GW astronomy in 2030

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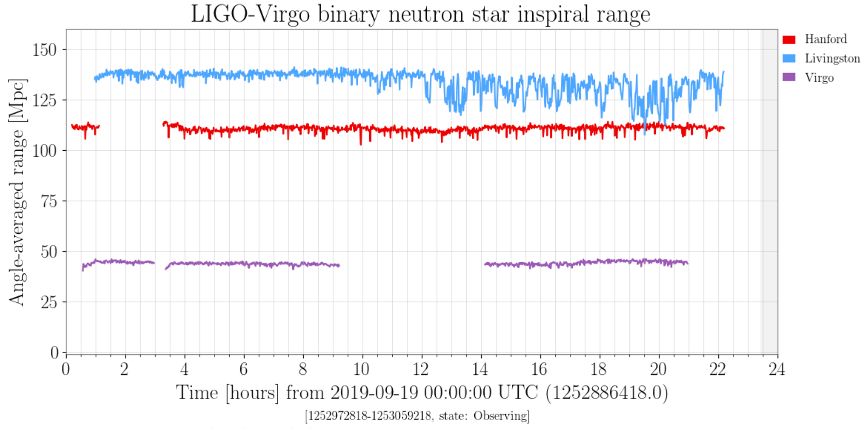
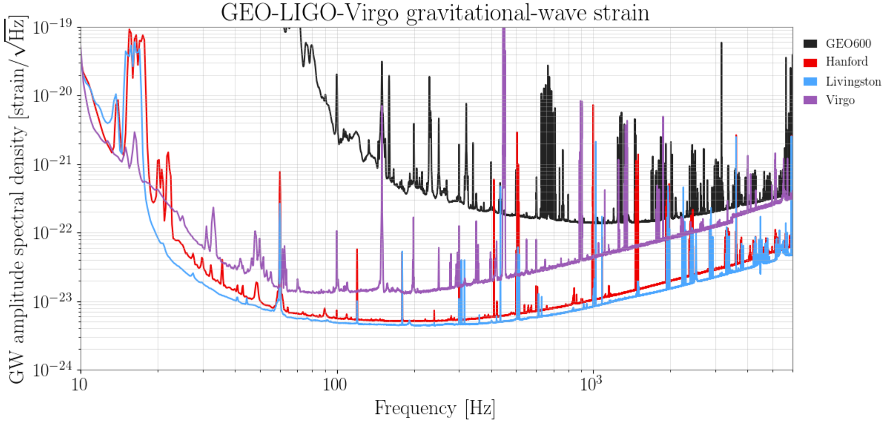
CNRS/IN2P3 AstroParticule et Cosmologie

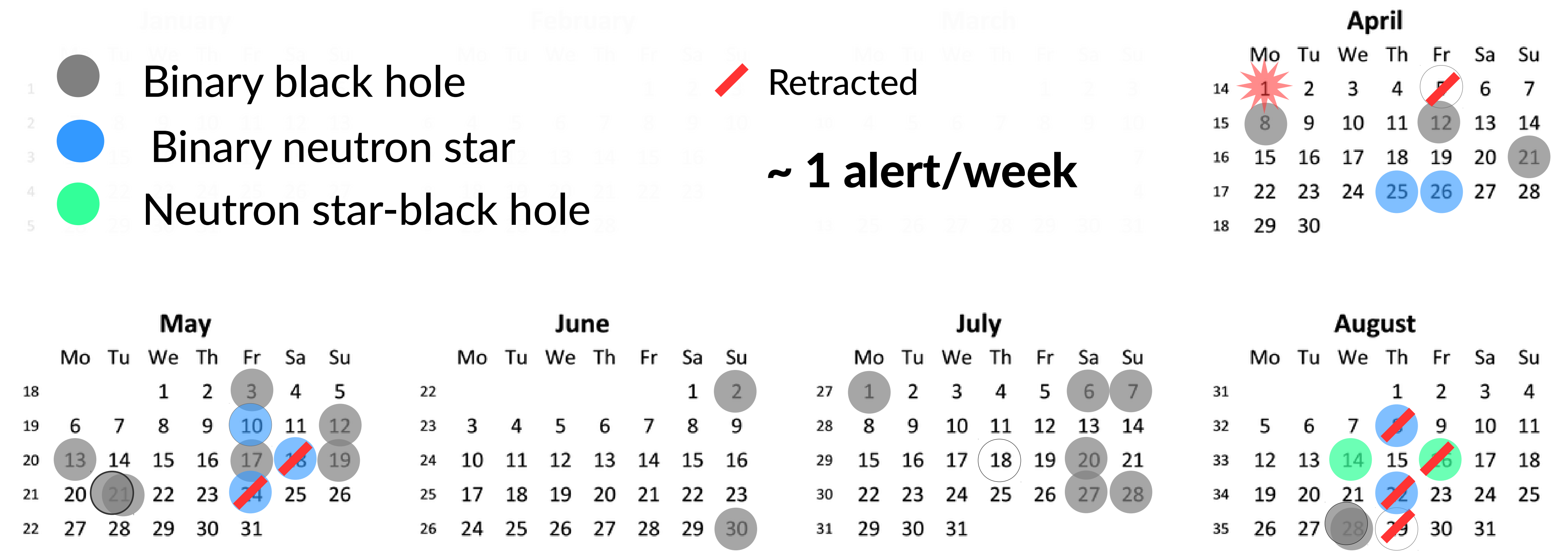
GW astronomy today





- **2015-2017: two observing runs**
  - 10 binary black hole (BBH) mergers
  - 1 binary neutron star (BNS) merger

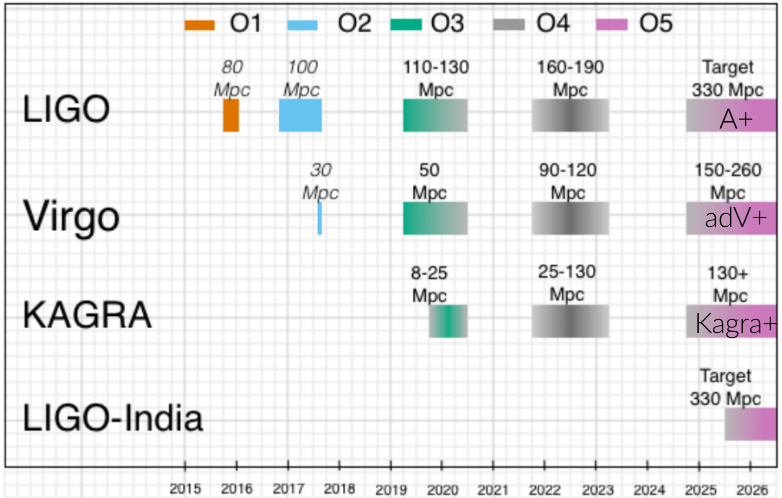
  `https://www.gw-openscience.org/catalog`
- **Advanced LIGO and Virgo observing**
  - Stable operation (~70 %) since April 1st 2019
  - 36 GW alerts – 7 retractions
  - 21 events classified as BBH, 4 as BNS and 2 events as **NS-BH**
- **No electromagnetic counterpart detected so far**



Observation Run	Network	Expected BNS Detections	Expected NSBH Detections	Expected BBH Detections
O3	HLV	2^{+8}_{-2}	0^{+19}_{-0}	15^{+19}_{-10}
O4	HLVK	8^{+42}_{-7}	2^{+94}_{-2}	68^{+81}_{-38}

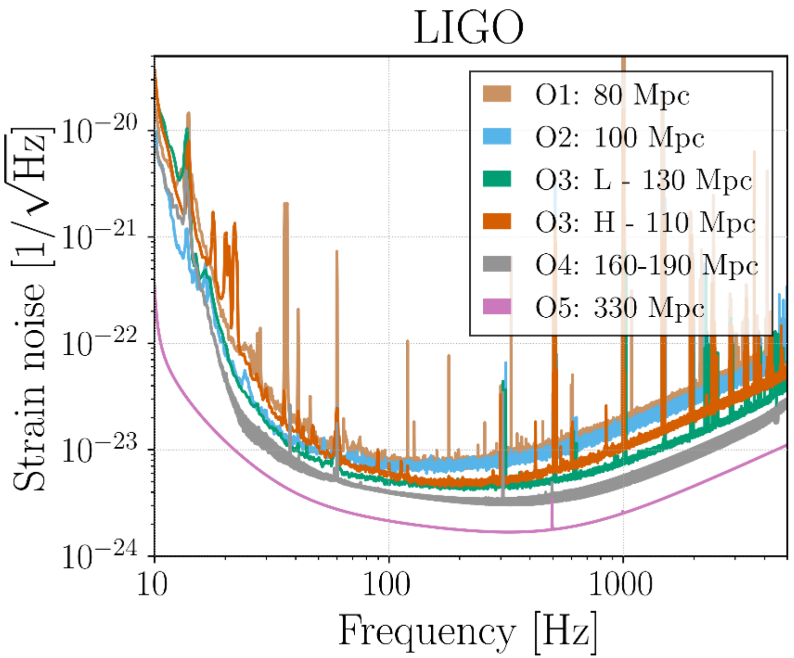
https://arxiv.org/abs/1304.0670

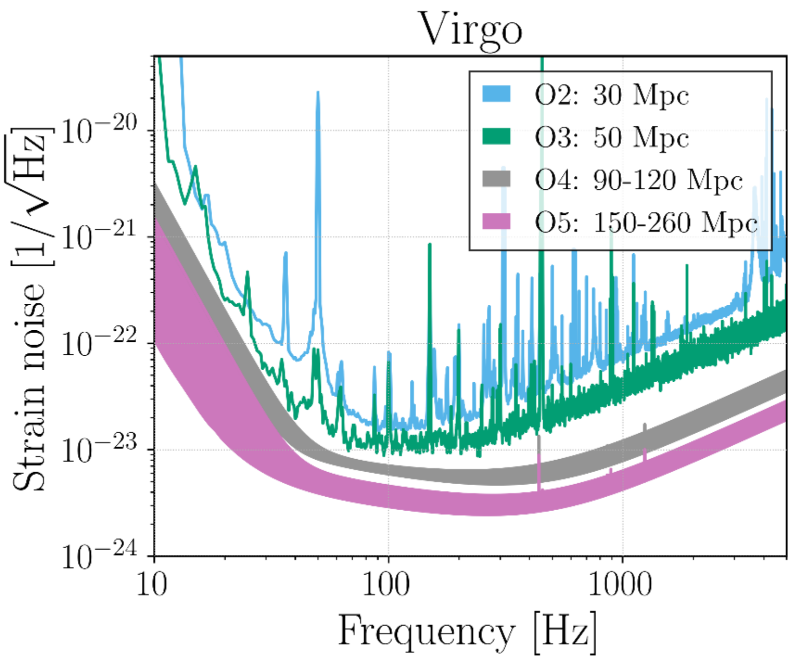
GW astronomy in 2025



- **Five large-scale detectors in operation**
  - Best BNS range ~ 300 Mpc – Horizon z ~ 0.15
  - ~3 x current sensitivity
    rough extrapolation from O3 → ~4 events/day (!)
  - O(100) BBH and O(10) BNS per year
    [rates will be revised after O3]

GW astronomy in 2025

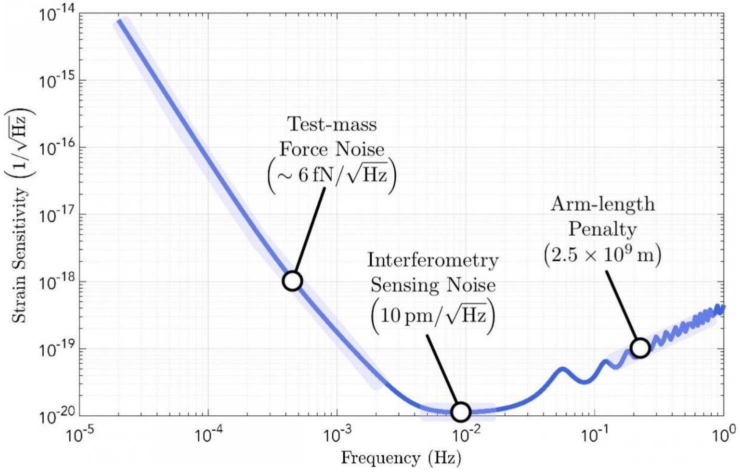


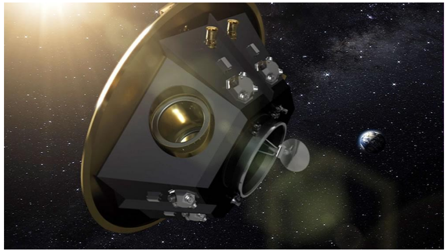


GW astronomy in 2032

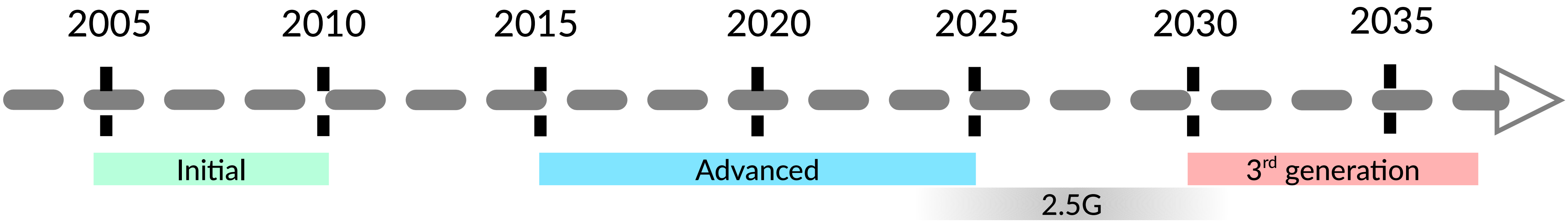
- Transition from 2.5G to 3G detectors
  - Final objective: 10 x (or more) increase wrt 2G
  - BNS range z ~ 1, BBH z ~ 10

- LISA space-mission close to launch pad
  - GW in the mHz range
  - Now in phase A

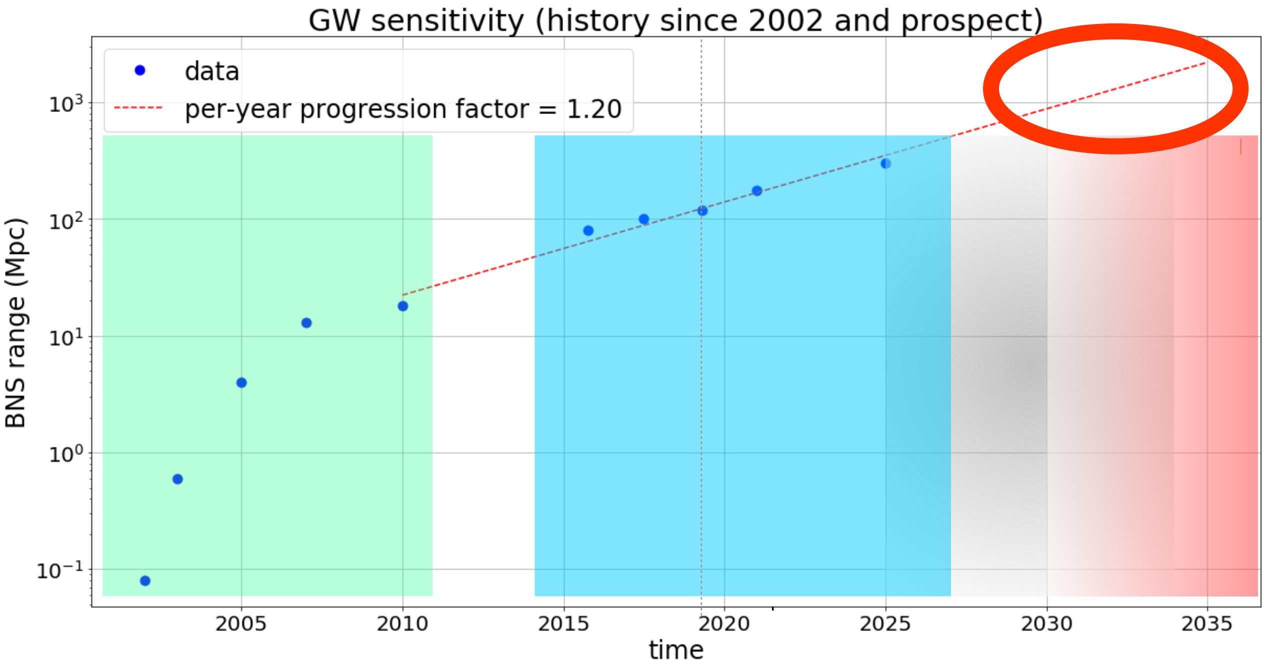




GW sensitivity over 3 decades



+ 20 % / yr or
x ~2 every 4 yrs
x ~10 in 15 yrs

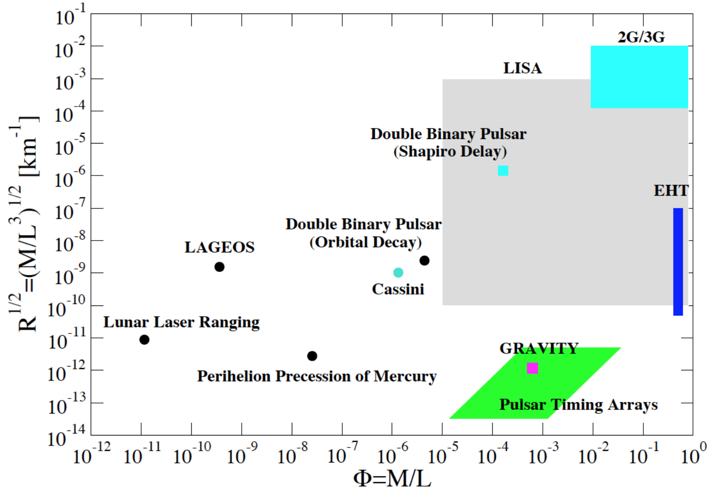


z ~ 0.2

3rd generation of GW detectors

- **In the major roadmaps for large infrastructures**
  - In the US: Astro2020 decadal survey
  - In Europe: European Strategy for Particle Physics (ESPP) and European Strategy Forum on Research Infrastructures (ESFRI)
  - Lagging behind at national level in France
    - Prospectives IN2P3 and INSU

3rd generation of GW detectors



Gravitational Wave International Commitee

GWIC 3G

https://gwic.ligo.org/3Gsubcomm

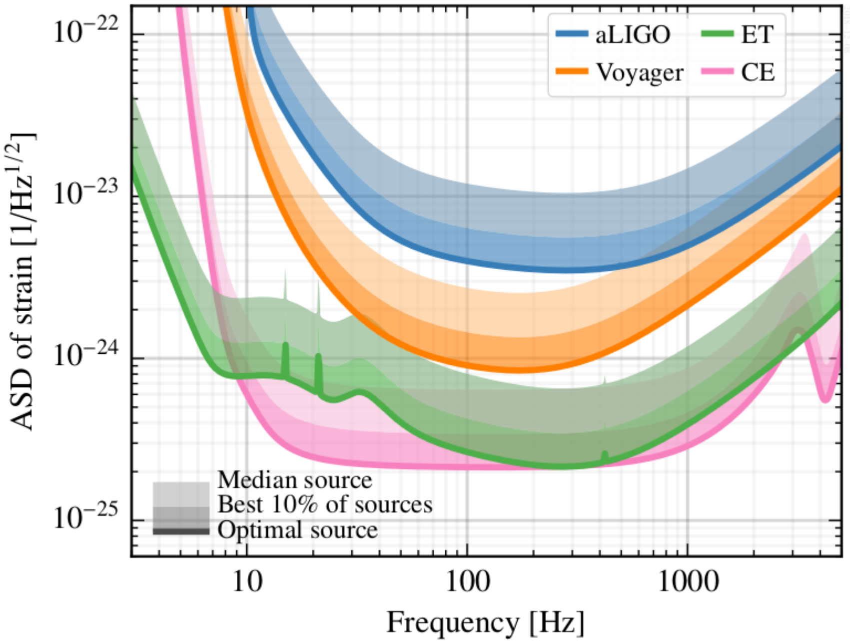
International coordination (US, EU, AU)

Scientific program – 5 main targets

- Extreme gravity – Physics of black holes
- Extreme matter
- Reach current observational limits
- Observe stellar-mass binary black holes throughout the universe
- Cosmology, early universe and dark sector

Underline the importance of a 3rd instrument in the southern hemisphere or Asia

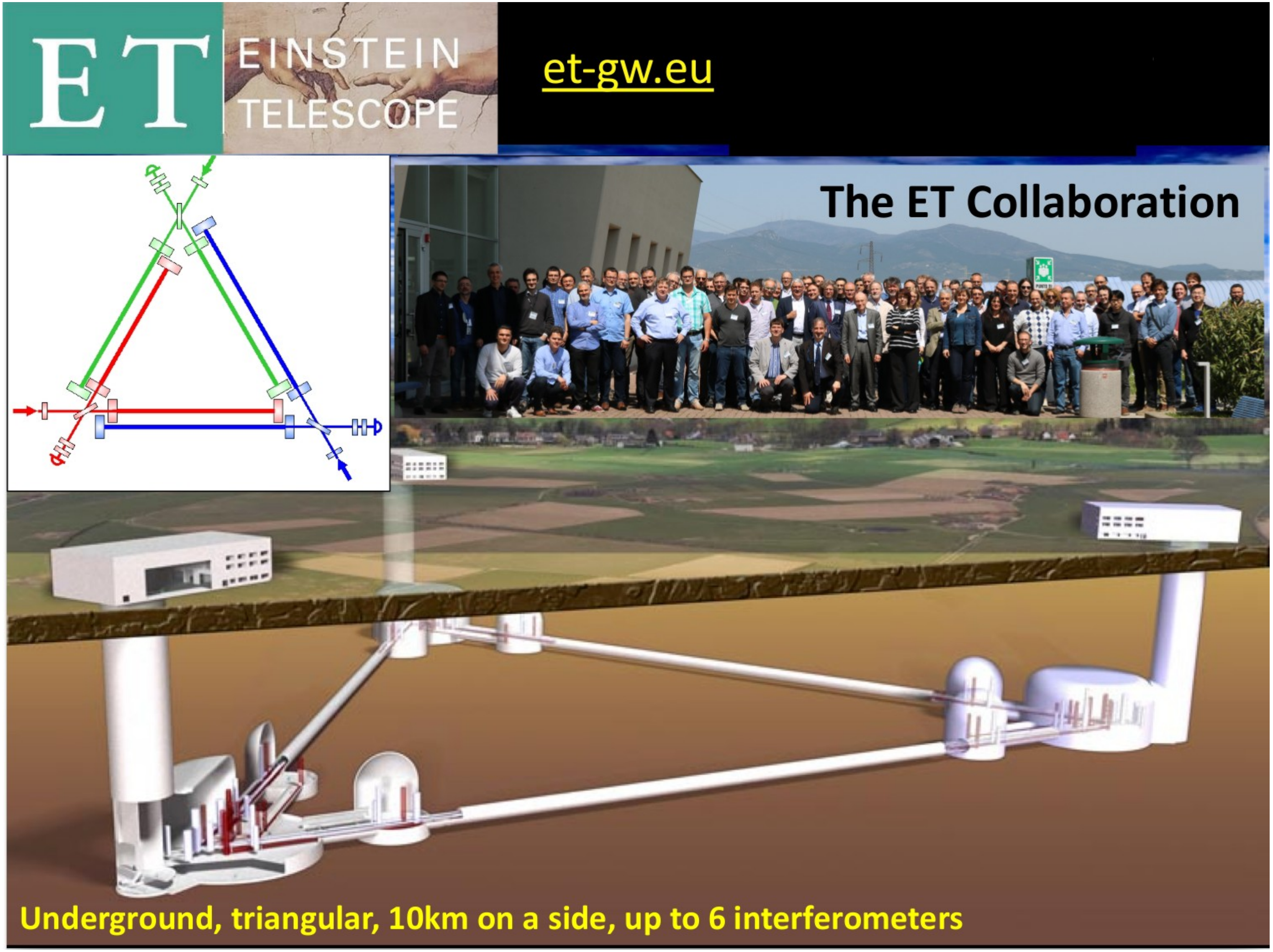
2.5G and 3G detector concepts



- **Voyager**: use LIGO infrastructure, heavy test masses, cryo
- **OzHF**: km size, heavy test masses, > 1 kHz

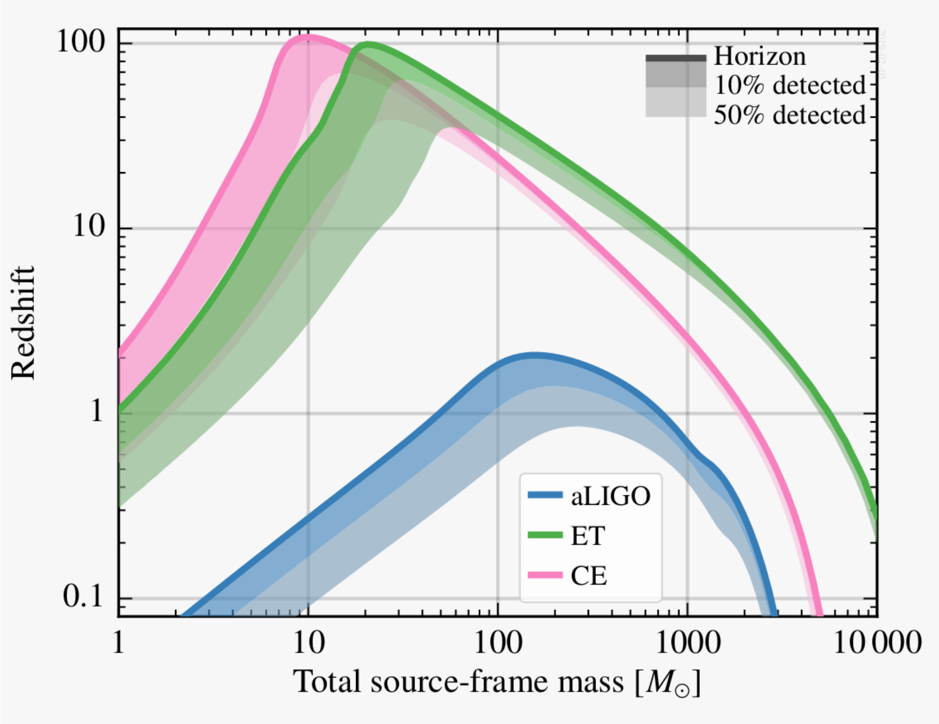
- **Cosmic Explorer**: 40 km, L-shaped
- **Einstein Telescope**: underground, 10 km, triangular, xylophone design
  'hot' (high laser pow) + 'cold' (cryo, low pow)

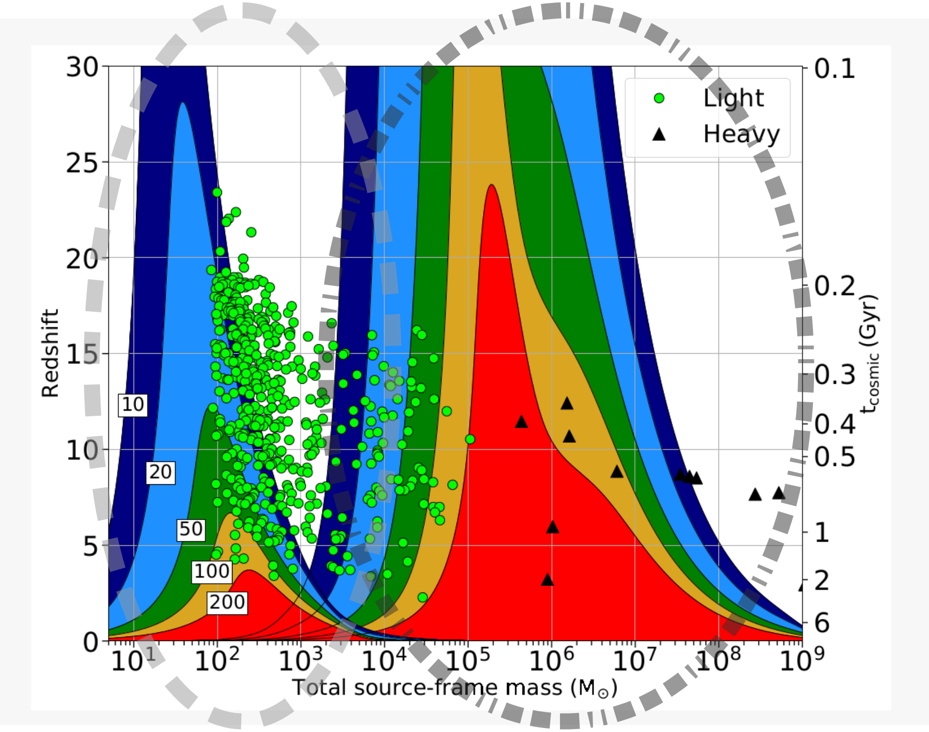
Different levels of maturity



- 2010 Conceptual study
- 2018 ET collaboration
  Site qualification
- 2019 “light” TDR (in progress)
- 2022 Site selection
- 2023 Technical design
- 2025 Work on infrastruc. begins
- 2032+: Installation, commissioning, operation

Compact binaries in the 3G era (1)



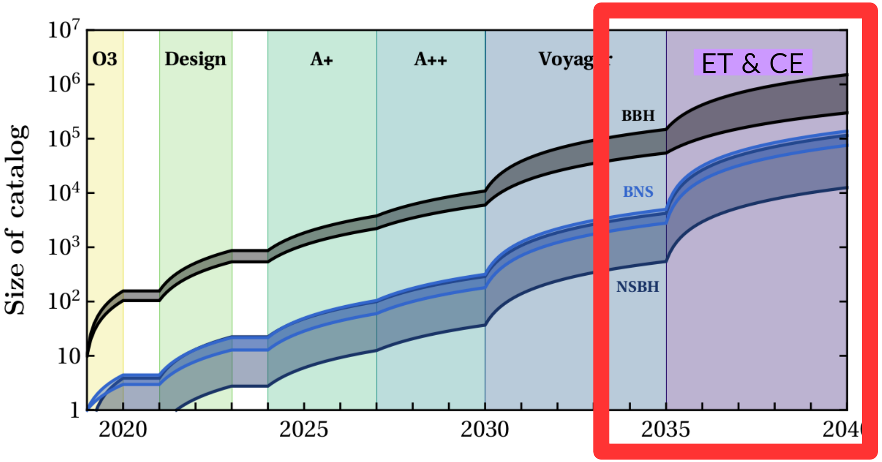


sub M_{sun} to ~1000 M_{sun}

3G detectors **LISA**

Compact binaries in the 3G era (2)

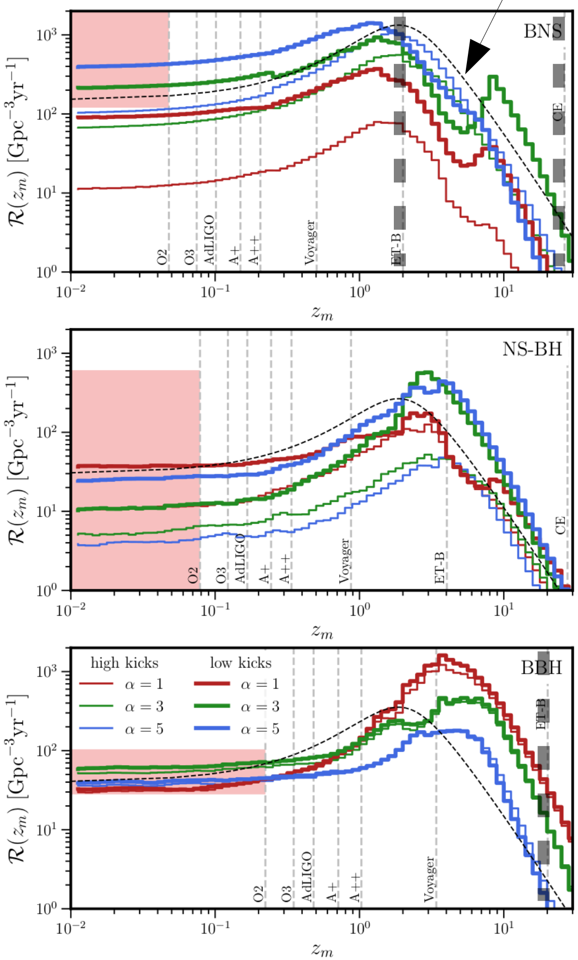
Detector	BNS	NSBH	BBH
O2	0.028 - 0.91	0.12 - 1.1	27 - 40
O3	0.11 - 3.4	0.46 - 3.9	94 - 1.5 $\times 10^2$
AdLIGO	0.27 - 8.6	1.2 - 9.3	2.2×10^2 - 3.6×10^2
A+	0.88 - 28	3.2 - 26	5.6×10^2 - 9.7×10^2
A++	2.3 - 71	8.1 - 63	1.3×10^3 - 2.4×10^3
Voyager	32 - 9.4×10^2	1.0×10^2 - 7.8×10^2	9.7×10^3 - 2.7×10^4
ET-B	1.1×10^3 - 2.7×10^4	2.4×10^3 - 2.2×10^4	4.9×10^4 - 2.7×10^5
CE	1.6×10^4 - 2.7×10^5	1.6×10^4 - 1.4×10^5	8.6×10^4 - 5.4×10^5
Noiseless	2.8×10^4 - 4.5×10^5	2.0×10^4 - 1.8×10^5	9.2×10^4 - 5.7×10^5



> 10^5 BNS/yr →
+ 1 BNS every 5 mins
~50 % of all BNS mergers

10^6 BBH/yr →
1 BBH every 30 sec
~90 % of all BBH mergers

Prop to SFR



Baibhav et al, arxiv:1906.04197

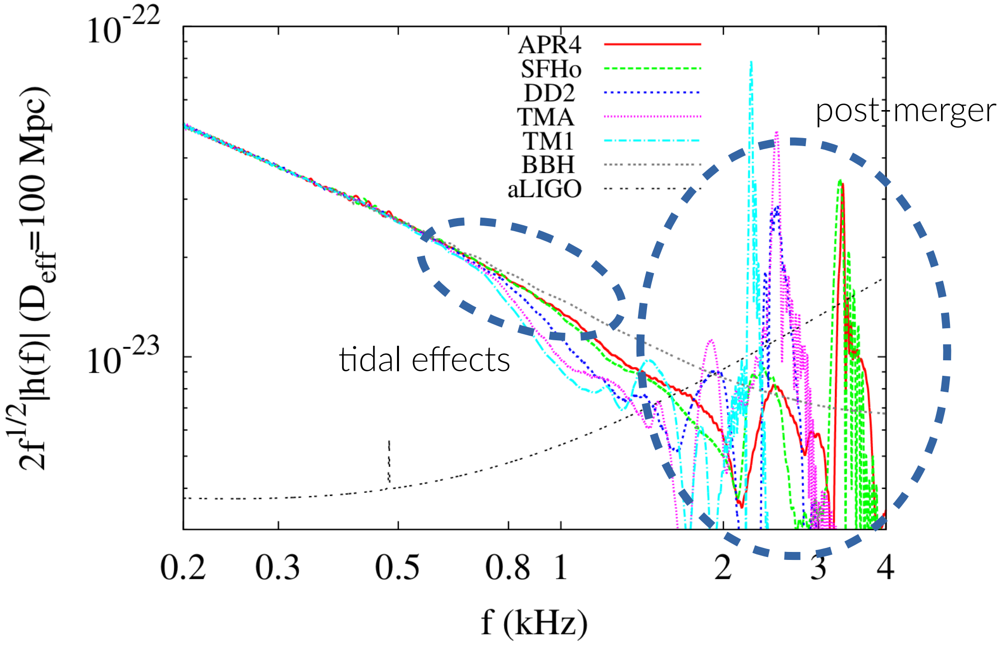
Neutron star binaries in the 3G era (1)

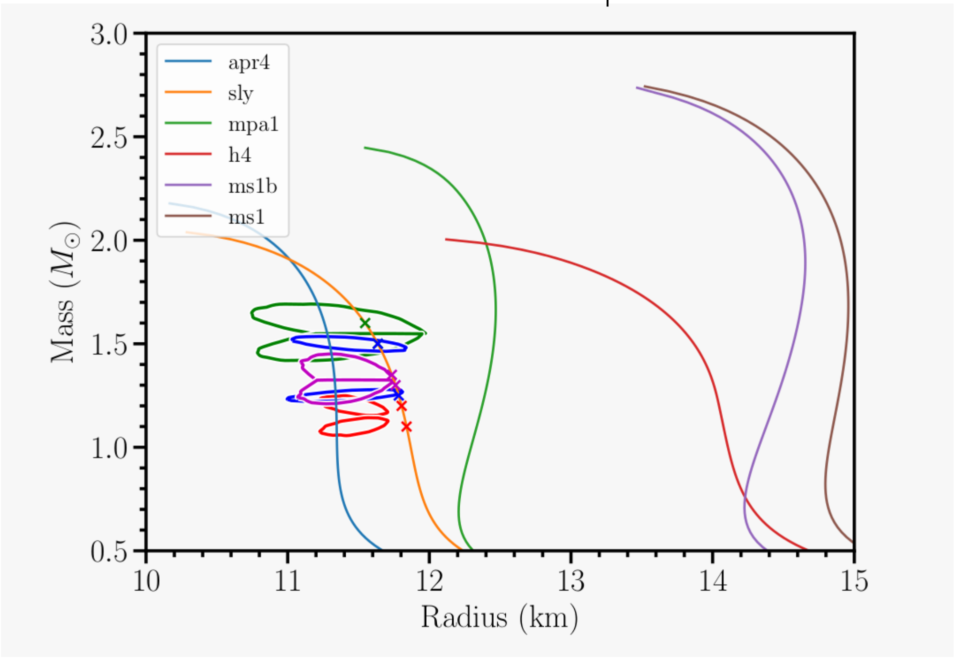
- A small fraction of **very bright “nearby” sources**
  - O(10)/yr BNS at 400 Mpc with SNR ~ 100-140

    GW170817 observed with 3G: SNR ~ 1000-1400 (!)
  - Allow for detailed tests of pre- and post- merger signal
    - NS tidal deformability and nature of remnant
  - Allow for early detection and warning
    - Could achieve one hour before merger

Neutron star binaries in the 3G era (2)

BNS at 400 Mpc



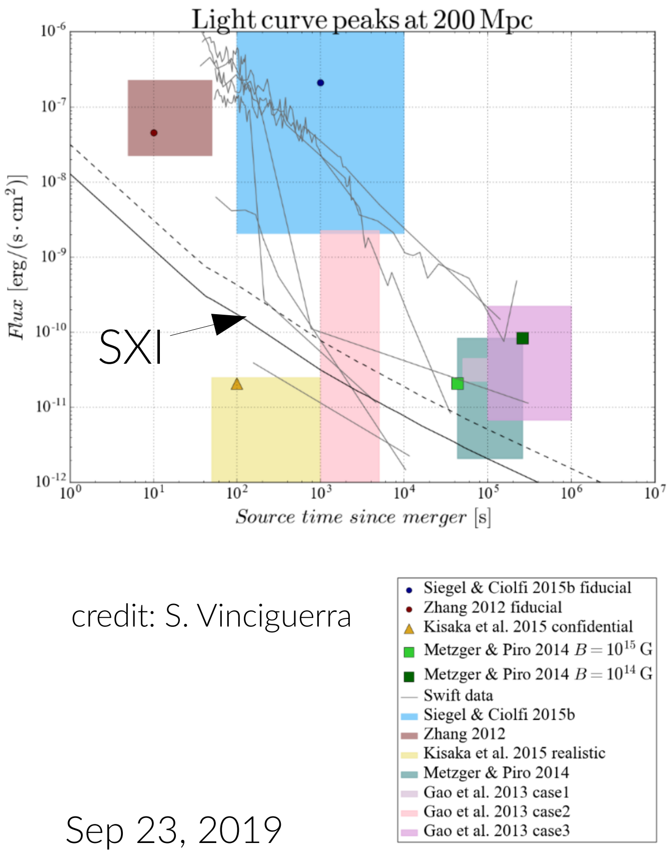


arXiv:1603.01286

NS radius to +/- 1 km

condensates of exotic particles or quark matter phases ?

Multimessenger astronomy with Theseus



credit: S. Vinciguerra

Assume GW network of 2 CE & 1 ET

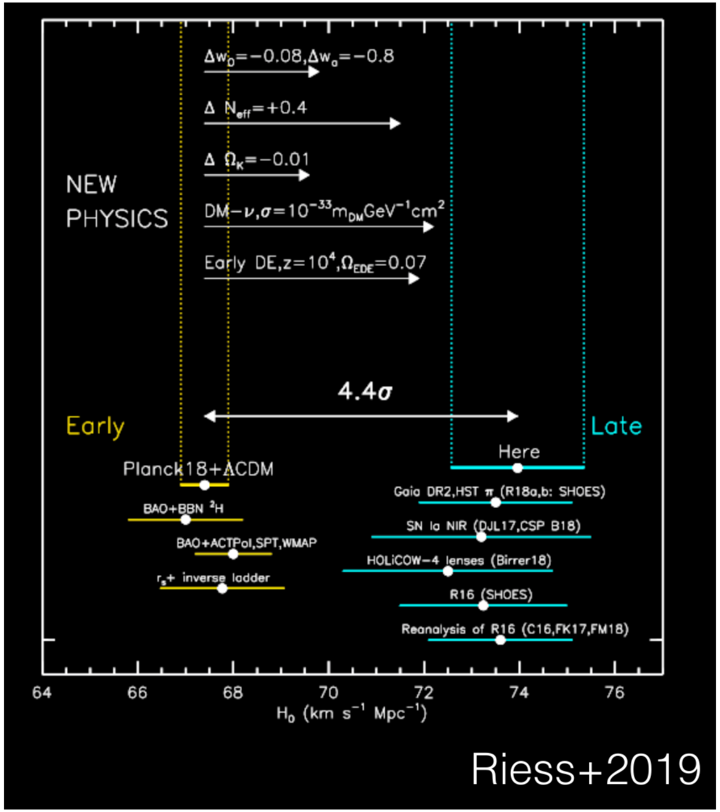
- 10^6 detectable BNS per yr out to z ~ 30
- 1 % (15k) of the detected BNS per yr are resolved to better than 1 square degree

Joint 3G – Theseus observations

- All "on-axis" short GRB detectable by XGIS – 20 sGRB/yr
- Structured jet from short GRB sources at 400 Mpc up to 5 θ_{jet} with XGIS
- Late off-axis afterglow from "magnetar wind" with SXI
- Kilonova with IRT

For what science?

Cosmography with standard sirens

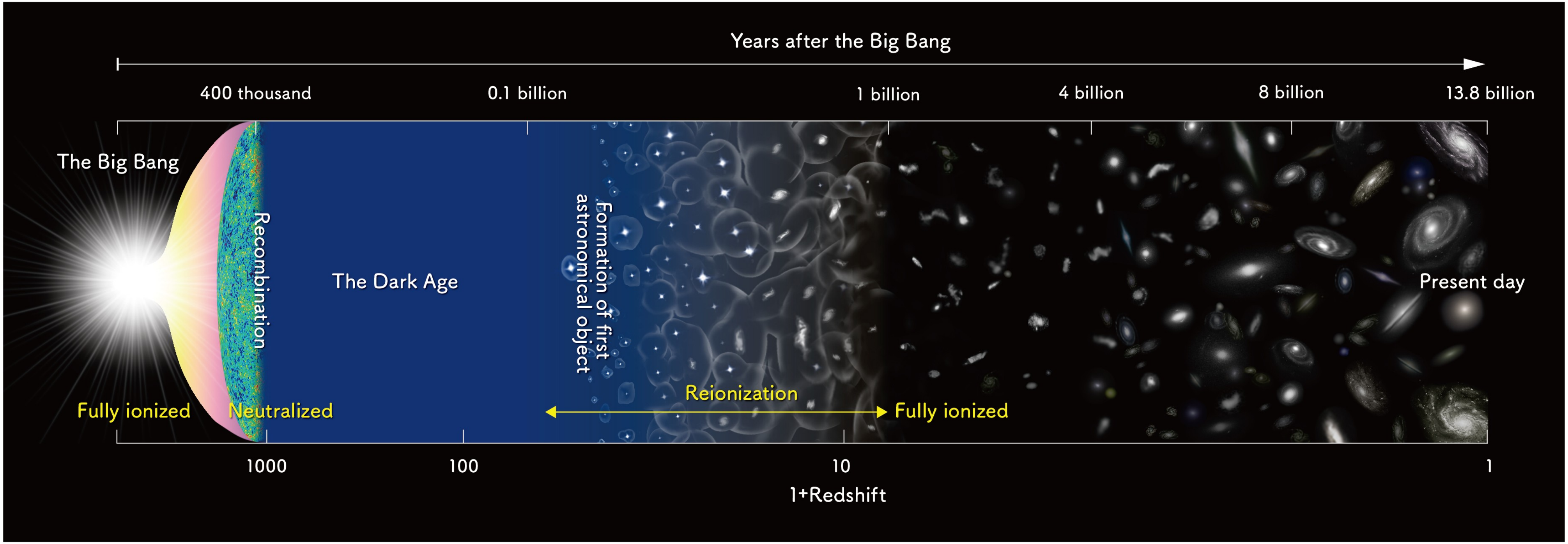


- Tension in the current H_0 measurements from early/late times
- Infer H0 from D-z measurement from BNS “standard sirens”
  - Demonstrated with GW170817
- Need ~200 BNS D-z measurement to reach the percent level
  - May reach this goal with 2G
  - This will depend on our ability to find EM counterparts
  - We see in O3 this is difficult – 10-100 sq degrees loc

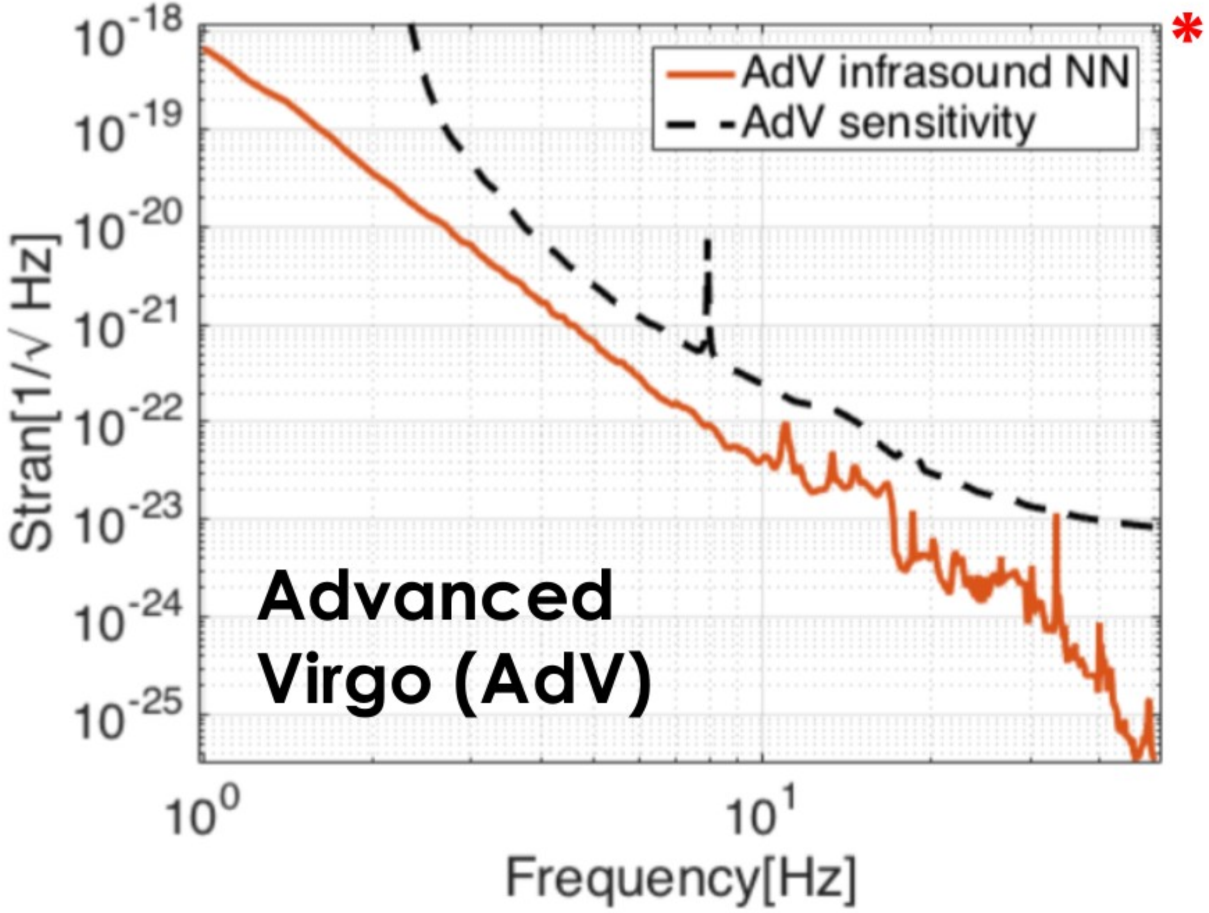
- A network 3G instruments will localize 10^4 BNS / yr within 1 square degree
- 3G will observe more distant BNS
  Allow to measure other cosmological parameters

Concluding remarks

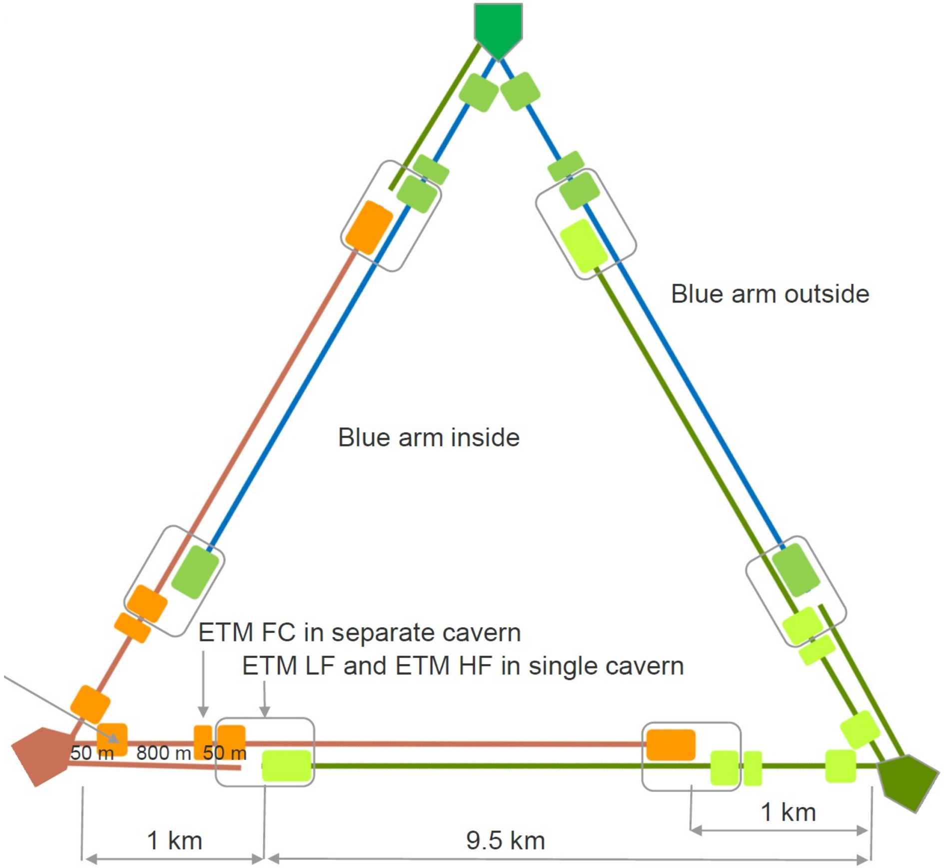
- Current generation of gravitational-wave detectors are detecting the tip of the iceberg
- The world-wide GW community is getting organized to build a third-generation detector network to observe gravitational waves throughout cosmic history
- Opens new opportunities for multi-messenger observations
  - Theseus has the potential to play a key role in this field

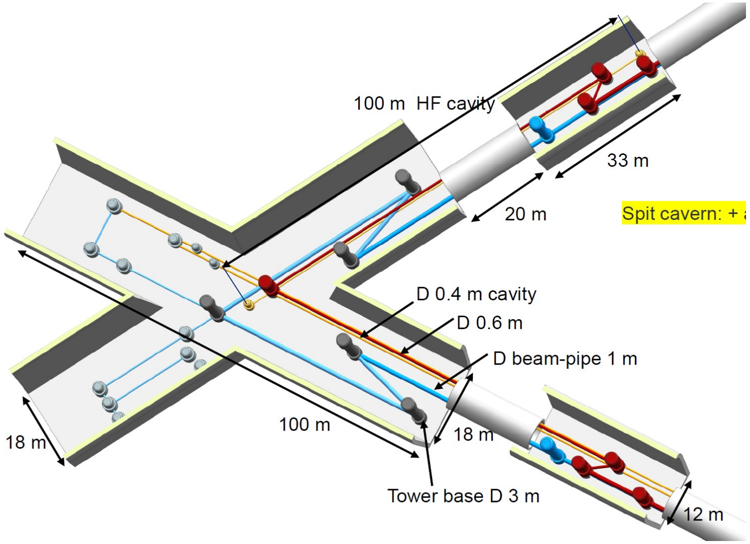


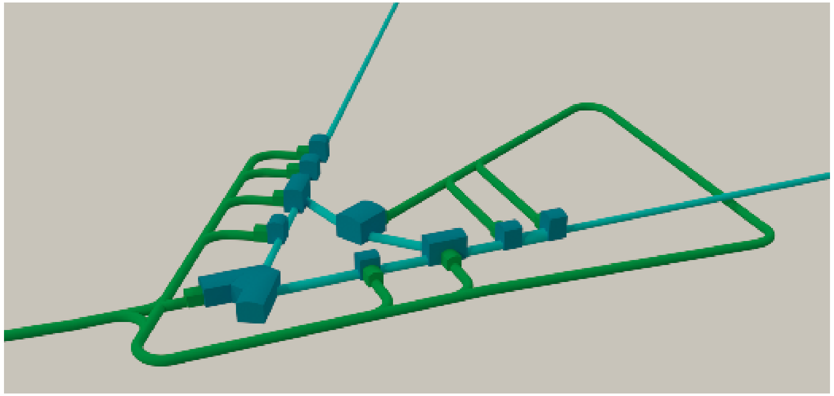
Years after the Big Bang
400 thousand
0.1 billion
1 billion
4 billion
8 billion
13.8 billion
The Big Bang
Recombination
The Dark Age
Formation of first astronomical object
Present day
Fully ionized
Neutralized
Reionization
Fully ionized
1000
100
10
1
1+Redshift



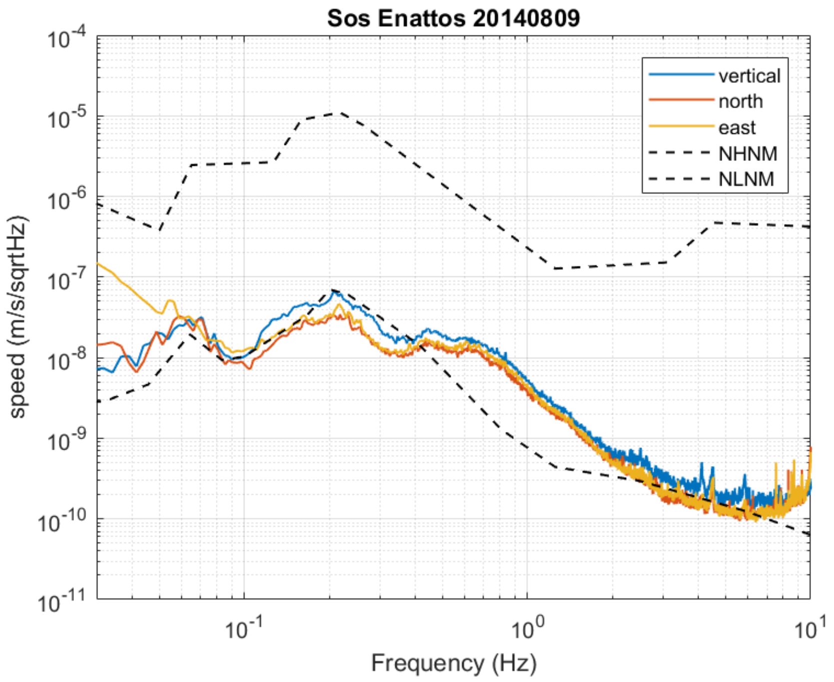
*
AdV infrasound NN
AdV sensitivity
Advanced Virgo (AdV)
Stran[1/√ Hz]
Frequency[Hz]
10^-18
10^-19
10^-20
10^-21
10^-22
10^-23
10^-24
10^-25
10^0
10^1

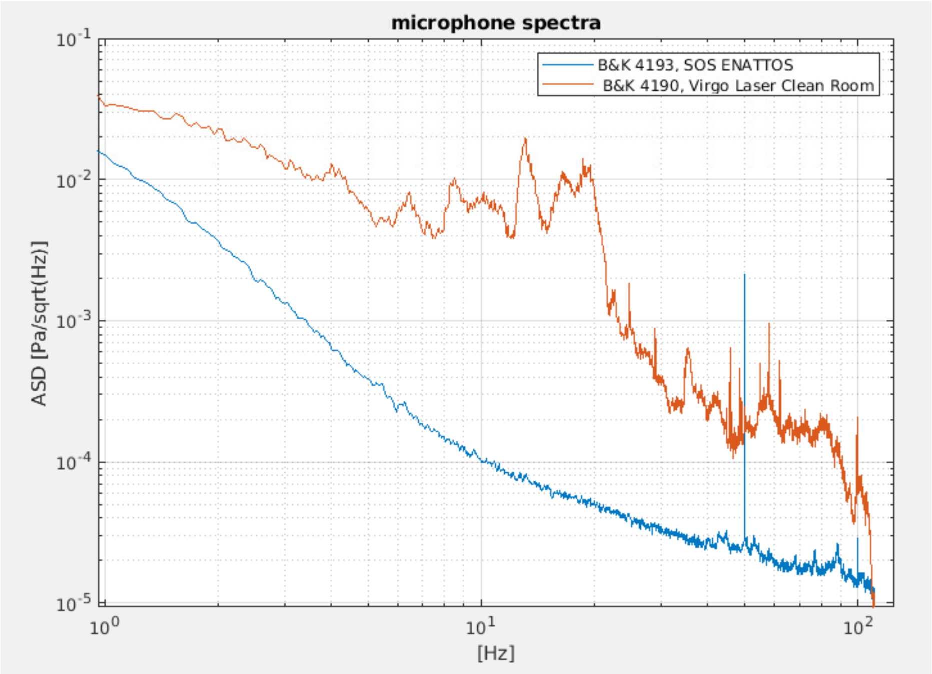

Blue arm outside
Blue arm inside
ETM FC in separate cavern
ETM LF and ETM HF in single cavern
50 m
800 m
50 m
1 km
9.5 km
1 km

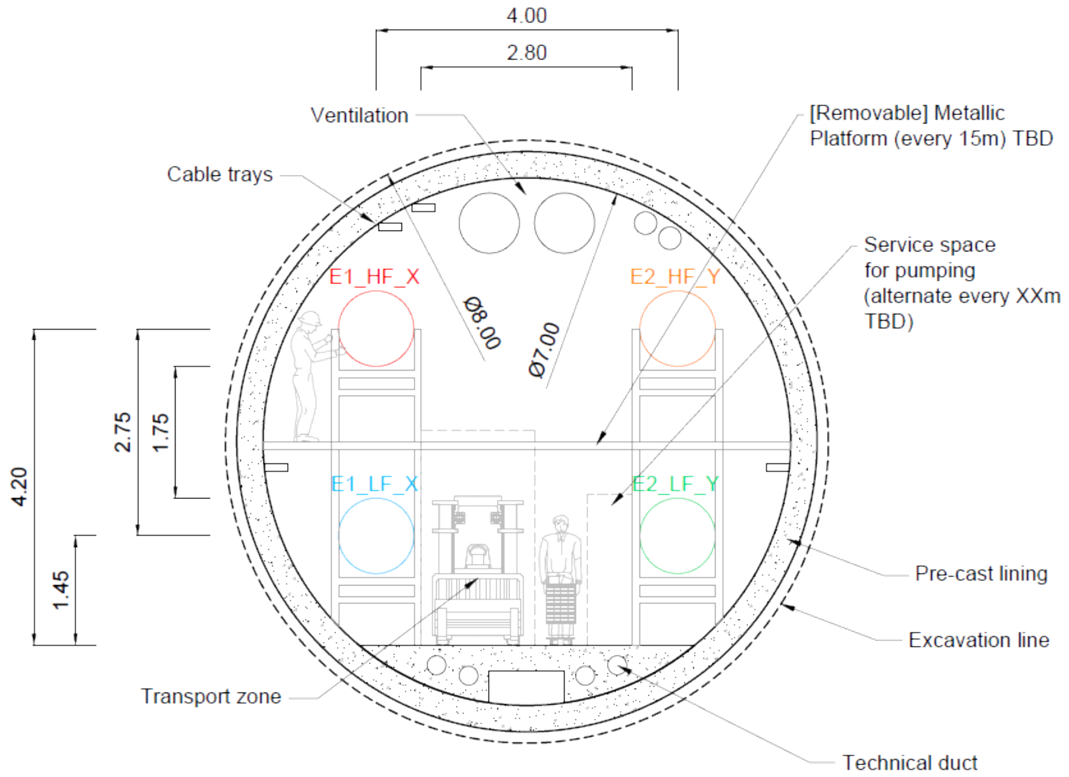

100 m HF cavity
33 m
20 m
Spit cavern: +
D 0.4 m cavity
D 0.6 m
D beam-pipe 1 m
18 m
100 m
18 m
Tower base D 3 m
12 m



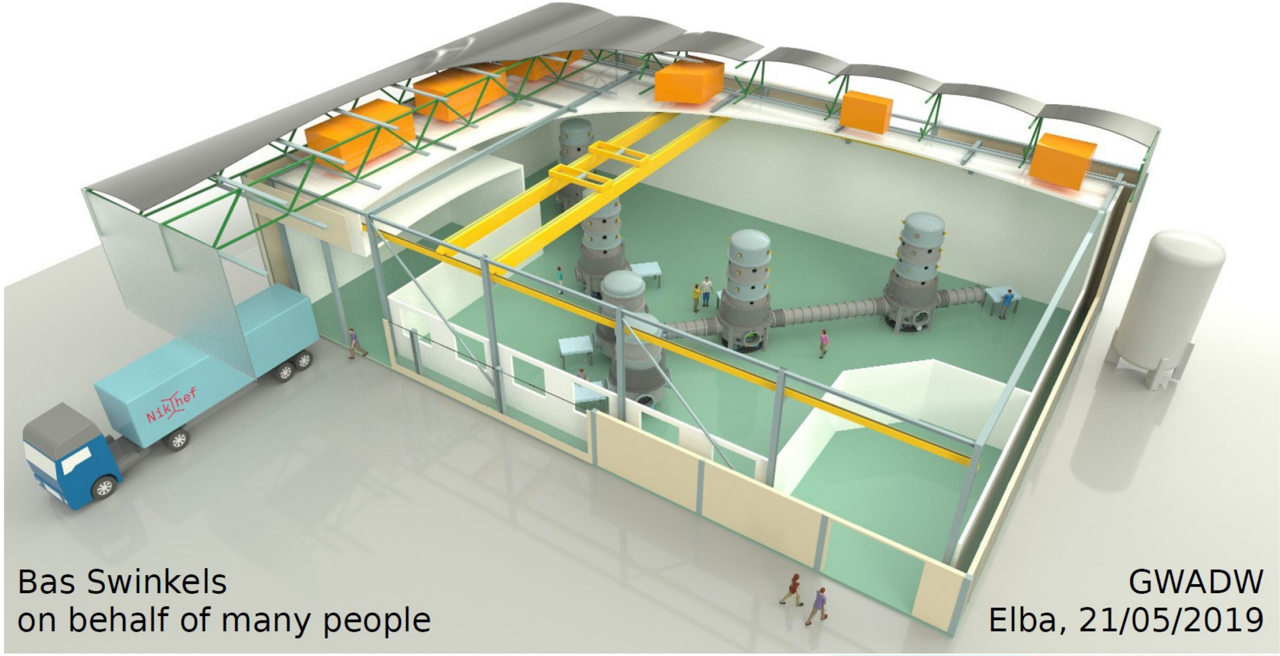
Microseismic (best)






4.00
2.80
Ventilation
[Removable] Metallic
Platform (every 15m) TBD
Cable trays
Service space
for pumping
(alternate every XXm
TBD)
E1_HF_X
E2_HF_Y
Ø8.00
Ø7.00
E1_LF_X
E2_LF_Y
4.20
2.75
1.75
1.45
Pre-cast lining
Excavation line
Transport zone
Technical duct

ET Pathfinder in Maastricht



Nikhef

ET EINSTEIN TELESCOPE