FUTURE PLANS FOR GW DETECTORS

PAOLA PUPPO (INFN – ROMA)

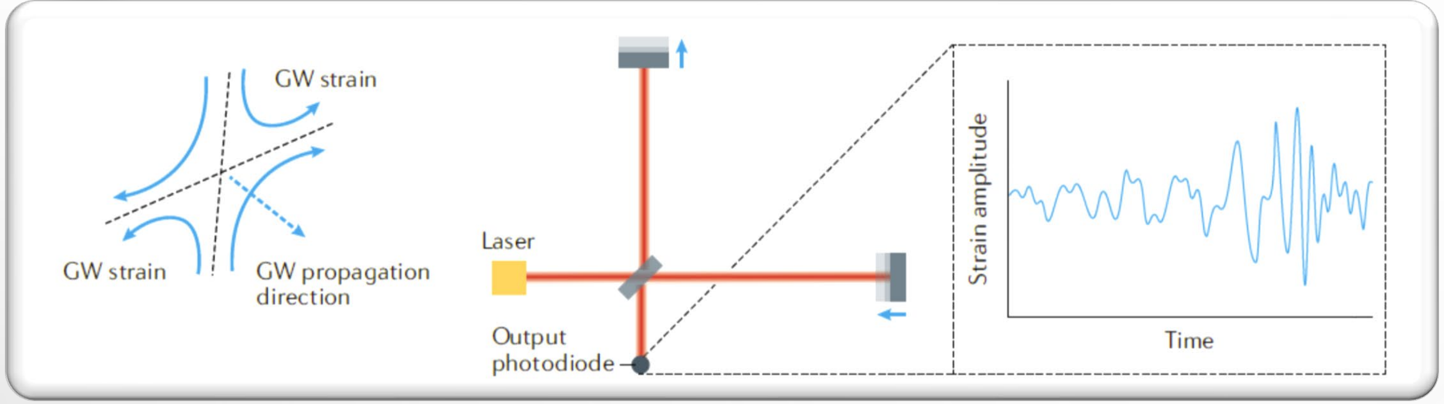
LIGO/VIRGO/KAGRA COLLABORATION

- **10TH INTERNATIONAL CONFERENCE ON NEW FRONTIERS IN PHYSICS (ICNFP 2021)**

OUTLINE

- CONTEXT AND BACKGROUND
  - GW INTERFEROMETERS: THE CONCEPT
  - THE DATA TAKING RUNS
  - A BRIEF VIEW OF THE MAIN RESULTS (talk of C. Lazzaro for details)
- THE NEXT DATA TAKINGS (O4 AND O5)
- FROM O5 TO THE THIRD GENERATION DETECTORS

GW DETECTOR CONCEPT



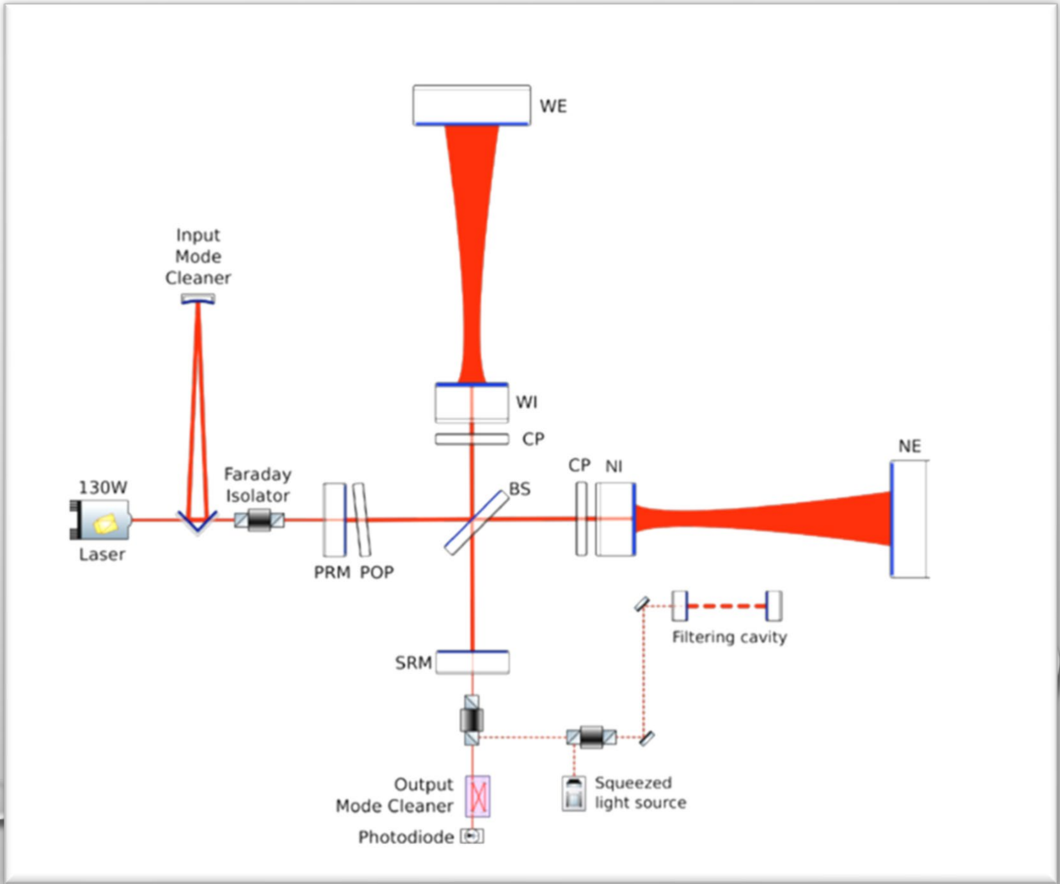
$h = \frac{\delta L}{L}$: GW STRAIN

Ground-based GW detector

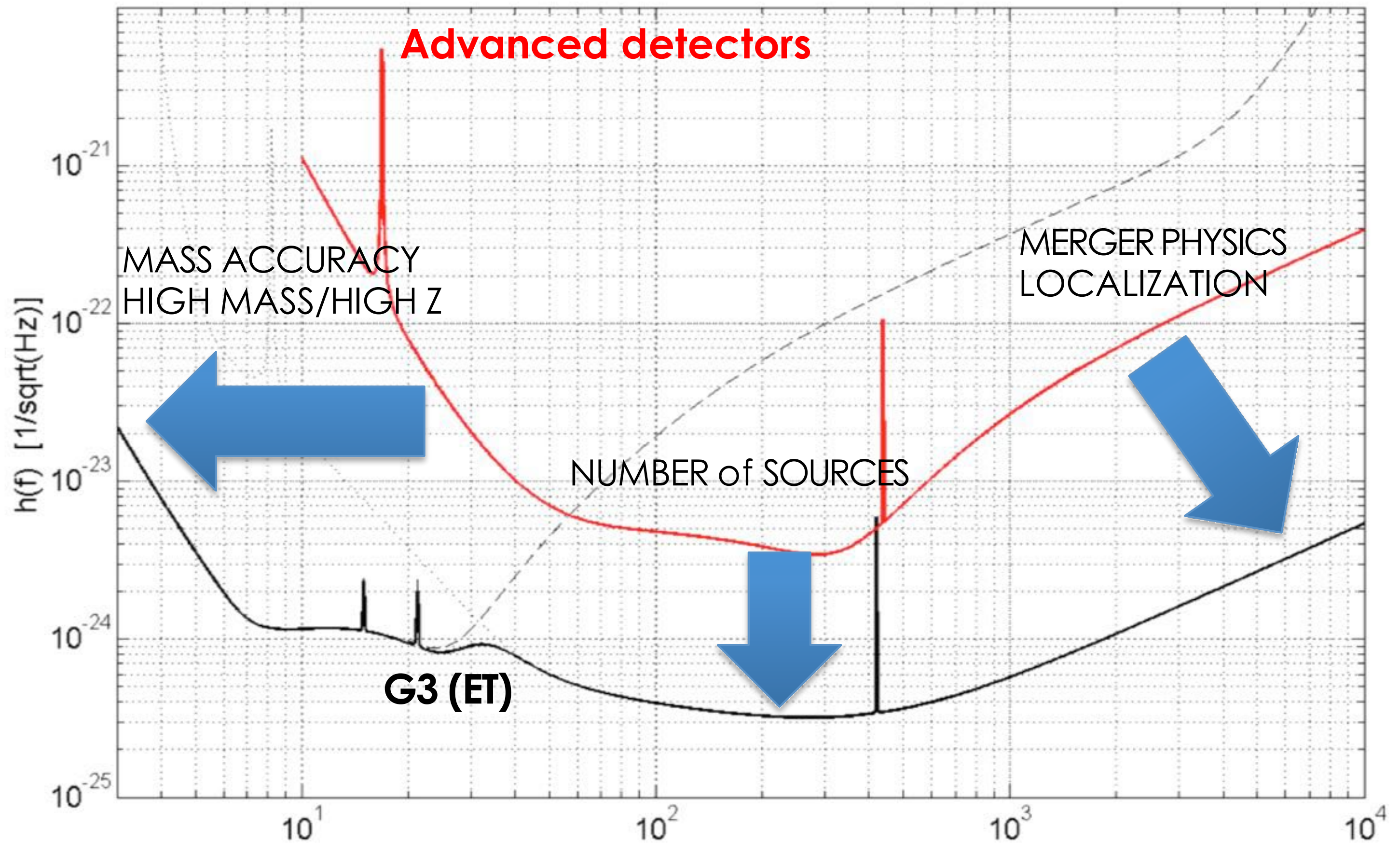
Frequency BW: 10Hz-10kHz
Strain amplitude: 10^{-21} from astrophysical sources

→ 10^{-18} m displacement on 3-4 km arms

→ Main noise sources:
→ Seismic and Thermal noise, Quantum noise, radiation pressure noise
→ Mirrors suspended, big masses, high laser power



DETECTOR SENSITIVITY



MIRRORS: large mass/diameter, good flatness/roughness, low absorption, good homogeneity, good coating uniformity, high Q

SUSPENSIONS: high pendulum Q, monolithic FS suspensions

Limitations to sensitivity

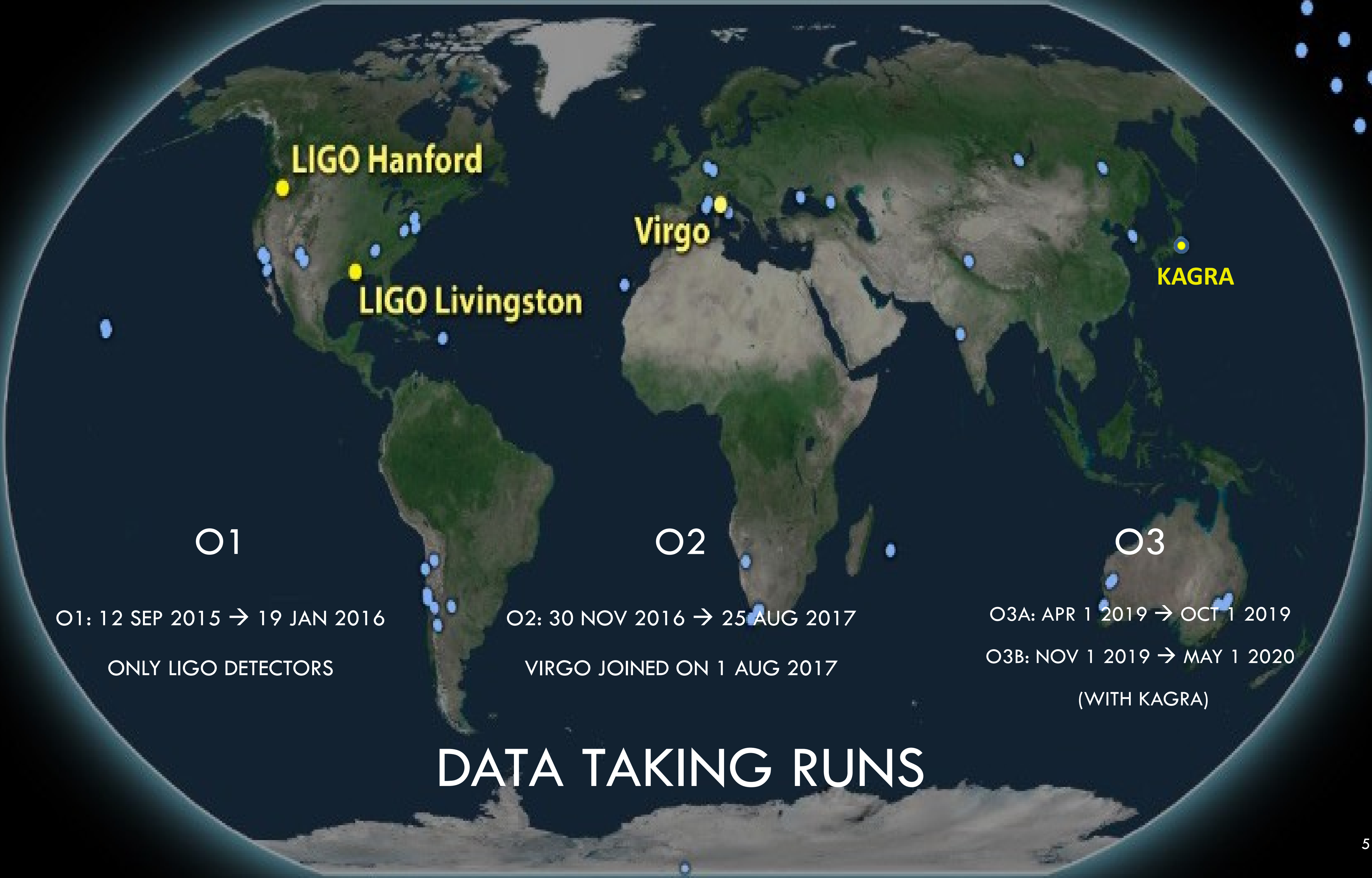
Mirror *geometry/flatness* may change the optical gain and, thus, the **SHOT NOISE**

RADIATION PRESSURE and **SUSPENSION THERMAL** noises depend on mirror *pendulum and mass*

Mid-frequency range dominated by *coating* **THERMAL NOISE**

Aberrations depend on coating absorption (thermal lensing) and substrate inhomogeneity

Scattered light from flatness/roughness



DATA TAKING RUNS

O1

O1: 12 SEP 2015 → 19 JAN 2016

ONLY LIGO DETECTORS

O2

O2: 30 NOV 2016 → 25 AUG 2017

VIRGO JOINED ON 1 AUG 2017

O3

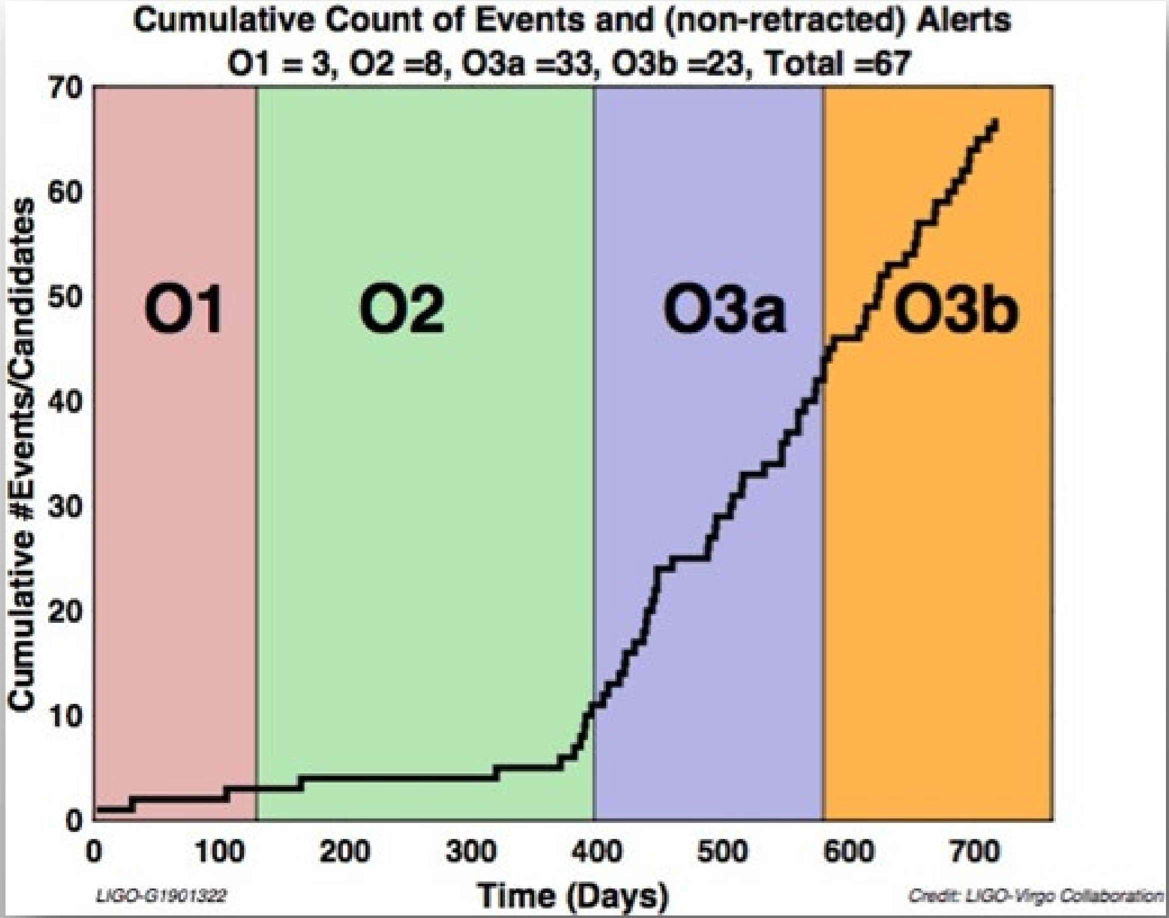
O3A: APR 1 2019 → OCT 1 2019

O3B: NOV 1 2019 → MAY 1 2020

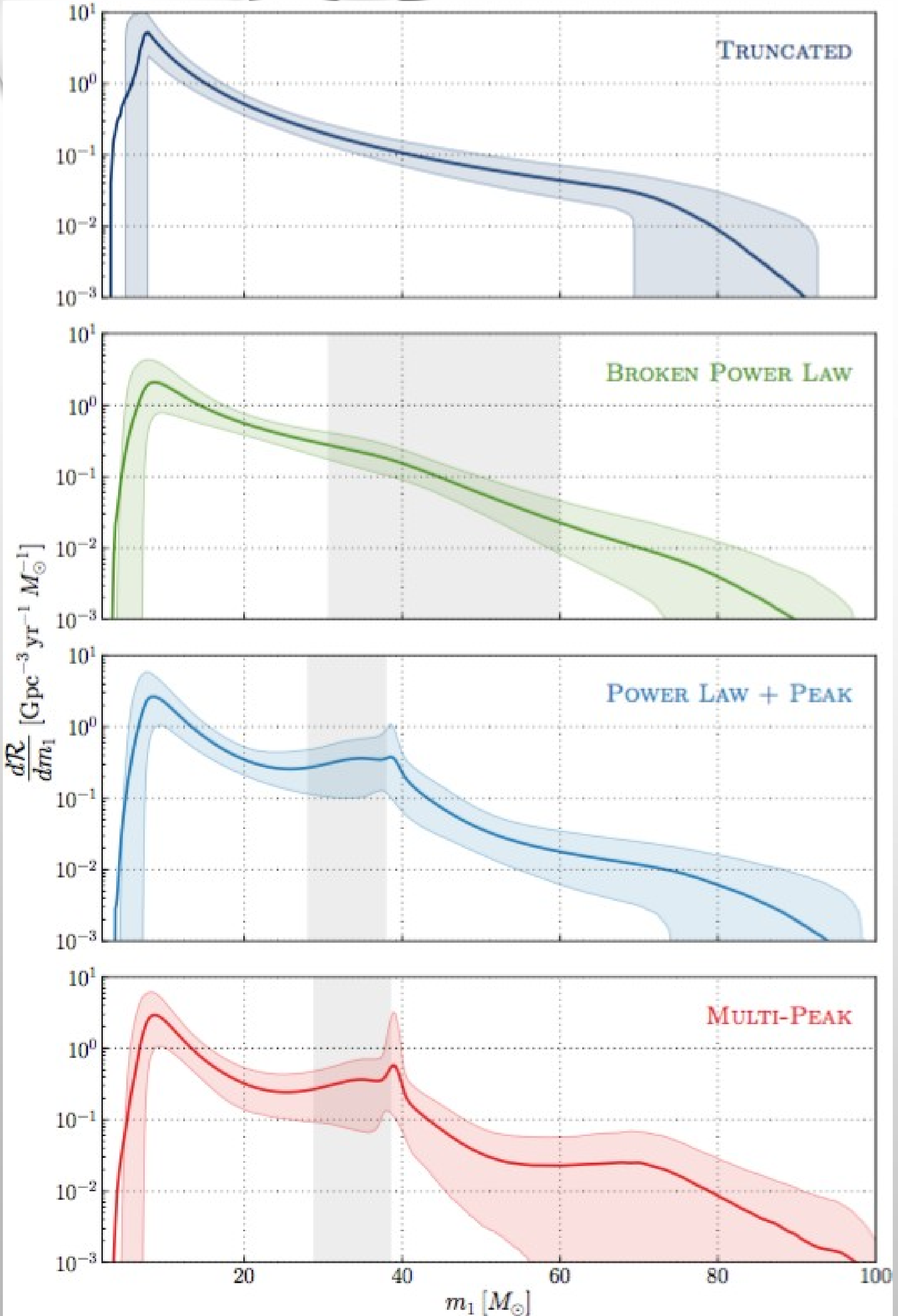
(WITH KAGRA)

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

O3 RESULTS



- 🏳 SIGNIFICANT IMPROVEMENT OF THE DETECTION RATE!
- 🏳 MORE DISTANT SOURCES DETECTED (Z ~ 0.5 → ~ 0.8)
- 🏳 6 NEW EXCEPTIONAL EVENTS PUBLISHED
- 🏳 BH POPULATION STUDIES
- 🏳 UPPER LIMITS ON SEVERAL SOURCES AND PHYSICAL EFFECTS (I.E. GW BACKGROUND, LENSING, SPECIFIC DARK MATTER CANDIDATES)



GWTC-2 (Second GW Transient Catalog): STATISTICS, POPULATION STUDIES

- What is the minimum mass of a BH?
- Does the merger rate evolve with z?
- Are there structures in the distribution of masses ?

Population Properties of Compact Objects from the Second LIGO–Virgo Gravitational-Wave Transient Catalog, LIGO and Virgo Collaborations , The Astrophysical Journal Letters, Vol 913, n. 1 (2021)

Next data takings will give us more useful data:

~ hundreds of events in O4
~ 1000 events for O5

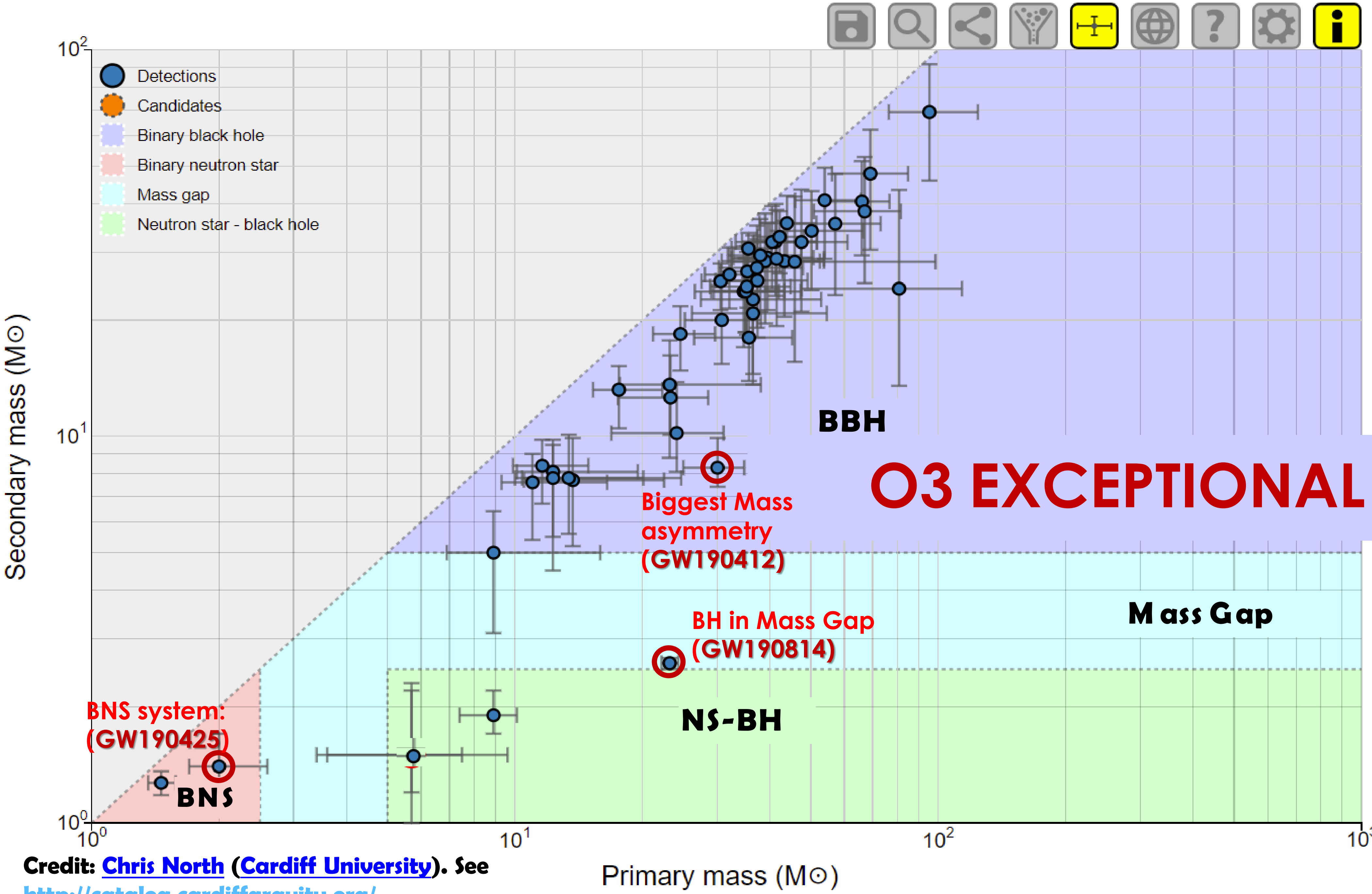
O3 EXCEPTIONAL EVENTS (1)

GW190412: first observation of a BBH with unequal masses: 8.3 and 30.1 Solar masses
Biggest Mass asymmetry → observable GW beyond the leading quadrupolar order
[Abbott et al. (LIGO/Virgo Coll.), Phys. Rev. D 102, 043015]

GW190814: the most asymmetric mass ratio merger ever observed (m1/m2 = 9)
The secondary mass of 2.6 Solar Masses lies in the lower **'mass gap'** either the lightest BH or the heaviest NS ever observed
[Abbott et al (LIGO/Virgo Coll.), ApJL 896 L44]

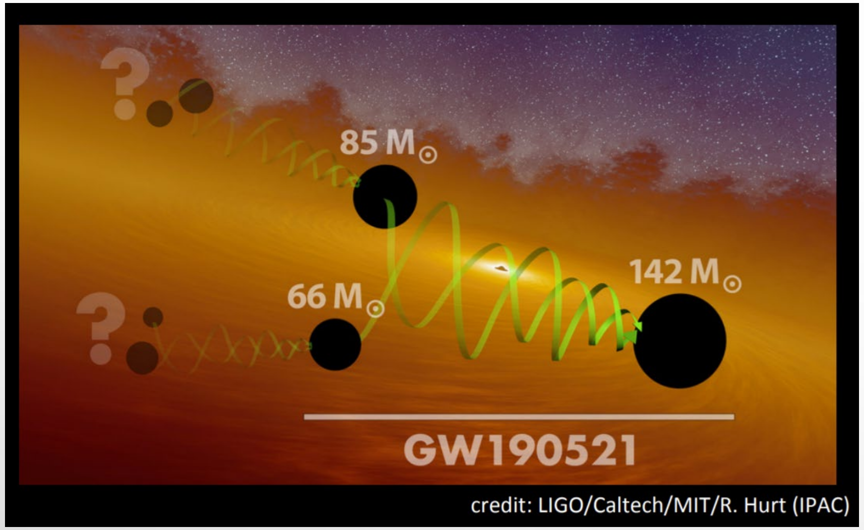
GW190425: BNS merger of total mass of ~3.4 Solar Masses: 2 and 1.4 Solar Masses
Significantly larger than any other known **BNS** system, no EM counterpart
[Abbott et al (LIGO/Virgo Coll.) ApJL 892 L3]

O3 EXCEPTIONAL EVENTS

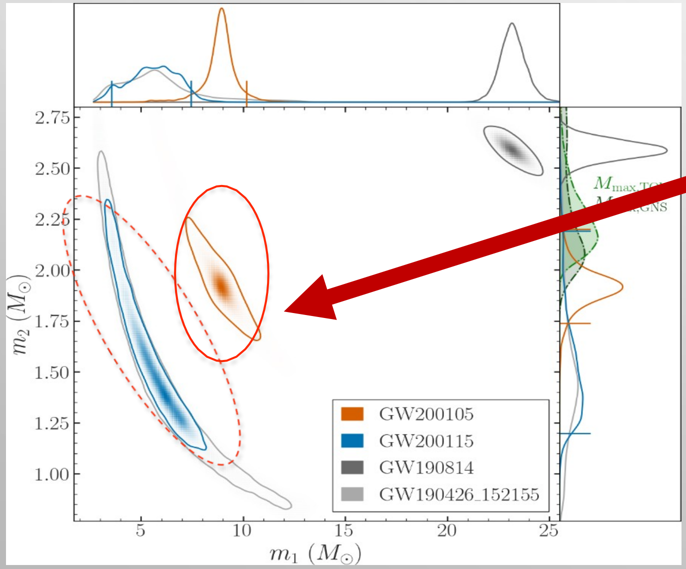


Credit: Chris North (Cardiff University). See http://catalog.cardiffgravity.org/

O3 EXCEPTIONAL EVENTS (2)

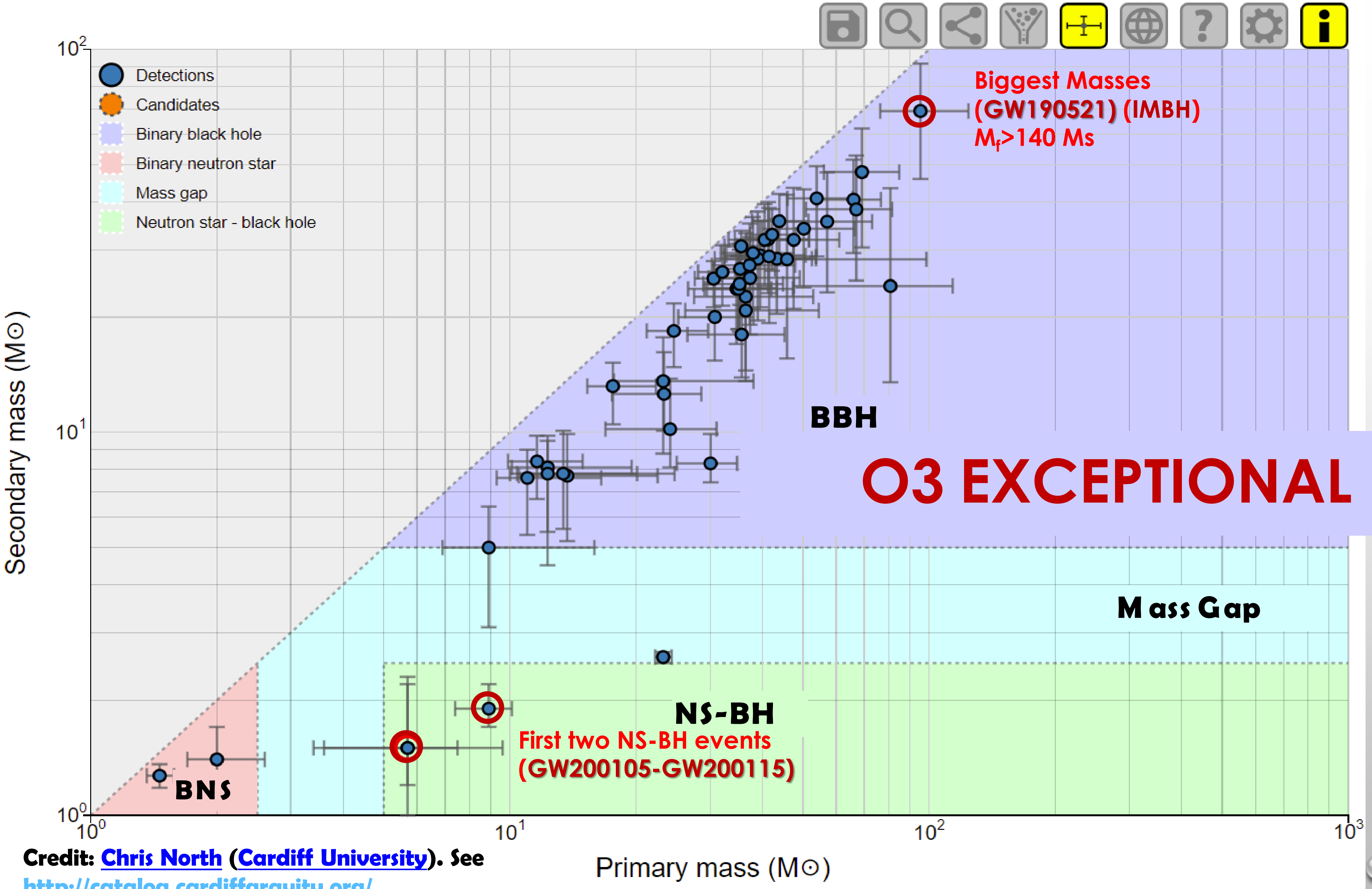


GW190521: BBH with component masses ~66 and 85 Solar masses
First observation of an **intermediate mass BH**(**IMBH**) formation (Mf ~ 142 Solar Masses).
Farthest source so far (z ~ 0.8)
[Abbott et al (LIGO/Virgo Coll.) Phys. Rev. Lett. 125, 101102]



GW200105-GW200115: 1st certified detection of NSBH (2 events)
[Abbott et al (LIGO/Virgo/KAGRA Coll.) ApJL 915 L5]

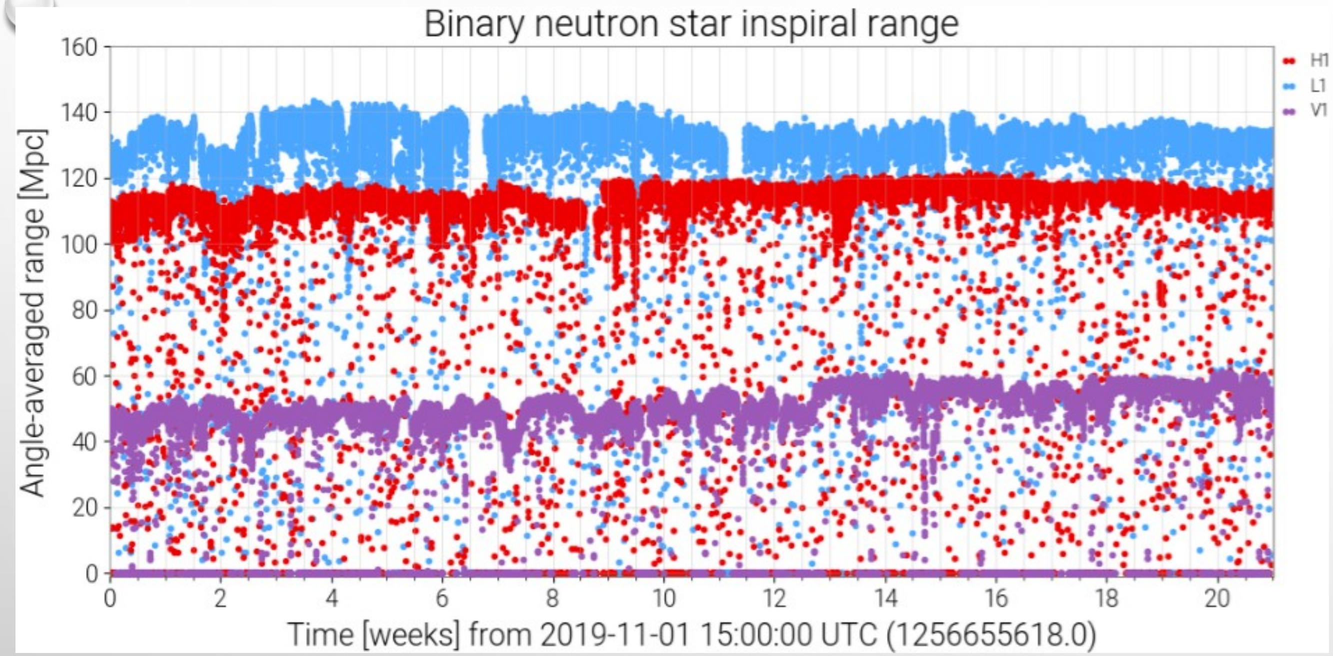
O3 EXCEPTIONAL EVENTS

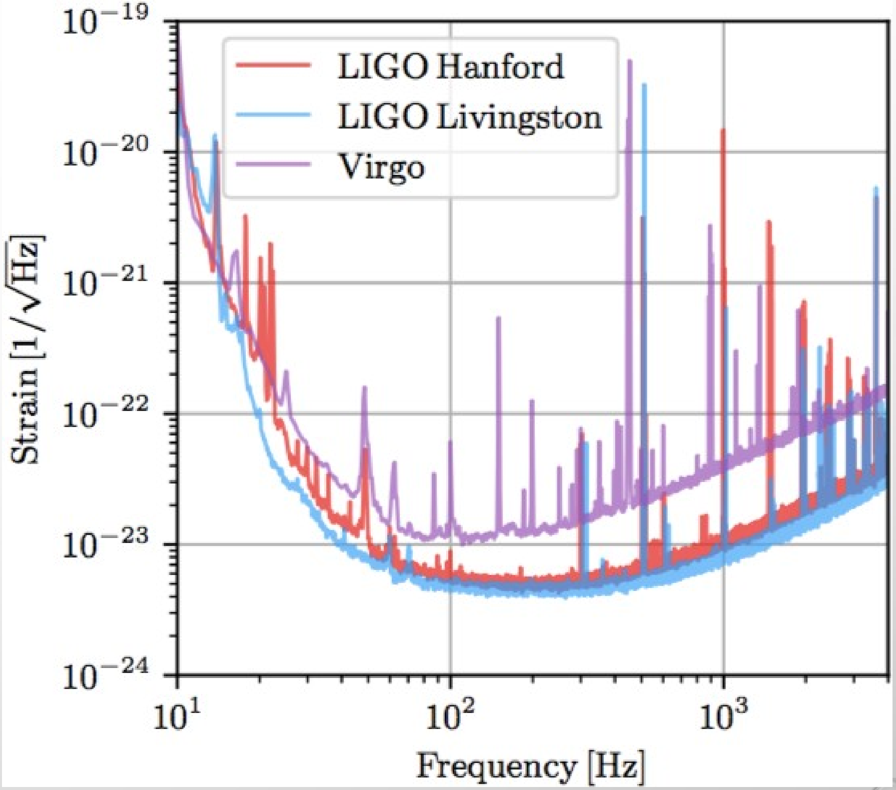


Credit: [Chris North](#) ([Cardiff University](#)). See http://catalog.cardiffgravity.org/

O3 : LIGO/VIRGO PERFORMANCES

April 2019 → March 2020 (1 month before the expected date because of the the COVID pandemic)



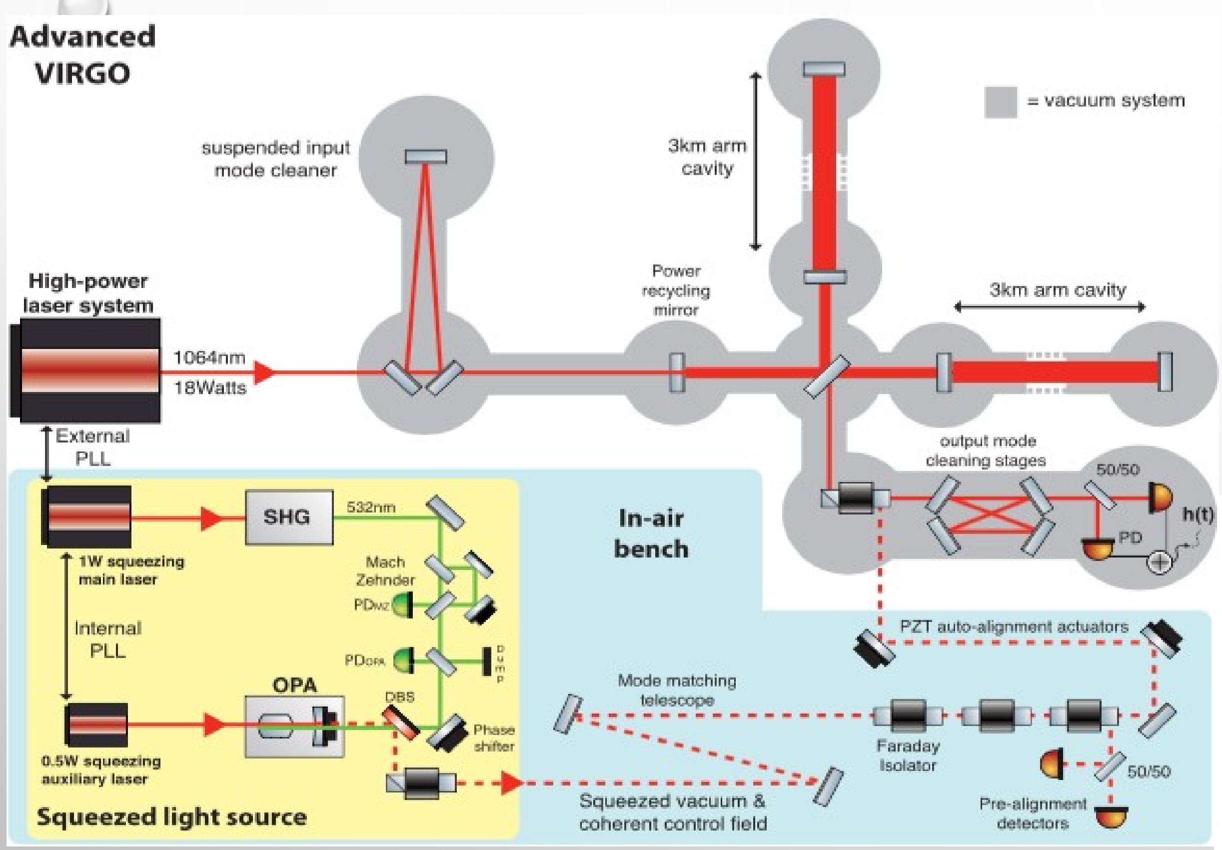


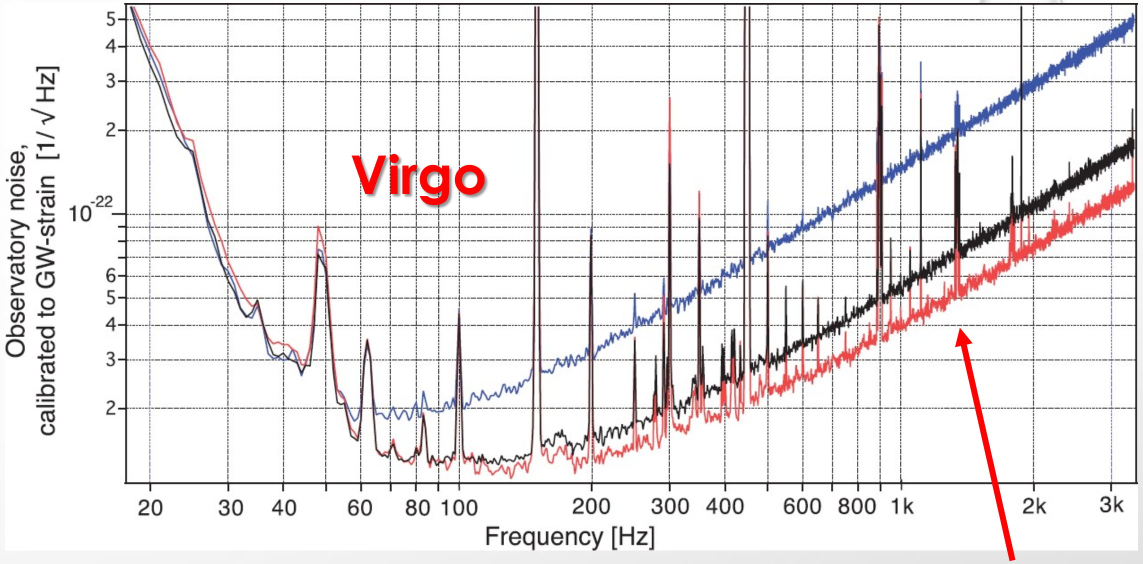
L1: 120-140 Mpc
H1: 110-120 Mpc
Virgo: 50 to 60 Mpc

Duty cycle

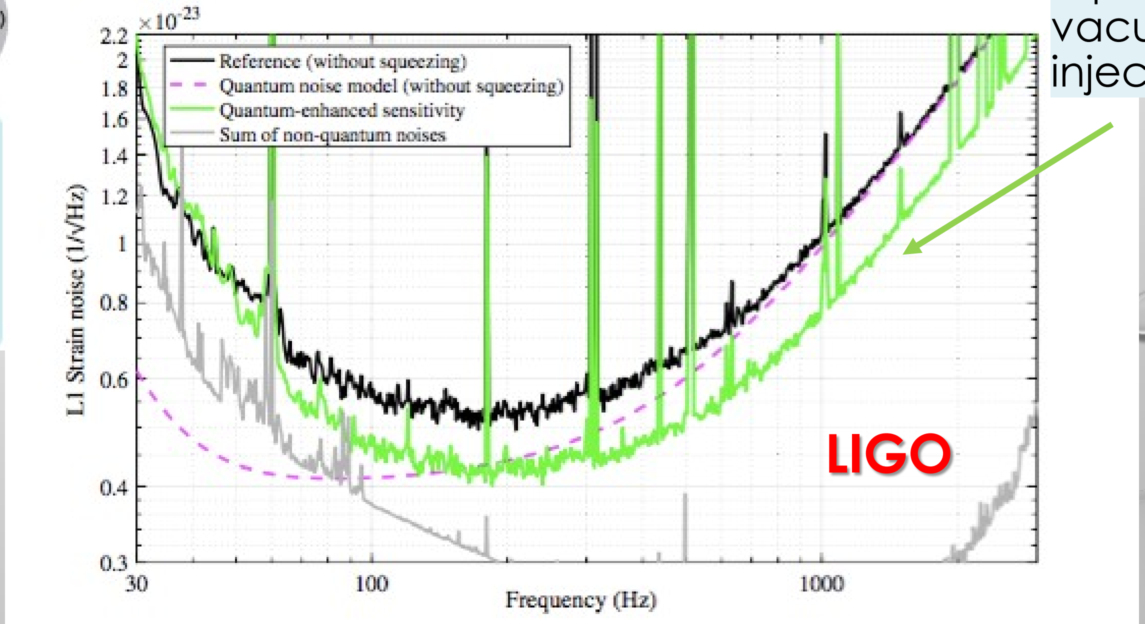
47% of the time 3 detectors
83% of the time at least 2 detectors

SQUEEZING IN VIRGO AND LIGO DURING O3





Squeezed vacuum injected



F. Arcenese, et al. (Virgo Collaboration), Phys. Rev. Lett. 123, 231108 (2019)

M. Tse *et al.*, Phys. Rev. Lett. 123, 231107 (2019)

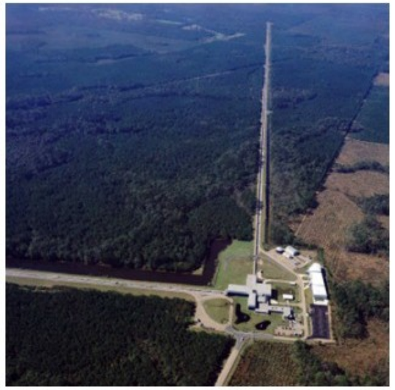
Gravitational Wave Open Science Center

Data ▾ Software ▾ Online Tools ▾ About GWOSC ▾

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

LIGO Hanford Observatory, Washington

(Credits: C. Gray)



LIGO Livingston Observatory, Louisiana

(Credits: J. Giaime)

Virgo detector, Italy

(Credits: Virgo Collaboration)

- **GW200105 and GW200115 event data available!**
- **New Event Portal Query Page!**
- **O3 IMBH marginal event data available!**
- **O3a data available!**
- **Begin with a Learning Path**
- **Download data**
- **Join the email list**
- **Open Data Workshops**

OPEN DATA [WWW.GW-OPENSCIENCE.ORG](http://www.gw-openscience.org)

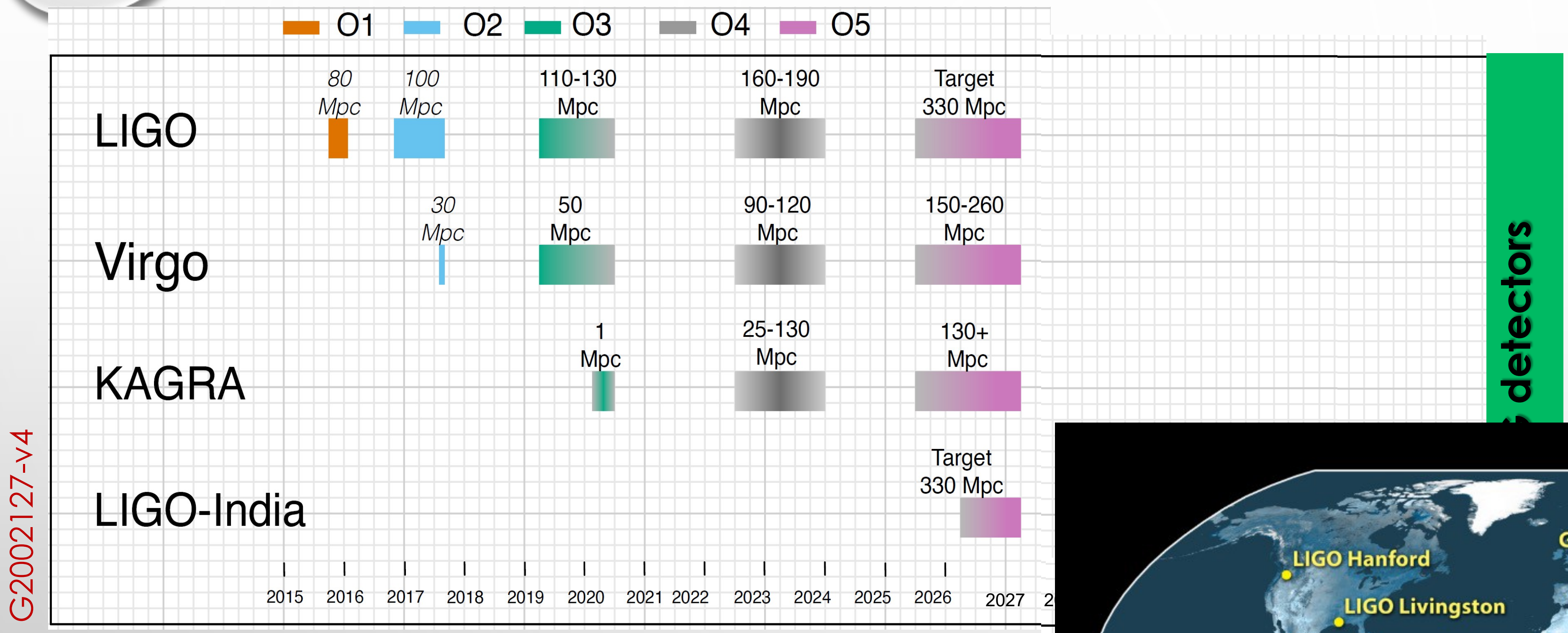
Open data from the first and second observing runs of Advanced Virgo and Advanced LIGO, Software X, SoftwareX 13 (2021) 10065

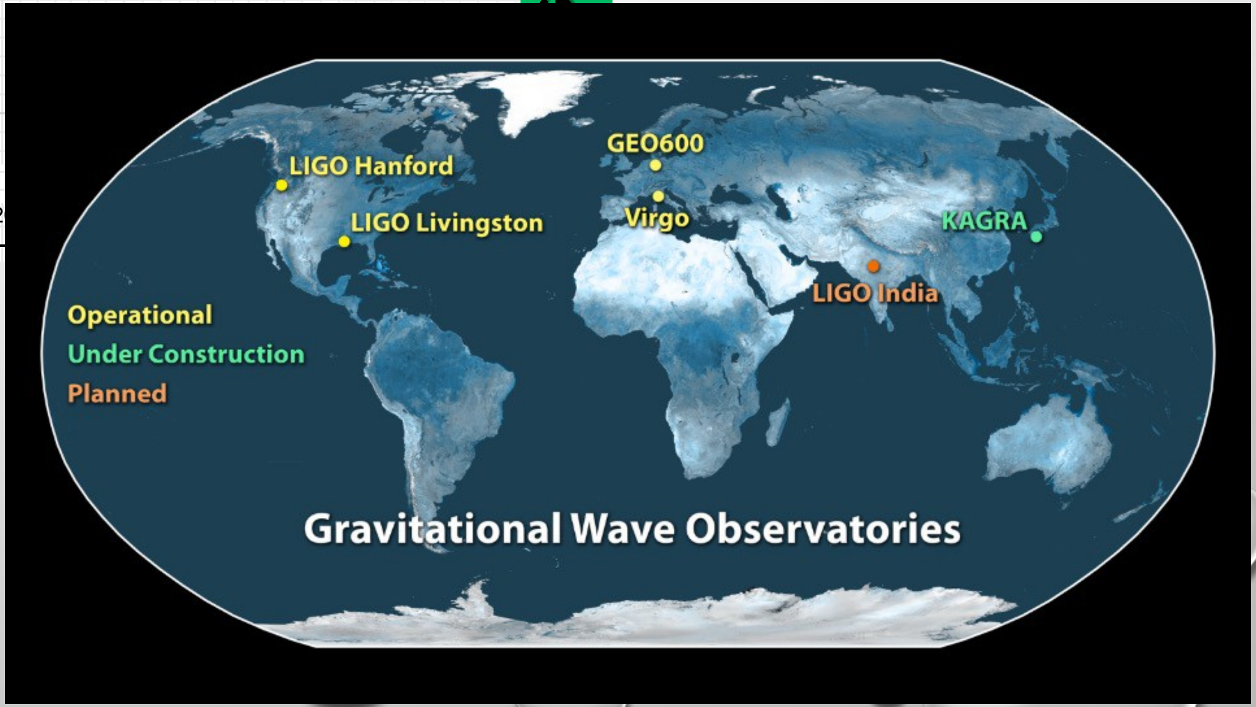
1-hour time-series data around each event

Also contains:

- Pointers to analysis software tools;
- Materials from Open Data Workshops;
- Online tutorials

MIDTERM PLANS (UNTIL 2027)





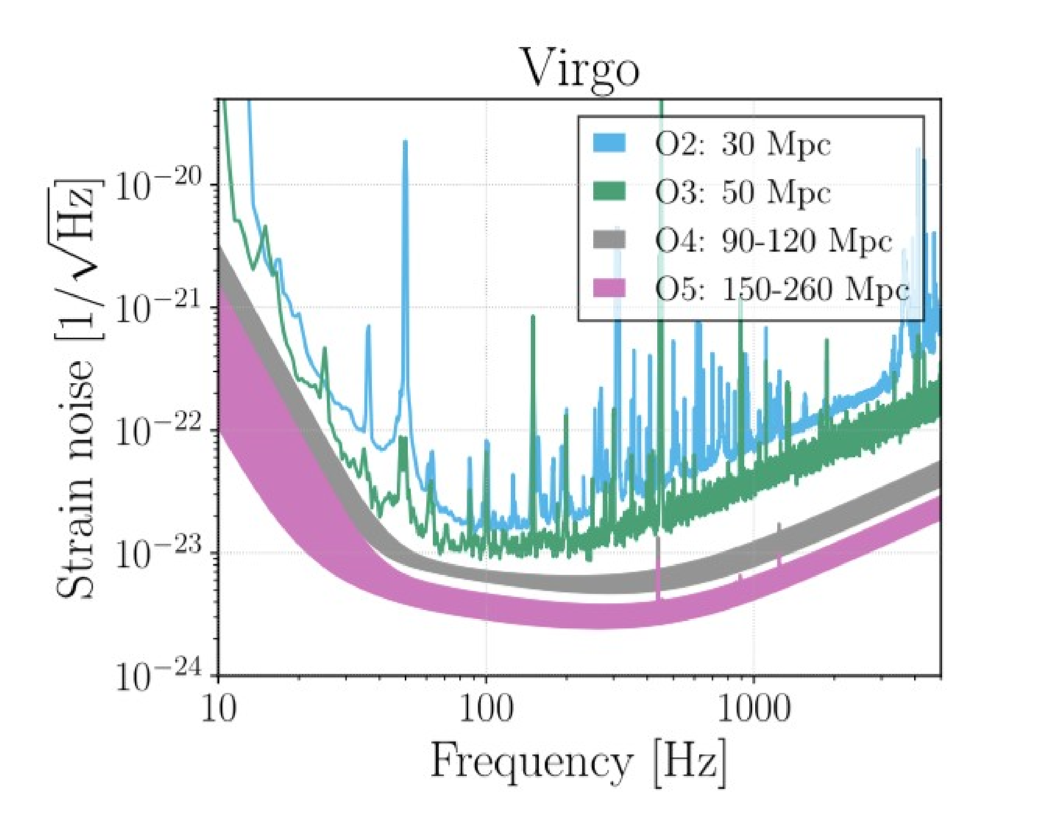
- KAGRA has joined the network in O3b
- Ligo/Virgo are being upgraded (A+/AdV+)
- Ligo India will join the network in ~202?

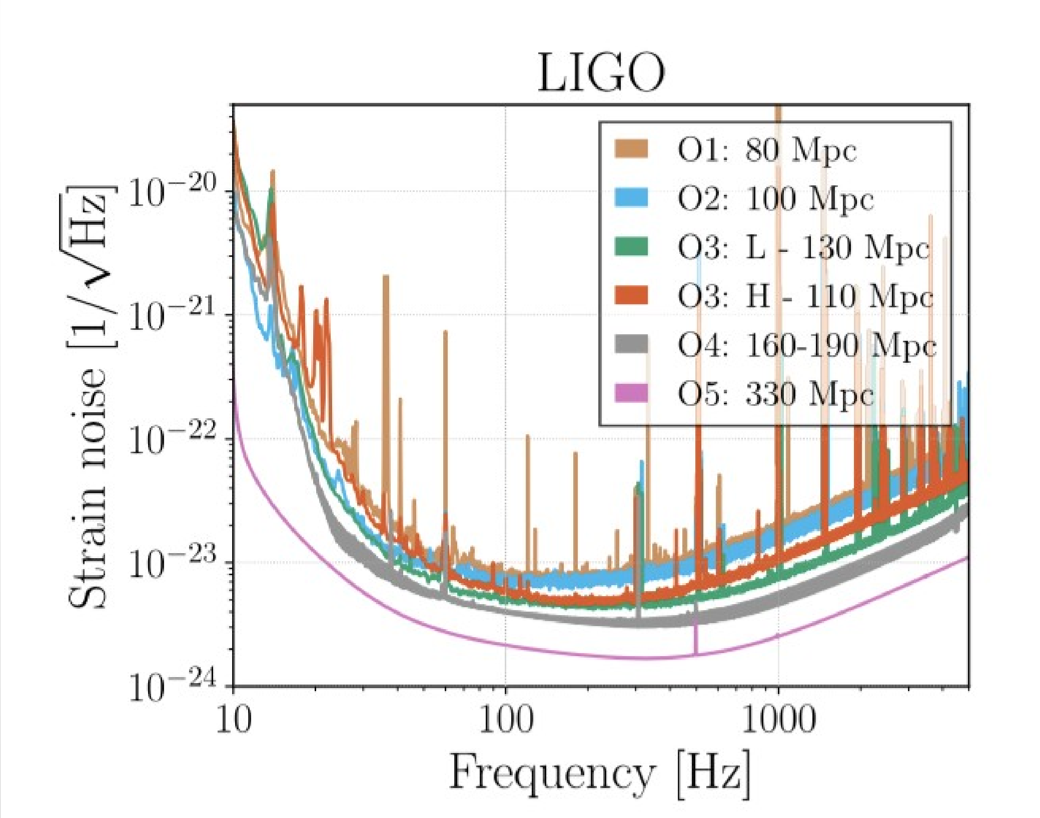
ADV+/A+

Virgo has a phased plan to increase its sensitivity: AdV+

- Phase 1: BNS range from 60 Mpc (O3) to 90-120 Mpc (O4)
- Phase 2: BNS range 150-260 Mpc (O5)

Similar upgrade for Advanced Ligo (A+)





ADV+

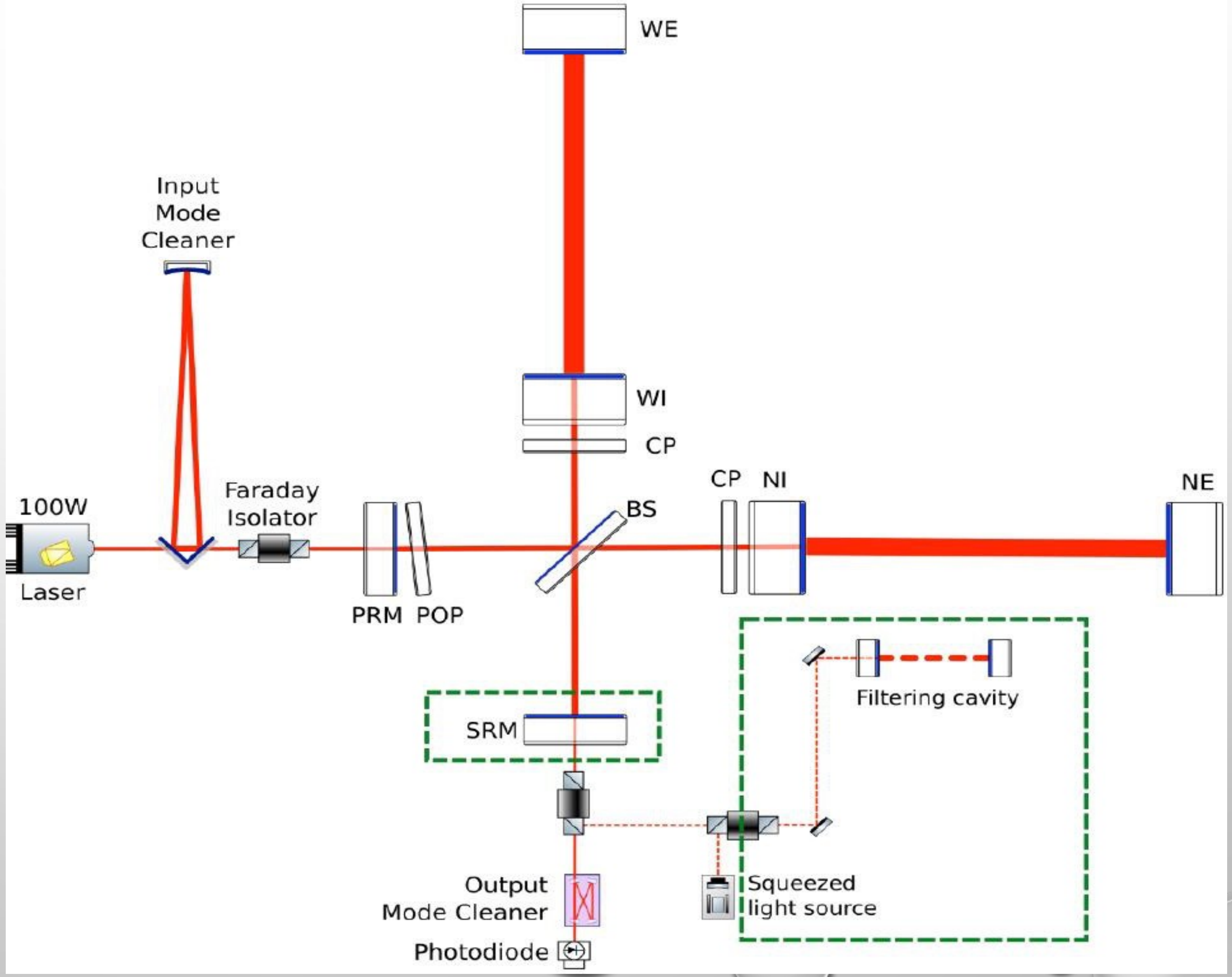
PHASE 1

QUANTUM NOISE REDUCTION:

- LASER POWER INCREASE

25 W → 40 W (already on O3b)

- SIGNAL RECYCLING
- FREQUENCY DEPENDENT SQUEEZING



ADV+

PHASE 2 (O5)

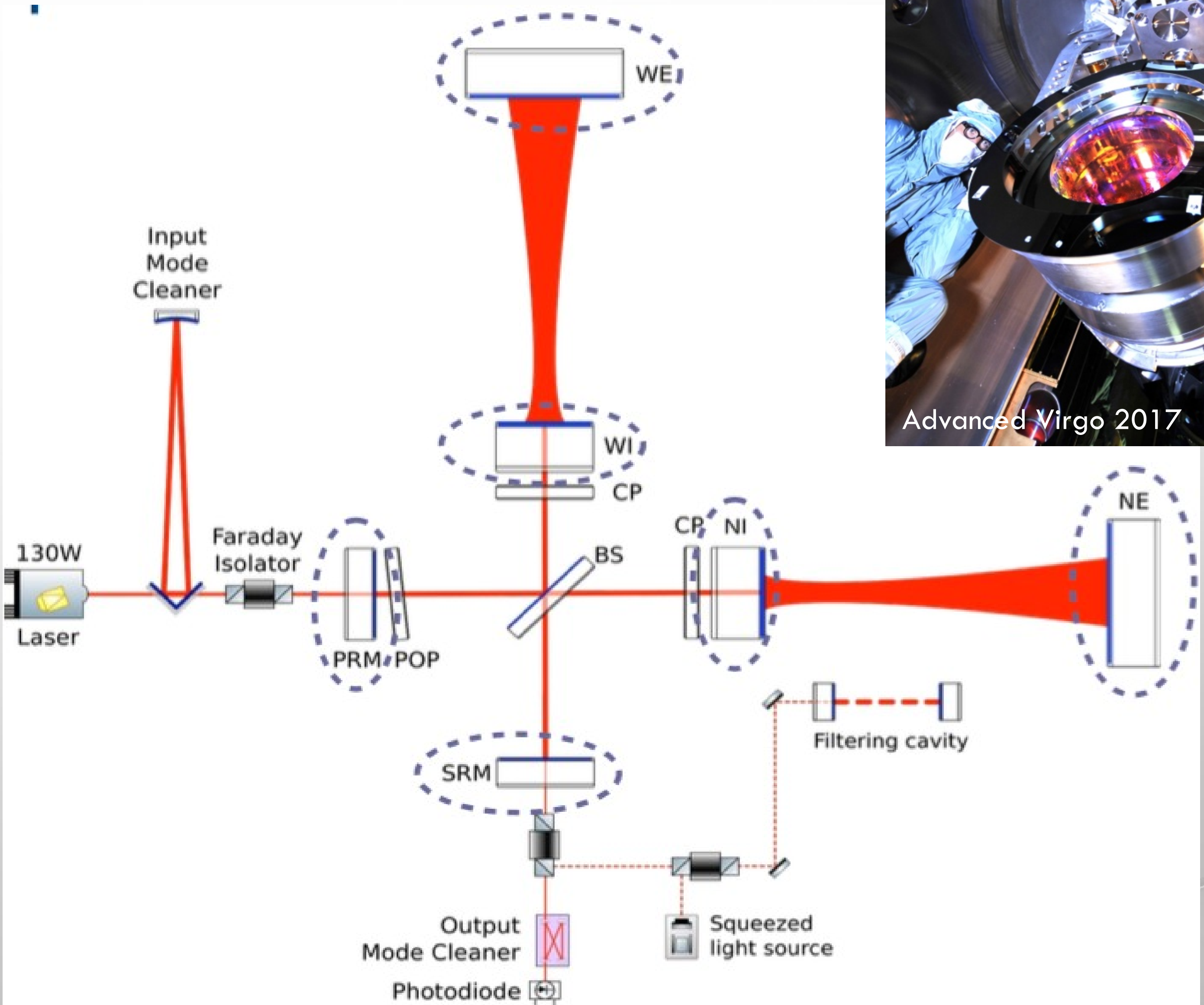
<u>*QUANTUM NOISE REDUCTION:*</u>

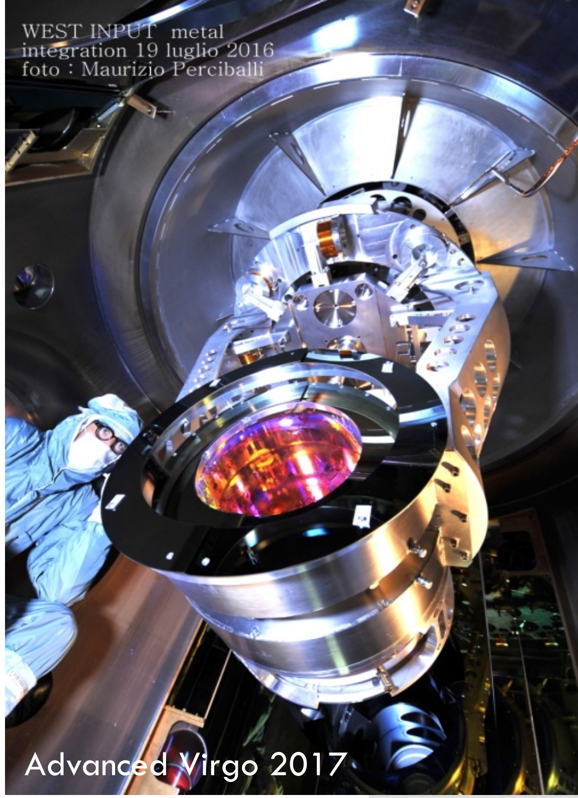
- LASER POWER INCREASE

40 W → 80 W

<u>THERMAL NOISE REDUCTION</u> LARGE END MASSES (ETM 40→100 kg)

- BIGGER BEAM SIZE ON ETM (5→10 cm)
- IMPROVEMENT OF COATING MECHANICAL AND OPTICAL LOSSES OF ALL THE TM (R&D)

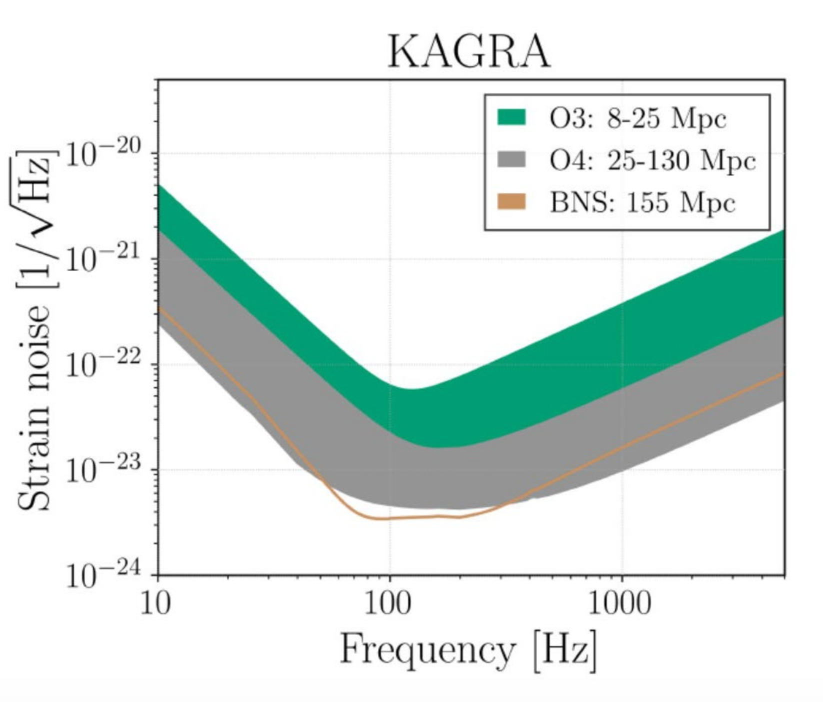




KAGRA+

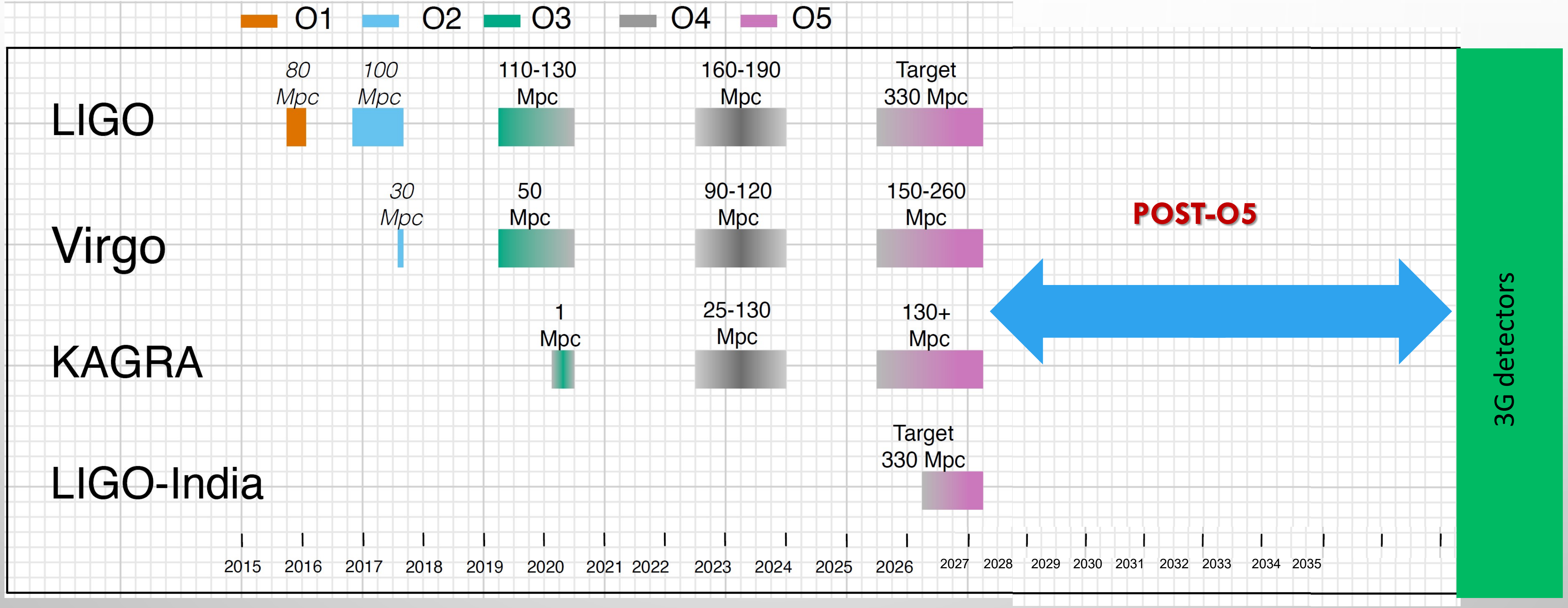
KAGRA
- Sapphire mirrors (23 kg)
- 20 K
- Hosted in the Kamioka mine, Gifu prefecture

Kagra+
- Large Sapphire masses (100 kg)
- FD Squeezing (5 dB)
- High power (3.5 kW on BS)



Y. Michimura et al., [PRD 102, 022008 (2020)]

PLANS FOR THE FUTURE



FROM PRESENT TO 3G

GWIC

- GWIC Mission: ***facilitate international collaboration and cooperation in the construction, operation and use of the major gravitational wave detection facilities world-wide***

https://gwic.ligo.org

Subcommittee to look at the 3G in a coordinated way

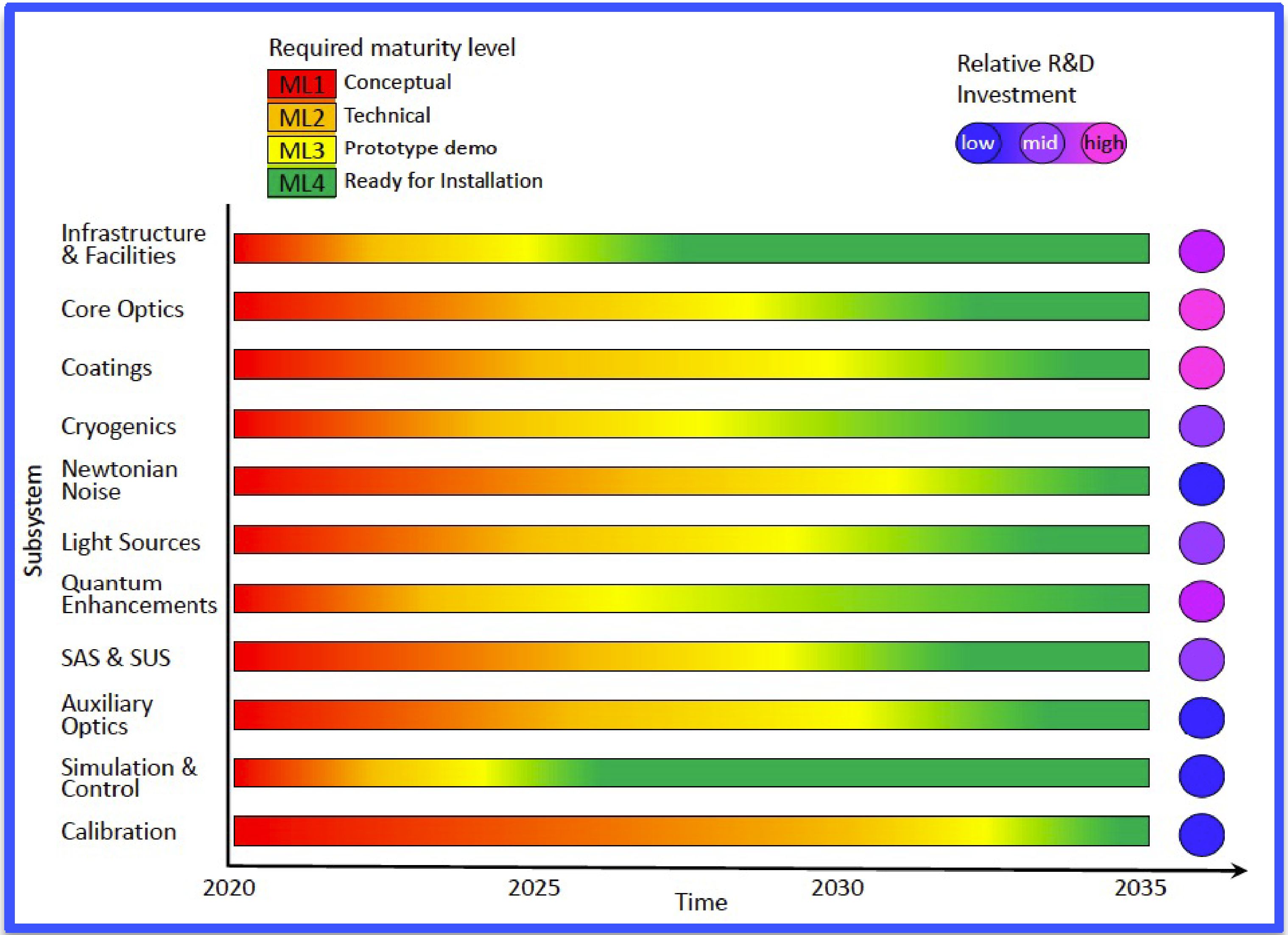
- D Reitze, M Punturo co-chairs

6 study groups

- 3G Science Case
- R&D Coordination
- Community Networking
- Agency Interfacing
- Investigation of Governance Structures
- Computing (added September 2018)

The GW community is engaged in a coherent effort to develop 3G

Technology Readiness Roadmap



D. Reize, talk on GWIC at 2nd EPS Meeting on Gravitation

POST-O5 STUDY GROUPS IN LIGO AND VIRGO

CHAIRS: PETER FRITSCHEL (MIT) FOR LIGO, VIVIANA FAFONE (ROME 2) AND SAMAYA NISSANKE (UVA) FOR VIRGO

- **DELIVERABLES:**
  - **Report** assessing the **scenarios** and makes **recommendations** that can form the basis for proposing an upgrade project to be implemented **after A+/ADV+**
  - Report to be shared with the funding agencies
- **TIMELINE & PROCESS**
  - The group engages widely the LSC/VIRGO groups
  - Workshop by the end of 2022
- **REQUESTS TO ASSES:**
  - Implementations of design choices and technologies to improve sensitivity
  - **Technical readiness** of the options and **needed R&D's**
  - **Balance of the observing time against improved sensitivity**

Options for upgrades for A+/AdV+

- Improvements to **seismic isolation and mirror suspensions** upgrades: to improve the low frequency sensitivity

- Continued improvements to **squeezed ligth** injection → 10 dB (also for 3G)
  - Ligo-Voyager designs call for 10 dB

- Interferometer modifications for **better high frequency** sensitivity
  - Increment of input power

- **Larger test masses** (>100 kg): reduce radiation pressure noise below 40 hz
- AlGaAs **crystalline coatings**: another factor 2 lower thermal noise

A COORDINATED WORK

Virgo

Virgo has not been considered a Voyager-like upgrade

- ❑ Similar situation as LIGO in terms of the detector possibilities: upgrades to the extisting 1um room temperature

Fused silica ITF

- ❑ Study of the possibility to include Stable recycling cavities (already in Ligo)

LIGO

- ❑ Ligo is considering a Voyager-like upgrade

LIGO India

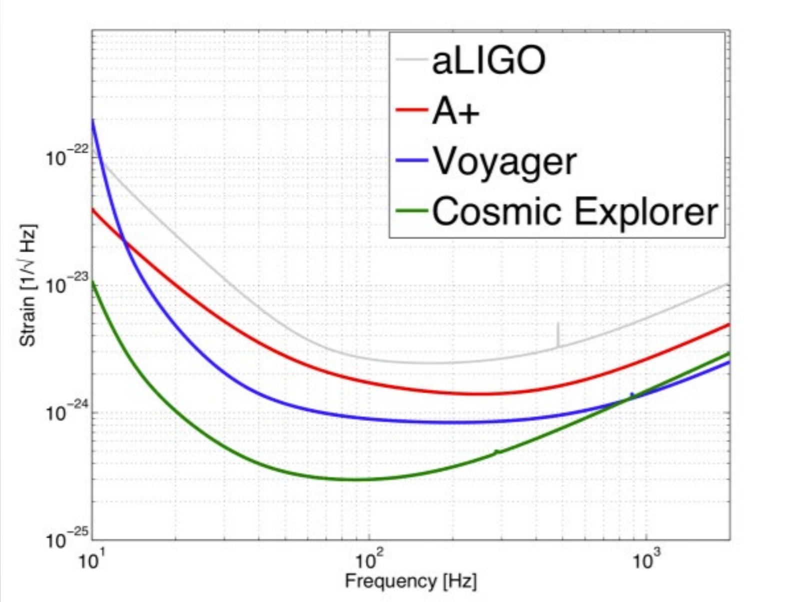
- ❑ Timeline already uncertain…

KAGRA

VOYAGER

- CONCEPT FOR A **NEW DETECTOR IN THE CURRENT FACILITIES;**
- DESIGNED TO MAXIMIZE THE OBSERVATIONAL REACH OF THE INFRASTRUCTURE AND **DEMONSTRATE THE KEY TECHNOLOGIES TO BE USED FOR 3G OBSERVATORIES** IN NEW INFRASTRUCTURES.
- USE **HEAVY (CA. 200 KG) CRYOGENIC MIRRORS** WITH **IMPROVED COATINGS** AND UPGRADED SUSPENSIONS MADE OF **ULTRA-PURE SILICON AT A TEMPERATURE OF 123 K**
- USE THE EXISTING VACUUM ENVELOPE
- A LASER WAVELENGTH OF VOYAGER ~ 1.5um – 2um

- **A FURTHER FACTOR OF 3 INCREASE IN BNS RANGE (TO 1100 MPC)** IS ENVISIONED ALONG WITH A REDUCTION OF THE LOW FREQUENCY CUTOFF.



LIGO-T1400316–v4

A Cryogenic Silicon Interferometer for Gravitational-wave Detection, R.Adhikari et al., arXiv:2001.11173

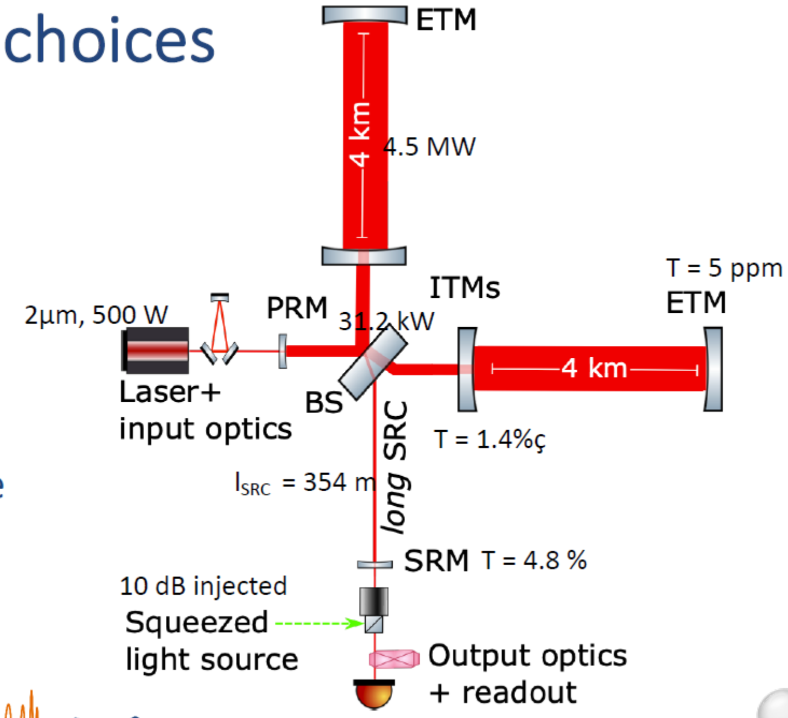
NEMO

NEUTRON STAR ESTREME MATTER OBSERVATORY
A HIGH FREQUENCY DETECTOR

- RECENTLY THE NEMO HAS BEEN PROPOSED BY AUSTRALIAN GROUPS
- IT MAY USE ASPECTS OF VOYAGER TECHNOLOGY, BUT IT IS OPTIMIZED FOR THE KHZ BAND IN ORDER TO MEASURE THE NEUTRON STAR STATE EQUATION OF STATE.

NEMO current design choices

- Test mass weight = 74.1 kg
- Test mass coating : AlGaAs/GaAs*
- ITM = 150 K, ETM = 123 K
- ROC_{ITM} = 1800 m; ROC_{ETM} = 2500 m
- Suspension material : steel*
- Test mass cooling method : radiative



OzGrav

Picture modified from : J. V. van Heijningen, NEMO paper

6

NEMO

NEUTRON STAR ESTREME MATTER OBSERVATORY
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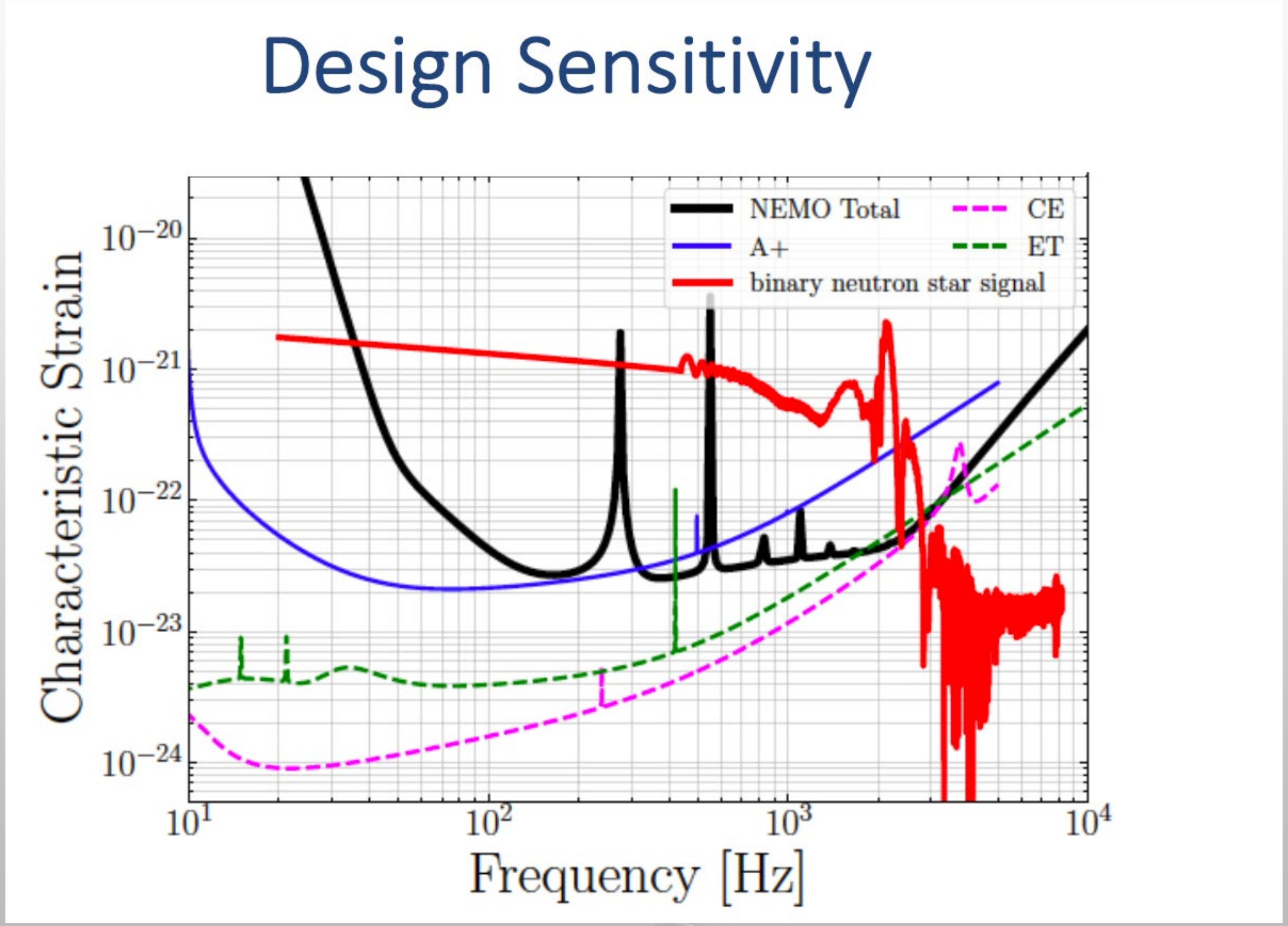
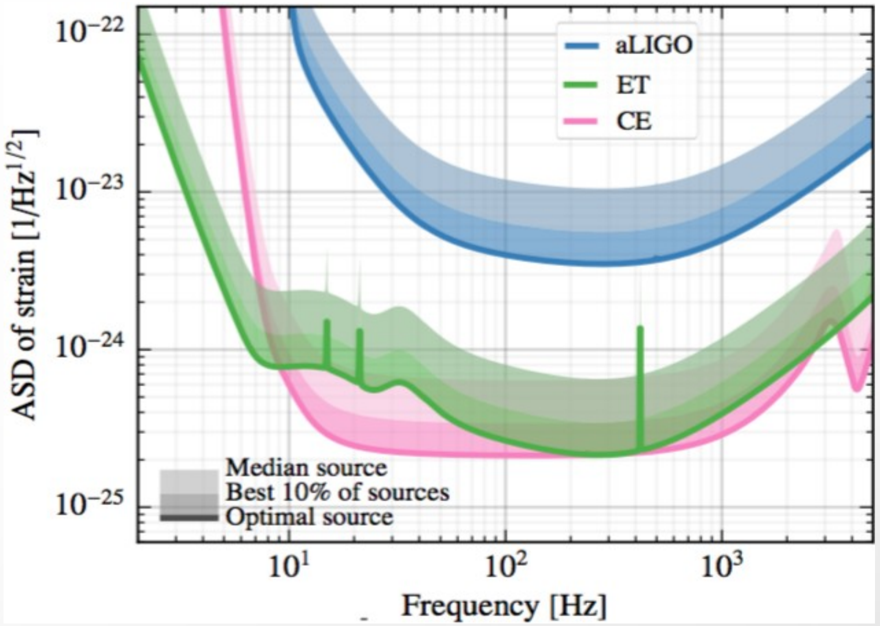


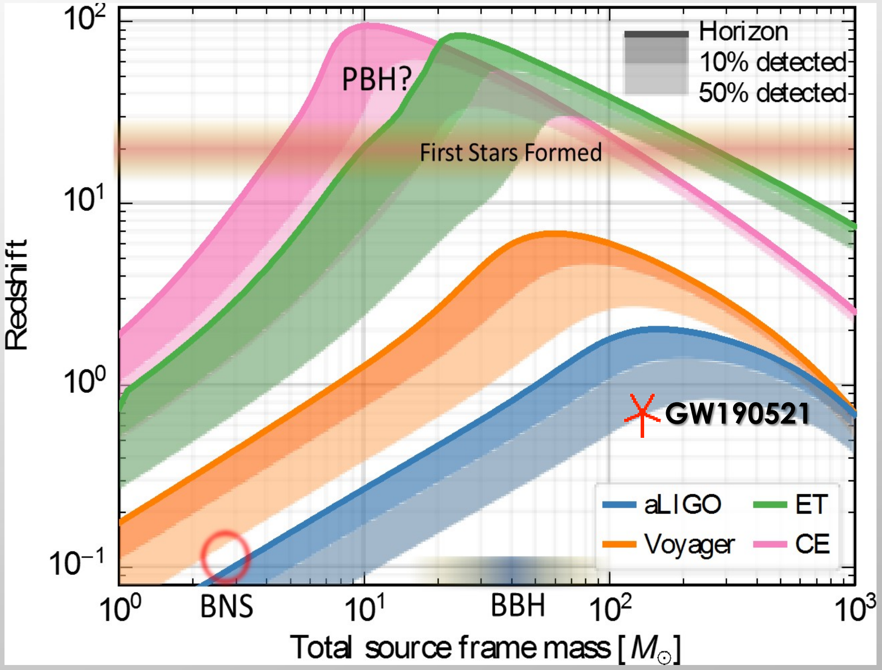
G3 DETECTORS SCIENCE

Factor 10 better (X1000 Volume) than 2G detectors
LF sensitivity improvement (1 Hz target)

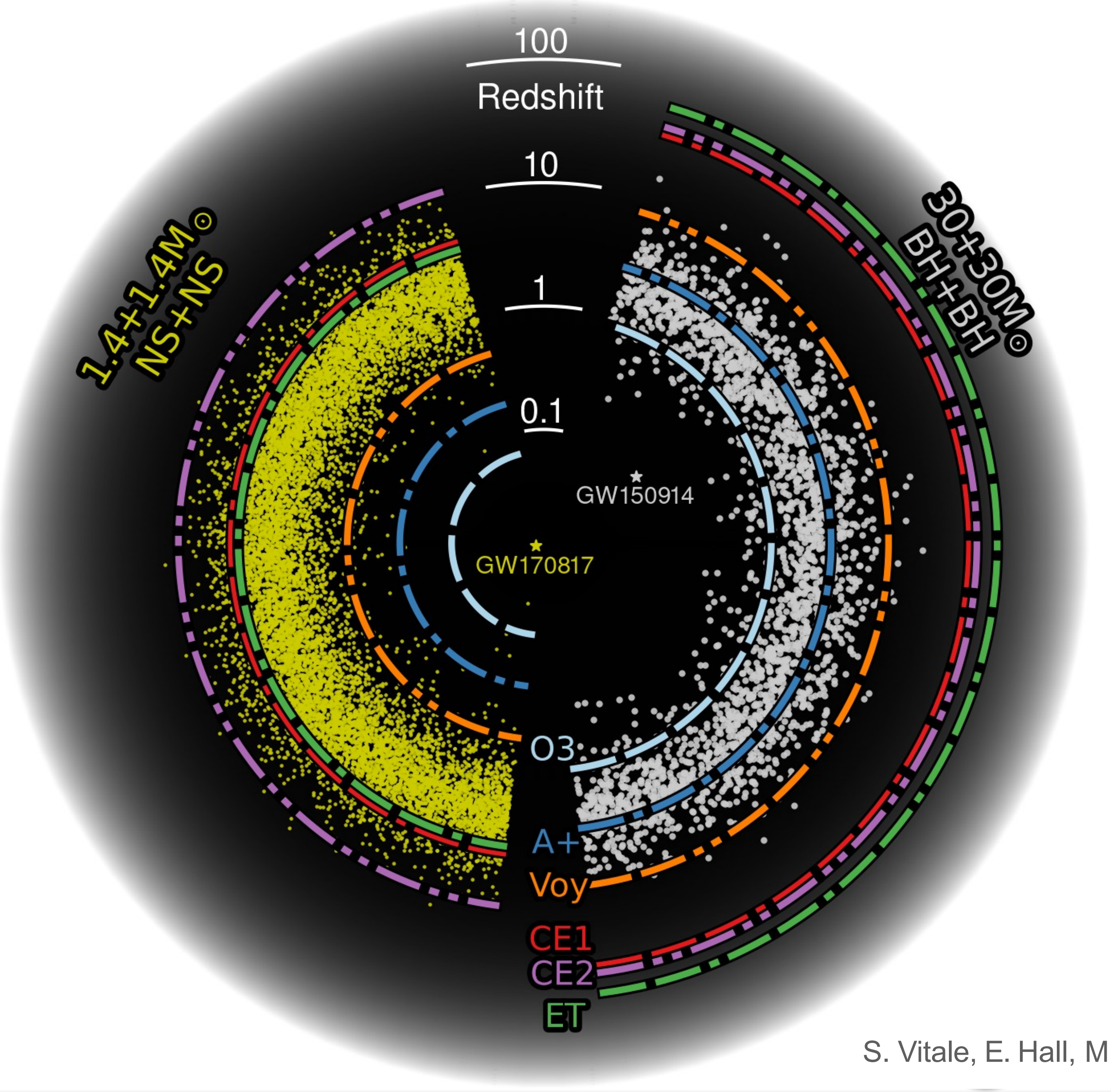
- Black-holes formation/ population studies
- Fundamental physics / nature of gravitation
- Cosmology / nature of dark energy
- Nuclear physics / ultra-dense matter
- Physics of Supernovae
- Multimessenger astrophysics
- Complementarity and synergies with LISA

https://arxiv.org/pdf/1912.02622
ET science case





Extreme matter
Extreme universe
Extreme gravity



S. Vitale, E. Hall, MIT

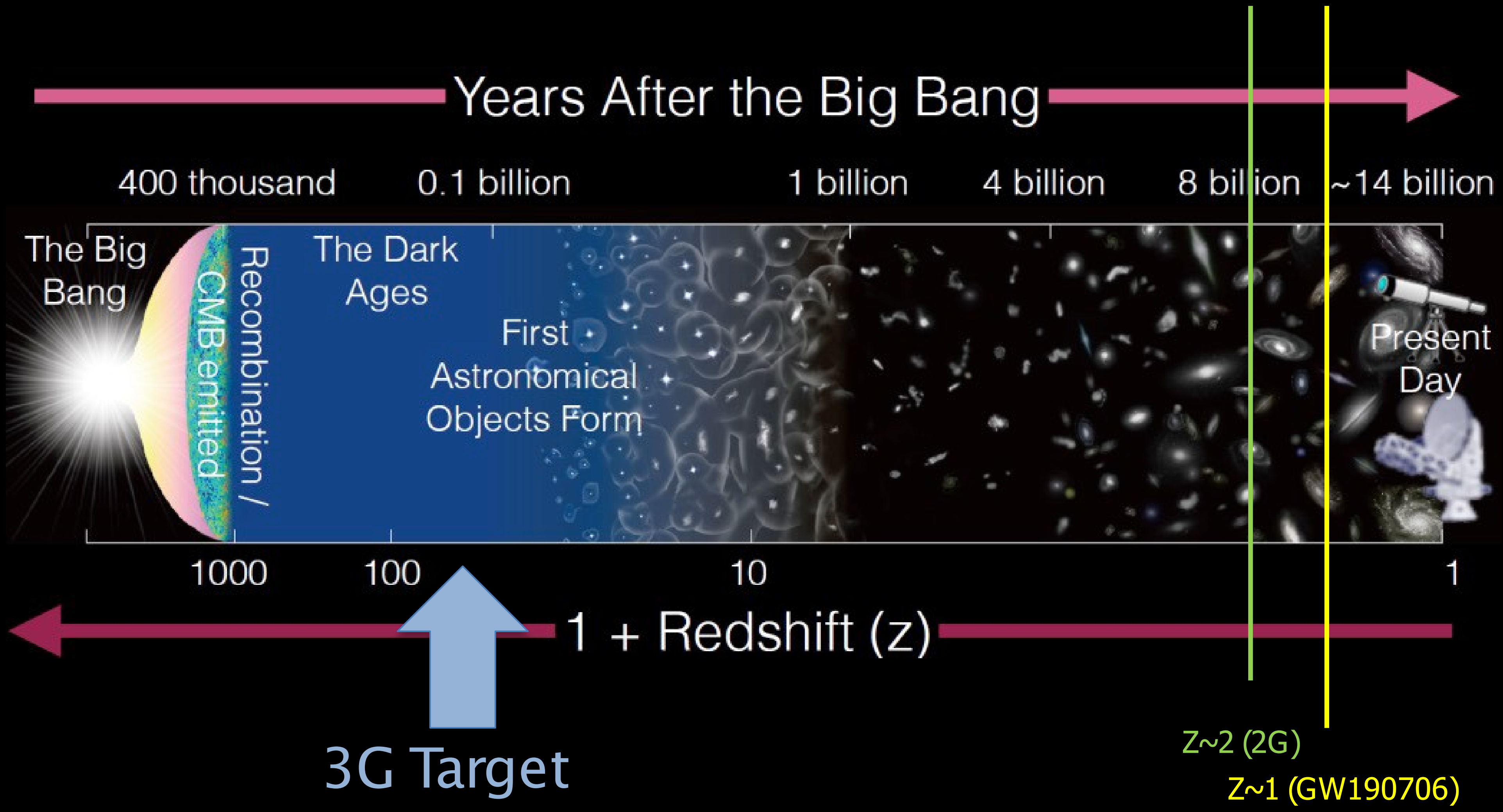
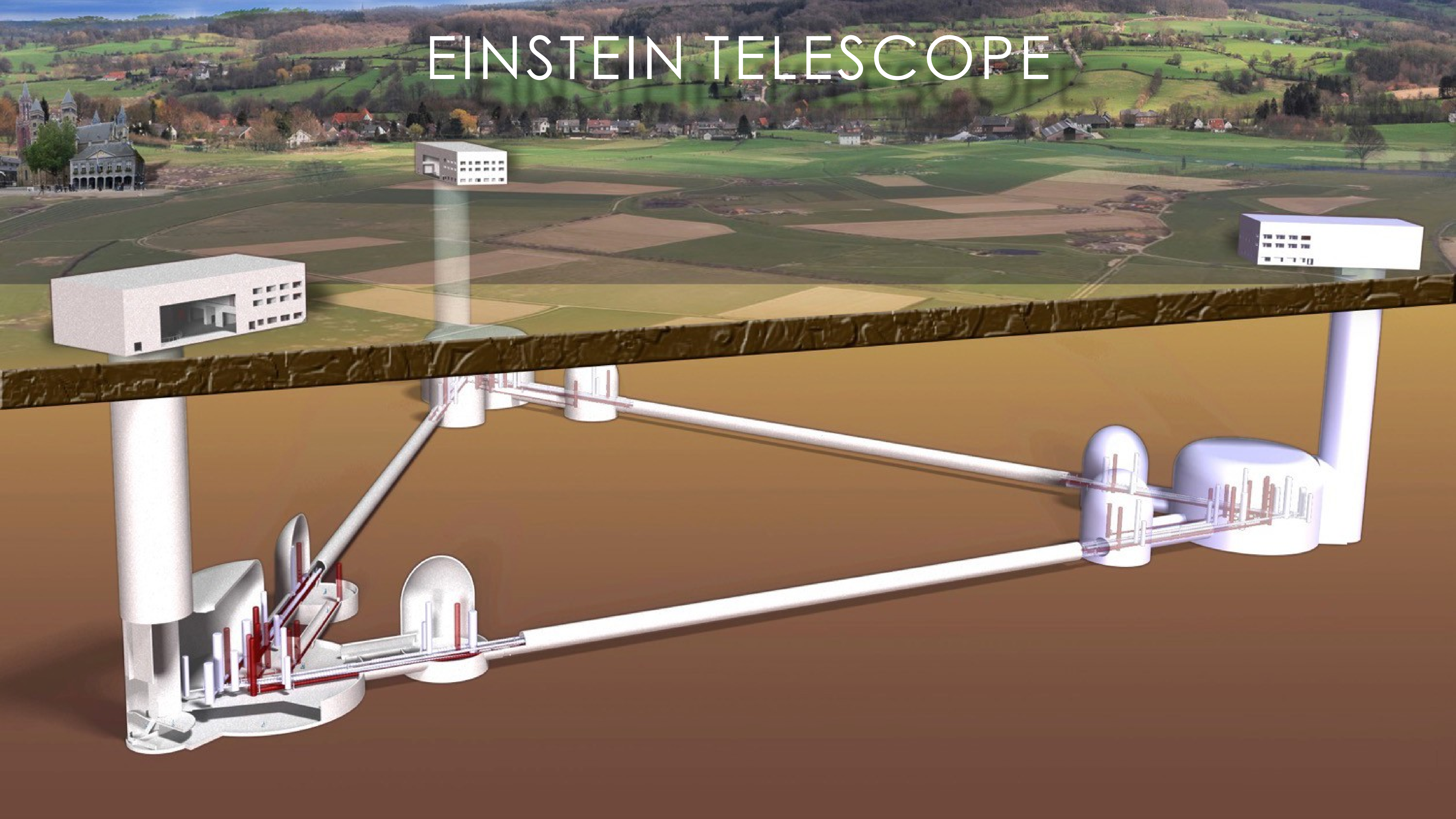


Image credit: NAOJ/ALMA http://alma.mtk.nao.ac.jp/

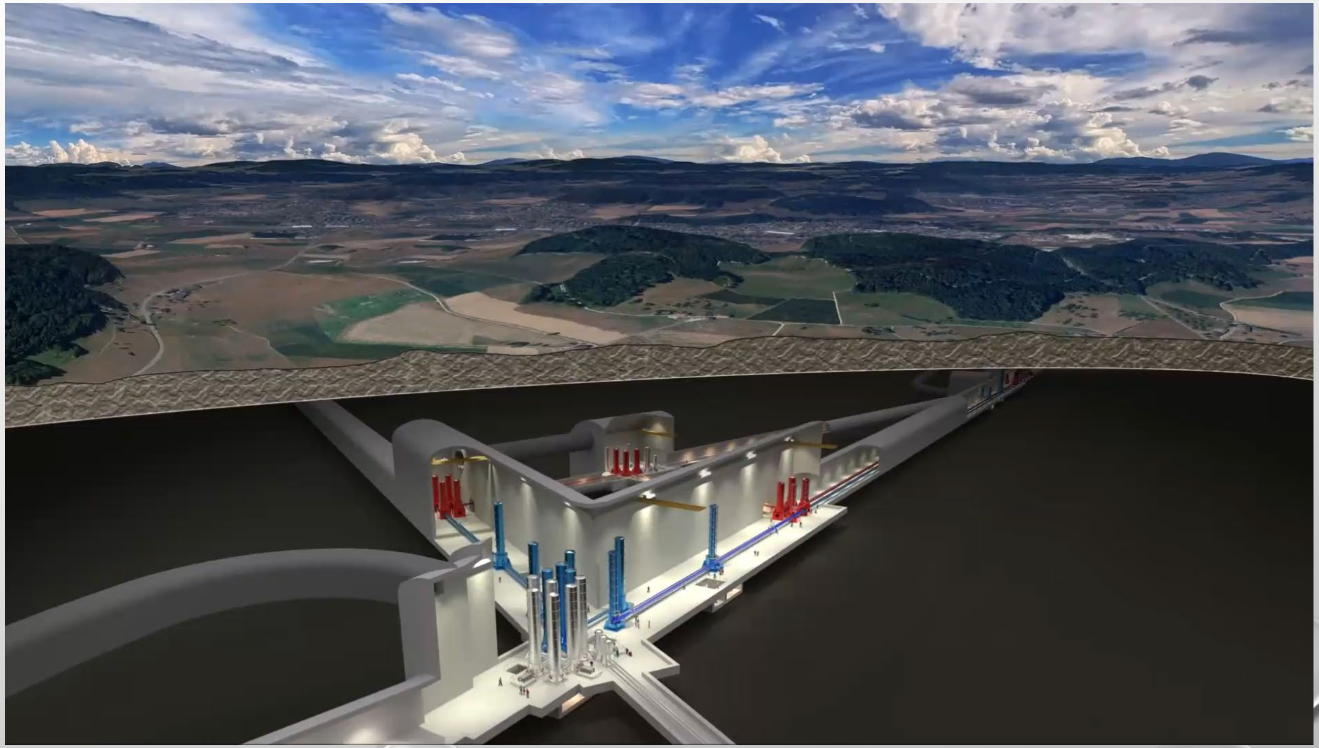
EINSTEIN TELESCOPE



ET DESIGN FEATURES

- Widen the bandwidth:
  - Underground (seismic noise reduction)
- 10 km long arms (signal increase)
- Triangle configuration
- « Xylophone » (two combined detectors) – hot (ET-HF) and cooled mirrors (ET-LF)
- Site qualification is ongoing (Italy, Hungary and Netherlands)

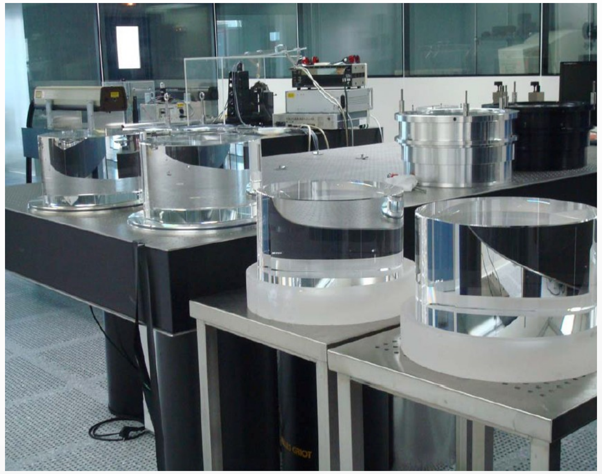
- **ET is in ESFRI**
  - **Italy (Lead country)**
  - **Netherlands**
  - **Belgium**
  - **Spain**
  - **Poland**

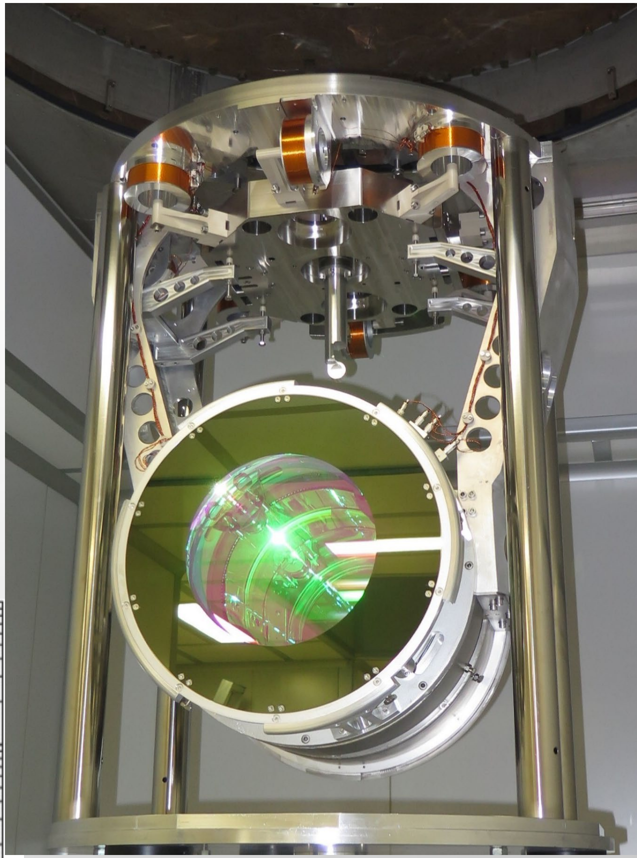


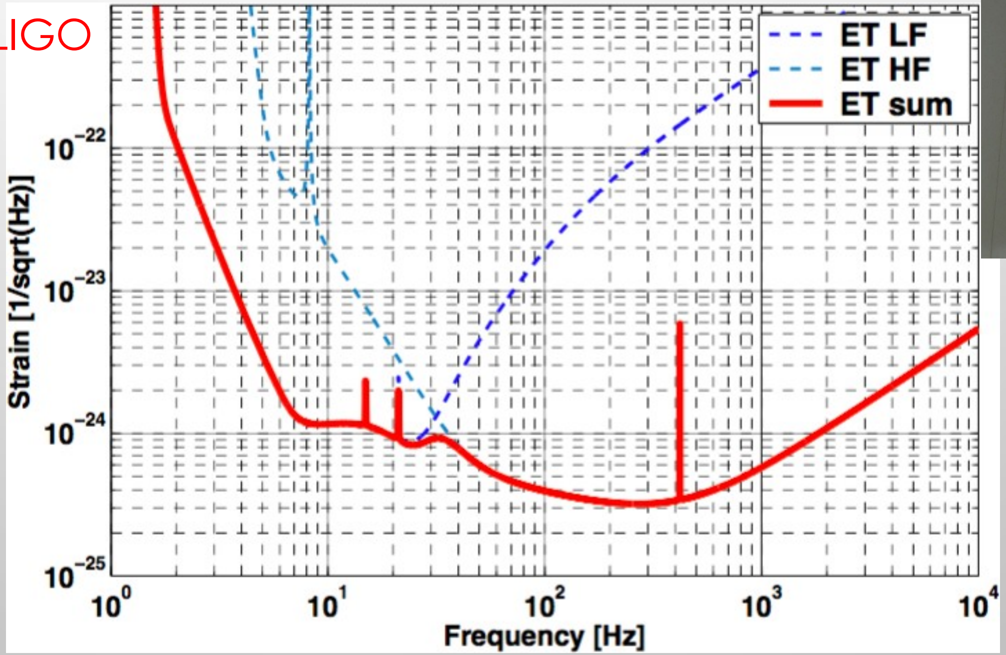
http://www.et-gw.eu/

THE ET TECHNOLOGIES AND CHALLENGES

- Extrapolation of current or planned technologies for Virgo and LIGO
  - Squeezing (non classical states of light)
  - High-power lasers
  - Large mirrors
  - New mirror's coatings
  - Thermal compensation techniques
  - Suspension systems
- Technologies not yet tested in Virgo and LIGO - some of them being tested in KAGRA
  - Cryogenics
  - New cryogenic materials
  - New laser wavelengths (1.5 or 2 microns)

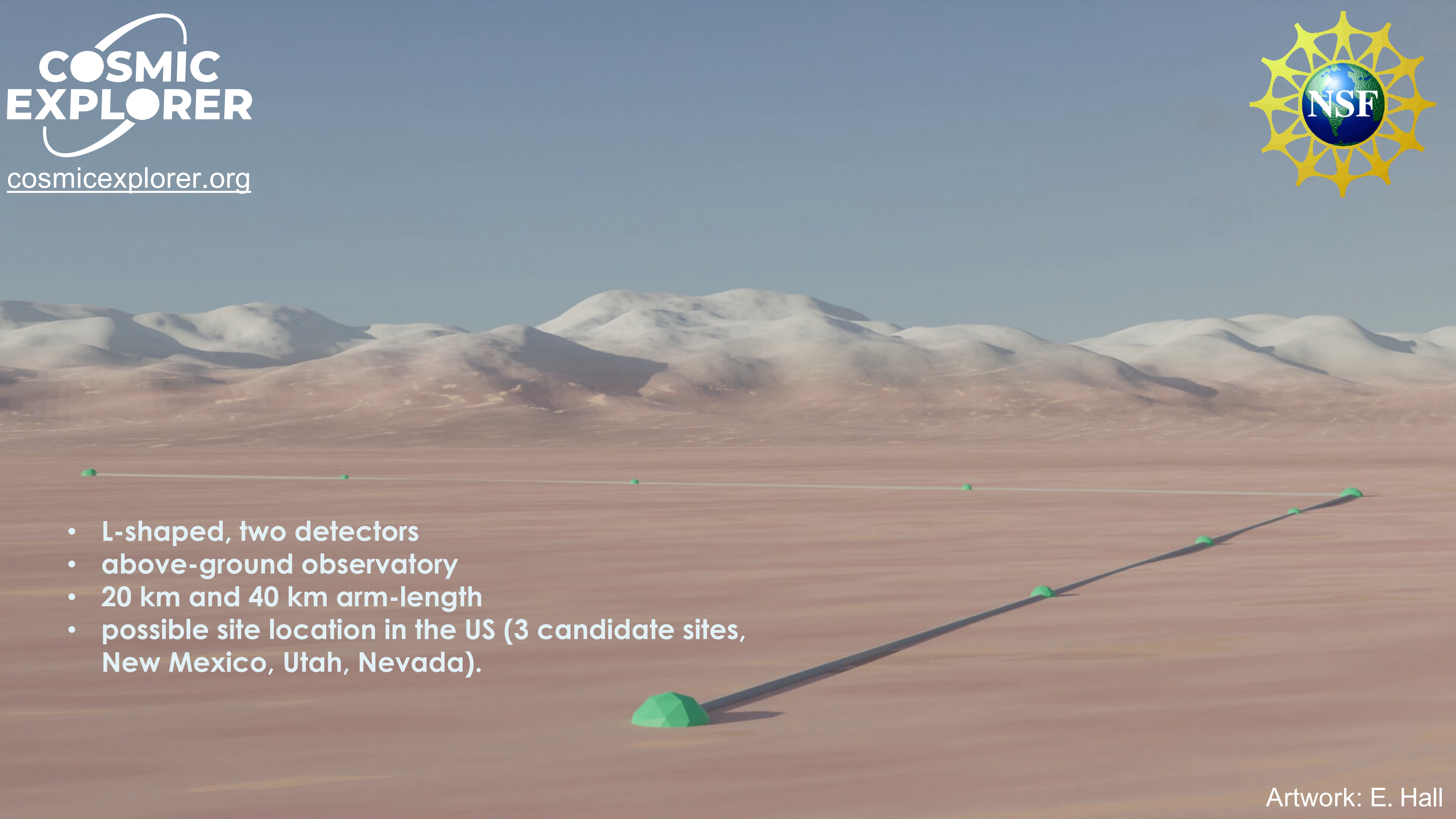






COSMIC EXPLORER

cosmicexplorer.org



- L-shaped, two detectors
- above-ground observatory
- 20 km and 40 km arm-length
- possible site location in the US (3 candidate sites, New Mexico, Utah, Nevada).

Artwork: E. Hall

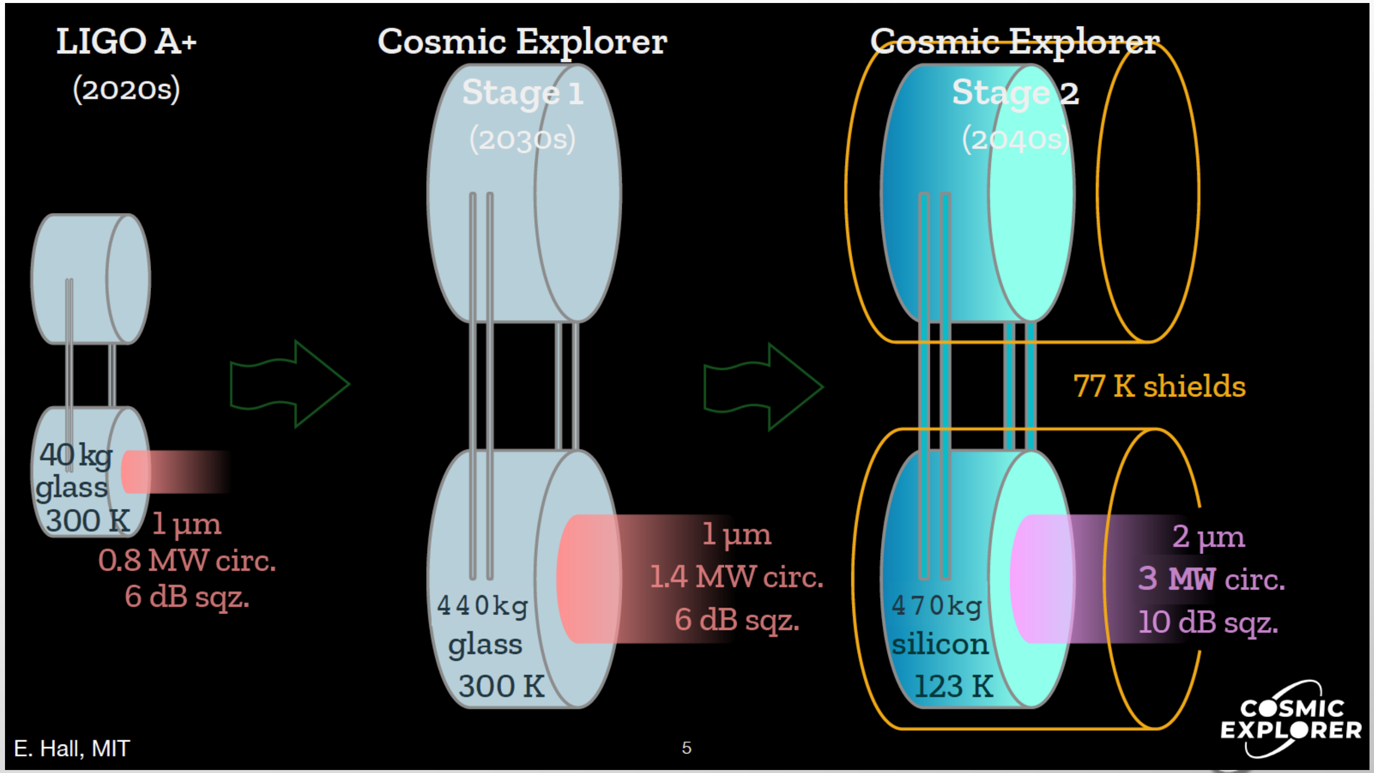
COSMIC EXPLORER

CE1: initial phase will employ scaled-up Advanced LIGO tecnology

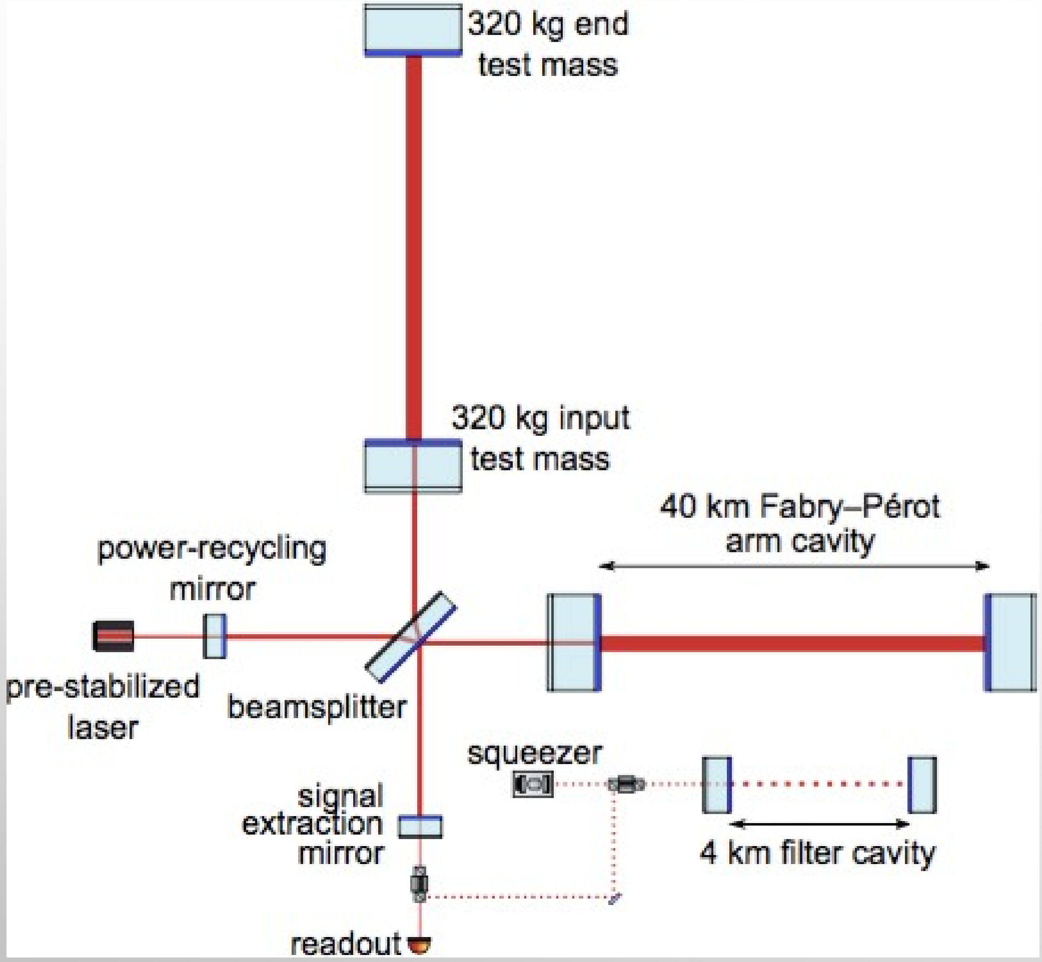
- High mass fused silica test masses
- 1.5 MW of optical power
- frequency-dependent squeezing

CE2: A major upgrade (R&D technologies)

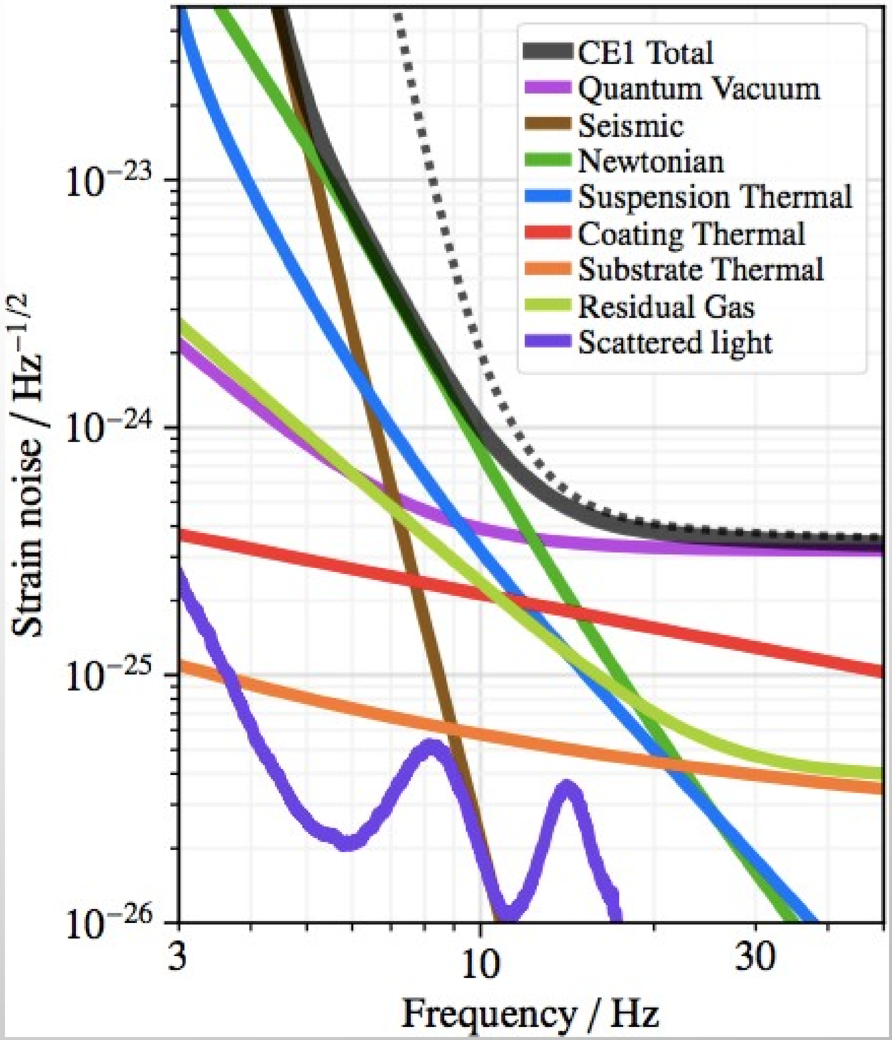
- new facility
- either using Voyager technology such as **silicon test masses** and amorphous silicon coatings operating at 123 K
- 1.5/2 μm laser light
- 3 MW of optical power in its arm cavities

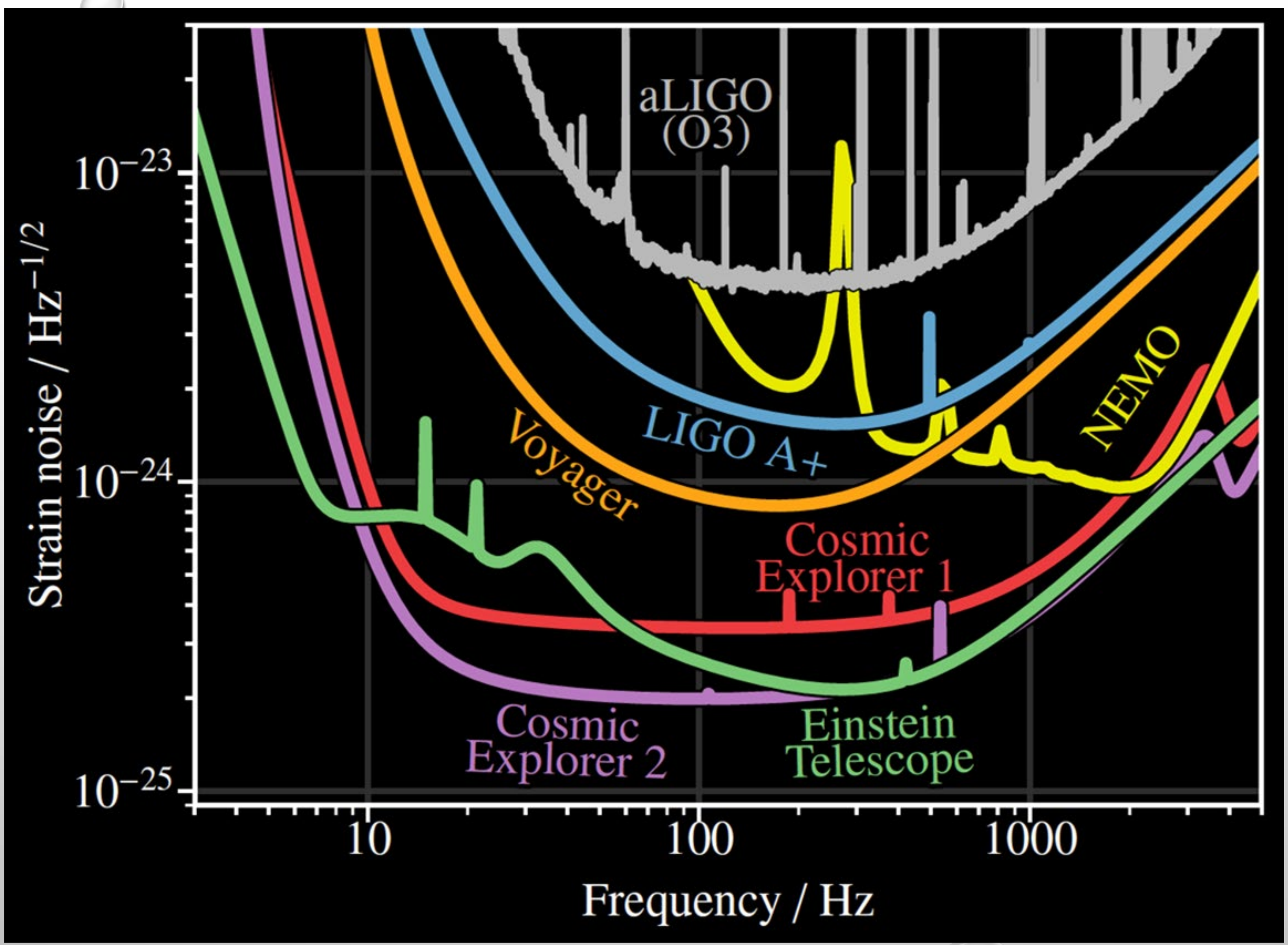


COSMIC EXPLORER



Gravitational-wave physics with Cosmic Explorer: Limits to low-frequency sensitivity
Evan D. Hall et al, Phys. Rev. D 103, 122004 (2021)





aLIGO
(O3)
LIGO A+
Voyager
NEMO
Cosmic
Explorer 1
Cosmic
Explorer 2
Einstein
Telescope
10^{-23}
10^{-24}
10^{-25}
Strain noise / $Hz^{-1/2}$
10
100
1000
Frequency / Hz

TO SUMMARIZE

- **ADVANCED DETECTORS ARE BEING UPDATES (PLUS DETECTORS) FOR O4 AND O5**
  - A+
  - ADV+
  - KAGRA+
- **FILLING THE GAP BETWEEN O5 AND G3**
  - **POST-O5** TECHNOLOGIES
    - INCREMENTAL UPGRADES: POWER, COATINGS, VARIOUS TECHNICAL NOISES, REACHING THE SENSITIVITY AT LOW FREQUENCY
    - IMPORTANT TO MOVE TOWARDS 3G INTERFEROMETERS BUT TRY TO KEEP THE DATA TAKING ON AS MUCH AS POSSIBLE
  - PROJECTS FOR 3G TECHNOLOGIES AND TO PUSH THE CURRENT INTERFEROMETER AT THEIR LIMIT
    - POST-O5 LIGO AND VIRGO
    - VOYAGER
    - NEMO
- **G3 DETECTORS**
  - **ET,** GREAT SCIENTIFIC POTENTIAL, **ET IN THE ESFRI ROADMAP !**
  - **THE FIRST VERSION OF THE COSMIC EXPLORER HORIZON STUDY HAS BEEN RELEASED:**
  https://dcc.cosmicexplorer.org/public/0163/p2100003/004/ce-horizon-study.pdf