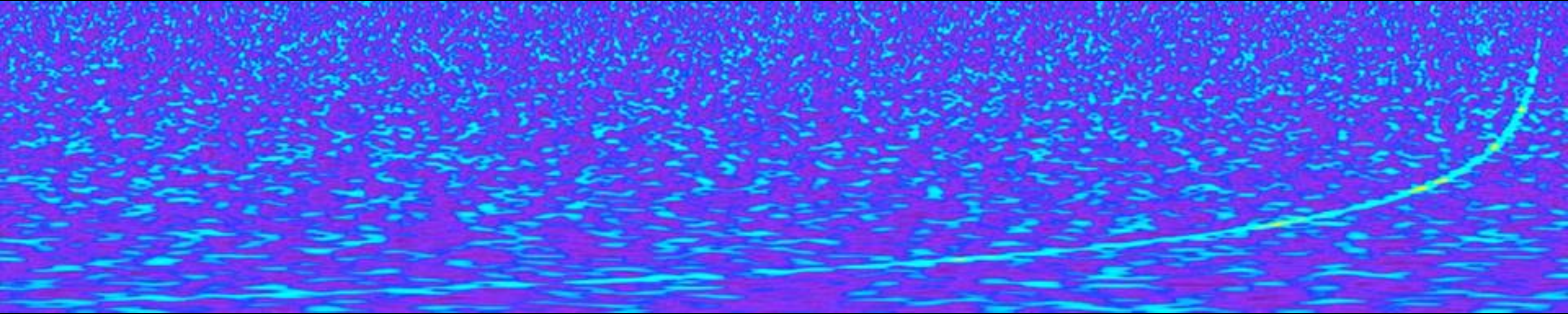


GROUND BASED GW DETECTORS

a review

Giovanni Losurdo – SNS & INFN

Presenting results of the
LIGO/Virgo/KAGRA and ET Collaborations

Drawing by Ilaria Nardecchia

10 YRS FROM GW150914

- LVK are preparing to celebrate 10 yrs from the monumental discover of GW
- A new window on the dark universe has been opened

Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

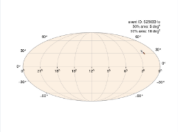
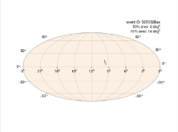
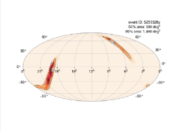
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4}M_\odot$ and $29^{+4}_{-4}M_\odot$, and the final black hole mass is $62^{+4}_{-4}M_\odot$, with $3.0^{+0.5}_{-0.5}M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102


LIGO Hanford
Virgo
KAGRA
LIGO Livingston
O4 OBSERVING RUN IN PROGRESS

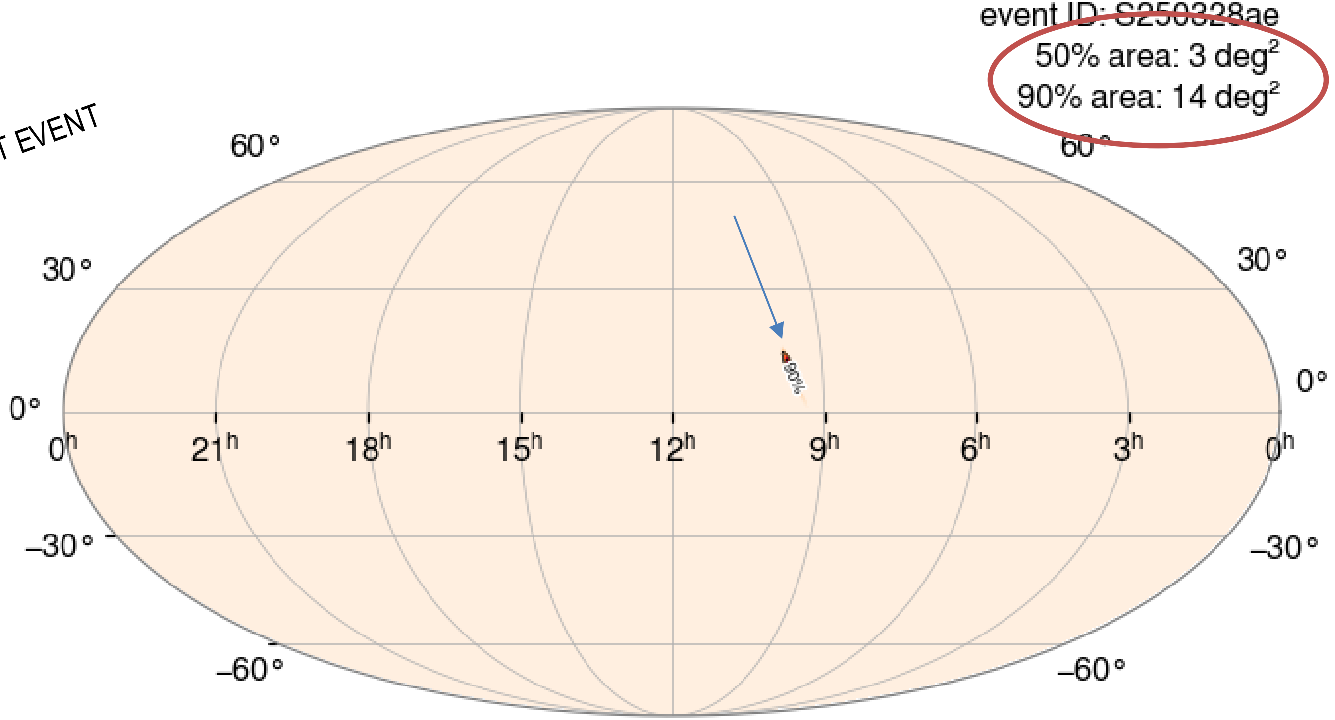
GraceDB Public Alerts Latest Search Documentation Login

Please log in to view full database contents.

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR
S250331o	BBH (>99%)	Yes	March 31, 2025 01:34:48 UTC	GCN Circular Query Notices | VOE		1 per 100.04 years
S250328ae	BBH (>99%)	Yes	March 28, 2025 05:40:27 UTC	GCN Circular Query Notices | VOE		1 per 100.04 years
S250326y	BBH (>99%)	Yes	March 26, 2025 01:54:06 UTC	GCN Circular Query Notices | VOE		1 per 8890.9 years

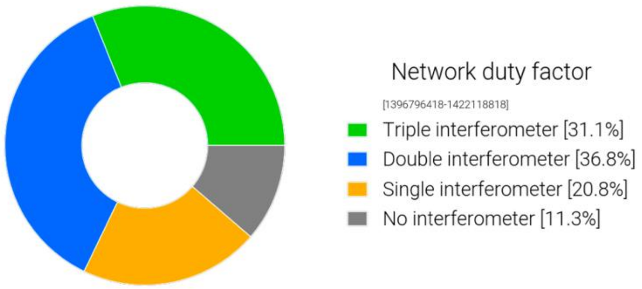
S250328ae

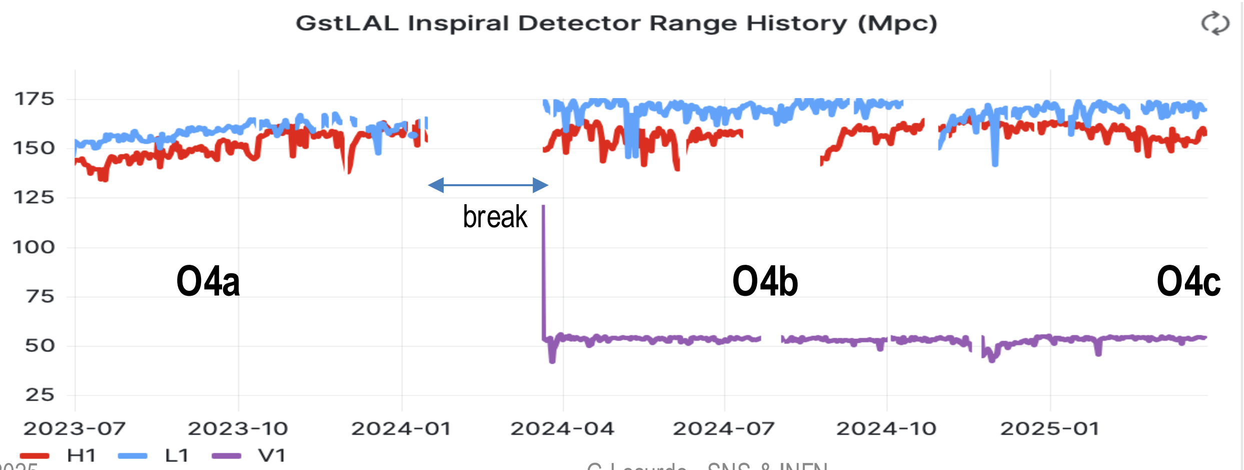
RECENT EVENT



O4 HISTORY

- O4a: May 23 – Jan 24
  - Ligo H + Ligo L (+ KAGRA for the first 4 weeks)
- O4b: Apr 24 – Jan 25
  - Virgo observing
- O4c: Jan 25 – *Oct 25*

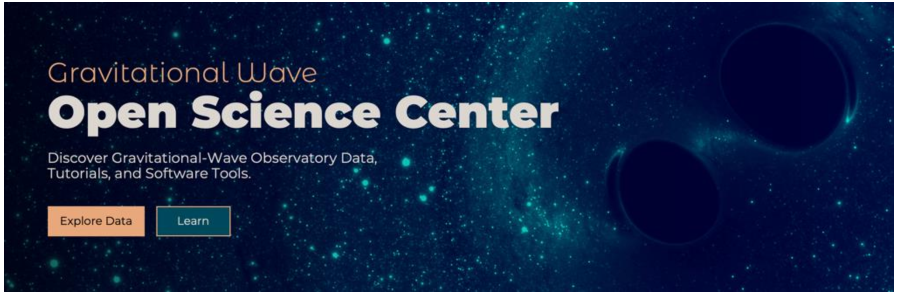


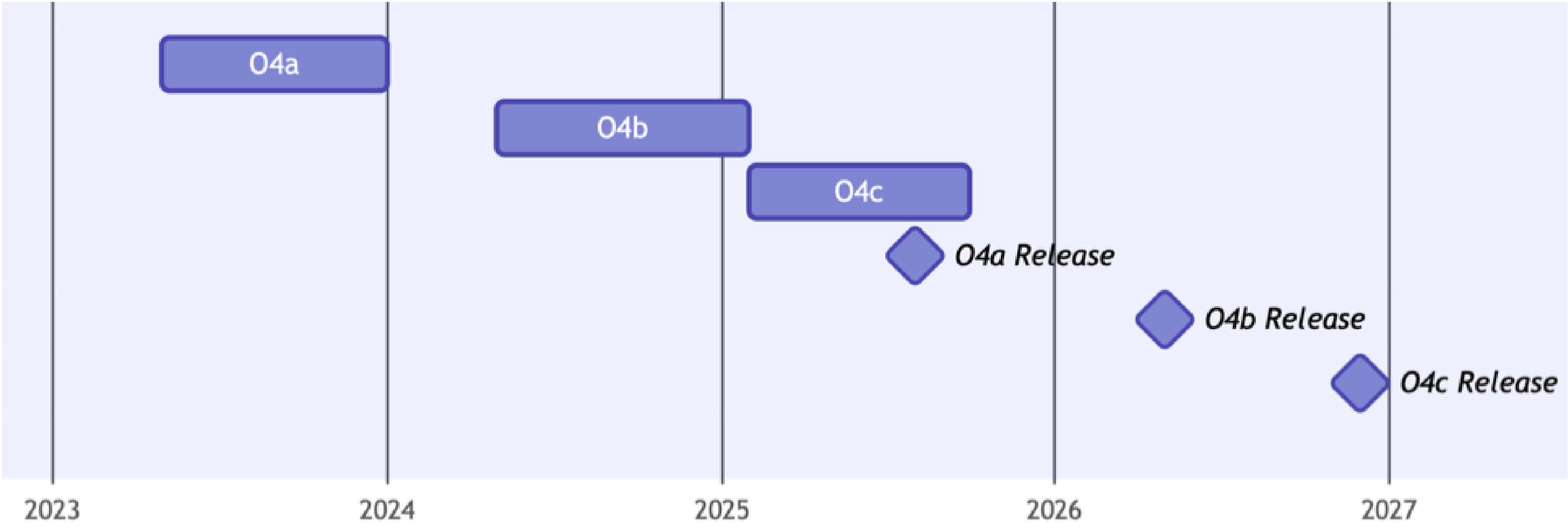


DATA RELEASE

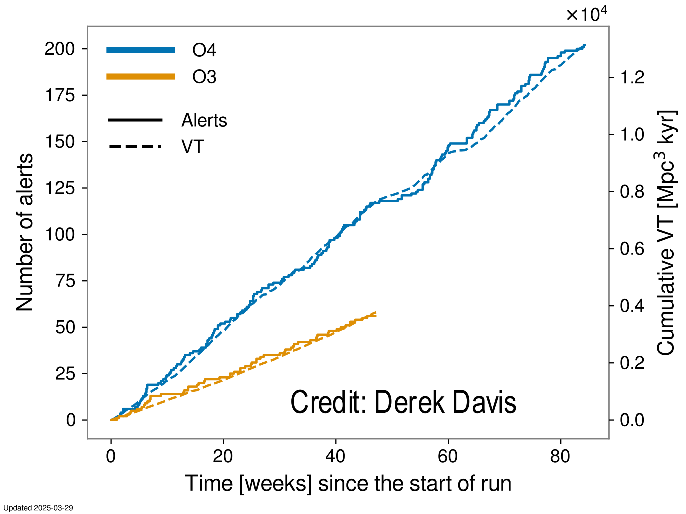
https://gwosc.org

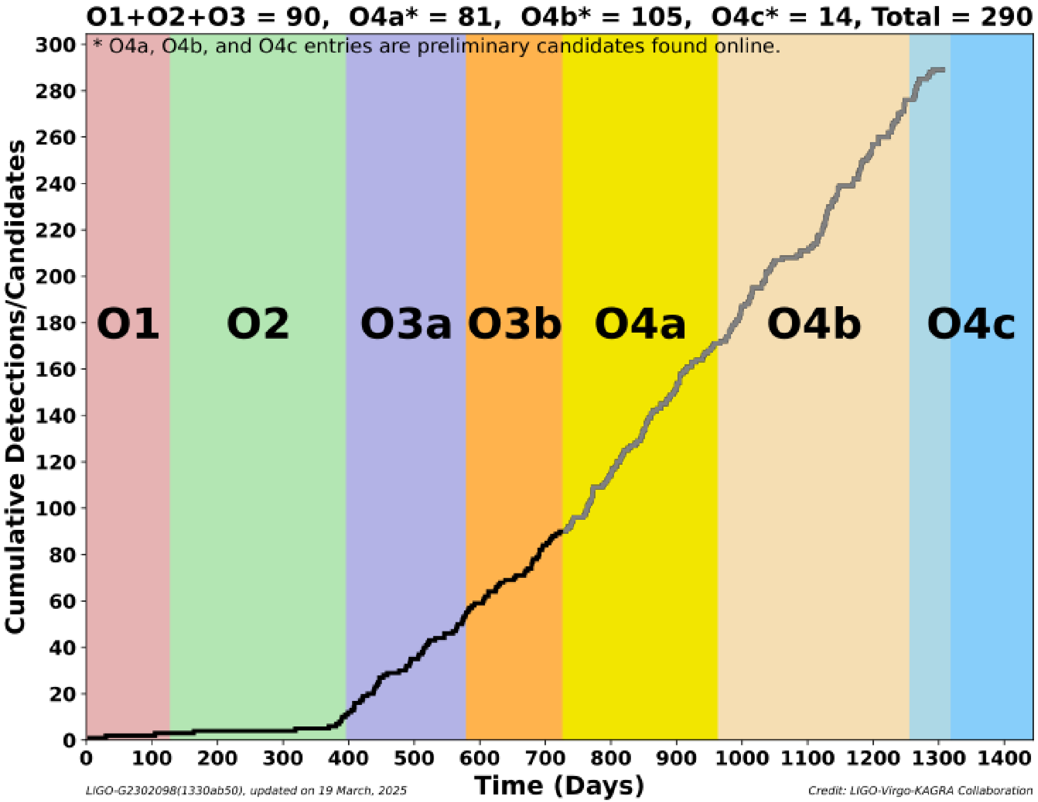
Data set	Data collection date range	Months of data	h(t) release date
O4a	2023-05-24 to 2024-01-16 16:00:00 UTC	7.7	2025-08-23
O4b	2024-04-10 to 2025-01-28 17:00:00 UTC	9.5	2026-05-23
O4c	2025-01-28 17:00:00 UTC to 2025-10–07 17:00:00 UTC	8.5	2026-12-16





The number of discovered BH is approaching 1000



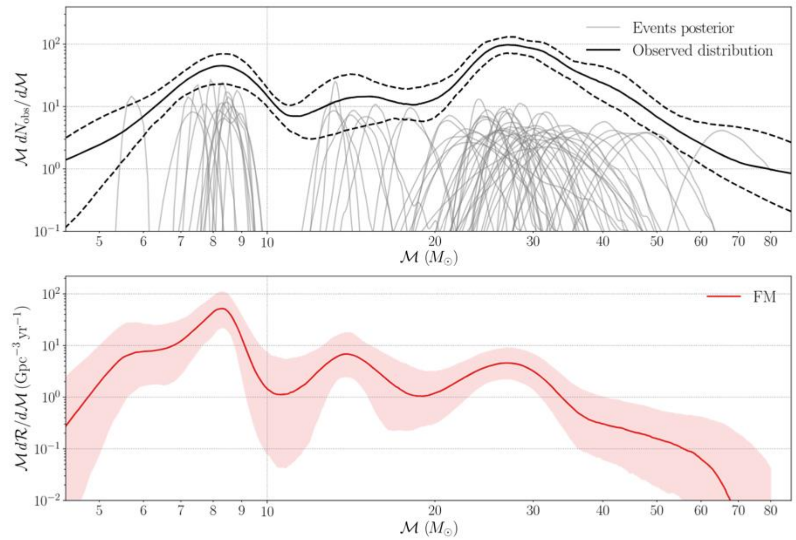


FROM ONE TO MANY: POPULATIONS

- LVK coalescing binaries science entering in the «statistical information driven» regime
- Evidence of substructures in the BH mass distribution
- Looking forward to adding O4 data!

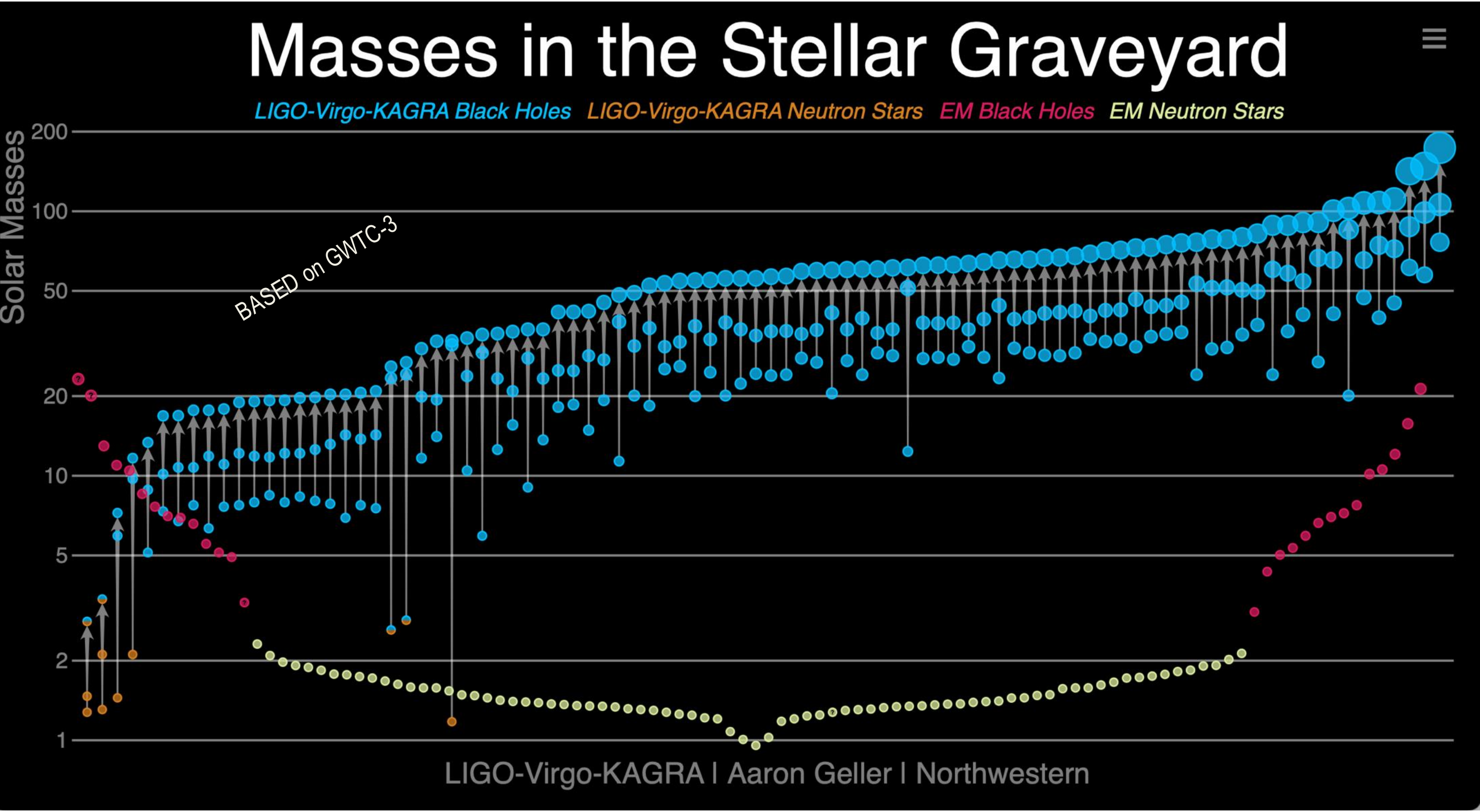
LVK Coll., PRX, 2023

POPULATION OF MERGING COMPACT BINARIES INFERRED ... PHYS. REV. X **13**, 011048 (2023)

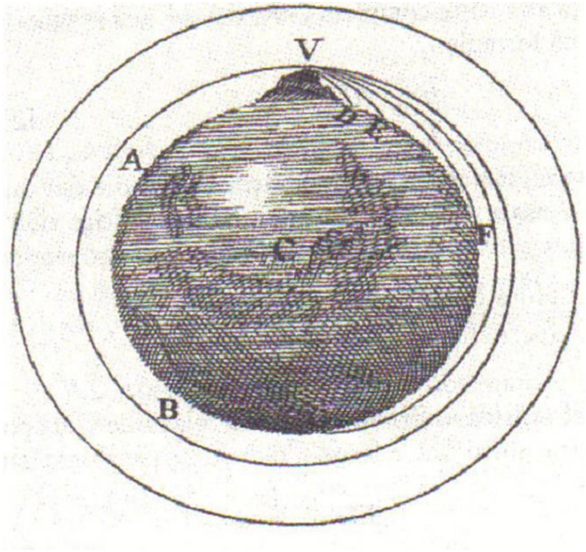


B. Mass distribution has substructure

With new discoveries in O3, we are now confident the mass distribution has substructure, with localized peaks in the component mass distribution. For example, we find overdensities in the merger rate (> 99% credibility) as a function of primary mass, when compared to a power law, at $m_1 = 10^{+0.29}_{-0.59} M_\odot$ and $m_1 = 35^{+1.7}_{-2.9} M_\odot$.



Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
BASED on GWTC-3
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern



Credit: Alain Riazuelo, IAP/UPMC/CNRS

"A CLASH OF PRINCIPLES"

Cit. L Susskind

- Standard Model vs General Relativity
  - No experiment so far has discovered new physics inside either theory
- Black Holes are a lab that smashes the two theories together, squeezing big masses in small volumes
- Detecting BBH mergers at high SNR might help finding new physics

TESTING GR

- LIGO/Virgo data are used to perform several model agnostic tests of GR
- No deviations found so far (SNR up to few 10s)
- High SNR signals will give access to waveform details and disclose BGR physics

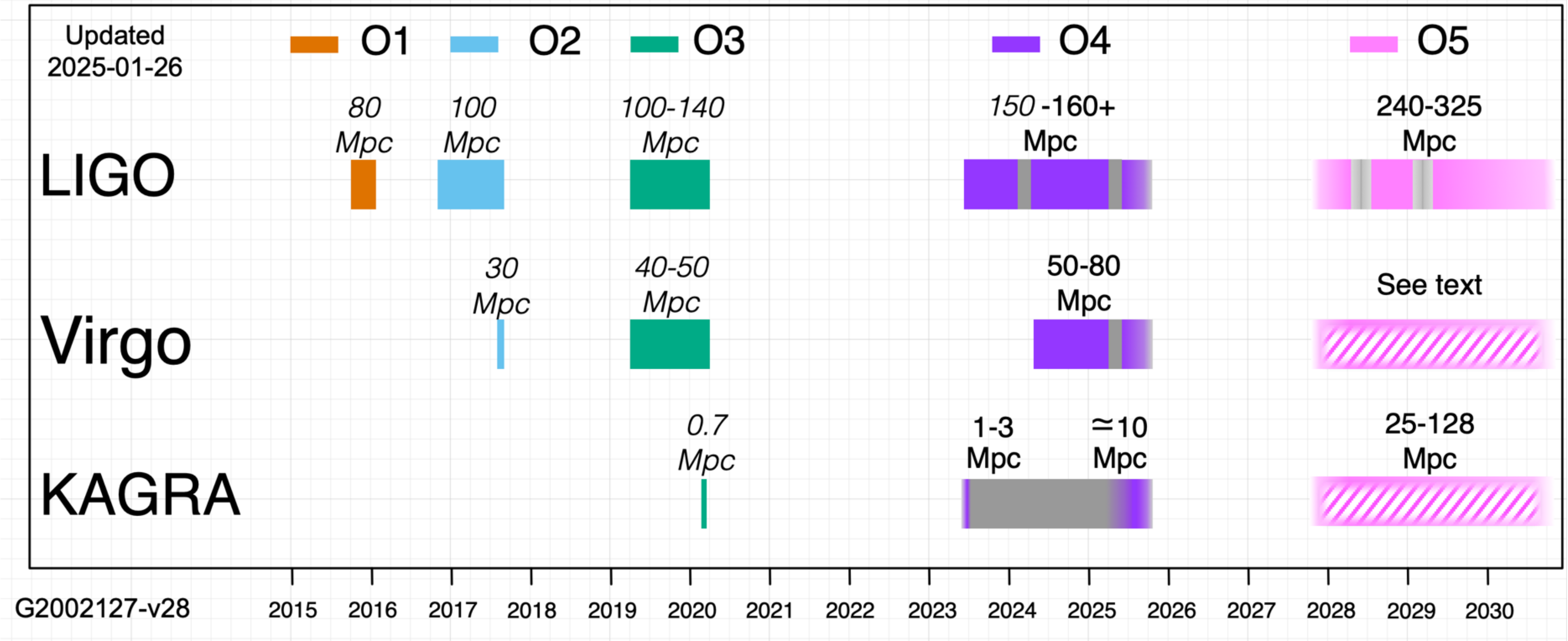
Tests of General Relativity with GWTC-3

arXiv 2112.06861

R. Abbott,[1] H. Abe,[2] F. Acernese,[3,4] K. Ackley,[5] N. Adhikari,[6] R. X. Adhikari,[1] V. K. Adkins,[7] V. B. Adya,[8] C. Affeldt,[9,10]
D. Agarwal,[11] M. Aga…
T. Akutsu,[20,21] R…

Test	Section	Quantity	Parameter	Improvement w.r.t. GWTC-2
RT	IV A	p-value	p-value	Not applicable
IMR	IV B	Fractional deviation in remnant mass and spin	$\left\{\frac{\Delta M_f}{\bar{M}_f}, \frac{\Delta\chi_f}{\bar{\chi}_f}\right\}$	1.1–1.8
PAR	V A	PN deformation parameter	$\delta\hat{\phi}_k$	1.2–3.1
SIM	V B	Deformation in spin-induced multipole parameter	$\delta\kappa_s$	1.1–1.2
MDR	VI	Magnitude of dispersion	$\lvert A_\alpha\rvert$	0.8–2.1
POL	VII	Bayes Factors between different polarization hypotheses	$\log_{10}\mathcal{B}^{\mathrm{X}}_{\mathrm{T}}$	New Test
RD	VIII A 1	Fractional deviations in frequency (pyRing)	$\delta\hat{f}_{221}$	1.1
	VIII A 2	Fractional deviations in frequency and damping time (pSEOB)	$\{\delta\hat{\tau}_{220}, \delta\hat{f}_{220}\}$	1.7–5.5
ECH	VIII B	Signal-to-noise Bayes Factor	$\log_{10}\mathcal{B}_{\mathrm{S/N}}$	New Test

OBSERVING PLANS

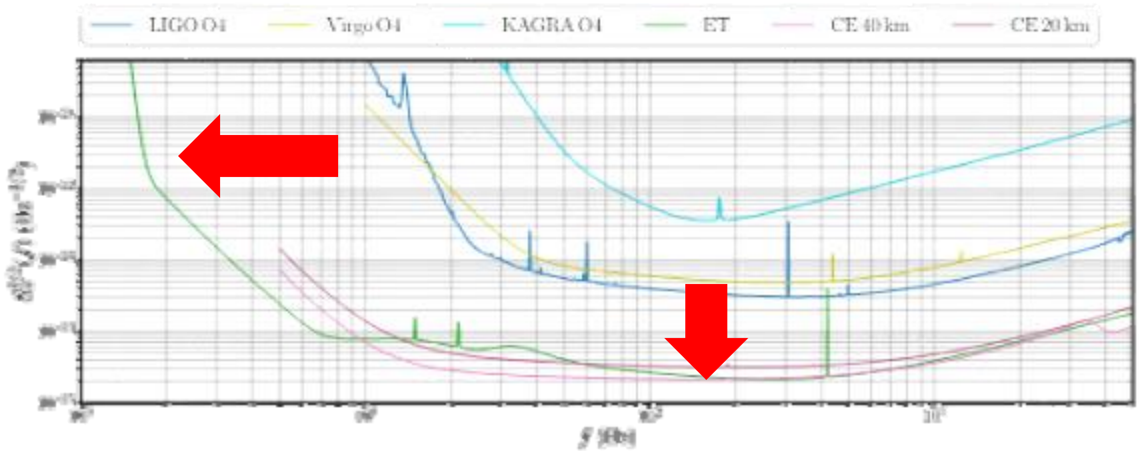


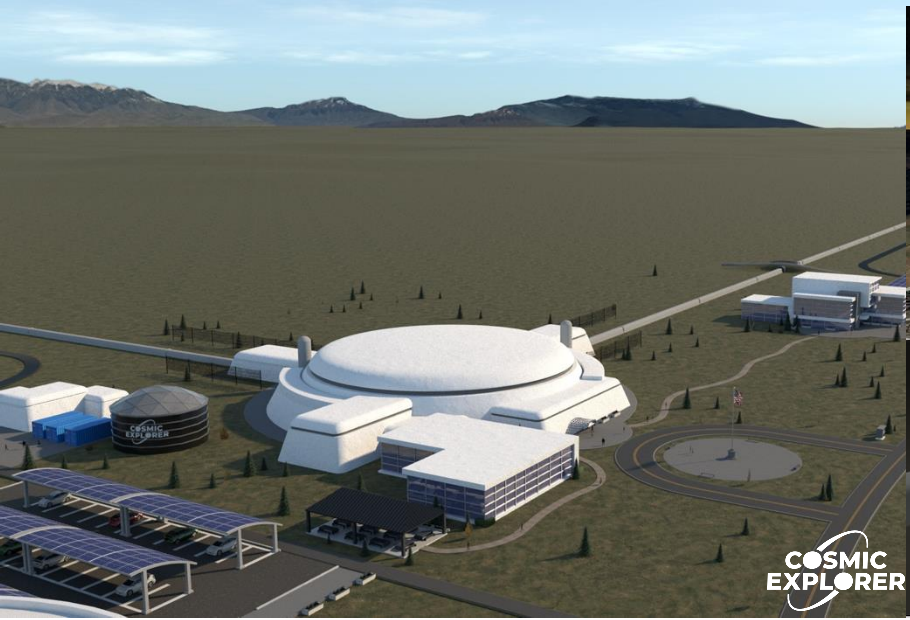
https://observing.docs.ligo.org/plan/

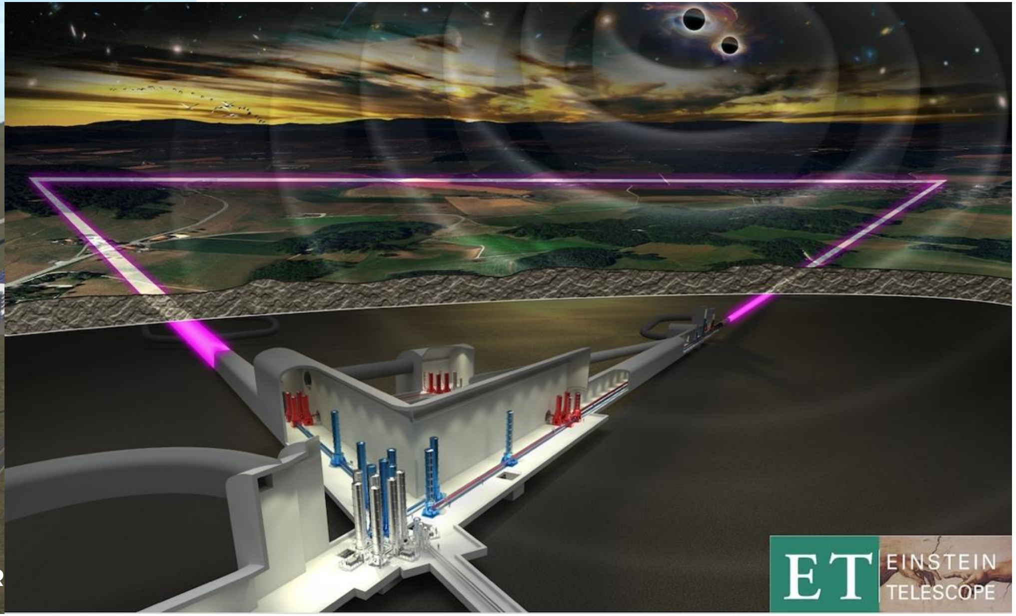
* The O5 start dates, duration, and sensitivities are current best guesses, and will likely be adjusted as we approach that run for all the detectors

O4 will continue through October 2025

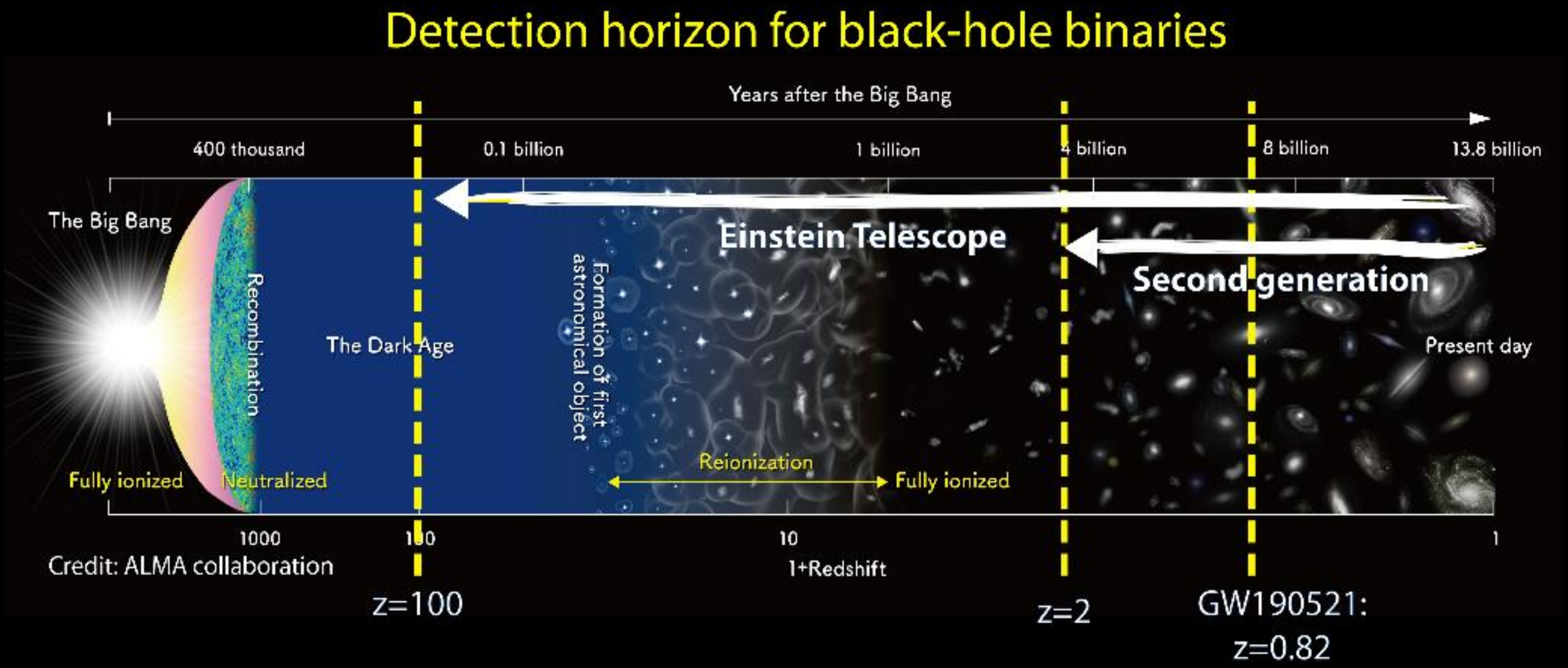
3G


LIGO O4
Virgo O4
KAGRA O4
ET
CE 40 km
CE 20 km


COSMIC EXPLORER


ET EINSTEIN TELESCOPE

3G POTENTIAL



arXiv 2503.12263

The Science of the Einstein Telescope

Einstein Telescope collaboration

Adrian Abac,[1] Raul Abramo,[2] Simone Albanesi,[3,4] Angelica Albertini,[5,6] Alessandro Agapito,[7,8,9] Michalis Agathos,[10,11] Conrado Albertus,[12] Nils Andersson,[13] Tomás Andrade,[14] Igor Andreoni,[15,16] Federico Angeloni,[7,17,8,18] Marco Antonelli,[19] John Antoniadis,[20,21] Fabio Antonini,[22] Manuel Arca Sedda,[23,24,25,26] M. Celeste Artale,[27,28] Stefano Ascenzi,[23] Pierre Auclair,[29] Matteo Bachetti,[30] Charles Badger,[31] Biswajit Banerjee,[23] David Barba-González,[12] Dániel Barta,[32] Nicola Bartolo,[26,33,34] Andreas Bauswein,[35] Andrea Begnoni,[26,33] Freija Beirnaert,[36] Michał Bejger,[37,38] Enis Belgacem,[39,40] Nicola Bellomo,[26,33,34] Laura Bernard,[41] Maria Grazia Bernardini,[42] Sebastiano Bernuzzi,[3] Christopher P. L. Berry,[43] Emanuele

15 Mar 2025

COSMOLOGY

- Compact binary coalescences → luminosity distance: $$d_L(z) = \frac{1+z}{H_0}\int_0^z \frac{d\tilde{z}}{\sqrt{\Omega_M(1+\tilde{z})^3 + \rho_{\rm DE}(\tilde{z})/\rho_0}}$$
- Access to cosmological parameters with an independent method
  - Need to measure z (direct meas., statistical methods)
  - No need of distance ladder

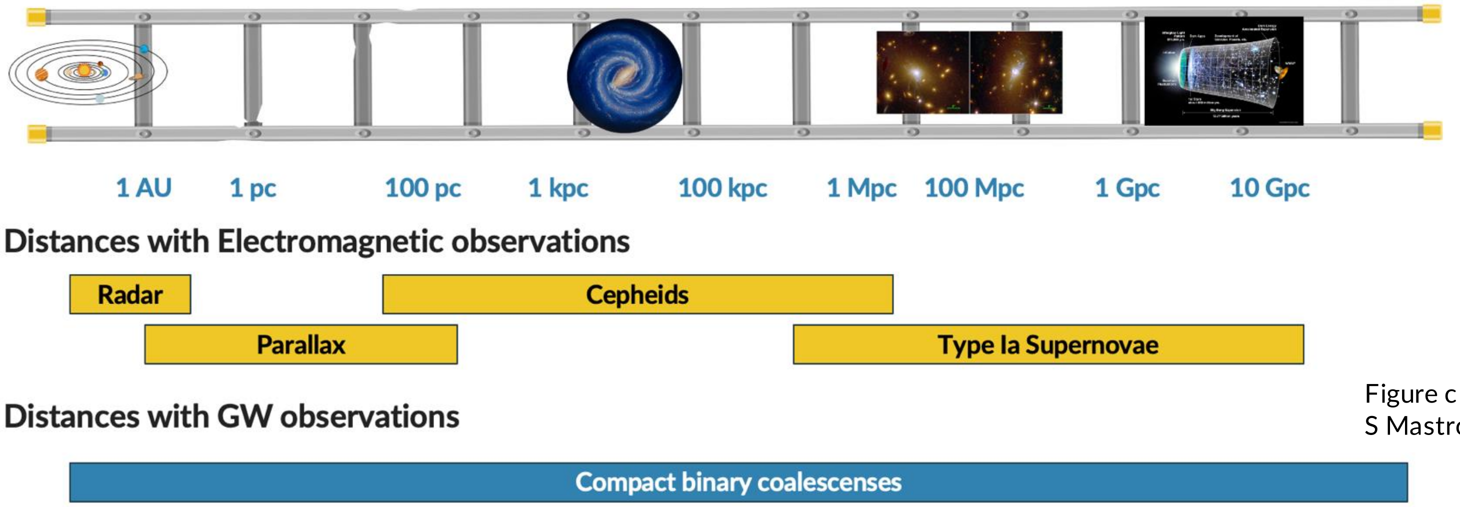


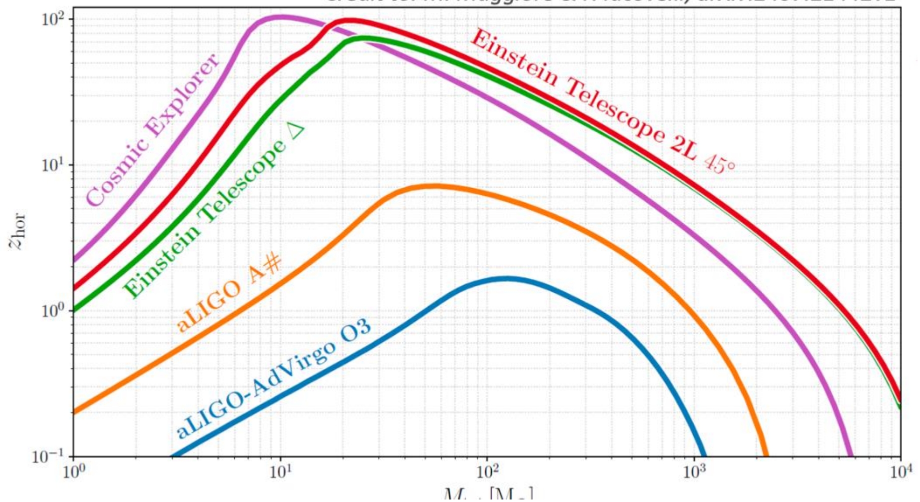
Figure credit:
S Mastrogiovanni

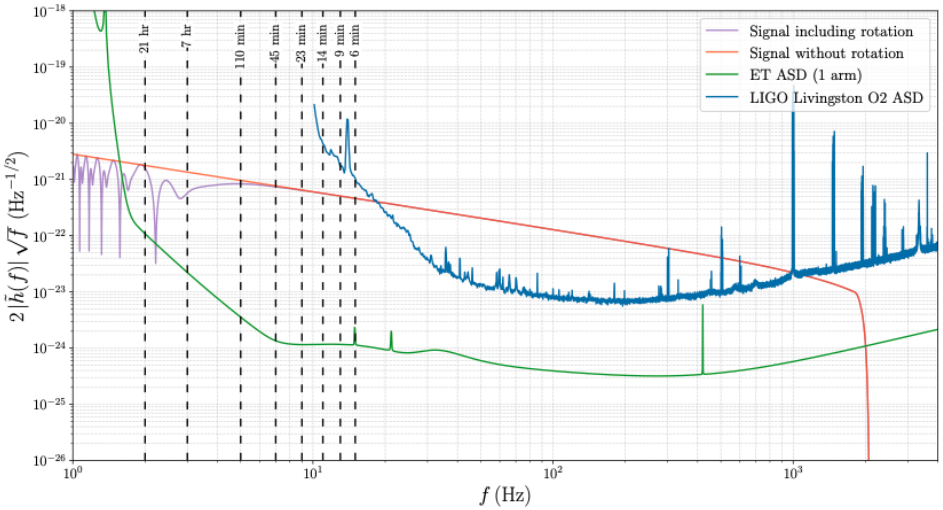
IMPACT OF LF SENSITIVITY

EXTENDING THE BANDWIDTH TO LOWER FREQUENCIES: ACCESS TO BIGGER MASSES, LONGER SIGNALS

Signals may last many hours…
will allow to prepare e.m. follow up well in advance

Credit to: M. Maggiore & F. Iacovelli, arXiv:2407.21442v1

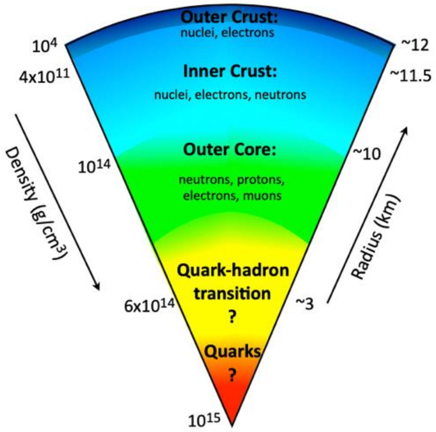


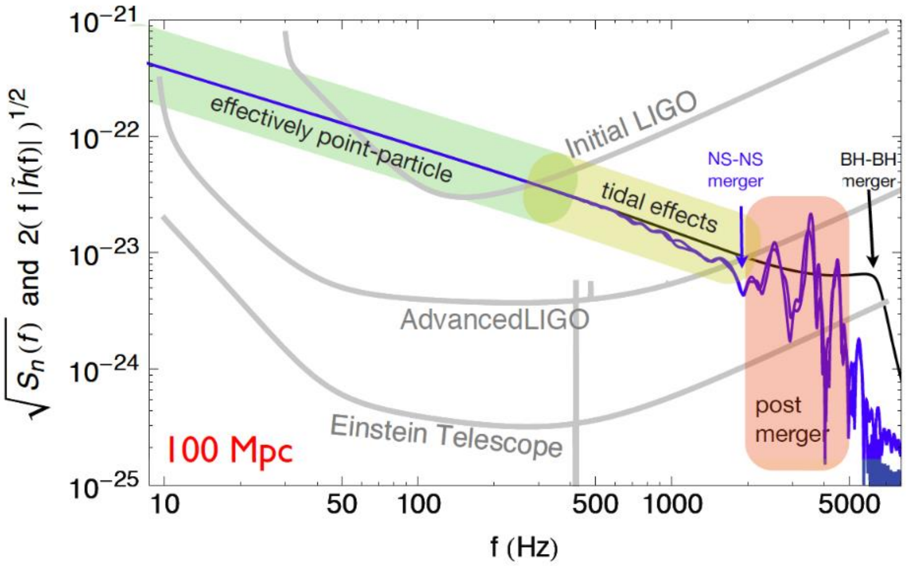


From Iacovelli et al, ApJ, 2022

NS: FROM NUCLEAR PHYSICS TO QCD

- Influence on the GW waveform in mergers involving a NS
  - Tidal effects, internal oscillation modes, spin-tidal couplings,…
- High SNR detection of BNS or NSBH mergers are a lab for nuclear physics and even QCD





Figures from ArXiv 1912.02622

DETECTING DM WITH GW

- **Primordial black holes**
  - ***Signature:*** *Subsolar mass BH evidence, High redshift mergers*
- **Environmental effects on compact objects**
  - The **compact object structure** can be changed: accretion disk, spin down effects, formation of a DM core
  - The GW **production mechanism** can be changed
  - **Impact on propagation** of generated GW and EM waves
  - ***Signature:*** *Unusual waveform*
- **Exotic objects**
  - **GW190521:** two complex vector boson star? [PRL 126, 081101]

Dark matter, black holes, and gravitational waves

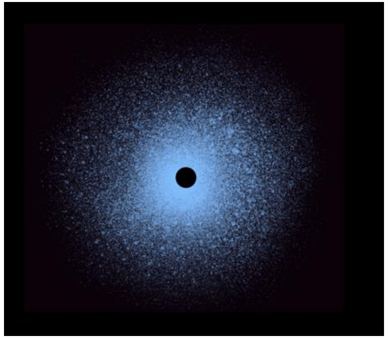
Gianfranco Bertone[1]

[1] *Gravitation Astroparticle Physics Amsterdam (GRAPPA), University of Amsterdam, Amsterdam, 1098 XH, Netherlands*

The formation and growth of black holes can strongly influence the distribution of dark matter around them. I discuss here the different types of dark matter overdensities around black holes, including dark matter cusps, spikes, mounds, crests, and gravitational atoms. I then review recent results on the evolution of a black holes binary in presence of dark matter, focusing on the energy transfer between binary and dark matter induced by dynamical friction. Finally, I present the prospects for studying dark matter with gravitational wave observations, and argue that future interferometers might be able to detect and characterise dark matter overdensities around black holes.

arXiv 2404.11513

"GW offer a unique window into the fabric of the universe, and might hold the key to unlock the longstanding mystery of dark matter."



SOME BIG QUESTIONS

(Where) Does GR break down?

What is the fundamental nature of BH?
Are they truly 'bald'?

How does matter behave under the most extreme conditions in nature?

How do massive stars explode?

Can we find clues to the nature of DM and DE in GW observations?

Where do heavy elements come from?

What else we will find that we don't know about?

SOME BIG QUESTIONS

(Where) Does GR break down?

What is the fundamental nature of BH? Are they truly 'bald'?

How does matter behave under the most extreme conditions in nature?

High event rate

Network

High redshift events

ET/CE

Wider mass spectrum

High-SNR detections

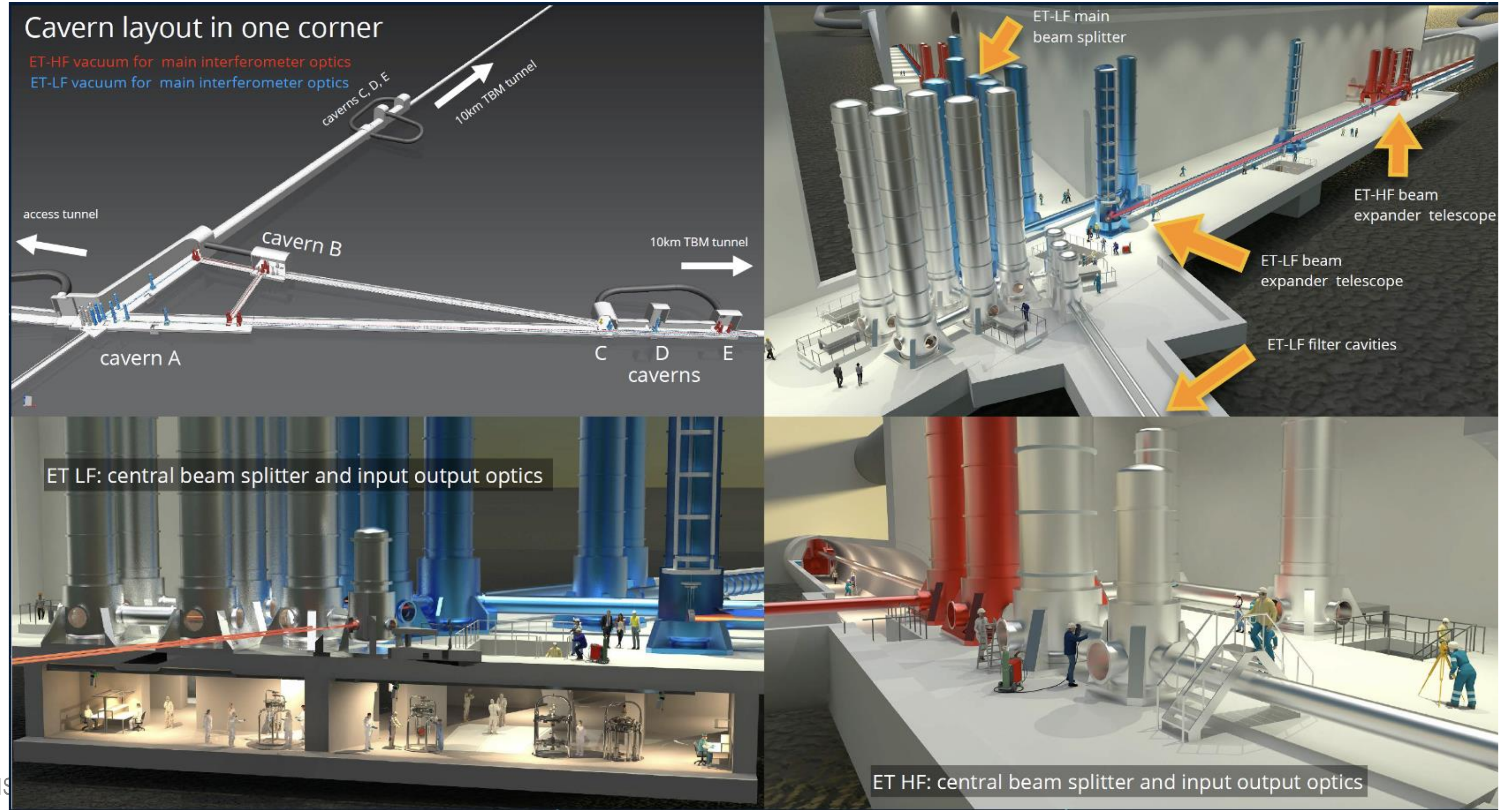
How do massive stars explode?

Can we find clues to the nature of DM and DE in GW observations?

Where do heavy elements come from?

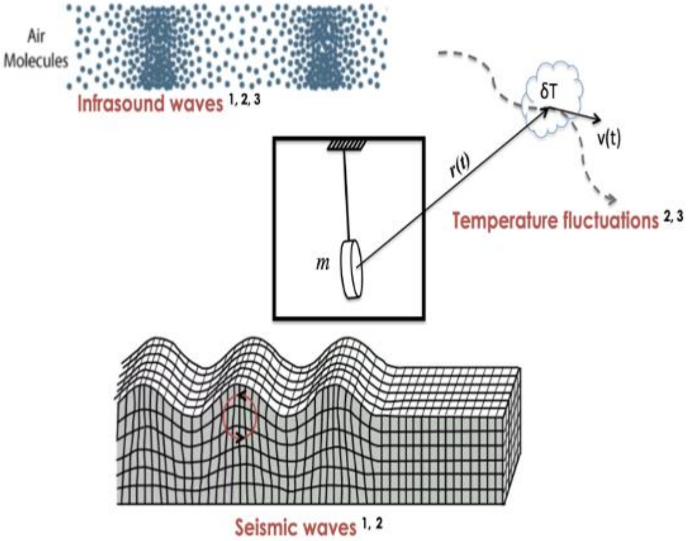
What else we will find that we don't know about?

ET: LARGE SCALE UNDERGROUND INFRASTRUCTURE



Credit: A.Freise, 2020 XI ET Symposium

WHY UNDERGROUND?



[1] Saulson Phys. Rev. D **30**, 732, [2] J. Harms Terrestrial Gravity Fluctuations,
[3] Creighton CQG. **25** (2008) 125011, C.Cafaro, S. A. Ali arXiv:0906.4844 [gr-qc]

- Fluctuations of mass density (seismic waves), temperature, pressure…

$$\rho(x,t) = \rho_0(x) + \delta\rho(x,t)$$

- …generate fluctuations of the local gravitational field…

$$\delta\Phi(x,t) = G\int \frac{\vec{\nabla}\cdot[\rho_0(x')\vec{u}(x',t)]}{|x-x'|}d^3x'$$

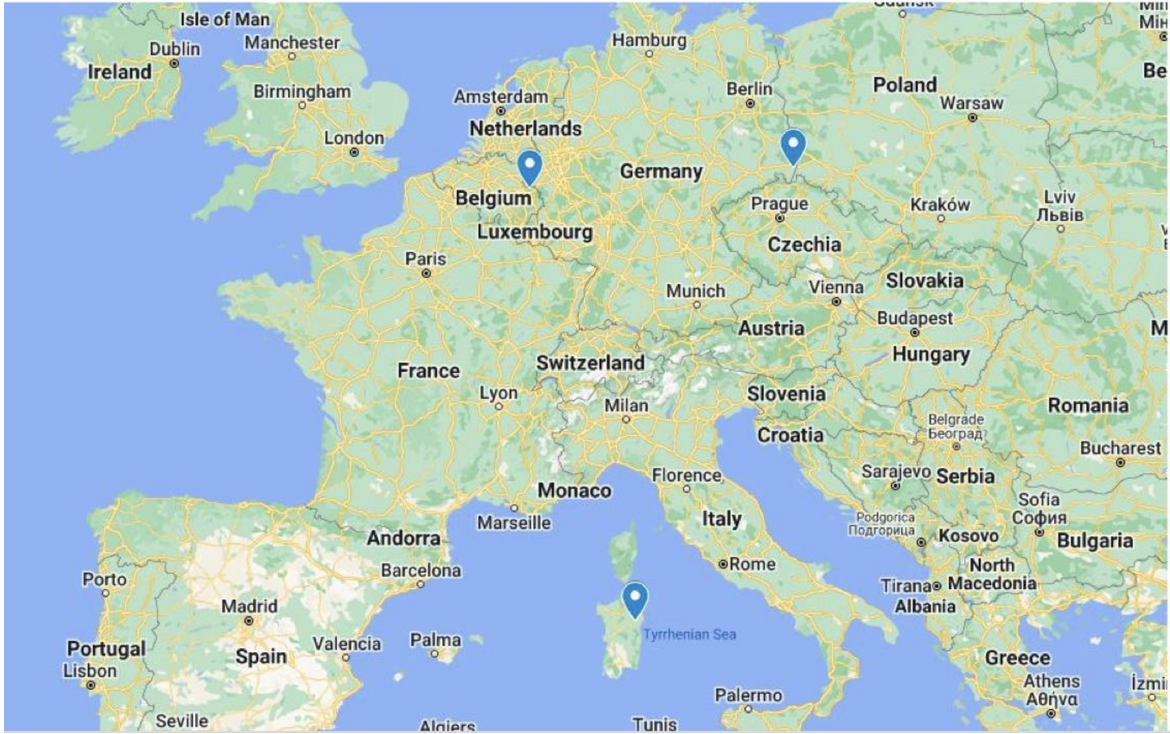
- …which couples directly to the test masses short-circuiting the vibration isolation system

→ "NEWTONIAN" NOISE

- Underground environment: seismic noise and atmospheric disturbances are significantly lower

WHERE?

- Two formal candidate sites:
  - North of Sardinia (Sos Enattos)
  - EMR EURegio (B,NL,D border)
- Proposed 3rd site:
  - Lausitz (Saxony), Germany
- Site evaluation criteria
  - Geophysics, environment
  - Finances and organization
  - Services and infrastructures

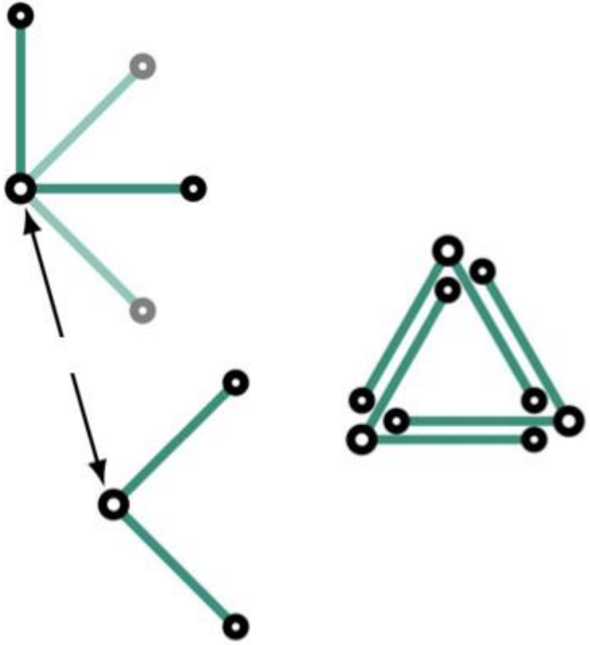


GEOMETRY?

- 10 km triangle vs 2 15 km L?
- Compare
  - Scientific performance
  - Cost
  - Complexity

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

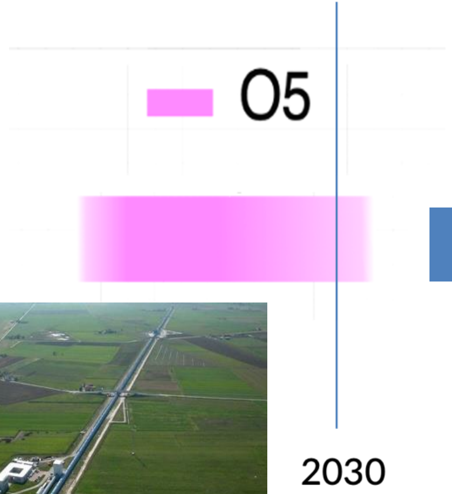
Science with the Einstein Telescope: a comparison of different designs

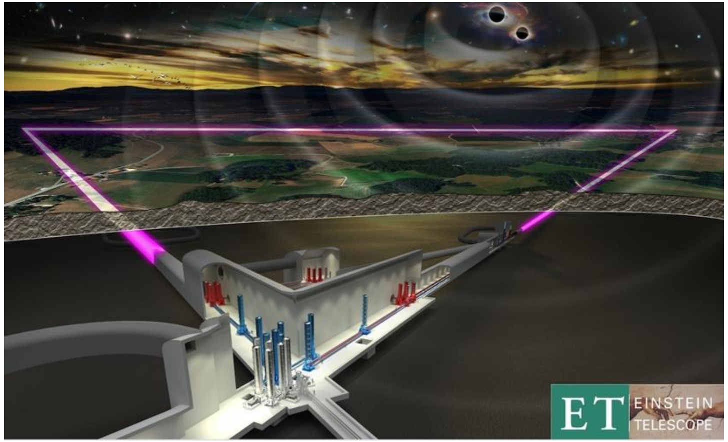


Branchesi et al., JCAP 2023

TIMING

- 3G detectors will not produce science before ~2040
- There is a big technology/engineering leap between 2G and 3G (with associated risks…)





A 2.5G LIGO/VIRGO UPGRADE

- **Extend and enhance the Virgo/LIGO science program** until the advent of 3G detectors
  - Existing detector will still play a crucial role for ~ a decade after O5
  - Target: ~ 2x sensitivity improvement wrt AdV+/aLIGO+
  - Ensures continuity in the flow of data
- **Intermediate step in technology developments** between 2G+ and 3G
  - Framework: same Virgo/LIGO wavelength, room temperature, "same" infrastructure
  - Pathfinder and risk reducer for Einstein Telescope
  - Strong synergies on common R&Ds
- **Keep the community together**, allowing to form a new generation of GW interferometry experts
- Ongoing programs: **A#, Virgo_nEXT**

LIGO India

- The "post-O5 network" will be even richer: Ligo India (with A+ technology) expected to come online in ~2030
- Favorable time and position. Will improve localization and 3-detector uptime

Trading Sensitivity and Observing Time
Compact Binary Detections

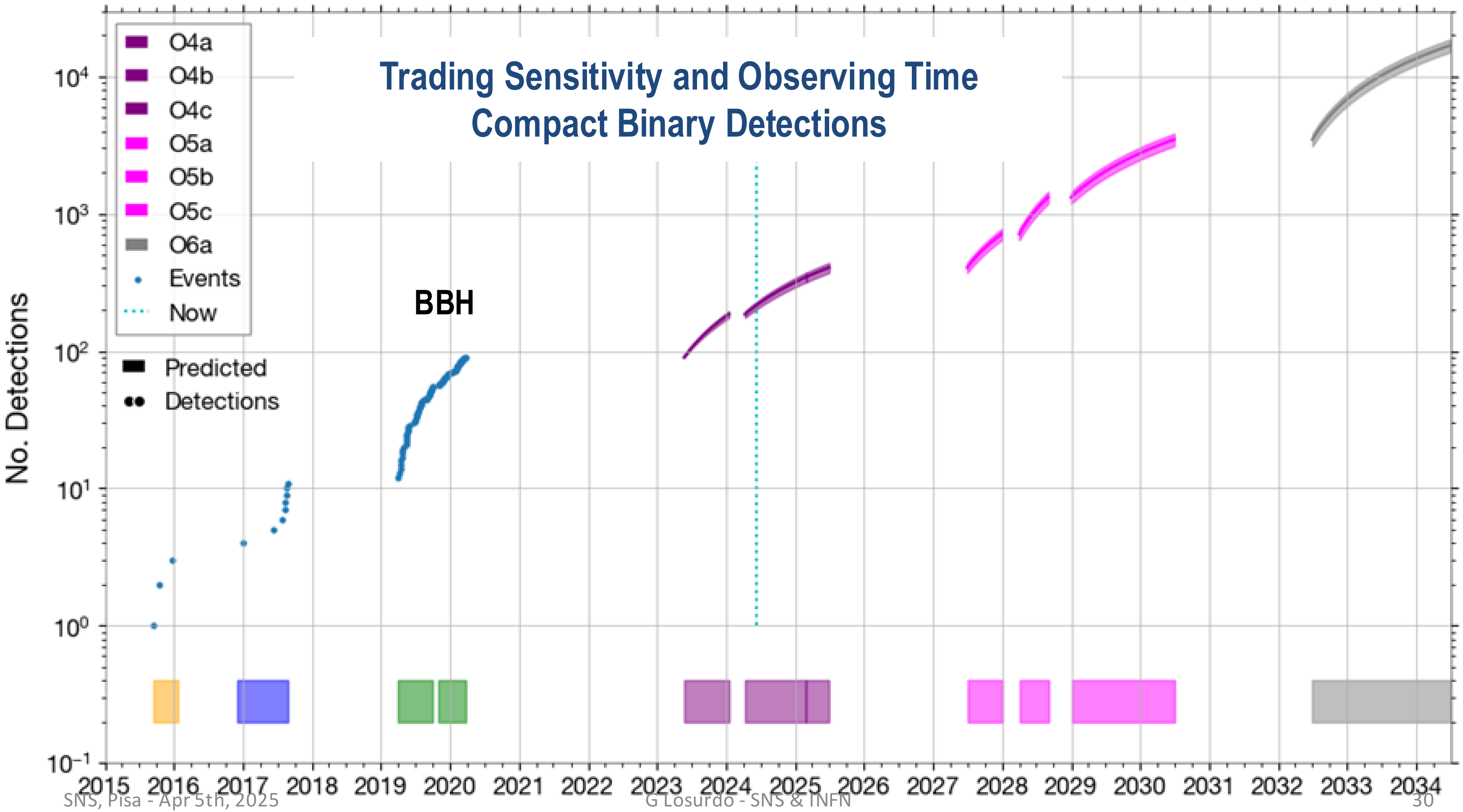
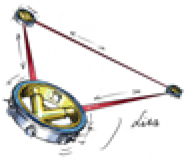
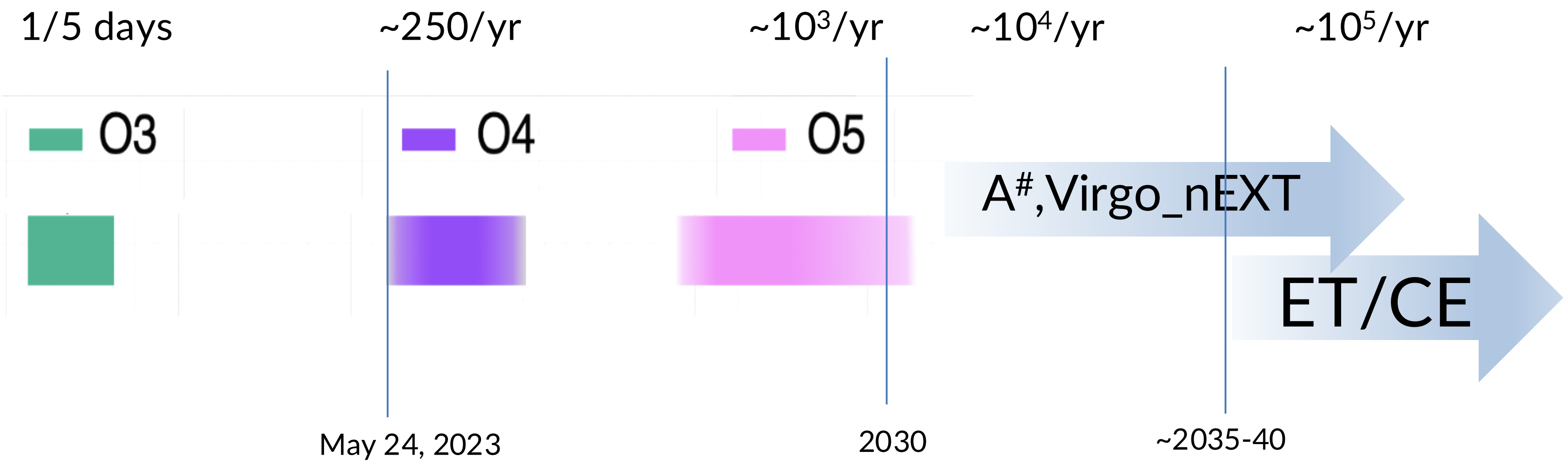


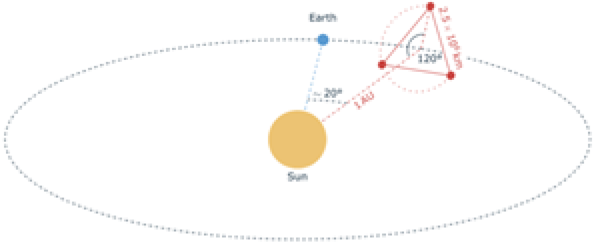
Figure: Amanda Baylor, Cody Messick, PRB



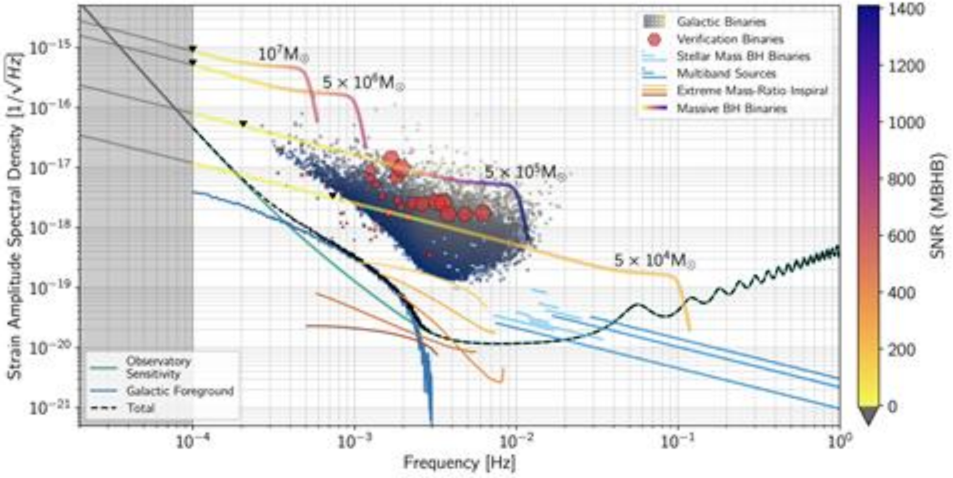


QUASI-CONTINUOUS DATA FLOW AT PROGRESSIVELY BETTER SENSITIVITY

LISA



- Adopted by ESA in 2024 (with a NASA contribution): launch expected in 2035
- With 3G detectors LISA will survey BH over a huge mass range in the entire universe



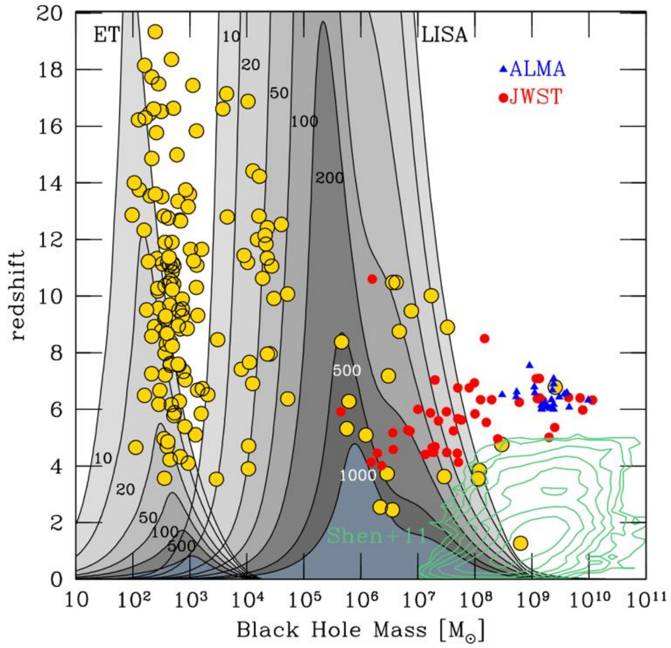


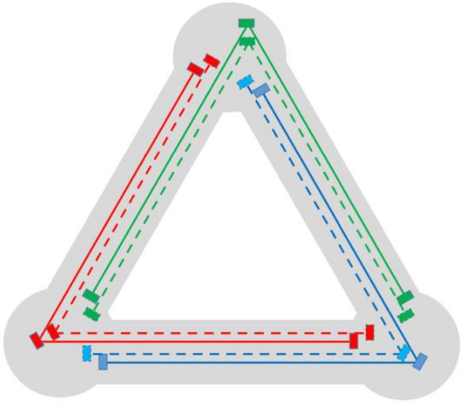
Fig. 5.10 in [arXiv 2503.12263]

CONCLUDING REMARKS

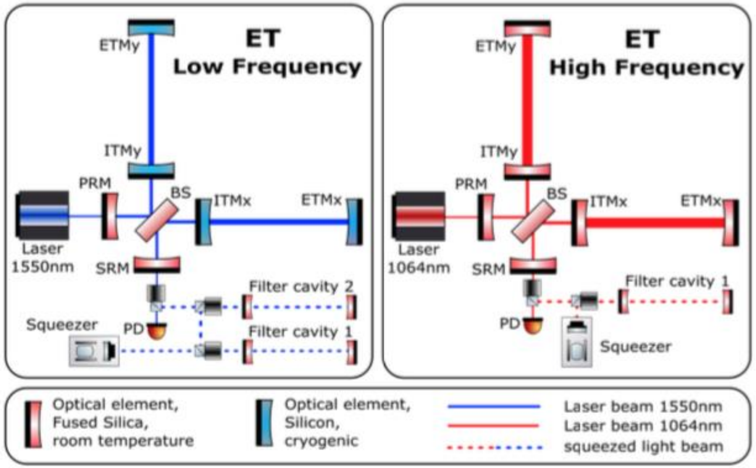
- The early LIGO/Virgo findings have shown that GW science has an enormous discovery potential for astrophysics, cosmology, fundamental physics
- The field is in its early phase and plans for the evolution of the detectors over the coming decades are being made with a manageable scale of investments
- In the next ~20 yrs the GW revolution will develop its full potential
  - LIGO/Virgo/KAGRA will complete their program up to O5
  - LIGO India will join the network
  - LIGO/Virgo are already planning their "2.5 G" upgrades, bridging the gap with 3G
  - ET/CE are expected to produce astonishing science in the 2040s

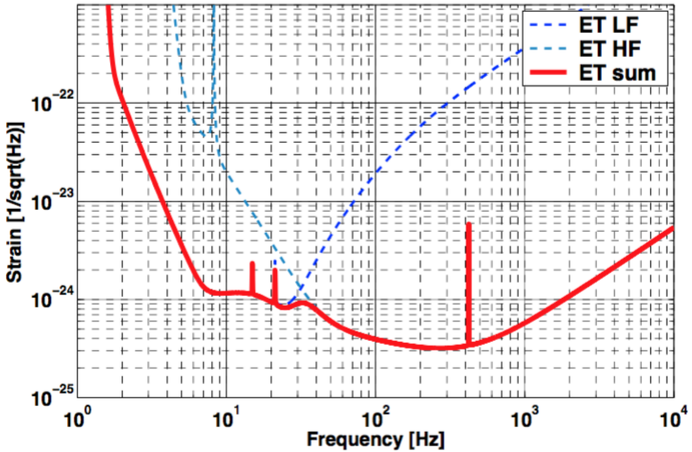
BACKUP SLIDES

ET - DETECTOR



- Underground infrastructure, 10km long
- 3 nested couples of interferometers
  - ET-HF: room temperature, high power, enhancing HF sensitivity
  - ET-LF: cryo, low power, enhancing LF sensitivity
- Ongoing discussion on the configuration: triangle or 2L?

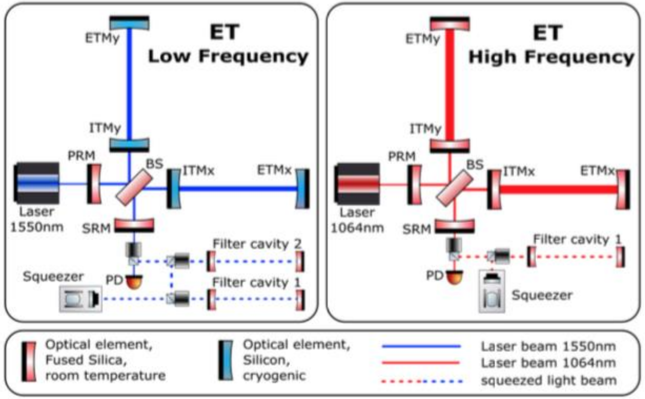




DETECTOR CHALLENGES

- The ET "xylophone" approach demands for parallel technology developments
  - Technologies already used in LIGO/Virgo (to be enhanced) → R&D, A#/Virgo_nEXT
  - Technologies never used in LIGO/Virgo → R&D

- Underground
- Cryogenics
- Silicon (Sapphire) test masses
- Large test masses
- New coatings
- New laser wavelength
- Seismic suspensions
- Frequency dependent squeezing



- High power laser
- Large test masses
- New coatings
- Thermal compensation
- Frequency dependent squeezing