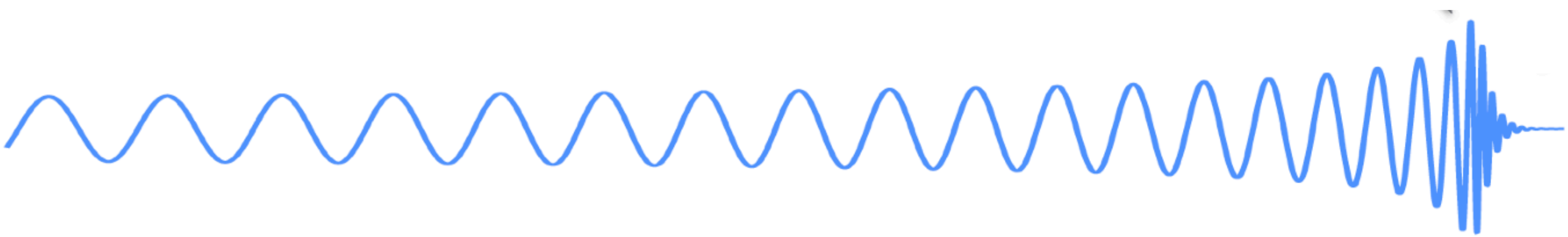
www.uv.es/virgogroup

Gravitational waves from compact objects

José Antonio Font



Einstein's gravitational field equations

GEOMETRY $$\boxed{G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu}}$$ MATTER

Sufficiently far from the sources of the gravitational field, where the field is weak, Einstein's equations reduce to a wave equation.

Weak field: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ (Minkowski + perturbation)

$$\Box \, \bar{h}_{\mu\nu} := \left(\Delta - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) \bar{h}_{\mu\nu} = 16\pi T_{\mu\nu} \qquad \bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2} \eta_{\mu\nu} \, h$$

Existence of GW predicted by Einstein over 100 years ago.

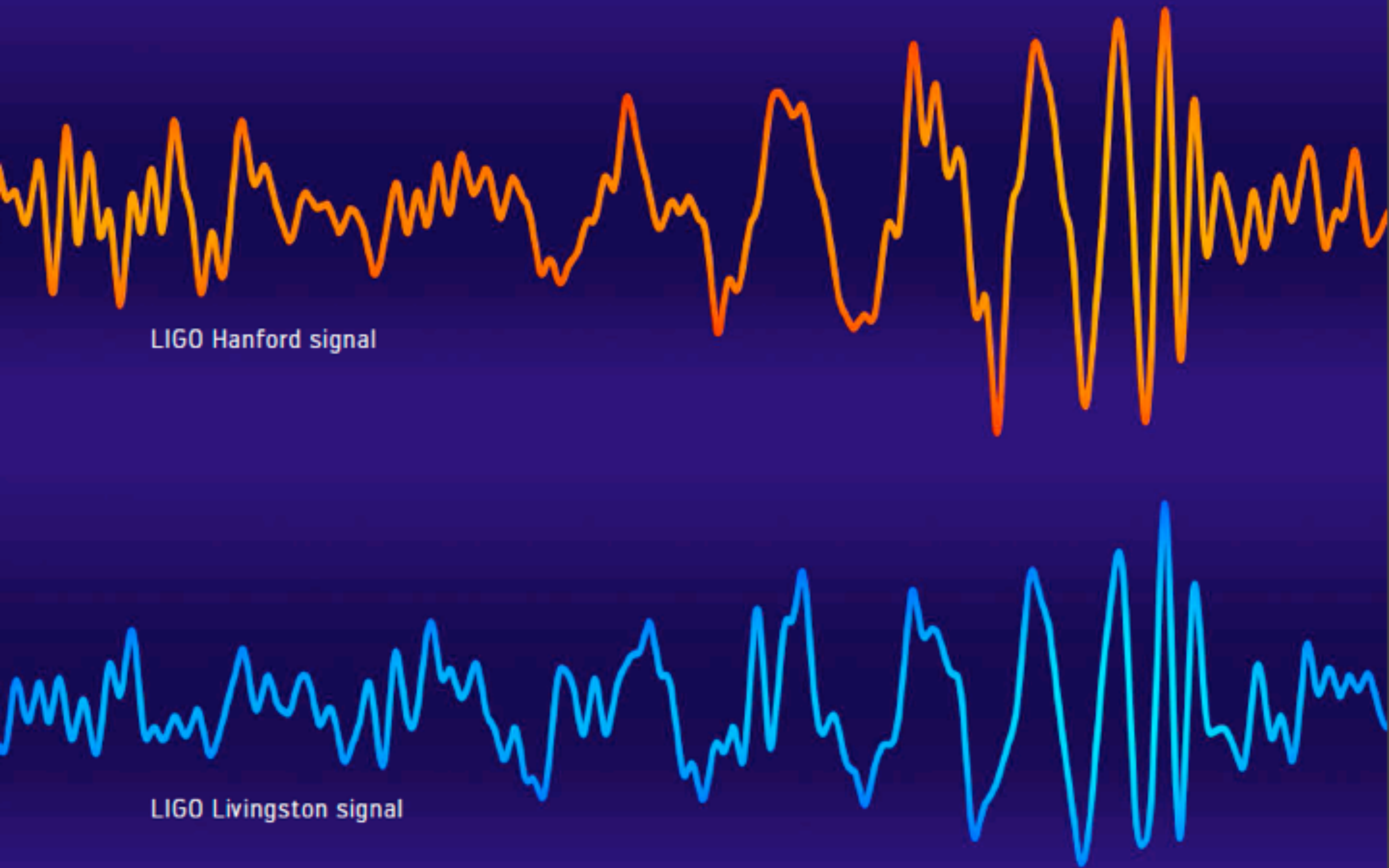
Convincing observational evidence obtained 60 years after prediction (Hulse-Taylor binary pulsar, 1974).

We had to wait until Sep 14, 2015 to accomplish the direct detection.

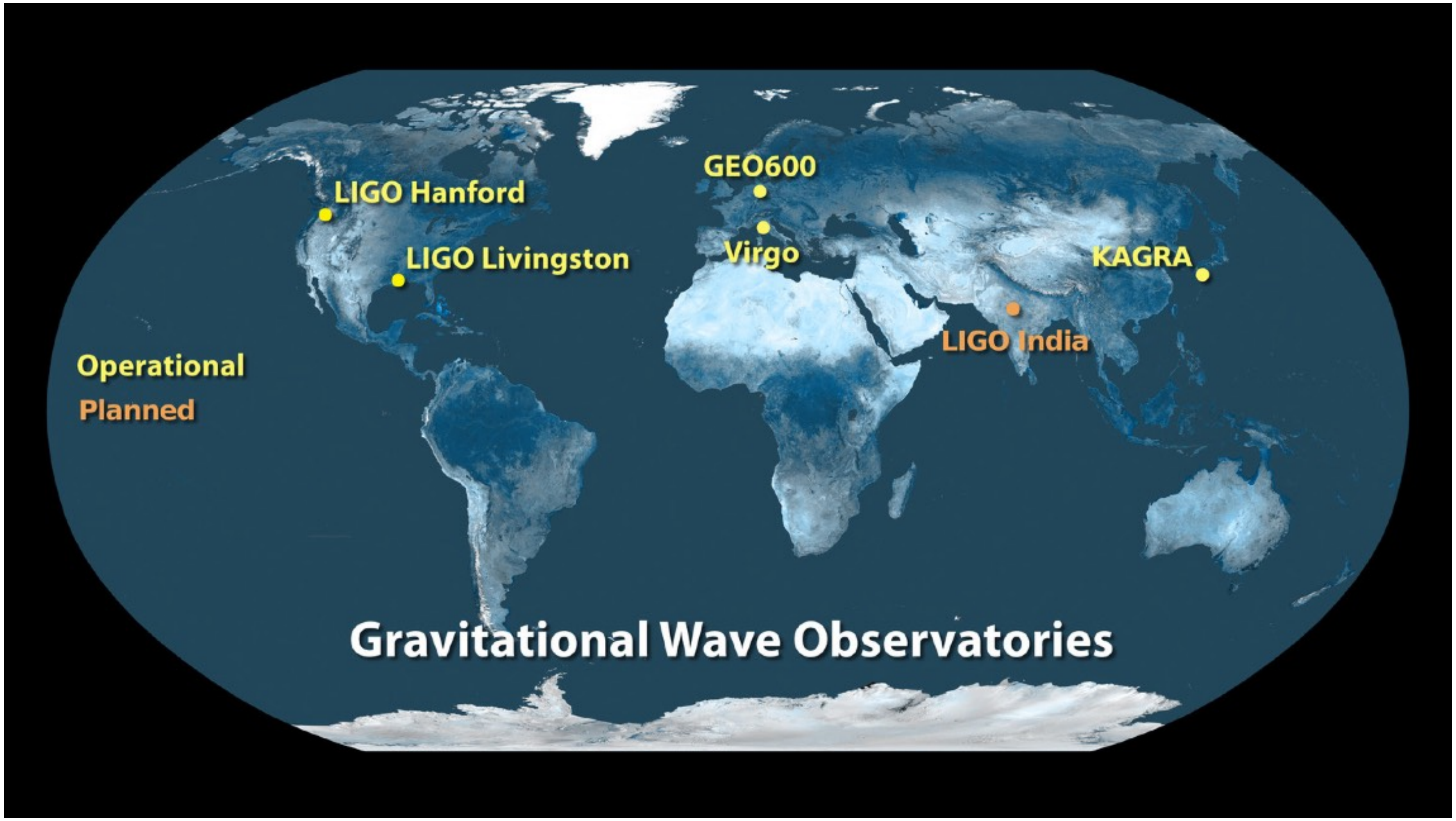
GW150914

First detection!

9:50:45 UTC, 14 September 2015



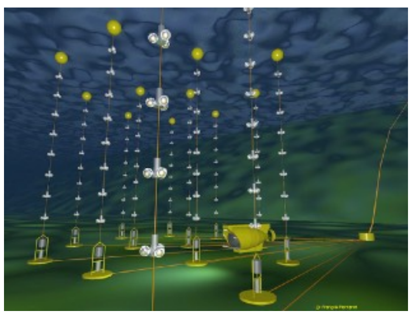
A global GW detector network



- km-scale interferometers
- sensitive to GWs between a few Hz to a few kHz
- simultaneous detection increases detection confidence
- improved sky localisation and polarization

Multi-Messenger Astrophysics - GW + Light + Neutrinos

gravitational
waves



cosmic rays
neutrinos

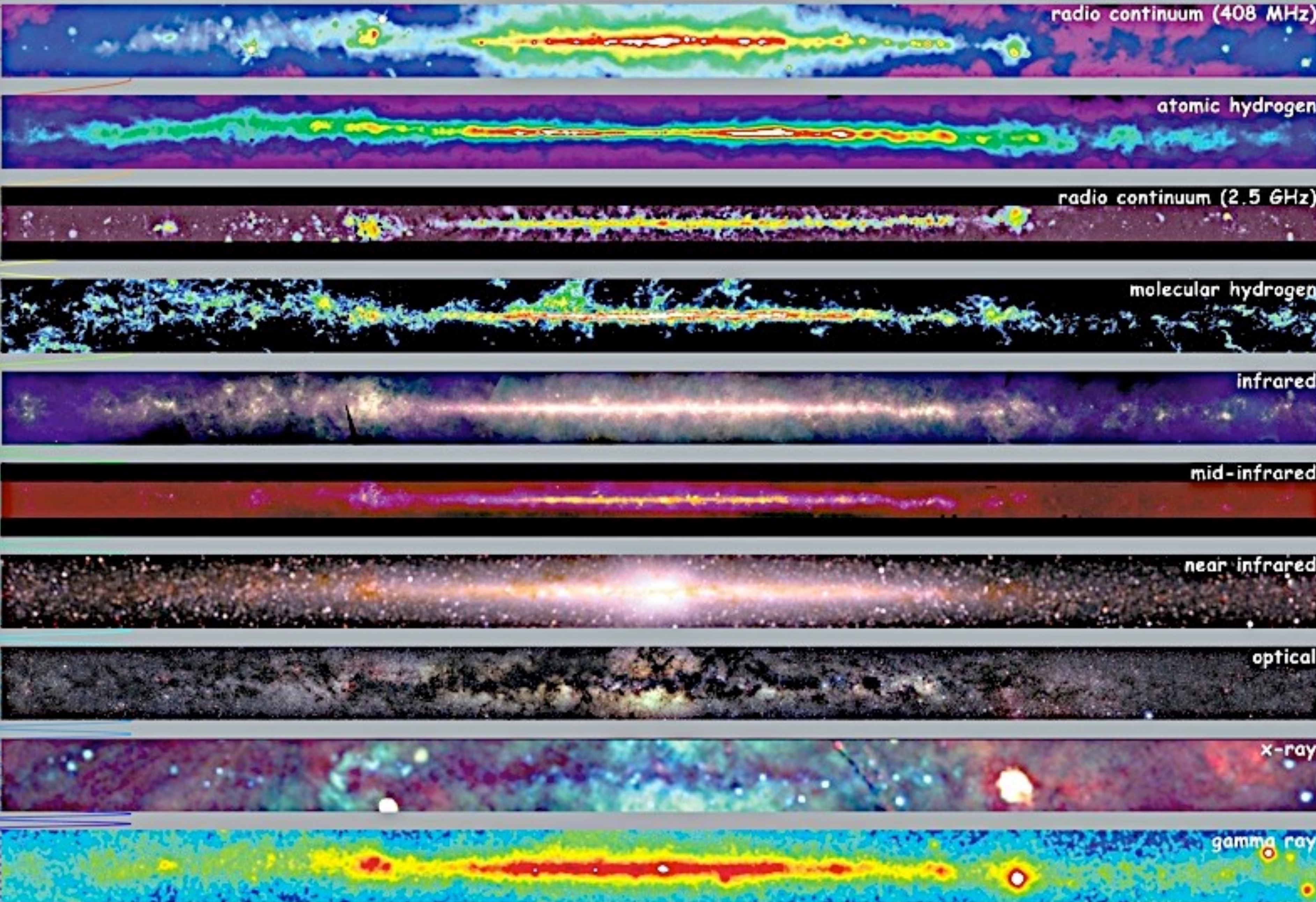
gamma rays
X rays

ultraviolet
visible / infrared

radio

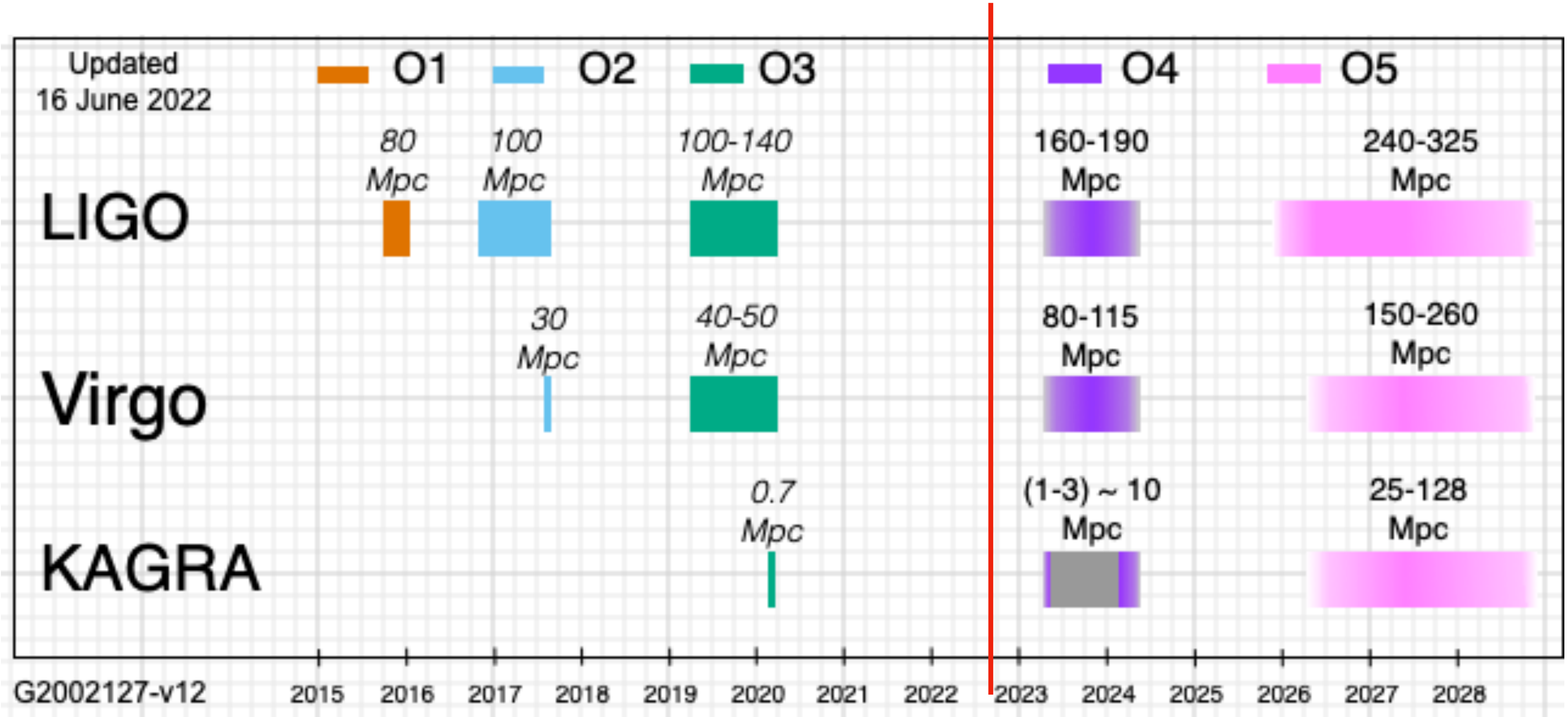
O1/O2: LIGO/Virgo signed MoU with astronomers, comprising about 200 instruments across the entire EM spectrum. O3: public alerts.

MMA dramatically accomplished with GW170817



Multiwavelength Milky Way

Observing timeline



More details at: https://observing.docs.ligo.org/plan/

(15 June 2022 update; next update by 15 September 2022)

All data is **public**: Gravitational Wave Open Science Center (www.gw-openscience.org)

GW observations

GWTC-1:

11 GW events from O1 & O2

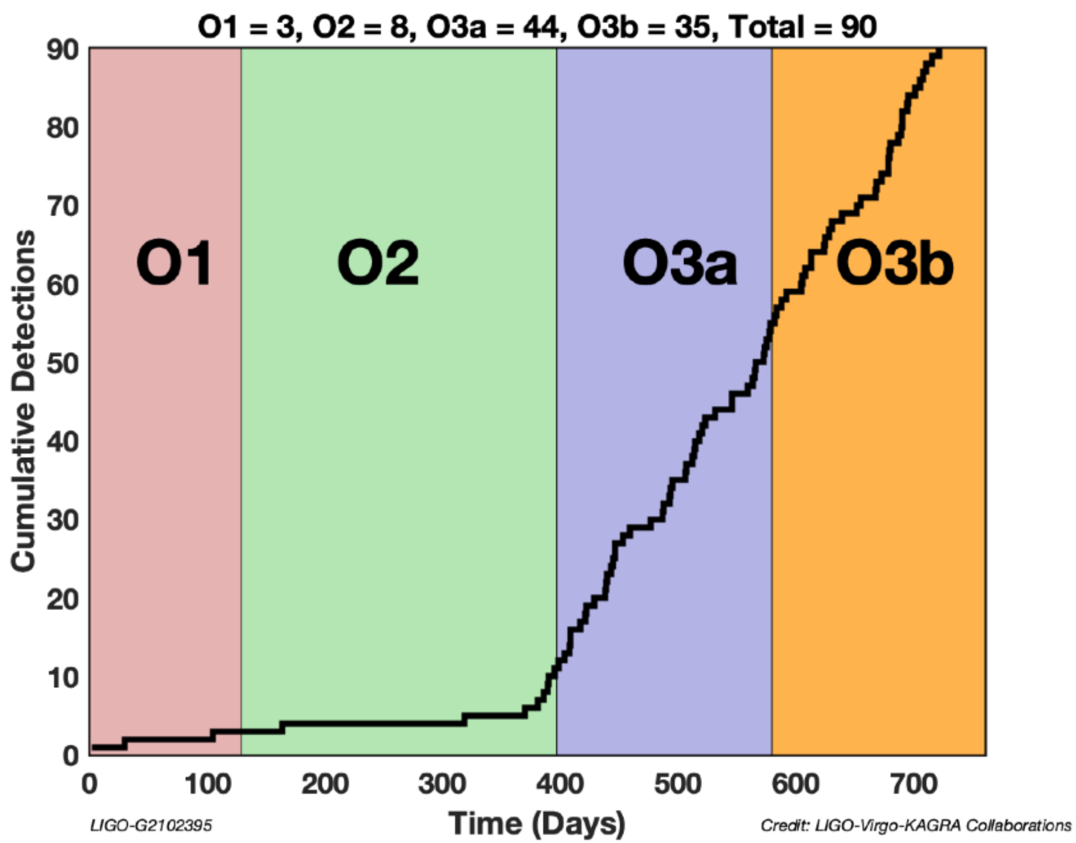
Including GW150914 & GW170817

GWTC-2 & GWTC-2.1:

44 new GW events (O3a)

GWTC-3:

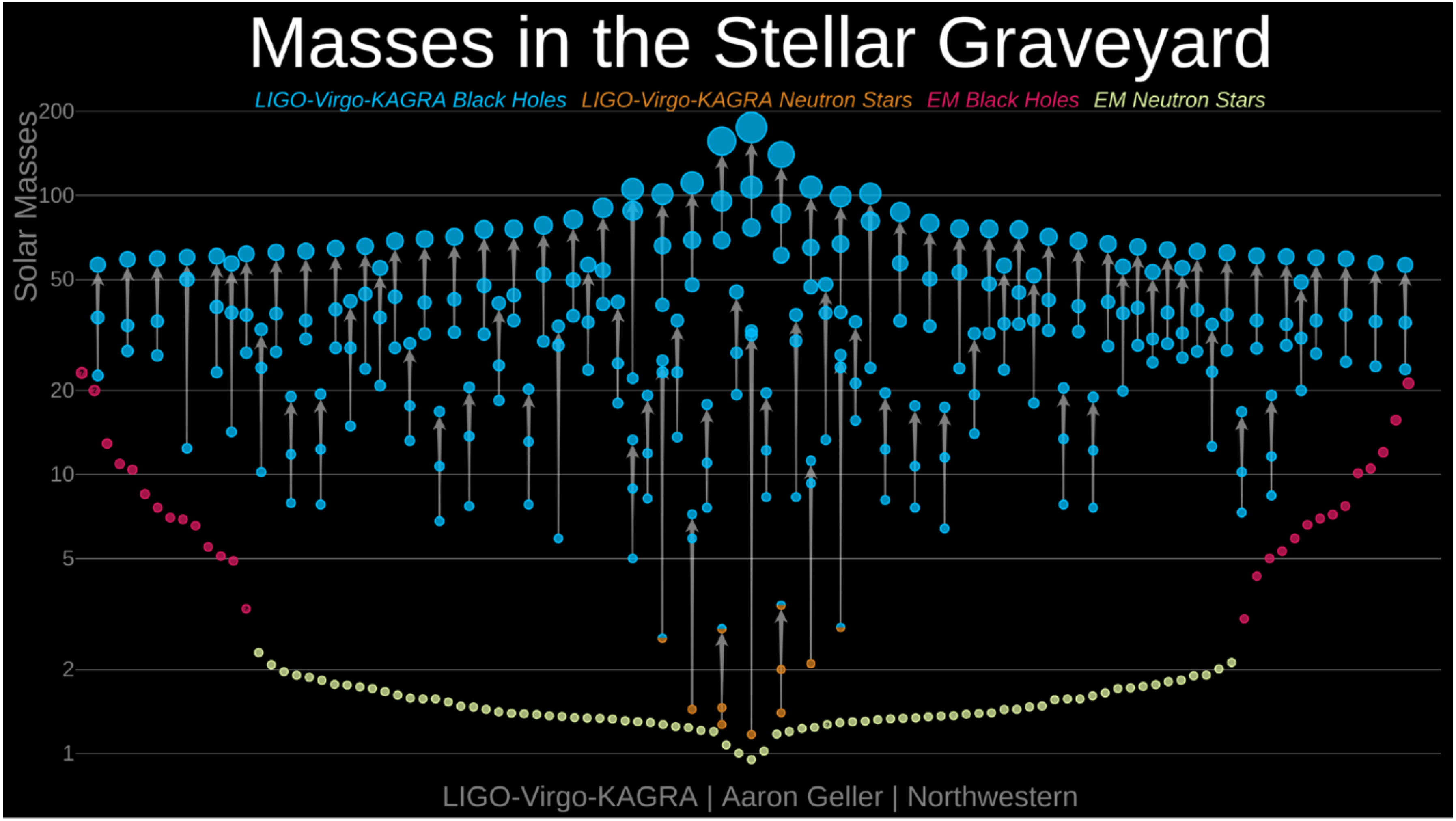
35 new GW events (O3b)



O3 detection rate ~ 1 event every 5 days

O4-O5 detection rate ~ 1-few events per day

GW observations

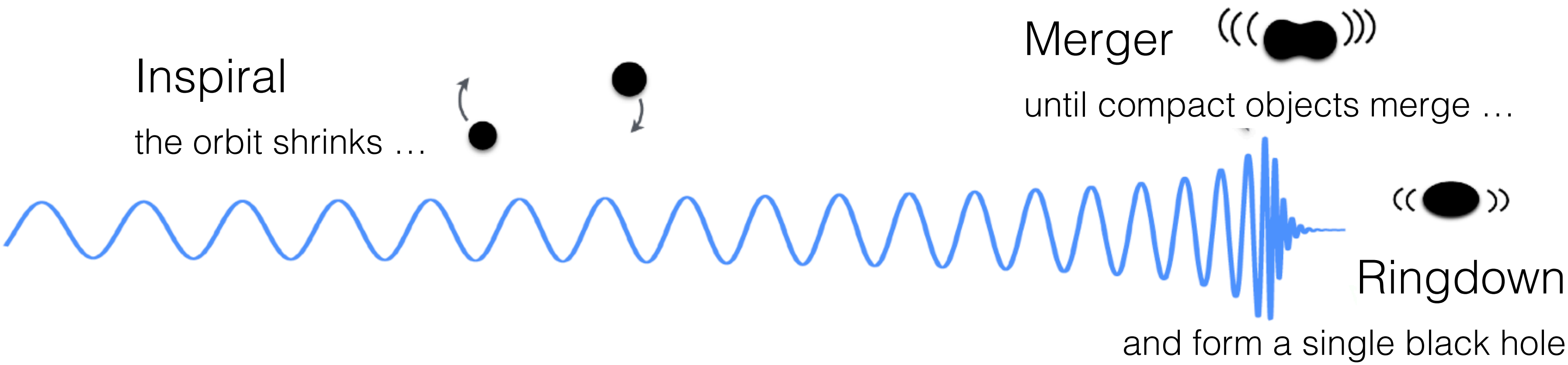


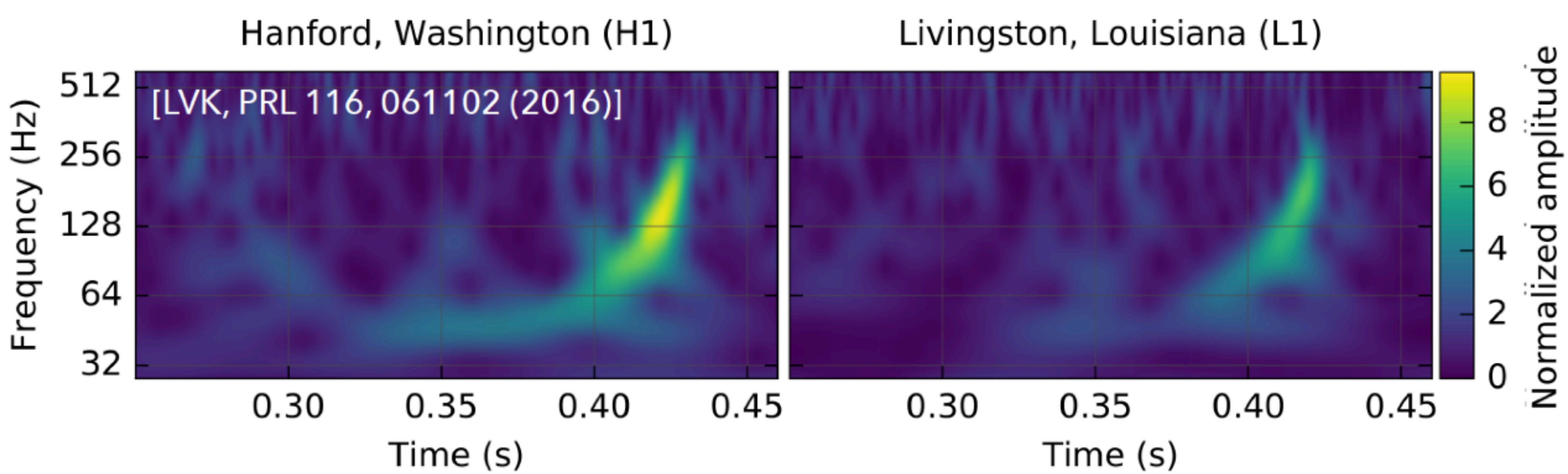
All events through end of O3 with p_astro > 0.5

GW observations

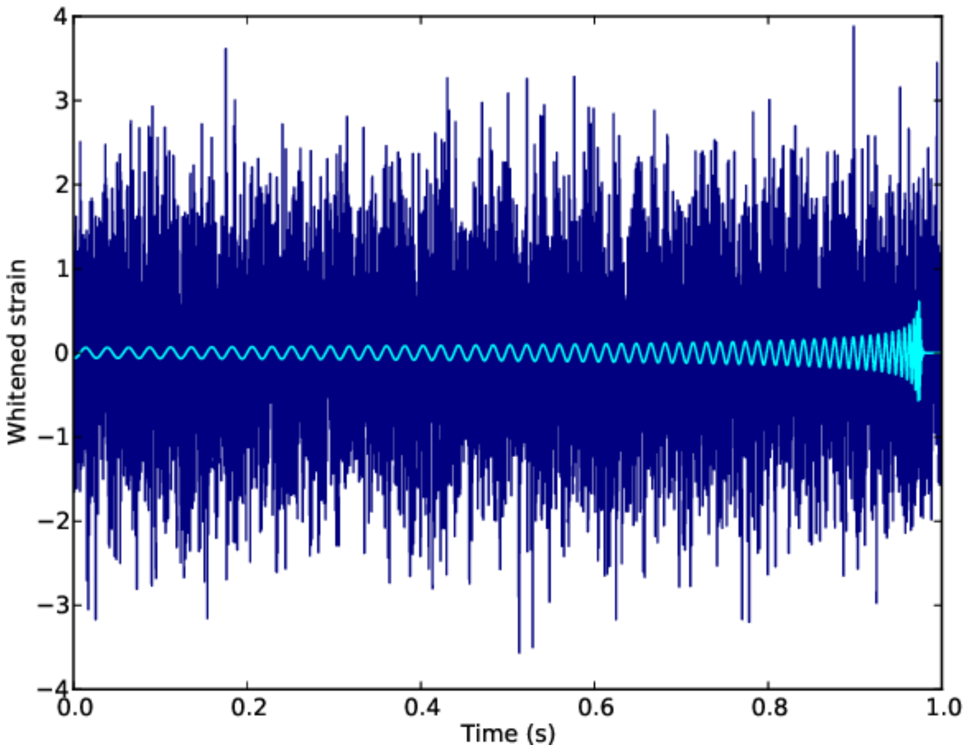
All events detected so far are consistent with **compact binary mergers**.

Signal “chirps” in the sensitivity band of the detector.





CBC sources - modelled sources



Searches based on matched-filtering using template banks from GR (waveform approximants from NR, pN approximation, EOB).

Particularly useful for inspiral and for BBH mergers.

For BNS and BH-NS mergers, matter effects important in the signal, especially post-merger.

Template banks incomplete in some regions of the parameter space (large q, HM, precession).

Machine Learning approaches can help completing banks (waveform generation) and aiding searches.

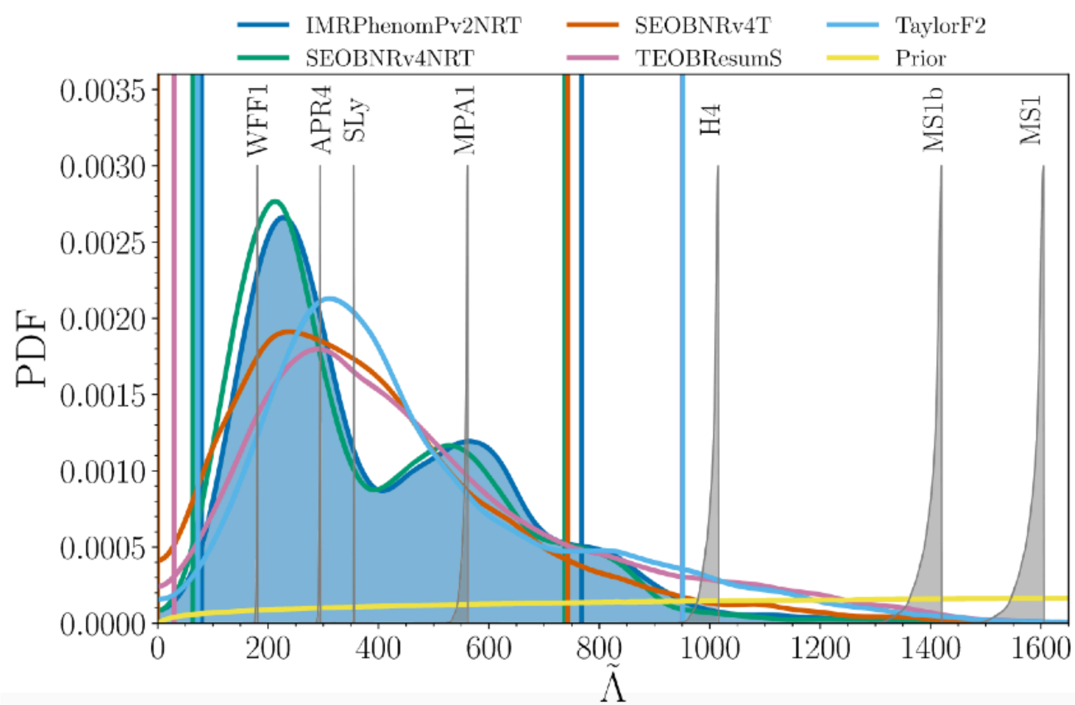
Binary neutron stars

GW170817 & GRB170817A & AT2017gfo

Dozens of EM follow-up observations: **multi-messenger astronomy**

Large impact in astrophysics, cosmology, and nuclear physics:

- BNS/sGRB association
- Support for the kilonova model, heavy element nucleosynthesis
- Measurement of H_0 (BNS as standard siren)
- Constraints on EOS of high-density matter (tidal deformability)



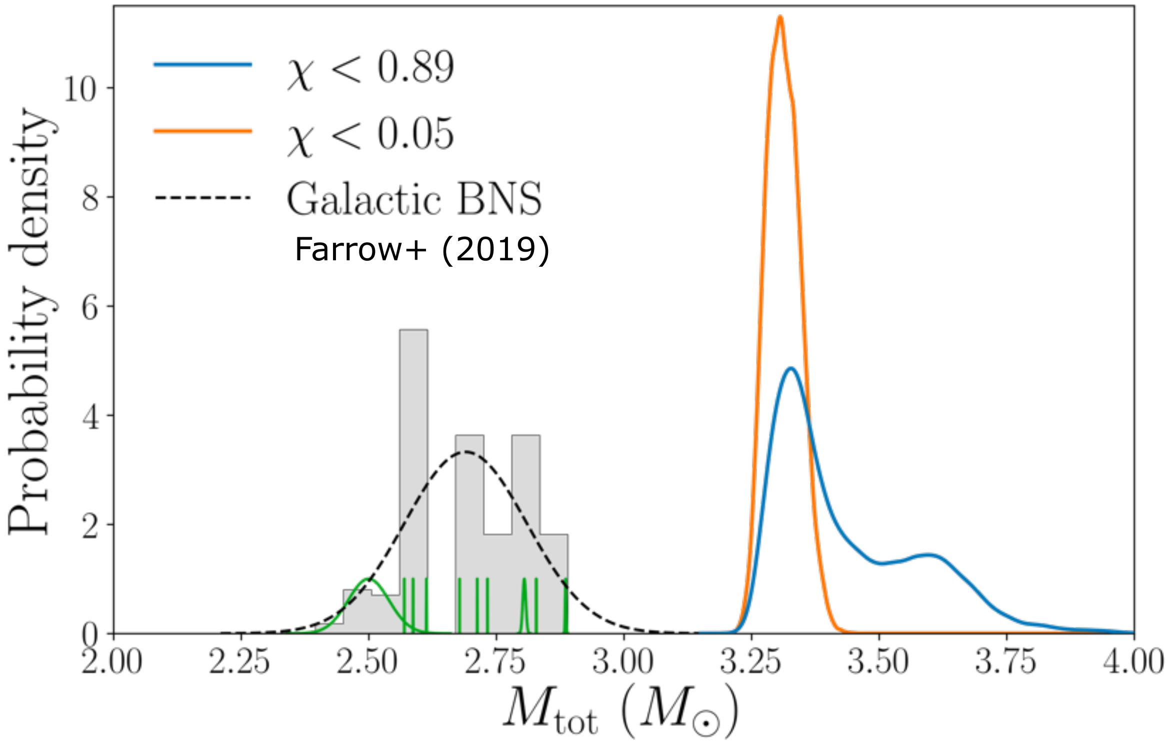
LVK
PRX 9, 031040 (2019)

O3 Highlights - GW190425

GW190425: Observation of a Compact Binary Coalescence with Total Mass ~ 3.4 $M_\odot$
(LVC, ApJL, 892:L3, 2020)

Most likely 2nd BNS merger after GW170817 (BBH or NSBH cannot be ruled out)

2 interferometer detection: L1 + Virgo (poor sky localisation; no EM counterpart)



Total mass larger than any known system so far. A new population?

O3 Highlights - GW190814

GW190814: Gravitational Waves from Coalescence of a 23 $M_\odot$ Black Hole with a 2.6 $M_\odot$ Compact Object (LVC, ApJL, 896:L44, 2020)

3 detector (L1,H1,V1) observation with network SNR of 25.

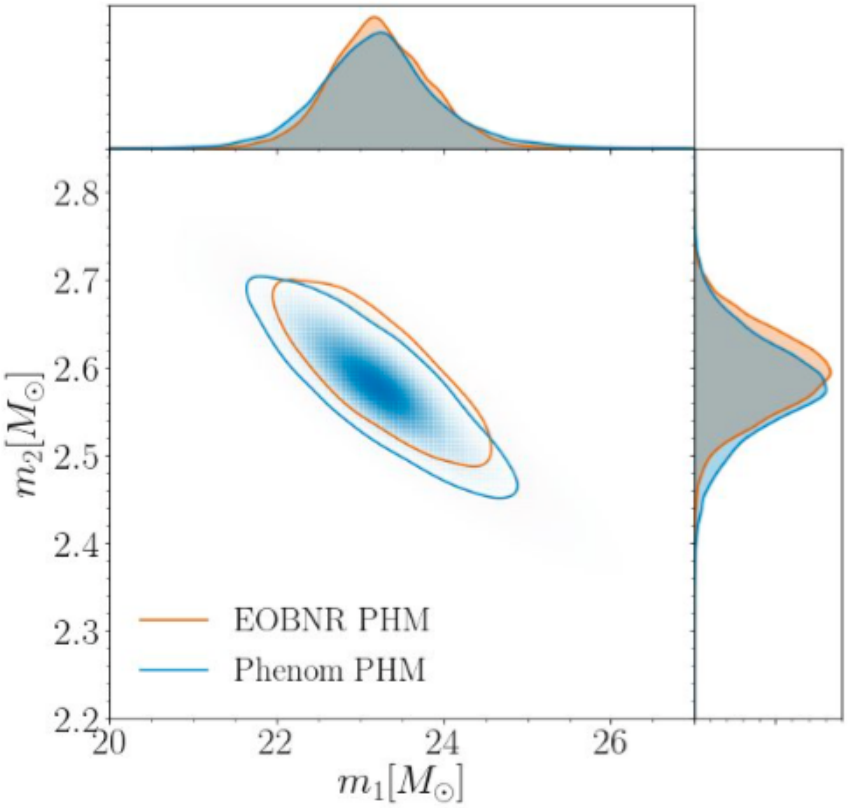
Difficulties to identify the source:

- Asymmetric masses (9:1 ratio)
- No EM counterpart
- No clear signature of tides on inspiral waveform

Compact object of 2.6 $M_\odot$ in mass gap:

compatible with NS or BH depending on maximum mass supported by NS EOS.

Nature of secondary component uncertain: BBH or NSBH?

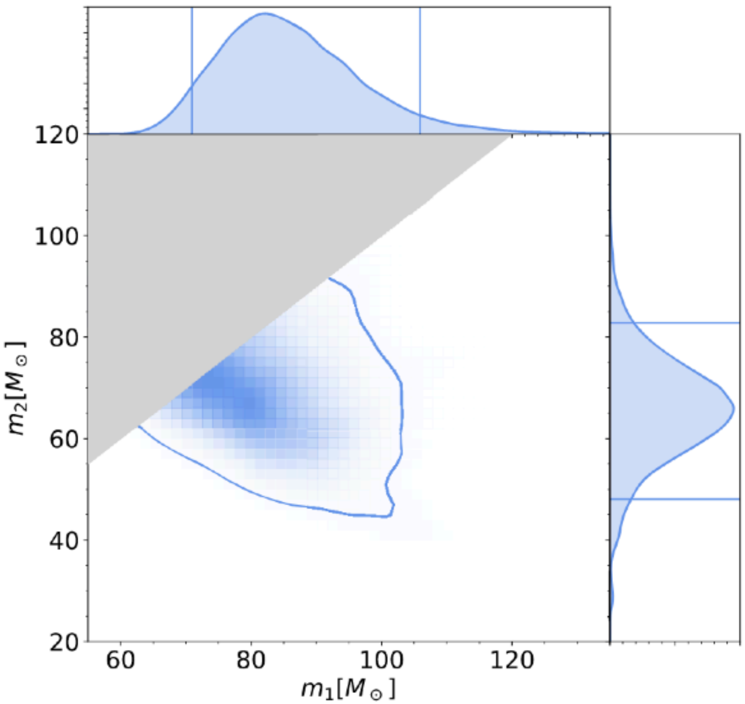


O3 Highlights - GW190521

GW190521: A binary black hole merger with a total mass of 150 $M_\odot$
(LVC, PRL, 125, 101102 (2020))

First observation of an intermediate mass BH (M >100 $M_\odot$)

High-mass progenitor: first direct observation of a BH (the primary) in the pair instability supernova mass gap [65,120] $M_\odot$



Stellar evolution models?
Type of source?

$$m_1 = 85^{+21}_{-14} M_\odot$$
$$m_2 = 66^{+17}_{-18} M_\odot$$

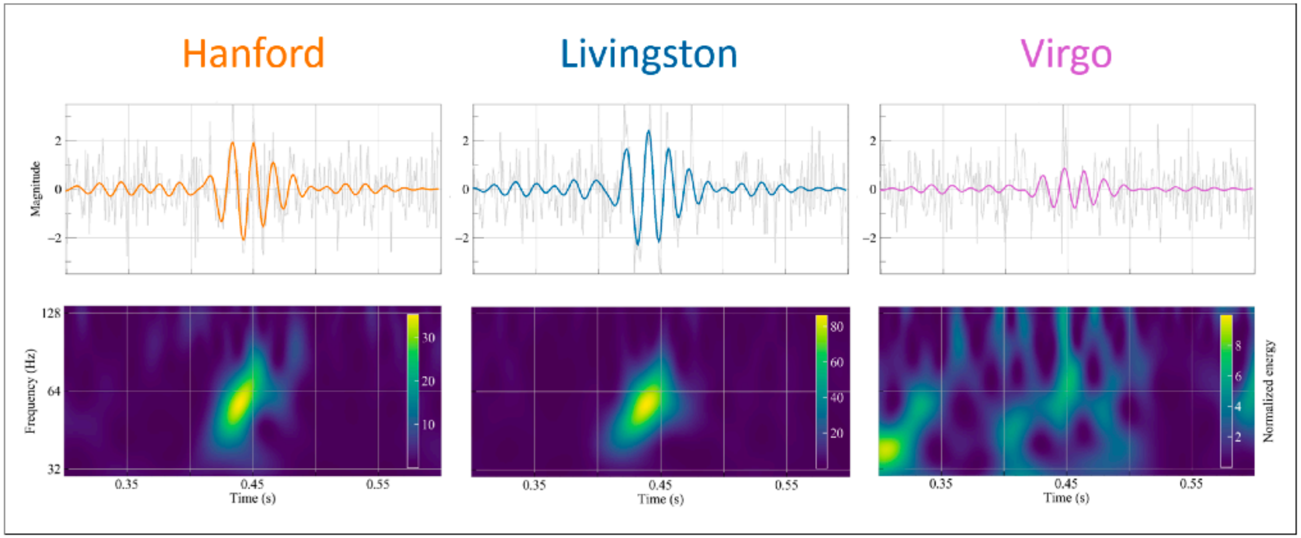
$$M_f = 142^{+28}_{-16} M_\odot$$

Farthest source observed so far (z~0.8)

O3 Highlights - GW190521

Absence of pre-merger emission in GW190521 hampers interpretation of the source (influence of priors)

LVC
PRL, 125, 101102 (2020)



Interpretations involving BH mergers:

- LVK: quasi-circular BBH merger, precession, primary mass in PISN gap
- Romero-Shaw+ 2020: weakly eccentric BBH merger
- Fishbach+ 2020: straddling binary
- Gamba+ 2021; dynamical encounter
- Gayathri+ 2022: highly eccentric BBH merger

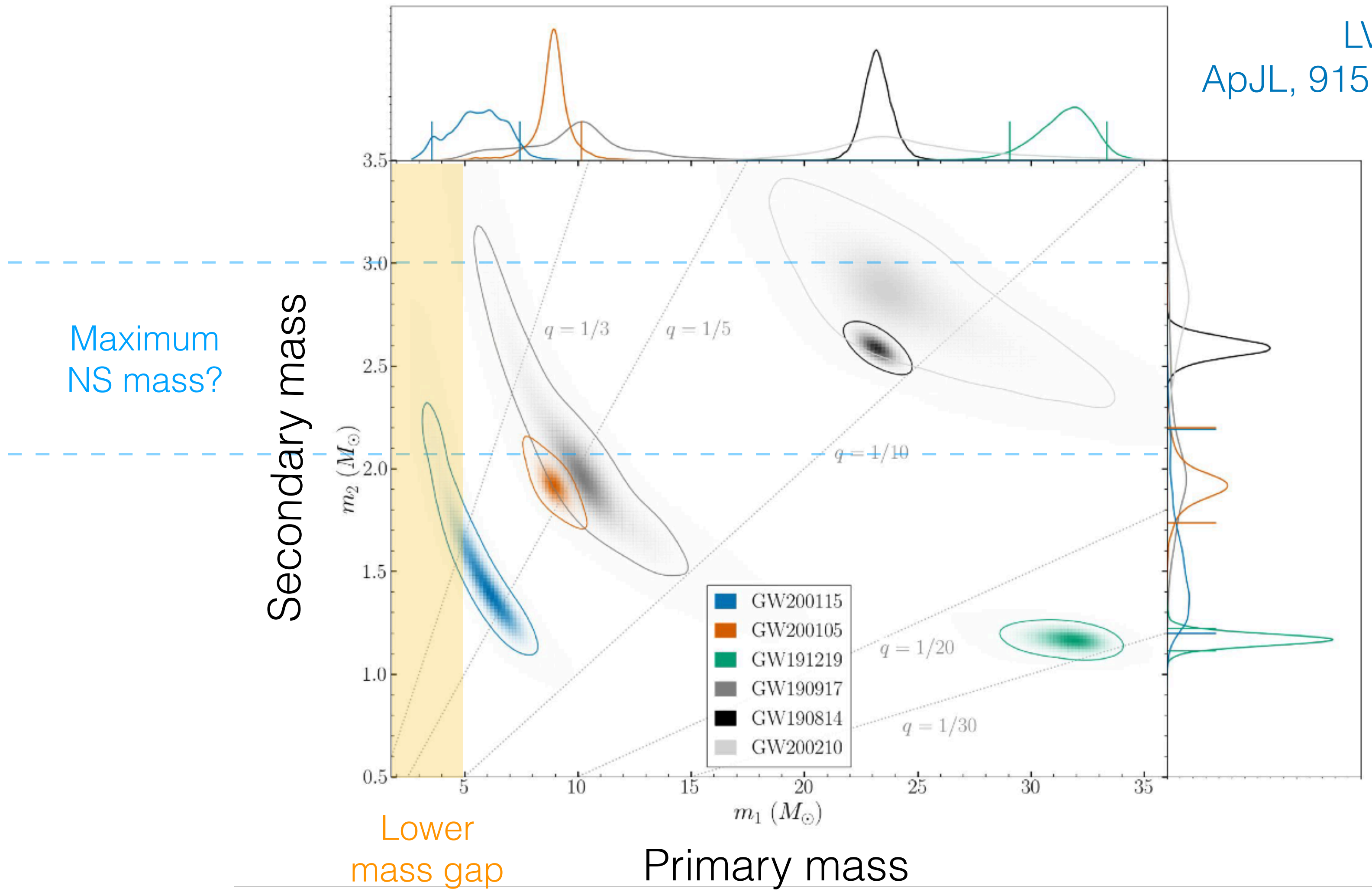
Other proposals:

- Calderón-Bustillo+ 2021: collisions of boson stars
- De Luca+ 2021: PBH origin
- Shibata+ 2021: high-mass disk-BH system
- Palmese+ 2021: merger of ultradwarf galaxies
- …

O3 Highlights - NSBH binaries

First detections of binaries consistent with NSBH mergers (based on component masses)

LVK
ApJL, 915, L5 (2021)

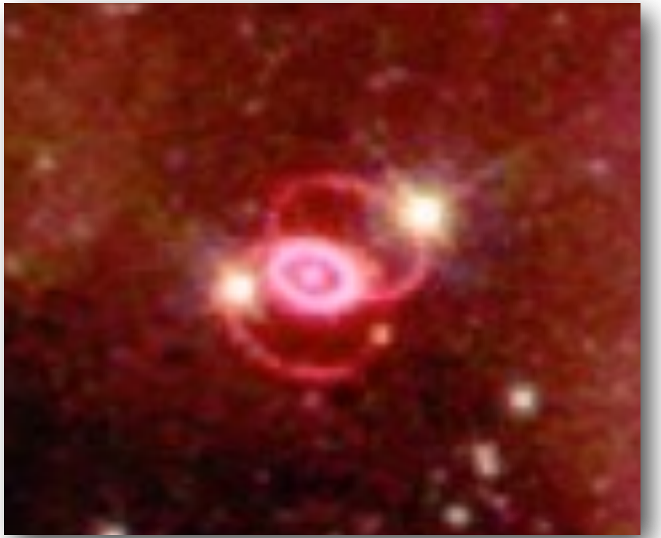


Burst sources - unmodelled sources

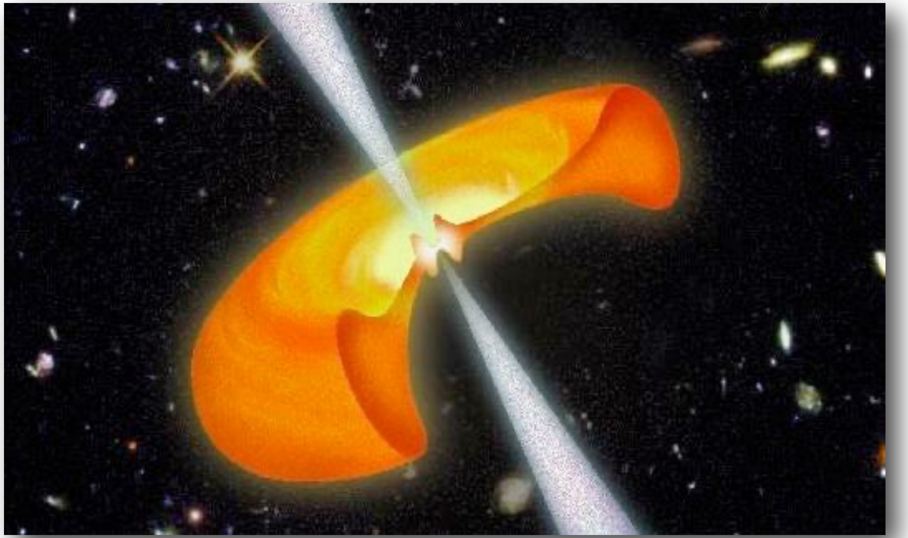
Supernovae / Gamma-ray bursts / Magnetars / Accreting BHs / …

- Very short transient signals (ms), parameter dependent, unmodelled (extremely expensive NR simulations needed).
- GW signal in coincidence with EM signals and neutrinos

SN1987A



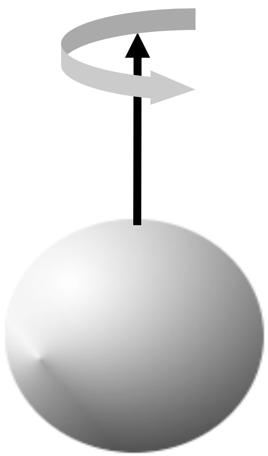
GRB engine: BH + torus



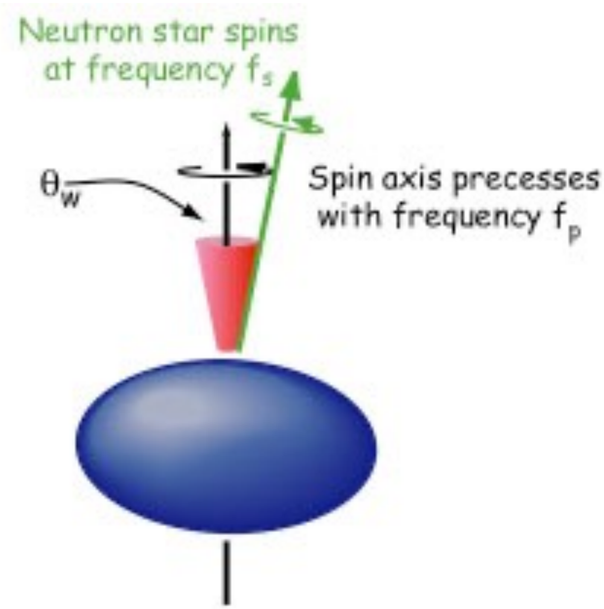
Continuous sources - periodic signal (weak but always there)

Radio pulsars (rapid rotation) / Galactic LMXBs / Ultralight boson clouds

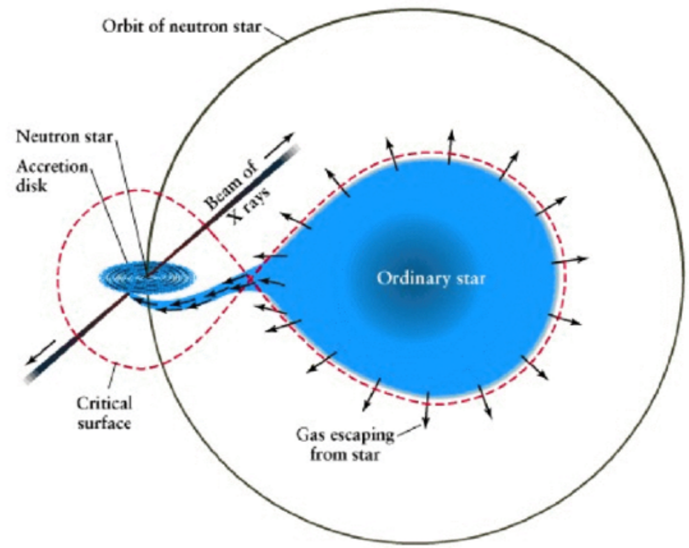
- Spinning NS emit GWs if they are not perfectly axisymmetric



Bumpy NS



Wobbling NS



LMXBs

(f-mode, r-mode excitation)

The story so far …

The LVK Collaboration has conducted three observing runs. O4 to start in March 2023 with an expected rate of detections (CBCs) of about 1 per day.

GWTC-3 contains 90 GW detections, all consistent with CBCs.

LVK observations

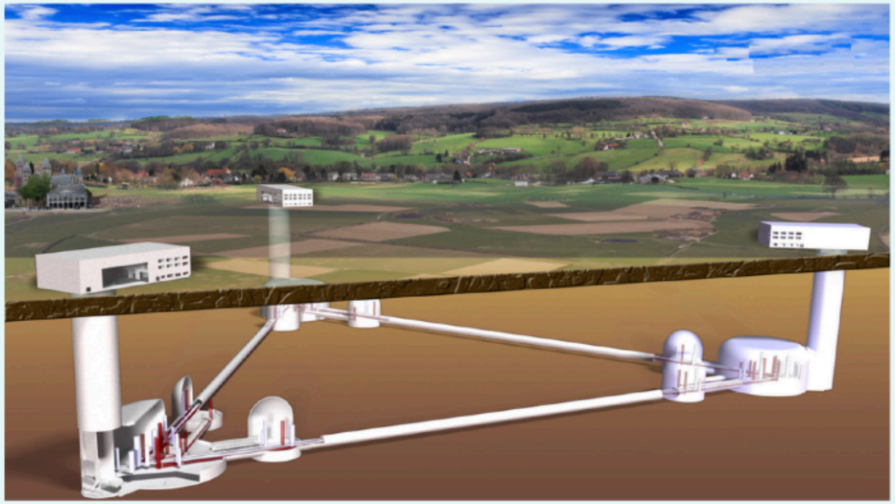
- are unveiling new populations of compact object binaries.
- are impacting different fields:
    - Fundamental physics
    - Gravitational physics
    - Nuclear physics
    - Astronomy
    - Astrophysics
    - Cosmology

O4+O5: GW detection rates will increase steeply as the surveyed volume of Universe. Likely to boost multimessenger observations

Bright future ahead: Multiband GW astronomy across several orders of magnitude in frequency (3G+LISA) will bloom in the next decade

3G Detectors

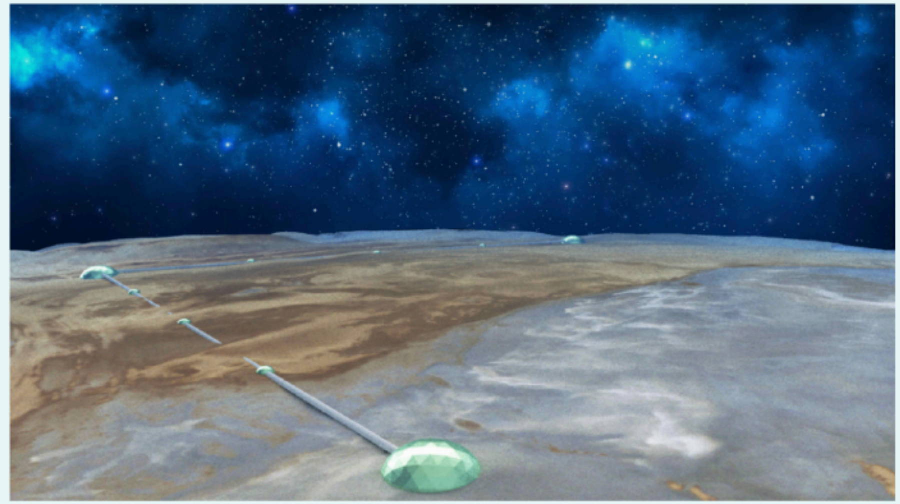
Einstein Telescope



Einstein Telescope conceived to be six, V-shaped, underground interferometers, formed out of 10 km sides of an equilateral triangle

http://www.et-gw.eu

Cosmic Explorer

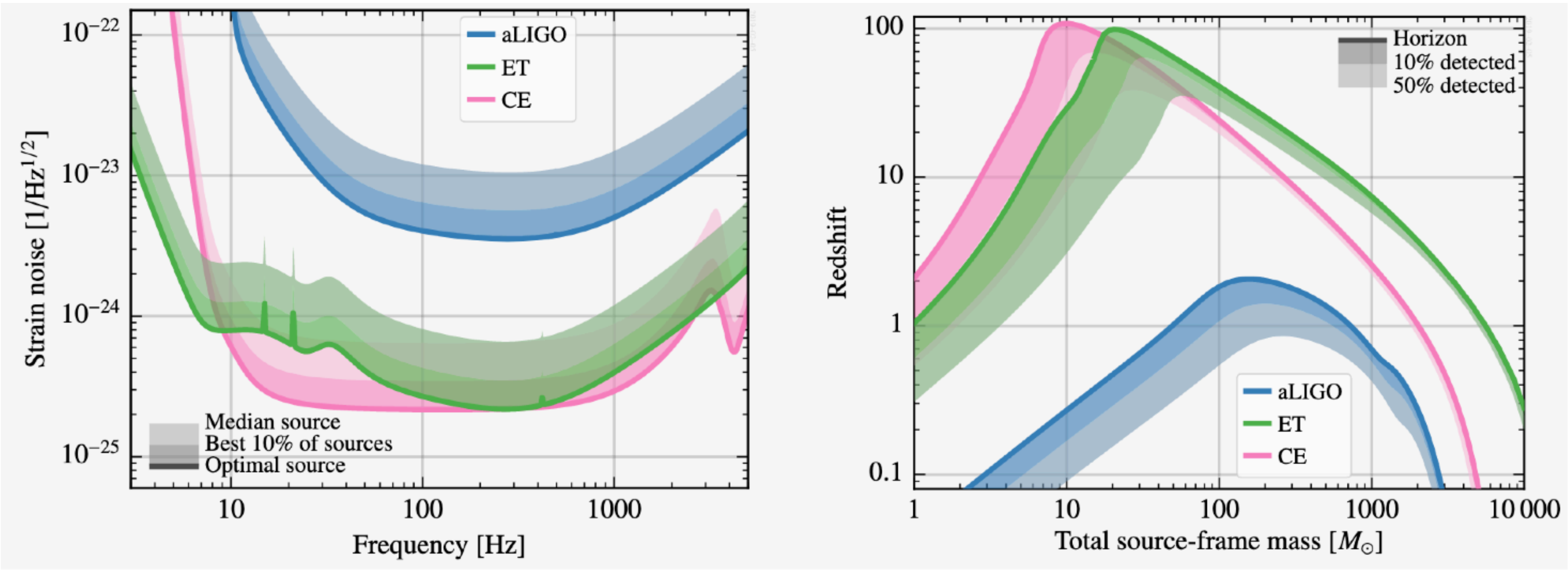


Cosmic Explorer conceived to be an L-shaped, overground interferometer, with 40 km arms

https://dcc.cosmicexplorer.org/P2100003/public

GWIC 3G reports https://gwic.ligo.org/3Gsubcomm/

3G Detectors



Sensitivity of ET and CE compared to Advanced LIGO

Reach for equal-mass non spinning binaries for 3G Observatoires

GWIC 3G reports https://gwic.ligo.org/3Gsubcomm/

3G Detectors

Improved low and high frequency sensitivity

NS science:

- Detection of the post-merger (HMNS) signal
- Precise measurements of tidal formability parameter and EOS
- Asteroseismology
- Phase transitions

BH science:

- More massive BHs
- High redshifts
- Precise spin measurements
- Black hole spectroscopy

Further key science targets:

- Supernovae
- Continuos waves, NS bursts
- Dark matter candidates and ECOs
- Cosmological stochastic GW background

3G Detectors

With ET and CE, GW observatories will leap from monitoring only the nearby Universe to surveying the entire Universe for BH mergers

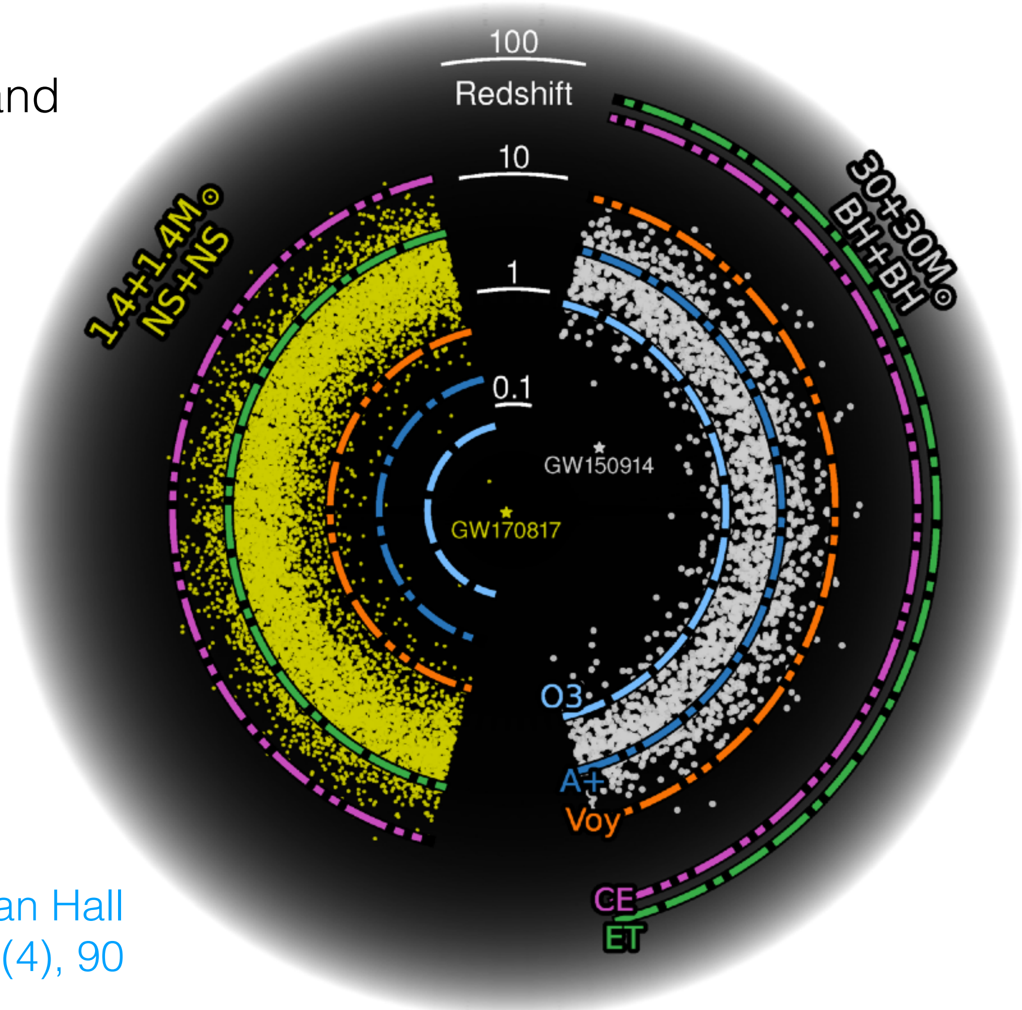
Redshift reach of LIGO Voyager, ET, and CE. Shown are the redshifts for:

- BNS mergers
- BBH mergers

Assumptions:

- Madau-Dickinson SFR
- Time from binary formation to merger is 100 Myr

Most binaries merge at z~2



Evan Hall
Galaxies **2022**, 10(4), 90

The Valencia Virgo Group

www.uv.es/virgogroup

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M. Miravet

M. Berbel

O. Freitas

The Advanced Virgo detector

The project of the Virgo GW detector started in the late 1980s as a French-Italian initiative. The **Virgo** detector began scientific observations in 2007. **Advanced Virgo** made its first detection in 2017 (GW170814).

Research interests of the VVG

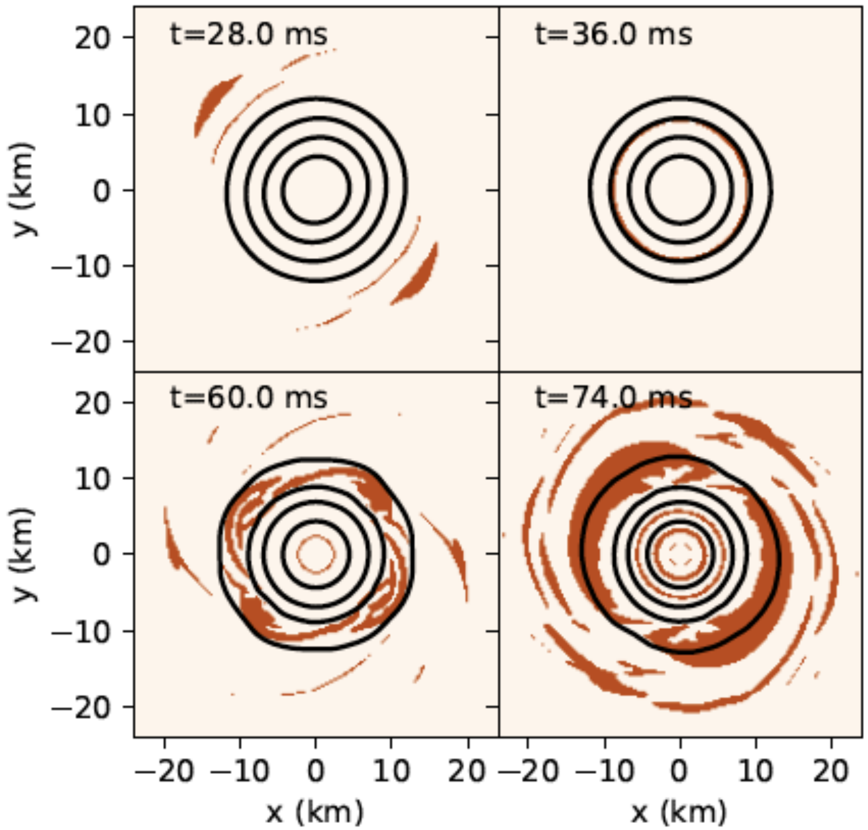
- Numerical relativity: long-term expertise in numerical simulations of astrophysical sources of gravitational radiation, i.e., waveform generation through numerical relativity simulations.

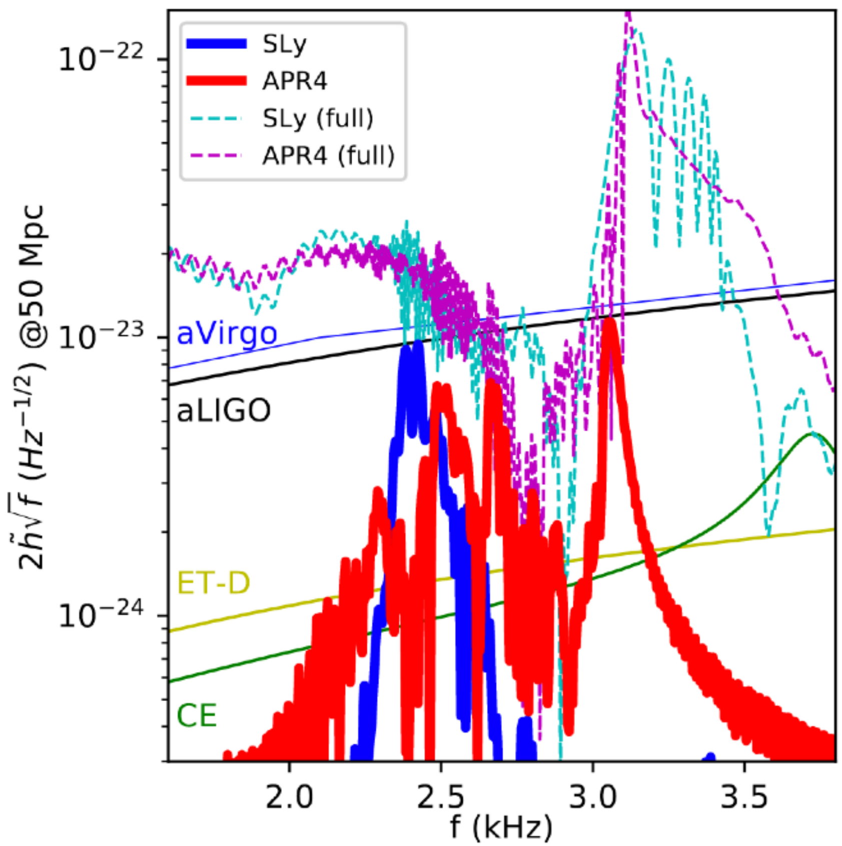
  RNS, BNS, BBH, CCSNe, BH accretion, fundamental fields (ECO/BH mimickers).

- GW data analysis: use of TV techniques for GW denoising and waveform reconstruction. ROF model. Machine learning for GW DA.
- Detector characterization: classification and denoising methods for noise transients (glitches) in GW detectors.
- Parameter estimation: CCSNe, BBH mergers, "exotic" mergers.
- EM follow-up: EM observations of GW counterparts (O3/O4/O5)
- 3G detectors: VVG participates in the Einstein Telescope Collaboration.
- LVK service work: Advanced Virgo detchar shifts, noise characterization, searches, pipeline development, code and paper reviews, PWT.

Research interests of the VVG - BNS mergers

BNS: Excitation of inertial modes in long-lived simulations of HMNS



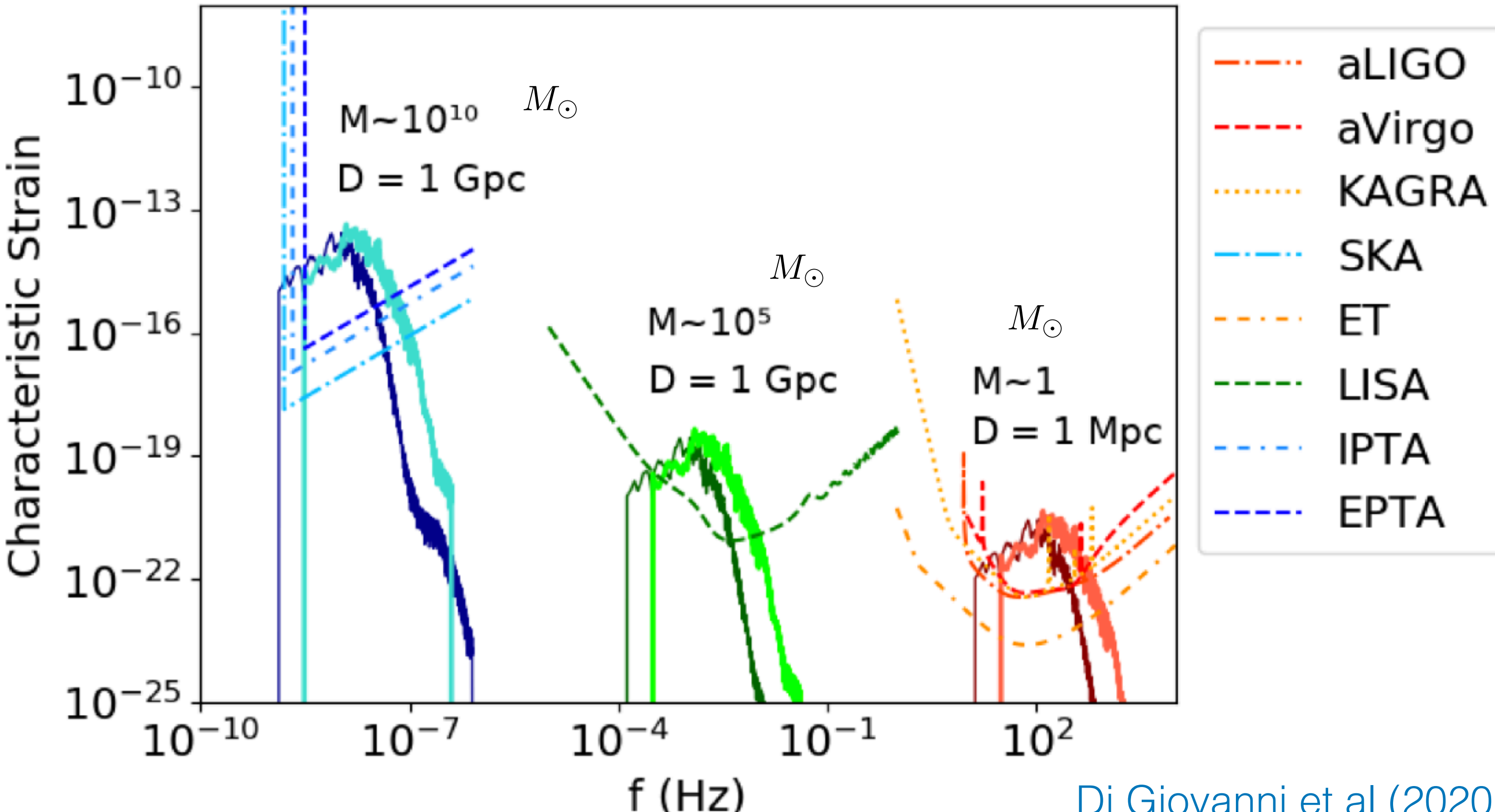


Detection of inertial modes in HMNS may provide an opportunity to infer the rotational and thermal properties of remnants.

De Pietri et al, PRL (2018); PRD (2020)

Research interests of the VVG - Bosonic stars (see Carlos talk)

Bar-mode unstable spinning bosonic stars.



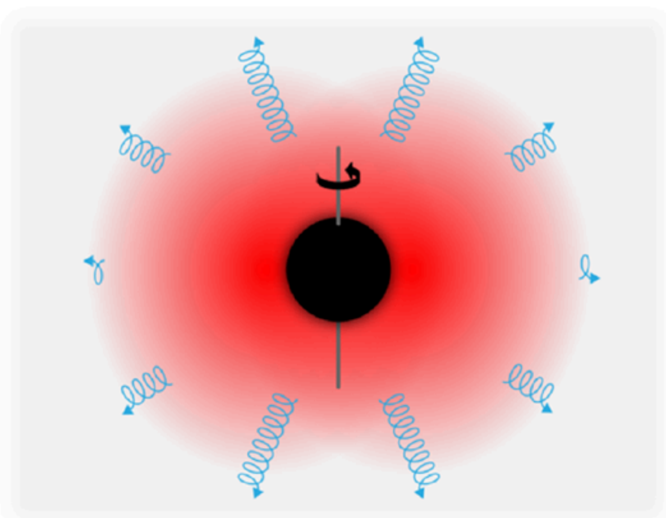
Di Giovanni et al (2020)

Signal within the reach of future experiments. Potential means to establish the existence of such stars and to place constraints on the mass of the bosonic particle.

Research interests of the VVG - ECOs (see Carlos talk)

VVG effort led by Nico Sanchis-Gual and Fabrizio Di Giovanni.

GW190521 compatible with a merger between two complex vector boson stars with $m_b \sim 8.7 \times 10^{-13}$ eV (Calderon-Bustillo+, PRL, 2021)



From: https://physics.aps.org/articles/v10/83

Superradiance effects:

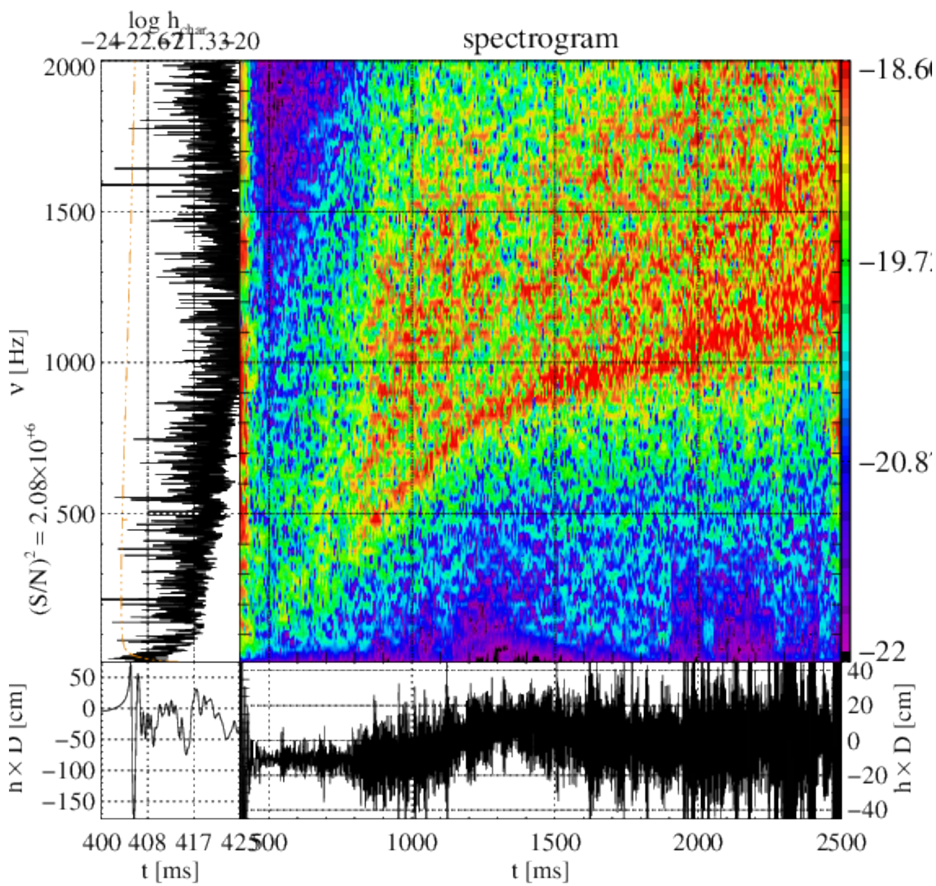
- A Kerr BH can transfer efficiently its energy to a cloud of ultralight bosons when $\lambda_c \sim R_s$ (which means that 10^{-21} eV < m_b < 10^{-11} eV)
- The cloud can emit a nearly monochromatic, long-duration GW signal potentially detectable by LVK if 10^{-13} eV < m_b < 10^{-11} eV

PRL 123, 171101 (2019); PRD 101, 063020 (2020)
PRD 99, 084042 (2019); PRD 98, 103017 (2018)

Research interests of the VVG - CCSN

Neutrino-driven CCSN explosions expected to be observable by LIGO/Virgo within our galaxy at a rate of ~3/century (Gossan+ (2016); Adams+ (2013)).

Martin Obergaulinger leads VVG efforts on 2D and 3D simulations of rapidly rotating and strongly magnetized stars with self-consistent neutrino transport.



GWs from CCSN:

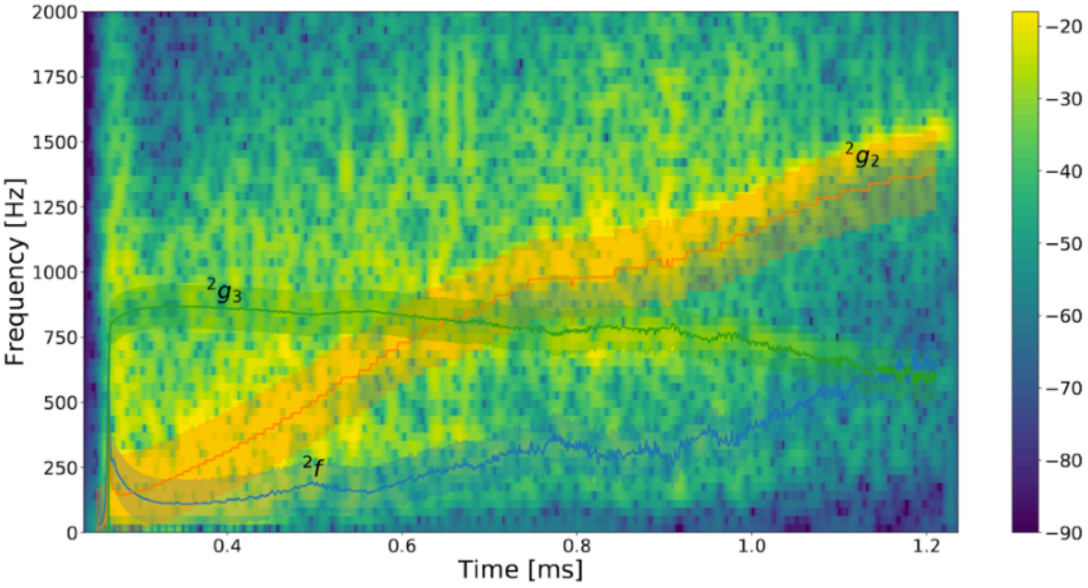
- strong GW emission in the LVK-relevant frequency range
- waveforms of 2D and 3D models provided to LVK SN group for analysis

Research interests of the VVG - PNS asteroseismology

Main source of GWs in CCSN is excitation of PNS oscillation modes during post-bounce evolution.

Our work has established that features in GW spectrograms can be matched to specific PNS eigenmodes.

GW spectrogram for a $20M_{sun}$ progenitor
(Cerdá-Durán et al, ApJL (2013))



Torres-Forné et al, PRL (2019)

Universal relations relating frequencies of most common oscillation modes (g-modes, p-modes) with fundamental properties of the system (PNS surface gravity, mean density in post-shock region).

Relations independent of EoS, neutrino treatment, and progenitor mass.
Can be used to **infer PNS properties from GW observations** alone.

Machine Learning efforts

Goal: develop and apply ML techniques to analyze existing and upcoming GW data and to reinforce the chances of detection of new GW signals.

Focus mainly in transient signals (CBC and burst) but also CWs.

Ongoing joint collaboration with groups in Aveiro-Coimbra-Minho-Valencia.

Classification:

- Automatic identification of g-modes and p-modes in PNS using ML classification algorithms (K-means, Gaussian mixture)
- Classification and Parameter Estimation using NN (CCSN, BBH, BNS) (see talks by Osvaldo, Solange, and Tiago)
- Dictionary Learning for glitch classification and denoising (see talk by Alex)
- ML for noise/signal classification (see talks by Tiago and Samuel)
- Classification of the neutron star EOS using ML (see talk by Gonçalo)

Machine Learning efforts

Detection:

- Detection of CCSN using ML (CNN + cWB)
- Detection of CBC signals using ML (ResNet) (see talk by Osvaldo)
- Detection of BNS signals using object-detection ML models (see talk by Joao)

Waveform generation:

- Waveform generation for CBC signals (including ECOs) (GAN, led by Felipe)
- NR surrogate waveform approximant for BBH mergers based on ML.

Misc:

- Physics-informed NN for time-dependent problems in computational astrophysics

Summary

LVK observations

- are unveiling new populations of compact object binaries
- are impacting different fields across physics
- O4/O5: few CBC events per day!

Bright future ahead: Multiband GW astronomy across several orders of magnitude in frequency (3G+LISA) will bloom in the next decade

Machine learning may become a fundamental tool in GW astronomy to help process the huge amounts of data expected to be collected

Extra

Research interests of the VVG - PNS asteroseismology

Universal relations relating the frequencies of most common oscillation modes (g-modes, p-modes and the f-mode) with fundamental properties of the system (surface gravity of the PNS or mean density in post-shock region) found.

Torres-Forné et al, PRL (2019)

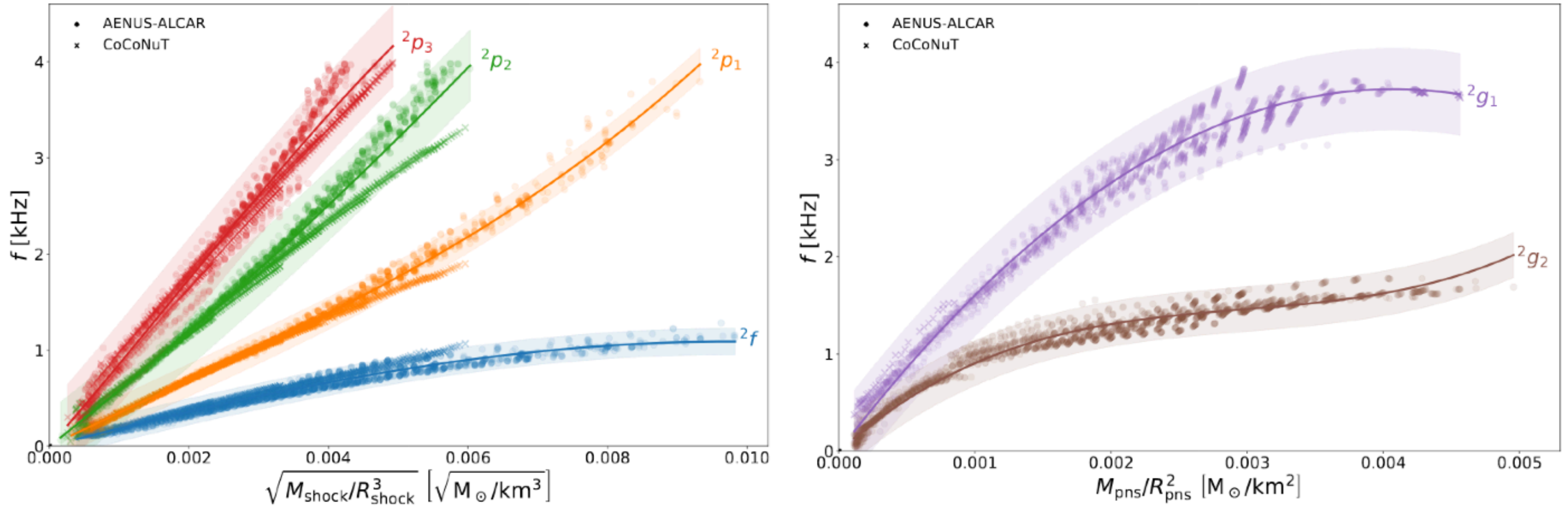
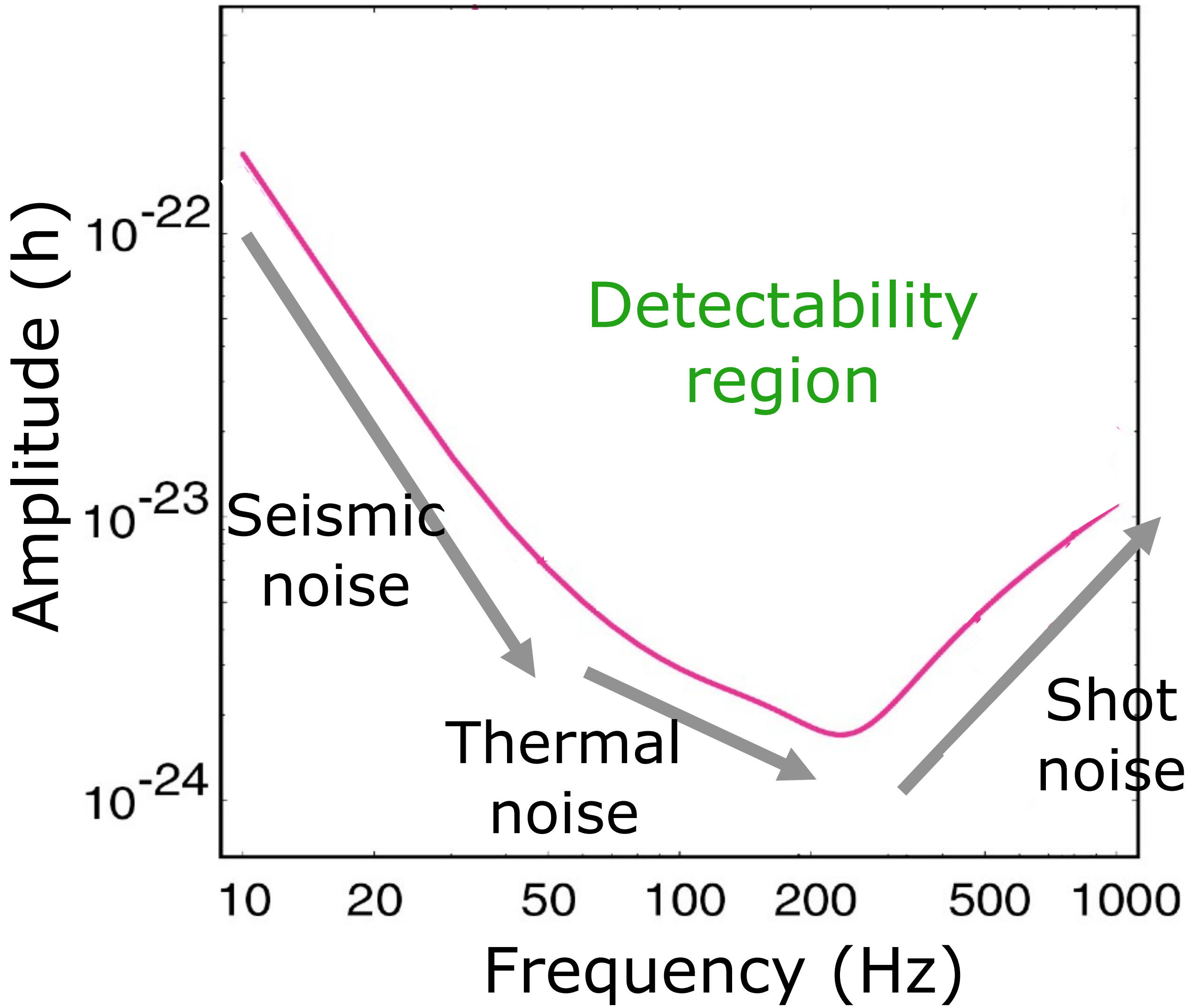


FIG. 2. Fits of the different modes. The left panel shows the f-mode and the first three p-modes while the right panel shows the first two g-modes. The results from **AENUS-ALCAR** and **CoCoNuT** are represented with solid circles and crosses, respectively. Shaded areas indicate 2σ error intervals.

Relations independent of EoS, neutrino treatment, and progenitor mass.
Can be used to infer PNS properties from GW observations alone.

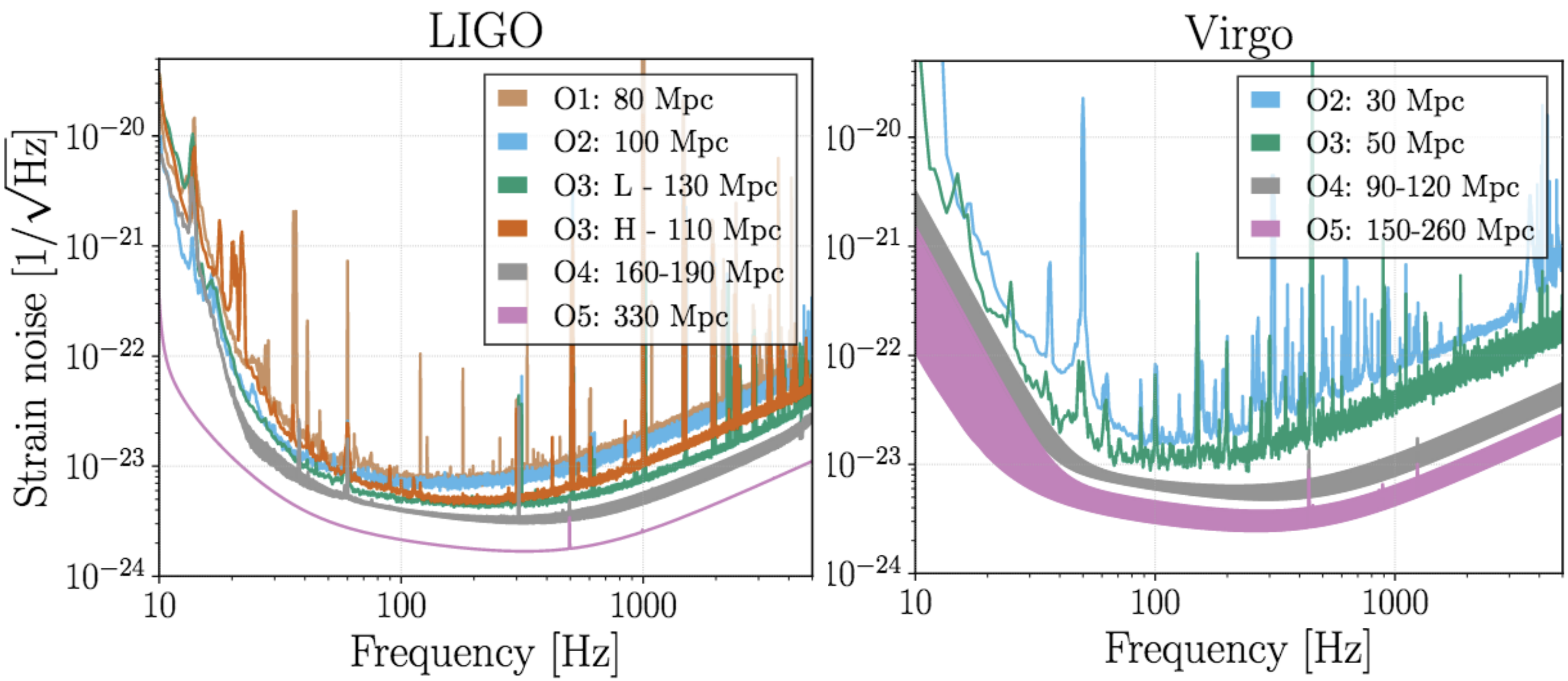
Noise-dominated observations

The small amplitude of gravitational waves calls for an extreme reduction of the sources of noise



Observing timeline - the near future

LVK, DCC-P1200087 (Observing Scenarios) https://observing.docs.ligo.org/plan/



BNS:

- Estimated O4 detection rate for LVK network: 0-62 (90%)
- Estimated median localisation: 33 deg^2

NSBH:

- Estimated O4 detection rate for LVK network: 0-92 (90%)
- Estimated median localisation: 50 deg^2

Start of O4 run
March 2023