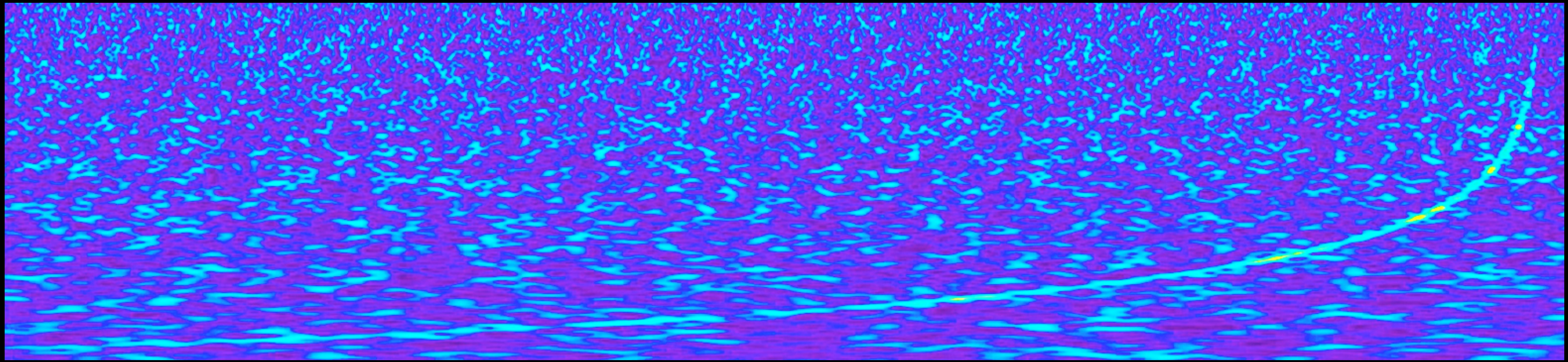
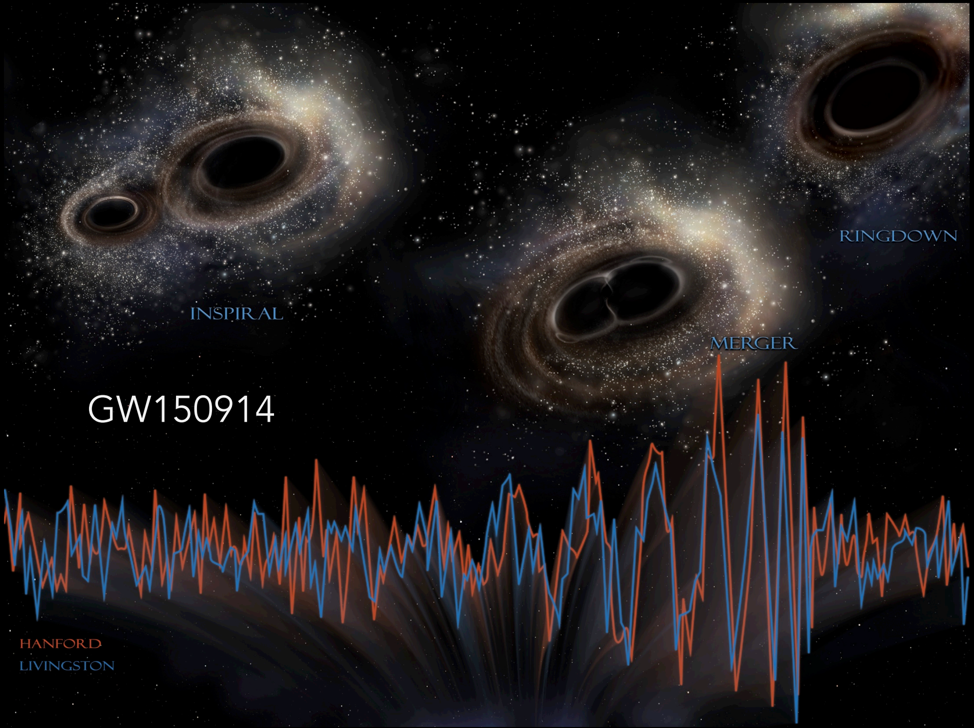


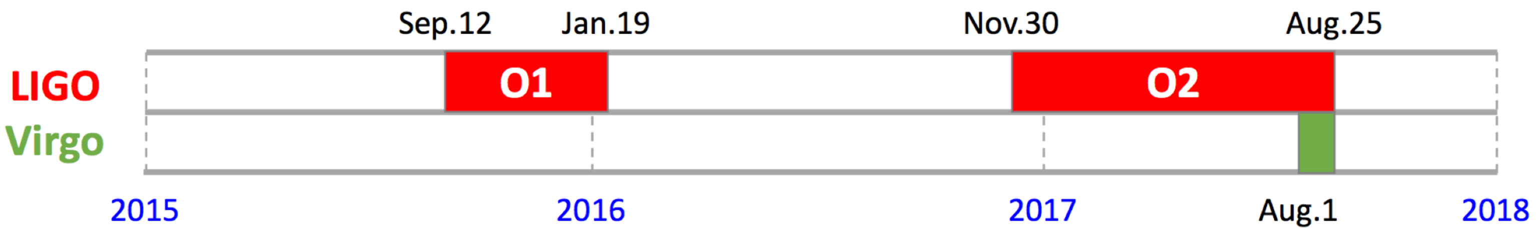
GW OBSERVATIONS ON THE EARTH

Giovanni Losurdo – INFN Pisa

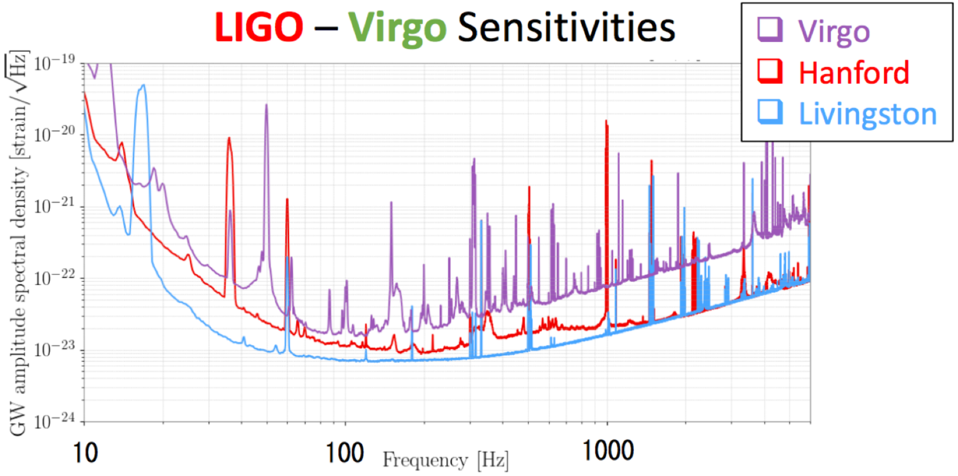
TWO GROUND-BREAKING DISCOVERIES
A NEW ERA IN THE OBSERVATION OF THE UNIVERSE



LIGO/VIRGO DATA TAKING SO FAR



- O1 ~49 *days* of coincident LIGO data
- O2 ~120 *days* of coincident LIGO data
  ~16 *days* of coincidence with Virgo data
  10 GW alerts for EM follow-up

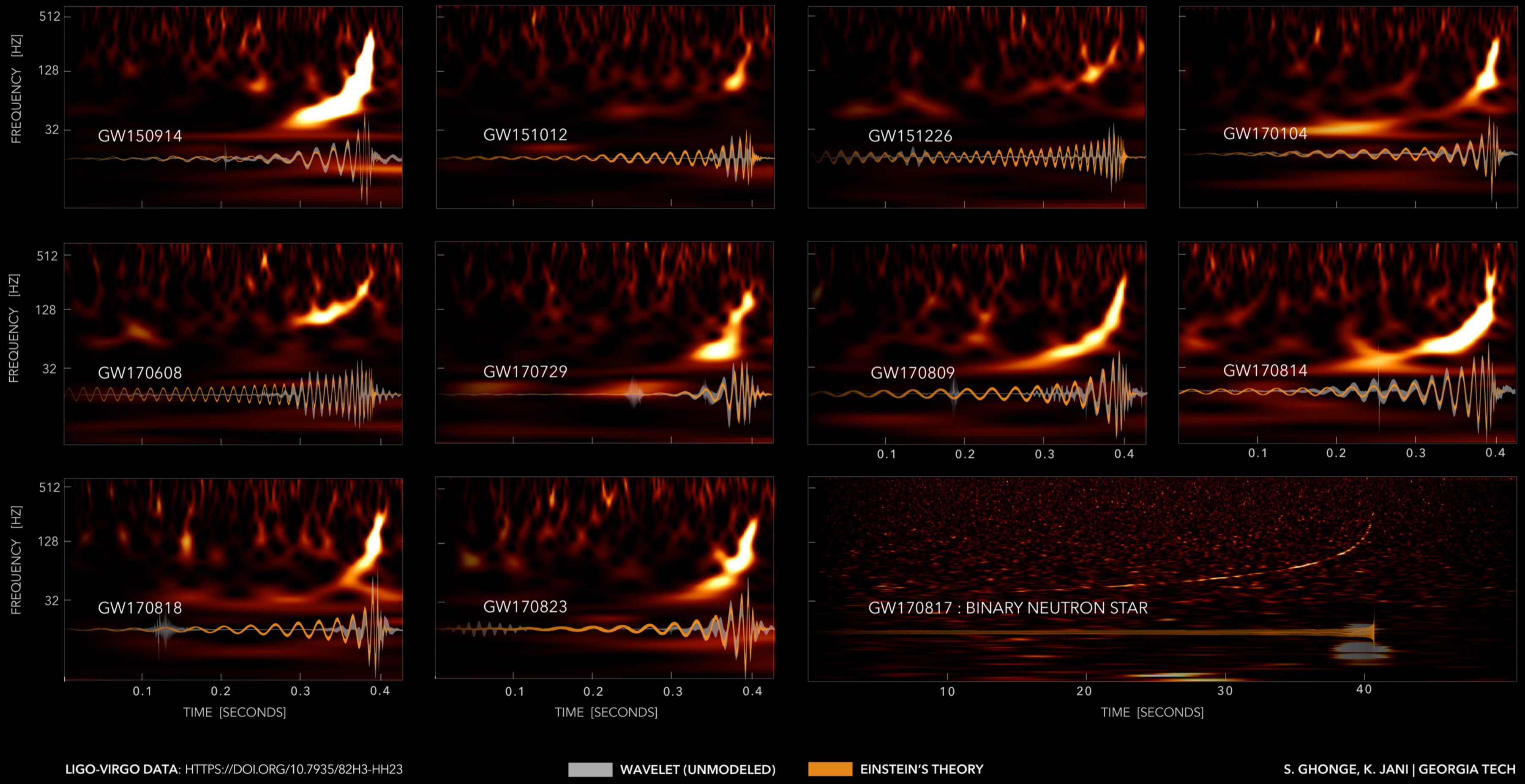


Averaged distances to which Binary Neutron Star could be detected

VIRGO : 26 Mpc
HANFORD : 55 Mpc
LIVINGSTON : 100 Mpc

❑ observations 2015-17 vs 2010:

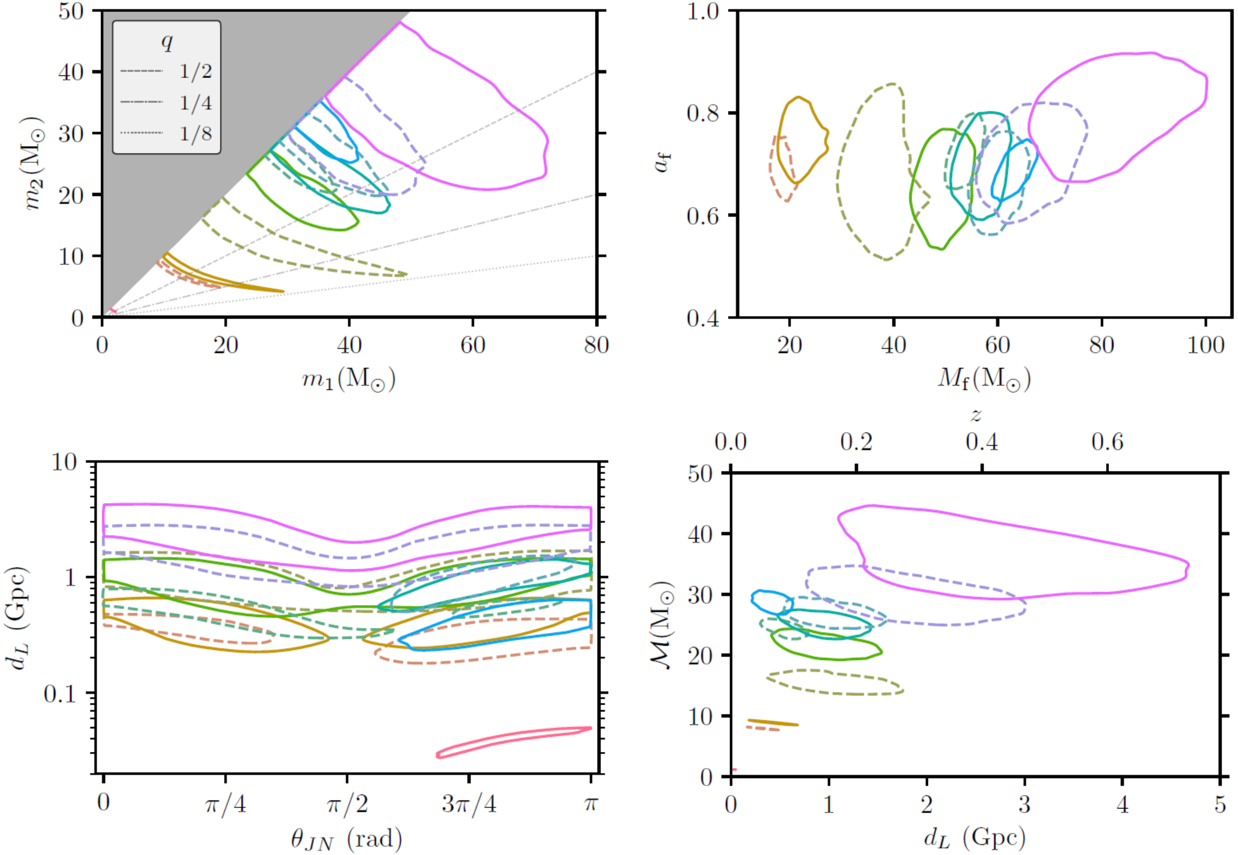
averaged observable volume of Universe : **~100x** gain for **BBH** like GW150914
~30x gain for **BNS** coalescence events

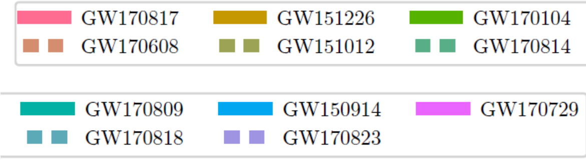


B. P. Abbott, et al., (LIGO Virgo Collaboration), "GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs" , https://arxiv.org/abs/1811.12907

Parameter estimation

B. P. Abbott, et al., (LIGO Virgo Collaboration), https://arxiv.org/abs/1811.12907





Extract information on masses, spins, energy radiated, position, distance, inclination, polarization. Population distribution may shed light on formation mechanisms

The Catalog

10 BBH + 1 BNS in the «catalog». So far…

B. P. Abbott, et al., (LIGO Virgo Collaboration), https://arxiv.org/abs/1811.12907

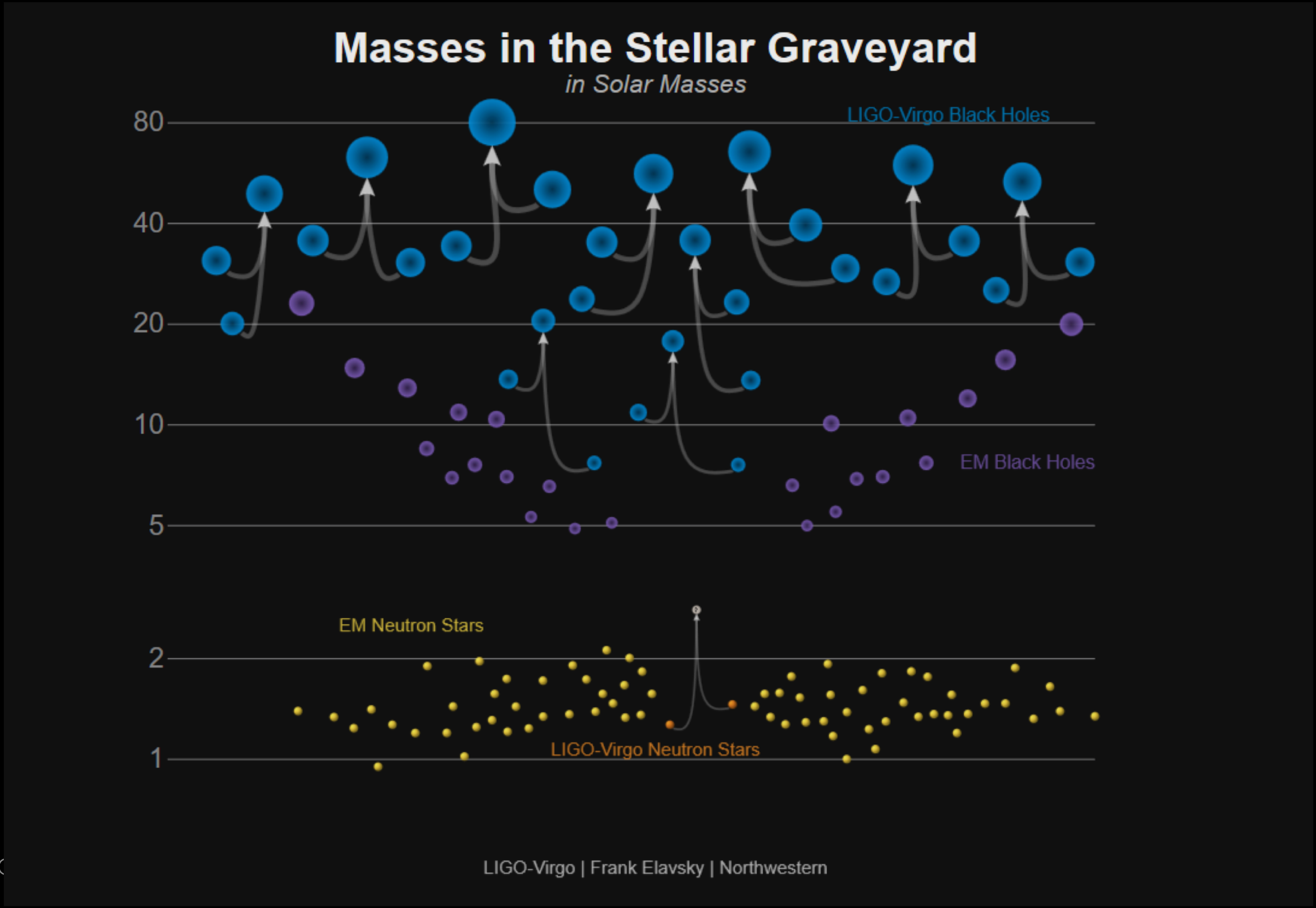
Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	$\chi_{\rm eff}$	$M_{\rm f}/M_\odot$	$a_{\rm f}$	$E_{\rm rad}/(M_\odot c^2)$	$\ell_{\rm peak}/({\rm erg\ s^{-1}})$	$D_{\rm L}/{\rm Mpc}$	z	$\Delta\Omega/{\rm deg}^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4} \times 10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	194
GW151012	$23.2^{+14.0}_{-5.4}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.2}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.7}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7} \times 10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1491
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7} \times 10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1075
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.4^{+5.2}_{-3.9}$	$0.66^{+0.09}_{-0.11}$	$2.2^{+0.5}_{-0.5}$	$3.2^{+0.7}_{-1.0} \times 10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	912
GW170608	$11.2^{+5.4}_{-1.9}$	$7.5^{+1.5}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.04^{+0.19}_{-0.06}$	$17.9^{+3.4}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.8^{+0.1}_{-0.1}$	$3.4^{+0.5}_{-1.3} \times 10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	524
GW170729	$50.7^{+16.3}_{-10.2}$	$34.4^{+8.9}_{-10.2}$	$35.8^{+6.3}_{-4.9}$	$0.37^{+0.21}_{-0.26}$	$80.3^{+14.5}_{-10.3}$	$0.81^{+0.07}_{-0.13}$	$4.9^{+1.6}_{-1.7}$	$4.2^{+0.8}_{-1.5} \times 10^{56}$	2760^{+1290}_{-1350}	$0.48^{+0.18}_{-0.21}$	1069
GW170809	$35.2^{+8.3}_{-5.9}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.17}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9} \times 10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	310
GW170814	$30.7^{+5.5}_{-2.9}$	$25.6^{+2.8}_{-4.0}$	$24.3^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.6^{+3.2}_{-2.5}$	$0.73^{+0.07}_{-0.05}$	$2.8^{+0.4}_{-0.3}$	$3.7^{+0.5}_{-0.5} \times 10^{56}$	560^{+140}_{-210}	$0.12^{+0.03}_{-0.04}$	99
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1 \times 10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	22
GW170818	$35.5^{+7.5}_{-4.7}$	$26.9^{+4.4}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.7}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7} \times 10^{56}$	1020^{+430}_{-370}	$0.20^{+0.07}_{-0.07}$	35
GW170823	$39.5^{+10.1}_{-6.6}$	$29.4^{+6.5}_{-7.1}$	$29.3^{+4.2}_{-3.1}$	$0.08^{+0.19}_{-0.22}$	$65.6^{+9.3}_{-6.5}$	$0.71^{+0.08}_{-0.09}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9} \times 10^{56}$	1860^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1780

Some records

- Furthest BBH is GW170729 at d_L ~2.75 Gpc (z~0.5)
- Closest BBH is GW170608 at d_L ~320 Mpc
- Closest event is GW170817 (BNS) at d_L ~40 Mpc

- Heaviest BH remnant is GW170729: M ~ 80 $M_\odot$
- Lightest BH remnant is GW170608: M ~ 18 $M_\odot$

- Best localized BBH is GW170818: $\Delta\Omega$ ~ 35 deg^2
- Best localized event is GW170817 (BNS): $\Delta\Omega$ ~ 16 deg^2


Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

Main results in 2 years

First detection of GW

GW travel at the speed of light

New test of Lorentz invariance

First test of GW polarization

Test of GR in strong field regime

Alternative measurement of H_0

First observations of BBH mergers

A new population of BH with higher masses

First observation of a BNS merger

First measurement on NS tidal deformability

Link between GRB and neutron star mergers

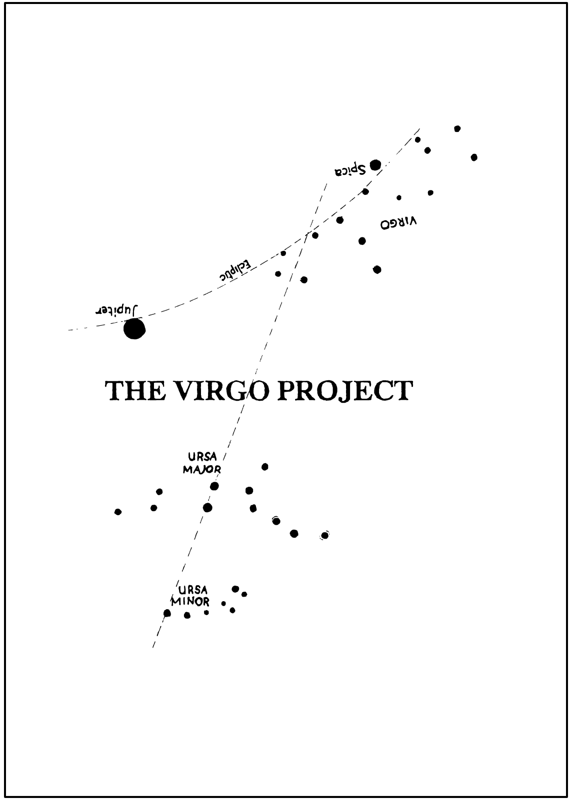
Kilonova powered by binary NS merger

Evidence of formation of heavy elements upon a BNS merger

SOME CRUCIAL STEPS WALKED SO FAR

1989: there was a long-term vision there...

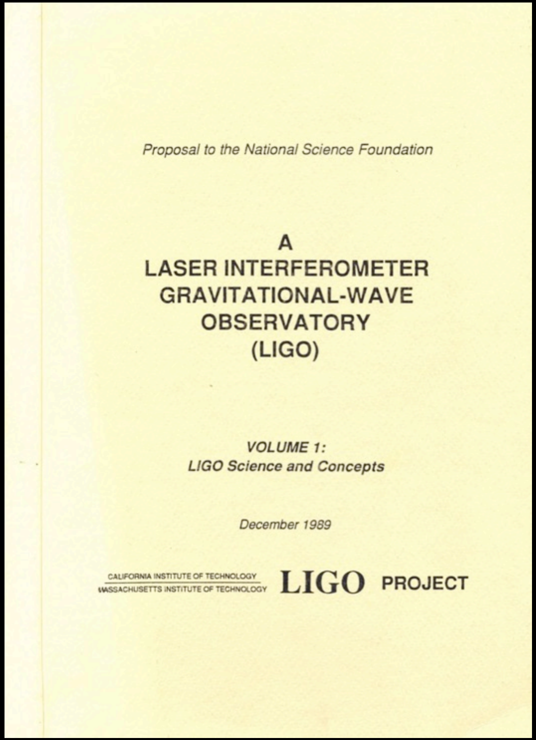
1989



VIRGO must be considered both as an experiment and as a step towards a future observatory. The immediate goal of the VIRGO experiment is to realize, or to participate in, the first detection of gravitational radiation, but it also has the long term goal of being one component of the gravitational wave detectors network which will involve other detectors in other countries, and provide data of astrophysical interest. These goals imply a collaboration with the other groups having similar projects, without excluding some competition. The group leaders from Italy, France, Germany, Scotland, and the USA have agreed to exchange all information and to collaborate on all the aspects of the construction of large interferometers in order to generate the international effort required by the birth of gravitational astronomy.

A BRILLET & A GIAZOTTO

1989


Proposal to the National Science Foundation

A
LASER INTERFEROMETER
GRAVITATIONAL-WAVE
OBSERVATORY
(LIGO)

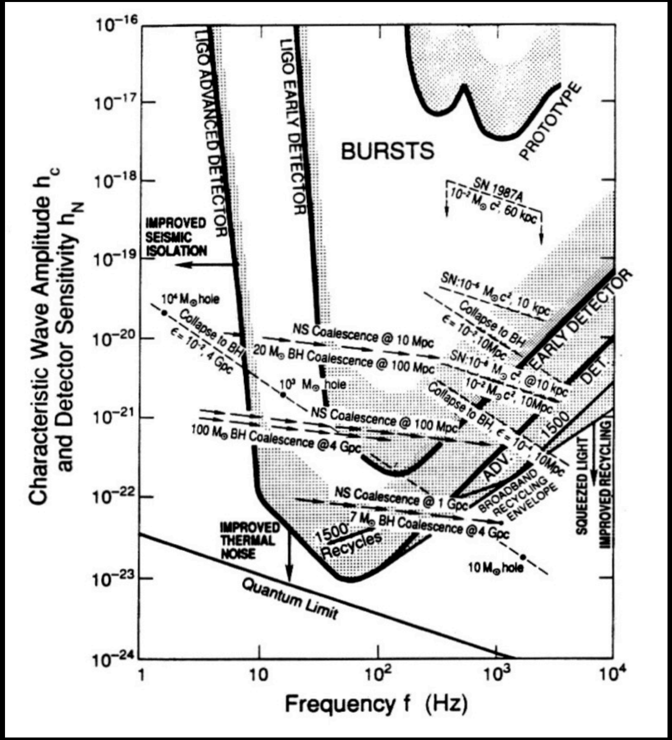
VOLUME 1:
LIGO Science and Concepts

December 1989

CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LIGO PROJECT

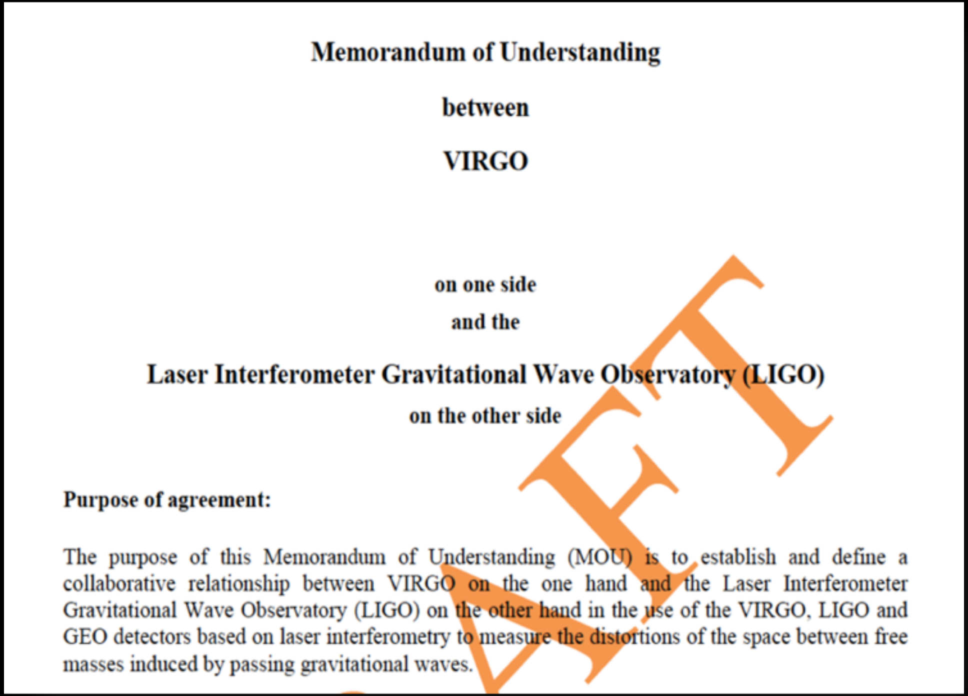
THE CONCEPT OF AN "ADVANCED" DETECTOR IS ALREADY IN THE LIGO PROPOSAL TO NSF

This set the framework for substantial R&D funding



2007: LSC-Virgo MoU

2007: LSC-VIRGO MoU for a "SINGLE MACHINE"
A MAJOR STEP TOWARDS GW ASTRONOMY



Memorandum of Understanding

between

VIRGO

on one side

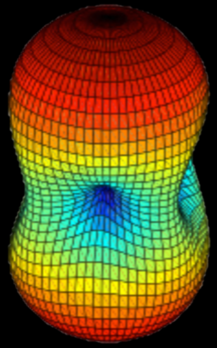
and the

Laser Interferometer Gravitational Wave Observatory (LIGO)

on the other side

Purpose of agreement:

The purpose of this Memorandum of Understanding (MOU) is to establish and define a collaborative relationship between VIRGO on the one hand and the Laser Interferometer Gravitational Wave Observatory (LIGO) on the other hand in the use of the VIRGO, LIGO and GEO detectors based on laser interferometry to measure the distortions of the space between free masses induced by passing gravitational waves.



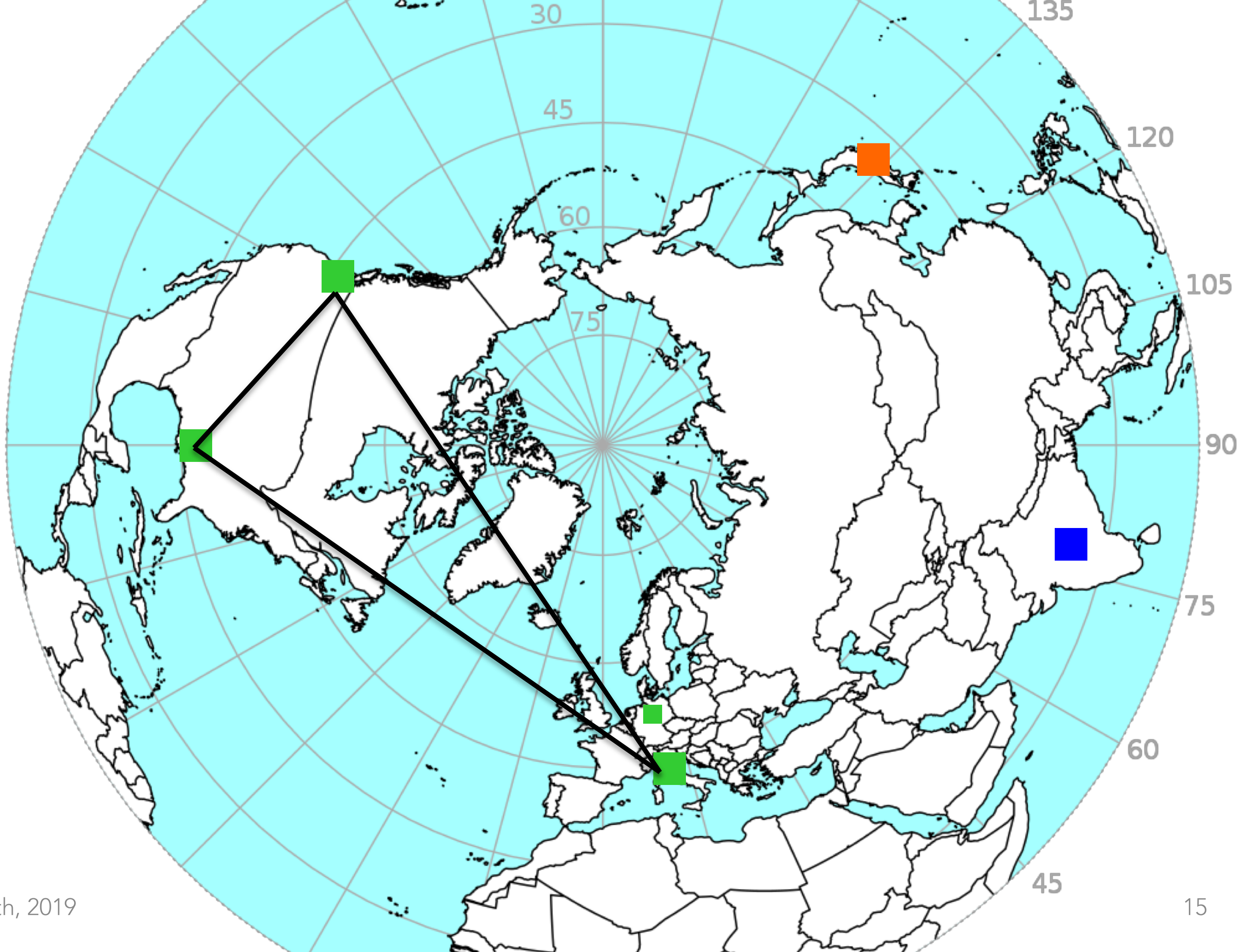
IMPROVING EVENT SIGNIFICANCE AND LOCALIZATION, SKY AND TIME COVERAGE

OPERATION

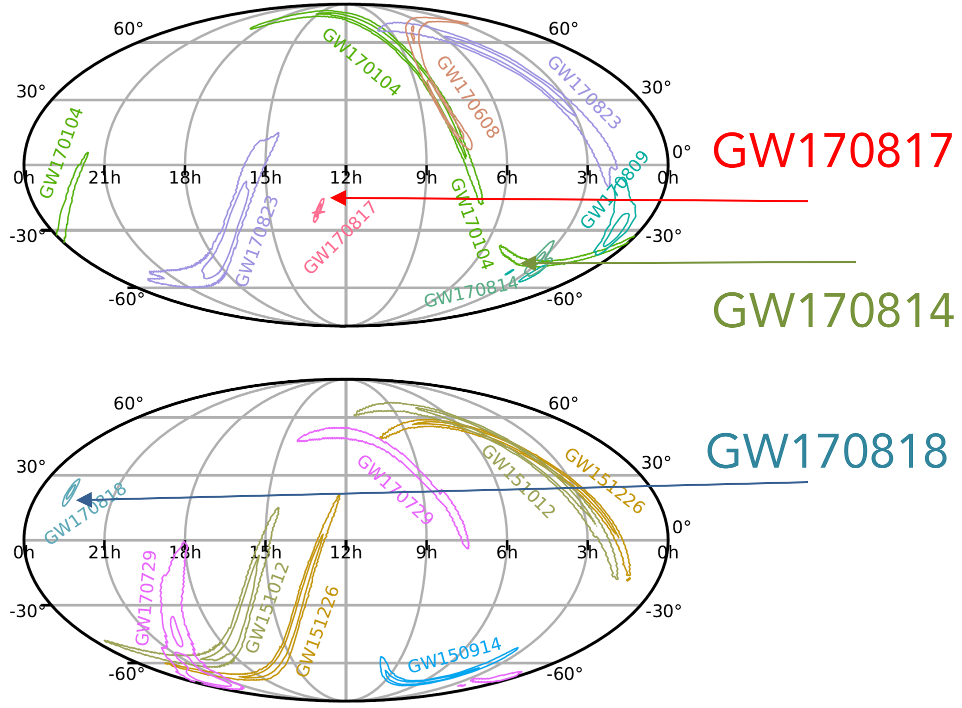
COMMISSIONING

CONSTRUCTION

APPROVED

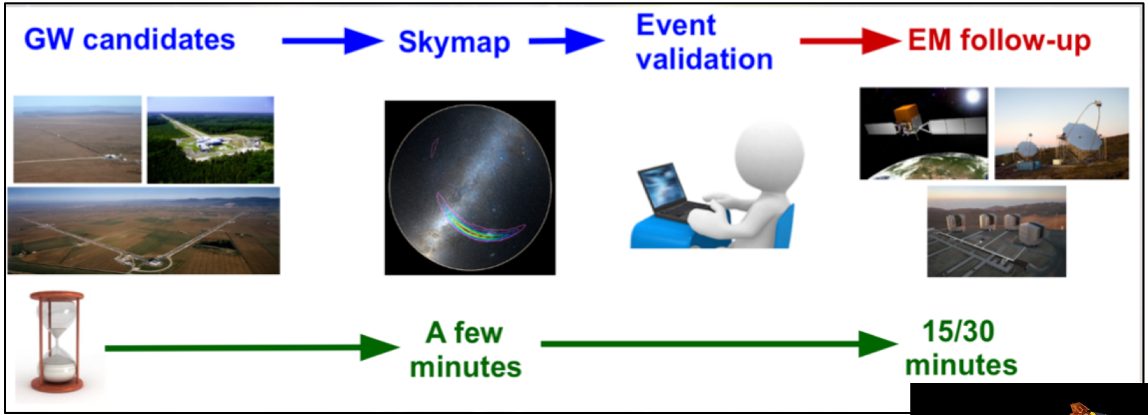


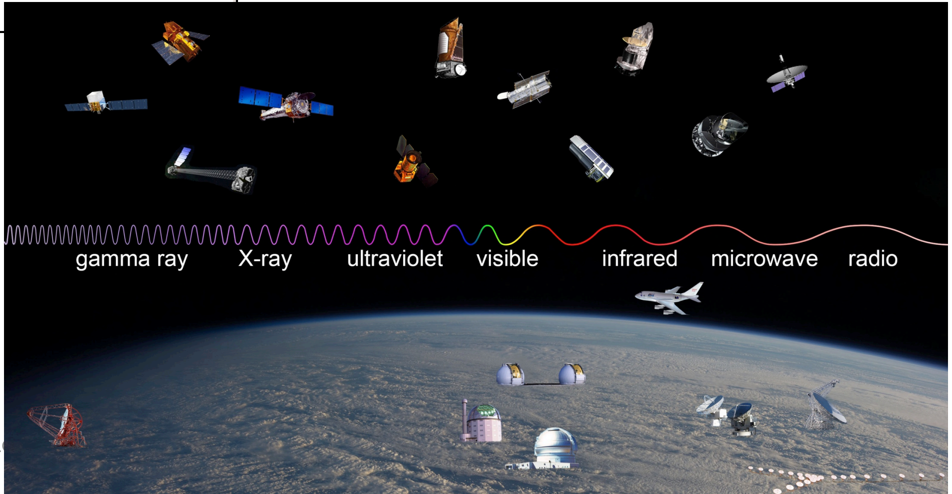
B. P. Abbott, et al., (LIGO Virgo Collaboration), https://arxiv.org/abs/1811.12907



- Sky areas scale inversely with SNR^2
- Inclusion of Virgo improves sky localization: importance of a global GW detector network for accurately localizing GW sources
- Extending further the network will be valuable!

The multi-messenger network



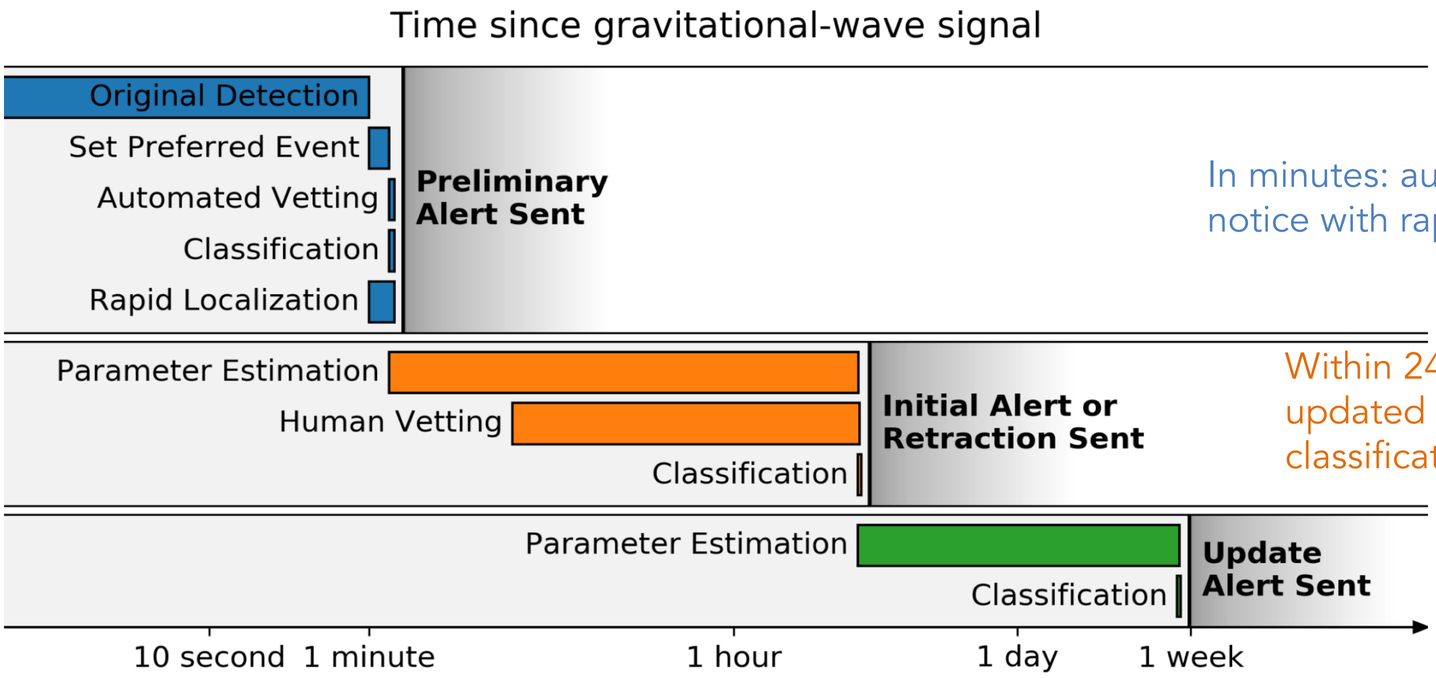


BEFORE O3

93 groups (>200 instruments) have signed the MoU with the LVC

Open Public Alerts

LIGO-Virgo will issue Open Public Alerts during the O3 run



In minutes: automatic preliminary notice with rapid localization

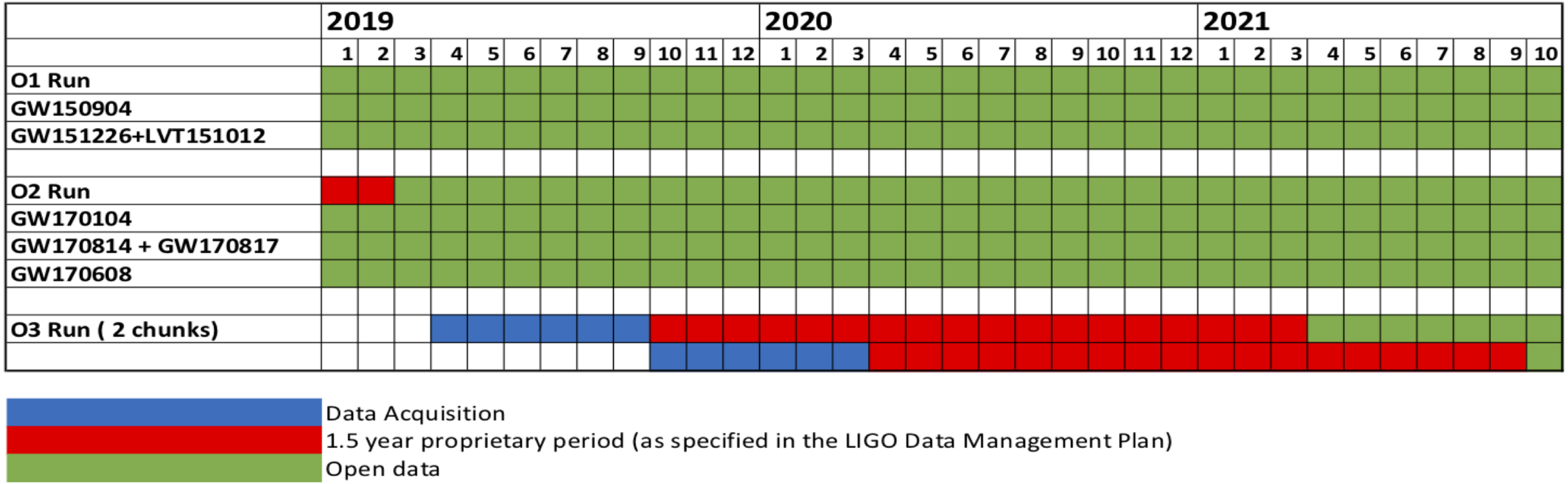
Within 24 hrs: retraction or updated localization, source classification

Significant updates

Open Data

- O1 data are public since end of January 2018 (24 months after end of run)
- O2 data will be public end of February 2019 (24 months after end of run)

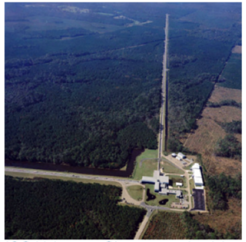
- Future bulk releases are planned to be (no later than) **18 months after the end of a 6-month data acquisition period**
  e.g., if O3 starts in April 2019, the first planned bulk data release would be **April 2021**



Gravitational Wave Open Science Center

- Getting Started
- Data
  - Catalogs
  - Bulk Data
- Tutorials
- Software
- Detector Status
- Timelines
- My Sources
- GPS ↔ UTC
- About the detectors
- Projects
- Acknowledge GWOSC

LIGO Hanford Observatory, Washington
(Credits: C. Gray)



LIGO Livingston Observatory, Louisiana
(Credits: J. Giaime)

Virgo detector, Italy
(Credits: Virgo Collaboration)

The Gravitational Wave Open Science Center provides data from gravitational-wave observatories, along with access to tutorials and software tools.

Get started!

Download data

GWTC-1: Catalog of Compact Binary Mergers

Join the email list

Attend an open data workshop

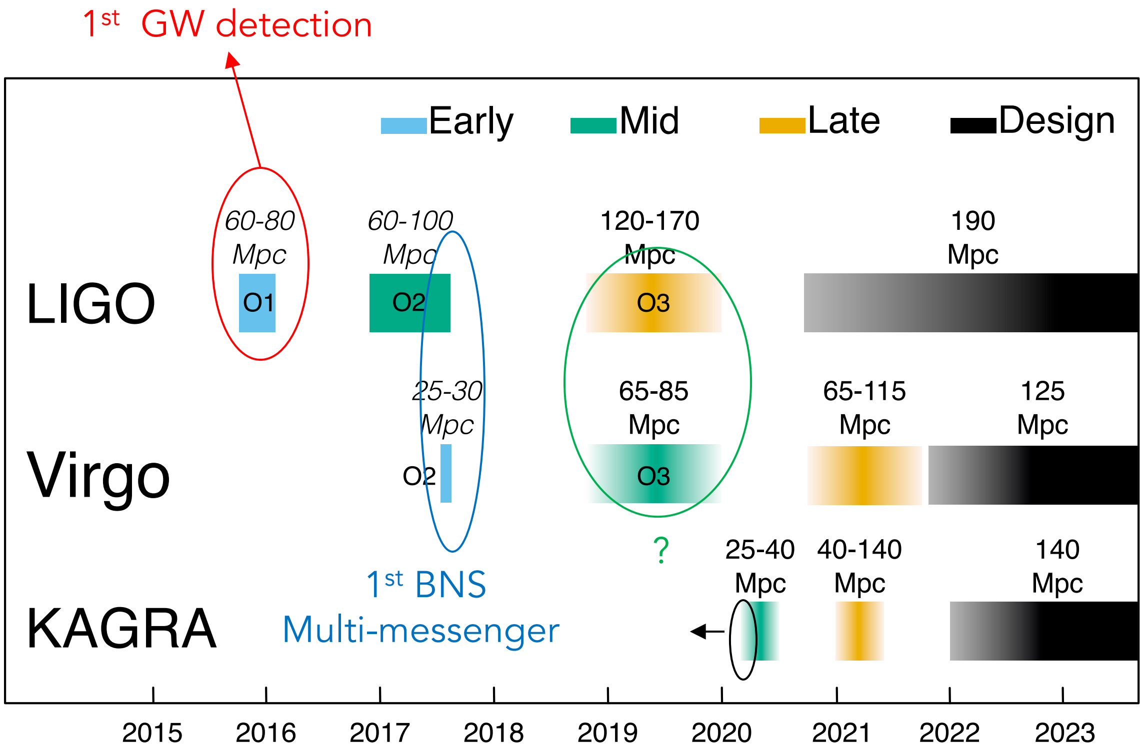
SHORT/MID-TERM PLANS

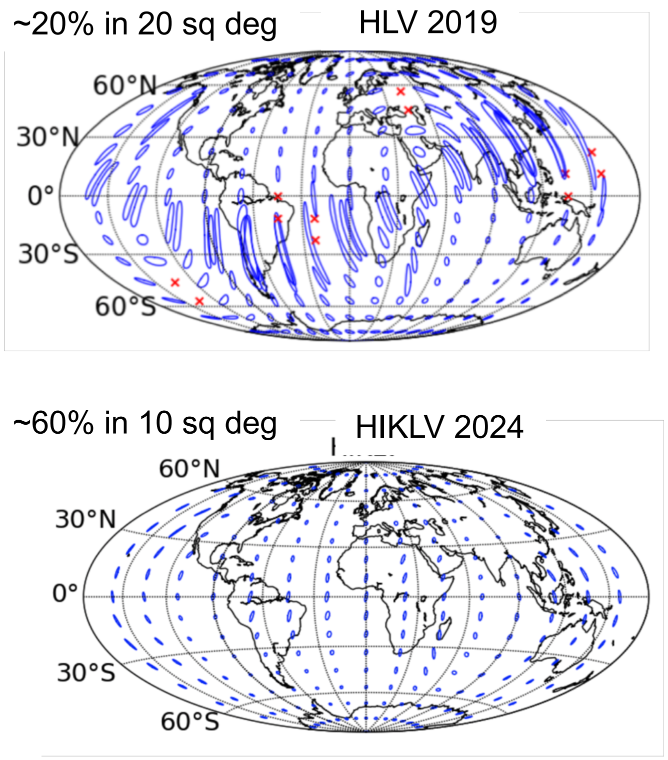
THE CASE FOR BETTER DETECTORS

$$\# \text{ EVENTS} \propto d^3\, T$$

1 day of data at a range of 80 Mpc (Advanced LIGO in O1)
is equivalent to 64 days at 20 Mpc (LIGO, 2009)

Observing for a long time is good,
improving the sensitivity further is better.



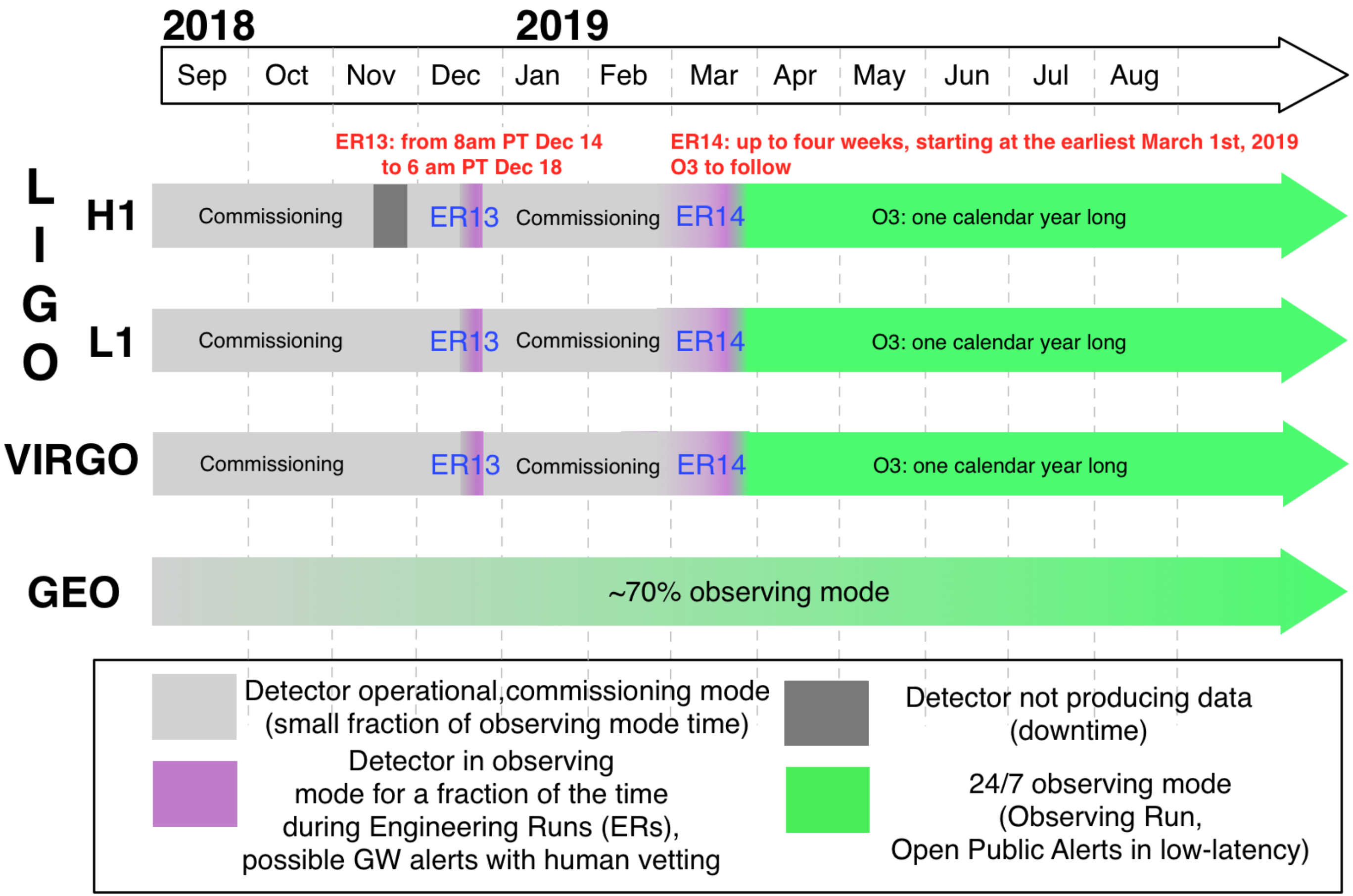


B. P. Abbott et al., *Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA*, 2016, Living Rev. Relativity 19

LIGO-VIRGO Joint Run Planning Committee

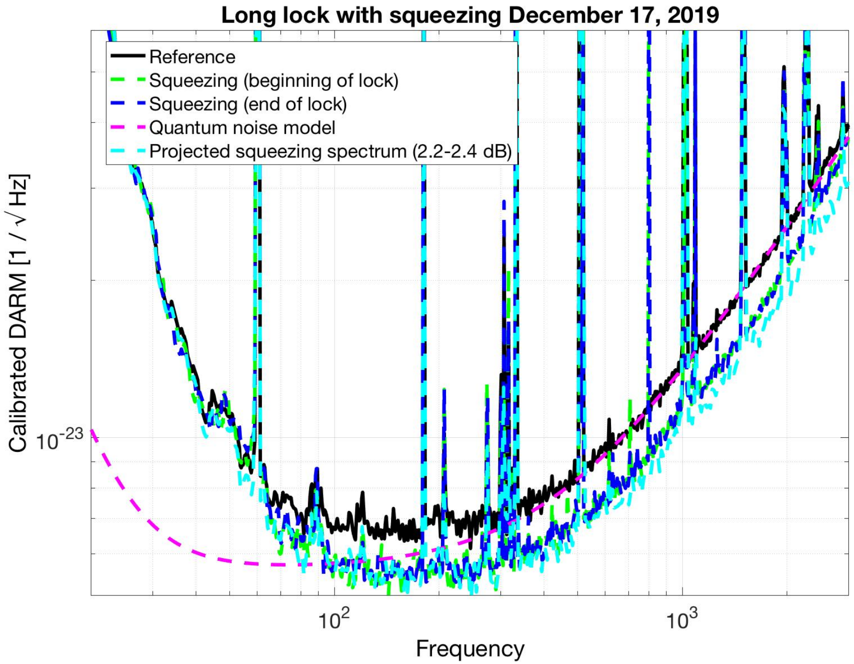
Working schedule for O3

(Public document G1801056-v4, based on G1800889-v7)

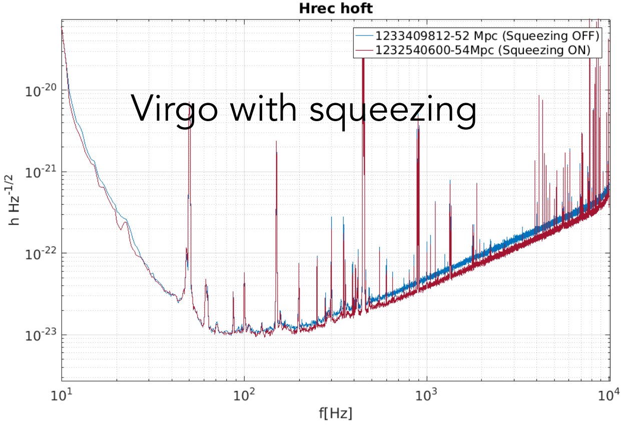


LIGO

- Squeezing
- New 70 W laser (50 W in the interferometers)
- Some test masses replaced
- Improved stray light control
- Parametric instabilities risk mitigation (acoustic mass dampers)
- O3 Goal: 120 Mpc BNS range
- Status (best result): L1 135 Mpc, H1 90 Mpc

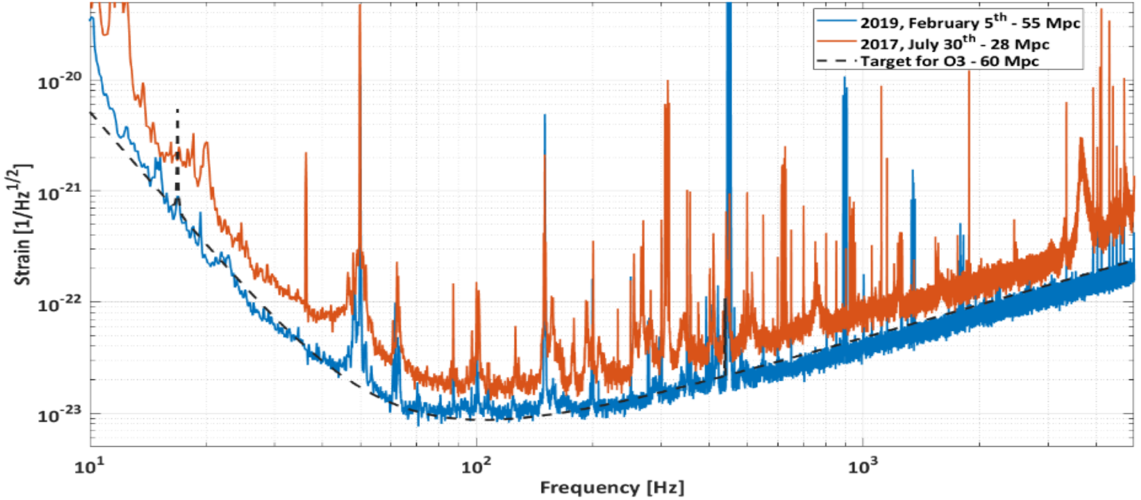


Virgo



- Monolithic suspensions installed
- Squeezing (collaboration with AEI Hannover)
- Improved stray light control, TCS
- Goal: 60 Mpc for BNS (55 Mpc achieved, 2x O2), 600 Mpc for BBH (630 achieved)

See talk by A Allocca



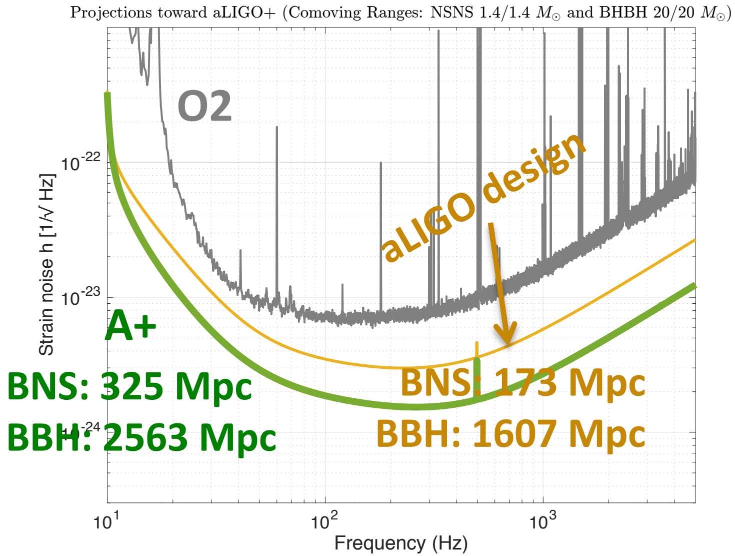
KAGRA

- Currently operating a simple Michelson, partially cryogenic
- Plan to operate a dual-recycled FP, fully cryogenic and join O3 at a later stage in this configuration

LIGO A+

'Mid-scale' upgrade of the Advanced LIGO interferometers

- Sensitivity improvement over aLIGO:
  - 1.4/1.4 $M_\odot$ BNS inspiral range by ~ 1.9 to 325 Mpc
  - 30/30 $M_\odot$ binary black hole inspiral range by ~1.6 to > 2.5 Gpc
- Employs frequency-dependent squeezing & lower thermal noise mirror coatings
- Currently planning for a 1.5-2 year run duration beginning mid 2024 or early 2025
- LIGO-India to come online in 2025 in the A+ configuration

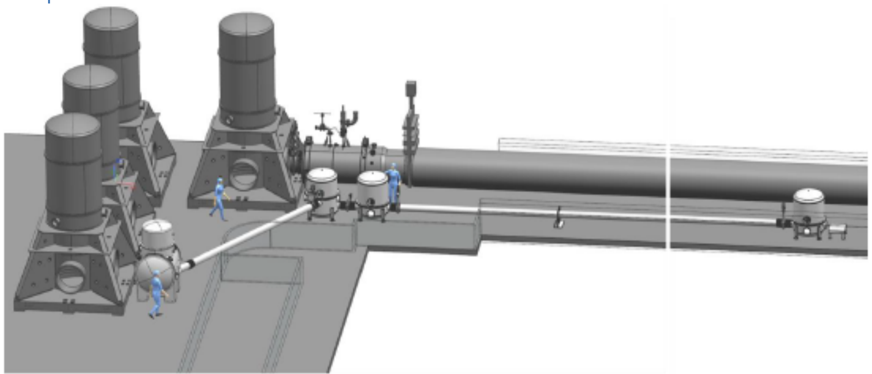


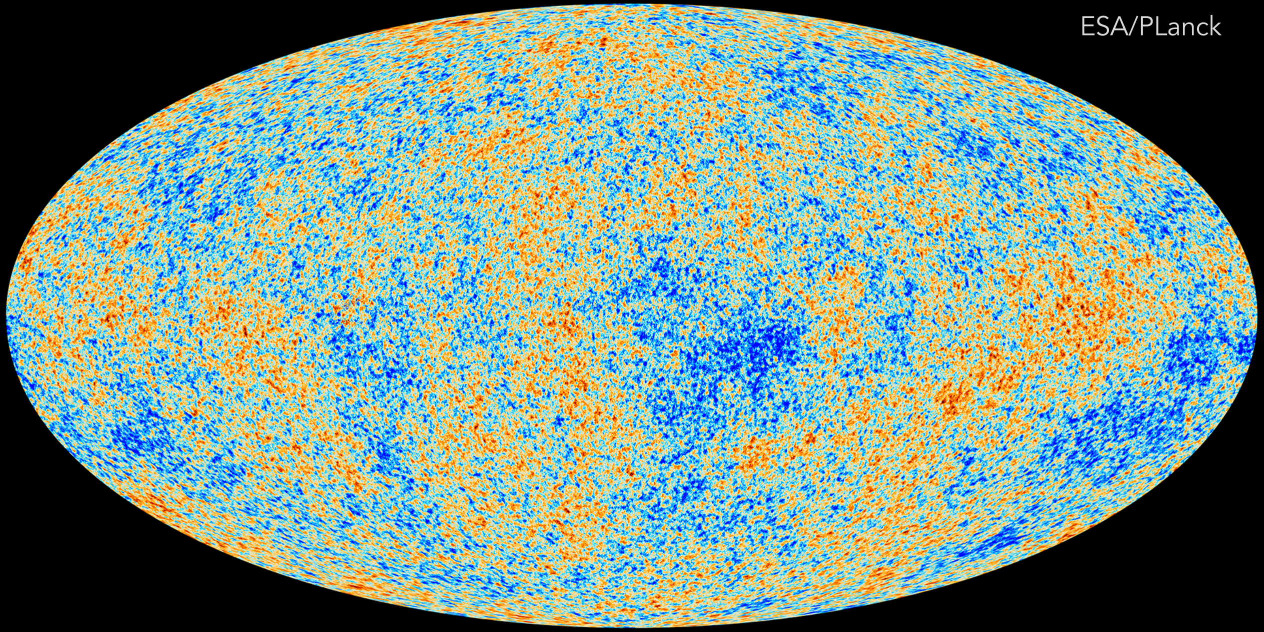
AdV+

- Upgrade of fully exploit the existing infrastructure: detection rate up to 10x wrt Advanced Virgo
- List of upgrades
  - Signal recycling (already foreseen in AdV)
  - Frequency dependent squeezing
  - Newtonian noise cancellation
  - Larger mirrors
  - Improved coatings

Before O4

After O4





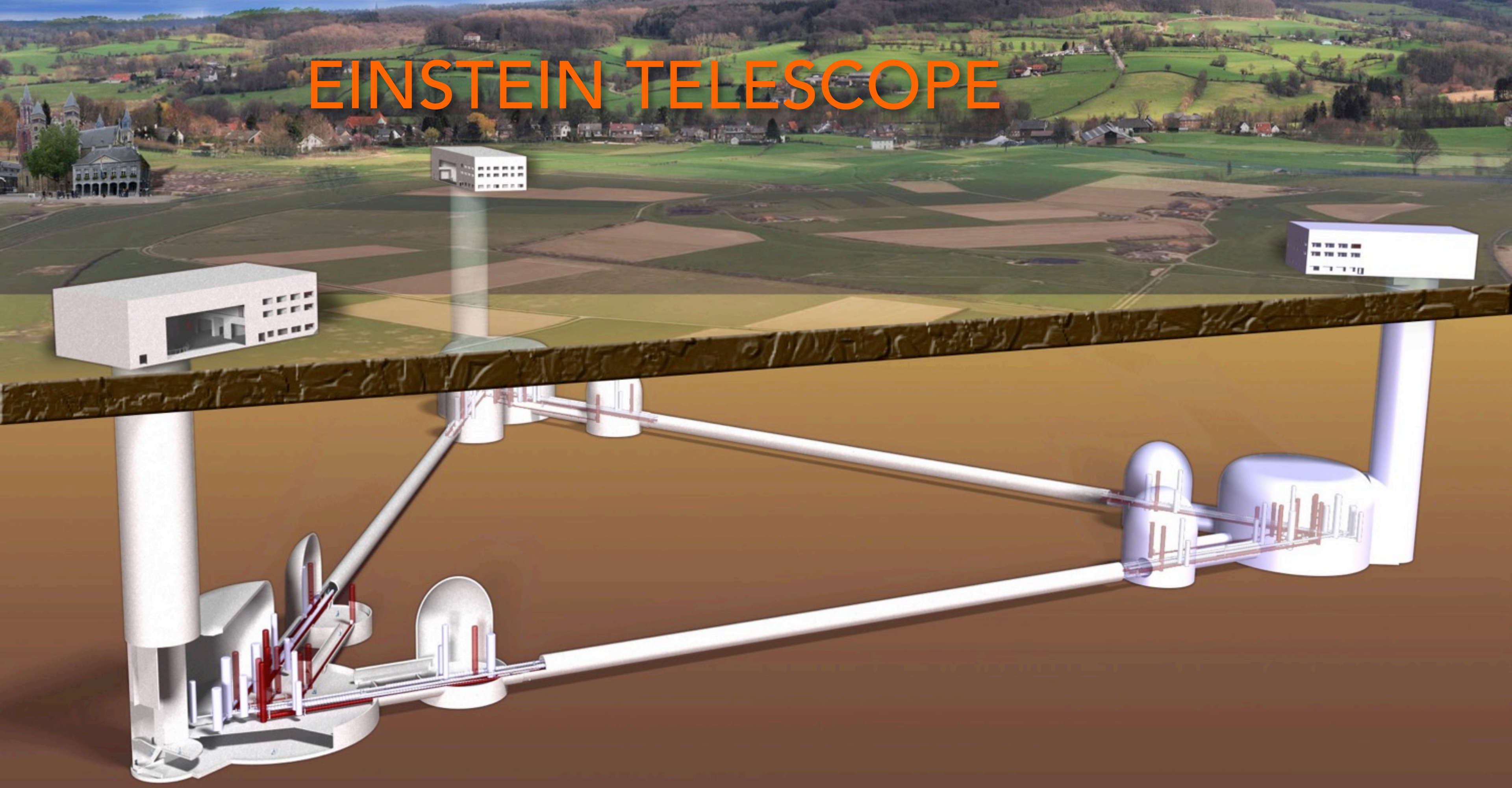
LONG-TERM OUTLOOK

From here to 3G - GWIC

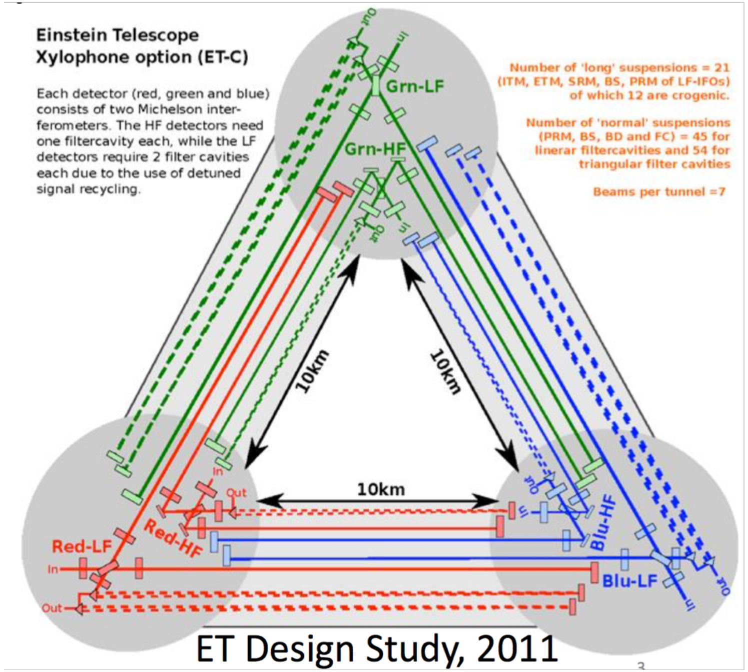
- 2016: subcommittee to look at the 3G in a coordinated way
  - D Reitze, M Punturo co-chairs
- 2019: report of actions/recommendations to be delivered
  - Science drivers for 3G detectors
  - Coordination of the ground-based GW community
  - Networking
  - Funding agencies interfacing and advocacy
  - Investigate 3G detectors governance schemes
  - Computing

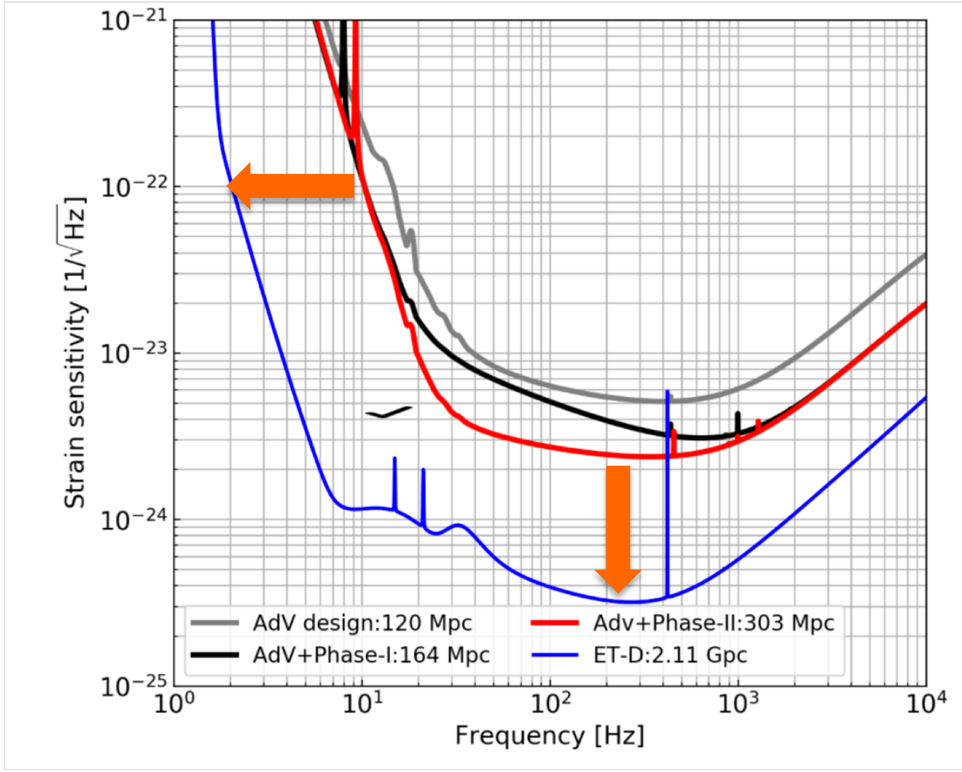
MAIN MESSAGE: The GW community is engaged in a coherent planning exercise to develop 3G

EINSTEIN TELESCOPE



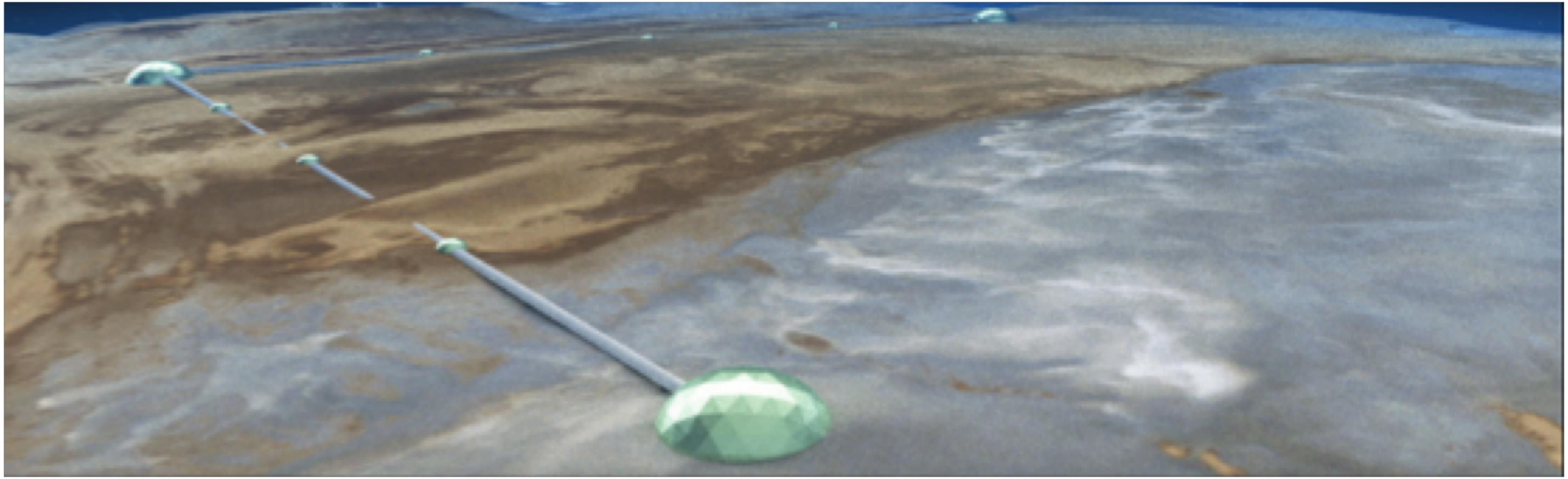
EINSTEIN TELESCOPE





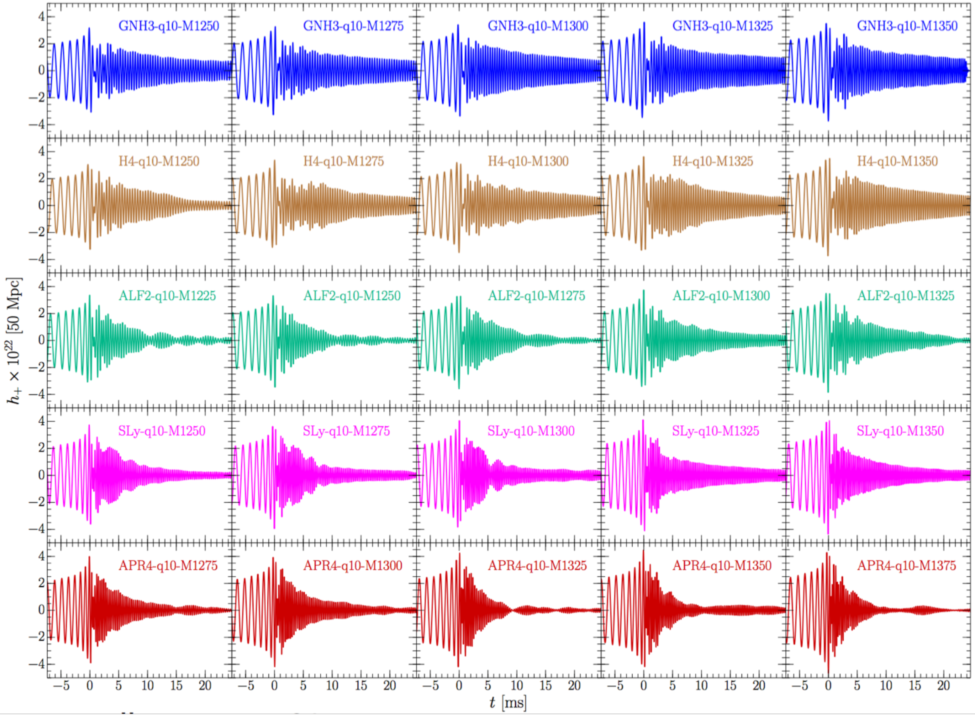
COSMIC EXPLORER

- 3rd generation observatory in the US
- Above ground, L shaped, 40 km
- NSF funded design study under way (www.cosmicexplorer.org)



EXTREME MATTER

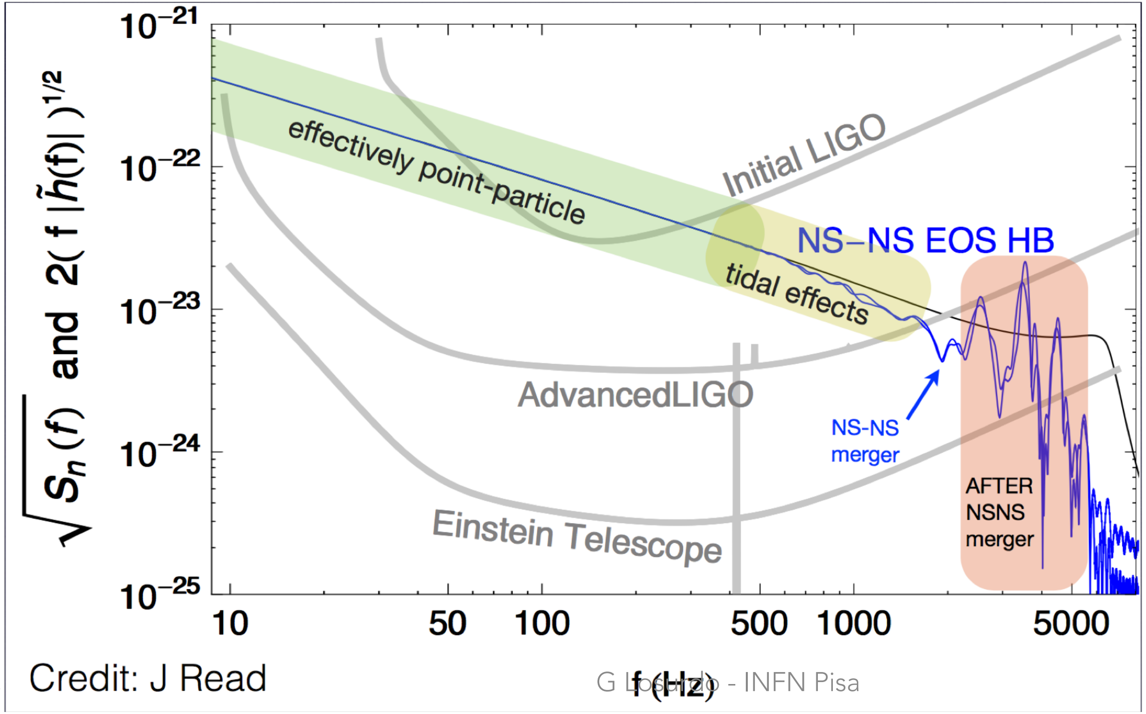
NS: WE ARE ABLE TO COMPUTE THE WAVEFORMS FOR THE VARIOUS EOS



Takami, Rezzolla, Baiotti (2014)

EXTREME MATTER

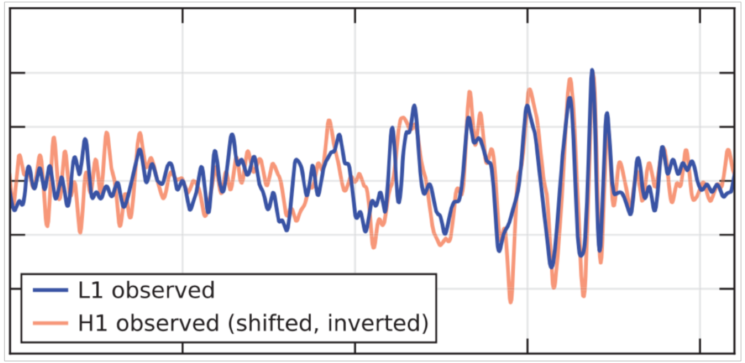
A 3G DETECTOR IS NEEDED TO MEASURE WHICH EOS IS THE RIGHT ONE



Credit: J Read

EXTREME GRAVITY

- Precision tests of alternative theories
  - polarizations
  - graviton mass
  - Lorentz invariance
- Exotic compact objects
- BH QNM (quantum gravity?)

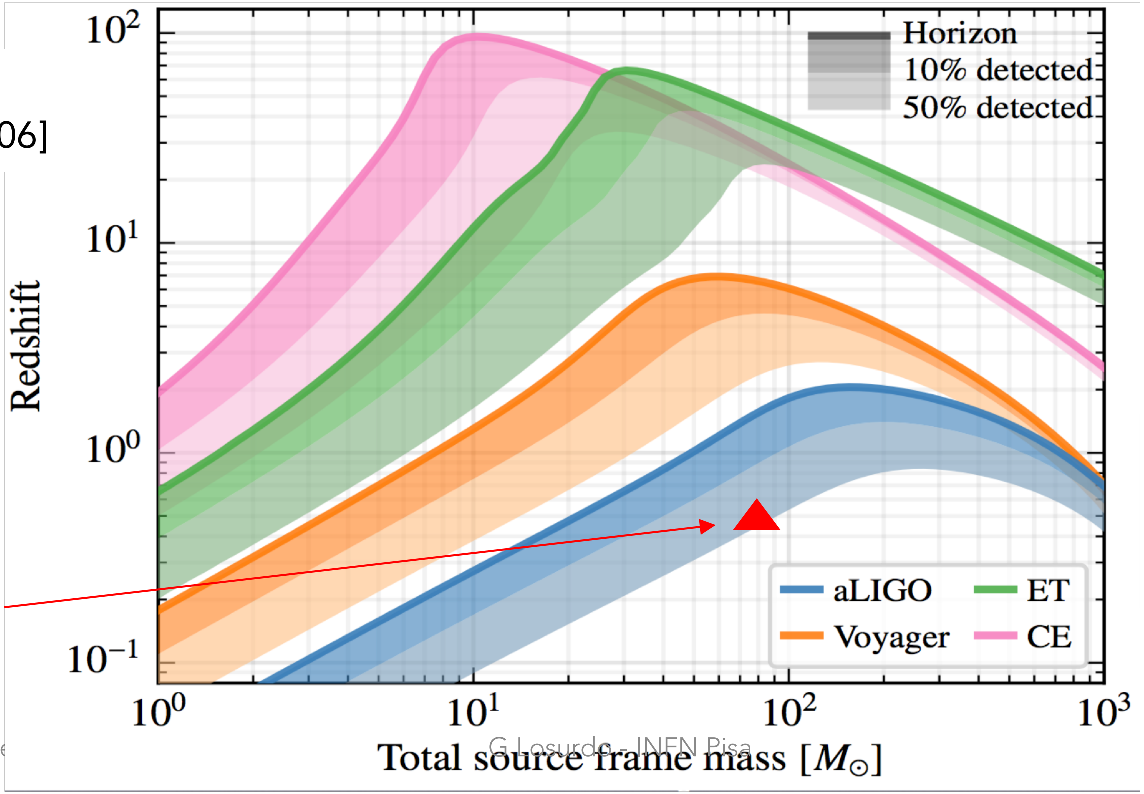


Detector	GW150914 SNR	QNM SNR
O1	25	7
Advanced LIGO	80	20
LIGO-India ALIGO+ (2024)	250	80
ET (2030)	800	200
Cosmic Explorer (2034)	2400	800

EXTREME UNIVERSE

E Hall, M Evans, paper in prep.

1000s detections/yr
[Mills et al 1708.00806]

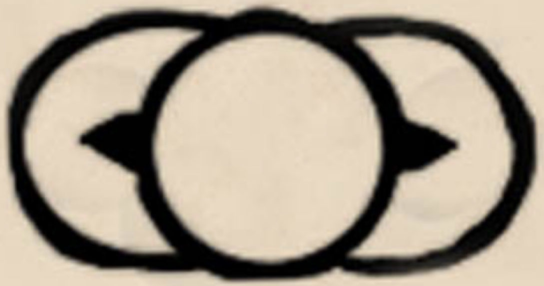


GW170729

Galileo, 1610

Galileo, 1610

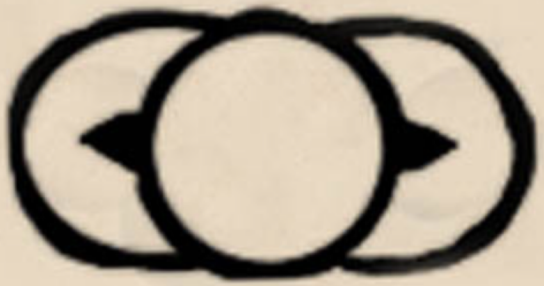
Galileo, 1616

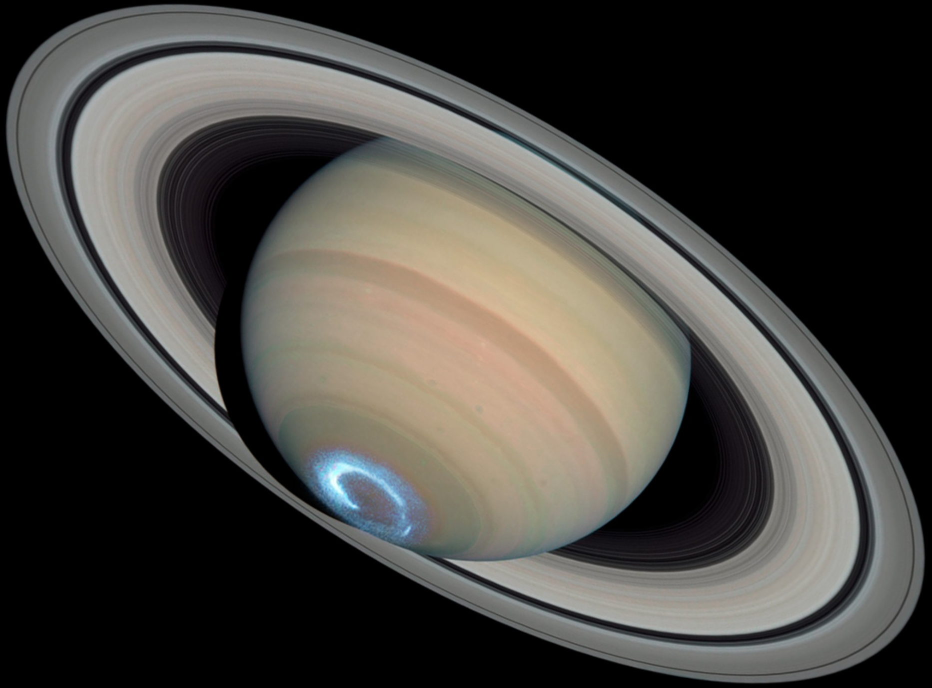


WE HAVE THE RIGHT INSTRUMENT.
NOW WE NEED TO MAKE IT BETTER AND BETTER AND BETTER…

Galileo, 1610

Galileo, 1616

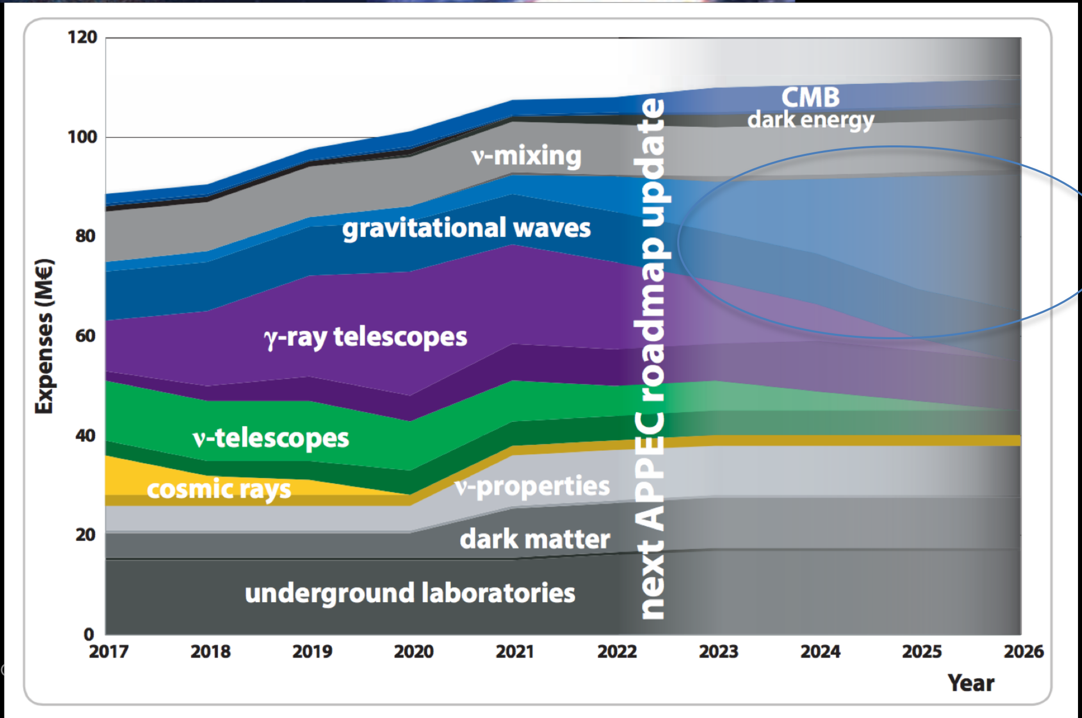




HST, 400 yrs later

European Astroparticle Physics Strategy 2017-2026

APPEC



ET: the big investment for the next decade (recommendation…)

THE POSSIBLE ROLE OF CERN

- The GW community looks at CERN as a model to many extents
- We have a lot to learn from CERN:
  - Model of governance
  - Management of big projects
  - Technology: underground infrastructure, vacuum, cryogenics
- A commitment of CERN on ET (in some form) might be a game changer