Model-independent cWB searches

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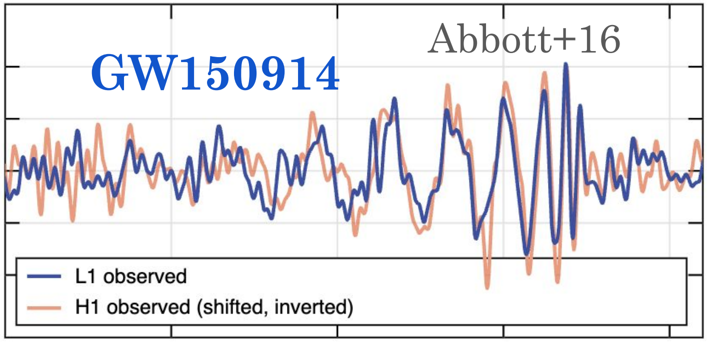


HEP Software Foundation India - IUCAA Joint Computing Workshop
Pune, 20-24.04.2026

Outline

- Part 1: Model-independent searches
  - Exceptional GW sources
  - Coherent WaveBurst
  - Searches
- Part 2: Hands-on exercises
  - Core-Collapse Supernova

After lunch:

- Binary black holes and post-production

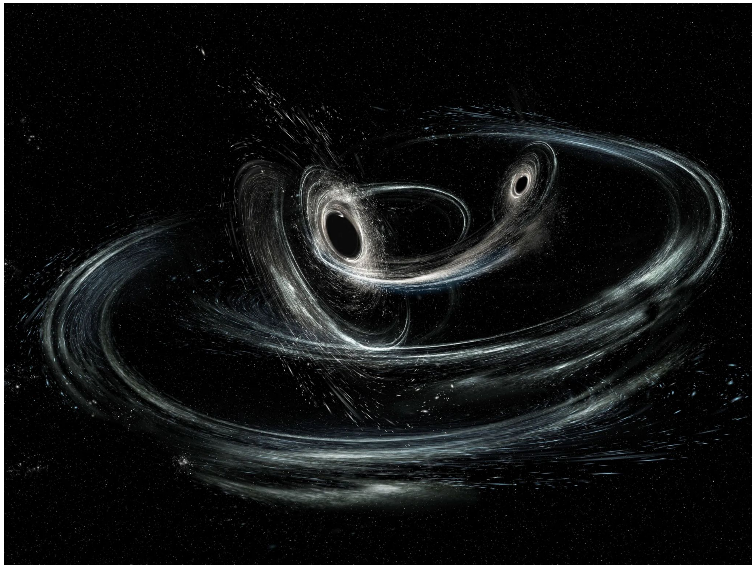
Part I
Model-independent searches

The Dynamic Universe

- **“Conventional” or time-domain Astronomy** (“looking” at the Universe): observing Universe using electromagnetic waves (e.g. visible light), cosmic rays or neutrinos.
- **“Gravitational-Wave” Astronomy** (“listening” to the Universe): observing Universe using gravitational-waves, the ripples of spacetime
  - Priority science area of **“New windows on the Dynamic Universe”** - the study of neutron stars, white dwarfs, collisions of black holes, and stellar explosions – Astro 2020 Survey

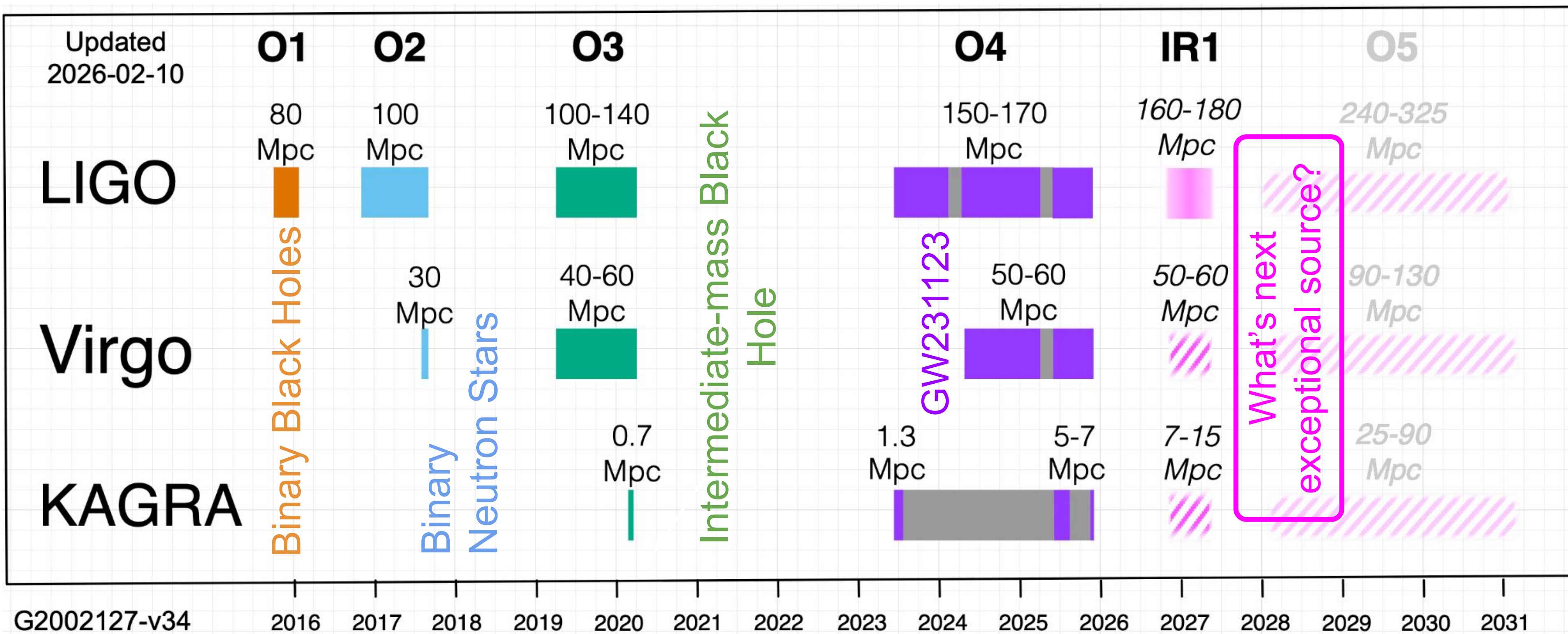
GW sources (need aspherical mass-energy movement):

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



AURORE SIMONNET/LIGO/CALTECH/MIT/SONOMA STATE

Observing Timeline



- O4: 24 months total, until 18 Nov 2025
- LIGO: up to 180 Mpc, around 160 Mpc
- Virgo: around 55 Mpc
- KAGRA: up to 10 Mpc, not yet observing, reached 7 Mpc

https://observing.docs.ligo.org/plan/

Exceptional/special GW sources
(and my top picks for O5 in blue)

Exceptiona/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 supernova (CCSN), neutron star or pulsar glitches, cosmic strings — The prime burst source, the second part of the lecture
- **Multi-messenger GW sources** (electromagnetic waves, neutrinos, cosmic rays): CCSN, binary neutron stars merger and post-merger, neutron-star - black hole
- **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

Is it possible to model accurately every GW source? Not really…

→ Model-independent (GW bursts) searches

GW Sources and Searches

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

PyCBC (Tuesday)
Bilby (Wednesday)

Table 1. Candidate GW signals from O4a with a FAR $\leq 1\,\mathrm{yr}^{-1}$ in at least one analysis and for which $p_{\mathrm{astro}} > 0.5$.

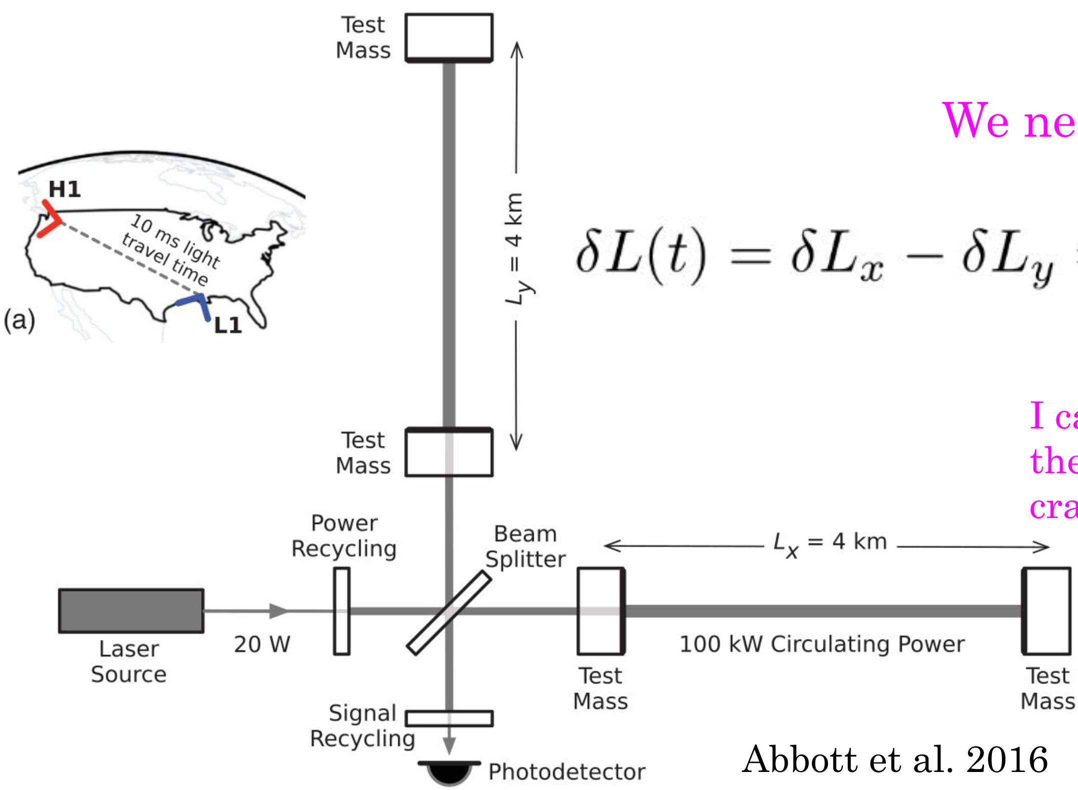
Complementary searches

Candidate	Inst.	cWB-BBH			GstLAL			MBTA			PyCBC		
		FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}

Abbott et al 2025, GWTC-4

Gravitational-Wave detectors

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



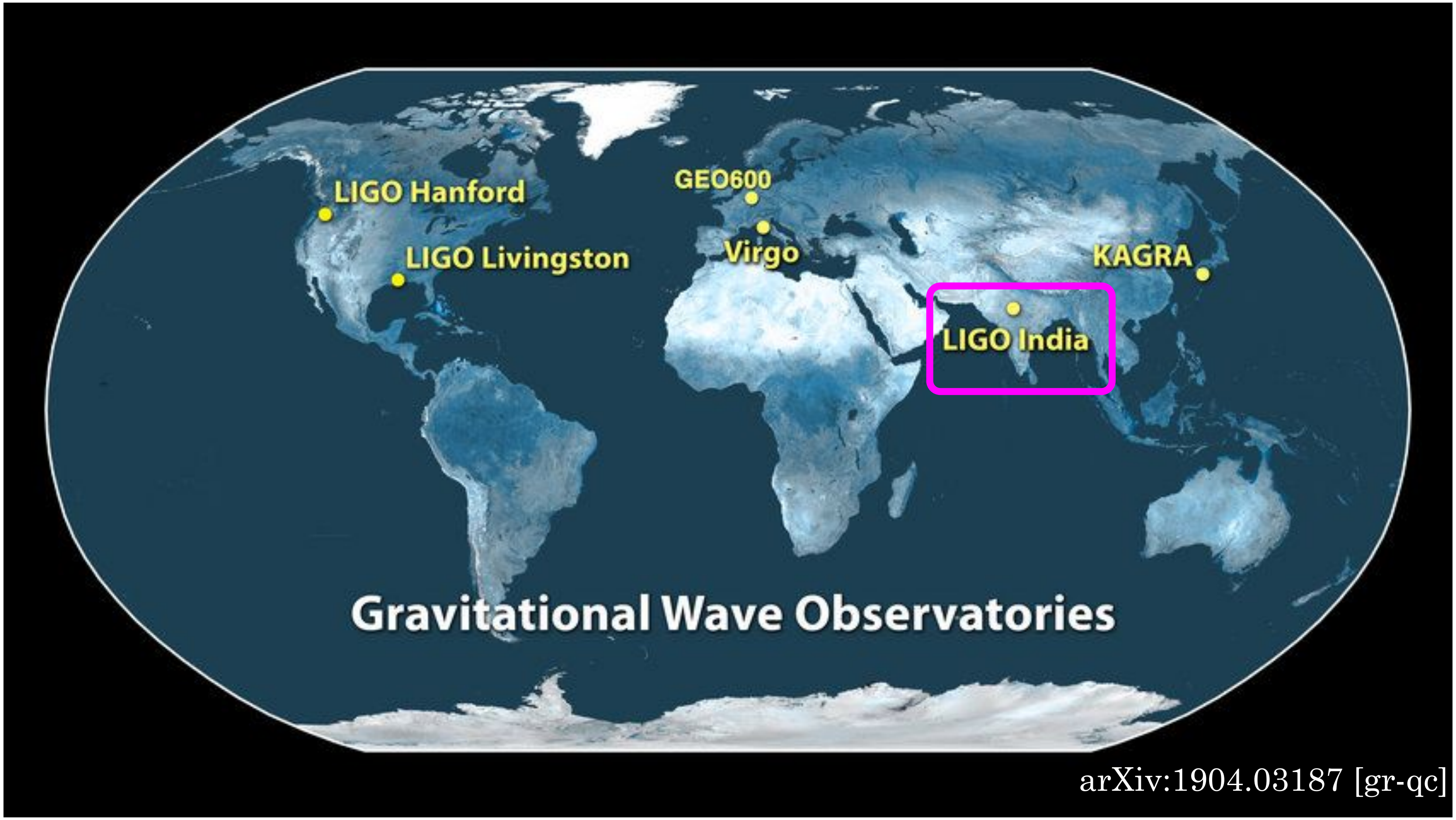
We need this:

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

Abbott et al. 2016

I can't wait for the LIGO India crazy stories!

Detectors network

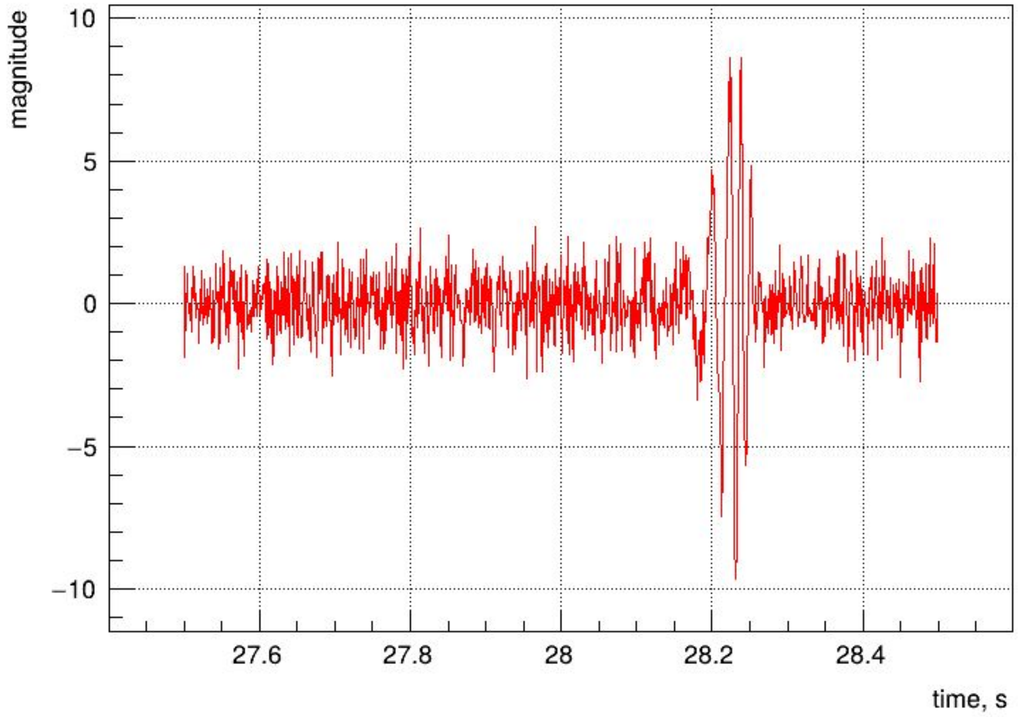


- KAGRA - recently joined observations
- LIGO India - under construction!
- Planned Australian detector

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)

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:

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

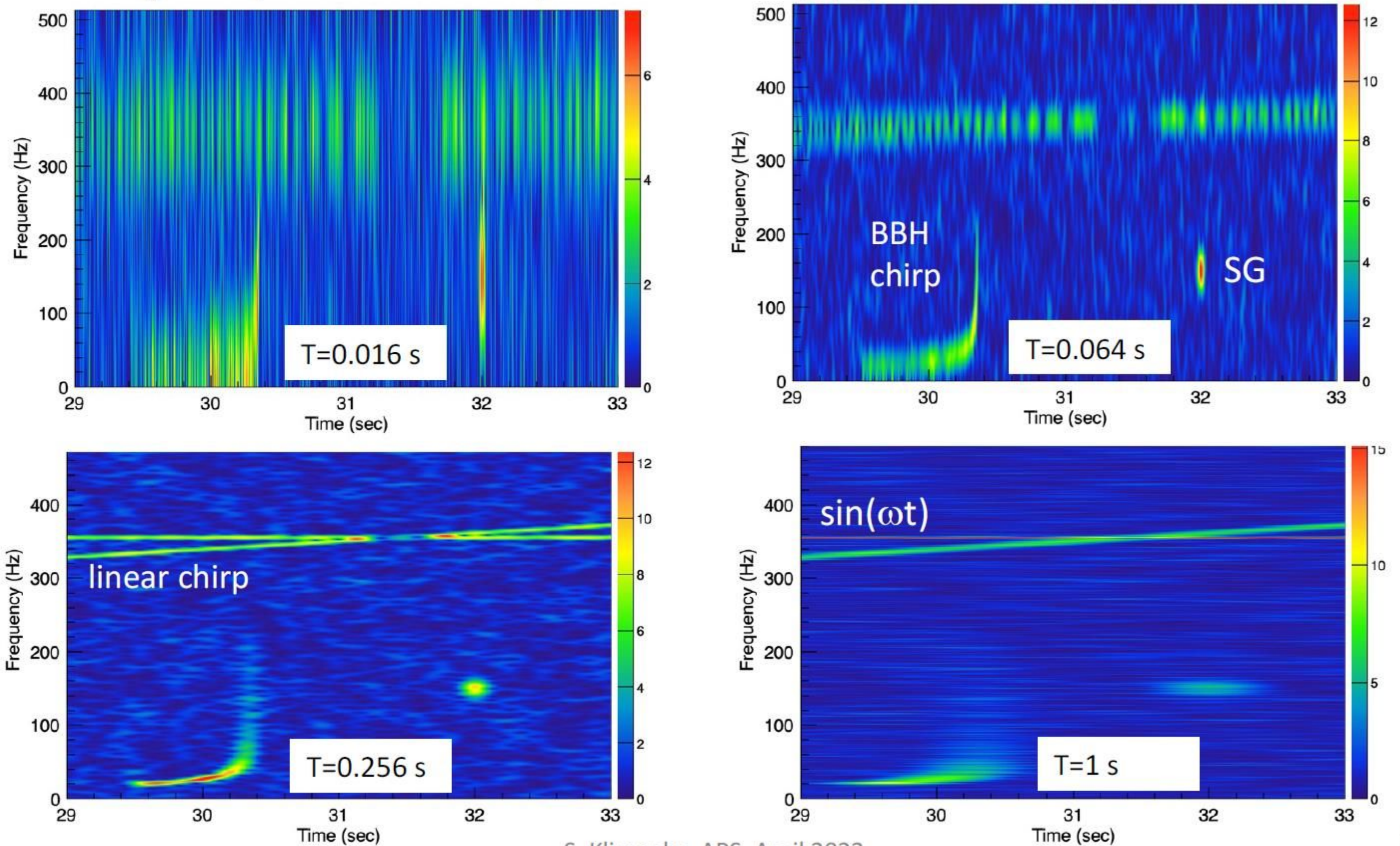
More at the second Lecture

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 $P(\omega, t)$ of the time-varying spectrum?



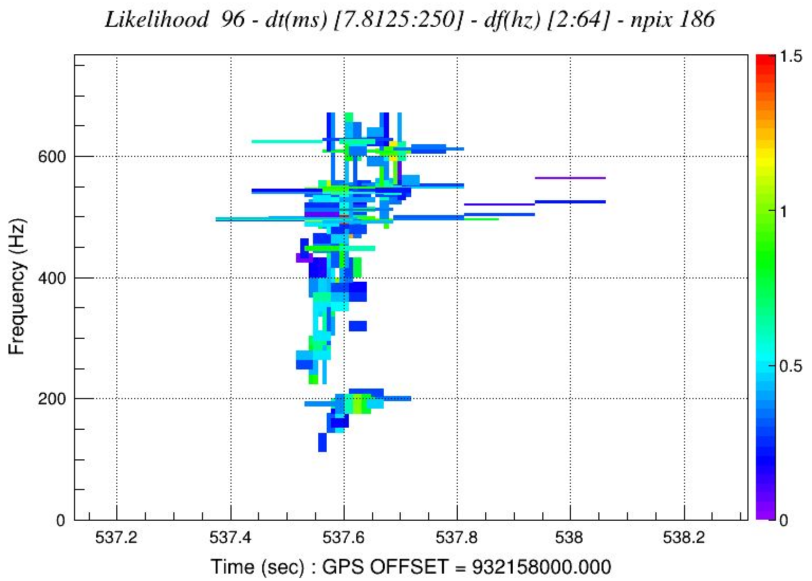
S. Klimenko, APS, April 2022 3

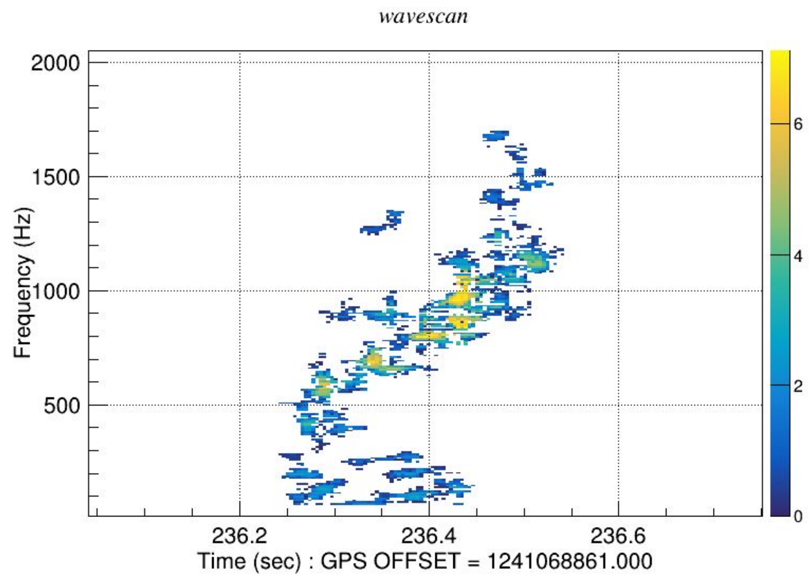
Multiresolution wavelet decomposition

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

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

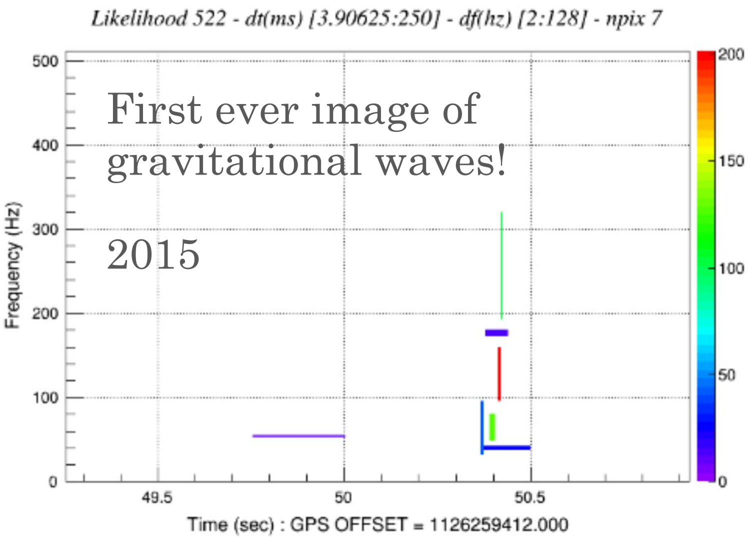
  (Heisenberg rule for signal processing)
- Detectability of signals depends on setting up appropriately Δt and Δf.
- cWB uses 7 multiresolution decomposition layers

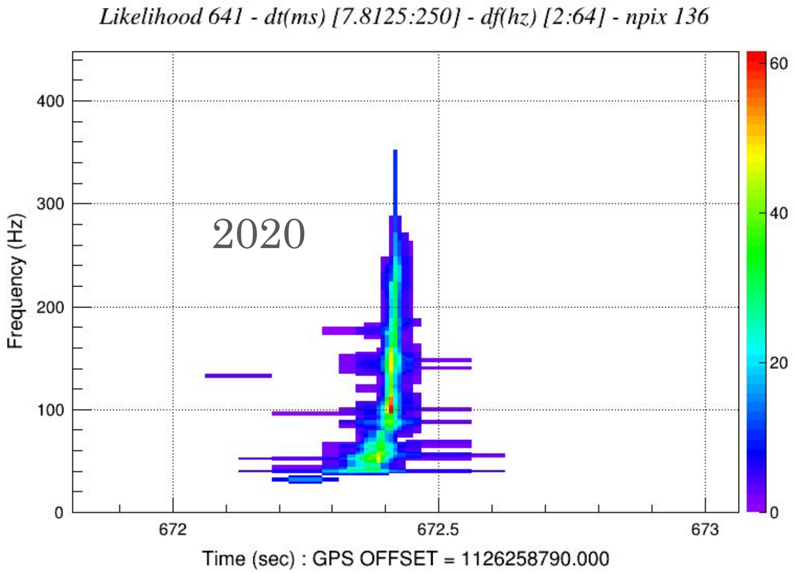


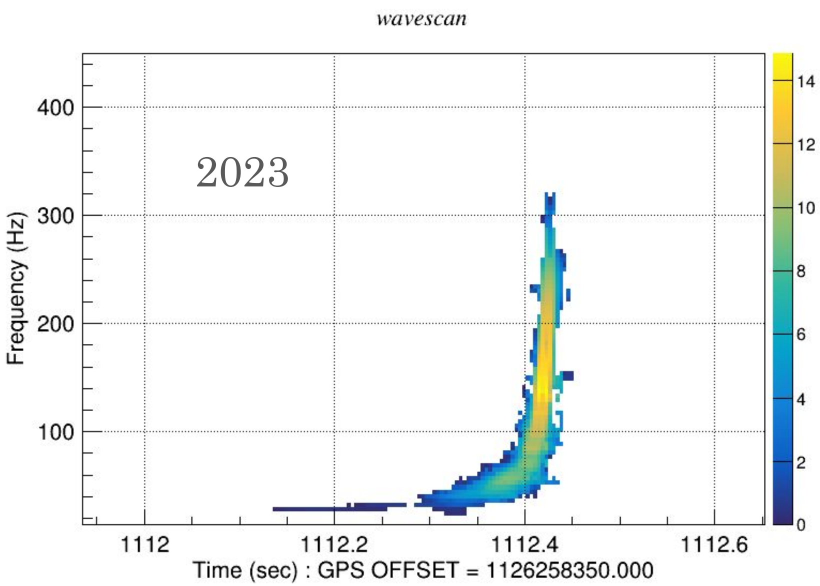


Improvements: GW150914 example

- Challenges:
  - Temporal leakage (time domain)
  - Spectral leakage (frequency domain)
  - Combining resolutions
- Latest developments: high-resolution time-frequency transform and minimize leakage

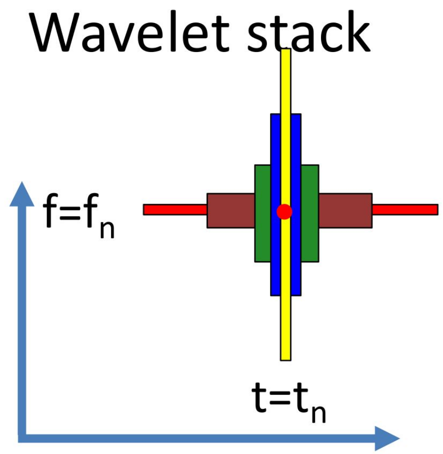


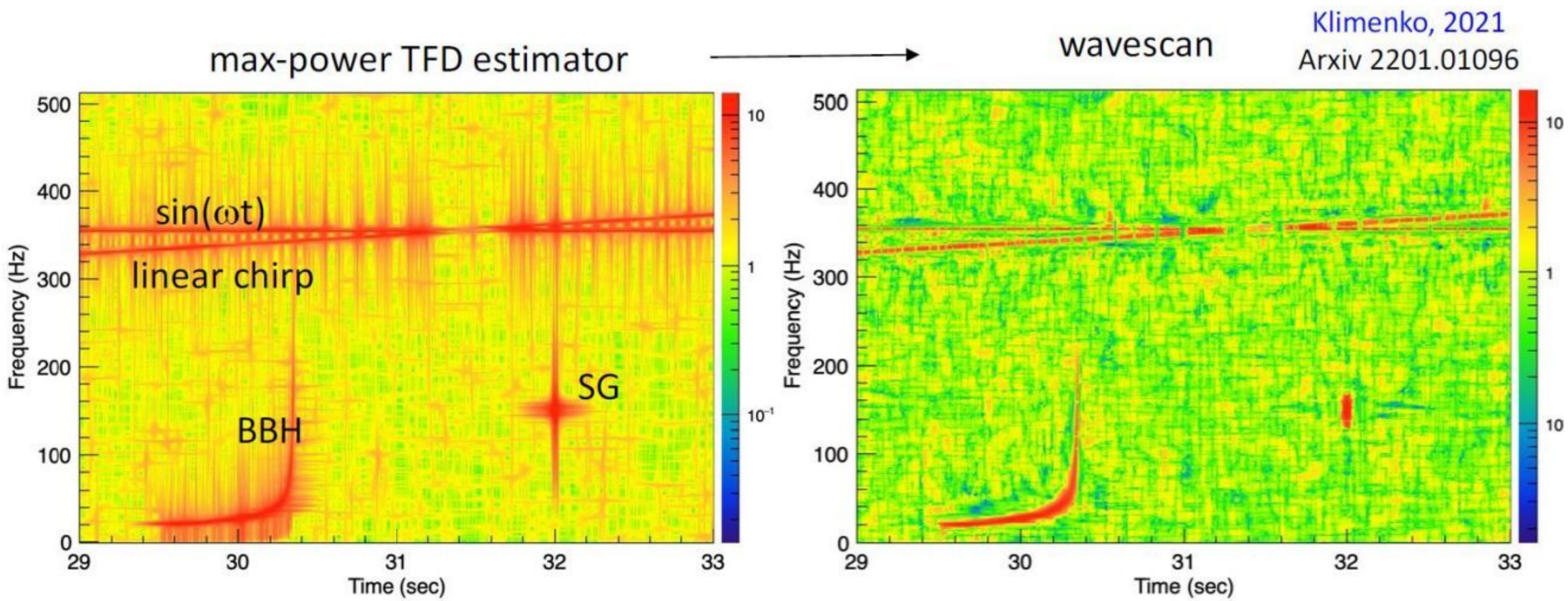




Wavescan

- Wavescan (Klimenko+22, 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.



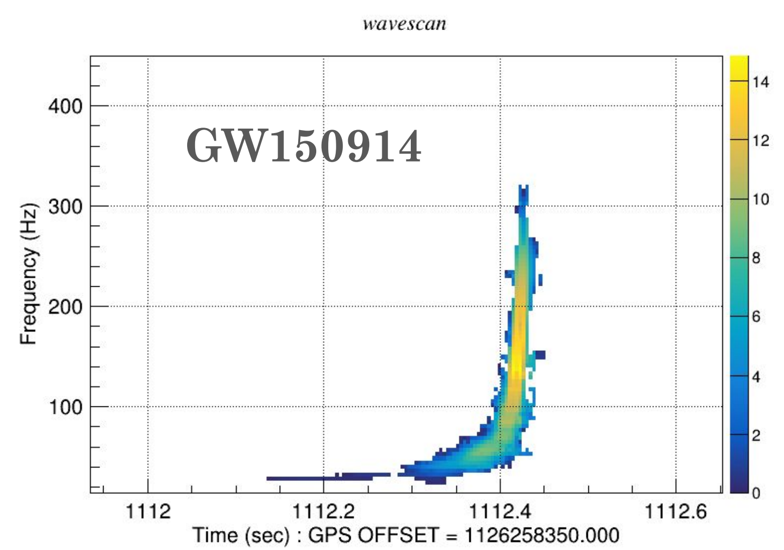


Model-independent searches

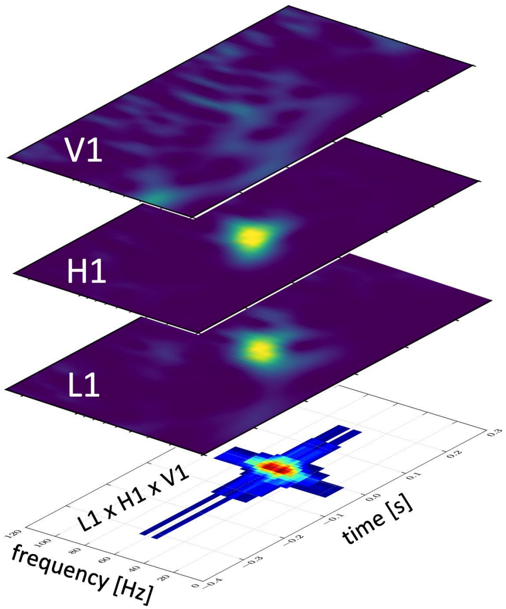
- **Coherent WaveBurst** (cWB, Klimenko+16) is a software designed to detect a wide range of burst transients without prior knowledge of the signal morphology
- cWB may use **minimal assumptions**, for example growing frequency over time in case of binaries
- **Complementing template-based searches**
- cWB has detected:
  - **GW150914** - the very first GW
  - **GW190521 and GW231123** - intermediate-mass binary black holes
  - 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/



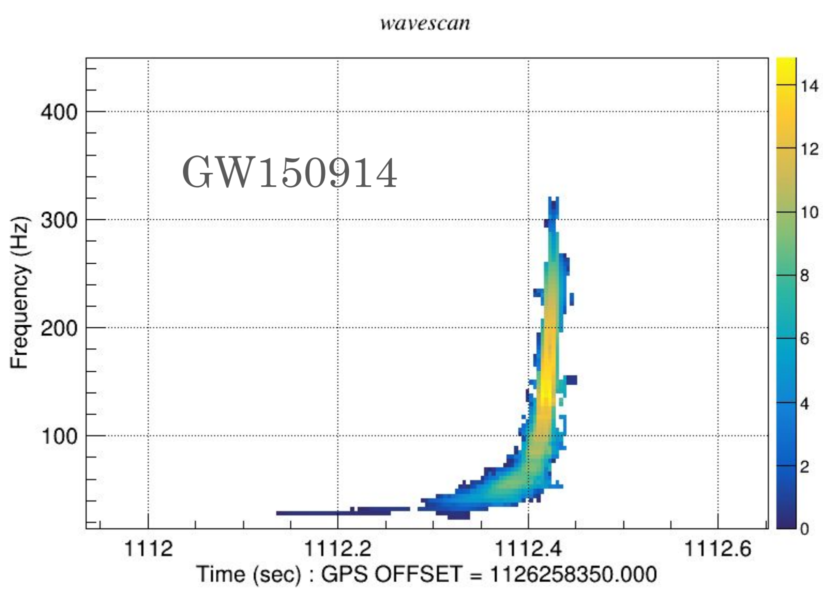
coherent WaveBurst (cWB)



x(t) —Wavelet Transform→

- Time-Frequency Decomposition
- Cluster Selection
- Constrained Likelihood

—Inverse Transform→ h(t)

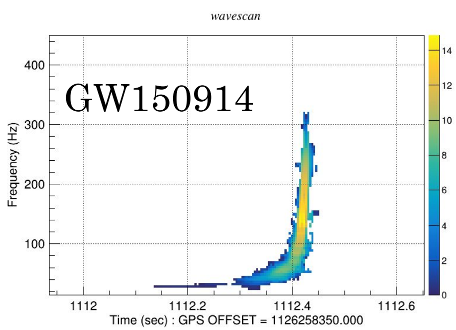


Model-independent searches classification

Compact binary searches (minimally modeled)

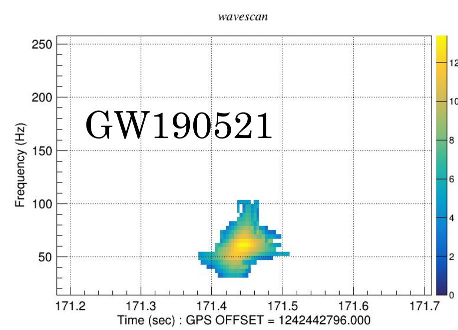
Generic searches (unmodeled)

Binary black holes
Binary neutron stars
Black hole - neutron star



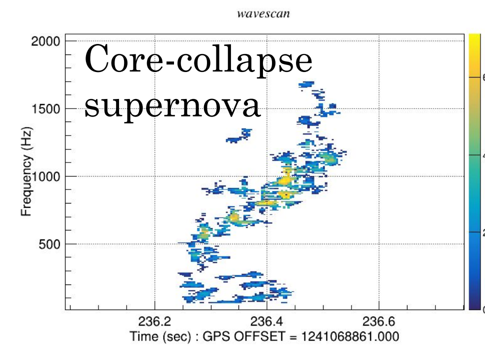
e.g. Mishra+23 (2201.01495)

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



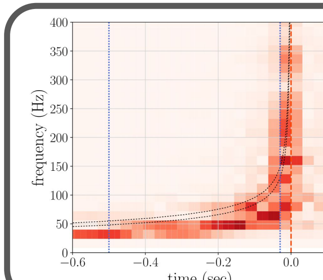
e.g. MS+24 (2305.16146)

Low-latency searches

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

e.g. Chaudhary+24 (2308.04545)

Searches for new phenomena

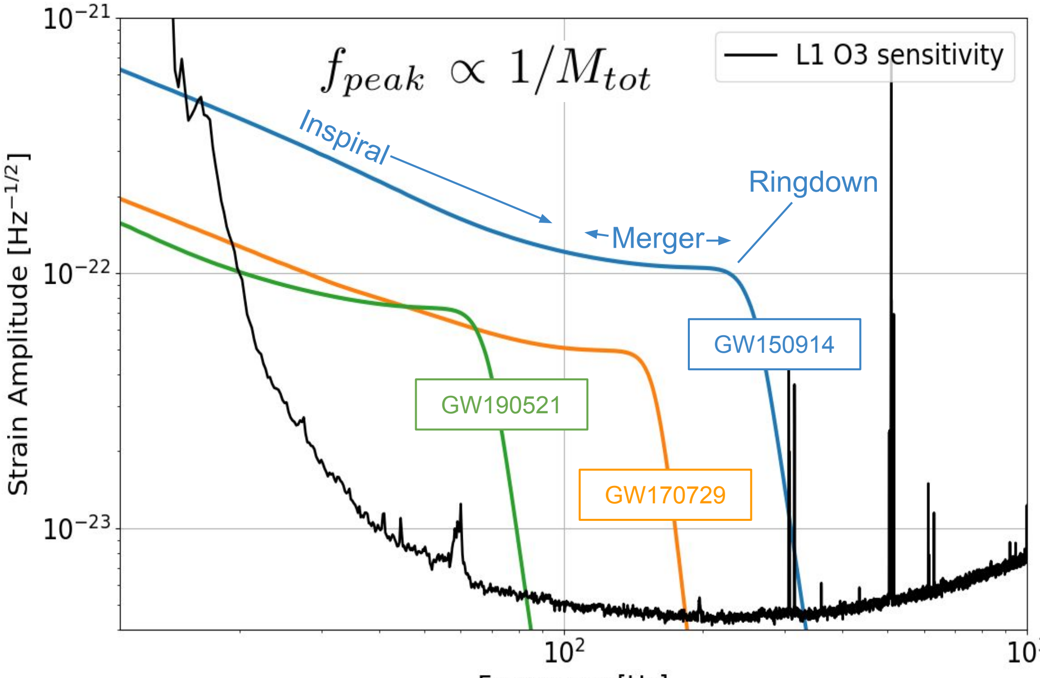


Higher harmonics
GW cross-polarization
Deviations from GR

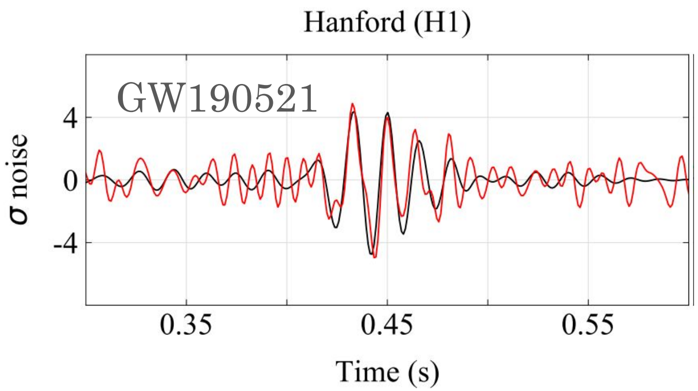
e.g. Vedovato+22 (2108.13384)

GW190521 and GW231123

- **Intermediate-mass black holes** (IMBHs) - between stellar mass (100 $M_\odot$ and supermassive (10^5 $M_\odot$). The origin is not yet well understood. Exploring:
    - Probing pair-instability mass gap (Stars with He mass in (64 $M_\odot$, 135 $M_\odot$)
    - Formation channels
    - Most distant GW sources
- No chirping structure
- Peak frequency is inversely proportional to the total mass.
- **GW190521** - first conclusive evidence of an IMBH (see MS+21, 2009.11336)
- **GW231123** - the heaviest black hole detected so far.

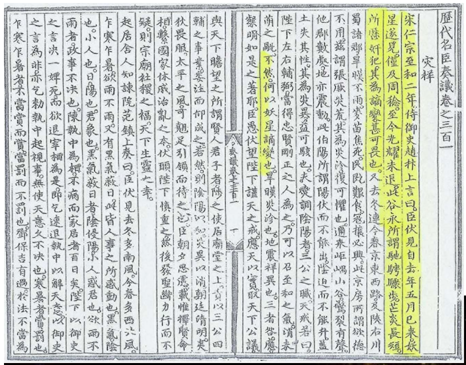


GW190521 webinar



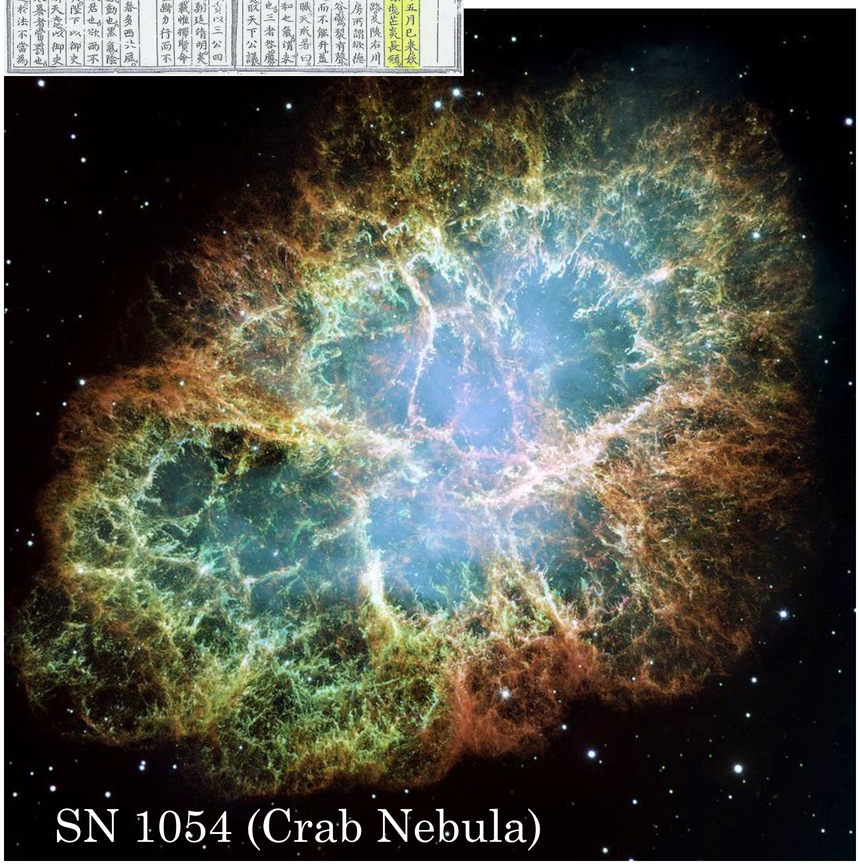
Part II
Hands-on exercises

Core-Collapse Supernova (CCSN)



"Guest star"

Zhao Bian's memorial to Emperor Renzong

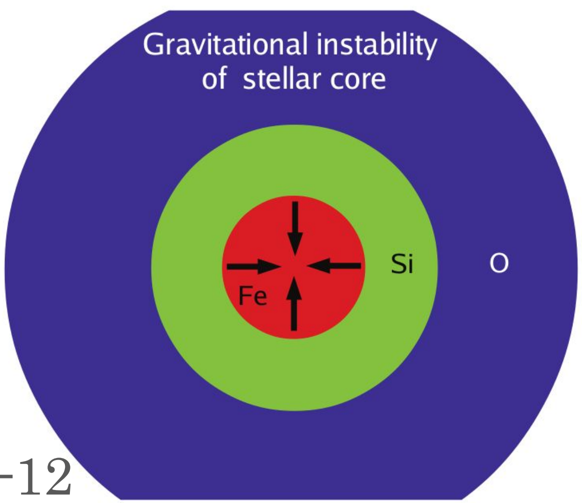


SN 1054 (Crab Nebula)

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!
- Supernova problem: **why do the stars explode?**
- Explosion mechanism(s) is still unknown

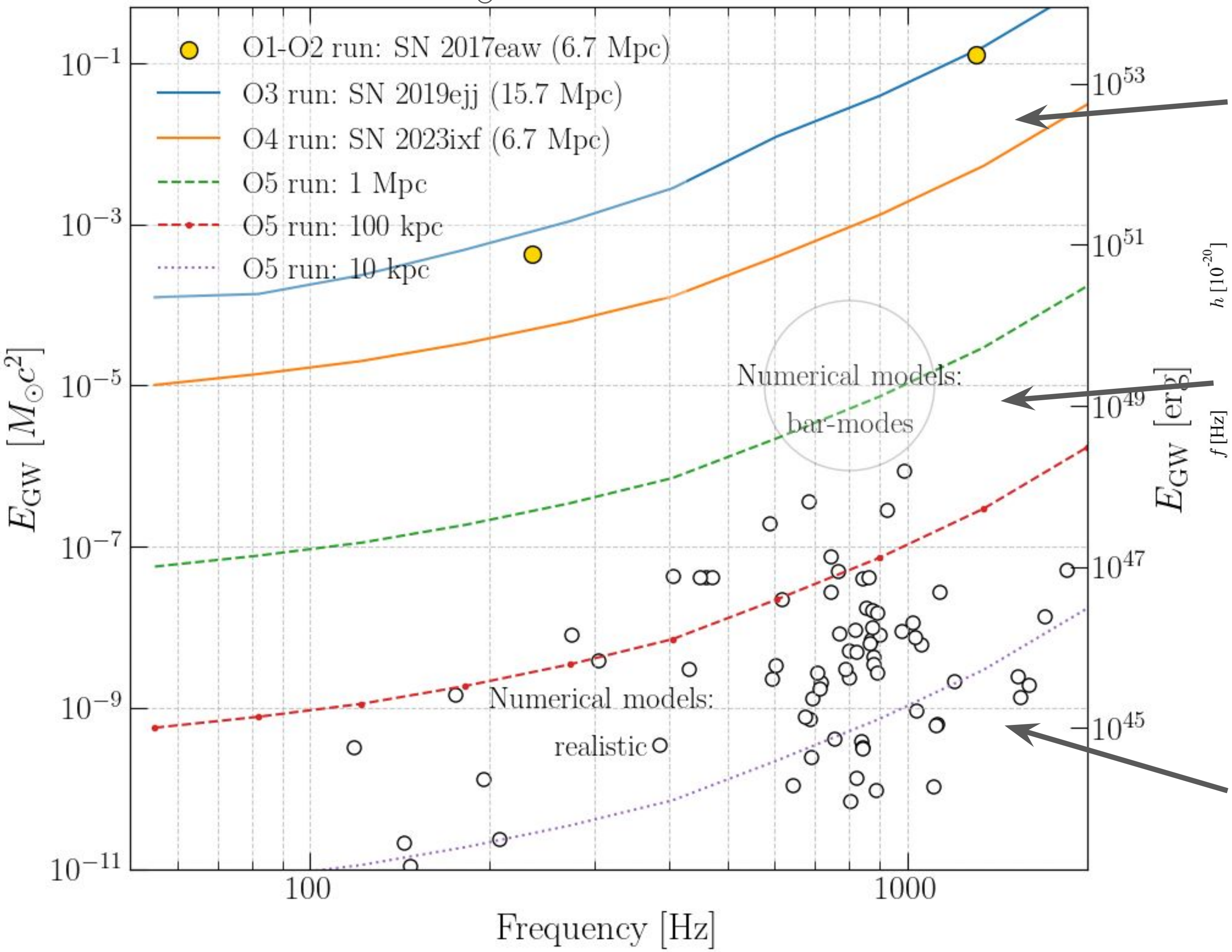


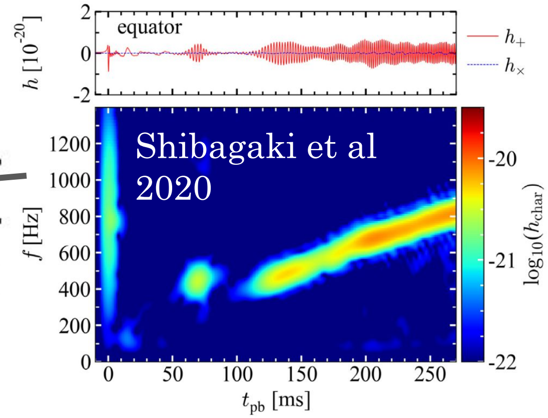
Janka+12

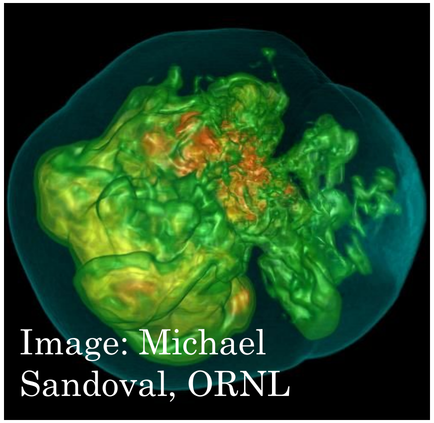
When will we discover GWs?

(realistically: Galactic CCSN)

Binary black holes: ~3 $M_{\odot}c^2$

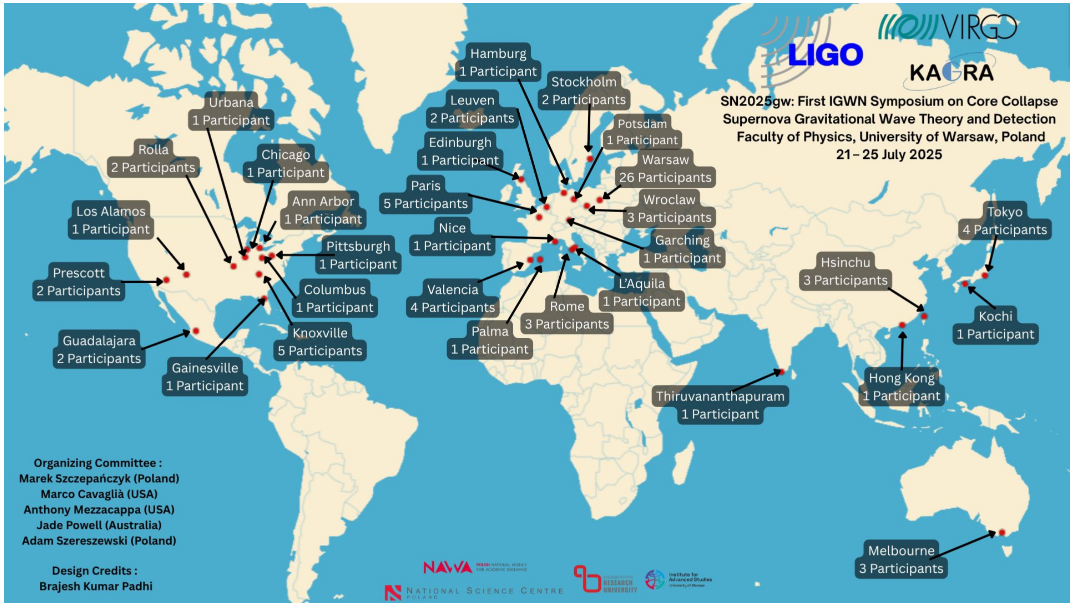




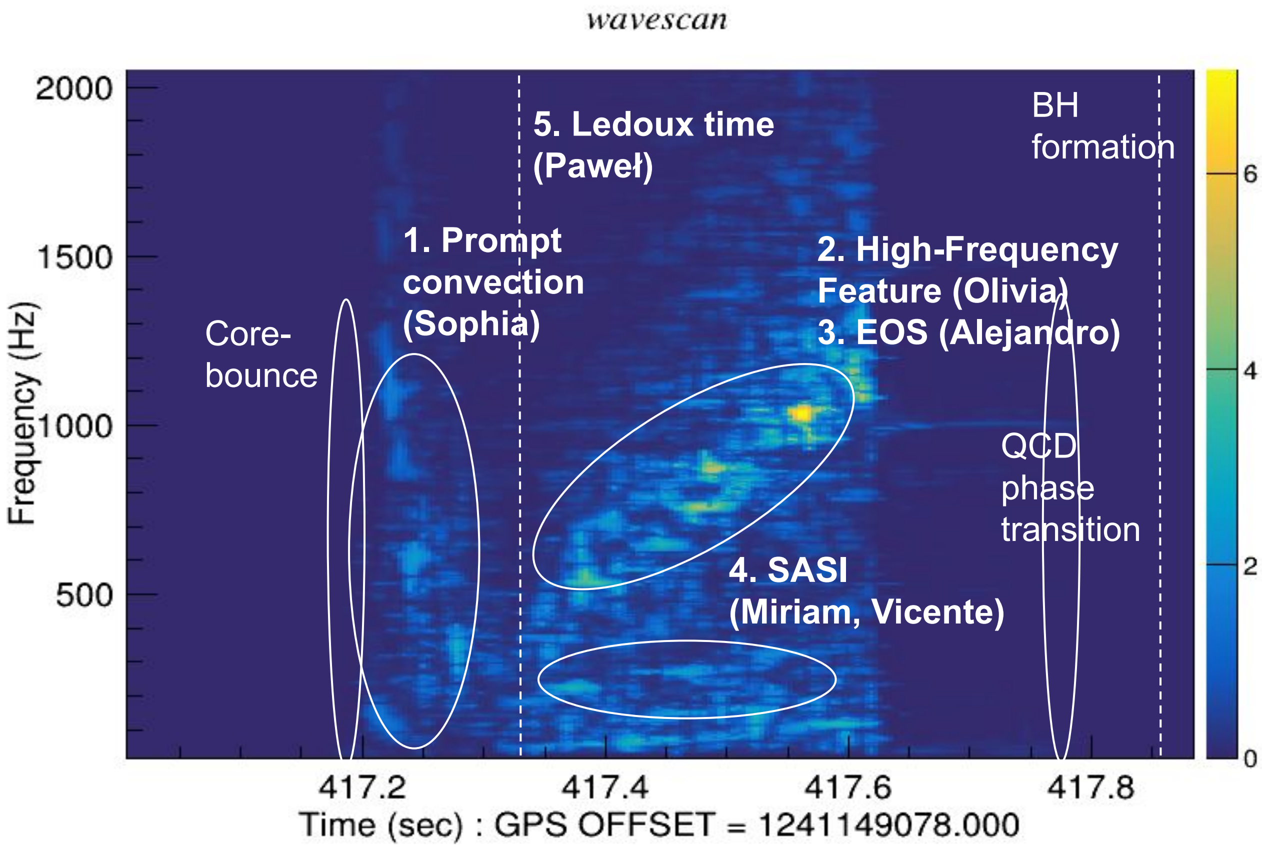


SN2025gw: IGWN Symposium on CCSNe Bridging the Gap

- IGWN - International Gravitational-Wave Network, to replace LVK
- Symposium webpage: https://indico2.fuw.edu.pl/event/17/overview
- CCSNe are the most challenging astronomical events to model
    - Theory, GW, neutrino, EM, next 10 years
- Slack channel: please ask me to add you
- Youtube: playlist
- Large attendance of the Symposium



SN2025gw: Physical inference



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

Hands on exercises

We go straight an making
our first example cWB
waveform reconstruction!

Create your first waveform reconstruction!

Instructions: `/home/marek.szczepanczyk/O4/SEARCHES/OFFLINE/SN/LH/SIM/README.txt`

Login:

```
$ ssh albert.einstein@ldas-pcdev7.gw.iucaa.in
```

Setup cWB:

```
$ cp /home/marek.szczepanczyk/.rootrc ~/ # you do it only one time!
$ source /home/tanmaya.mishra/git/library_XP/sarathi_watenv_cmake.sh # every time you login
$ root # check if the environment is properly loaded
```

```
*****************************************************************************
*                                                                           *
*             W E L C O M E  to  C W B                                      *
*                                                                           *
*             cWB    Version  7.0.1.0 (XIFO=4)                              *
*                     Branch  (HEAD                                         *
*                       Hash  f1aaee5ef5f907372457c4c65792c1277ec9795a      *
*                 Short Hash  f1aaee5e                                      *
*                                                                           *
*             LAL     Branch  7.2.4                                         *
*             FRLIB  Version  8.42                                          *
*                                                                           *
*             Based  on ROOT  6.26/08                                       *
*                                                                           *
*             CPP             ENABLED                                       *
*             EBBH            DISABLED                                      *
*             TEOBRESUMS      ENABLED                                       *
*             ANALYSIS        XP                                            *
*                                                                           *
*             CONFIG          Undefined                                     *
*             DATA            UNDEFINED                                     *
*                                                                           *
*****************************************************************************
```

Create your first waveform reconstruction!

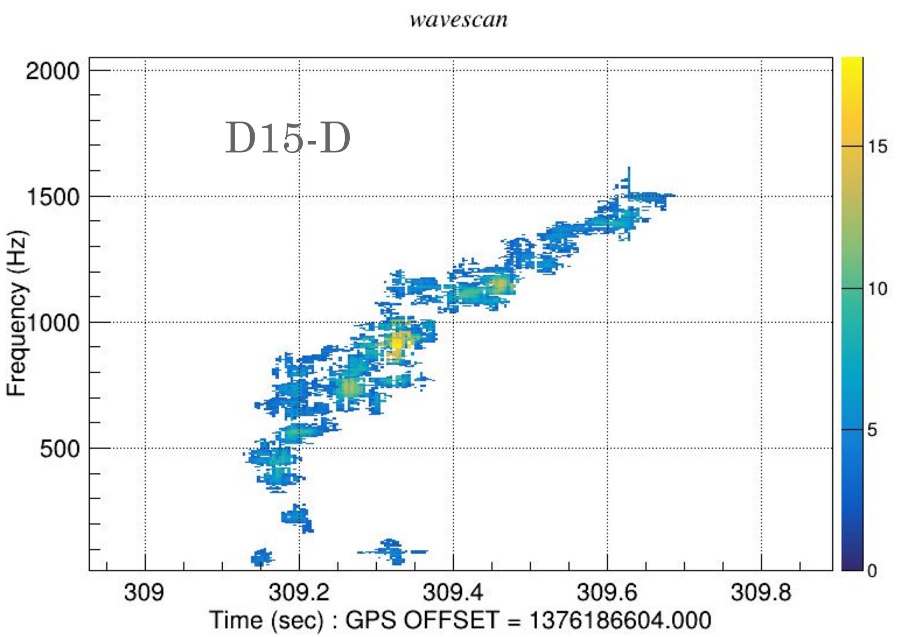
```
$ cwb_mksdirs --idir /home/albert.einstein/O4 # directory structure, useful
to the afternoon
$ mkdir -p O4/SEARCHES/OFFLINE/SN/LH/SIM/ # create a specific SN directory
$ cd O4/SEARCHES/OFFLINE/SN/LH/SIM/ # go there
$ cwb_clonedir
/home/marek.szczepanczyk/O4/SEARCHES/OFFLINE/SN/LH/SIM/O4_K07_C00_LH_SN_SIM_
template_dev1 O4_K07_C00_LH_SN_SIM_dev1 # clone the working directory
$ cd O4_K07_C00_LH_SN_SIM_dev1 # go to your working directory
$ pwd # check if you are there, it should be:
/home/albert.einstein/O4/SEARCHES/OFFLINE/SN/LH/SIM/O4_K07_C00_LH_SN_SIM_dev
1
$ cwb_compile macro/CWB_Plugin_xQveto_xConditioning_MDC_OTF.C # compile
analysis-specific code
$ cwb_inet 1 1376186913 ced # create a reconstruction for D15-3D waveform
$ cwb_inet 2 1376188121 ced # create a reconstruction for mesa20_pert
waveform
$ mv data/* ~/public_html/ # move these reconstruction to the public pages
```

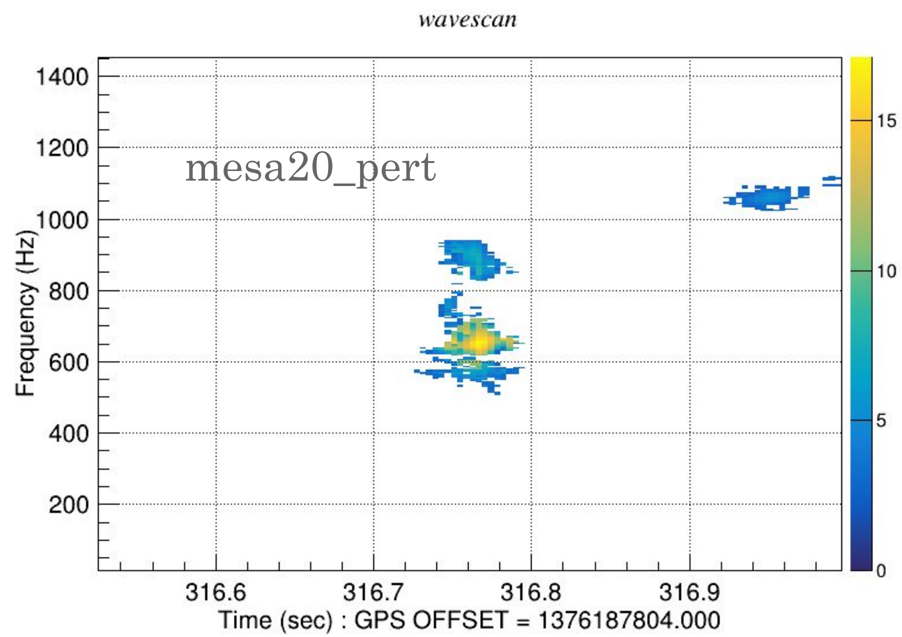
You can access these reconstructions in your page (albert.einstein):
`https://ldas-jobs.gw.iucaa.in/~marek.szczepanczyk/`

Coherent Event Display (CED)

Assuming a CCSN explodes 1 kpc away, we expect the possible morphologies according to the following models:

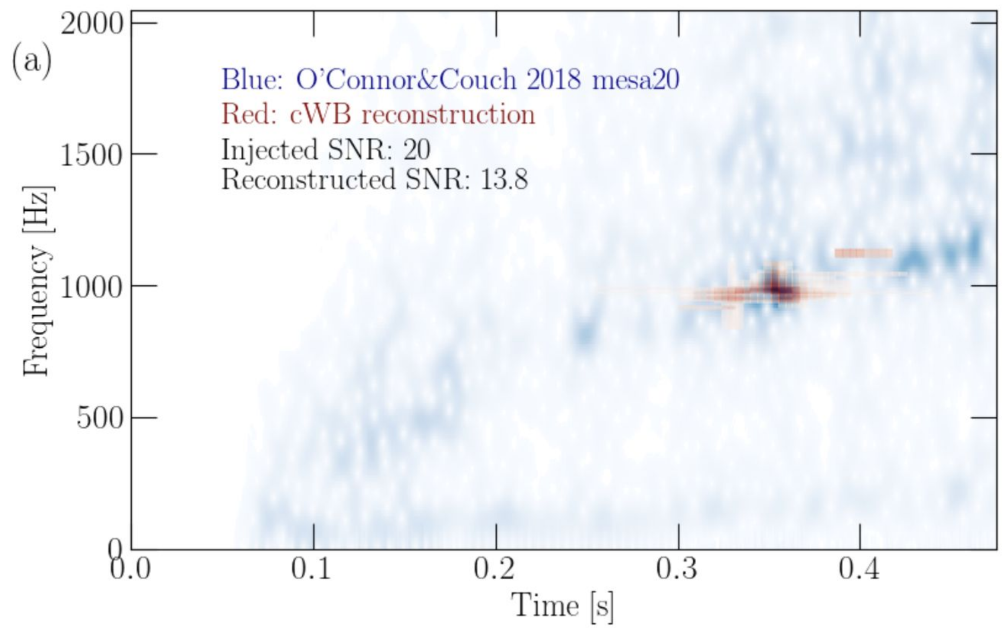
- Mezzacappa et al 2023, D15-D: CED
- O’Connor&Couch 2018, mesa20_pert: CED





CCSN physical inference

- Your task: **how strong (how close) a CCSN need to be to have detectable physical features?**
- Use CEDs:
  `cwb_inet 1 1376186913 ced 10`
  where the last number is a scale factor that converts to a distance:
  10 → 1 kpc, 1 → 10 kpc, 5 → 10/5 kpc = 2 kpc, 2 → 10/2 kpc = 5 kpc
- Reference distance, Milky Way center: 8.5 kpc.
- For CCSN waveform reconstruction challenges:
  - Szczepanczyk et al 202, Detecting and reconstructing gravitational waves from the next Galactic core-collapse supernova in the Advanced Detector Era: https://arxiv.org/abs/2104.06462



Part III
Friday Hackathon

Producing waveforms

Produce waveforms with pycbc:

```
/home/marek.szczepanczyk/O4/SEARCHES/OFFLINE/BBH/LH/SIM/O4_K07_C00_LH_BBH_
SIM_template_dev1/input/README_wf.txt

$ conda deactivate   # Don't forget to activate back the conda env for cWB
$ conda activate igwn
$ python
>>> from pycbc import waveform
>>> waveform.td_approximants()
>>> import numpy as np

>>> hplus = []
>>> hcross= []
>>> R = 16384.0
>>> hplus,hcross =
waveform.get_td_waveform(mass1=36.0,mass2=29.0,approximant='SEOBNRv5PHM',d
elta_t=1.0/R,f_lower=20.0,distance=410,inclination=0.0) # GW150914
# Window the waveforms
>>> for i in range(int(R/4)): # R/4 = 0.25sec
>>>   hplus[i] = hplus[i] * np.sin(2*np.pi*i/R)
>>>   hcross[i]= hcross[i]* np.sin(2*np.pi*i/R)
>>> np.savetxt('BBH_hp.txt',np.transpose([hplus] ))
>>> np.savetxt('BBH_hc.txt',np.transpose([hcross]))
```

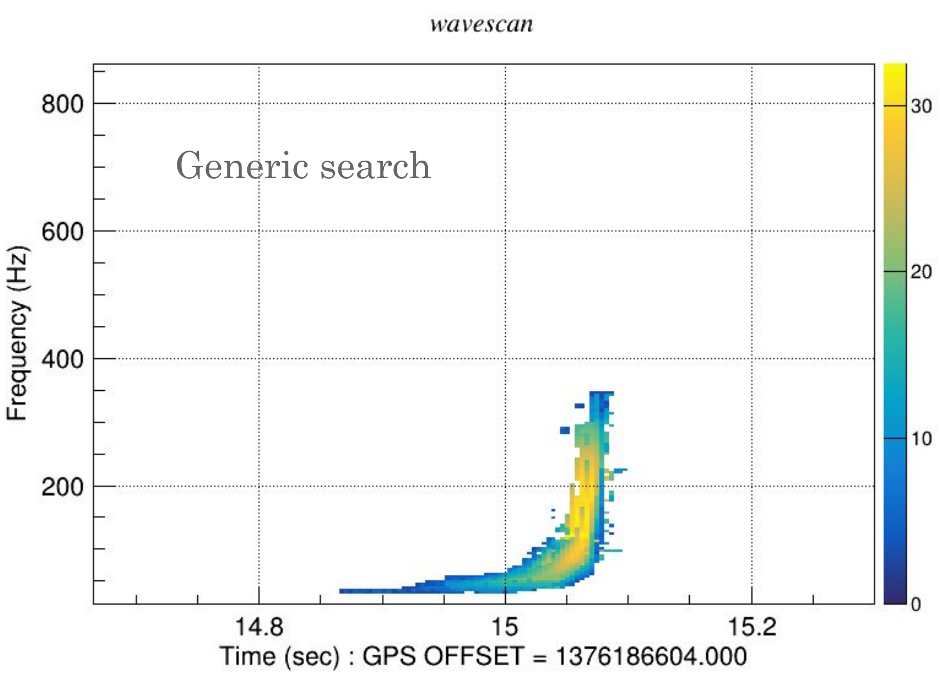
Producing CEDs

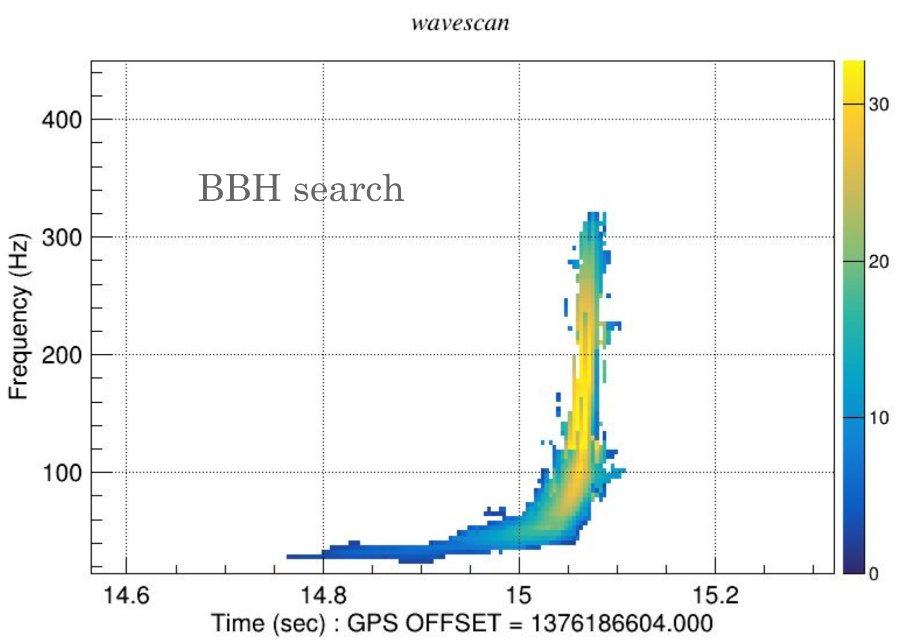
Produce CEDs:

```
$ cd ~/O4/SEARCHES/OFFLINE/BBH/LH/SIM/
$ cwb_clonedir
/home/marek.szczepanczyk/O4/SEARCHES/OFFLINE/BBH/LH/SIM/O4_K07_C00_LH_BBH_SIM_t
emplate_dev1 O4_K07_C00_LH_BBH_SIM_dev1
$ cd O4_K07_C00_LH_BBH_SIM_dev1
$ cwb_compile CWB_Plugin_xGating_xQveto_xConditioning_MDC_OTF.C
$ cwb_inet 1
$ mv data/wave_1376186608_1200_O4_K07_C00_LH_BBH_SIM_dev1_1_job1.root output/
$ root output/wave_1376186608_1200_O4_K07_C00_LH_BBH_SIM_dev1_1_job1.root
root [1] ScanWAVE("run:name:time[0]","","colsize=10")
***************************************************
*    Row   *        run *       name *    time[0] *
***************************************************
*        0 *          1 *        BBH * 1376186619 *
[...]
*       11 *          1 *        BBH * 1376187719 *
***************************************************
root [2] .q
$ cwb_inet 1 1376186619 ced
$ mv data/ced_1376186608_1200_O4_K07_C00_LH_BBH_SIM_dev1_1_job1/ ~/public_html/
```

Example CEDs - GW150914

- Comparing a reconstruction from a and generic search:
  - BBH search (16 - 320): [CED]
  - Generic search (32 - 2048): [CED]
- Pretty similar, but a generic search has a worse resolution for detailed analysis
- The main difference will be a post-production analysis! Different: frequency band, noise, cuts!
  - → Tanmaya's tutorial





Explore!

Explore BBH parameters:

```
$ cd input/ # produce your own waveforms
$ # Explore BBH parameters: mass1, mass2, spins, distance, inclination, etc
$ # https://pycbc.org/pycbc/latest/html/pycbc.waveform.html
$ cd macro/
$ # Here you define waveforms that you want to analyze: CWB_PluginConfig_BBH.C
$ #    TString hp_name = "/home/.../input/BBH_hp.txt";
$ #    TString hp_name = "/home/.../input/BBH_hc.txt";
$ #    MDC->AddWaveform("BBH",hp_name,hc_name,16384,sn_par);
$ # You can also explore different sky locations:
$ #    MDC->SetSkyDistribution(MDC_CELESTIAL_FIX,par,seed);
```

Example questions for BBHs:

- How does a waveform look for different mass ratio?
- How does the reconstruction (e.g. peak frequency) depends on the final mass?
- Is there any impact of the spin?
- How do the events look when they are weak (small SNR), chirping structure?
- Any impact of the sky location?
- How do the signal/reconstruction differ with respect to the inclination angle?
- etc.

With the BBH and SN/generic setup you can explore any waveform you want!

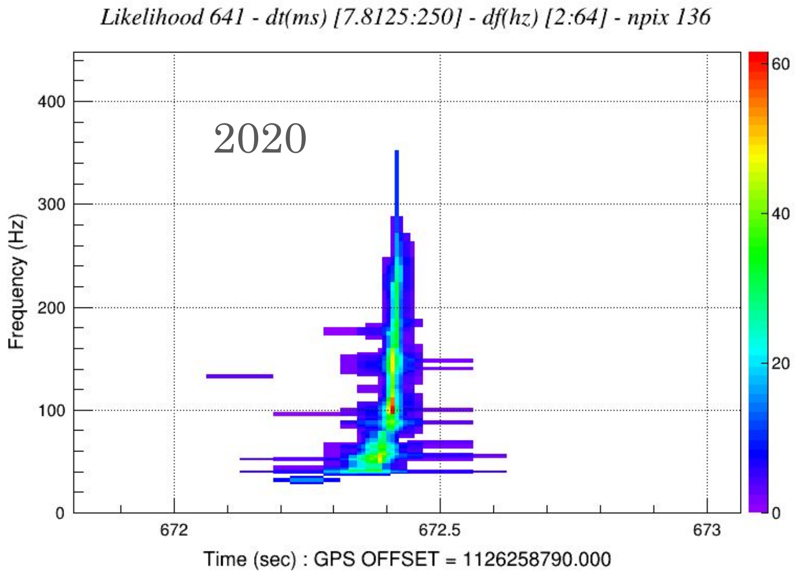
Summary

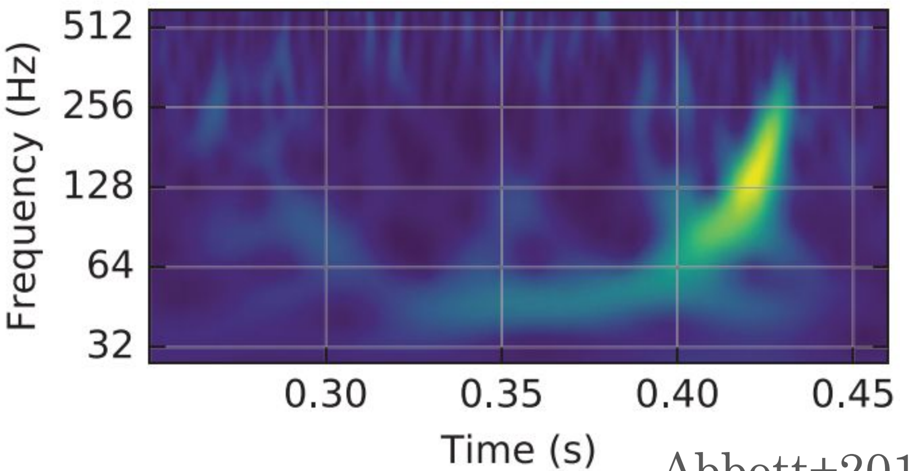
- Part I: Model-independent searches
  - Preparing for exceptional/special GW sources
  - Coherent WaveBurst
  - Complementary with template-based searches
- Part II: Hands-on exercises
  - “Supernova problem”: why do the stars explode?
  - When are the GW features detectable?
- Part III: Friday Hackathon

Extras

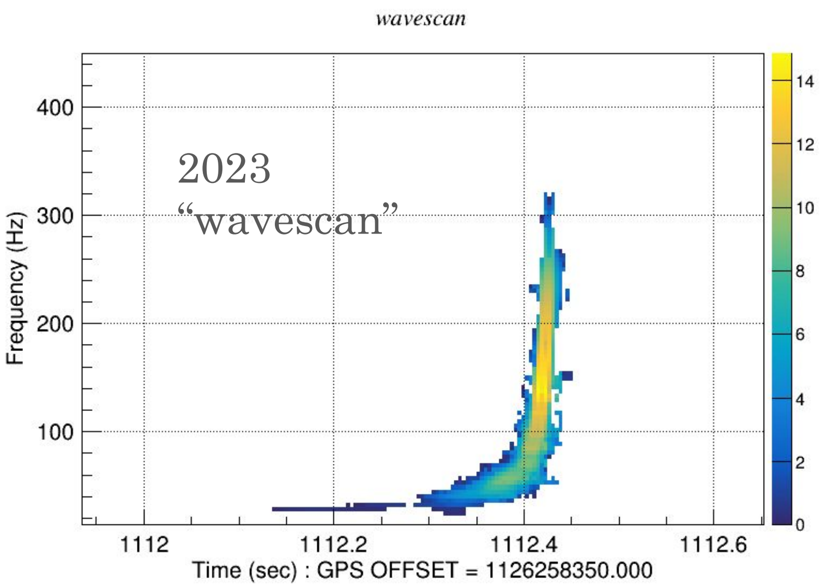
Time-frequency maps (GW150914 example)

- 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))



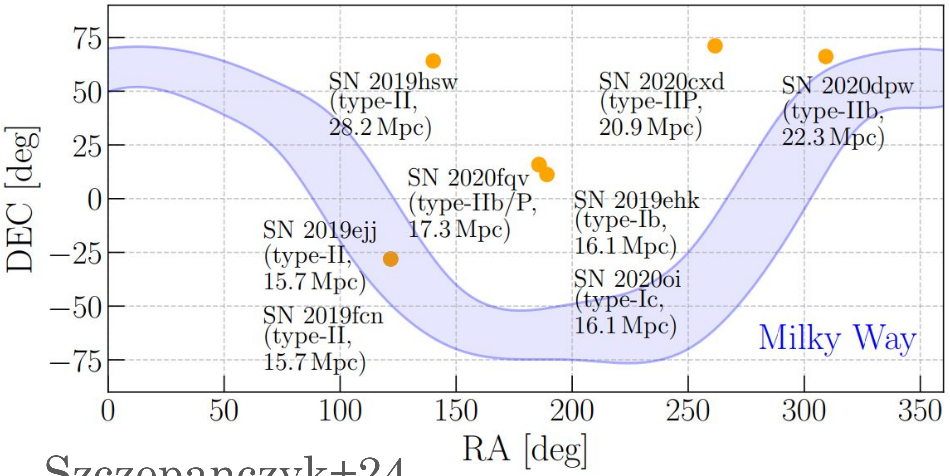


Abbott+2016

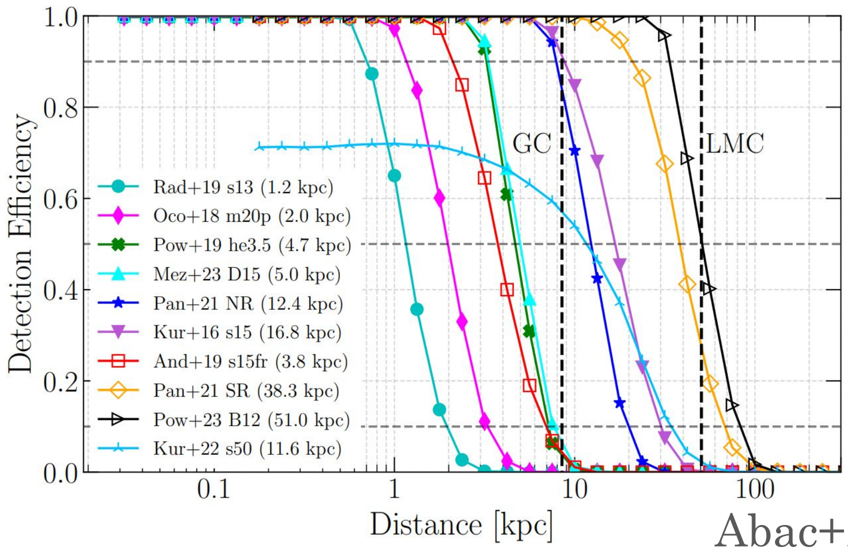


Optically targeted searches

- While waiting for a Galactic CCSN, we can systematically constrain its engine with CCSNe at MPc range -> optically targeted searches
- O1-O2 search (Abbott+19, [1908.03584]):
  - First observational constraints of a CCSN engine (my main PhD thesis result)
- O3 search (Szczepanczyk+24, [2305.16146]):
  - We could not beat previous limits
- SN 2023ixf search (Abac+24, [2410.16565], special O4 paper):
  - GW energy emission: constraints improved by an order of magnitude

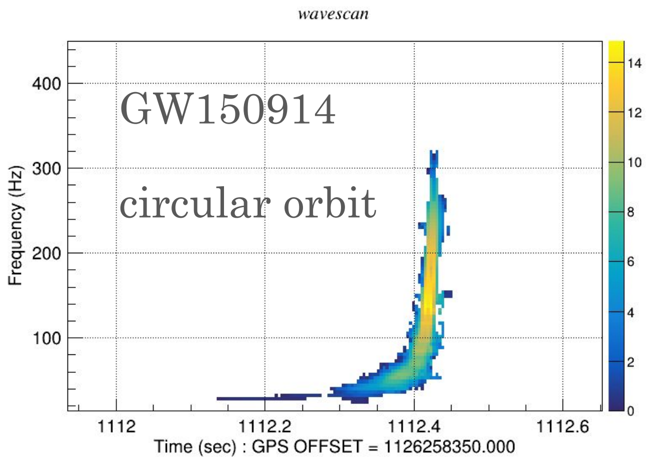


Szczepanczyk+24



Abac+24

Eccentric binaries



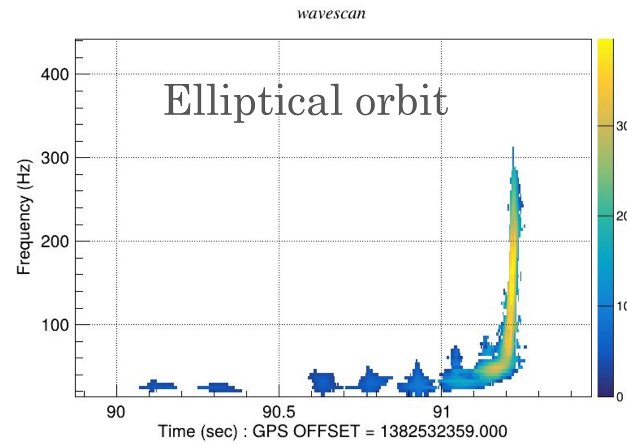
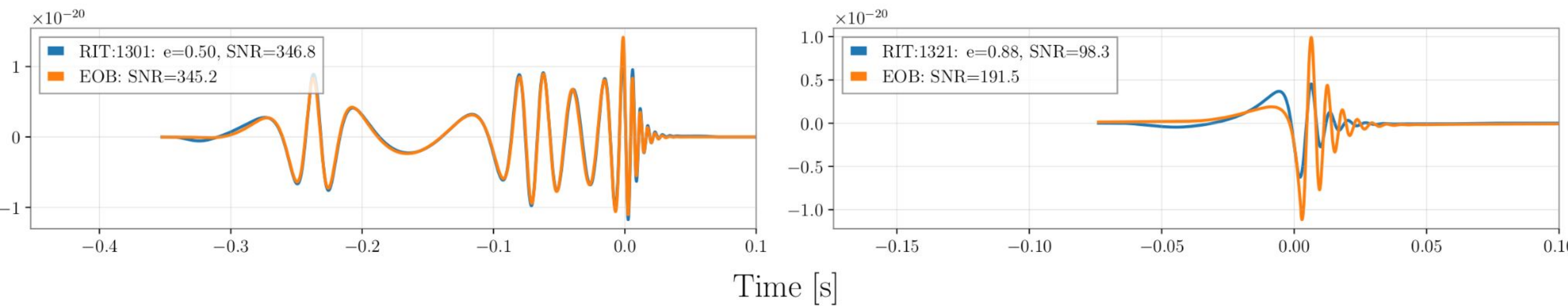
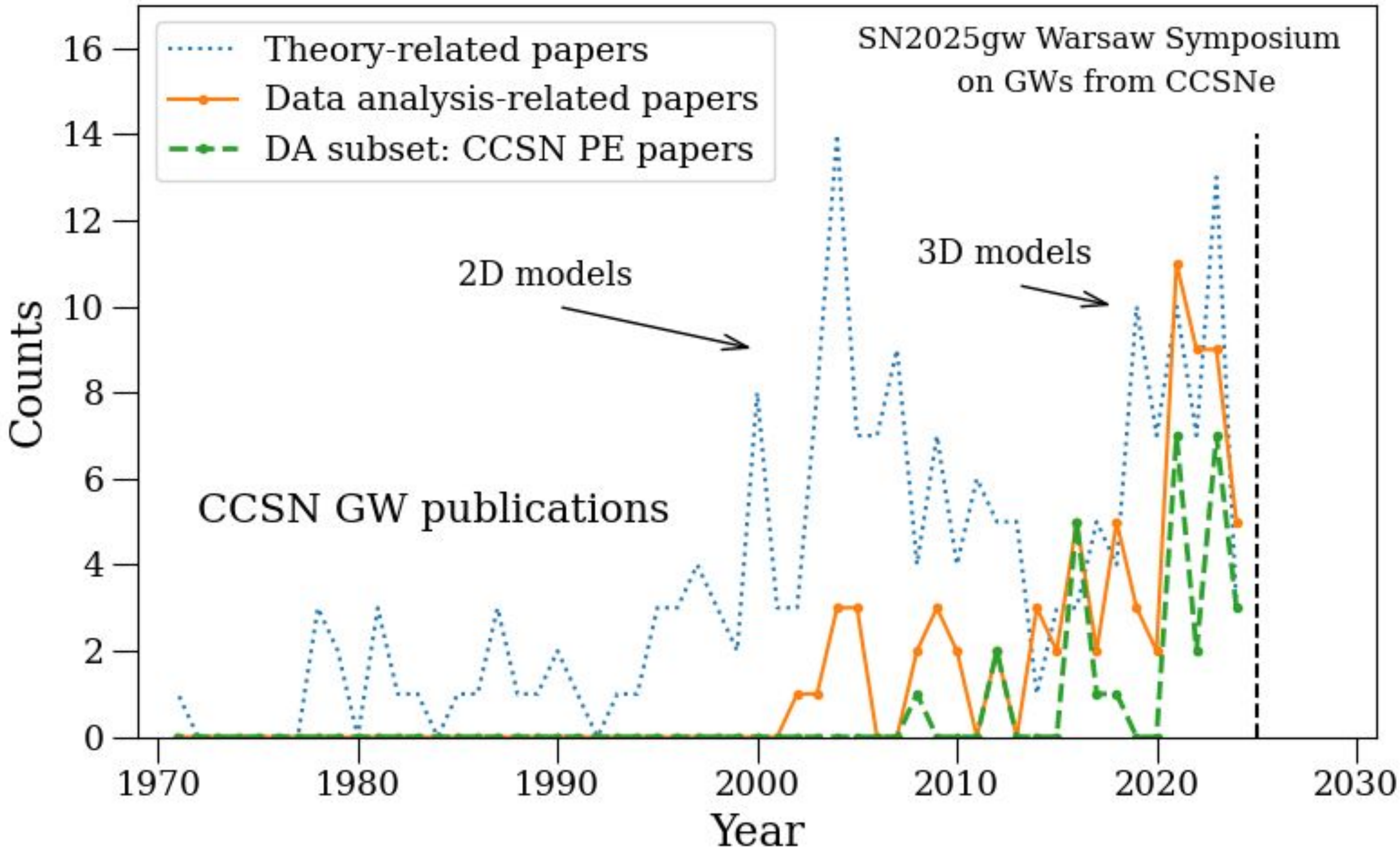


Image: Bhaumik

- Eccentric binaries: compact binaries elliptical orbits. “Smoking gun” of the dynamical formation
- Bhaumik et al (MS) 2024 (2410.15192)
  - Comparison between waveform models
  - Sensitivity studies and recommendations



SN2025gw: maturity of CCSN models



CCSN GW Literature, by Ewald Mueller:
https://wwwmpa.mpa-garching.mpg.de/rel_hydro/GWlit_catalog.shtml

SN2025gw: proceedings and White Paper

- Classical and Quantum Gravity focus issue proceedings and White Paper (in progress): https://iopscience.iop.org/collections/cqg-250513-841
- A White Paper will summarize the state of the art of the fields and provide recommendations
- **Everybody can contribute**, regardless of attending the Symposium:
  - Regular articles
  - Proceedings papers
- Pretty successful (12 submissions so far and around 10 to be submitted)

Classical and Quantum Gravity

Focus on Core Collapse Supernova Gravitational Wave Astronomy and Astrophysics: Past, Present, and Future

Guest Editors

Marek Szczepańczyk, *University of Warsaw, Poland*
Marco Cavaglia, *Missouri University of Science and Technology, United States*
Anthony Mezzacappa, *University of Tennessee Knoxville, United States*
Jade Powell, *Swinburne University of Technology, Australia*

Scope

The LIGO, Virgo, and KAGRA (LVK) observatories are designed to detect gravitational waves (GWs) from a wide variety of sources, including compact binary mergers, core-collapse supernovae, and isolated pulsars, among others. Only the