Science with Gravitational Waves (GWs) in the Era of LIGO-Virgo-KAGRA (LVK) Discoveries

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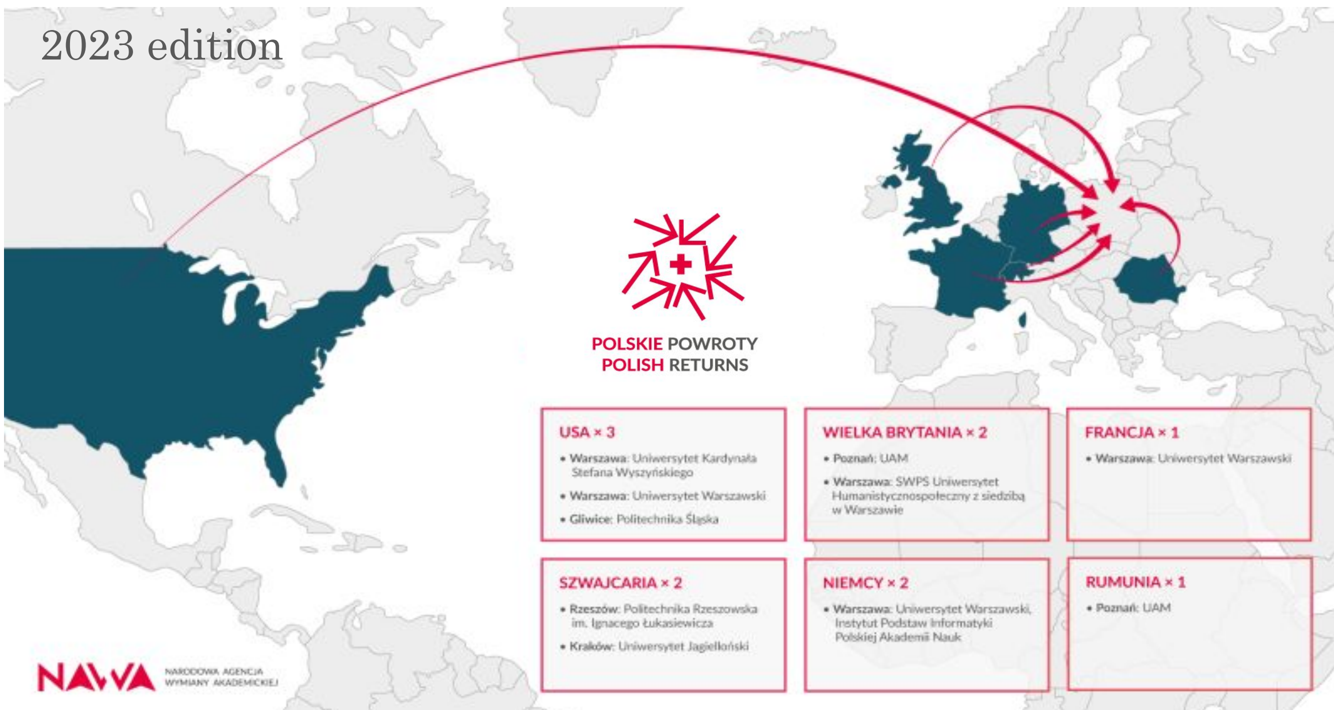
Return to Poland

- Ph.D., ~5 years: Embry-Riddle Aeronautical University (Arizona)
- Postdoc, ~5 years: University of Florida
- Assistant Professor, present: University of Warsaw
  - Permanent position and a Polish Returns grant

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

Prof. Jerzy Lewandowski invited me when I got the Polish Returns grant



Outline

- Gravitational-Wave Astrophysics
  - Introduction
  - Observing Run 4
- Searching for exceptional GW sources
  - Model-independent searches
- Summary

See dr. Świeżewska's presentation about the space-based detector LISA

Gravitational-Wave Astrophysics

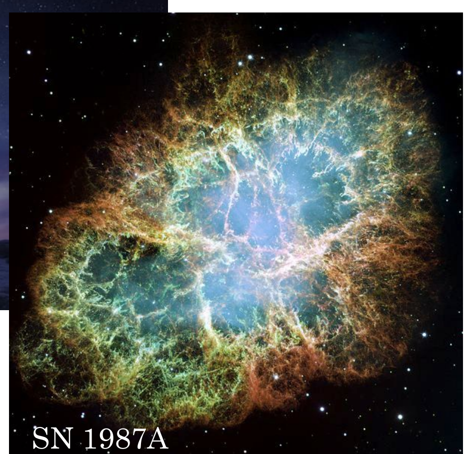
"Conventional" and "Gravitational-Wave" Astronomy

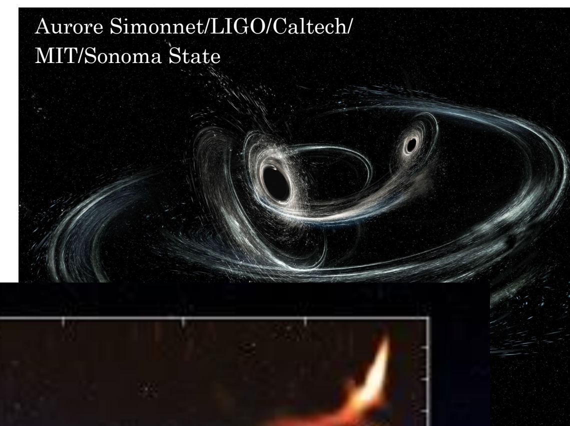
"Conventional" or time-domain Astronomy:
observing Universe using electromagnetic waves (e.g. visible light), cosmic rays or neutrinos.

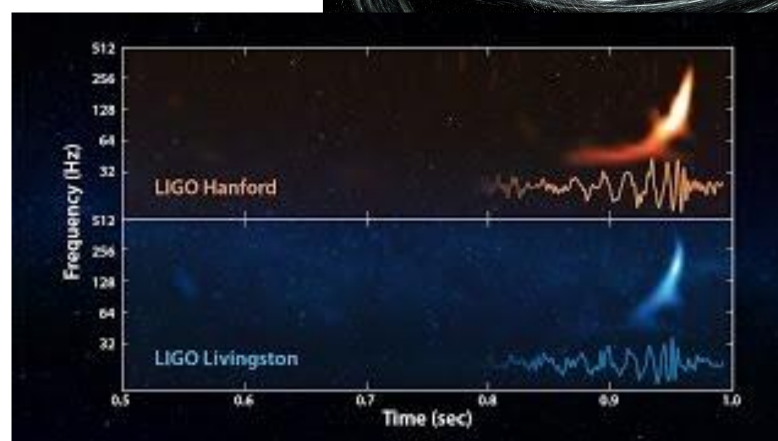
Looking at the Universe

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

Listening to the Universe







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.

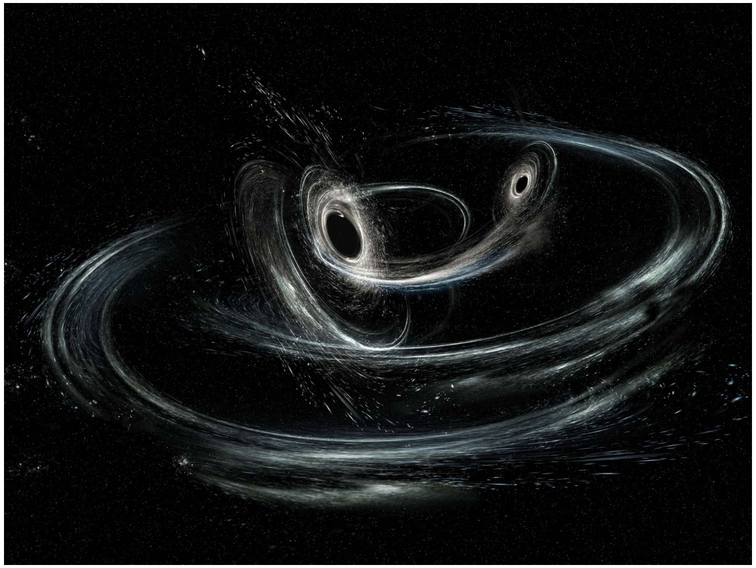
The Dynamic Universe

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



AURORE SIMONNET/LIGO/CALTECH/MIT/SONOMA STATE

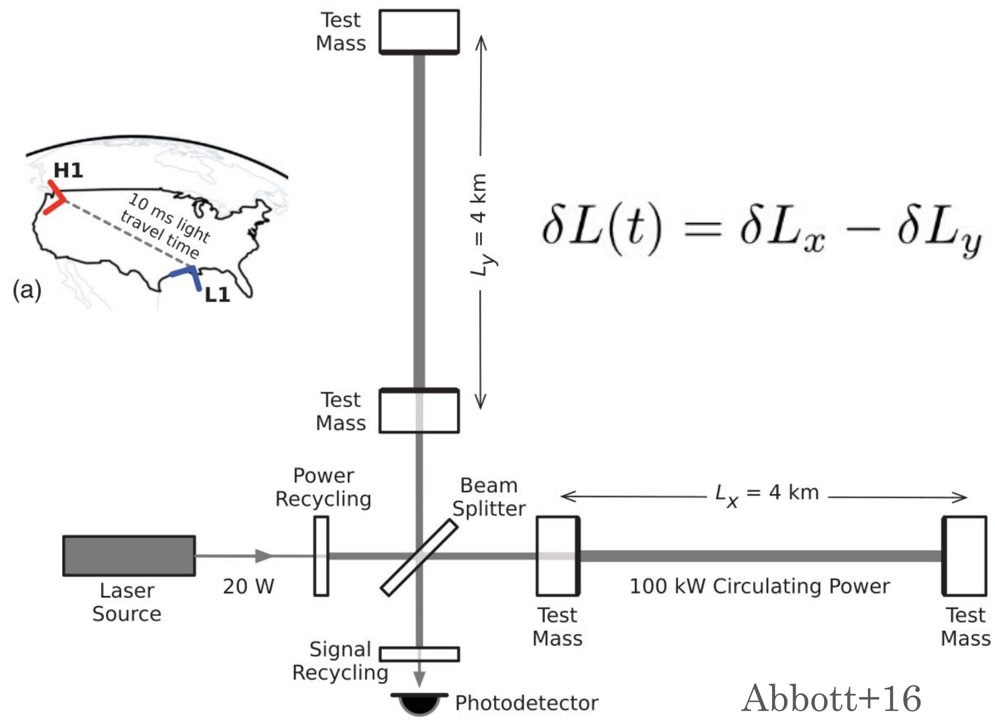
GW sources:

- Standard, e.g. stellar-mass binary black holes
- **Exceptional!**

Second part of the presentation

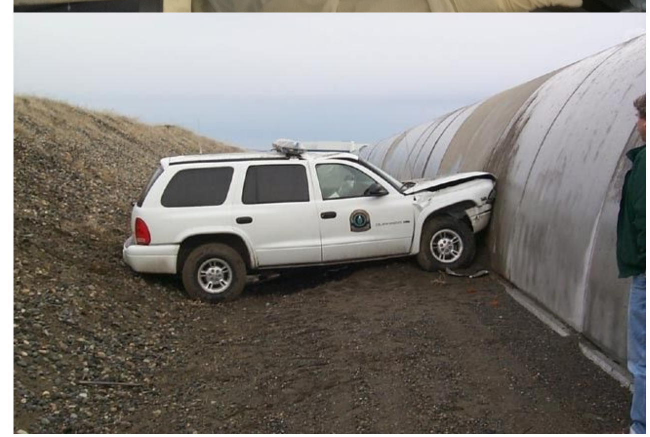
Gravitational-Wave detectors

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

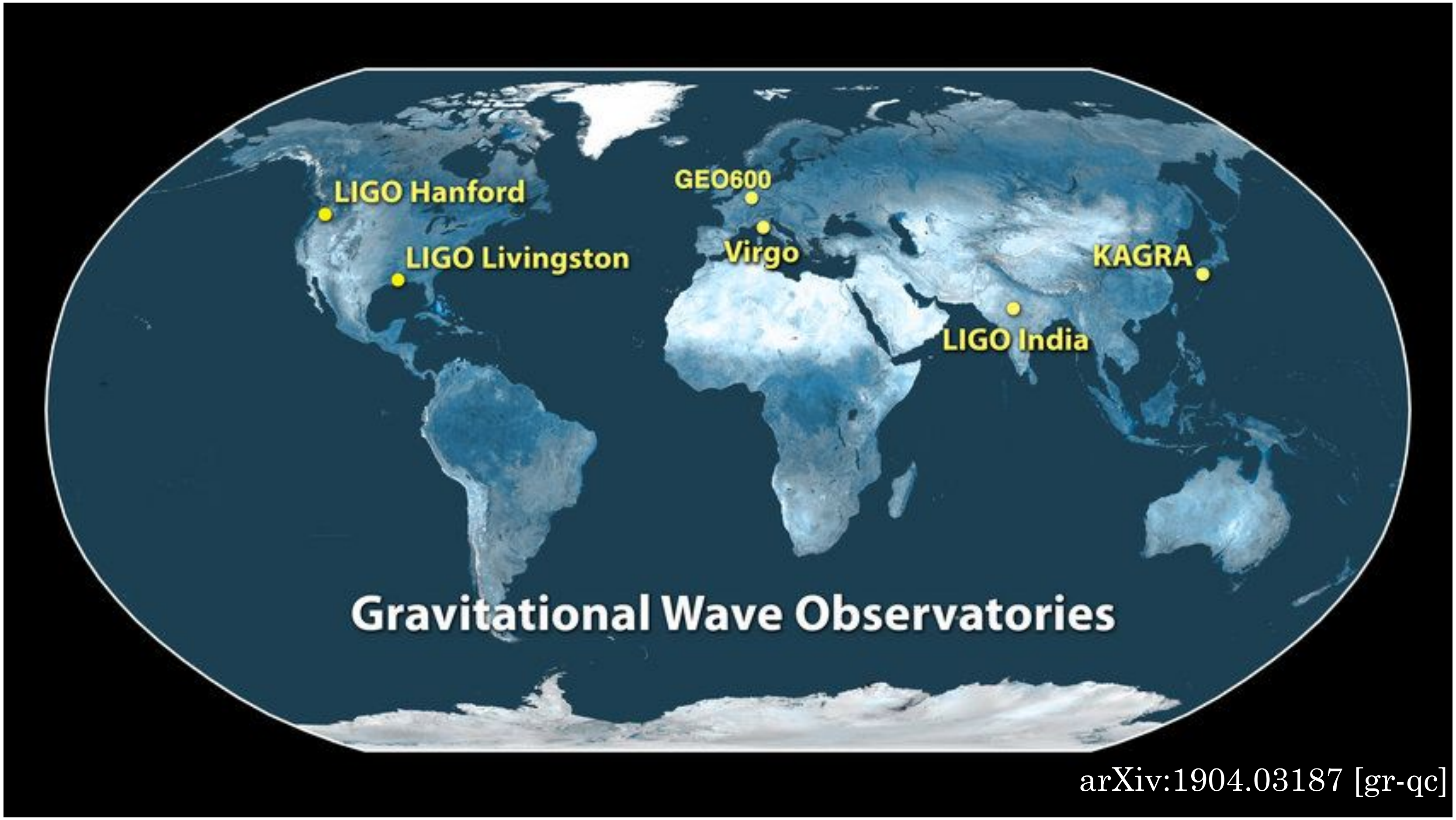


$$\delta L(t) = \delta L_x - \delta L_y = h(t)L$$

Abbott+16

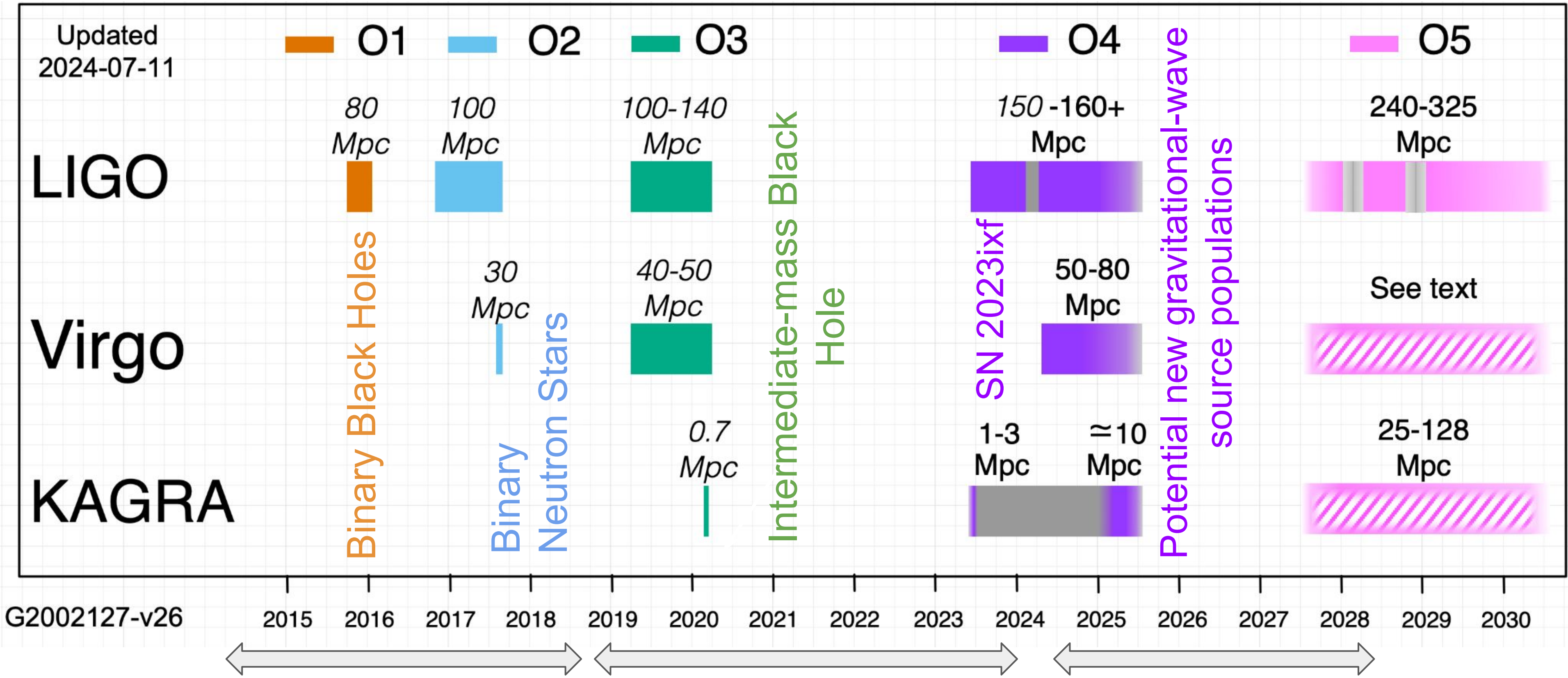


Detectors network



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

Observing Timeline



Ph.D. expertise:
Core-collapse supernova (CCSN)

University of Florida. expertise:
compact binaries, low-latency

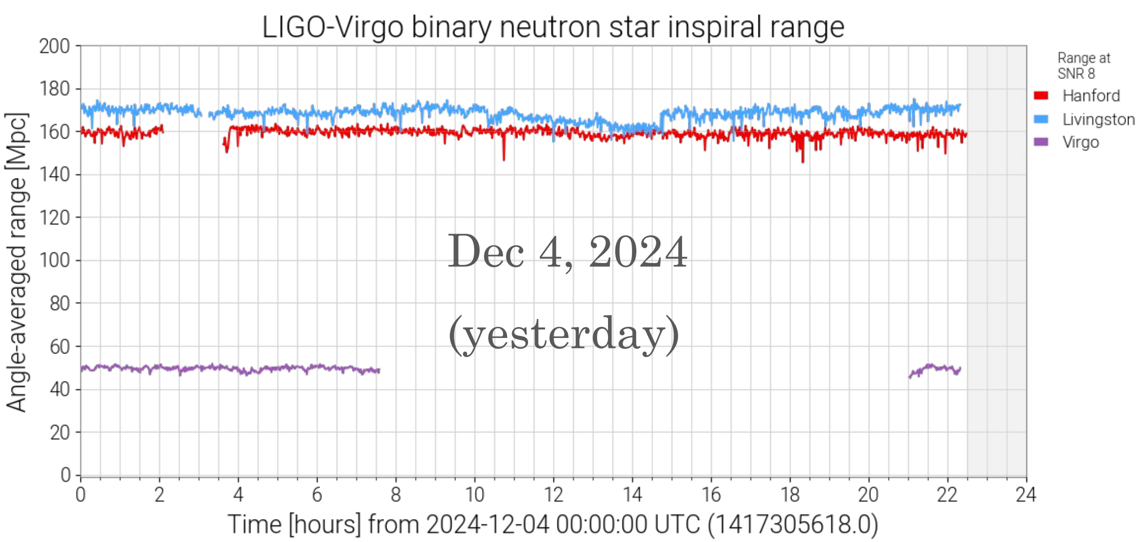
University of Warsaw

Observing Run 4

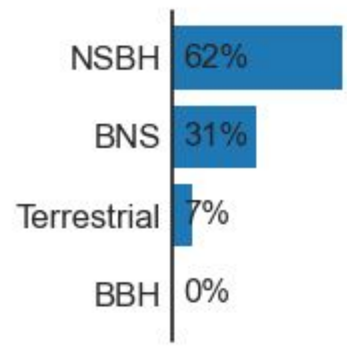
- 24 months total, until June 2025
- GW candidates: 167 so far (**3 per week)**
- Almost all events are BBHs (17 might have NS)
- Searches:
  - Model-dependent
  - Model-independent

Second part of the presentation

- Plans: https://observing.docs.ligo.org/plan/
- Daily detector status: https://gwosc.org/detector_status/



- KAGRA:
  - Hit by 7.6 magnitude earthquake on Jan 1
  - Planned joining before the end of O4 with 10 Mpc

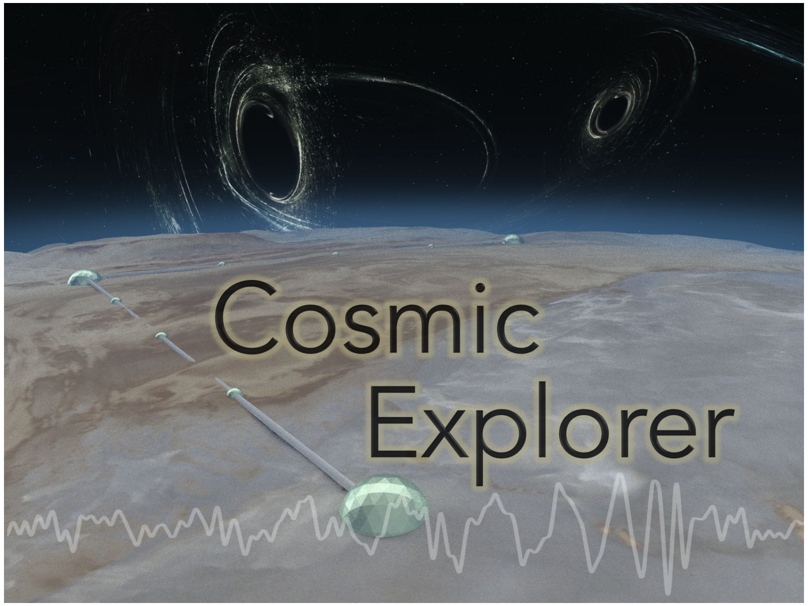


S230529ay

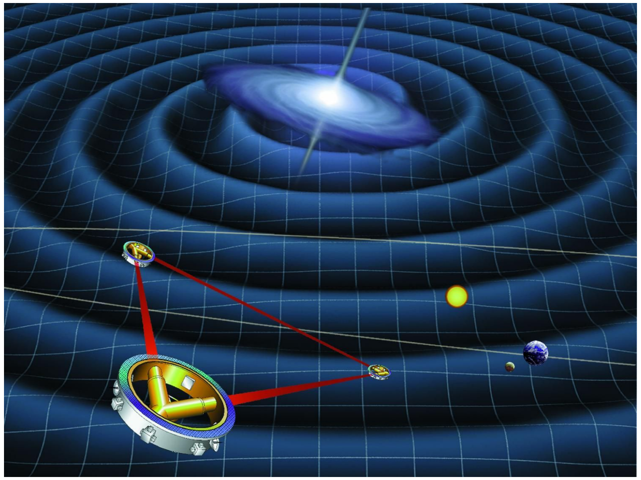
GW230929 (Abbott+24): 2.5-4.5 Mo Compact Object and a Neutron Star

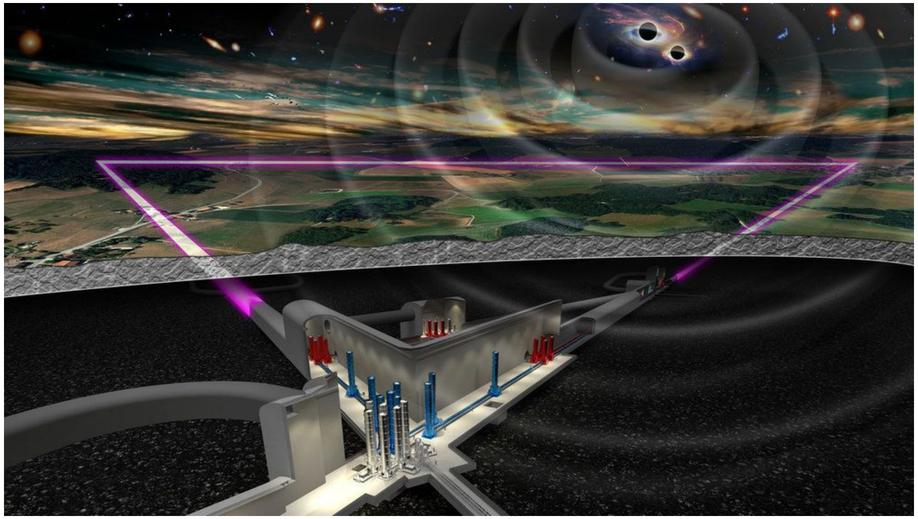
The future of observations

- The third generation (3G) detectors will be 10x more sensitive
- Rate of detections per week:
  - now: a few
  - future: thousands!
- Projects:
  - LISA: space-based detector
  - Cosmic Explorer (US)
  - Einstein Telescope (Europe)



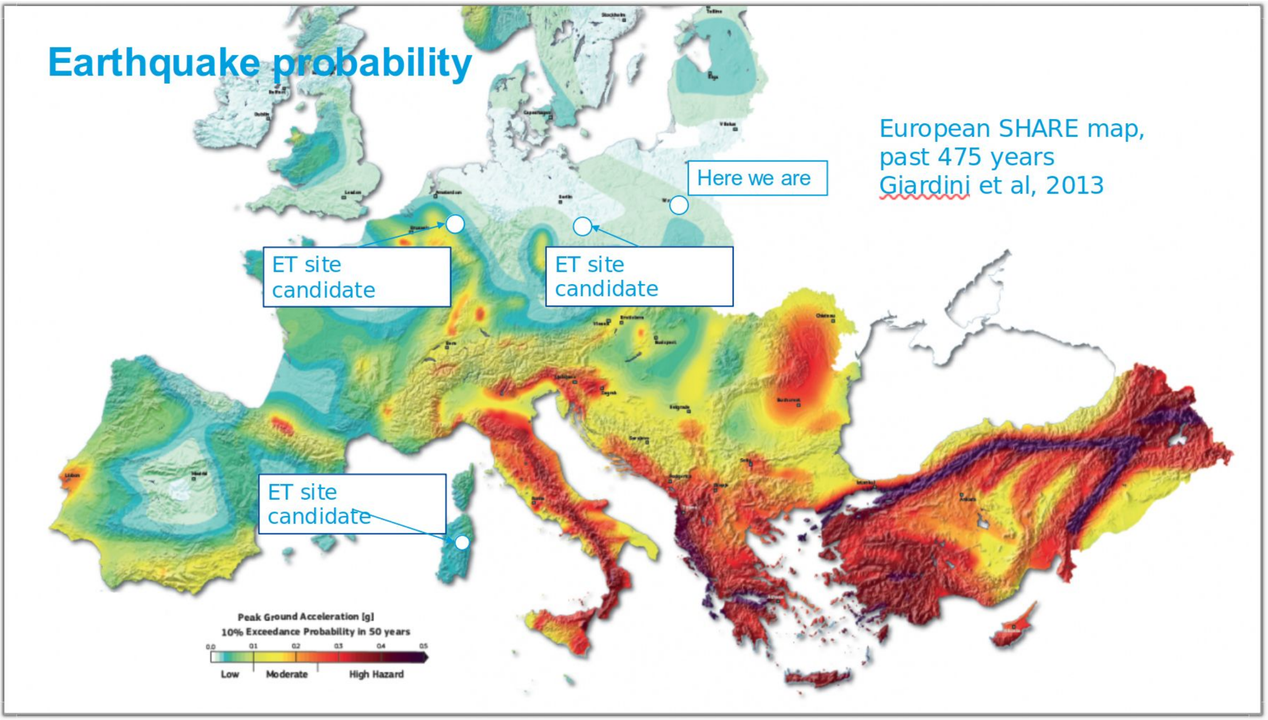
LISA: dr Świeżewska presentation





Einstein Telescope - 3G observatory

- 3rd Annual Meeting in Warsaw:
  - https://indico.ego-gw.it/event/764/
  - 3 possible sites for ET
- Challenges:
  - L vs triangular shape
  - Location



Searches for exceptional GW sources

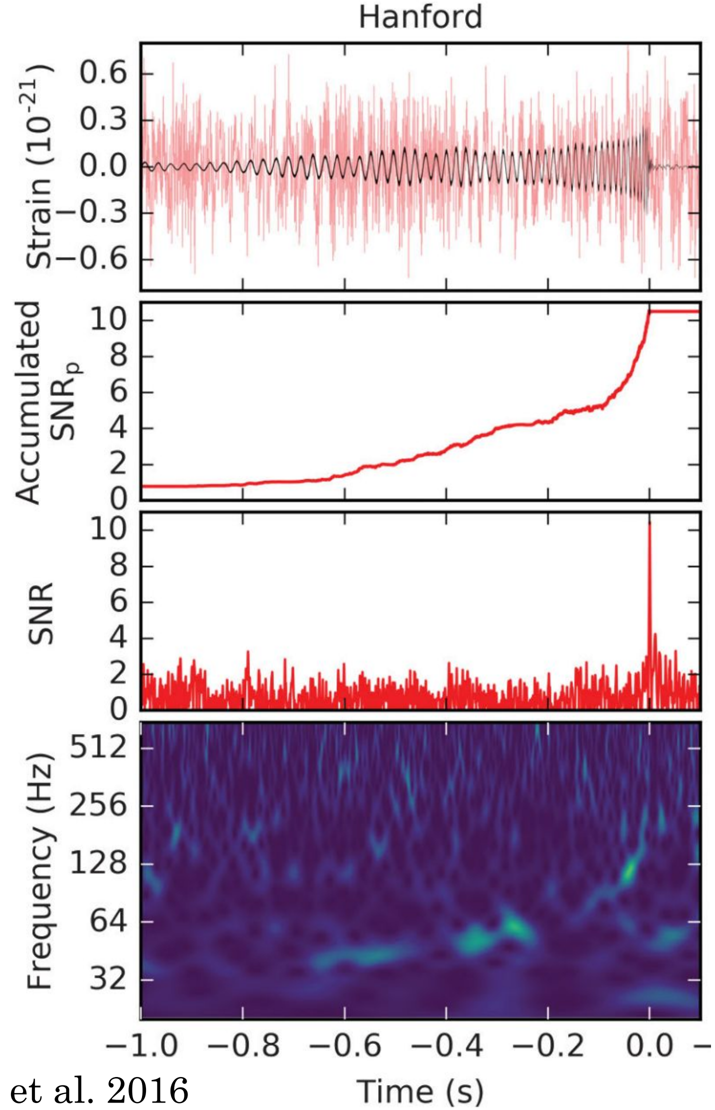
Exceptional GW sources

Exceptional astrophysical sources might play an important role in our exploration of the Universe.

- **New GW source populations**:
  - Compact binaries: binaries with eccentric orbits, hyperbolic encounters, head-on collisions, sub-solar mass binaries, extreme mass ratio
  - 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 etc.
  - 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.



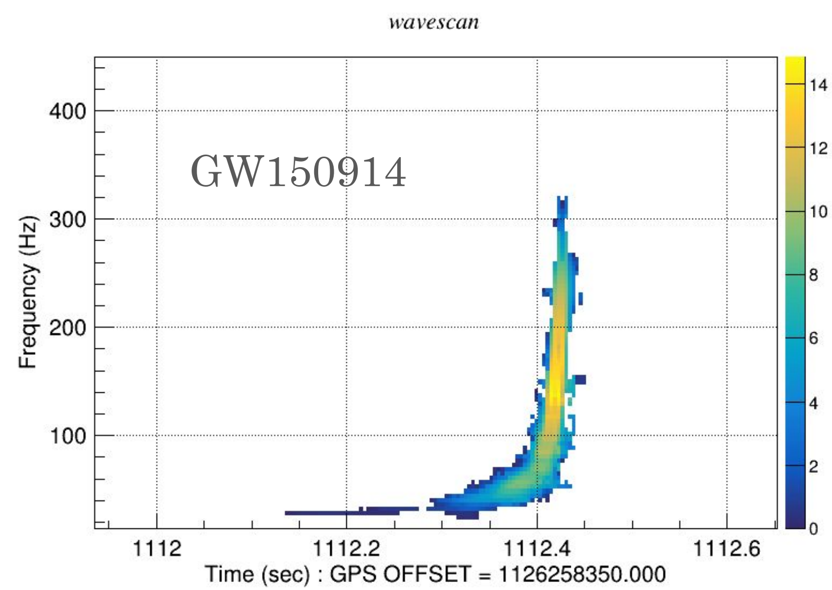
Abbott et al. 2016

Model-independent searches
coherent WaveBurst

- **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 matched filtering
- cWB has detected:
    - **GW150914 - the very first GW (PRL 116, 061102)**
    - **GW190521 - an intermediate mass binary black hole (PRL 125, 101102)**
    - several GWs together with template based searches
- **The cWB is the most sensitive burst algorithm in O4**

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

https://gwburst.gitlab.io/

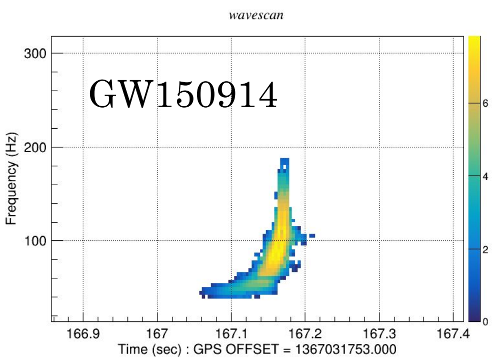


Model-independent searches classification

Compact binary searches (minimally modeled)

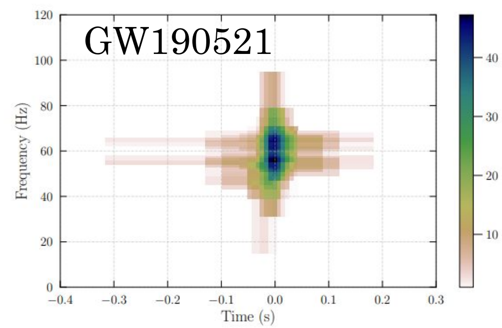
Generic searches (unmodeled)

Binary black holes
Binary neutron stars
Black hole - neutron star



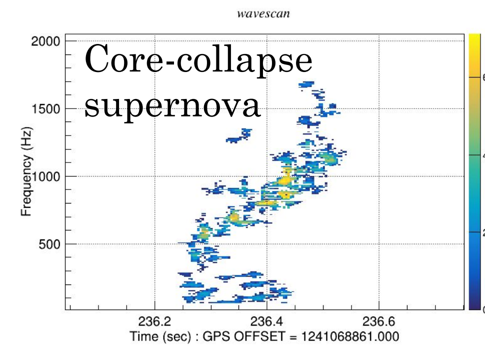
e.g. Mishra+23 (2201.01495)

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

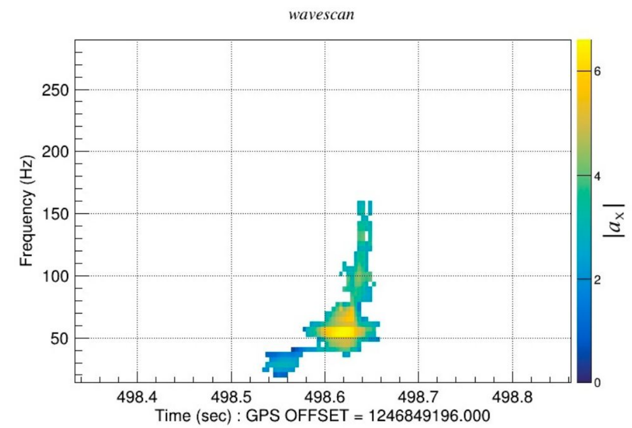
e.g. Vedovato+22 (2108.13384)

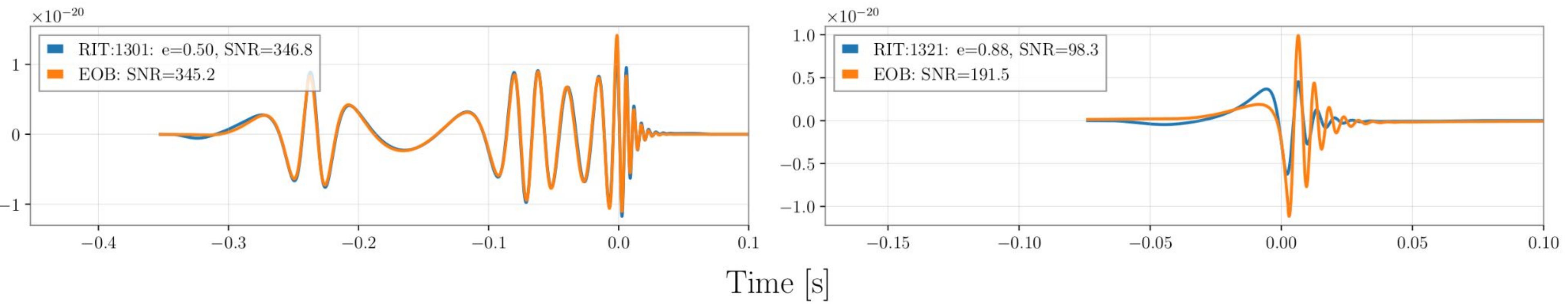
Low-latency searches

- cWB-generic:
  - Wide range of GW sources
- cWB-BBH:
  - Search for compact binaries
  - **It's capable to detect standard and special/exceptional compact binaries**
  - Complementing matched filtering
  - It detects around 80% of BBHs identified by matched filtering searches (for the Hanford-Livingston network)
  - So far 3 alerts were sent publicly (non-significant)

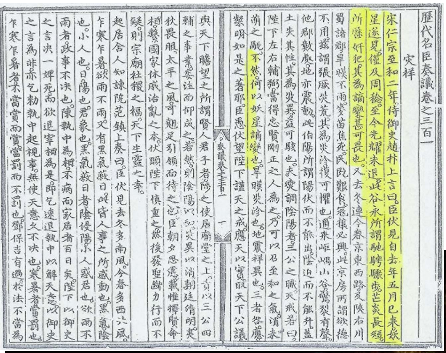
Eccentric binaries

- Eccentric binaries: compact binaries elliptical orbits.
  - Dynamical formation
  - They could be the next LVK discovery
- 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)
- Bhaumik et al (MS) 2024 (2410.15192)
  - Comparison between waveform models
  - Sensitivity studies





Core-Collapse Supernova (CCSN)



歷代名臣奏議卷之三百一
災祥
宋仁宗至和二年侍御史趙抃上言曰臣伏見自去年五月巳來妖
星遂見僅及周稔至今光耀未退此谷永所謂馳騁驟步芒炎長短
所歷奸犯其為譴變甚可畏也又去冬連今春京東西路及陝右川
蜀諸郡旱暵不雨麥苗焦死民既艱食寇攘必興此京房所謂欲德
不用茲謂張厥災荒其為災沴損可懼也邇來岷峨山谷鳴裂有聲
他郡數處地亦震動此伯陽所謂陽伏而不能出陰迫而不能升蓋
土失其性其為災異益可駭也夫燮調陰陽者三公之職天戒若曰
陛下左右輔弼當得忠賢剛正之人為之乃可以召至和之氣消未
萌之亂不然何以妖星譴變也旱暵災沴也地震祥異也三者皆應
昭明如是之著耶臣愚伏望陛下謹天之戒應天以實取天下公議
奏議卷之三百一　十
與天下瞻望之所謂賢人君子者陟之使居廟堂之上貢以三公四
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疑則宗廟社稷之福天下生靈之幸
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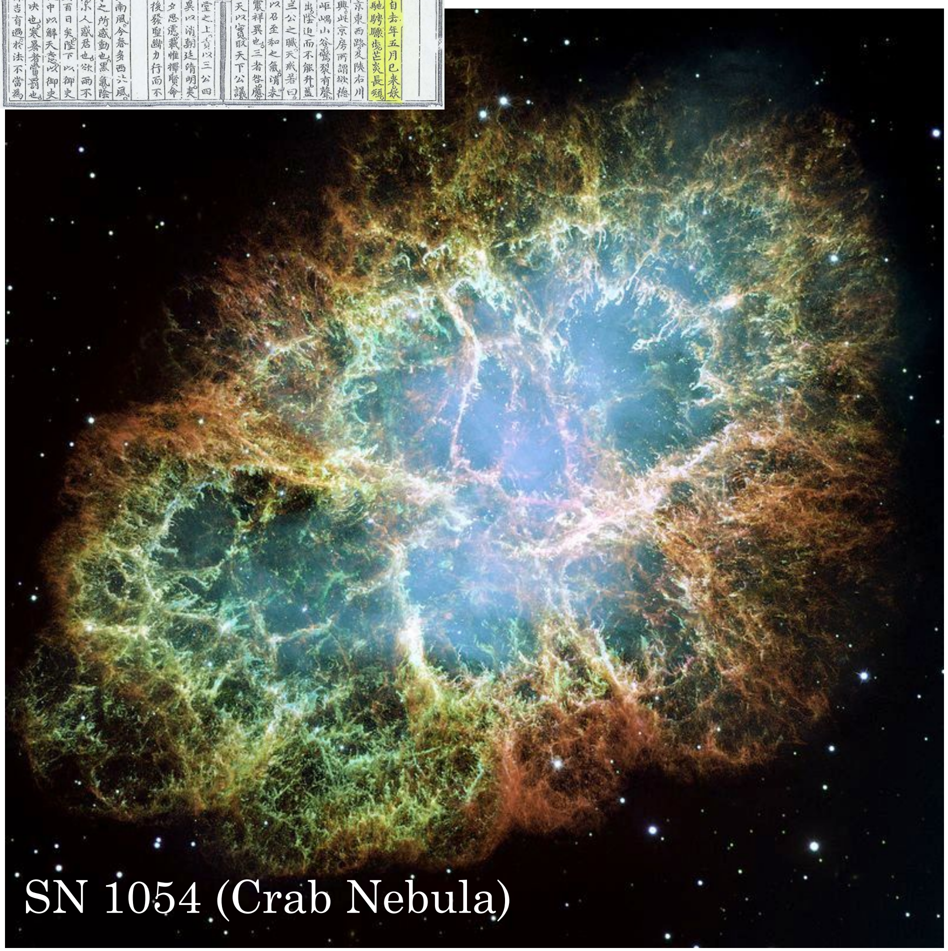
也小人也日陽也君象也黑氣蔽日者陰侵陽小人惑君也欲雨不
雨者政事不決也陳執中為相不病而家居者百日矣陛下以御史
之言決一婢死而欲退宰相為是耶乞速退執中以解天意以御史
之言為非耶乞勅執中起視事無使天意久不決也寒暑者賞罰也
乍寒乍暑者宜賞而賞當罰而不罰也鄧保吉有過於法不當為

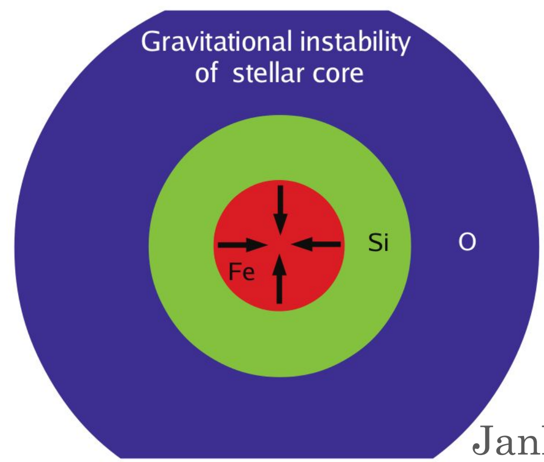
Nova / Guest Star on the sky!
1-2 per century in Milky Way (?)



SN 1054 (Crab Nebula)

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

Explosion mechanism is still unknown



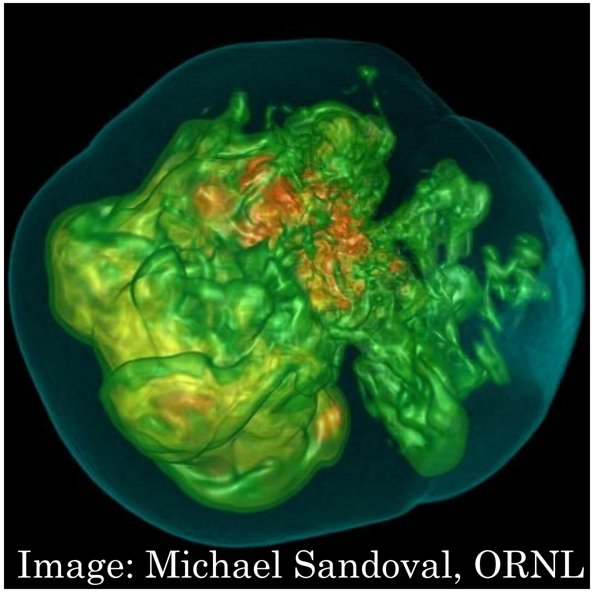
Janka+12

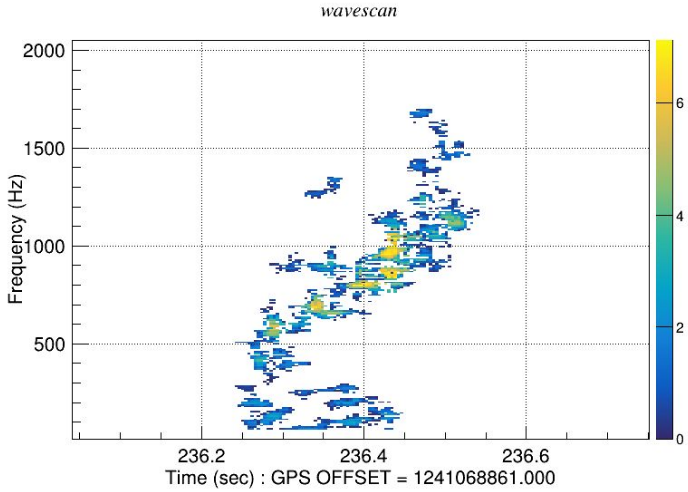
LVK and CCSN Theory

Example: Mezzacappa et al 2023

- CCSNe are the most challenging astronomical events to model:
  - All four fundamental forces are important
  - Neutrino transport
  - Computational challenges
- A joint workshop between LVK and CCSN modellers happened at Caltech in 2017
  - Supernova Multimessenger Consortium is created

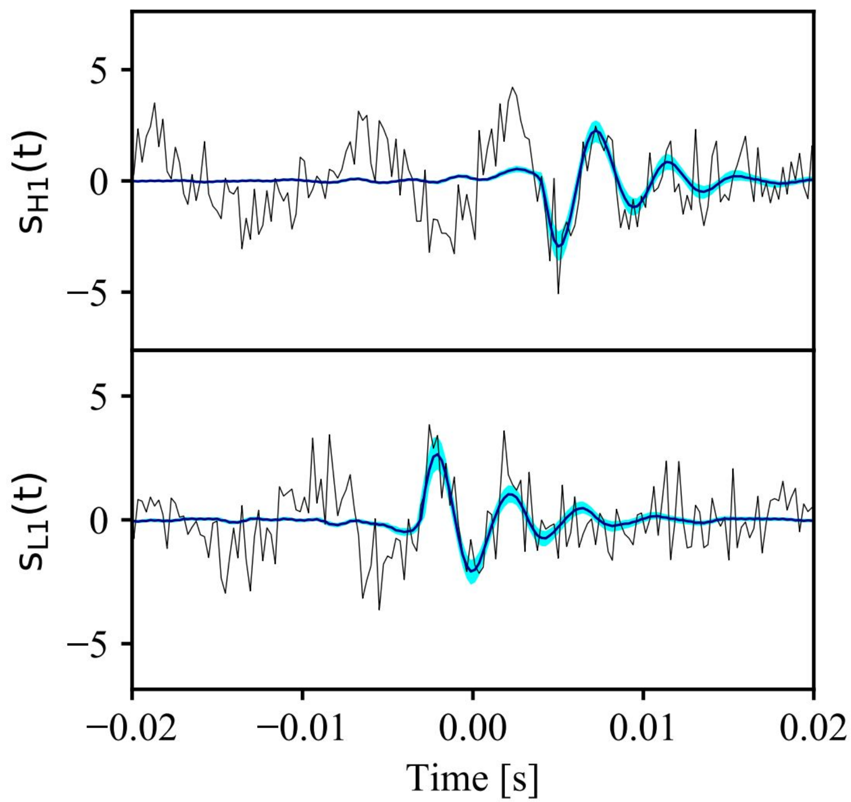
Next LVK workshop: summer 2025 in Warsaw - stay tuned!





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.



Carullo et al 2019

December 20: seminar about BH ringdowns, Anna Liu from Hong-Kong

Summary

- Gravitational-Wave Astrophysics
  - Observing Run 4: 167 GW events so far
  - It's just a beginning!
- Searches for exceptional GW sources
  - Model-independent searches are suitable for discovery
  - Eccentric binaries: potential next discovery
  - Galactic core-collapse supernova is a once-in-a-lifetime opportunity.

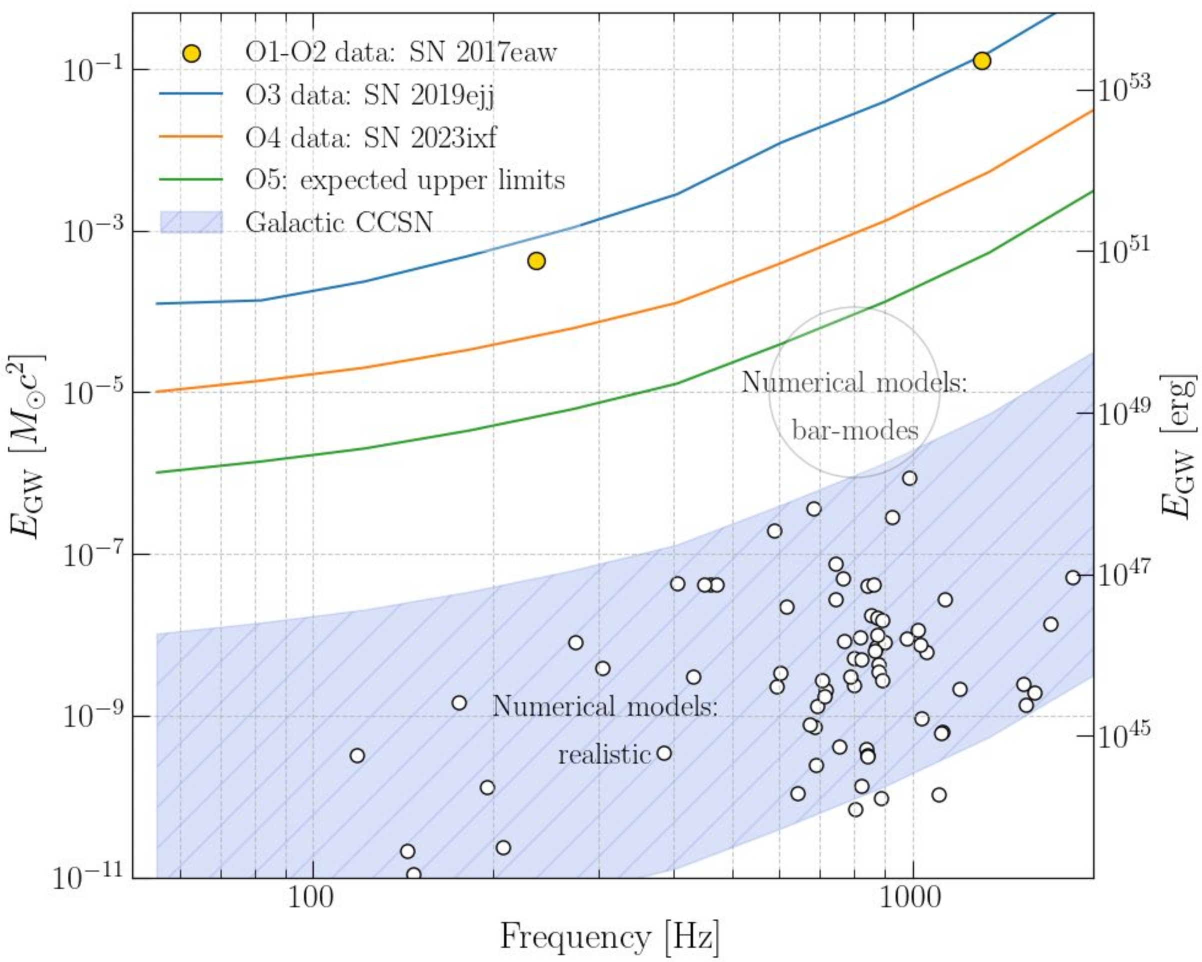
    Summer 2025: LVK workshop with CCSN modelers in Warsaw

(P.S. looking for students!)

Extra slides

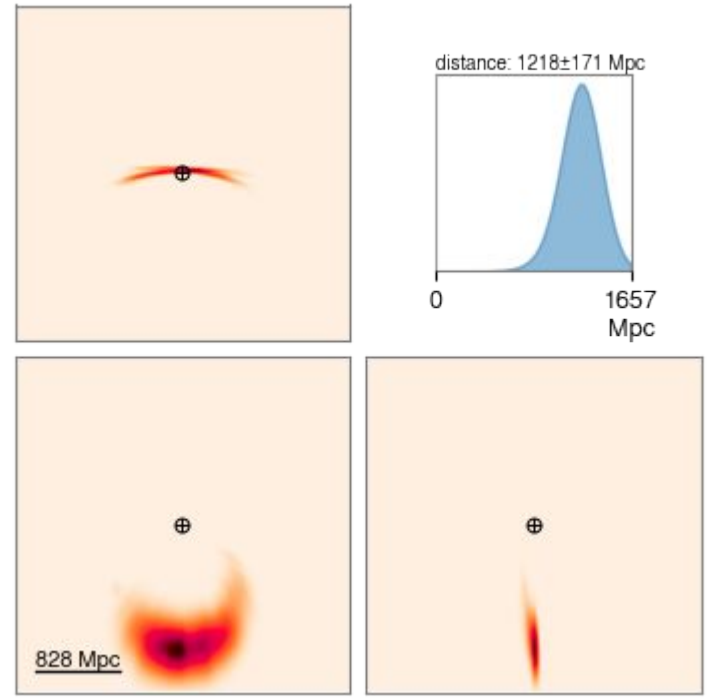
How far are we from a discovery?

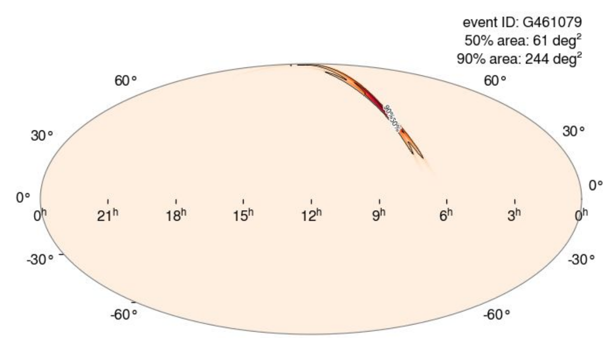
- SN 2017eaw - first observational constraints of CCSN engine
- SN 2023ixf - recent special LVK paper: 2410.16565
- O5 - we should start constraining numerical models
- **Realistically we need a Galactic CCSN.**



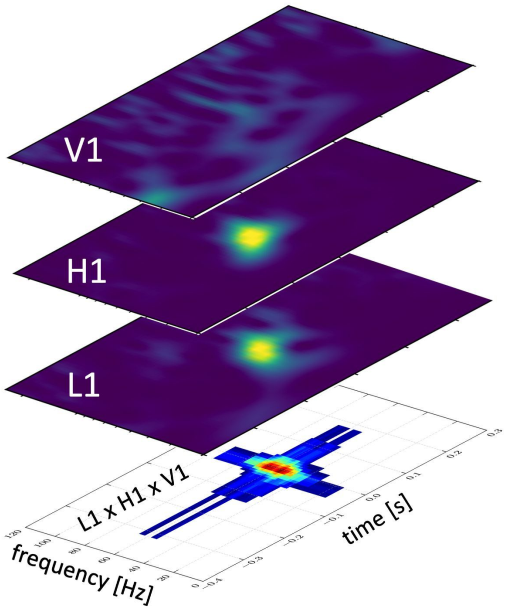
Public alerts

- Binaries (example plots: S231226av):
  - Sky localization
  - Distance
  - Source classification
- Burst event alerts:
  - "Fluence" ~ GW energy
  - Peak frequency
  - Duration
- S200114f - a burst public alert in O3, later classified as noise
- No burst public alerts so far in O4





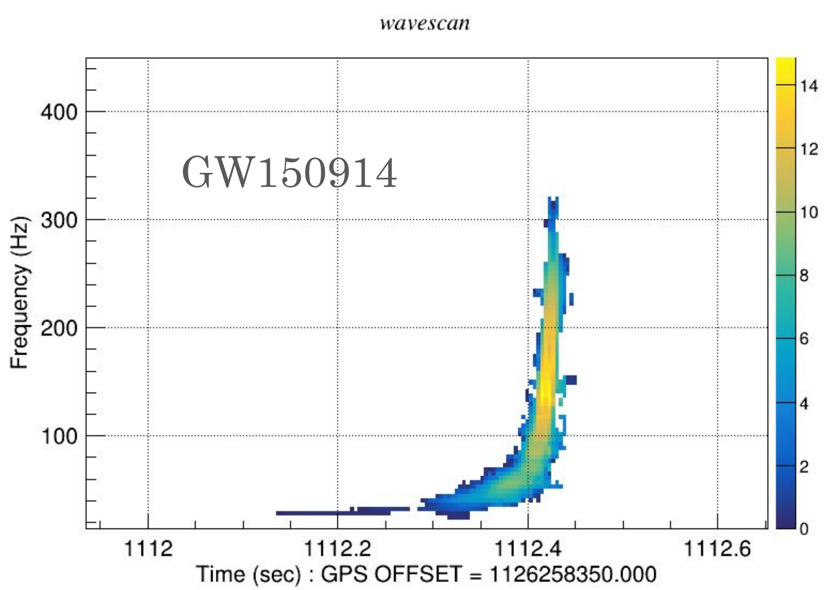
coherent WaveBurst (cWB)



x(t) → Wavelet Transform →

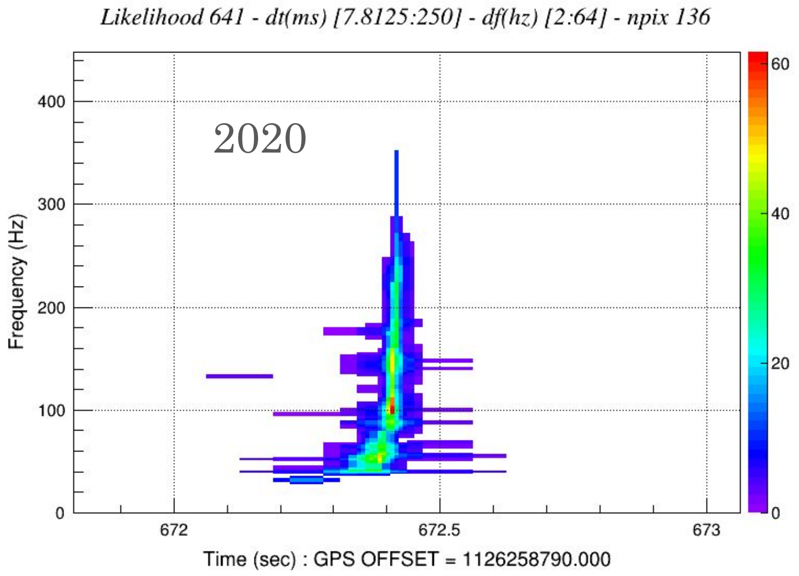
- Time-Frequency Decomposition
- Cluster Selection
- Constrained Likelihood

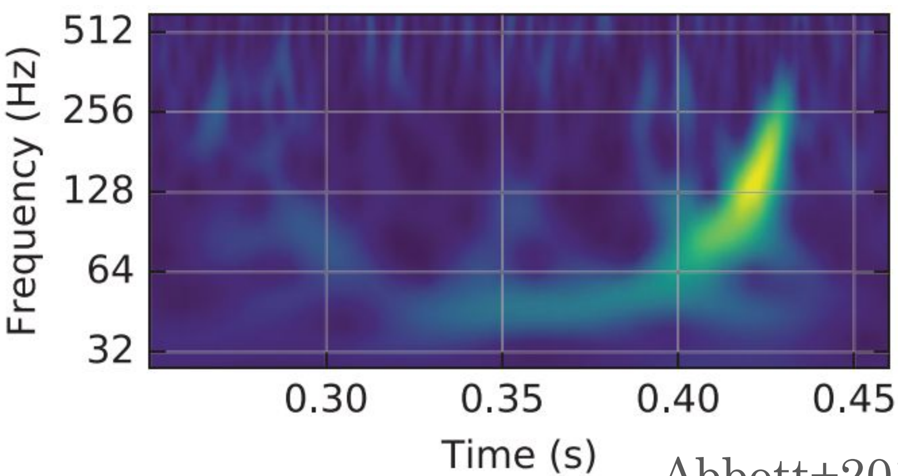
→ Inverse Wavelet Transform → h(t)



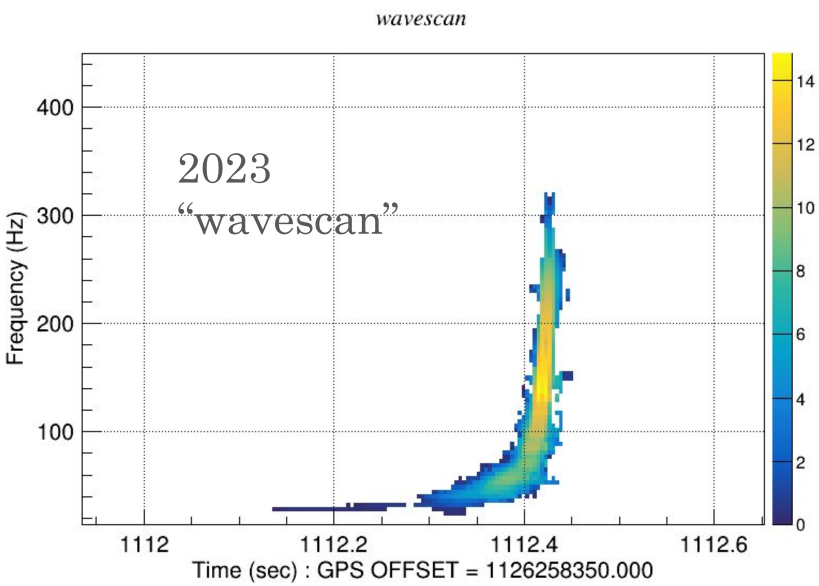
Time-frequency maps (GW150914 example)

- 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)



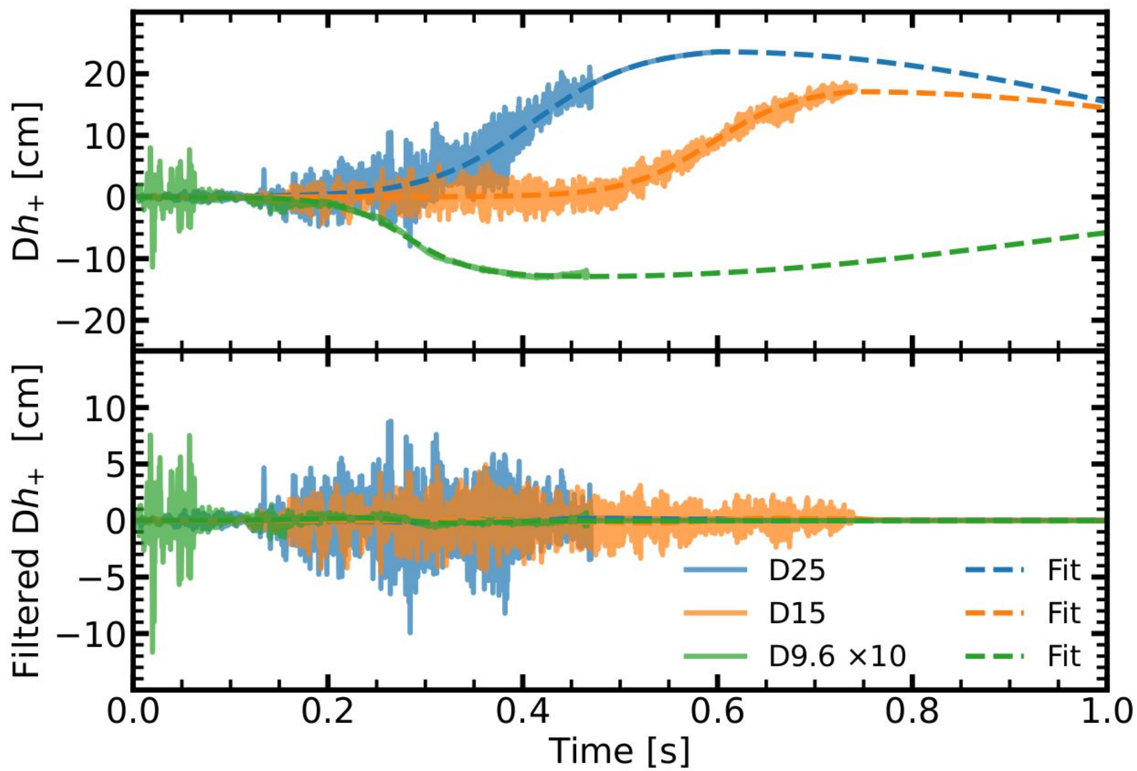


Abbott+2016



GW memory from CCSN

- Richardson et al (MS) 2024 (2404.02131) Accepted in PRL, Editors choice
- Prospect of detecting linear GW memory in Galactic CCSN
- A "jump" in GW strain below 10 Hz could be detectable with the current detectors



Compact binaries - potential future

“ After the Thomson discovery of the electron in 1897, the zoo of elementary particles remained almost unpopulated for decades. [...] Larger and more sensitive particle accelerators had been instrumental to discover **dozens of new species of elementary particles**.

[...] it is therefore natural to expect that the latest advance in GW astronomy and very long baseline interferometry can unveil new species in the **zoo of astrophysical compact objects**.
“

Cardasso & Pani 2015 *Testing the nature of dark compact objects: a status report* (1904.05363)

- In order to understand the inner structure of **elementary particles**, one must smash them!
- In order to understand the inner structure of **compact objects**, one must smash them!