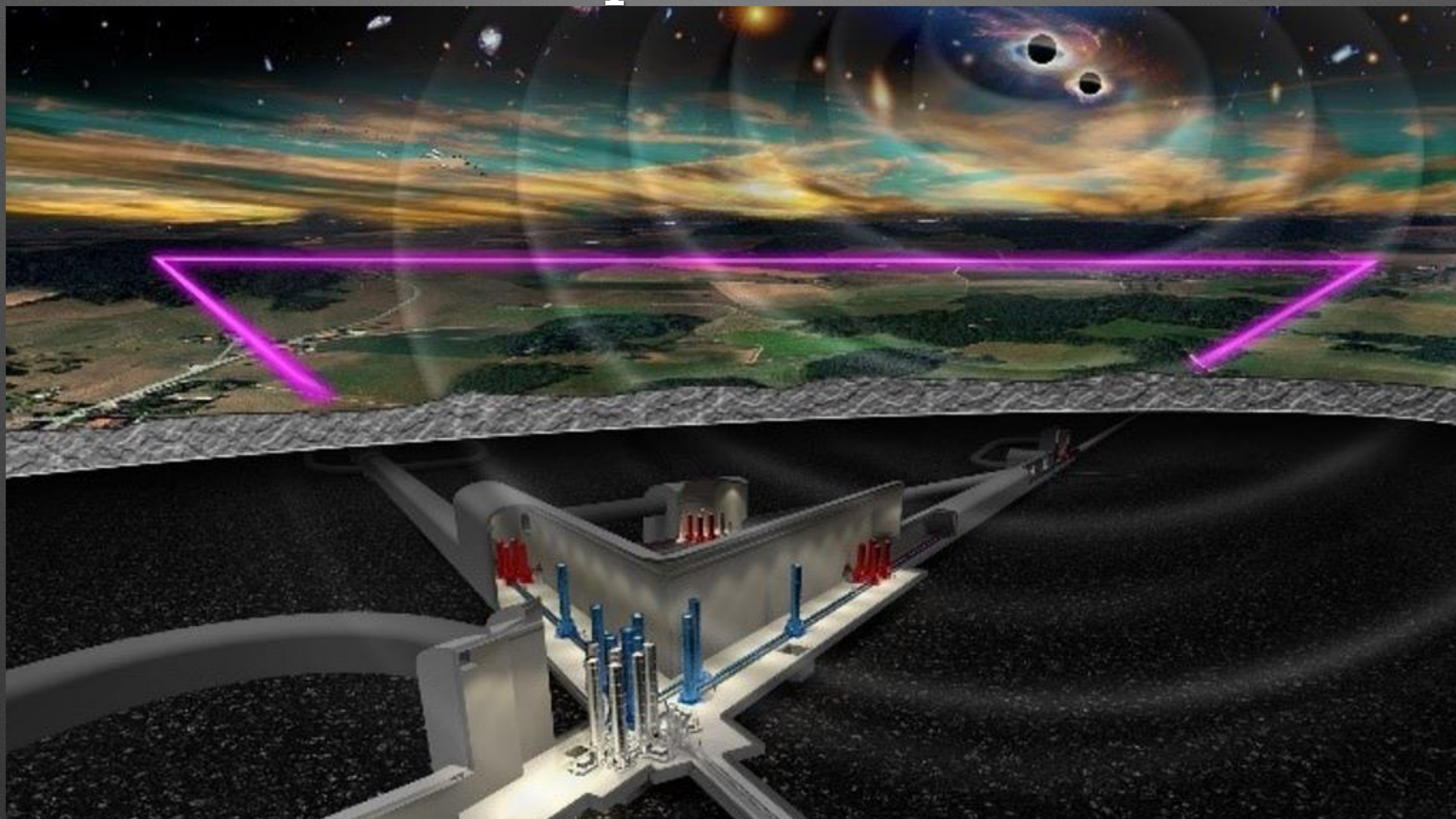
Gravitational waves
EinsteinTelescope, a future 3G experiment



GSSI
GRAN SASSO SCIENCE INSTITUTE

INTERNATIONAL SYMPOSIUM ON NEUTRINO PHYSICS AND BEYOND (NPB 2024)

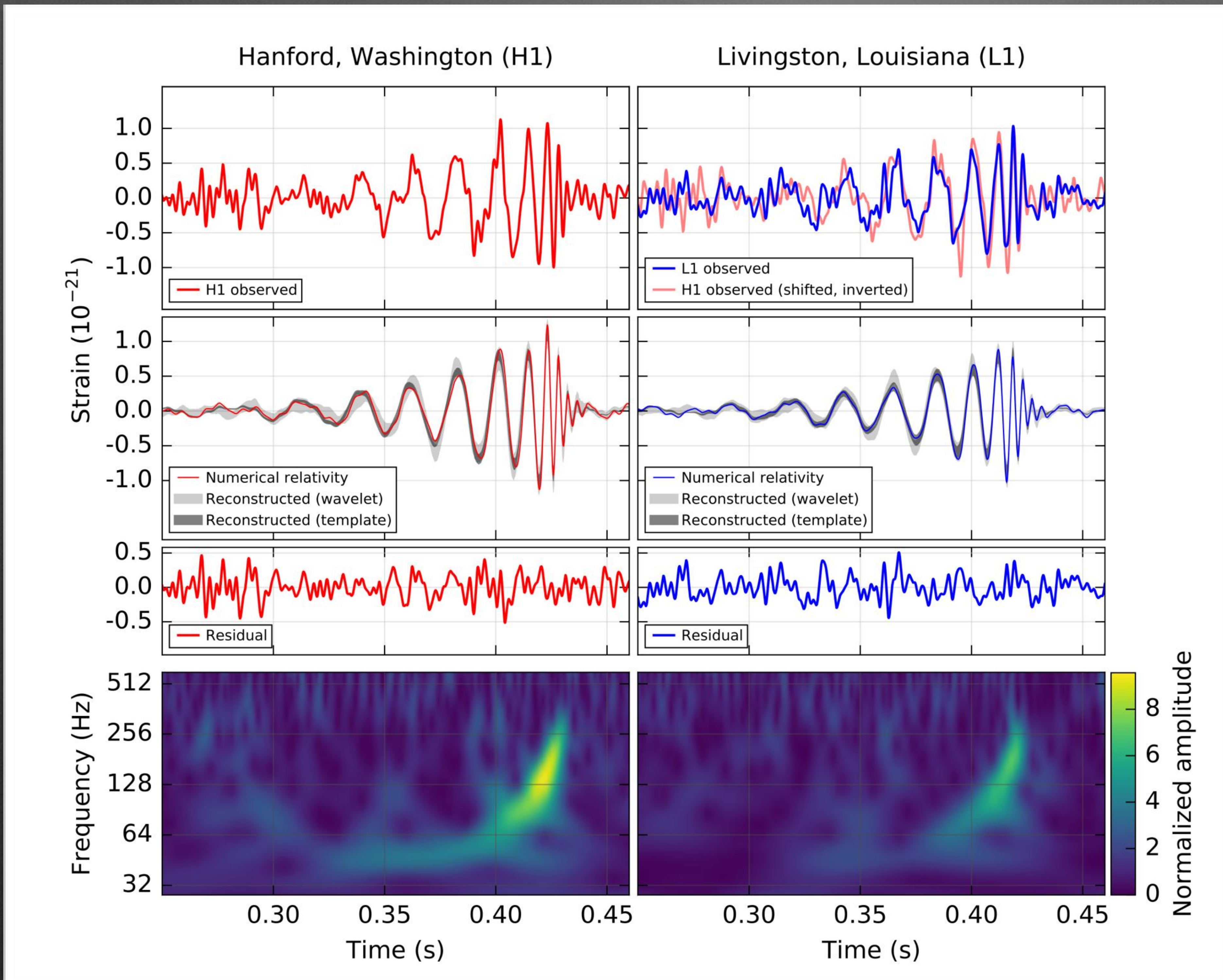
INFN

Fernando Ferroni
Gran Sasso Science Institute & INFN

The way to explore the dawn of the Universe

- The two landmark events that opened a new field
- LVK science collaboration
- The path to 3rd Generation experiments

The first landmark event: GW150914

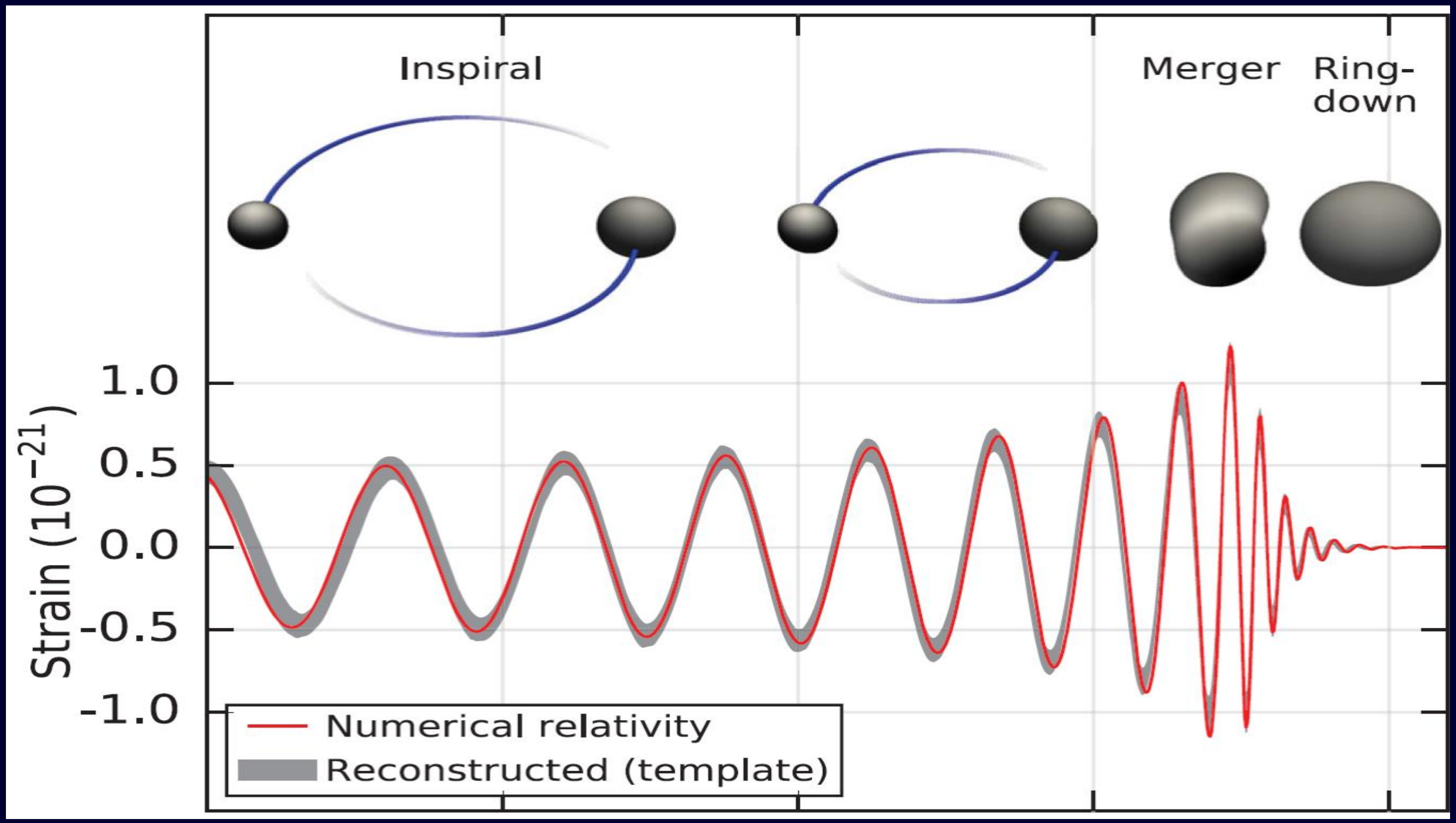


Nobel Prize in Physics 2017

Rainer Weiss, Barry C. Barish and Kip S. Thorne

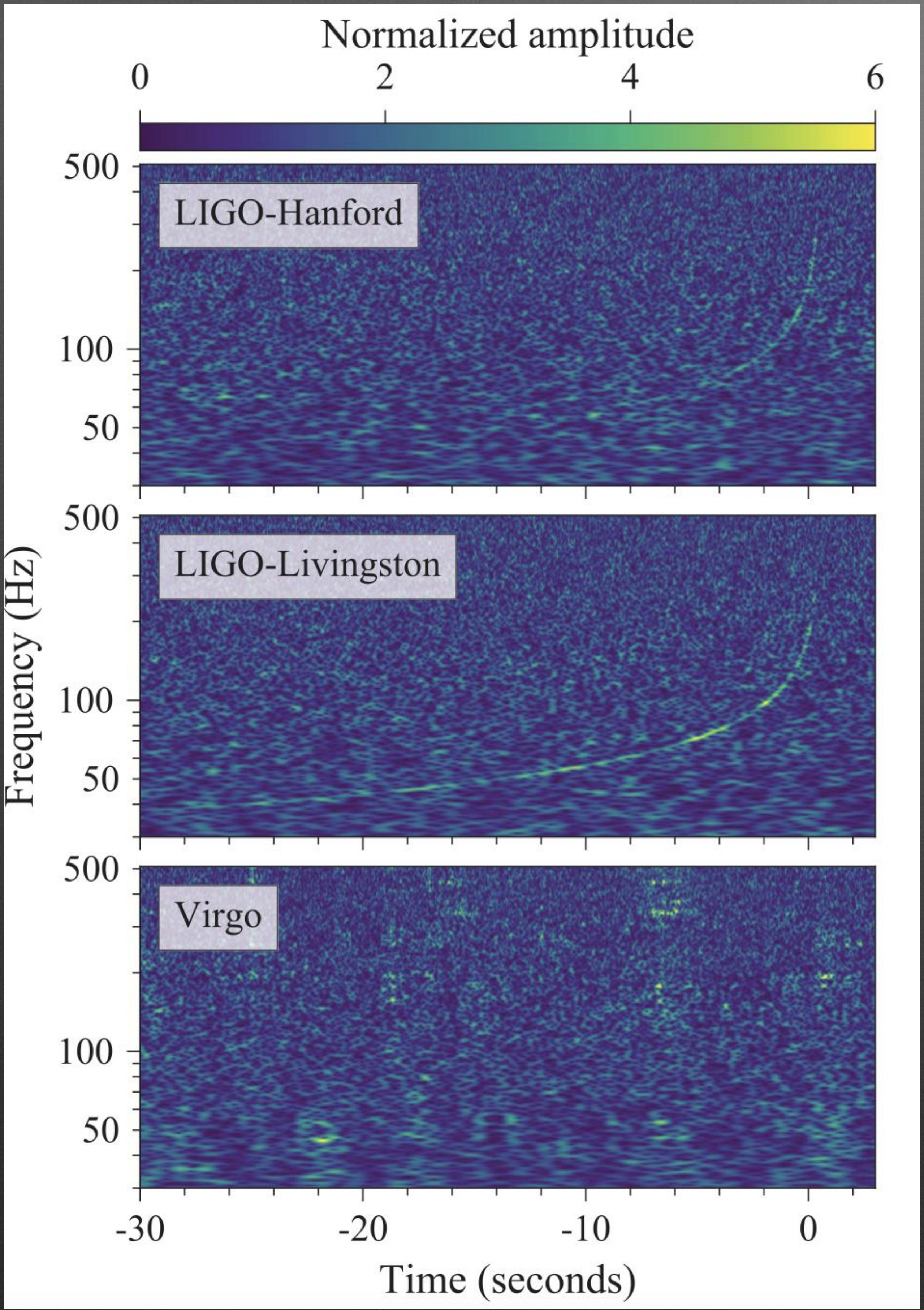
"for decisive contributions to the LIGO detector and the observation of gravitational waves"

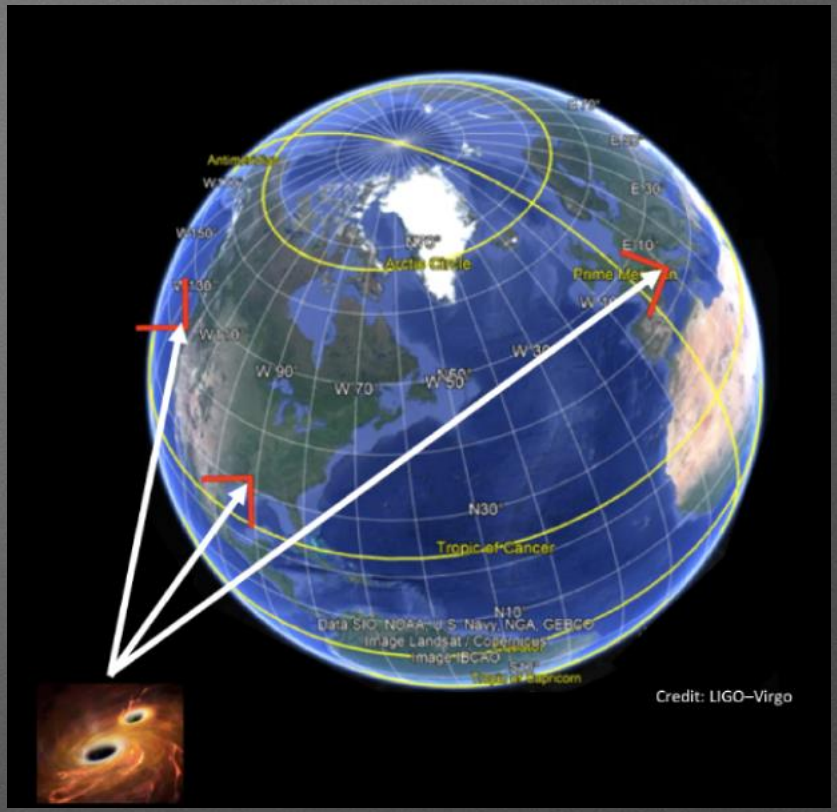
GW150914

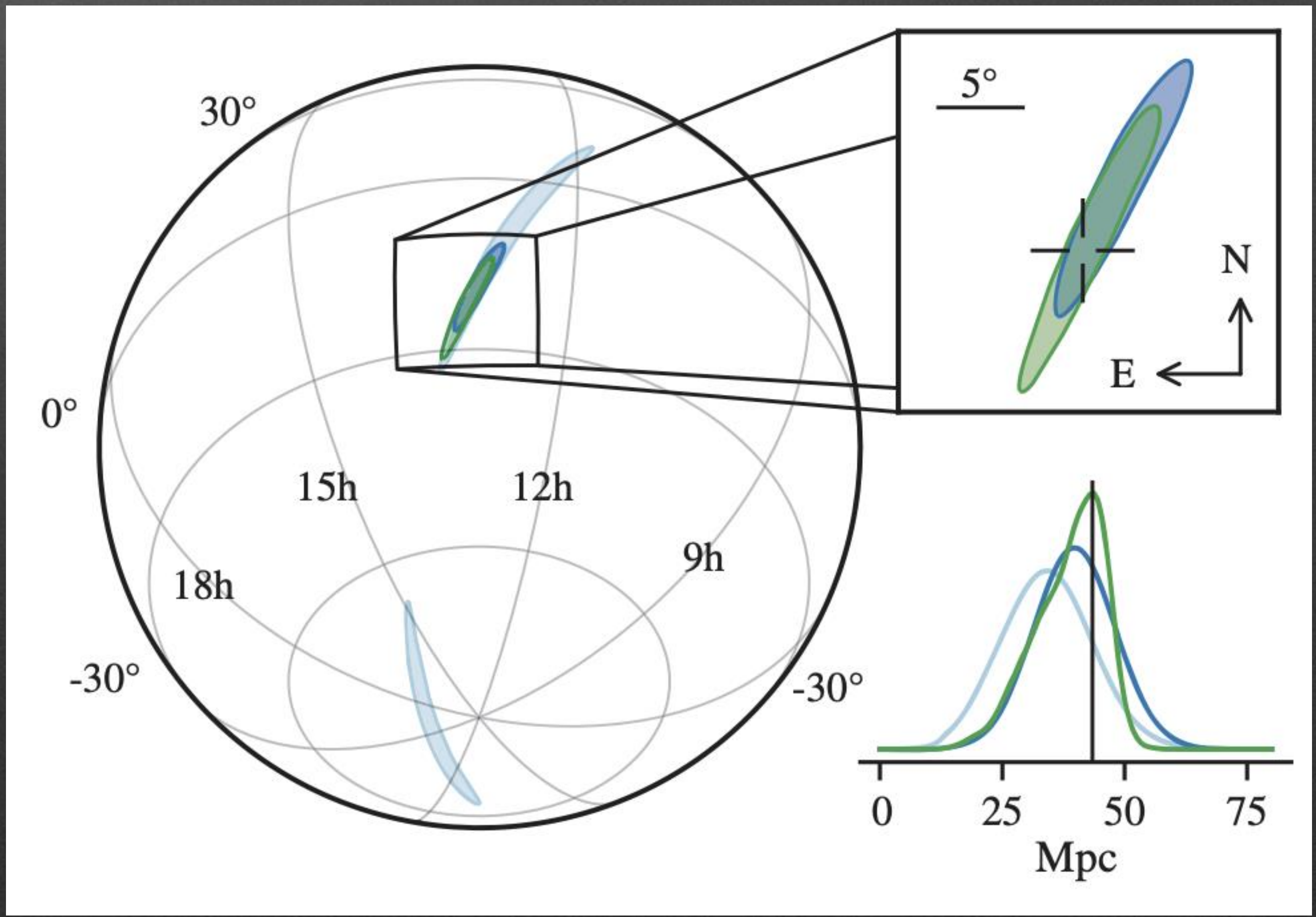


Phys. Rev. Lett. 116, 061102

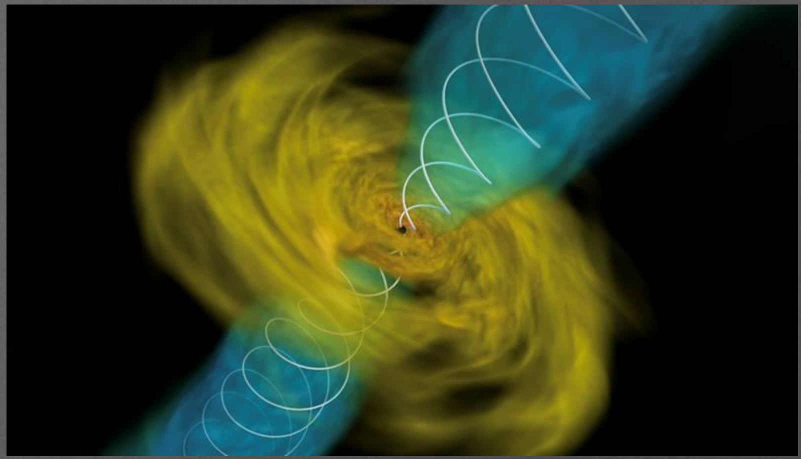
NS-NS merger : GW170817

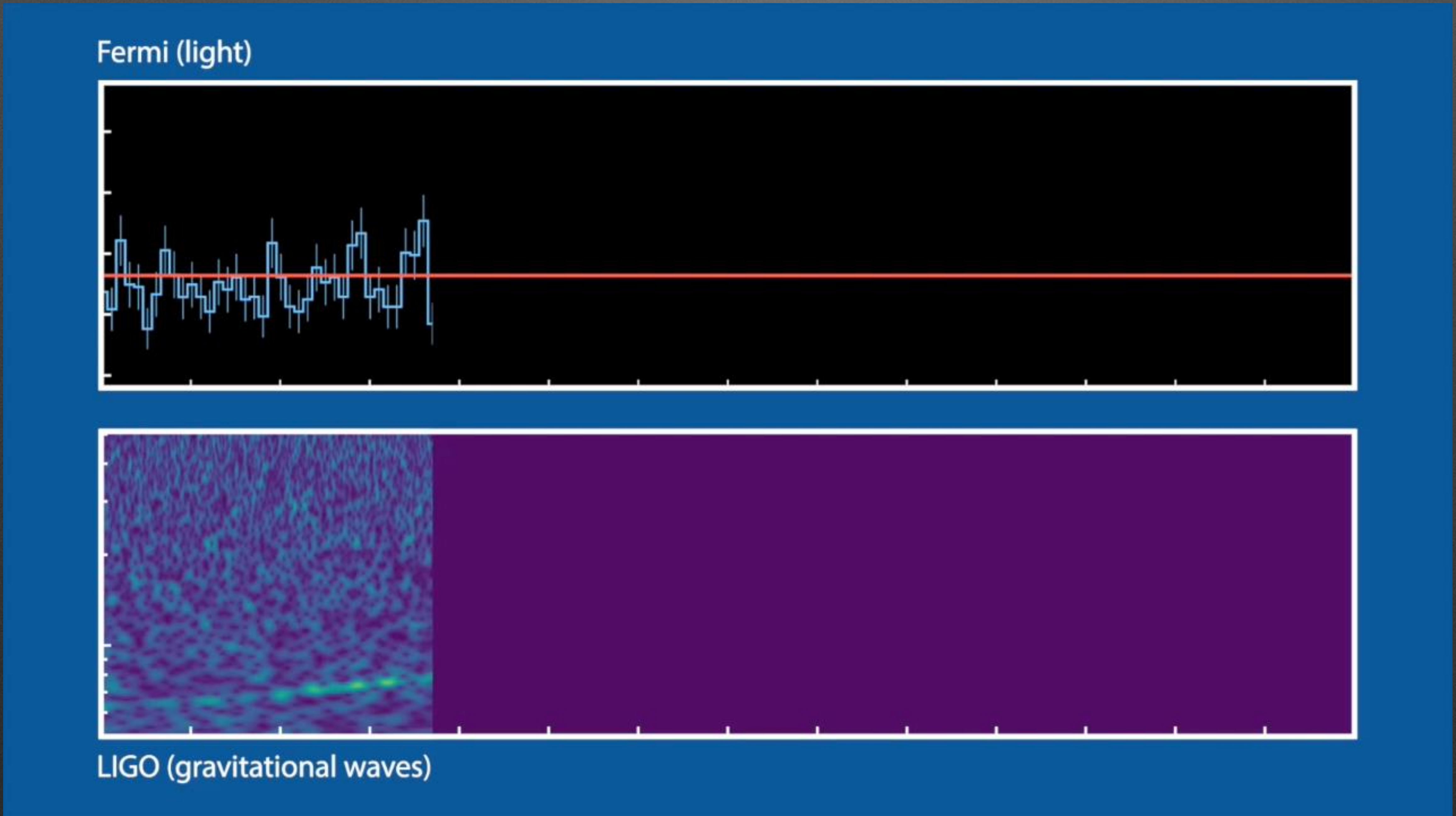






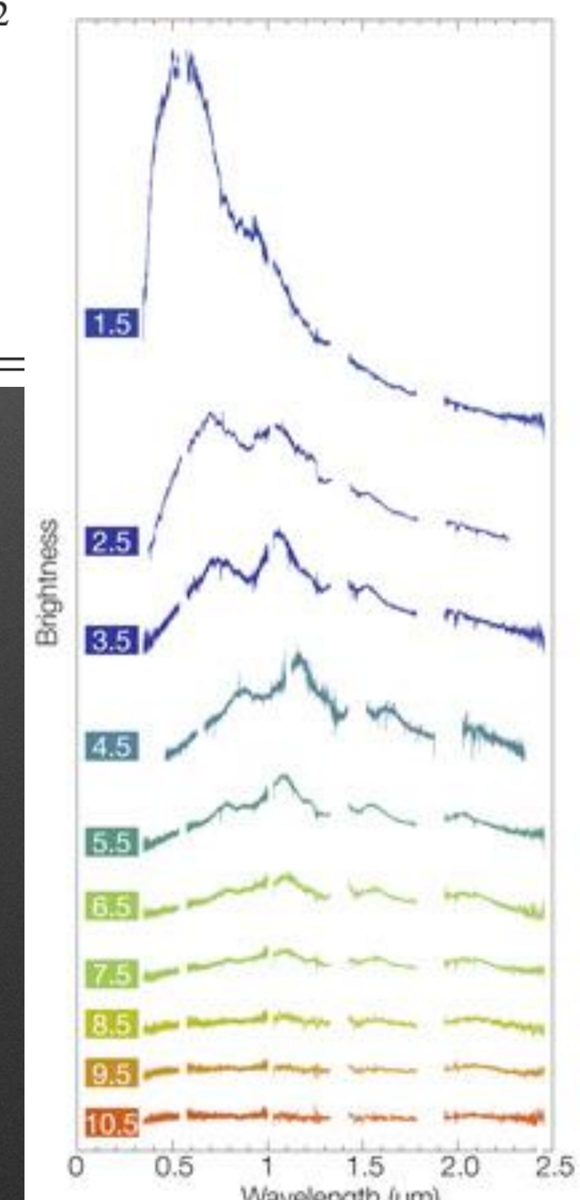
Multimessenger astronomy is born



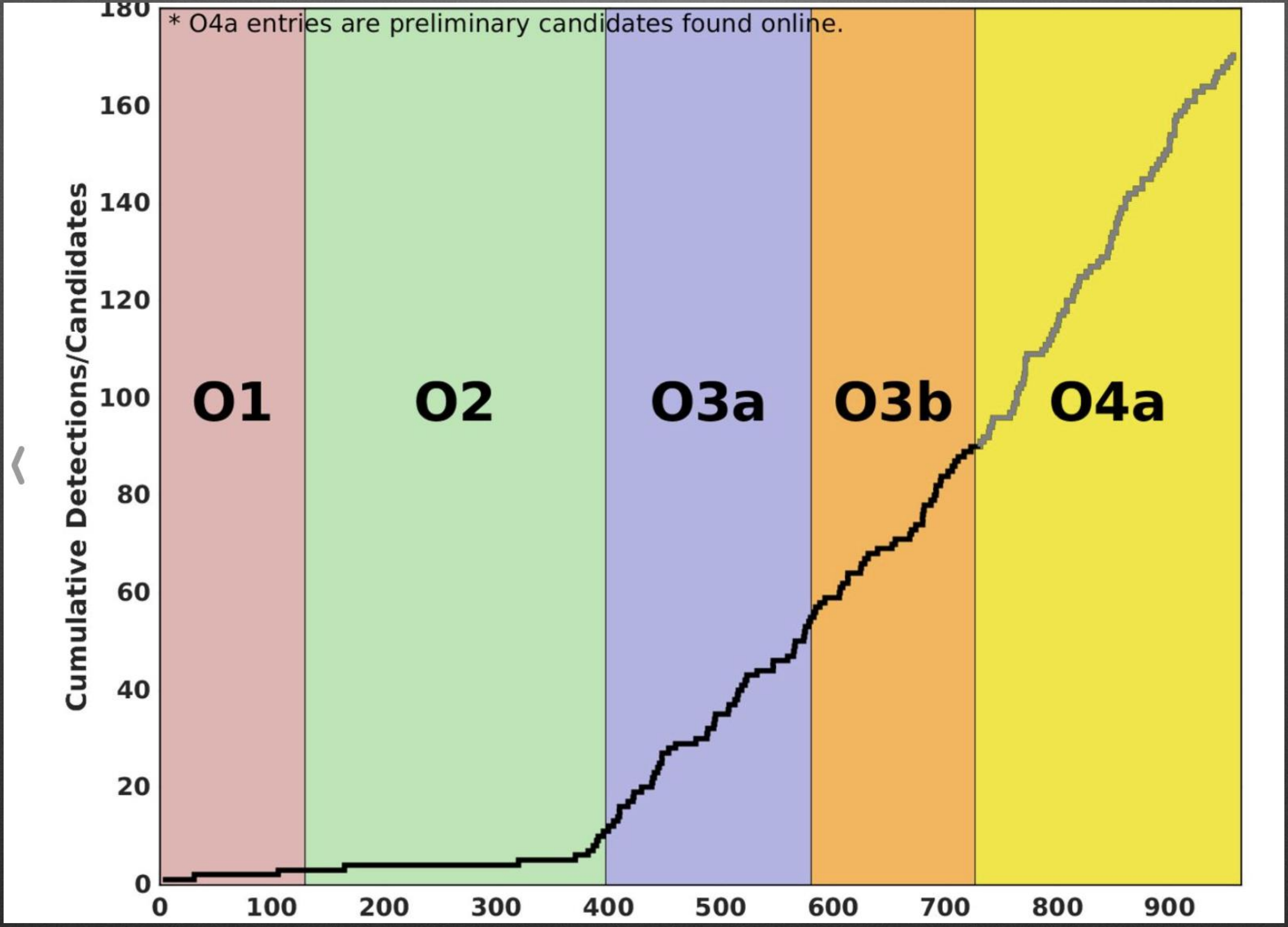


A lot of info !

	Low-spin priors ($\|\chi\| \leq 0.05$)	High-spin priors ($\|\chi\| \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_{L}	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

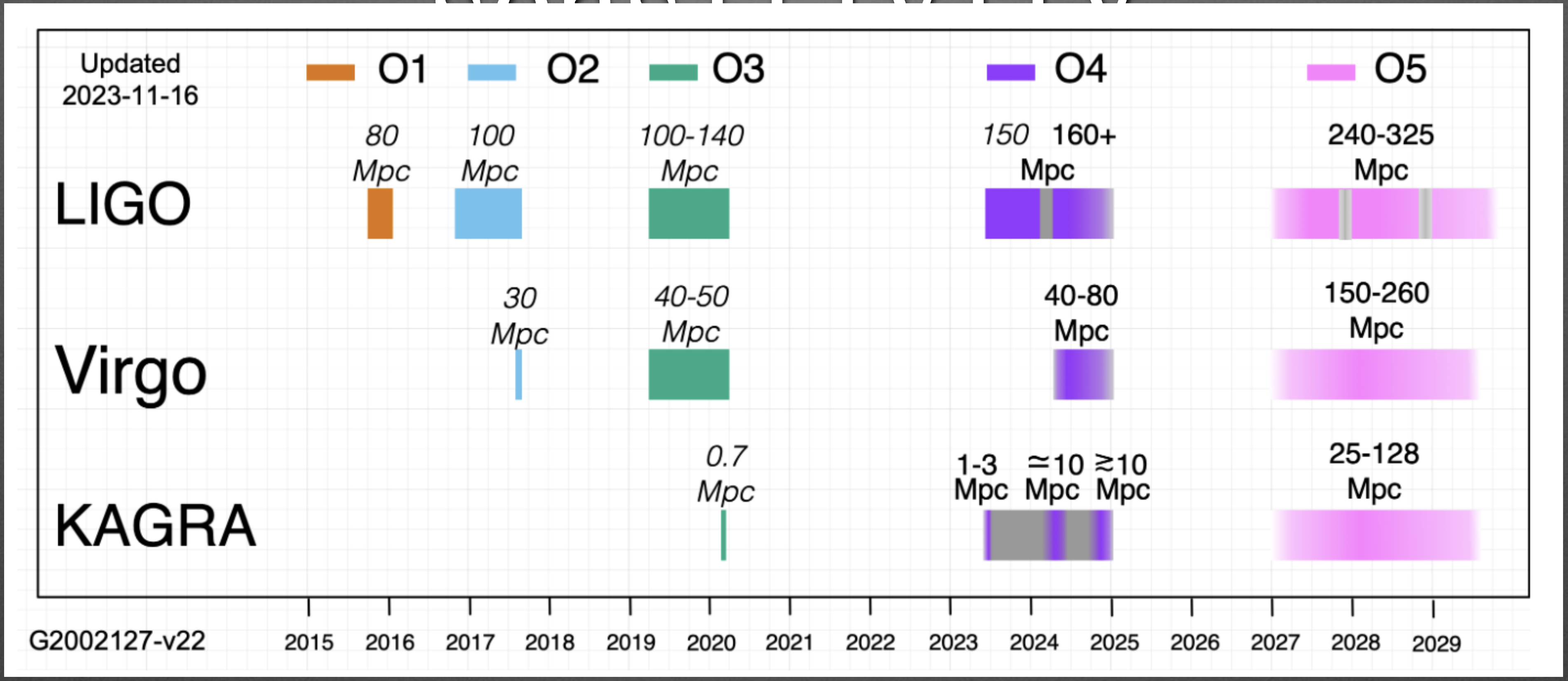


As of today



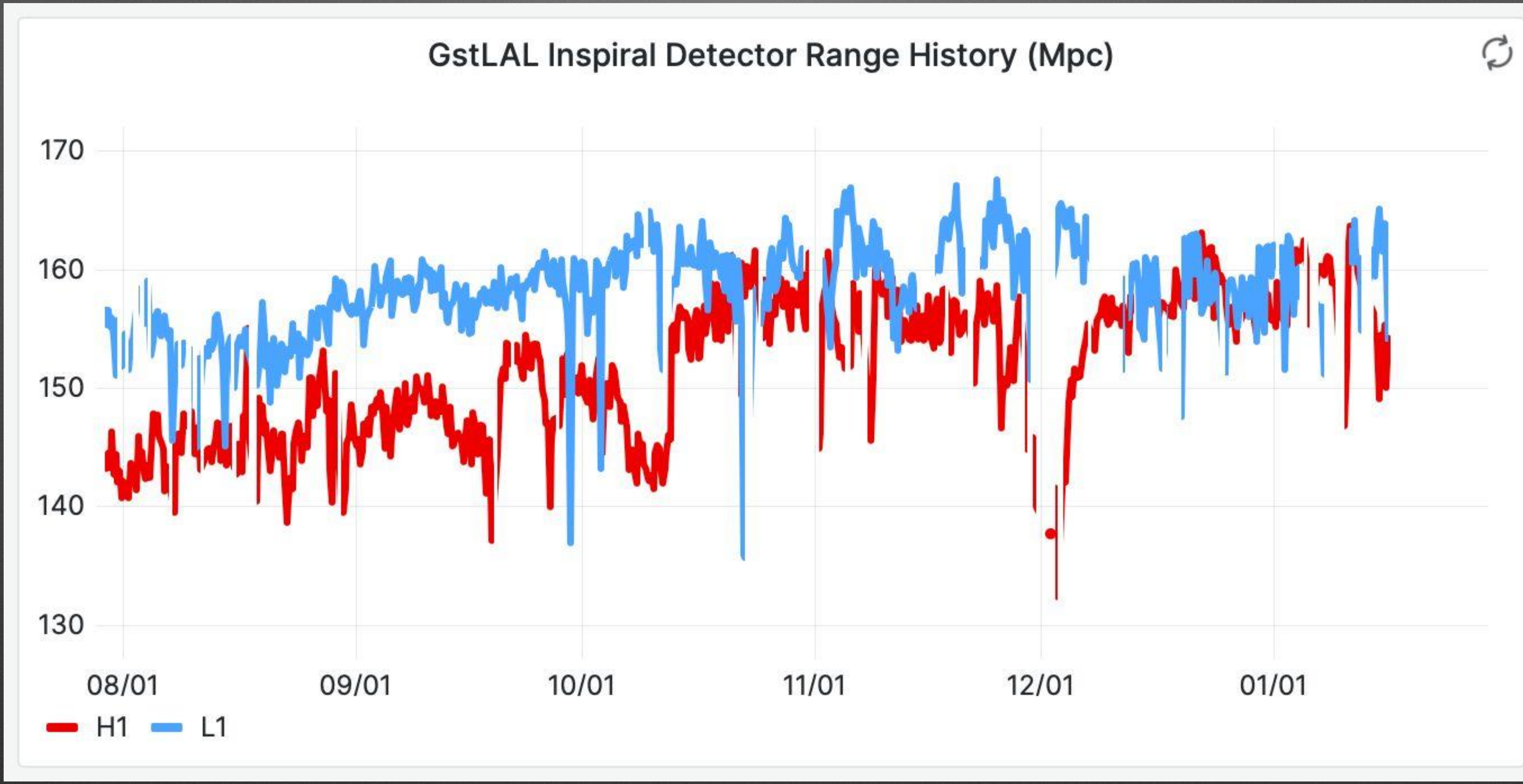
* O4a entries are preliminary candidates found online.
Cumulative Detections/Candidates
O1
O2
O3a
O3b
O4a
0
20
40
60
80
100
120
140
160
180
0
100
200
300
400
500
600
700
800
900

Thanks to the increase in sensitivity



- LIGO proceed successfully with the plan
- VIRGO has got a problem after the upgrade (O3 > O4), will rejoin in April
- KAGRA is slowly improving (the recent earthquake did not help)

LIGO recent sensitivity curves



* the sensitivity refers to NS-NS events

Science requires statistics

- A couple of hundreds BBH
- A couple of BNS
- Not enough for an ambitious program like :

A lot of potentialities

Einstein Telescope's science in a nutshell

ET will serve a vast scientific community: fundamental physics, astronomy, astrophysics, particle physics, nuclear physics and cosmology

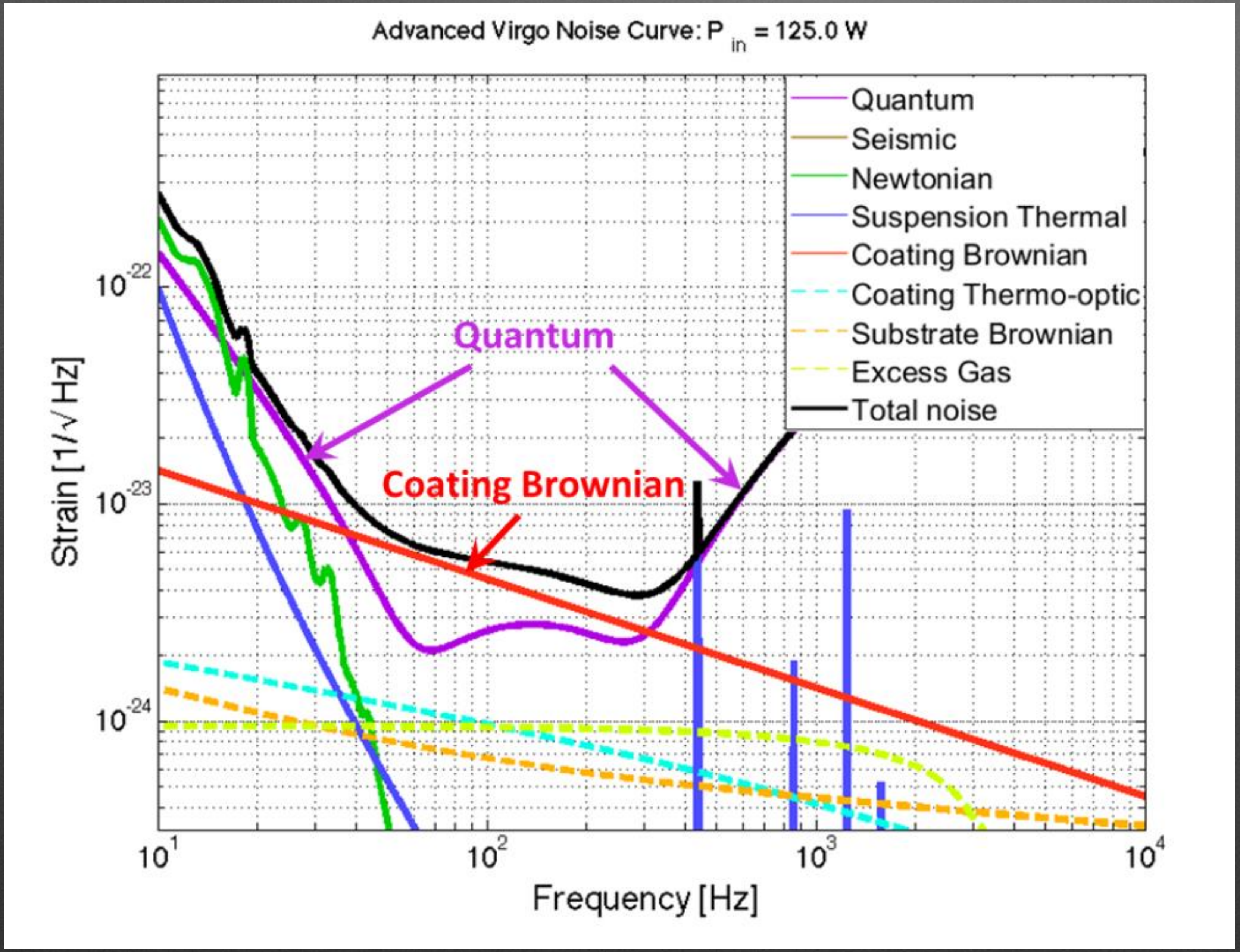
ASTROPHYSICS

- **Black hole properties**
  - origin (stellar vs. primordial)
  - evolution, demography
- **Neutron star properties**
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- **Multi-band and -messenger astronomy**
  - joint GW/EM observations (GRB, kilonova,...)
  - 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

- **The nature of compact objects**
  - near-horizon physics
  - tests of no-hair theorem
  - exotic compact objects
- **Tests of General Relativity**
  - post-Newtonian expansion
  - strong field regime
- **Dark matter**
  - primordial BHs
  - axion clouds, dark matter accreting on compact objects
- **Dark energy and modifications of gravity on cosmological scales**
  - dark energy equation of state
  - modified GW propagation
- **Stochastic backgrounds of cosmological origin**
  - inflation, phase transitions, cosmic strings

One direction: suppress the noise



Thermal
Quantum
Newtonian

ET 3G concept
extend the band

WIDEN THE BAND: XYLOPHONE

ET EINSTEIN TELESCOPE

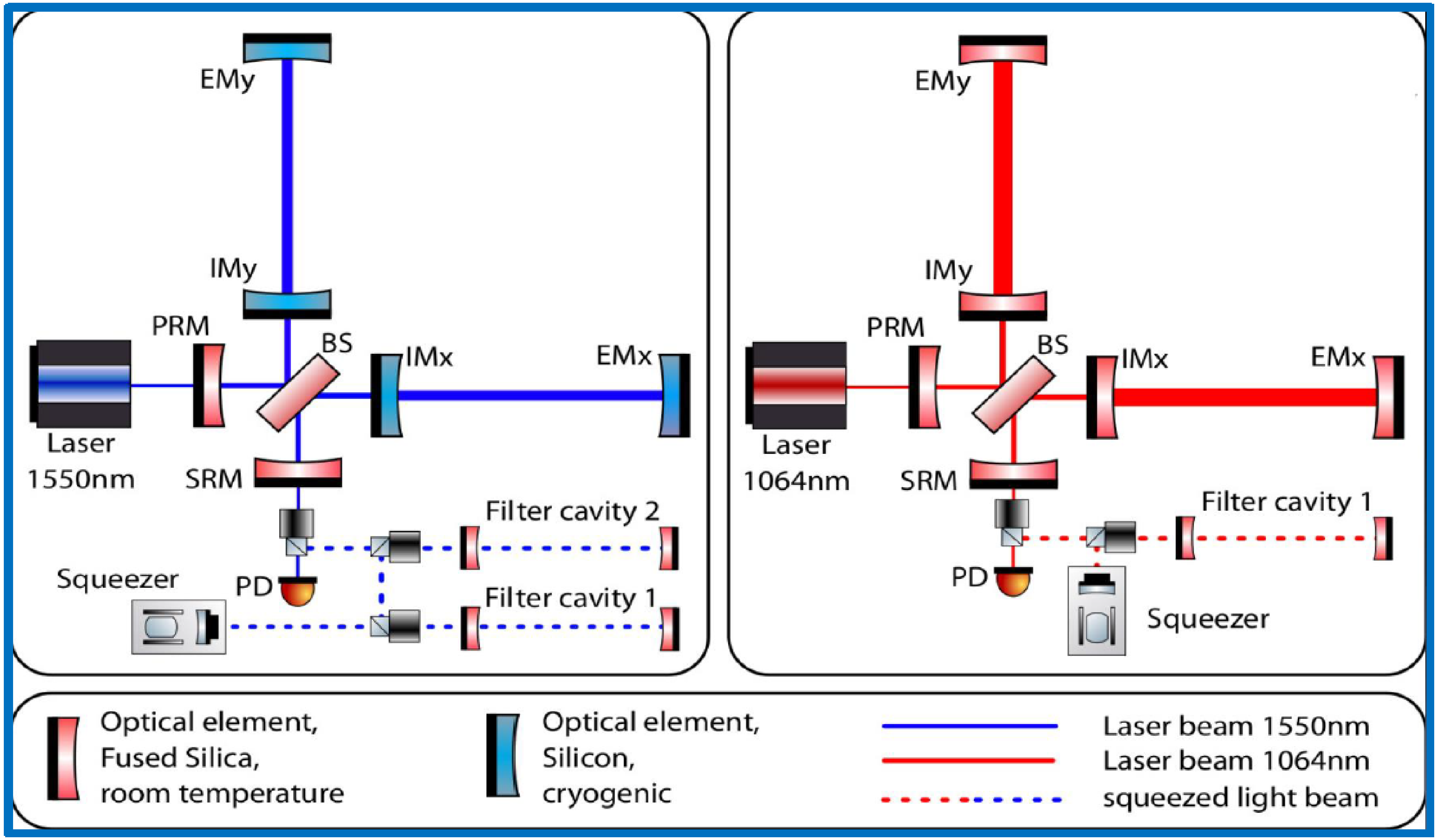
- Improving al low and high frequency with a single detector is very challenging
  - HF requires more laser power
  - LF requires cold mirrors
- Idea: split the detection band over 3 “specialized” instruments

+ go underground !

Xylophone detector design

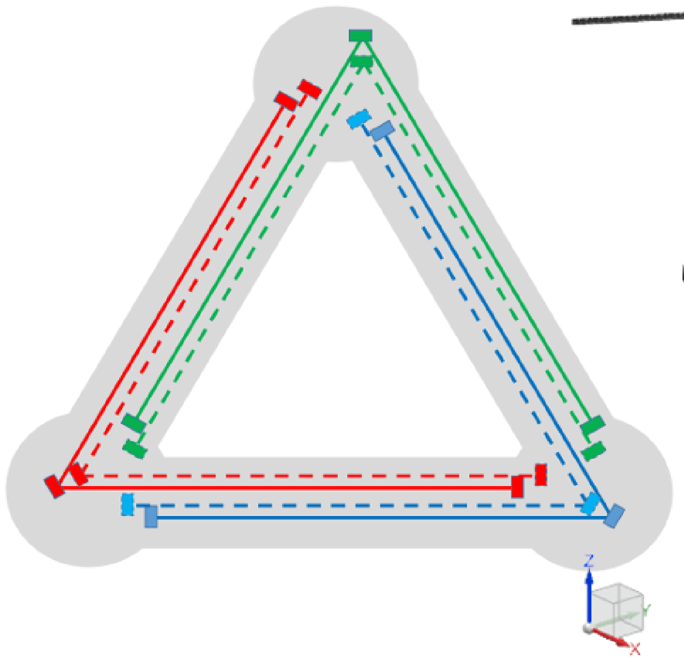
Einstein Telescope splits the detection band over two instruments: an interferometer optimized for measuring low-frequency gravitational waves and an optimized high-frequency interferometer

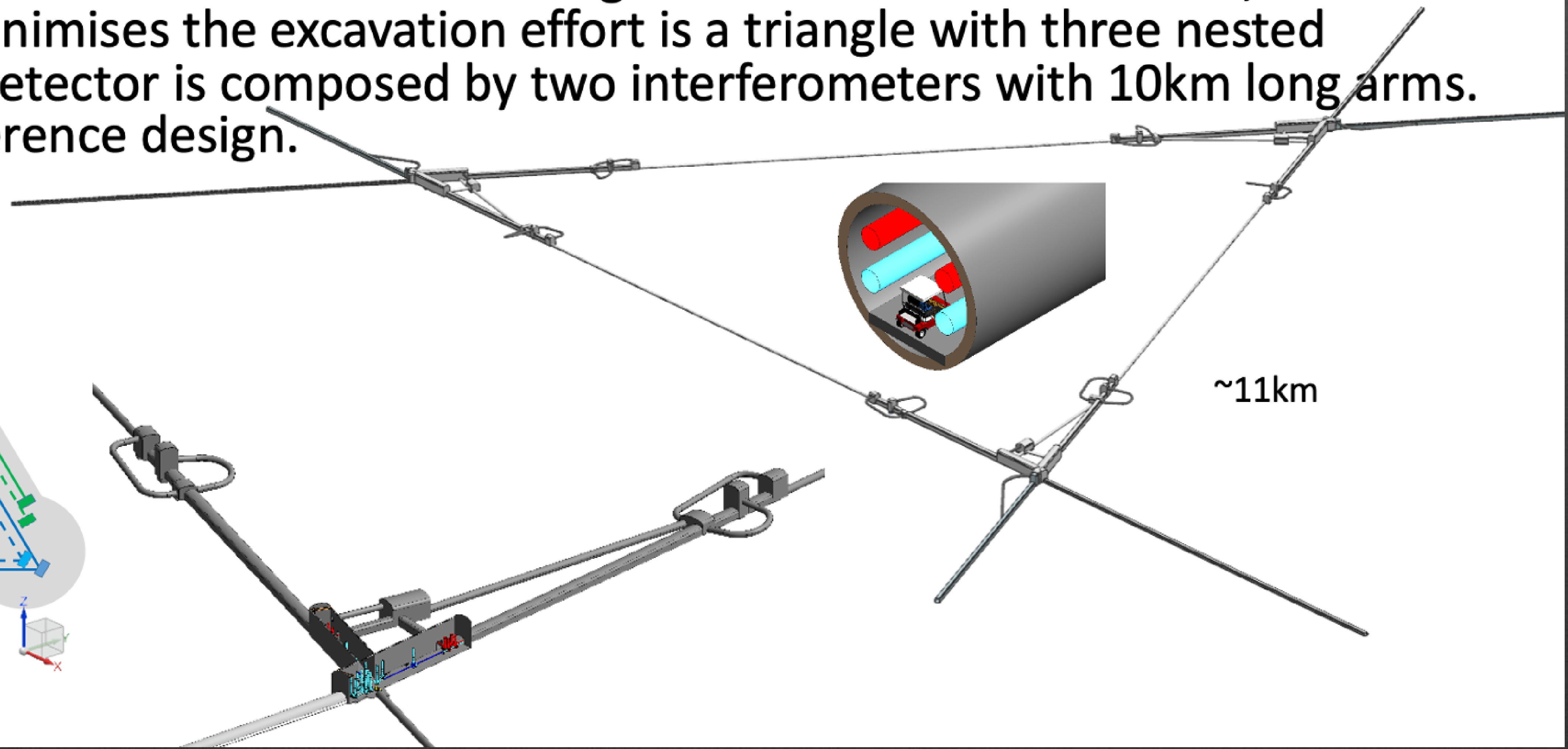
ET-LF: large cryogenic (10 - 20 K) silicon test masses, seismic suspensions, new wavelength, FDS, ..
ET-HF: high power laser, high circulating light power, thermal compensation, large test masses, FDS, ..



Why a Δ ?

- **Triangular geometry:** to satisfy the localisation capability, the polarisation disentanglement, the sky coverage and the high reliability requirements, a multiple detector configuration is needed. For underground co-located detectors , the geometry that minimises the excavation effort is a triangle with three nested detectors; each detector is composed by two interferometers with 10km long arms. This is the ET reference design.



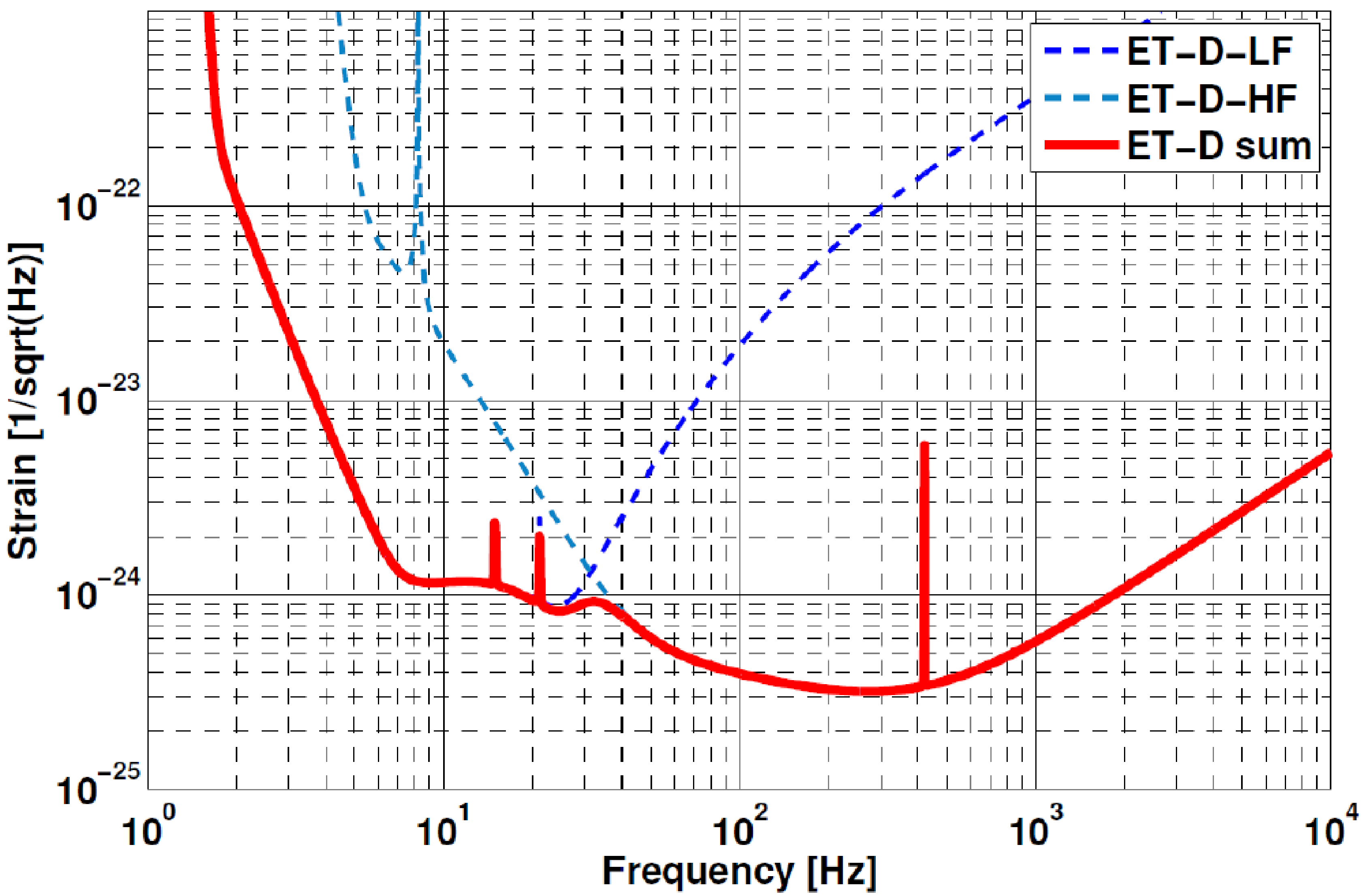


Conceptual performance

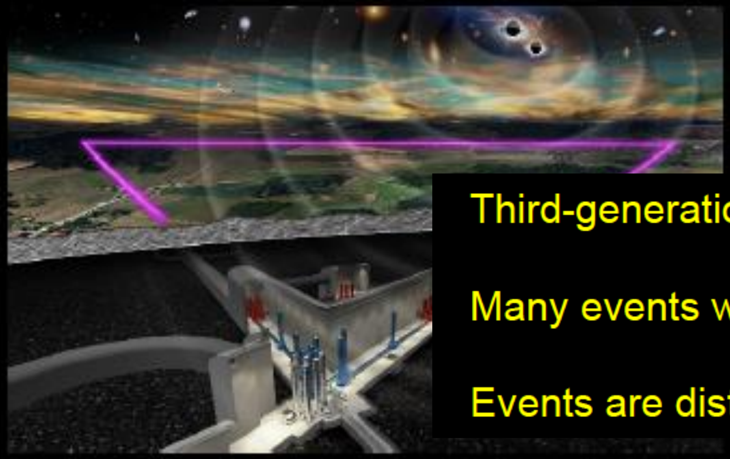
Einstein Telescope xylophone sensitivity

Three detectors with arm length of 10 km

Each detector consists of a low-frequency and a high-frequency interferometer
All six interferometers will be sited in hard-rock up to a few hundred meters underground



A travel back in time

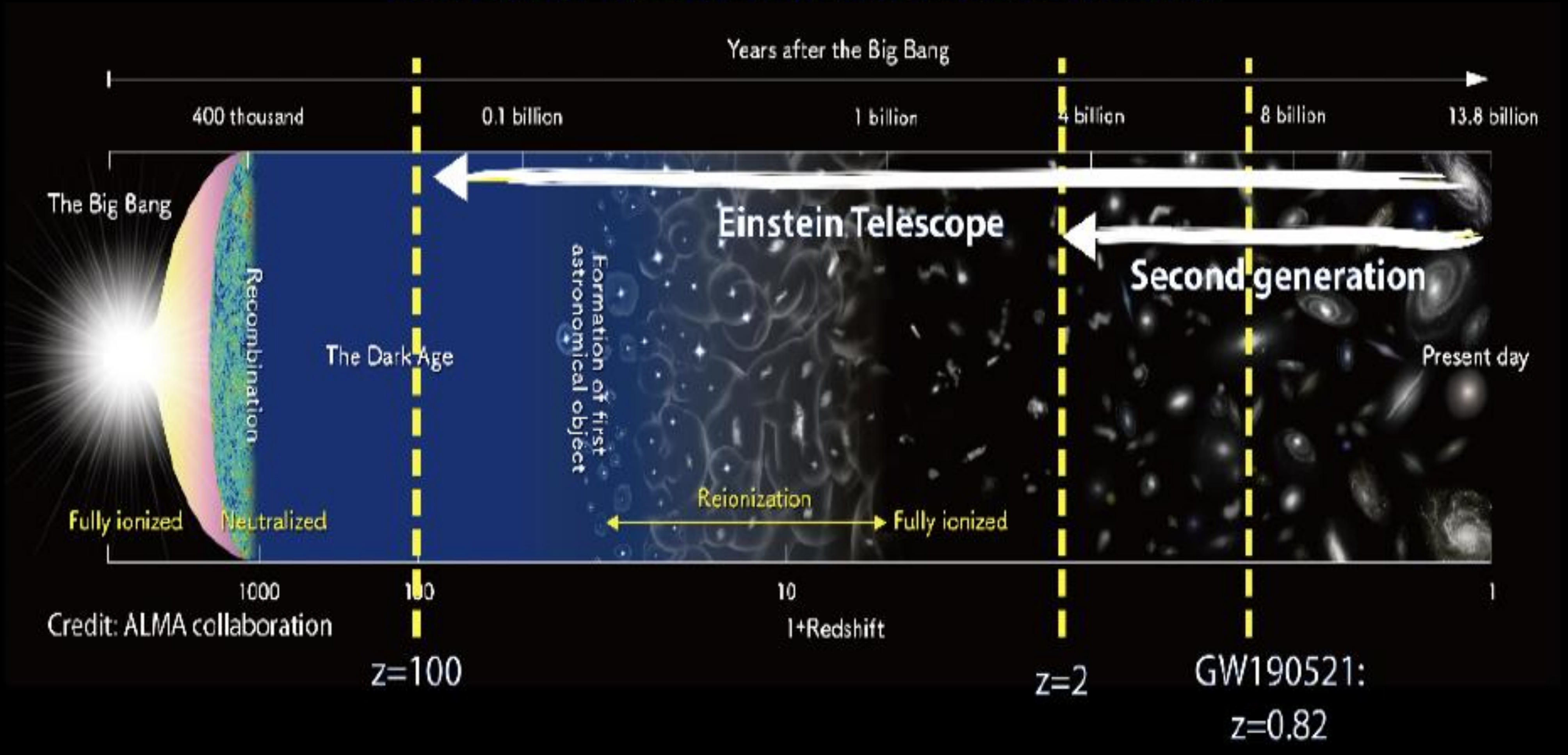


Third-generation instruments will observe hundreds of thousands of black hole mergers per year

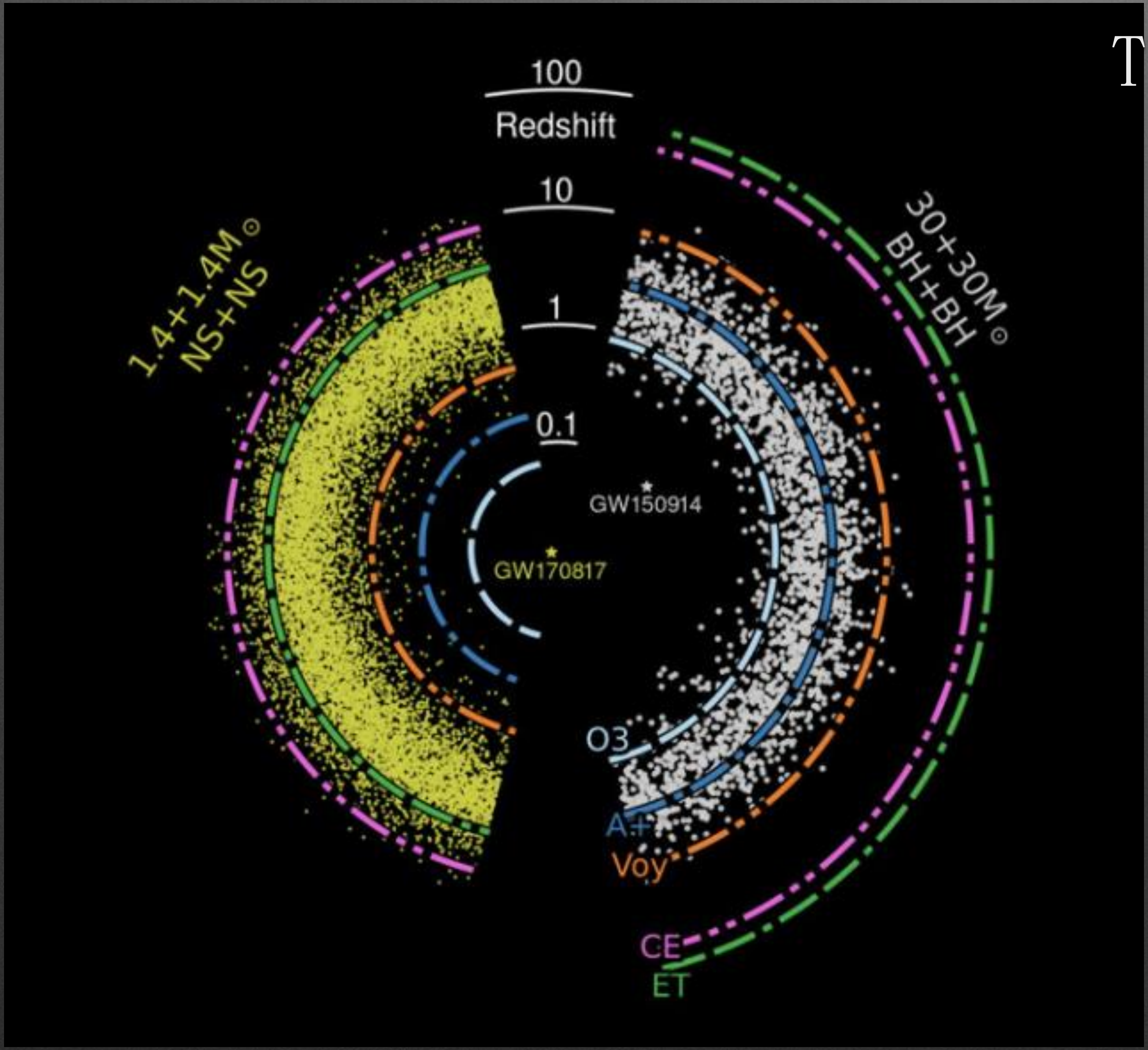
Many events will have signals with an SNR up to 1,000 allowing precision black hole science

Events are distributed through the entire Universe allowing cosmography

Detection horizon for black-hole binaries



Where 3G will bring us !



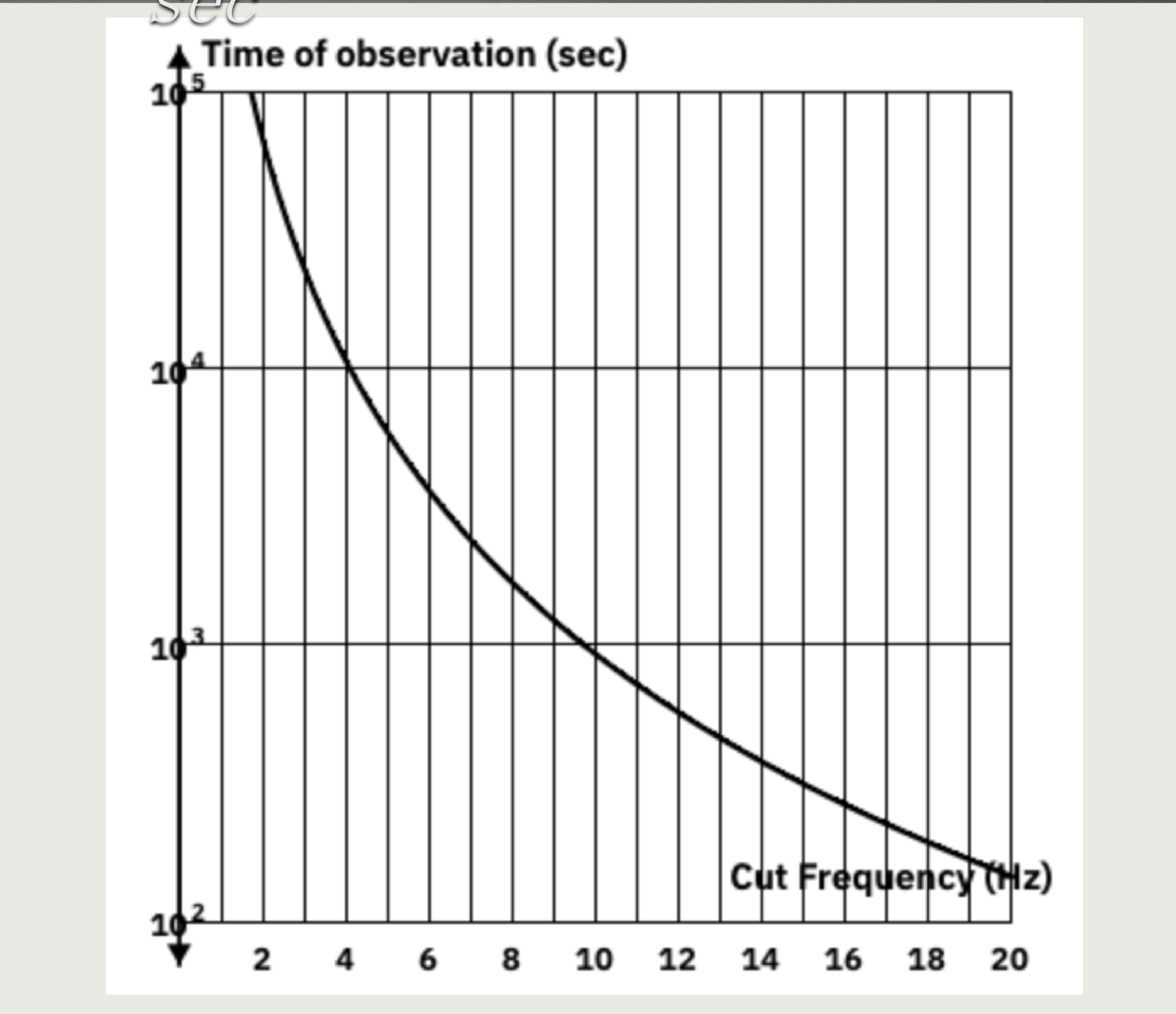
The Pillars of Hercules

z=10
is close to where
everything started !

The reason for LF
Relation Time-Frequency

$\tau_c \sim 2(f_0/100Hz)^{(-8/3)}$ sec

For a BNS coalescence 1.4 solar masses each



ET Collaboration to-date

Site choices

A billion Euro question

Why a Δ and not 2L ?

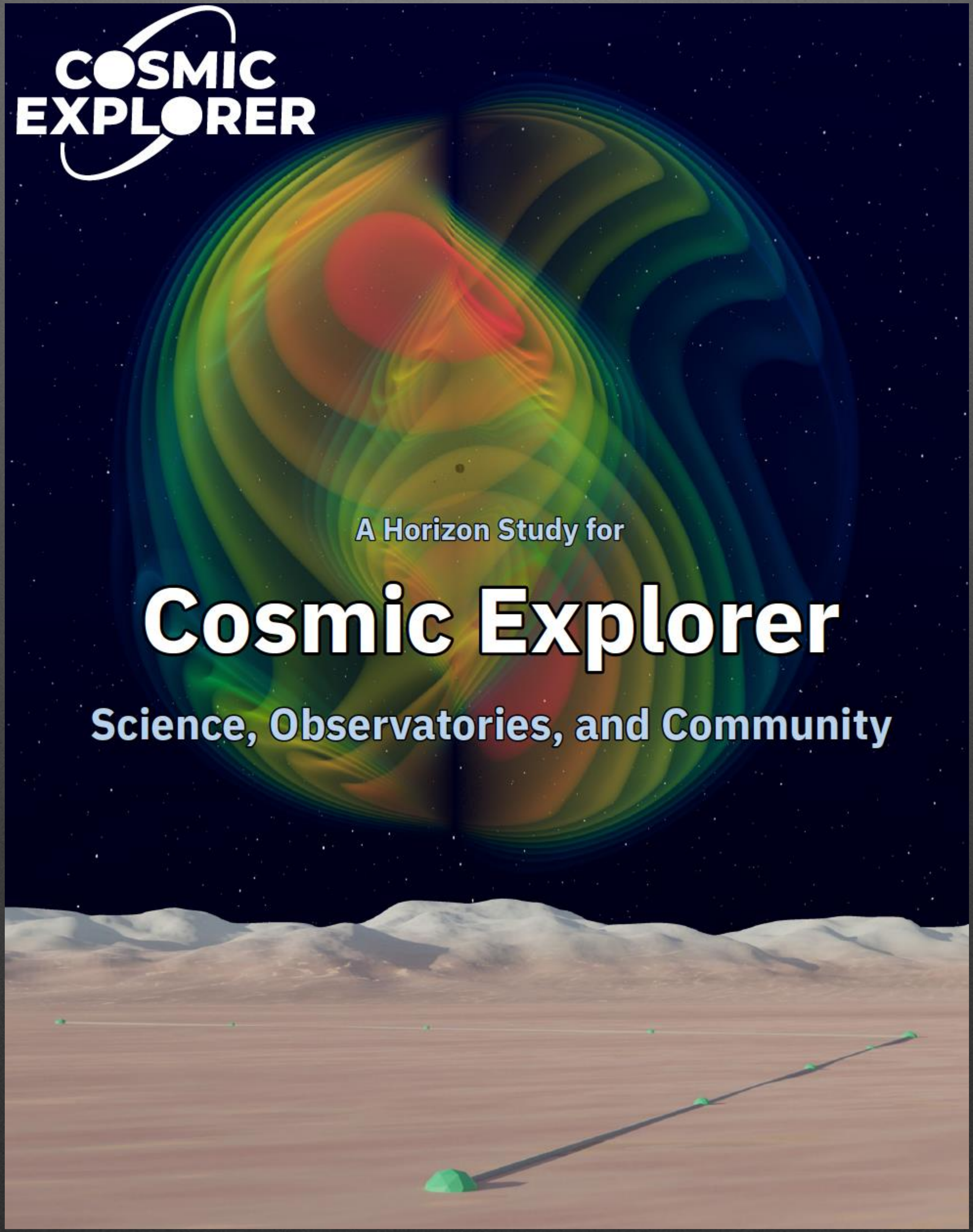
Simple answers (given long ago)

- Self sufficiency (what US will do ?)
- Cost (building infrastructure in two sites costs more, maintenance & operations almost double !)
- Manpower (community was not large enough to operate two sites)

Nowadays

- Two countries willing to provide money for the excavation
- Community has grown
- US is engaging in Cosmic Explorer

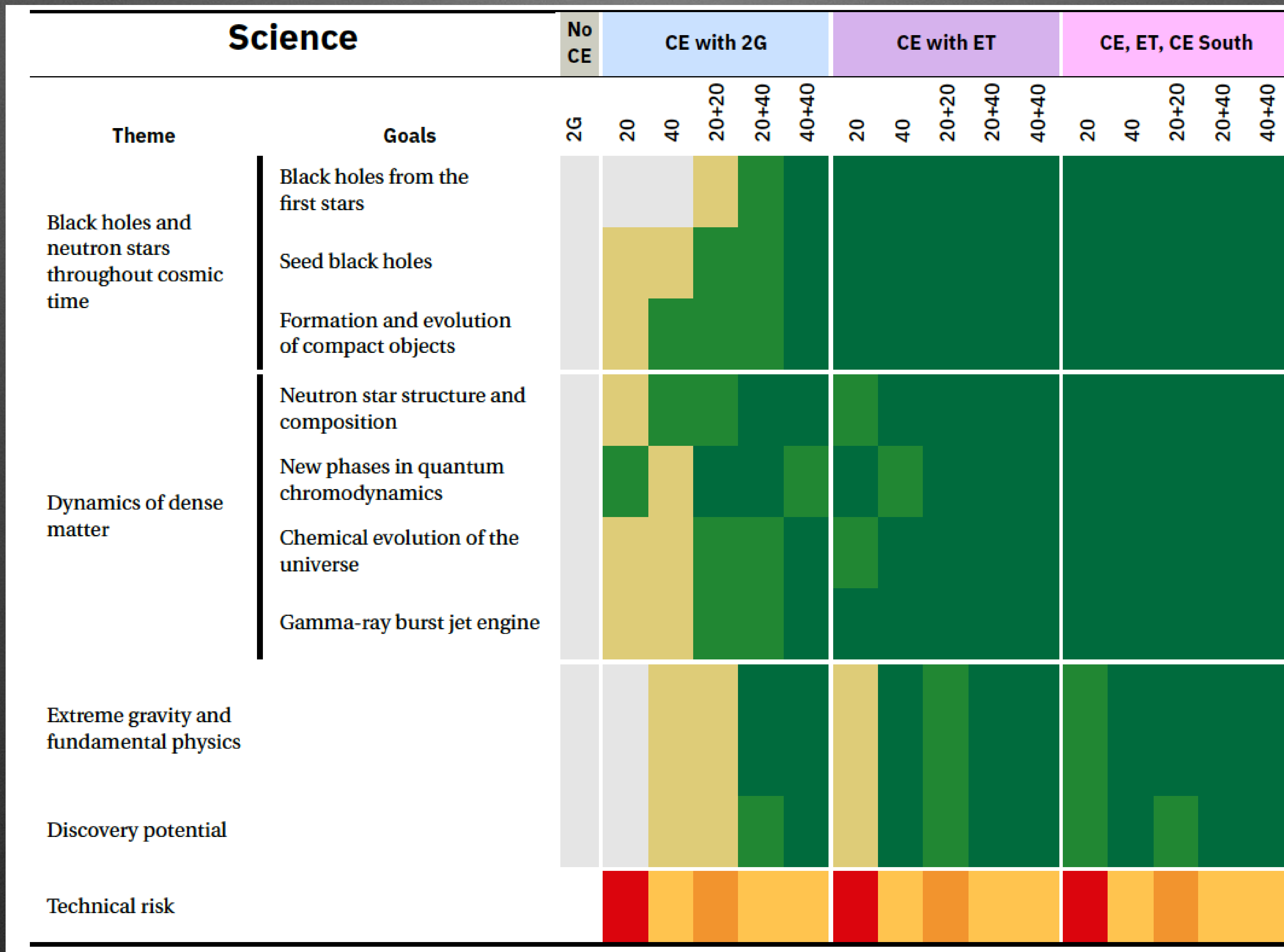
COSMIC EXPLORER in USA



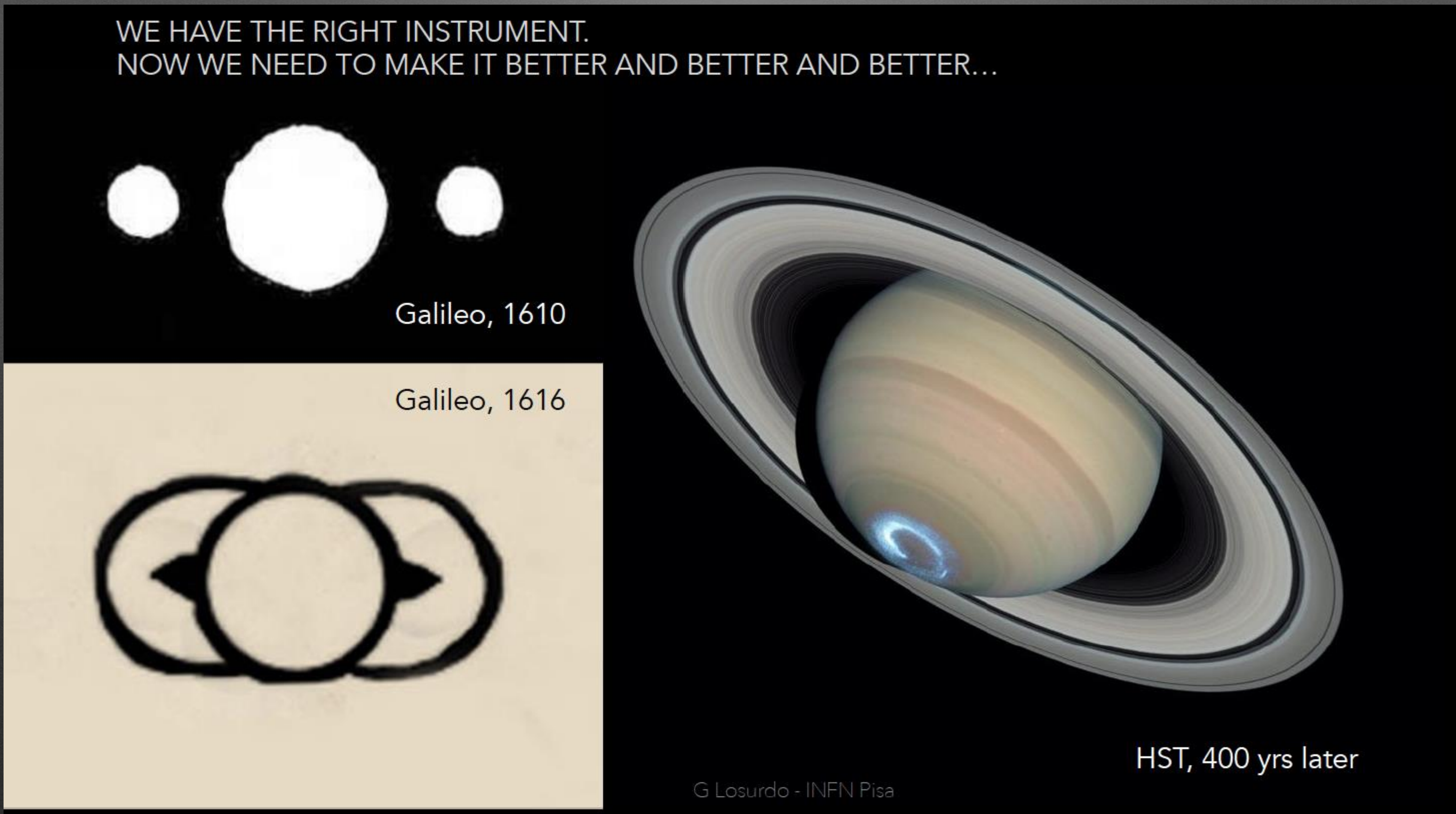
The working hypothesis

- Whatever combination is above ground
- Shape is always L-like
- Different length considered : 20 km , 40 km
- Calculations made for a single 20, a single 40, a 20+40 and 40+40
- Both L’s in USA and also a comparison with one of the two in Southern Hemisphere

The possible futures



Matter of technology



No matter what

At the end of 2030’s we will have a much better knowledge of our Universe

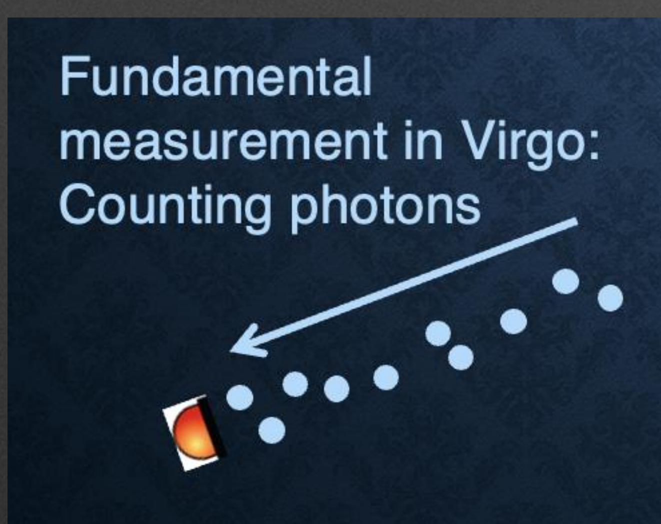
Quantum squeezing

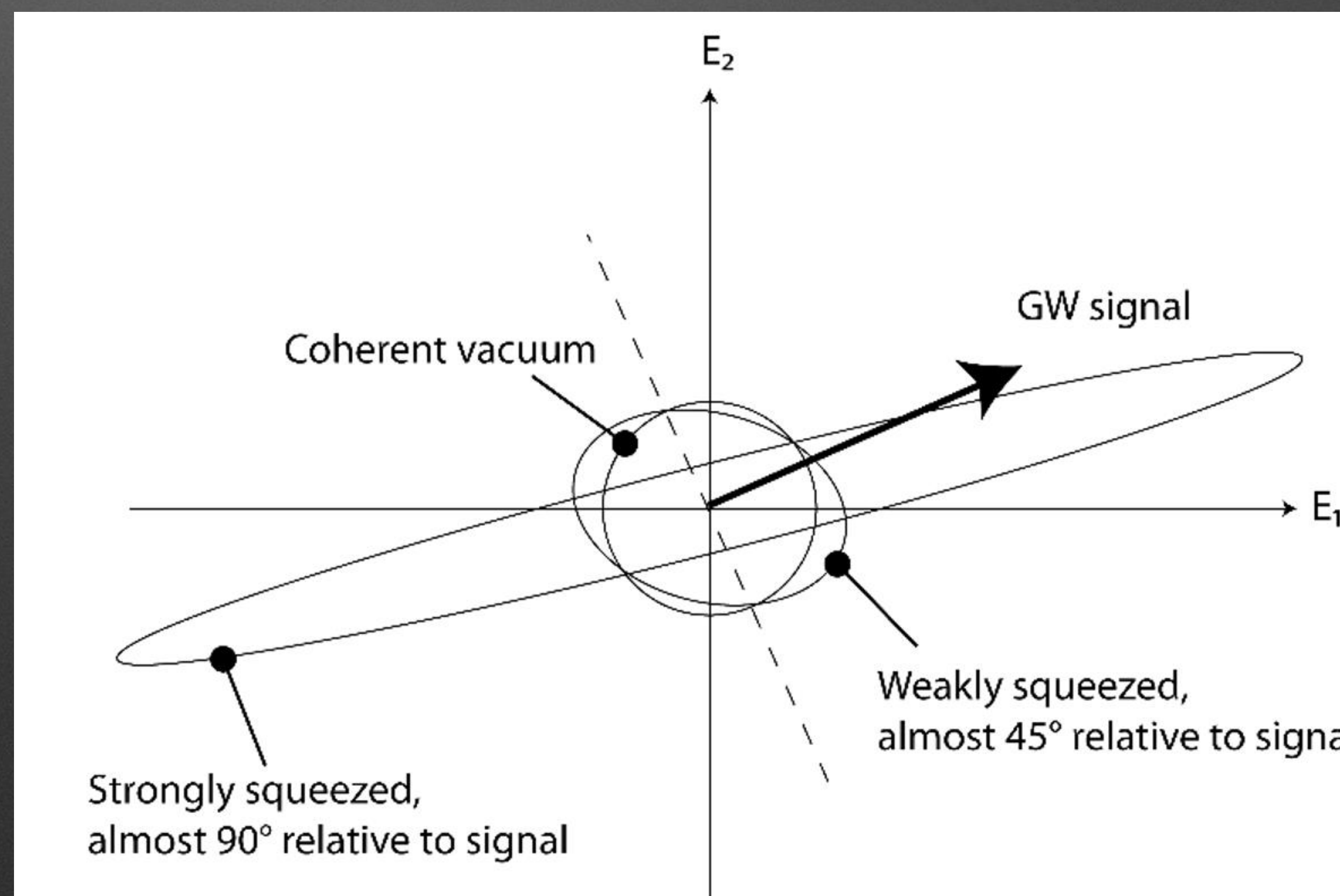
$$\Delta p \, \Delta x \geq \frac{\hbar}{2}$$

What are the position and momentum variables in the case of light?

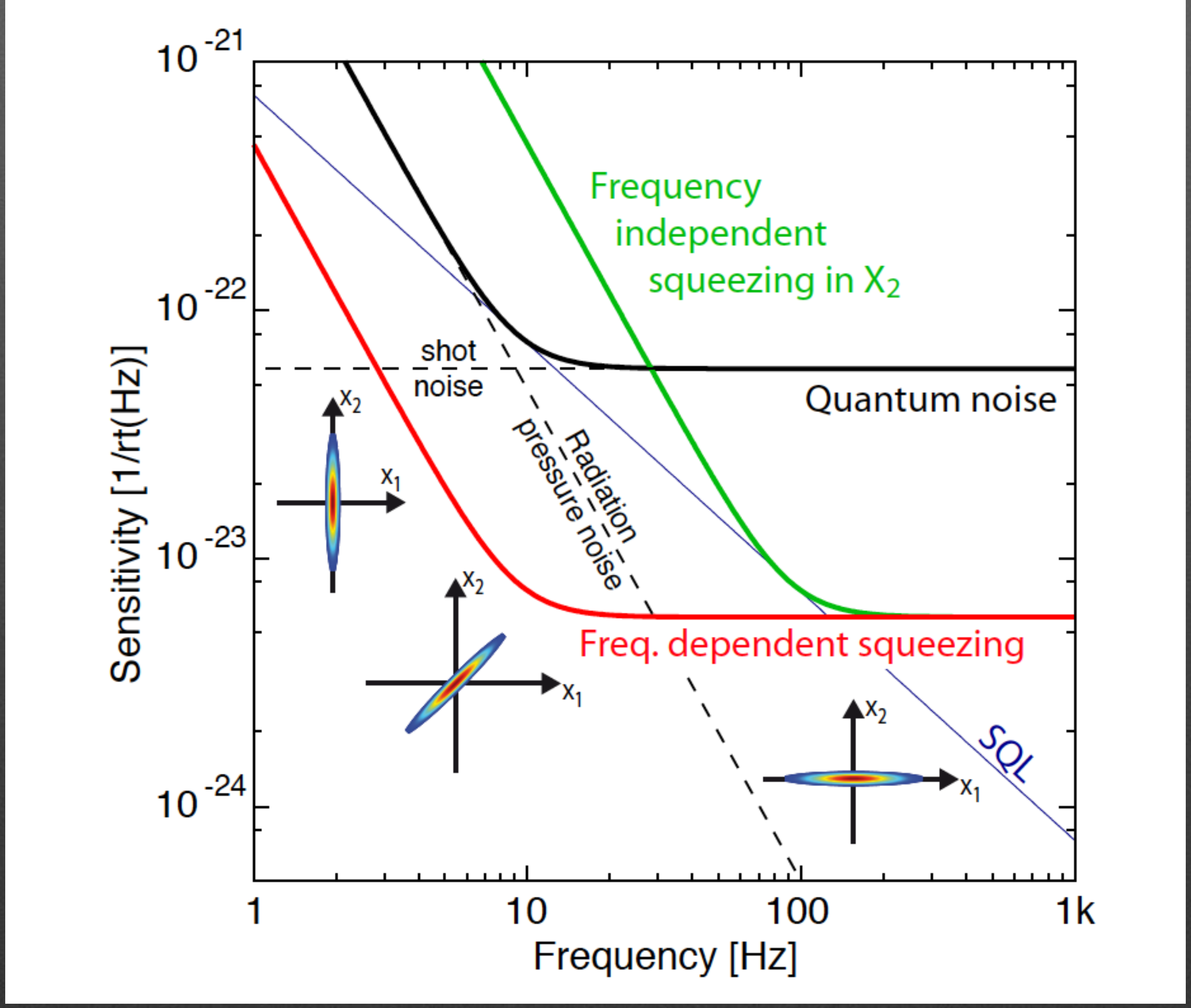
Multiple answers, but for GW detectors, the conjugate variables are the **quadratures of the EM field**:

$$E(t) = E_1(t)\cos(\omega_0 t) + E_2(t)\sin(\omega_0 t)$$

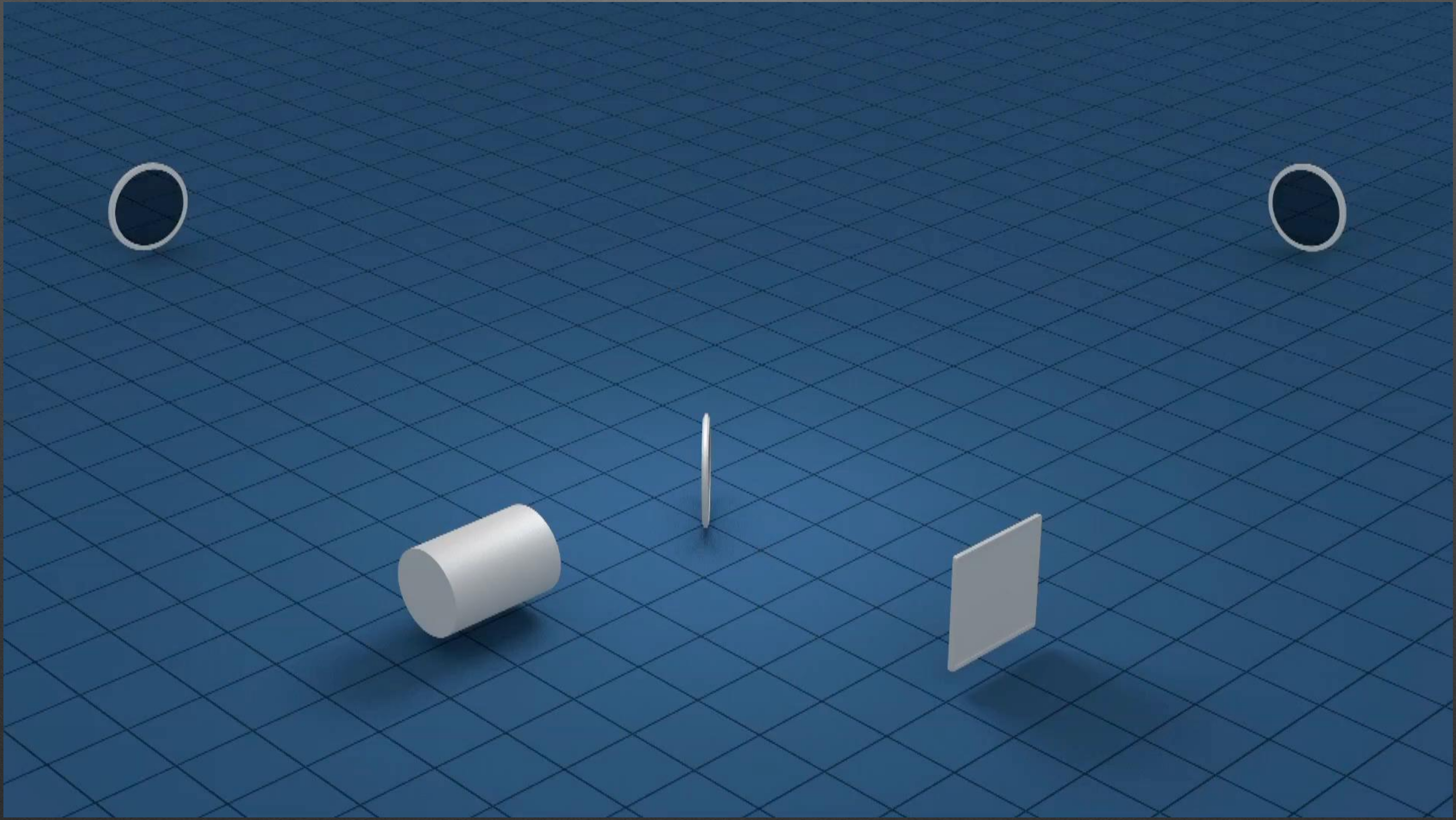




Going toward a quantum limit



As simple as such



The difficulty

$$\delta L/L \simeq 10^{-21}$$

Try this ….the distance Earth-Sun is 150×10^9

$\delta L \simeq (150 \times 10^9 m) \times 10^{-21} = 1.5 \times 10^{-10} m$

The radius of a typical atom is $10^{-10} m$