LIGO/VIRGO/KAGRA NETWORK

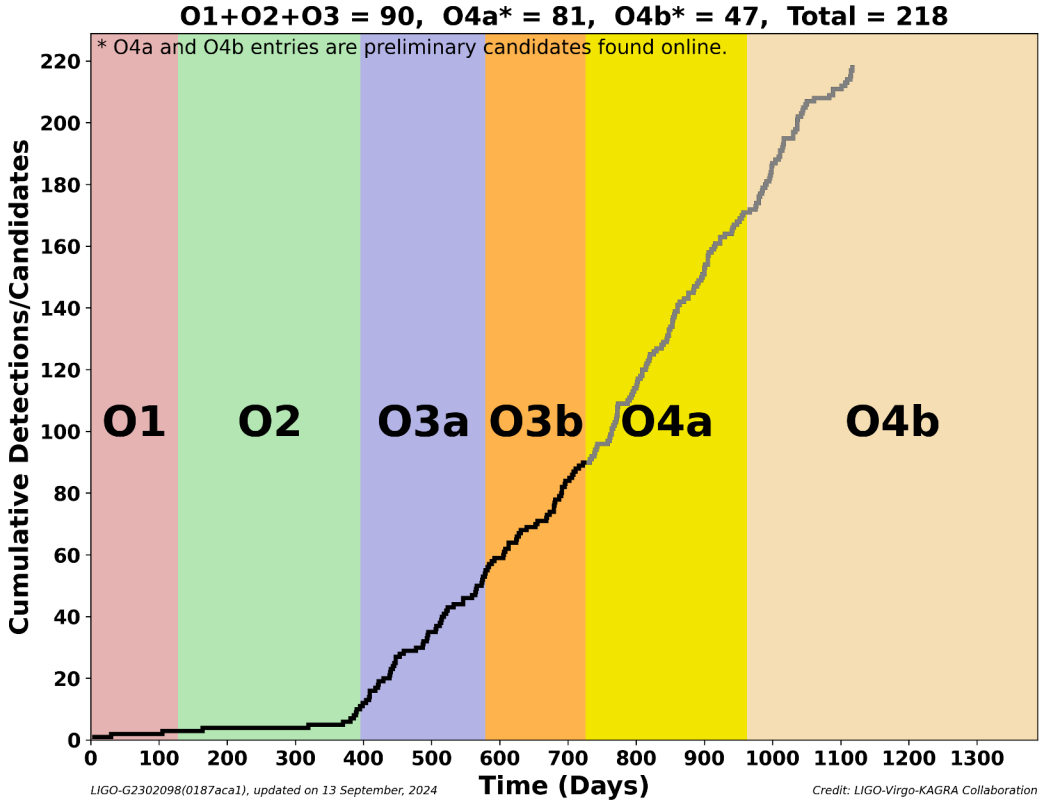
Current Status and Future Directions

VIR-0751A-24

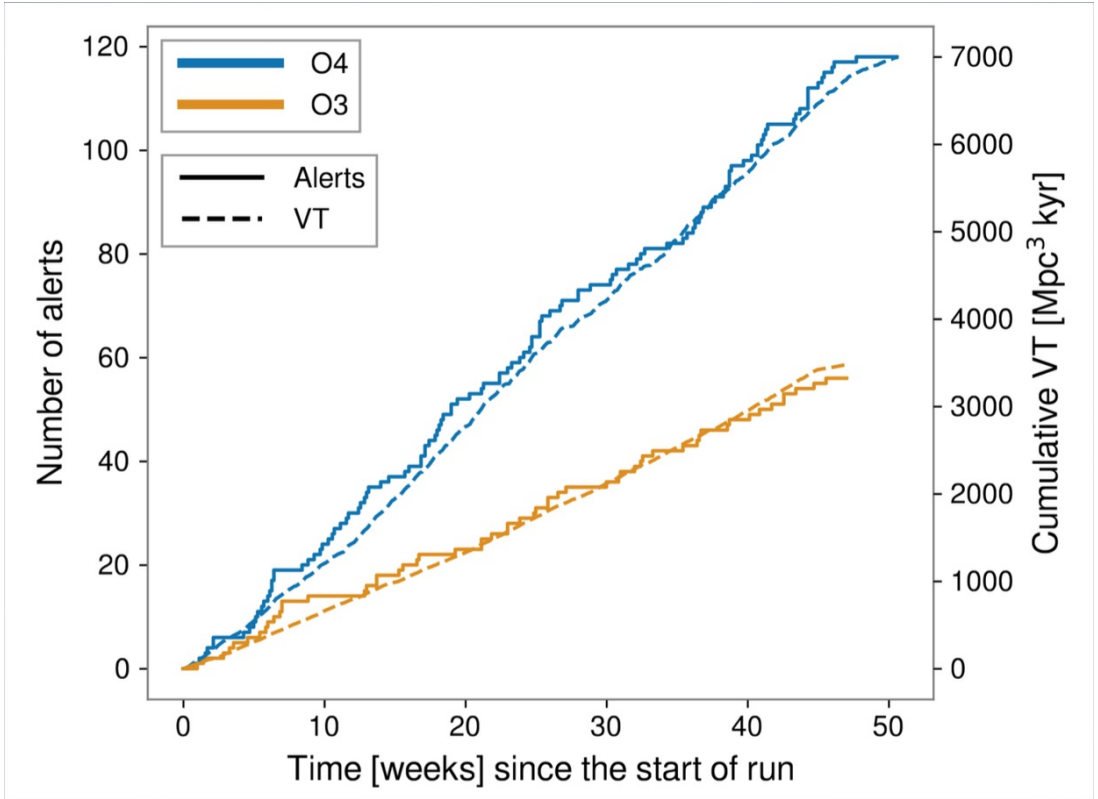
Giovanni Losurdo – 

Pisa
On behalf of
LIGO/Virgo/KAGRA Collaborations

SO FAR


O1+O2+O3 = 90, O4a* = 81, O4b* = 47, Total = 218
* O4a and O4b entries are preliminary candidates found online.
Cumulative Detections/Candidates
O1
O2
O3a
O3b
O4a
O4b
Time (Days)
LIGO-G2302098(0187aca1), updated on 13 September, 2024
Credit: LIGO-Virgo-KAGRA Collaboration

THE GOOD OF UPGRADING

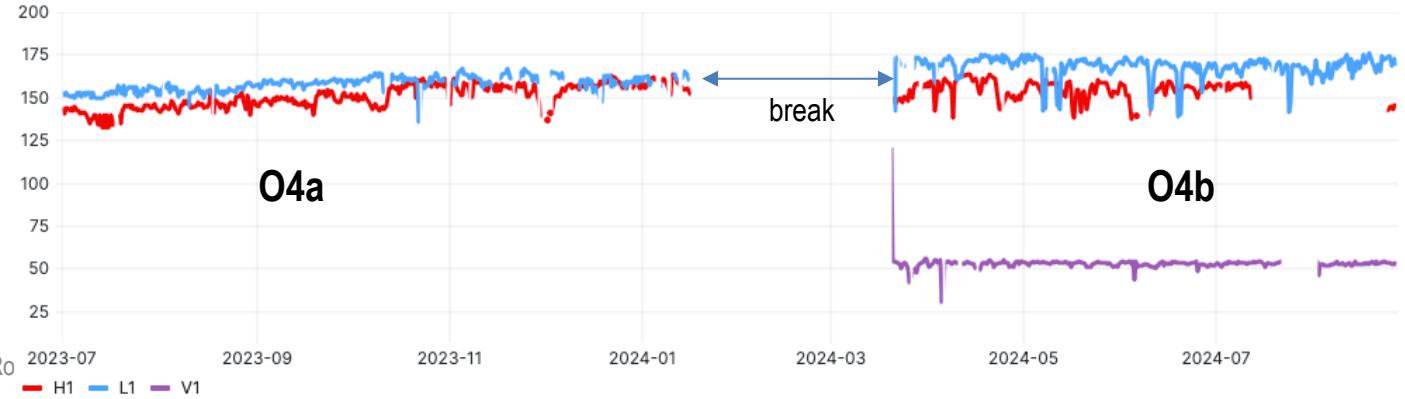


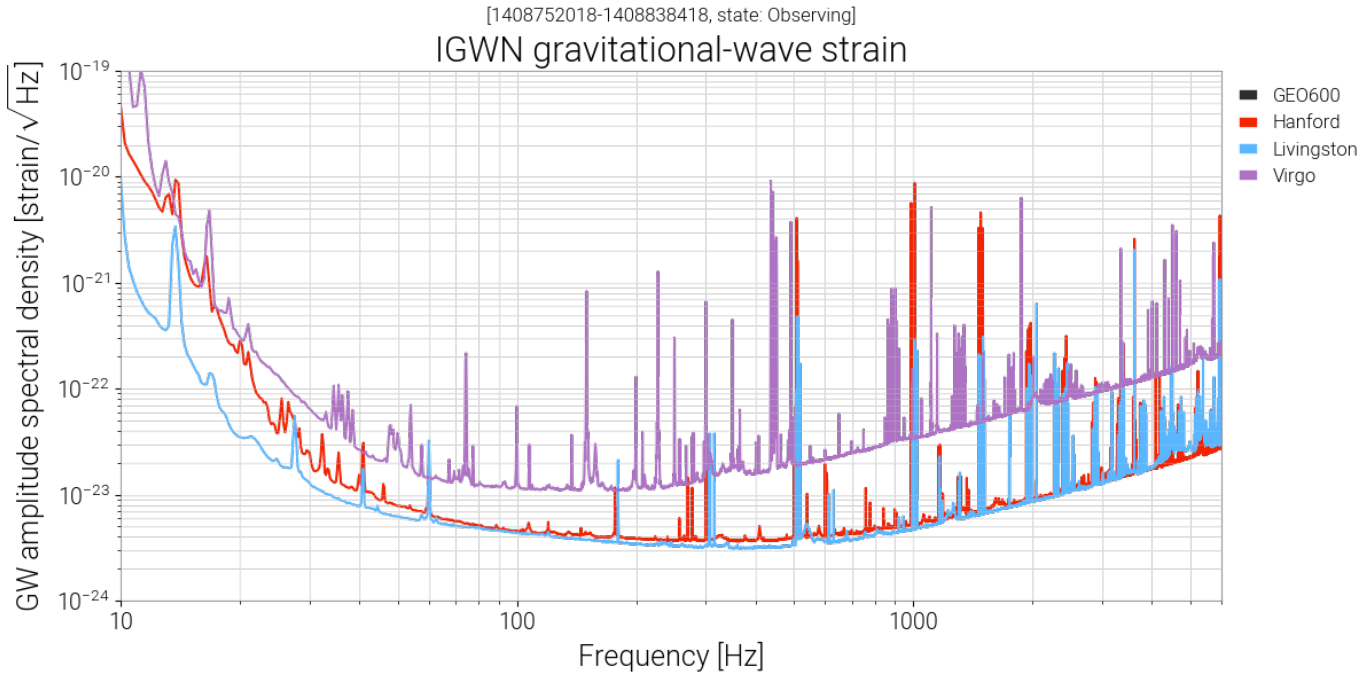
O4 – SO FAR

- O4a: May 23 – Jan 24
  - Ligo H + Ligo L (+ KAGRA for the first 4 weeks)
  - HL 2 detector uptime: 53%
  - At least one detector up: 70%

- O4b: Apr 24 – current
  - Virgo observing
  - Pause for some interferometers in July-August for in vacuum interventions
  - 3 detector uptime: 31% (45% before the July pause)
  - At least one detector up: 88%

O4b extended to June 2025

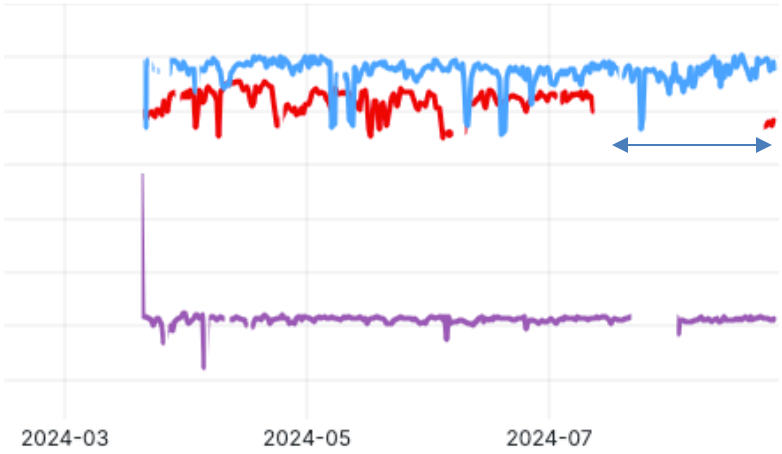


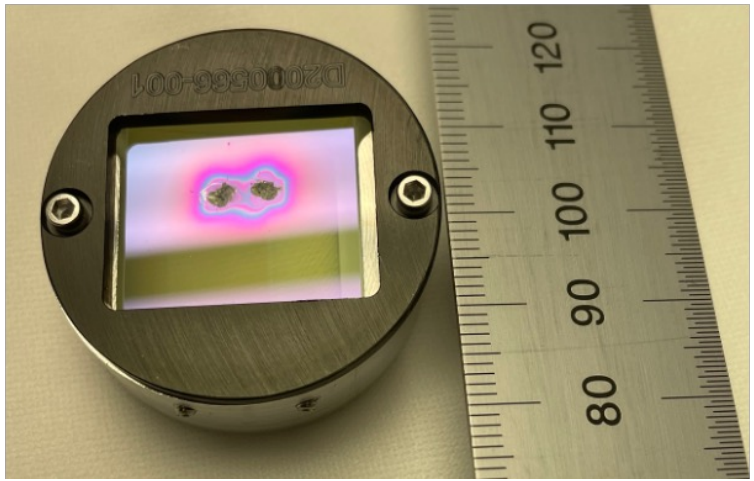


STATUS OF THE DETECTORS

LIGO

- Smooth running with range ~ 150 (H) – 170 (L) Mpc
- Hanford down for ~8 wks due to a hardware problem, now fully recovered
  - In-vacuum replacement of damaged crystal causing excess losses





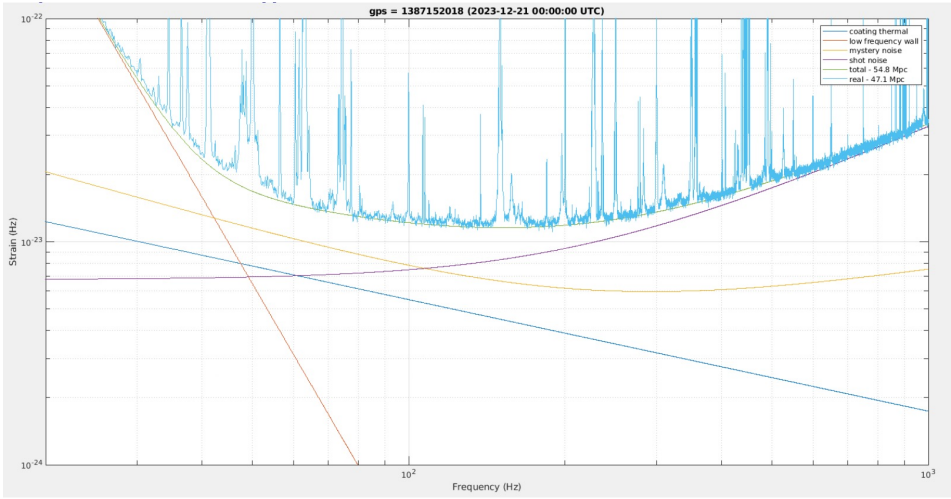
LHO alog 79331

VIRGO

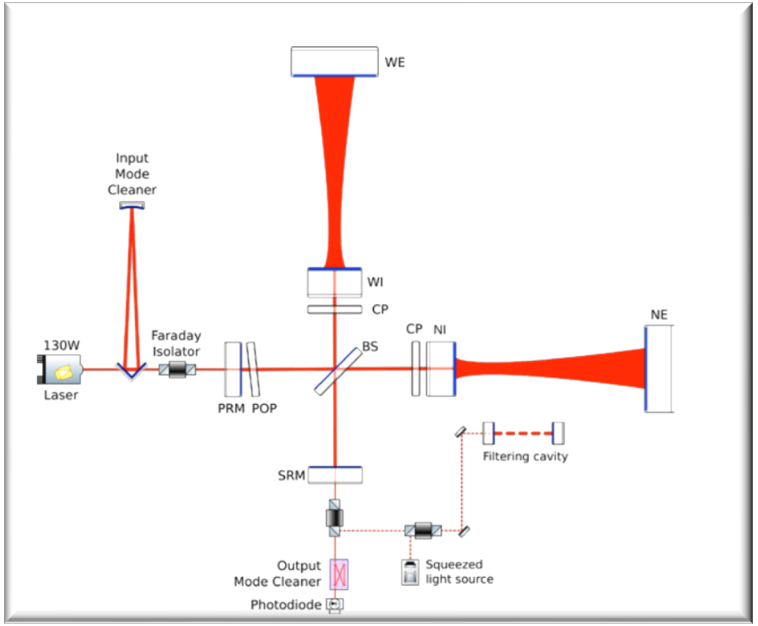
- After a troublesome commissioning, Virgo joined O4 in April 2024
- Sensitivity limited at ~ 55 Mpc (BNS inspiral range)
- The configuration of the recycling cavities (marginally stable), makes the detector very sensitive to aberrations and thermal effects
  - Impact on the commissioning complexity and schedule
  - Virgo running at redued input power (18 W)
- Sensitivity in the "bucket" constrained by an unidentified noise source

VIRGO – The excess noise

- Virgo sensitivity in the bucket limited by a noise not yet understood
  - Spectral dependence: $f^{-2/3}$
  - Reducing the BNS range by ~15 Mpc
- Intense effort being pursued to identify and tackle it
  - Scaling with SR alignment (sensitivity-bandwidth tradeoff)
  - It is not: a displacement noise, a frequency noise…
  - Dedicated group in place
  - Many tests done, more planned
- Currently under investigation:
  - Polarization fluctuation noise
  - Thermal noise in the compensation plates
  - Some HOM
  - …

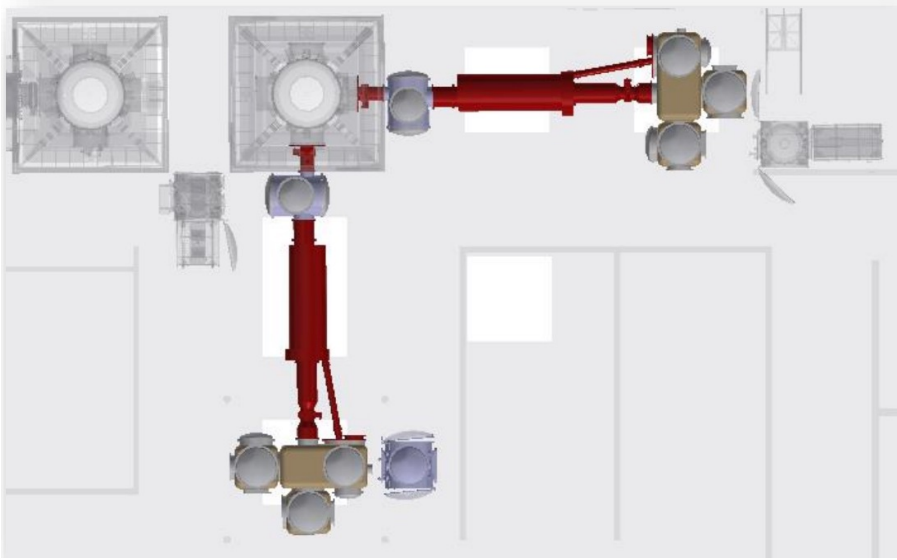


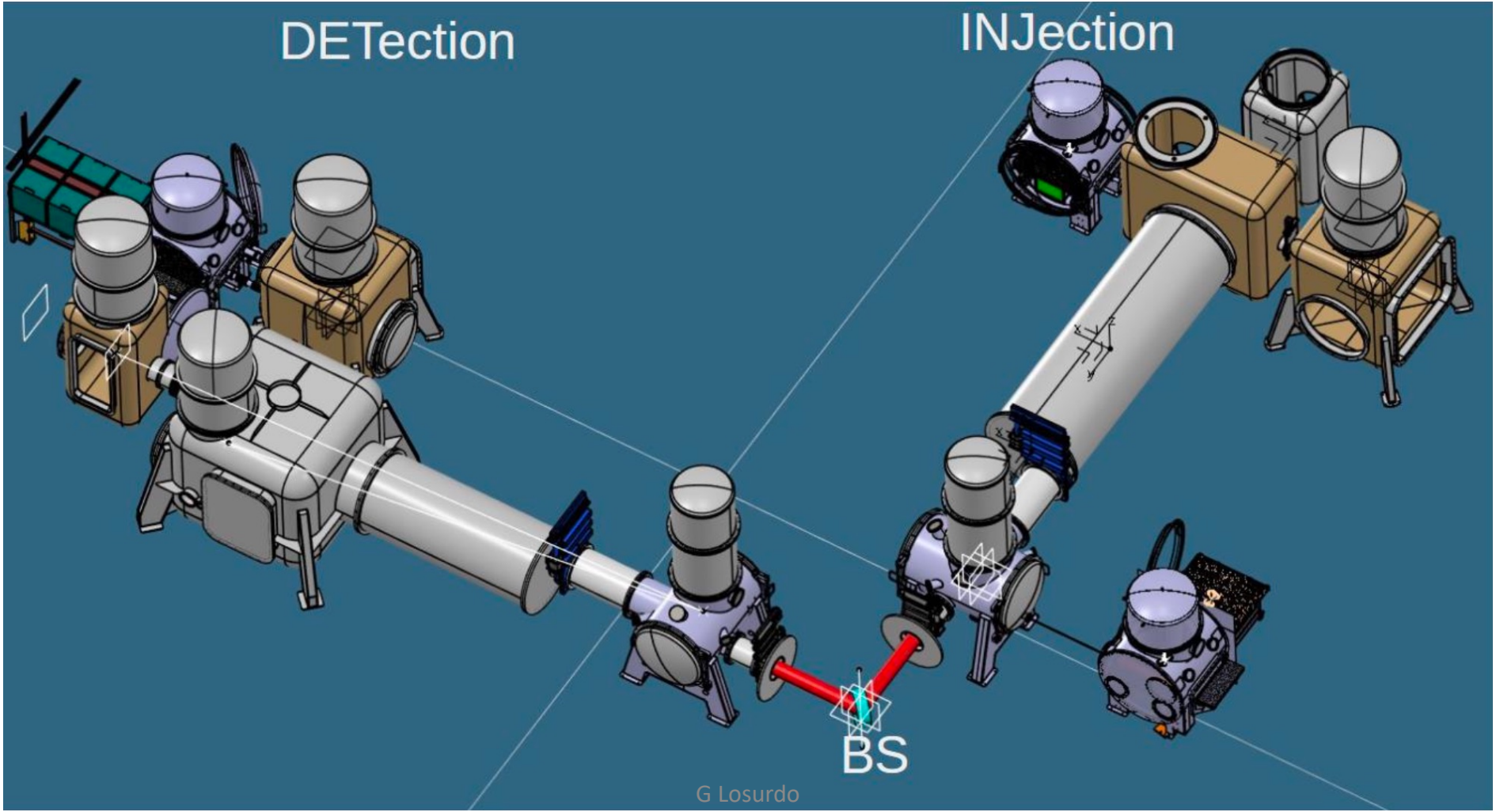
- AdV+ post-O4 original plan
  - Enlarge the beam on end test masses. Requires new mirrors (100 kg, 55cm diameter) and upgraded superattenuators
  - Better coatings (if available)
  - Increased input power (up to 80W)
- Target BNS range: 145-260 Mpc
- Current plan (plan A):
  - Install stable cavities at the cost of a later start of O5
  - Postpone installation of 100 kg end test masses to after O5



VIRGO – STABLE CAVITIES

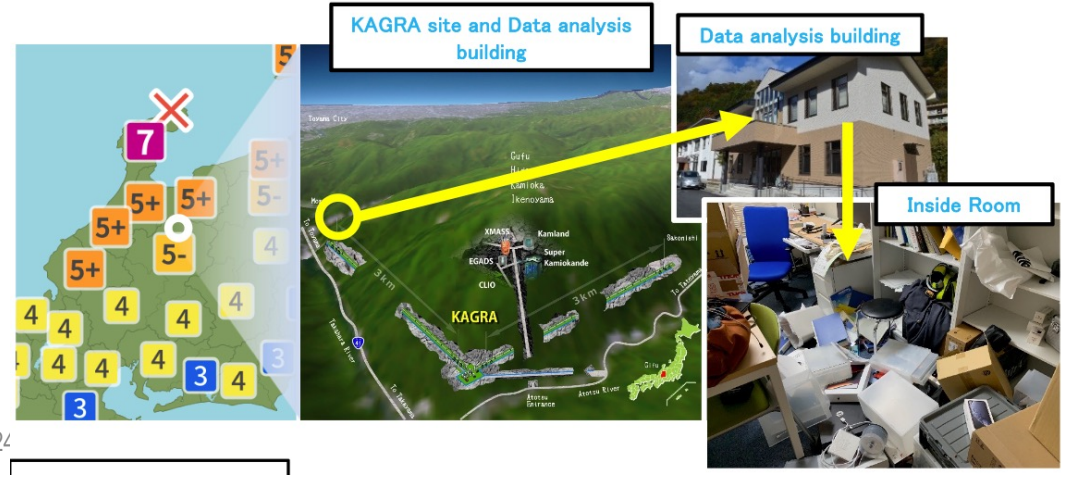
- Design choice: "Short cavities"
- Can be implemented within the main building
  - Removal of some big vacuum chambers
  - Compact suspensions
- Installing stable cavity is a priority (Plan A). But schedule for installation/recommissioning hardly compatible with O5
- A Plan B has been also prepared: install several minor upgrades before O5 and postpone stable cavities to after O5
  - Compatible with O5 schedule, but sensitivity limited and higher risk
- Decision (Plan A or B) by spring 2024




DETection
INJection
BS

KAGRA

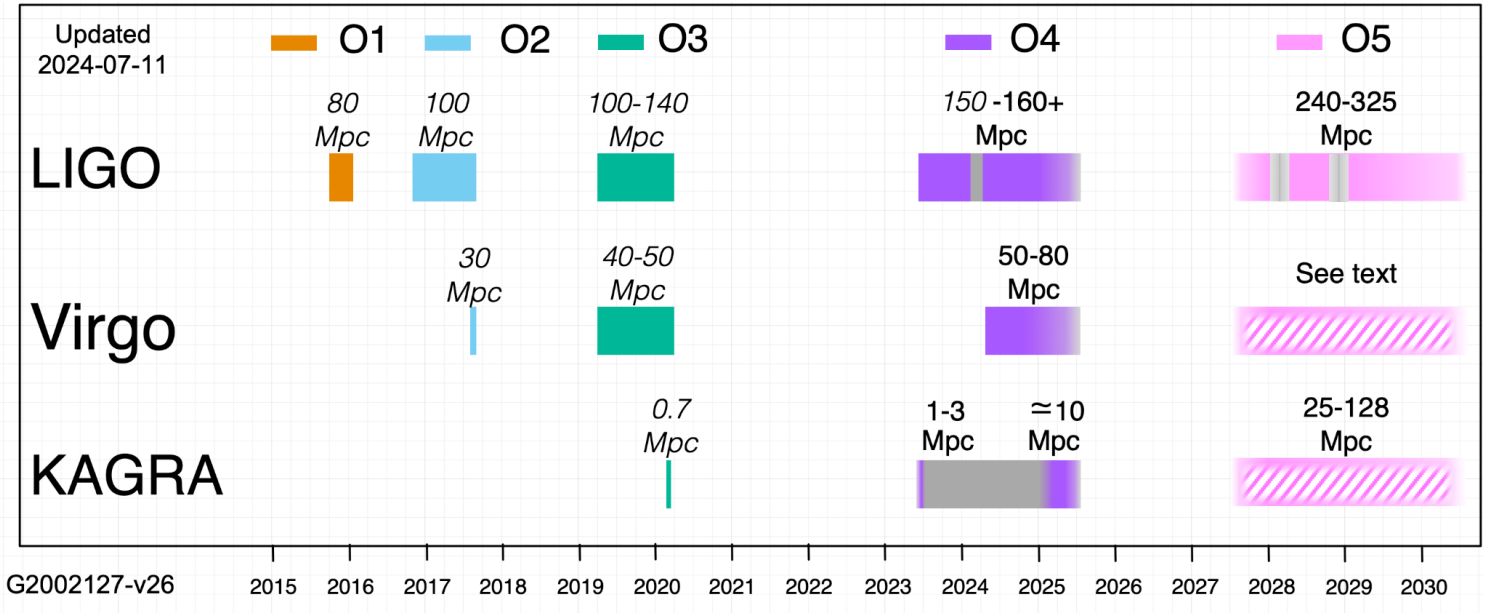
- Jan 1st 2024: M7.6 earthquake at Noto peninsula, significant damage to KAGRA
- Impossible to join O4b in spring (original target)
- Recovery of mechanical damages in 10 isolators completed in July
- Some vacuum leaks found, repair in September
- Goal to rejoin O4 with BNS range of ~ 10 Mpc



TOWARDS O5

Post-O4 upgrades

OBSERVING PLANS



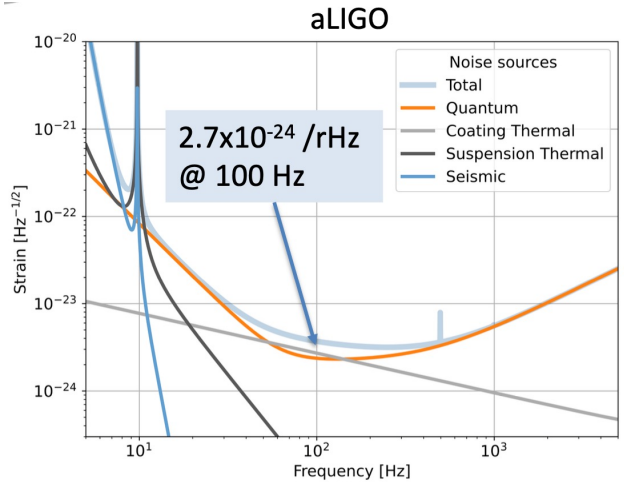
https://observing.docs.ligo.org/plan/

* 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 June 2025

LIGO/VIRGO

- In the original plans the most significant upgrade expected for Virgo and LIGO between O4 and O5 is the implementation of new test mass coatings with reduced losses. This would significantly improve the sensitivity in the bucket
- Joint LIGO-Virgo R&D ongoing to find the right "recipe".
- Target: reduce coating thermal noise by 2
- Current status:
  - Achieved coating thermal noise: 68% of current one (target: 50%)
  - Achieved optical absorption at LMA: 1.3 ppm (target: 0.5 ppm)
- Pathfinder coating of a full scale sample in progress at LMA
  - Decision on new coatings by October



- Beside coatings, LIGO has plans for several post-O4 upgrades, focused on LF sensitivity improvement

A NEW FRAMEWORK: IGWN

BACKGROUND

- **2007:** LIGO-Virgo MoU, “to carry out the search for gravitational waves in the spirit of teamwork, not competition”
- **2015-2017:** the start of a "golden era" for the GW physics
- **2019:** LVK MoU. The network grows, O3 starts

- LV-LVK is a great success story. Now the field is mature and a new step forward is needed to face the new challenges

IGWN

- The LVK recognizes that a new organizational structure is needed to fully exploit the scientific potential of the LVK network
- Need to strengthen the level of coordination in the network to achieve the scientific goals:
  - A single program to set the goals and prioritize them according to scientific merit and resource availability
  - Get rid of parallel and independent decision-making processes
- Many activities can be shared rather than multiplied. We need
  - To support operations of a unified network by acquiring more resources
  - To enable an equitable and efficient sharing of resources
  - To integrate infrastructures and operations across the network

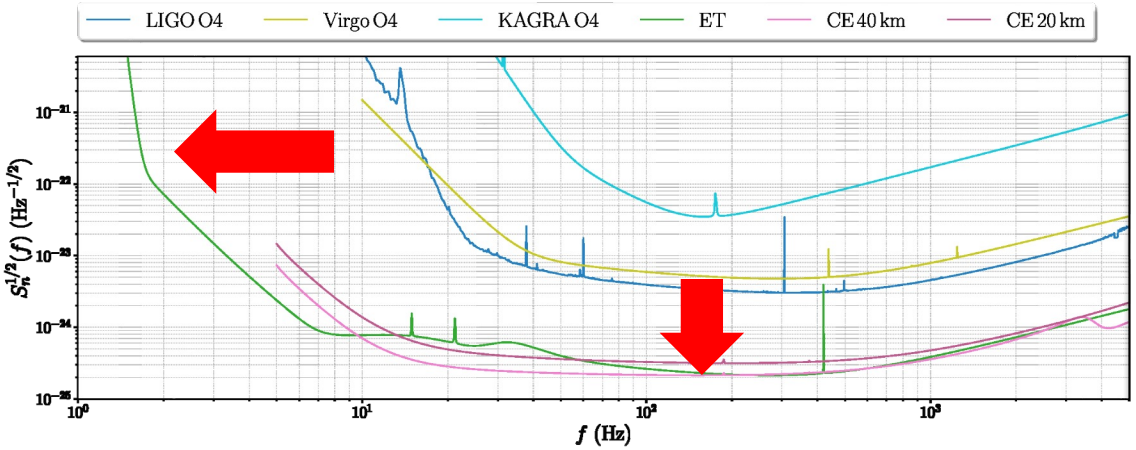
STATUS OF IGWN

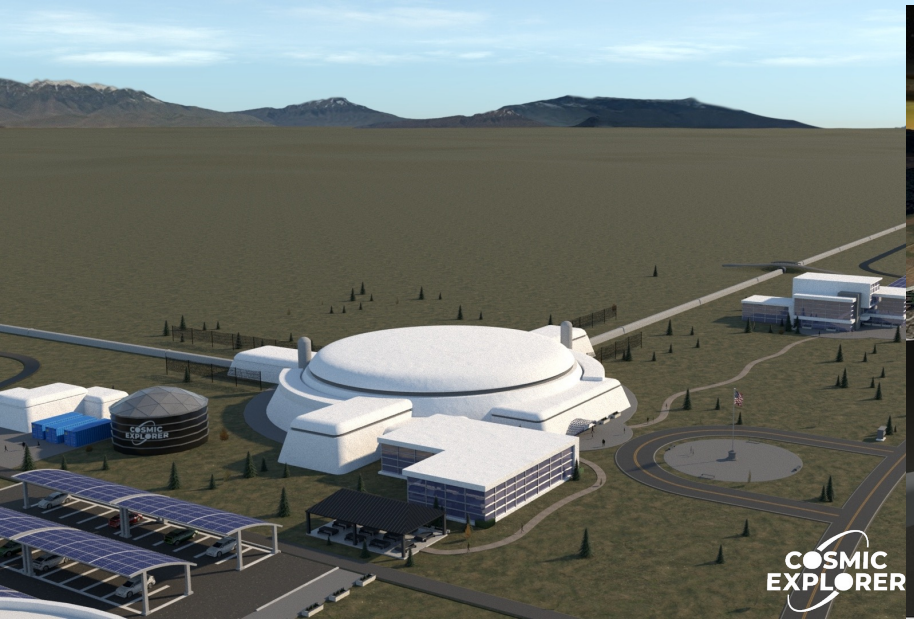
- LVK Committee at work to draft the IGWN Charter (scope and purpose) and Bylaws
  - Secure contributions to detector-related activities from member groups
  - Share funds and manage resources to support IGWN activities
  - Avoid redundancies deriving from multiple venues where decisions are taken
  - Respect the specific needs and regional realities
- Draft IGWN charter released to LVK, Bylaws to follow soon
- Target: IGWN kickoff by mid 2025

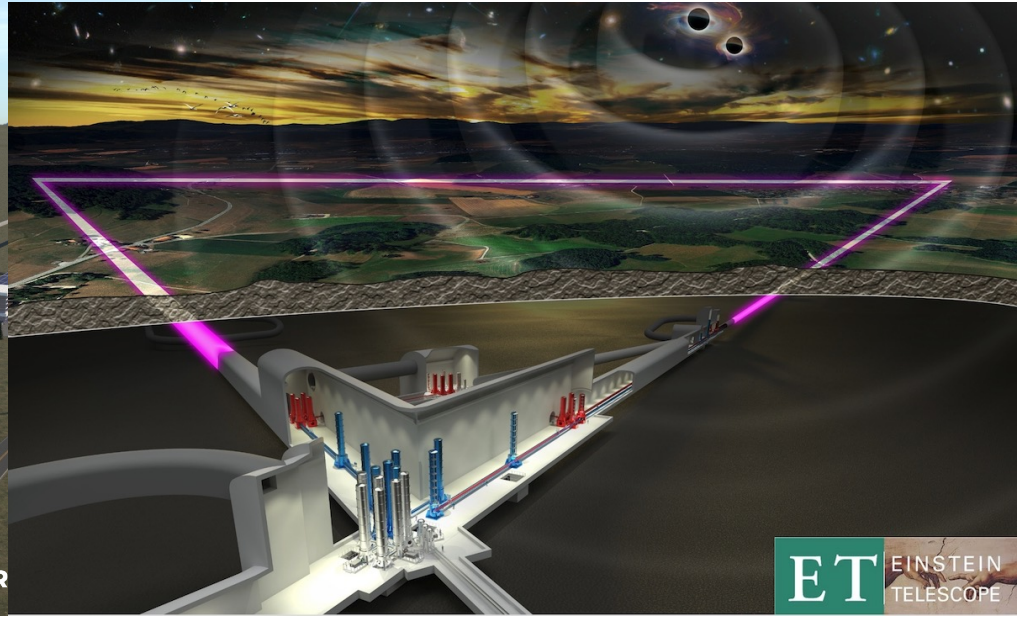
POST-O5: BRIDGING 2G AND 3G

LIGO
VIRGO
KAGRA

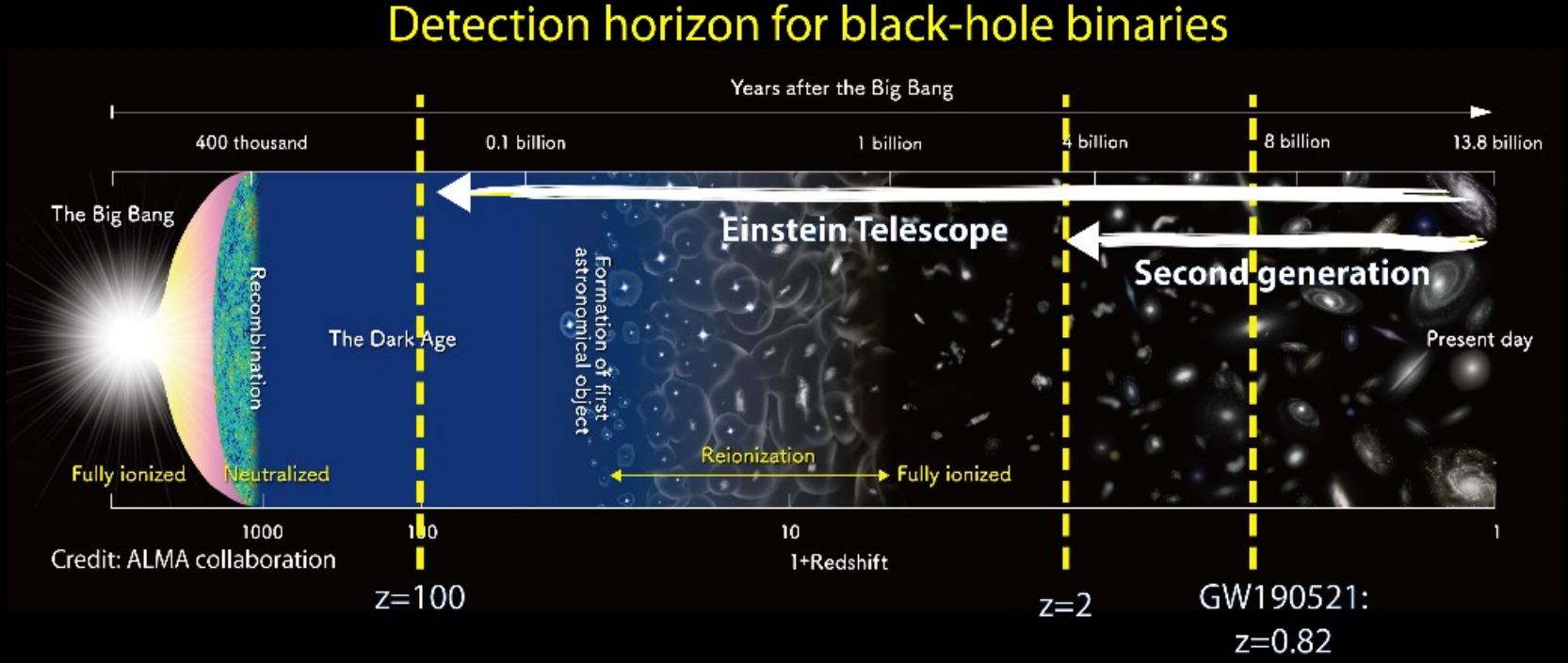
3G







3G POTENTIAL

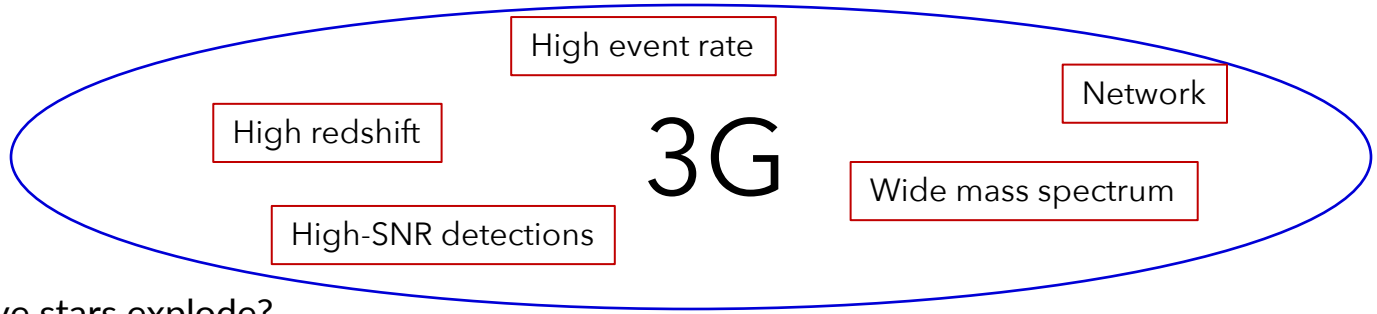


SOME BIG QUESTIONS

(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?

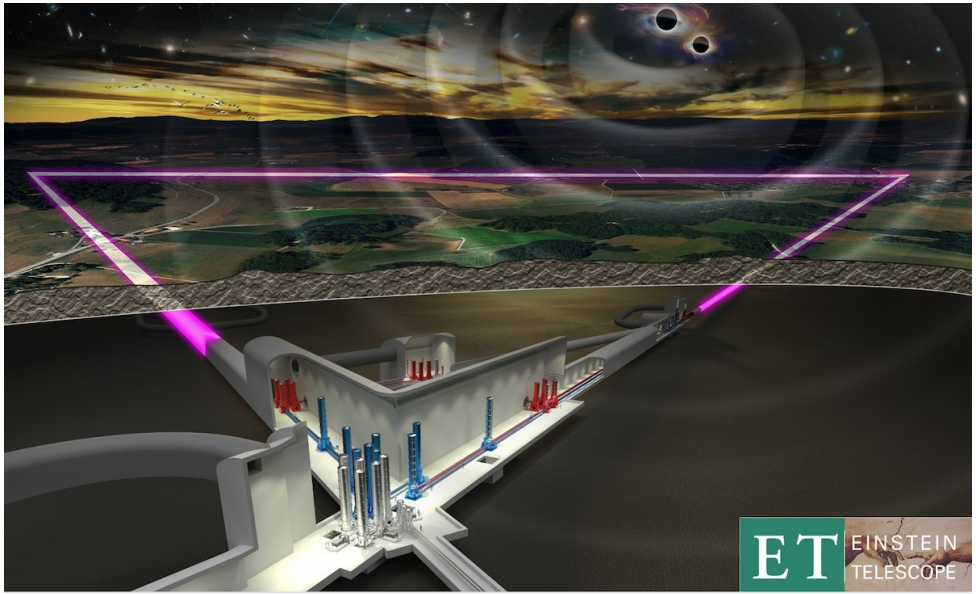
Can we find clues to the nature of DM and DE in GW observations?

Where do heavy elements come from?

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

HOWEVER…

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



A NEW UPGRADE: GOALS

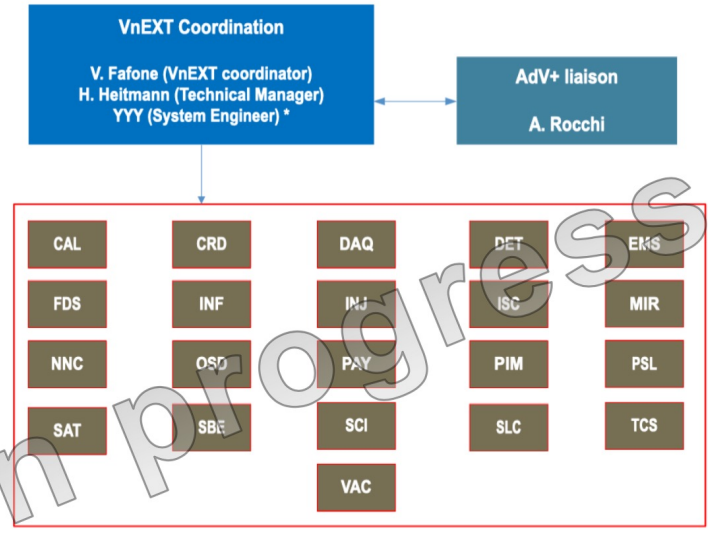
- **Extend and enhance the Virgo/LIGO science program** until the advent of 3G detectors
  - Existing detector will still play a crucial role for ~ a decade after O5
  - Target: ~ 2x sensitivity improvement wrt AdV+/aLIGO+
  - Ensures continuity in the flow of data
- **Intermediate step in technology 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

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

	AdV+ best	V_next best	ET HF
Power inj.	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

- Preliminary R&D plan released in 11/23
- Organization Breakdown Structure being set up
- Baseline Design Report expected by June 2025



A#

- Post-O5 study group set up in mid 2021
- Report released in 2022 and approved by LSC in 01/23
- Grand plan:
  - Larger test masses, improved suspensions
  - Seismic isolation improvements
  - Higher power, higher squeezing
  - Reduced coating thermal noise (crystalline?)

All elements in the CE plan

Design parameter	A+	A♯	CE
Arm length	4 km	4 km	20 km, 40 km
Arm power	750 kW	1.5 MW	1.5 MW
Squeezing level	6 dB	10 dB	10 dB
Mass of test-mass	40 kg	100 kg	320 kg
Test-mass coatings	A+	A+/2	A+
Suspension length	1.6 m	1.6 m	4 m
Newtonian suppression	0 db	6 db	20 db

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

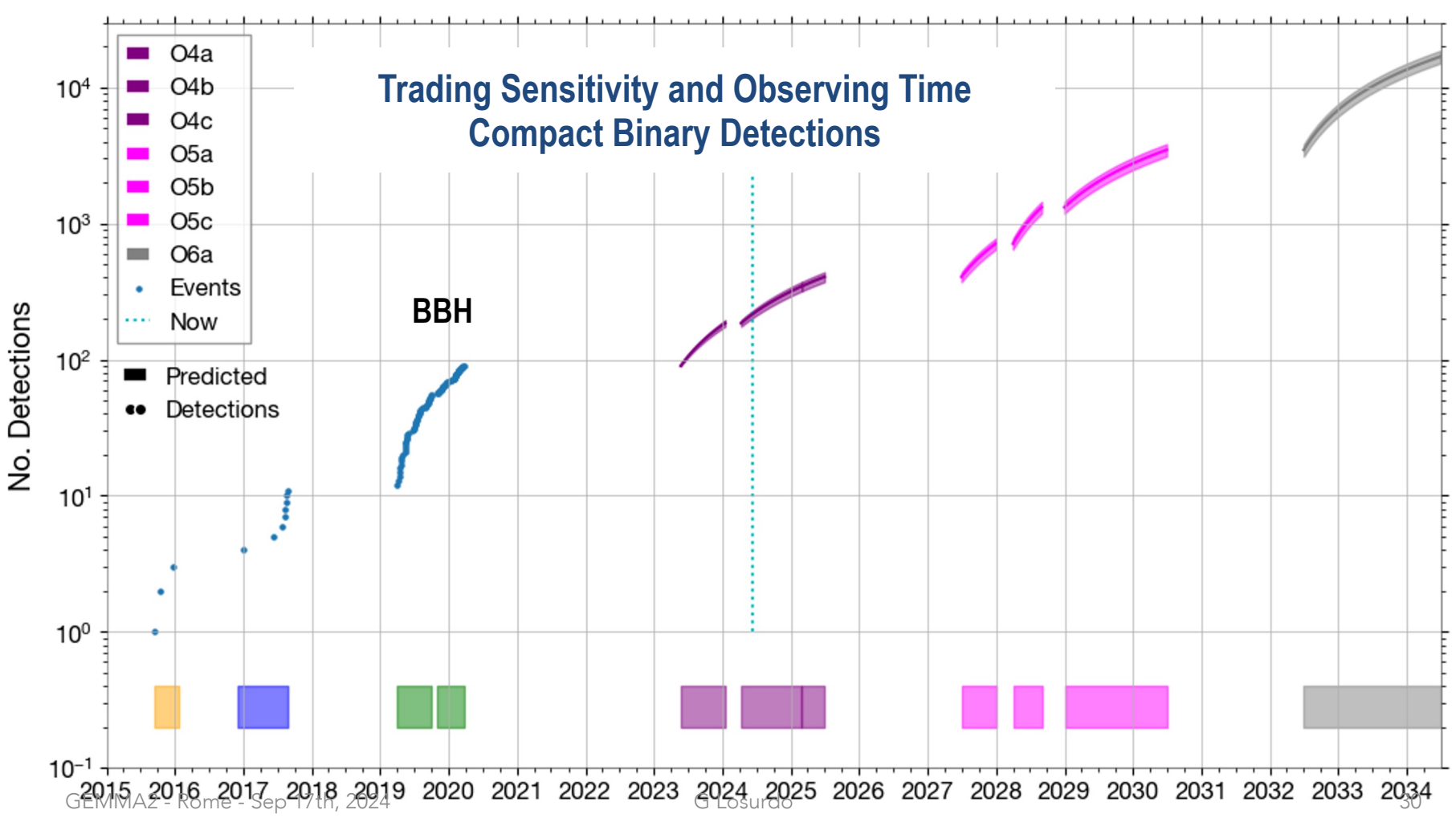
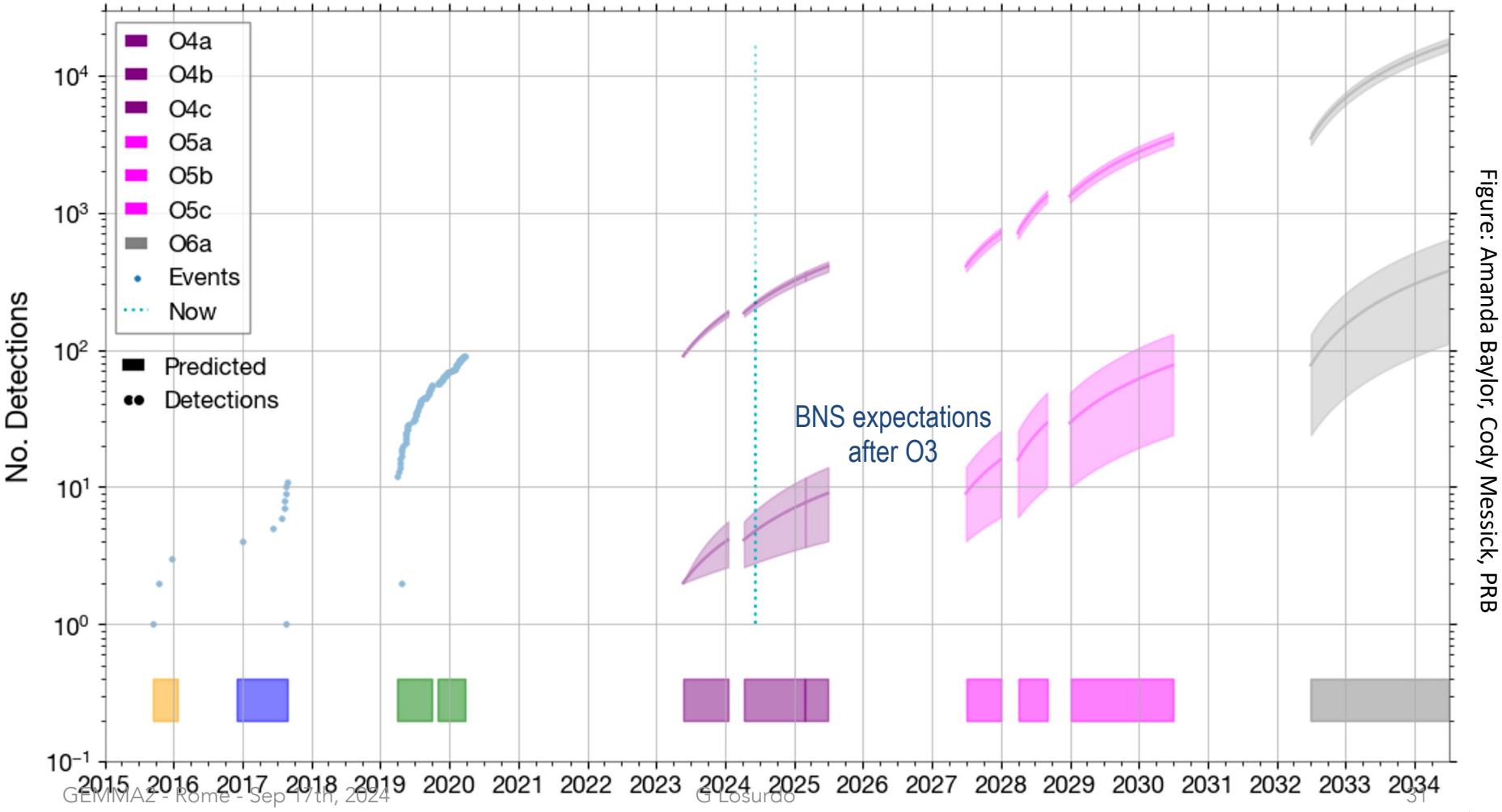


Figure: Amanda Baylor, Cody Messick, PRB



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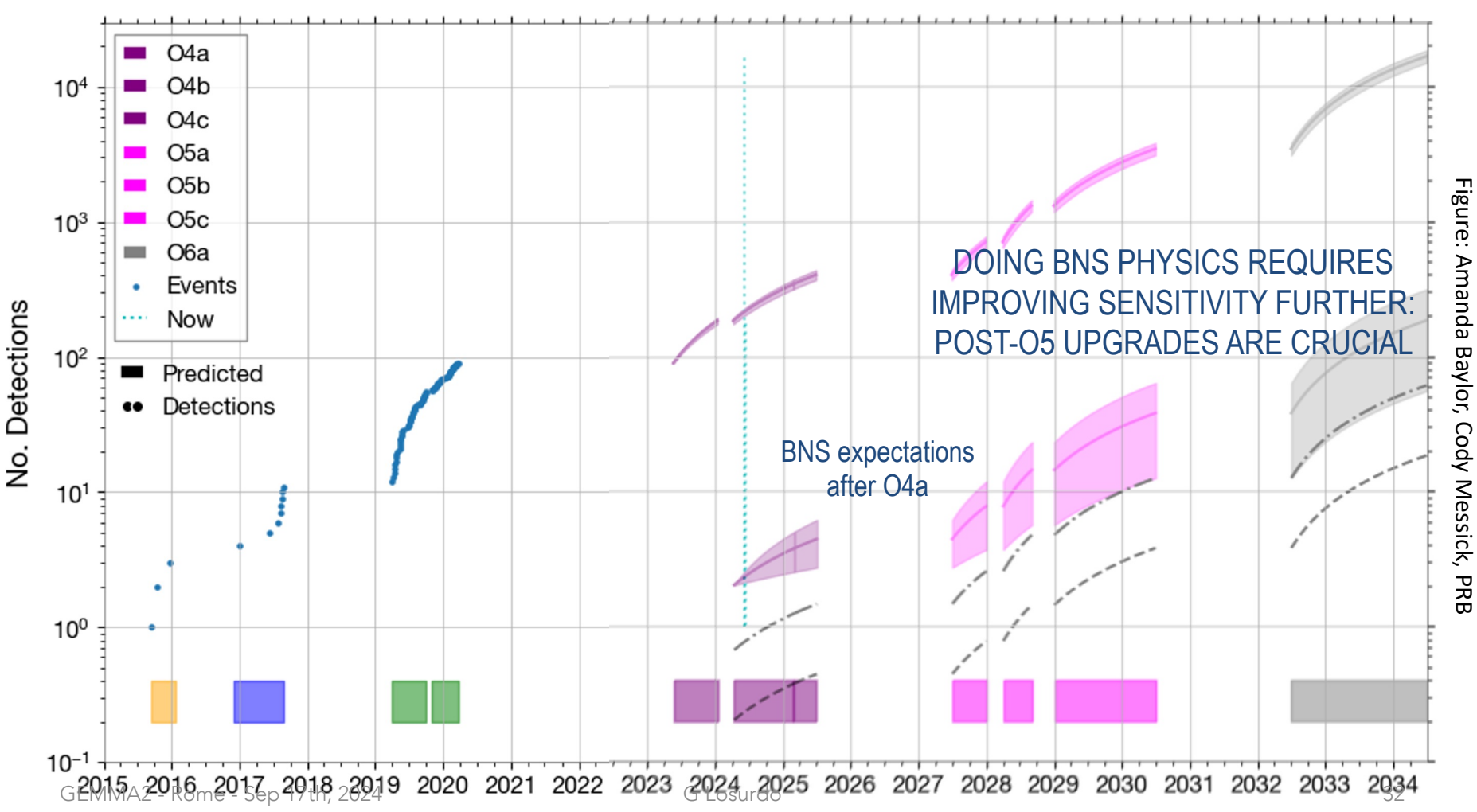

Figure: Amanda Baylor, Cody Messick, PRB

events 1/5 days ~250/yr ~10^3/yr ~10^4/yr ~10^5/yr

O3 O4 O5

A#,Virgo_nEXT

ET/CE

May 24, 2023 2030 ~2035-40

QUASI-CONTINUOUS DATA FLOW AT PROGRESSIVELY BETTER SENSITIVITY

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