Continuous gravitational waves II

Detection methods

M. Alessandra Papa - New Horizons for Psi School - Lisbon 1-5 July 2024
Max Planck Institute for Gravitational Physics and Leibniz Univ. Hannover

Plan

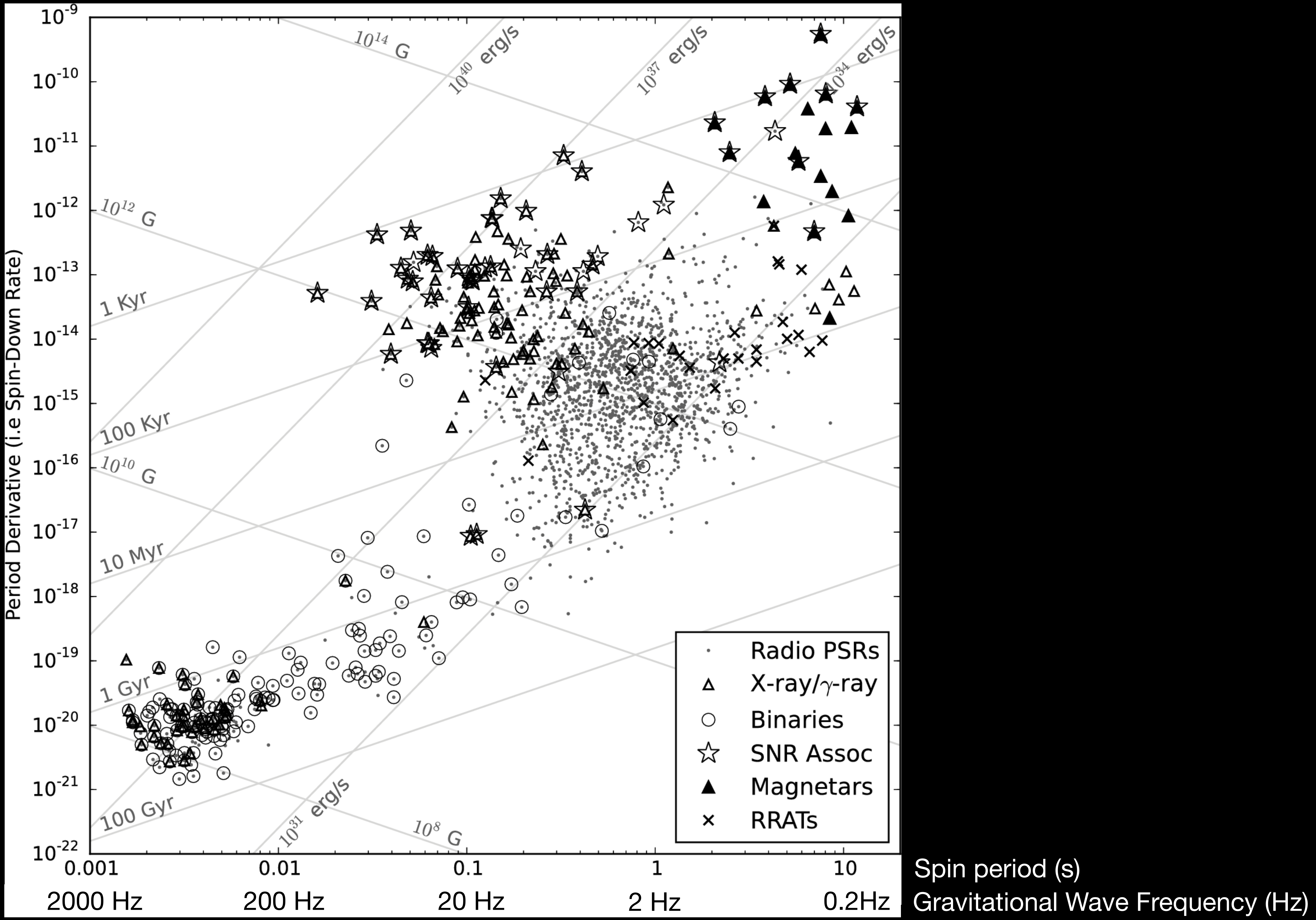
- Lecture I
  - Continuous Gravitational Waves, generalities and motivation
  - Detection methods

- Lecture II, actual searches
  - Known pulsars, all known
  - Only sky position known → supernova remnants / accreting LMXBs
  - Nothing known (blind surveys)
  - Could these searches detect something else ?

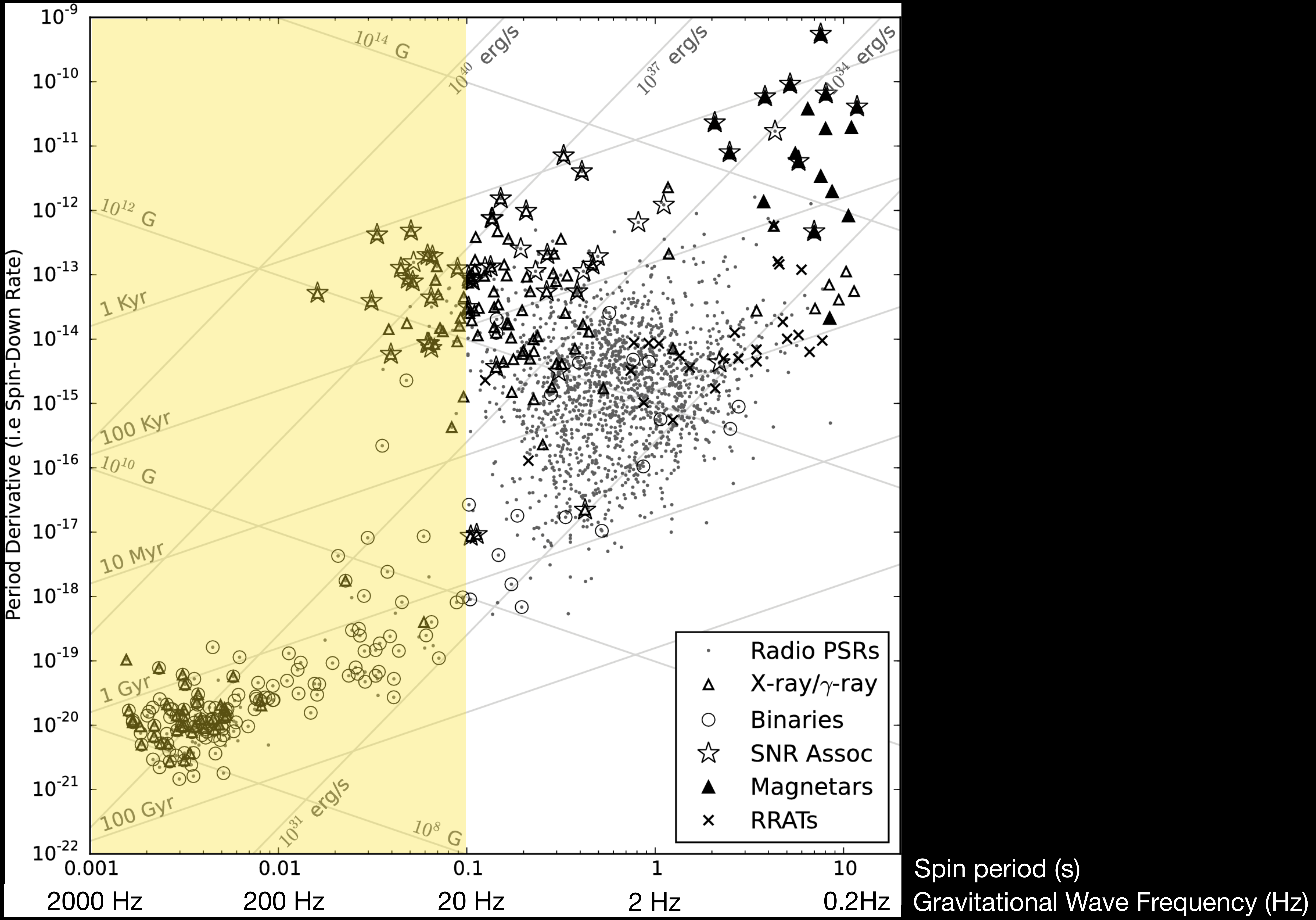
TAKE AWAY an idea of what is feasible

- Order of magnitude detectable strain
- It depends on how many waveforms are searched
- Typical waveform parameter ranges
- Idea of computing cost

KNOWN PULSARS



KNOWN PULSARS GROUND GW DETECTORS' BAND



SEARCHES FOR EMISSION FROM KNOWN PULSARS

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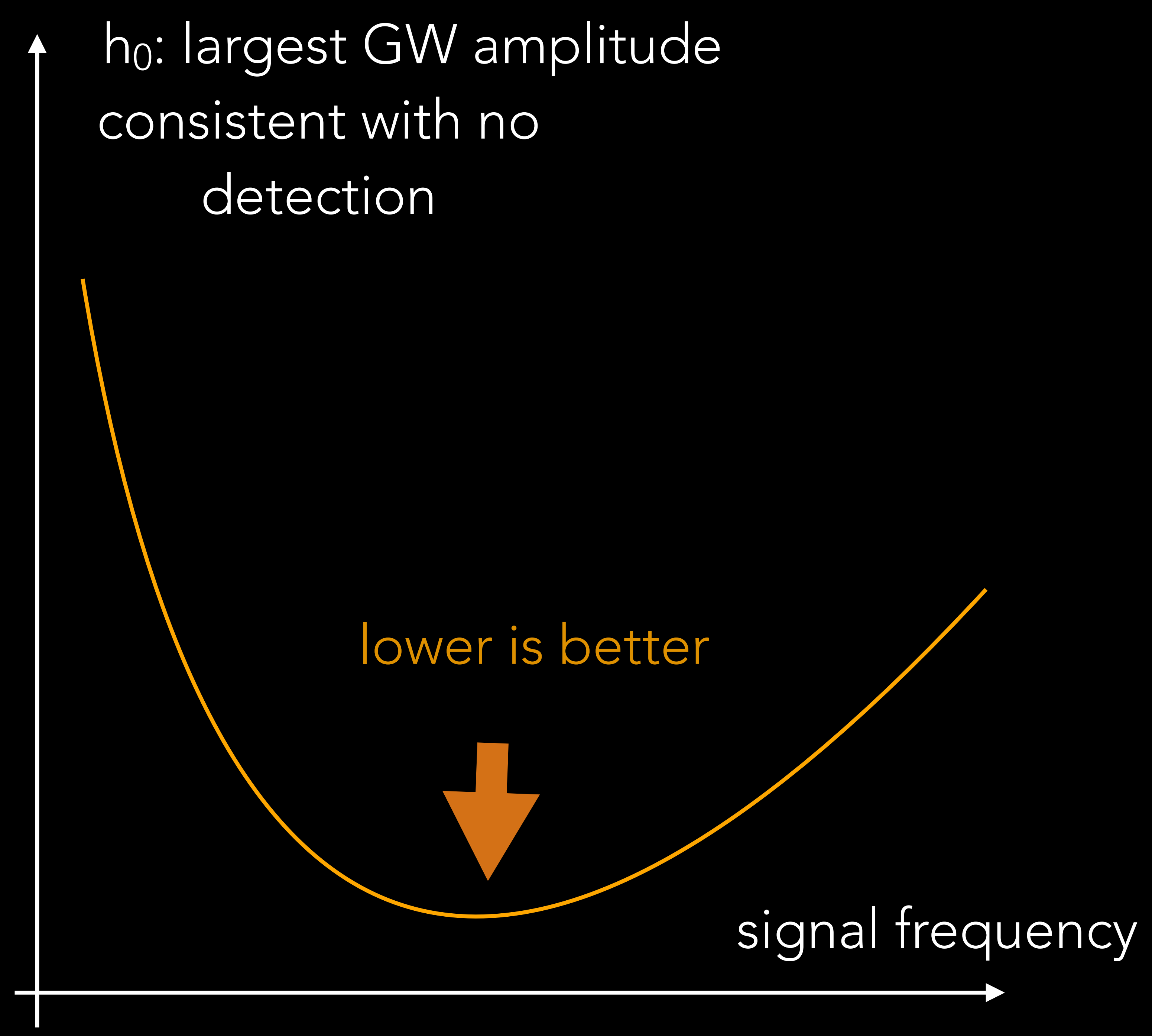


SEARCHES FOR EMISSION FROM KNOWN PULSARS

- routinely done
- no detections
- important benchmark: spin-down upper limit

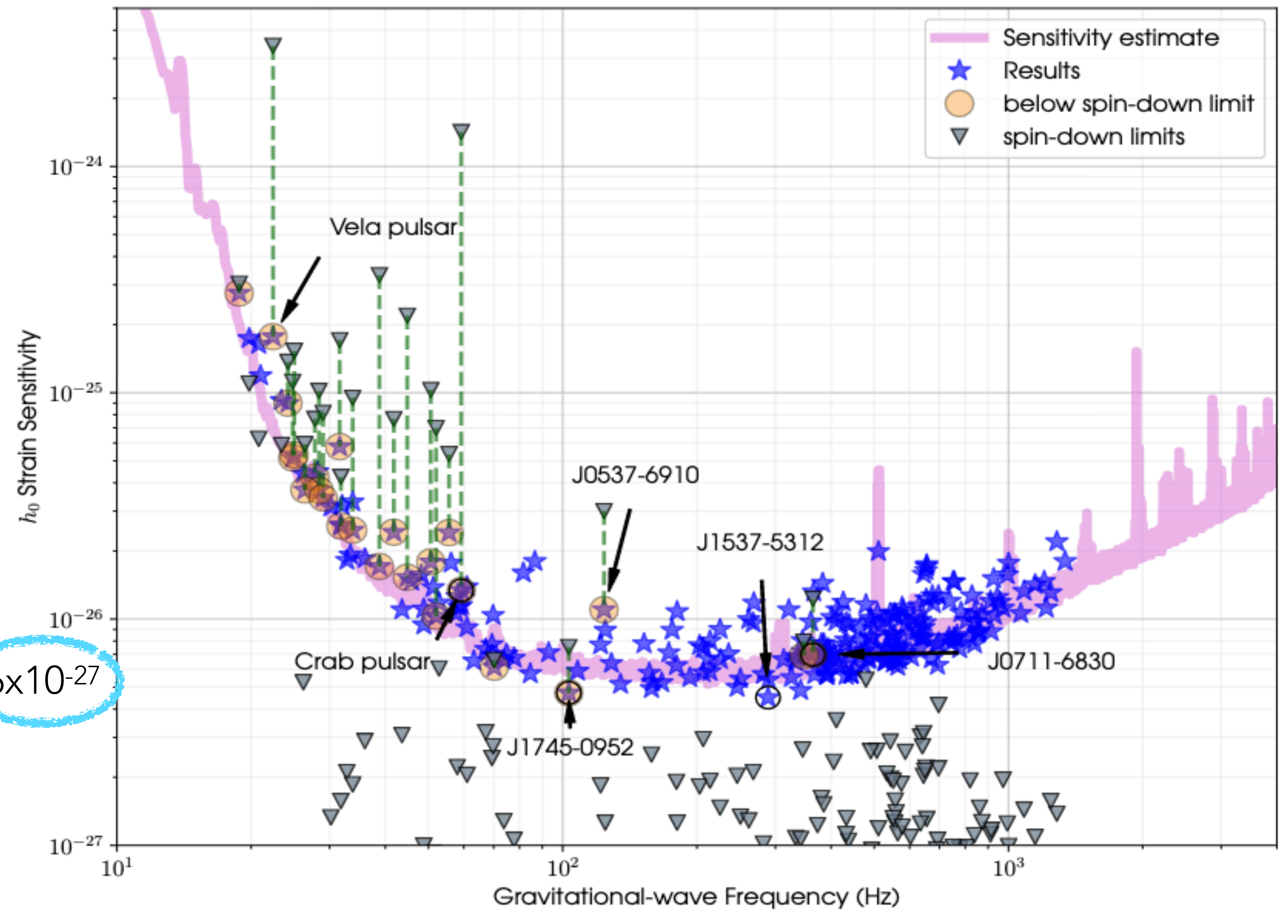
SPIN-DOWN UPPER LIMIT

- all rotational energy lost (which we know) is radiated away by (continuous) GWs, then

$$h_0^{spdwn} = \frac{1}{D}\sqrt{\frac{5GI}{2c^3}\frac{|\dot{f}_{GW}|}{f_{GW}}}$$

GW amplitude at distance D from star

CONTINUOUS GWS FROM KNOWN PULSARS



6×10^{-27}

Abbott et al, ApJ 953,1 (2022)

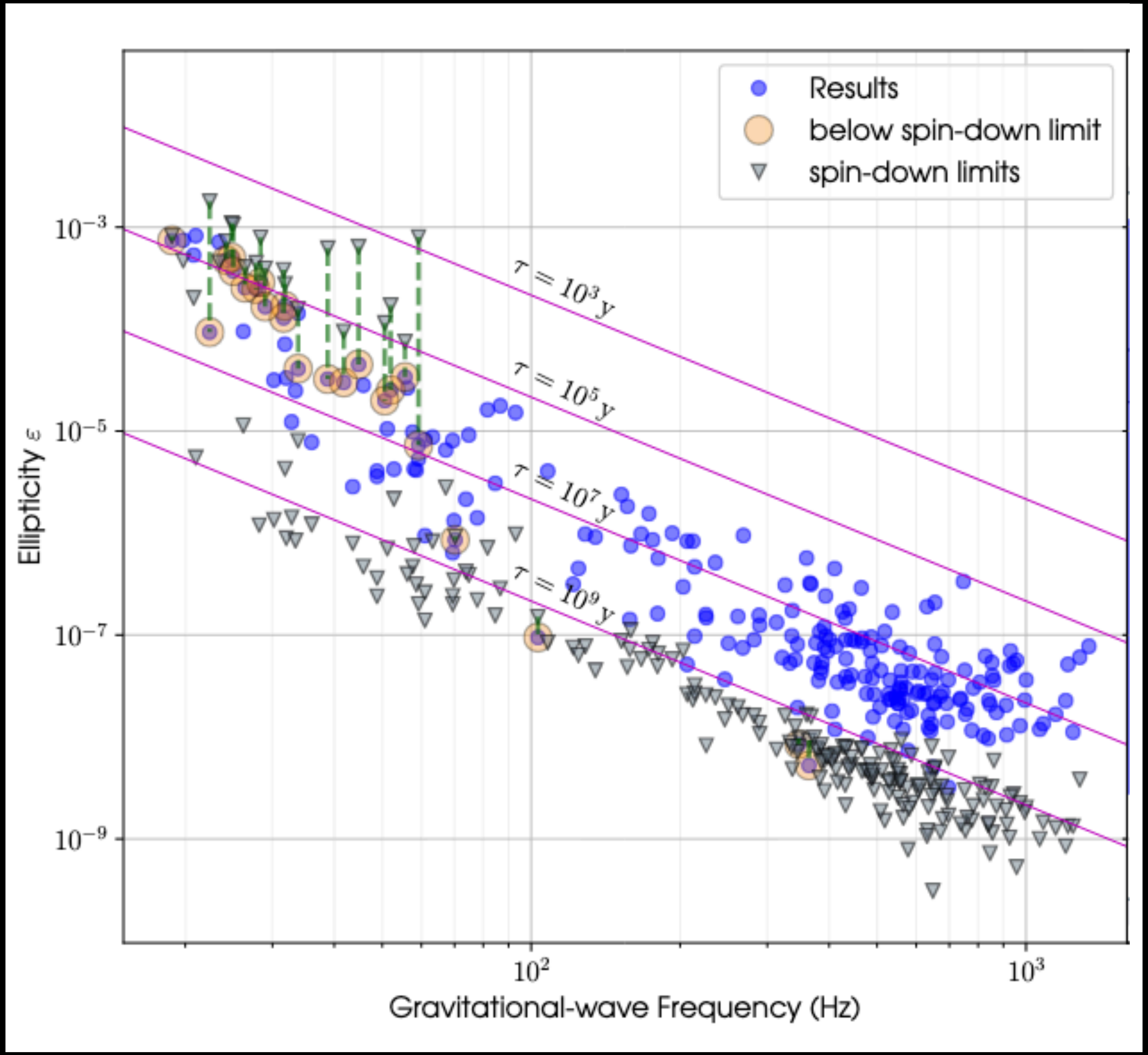
RECALL :

GW AMPLITUDE ⟷ ELLIPTICITY

$$h_0 = \frac{2\pi^2 G}{c^4} \frac{I \varepsilon f_{gw}^2}{D} =$$

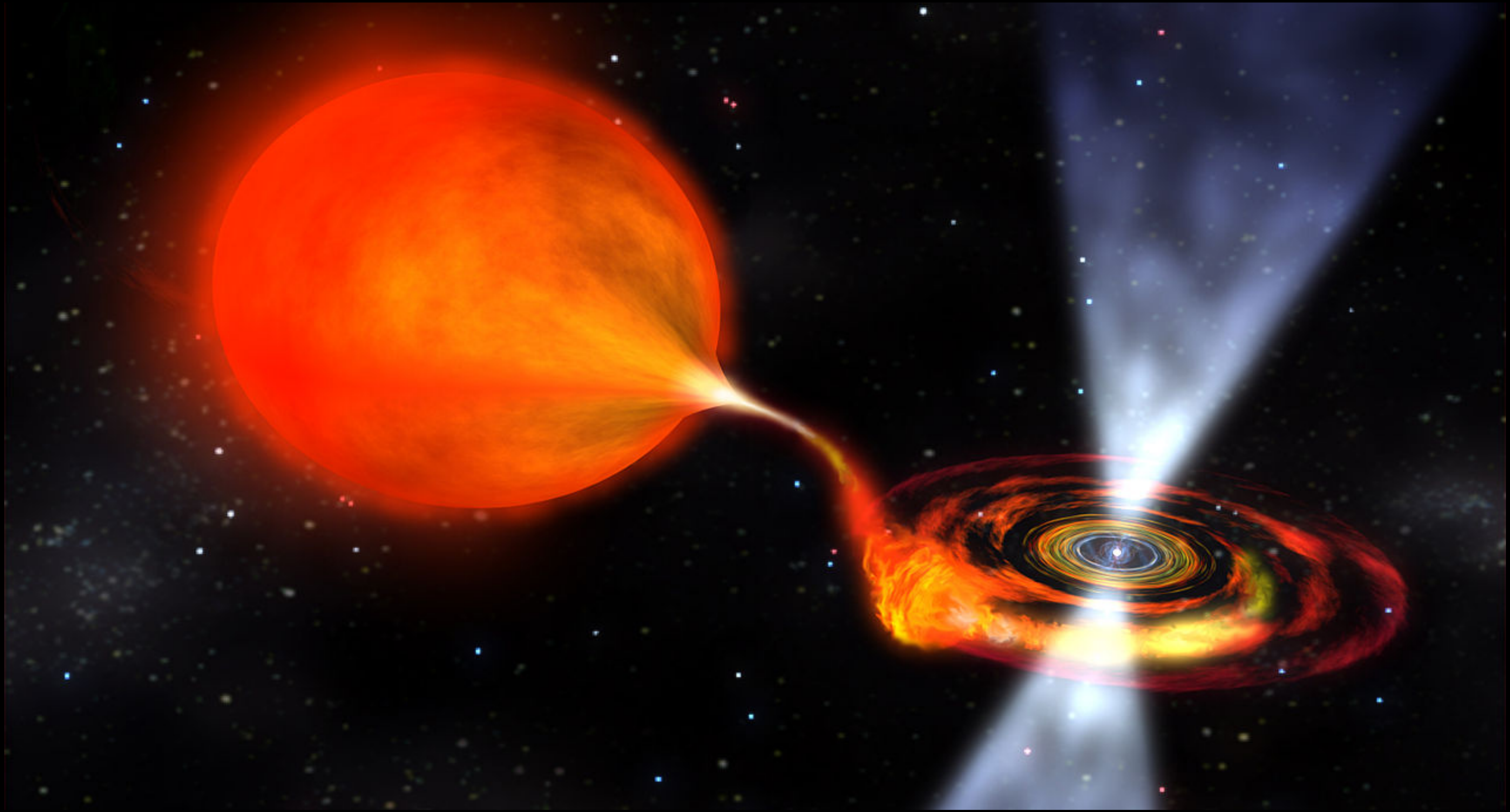
$$= 2 \times 10^{-25} \left[\frac{I}{10^{38}\ \mathrm{kg\ m^2}}\right] \left[\frac{\varepsilon}{10^{-6}}\right] \left[\frac{f_{gw}}{10^3\ \mathrm{Hz}}\right]^2 \left[\frac{1\ \mathrm{kpc}}{D}\right]$$

KNOWN PULSARS: CONSTRAINING THE ELLIPTICITY

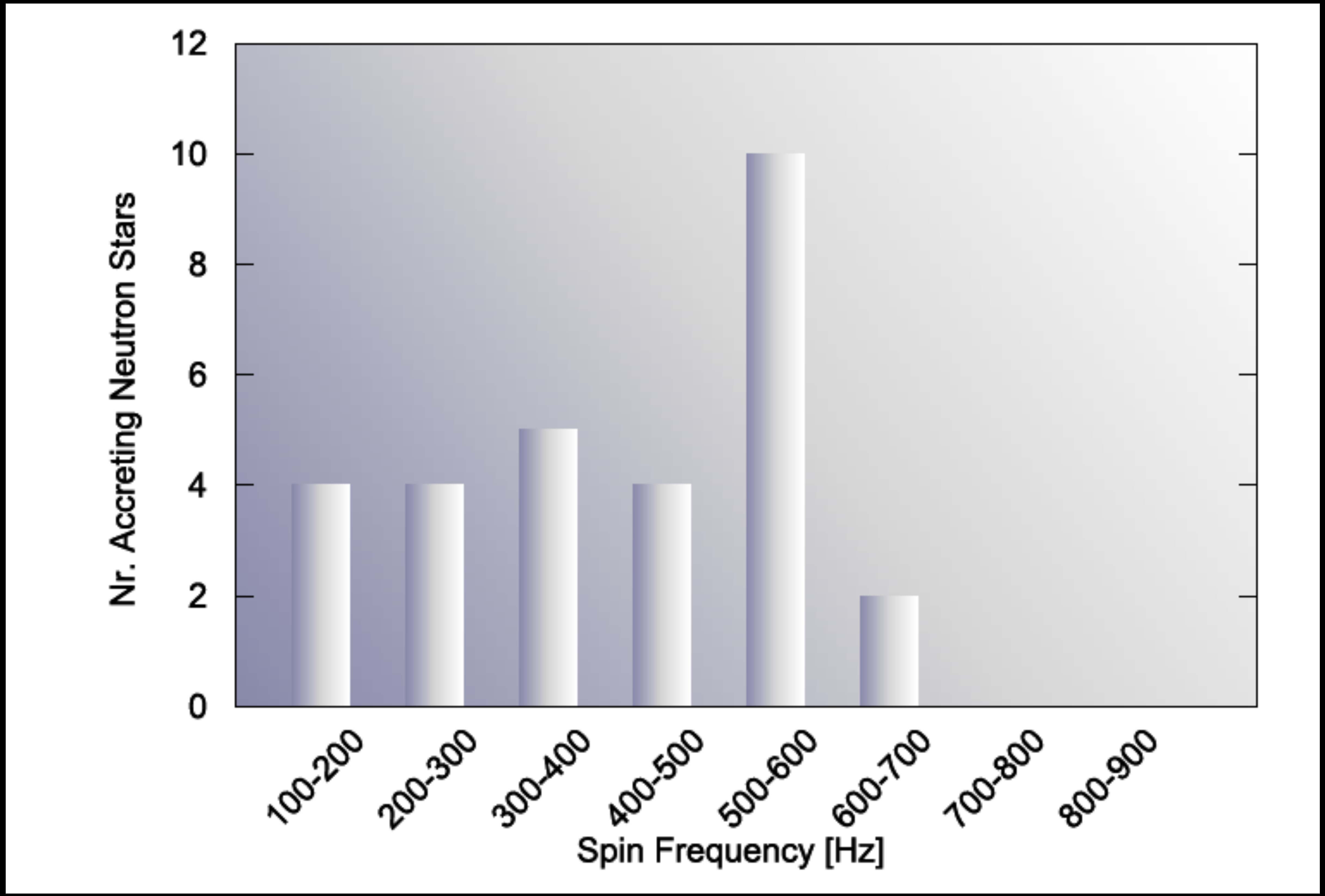


- most constraining: $\varepsilon < 5 \times 10^{-9}$ J0711-6830,100 pc away, ≈ 364 Hz, x1.8 below h_0^{spdwn}
- above 300 Hz, $\lesssim 10^{-6}$
- below 60 Hz spindown limit is beaten (x100 for Crab, x20 for Vela), but corresponding ellipticities are higher

ACCRETING NEUTRON STARS



SPINS OF ACCRETING NEUTRON STARS



Patruno Haskell Andersson, ApJ 850 (2017)

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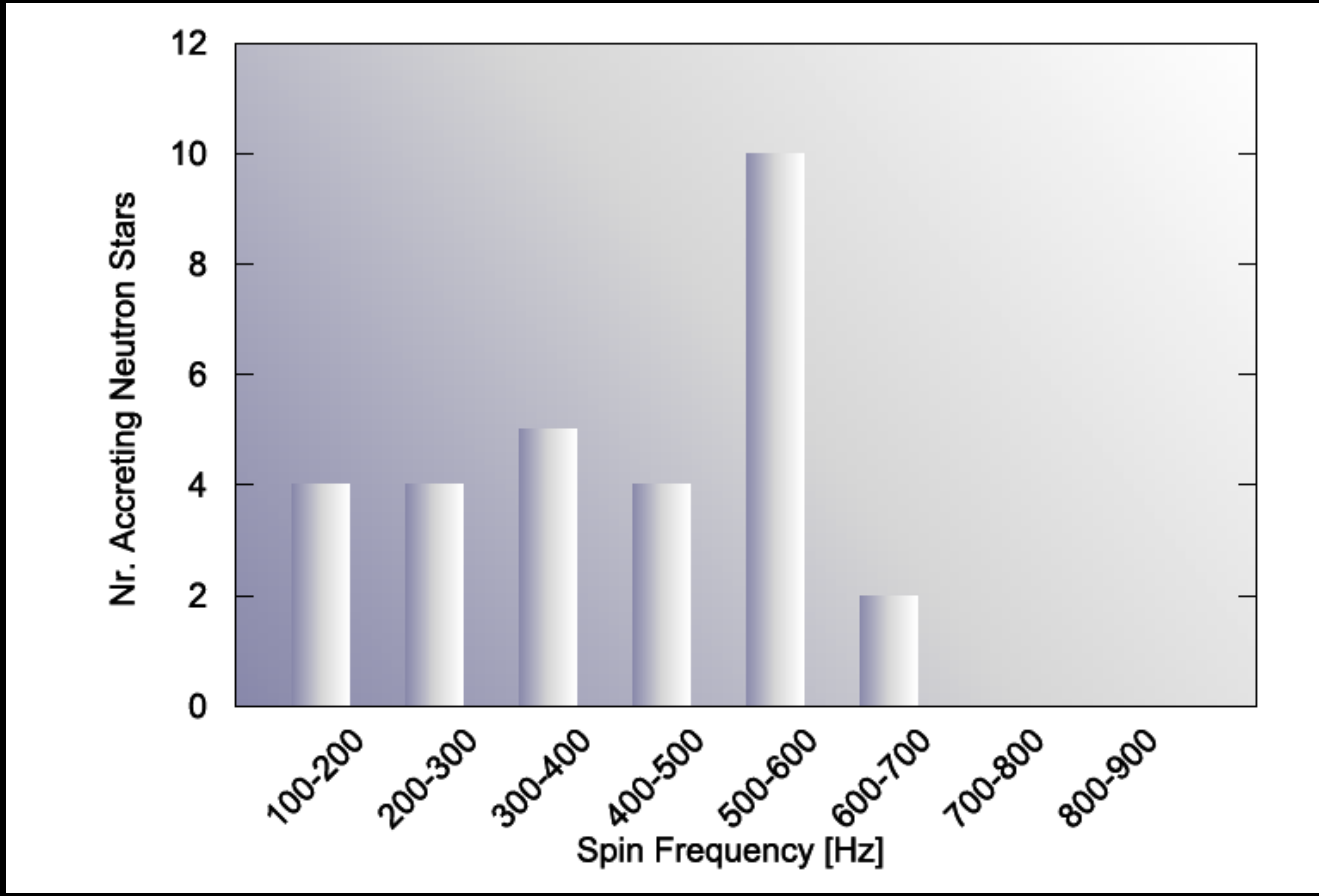
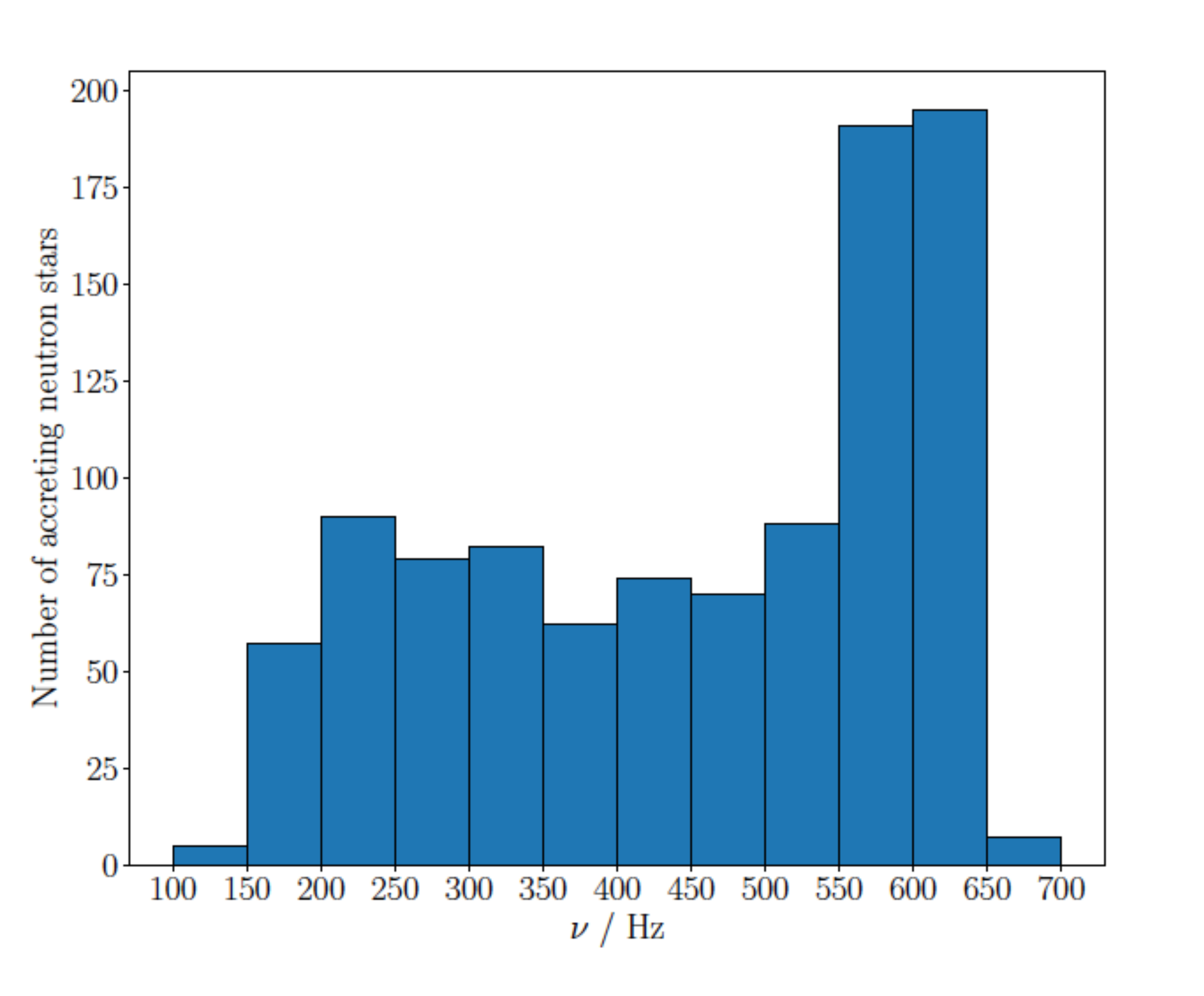


Patruno Haskell Andersson, ApJ 850 (2017)

IDEA: TORQUE BALANCE, GW EMISSION BALANCING ACCRETION TORQUE

A GOOD IDEA



F. Gittins, N. Andersson, *Mon.Not.Roy.Astron.Soc.* 488 (2019)

TORQUE BALANCE

$$h_0^{torq.bal.} \propto M^{-\frac{1}{4}} \, r_m^{\frac{1}{4}} \, F_X^{\frac{1}{2}} \, R^{\frac{1}{2}} \, f_{GW}^{-\frac{1}{2}}$$

NS mass

torque arm

GW frequency

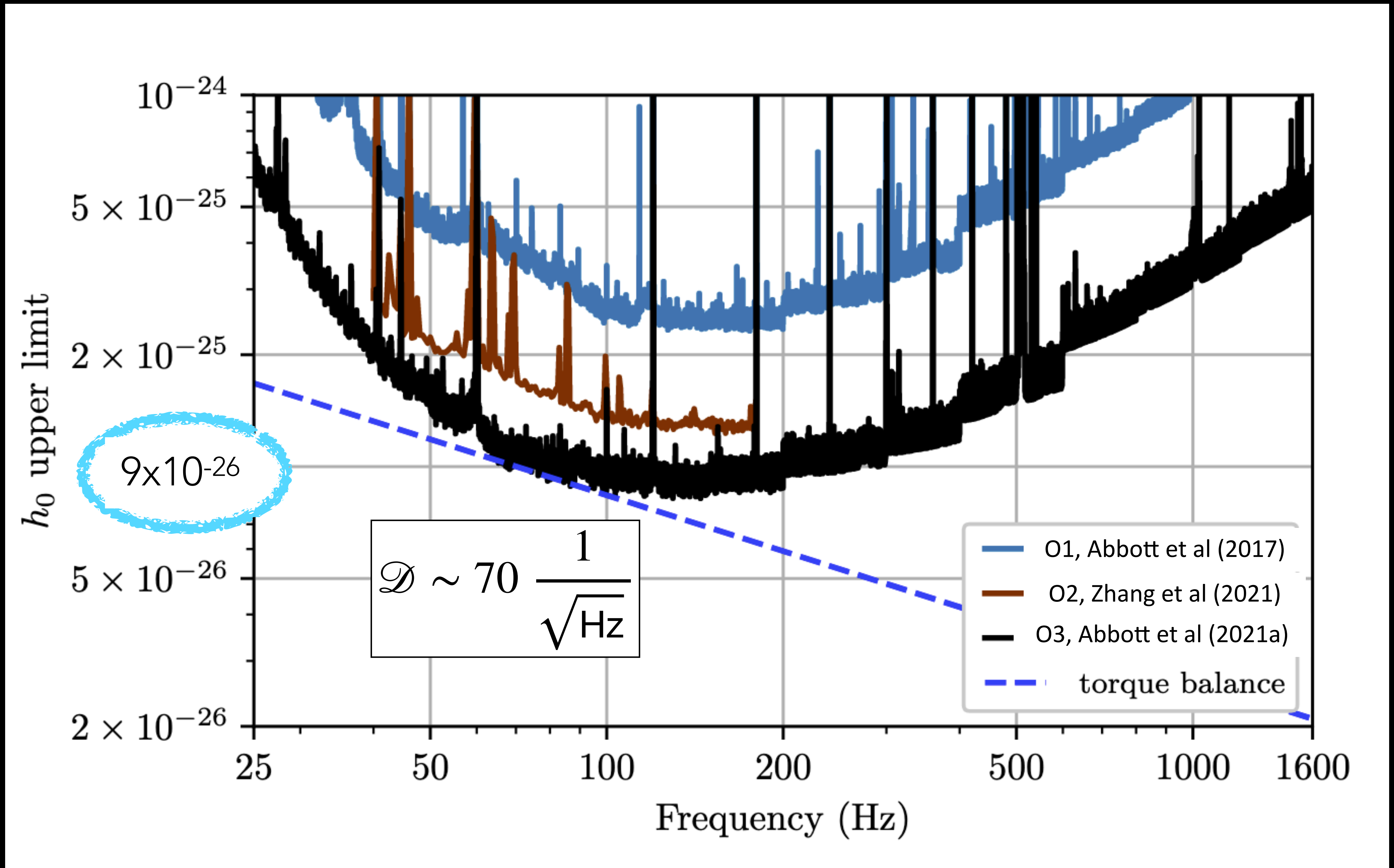
NS radius

observed X-ray flux

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

no detections

requires large computer cluster for weeks



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)

Sco X-1 searches

$\approx 10^{10} - 10^{12}$ templates

"Blueprint" to search for emission from :

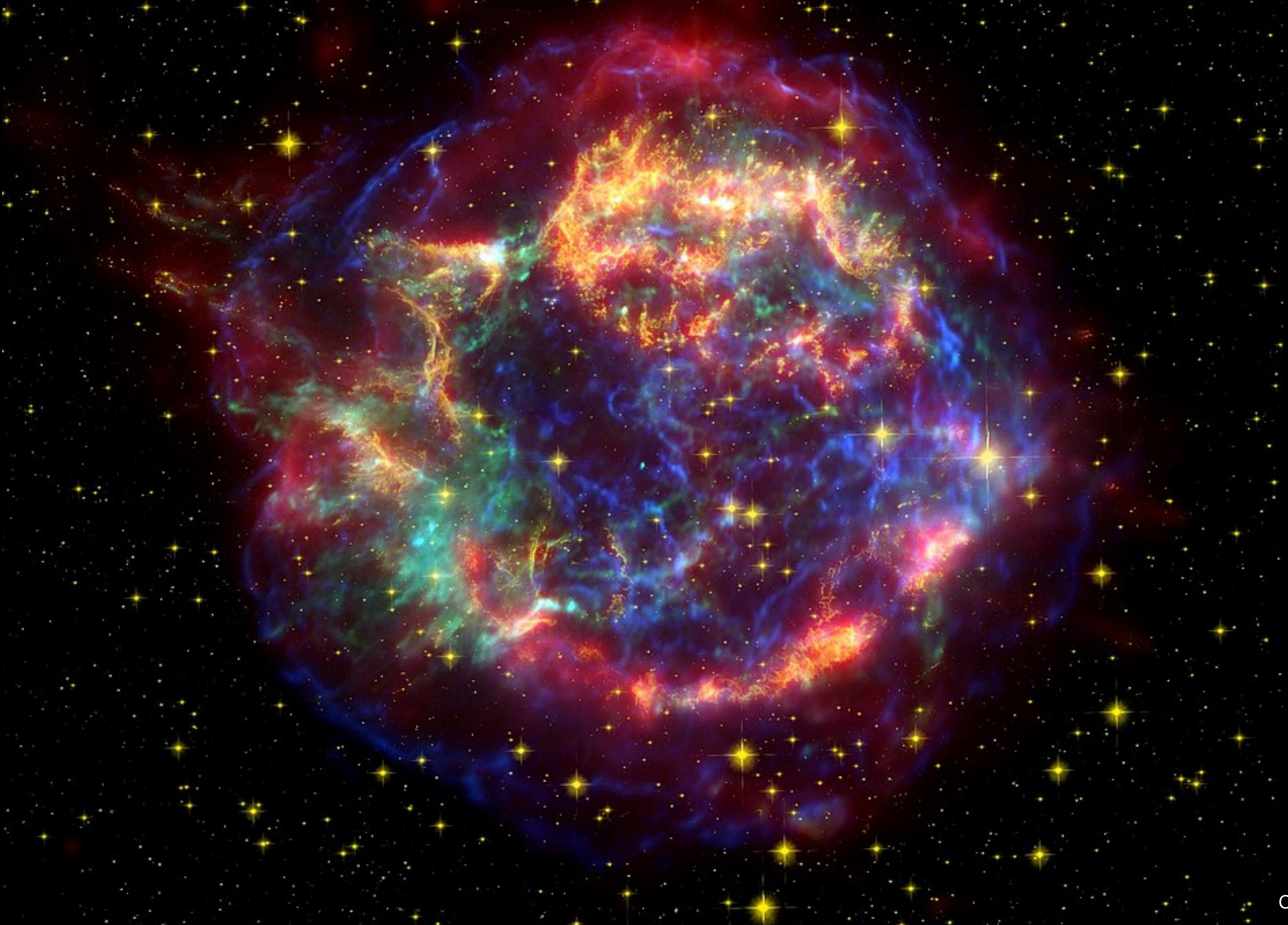
Object in a binary system with *some* constraint on orbital parameters

Sky position known

f_{GW} not known

$\dot{f}_{GW}$ assumed $= 0$

SUPERNOVA REMNANTS



Courtesy NASA/JPL-Caltech

SUPERNOVA REMNANTS MAY HOST YOUNG NEUTRON STARS

Pulsar spin decreases, so the younger the object, the higher is the spindown, i.e. the kinetic energy loss, a fraction of which, might go in GWs

$$\dot{f}_{spin} \propto f_{spin}^{n}$$

n: braking index

↓

characteristic age

$$\tau_c := \frac{1}{n-1}\frac{f_{spin}}{\dot{f}_{spin}}$$

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$$h_0^{\text{spindown}} \geq \sqrt{\frac{5GI}{2c^3}\frac{1}{\tau_c}}$$

EMISSION FROM NEUTRON STARS IN YOUNG SUPERNOVA REMNANTS: NO PULSATIONS OBSERVED

so have to search over frequency, frequency derivatives:

EMISSION FROM NEUTRON STARS IN YOUNG SUPERNOVA REMNANTS: NO PULSATIONS OBSERVED

so have to search over frequency, frequency derivatives:

Assume frequency. Characteristic age

$$\tau_c := \frac{1}{n-1}\frac{f}{\dot{f}} \quad \Rightarrow \quad -\frac{f_{GW}}{\tau} \le \dot{f}_{GW} \le 0$$

when n=2 this is the smallest.

EMISSION FROM NEUTRON STARS IN YOUNG SUPERNOVA REMNANTS: PARAMETER SPACE

Assume frequency. Characteristic age

$$\tau_c := \frac{1}{n-1}\frac{f}{\dot{f}} \quad \Longrightarrow \quad -\frac{f_{GW}}{\tau} \leq \dot{f}_{GW} \leq 0$$

braking index $n = \frac{f\ddot{f}}{\dot{f}^2}$

$$\Longrightarrow \quad 0\ \mathrm{Hz}/s^2 \leq \ddot{f}_{GW} \leq 7\frac{|\dot{f}_{GW}|^2_{max}}{f_{GW}}$$

when n=7 this is the largest.

EMISSION FROM NEUTRON STARS IN YOUNG SUPERNOVA REMNANTS: PARAMETER SPACE

Assume frequency. Characteristic age

$$\tau_c := \frac{1}{n-1}\frac{f}{\dot{f}} \quad \Longrightarrow \quad -\frac{f_{GW}}{\tau} \leq \dot{f}_{GW} \leq 0$$

$$|\dot{f}_{GW}|_{max} = 10^{-7}\ \text{Hz/s} \left(\frac{f}{1\text{kHz}}\right)\left(\frac{300\text{yrs}}{\tau}\right)$$

braking index $n = \frac{f\ddot{f}}{\dot{f}^2}$

$$\Longrightarrow \quad 0\ \text{Hz}/s^2 \leq \ddot{f}_{GW} \leq 7\frac{|\dot{f}_{GW}|^2_{max}}{f_{GW}}$$

$$|\ddot{f}_{GW}|_{max} = 10^{-17}\ \text{Hz/s}^2 \left(\frac{f}{1\text{kHz}}\right)\left(\frac{300\text{yrs}}{\tau}\right)^2$$

EMISSION FROM NEUTRON STARS IN YOUNG SUPERNOVA REMNANTS: PARAMETER SPACE → **IT'S BIG**

$$f_{GW}|_{max} \sim 1 \text{ kHz}$$

$$|\dot{f}_{GW}|_{max} = 10^{-7} \text{ Hz/s} \left(\frac{f_{GW}}{1\text{kHz}}\right)\left(\frac{300\text{yrs}}{\tau}\right)$$

$$|\ddot{f}_{GW}|_{max} = 10^{-17} \text{ Hz/s}^2 \left(\frac{f_{GW}}{1\text{kHz}}\right)\left(\frac{300\text{yrs}}{\tau}\right)^2$$

$$\delta f_{GW} \sim 3 \times 10^{-8} \text{ Hz} \left(\frac{1 \text{ yr}}{\text{T}_{coh}}\right)$$

$$\delta \dot{f}_{GW} \sim 10^{-15} \text{ Hz/s} \left(\frac{1 \text{ year}}{\text{T}_{coh}}\right)^2$$

$$\delta \ddot{f}_{GW} \sim 3.7 \times 10^{-23} \text{ Hz/s}^2 \left(\frac{1 \text{ year}}{\text{T}_{coh}}\right)^3$$

DECISIONS...

SNR (G name)	Other name	RA+dec (J2000)	D (kpc)	τ (kyr)
1.9+0.3	—	174846.9−271016	8.5	0.1
15.9+0.2	—	181852.1−150214	8.5	0.54
18.9−1.1	—	182913.1−125113	2	4.4
39.2−0.3	3C 396	190404.7+052712	6.2	3
65.7+1.2	DA 495	195217.0+292553	1.5	20
93.3+6.9	DA 530	205214.0+551722	1.7	5
111.7−2.1	Cas A	232327.9+584842	3.3	0.3
189.1+3.0	IC 443	061705.3+222127	1.5	3
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266.2−1.2	Vela Jr.	085201.4−461753	0.2	0.69
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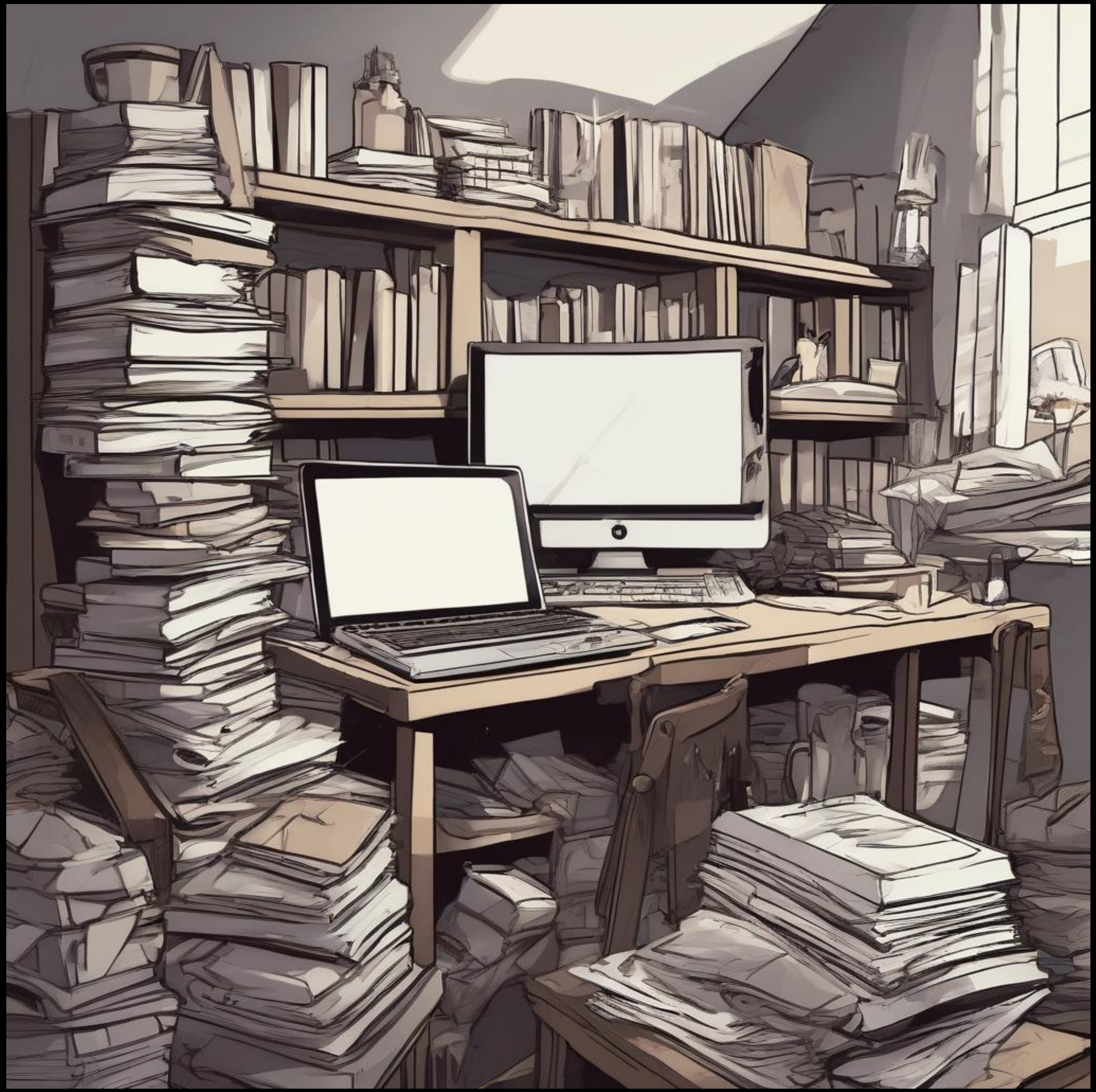
291.0−0.1	MSH 11−62	111148.6−603926	3.5	1.2
330.2+1.0	—	160103.1−513354	5	1
347.3−0.5	—	171328.3−394953	0.9	1.6
350.1−0.3	—	172054.5−372652	4.5	0.6
353.6−0.7	—	173203.3−344518	3.2	27
354.4+0.0	—	173127.5−333412	5	0.1
354.4+0.0	—	173127.5−333412	8	0.5

- Which objects to target ?
  - Youngest ?
  - Closest ?
- What signal frequency range ?
- What spindown spindown range ?

- what search ?
  - What frequency and frequency-derivative grid spacings ?
  - What search set-up (Tcoh) ?

- Ming et al, Optimally setting up directed searches […], Phys Rev 97 (2018) , Phys Rev D 93 (2016)

THE BACKPACK-PROBLEM



THE CONTINUOUS WAVES BACKPACK-PROBLEM

- Assume distribution of signal parameters (most difficult part)
- Pick among different targets, different search set-ups and different ranges of searched signal frequency
  - Computing cost
  - Detection probability
- Maximize detection probability at fixed computing budget

- J.Ming et al, Phys. Rev. D 97, 024051 (2018)
- J.Ming et al, Phys. Rev. D 93, 064011 (2016)

SUPERNOVA REMNANTS

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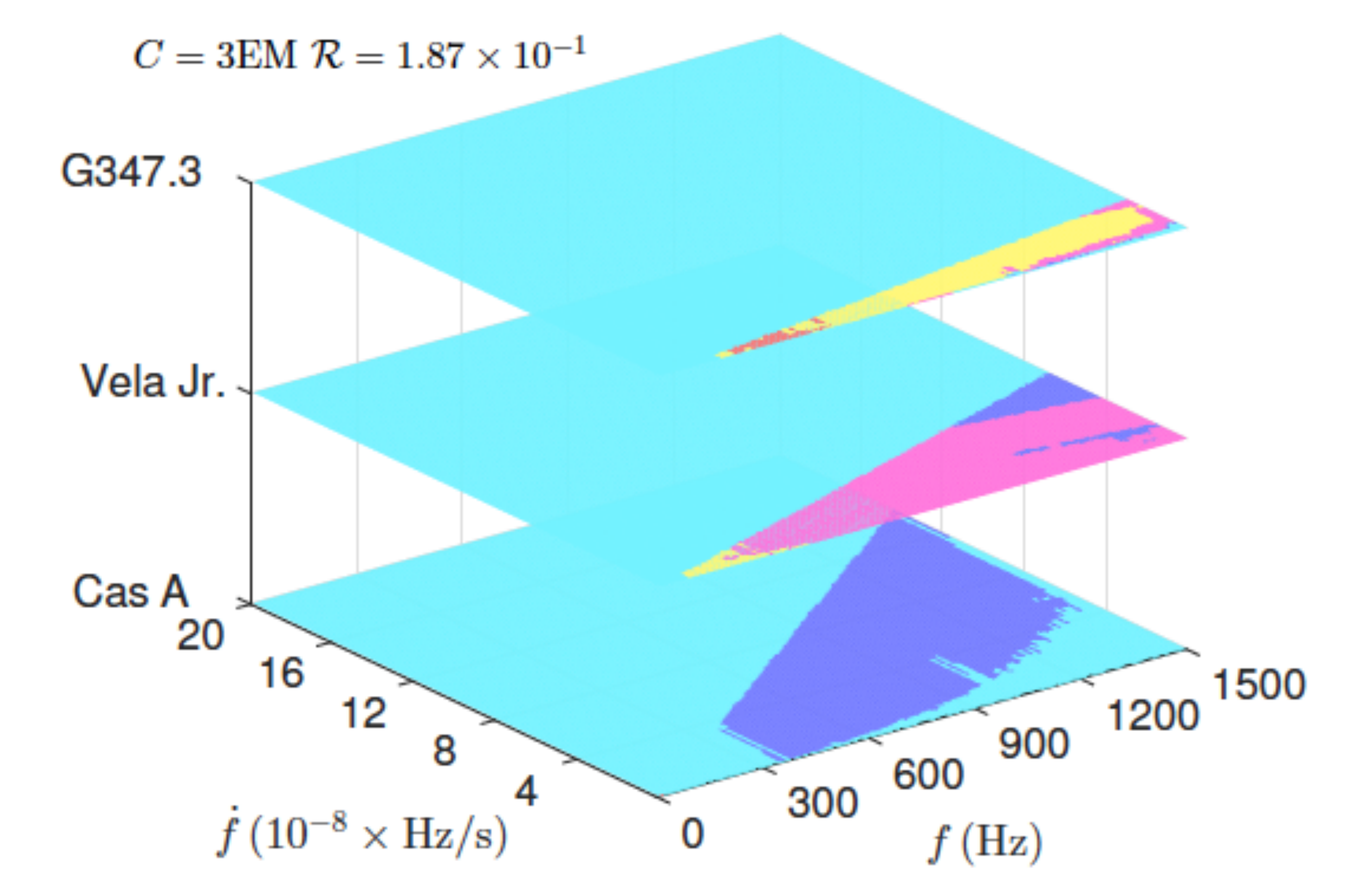
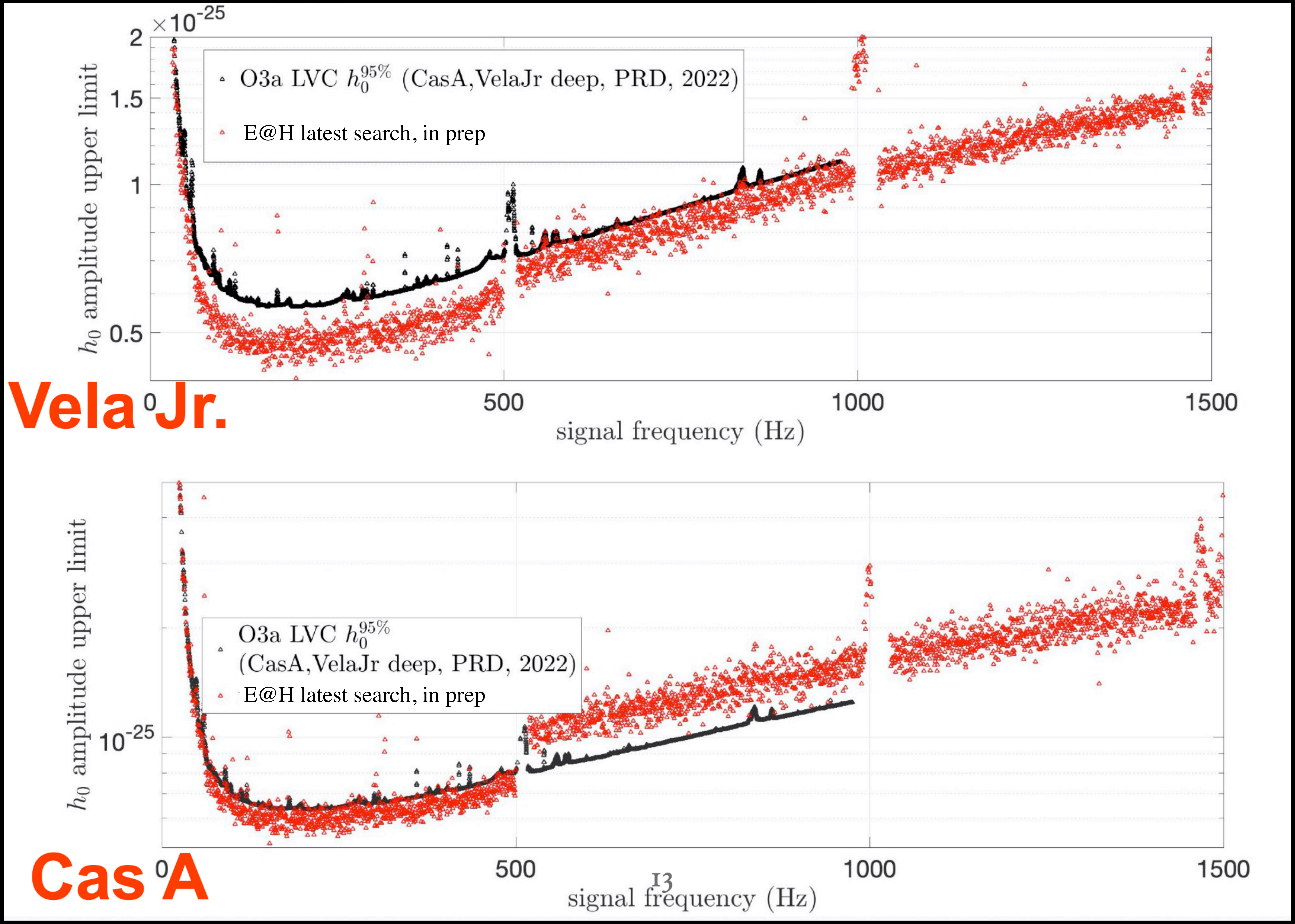
SUPERNOVA REMNANTS TO TARGET:



Results: lowest $h_0^{\text{upper limit}} \sim$ a few 10^{-26}



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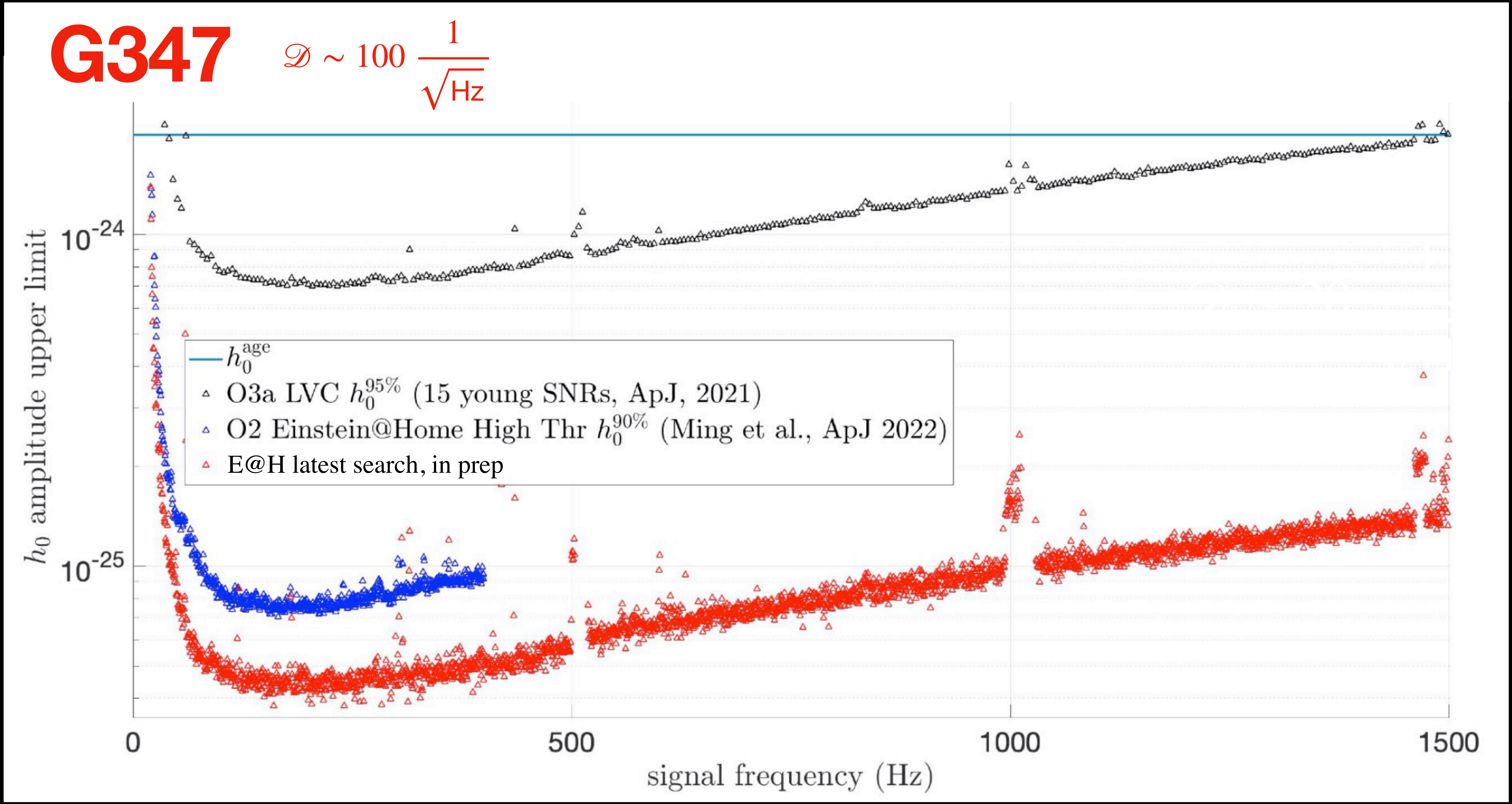
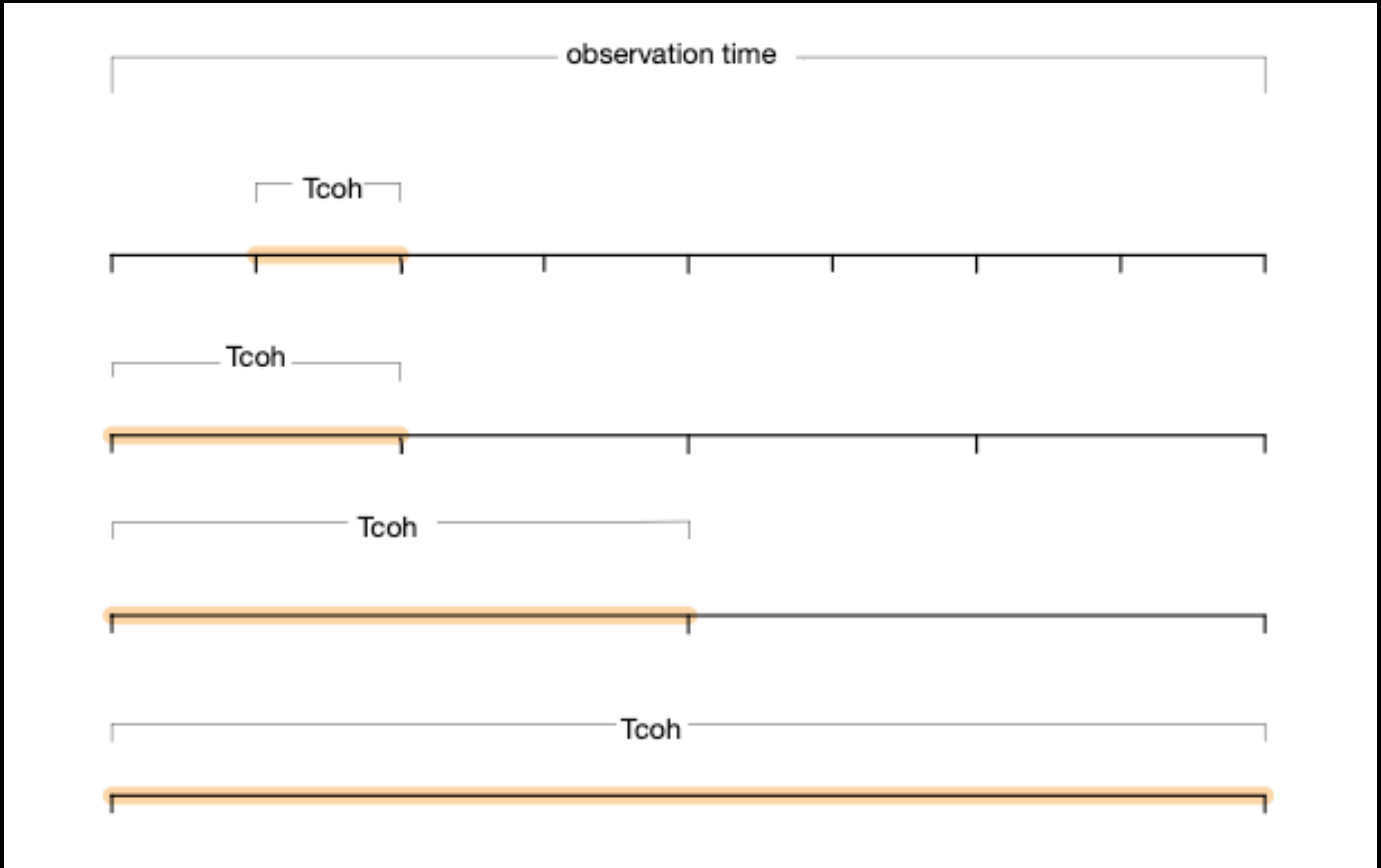


Translated into ellipticity upper limits :

A HIERARCHY OF SEMI-COHERENT SEARCHES WITH INCREASING T_{COH}



FIRST STAGE IS THE MOST EXPENSIVE

Einstein@Home volunteer distributed computing project

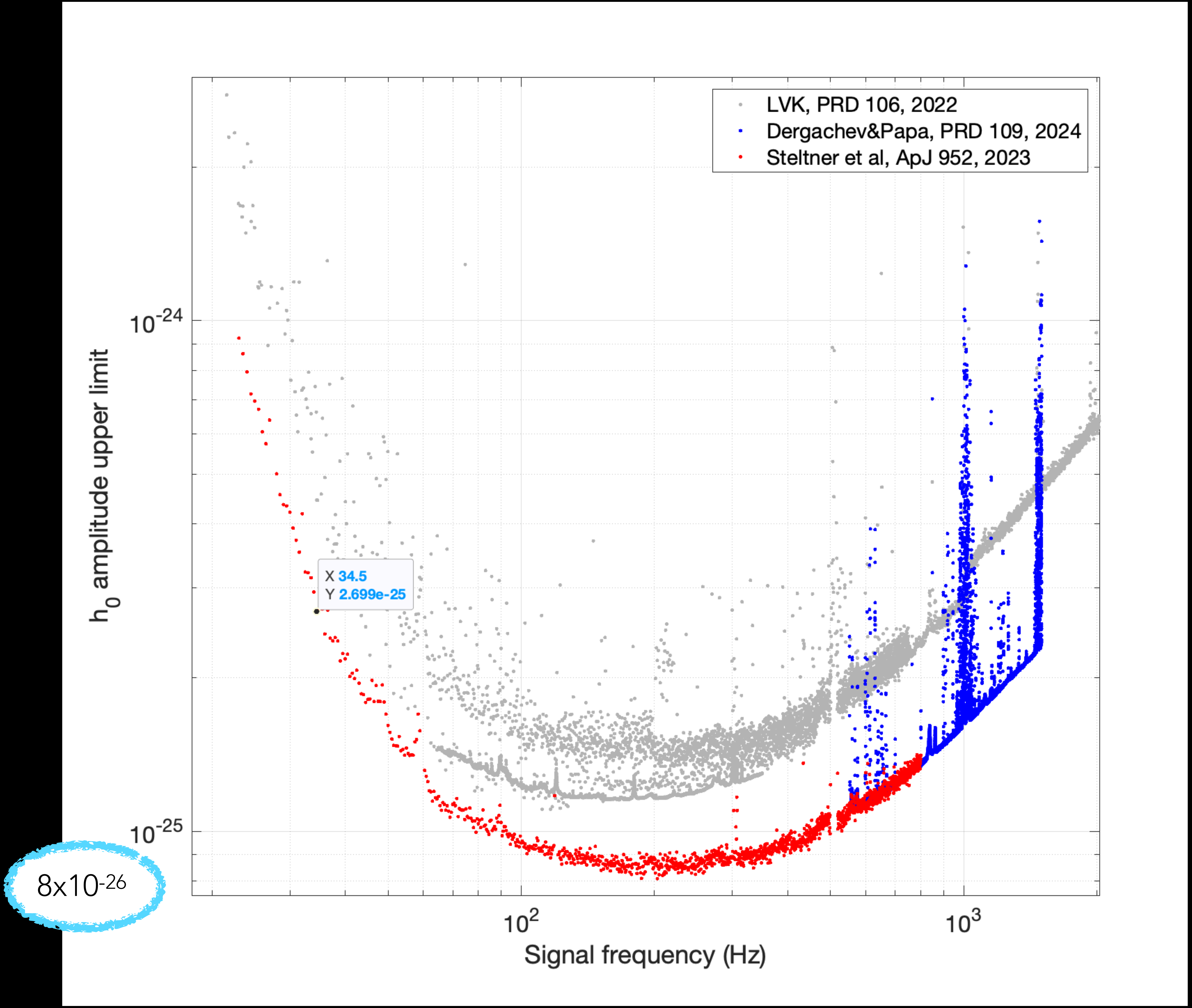
https://einsteinathome.org/

Successive stages: super computing cluster

ALL-SKY SURVEYS

I have to explicitly search over all possible sky positions

UPPER LIMITS ON EMISSION FROM ISOLATED OBJECTS



UPPER LIMITS ON EMISSION FROM ISOLATED OBJECTS

$$-10^{-8}\ \text{Hz/s} \leq \dot{f}_{GW} \leq 10^{-9}\ \text{Hz/s}$$

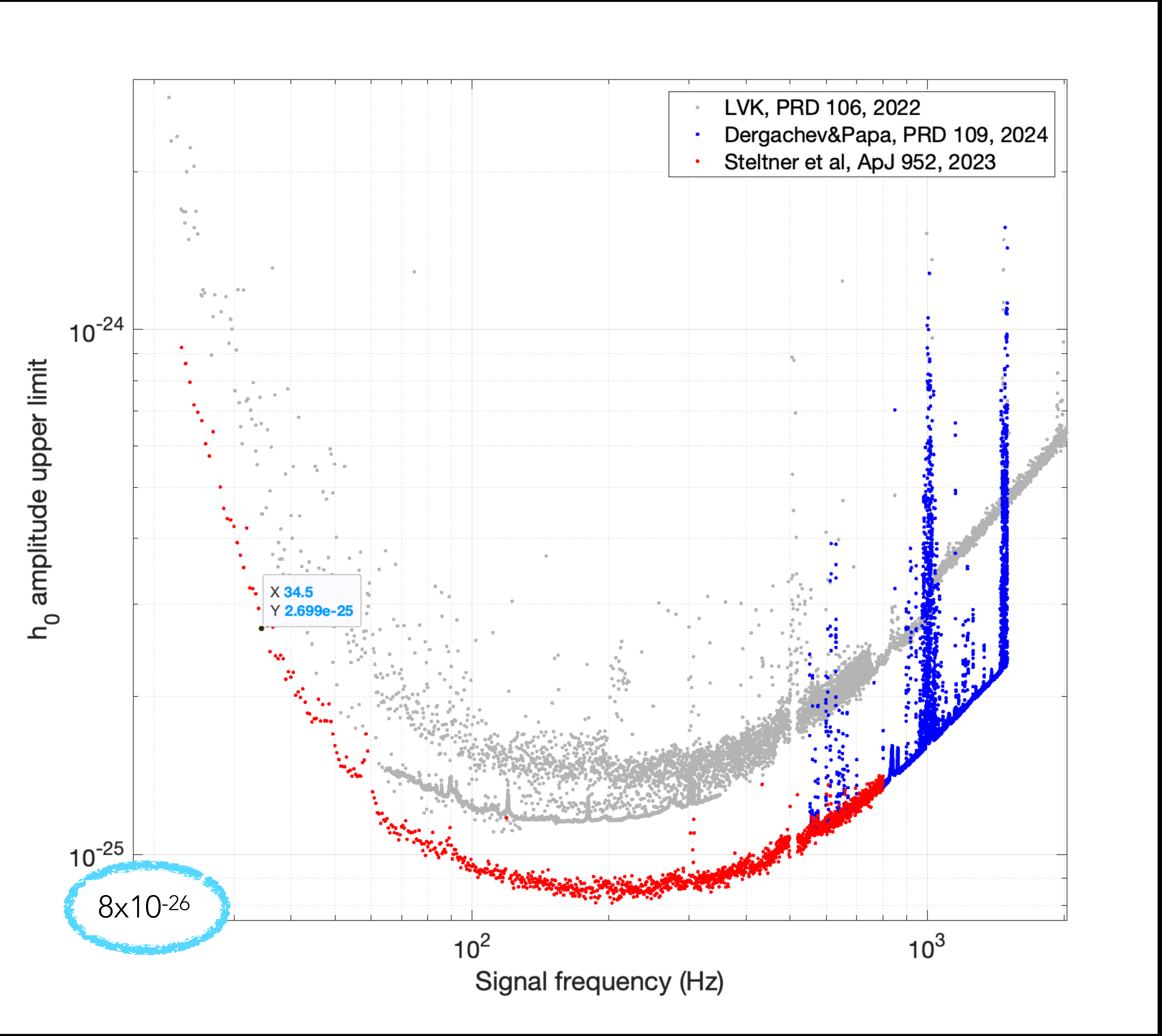
require large computer cluster for weeks

$$|\dot{f}_{GW}| \leq 5 \times 10^{-10}\ \text{Hz/s}$$

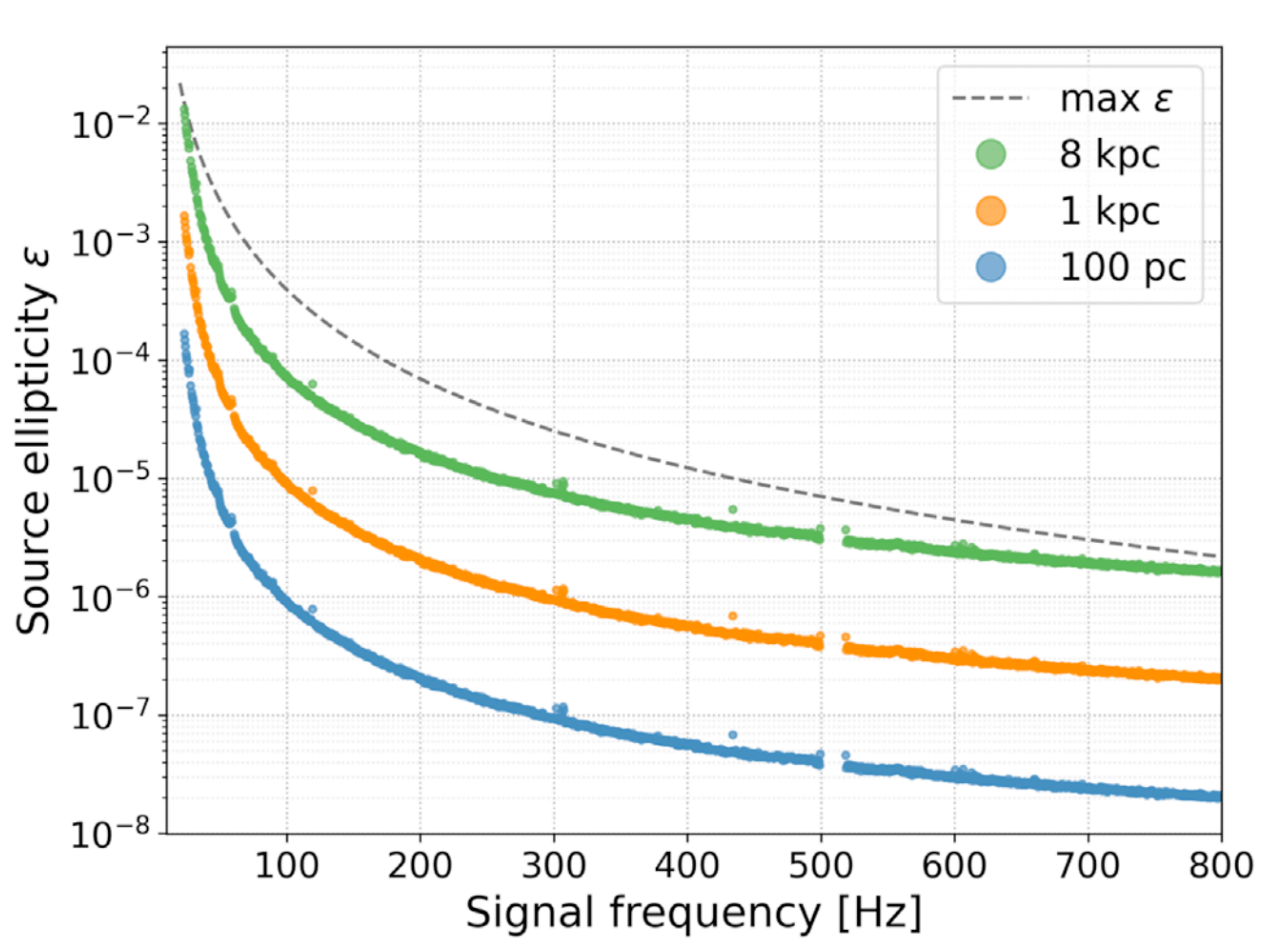
$$-2.6 \times 10^{-9}\ \text{Hz/s} \leq \dot{f}_{GW} \leq 2.6 \times 10^{-10}\ \text{Hz/s}$$

requires Einstein@Home for months

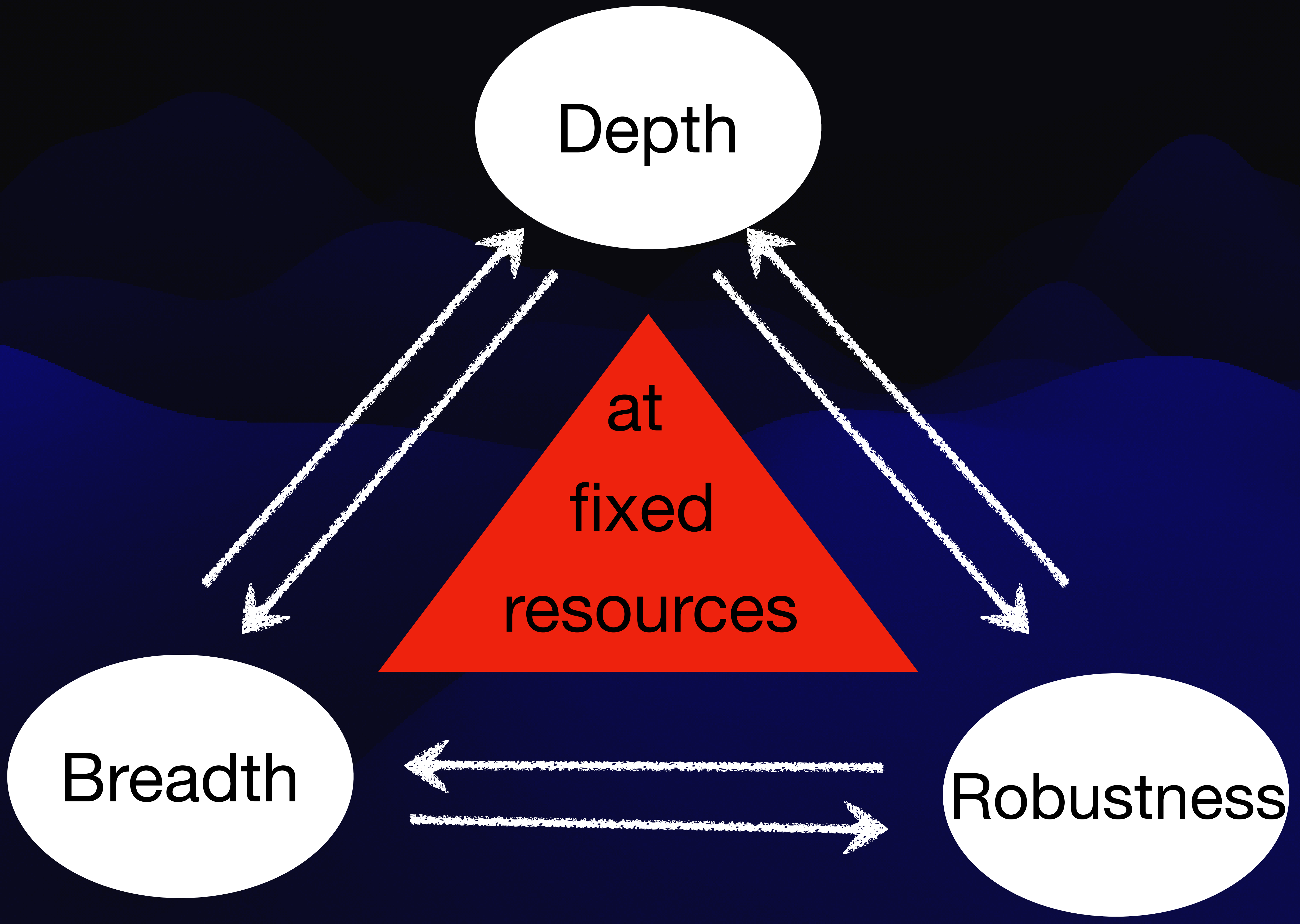
$$\mathscr{D} \sim 55\ \frac{1}{\sqrt{\text{Hz}}}$$



ELLIPTICITY UPPER LIMITS



Broad parameter space searches require choices, i.e. trade-offs

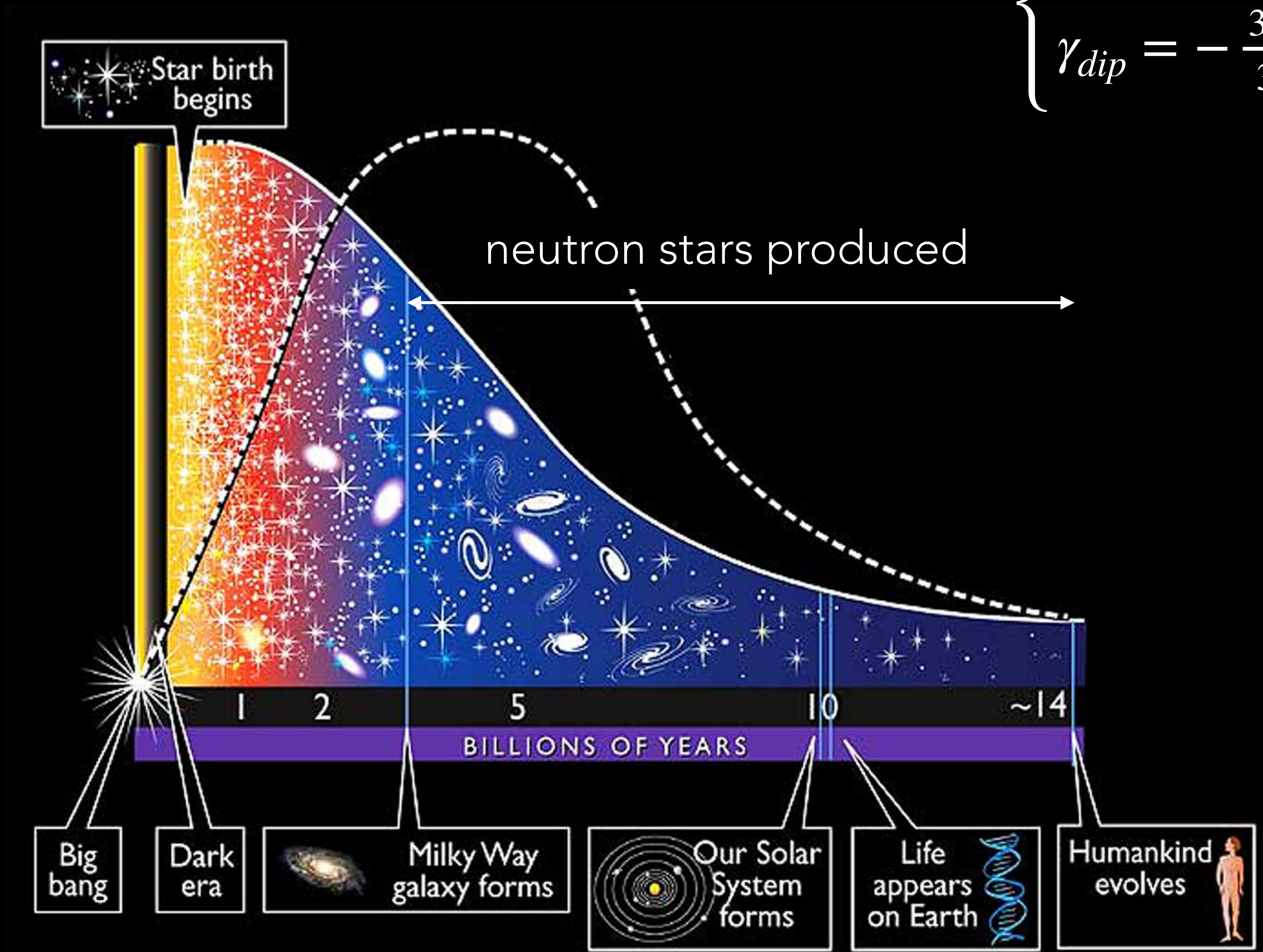


different algorithms and implementations encode those choices

WHAT ARE THE CHANCES OF DETECTION?

Synthetic isolated 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)

CHANCES OF DETECTION NOW

different synthetic populations of non-recycled neutron stars:

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”

NEXT GENERATION DETECTORS

Model	expected # of detectable signals $\overline{n}$ ET	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

boson annihilations following the formation of gravitationally bound states of ultralight bosons around black holes (through super radiance instability) will source continuous gravitational waves

UPPER LIMITS ON h_0

↓

UPPER LIMITS ON BOSON MASS

boson annihilations following the formation of gravitationally bound states of ultralight bosons around black holes (through super radiance instability) will source continuous gravitational waves

UPPER LIMITS ON h_0

↓

UPPER LIMITS ON BOSON MASS

- Re-interpreting results from all-sky searches
- Setting up specific searches

UPPER LIMITS ON BOSON MASS

scenario: boson annihilations following the formation of gravitationally bound states of ultralight bosons around black holes, through super radiance instability.

$$h_{0,\mathrm{peak}} \approx 3 \times 10^{-24} \left(\frac{\alpha}{0.1}\right)^7 \left(\frac{\chi_i - \chi_c}{0.5}\right) \left(\frac{M_{\mathrm{BH}}}{10 M_\odot}\right) \left(\frac{1\ \mathrm{kpc}}{d}\right)$$

$$f_{\mathrm{GW}} = f^0_{\mathrm{GW}} - \Delta f^{\mathrm{BH}}_{\mathrm{GW}} - \Delta f^{\mathrm{cloud}}_{\mathrm{GW}}$$

$$\alpha \equiv \frac{G M_{\mathrm{BH}} \mu_{\mathrm{b}}}{\hbar c^3} \approx 0.0075 \left(\frac{M_{\mathrm{BH}}}{10 M_\odot}\right) \left(\frac{\mu_{\mathrm{b}}}{10^{-13}\ \mathrm{eV}}\right)$$

$$\Delta f^{\mathrm{BH}}_{\mathrm{GW}} \approx f^0_{\mathrm{GW}} \left(\frac{\alpha^2}{8} + \frac{17\alpha^4}{128} - \frac{\chi_i \alpha^5}{12}\right),$$

$$\Delta f^{\mathrm{cloud}}_{\mathrm{GW}} \approx f^0_{\mathrm{GW}} \left(0.2\alpha^2 \frac{M_{\mathrm{cloud}}}{M_{\mathrm{BH}}}\right).$$

$$\chi_c \approx \frac{4\alpha}{1 + 4\alpha^2}.$$

super radiance will take place (level will grow) if $\chi_i > \chi_c$

As the boson annihilate the cloud is depleted so:

$$h_0(t) = \frac{h_{0,\mathrm{peak}}}{1 + t/\tau_{\mathrm{GW}}}$$

$$\tau_{\mathrm{GW}} \approx 5 \times 10^5\ \mathrm{yr} \left(\frac{M_{\mathrm{BH}}}{10 M_\odot}\right) \left(\frac{0.1}{\alpha}\right)^{15} \left(\frac{0.5}{\chi_i - \chi_c}\right)$$

Cloud mass decreases, grab. Potential energy increases => positive $\dot{f}_{GW}$

$$\dot{f}_{\mathrm{gw}}(t) \approx 0.2\alpha \frac{f_{\mathrm{GW}}}{\tau_{\mathrm{GW}}} \left(\frac{M_{\mathrm{cloud}}(t)}{M_{\mathrm{BH}}}\right)^2.$$

Considering only first super radiant level n,l,m=(0,1,1)

UPPER LIMITS ON BOSON MASS

assuming super radiant emission

- Setting up specific searches, and parametrising results as a function of source parameters

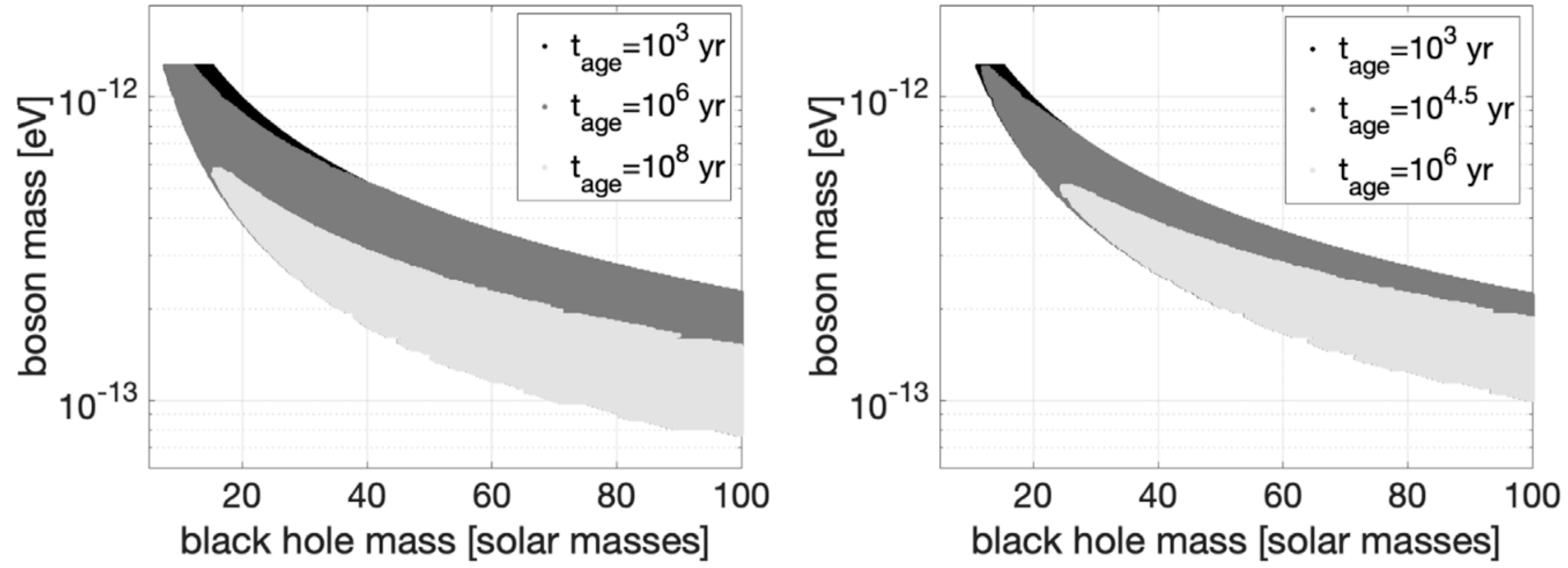


FIG. 6. Exclusion regions in the boson mass (m_b) and black hole mass ($M_{\rm BH}$) plane for an assumed distance of $D = 1$ kpc (left) and $D = 15$ kpc (right), and an initial black hole dimensionless spin $\chi_i = 0.9$. For $D = 1$ kpc, three possible values of the black hole age, $t_{\rm age} = 10^3, 10^6, 10^8$ years, are considered; for $D = 15$ kpc, $t_{\rm age} = 10^3, 10^{4.5}, 10^6$ years are considered.

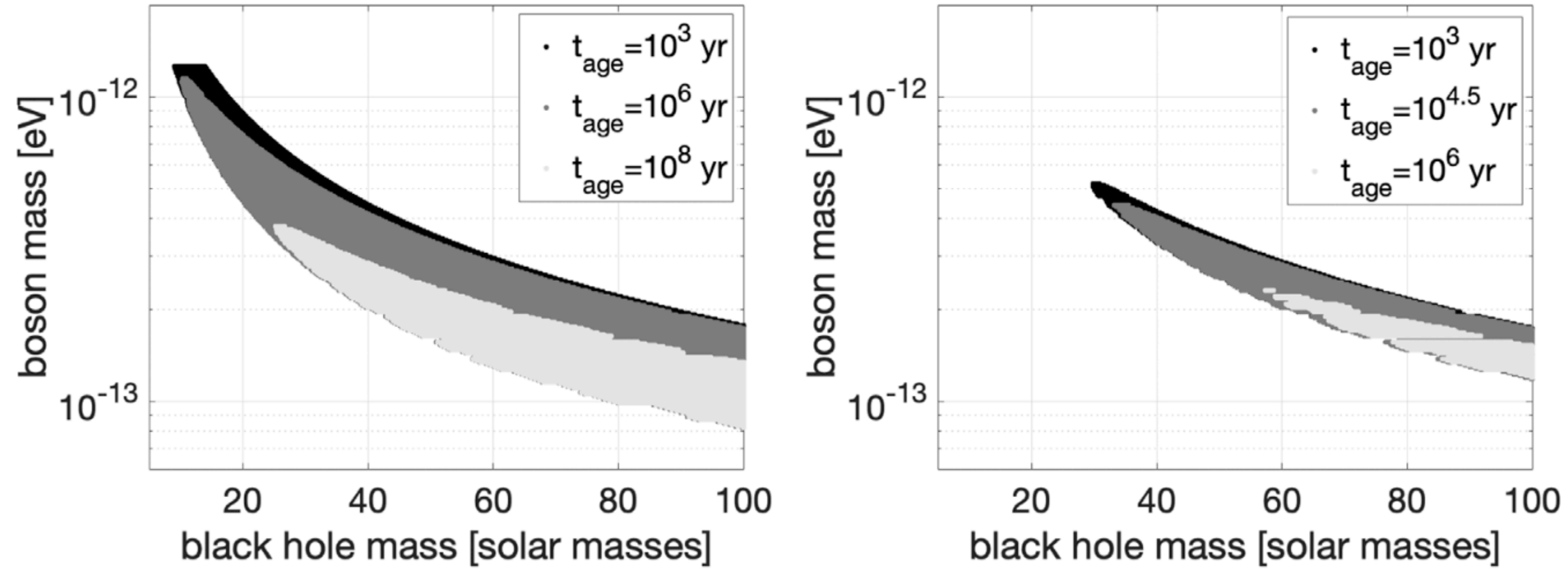


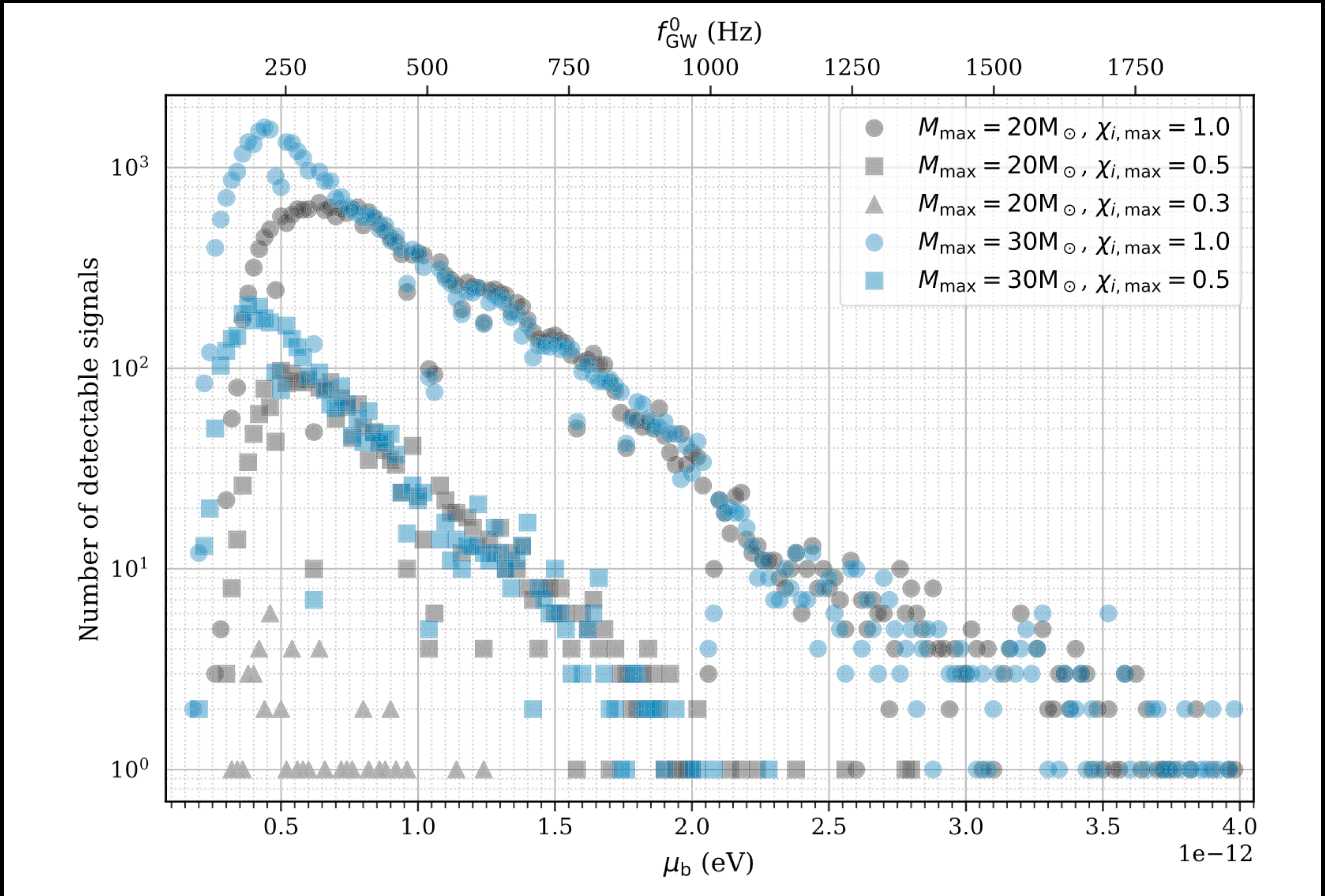
FIG. 7. Same as Fig. 6 but for black hole initial spin $\chi_i = 0.5$. The assumed distance is $D = 1$ kpc (left), and $D = 15$ kpc (right).

LVK, All-sky search for gravitational wave emission from scalar boson clouds around spinning black holes in LIGO O3 data, PRD 105, (2022)

UPPER LIMITS ON BOSON MASS

assuming super radiant emission

- Re-interpreting results from all-sky searches, assuming distributions of source parameters



Zhu et al, Characterizing the continuous gravitational-wave signal from boson clouds around Galactic isolated black holes, PRD 102, 2020

DO YOUR SEARCH BY MINING RELEASED RAW RESULTS

- Dergachev et al, Early release of the expanded atlas of the sky in continuous gravitational waves, *Phys.Rev.D* 109 (2024) 2, 022007
  - 20 Hz $\leq f_{GW} \leq 1500$ Hz $\qquad |\dot{f}_{GW}| \leq 5 \times 10^{-10}$ Hz/s
  - a sky-map every 45 mHz
    - h_0 upper limits as function of sky position, ι, ψ
    - In every sky pixel and frequency band : parameters of largest SNR template, and SNR value
    - Big data set: ~ 800 GB, specific library (MVL) developed to allow fast access on laptop (can also use it on GAIA data)

Download here: https://www.atlas.aei.uni-hannover.de/work/volodya/O3a_2_atlas/

CAVEAT

- Confident boson-cloud signal detection :
  - Requires being sure that there is a black hole of consistent mass and spin where the signal is coming from

BUT MOST PULSARS IN GROUND-BASED DETECTORS BAND ARE IN BINARIES…

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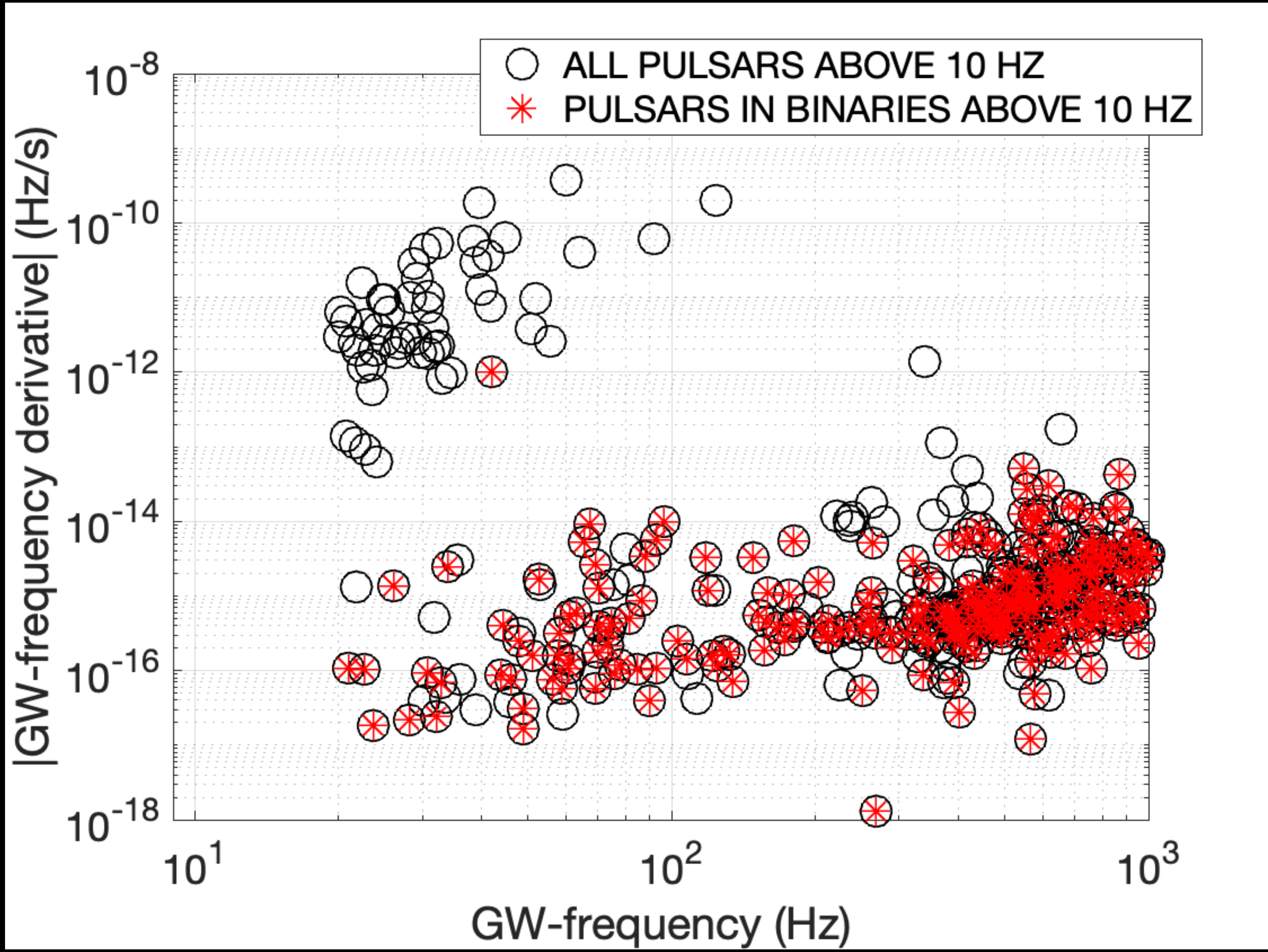
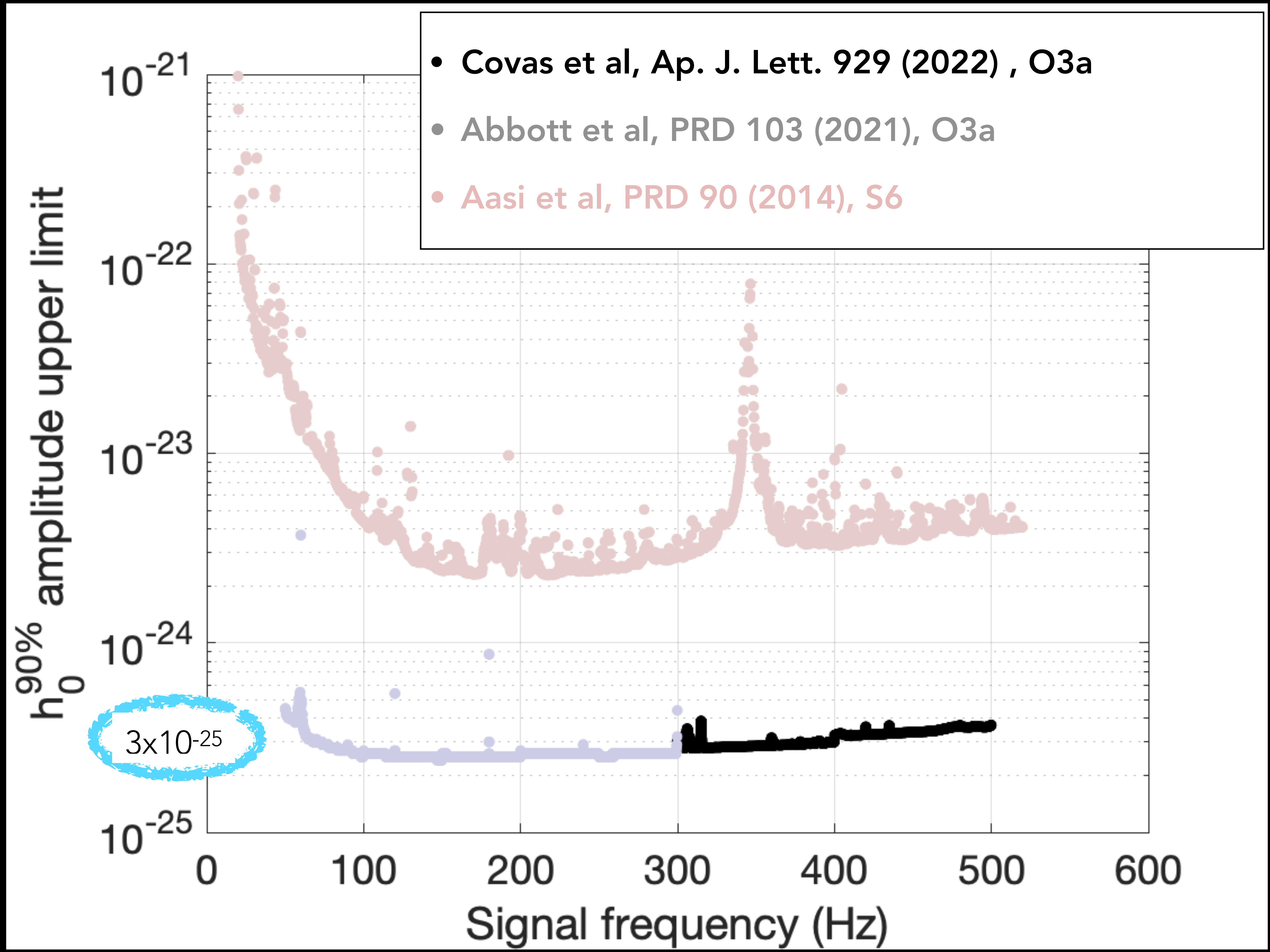


ALL-SKY SEARCH FOR EMISSION FROM NEUTRON STARS IN BINARY SYSTEMS



requires large computer cluster for weeks

$$\mathscr{D} \sim 20 \frac{1}{\sqrt{\text{Hz}}}$$

- $|\dot{f}_{GW}| \leq$ a few 10^{-10} Hz/s
- Orbital parameters additionally searched
- Less sensitive search than for isolated objects

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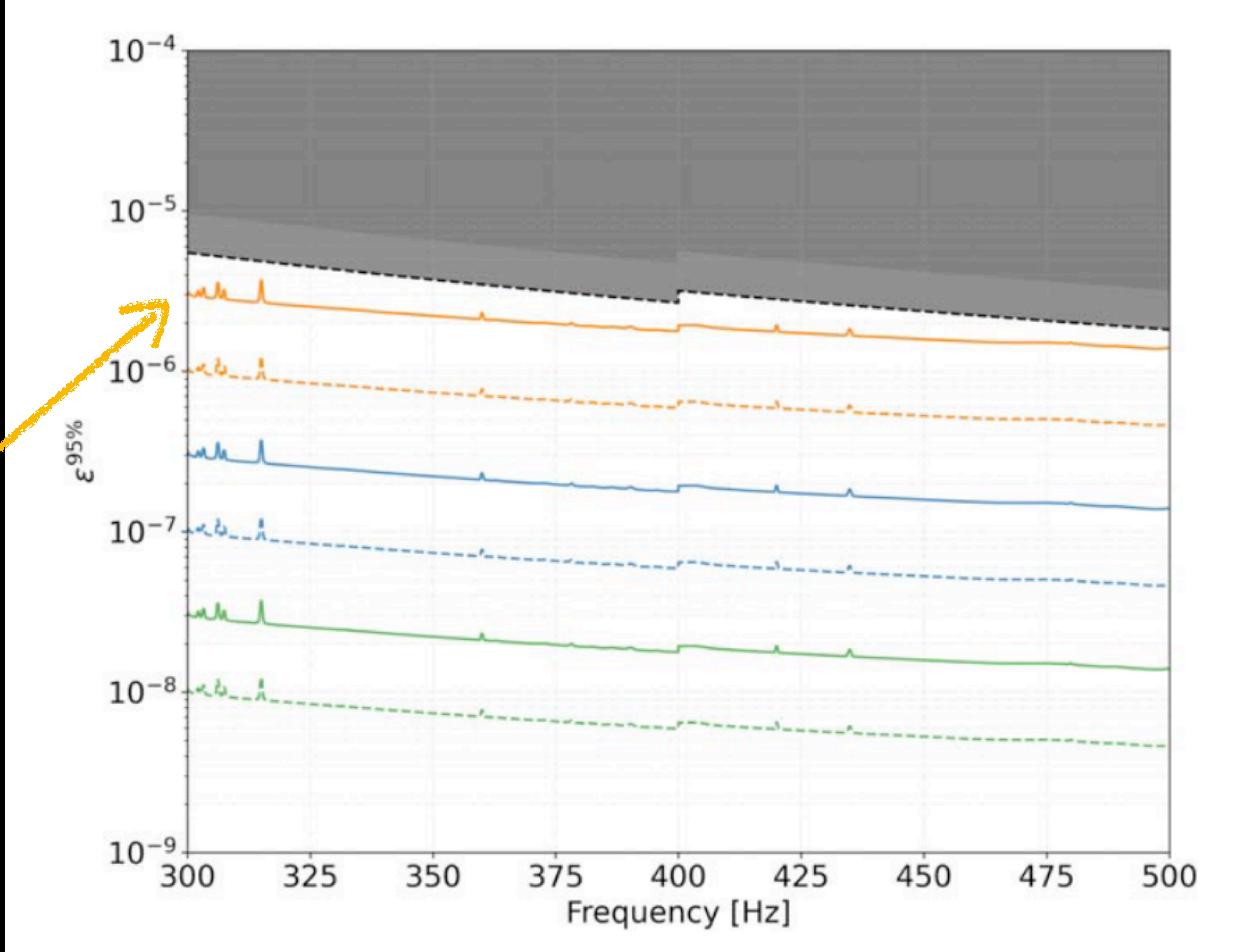

$I_{zz} = 10^{38}$ kg m^2

$I_{zz} = 3 \times 10^{38}$ kg m^2

1 kpc

100 pc

10 pc

Excludes NSs in binaries with ellipticities $> 3 \times 10^{-6}$ within 1 kpc

- $|\dot{f}_{GW}| \leq$ a few 10^{-10} Hz/s
- Orbital parameters additionally searched
- Less sensitive search than for isolated objects

…SUMMARISING

- the first detection of a continuous GW from a neutron star will open the field of GW-pulsar-astronomy
- now probing interesting source parameter-range
- broad surveys are hard
- might uncover unexpected exotic signal
- 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!

 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.

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.

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

To LIGO's supporters, however, much of the latest criticism smacks of sour grapes. They argue that th[illegible] technical co[illegible] being raised a[illegible] ing new and [illegible] been tho[illegible]ly investigated. [illegible] project is risky, they [illegible]ede, 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."

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 declined to speak with S[illegible]. Colleagues of Vogt [illegible]d Drever provided [illegible]ounts of the disput[illegible]

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

D[illegible]er is not som[illegible]dy to be taken l[illegible]tly: Brilliant is the description most often given of him, and he is viewed by almost all 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