Vulcano Workshop2024

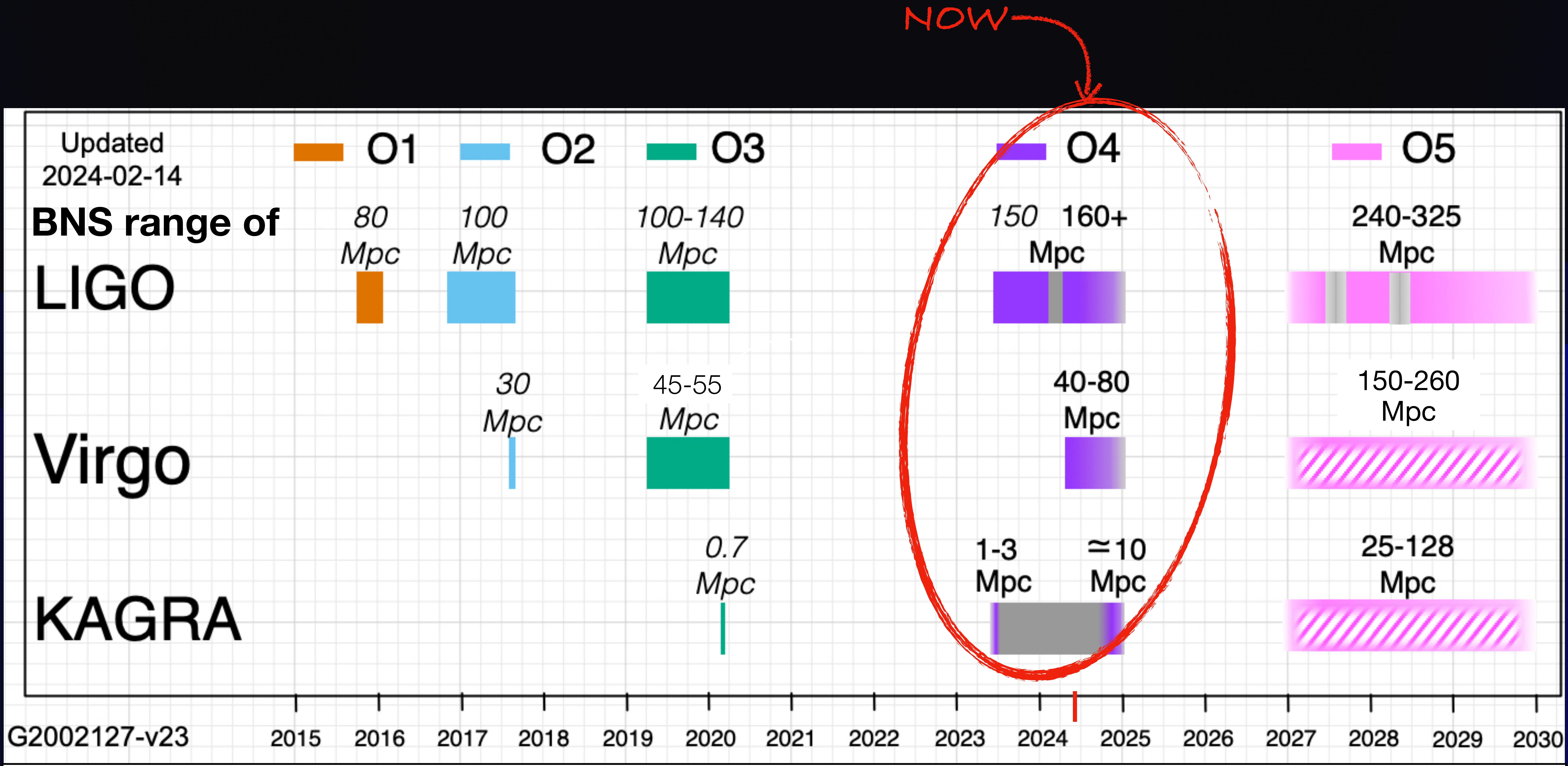
Frontier Objects in Astrophysics and Particle physics

Gravitational Waves

Latest results

M. Alessandra Papa
Max Planck Inst. for Gravitational Physics and Leibniz Univ. Hannover, Germany

Observing runs of the GW network



credit: LIGO-Virgo-Kagra DCC G2002127-23 and Abbott et al, "Open data from the third…", ApJ Suppl. Series,267:29 (2023)

Latest results

https://pnp.ligo.org/ppcomm/Papers.html

detections

- Formation and evolution of compact objects
- Multi-messenger picture of high-energy astrophysical phenomena
- CBCs are standard sirens ==> probe of Hubble parameters
- General relativity to the test

TALKS BY:

S. Mastrogiovanni, Tuesday morning)

I. Di Palma, B. Patricelli, M. Punturo (up next), E. Battista (next session)

C. Fryer, A. Rossi, H.J. van Eerten, E. Troja (afternoon today)

M. Spurio (Tuesday afternoon), S. Dichiara (Thursday morning),

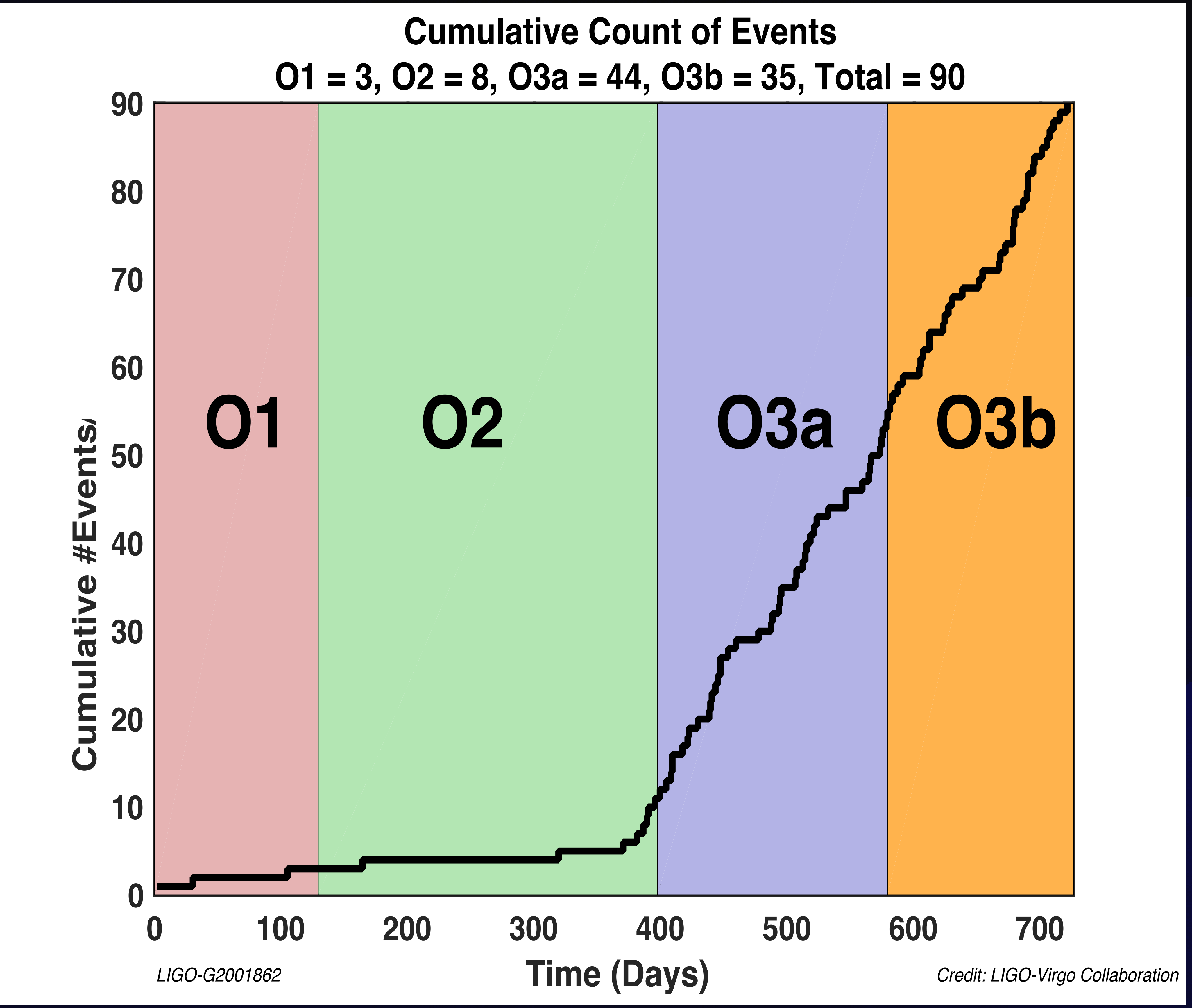
E. Di Valentino , G. Gianfagna (both Tuesday morning)

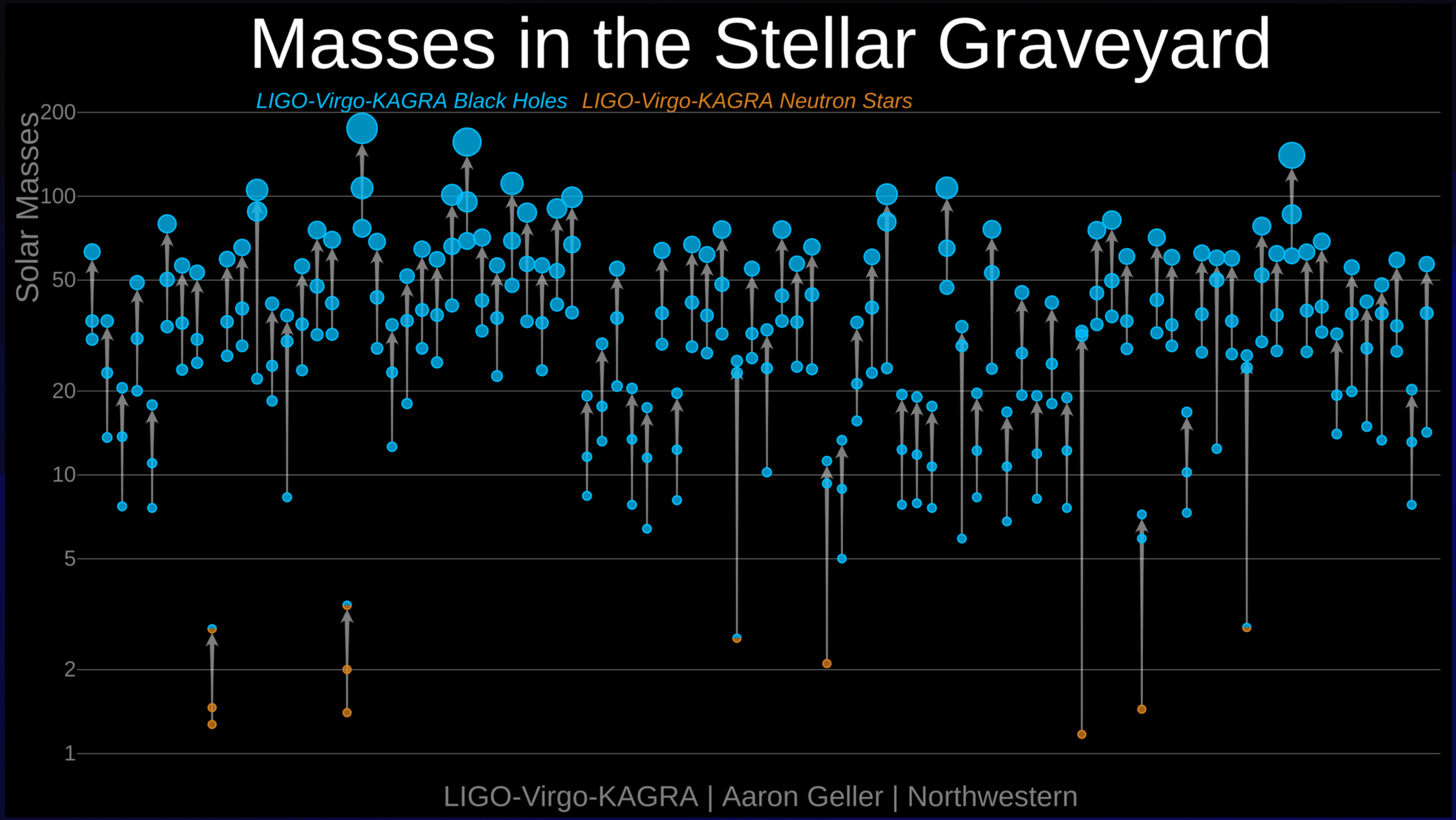
non-detections

- lots
- continuous signals

Abbott et al., Phys. Rev. X 13, 041039 (2023) (Populations of merging…), Abbott et al., ApJ 949 (2023) (Constraints on the Cosmic expansion history …), Abbott et al., arxiv:2112.06861 (2023) (Tests of GR …)

Gravitational waves from compact binary coalescences



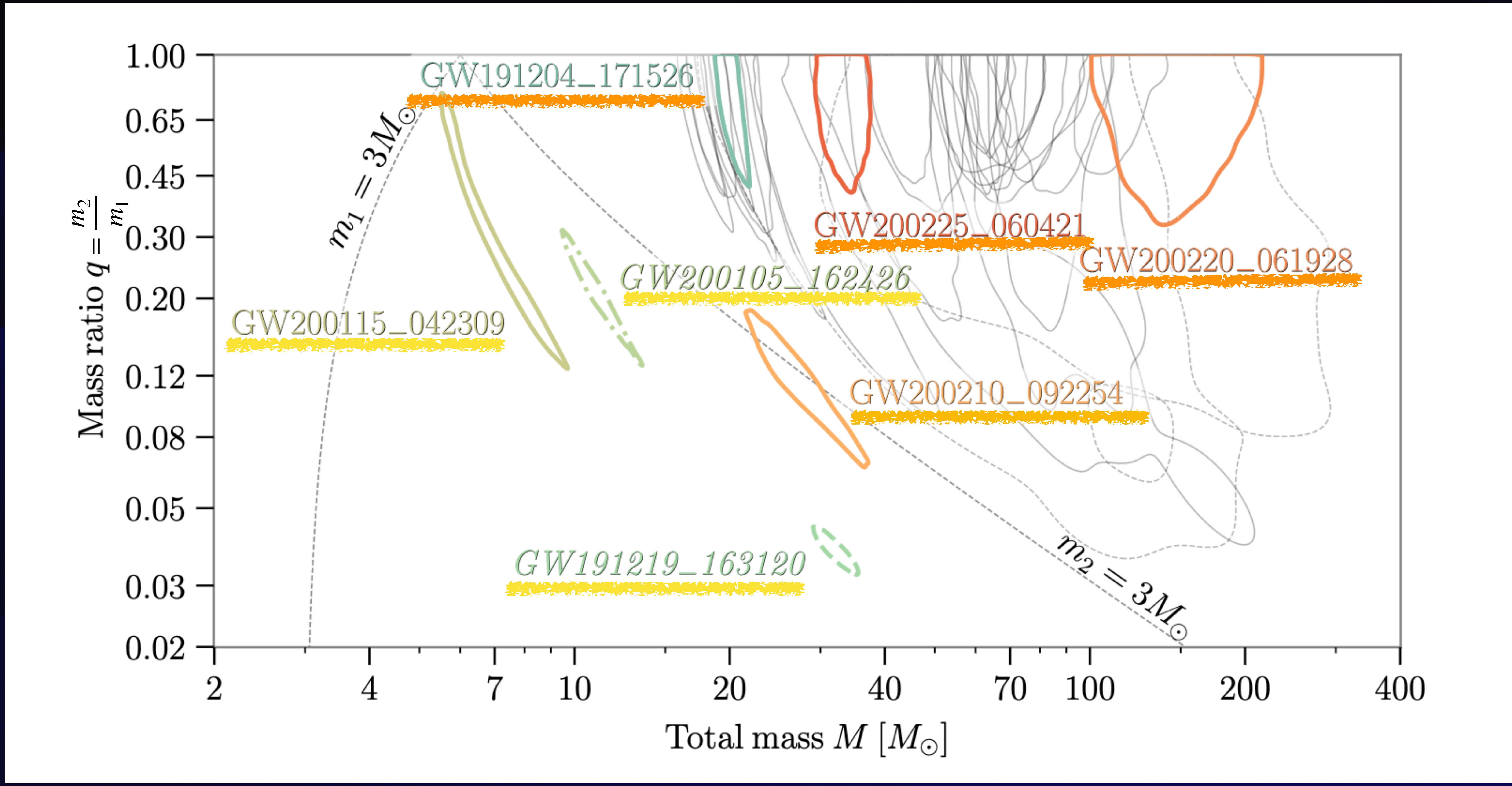


Abbott et al.,GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run, Phys. Rev. X 13, 041039 (2023)

Features of the O3b signals

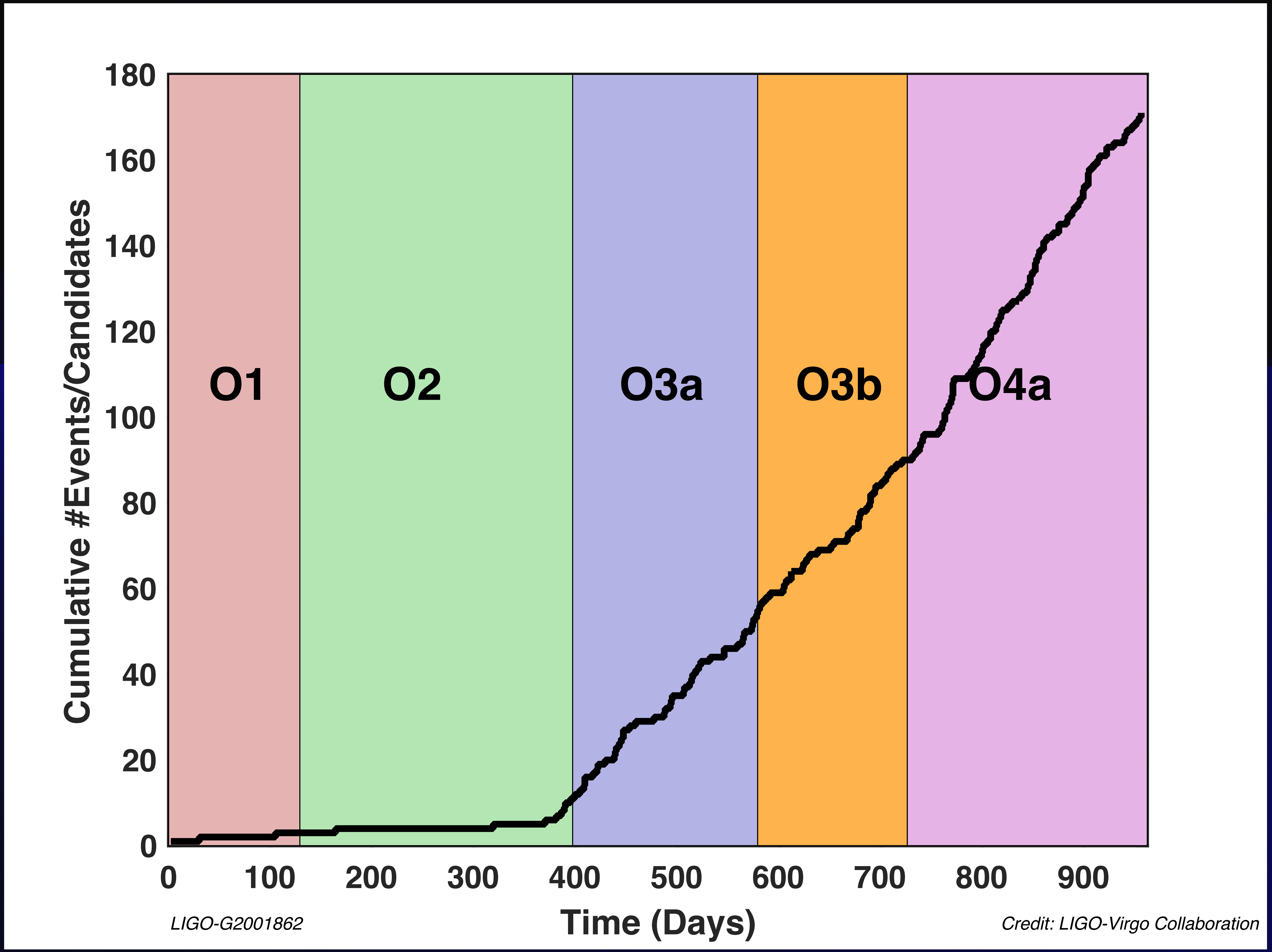
similar to previous signals

- Most signals come from BBH mergers
- Most BBHs have similar masses
- Seeing intermediate mass BHs
- The astrophysical original of 2 of the 3 NS-BH candidates is less certain than for other candidates



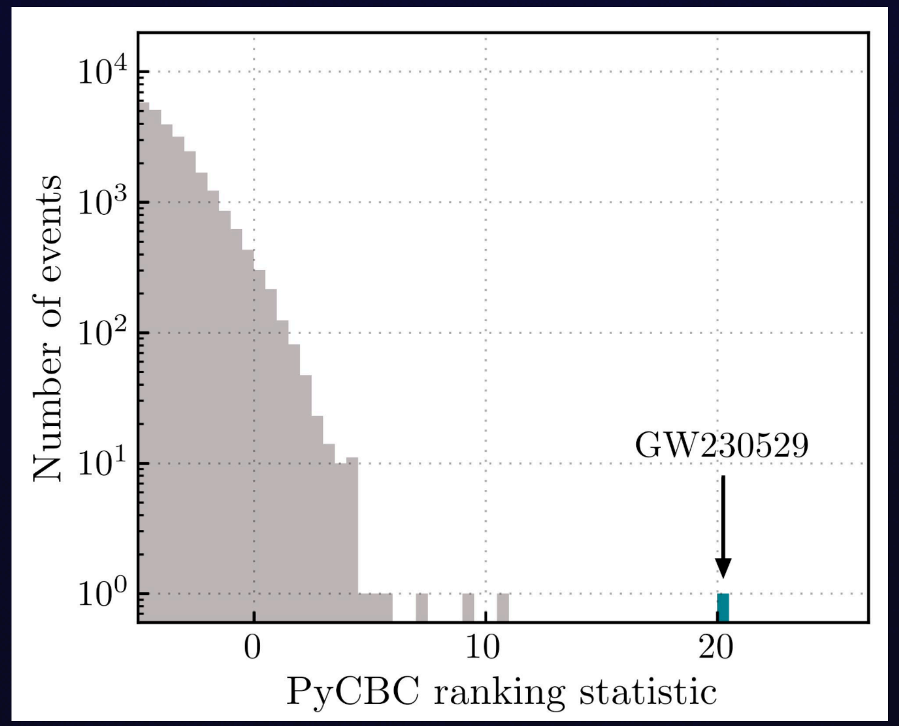
Abbott et al., Phys. Rev. X 13, 041039 (2023) (GWTC-3 paper)

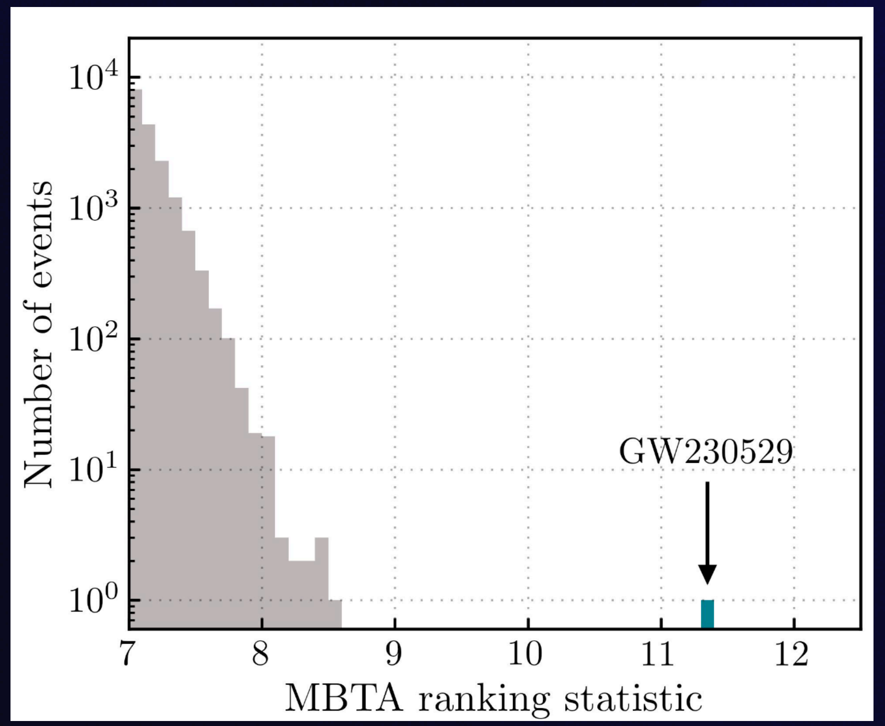
O4 run (ongoing, with O4b having started in April)

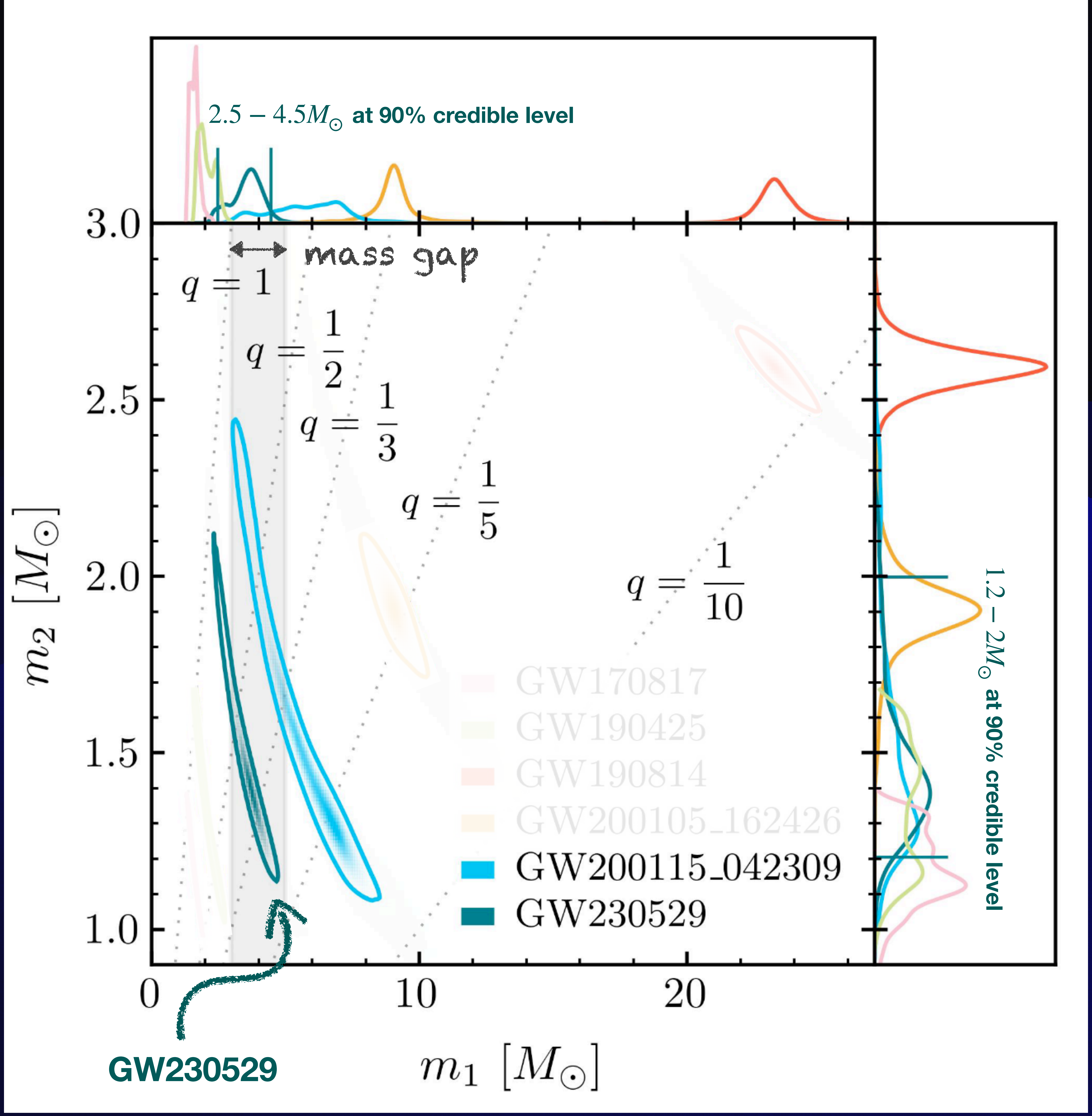


GW230529

- NS-BH
- BH in “mass gap” at 99% confidence
  - mass gap: $3M_\odot - 5M_\odot$
- Only 1 detector
- Very confident detection



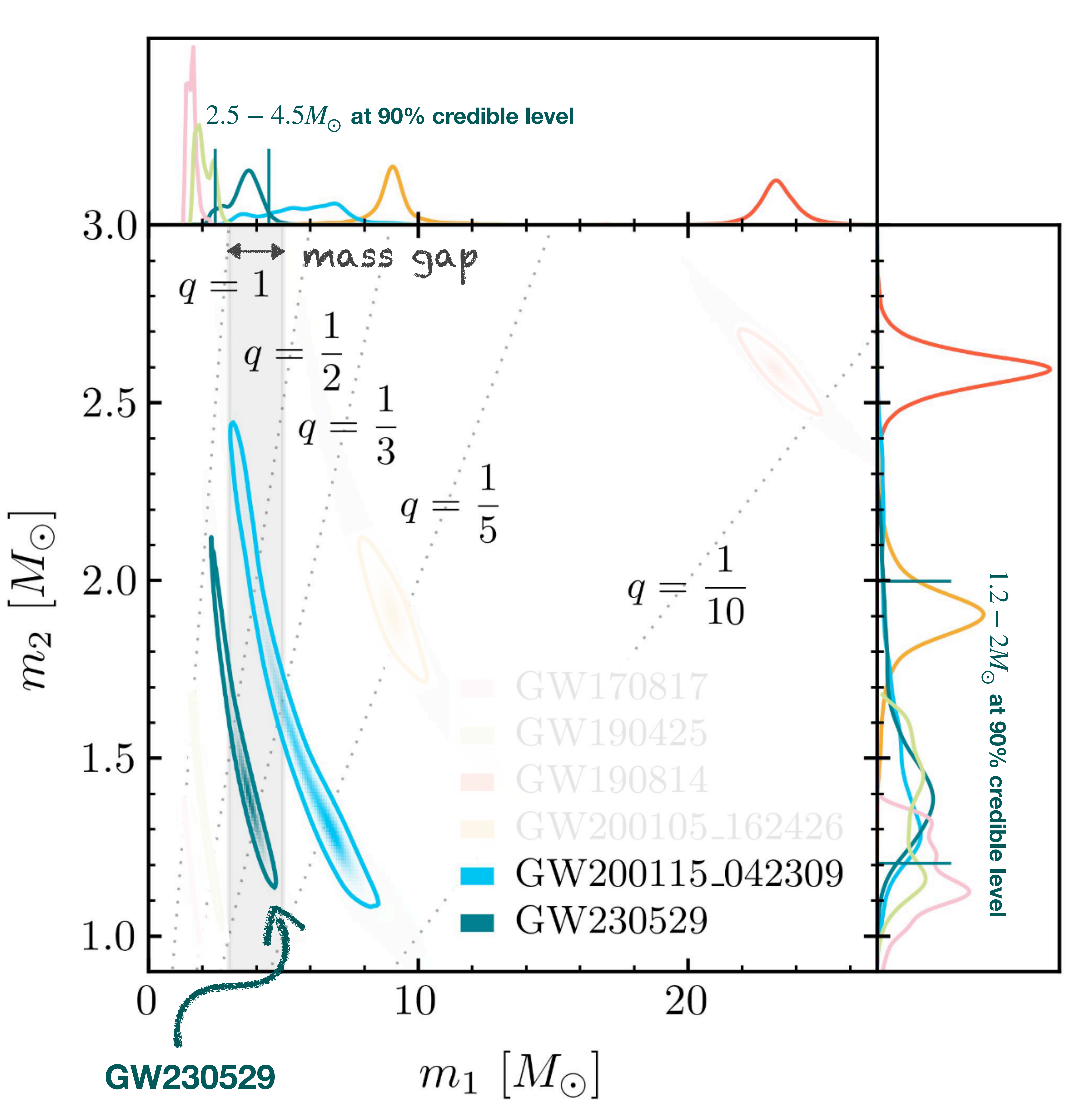




Paper available at https://dcc.ligo.org/LIGO-P2300352/public

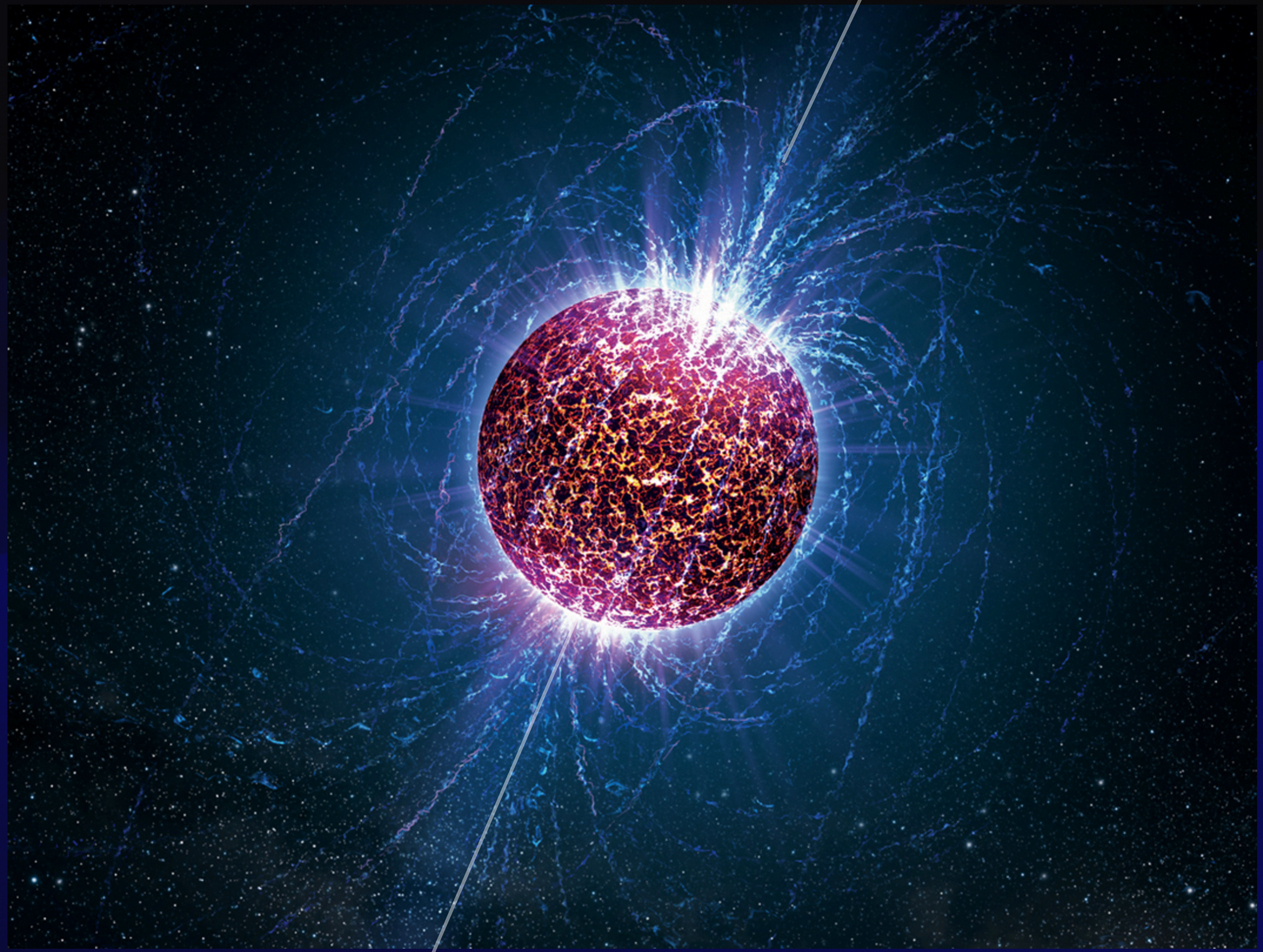
GW230529

- NS-BH
- BH in "mass gap" at 99% confidence
  - mass gap: $3M_\odot - 5M_\odot$
- Only 1 detector
- highest chance of EM counterpart



Paper available at https://dcc.ligo.org/LIGO-P2300352/public

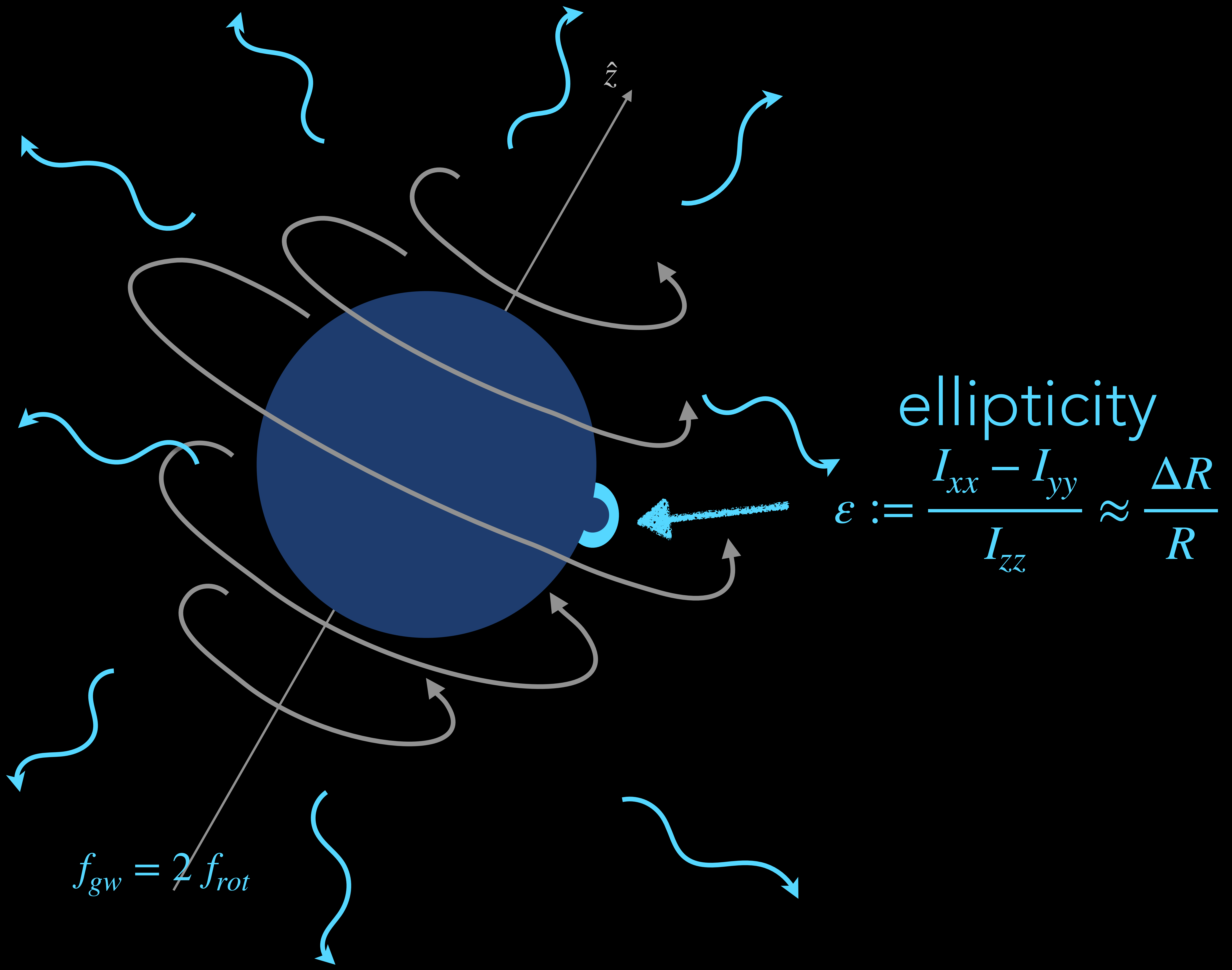
There's not just the transient GW sky



gravitational waves from
spinning neutron stars

SIMPLE MODEL: SPINNING NEUTRON STAR WITH EQUATORIAL ELLIPTICITY

- signal always there

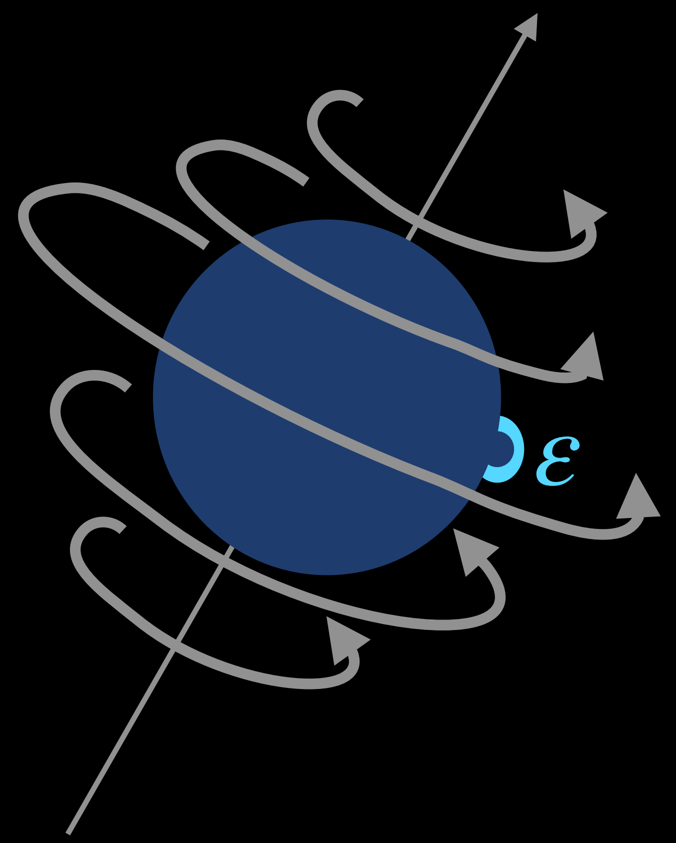


sinusoidal signal

WHAT COULD WE LEARN ?

- ellipticity of object, internal structure of NS
- access to invisible NS population
- tests of GR (non-GR polarisations)
- if in conjunction with EM timings
  - emission mechanism
  - differential rotation ?
- even more intriguing, if signal does not come from a neutron star

VERY WEAK SIGNALS



- signal always there

- very weak:

$$h_0 = \frac{2\pi^2 G}{c^4}\frac{I\varepsilon f_{gw}^2}{D} = 2 \times 10^{-25}\left[\frac{I}{10^{38}\ \mathrm{kg\ m^2}}\right]\left[\frac{\varepsilon}{10^{-6}}\right]\left[\frac{f_{gw}}{10^3\ \mathrm{Hz}}\right]^2\left[\frac{1\ \mathrm{kpc}}{D}\right]$$

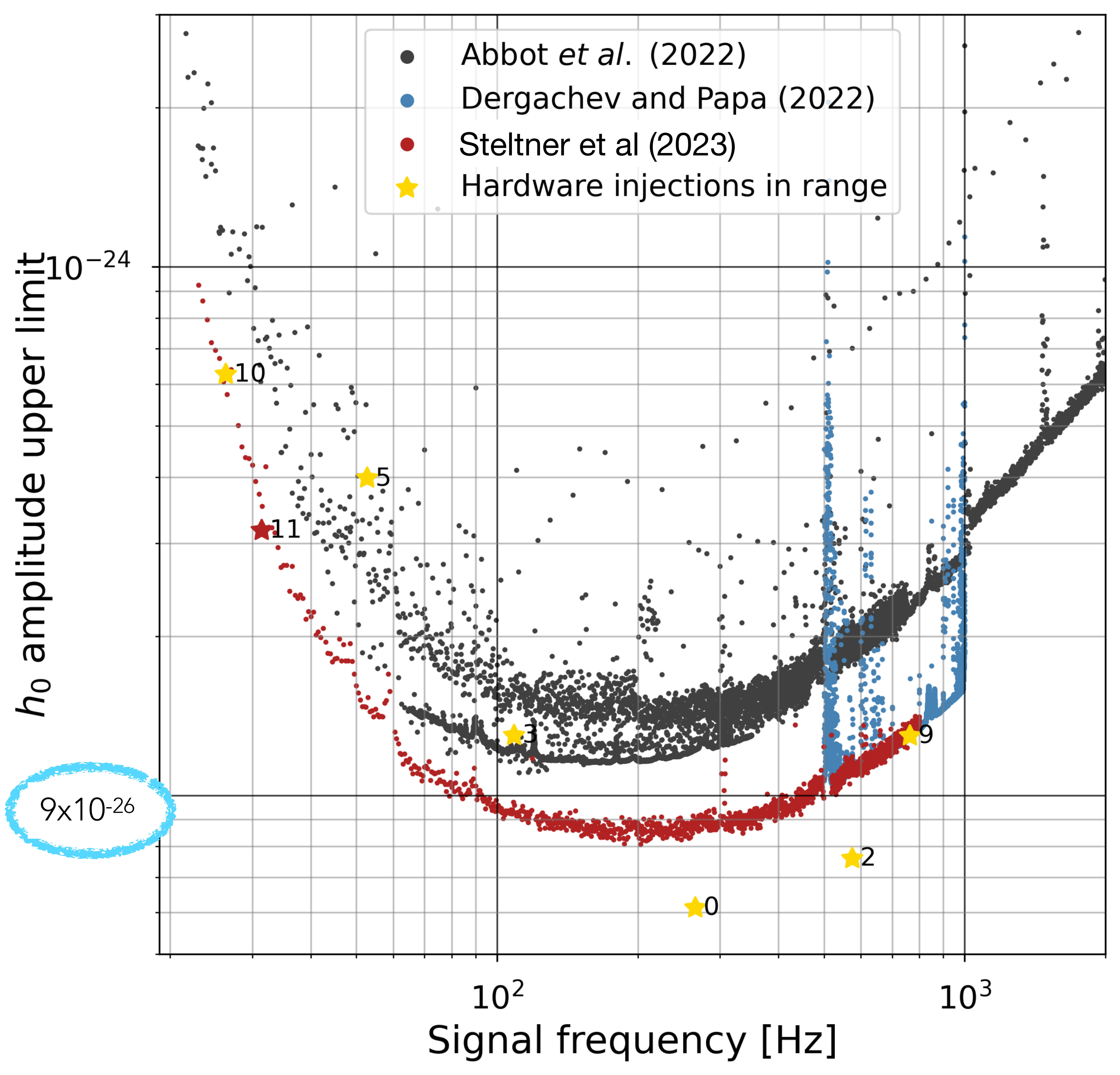
compare: $h_0^{binaries} \approx 10^{-21}$

MOST CHALLENGING DETECTION PROBLEM OF GW ASTRONOMY

ALL-SKY SURVEYS OF CW EMISSION FROM ISOLATED STARS

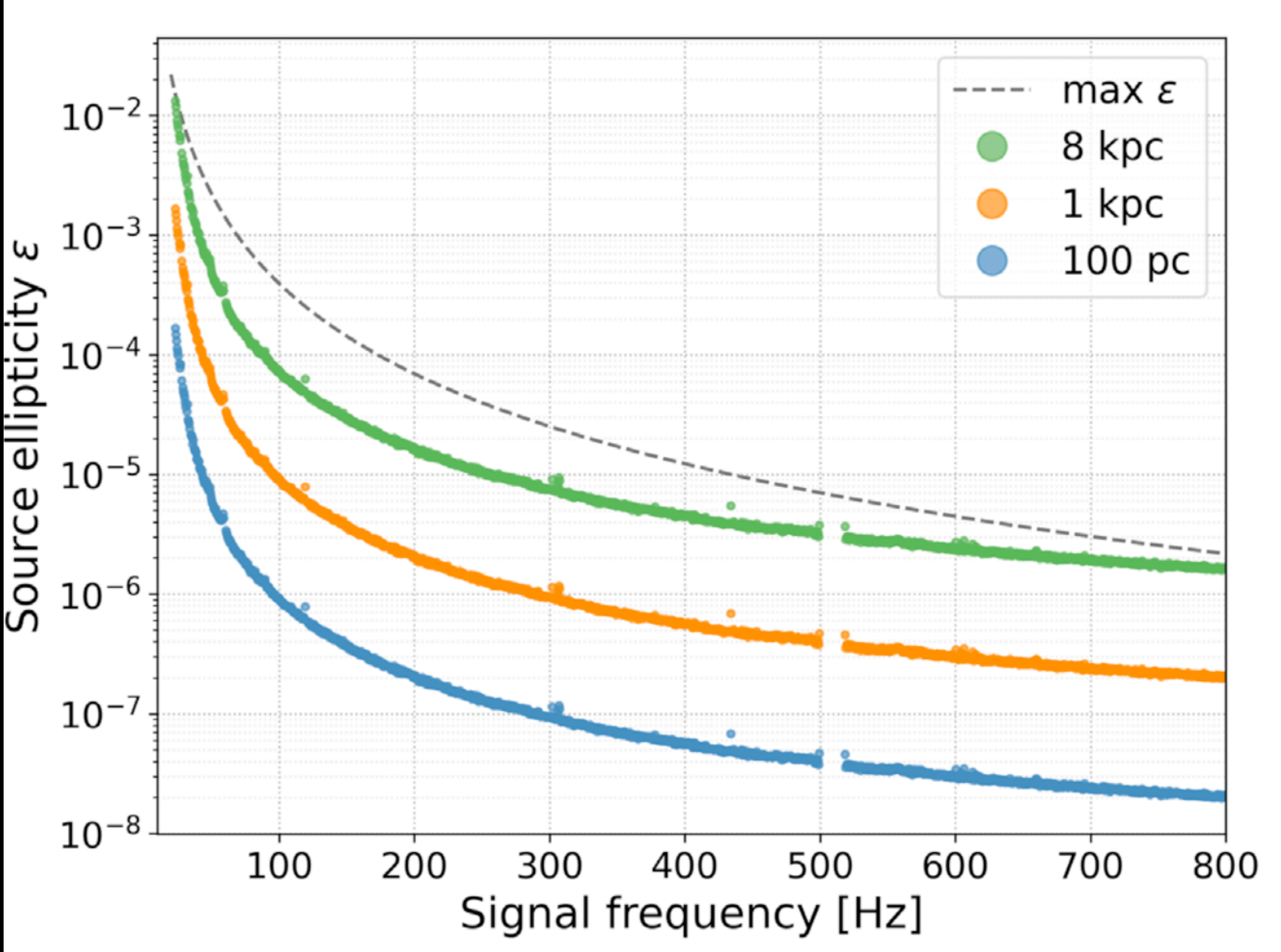
smallest detectable $h_0 \lesssim 10^{-25}$

ALL-SKY SURVEY OF CW EMISSION FROM ISOLATED STARS



9x10-26

ALL-SKY SURVEY OF CW EMISSION FROM ISOLATED STARS



ELLIPTICITY: WHAT DO WE EXPECT ?

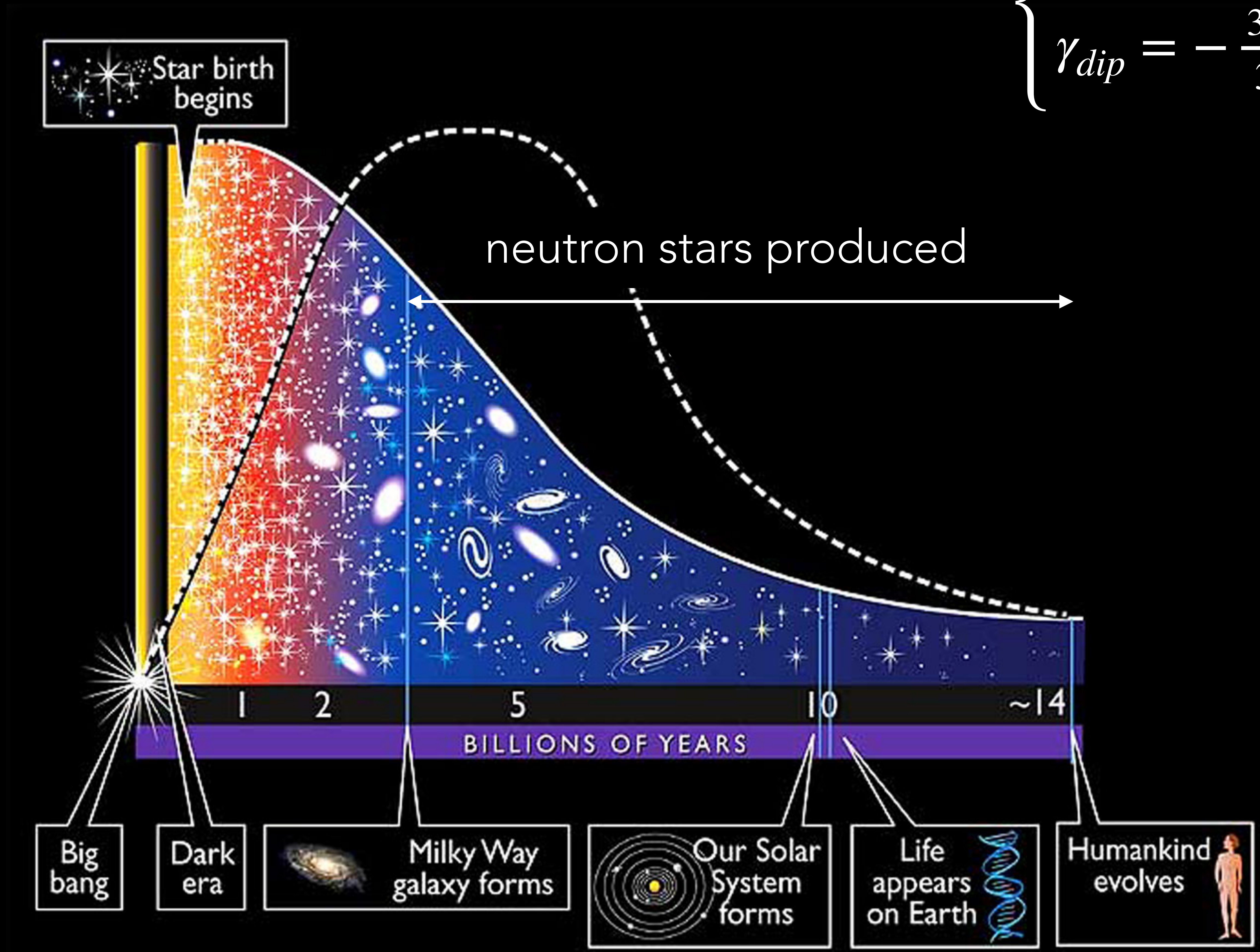
- what could source ellipticity ?
  - deformation frozen-in at birth
  - star-quakes
  - *internal* magnetic fields*
  - hot-spot (in accreting systems, very interesting)
- maximum ellipticity** $\approx (10^{-3}) 10^{-5} - 10^{-8}$
  - i.e. before crust breaks, very uncertain
- smallest ellipticity $\approx 10^{-14}$
  - magnetic fields, very low

* Mastrano et al, MNRAS 417 (2011) - **Johnson-McDaniel & Owen, PRD 88 (2013) - Gittins et al, PRD 101 (2020), Gittins & Andersson, MNRAS 507 (2021) - Morales & Horowitz, MNRAS 517 (2022)

WHAT ARE THE CHANCES OF DETECTION?

Synthetic isolated "normal" neutron star population, whose spin-frequency ν is evolved in time

$$\begin{cases} \dot{\nu} = \gamma_{dip}\nu^3 + \gamma_{GW}\nu^5 \\ \gamma_{dip} = -\dfrac{32\pi^3 R^6}{3Ic^3\mu_0}B^2, \quad \gamma_{GW} = -\dfrac{512\pi^4 GI}{5c^5}\varepsilon^2 \end{cases}$$



Pagliaro et al, ApJ 952 (2023)

NON-RECYCLED NEUTRON STARS: CHANCES OF DETECTION **NOW**

Model	expected # of detectable signals $\overline{n}$
$A2_{low}$	1.4 ± 1.16
$A2_{high}$	3.62 ± 1.91
$E2_{norm}$	0.01 ± 0.1
$E2_{unif}$	0.01 ± 0.1
A1	< 0.01
E1	< 0.01

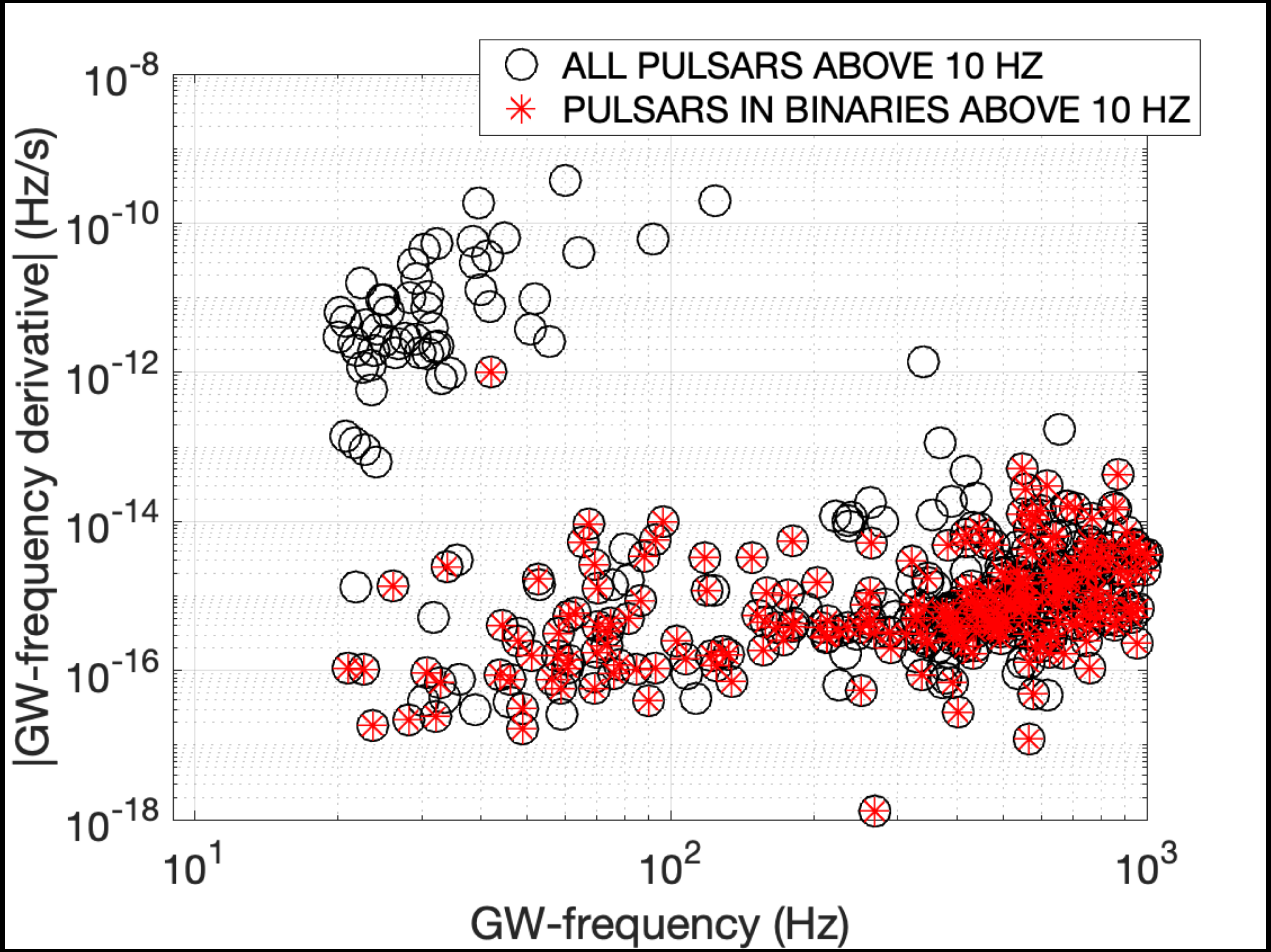
Pagliaro et al, ApJ 952 (2023), arxiv:2303.04714,``Continuous gravitational waves from Galactic neutron stars: demography, detectability and prospects"

WITH NEXT GENERATION DETECTORS

Model	expected # of detectable signals $\overline{n}$ ET	$\overline{n}$ CE
$A2_{low}$	231.9 ± 14.6	338.1 ± 16.8
$A2_{high}$	387.2 ± 19.4	524.3 ± 22.6
$E2_{norm}$	0.5 ± 0.6	2.0 ± 1.4
$E2_{unif}$	1.7 ± 1.3	5.2 ± 2.2

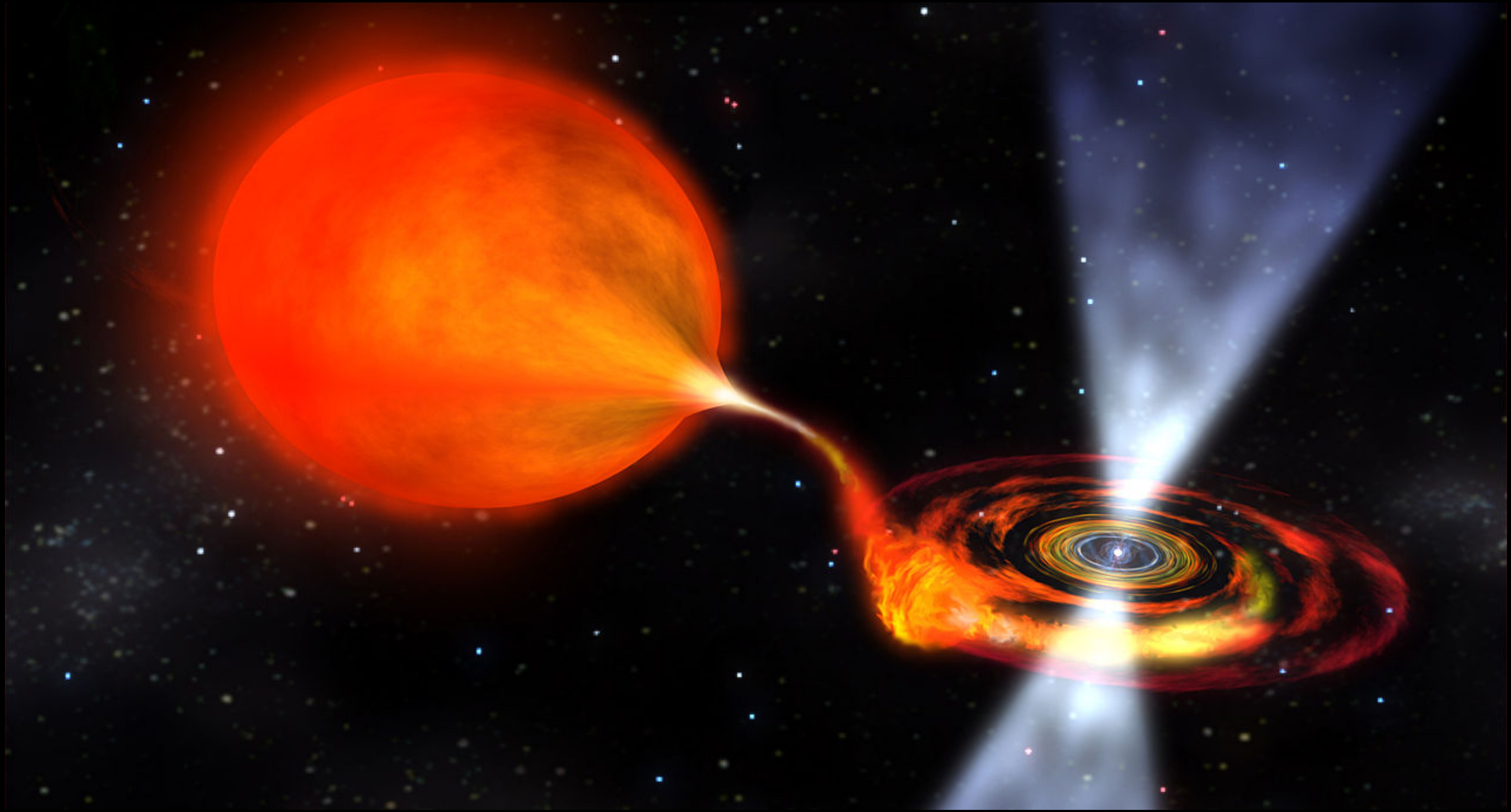
M. Punturo, in this session

BUT MOST PULSARS IN GW-BAND ARE IN BINARIES...

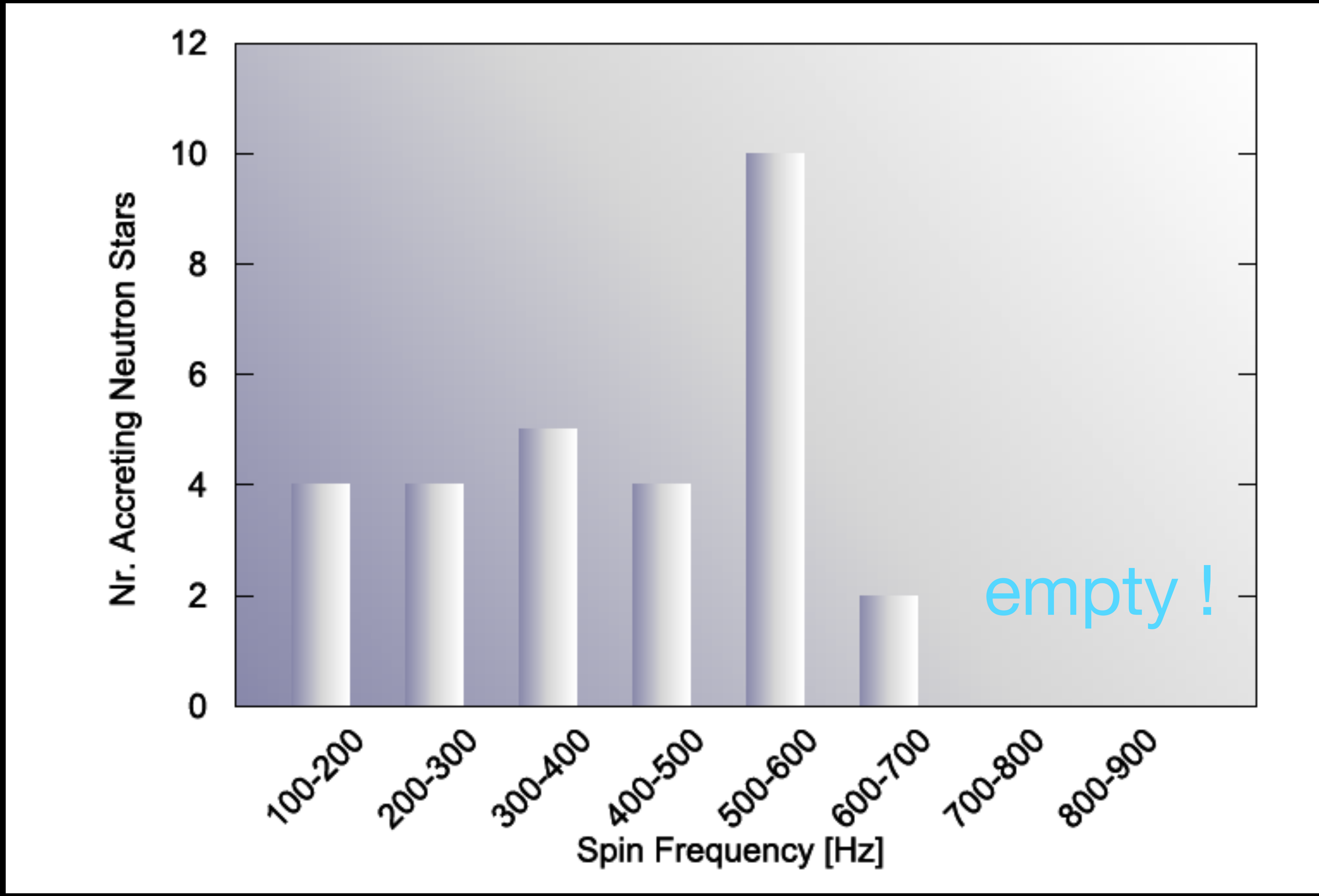


ACCRETING NEUTRON STARS

HIGHLIGHTING SCO X-1



SPINS OF ACCRETING NEUTRON STARS

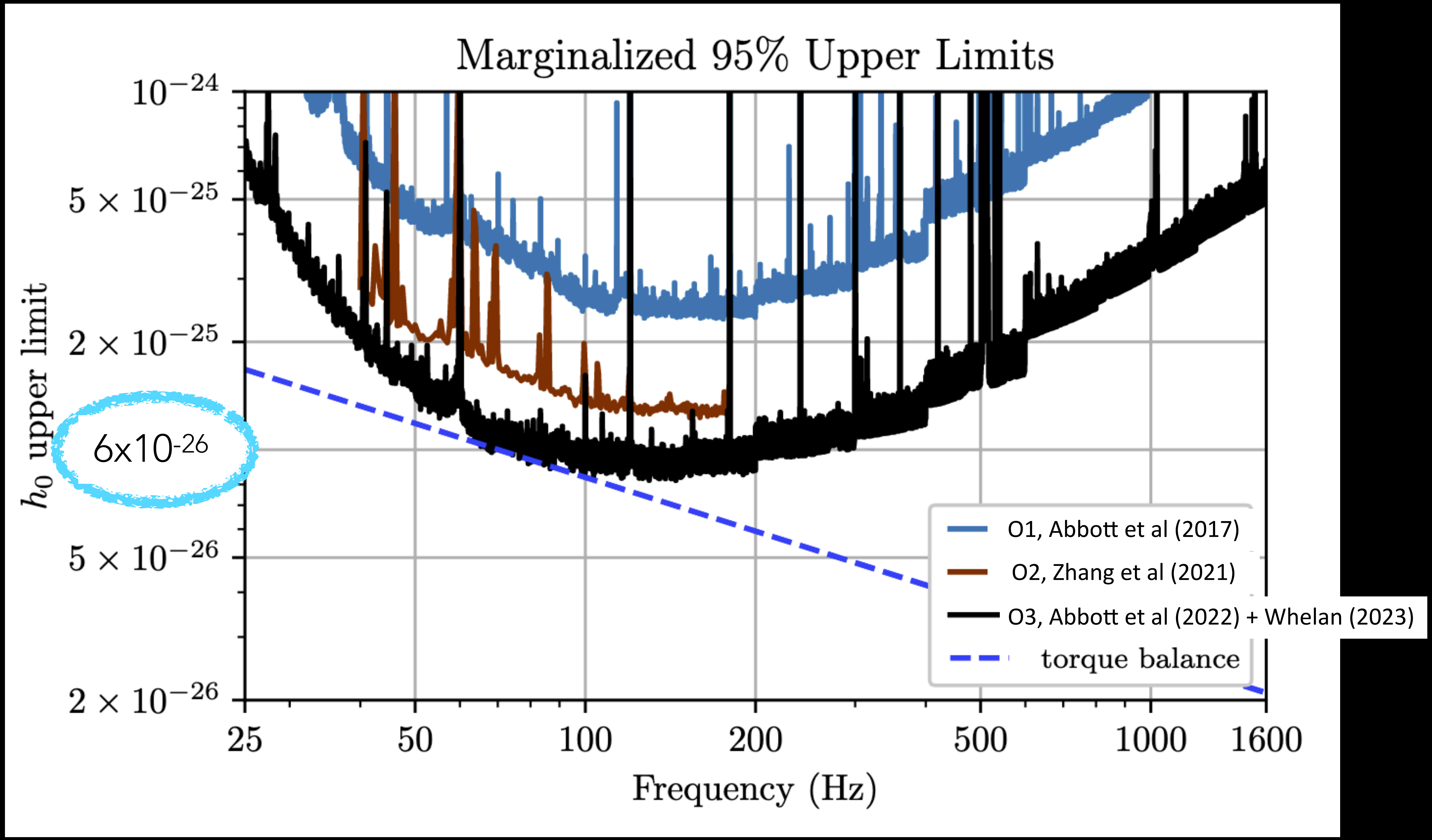


Patruno Haskell Andersson, ApJ 850 (2017)

IDEA: TORQUE BALANCE, GW EMISSION BALANCING ACCRETION TORQUE

SCORPIUS X-1
BRIGHTEST X-RAY SOURCE (AFTER SUN)

no detections but probing interesting plausible emission strengths



Abbott et al, *Astrophys.J.Lett.* 941 (2022) 2, L30, Whelan et al, *Astrophys.J.* 949 (2023) 2, 117

caveat: spin wandering (Mukherjee et al , PRD97 (2018)

…SUMMARISING

- hundreds of binary coalescences detected + 1 in the 3-5$M_\odot$ mass gap
- the next big thing:
    - the first detection of a continuous GW will open the field of GW-pulsar-astronomy
    - now probing interesting source parameter-range
    - broad surveys are hard
    - high-risk/high-gain enterprise, but remember the history of GWs…

LIGO – Not without Controversy!

Congressional Testimony to the House Committee on Science, March 1991

- "the sources we think we know are out there are too weak to be detected in gravity waves by LIGO."
- "LIGO is at best, a physics experiment, not an astronomical observatory."
- " ... astronomers can think of cheaper experiments that are much more likely to yield fundamental advances."
- "…even if all the estimated improvements over the LIGO prototype are achieved in LIGO, the resulting sensitivity of LIGO falls at least ten times short of being useful astronomically"

At the time, these criticisms were all very valid!

NEWS & COMMENT **Science Magazine 30 April 1993**

LIGO: A $250 Million Gamble

The potential prize would be great: the first glimpses of gravitational waves. But a messy dispute at Caltech has again raised the question of whether it's too long a shot

In February 1992, then National Science Foundation (NSF) director Walter Massey called in the press to announce that his agency had selected areas in Hanford, Washington, and Livingston, Louisiana, as the two sites for an ambitious physics facility: the Laser Interferometer Gravitational-Wave Observatory, otherwise known as LIGO. Later that summer, Congress dramatically stepped up LIGO's budget, approving $38 million in construction startup funds to scale up from a 40-meter prototype detector to two 4-kilometer behemoths—big enough, supporters claimed, to have a good chance of snaring the first direct evidence of the gravitational waves predicted by Einstein's theory of general relativity. LIGO seemed well on its way, and it was a proud time for its director Rochus Vogt, NSF, and the rest of the scientists that made up the joint MIT-Caltech project.

Odd man out. Ronald Drever (center) has been shut out of the project. Team members Kip Thorne (left) and Rochus Vogt.

The euphoria was short lived, however. For more than a year, LIGO has been under siege from inside and outside. In the latest chapter in a bitter internal battle that many say has paralyzed the endeavor, a committee of Caltech faculty members recently concluded that Vogt and LIGO's management had unfairly fired one of the project's chief scientists. The battle is more than a personality clash, for it revolves around the crucial issue of whether the current LIGO effort offers the best chance of success in what all admit is an incredibly difficult task—a question that is reverberating among researchers outside the LIGO community as well. Adding to the acrimony is LIGO's $250 million price tag, which some hold responsible for NSF's recent funding woes. Since 1991, a number of astronomers and physicists have attacked the decision to proceed with the scale up, expressing concerns about whether LIGO will be able to detect gravitational waves, let alone fulfill its promise of being an observatory.

Now, even as bulldozers prepare to move land at each site, the level of discord is rising. "I think LIGO could come back to greatly haunt the scientific community if we spend $250 million and see nothing," warns one astronomer who, like many of the officials and scientists interviewed for this article, requested anonymity. "There's been so much unhappiness out there about all this that I don't think we will be able to easily forget it," adds University of California, Los Angeles, space plasma physicist Charles Kenel, who chairs the National Research Council's (NRC) board on physics and astronomy.

To LIGO's supporters, however, much of the latest criticism smacks of sour grapes. They argue that th[illegible] technical con[illegible] being raised a[illegible] nothing new an[illegible] have all been tho[illegible]hly investigated. T[illegible] project is risky, they [illegible]cede, but the return [illegible] enormous. By u[illegible] lasers to measure, for the [illegible] quisitely small ripples in space that passing gravitational waves from astronomical sources produce, researchers believe they can greatly improve their understanding of general relativity. More stirring is the hope that a series of gravitational wave detectors around the world will usher in a new day in astronomy, providing a novel way of watching supernovae, colliding neutron stars, and perhaps offering definitive proof for the existence of black holes. Says Kip Thorne, Caltech theoretical physicist and member of the LIGO team: "The payoff, when it comes, is so exciting that it's worth the risk."

> "The payoff, when it comes, is so exciting that it's worth the risk."
> –Kip Thorne

A pink slip from LIGO

Part of the debate over LIGO has been played out in the pages of technical journals and the general media. But one key aspect has remained hidden from public view: the ongoing troubles between Caltech experimental physicist Ronald Drever and the rest of the LIGO team, specifically director Vogt. For the past 2 years or so, Drever has been, in the words of one Caltech faculty member, "frozen out of LIGO" in a messy feud that peaked last year on 6 July, when Drever was fired from the project apparently without explanation. "He was thrown off the project, forced to turn in his keys, kicked out of the lab, and told he was persona non grata," says one Caltech faculty member familiar with the events. (*Newsday* also reported some of these events earlier this week.) Within hours of the dismissal, Vogt sent out an e-mail letter to the LIGO community saying that Drever was no longer associated with the project, would be allowed to remove his personal possessions from the LIGO offices only under staff supervision, and had been instructed not to enter LIGO premises or disturb project scientists. (Vogt was traveling last week, but he declined through a spokesman to discuss [illegible] rift with Drever; Drever also [illegible]clined to speak with [illegible]. Colleagues of Vog[illegible] Drever provided [illegible]ounts of the disput[illegible]

D[illegible]er is not som[illegible]dy to be taken [illegible]tly: Brilliant is the description most often given of him, and he is viewed by almost [illegible] as one of the key physicists whose research in the 1980s transformed LIGO from a dream into a realistic undertaking. Caltech imported Drever from the University of Glasgow in Scotland specifically to work on the detection of gravitational waves, and when NSF merged the parallel efforts at MIT and Caltech into a single project in 1984, Drever's design was chosen over another proposal from MIT physicist Rainer Weiss. Furthermore, from

"The only guarantee for failure is to stop trying."

–JOHN C. MAXWELL