Gravitational Waves

KAT Meeting, 17.10.2024

Michèle Heurs, Leibniz Universität Hannover

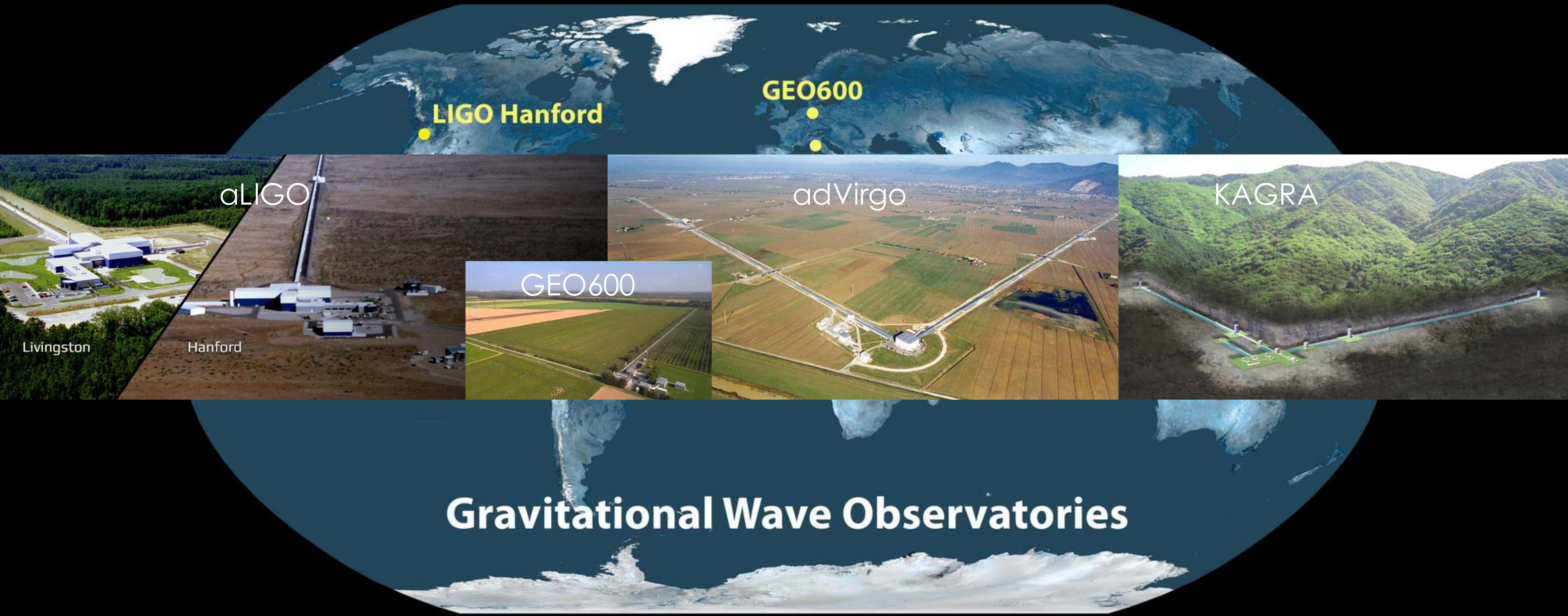
OVERVIEW

- 2G Groundbased Gravitational Wave Detection (GWD)
  - Current status
  - Technical developments: e.g. frequency-dependent squeezing
- Future groundbased GWD
  - Einstein Telescope (ET) *=> see also talk by Harald Lück tomorrow morning!*
  - Cosmic Explorer (CE, in the US)
  - Intermediate iterations:

    A+, A#, Voyager
- LISA (Laser Interferometer Space Antenna)
- PTA (Pulsar Timing Arrays): recent results

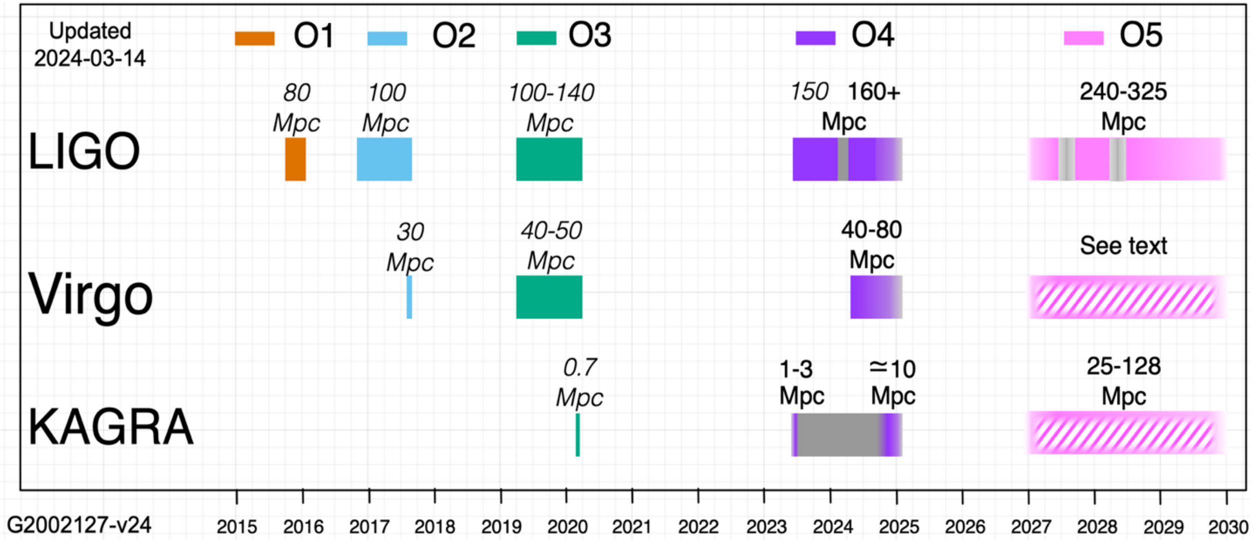
Key science questions

WORLDWIDE GWD NETWORK (CURRENT, 2G)

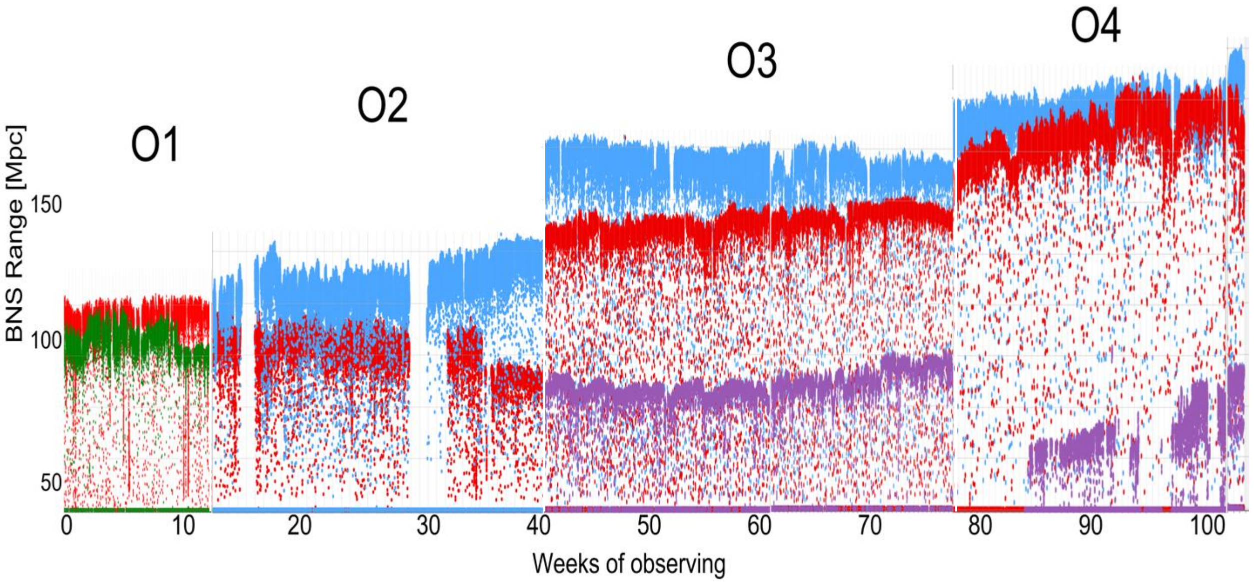


Developments in aLIGO

- Observation runs
- Astrophysical reach
- Instrumentation example: Frequency-dependent squeezing



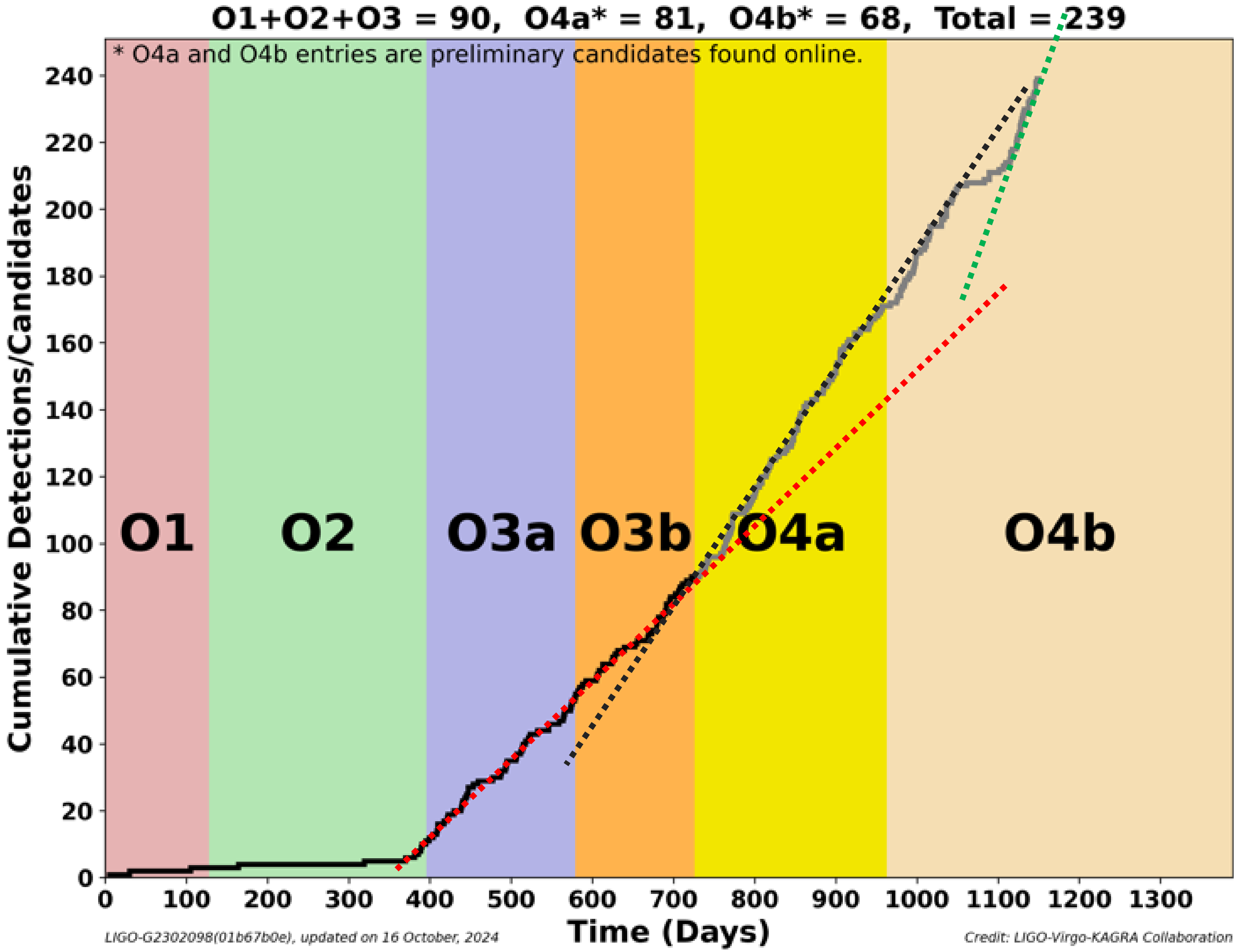
observing.docs.ligo.org/plan/



https://ldas-jobs.ligo.caltech.edu/~detchar/summary

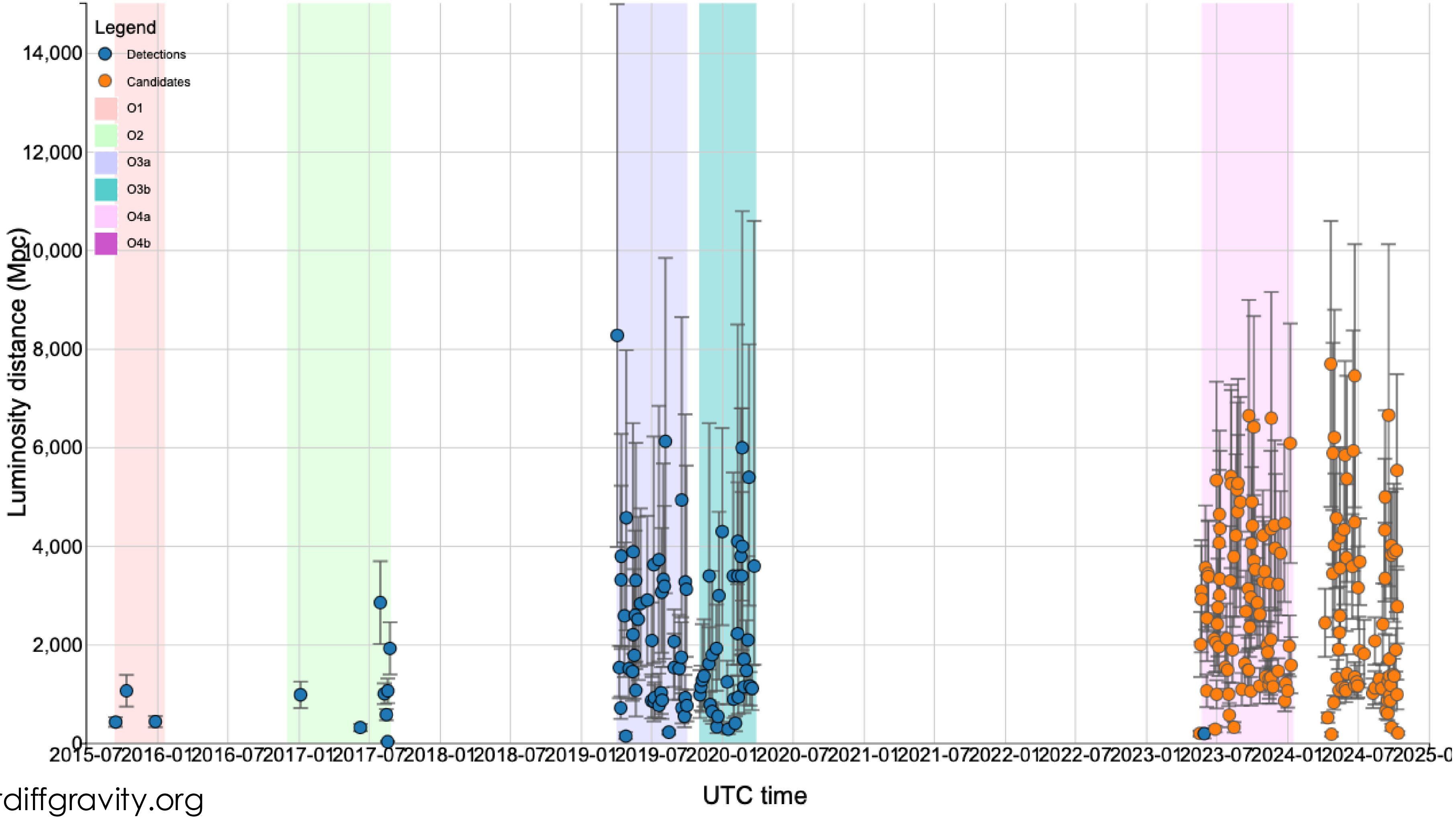
Definition BNS inspiral range:
= Distance at which a GW signal
from a **BNS merger with 1.4$M_\odot$ /1.4$M_\odot$**
would be detected with
a **signal-to-noise ratio (SNR) of 8**,
averaged over **all possible sky locations and inclinations**
without considering cosmological corrections.

OBSERVATIONS TO DATE (16.10.24)

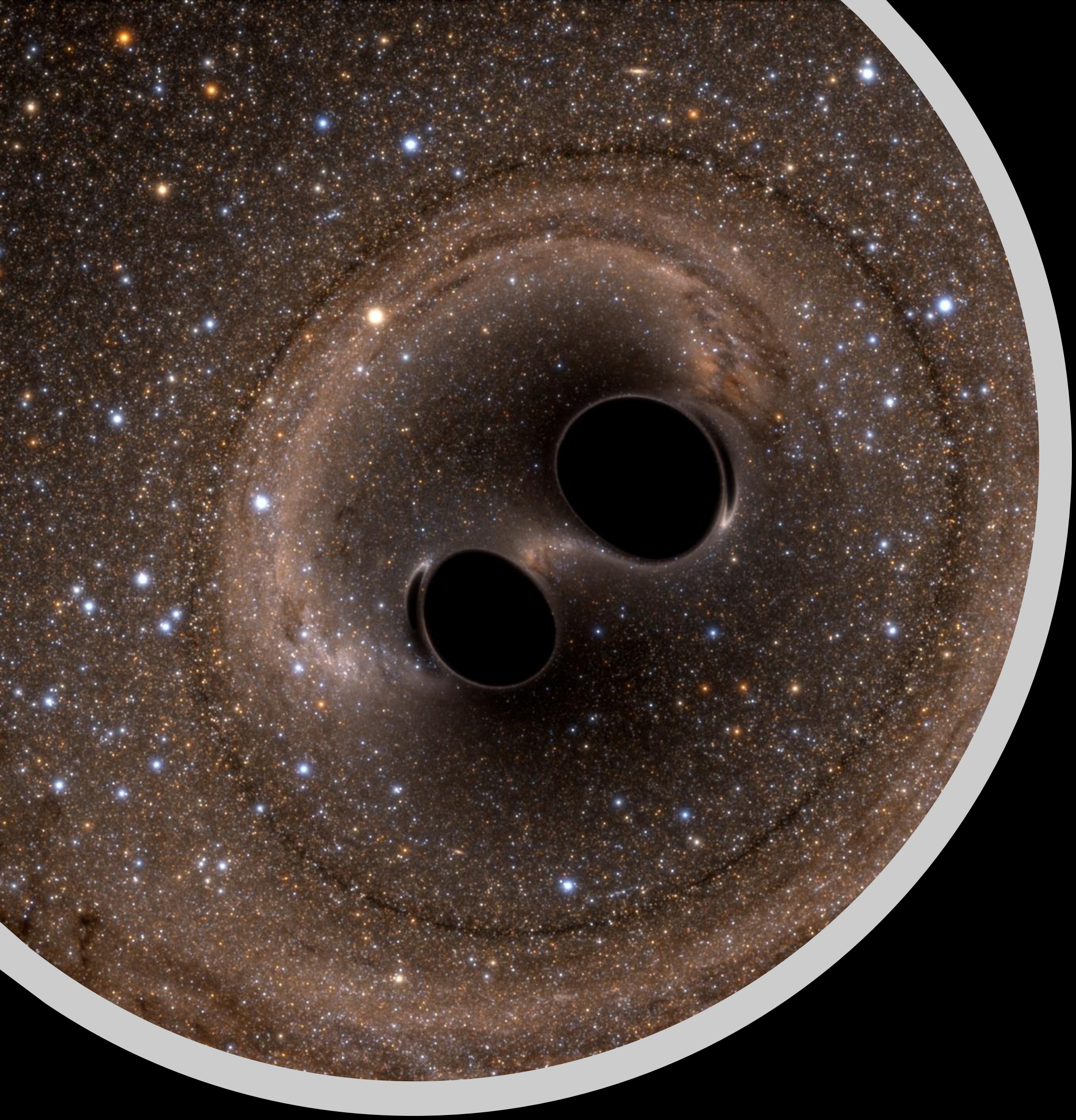


http://gracedb.ligo.org

LIGO-VIRGO-KAGRA COMPACT BINARY CATALOGUE



http://catalog.cardiffgravity.org



What have we already learned?

- **First detection of GWs** from a BBH system (GW150914)
  - Physics of BHs
- First detection of **GWs from a BNS** system (GW170817)
  - Birth of multimessenger astronomy with GWs
  - Constraining the equations of state of neutron stars
- **Localisation** capabilities of a GW source
- Measurement of the GW propagation speed
- **Test of General Relativity**
- Alternative measurement of the **Hubble constant**
- GW polarisations
- **Intermediate mass black hole** (GW190521)

[Slide modified from M. Punturo, APS Talk 2022 „GW Perspectives"]

adVirgo test mass (42 kg, f = 350 mm, d = 200 mm)

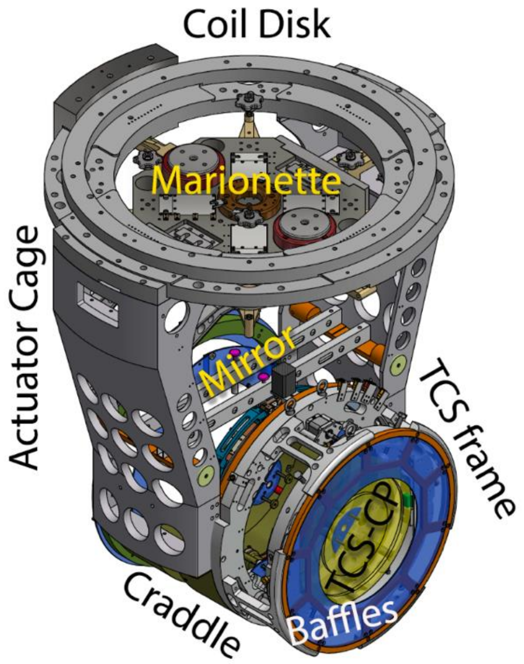


Figure 3. Input Payload, CAD drawing.

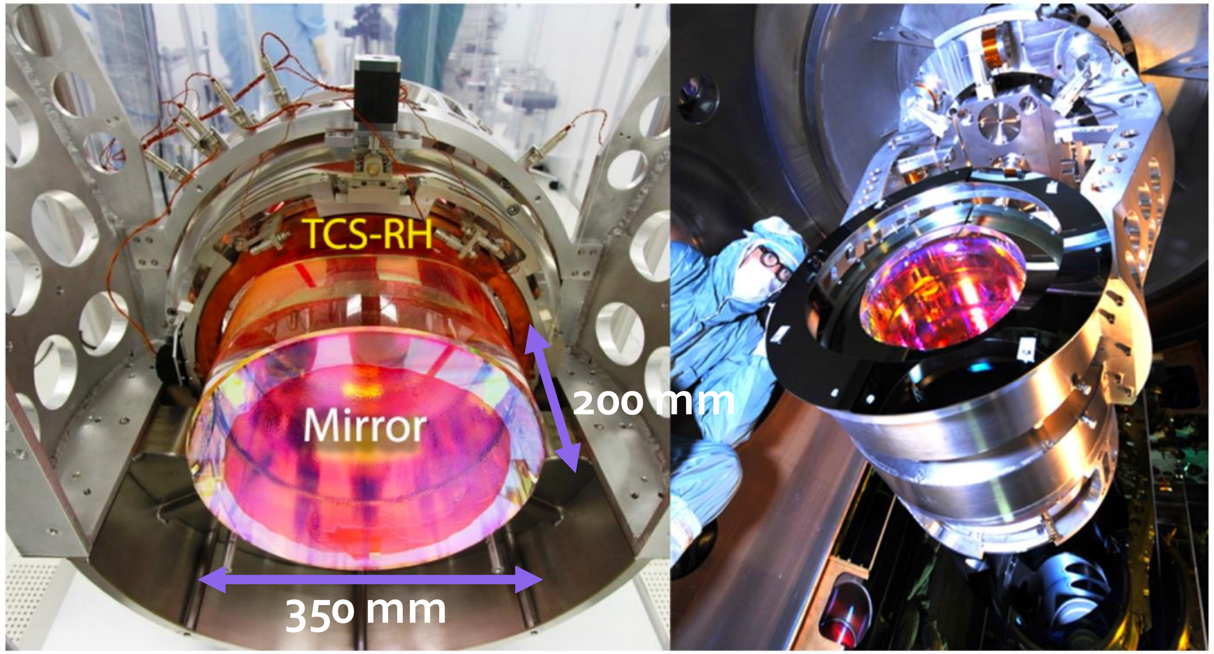
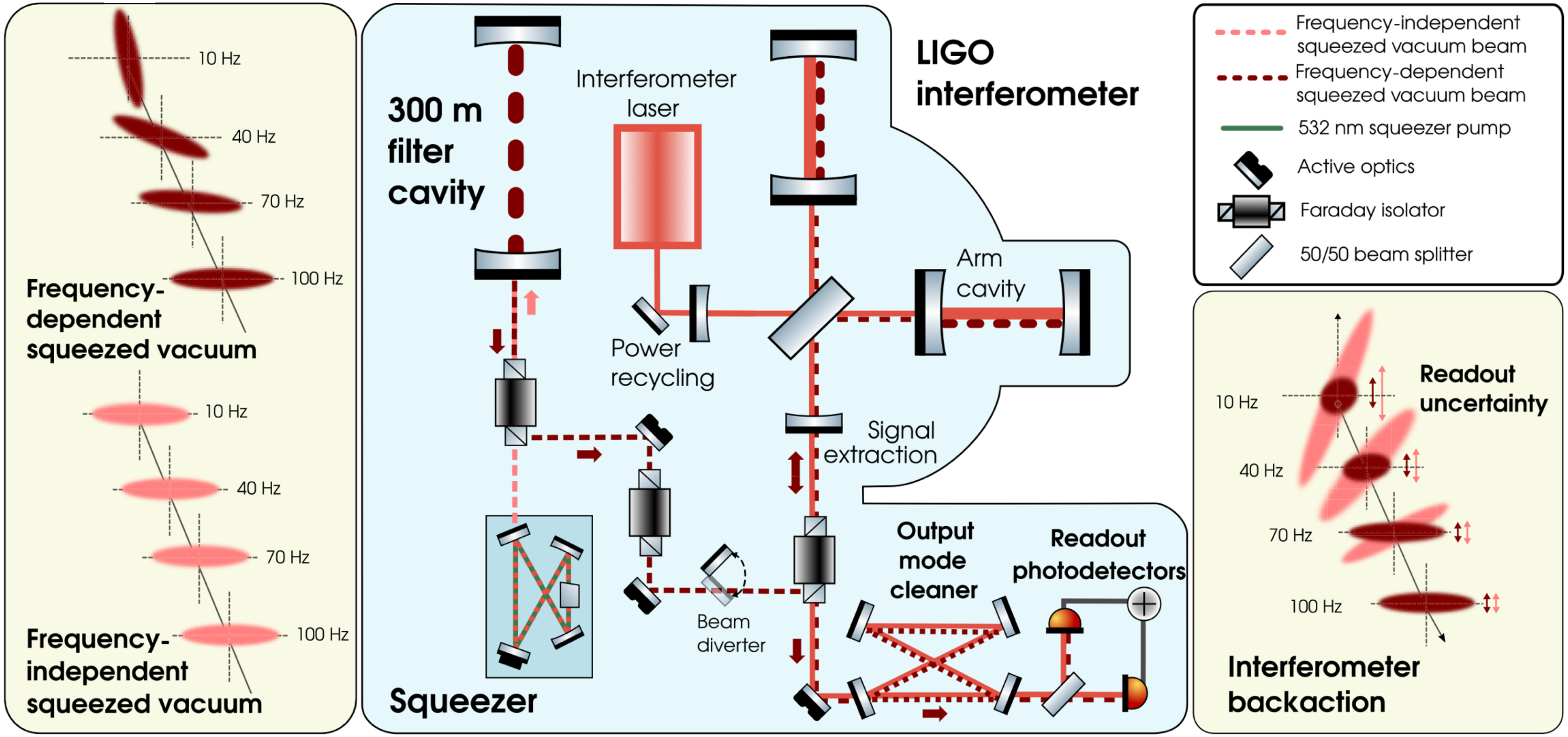


Figure 4. Input Payload during assembly (left) and its integration with SA (right).

modified from: L. Naticchioni and on behalf of the Virgo Collaboration, J. Phys.: Conf. Ser. **957** 012002 (2018)

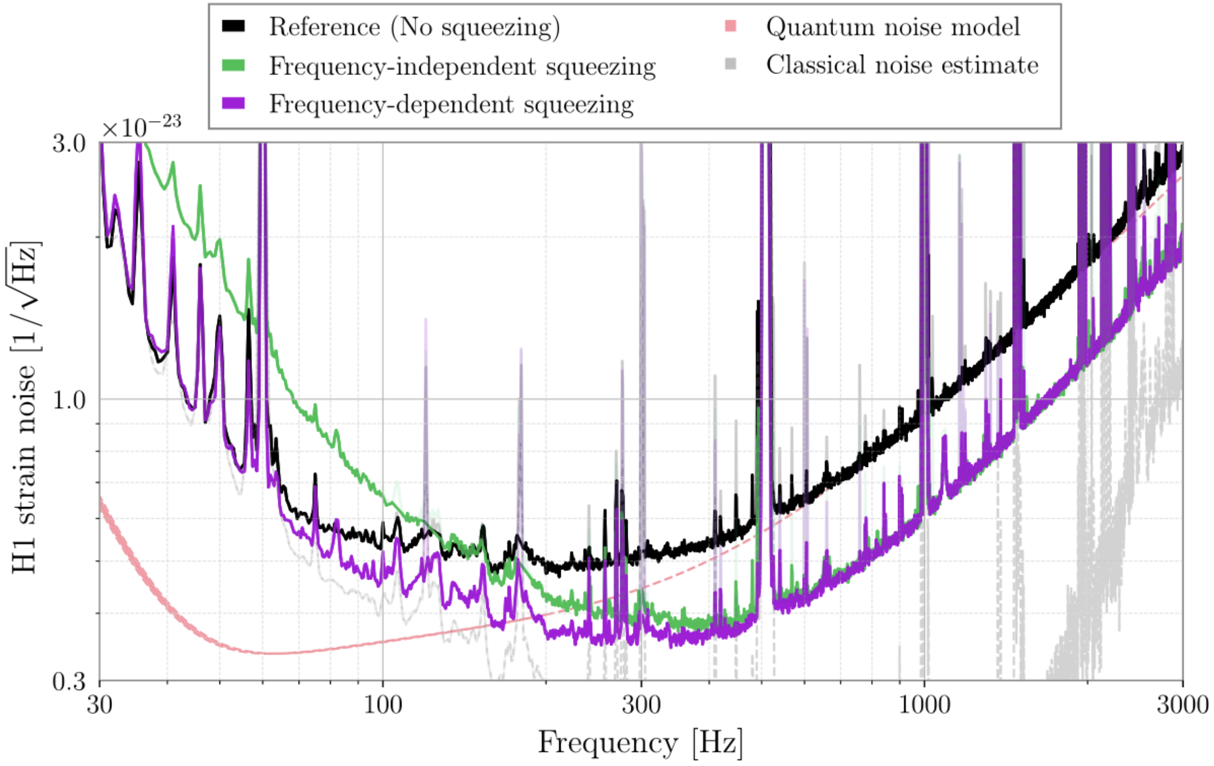
Frequency-dependent squeezing in aLIGO



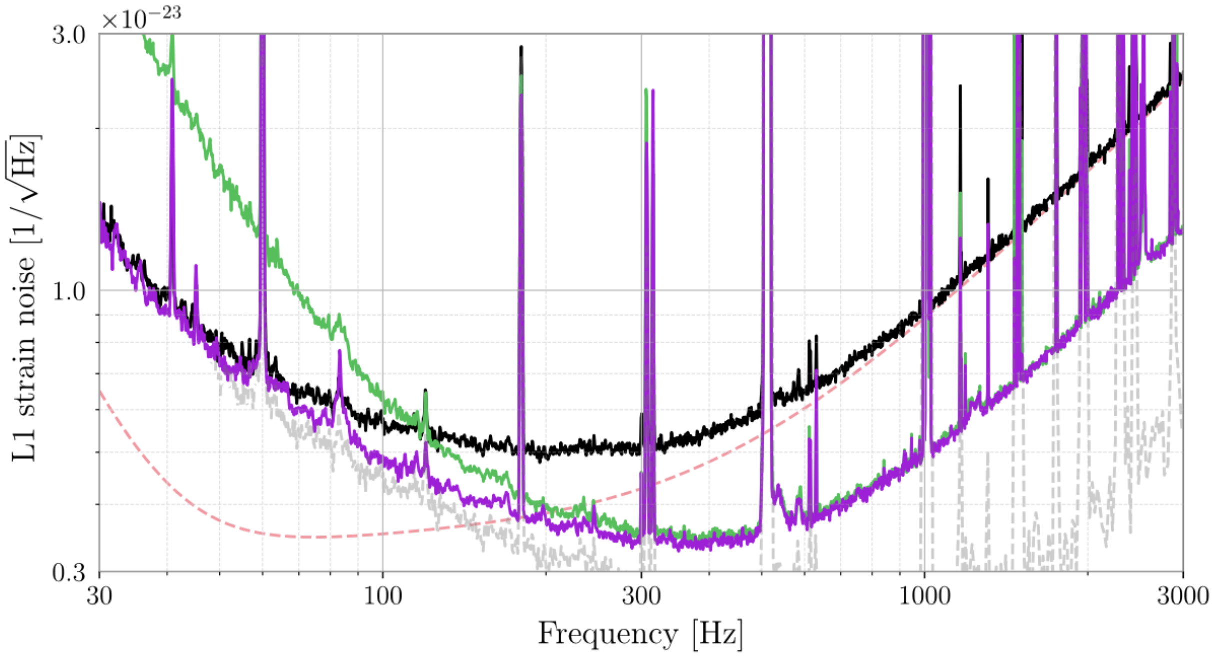
D. Ganapathy et al. (The LIGO O4 Detector Collaboration), „Broadband Quantum Enhancement of the LIGO Detectors with Frequency-Dependent Squeezing“, Phys. Rev. X **13**, 041021 (2023)]

Frequency-dependent squeezing in aLIGO

LIGO Hanford



LIGO Livingston



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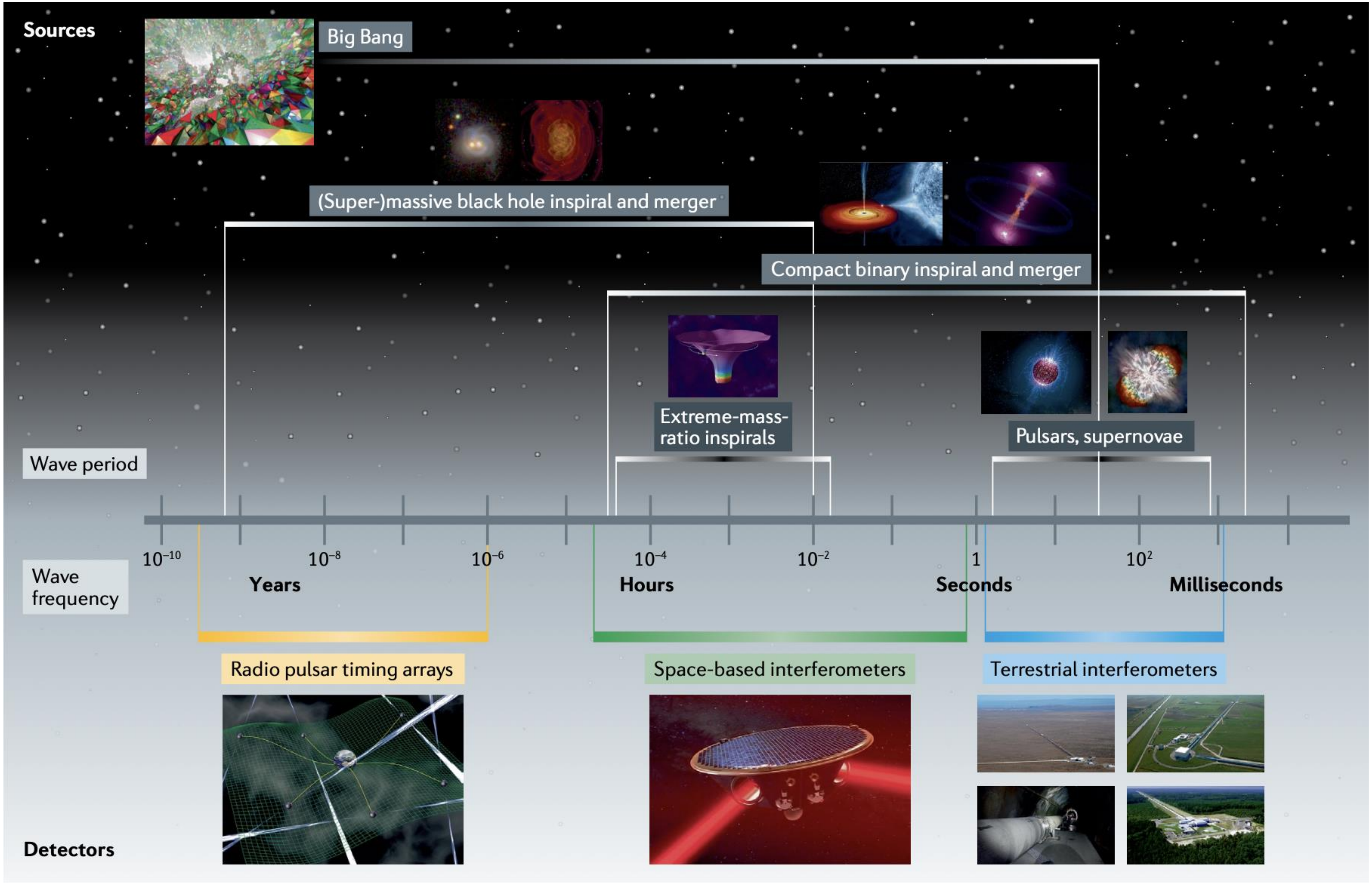
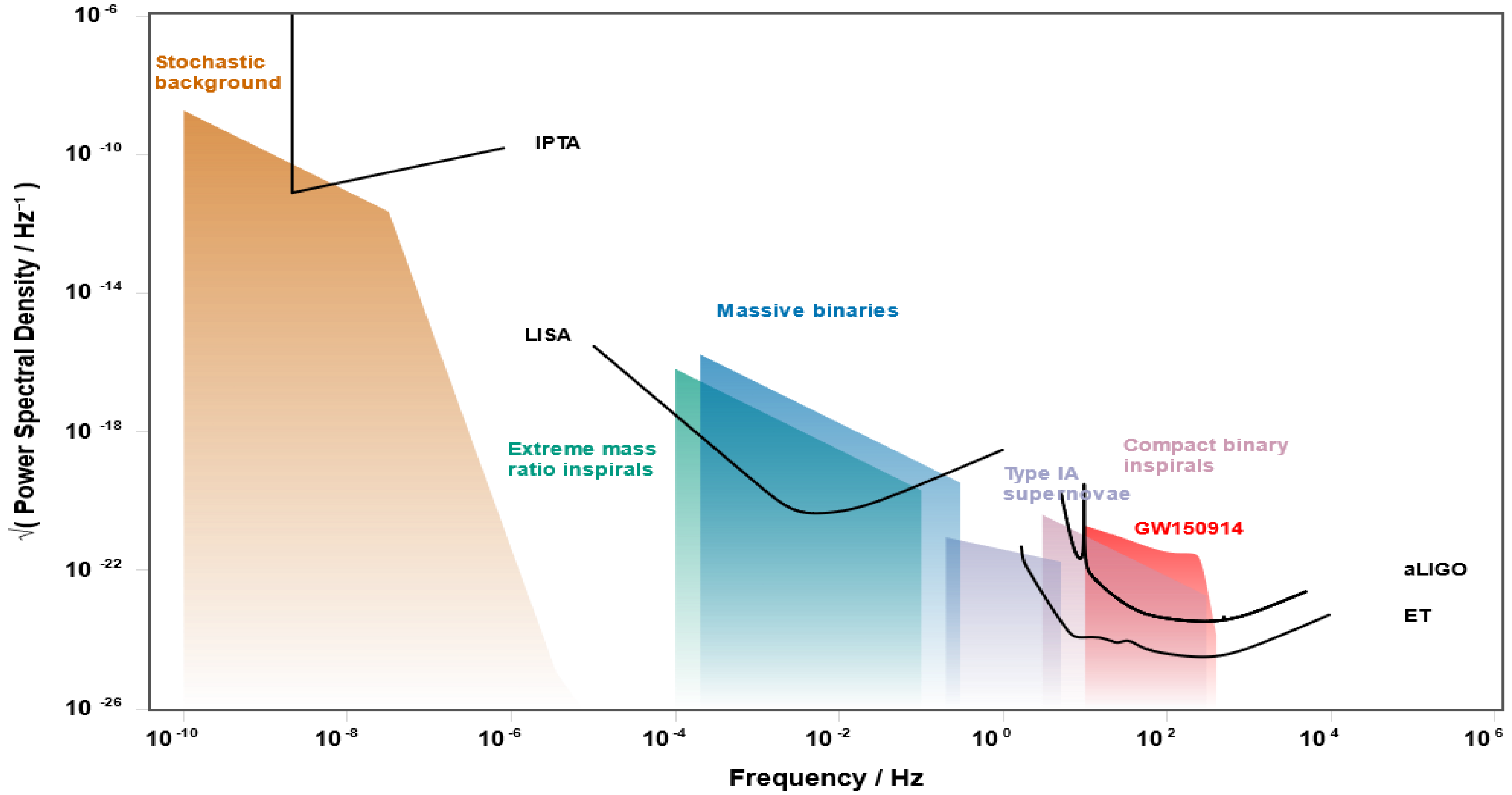
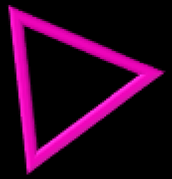


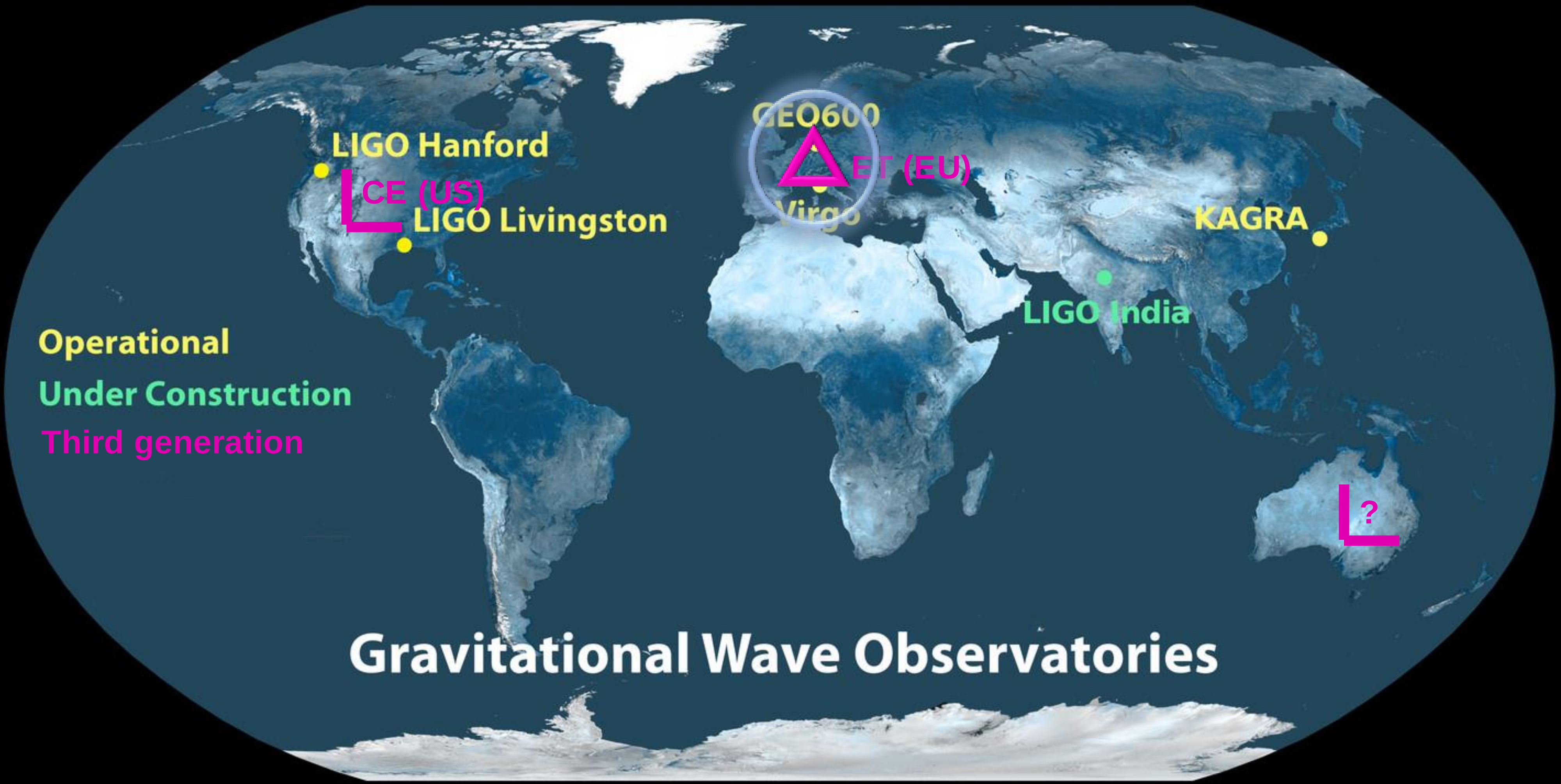
Bailes, M., Berger, B.K., Brady, P.R. et al., Gravitational-wave physics and astronomy in the 2020s and 2030s, Nat Rev Phys 3, 344–366 (2021), https://doi.org/10.1038/

ASTROPHYSICAL SOURCES



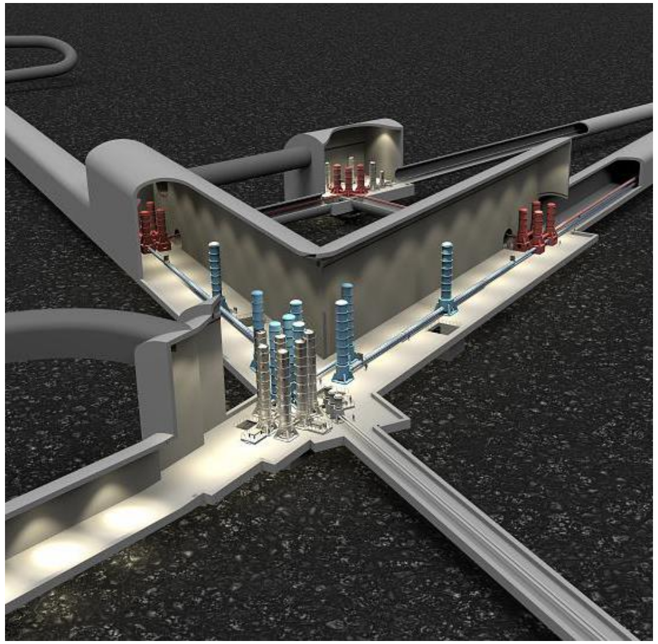
FUTURE GWD NETWORK


LISA



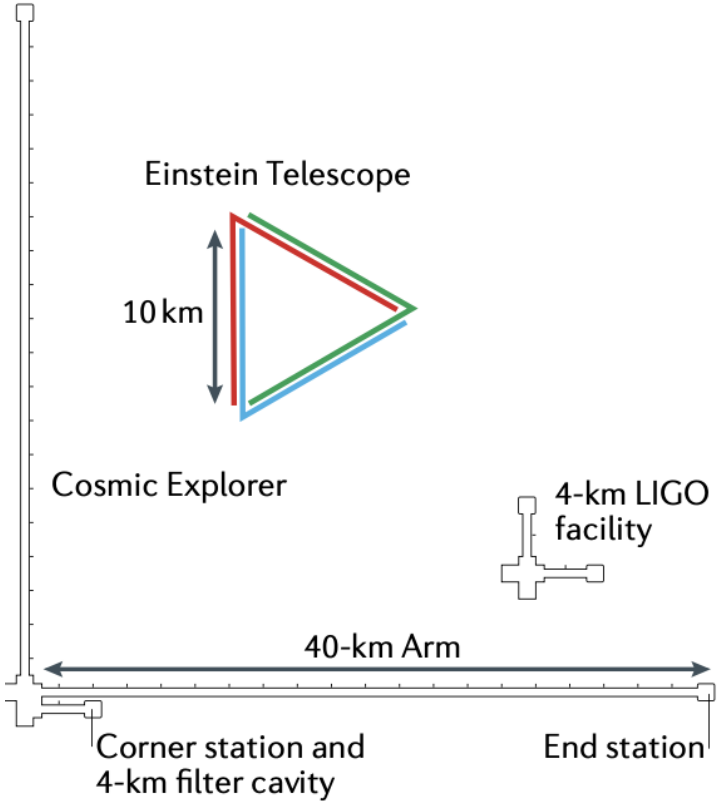
3G GROUNDBASED GWD

Einstein Telescope



Baseline: Triangular configuration with 10 km length
Underground (200 – 300 m) construction
3 detectors with 2 interferometers each
Xylophone design (LF and HF)

https://www.einstein-teleskop.de



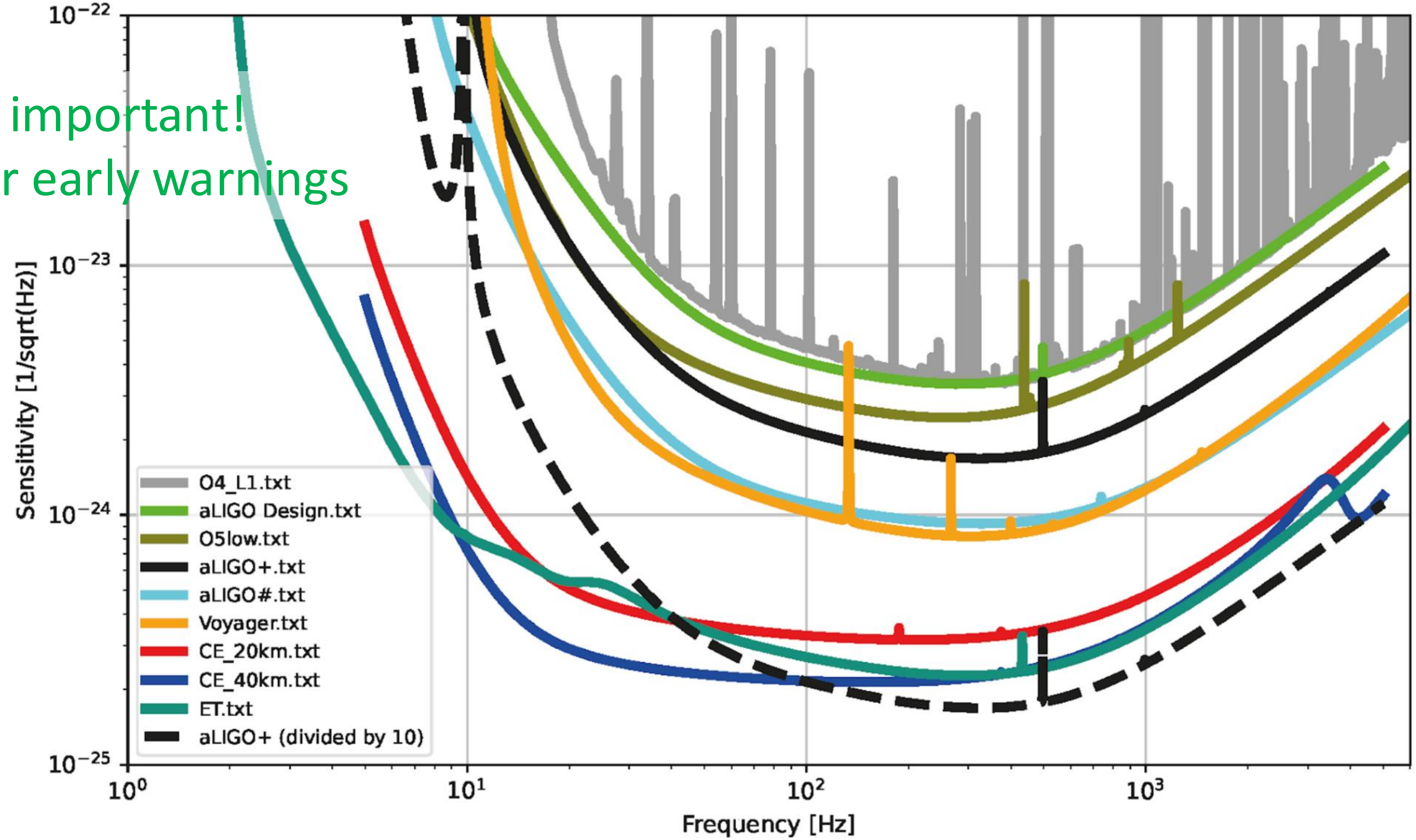
Bailes, M., Berger, B.K., Brady, P.R. et al. Nat Rev Phys 3, 344–366 (2021)

Cosmic Explorer

From: https://physics.mit.edu/
Image: Angela Nguyen, Virginia Kitchen, Eddie Anaya, California State University Fullerton

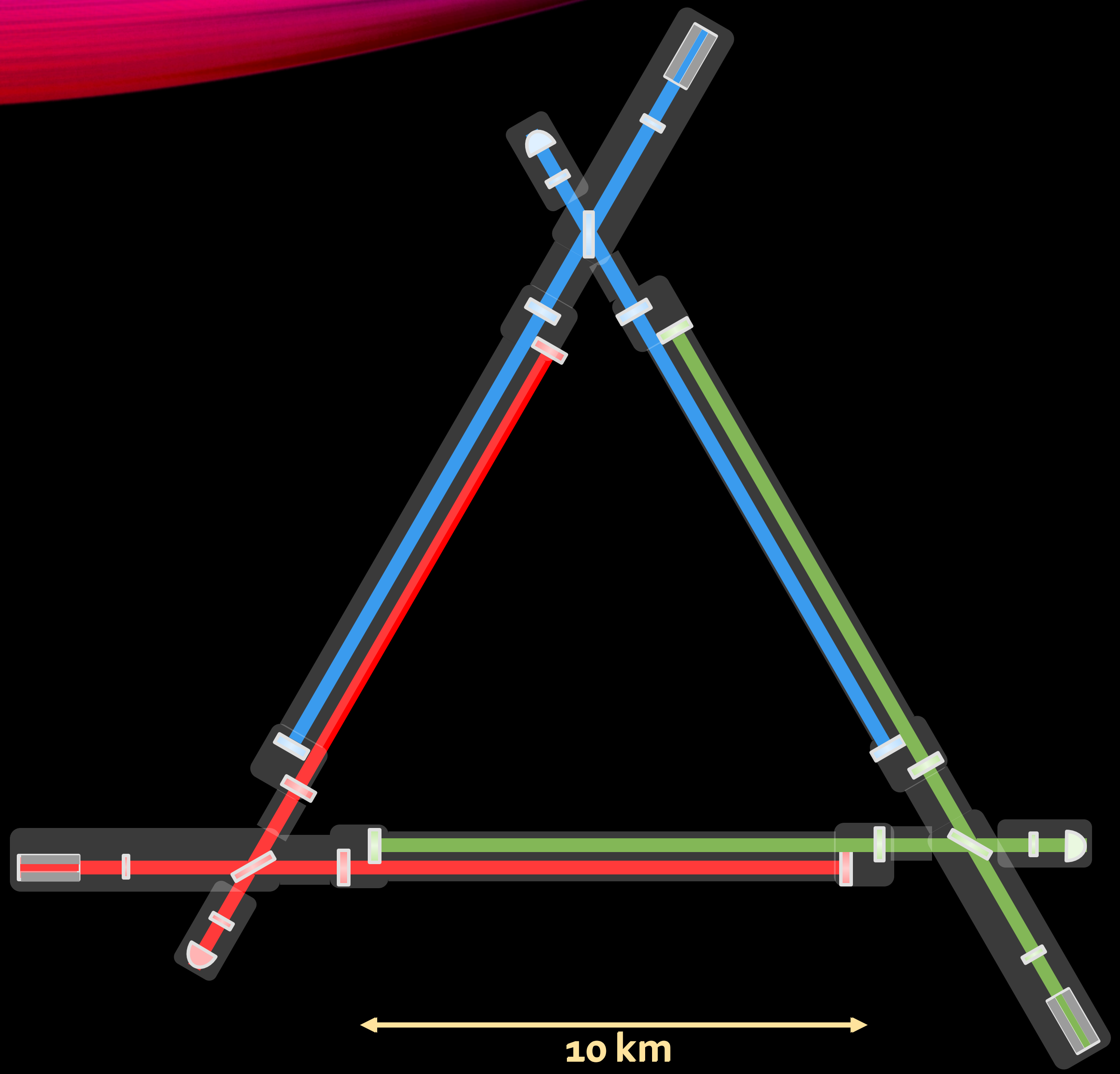
ASTROPHYSICAL SENSITIVITY

LF is important!
Allows for early warnings



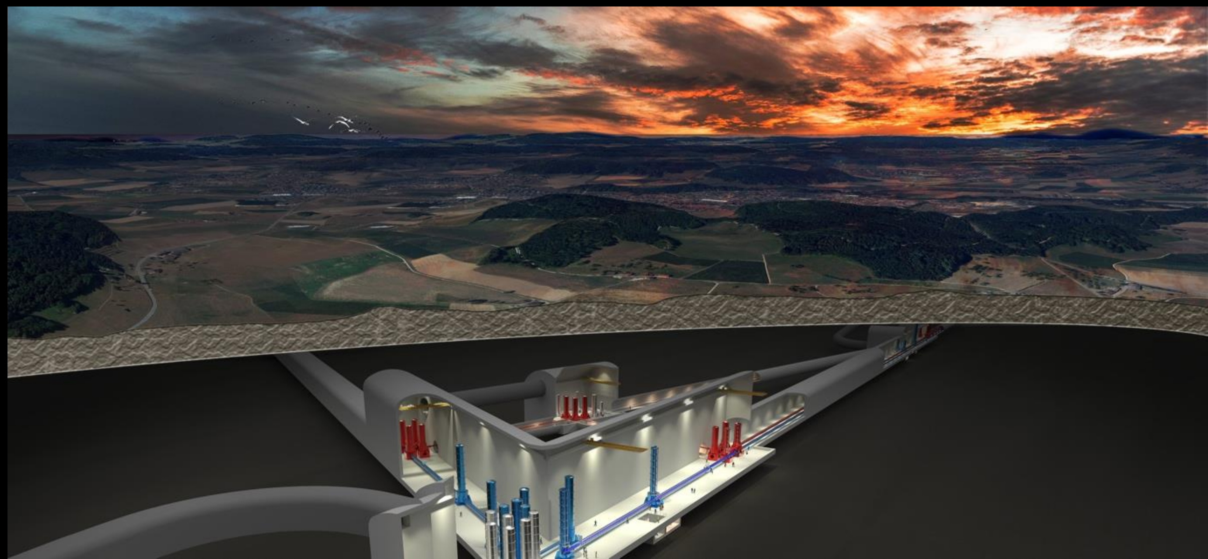
Source: V. Kalogera, Report from the Next-Generation Gravitational-Wave (ngGW) Detector Concept Subcommittee of the Advisory Committee to the NSF MPS Directorate, APS April 2024 Meeting

ET BASELINE DESIGN



- A **European** project!
- Triangular* configuration with 10 km length
- Underground (200 – 300 m) construction
- 3 detectors with 2 interferometers each
  - Xylophone design (LF and HF)

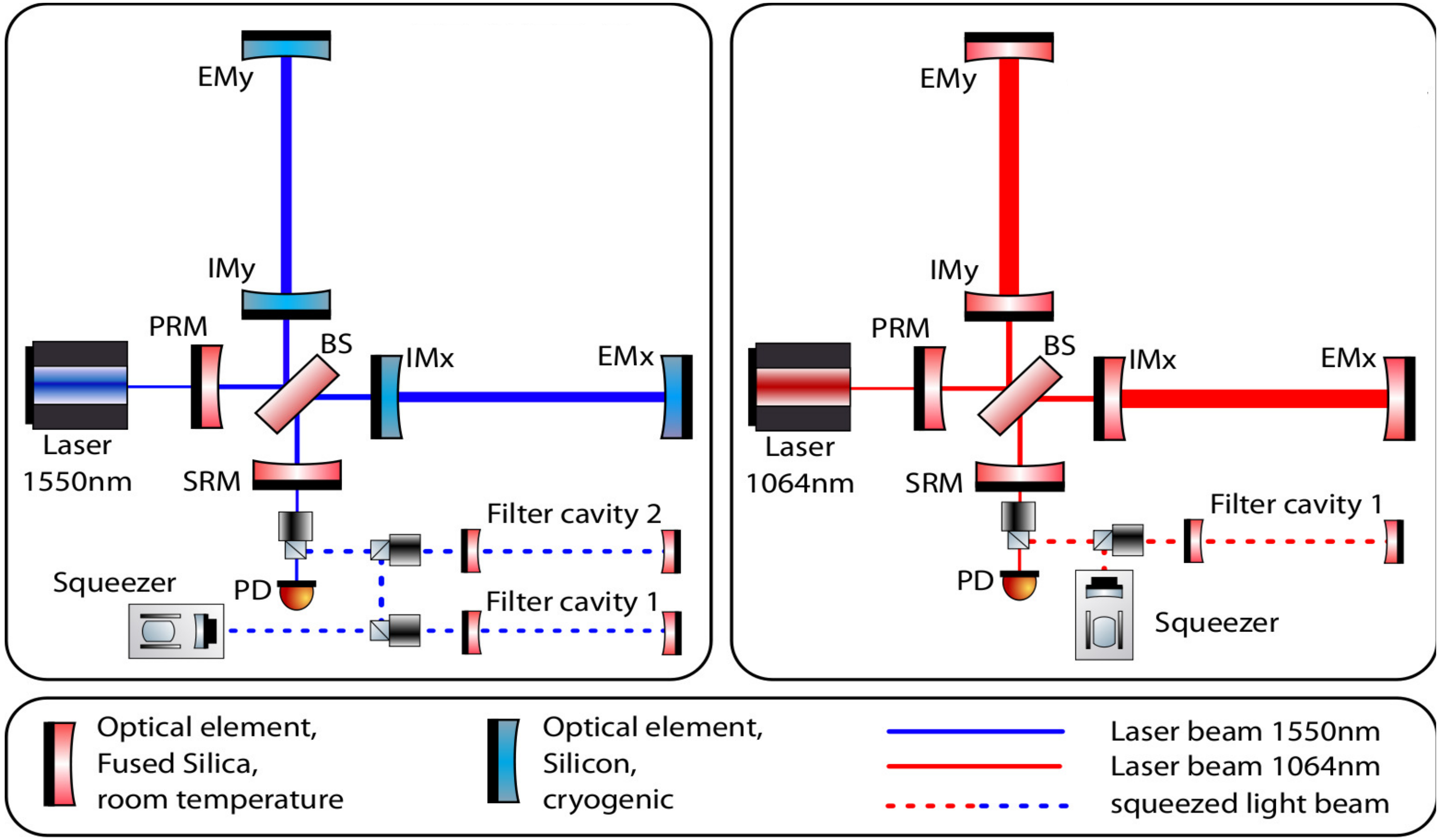
*: other topologies are being considered



ET XYLOPHONE CONCEPT

ET - LF
low-power, cryogenic
low-frequency detector

ET – HF
high-power, room-temperature
high-frequency detector



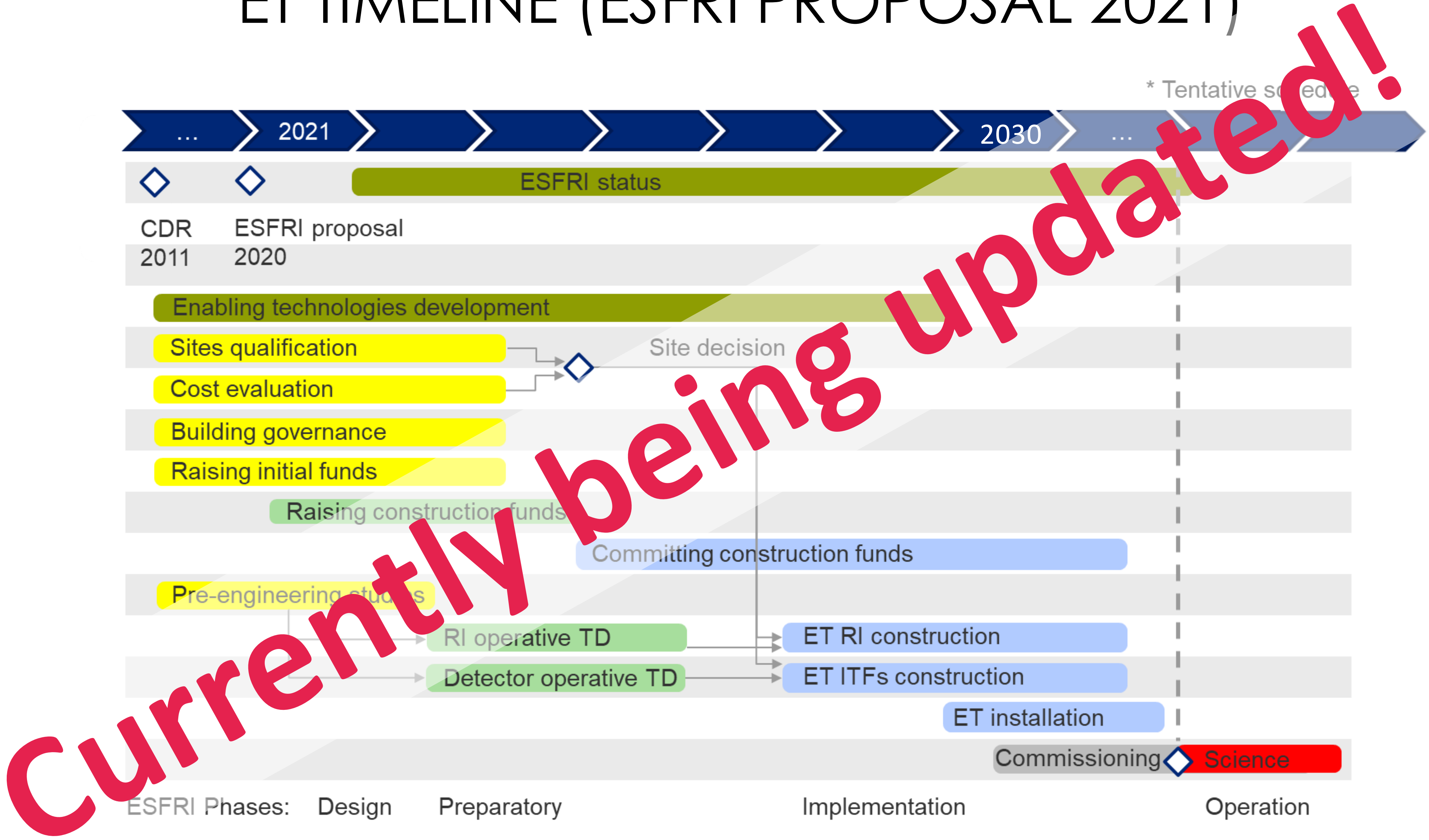
ET-HF: 300 K

- 1064 nm Laser (500W)
- High circulating light power, 3MW
- Thermal compensation
- Large test masses (SiO2, 200kg)
- New coatings
- Frequency dependent squeezing

ET-LF: 10 – 20 K

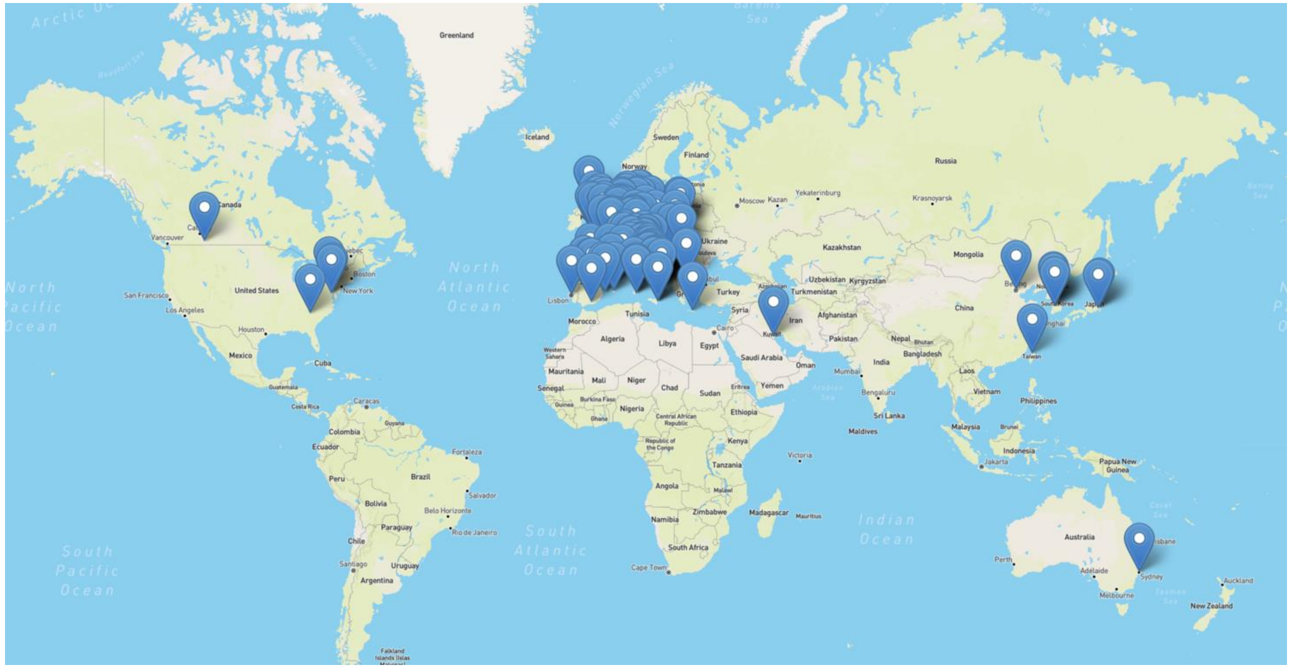
- Cryogenics
- Long Seismic suspensions (17m towers)
- Silicon (Sapphire) test masses
- Large test masses (200kg, 45cm diam.)
- New coatings
- New laser wavelength (1550nm)
- + low power
- Frequency-dependent squeezing

ET TIMELINE (ESFRI PROPOSAL 2021)



The ET Collaboration

- Formed June 2022
- Currently, the ET collaboration is composed by >1500 members, organized in >80 Research Units (RU), affiliated to >205 institutions distributed over 22 countries
- Applications for new RUs are regularly submitted
- **Germany**: currently 13 RUs and more than 220 members!



Slide: Harald Lück (modified)

GERMAN ET COORDINATION TEAM

- ...is composed of the German RU Leaders, communication experts, executive assistants, ex-officio members, and the FNR representative
- ...currently meets weekly (8 am on Thursday mornings) in preparation for the FIS proposal => Harald's talk tomorrow
- ...enables communication and information exchange (community building, meetings) amongst German ET members
- ...interfaces with ET-Organisation, politics, and industry
- ...works on the whole range of ET Science: instrumentation, data analysis, observational science, modelling, site preparation,...
- ...and more!

UNITED STATES DETECTOR TIMELINES

	Now-2025	2025-2030	2030-2035	2035-2040
LIGO A+	O4	O5		
LIGO A$^{\sharp}$	R&D, Proposal	Procurement, Installation	Commissioning, Operation (6yrs after funding)	Operation
Voyager	R&D, Proposal	R&D, Proposal, Procurement	Installation, Commissioning, Operation (3.5yrs after funding)	Operation
CE	R&D, Design	Site selection, Design (Concept, preliminary and final reviews)	Construction	Commissioning, Operations (~5yrs after funding)

Source: V. Kalogera, Report from the Next-Generation Gravitational-Wave (ngGW) Detector Concept Subcommittee of the Advisory Committee to the NSF MPS Directorate, APS April 2024 Meeting

Scientific discovery potential for ngGW facilities

Black Holes and Neutron Stars across the Universe

- Complete sample of black-hole mergers out to beginnings of star formation
- Intermediate-mass black holes (IMBH)
- Precision GW Astrophysics for both black holes and neutron stars

Physics of Dense Matter and Multi-Messenger Astrophysics

- Deep probes of QCD physics through high-precision measurements of neutron-star tidal deformability and radii
- Post-merger neutron-star GW signal detection
- GW counterparts for all short gamma-ray bursts
- Possible three-way multi-messenger detection of stellar core collapse

Cosmology Probes and the Dark Sector

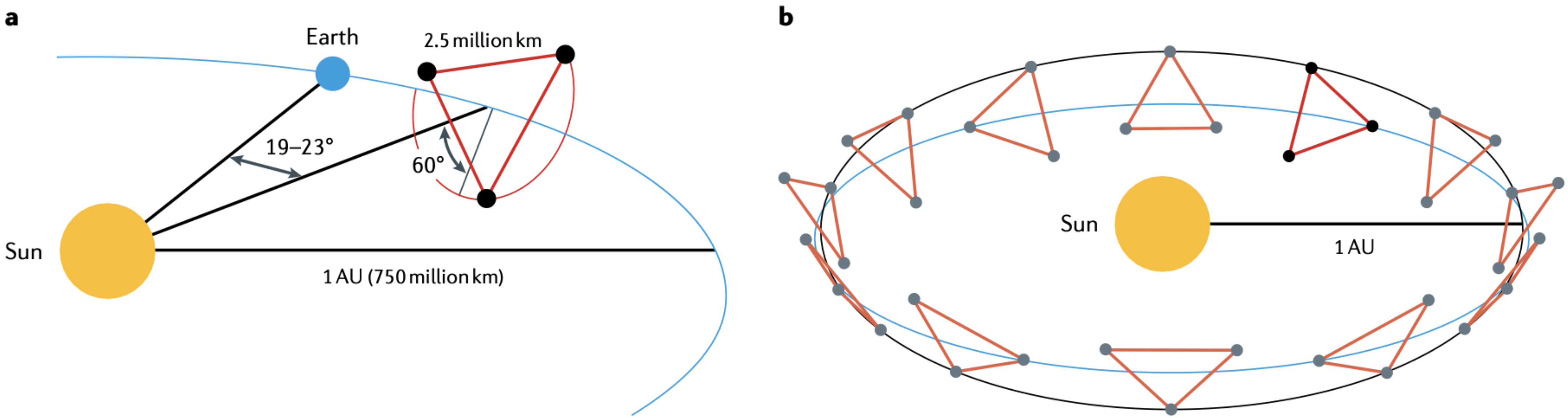
- Precision Hubble constant measurements and probe of dark energy through both neutron-star and black-hole mergers
- Probes of dark matter and particle physics through the detection of ultra-light boson clouds around spinning black holes ('gravitational atoms')
- Potential evidence of primordial black holes through very high redshift detections

Fundamental Physics and Novel Sources

- Multiple tests of General Relativity are possible
- Detection of unanticipated signals revealing new physics

Source: V. Kalogera, Report from the Next-Generation Gravitational-Wave (ngGW) Detector Concept Subcommittee of the Advisory Committee to the NSF MPS Directorate, APS April 2024 Meeting

LISA (LASER INTERFEROMETER SPACE ANTENNA)



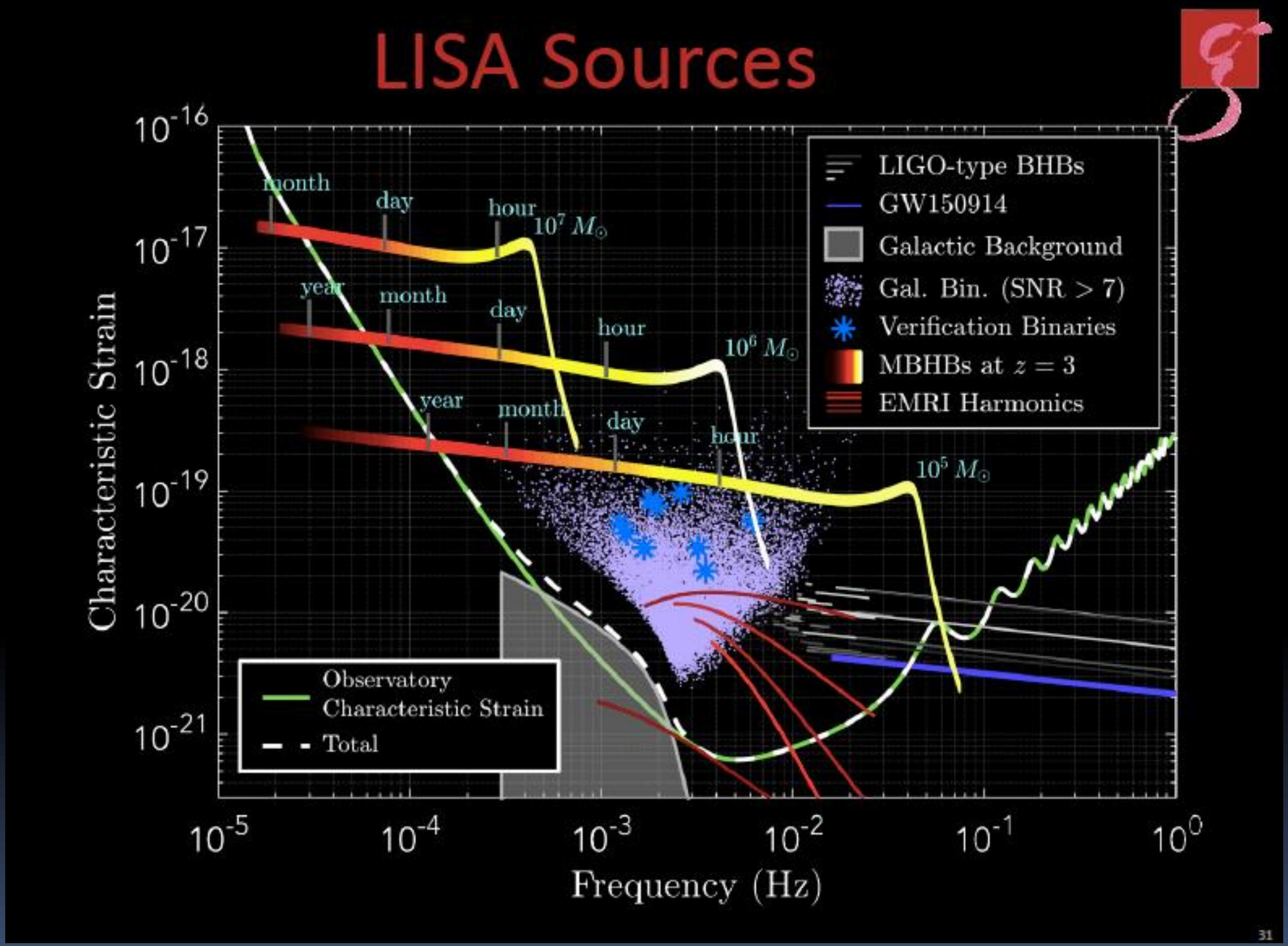
- **Massive Black Holes:** Monitoring the long inspirals of supermassive black hole binaries.
- **Cosmic Measurements:** Using gravitational waves to refine our knowledge of the universe's expansion.
- **Early Universe:** Probing cosmic dawn with gravitational waves.
- **Fundamental Physics:** Investigating theories beyond Einstein's, including exotic objects and dark matter signals

Image: Bailes, M., Berger, B.K., Brady, P.R. et al. Gravitational-wave physics and astronomy in the 2020s and 2030s. Nat Rev Phys 3, 344–366 (2021). https://doi.org/10.1038/s42254-021-00303-8

THE LISA MISSION

- LISA was selected as ESA's 3rd large mission in the Cosmic Vision program
- Originally scheduled for launch in 2034, schedule currently „in flow“
- Builds on the success of the LISA Pathfinder mission
- Development is in full swing
- Junior partnership with NASA
- LISA Consortium brings together the national agencies of Europe and scientists from around the world

LISA – scientific goals



- *Compact galactic binaries:*
  - *Study formation and evolution*
  - *Distribution within Milky Way Galaxy*
- *Massive Black Hole Binaries*
  - *Trace their origin, growth and merger history across cosmic epochs*
  - *Study growth mechanism of MBH dating back to earliest quasars*
  - *Search for black holes at cosmic dawn*
- *Extreme and intermediate mass-ratio inspirals*
  - *Probe the properties and immediate environments of black holes in the local Universe*
- *Probe the rate of expansion of the Universe with standard sirens (Multi-messenger astronomy)*
- *Stochastic gravitational wave background*
  - *Early Universe and TeV-scale particle physics*
- *….*

Slide: Guido Müller

LISA – project status

Implementation Schedule – ESA Major Milestone Dates – Proposed (TBC)

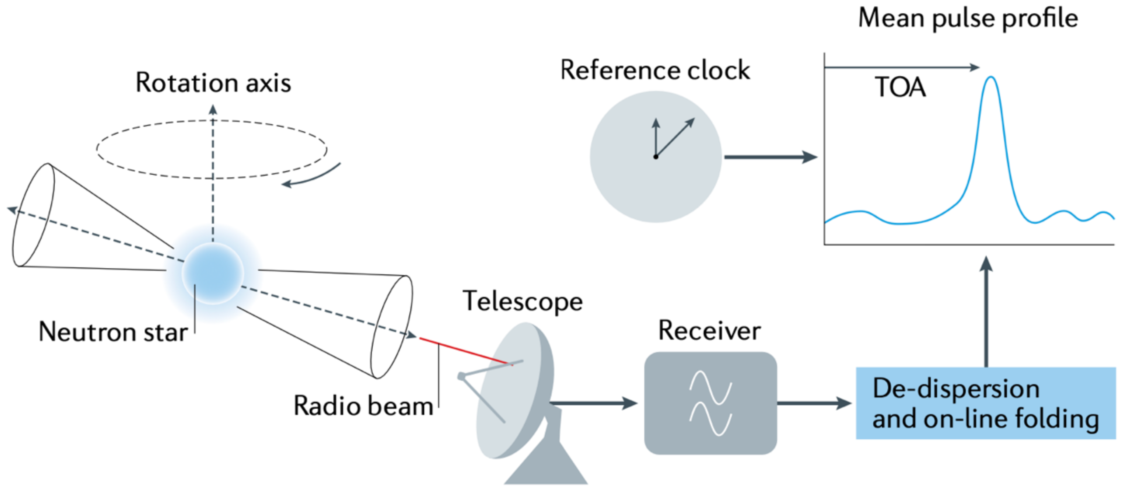
esa

Review	Date	Instrument Level
Adoption	25. January 2024	
Prime Kick-Off	Oct/Nov 2024	
Mission SRR (after co-engineering)	April 2025	Q2/2023
Mission PDR	Nov 2027/Feb 2028	In Q3/Q4 2024 - Q1/Q2 2025
Mission CDR	January 2031	Q4/2027
Target for Launch	2035	

- LISA Adoption during ESA-SPC January meeting
- Following adoption, the LISA Science Team (LST) will be selected
    - LST is expected to set up working groups which target specific science investigations
    - LISA Consortium will be heavily involved in scientific work
        - LISA Consortium Is currently being restructured to adapt to new structure

Slide: Guido Müller

PULSAR TIMING ARRAYS



Studying mergers of **supermassive black hole binaries**.
Cosmic Background: Sensing a background hum from countless unresolved black hole binaries.
Astrophysical Phenomena: Leveraging pulsar data for broader astronomical insights.

Images: Bailes, M., Berger, B.K., Brady, P.R. et al. Gravitational-wave physics and astronomy in the 2020s and 2030s. Nat Rev Phys 3, 344–366 (2021). https://doi.org/10.1038/s42254-021-00303-8

PULSAR TIMING ARRAYS

Marginal evidence for a Gravitational Wave Background in EPTA (25 years) and InPTA (10 years) data (publications 2023)

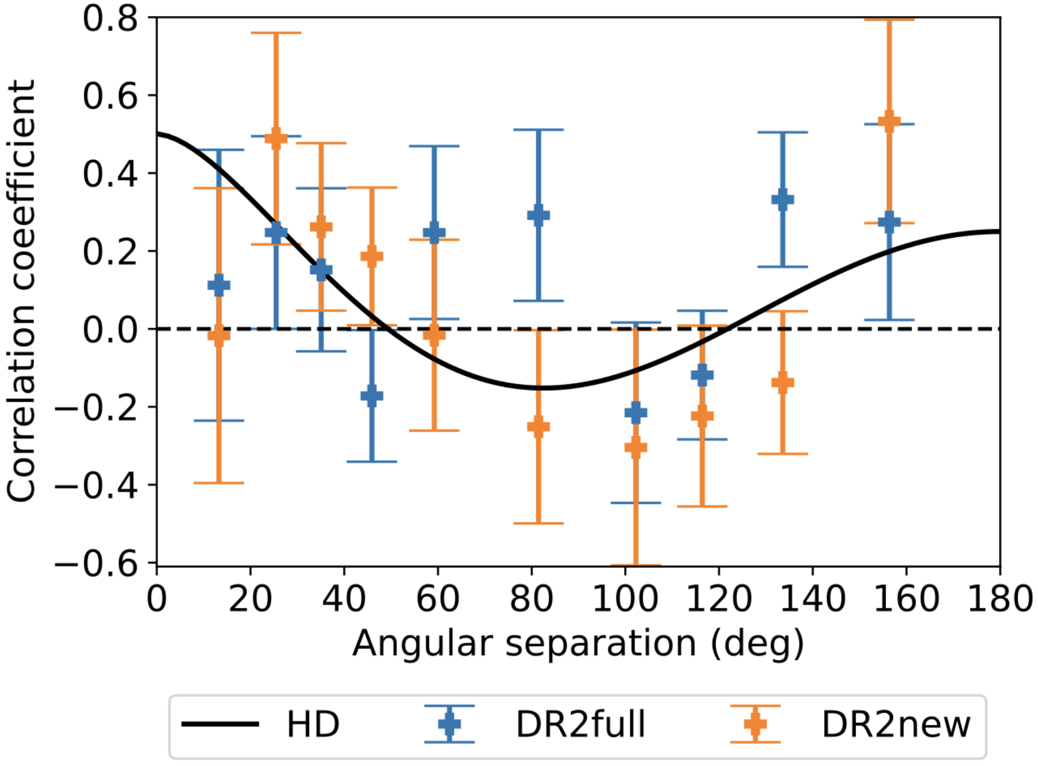
No individual SMBBH source of GWs yet(?)
soon to be able to observe with EM Telescopes

- MM astronomy of nano-Hz GW detection
- Hoping for (less well understood) exotic sources.

Key science: Properties of SMBBH; maybe primordial GWs?

Future facilities will join:

- SKA (Square Kilomter Array) - 2027?
- ngVLA (next-gen Very Large Array) > 2031
- DSA-2000 (Deep Synoptic Array) - 2026?



EPTA Collaboration and InPTA Collaboration, „The second data release from the European Pulsar Timing Array III. Search for gravitational wave signals ", A&A 678, A50 (2023), https://doi.org/10.1051/0004-6361/202346844

DISCUSSION?