becoming possible: → O4 → O5



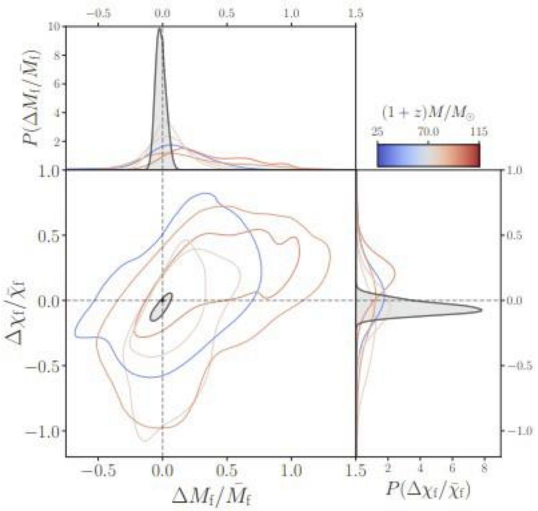
GWs are probing GR in strong field conditions

BBH coalescences allow to test GR in strong field conditions



Yunes N. et al.
Phys. Rev. D 94, 084002 (2016)
Edited by ET science case team

Testing GR with O3 events



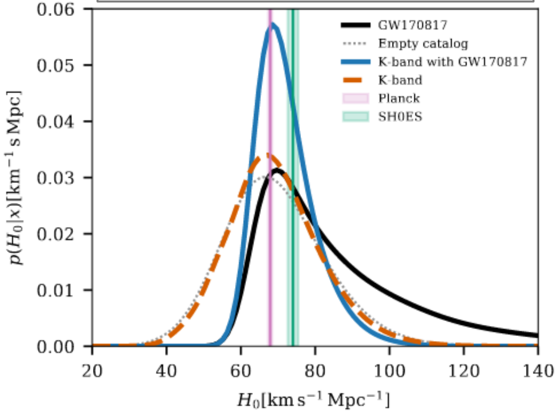
- Residuals from best-fit waveforms consistent with detector noise
- Consistency of parameters inferred from inspiral and ringdown phases of the signal
- Consistency with no dispersion of GWs and massless graviton
- Ringdown frequencies and damping times consistent with GR
- No detection of echoes
- Tensorial polarizations preferred wrt scalar and/or vector polarizations

https://arxiv.org/abs/2112.06861

- Improved constraints on Lorentz violation
- Graviton mass $m_g < 1.27\times10^{-23}\ eV/c$
- Constraints on post-Newtonian parameters improved by a factor of 2

Cosmology with BBHs

https://arxiv.org/abs/2111.03604
Astrophys. J. 949, 76 (2023)

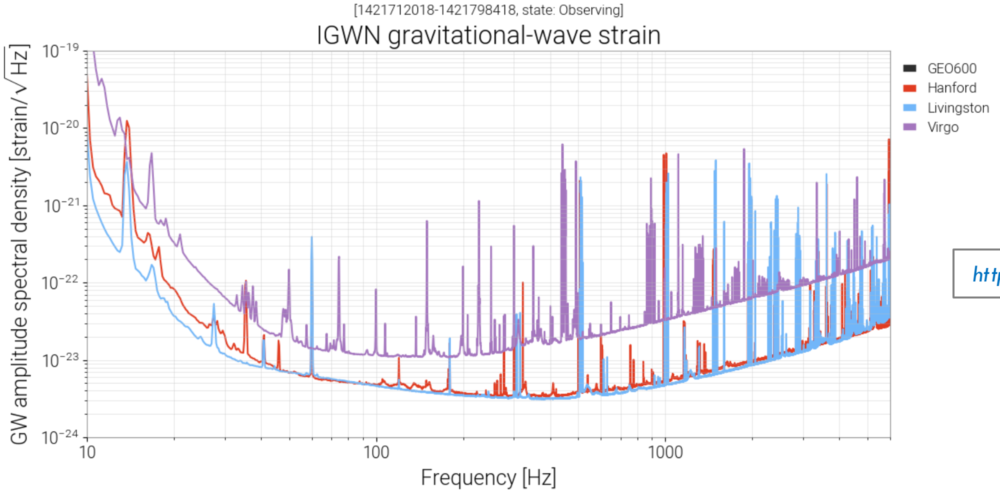


Hubble constant posterior.

- Based on 47 highly significant (FAR<0.25/yr, SNR>11) CBC observations:
- 42 BBH, 2 BNS, 2NSBH, GW190814
- GW detection: measurement of luminosity distance
- Different methods to constrain H0:
  - **Gray dotted**: obtained using all dark standard sirens without any galaxy catalog information and fixing the BBH population model.
  - **Orange dashed**: using all dark standard sirens with GLADE+ Kband galaxy catalog information and fixed population assumptions.
  - **Black solid** : GW170817 and its EM counterpart.
  - **Blue solid**: combining dark standard sirens and GLADE+ Kband catalog information (orange dashed line) with GW170817 and its EM counterpart (black solid line).
  - The pink and green shaded areas identify the 68% CI constraints on H0 inferred from the CMB anisotropies (Ade et al. 2016) and in the local Universe from SH0ES (Riess et al. 2019) respectively.

The O4 run

- O4 started in May 2023 → O4a
- Commissioning break January - April 2024 → O4b
- Third and last tranche of the run from Januart 28th 2025 → O4c
- Commissioning break April - June 2025
- Current official end date: 7th of October 2025

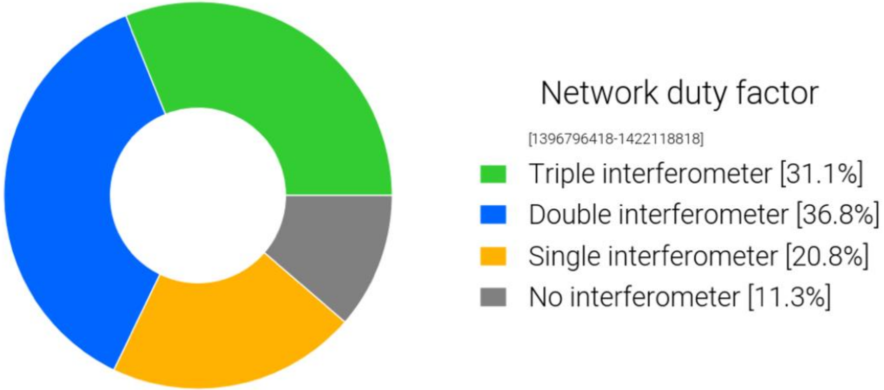


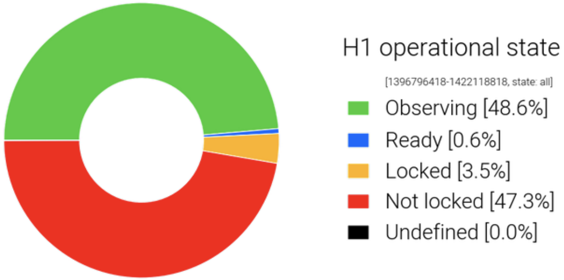
https://gwosc.org/detector_status/today

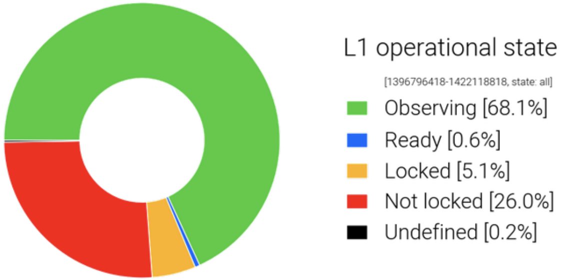
The O4 run

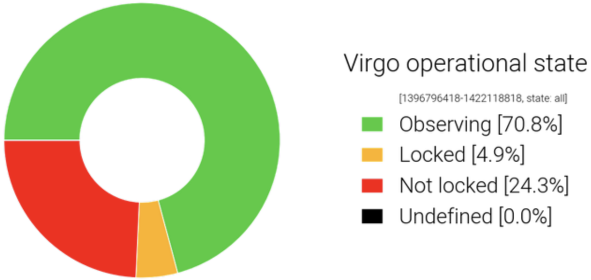
- GW interferometers are robust detectors
- Good network duty cycle

https://gwosc.org/detector_status/O4b/

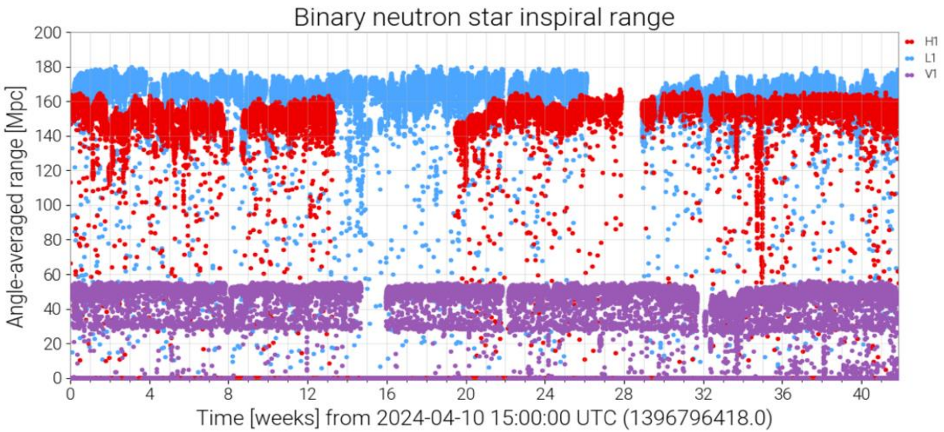




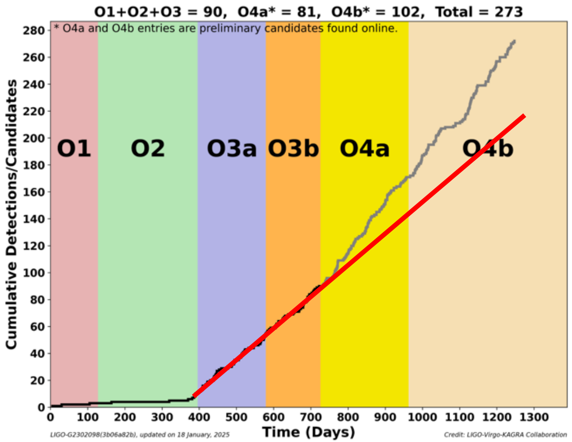




The O4 run



https://gwosc.org/detector_status/O4b/

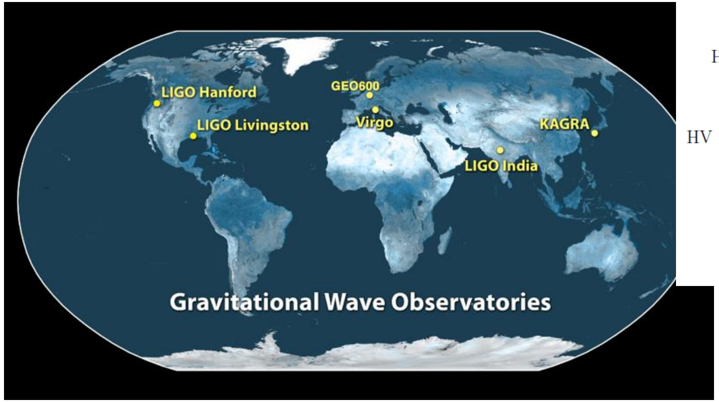


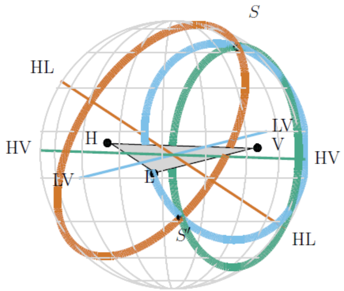
- Significant increase in detection rate
- Events scaled as expected according to sensitivity improvement
- Large number of alerts sent to the scientific community

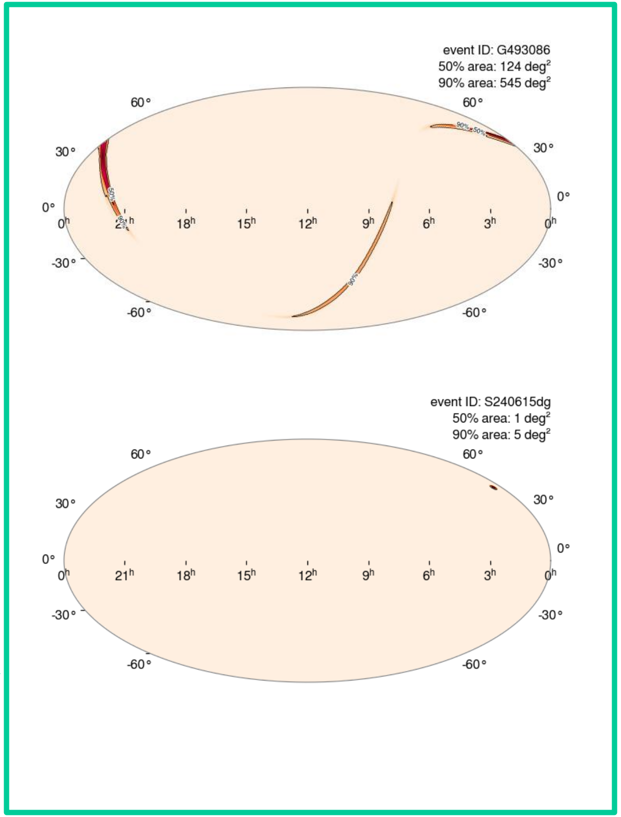
https://dcc.ligo.org/public/0190/G2302098/026/cumulative_events.png

The O4 run

- Virgo joined the run starting from O4b



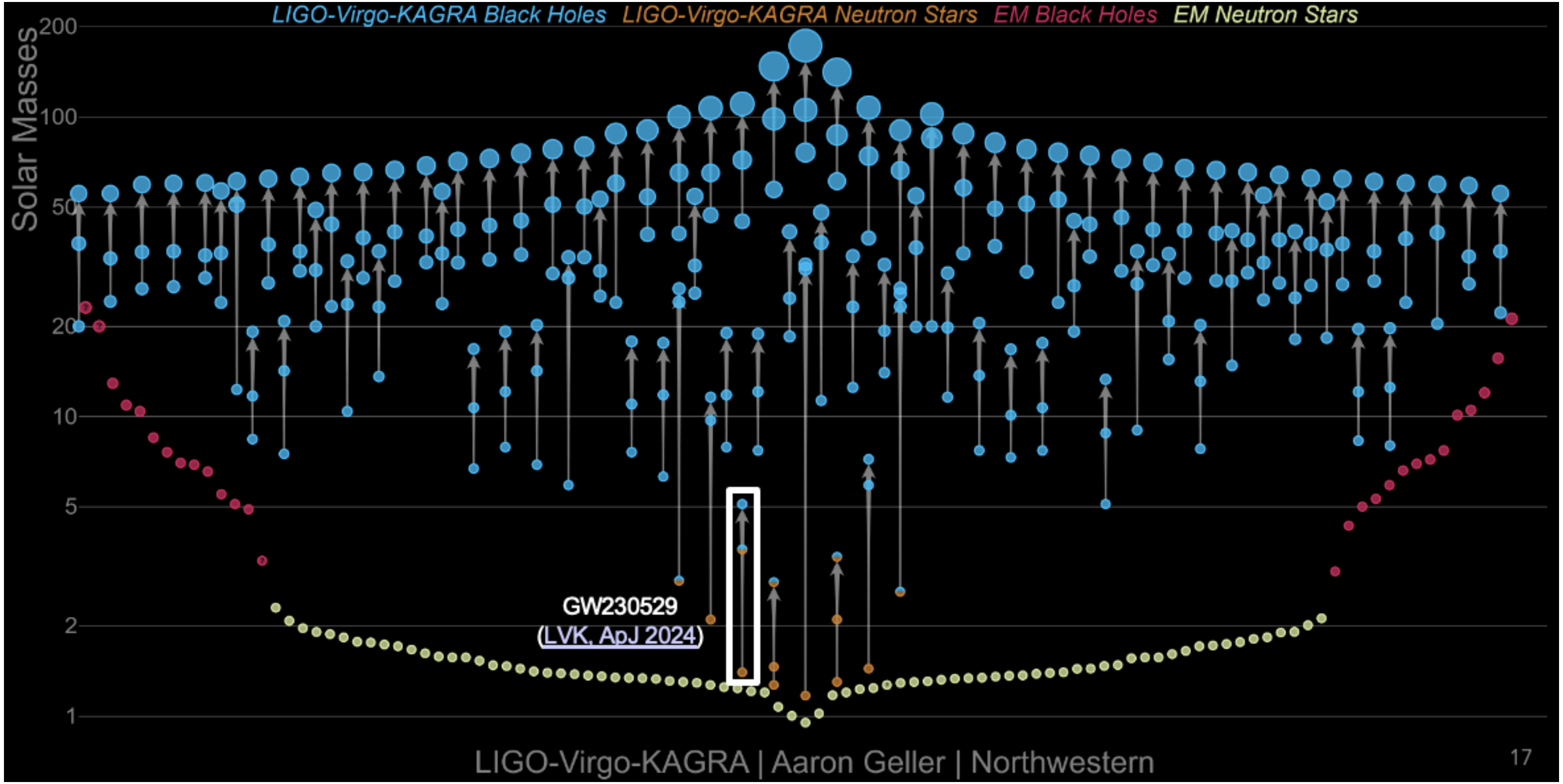




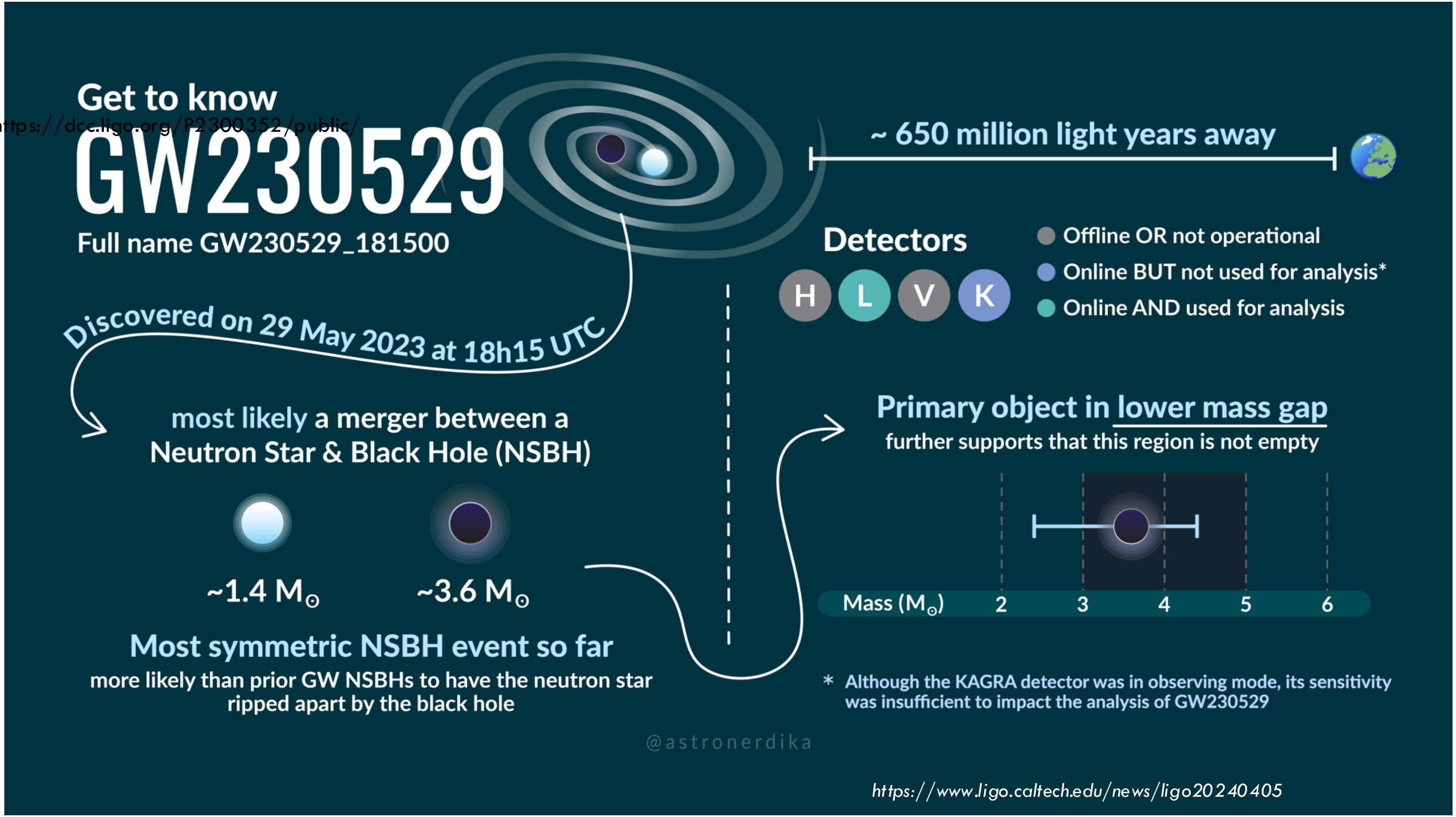
Having 3 detectors is crucial for good localisation:

- best O4a (Virgo off) is 80 deg^2
- best O4b (Virgo on) is 5 deg^2

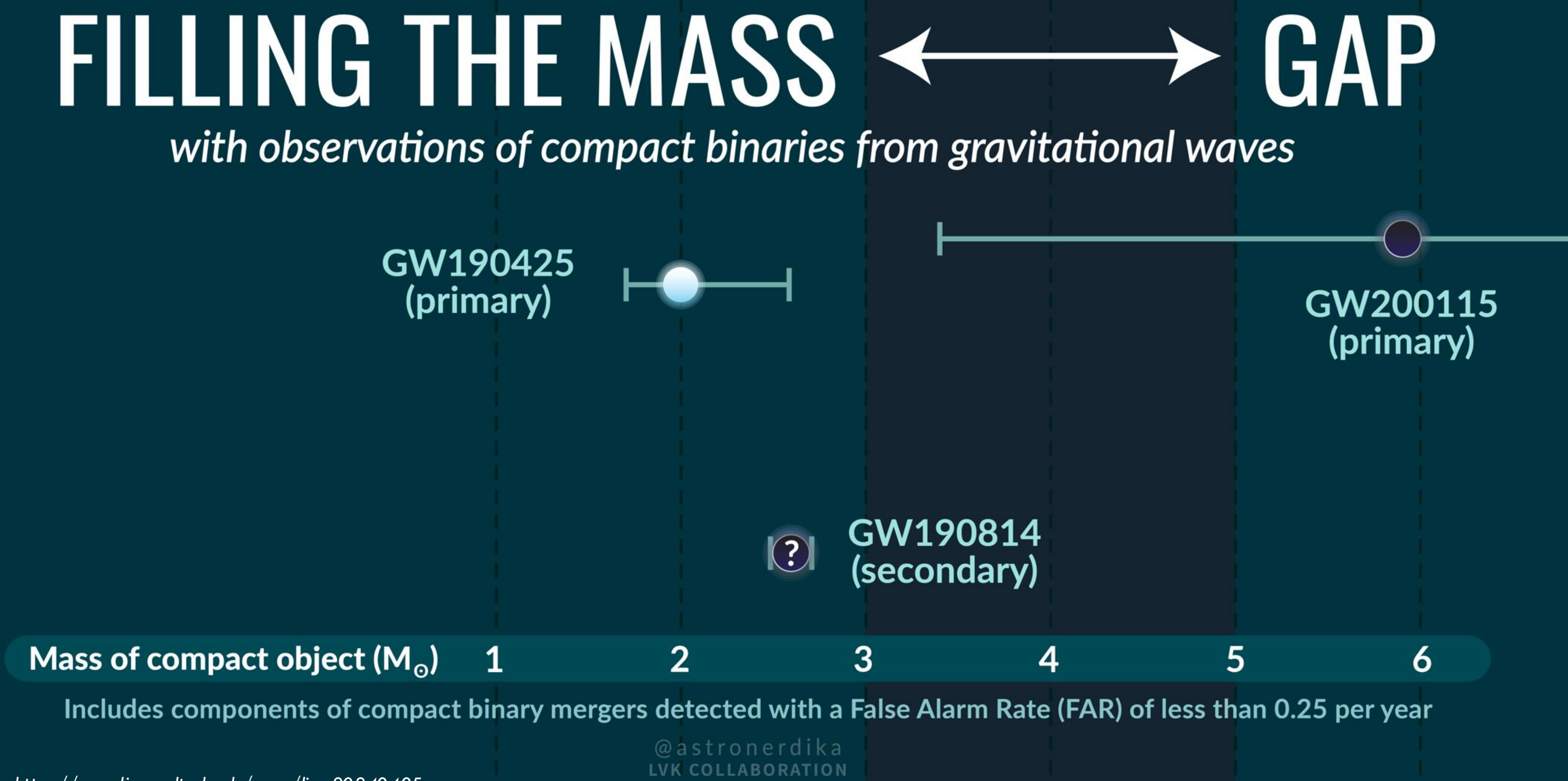
First exceptional event from O4 published



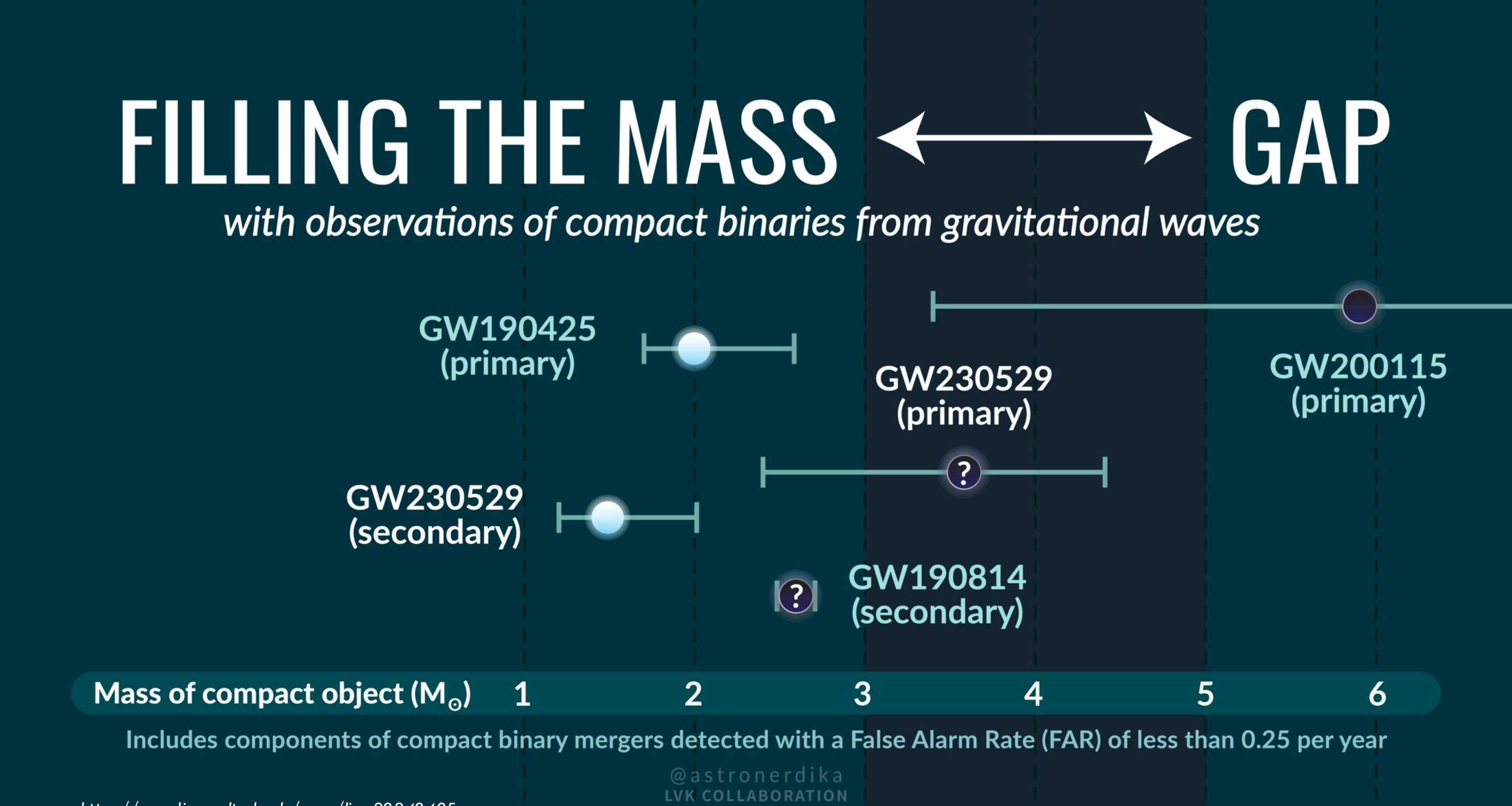
https://dcc.ligo.org/P2300352/public/



https://www.ligo.caltech.edu/news/ligo20240405



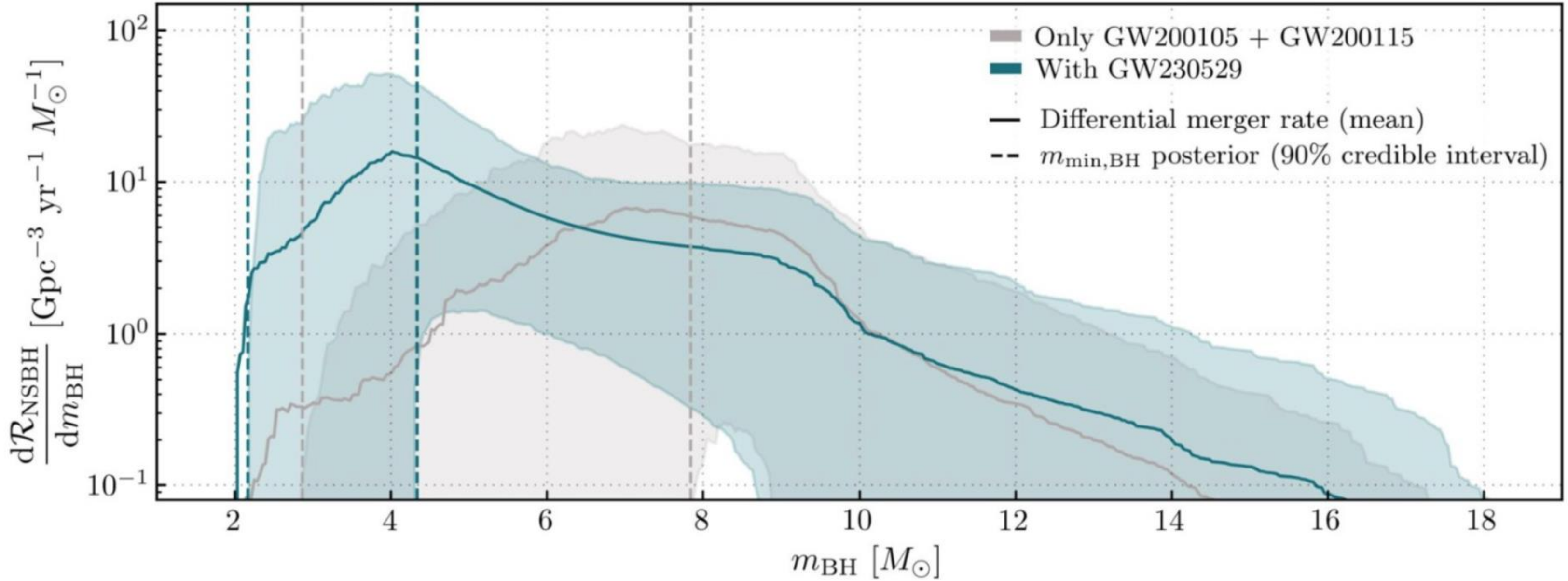
https://www.ligo.caltech.edu/news/ligo20240405



https://www.ligo.caltech.edu/news/ligo20240405

Including GW230529 decreases the minimum mass of black holes in the NSBH population

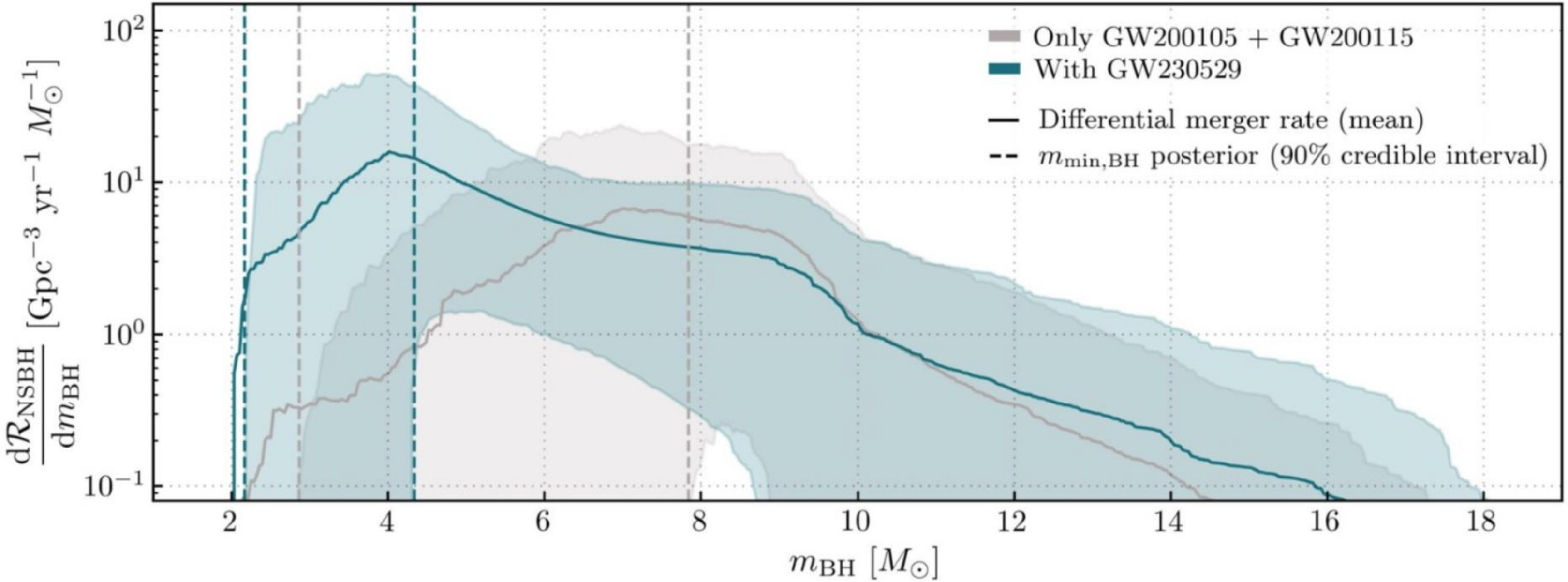
https://dcc.ligo.org/P2300352/public/



Merger rate of NSBH binaries (vertical axis) as a function of the mass of the BH (horizontal axis) in the system. The solid curves show the merger rates for two different models and the shaded areas show the uncertainties corresponding to these models. The dashed vertical lines show the expected range for the minimal mass of a BH, with 90% probability. The grey color considers an NSBH-only population model excluding GW230529. The blue color also includes GW230529 in the NSBH population model.

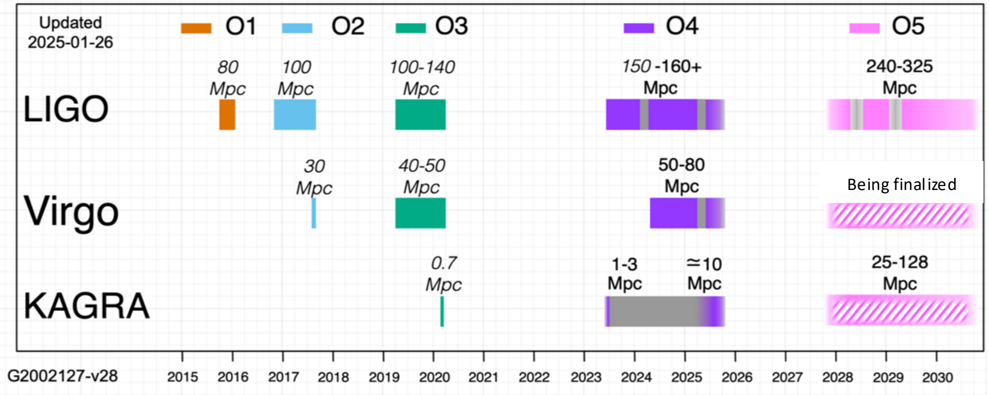
Including GW230529 decreases the minimum mass of black holes in the NSBH population

https://dcc.ligo.org/P2300352/public/



Probability of the existence of a mass gap (in NSBH) decreases from 98.6% to 7.2%

Next steps



Adapted from https://observing.docs.ligo.org/plan/

Plans for the upgrades in view of O5

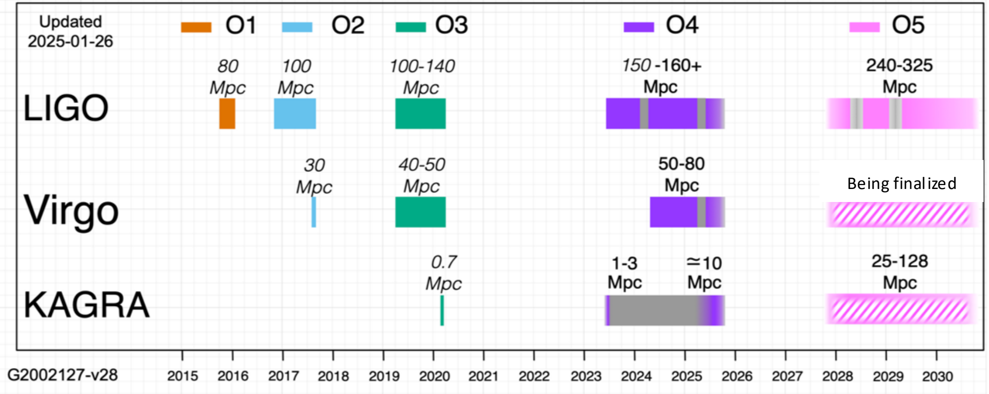
LIGO

- New mirror coatings with x2 better thermal noise
- Homodyne detection → more flexible, more precise
- Larger beam splitter → less clipping loss
- New thermal compensation, etc.

Virgo

- Stable signal recycling
- New mirror coatings with x2 better thermal noise
- Possible other updates: laser & optical systems

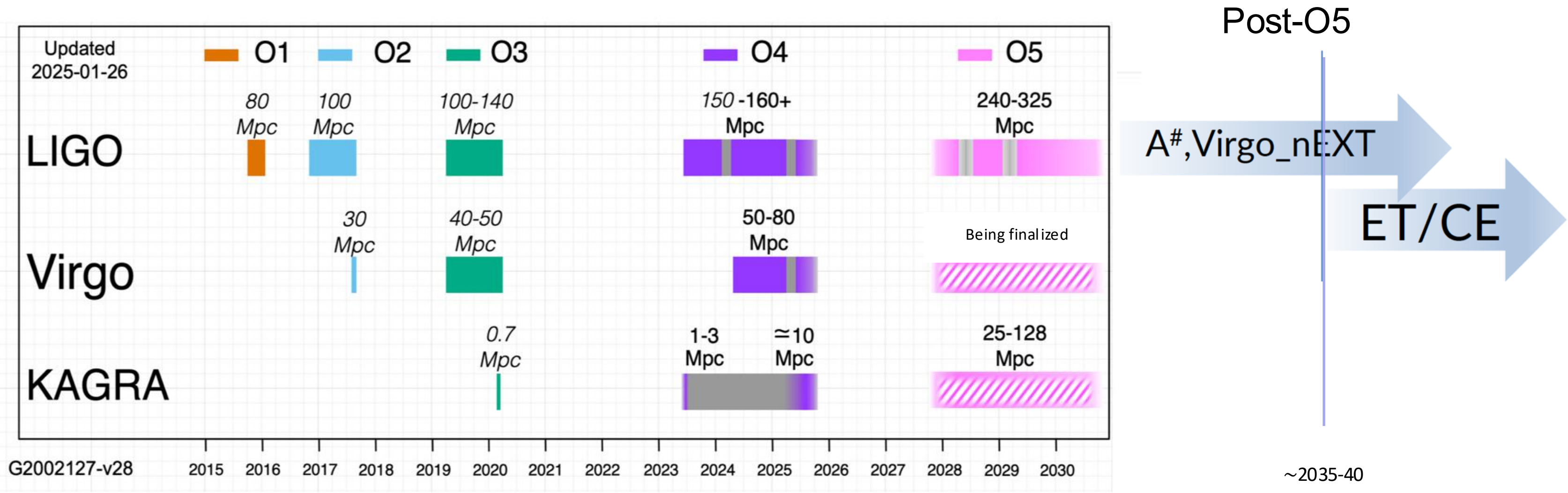
Next steps



Adapted from https://observing.docs.ligo.org/plan/

- Current thinking
  - Start is paced by upgrades after O4: 1.5-2 years gap.
  - Intersperse commissioning and observations
- Binary detection rates
  - O3 ~ 1 / 5 days
  - O4 ~ 1 / (2-3) days
  - O5 ~ 3 / day
- Other science
  - Improved SNR
  - New sources?

What about the post O5?



Virgo_nEXT and A#

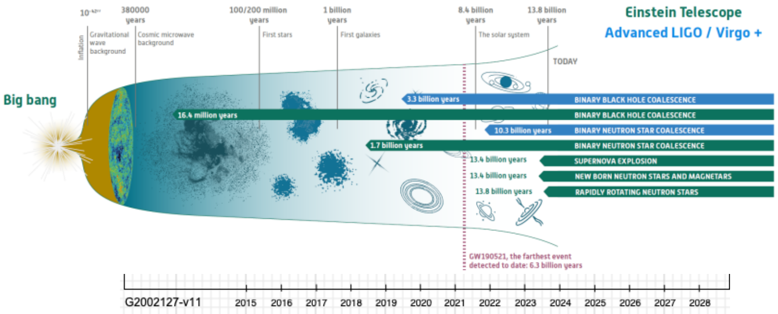
- Goal: get the most out of the facility w/o cryogenics and other wavelength
  - Higher power: 1.5MW
  - Better coatings
  - 100kg test masses
  - 10dB squeezing
- Achieve close to a factor of 2 amplitude sensitivity improvement
- Starting observations at beginning of 2030s and observe for several years, till 3rd generation detectors (ET, Cosmic Explorer) start their operations.
- An engine for observational science and a pathfinder for next-generation technologies.

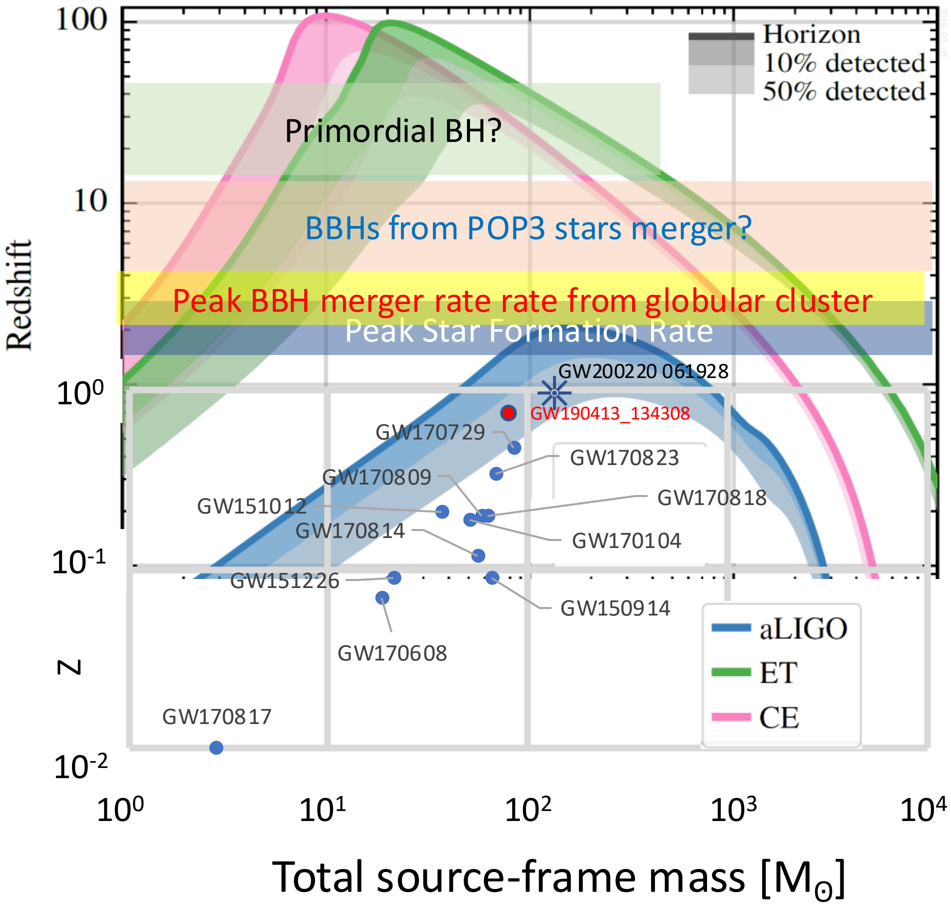
Monumental successes of the Advanced detectors

- First detection of GWs from a BBH system (GW150914)
  - Physics of BHs
- First detection of GWs from a BNS system (GW170817)
  - Birth of the multimessenger astronomy with GWs
  - Costraining EOS of NS
- Localisation capabilities of a GW source
- Measurement of the GW propagation speed
- Test of GR
- Alternative measurement of H_0
- GW polarisations
- Intermediate mass black hole (GW190521)

Toward next generation

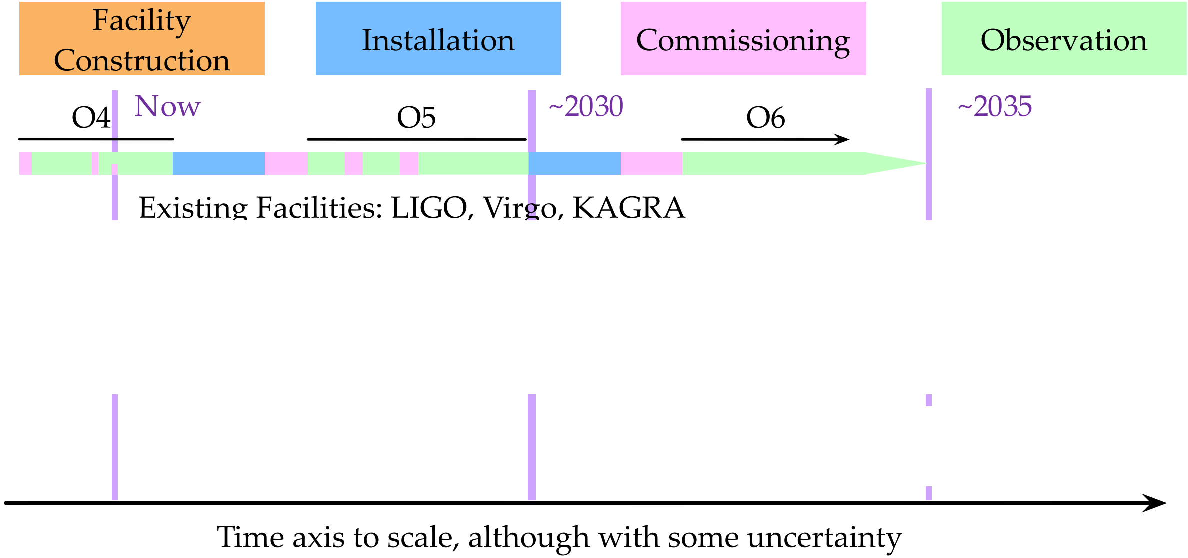
- 2nd generation GW detectors will explore the local Universe, even in their post-O5 configuration, initiating precision GW astronomy, but to have cosmological investigations a factor of 10 improvement in terms detection distance is needed





3G ground-based detectors will be required to access the high redshift Universe

Moving toward future facilities

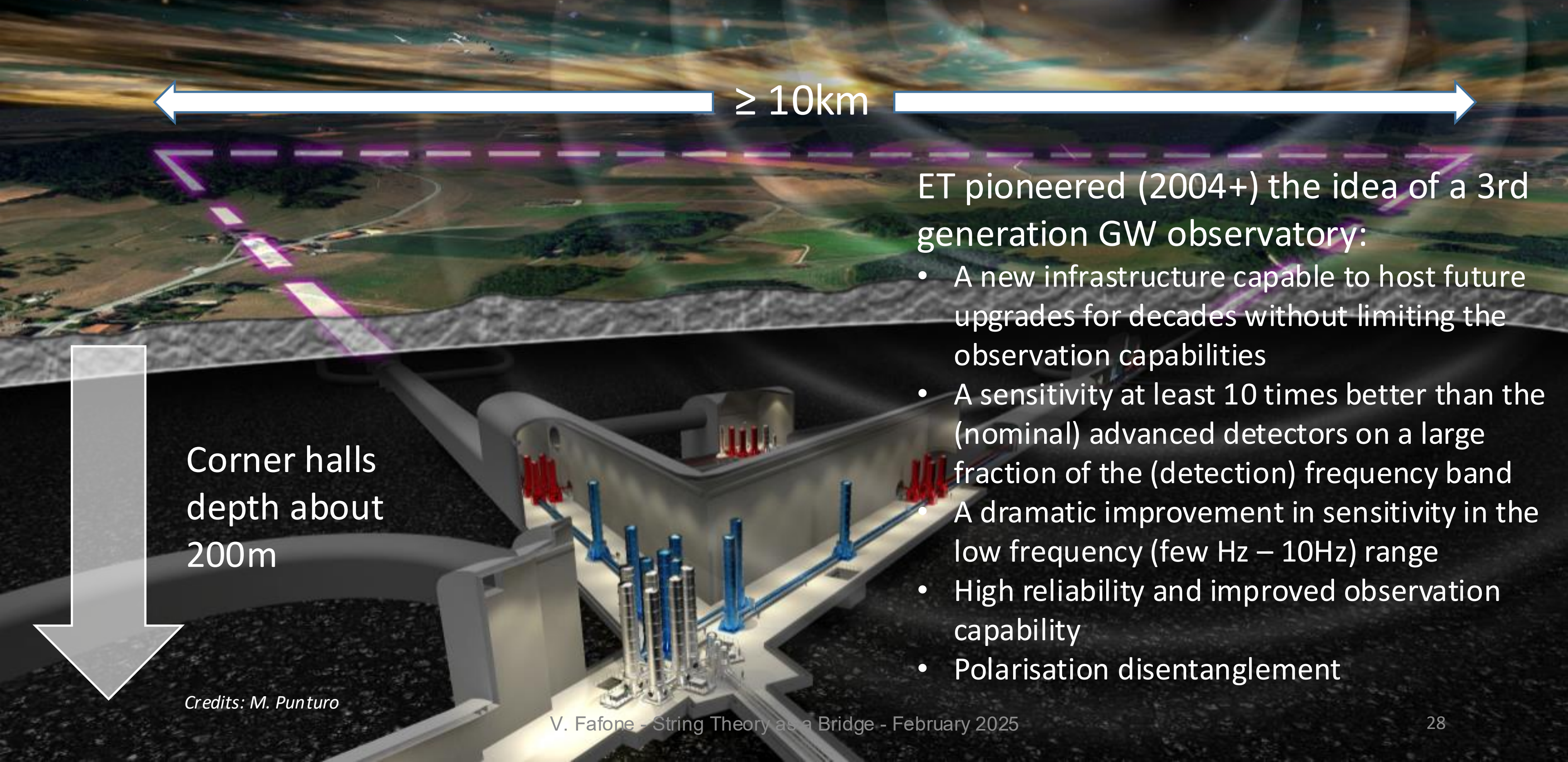


- Future ground-based facilities will be well-separated around the Earth, with exquisite sensitivity
- A network including more sensitive post-O5 detectors would be a cornerstone for future discoveries.

Timeline compiled from LVK Observing Plans, CE Horizon Study, NSF MPSAC ngGW Subcommittee, and LISA Factsheet

Credits: Driggers IAU GA WG 1-4, 14 Aug 2024

Einstein Telescope (ET)

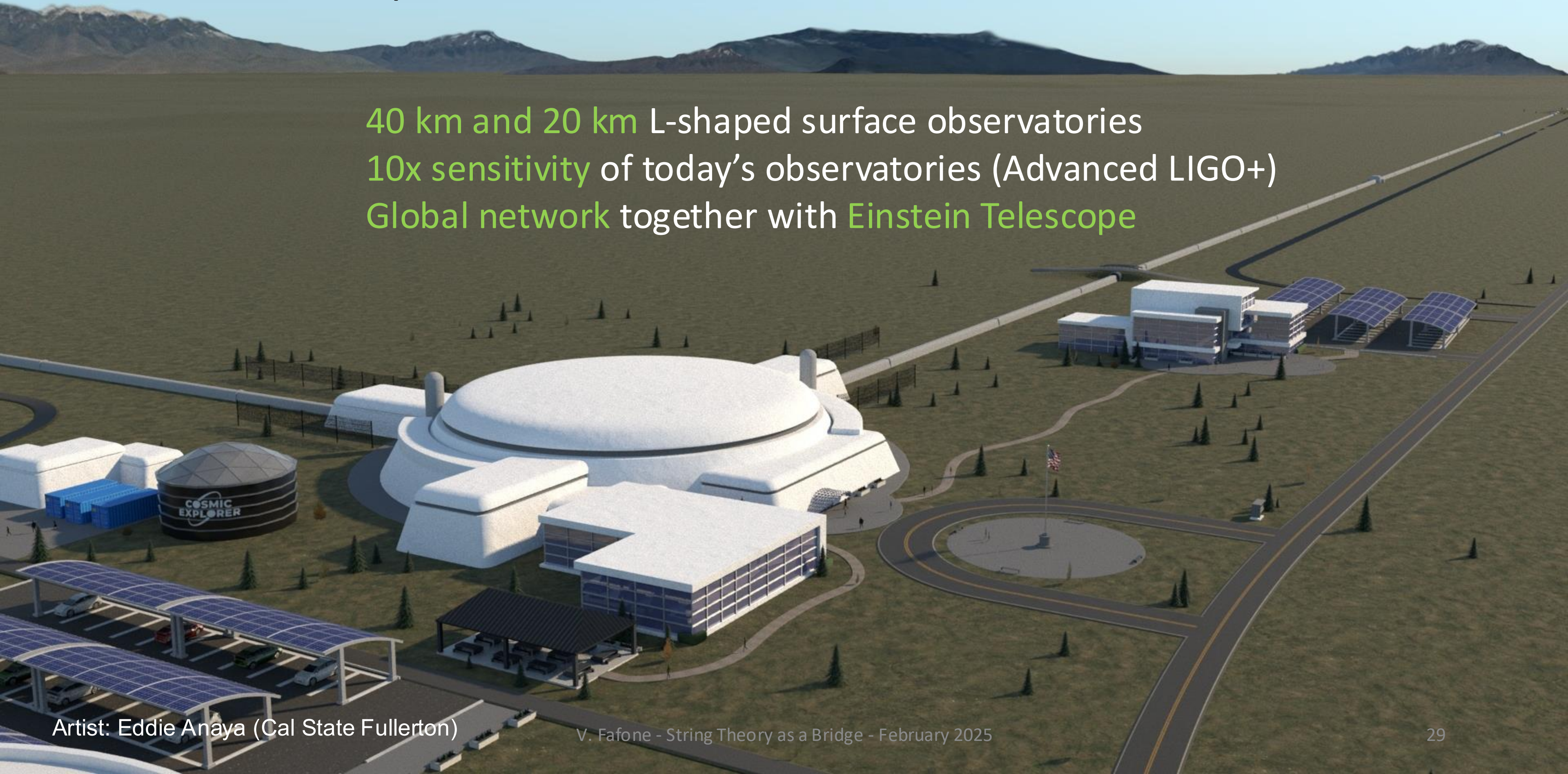


ET pioneered (2004+) the idea of a 3rd generation GW observatory:

- A new infrastructure capable to host future upgrades for decades without limiting the observation capabilities
- A sensitivity at least 10 times better than the (nominal) advanced detectors on a large fraction of the (detection) frequency band
- A dramatic improvement in sensitivity in the low frequency (few Hz – 10Hz) range
- High reliability and improved observation capability
- Polarisation disentanglement

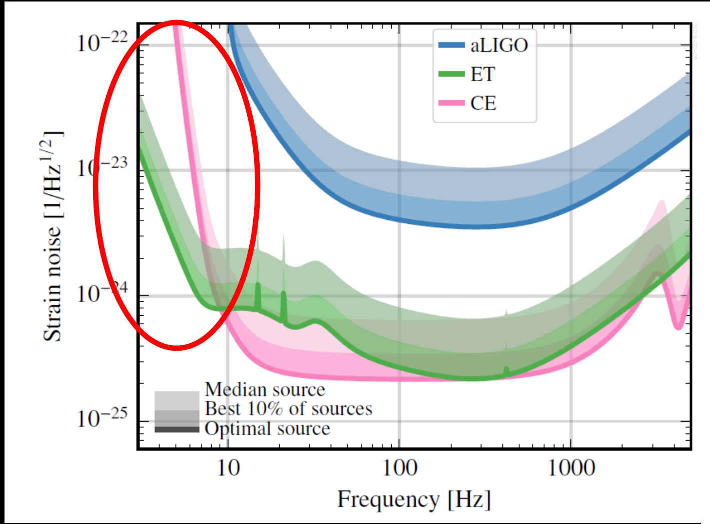
Cosmic Explorer (CE)

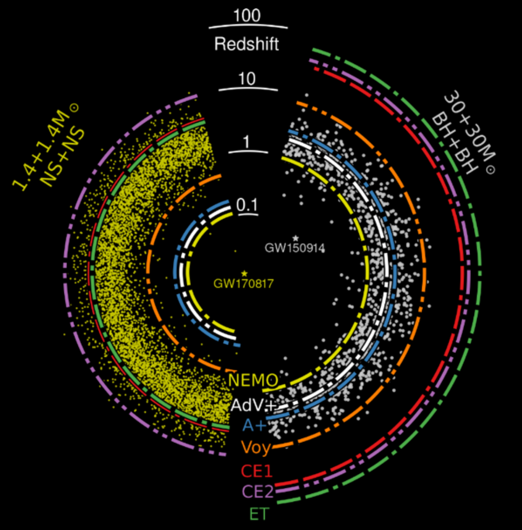
40 km and 20 km L-shaped surface observatories
10x sensitivity of today's observatories (Advanced LIGO+)
Global network together with Einstein Telescope



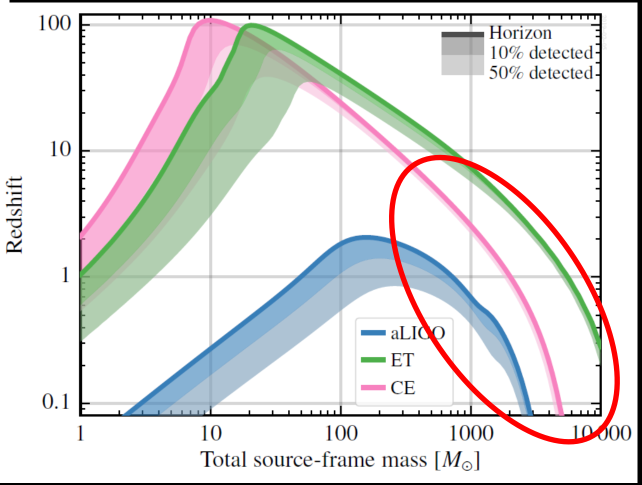
Artist: Eddie Anaya (Cal State Fullerton)

Observation performance of ET & CE



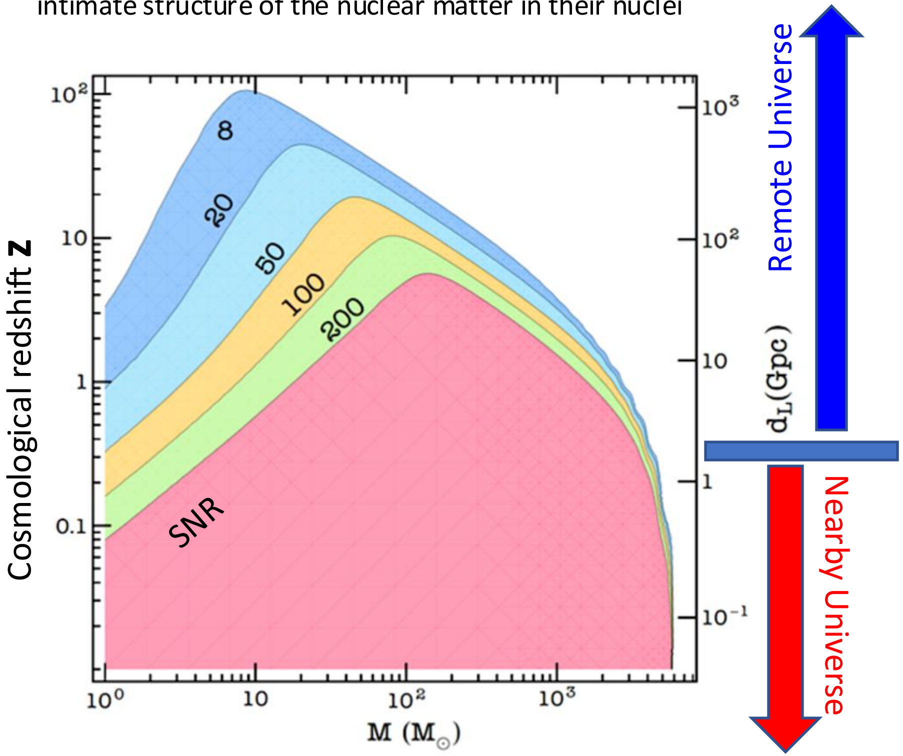


- BBH up to z~50-100
- 10^5 BBH/year
  - Masses $M_T \gtrsim 10^3\ M_\odot$
- BNS to z~2
  - 10^5 BNS/year
  - Possibly O(10-100)/year with e.m. counterpart
- High SNR

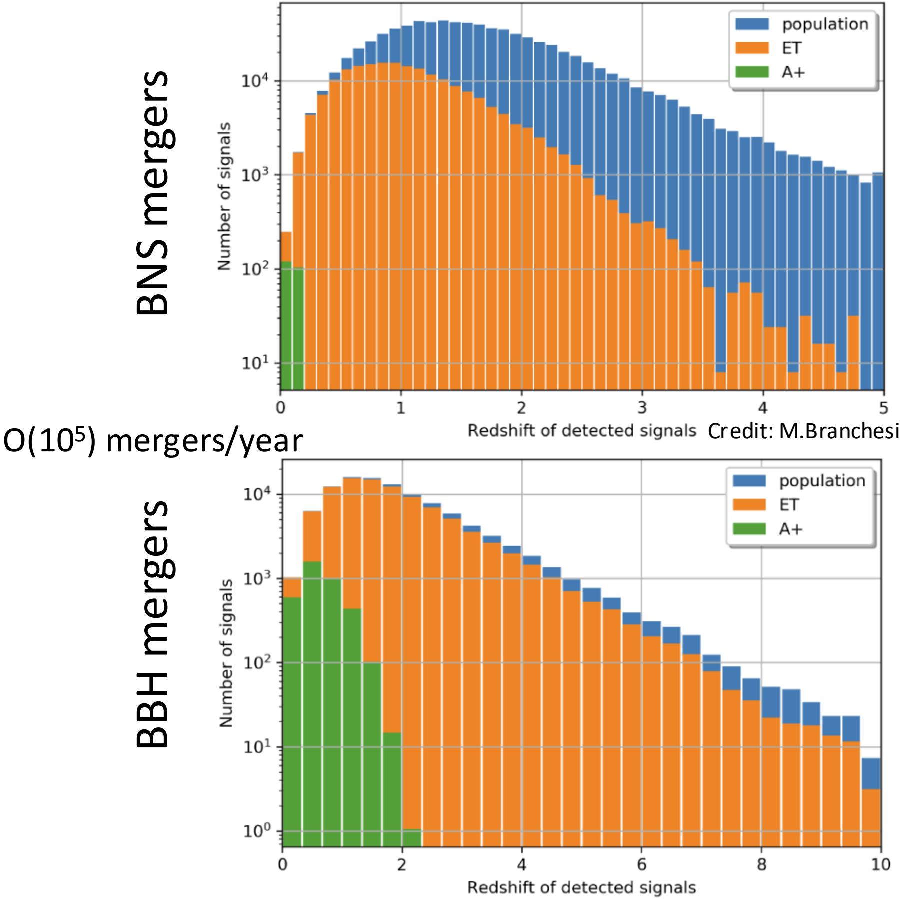


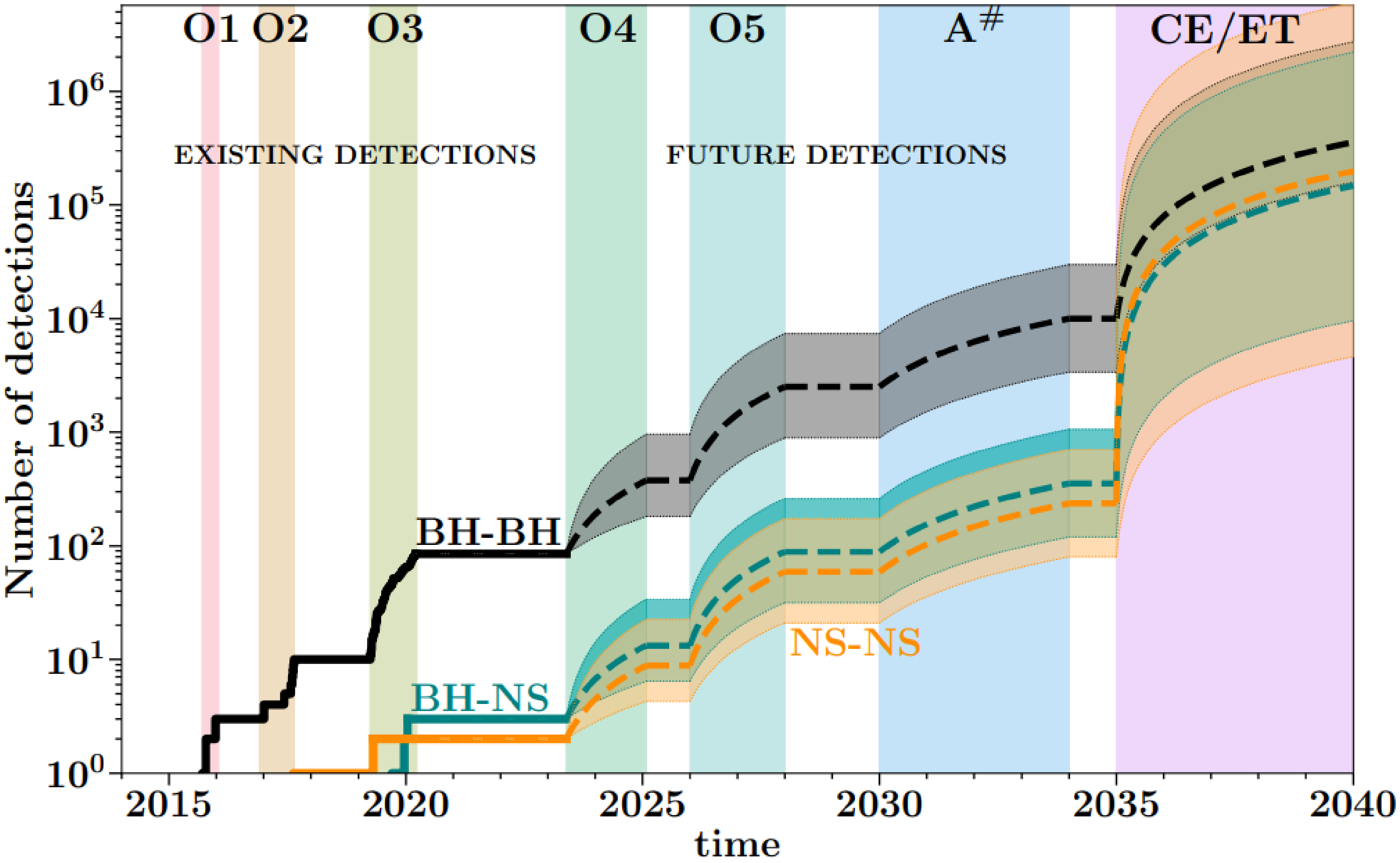
ET Science in a nutshell

- ET will explore almost the entire Universe listening the gravitational waves emitted by black hole, back to the dark ages after the Big Bang
- ET will detect, with high SNR, hundreds of thousands coalescences of binary systems of Neutron Stars per year, revealing the most intimate structure of the nuclear matter in their nuclei



Compact Object Binary Populations





Broekgaarden et al [arXiv:2303.17628](https://arxiv.org/abs/2303.17628)

ET Observational Science in a nutshell

ASTROPHYSICS

- **Black hole properties**
  - origin (stellar vs. primordial)
  - evolution, demography
- **Neutron star properties**
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- **Multi-band and -messenger astronomy**
  - joint GW/EM observations (GRB, kilonova,...)
  - multiband GW detection (LISA)
  - neutrinos
- **Detection of new astrophysical sources**
  - core collapse supernovae
  - isolated neutron stars
  - stochastic background of astrophysical origin

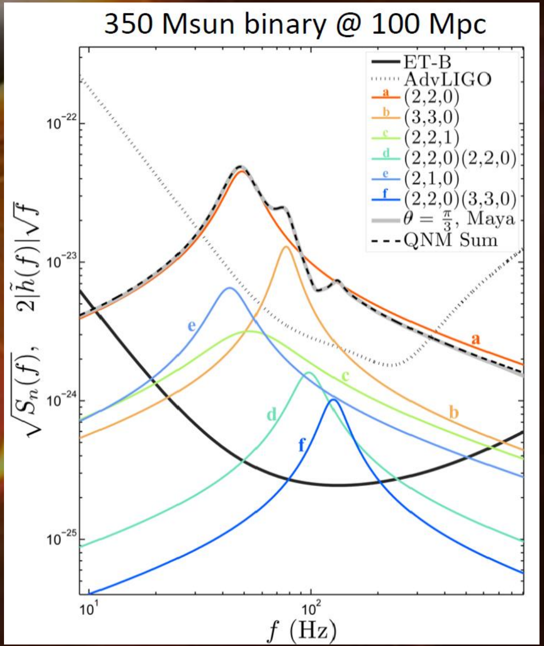
FUNDAMENTAL PHYSICS AND COSMOLOGY

- **The nature of compact objects**
  - near-horizon physics
  - tests of no-hair theorem
  - exotic compact objects
- **Tests of General Relativity**
  - post-Newtonian expansion
  - strong field regime
- **Dark matter**
  - primordial BHs
  - axion clouds, dark matter accreting on compact objects
- **Dark energy and modifications of gravity on cosmological scales**
  - dark energy equation of state
  - modified GW propagation
- **Stochastic backgrounds of cosmological origin**
  - inflation, phase transitions, cosmic strings

GW Science with ET

Extreme Gravity conditions

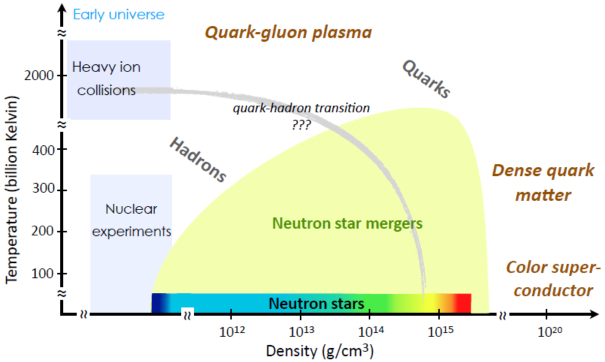
- In GR, no-hair theorem predicts that BHs are described only by their mass and spin (and charge)
  - However, when a BH is perturbed, it reacts (in GR) in a very specific manner, relaxing to its stationary configuration by oscillating in a superpositions of quasi-normal (QN) modes, which are damped by the emission of GWs.
  - A BH, a pure space-time configuration, reacts like an elastic body → Testing the “elasticity” of the space-time fabric
  - Exotic compact bodies could have a different QN emission and have echoes.

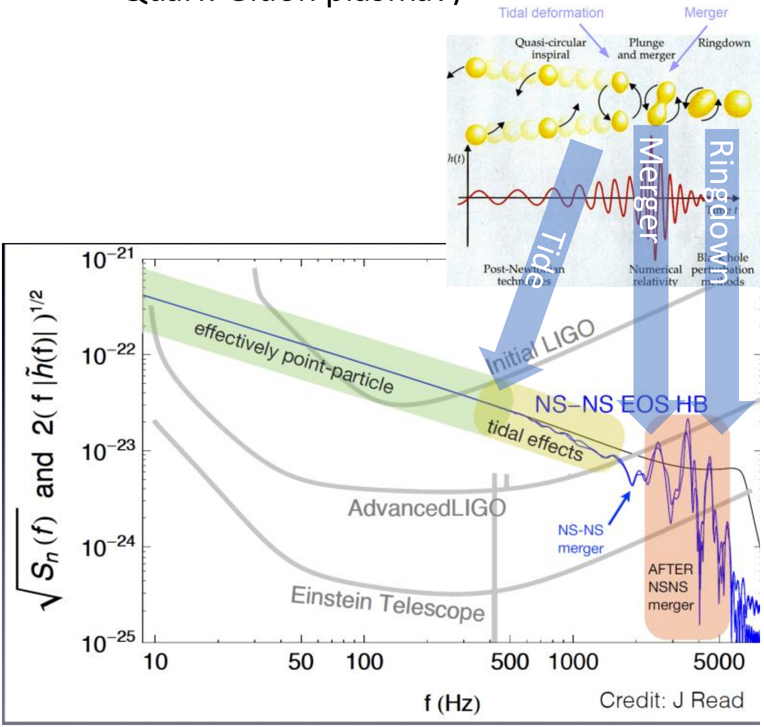


London et al. 2014

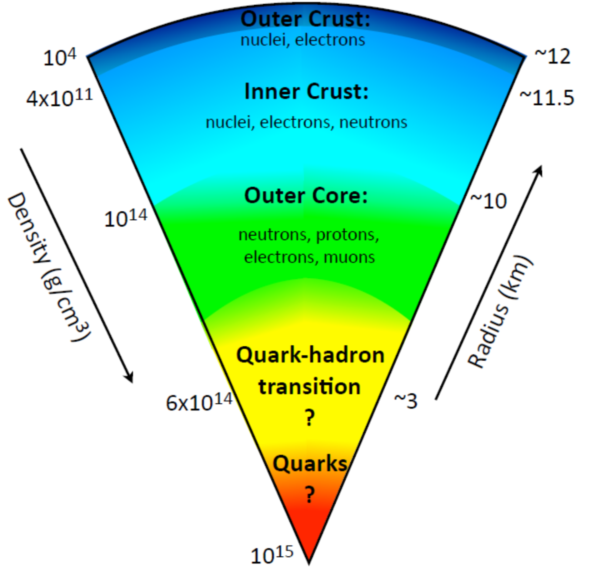
GW Science with ET

- Neutron stars are an **extreme laboratory for nuclear physics**
  - The external crust is a Coulomb Crystal of progressively more neutron-reach nuclei.
  - The core is a Fermi liquid of uniform neutron-rich matter ("Exotic phases"? Quark-Gluon plasma?)





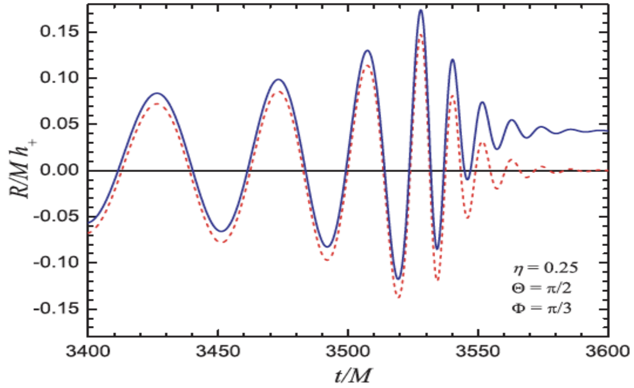
- Tidal deformation from the dephasing in the GW signal → constrain the EOS of the NS.
- EM information → more stringent constrain.
- EOS describes the status of the matter in the over-critical pressure condition.



ET primary science target: low frequency

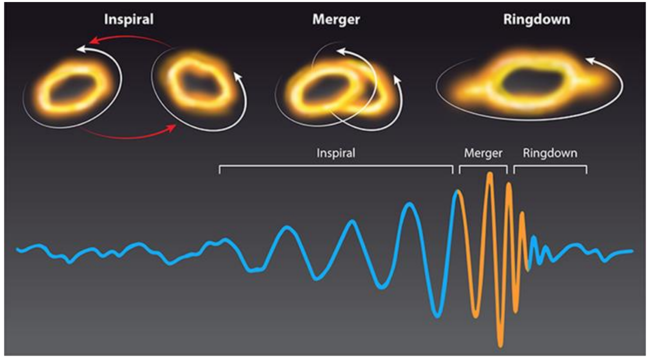
- One of the primary science targets of ET is to access the 1-10Hz frequency range
  - Intermediate mass black holes
    - Fill the gap between the stellar mass black holes (à la LIGO/Virgo) and the supermassive black holes (à la LISA)
  - Cosmology
    - high red-shift → low frequency
    - Primordial BH and the Dark Matter quest
  - Early warning in multimessenger astronomy with GW emitted by BNS
  - Even more: gravitational-wave memory effect, …

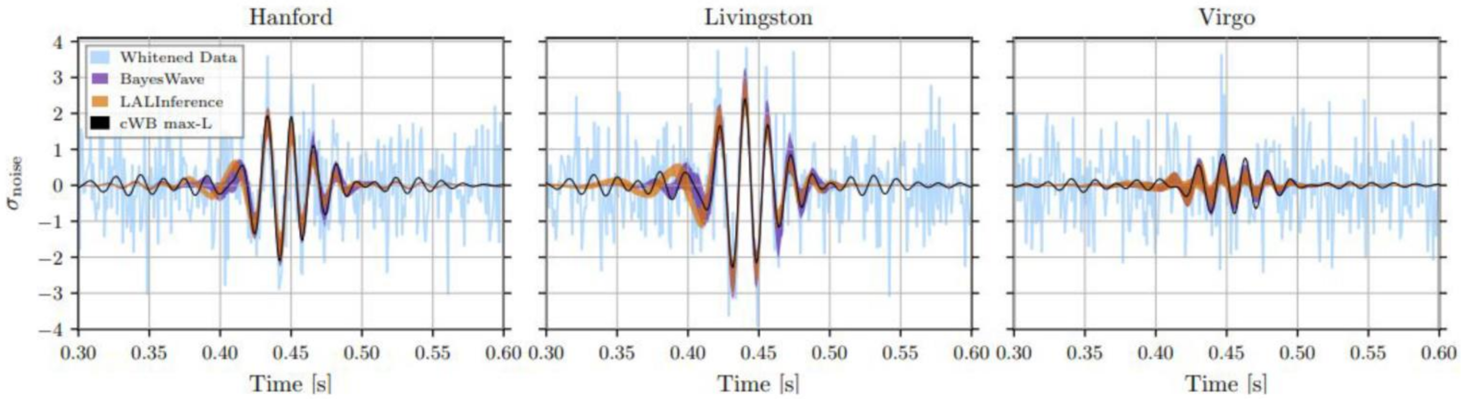
M. Favata 2010 Class. Quantum Grav. 27 084036



Why low frequency focus?
GW190521

$M_1 = 85^{+21}_{-14} M_\Theta$, $M_2 = 66^{+17}_{-18} M_\Theta$
at z~0.82 (5.3Gpc)
Remnant $M_f = 142^{+28}_{-16} M_\Theta$

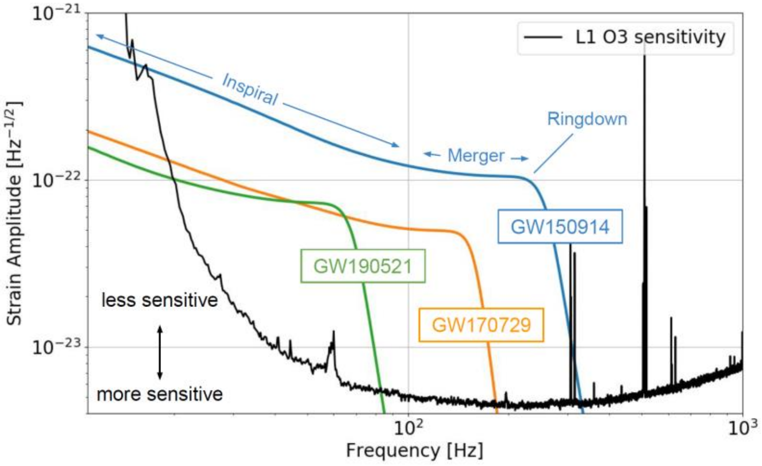




Where is the chirp?

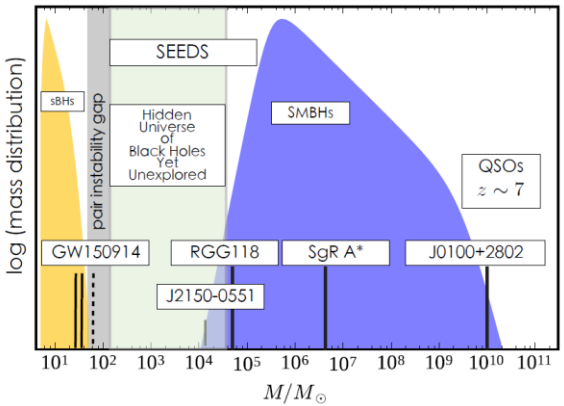
Phys. Rev. Lett. 125, 101102 (2020)
Astrophys. J. Lett. 900, L13 (2020)

Why low frequency focus?
Intermediate Mass Black Holes: seeds of SMBH?

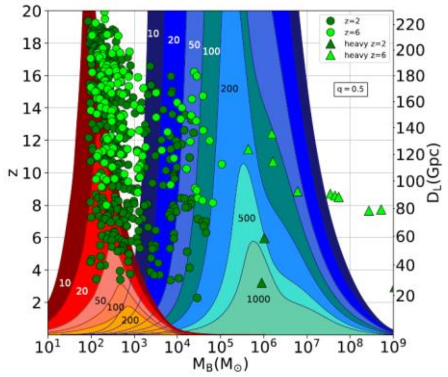


- Supermassive Black Holes (SMBHs) are present at the center of many galaxies:
  - What is their history? How have they formed? What are the seeds?

- Higher masses correspond to lower frequency GW emission

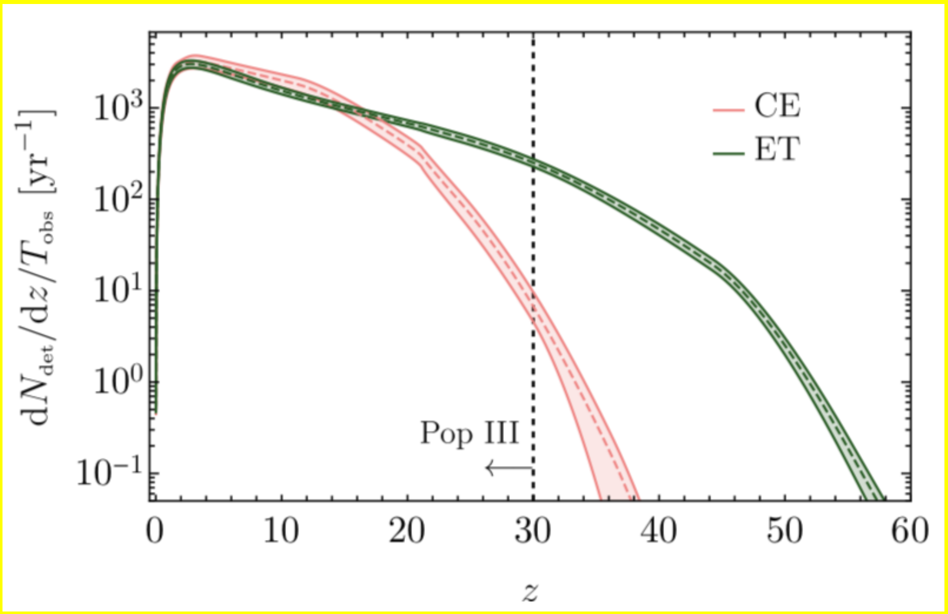


Black Holes in the Gravitational Universe



Why low frequency focus?
Primordial Black Holes

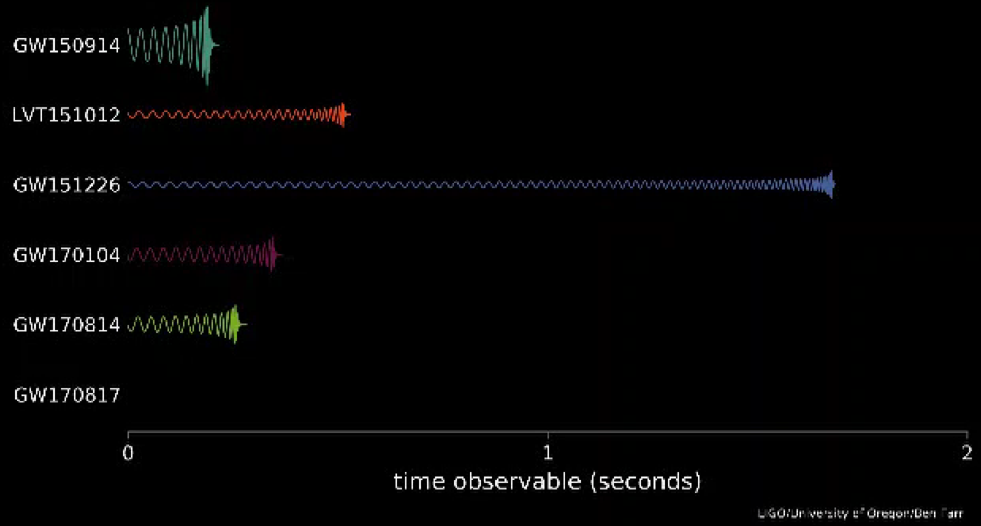
- ET (and CE) will detect BBH well beyond the SFR peak z~2
  - comparing the redshift dependence of the BH-BH merger rate with the cosmic star formation rate to disentangle the contribution of BHs of stellar origin from that of possible BHs of primordial origin: **any BBH merger at z>30 will be of primordial origin**.

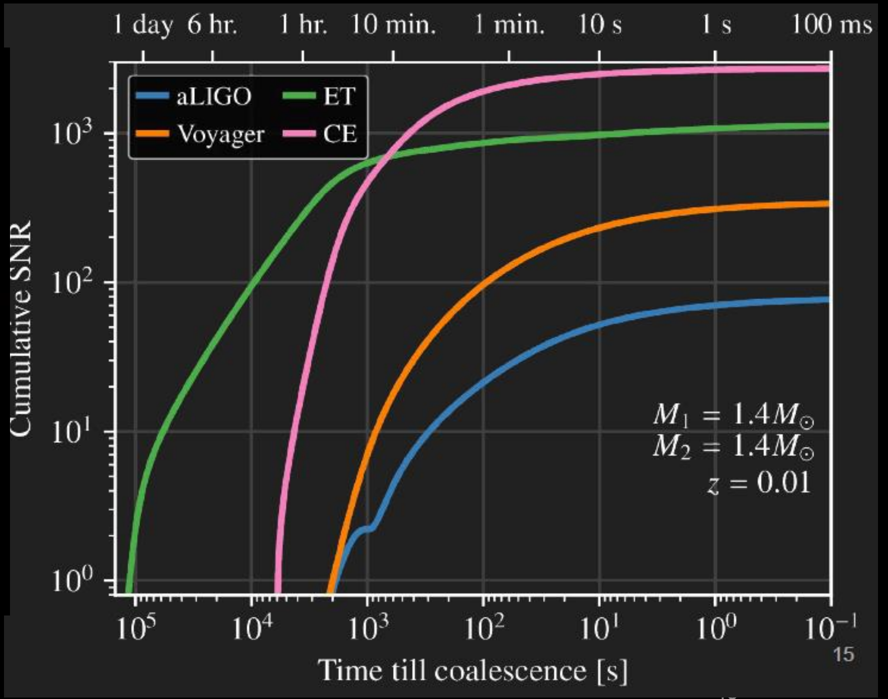


London et al. 2014

Low frequency: Multi-messenger astronomy

- If we are able to cumulate enough SNR before the merging phase, we can trigger e.m. observations before the emission of photons
- Keyword: low frequency sensitivity:





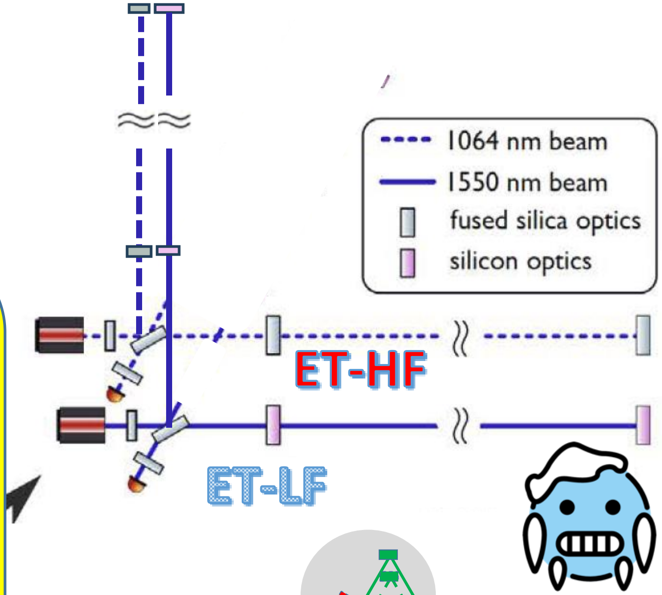
ET key elements

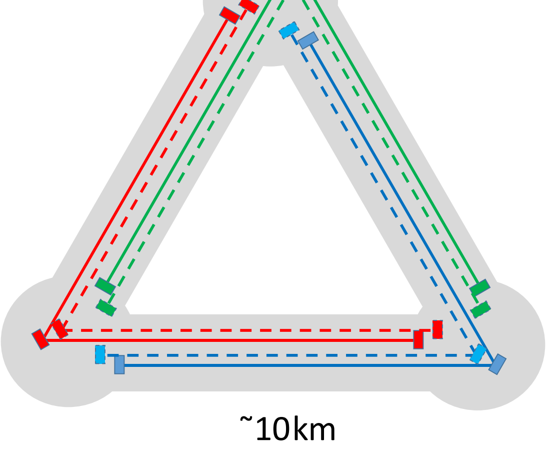
Requirements

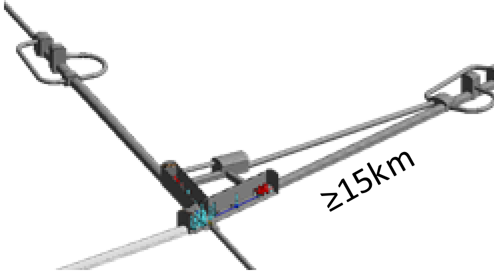
- Wide frequency range
- Massive black holes (LF focus)
- Localisation capability
- (more) Uniform sky coverage
- Polarisation disentanglement
- High Reliability (high duty cycle)
- High SNR

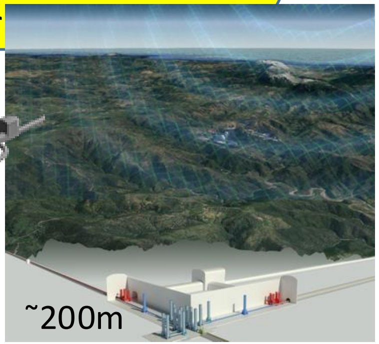
Design Specifications

- Xylophone (multi-interferometer) Design
- Underground
- Cryogenic
- Triangular shape (2011)
- Multi-detector design
- Longer









Credits: M. Punturo

Underground location

Image: St. Patrick's well, Orvieto, Italy, 1537

Pro

- Access to the low frequency:
  - 2-10Hz for ET
  - Reduction of the seismic and Newtonian Noise
  - Suppression of the atmospheric Newtonian Noise and of the wind impact
  - Reduction of the anthropogenic noise
    - Magnetic
    - Acoustic
    - Vibration
- Easier compatibility with the urbanization of the hosting region
  - Europe is generally a strongly urbanized continent
- Landscape impact

Cons

- Cost
- Challenging civil engineering
- Time needed to build it
- Limited possibility to upgrade the civil infrastructure in a medium-long term timeline
- More difficult operating environment in all the observatory phases (construction, integration, commissioning, maintenance and upgrade)

Credits: M. Punturo

ET geometry debate: Δ or (two) L

In the last two of years, the collaboration started the evaluation of the best configuration for ET, considering the alternative of two L configuration (as LIGO, Cosmic Explorer) to maximize the science return and reduce risks.

Since 2011 (CDS, triangle configuration) the situation drastically changed:

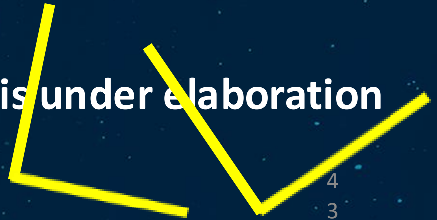
- ❑ First detections, GTWC-3 catalog → BH population → new evolution models;
- ❑ Science case developed;
- ❑ Know-how with advanced (L) detectors;
- ❑ International scenario (+ Cosmic Explorer in US);
- ❑ Two candidate sites strongly supported (and a potential third site…).

The collaboration is analyzing both configurations: **optimizing science return, differential risk assessment.**

First results on the science return published in Marica Branchesi et al JCAP07(2023)068:

The 2L 15 km geometry shows an improved science return in a relevant number of science targets

A preliminary differential risk analysis, provided by a specific committee, is under elaboration



Credits: M. Punturo

ET Enabling Technologies

- The multi-interferometer approach asks for two parallel technology developments:
  - ET-LF:
    - Underground
    - Cryogenics
    - Silicon (Sapphire) test masses
    - Large test masses
    - New coatings
    - New laser wavelength
    - Seismic suspensions
    - Frequency dependent squeezing
  - ET-HF:
    - High power laser
    - Large test masses
    - New coatings
    - Thermal compensation
    - Frequency dependent squeezing

Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10-20 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	45 cm/ 57 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase (rad)	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1×300 m	2×1.0 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	TEM_{00}	TEM_{00}
Beam radius	12.0 cm	9 cm
Scatter loss per surface	37 ppm	37 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$
Gravity gradient subtraction	none	factor of a few

Challenging engineering

New technology in cryo-cooling

New technology in optics

New laser technology

High precision mechanics and low noise controls

High quality opto-electronics and new controls

Evolved laser technology

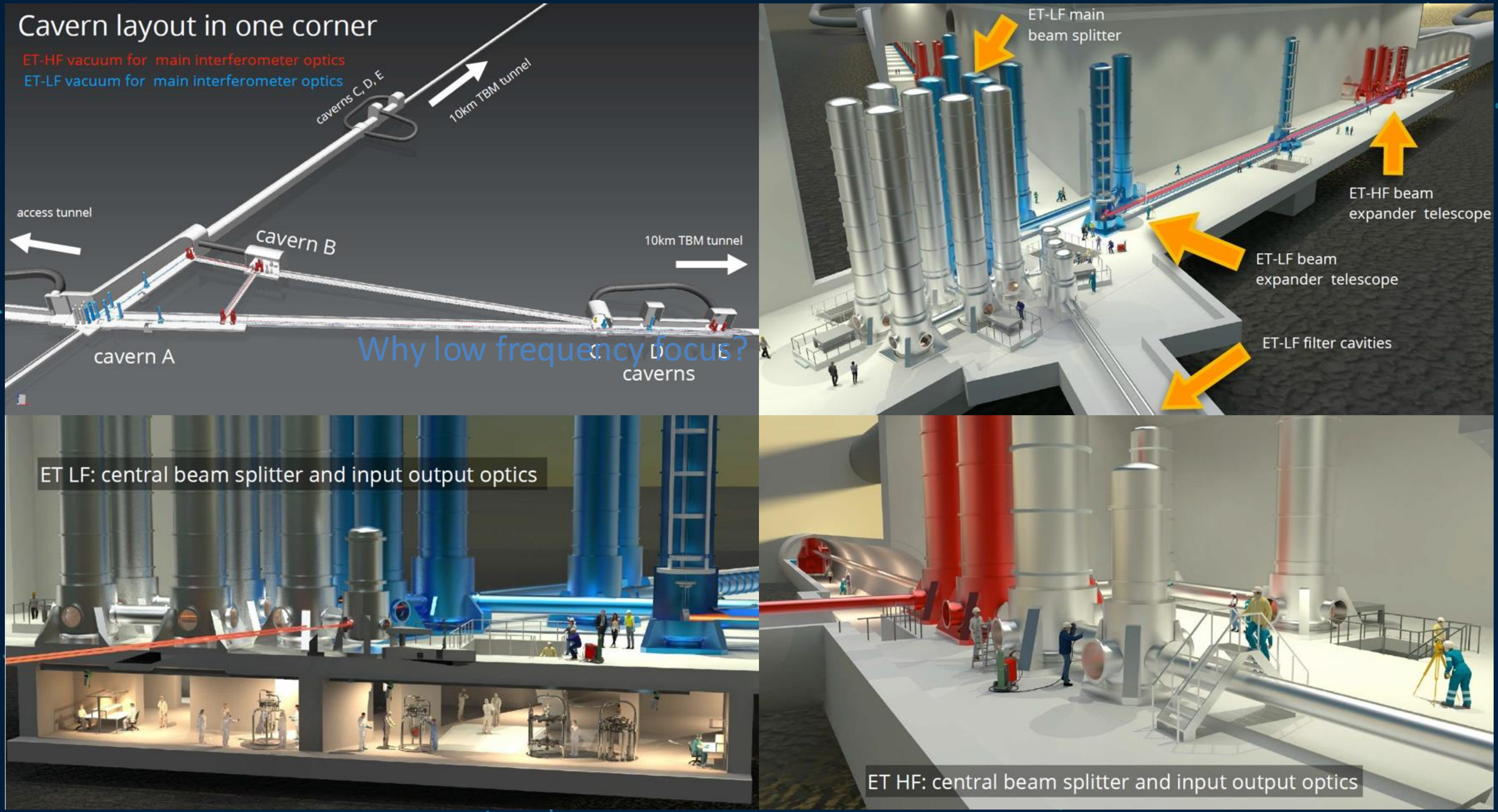
Evolved technology in optics

Highly innovative adaptive optics

High quality opto-electronics and new controls

Credits: M. Punturo

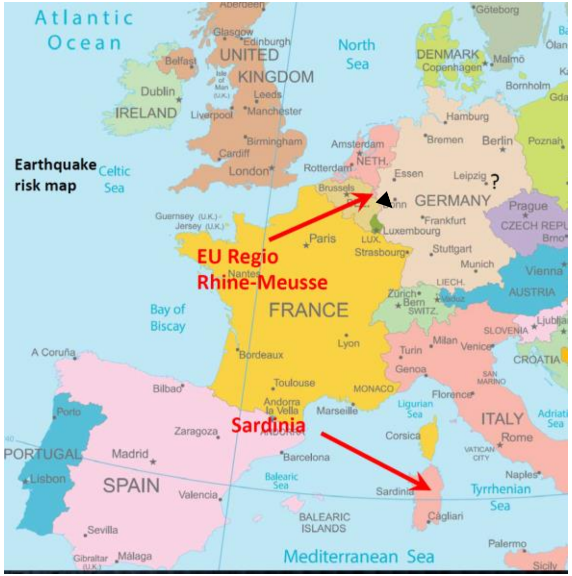
ET: large scale and complex infrastructure



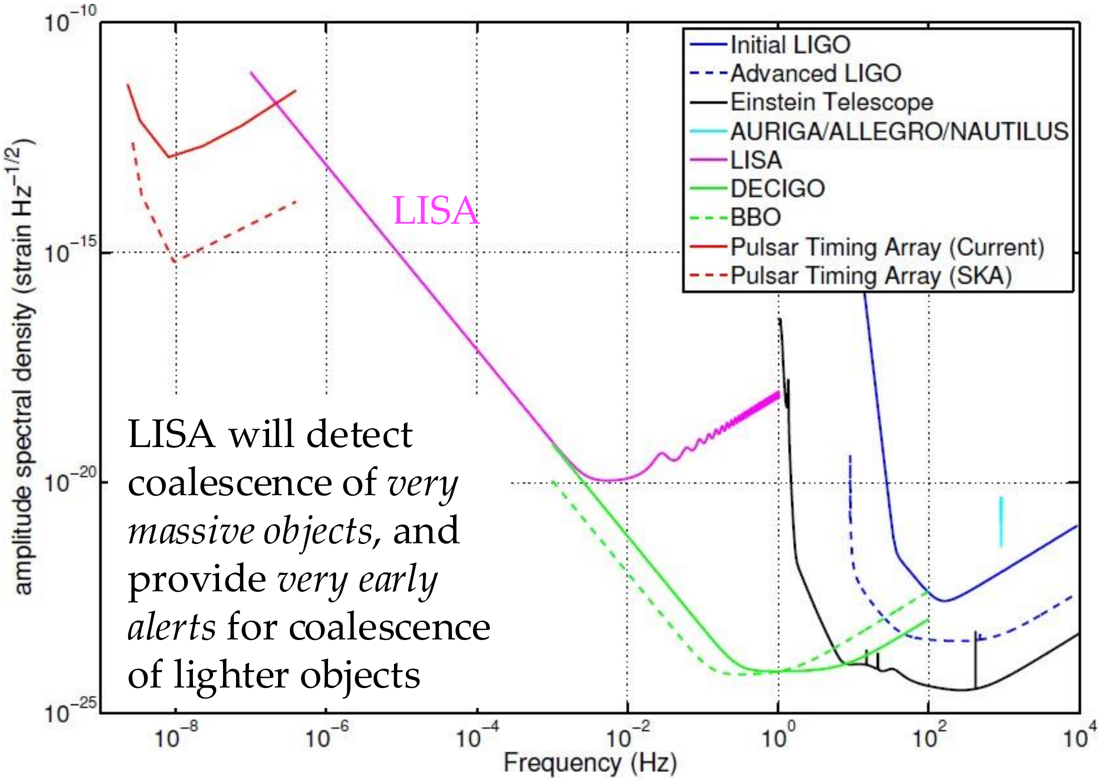
Credit: A.Freise, 2020 XI ET Symposium

ET candidate sites

- Two sites officially candidate to host ET:
  - EMR EUregio, border region between Nederland, Belgium and Germany
  - Sardinia (Lula area, Barbagia)
- A third potential site is located in Saxony (Lusatia), public announcement done in November 2024 to be formalized.
- Overall site evaluation is a complex task depending on:
  - Geophysical and environmental quality
  - Financial and organization aspects
  - Services, infrastructures



Space vs. Ground Detectors



Pitkin, M., et al., *Living Rev. Relativ.* **14**, 5 (2011)

The GW spectrum