Multi-messenger Astronomy with current and future gravitational-wave facilities

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INTEGRAL Workshop 2024
22 years of INTEGRAL catching results and discoveries

ESA/ESAC, Madrid, Spain, October 21-24, 2024
https://www.cosmos.esa.int/web/integral-workshop-2024

Universitat de les Illes Balears
IAC3 Institute of Applied Computing & Community Code.

A new window onto the Universe

The history of Astronomy: new bands of the EM spectrum opened --> major discoveries!

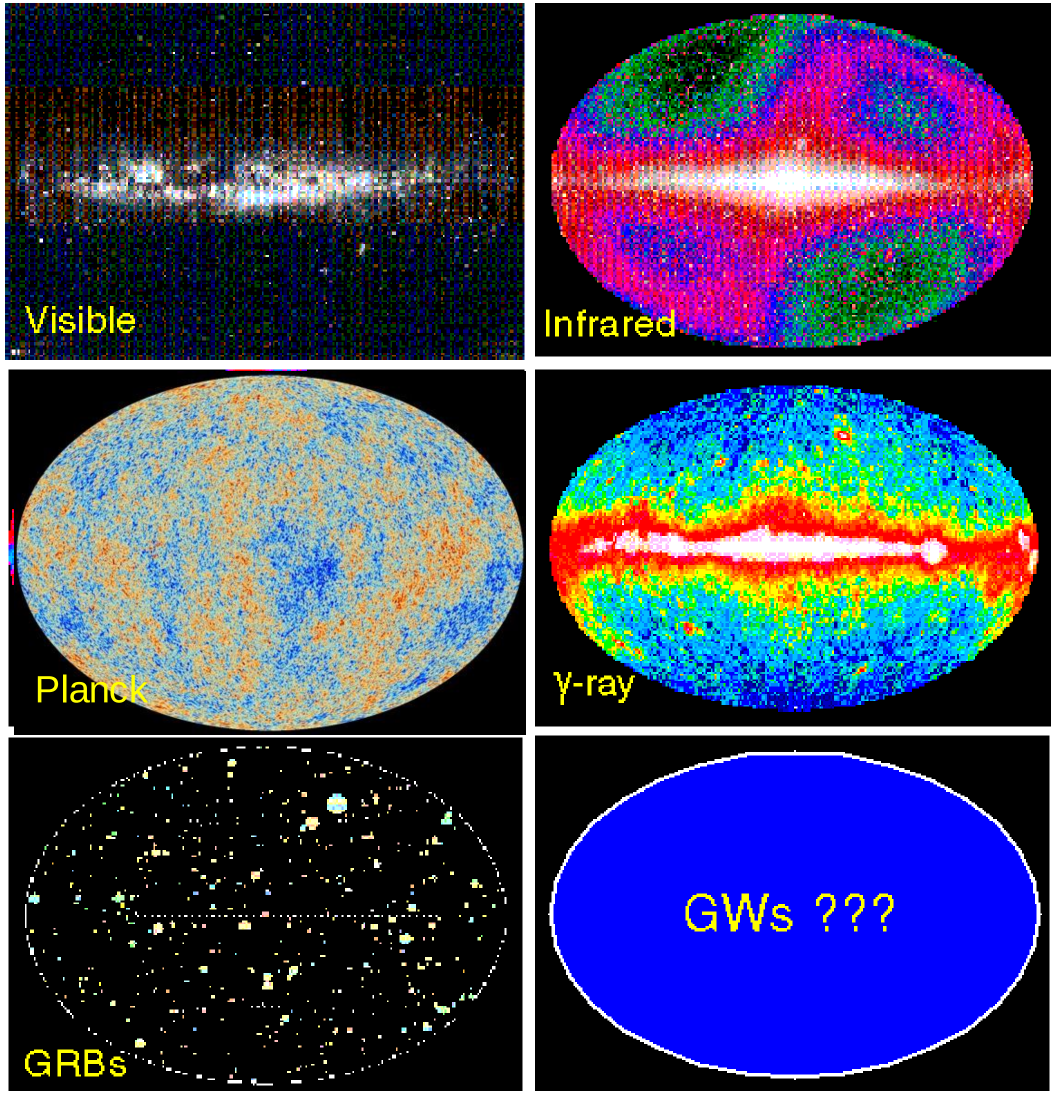
GWs aren't just a new band, they're a new spectrum, with very different and complementary properties to EM waves.

Distortions of space-time (not in space-time), propagating at the speed of gravity (light)

Generated by accelerating mass/energy, e.g., coherent motion of huge masses; not vibrations of electrons in atoms

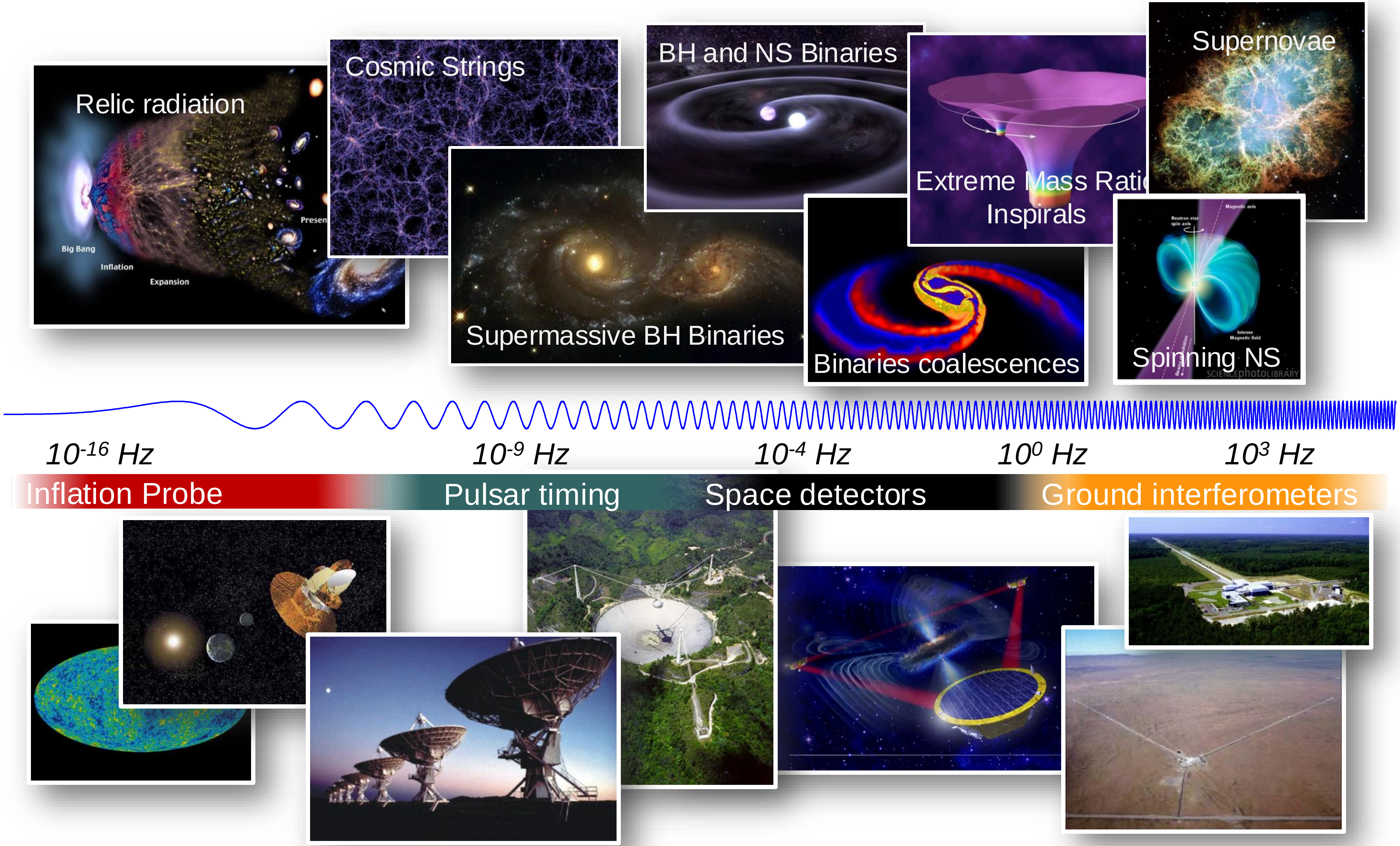
GWs are ~immune to scattering / obscuration / absorption… not immune to gravitational lensing

Detectors are rulers as opposed to buckets.
Sensitive to amplitude instead of power— signal falls off as 1/r.
Direct measure of Luminosity Distance

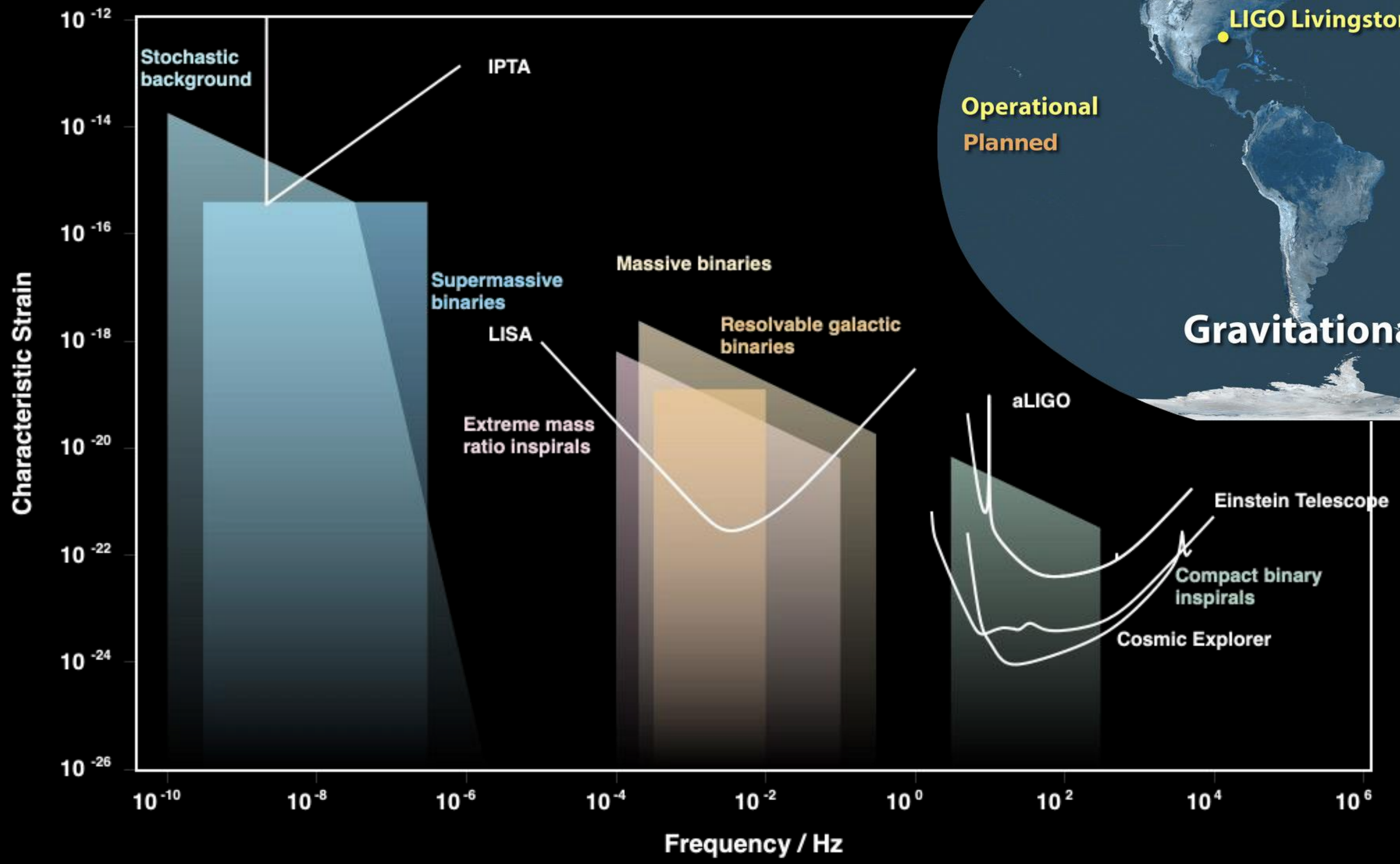


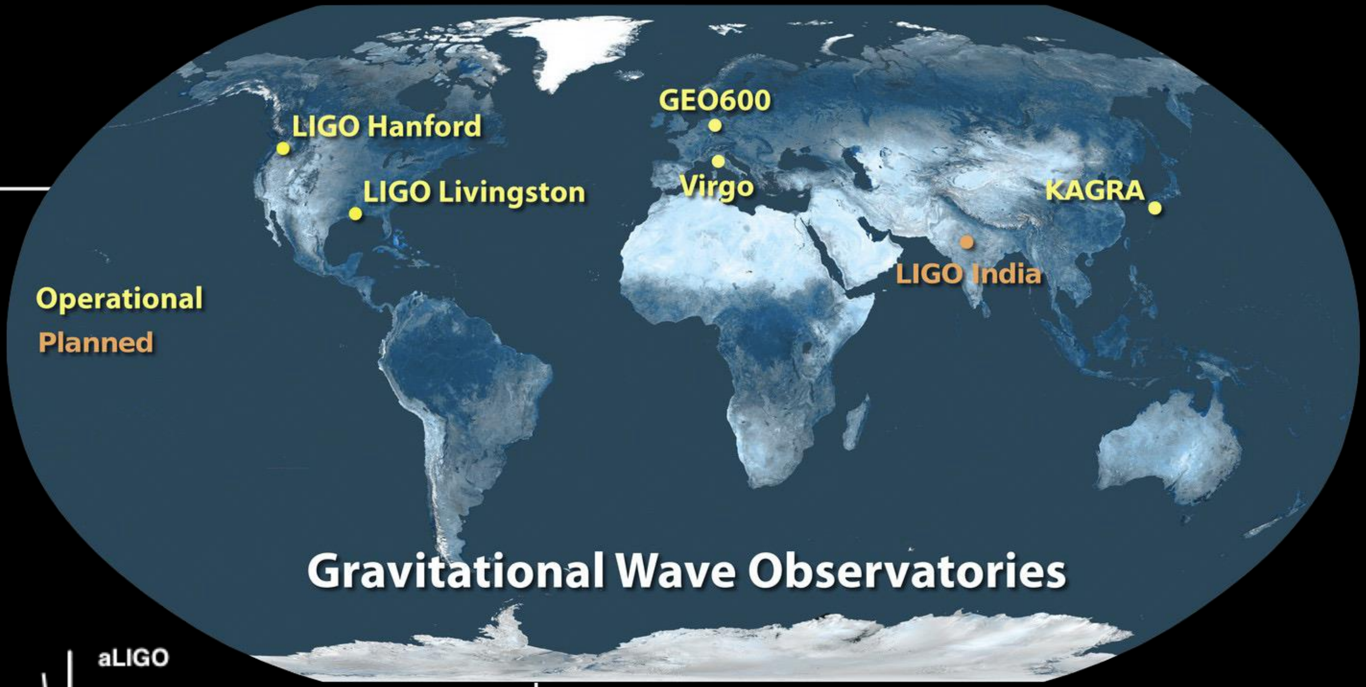
Gravitational waves offer a unique probe into some of the most extreme systems in the Universe. They originate from merging black holes; from binary stars orbiting at close to the speed of light; from supernovae, and from the Big Bang itself.

Gravitational Wave Spectrum



Our observational landscape

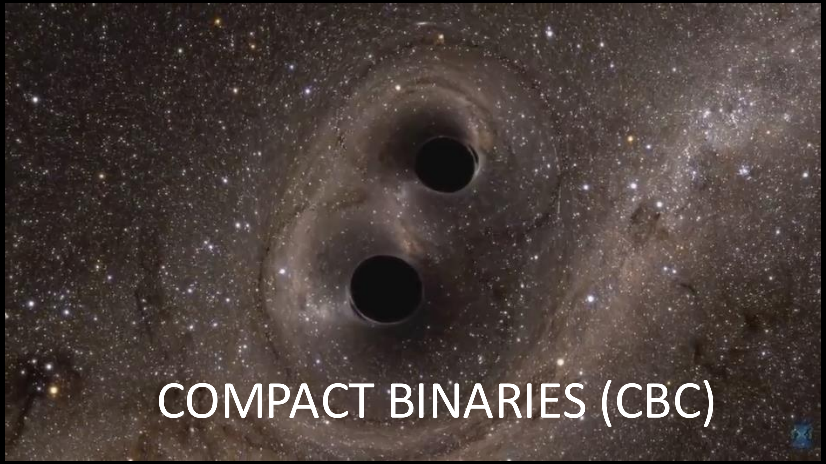


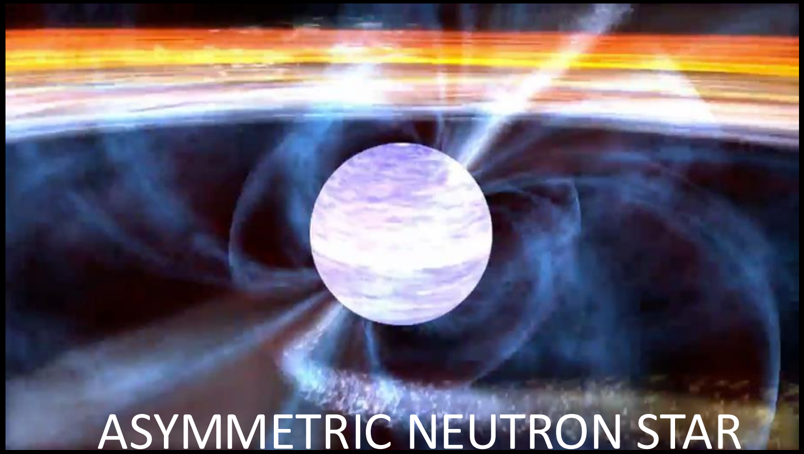


Potential Gravitational Wave Sources

TRANSIENT

PERSISTENT





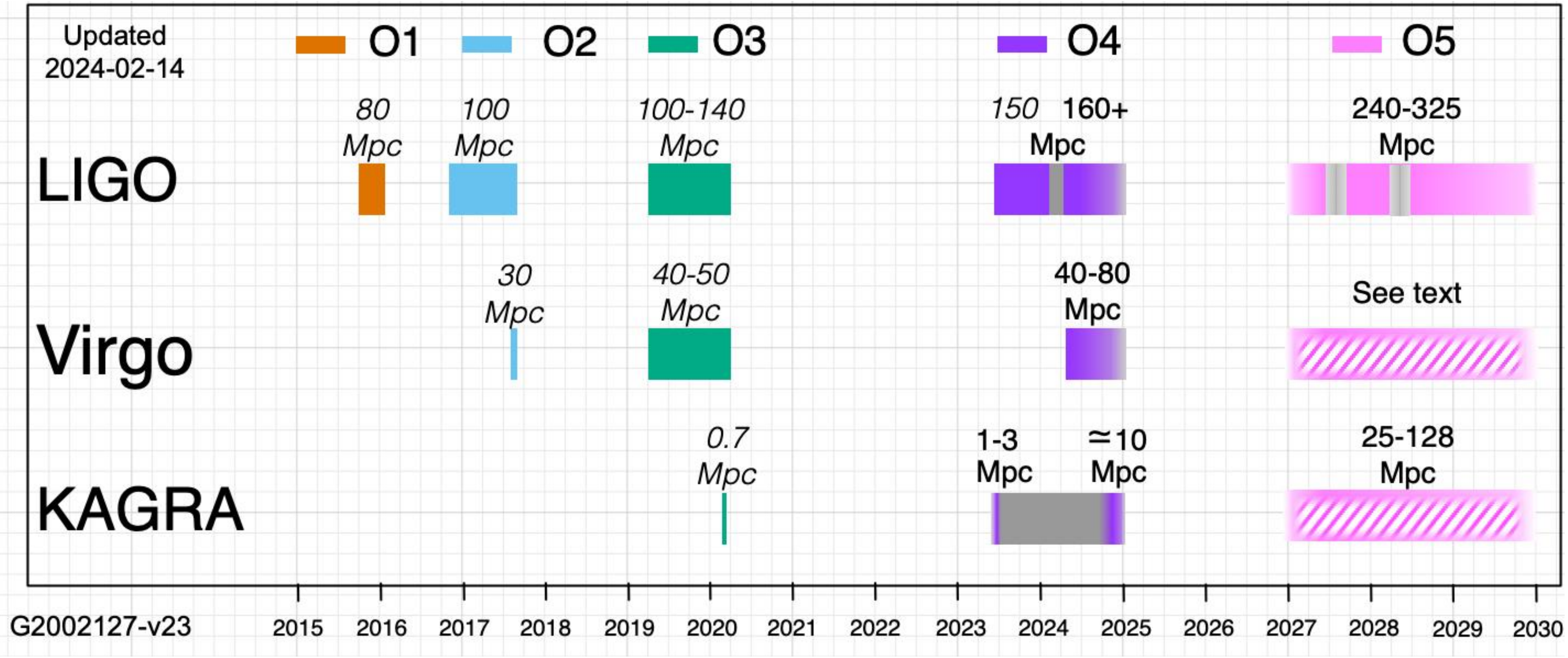
MATCHED FILTER

UNMODELED

LVK current and future observing runs:

Important detector improvements between O3 and O4
- Higher laser power
- Frequency-dependent squeezing
- Noise reduction & duty cycle improvements
- + Improvements to processing of data for use by searches

Not comprehensive! These are just some highlights.



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

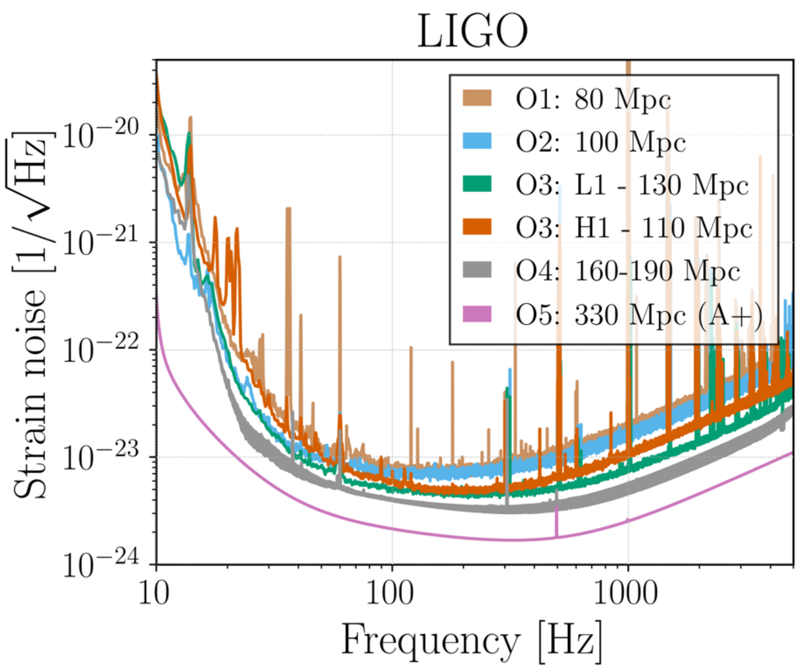
O4 observing run:

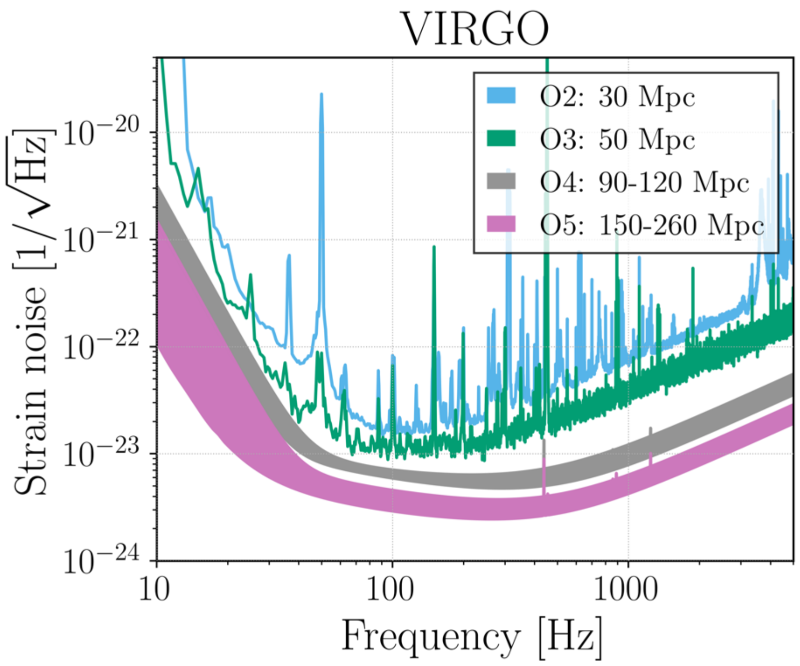
O4a: May 24th 2023- January 16th 2024
O4b: April 10th 2024- January 23rd 2025
O4c: January 24th 2025- June 9th 2025

KAGRA delayed due to 7.6 magnitude earthquake on Jan 1, 2024

The GW network will continue improving in sensitivity...
- ...and thanks to that 1/r thing, make substantial improvements in sensitive volume...
- ...which means more opportunity for multi-messenger events

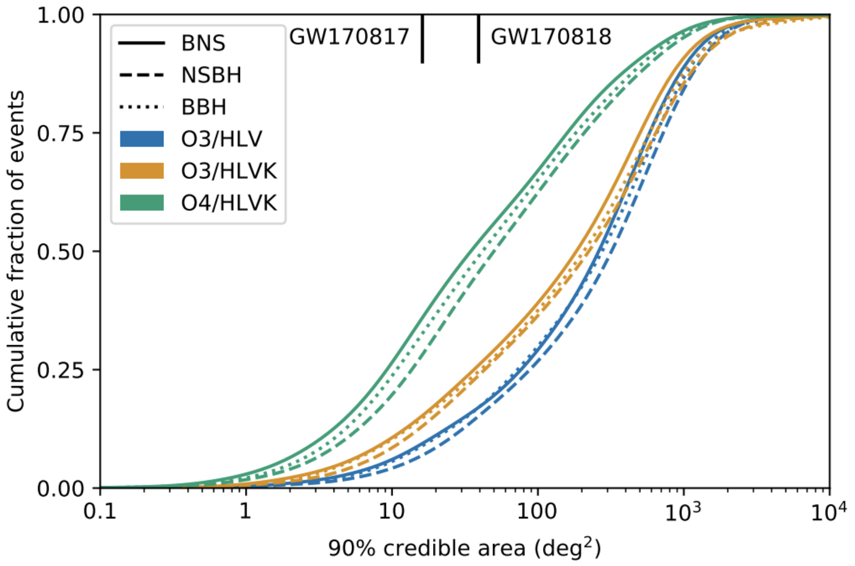
LVK- Observing runs

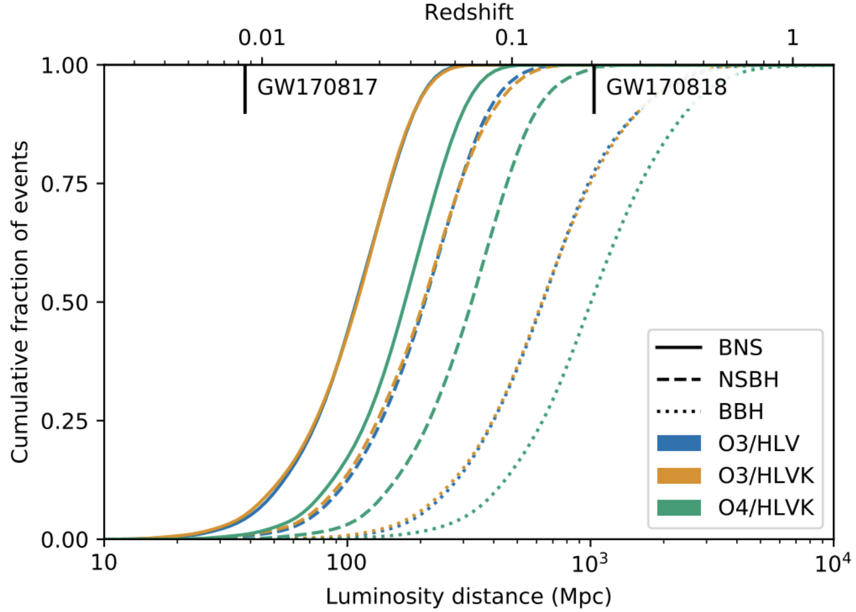




- Events will also be better localized thanks to
  - increased sensitivity of detectors
  - increased capabilities of the global network

- Current forecasts for localization suggest that ~50% of BNS to be localized w/in ~30 sq deg.





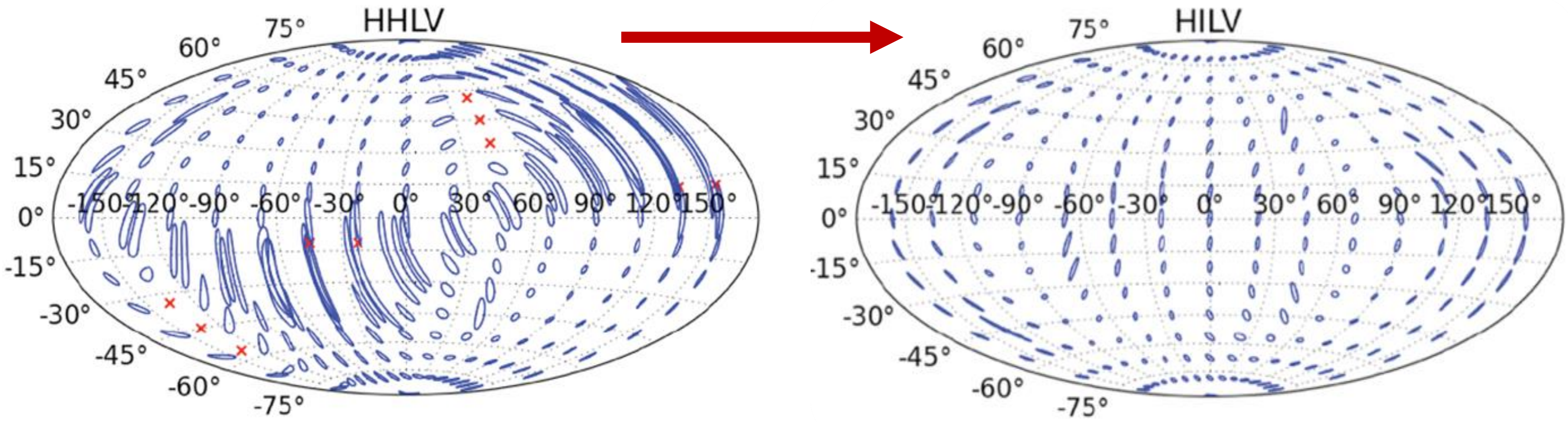
Credit: LIGO-P1200087

Impact of LIGO-India on Localizing Events

Adding LIGO-India to the Hanford-Livingston-Virgo-KAGRA network helps localization, but additional benefit comes from increasing the fraction of the time when there are 4 or 3 sensitive detectors operating

e.g., 80% duty cycle sounds good, but $(0.8)^5 = 0.33$; would have <u>4</u> detectors working 41% of the time

Example: improvement from going from 3 sites to 4:

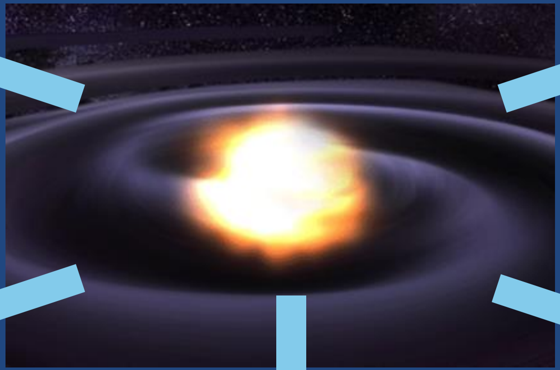


Red crosses denote regions where the network has blind spots

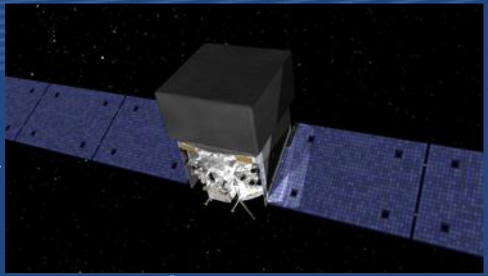
Fairhurst 2011

Multi-messenger Astronomy with Gravitational Waves

Binary Neutron Star Merger



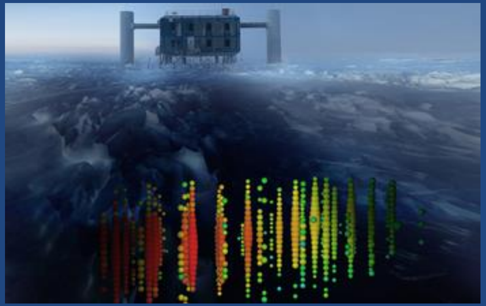
Gravitational Waves



X-rays/Gamma-rays

Visible/Infrared Light

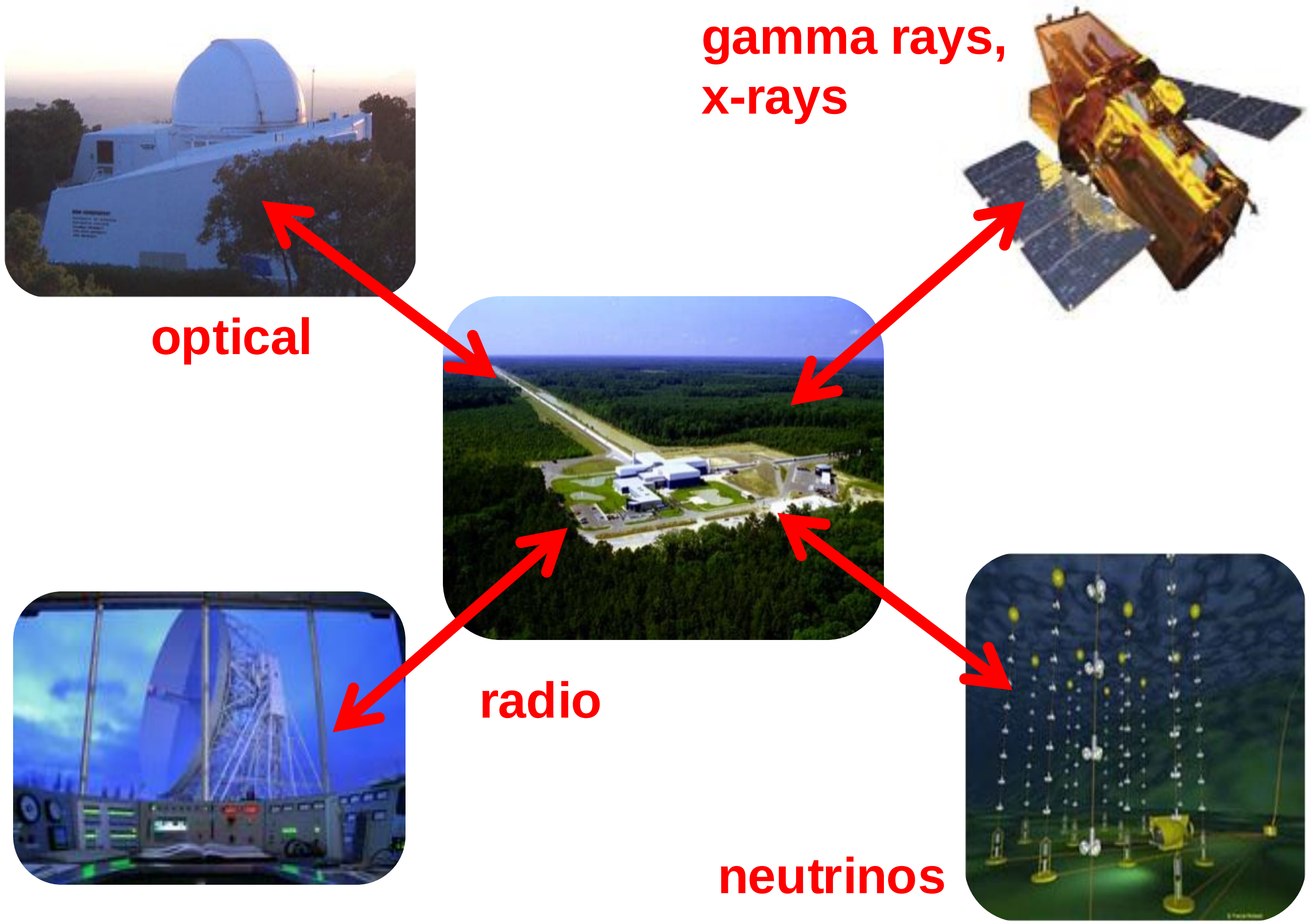
Radio Waves



Neutrinos

High energy cataclysmic astrophysical events can reveal themselves through the emission of gravitational-waves, electromagnetic radiation (photons), neutrinos, and cosmic rays

Multi-messenger Astronomy with Gravitational Waves

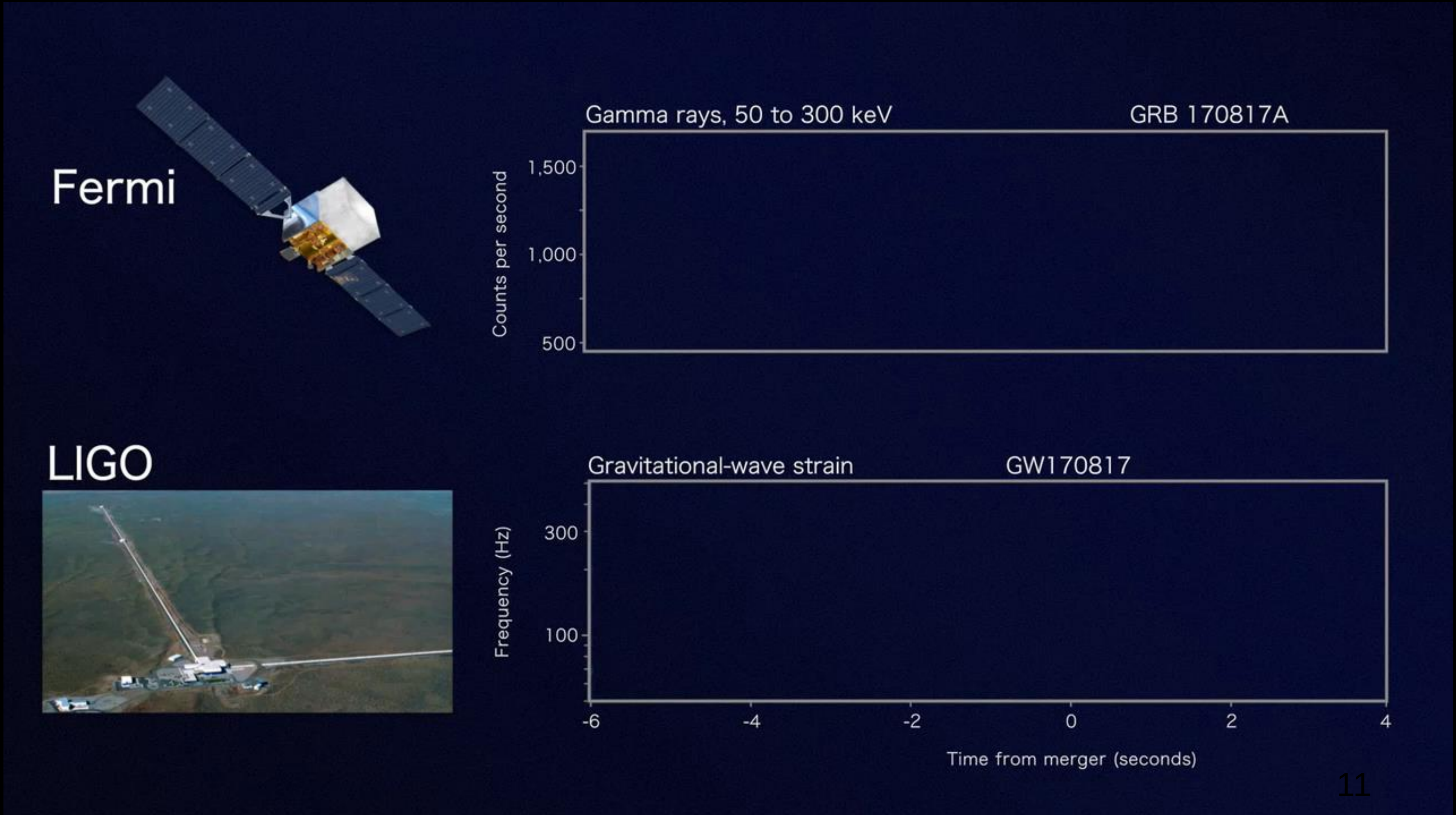


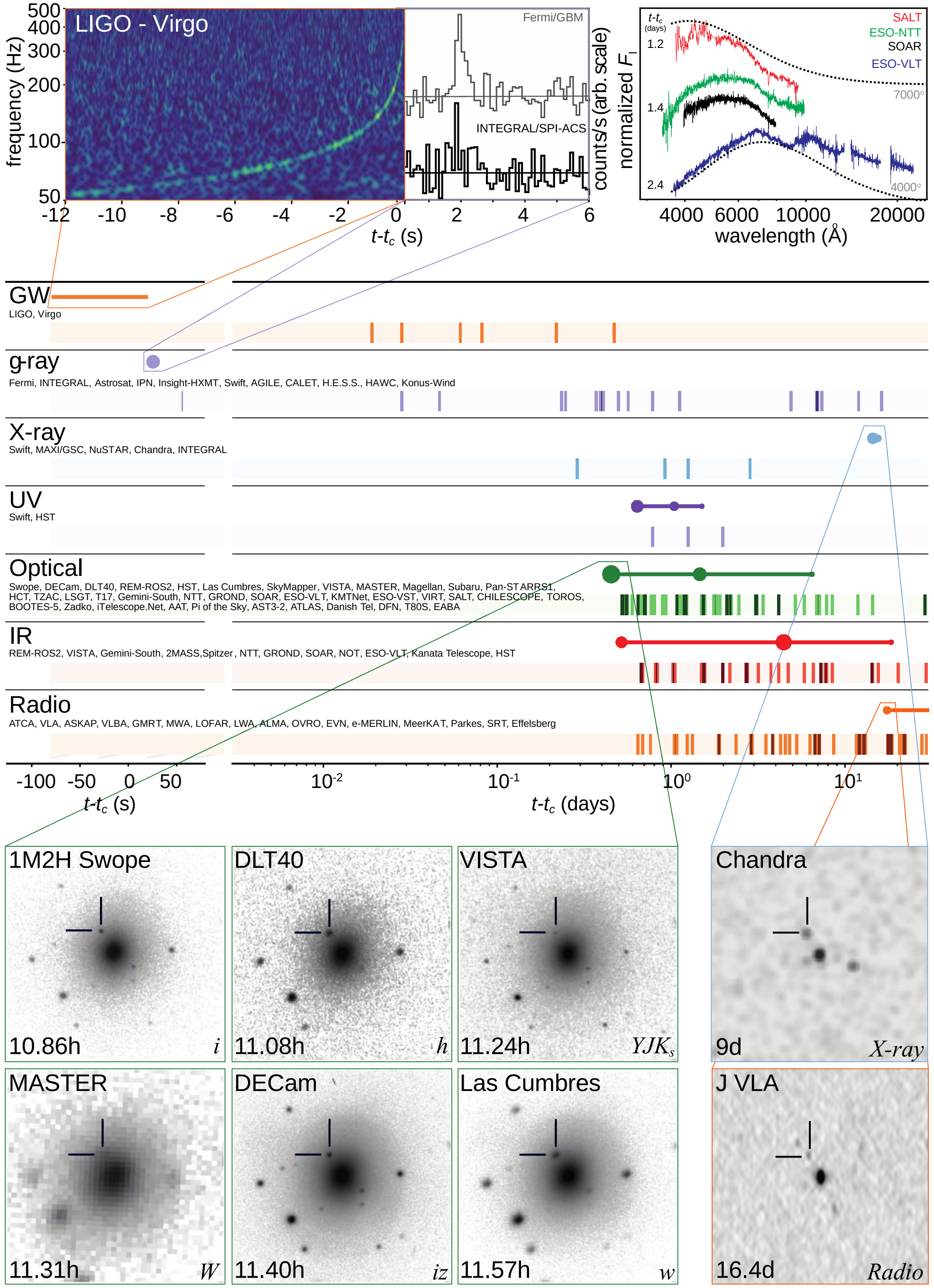
- EM triggers ⇒ GW detector analysis
  - From, e.g., space-based X-ray and gamma ray telescopes
  - Knowing precise time and sky location of event reduces noise contamination in GW detector network; searches can go deeper
- GW detections ⇒ Pointing EM telescopes
  - To catch prompt emission, must point quickly
  - We have developed low-latency GW detection and sky localization pipelines, protocols to pass info, telescope scanning strategies and coordination
- GW detections + all-sky telescopes
  - E.g., neutrino detectors, optical transient surveys, wide-field radio transient surveys
  - Can be done offline, using data “in the can” – “data mining”

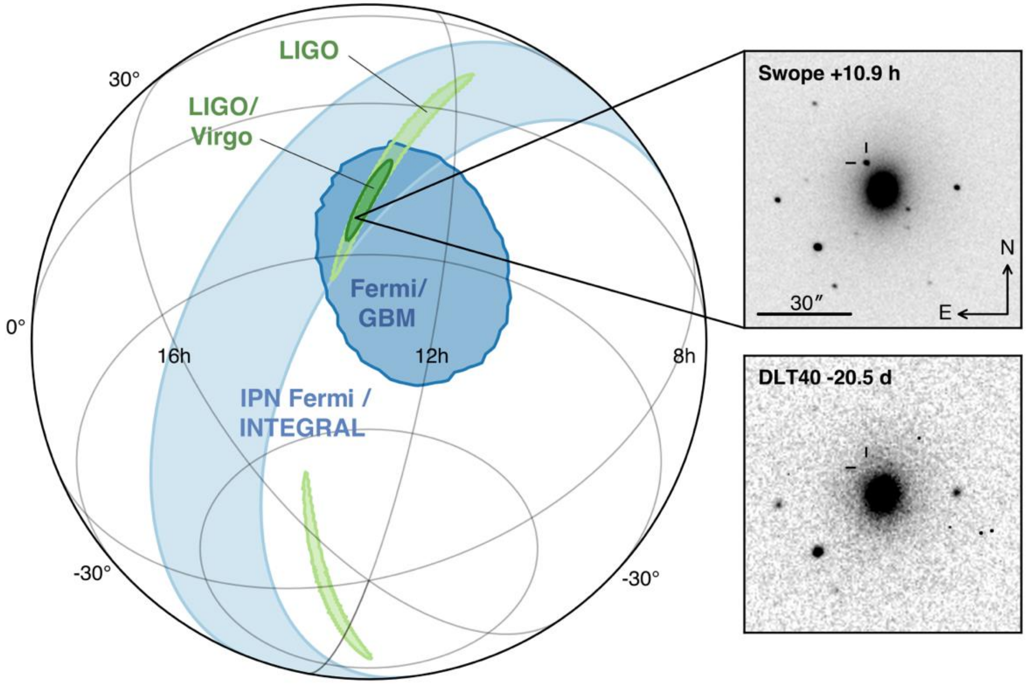
GRB 170817A - GW170817: The Dawn of GW MMA

Coincident Detection with Gravitational Waves and Gamma Rays.

LIGO and Virgo and partners made first detection of gravitational waves and light produced by colliding neutron stars







GW170917/GRB170817A :

"Multi-Messenger Observations of a Binary Neutron Star Merger"

B. Abbott et al., ApJL 848 (2017) L12

59-page "letter" (!). More than 3000 authors,~70 collaborations

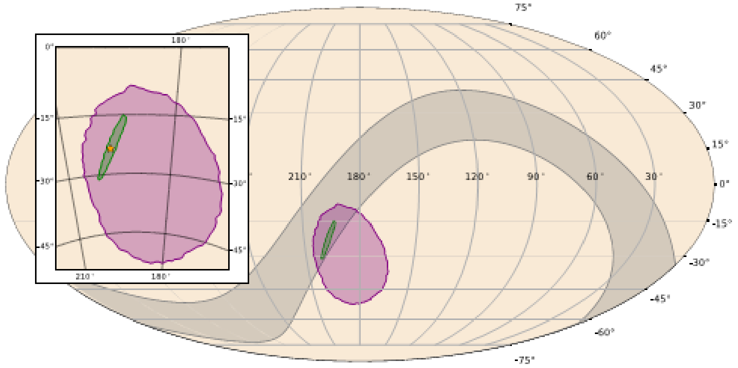
First unambiguous EM counterpart to a GW source

- Gamma Ray transient classified as sGRB detected by *Fermi*-GBM 2s after inferred GW merger time.
- Host galaxy discovered by dedicated optical follow-up.
- "Whole of astronomy" broadband analysis of kilonova and host galaxy.

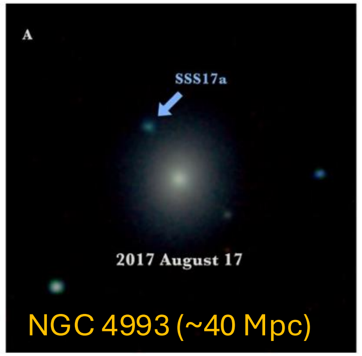
- **Vivid demonstration that joint observations are > sum of their parts**.

GW170817: Multi-Messenger Breakthrough!

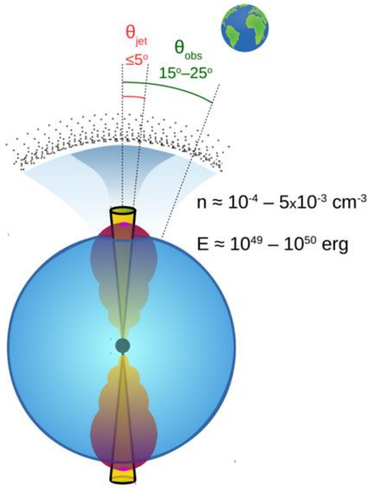
The BNS merger "chirp" was very strong in the gravitational-wave (GW) data and was accompanied by a short GRB detected by *Fermi*/GBM and INTEGRAL/SPI-ACS.
An optical counterpart was found in the galaxy NGC 4993 and studied intensely at all wavelengths, tracing out a kilonova light curve which was visible for weeks plus X-ray and radio emission which peaked after ~100 days and was detectable for over a year.



[Abbott et al., PRL 119, 161101; ApJ 848, L13; ApJ 848, L12]



[Drout et al. 2017, Science 10.1126/science.aaq0049]



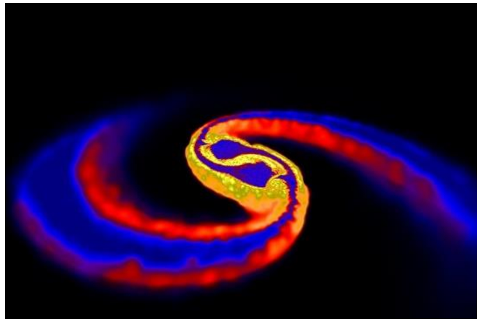
➔ Confirmed picture of BNS mergers as progenitors of short-hard GRBs — in this case, detected off-axis by 15±5°, corroborated by VLBI imaging *[Mooley et al., Nature 561, 355]*

➔ Verified to high precision that GWs travel at the speed of light

$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\mathrm{EM}}} \leqslant +7 \times 10^{-16}$$

➔ Enabled new measurement of the Hubble constant *[Eight teams, Nature 551, 85]*

➔ GRB170817 was anomalously faint compared to other sGRBs w/ known redshift

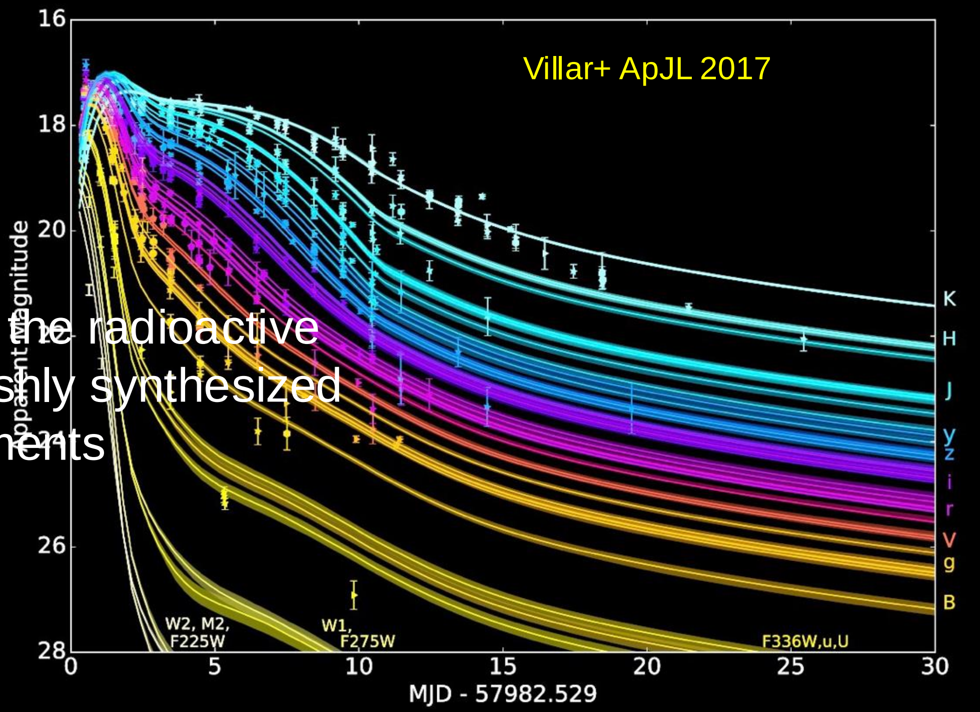


Price/Rosswog/Press

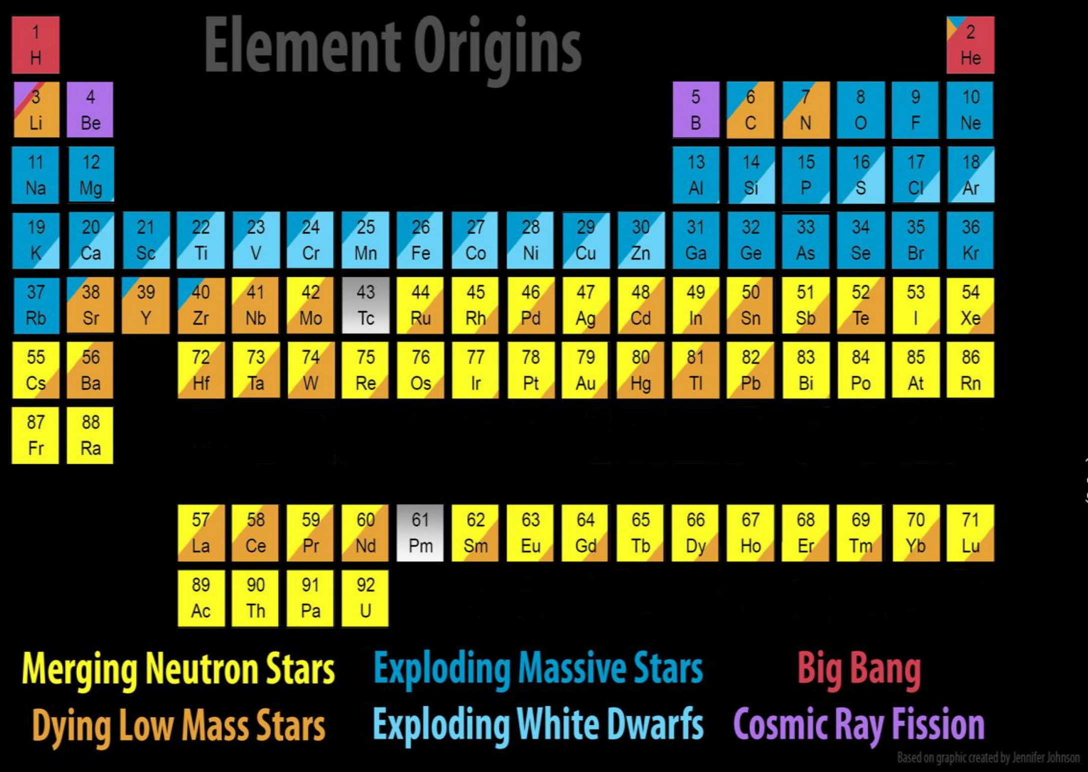
What we learned from GW170817

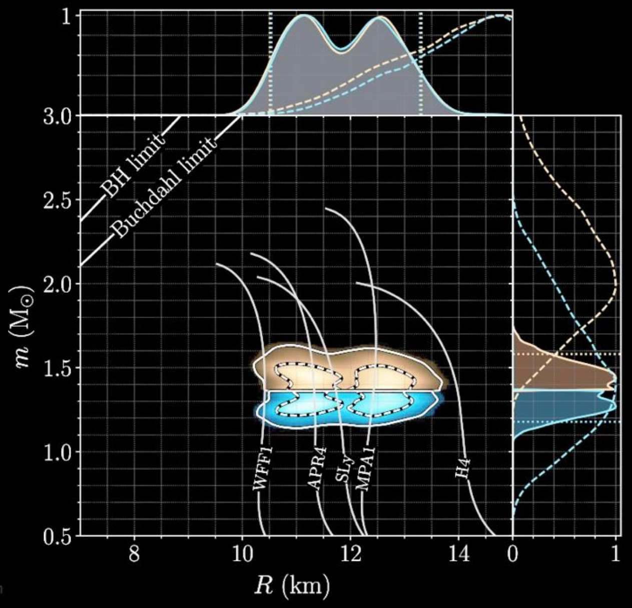
BNS mergers are the progenitors of some short gamma-ray burst –the most energetic electromagnetic explosions in the universe

BNS mergers are the sites of heavy element nucleosynthesis, where most of the heavy elements are produced



Kilonova – the radioactive glow of freshly synthesized heavy elements





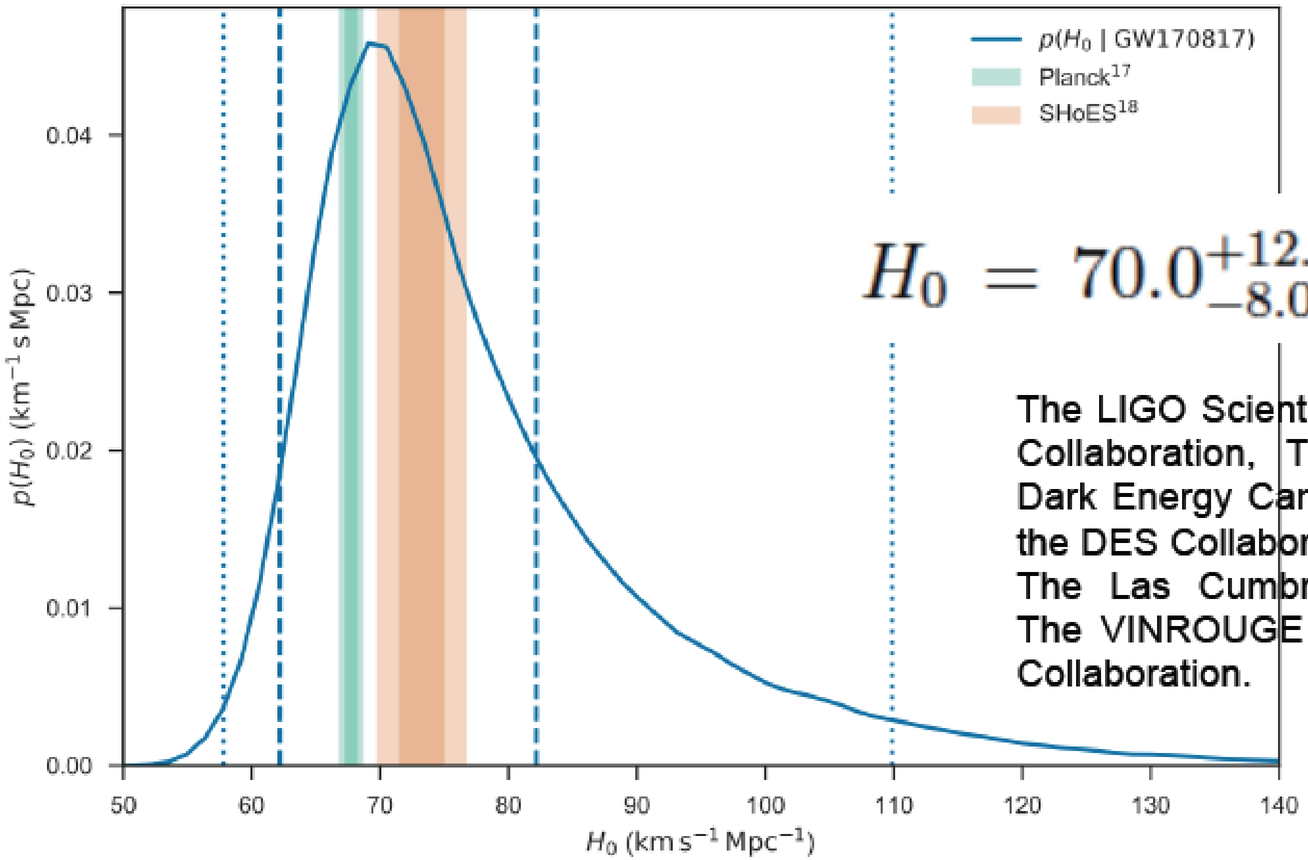
Constraints on the neutron star mass-radius relation, nuclear equation of state

LVC PRL 2018

GW170817: inicio de la **cosmología** de GW

GW170817 puede usarse como una **"sirena estándar"**: combinando la **distancia** (inferida de la señal gravitacional) con la **velocidad** de recesión de la fuente (corrimiento al rojo; inferida de la señal electromagnética) se determina la **constante de Hubble.**

$$v_H = H_0 \, d$$



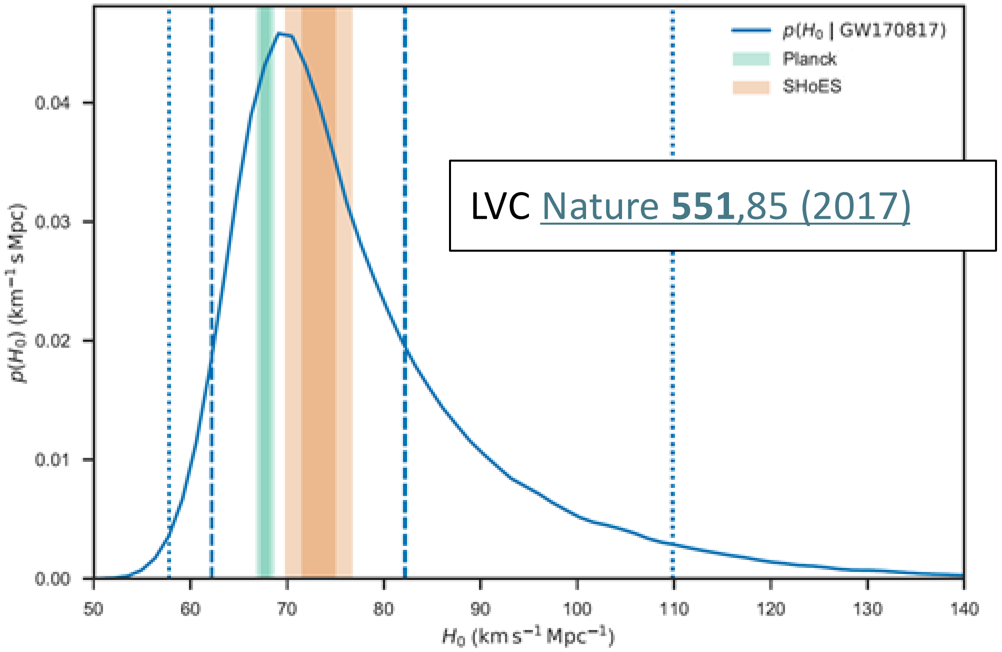
$$H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

The LIGO Scientific Collaboration and The Virgo Collaboration, The 1M2H Collaboration, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, The Las Cumbres Observatory Collaboration, The VINROUGE Collaboration & The MASTER Collaboration.

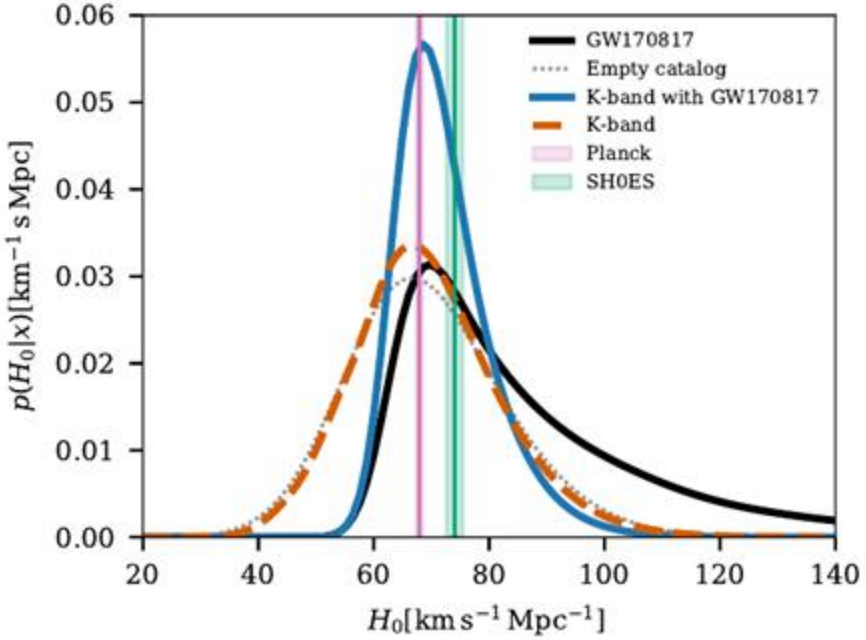
Nature (2017)

GW cosmology

- CBCs are “standard sirens”: can measure luminosity distance directly from signal waveform
- distance *and* redshift → measure Hubble constant
- best constraints from “bright sirens” like GW170817 with electromagnetic counterpart for redshift
- statistical “dark sirens” approach for GWs without counterpart:
    - compare with galaxy catalogs
    - jointly infer cosmology with population model

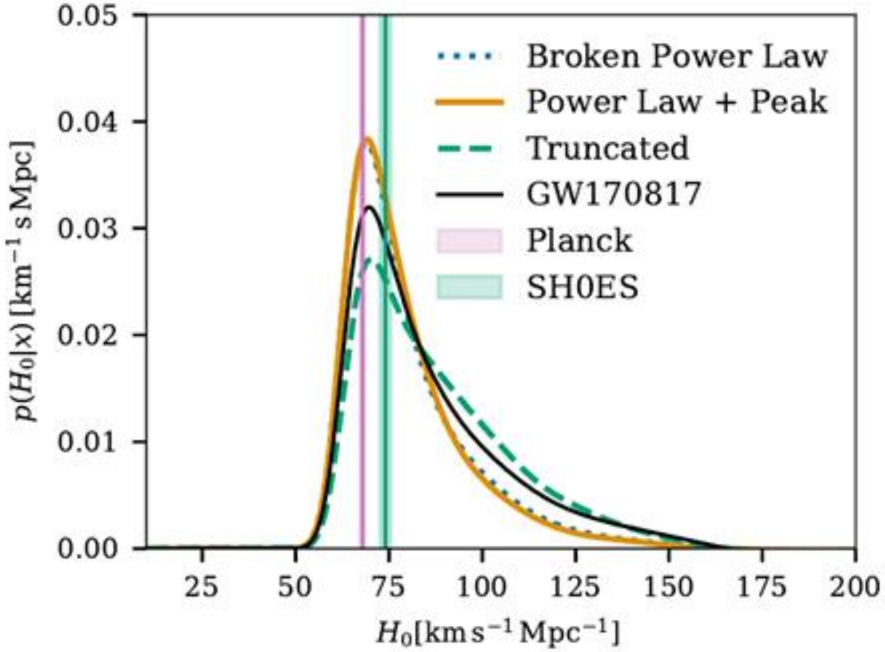


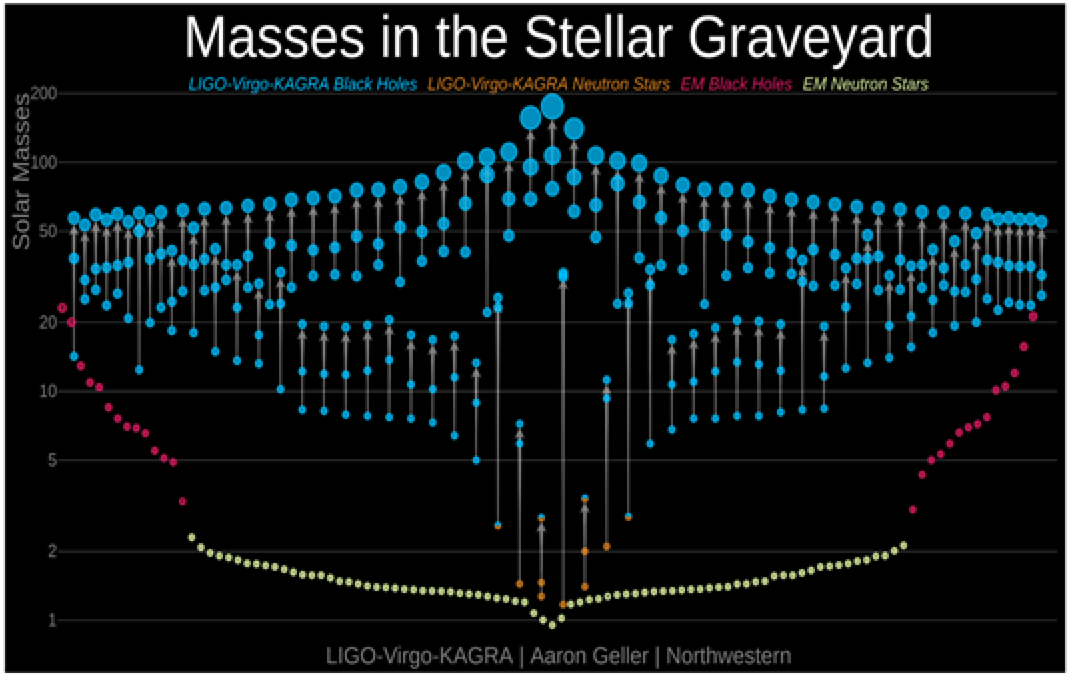
LVC Nature **551**,85 (2017)

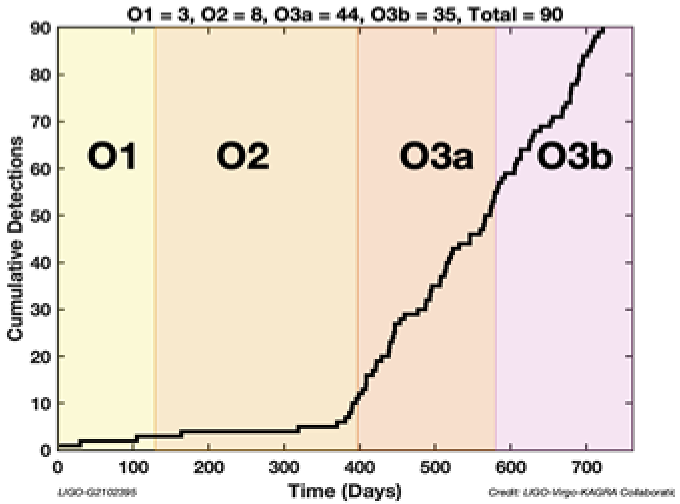


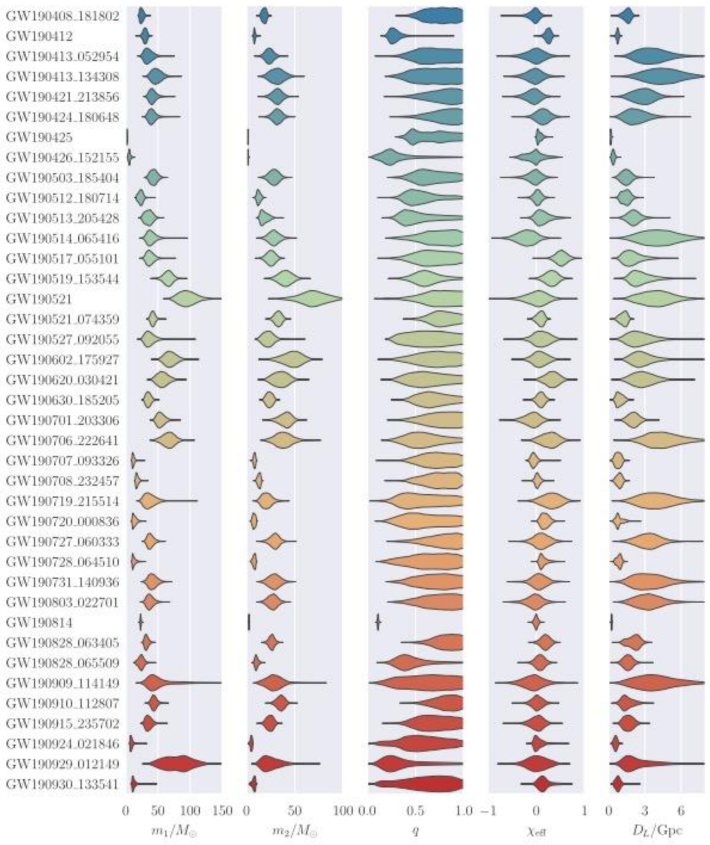
latest results based on GWTC-3 events:

LVK, ApJ arXiv:2111.03604









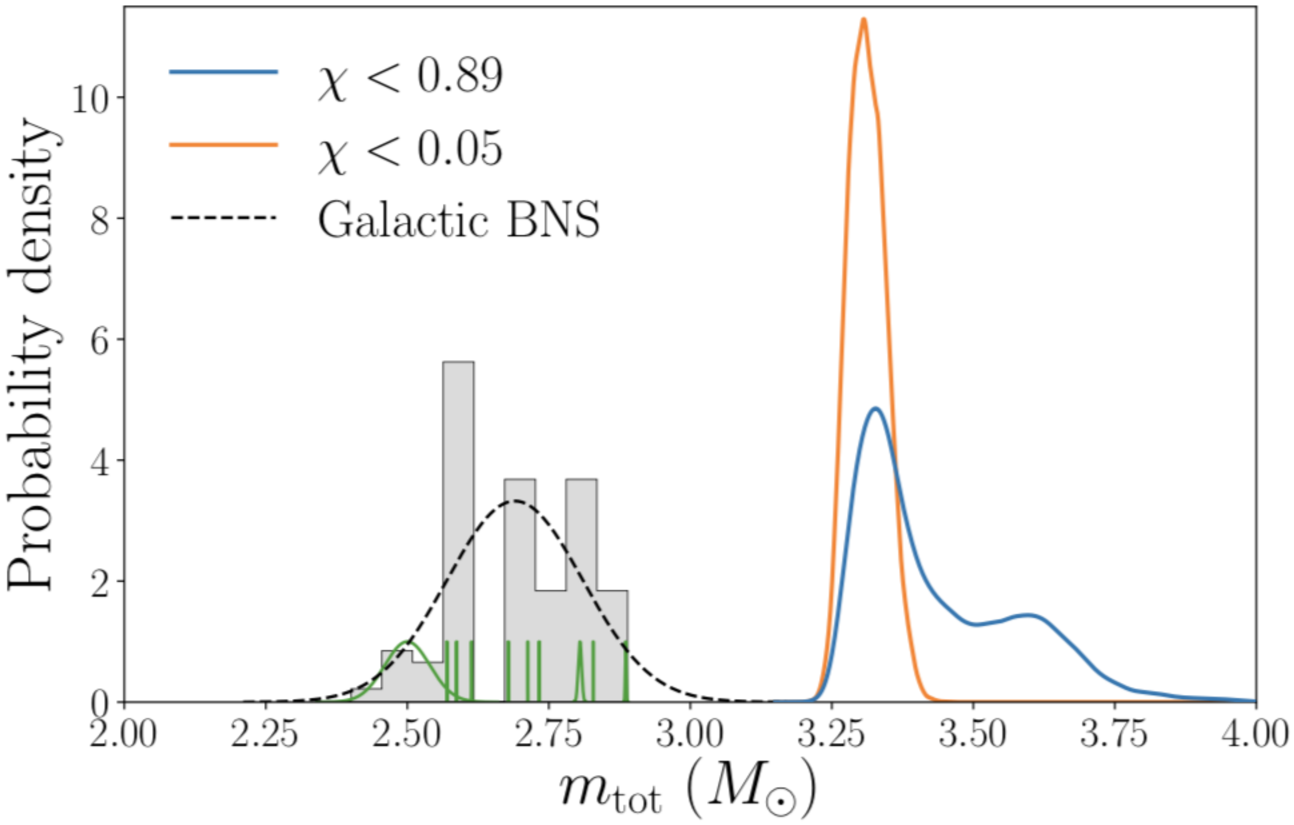
O3 campaign and beyond

O3 marked a phase change in GW astronomy, with public GW alerts in low latency and a lot of GW candidates!

- Wide range of masses
- most events: binary black holes
- redshifts up to ~0.8
- Spins:
  - Key signatures to discriminate BH populations: shed light on formation mechanism
  - Some events with clear indication of a net positive $X_{\rm eff}$

- No counterparts found in low latency
- But low mass candidates were poorly localized and/or poorly located on the sky

GW190425



m_1	m_2	m_{tot}
$1.6 - 2.5\,\mathrm{M}_\odot$	$1.1 - 1.7\,\mathrm{M}_\odot$	$\sim 3.4\,\mathrm{M}_\odot$

A massive binary neutron star merger

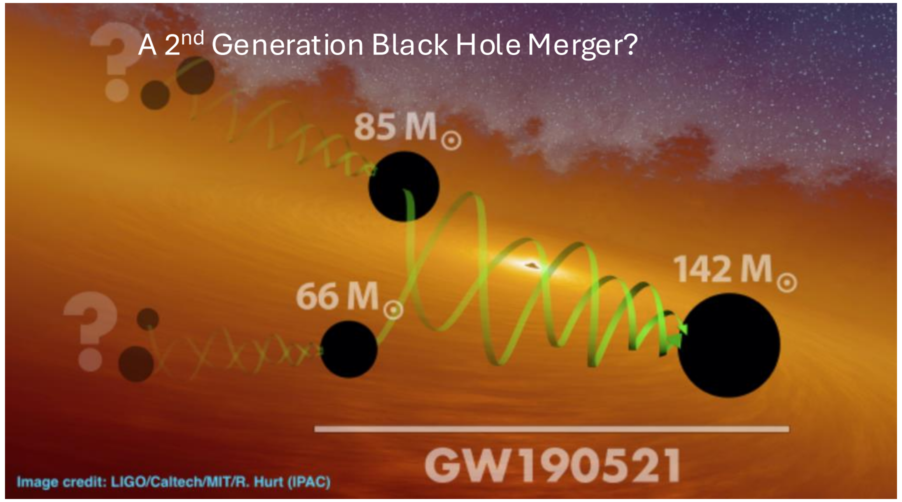
Abbott et al. ApJ Lett. 896, L44 (2020)

- Both component masses < 3 $M_\odot$
- No EM counterpart
- Total mass larger than any known BNS (5σ from mean of Galactic BNS)
- Initial sky map had a 90% credible region of 10,200 deg^2 at luminosity distance of 159^{+69}_{-72} Mpc

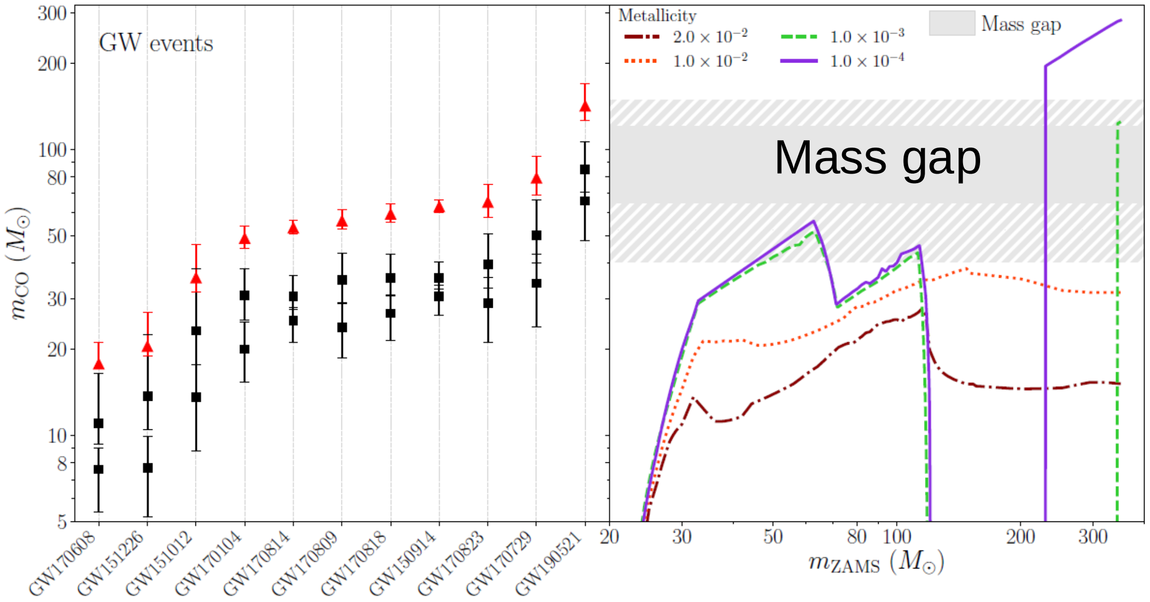
May indicate population of short period BNSs invisible to radio pulsar surveys

The possibility that one or both binary components are black holes cannot be ruled out

GW190521



m_1	m_2	$m_{\rm tot}$
$\sim 85\,\mathrm{M}_\odot$	$\sim 66\,\mathrm{M}_\odot$	$\sim 150\,\mathrm{M}_\odot$

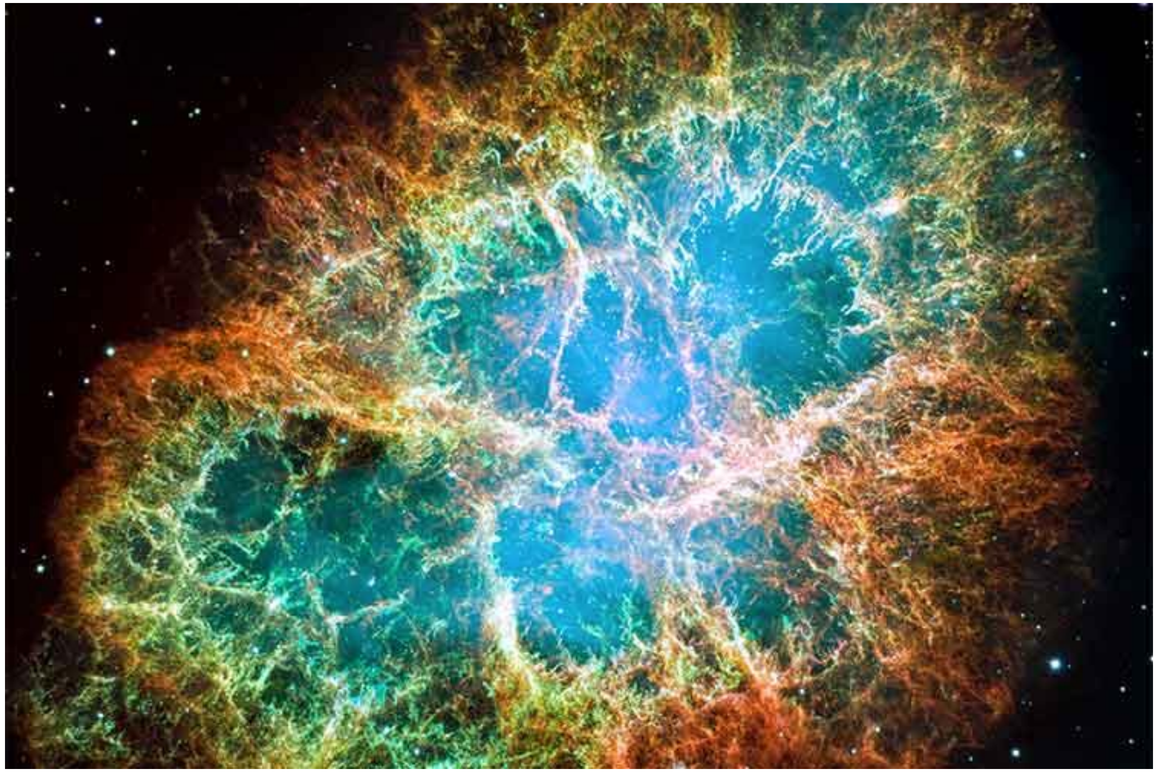


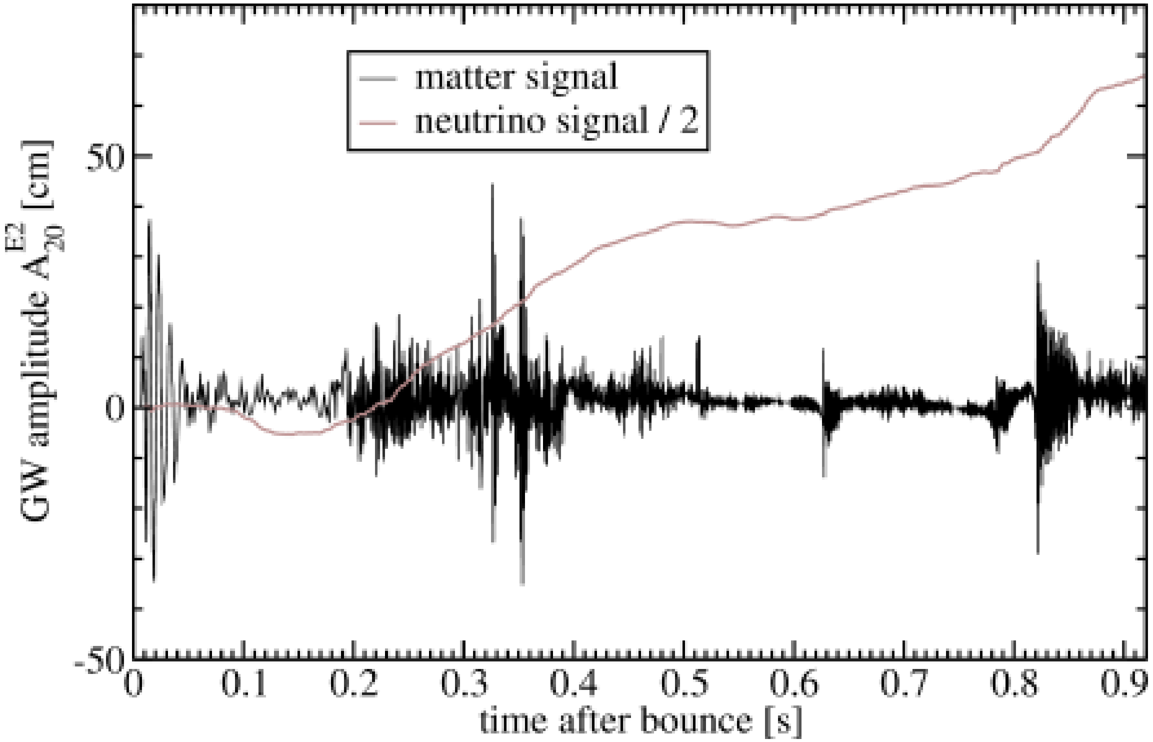
A massive binary black hole merger encroaching on the pair-instability mass gap

Abbott et al. Phys. Rev. Lett. 125, 101102 (2020)

Abbott et al. ApJ Lett. 900, L13 (2020)

- Most massive GW binary observed to-date
- The furthest GW event ever recorded: ~ 7 Glyr distant
- First clear detection of "intermediate mass" black hole
- At least one of the progenitor black holes (85 Msun) lies in the pair instability supernova mass gap (between 50 and 120)
- Evidence that GW190521 might be a 2nd generation merger!!
- Also challenging for standard formation scenarios!
- Detailed reanalysis: Estellés+ , ApJ, 902, 79 (2022)





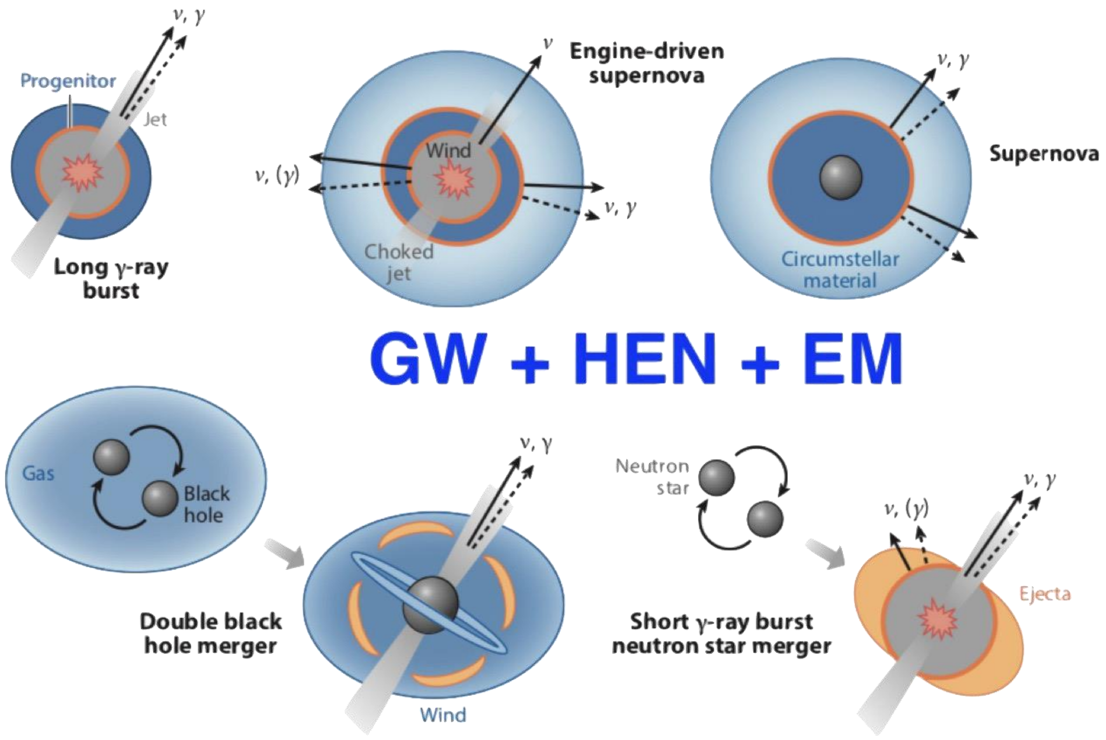
Beyond Binary Mergers

Core collapse supernovae

- A galactic supernova is the ultimate multimessenger prize
- GW emission encodes the internal dynamics of the supernova
- Detector range beyond the galaxy is limited, depending on explosion mechanism, so keep your fingers crossed.

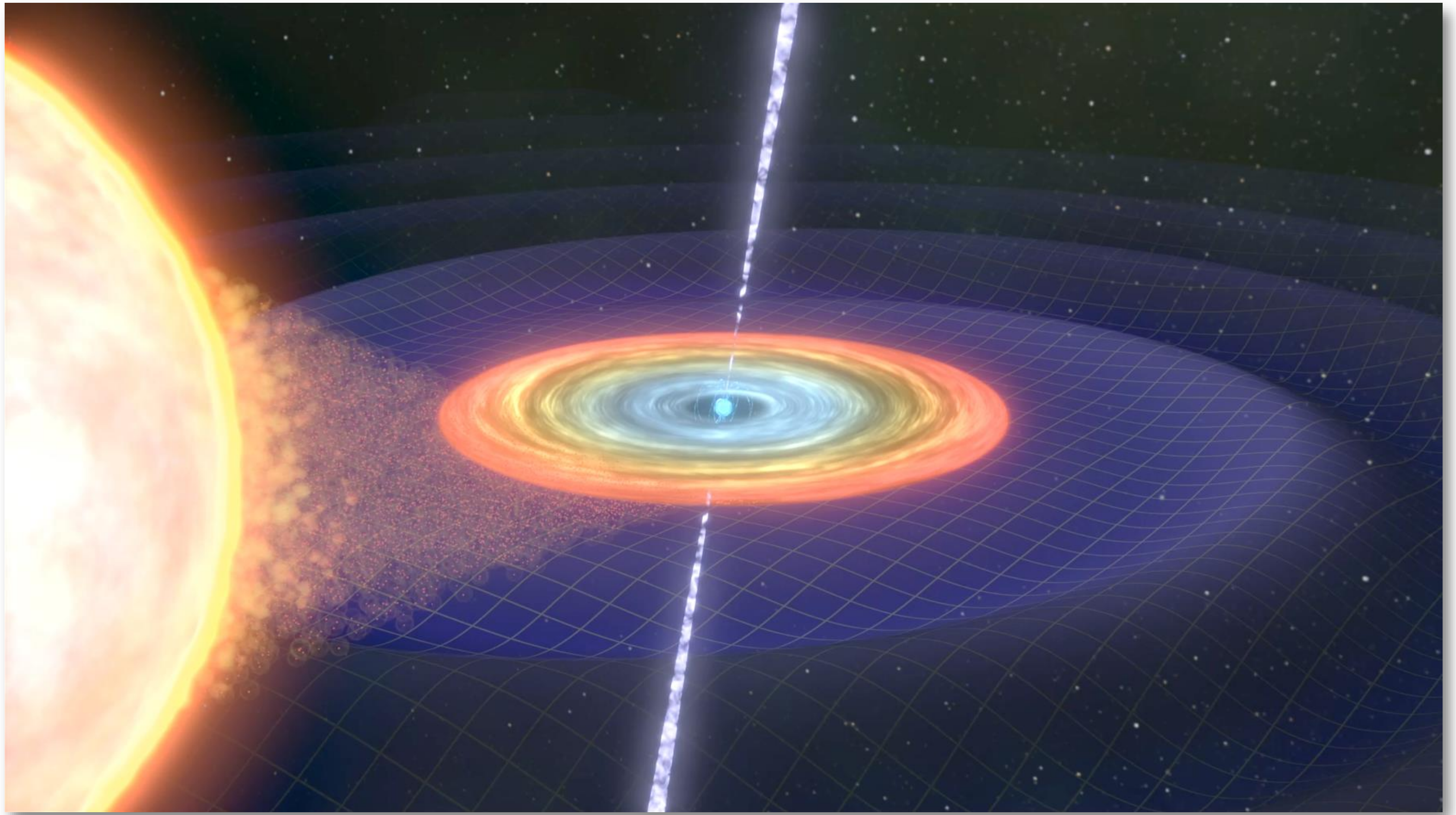
Neutrino Connection

- Upper limits on the neutrino flux spatially and temporally coincident with public GW alerts from O3
  - Super-K (ApJ 2021), IceCube (ApJ 2023), ANTARES (JCAP 2023), KM3Net (JCAP 2024)
- Realtime IceCube follow-up of GW public alerts
- Future possibilities in development
  - LVK RAVEN pipeline search for GraceDB coincidences between GW and IceCube public alerts
  - Joint GW + neutrino sub-threshold search using IceCube and KM3Net
  - Reranking GW candidates based on external neutrino coincidence



What can we learn from continuous waves?

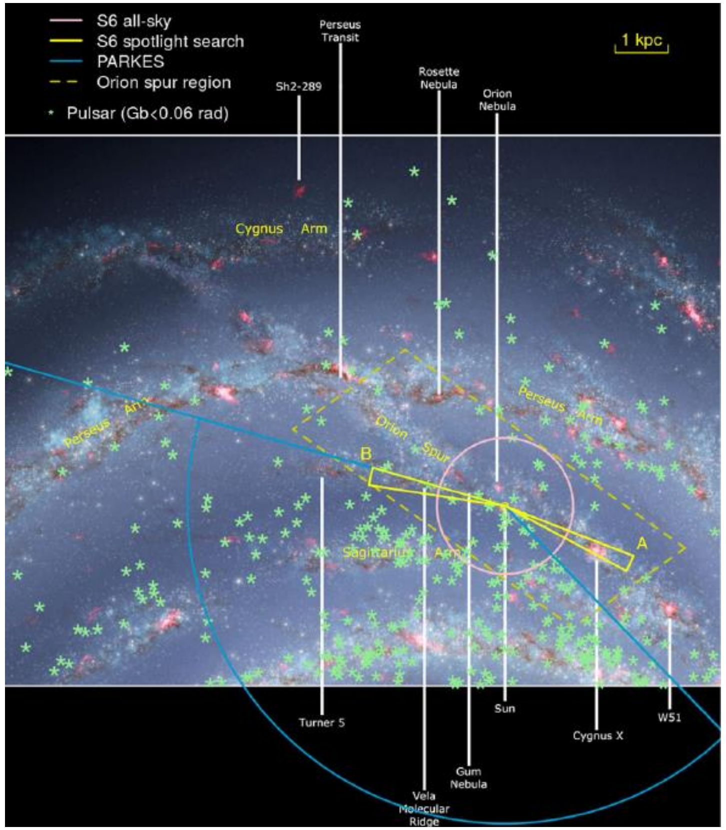
- *Possible EM emission from two scenarios: NS crustal deformations, accretion from binary companion*

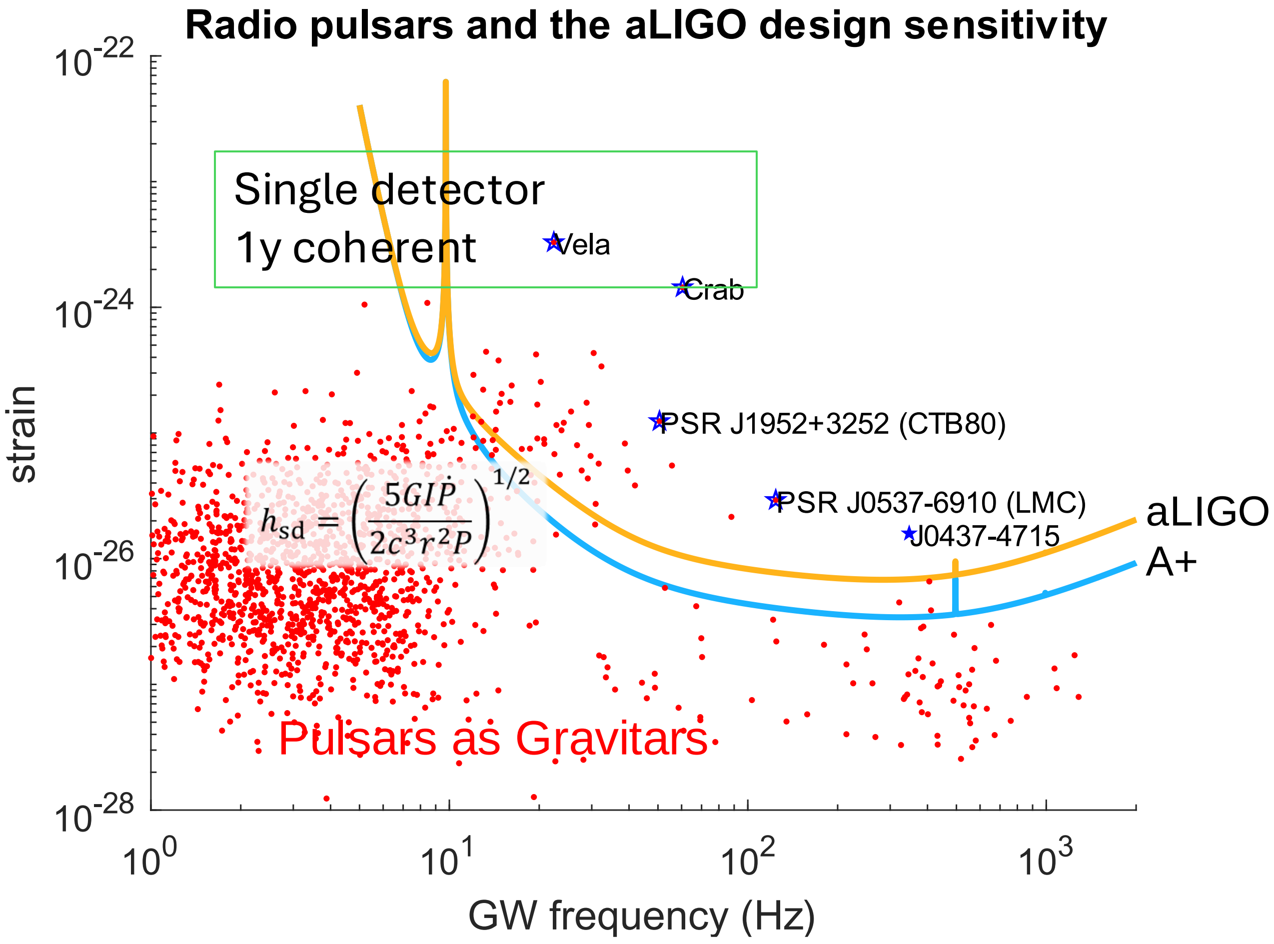


Credit: Mark Myers, OzGrav-Swinburne

- *Interior structure of neutron star*
- *Neutron star properties, e.g., mass, spin, ellipticity*
- *Nuclear equation of state*
- *May discover exotic states of matter*
- *Detecting deviations from General Relativity (speed of GWs, existence of other polarizations)*
- *… and so on*

- *CW-like signals can be also associated to Dark Matter*





Pulsars:

Source of continuous GWs

- We have no idea how many CW signal detections to expect in aLIGO/AdV.
- Guided searches:
  - Some extended regions on the sky (e.g. galactic spiral arms) are expected to be overdense in NSs.
  - Can also choose to guide frequency or spindown ranges by EM-observed pulsar population, or by population modelling.

TARGETED: 236 known pulsars

(168 in binary systems & 161 millisecond pulsars with frequencies above 100 Hz)

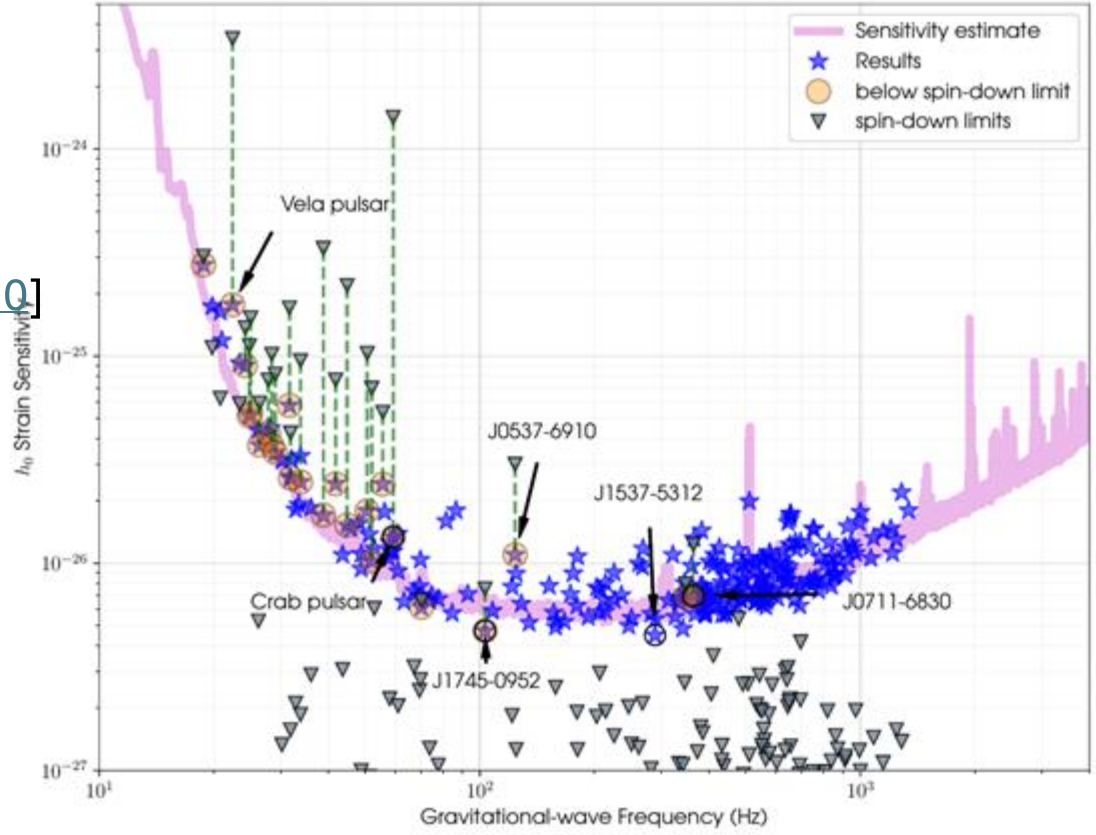
- Upper limits on 236 targets, at both once and twice the rotation frequency of the pulsar. Abbott+2021, “Searches for Gravitational Waves from Known Pulsars at Two Harmonics in the Second and Third LIGO-Virgo Observing Runs”

- Glasgow time-domain Bayesian method [Dupuis&Woan2005, Pitkin+2017]

- Warsaw time-domain *F*-statistic [Jaranowski-Królak-Schutz1998, Jaranowski&Królak2010]

- Rome 5n-vector method [Astone+2014, Mastrogiovanni+2017]

- Searches with non-GR templates can constrain non-standard polarisation content (scalar, vector modes: Isi+2015, Isi+2017, Verma2021)



- Non-LVK searches: e.g. Nieder+2021 on Einstein@Home gamma-ray pulsars,

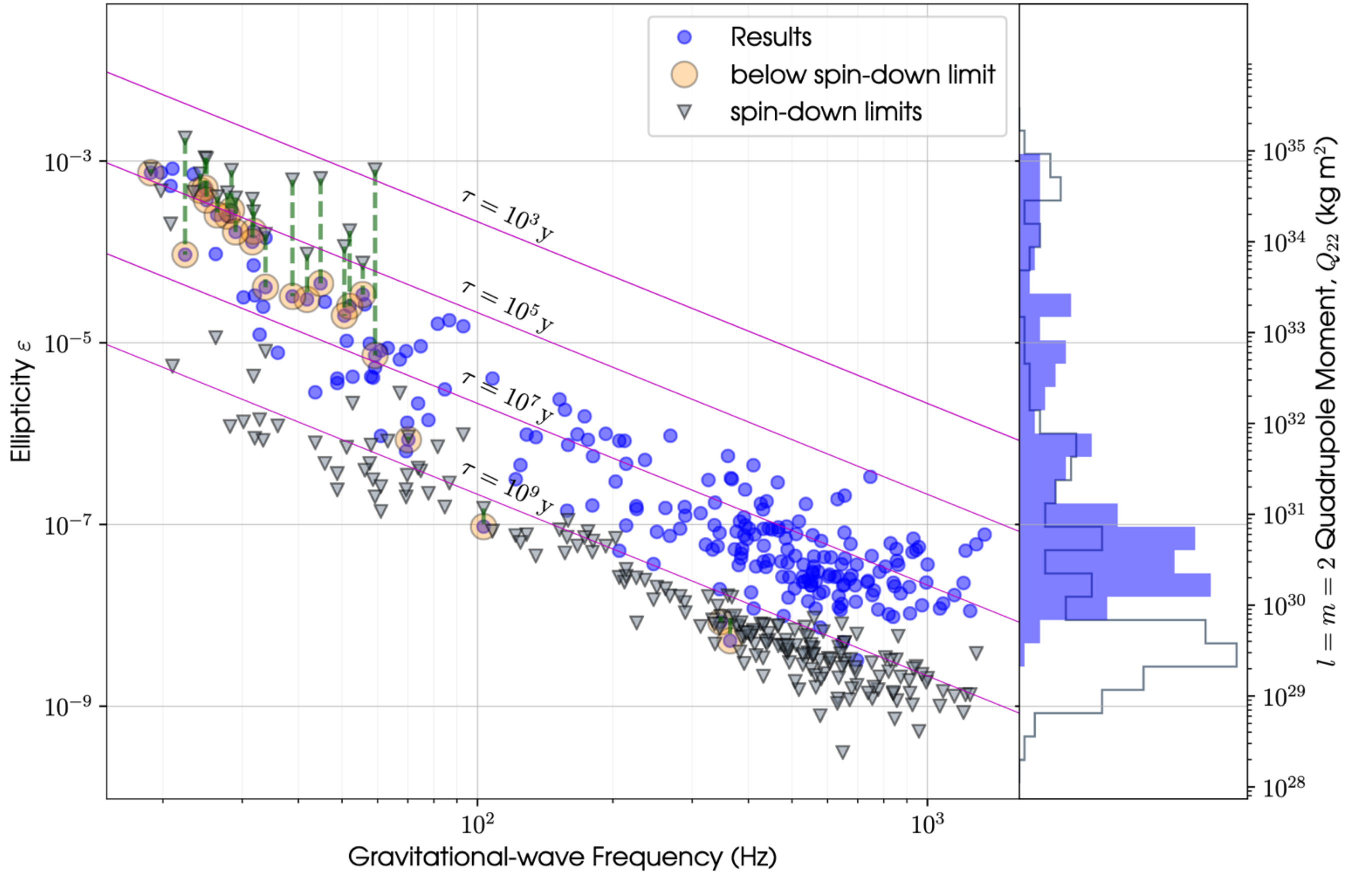
O2+O3 HLV, arXiv:2111.13106 (2021)

TARGETED: 236 known pulsars

(168 in binary systems & 161 millisecond pulsars with frequencies above 100 Hz)

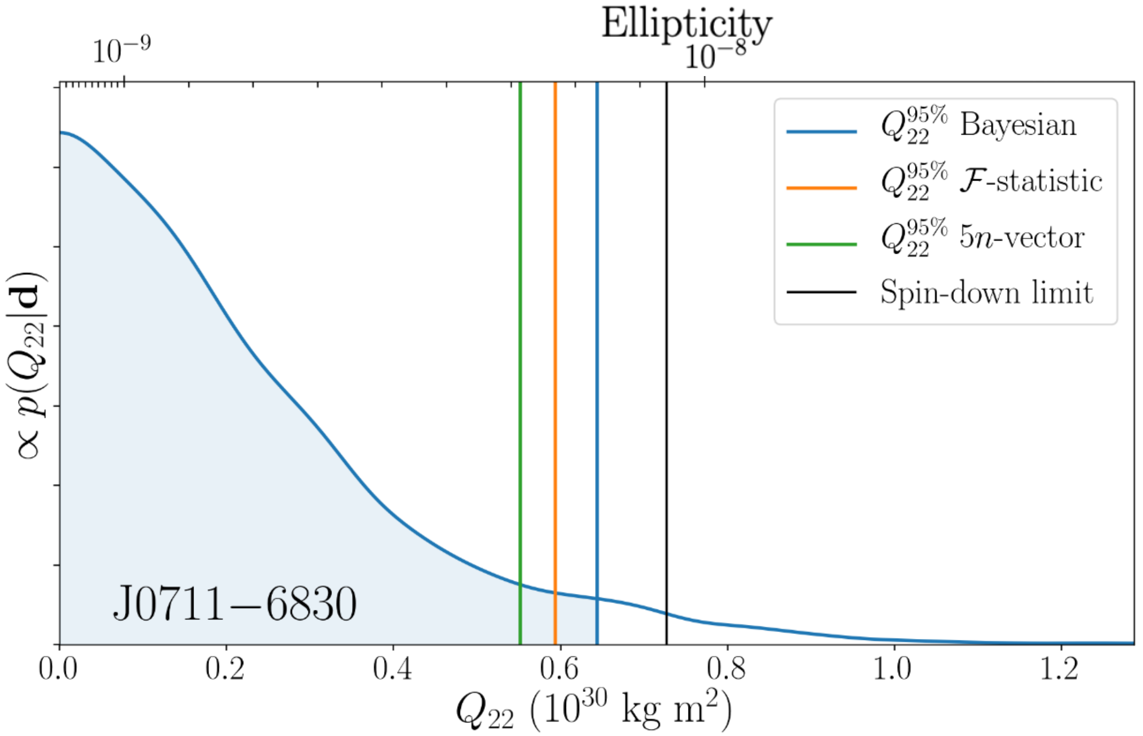
- *Search at both once and twice the rotation frequency of the pulsar.*
- *A new search method designed to detect the dipole radiation present in Brans-Dicke theory.*
- *For **23** pulsars, resulting upper limits have surpassed EM measured spin-down limits.*
- *For **9** pulsars, their spin-down limits have been surpassed for the first time.*
- *For **Crab** & **Vela**, our limits are factors of **~100** and **~20** more constraining than the spin-down limits, respectively.*

For the Crab pulsar, the GW upper limit is less than 0.009% (previously ~0.02%) of spin-down limit. With an ellipticity of 7.2×10^{-6} (maximum mountain height of ~2 cm).



TARGETED: Constraints on equatorial ellipticity of millisecond pulsars

- *Targeted at 5 radio pulsars: 2 recycled millisecond pulsars, 1mildly recycled pulsar, and 2 young pulsars (Crab, Vela)*
- *Assume a tight coupling between GW and EM signal phase evolution*
- *Search assuming emission at once or twice the rotational frequency*
- *For the first time, a constraint on the fraction of spin-down energy due to GWs emission has been obtained for a millisecond pulsar and constraining ellipticities < 10^{-8}*



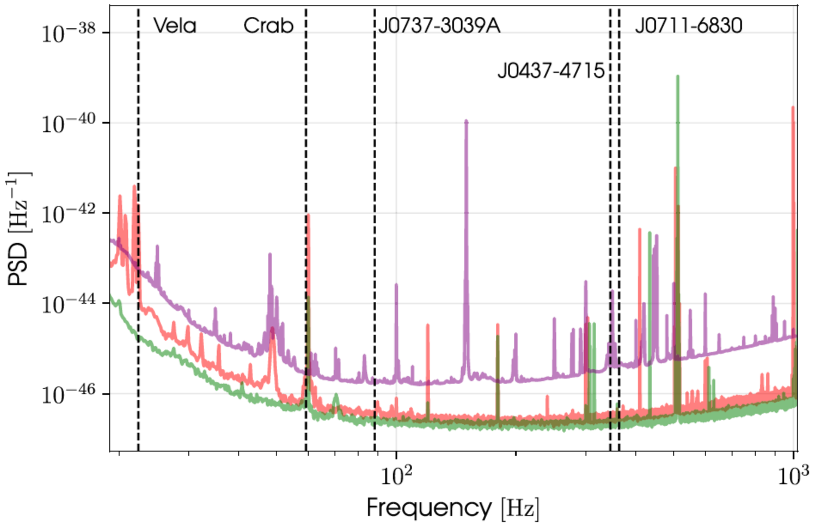
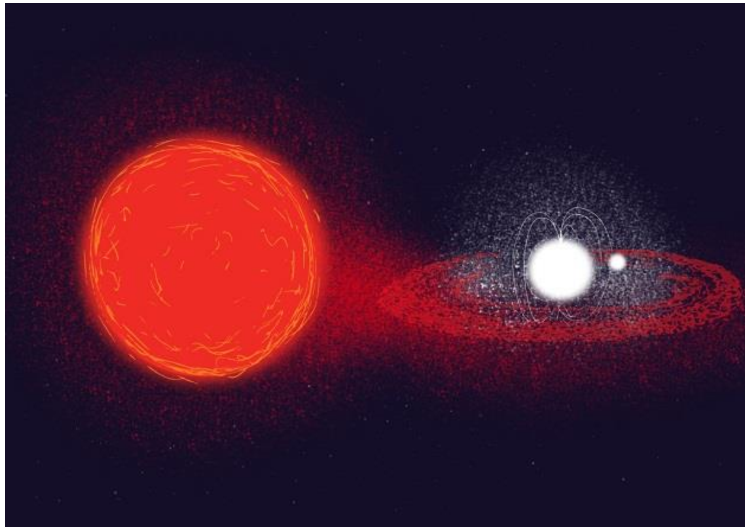


Figure 1. O3a noise PSD for H1, L1, and V1 shown in red, green, and purple. The H1 and L1 PSDs are calculated during a time period of optimal performance for the detector, while the Virgo PSD is averaged over the run. The vertical dashed lines indicate the searched frequency region for each of the five pulsars.

Artist's impression of a millisecond pulsar [Credit: European Space Agency]



O1+O2+O3a HLV, ApJL 902, L21 (2020)

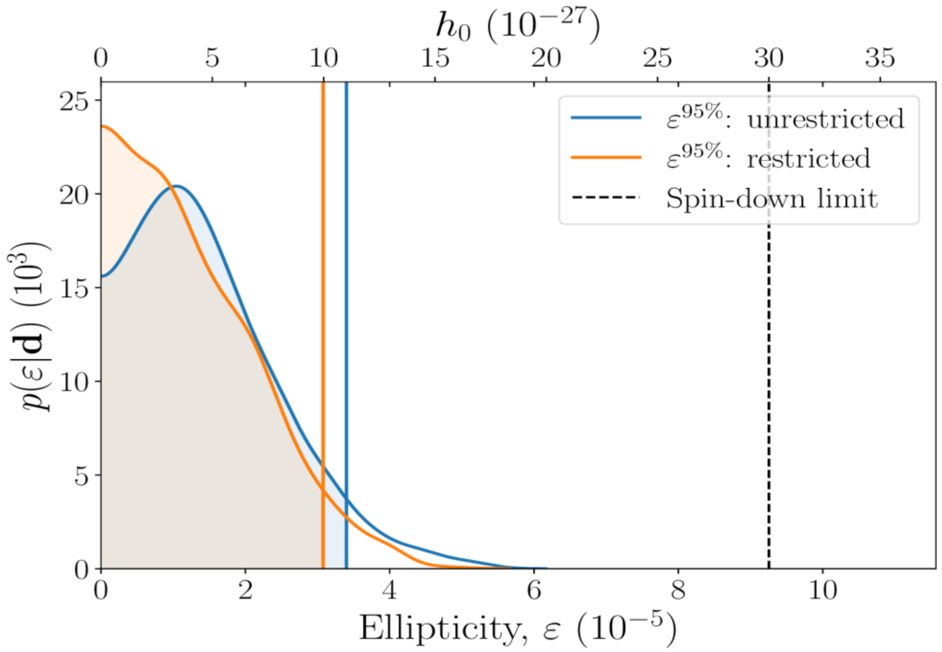
TARGETED: Energetic young pulsar PSR J0537-6910 (“The Big Glitcher”)

X-ray pulsar, largest spin-down luminosity, frequent and strong glitches, unusual braking index could point at pulsar being spun-down by GWs;

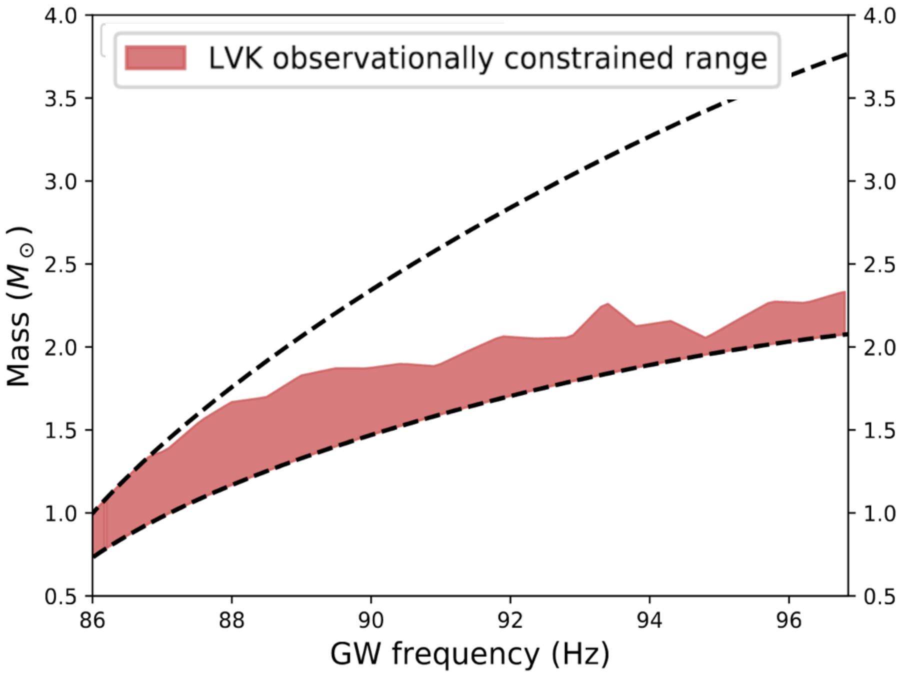
LVK and NICER collaborated to look for continuous GWs.

Use a NICER timing ephemeris (NICER — Neutron star Interior Composition Explorer)

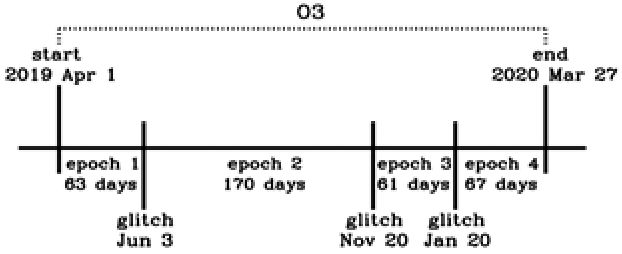
- *Searched at once and twice the spin frequency 62 Hz*
- *First time reach **below GW spin-down limit** for this star by more than **a factor of 2** and limit GWs to account for **<14%** of the spin-down energy budget.*
- *No GWs but we are now 95% confident that the ellipticity is < 0.00003*



O2+O3 HLV, ApJL 913, L27 (2021)



- *Inter-glitch braking index suggests that **r-mode** oscillations may be important to GW emission.*
- *Search in a narrow band 86—97 Hz to deal with EOS uncertainty*
- *Searches exclude the possibility that PSR J0537-6910 could be a high mass neutron star emitting GWs due to r-modes. But could still be possible for low mass neutron stars.*



O3 HL, ApJ 922, 71 (2021)

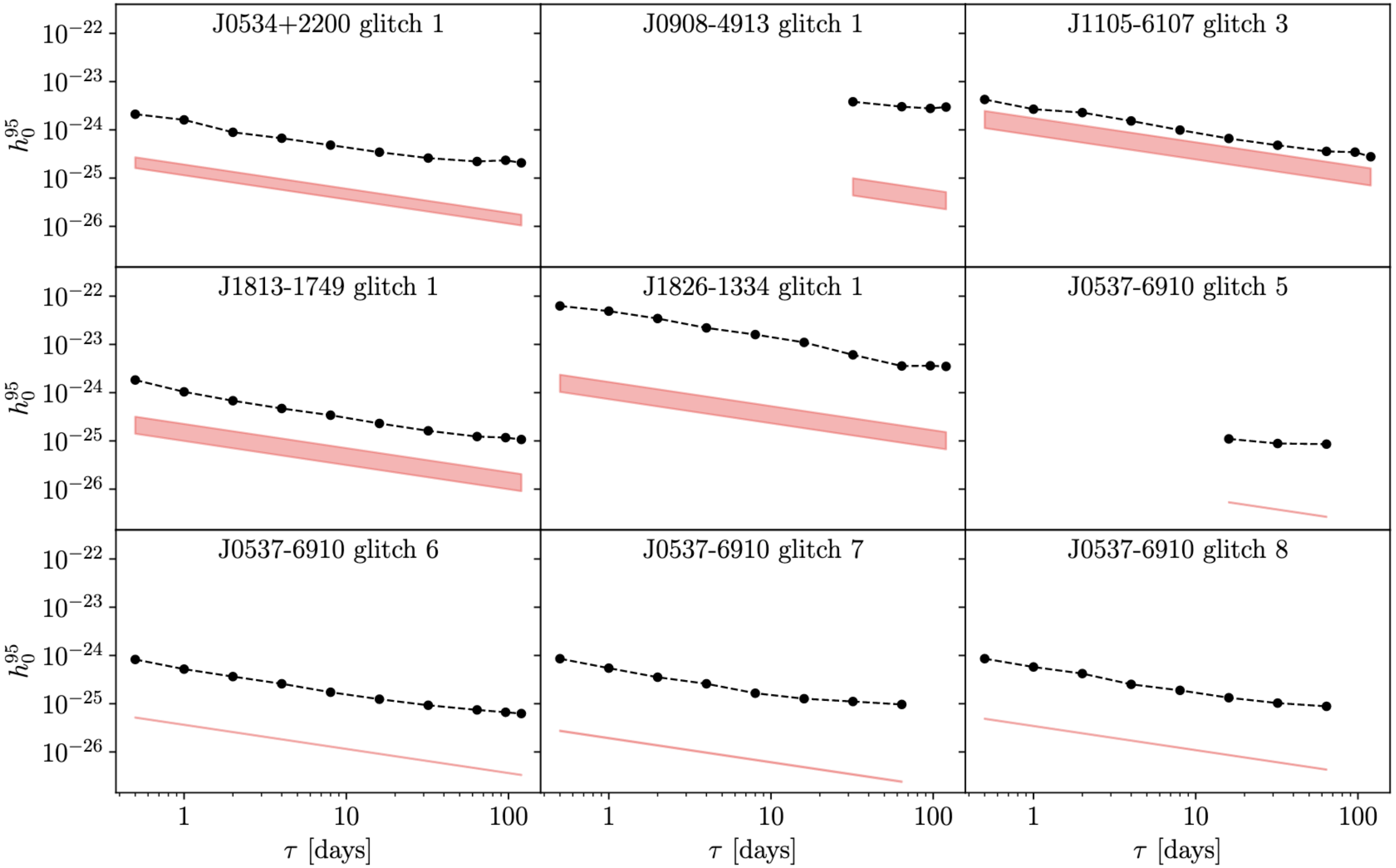
NARROW-BAND: 18 known pulsars & 9 glitches

- *Relax the assumption that GW emission is phase-locked to EM emission, allowing the GW frequency to vary from EM expectation in a narrow band —— **surpassed spin-down limits for 7 pulsars (2 for first time)***

- *Also search for long-duration (hours–months) transient GWs after pulsar glitches for 6 targets (9 glitches in O3)*

- ***"glitches"** —— events where the star suddenly rotates faster than before*

- ***Black:** strain upper limits obtained from the search*
- ***Red:** indirect glitch excess energy upper limits*

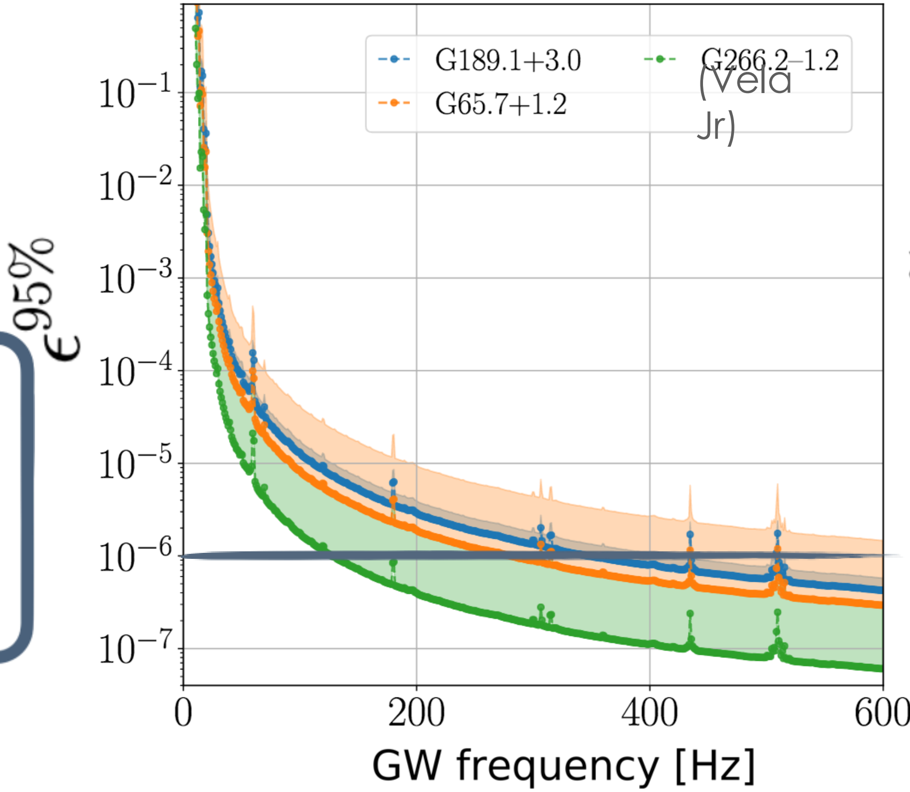


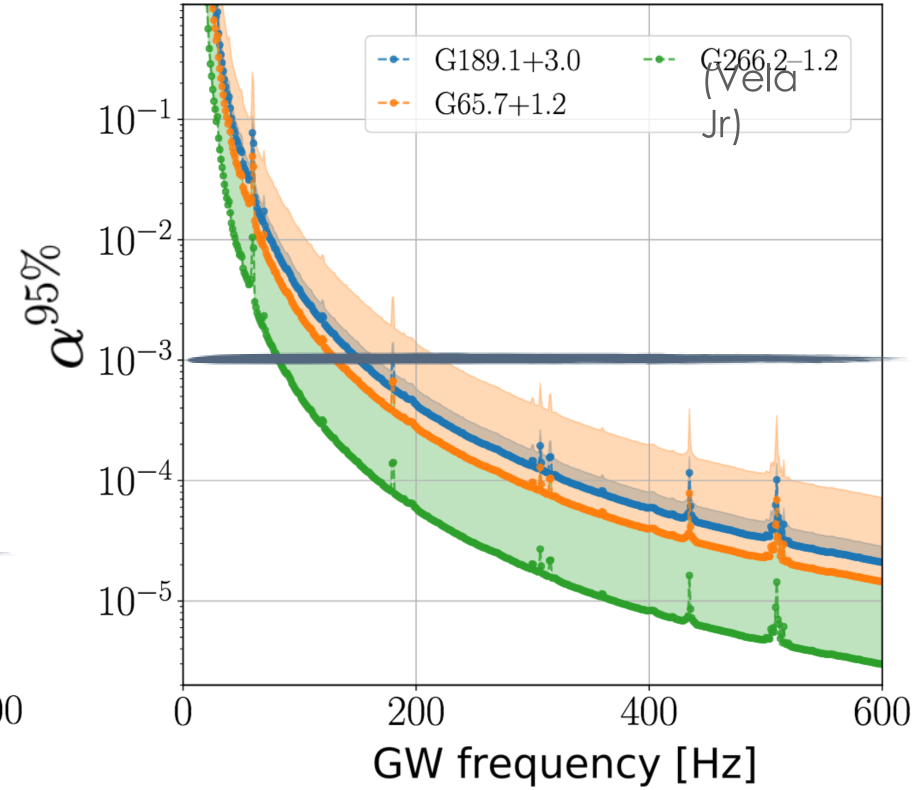
O3 HLV, arXiv:2112.10990 (2021) ApJ

DIRECTED: Young supernova remnants

- *Search for **15 young supernova remnants** in frequency bands within **[10, 2000] Hz***
- *Take into consideration **spin-wandering** and **dual-harmonic** emission (3 algorithms).*
- *No detections ($h_{0,min}$~$7.7x10^{-26}$ for G65.7+1.2) but constraints placed on ellipticities and r-mode oscillation amplitudes*
- ***Ellipticity <10^{-6}** for most of the sources; reaching below the rough theoretical upper limit for normal neutron stars. ε_{min}~$6x10^{-8}$ for G266.2-1.2/Vela Jr.*
- ***r-mode amplitude < 10^{-3}**, reaching below the theoretical prediction level expected for the nonlinear saturation mechanisms*

- *A deeper O3a search in band **[20, 976] Hz** achieved the **best** sensitivities for **Cassiopeia A and Vela Jr.**, setting limits ~30% lower below 600 Hz.*



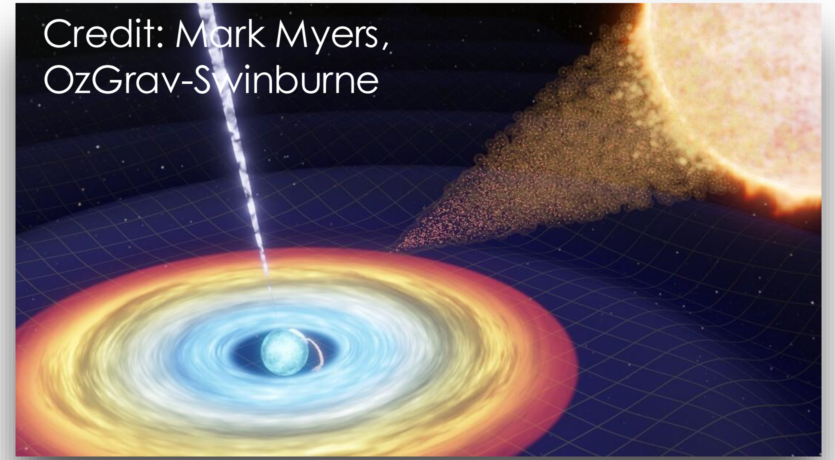


O3a HLV, ApJ 921, 80 (2021)

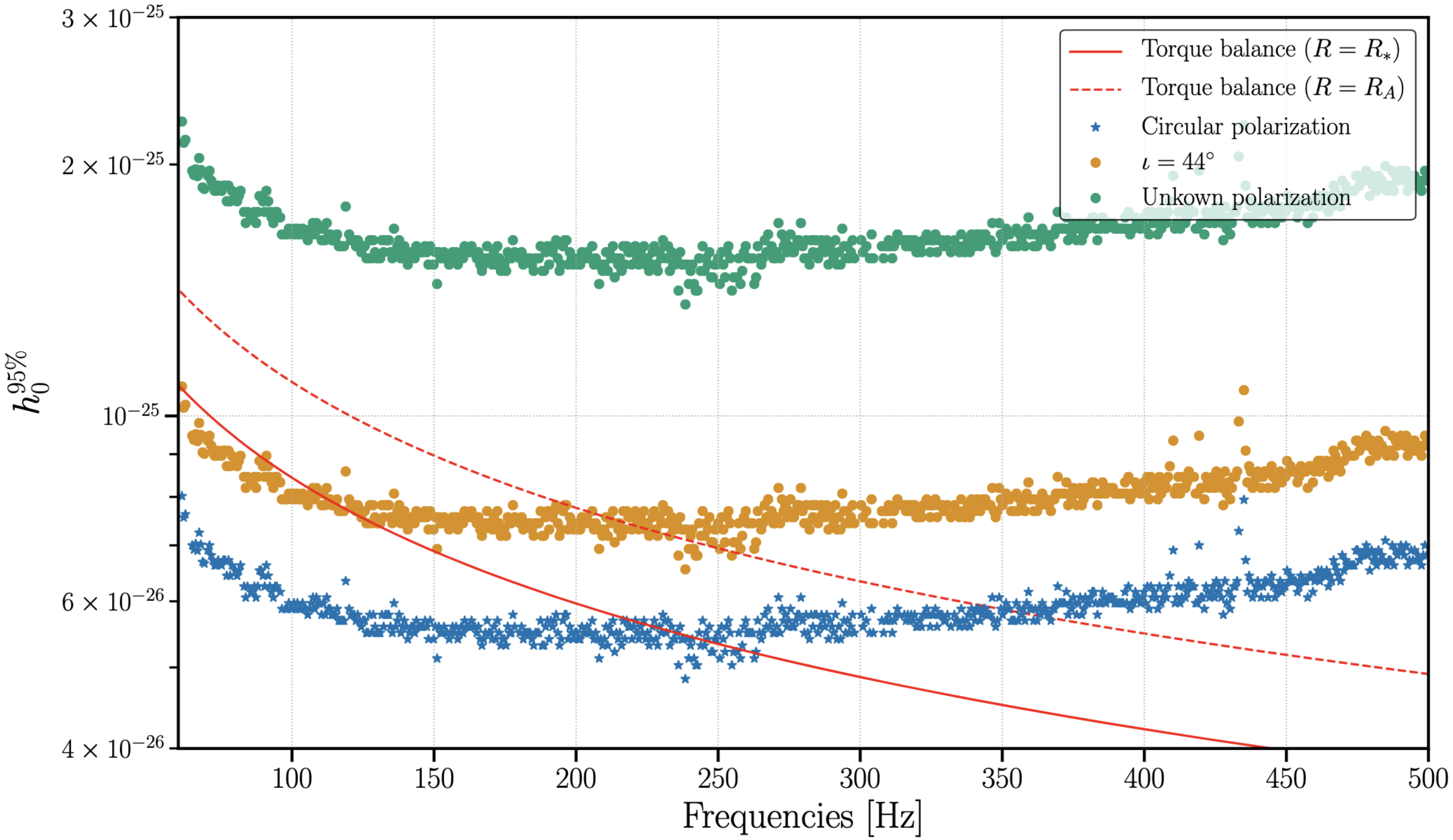
O3a HL, PRD 105, 082005 (2022)

DIRECTED: Scorpius X-1

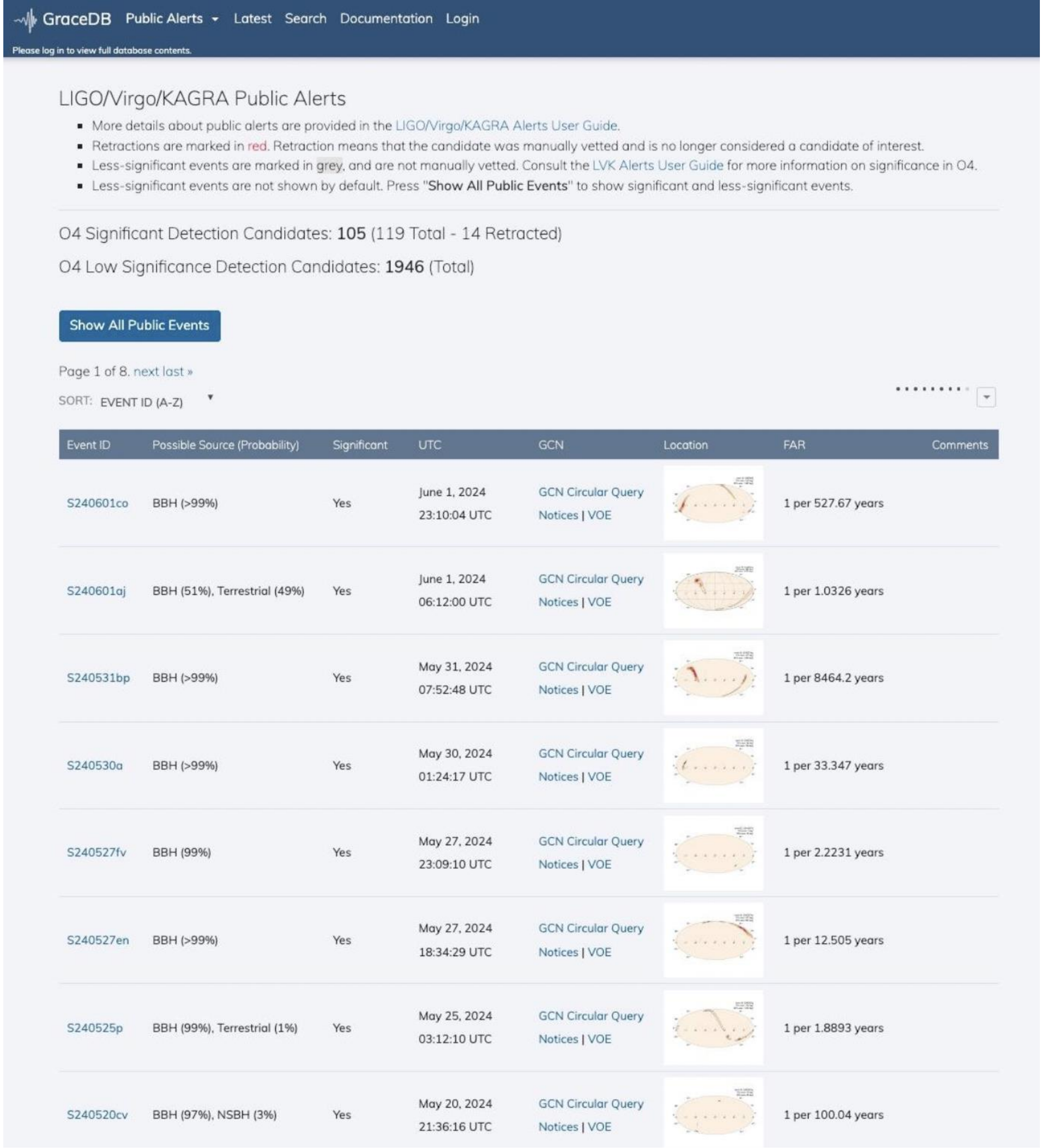
- *Scorpius X-1 is the most X-ray-luminous low-mass X-ray binary*
- *Covered broad frequency range* ***[60, 500] Hz****, accounting for* ***spin wandering***



- *A deeper search using a model-based technique is in progress*



O3 HL, arXiv:2201.10104 (2022)



GraceDB Public Alerts Latest Search Documentation Login

Please log in to view full database contents.

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: **105** (119 Total - 14 Retracted)

O4 Low Significance Detection Candidates: **1946** (Total)

Show All Public Events

Page 1 of 8. next last »

SORT: EVENT ID (A-Z)

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S240601co	BBH (>99%)	Yes	June 1, 2024 23:10:04 UTC	GCN Circular Query Notices | VOE		1 per 527.67 years	
S240601aj	BBH (51%), Terrestrial (49%)	Yes	June 1, 2024 06:12:00 UTC	GCN Circular Query Notices | VOE		1 per 1.0326 years	
S240531bp	BBH (>99%)	Yes	May 31, 2024 07:52:48 UTC	GCN Circular Query Notices | VOE		1 per 8464.2 years	
S240530a	BBH (>99%)	Yes	May 30, 2024 01:24:17 UTC	GCN Circular Query Notices | VOE		1 per 33.347 years	
S240527fv	BBH (99%)	Yes	May 27, 2024 23:09:10 UTC	GCN Circular Query Notices | VOE		1 per 2.2231 years	
S240527en	BBH (>99%)	Yes	May 27, 2024 18:34:29 UTC	GCN Circular Query Notices | VOE		1 per 12.505 years	
S240525p	BBH (99%), Terrestrial (1%)	Yes	May 25, 2024 03:12:10 UTC	GCN Circular Query Notices | VOE		1 per 1.8893 years	
S240520cv	BBH (97%), NSBH (3%)	Yes	May 20, 2024 21:36:16 UTC	GCN Circular Query Notices | VOE		1 per 100.04 years	

LVK- O4:

1) Observing Run #4 (O4) started on May 24, 2023.
2) The LIGO Virgo KAGRA collaborations had our 100th O4 gravitational wave candidate a week ago on May 27th. (Named S240527en observed on Memorial Day).

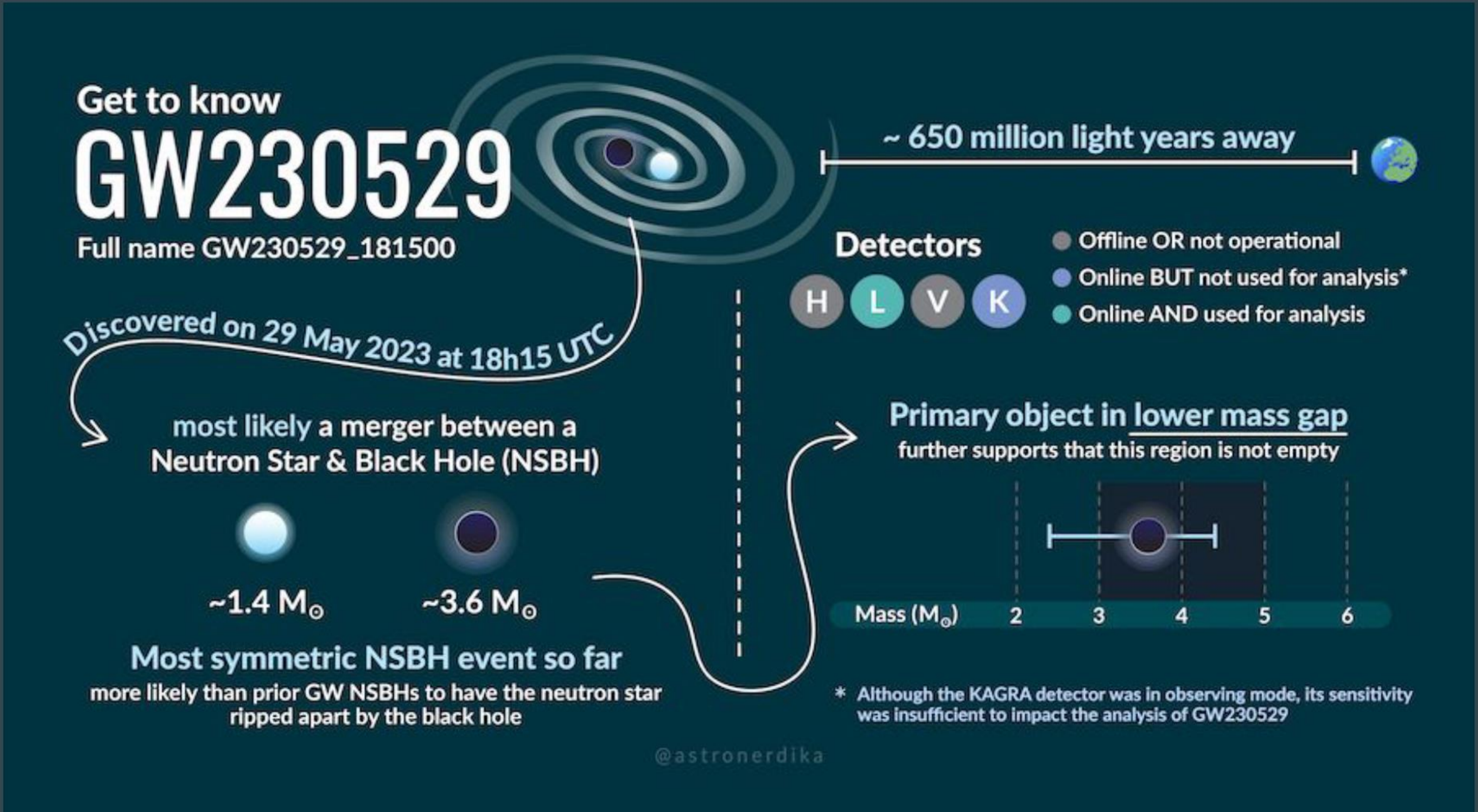
You can always follow along with O4 Public Alerts here: https://gracedb.ligo.org/superevents/public/O4/

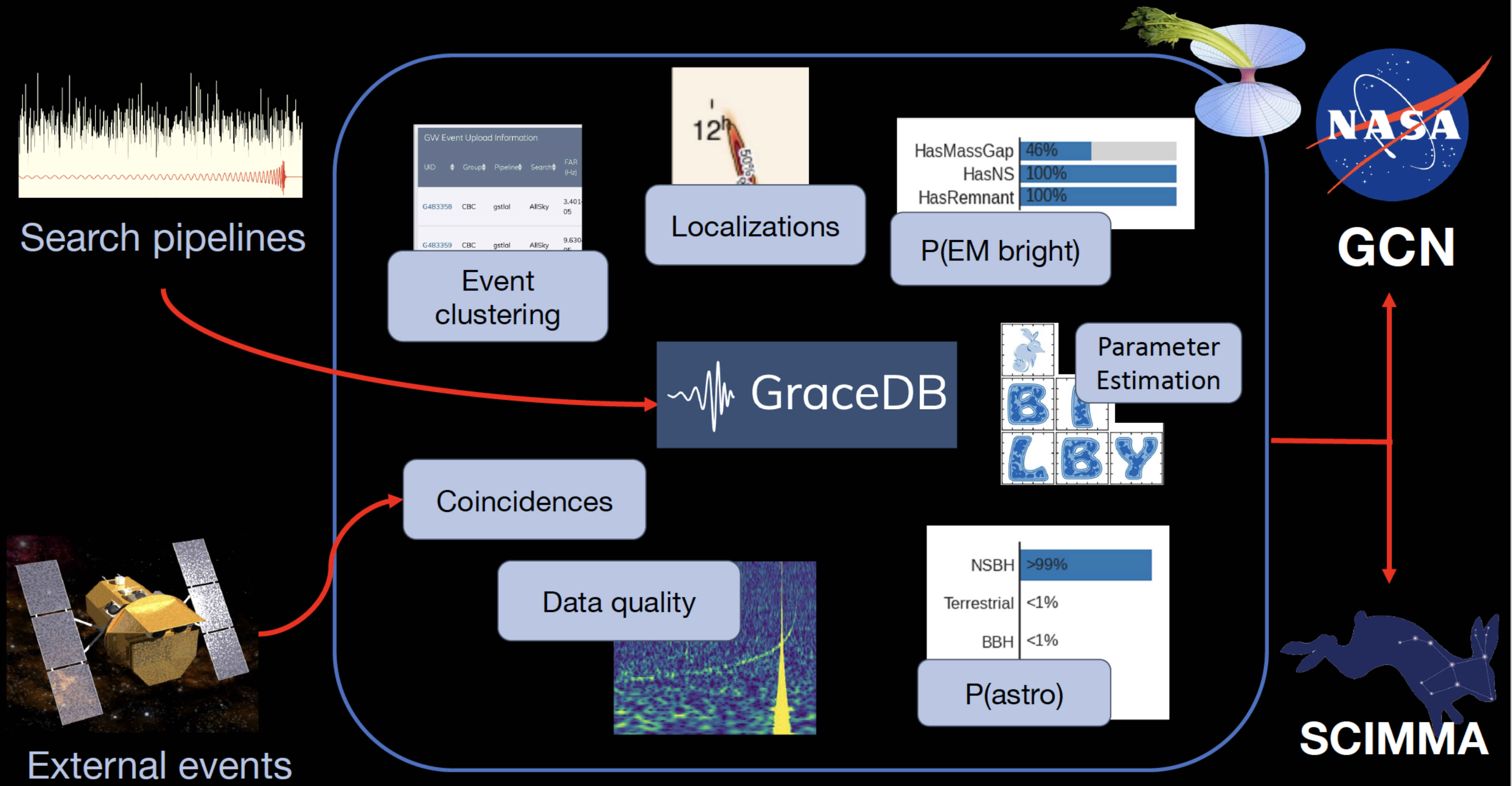
--As of today, there have been 149 O4 Significant Detection Candidates: 149 (166 Total - 17 Retracted).
O4 Low Significance Detection Candidates: 2560 (Total)

--Our first exceptional O4 gravitational wave detection (GW230529) was announced on April 5, 2024 (more info here: https://www.ligo.org/detections/GW230529.php).

--O4a went from May 24, 2023 to Jan 16, 2024.
--The O4 break + Engineering Run 16 (ER16) was from Jan 16 to April 12 this year.
--O4b/c started on April 12, 2024 and will tentatively end in June 9, 2025.

First O4 result: GW230529 [Abac+ (LVK) ApJL970:L34 / arXiv:2404.04248]





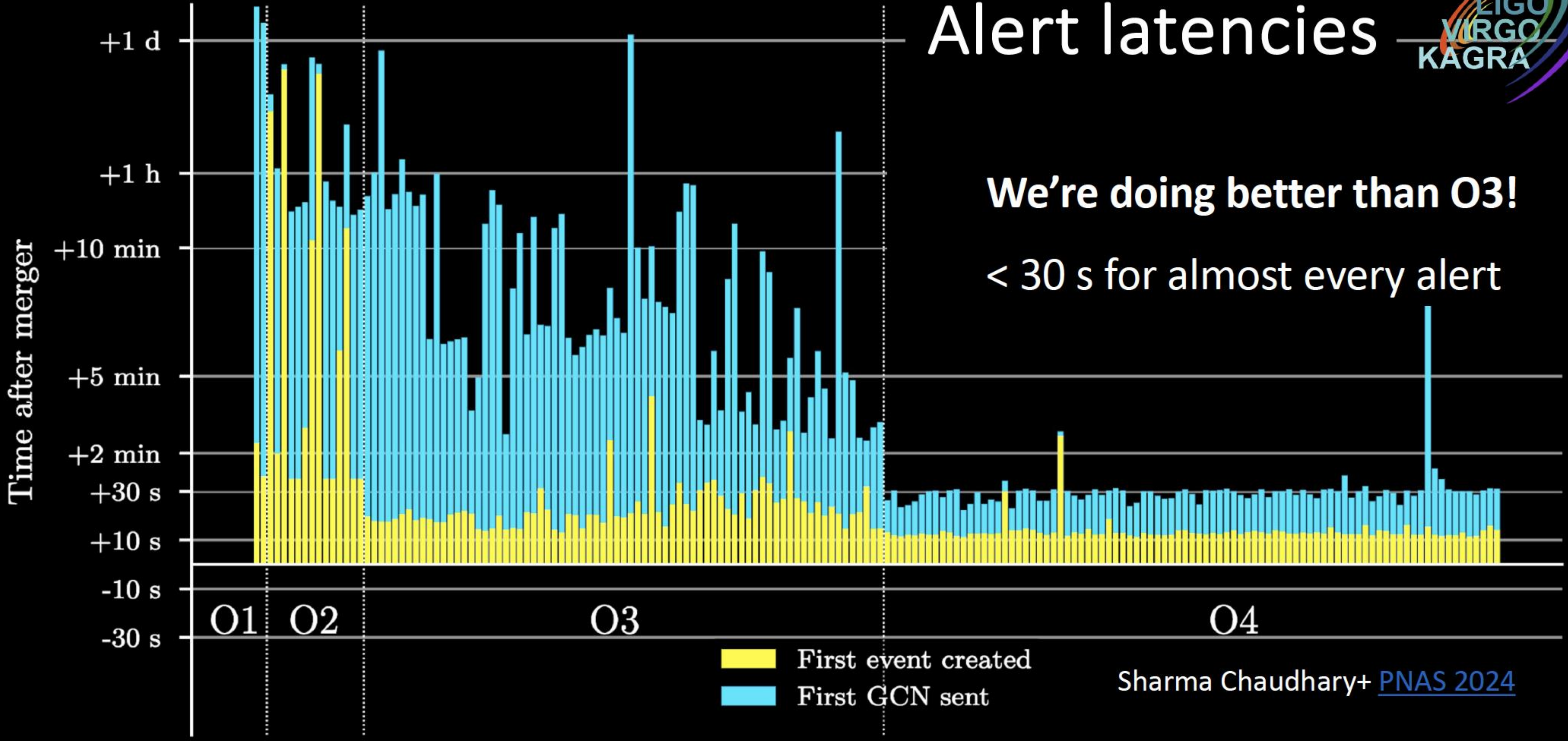
Slide credit: Geoffrey Mo, MIT

gwcelery.readthedocs.io/

Alert latencies

We're doing better than O3!

< 30 s for almost every alert



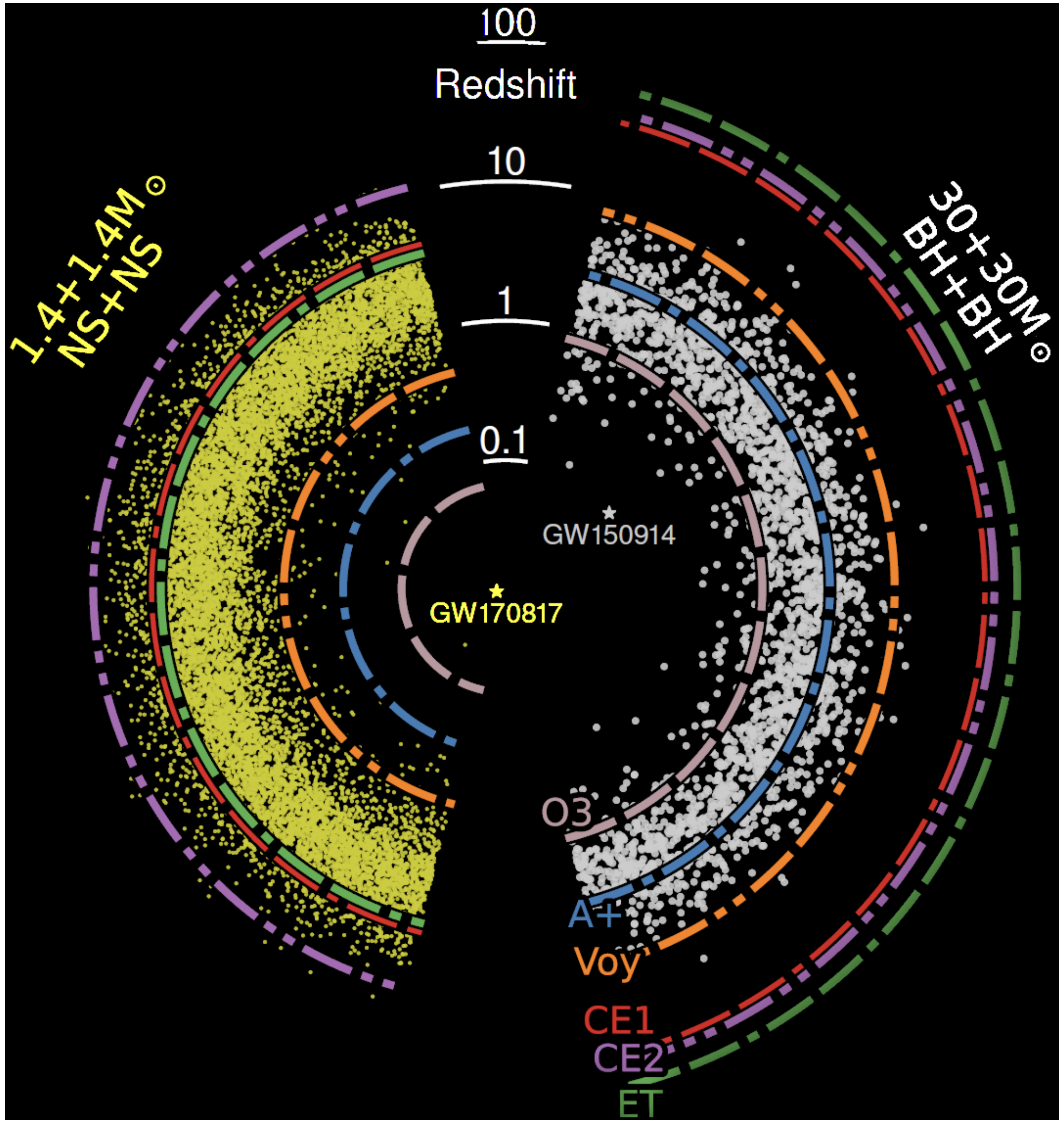
Sharma Chaudhary+ PNAS 2024

Slide credit: Geoffrey Mo, MIT

Next Generation Observatories

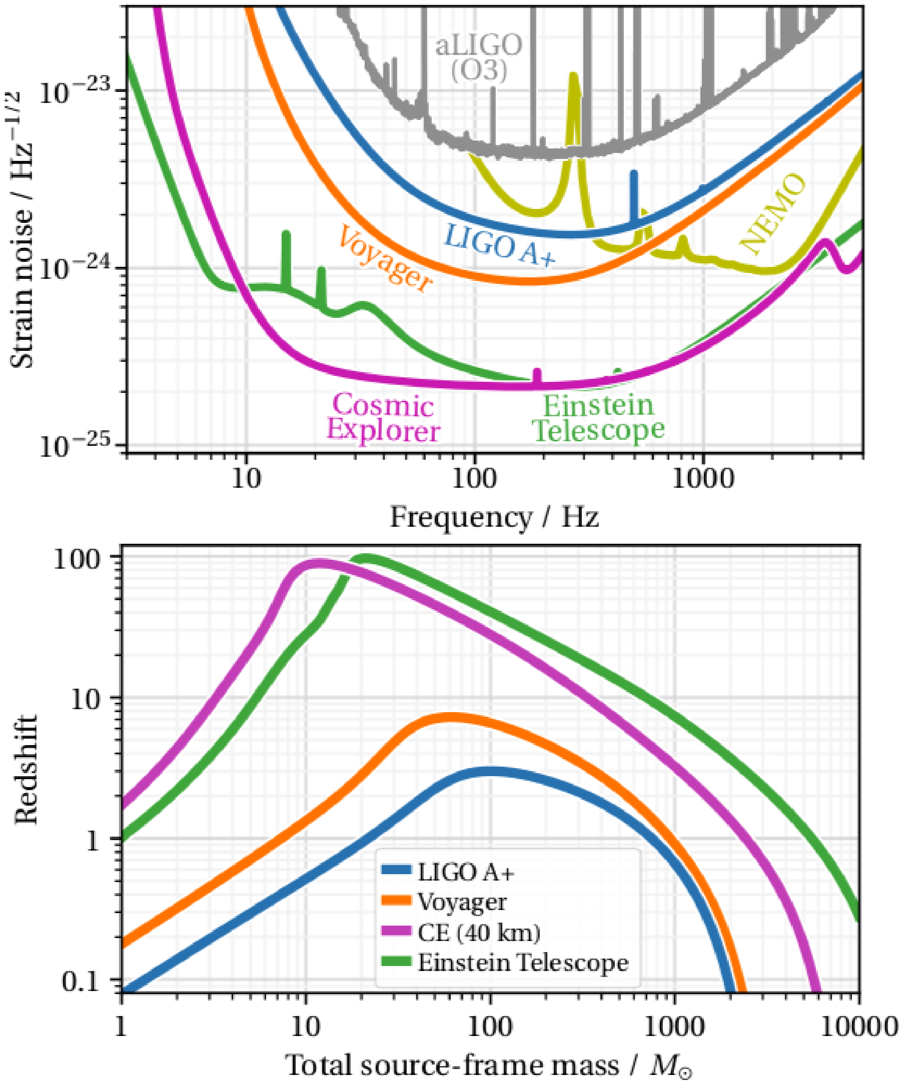
- O5 will be "LIGO A+", significant further upgrades for Virgo and KAGRA too.
- LIGO India is coming! [Unnikrishnan IJMPD33,2450025 (2024)]
- Next upgrade plan "LIGO A♯" [LIGO-T2200287 / LIGO-T2200287]

- "3rd generation" detectors enable a ~complete census of BNS and BBH mergers
    - Robust statistics on GRB+BNS merger association, and how that correlates with orientation & distance
- BNS signals will be in band and detectable for O(100s) of seconds to several hours
    - Advanced warning for EM follow-up (though localization will be rough)



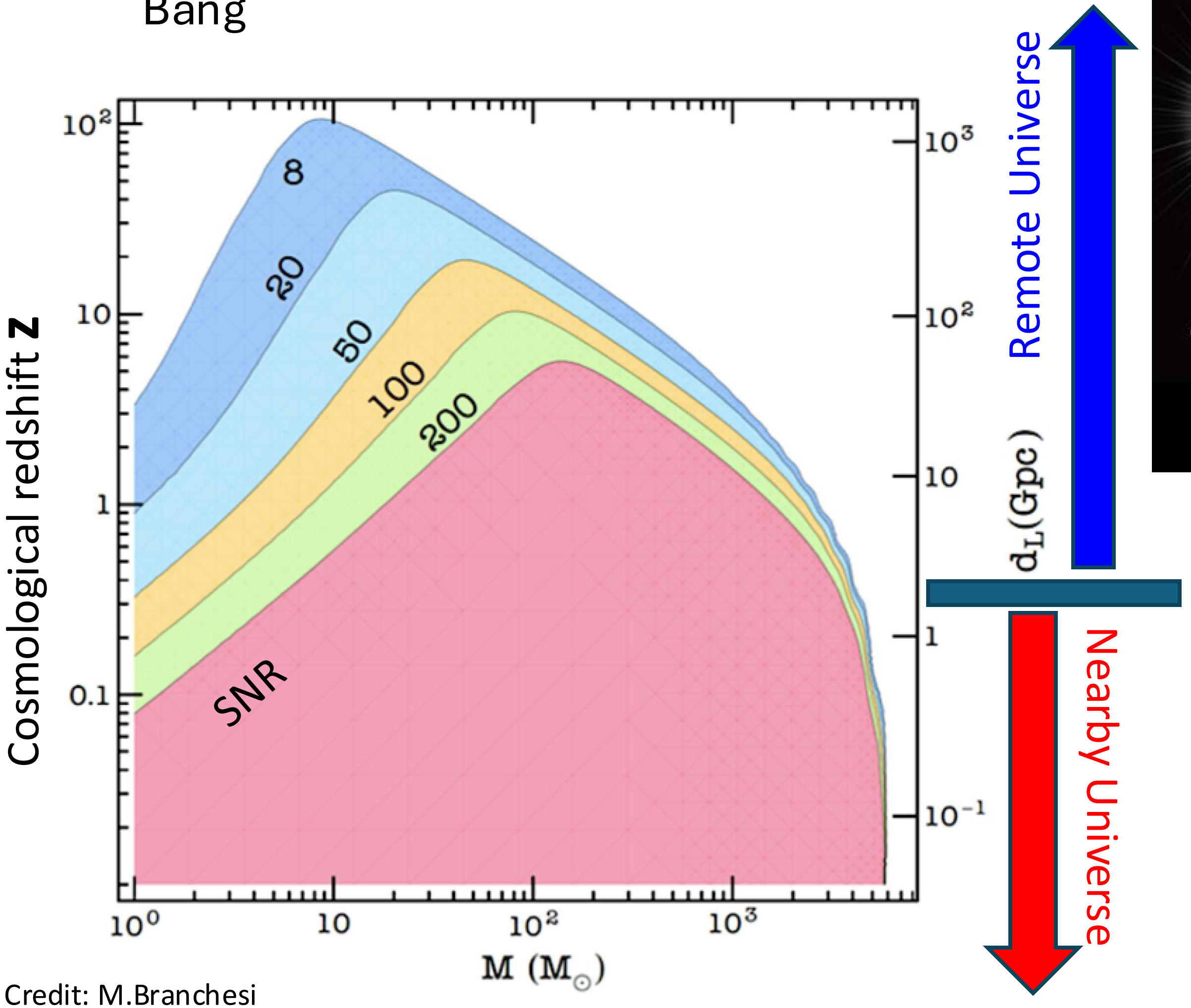
From 2G to XG

- Gain of a factor of 10 and lower frequency bound
- Triangle configuration for Einstein Telescope.
- Two widely separated, L-shaped surface facilities in the US CE40 and CE20 for Cosmic Explorer
- New possibilities (null stream, new algorithms, new computing technology, new synergies)
- New challenges (long-waveforms, overlapping signals, strong foreground, correlated noise)
- XG observatories will detect thousands of signals every day
    - Weak signals, loud mergers,
    - BNS, NSBH, BBH, SN bursts, CW, …
- Current algorithms are woefully inadequate for parameter inference

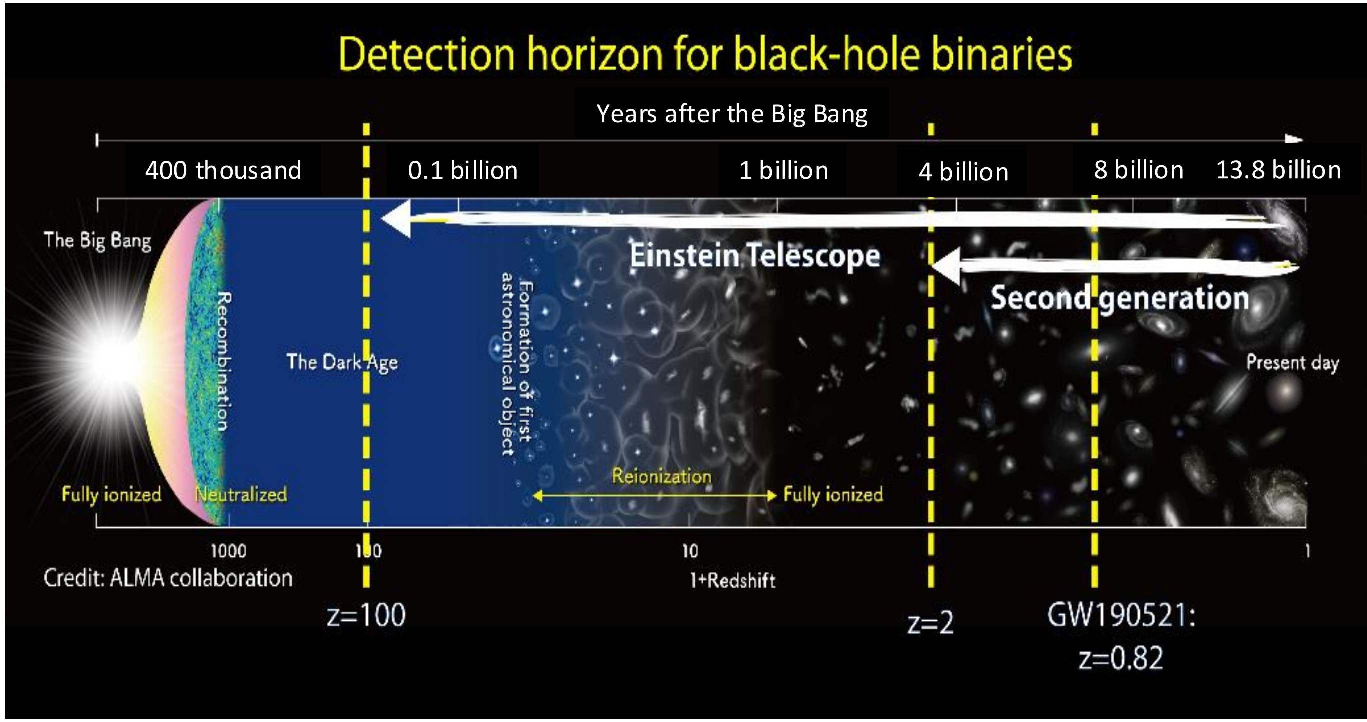


The next generation

- ET/CE will be a new discovery machine:
  - ET/CE will explore almost the entire Universe listening the gravitational waves emitted by black hole, back to the dark ages after the Big Bang



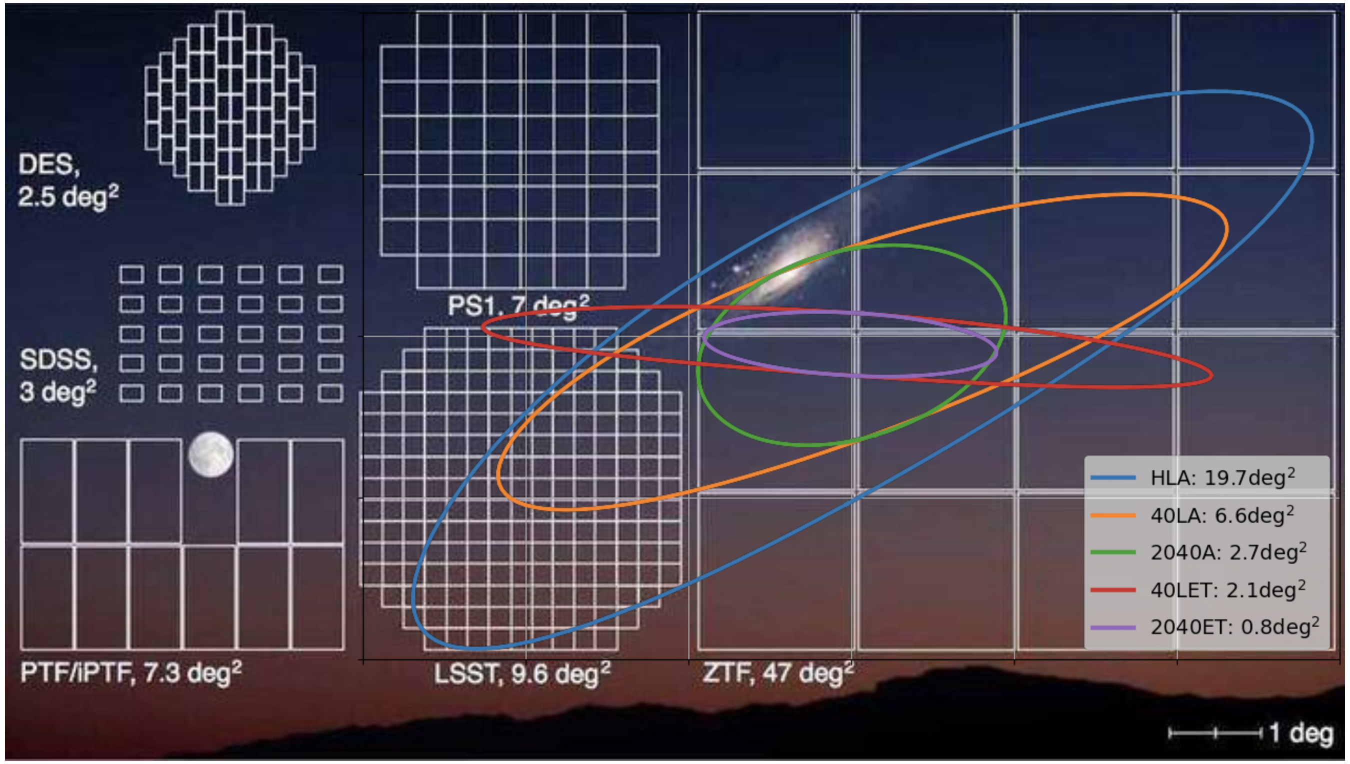
Credit: M.Branchesi



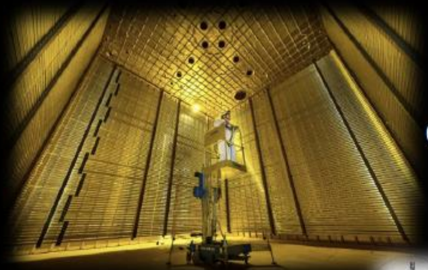
- ET/CE will be a precision measurement observatory:
  - ET/CE will detect, with high SNR, hundreds of thousands coalescences of binary systems of Neutron Stars per year, revealing the most intimate structure of the nuclear matter in their nuclei

Multi-messenger Astrophysics

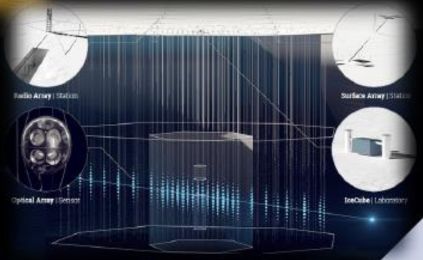
- At least one 40km CE →100x higher BNS detection rate
- BNS redshift reach of $z \approx 2$
  - Map the progenitors of short gamma-ray bursts
  - Measure time delays
- With at least 2 XG detectors:
  - Tens of signals localized to < 1 deg^2
  - Thousands to < 10 deg^2
  - Few – tens < 10 deg^2 5 mins before merger



Multimessenger synergies



Galactic core-collapse supernova



Gamma-ray bursts from neutron star mergers

Neutrino:

DUNE, NKM3Net, IceCube Gen2

Radio:

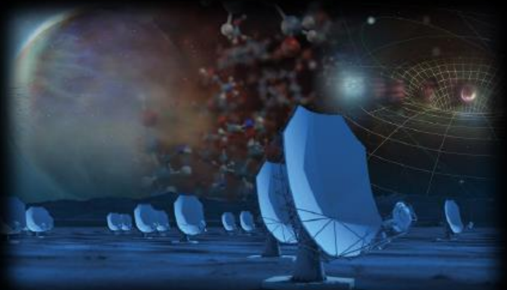
ng VLA, SKA

X-ray/Gamma-ray:

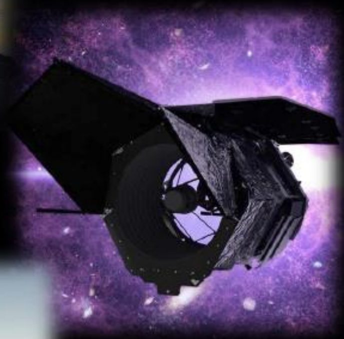
Einstein Probe, Athena, THESEUS, HERMES

Optical/IR:

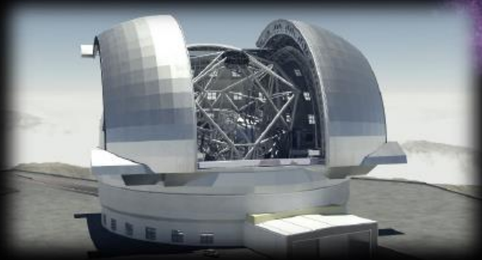
Nancy Grace Roman, ELTs, VRO LSST



Elliptical, single, rapidly-rotating neutron stars



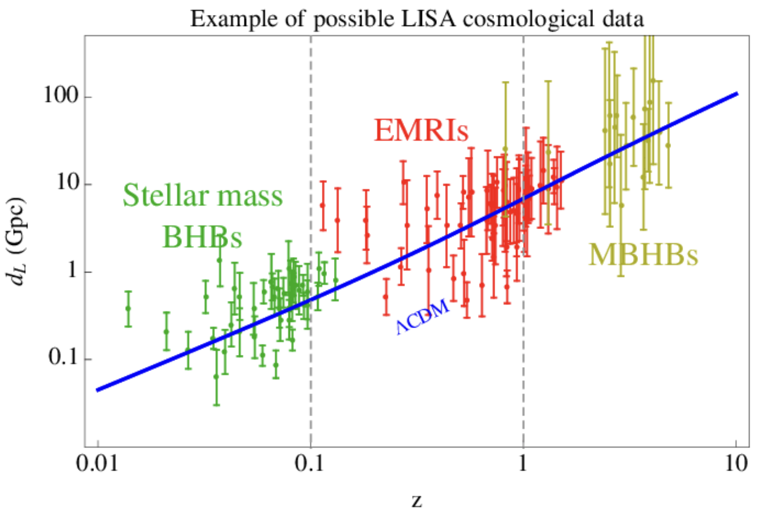
Kilonova, GRB afterglow

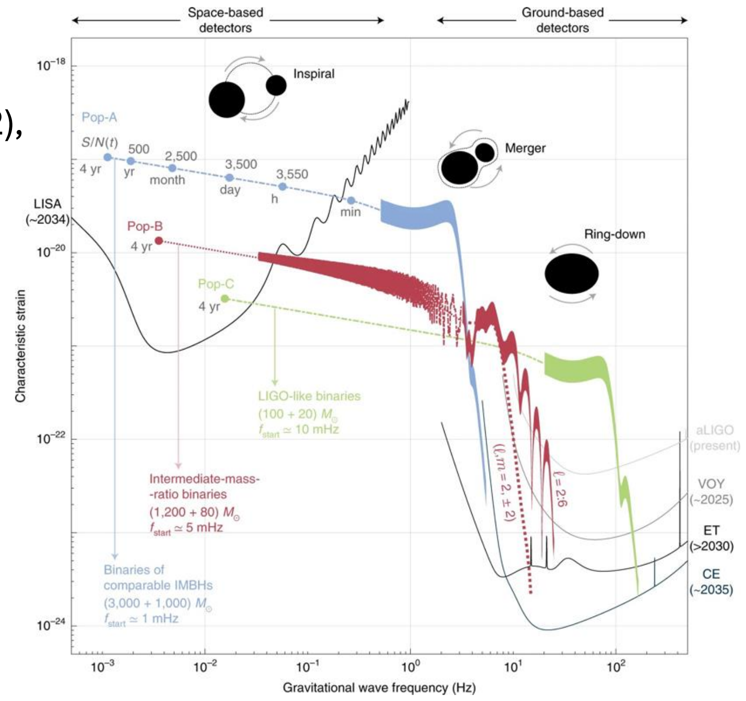


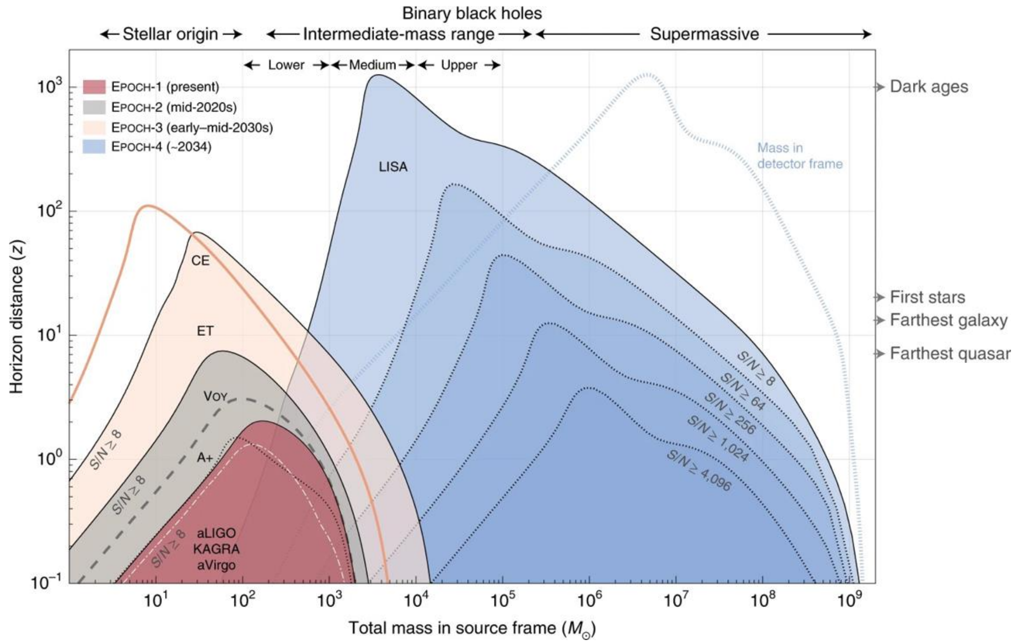
The Science of LISA

- LISA will be the first ever mission to survey the entire Universe with Gravitational Waves.
- LISA will allow us: To investigate the formation of binary systems in the Milky Way; to detect the guaranteed signals from the verification binaries; to study the history of the Universe out to redshifts beyond 20, when the Universe was less than 200 million years old; to test gravity in the dynamical sector and strong-field regime with unprecedented precision; and to probe the early Universe at TeV energy scales.
- Multiband GW Astronomy with LISA and ET/CE

- LISA will probe the expansion history of the Universe using GW sirens at high redshifts (**WARNING**: provided we can obtain the redshift): SOBH binaries (z < 0.2), EMRIs (z < 1.5), MBHBs (z < 6).



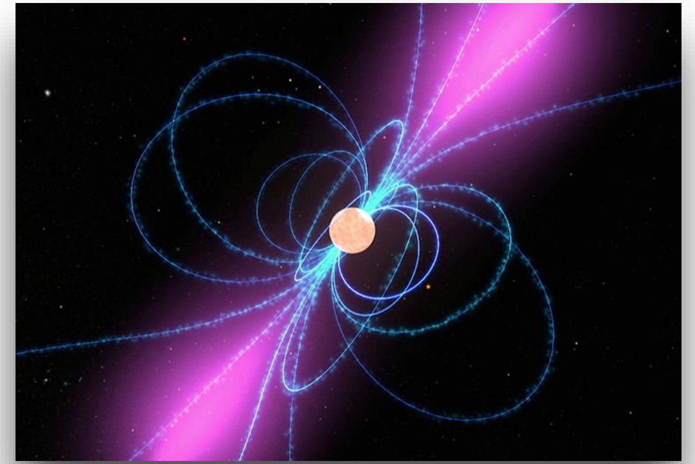


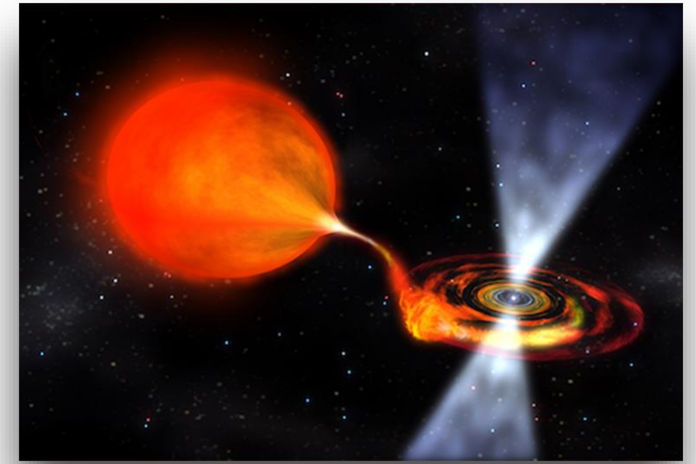


From: Jani, K., Shoemaker, D. & Cutler, C. (2020): *Detectability of* ***intermediate-mass black holes*** *in multiband gravitational wave astronomy*. Nat Astron **4**, 260–265

Summary

- *LIGO-Virgo-KAGRA detectors currently taking data, uploading alerts to enable MMA*
- *Multiple types of searches for multiple types of signals*
- *Considering joint subthreshold searches for GWs coincident with high-energy neutrinos with observing partners*
- *Next-generation ground-based detectors will enable a multimessenger revolution*
- *LISA and ET will become complementary given that the same signal can be followed by LISA and ET in different Hz ranges (LISA pre-warns ET).*





Acknowledgments

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