43rd International Symposium on Physics in Collision

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on behalf of the Virgo collaboration

The Virgo experiment and the hunt for gravitational waves: status, recent results and prospects

Istituto Nazionale di Fisica Nucleare

ICSC
Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

Presentation outline

- Introduction: gravitational waves and detectors
- The O4 run and the status of Virgo
- Observations during the O4 run
- Future developments: O5 and post-O5

Gravitational Waves

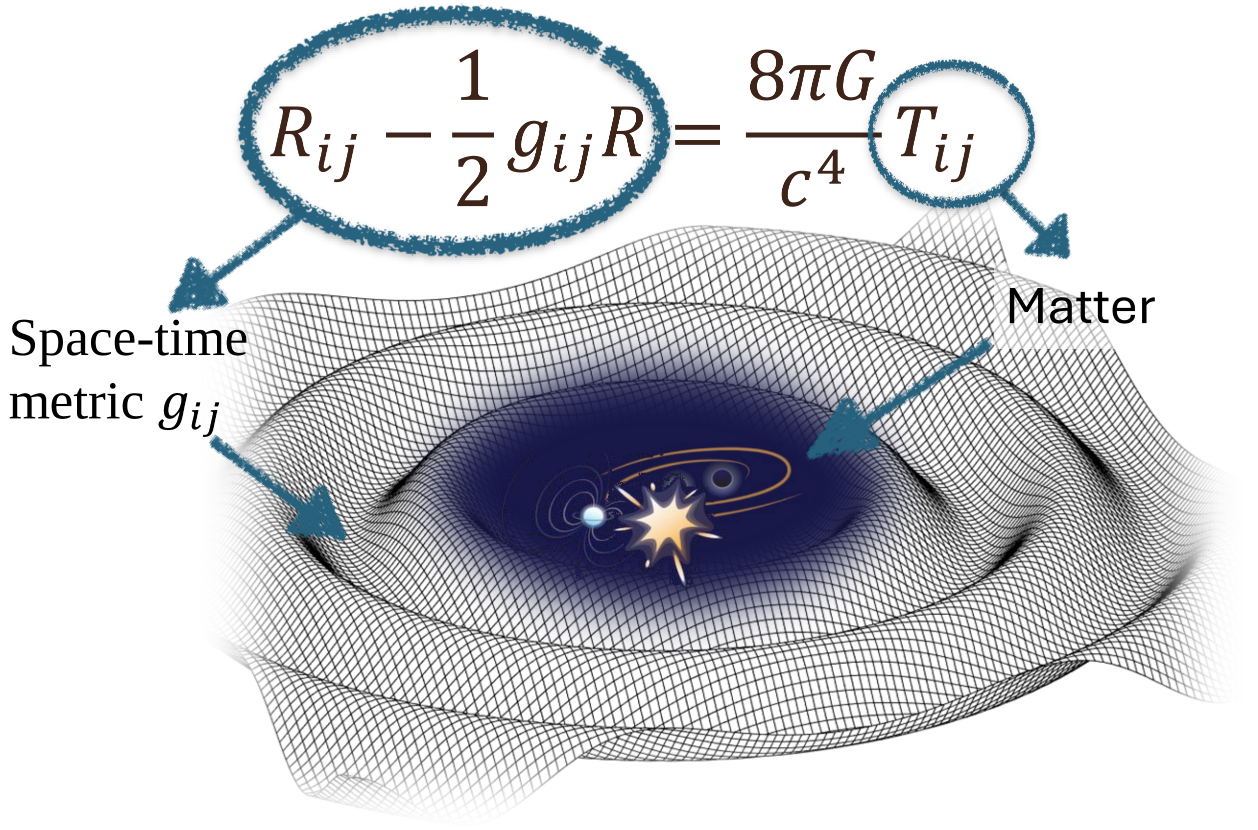
- Gravitational Waves are solutions of the linearized Einstein field equations in vacuum.

- Produced by the bulk motion of matter.

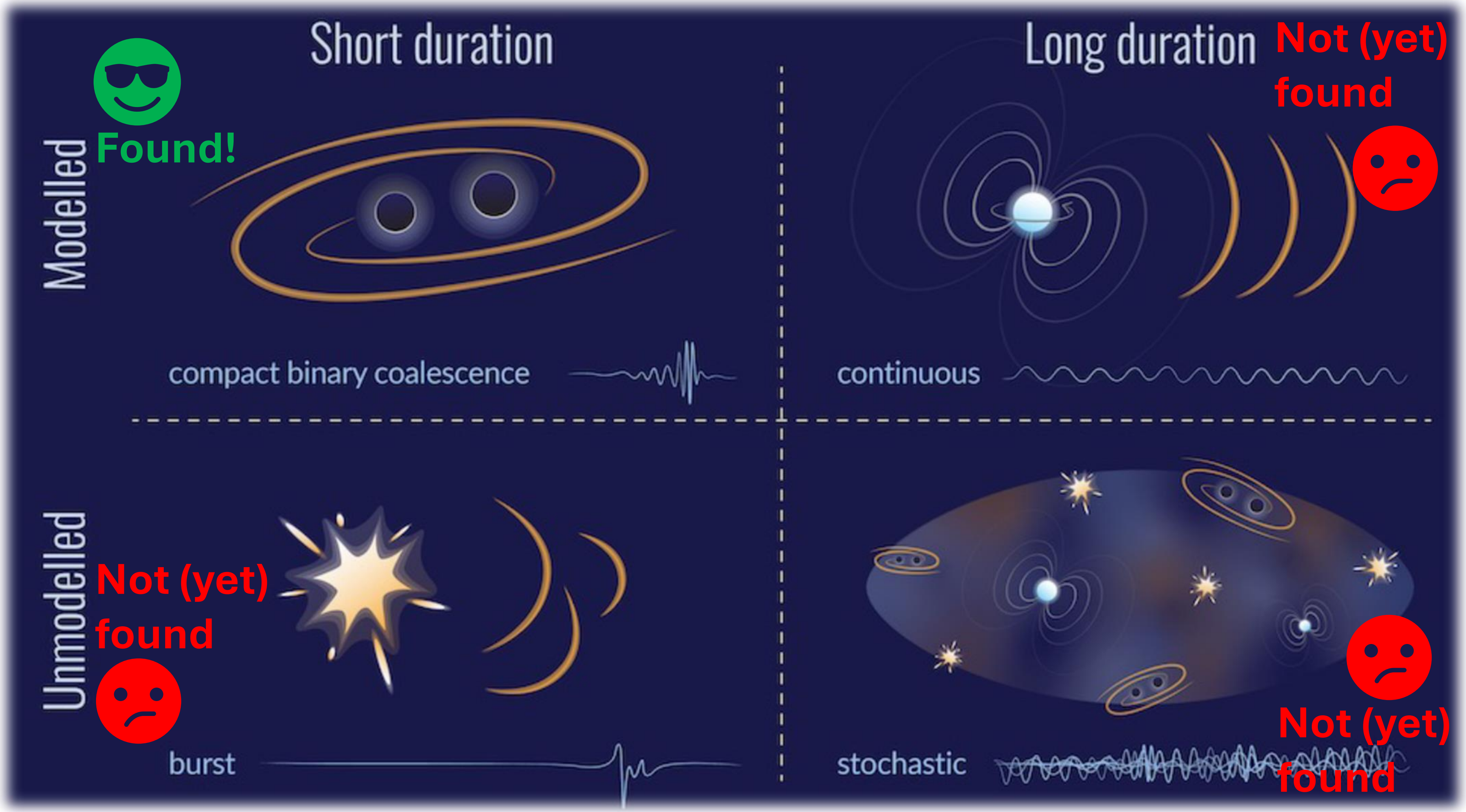
- In absence of matter, they propagate as a wave at the speed of the light.

$$T_{ij} = 0$$
$$g_{ij} \simeq \eta_{ij} + h_{ij}$$
$$|h_{ij}| \ll 1$$

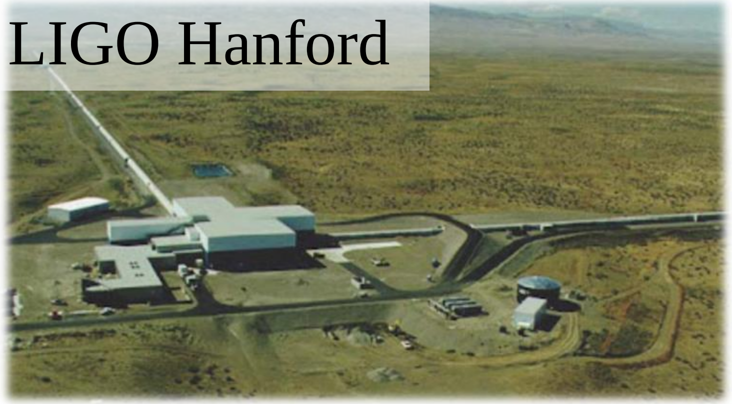
$$\Box h_{ij} = 0$$

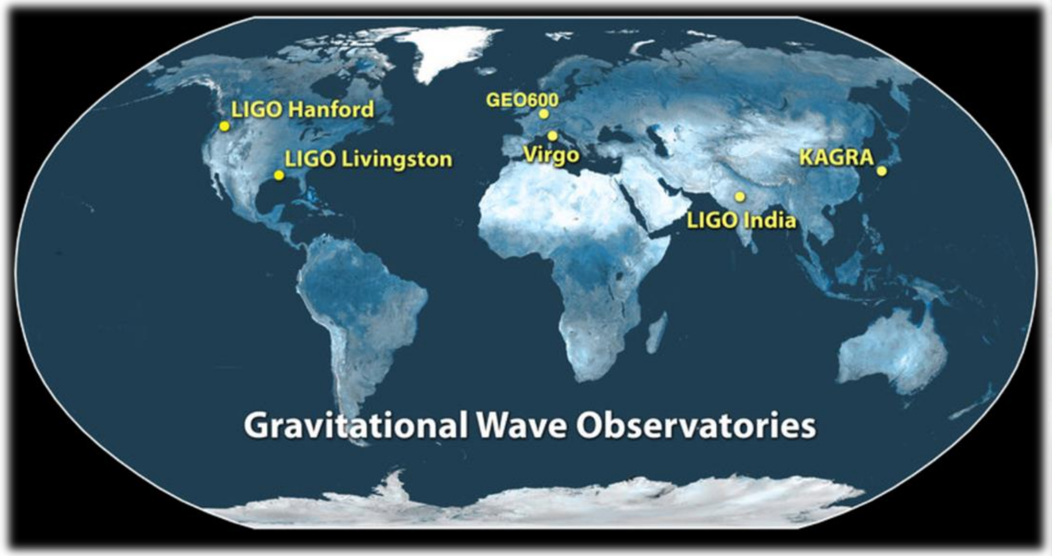


Sources and signals



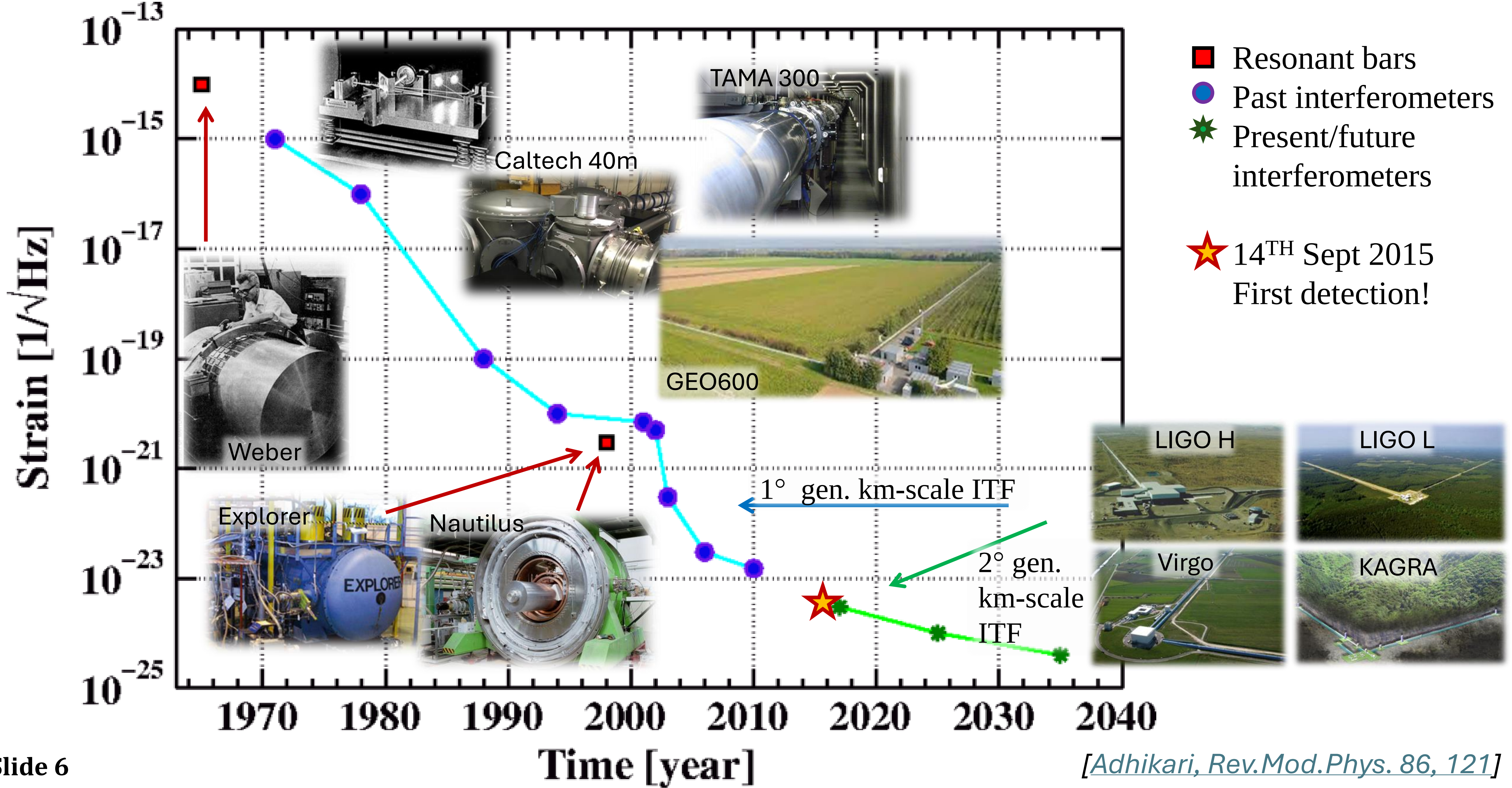
Gravitational-wave detectors network





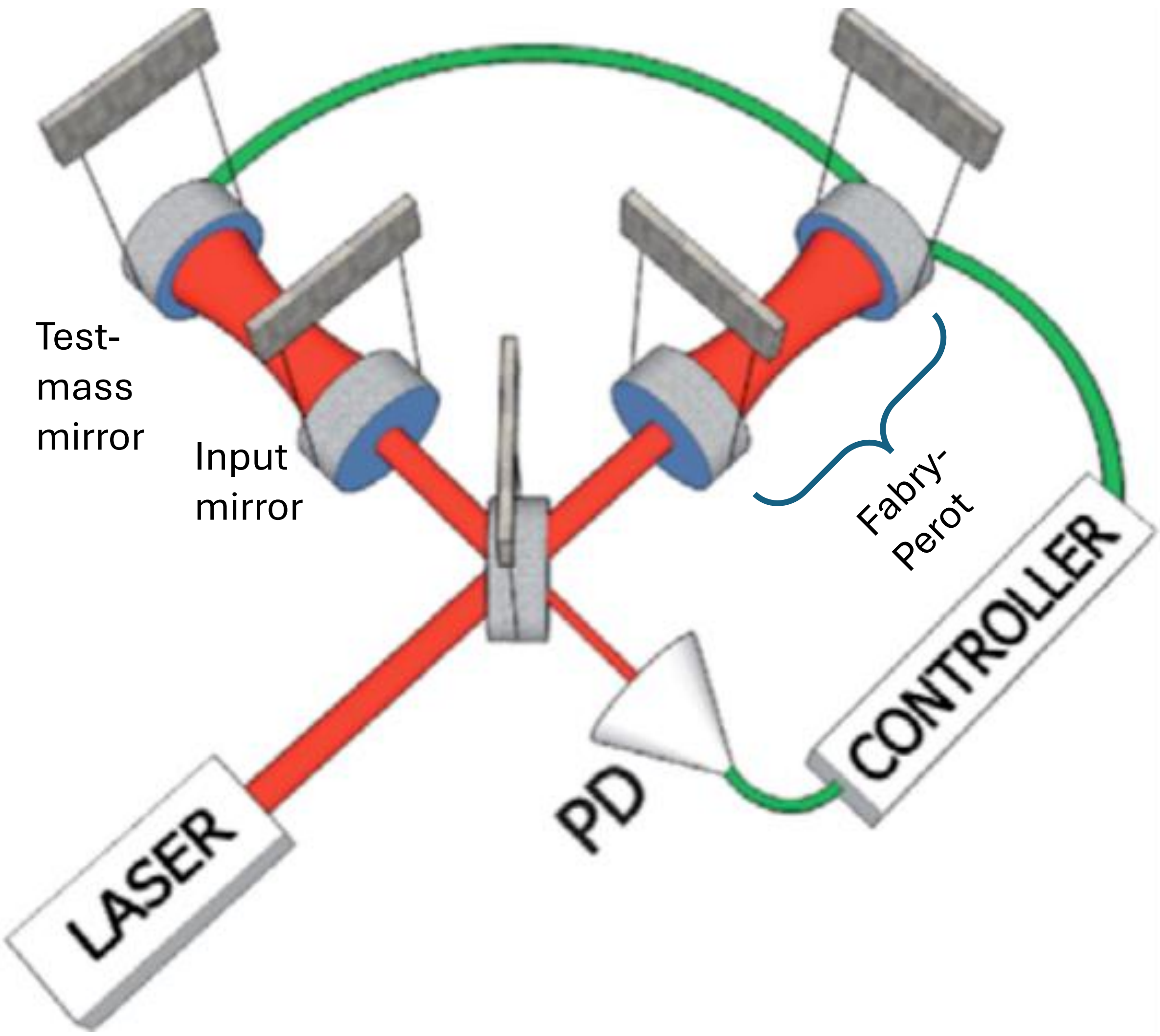
- Three runs concluded in the Advanced configuration so far (O1-O3).
- Run O4 started on May 2023, currently ongoing.

The long journey of the hunt for gravitational waves

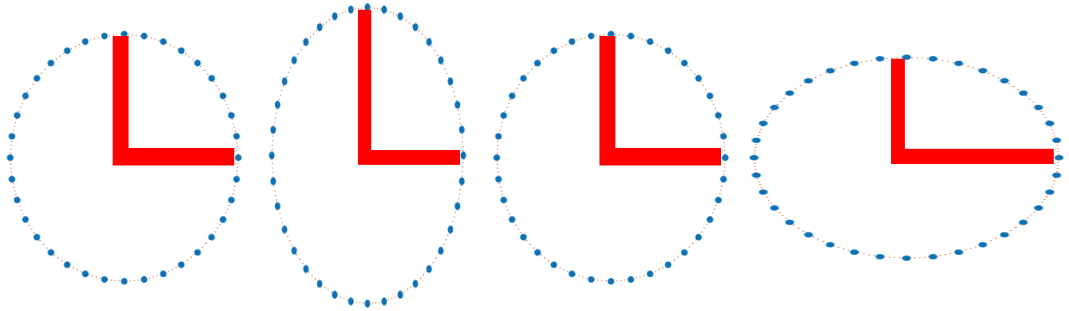


[Adhikari, Rev.Mod.Phys. 86, 121]

Gravitational-wave detectors basics



- Basic layout: suspended Michelson interferometers with Fabry-Perot cavities as arms.
- GW effect: deformation of the interferometer arms.



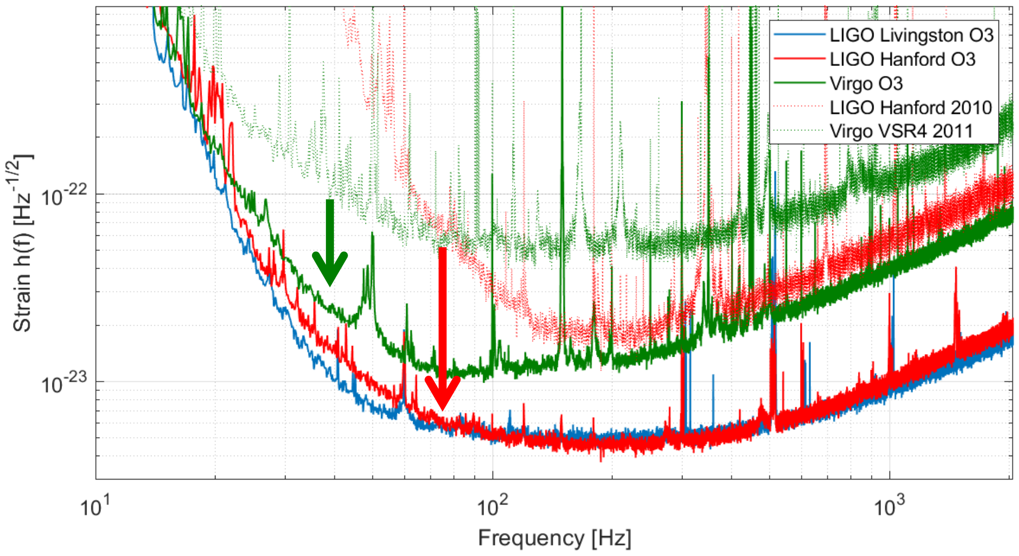
- From the output laser power, we measure the phase difference between two recombined laser beams.
- $\rightarrow h(t)$ time series.

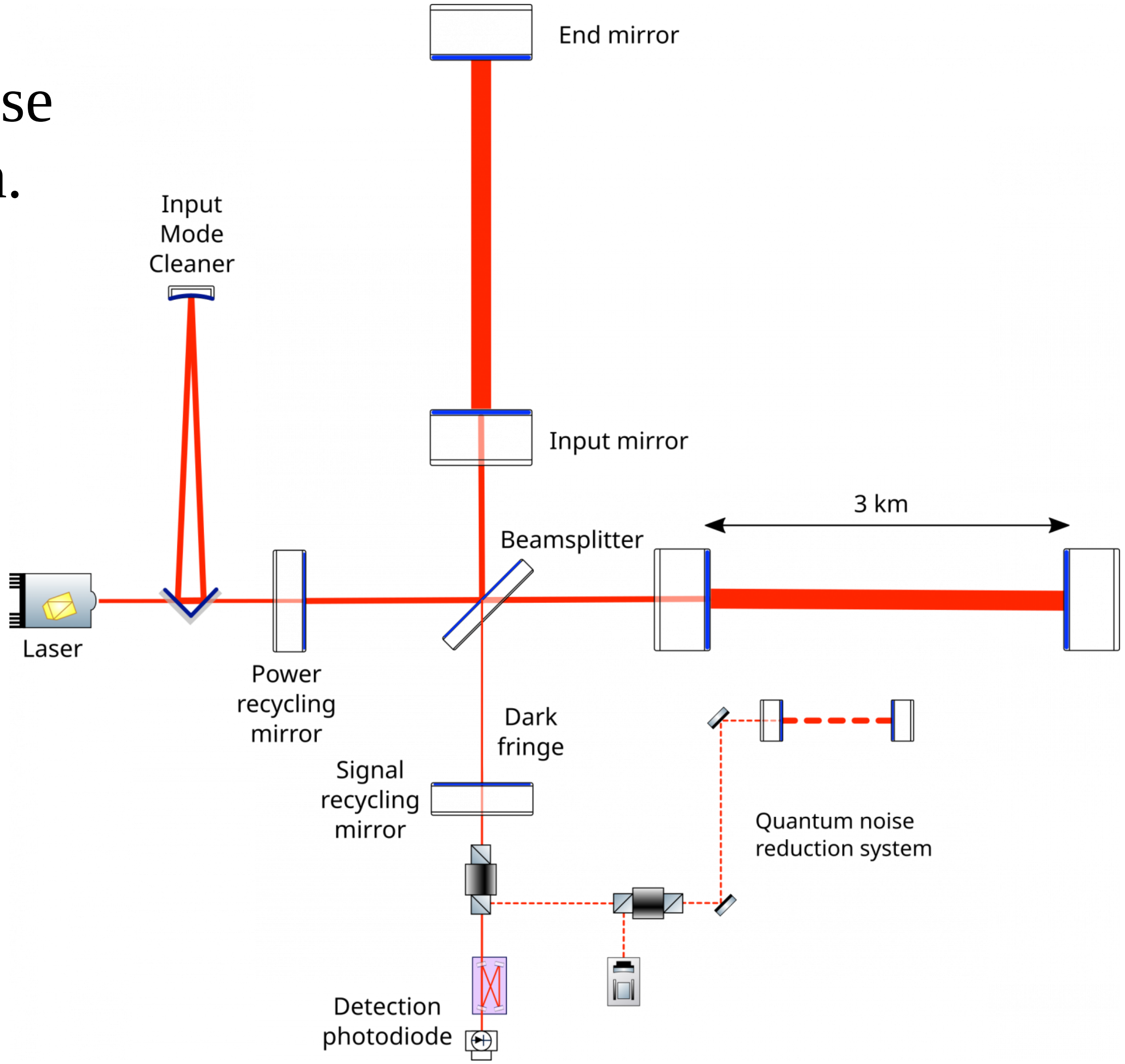
The jump from 1st to 2nd generation

- Monolithic silica suspensions.
- Dual recycling: two additional cavities to increase the circulating power and enlarge the bandwidth.
- High-power optomechanics.
- Squeezing techniques to beat quantum noise.
- ⋮ (etc)

➢ Sensitivity jump by one order of magnitude.

  ➢ First GW detection!

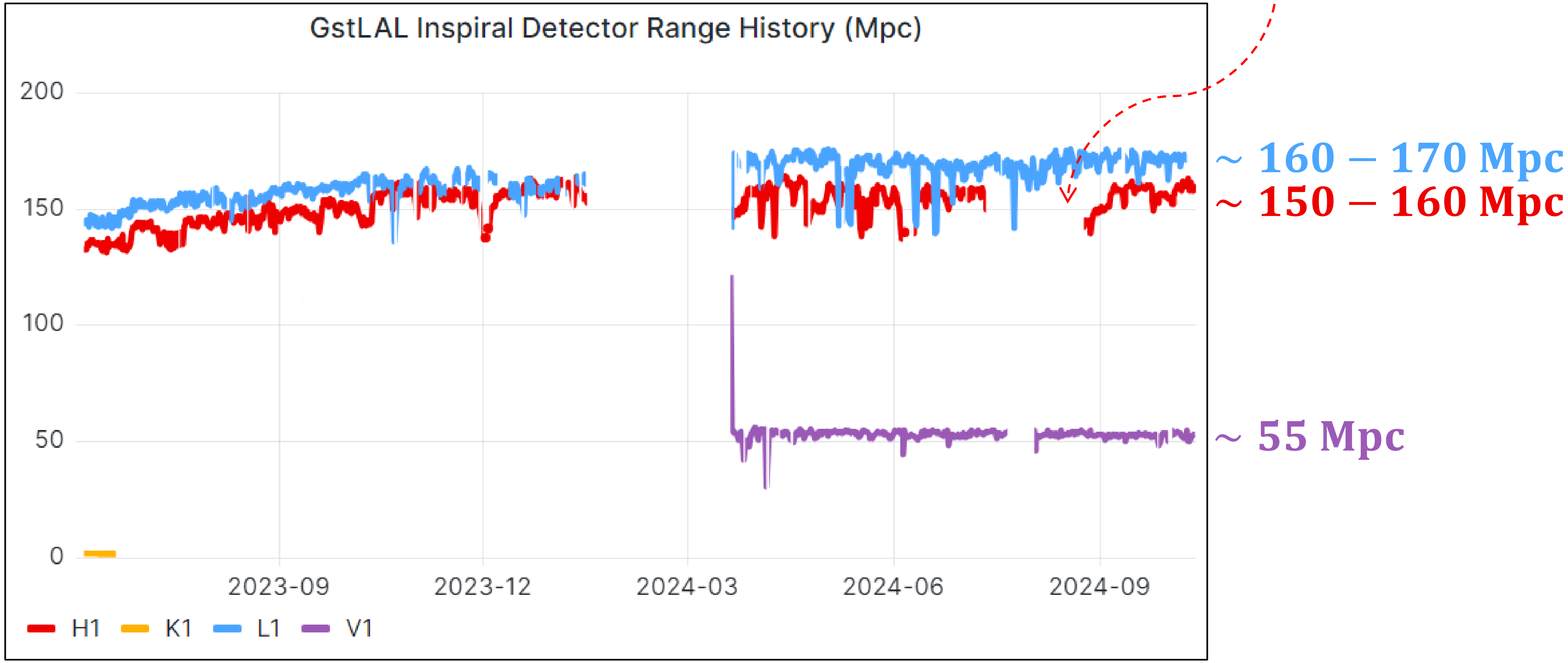




STATUS
OF VIRGO

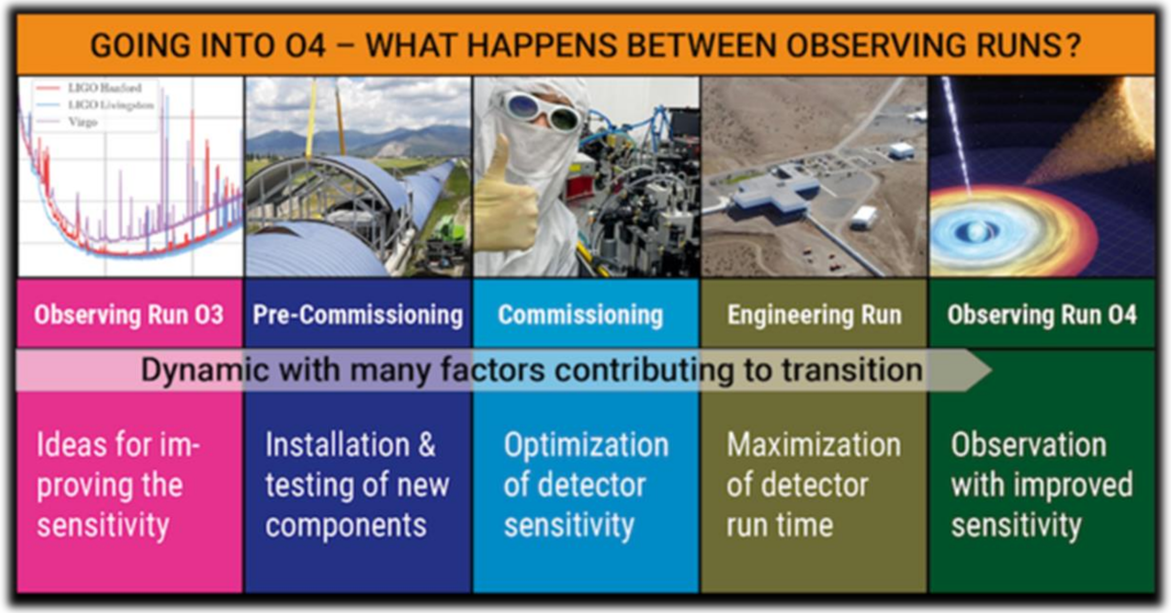
The current observing run: O4

- First part (O4a) from May 2023 to Jan 2024
  - Joint observation of LIGO H + L (+ KAGRA the first 4 weeks) → 53% HL uptime
- Second part (O4b) from Apr 2024 to Jun 2025
  - Virgo joined the run (+ KAGRA at the end) → 45% HLV uptime (excluding breaks)



Virgo joining O4

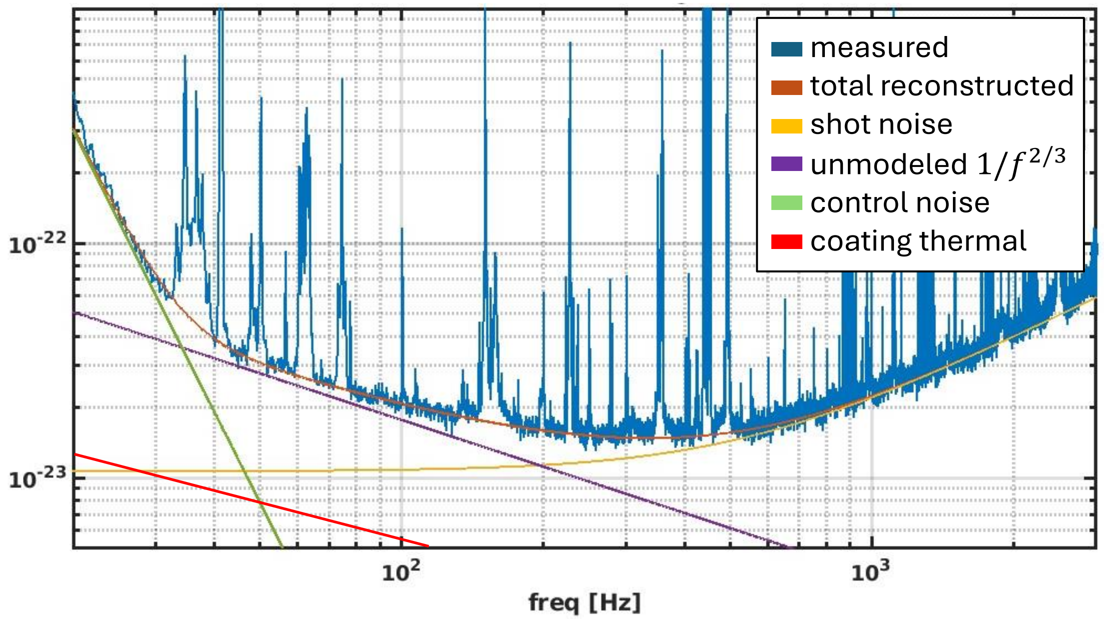
- Long and troublesome commissioning.
- Virgo joined O4 in April 2024, at the beginning of the second phase (O4b).
- Sensitivity in terms of Binary Neutron Star (BNS) range: 55 Mpc (comparable with the one in O3)

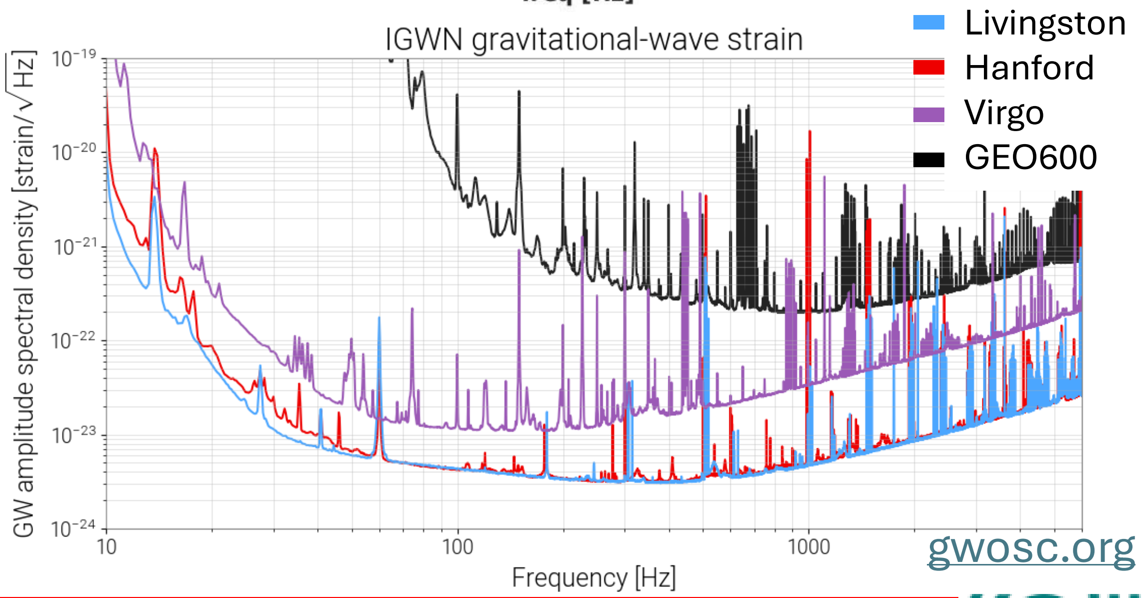


- Two main issues:
  - In Virgo the recycling cavities are in a marginally stable configuration, making the detector very sensitive to aberrations and thermal effects.
    This negatively impacts the controllability of the interferometer, ant thus the commissioning complexity and schedule.
    Injected input power limited to 18W (planned 40W).
  - The presence of an unmodeled noise in the bucket, which limits the sensitivity.

The noise budget in Virgo

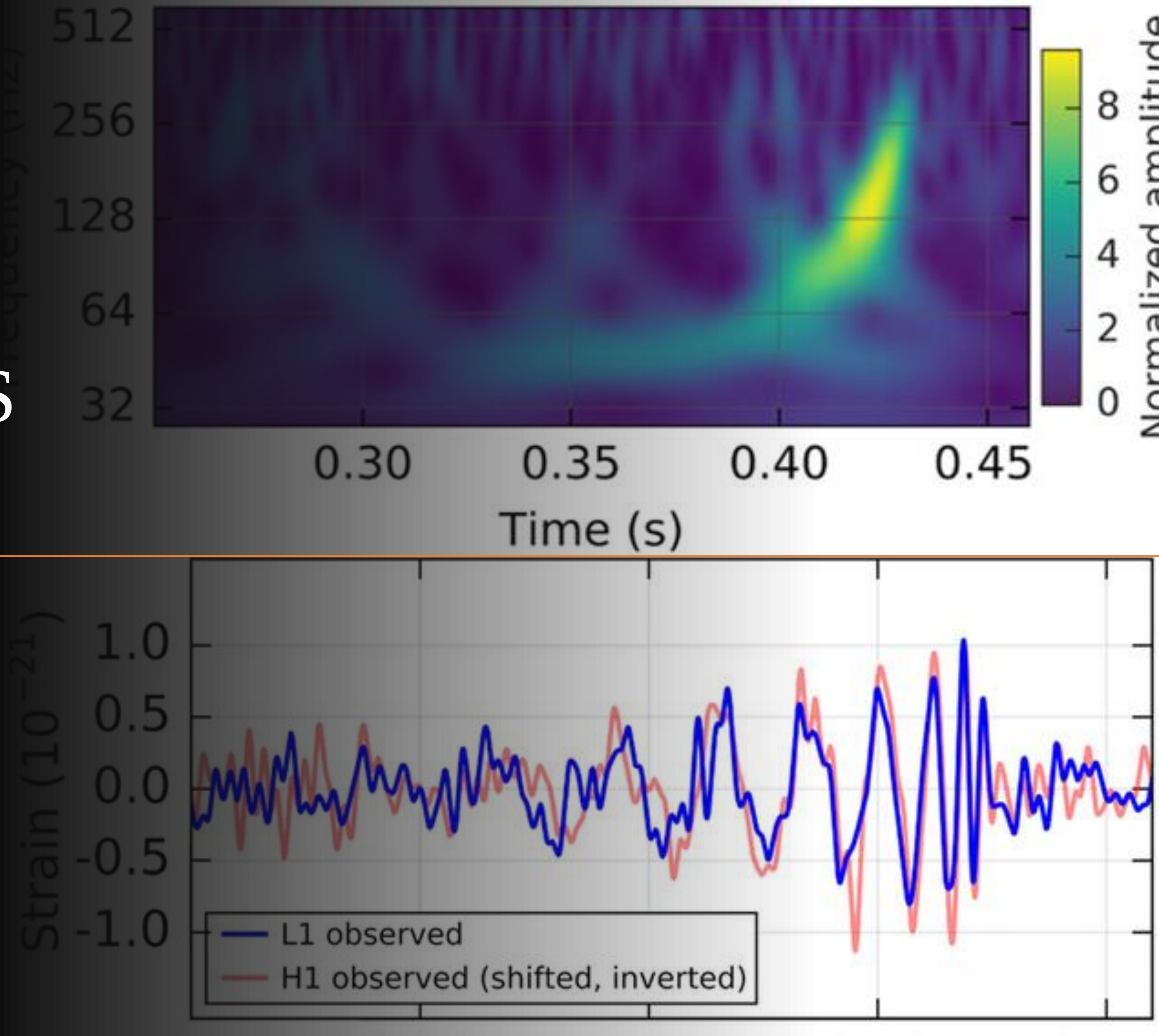
1) Low frequencies:
   - Noise from local controls dominates over fundamental noises (quantum radiation pressure, seismic noise..)
2) Mid frequencies:
   - An unmodeled noise, not yet understood, dominates over fundamental noises (thermal noise of mirrors coating, optical quantum noise).
     Costs ~ **15 Mpc** in terms of BNS range.
     Intense and continuous effort to identify the source and mitigate it.
3) High frequencies:
   - Quantum shot noise.





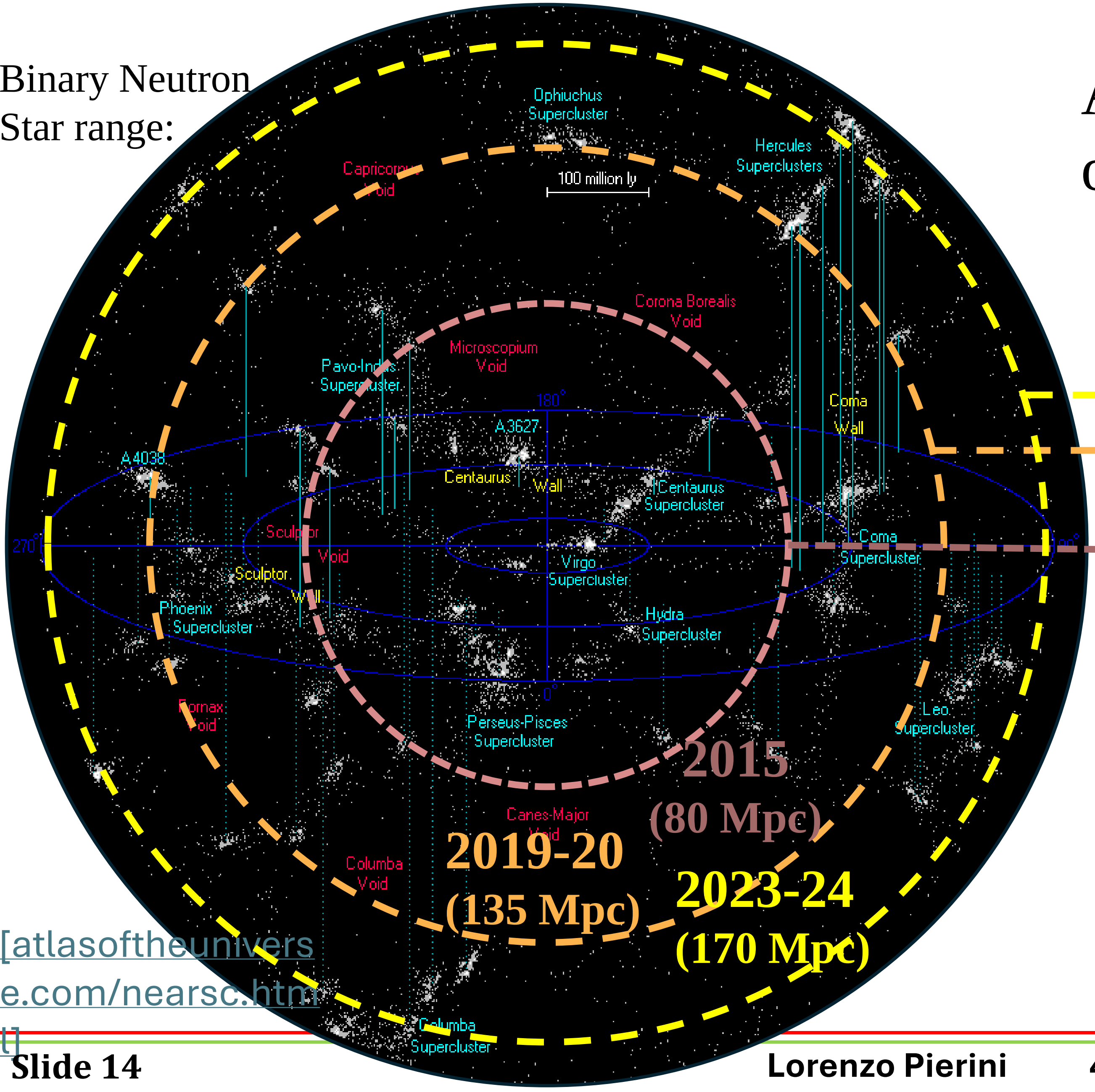
gwosc.org

OBSERVATIONS DURING O4



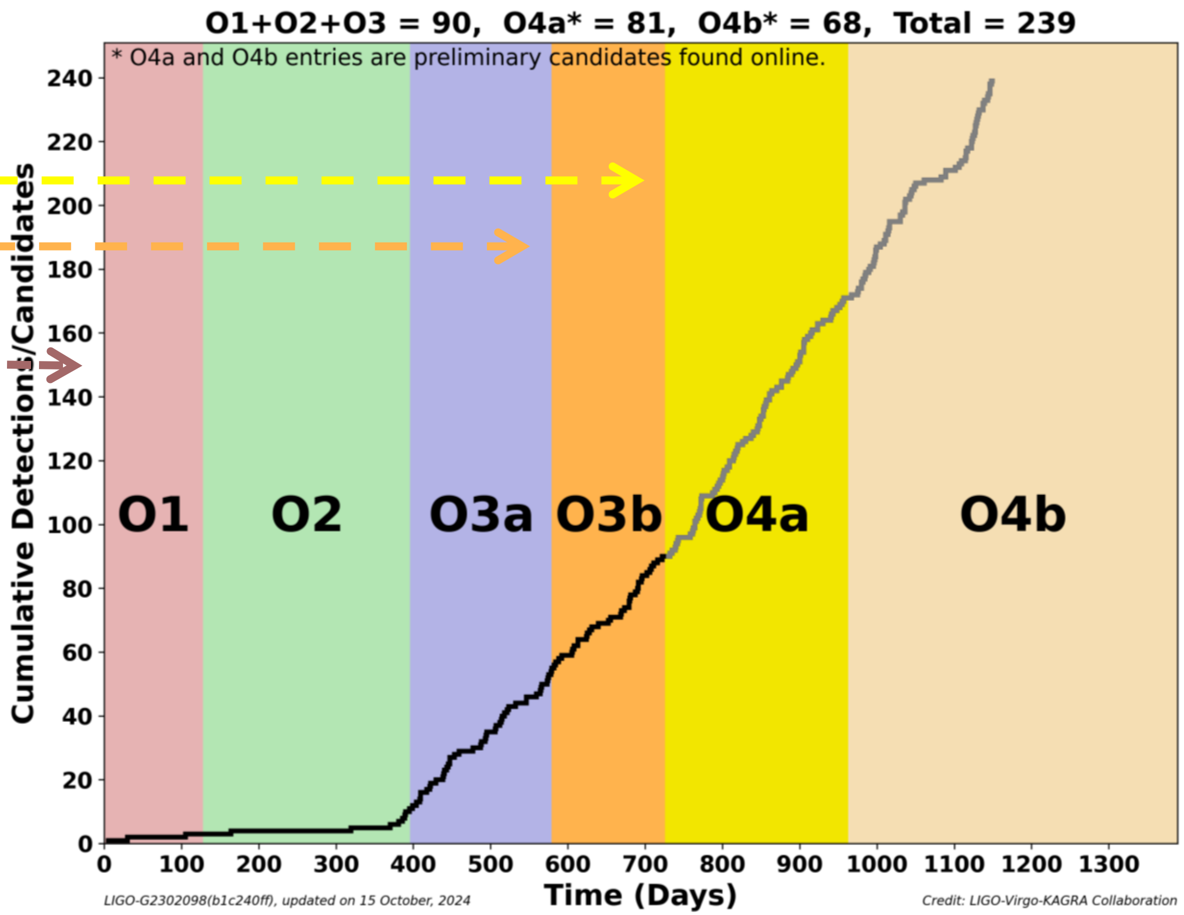
The rate of detections is continuously growing

Binary Neutron Star range:

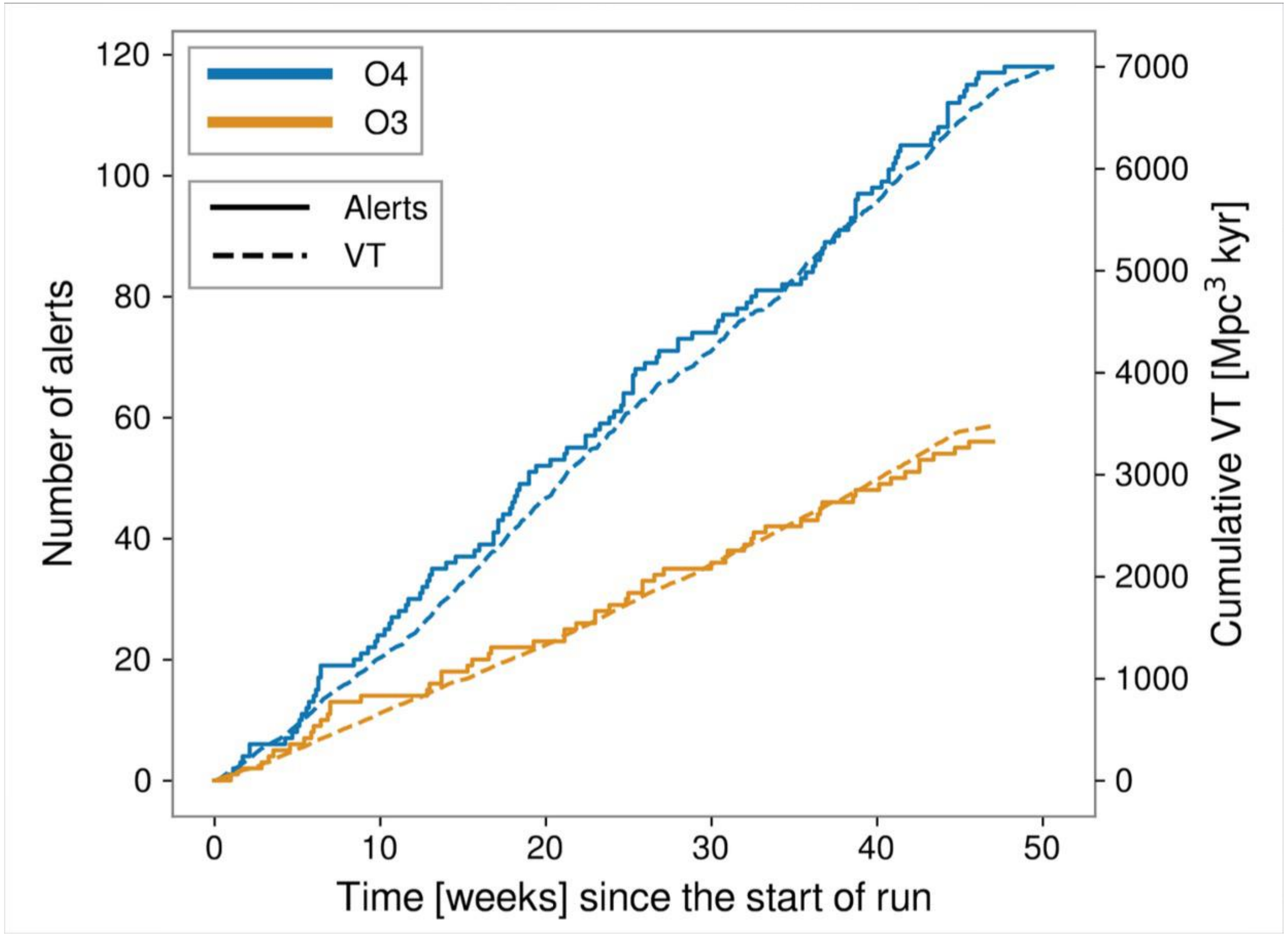


[atlasoftheuniverse.com/nearsc.html]

As the sensitivity increases, the volume of inspected universe scales as r^3



The improvement with respect to O3



We are currently observing twice as much of the universe as in O3.

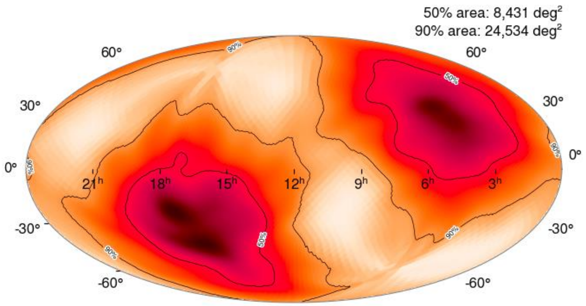
$$\left.\frac{O4}{O3}\right|_{range} \sim 1.25 \qquad \left.\frac{O4}{O3}\right|_{vol} \sim 2$$

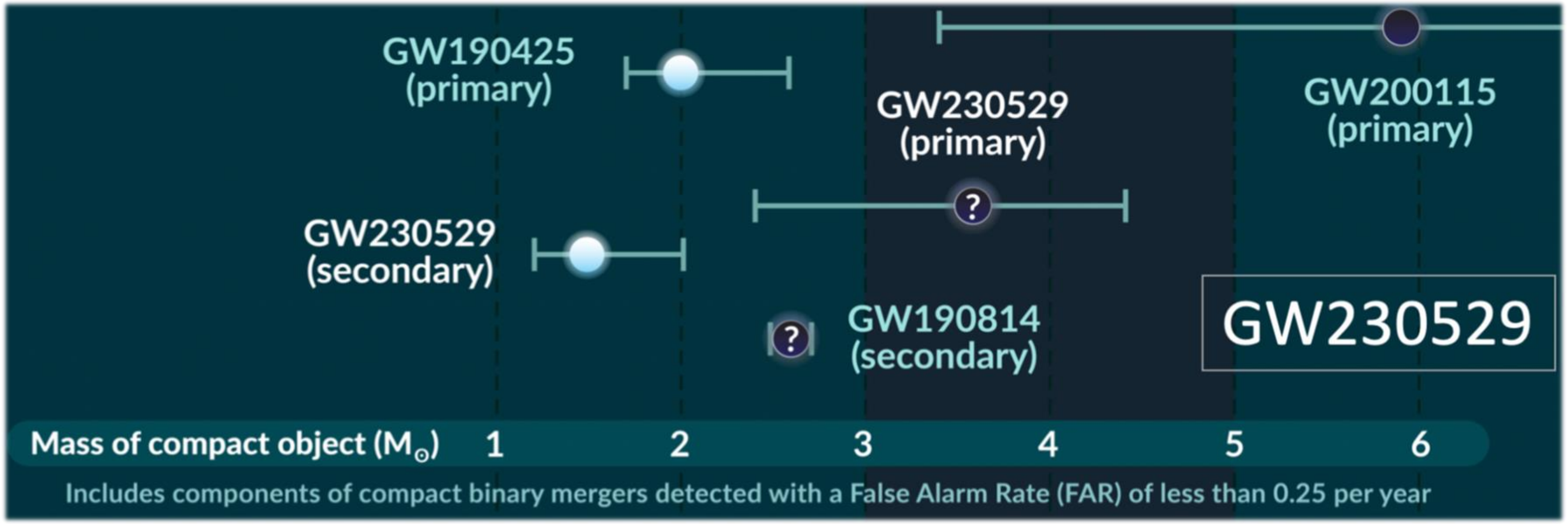
- 79 confirmed detections in O3. (11 months)
- 81 significant candidates in O4a. (9 months)
- 68 significant candidates in O4b. (8 months, in progress)

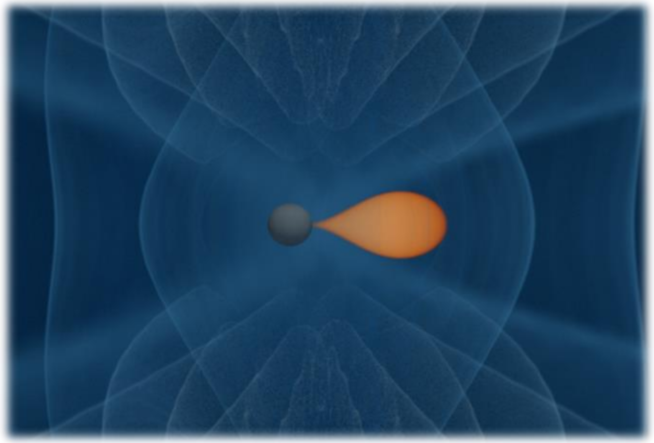
GW230529 - Filling the mass gap

- During O4a: detected GW from the coalescence of a neutron star with a mass-gap compact object (most likely a black hole).
- Poor sky localization, no electromagnetic counterpart.
- GW230529 provides best evidence of compact objects existing in the lower mass gap: how did it form?
  - ➢ Incomplete understanding of core collapse in massive stars.
  - ➢ Possible outcome of a hierarchical merger of a triple system?

$m_1/M_\odot$	$3.6^{+0.8}_{-1.2}$
$m_2/M_\odot$	$1.4^{+0.6}_{-0.2}$
D_L/Mpc	201^{+102}_{-96}





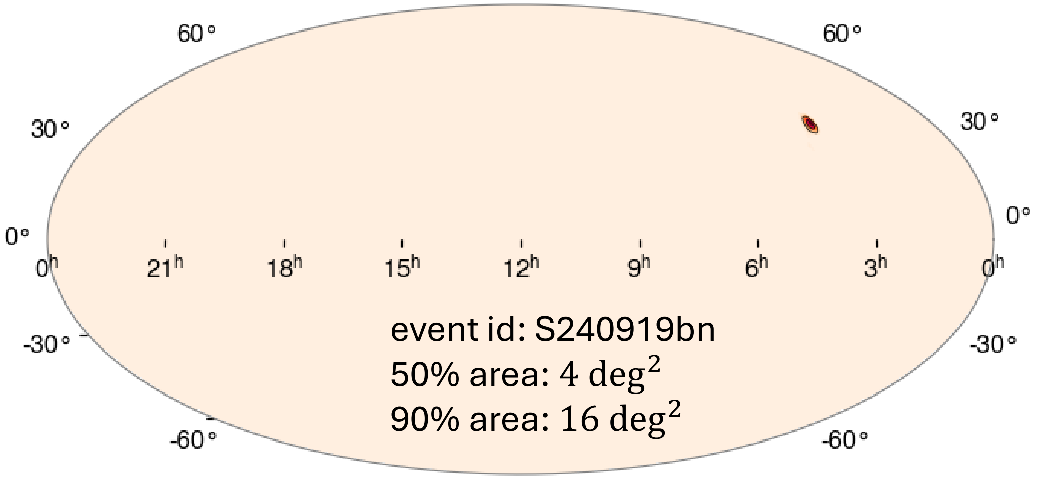


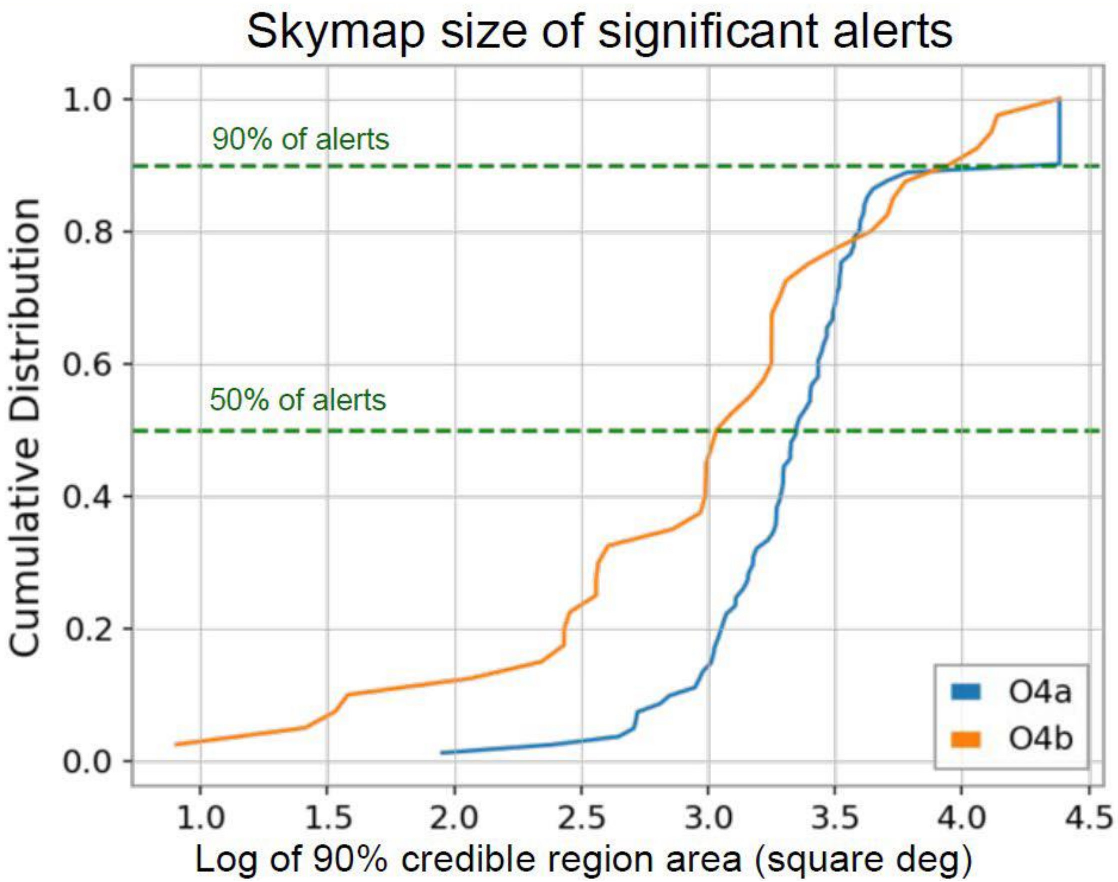
[Abac et al 2024 ApJL **970** L34]

Impact of Virgo in O4b

- The two LIGO detectors are running at 150-170 Mpc, with 60-75% duty cycle.
- Virgo is running at 50-55 Mpc, with 80% duty cycle.
  Virgo downtimes are synchronized with LIGO to maximize triple-detector time.

- Great impact on the sky localization of GW events: multimessenger astronomy is possible!





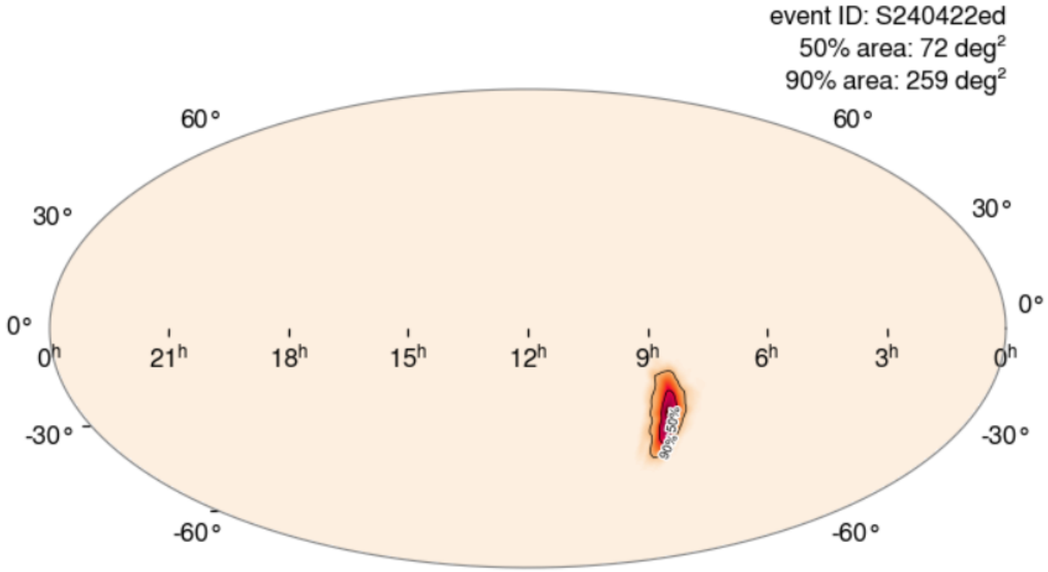
[Credit: Mervyn Chan, UBC]

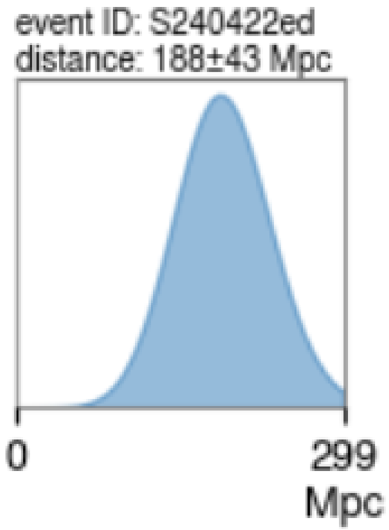
How is O4b going?

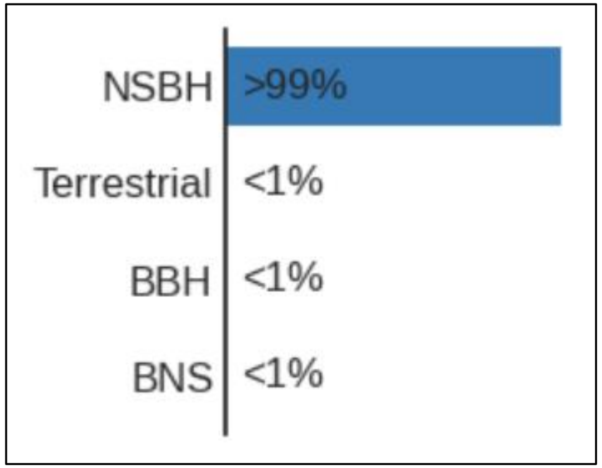
68 significant candidates up to 22/10/2024

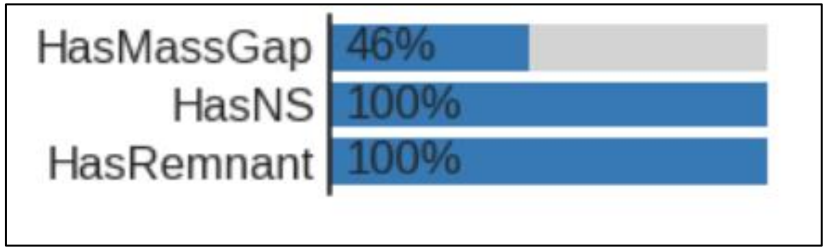
- They are mostly BBH events.
- 4 candidates have weak probability (10-30%) to be NSBH.
- 1 strong candidate NSBH: **S240422ed**
  Observed by both LIGO H,L and Virgo

  https://gracedb.ligo.org/superevents/S240422ed/view/



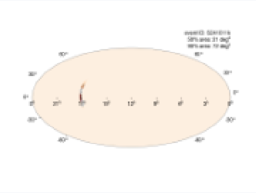
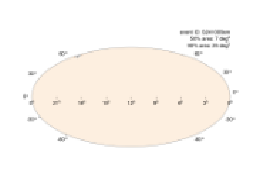
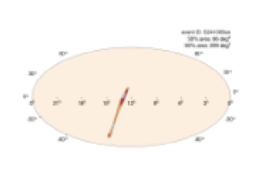
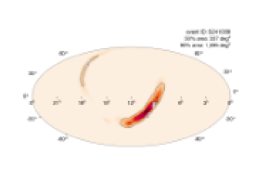




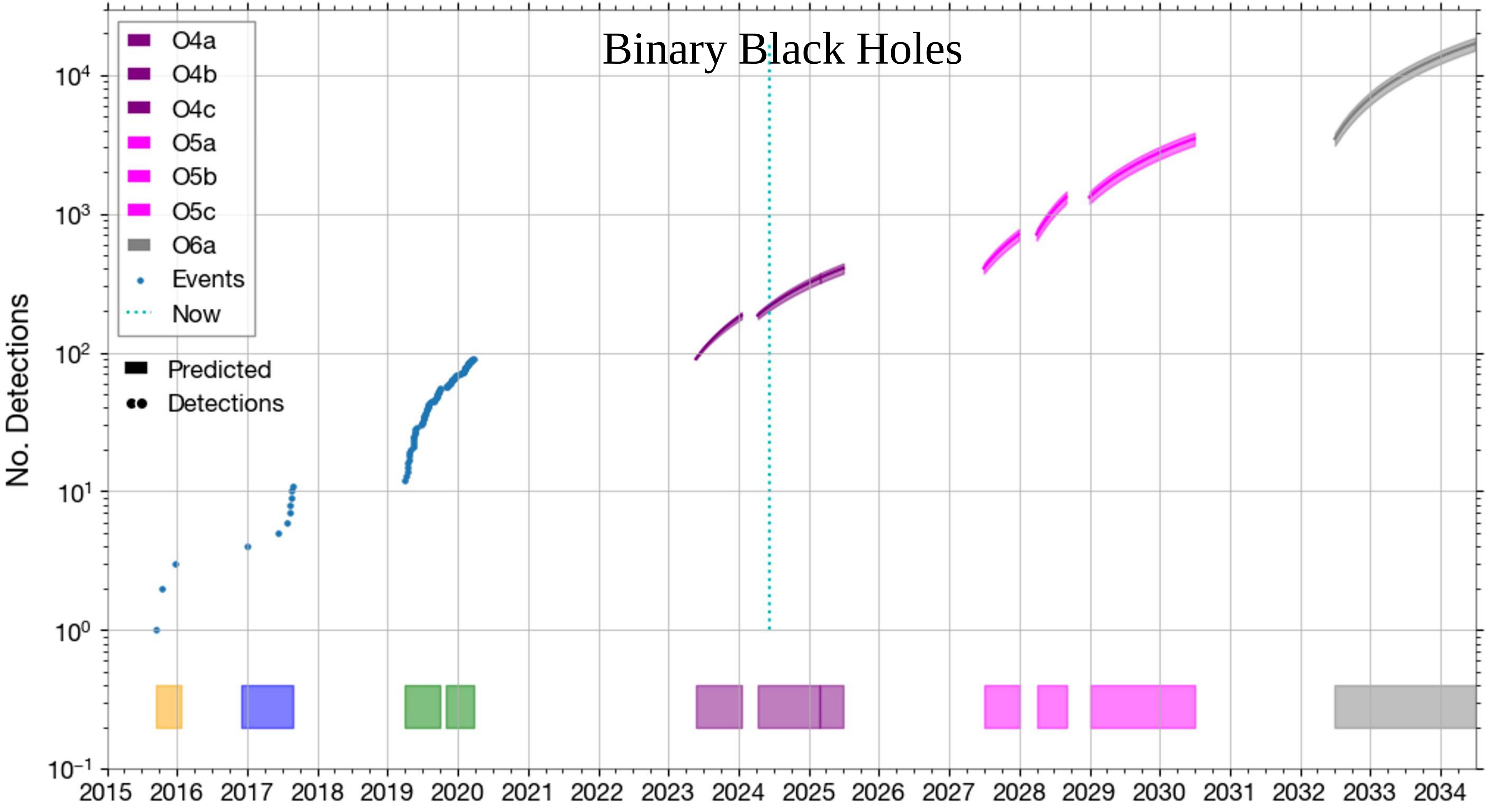


GraceDB: check yourself!

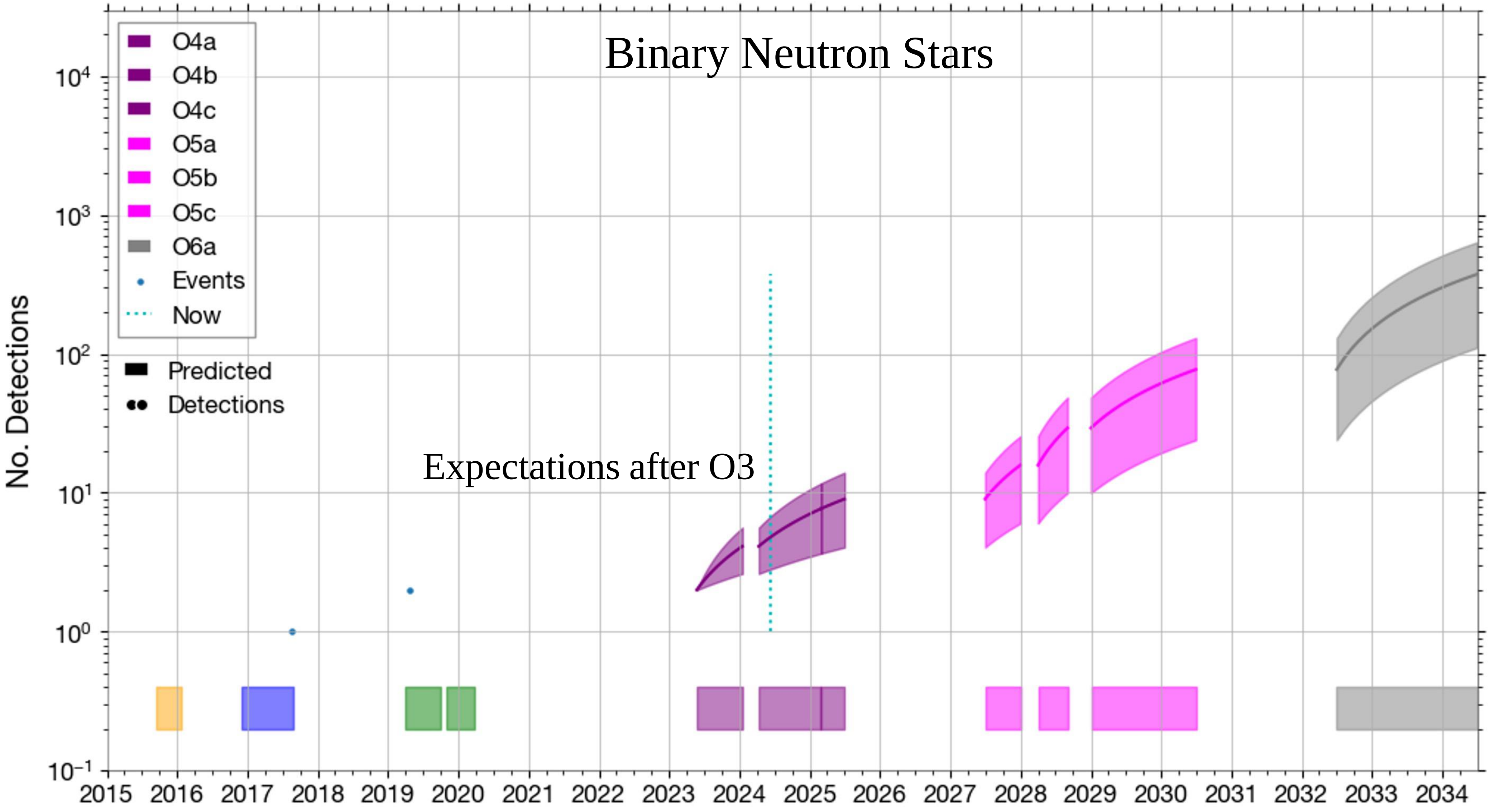
In the **Gra**vitational-Wave **C**andidate **E**vent **D**ata**b**ase (GraceDB) you can find all the GW candidates in real time, together with circulars, sky maps and so on. → **gracedb.ligo.org**

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S241011k	BBH (>99%)	Yes	Oct. 11, 2024 23:38:34 UTC	GCN Circular Query Notices | VOE		1 per 1.252e+26 years	
S241009em	BBH (>99%)	Yes	Oct. 9, 2024 22:04:55 UTC	GCN Circular Query Notices | VOE		1 per 11.246 years	
S241009an	BBH (>99%)	Yes	Oct. 9, 2024 08:48:16 UTC	GCN Circular Query Notices | VOE		1 per 16402 years	
S241009l	BBH (98%), Terrestrial (2%)	Yes	Oct. 9, 2024 02:28:35 UTC	GCN Circular Query Notices | VOE		1.0446 per year	

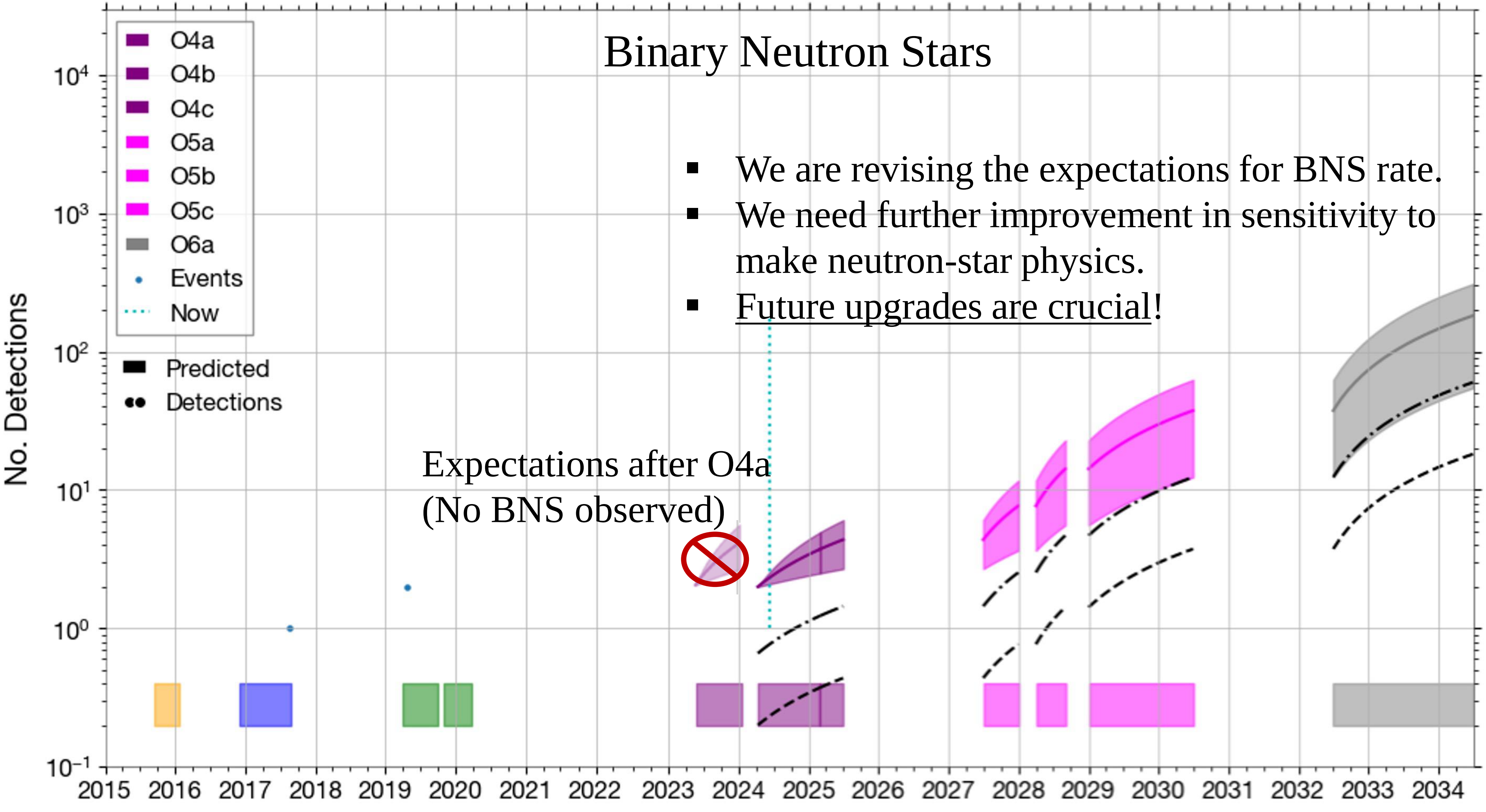
Sensitivity VS observing time



Sensitivity VS observing time



Sensitivity VS observing time

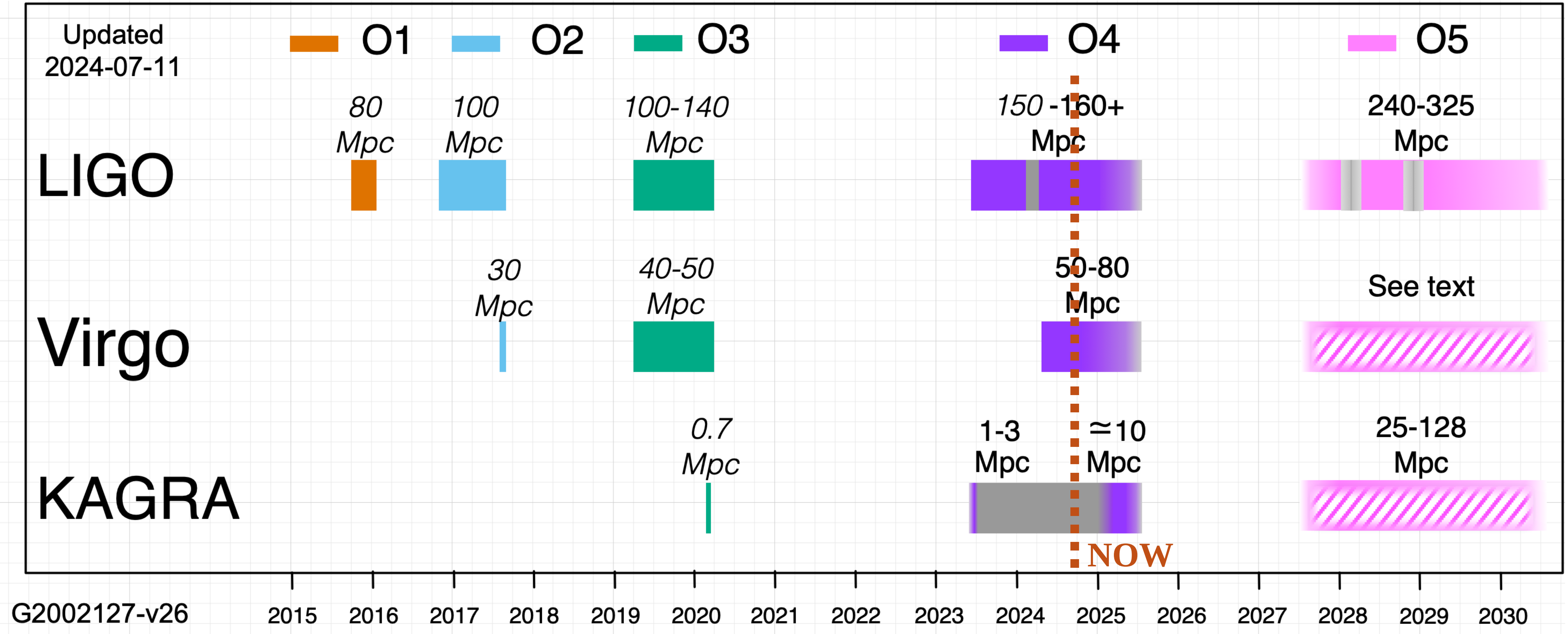


- We are revising the expectations for BNS rate.
- We need further improvement in sensitivity to make neutron-star physics.
- <u>Future upgrades are crucial</u>!

FUTURE PROSPECTS FOR VIRGO

The roadmap to O5

- O5 is planned to start during 2027. Planned duration: 3 years
- Quasi-continuous data flow at progressively better sensitivity.
- What to do after 2030?



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

The new plans for O5

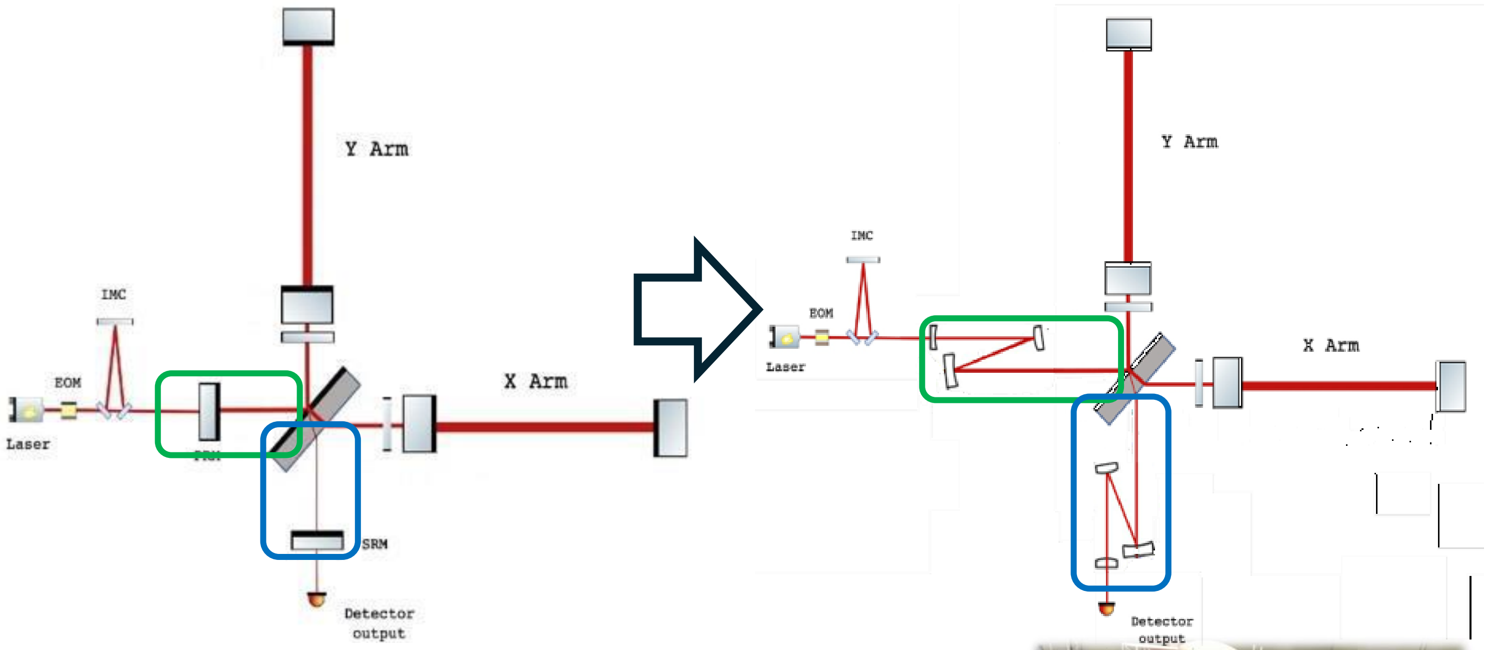
Original plans:

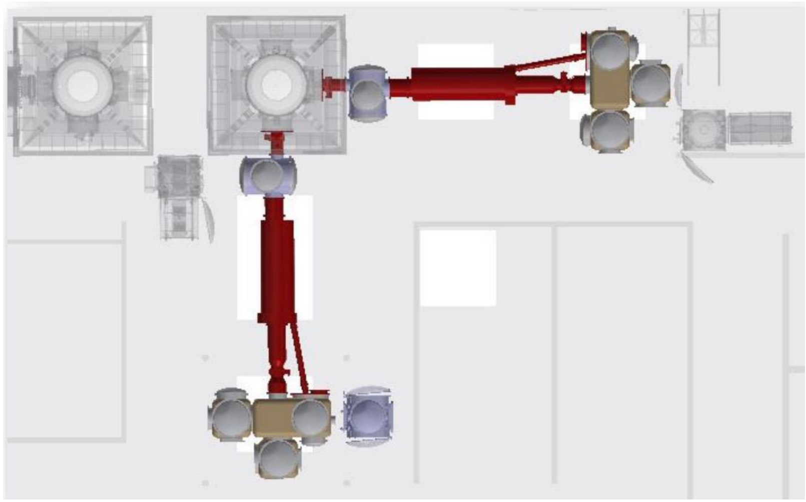
- Install heavier end test mirrors, enlarge the beam size.
- Better coatings.
- Increase input power up to 80W.

Hard/impossible with marginally stable cavities!

Current plan:

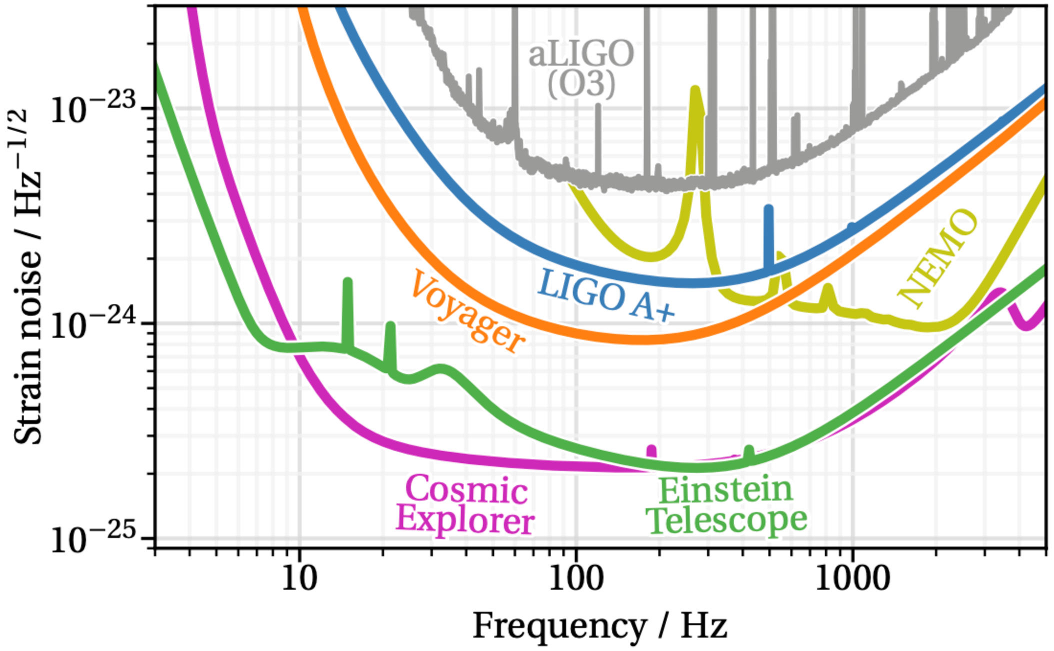
- PRIORITY: Install stable (folded) cavities, at the cost of a later start of O5. It implies the removal and substitution of some big vacuum chambers.
- Postpone the installation of heavier test mirrors at post-O5.

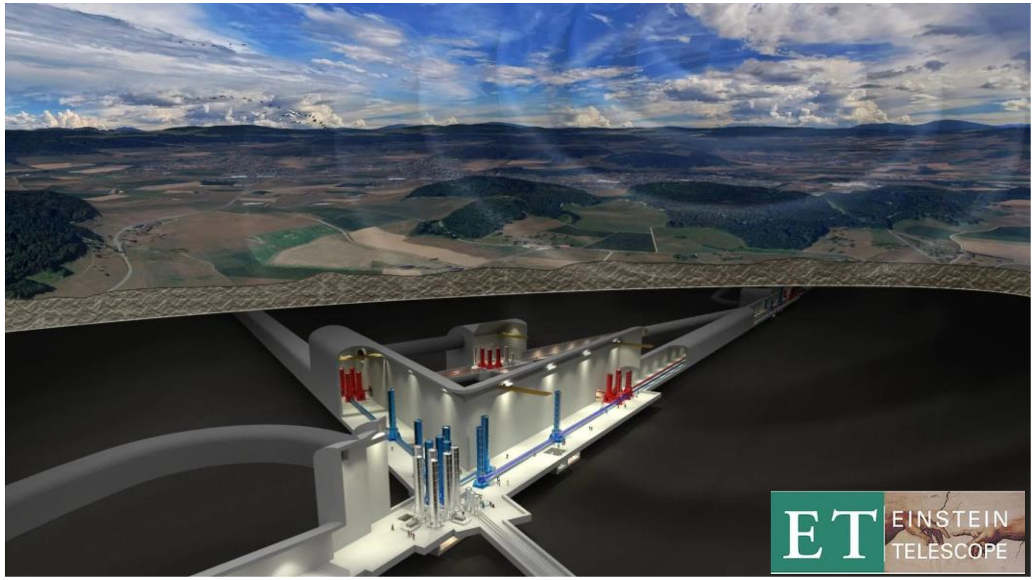




The future is 3G…

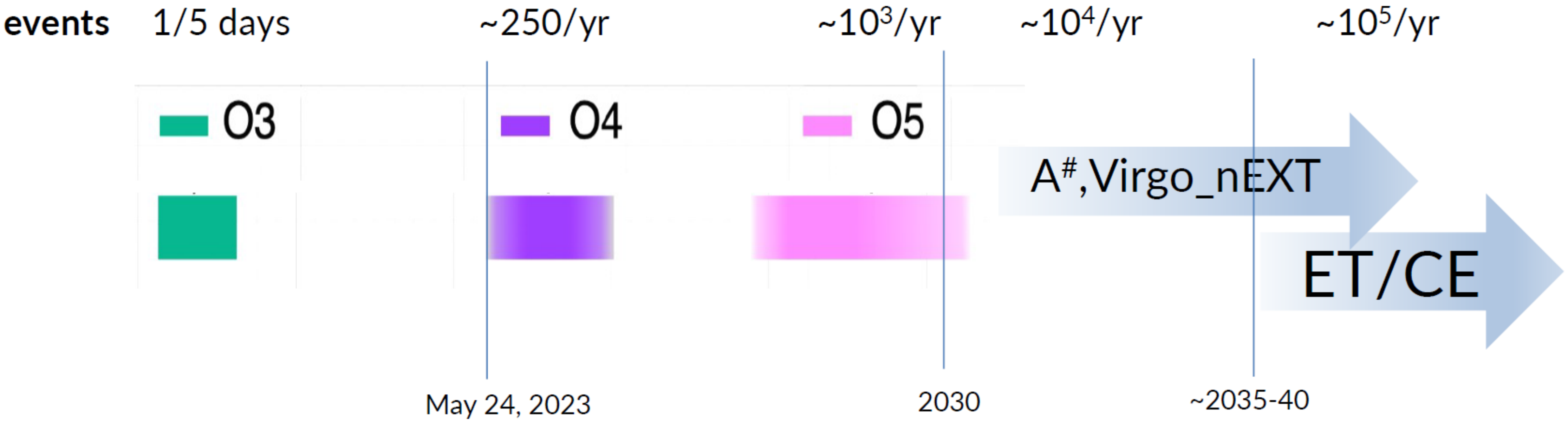
- Next generation 3G detectors: Einstein Telescope and Cosmic Explorer.
- Facilities to improve the sensitivity by one order of magnitude in full bandwidth.
- Extend the sensitivity down to few Hertz.
- Enlarge the observed universe up to the Dark Age, at z=100 redshift.





… but the future is far!

- 3G detector will not produce observational science before 2040.
- Many technological/engineering challenges must be overcome to move from 2G to 3G. The technological gap between 2G and 3G is highly risky!
- Need to extend the LIGO/Virgo/KAGRA scientific program until the advent of 3G.
- Keep the community together, allowing to form a new generation of experts.
  - Projects: A#, Virgo_nEXT.



Virgo_nEXT

- "Post-O5 study" committee set up in 01/21.
- Virgo_nEXT concept study released in 02/23.

- All design choices made within a Virgo-compatible framework:
  same infrastructure, same laser wavelength, room temperature mirrors.

Some foreseen upgrades:

- O(MW) intracavity power
- Enhanced squeezing
- Large test masses, better coatings
- NN subtraction
- Improved LF sensitivity

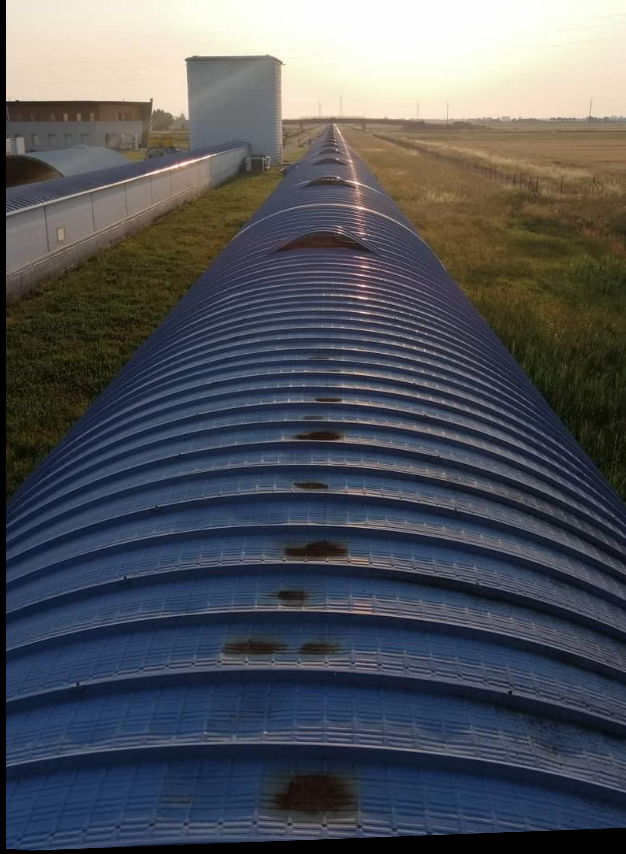
Baseline Design Report by June 2025.

	AdV+ best	V_nEXT best	ET HF
Power injected	125 W	277 W	500 W
Arm power	390 kW	1.5 MW	3 MW
FDS detected	6 dB	10 dB	10 dB
Mirror mass	42/105 kg	105 kg	200 kg
Beam radius	49/91 mm	91 mm	120 mm
Coating losses	5.4e-5	6e-6	1.25e-5
NN reduction	1/5	1/5	0-1/3

Conclusions

- Virgo joined O4 in April 2024 and is currently in data taking with LIGO detectors.
- O4 currently scheduled to end in June 2025.
- So far, LIGO/Virgo observations have shown that GW science has an enormous discovery potential both for fundamental physics, astrophysics and cosmology.
- However, the field is just in its early phase and in the next ~20 years the GW science will develop its full potential.
- Preparation of O5 and post-O5 longer-term plans (Virgo_nEXT) are ongoing.





THANK YOU FOR YOUR ATTENTION!

Acknowledgements (I)

- This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation, as well as work supported by the Italian Istituto Nazionale di Fisica Nucleare (INFN), the French Centre National de la Recherche Scientifique (CNRS) and the Netherlands Organization for Scientific Research (NWO) for the construction and operation of the Virgo detector and the creation and support of the EGO consortium.

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Centro Nazionale di Ricerca in HPC,
Big Data and Quantum Computing

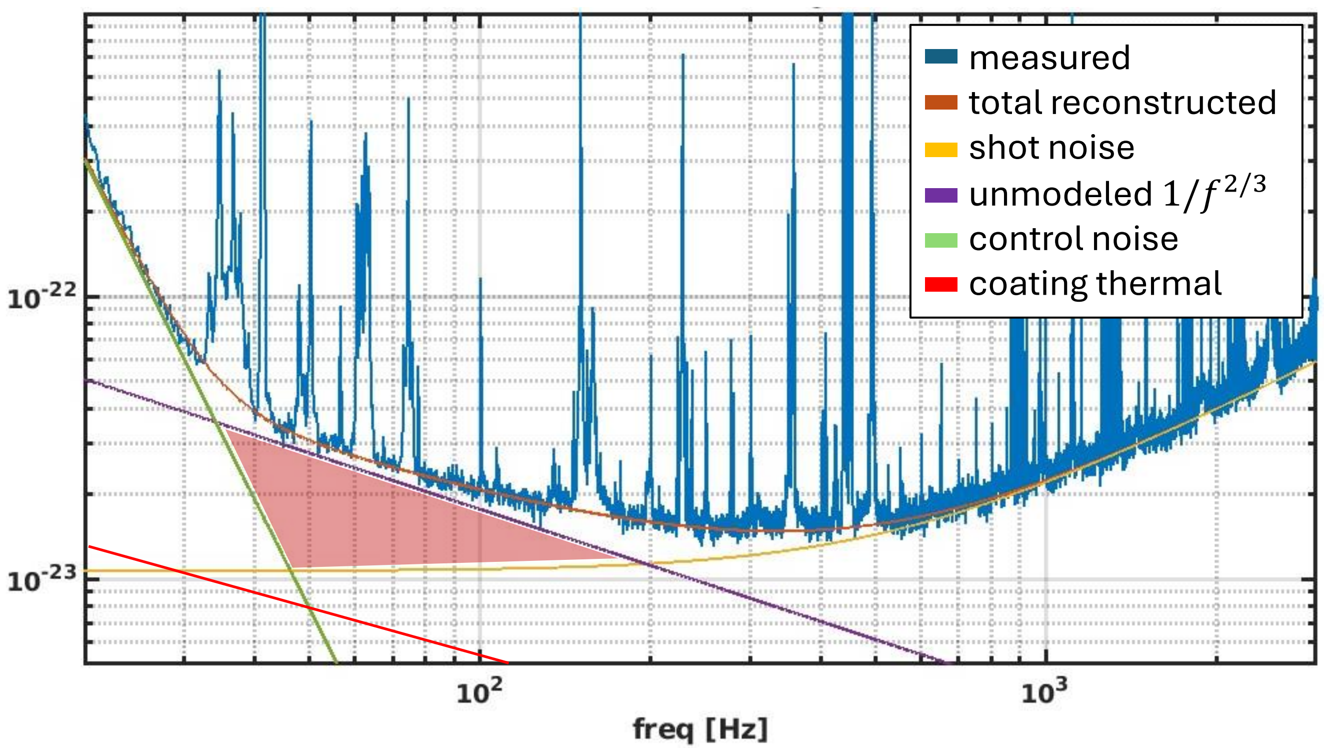
Acknowledgements (II)

This work is partially supported by ICSC – Centro Nazionale di Ricerca in High Performance Computing, Big Data and Quantum Computing, funded by European Union – NextGenerationEU

EXTRA SLIDES

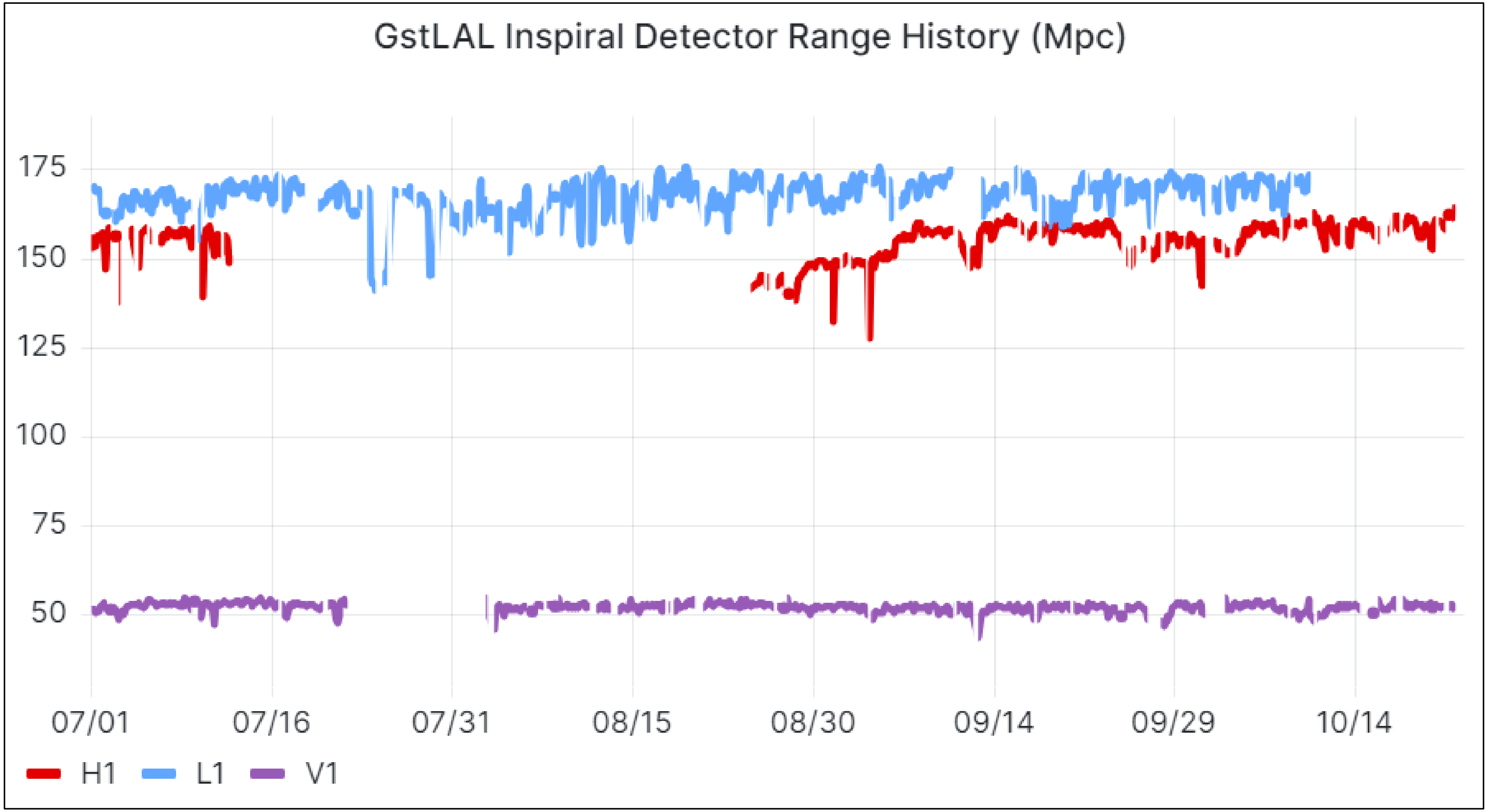
The excess noise in Virgo

- Virgo sensitivity in the bucket limited by a a noise not yet understood.
- Spectral dependence as $\propto \mathbf{1/f^{2/3}}$
- This noise is reducing the sensitivity by **15 Mpc** in terms of BNS range.
- Intense and continuous effort to identify the source and mitigate it.
- Dedicated task force in place.



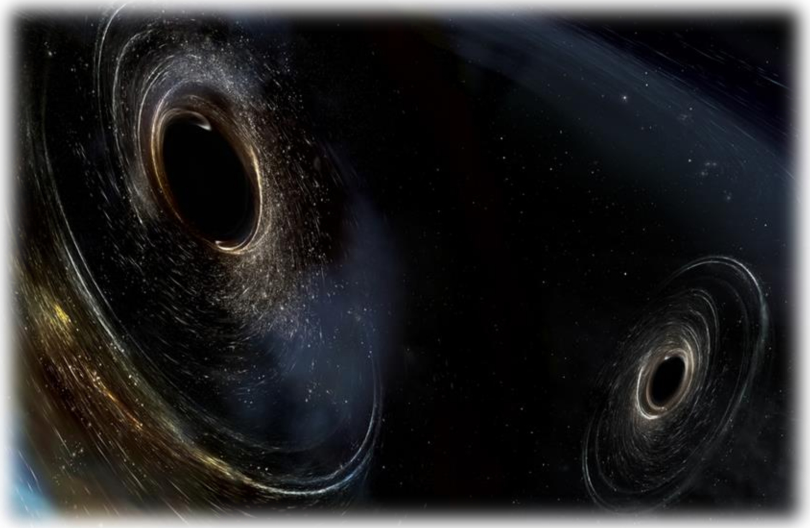
- It is a <u>noisy optical field</u>, scaling with the interferometer parameters.
- Excluded sources: displacement noise, frequency noise, electronic noise, quantum noise..
- Under investigation: polarization fluctuation noise, thermal noise in the compensation plates, non-dominant higher-order modes, alignment fluctuations..

The last troublesome months

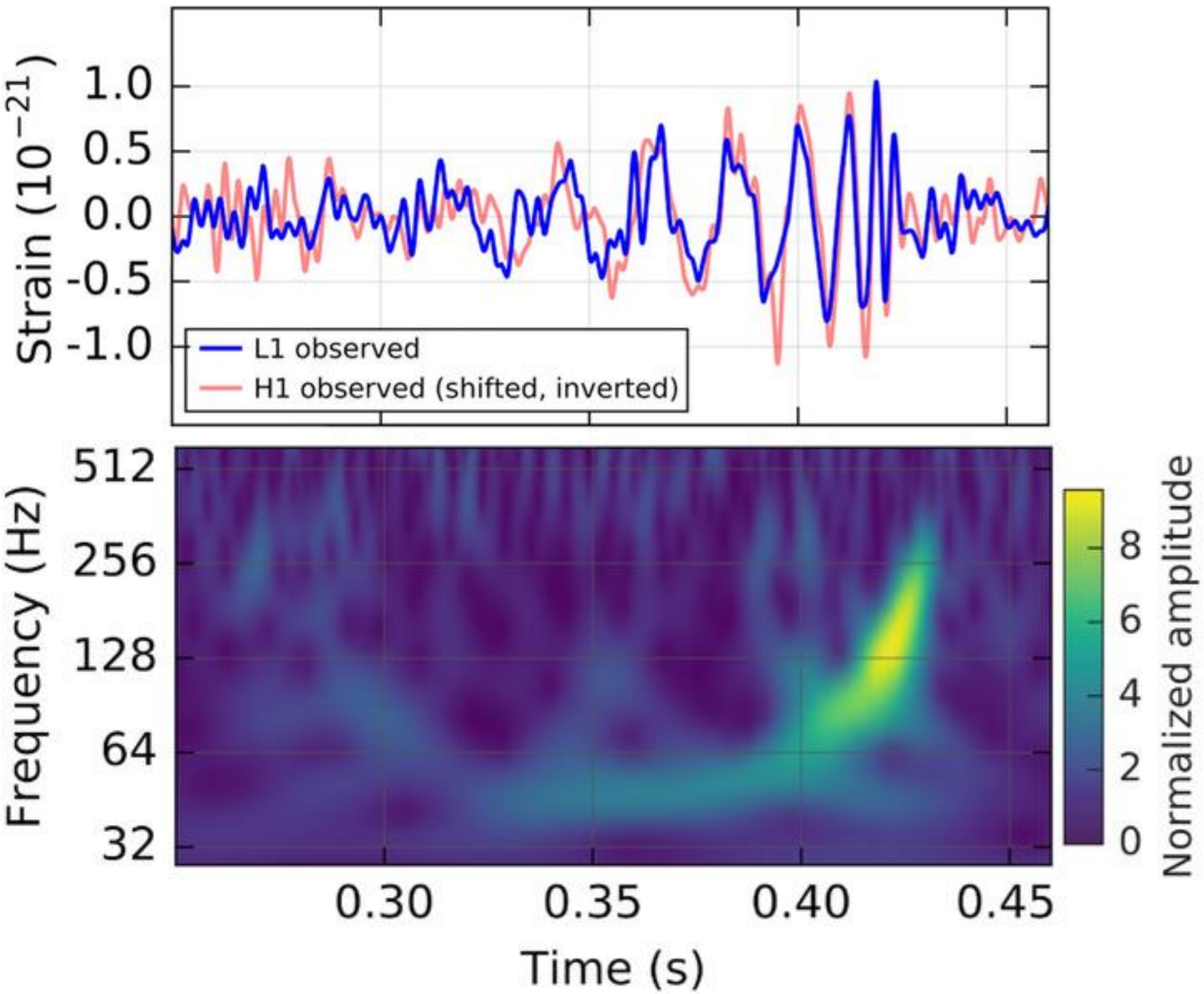


The first GW detection

14th September 2015



- Coalescence of two black holes.
- Pair masses: ~36 , 29 $M_\odot$.
- Luminosity distance: ~410 Mpc.
- Resulting black hole: ~62 $M_\odot$.
- Radiated energy in GWs: $\sim 3 M_\odot c^2$.

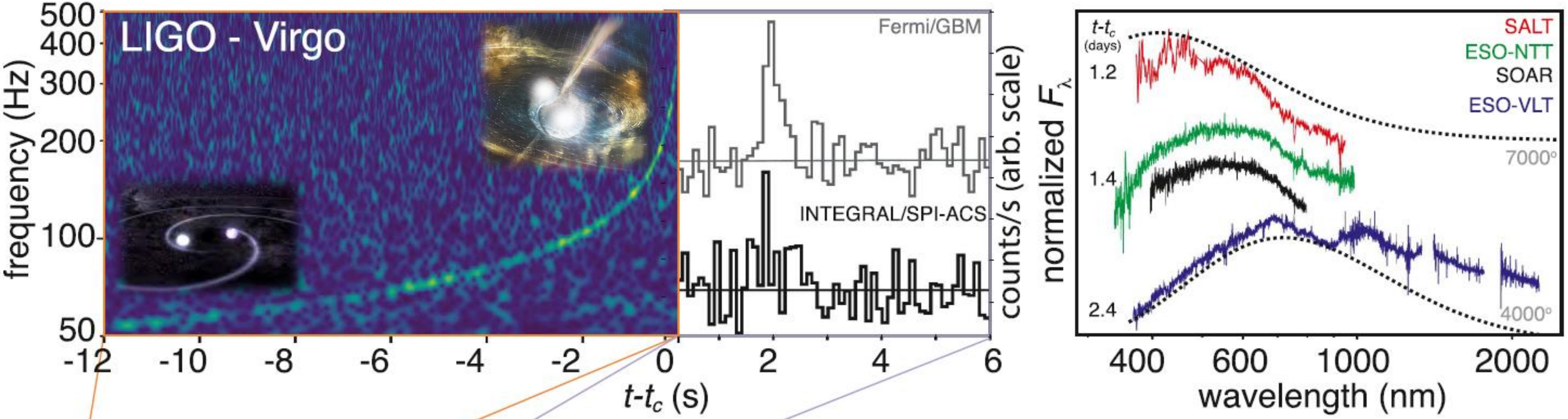


[Abbott *et al.* (2016) **PRL 116**, 061102]

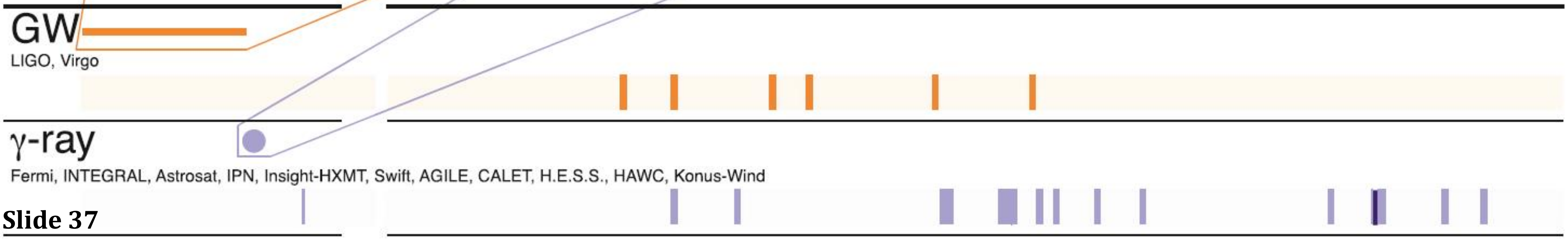
The beginning of multimessenger astronomy

17th August 2017

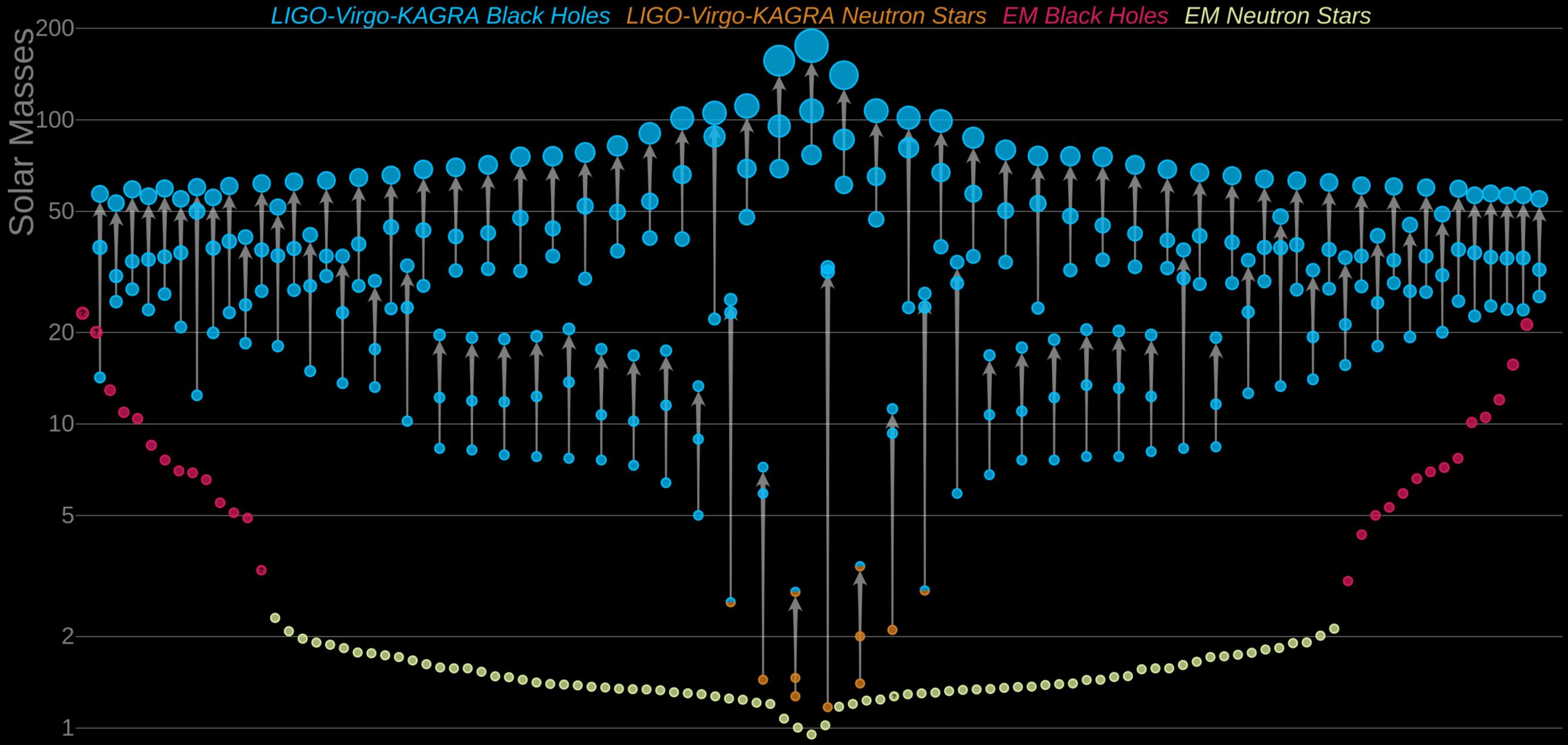
First coalescence of a binary neutron star system. Observed in all electromagnetic wavelengths.



[Abbott *et al*. (2017) **ApJL 848**, L12]



Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern