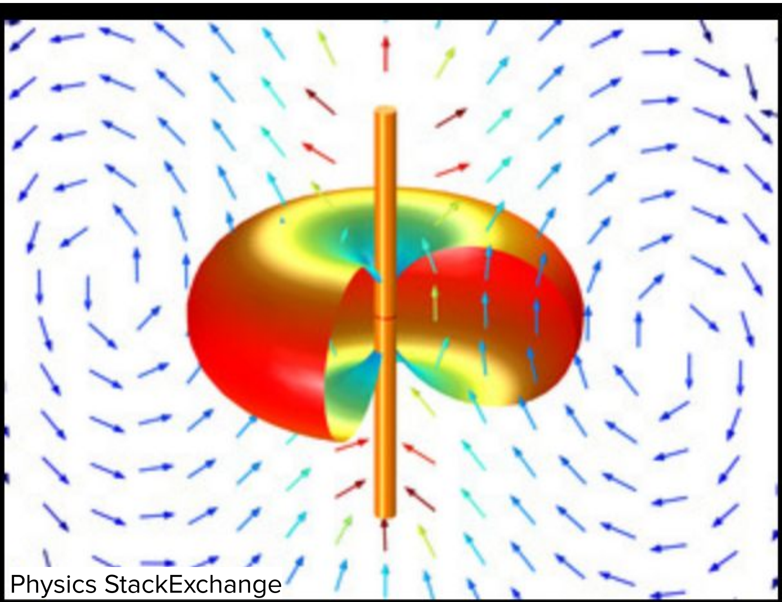
LIGO-Virgo-KAGRA gravitational-wave sources and observational results

Michal Bejger (for the LIGO-Virgo-KAGRA collaboration)

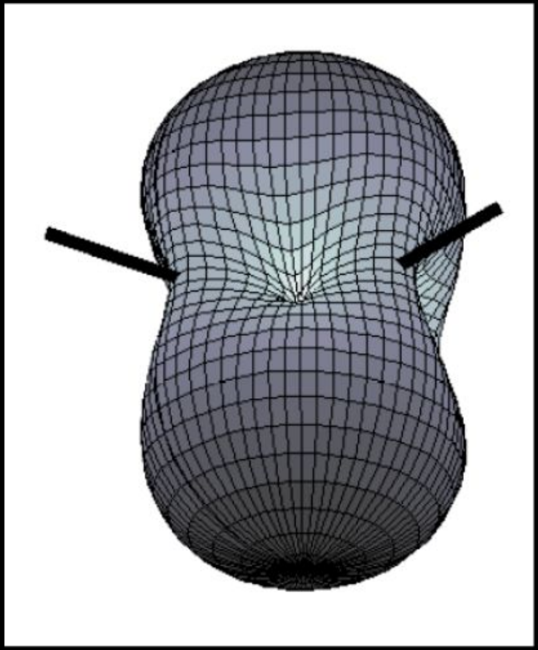
Theory meeting experiments (TMEX-2025), 09.01.25, Quy Nhon Vietnam

Interferometer = GW antenna

Very precise ruler to measure distances between free-falling bodies using laser light



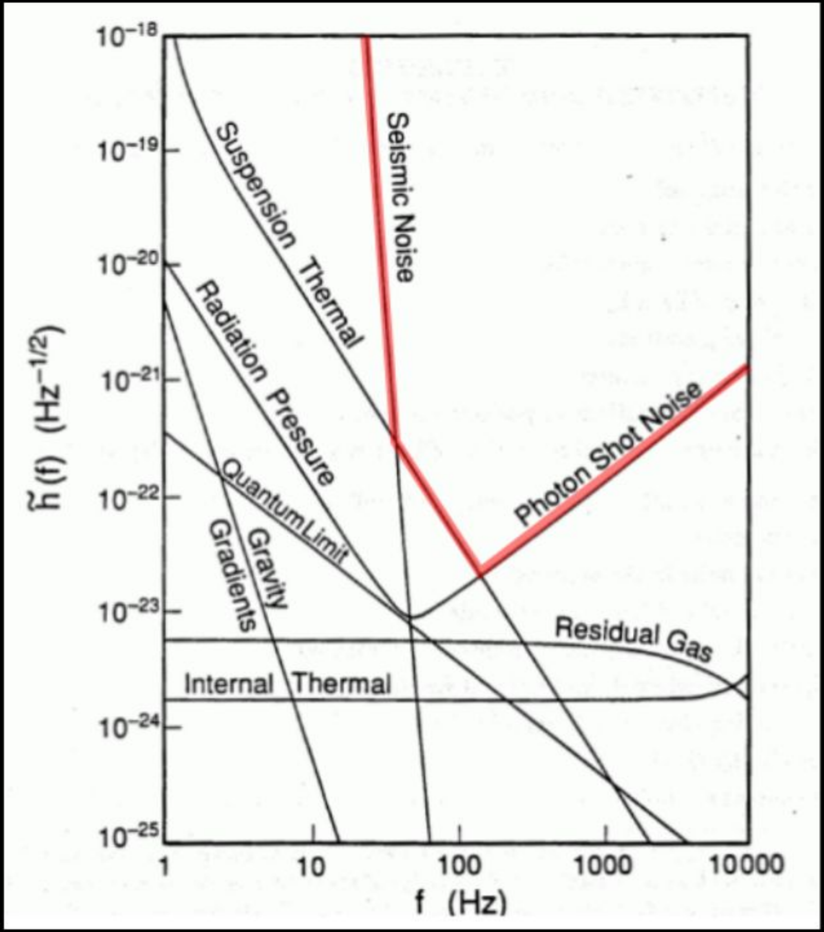
Physics StackExchange



Wikimedia Commons,
Schwarzbeck Mess-Elektronik

© LIGO Hanford, LIGO Livingston, Virgo, KAGRA, GEO600

Ground-based detector broadband sensitivity



Initial LIGO proposal (1989)

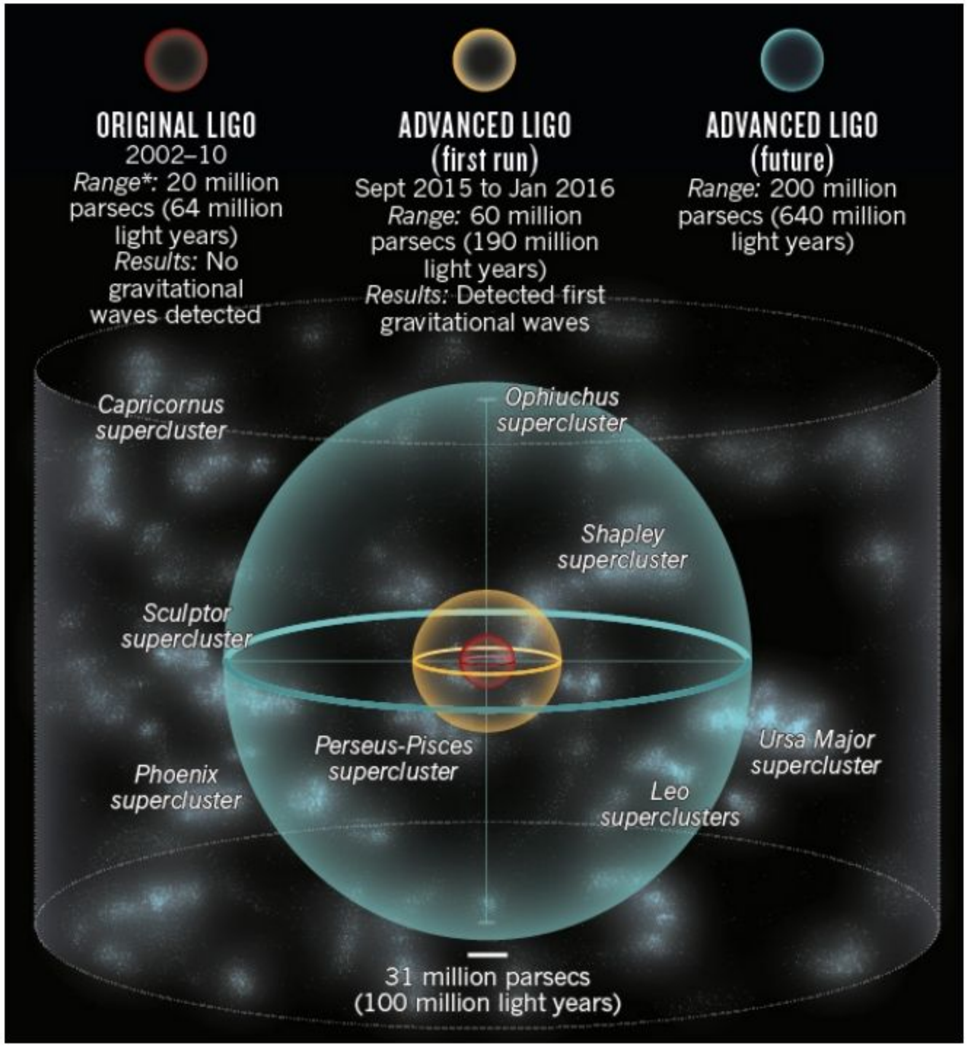
- ★ Range of frequencies similar to human ears:

Wikimedia Commons

From 20 Hz (H0) to a few thousands Hz (3960 Hz, H7) - 8 octaves.

- ★ Poor, like for an ear, angular resolution.

Sensitivity → amplitude → volume

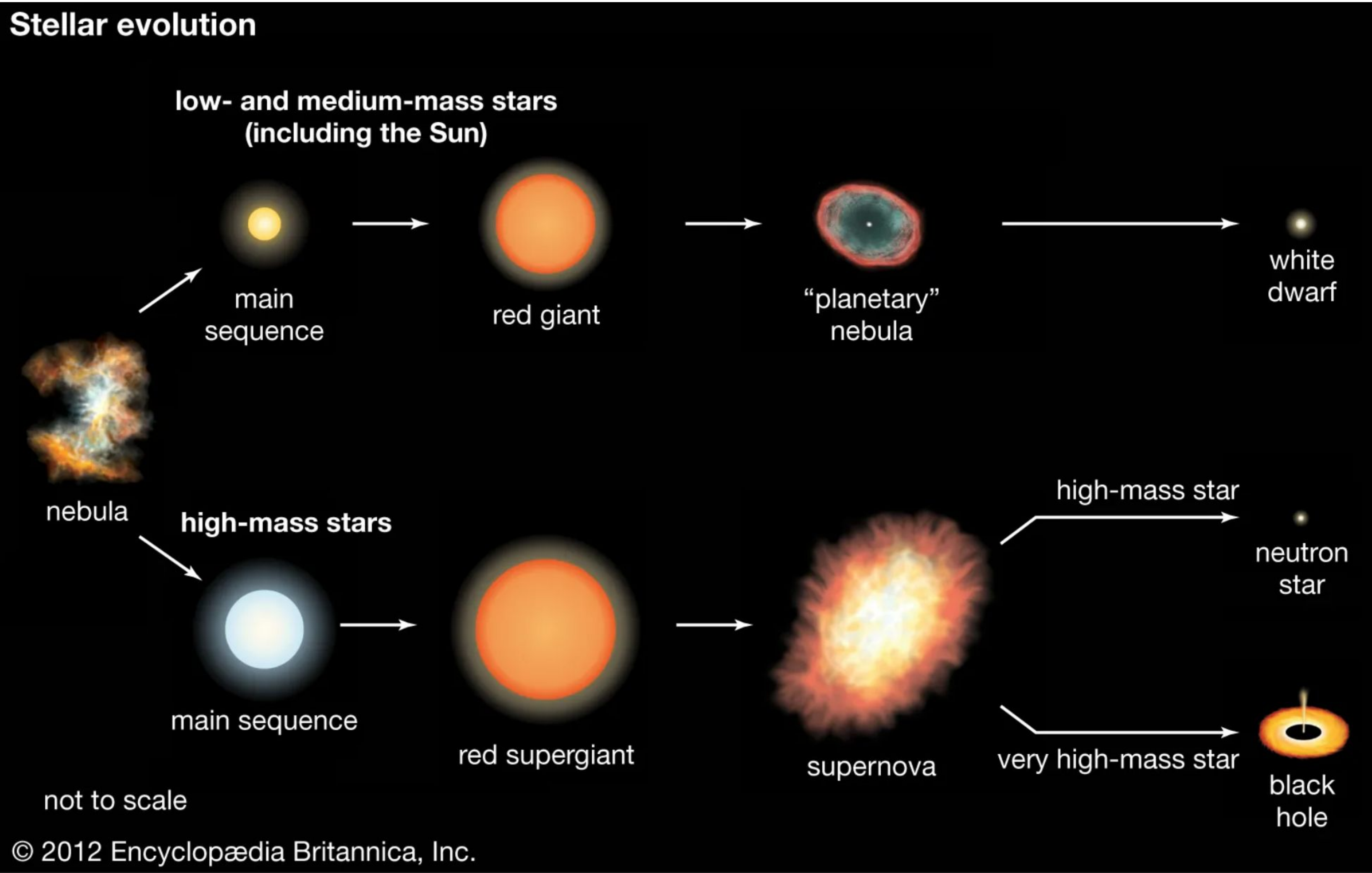


- ⋆ Detector's sensitivity (registering waves of amplitude h) is related to maximal range r, $h \propto 1/r$

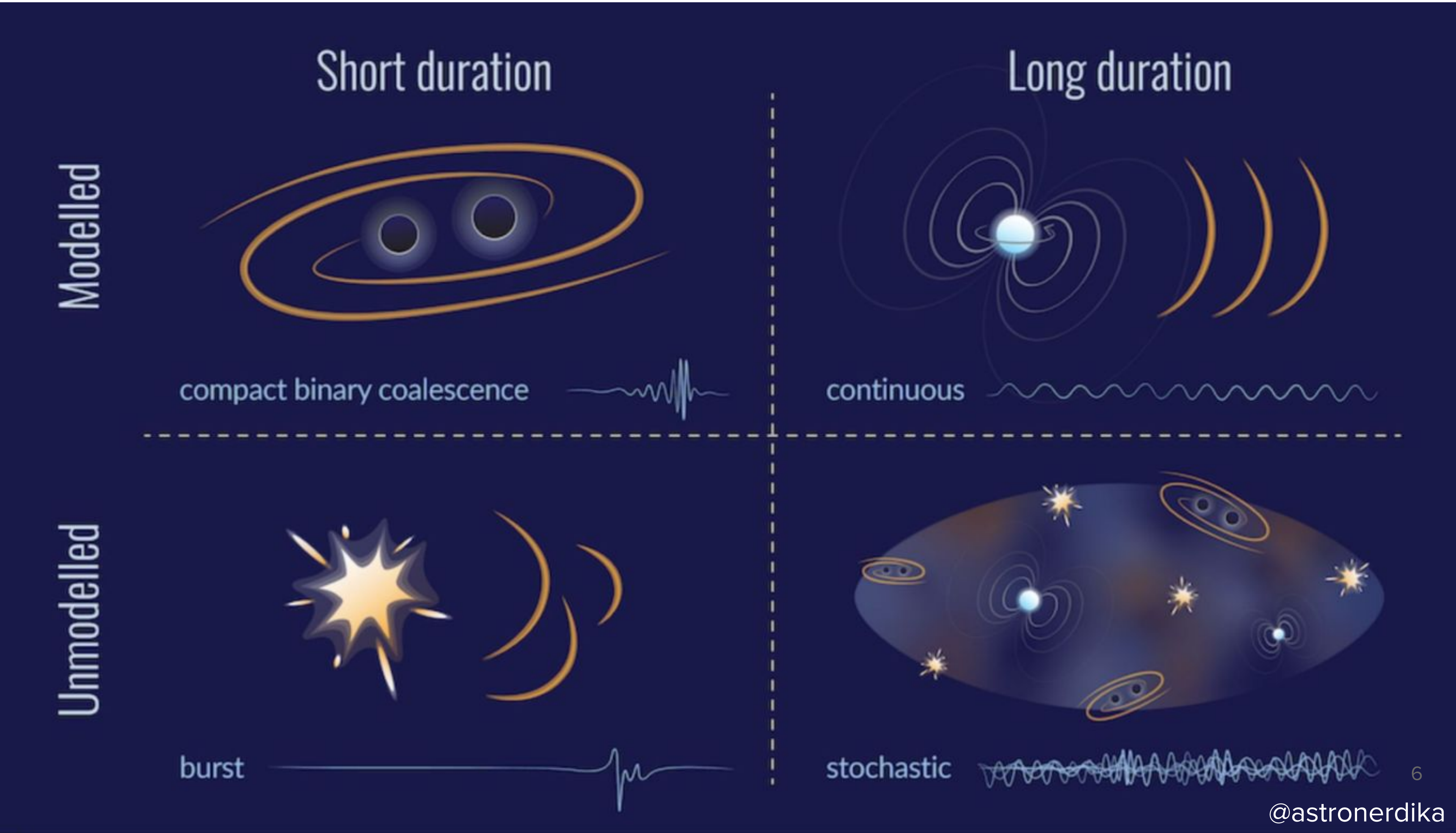
- ⋆ Reachable cosmic volume $V \propto r^3$

- ⋆ Increase of sensitivity $h \to 0.1h$ gives $r \to 10r$, that is $V \to 1000V$.

LVK targets are compact stellar remnants

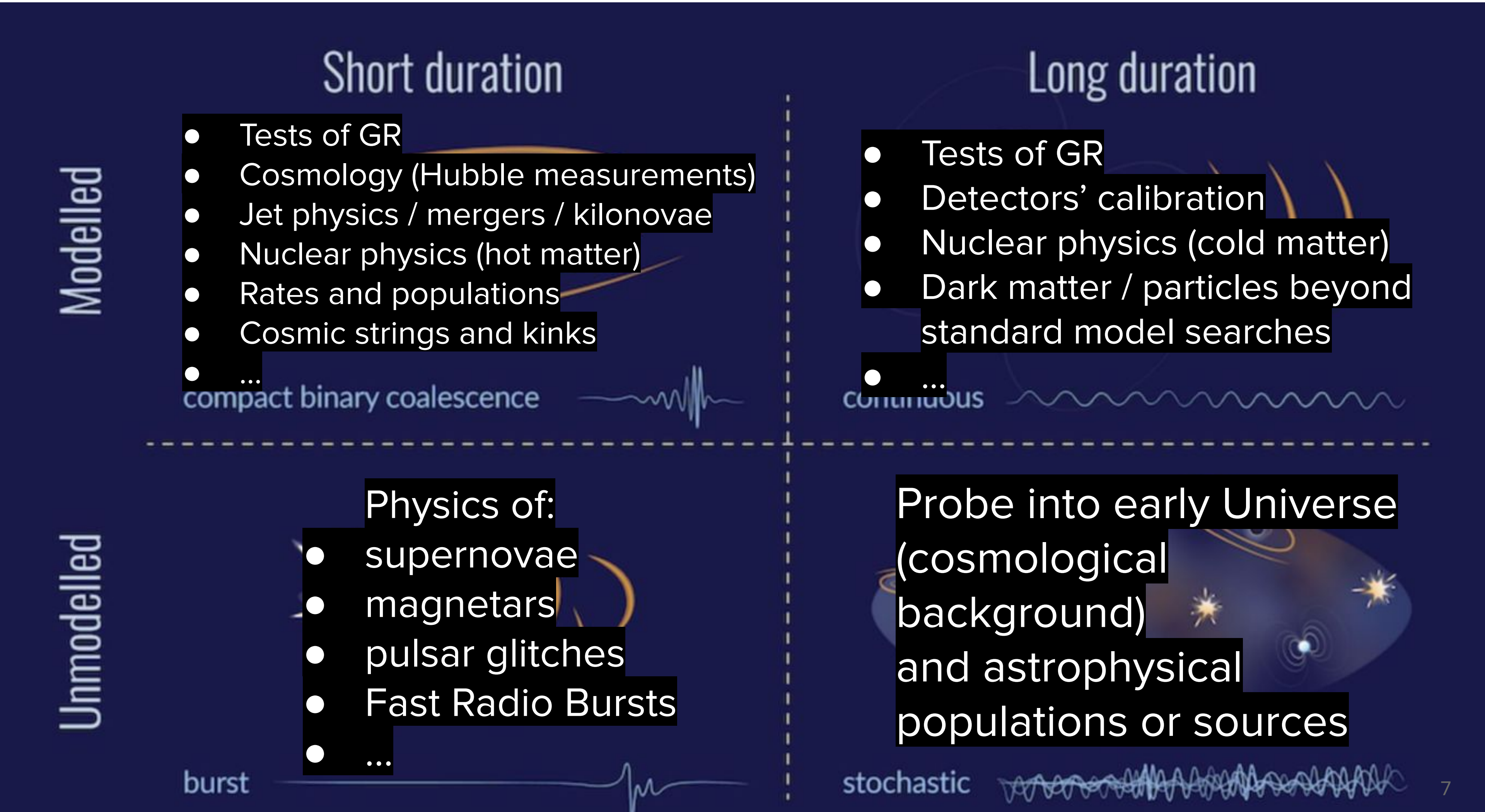


Gravitational-wave signal types of interest to the LVK…



@astronerdika

…and why they are interesting and useful



- Tests of GR
- Cosmology (Hubble measurements)
- Jet physics / mergers / kilonovae
- Nuclear physics (hot matter)
- Rates and populations
- Cosmic strings and kinks
- …

- Tests of GR
- Detectors' calibration
- Nuclear physics (cold matter)
- Dark matter / particles beyond standard model searches
- …

Physics of:

- supernovae
- magnetars
- pulsar glitches
- Fast Radio Bursts
- …

Probe into early Universe (cosmological background) and astrophysical populations or sources

Electromagnetic vs gravitational waves

EM:

- ⋆ Created in microscopic processes by accelerated charges,
- ⋆ lowest multipole: dipole radiation,
- ⋆ scatters & is processed by matter.

Timing, spectrum, redshift, particle acceleration and thermal signatures → standard candles, outflows, last scattering surface . . .

GW:

- ⋆ Created in macroscopic processes by accelerated masses,
- ⋆ lowest multipole: quadrupole radiation (in GR),
- ⋆ once emitted interacts very weakly with matter.

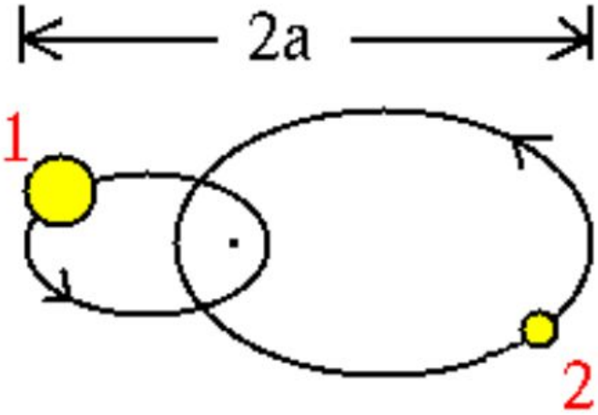
Timing, mass & spin parameters → standard sirens (direct luminosity distance), core engine, cosmology, gravity theory tests . . .

Binaries emitting GWs: some intuitions

GWs correspond to accelerated movement of masses.

Consider a binary system of m_1 and m_2, semiaxis a with

- ⋆ total mass $M = m_1 + m_2$,
- ⋆ reduced mass $\mu = m_1 m_2 / M$,
- ⋆ mass quadrupole moment $Q \propto Ma^2$,
- ⋆ Kepler's third law $GM = a^3 \omega^2$.



$$h(r) \propto \frac{1}{r} \frac{\partial^2 (Ma^2)}{\partial t^2} = \boxed{\frac{G^2}{c^4} \frac{1}{r} \frac{M\mu}{a} = \frac{G^{5/3}}{c^4} \frac{1}{r} M^{2/3} \mu\, \omega^{2/3}.}$$

Compact binaries and their GW properties

- ⋆ Chirp mass $\mathcal{M} = \left(\mu^3 M^2\right)^{1/5} = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$,

- ⋆ Mass ratio $q = m_2/m_1$ (at 1PN), alternatively
  $\nu = m_1 m_2/(m_1 + m_2)^2$,

- ⋆ Spin-orbit and spin-spin coupling (at 2PN and 3PN, resp.) →

  $$\chi_{eff} = (m_1 \chi_{1z} + m_2 \chi_{2z})/(m_1 + m_2)$$

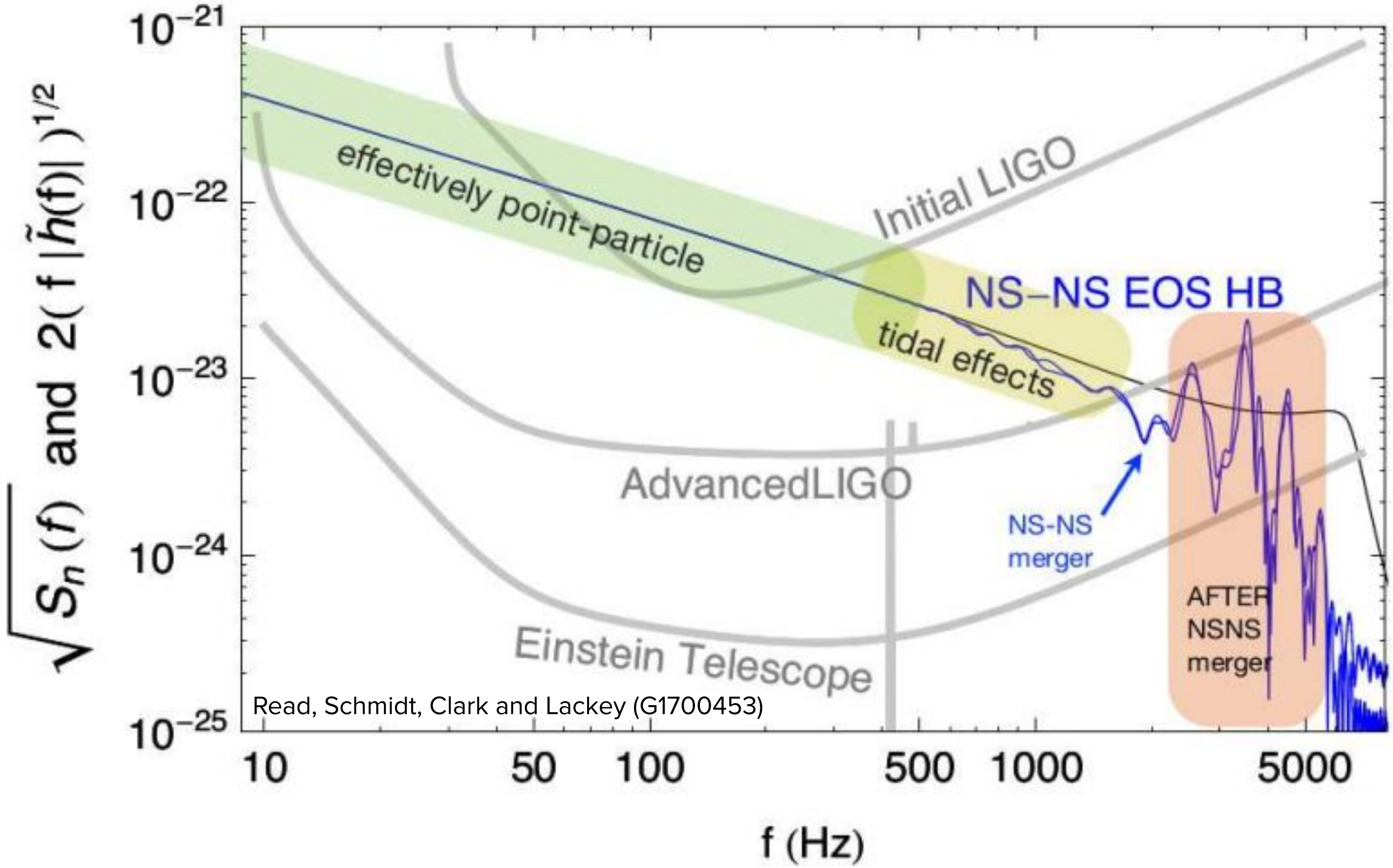
  where χ_{iz} are spin components along system's total angular momentum,

- ⋆ Tidal deformability Λ (at 5PN) →

  $$\tilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12 m_2) m_1^4 \Lambda_1}{(m_1 + m_2)^5} + (1 \leftrightarrow 2)$$

- ⋆ Direct "luminosity" ("loudness") distance: binary systems are "standard sirens".

GW spectrum of 'material' binaries (for example, binary neutron stars)



Read, Schmidt, Clark and Lackey (G1700453)

For extended-body interactions, phase evolution differs from point-particle description,

$$\Psi(f) = \Psi_{PP}(f) + \Psi_{tidal}(f)$$

Testing gravity theories with inspiral-merger-ringdown signals

Karl Popper (1902-1994): falsifiability of the theory is the fundamental scientific criterion.

With hundreds of significant events already, one may think of various tests:

- ★ „residual” (does the data contain anything unexpected after subtracting the signal model?)
- ★ „astrophysical parameters” (are the parameters consistent with each other in various regimes?)
- ★ „parameters of the theory” (are the coefficient values consistent with the theory?)
- ★ „dispersion relation” (do gravitational waves propagate like photons?)
- ★ „ringdown” (are we observing horizons as predicted by GR?)
- ★ „echoes” (are observed objects really GR black holes?)
- ★ „polarizations” (do gravitational waves interact with matter as GR predicts?)

GW170817: speed of gravitation

Relative speed difference between GWs and photons:

$$\frac{v_{GW} - c}{c} = \frac{\Delta v}{c} \approx \frac{c \Delta t}{d}.$$

Assuming very conservative values:

- ⋆ Distance $d = 26$ Mpc (lower bound from 90% credible interval on luminosity distance derived from the GW signal),
- ⋆ Time delay $\Delta t = 10$ s (actual delay between GW170817 and GRB170817A was $\simeq 1.7$ s)

$$-3 \times 10^{-15} \leq \frac{\Delta v}{c} \leq 7 \times 10^{-16}$$

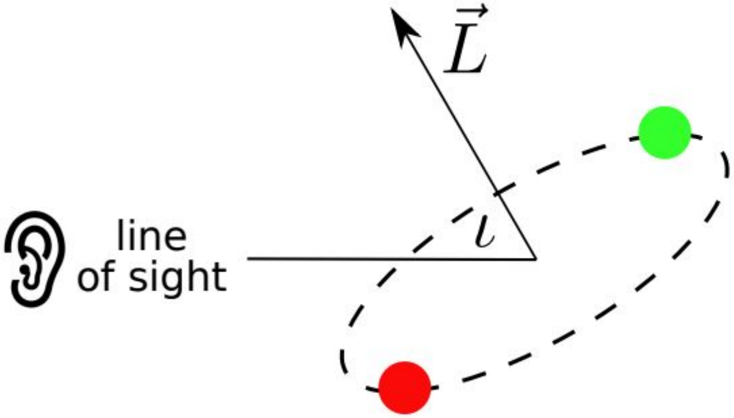
$$\boxed{v_{GW} = 299792458^{+0.000001}_{-0.000006}\ \mathrm{m/s} = c^{+0.000001}_{-0.000006}\ \mathrm{m/s}}$$

Binary system: distance-inclination degeneracy

Luminosity distance $\sim 1/h$, and

$$h = h_+ F_+ + h_\times F_\times$$

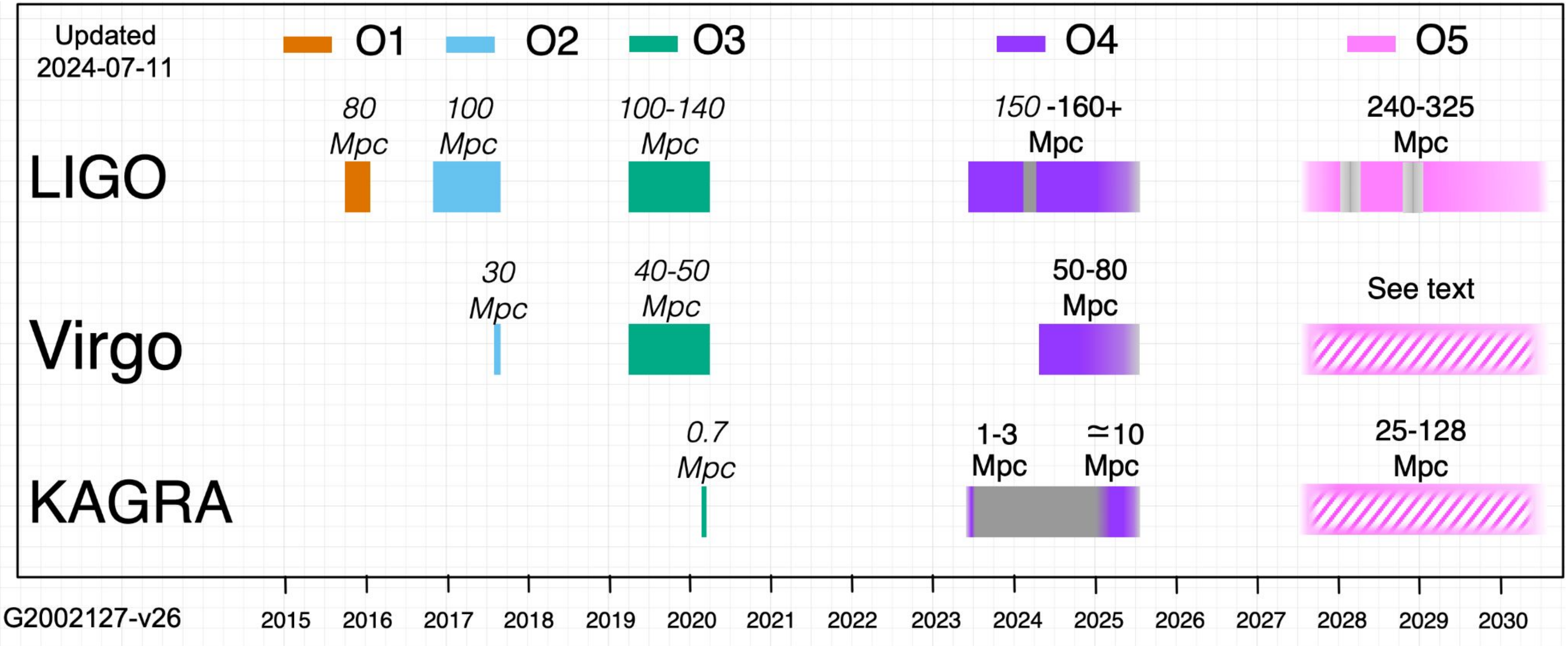
depends on the inclination of the binary with repect to the ”line of sight”.



Two independent polarizations h_+ and $h_\times$:

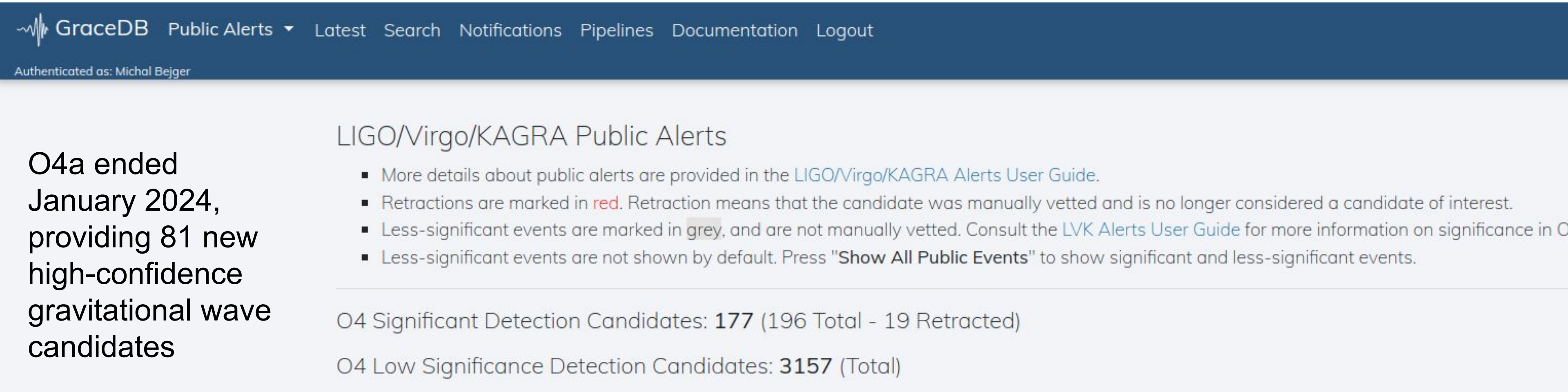
$$\begin{aligned} h_+ &= \frac{2\mu}{r} (\pi M f_{GW})^{2/3} \left(1 + \cos^2\iota\right) \cos\left(2\phi(t)\right), \\ h_\times &= \frac{4\mu}{r} (\pi M f_{GW})^{2/3} \cos\iota \sin\left(2\phi(t)\right). \end{aligned}$$

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



- O4a (LIGO detectors): 24 May 2023 - 16 Jan 2024
- O4b started 15:00 UTC on 10 April 2024
  - Virgo joined O4b
- Current plan: O4 ends 9 June 2025
  - Next update to the plan: 15 Jan 2025

LIGO/Virgo/KAGRA Public Alerts: https://gracedb.ligo.org/superevents/public/O4/



Authenticated as: Michal Bejger

O4a ended January 2024, providing 81 new high-confidence gravitational wave candidates

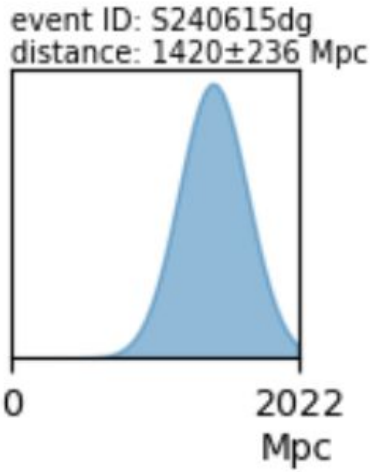
LIGO/Virgo/KAGRA Public Alerts

- 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 O
- Less-significant events are not shown by default. Press "**Show All Public Events**" to show significant and less-significant events.

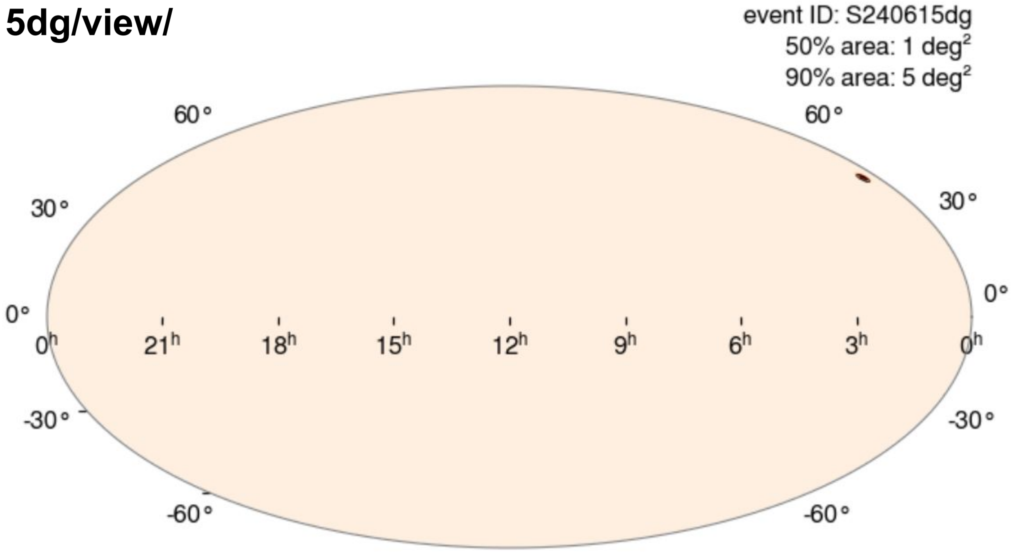
O4 Significant Detection Candidates: **177** (196 Total - 19 Retracted)

O4 Low Significance Detection Candidates: **3157** (Total)

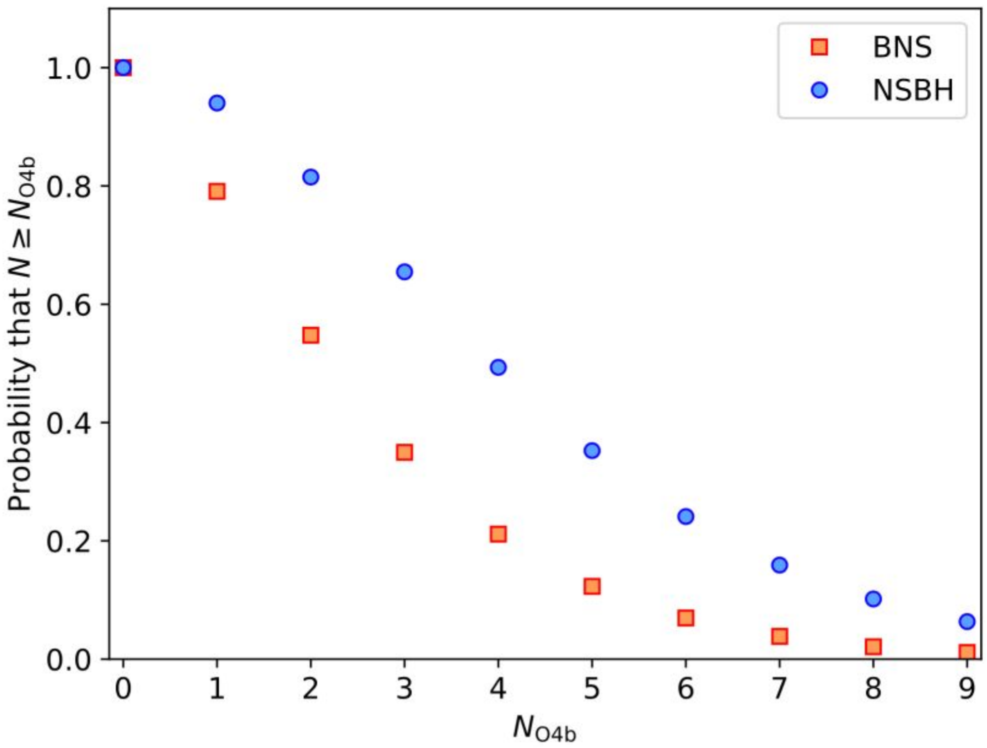
Example of a well localized candidate event in O4:
https://gracedb.ligo.org/superevents/S240615dg/view/



Bilby constraints:



Estimating the probability of BNS and NSBH in O4



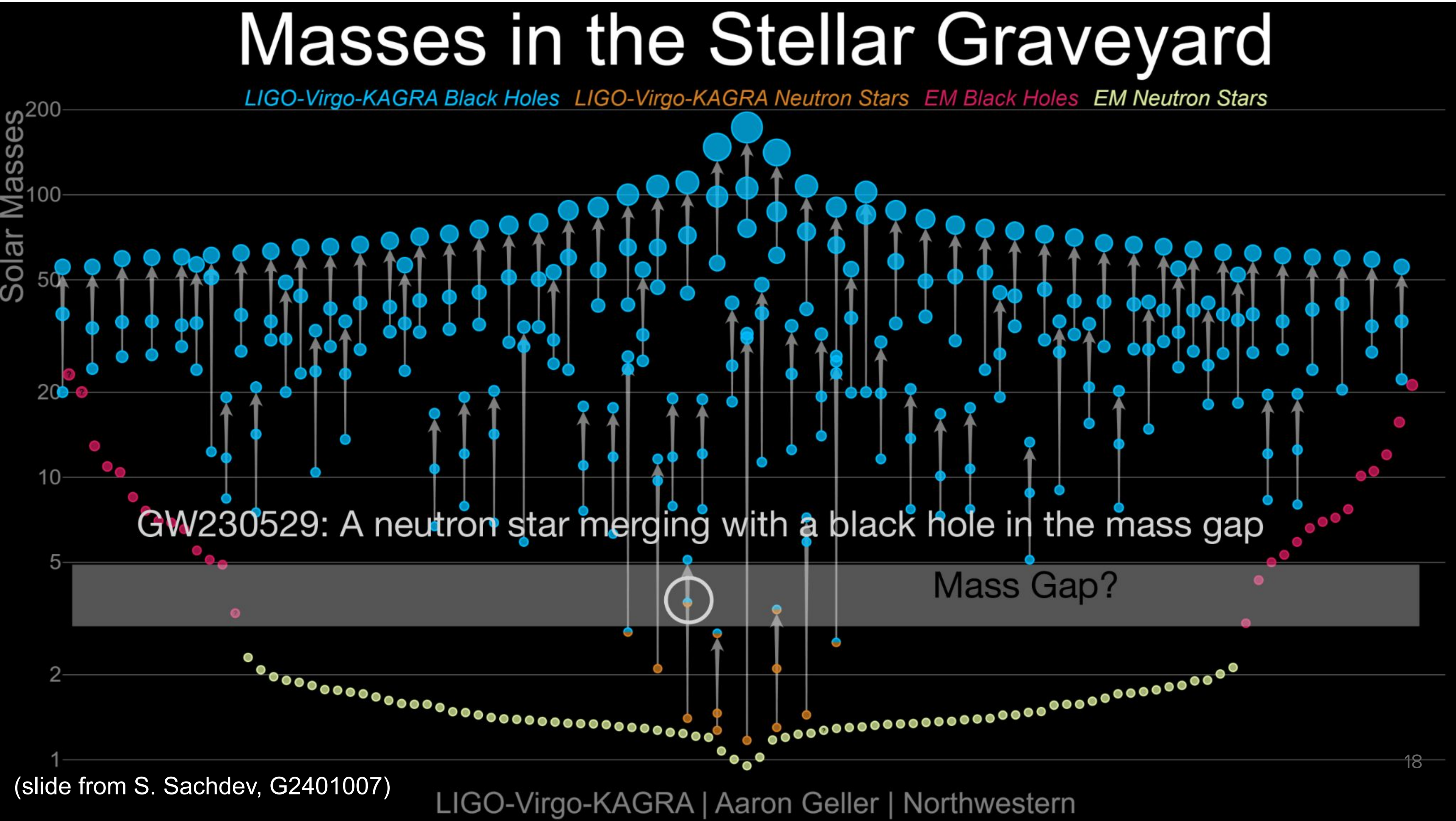
- The probability of having at least one **BNS** detection is around 80%.
  BNS rate: 5 - 920 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

- The probability of having at least one **NSBH** detection is 94%

An estimate of the probability of a number N of detections is obtained based on the number N' of previous detections (assuming they were of astrophysical origin), and on the ratio of the sensitive time-volume surveyed in the new run to that of previous runs, C=VT/V'T'

https://emfollow.docs.ligo.org/userguide/capabilities.html

04: GW230529 and mass gap objects



(slide from S. Sachdev, G2401007)

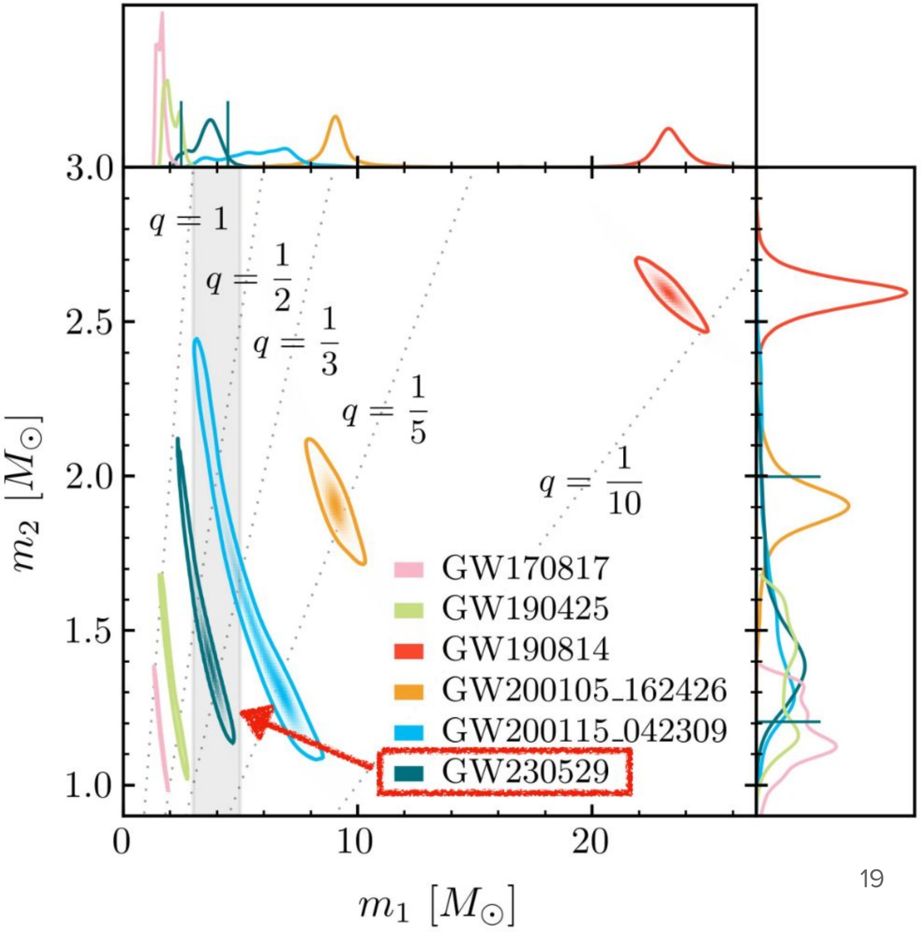
GW230529 properties

Online L1-only detection with GstLAL, MBTA, PyCBC (IFAR > 60 yr)

No confirmed EM counterpart, no clear tidal constraints

SNR ~11.5

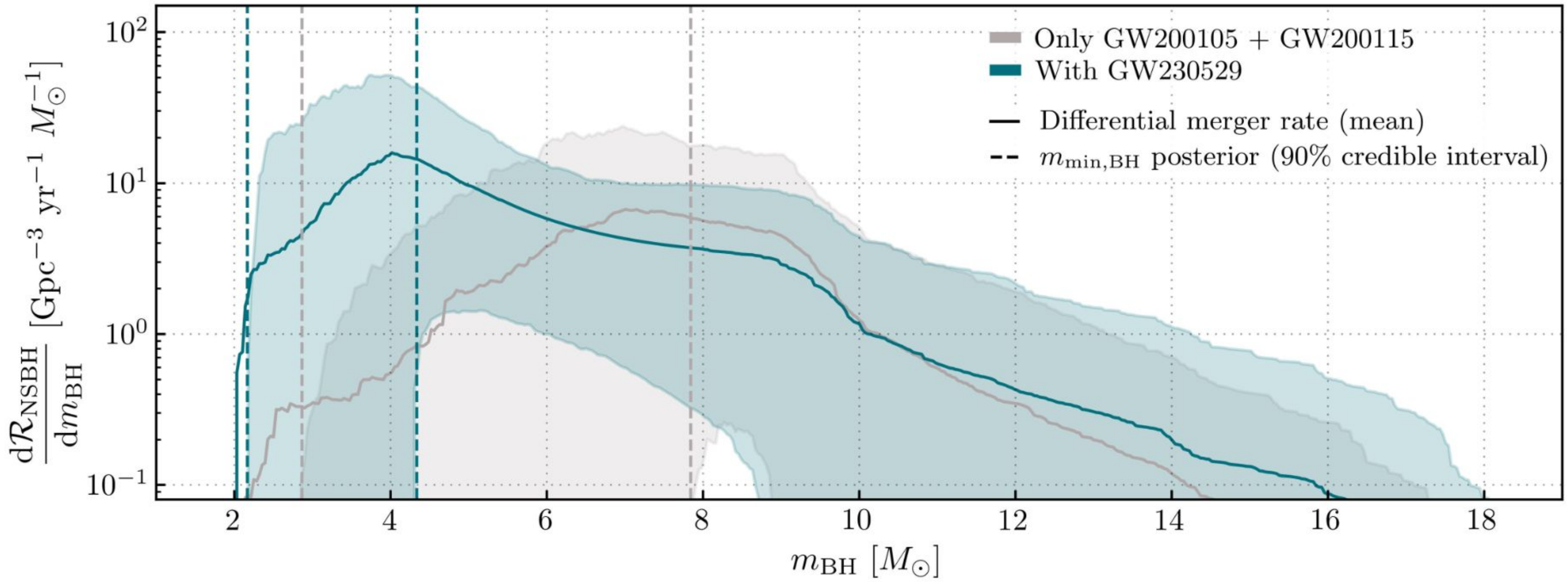
Primary mass $m_1/M_\odot$	$3.6^{+0.8}_{-1.2}$
Secondary mass $m_2/M_\odot$	$1.4^{+0.6}_{-0.2}$
Mass ratio $q = m_2/m_1$	$0.39^{+0.41}_{-0.12}$
Total mass $M/M_\odot$	$5.1^{+0.6}_{-0.6}$
Chirp mass $\mathcal{M}/M_\odot$	$1.94^{+0.04}_{-0.04}$
Detector-frame chirp mass $(1+z)\mathcal{M}/M_\odot$	$2.026^{+0.002}_{-0.002}$
Primary spin magnitude χ_1	$0.44^{+0.40}_{-0.37}$
Effective inspiral-spin parameter $\chi_{\rm eff}$	$-0.10^{+0.12}_{-0.17}$
Effective precessing-spin parameter $\chi_{\rm p}$	$0.40^{+0.39}_{-0.30}$
Luminosity distance $D_{\rm L}/{\rm Mpc}$	201^{+102}_{-96}
Source redshift z	$0.04^{+0.02}_{-0.02}$



Abac et al., Astrophys. J. Lett. 970, L34 (2024)

GW230529: minimum black hole mass

- inferred minimum mass of black holes in the NSBH population decreases with the inclusion of GW230529
- GW230529 increases the inferred rate of compact binary mergers with a component in the 3–5 $M_\odot$ range

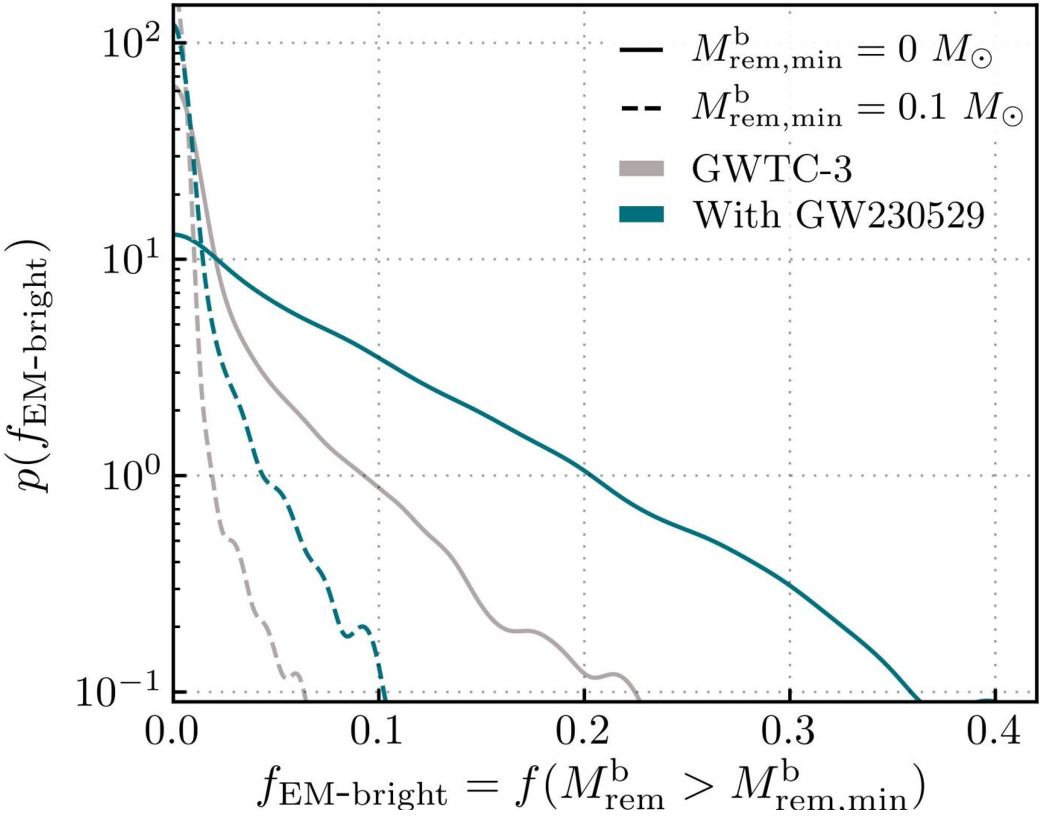


Minimum inferred BH mass in NSBH systems: $m_{\rm min,BH} = 3.4^{+1.0}_{-1.2}\ M_\odot$ with GW230529

$m_{\rm min,BH} = 6.0^{+1.8}_{-3.2}\ M_\odot$ without.

Abac et al., Astrophys. J. Lett. 970, L34 (2024)

GW230529: influence on EM brightness



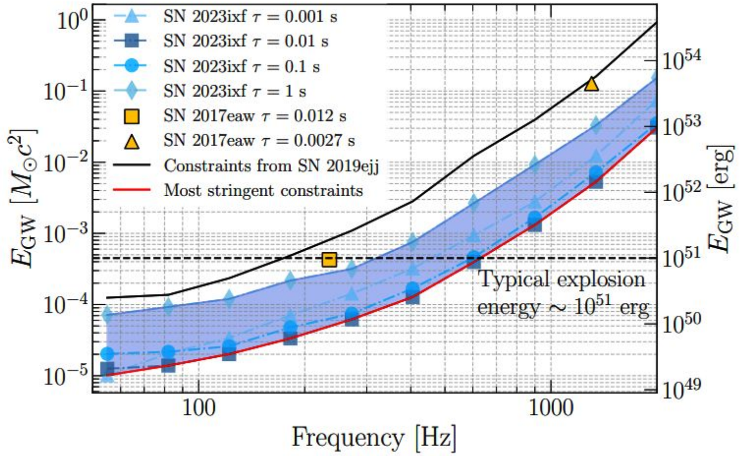
Posterior on the fraction of NSBH systems detected with GWs that may be EM bright, $f_{\text{EM-bright}}$, depending on the threshold remnant mass required to power a counterpart, $f(M^{b}_{rem} > M^{b}_{rem,min})$. The solid and dashed curves represent different values of the minimum remnant mass $M^{b}_{rem,min}$.

- Fraction of EM bright NSBHs increases if we include GW230529 in the population
    - less massive black holes are more likely to tidally disrupt neutron stars

Abac et al., Astrophys. J. Lett. 970, L34 (2024)

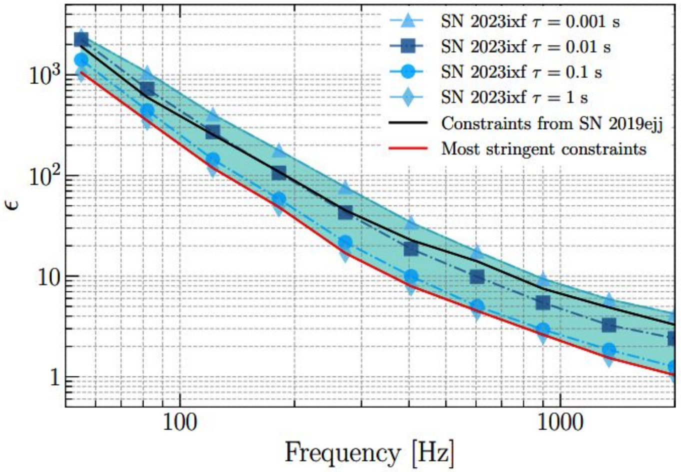
SN 2023ixf (Abac et al., [arXiv:2410.16565](https://arxiv.org/abs/2410.16565))

Core collapse SN observed in Messier 101 (distance: 6.7 Mpc) in EM on 2023 May 19th, during the LVK 15th Engineering Run

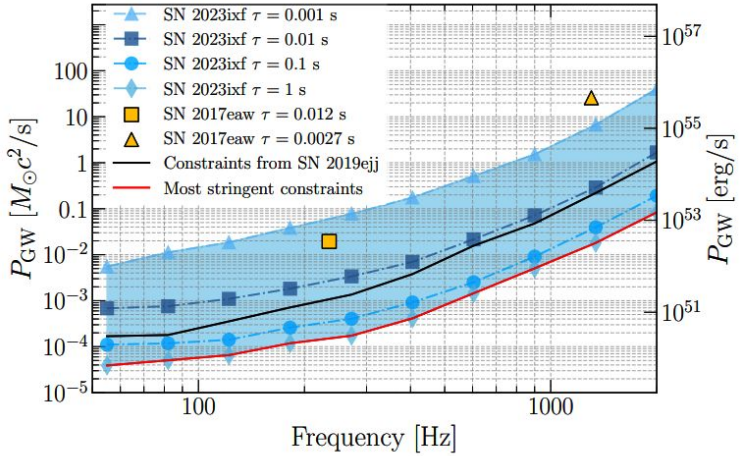


$$h_0 = \frac{2}{D}\frac{G}{c^4}\frac{I_{zz}\epsilon}{2}(2\pi f_0)^2$$

(amplitude of a rotating NS "bar", with ellipticity ϵ)



$$I_{zz}\epsilon = \frac{Dc^4}{G(2\pi f_0)^2}\left(\frac{2}{\pi\tau^2}\right)^{1/4} h_{\rm rss}.$$



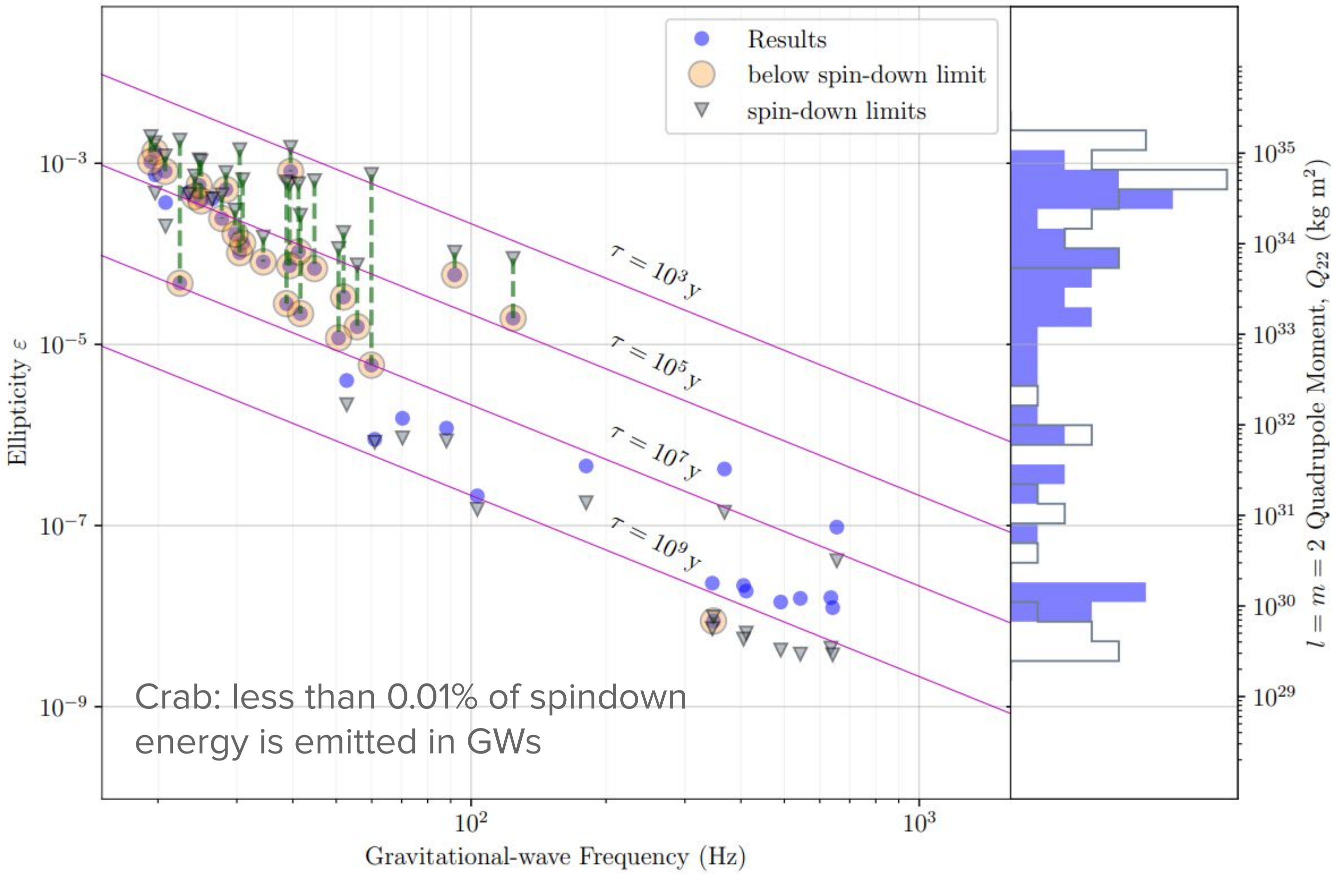
$$E_{\rm GW} = \frac{2}{5}\frac{\pi^2 c^3}{G} D^2 f_0^2 h_{\rm rss}^2$$

where $h_{\rm rss}$ is the source root-sum-squared GW strain for an optimally oriented source.

O4a limits on GW emission from known pulsars (Abac et al., arXiv:2501.01495)

For triaxial rotating NS, $h_0 = 2C_{22} = \frac{16\pi^2 G}{c^4}\frac{I_{zz}\varepsilon f_{\rm rot}^2}{d}$

to be compared with a ''spindown limit'' on amplitude $h_0^{\rm sd} = \frac{1}{d}\left(\frac{5GI_{zz}}{2c^3}\frac{|\dot{f}_{\rm rot}|}{f_{\rm rot}}\right)^{1/2}$

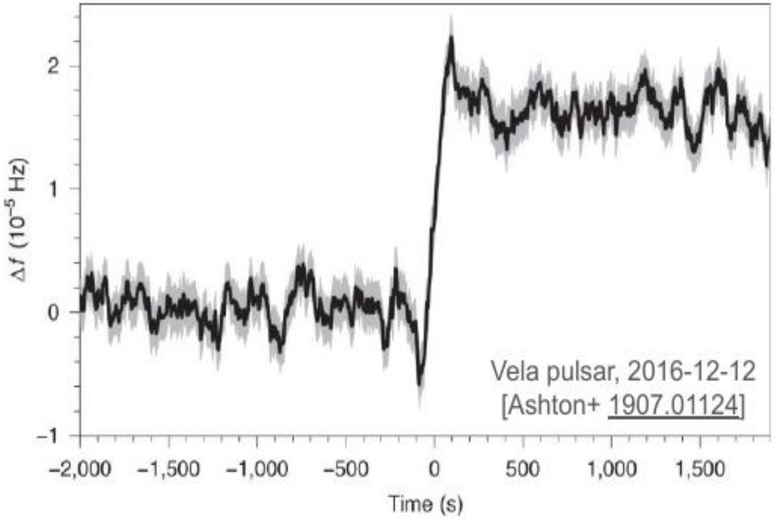


Crab: less than 0.01% of spindown energy is emitted in GWs

- The lowest upper limit on the amplitude is 6.4 ×10−27 for the young energetic pulsar J0537−6910, while the lowest constraint on the ellipticity is 8.8 ×10−9 for the bright nearby millisecond pulsar J0437−4715
- no evidence of non-standard polarizations as predicted by the Brans-Dicke theory

Pulsar glitches and their relation to GWs

Some pulsars experience sudden **spin-up events**, caused by - we hope - internal redistribution of energy and angular momentum (starquakes and/or superfluid recoupling).



Vela pulsar, 2016-12-12
[Ashton+ 1907.01124]

Possible GW signatures:

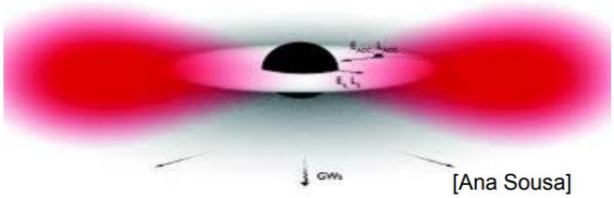
- Short-duration bursts: mainly from f-modes (high-frequency)
- "tCWs" (long-duration monochromatic transients): Whatever goes on in the neutron star at the glitch, it might cause a temporarily augmented quadrupole moment (an instability like an r-mode, or a ''mountain'')

The Vela pulsar (J0835–4510)

- One of LVK standard target for CW searches: young, nearby (287 pc), frequency low but in sensitivity range (f_{rot} ~11 Hz, f_{gw} ~22 Hz). Indirect spindown upper limit for persistent CWs already beaten with initial LIGO-Virgo (Abadie et al., 2011a).
- Strong glitches ($\Delta f / f \sim 10^{-6}$) every 1.5 years or so. Not as frequent or regular as J0537–6910 (the ''big glitcher''), but much closer.
- First LSC search for short bursts from 2006 glitch (Abadie et al., 2011b).
- First tCW search on O2 open data for 2016 glitch (Keitel et al., 2019).
- No glitch during O3.
- Last glitch in 2021.
- **Now a glitch during O4b with all three (LHV) detectors online!**

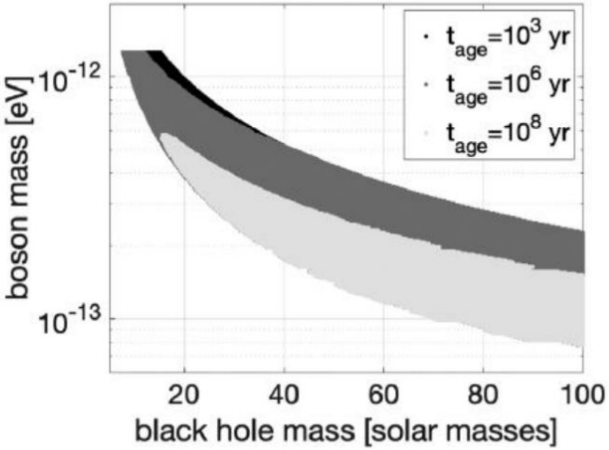
[Chandra/NASA]

Dark matter searches

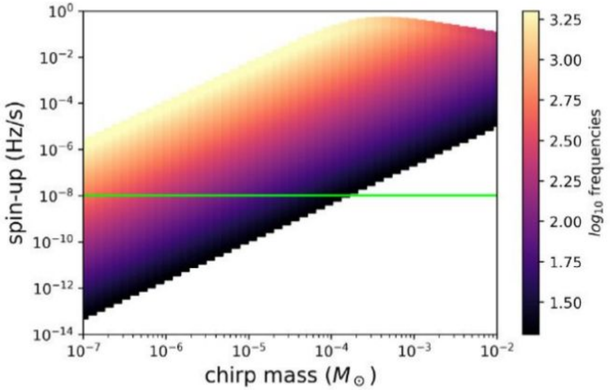


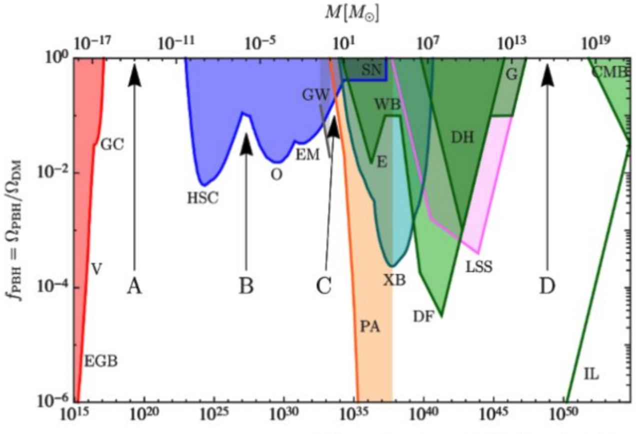
[Ana Sousa]

- **Boson clouds** around spinning black holes: superradiant energy extraction and CW-like emission, frequency related to particle mass
  → O3 search: Abbott+ PRD105,102001 (2022)



- low-mass compact binaries: CW-like early inspiral, e.g. **primordial black holes** [Miller+ PhDU32,100836 (2021)].



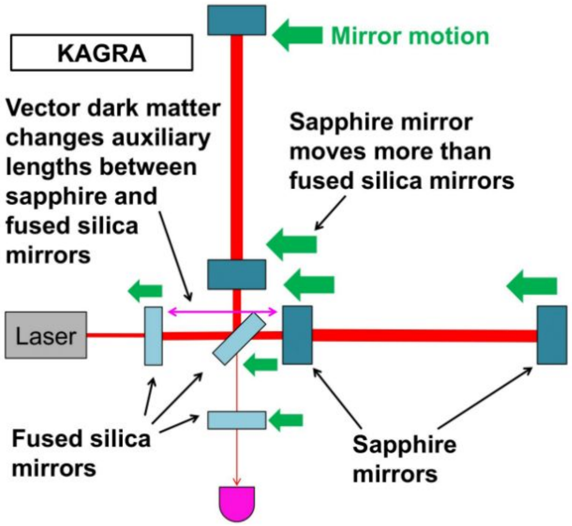


Carr & Kuhnel, SciPost Phys. Lect. Notes 48 (2022)

(From G2401742 by David Keitel)

Dark matter searches

- direct **dark matter** interaction with GW detectors
- no actual GWs involved
- “dark photon” search in O3 LIGO data: [Abbott+ PRD105,063030 (2022)]
- “B-L” coupling vector DM search in O3 KAGRA data: [Abac+ PRD110,042001 (2024)]

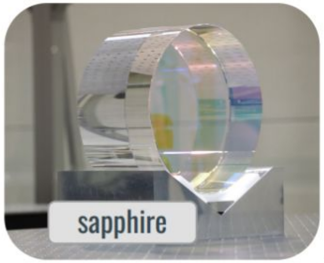


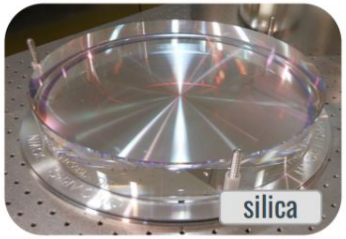
Vector dark matter changes auxiliary lengths between sapphire and fused silica mirrors

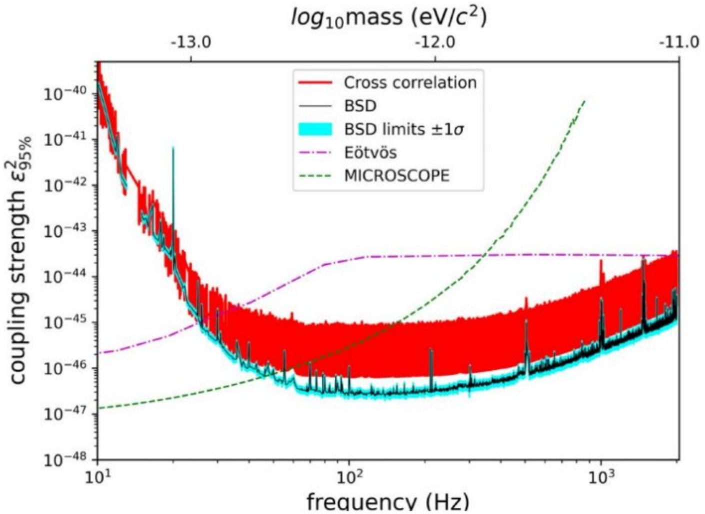
Sapphire mirror moves more than fused silica mirrors

Fused silica mirrors

Sapphire mirrors







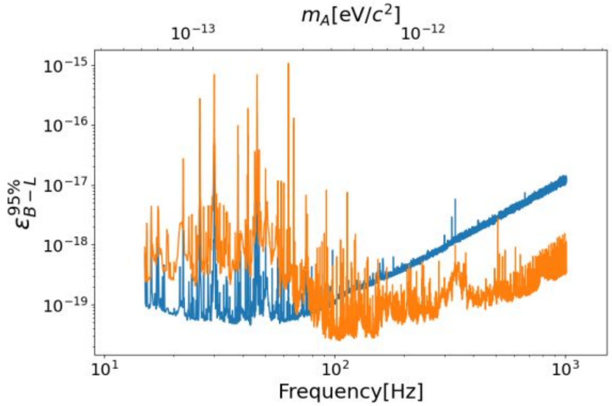


FIG. 5. 95% upper limit on the $B-L$ gauge coupling constant derived from MICH data (blue line) and PRCL data (orange line). Many narrow peaks observed in lower mass range are due to unknown line artifacts in the lower frequency range.

(From G2401742 by David Keitel)

Summary and outlook

At least 6 months more of observations in O4 - exciting data to explore and signals to detect:

- ~100 more compact binary coalescence events (hopefully an EM bright one?) to broaden our understanding on astrophysics of compact objects, cosmology, gravity theory.

We search for

- short transient signals
  - very heavy (primordial, intermediate mass?) binary black holes
  - supernovae, magnetar outbursts, GRBs, FRBs…
- intermediate duration signals
  - post-glitch, r-modes from rotating neutron stars
- long/persistent signals
  - stochastic background, asymmetric rotating neutron stars
  - very light (primordial, asteroid/planetary mass?) binary black holes
  - dark matter and exotic particles - as astrophysical sources, but also directly interacting with interferometers (‘’direct detection’’)
- lensed gravitational waves

using various state-of-the-art data analysis methods (also machine learning)