The quest to detect gravitational-waves sources with ground-based detectors

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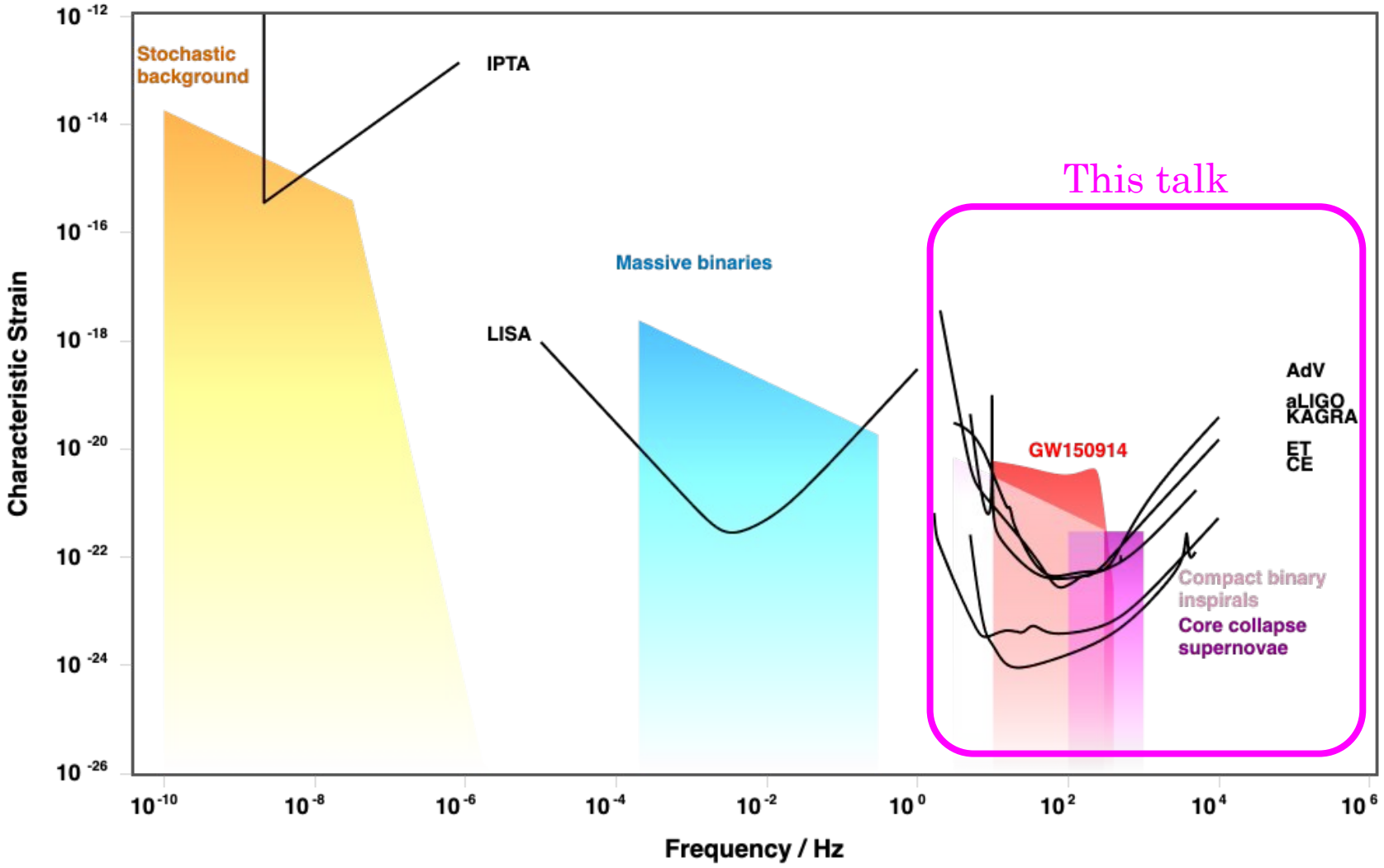
Gravitational Wave Probes of Physics Beyond Standard Model 4
Warsaw, 23-27.06.2025

GW Spectrum



http://gwplotter.com/

Outline

- Gravitational-Wave Observations
- Model-independent searches
  - Exceptional GW sources
- Core-Collapse Supernova
  - Properties, predictions
  - LVK Symposium announcement

Gravitational-Wave Observations

The Dynamic 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.

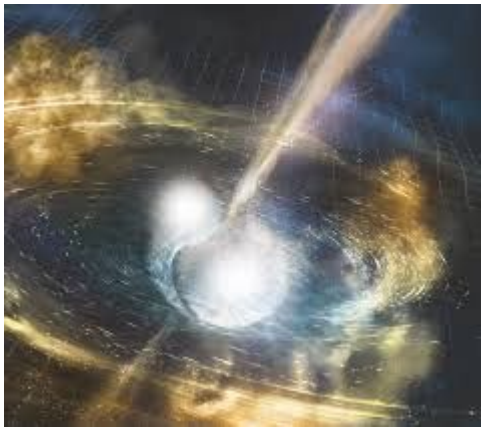
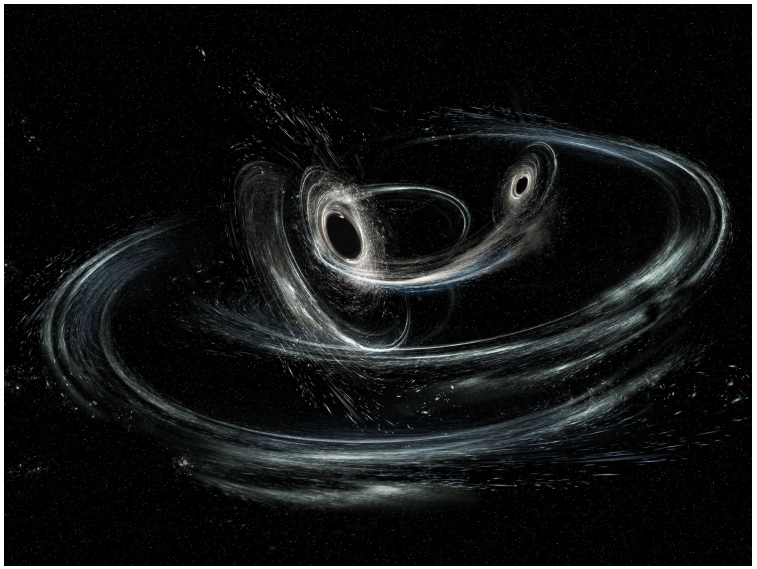


Image: NSF/LIGO/Sonoma/A. Simonnet

GW sources:

- Standard, e.g. stellar-mass binary black holes
- **Special, e. g. cosmic strings, primordial BHs, microlensing effects**



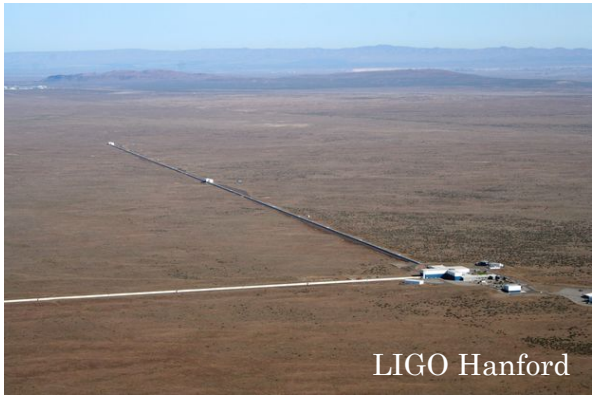
AURORE SIMONNET/LIGO/CALTECH/MIT/SONOMA STATE

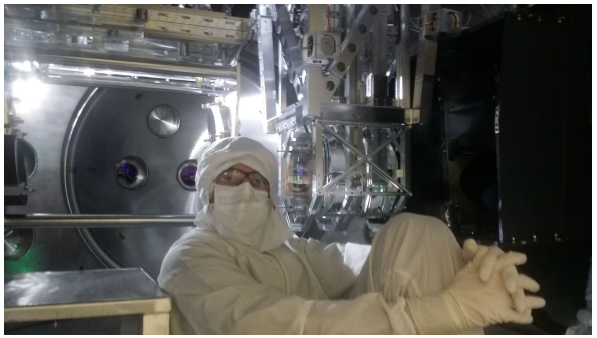
Gravitational-Wave detectors

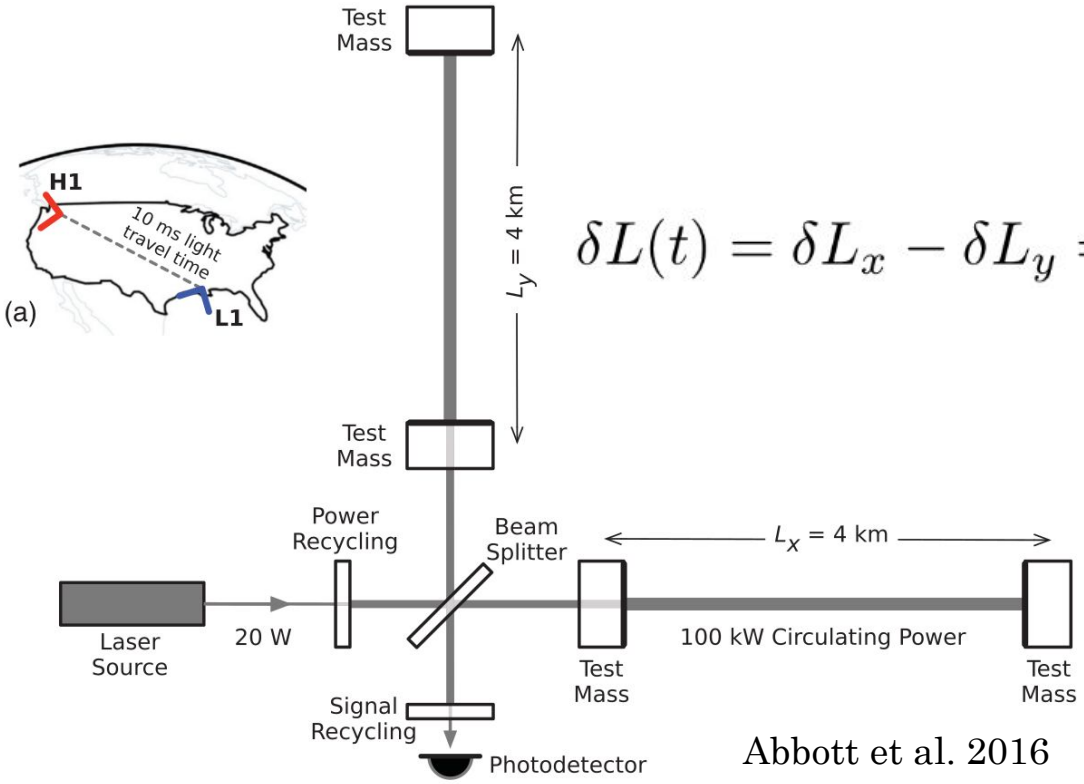
- GW detectors: interferometers

  (the longer the more sensitive)
- Preferably far away from human activities.

  But noise is inevitable…



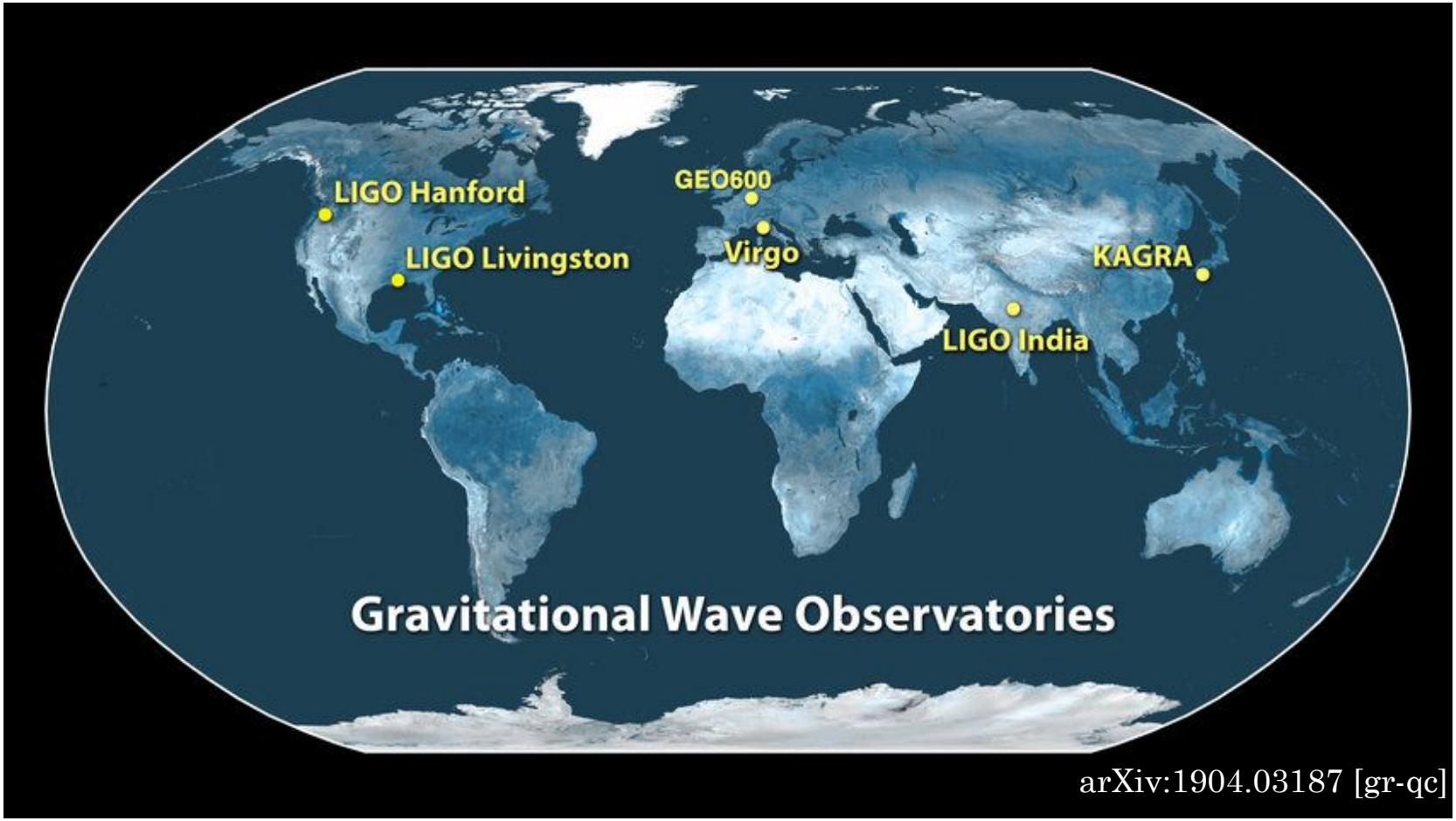




$$\delta L(t) = \delta L_x - \delta L_y = h(t) L$$

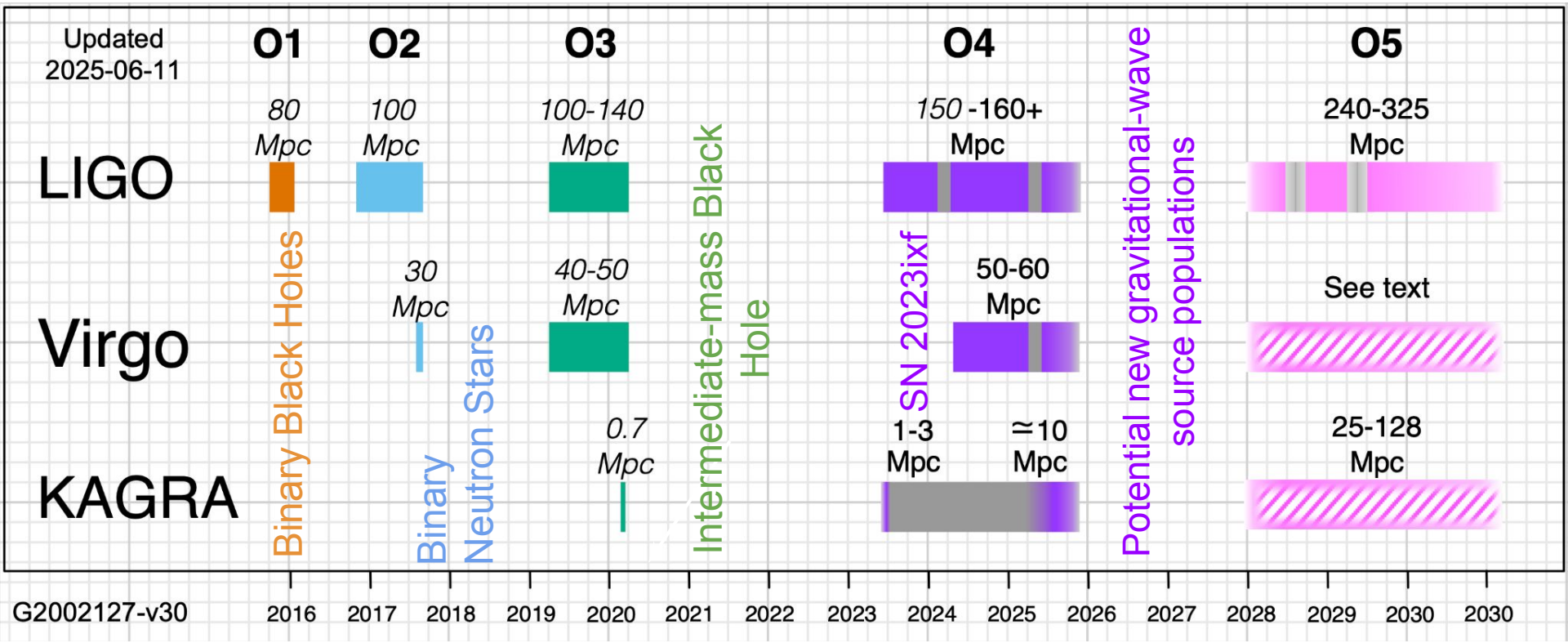
Abbott et al. 2016

Detectors network



- GEO and KAGRA - recently joined observations
- LIGO India - under construction
- NEMO - planned Australian high-frequency detector

Observing Timeline

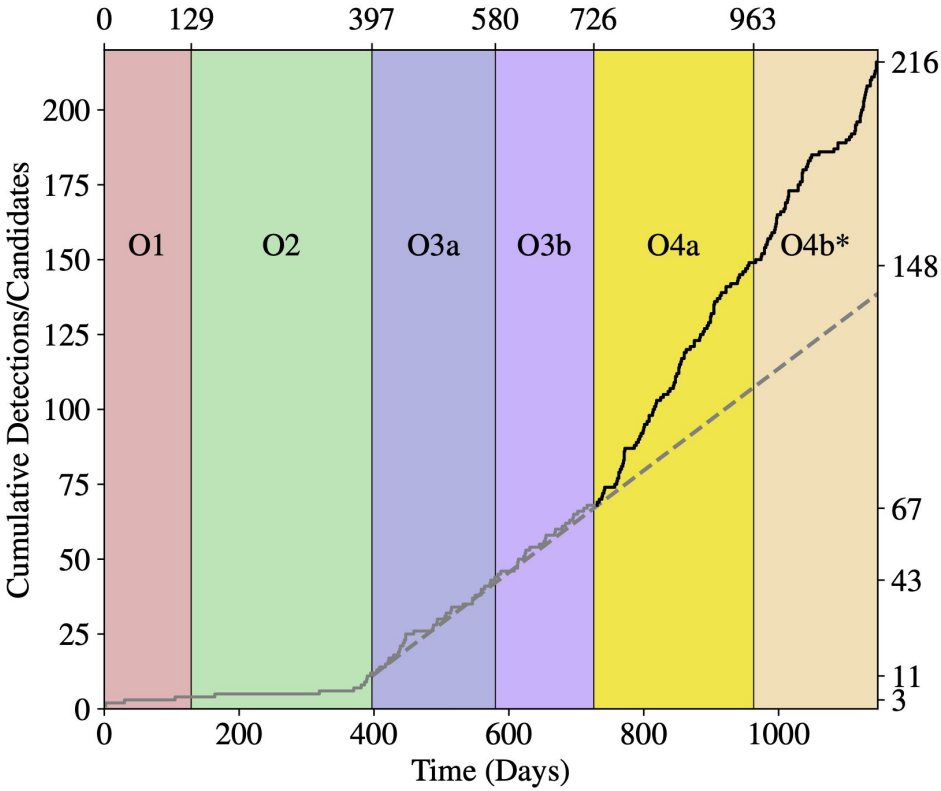


- O4: 24 months total, until 18 Nov 2025 https://observing.docs.ligo.org/plan/
- LIGO: up to 180 Mpc, currently 160 Mpc
- Virgo: around 55 Mpc
- KAGRA: up to 10 Mpc, not yet observing, reached 6 Mpc

Observing Run 4

GW candidates: 201 so far **(3 per week)**

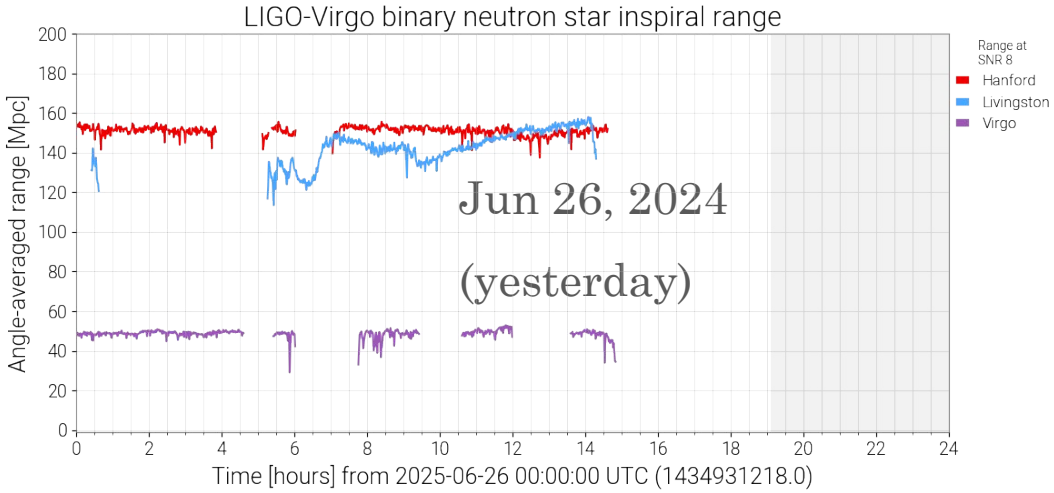
- Low-latency searches are crucial for astronomical observations, resources:
  - https://gracedb.ligo.org
  - https://emfollow.docs.ligo.org/userguide/
- Published results:
  - GW230529, low-mass binary (2404.04248)
  - Search with SN 2023ixf, a core-collapse supernova at 6.7 Mpc (2410.16565)
  - Search with 45 known pulsars (2501.01495)

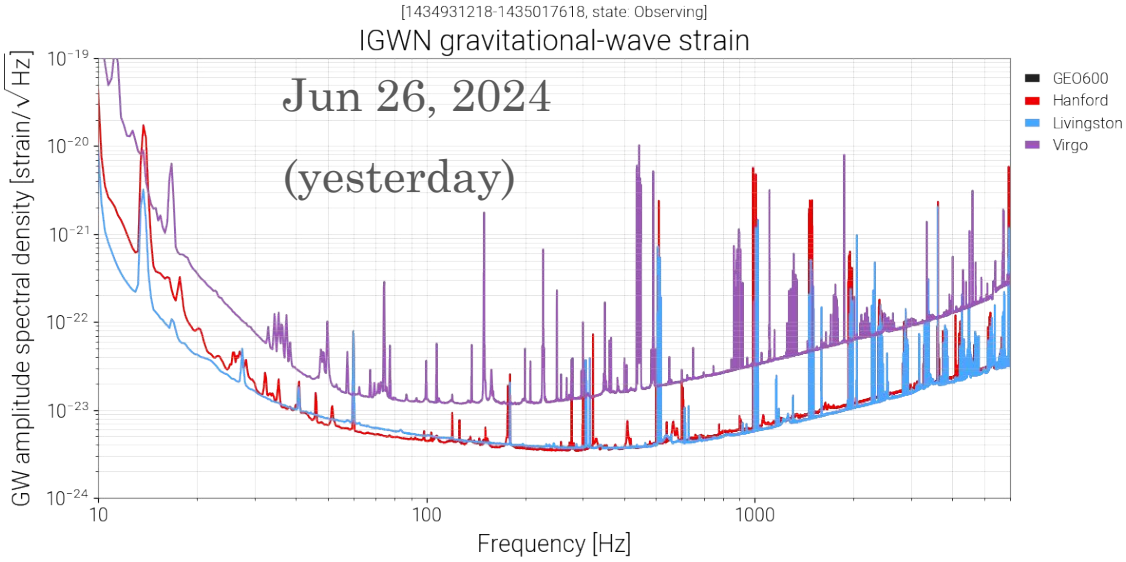


Capote+25 (2411.14607)

Observing Run 4

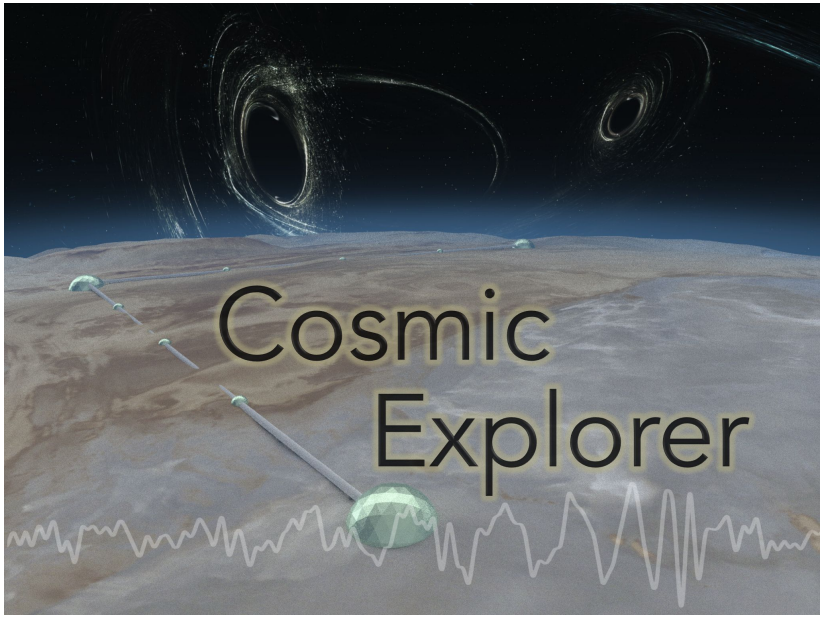
- Live detector status: https://online.igwn.org/
- Daily detector status: https://gwosc.org/detector_status/
- Public data release is 18 months after data collection

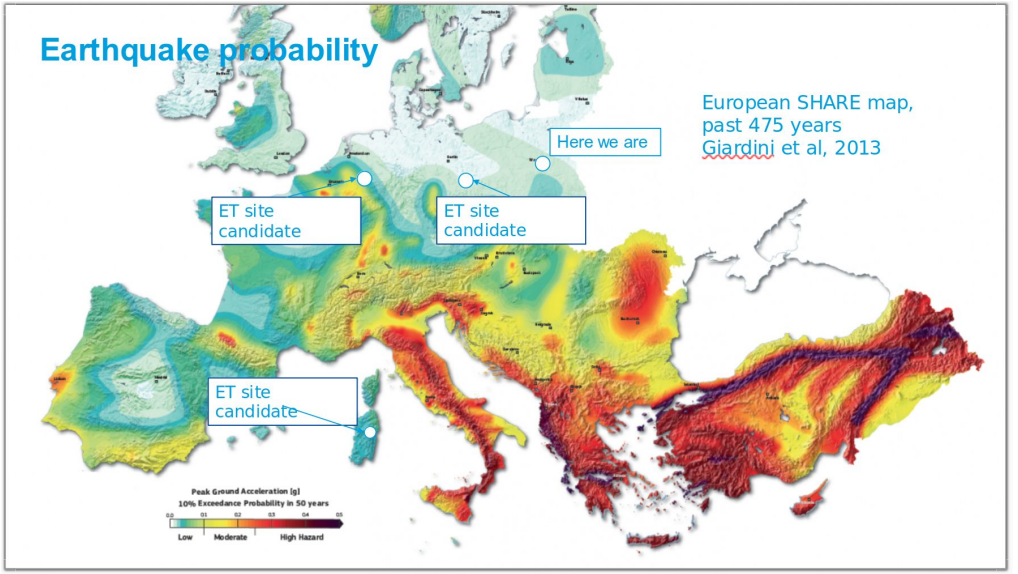




Einstein Telescope and Cosmic Explorer 3G observatories

- 3rd Annual Meeting in Warsaw:
  - https://indico.ego-gw.it/event/764/
  - ET challenges: shape and location
  - ET science case: Abac+25 (2503.12263)
- CE: observe all merging BHs in the Universe





Model-independent searches

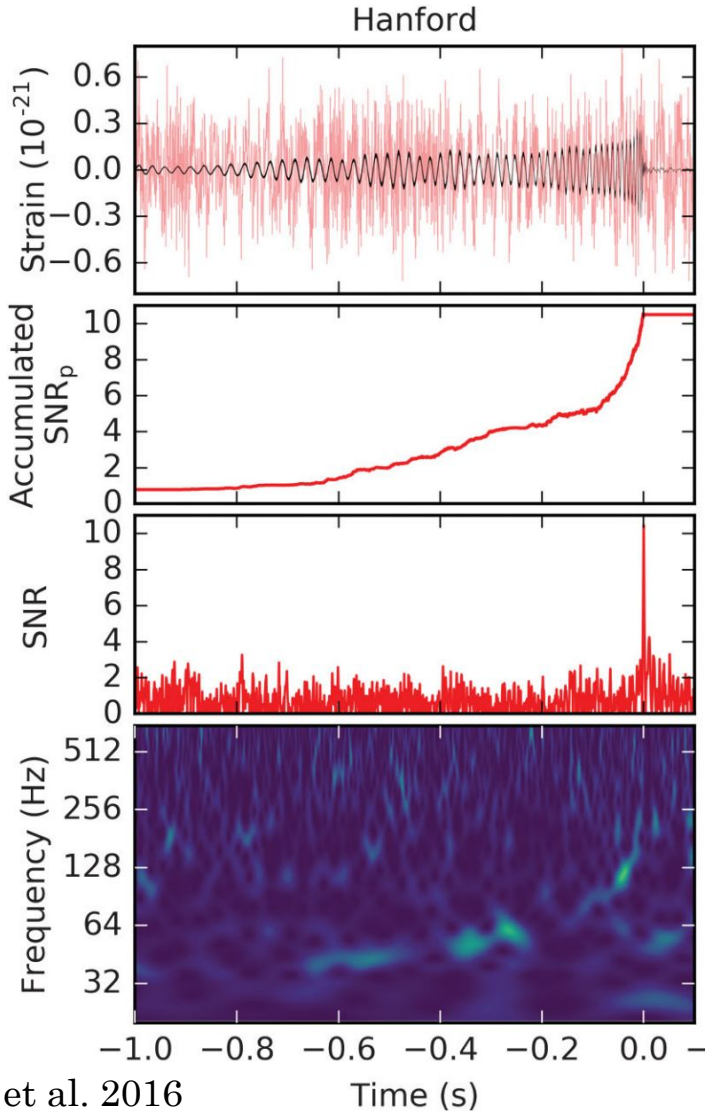
Exceptional GW sources

Exceptional 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
  - 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, lensed binaries
  - Beyond GR: GW echo, beyond-quadrupolar GW polarizations,

Model-dependent searches
Matched-filtering

- The template signals from compact binaries are derived from General Relativity.
- **Cross-correlating data with waveform templates**
- The method requires accurate waveform models. To the leading order, the waveform morphology depends on the chirp mass and effective spin.
- Missing parameter space or having an inaccurate model may result in missing a detection.



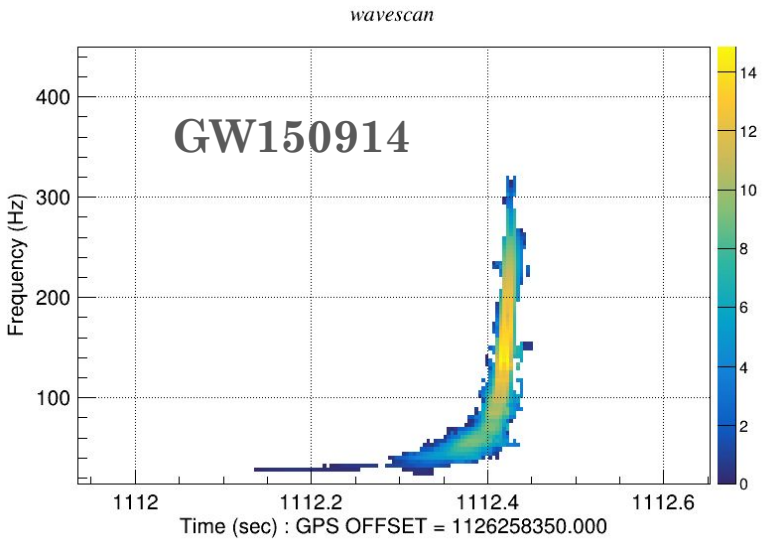
Abbott et al. 2016

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
- **Complementing template-based searches**
- cWB has detected:
  - **GW150914** - the very first GW (PRL 116, 061102)
  - **GW190521** - an intermediate mass binary black hole (PRL 125, 101102)
  - 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

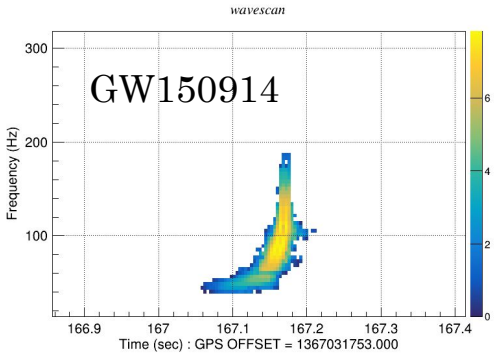
https://gwburst.gitlab.io/



Model-independent searches classification

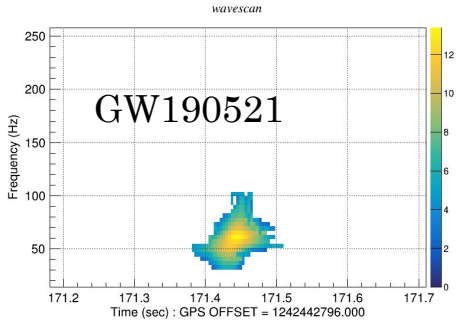
Compact binary searches (minimally modeled)

Binary black holes
Binary neutron stars
Black hole - neutron star



e.g. Mishra+23 (2201.01495)

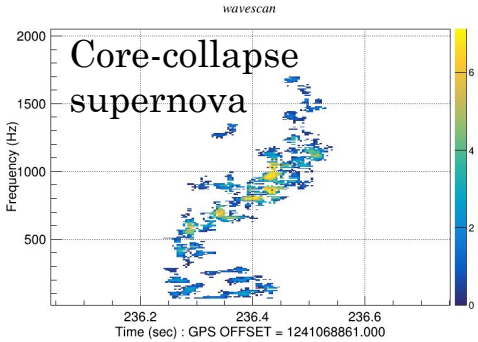
Binaries with eccentric orbits
Intermediate-mass black holes
Hyperbolic encounters
Extreme mass-ratio



e.g. MS+21 (2009.11336)

Generic searches (unmodeled)

Core-collapse supernovae
Pulsar glitches
Cosmic strings
Unknown



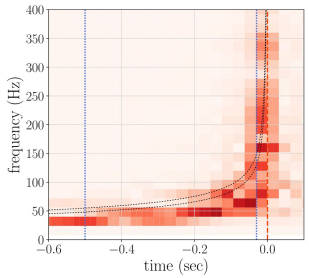
e.g. MS+24 (2305.16146)

Low-latency searches

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

e.g. Chaudhary+24 (2308.04545)

Searches for new phenomena

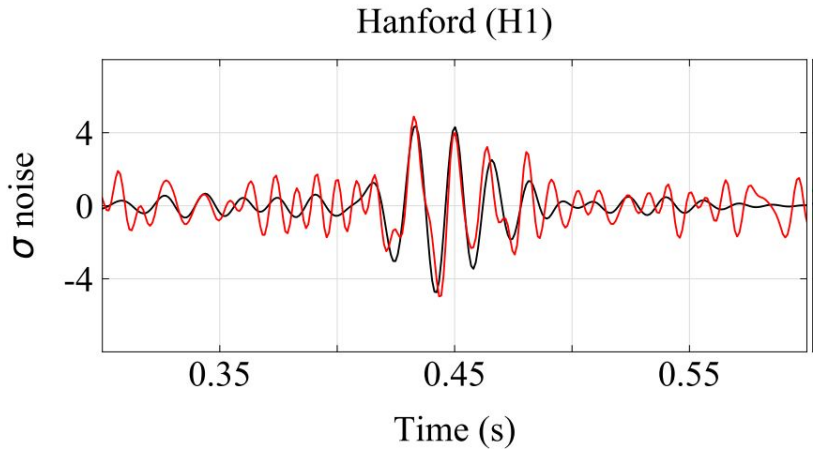


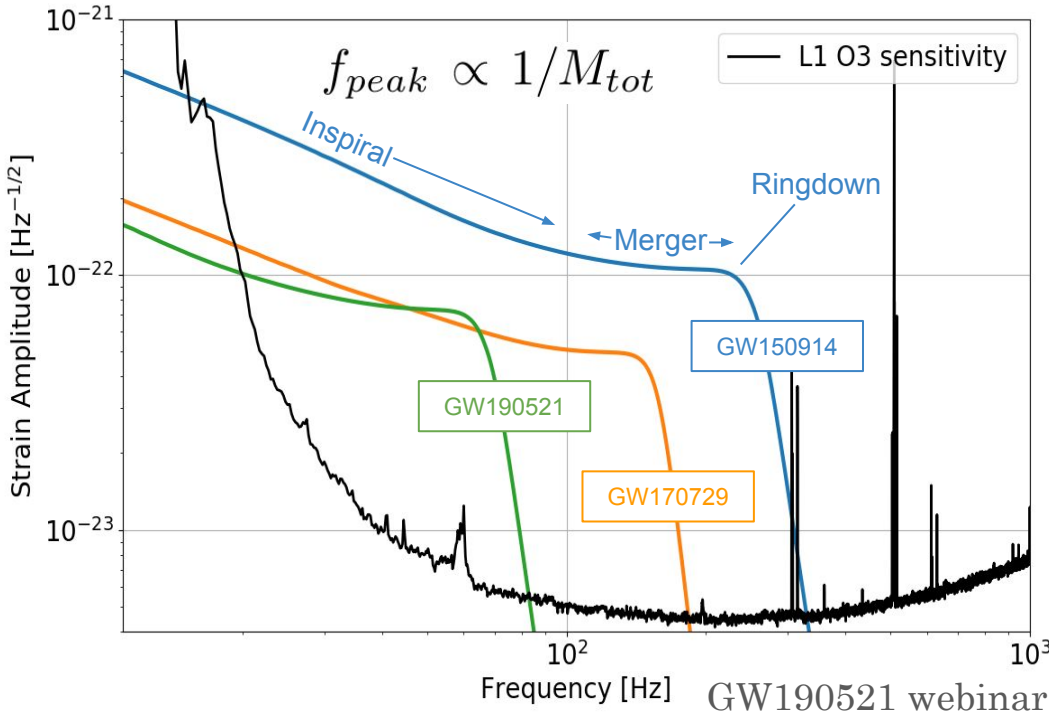
Higher harmonics
GW cross-polarization
Deviations from GR

e.g. Vedovato+22 (2108.13384)

GW190521

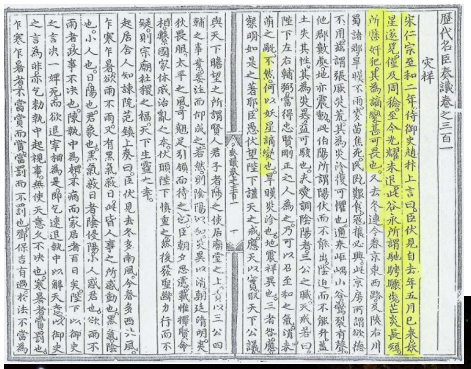
- Intermediate-mass black holes (IMBHs) - between stellar mass (100 $M_\odot$) and supermassive (10^5 $M_\odot$). The origin is not yet well understood.
  - Probing pair-instability mass gap (Stars with He mass in (64 $M_\odot$, 135 $M_\odot$)
  - Formation channels
  - Most distant GW sources
- GW190521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





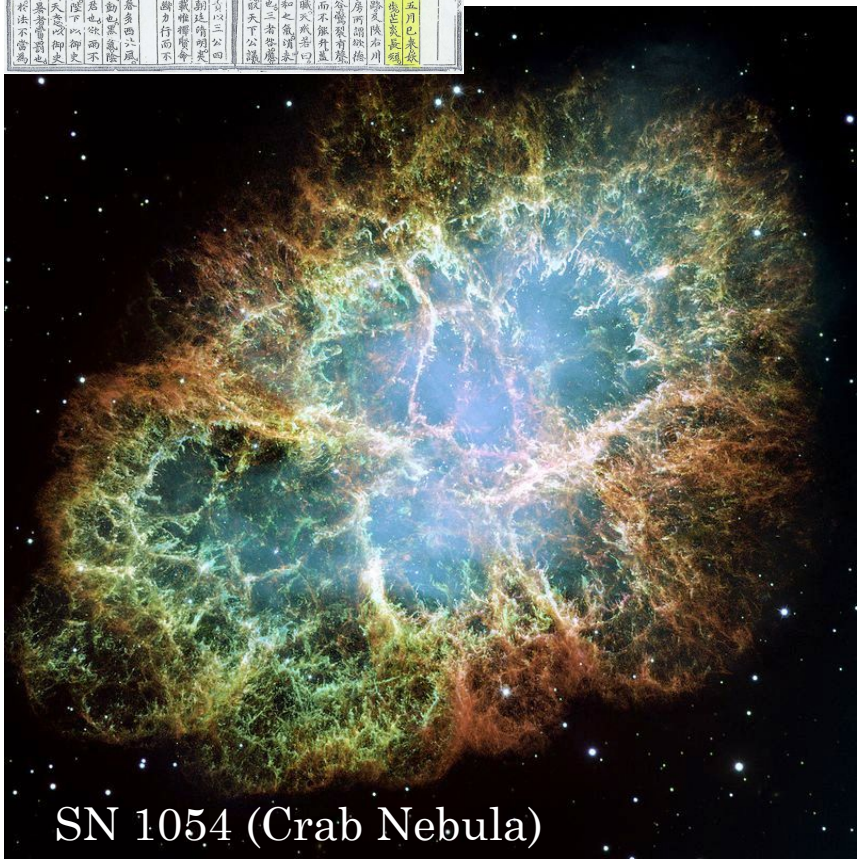
Core-Collapse Supernova

Core-Collapse Supernova (CCSN)



"Guest star"

Zhao Bian's memorial to Emperor Renzong

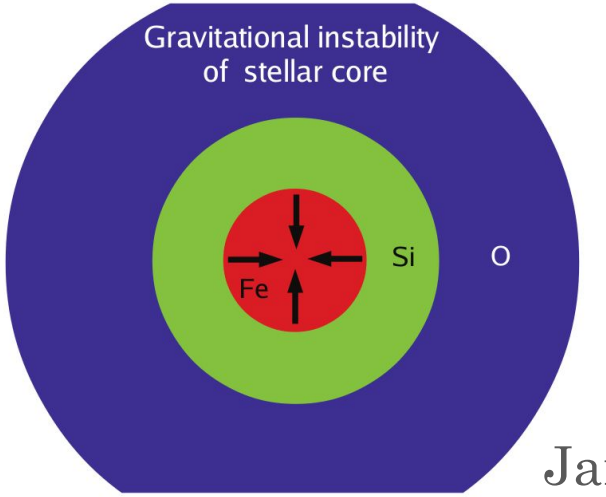


SN 1054 (Crab Nebula)

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

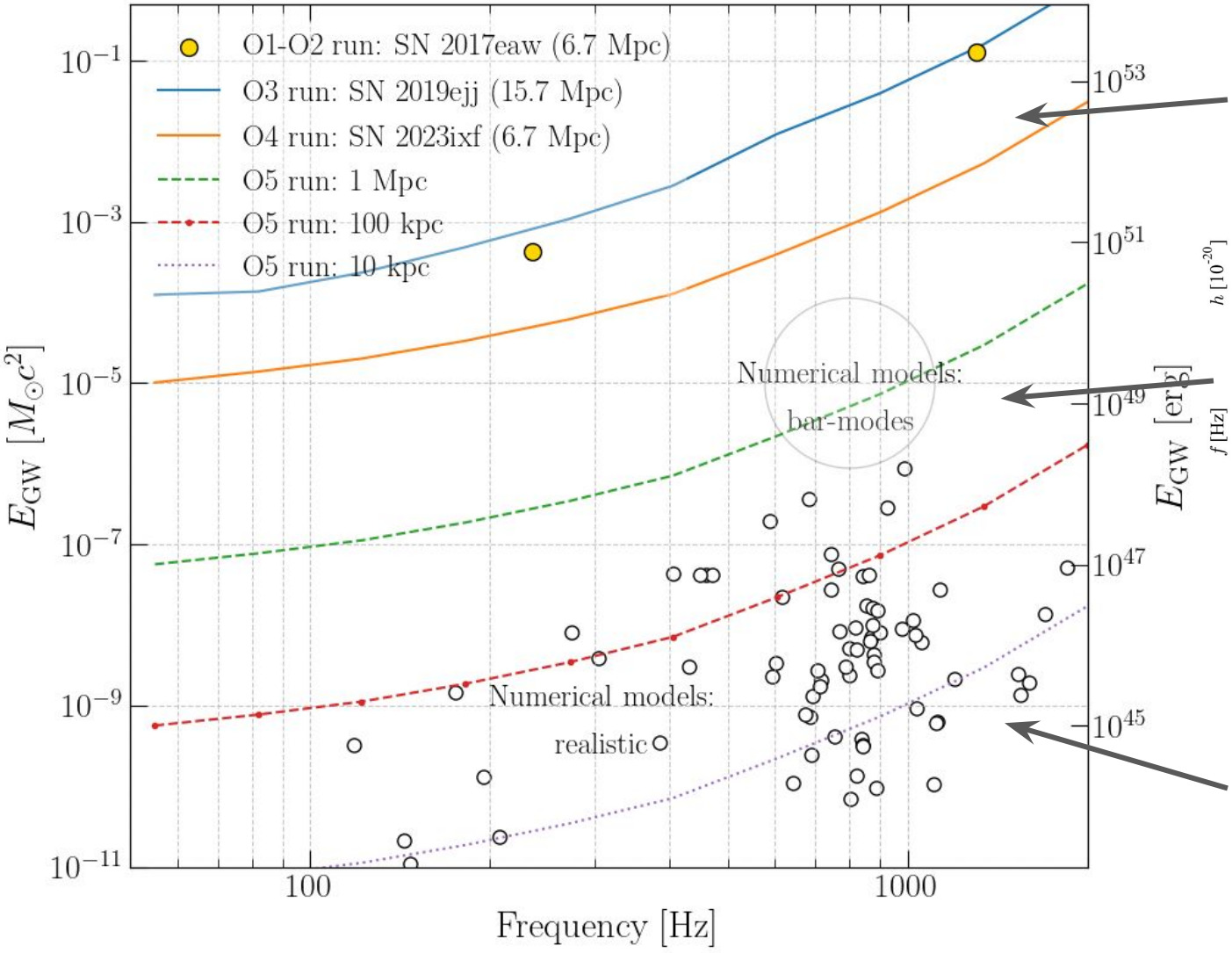
- Burning of a star: H → He → … → Fe
- After exceeding Chandrasekhar mass of 1.4 $M_\odot$ the iron core collapses.
- 99% of explosion energy escapes with neutrinos!

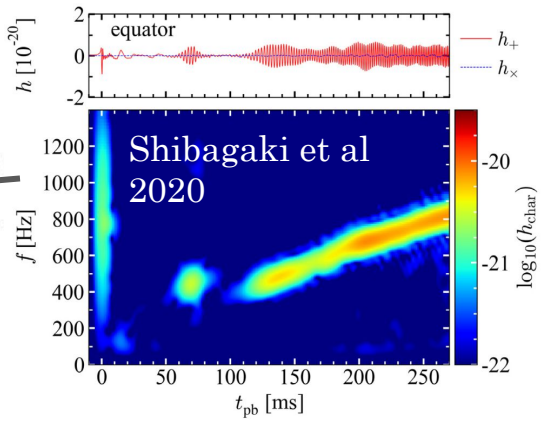
Explosion mechanism(s) is still unknown

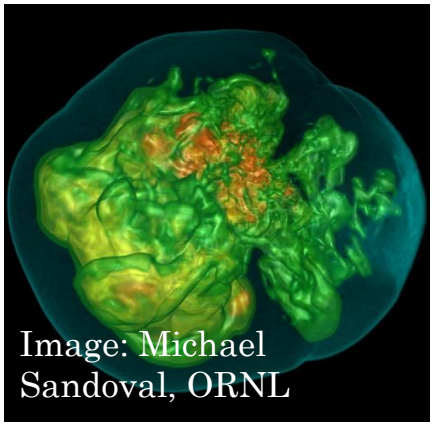


Janka+12

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



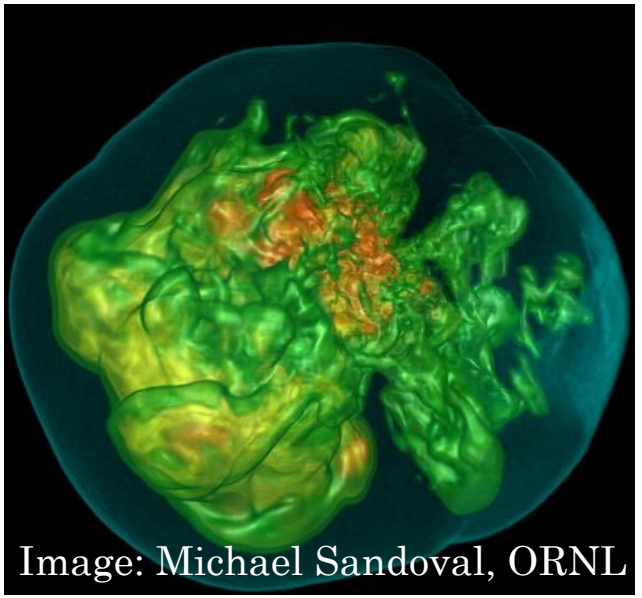


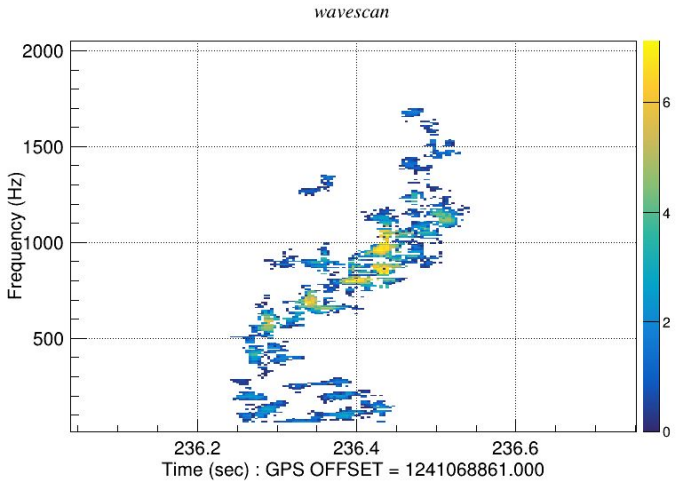


IGWN Symposium on CCSNe
(IGWN - International GW Network)

- CCSNe are the most challenging astronomical events to model
- Agenda/webpage: https://indico2.fuw.edu.pl/event/17/overview (registration till the end of June)
  - Day 1: CCSN Theory
  - Day 2: CCSN Gravitational Wave Detection and Parameter Estimation
  - Day 3: CCSN Neutrino Detection
  - Day 4: CCSN across the Electromagnetic Spectrum
  - Day 5: CCSNe over the Next Ten Years
- Classical and Quantum Gravity focus issue proceedings: https://iopscience.iop.org/collections/cqg-250513-841

Example: Mezzacappa et al 2023





July 21-25, 2025, in Warsaw

Summary

- GW Observations: 201 events in O4 so far
  - End: 18 Nov 2025
- Model-independent searches
  - Preparing for detecting exceptional GW sources
- Core-Collapse Supernova
  - “Supernova problem”: why do the stars explode?
- SN2025gw: IGWN Symposium on CCSNe:
  July 21-25, 2025 in Warsaw