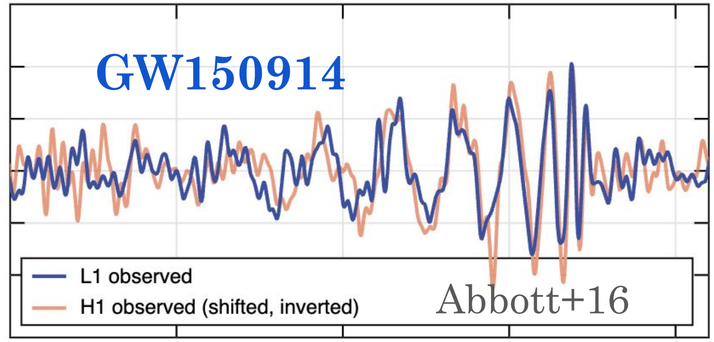


The Quest to Detect Gravitational Wave (GW) Bursts

Marek Szczepańczyk
Department of Physics,
University of Warsaw

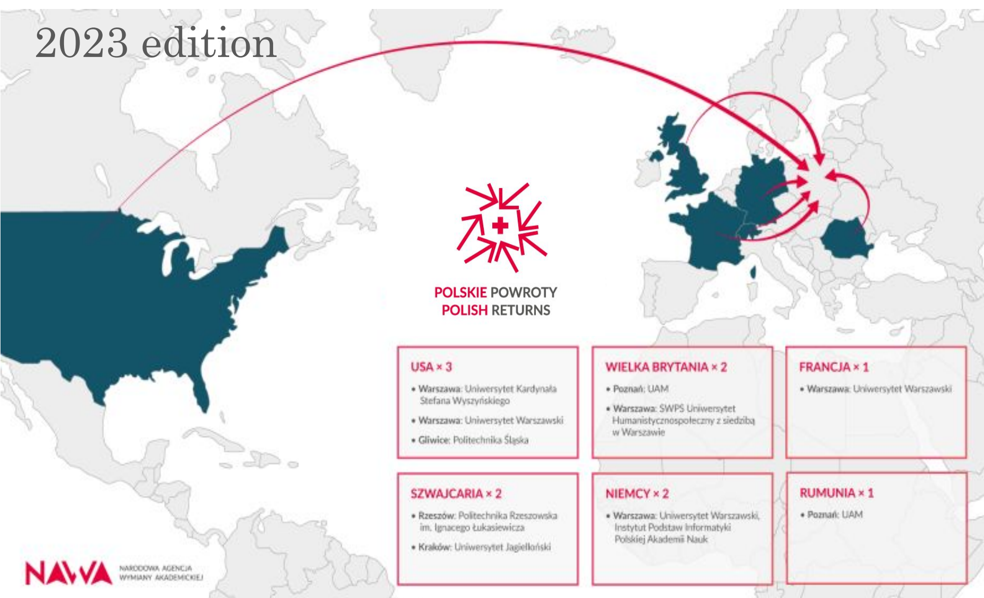
Slides:
fuw.edu.pl/~mszczepanczyk/news.html

International Training Workshop on Frontiers from Quanta to Cosmos Physics (FQCP2025)
Beijing, 04.11.2025

Return to Poland

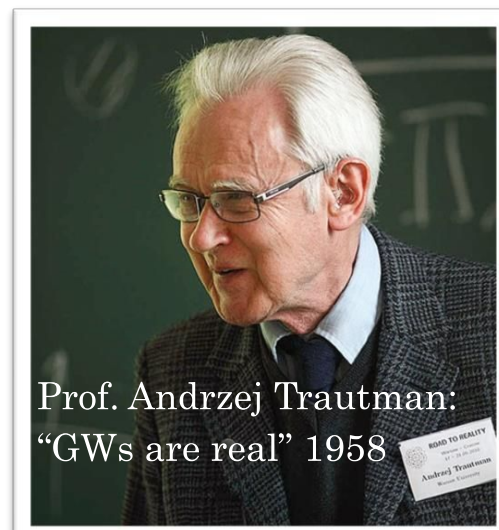
- B.A., M.Sc., University of Warsaw
- Ph.D., ~5 years: Embry-Riddle Aeronautical University (Arizona)
- Postdoc, ~5 years: University of Florida
- Assistant Professor, present: University of Warsaw

https://www.fuw.edu.pl/~mszczepanczyk/

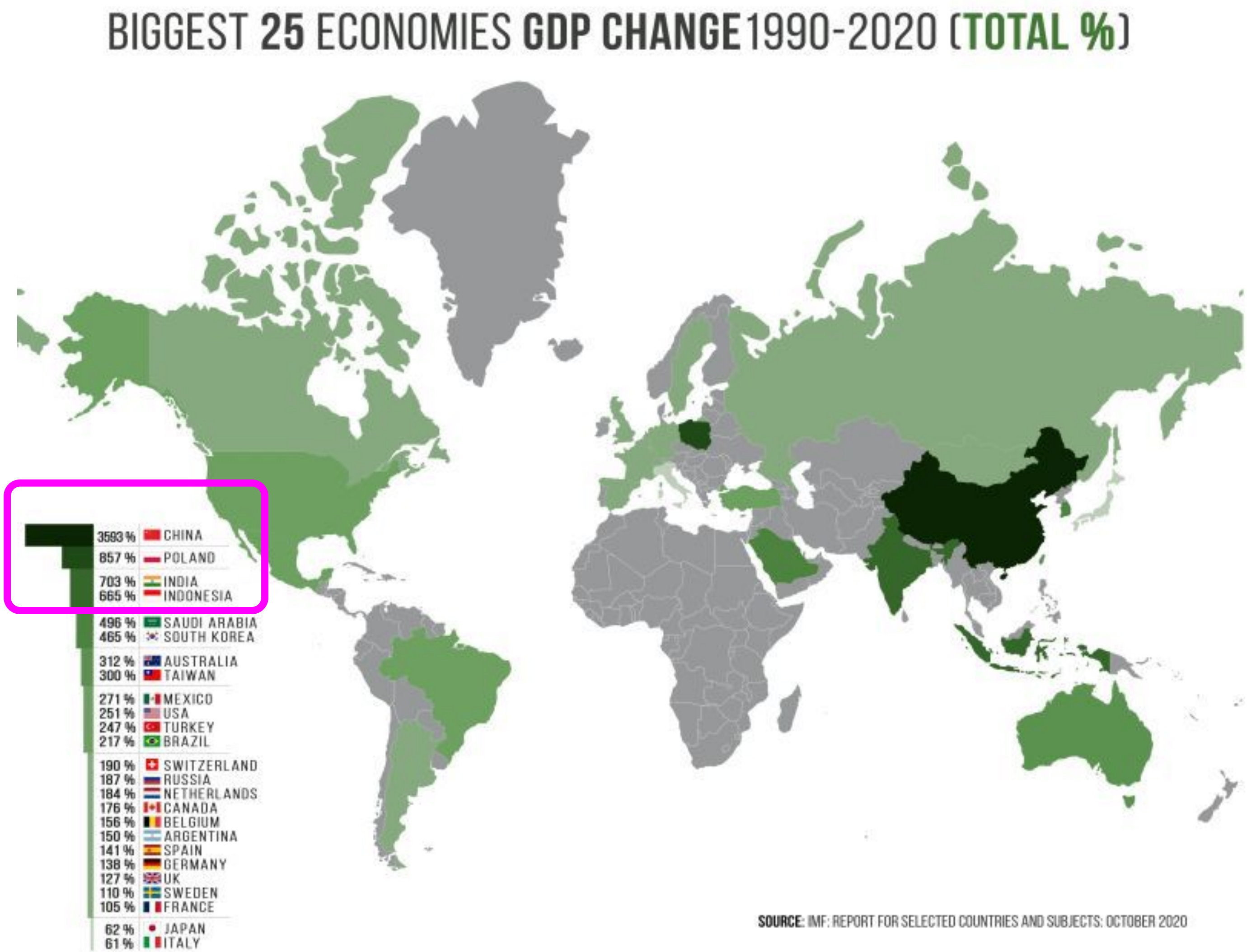


Chair of Theory of Relativity and Gravitation

- Classical and Quantum Gravity
- Proof that GWs are real (prof. Andrzej Trautman, the story)
- Loop Quantum Gravity (prof. Lewandowski, prof. Ashtekar at Princeton)
- Isolated and Dynamic Horizons (prof. Lewandowski, prof. Ashtekar at Princeton)
- Einstein–Infeld–Hoffmann equations (prof. Infeld with Einstein)


Prof. Andrzej Trautman: “GWs are real” 1958

Fun Facts



Also,
word "beer":

piwo (Polish)

↓

啤酒 (píjiǔ)

Outline

- Part I: Basics
  - Introduction to GW Astrophysics
  - GW Burst Searches
- Part II: Future (Next 10 Years and Beyond)
  - Observing Run 4 (O4)
  - Future discoveries
- Summary

Part I:
Basics

Introduction to GW Astrophysics

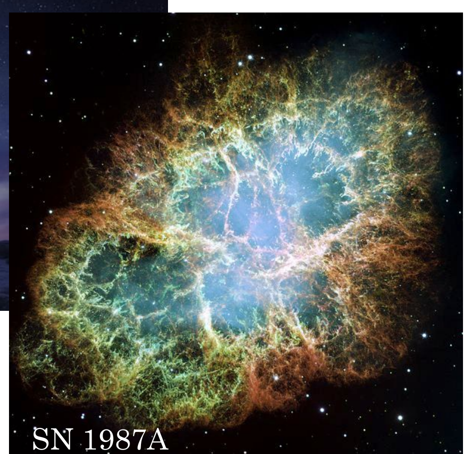
“Conventional” and “Gravitational-Wave” Astronomy

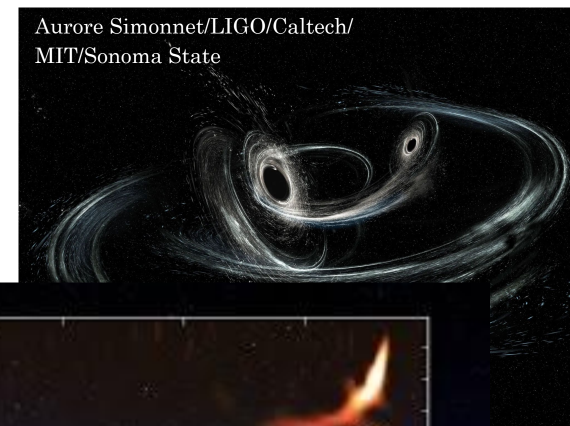
“Conventional” or time-domain Astronomy:
observing Universe using electromagnetic waves (e.g. visible light), cosmic rays or neutrinos.

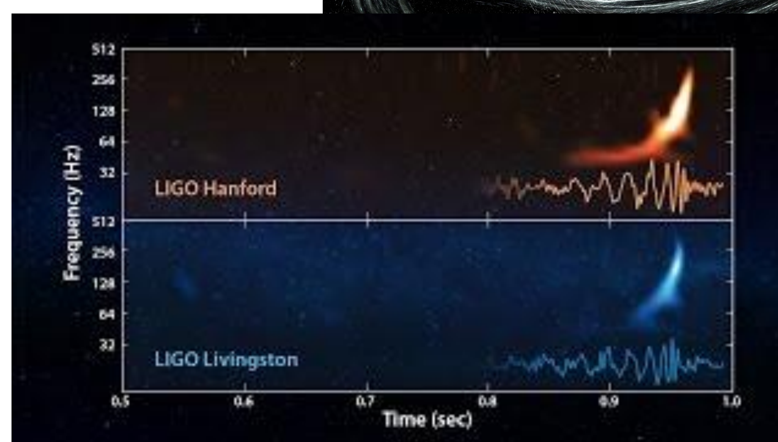
Looking at the Universe

“Gravitational-Wave” Astronomy:
observing Universe using gravitational-waves, the “ripples of spacetime”.

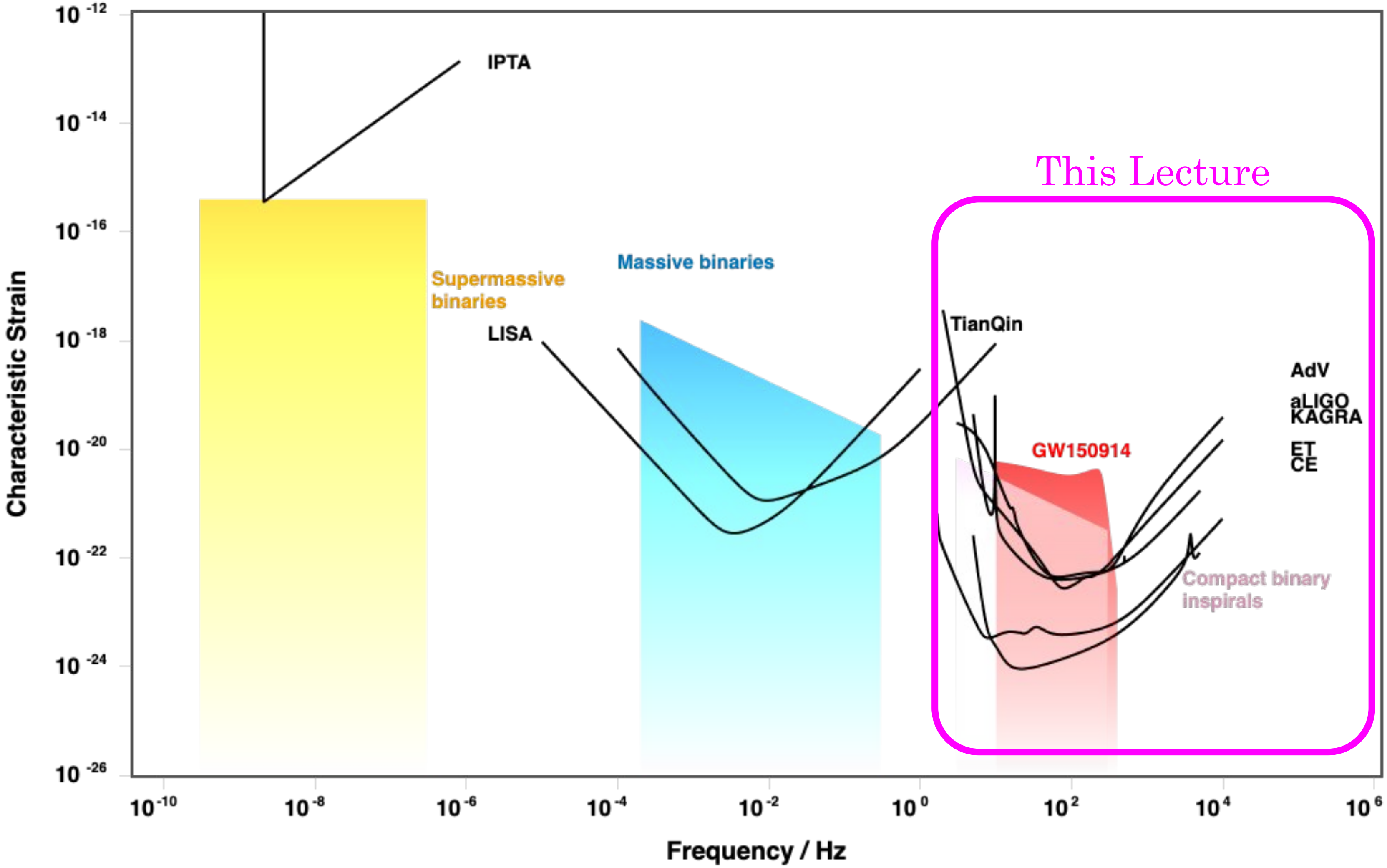
Listening to the Universe







GW Spectrum



http://gwplotter.com/

GW Sources and Searches

	Model-dependent searches (also, templated-based)	Model-independent searches (also, GW burst)
Short GWs	Compact binaries (black holes, neutron stars)	This Lecture: GW bursts (compact binaries, supernovae)
Long GWs	Pulsars, continuous waves	Stochastic GWs (e.g. sum of pulsars in Milky Way)

See Lectures of
Prof. Pep Covas Vidal

Einstein Equation and Experimental Gravitation

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

- *Space-time tells matter how to move; matter tells spacetime how to curve* J. Wheeler
- Einstein Equation:
  - Solving it analytically/numerically, or
  - **Let the Nature solve it for us**
- An abundance of gravitational-wave sources are to discover, but only handful are precisely modelled.

响亮 The Dynamic Universe (The Loud Universe)

Quadrupole formula for GW production:

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

We need aspherical mass-energy movement.

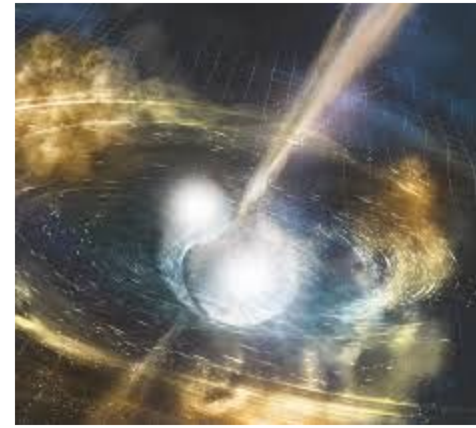
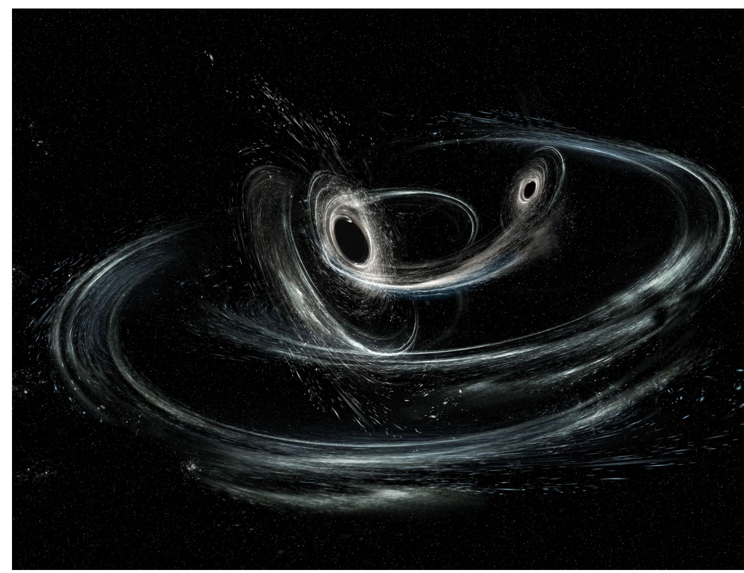


Image: NSF/LIGO/Sonoma/A. Simonnet

GW sources:

- Standard, e.g. stellar-mass binary black holes
- **Special, e. g. binaries with elliptical orbits, lensed events, core-collapse supernova**

More examples in Part II

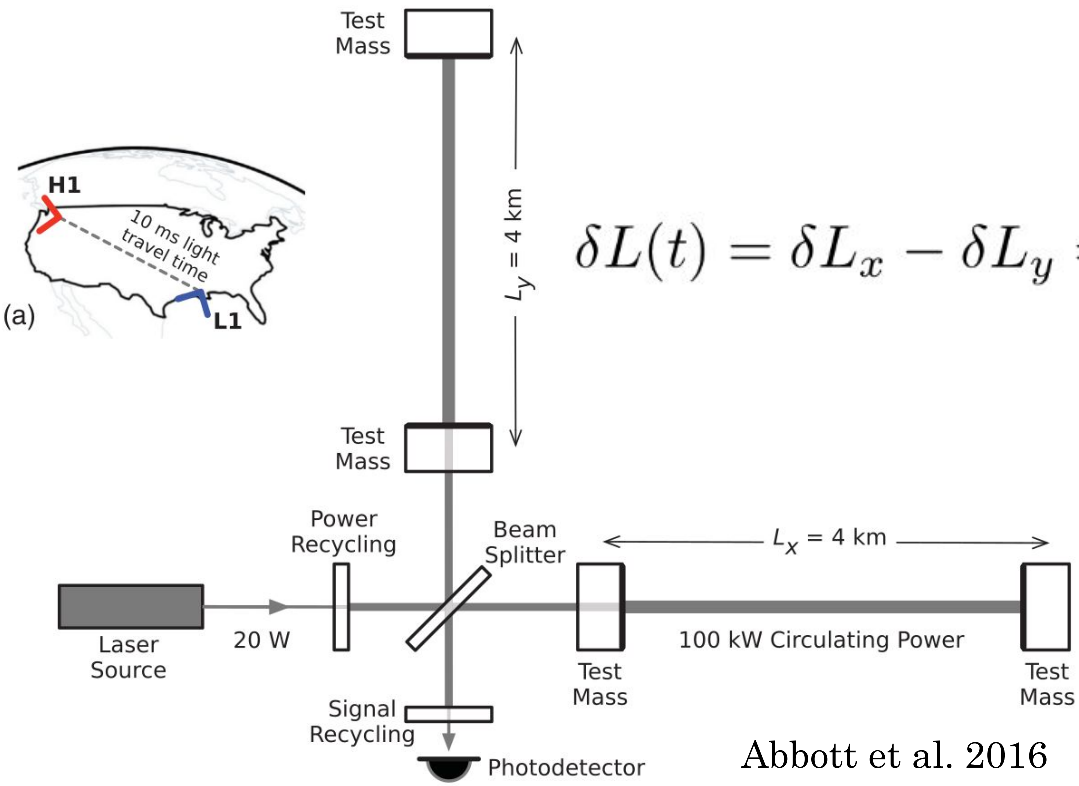


AURORE SIMONNET/LIGO/CALTECH/MIT/SONOMA STATE

Gravitational-Wave detectors

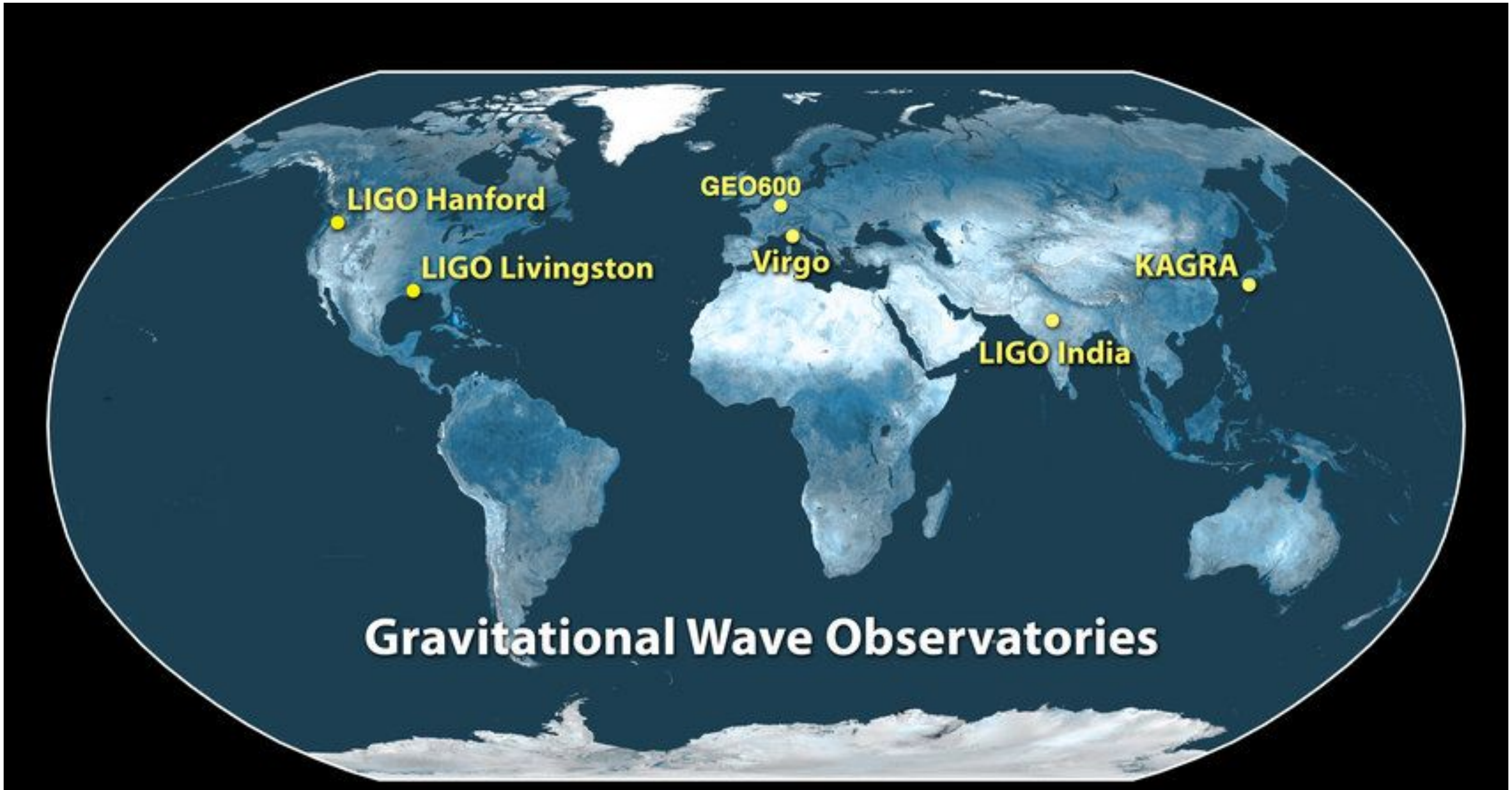
- GW detectors: interferometers
  (the longer the more sensitive)
- Preferably far away from human activities.
  But noise is inevitable…

$$\delta L(t) = \delta L_x - \delta L_y = h(t)L$$



Abbott et al. 2016

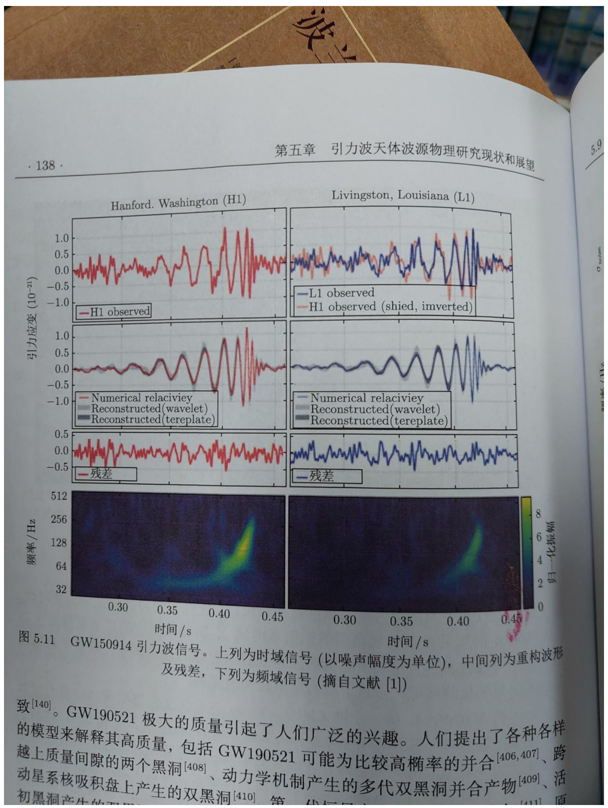
Detectors network



arXiv:1904.03187 [gr-qc]

- KAGRA - recently joined observations
- LIGO India - under construction
- Planned Australian detector (e.g. NEMO)

GW Burst Searches



· 138 · 第五章 引力波天体波源物理研究现状和展望

图 5.11 GW150914 引力波信号。上列为时域信号 (以噪声幅度为单位)，中间列为重构波形及残差，下列为频域信号 (摘自文献 [1])

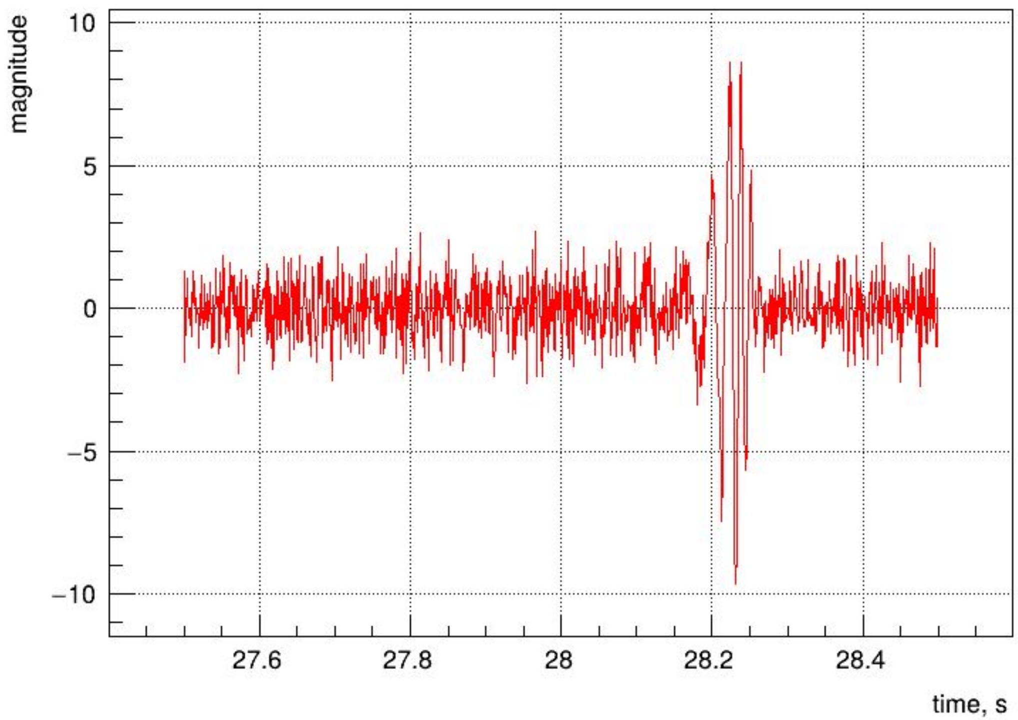
致[140]。GW190521 极大的质量引起了人们广泛的兴趣。人们提出了各种各样的模型来解释其高质量，包括 GW190521 可能为比较高椭率的并合[406,407]、跨越上质量间隙的两个黑洞[408]、动力学机制产生的多代双黑洞并合产物[409]、活动星系核吸积盘上产生的双黑洞[410]

Psst!
Discovery of GWs was made
by the GW burst searches

GW Bursts

Bursts – short-duration transients. Examples:

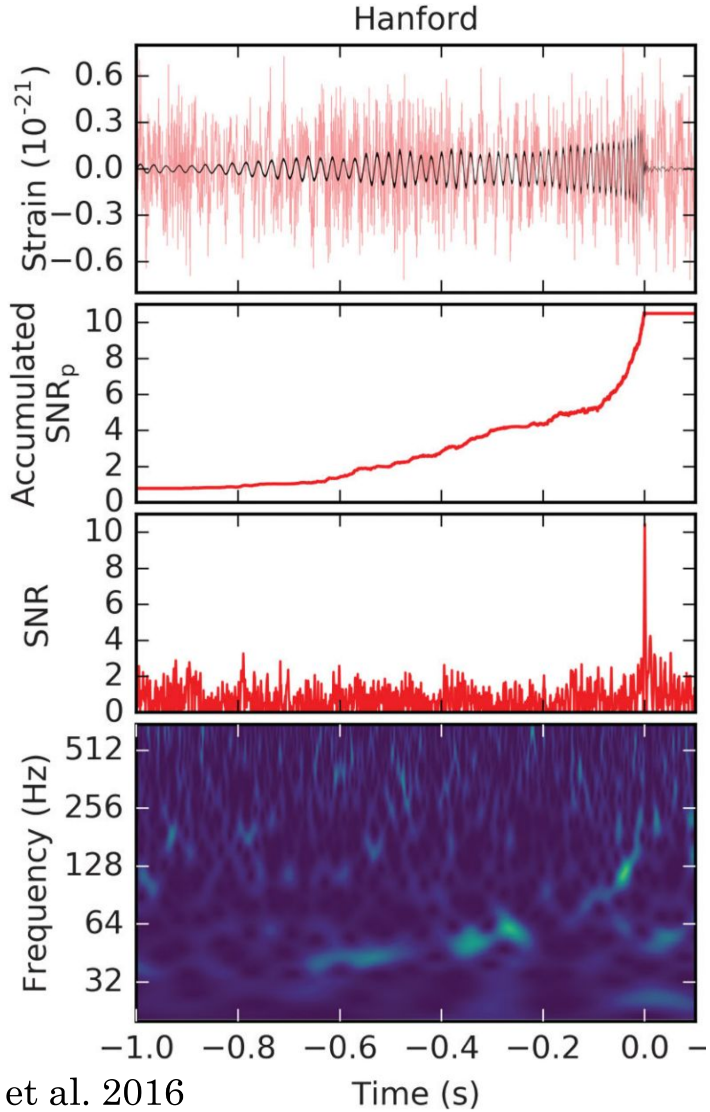
- Electromagnetic: gamma ray burst, fast radio burst, optical, X-ray, etc.
- Neutrino bursts
- Cosmic rays
- **GW Bursts ← how to search for them?**



Example of binary black hole in the data, signal-to-noise ratio of around 30 (very strong)

Model-dependent searches (template based, matched-filtering)

- Template waveforms from compact binaries are derived from General Relativity.
- **Template-based searches: cross-correlating data with the templates**
- Mathematically an optimal method given:
  (1) data is Gaussian
  (2) we know a waveform accurately
- Missing parameter space or having an inaccurate model may result in missing a detection.
- How about when you cannot create a template?
  - **Matched filtering is not useful to search for GW bursts**



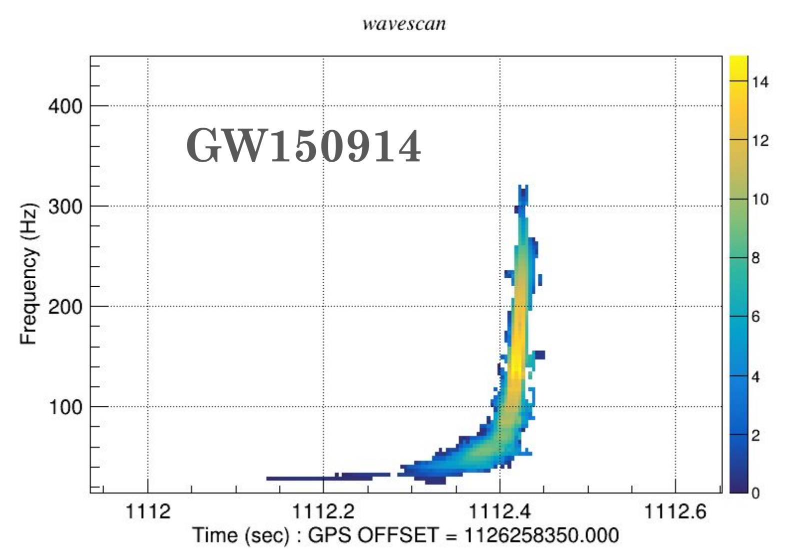
Abbott et al. 2016

Model-independent searches

- **Coherent WaveBurst** (cWB, Klimenko+16) is a software designed to detect a wide range of burst transients without prior knowledge of the signal morphology
- cWB uses minimal assumptions, for example growing frequency over time in case of binaries
- **Model-independent and template-based searches complement each other**
- cWB has detected:
  - **GW150914** - the very first GW (PRL 116, 061102)
  - **GW190521** - an intermediate mass binary black hole, 150 Msun (PRL 125, 101102)
  - **GW231123** - ~200 Msun BH (2507.08219)
  - It regularly detects GWs together with template-based searches
- The cWB contributes results to several LVK papers during each observing run.

coherent WaveBurst
an open source software for gravitational-wave data analysis

https://gwburst.gitlab.io/



Data Transforms

- Fourier Transform:

$$\hat{X}(f) = \int_{-\infty}^{\infty} x(t) e^{-i2\pi f t} \, dt$$

- Short-Time Fourier Transform:

$$X(\tau, \omega) = \int_{-\infty}^{\infty} x(t) w(t - \tau) e^{-i\omega t} \, dt,$$

- Wavelet Transform:

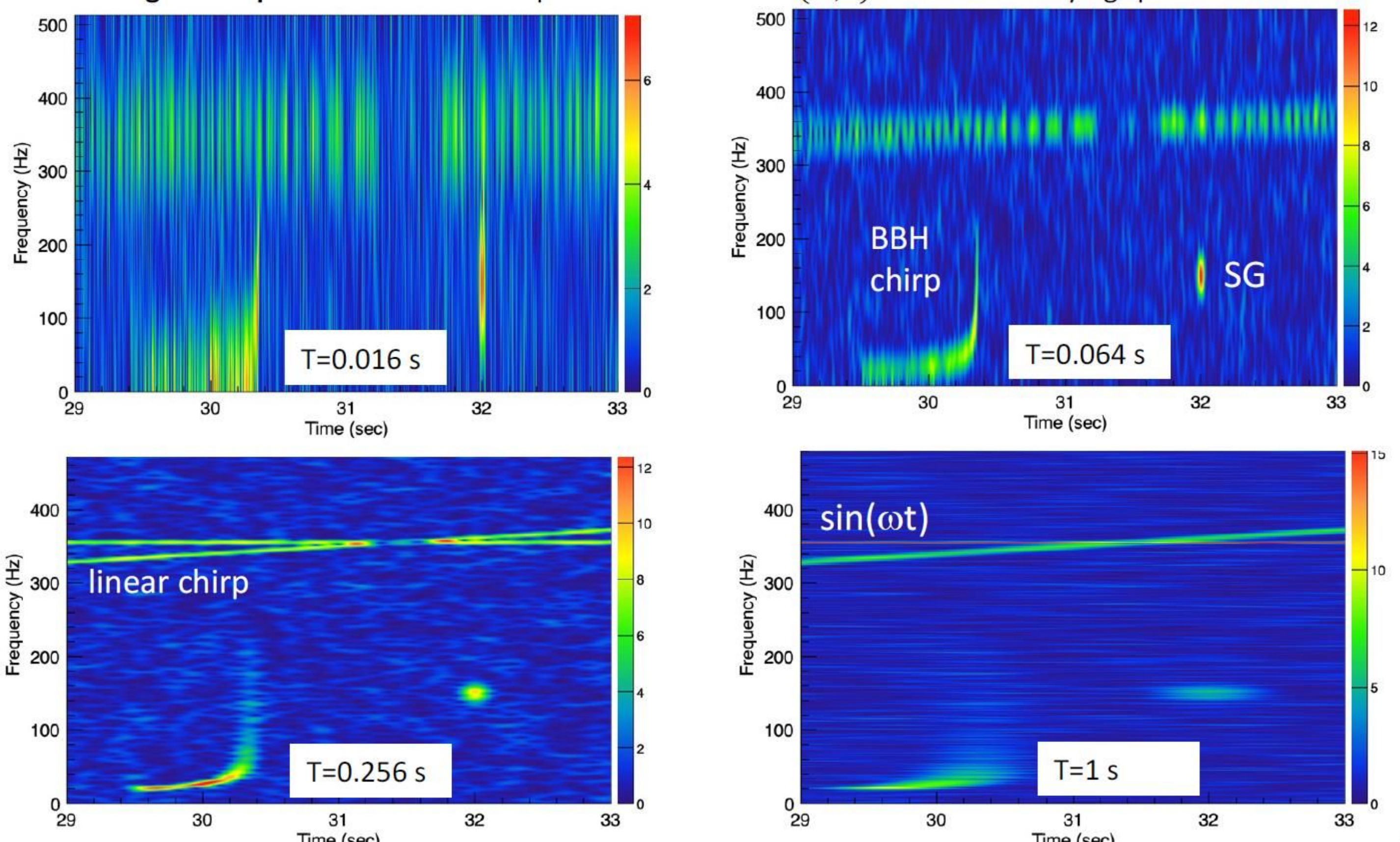
$$X(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} \overline{\Psi\left(\frac{t-b}{a}\right)} x(t) \, dt$$

Time-Frequency Transform

Time-Frequency Distribution $P(\omega, t) = |\hat{x}(t)|^2$

Short Time Fourier Transform: $\hat{x}(t,\omega) = \int_{-\infty}^{\infty} x(\tau)w(\tau - t)e^{-i\omega\tau}\, d\tau$

Which window w(t) is optimal? – The answer depends of the type of the signal we try to resolve
More general question: what is the optimal distribution $\boldsymbol{P}(\boldsymbol{\omega}, \boldsymbol{t})$ of the time-varying spectrum?



S. Klimenko, APS, April 2022

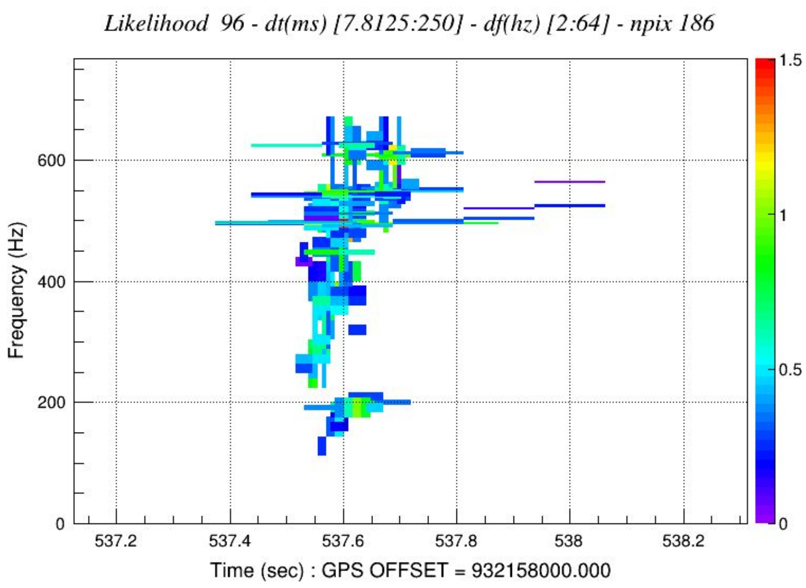
3

Multiresolution wavelet decomposition

- It is not possible to measure both frequency and time with at arbitrary resolution:

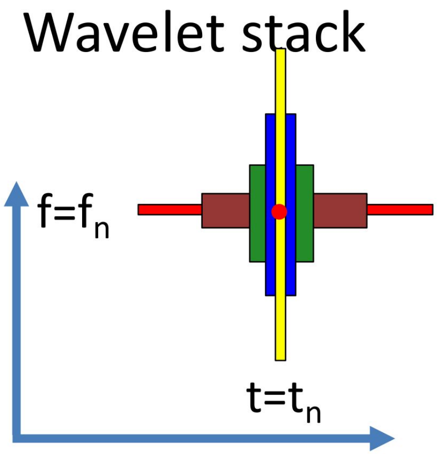
$$\sigma_t^2\,\sigma_\omega^2 \geq \frac{1}{4}$$

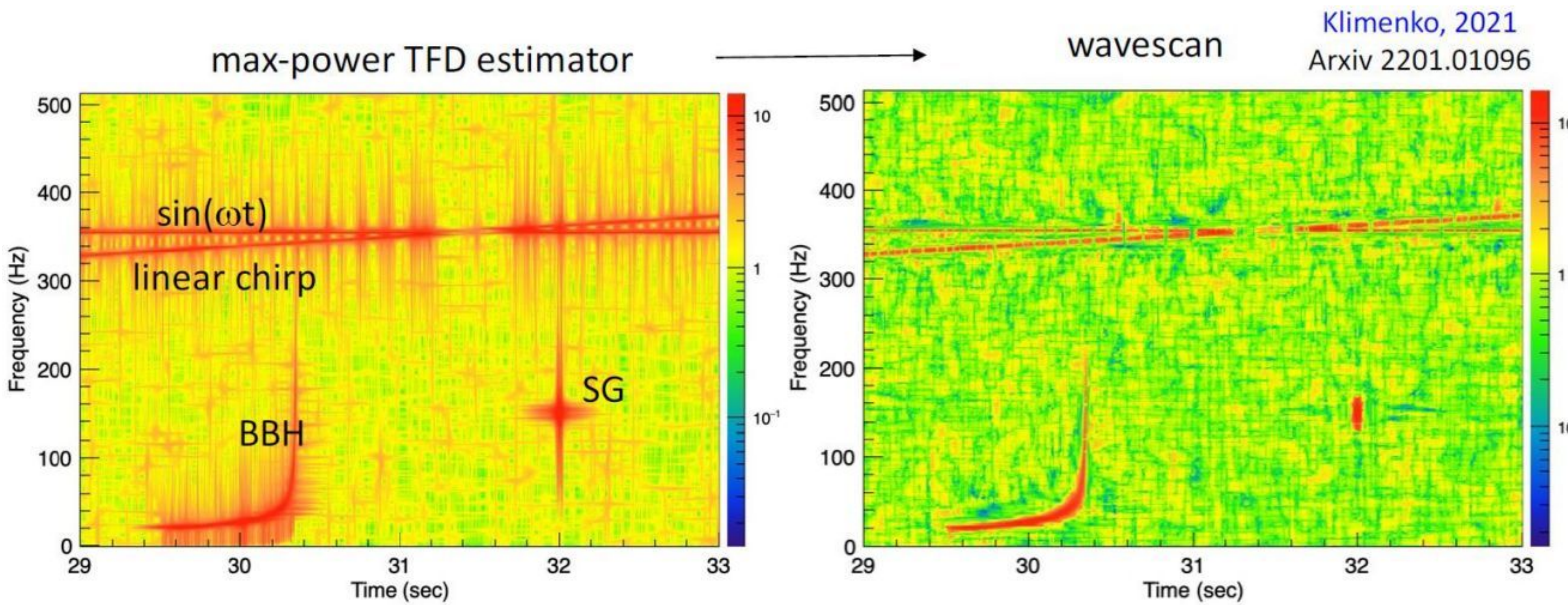
  (Heisenberg rule for signal processing)
- Detectability of signals depends on setting up appropriately Δt and Δf.
- cWB uses 7 multiresolution decomposition layers



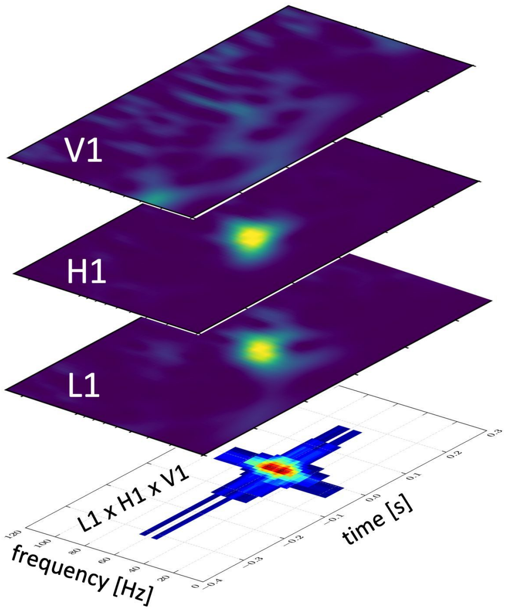
Wavescan

- Wavescan (Klimenko+22, [2201.01096](https://arxiv.org/abs/2201.01096)): high-resolution time-frequency transform
- Heisenberg rule for signal processing: $\sigma_t^2\,\sigma_\omega^2 \geq \frac{1}{4}$
  - Multiresolution analysis and wavelet stack
- Wavescan transform combines the maps from different resolution into a single time-frequency map
  - Spectral and temporal leakage is minimized.





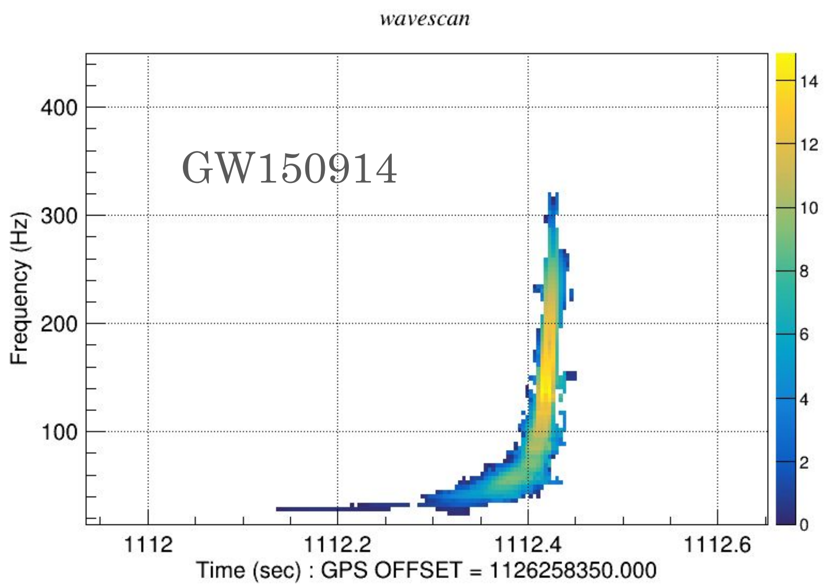
coherent WaveBurst (cWB)



x(t) $\xrightarrow[\text{Transform}]{\text{Wavelet}}$

- Time-Frequency Decomposition
- Cluster Selection
- Constrained Likelihood

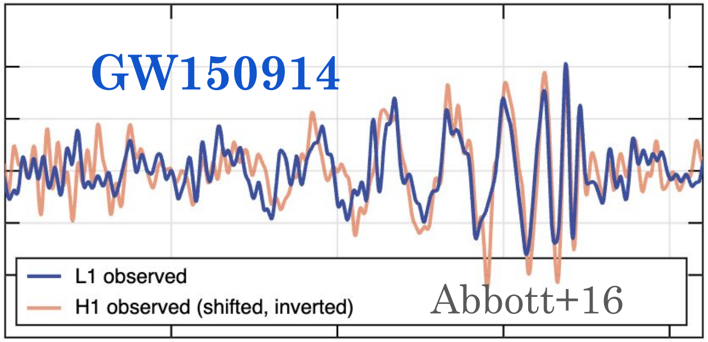
$\xrightarrow[\text{Transform}]{\text{Inverse}}$ h(t)



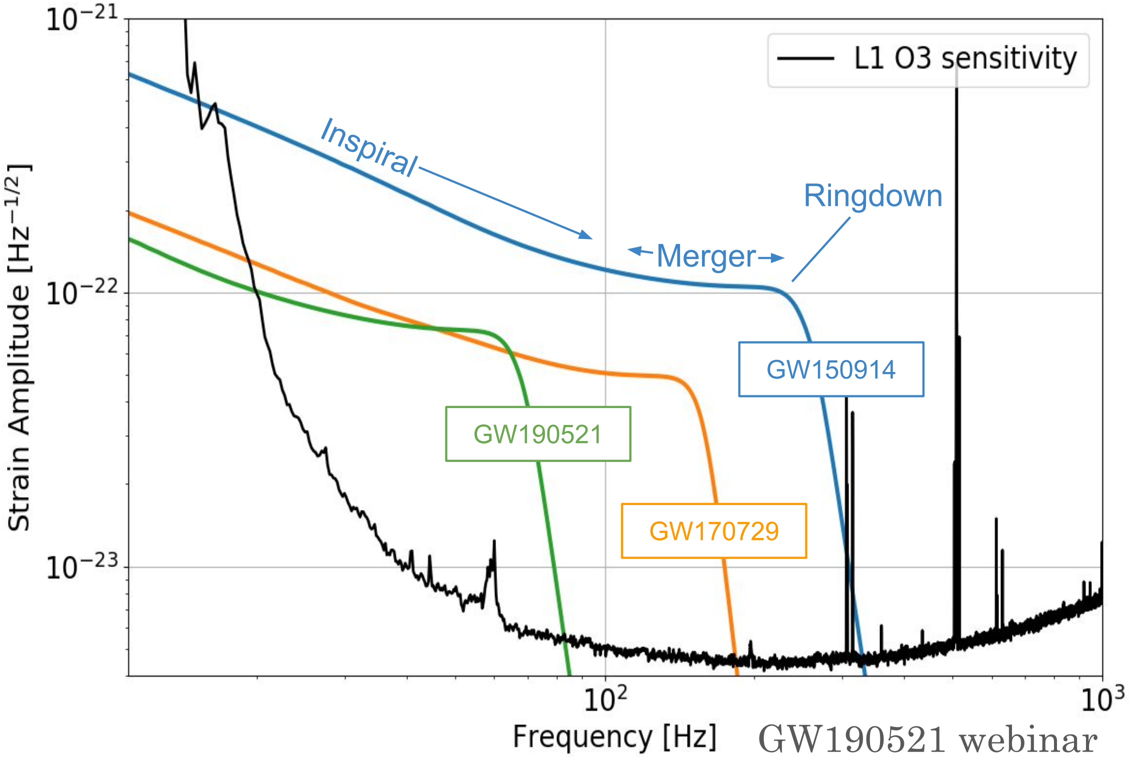
Frequency evolution of binary black holes

- Phases of inspiral:
  Inspiral, Merger, Ringdown
- The heavier binary the smaller peak frequency:

$$f_{peak} \propto 1/M_{tot}$$



Abbott+16



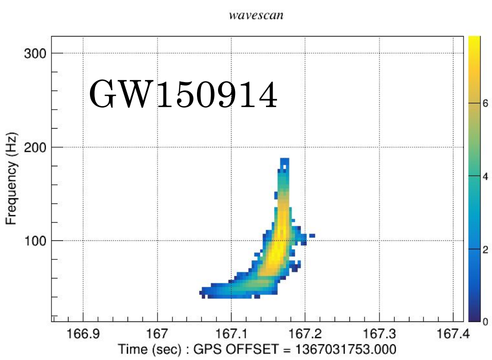
GW190521 webinar

Model-independent searches classification

Compact binary searches (minimally modeled)

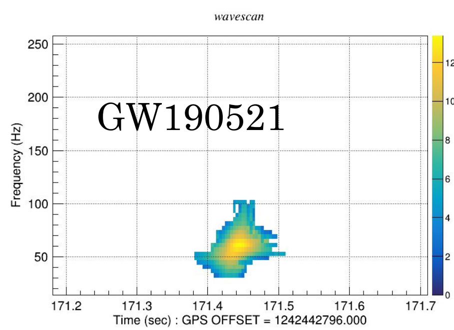
Generic searches (unmodeled)

Binary black holes
Binary neutron stars
Black hole - neutron star



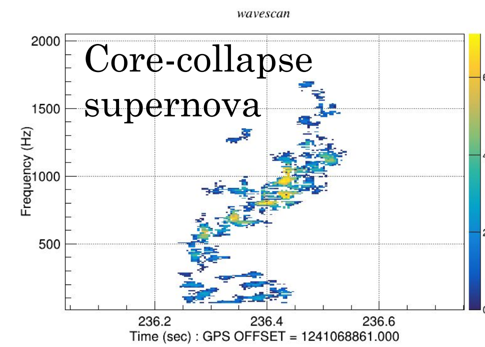
e.g. Mishra+23 (2201.01495)

Binaries with eccentric orbits
Intermediate-mass black holes
Hyperbolic encounters
Extreme mass-ratio



e.g. MS+21 (2009.11336)

Core-collapse supernovae
Pulsar glitches
Cosmic strings
Unknown



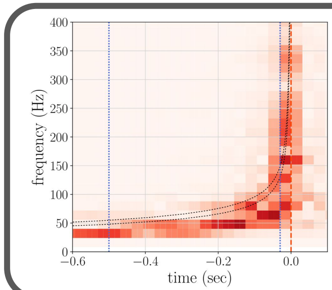
e.g. MS+24 (2305.16146)

Low-latency searches

Public alerts for multi-messenger observations: electromagnetic, cosmic rays, and neutrino

e.g. Chaudhary+24 (2308.04545)

Searches for new phenomena

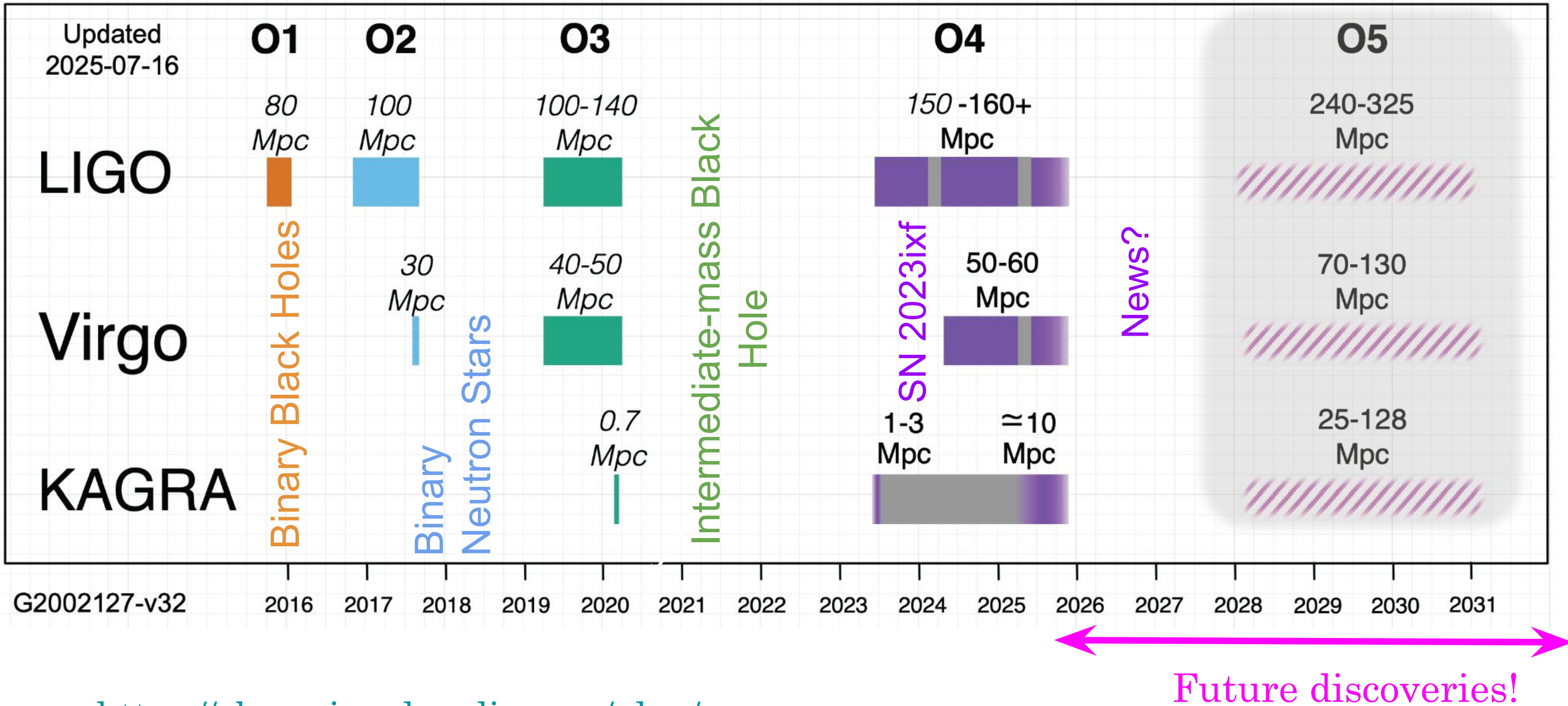


Higher harmonics
GW cross-polarization
Deviations from GR

e.g. Vedovato+22 (2108.13384)

Part II: Future (Next 10 Years and Beyond)

Observing Timeline



- https://observing.docs.ligo.org/plan/
- O4: 24 months total, until 18 Nov 2025
- LIGO: up to 180 Mpc, currently 160 Mpc
- Virgo: around 55 Mpc
- KAGRA: reached 7.5 Mpc, observed briefly

- Also: GEO600, a few Mpc
- LIGO-India - under construction
- Australian detector

Observing Run 4
(What we have discovered)

Observing Run 4

双黑洞

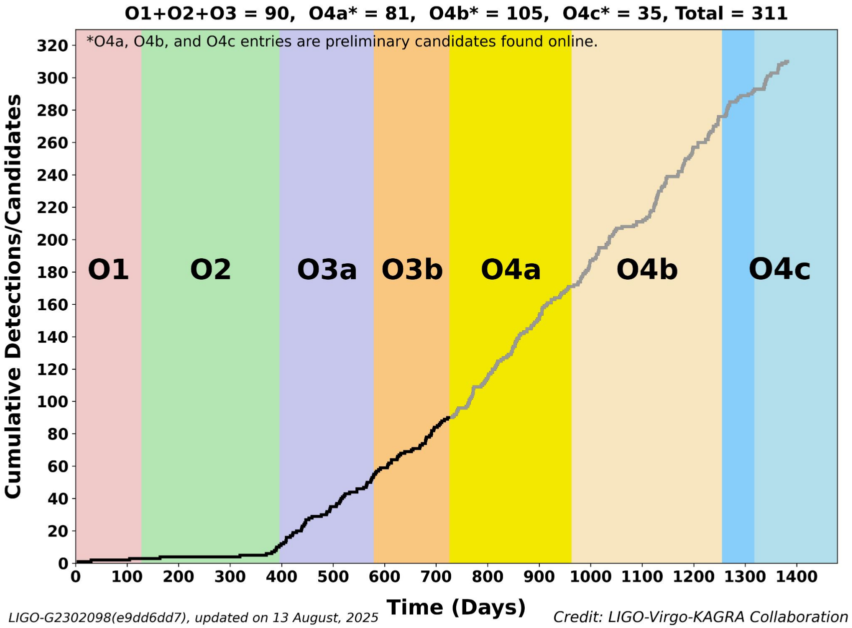
- Low-latency searches are crucial for astronomical observations, resources:
  - https://gracedb.ligo.org
  - https://emfollow.docs.ligo.org/userguide/
- Published results:
  - 21 papers and counting!
  - GWTC-4, O4a catalog (2508.18082)
    - Introduction (2508.18080)
    - Methods (2508.18081)
    - Populations (2508.18083)

GW candidates so far **(3 per week)**:

O4a: 128 GWs

O4b: 105 GW candidates

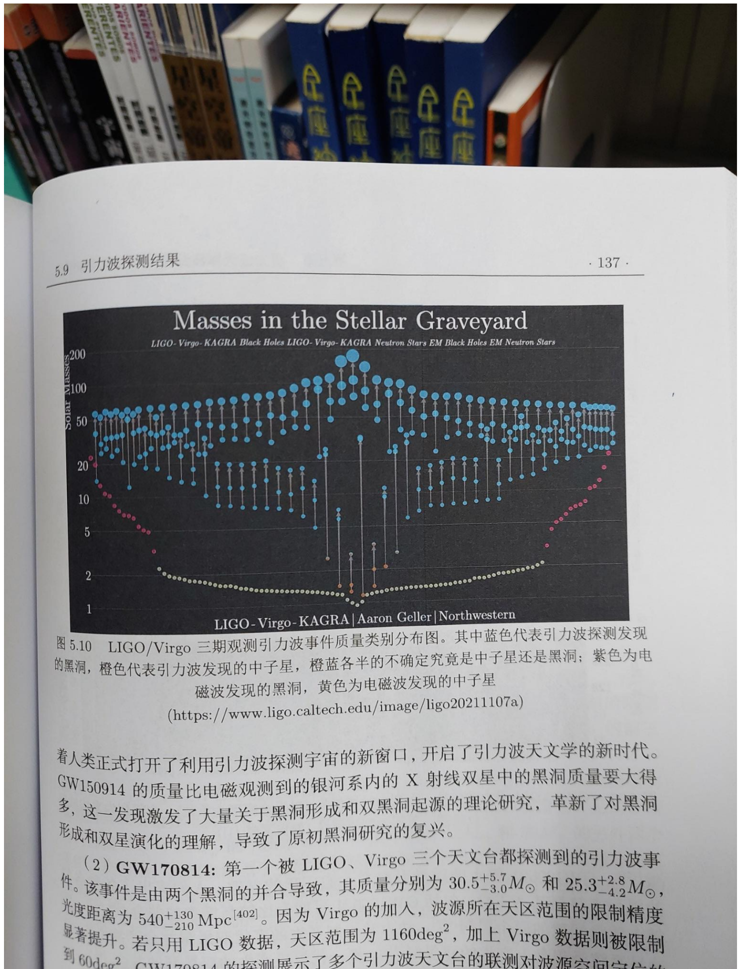
O4c: 61 GW candidates



Rapidly evolving field

GW Catalog:

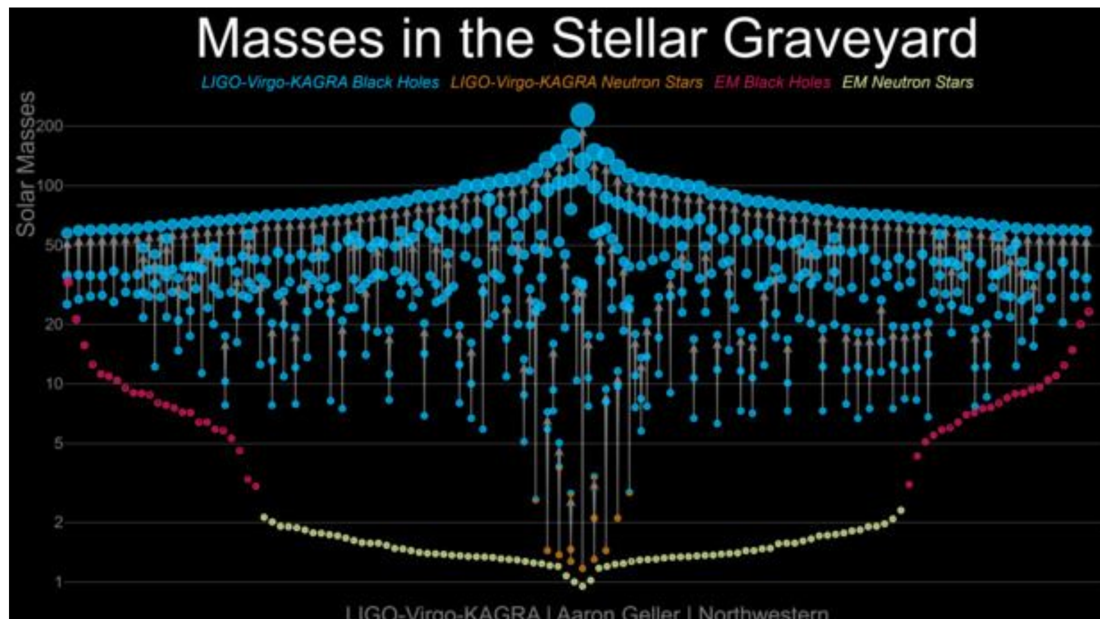
O1 + O2 + O3



Books are getting outdated quickly…

GW Catalog:

O1 + O2 + O3 + O4a



Latest News

- The field is evolving quickly, where to get the latest news summaries?
- All LVK papers: https://pnp.ligo.org/ppcomm/Papers.html
- Recommendation: Science Summaries

LIGO-Virgo-KAGRA Publications

The LIGO Scientific Collaboration and Virgo collaboration have been co-authoring observational result papers since 2010. Beginning in 2021, the KAGRA Collaboration too is co-authoring observational results from the full O3 run. See here for additional information.

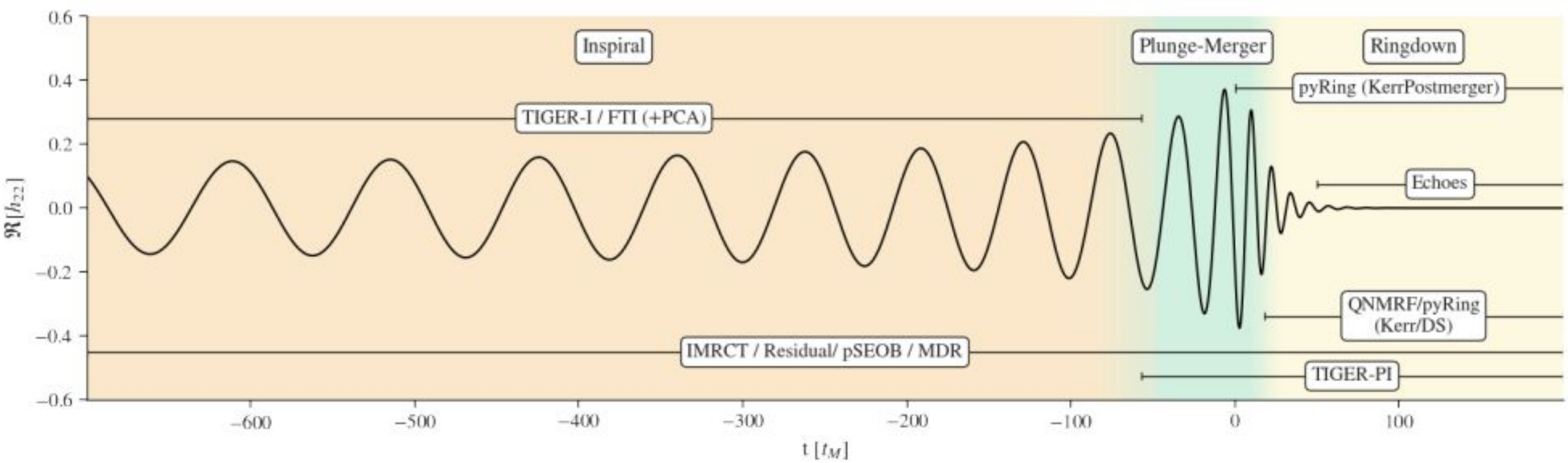
BibTeX file for these papers | Click to toggle doi information | Click on any keyword to filter on that keyword | Highlighting: Event discoveries | Multi-messenger

Release Date	Title	Keywords (clear filter)	Science Summary	Journal citation	arXiv Preprint	Public Report
Oct 28, 2025 *Recent*	**GW241011 and GW241110: Exploring Binary Formation and Fundamental Physics with Asymmetric, High-spin Black Hole Coalescences** *(by LSC, Virgo and KAGRA)*	O4 CBC LVK	summary	Astrophys. J. Lett. **993**, 21 (2025)	2510.26931	P2500402
Oct 20, 2025 *Recent*	**Directional search for persistent gravitational waves: Results from the first part of LIGO, Virgo, and KAGRA's fourth Observing Run** *(by LSC, Virgo and KAGRA)*	O4 Stochastic LVK	summary	*Submitted to PRD*	2510.17487	P2500380
Sep 10, 2025 *Recent*	**GW250114: Testing Hawking's area law and the Kerr nature of black holes** *(by LSC, Virgo and KAGRA)*	O4 CBC GW250114 LVK	summary	Phys. Rev. Lett. **135**, 111405 (2025)	2509.08054	P2500421
Sep 10, 2025 *Recent*	**Black Hole Spectroscopy and Tests of General Relativity with GW250114** *(by LSC, Virgo and KAGRA)*	O4 CBC GW250114 TGR LVK	summary	*Submitted to PRL*	2509.08099	P2500461
Sep 9, 2025 *Recent*	**GW230814: investigation of a loud gravitational-wave signal observed with a single detector** *(by A. G. Abac et al. (LSC, Virgo and KAGRA))*	O4 GW230814 LVK	summary	*Submitted to ApJL*	2509.07348	P230814
Sep 9, 2025 *Recent*	**Directed searches for gravitational waves from ultralight vector boson clouds around merger remnant and galactic black holes during the first part of the fourth LIGO-Virgo-KAGRA observing run** *(by LSC, Virgo and KAGRA)*	O4 CW LVK	summary	*Submitted to PRD*	2509.07352	P2500256
Sep 4, 2025 *Recent*	**GWTC-4.0: constraints on the cosmic expansion rate and modified gravitational-wave propagation** *(by LSC, Virgo and KAGRA)*	O4 CBC LVK	summary	*Submitted to ApJL*	2509.04348	P2400152
	Upper Limits on the Isotropic Gravitational-Wave Background from	O4				

Observing Run 4: GW230814

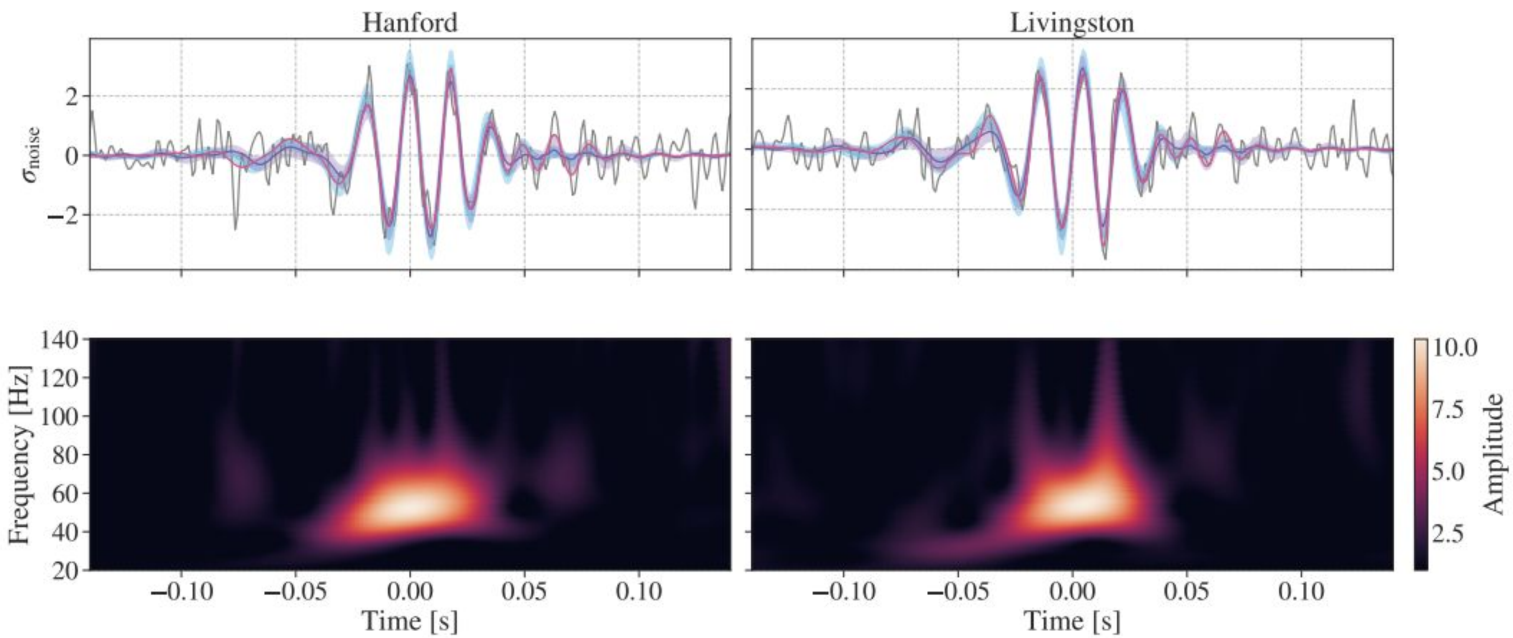
- GW230814: investigation of a loud gravitational-wave signal observed with a single detector
  - High signal-to-noise ratio of 42, single detector
  - New post-merger higher harmonic detected: (l,m,n) = (4,4,0)

$$h_+ - ih_\times = \sum_{\ell \geq 2} \sum_{-\ell \leq m \leq \ell} \frac{h_{\ell m}(t, \boldsymbol{\lambda})}{D_\mathrm{L}} {}_{-2}Y_{\ell m}(\theta, \phi)$$



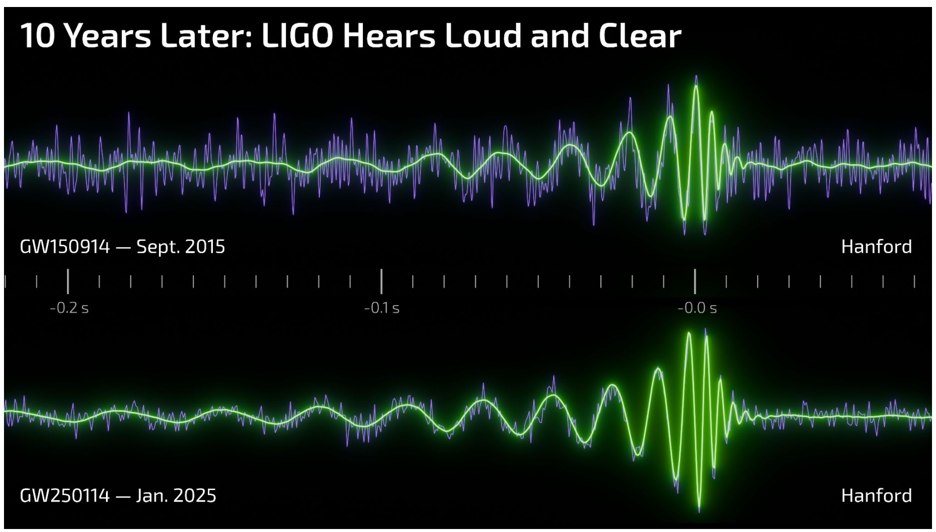
Observing Run 4: GW231123

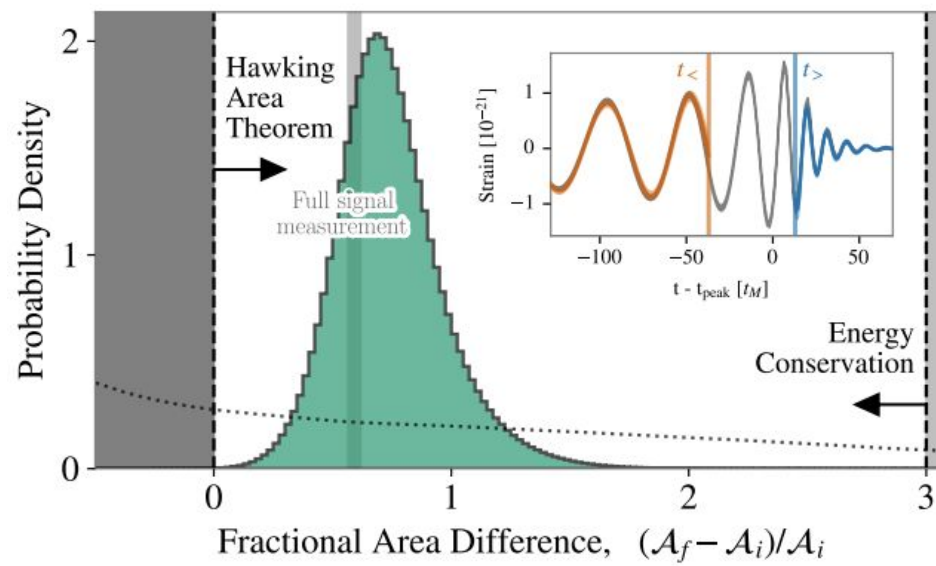
- GW231123: a Binary Black Hole Merger with Total Mass 190-265 M☉ ([2507.08219]())
  - The heaviest confident black hole detection
  - New post-merger higher harmonic detected: (2,2,1)



Observing Run 4: GW250114

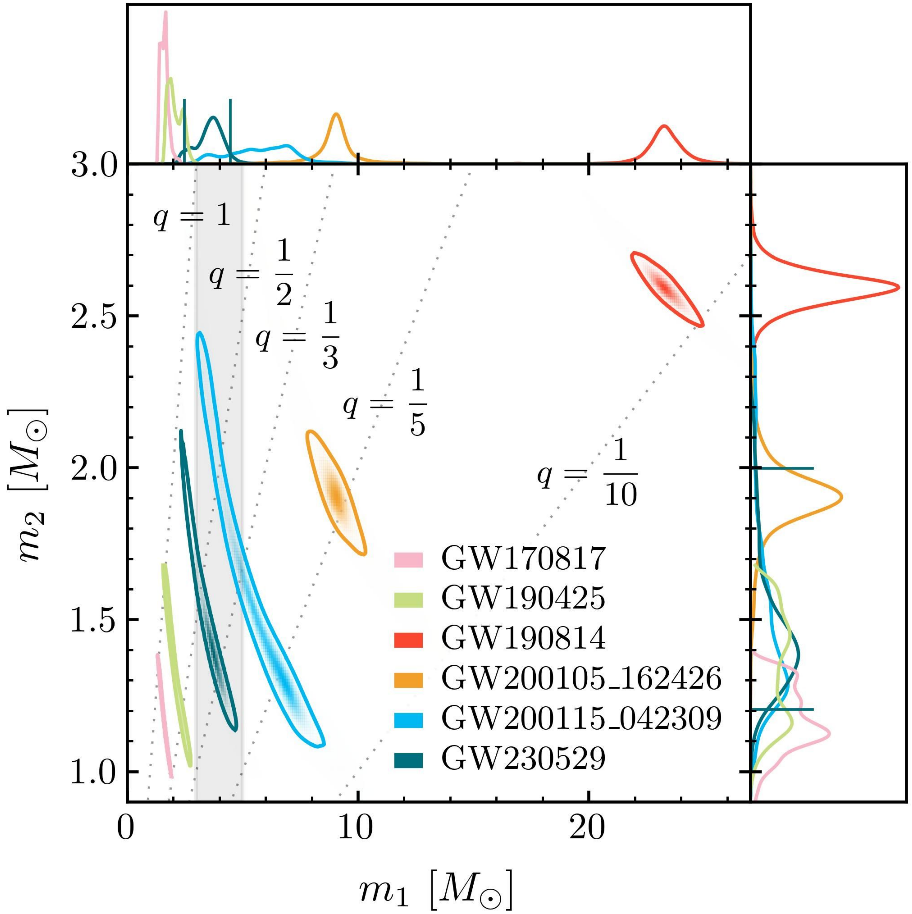
- GW250114: testing Hawking's area law and the Kerr nature of black holes
  - Highest so far signal-to-noise ratio of 80
  - Precise test on Hawking area theorem: an area of a black hole can only grow





Observing Run 4: GW230529

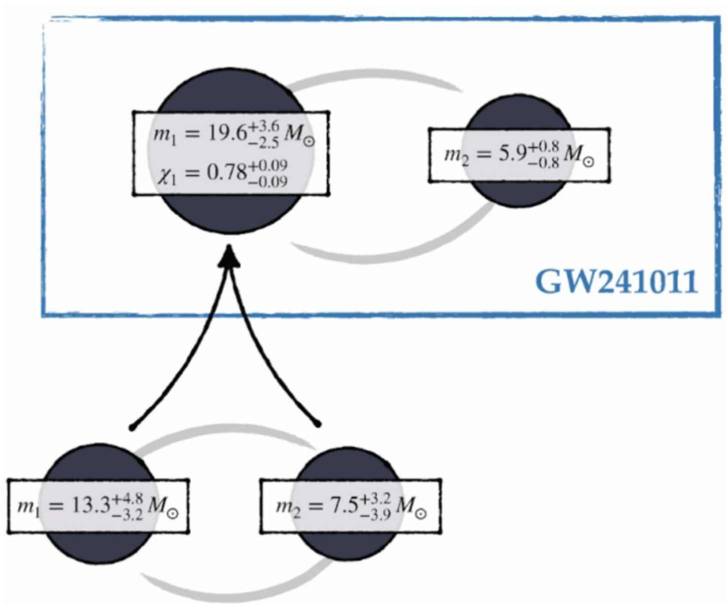
- GW230529: Observation of Gravitational Waves from the Coalescence of a 2.5-4.5 M☉ Compact Object and a Neutron Star
  - A light binary, in a lower mass gap
  - Neutron Star - Black Hole rate increases

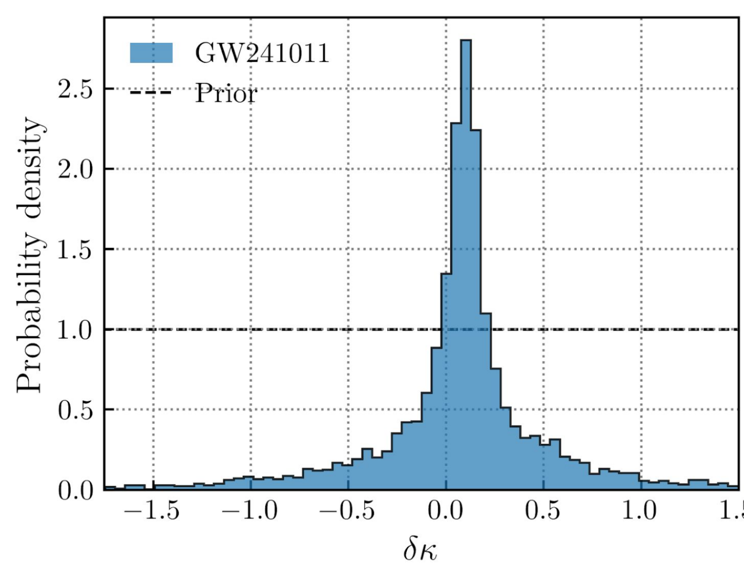


Observing Run 4: GW241011 and GW241110

- GW241011 and GW241110: Exploring Binary Formation and Fundamental Physics with Asymmetric, High-spin Black Hole Coalescences
  - Hierarchical mergers
  - Testing GR's spin-induced quadrupole moment: Einstein was right (again)

$$Q = -\kappa S^2/(mc^2)$$





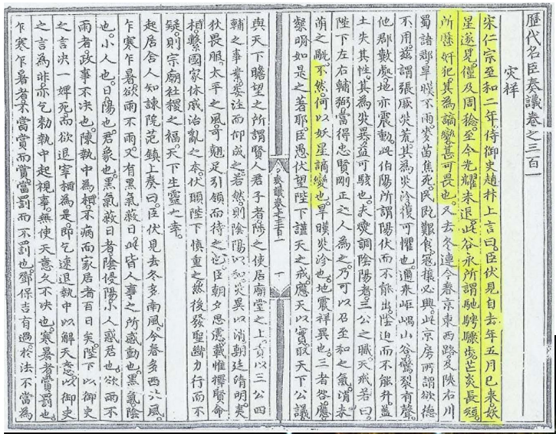
Future
(What we will, hopefully, discover)

What's next?
The next 10 years and Beyond

Special astrophysical sources might play an important role in our endeavor of exploring the Universe.

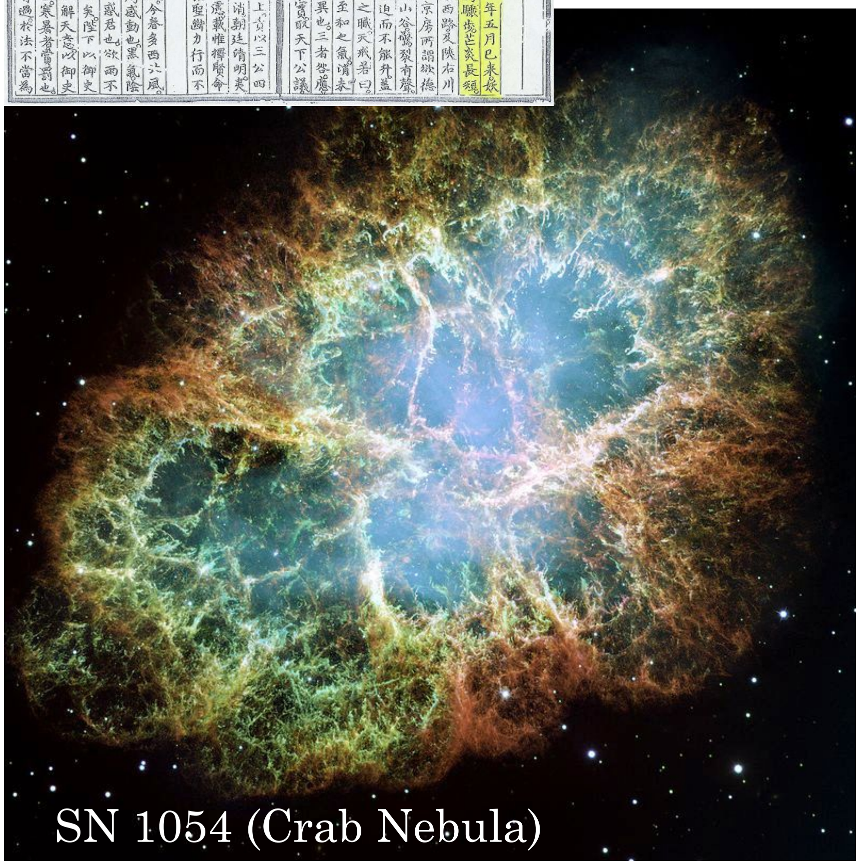
- **New GW source populations**:
  - Compact binaries: binaries with eccentric orbits, hyperbolic encounters, head-on collisions, extreme mass ratio, sub-solar mass binaries, lensed binaries
  - GW bursts: core-collapse supernovae, neutron star or pulsar glitches, cosmic strings
- **Multi-messenger GW sources (electromagnetic waves, neutrinos, cosmic rays)**: BNS, NSBH, BNS post-merger
- **GW sources with new phenomena (usually weaker effects)**:
  - GR: pre- and post-merger higher harmonics, GW cross-polarization, black hole kicks, GW memory, effects of precession, high spins, black hole formation
  - Beyond GR: GW echo, beyond-quadrupolar GW polarizations,

Core-Collapse Supernova (CCSN)



"Guest star"

Zhao Bian's memorial to Emperor Renzong

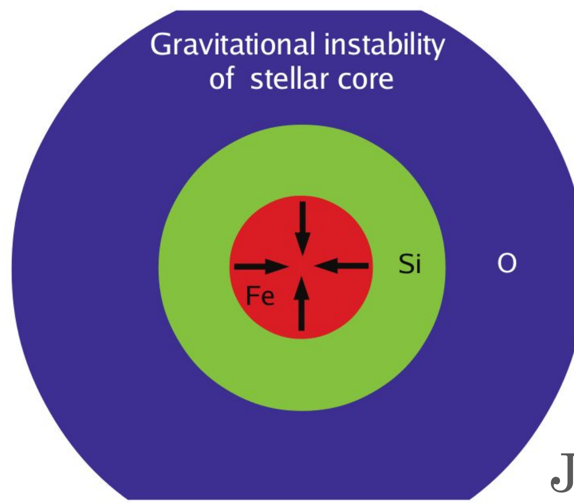


SN 1054 (Crab Nebula)

Nova on the sky!
1-2 per century in Milky Way (?)

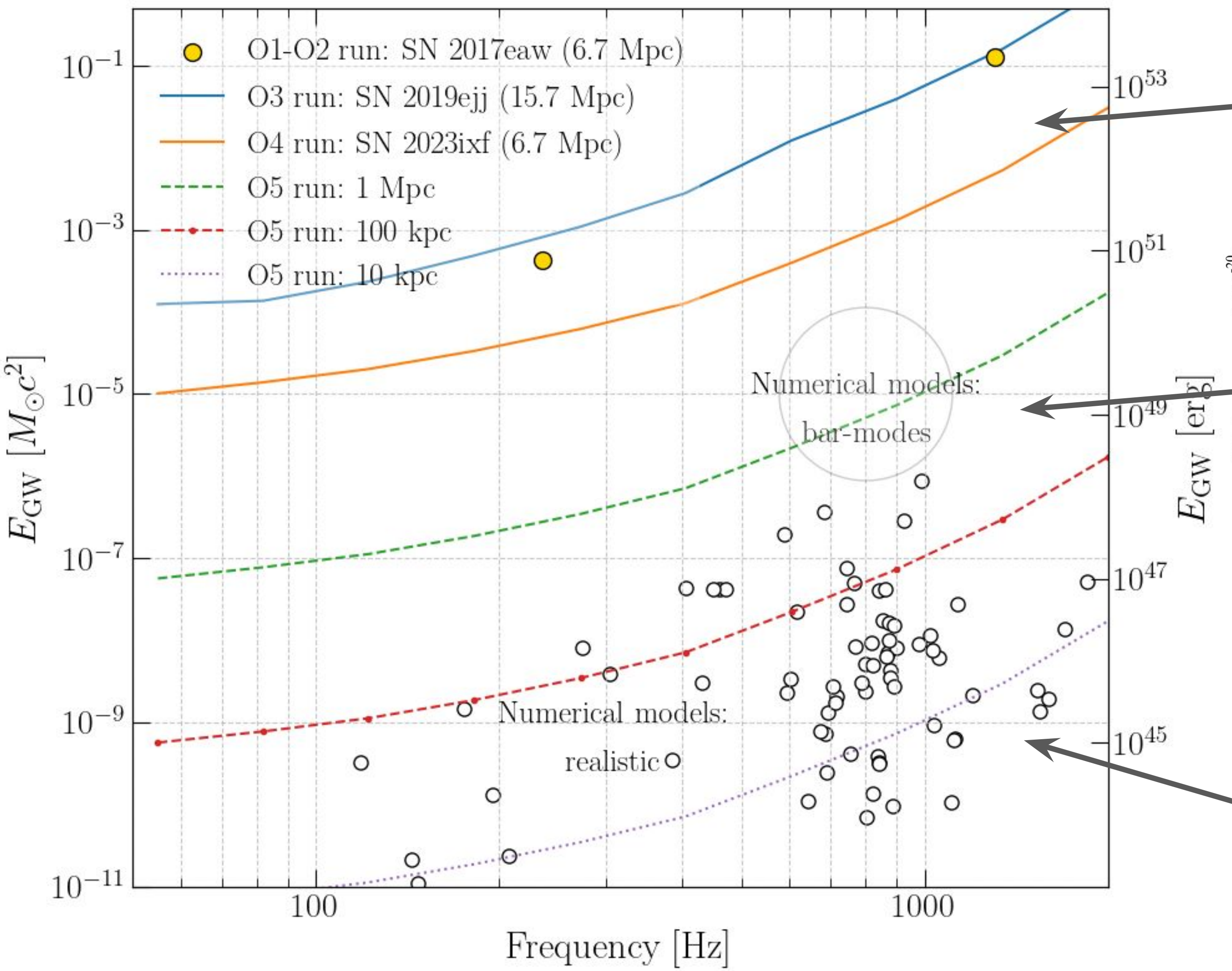
- Burning of a star: H → He → … → Fe
- After exceeding Chandrasekhar mass of 1.4 $M_{\odot}$ the iron core collapses.
- 99% of explosion energy escapes with neutrinos!

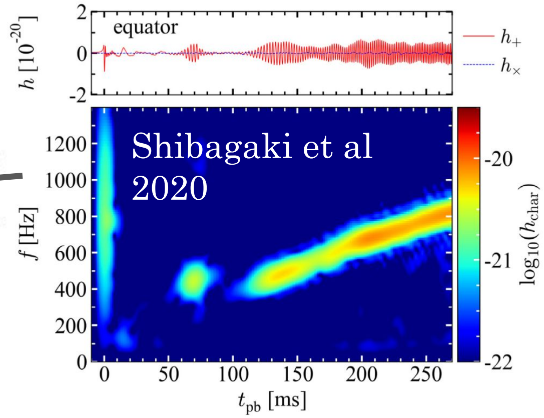
Explosion mechanism(s) is still unknown

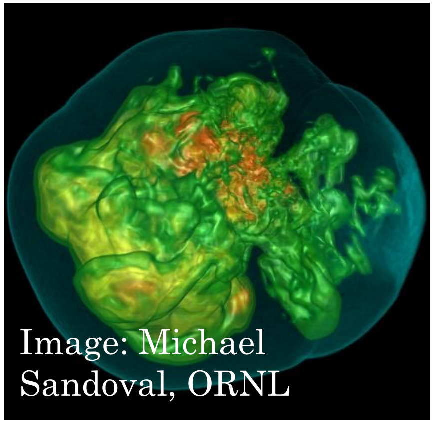


Janka+12

When will we discover GWs?
(realistically: Galactic CCSN)

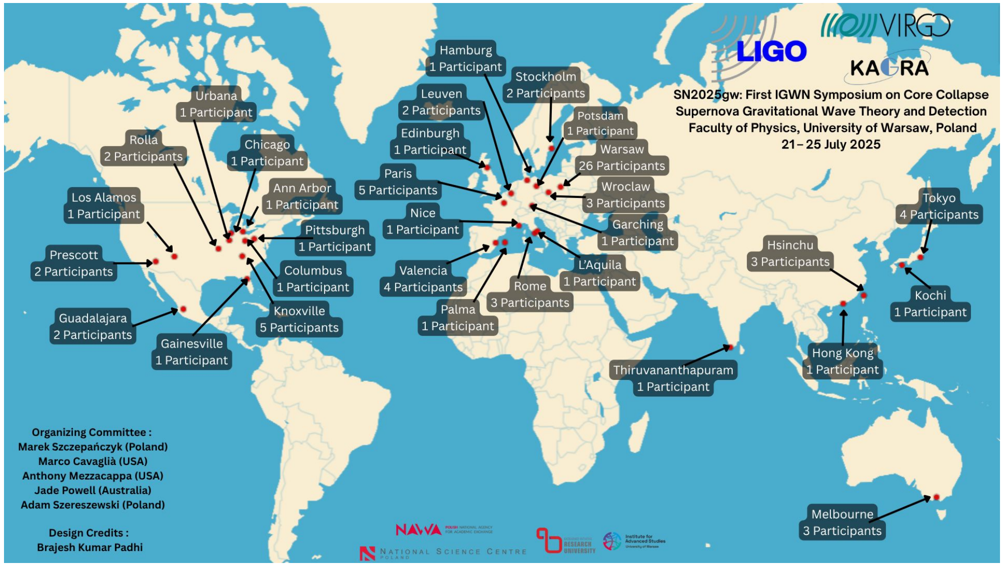






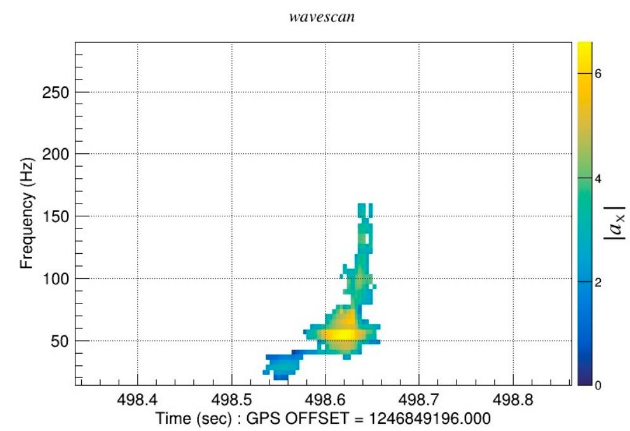
SN2025gw: IGWN Symposium on CCSNe

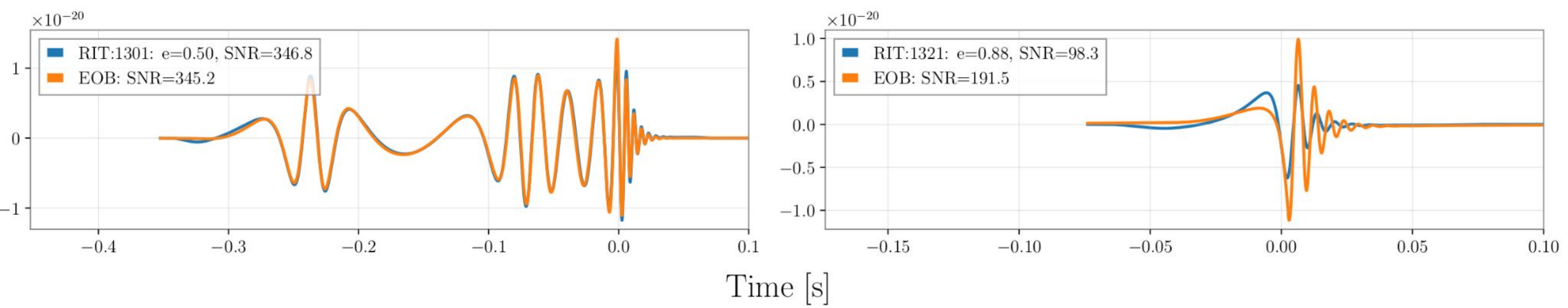
- IGWN - International Gravitational-Wave Network
- Symposium webpage: https://indico2.fuw.edu.pl/event/17/overview
- CCSNe are the most challenging astronomical events to model
  - Theory, Gravitational Wave Detection and Parameter Estimation, Neutrino Detection, CCSN across the Electromagnetic Spectrum, CCSNe over the Next Ten Years
- Youtube: playlist
- Classical and Quantum Gravity focus issue proceedings and White Paper (in progress): https://iopscience.iop.org/collections/cqg-250513-841
- Large attendance of the Symposium: **Galactic CCSN - the next big thing?**



Eccentric binaries

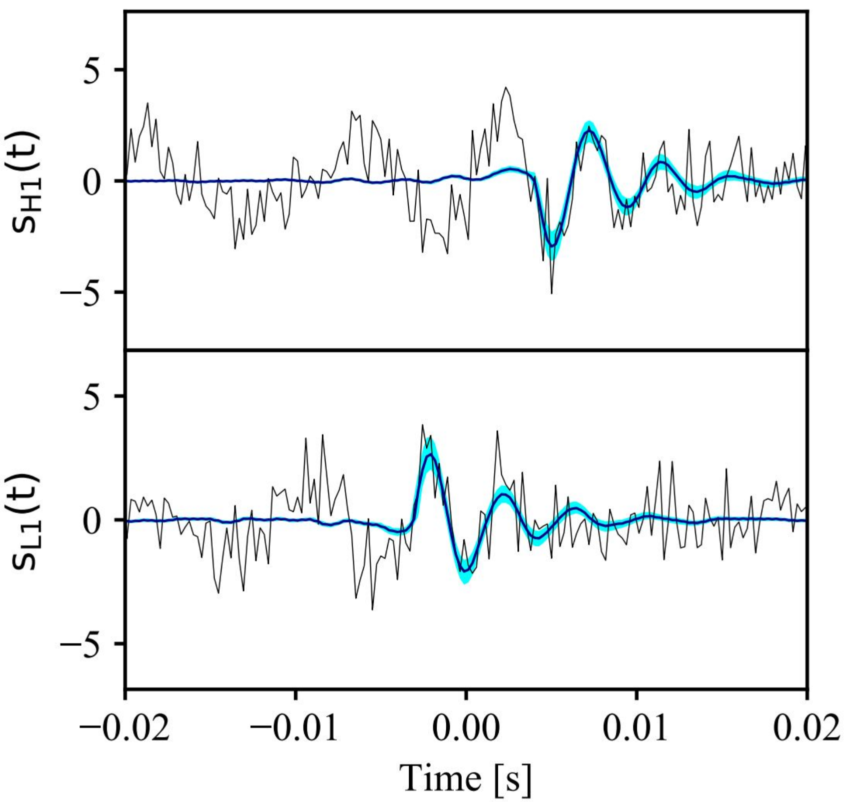
- **Eccentric binaries**: compact binaries elliptical orbits.
    - Dynamical formation
- Bhaumik et al (MS) 2024 (2410.15192)
    - Comparison between waveform models
    - Sensitivity studies and recommendations
- Mishra et al (MS) 2024 (2410.15191)
    - O3 data reanalysis
    - 3 new GWs: consistent with stellar BHs, one event has large mass-ratio (possible dynamic formation)





Black Hole Spectroscopy

- Black holes are very simple objects! According to the no-hair theorem black hole geometry depends only on:
  - mass, spin, electric charge
- Black hole spectroscopy: measuring black hole oscillations
- **Quasi-normal modes (QNM)** - dumped perturbations of BH resonances.
  - Intuitively: waves traveling around BH.
  - Precise measurements of the BH mass and spin and testing GR.
- **Systematically we will be discovering more higher harmonics**

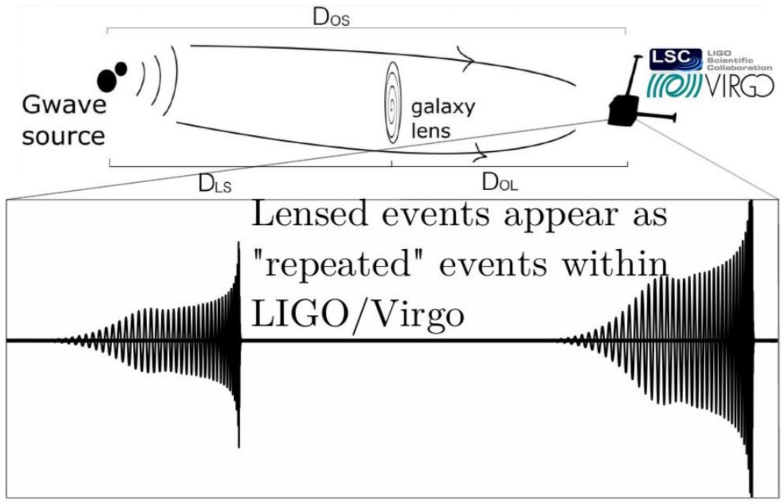


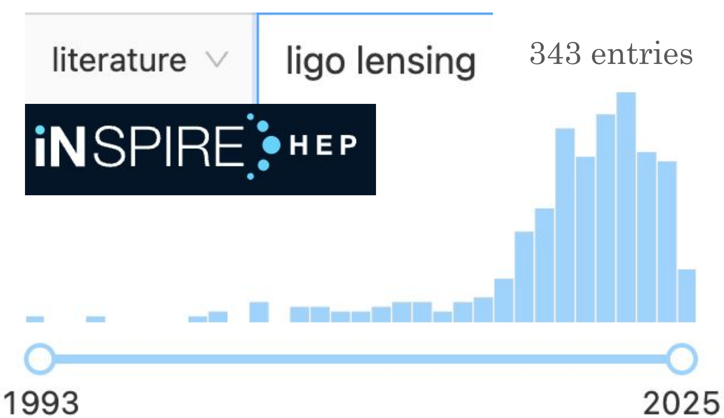
Carullo et al 2019

$$h_+ - ih_\times = \sum_{\ell \geq 2} \sum_{-\ell \leq m \leq \ell} \frac{h_{\ell m}(t, \lambda)}{D_\mathrm{L}} {}_{-2}Y_{\ell m}(\theta, \phi)$$

GW lensing

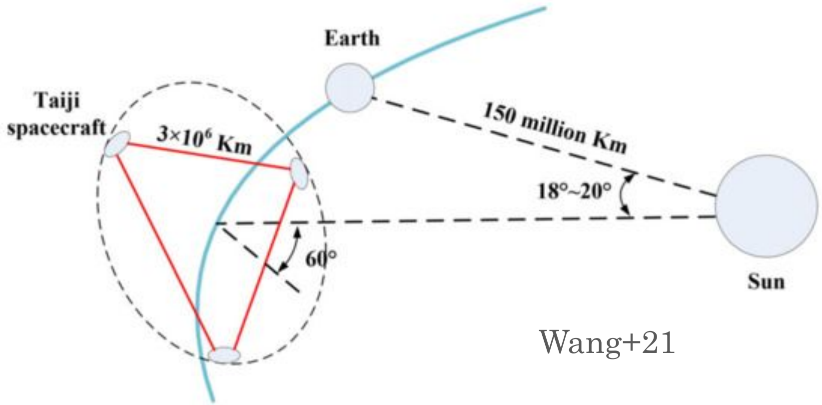
- GW lensing: bending of GW propagation path near a massive object
- **Potential next GW discovery (even in the next couple of years)**
- Comparison with electromagnetic wave lensing:
  - Similar to light, GWs can be gravitationally lensed
  - But, very different methodology and science case
- New studies of astrophysics, cosmology and fundamental physics.
- GW lensing: magnification, multiple images, frequency-dependent deformation
- Growing interest in GW lensing



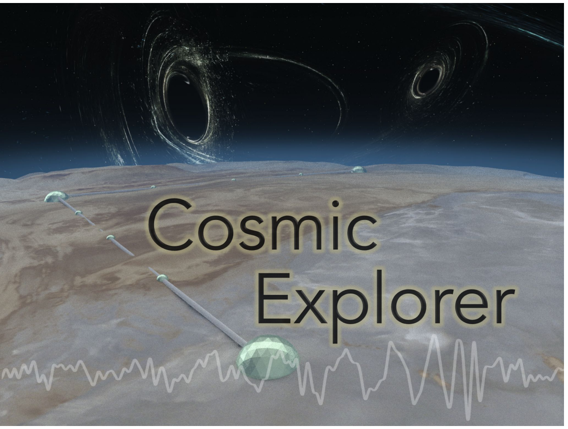


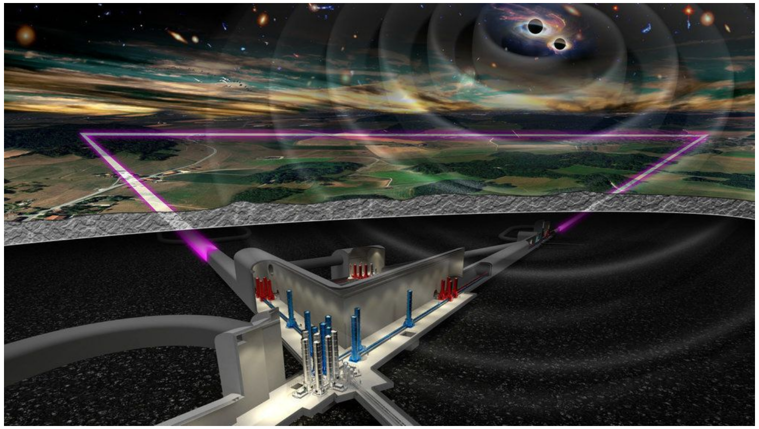
The future of observations

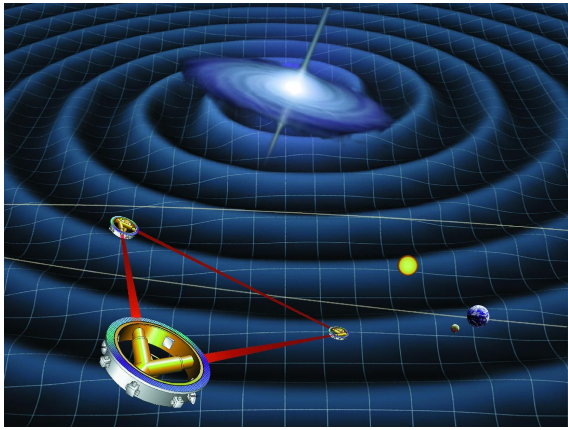
- The third generation (3G) detectors will be 10x more sensitive: thousands of detections!
  - Cosmic Explorer (US)
  - Einstein Telescope (Europe)
- LISA and Taiji: space-based detector



Wang+21

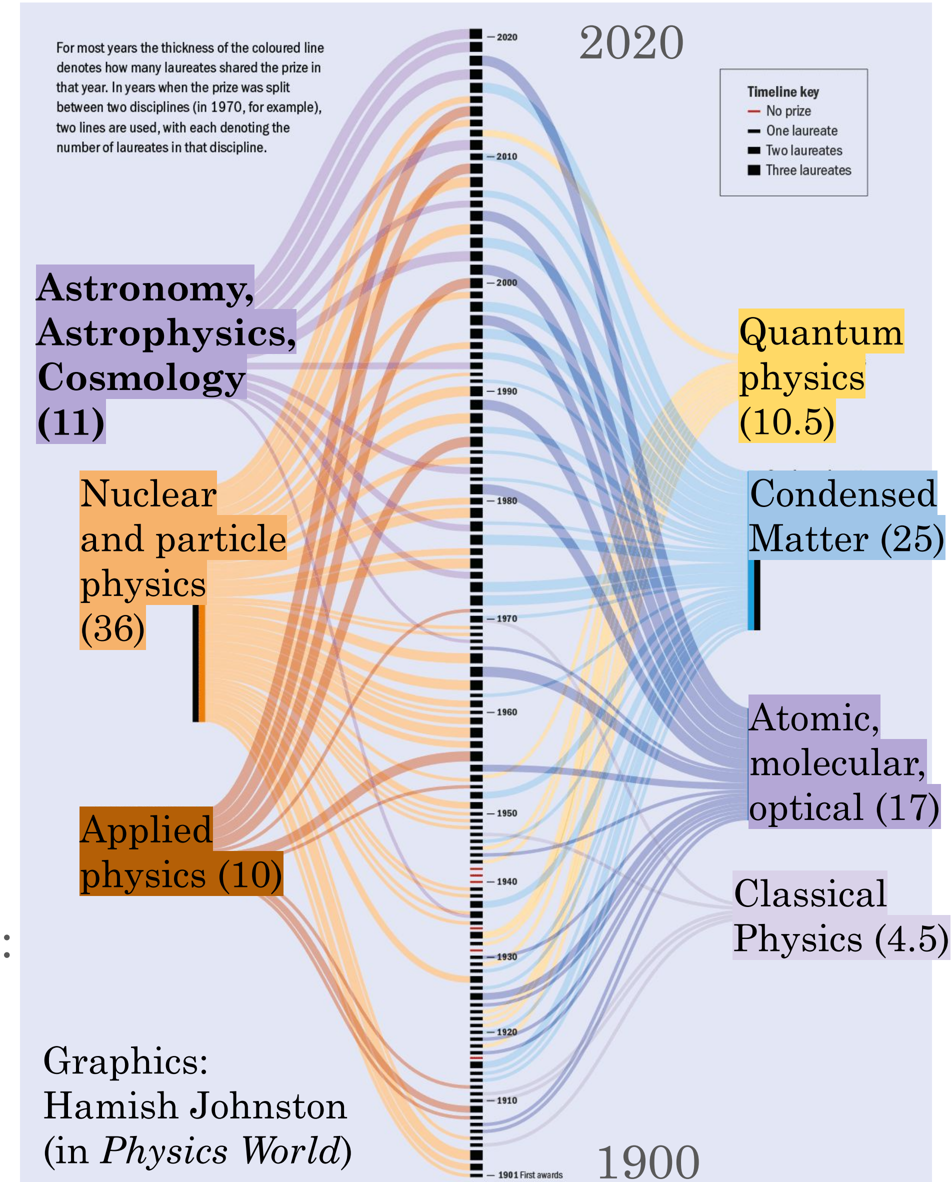






Extraordinary period of discovery in Astrophysics
(It's worth looking at the sky)

- **The role of Astronomy, Astrophysics & Cosmology in discovery has grown greatly in the recent years.**
- Since 1900: around 15 Nobel Prizes
- Last decade: 7 Nobel Prizes
    - 4 are directly linked to General Relativity (2017: gravitational waves, 2019: theoretical cosmology, 2020: supermassive BH, 2020: BHs are consequence of GR)
    - 3 use astronomical data (2011: expansion of the Universe, 2015: neutrino oscillations, 2019: exoplanets)



Summary

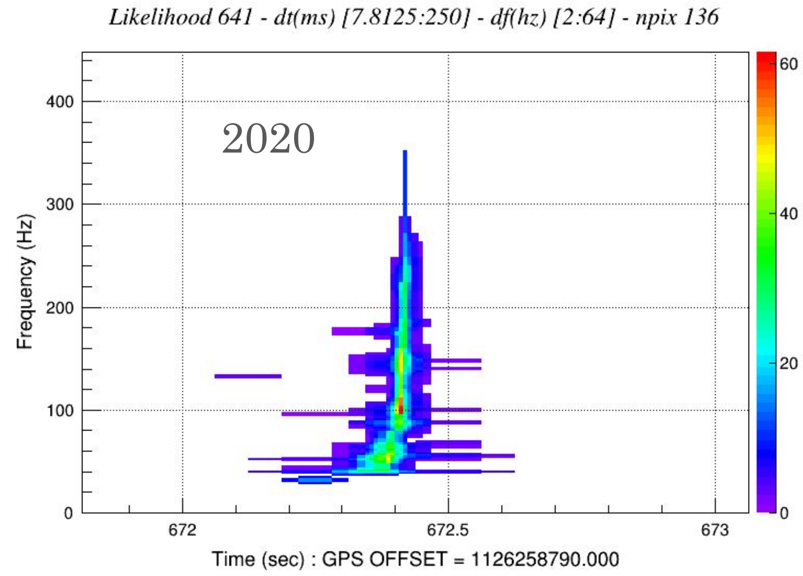
引力波：黄金時代
(gravitational waves: golden age)

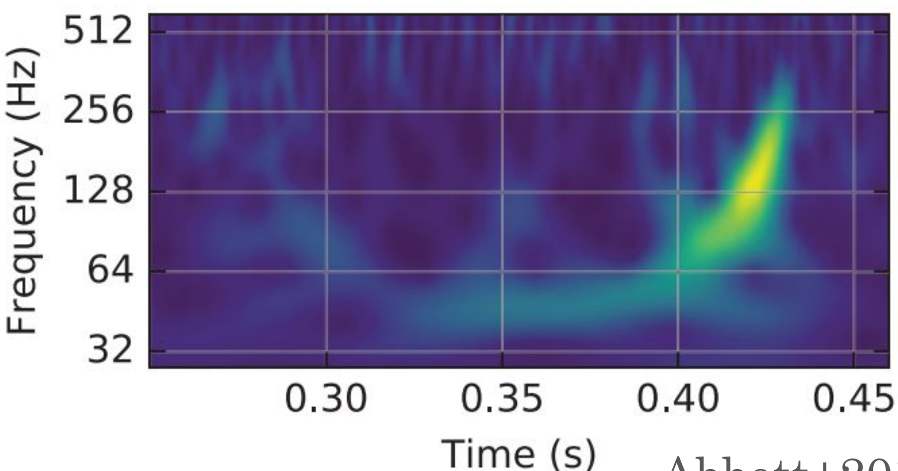
- Part I: Basics
  - GW observations
  - Model-independent methods are suitable for discoveries
- Part II: Future
  - O4: ~400 GWs and GW candidates,
    several high profile results
  - Much is still waiting to be discovered
  - Future discoveries: core-collapse supernova,
  - Future is “loud”!
- Slides: fuw.edu.pl/~mszczepanczyk/news.html

Extras

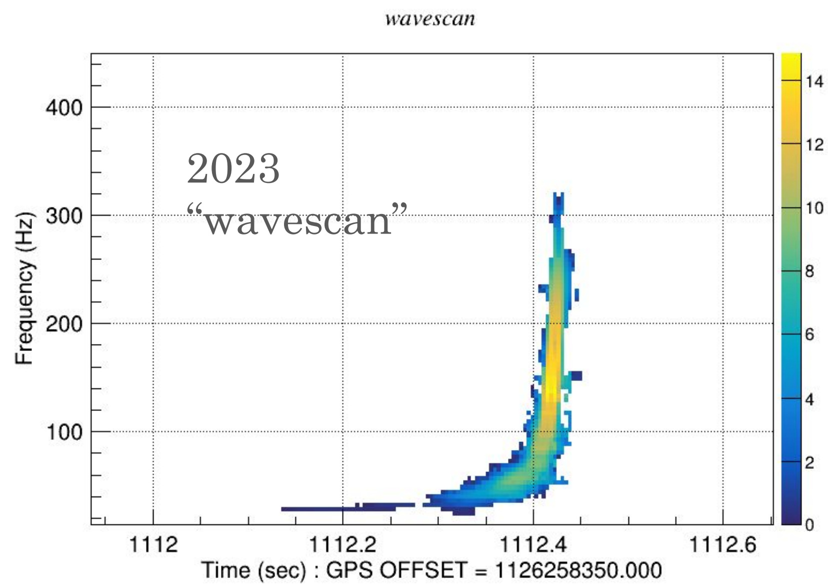
Time-frequency maps (GW150914 example)

- Challenges:
    - Temporal leakage (time domain)
    - Spectral leakage (frequency domain)
    - Combining resolutions
- Latest developments on high-resolution time-frequency transform and minimizing leakage:
  Klimenko+22 “wavescan” ([2201.01096](2201.01096))





Abbott+2016



Astronomy and Astrophysics for the 2020s

Astronomy and Astrophysics for the 2020s is a Decadal Survey by the American National Science Foundation.

New Messengers and New Physics:
most energetic processes in the Universe, nature of dark matter, dark energy, and cosmological inflation.

Worlds and Suns in Context:
exoplanets and stars, their formation, evolution, characterize other solar systems, potentially habitable analogs to our own.

Cosmic Ecosystems:
link observations and modeling of the stars, galaxies, and the gas and energetic processes that couple their formation, evolution.

Priority Area: “New Windows on the Dynamic Universe”

Priority Area: “Pathways to Habitable Worlds”

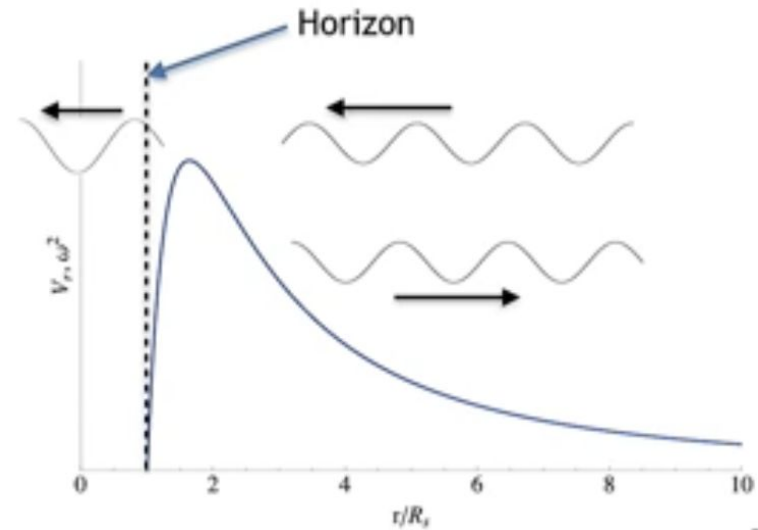
Priority Area: “Unveiling the Drivers of Galaxy Growth”

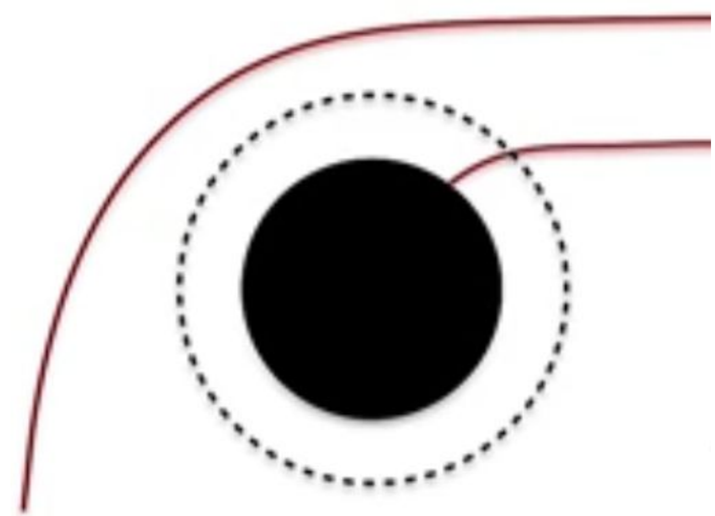
Black Hole spectroscopy

- BH perturbation theory predicts the BH resonances, quasi-normal modes (QNM), intuition:
  - waves traveling around the BH (similarly to Earth's free modes of oscillation, Berti+09)
  - light rays scattered (like in quantum mechanics) around BH spacetime potential and slowly leaking out (Goebel+72)
- The same equations need to be solved as for hydrogen atom in quantum mechanics. Scalar wave equation in Schwarzild:

$$\Box_g \psi = 0$$

- **Future strong GW detections will allow measuring BH oscillations**

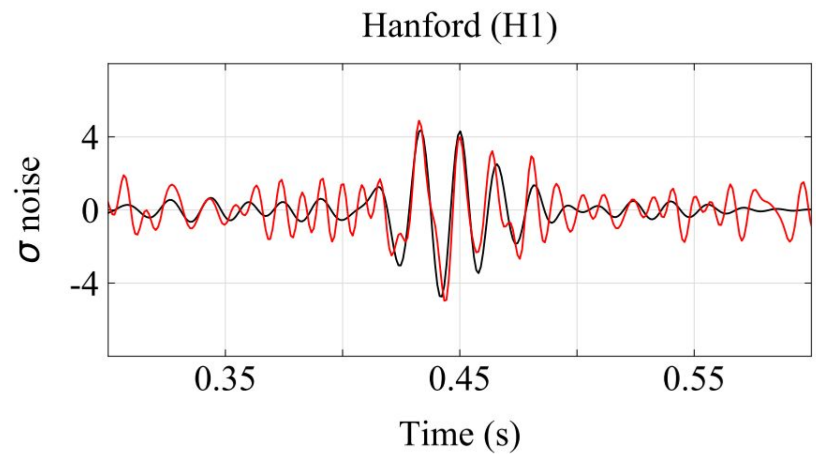


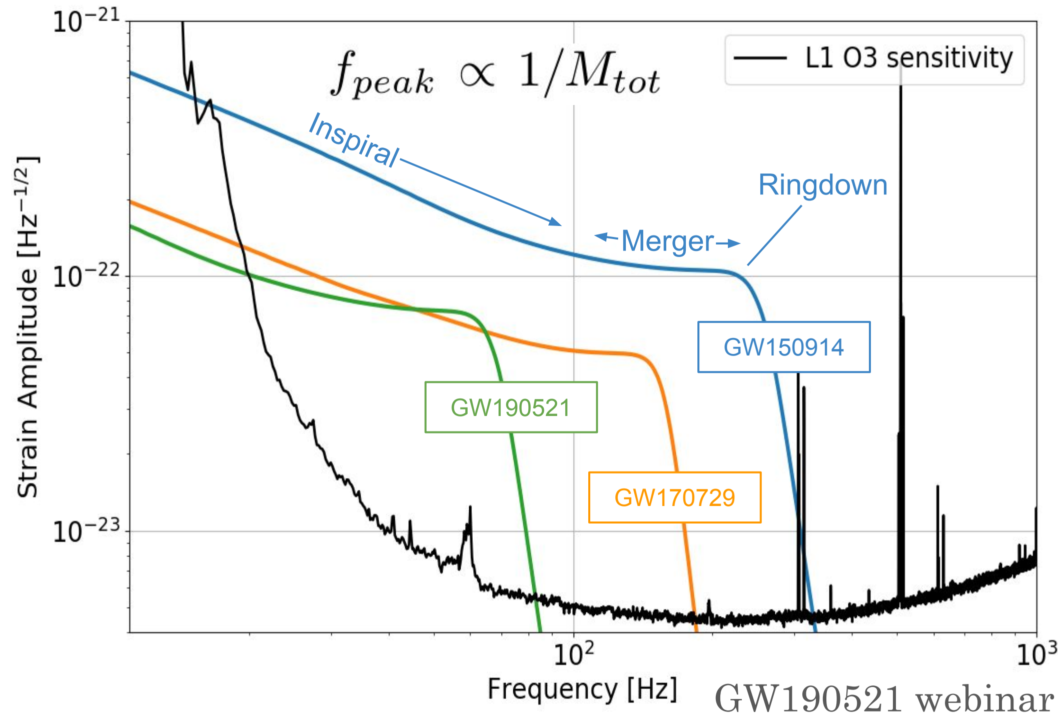


Figures: A. Zimmerman

GW190521

- Intermediate-mass black holes (IMBHs) - between stellar mass (100 $M_\odot$) and supermassive (10^5 $M_\odot$). The origin is not yet well understood.
  - Probing pair-instability mass gap (Stars with He mass in (64 $M_\odot$, 135 $M_\odot$)
  - Formation channels
  - Most distant GW sources
- GW190521 - first conclusive evidence of an IMBH.
- No chirping structure
- Detection significance (see MS+21, [2009.11336](2009.11336)):
  - Online: 1 per 28 years
  - Offline: 1 per 4900 years (established by cWB)
  - Challenges: scatter noise, blips

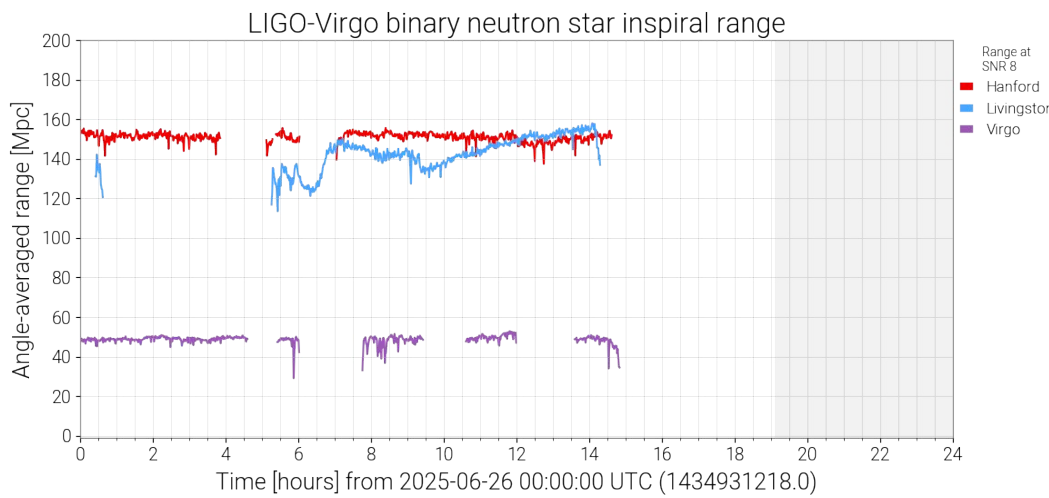


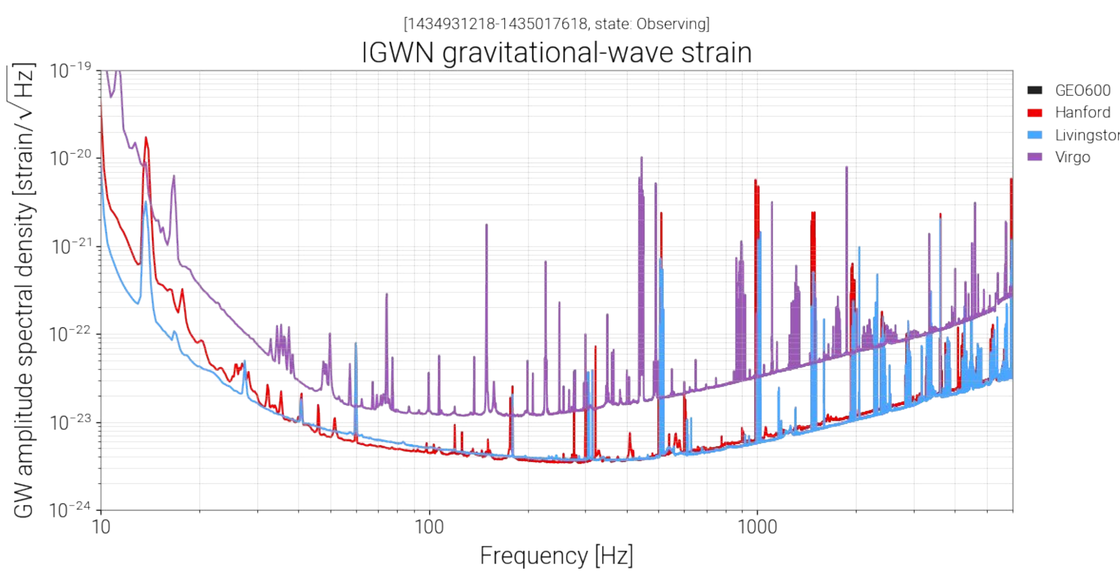


GW190521 webinar

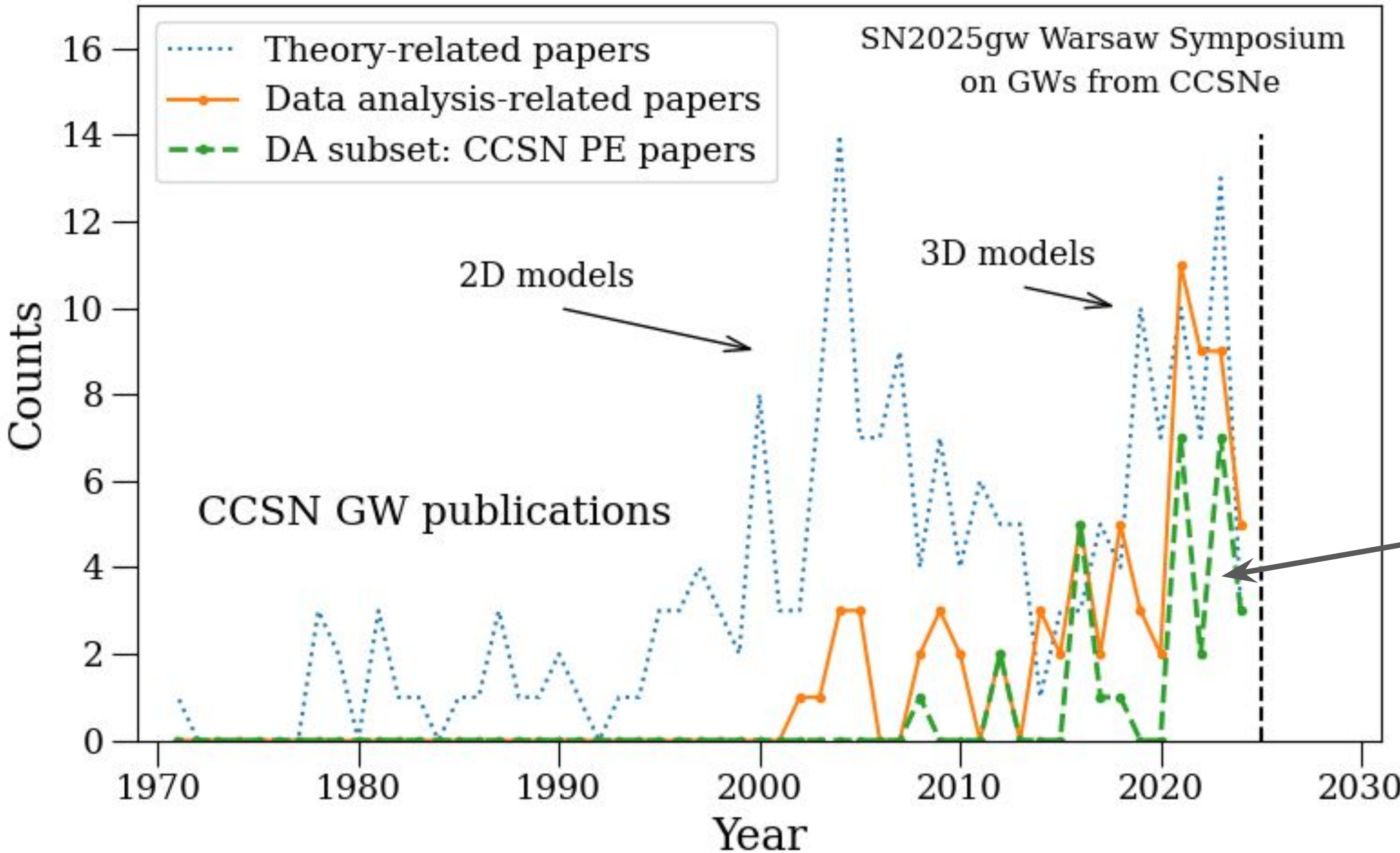
Observing Run 4

- Live detector status: https://online.igwn.org/
- Daily detector status: https://gwosc.org/detector_status/
- Public data release is 18 months after data collection





SN2025gw: IGWN Symposium on CCSNe FUW contribution



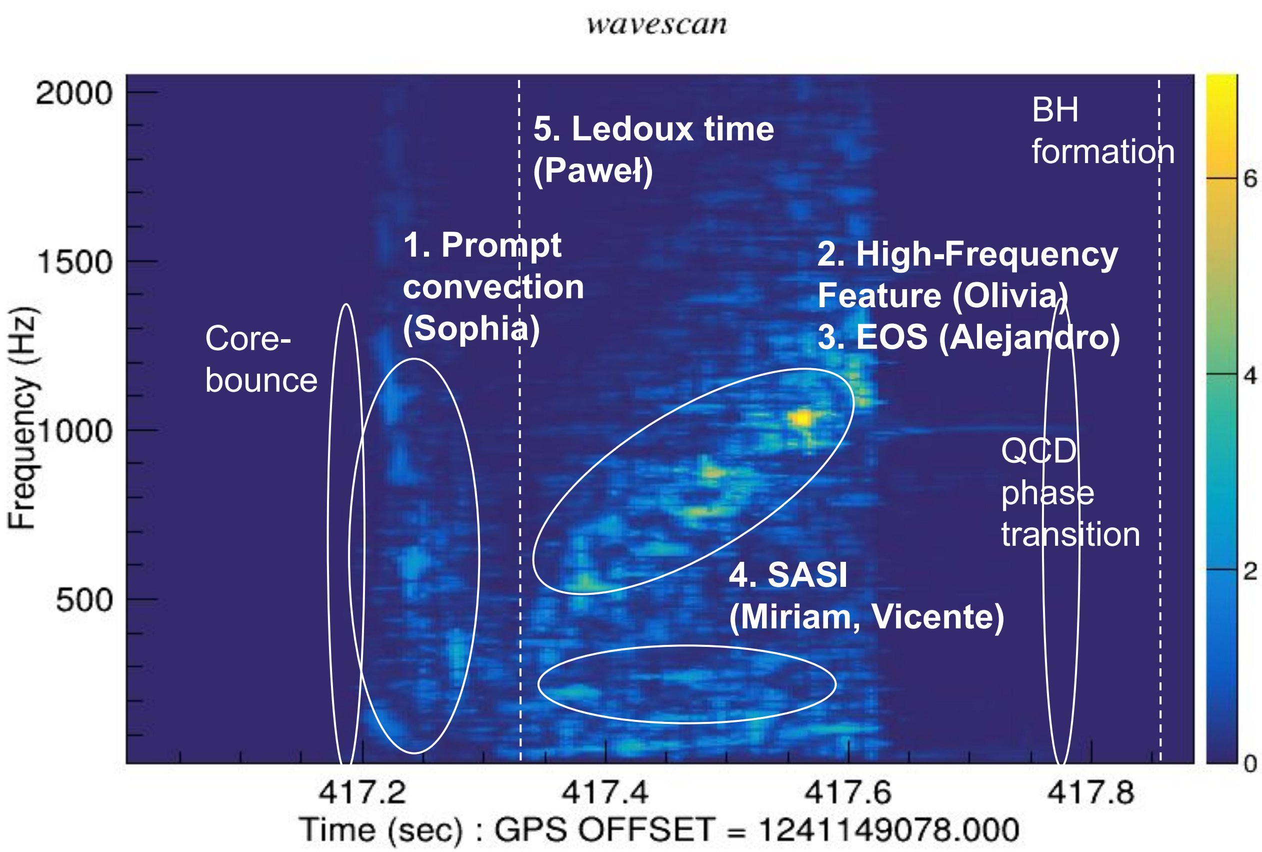
Approach:

take existing methods and implement them in low-latency

CCSN GW Literature, by Ewald Mueller:

https://wwwmpa.mpa-garching.mpg.de/rel_hydro/GWlit_catalog.shtml

SN2025gw: IGWN Symposium on CCSNe FUW contribution



6. Emission Regions (Brajesh)
7. GW energy (Sreeta)
8. Source Orientation (Pratul)
9. CCSN Sound (Jan)
10. GW Representation (Stanisław)

Sound of gravitational waves from CCSNe:
https://www.fuw.edu.pl/~mszczepanczyk/gwsound.html

SN2025gw: IGWN Symposium on CCSNe

Some lessons learned (work in progress on a White Paper):

- **A multimessenger (GW+nu+EM) detection program** for CCSNe is underway. Detailed discussion/decisions needed on the conditions for declaring a detection with a CCSN candidate (statistical significance, morphological constraints).
- **A multimessenger (GW+nu+EM) parameter estimation program** for CCSNe is underway. More areas can be expanded further like multi feature. There are indications that GW memory could be detected as well (thanks also to current hardware improvements).
- **The interaction between EM, nu and GW communities could be improved**, for example what will we do explicitly if we have a Galactic CCSNe?
- While there is a consensus on predicted GWs, it is still not known what waveform amplitudes we may expect.
- Many uncertainties (**progenitor structure**...) and hidden assumptions (**transport treatment**...) are baked into the multi-physics supernova problem.
- Important to consider how supernova modelling needs to **evolve technically and organisationally** to make further progress and aid gravitational wave and multi-messenger astronomy.