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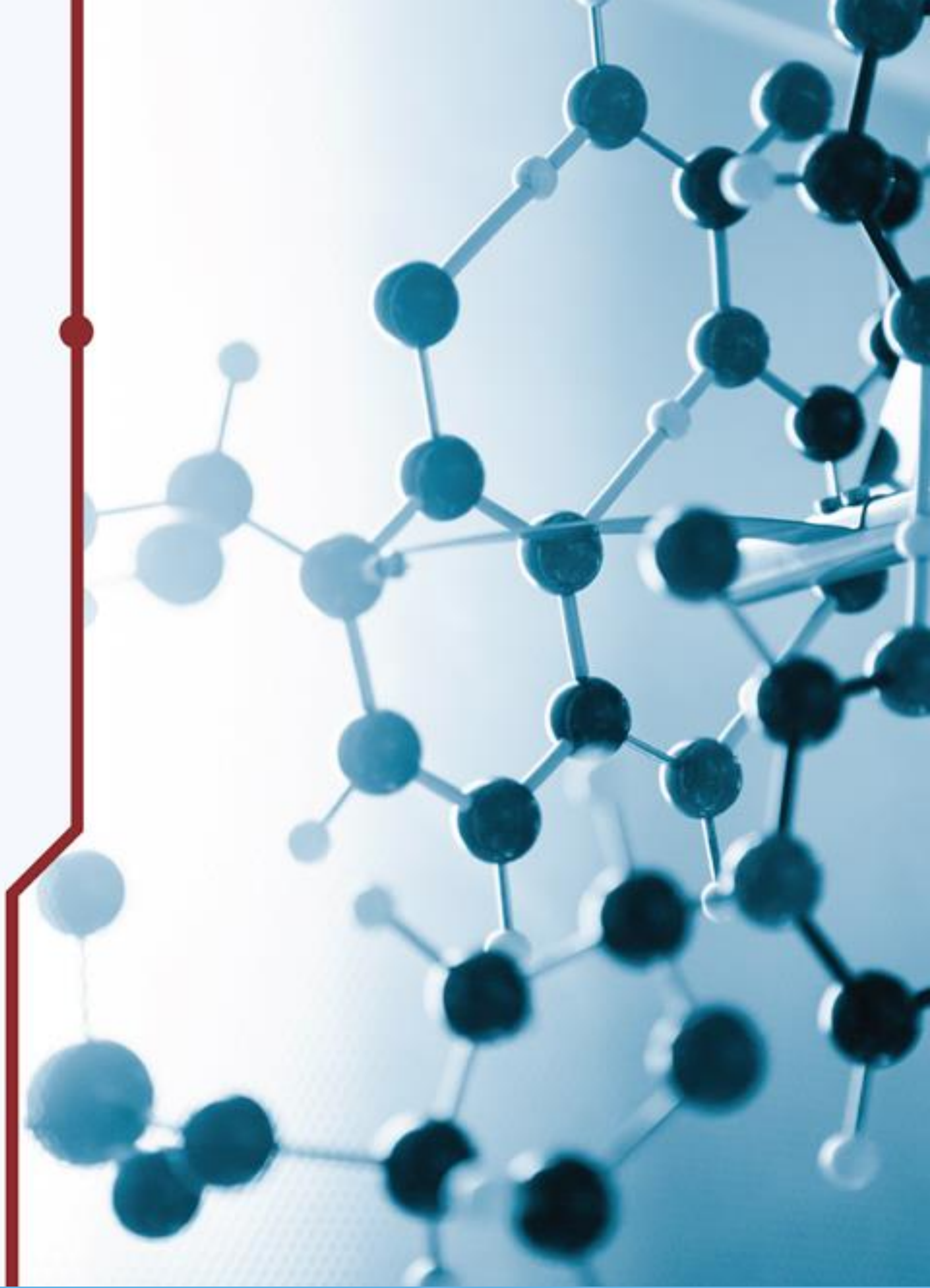
Gravitational Waves
Recent News and Results

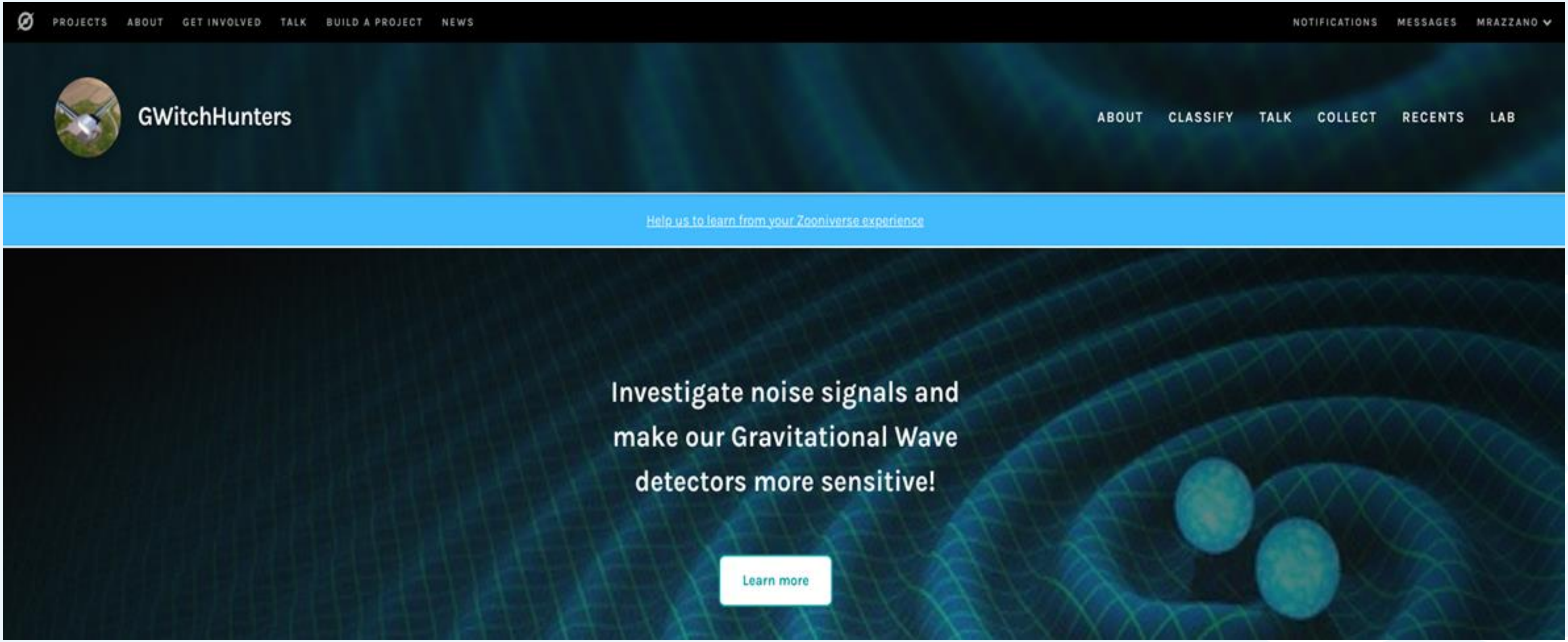
REINFORCE Summer School
11 July 2022

Massimiliano Razzano [(1)]
on behalf of REINFORCE Consortium
& WP3 GWitchHunters team

(1) - University of Pisa



Welcome to GWitchHunters



The nature of spacetime

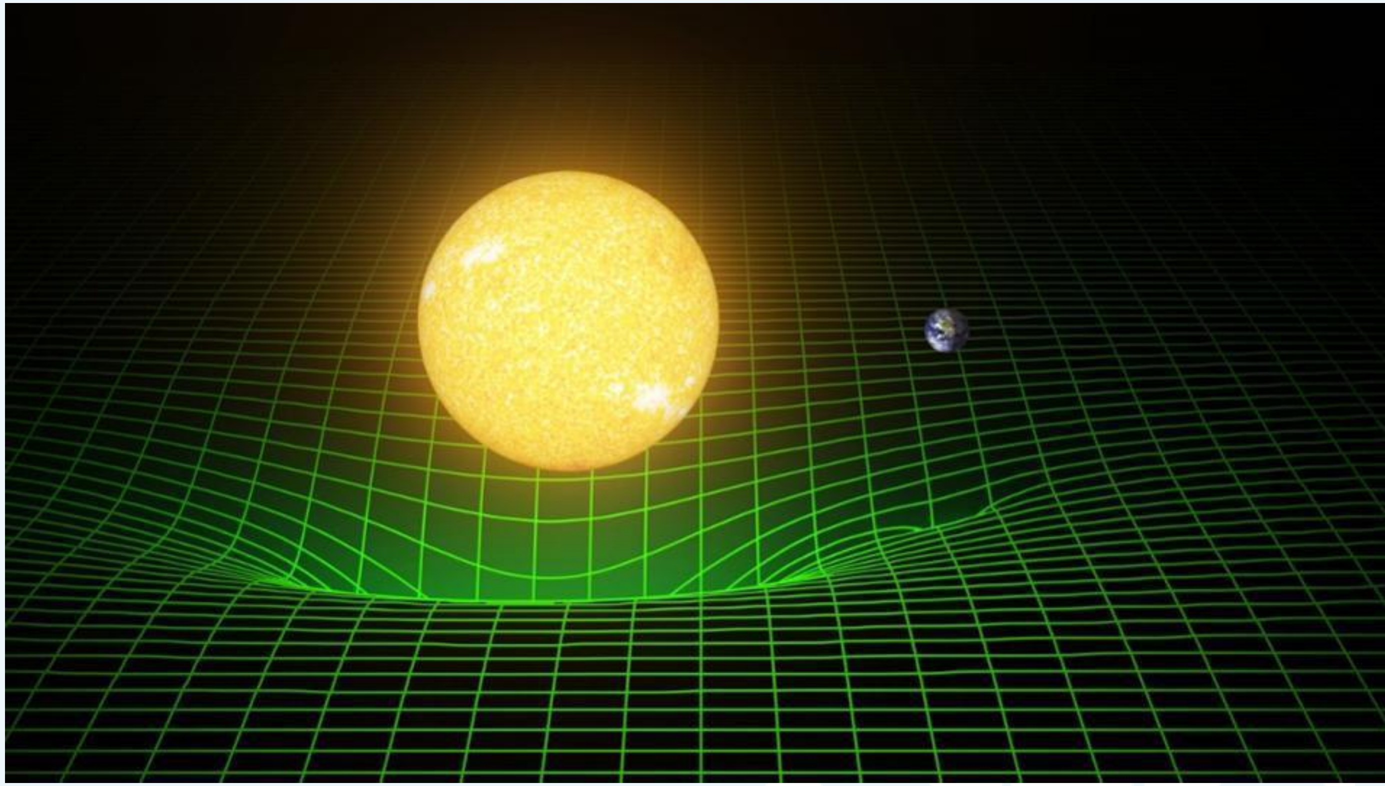
The spacetime is curved

- General Relativity by Einstein (1915)
- "Spacetime tells matter how to move;

matter tells spacetime how to curve" (J. Wheeler)

What is gravity?

- No longer a force a-là Newton
- Consequence of curvature of spacetime



Credits: T Pyle/Calteh/MT/LIGO

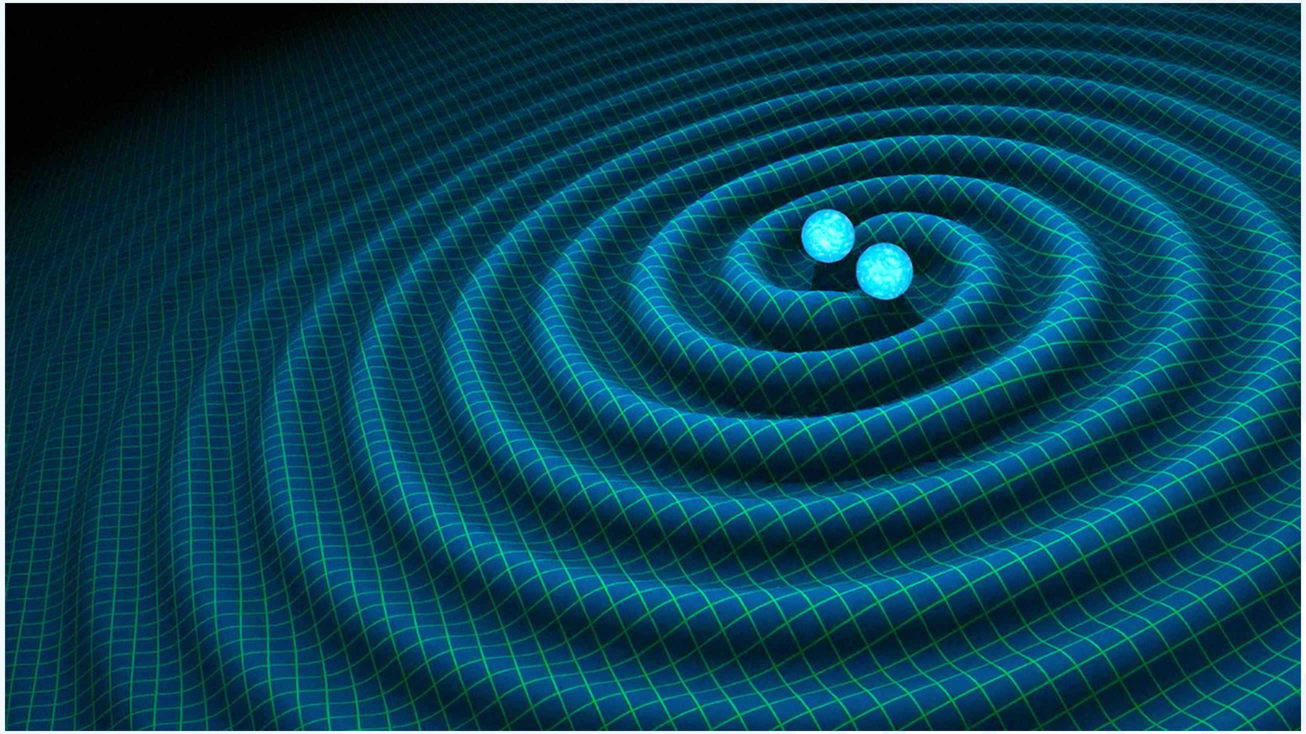
What are Gravitational Waves?

Ripples in spacetime

- Travel at speed of light
- Distort spacetime
- Polarizations

How they are generated?

- Accelerating masses
- Orbiting astrophysical bodies
- Explosions
- Violent astrophysical phenomena



Credits: LIGO/Caltech

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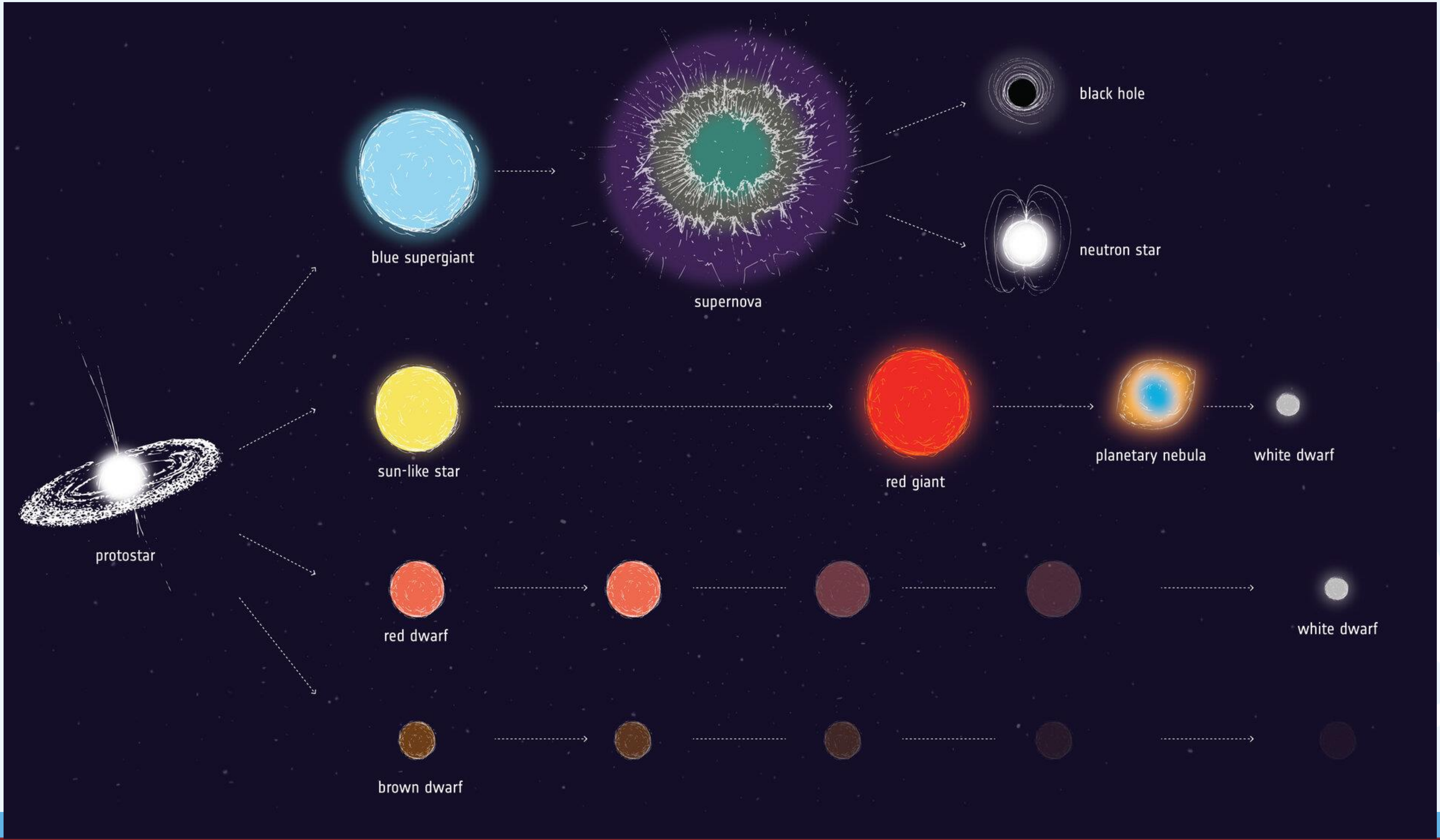
Stellar evolution



Credits: ESA

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The Menu of expected GW sources

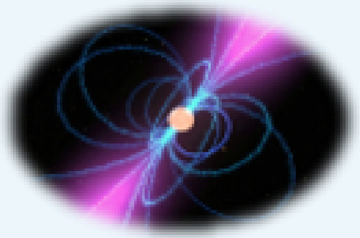
Transients

- **Coalescence of compact binary systems (NSs and/or BHs)**
  - Known waveforms (matched filter with template banks)
  - Only source class detected so far

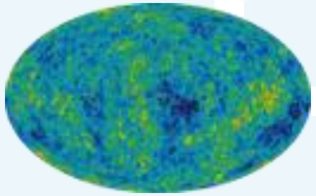
- **Core-collapse of massive stars**
  - Uncertain waveforms

Continuous

- **Rotating neutron stars**
  - Quadrupole emission from stellar asymmetry
  - Continuous and periodic



- **Stochastic background**
  - Continuous, due to unresolved sources/Big Bang relics

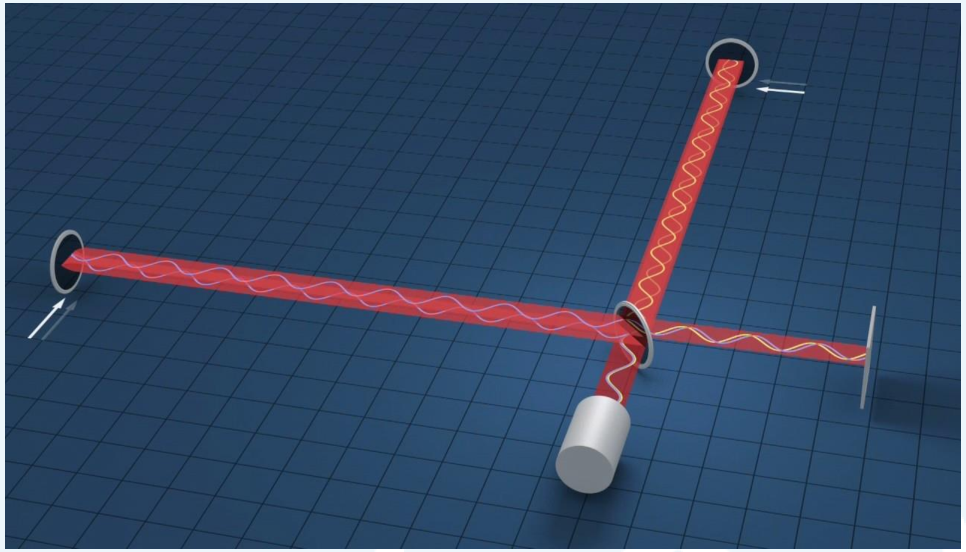


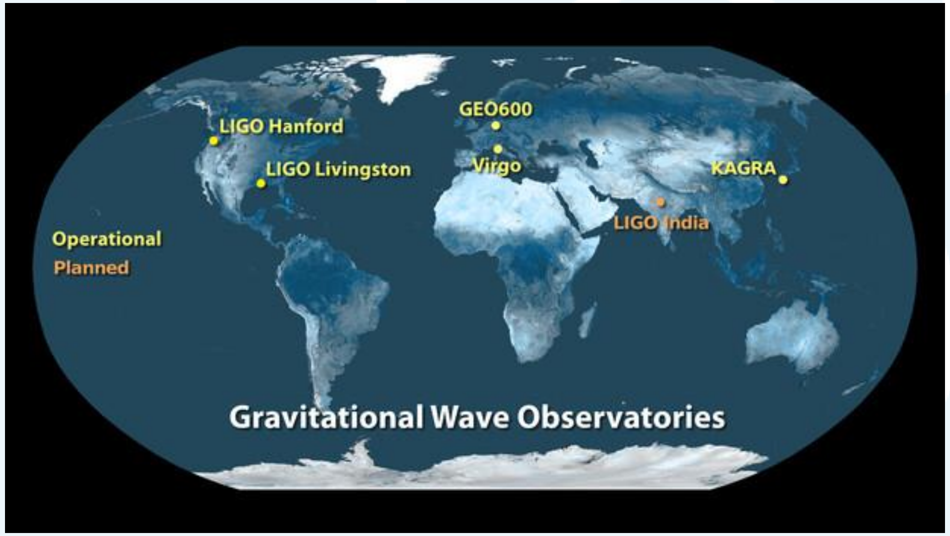
???

How to detect gravitational waves

- **Extremely tiny signals**
  - Typical GW sources induce a deformation of 10^{-18} m over a length of ~ few km
  - High background noise!

- **Laser interferometers**
  - Exploiting interference between orthogonal laser beams
  - Typical km-long scale + Fabry-Perot cavities
  - Frequency range ~20-20000 Hz
  - Advanced methods to reduce noise
  - Detectors working as a network



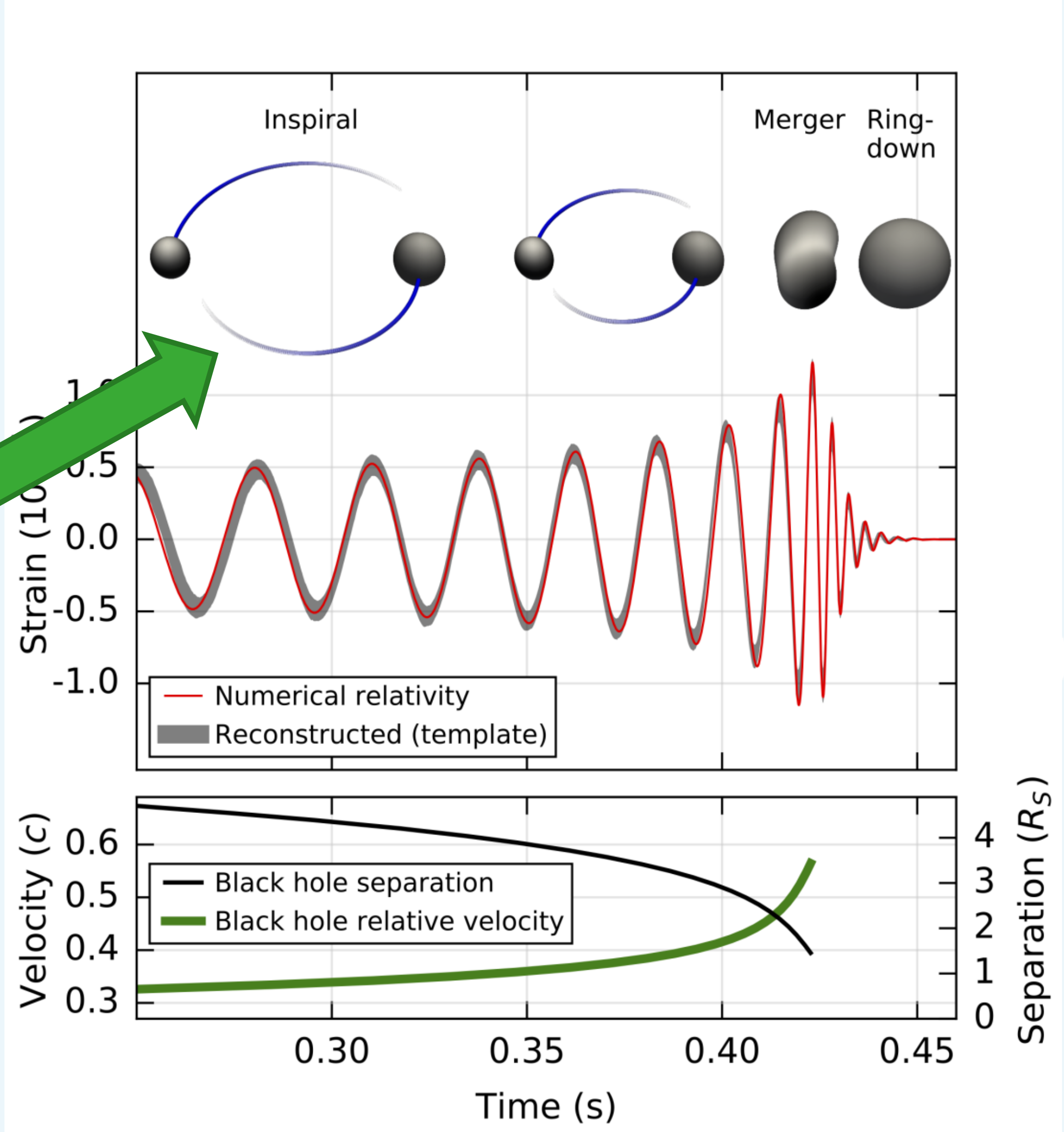


Credits: LIGO/T Pyle; Caltech/MIT/LIGO Lab

When two black holes collide

- **Energy lost by gravitational wave emission**
  - Energy decreases, system shrinks
  - Orbital speed increases
  - Larger emission
  - **Runaway process!**

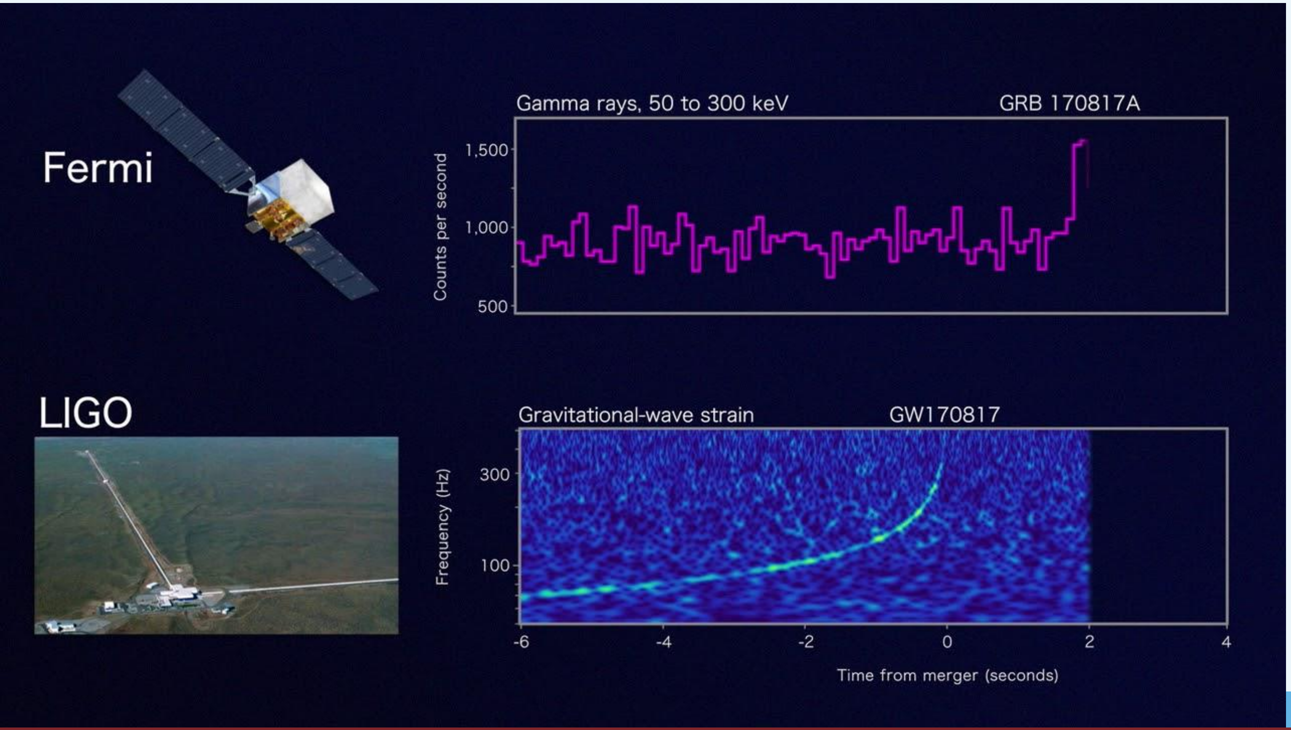
Coalescence!

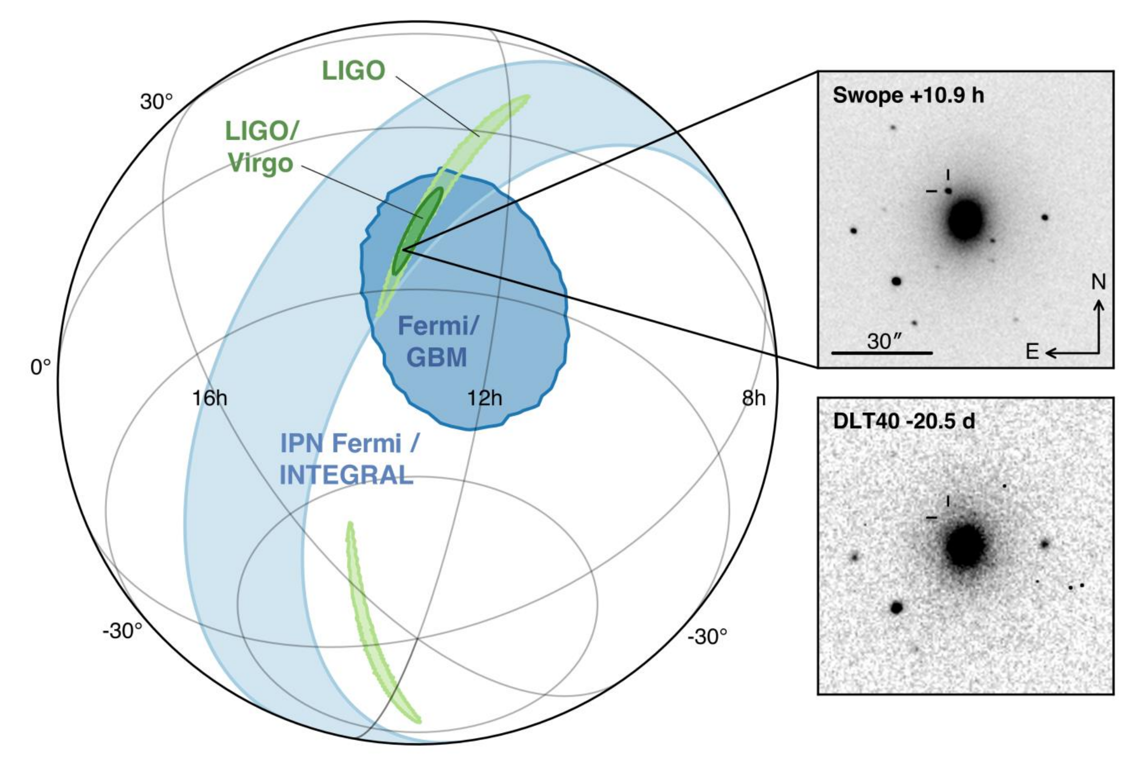


Credits: LIGO/Virgo Collaboration

Not just black holes

- **GW170817 : Neutron Star coalescence**
  - First event of its kind
  - Observed by LIGO and Virgo
  - Observed counterparts by electromagnetic telescopes
  - First multimessenger observation





Credits: LIGO/Virgo Collaboration

Mixed Pairs

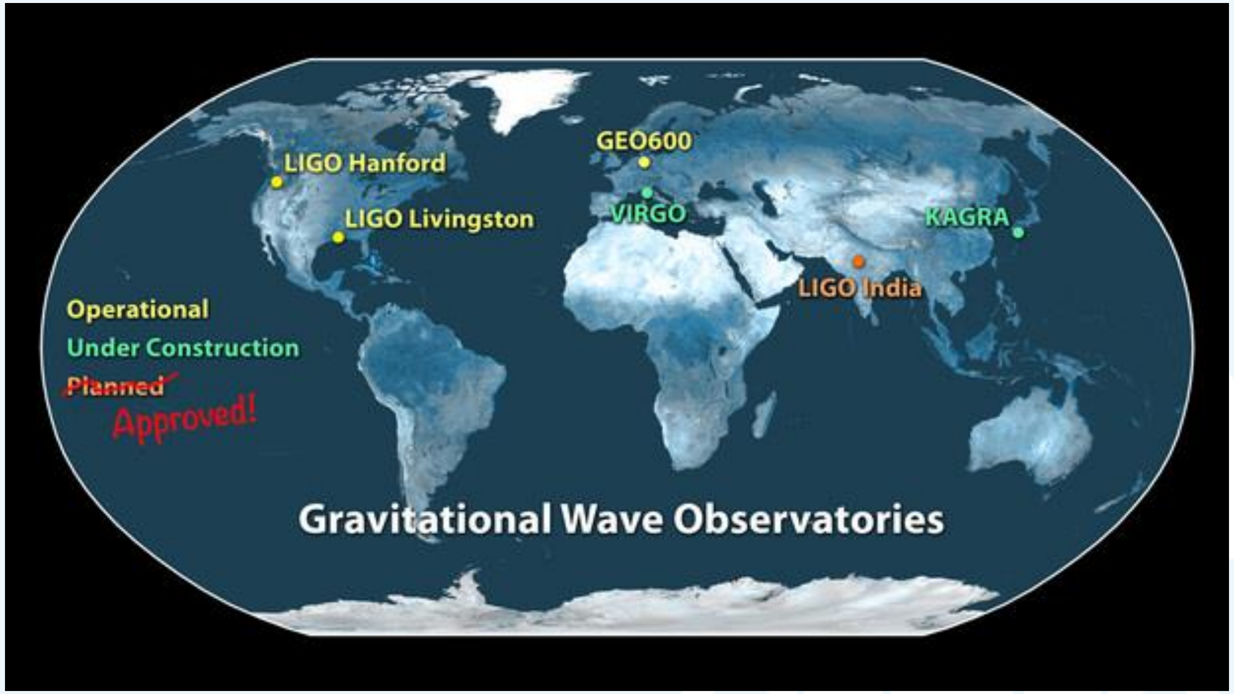
- **10 & 15 January 2020**
  - Neutron star + Black hole
  - Masses inferred from wave shape

Credits: Carl Knox, OzGrav-Swinburne University.

The story so far

Advanced LIGO and Virgo completed 3 joint runs

- O1 (H1+L1) - Sep 12, 2015 - Jan 19, 2016
- O2 (H1+L1+V1) - Nov 30, 2016 - Aug 25, 2017
- O3a (H1+L1+V1) - Apr 1 - Oct 1, 2019
- O3b (H1+L1+V1) - Nov 1, 2019 - Mar 27, 2020



Credit: Caltech/MIT/LIGO Lab

Detection method

- km-scale Michelson interferometers
- Fabry-Perot cavities
- Hardware and software methods to suppress noise

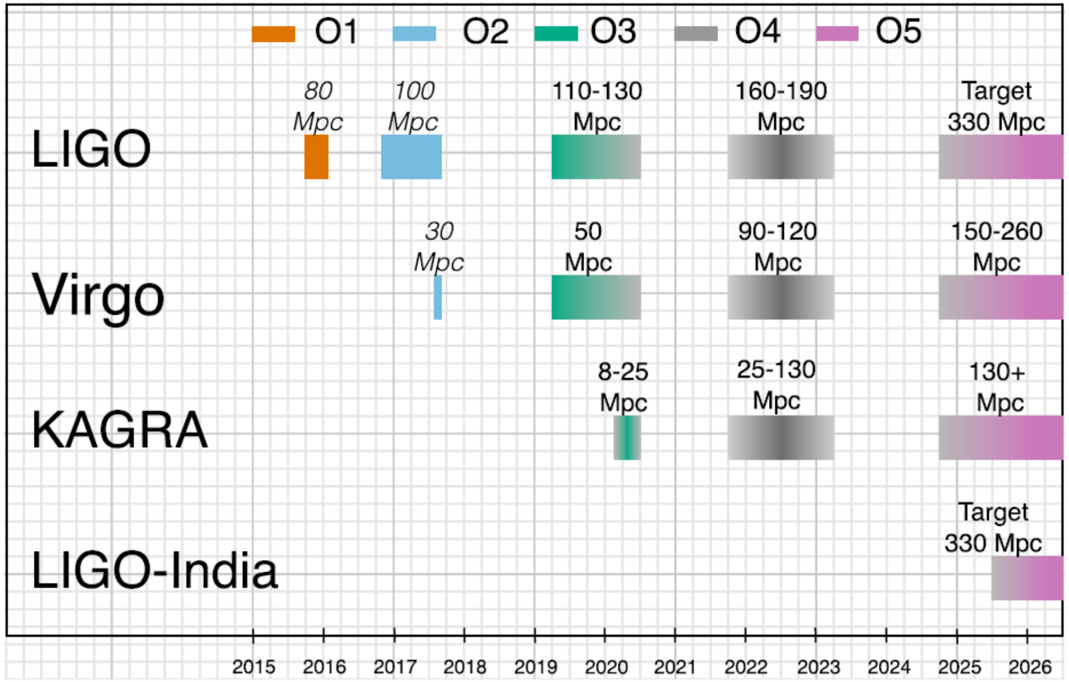
Better sensitivity

- ~10x wrt previous generation (2002-2011)
- ~1000x more volume → ~1000x higher rates

Our observing scenario

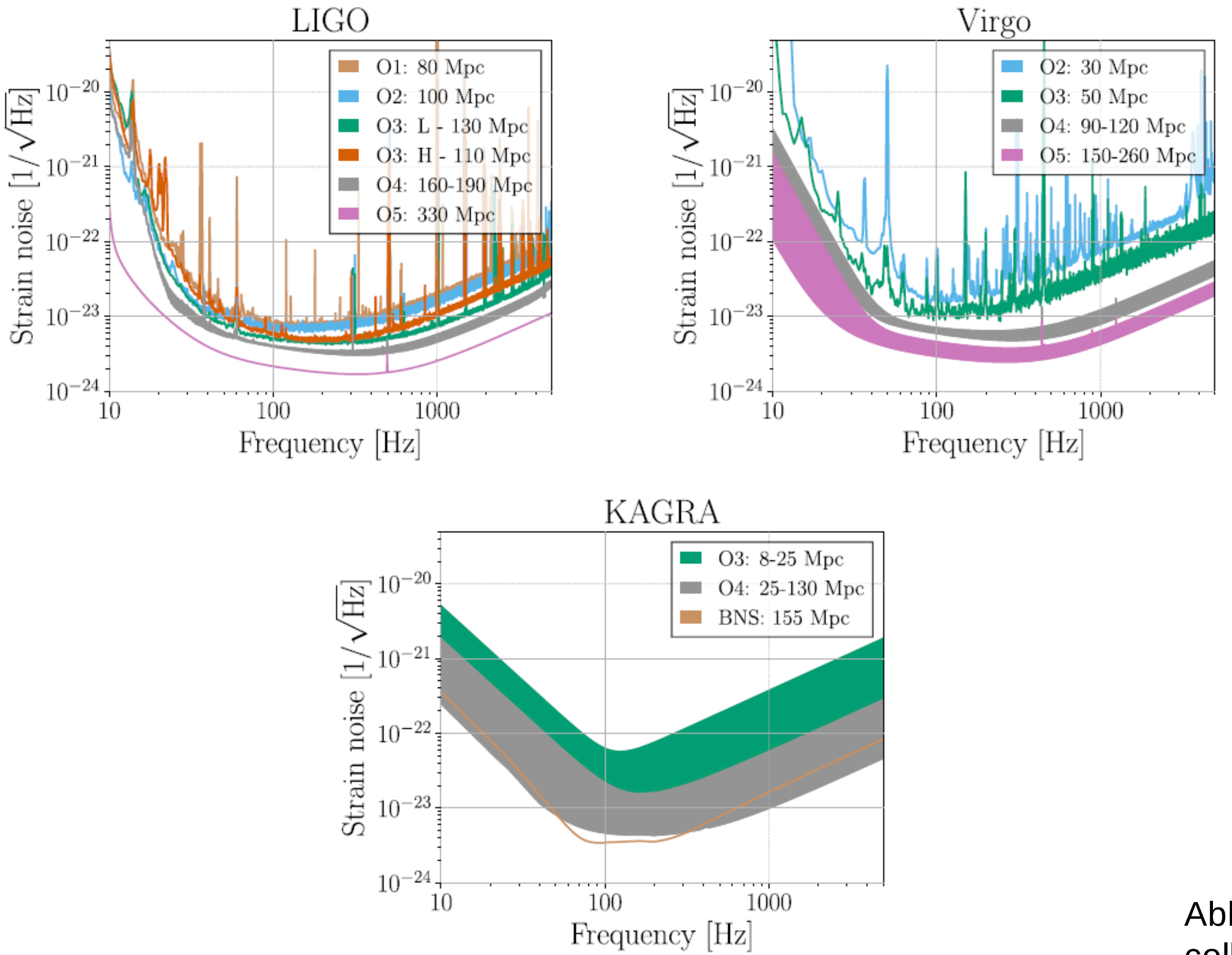
Run schedule

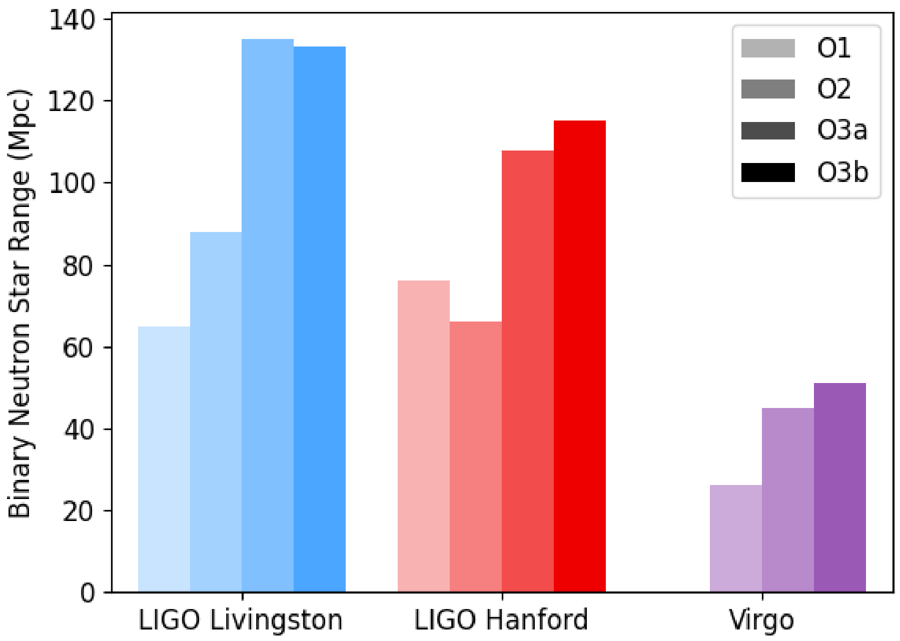
- Each run longer and more sensitive
- Commissioning breaks (e.g. 1 month in O3 in Oct 2019)
- Adv Virgo joined in O2
- Oct 2019 KAGRA signed MoU with LIGO/Virgo



Abbott et al, (LVK collaborations) 2020, LRR, 23, 3

Our observing scenario and O3



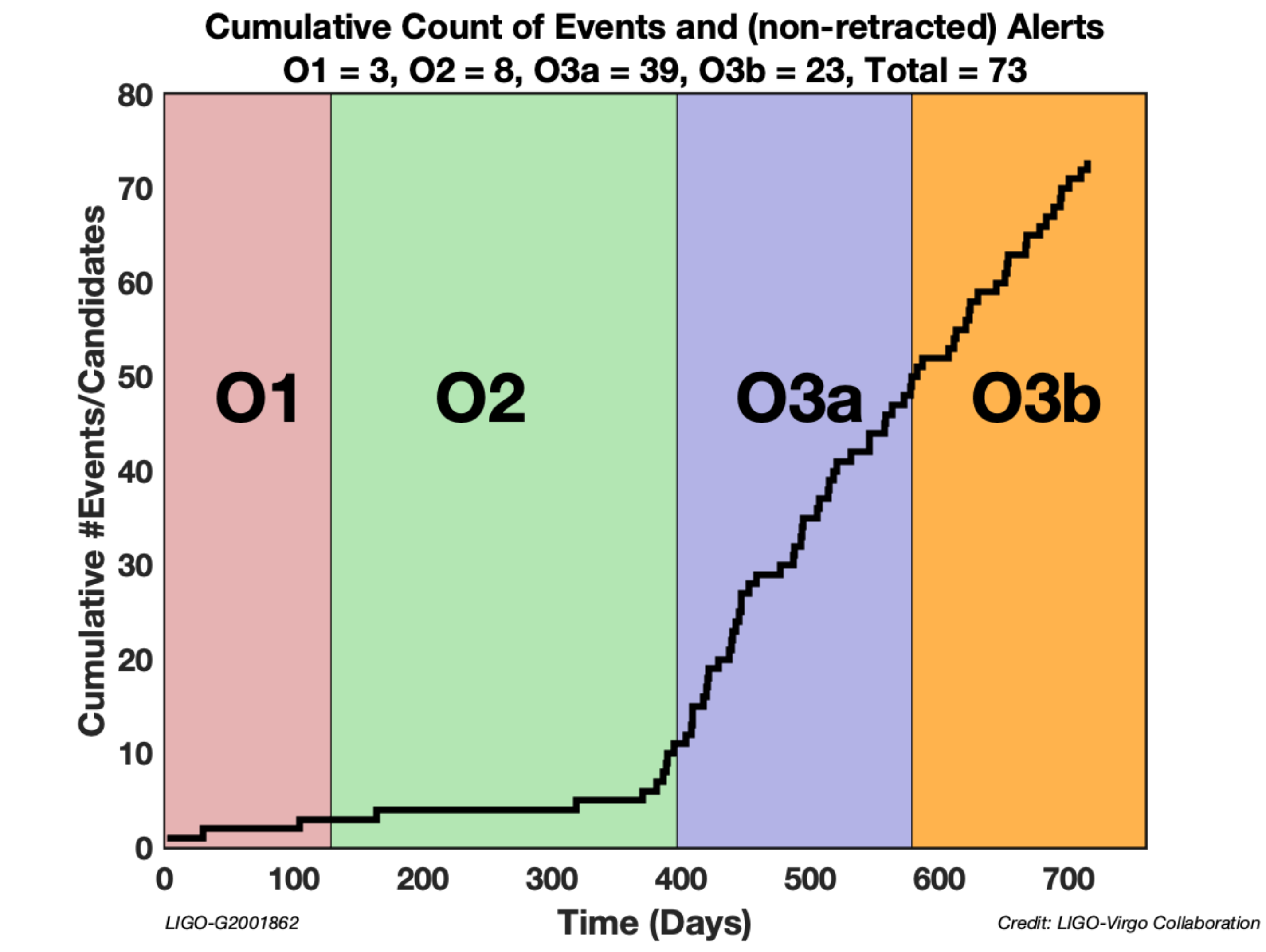


Credits: LIGO-Virgo-KAGRA Collaborations/Hannah Middleton/OzGrav.

Abbott et al, (LVK collaborations) 2020, LRR, 23, 3

The 3rd GW Event Catalog

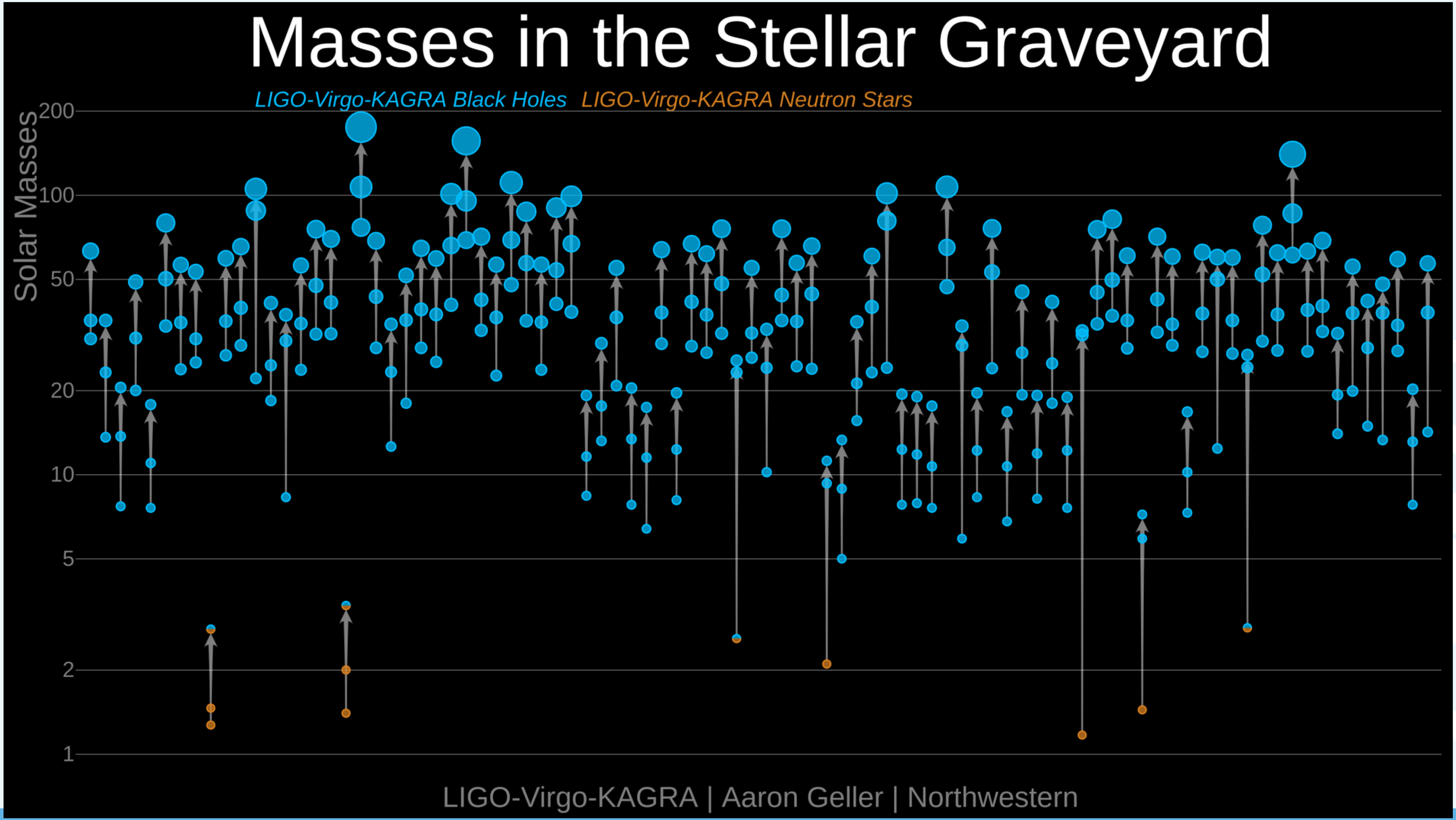
Cumulative events up to O3



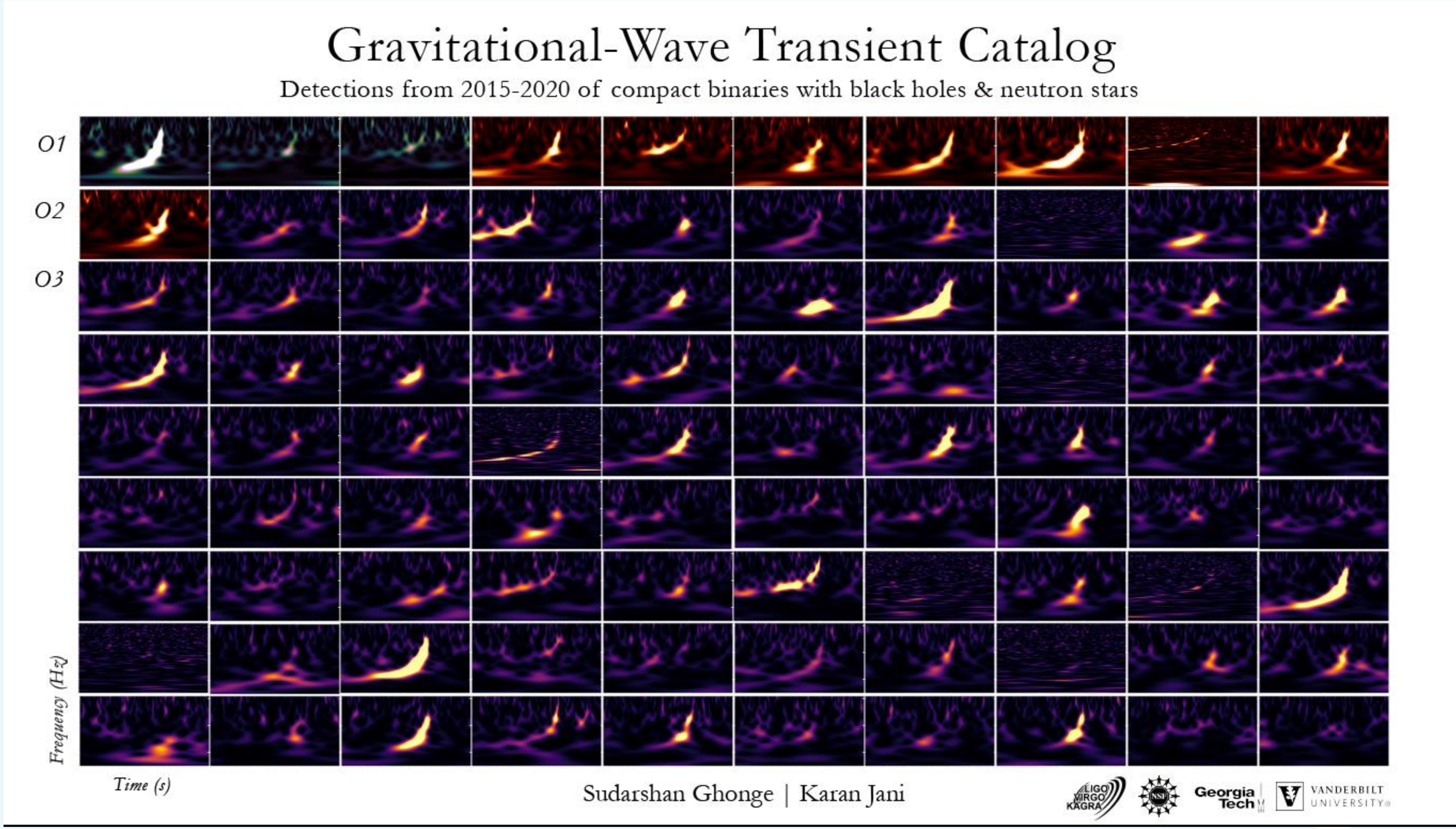
The GW Event Catalogs

- **GWTC-1:**
  - 11 events from O1+O2
- **GWTC-2:**
  - +39 events (total 50 events from O3a)
- **GWTC-2.1:**
  - +8 candidates (revised analysis) - 3 from GWTC-2 with <50% of being astrophysical
- **GWTC-3:**
  - + 35 events from O3b (total 90)

The GWTC-3

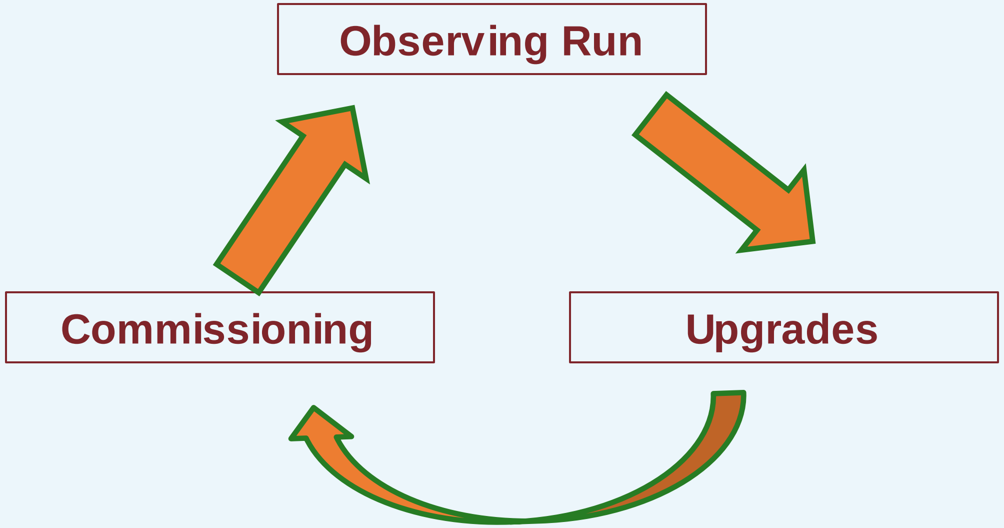


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

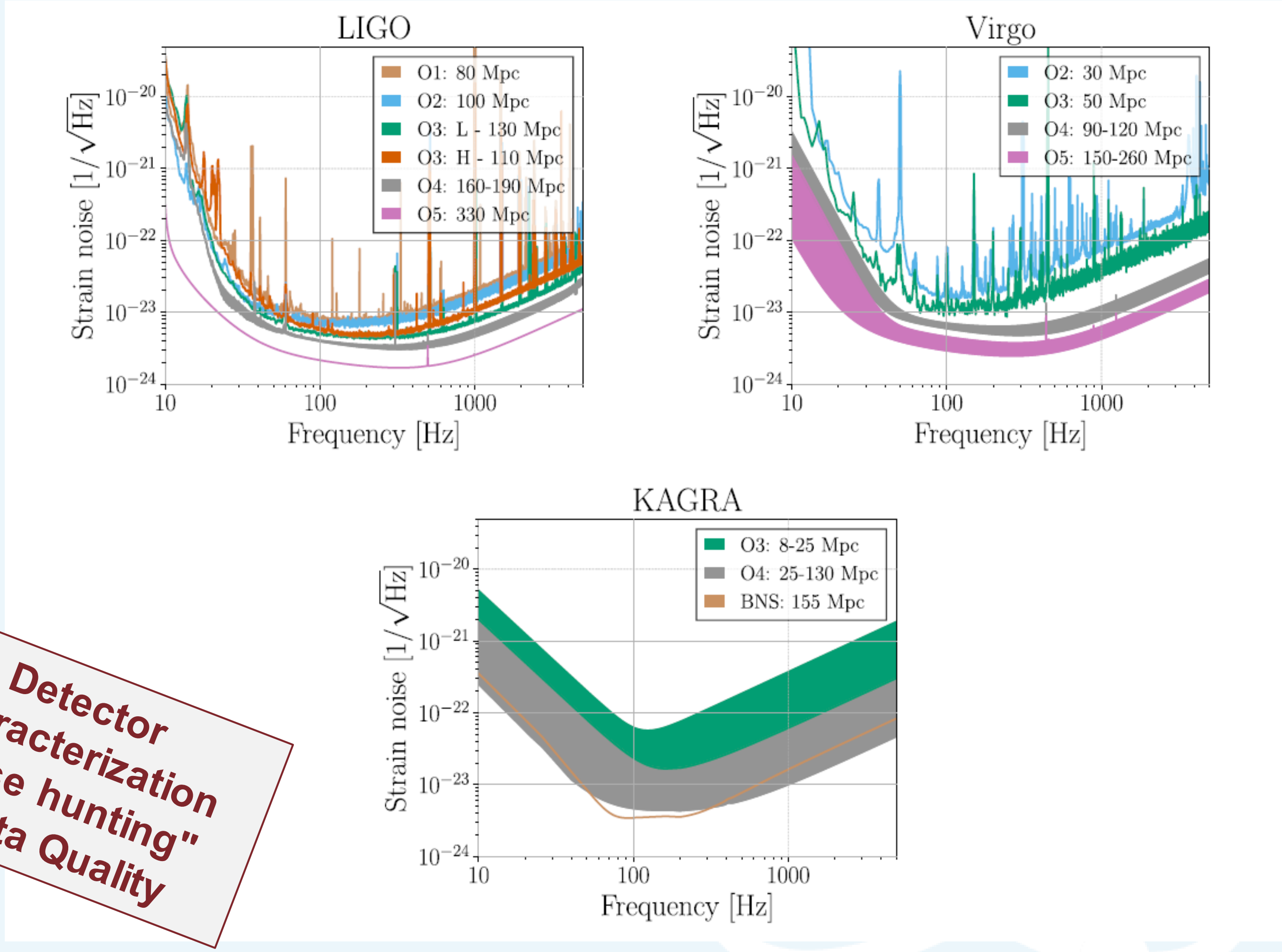

Gravitational-Wave Transient Catalog
Detections from 2015-2020 of compact binaries with black holes & neutron stars
O1
O2
O3
Frequency (Hz)
Time (s)
Sudarshan Ghonge | Karan Jani
LIGO
VIRGO
KAGRA
Georgia Tech
VANDERBILT UNIVERSITY

Detecting Gravitational Waves

- **Sensitivity varies with frequency: main noise sources**
  - Low frequencies: Newtonian, seismic
  - Mid frequencies: thermal processes
  - High frequencies: quantum noise



Detector Characterization "noise hunting" & Data Quality

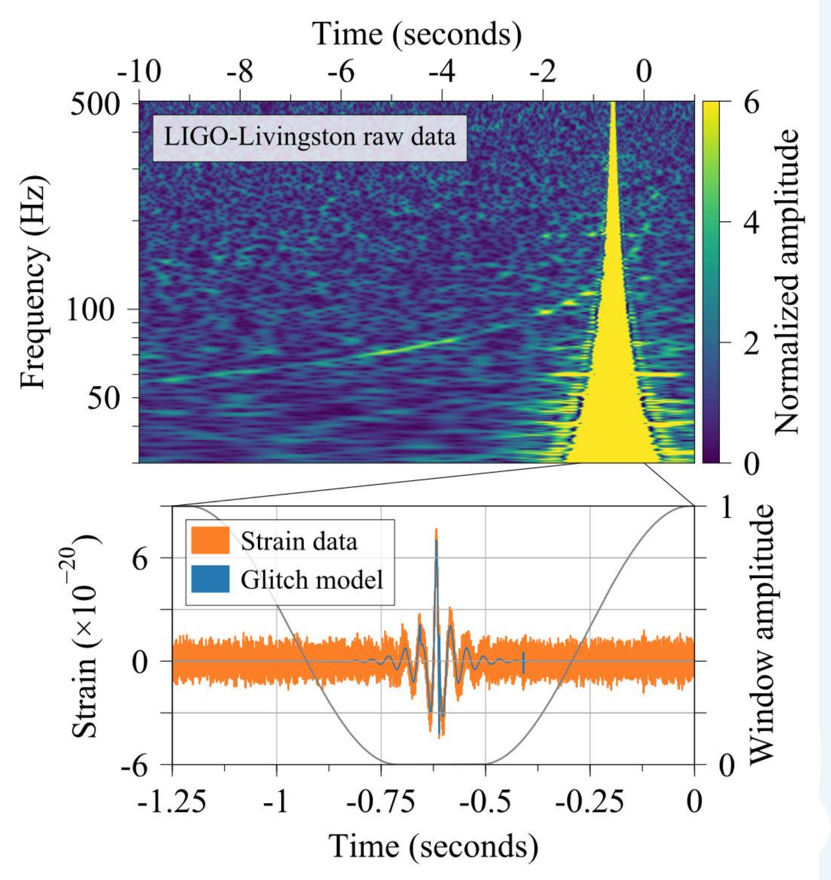


"Observing Scenario" paper
Abbott et al, (LVK collaborations) 2020, LRR, 23, 3

Noise glitches

- **Noise is not stationary**
  - Transient events can happen
  - Not related to astrophysical source, but local disturbances
  - Different timescales/frequency ranges
  - Affect data quality, stability and GW detection

- **Noise hunting & characterization is critical**
  - Detect and classify glitches to find their origin and remove them
  - Hardware/software origin
  - Glitches have complex time-frequency morphologies
  - Data from auxiliary sensors important to understand origin
  - Machine learning offers promising approach (e.g. George&Huerta2017, Razzano&Cuoco 2018)



Glitch in LIGO L1 detector during GW170817
Abbott et al 2017

Glitch morphologies

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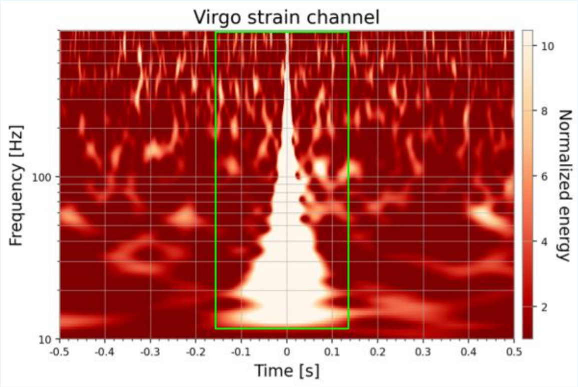
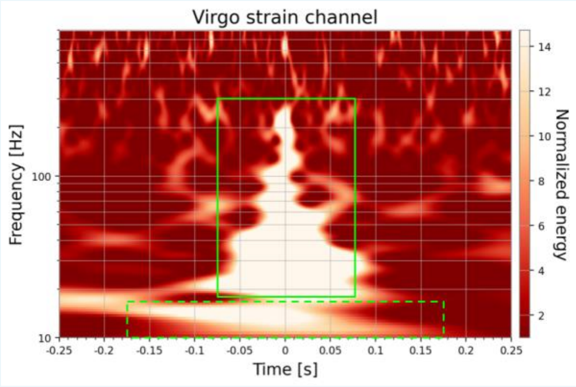
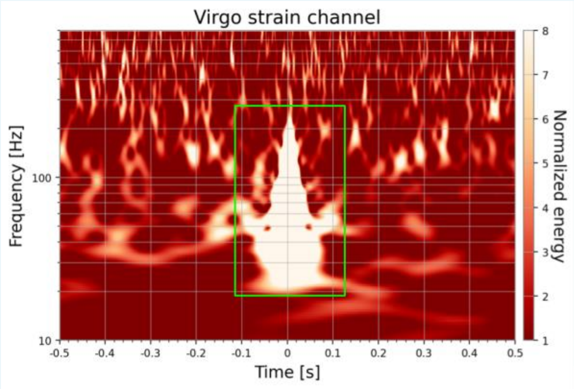


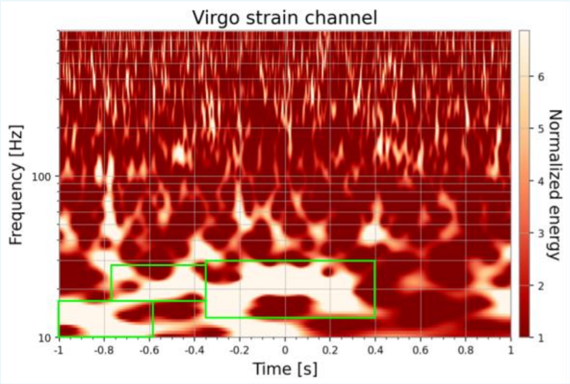
Blip



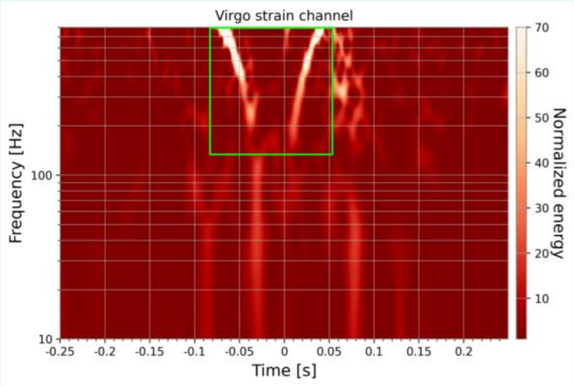
Helix



Koi Fish

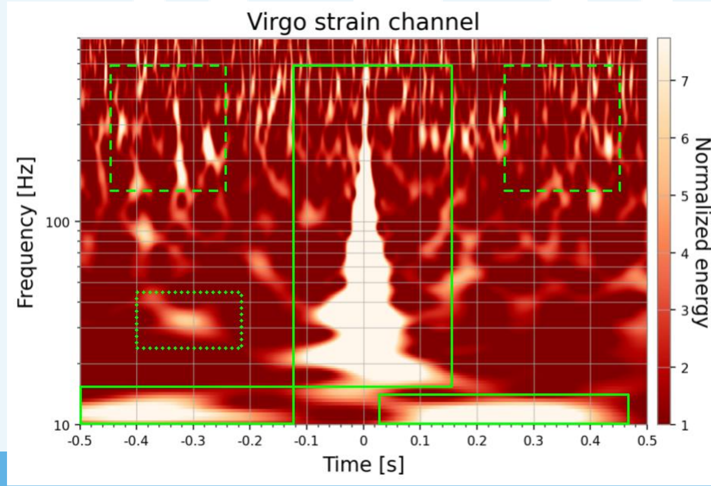


Scattered Light



Whistle

Many Glitches



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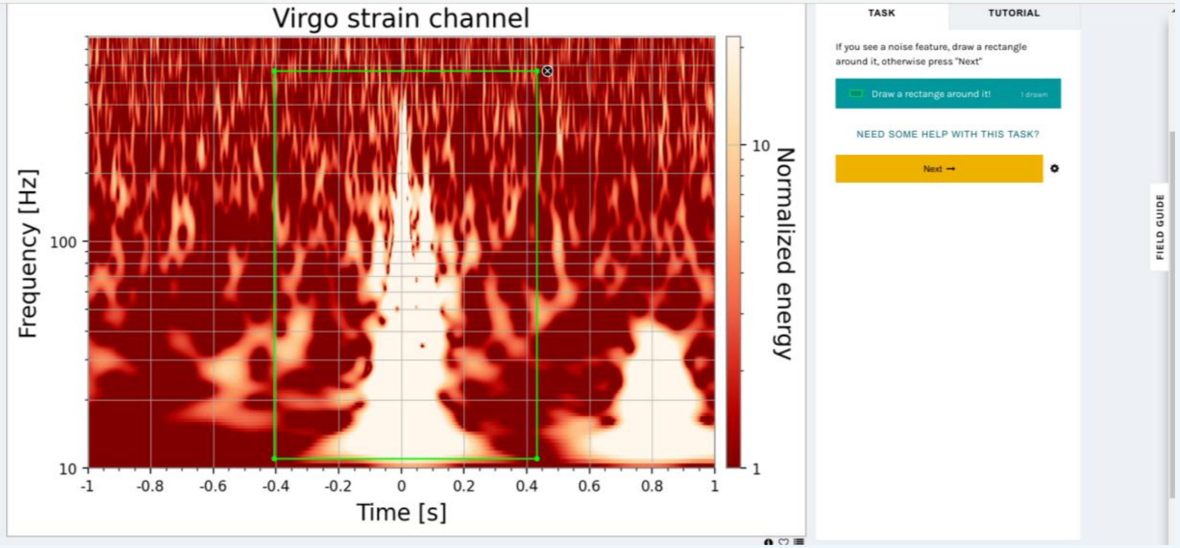
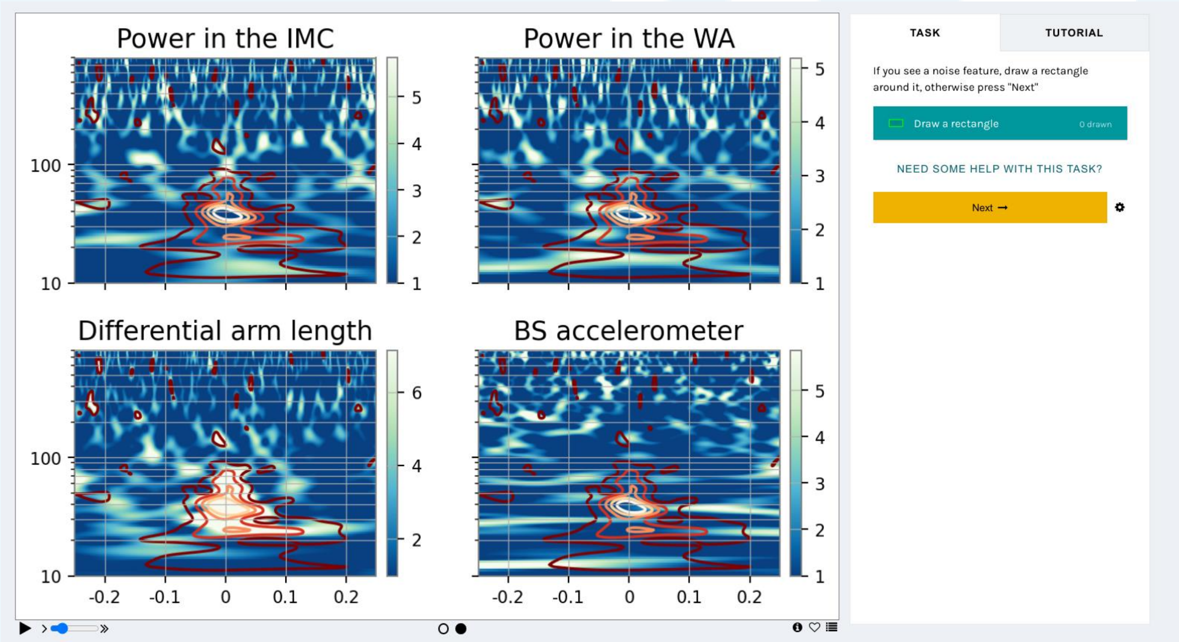
The Challenges of GWitchHunters

- Classify, locate glitches and find correlations with Aux Channels
- See tomorrow's presentation

Desktop →

Mobile →





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