The Einstein Telescope project

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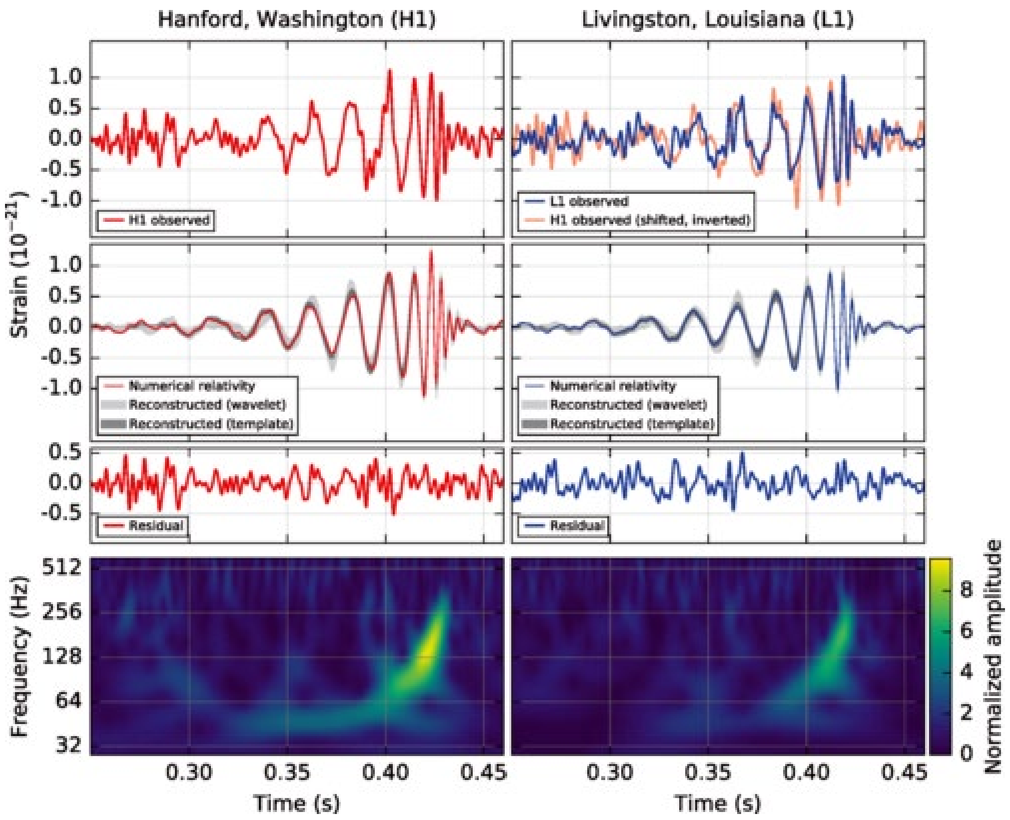
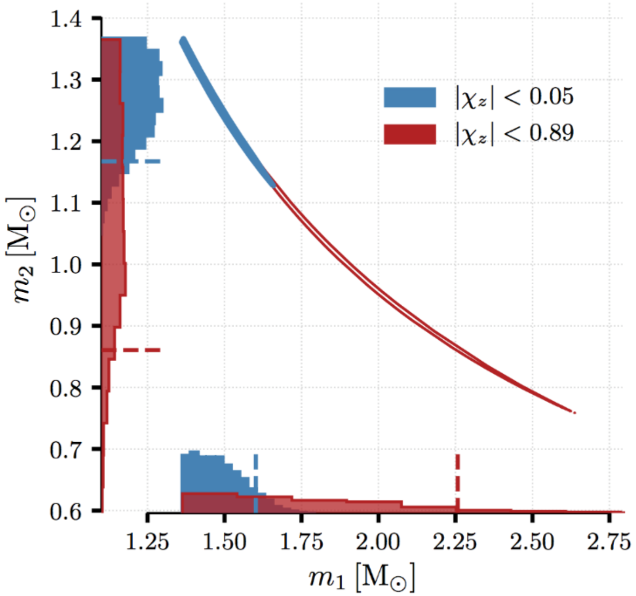
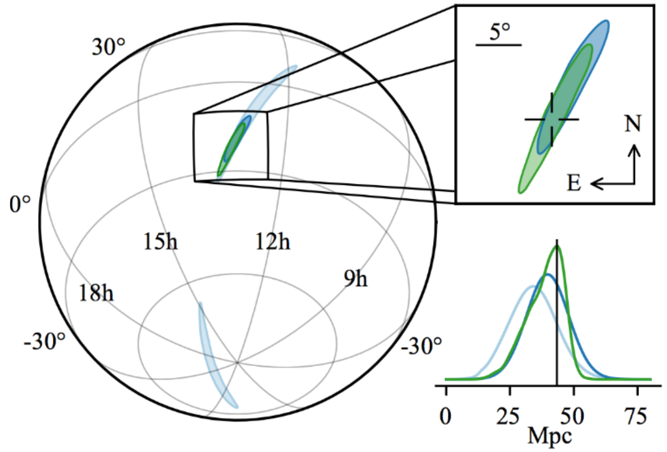
The beginning of GW astronomy

September 2015: first direct observation of GW



August 2017: first multi-messenger observation of a Neutron star merger

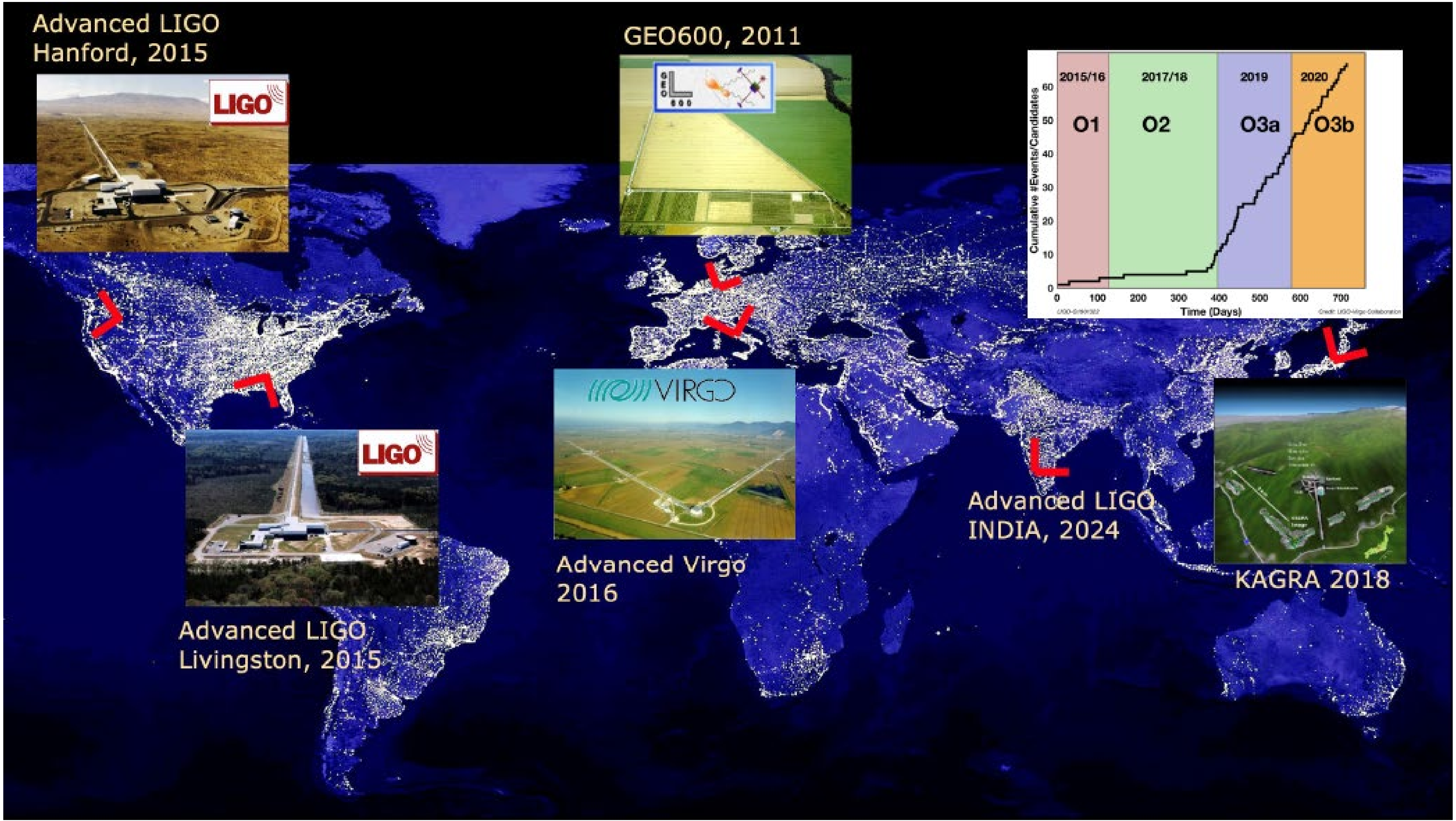




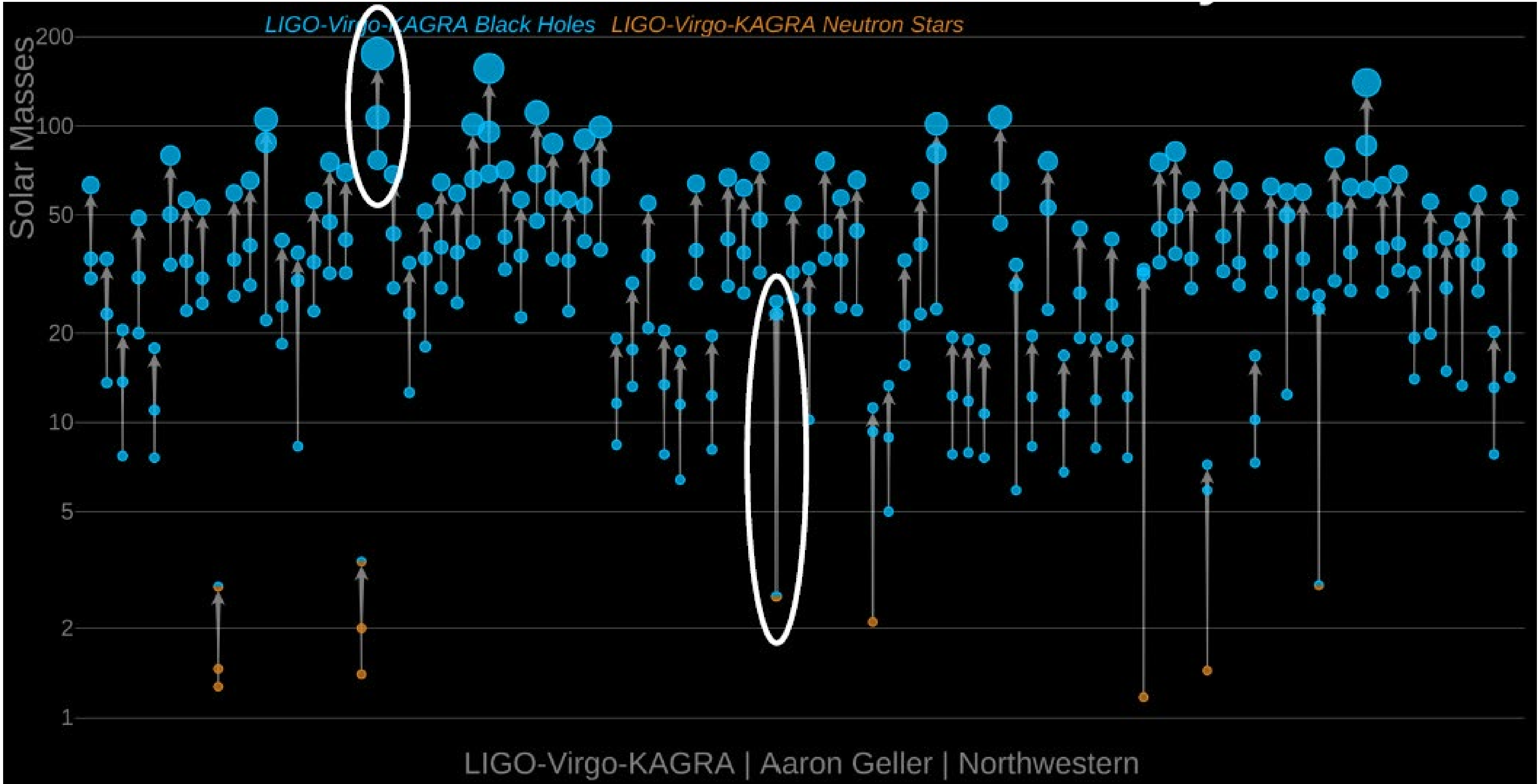
$$\frac{S}{N} = \frac{\int_{-\infty}^{\infty} dt \, \langle s(t) \rangle K(t)}{\left[\int_{-\infty}^{\infty} df \, (1/2) S_n(f) |\tilde{K}(f)|^2 \right]^{1/2}}$$

Classical signal treatment (matched filtering) and parameter estimation

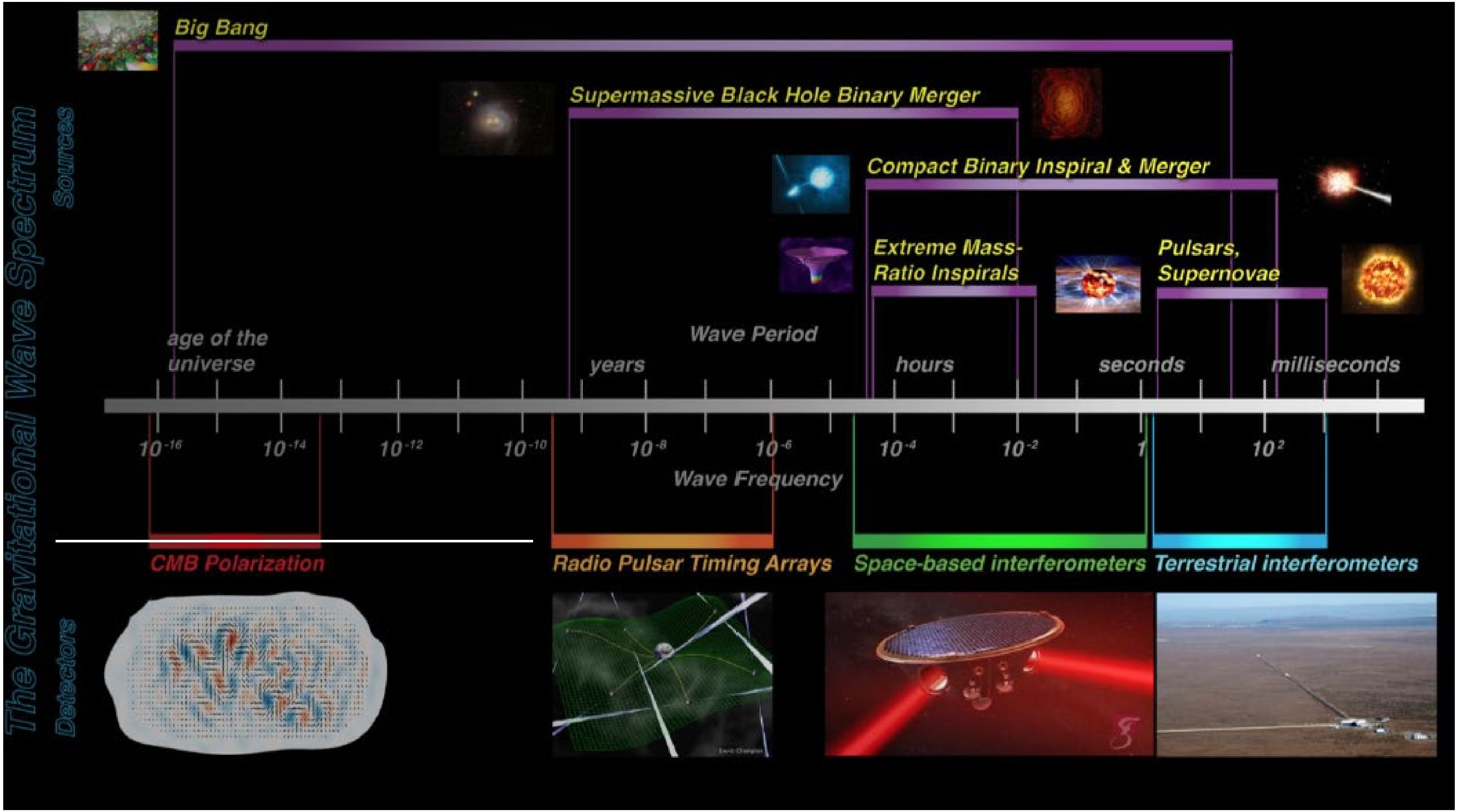
The network of GW laser interferometers



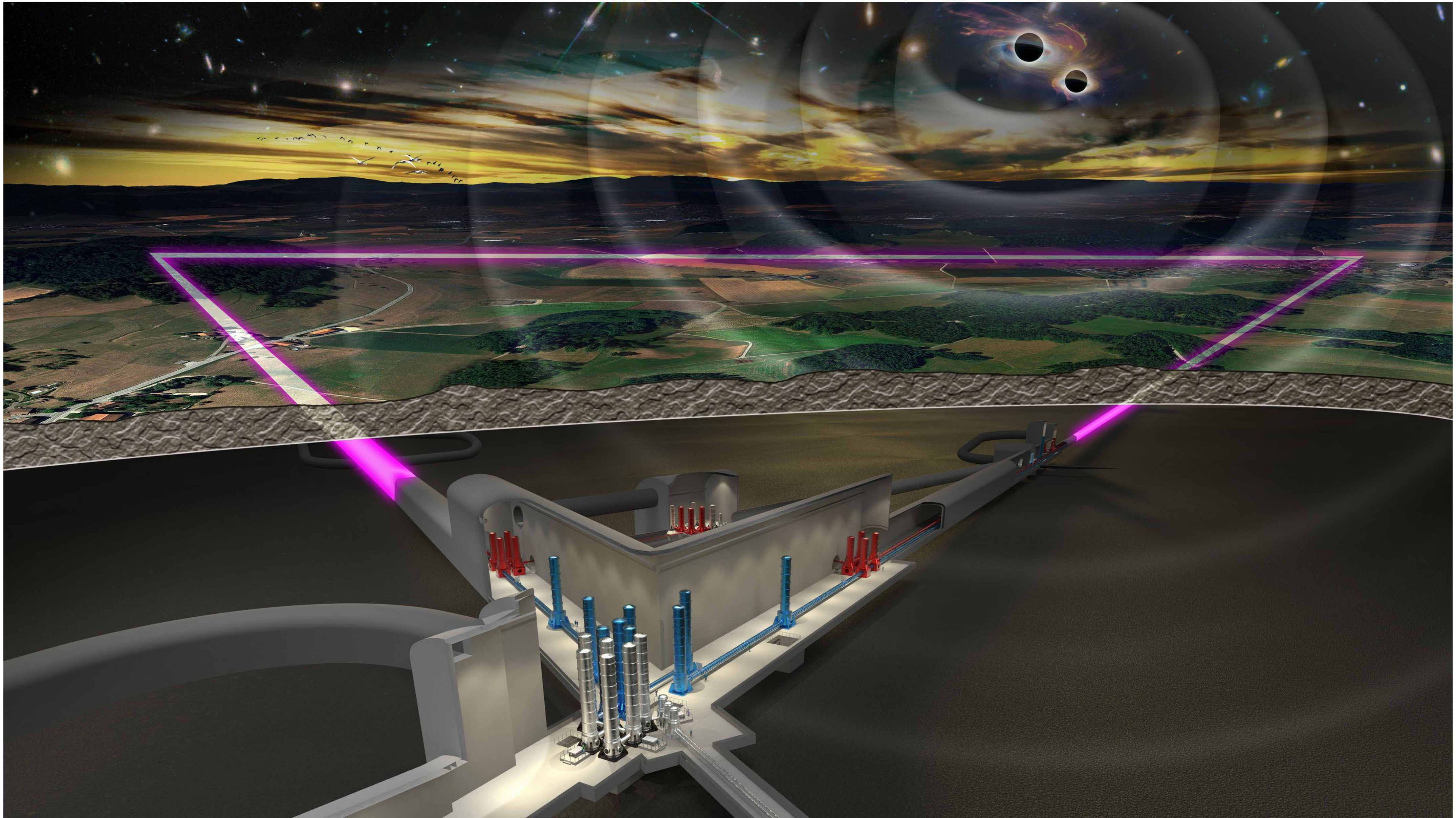
Observations so far



GW global landscape



ET : the next-generation terrestrial GW laser interferometer



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Examples of ET physics potential

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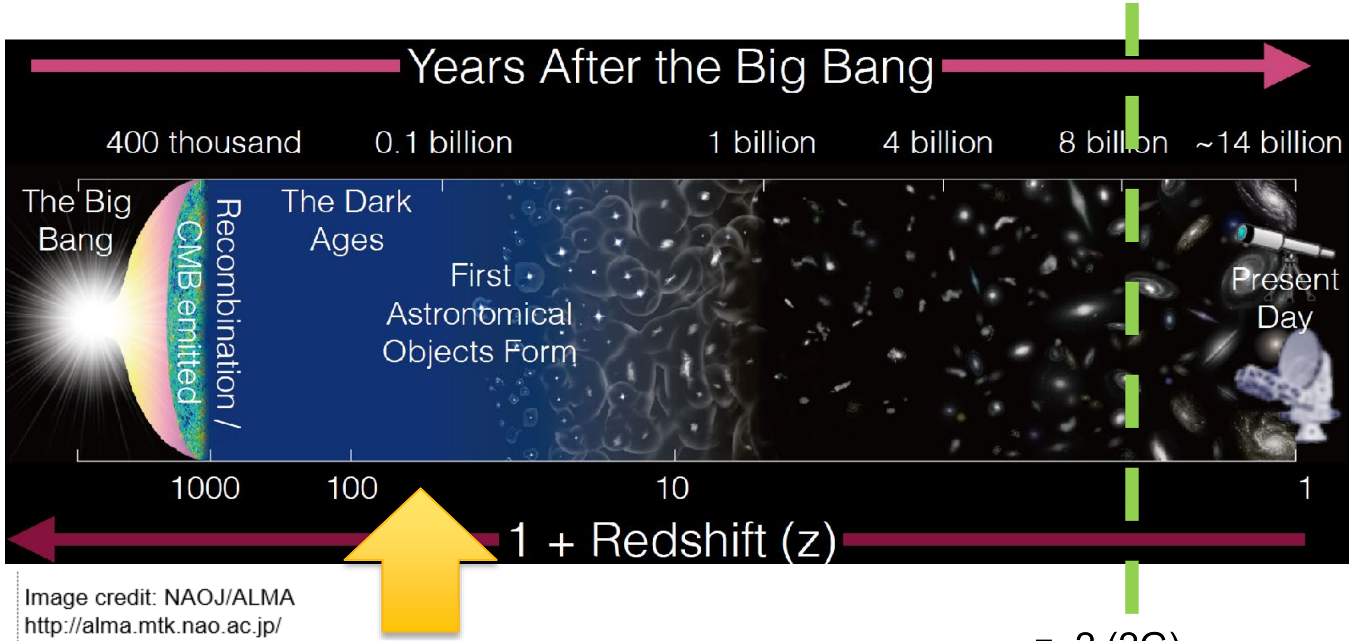
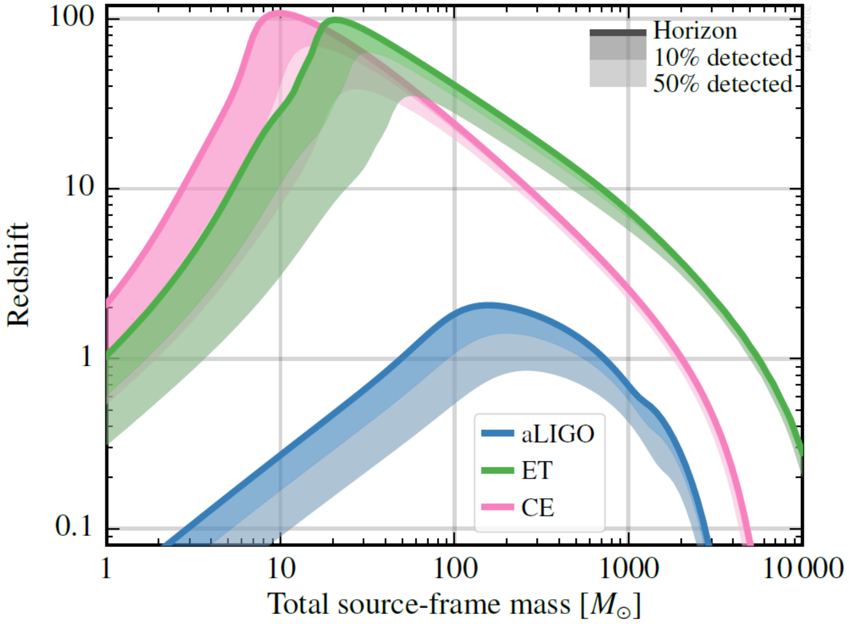
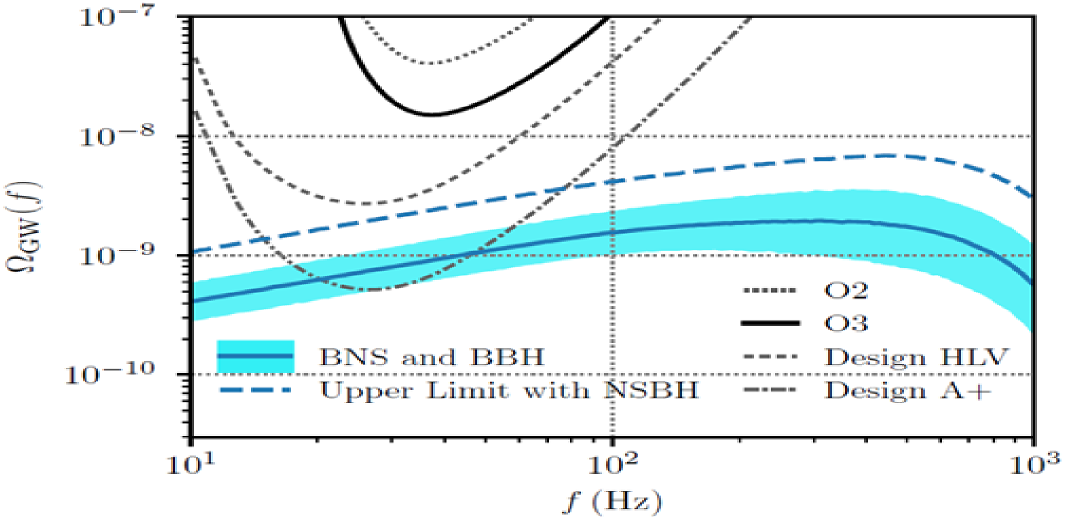
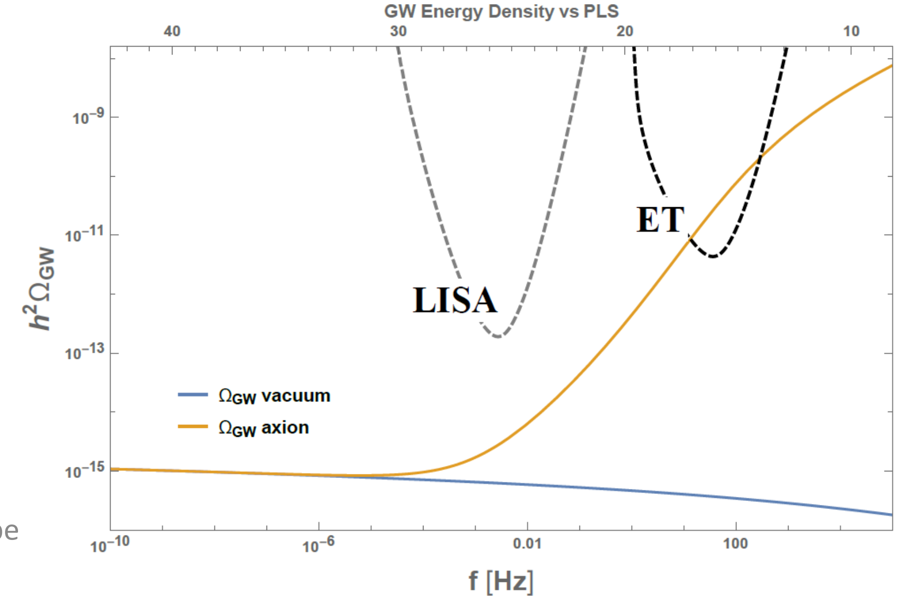








ET science case

Astrophysics

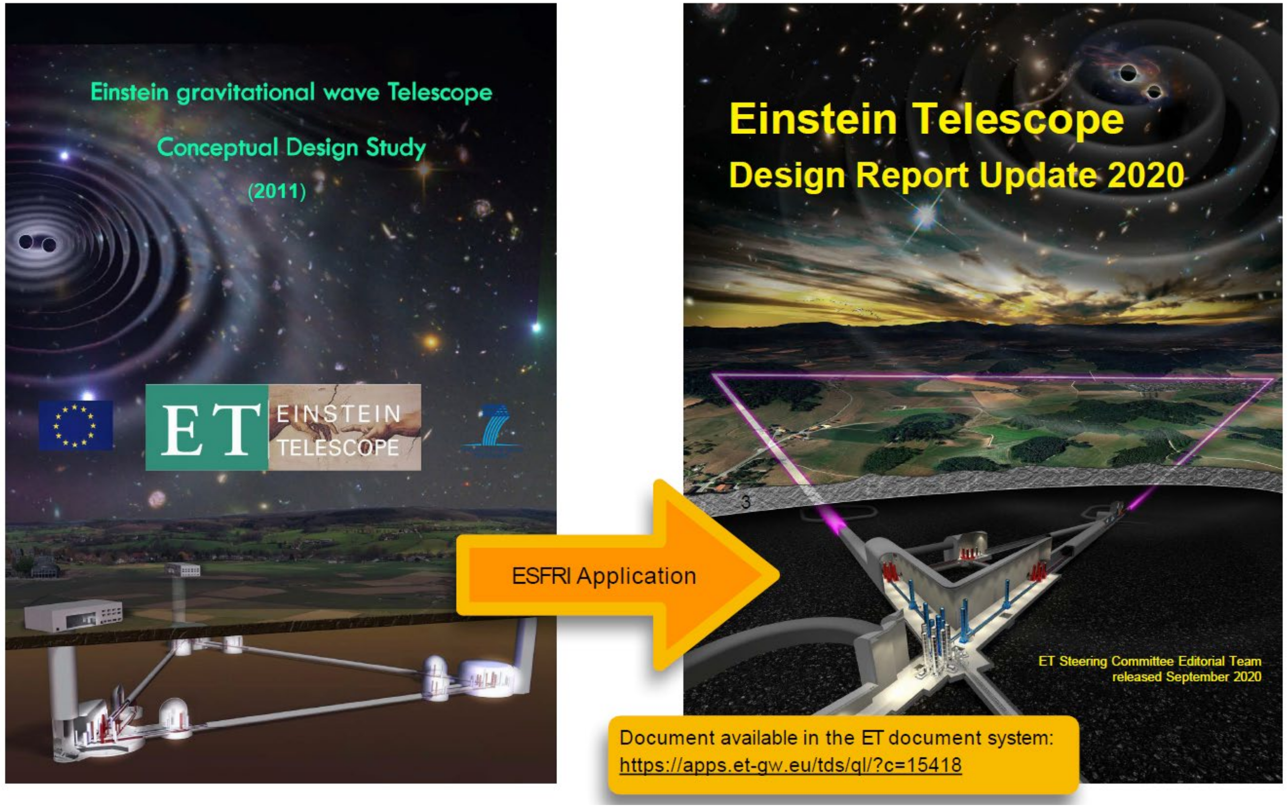
- Black hole properties
  - origin (stellar vs. primordial)
  - evolution, demography
- Neutron star properties
  - demography, equation of state
- Multi-messenger astronomy
  - joint GW/EM observations
  - multiband GW detection (LISA)
  - neutrinos
- Detection of new astrophysical sources
  - core collapse supernovae
  - isolated neutron stars
  - stochastic background of astrophysical origin

Fundamental physics and cosmology

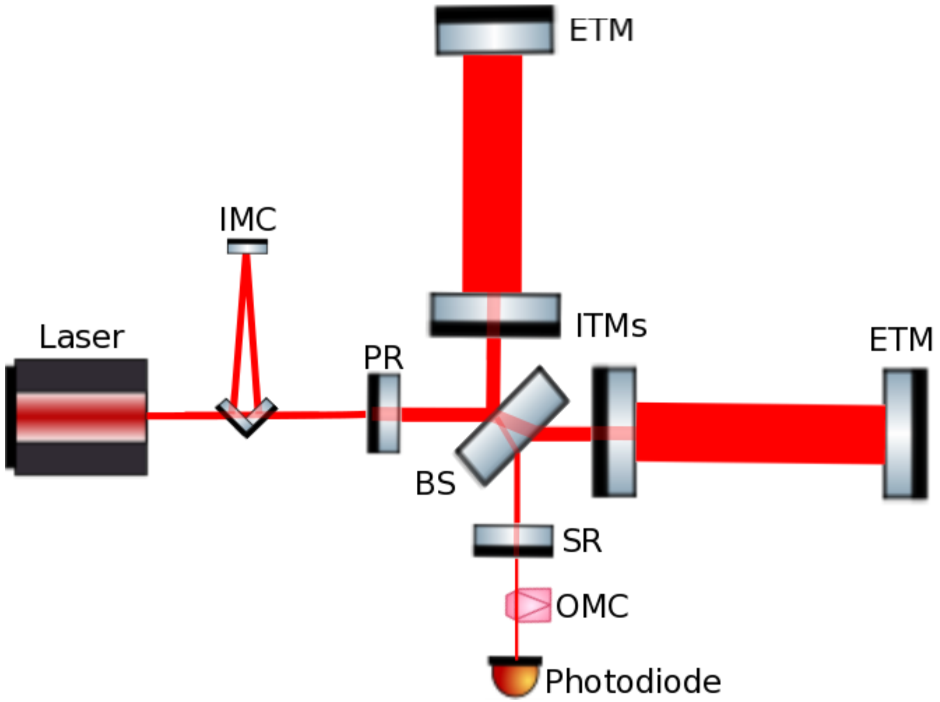
- Tests of GR
- QCD
  - interior structure of neutron stars probe QCD at ultra-high temperatures and densities
- Dark matter/new particles
  - primordial BHs, new bosons (e.g axions) accreting around compact objects
- Dark energy and modifications of gravity on cosmological scales
- Stochastic backgrounds of cosmological origin and connections with high-energy physics
  - Inflation, phase transitions, cosmic strings...

ET status

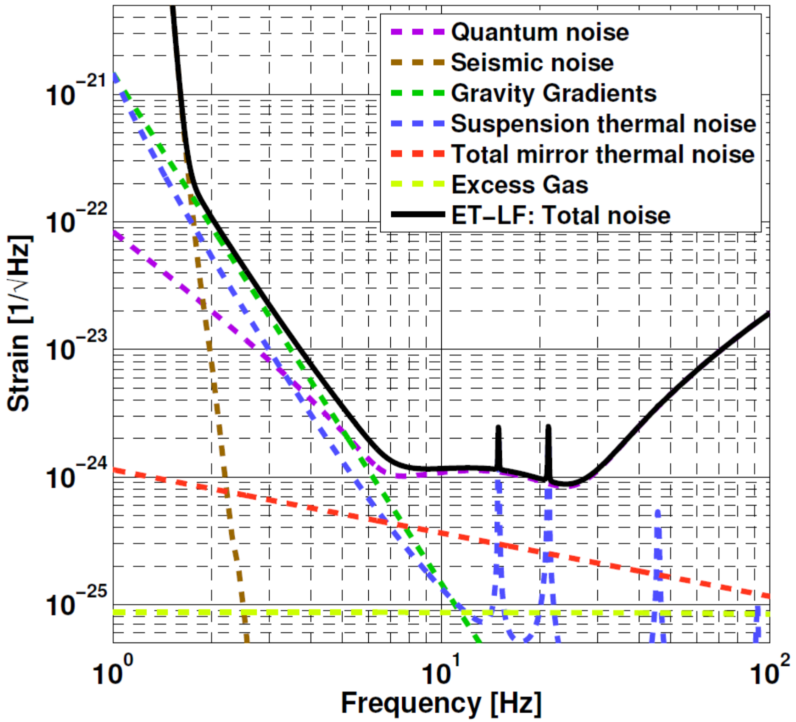
- ET on ESFRI roadmap since 2021
- ET Collaboration launched in June 2022
  - ~80 groups; ~1200 members
- Construction to start in 2026
  - Site selection in 2025
- Operation in ~2035



Laser interferometers and their noise



ET Conceptual Design Study - ET-0106C-10



- Seismic noise
- Gravity gradient noise
- Thermal noise
- Quantum noise
- Excess gas

.. and myriad of technical noise sources

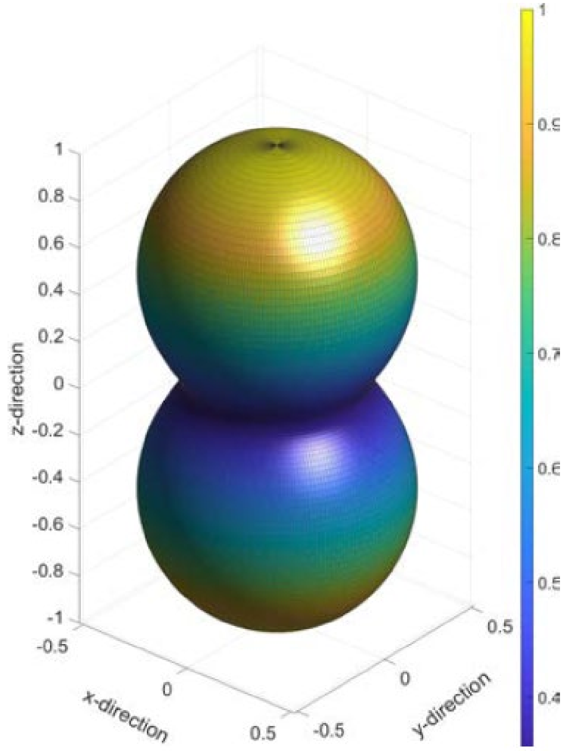
ET basic design concepts

- Longer arms
  - Effect of GW is equivalent to a relative change in the arm lengths (ΔL/L)

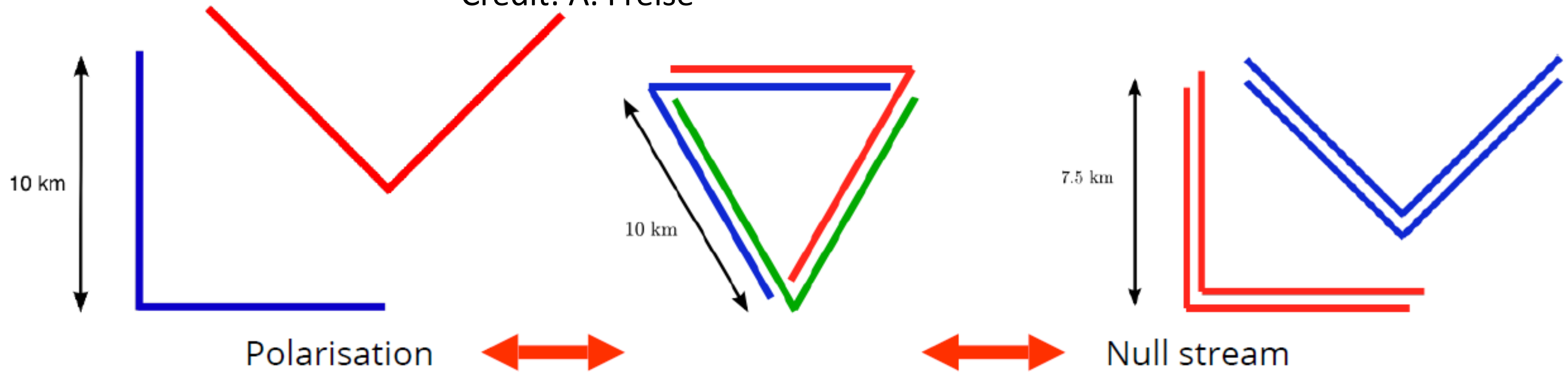
  → All mirror displacement noise sources reduced by making L larger

  but this increases laser beam size (need for large mirrors)
- Underground operation
  - Reduction of seismic and gravity gradient noise

  → key for sensitivity at low frequency
- Triangular shape
  - Wave polarizations
  - Null streams
  - Redundancy
  - Antenna pattern
  - Single compact infrastructure



Credit: A. Freise



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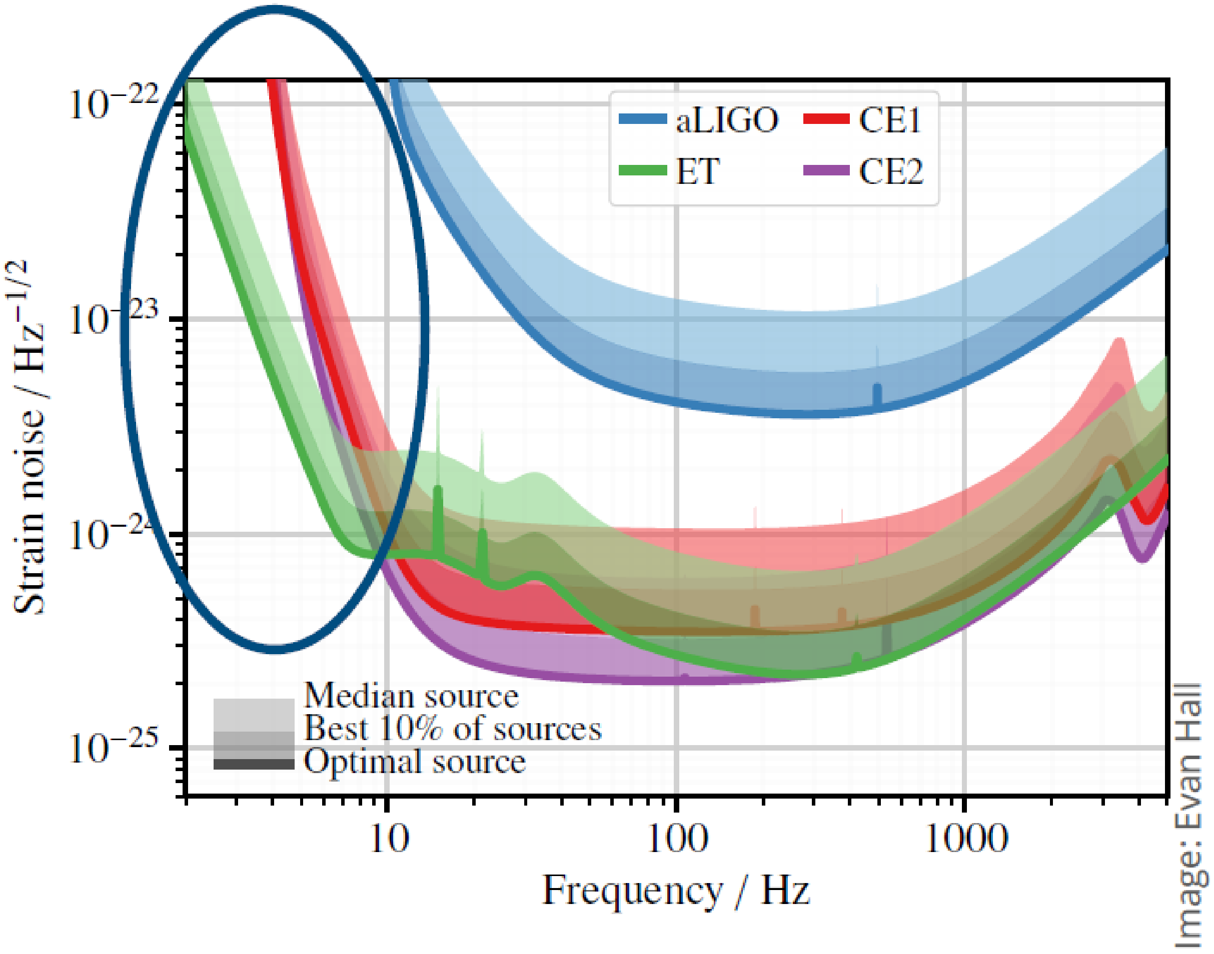
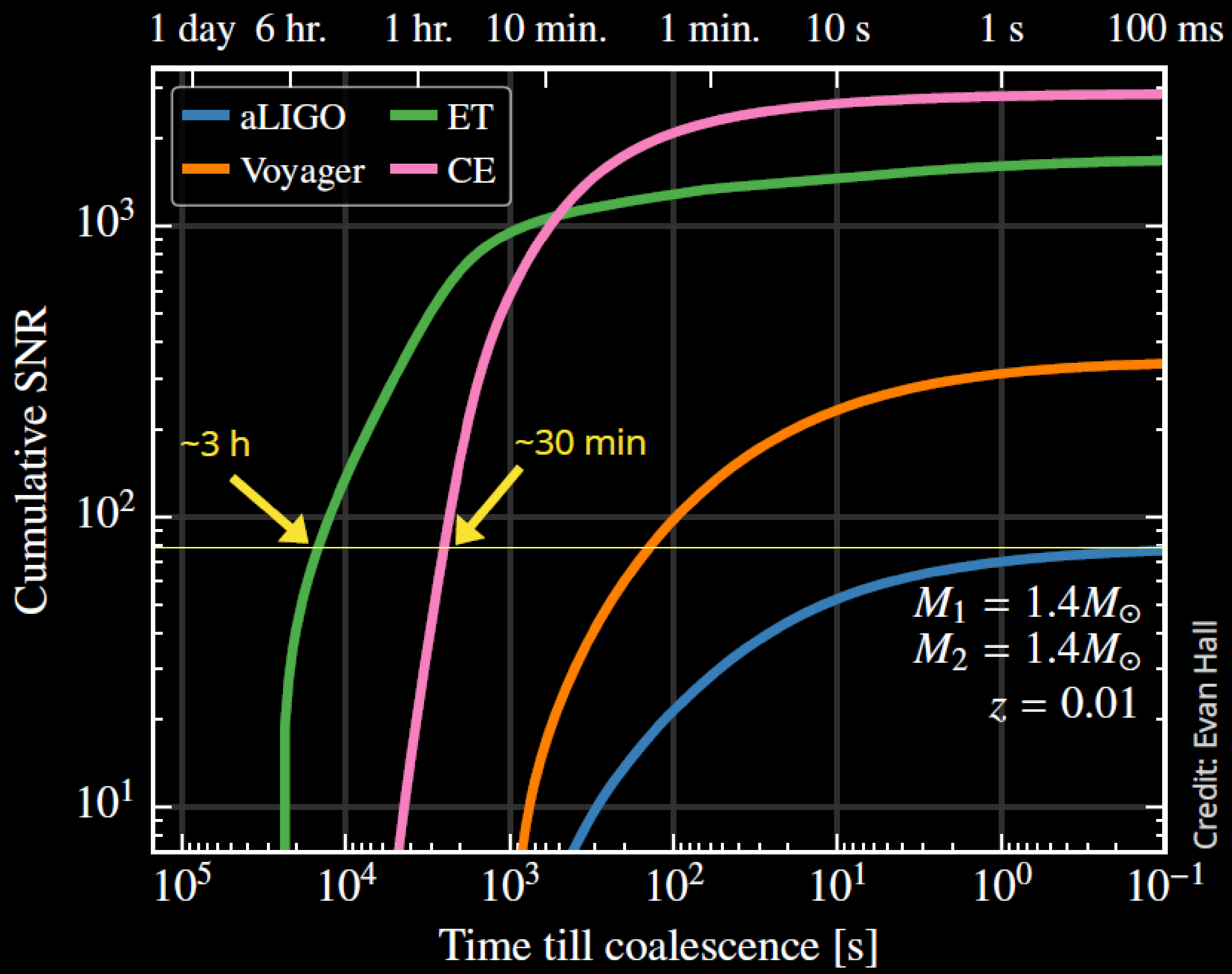
Low-frequency target

- Intermediate mass BHs
  - Larger masses (and redshift)
- Larger redshift → dark energy and GR tests at cosmological distances
- Multi-messenger observations
  - Early detections
- NS physics (QCD)
  - Many radio and young pulsars spinning at low frequencies

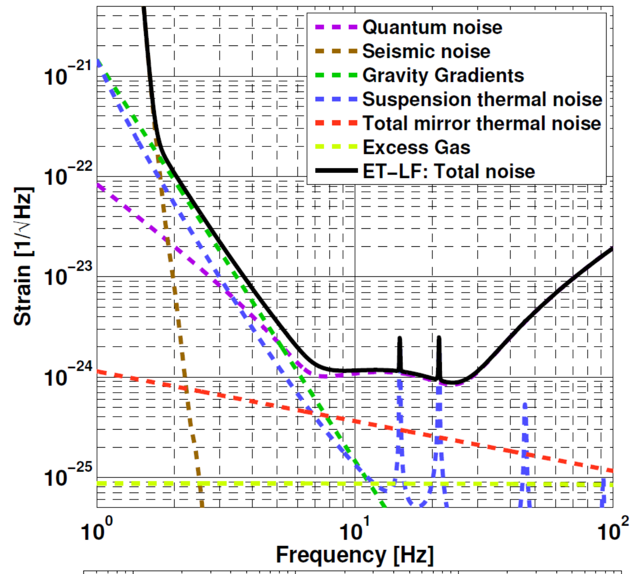


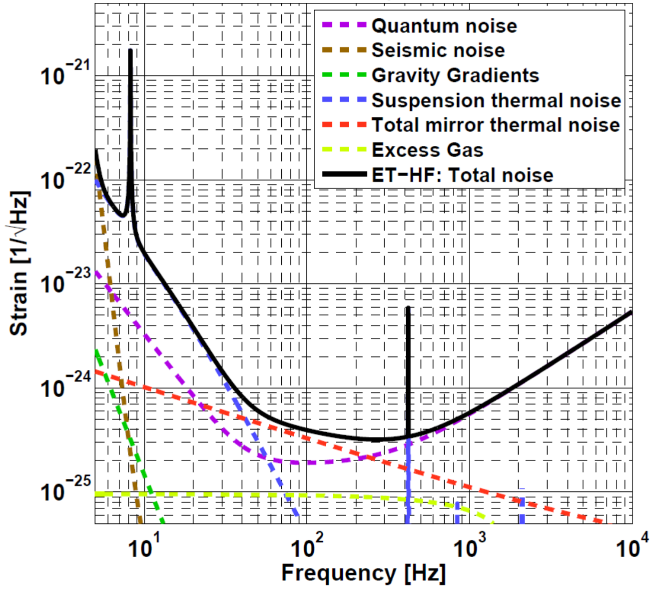
Low frequency performance drives some of the most significant design choices

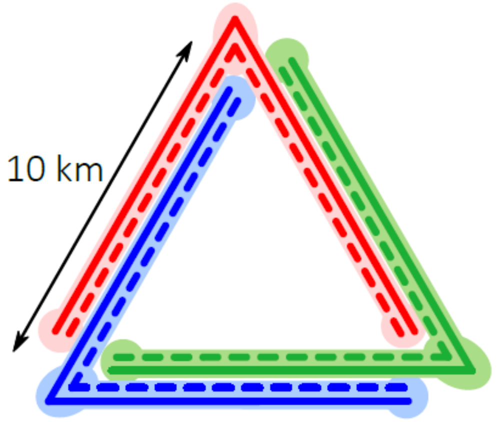


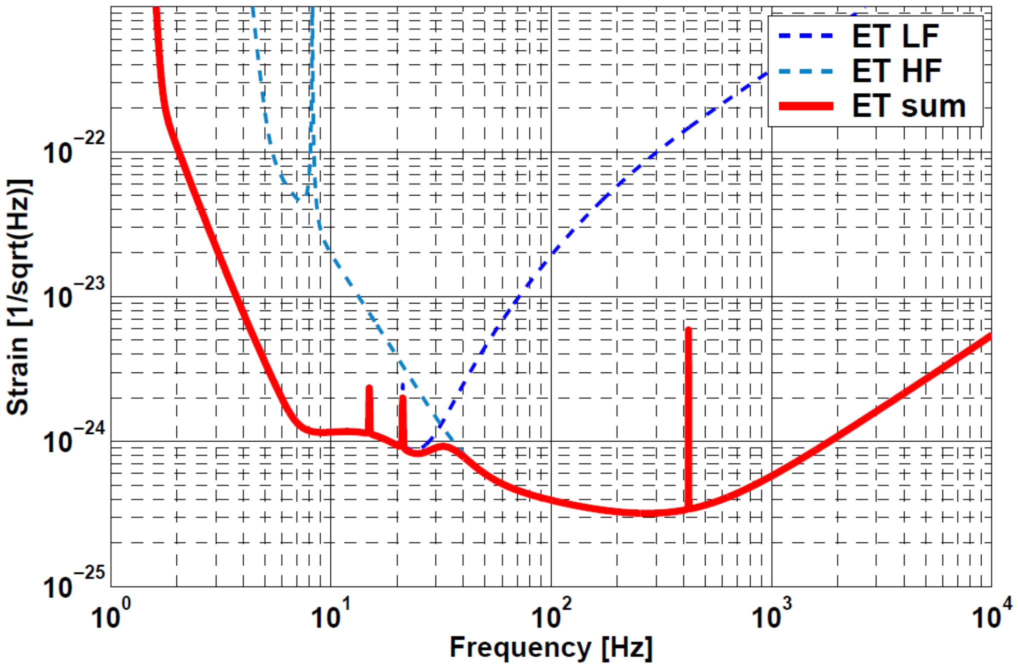
1 day
6 hr.
1 hr.
10 min.
1 min.
10 s
1 s
100 ms
aLIGO
ET
Voyager
CE
Cumulative SNR
10^3
10^2
10^1
~3 h
~30 min
$M_1 = 1.4M_\odot$
$M_2 = 1.4M_\odot$
$z = 0.01$
Credit: Evan Hall
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
Time till coalescence [s]

Xylophone design









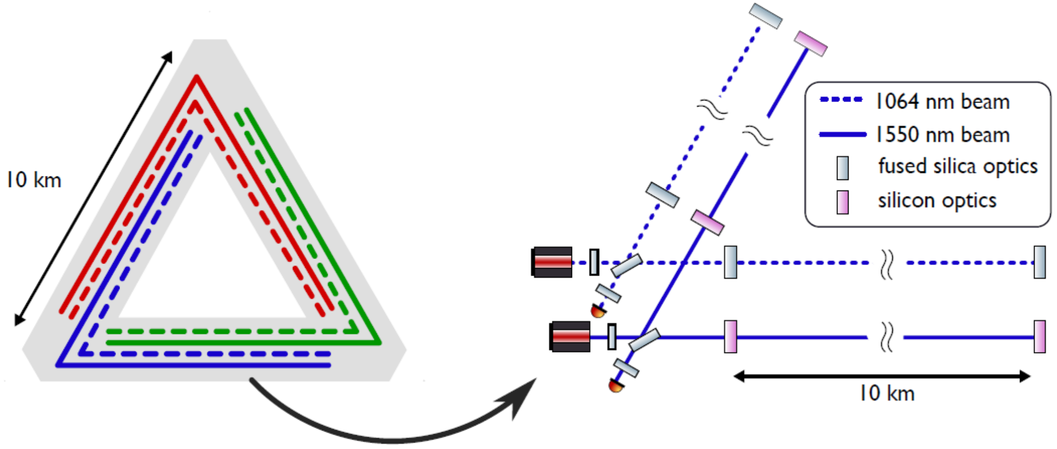
Xylophone is the solution to **conflicting requirements**:

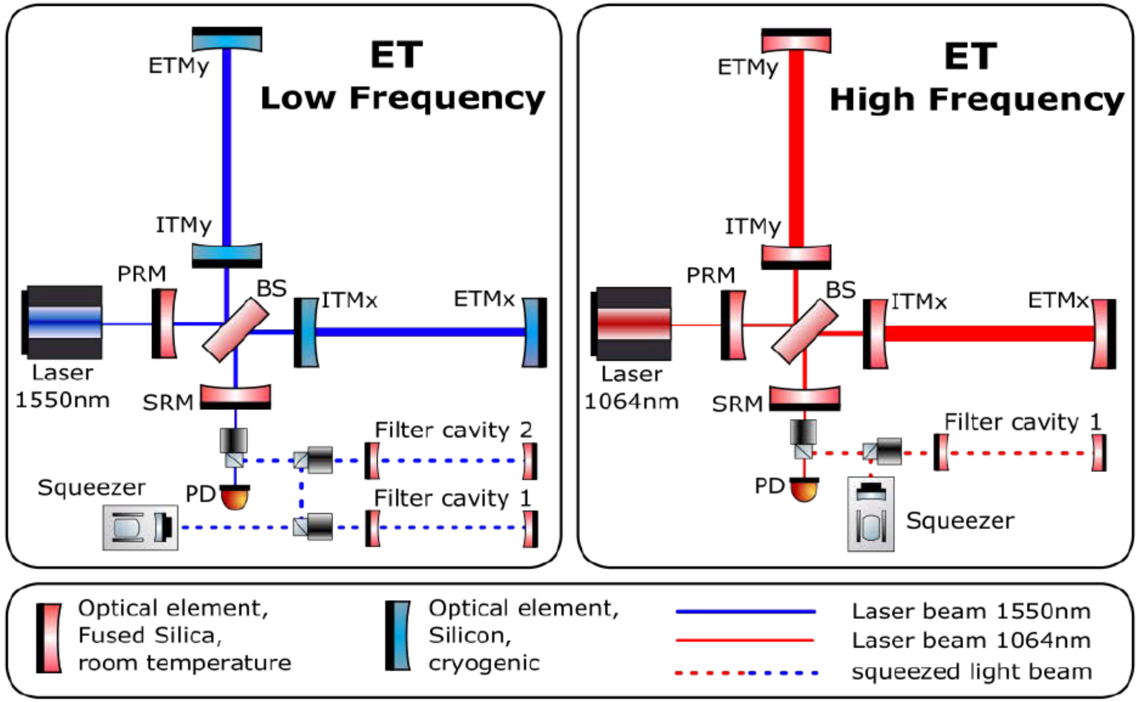
- **High frequency** needs **high laser power** (shot noise)
- **Low frequency** needs **cryogenic mirrors** (thermal noise) and **low laser power** (rad. pressure) . Control noise at low frequency also increased by high power

- ET-HF : high laser power; extend current technology
- ET-LF : Low laser power, cryogenic mirrors (new materials, new wavelength, …)

ET design

Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10-20 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	45 cm/ 57 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase (rad)	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1×300 m	2×1.0 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	TEM_{00}	TEM_{00}
Beam radius	12.0 cm	9 cm
Scatter loss per surface	37 ppm	37 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}$ m$/f^2$	$5 \cdot 10^{-10}$ m$/f^2$
Gravity gradient subtraction	none	factor of a few





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Site

EMR site

Saxony site

Sos Ennatos site

- Science
  - Seismic, Newtonian, anthropogenic noise
- Cost and feasibility
  - Geology, topography, climate, access, services, local regulations
- Socio-political factors
  - Availability of funds

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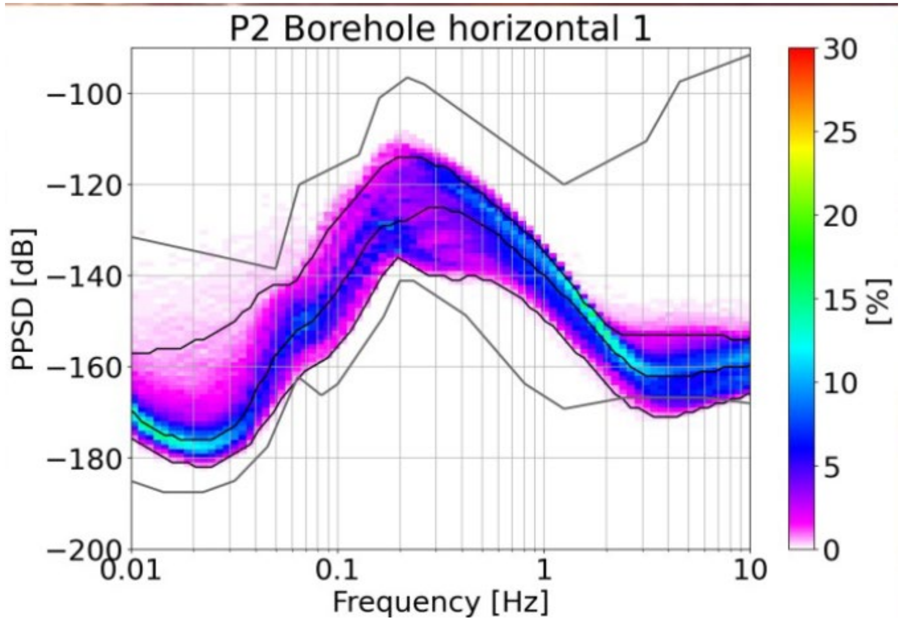
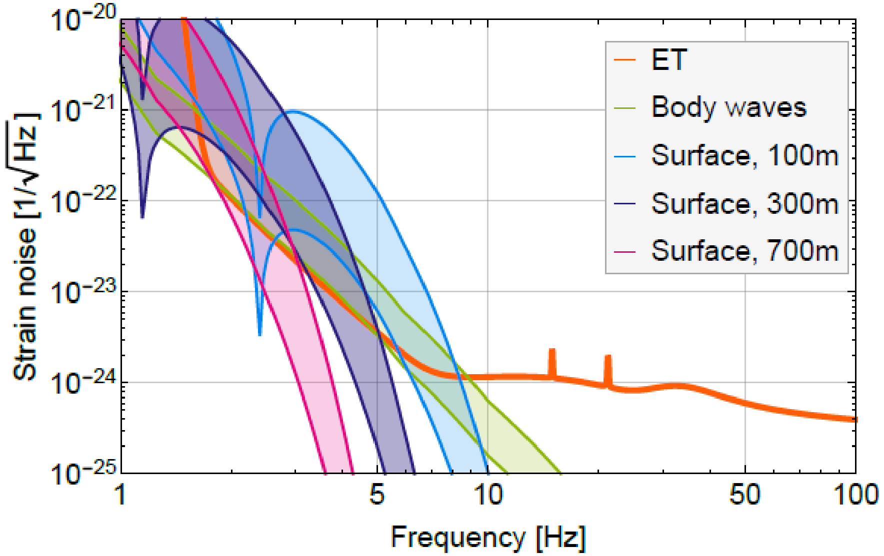
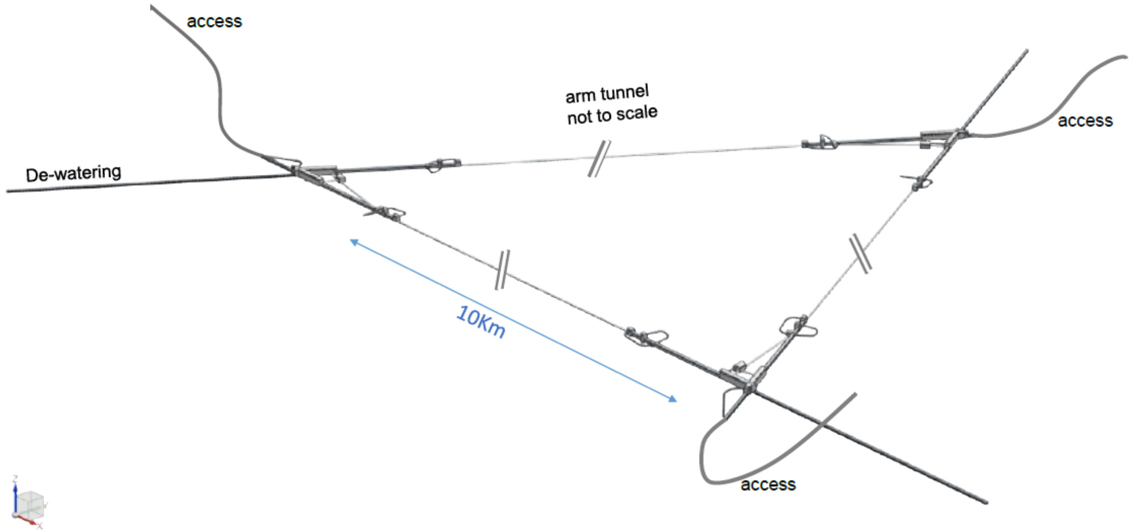
Environmental noise

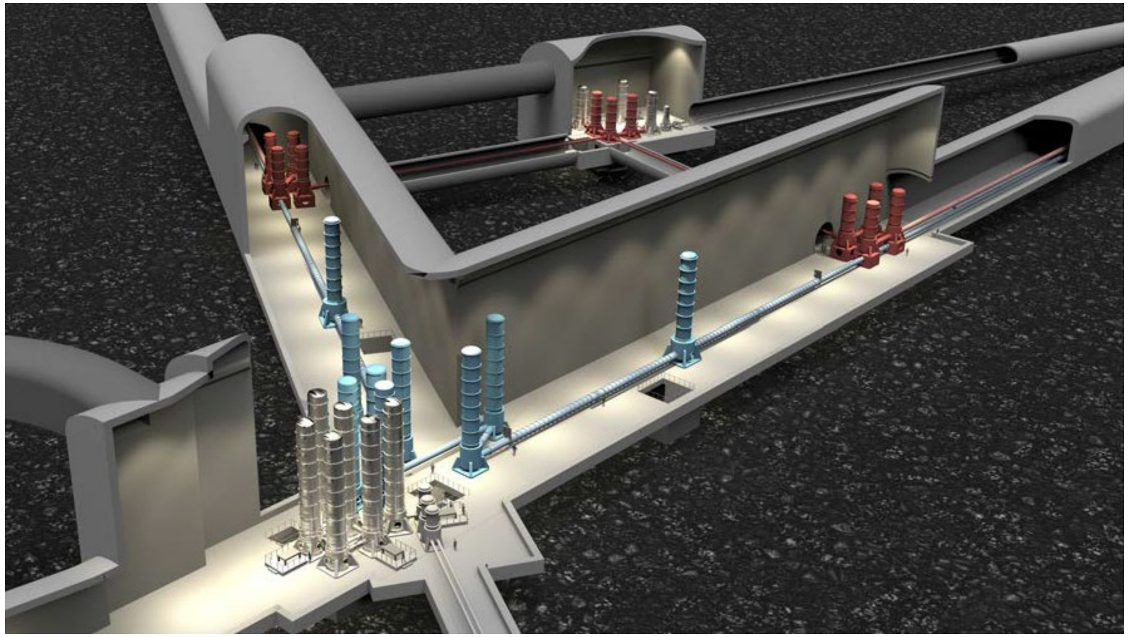
- Seismic and geology studies ongoing
- Newtonian noise
  - Highly reduced underground
    - ➢ Seismic NN
  - Cancellation
    - ➢ Wave properties: speed, polarization, sources,
    - ➢ Geology, topography
    - ➢ Optimal number and placement of sensors

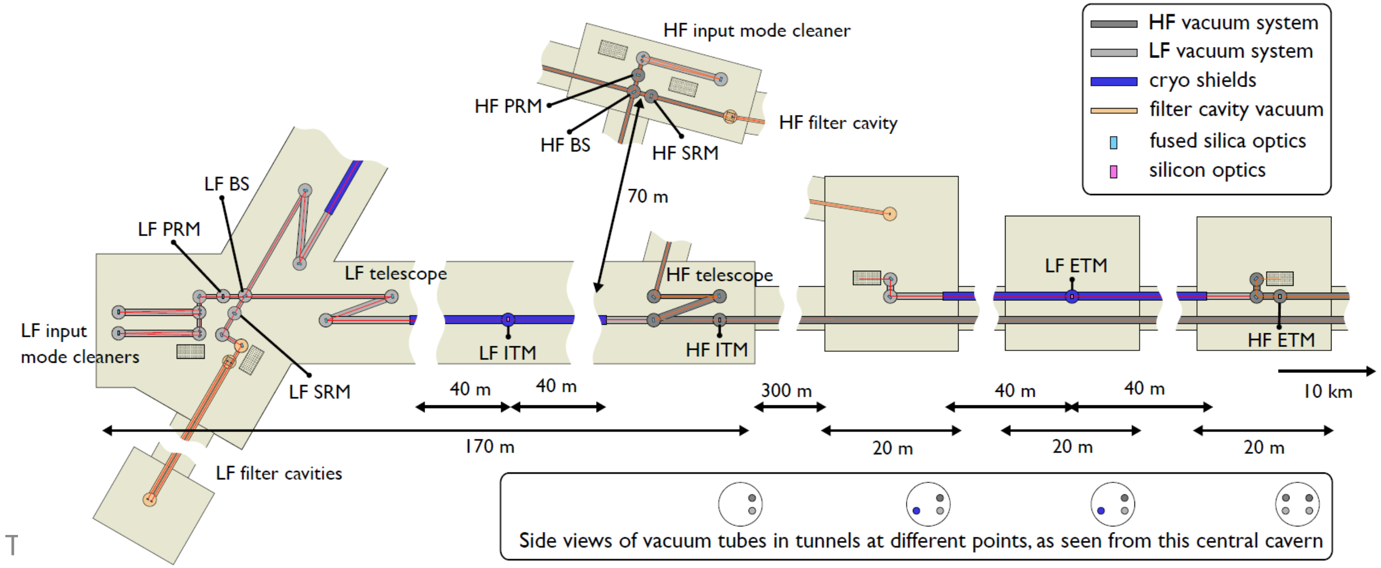




Infrastructure





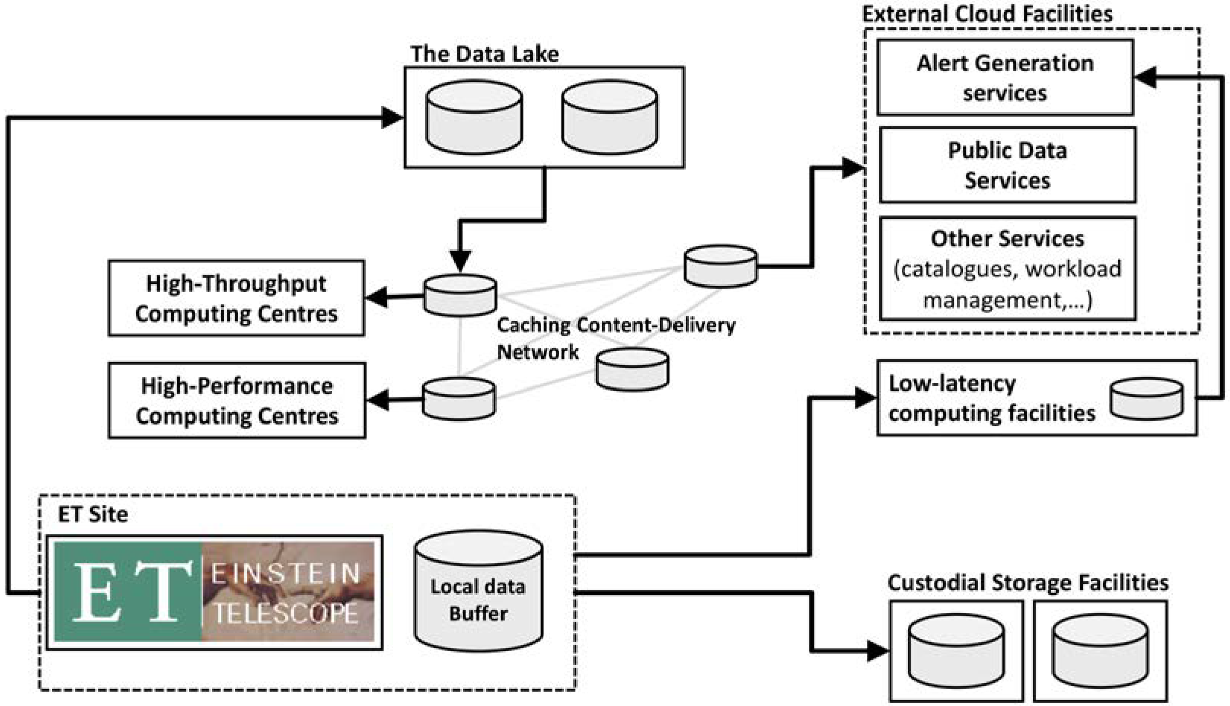


Feasibility study of beam-expanding telescopes in the interferometer arms for the Einstein Telescope https://arxiv.org/abs/2011.02983

Computing

- Data management
  - O(PB/year) similar to current detectors
    - ➢Not critical
- Computing power
  - $>10^3$ current needs
    - ➢Driven by CBC detections
    - ➢Very challenging
  - Optimise algorithms
  - HW (GPUs, parallelization,..)
  - SW (deep learning, etc)
  - New technologies

- On-site: control, DAQ and preprocessing, buffering
- Low-latency alerts for multi-messenger astronomy
  - Dedicated facility serving triggers to external cloud-computing facility providing also catalogues
- Expect global EU infrastructure (HL-LHC, SKA, CTA, ET,...)
  - Data lake feeding HTC/HPC facilities



Summary

- ET project has highly relevant scientific case
- ET is making steady progress toward realization
  - ESFRI, official Collaboration
- Basic design is in place
- Large number of R&D challenges