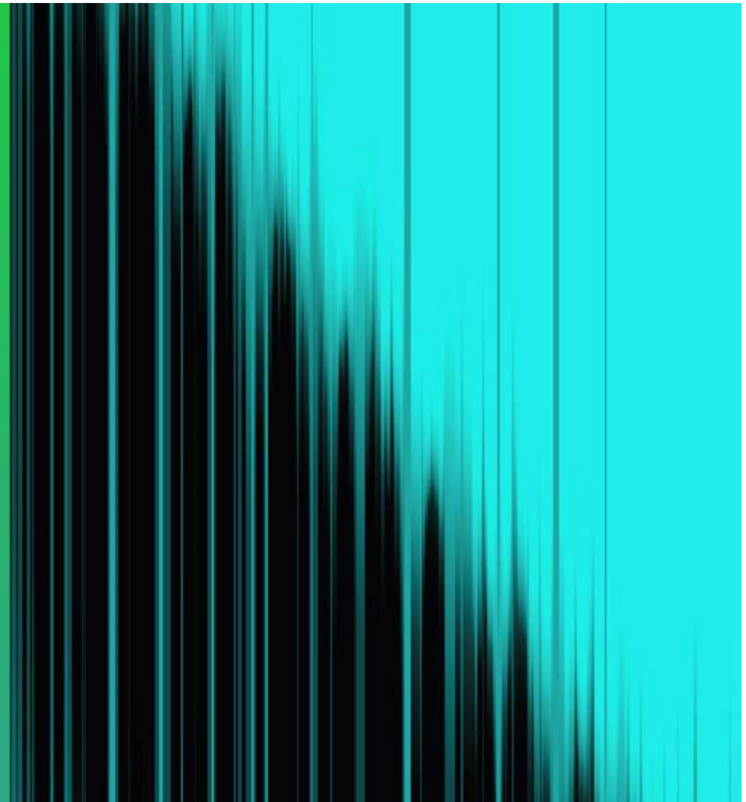
The Present and Future of Gravitational Wave Astrophysics

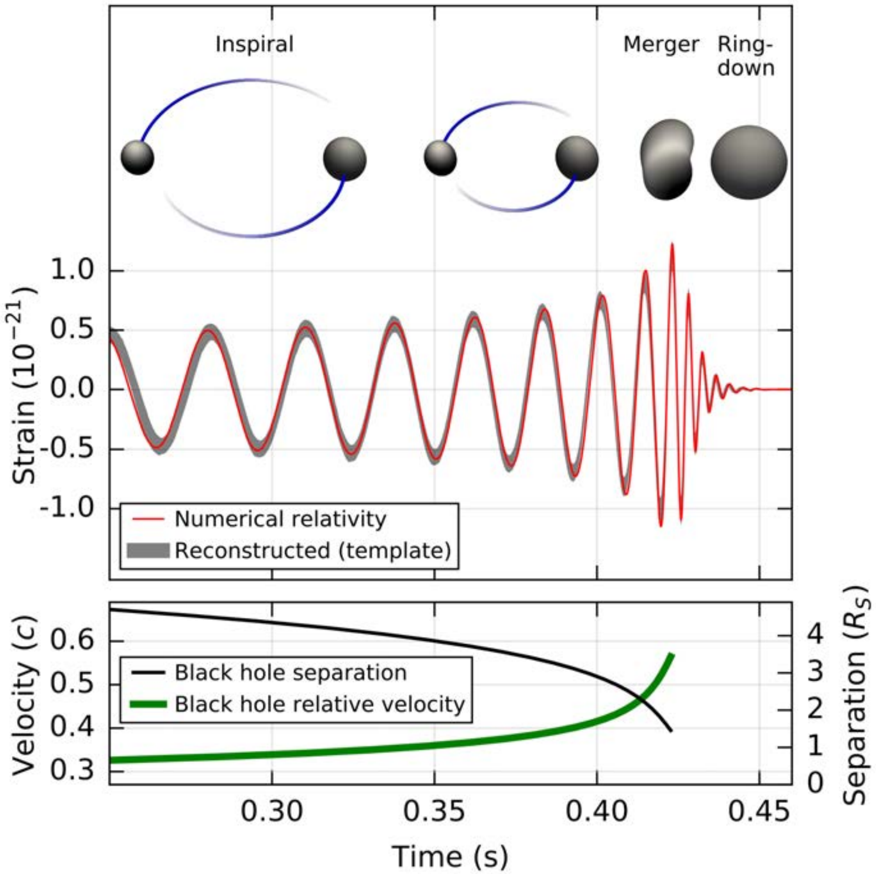
A short summary of team Taiwan

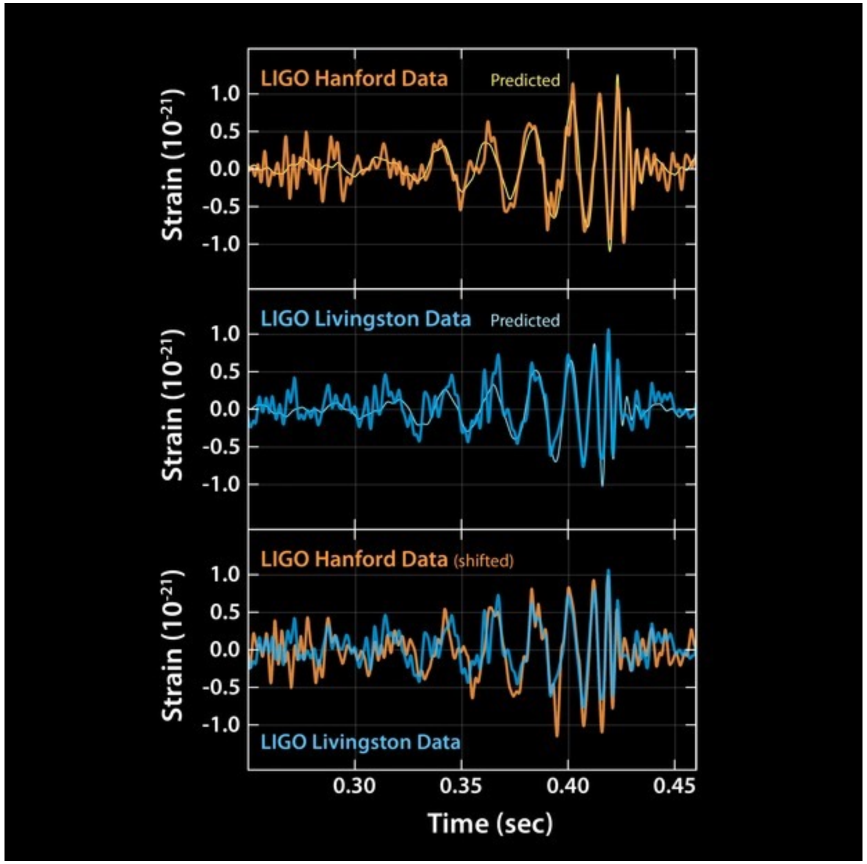


Albert Kong 江國興
Institute of Astronomy
National Tsing Hua University

Gravitational Wave Exhibition @NTHU Library

The first gravitational wave event GW150914





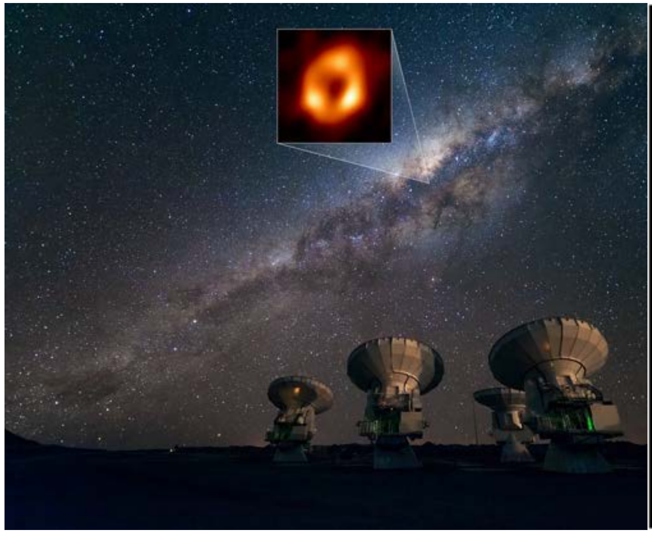
Key Messages from the First Discovery

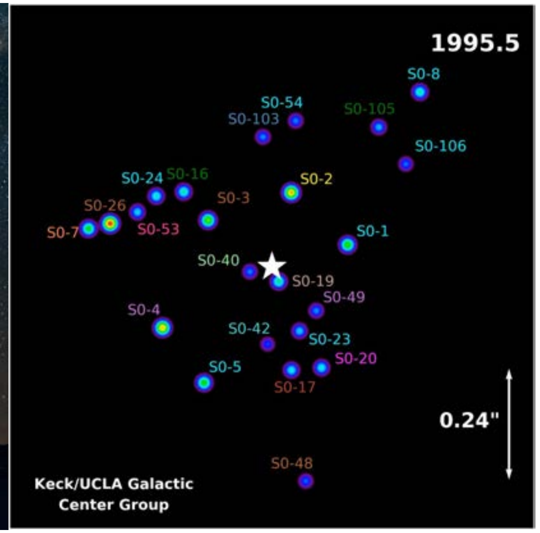
- Gravitational wave is real
- Further confirmation of Einstein's General Relativity
- Black hole is real and multiple black holes can merge together

Stellar-mass BH
(~10-100 M_{sun})

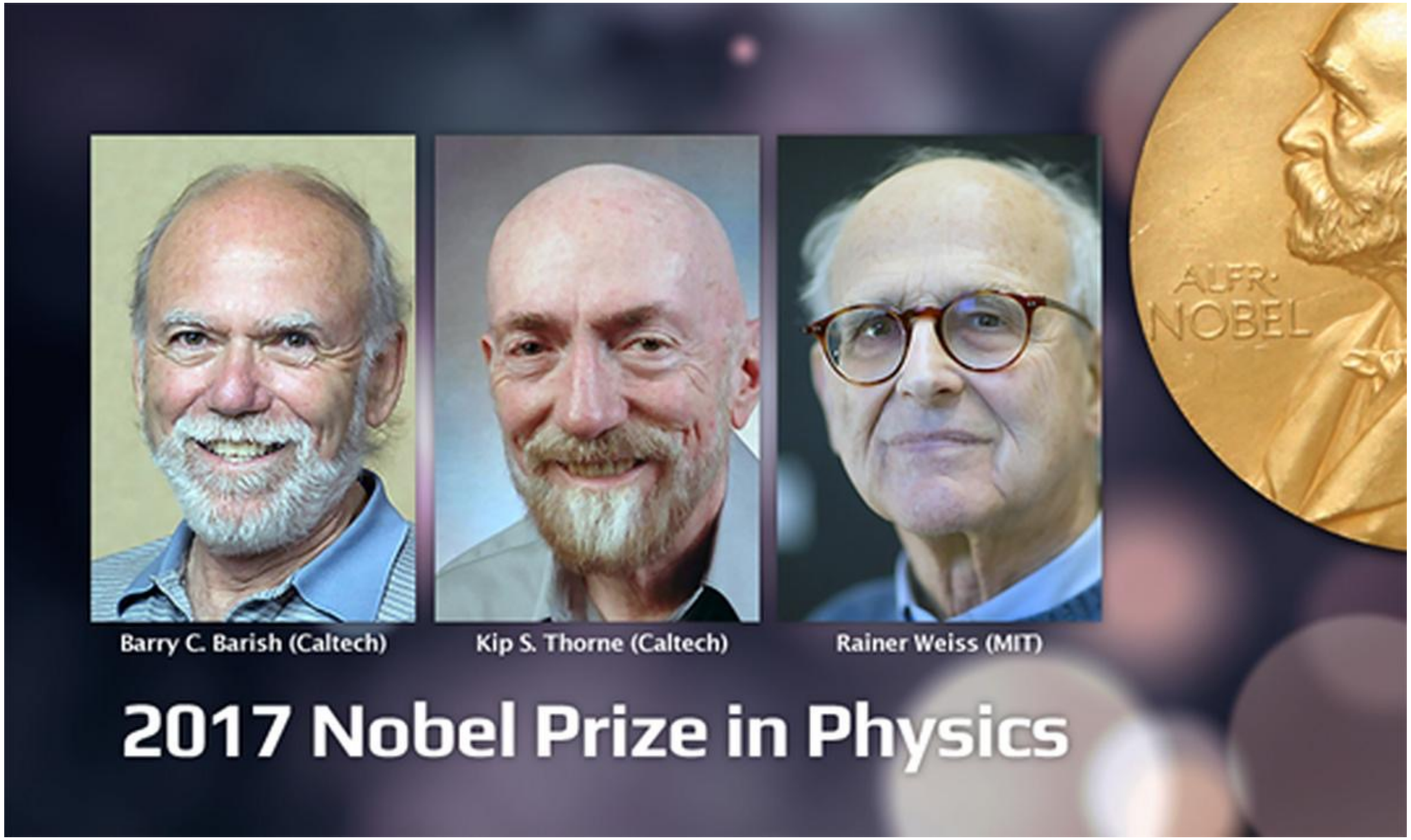
?

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

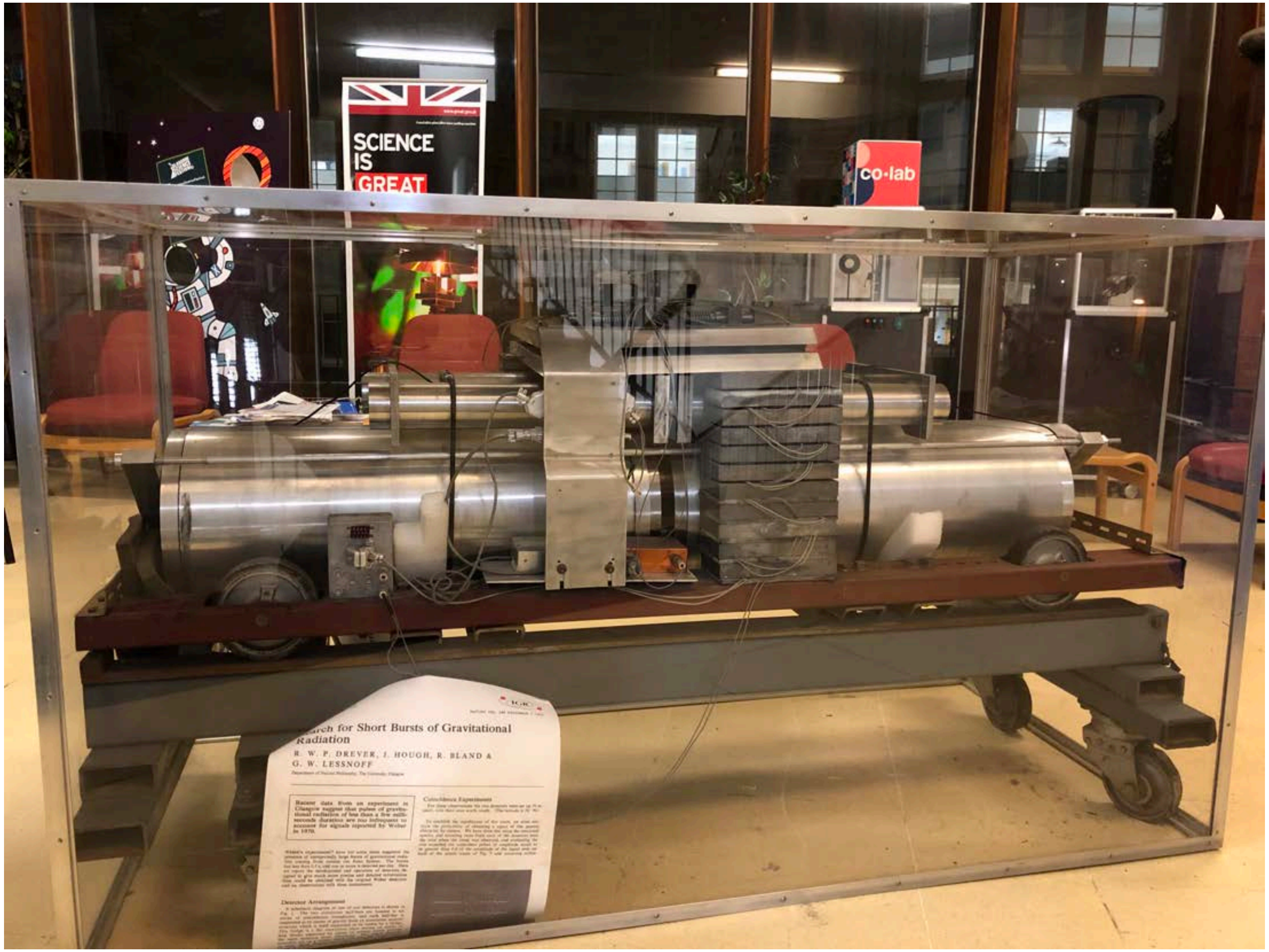




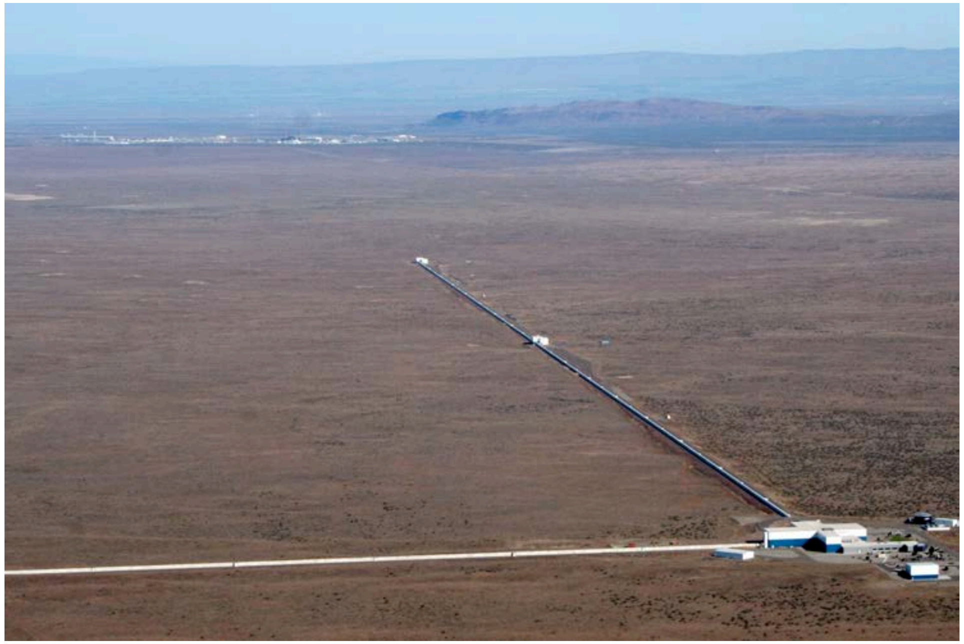
2017 Nobel Prize in Physics



Weber bar
韋伯棒

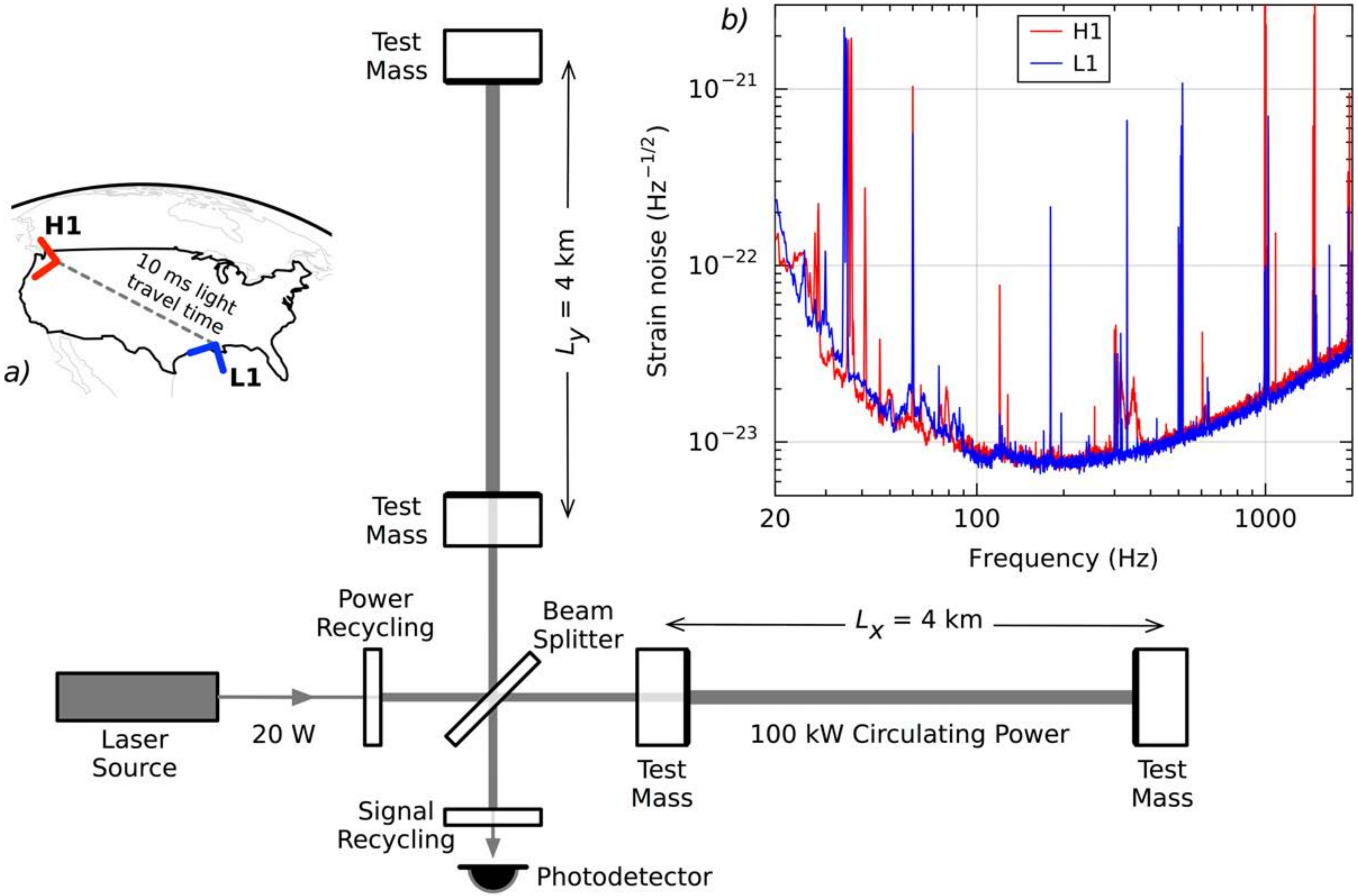


Laser Interferometer Gravitational-Wave Observatory (LIGO)



LIGO Hanford Observatory

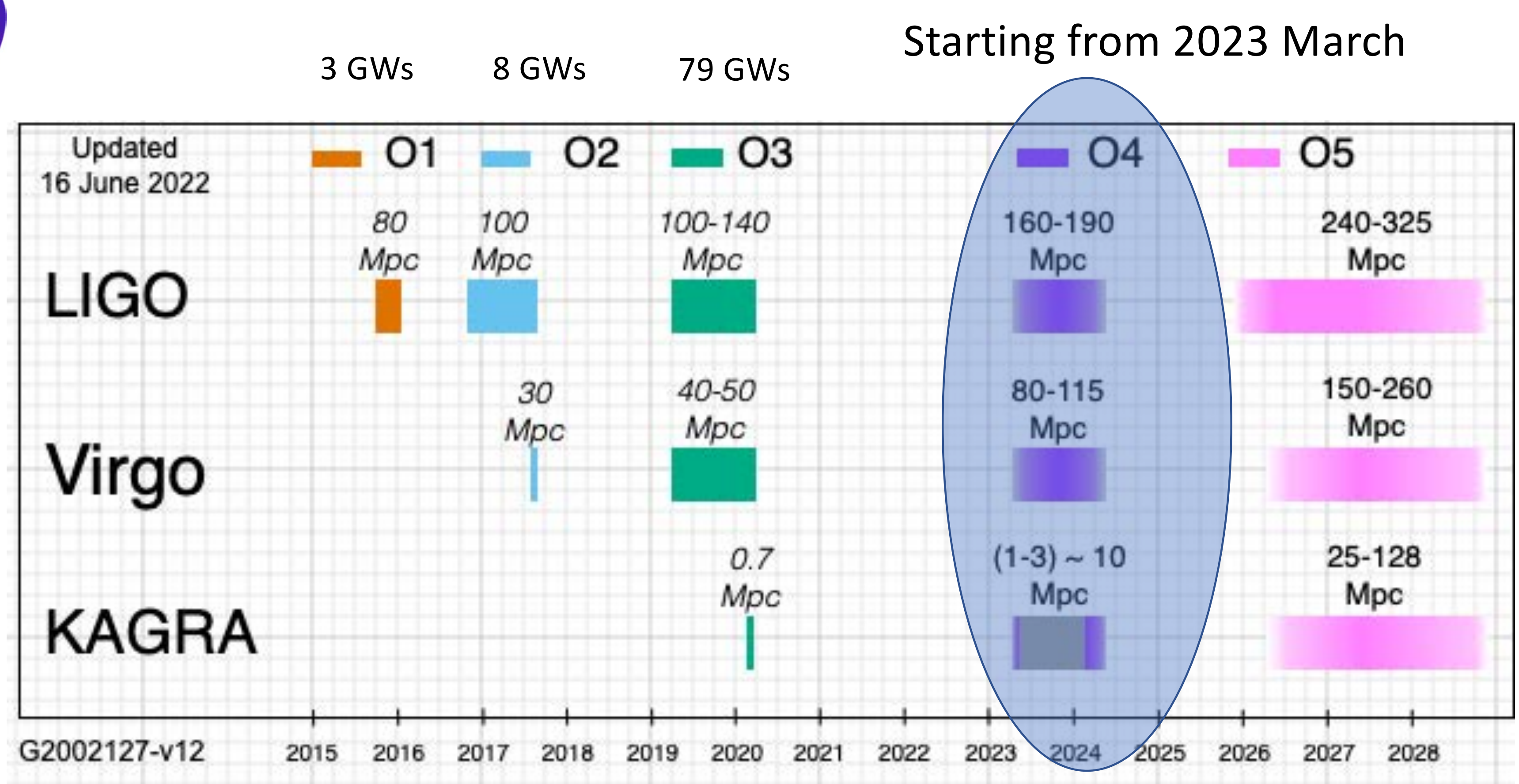
LIGO Livingston Observatory

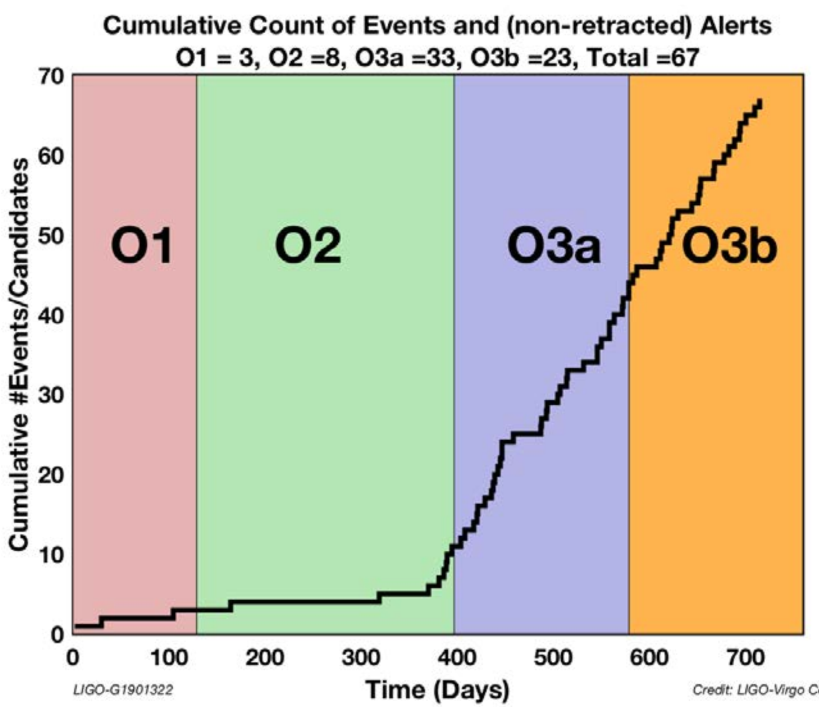

a)
H1
L1
10 ms light travel time
b)
H1
L1
Strain noise (Hz$^{-1/2}$)
10^{-21}
10^{-22}
10^{-23}
20
100
1000
Frequency (Hz)
Test Mass
Test Mass
L_y = 4 km
Laser Source
20 W
Power Recycling
Beam Splitter
L_x = 4 km
Test Mass
100 kW Circulating Power
Test Mass
Signal Recycling
Photodetector

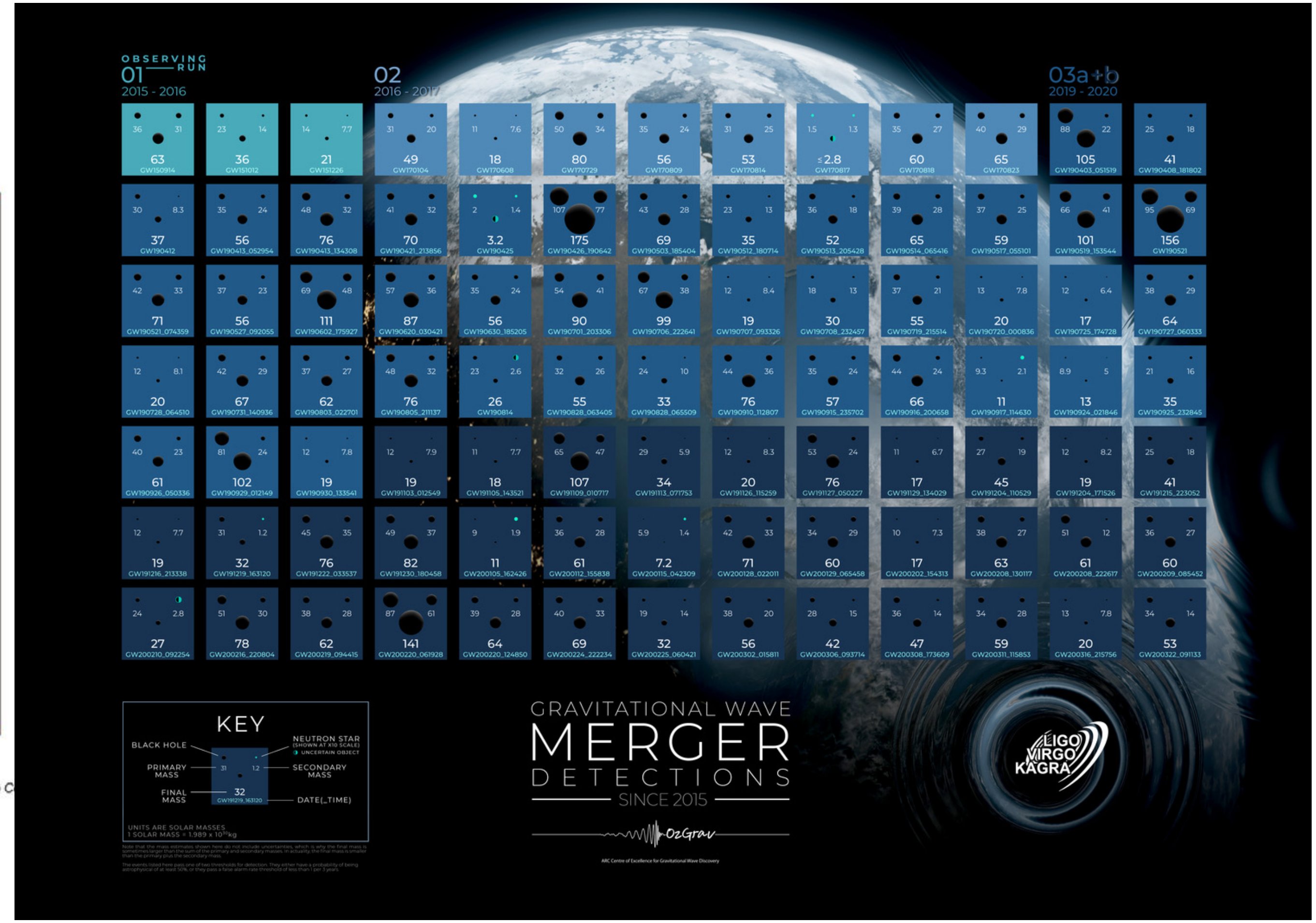
Virgo

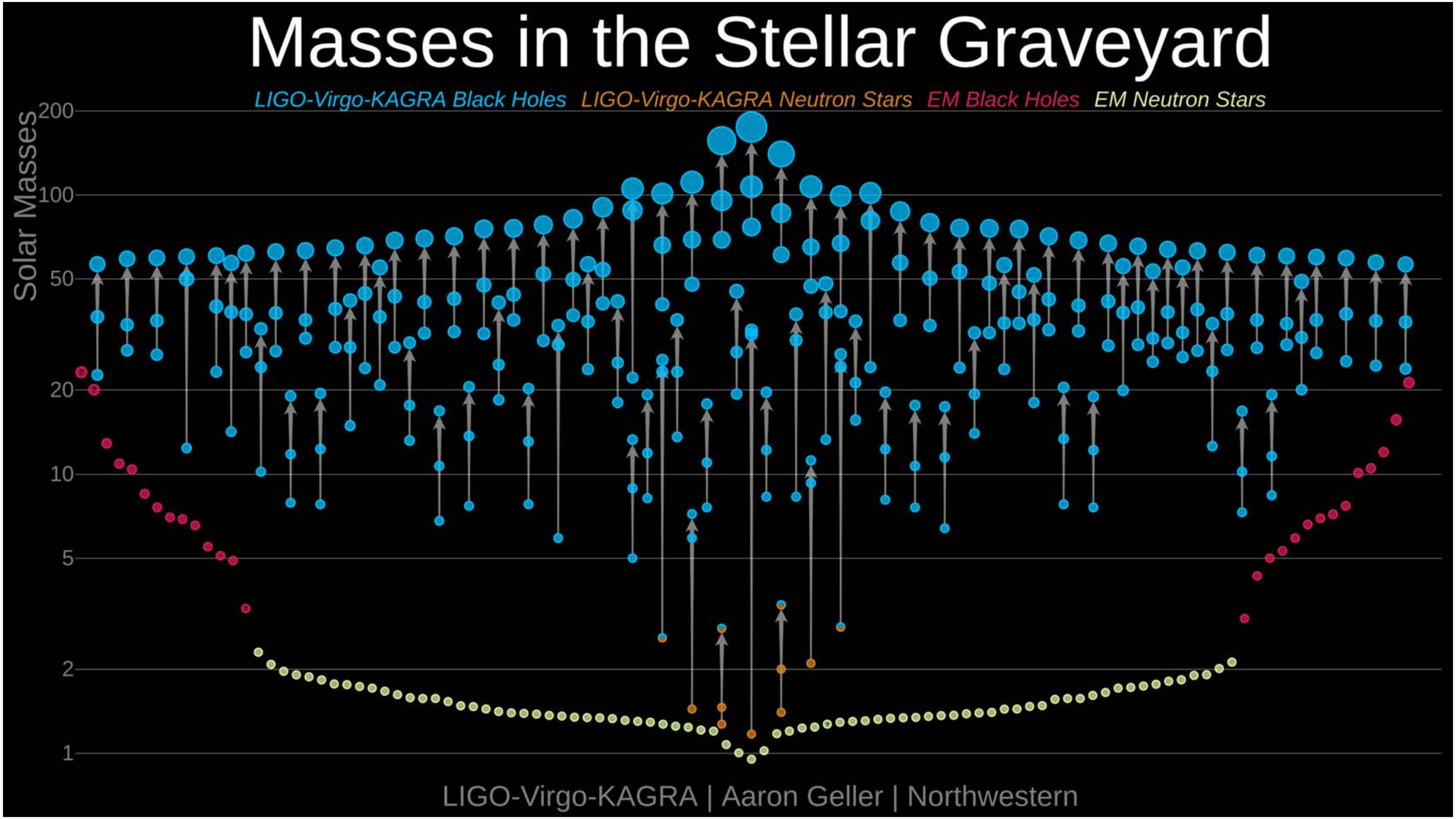
VIRGO

LIGO
VIRGO
KAGRA




Cumulative Count of Events and (non-retracted) Alerts
O1 = 3, O2 =8, O3a =33, O3b =23, Total =67
O1
O2
O3a
O3b
Cumulative #Events/Candidates
Time (Days)
LIGO-G1901322
Credit: LIGO-Virgo C


OBSERVING RUN
O1
2015 - 2016
O2
2016 - 2017
O3a+b
2019 - 2020
KEY
BLACK HOLE
NEUTRON STAR
PRIMARY MASS
SECONDARY MASS
FINAL MASS
DATE(_TIME)
GRAVITATIONAL WAVE
MERGER
DETECTIONS
SINCE 2015
OzGrav
LIGO
VIRGO
KAGRA

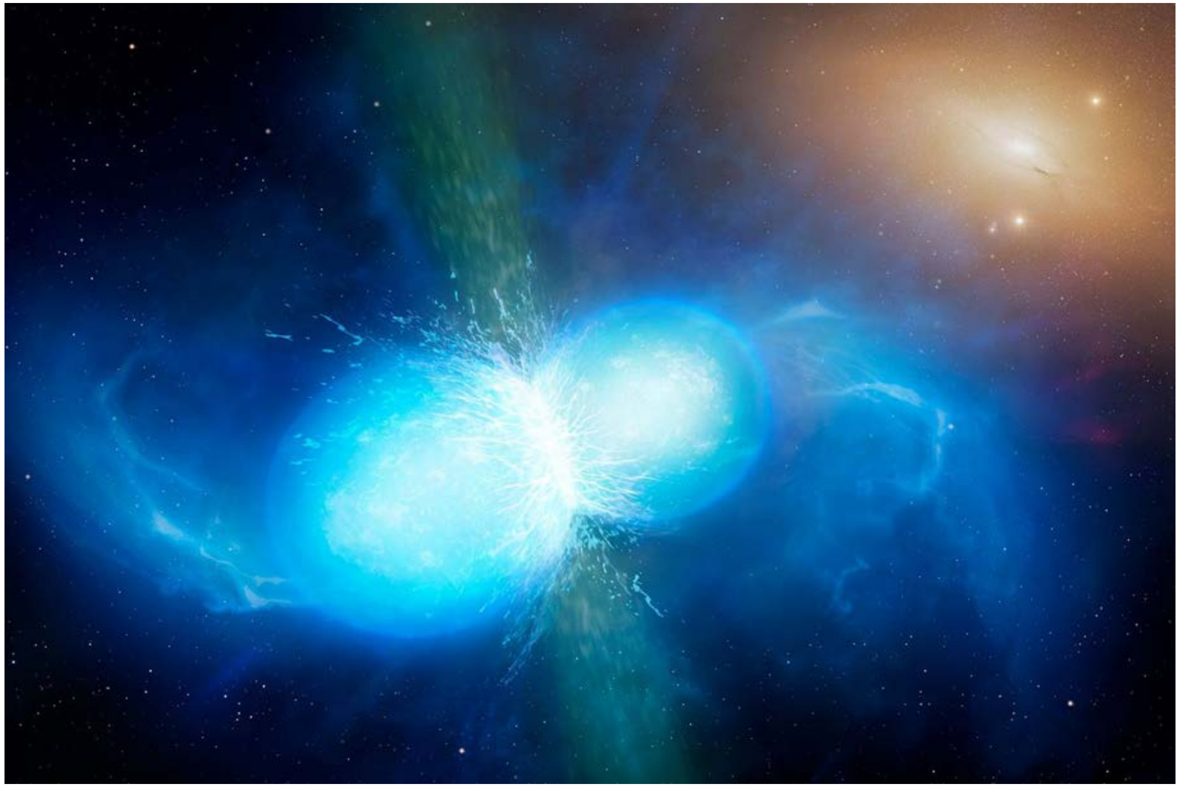

Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

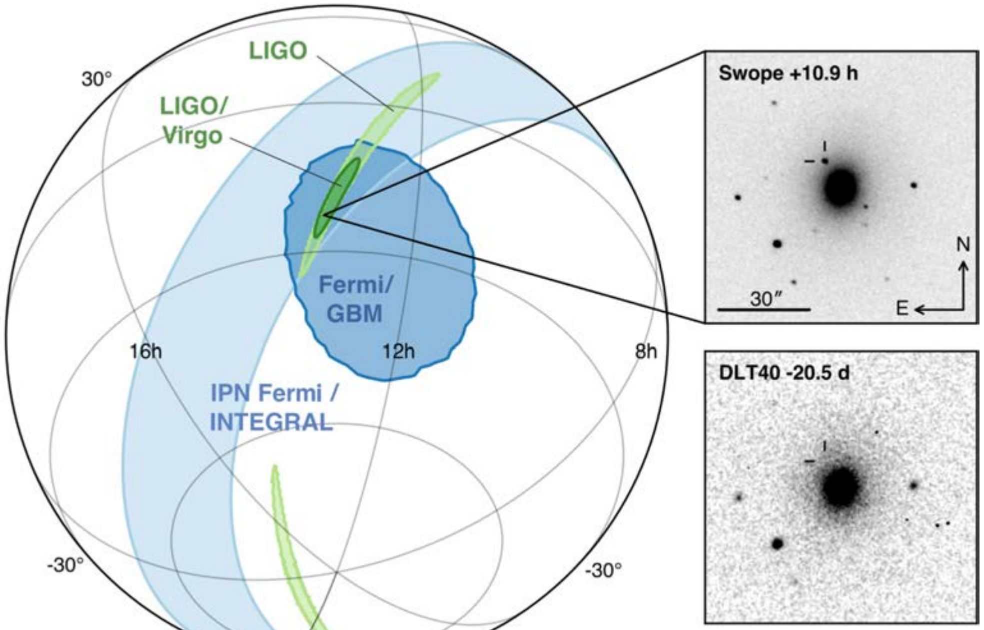
Major Discoveries in 2015-2020

- GW from merging binary neutron stars and associated EM counterparts
- GW from neutron star-black hole mergers
- Formation of intermediate-mass black hole
- GW from compact objects in the mass gaps

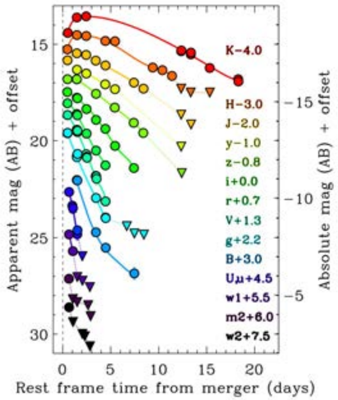
GW from merging binary neutron stars and associated EM counterparts

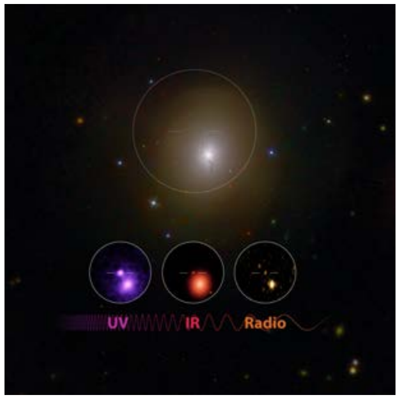
- Two in total (GW170817 and GW190425)
- GW170817 is assocated with a short gamma-ray burst and has gamma-ray, X-ray, optical, IR, and radio counterparts
- The combined mass of GW190425 is 3.4 $M_{\odot}$

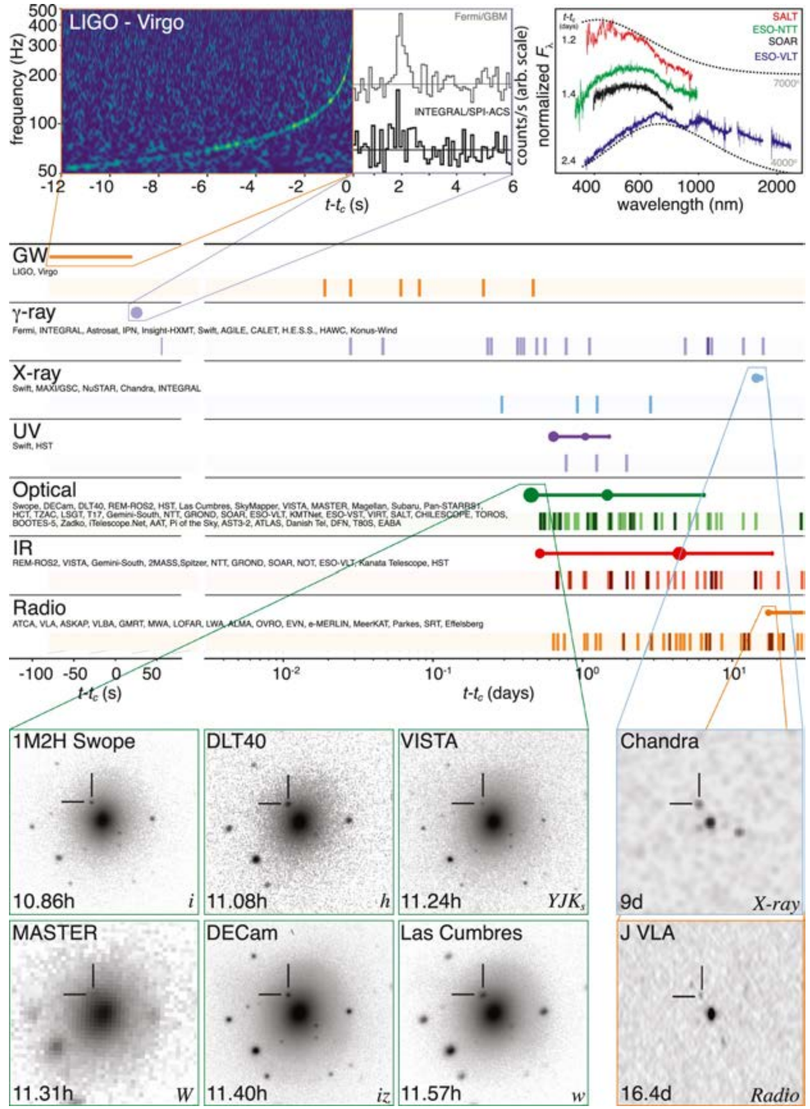




Abbott et al. 2017

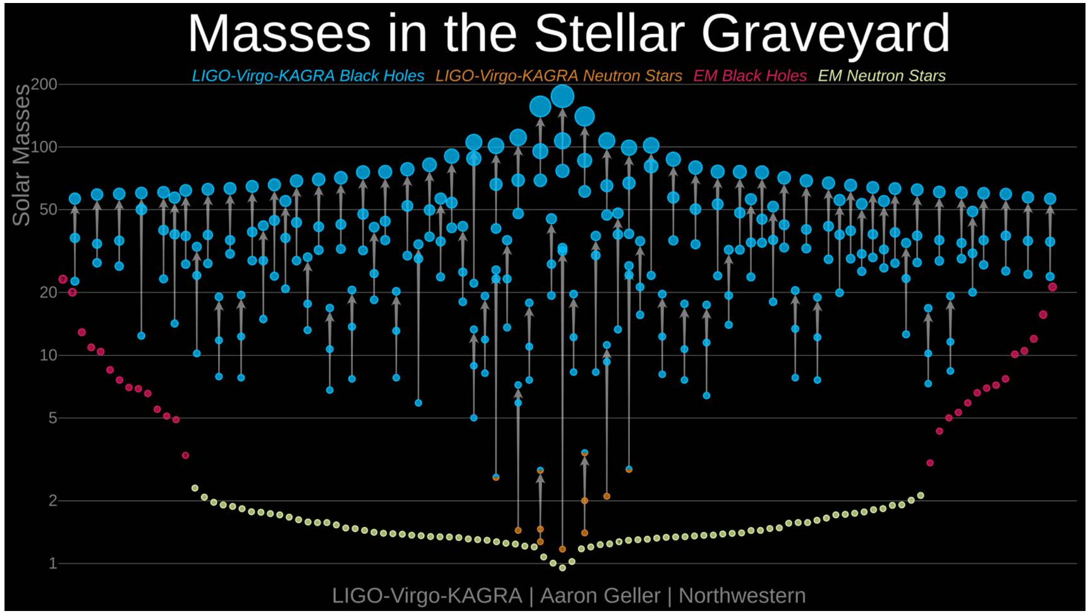


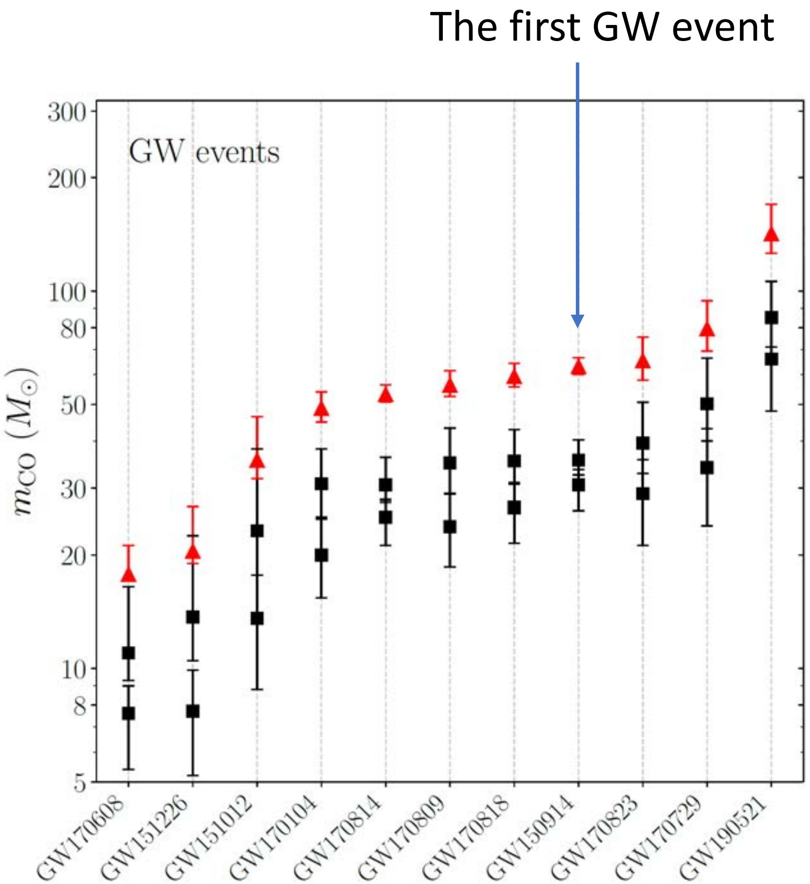




Formation of Intermediate-mass BHs

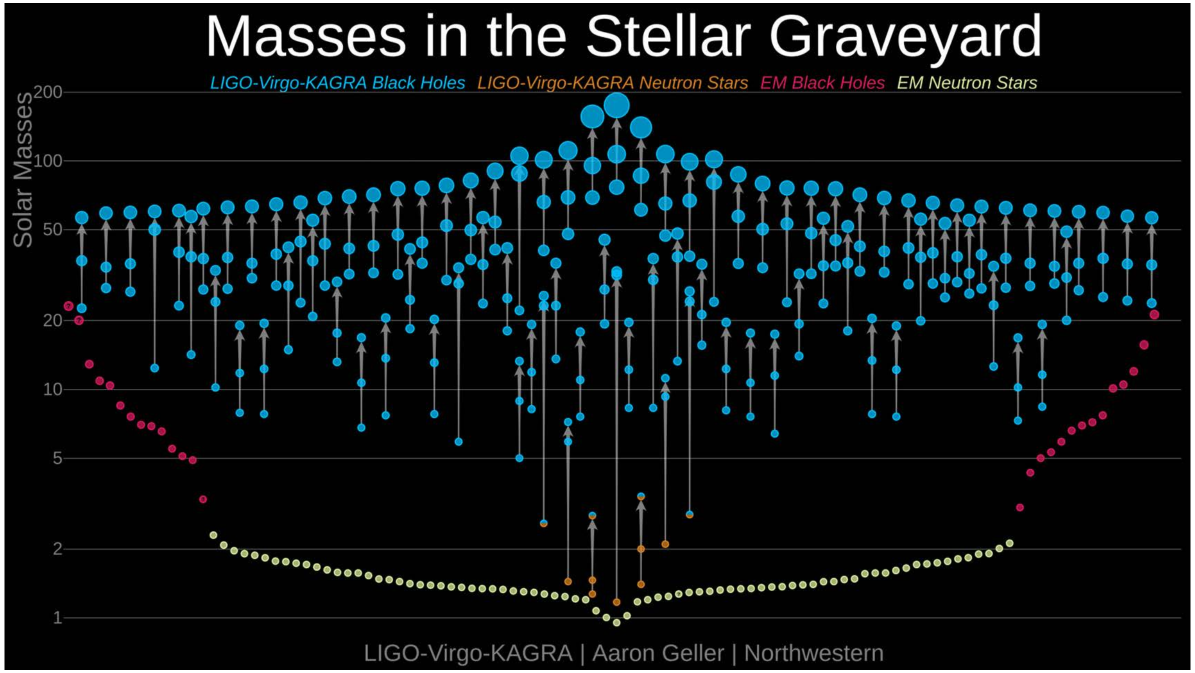
- Three in total
- The most massive one is 142 $M_{\odot}$
  - GW190521 (85+66 $M_{\odot}$)



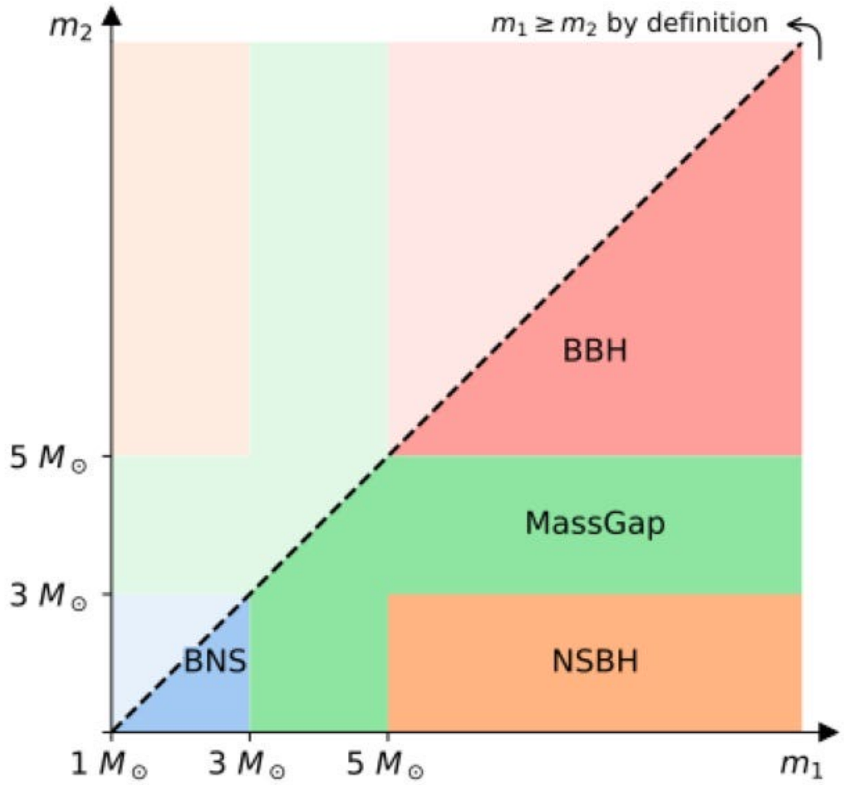


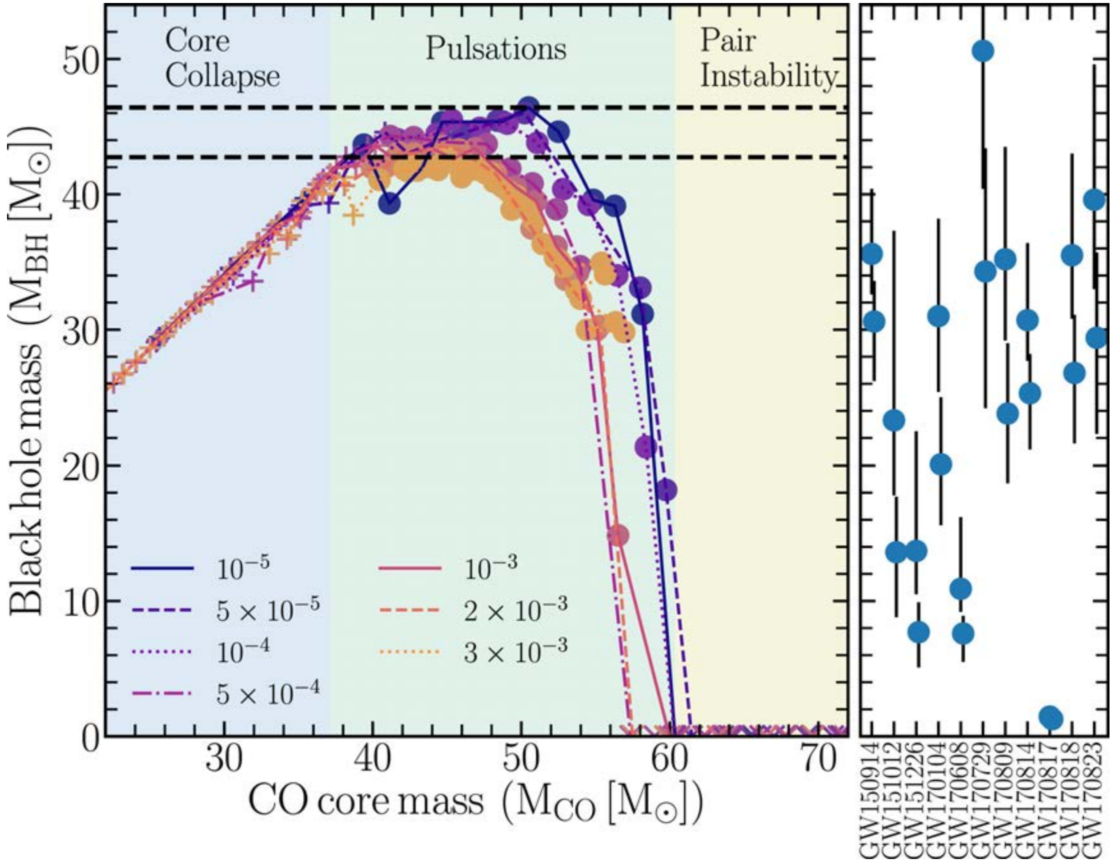
Mergers of Neutron Star and Black Hole

- Three in total
- One of them has an extreme mass ratio (31 $M_\odot$ BH and 1.2 $M_\odot$ NS)



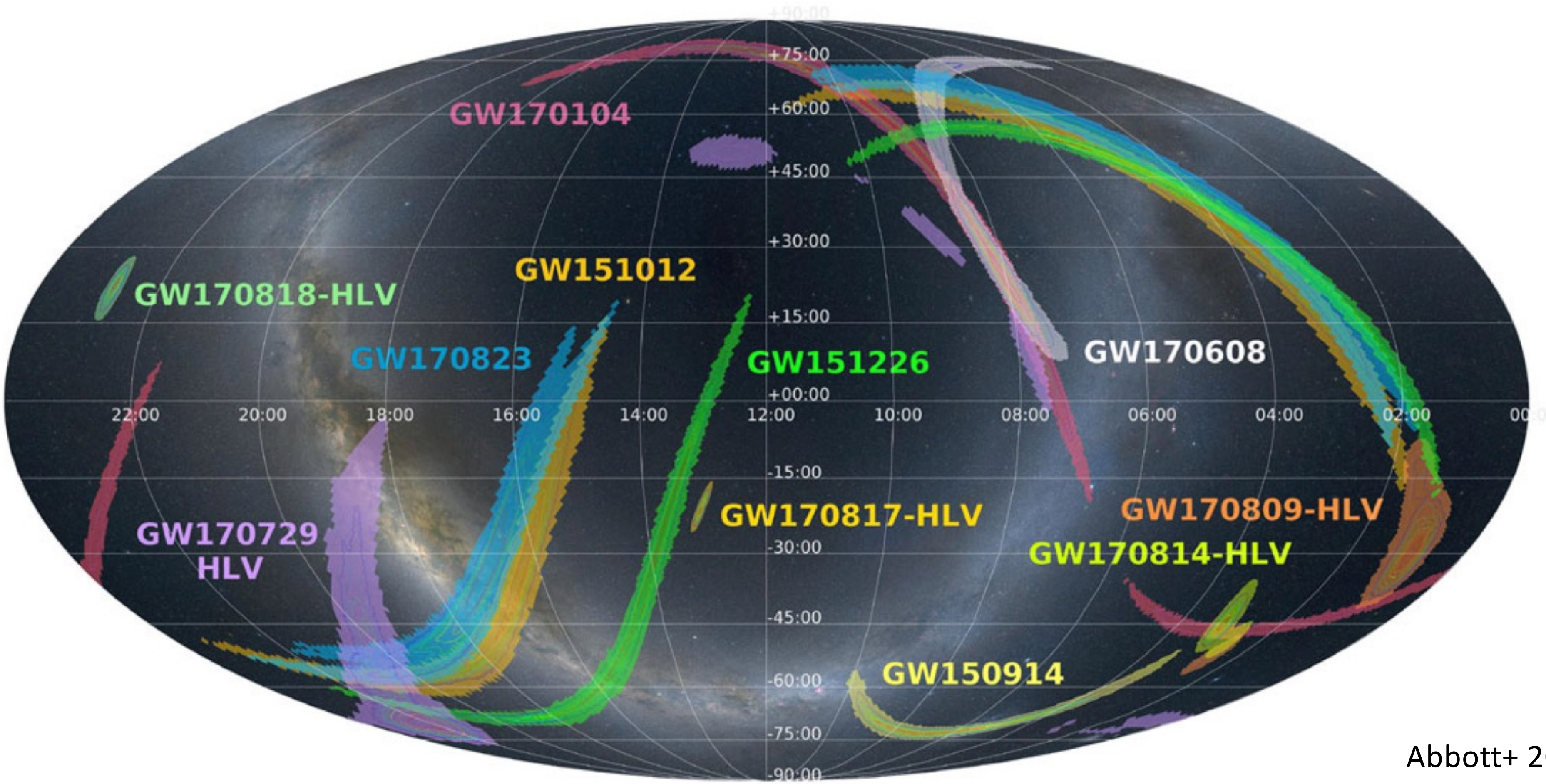
Mass Gaps





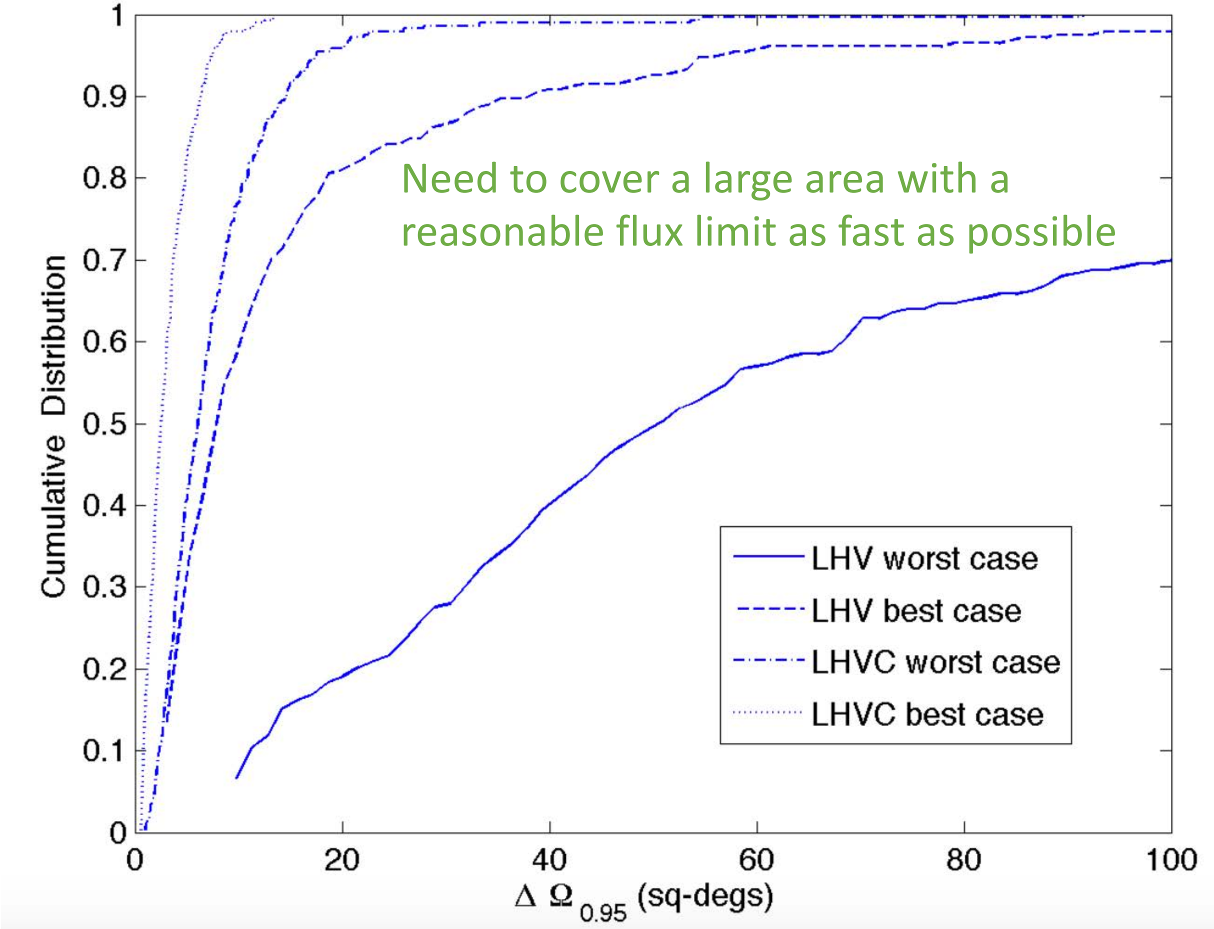
Farmer+ 2019

Localisation is difficult

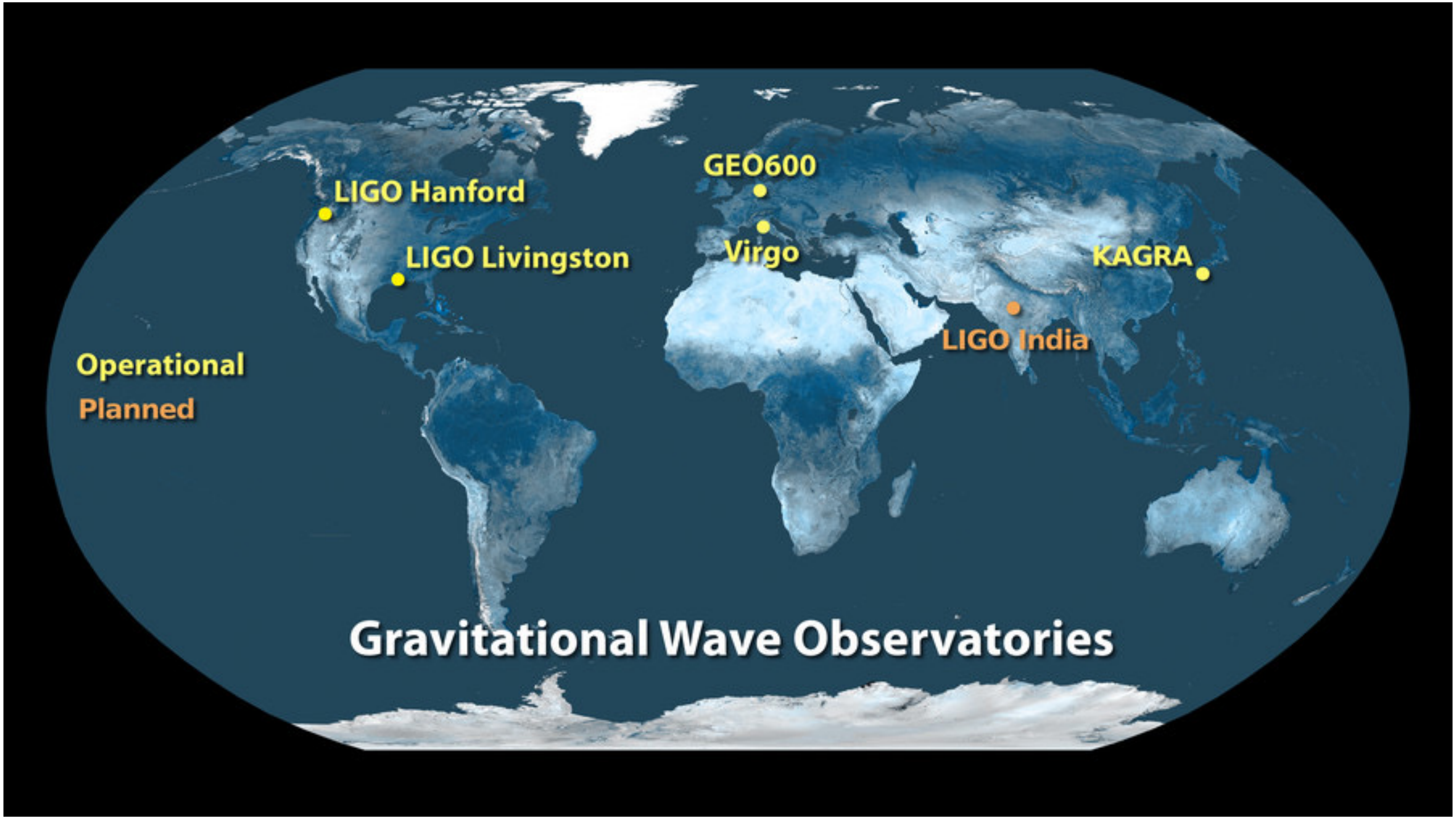


Abbott+ 2020

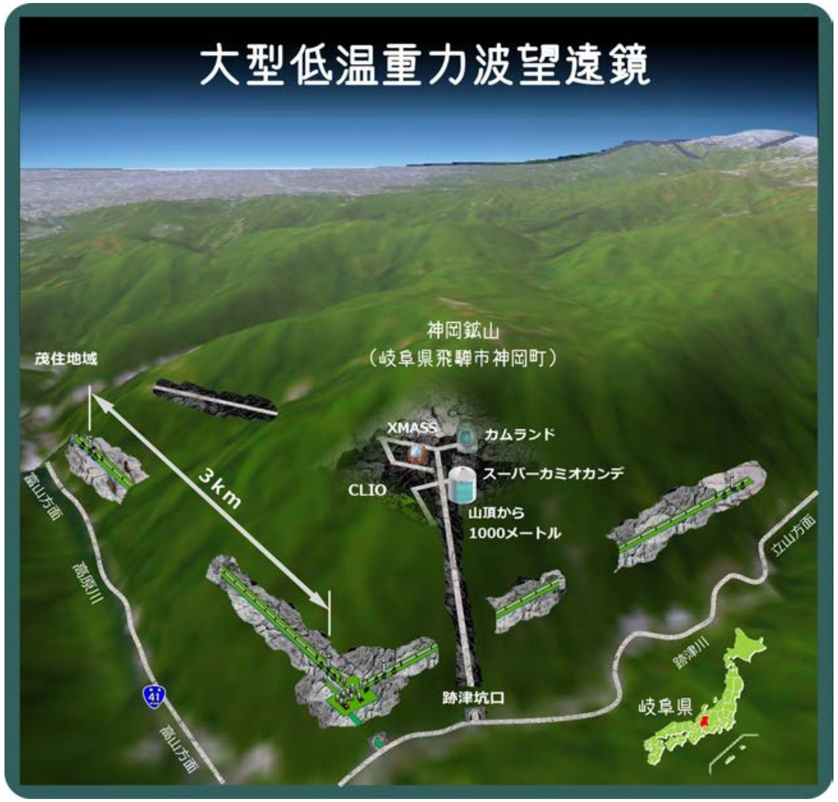
Localisation is difficult



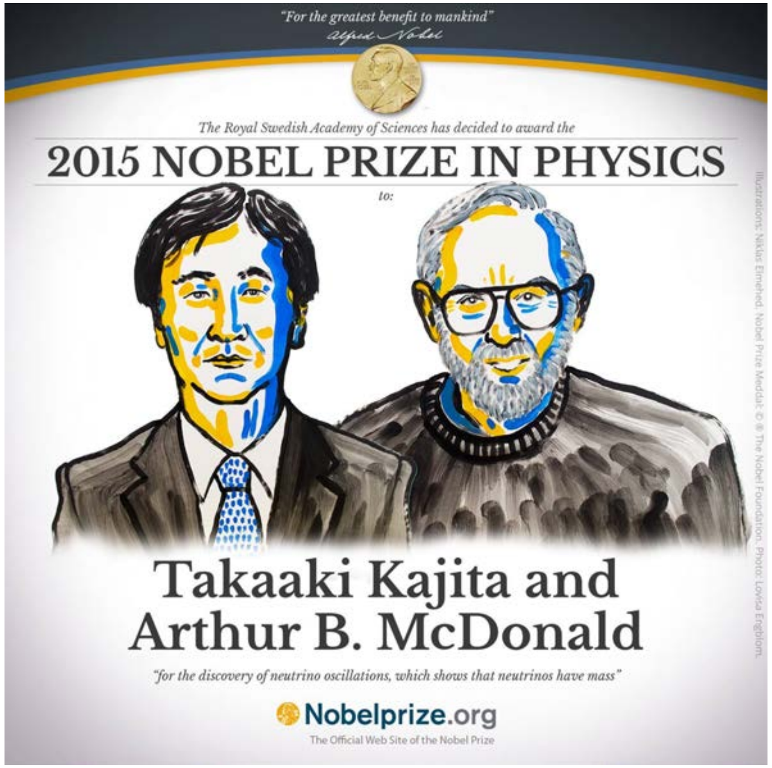
Wen et al. 2010


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

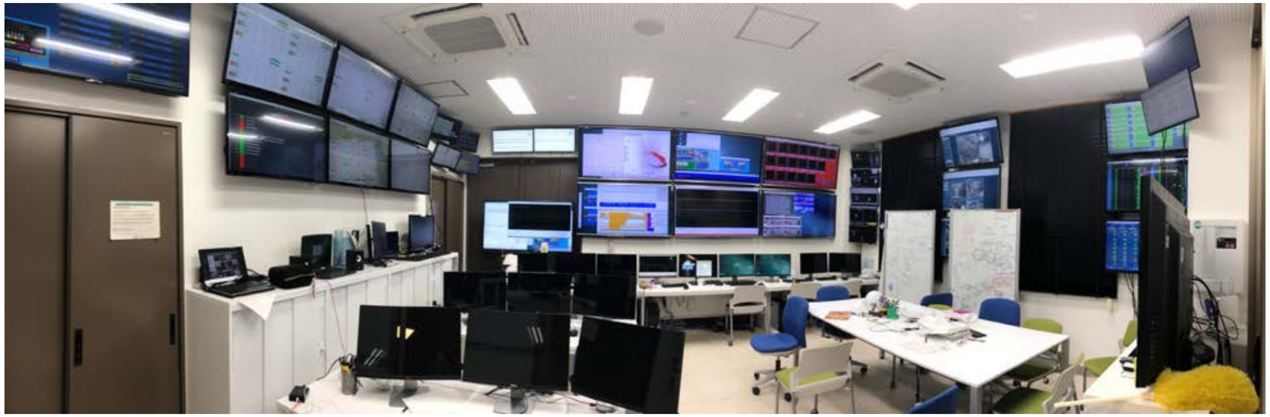
Kamioka Gravitational Wave Detector KAGRA

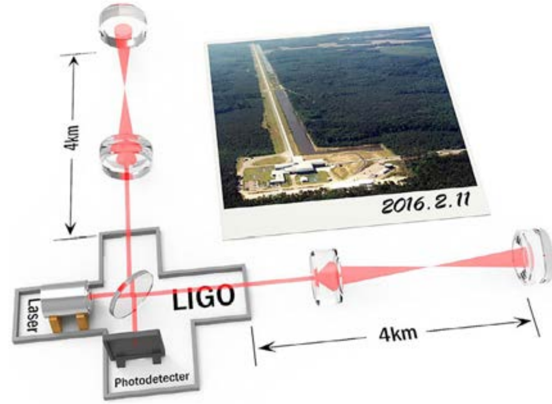


火之神神樂 Hinokami Kagura

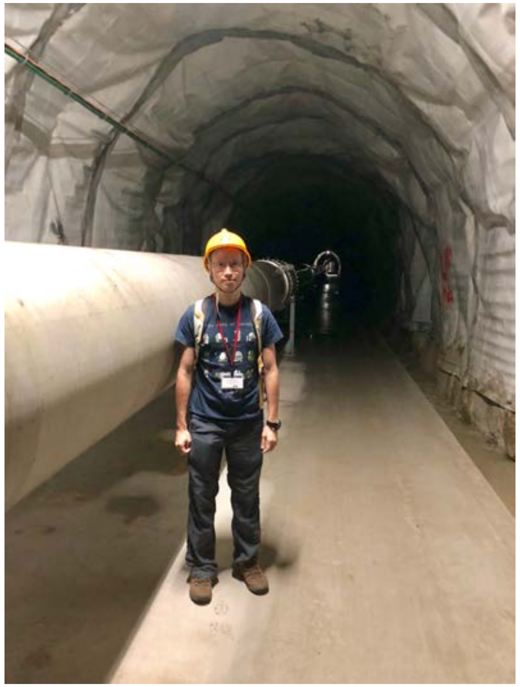


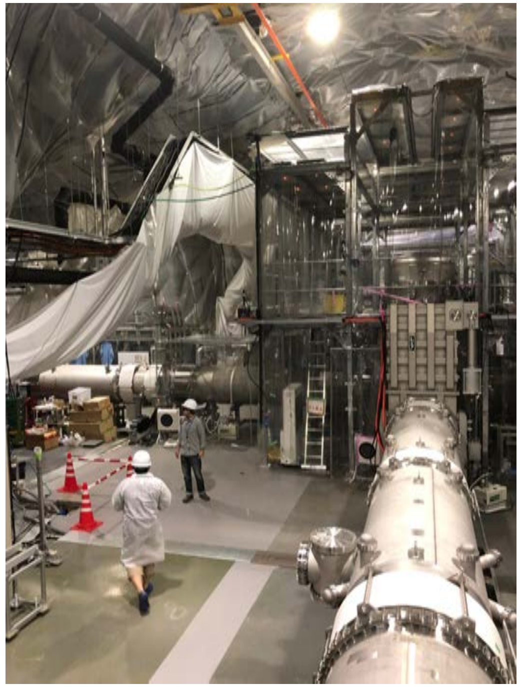
梶田隆章教授
Prof. Takaaki Kajita




4km
2016.2.11
Laser
LIGO
Photodetecter
4km


かぐらトンネル

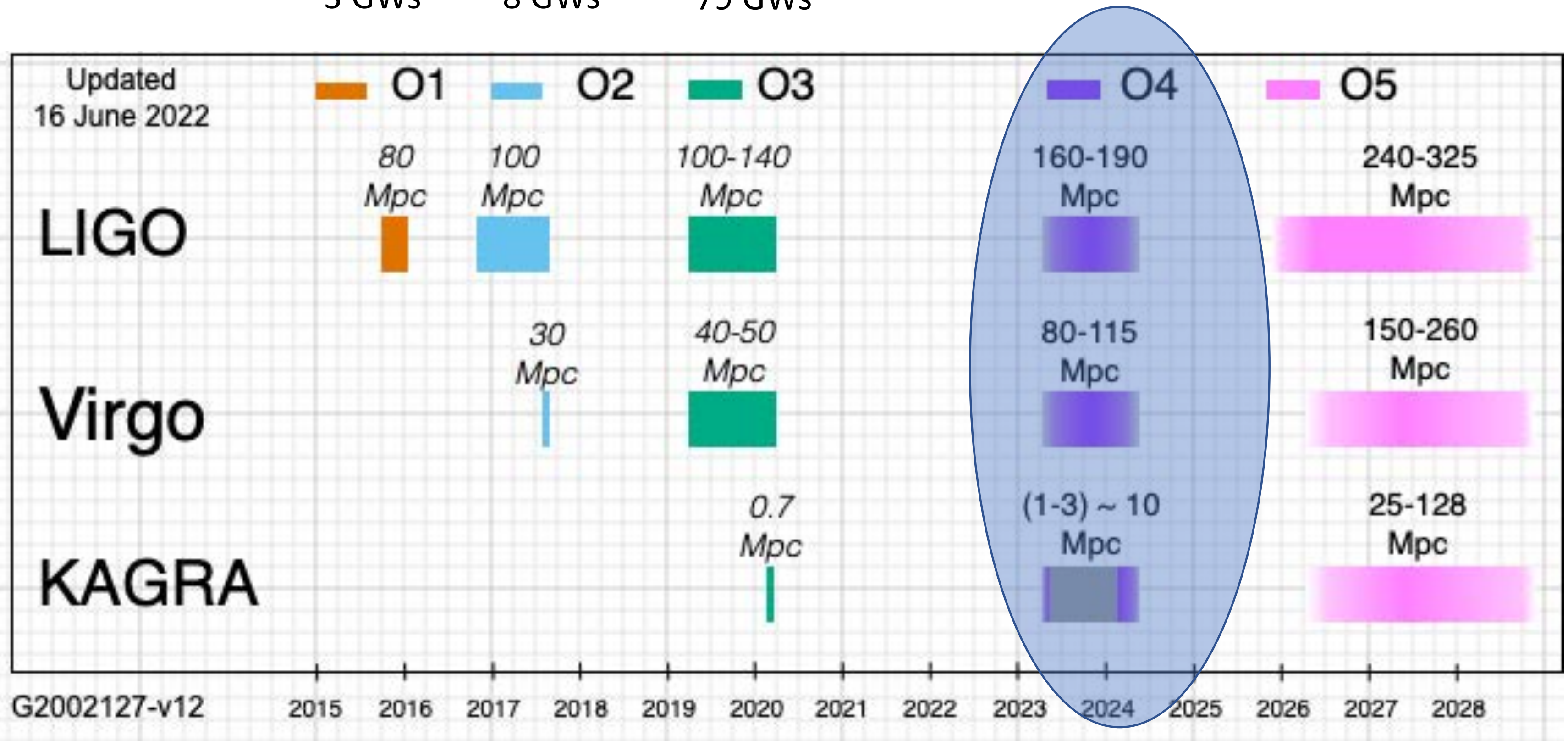




LIGO
VIRGO
KAGRA

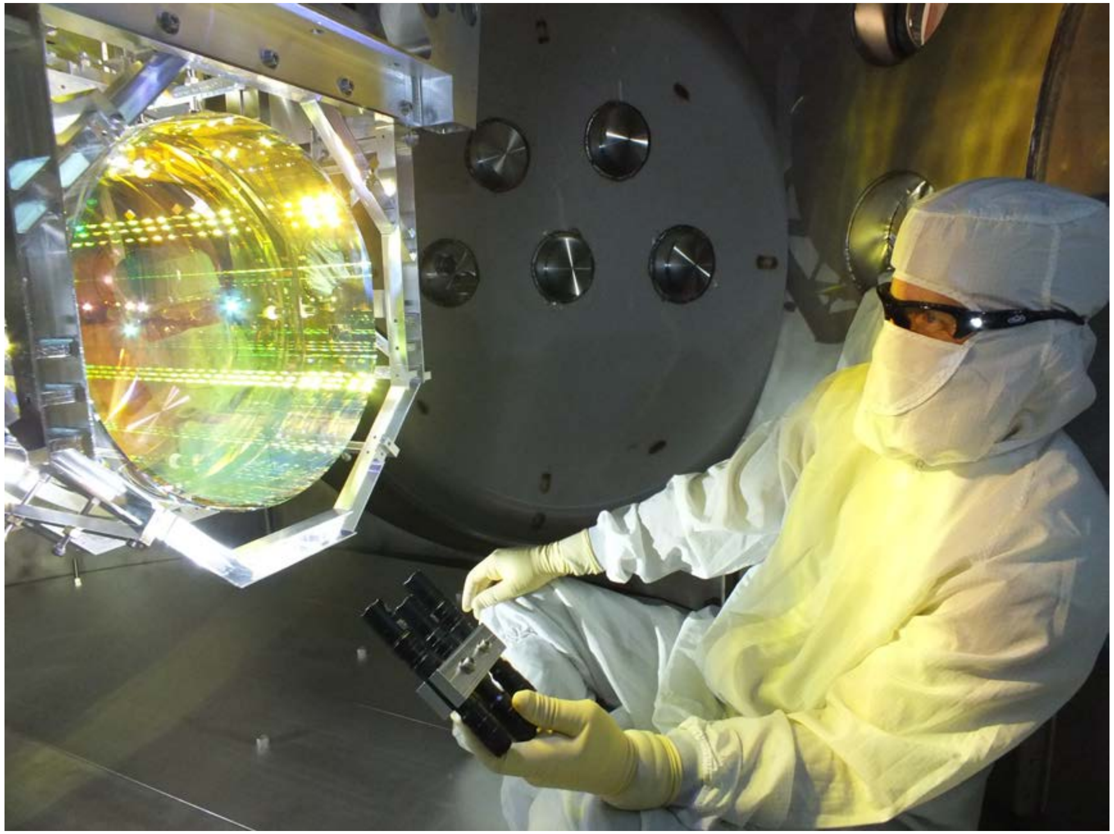
Starting from 2023 March

3 GWs 8 GWs 79 GWs

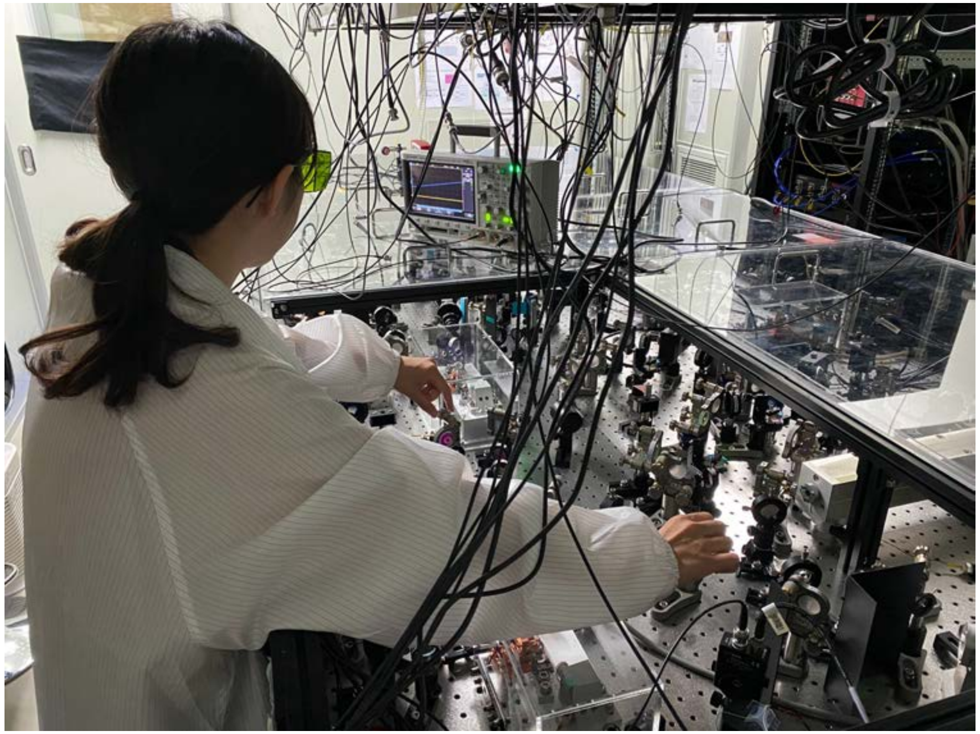


- NTHU, NTNU, NYCU, NCU, NCKU, TKU, AS/IoP, and NCHC are members of KAGRA
- KAGRA is in a collaboration with LIGO and Virgo (LVK Collaboration)
- All KAGRA members can work inside LVK for data analysis
- KAGRA performed the first science run in April 7-21, 2020
  - Only GEO600 is available. LIGO and Virgo were shut down

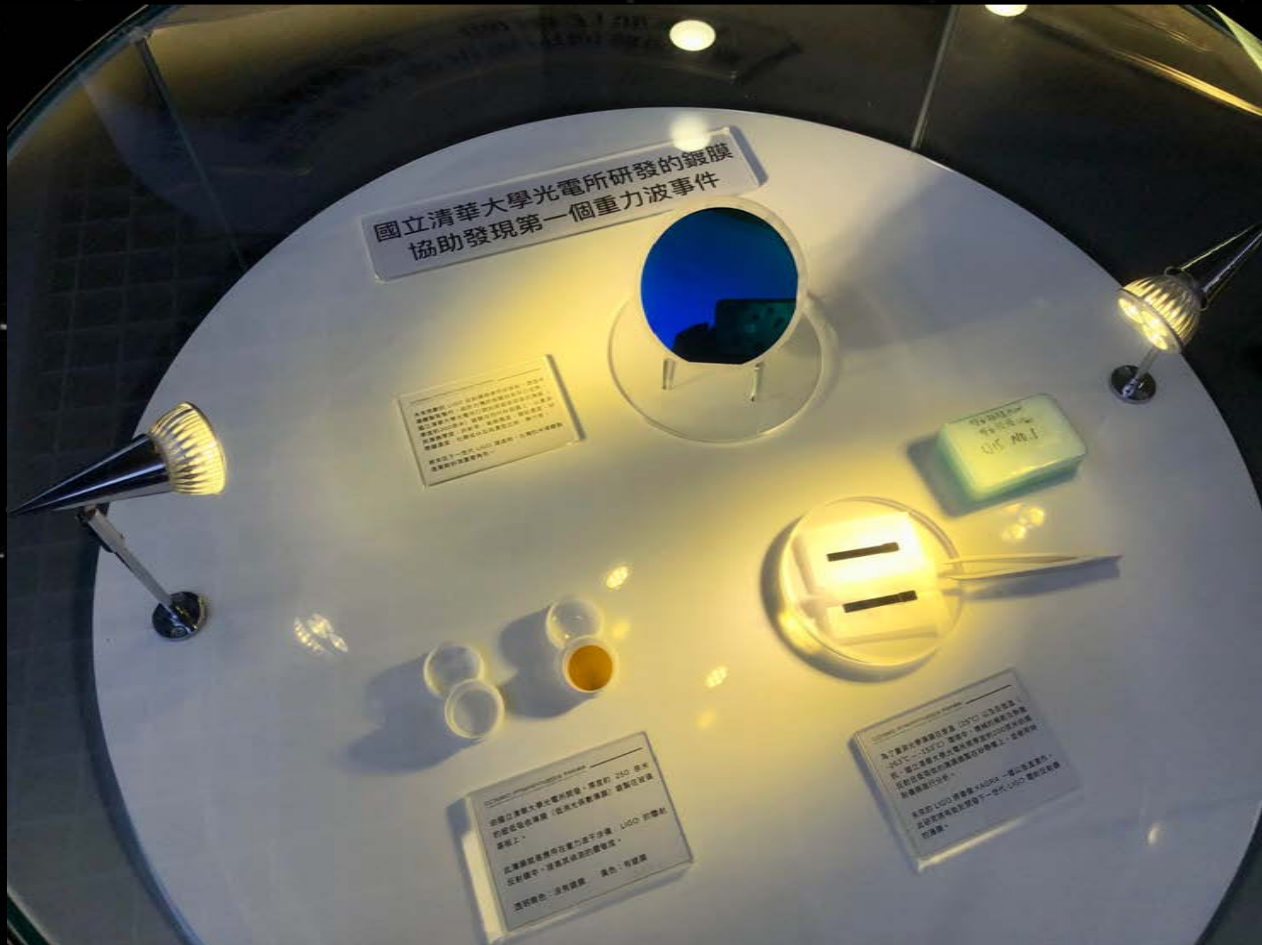
Coating of LIGO's mirrors (PI: S. Chao @NTHU)



Squeezing in KAGRA (PI: R.-K. Lee @NTHU)



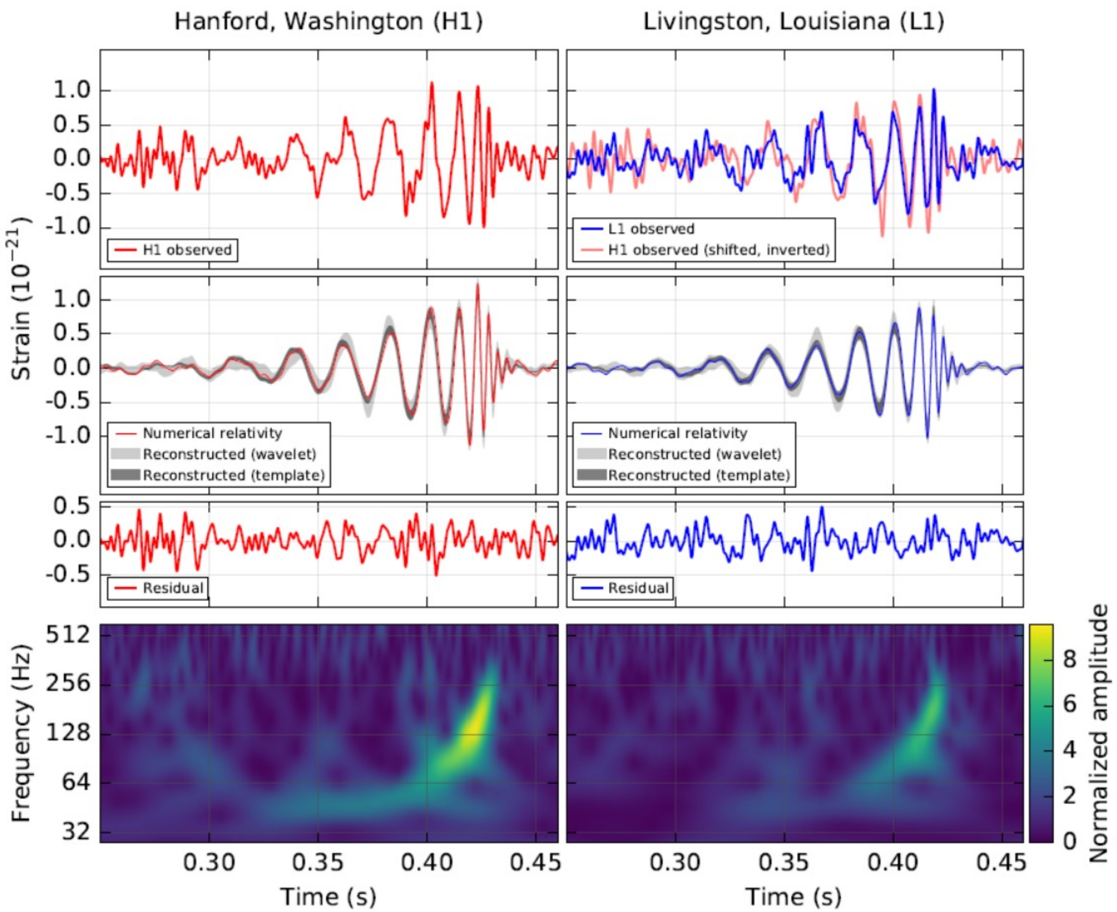
Coating of LIGO’s mirror developed at NTHU



GW Data Analysis in Taiwan

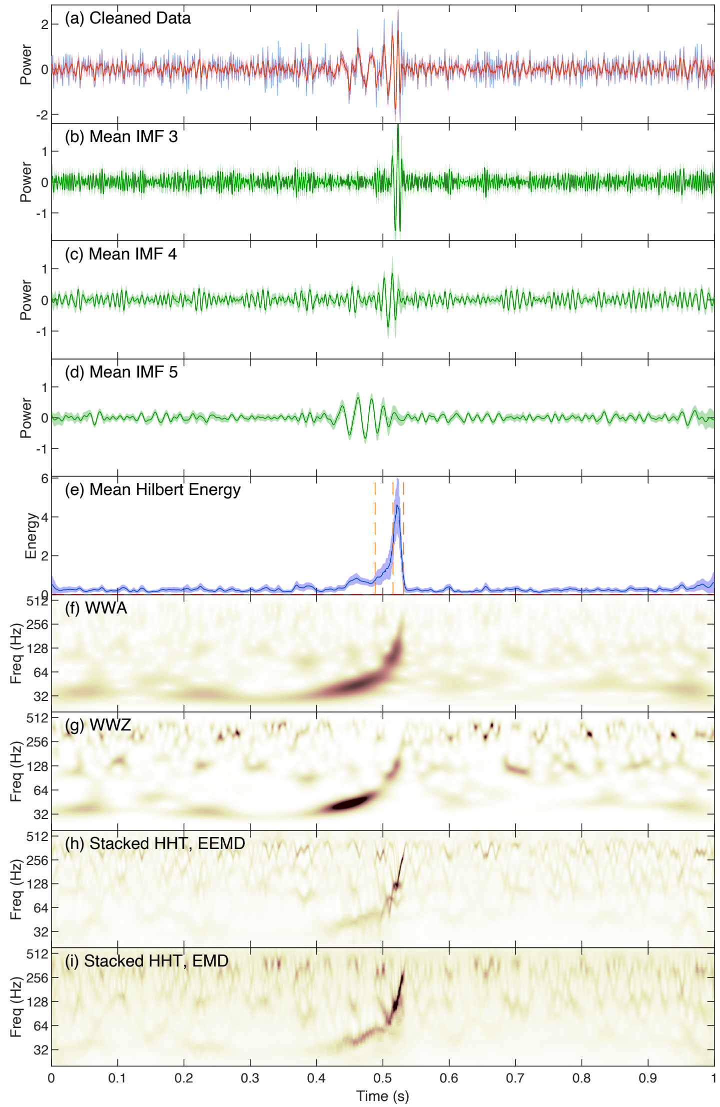
- “Service” data analysis with standard pipelines (NTHU)
  - GRB search (ApJ, 2022, 928, 186)
  - Fast radio burst (FRB) search will start soon
  - Core collapse supernova search
  - Offline parameter estimation
- Waveform development of core collpase supernova (NTHU)
- Machine learning development on GW data analysis
  - Parameter esimation with ML (AS and NTNU)
  - GW detection with ML (NTHU, NYCU, NCKU)
  - DeepClean method on noise reduction (NYCU, NTHU)

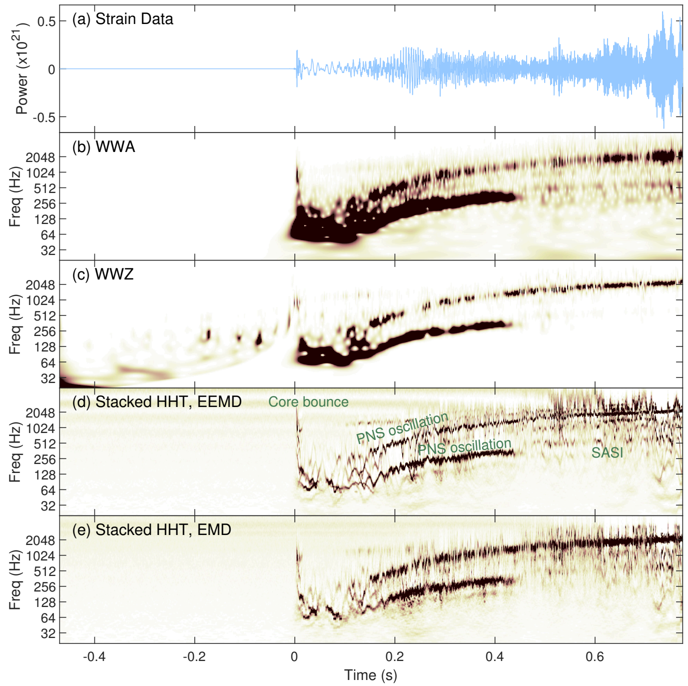
Matched filtering technique



Development of Hilbert-Huang Transform (NCUE+NCKU+NTHU)

- HHT search for binary BH mergers →
- HHT search for core-collapse supernovae

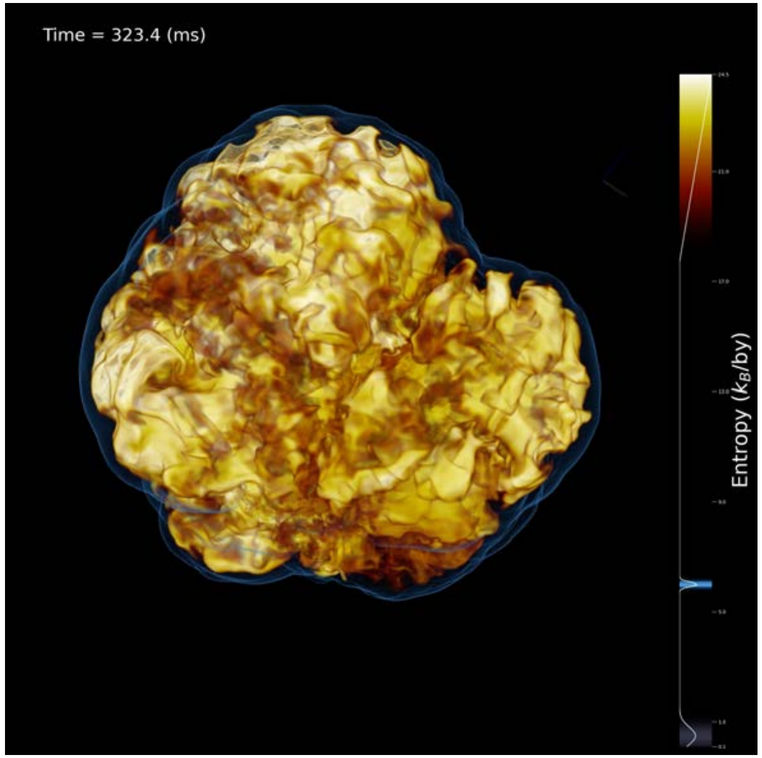




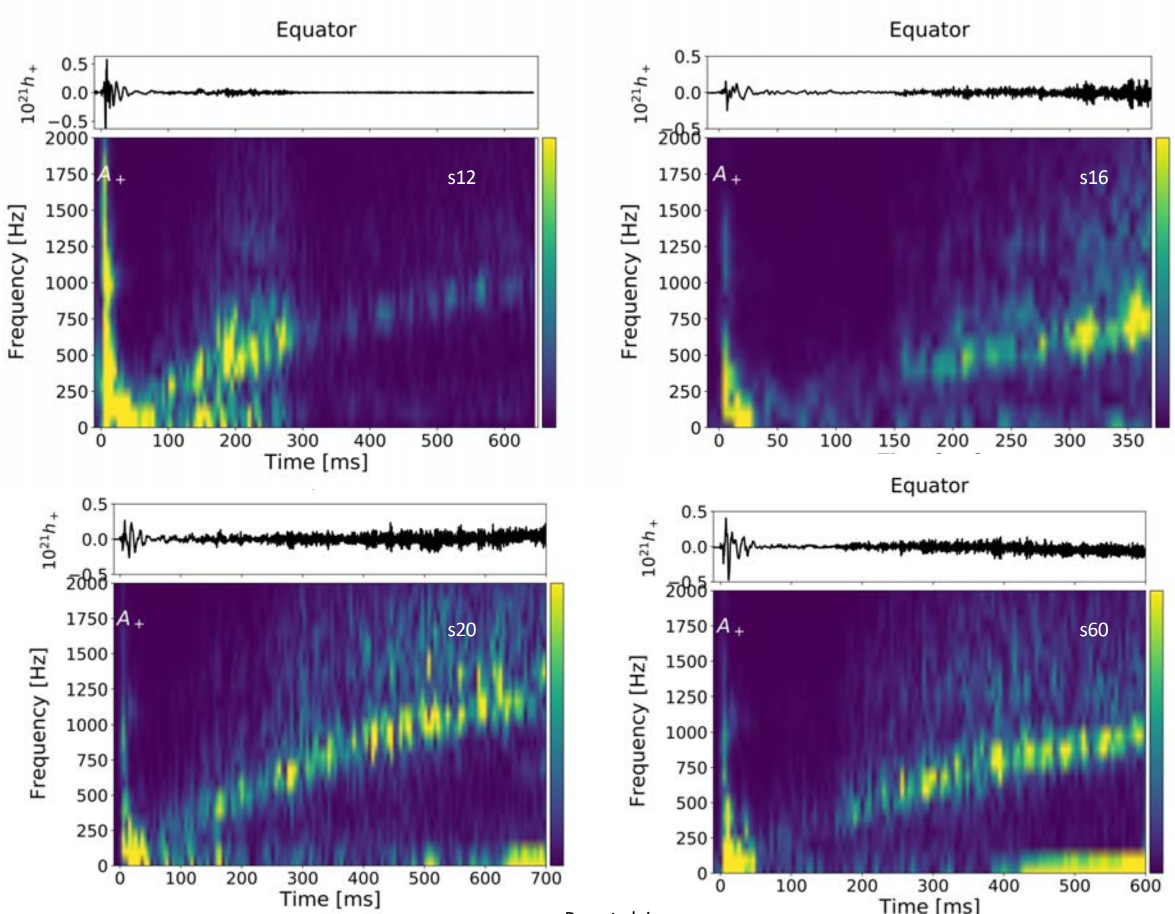
Hu+ submitted

Core-collapse SNe (K.-C. Pan@NTHU)

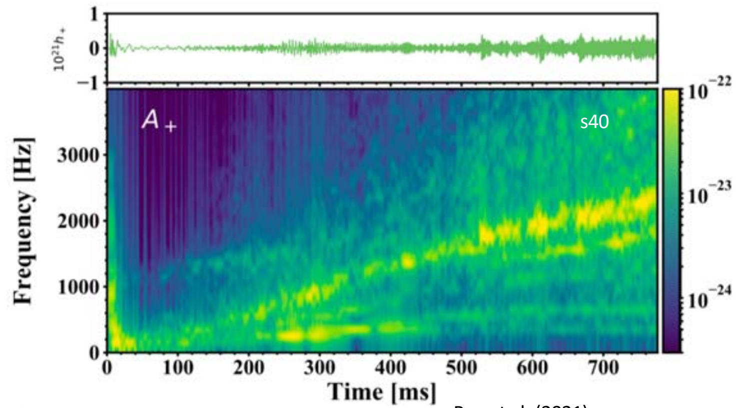
- Construction of waveforms of CCSNe via 3D simulations
  - Provided waveforms (s40 models; Pan et al. 2021) https://git.ligo.org/bursts/supernova/waveforms (with F.-K Thielemann, S. Couch)
  - New High-Res. Simulations (in prep.)
  - SPH CCSN simulaations (in prep.)
  - GPU-based CCSN simulation
- Machine learning methods for CCSN parameter estimation and waveform generation
  - Rotational rates and nuclear EoS estimation



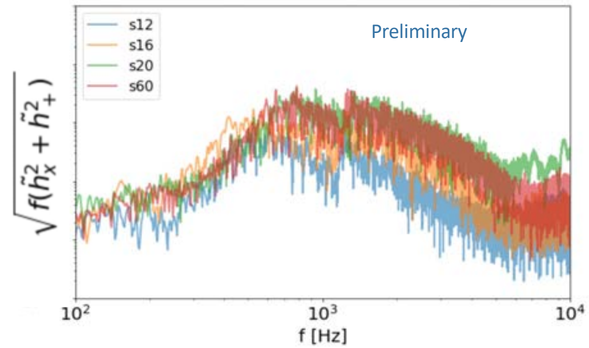
GW Spectrograms of CCSNe



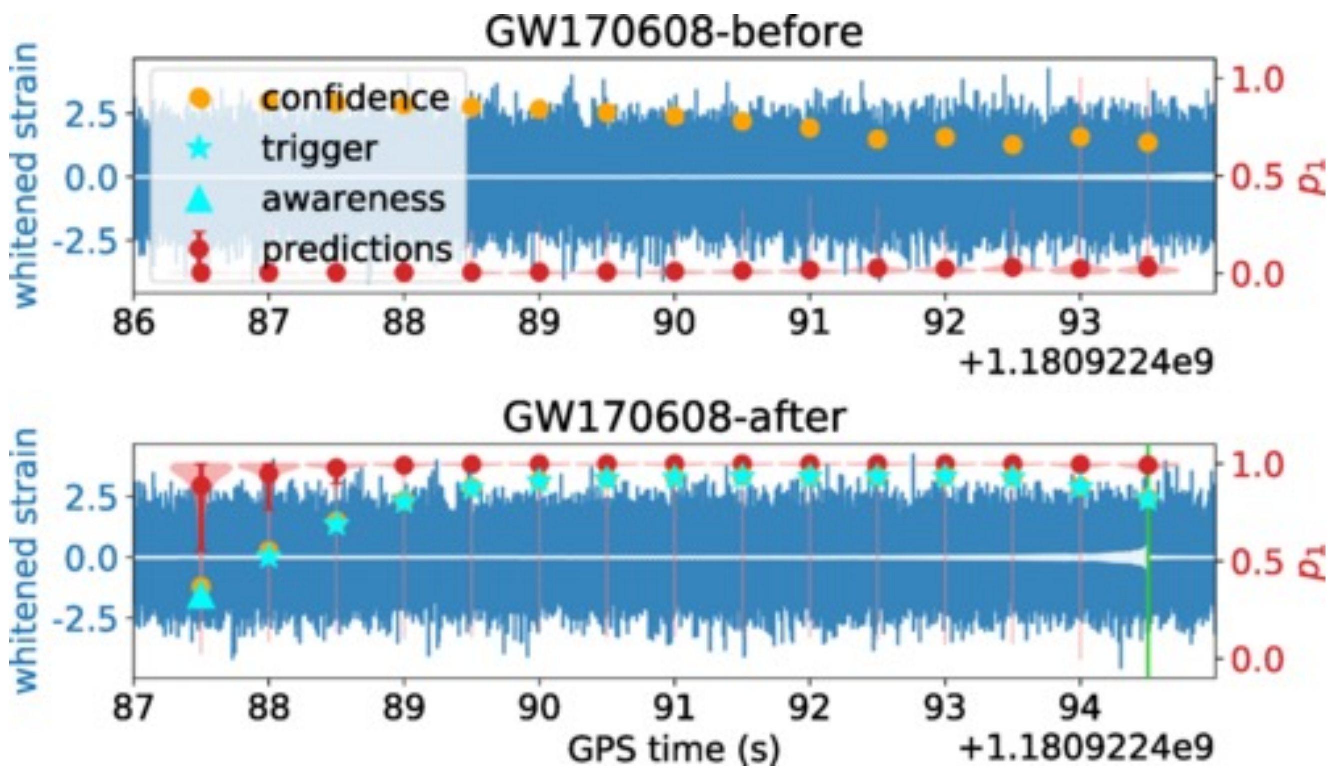
Pan et al. in prep.



Pan et al. (2021)



Bayesian Neutral Network on GW Detection



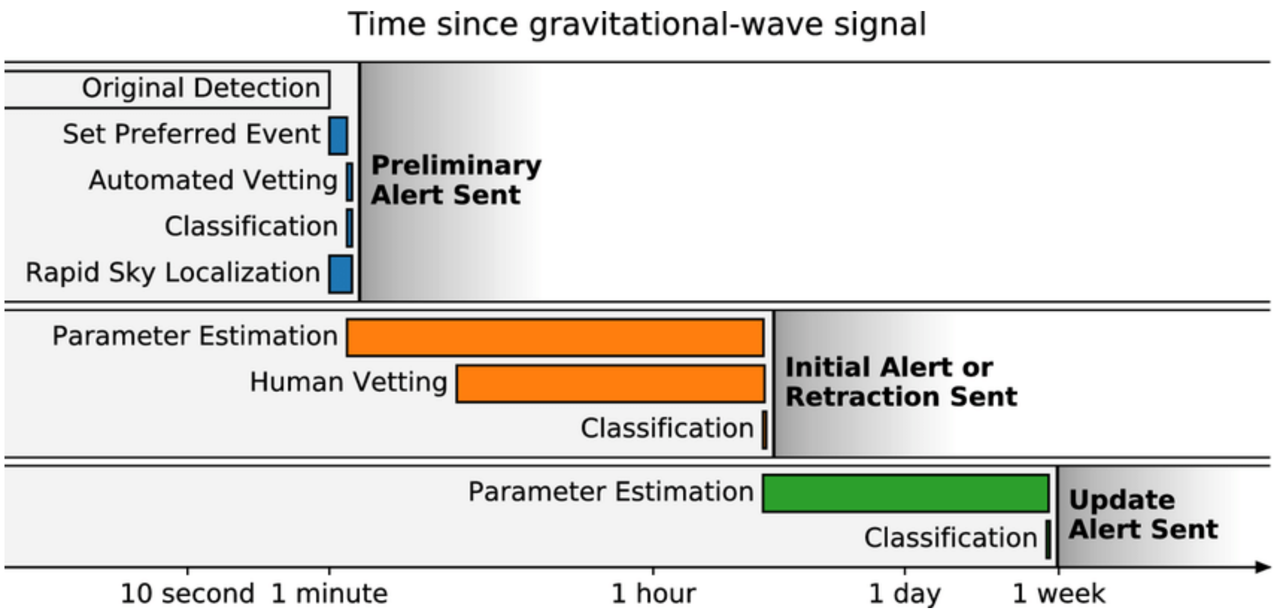
- Ability to assign uncertainty for a possible event
- Low latence alerts
- Possibility for forecasting
- Redesign for noise hunting (e.g. Gravity Spy)

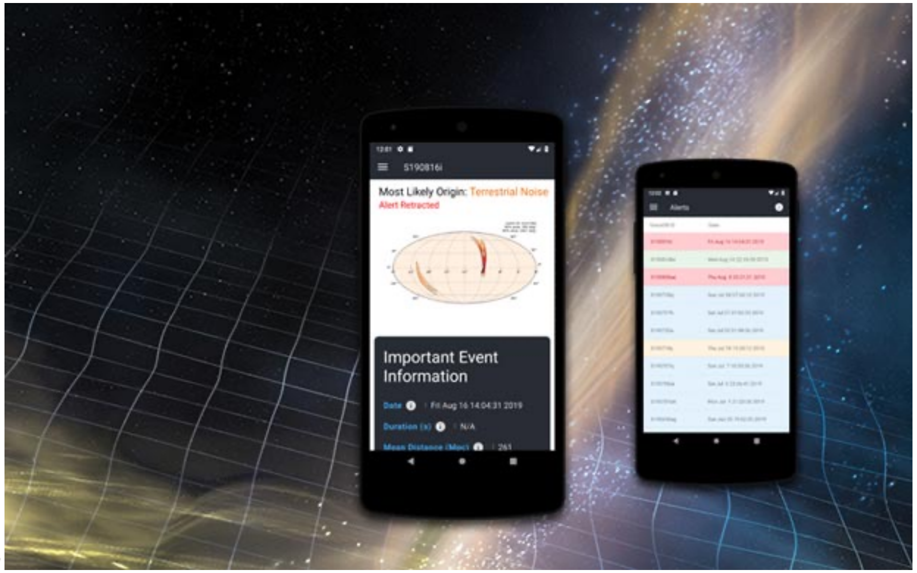
Lin & Wu 2021

GW Background (PI: G.-C. Liu @TKU)

- Development of python based isotropic GWB pipeline
- All sky GWB map making method using Maximum Entropy Method
  - New algorithm to make anisotropic GWB sky map
- Searching intermittent signals using Deep Learning
  - Deep learning method is used to search the intermittent signals
  - Have demonstrated with a toy model. Will update the method to a more realistic case

Public Alerts





Why multi-wavelength and multi-messenger?

Gravitational Wave

- Dynamics
- Progenitor mass and nature
- Distance
- Probe of central engine

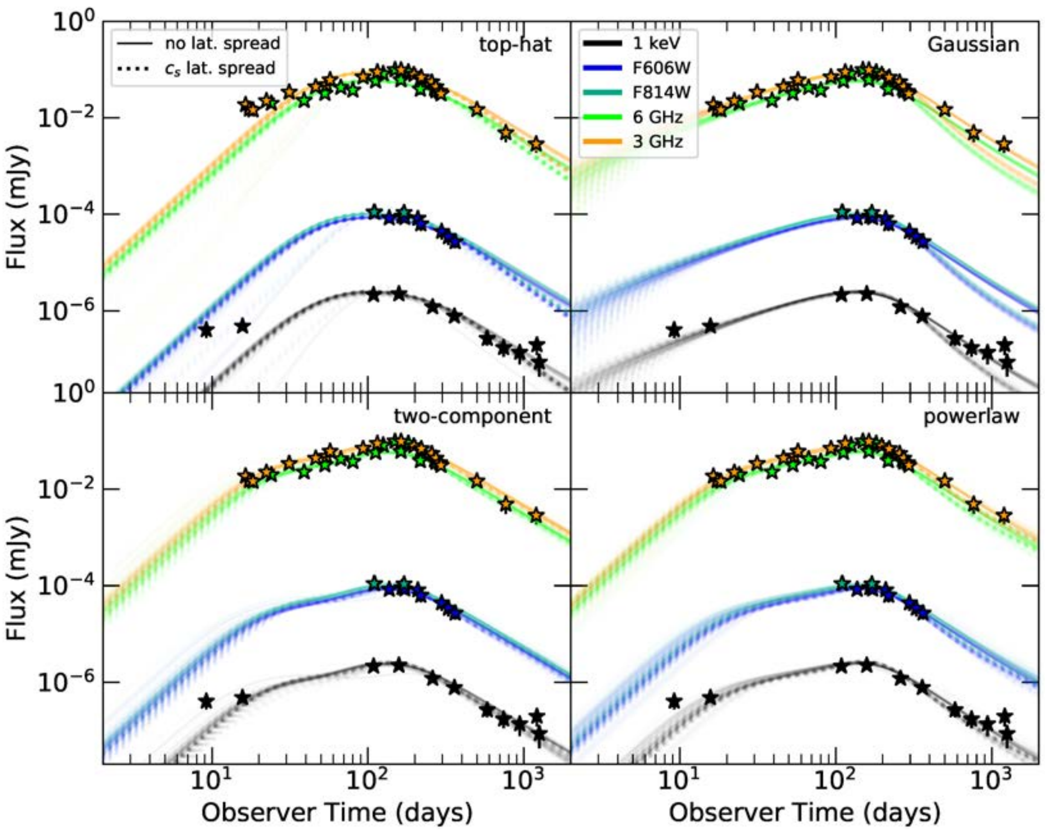
Electromagnetic Wave

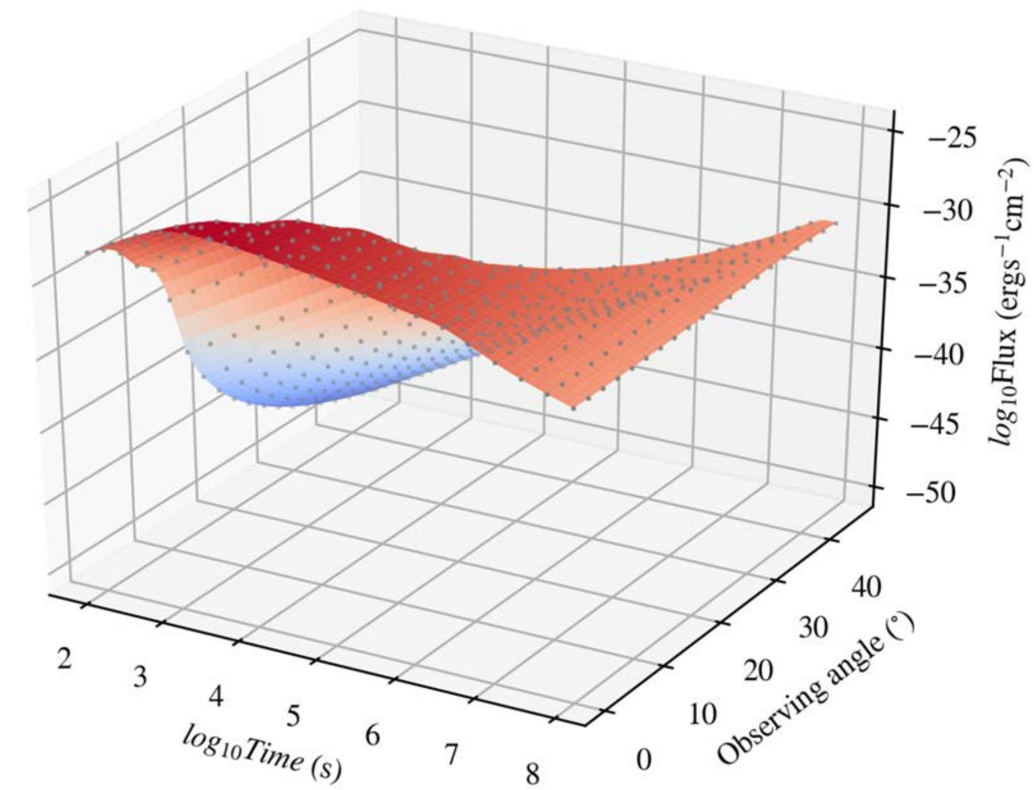
- Localisation
- Physical origin & evolution
- Environment (stellar population, age, gas…)
- Host (if extragalactic)
- Distance
- Increase the confidence of a GW detection

How to trigger?

- A trigger can be in two ways
- GW -> EM
  - A quick response is required
  - Positions should be sent to telescopes asap (within minutes)
- EM -> GW
  - A targeted search for GW
  - It is not time critical but requires coordination
  - GW data analysis is critical

Constraining the jet structure of GW170917





Lamb+ 2021; Lin+ 2021

What do we expect for O4?

- More GW sources with EM counterparts
  - What about systems with BH?
- Physical nature of mass gap sources
- The maximum mass of BH and NS
- BH spin
- GW from exotic binaries such as FRB and magnetar
- Continuous GW from neutron stars
- GW background
- If we are really lucky, GW from a nearby core collapse supernova