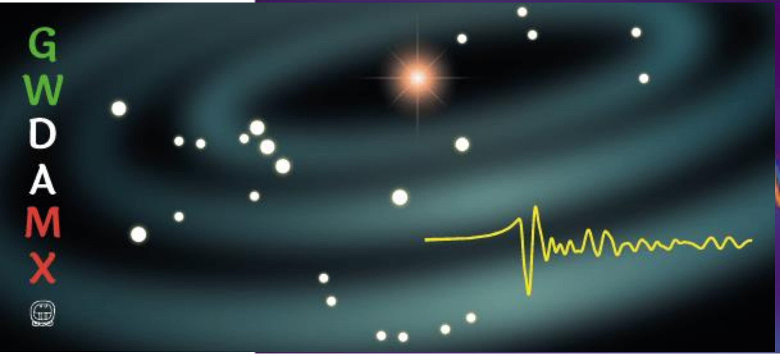

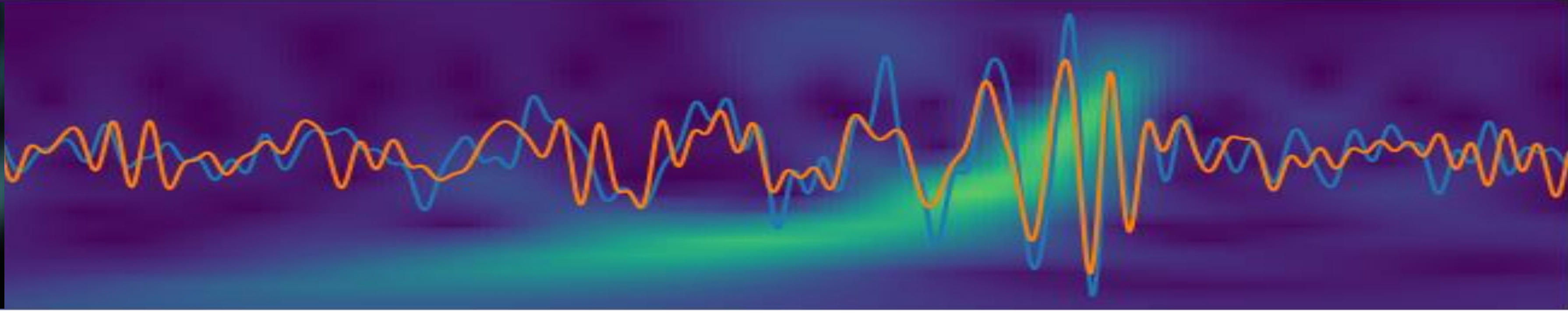

GRAVITATIONAL WAVES AND THEIR FUTURE PERSPECTIVES

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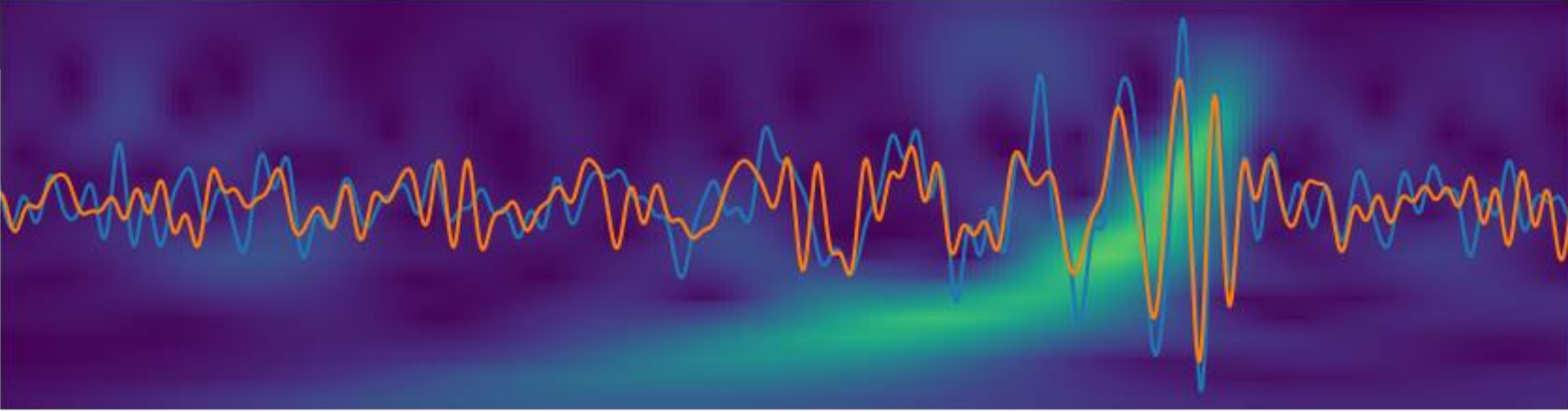
CONACYT

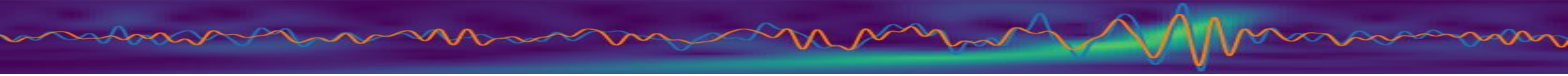
UNIVERSIDAD DE GUADALAJARA

Tecnológico de Monterrey

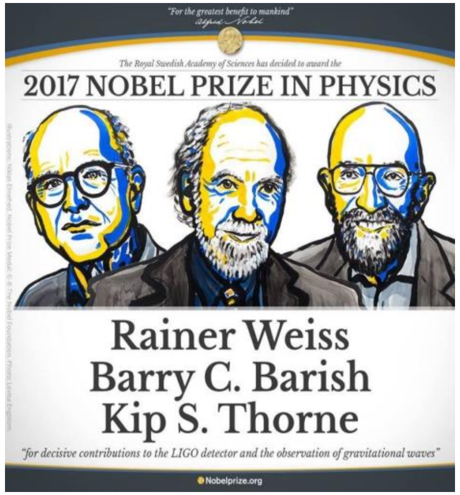
XV Latin America Symposium on High Energy Physics
November 05, 2024



MOTIVATION

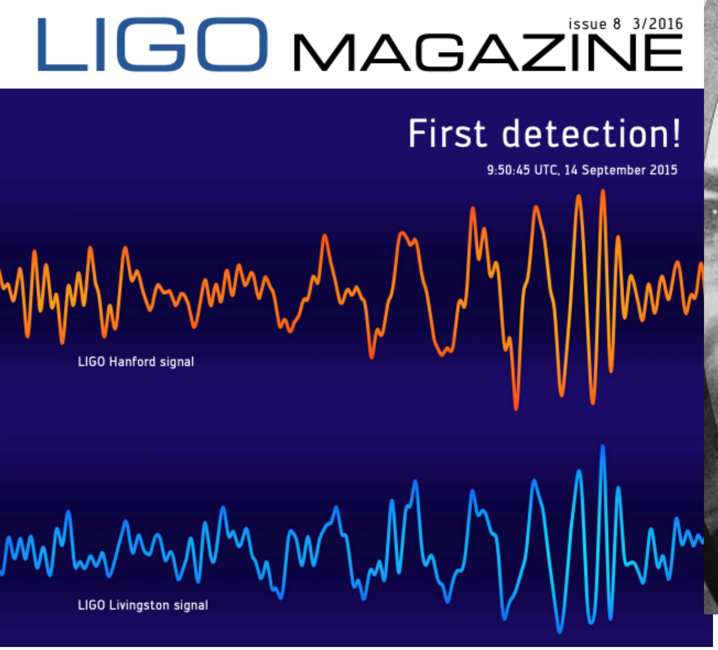


Big people, big discovers



LSC LIGO Scientific Collaboration

GW150914



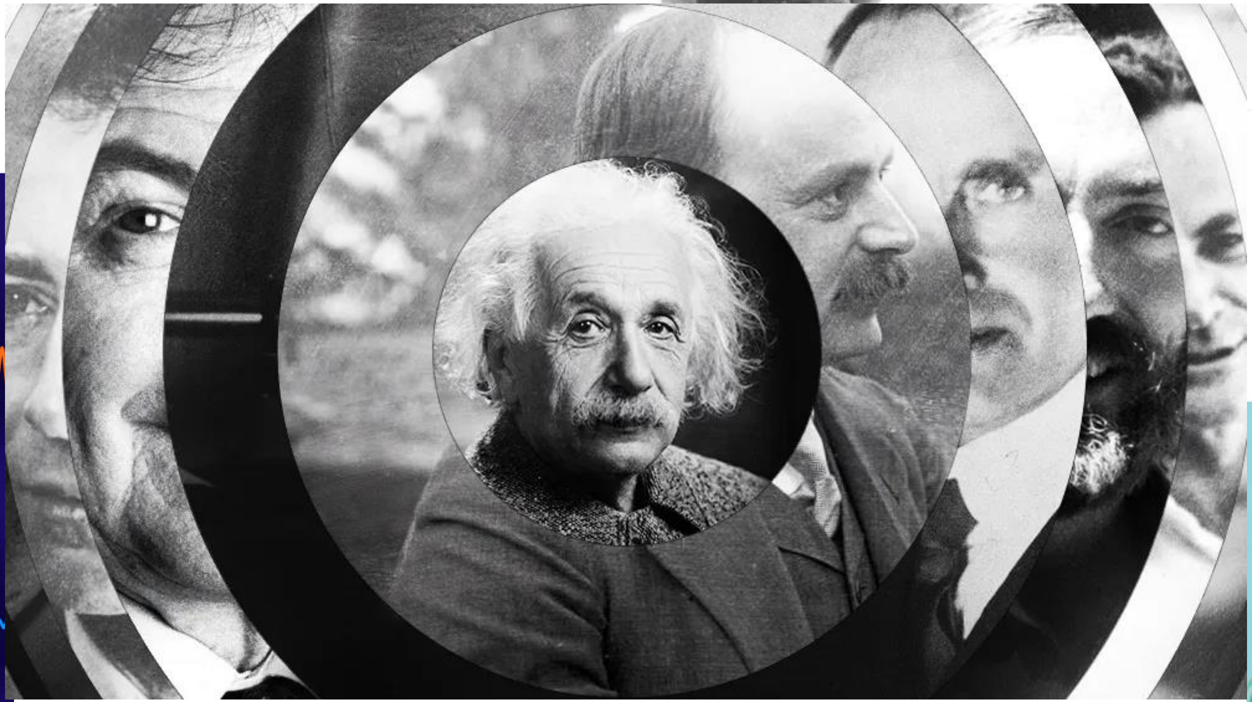


Image: Olena Shmahalo/quanta magazine

Image: phys.org

www.ligo.org

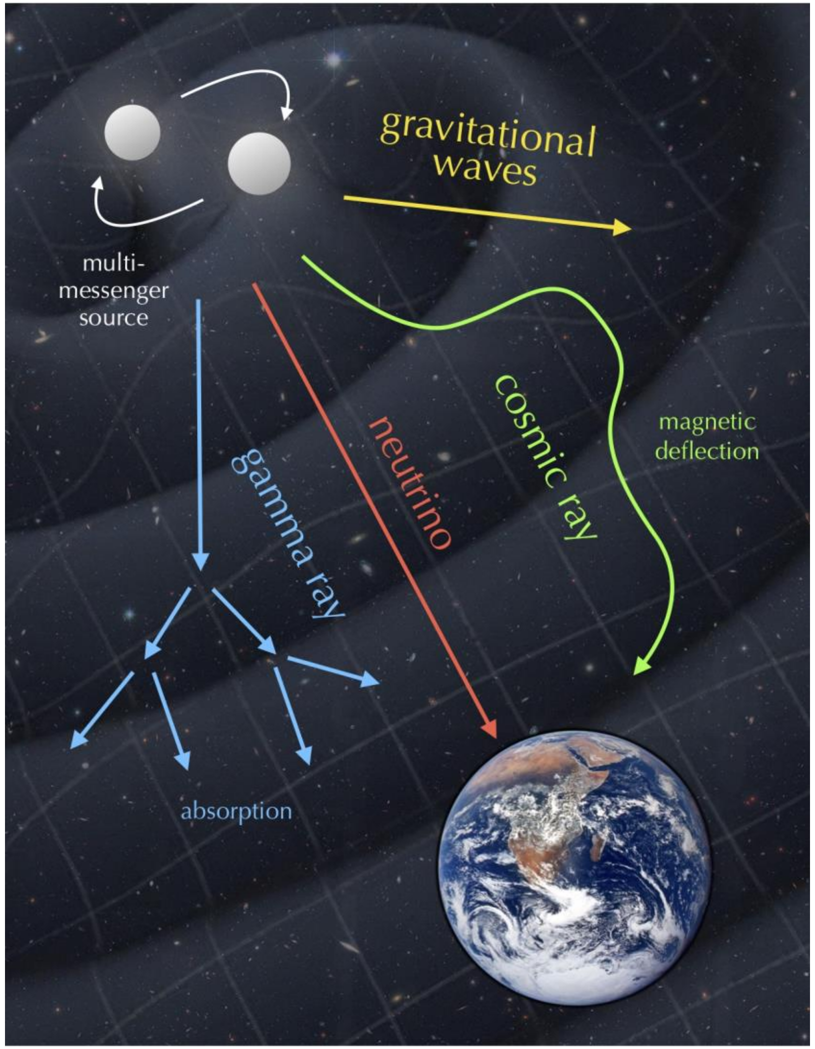
LSC LIGO Scientific Collaboration

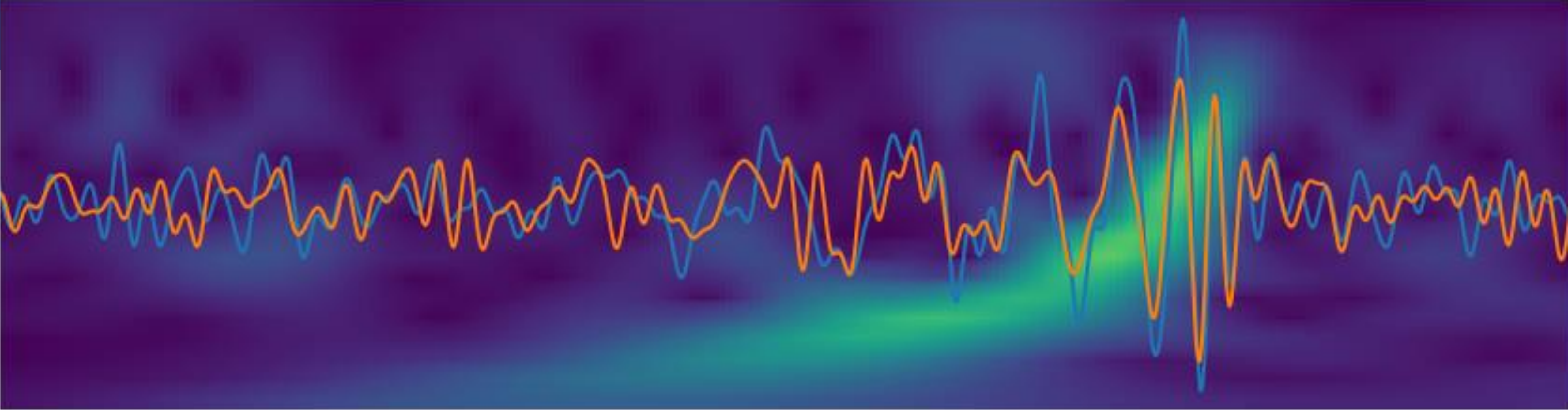
GW170817

Multimessenger astronomy

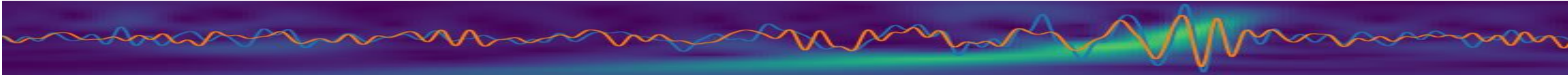
"Messengers" - distinctive signals carrying unique information about a source. They provide deeper insight into the most extreme events in the Universe.

	BBH	BNS	CCSN
Gravitational Waves (dynamics, mass distribution)	Observed	Observed	Possible
Electromagnetic Radiation (emission processes, environment, temperature, density)	Possible	Observed	Observed
Neutrino (mainly thermodynamics, hadronic/nuclear processes)		Possible	Observed
Cosmic Rays (acceleration processes, nucleosynthesis)		Possible	Possible





GRAVITATIONAL WAVES



Signal theory

Einstein equations, 1915

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = 8\pi T_{\mu\nu}$$

Linear equations, 1916

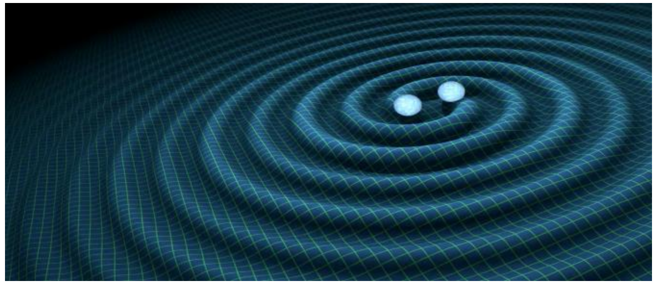
$$\left(\frac{\partial^2}{\partial t^2} + \nabla^2\right) h_{\mu\nu} = 0$$

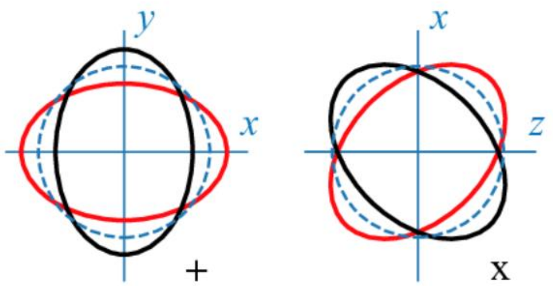
Solution to the equation

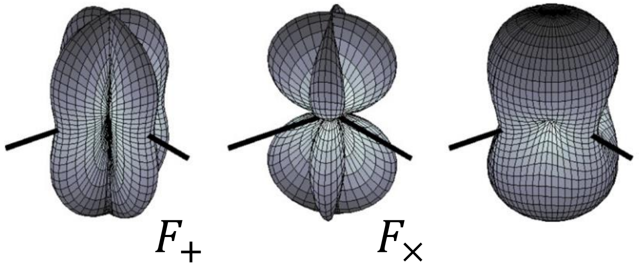
$$h_{\mu\nu} = C_{\mu\nu} e^{(ik_\lambda x^\lambda)}$$

Their amplitude

$$C^{\mu\nu} = h_+ e_+^{\mu\nu} + h_\times e_\times^{\mu\nu}$$







- Gravitational Waver, Michele Maggiore, Oxford
- Gravity, Poisson and Will, Cambridge

Characteristic signal

$$h = F_+ h_+ + F_+ h_\times$$

Gravitational wave strength

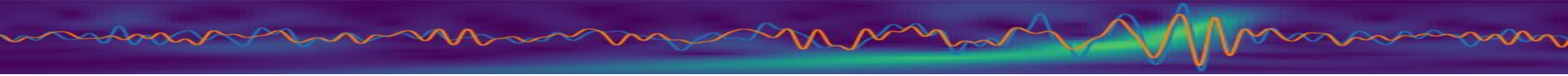
$$h_{rss} = \sqrt{\int h_+^2 + h_\times^2 dt}$$

Fourier transform of the interferometer response

$$\tilde{h}(f) = \sqrt{\tilde{h}_+^2(f) + \tilde{h}_\times^2(f)}$$

The total energy

$$E_{GW} = \frac{c^3}{G} \pi^2 D^2 \int_{-\infty}^{\infty} \left(\left| \tilde{h}_\times(f) + \tilde{h}_+(f) \right|^2 \right) f^2 df$$



The dynamic Universe

Quadrupolar formula for GW production:

$$\mathbf{h}_{ij}^{TT}(t,\mathbf{x}) = \frac{1}{D}\ddot{Q}_{ij}(t - D/c, \mathbf{x})$$

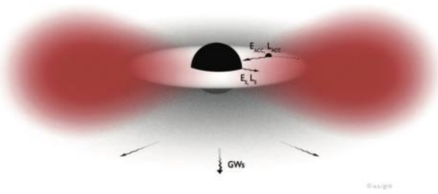
To produce GW we need **aspherical** mass-energy movement.

Compact Binaries:

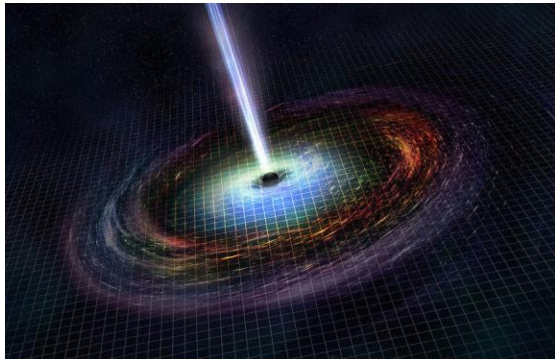
- BBH with circular/elliptical orbits
- Black hole – neutron star
- Binary neutron stars
- Intermediate-mass black hole
- Primordial black holes

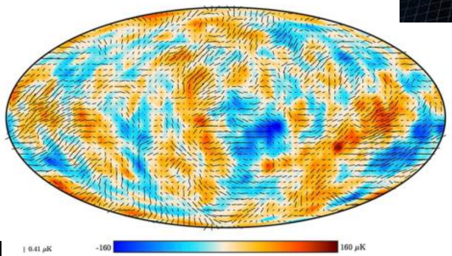
Other:

- Core-collapse supernovae
- Gamma ray burst
- Cosmic strings
- Boson cloud
- Background polarizations, etc.

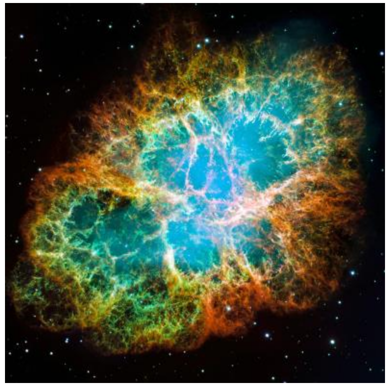


olemiss.edu

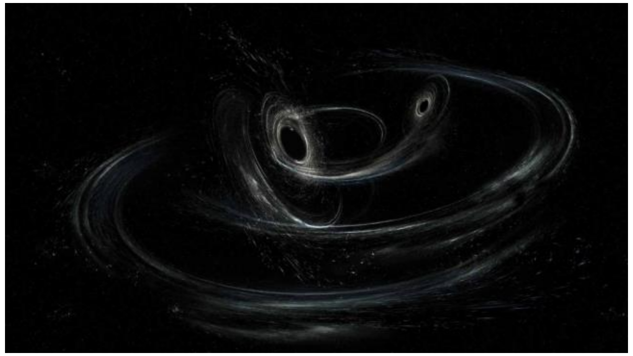




ESA and Planck Collaboration



NASA, ESA, J. Hester y A. Loll

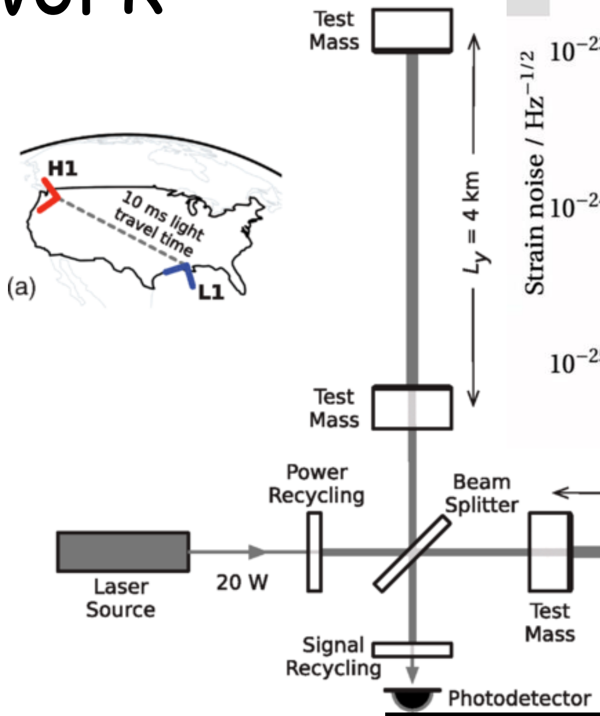


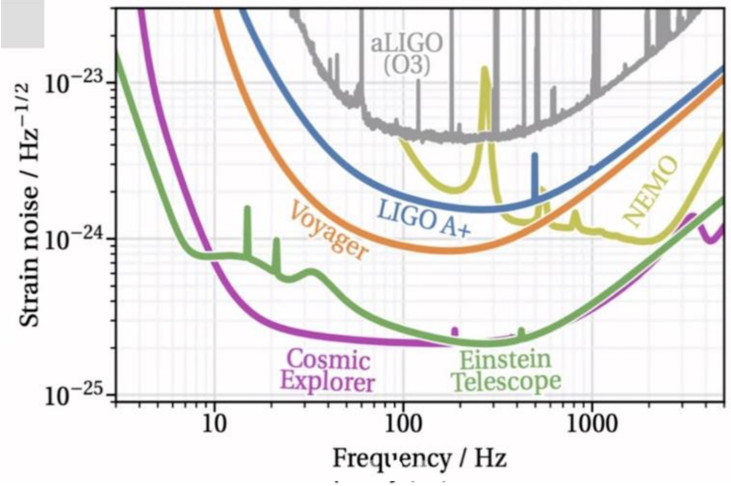
URORE SIMONNET/LIGO/CALTECH/MIT/SONOMA STATE

Detectors network

Some characteristics

- LIGO arms 4km and time lag of 10ms
- Sensitivity from 10^{-21} to 10^{-23}
- LIGO BNS range: 140 and 165 Mpc
- Virgo (<45Mpc)
- Kagra and GEO with some delay problems
- LIGO India under construction
- Einstein Telescope and Cosmic Explorer will reach around 10^{-25}, under construction

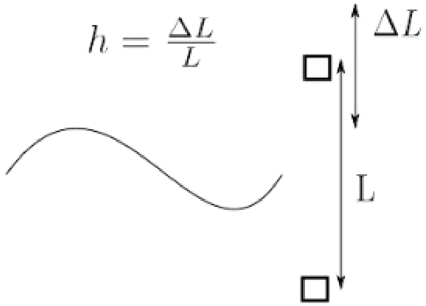


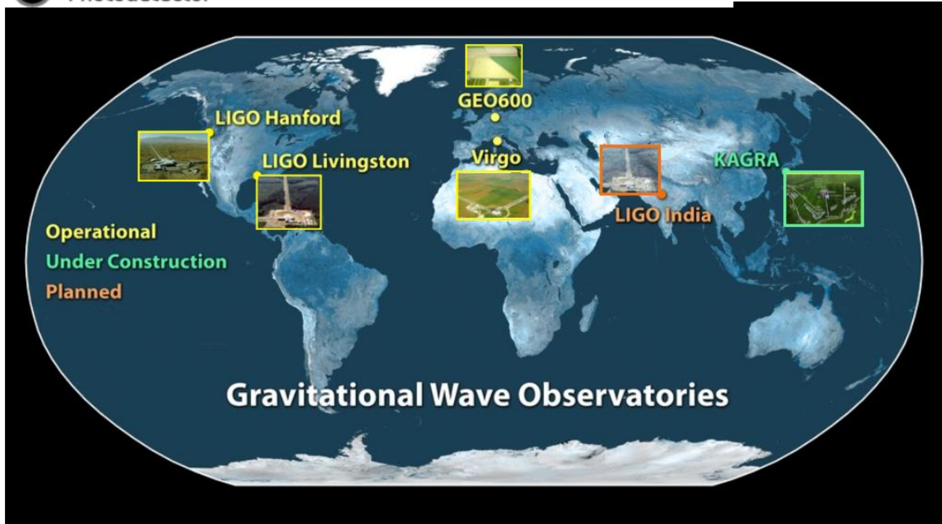


The software used for these detections are:

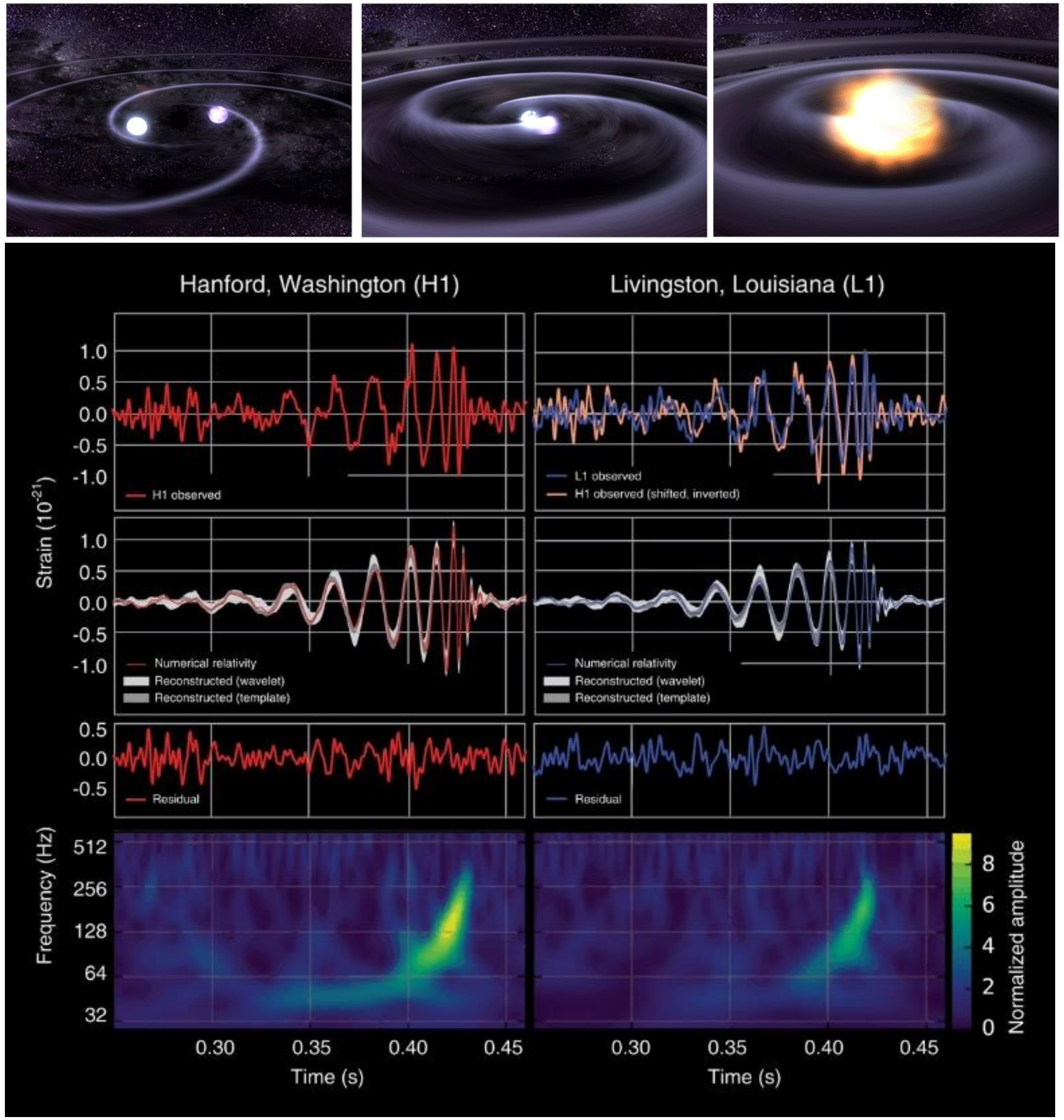
- Mached filtering: GstLAL, PyCBC, SPIIR, MBTA
- GW Burst: cWB, oLIB

https://gwosc.org/





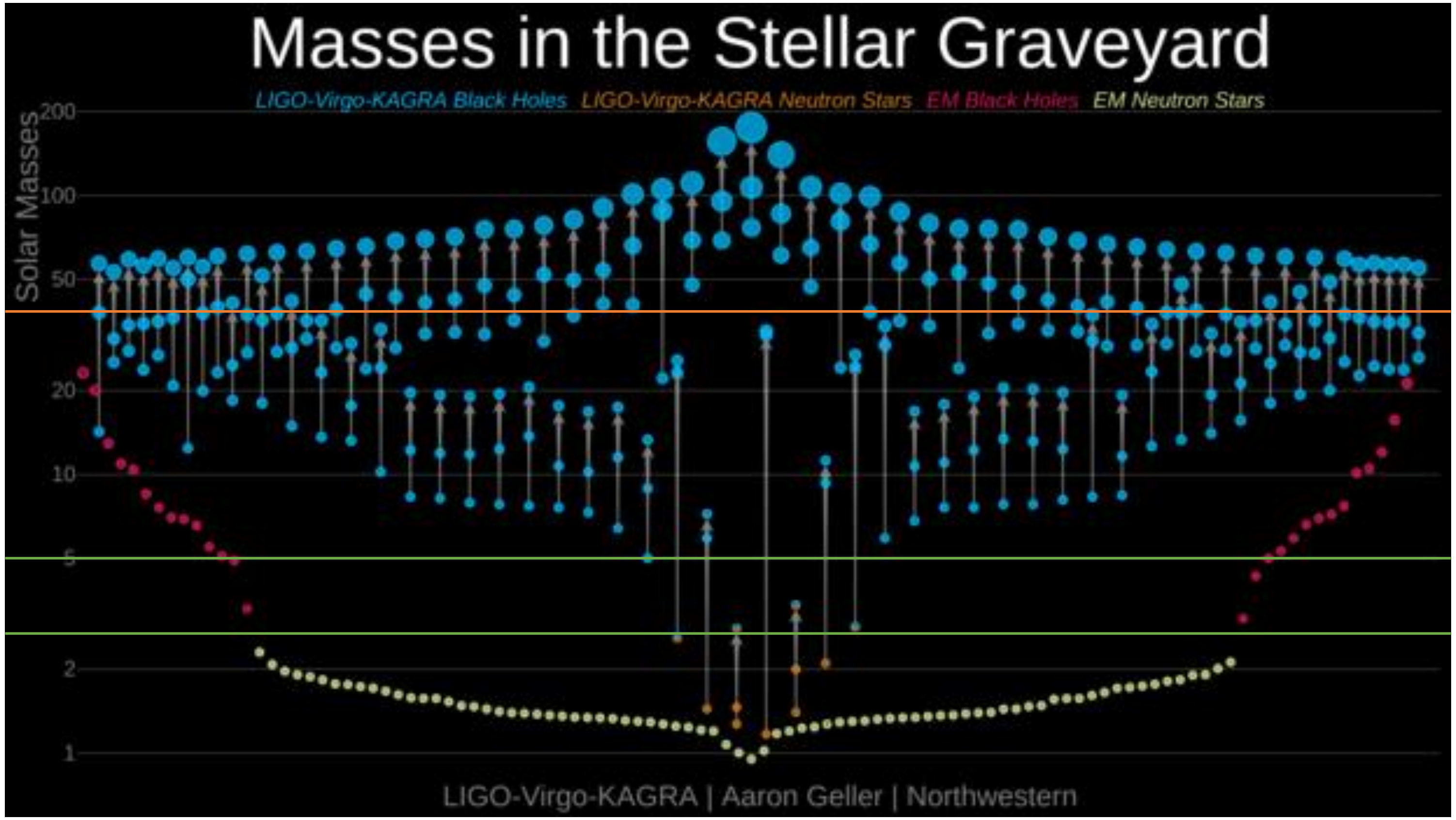
GW150914: *first observation of GW from BBH*



- GW150914 - first observation of gravitational waves and binary black holes (36 $M_\odot$ and 29 $M_\odot$)
- Many BBH with masses not expected
- However, Belczynski et al 2010 predicted existence of such heavy black holes
- If the Femi Gamma-ray Burst Monitor signal is an actual counterpart to GW150914, this observation places more stringent constraints on GW propagation mechanism than GW150914 alone

DOI: [10.1103/PhysRevLett.116.061102](https://doi.org/10.1103/PhysRevLett.116.061102)

Deteccciones de OG



- GWTC-1 presents 7 events
- GWTC-2 adds 39 events
- GWTC-3 adds 35 events (total number is around 90)
- GWTC-3 algorithms: matched-filtering (GstLAL, MBTA, PyCBC) and model-independent (cWB)

https://www.ligo.caltech.edu/WA/news/ligo20211107

coherent WaveBurst cWB
(Model-independent searches)

WB coherent WaveBurst
an open source software for
gravitational-wave data analysis
https://gwburst.gitlab.io/

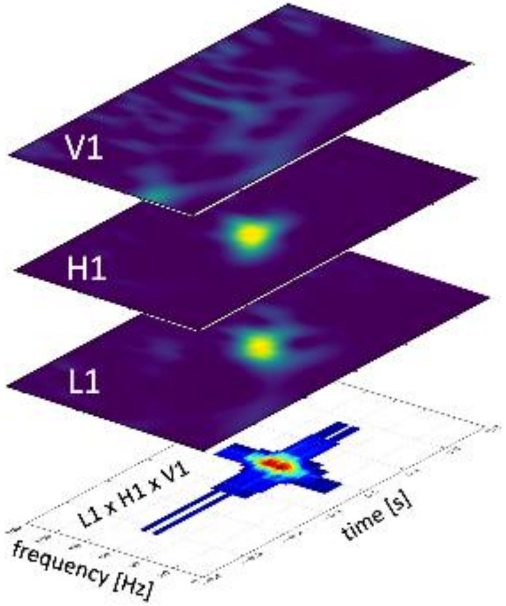
• cWB is a software designed to detect a wide range of burst transients without prior knowledge of the signal morphology
S. Klimenko et al. 2008, 2016, S. Klimenko et al. 2008, Drago et al. 2021

•cWB uses minimal assumptions about morphology

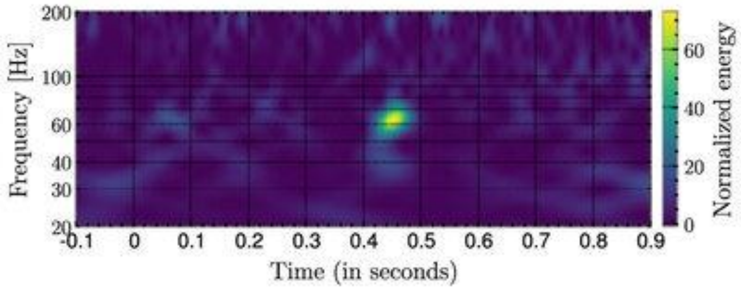
• cWB was the only algorithm capable of detecting CCSN in real time during O3
- Based on: Excess-power, Wavelet analyses, Coincident tests

- Reconstructs the waveform and estimates some signal parameters

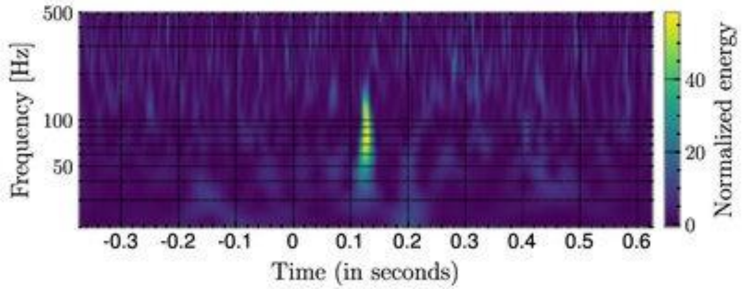
- Essential for CCSNe GWs in O3, O4 and upcoming observation runs:
  M. Szczepanczyk et al., 2021
  https://arxiv.org/abs/2305.16146



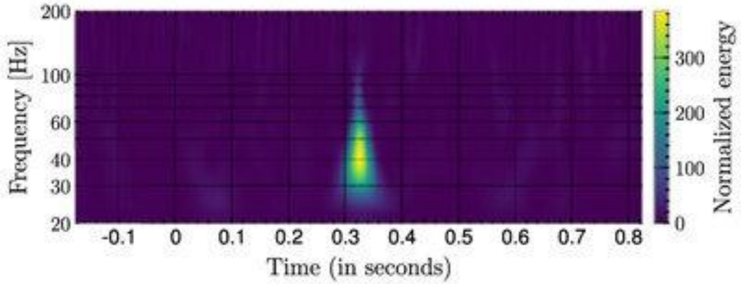
Detector glitches



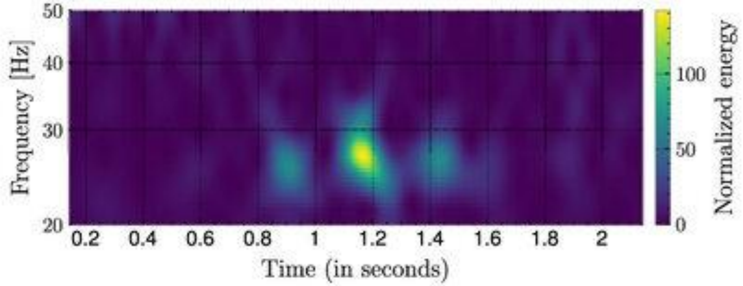
(a) GW190521



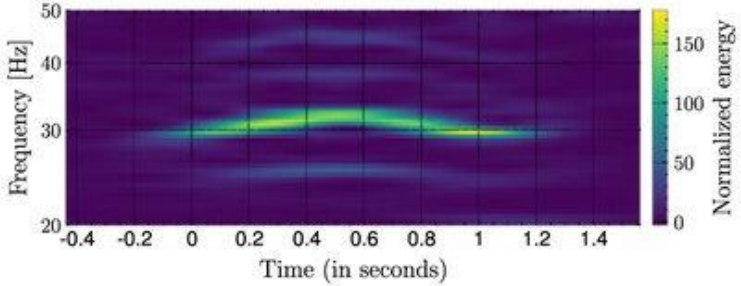
(b) Blip



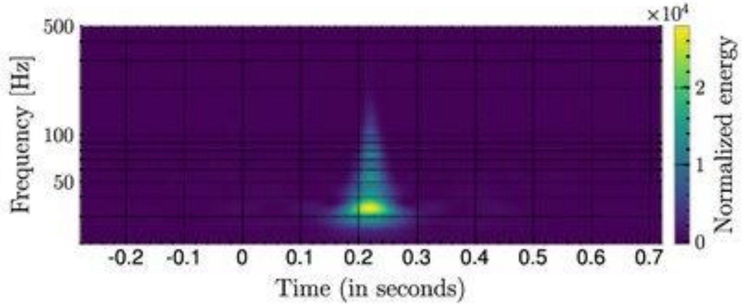
(c) Tomte



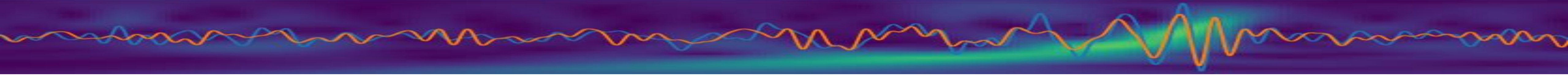
(d) Fast Scattering



(e) Scattered Light



(f) Koi Fish



Public alerts

General characteristics

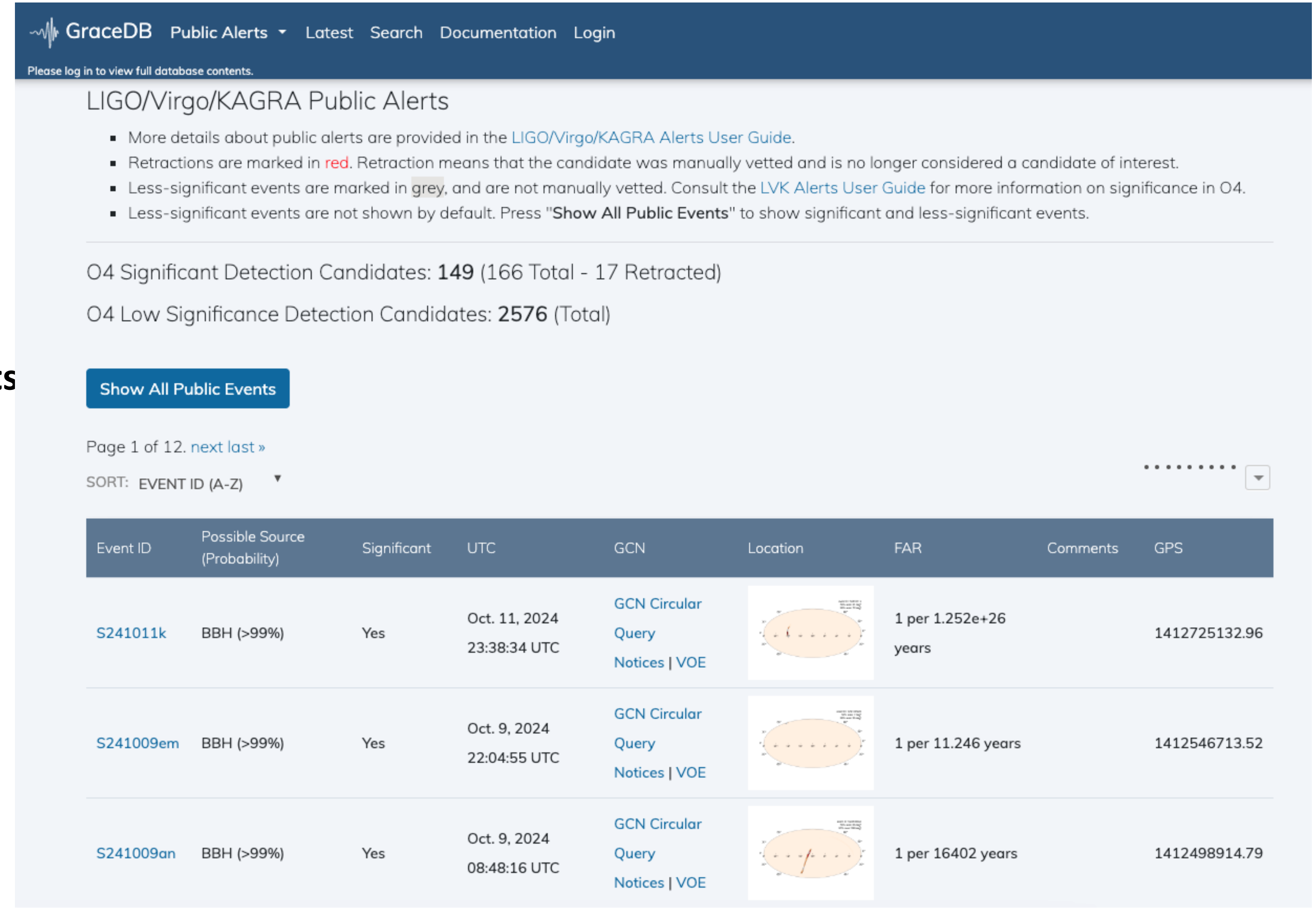
- Sky localization
- Distance
- Source classification
- Detection pipeline

Additional information for burst event alerts

- "Fluence" ~ GW energy
- Peak frequency
- Duration

- Public alert in O3,
many times are classified as noise

- No burst public alerts so far in O4



GraceDB Public Alerts Latest Search Documentation Login

Please log in to view full database contents.

LIGO/Virgo/KAGRA Public Alerts

- More details about public alerts are provided in the LIGO/Virgo/KAGRA Alerts User Guide.
- Retractions are marked in red. Retraction means that the candidate was manually vetted and is no longer considered a candidate of interest.
- Less-significant events are marked in grey, and are not manually vetted. Consult the LVK Alerts User Guide for more information on significance in O4.
- Less-significant events are not shown by default. Press "**Show All Public Events**" to show significant and less-significant events.

O4 Significant Detection Candidates: **149** (166 Total - 17 Retracted)

O4 Low Significance Detection Candidates: **2576** (Total)

Show All Public Events

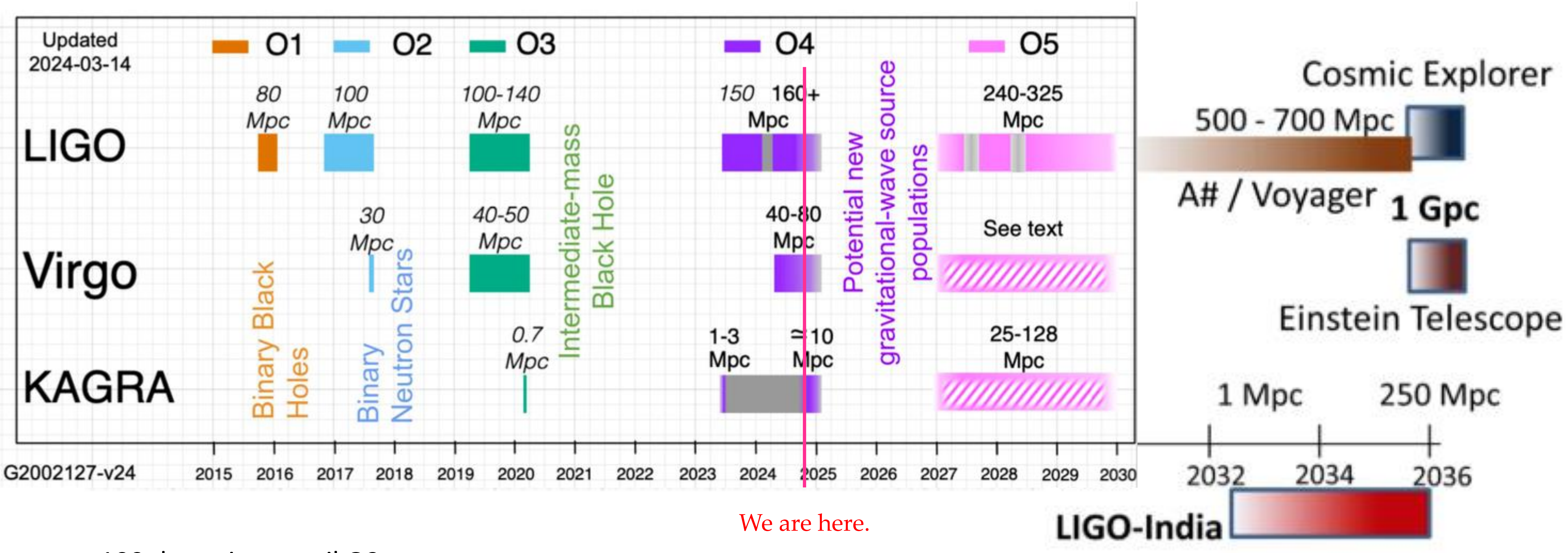
Page 1 of 12. next last »

SORT: EVENT ID (A-Z)

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments	GPS
S241011k	BBH (>99%)	Yes	Oct. 11, 2024 23:38:34 UTC	GCN Circular Query Notices | VOE		1 per 1.252e+26 years		1412725132.96
S241009em	BBH (>99%)	Yes	Oct. 9, 2024 22:04:55 UTC	GCN Circular Query Notices | VOE		1 per 11.246 years		1412546713.52
S241009an	BBH (>99%)	Yes	Oct. 9, 2024 08:48:16 UTC	GCN Circular Query Notices | VOE		1 per 16402 years		1412498914.79

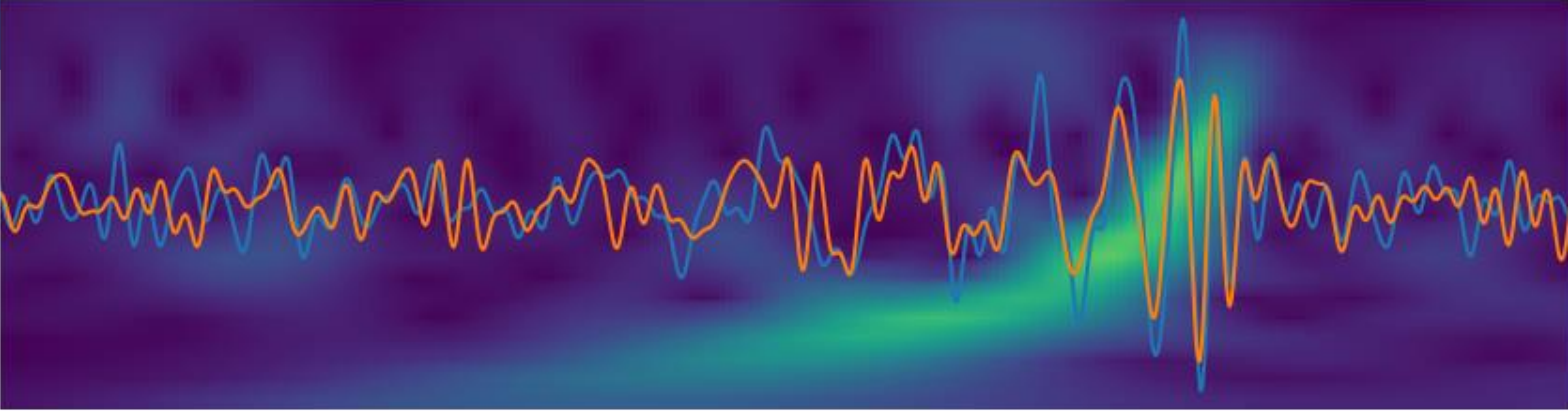
https://gracedb.ligo.org/superevents/public/O4/

Observing Timeline



- 100 detections until O3
- 90 candidates for 04

Credits: LIGO, Tata Institute of Fundamental Research, India



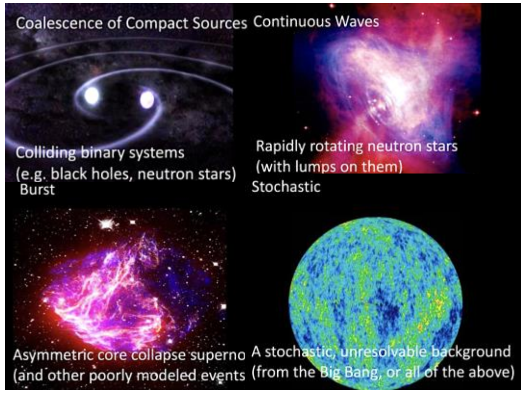
PROJECTS

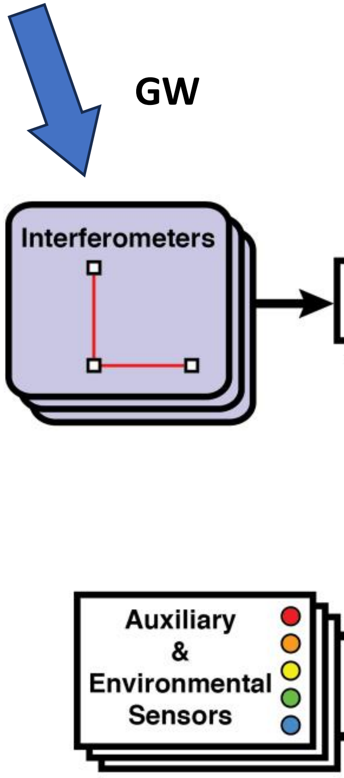
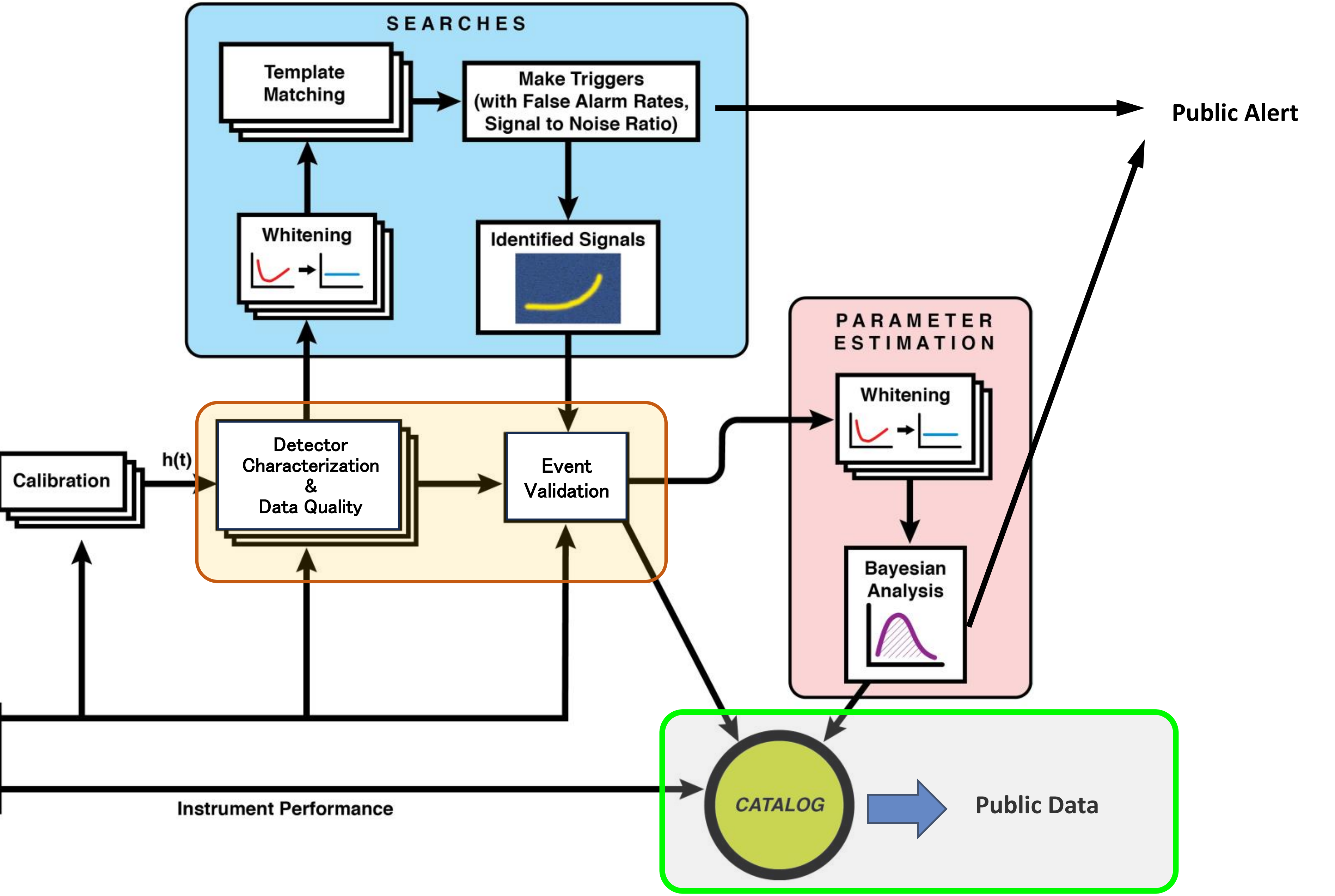
Detection, localization and parameter estimation

LVK Dataflow (simplified)

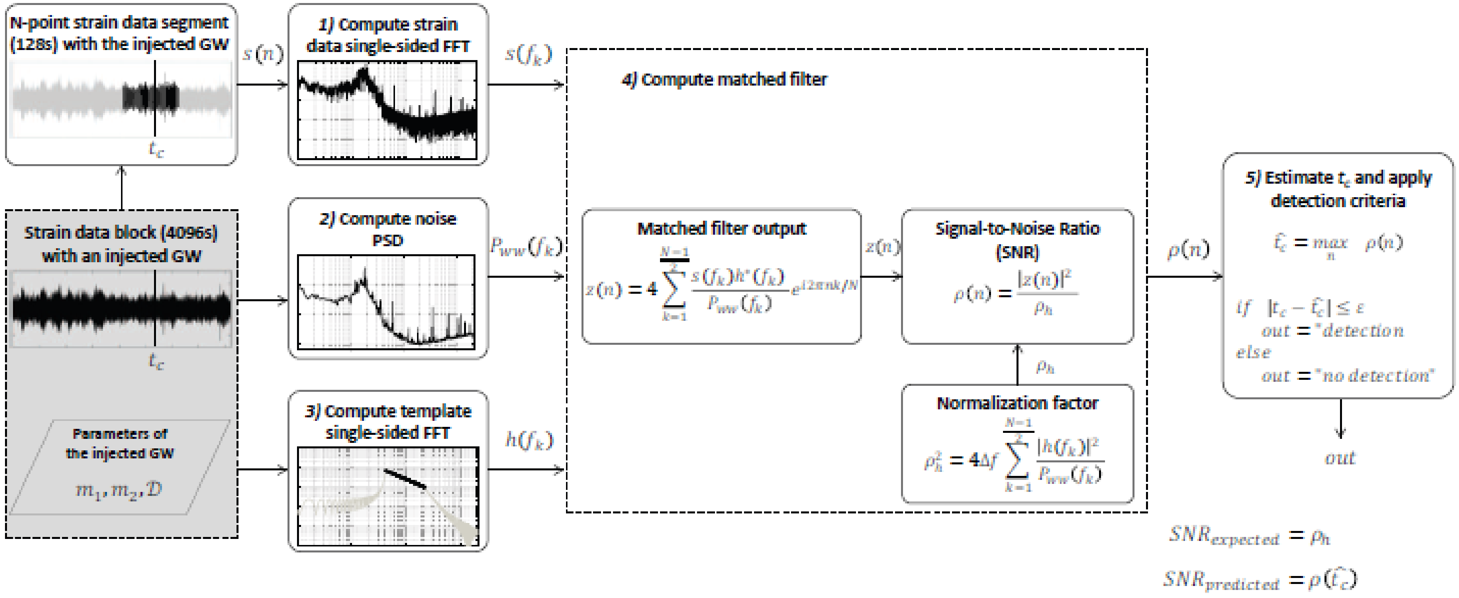
B. P. Abbott et al., 2020 Class. Quantum Grav. 37 055002

Gravitational-Wave (GW) sources



Searching GW from inspiral systems using LIGO data

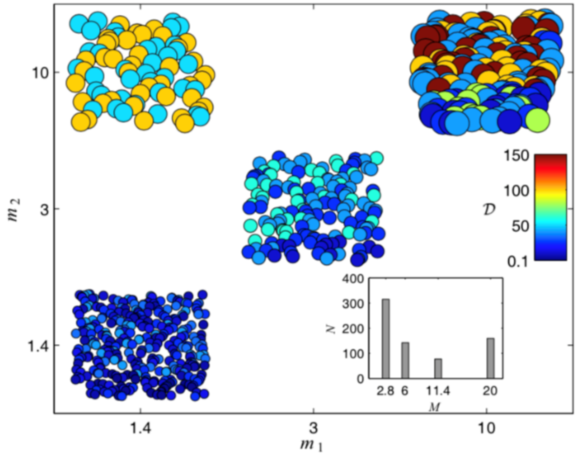


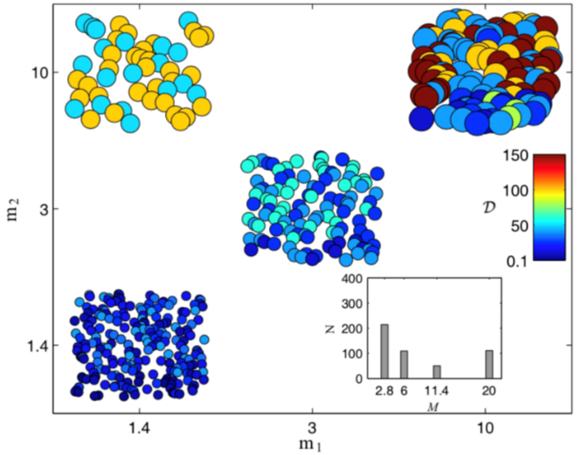
H1

	Total mass (units of $M_\odot$)				
	2.8	6.0	11.4	20.0	**All**
Injections	214	109	50	112	**486**
Detections	162	102	31	105	**400**
ACC (%)	76	94	62	94	**82**

L1

	Total mass (units of $M_\odot$)				
	2.8	6.0	11.4	20.0	**All**
Injections	315	142	77	160	**694**
Detections	264	138	57	150	**609**
ACC (%)	84	97	74	94	**88**





Antelis and Moreno 2017, EPJP
Antelis et. al. 2018, IOP Journal of Physics

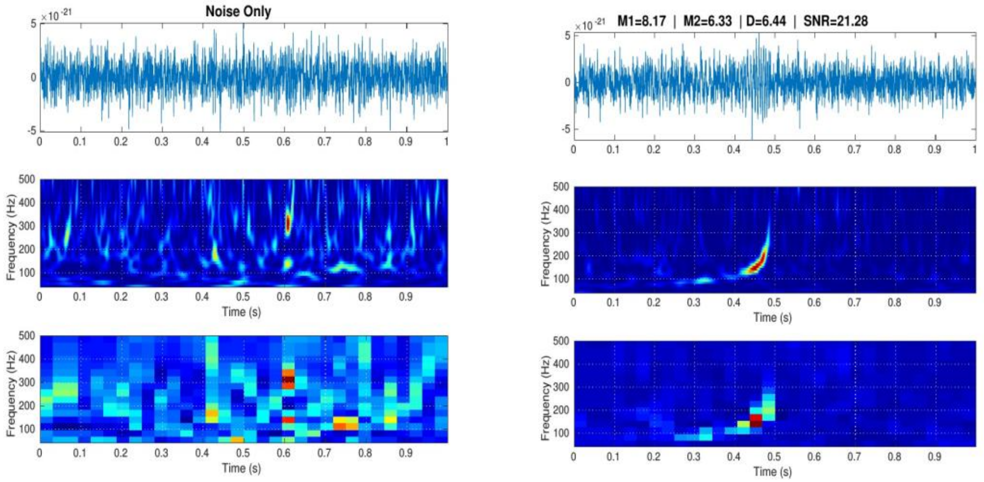
Detection of GW signals from BBHs using CNNs

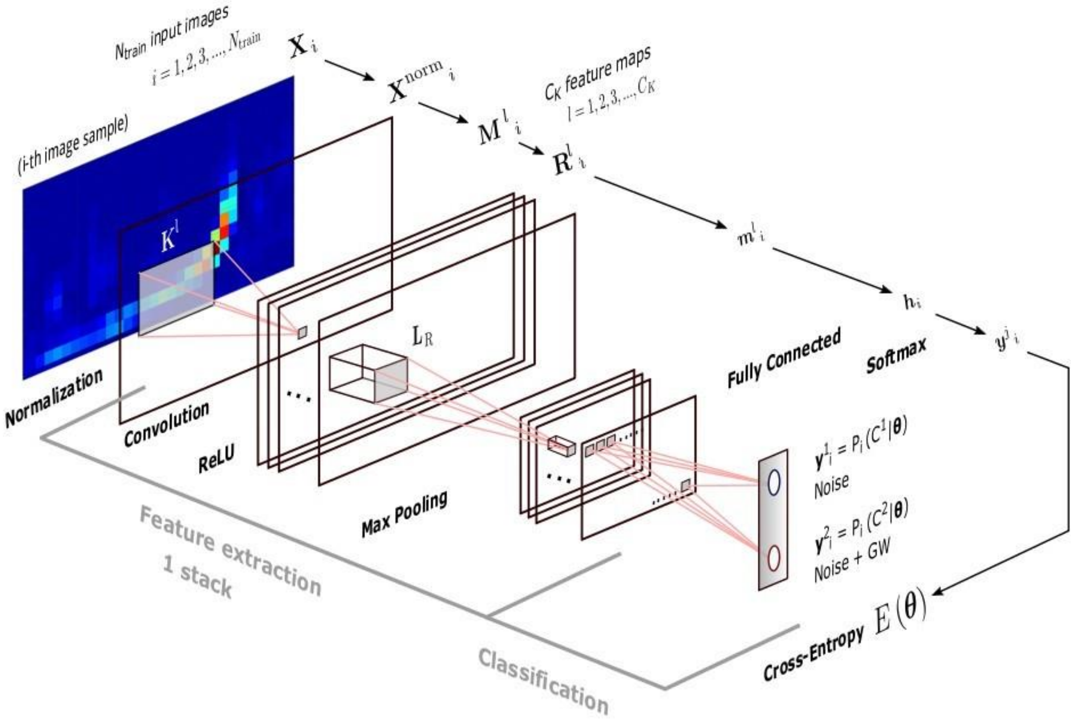
Raw single-interferometer strain data:

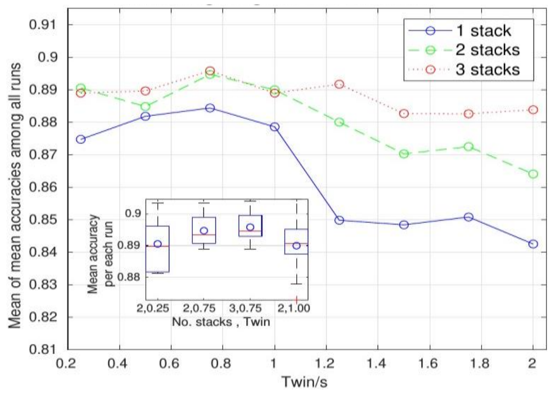
$$s_{\text{raw}}{}^{i}(t) = \left[s^{i}(t_0{}^{i}), s^{i}(t_1{}^{i}), ..., s^{i}(t_{N-1}{}^{i})\right]^{T} \ ,$$

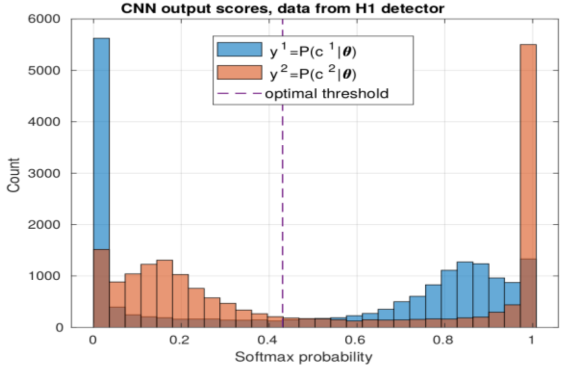
Model:

$$s_{\text{raw}}{}^{i}(t) = \begin{cases} n^{i}(t) & \text{if there is not a GW} \ , \\ n^{i}(t) + h^{i}(t) & \text{if there is a GW} \ , \end{cases}$$



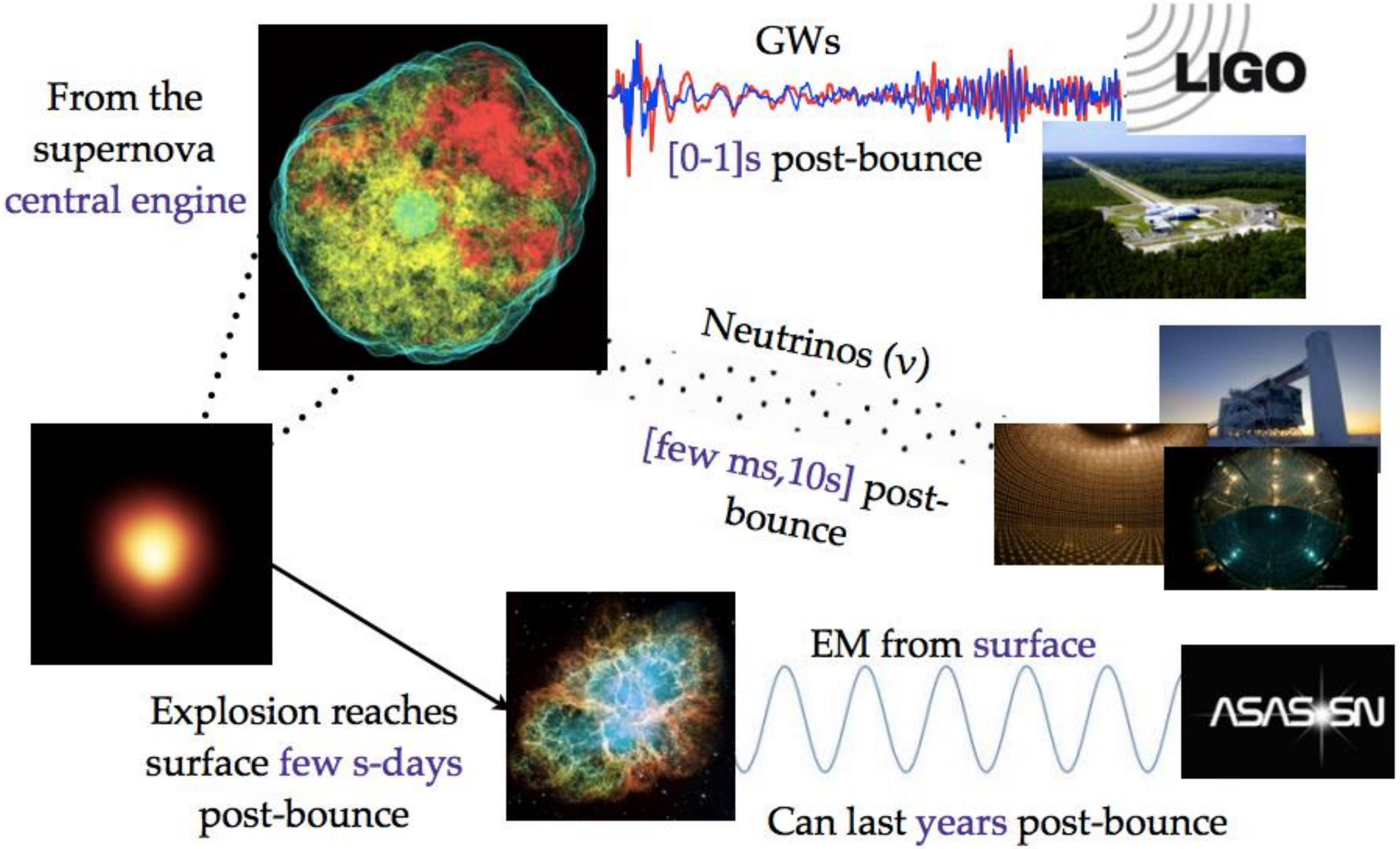




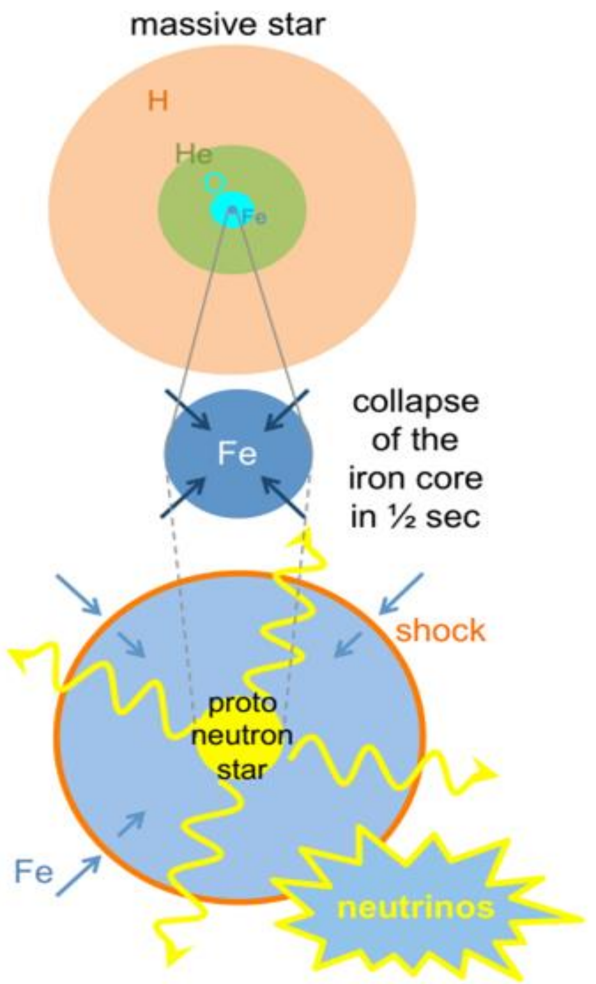


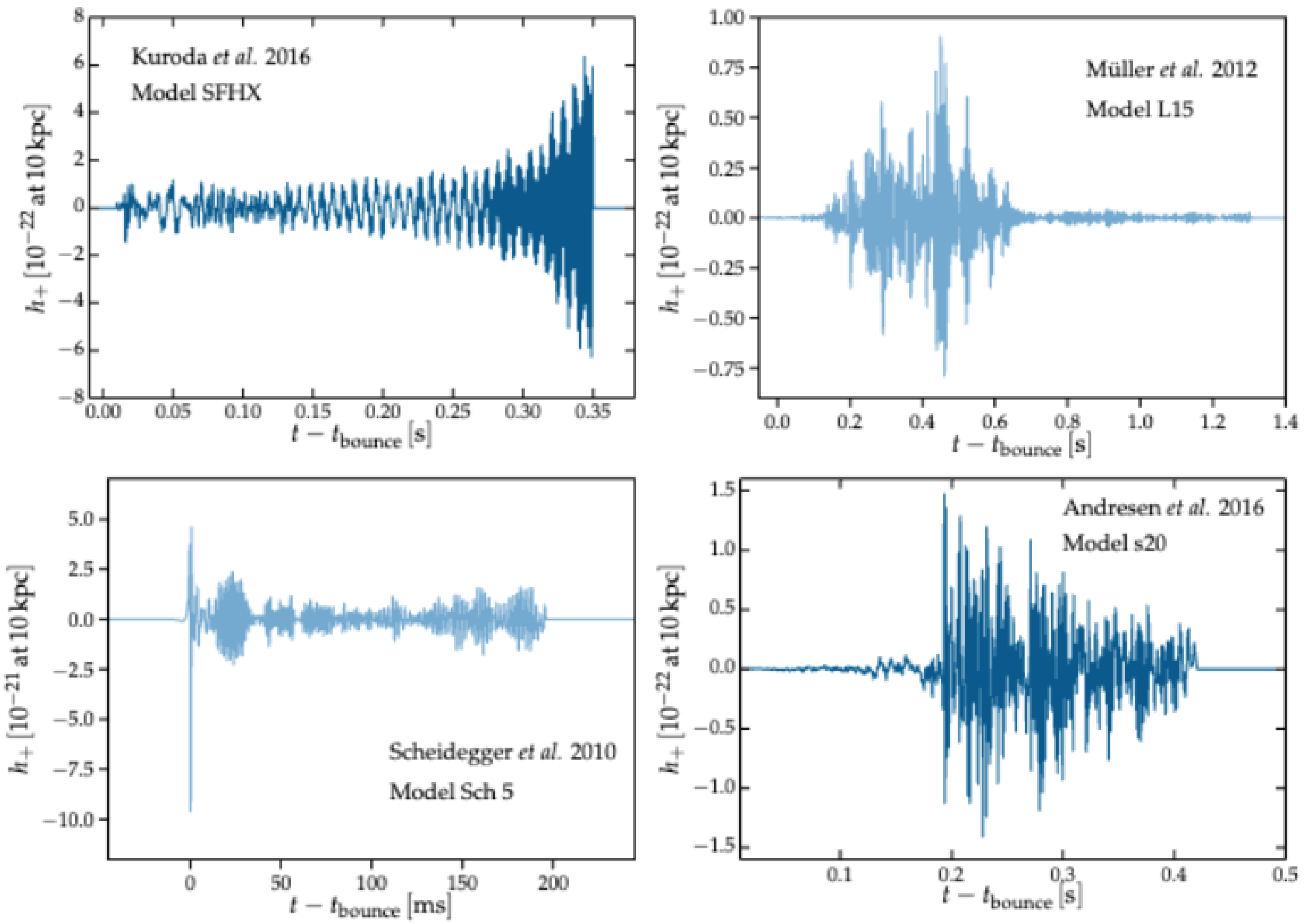
Morales 2021, sensors

Supernovas

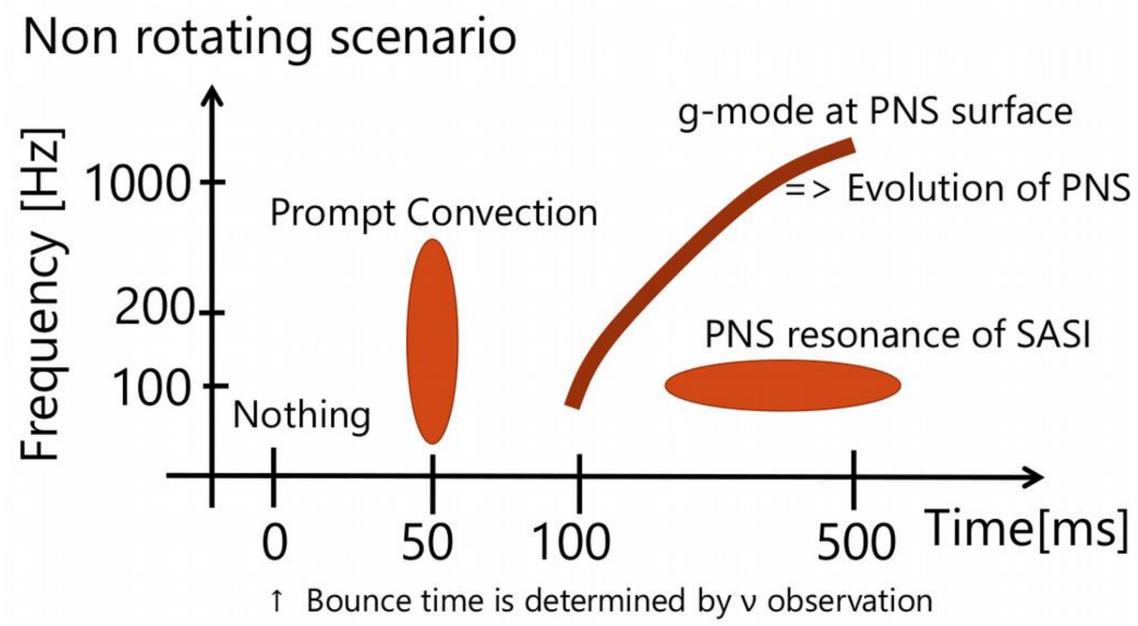

From the supernova central engine
GWs
[0-1]s post-bounce
LIGO
Neutrinos (ν)
[few ms,10s] post-bounce
Explosion reaches surface few s-days post-bounce
EM from surface
ASAS-SN
Can last years post-bounce

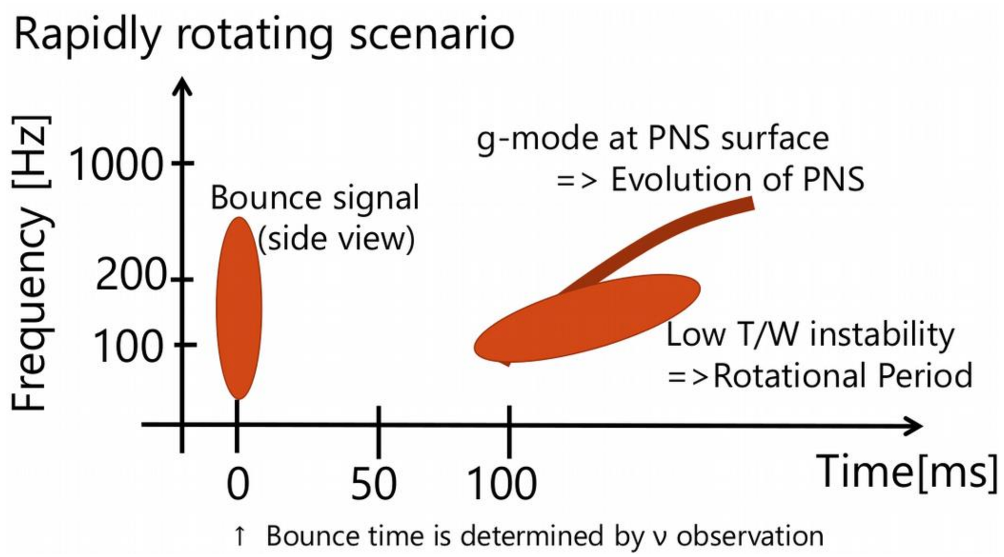
Supernova waveforms





Supernova spectrogram



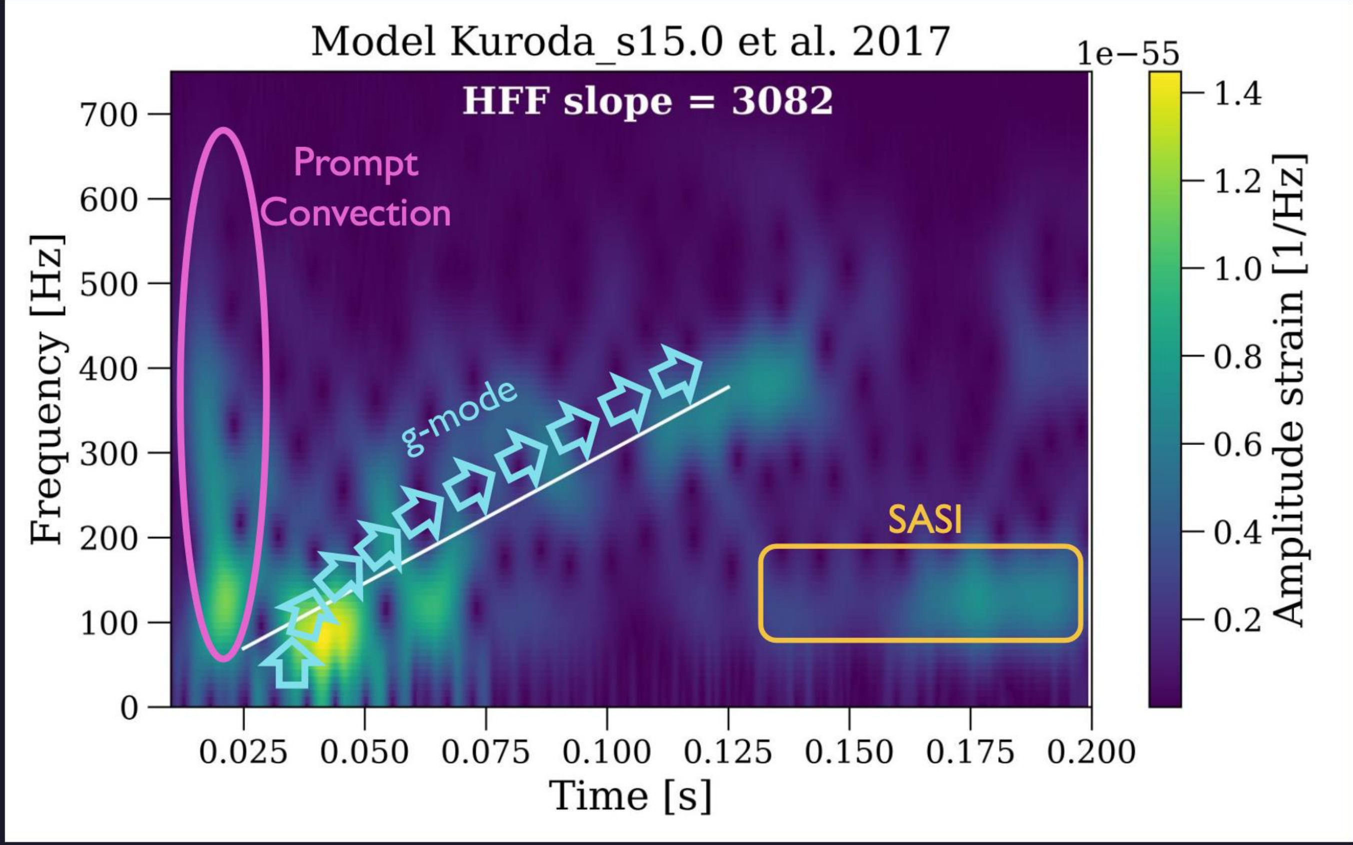


From T. Tokiwaki

- Slowly rotating progenitor
- Rapidly rotating progenitor
- Neutrino-driven explosion
- Extreme emission models

- Non deterministic: mostly stochastic
- Deterministic features (ramp up of f/g mode, SASI)
- Bounce part with regular shape (template-based searches?)
- Short duration signal
- Broadband signals
- High frequency components

The CCSN GW features



Prompt convection helps to revive *the stalled shock wave*

(Kuroda et al. 2018)
(Muller et al. 2013, 2014)
(Morozova et al. 2018)

hydrodynamic instabilities that describes the dynamics of the SN explosion and the subsequent *evolution of the shock wave*.

Phenomenological GW signals from CCSNE with slope

From oscillator wave equation

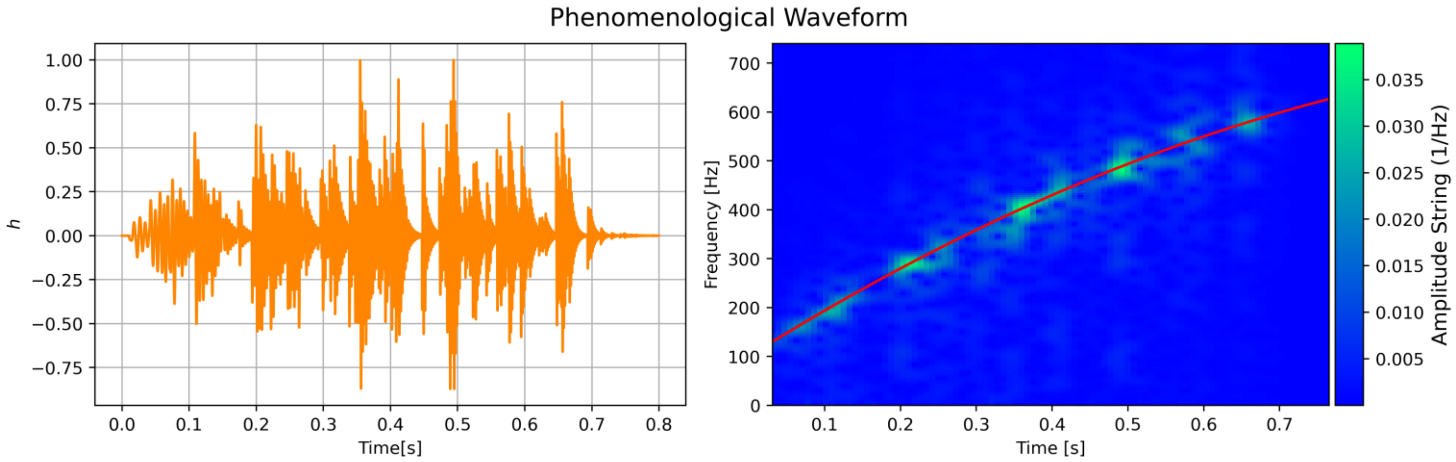
$$\ddot{x} + 2\gamma\dot{x} + \omega_0^2 x = 0$$

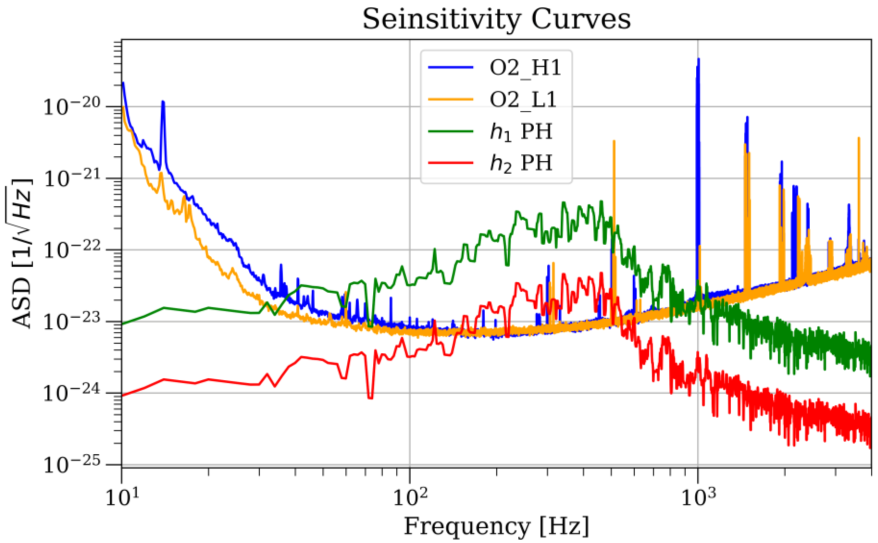
i) Overdamping $\gamma > 0$
ii) Critical Damping $\gamma = \omega_0$
iii) Underdamping $\omega < 0$

Model iii) let us to have a stochastic gravitational wave

$$\partial_{tt}h + \frac{\omega(t)}{Q}\partial_t h + \omega(t)^2 h = s(t)$$

$s(t) = s_n\delta(t - t_n)$ is a driving force
Q let to have a dissipative model





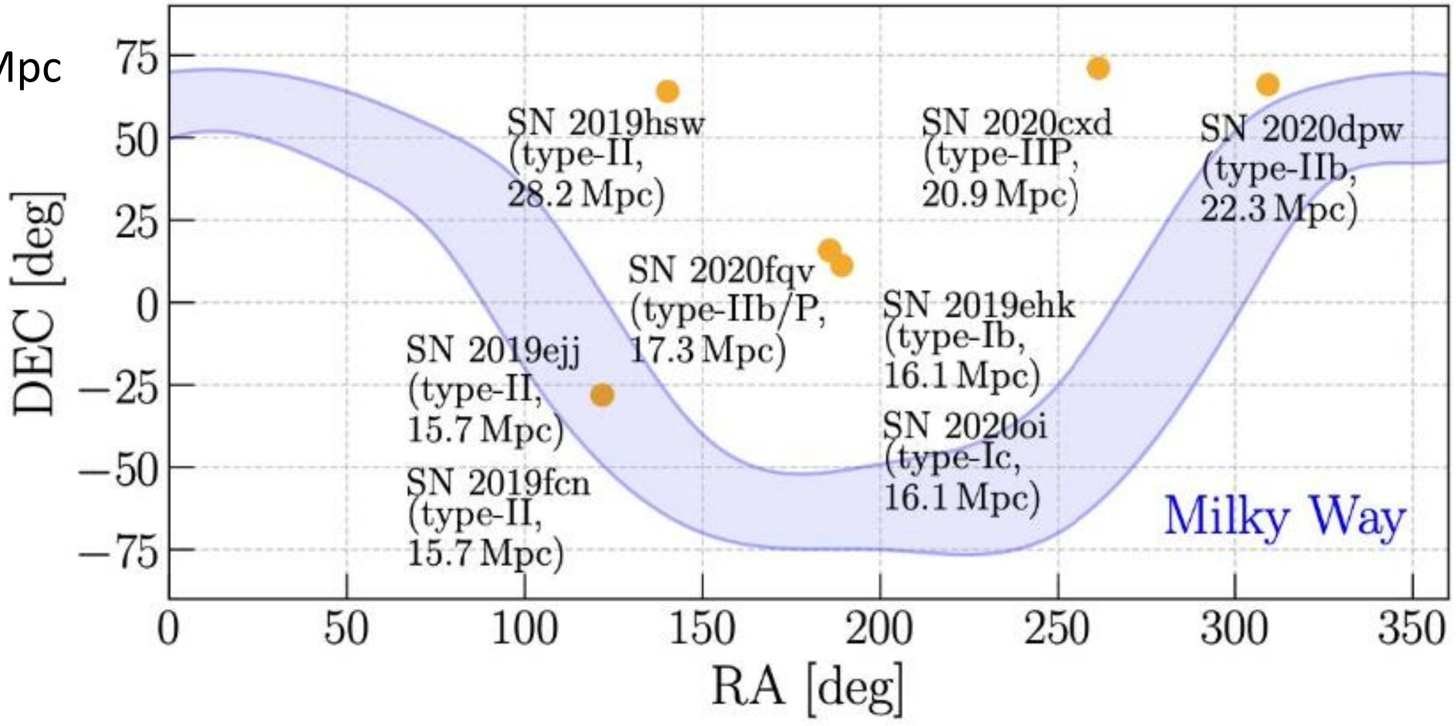
Published: Revista Mexicana de Física (2024)

GW search in LIGO-VIRGO O3 run

During the O3 run, the SN team selected 8 SN candidates.

Selection criteria:

- The distance is less than approximately 300 Mpc
- Frequency range from 50 Hz to 2 kHz
- The closet SN is SN2019ejj and SN2019fcn (15.7 Mpc)
- Energies are below 1051 erg, typical CCSN explosion energy)



Sky locations of CCSNe candidate [1].

Szczepańczyk et al. 2024, Physical Review D

GW long gamma-ray burst jets

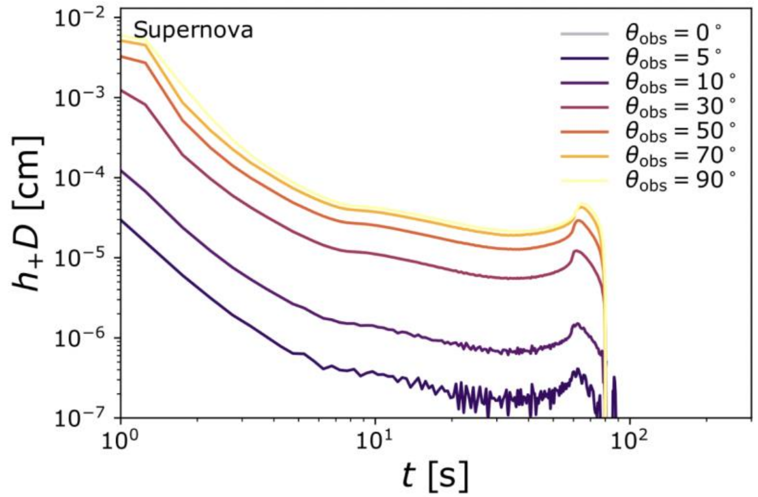
- Eulerian Special Relativistic Hydrodynamics (SRHD) code
- HLL and HLLc solver
- Adaptative Mesh Refinement (AMR)
- Multiple core runs (MPI)

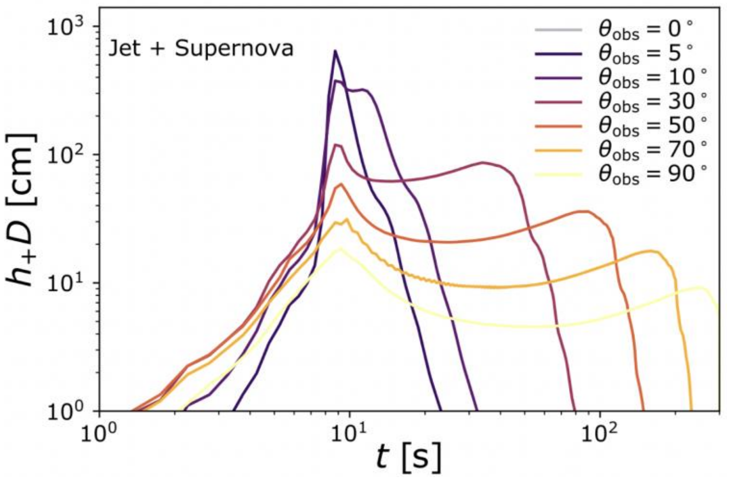
$$\frac{\partial}{\partial t}[\Gamma\rho] + \nabla \cdot [\Gamma\rho\vec{v}] = 0$$

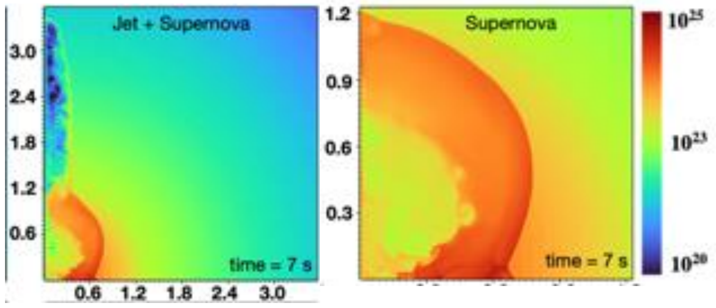
$$\frac{\partial}{\partial t}[\Gamma^2\rho h\vec{v}] + \nabla \cdot [\Gamma^2\rho h\vec{v}\vec{v} + p\,I] = 0$$

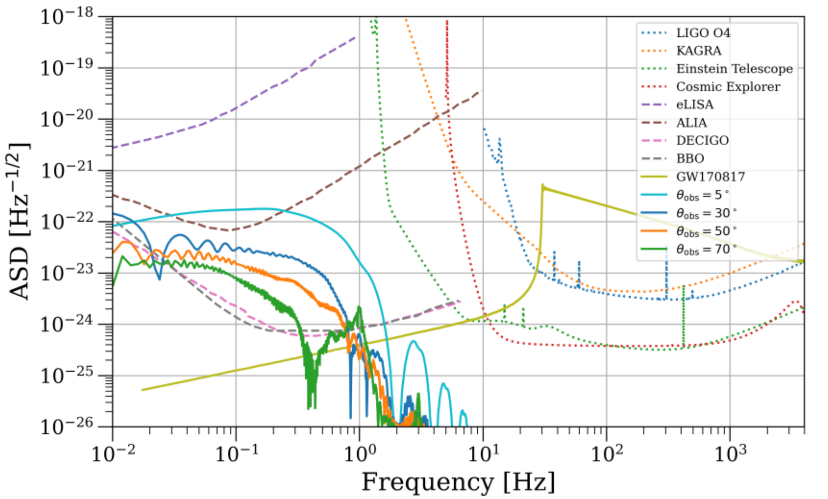
$$\frac{\partial}{\partial t}[e] + \nabla \cdot [e\vec{v} + p\vec{v}] = 0$$

$$e = \Gamma^2\rho h c^2 - p - \Gamma\rho c^2$$

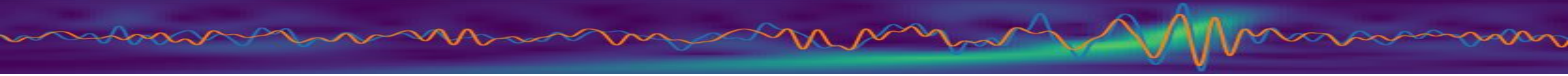








Urrutia 2022, MNRAS



Head on collision of l-boson stars

Einstein Klein Gordon model

$$G_{\mu\nu} = \frac{4\pi G}{c^4} T_{\mu\nu}$$

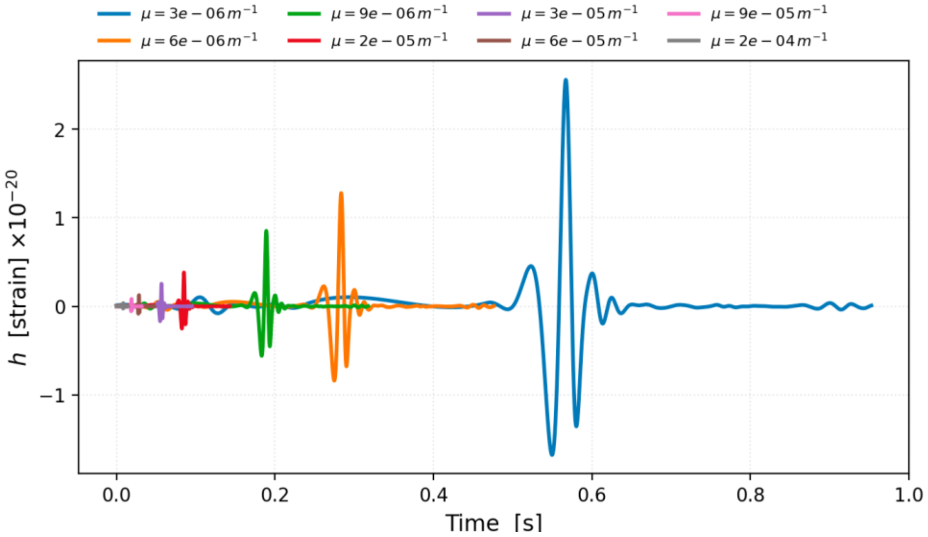
$$\partial_\mu \partial^\mu \Phi = \mu^2 \Phi$$

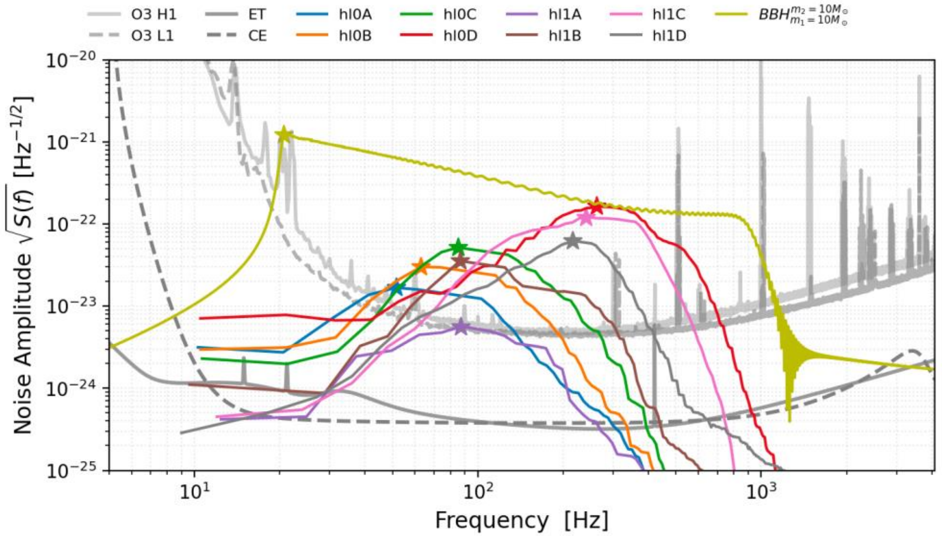
where $\mu = \frac{m_\phi c}{\hbar}$

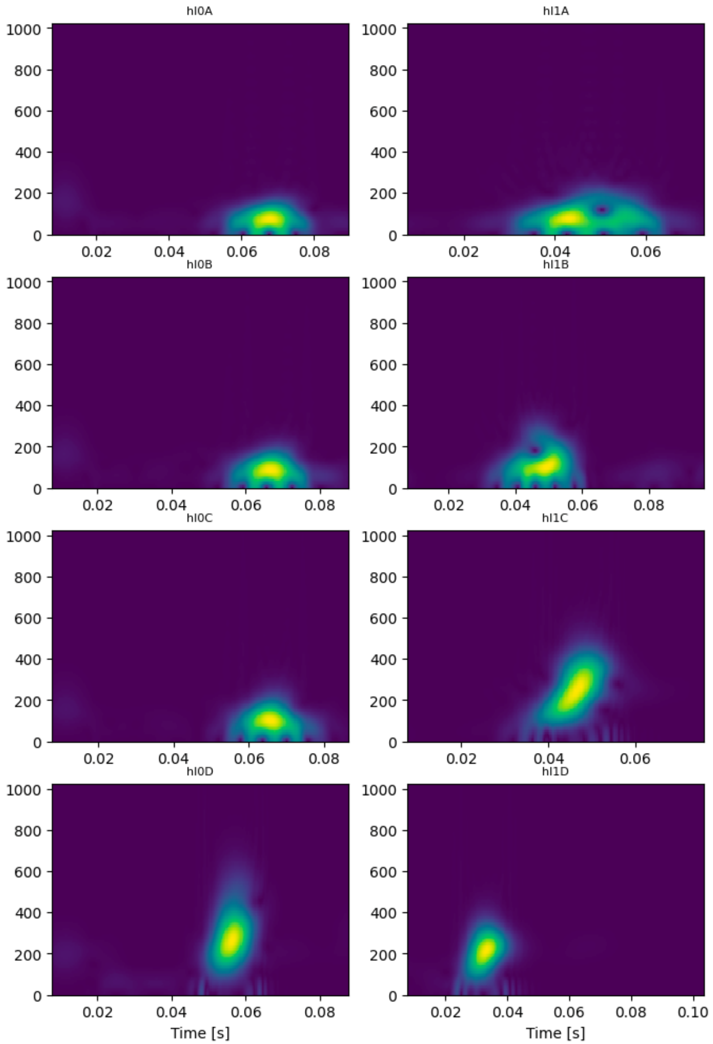
$$10^{-13} \leq \mu \leq 10^{-10}$$

total mass 1 to 1000 $M_\odot$

In preparation to published







Past LSC participation and contributions

Projects

- Machine and deep learning models to identify and reduce noises
  - https://dcc.ligo.org/P2100263/
  - https://doi.org/10.1103/PhysRevD.105.084054
- Theory and simulations of GW from long gamma-ray burst jet
  - https://dcc.ligo.org/LIGO-P2200245
  - https://doi.org/10.1093/mnras/stac3433
- Post-Newtonian Gravitational Waves with cosmological constant Λ from the Einstein-Hilbert theory
  - https://doi.org/10.1103/PhysRevD.109.064051

Participation in studies with cWB

- Detecting and reconstructing GW from the next galactic CCSNe
  - https://dcc.ligo.org/LIGO-G2100101
  - https://doi.org/10.1103/PhysRevD.104.102002
- Targeted searches of CCSN GW in O3 (send PRD, in corrections)
  - https://dcc.ligo.org/LIGO-P2200361

Outreach


Past projects:

Workshops with telescopes and small prototypes of EM and GW detectors

- To motivate Mexican and latin-american young girls and boys (emphasis in marginalized sectors) to study STEM careers
- To disseminate Physics and EM-GW through live-on experiments
- Consolidation of the *Grupo Latinoamericano de Análisis de Datos en Ondas Gravitacionales*
  - Current interactions with students and scientists from Mexico, Colombia, and Chile



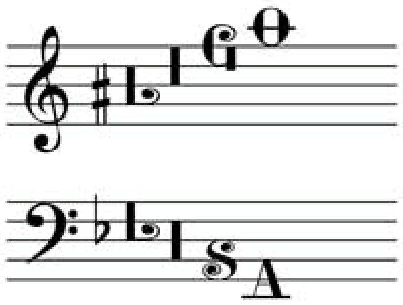

Present projects:

Several schools and seminars related to GW

- Promote GW topics in middle, high school and general public with seminars and workshop
- Participation in the *Congreso Nacional de la Sociedad Mexicana de Física (SMF)*
- Organization and participation in the *División de Gravitación y Física-Matemática of the SMF*

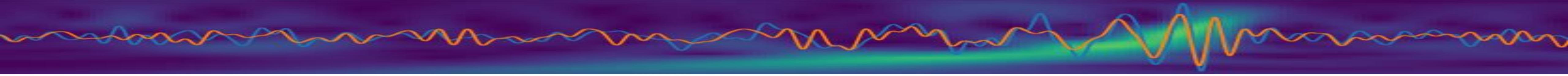
Remarks

- The Dynamical Universe is one of the priority areas in Astronomy
- Gravitational waves, together with other messengers, are great probes for studying the fundamental physics and exploring the Universe
- Model-independent searches has already shown that they are suitable to detect the unexpected phenomena.
- Search, detection and parameter estimation for gravitational waves using LIGO data
- Creation of templates in supernova models
- Improvements in LIGO interferometer with prototype models
- Search for Gravitational Waves in alternative theories and cosmological models
- Great opportunities for the discoveries!

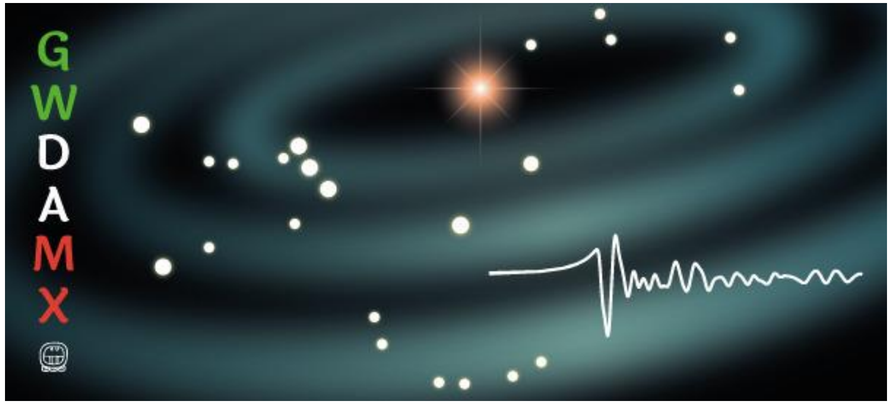


Join us to discover the Einstein's Symphony

Albert Einstein plays Gravitational Waves
bobonart



Join our Guadalajara group



Tecnológico de Monterrey

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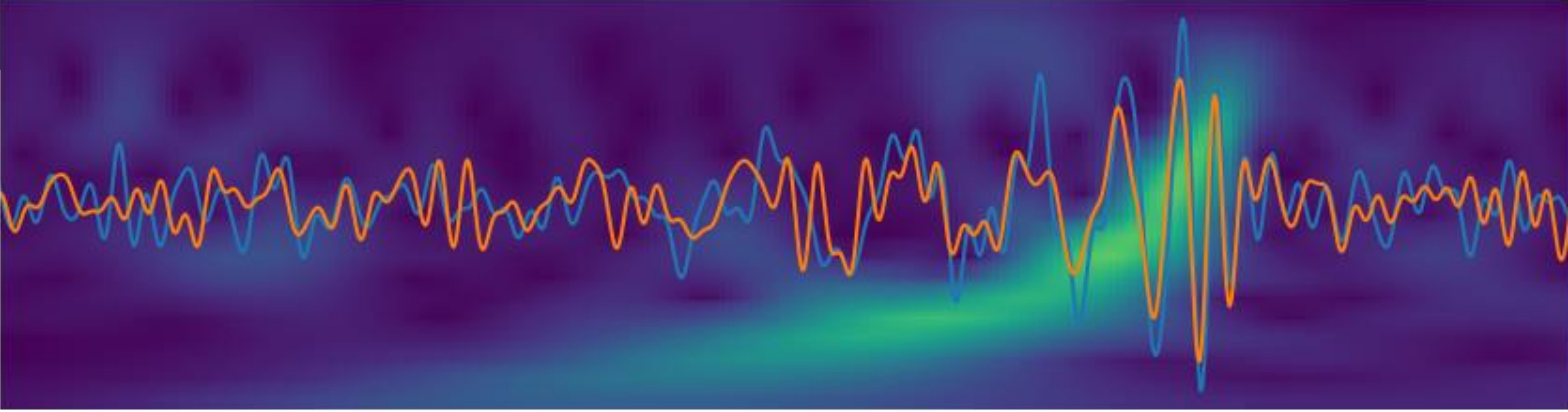
ET EINSTEIN TELESCOPE

[Grupo de Gravitación y análisis de datos en GW](#)

[www.gravitationalwaves.mx](#)



Thank you for your attention

Questions?