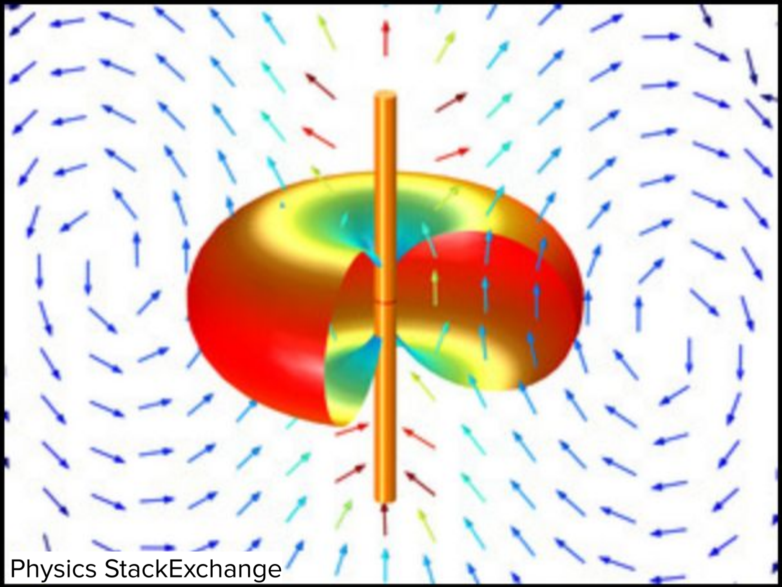
LIGO-Virgo-KAGRA gravitational-wave sources and observational results

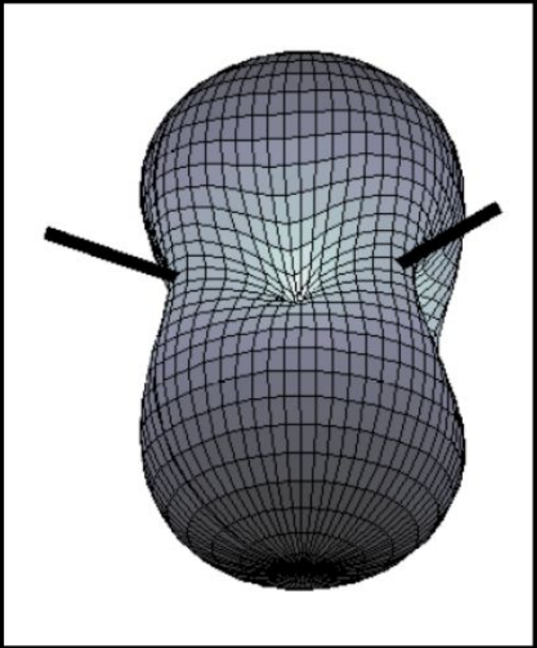
Michał Bejger (for the Polish Virgo group)
PAiP 2025 - 21 Feb 2025

Interferometer = GW antenna

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



Physics StackExchange



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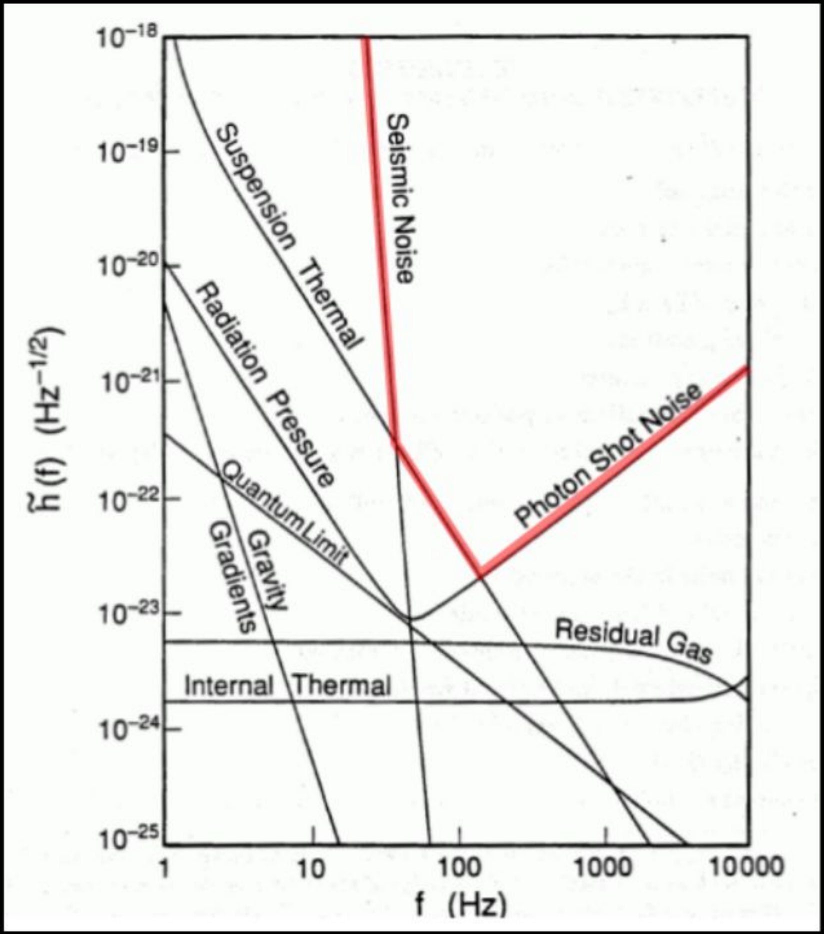
Ground-based detector broadband sensitivity



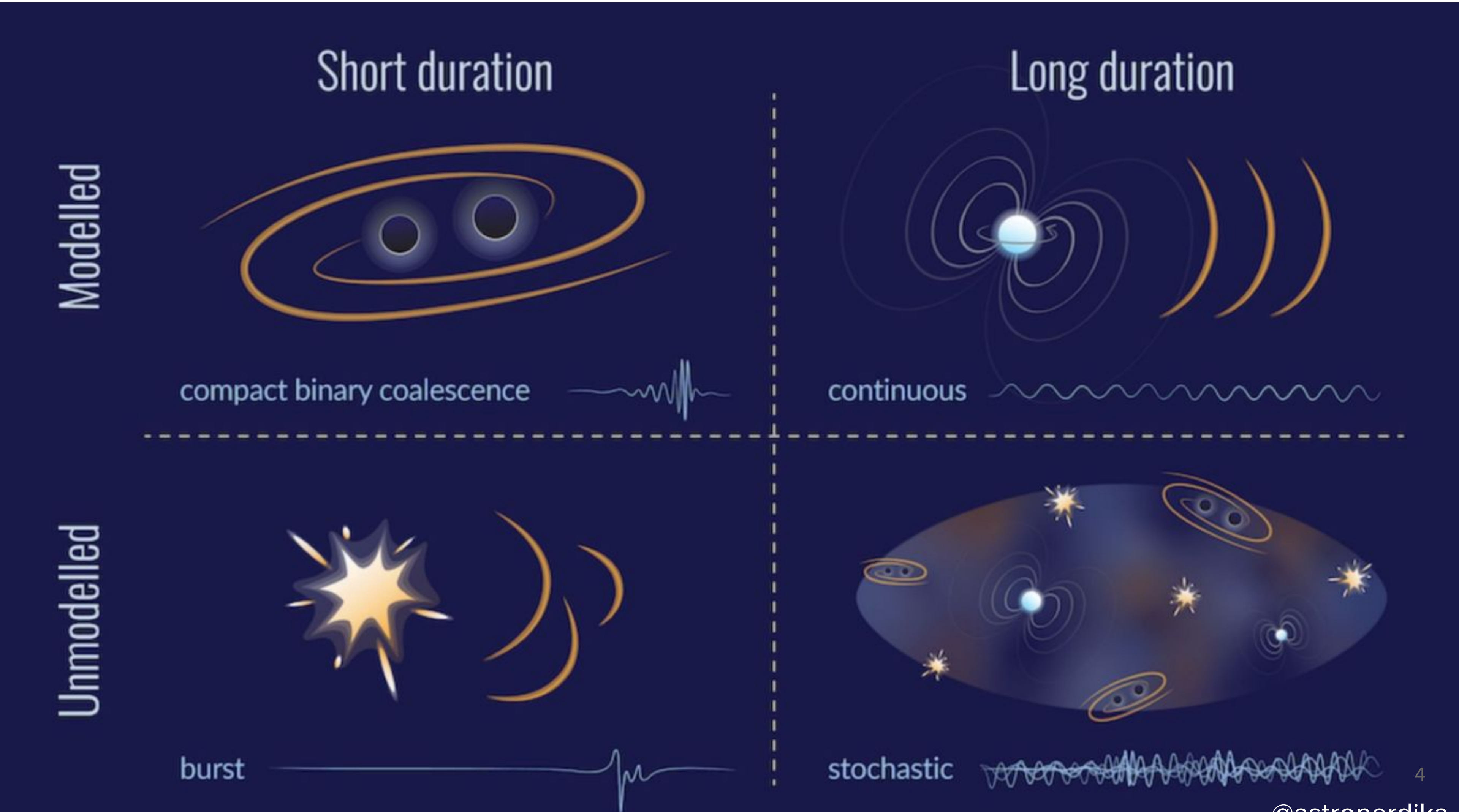
Initial LIGO proposal (1989)

★ Range of frequencies similar to human ears:

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

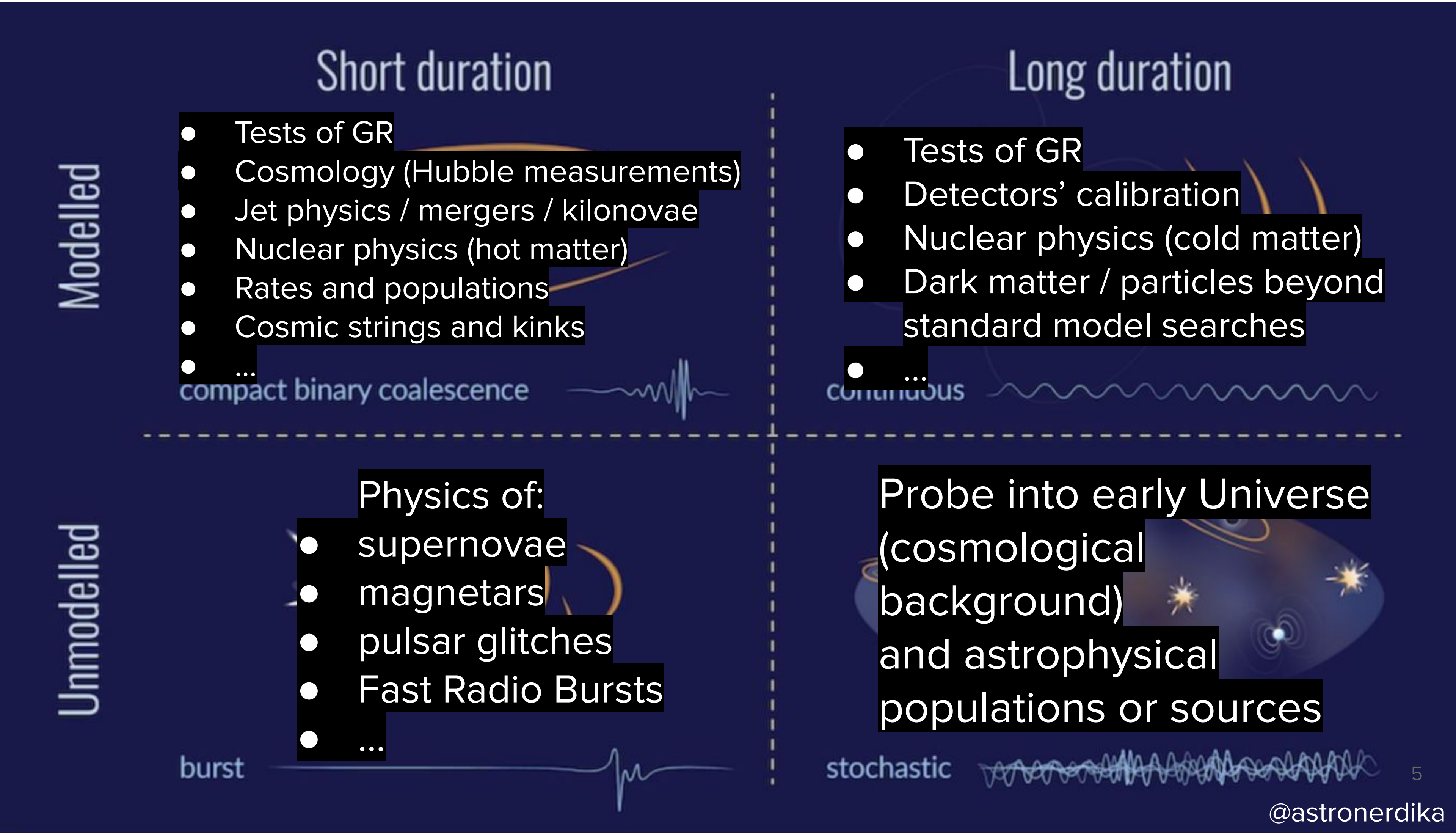
★ Poor, like for an ear, angular resolution.

Gravitational-wave signal types of interest to the LVK...



@astronerdika

...and why they are interesting and useful



Short duration – Modelled

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

Long duration – Modelled

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

Short duration – Unmodelled

Physics of:

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

Long duration – Unmodelled

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 $\rightarrow$ 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 $\rightarrow$ standard sirens (direct luminosity distance), core engine, cosmology, gravity theory tests . . .

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.) $\rightarrow$

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

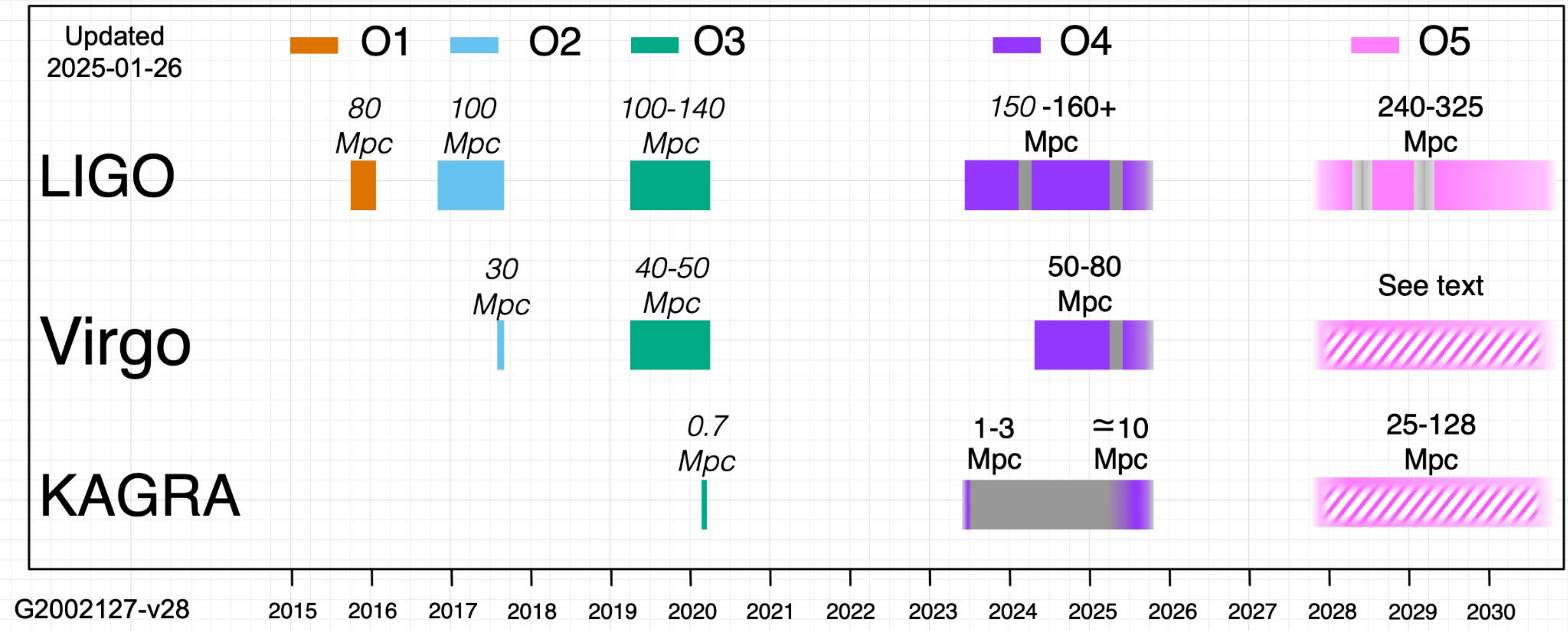
where χ_{iz} are spin components along system's total angular momentum,

- ⋆ Tidal deformability Λ (at 5PN) $\rightarrow$

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

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

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 7 Oct 2025
  - Next update to the plan: 15 Mar 2025

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

GraceDB Public Alerts Latest Search Notifications Pipelines Documentation Logout

Authenticated as: Michal Bejger

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

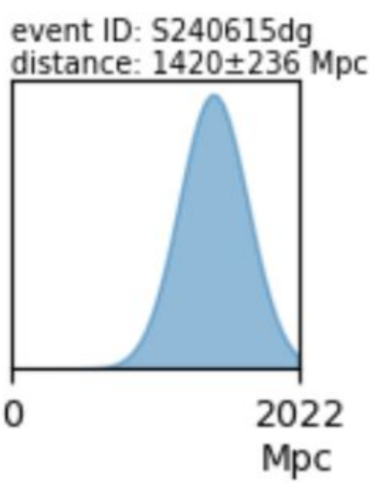
LIGO/Virgo/KAGRA Public Alerts

- 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 O4.
- Less-significant events are not shown by default. Press "**Show All Public Events**" to show significant and less-significant events.

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

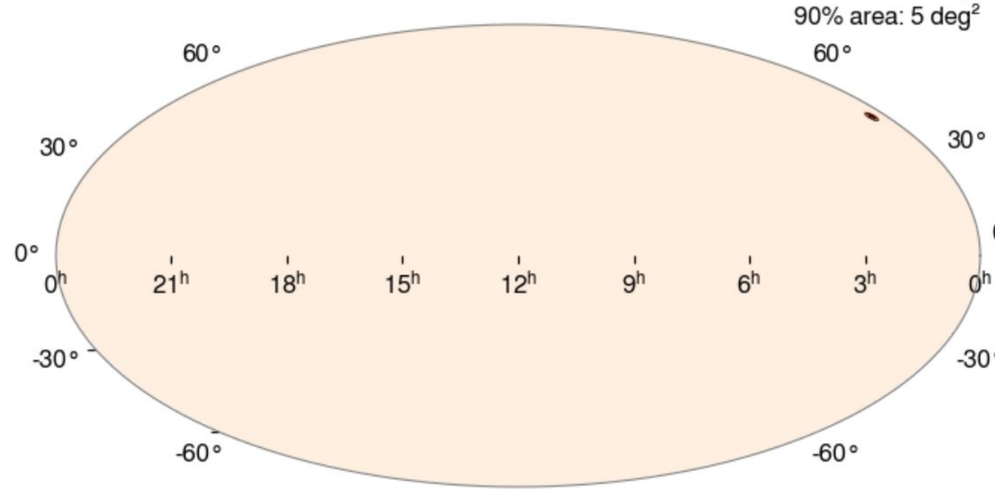
O4 Low Significance Detection Candidates: **3483** (Total)

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

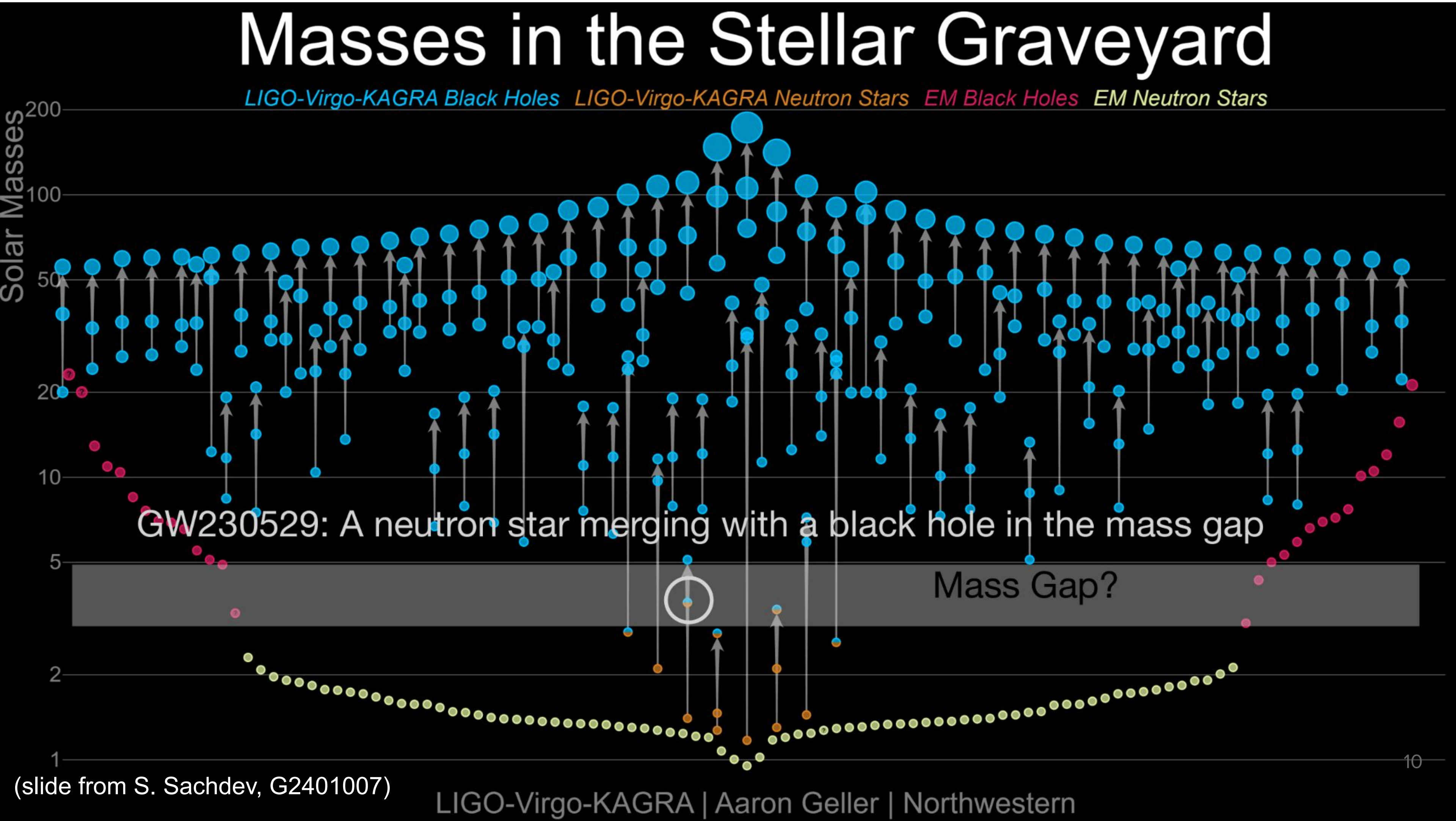


Bilby constraints:

event ID: S240615dg
50% area: 1 deg²
90% area: 5 deg²



04: GW230529 and mass gap objects



(slide from S. Sachdev, G2401007)

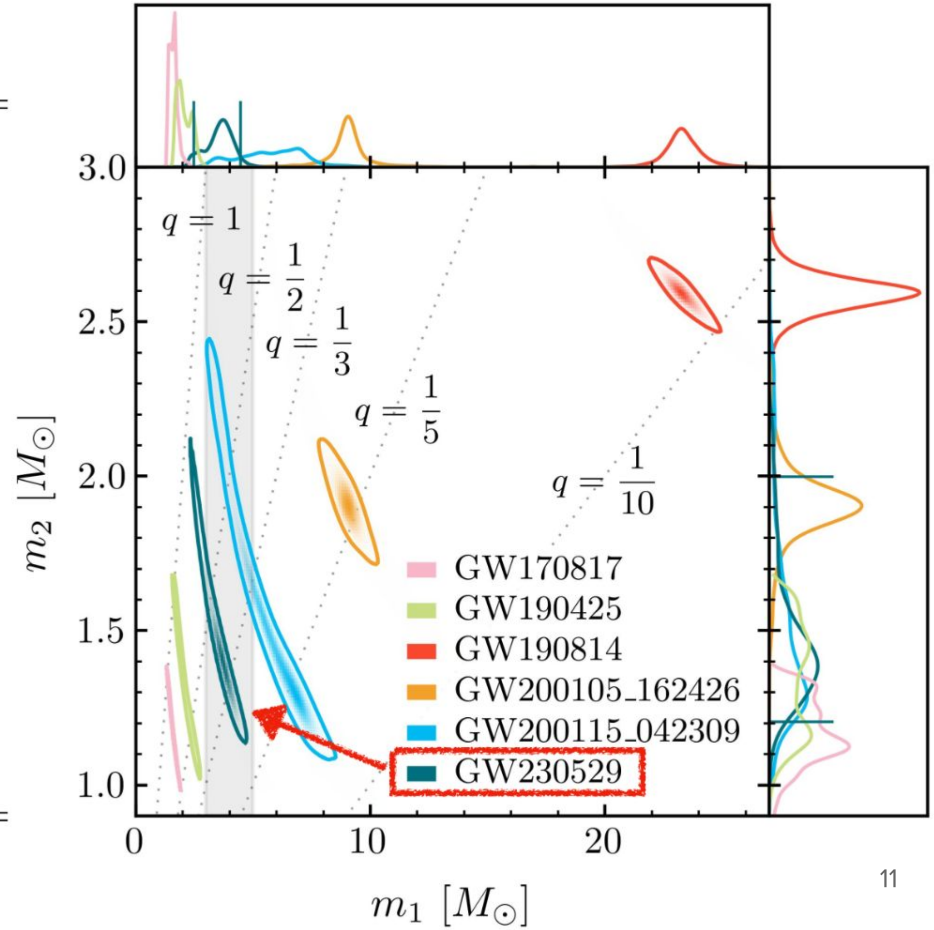
GW230529 properties

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

No confirmed EM counterpart, no clear tidal constraints

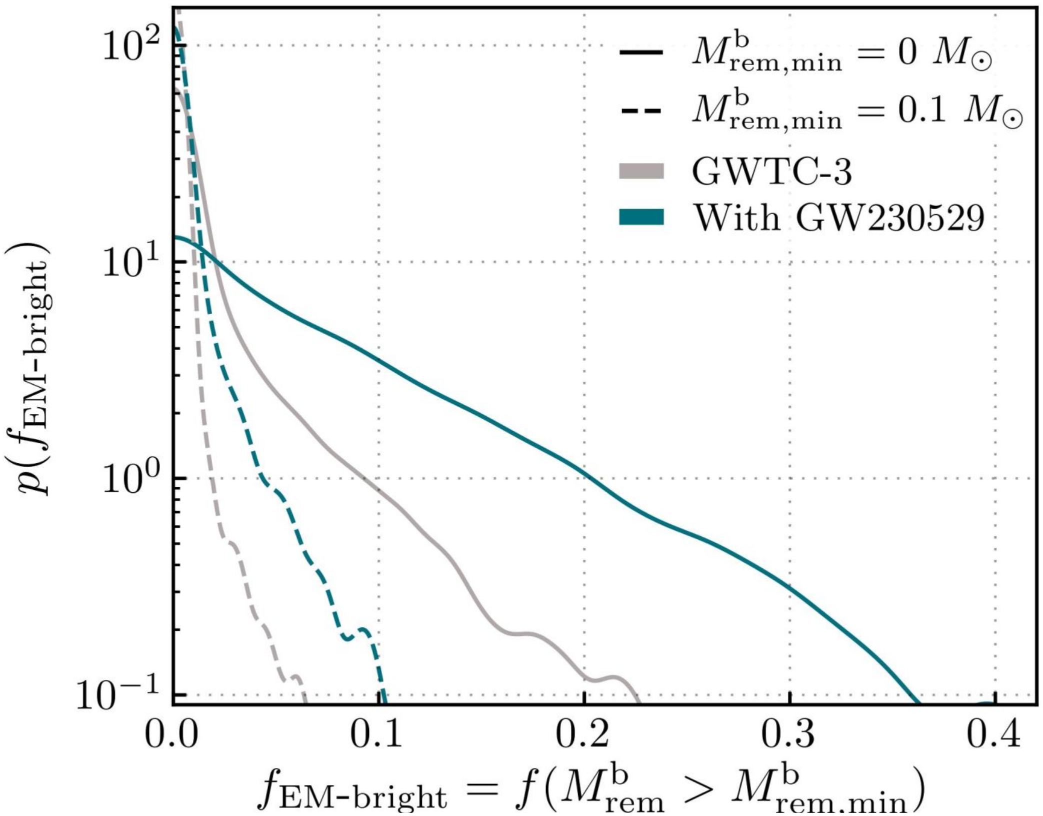
SNR ~11.5

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: influence on EM brightness



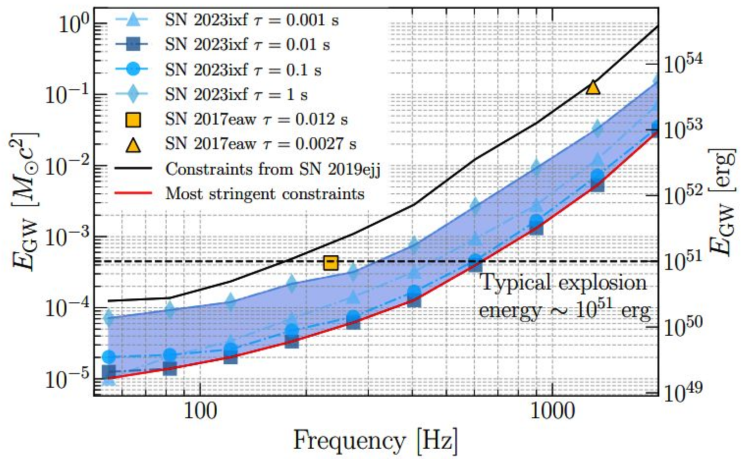
Posterior on the fraction of NSBH systems detected with GWs that may be EM bright, $f_{EM\text{-}bright}$, depending on the threshold remnant mass required to power a counterpart, $f(M^{b}_{rem} > M^{b}_{rem,min})$. The solid and dashed curves represent different values of the minimum remnant mass $M^{b}_{rem,min}$.

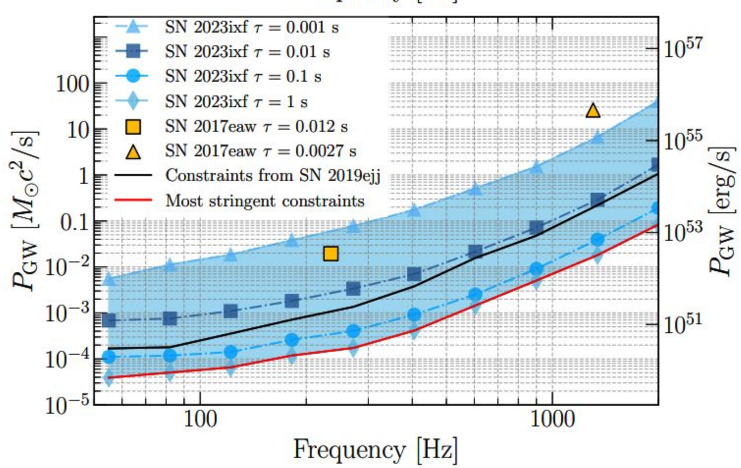
- Fraction of EM bright NSBHs increases if we include GW230529 in the population
  - less massive black holes are more likely to tidally disrupt neutron stars

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

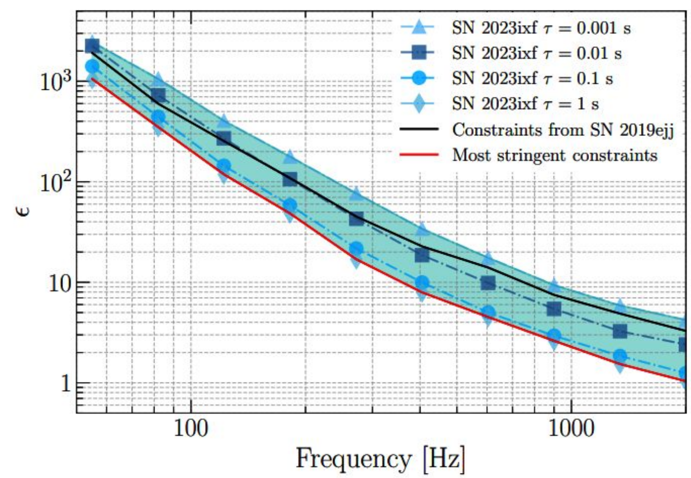
SN 2023ixf (Abac et al., [arXiv:2410.16565](https://arxiv.org/abs/2410.16565))

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)



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

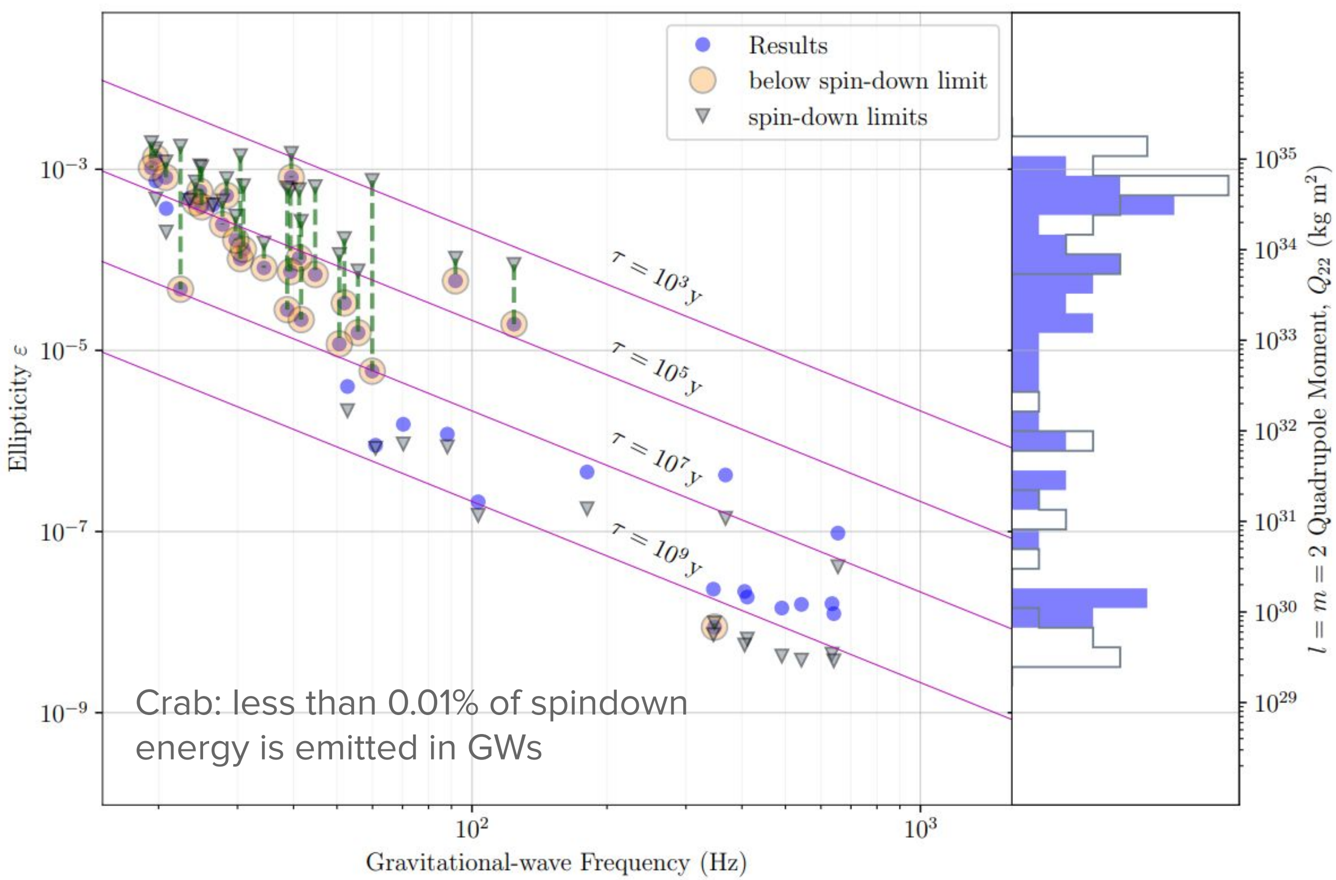
$$E_{\rm GW} = \frac{2}{5}\frac{\pi^2 c^3}{G} D^2 f_0^2 h_{\rm rss}^2$$

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

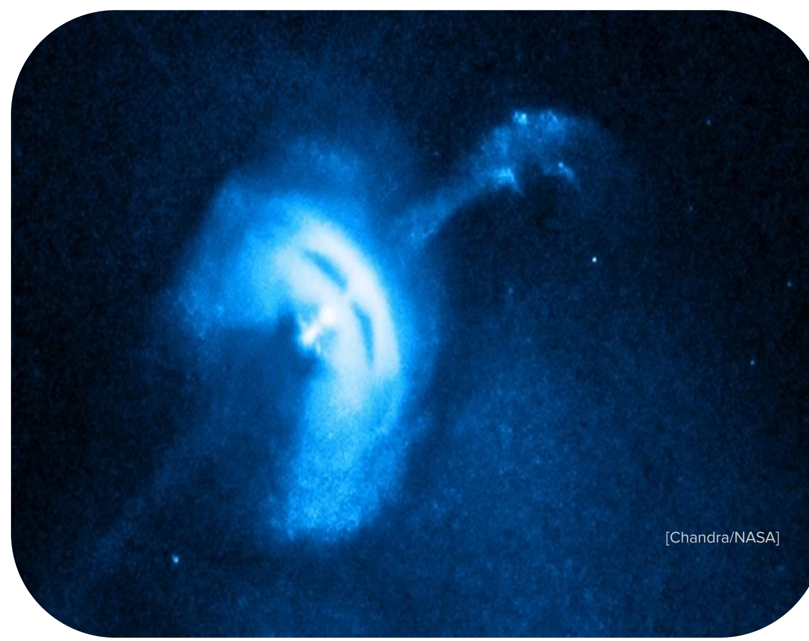
to be compared with a "spindown limit" on amplitude $h_0^{\rm sd} = \frac{1}{d}\left(\frac{5GI_{zz}}{2c^3}\frac{|\dot{f}_{\rm rot}|}{f_{\rm rot}}\right)^{1/2}$



- 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

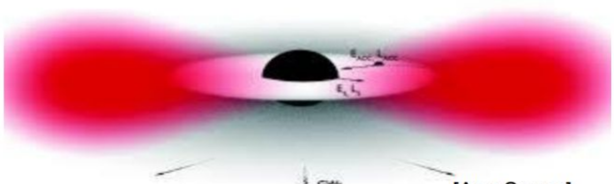
The Vela pulsar (J0835–4510)

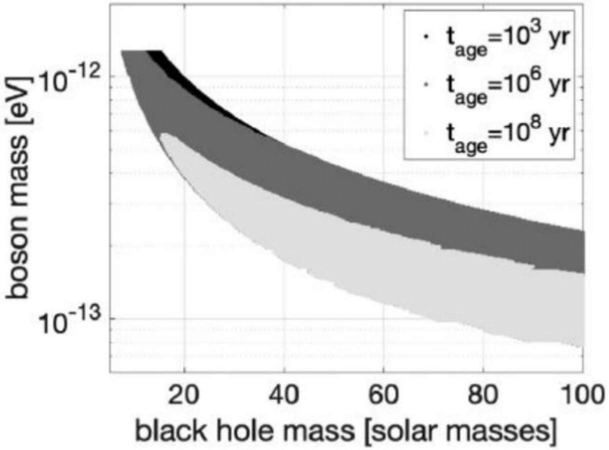
- One of LVK standard target for CW searches: young, nearby (287 pc), frequency low but in sensitivity range (f_{rot} ~11 Hz, f_{gw} ~22 Hz). Indirect spindown upper limit for persistent CWs already beaten with initial LIGO-Virgo (Abadie et al., 2011a).
- Strong glitches ($\Delta f\,/\,f \sim 10^{-6}$) 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!**



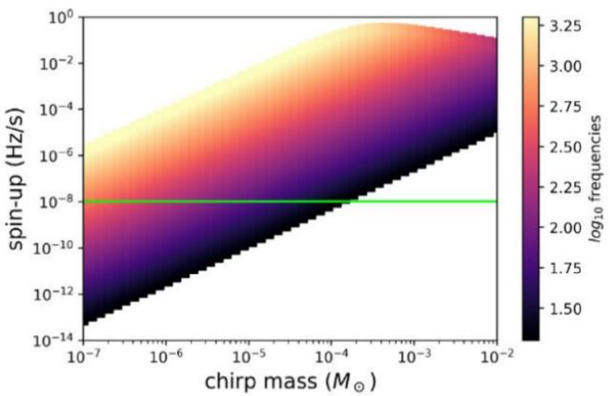
Dark matter searches

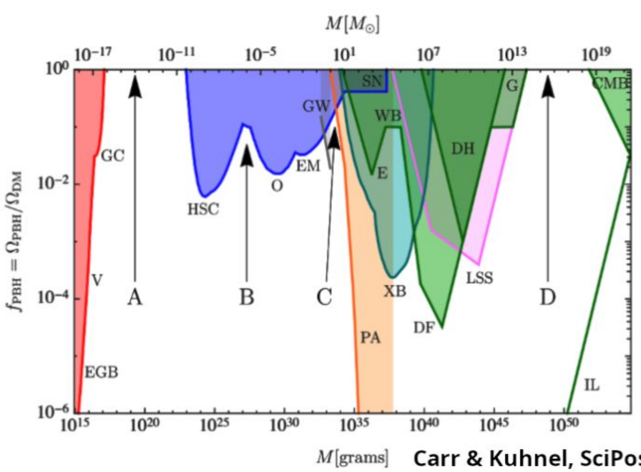
- **Boson clouds** around spinning black holes: superradiant energy extraction and CW-like emission, frequency related to particle mass
  → O3 search: Abbott+ PRD105,102001 (2022)





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



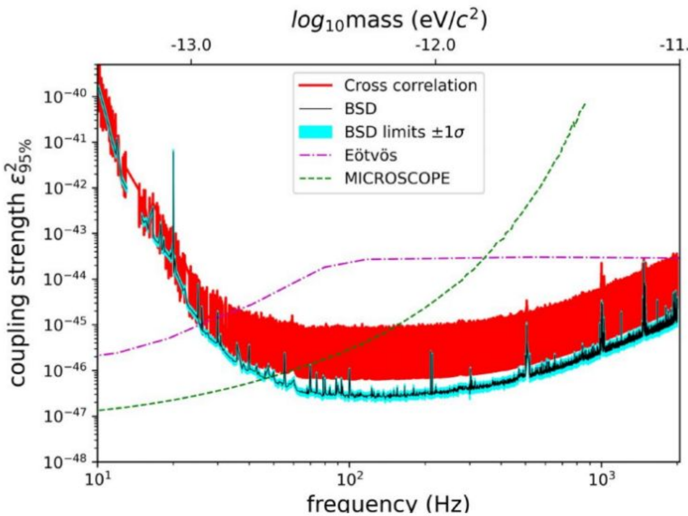


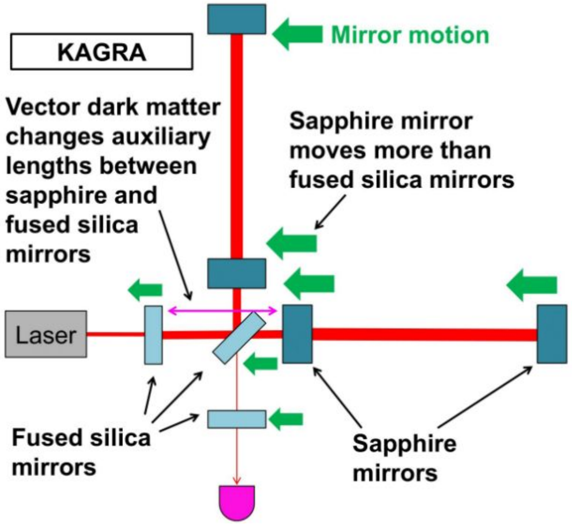
Carr & Kuhnel, SciPost Phys. Lect. Notes 48 (2022)

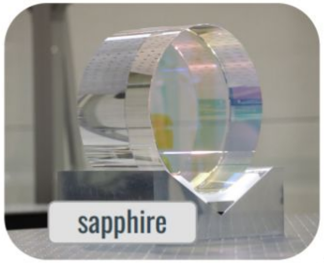
(From G2401742 by David Keitel)

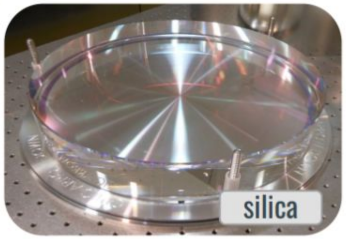
Dark matter searches

- 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)]









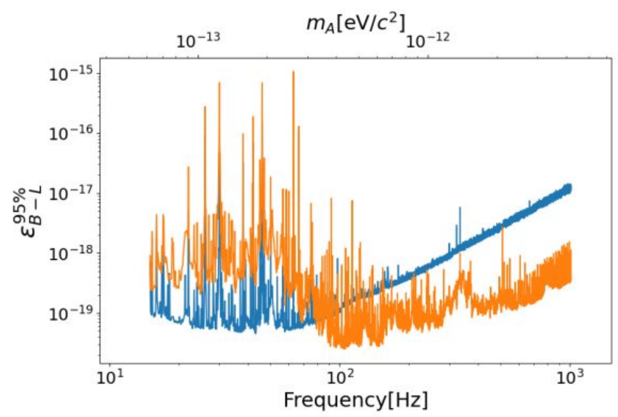


FIG. 5. 95% upper limit on the $B-L$ gauge coupling constant derived from MICH data (blue line) and PRCL data (orange line). Many narrow peaks observed in lower mass range are due to unknown line artifacts in the lower frequency range.

(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:

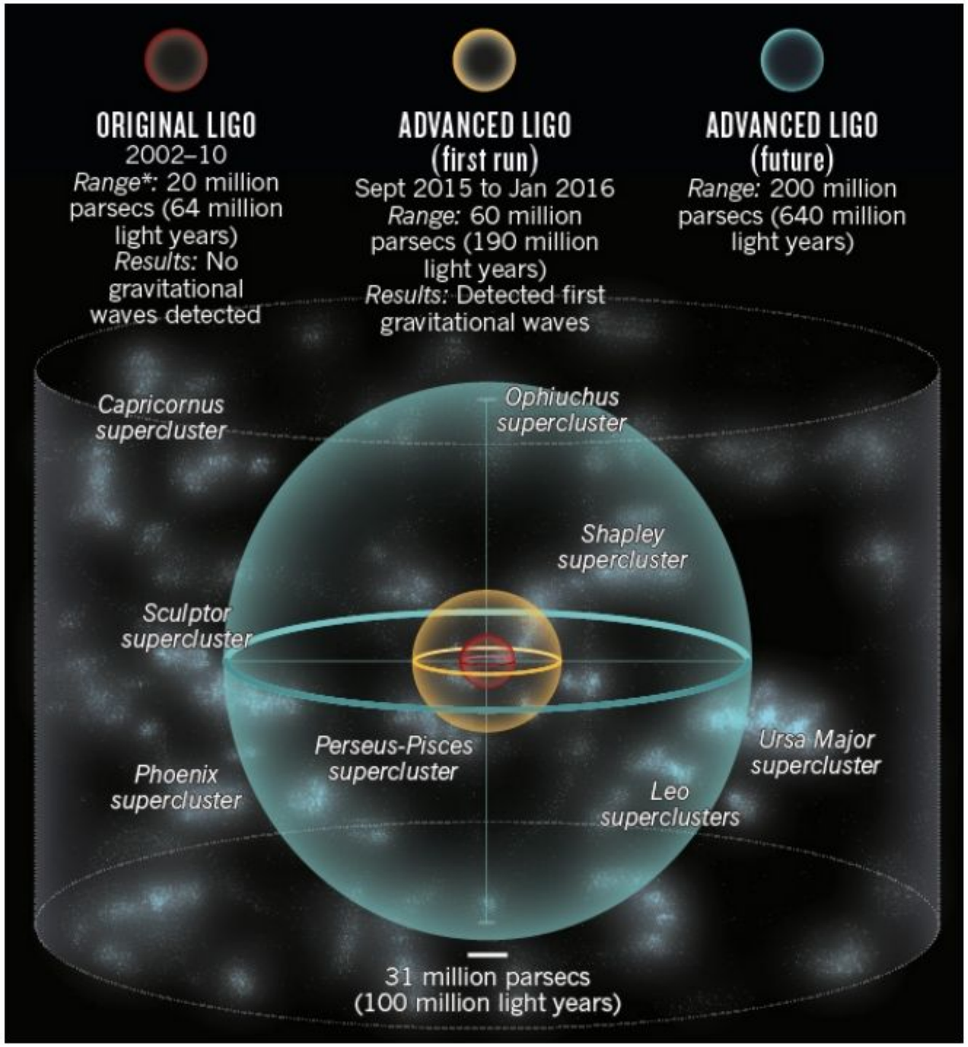
- ~100 more compact binary coalescence events (hopefully an EM bright one?) to broaden our understanding on astrophysics of compact objects, cosmology, gravity theory.

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

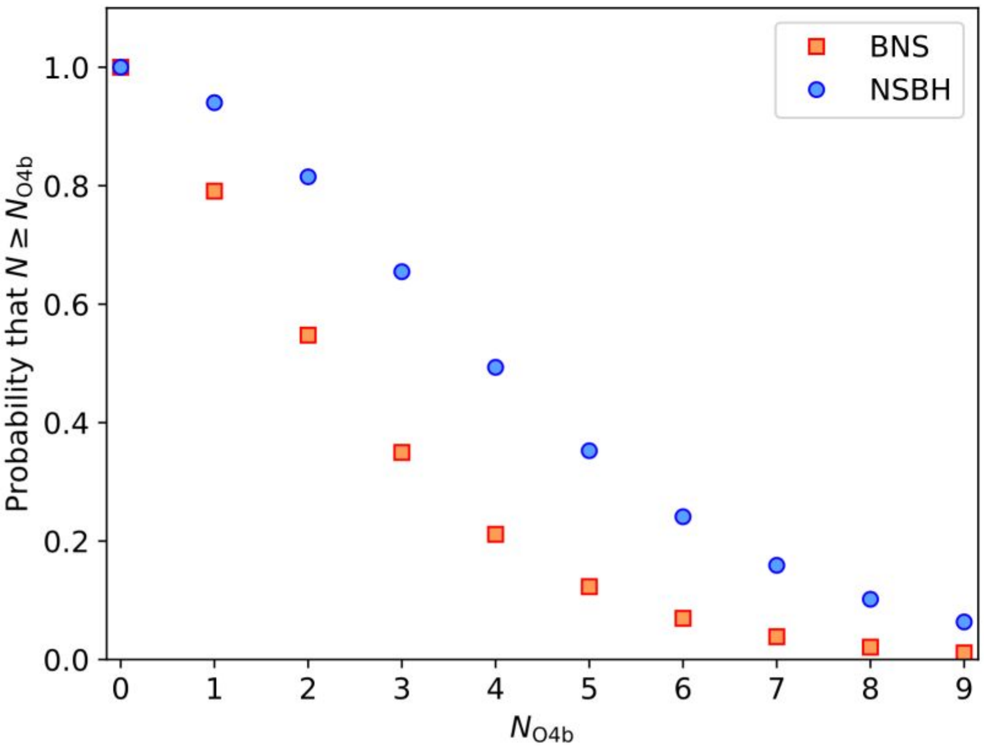
using various state-of-the-art data analysis methods (also machine learning)

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 $V \to 1000V$.

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 Gpc^{-3} 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'

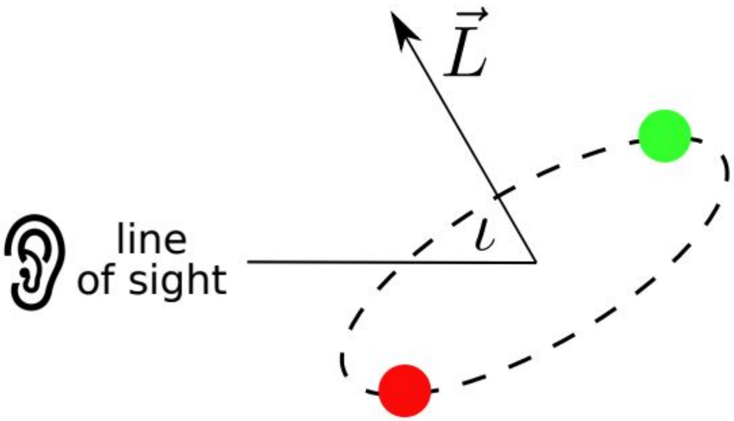
https://emfollow.docs.ligo.org/userguide/capabilities.html

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 $h_\times$:

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

Effects of various parameters on inspiral waveform

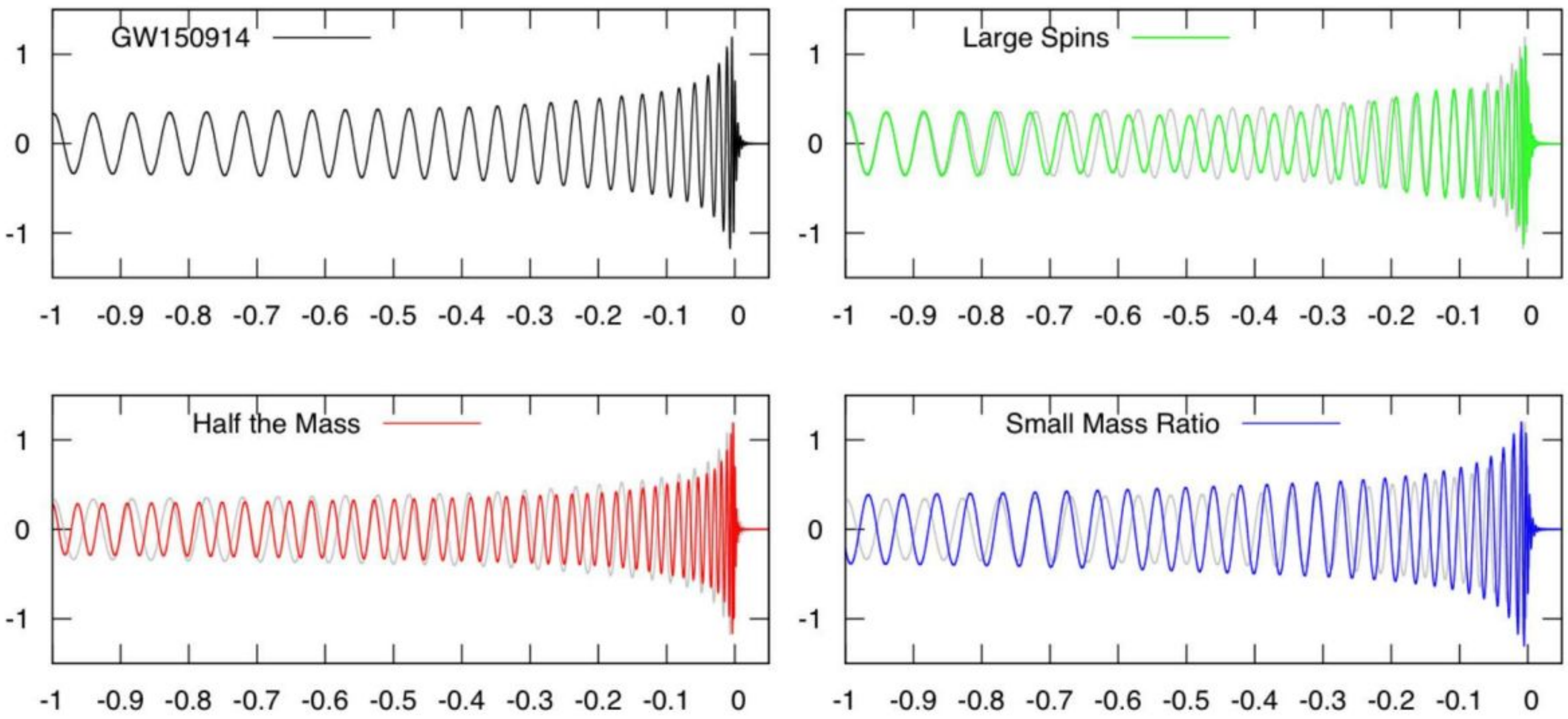


Illustration by N. Cornish and T. Littenberg