Gravitational Wave: Status and Selected Results

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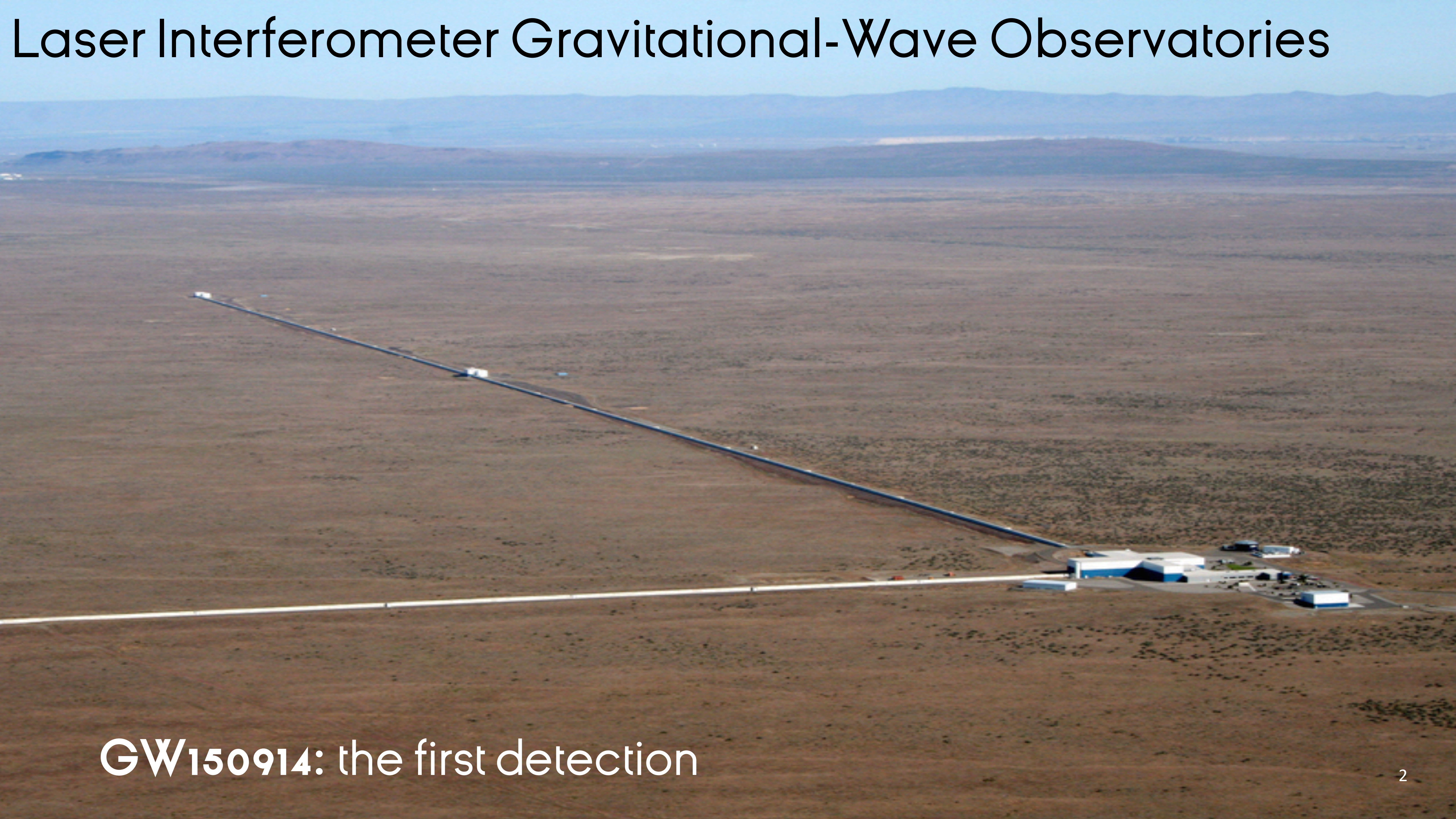
Centro de Ciencias de Benasque Pedro Pascual,
September 5-10, 2022

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

LIGO VIRGO KAGRA

Laser Interferometer Gravitational-Wave Observatories



GW150914: the first detection

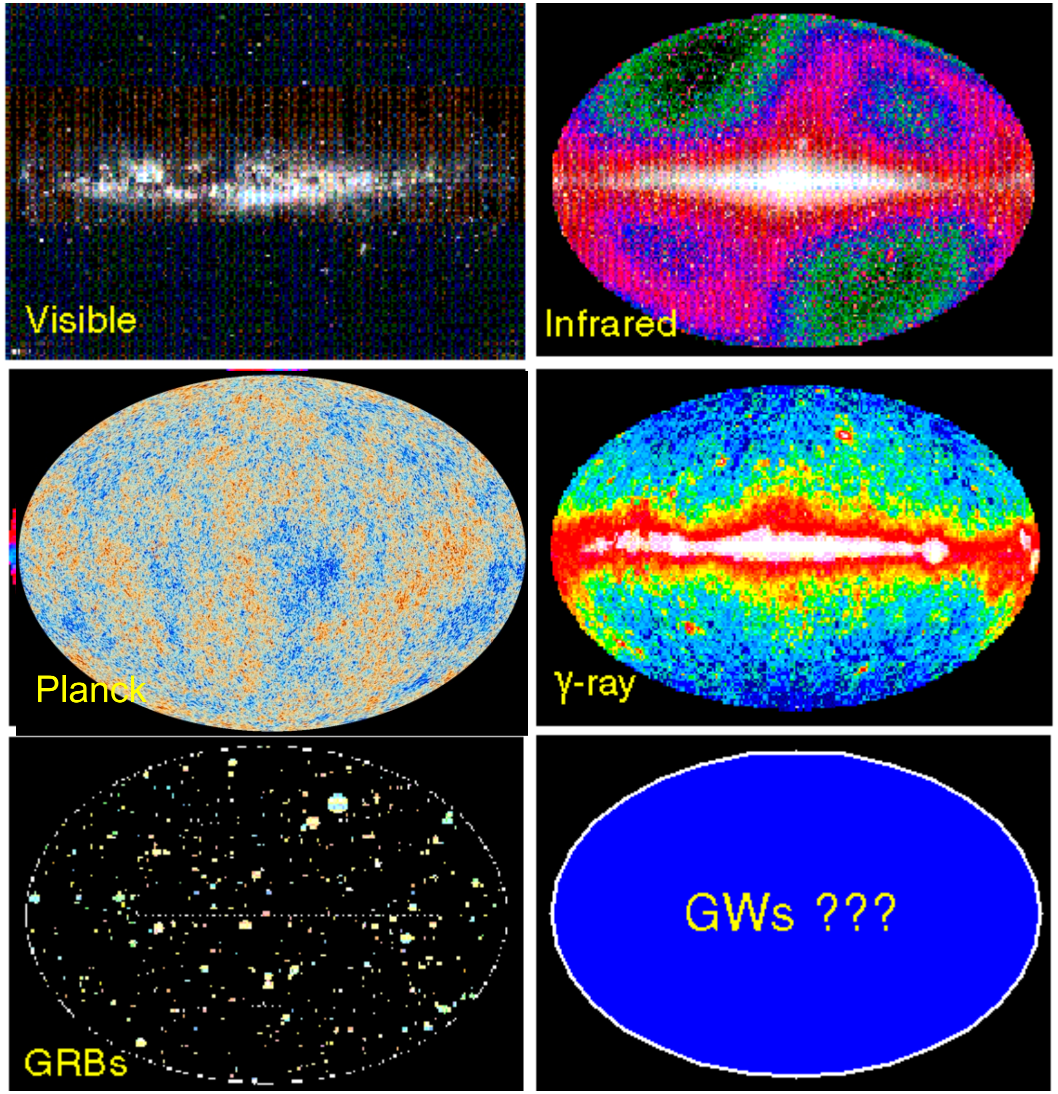
A new window onto the Universe

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.

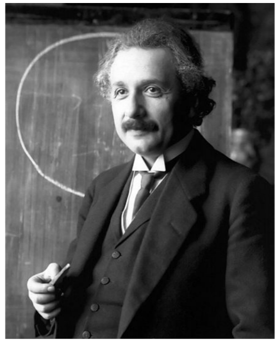
- Vibrations *of* space-time, not *in* space-time
- Emitted by coherent motion of huge masses moving at near light-speed; not vibrations of electrons in atoms
- Can't be absorbed, scattered, or shielded.

GW astronomy is a totally new, unique window on the universe

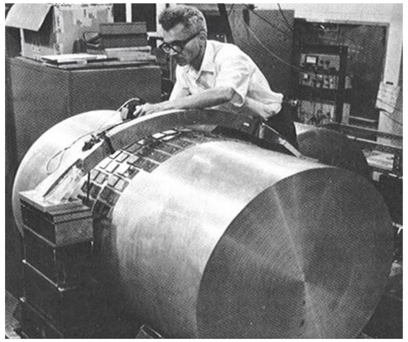


Gravitational Waves - the long road to observational reality

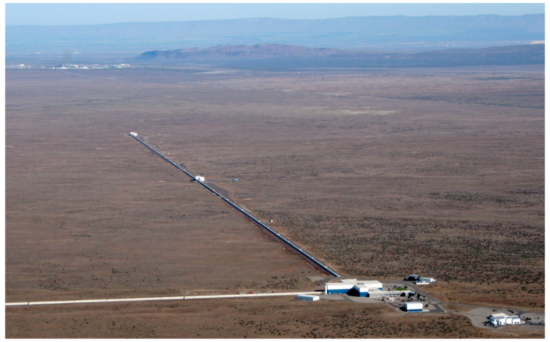
1915 — **1968** — **2002–2010** — **2015** — **2017** — **2021**



GR



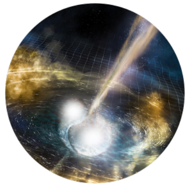
Weber bars



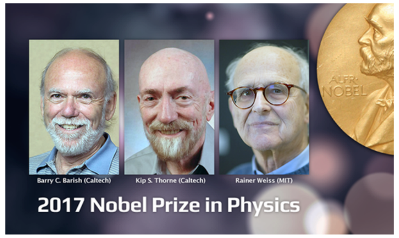
initial LIGO+Virgo operations

aLIGO upgrade

first detection

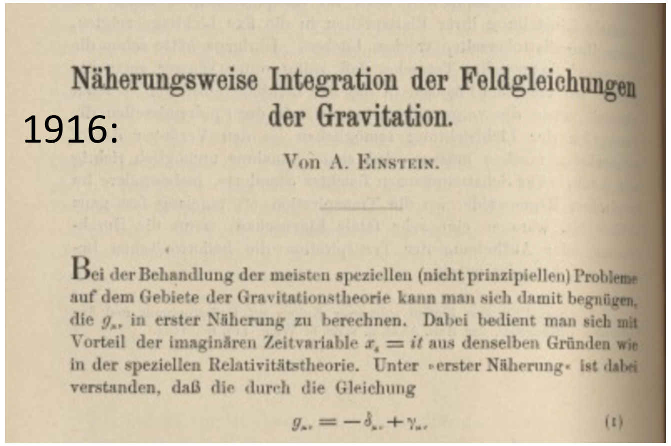


adVirgo joins multi-messenger



90+ detections KAGRA joins

1916:



Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

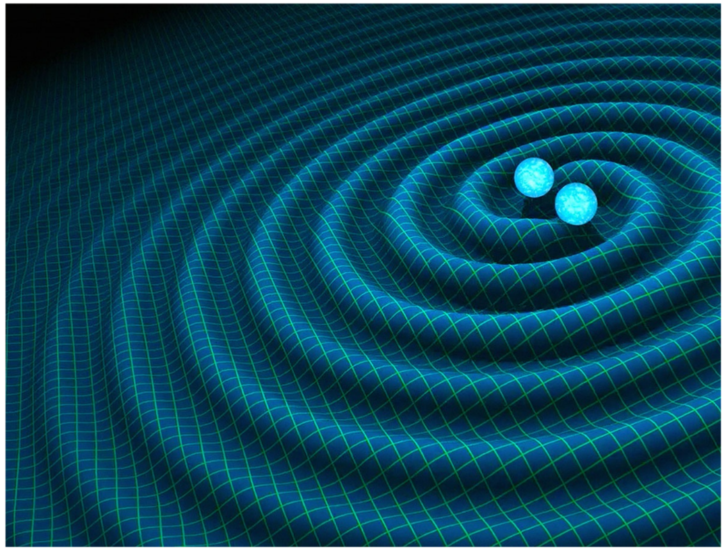
$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \quad (1)$$

Sir Arthur Eddington 1922

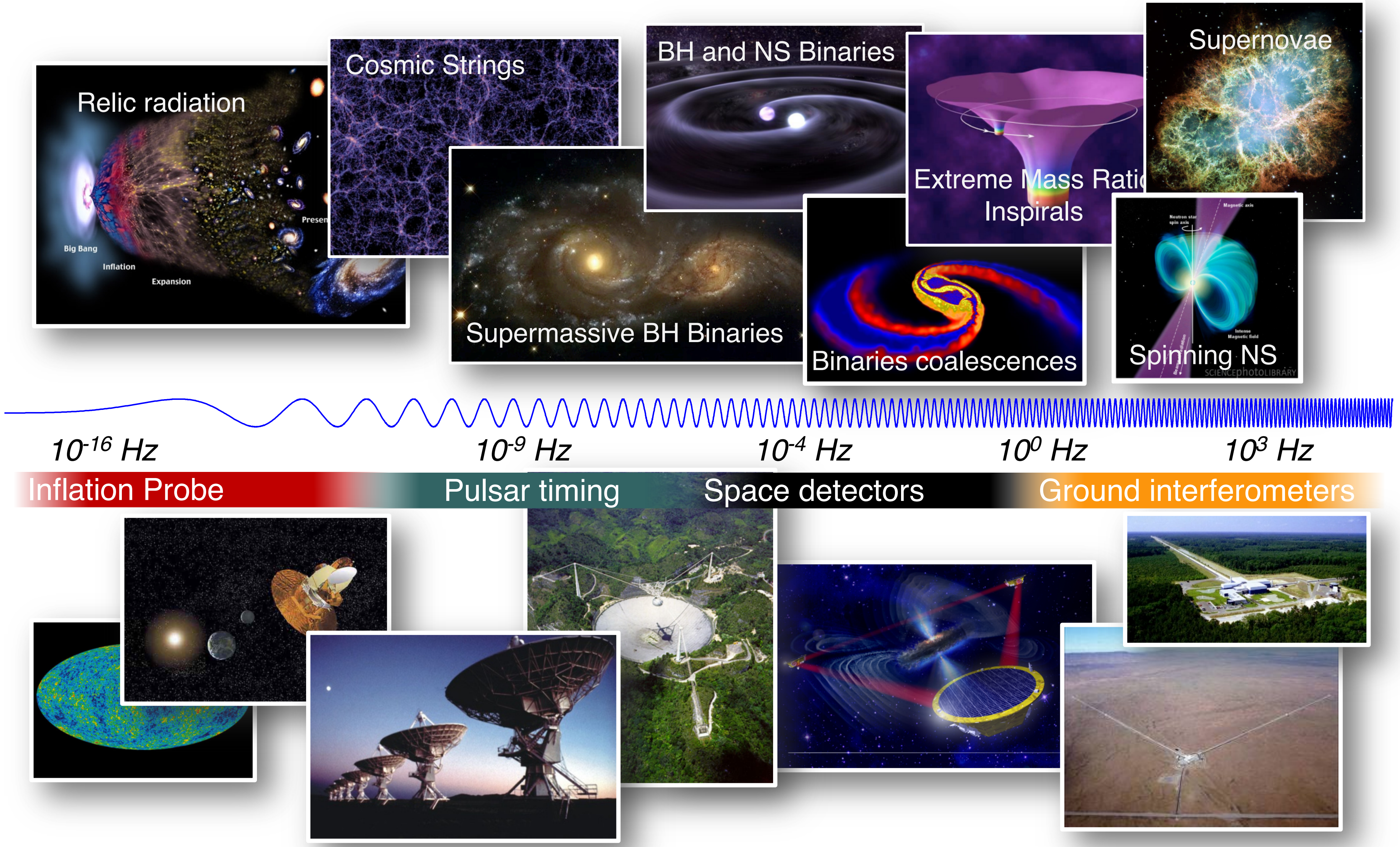
… even for Einstein.
The theory was so subtle, Einstein was never sure that this prediction was correct.
Could the waves be just a math mistake, with no physical reality? Einstein didn't live long enough to learn the answer.

1936: Einstein + Rosen

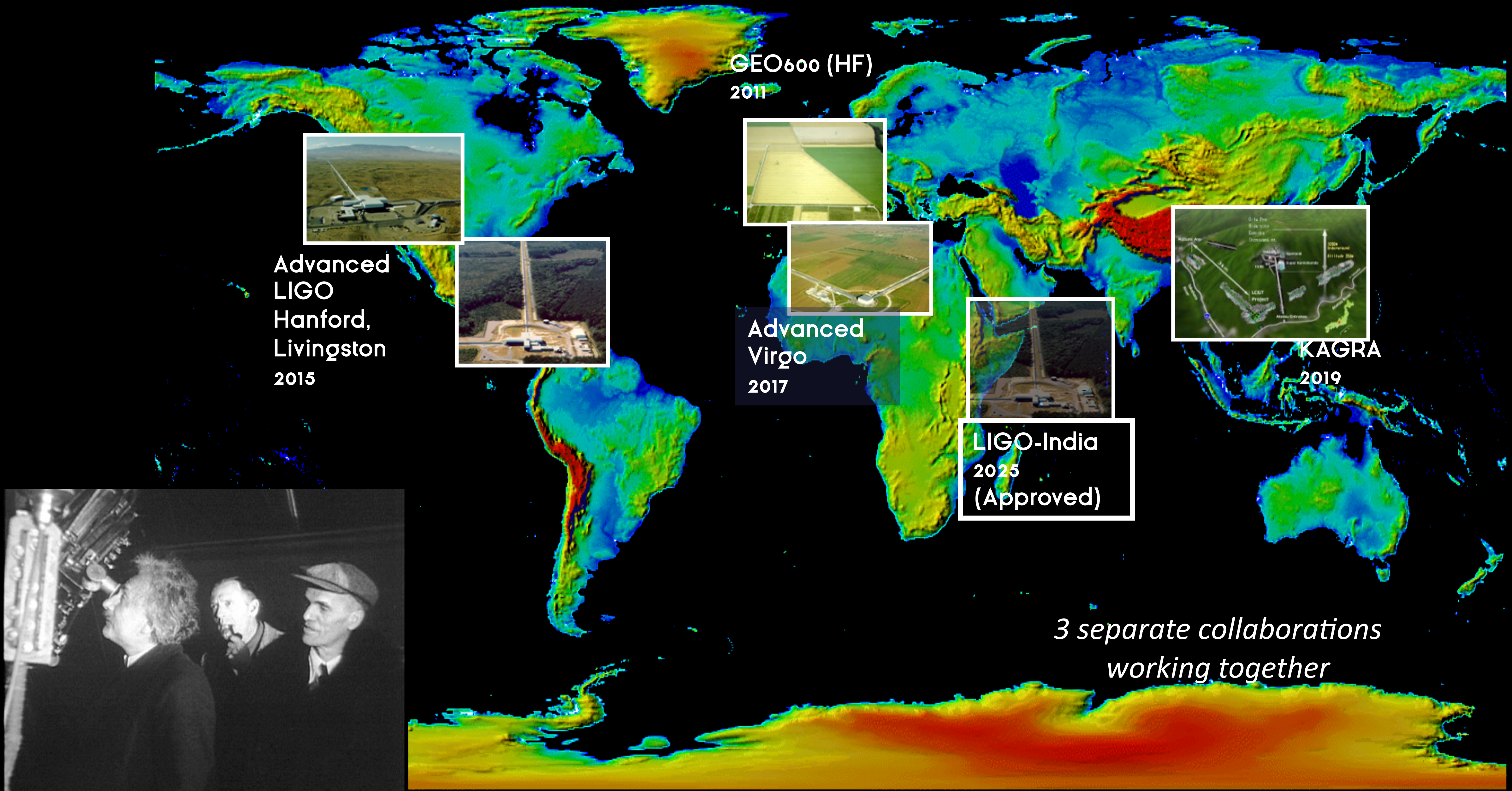
1957: Chapel Hill Conference



Gravitational Wave Spectrum



The growing network of advanced GW detectors

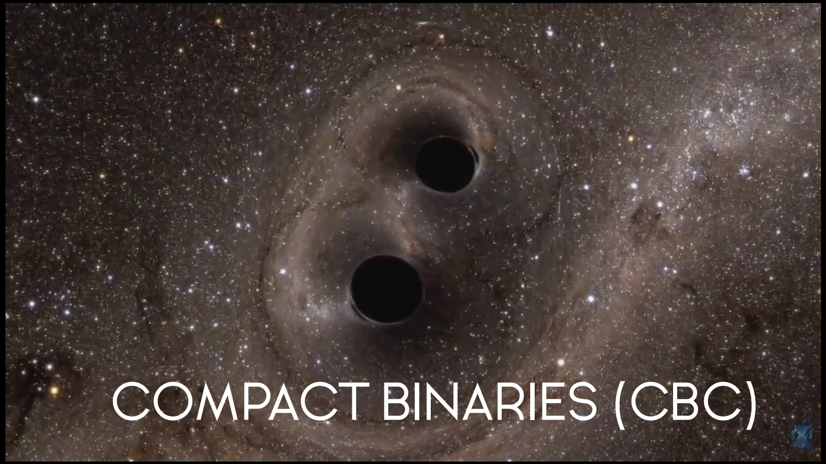


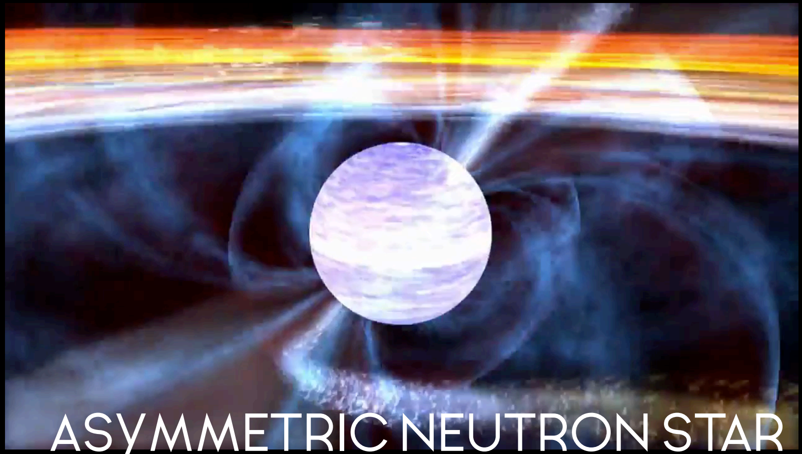
3 separate collaborations working together

Potential Gravitational Wave Sources

TRANSIENT

PERSISTENT





MATCHED FILTER

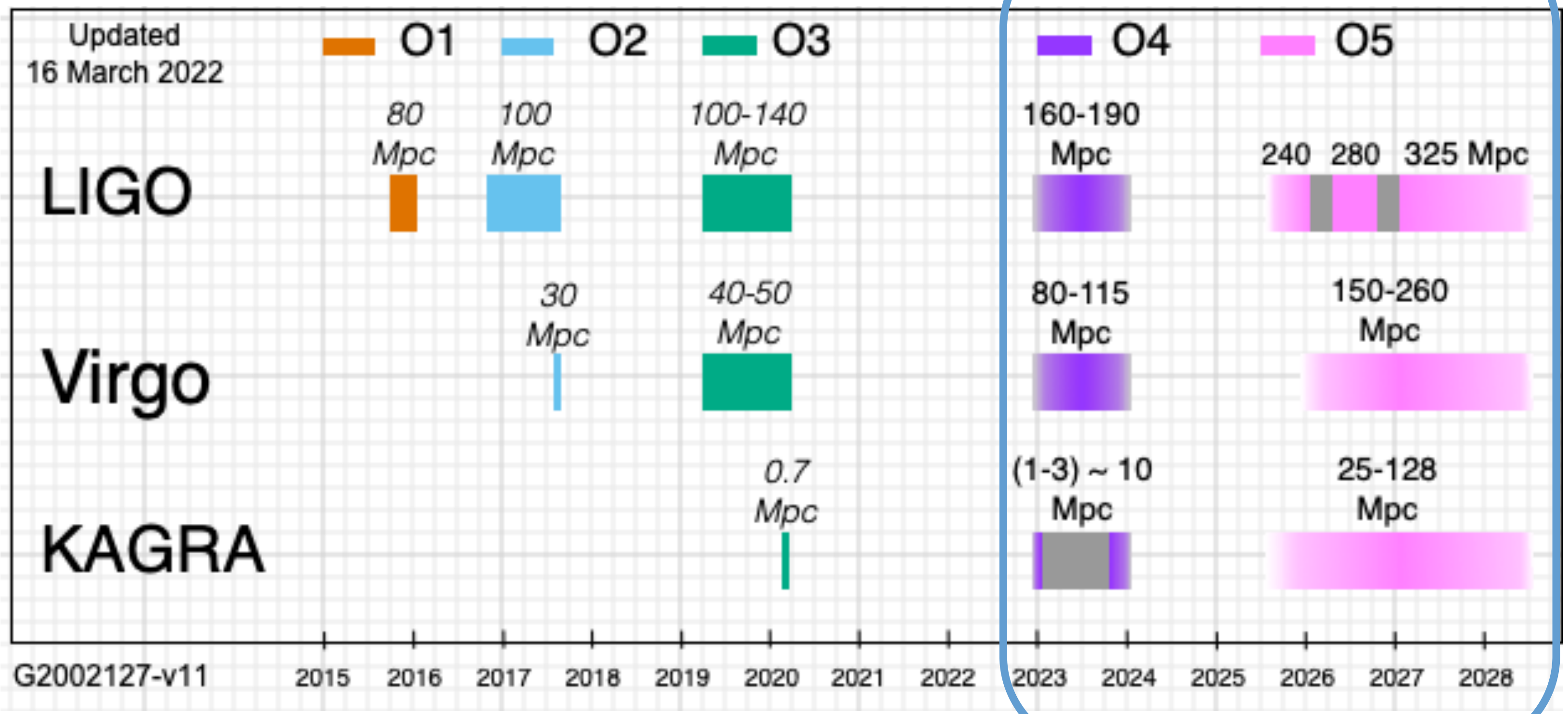
UNMODELED

Observing runs:

On-going Advanced LIGO+ (“A+”)/adVirgo+ upgrades in two main steps:

O4: frequency-dependent squeezing, higher power

O5: improved mirror coatings, full power, …

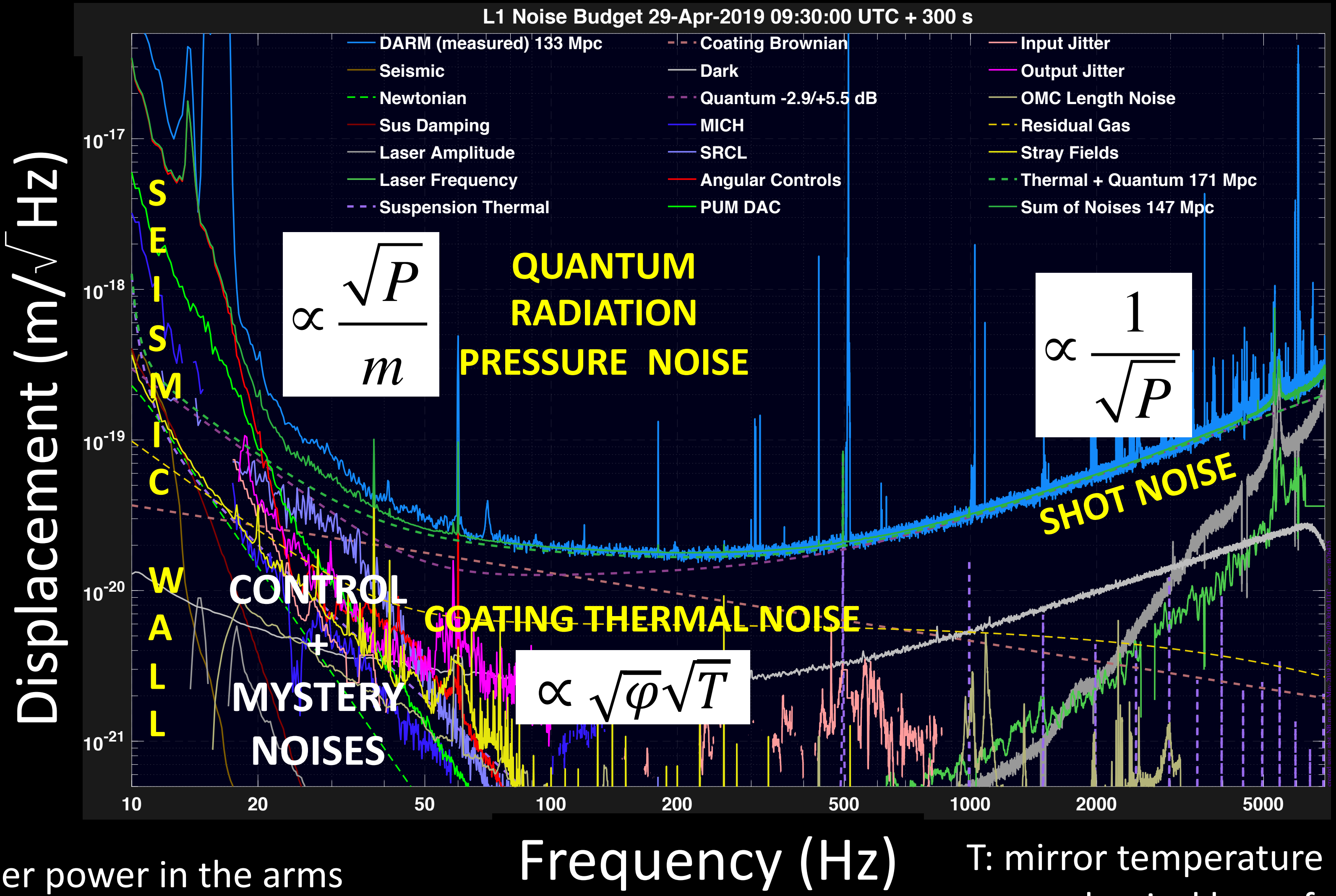


Latest update:
O4 start planned for March 2023.

Work in progress to define the “post-O5” timeline.

LIGO-Virgo-KAGRA observing scenarios: LRR23,3 (2020)

LIGO L1 Noise Budget in O3

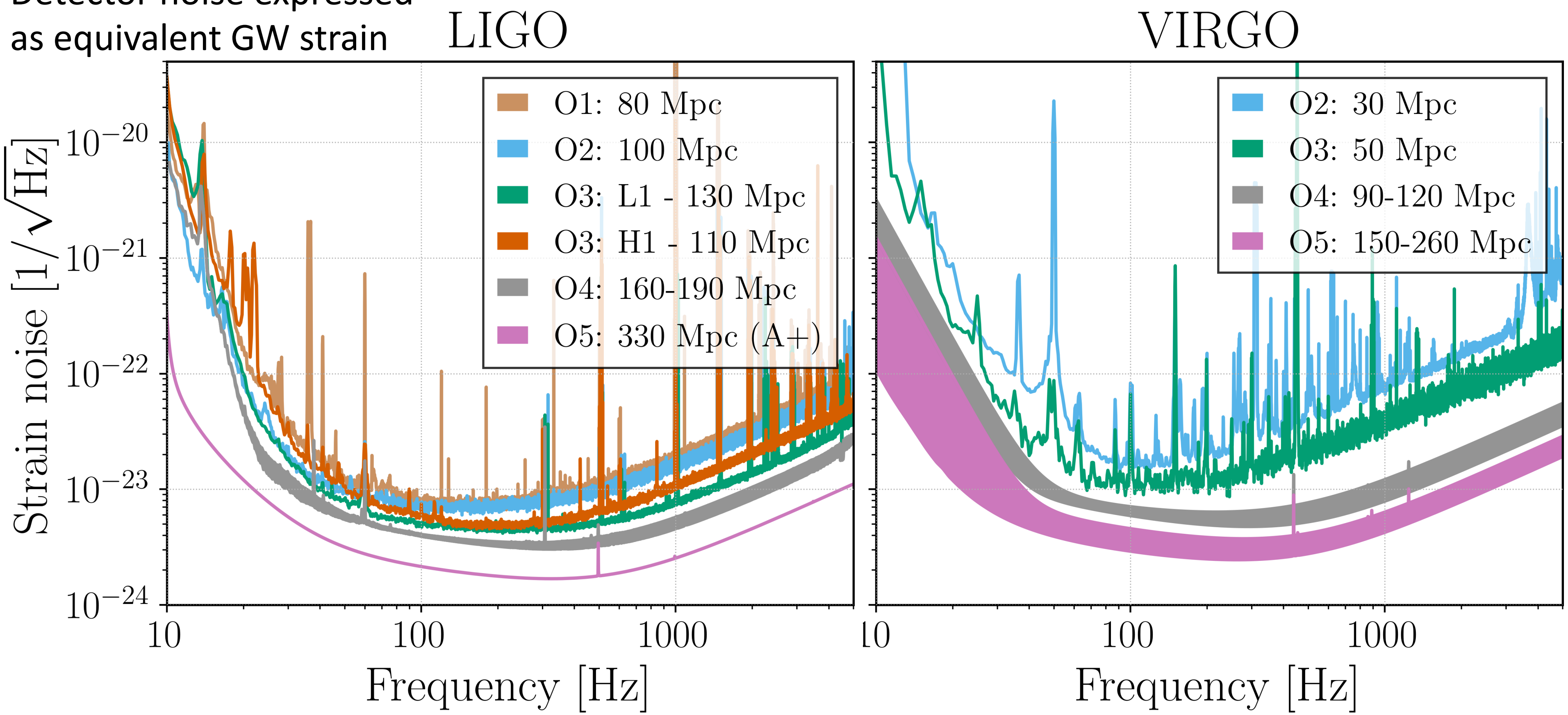


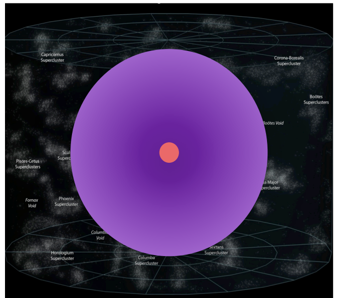
P: laser power in the arms
m: mirror mass

T: mirror temperature
φ: mechanical loss of mirror coating

A+/adVirgo+ Target Sentivities

Detector noise expressed as equivalent GW strain





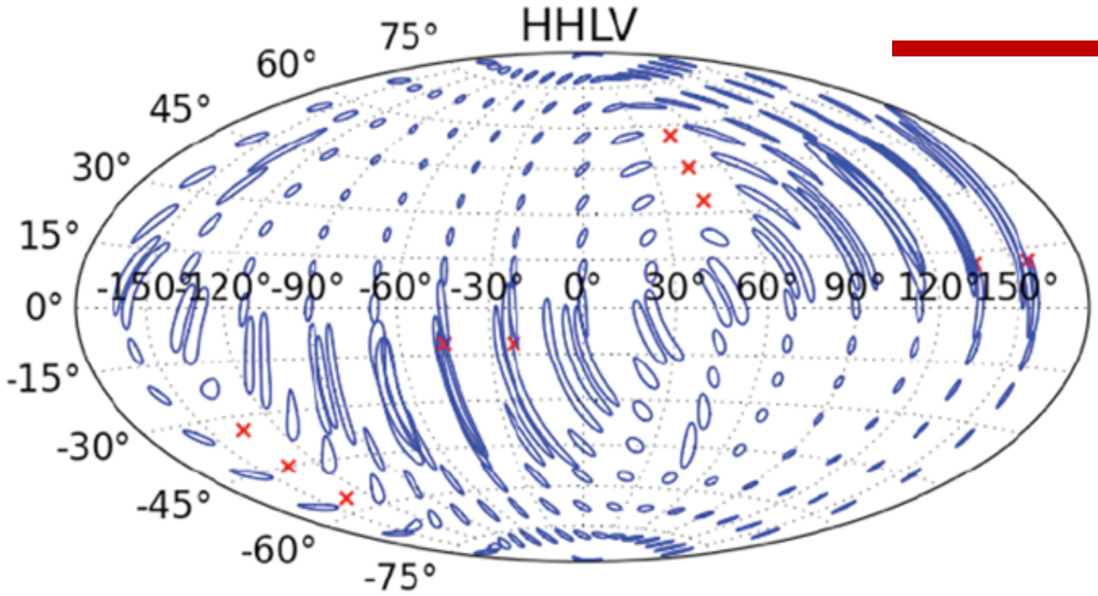
LIGO-Virgo-KAGRA observing scenario

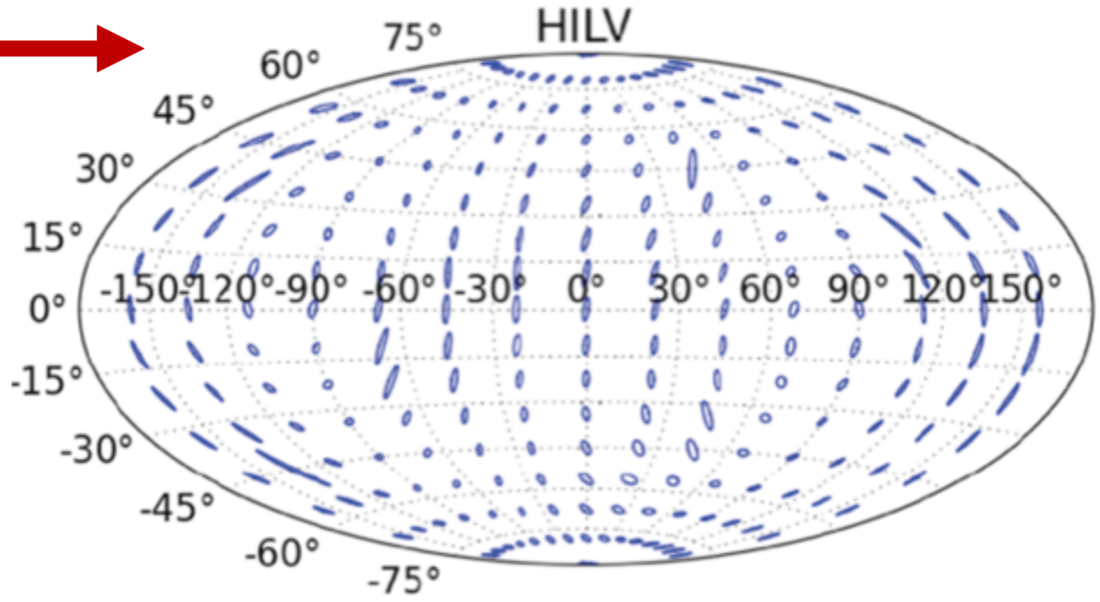
Impact of LIGO-India on Localizing Events

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 4 detectors working 41% of the time

Example: improvement from going from 3 sites to 4:





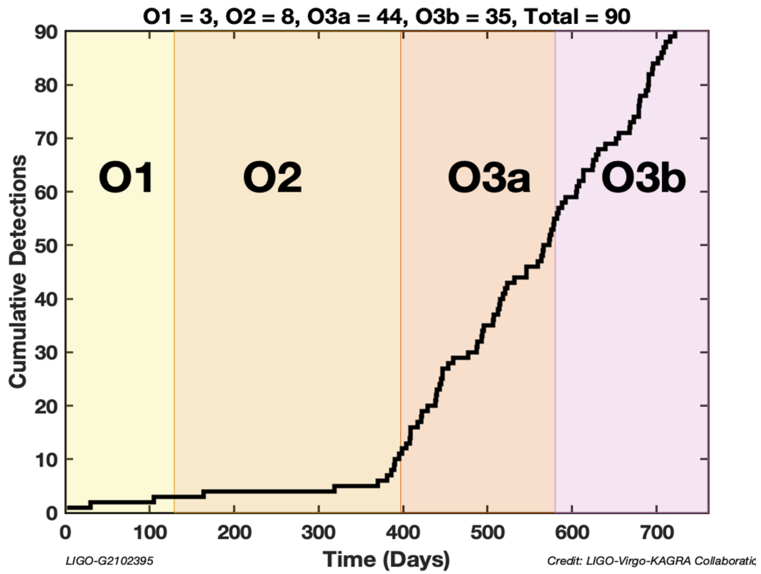
Fairhurst 2011

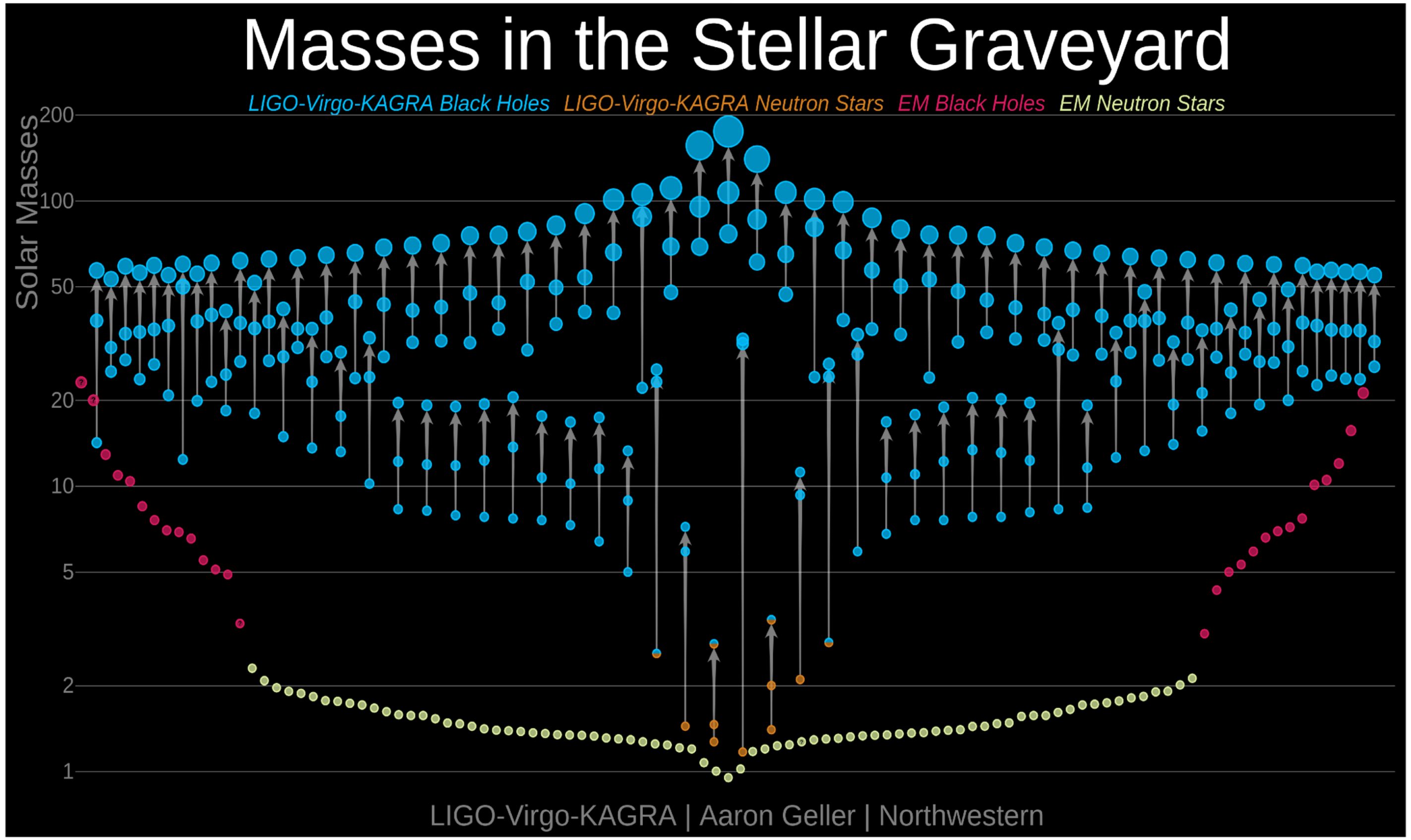
Red crosses denote regions where the network has blind spots

Benefits of a global network

- Improved duty cycle
  - Less likely that event occurs when no detectors are looking
- Increased signal to noise ratio
  - Coherently sum signals from multiple detectors
- Improved detection confidence
  - Multi-detector coincidence greatly reduces false rate
  - Coherent consistency tests can differentiate between gravitational-wave signals and instrumental anomalies
- Permits improved directional searches
  - Gamma ray burst progenitors
  - Supernovae
- Improved source reconstruction
  - "Inverse problem" requires 3 non-aligned detectors
  - Provides sky position and both polarizations of waveform
  - Permits comparison with theory
- Shared best practices
  - Learn from each other's approaches

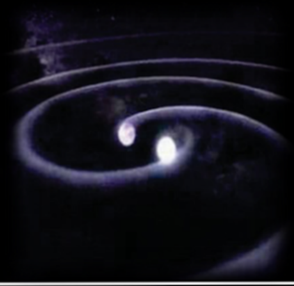
7 years after the first detection:





Recap on GW sources

- Compact Binary Coalescing systems *(CBC)*, well **modeled waveforms** –> numerical and analytical relativity, phenomenological models

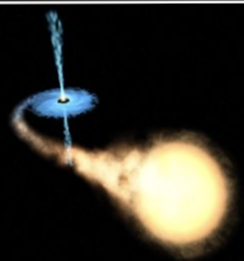


Two Black Holes (BHs)	Two Neutron Stars (NSs)	BH-NS
✓2015	✓2017	✓2020

- Supernovae, GRBs (*bursts*), **unmodeled waveforms;** short-duration GW events in coincidence with signals in electromagnetic (EM) radiation/neutrinos

X

- Fast-spinning NSs in our galaxy (either <u>isolated</u> or in <u>binary systems</u>); monochromatic waves; **modeled waveform**



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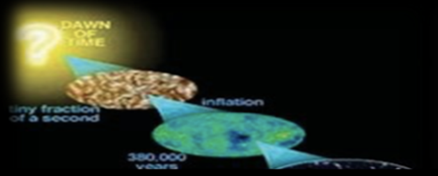
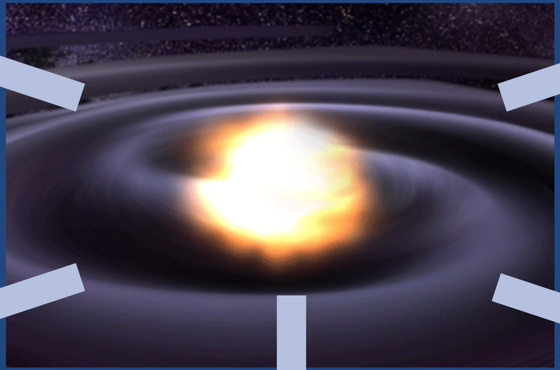
- Cosmological GW (*stochastic background*); A background of primordial and/or astrophysical GWs; **unmodeled waveform**



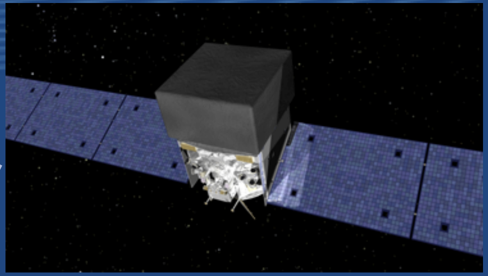
X

Multi-messenger Astronomy with Gravitational Waves

Binary Neutron Star Merger

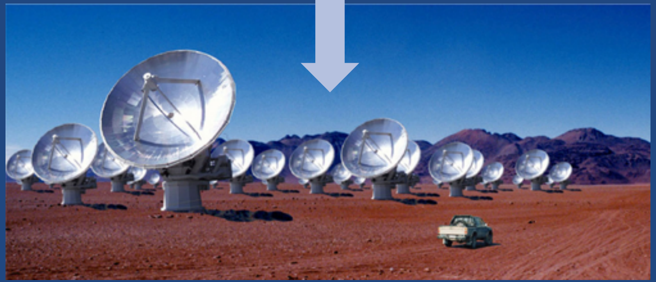


Gravitational Waves

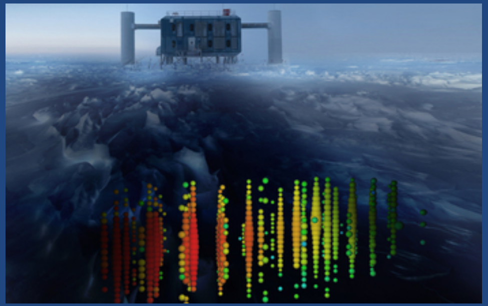


X-rays/Gamma-rays

Visible/Infrared Light

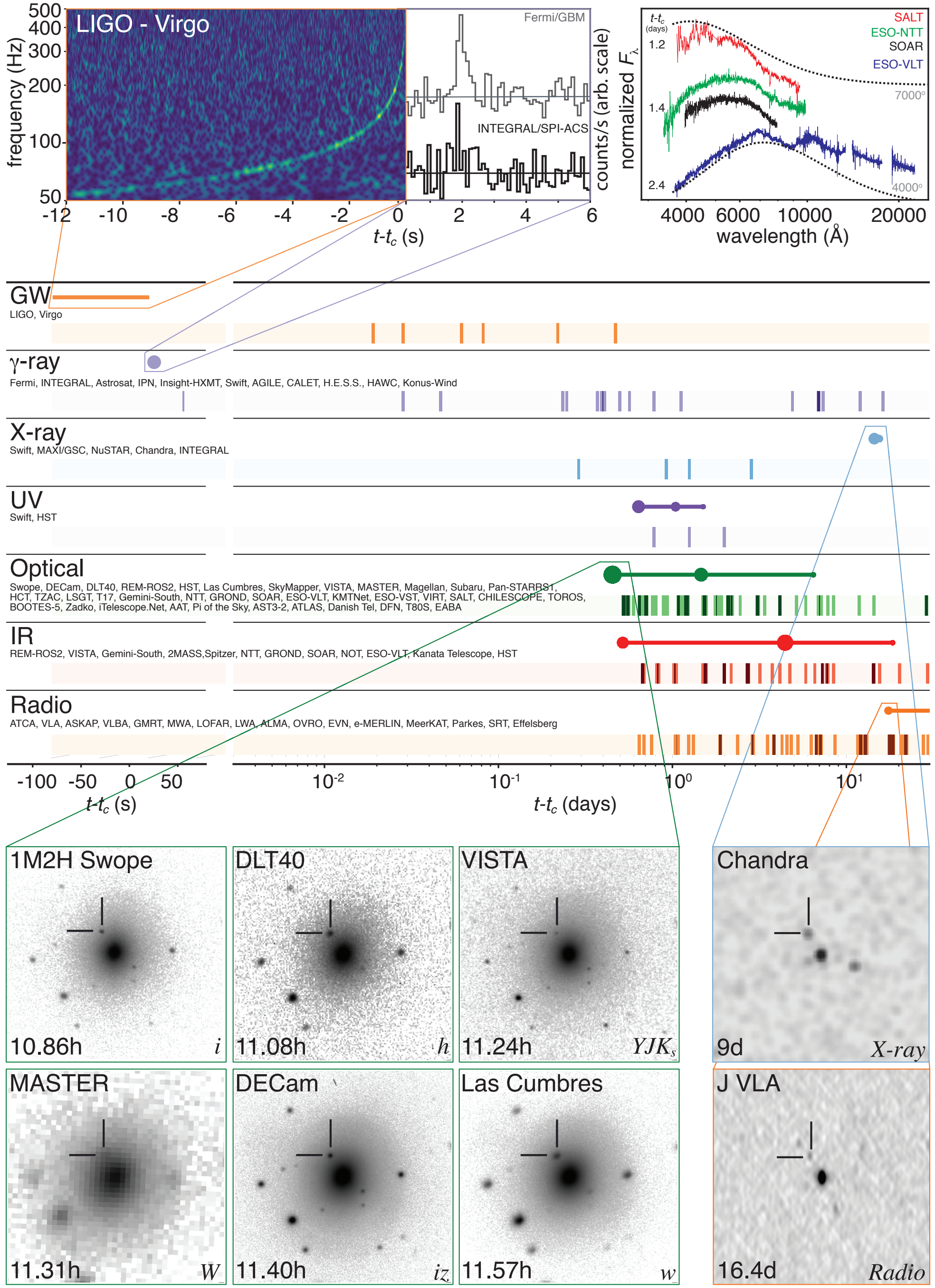


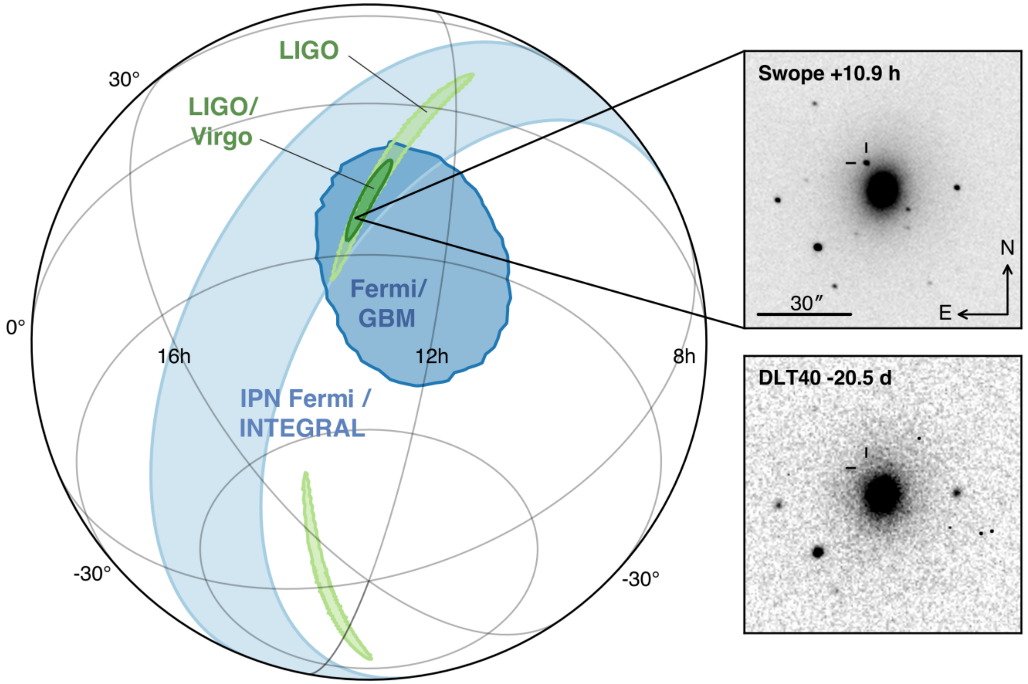
Radio Waves



Neutrinos

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



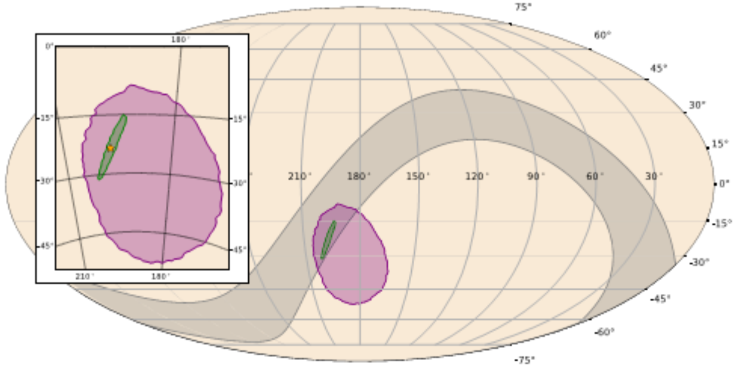


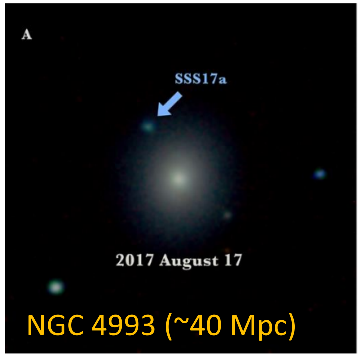
“Multi-Messenger Observations of a Binary Neutron Star Merger”
B. Abbott et al., ApJL 848 (2017) L12
59-page “letter” (!)
More than 3000 authors,~70 collaborations

There have been important contributions from the Spanish groups that are part of INTEGRAL, AGILE, Fermi-LAT, DES, Vinrouge, Master, ePESSTO, TOROS, Red Global BOOTES, VLT, HAWK, Chandra, Gemini, Pierre Auger, ANTARES, EURO VLBI, among others.

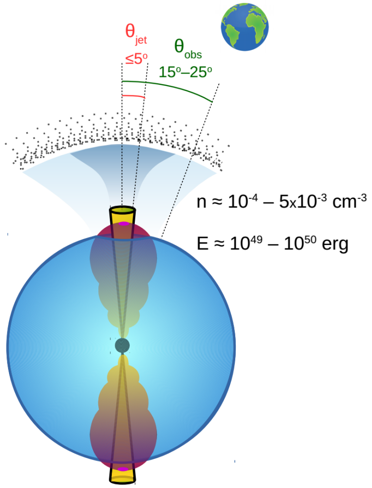
GW170817: Multi-Messenger Breakthrough!

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.





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



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

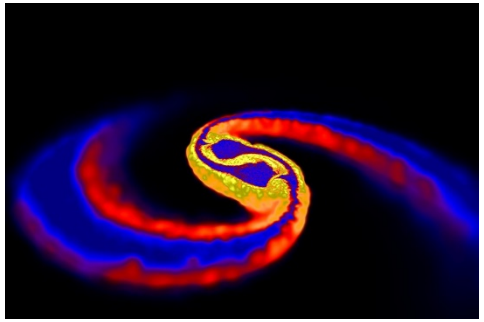
➔ Confirmed picture of BNS mergers as progenitors of short-hard GRBs — in this case, detected off-axis by 15±5°, corroborated by VLBI imaging
[Mooley et al., Nature 561, 355]

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

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

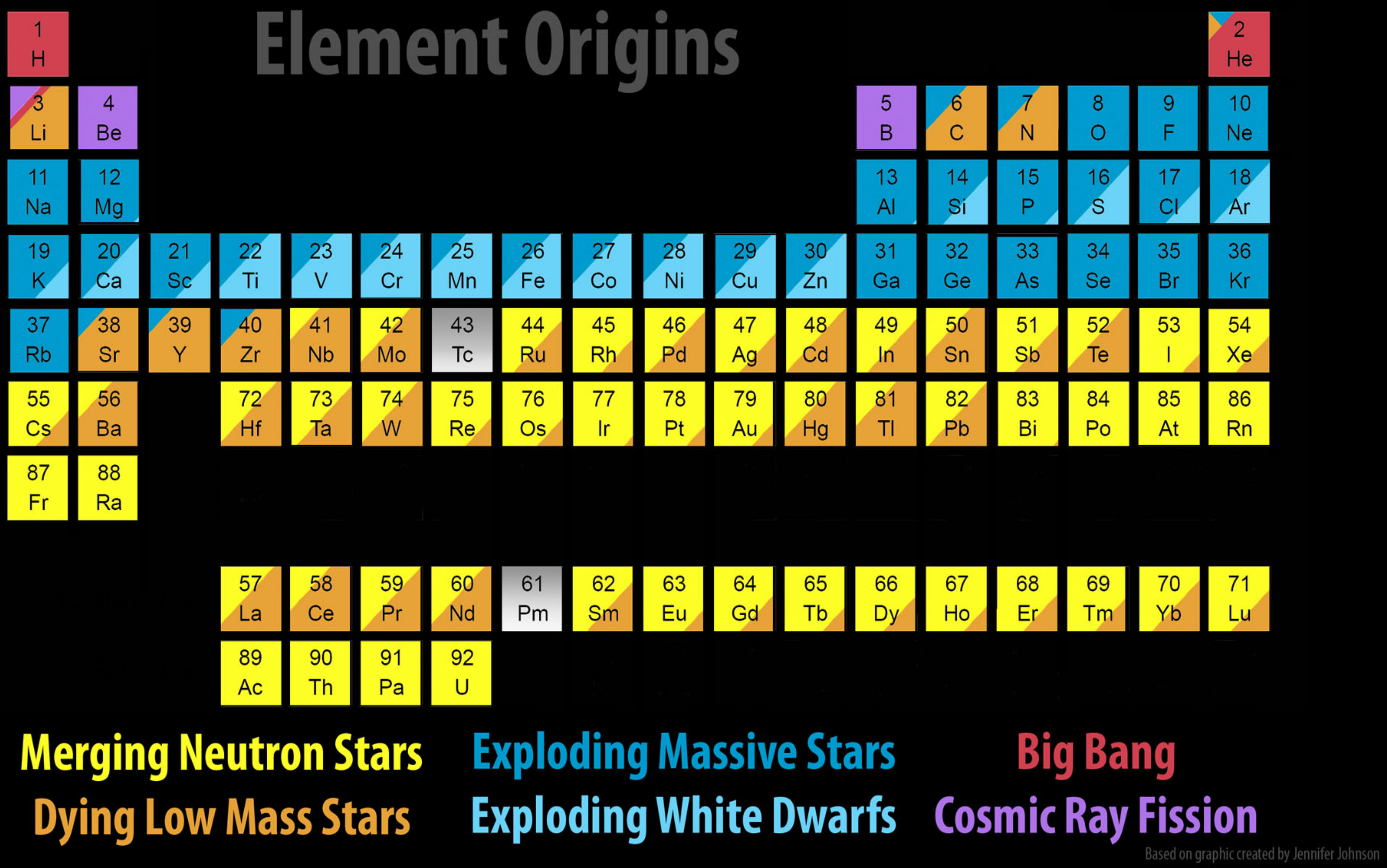
➔ Enabled new measurement of the Hubble constant
[Eight teams, Nature 551, 85]

➔ Provided constraints on NS equation of state and size



Price/Rosswog/Press

Binary Neutron Star Collisions Are the Foundries of Heavy Elements



Challenges & Payoffs

Many major challenges in the new era of gravitational wave astronomy

Commissioning detectors;
achieving desired sensitivity

Building and installing
advanced detector hardware

Sources

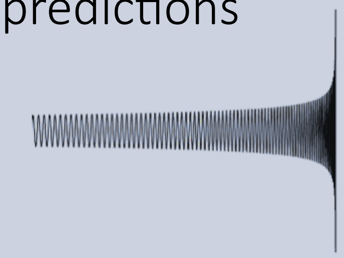
Data Analysis

Computing

Searching the data for
gravitational wave signals

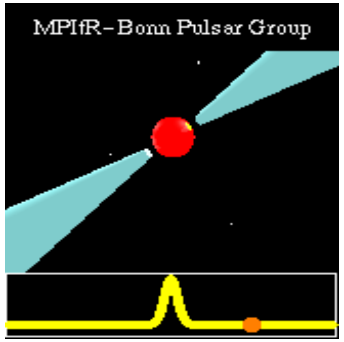
Understanding the detectors
and the data they produce

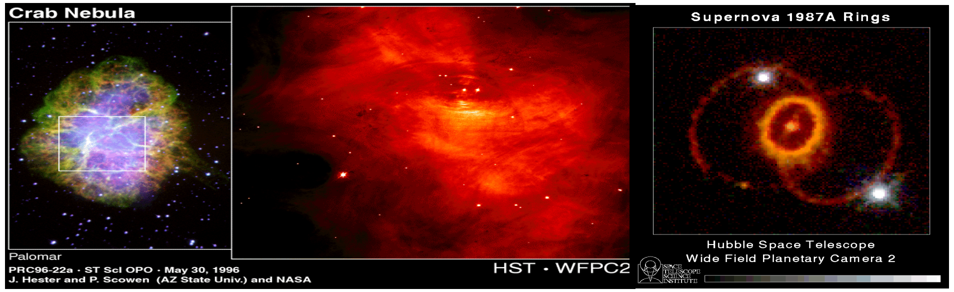
Waveform
predictions



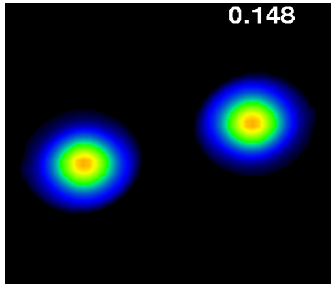
Using GW observations in astronomy,
cosmology, fundamental physics

GW sources and methods

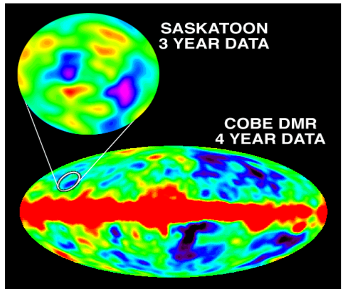




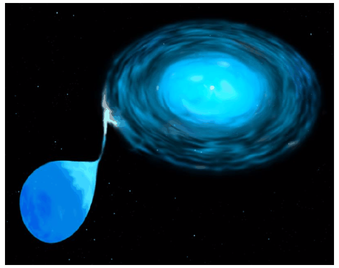
Supernovae, BH/NS formation



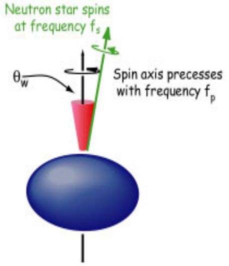
BH and NS Binaries



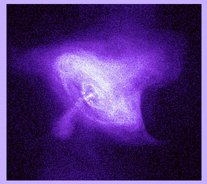
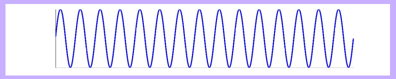
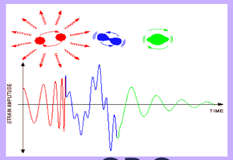
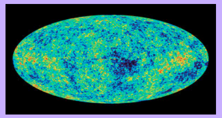
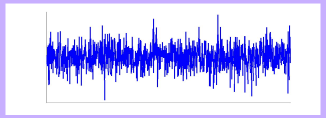
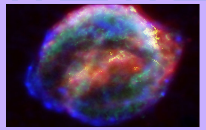
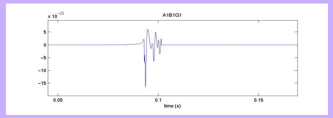
Stochastic background



Spinning NS
in X-ray binaries



Wobbling NS

	Long duration	Short duration
Matched filter	 CW 	  CBC
Template-less methods	 	 

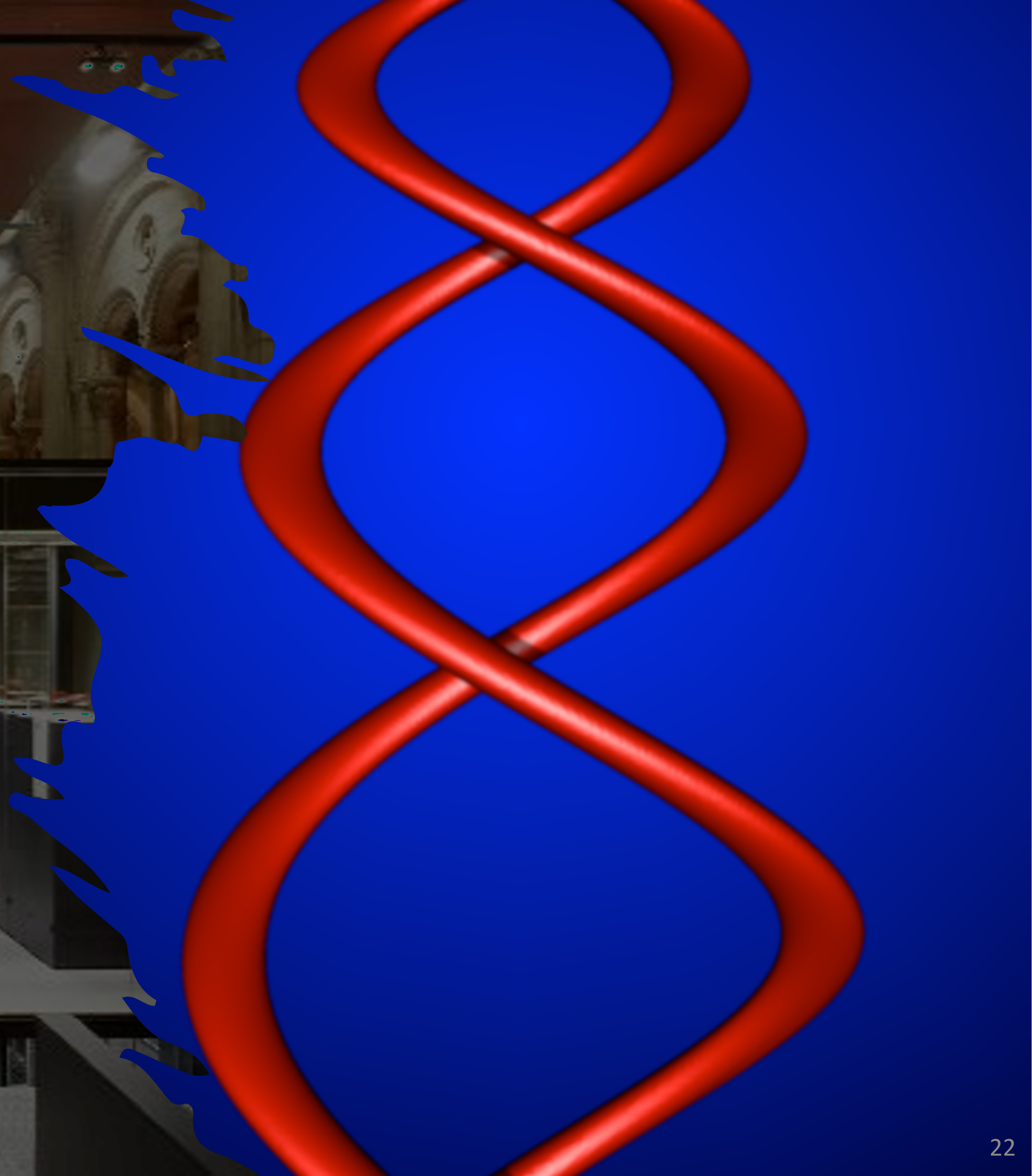
UIB group activities

- We focus on gravitational wave searches from binary black holes and neutron stars and the computational modeling needed to identify those sources.
- Data and detector characterization.

- CBC **waveform development** – IMRPhenom
    - Parameter estimation of special events; **fast PE for LVK**.
    - Lead **LISA work package** on efficient waveform models
- **Numerical Relativity** for BBH – largest catalog of eccentric waveforms.
- Leading **all-sky CW searchers** for spinning neutron starts in isolated and binary systems based on Hough transform.
- Leading **long transient searches** for BNS merger remnants
- **Lensing** of GWs – preparing for first detection.
- **Noise modelling**: Line noise investigation and mitigation
- **EPO** efforts

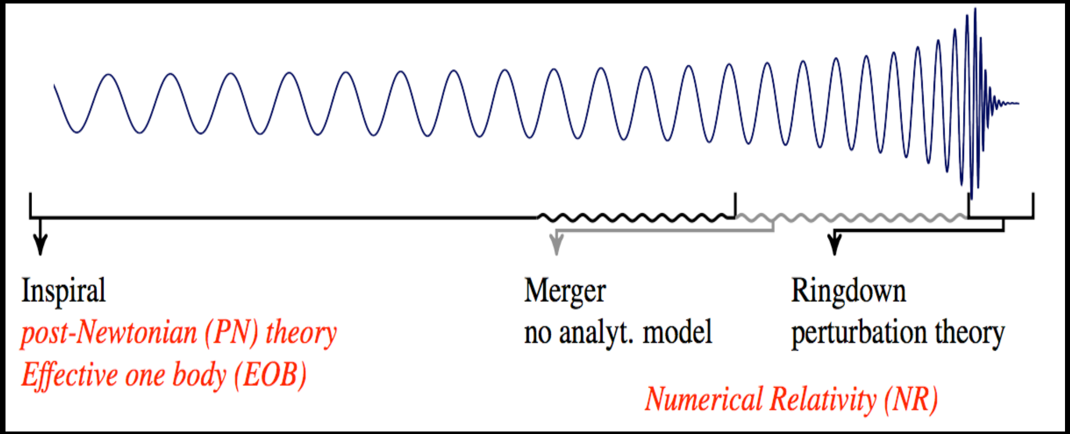
Numerical Relativity

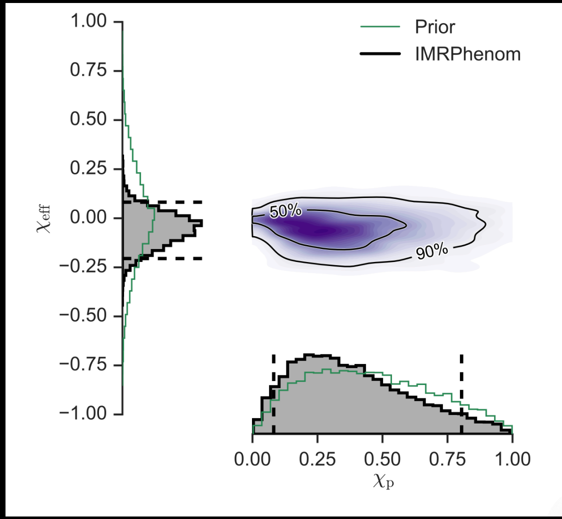
- Einstein's equations are so complex, that we usually need supercomputers to solve them.
- Starting with an initial configuration of the gravitational field, we can use them to predict the future dynamics.
- Computing a few milliseconds of a collision of neutron stars or black holes, or a supernova explosion, can take many weeks on hundreds of processors.



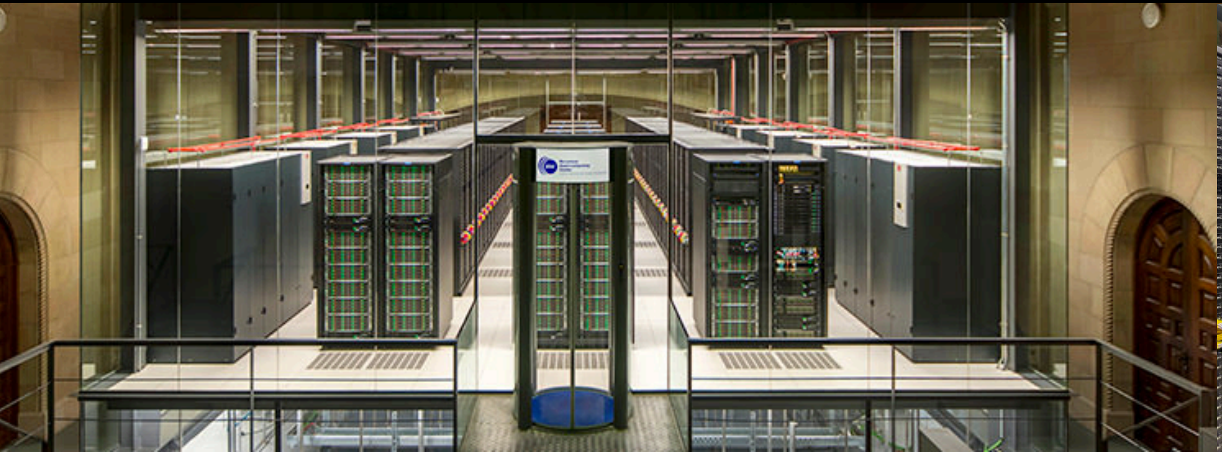
How do we identify the sources?

Compare with theoretical models of waveforms, calibrated to numerical solutions of the Einstein equations.

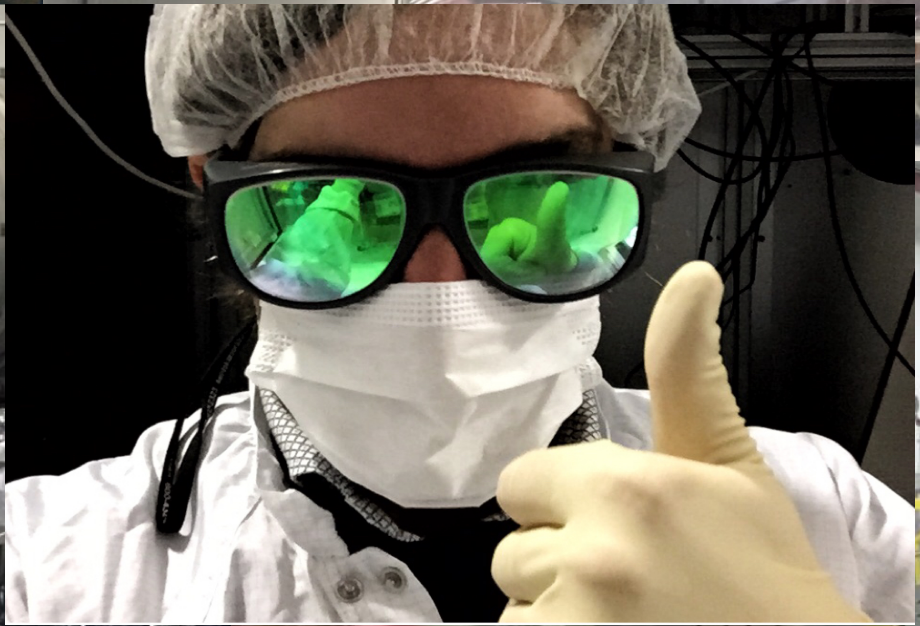




Sascha Husa leads phenomenological waveform program to develop computationally efficient models – used to identify sources for all events detected to date.



Sascha Husa and CBC@UIB pioneered the use of supercomputers for fast parameter estimation – among top users of MareNostrum4 @BSC-CNS



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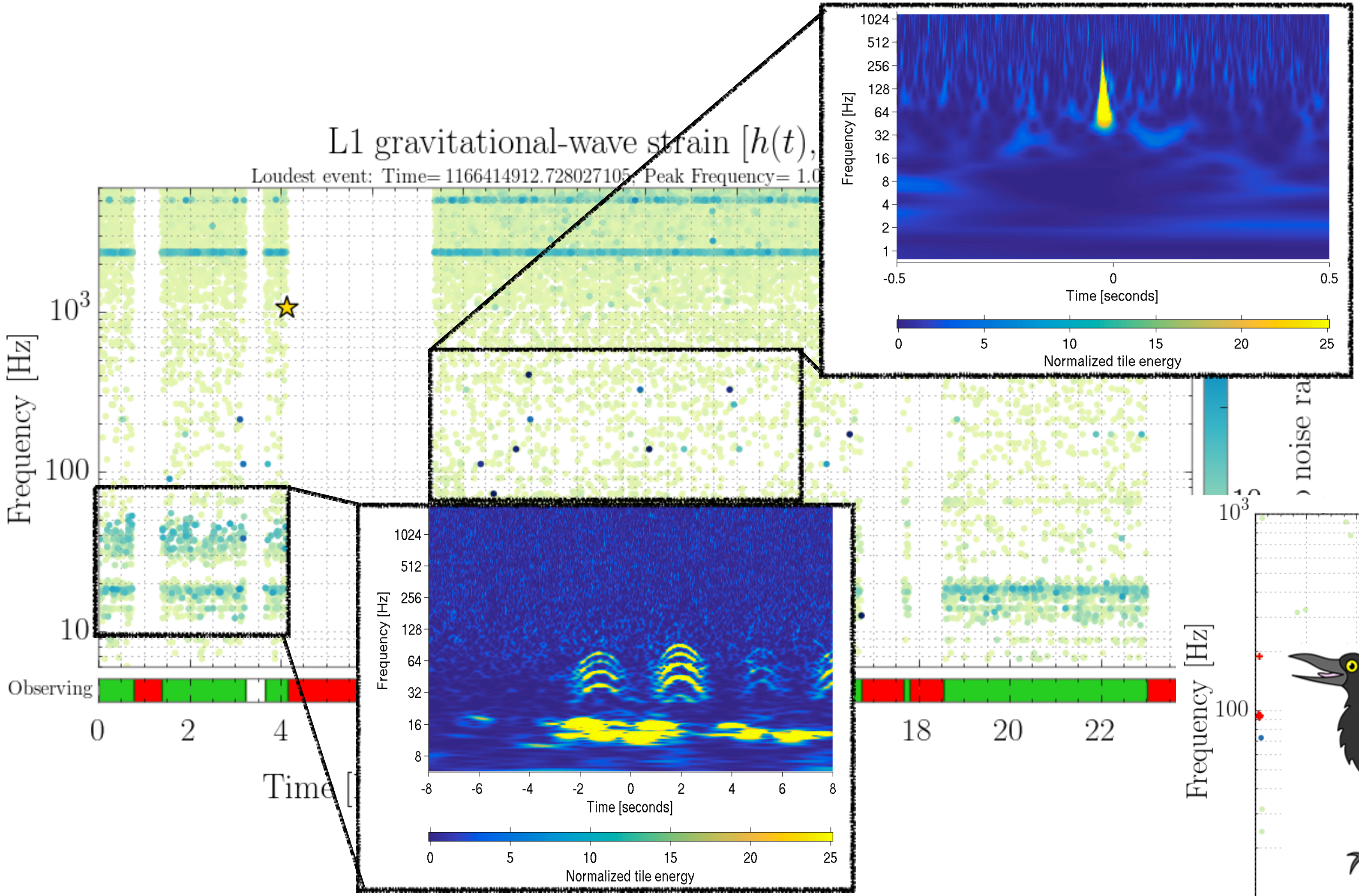
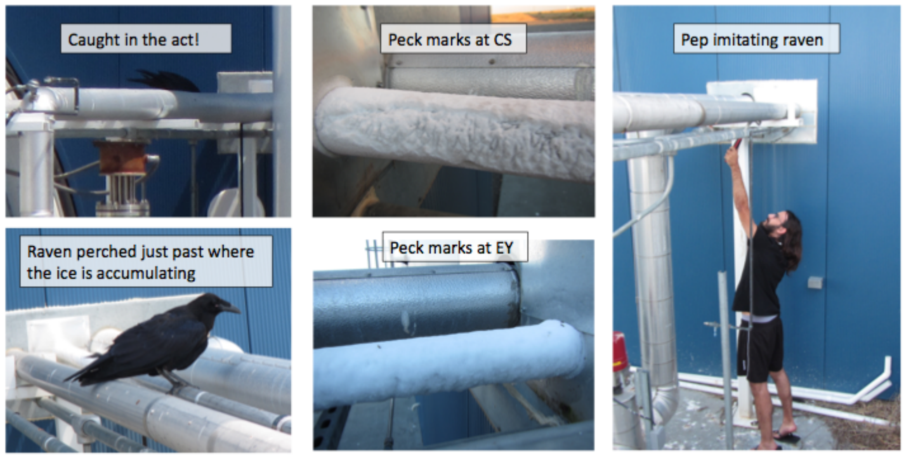
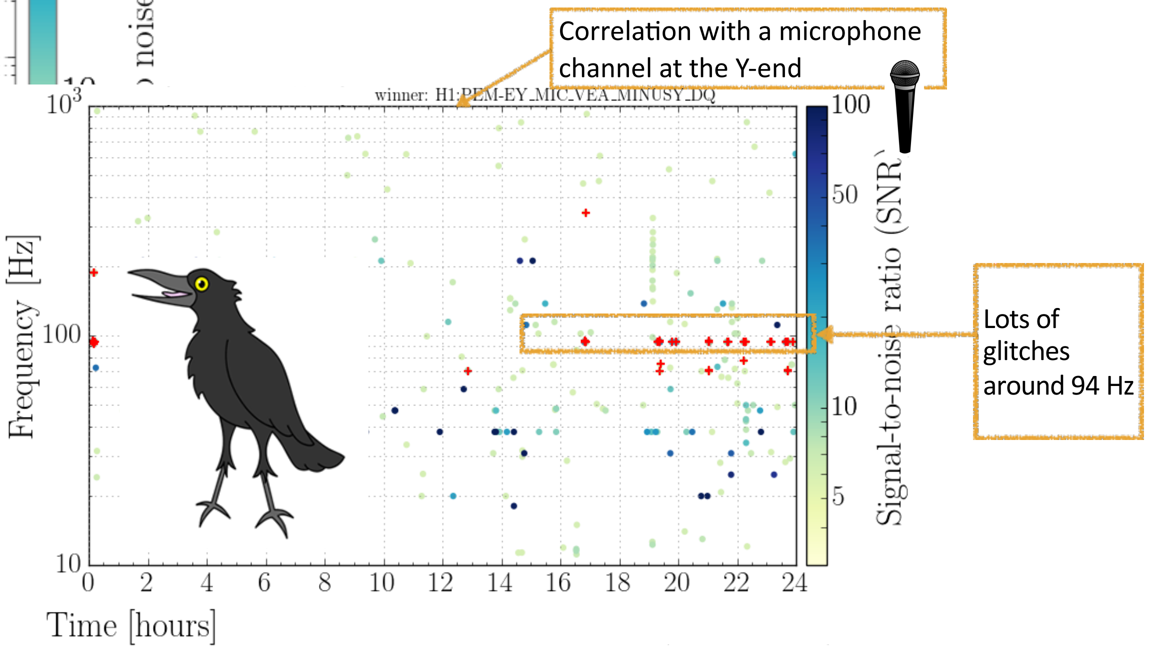
LIGO noise studies and mitigation

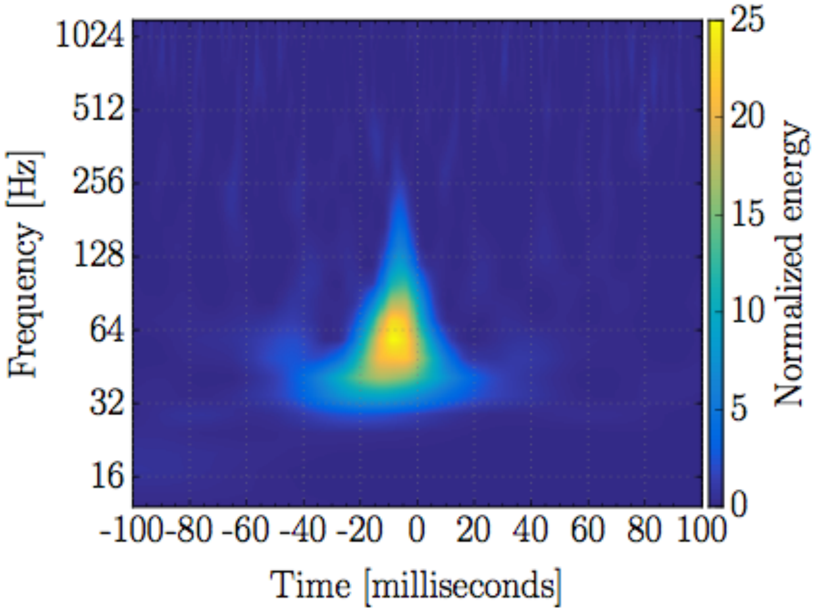


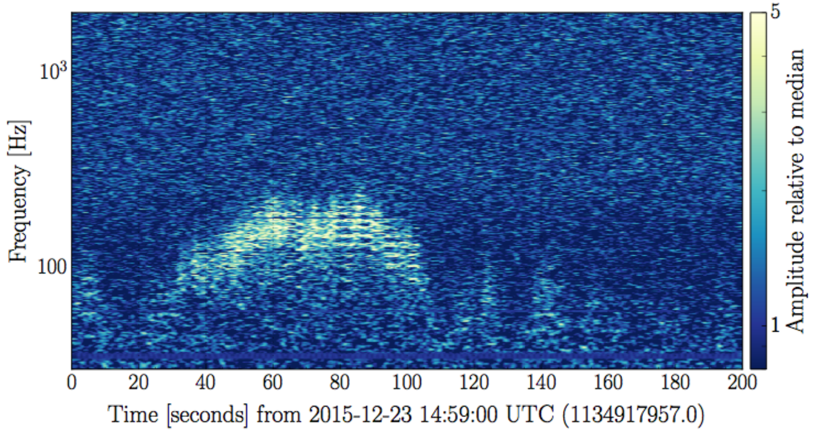




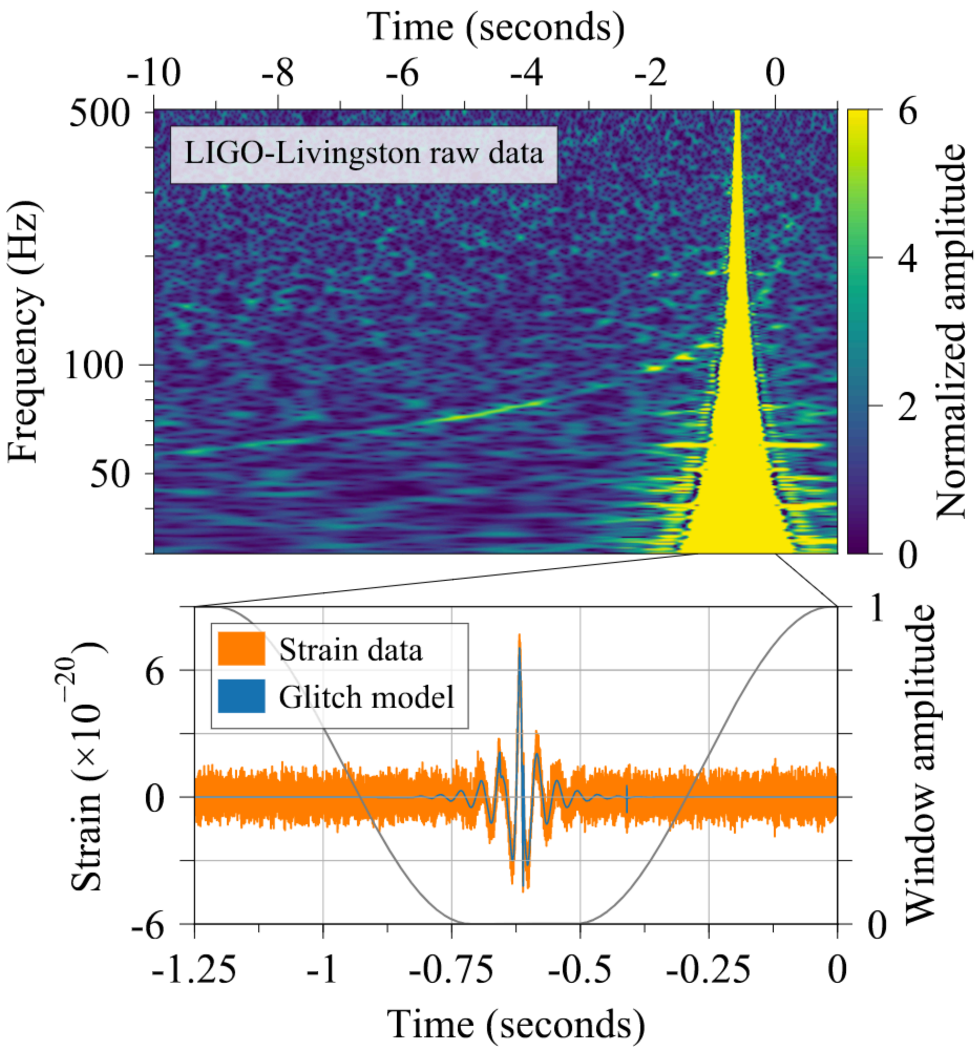
Data processing and visualisation with GWpy: https://gwpy.github.io

Challenge: LIGO data is non-stationary!





B.P Abbott et al. CQG (2018)



gravityspy.org

DetChar: Line Identification & Mitigation

Persistent instrumental noise impacts CW searches

- It looks essentially like a CW!
- identification and mitigation of instrumental and environmental noise sources
- study of non-linear coupling effects amongst instrumental noise
- P. B. Covas+ Phys. Rev. D 97, 082002 (2018), D. Davis et al. (P. B. Covas, D Keitel, A. M. Sintes, R. Tenorio) Class. Quantum Grav. 38 135014 (2021)

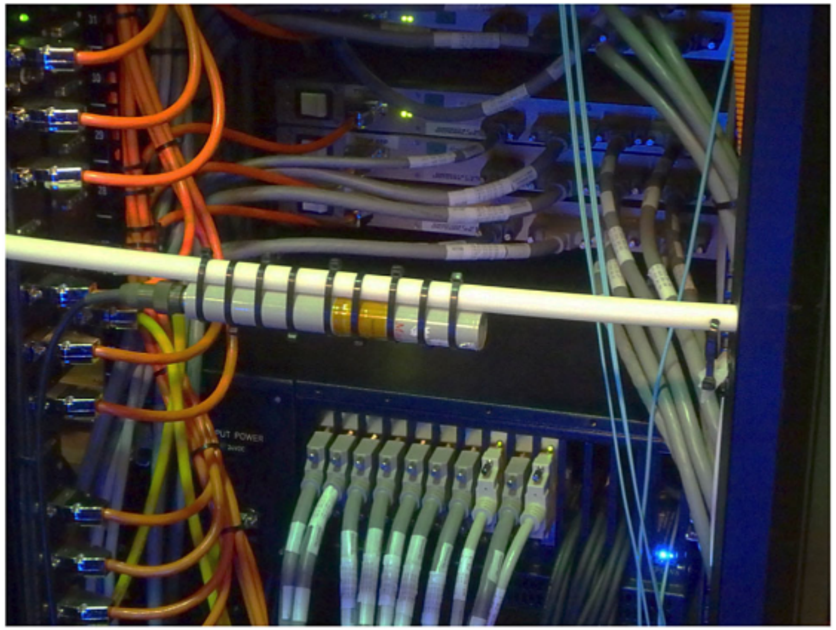
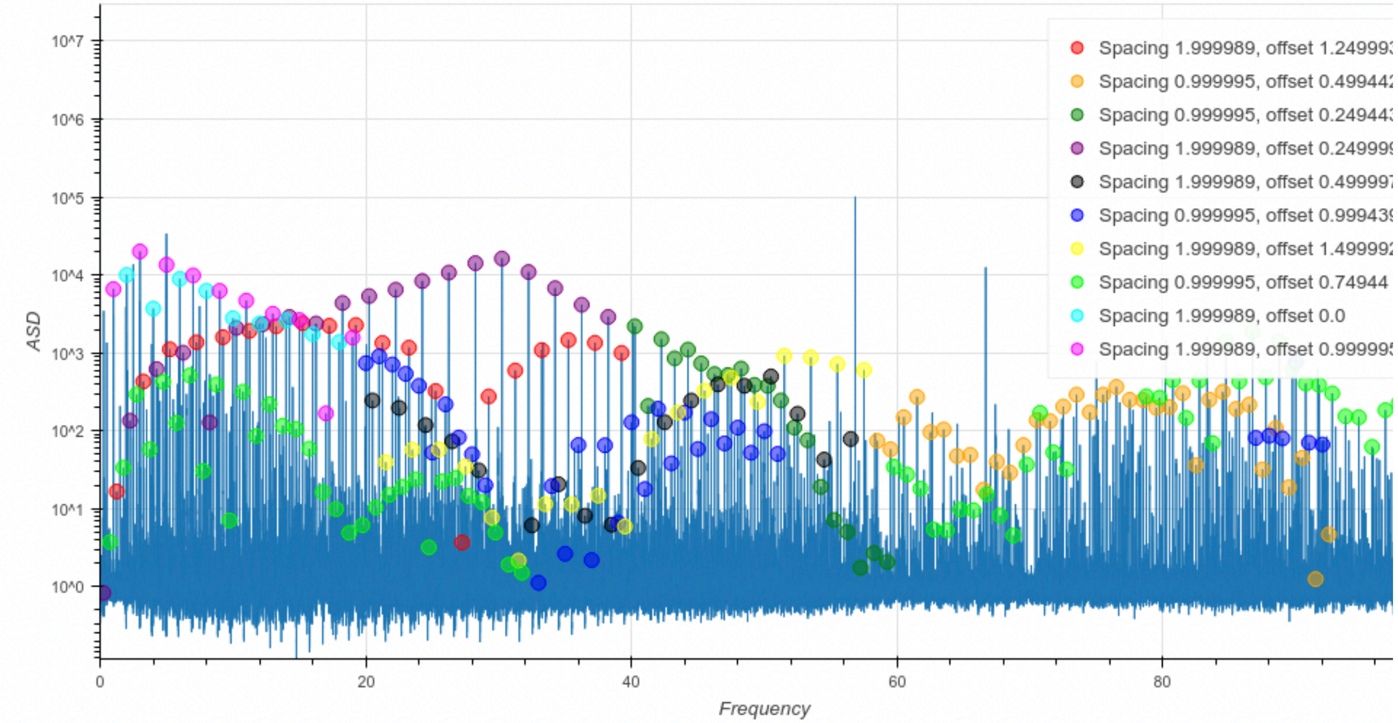


FIG. 3. Method of monitoring electronic components and cables for frequencies of instrumental lines found in the data.

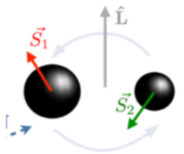


PHYSICAL REVIEW X **11**, 021053 (2021)

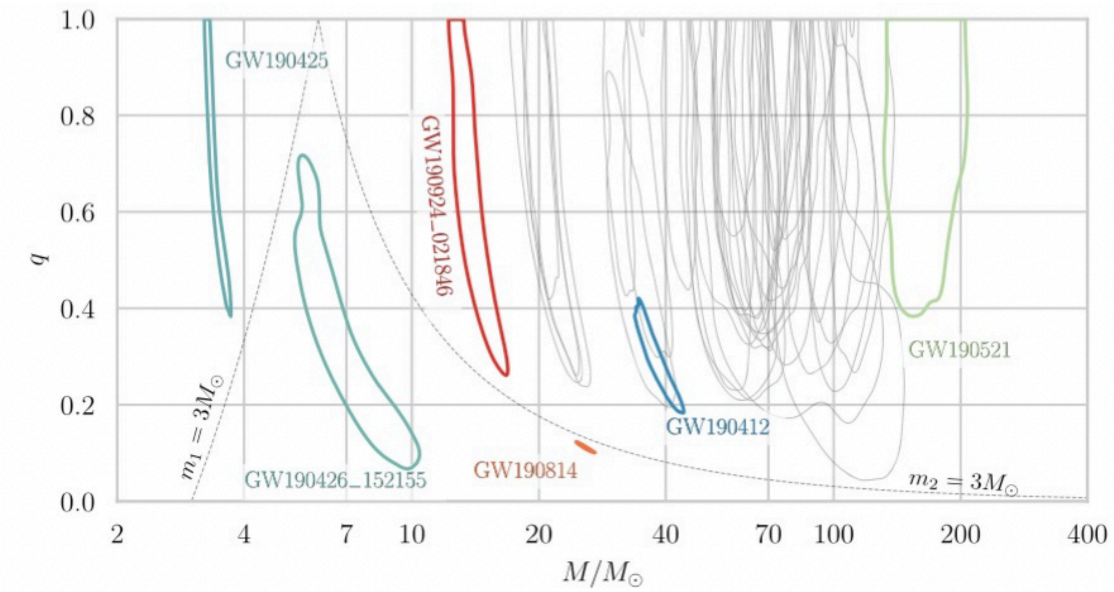
GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo during the First Half of the Third Observing Run

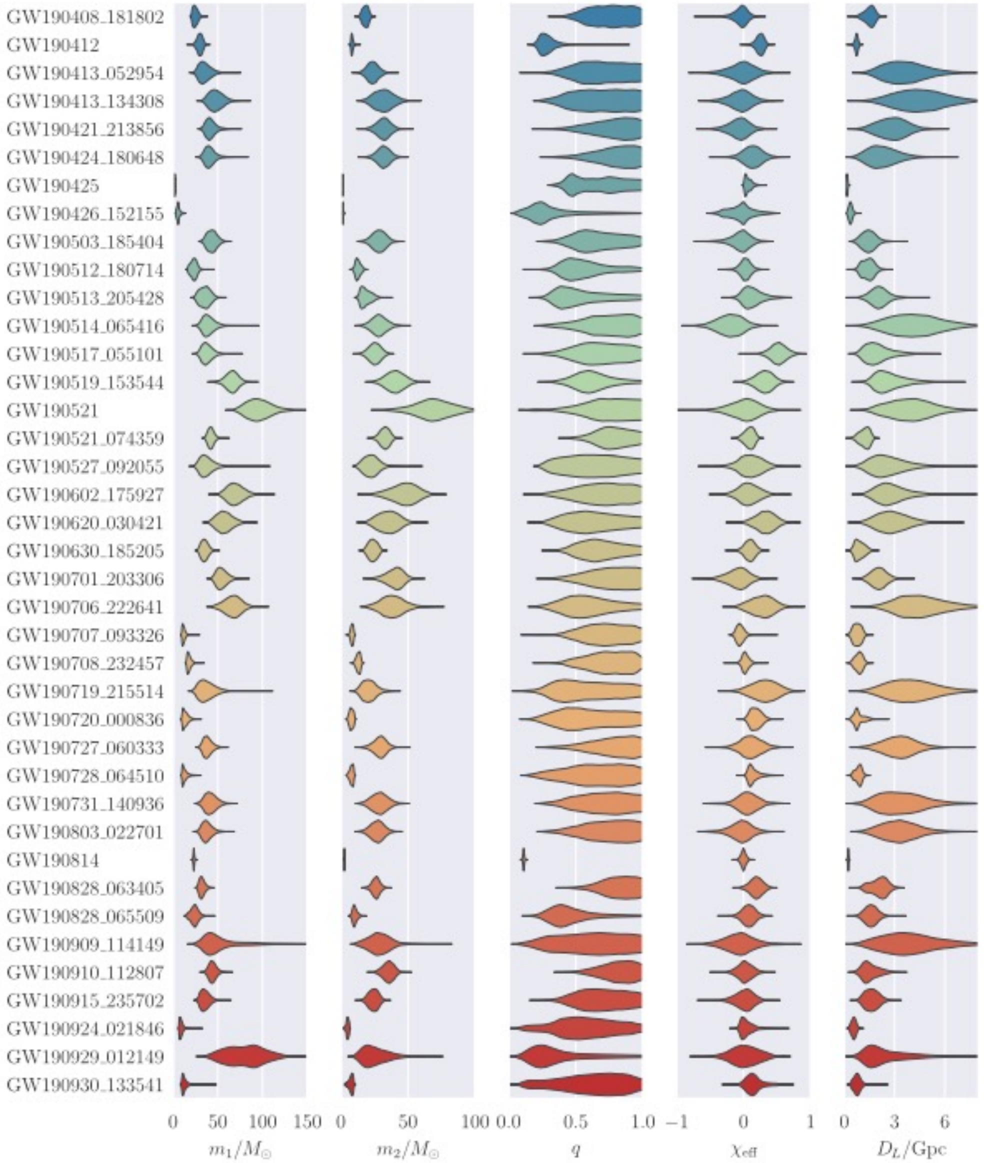
R. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

- 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_{eff}



$$\chi_{\text{eff}} = \frac{(m_1\vec{\chi}_1 + m_2\vec{\chi}_2)\cdot\hat{L}_N}{M}$$





Evidence for deviations from general relativity

Learning about gravity with LIGO and Virgo
See Abbott et al. Phys. Rev D. 103, 122002 (2021)

Observations

- Residuals from best-fit waveforms consistent with noise ✓
- Consistency of parameters inferred from inspiral and merger-ringdown phases ✓
- No evidence for deviations from the PN coefficients predicted by GR ✓
- Consistency with no dispersion of GWs and massless graviton ✓
- BH spin-induced quadrupole moments are consistent with their Kerr values ✓
- Ringdown frequencies and damping times consistent with GR ✓
- No detection of echoes ✓
- No evidence for pure scalar or pure vector polarizations ✓

- New bound on mass of graviton: $m_g \leq 1.76 \times 10^{-23} \mathrm{eV/c^2}$

O3 Exceptional Detections

GW190412: first observed BBH possessing unequal mass ratio

- Masses: ~3, ~8 Msun
- [Abbott et al. (LIGO/Virgo Coll.), Phys. Rev. D 102, 043015]

GW190814: the most asymmetric mass ratio merger ever observed

- (m1/m2 = 9)
- The secondary mass of 2.6 Msun lies in the lower 'mass gap' either the lightest BH or the heaviest NS ever observed
- [Abbott et al (LIGO/Virgo Coll.), ApJL 896 L44]

GW190425: BNS merger of total mass of ~3.4 Msun

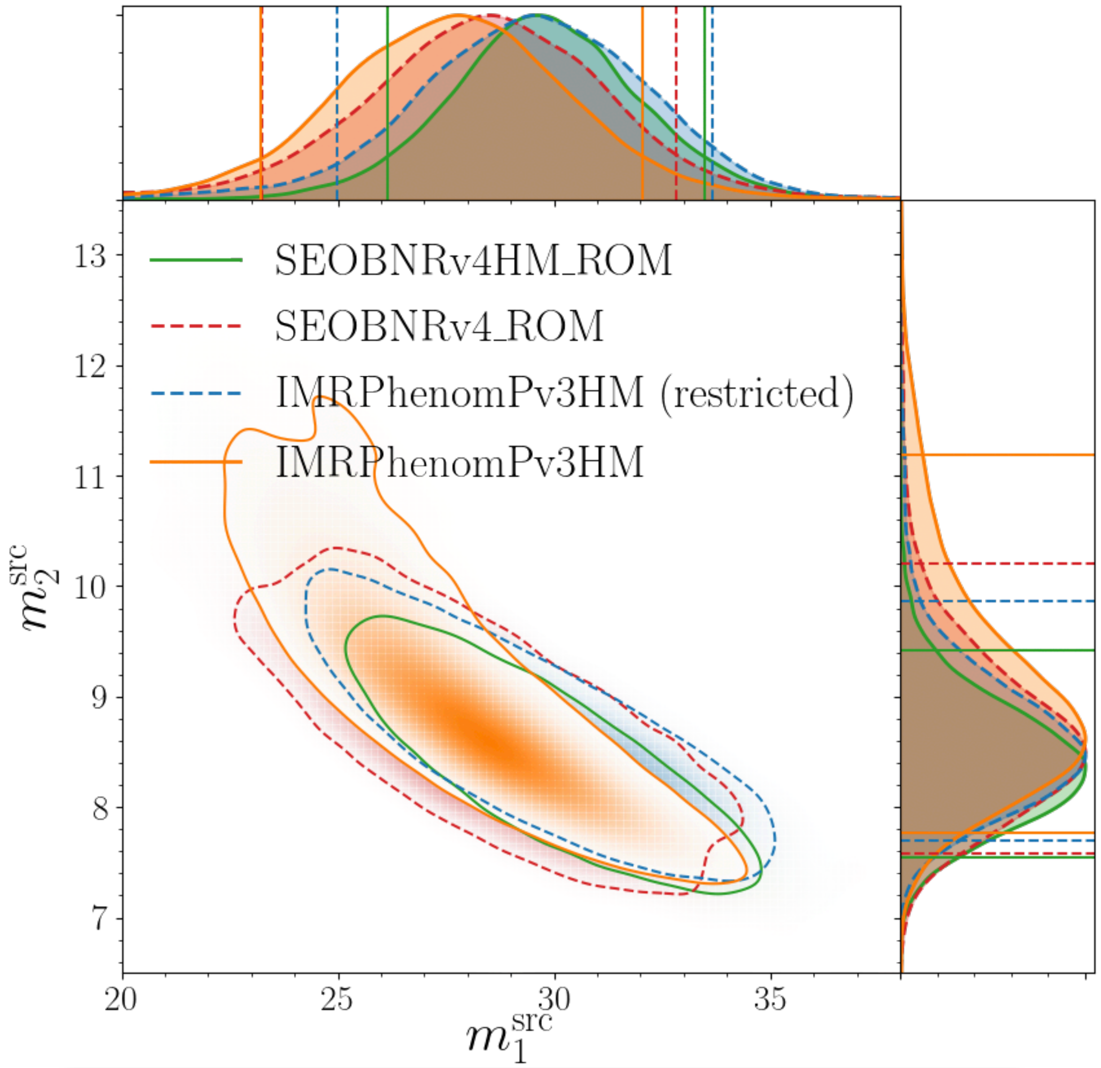
- Significantly larger than any other known BNS system
- [Abbott et al (LIGO/Virgo Coll.) ApJL 892 L3]

GW190521: BBH with component masses ~66 and 85 Msun

- First observation of an intermediate mass BH (Mf > 100).
- First observation of a BH in the (pulsational) pair instability upper mass gap 65 - 120 Msun .
- Farthest source so far (z ~ 0.8)
- [Abbott et al (LIGO/Virgo Coll.) Phys. Rev. Lett. 125, 101102]

GW200105-GW200115: 1st unambiguous detection of NSBH (2 events)

- [Abbott et al (LIGO/Virgo/KAGRA Coll.) ApJL 915 L5]



m_1	m_2	q
$\sim 30\,\mathrm{M}_\odot$	$\sim 8\,\mathrm{M}_\odot$	~ 0.28

GW190412

An unequal mass binary black hole merger

Abbott et al. Phys. Rev. D 102, 043015 (2020)

Asymmetric systems are predicted to emit gravitational waves with stronger contributions from higher multipoles

First:

- Clear evidence for unequal mass components
- Clear measurement of higher-order multipoles

Mass-ratio measurement of GW190412 is robust against modeling systematic

GW190412: an unequal mass binary black hole merger

First clear evidence for unequal mass components and a clear measurement of higher-order multipoles
See Abbott et al. Phys. Rev. D 102, 043015 (2020)

m_1	m_2	q
$\sim 30\,\mathrm{M}_\odot$	$\sim 8\,\mathrm{M}_\odot$	~ 0.28

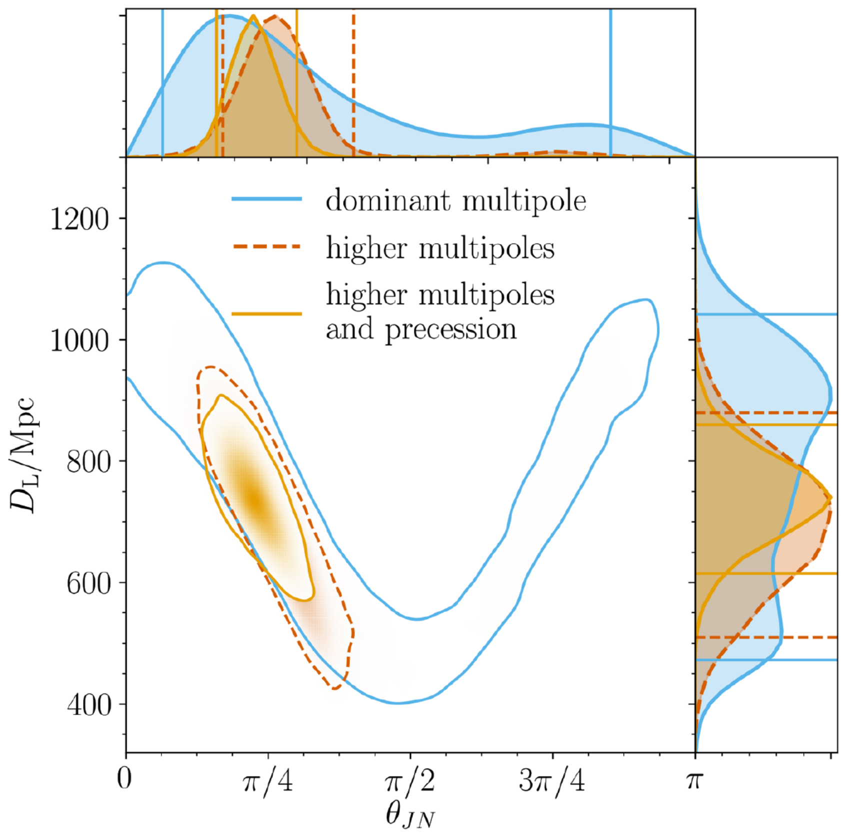
Still consistent with BBH population inferred from O1/O2

Gravitational radiation beyond the leading quadrupolar order in the observed signal

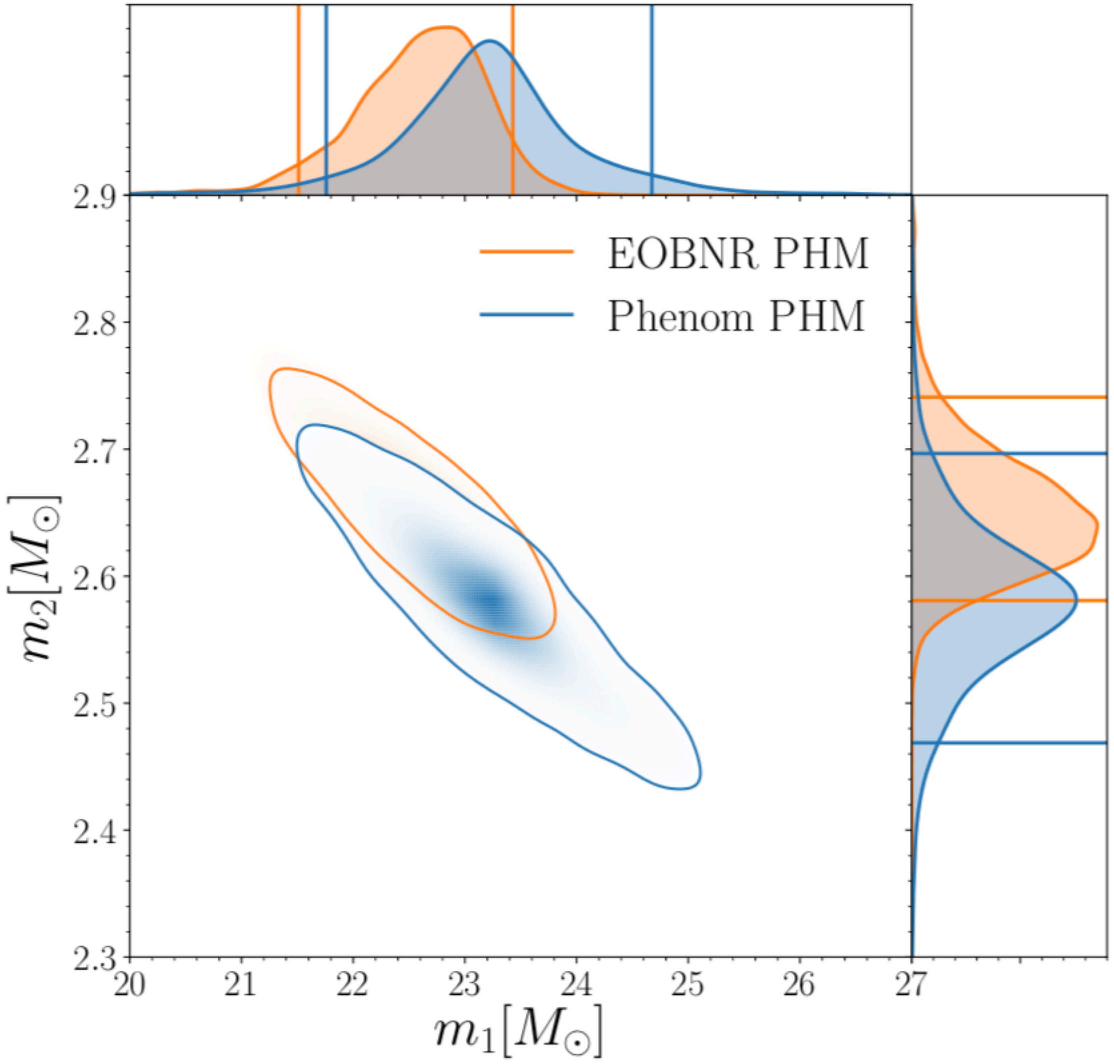
$$h_+ - i h_\times = \sum_{\ell \geq 2} \sum_{-\ell \leq m \leq \ell} \frac{h_{\ell m}(t, \boldsymbol{\lambda})}{D_\mathrm{L}} \, {}_{-2}Y_{\ell m}(\theta, \phi)$$

More massive black hole rotated with a dimensionless spin magnitude between 0.22 and 0.60 (90% probability)

Posterior is constrained by including HOMs and precession



Mystery Merger: GW190814



m_1	m_2	q
$\sim 23.2\,M_\odot$	$\sim 2.6\,M_\odot$	~ 0.112

A very unequal mass binary merger with a secondary of uncertain type

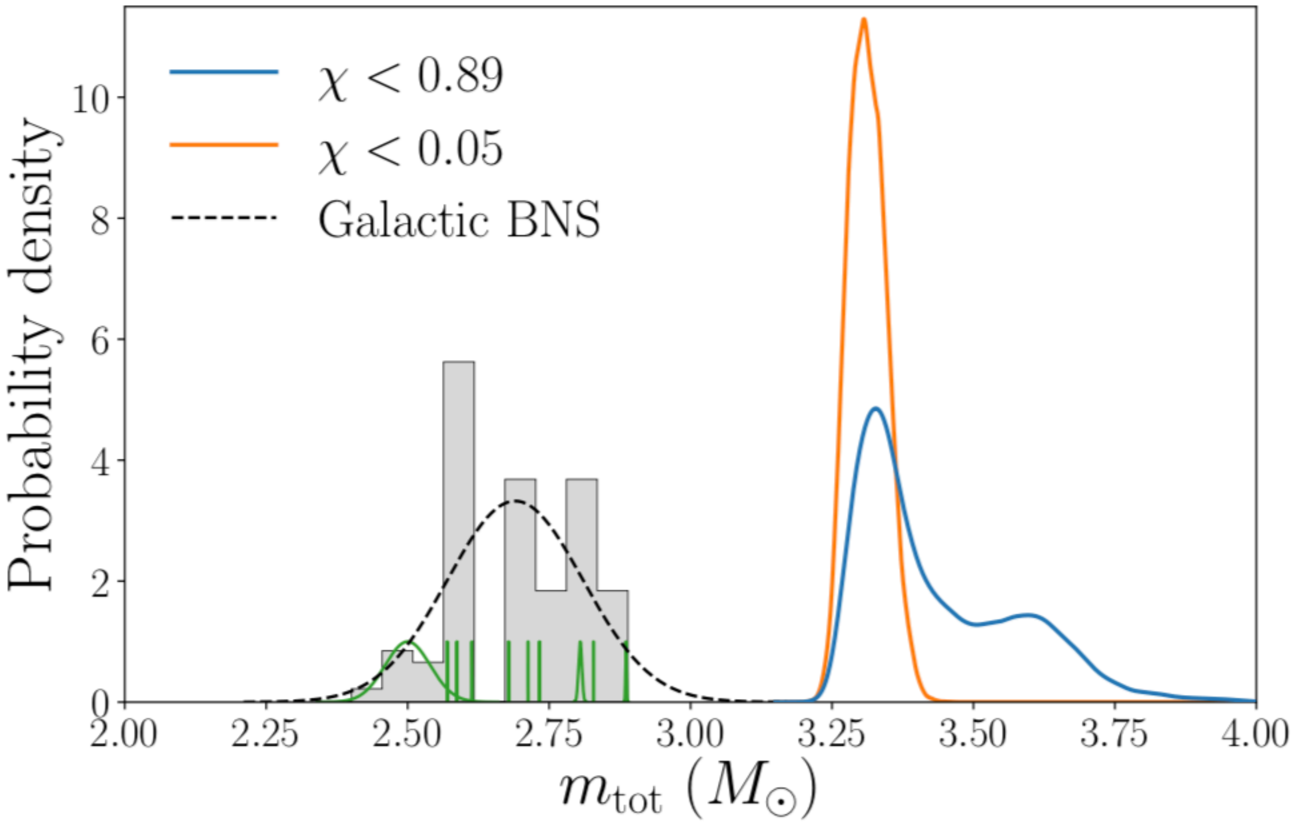
Abbott et al. ApJ Lett. 896, L44 (2020)

- Most unequal mass ratio yet observed of 9:1
- Secondary is either **lightest black hole or heaviest neutron star** ever discovered in system of two compact objects
- Strongest evidence for multipole emission observed so far, and in agreement with General Relativity
- Sky map had a 90% credible region of 18.5 deg^2
- Luminosity distance of 241^{+41}_{-45} Mpc

Challenging for standard formation scenarios
Represents a new class of compact binary merger

Comparisons between the secondary mass and estimates of the maximum NS mass suggest that this signal is unlikely to originate in a NSBH coalescence.

GW190425



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

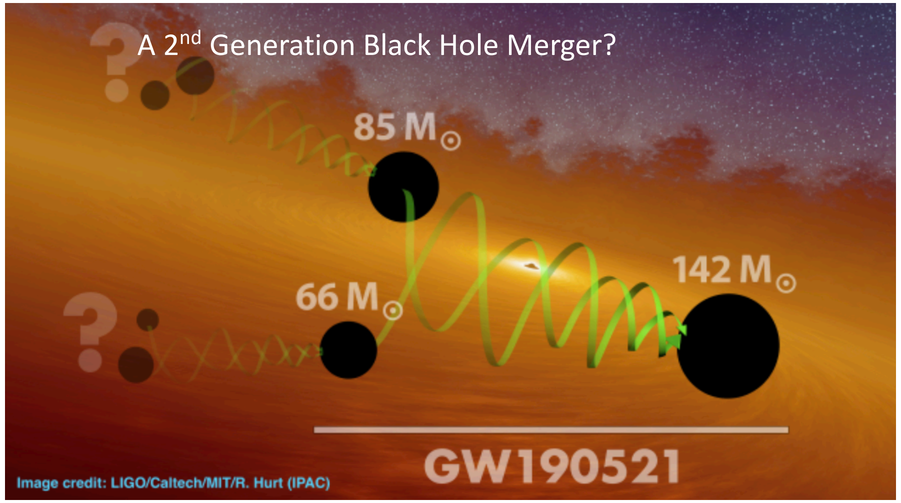
A massive binary neutron star merger

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

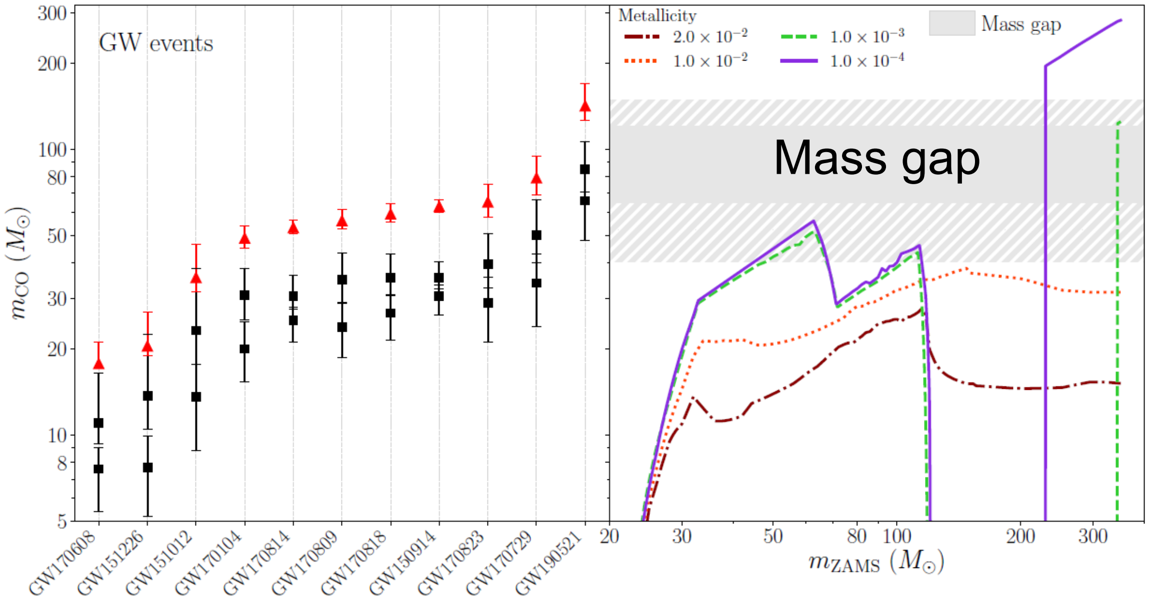
- Both component masses < 3 $M_\odot$
- No EM counterpart
- Total mass larger than any known BNS (5σ from mean of Galactic BNS)
- Initial sky map had a 90% credible region of 10,200 deg^2 at luminosity distance of 159^{+69}_{-72} Mpc

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



m_1	m_2	m_{tot}
$\sim 85\,M_\odot$	$\sim 66\,M_\odot$	$\sim 150\,M_\odot$



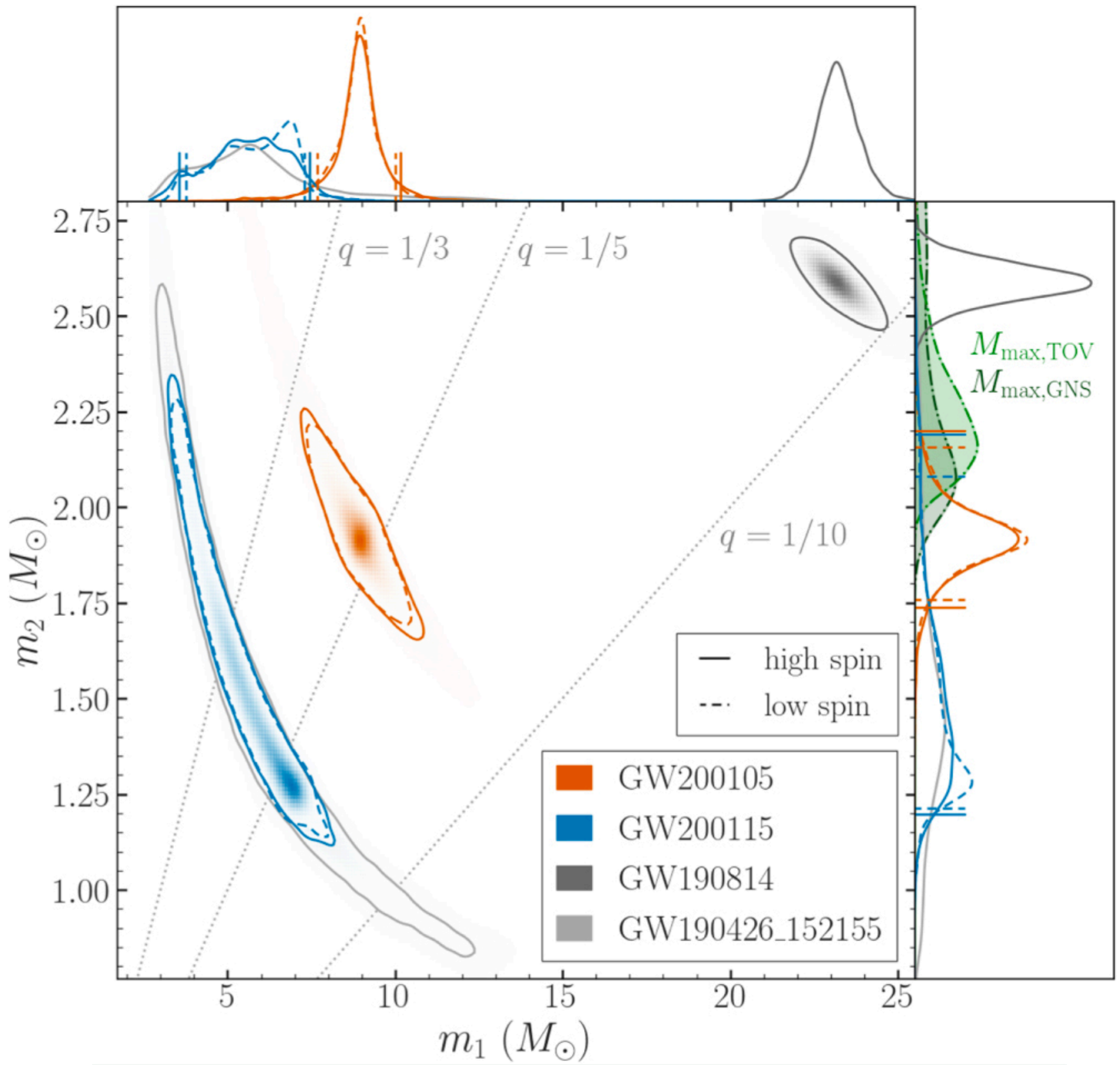
GW190521

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)



	m_1	m_2
GW200105	$\sim 8.9\,M_\odot$	$\sim 1.9\,M_\odot$
GW200115	$\sim 5.7\,M_\odot$	$\sim 1.5\,M_\odot$

GW200105 & GW200115

Observation of Gravitational Waves from Two Neutron Star-Black Hole Coalescences

Abbott et al. ApJ Lett. 915, L5 (2021)

- First detections of neutron star-black hole systems
- No EM counterpart observed (as expected)
- Luminosity distances 280 and 300 Mpc

- GW200115: preference for spin to be anti-aligned with orbital angular momentum
- Some of the most expensive parameter estimation runs done by UIB group on MareNostrum

CBC challenges

Waveforms

- Ideally: Account for inspiral + merger + ringdown, with precessing spins, tidal effects, higher harmonics, eccentricity… and with fast computation
- Not everything matters everywhere in the parameter space
- Progress still needed to fully explore the spin - mass ratio space for IMR waveforms

Getting the background under control

Signal based consistency cuts (i.e. c^2, MFO)

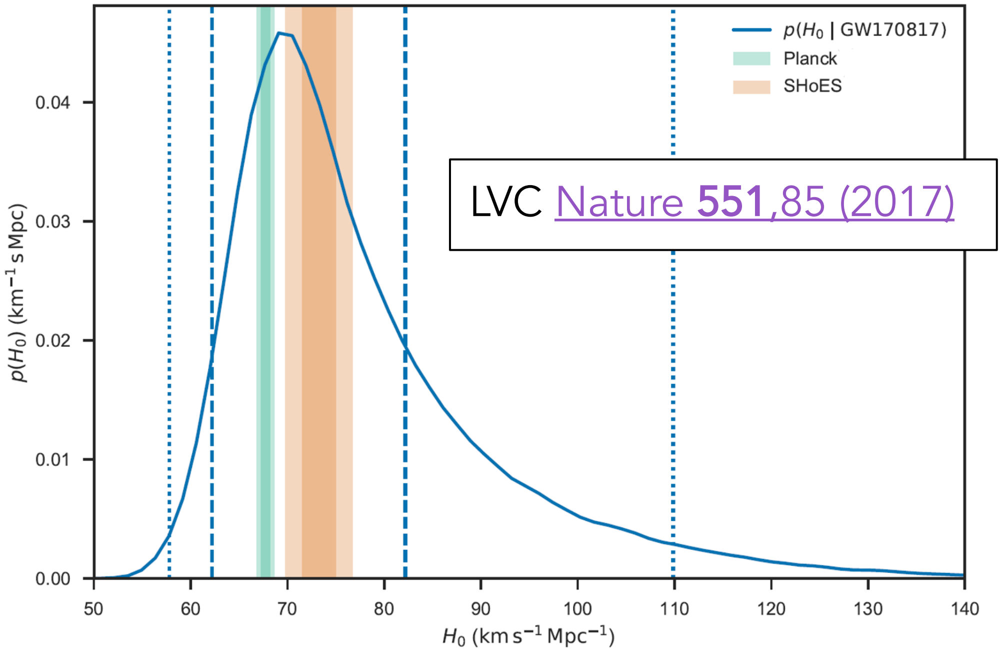
Data quality and vetoes

Advanced detectors are new detectors

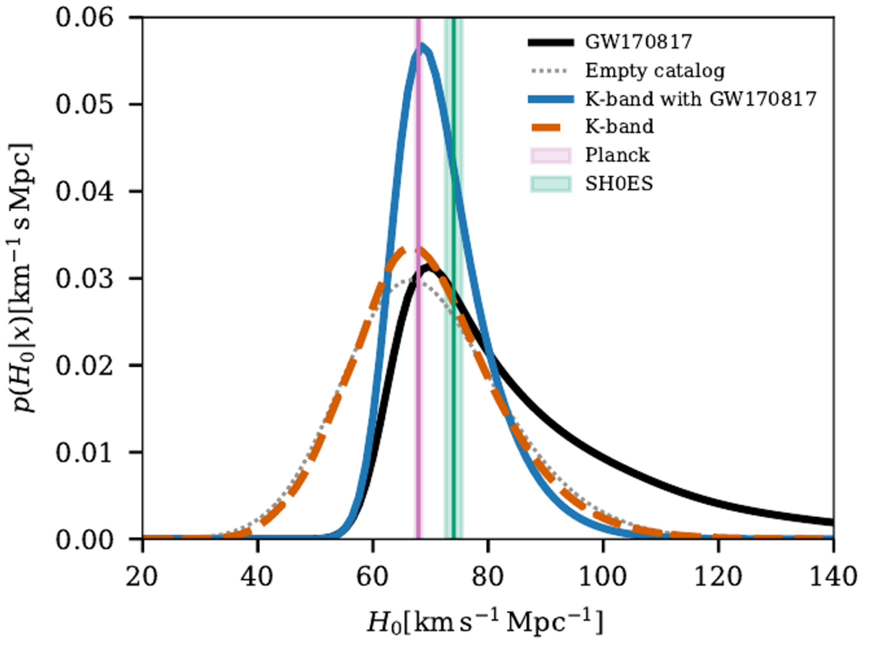
- Data quality not granted a priori!

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

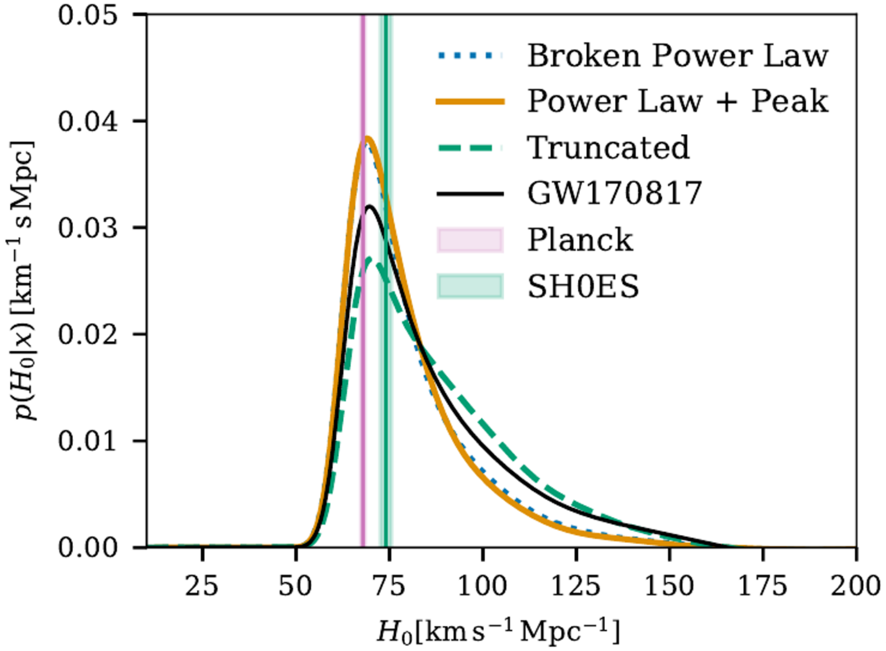


LVC Nature 551,85 (2017)



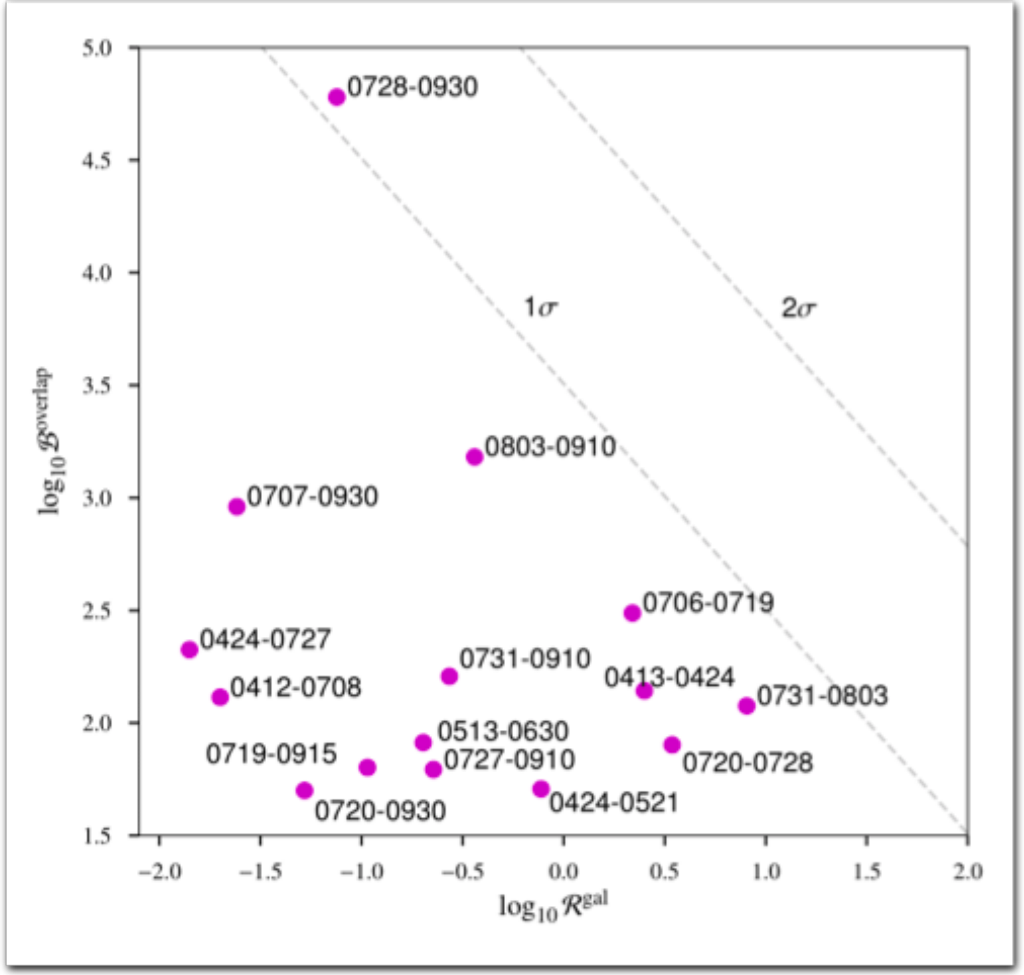
latest results based on GWTC-3 events:

LVK, ApJ arXiv:2111.03604

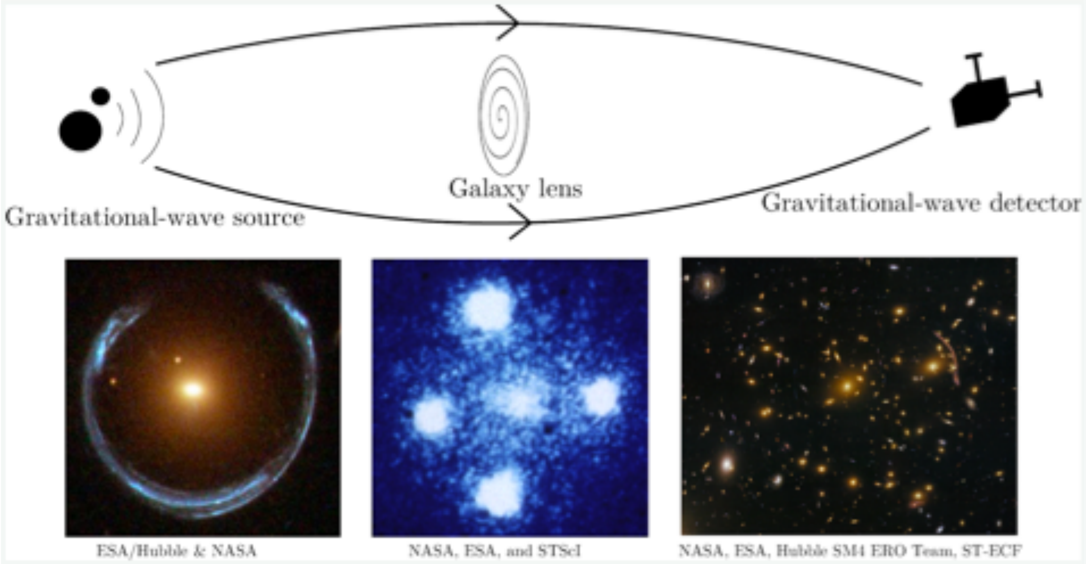


Are any O3a CBC detections gravitationally lensed?

Abbott et al. Astrophys. J. 923, 14 (2021)



Study for gravitational-wave magnification, multi-image, and microlensing signatures on O3a data has uncovered no compelling evidence of gravitational lensing.

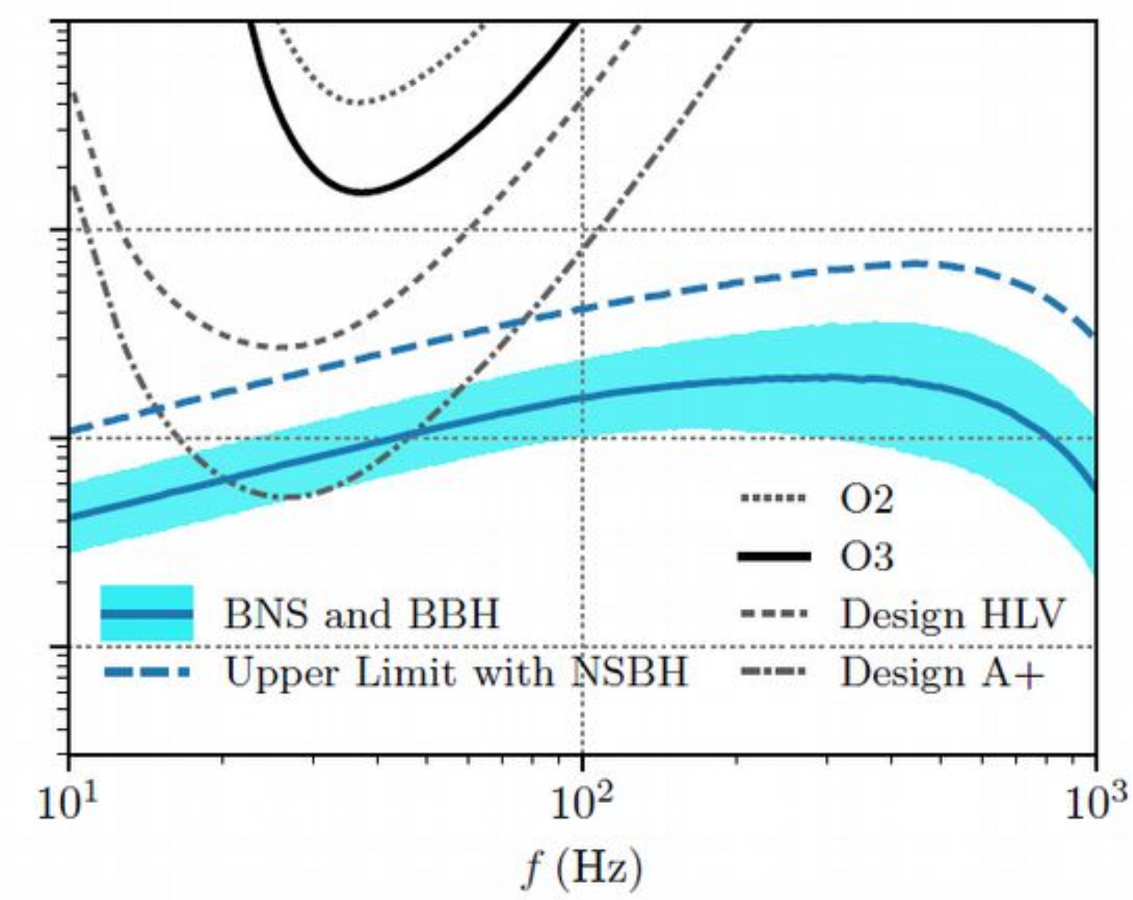


Searches for GW background

Abbott et al. Phys. Rev. D 104, 022004 (2021)

Search for isotropic GW background (astrophysical and cosmological):

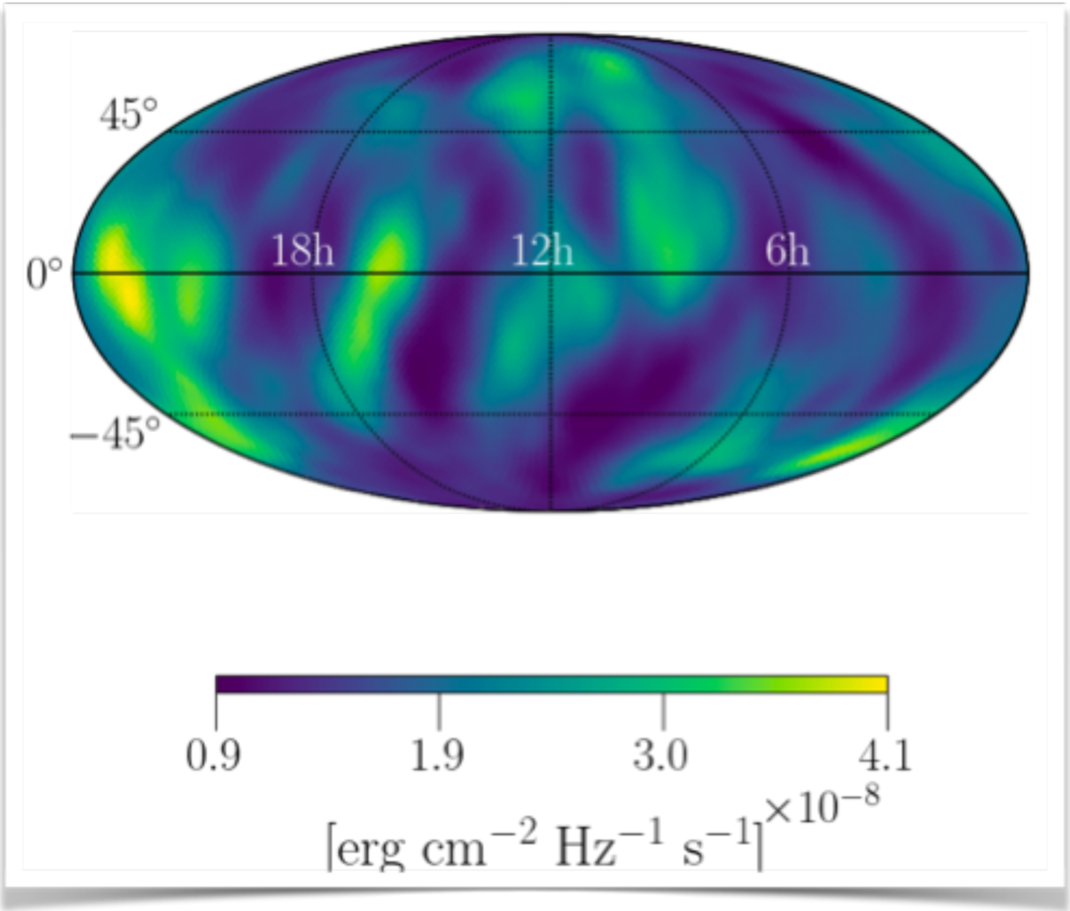
- O3 data from Advanced LIGO's and Advanced Virgo
- no significant evidence for a GW background
- up to date most stringent limits on strength of background (upper limits improved previous bounds by about a factor of 6.0 for a flat background)



Fiducial model predictions for the GWB from BBHs, BNSs, and NSBHs, along with current and projected sensitivity curves

Search for anisotropies in the gravitational-wave background

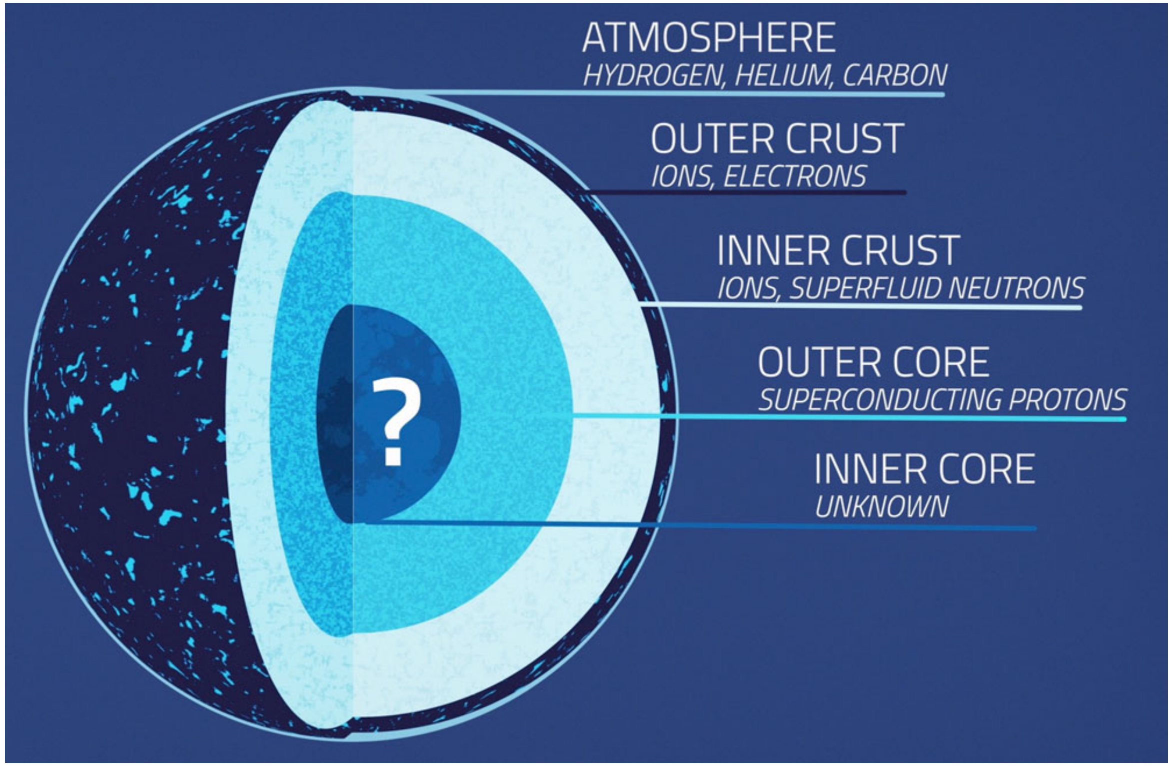
Abbott et al. Phys. Rev. D 104, 022005 (2021)



Search for anisotropic GW background (direction-dependent features)

- No significant evidence for a gravitational-wave background.
- Upper limits set on the strength of gravitational-wave background in every direction in the sky

What can we learn from continuous waves?

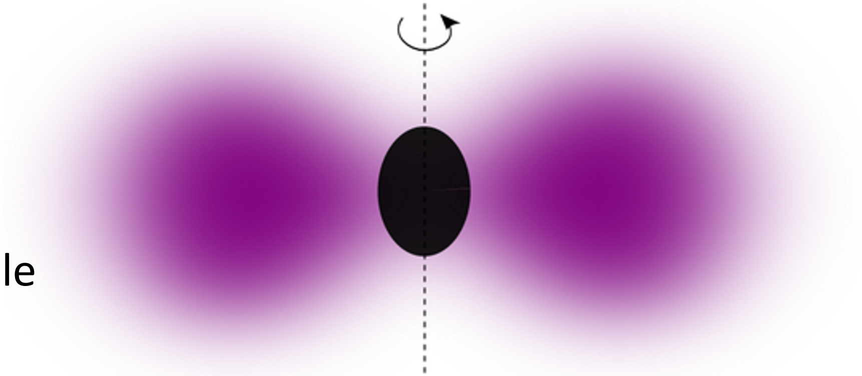


NASA's Goddard Space Flight Center / Conceptual Image Lab

- *Interior structure of neutron star*
- *Neutron star properties, e.g., mass, spin, ellipticity*
- *Nuclear equation of state*
- *May discover exotic states of matter*
- *Multi-messenger studies, e.g., mass and magnetic field structure inferred from GW/EM relative phase*
- *Detecting deviations from General Relativity (speed of GWs, existence of other polarizations)*
- *… and so on*

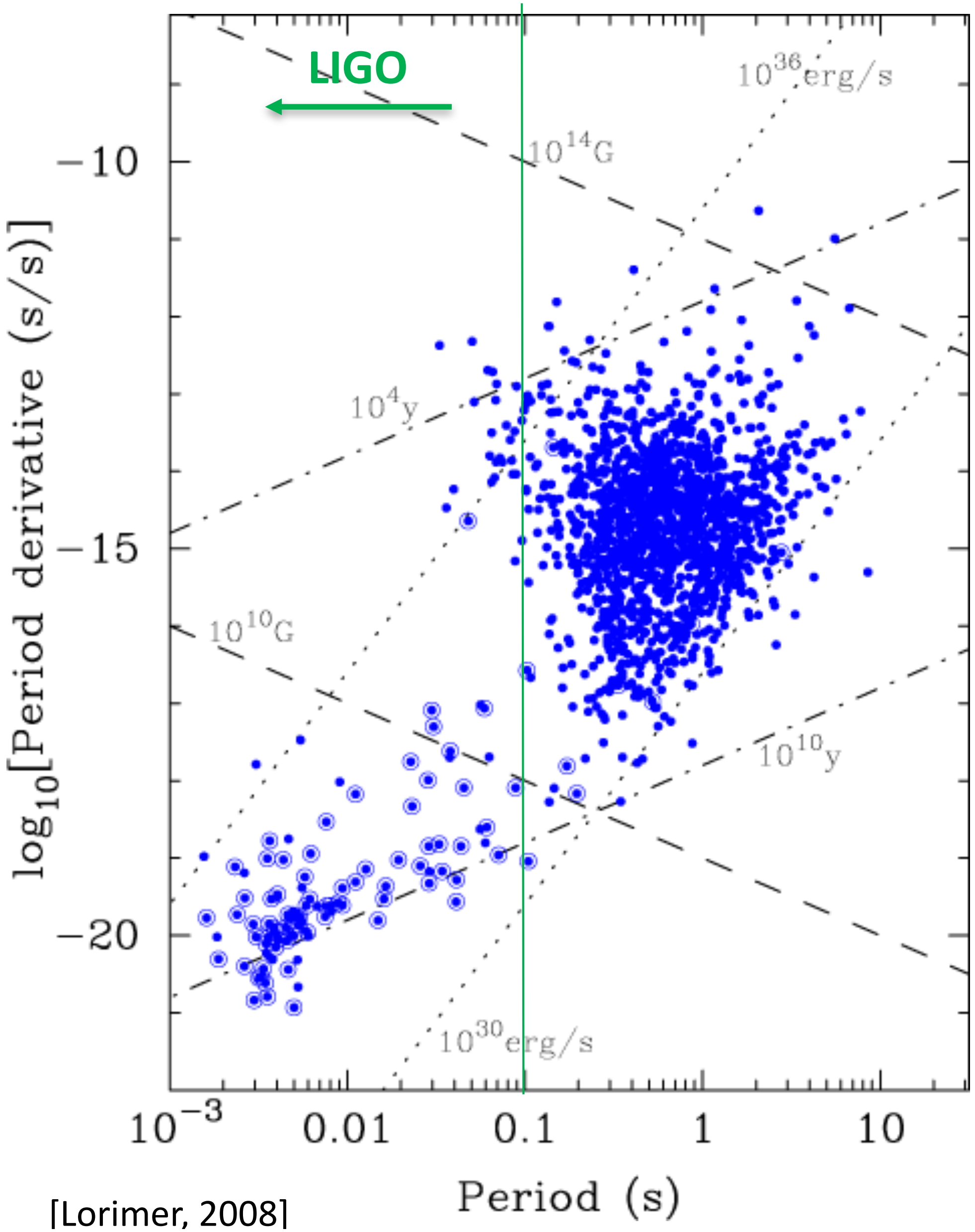
CW-like signals can be also associated to Dark Matter:

- ultra-light boson "clouds" around spinning BHs
  - Probe a parameter space that is inaccessible by conventional lab particle physics experiments; may detect new particles
- direct interaction of ultra-light DM particles with ITF mirrors
- sub-solar mass binary BHs



[KIPAC Stanford / X.Huang / M. Baryakhtar]

Searching CW signals



[Lorimer, 2008]

- **We KNOW that potential sources of CW exist:** more than 3,000 NS are observed through their EM emission, up to 1 billion are expected to exist in the Galaxy
  - 40,000 millisecond pulsars in our galaxy [Lorimer, Living Rev. Relativity, 11 2008]
  - O(10^6 – 10^7) undiscovered EM quiet NS within 5kpc [Narayan. *ApJ*, 1987]
- **We DO NOT KNOW the amplitude** of the emitted signals

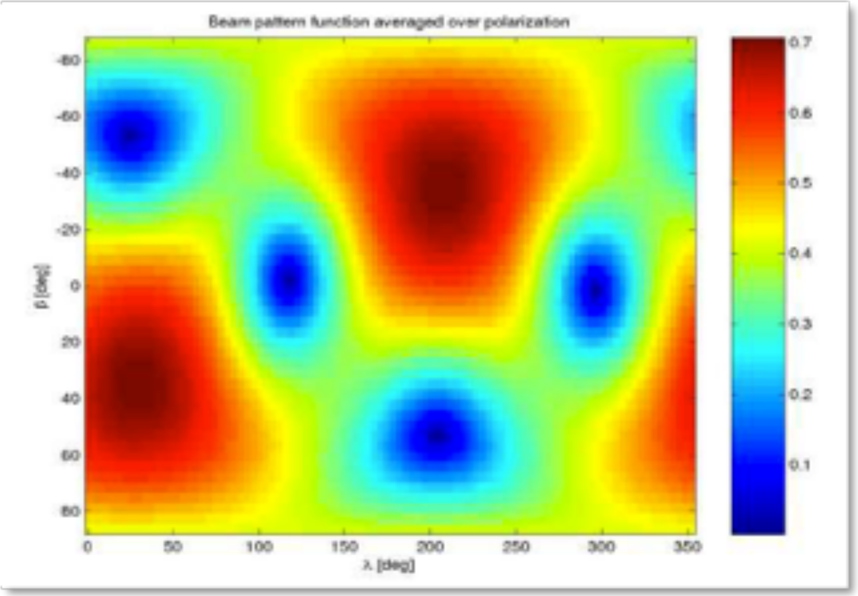
$$h_0 \simeq 10^{-27}\left(\frac{I_{zz}}{10^{38}\,kg\cdot m^2}\right)\left(\frac{10kpc}{d}\right)\left(\frac{f}{100Hz}\right)^2\left(\frac{\varepsilon}{10^{-6}}\right)$$

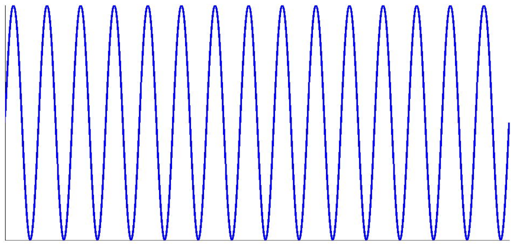
- Expected signal maximum frequency below ~2kHz.
- The source we are searching for are in the Galaxy, d<O(10kpc)
- The ellipticity is largely unknown; ε_{max}~10^{-6} for standard NSs, but some exotic EOS foresee ε_{max}~10^{-4} or even more.

The signal from a NS

At the source

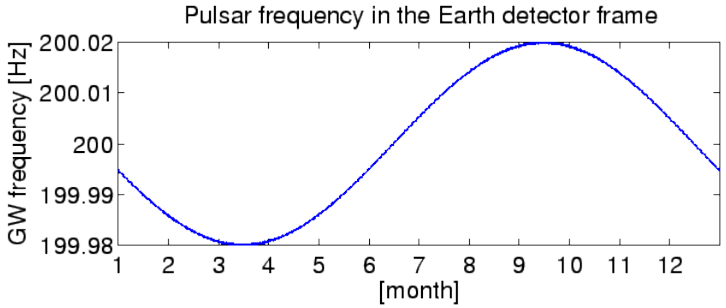
Intrinsic signal frequency changes due to spin-down (up) ⇒ phase evolution

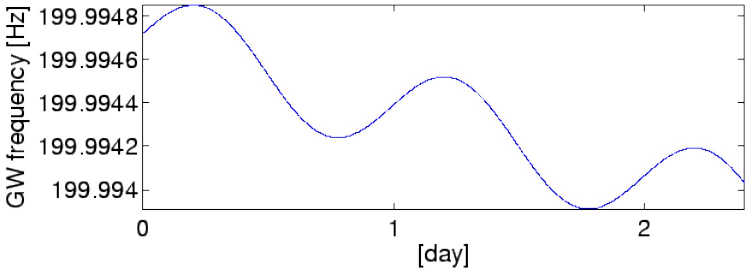




- Annual variation: up to ~10^{-4}
- Daily variation: up to ~10^{-6}

At the detector

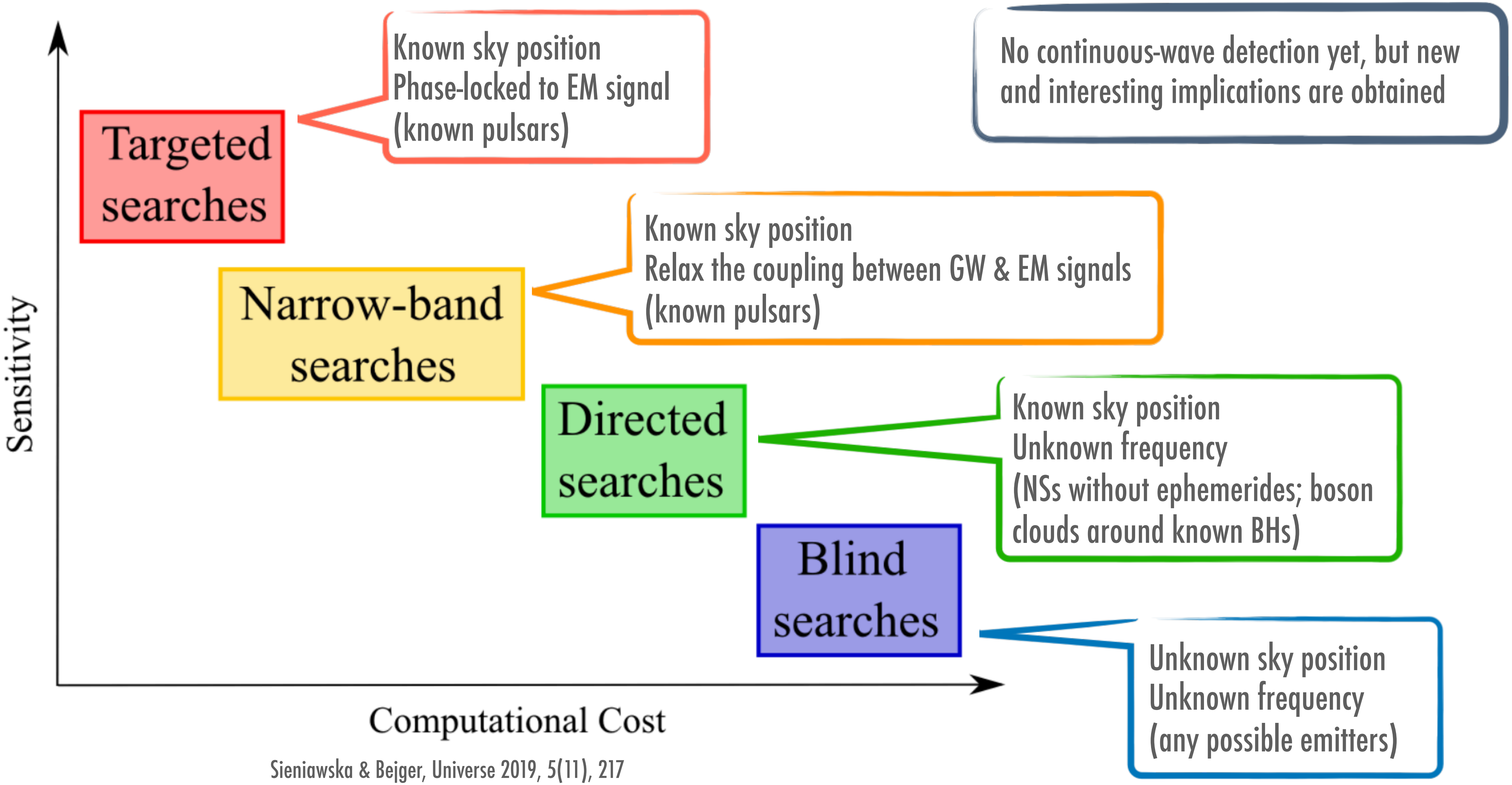




Received signal frequency is affected by Doppler modulation (with a further modulation if the source is in a binary system)
There is a sidereal phase and amplitude modulation due to the detector non- uniform response function

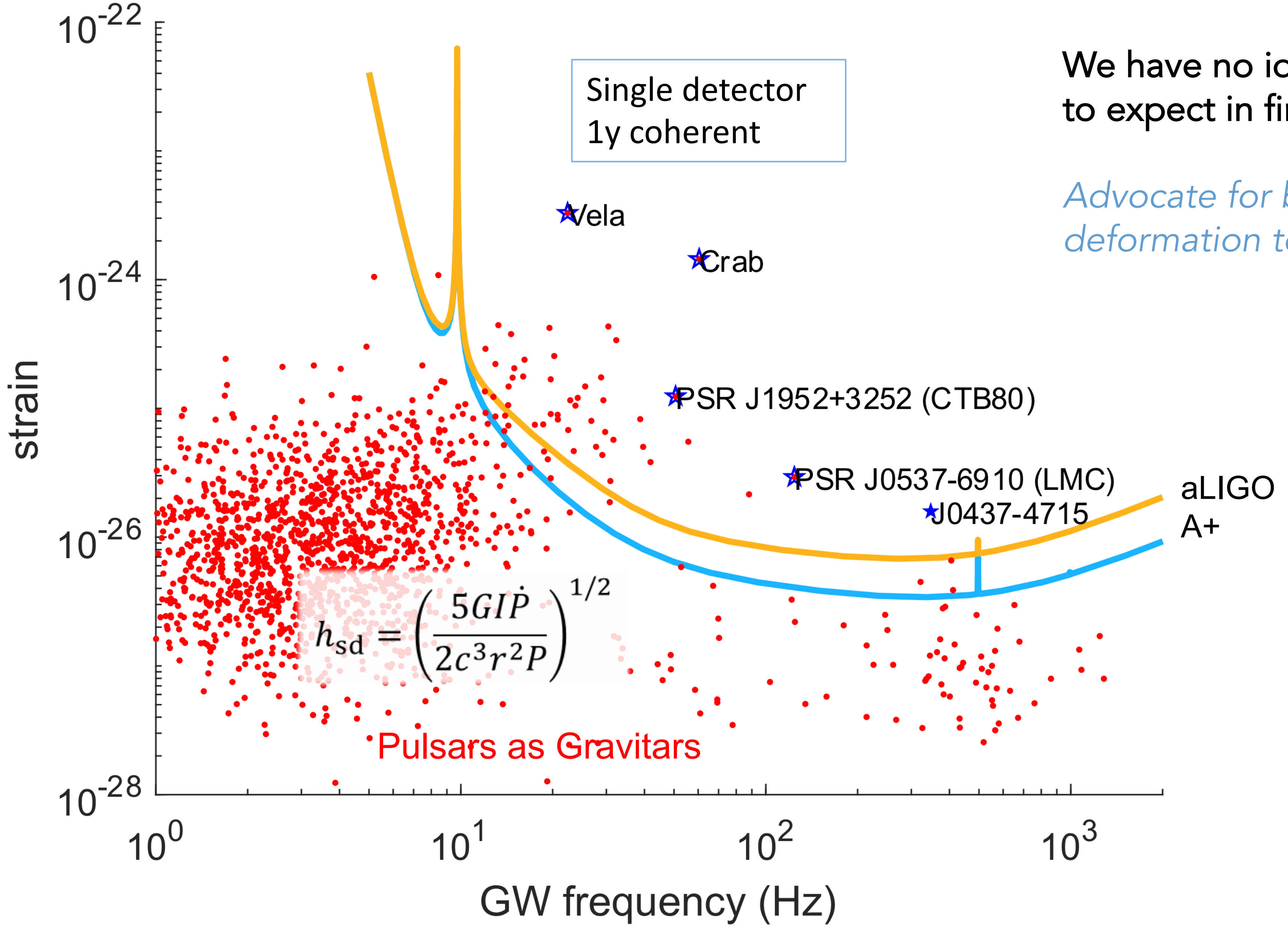
Small relativistic effects (namely, Einstein and Shapiro delay) may play a role.
Pulsar glitches are likely to produce GW signal phase discontinuities
Signal frequency random fluctuations can also be present

Continuous waves searches



Sieniawska & Bejger, Universe 2019, 5(11), 217

Radio pulsars and the aLIGO design sensitivity



We have no idea how many signal detections to expect in first years of aLIGO/AdV.

Advocate for better modeling of neutron star deformation to enhance science case?

Targeted searches for 221 known pulsars in O1 / O2 data

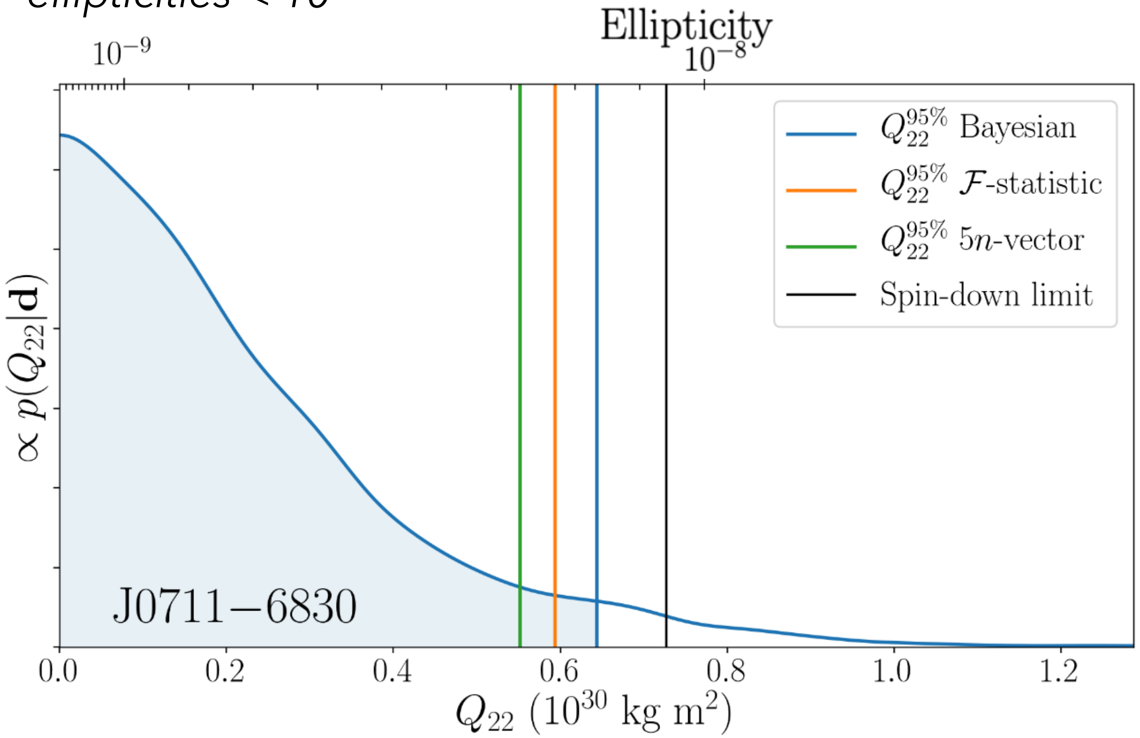
Spindown limit beaten for 20 pulsars

Lowest upper limit on strain:
(J1623-2631) $h_0 < 8.9 \times 10^{-27}$

Lowest upper limit on ellipticity:
(J0636+5129) $\varepsilon < 5.8 \times 10^{-9}$

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}*



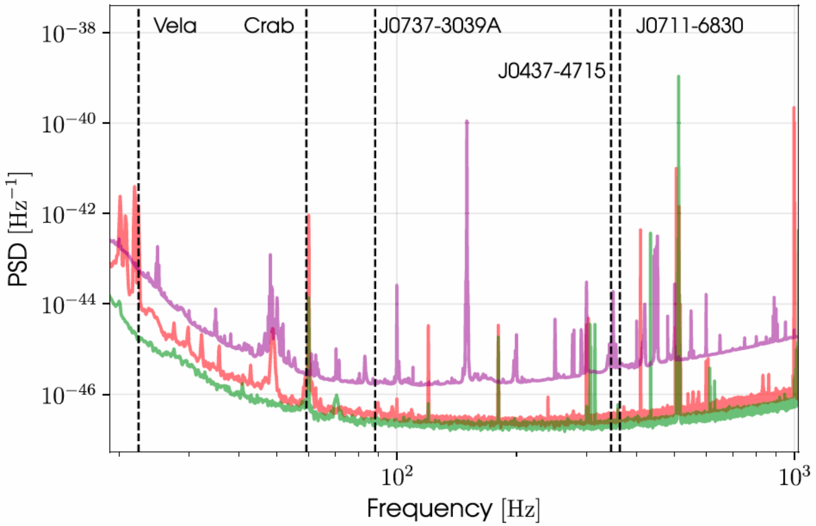
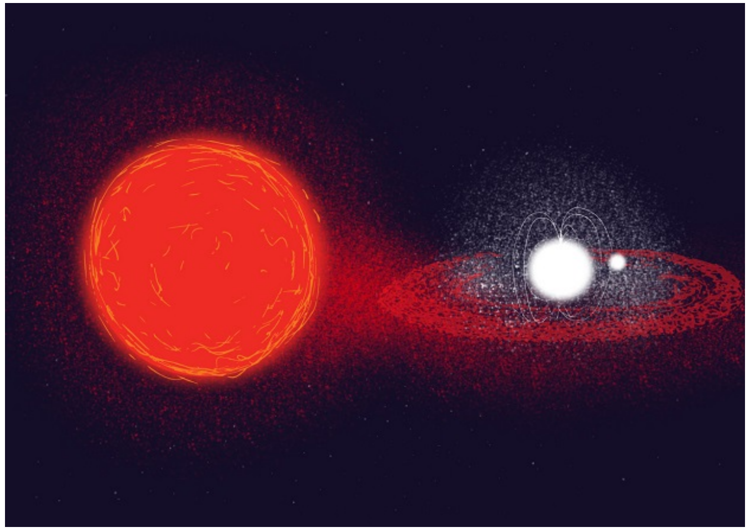


Figure 1. O3a noise PSD for H1, L1, and V1 shown in red, green, and purple. The H1 and L1 PSDs are calculated during a time period of optimal performance for the detector, while the Virgo PSD is averaged over the run. The vertical dashed lines indicate the searched frequency region for each of the five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

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

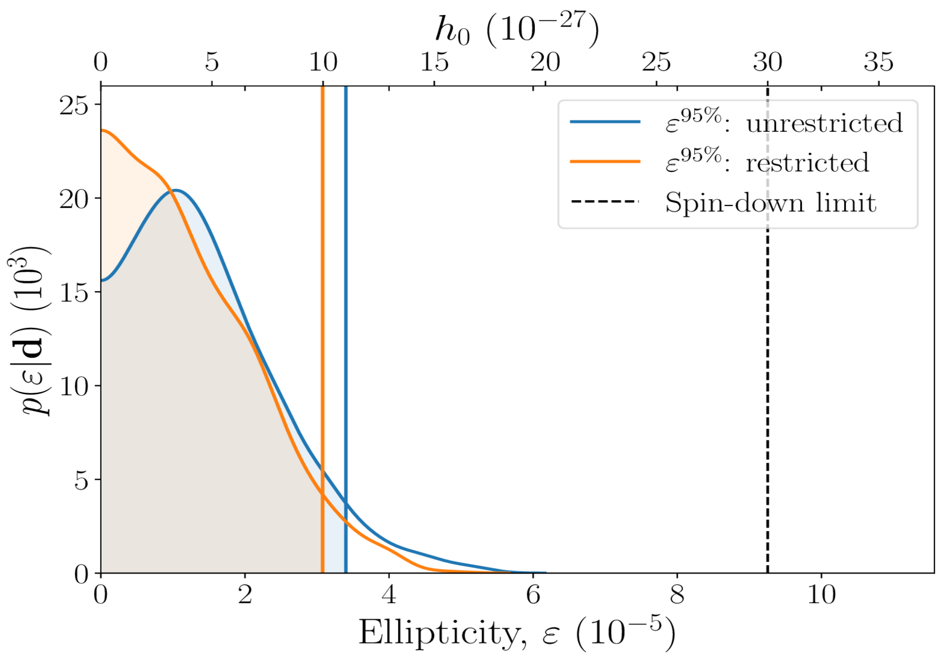


O1+O2+O3a HLV, ApJL 902, L21 (2020)

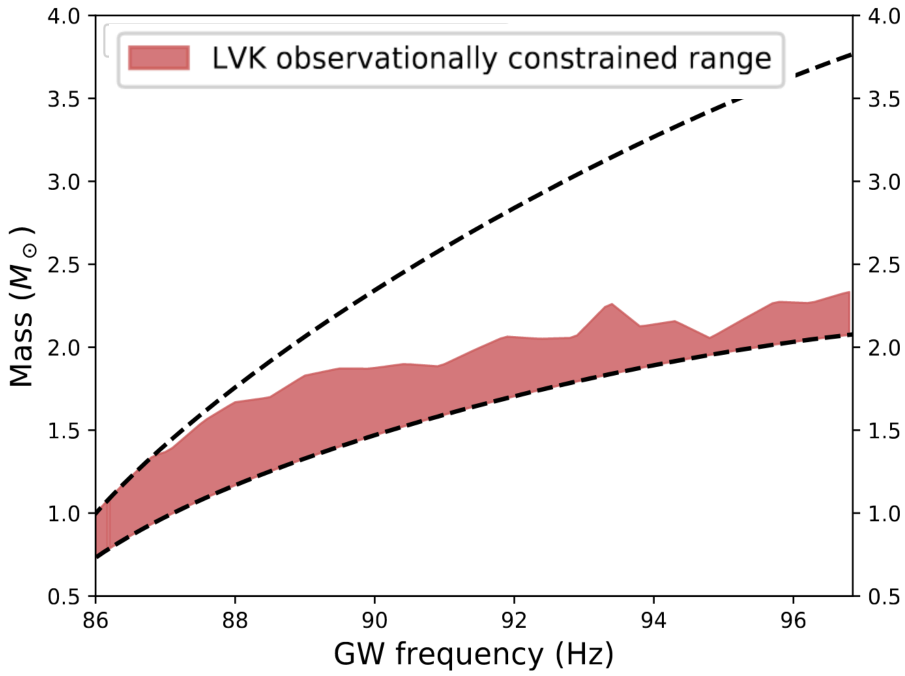
TARGETED: Energetic young pulsar PSR J0537-6910 (“The Big Glitcher”)

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)

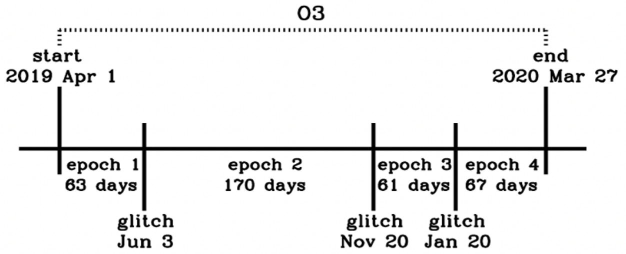
- *Searched at once and twice the spin frequency 62 Hz*
- *First time reach **below GW spin-down limit** for this star by more than **a factor of 2** and limit GWs to account for **<14%** of the spin-down energy budget.*
- *No GWs but we are now 95% confident that the ellipticity is < 0.00003*



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.*



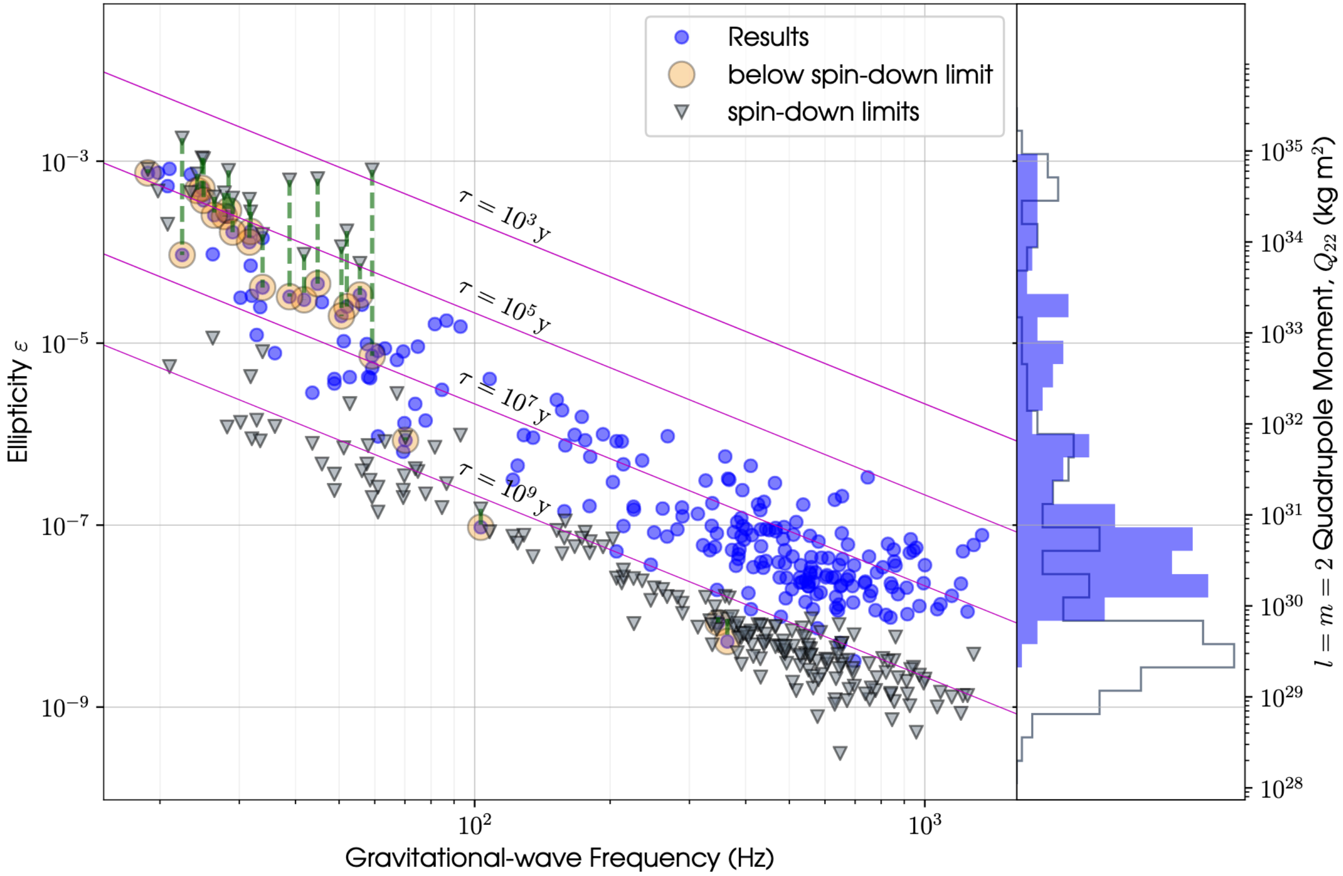
O3 HL, ApJ 922, 71 (2021)

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 $7.2\text{x}10^{-6}$ (maximum mountain height of ~2 cm).



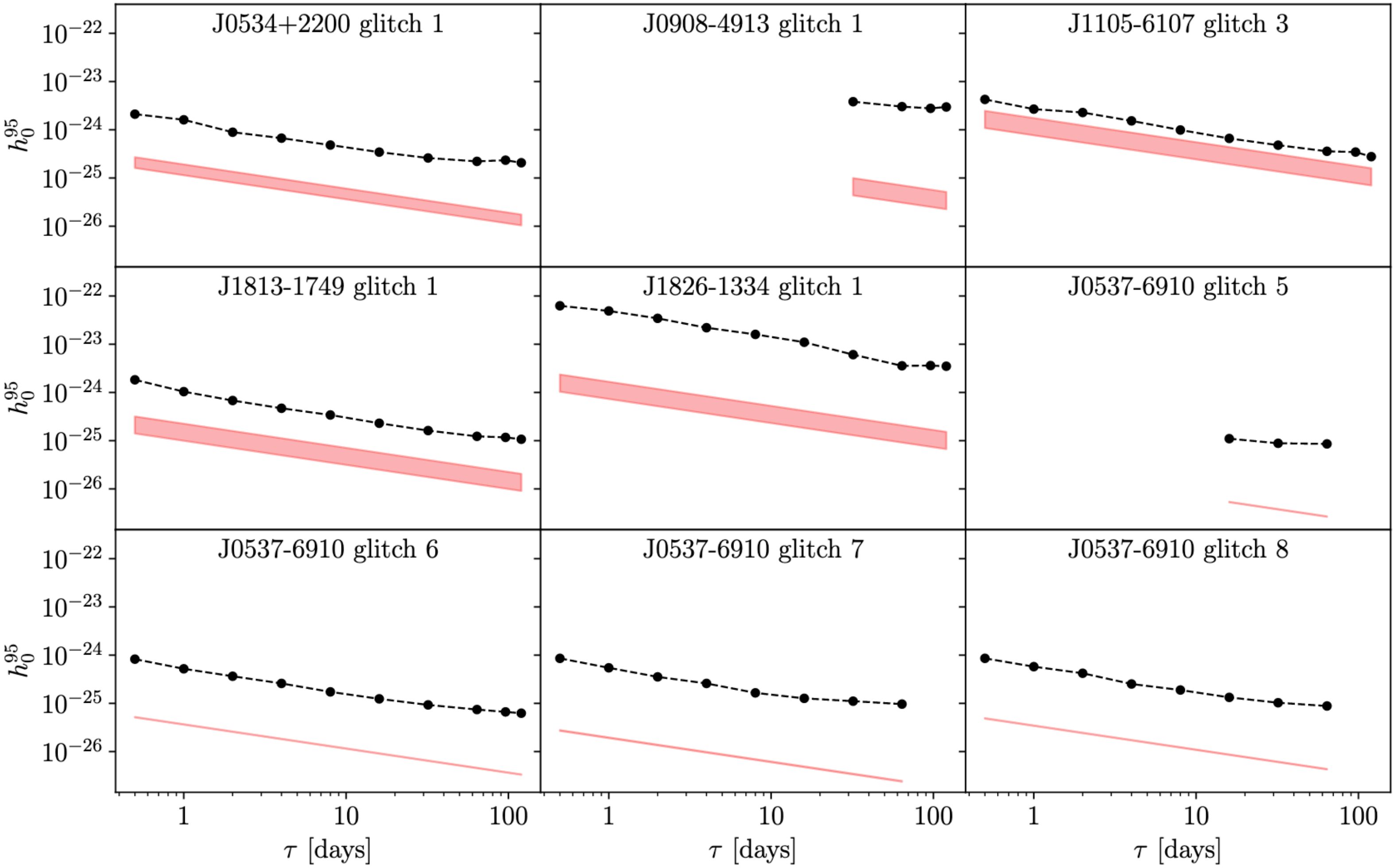
O2+O3 HLV, Astrophys. J. 935, 1 (2022)

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*

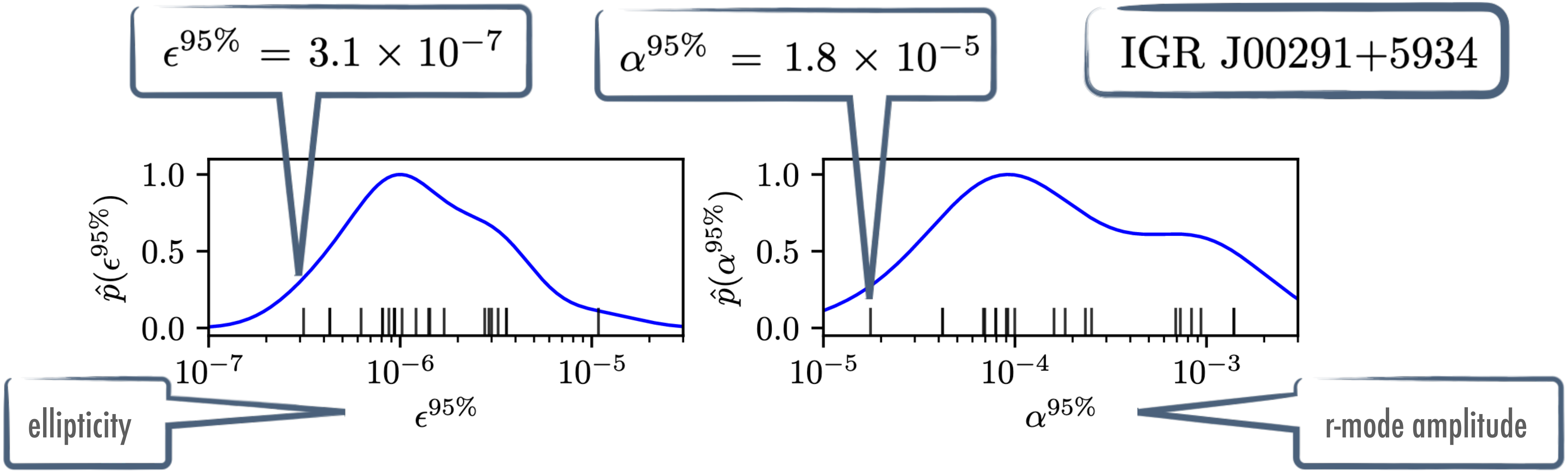
- ***Black:*** *strain upper limits obtained from the search*
- ***Red:*** *indirect glitch excess energy upper limits*



O3 HLV, ApJ Astrophys. J. 932, 133 (2022)

NARROW-BAND: 20 accreting millisecond X-ray pulsars

- *Three narrow sub-bands are searched for each target, centered on* $\{1, 4/3, 2\}f_\star$
- *Accommodating frequency wandering within those sub-bands*
- *The most comprehensive and sensitive CW search targeting accreting millisecond X-ray pulsars to date*



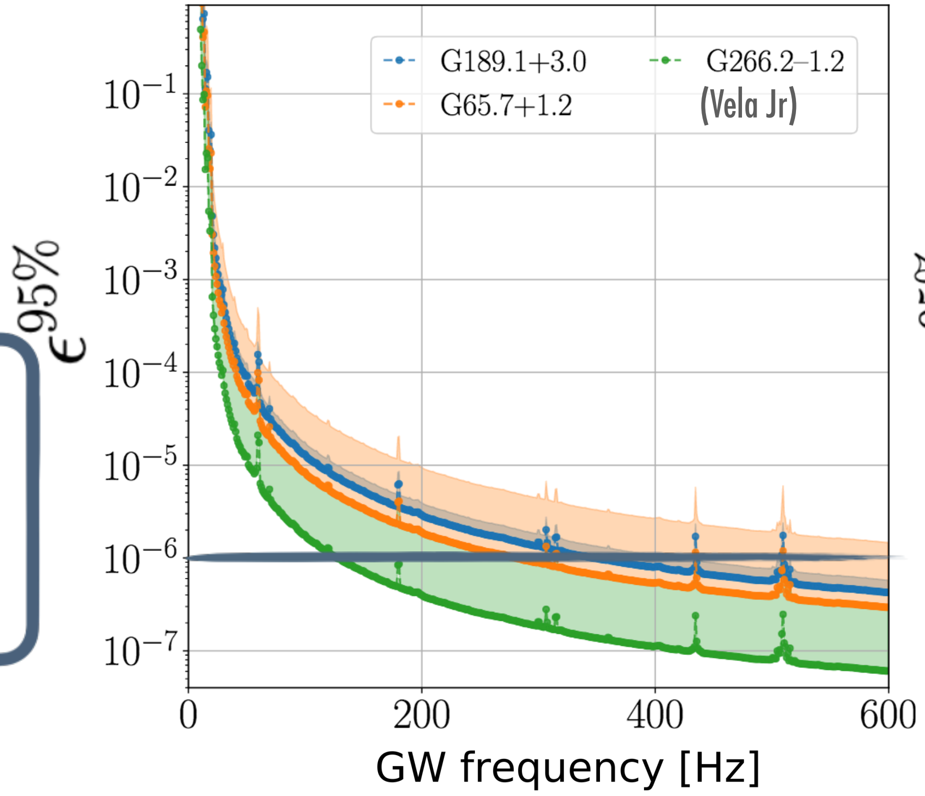
Blue curves — kernel density estimate of the PDF of the constraints on ellipticity and r-mode amplitude

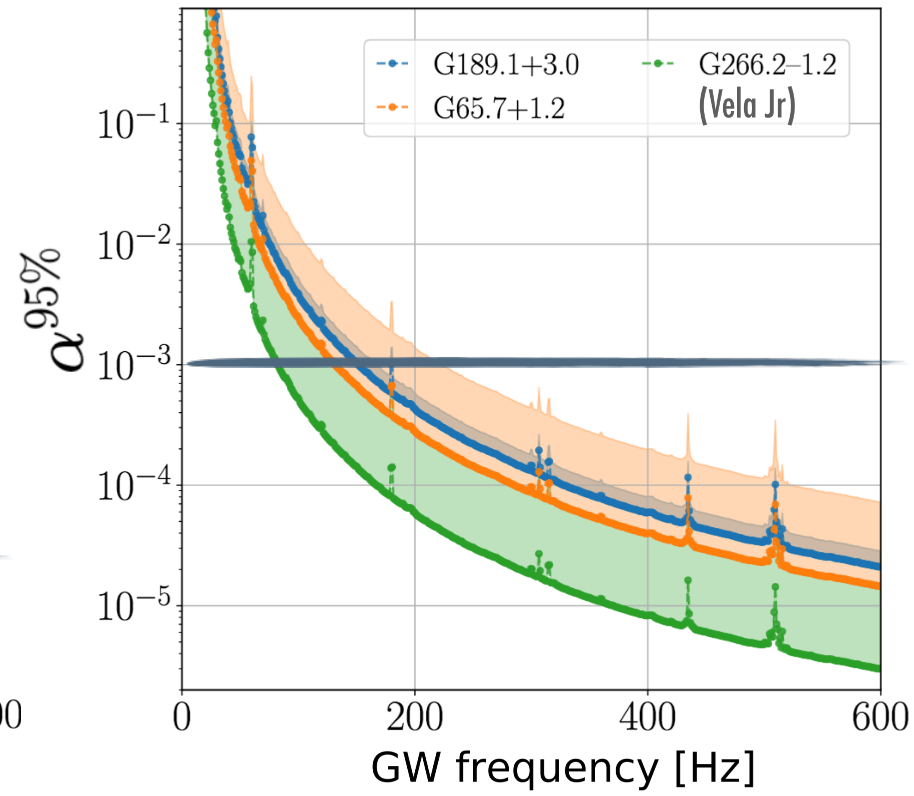
O3 HL, PRD 105, 022002 (2022)

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 ($h_{0,min}$~7.7×10^{-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}~6×10^{-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.*



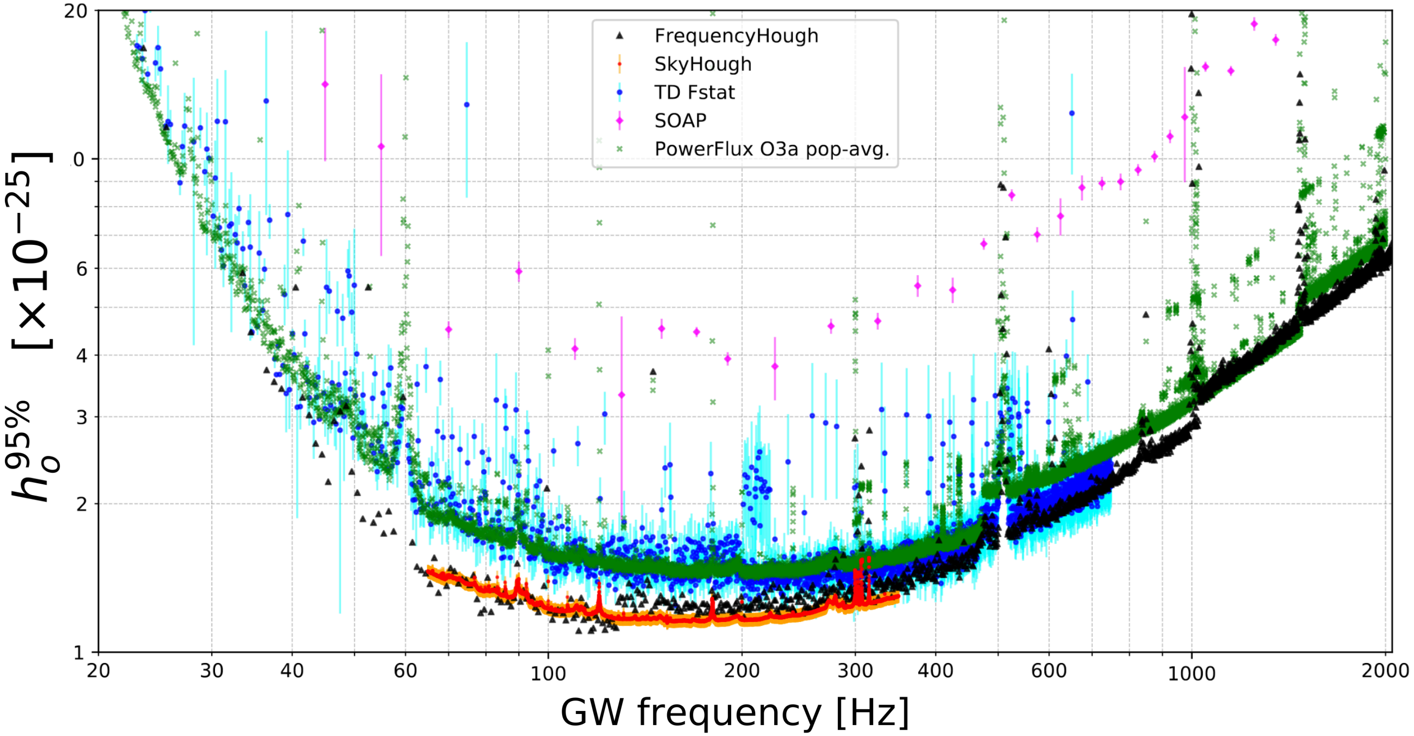


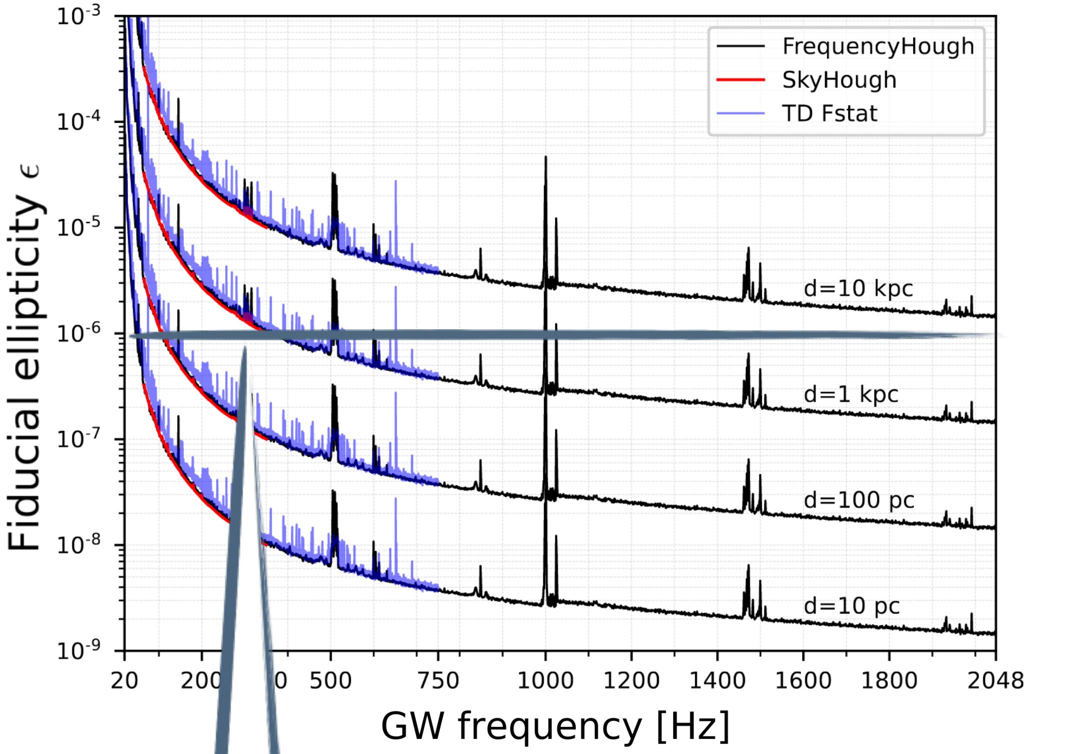
O3a HLV, ApJ 921, 80 (2021)

O3a HL, PRD 105, 082005 (2022)

BLIND ALL-SKY: Isolated neutron stars

- *Use model-based & unmodeled algorithms*



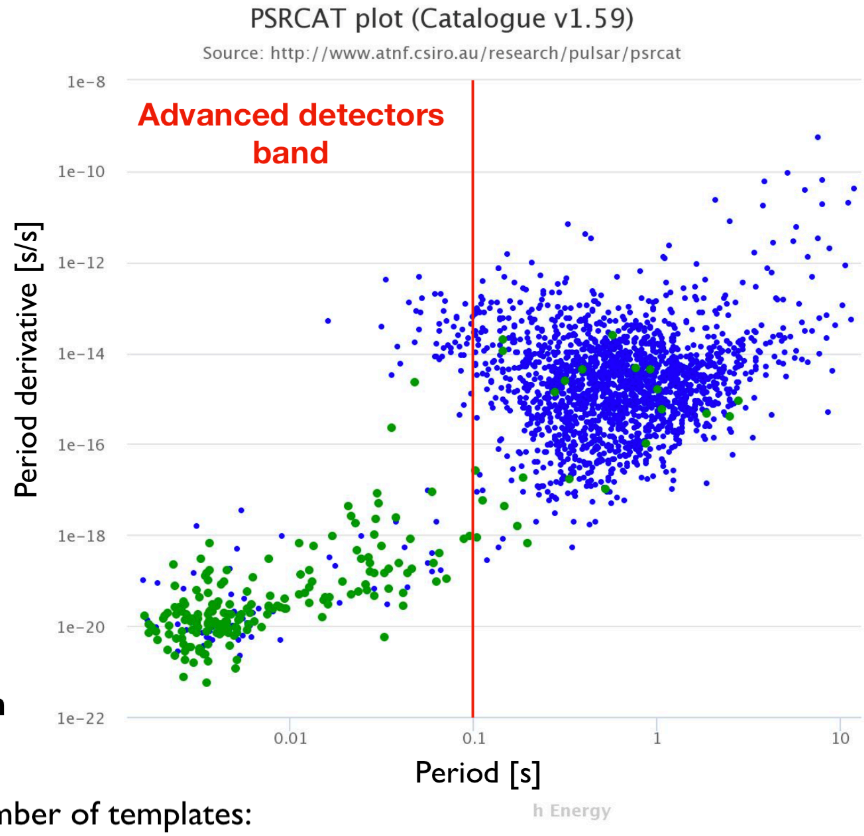


Frequency band: [10, 2048] Hz
Frequency derivative: $[-1.0, +0.1] \times 10^{-8}\ \mathrm{Hz/s}$

- *Can probe the ellipticity that may be supported by the crust of a NS described by a realistic equation of state within ~1 kpc*

O3a HL, PRD 104, 082004 (2021)
O3 HLV, arXiv:2201.00697 (2022)

NS in binary systems



Spin-down of NS in binary systems smaller than isolated NS

286 binary
2659 total

f_0>10 Hz:
263 binary
458 total

Isolated:	**Binary:**	**Circular binary:**
• Frequency • Sky position • Spin-down	• Frequency • Sky position • Projected amplitude • Period • Time of ascension • Eccentricity • Argument of periapse	• Frequency • Sky position • Projected semi-major axis • Period • Time of ascension
4 parameters	**8 parameters**	**6 parameters**

- Number of templates:
  - Binary: $dN \propto T_c^6 T_{obs} f^5 \Omega^4 a_p^2 d\lambda$
  - Isolated: $dN_I \propto T_c^4 T_{obs} f^2 d\lambda$

$$\Delta a_p = \frac{\sqrt{6m}}{\pi T_c f_0 \Omega} \qquad \Delta\Omega = \frac{\sqrt{72m}}{\pi T_c f_0 a_p T_{obs} \Omega} \qquad \Delta t_{asc} = \frac{\sqrt{6m}}{\pi T_c f_0 a_p \Omega^2}$$

$$\Delta f = \frac{1}{T_c} \qquad \Delta\theta = \frac{1}{\frac{v}{c} T_c f_0 P_F}$$

$$f_\lambda(t) = f_0 \cdot \left(1 + \frac{v(\vec{t})}{c} \cdot \vec{n}\right)$$

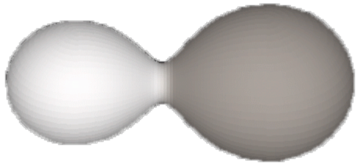
$$f(t) = f_0 \left(1 + \frac{\vec{v}}{c} \cdot n - a_p \Omega \cos\left[\Omega(t - t_{asc})\right]\right)$$

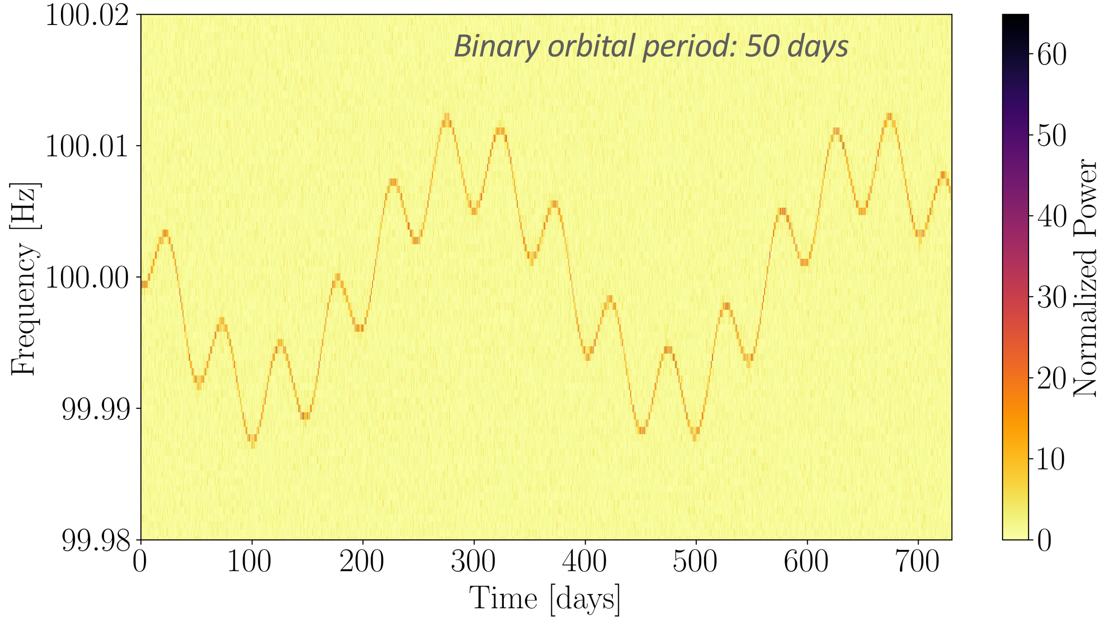
Doppler modulated due to the presence of a binary companion.

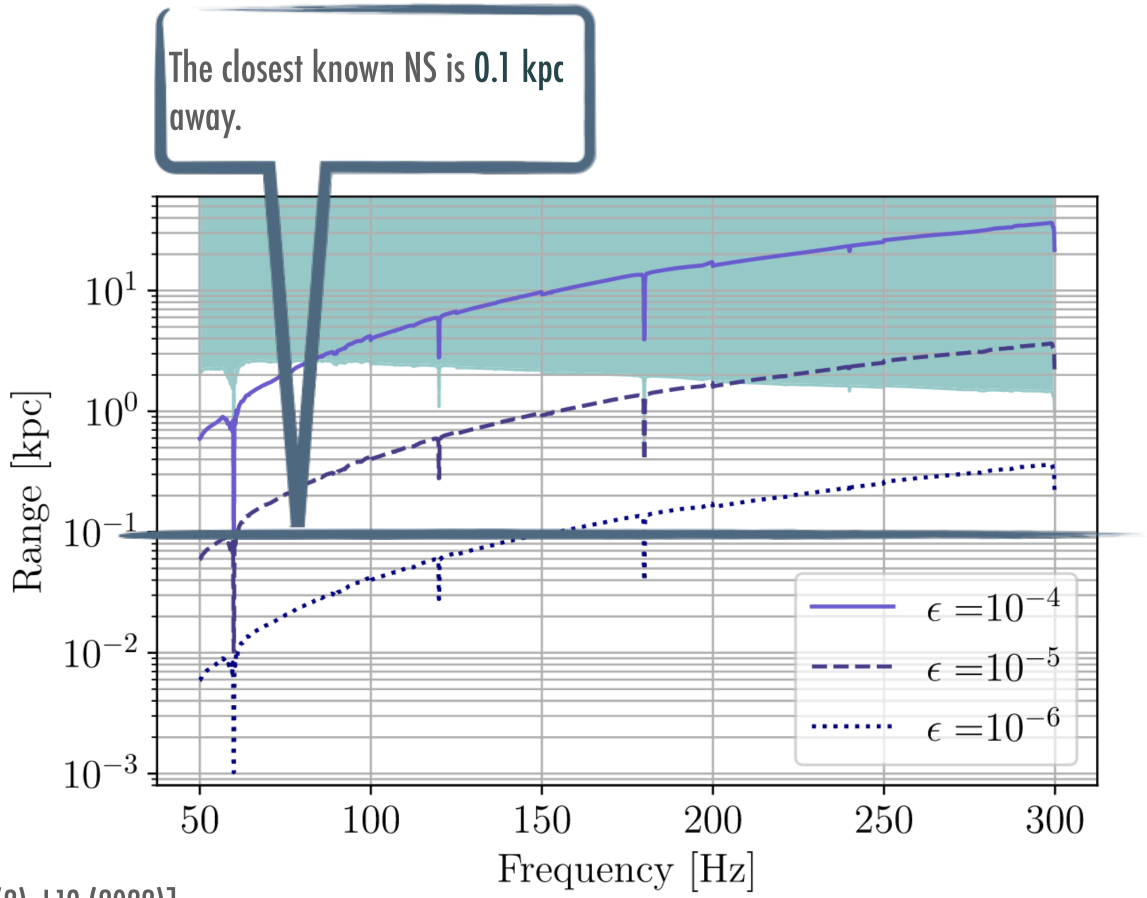
BLIND ALL-SKY: Neutron stars in binary systems

- *Search frequency band* ***[50, 300] Hz***
- *Need to account for the modulation due to the binary orbit*
- *Binary orbital parameters: orbital period* ***[3, 45] days*** *and projected semimajor axis* ***[2, 40] light-sec***

➔ Most sensitive results to date in the probed parameter-space region.
➔ Ellipticity constrained to (10^{-5}-10^{-4}) at (1-2) kpc depending on frequency.
➔ Approaching regime of exotic equations of state (10^{-5}), but still a while until realist ones (10^{-7}- 10^{-6}).

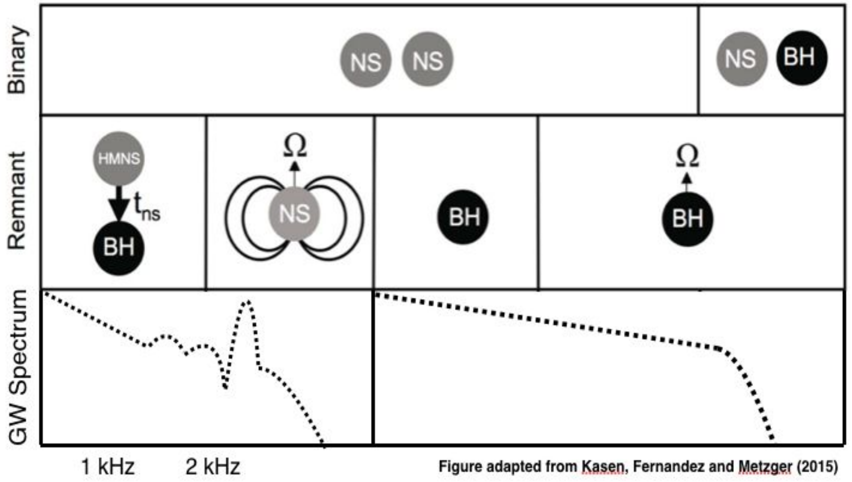






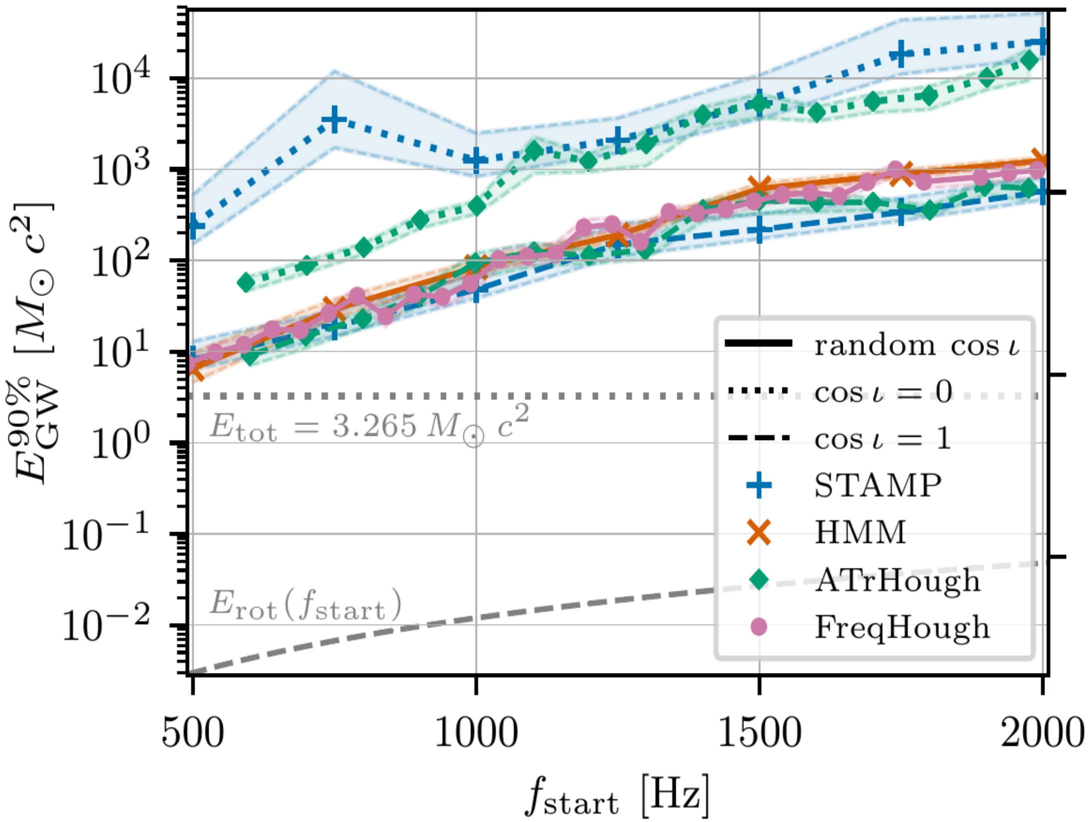
O3a HL, PRD 103, 064017 (2021)

[Also see new external all-sky search results: Dergachev & Papa, arXiv:2202.10598 (2022), Covas et al., ApJL 929 (2), L19 (2022)]



Long-duration transients: BNS postmerger

- GW170817: first BNS detected in GWs,“nearby” at ≈ 40 Mpc
- remnant: BH, NS→BH, or NS?
- LVC searches for short- and long-duration signals from potential NS remnant ApJL851:L16 (2017) / ApJ875:160 (2019)



Periodic signal with power law frequency evolution depending on the braking mechanisms

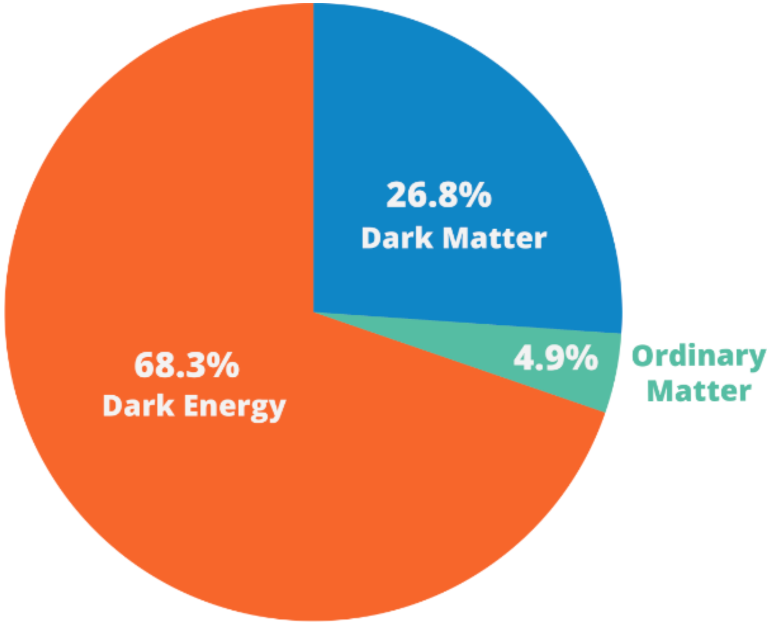
$$\dot{\Omega} = -k\Omega^n$$

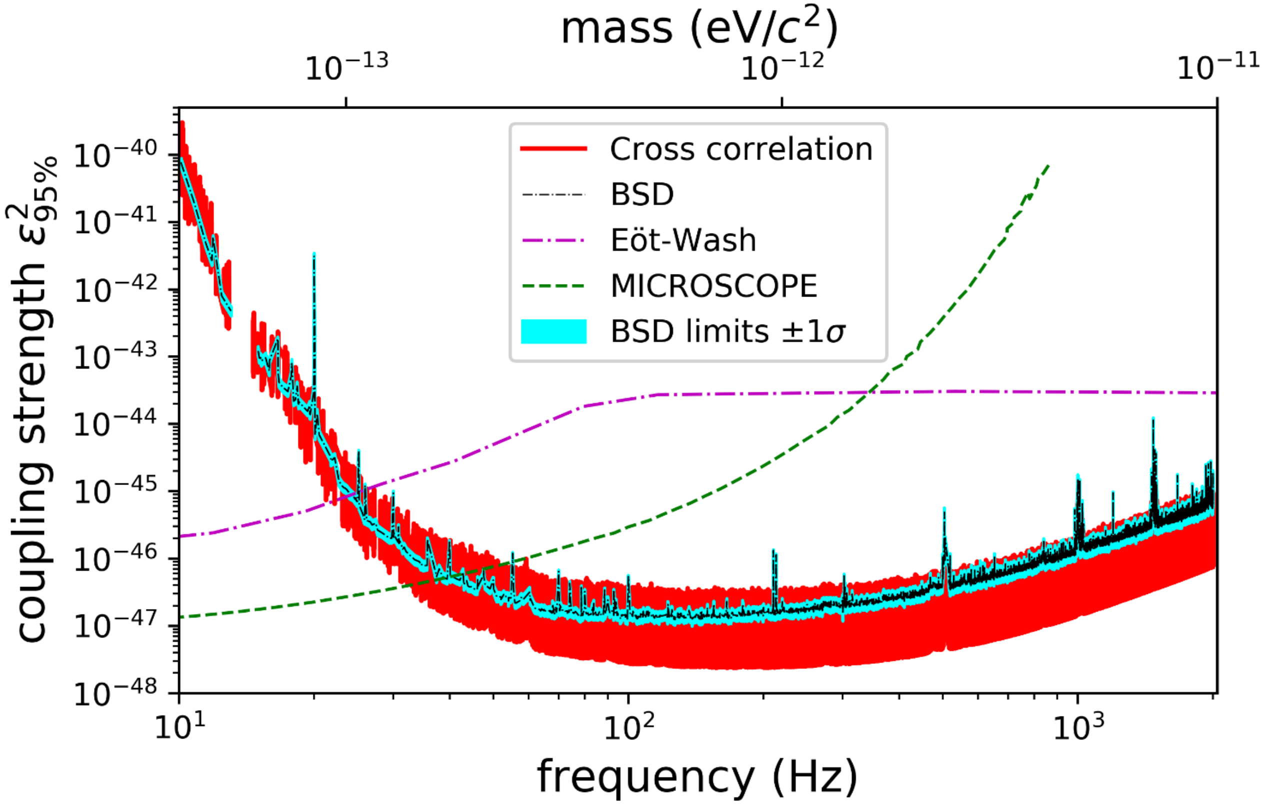
Due to fast spin-down the GW signal frequency may become too small after hours-days

$$f_{gw}(t) = f_{gw,0}\left(1 + \frac{t}{\tau}\right)^{\frac{1}{1-n}} \qquad \tau = \frac{-\Omega_0^{1-n}}{k(1-n)}$$

CWs and fundamental physics: constraints on dark photon dark matter using O3

- *This is NOT a GW search, but a direct dark matter search*
- *Dark matter could interact directly with detector mirrors via dark photons and cause an oscillatory force on the detector.*
- *The expected signal in data is similar to a continuous-wave signal, frequency depending on particle mass.*
- *The explored dark photon mass range: 10^{-14} – 10^{-11} eV/c^2*
- *The limits improve upon those obtained in direct dark matter detection experiments by a factor of ~10 to 100 at many frequencies*

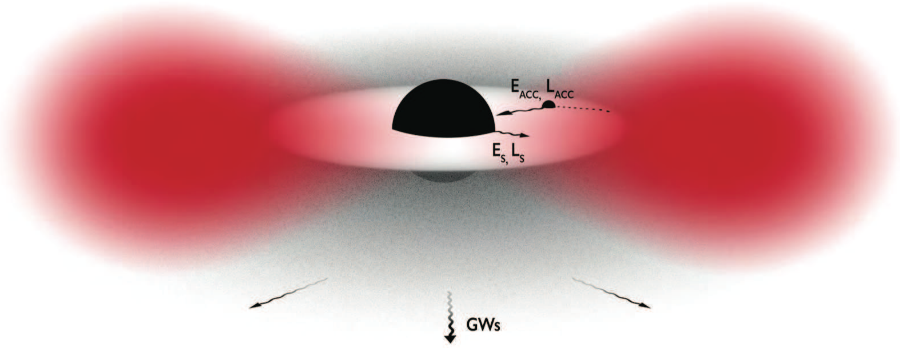




O3 HLV, PRD 105, 063030 (2022)

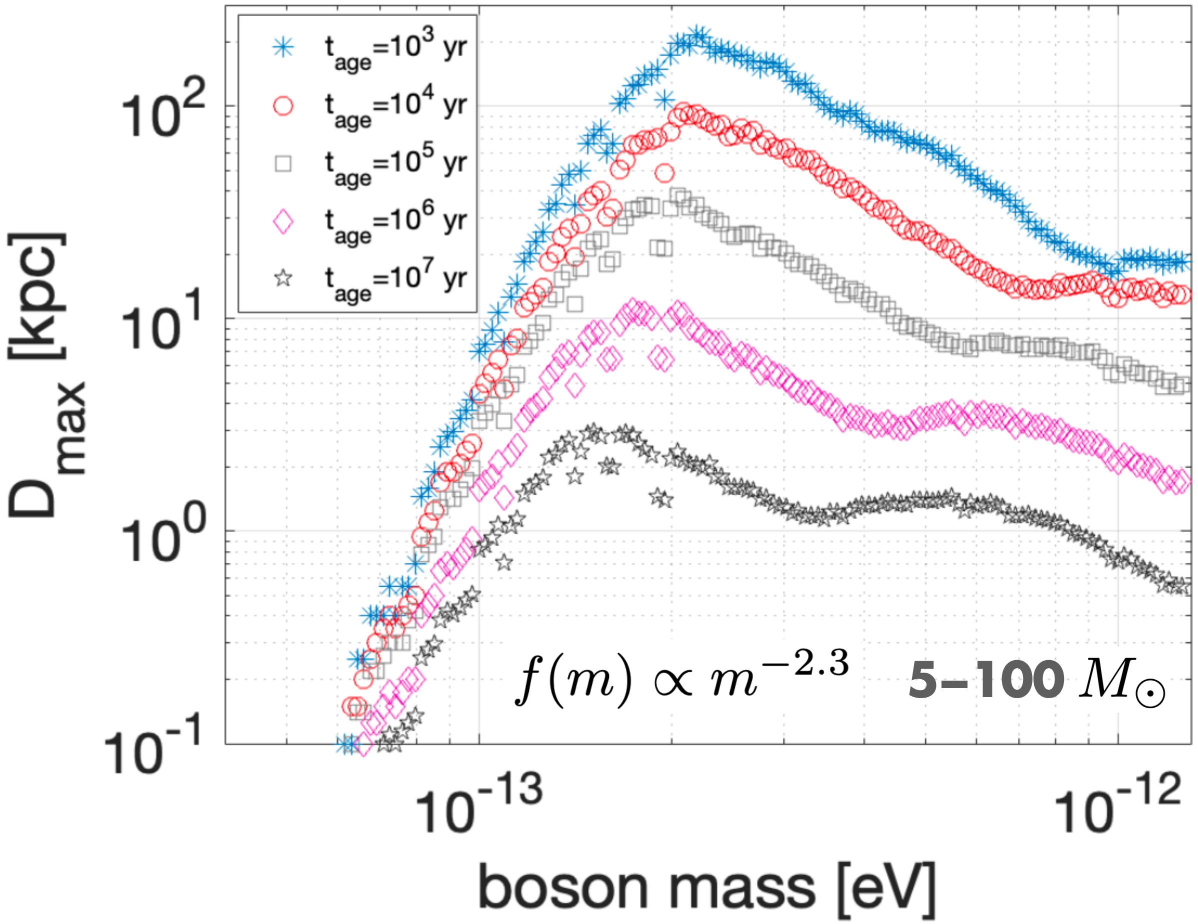
BLIND ALL-SKY: Scalar ultralight boson clouds

- *First all-sky search tailored for scalar boson clouds; search frequency band* ***[20, 610] Hz***



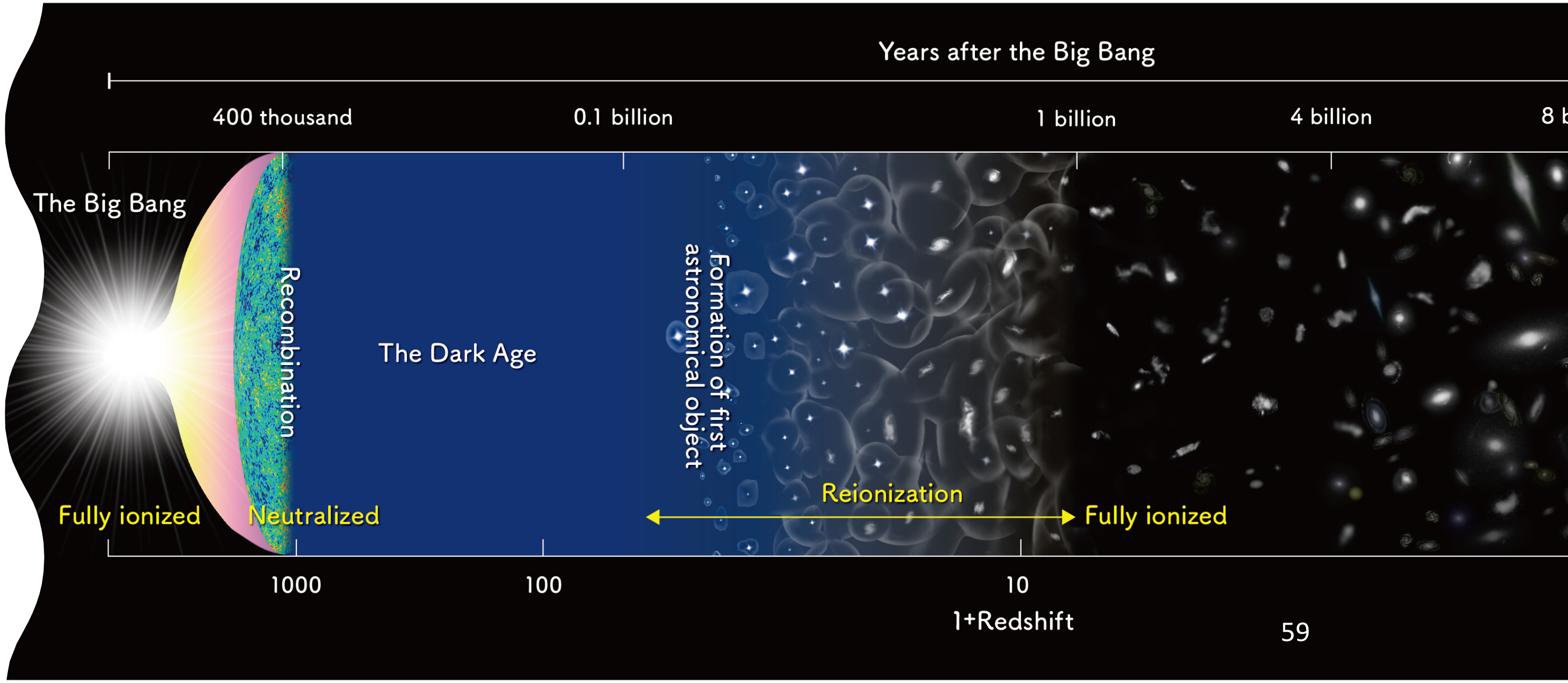
Brito, Cardoso, Pani (2015)

- *Scalar boson clouds younger than 1000 years, formed by bosons with mass ~1e-13eV, are not likely to exist in our Galaxy.*

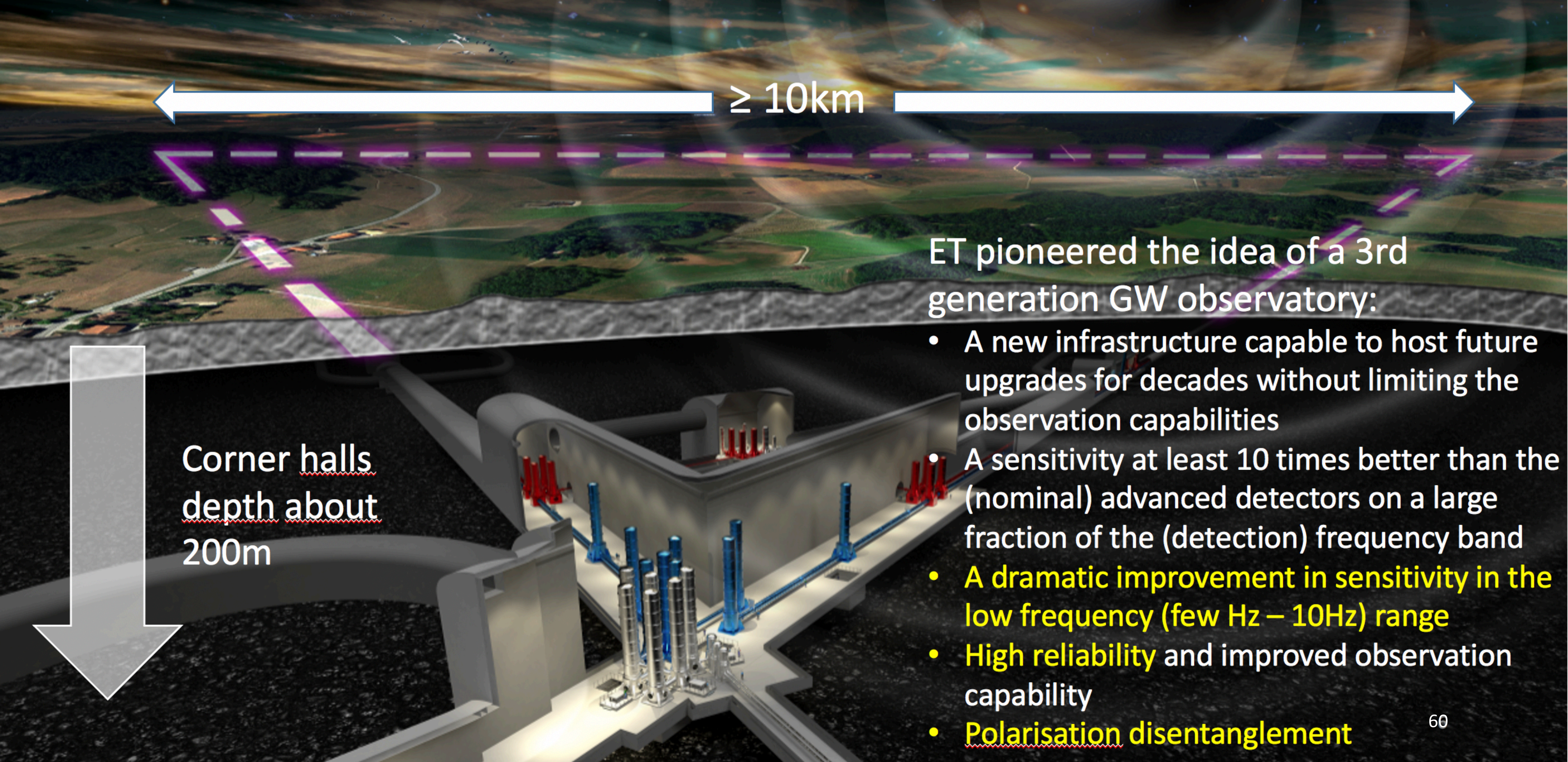


The Message

- Current generation of gravitational wave instruments have opened a new era in astronomy…
- …but they are detecting only the tip of the iceberg
- We are probing only a very small part of the Universe



Einstein Telescope (ET)



ET pioneered the idea of a 3rd generation GW observatory:

- A new infrastructure capable to host future upgrades for decades without limiting the observation capabilities
- A sensitivity at least 10 times better than the (nominal) advanced detectors on a large fraction of the (detection) frequency band
- A dramatic improvement in sensitivity in the low frequency (few Hz – 10Hz) range
- High reliability and improved observation capability
- Polarisation disentanglement

Einstein Telescope

ET Design Studies

Conceptual Design Study (2008-2011): https://tds.virgo-gw.eu/?call_file=ET-0106C-10.pdf
Design Report Update (2020): https://apps.et-gw.eu/tds/?content=3&r=17245

ET Consortium Agreement

Signed by 41 institutions institutions submitted to ESFRI
(European Strategy Forum on Research Infrastructures)
Light agreement at this level.
Coordinated by INFN and Nikhef

Milestones

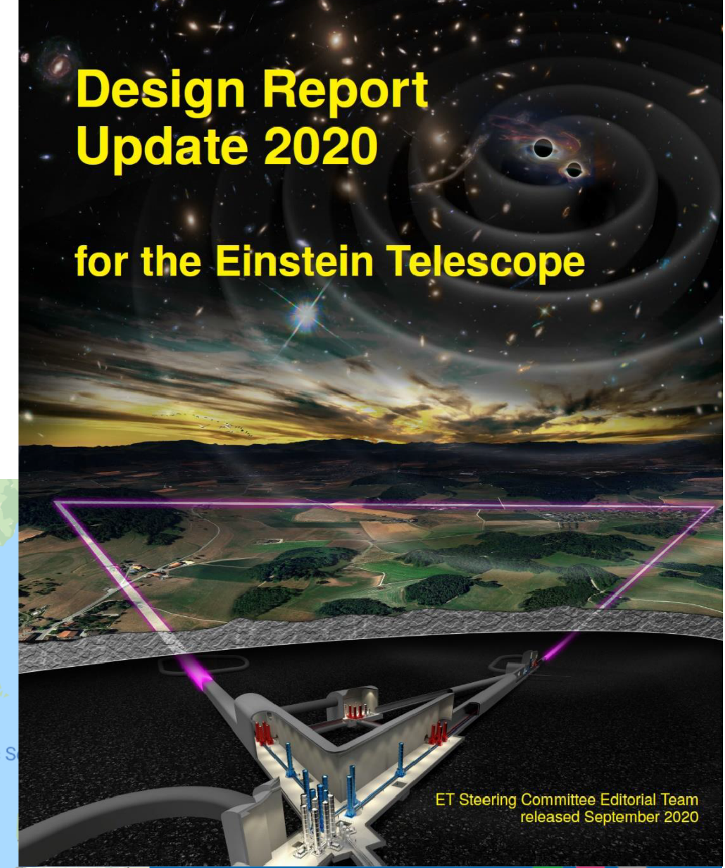
ESFRI approval: June 30, 2021
https://www.esfri.eu/latest-esfri-news/new-ris-roadmap-2021

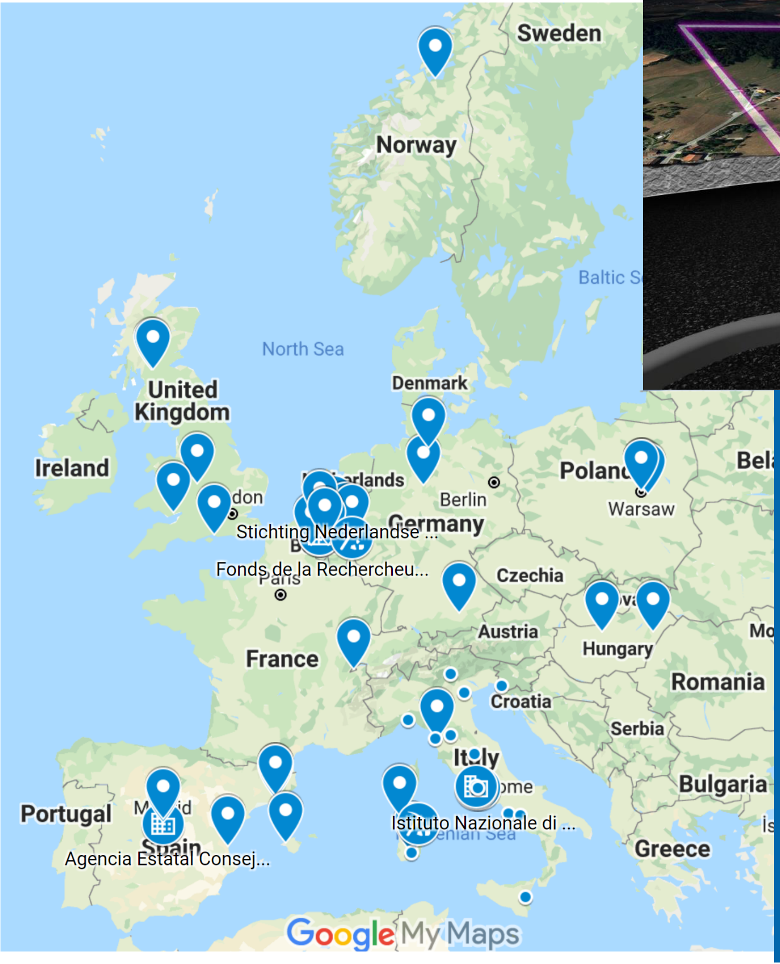
ET Scientific Collaboration

Kick off meeting Budapest 7-8 June 2022
& first meeting of the Einstein Telescope Collaboration Board

ET-PP INFRA DEV

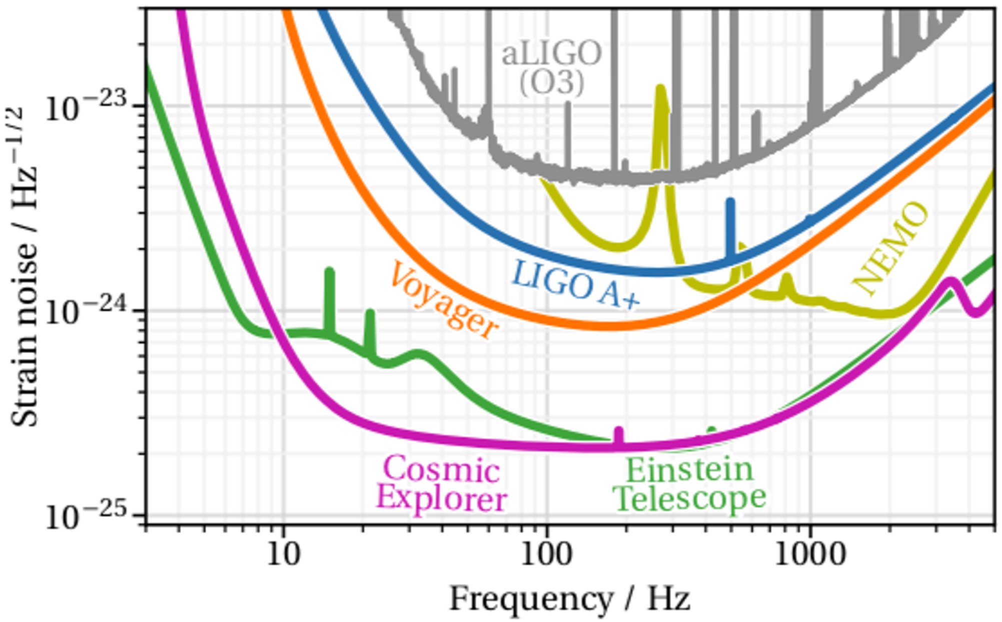
Preparatory Phase for the Einstein Telescope
Gravitational Wave Observatory
PI Mario Martinez, IFAE
kick-off Meeting, Barcelona 19-20 July, 2022

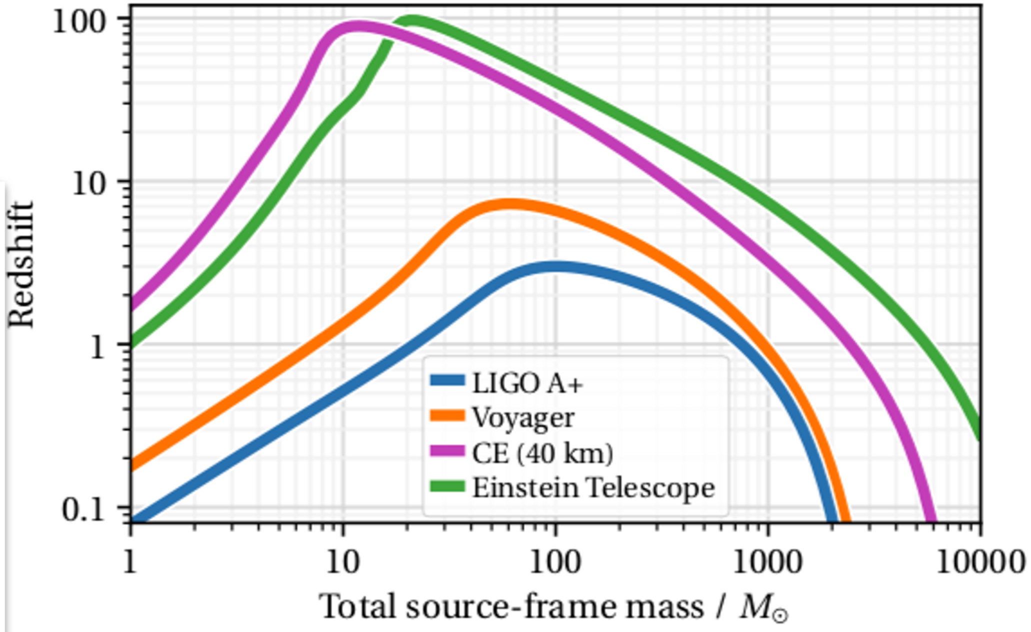


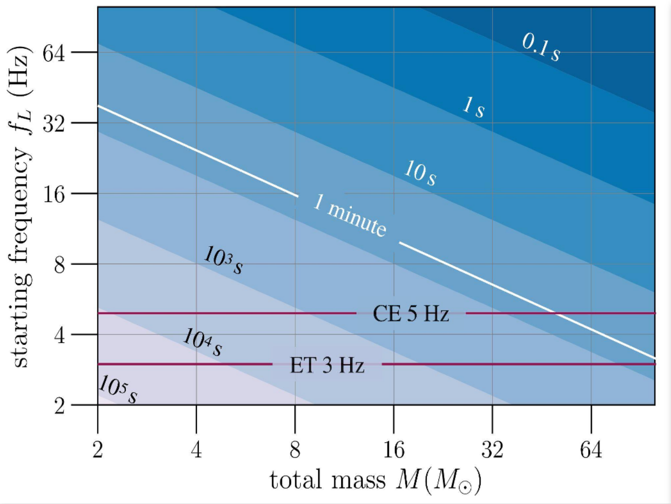


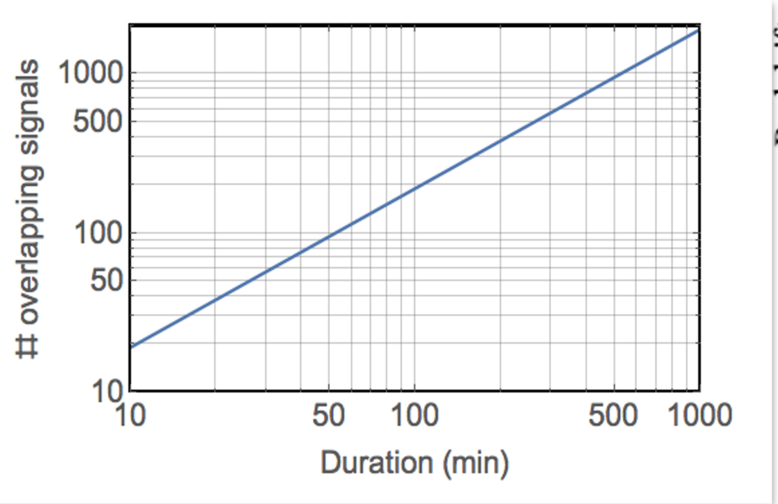
From 2G to XG

- 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



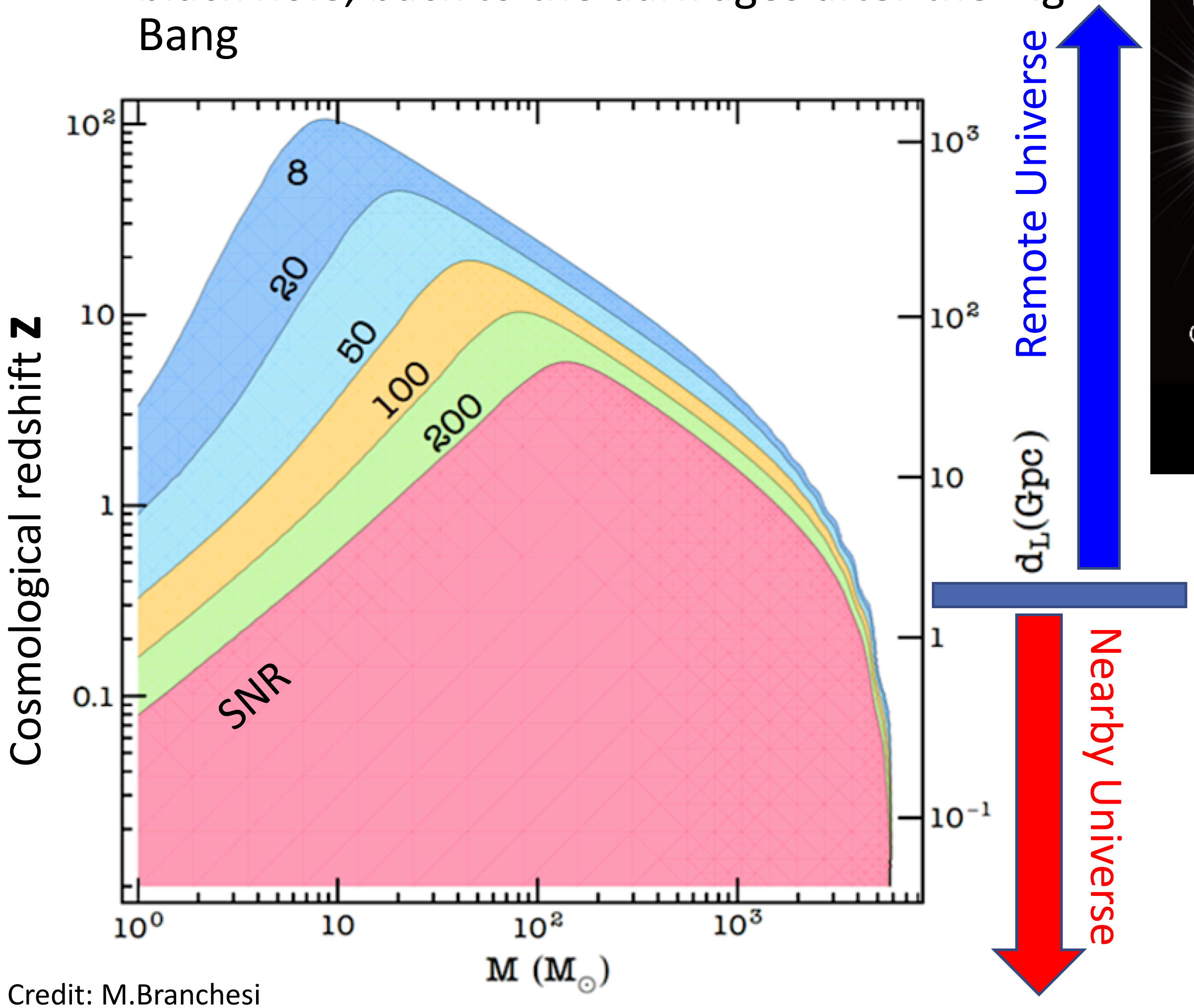




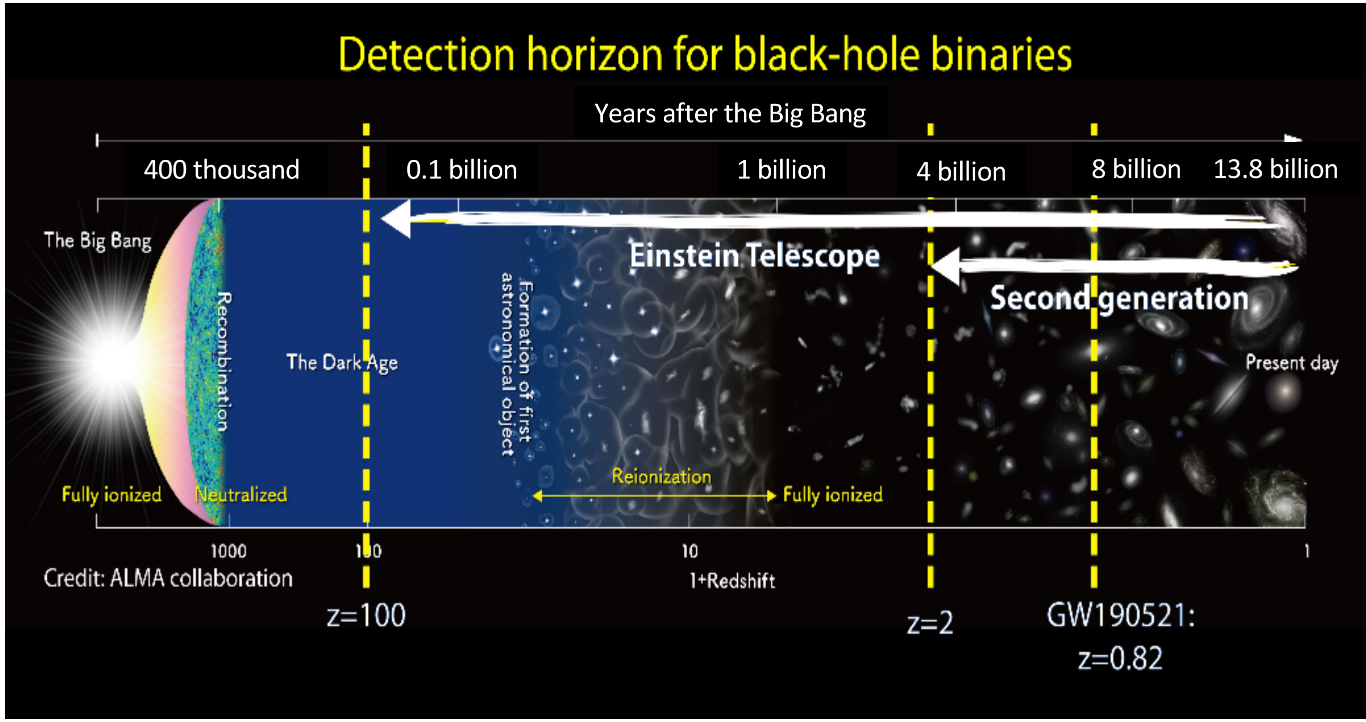


ET Science in a nutshell: double nature

- ET will be a new discovery machine:
  - ET 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 will be a precision measurement observatory:
  - ET 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

ET Science Case in a nutshell

EINSTEIN TELESCOPE

ASTROPHYSICS

- **Black hole properties**
  - origin (stellar vs. primordial)
  - evolution, demography
- **Neutron star properties**
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- **Multi-band and -messenger astronomy**
  - joint GW/EM observations (GRB, kilonova,...)
  - multiband GW detection (LISA)
  - neutrinos
- **Detection of new astrophysical sources**
  - core collapse supernovae
  - isolated neutron stars
  - stochastic background of astrophysical origin

FUNDAMENTAL PHYSICS AND COSMOLOGY

- **The nature of compact objects**
  - near-horizon physics
  - tests of no-hair theorem
  - exotic compact objects
- **Tests of General Relativity**
  - post-Newtonian expansion
  - strong field regime
- **Dark matter**
  - primordial BHs
  - axion clouds, dark matter accreting on compact objects
- **Dark energy and modifications of gravity on cosmological scales**
  - dark energy equation of state
  - modified GW propagation
- **Stochastic backgrounds of cosmological origin**
  - inflation, phase transitions, cosmic strings

Summary and Outlook

- O3 detector sensitivities significantly better than O1/O2
- **<u>90 detections published</u>**; many BBHs, some BNS and NS-BH. Waveform modelling is crucial for these results, and at UIB we are at the forefront of it
- Multiple types of searches for multiple types of signals. Opened up new avenues for studying particle physics using GW detectors & CW search methods
- For a quick overview of all LVC/LVK papers, see our **Science Summaries** available in multiple languages: https://www.ligo.org/science/outreach.php
- **O1, O2 & O3 bulk data** has been released: https://www.gw-openscience.org/data/ .

- LVK O4 observing run start planned for March 2023. With further improved detectors in the near future, new discoveries are at the horizon!

- If you'd like to receive alerts about new GW detections in O4, check out our **LIGO/Virgo Public Alerts User Guide**: https://emfollow.docs.ligo.org/userguide/ , and the app from chirp.sr.bham.ac.uk . You can also find tutorials, GW data analysis software and other tools at our **Gravitational Wave Open Science Center**: https://www.gw-openscience.org/about/

- 3G (third-generation) GW detectors + LISA are firmly in our future plans

- Order-of-magnitude better strain sensitivities are feasible, and the science case is very strong.

UIB Universitat de les Illes Balears

IAC3 Institute of Applied Computing & Community Code.

Gracias

Grupo de Física Gravitacional /LIGO

Acknowledgments

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