# The KAGRA Detector in the MM Era

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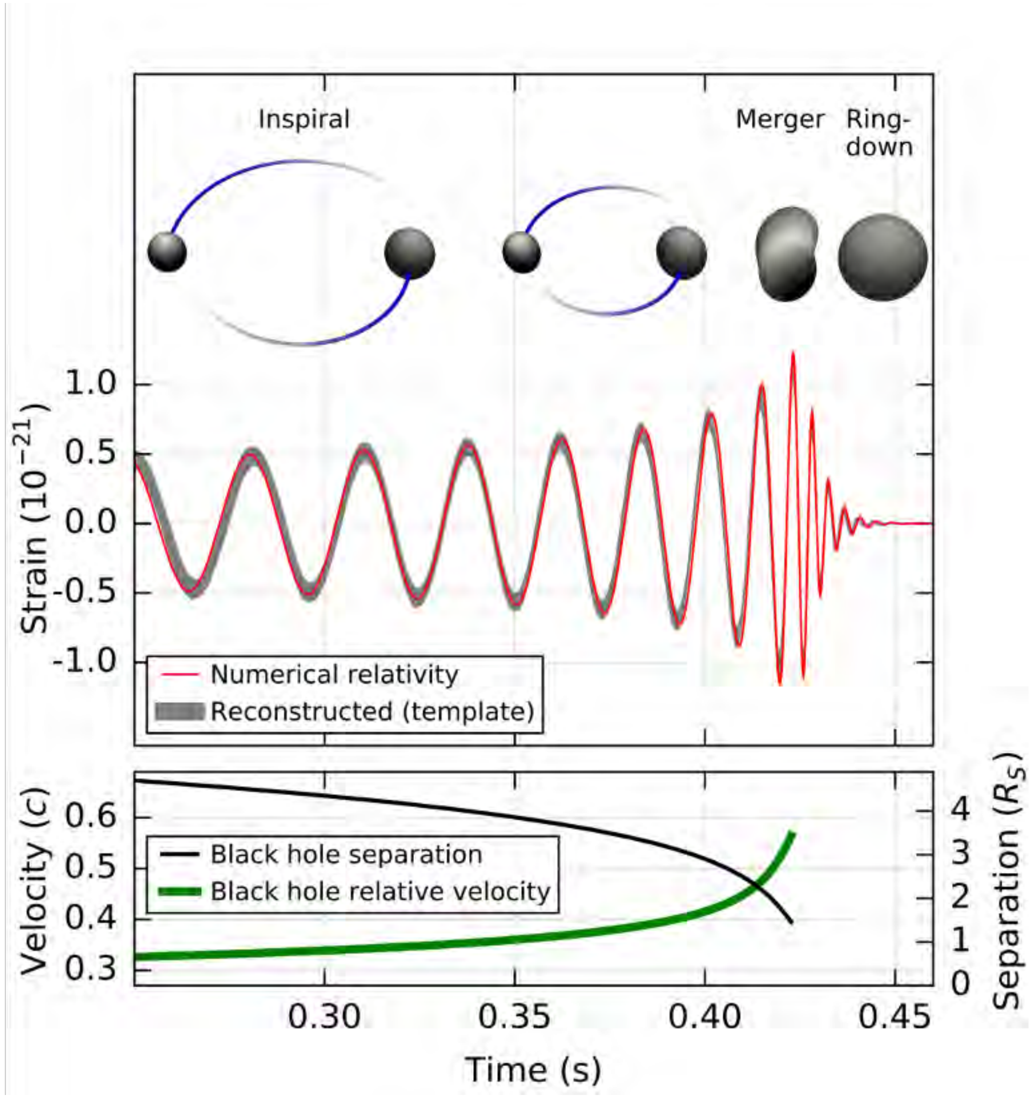
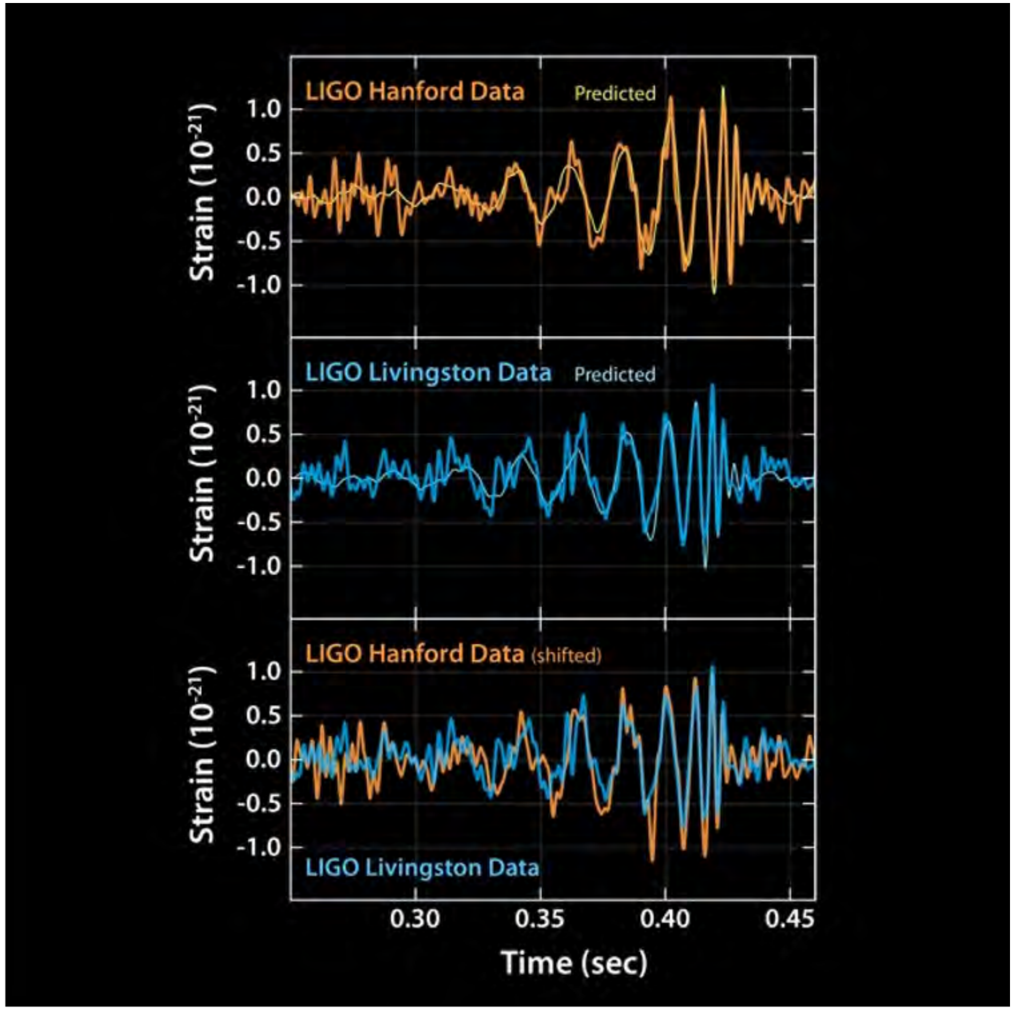
LIGO VIRGO KAGRA

# The first gravitational wave event GW150914

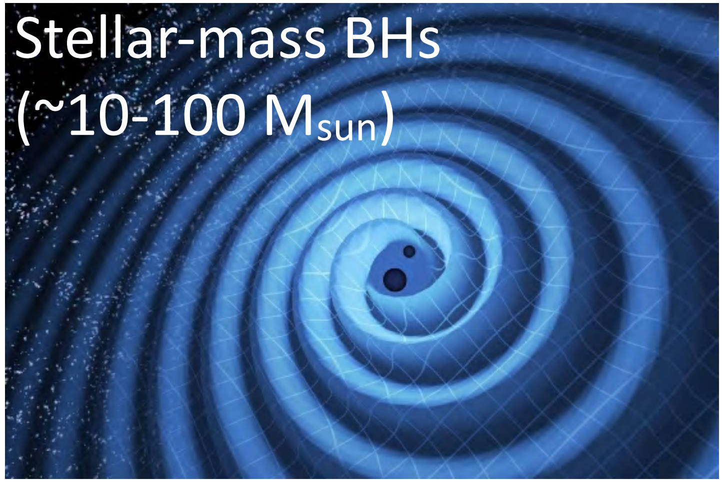


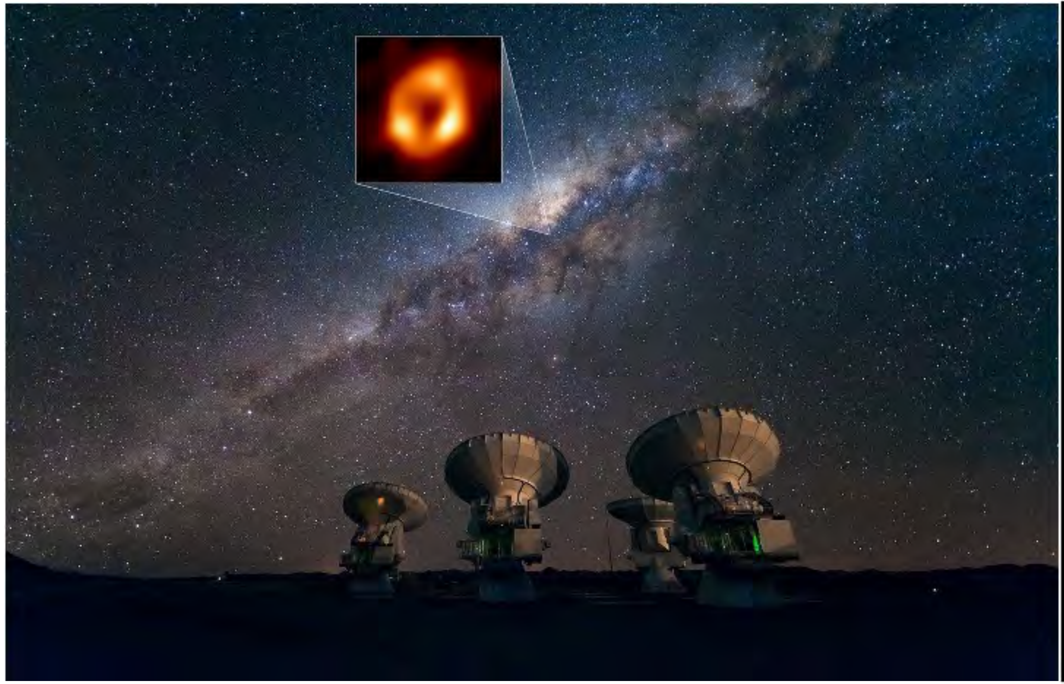



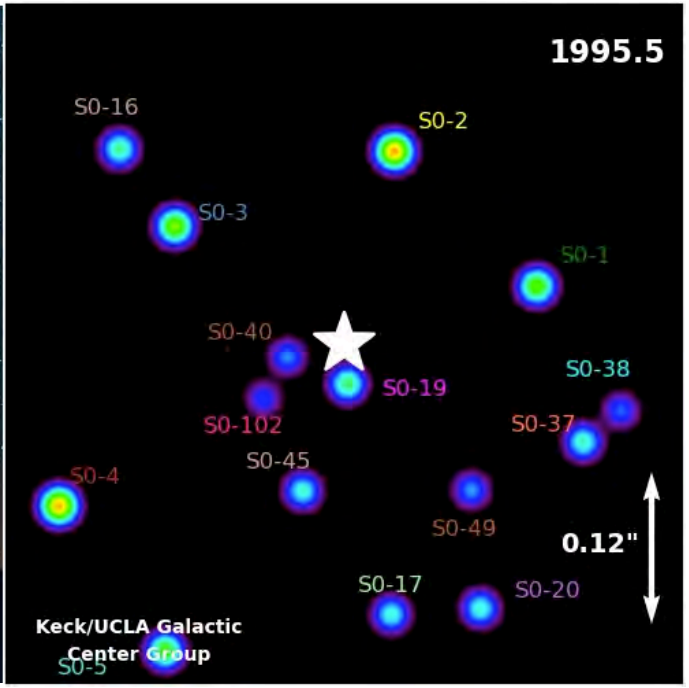
# Key messages from GW detections

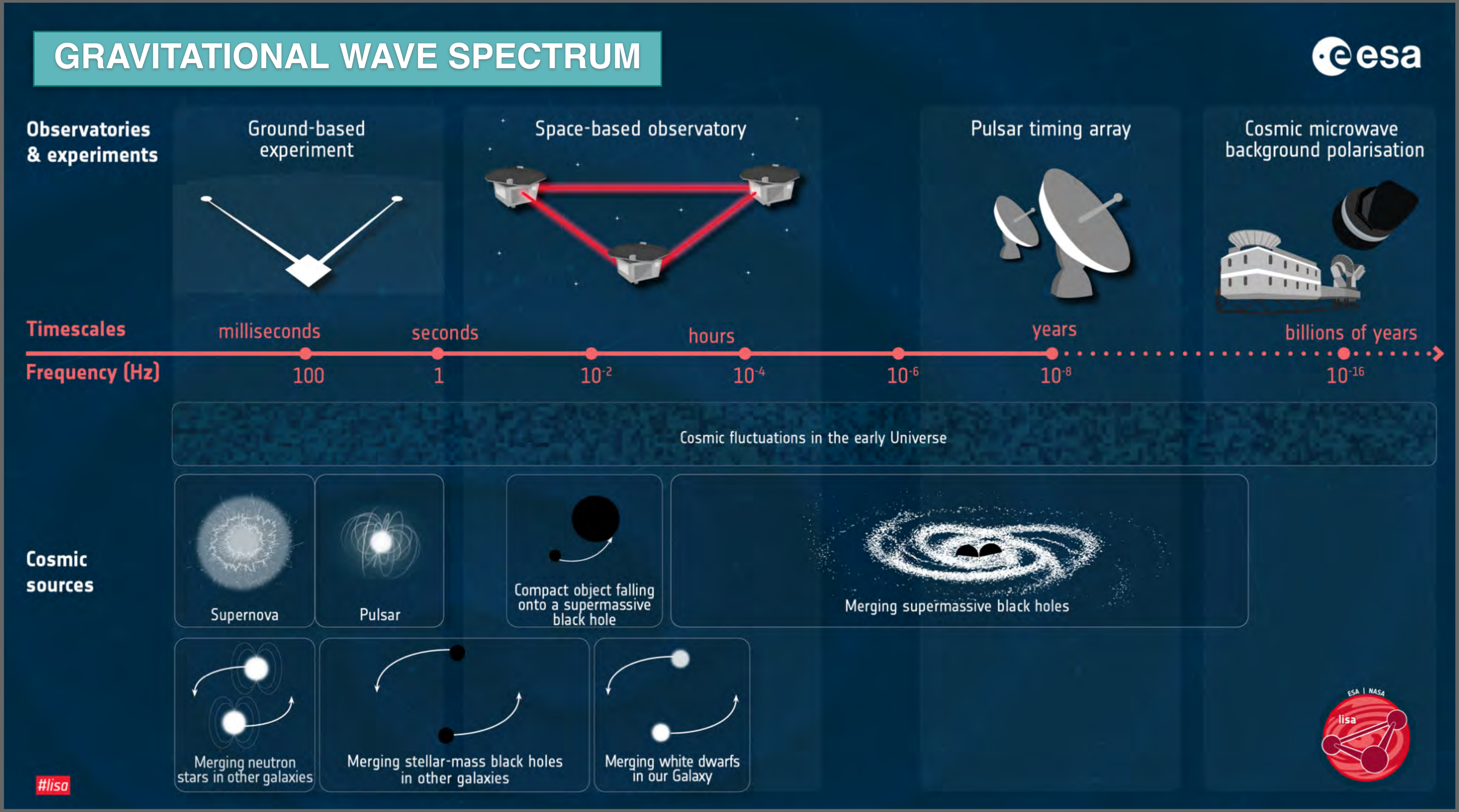
- Black hole is real!
- Further confirmation of Einstein's General Relativity
- Multiple black holes can merge together
- **A new window to observe the universe**

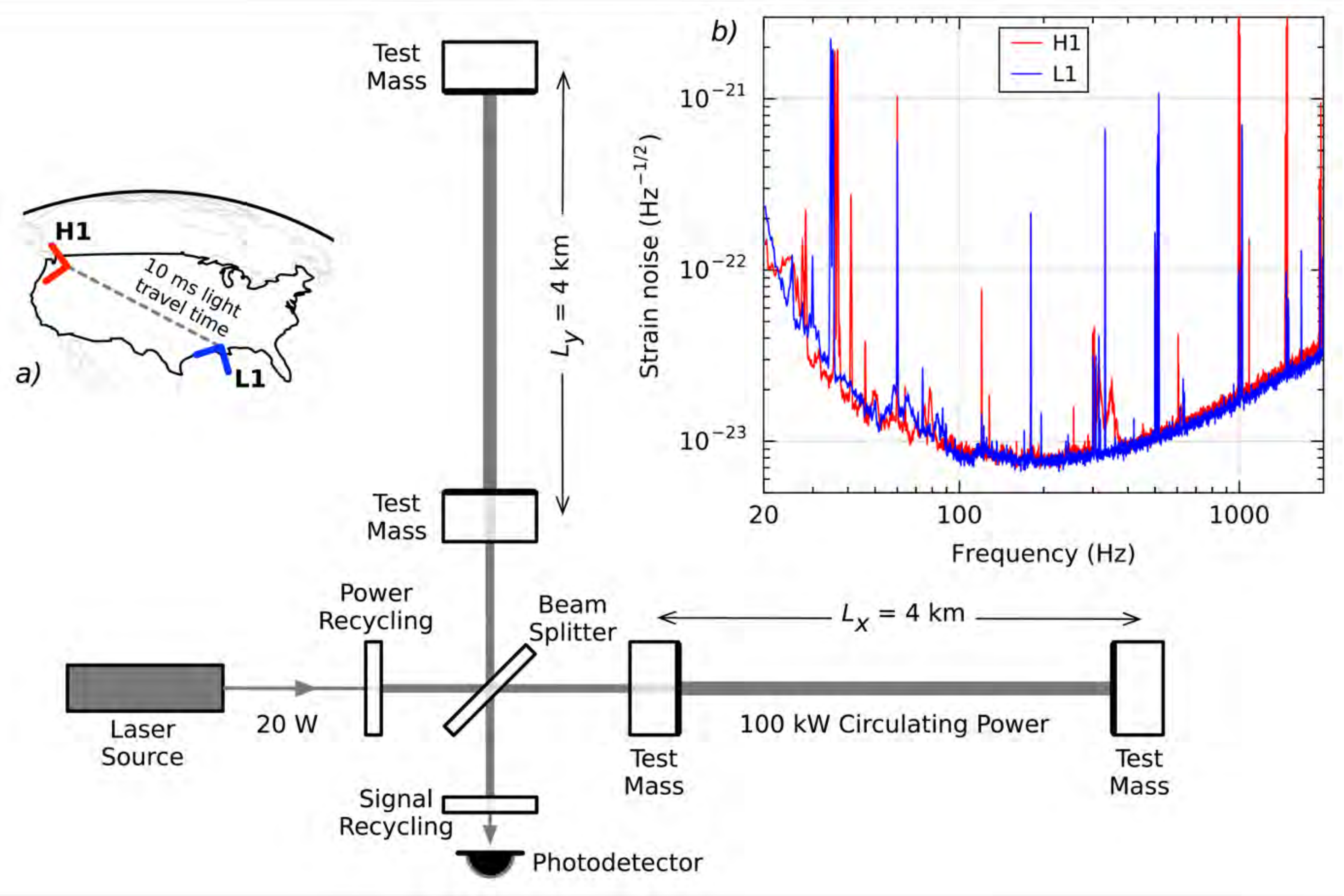
Supermassive BHs (~$10^{6\text{-}9}$ $M_{sun}$)



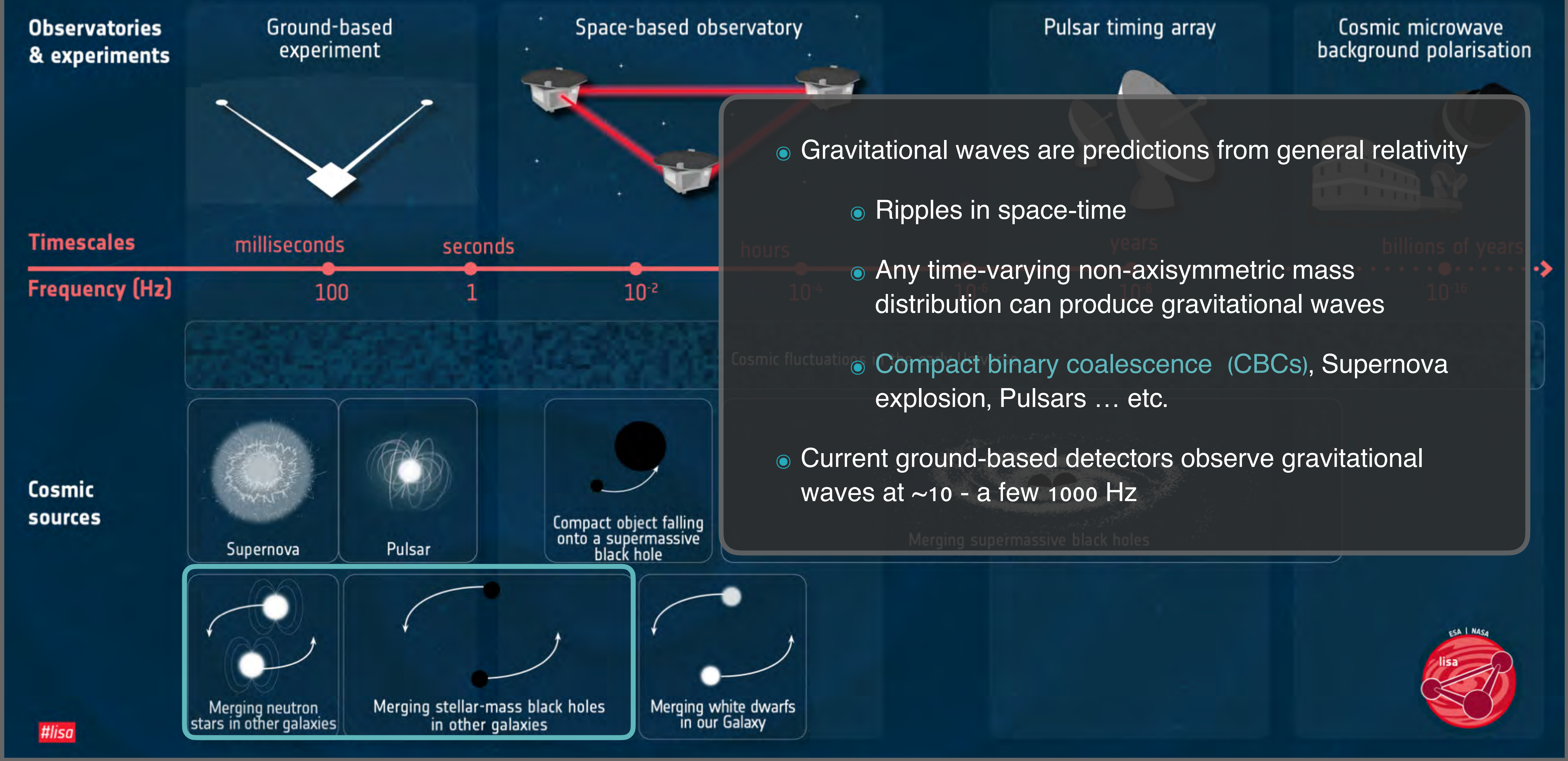





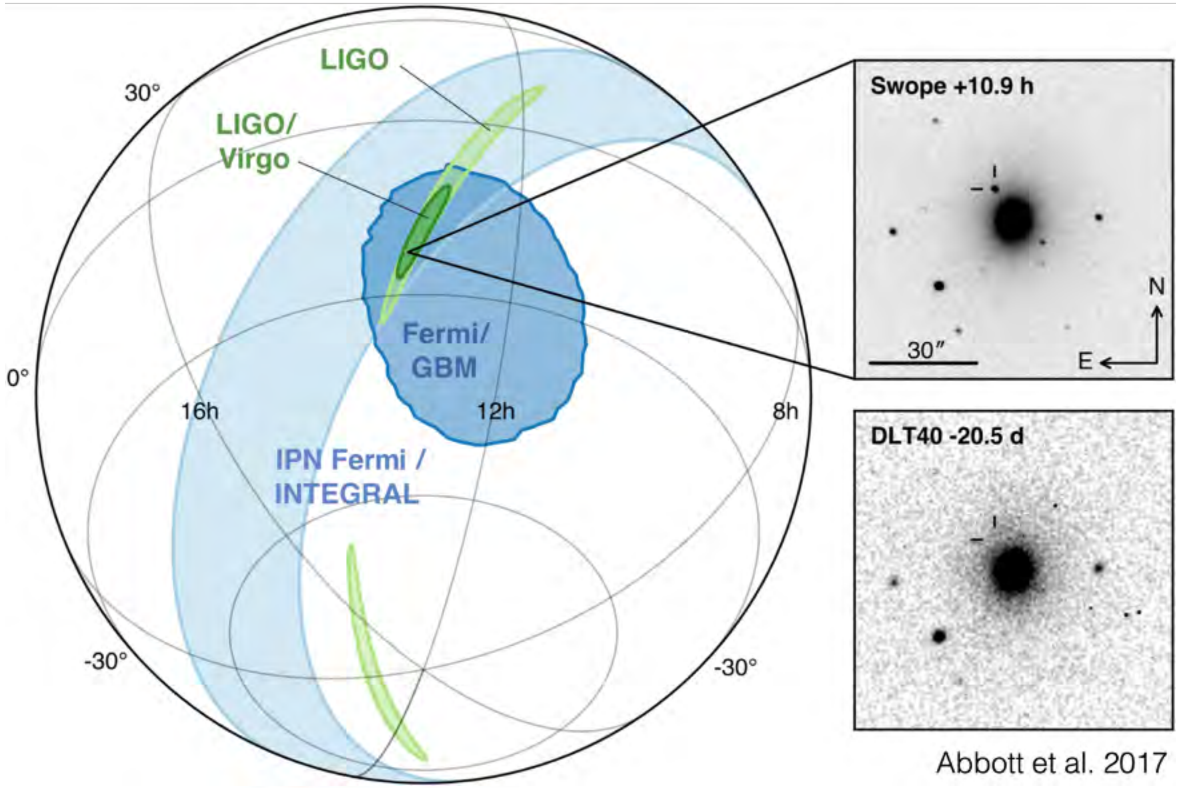

GRAVITATIONAL WAVE SPECTRUM
esa
Observatories & experiments
Ground-based experiment
Space-based observatory
Pulsar timing array
Cosmic microwave background polarisation
Timescales
milliseconds
seconds
hours
years
billions of years
Frequency (Hz)
100
1
10-2
10-4
10-6
10-8
10-16
Cosmic fluctuations in the early Universe
Cosmic sources
Supernova
Pulsar
Compact object falling onto a supermassive black hole
Merging supermassive black holes
Merging neutron stars in other galaxies
Merging stellar-mass black holes in other galaxies
Merging white dwarfs in our Galaxy
#lisa
ESA | NASA
lisa


a)
H1
10 ms light travel time
L1
Test Mass
Test Mass
$L_y$ = 4 km
Power Recycling
Beam Splitter
$L_x$ = 4 km
Laser Source
20 W
100 kW Circulating Power
Test Mass
Test Mass
Signal Recycling
Photodetector
b)
H1
L1
Strain noise ($Hz^{-1/2}$)
$10^{-21}$
$10^{-22}$
$10^{-23}$
20
100
1000
Frequency (Hz)

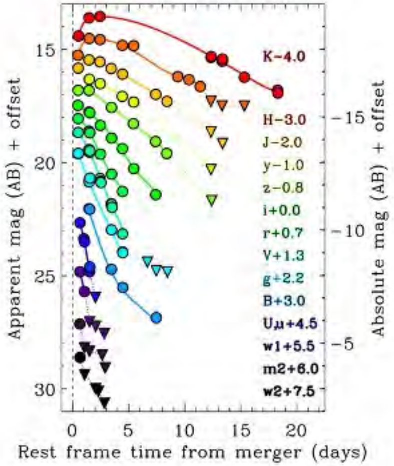
# GRAVITATIONAL WAVE SPECTRUM

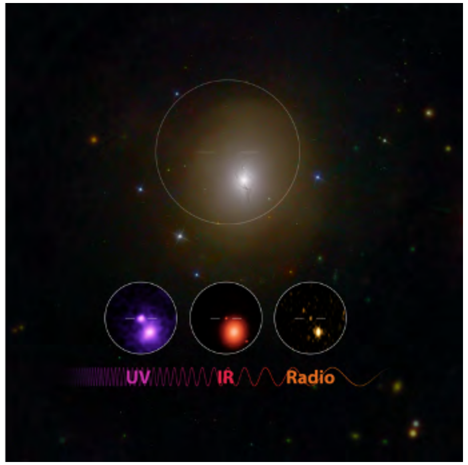


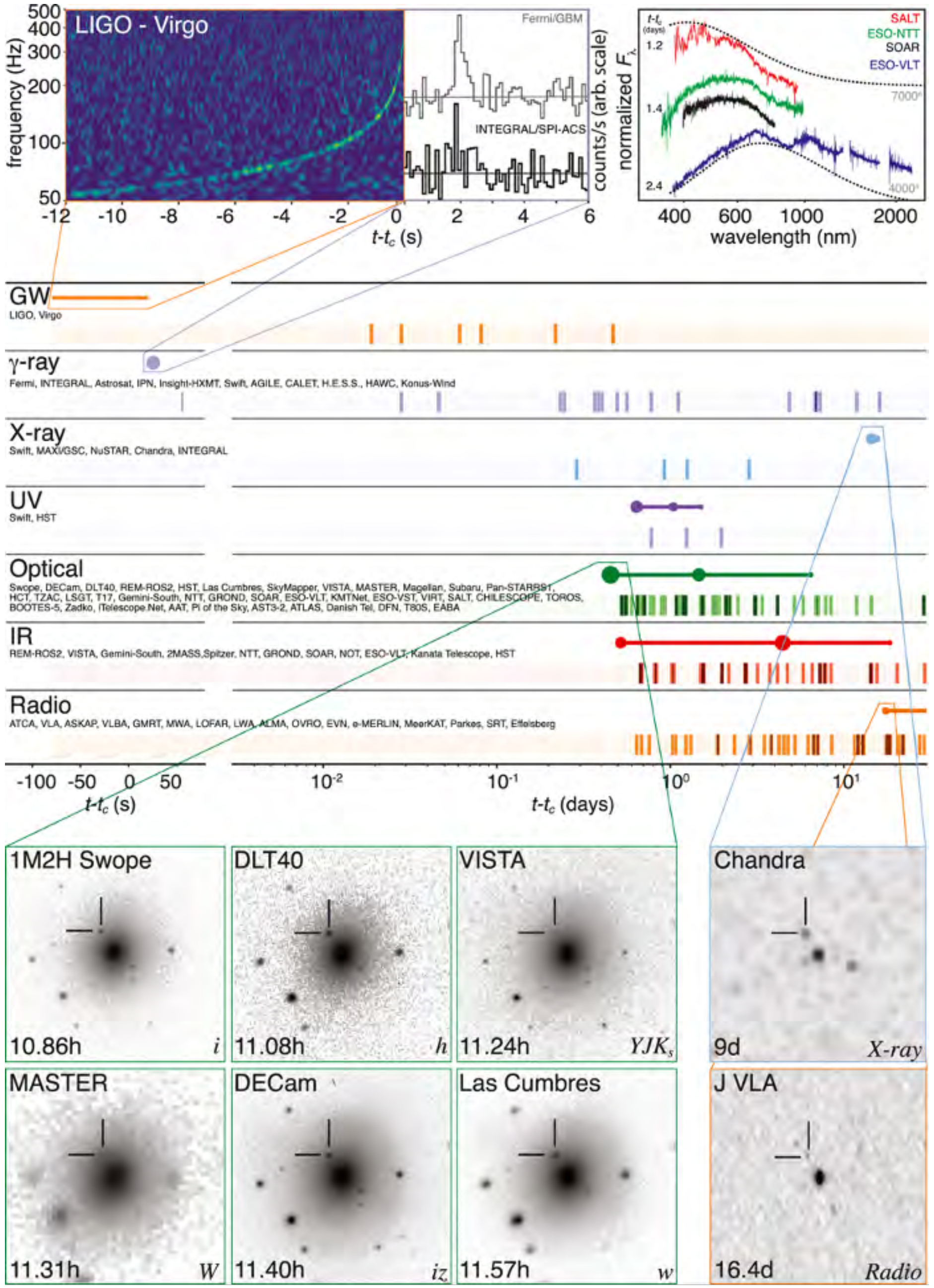

- Gravitational waves are predictions from general relativity
  - Ripples in space-time
  - Any time-varying non-axisymmetric mass distribution can produce gravitational waves
  - Compact binary coalescence (CBCs), Supernova explosion, Pulsars … etc.
- Current ground-based detectors observe gravitational waves at ~10 - a few 1000 Hz

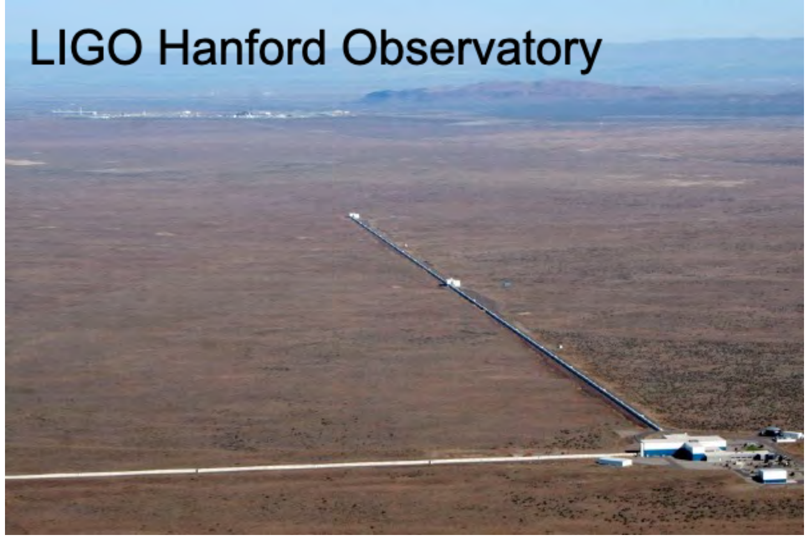



Abbott et al. 2017



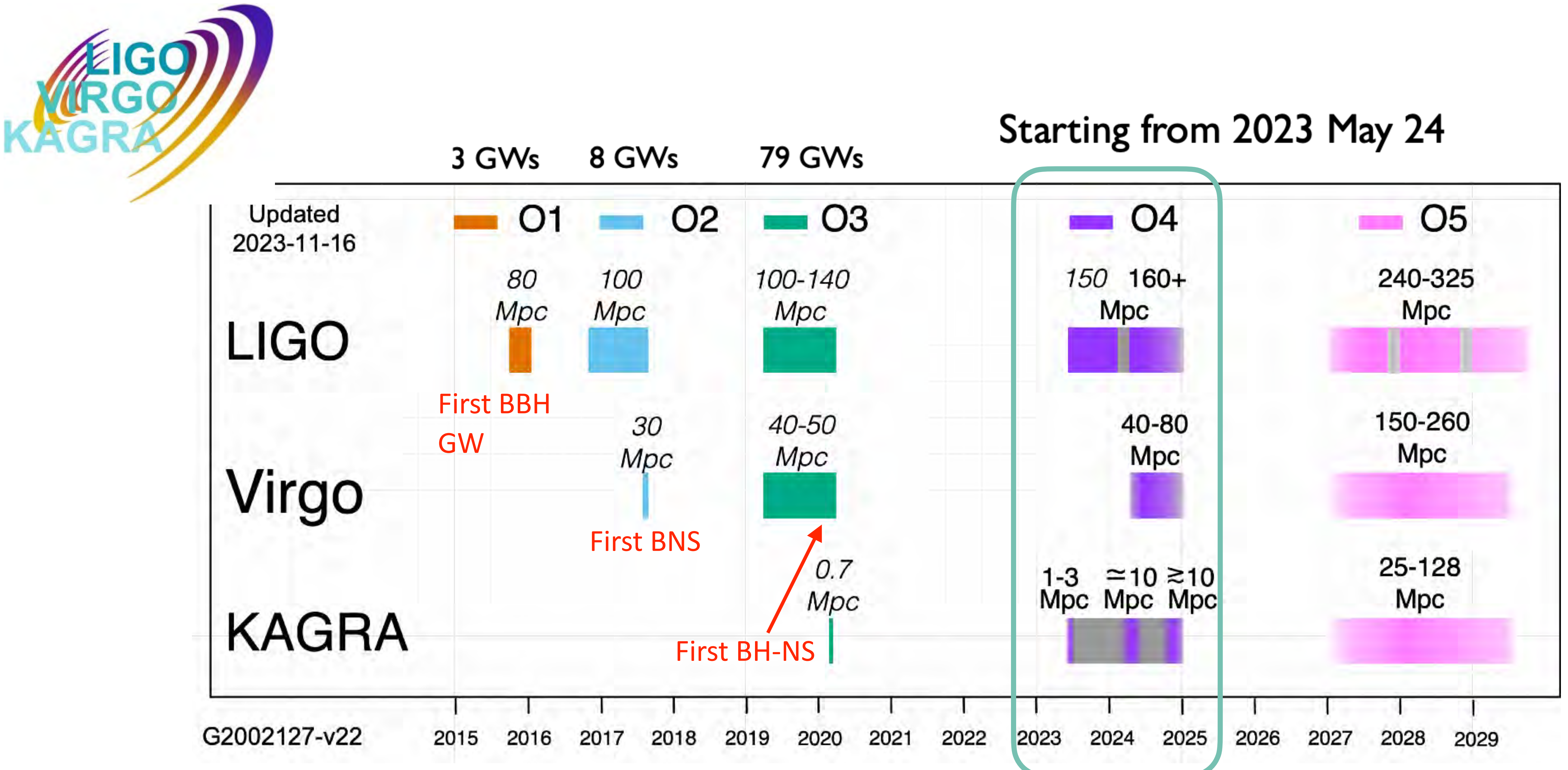



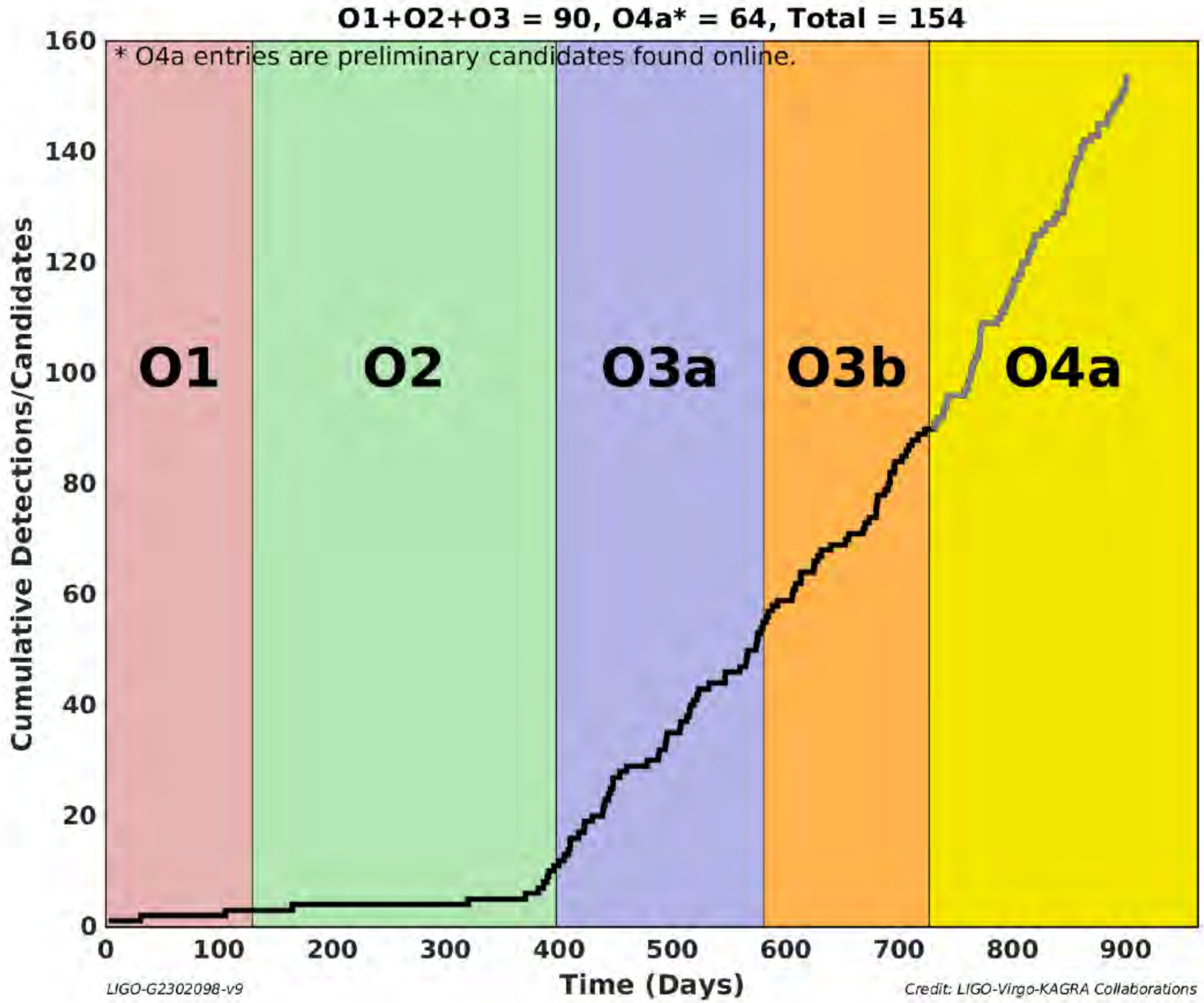




LIGO Livingston Observatory

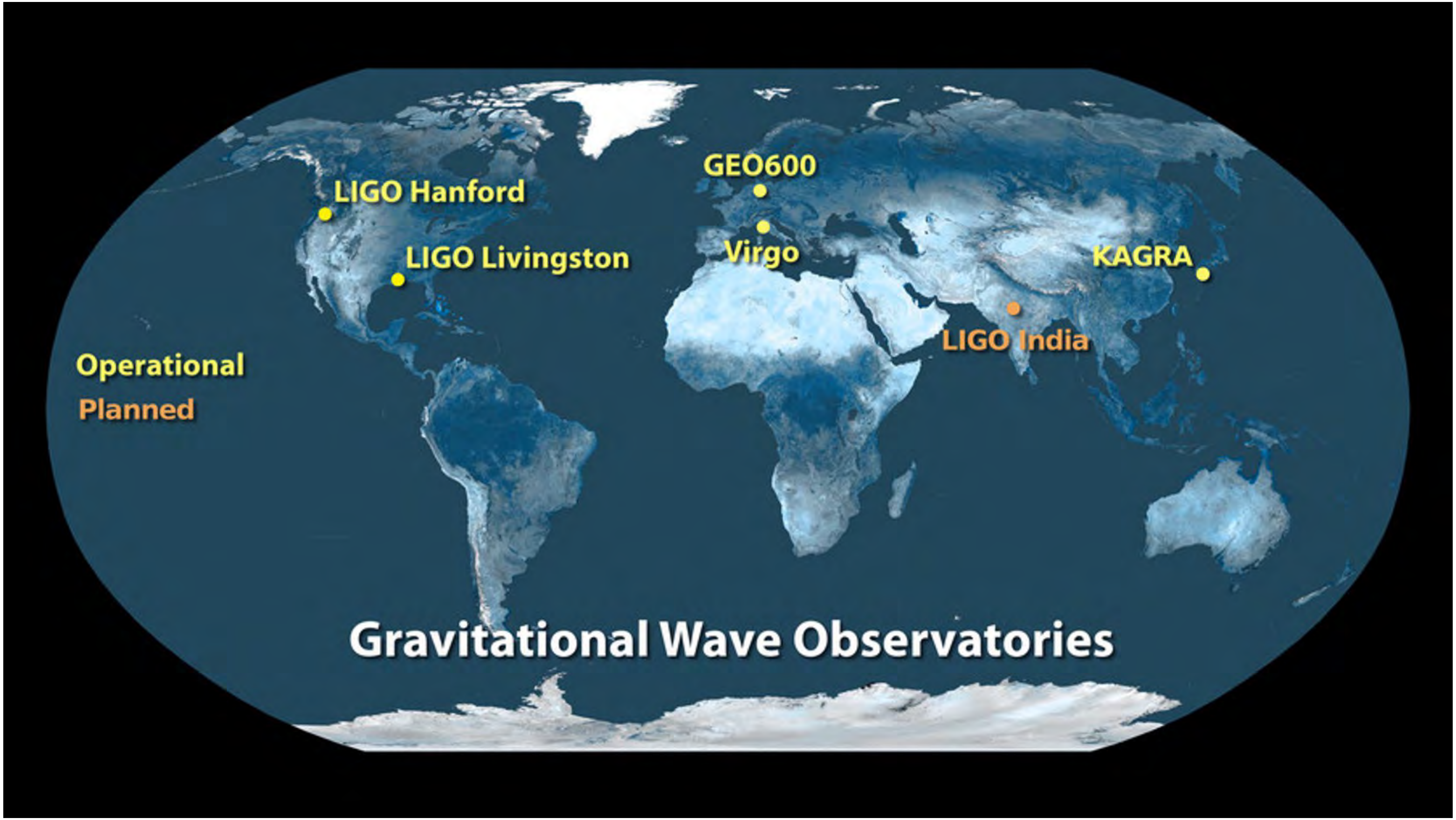
Starting from 2023 May 24



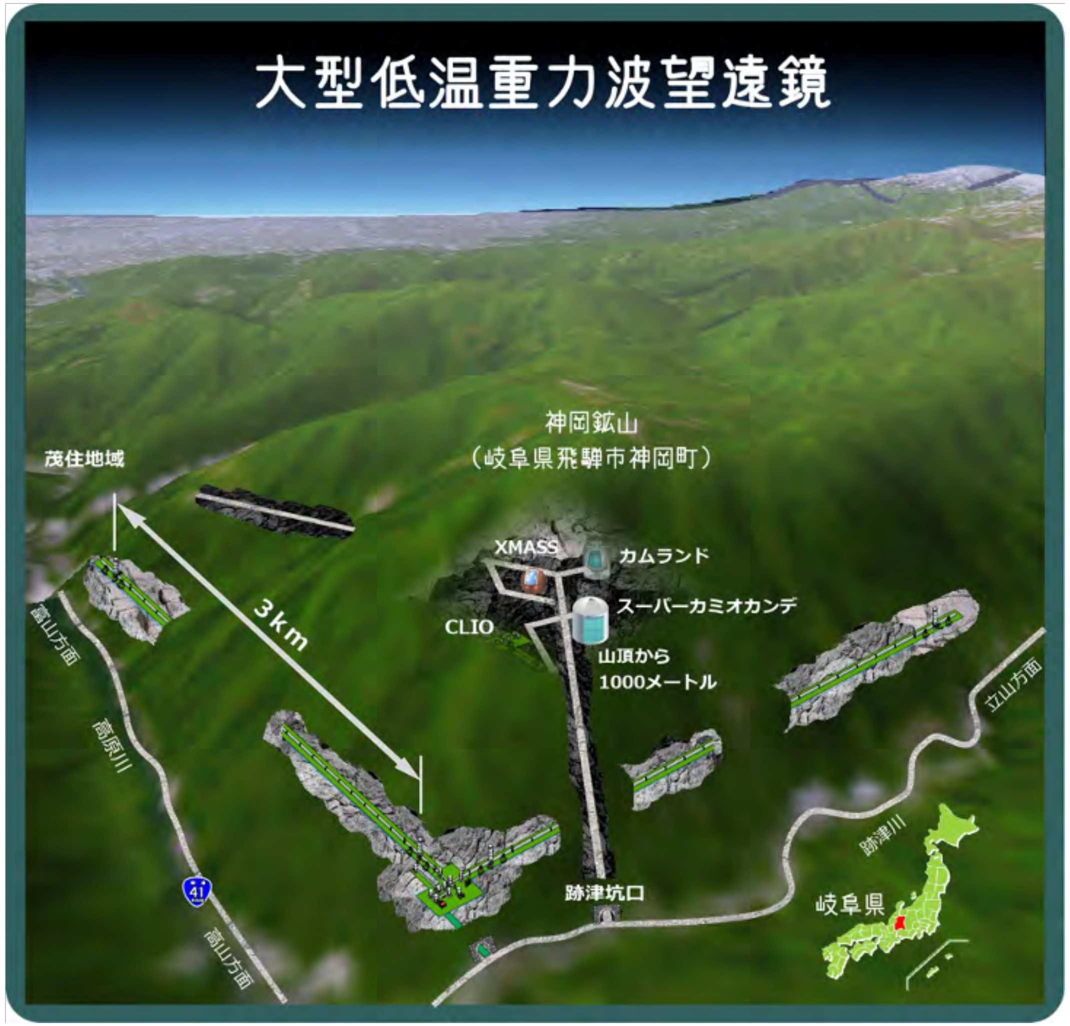



LIGO-G2302098

- O4a: 71 detections from LIGO so far (updated on Dec 4)
- KAGRA observed with LIGO during the first month of O4a and is currently in commissioning
- O4a will end on Jan 16, 2024
- O4b will start in late-March
- Virgo is expected to join in O4b
- KAGRA will join again in O4b


LIGO Hanford
LIGO Livingston
GEO600
Virgo
KAGRA
LIGO India
Operational
Planned
Gravitational Wave Observatories

# Kamioka Gravitational Wave Detector KAGRA





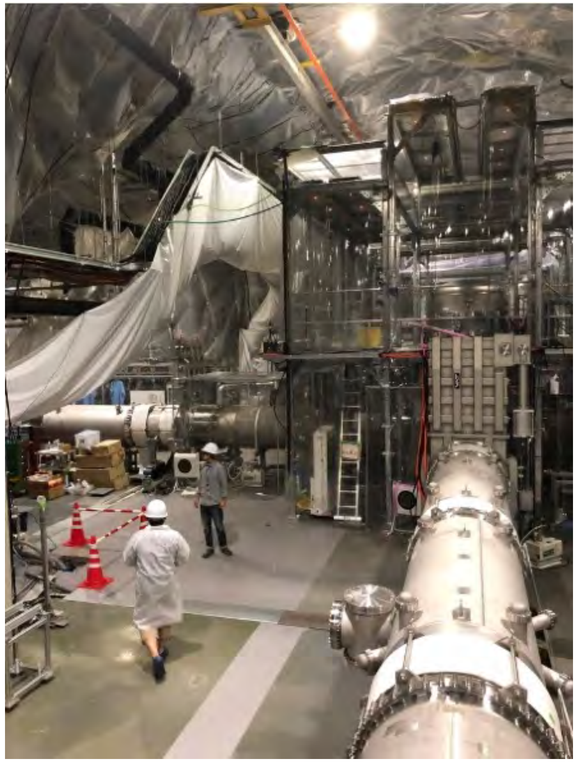
# KAGRA

- Underground -> smaller seismic noise
- Cryogenic mirrors -> smaller thermal noises

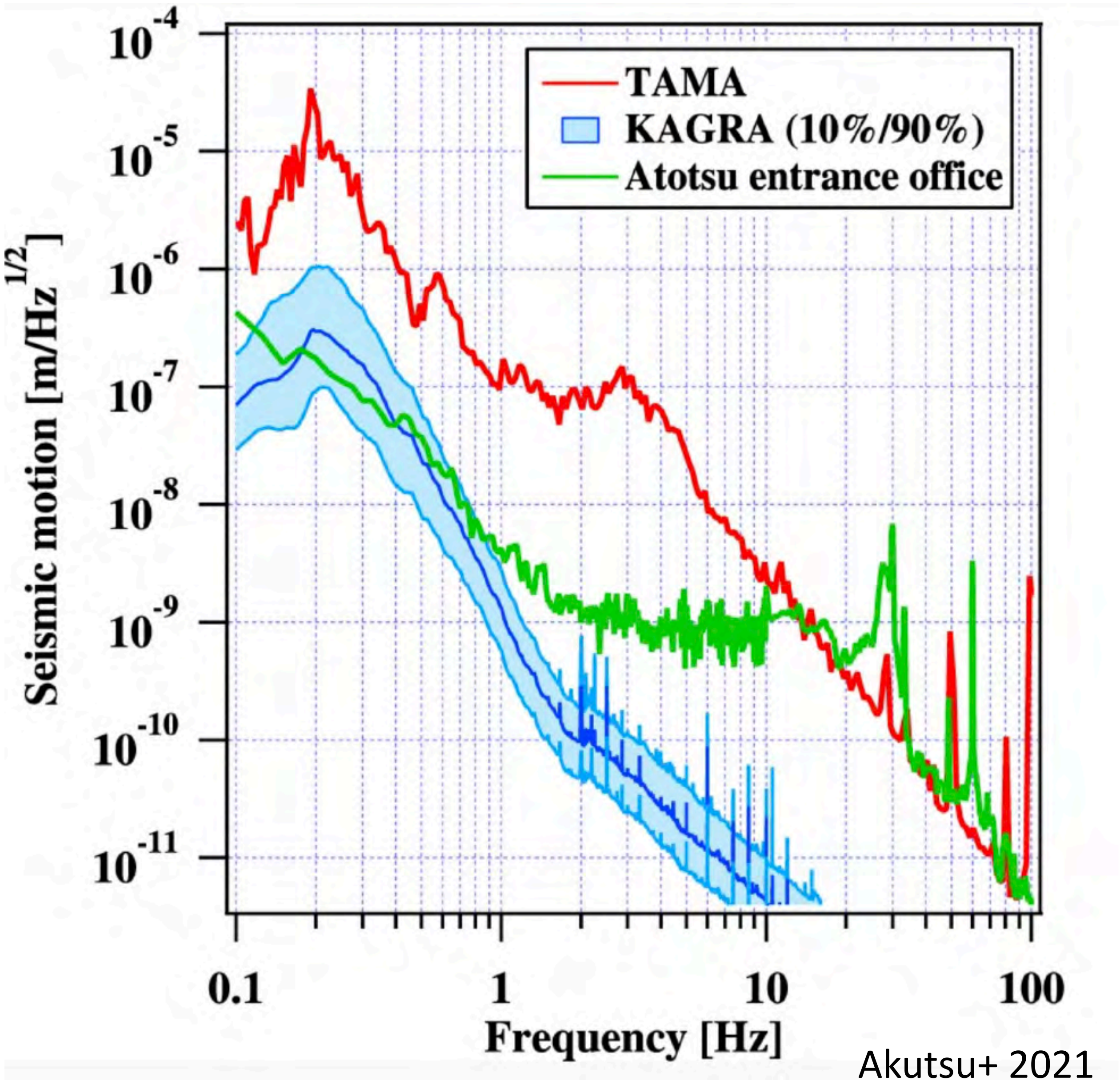


Room 103
KAGRA Control Room
KAGRA
KAGRA 制御室


かぐらトンネル

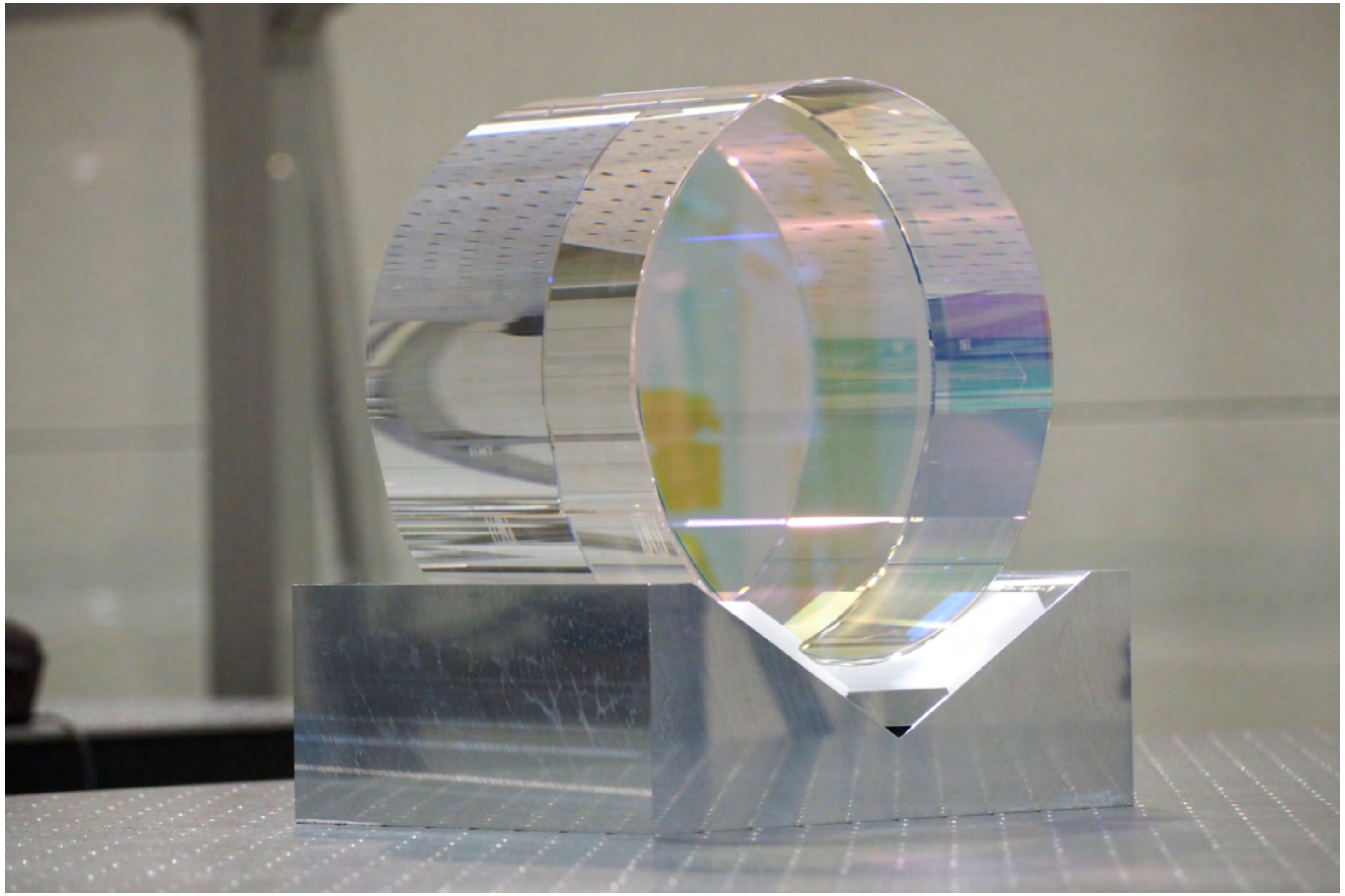


# Seismic noise



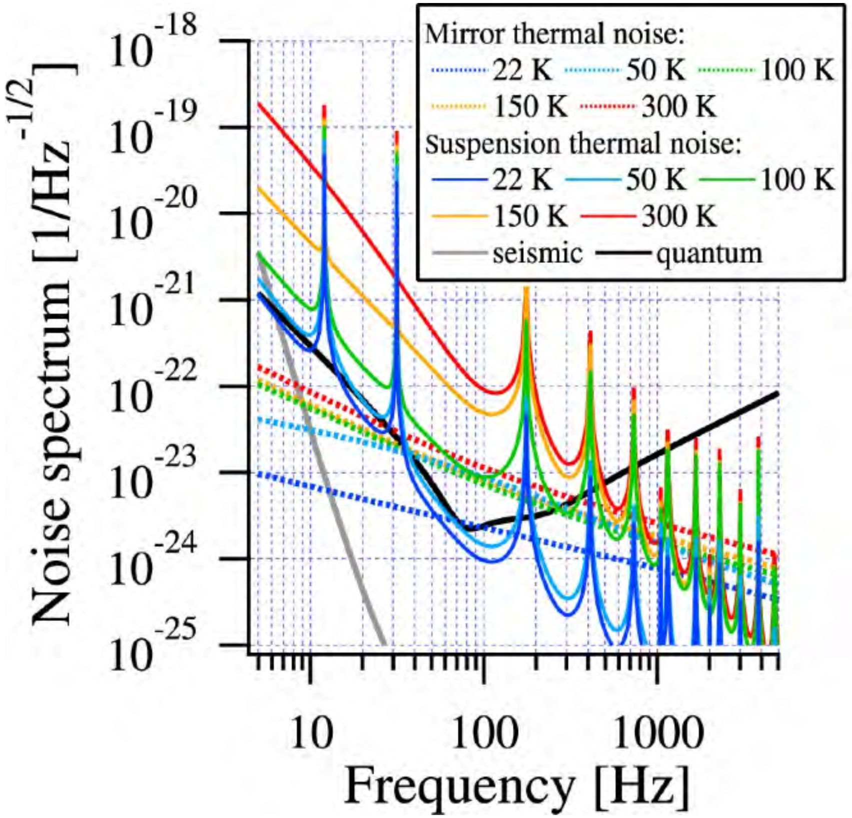

Akutsu+ 2021

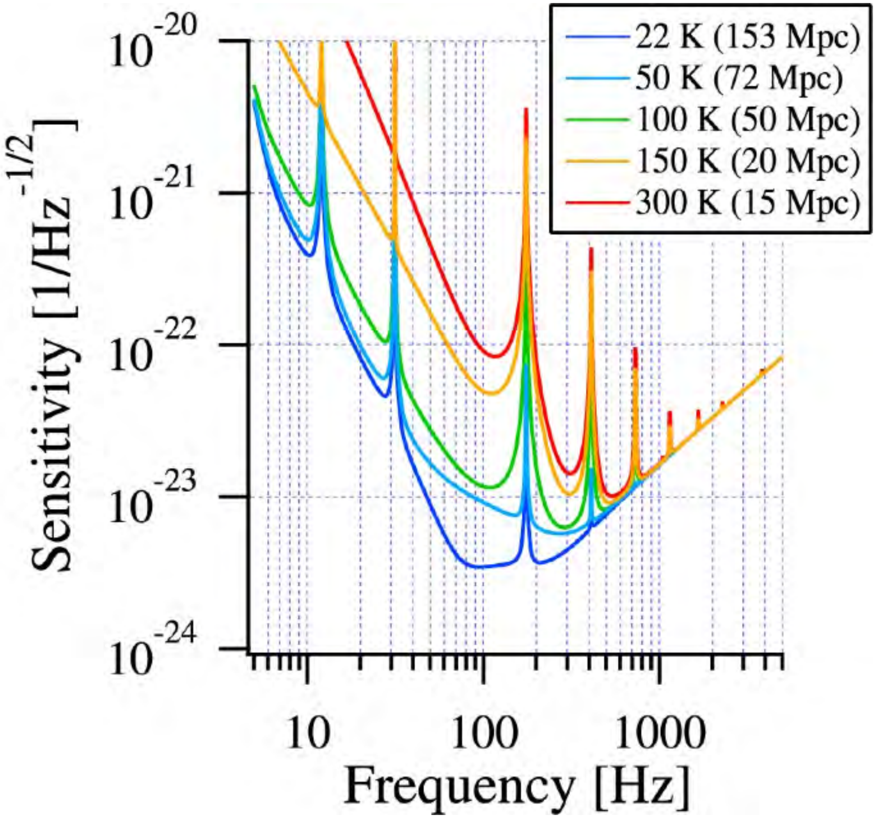
# KAGRA’s mirrors



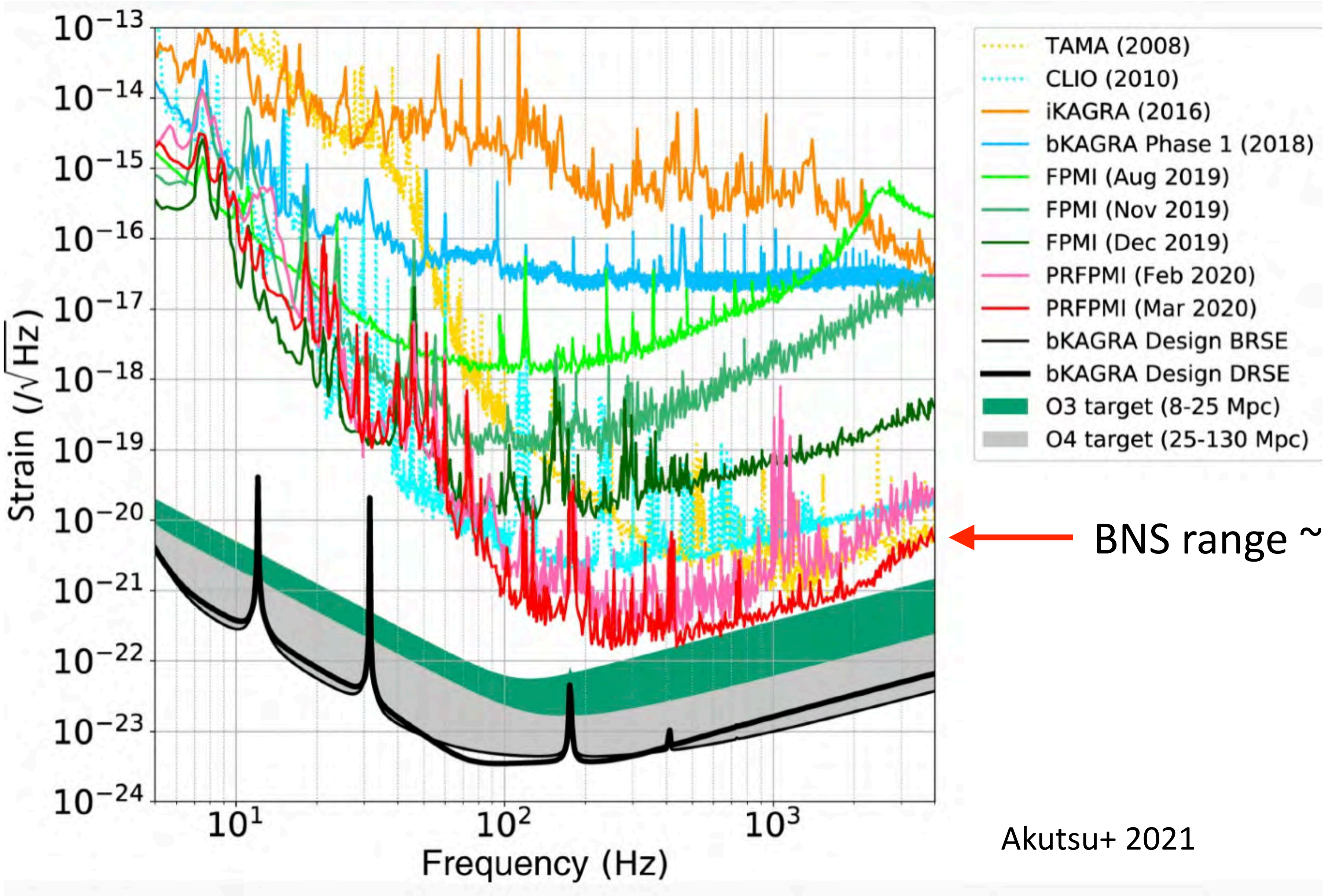
- Cryogenic mirror (~20 K)
- 22cm in diameter
- 15cm in thickness
- 23 kg
- Sapphire (fused silica in LIGO and Virgo)
- Room temperature during O3GK and O4a
- Will cool down the mirror in O4b


KAGRA CRYOGENICS
ICRR
KEK
NAOJ


Mirror thermal noise:
22 K
50 K
100 K
150 K
300 K
Suspension thermal noise:
22 K
50 K
100 K
150 K
300 K
seismic
quantum
Noise spectrum [1/Hz$^{-1/2}$]
$10^{-18}$
$10^{-19}$
$10^{-20}$
$10^{-21}$
$10^{-22}$
$10^{-23}$
$10^{-24}$
$10^{-25}$
10
100
1000
Frequency [Hz]

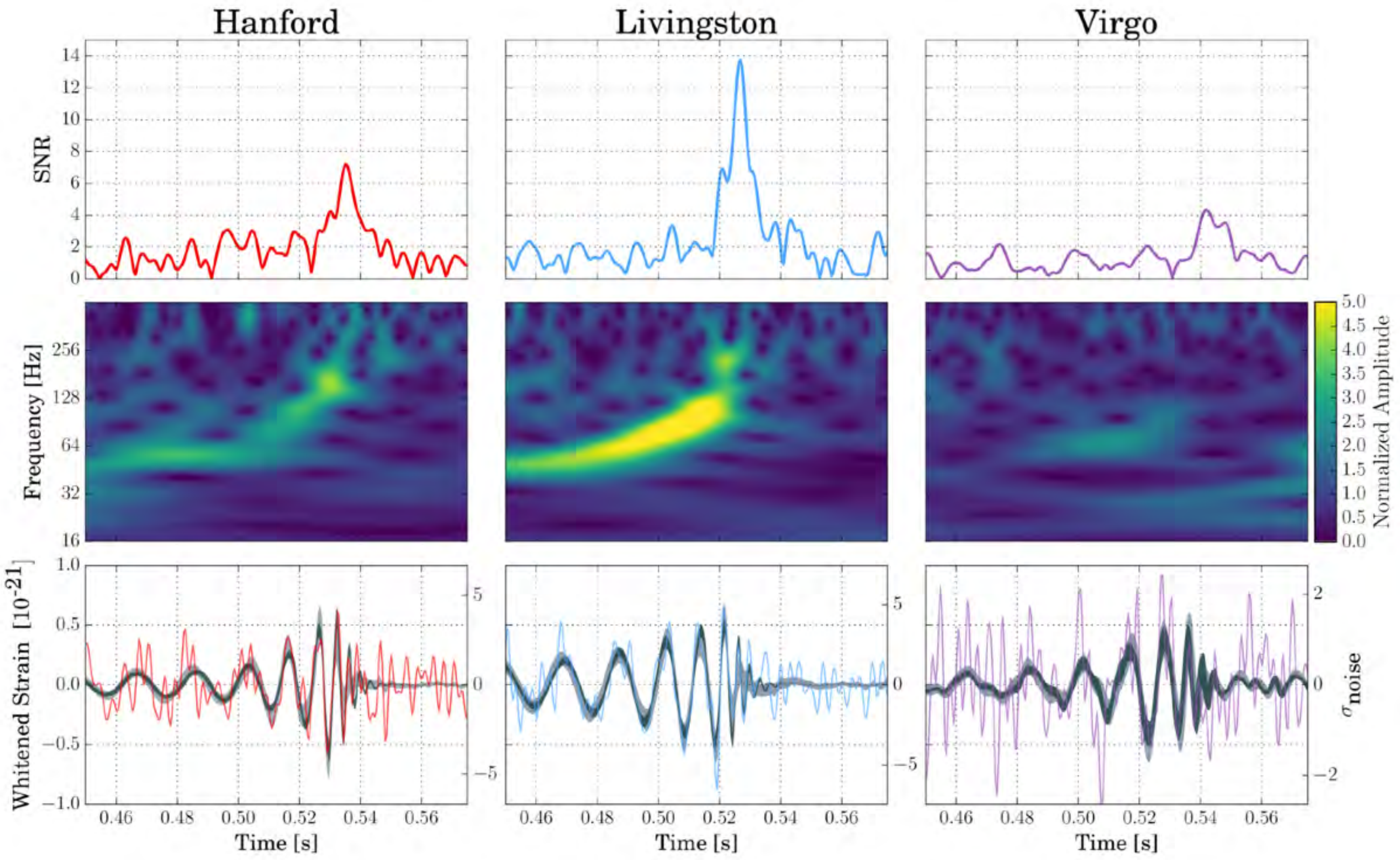

22 K (153 Mpc)
50 K (72 Mpc)
100 K (50 Mpc)
150 K (20 Mpc)
300 K (15 Mpc)
Sensitivity [1/Hz$^{-1/2}$]
$10^{-20}$
$10^{-21}$
$10^{-22}$
$10^{-23}$
$10^{-24}$
10
100
1000
Frequency [Hz]

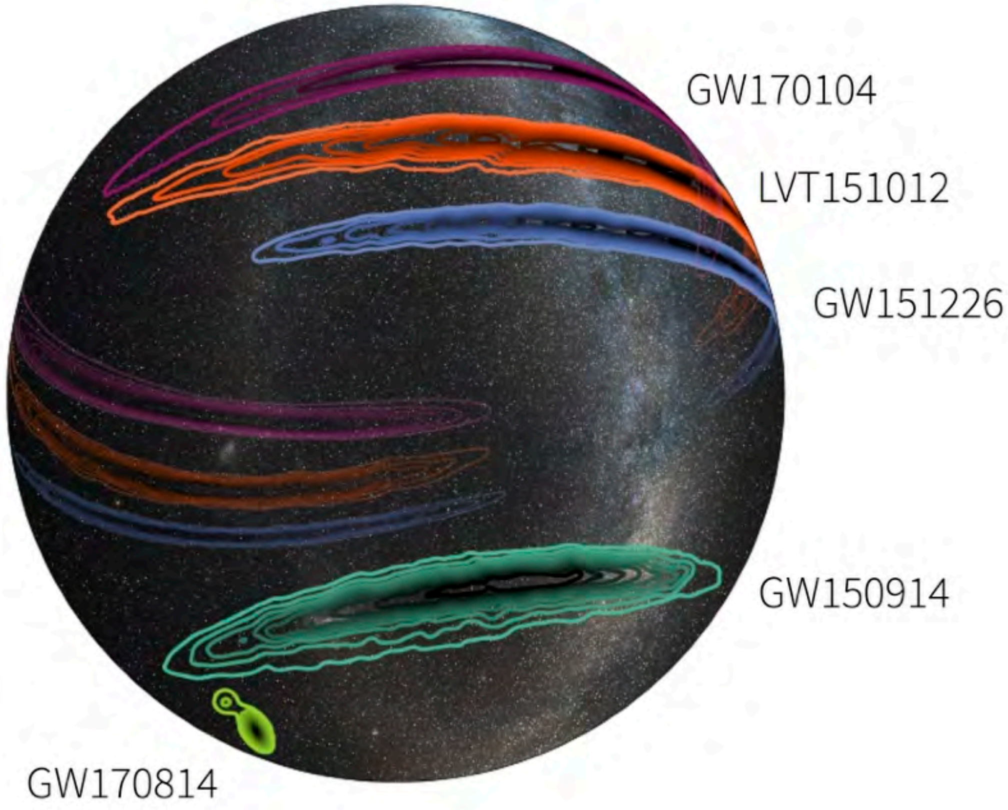
Akutsu+ 2021




BNS range ~ 1 Mpc

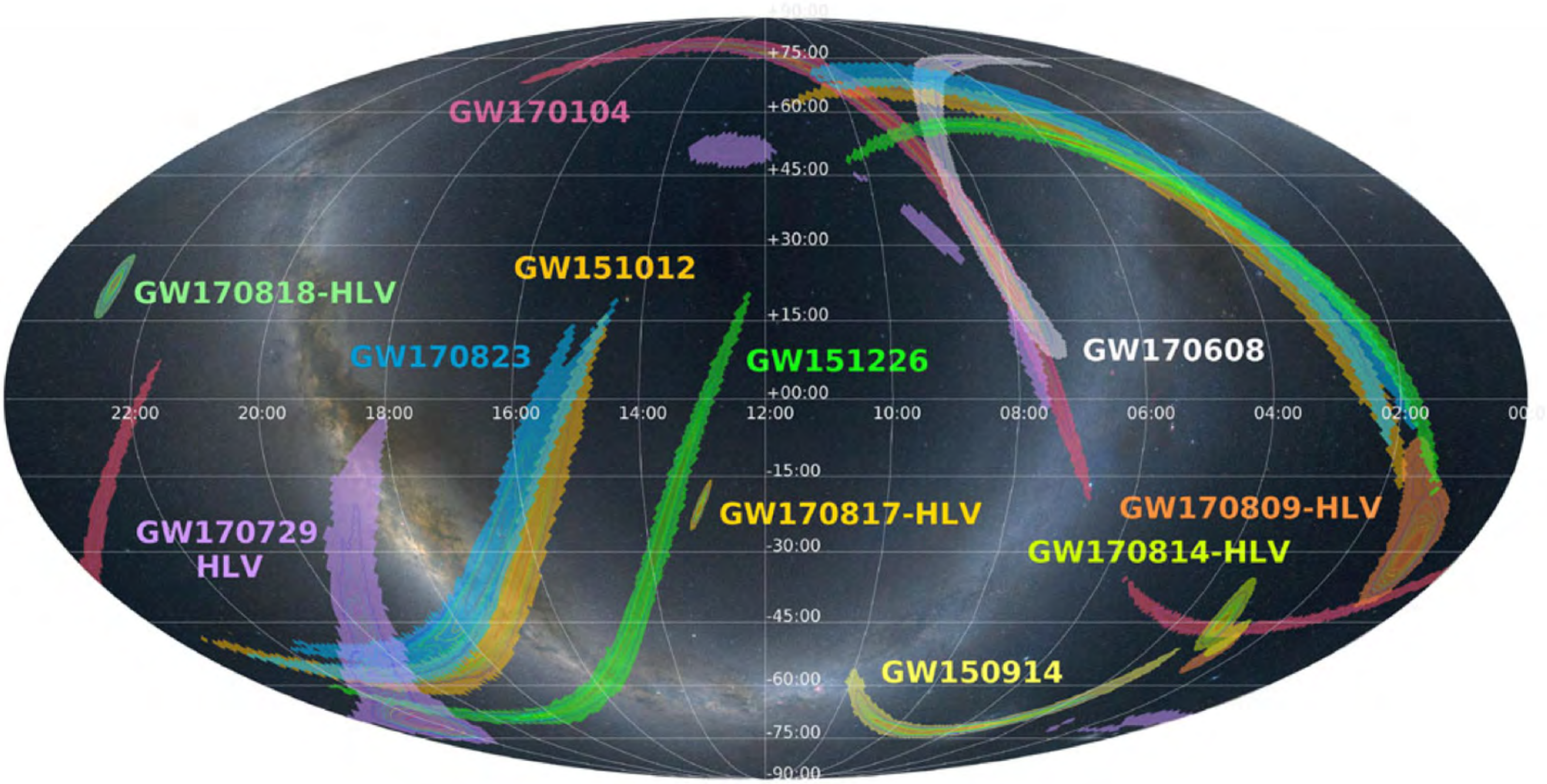
Akutsu+ 2021


Hanford
Livingston
Virgo
SNR
Frequency [Hz]
Normalized Amplitude
Whitened Strain [10^-21]
σnoise
Time [s]
Time [s]
Time [s]

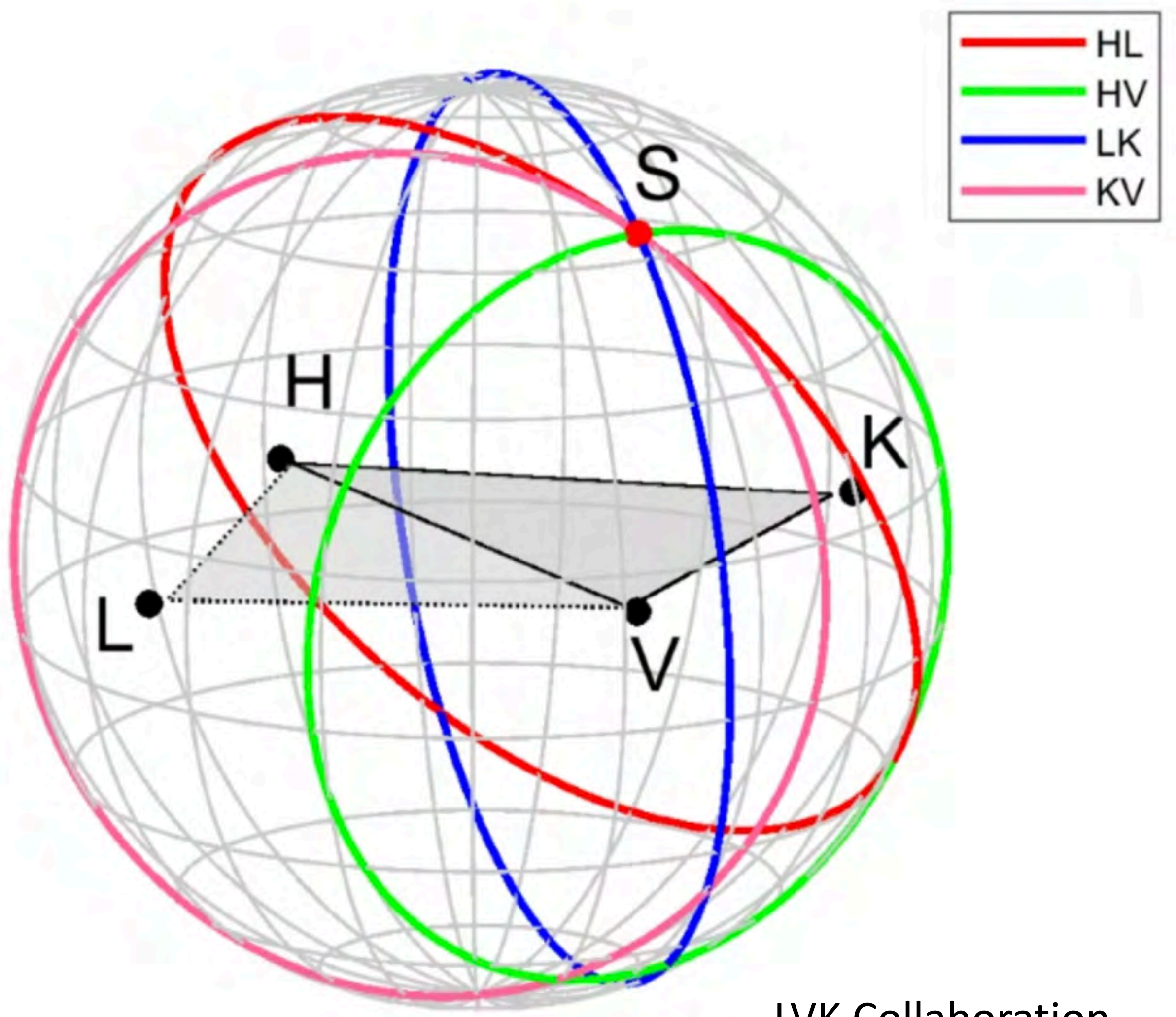

GW170104
LVT151012
GW151226
GW150914
GW170814

# GW170814

# Localisation is difficult

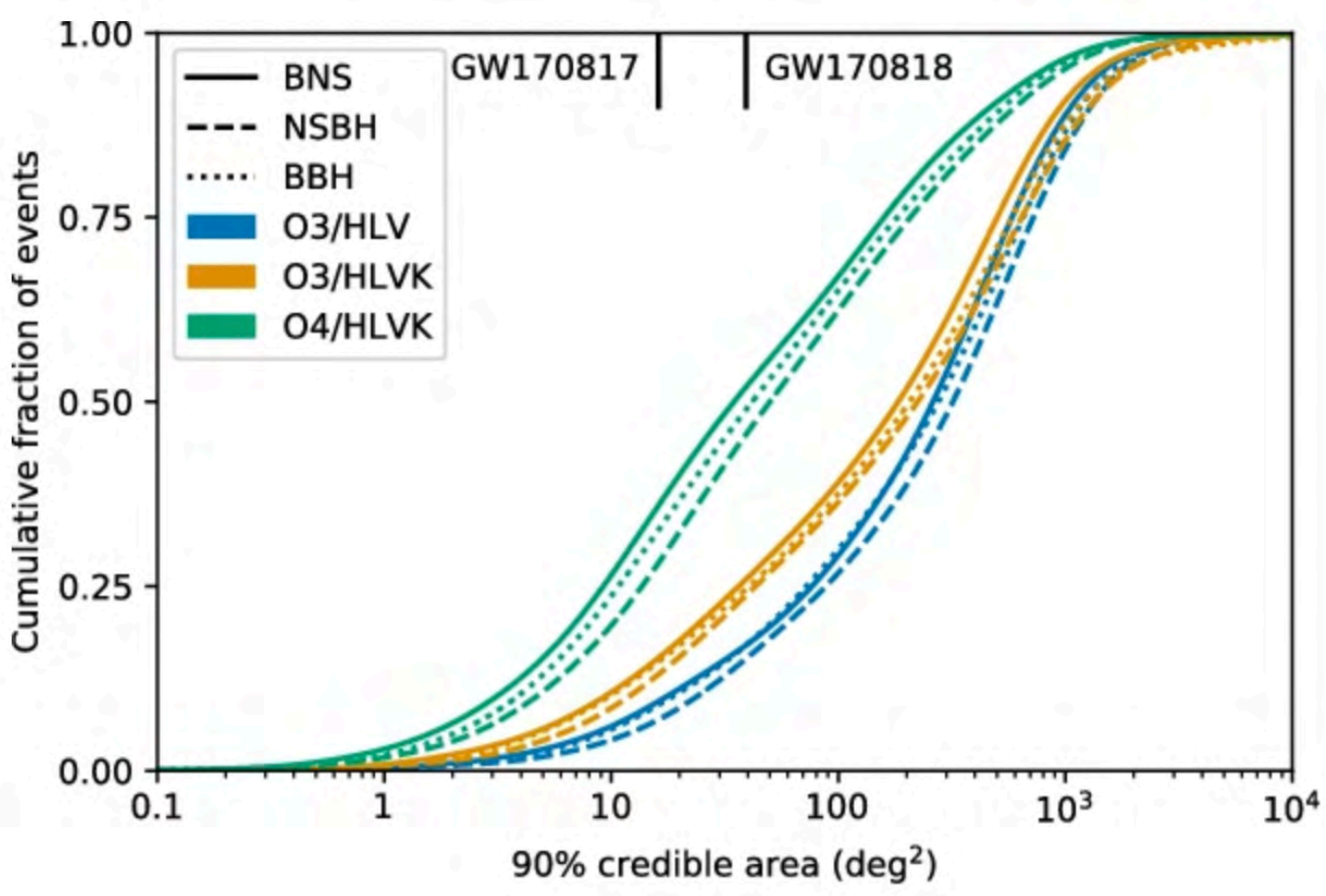


# Localisation



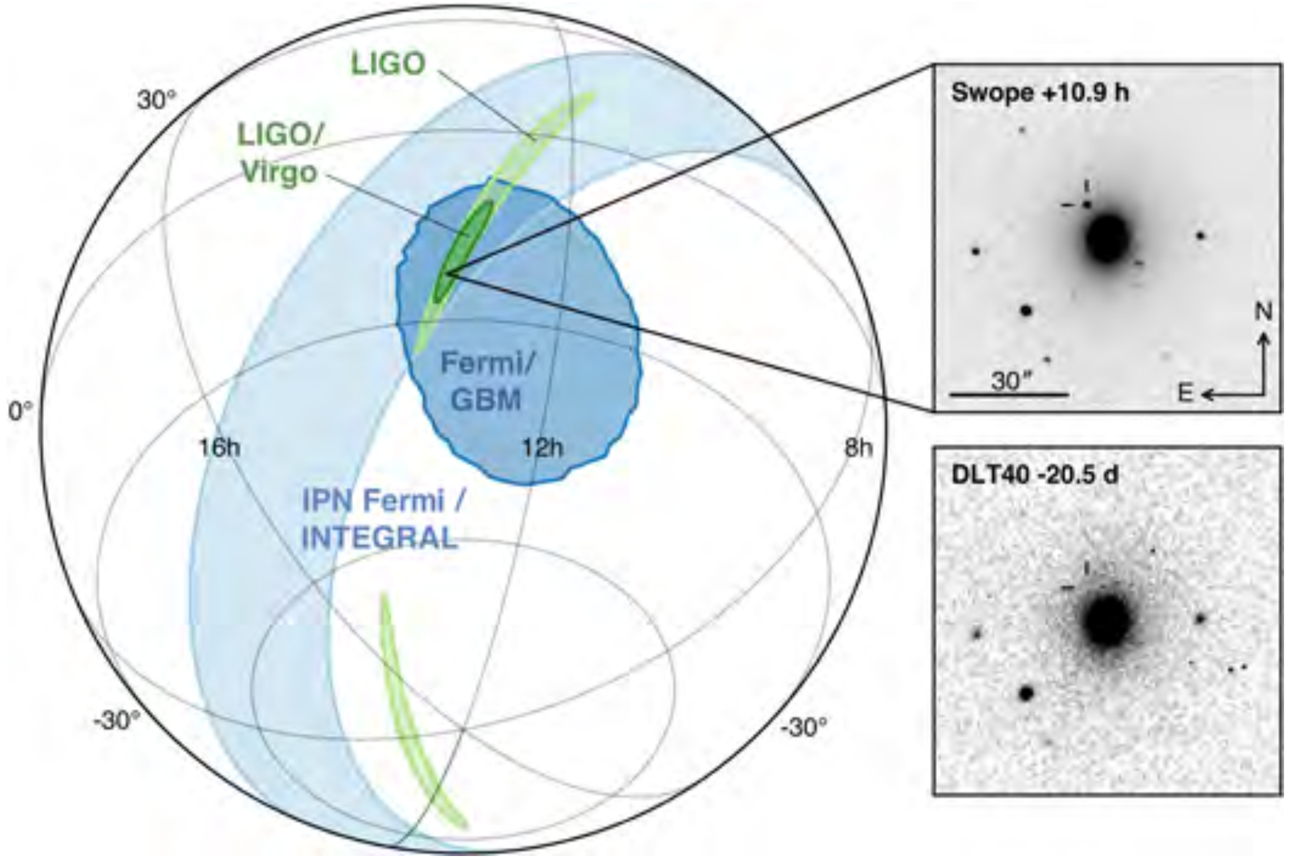

LVK Collaboration 2020, LRR

# Localisation is difficult



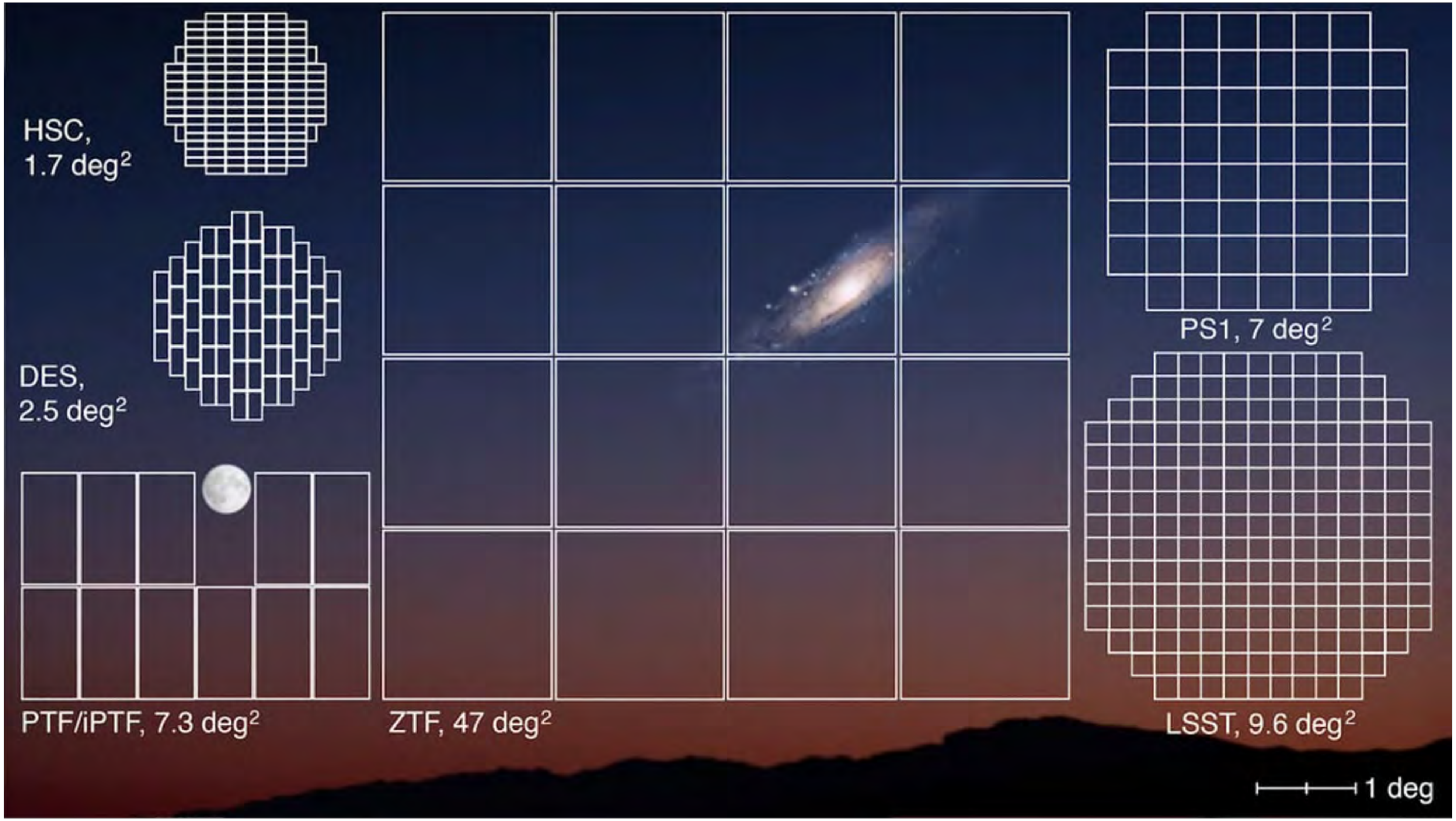

LVK Collaboration 2020, LRR

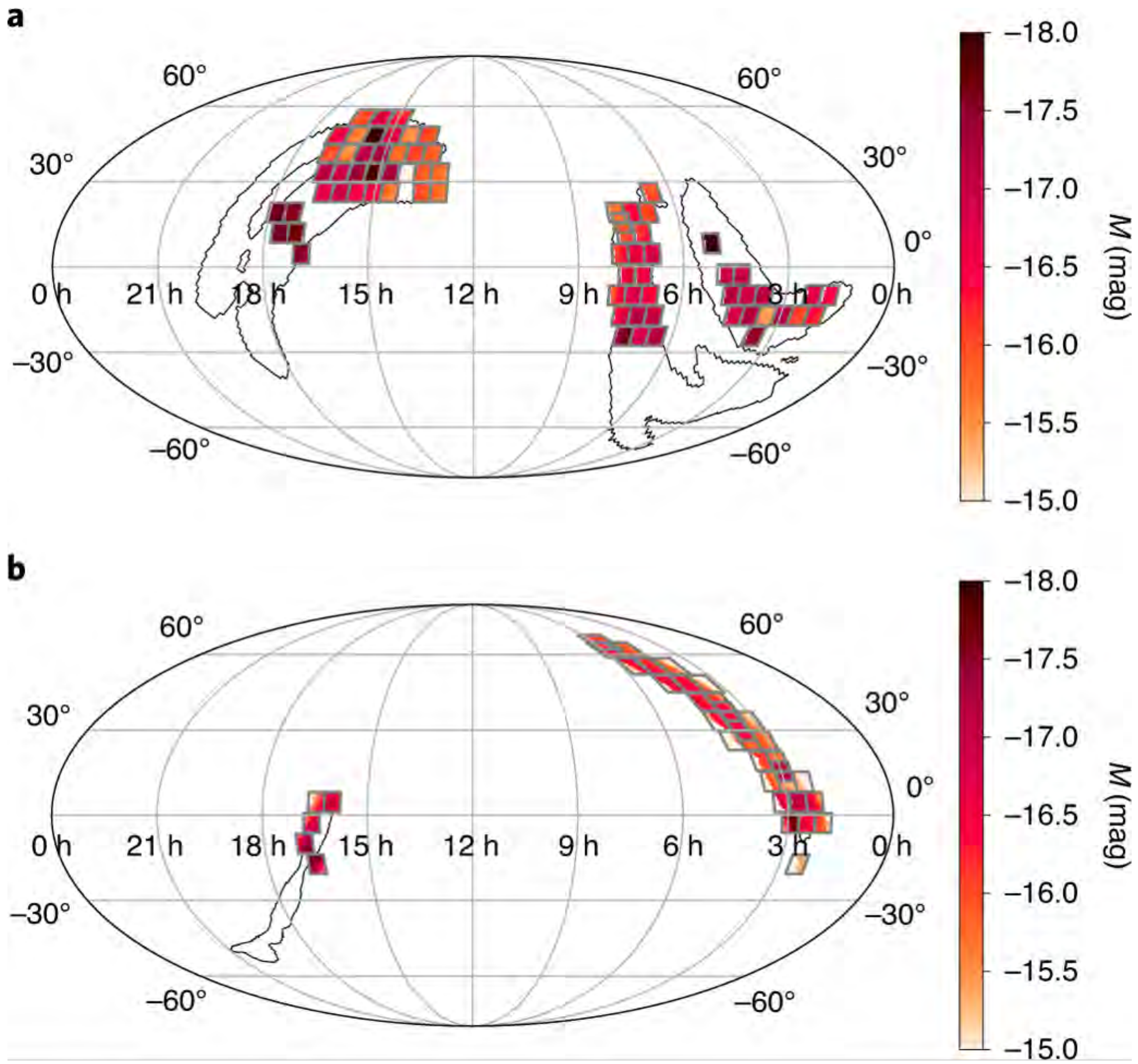
# Multi-messenger is difficult for GW events



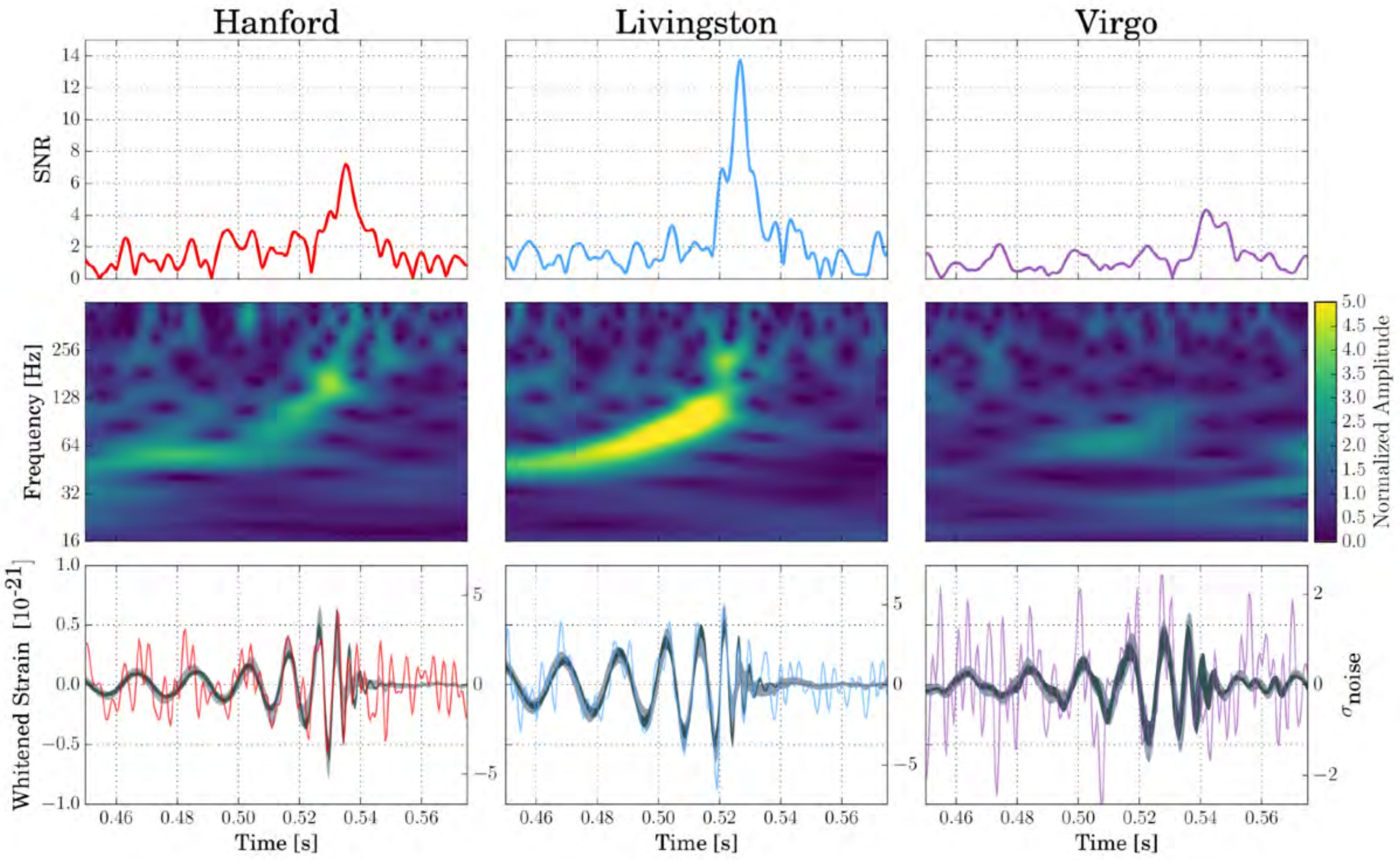

- With LIGO's Hanford and Livingston only
- Localisation: O(100) $deg^2$
- GW170817: 190 $deg^2$ (LIGO only)
  31 $deg^2$ (LIGO+Virgo)
- Three or more detectors are required for triangulation
- Four detectors can localise a unique position by just using time delay

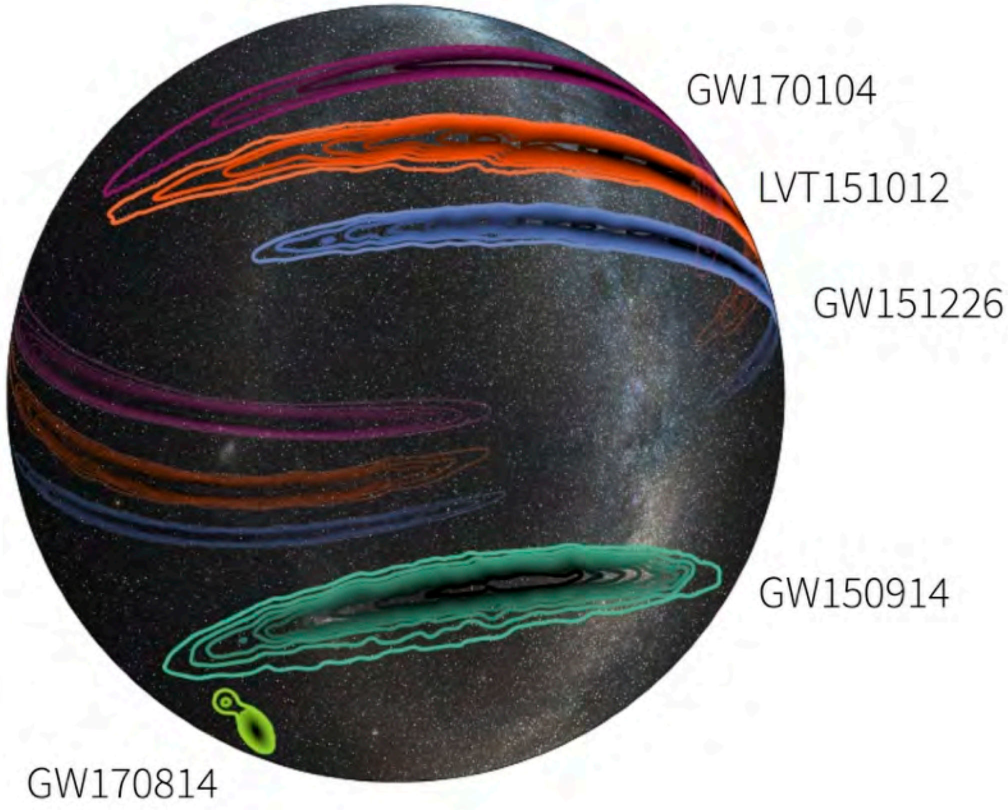
# Field-of-view of optical survey telescopes




a
60°
60°
30°
30°
0°
0 h
21 h
18 h
15 h
12 h
9 h
6 h
3 h
0 h
−30°
−30°
−60°
−60°
−18.0
−17.5
−17.0
−16.5
−16.0
−15.5
−15.0
M (mag)
b
60°
60°
30°
30°
0°
0 h
21 h
18 h
15 h
12 h
9 h
6 h
3 h
0 h
−30°
−30°
−60°
−60°
−18.0
−17.5
−17.0
−16.5
−16.0
−15.5
−15.0
M (mag)

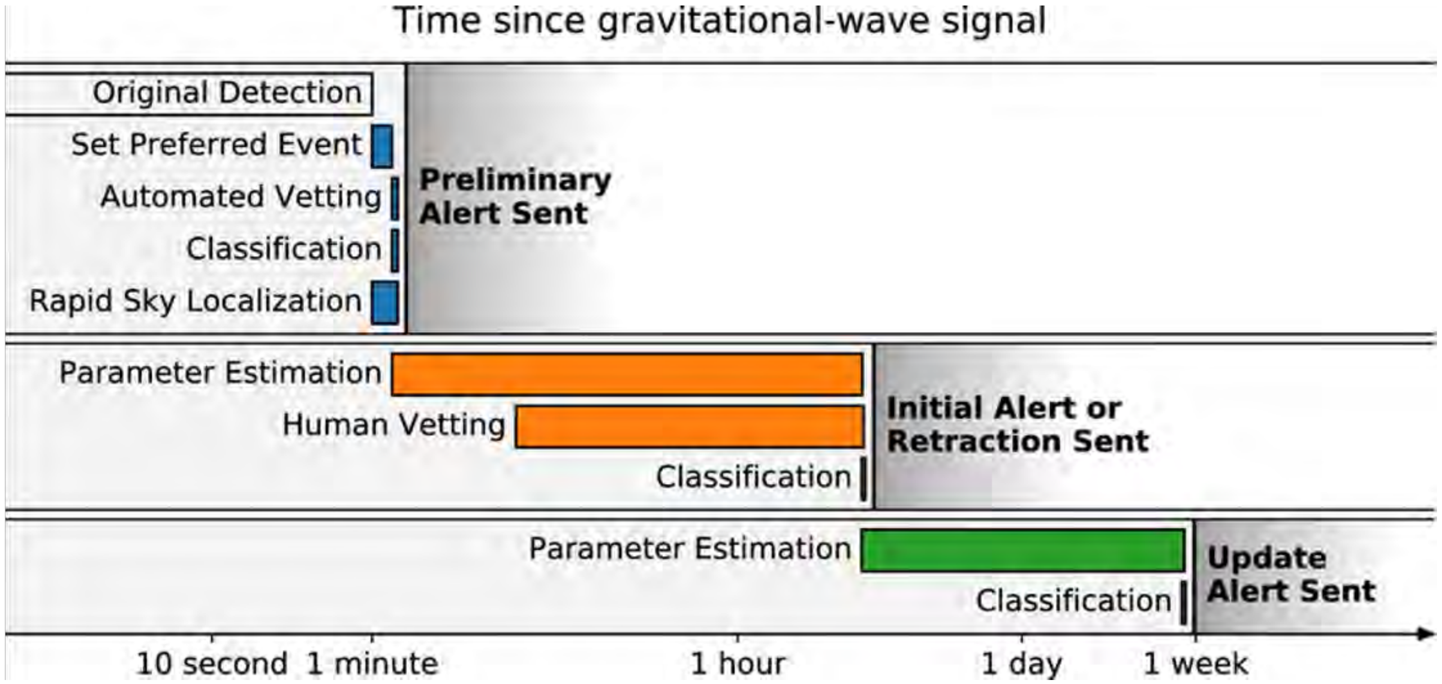
Anand+ 2021

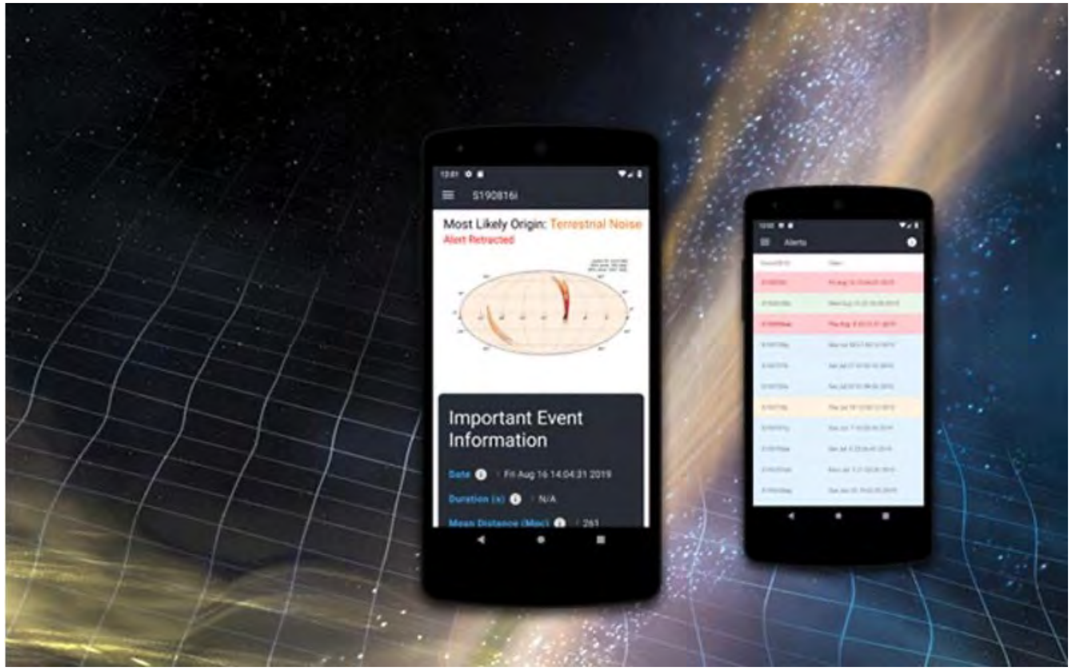

Hanford
Livingston
Virgo
SNR
Frequency [Hz]
Normalized Amplitude
Whitened Strain [10^-21]
$\sigma_{noise}$
Time [s]


GW170104
LVT151012
GW151226
GW150914
GW170814

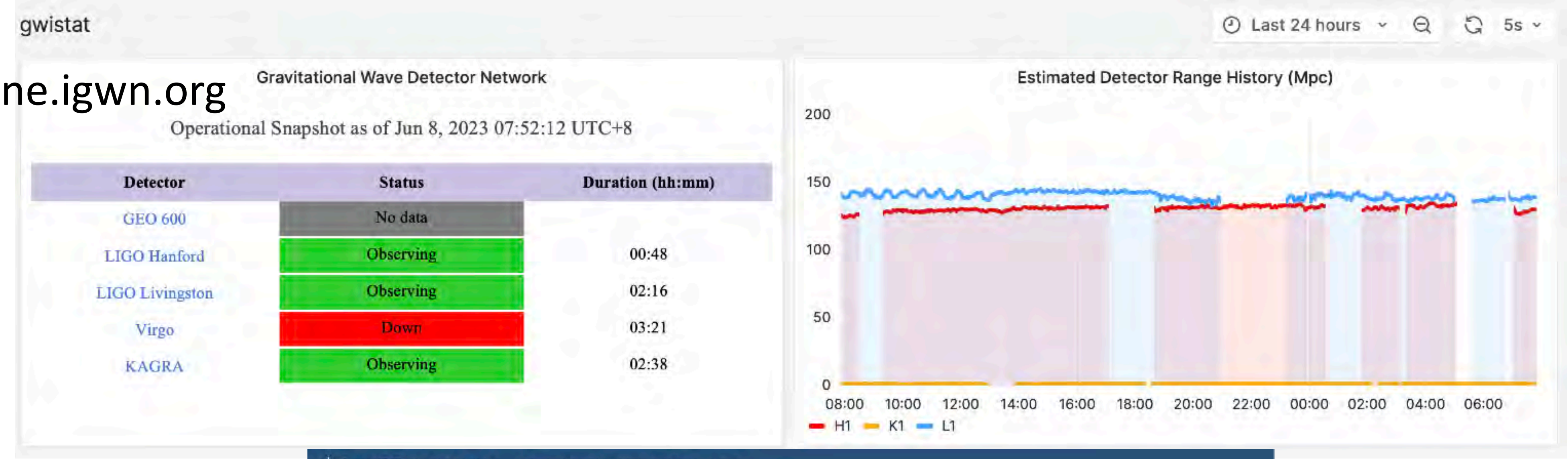
# GW170814

# Public Alerts

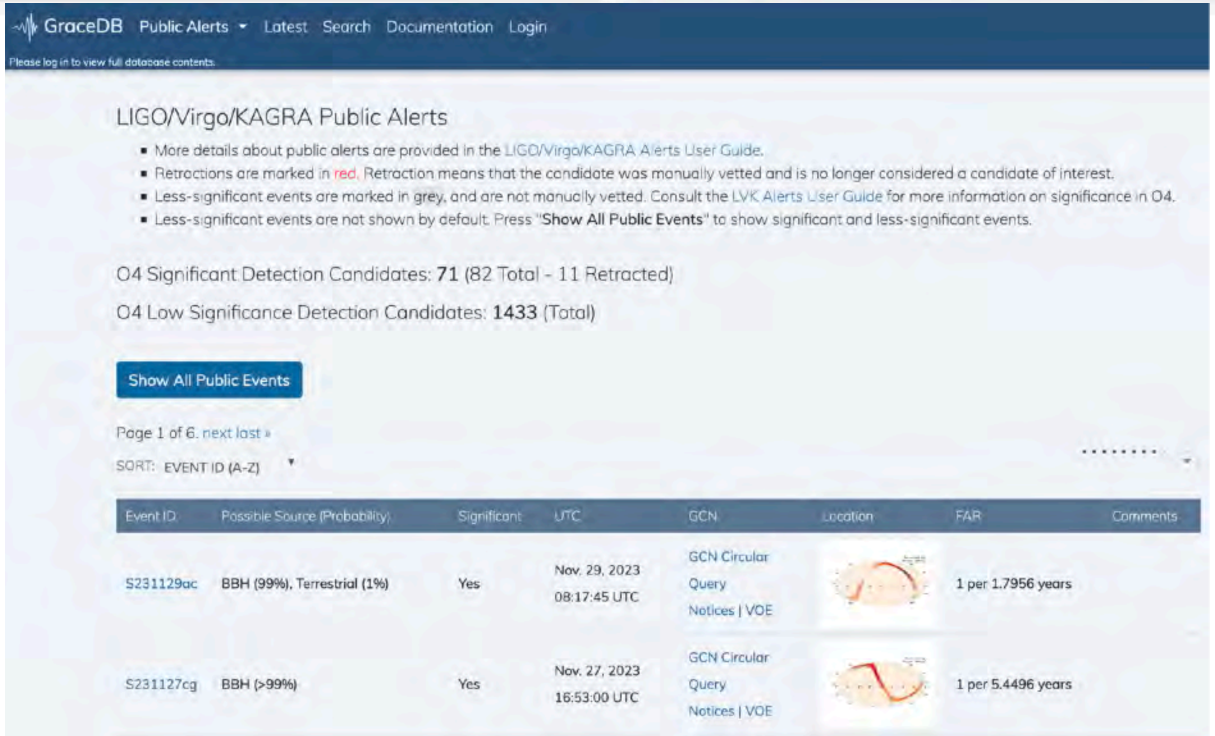



https://online.igwn.org



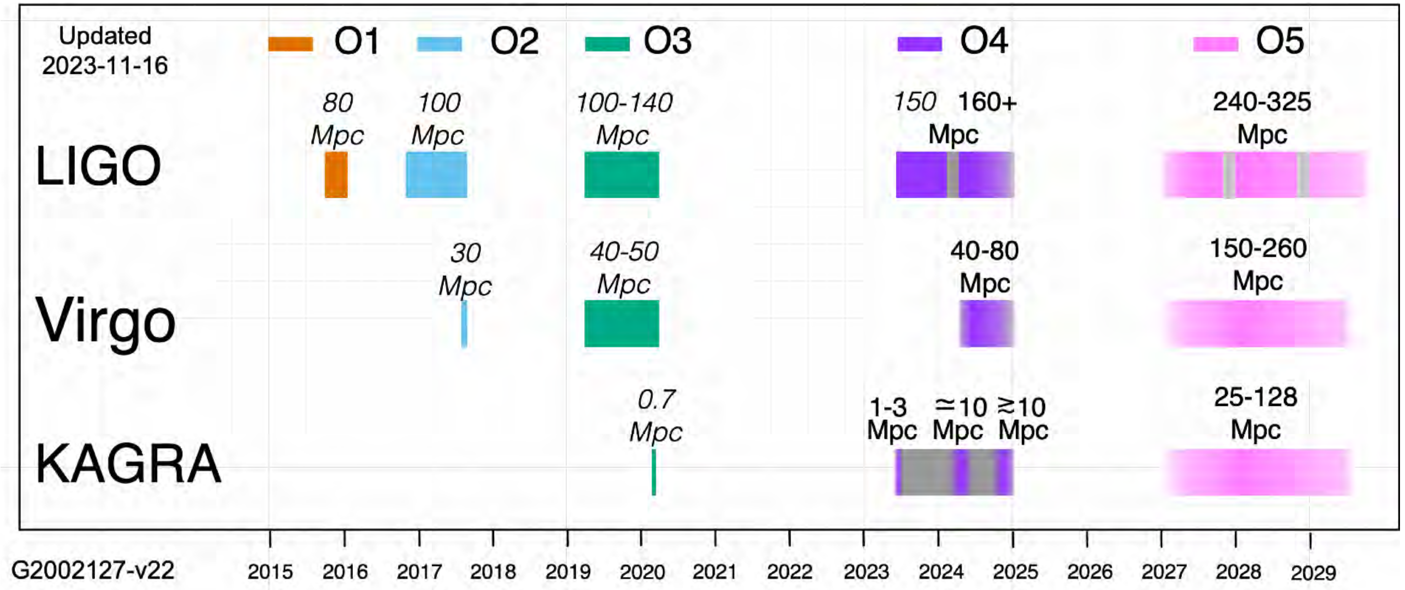

https://gracedb.ligo.org/



# What do we expect in O4 (20 months)? My very biased comments

- Expect O(300) binary black holes
- Expect O(10) events containing neutron stars (Colombo+ 2022)
  - Hopefully ~1 MMA event
  - Virgo and KAGRA will be crucial (localisation may be improved by including low S/N KAGRA data)
- Early warning pipelines have been implemented
- Constraints on the maximum mass of black hole and neutron star
- Better constraints on rates, populations, formation channels, and cosmological parameters
- GW from exotic binaries such as FRBs and magnetars
- Continuous GW from neutron stars
- If we are really lucky, GW from a nearby core collapse supernova

# Summary




- KAGRA is critical to multi-messenger astrophysics by providing better localisation
- As a 2.5G GW detector, KAGRA demonstrates key technologies (underground and cryogenics) for the next generation detectors
- KAGRA will join O4b in 2024 Spring with a BNS range of ~10 Mpc
- Various upgrade plans are being considered for O5