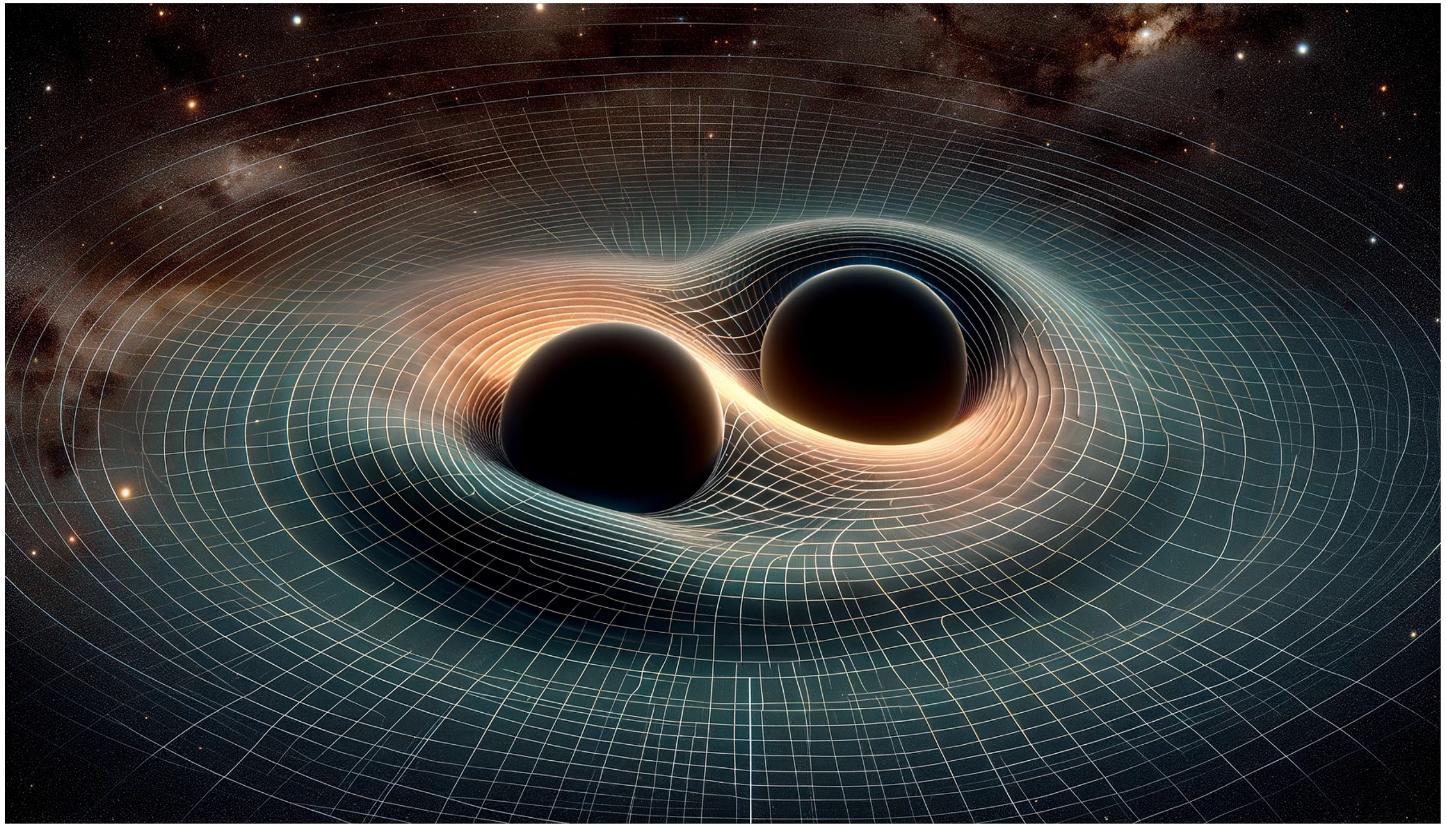
Seminar - University of Bologna - Dipartimento di Fisica e Astronomia – 19/02/2025

Gravitational Waves: A New Frontier Across Scales and Disciplines



Gianluca Inguglia

HEPHY
INSTITUT FÜR HOCHENERGIEPHYSIK

ÖAW
ÖSTERREICHISCHE
AKADEMIE DER
WISSENSCHAFTEN

BELLE

Belle II

EINSTEIN
TELESCOPE

InterLeptons

erc
European Research Council
Established by the European Commission

While studying Astronomy here in Bologna I got attracted by the topics of quantum mechanics and particle physics. In particular, one question accompanied me through switching from the largest to the smallest structures of the Universe

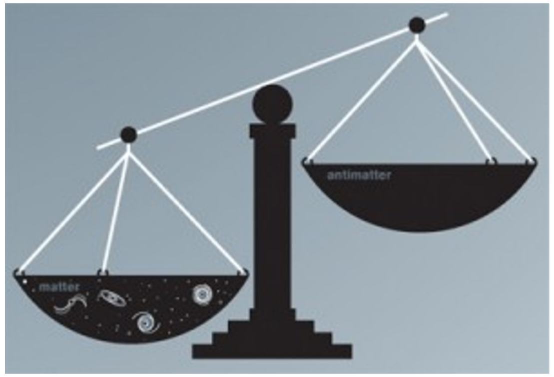
According to the theory of the Big Bang, at the time of the Big Bang, matter and antimatter were produced in equal amounts...

...where is the antimatter then?

Sakharov conditions

A Universe balanced in terms of the amount of matter and antimatter can evolve into a matter dominated Universe if three conditions are satisfied*:

- Baryon number violation
- C & CP violation
- Departure from thermal equilibrium



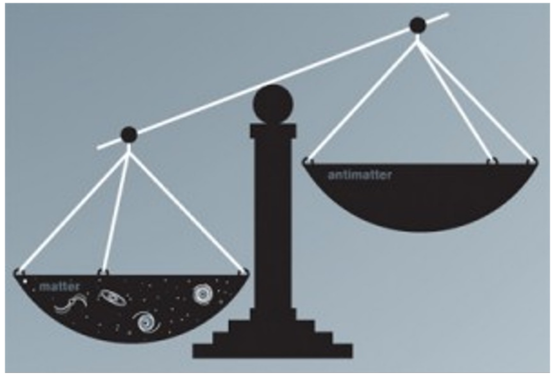
*A. D. Sakharov, "Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe". Journal of Experimental and Theoretical Physics 5: 24–27, (1967)

- Baryon number violation

  Requires sphaleron processes (not observed) that violate the baryon number and the lepton number but preserve B-L, **not observed**

- C & CP violation

  Observed experimentally in several transitions, understood theoretically (CKM matrix), **but**…

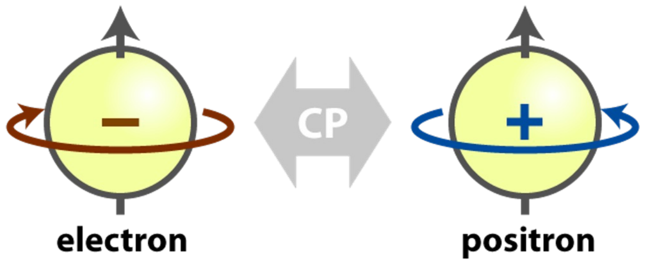


- Departure from thermal equilibrium

  Requires first-order phase transitions in the early Universe, **not observed**

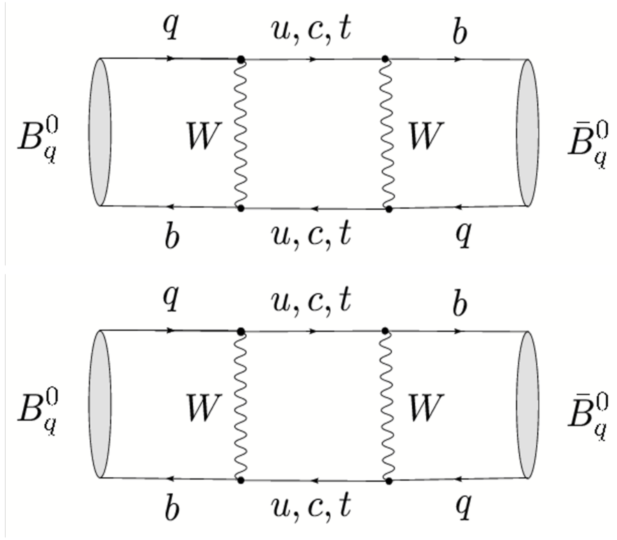
.CP violation

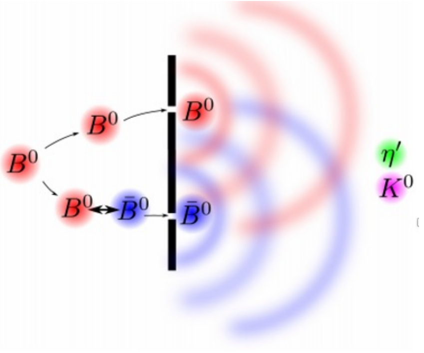
Observed experimentally in several transitions, understood theoretically (CKM matrix), **but**…



$$CP\Psi(r,t) \to \Psi^*(-r,t)$$

$$A_{CP}(f_{CP}) = \frac{N(B^0 \to f_{CP}) - N(\overline{B^0} \to f_{CP})}{N(B^0 \to f_{CP}) + N(\overline{B^0} \to f_{CP})}$$





By observing the interference pattern we measure the phase difference of two paths

$$\mathcal{S}_f = \sin[\arg(q/p) + \arg(\bar{A}_f/A_f)]$$

$$\eta_{obs} = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6\times10^{-10}, \eta_{CP}^{CKM} \sim 10^{-18}$$

$$\frac{\eta_{CP}^{CKM}}{\eta_{obs}} = \frac{10^{-18}}{10^{-10}} = 10^{-8} \longrightarrow$$

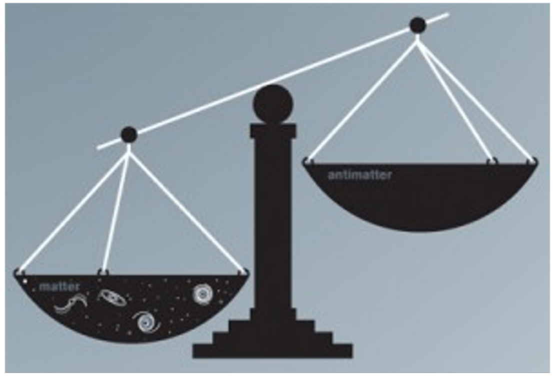
Additional sources of CP violation are needed to explain the observed matter-antimatter asymmetry! In the worst-case scenario, these could be particles at masses that we cannot probe experimentally (colliders) in any foreseeable future.

- **Baryon number violation**

Requires sphaleron processes (never observed) that violate the baryon number and the lepton number but preserve B-L, **not observed**

- **C & CP violation**

Observed experimentally in several transitions, understood theoretically (CKM matrix), **but not enough**



- **Departure from thermal equilibrium**

Requires first-order phase transitions in the early Universe, **not observed**

Finally, after my PhD in CP violation and particle phenomenology, I could answer my question

According to the theory of the Big Bang, at the time of big bang, matter and antimatter were produced in equal amounts...

...where is the antimatter then?

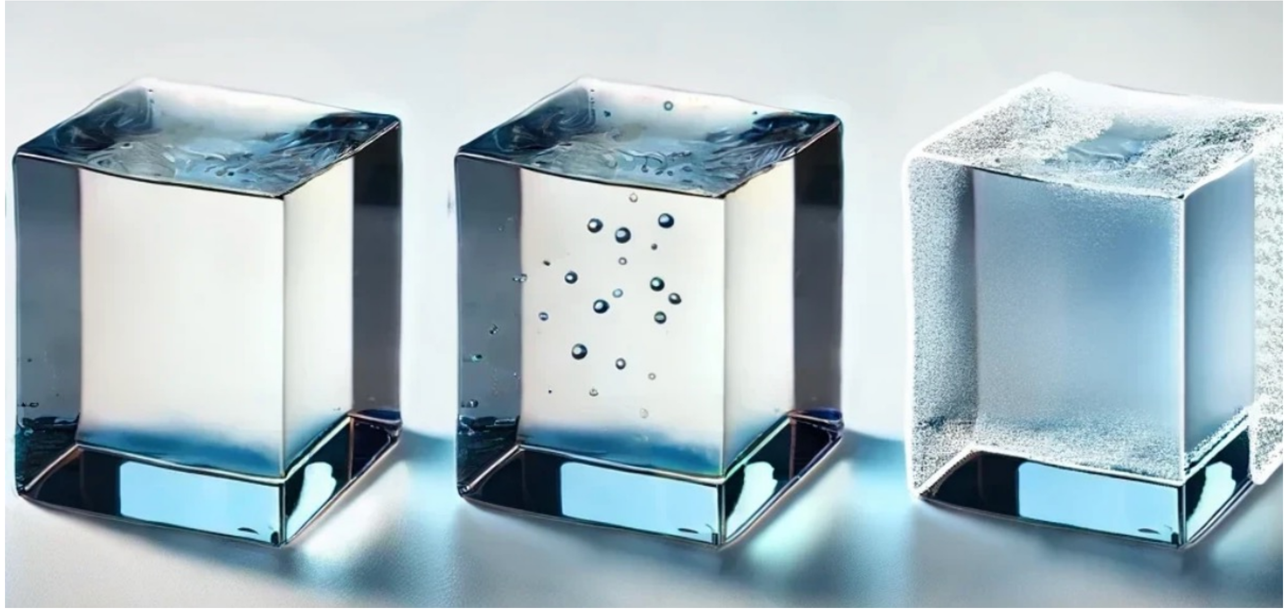
Finally, after my PhD in CP violation and particle phenomenology, I could answer my question

According to the theory of the Big Bang, at the time of big bang, matter and antimatter were produced in equal amounts...

...where is the antimatter then?

Nobody really knows...

A way out: first-order phase transitions



Water (liquid) has a random molecular arrangement, with molecules free to move. System at equilibrium

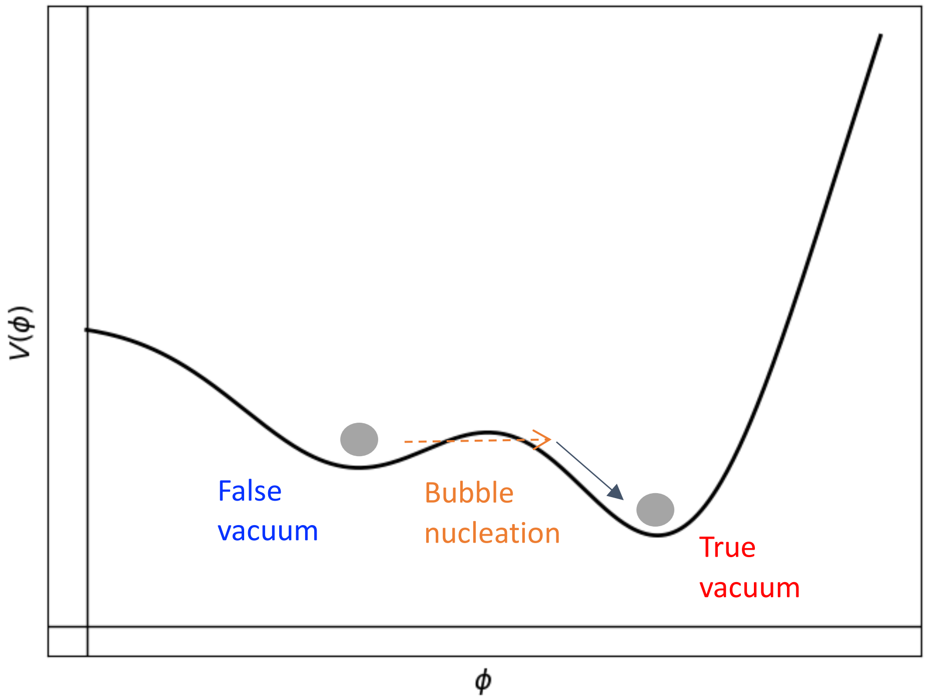
The phase transition begins. Small ice crystals start forming as nuclei of the solid phase, heat is removed. Nucleation started.

Ice (solid) has an ordered, crystalline lattice structure, and more heat is removed: temperature remains constant at the freezing point until the transition is complete.

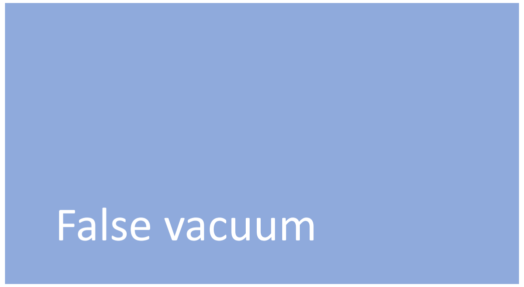
Transformations between phases of matter characterized by a **discontinuous change** in an order parameter (e.g., density or structure) and the release or absorption of **latent heat**.

During the transition, both phases can coexist in equilibrium (e.g., liquid and solid water at 0°C), and the process often involves overcoming an energy barrier, leading to phenomena like bubble nucleation or phase separation.

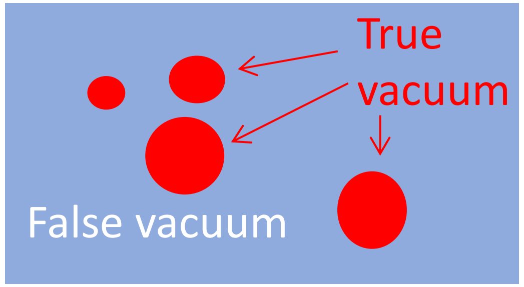
A way out: first-order phase transitions in the early Universe



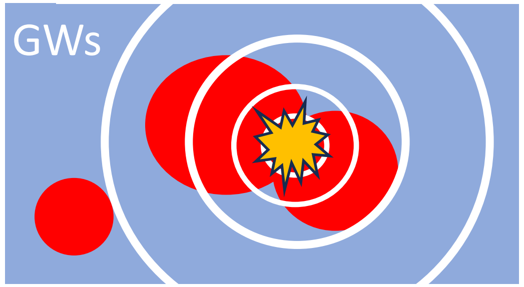
The Universe is is a false vacuum state (local minima)



True vacuum bubble nucleation starts (ex. Via tunneling)



Bubbles expand and eventually collide, producing GWs



The Universe reaches a true vacuum state (global minimum)

time →

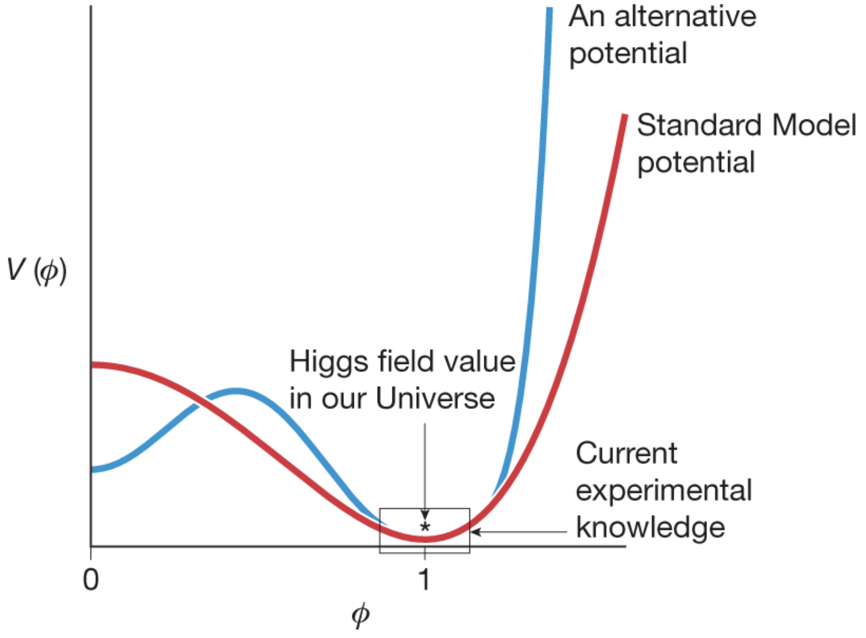
What could trigger a first-order phase transition in the early Universe?

In the **Standard Model (SM)**, the electroweak phase transition is a **smooth crossover**, meaning it does not generate bubble nucleation and cannot drive baryogenesis.

BSM models (such as in a **Two-Higgs-Doublet Model (2HDM)**, **Singlet-Scalar Extensions**, or **Composite Higgs Models**) can introduce a **barrier** in the Higgs potential, making the **EW phase transition first-order**.

This leads to **bubble nucleation and expansion**, ensuring the system is **out of thermal equilibrium**—one of Sakharov's conditions.

Nature **volume 607**, pages 41–47 (2022)



A **new CPV phase can be introduced by the 2HDM (or other extension)** which diffuses outside the bubble. In the unbroken phase, sphalerons convert the CP asymmetry into a net baryon asymmetry before the electroweak phase transition completes

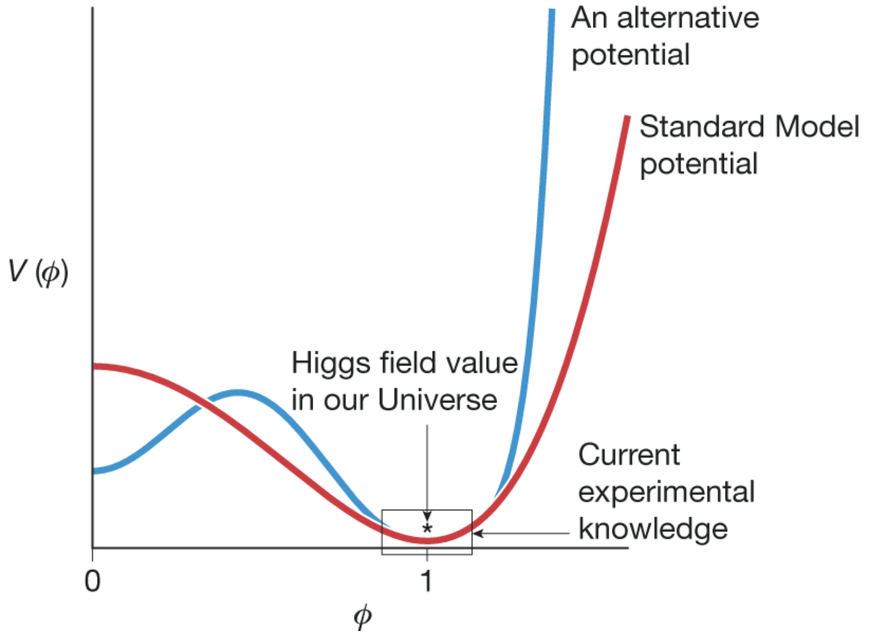
How can this induce a matter-dominated Universe?

First-order phase transitions in the early universe can produce gravitational waves—could we use them to learn about baryogenesis?

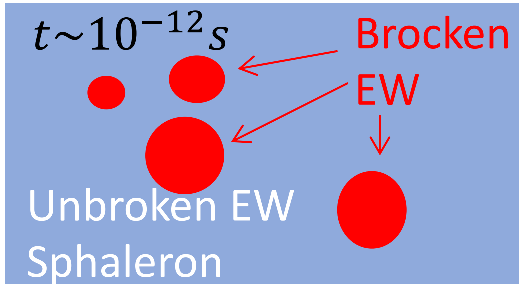
The Universe is in a false vacuum state (local minima)

$t < 10^{-12} s$
Unbroken EW, balanced matter/antimatter content

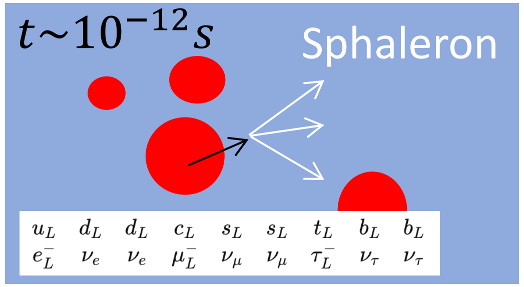
Nature **volume 607**, pages 41–47 (2022)



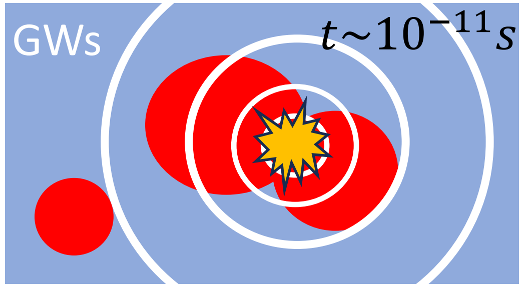
True vacuum bubble nucleation start, large CPV



CPV diffuses through bubbles wall, sphalerons convert it in baryon number violation



Bubbles expand and eventually collide, producing GWs



The Universe reaches a true vacuum state (global minimum)

$t \sim 10^{-10} s$
Broken EW, frozen baryon asymmetry, matter - dominated content

time

How can this induce a matter-dominated Universe?

The Universe is in a false vacuum state (local minima)

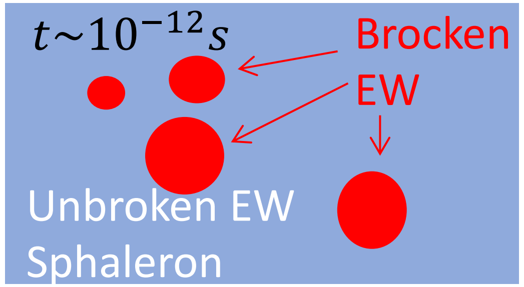
$t < 10^{-12} s$

Unbroken EW, balanced matter/antimatter content

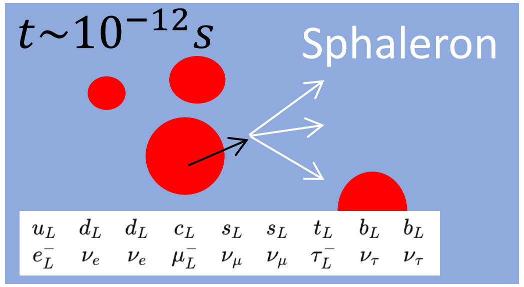
These chain of events would produce:

- **A matter-dominated Universe**
- **A gravitational wave signal** from the **strong first-order phase transition** that broke the (extended) electroweak symmetry.
- If the mass of the new boson in the **extended Higgs sector** (or another BSM scenario) is **beyond the reach of collider experiments**, then **gravitational waves may be the only detectable signature of this physics.**

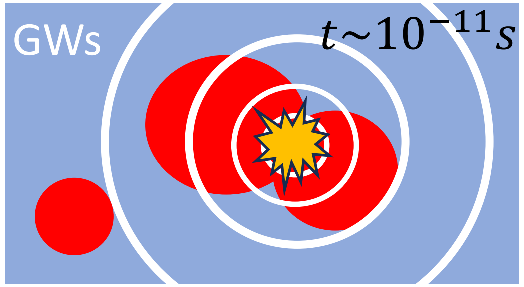
True vacuum bubble nucleation start, large CPV



CPV diffuses through bubbles wall, sphalerons convert it in baryon number violation



Bubbles expand and eventually collide, producing GWs

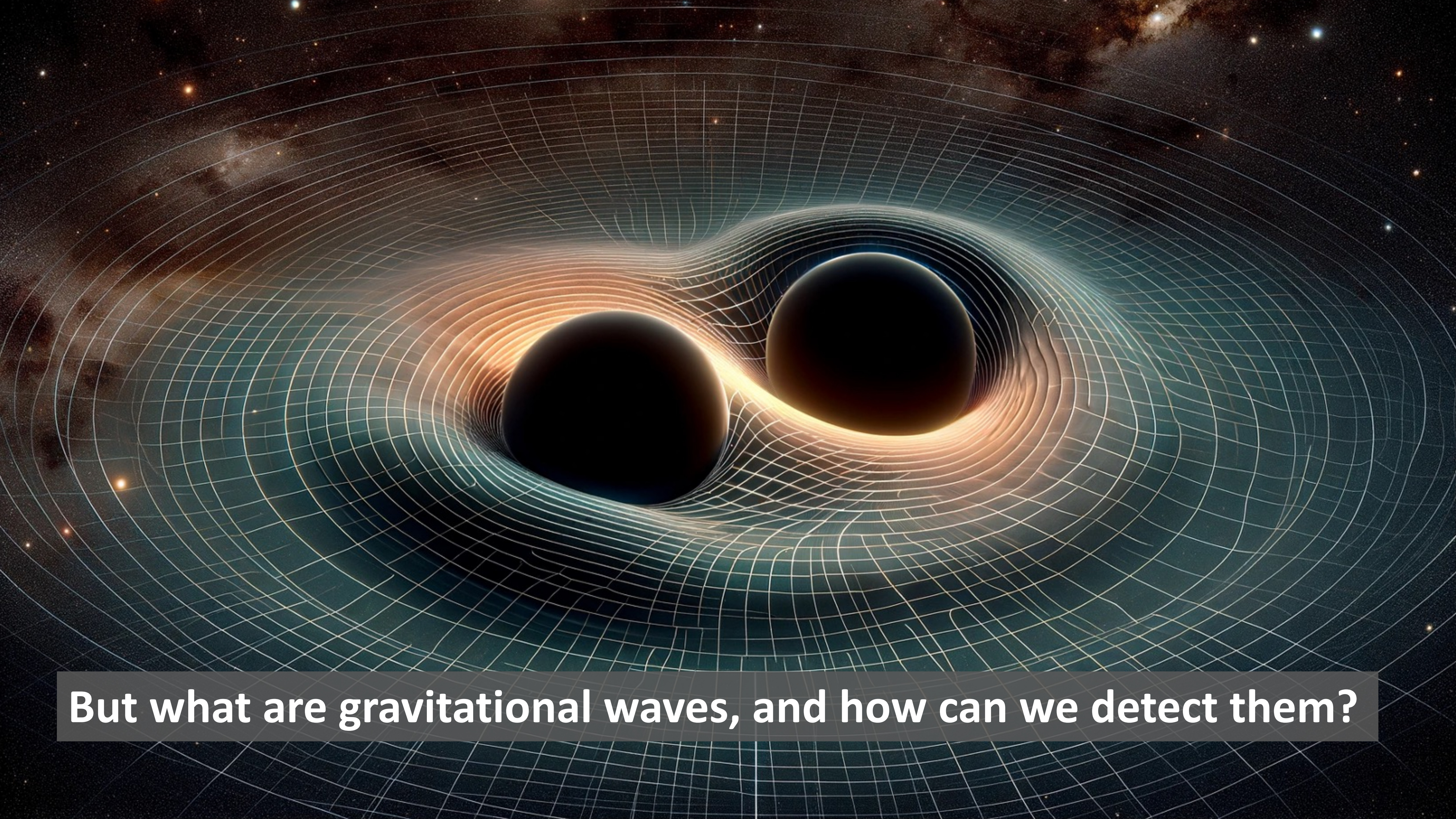


The Universe reaches a true vacuum state (global minimum)

$t{\sim}10^{-10}s$

Broken EW, frozen baryon asymmetry, matter - dominated content

time →



But what are gravitational waves, and how can we detect them?

What are gravitational waves?

Gravitational waves are ripples (or perturbations) in the space-time geometry that are predicted by Einstein theory of general relativity:

Energy-impulse tensor, source of space-time deformations

$$T_{\mu\nu} = -\frac{c^4}{8\pi G} G_{\mu\nu}$$

$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{g_{\mu\nu} R}{2}$$

Deformation (Einstein) tensor, effect of the space-time deformation

Flat Minkowski metric

$$g_{\mu\nu} = \eta_{\mu\nu} + \mathbf{h}_{\mu\nu}, if \left|h_{\mu\nu}\right| \ll 1 \rightarrow \left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) h_{\mu\nu} = 0$$

Small perturbation

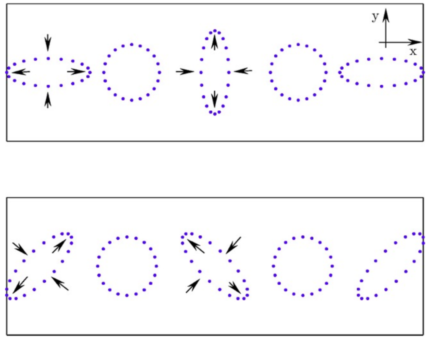
Wave equation

$$h_{\mu\nu}(z,t) = e^{i(\omega t - kz)} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_x & 0 \\ 0 & h_x & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

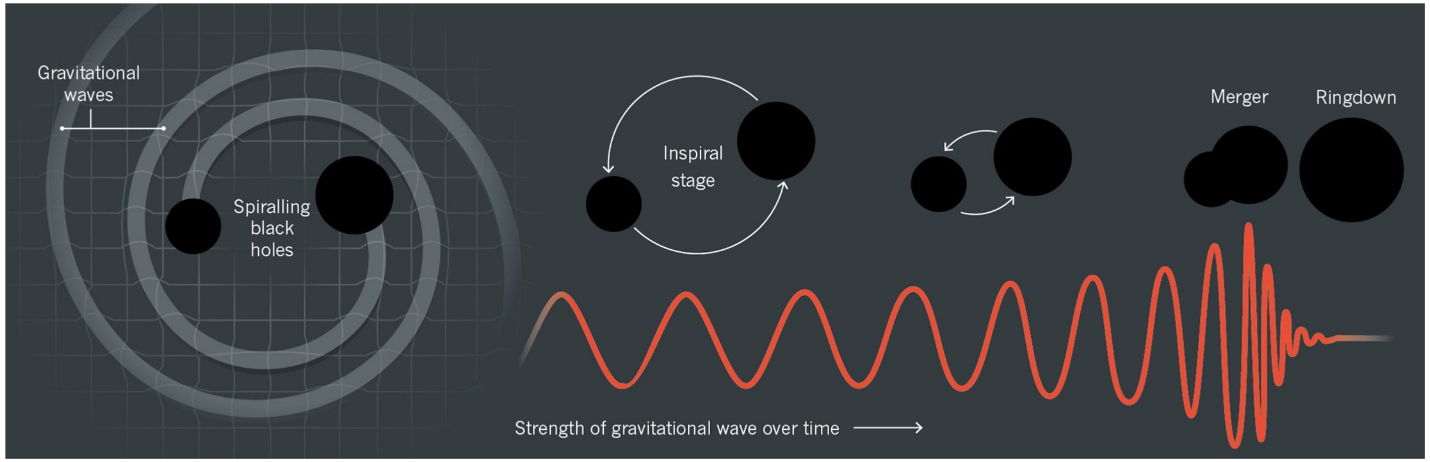
$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

Distance between 2 points

Gravitational wave propagating in the z-direction with 2 polarizations: x and +



Gravitational waves emerge from specific motions of massive objects in space (for example compact binaries)



Example of gravitational waves production during binary black holes coalescence

To put this in perspective:

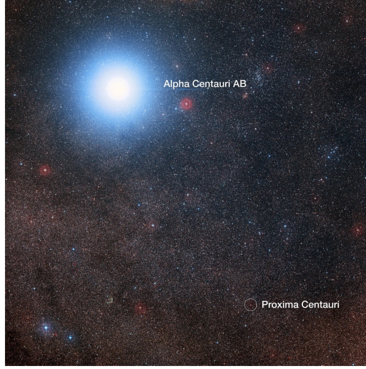
$$E_{BBHC}^{GW,peak} > \sum_{allgalaxies}^{Universe} \sum_{allstars}^{galaxy} E_{star}^{EM}$$

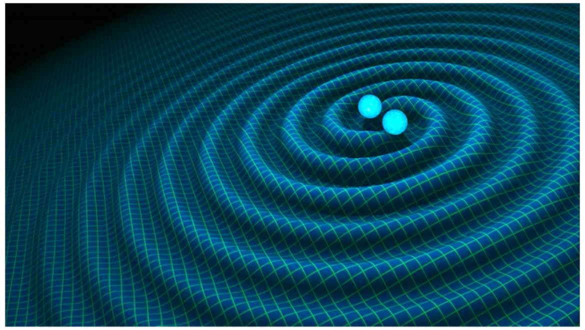
How gravitational waves propagate to our planet and how we detect them with laser interferometry

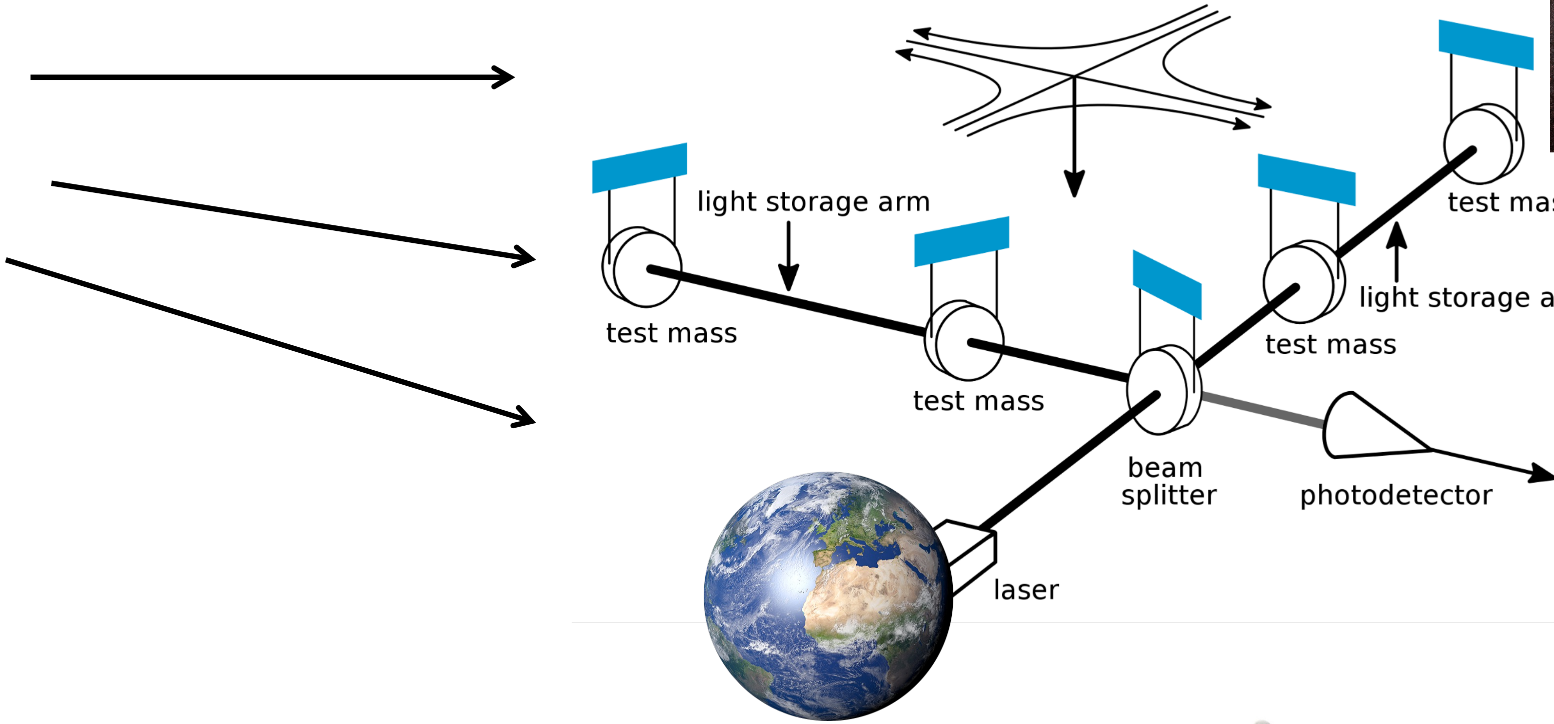
Stretch and contract

Form interference patterns

An example, 2 coalescing neutron stars, arms length ~Proxima Centauri distance





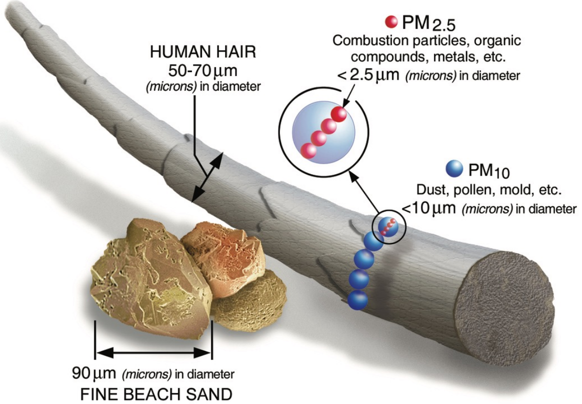


$$h_{\mu\nu} = 2\frac{G}{c^4}\frac{1}{r}\ddot{Q}_{\mu\nu}$$ $Q_{\mu\nu}$ quadrupolar moment of GW source

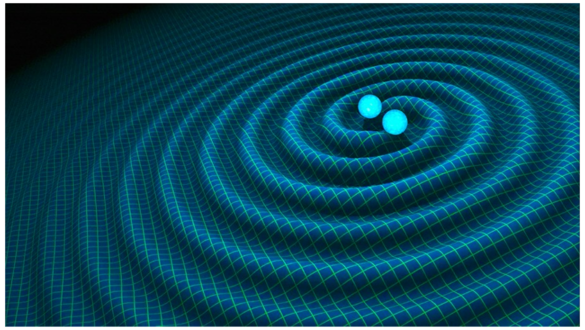
For 2 coalescing neutron stars at d~50 ly (15Mpc) ~Virgo cluster: $h \sim 10^{-21}$.

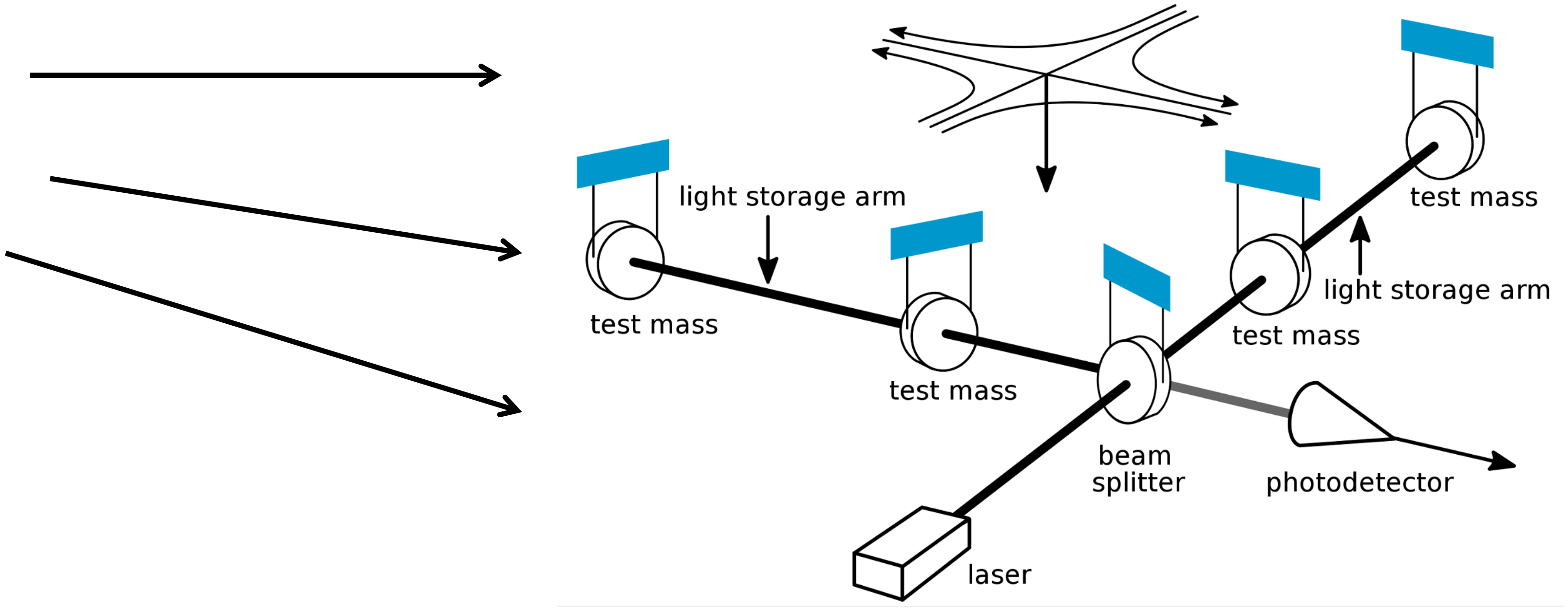
For a test detector of length $L_0 \sim 4\times10^{16}$m (~4ly)~distance of Proxima Centauri:

$\delta L \approx \frac{h}{2} L_0 \sim 20\mu m$ on each arm



An example, 2 coalescing neutron stars



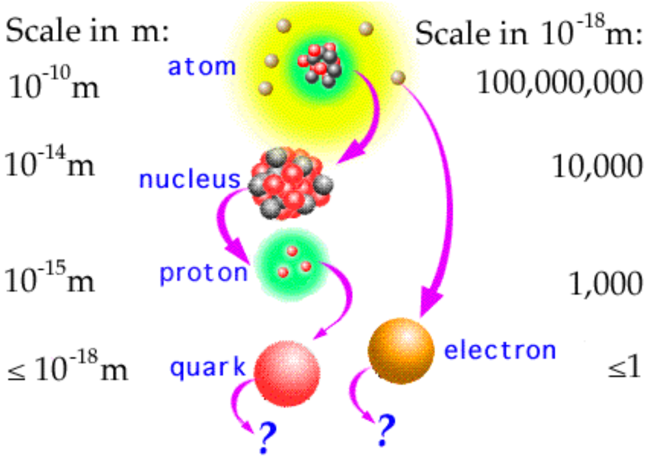


$$h_{\mu\nu} = 2\frac{G}{c^4}\frac{1}{r}\ddot{Q}_{\mu\nu}$$ $Q_{\mu\nu}$ quadrupolar moment of GW source

For 2 coalescing neutron stars at r~15Mpc (~Virgo cluster): $h \sim 10^{-21} - 10^{-22}$.

For a test detector of length $L_0 \sim 3\times10^3$m:

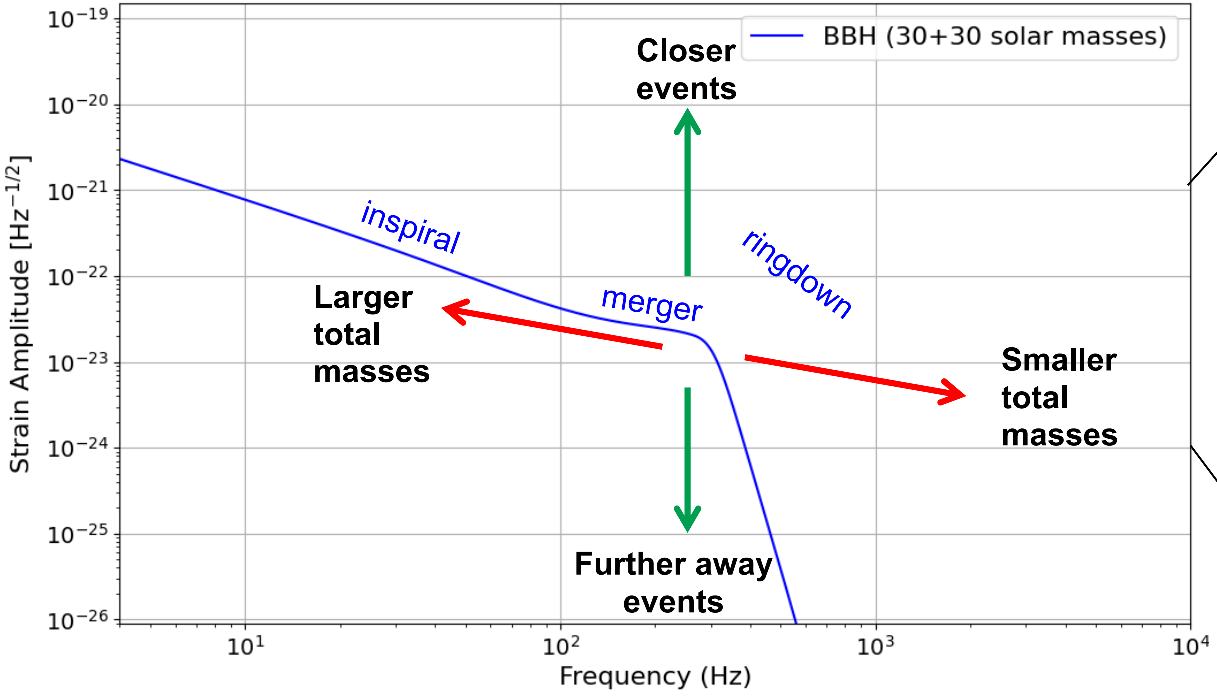
$$\delta L \approx \frac{h}{2}L_0 = 3(10^{-18} - 10^{-19})m$$ (on each arm)

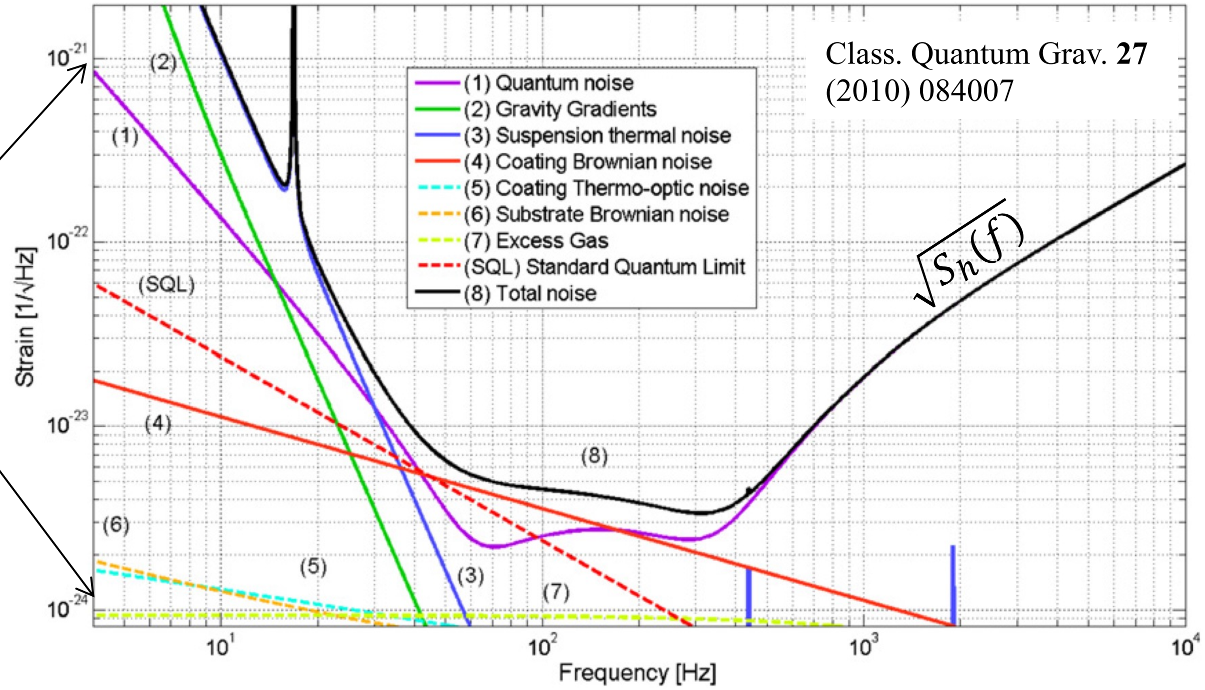


Gravitational wave detectors have to copy with noise and with signals that might be not so loud

In a detector, the differential test mass displacement is $\delta L = h \cdot L_0$

In the same detector, the minimal detectable displacement is $\delta L_{min} = \sqrt{f S_h(f)} \cdot L_0$



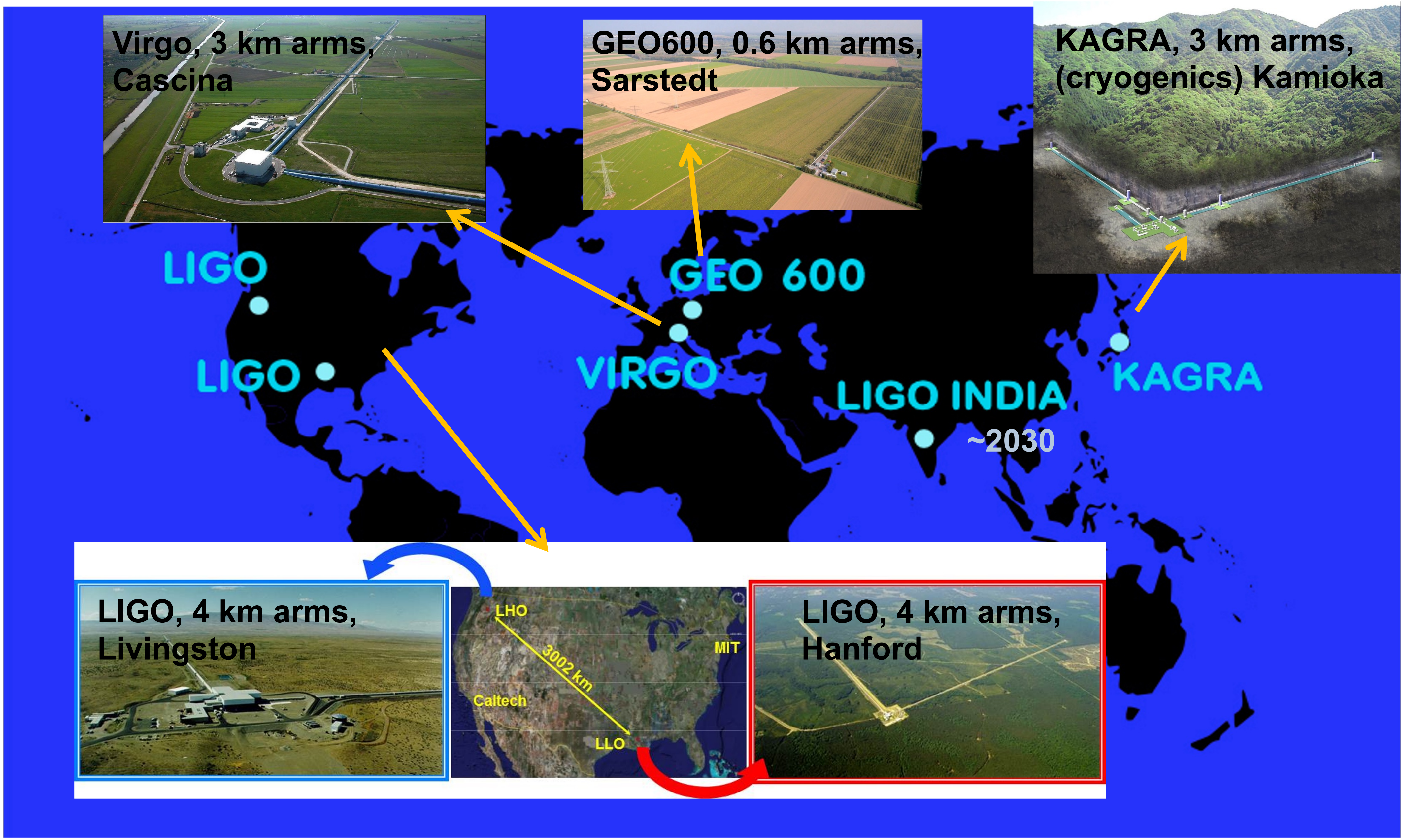


Class. Quantum Grav. **27** (2010) 084007

For (quasi-)circular orbits of merging compact objects with a redshifted mass $M_z = (1+z)M_T (= M_1 + M_2)$, the peak of emission of the dominating modes (*l*, *m*, *n*= 2, 2, 0) can be approximated by

$$f_{220} \approx \frac{c^3}{2\sqrt{2}\pi G M_z}$$

Current network of 2-G GW detectors



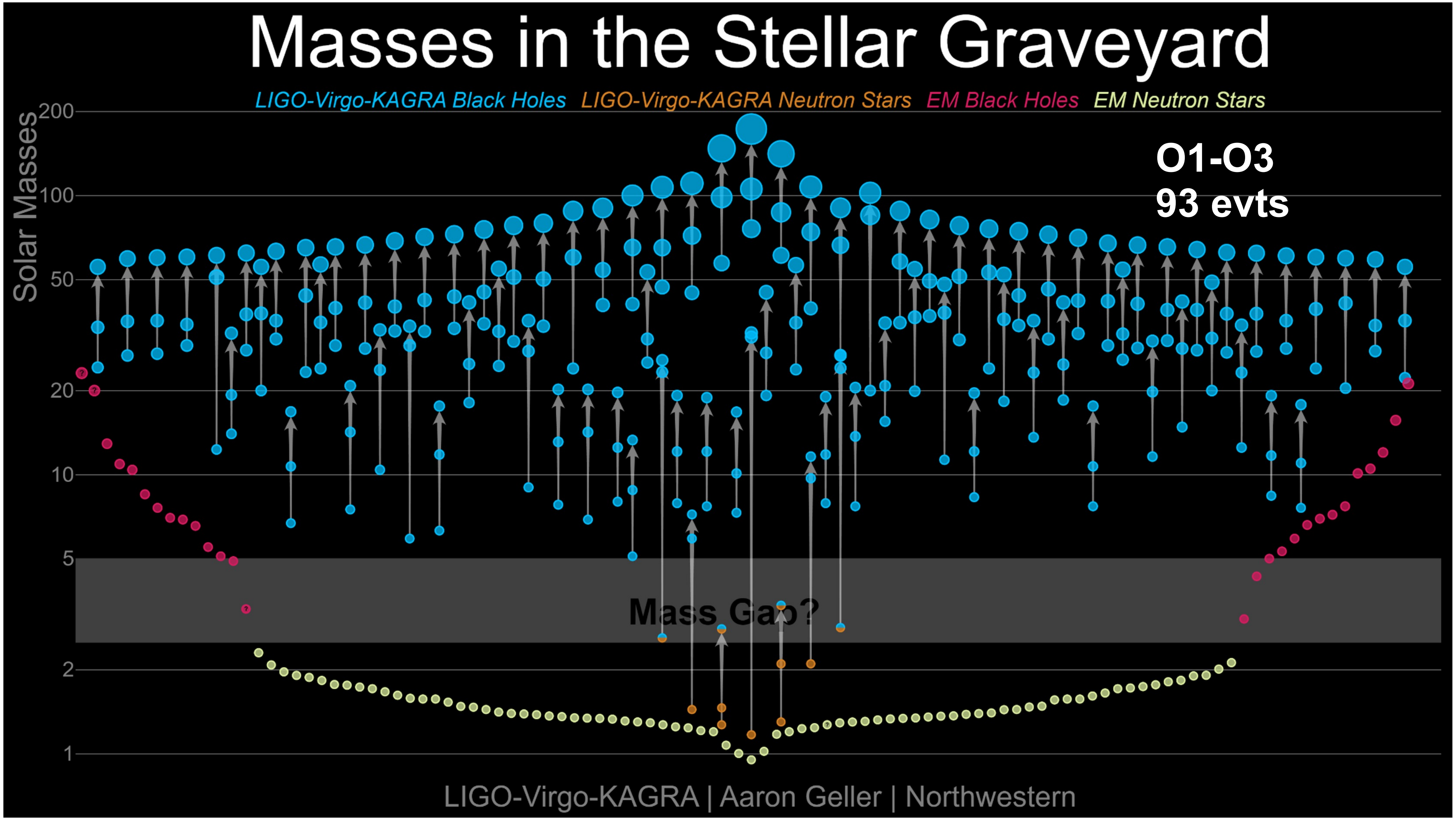
Virgo, 3 km arms, Cascina

GEO600, 0.6 km arms, Sarstedt

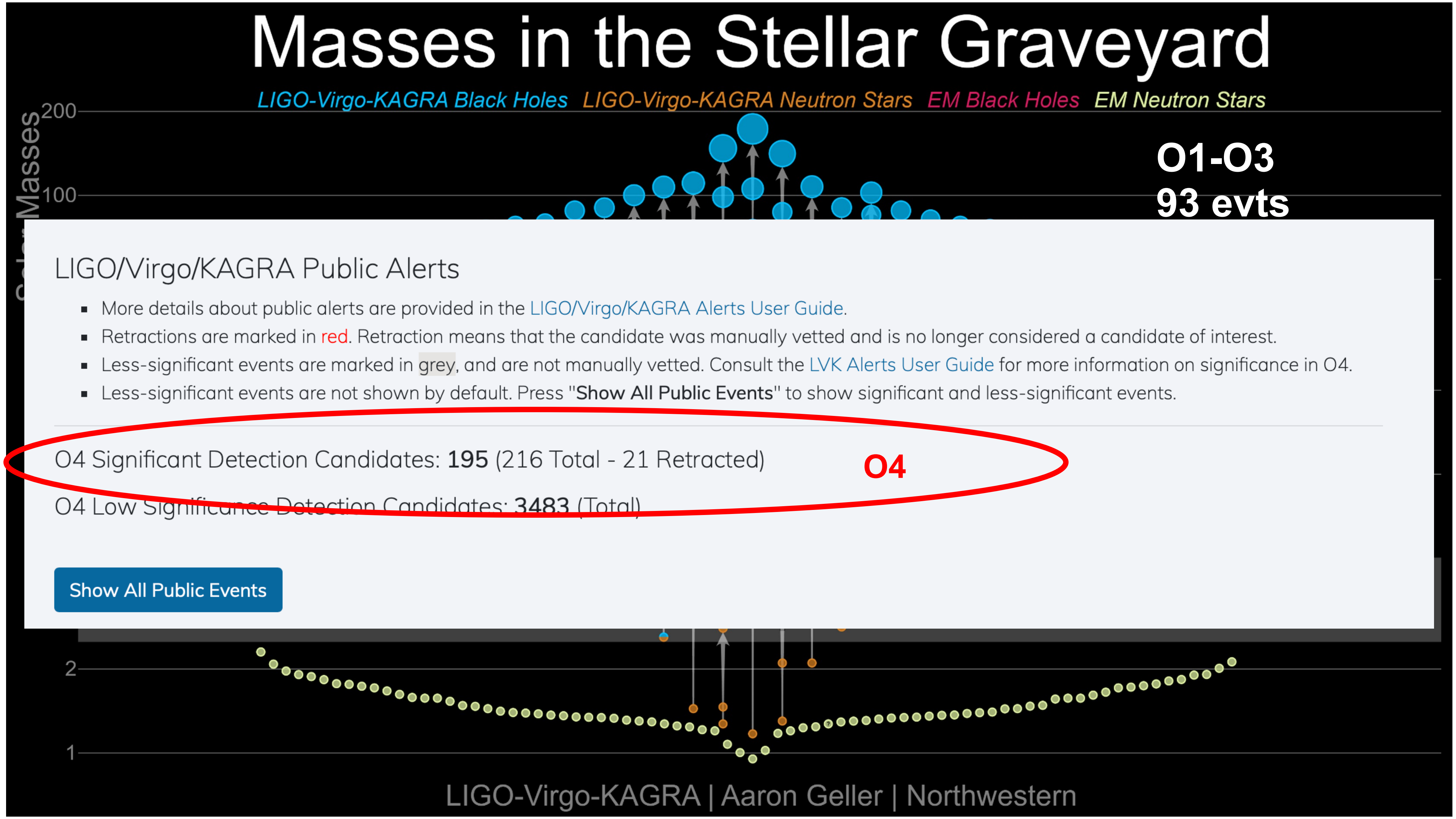
KAGRA, 3 km arms, (cryogenics) Kamioka

LIGO, 4 km arms, Livingston

LIGO, 4 km arms, Hanford



*Check the GWTC 3 population study and the recent GW230529_181500



O1-O3
93 evts

LIGO/Virgo/KAGRA Public Alerts

- More details about public alerts are provided in the LIGO/Virgo/KAGRA Alerts User Guide.
- Retractions are marked in red. Retraction means that the candidate was manually vetted and is no longer considered a candidate of interest.
- Less-significant events are marked in grey, and are not manually vetted. Consult the LVK Alerts User Guide for more information on significance in O4.
- Less-significant events are not shown by default. Press "**Show All Public Events**" to show significant and less-significant events.

O4 Significant Detection Candidates: **195** (216 Total - 21 Retracted)

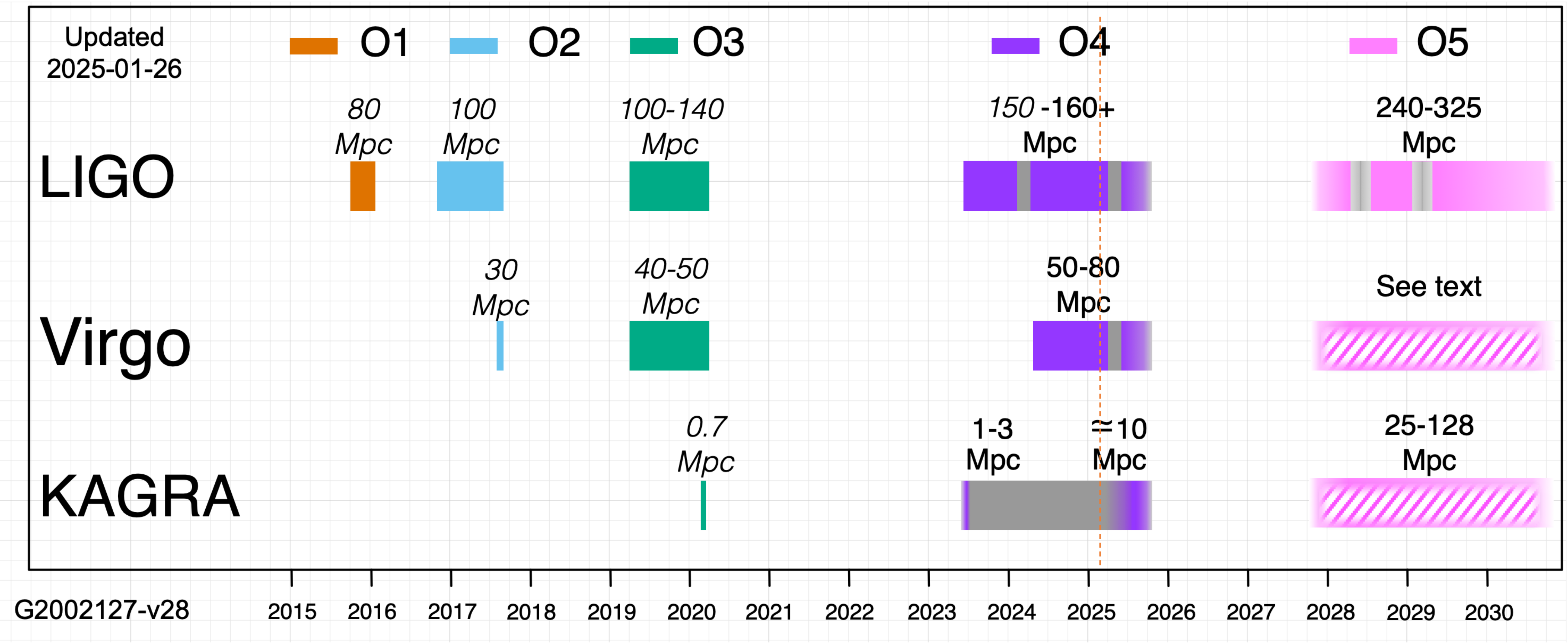
O4

O4 Low Significance Detection Candidates: **3483** (Total)

Show All Public Events

*Check the GWTC 3 population study and the recent GW230529_181500

LIGO-Virgo-KAGRA observing plans.

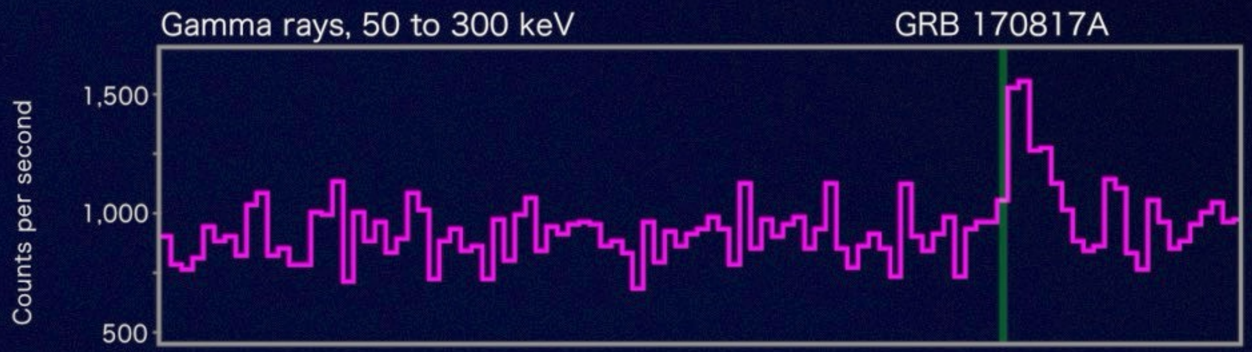


By the end of O4 in the fall, we can expect to have up to ~250 signals in addition to the 93 of O1-O3.
Lot’s of opportunities!

Multimessenger astronomy from a remarkable event: GW170817

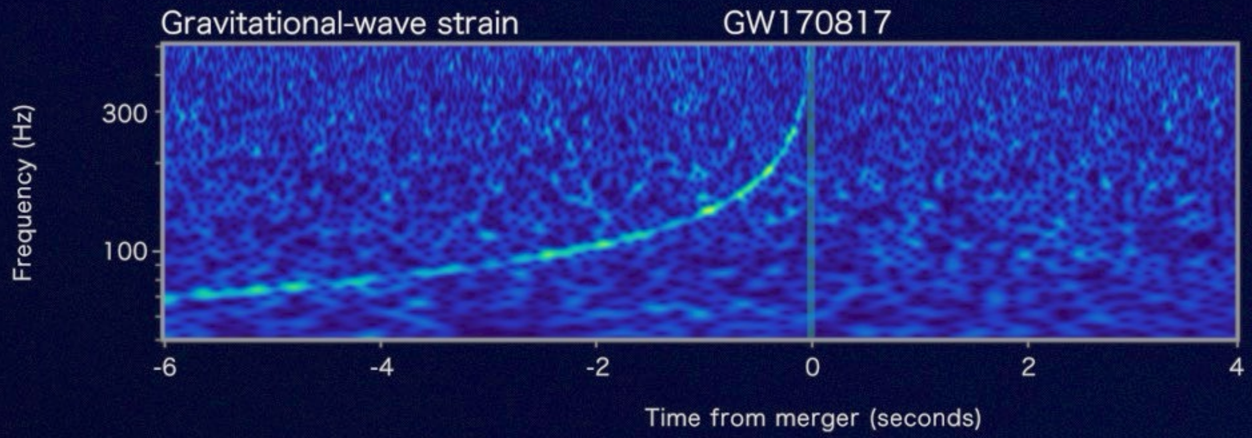
Fermi

Reported 16 seconds after detection



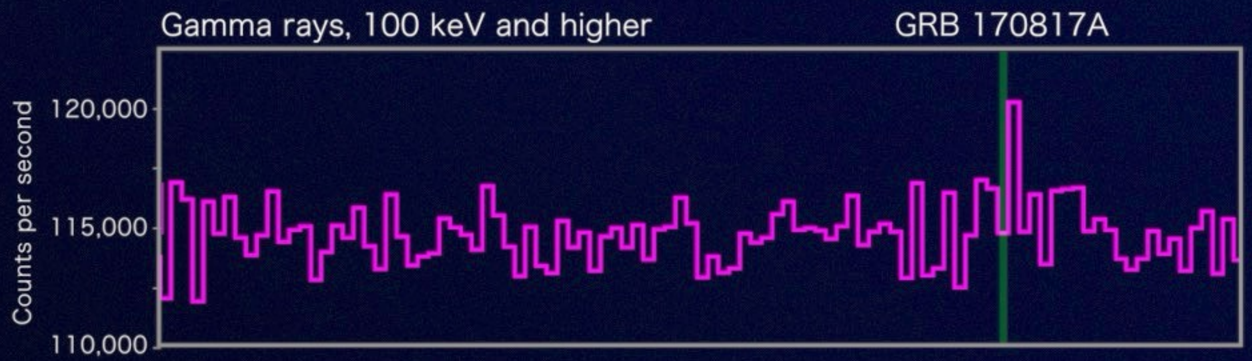
LIGO-Virgo

Reported 27 minutes after detection

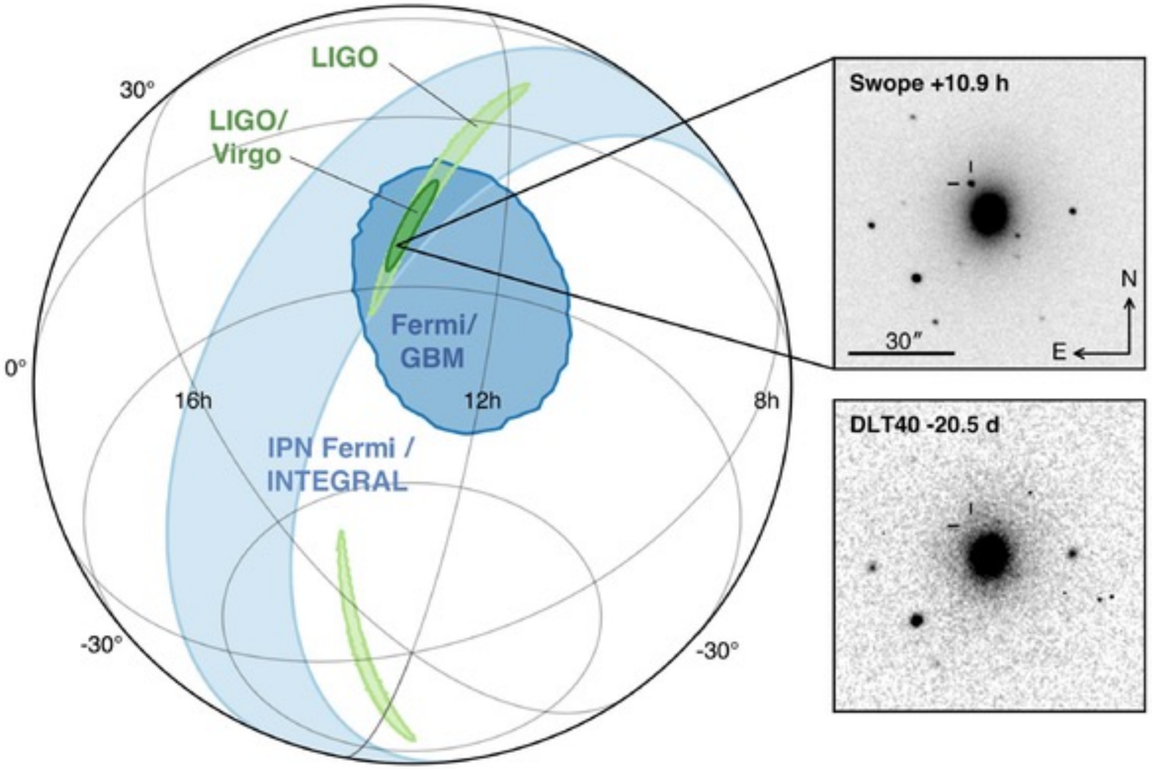


INTEGRAL

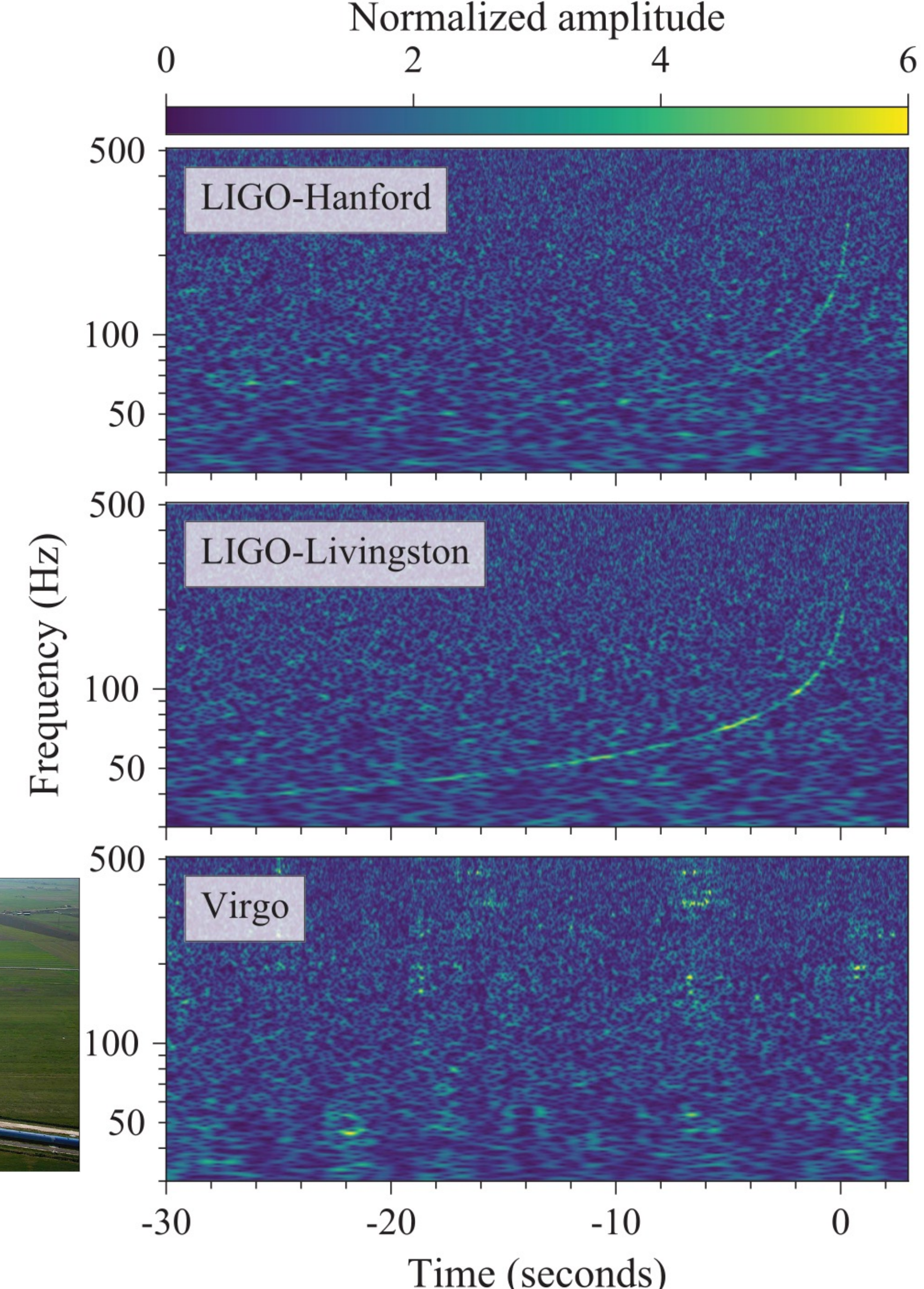
Reported 66 minutes after detection



Multimessenger astronomy: GW170817

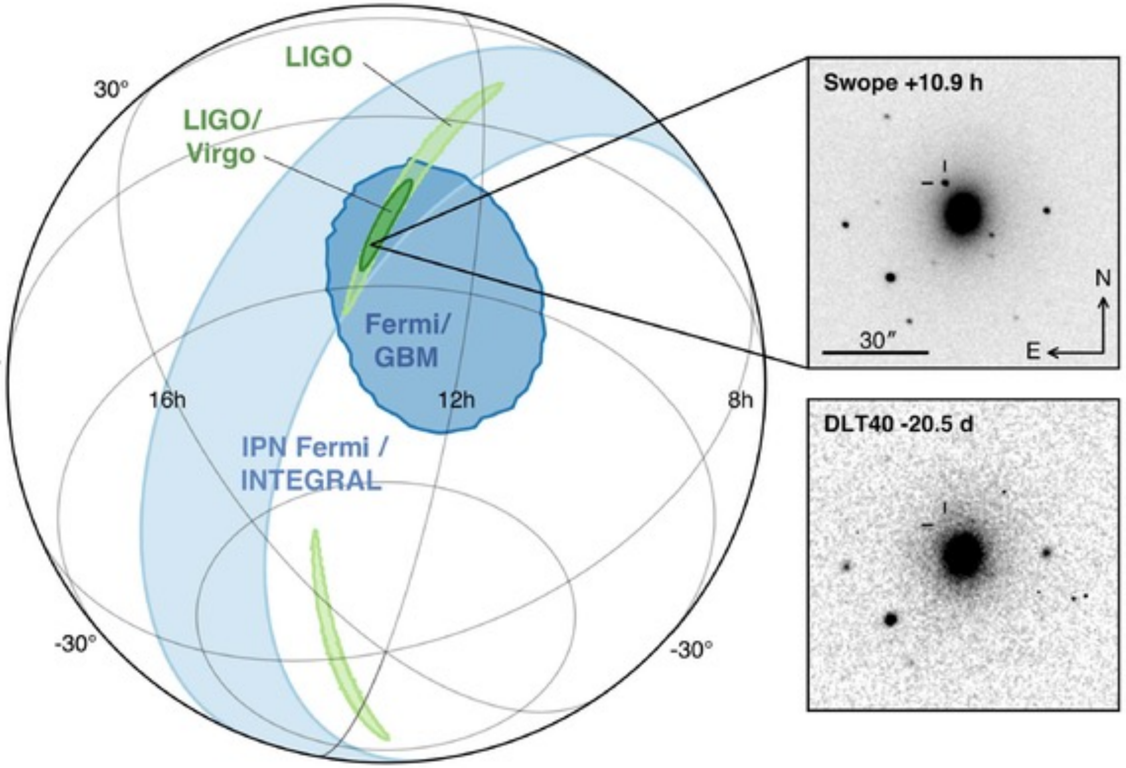


PRL 119, 161101 (2017)

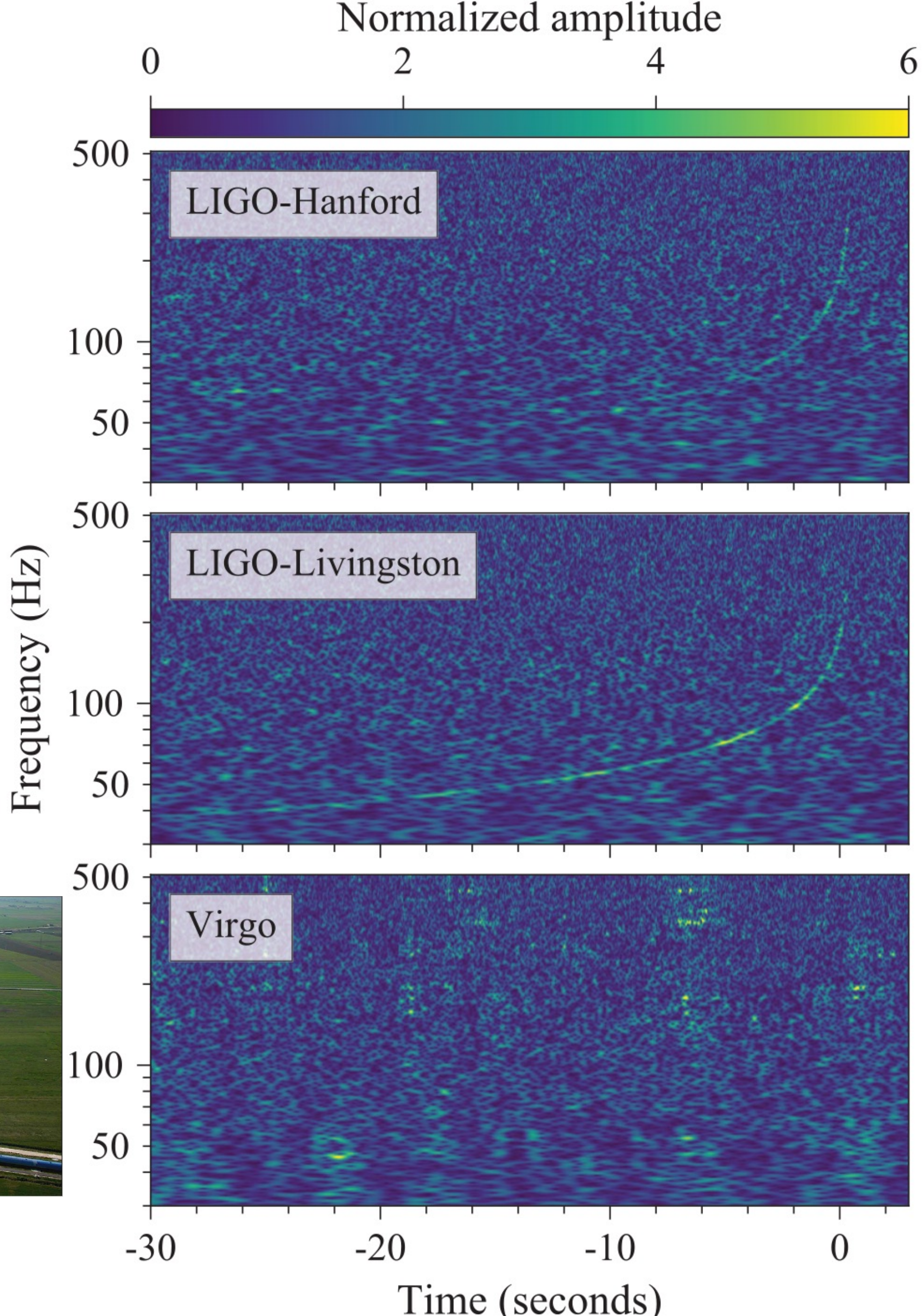


Interestingly the fact that Virgo didn’t observe a strong signal implies that the event was located in its blind spot (low-sensitivity region)

Multimessenger astronomy: GW170817



PRL 119, 161101 (2017)



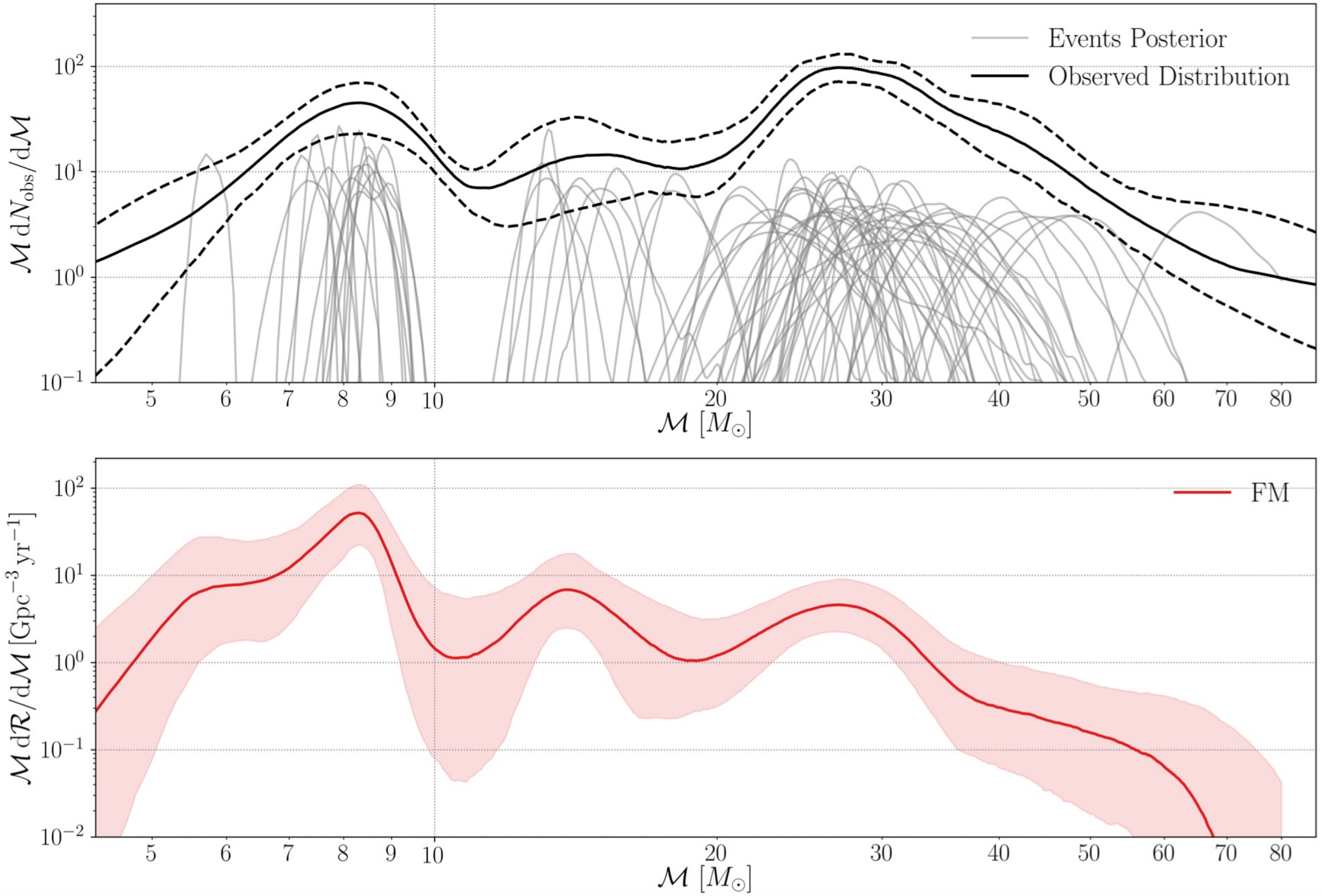
Interestingly the fact that Virgo didn't observe a strong signal implies that the event was located in its blind spot (low-sensitivity region)

Check a new candidate with neutrinos seen in IceCube?
s250206 https://gcn.nasa.gov/circulars/39176

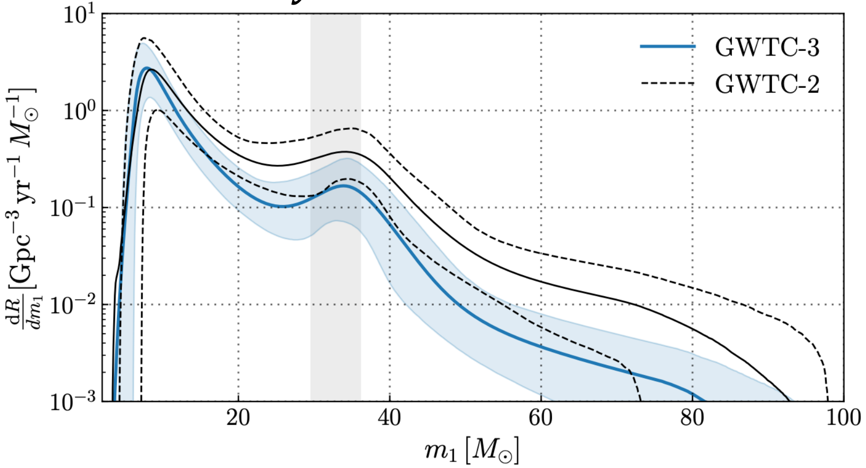
Studies of populations with GWTC3 data

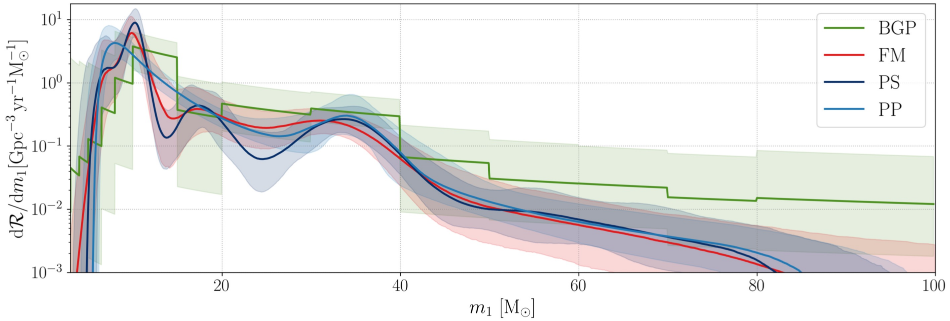
ArXiv: 2111.03634

Substructures present in the **chirp mass** distribution of BBH events with FAR< 1 yr^{-1}

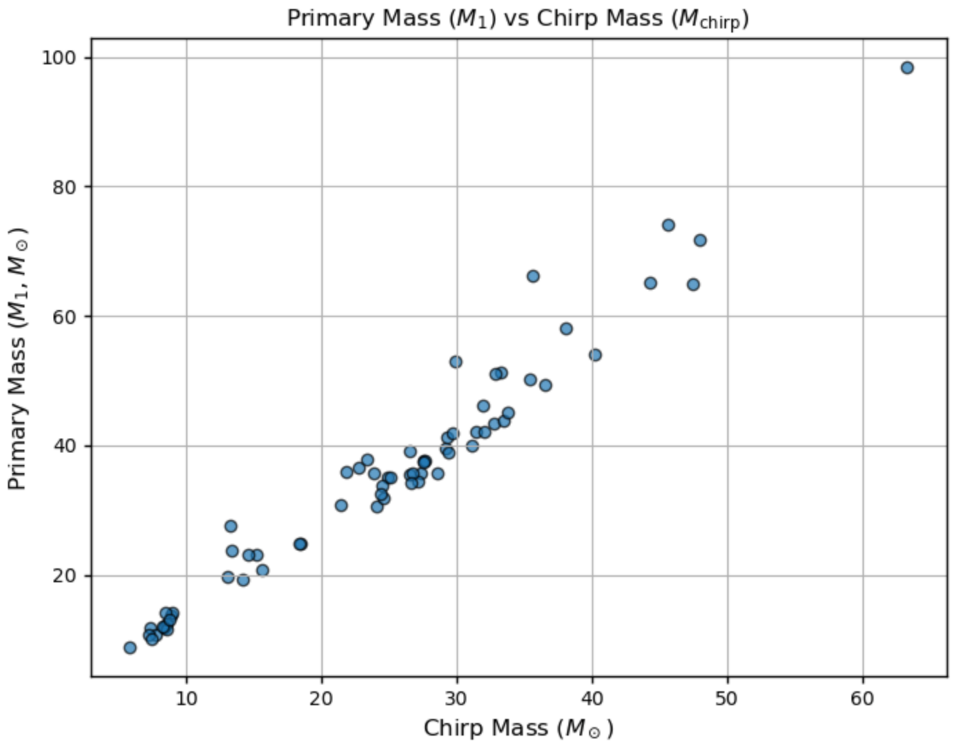


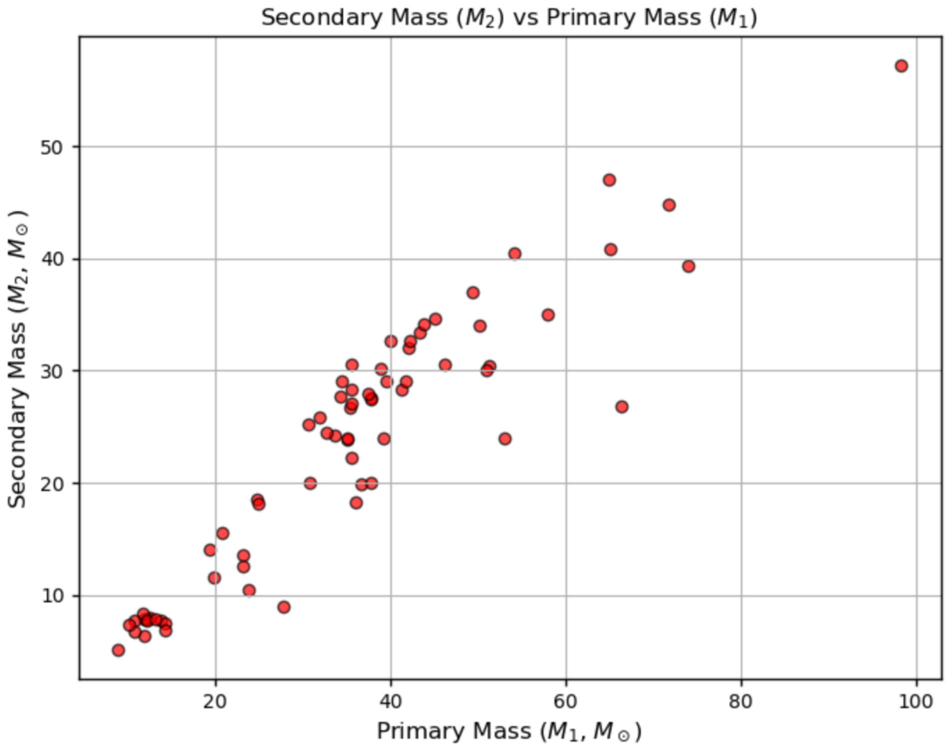
Substructures present in the **primary component mass** distribution of BBH events with FAR< 0.25 yr^{-1}





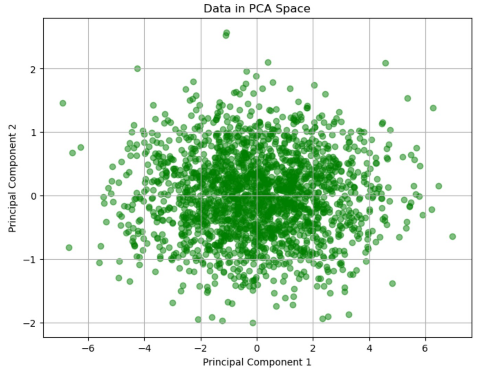
Studies of GWTC3 data with machine learning: dimensionality reduction and clustering





Principal Component Analysis (PCA) is a dimensionality reduction technique that transforms a set of correlated variables into a smaller set of uncorrelated ranked variables called principal components.

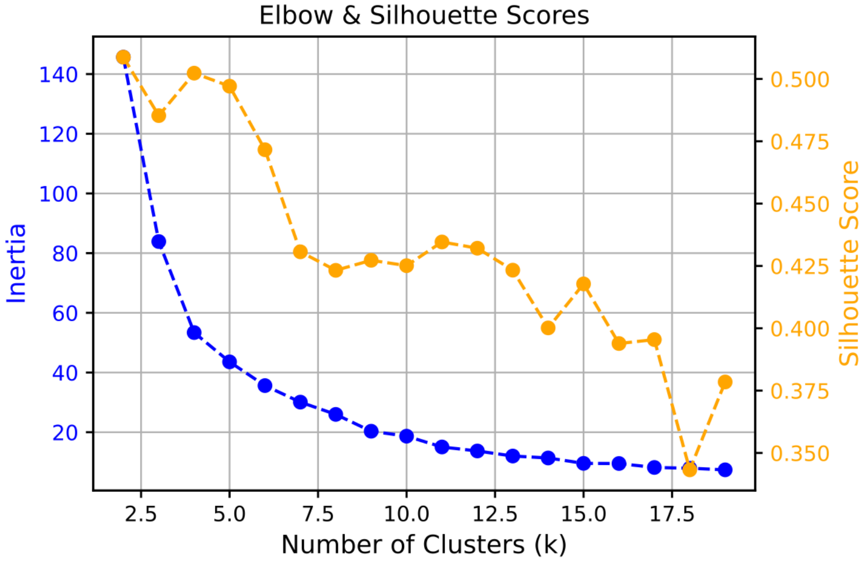
PCA



Studies of GWTC3 data with machine learning: dimensionality reduction and clustering

I now use a 5D clustering k-means algorithm to search for clusters in GWTC3: $M_1, M_2, M_{chirp}, L_D, M_{Tot}$

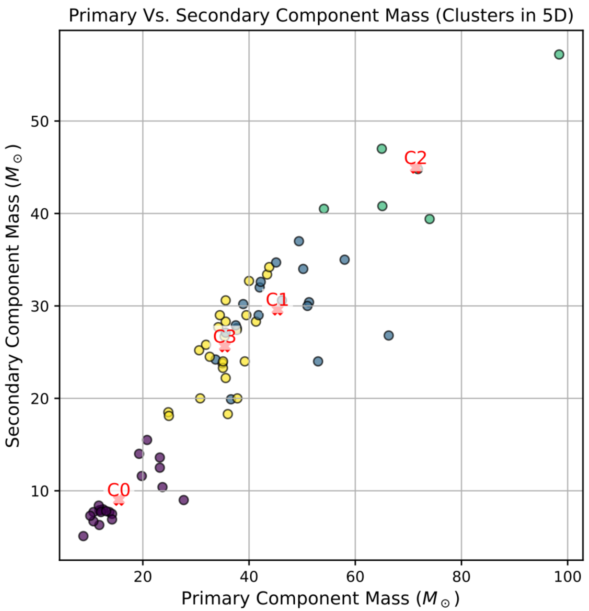
- By inspection , I chose k=4 as the best number of clusters

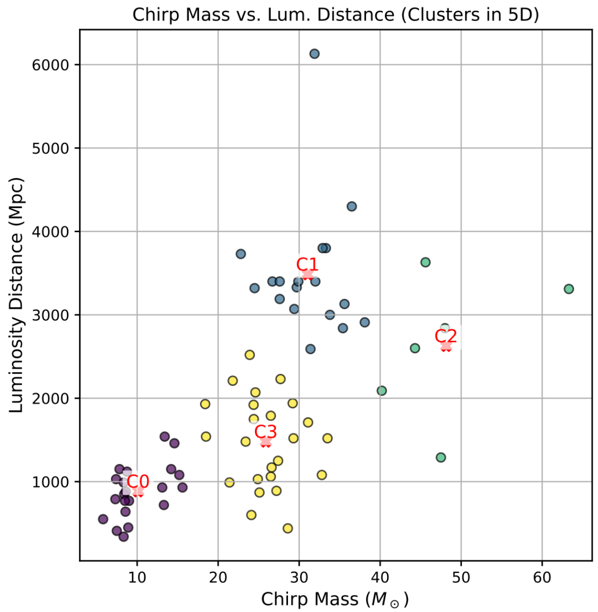


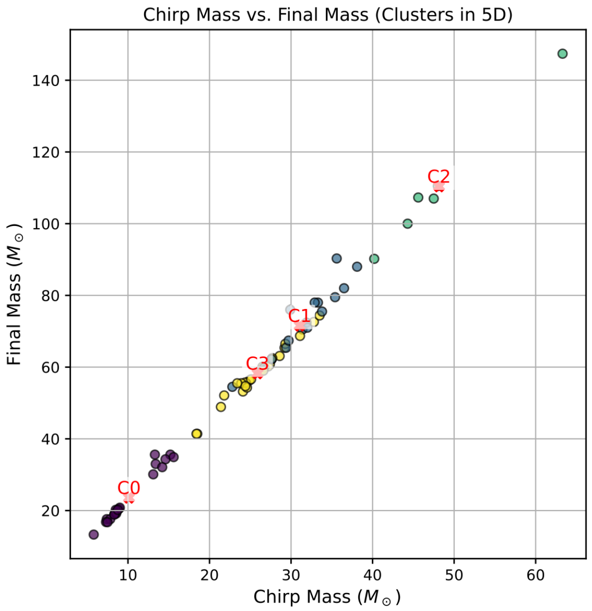
$$d(x,y)^2 = \sum_{j=i}^{j=m} \left(x_j - y_j\right)^2 = \|x - y\|^2$$

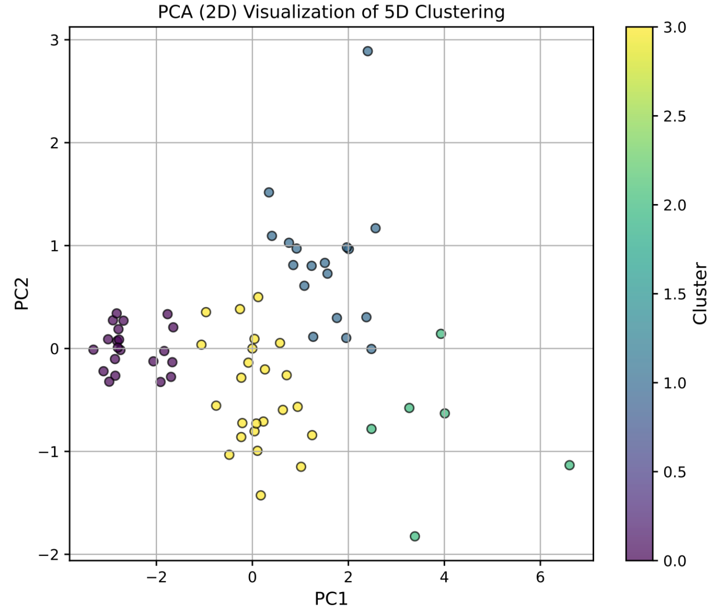
$$SSE(\text{inertia}) = \sum_{i=1}^{i=m} \sum_{j=1}^{j=n} w^{(i,j)} \left\|x^{(i)} - \mu^{(j)}\right\|^2$$

$$s = \frac{b-a}{\max(a,b)}$$



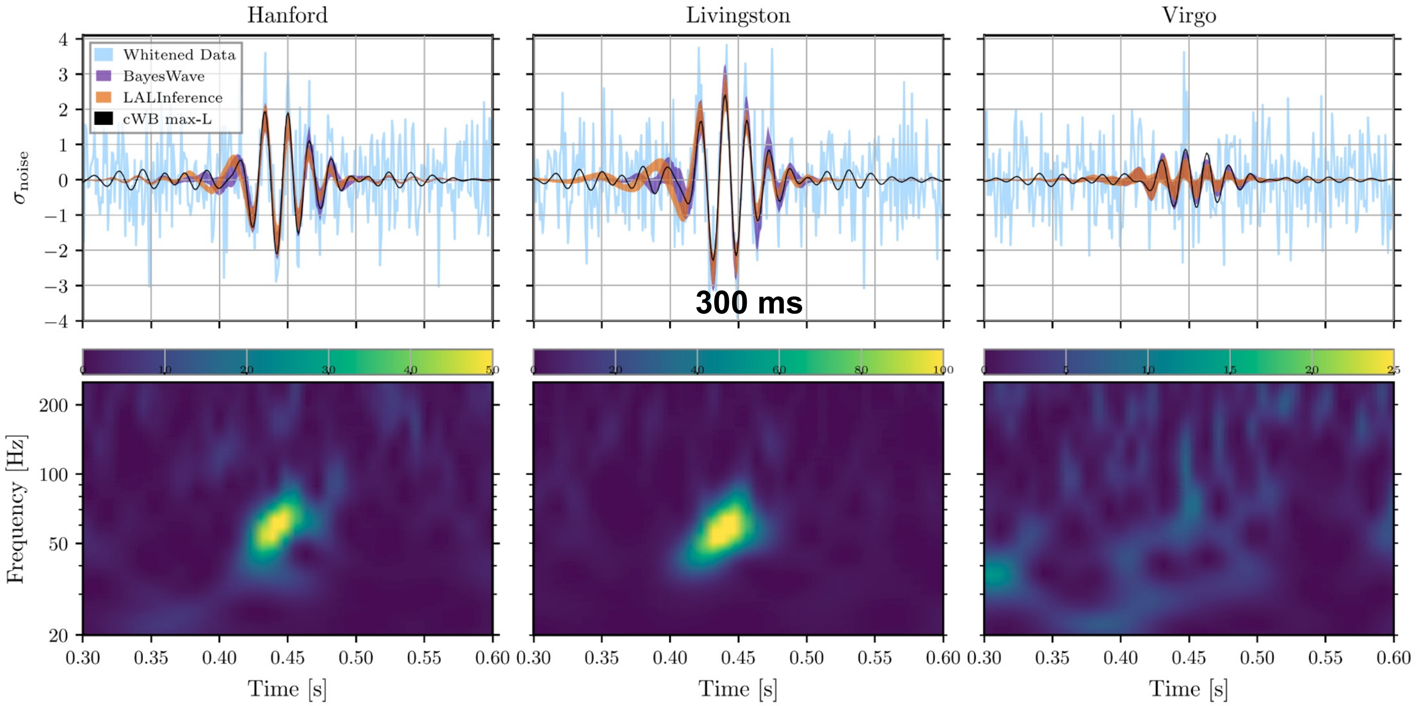






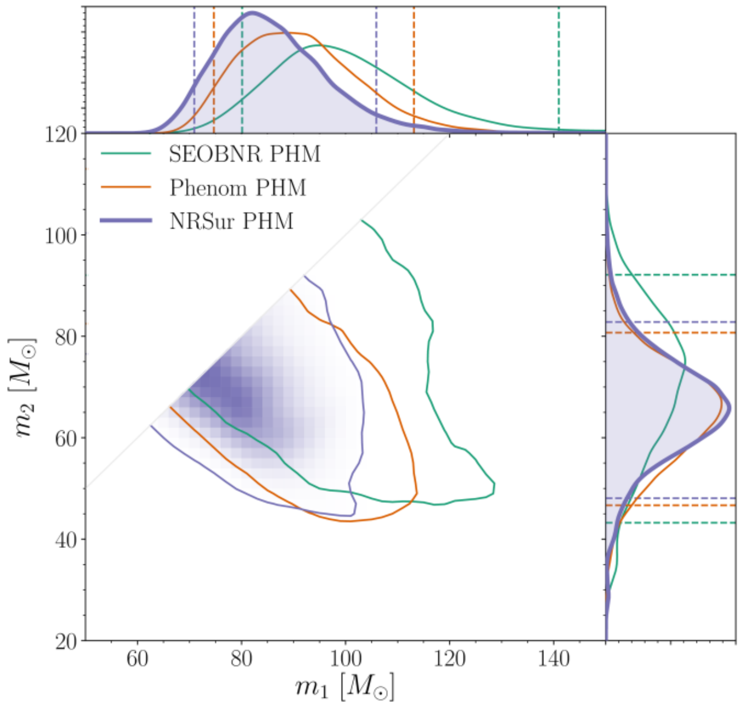
There is an outlier: GW190521, a 150 $M_\odot$ binary BH merger

Phys. Rev. Lett. 125, 101102 (2020), arXiv:2009.01075



300 ms

Astrophys. J. Lett. 900, L13 (2020), ArXiv: 2009.01190



Very “short” signal → a “**burst**”

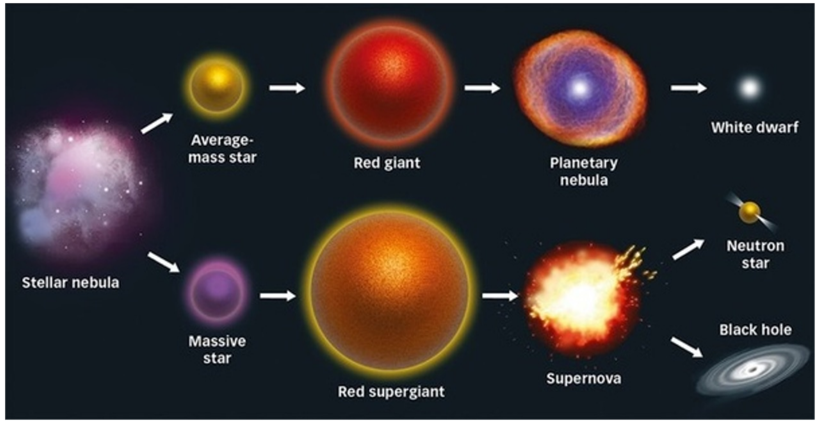
This is a very important event, as it is the observation of a possibly special class(es) of BHs

See also this presentation from the 2024 ET symposium in Maastricht (see here).

Stellar, supermassive and intermediate-mass black holes

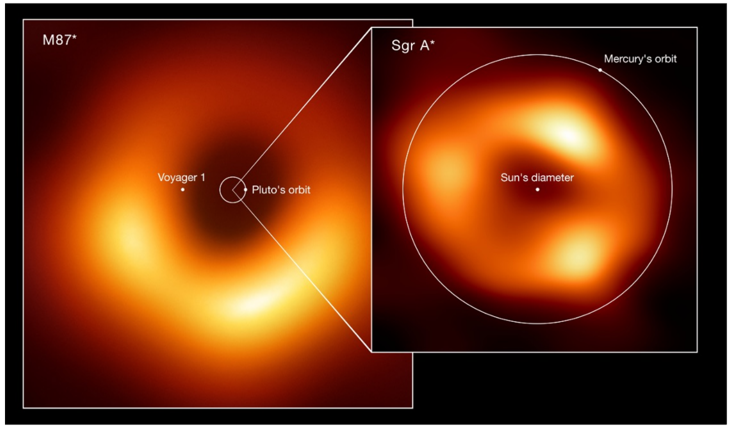
Stellar black holes (SBHs)

- Masses ranging from 5* to few x10 $M_\odot$
- Forms in the final stage of evolution of stars from stellar collapse
- Can exist isolated or in binary systems



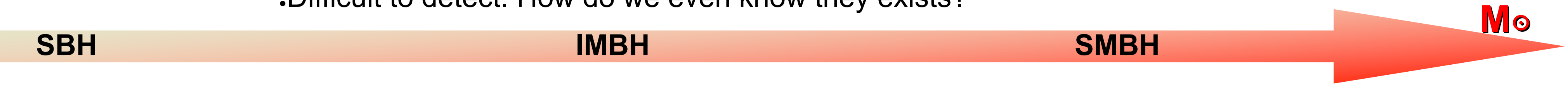
Supermassive black holes (SMBHs)

- Very large masses of $10^6 – 10^9$ $M_\odot$
- Typically located in the center of galaxies
- Grow through accretion disk of gas and dust around them
- Core of AGNs



Intermediate-mass black holes (IMBHs)

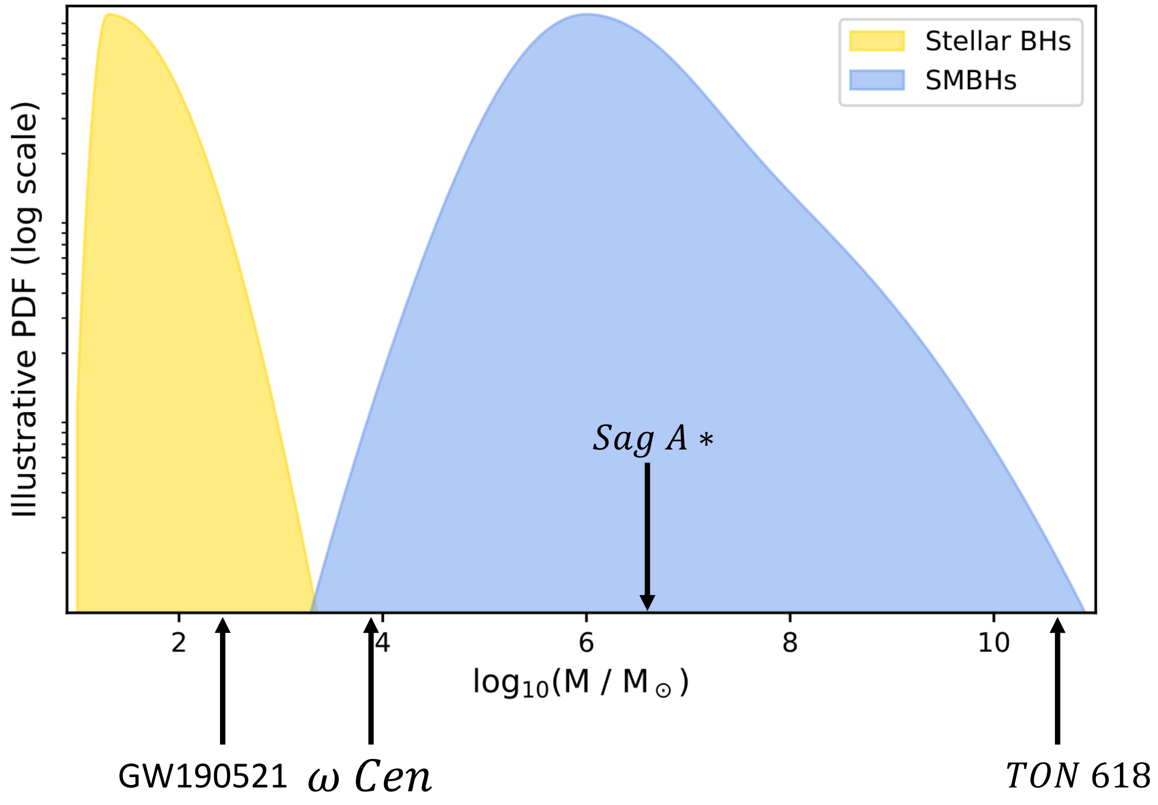
- Masses of the order of $10^2 – 10^5$ $M_\odot$
- Various models for their origin – no general consensus (ex. population III stars vs. hierarchical mergers)
- Difficult to detect. How do we even know they exists?

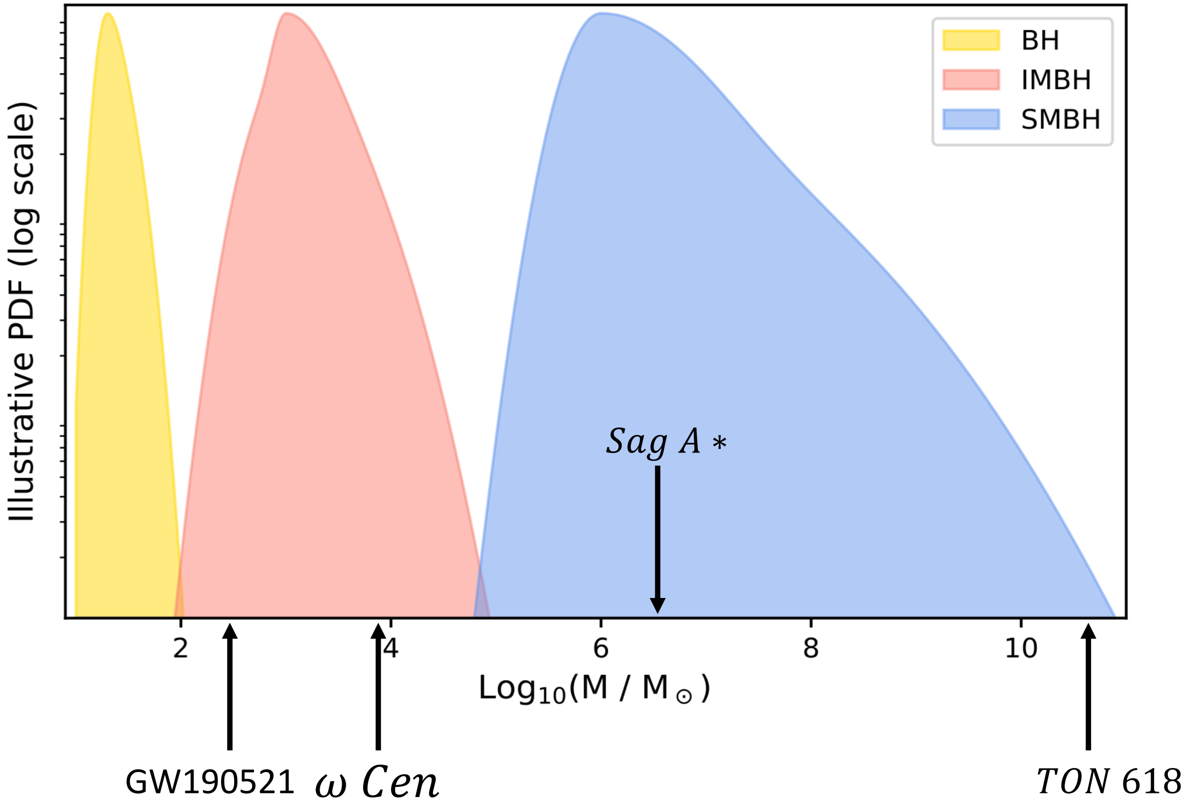


GW190521, $M \sim 142 M_\odot$ PhysRevLett.125.101102

In $\omega\ Cen$, $M \sim 8200 M_\odot$ Nature 631, 285-288 (2024)

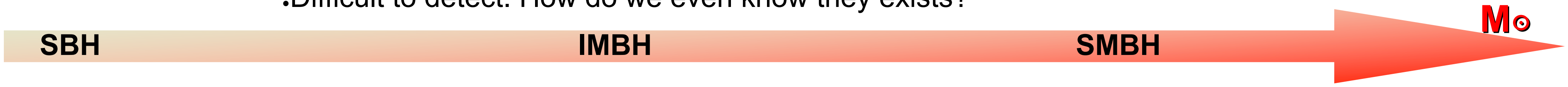
Do IMBHs constitute a class/population of BHs or do they belong to the tails of stellar/supermassive BH distributions?





Intermediate-mass black holes (IMBHs)

- Masses of the order of $10^2 - 10^5\ M_\odot$
- Various models for their origin – no general consensus (ex. population III stars vs. hierarchical mergers)
- Difficult to detect. How do we even know they exists?

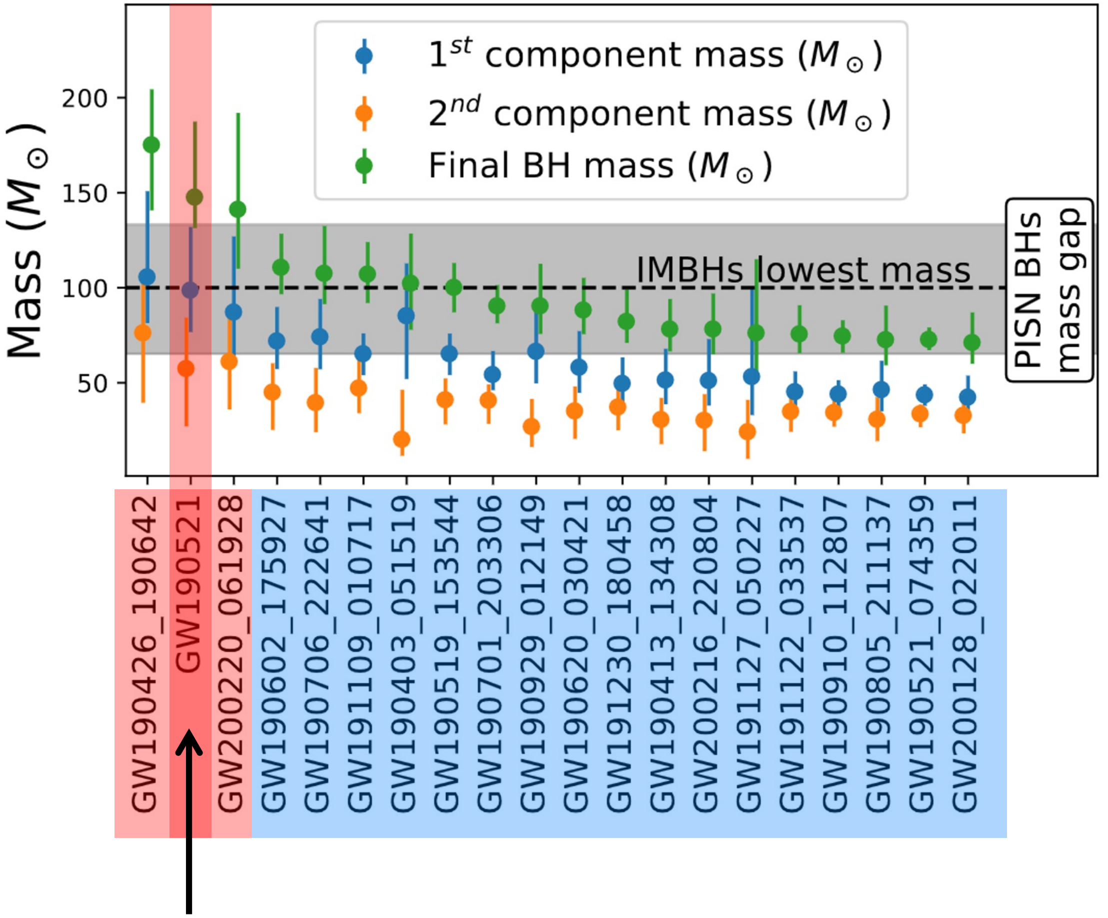


GW190521, $M{\sim}142M_\odot$ PhysRevLett.125.101102

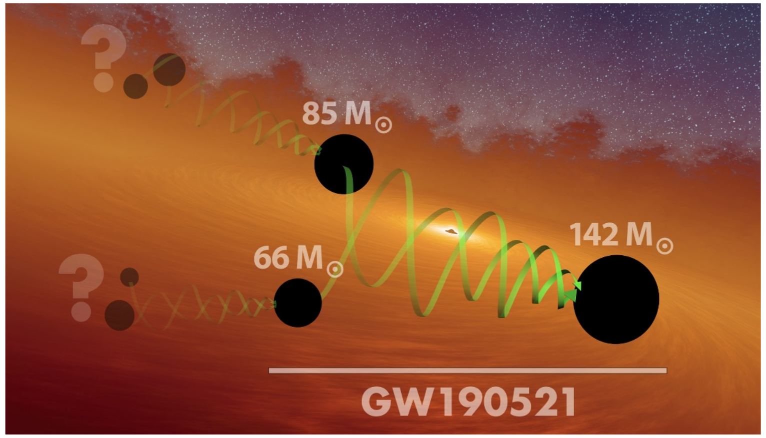
In $\omega\ Cen$, $M{\sim}8200M_\odot$ Nature 631, 285-288 (2024)

GW190521: The first observation of an IMBH, with an anomaly

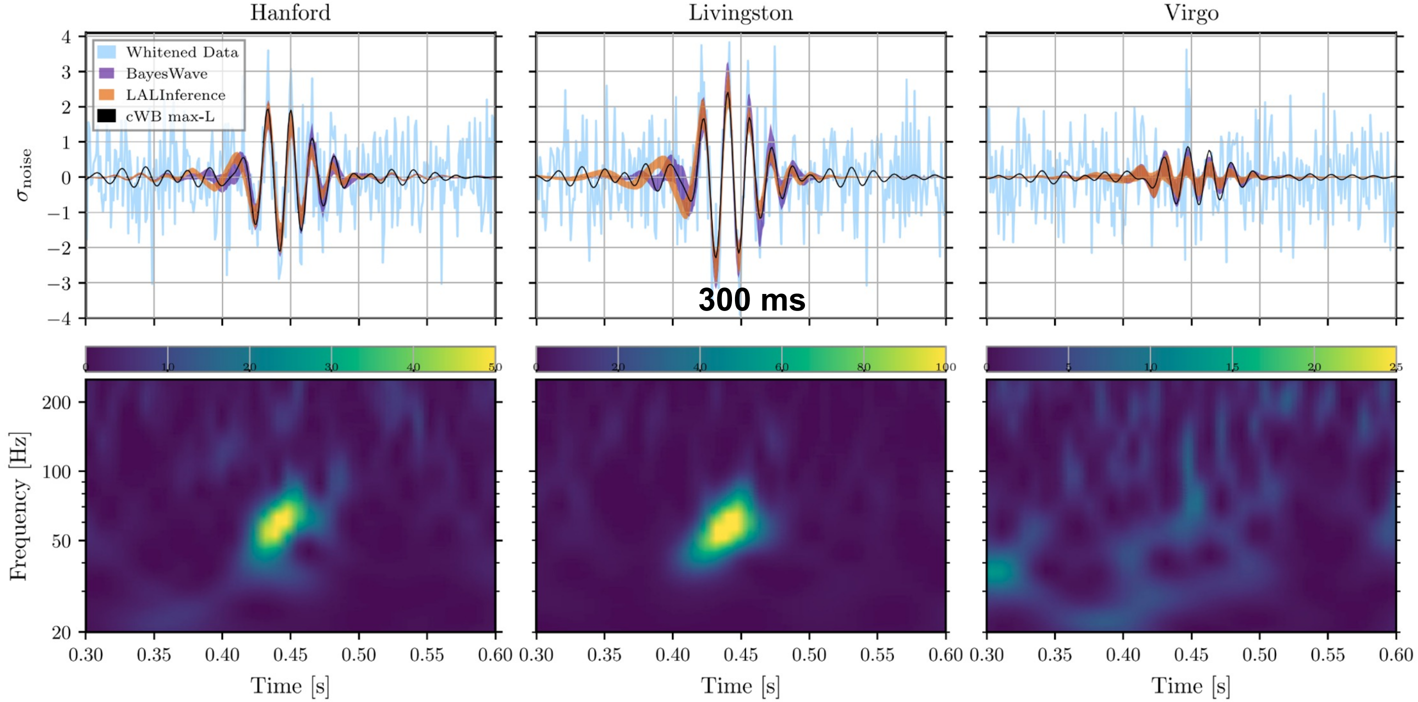
The 20 events detected in O1-O3 with the largest remnant masses



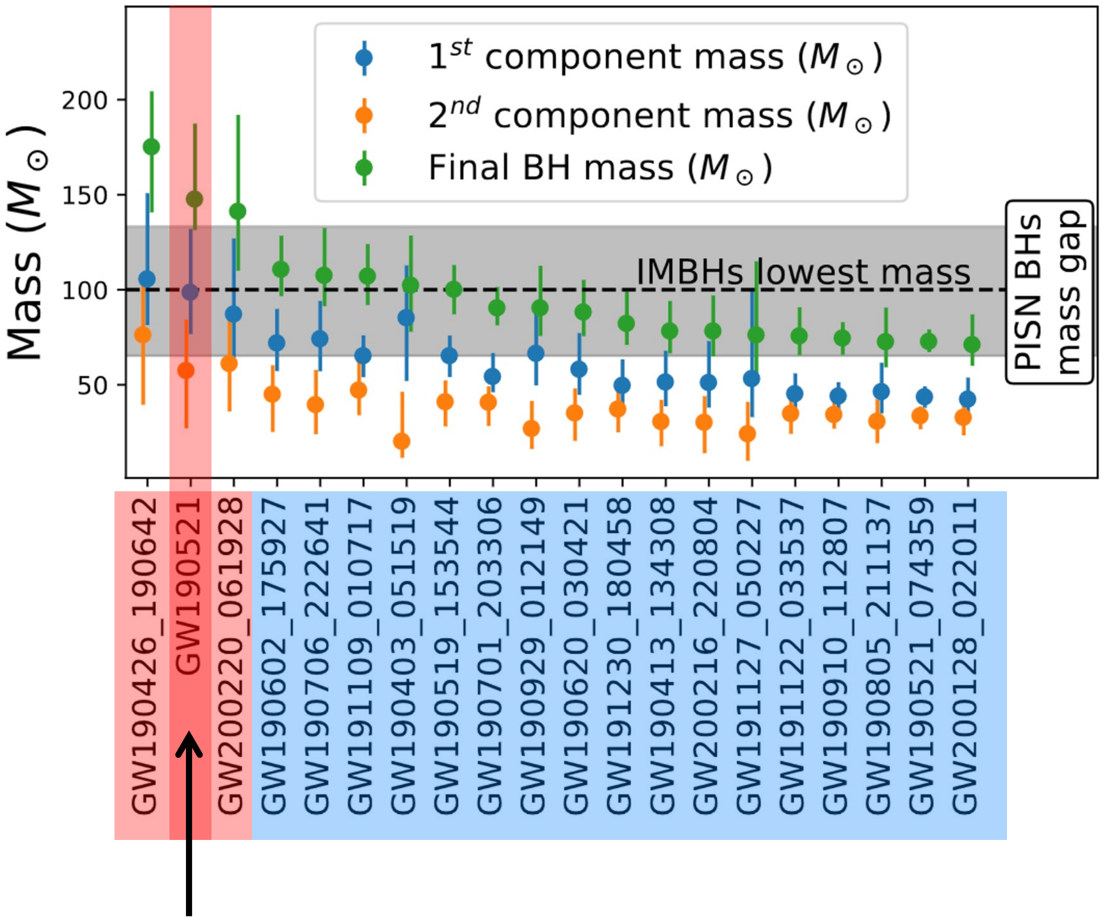
GW190521: First direct evidence of **IMBH**, but how did its 1st component form?



Phys. Rev. Lett. 125, 101102 (2020), arXiv:2009.01075

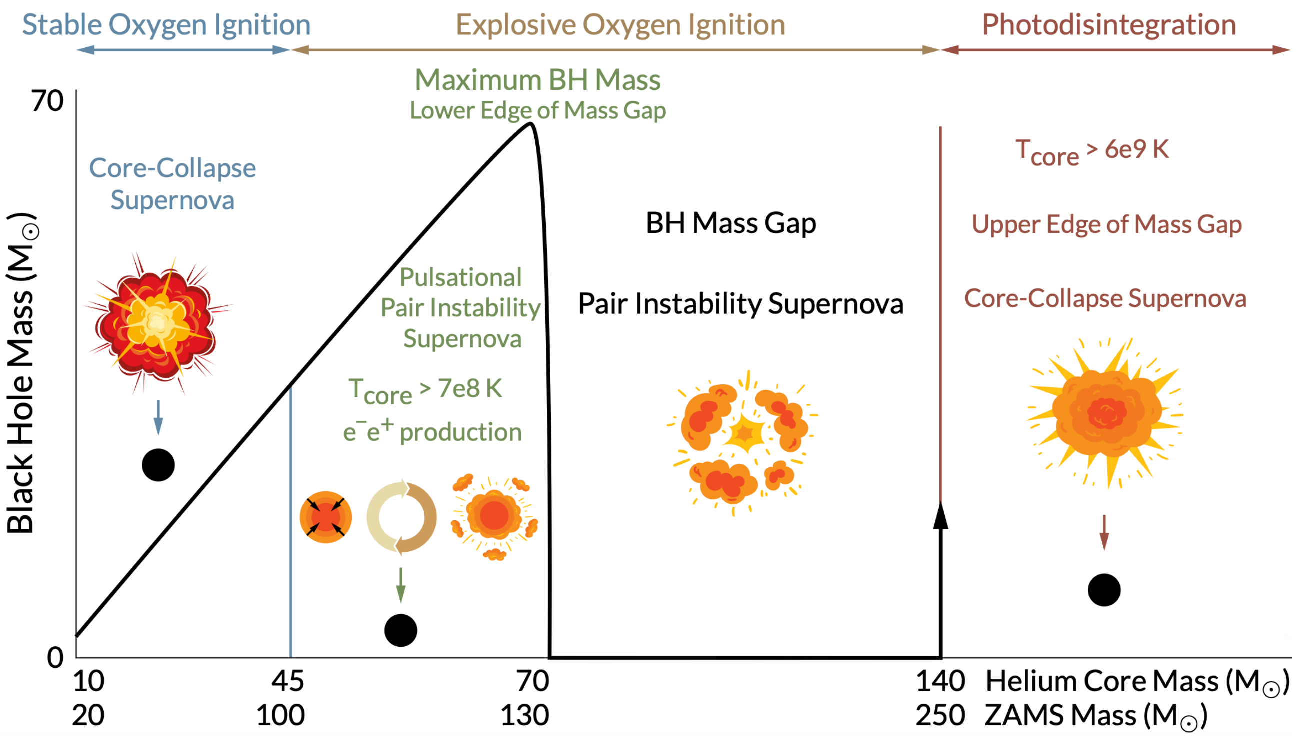


The 20 events detected in O1-O3 with the largest remnant masses



GW190521: First direct evidence of **IMBH**, but how did its 1^{st} component form?

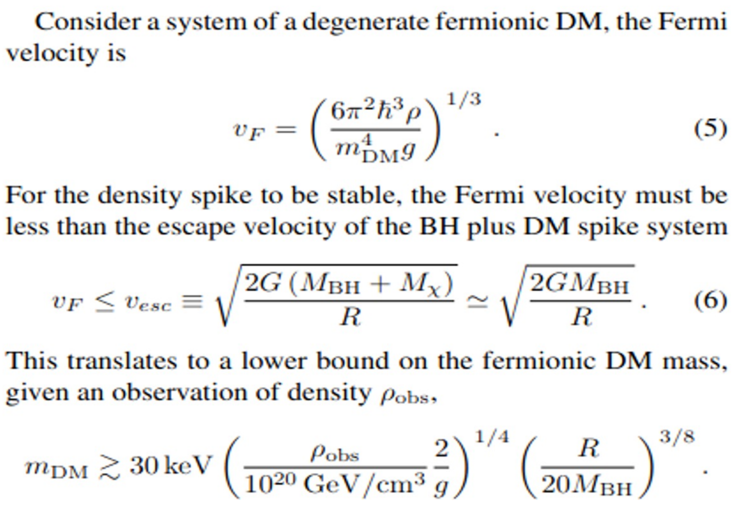
In sufficiently massive stars, **pair creation in the core inhibits radiation pressure**, triggering a runaway thermonuclear explosion (a pair-instability supernova) that **completely destroys** the star, leaving **no black hole remnant** in the ~50-120 $M_\odot$ range -> the **'PISN mass gap.**



Beyond astrophysics, IMBHs as laboratories to probe new physics scenarios

Dark Matter constitutes ~85% of the matter content of the Universe. Some models can be probed studying GWs related to IMBHs.

Ex. Fermionic dark matter "spikes" imprinted in GW signals



Consider a system of a degenerate fermionic DM, the Fermi velocity is

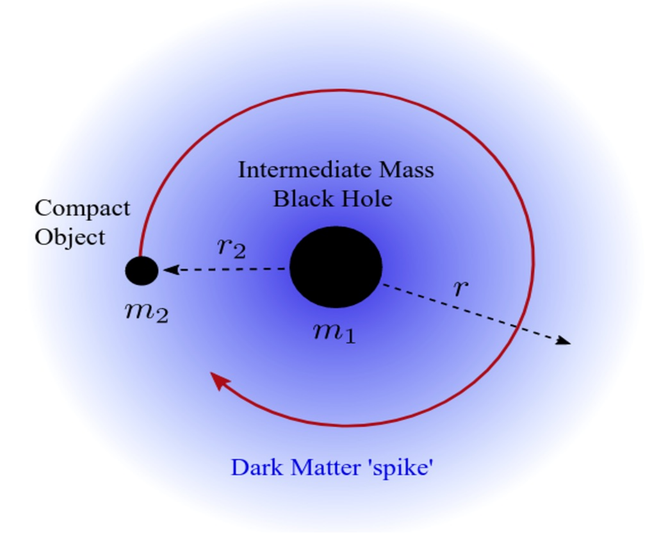
$$v_F = \left(\frac{6\pi^2\hbar^3\rho}{m_{\rm DM}^4 g}\right)^{1/3} . \tag{5}$$

For the density spike to be stable, the Fermi velocity must be less than the escape velocity of the BH plus DM spike system

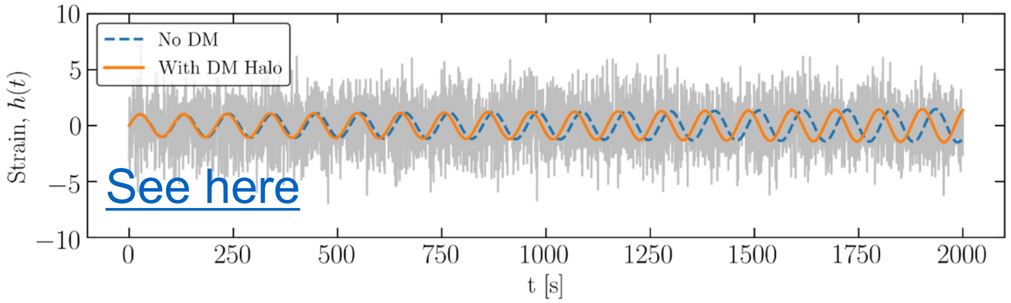
$$v_F \le v_{esc} \equiv \sqrt{\frac{2G\left(M_{\rm BH}+M_\chi\right)}{R}} \simeq \sqrt{\frac{2GM_{\rm BH}}{R}} . \tag{6}$$

This translates to a lower bound on the fermionic DM mass, given an observation of density $\rho_{\rm obs}$,

$$m_{\rm DM} \gtrsim 30\,{\rm keV}\left(\frac{\rho_{\rm obs}}{10^{20}\,{\rm GeV/cm^3}}\,\frac{2}{g}\right)^{1/4}\left(\frac{R}{20M_{\rm BH}}\right)^{3/8} .$$

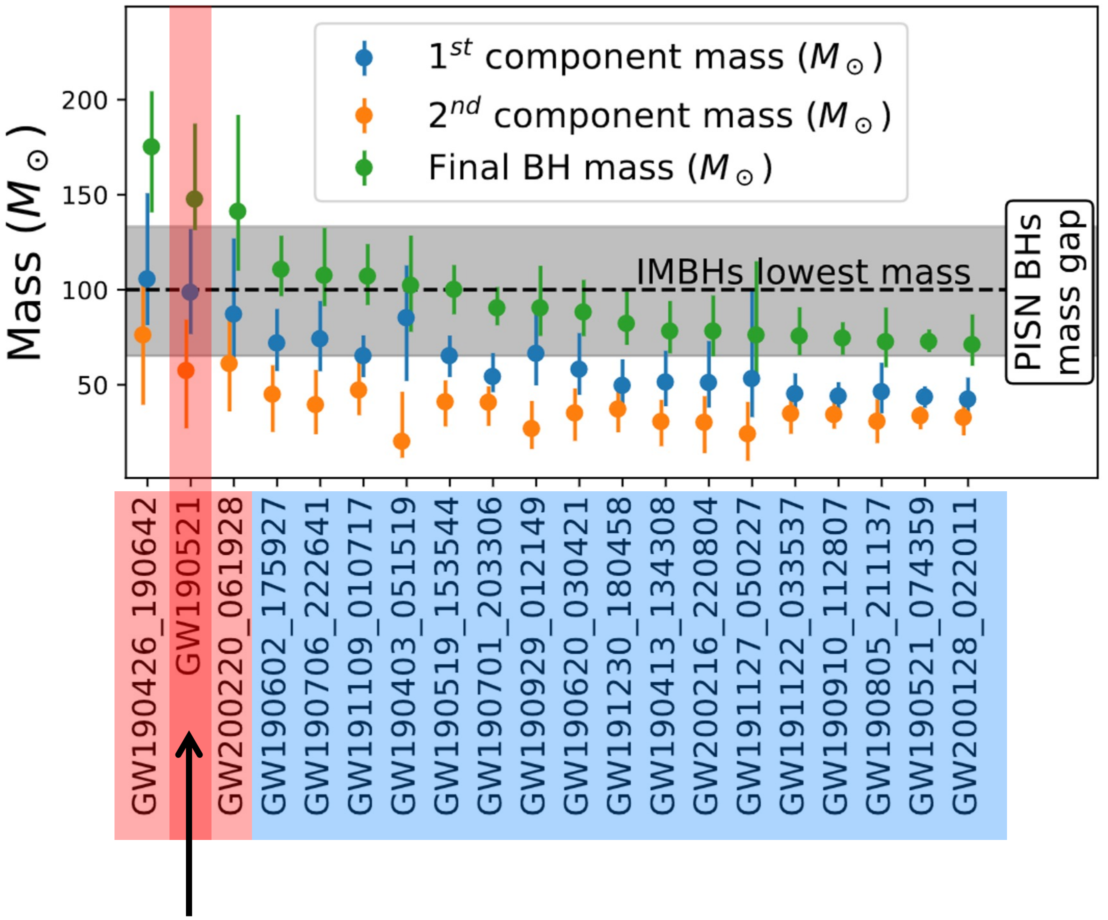


ArXiv: 1906.11845
ArXiv: 210804154

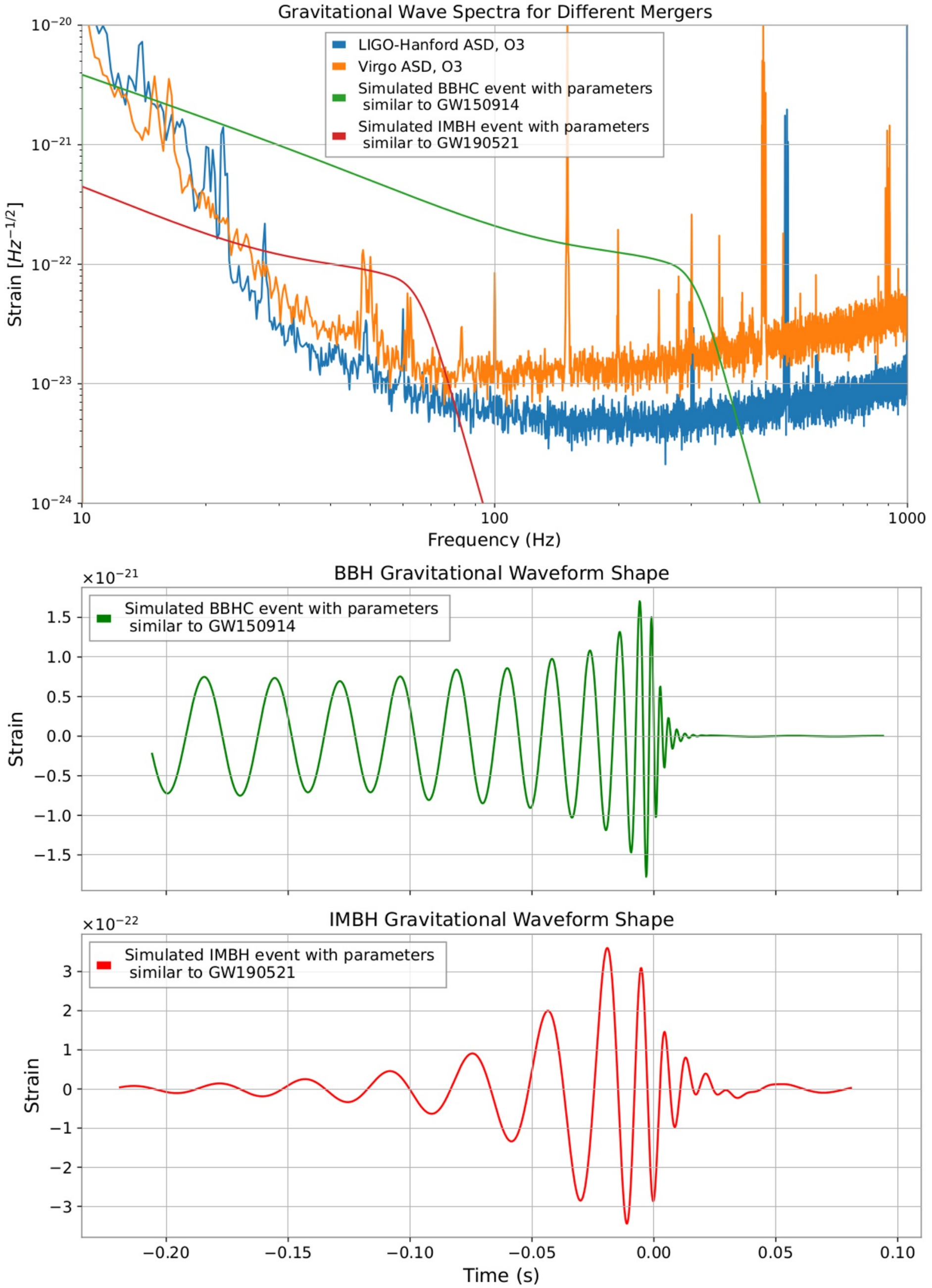


See here

GW transients associated with the production of an IMBH are difficult to detect

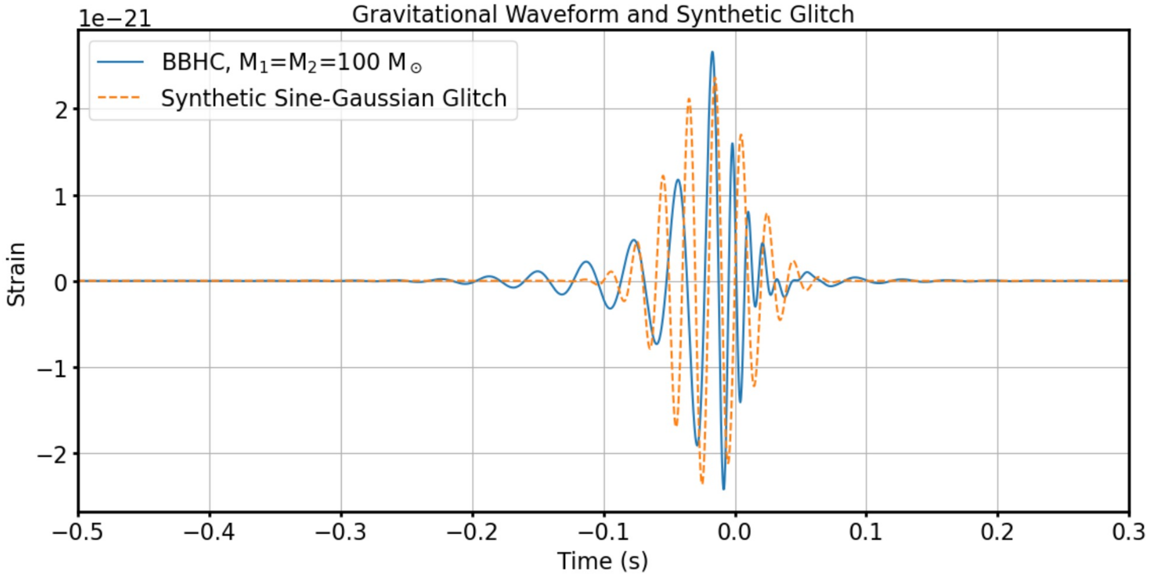


GW190521: First direct evidence of **IMBH**, but how did its 1st component form?



DATA (ASD, in blue and yellow) and simulations (GW spectra and waveforms) using PyCBC pipeline with phenomenological models

Environmental/Instrumental Transient Noise (AKA Glitches) can be a problem

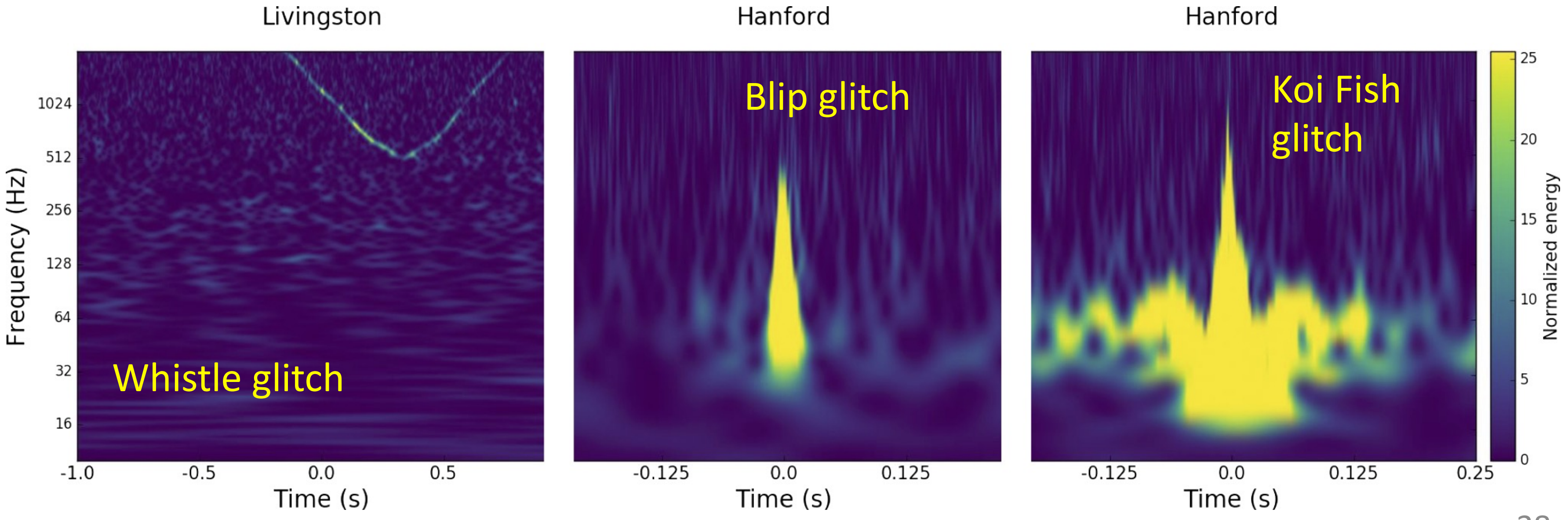


Comparison of a BBH merger with a pathological synthetic glitch of short duration, with a central frequency of 50 Hz, amplitude similar to the merger. Such a glitch could be caused by

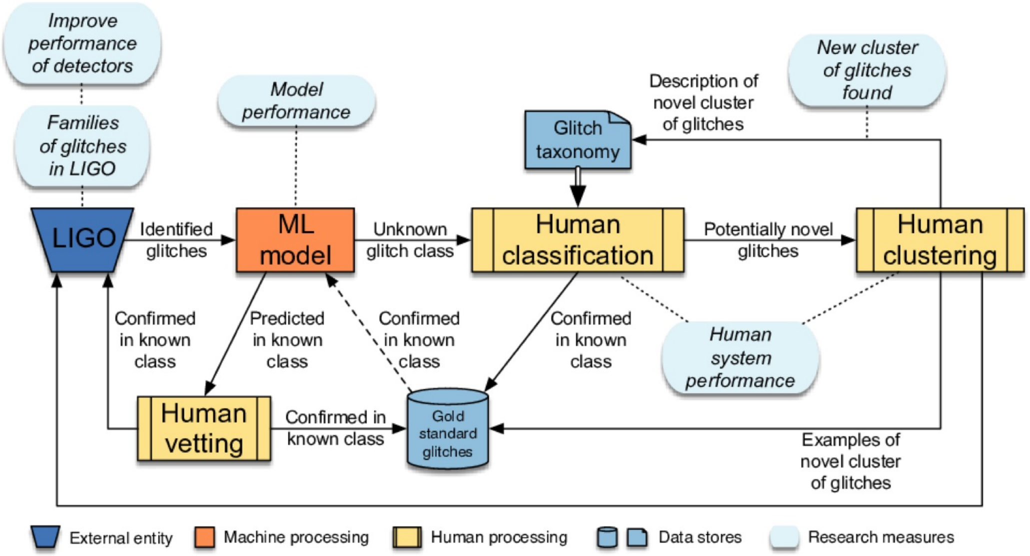
- Scattered light
- Mechanical vibrations
- Electronics (power supplies, ADC, etc.)
- Environment (wind, passing vehicles, etc.)

Gravity Spy: lessons learned and a path forward

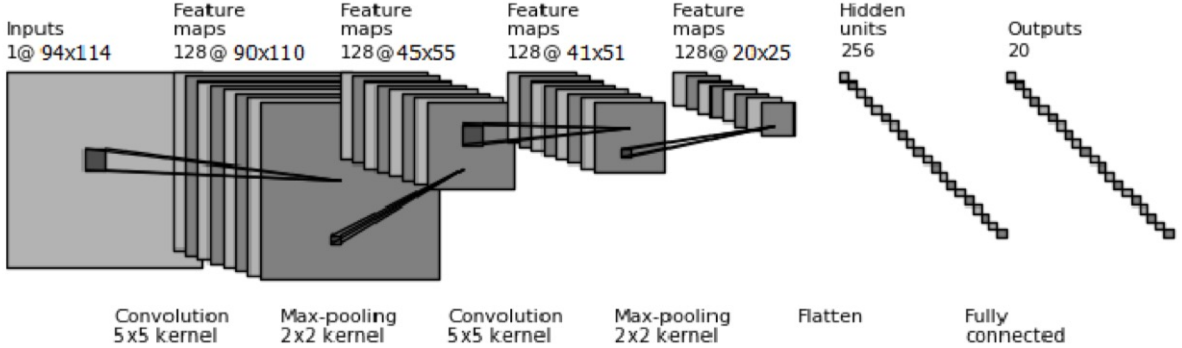
Eur. Phys. J. Plus **139**, 100 (2024)



GravitySpy: Combining deep learning and citizens science

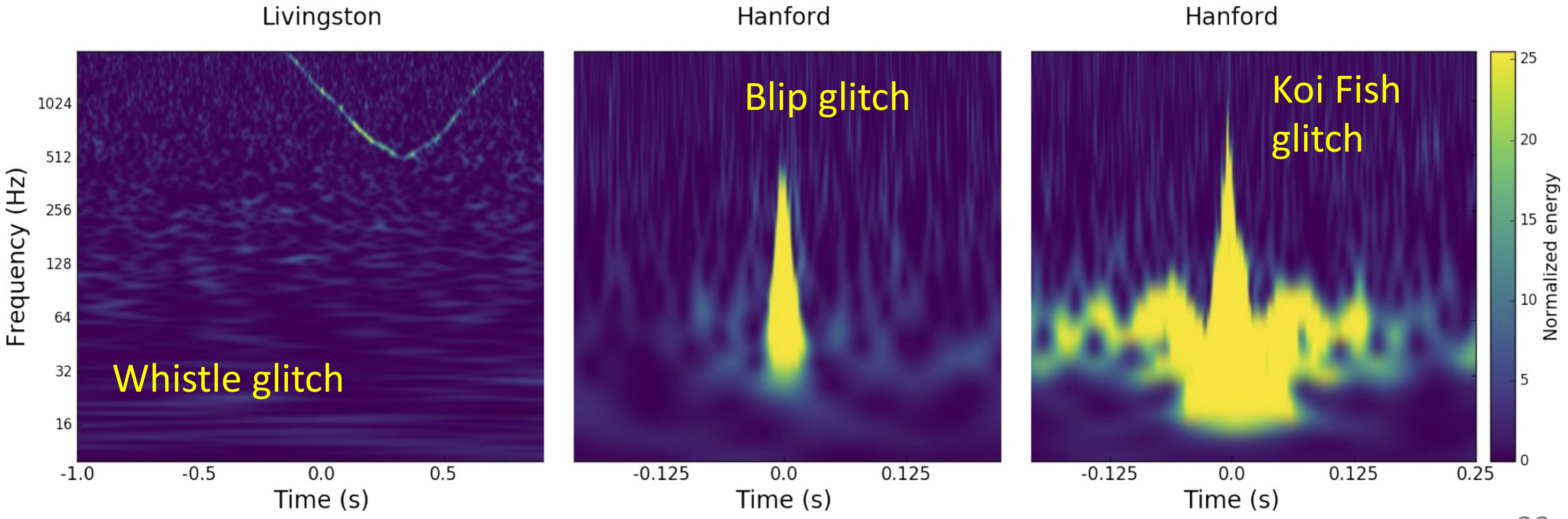


Deep convolutional neural network

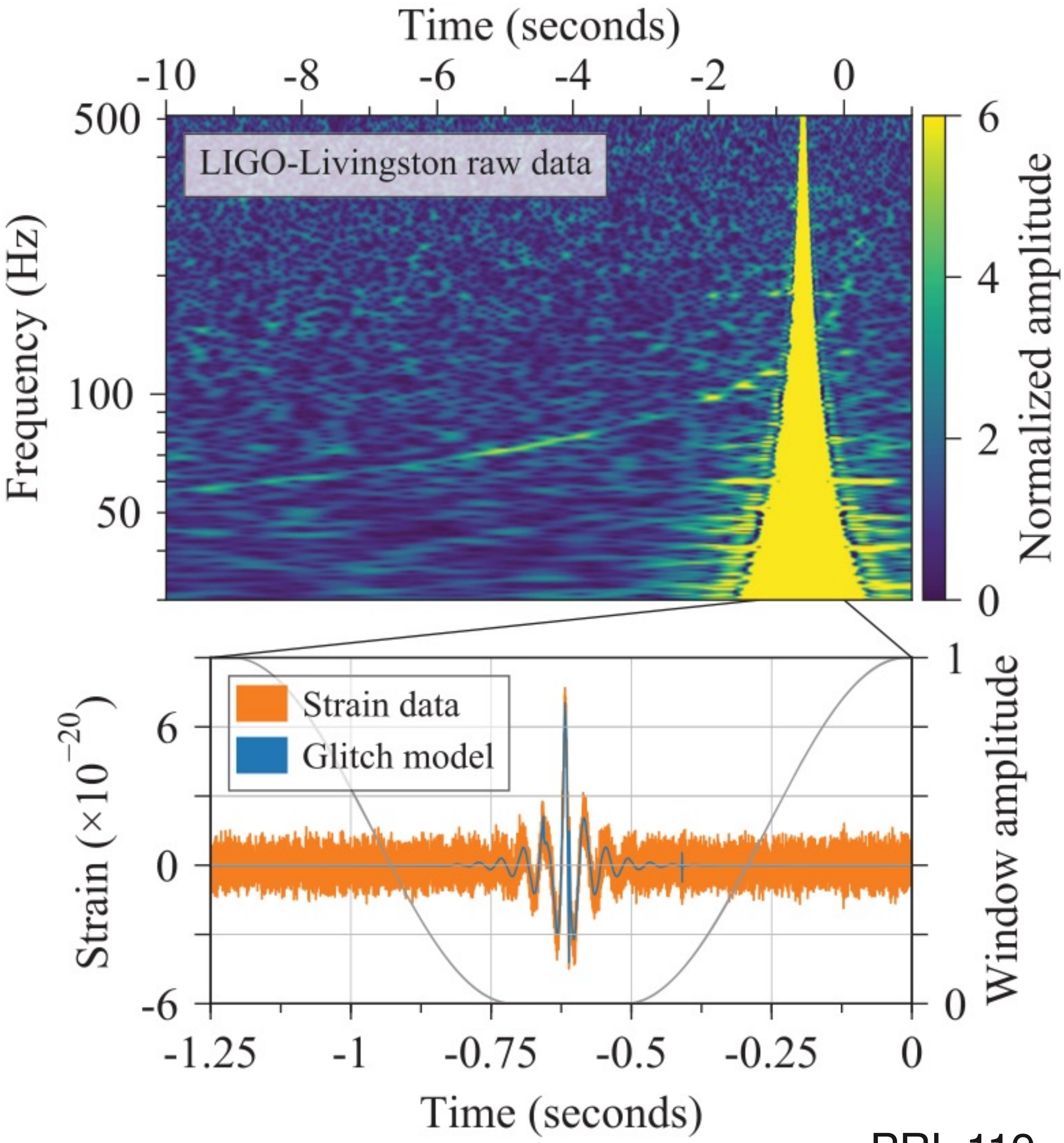


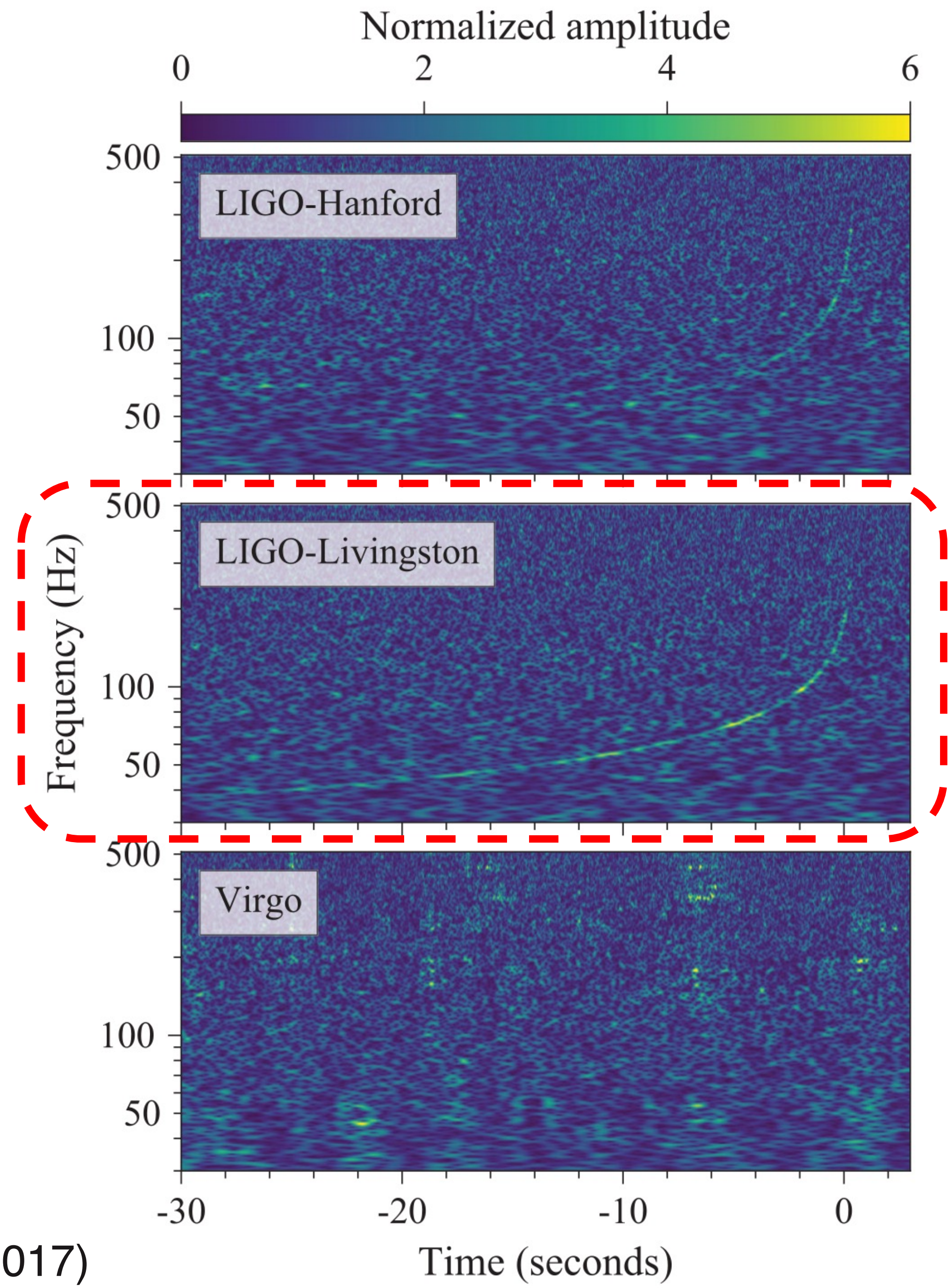
Gravity Spy: lessons learned and a path forward

Eur. Phys. J. Plus **139**, 100 (2024)



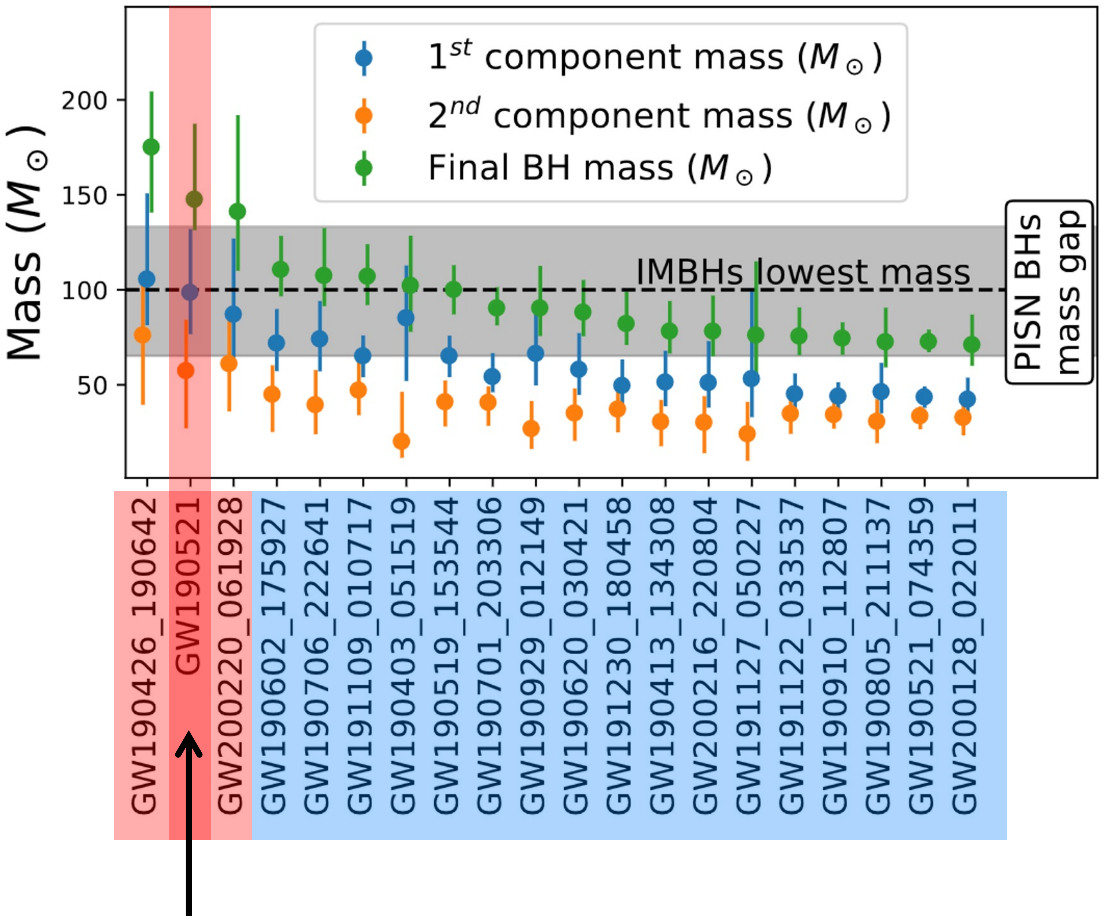
The glitch in GW170817



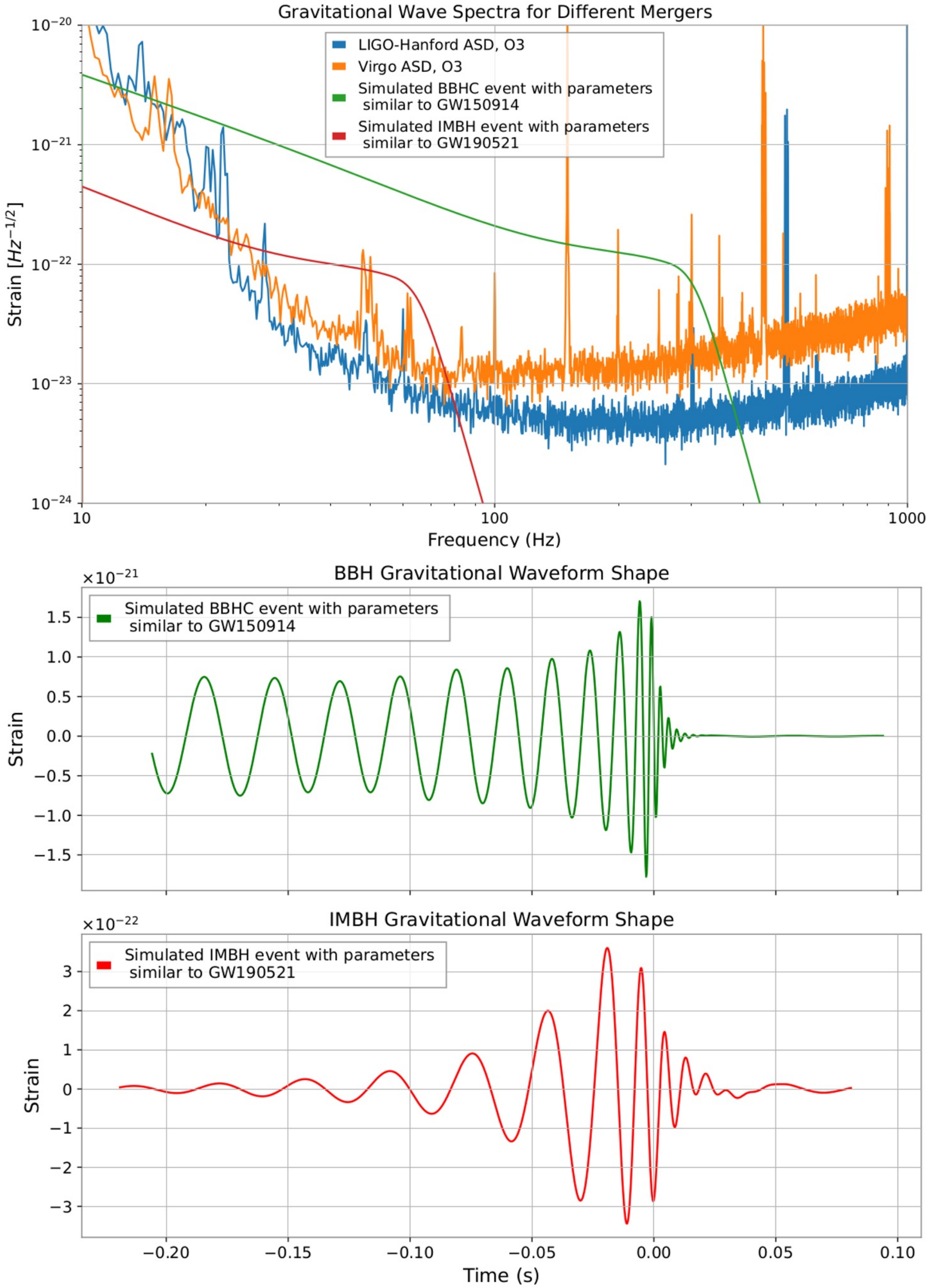


PRL 119, 161101 (2017)

GW transients associated with the production of an IMBH are difficult to detect



GW190521: First direct evidence of **IMBH**, but how did its 1st component form?

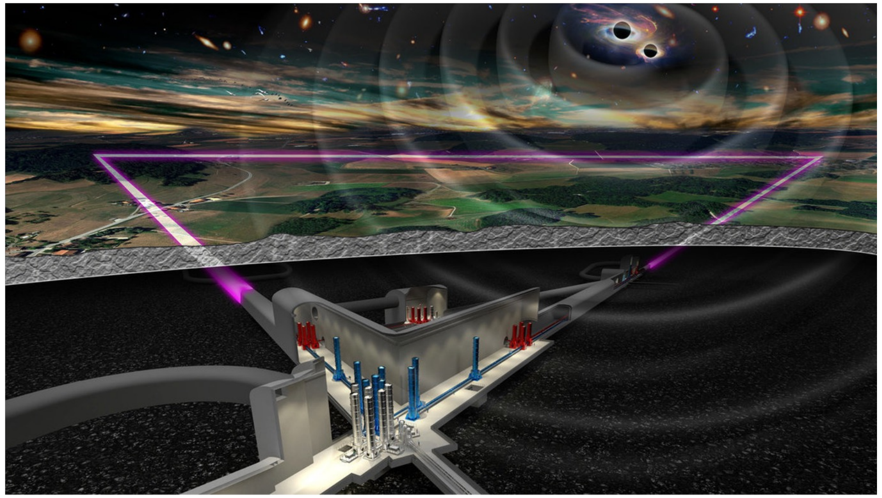


DATA (ASD, in blue and yellow) and simulations (GW spectra and waveforms) using PyCBC pipeline with phenomenological models

What could next-generation detectors do

- Increase the number of events detected (expect 1 order of magnitude improvement in sensitivity).
- Extend the frequency range, hence being sensitive to new classes of events, such as heavier source-frame mass systems.
- Study merger rates through the cosmic age.
- Participate in multiband GW detection.
- And much more (test GR, search for DM, early Universe, 1st order phase transitions, NS EoS, cosmology, etc.)

3-G GW detector in EU, the Einstein Telescope



Third-generation gravitational wave observatory consisting of

- 3 nested GW detectors arranged in a triangular shape
- 10 KM long arms per detector (vs. 3/4 of Virgo/LIGO)

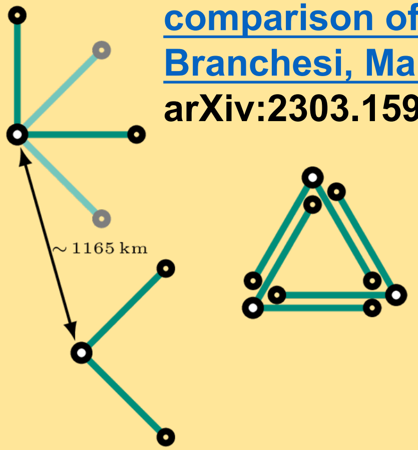
- Each detector will have 2 interferometers working at
- Low-frequency (~2-40 Hz) →low laser power, cryogenic mirrors
- High-frequency(40-several kHz) →high laser power, room temperature

To reduce gravity gradient **noise** and seismic noise (hence improving sensitivity at low frequencies)
ET will be built underground (current design is 200m)
Two (+1) candidate sites to host the telescope, with ongoing site characterization work

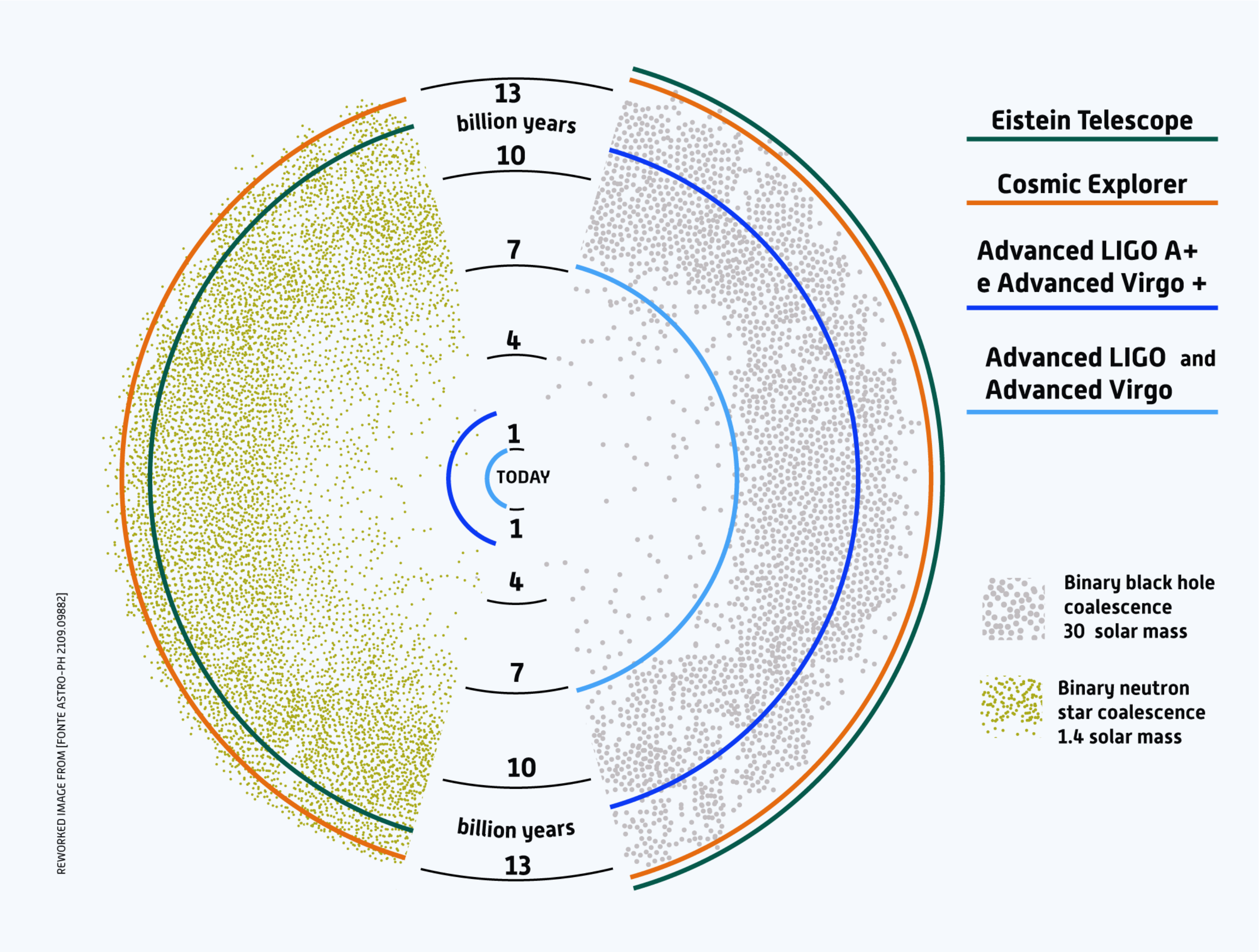
- Sardegna, Sos Enattos mine
- Euregio Meuse-Rhine
- Saxony (under discussion)

Why 3 detectors? Because it will be sensitive to both polarisations rather than their linear combination. However, a second option with two L-shaped antennas at ~1000 km distance and with a 45 deg angle wrt each other has better sensitivity overall

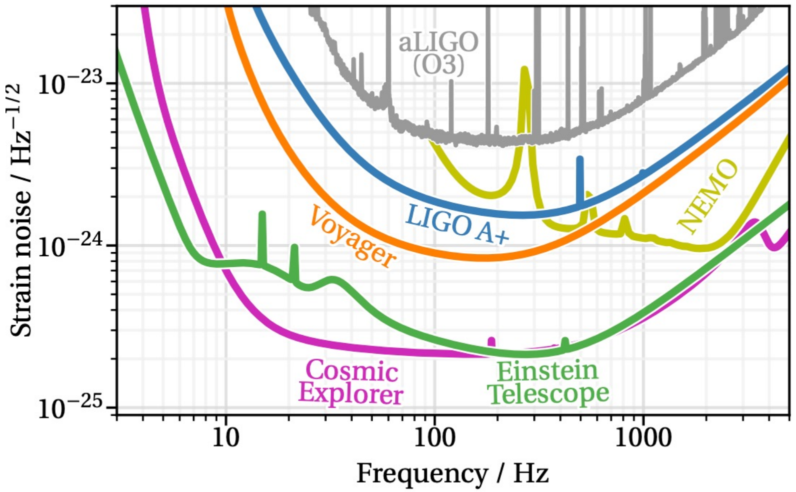
Science with the Einstein Telescope: a comparison of different designs – Branchesi, Marica et al – arXiv:2303.15923 ET-0084A-23

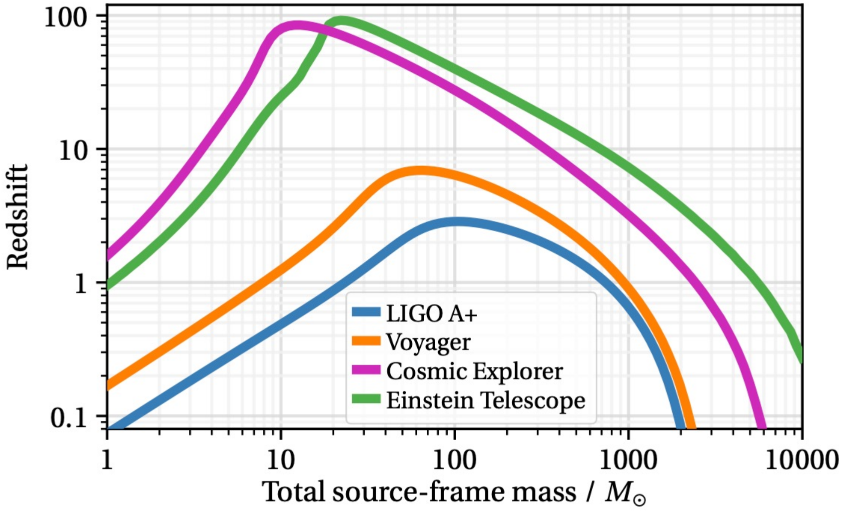


Why a 3G of GW detectors?



REWORKED IMAGE FROM [FONTE ASTRO-PH 2109.09882]



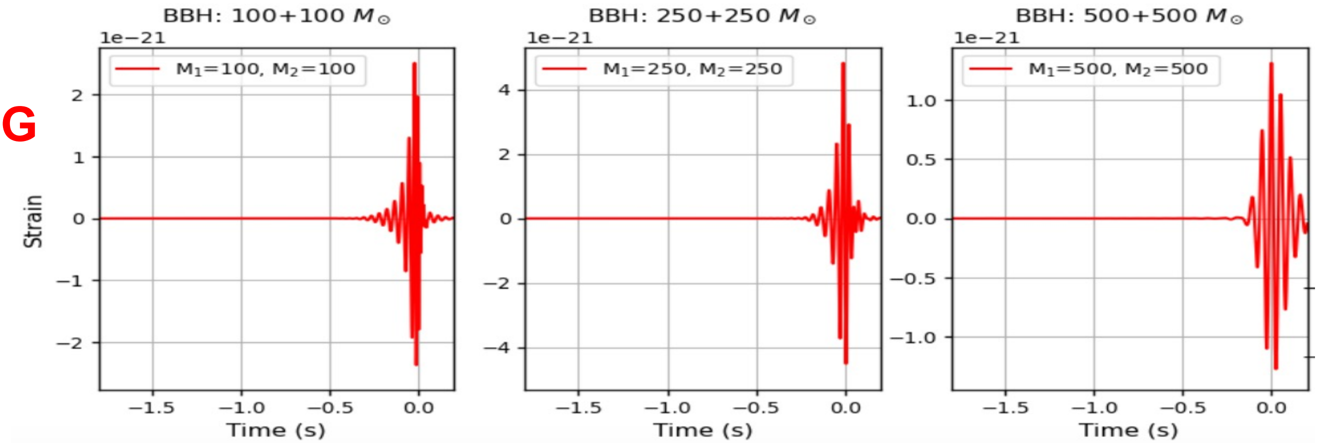


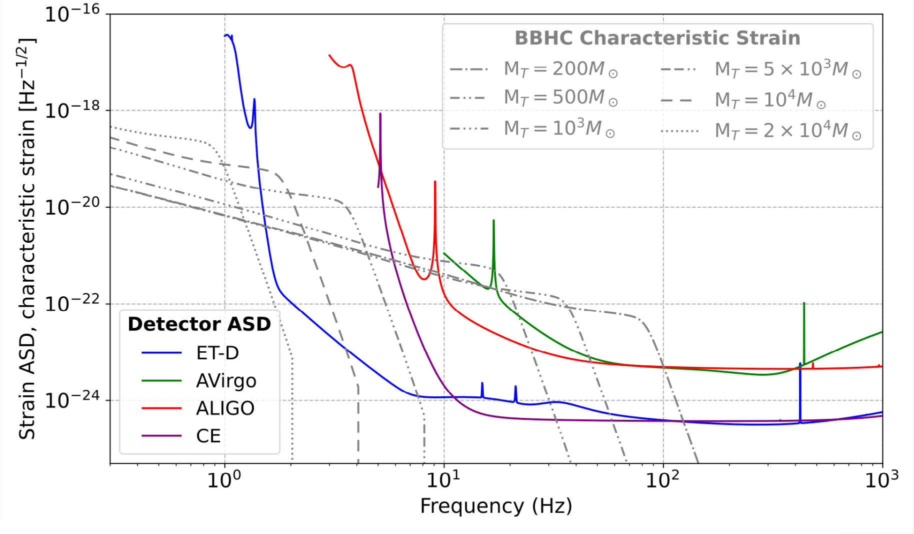
GW transients associated with IMBHs in 3G vs 2G detectors

Third-generation gravitational wave observatories can observe the inspiral phase of merging IMBHs up to $few\times10^3 M_\odot$, and also explore their rates through cosmic age (i.e. at different redshift)

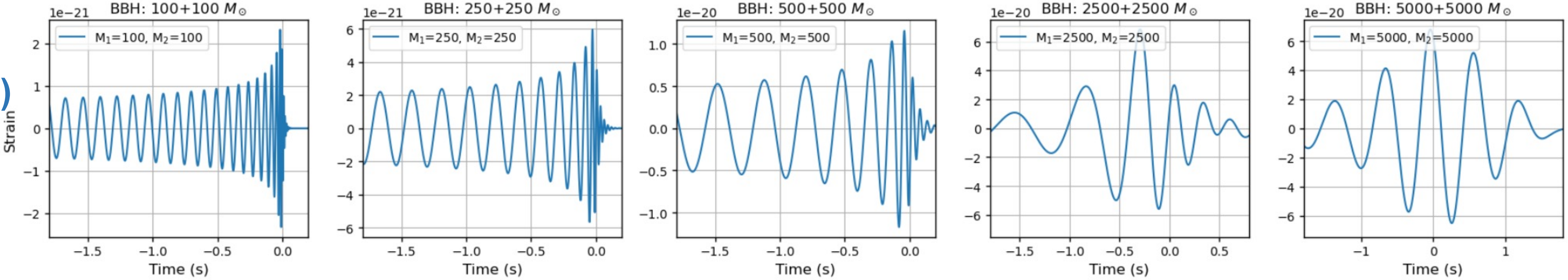
- All events below use IMRPhenomD and are located at 1 Gpc
- ET sensitivity for triangular configuration with 10 KM long arms per detector

2-G





3-G (ET)



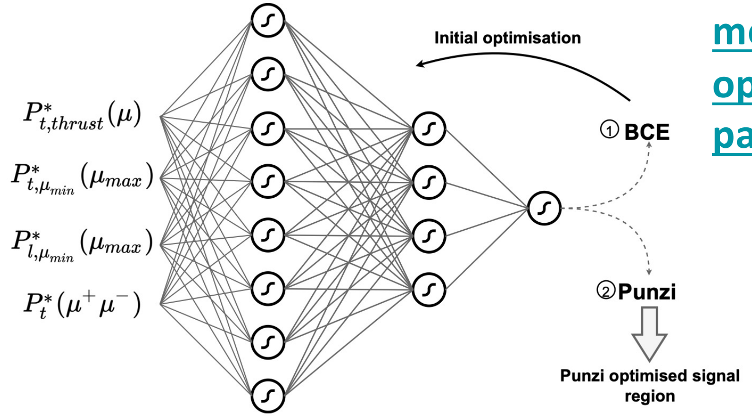
Machine learning/AI methods developed for HEP can be adapted to GWs

Künstliche Intelligenz sucht unbekannte Teilchen

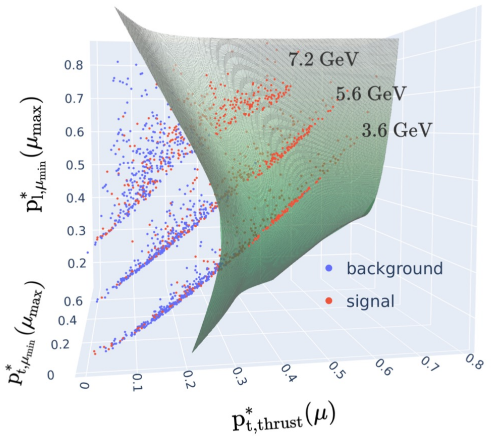
Web | 21.02.2022 12:58

(Bild: ©putilov_denis - stock.adobe.com)

Wenn in Beschleunigern Teilchen mit hoher Energie aufeinanderprallen, entstehen unzählige Zerfallsprodukte und bei deren Registrierung riesige Datenmengen. Deren Analyse ist komplex und zeitaufwändig. Daher lassen Physiker der Österreichischen Akademie der Wissenschaften (ÖAW) nun Künstliche Intelligenz (KI) nach neuen, bisher unbekannten Teilchen suchen, berichten sie im Fachjournal „European Physical Journal C".



Punzi-net



Eur. Phys. J. C **82**, 121 (2022) :
[Punzi-loss: A non-differentiable metric approximation for sensitivity optimisation in the search for new particles]

Loss-function and NN architecture we developed to search for invisible decays of new particles

Low-latency machine learning on FPGA

The Neural Network First-Level Hardware Track Trigger of the Belle II Experiment [ArXiv 2402.14962] (Accepted in NIM A)

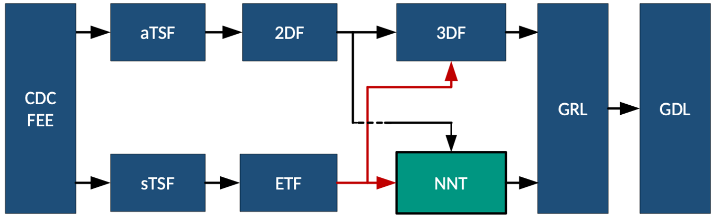
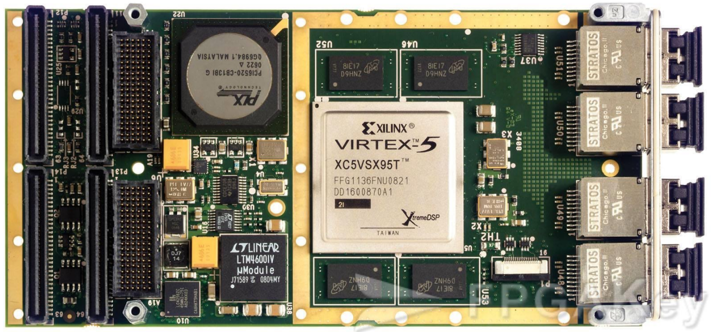


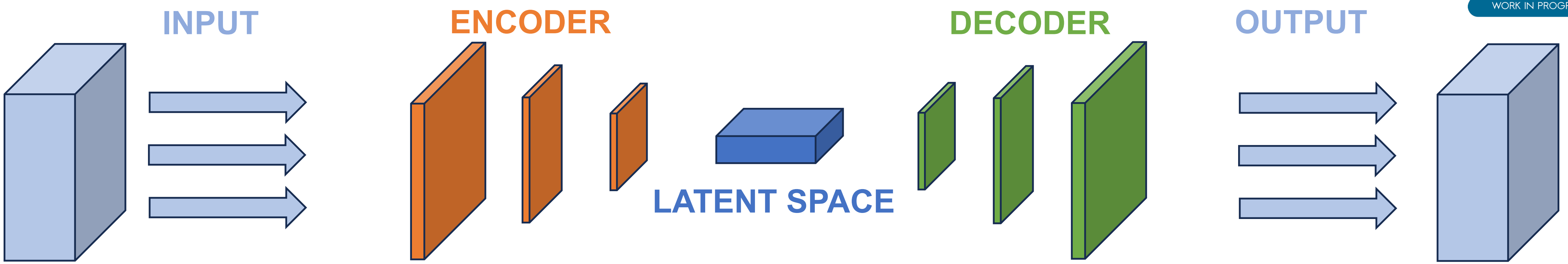
Figure 6: Integration of the neural trigger into the CDC trigger system. The various units are explained in the text. The unit "3DF", short for "3D fitter", has not been implemented and is therefore not discussed further.



Belle II data rate is few GB/s

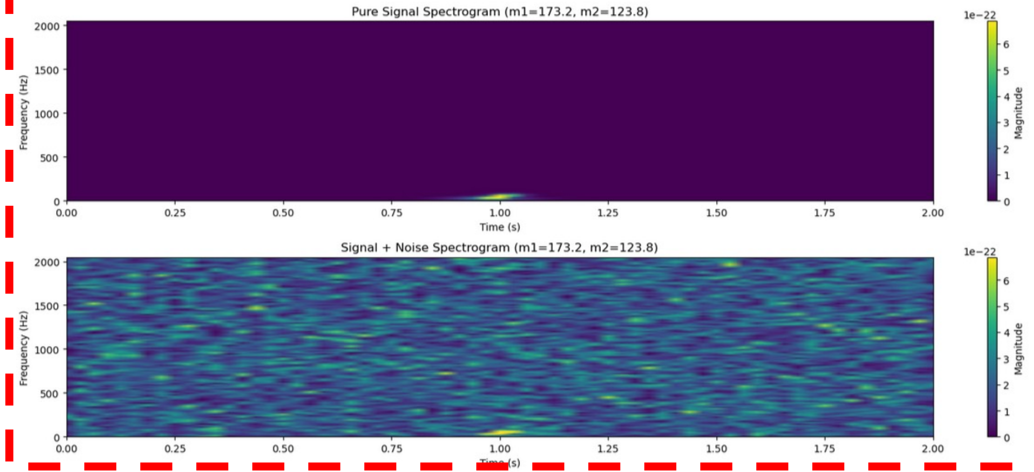
MADGrav: **M**ultilayer **A**nomaly **D**etection for **GRAV**itational waves science

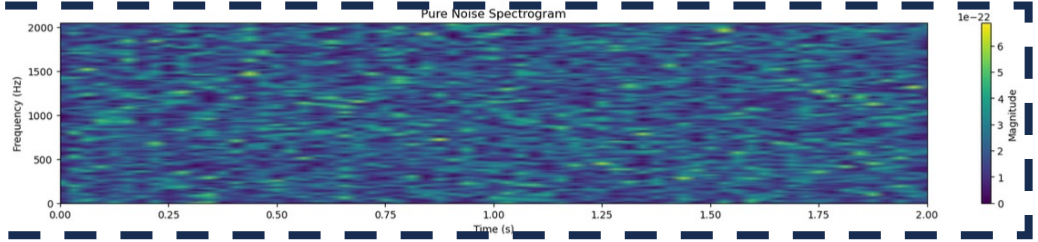
WORK IN PROGRESS

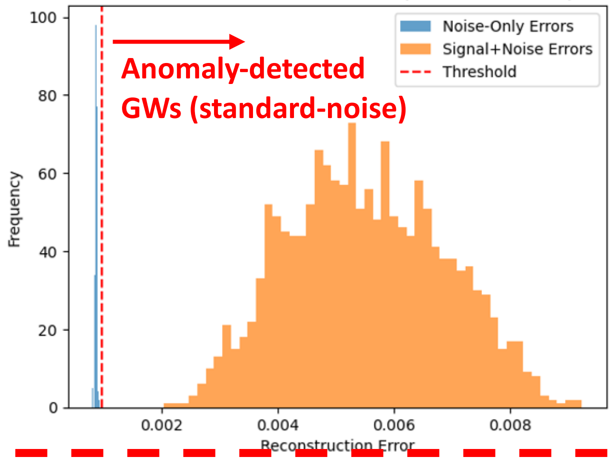


MADGrav training with noise

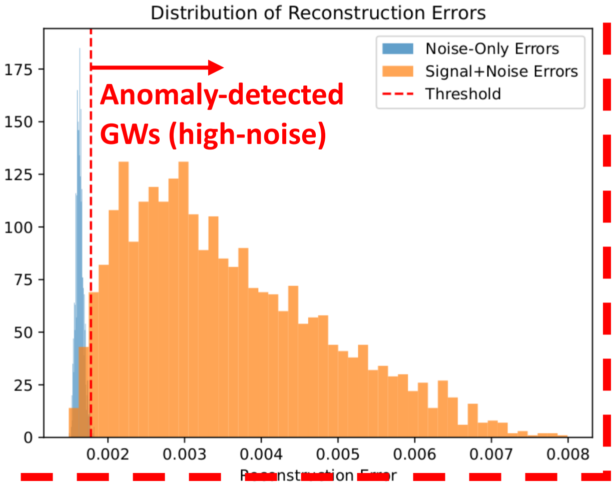
MADGrav test with noise + injected signals







Anomaly-detected GWs (standard-noise)



Anomaly-detected GWs (high-noise)

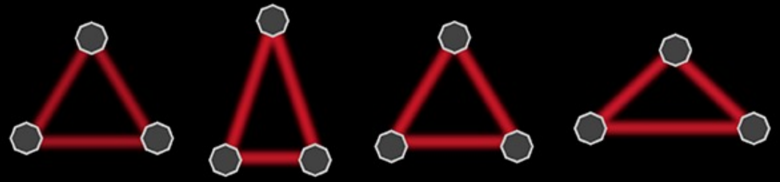
Tests using ET MDC 1 for BBH injections are ongoing now ($\varepsilon = 85 - 90\ \%$)

-> Plan to integrate this or advanced models on FPGA (8-20 MB/s compressed-uncompressed)

LISA - LASER INTERFEROMETER SPACE ANTENNA

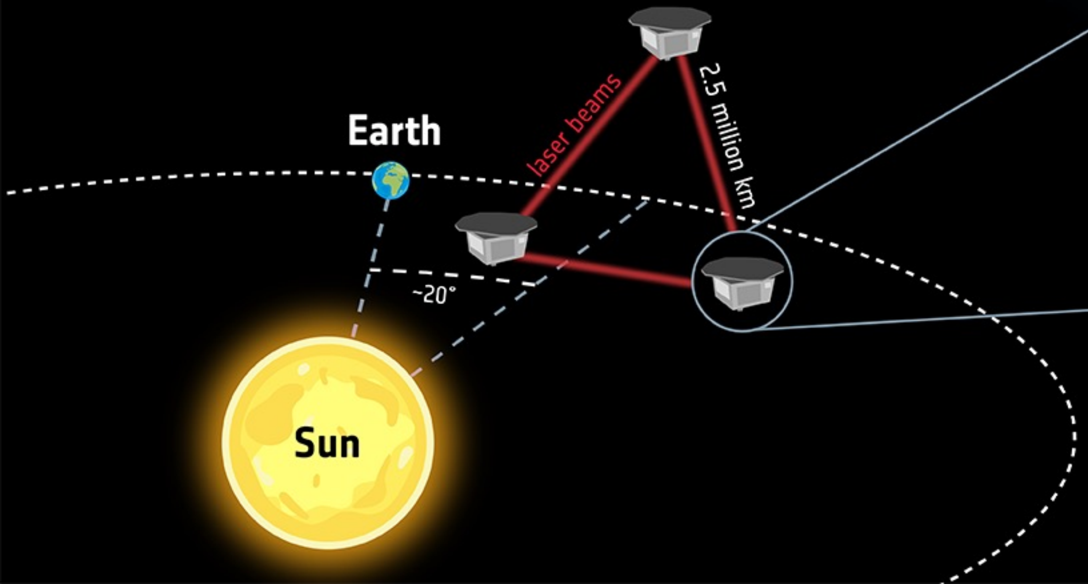
Gravitational waves are ripples in spacetime that alter the distances between objects. LISA will detect them by measuring subtle changes in the distances between **free-floating cubes** nestled within its three spacecraft.

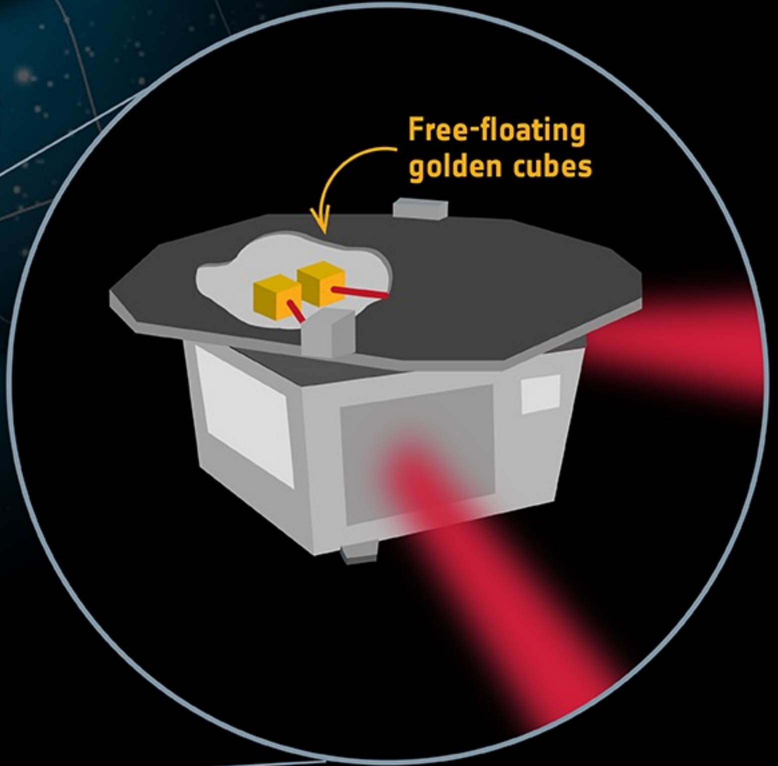
③ **identical spacecraft** exchange **laser beams**. Gravitational waves change the distance between the **free-floating cubes** in the different spacecraft. This tiny change will be measured by the laser beams.



* *Changes in distances travelled by the laser beams are not to scale and extremely exaggerated*

Powerful events such as **colliding black holes** shake the fabric of spacetime and cause gravitational waves

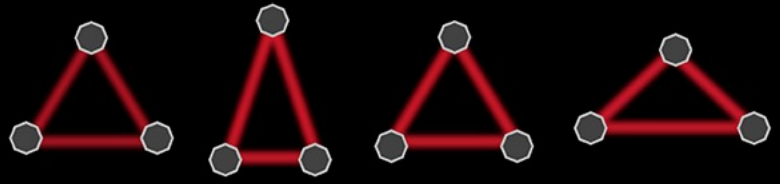




LISA - LASER INTERFEROMETER SPACE ANTENNA

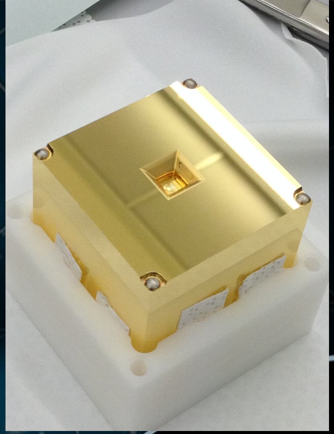
Gravitational waves are ripples in spacetime that alter the distances between objects. LISA will detect them by measuring subtle changes in the distances between **free-floating cubes** nestled within its three spacecraft.

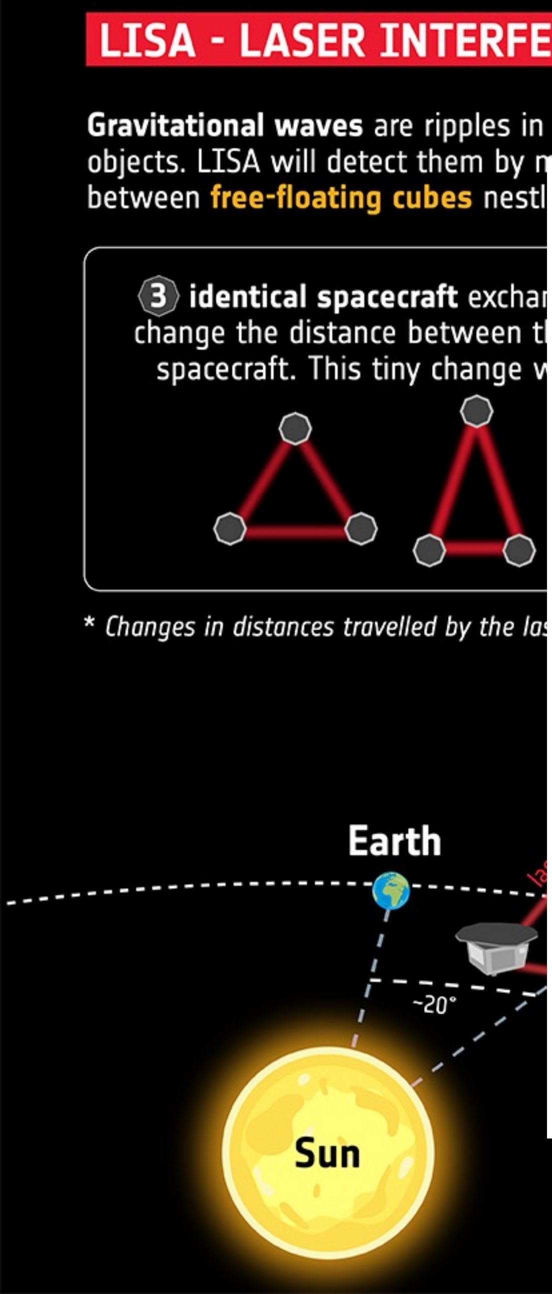
③ **identical spacecraft** exchange **laser beams**. Gravitational waves change the distance between the **free-floating cubes** in the different spacecraft. This tiny change will be measured by the laser beams.

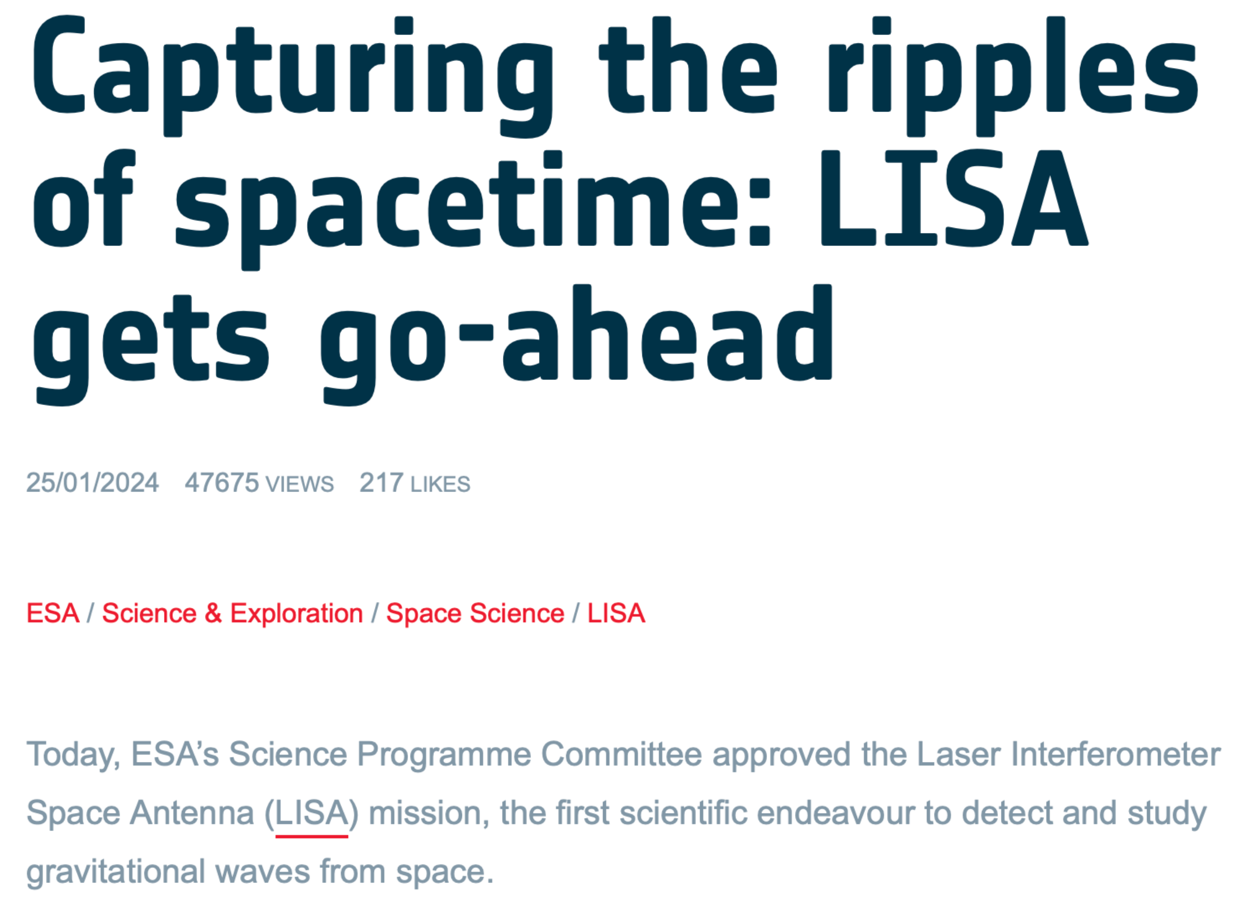


** Changes in distances travelled by the laser beams are not to scale and extremely exaggerated*

Powerful events such as **colliding black holes** shake the fabric of spacetime and cause gravitational waves





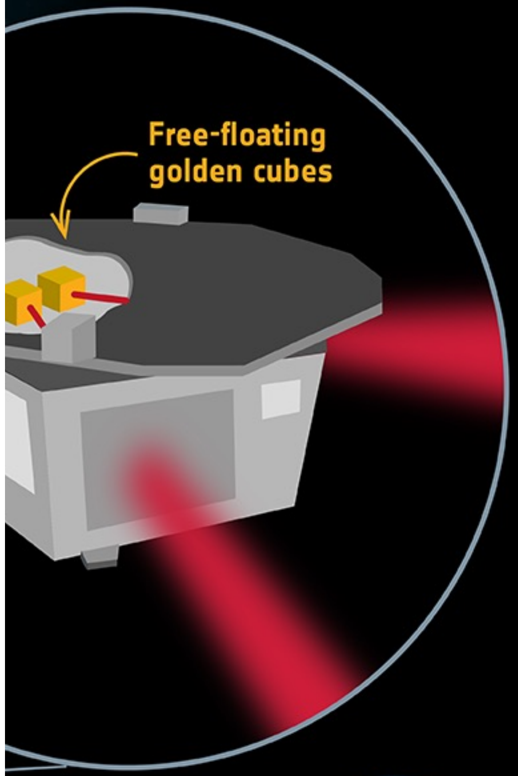


Capturing the ripples of spacetime: LISA gets go-ahead

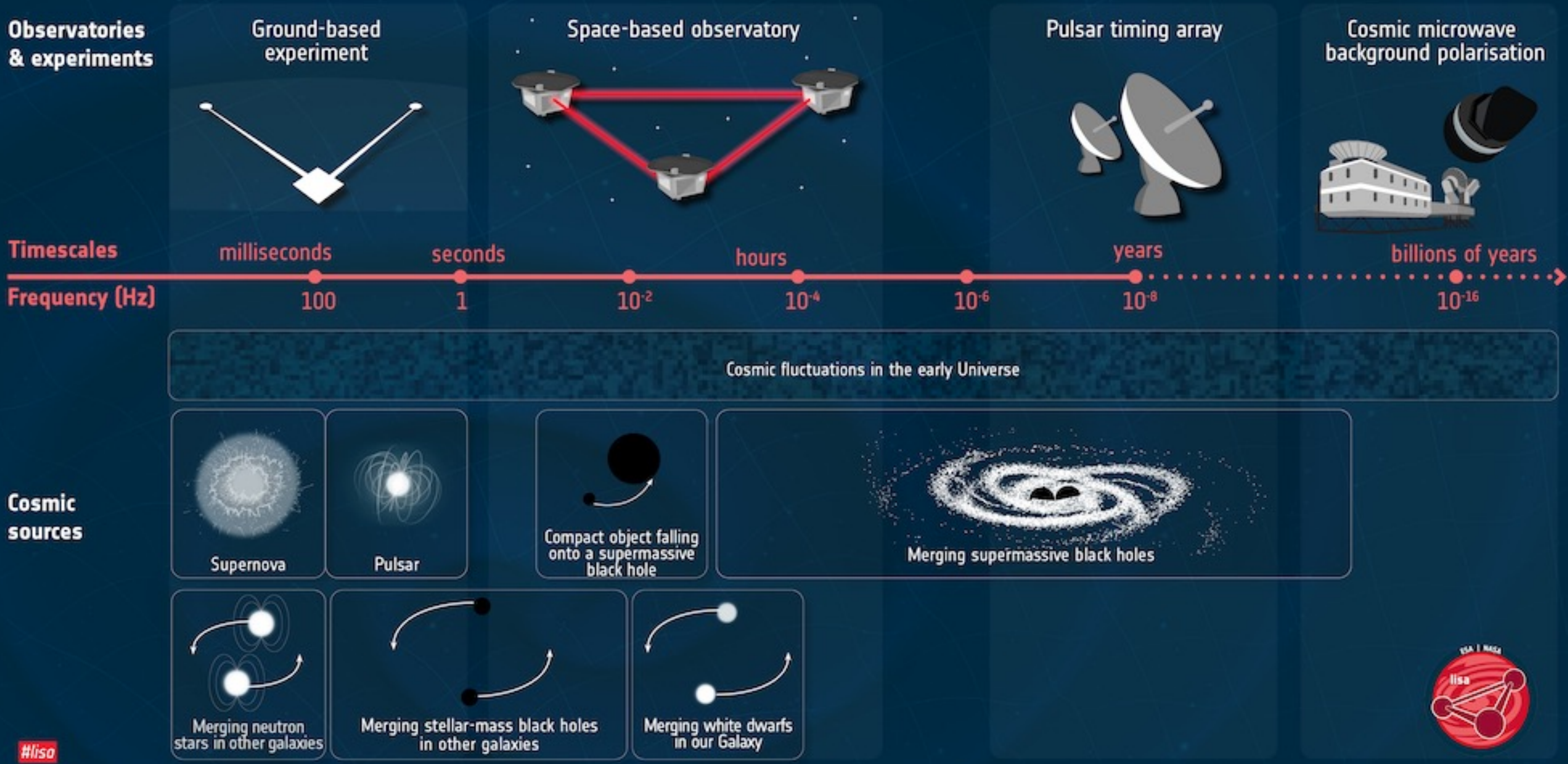
25/01/2024 47675 VIEWS 217 LIKES

ESA / Science & Exploration / Space Science / LISA

Today, ESA's Science Programme Committee approved the Laser Interferometer Space Antenna (LISA) mission, the first scientific endeavour to detect and study gravitational waves from space.



THE SPECTRUM OF GRAVITATIONAL WAVES



Observatories & experiments

Ground-based experiment

Space-based observatory

Pulsar timing array

Cosmic microwave background polarisation

Timescales

milliseconds

seconds

hours

years

billions of years

Frequency (Hz)

100

1

10^{-2}

10^{-4}

10^{-6}

10^{-8}

10^{-16}

Cosmic fluctuations in the early Universe

Cosmic sources

Supernova

Pulsar

Compact object falling onto a supermassive black hole

Merging supermassive black holes

Merging neutron stars in other galaxies

Merging stellar-mass black holes in other galaxies

Merging white dwarfs in our Galaxy

#lisa

THE SPECTRUM OF GRAVITATIONAL WAVES

Observatories & experiments

Grou
exp

Timescales

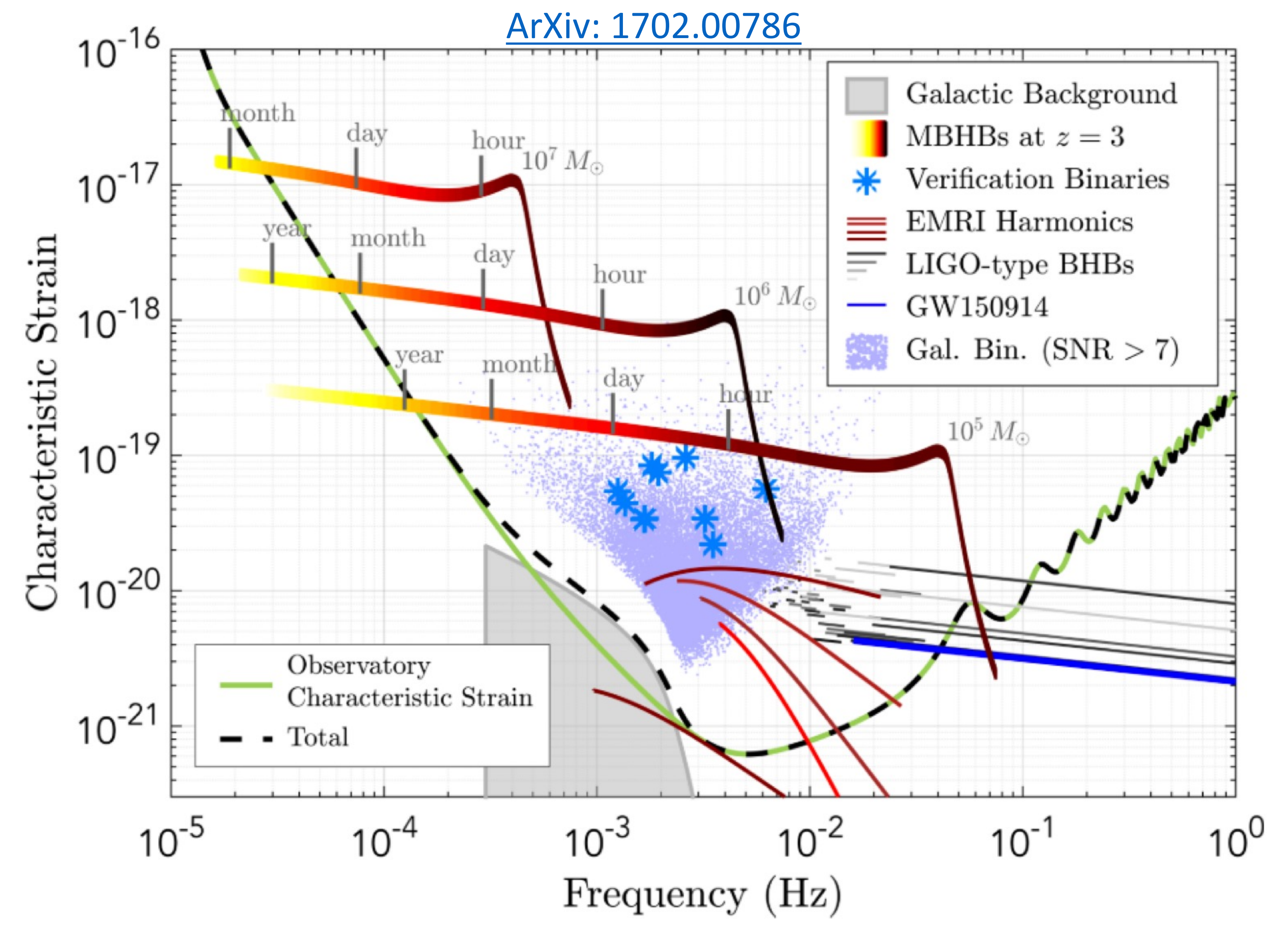
milliseco

Frequency (Hz)

Cosmic sources

Supernova

ArXiv: 1702.00786



Merging neutron stars in other galaxies

Merging stellar-mass black holes in other galaxies

Merging white dwarfs in our Galaxy

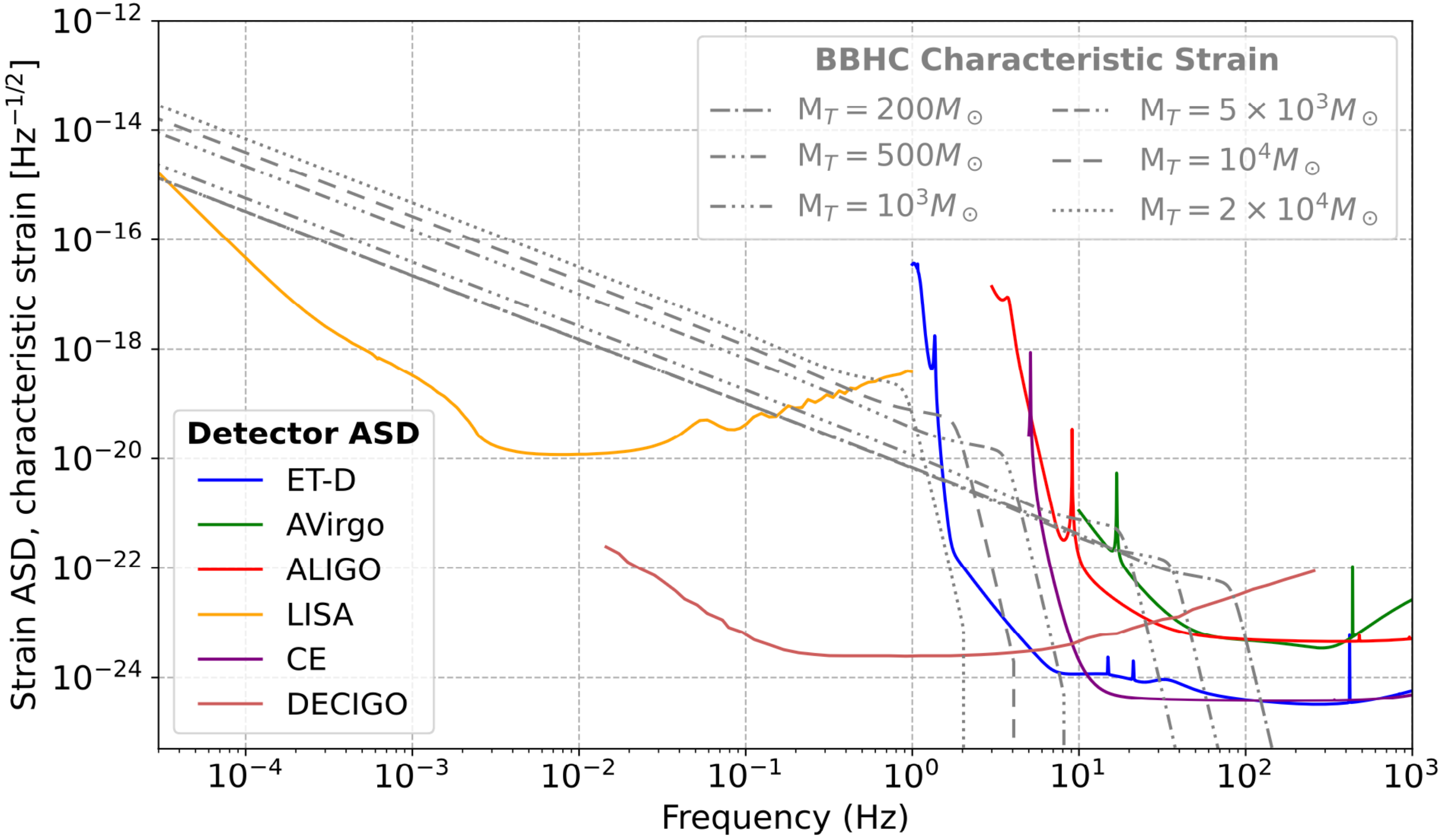
Cosmic microwave background polarisation

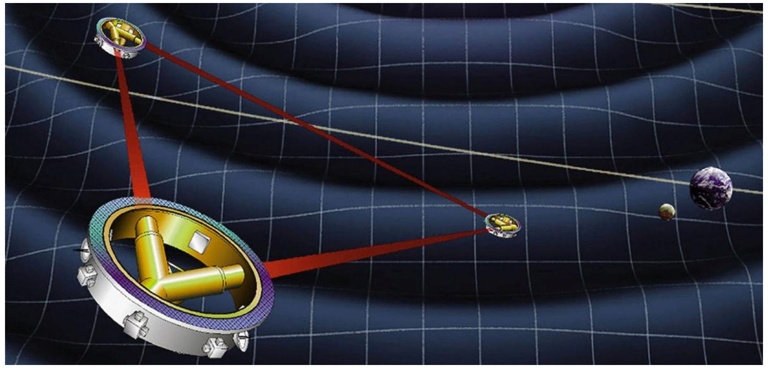
billions of years

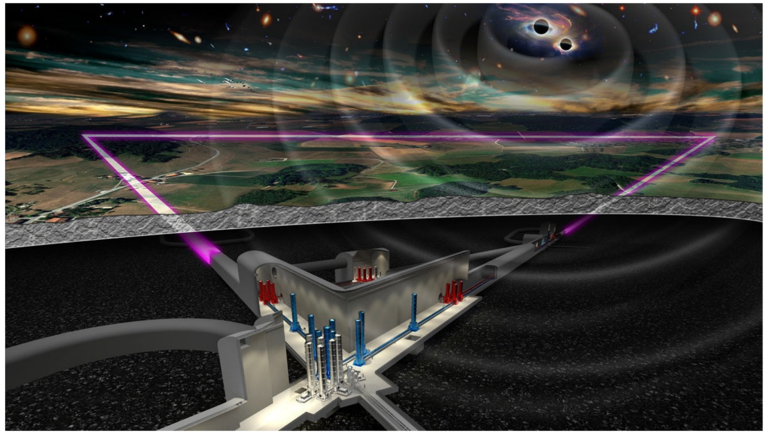
10^{-16}

#lisa

GW transients associated with IMBHs in ground- Vs. space-based GW observatories







From Peters' formula (1964)

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} \qquad t = \frac{5}{256}\left(\frac{c^3}{GM_c}\right)^{5/3}\left(\frac{1}{\pi f}\right)^{8/3}$$

→

IMBHs' coalescence will be for years within the sensitive region of LISA (inspiral/ inspiral+merger) who can in turn provide details to ET (merger): multiband GW studies!

Not only **complementarity**, but **interplay** between **ET** and **LISA**

If you are interested in furthering your (students') knowledge

ISAPP International School on AstroParticle Physics

ESI Erwin Schrödinger International Institute for Mathematics and Physics

Gravitational Waves
from theory
to detection
7–18 july 2025
vienna, austria

Confirmed Lecturers:

- Clifford M. Will (University of Florida)
- Michela Mapelli (University of Heidelberg)
- Tania Regimbau (Annecy, LAPP)
- Costantino Pacilio (University of Milano Bicocca)
- Jessica Steinlechner (University of Maastricht)
- Elena Cuoco (Bologna University)
- Lijing Shao (KAVLI - Peking University)
- Noemi Frusciante (University of Napoli)
- Chiara Mingarelli (Yale University)
- Gideon Koekoek (University of Maastricht)
- Haocun Yu (University of Vienna)

Registration is open
https://indico.cern.ch/event/1427417/overview

Outline

- I hope I could convince you how exciting the field of gravitational wave research is and how its interplay with other aspects of fundamental research will allow progress in our understanding of the Universe across scales

Thank you for your attention!

Backup material

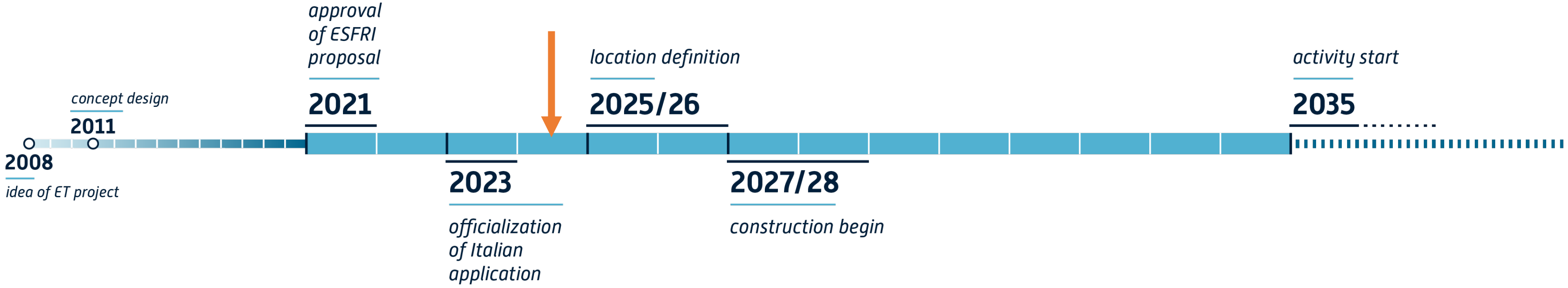
Activities at HEPHY have recently started

- HEPHY participate in ET, in collaboration with the group of Prof. M. Mapelli from Heidelberg University
  - Contributions to the Observational Science Board (various divisions).
  - Participation in the ET bluebook (on ArXiv in September).
  - Topics: intermediate-mass black holes, (fast) alert generation, population studies, etc.

- A local ET research unit in Vienna is planned and will be formed in the future
  - synergies possible with various Austrian institutes (ISTA, Leoben, Linz, Uni Wien, Uni Innsbruck).
  - synergies with other HEPHY groups (electronics, machine learning).

- HEPHY will also join Virgo in the coming months and participate in the analysis of data

- ISAPP 2025 Summer School on "Gravitational waves, from theory to detection" will take place in Vienna in July 2025.



2008
idea of ET project

concept design
2011

approval of ESFRI proposal
2021

2023
officialization of Italian application

location definition
2025/26

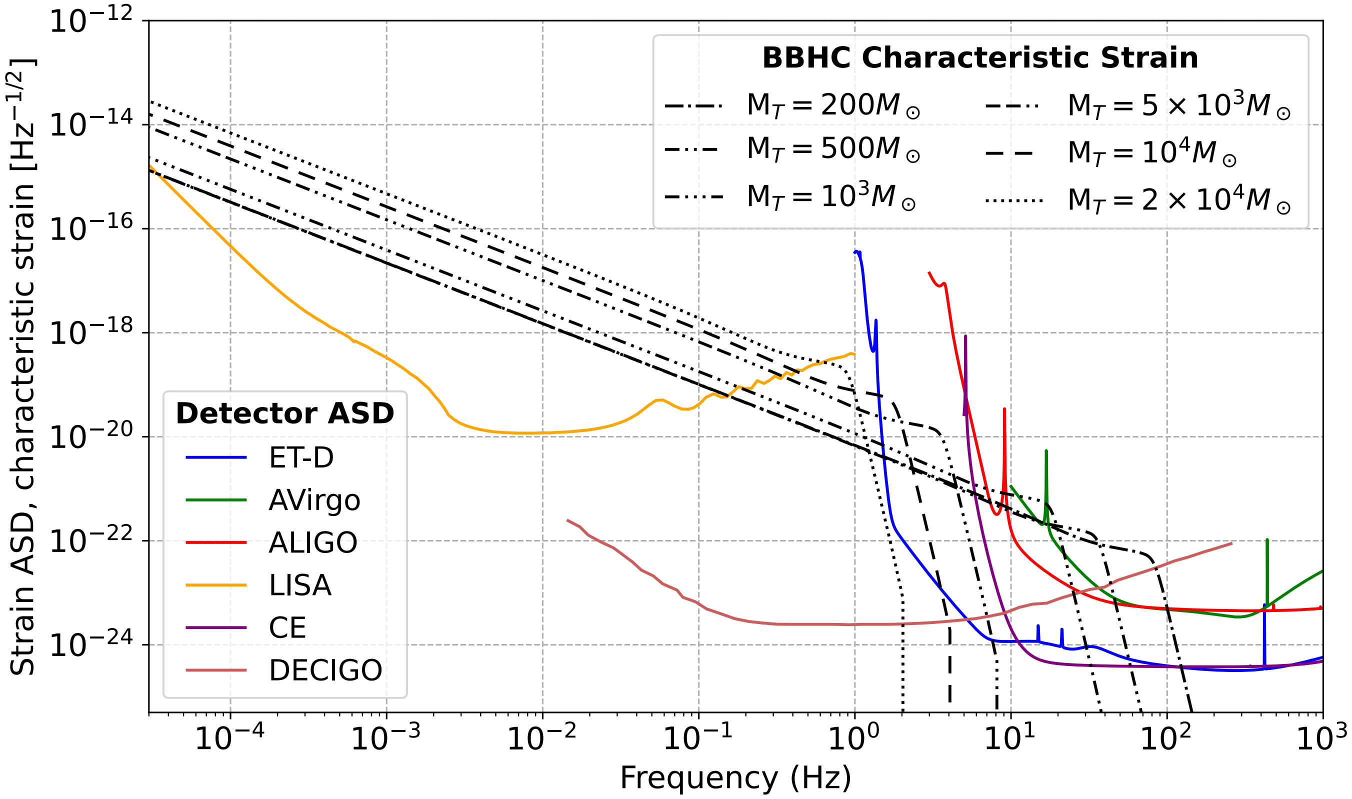
2027/28
construction begin

activity start
2035

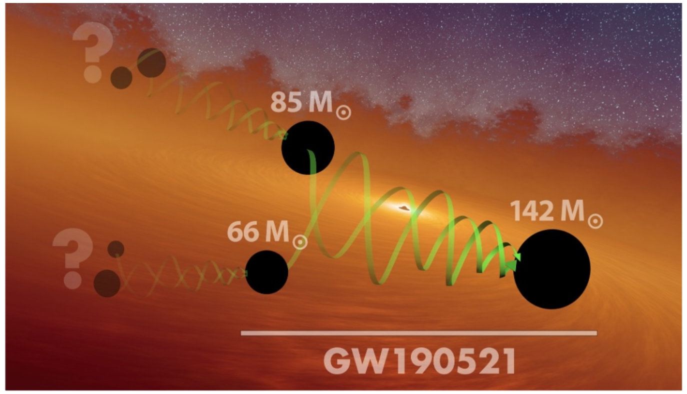
TOTAL INVESTMENT 1.912.0 million euros

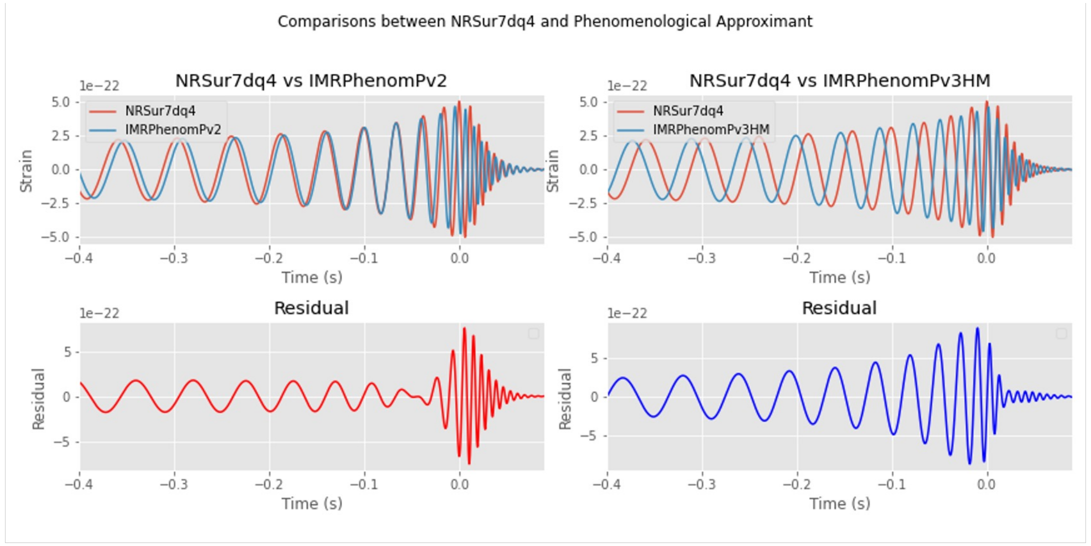
IMBH GW signals and detector sensitivities: mass and distance insights

Preliminary study, uses **IMRPhenomD** as waveform approximant.
Unofficial sensitivity curves obtained from https://dcc.ligo.org/LIGO-T1500293/public



The inspiral phase of IMBHs' coalescence will be for years within the sensitive region of LISA who can in turn provide details to ET: multiband GW studies!





Preliminary results presented at the ET Symposium in Maastricht, May 6-10

Different approximants produce very different waveforms, with differences as large as the original GW amplitude. Higher order modes becomes not negligible.

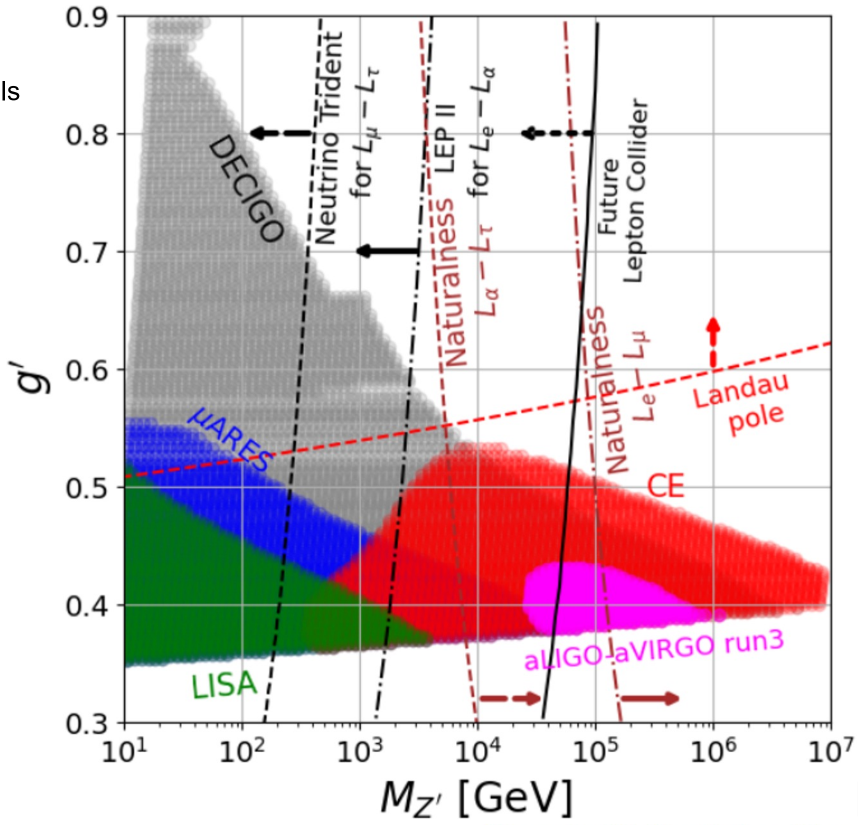
Gravitational waves probing fundamental physics, leptophilic Z’

First-order phase transition if scalar sector is conformally invariant:

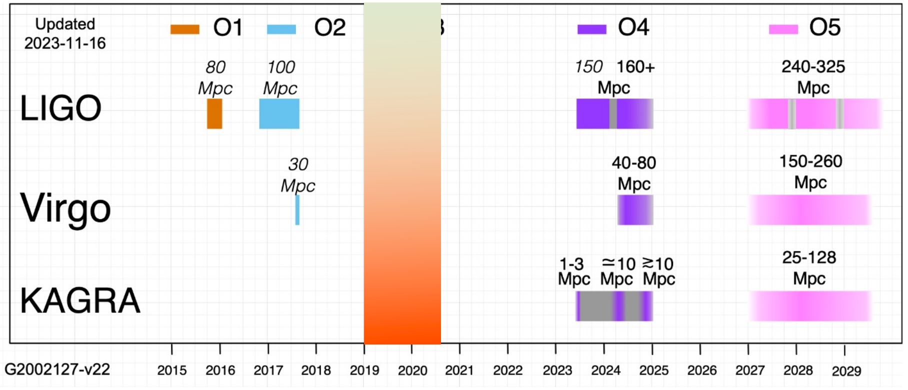
$$V_{\rm tree} = \lambda_H (H^\dagger H)^2 + \lambda(\Phi^\dagger\Phi)^2 - \lambda'(\Phi^\dagger\Phi)(H^\dagger H)\,.$$

Leptophilic Dark Portals

Bhupal Dev



[Dasgupta, BD, Han, Padhan, Wang, Xie, 2308.12804 (JHEP ’23)]



This data used

We are here

Enhanced sensitivity with already available new set of data

- Heavy boson fields might be responsible for phase transitions, strong enough to generate gravitational waves → stochastic, not observed so far → set upper limits
- New, complementary, way with respect to typical HEP measurements with even more accessible parameter space.
- More analysis methodologies and results can be expected in the very near future.