The quest to detect gravitational waves

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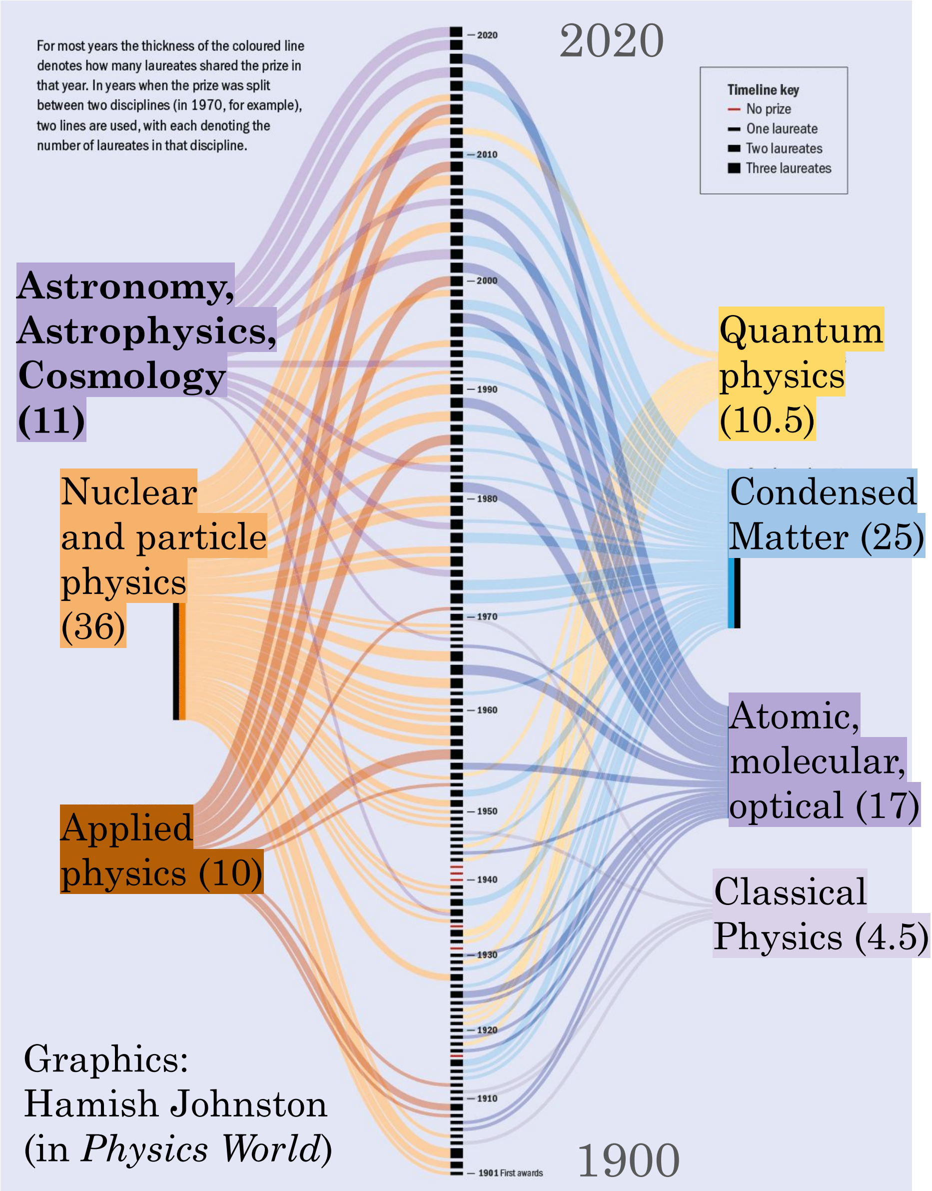
Outline

- Observing the sky
- Gravitational-Wave Detectors
- Model-independent searches
- Black Hole Spectroscopy
- Observing Run 4 (O4)
- Summary

Observing the sky

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)



For most years the thickness of the coloured line denotes how many laureates shared the prize in that year. In years when the prize was split between two disciplines (in 1970, for example), two lines are used, with each denoting the number of laureates in that discipline.

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.

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”

The Dynamic Universe

Quadrupole formula for GW production:

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

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

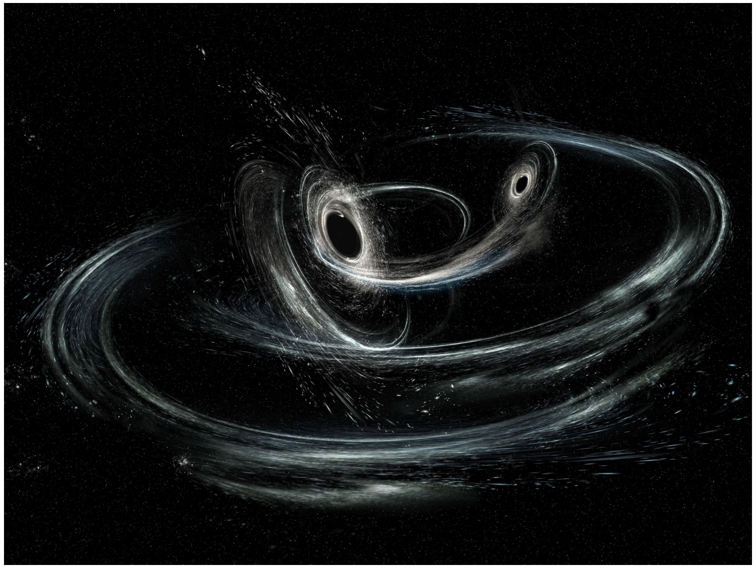
Image: NSF/LIGO/Sonoma/A. Simonnet

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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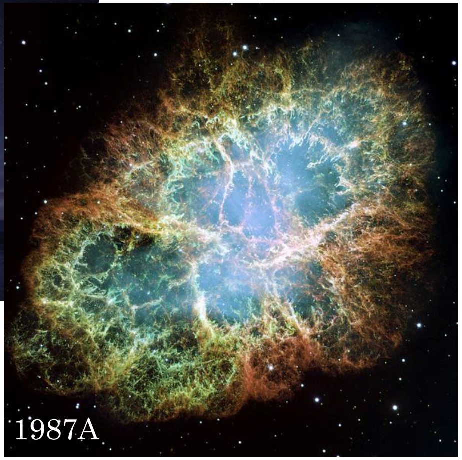
“Conventional” and “Gravitational-Wave” Astronomy

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

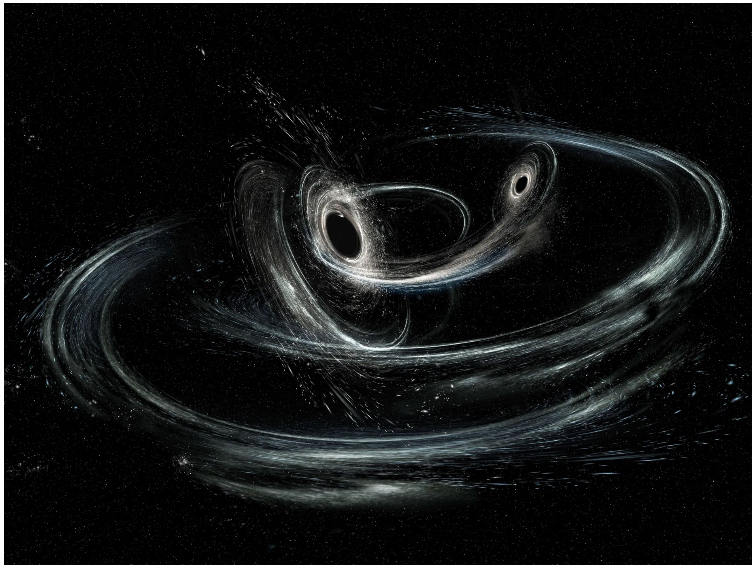
Looking at the Universe


timeshighereducation.com


1987A

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

Listening to the Universe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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

Compact Binaries - potential 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!

Gravitational-Wave Detectors

Einstein Equation and Experimental Gravitation

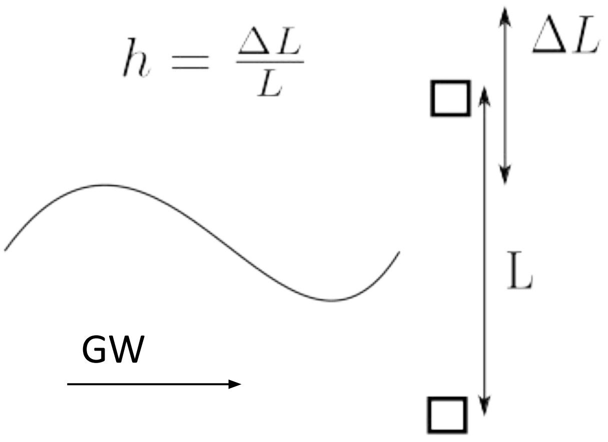
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- *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 Waves

1916 – Gravitational Wave solution, linear approximation:

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

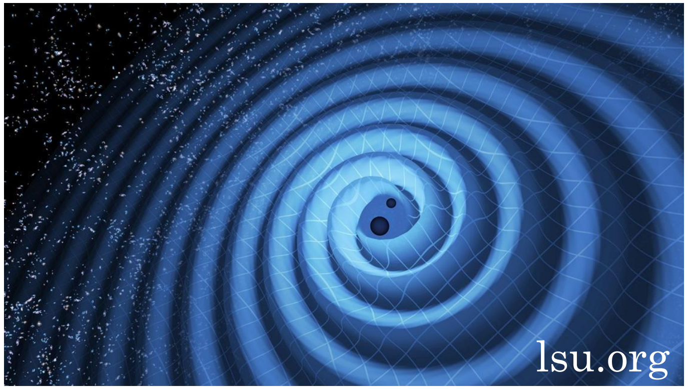


$$h = \frac{\Delta L}{L}$$

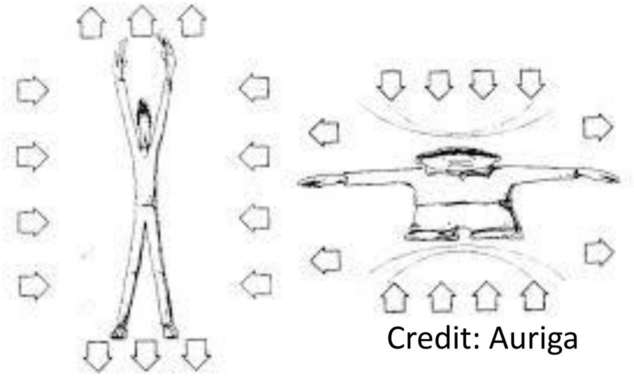
h – GW strain

14.09.2015 – Detection of Gravitational Waves!

- Generation of GWs: aspherical mass-energy movement
- GWs passing through two objects change distance between them.

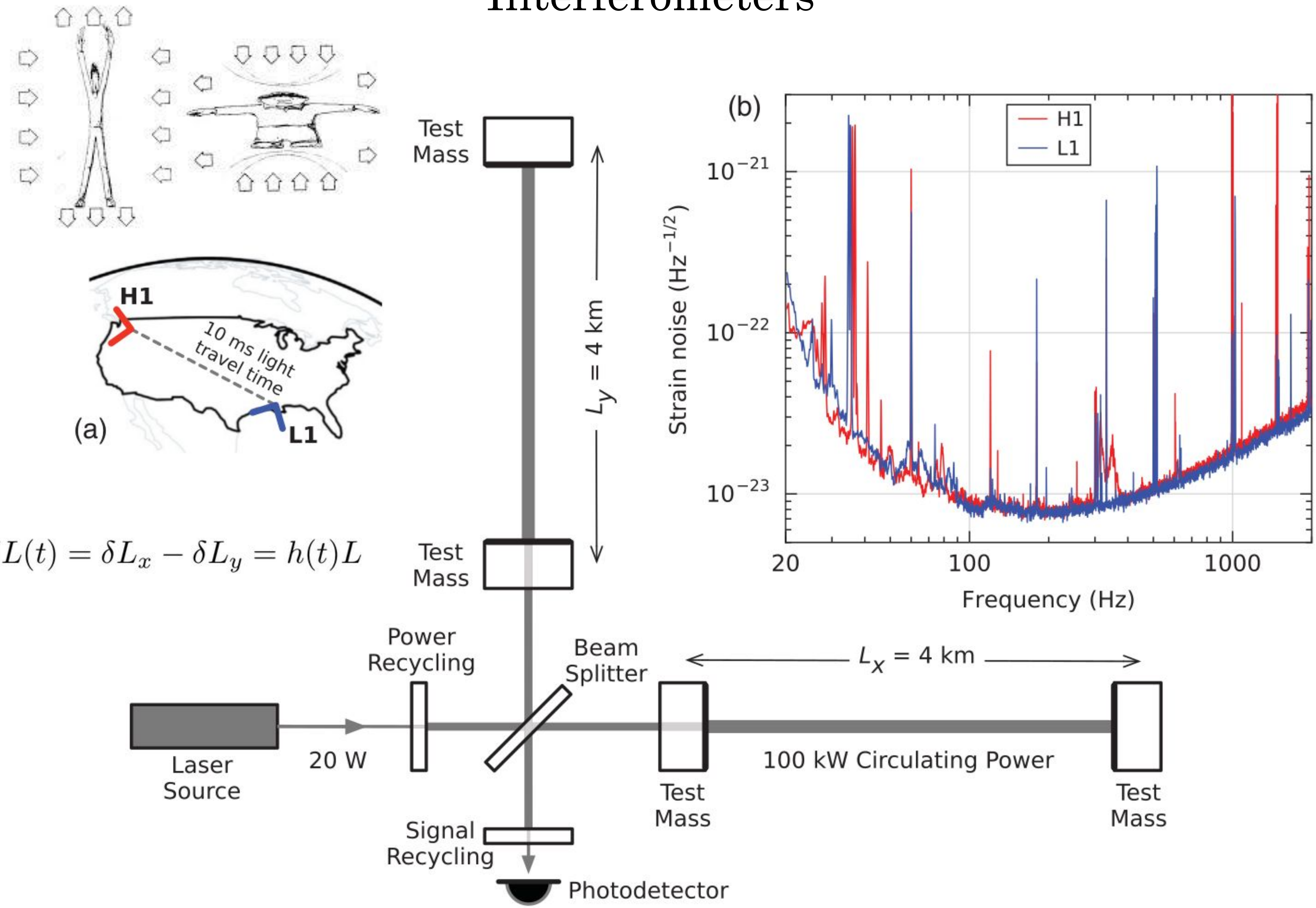


lsu.org



Credit: Auriga

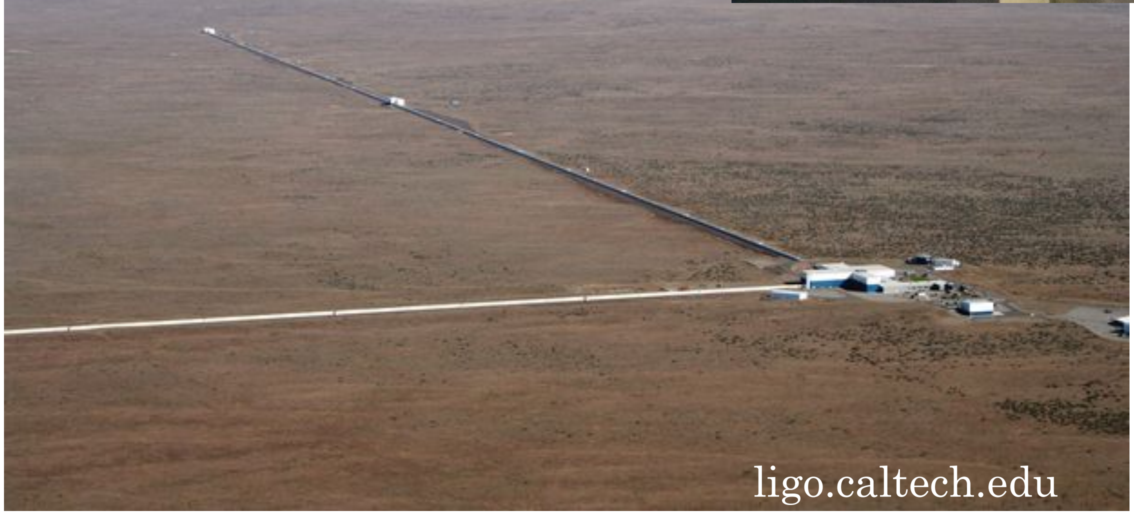
Interferometers



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

Interferometers

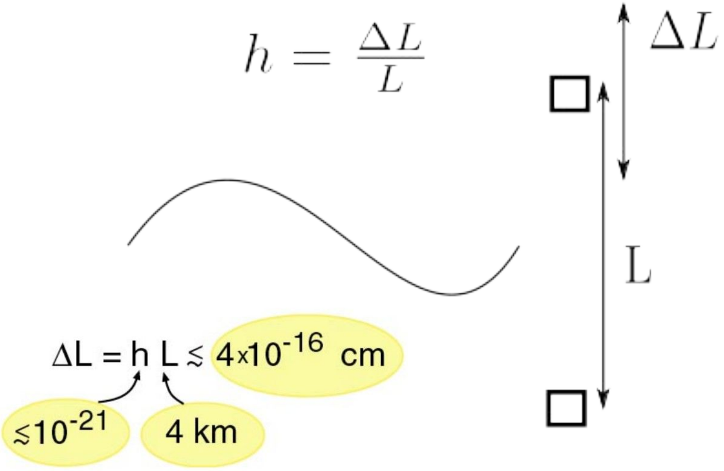
photo: author



ligo.caltech.edu

Detector noise

- GW detectors: interferometers (the longer, the more sensitive)
- Preferably far away from human activities.
- 200,000 monitors! (seismometers, magnetometers, microphones etc)



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

$\Delta L = h\,L \lesssim 4\times10^{-16}$ cm

$\lesssim 10^{-21}$

4 km

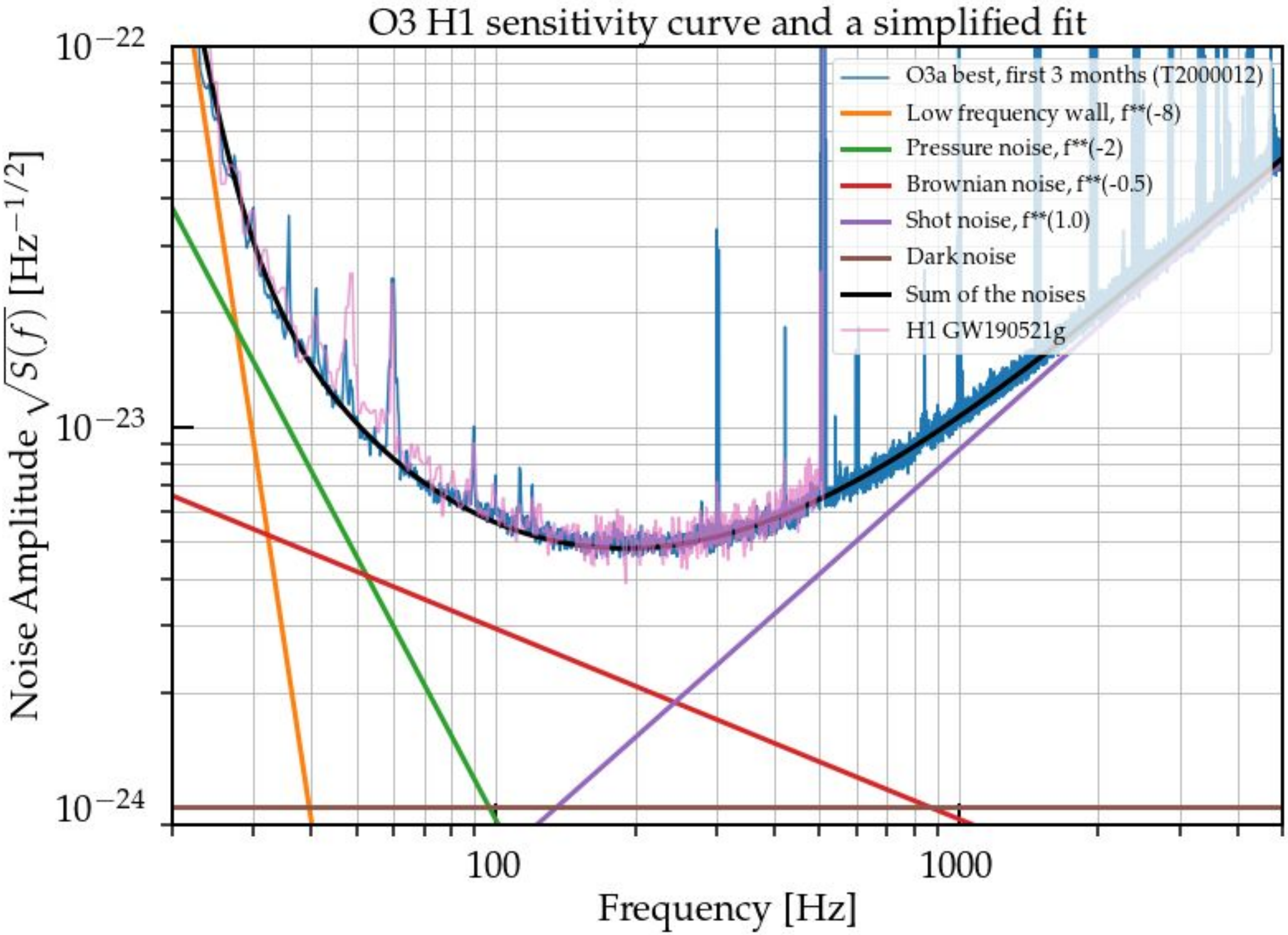
(proton size: 10^{-17} cm)

Sources of glitches:

- Raven with a thirst for shaved ice
- Earthquake and thunderstorm (somewhere on Earth)
- Planes, trains, cars
- Deforestation
- Fridge
- Nuclear tests

And many more…

Sensitivity curve (noise budget)



Pressure noise: fluctuations in radiation pressure on the masses

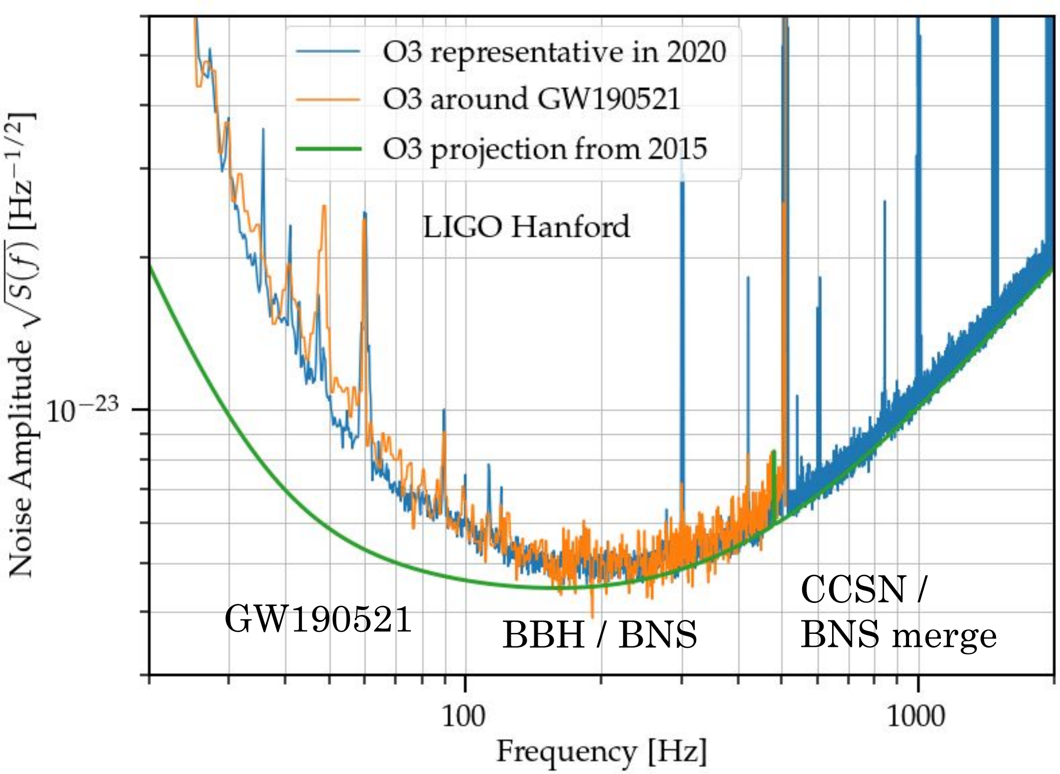
Shot noise: fluctuations in number of output photons

Detector control room

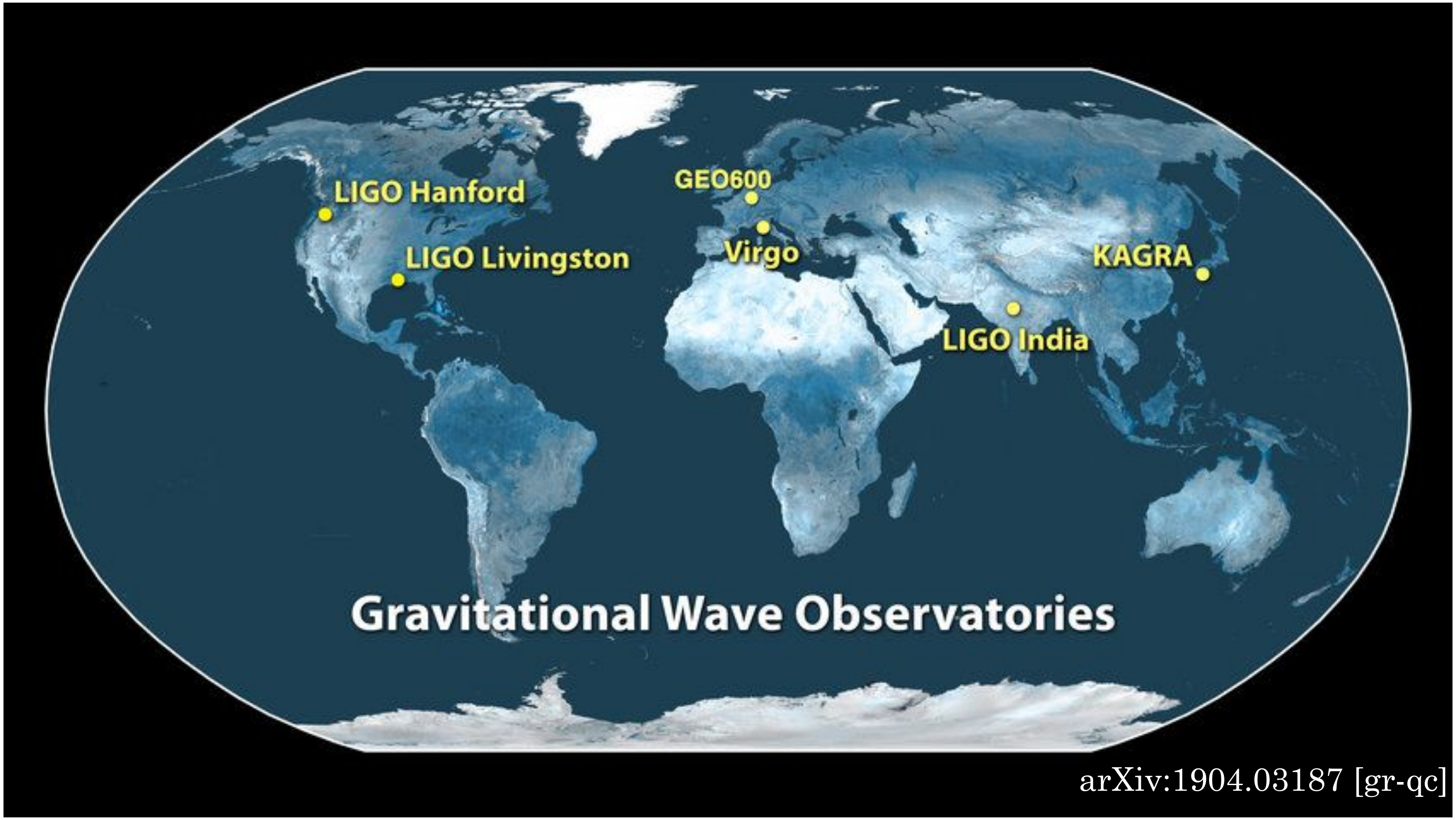
LIGO Hanford control room

Apr 13, 2019 (O3 start: Apr 1, 2019)

Photo: R. Droker
(flickr.com/)



Detectors network

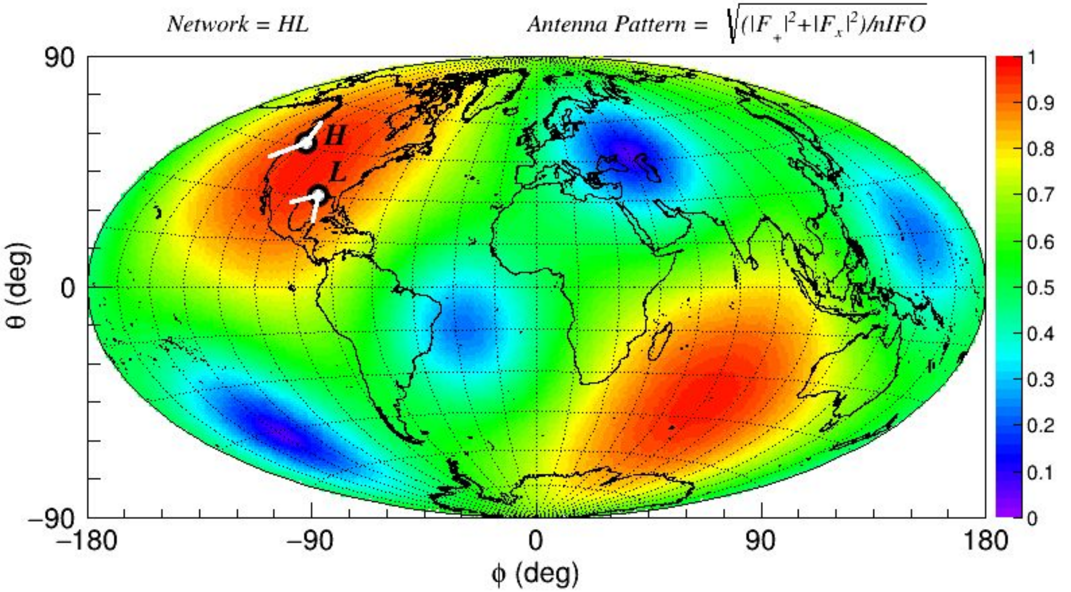


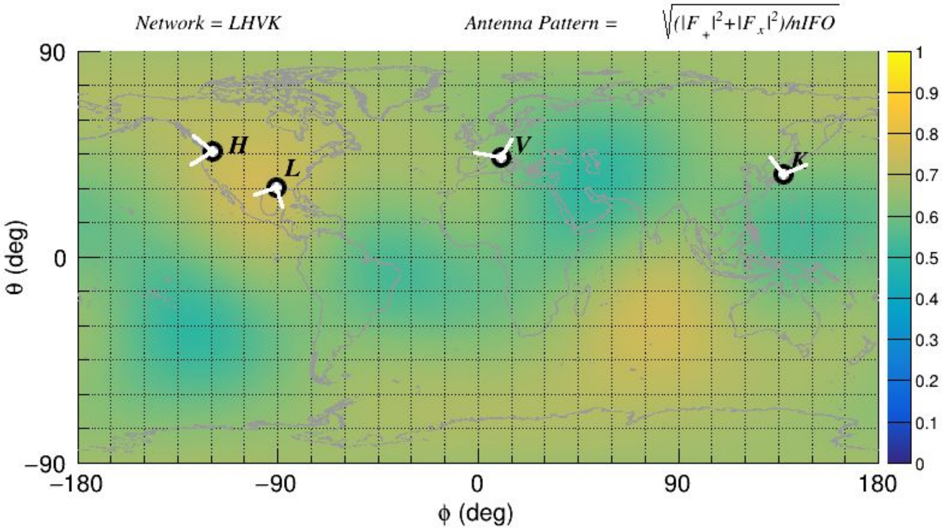
arXiv:1904.03187 [gr-qc]

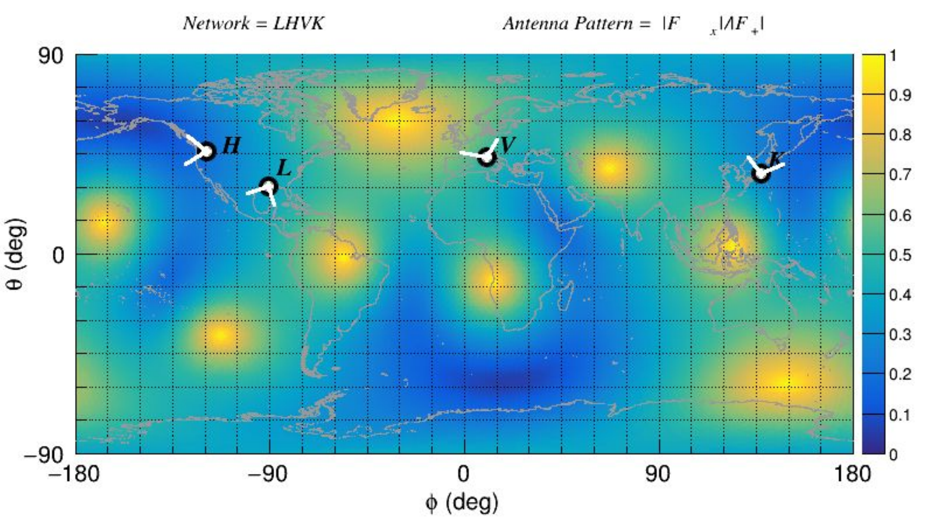
- Average BNS sensitivities: Livingston, Hanford ~160 Mpc and Virgo ~ 50 Mpc
- GEO and KAGRA - recently joined observations
- LIGO India - under construction

Detector Network – Antenna Pattern

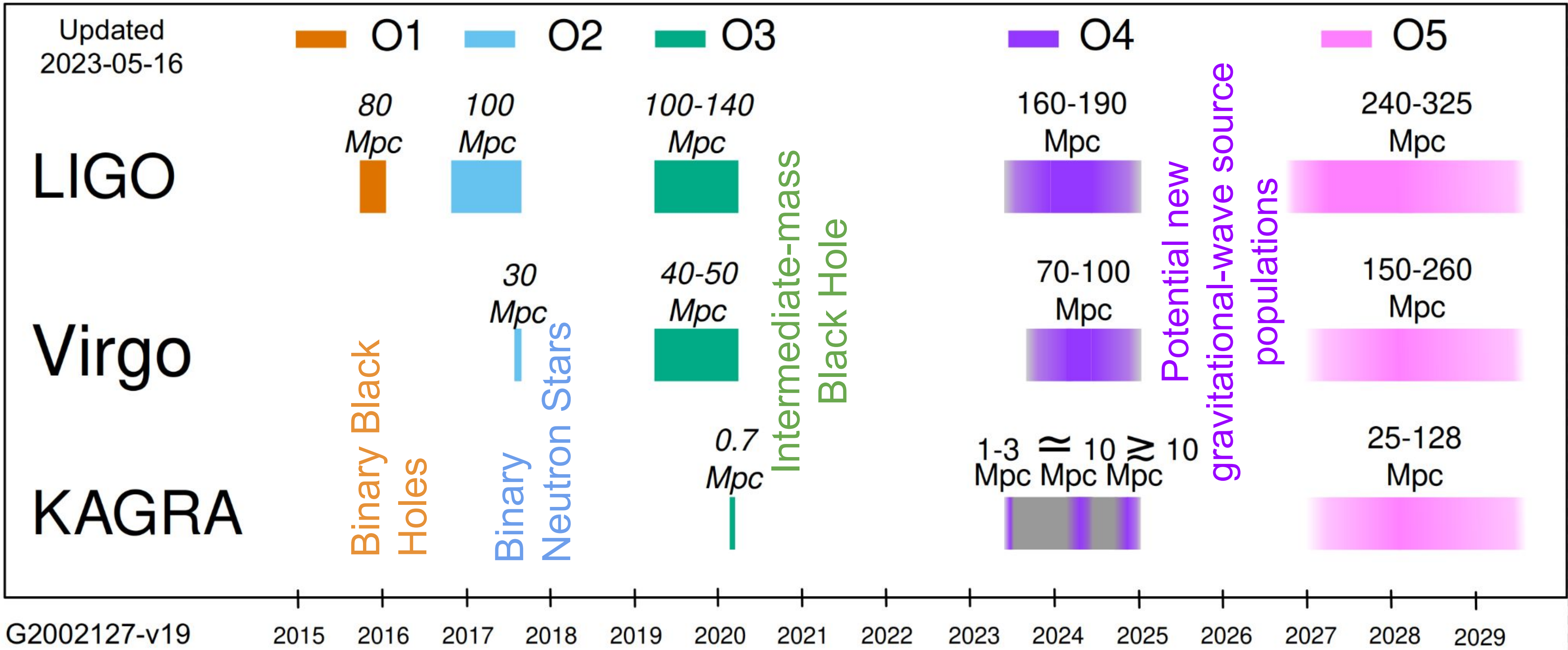
- Antenna Pattern – angular sensitivity of a detector or network of detectors
- Sensitivity: $F^2_+ + F^2_x$
- Alignment F_x/F_+
- LH network: the arms of interferometers are approximately parallel





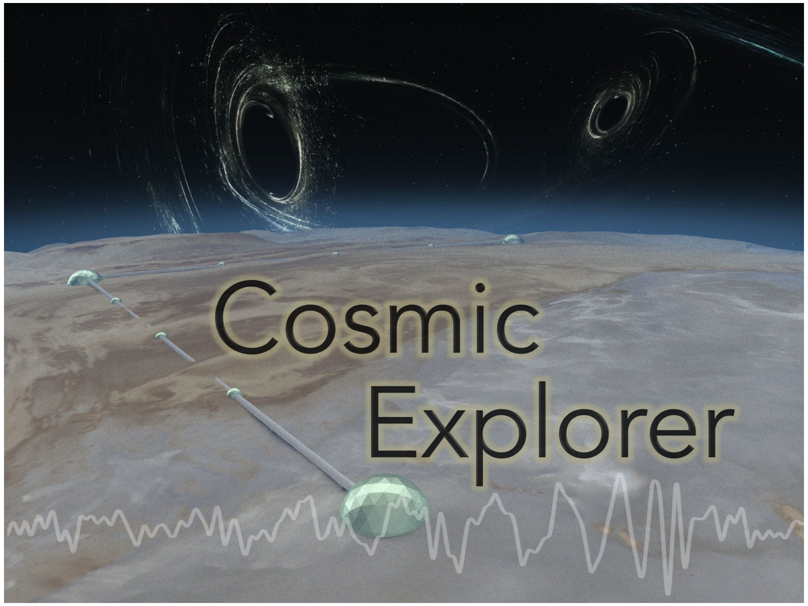


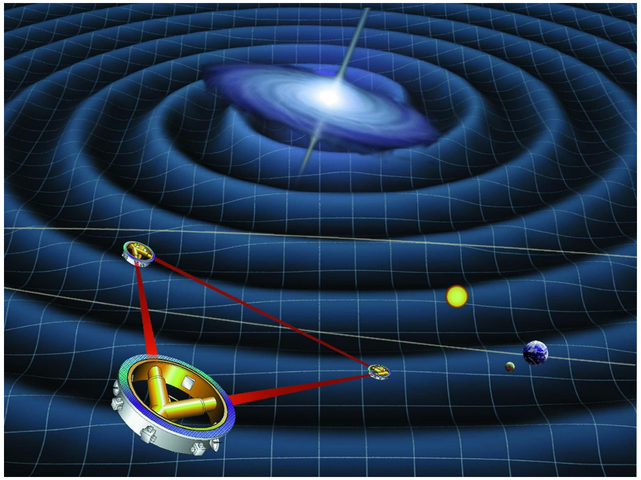
Observing timeline

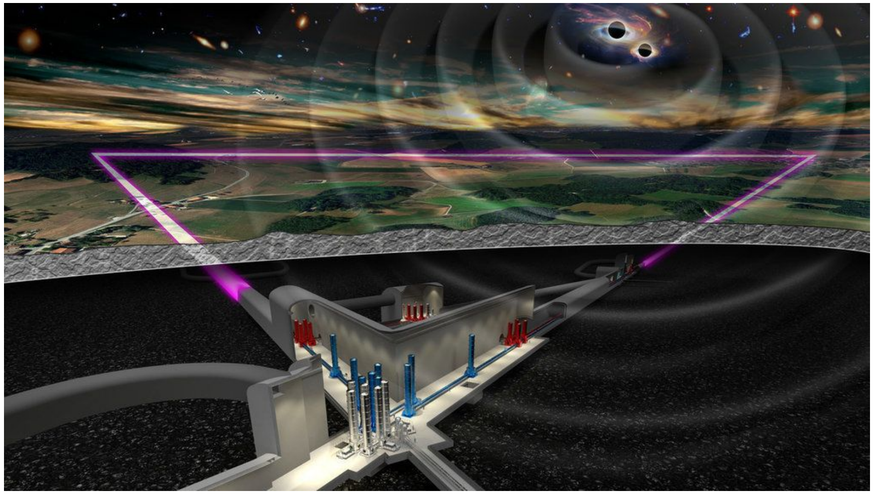


The future of observations

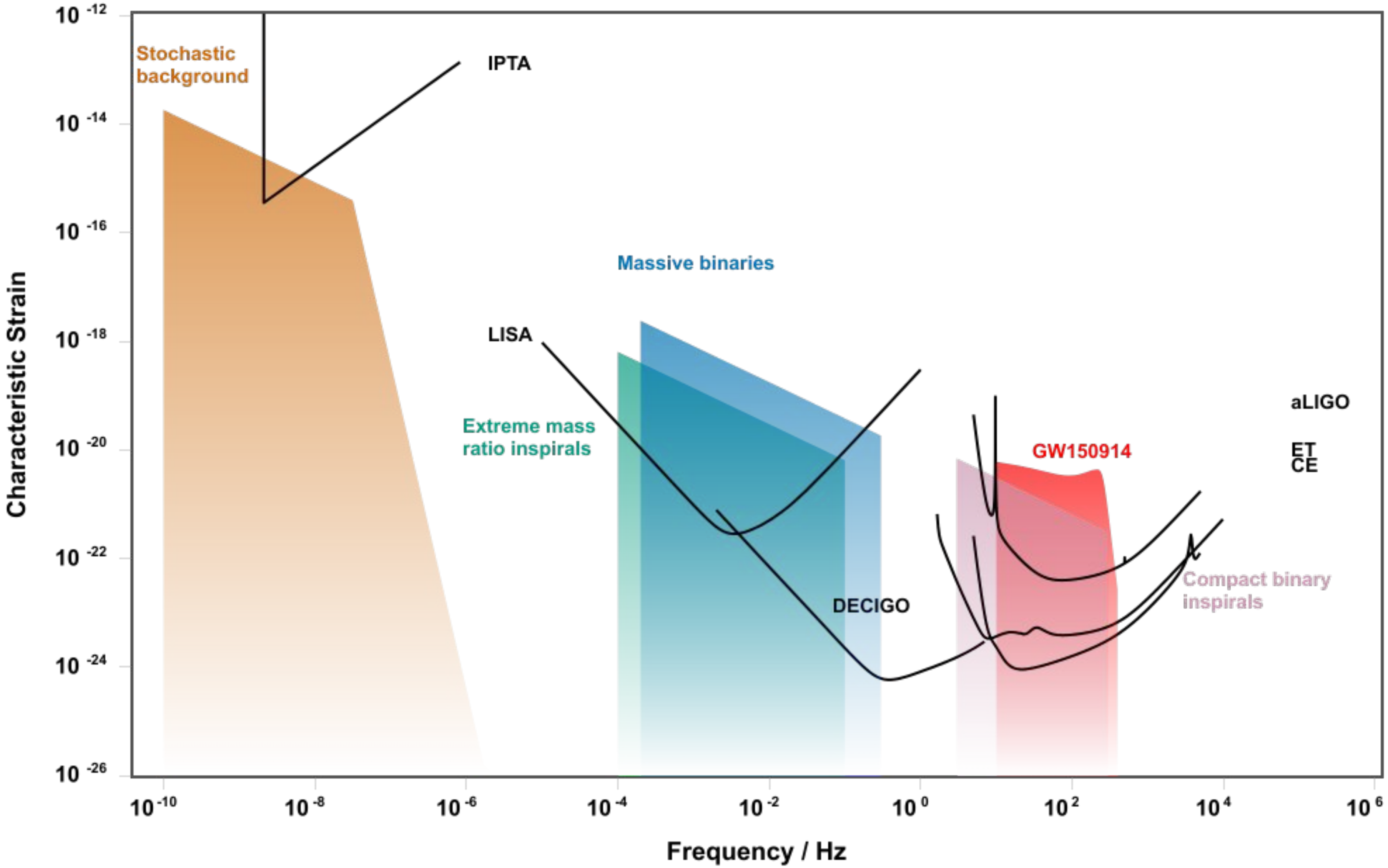
- The next generation of GW detectors will be 10 times more sensitive than current detectors
- Rate of detections per week:
  - currently: one-few
  - future: thousands!
- Projects:
  - LISA: space-based detector
  - Cosmic Explorer (US)
  - Einstein Telescope (Europe)







The future of observations



http://gwplotter.com/

The future of observations

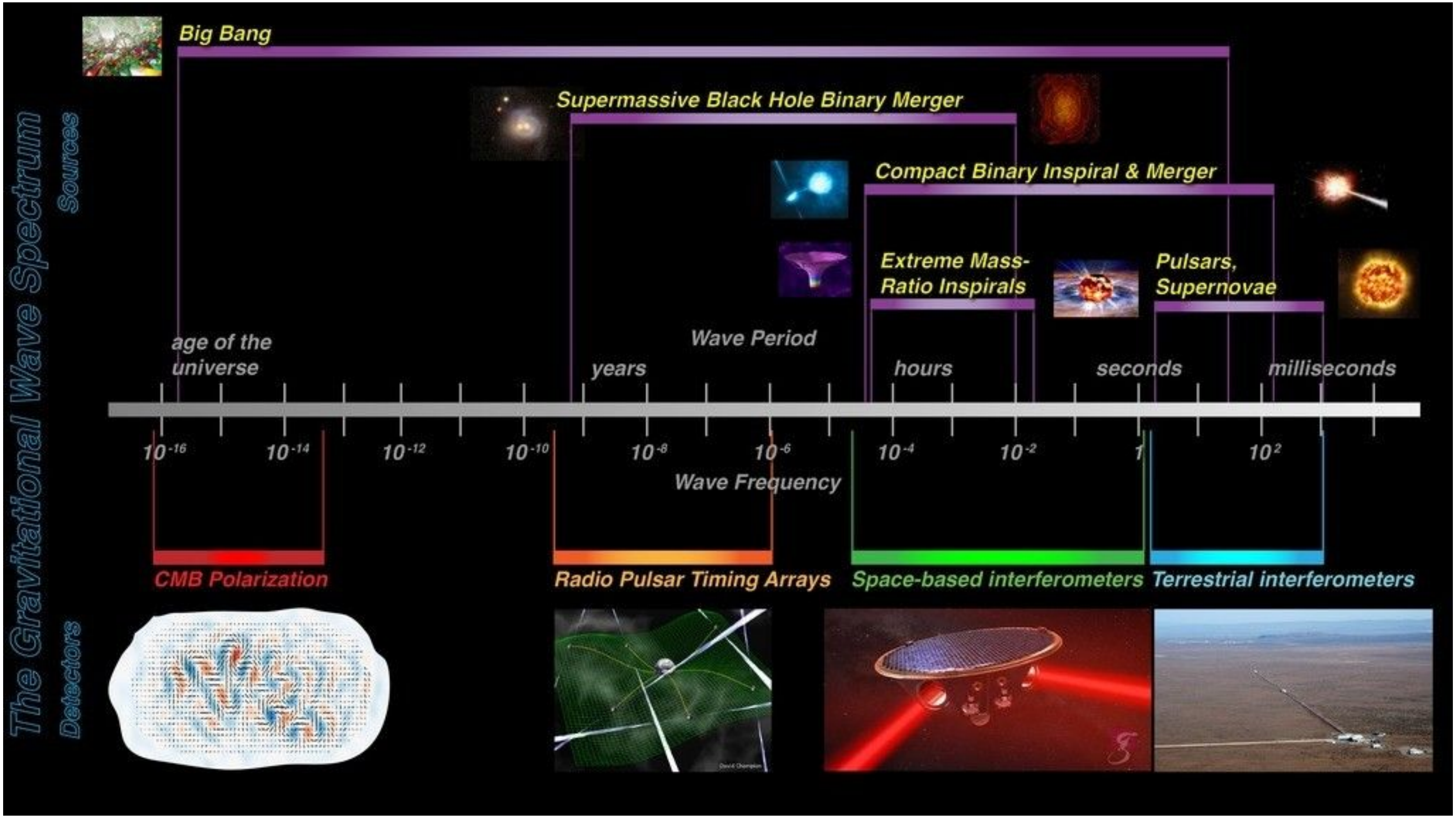


Photo: Ira Thorpe

Model-independent searches

GW bursts

	Modeled	Un-modeled
Short	CBC (BBH, BNS)	Burst (BNS, SN, cosmic string)
Long	Continuous Waves (pulsars)	Stochastic (sum of NS)

- GW burst signals: “un-modeled”, “poorly modeled”, “stochastic”, “non-deterministic”, “unknown origin”, “templates not possible to calculate”.

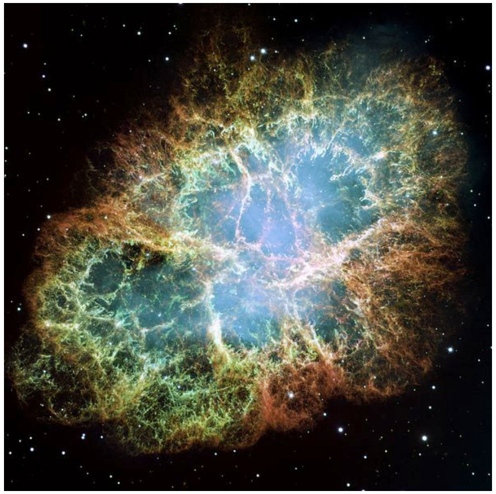
- Most representative bursts:
  GWs from Core-Collapse Supernovae

- Search method: energetic, anything that stands over an average noise is considered to be GW burst candidate

GW searches

- Searches:
    - **Model-dependent (matched-filtering, template-based):** binary black holes (BBH), binary neutron stars or binary black hole - neutron star
    - **Model-independent (template-independent) or "burst":** for example core-collapse supernovae, strings, as well as regular or special binaries, such as heavy/eccentric BBHs
- Latency of GW detection:
    - **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

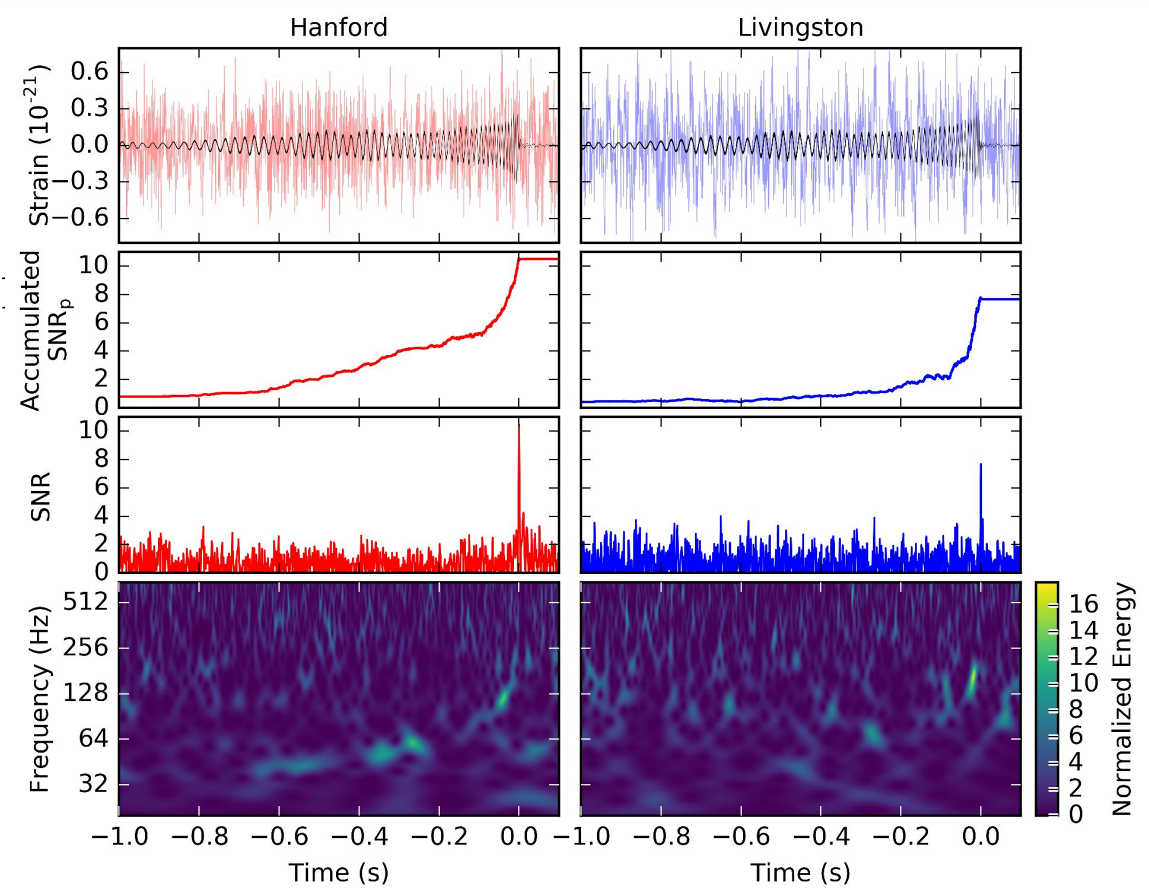
Matched Filtering (model-dependent)

- Cross-correlation of data with a template
- Template – a waveform calculated from theoretical prediction (General Relativity)
- Matched filtering SNR:

$$\rho^2(t) = \frac{1}{|\langle h|h\rangle|}|\langle s|h\rangle(t)|^2$$

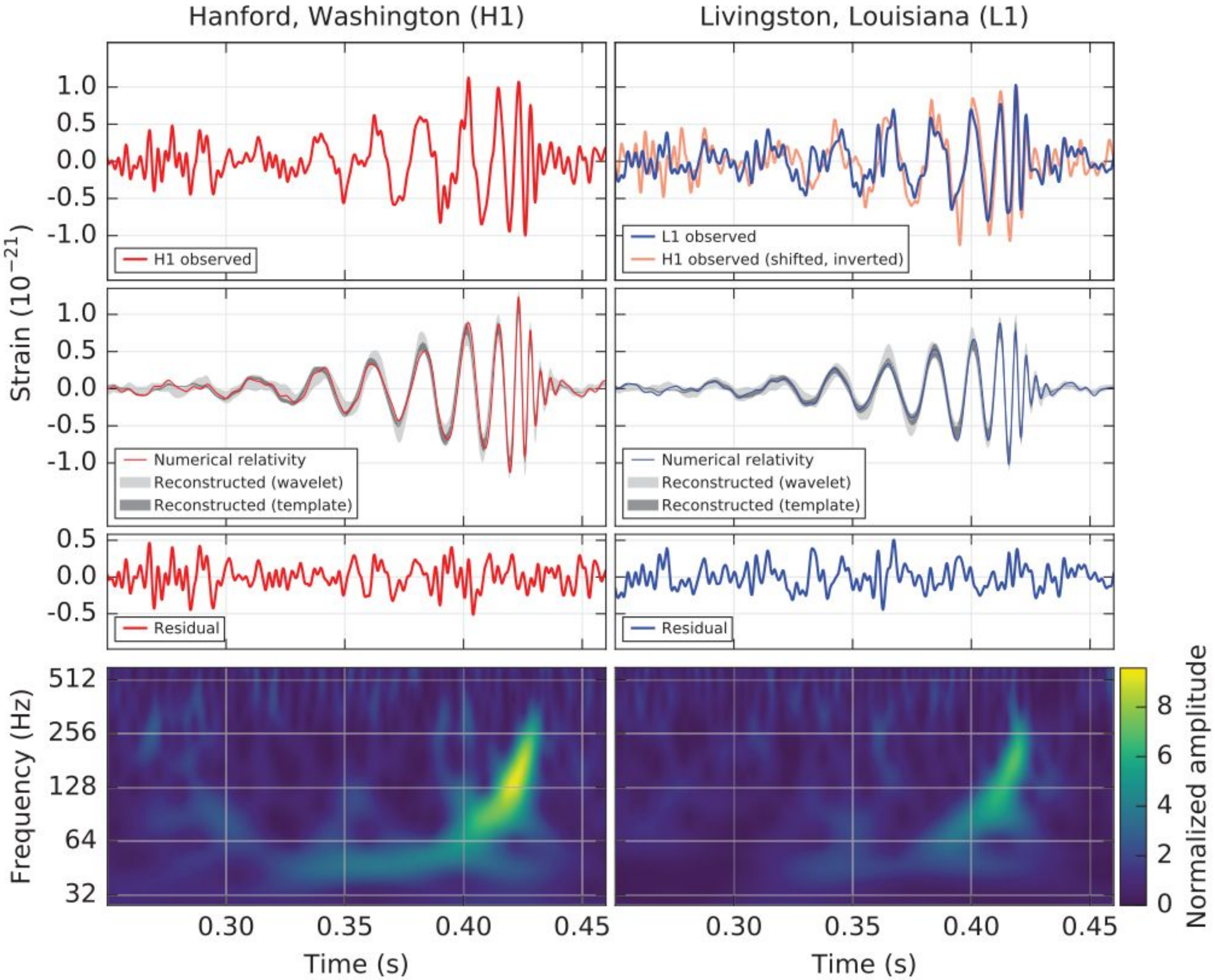
where scalar product is defined as:

$$\langle s|h\rangle(t) = 4\int_0^\infty \frac{\widehat{s}(f)\widehat{h}^*(f)}{S_n(f)}e^{i2\pi ft}df$$



Abbott et al 2017, Binary neutron star detection paper

First ever GW signal was detected solely by the model-independent cWB search



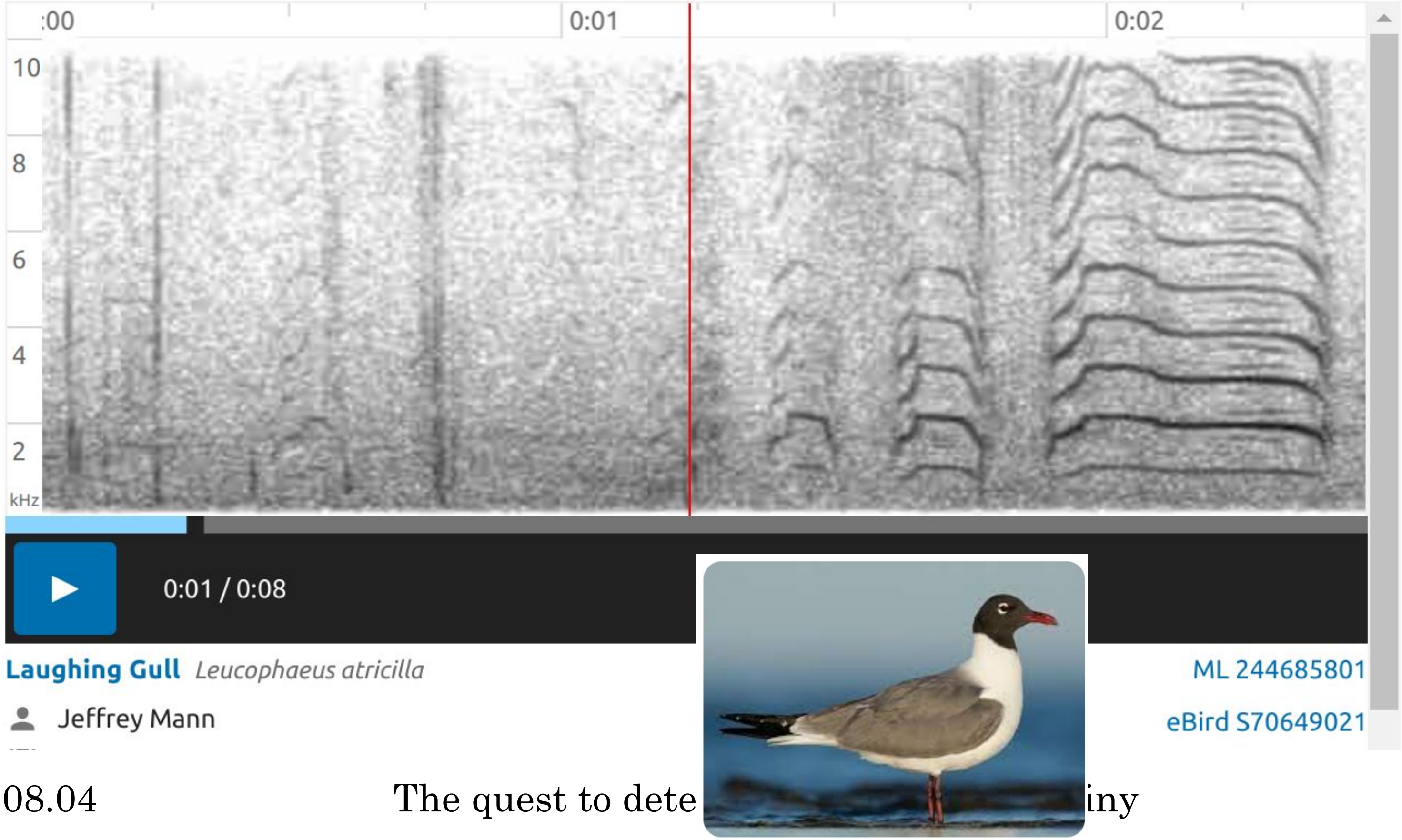
Chirpy Universe

Example chirp sound: LINK

Figure: Abbott et al 2017, Sound: LINK

Time-frequency domain - spectrogram

- Time-frequency domain (maps) allow to explore evolution of signal's frequency over time.
- Many possible realizations of time-frequency transform.
- Visualize bird's sound with spectrograms, example: https://becausebirds.com/visualize-bird-songs-with-spectrograms/

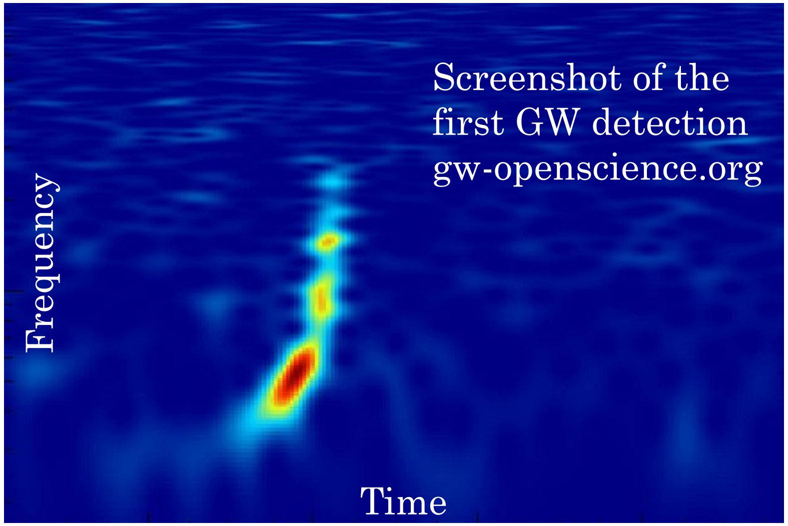


coherent WaveBurst (Model-independent searches)

- **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
- 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**

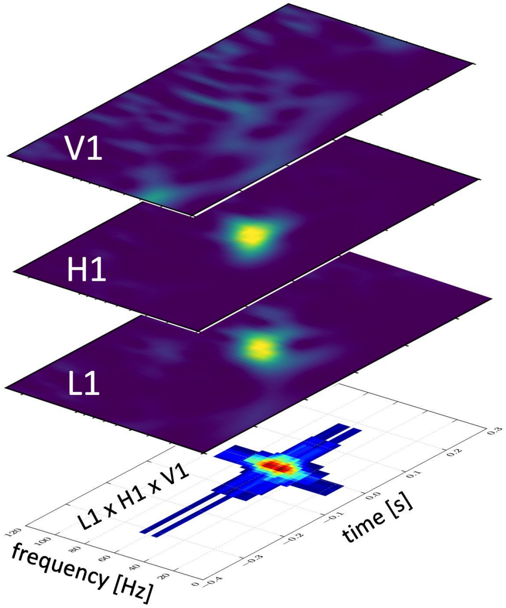
WB coherent WaveBurst
an open source software for
gravitational-wave data analysis

https://gwburst.gitlab.io/



Screenshot of the first GW detection gw-openscience.org

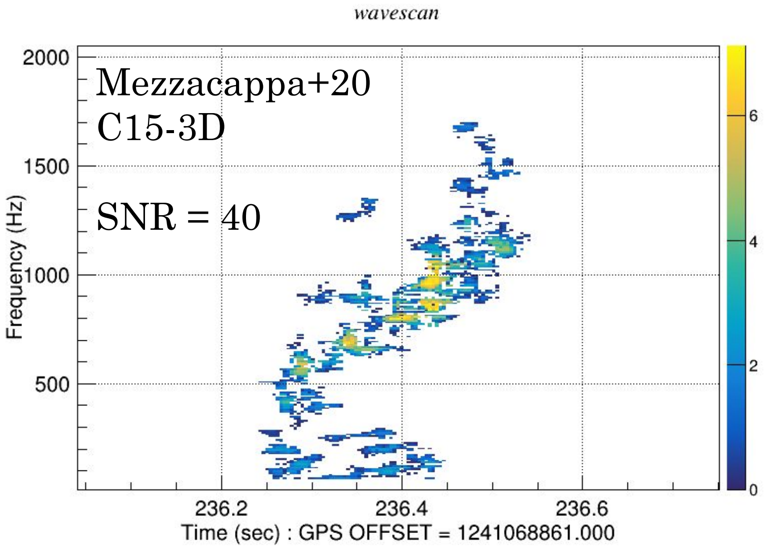
coherent WaveBurst (cWB)



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

- Time-Frequency Decomposition
- Cluster Selection
- Constrained Likelihood

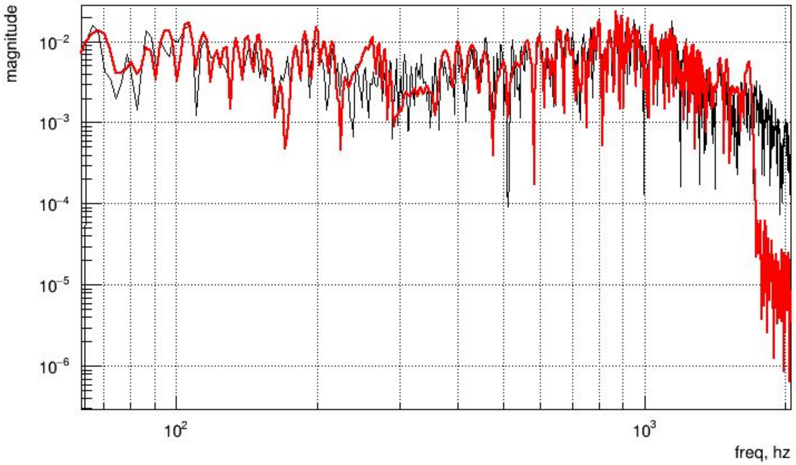
$\xrightarrow[\text{Transform}]{\text{Inverse Wavelet}} h(t)$



Mezzacappa+20
C15-3D

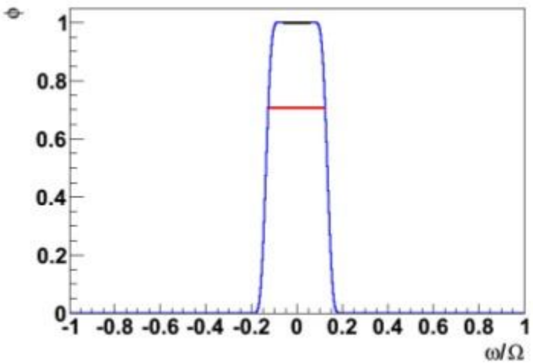
SNR = 40

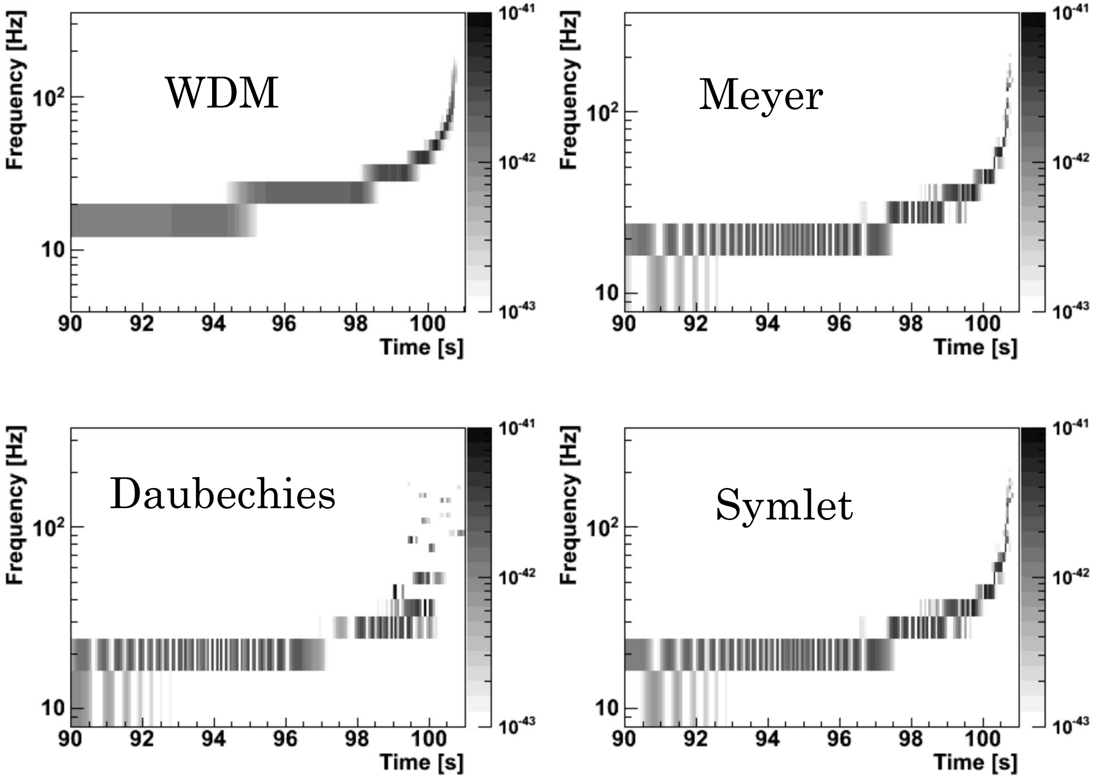
Injected (black) vs reconstructed (red)



Wavelet decomposition

- cWB uses a specially designed wavelet transformation, WDM (Wilson-Meyer-Daubechies):
  - Fast transformation using FFT
  - Shorter transformation filters (time localization)
  - Less spectral leakage (frequency localization)
- Each wavelet represents a time-frequency pixel





Necula et al 2012

Multiresolution wavelet decomposition

- It is not possible to measure both frequency and time with at arbitrary resolution:
  $\Delta t\, \Delta f \geq 1/2$ (Heisenberg rule for signal processing)
- Detectability of signals depends on setting up appropriately Δt and Δf.
- cWB uses 7 multiresolution decomposition layers

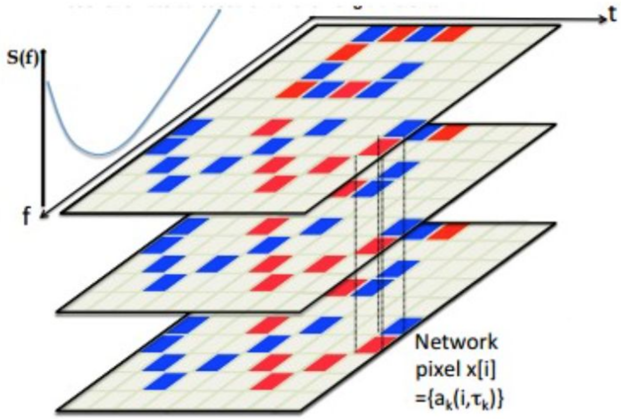
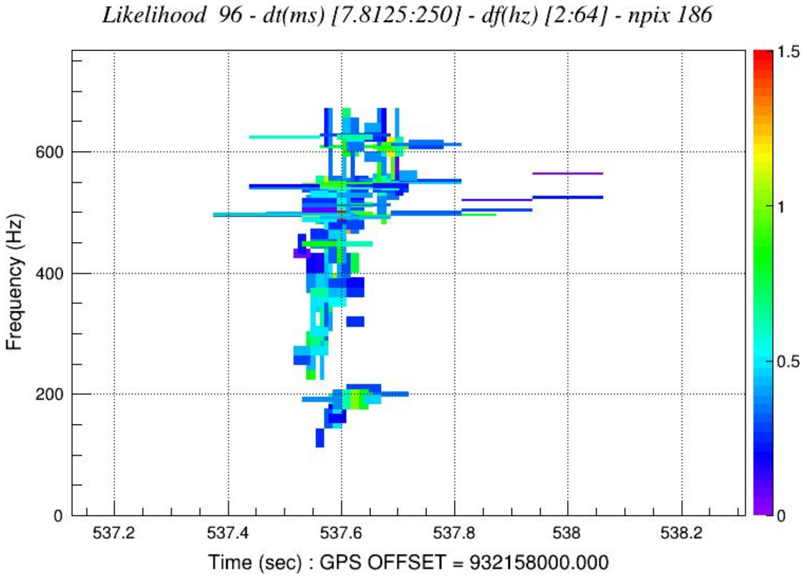
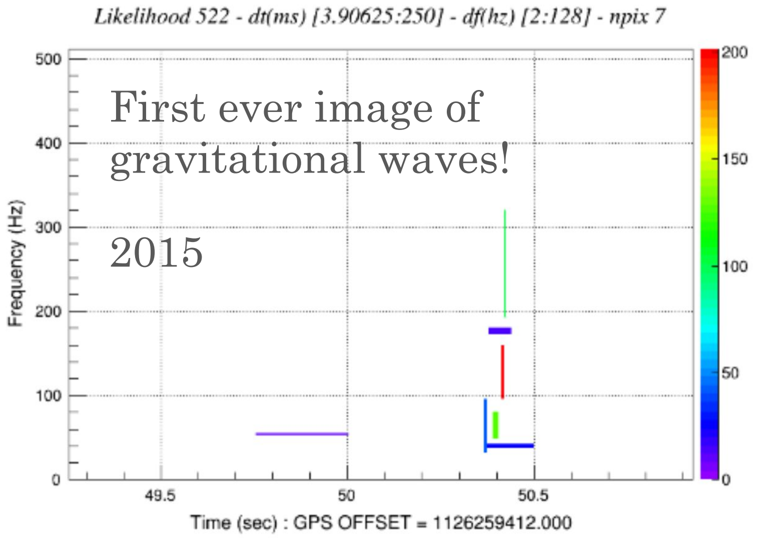


Figure: Klimenko



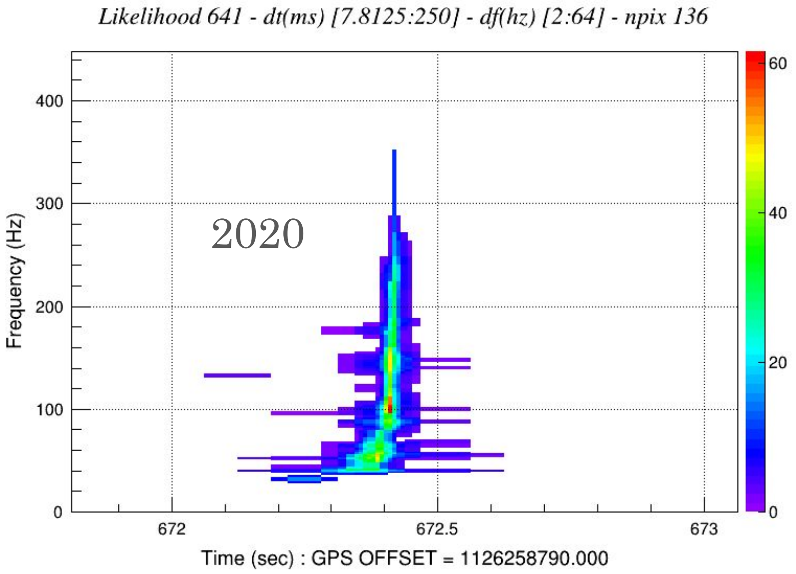
Improvements: GW150914 example

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

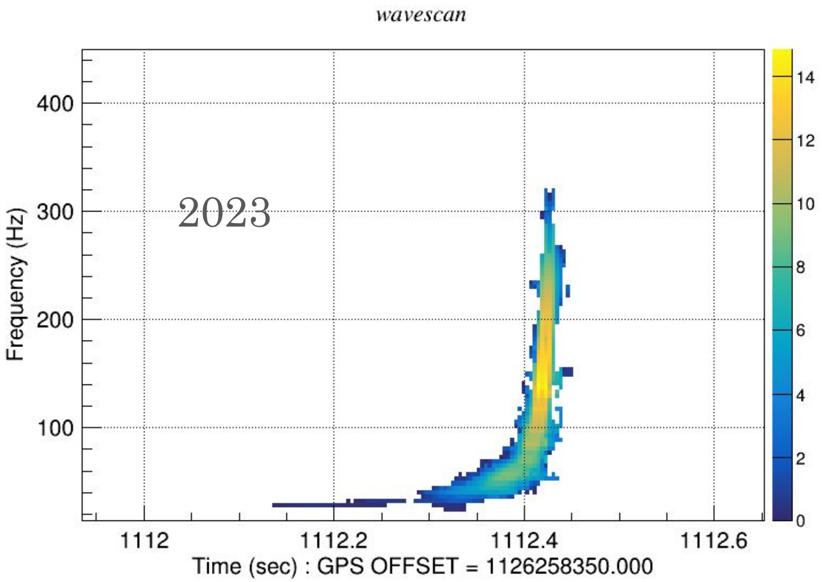


First ever image of gravitational waves!

2015



2020



2023

Background analysis

- Every physical experiment requires measurement of background, e.g. measurement of light flux.
- Background analysis in GW research: study to investigate how often detector, environmental etc noise can produce an event that can be identified as a GW burst.
- Requirements:
  - Every produced trigger is certainly not a GW,
  - The lifetime of an experiment can be enlarged.
- Solution: artificial time shifts between the detectors (usually 1s)

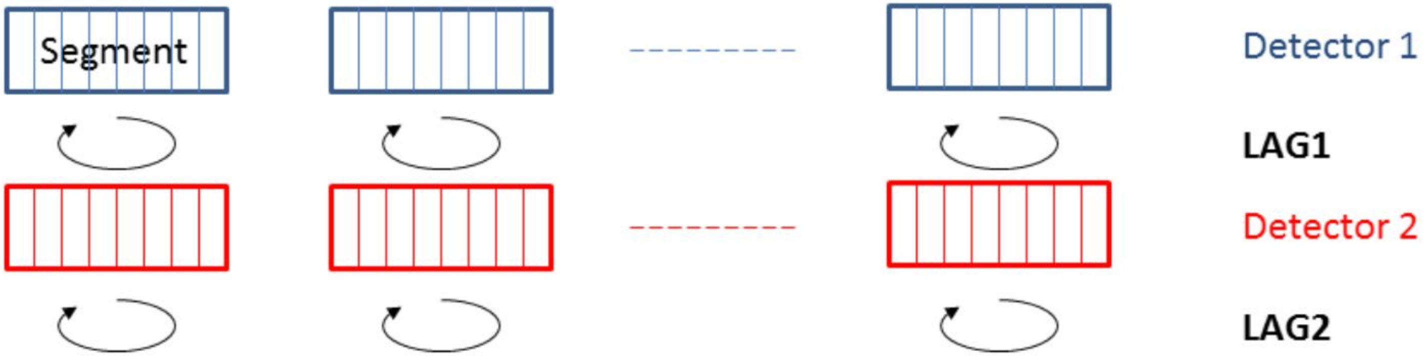


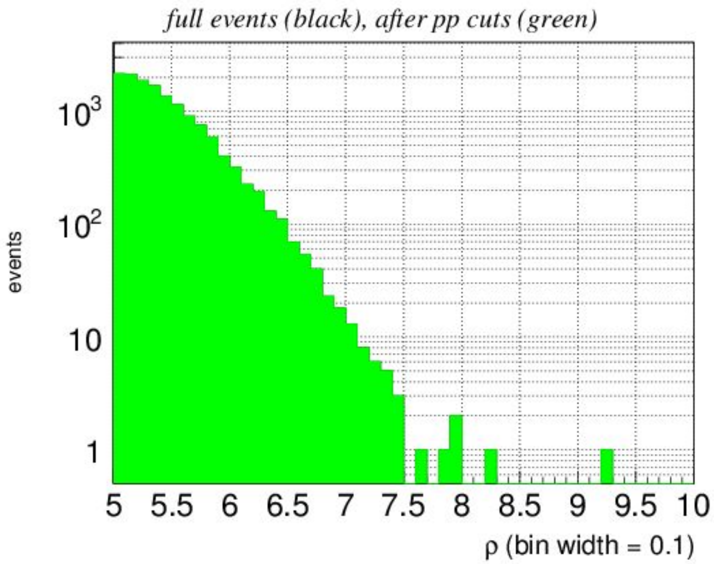
Figure: Klimenko

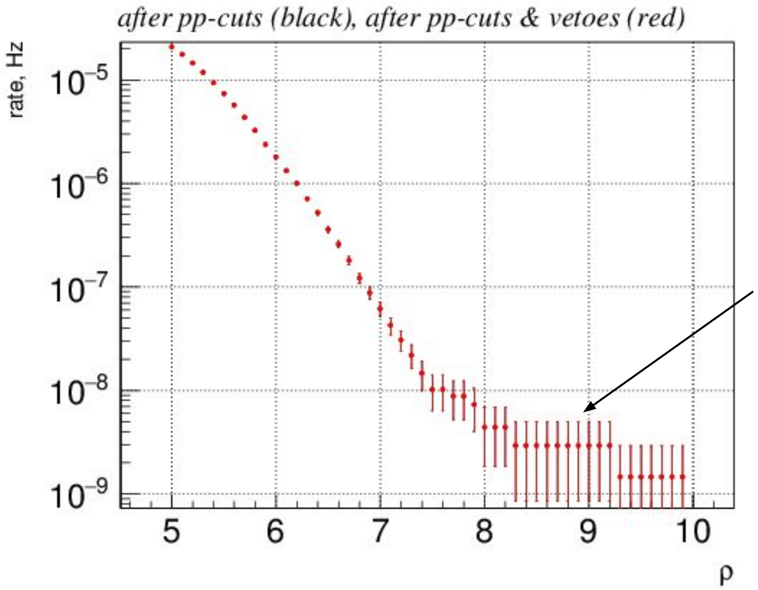
Background analysis
False Alarm Rate (FAR)

- False Alarm Rate, or false identification of GW:

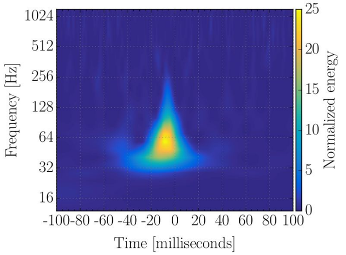
$$FAR = N/T_{\mathrm{bkg}}$$

  - N – number of falsely identified events
  - T_{bkg} – time of "running the background experiment"





Non-Gaussian glitches, e.g. blips



Abbott et al 2016

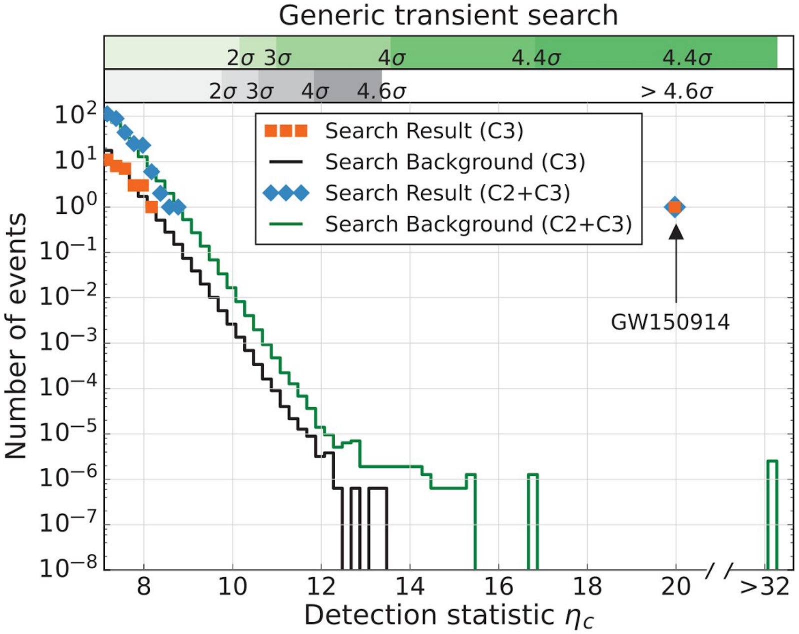
Excess Power and Matched Filtering (complementary methods)

Excess Power

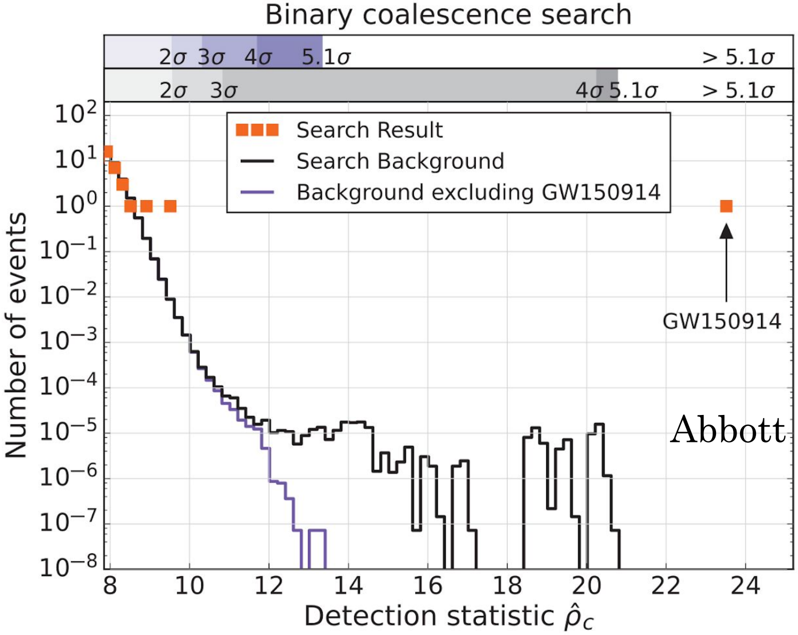
- The main method to detect waveforms that we cannot derive templates (like supernovae)
- The parameter space is much smaller
- Advantage: detection of burst sources
- Disadvantage: the estimation of source properties may be challenging

Matched Filtering

- The main method for detection of well modeled (inspiral sources)
- The most optimal method, assuming stationary Gaussian noise (!)
- Advantage: Good reconstruction of the waveform and source properties
- Disadvantage: if the waveform does not match the data, the detection is missed (e.g. first GW detection)



Generic transient search



Binary coalescence search

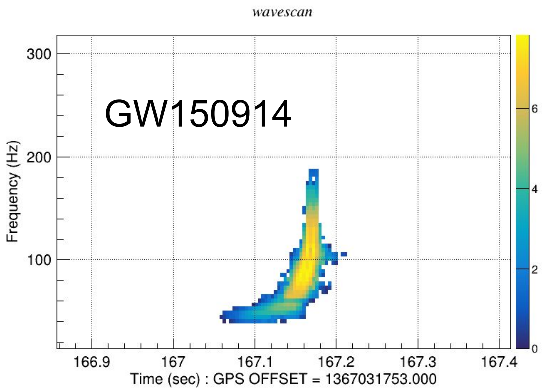
Abbott et al 2016

Model-independent searches

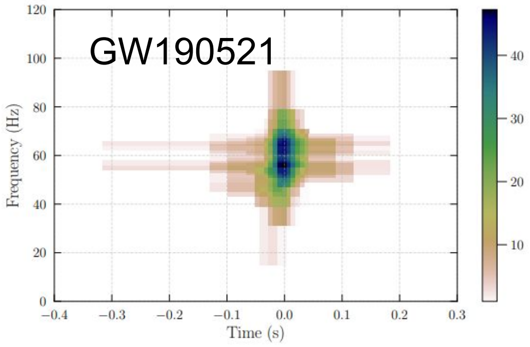
Compact binary searches (minimally modeled)

Generic searches (unmodeled)

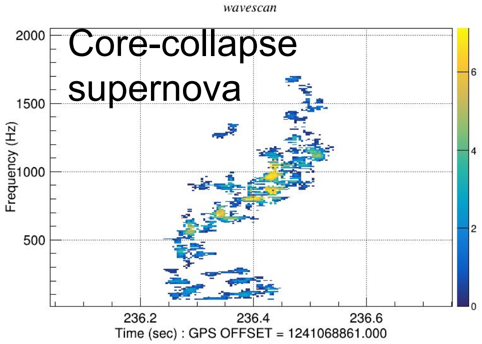
Binary black holes
Binary neutron stars
Black hole - neutron star



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



Core-collapse supernovae
Pulsar glitches
Cosmic strings
Unknown

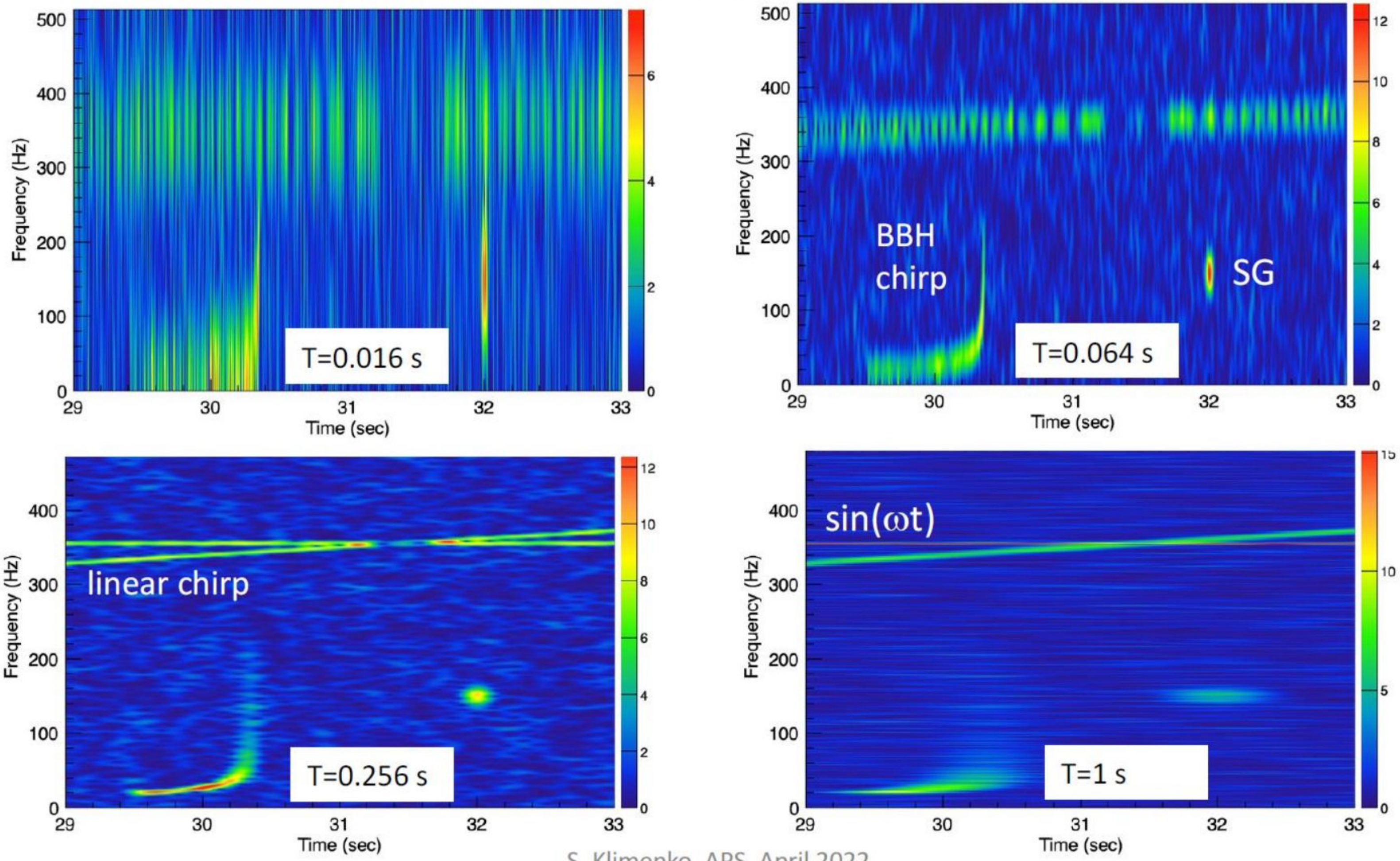


Black Hole Spectroscopy

Spectrogram

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

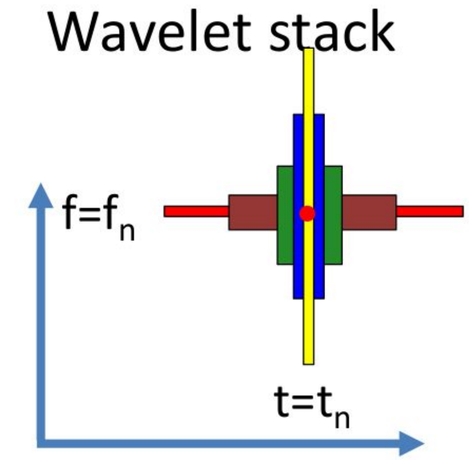
Which window w(t) is optimal? – The answer depends of the type of the signal we try to resolve
More general question: what is the optimal distribution $\boldsymbol{P(\omega, t)}$ of the time-varying spectrum?



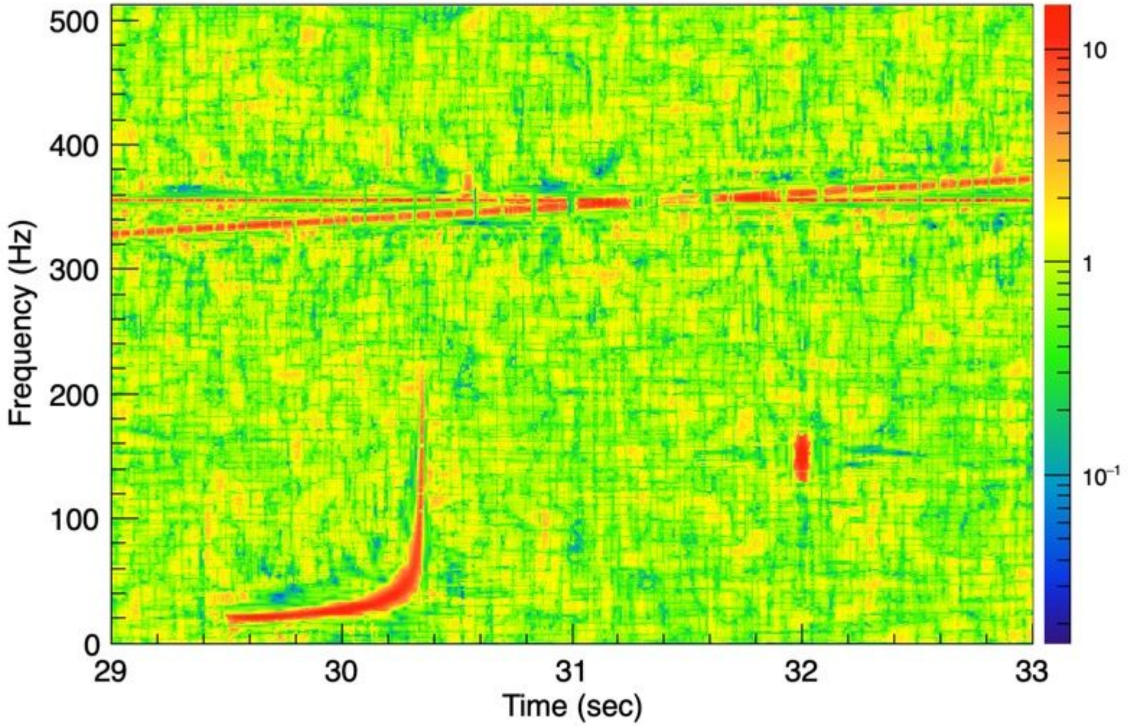
S. Klimenko, APS, April 2022

Temporal and Spectral Leakage

- To capture the time-varying spectrum, perform analysis at several resolutions, e.g. estimate power at a given TF location with wavelets of different durations (wavelet stacks)→How to combine several resolution into a single time-frequency distribution?



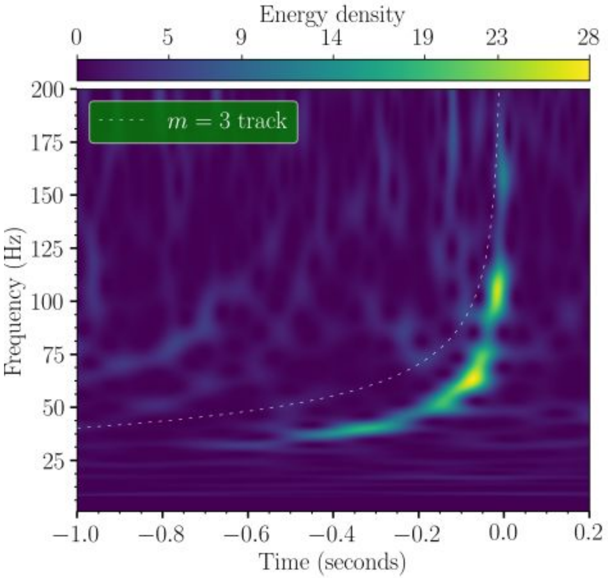
Artifacts due to temporal and spectral leakage

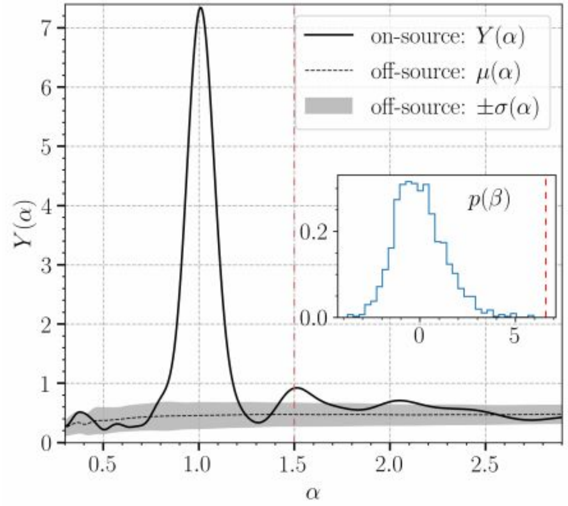


Figures: Klimenko

GW190412

- GW was identified on April 12, 2019 in low-latency by GstLAL, SPIIR, cWB, MBTA and PyCBC.
- cWB offline analysis with significance FAR > 1 per 10^3 years
- Novelty:
    - Very asymmetric masses (30 and 8 $M_\odot$)
    - Strong evidence of higher order modes





No-hair theorem

Credit: Matt Groening

- Black holes are very simple objects!
- No-hair theorem: black hole geometry depends only on:
    - Mass
    - Spin
    - Electric charge
- Black hole spectroscopy: measuring black hole oscillations
- When you model gravity, how does your compact object (black hole?) oscillate?

GW150914 - oscillating black hole

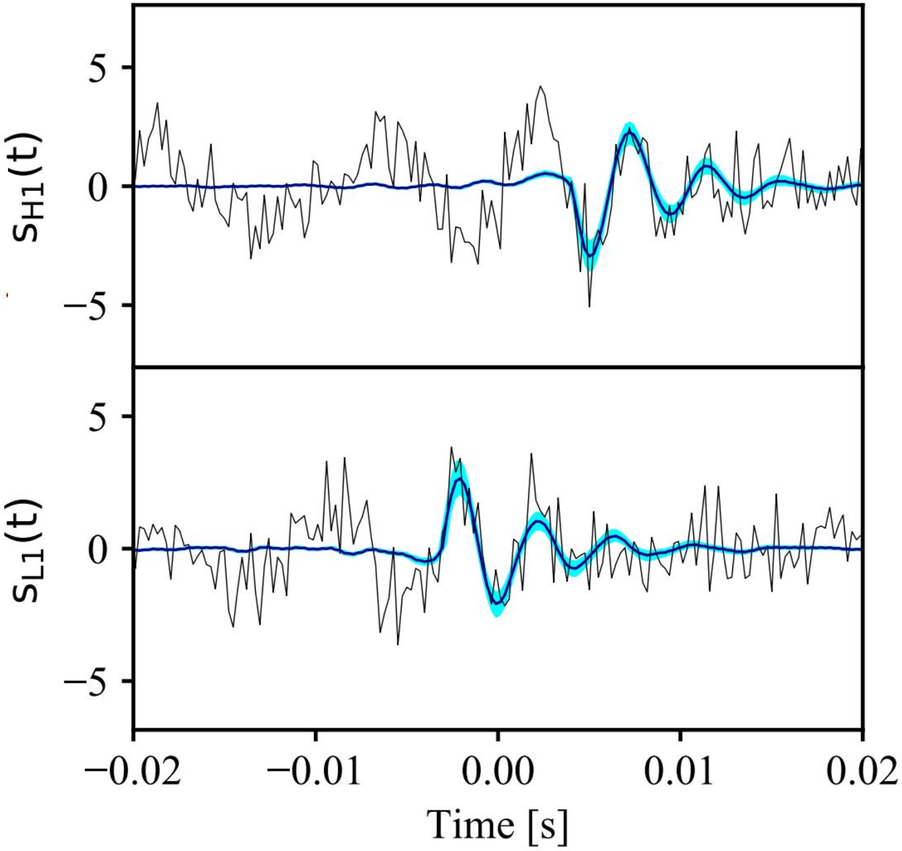
- **Quasi-normal modes (QNM)** - dumped perturbations of BH resonances.
  Intuitively: waves traveling around BH.

$$h(\theta,\varphi;t) = h_+(t) - ih_\times(t) = \sum_{\ell,m,n} Y^{-2}_{\ell,m}(\theta,\varphi)A_{\ell mn}e^{-t/\tau_{\ell mn}}e^{(i(2\pi f_{\ell mn}t+\phi_{\ell mn}))},$$

(l,m) - “tones”

n - “overtones”

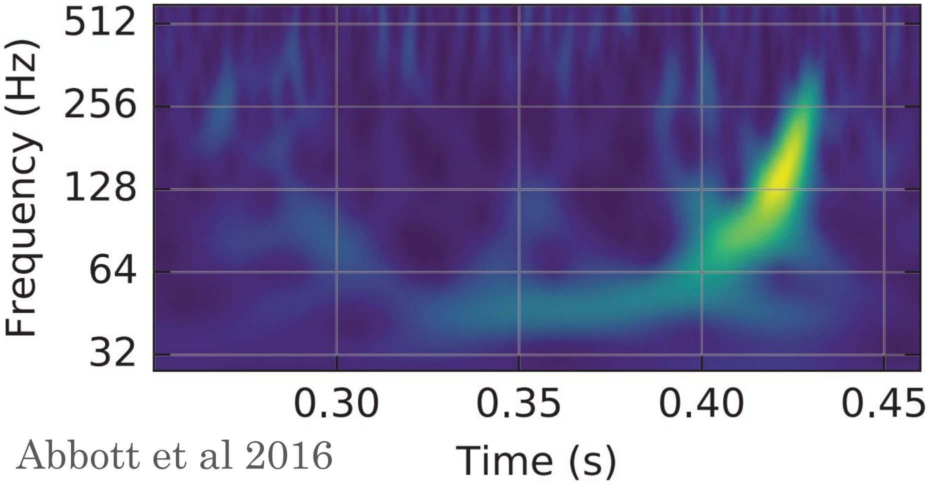
- QNM will allow precise measurements of the mass and spin of black holes and new tests of GR.



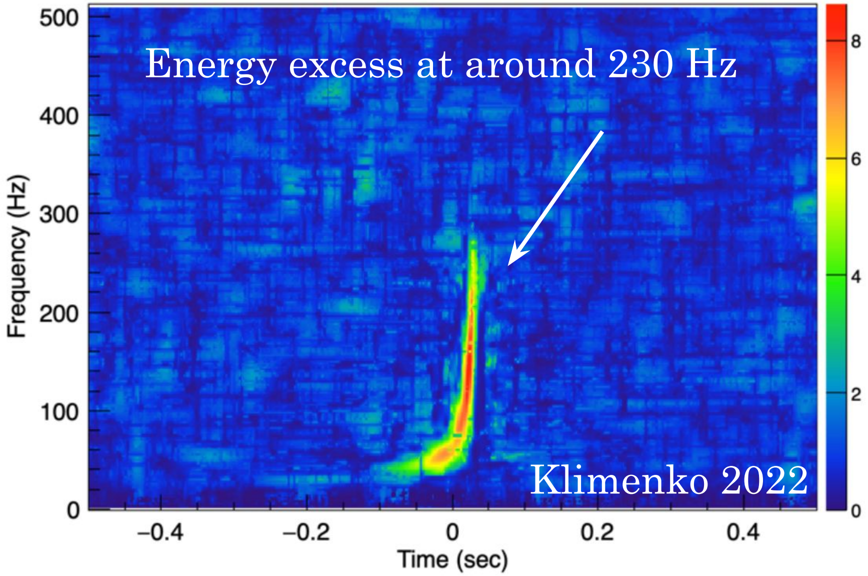
Carullo et al 2019

GW150914 - oscillating black hole

- GW150914 with large signal-to-noise ratio of 24 is a great laboratory for testing gravity in a strong regime.
- An ongoing debate in the literature whether the QNMs are detected
- A new high-resolution time-frequency resolution may reveal BH resonances and surprises.



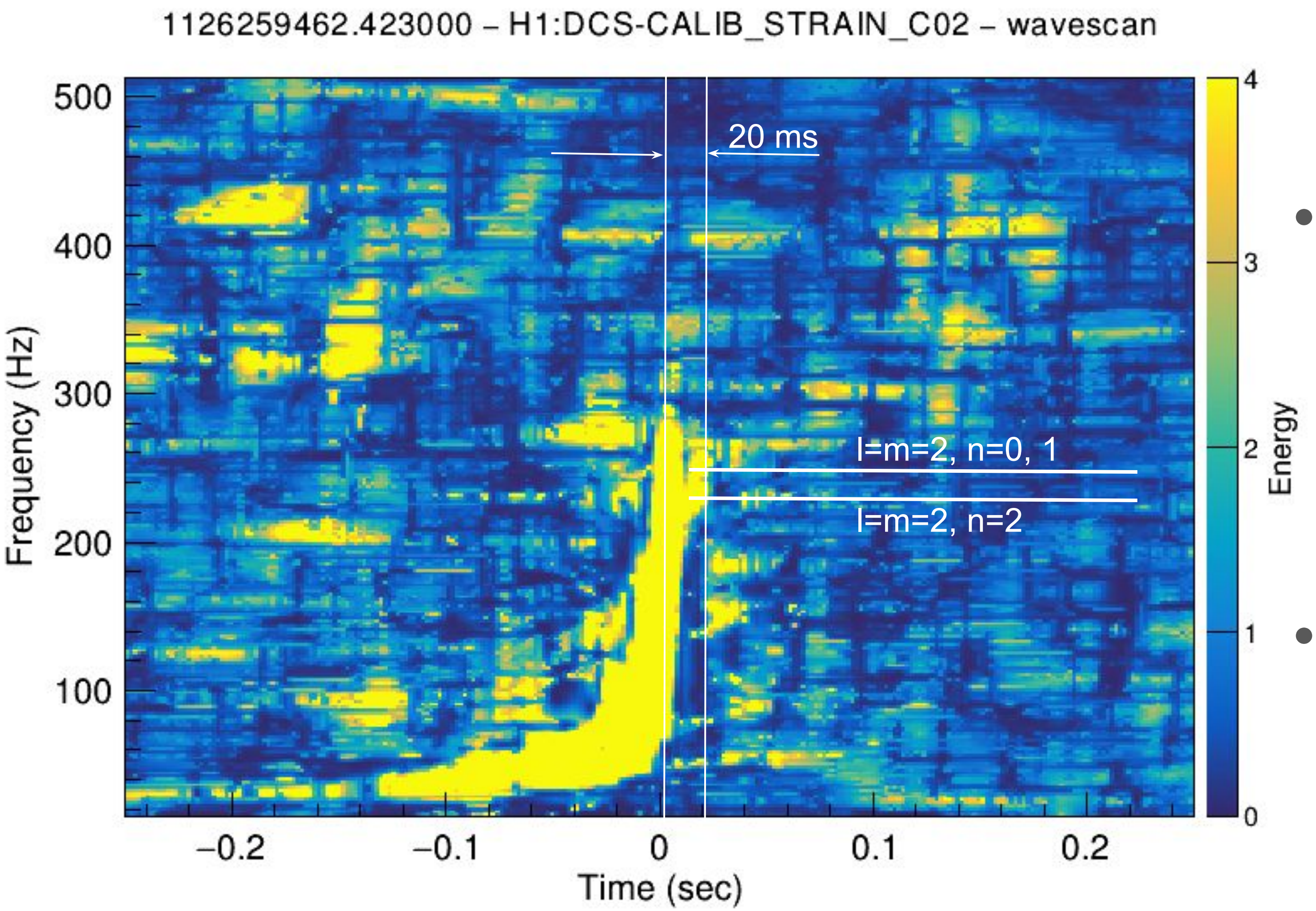
Abbott et al 2016



Energy excess at around 230 Hz

Klimenko 2022

GW150914 - oscillating black hole



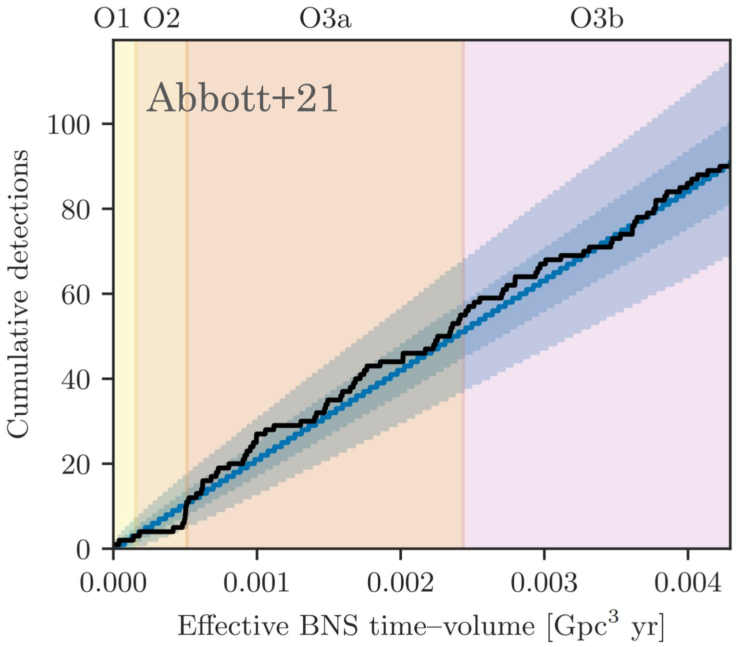
- Overtones:
  n = 0:
  (freq and tau)
  (249 Hz, 4.2 ms)
  n = 1:
  (244 Hz, 1.4 ms)
  n = 2:
  (234 Hz, 0.8 ms)
- Detection of QNM is debatable

Observing Run 4 (O4)

Exceptional GW sources

- Expected O4 detection rate: **1 per day**

- The future experiments (O4 and beyond) 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.

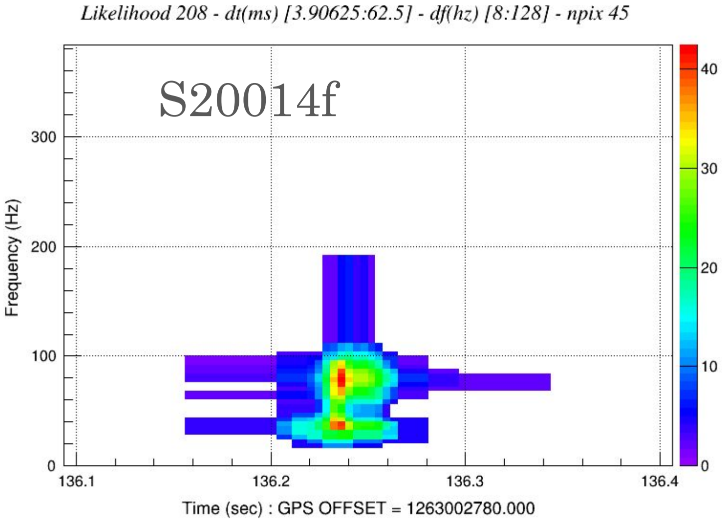


- **Exceptional astrophysical sources (new populations, special or unique source properties) might play the key role in this endeavor of exploring the Universe.**

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

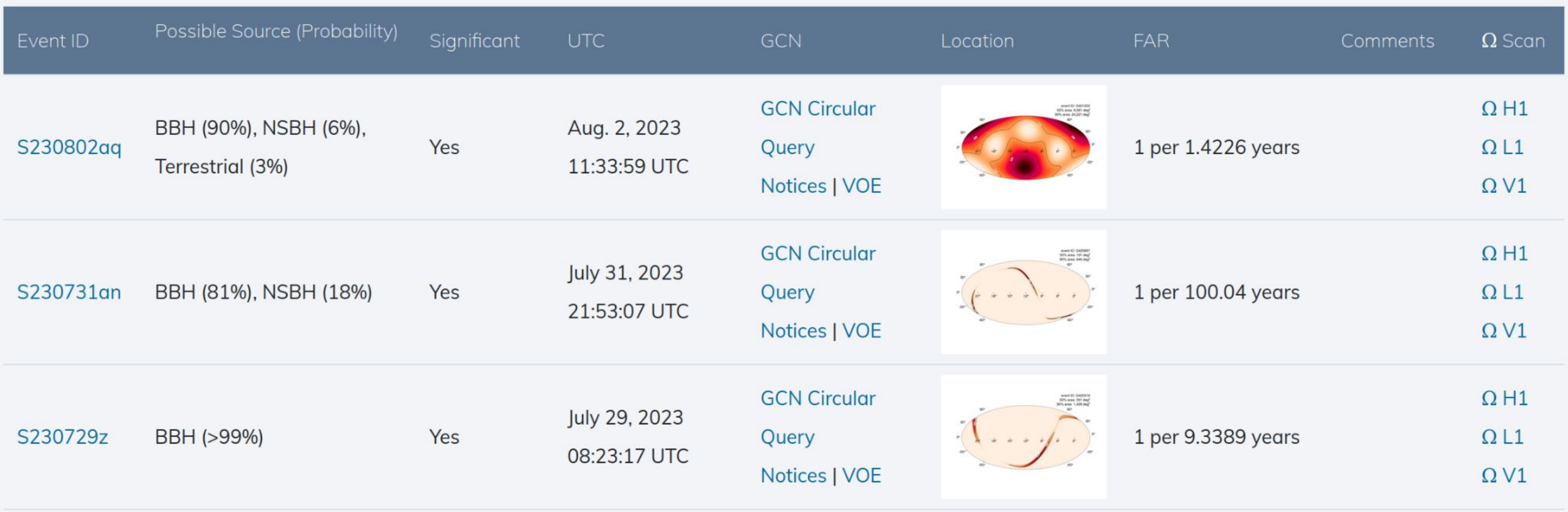


Observing Run 4 (O4)

- Observation started on May 24th, 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

O3 LIGO/Virgo public alerts

- GraceDB: https://gracedb.ligo.org/ (walking through the page)
- 24 GW candidates so far
- Public alert content: https://emfollow.docs.ligo.org/userguide/content.html (walking through the page)



Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments	Ω Scan
S230802aq	BBH (90%), NSBH (6%), Terrestrial (3%)	Yes	Aug. 2, 2023 11:33:59 UTC	GCN Circular Query Notices | VOE		1 per 1.4226 years		Ω H1 Ω L1 Ω V1
S230731an	BBH (81%), NSBH (18%)	Yes	July 31, 2023 21:53:07 UTC	GCN Circular Query Notices | VOE		1 per 100.04 years		Ω H1 Ω L1 Ω V1
S230729z	BBH (>99%)	Yes	July 29, 2023 08:23:17 UTC	GCN Circular Query Notices | VOE		1 per 9.3389 years		Ω H1 Ω L1 Ω V1

Summary

- **Gravitational-wave Detectors**

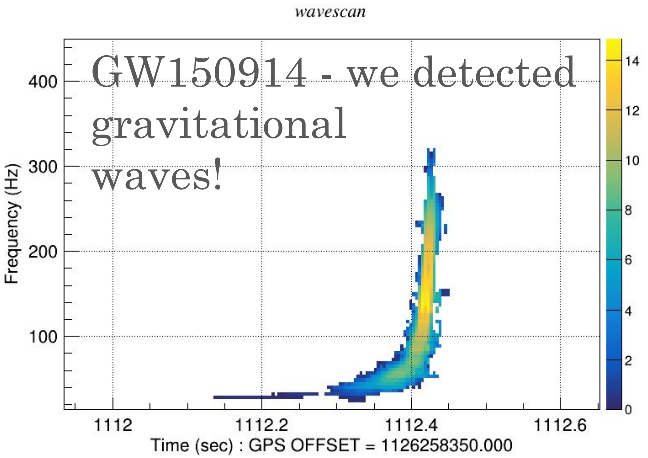
  We need a network of detectors,

  challenging experiment.

- **Model-independent searches**

  Matched filtering will detect 99% of binaries, we are especially interested in detecting missed 1%!

  (Note: both methods are complementary)



GW150914 - we detected gravitational waves!

- **Black hole spectroscopy**

  When you model gravity, how does your compact object (black hole?) oscillate?