# Multi-messenger Astrophysics with gravitational-wave sources - preparing for the unexpected

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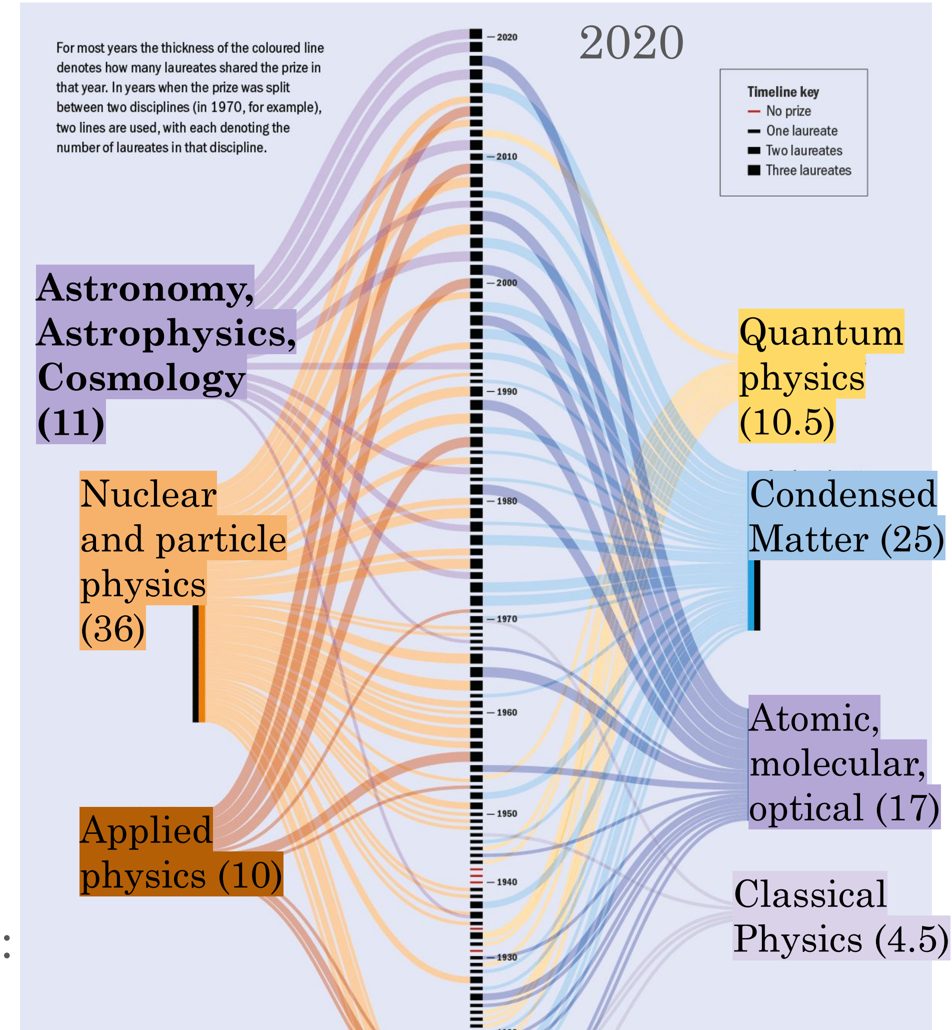
# Outline

- Multi-messenger Gravitational-Wave Astrophysics
  - As a significant area of Science
  - Overview and the future
- GW searches and detections
  - GW searches
  - GW150914
  - GW190521
  - GW transient catalogs
  - Core-Collapse Supernovae
  - Generic searches

# Multi-messenger Gravitational-Wave Astrophysics

# Extraordinary period of discovery in Astrophysics

- **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)




Graphics: Hamish Johnston (in *Physics World*)

# 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.

Priority Area: "New Windows on the Dynamic Universe"

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

Priority Area: "Pathways to Habitable Worlds"

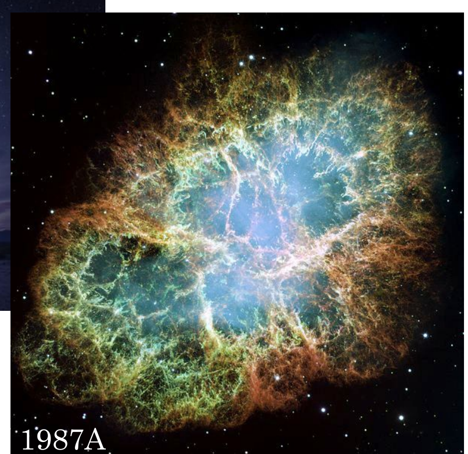
**Cosmic Ecosystems:**
link observations and modeling of the stars, galaxies, and the gas and energetic processes that couple their formation, evolution.

Priority Area: "Unveiling the Drivers of Galaxy Growth"

# “Conventional” and “Gravitational-Wave” Astronomy

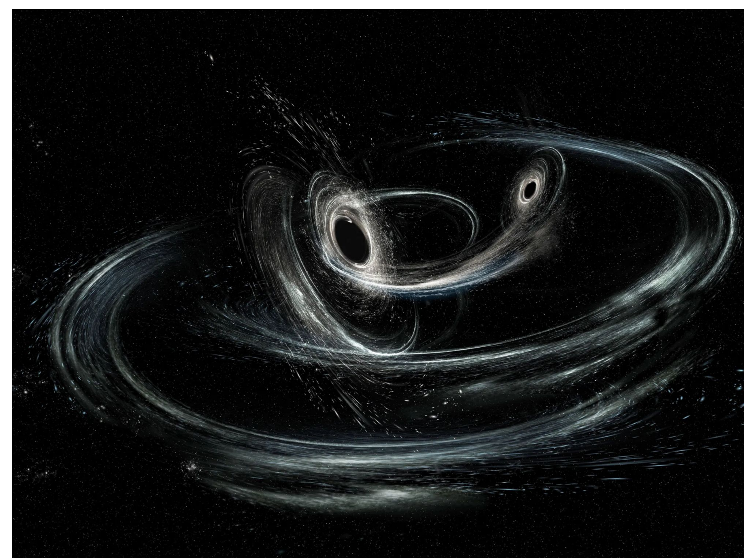
**“Conventional” or time-domain Astronomy**: observing Universe using electromagnetic waves (e.g. visible light), cosmic rays or neutrinos.

**Looking** at the Universe


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

**Listening** to the Universe



AURORE SIMONNET/LIGO/CALTECH/MIT/SONOMA STATE

# 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.

# Gravitational-wave sources

Quadrupole formula for GW production:

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

In simple words, we need **aspherical** mass-energy movement

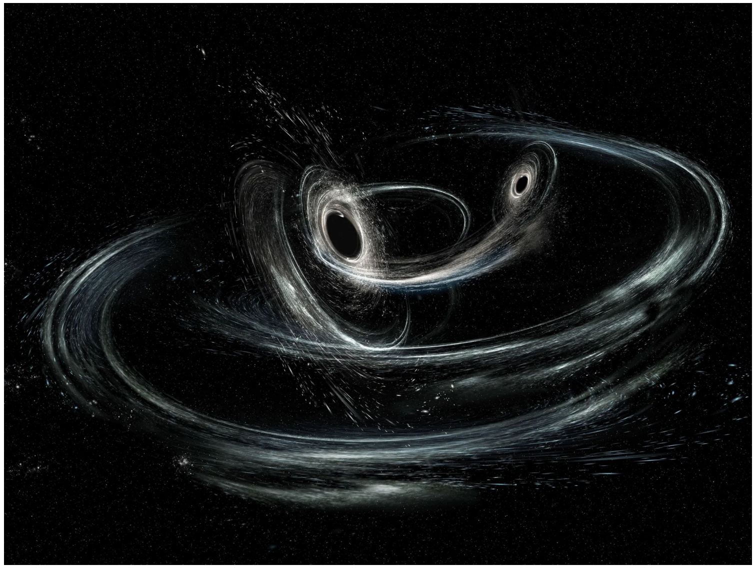
Image: NSF/LIGO/Sonoma/A. Simonnet

Compact Binaries:

- Binary black holes with circular/elliptical orbits
- Black hole - neutron star
- Binary neutron stars
- Intermediate-mass black holes
- Hyperbolic encounters

Other:

- Core-collapse supernovae
- Neutron star glitches
- Cosmic strings



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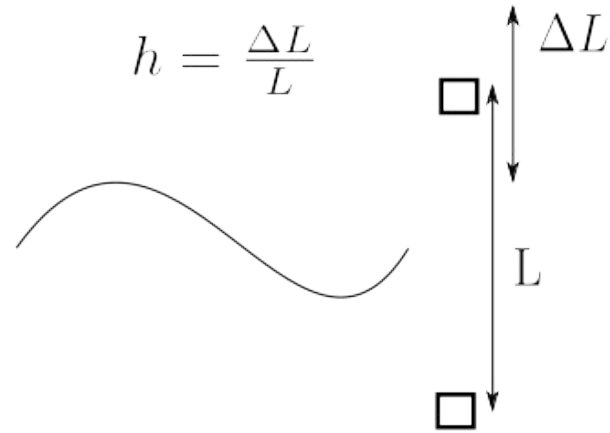
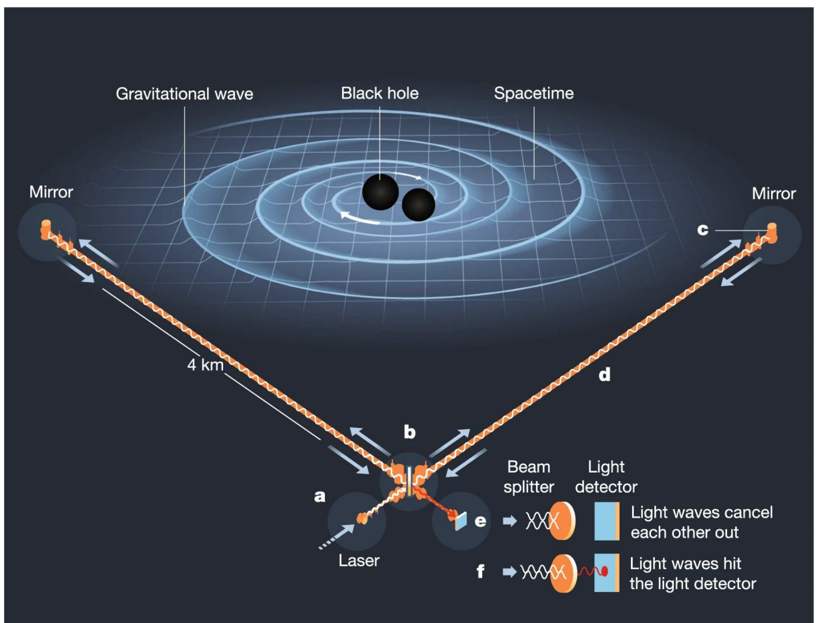
# Gravitational-Wave detectors

- GWs are the gravitational analog of electromagnetic waves
- GWs passing through two objects change distance between them.
- GW detectors: interferometers (the longer, the more sensitive)
- Preferably far away from human activities.

$$h = \frac{\Delta L}{L}$$

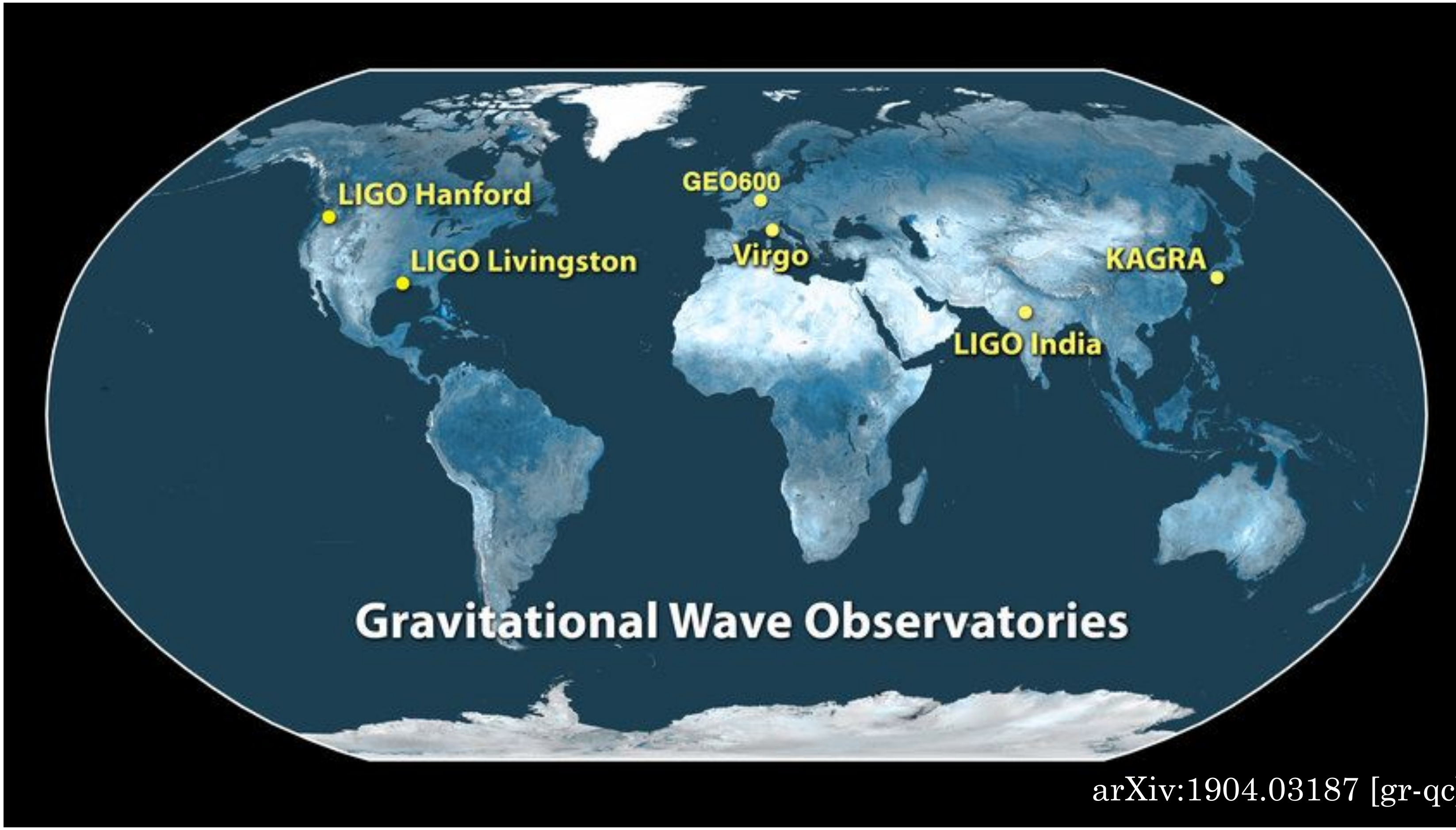



Nature 568, 469–476 (2019)

LIGO Hanford

# Detectors network




- Average BNS sensitivities: Livingston - 133 Mpc, Hanford - 115 Mpc and Virgo - 51 Mpc
- GEO and KAGRA - joint observations during O3
- LIGO India - under construction

# Multi-messenger Astronomy

**"Messengers"** - distinctive signals carrying unique information about a source.

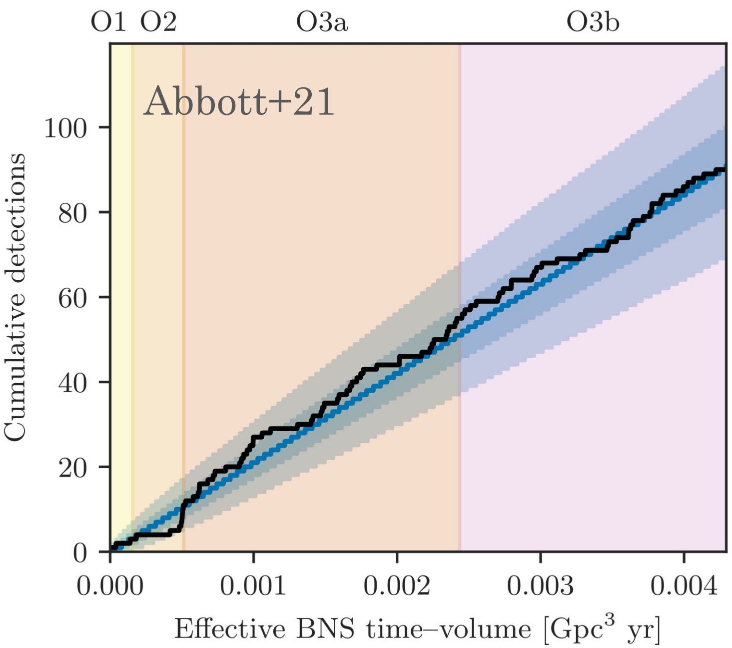
They provide deeper insight into the most extreme events in the Universe.

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

# Future of the Multi-messenger Gravitational-Wave Astrophysics

- The number of detections will grow rapidly in the future.

- The future experiments promise to explore the state of ultra-dense matter, discover QCD phase transition, determine cosmological parameters, study the nature of black holes, search for deviations from General Relativity, understand the nature of exploding stars, learn about the active galactic nuclei, and investigate densely stellar environments, etc.




- **The future discoveries of gravitational waves from unexpected astrophysical sources might play the key role in this endeavor of exploring the Universe.**

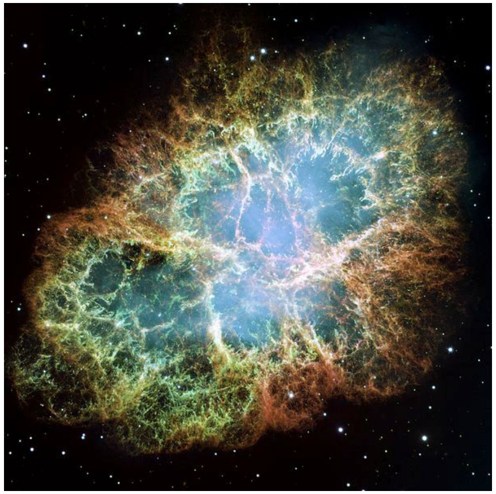
- “Unexpected” or “surprising” events - GWs with exceptional source properties, new sources or those that challenge astrophysical models

# GW searches and detections

# GW searches

- **Methods:**
    - **Template based (model-dependent):** binary black holes (BBH), binary neutron stars or binary black hole - neutron star
    - **Template-independent (model-independent) or “burst”:** for example core-collapse supernovae, strings, as well as regular or special binaries, such as heavy/eccentric BBHs
- **Searches:**
    - **Low-latency**: rapid (within seconds to minutes) identification of the GW sources and preliminary validation (within hour) for quick astronomical follow-up.
    - **Offline**: identification of GWs after data acquisition, weeks or even years.

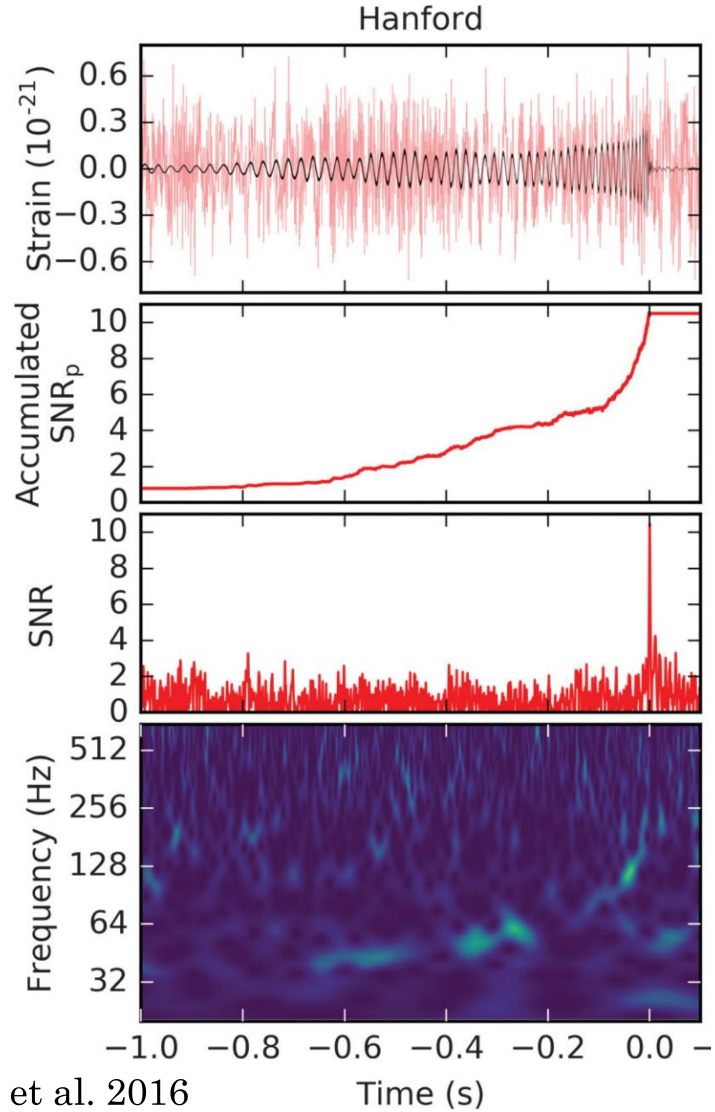
Image: NSF/LIGO/Sonoma/A. Simonnet



Crab Nebula

# Matched-filtering
# (Model-dependent searches)

- **Cross-correlating data with waveform templates**
- The template signals from compact binaries are derived from General Relativity.
- The method requires accurate waveform models. To the leading order, the waveform morphology depends on the chirp mass and effective spin.
- Example algorithms: GstLAL, PyCBC, SPIIR, MBTA




Abbott et al. 2016

# coherent WaveBurst
# (Model-independent searches)

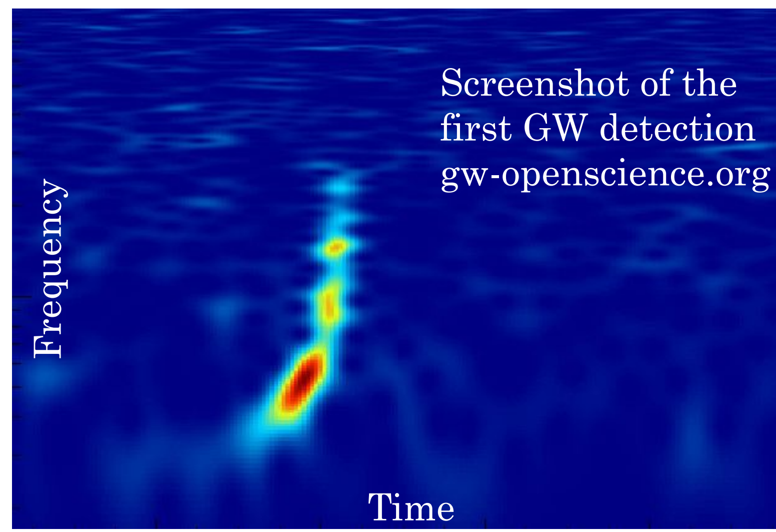
- **Coherent WaveBurs**t (cWB, Klimenko+16) is a software designed to detect a wide range of burst transients without prior knowledge of the signal morphology

- cWB uses minimal assumptions, for example growing frequency over time in case of binaries

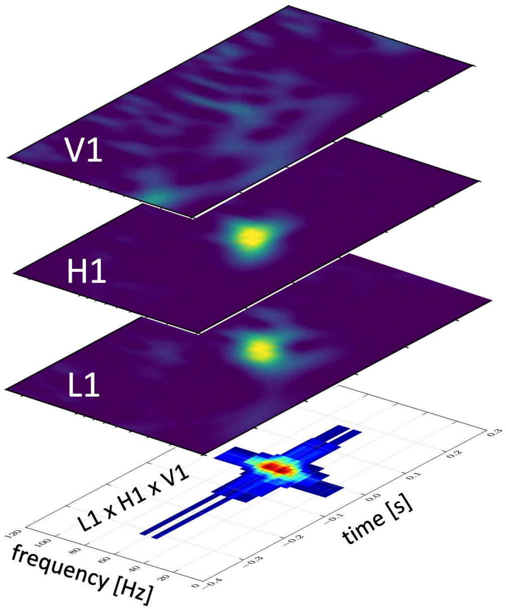
- cWB has detected:
  - **GW150914 - the very first GW (PRL 116, 061102)**
  - **GW170729 - the heaviest binary in O1-O2 (PRX 9, 031040)**
  - **GW190521 - an intermediate mass binary black hole (PRL 125, 101102)**
  - several GWs together with template based searches
  - **cWB was the only algorithm capable of detecting CCSN in real time during O3**

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

https://gwburst.gitlab.io/



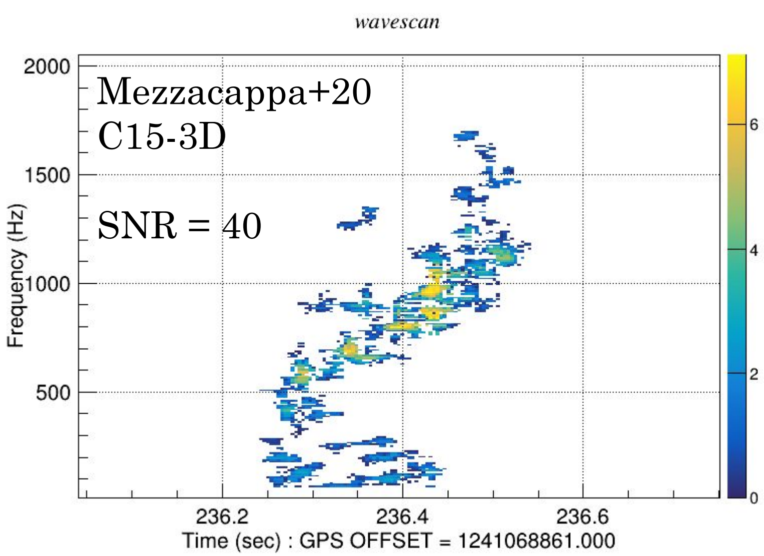
# coherent WaveBurst (cWB)
# Model-independent searches



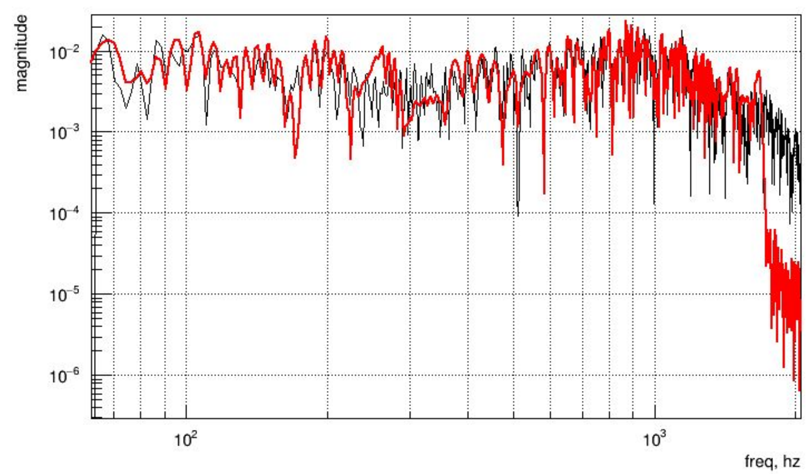

x(t) $\xrightarrow{\text{Wavelet Transform}}$

- Time-Frequency Decomposition
- Cluster Selection
- Constrained Likelihood

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



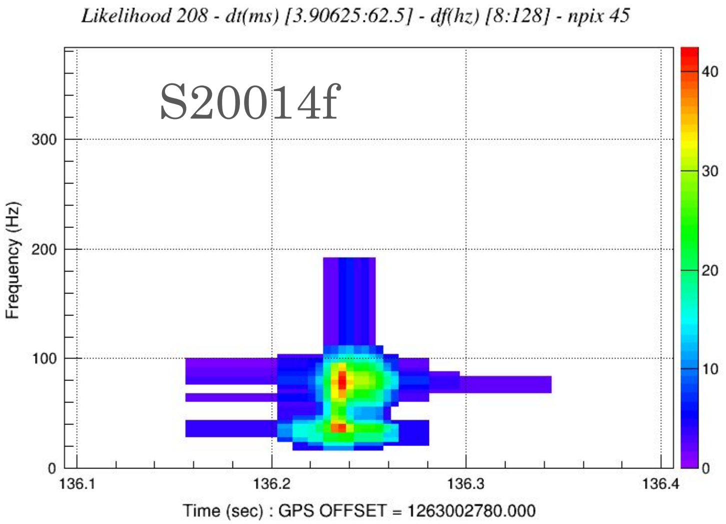

Injected (black) vs reconstructed (red)



# Low-latency searches

**Observing Run 3 (O3)**

- Model-independent searches were performed by cWB:
  - Burst transients: signals with unknown morphologies
  - Stellar-mass BHs: up to $10^2$ $M_\odot$
  - Intermediate-mass BHs: range between $10^2$ to $10^5$ $M_\odot$
    - It led to the discovery of an intermediate-mass BH!
- 56 GW candidates (30 were identified by cWB)
- 1 potential burst transient: [S200114f]
  - Over 30 follow-up observations (neutrino, X-ray, optical and others). No coincidences found

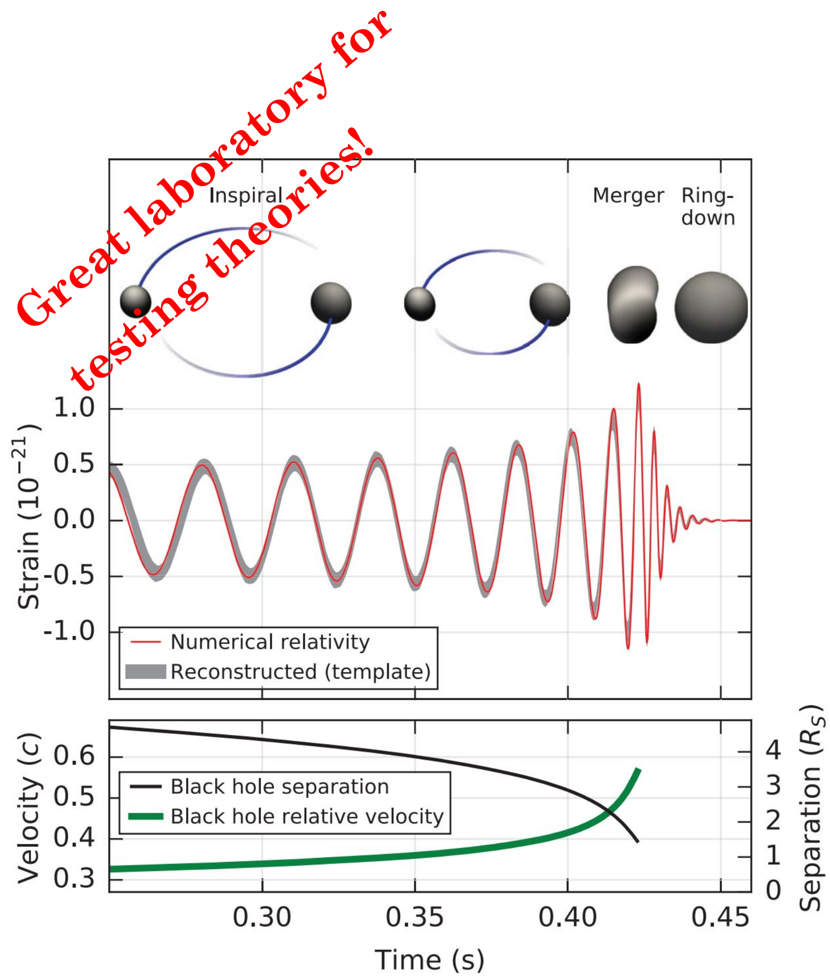



**Observing Run 4 (O4)**

- Observation is planned to start in March 2023
- Significantly improved sensitivity for all GW signal morphologies
- Anticipated detection rate: **1 per day!**
  - Great opportunities for the discoveries.
  - Sub-threshold O3 events give us hopes

# GW150914

- GW150914 - first observation of gravitational waves and binary black holes (36 $M_\odot$ and 29 $M_\odot$).
- Because heavy BHs were not observed astronomically, the model-dependent searches looked for binary black holes up to around 15 $M_\odot$.
- However, Belczynski et al 2010 predicted existence of such heavy black holes
- Because of the weak assumptions on the GW signal models of the model-independent searches, it was **detected in low-latency (3 minutes) by the cWB**.



# GW150914 - theoretical implications

From a review by Yunes et al 2016

**GW150914 and GW151226 constrain a plethora of emission mechanisms beyond GR radiation reaction.**

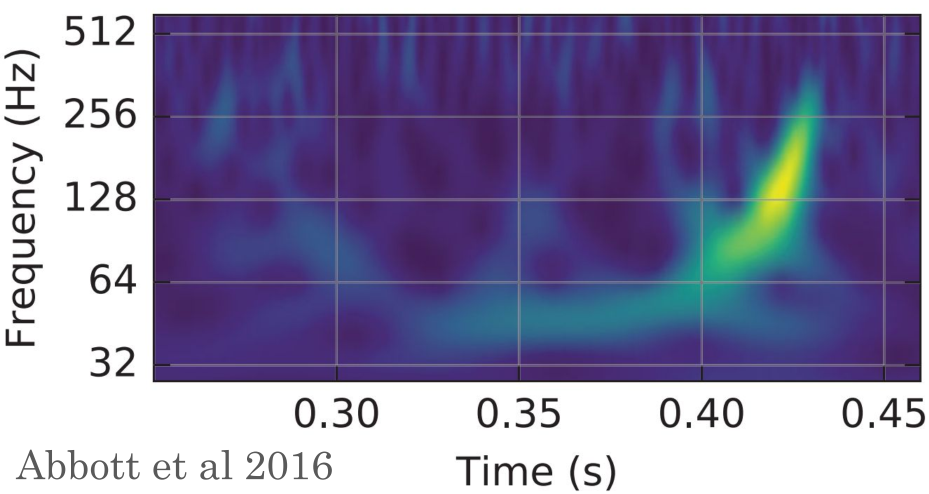
**GW150914 and GW151226 constrain a number of theoretical mechanisms that modify GW propagation.**

**GW150914 allows for inferences to be made regarding the validity of the Kerr hypothesis, and likewise it constrains properties of exotic compact object alternatives to Kerr BHs.**

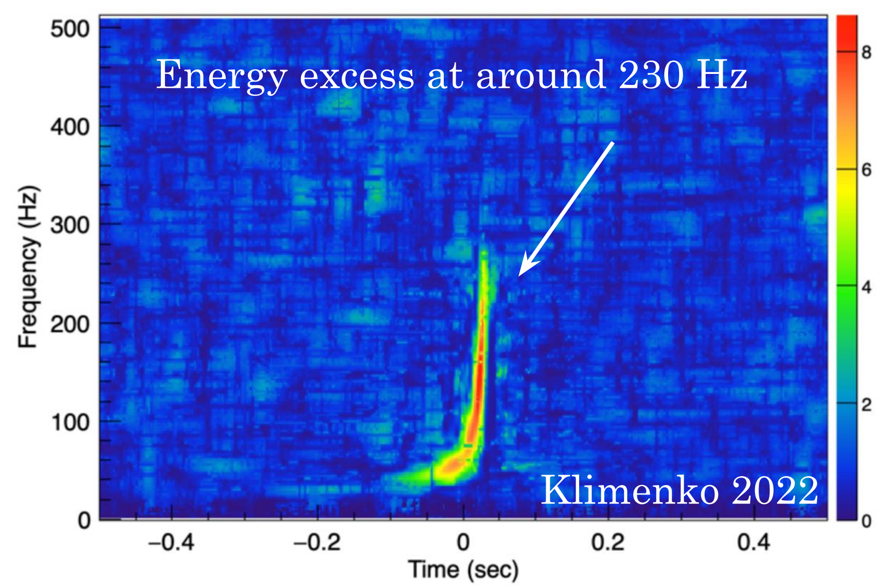
**If the Fermi Gamma-ray Burst Monitor (GBM) signal is an actual counterpart to GW150914, this observation places more stringent constraints on GW propagation mechanisms than GW150914 alone.**

# GW150914 - study of an event horizon

- Quasi-normal modes (QNM) - dumped perturbations of BH resonances. Intuitively: waves traveling around BH.
    - QNM will allow precise measurements of the mass and spin of black holes and new tests of GR.
- GW150914 with large signal-to-noise ratio of 24 is a great laboratory
- An ongoing debate in the literature whether the QNMs are detected
- A new improved time-frequency resolution may reveal surprises.




Abbott et al 2016



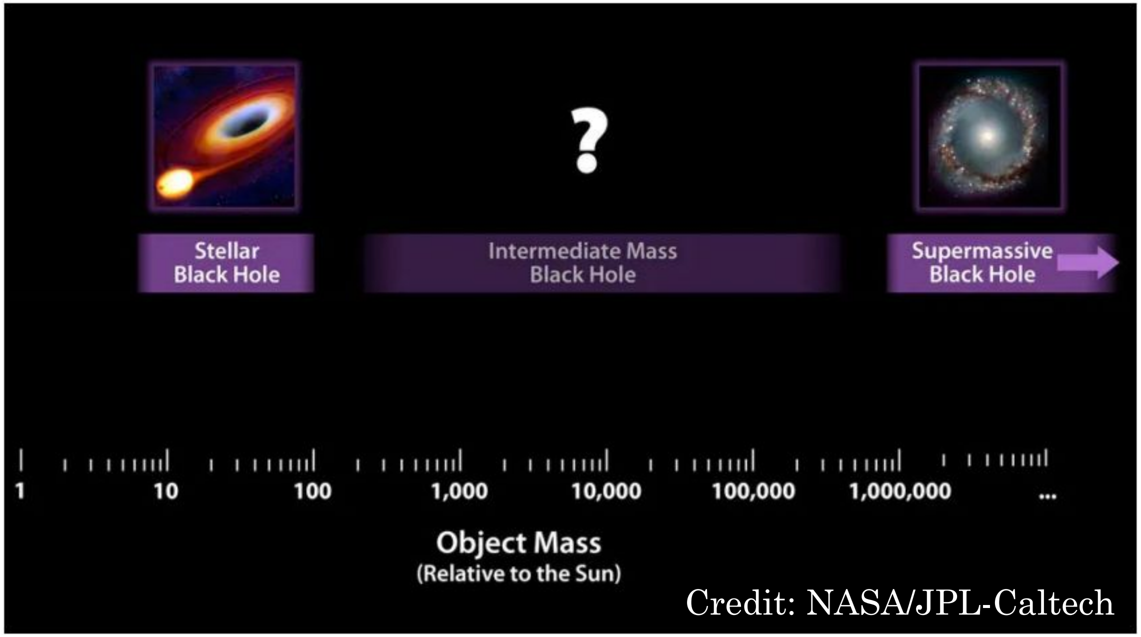
# GW190521 - Intermediate Mass Black Hole

- **Intermediate mass**: between $10^2\,M_\odot$ (stellar mass) and $10^5\,M_\odot$ (supermassive)
- Astrophysical origin: unknown, could be formed through hierarchical mergers, in AGN discs, accretion.
- So far no confirmed detection in EM spectrum
- **GW190521 - first detection of an intermediate-mass black hole (IMBH)!**
- First potential electromagnetic counterpart for a BH merger (Graham et al. 2020)

~~These Black Holes Shouldn’t Exist, but There They Are~~

~~The New York Times~~

See Belczynski et al. 2009

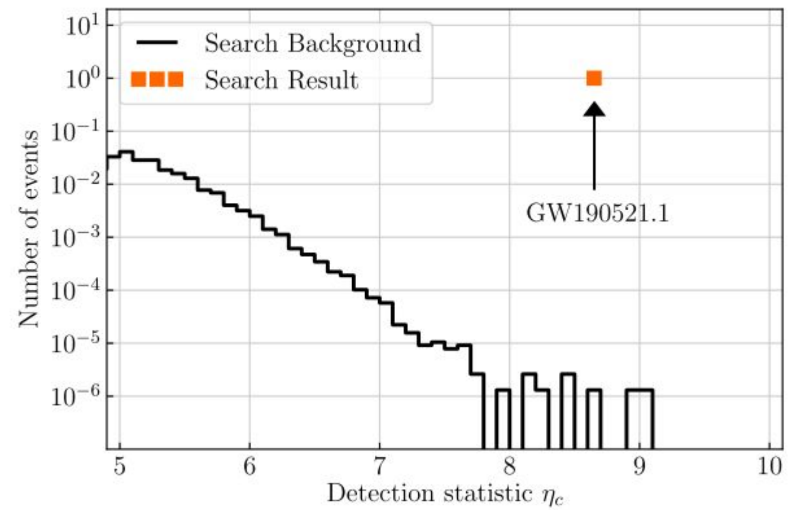


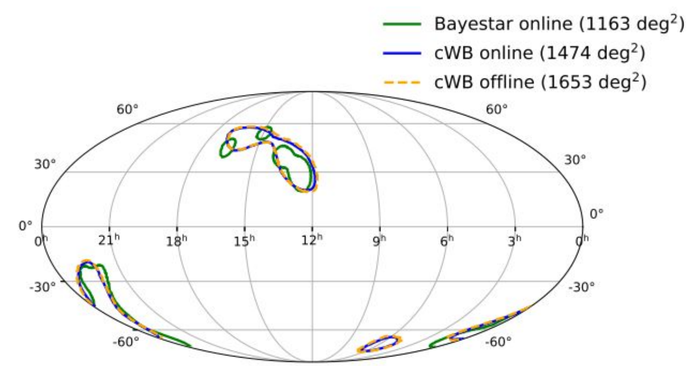
Credit: NASA/JPL-Caltech

# GW190521 detected with minimal assumptions

Szczepanczyk et al 2021 ([2009.11336](2009.11336))

- **Search procedure leading to a confident detection.**
- False-Alarm Rate in low-latency is 1 per 28 years, and offline 1 per 9,800 years
  - Noise mitigation for low frequency laser scatter
- The model-independent waveform analysis is consistent with the model-dependent analyses.
  - No chirping signature
  - Sky localization is consistent with modelled estimates
  - Testing waveform models

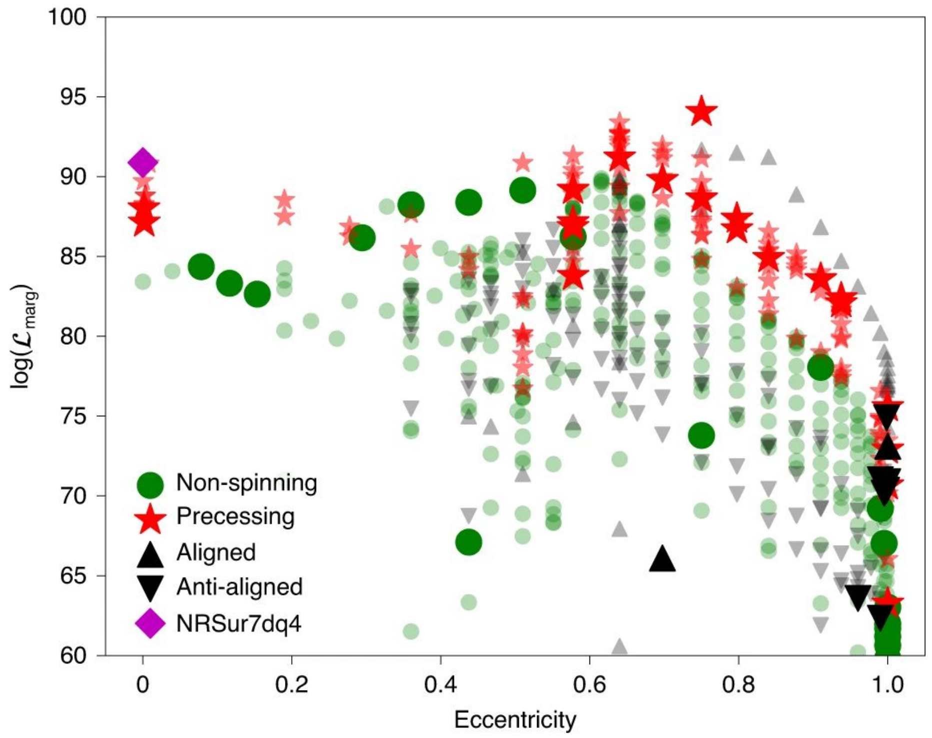


# GW190521 - as a potential eBBH

## Gayathri et al. (MS) Nature Astronomy 6, 344–349 (2022)

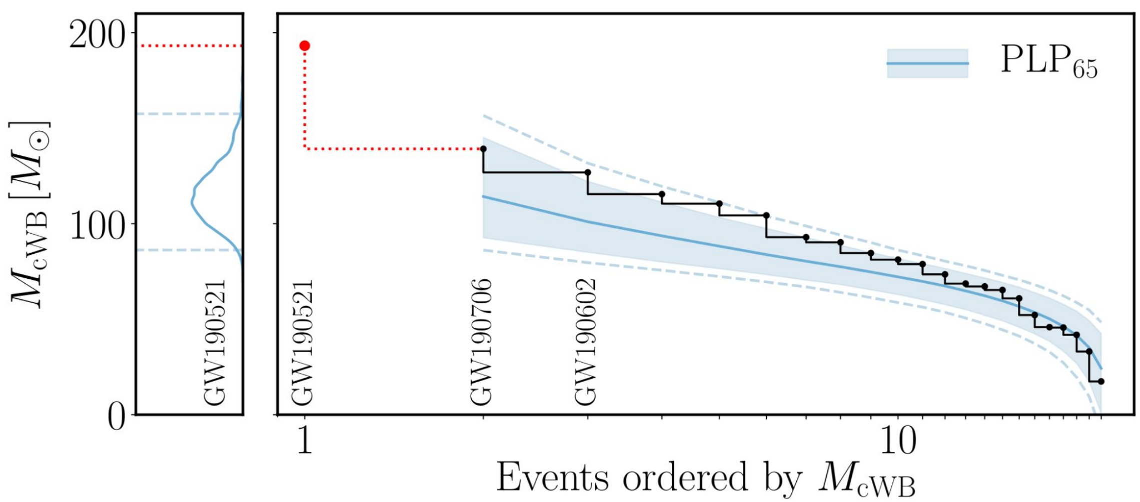
- Binary black holes with eccentric orbits (eBBH) are challenging to detect due to a lack of precise models and the templates
- GW190521 is most consistent with a highly eccentric system with an **eccentricity of 0.7**
- Possible origin: active galactic nuclei, globular clusters, triple systems and other scenarios



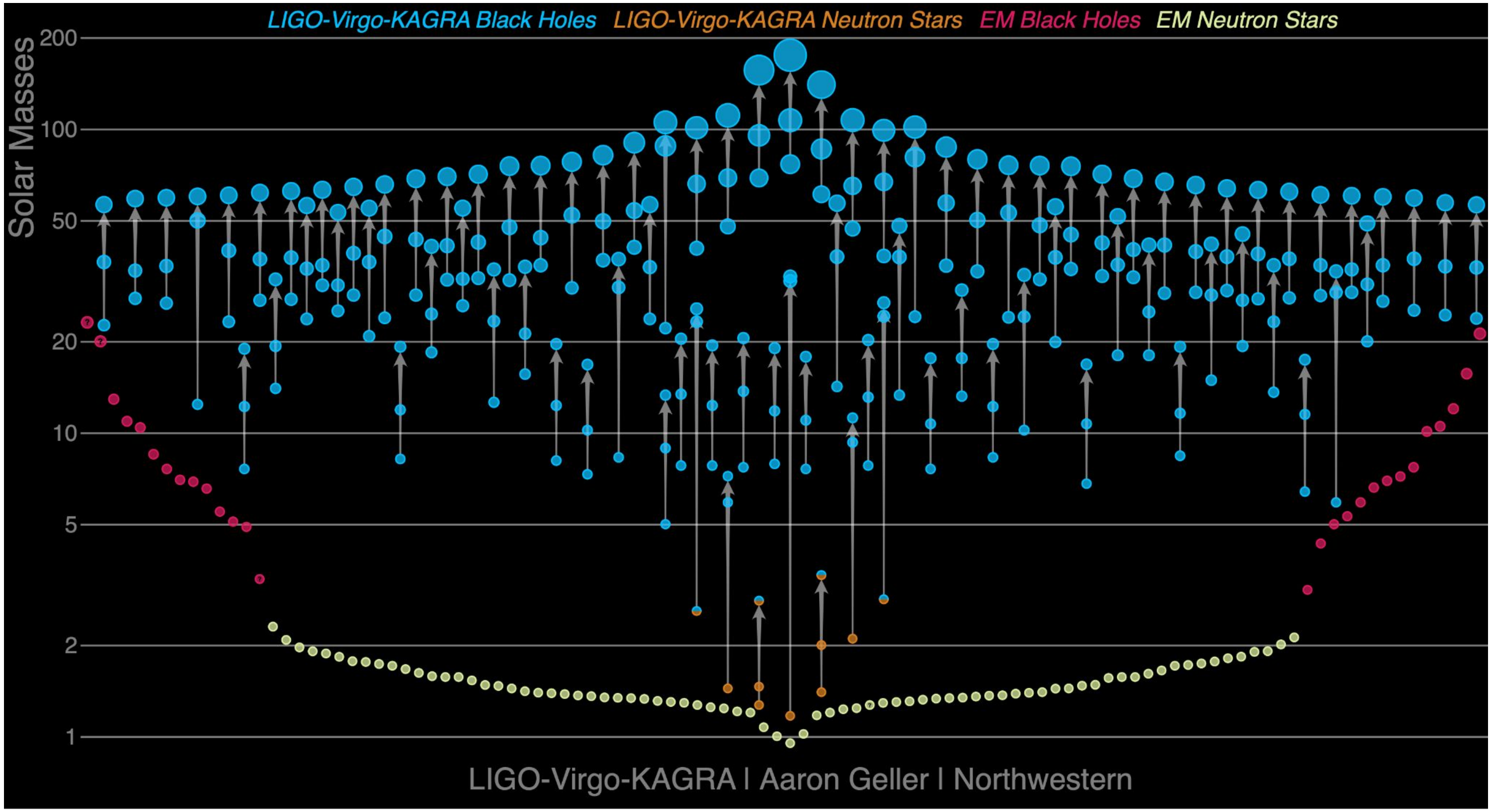
# GW190521 - pair-instability mass gap

O'Brien, MS et al. 2021 (2106.00605)

- A mechanism known as pair-instability (PI) supernovae is expected to prevent the formation of black holes in range from 40-65 $M_\odot$ to 120 $M_\odot$.
- For a PI mass limit of 65 $M_\odot$ or below, **we firmly establish GW190521 as an outlier** - cannot be explained as a statistical fluctuation
- We find it unlikely that the remaining 21 BBH events (excluding GW190521) are consistent with a PI mass limit of 50 $M_\odot$ or below.



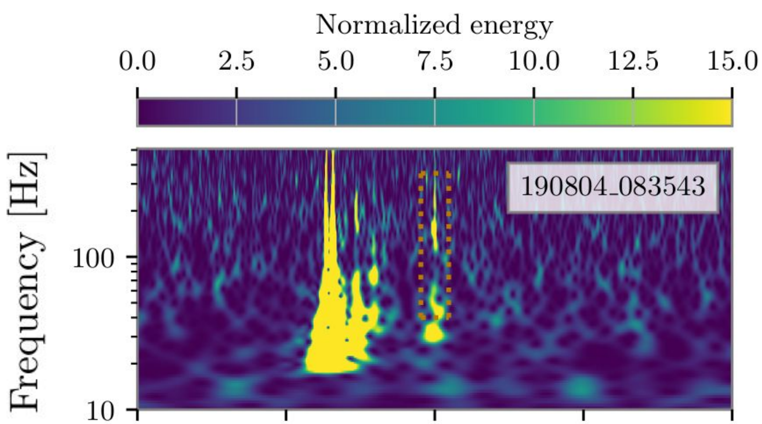
# Gravitational Waves Transient Catalogs

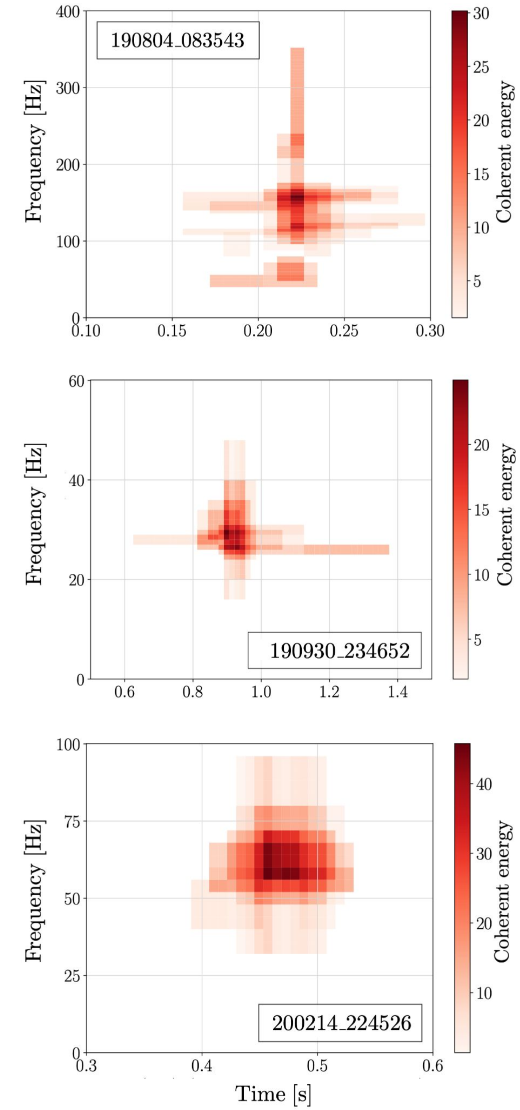



- GWTC-1 presents 7 events
- GWTC-2 adds 39 events
- GWTC-3 adds 35 events (total number is around 90)
- GWTC-3 algorithms: matched-filtering (GstLAL, MBTA, PyCBC) and model-independent (cWB)

# Gravitational Waves Transient Catalogs "cWB-only" events

- cWB-only events: events identified by cWB with p-astro>0.5 and FAR<2/year but not found by the matched-filtering searches
- **Potentially GW from unusual binary systems or other source population**
- Time-frequency maps do not show typical morphology of binary systems
- Instrumental glitches in single detectors are present for all 3 events



# Compact Binaries - (far) future prospects

“

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**.

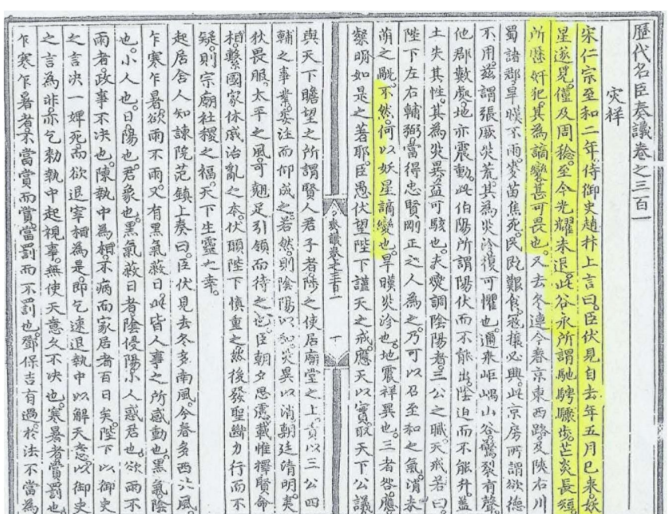
“

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!

# Core-Collapse Supernova (CCSN)


ancientpages.com



歷代名臣奏議卷之三百一

災祥

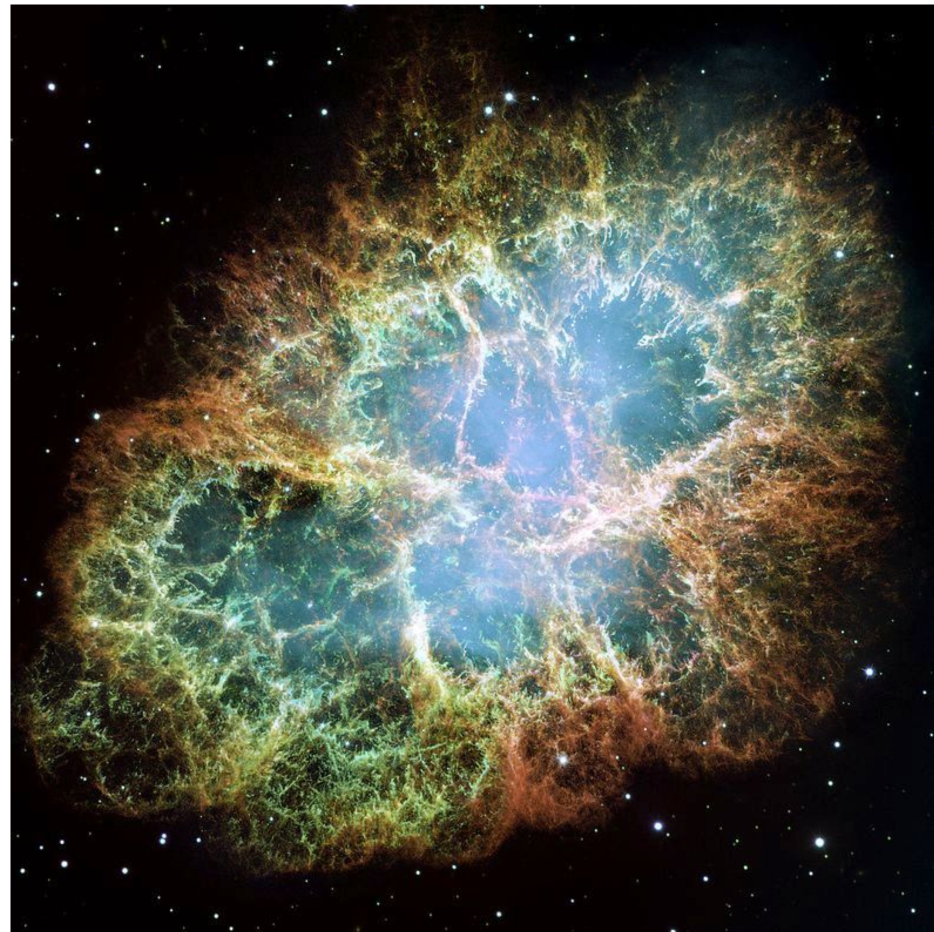
宋仁宗至和二年侍御史趙抃上言曰臣伏見自去年五月已來妖星遂見僅及周稔至今光耀未退此谷永所謂馳騁驟步芒炎長縟所懸奸犯其為譎變甚可畏也又去冬連今春京東西路及陝右川蜀諸郡旱暵不雨麥苗焦死民既艱食寇攘必興此京房所謂欲德不用茲謂張厥災荒其為災沴復可懼也邇來岷嶋山谷驚裂有聲他郡數處地亦震動此伯陽所謂陽伏而不能出陰迫而不能升蓋土失其性其為災異益可駭也夫變調陰陽者三公之職天戒若曰陛下左右輔弼當得忠賢剛正之人為之乃可以召至和之氣消未萌之亂不然何以妖星譎變也旱暵災沴也地震祥異也三者咎應繇明如是之著耶臣愚伏望陛下謹天之戒應天以實敢天下公議與天下瞻望之所謂賢人君子者陟之使居廟堂之上責以三公四輔之事業委注而仰成之若然則陰陽以和災異以消朝廷清明矣狀長服太平之風可翹足引領而待之也臣朝夕思慮載惟擇賢命相繫國家休戚治亂之本伏願陛下慎重之然後發聖斷力行而不疑則宗廟社稷之福天下生靈之幸

奏議卷之三百一　十

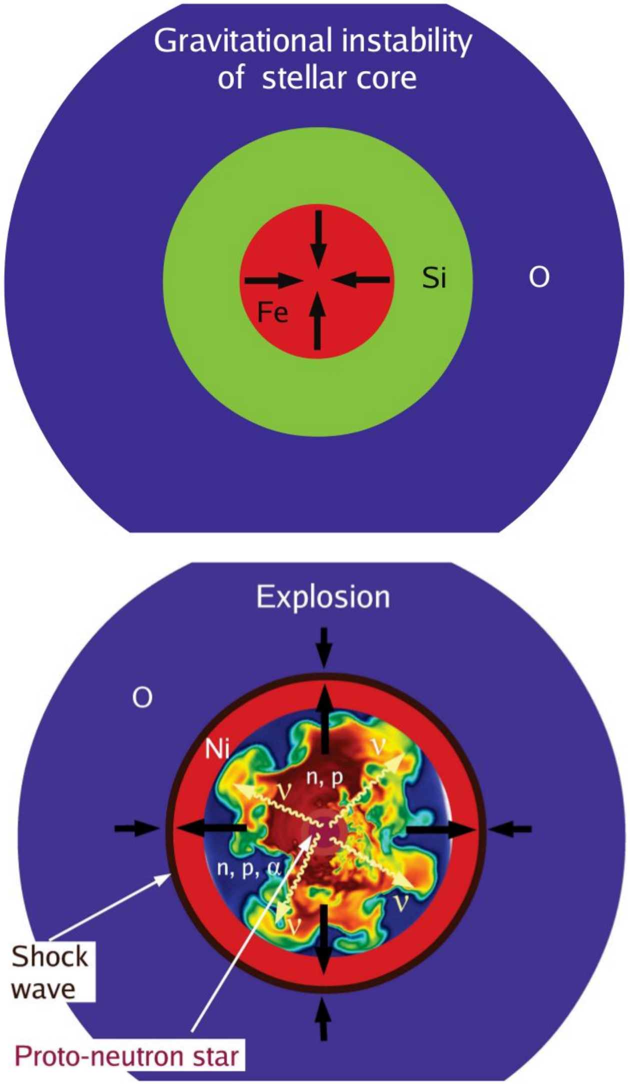
起居舍人知諫院范鎮上奏曰臣伏見去冬多南風今春多西北風乍寒乍暑欲雨不雨又有黑氣蔽日此皆人事之所感動也黑氣陰也小人也日陽也君象也黑氣蔽日者陰侵陽小人惑君也欲雨不雨者政事不決也陳執中為相不病而家居者百日矣陛下以御史之言決一嬖死而欲退宰相為是即乞速退執中以解天意以御史之言為非亦乞勅執中起視事無使天意久不決也寒暑者賞罰也乍寒乍暑者當賞而賞當罰而不罰也鄧保吉有過於法不當為

*Nova on the sky!*

1-2 per century in Milky Way (?)



# Core-Collapse Supernova




Janka+12

- Burning of the star: H → He → … → Fe
- Before collapse: Fe core of size 1000-2000km

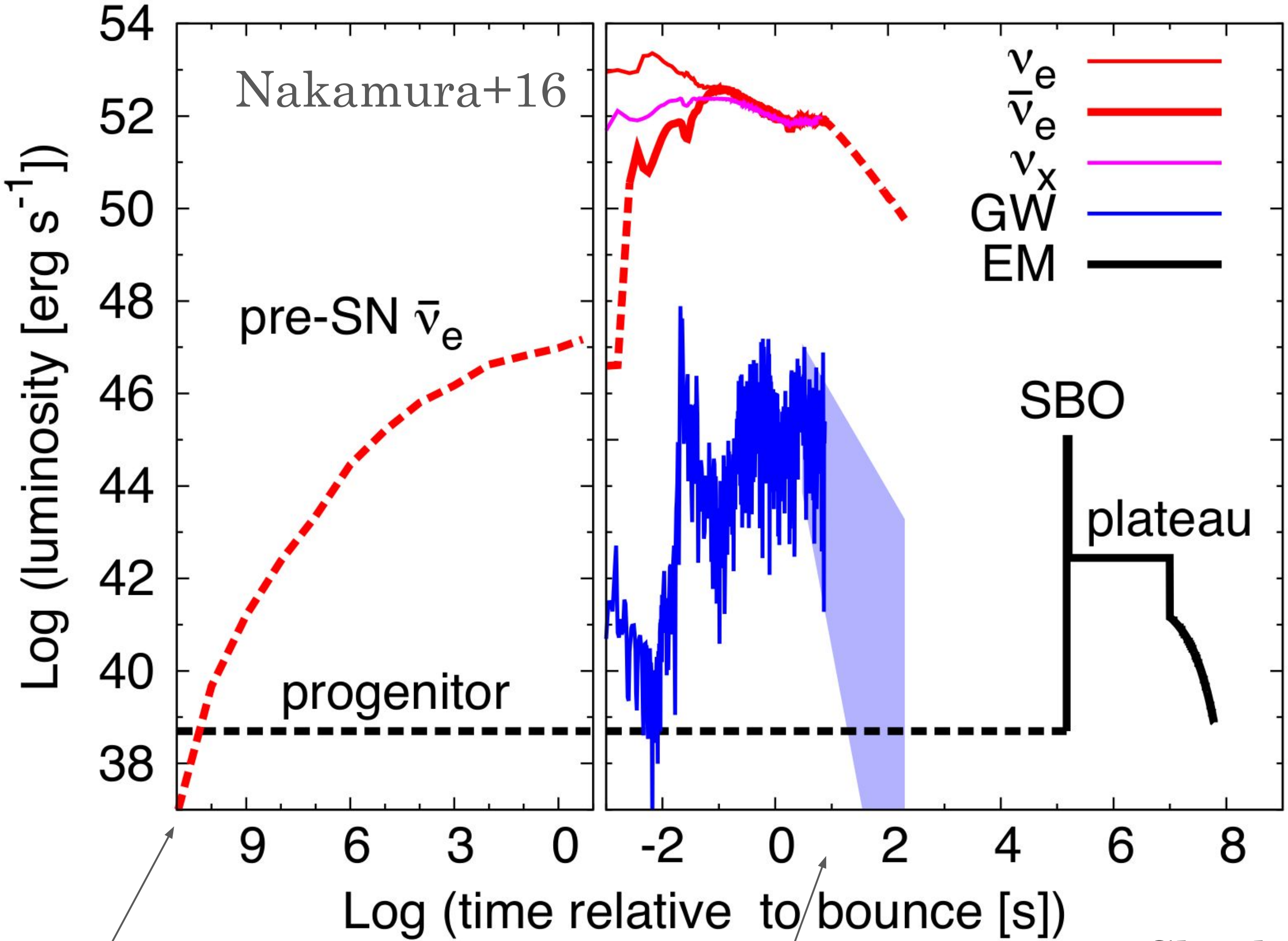
  After collapse: "nucleus" core of size ~50km
- Energy available ~ $3 \times 10^{46}$J ( ~ 0.15 $M_{\odot}c^2$)

  Energy observed ~ 3-10 × $10^{44}$J
- 99% of explosion energy escapes with neutrinos!

$$p + e^- \rightarrow n + \nu_e$$

- Extremely challenging to model, all fundamental forces are relevant.
- **Fundamental questions GWs can help us solving: nuclear equation of state, QCD phase transition, event horizon creation, neutrino mass**

# CCSNe - Multi-messenger Astronomy



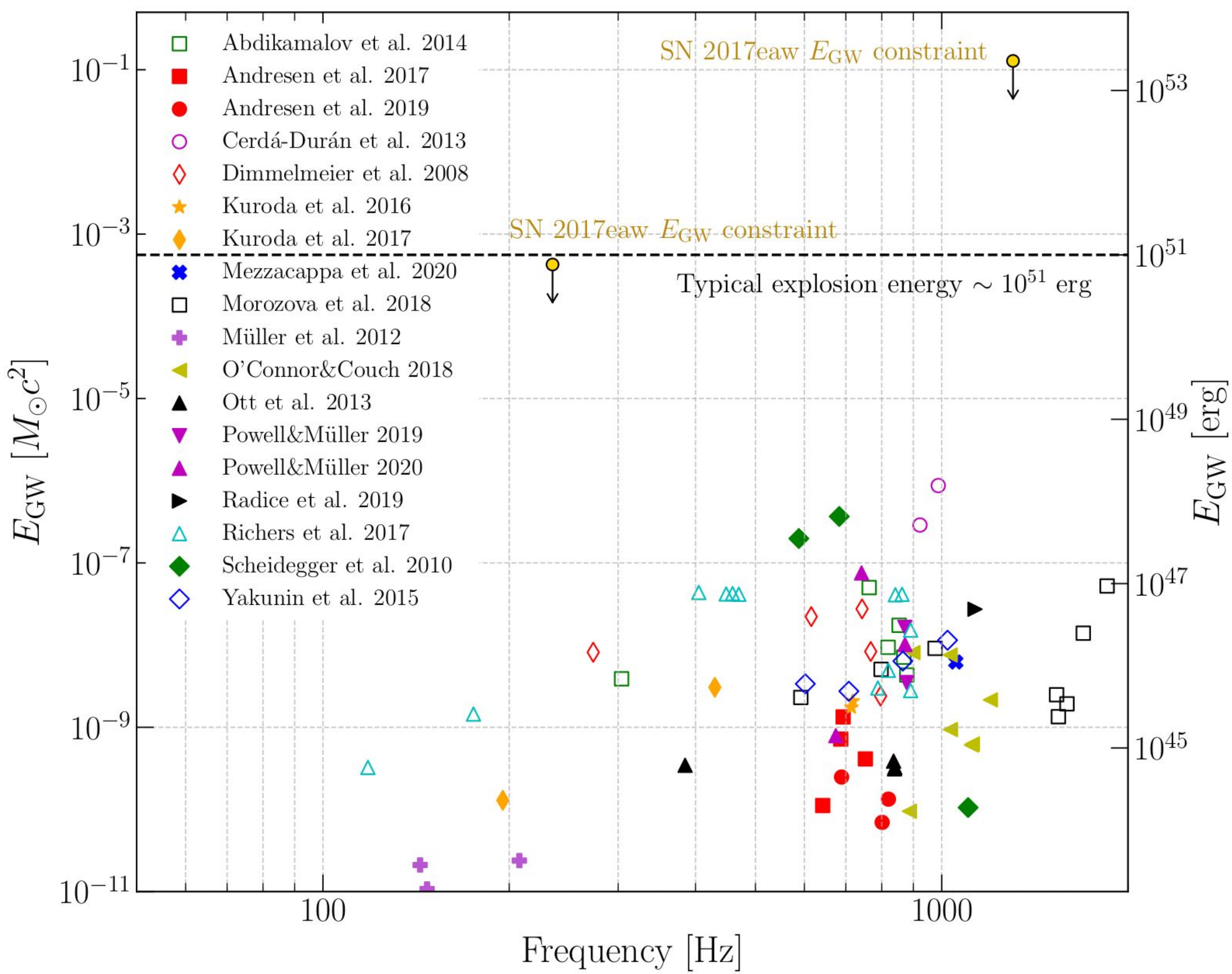

~30 years

few sec

Shock Breakout
hours - days

# Core-Collapse Supernova Detectability

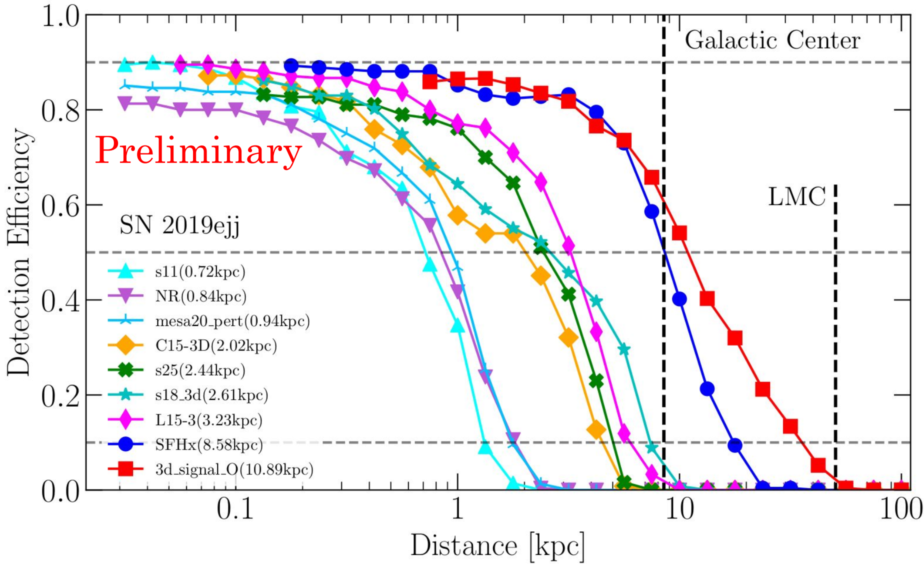
Szczepanczyk et al 2021 (2104.06462)

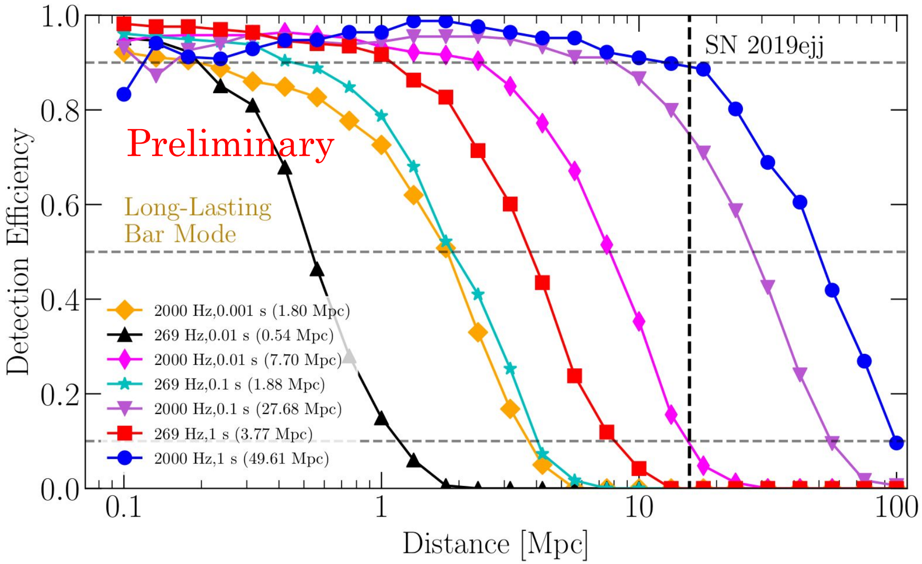


# Detection ranges

## Szczepanczyk et al 2022 (in prep)

- Detection range: distance at 50% detection efficiency
- Improvement with respect to the corresponding search with O1-O2 data: around 30-50% (Muller+12 L15-3)
- Neutrino-driven explosions: up to **13.7 kpc** (Kuroda+16 SFHx)
- Magnetorotationally-driven explosions: up to **15.9 kpc** (Obergaulinger+20 3d_signal_O)
- QCD phase transition: up to **2.1 kpc** (Kuroda+22 s50)
- Black hole formation: up to **0.8 kpc** (Pan+21 NR)
- Extreme emission models, long bar mode instability: **several Mpc**



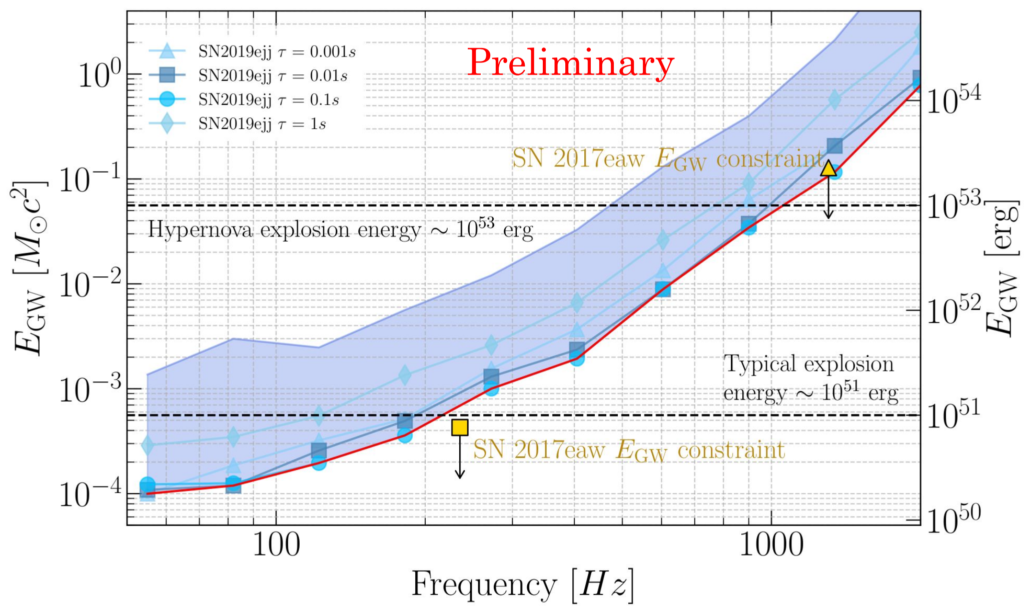
# GW energy upper limits

## Szczepanczyk et al 2022 (in prep)

- Reference values:
  - $10^{51}$ erg - typical explosion energy
  - $5\text{x}10^{52}$ erg - hypernova explosion energy
- Probing sensitivity with sine-Gaussians (peak frequencies and durations)
- At 50 Hz the stringent energy constraints are $\mathbf{10^{-4}\ M_{\odot}c^{2}}$ for signals 1 – 100 ms long.
  - Astrophysically meaningful
- Comparison for 235 Hz (12 ms):
  - O1-O2 search: $4.3\text{x}10^{-4}\ M_{\odot}c^2$
  - O3 search: around $8\text{x}10^{-4}\ M_{\odot}c^2$

GW emission assuming rotating CCSN:

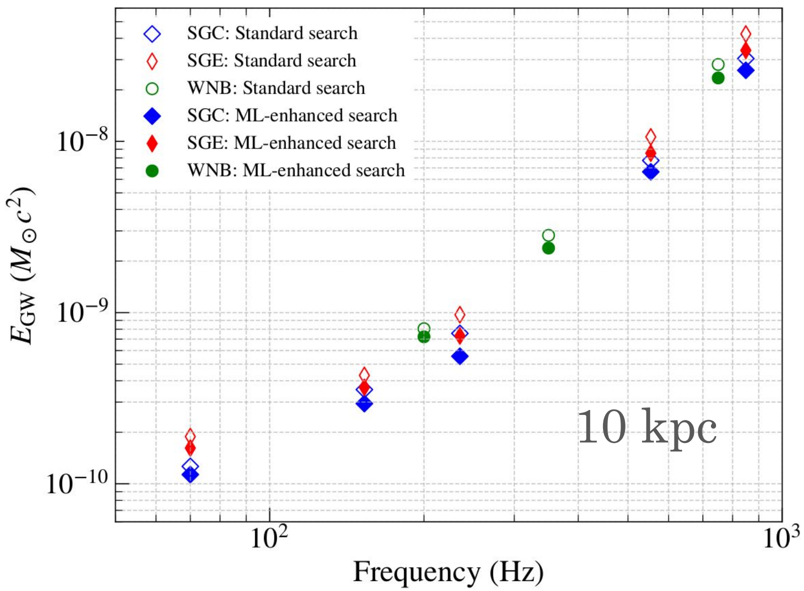
$$E_{\mathrm{GW}} = \frac{2}{5}\frac{\pi^2 c^3}{G} D^2 f_0^2 h_{\mathrm{rss50}}^2$$



# Generic search with O3 data

Szczepanczyk et al 2022 (2210.01754)

- Bursts: short-duration GW transients
- In the generic searches, we strive to be sensitive to largest possible GW signals
- „Unmodelled“ sources:
  - Core-collapse supernovae
  - Neutron star glitches
  - Cosmic strings
  - Unknown
- Compact binaries:
  - Binaries with circular/eccentric orbits
  - Intermediate-mass black holes
  - Head-on collisions
  - Hyperbolic encounters
  - etc




- Abbott+22: generic search with the O3 data - no new GW sources
- **Our re-analysis increased the sensitivity, but still null results**

# Summary

- The Dynamical Universe is one of the priority areas in Astronomy
- Gravitational waves, together with other messengers, are great probes for studying the fundamental Physics and exploring the Universe: state of ultra-dense matter, QCD phase transition, testing General Relativity, neutrino mass, nature of exploding stars, active galactic nuclei, and more.
- Anticipated detection rate in O4: one per day
  - Great opportunities for the discoveries!
  - Model-independent searches has already shown that they are suitable to detect the unexpected phenomena.