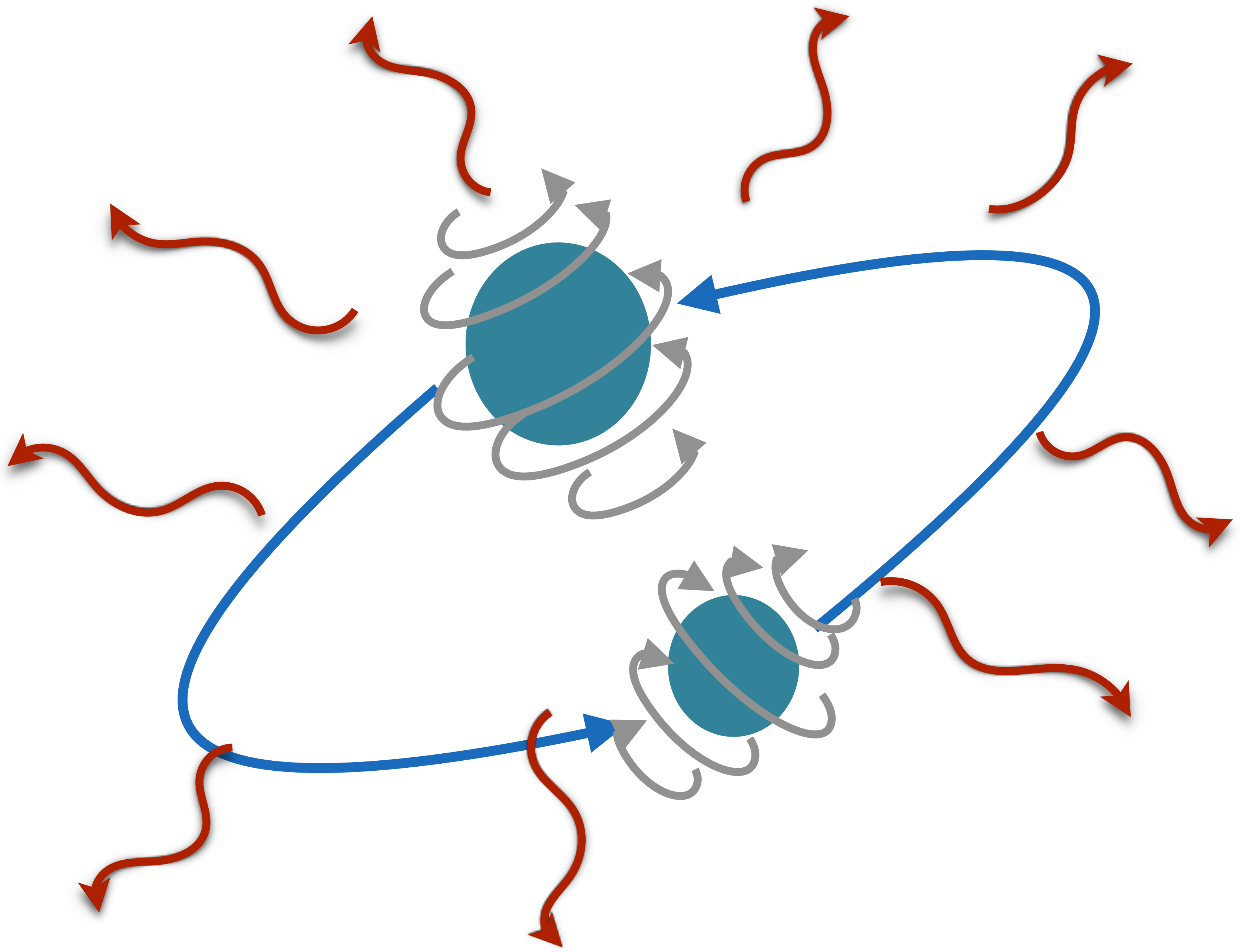
Continuous GW searches

M. Alessandra Papa, Max Planck Institute for Gravitational Physics and Leibniz University Hannover, Germany

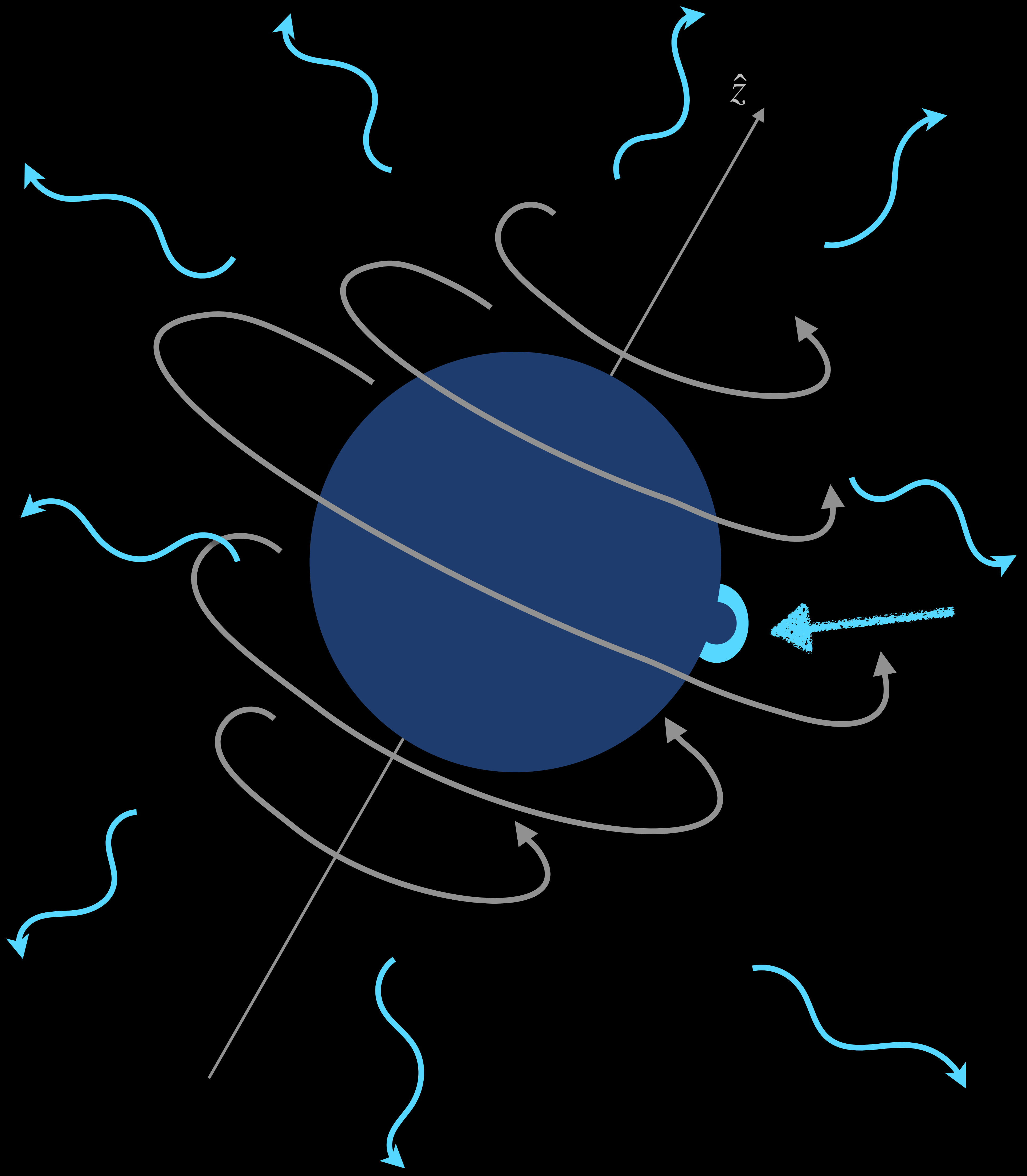
Binary merger signals, short-lived



Gravitational waves
from the varying
mass quadrupole

SIMPLE MODEL: SPINNING NEUTRON STAR WITH EQUATORIAL ELLIPTICITY

- signal always there



ellipticity $\varepsilon := \dfrac{I_{xx} - I_{yy}}{I_{zz}}$

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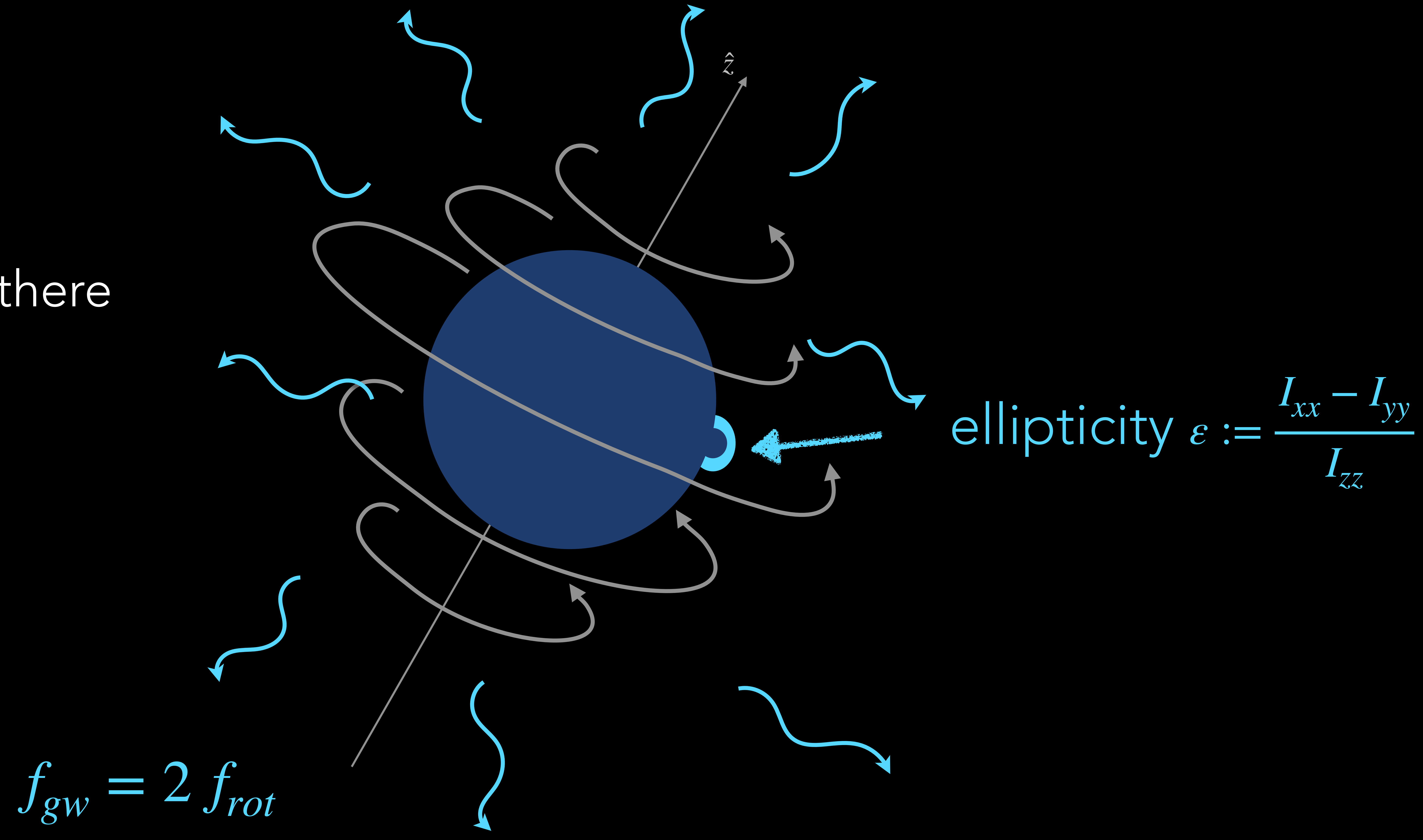


sinusoidal signal

WHAT COULD GENERATE SIGNAL ?

- what could source ellipticity ?
  - deformation frozen-in at birth
  - star-quakes
  - hot-spot (in accreting systems, very interesting)
  - *internal* magnetic fields*

HOW BIG IS THE DEFORMATION ?

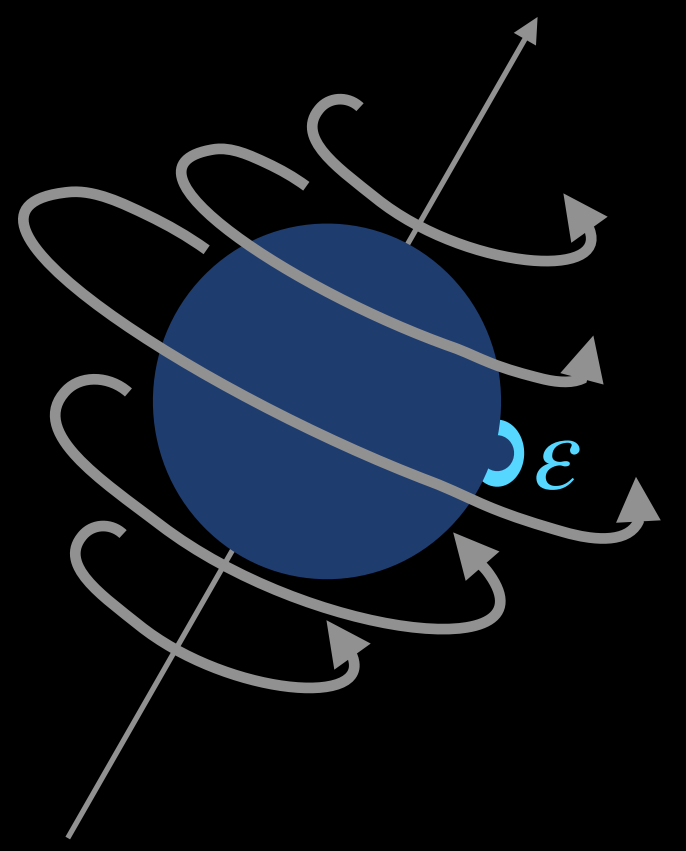
- maximum ellipticity**
  - i.e. before crust breaks, very uncertain $\approx (10^{-3})10^{-5} - 10^{-8}$
- smallest ellipticity
  - magnetic fields, very low $\approx 10^{-14}$

* Mastrano et al, MNRAS 417 (2011) - **Johnson-McDaniel & Owen, PRD 88 (2013) - Gittins et al, PRD 101 (2020), Gittins & Andersson, MNRAS 500 (2020), MNRAS 507 (2021) - Morales & Horowitz, MNRAS 517 (2022)

WHAT COULD WE LEARN ?

- ellipticity of object, internal structure of NS
- access to invisible population of neutron stars
- 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



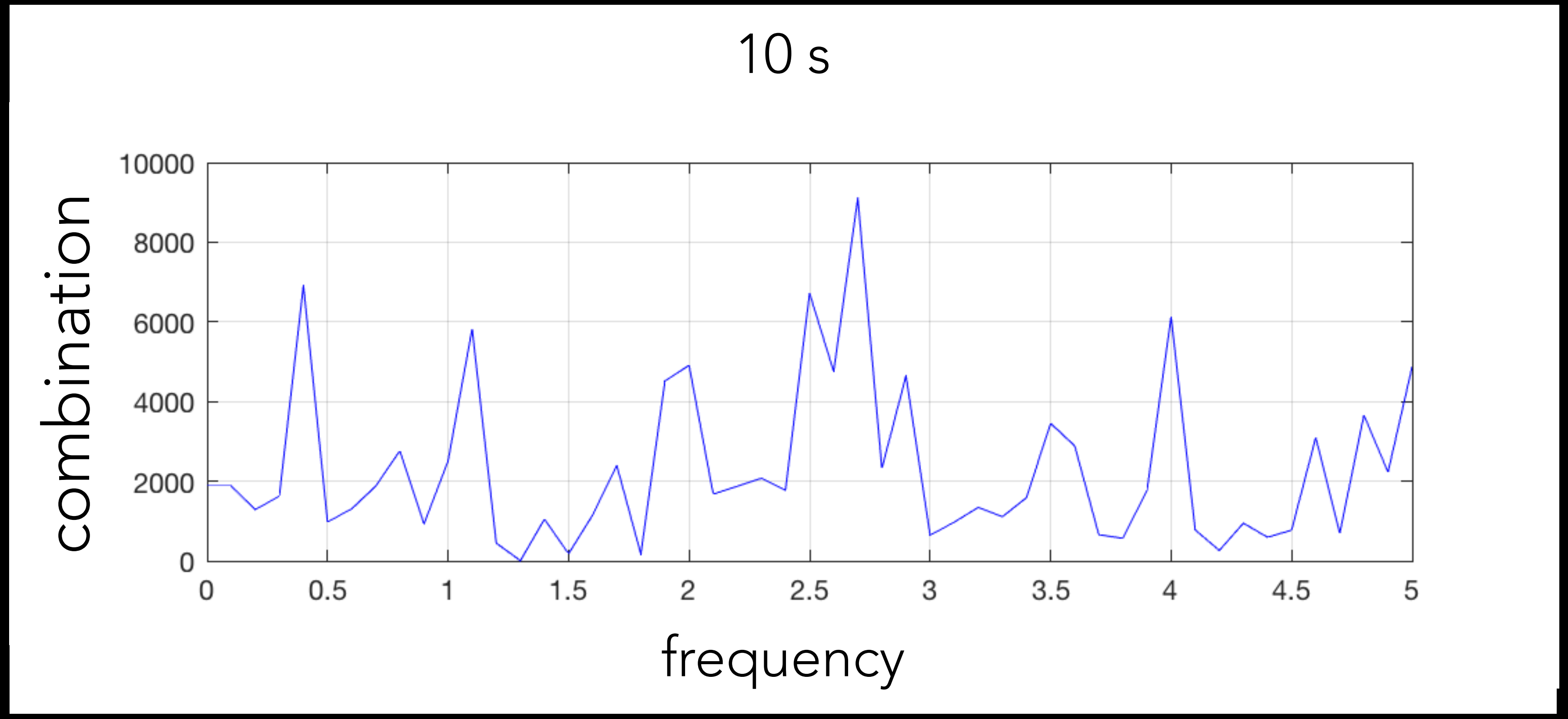
- signal always there
- very weak:

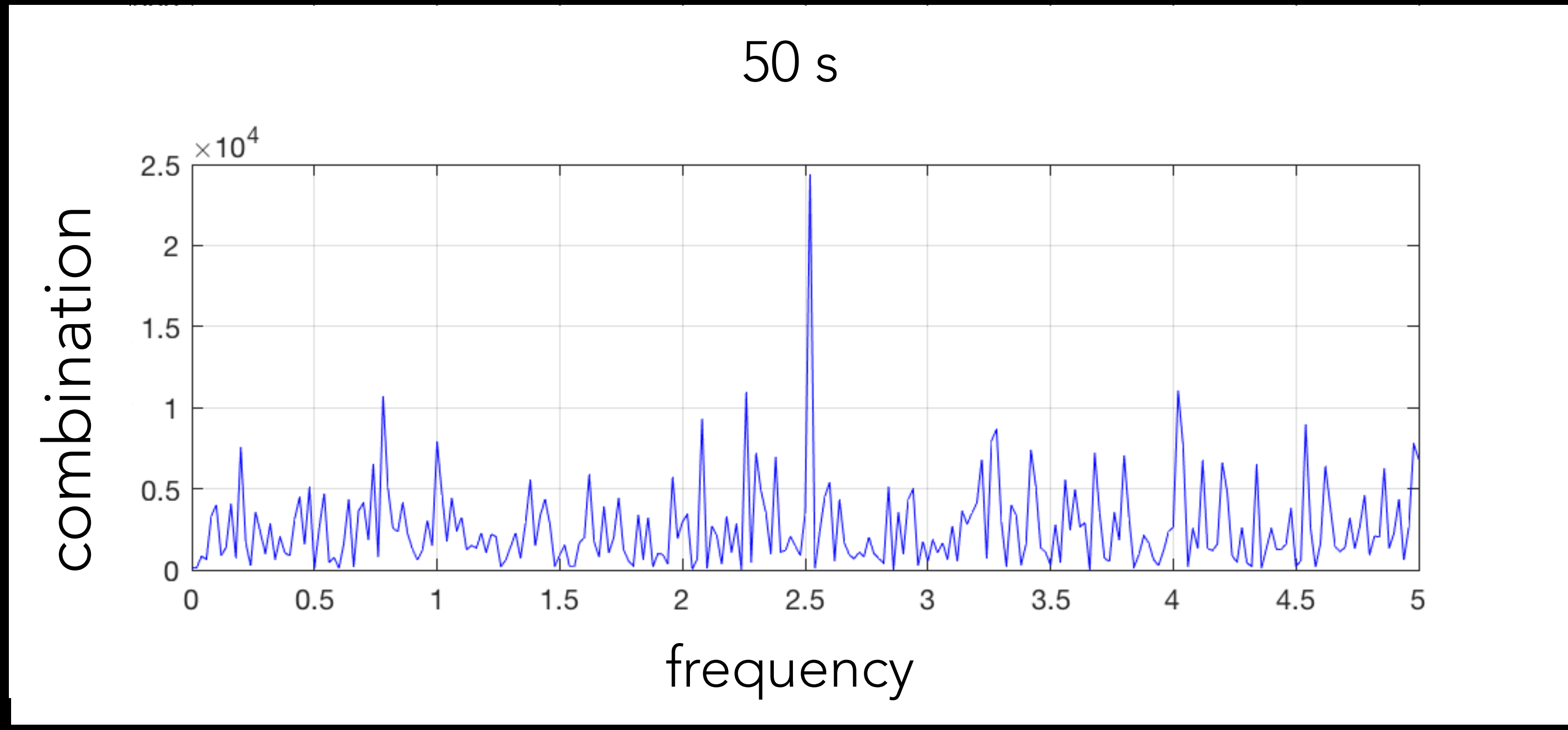
$$h_0 = \frac{4\pi^2 G}{c^4} \frac{I\varepsilon f_{gw}^2}{D} = 2 \times 10^{-25} \left[\frac{I}{10^{38}\ \mathrm{kg\ m^2}}\right] \left[\frac{\varepsilon}{10^{-6}}\right] \left[\frac{f_{gw}}{10^3\ \mathrm{Hz}}\right]^2 \left[\frac{1\ \mathrm{kpc}}{D}\right]$$

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

THE LONGER THE OBSERVATION IS, THE BETTER

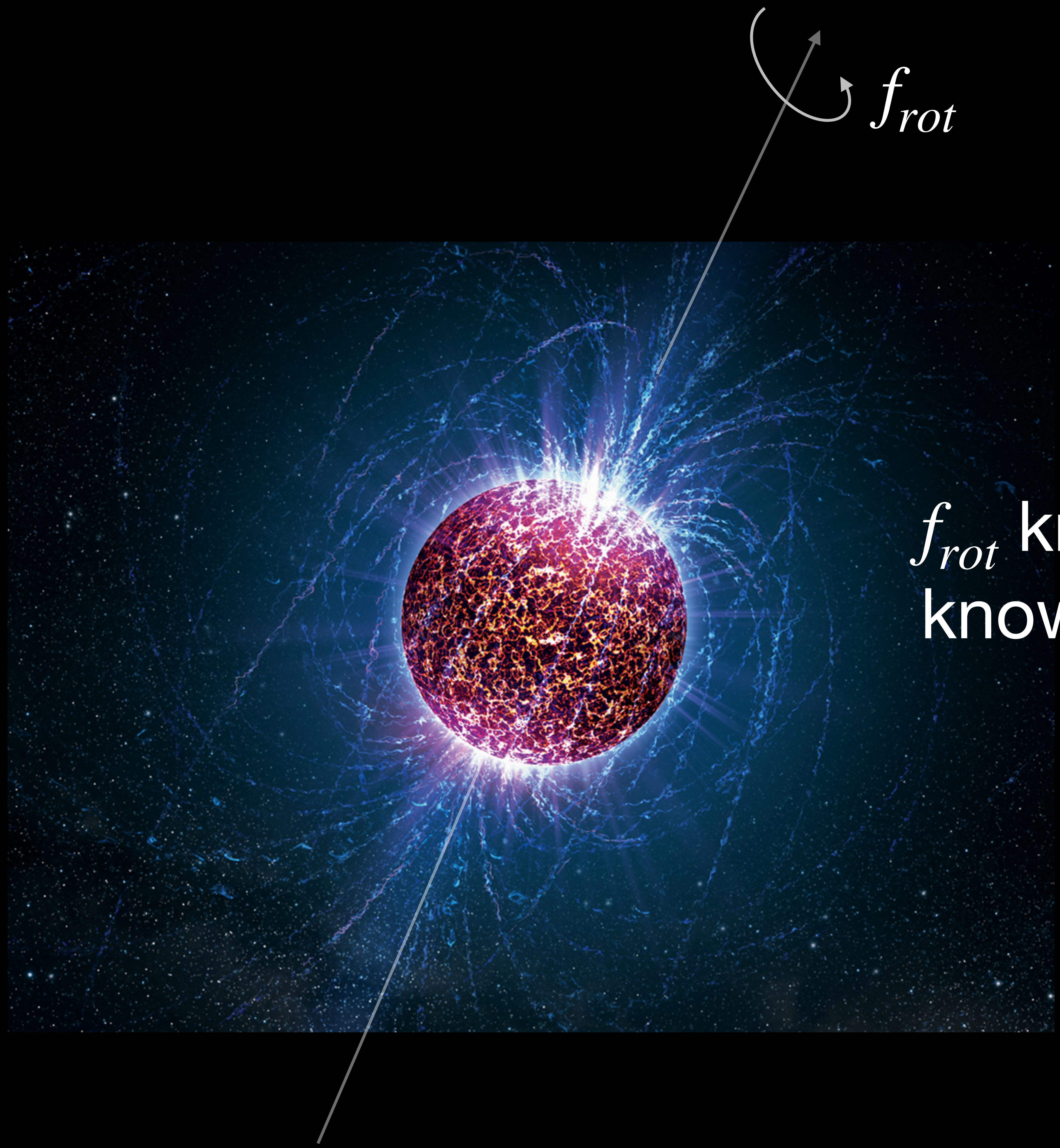
basic idea: combine the data (think FFT power), the signals adds coherently, the noise does not (matched filtering)





The longer is the time baseline, the higher is the SNR

KNOWN NEUTRON STARS: PULSARS



f_{rot} known from EM observations, so $f_{gw} = 2f_{rot}$ is known, so GW signal is known

SEARCHES FOR EMISSION FROM KNOWN PULSARS

- routinely done

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- no detections

upper limits

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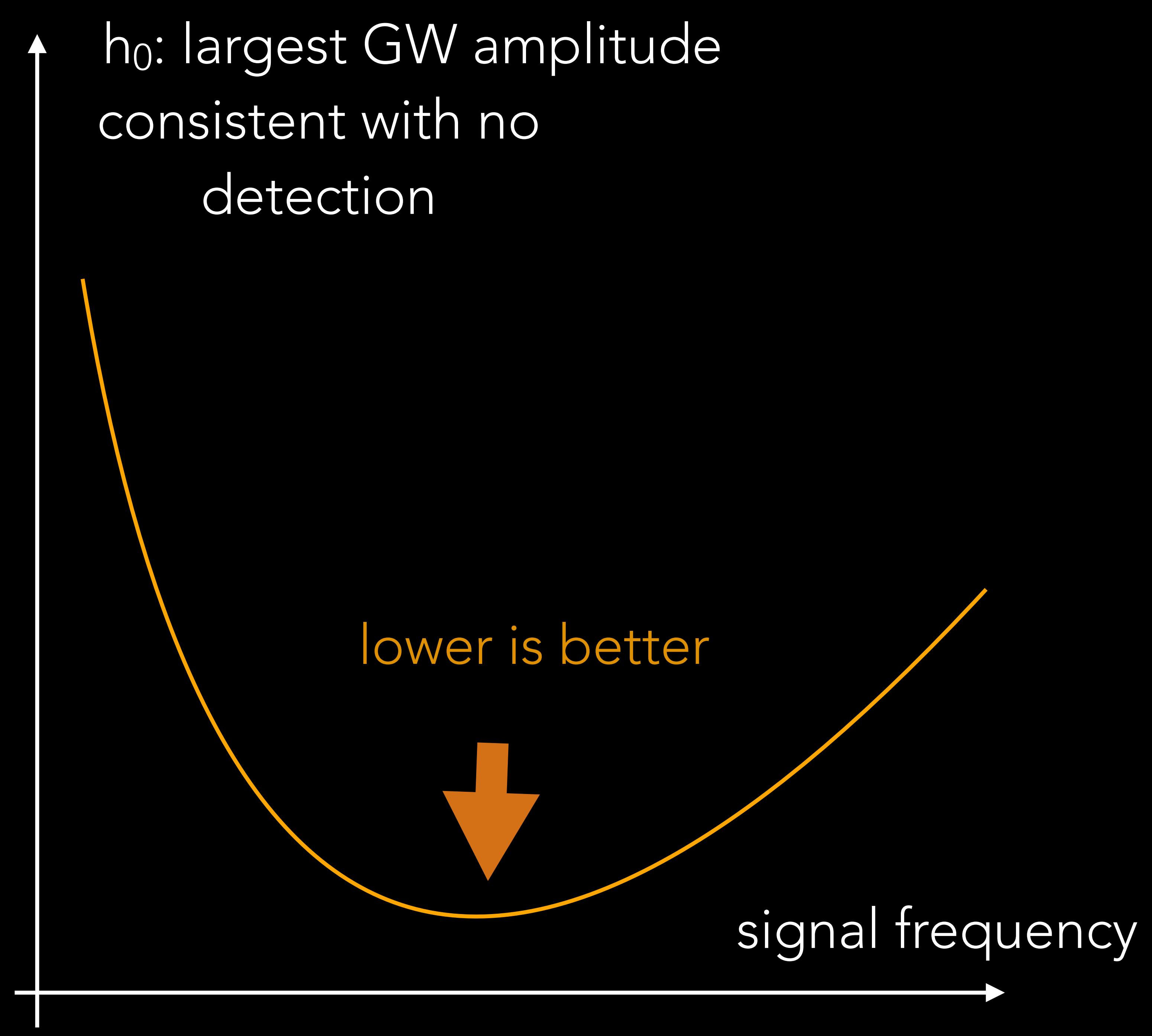


SEARCHES FOR EMISSION FROM KNOWN PULSARS

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

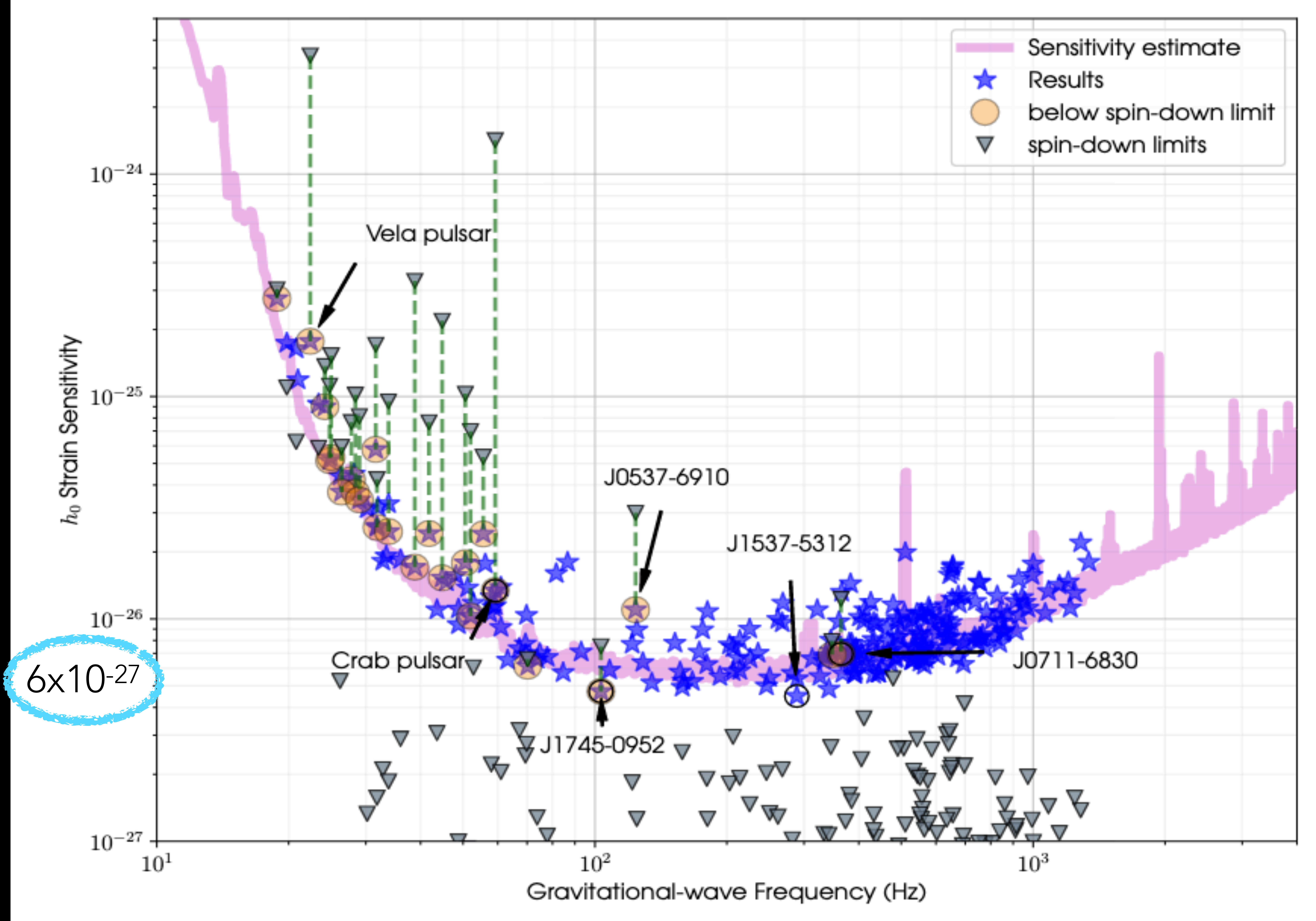
SPIN-DOWN UPPER LIMIT

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

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

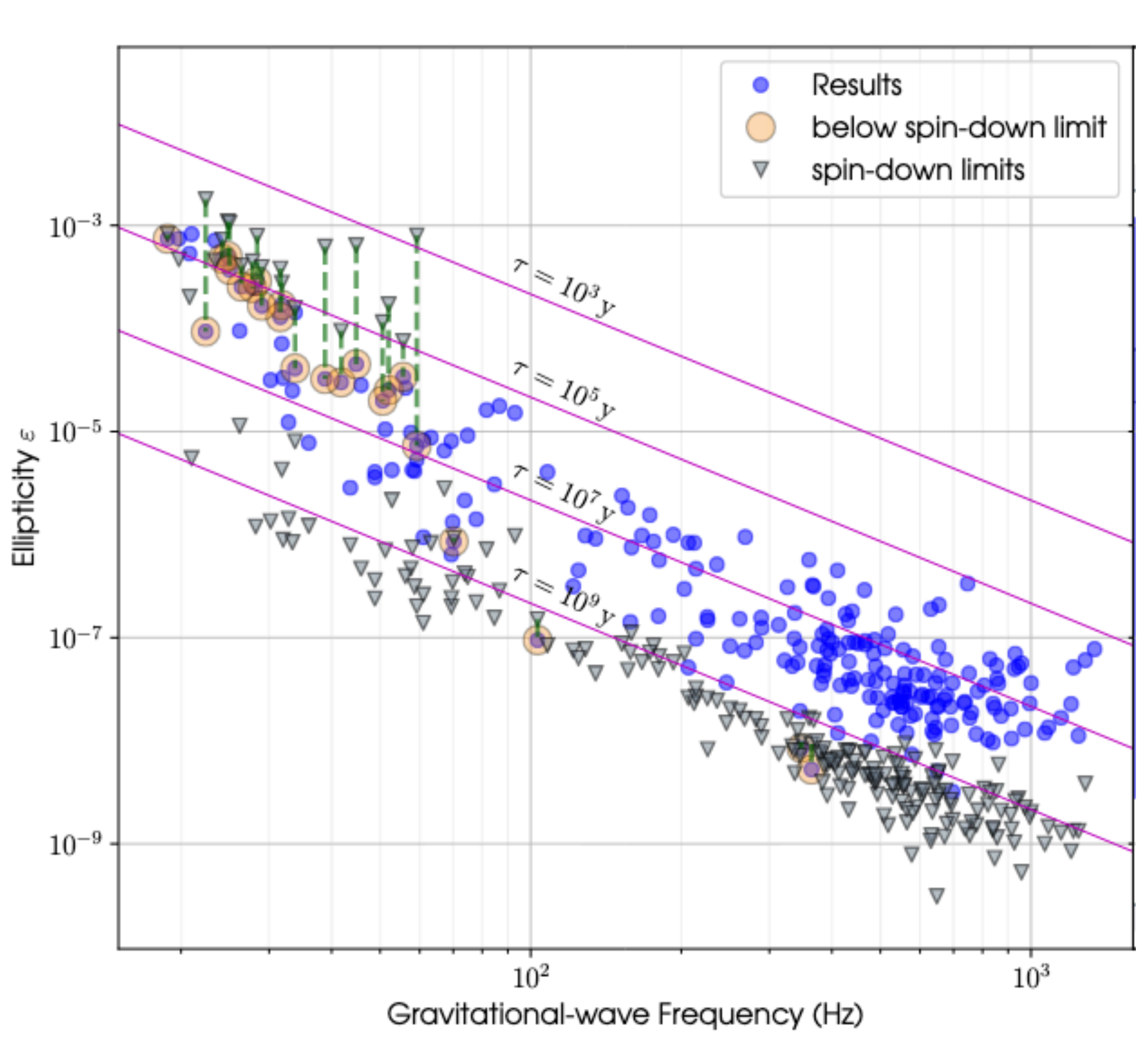
GW amplitude at distance D from star

CONTINUOUS GWS FROM KNOWN PULSARS



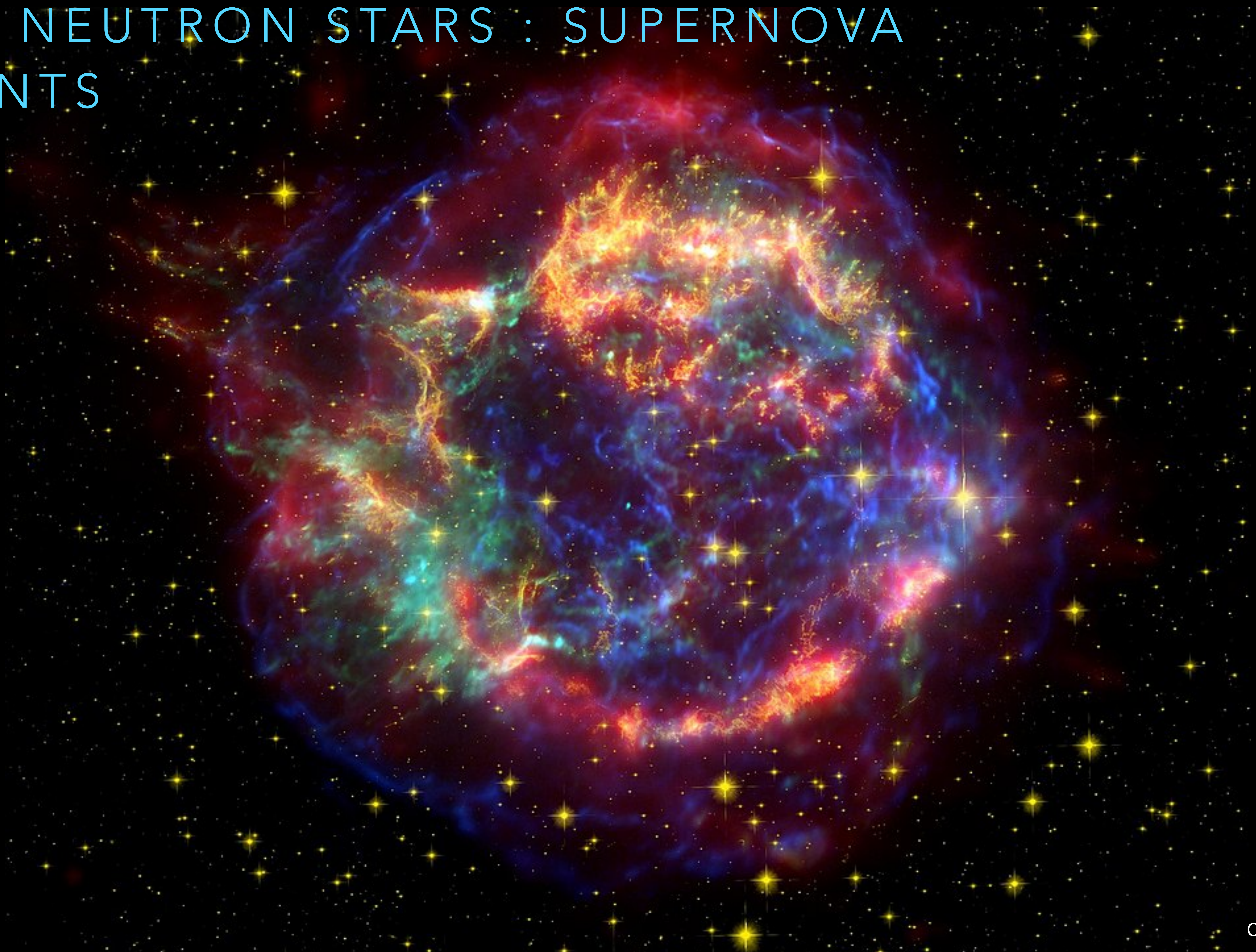
Abbott et al, ApJ 953,1 (2022) [very recent: arxiv:2501.01495 (2025), 45 pulsars]

KNOWN PULSARS: CONSTRAINING THE ELLIPTICITY



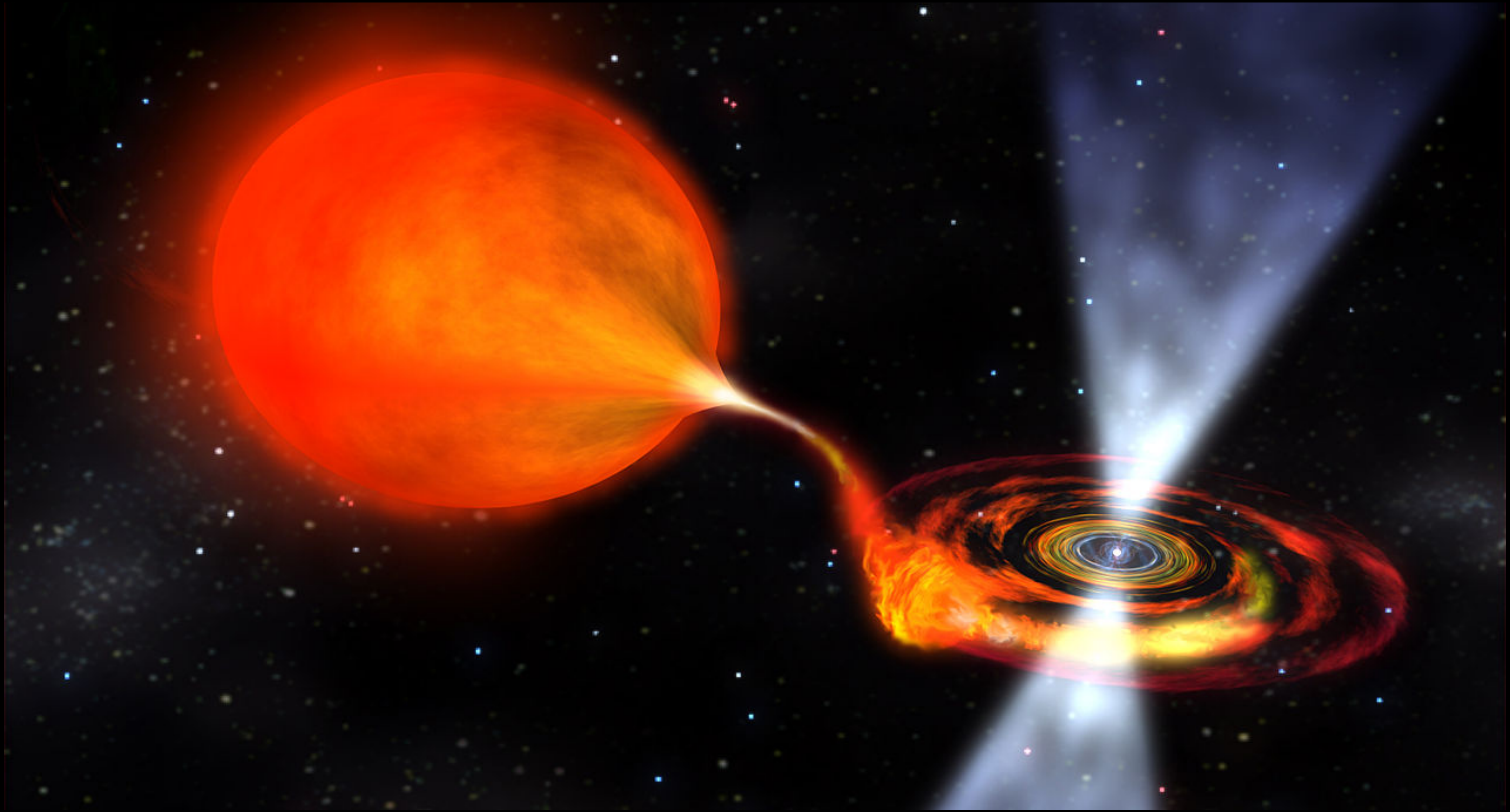
- most constraining: $\varepsilon < 5.3 \times 10^{-9}$ J0711-6830,100 pc away, ≈ 364 Hz, x1.7 below h_0^{spdwn}
- above 300 Hz, $\lesssim 10^{-6}$
- below 60 Hz spindown limit is beaten (x100 for Crab, x20 for Vela), but corresponding ellipticities are higher

YOUNG NEUTRON STARS : SUPERNOVA REMNANTS

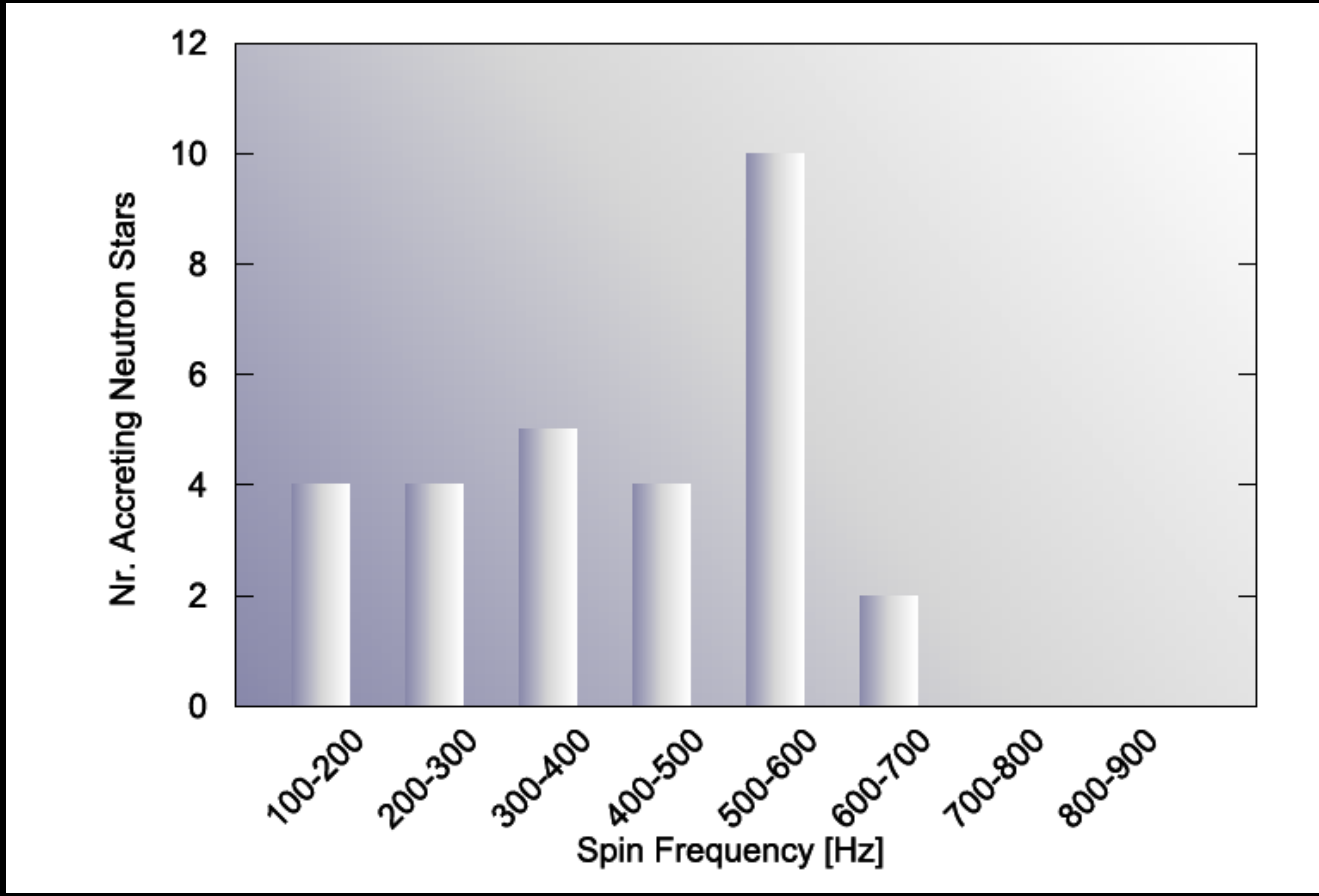


Courtesy NASA/JPL-Caltech

ACCRETING NEUTRON STARS



SPINS OF ACCRETING NEUTRON STARS



Patruno Haskell Andersson, ApJ 850 (2017)

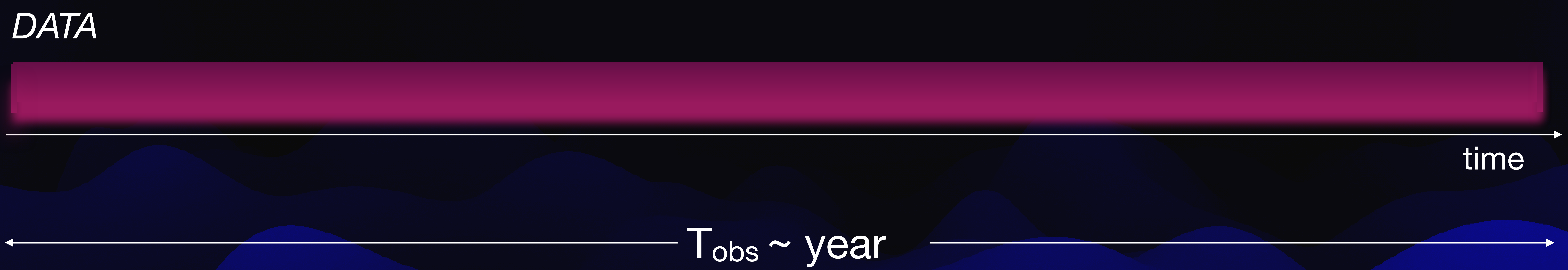
IDEA: TORQUE BALANCE, GW EMISSION BALANCING ACCRETION TORQUE

"BLIND SEARCHES" : SIGNALS FROM UNKNOWN SOURCES

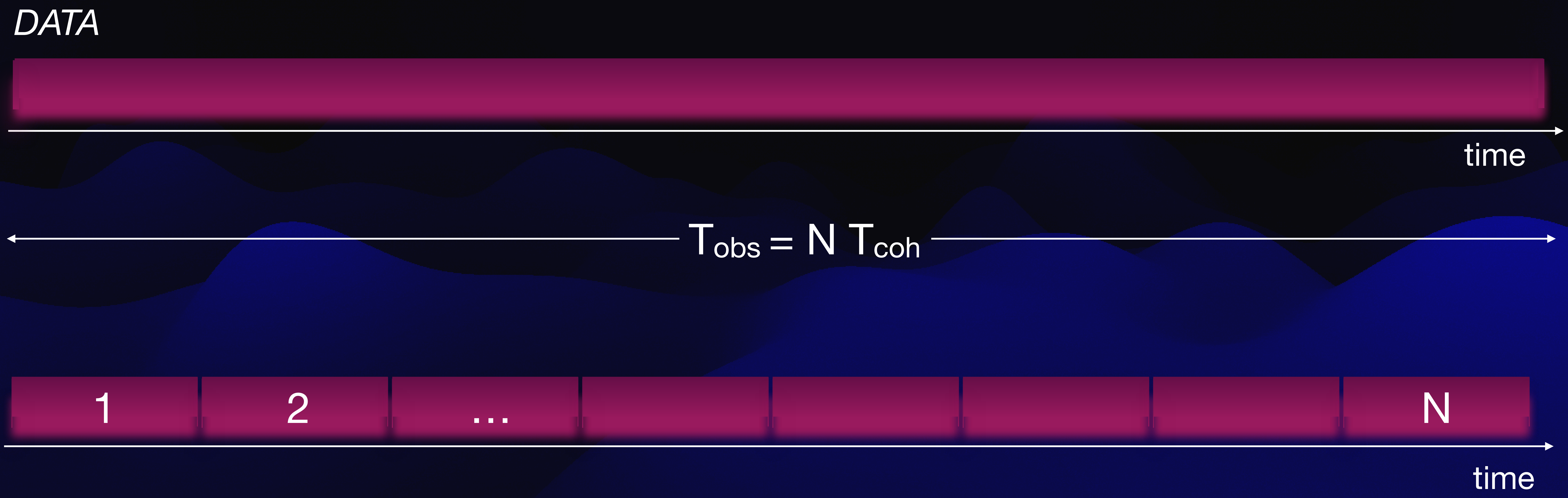
$\approx 10^{28}$ WAVEFORMS RESOLVABLE WITH 6 MONTHS OF DATA

OPTIMAL (FULLY COHERENT) SEARCH METHODS CANNOT BE USED

Semi-coherent searches



Semi-coherent searches

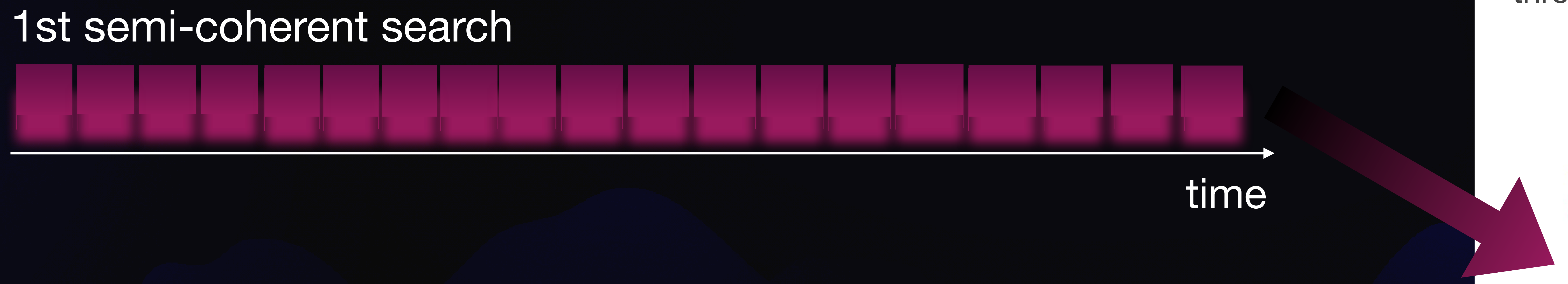


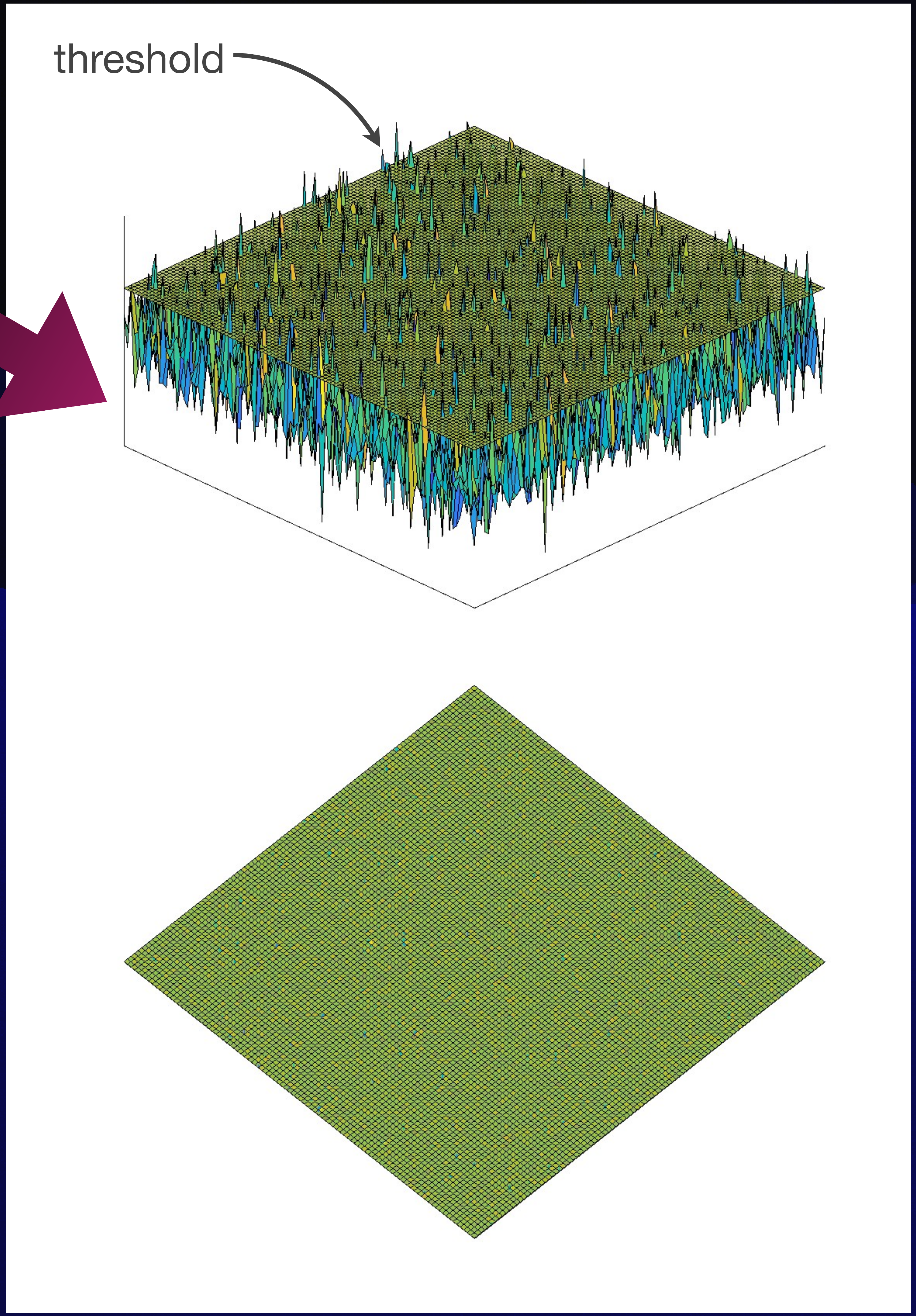
Brady et al, PRD 57 (1998), Brady&Creighton, PRD 61 (2000), Krishnan et al, PRD70 (2004), Dhurandhar et al, PRD 77 (2008), Astone et al, PRD90 (2014), Walsh et al, PRD 94 (2016), O. Piccinni et al, CQG 36 (2019), Dergachev&Papa, PRL 123 (2019)

We do a whole hierarchy of semi-coherent searches

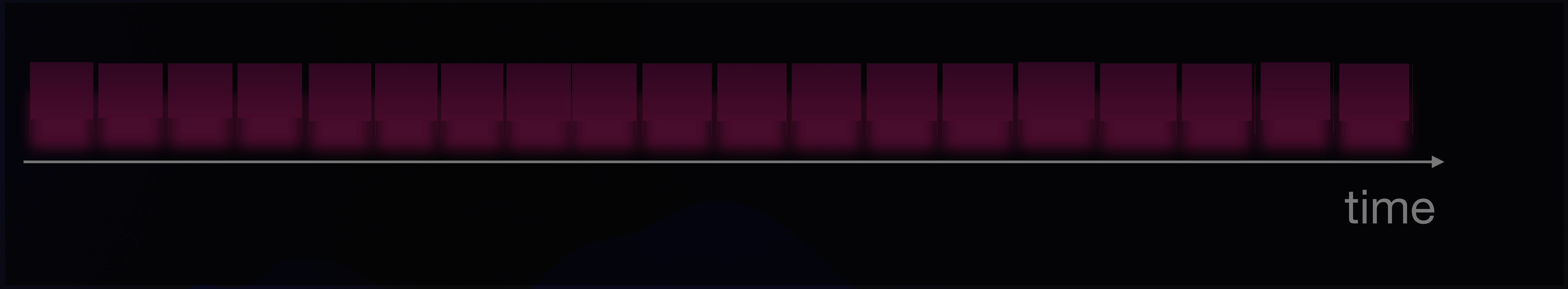
We do a whole hierarchy of semi-coherent searches

Noise rejection

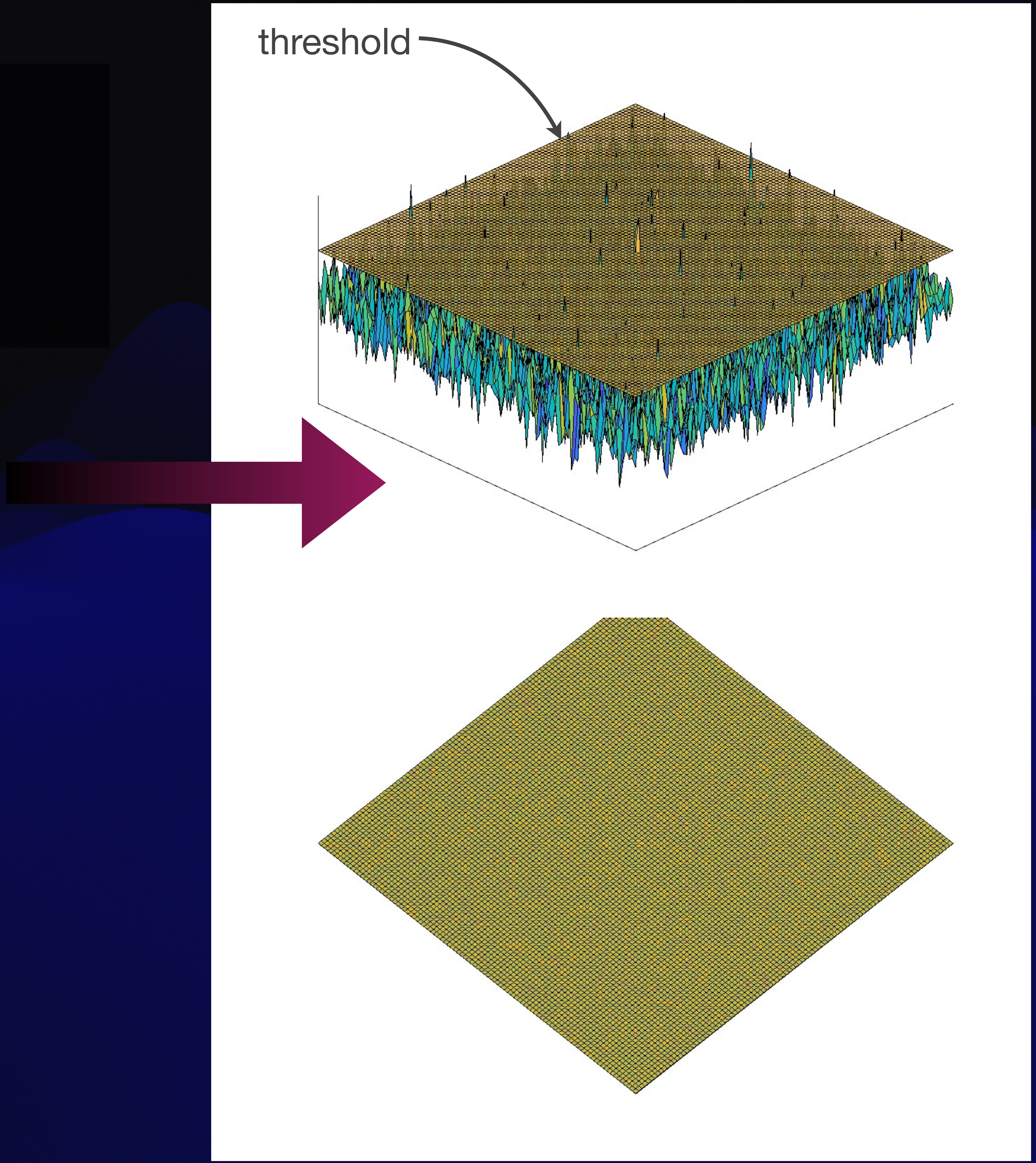




Noise rejection



2nd semi-coherent search



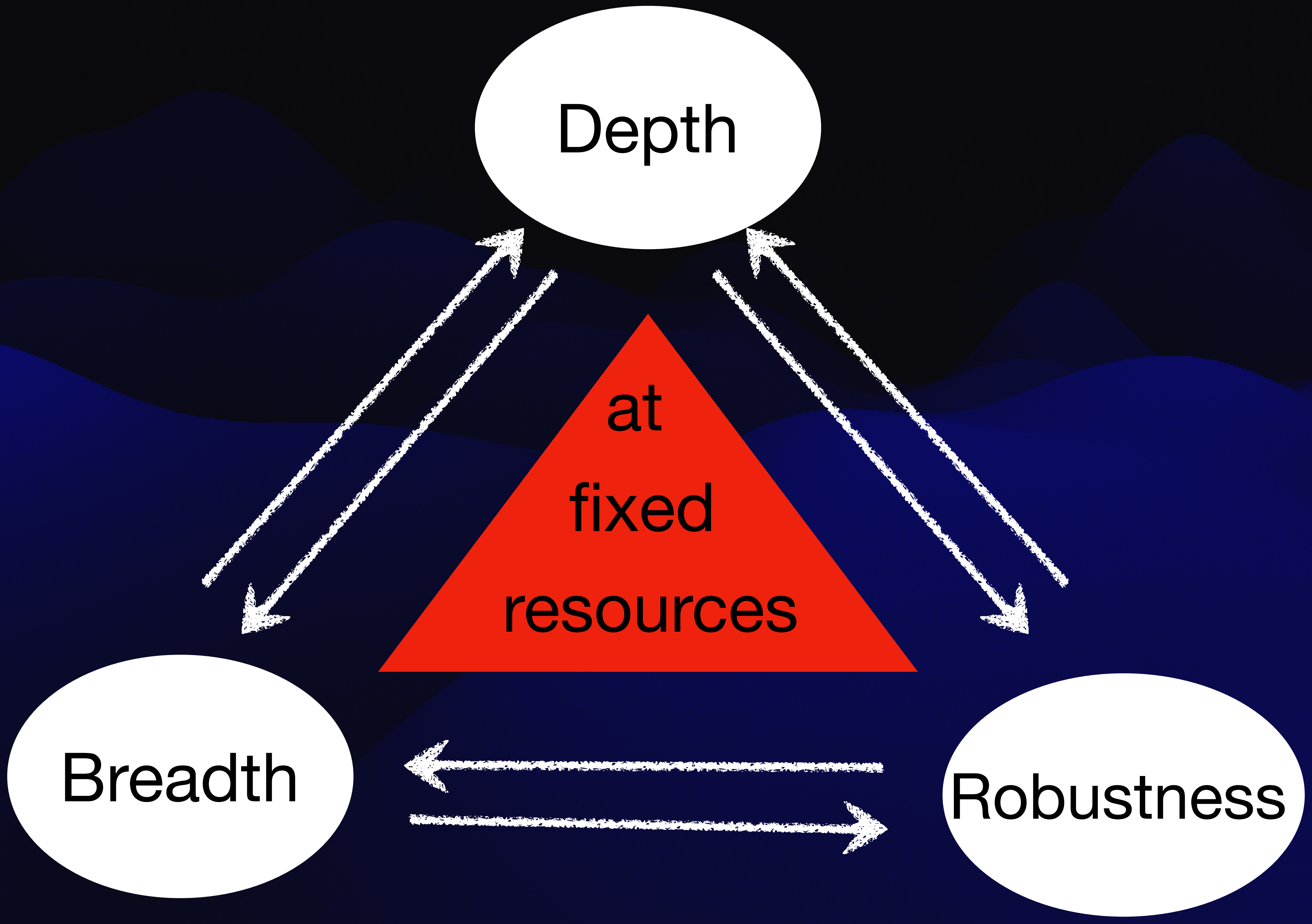
Noise rejection

Noise rejection

FROM POINT OF VIEW OF HIDDEN SIGNAL

FROM POINT OF VIEW OF HIDDEN SIGNAL

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



different algorithms and implementations encode those choices

ALL-SKY,20-800HZ, O3 DATA

The Astrophysical Journal, 952:55 (10pp), 2023 July 20
https://doi.org/10.3847/1538-4357/acdad4

CrossMark

Deep Einstein@Home All-sky Search for Continuous Gravitational Waves in LIGO O3 Public Data

B. Steltner[1,2], M. A. Papa[1,2], H.-B. Eggenstein[1,2], R. Prix[1,2], M. Bensch[1,2], B. Allen[1,2], and B. Machenschalk[1,2]
[1] Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Callinstrasse 38, D-30167 Hannover, Germany; benjamin.steltner@aei.mpg.de, maria.alessandra.papa@aei.mpg.de
[2] Leibniz Universität Hannover, D-30167 Hannover, Germany
Received 2023 March 10; revised 2023 May 31; accepted 2023 May 31; published 2023 July 18

ALL-SKY, 20-800HZ, O3 DATA

Search	T_{coh} (hr)	N_{seg}	N_{in}	N_{out}
Stage 0	120	37	6.7×10^{18}	3513855
Stage 1	120	37	3,513,855	386,429
Stage 2	120	37	386,429	35,635
Stage 3	240	19	35,635	5116
Stage 4	490	9	5116	1387
Stage 5	1100	4	1387	310
Stage 6	2200	2	310	54
Stage 7	Coherent	1	54	12
Stage 8	O3b coh.	1	12	6
Stage 9[b]	O3a+b coh.	1	6	6

these are fake signals → no real candidate surviving

VERY GOOD PARAMETER RECONSTRUCTION

(BASED ON THE HARDWARE INJECTION RECOVERY)

ID_{inj}	f (Hz)	$\dot{f}$ (Hz s^{-1})	Δf (Hz)	$\Delta \dot{f}$ (Hz s^{-1})	Sky Distance (deg:m:s)
0	265.57505348	-4.15×10^{-12}	-4.7×10^{-11}	9.5×10^{-16}	0:0:0.0741
2	575.16350527	-1.37×10^{-13}	-1.1×10^{-09}	-8.8×10^{-16}	0:0:0.0955
3	108.85715939	-1.46×10^{-17}	6.7×10^{-10}	-5.8×10^{-16}	0:0:0.3080
5	52.80832436	-4.03×10^{-18}	-6.2×10^{-10}	-4.2×10^{-16}	0:0:0.2212
9	763.84731649	-1.45×10^{-17}	9.4×10^{-10}	-5.6×10^{-17}	0:0:0.0023
10	26.33209638	-8.50×10^{-11}	-8.3×10^{-11}	2.4×10^{-16}	0:0:0.3109

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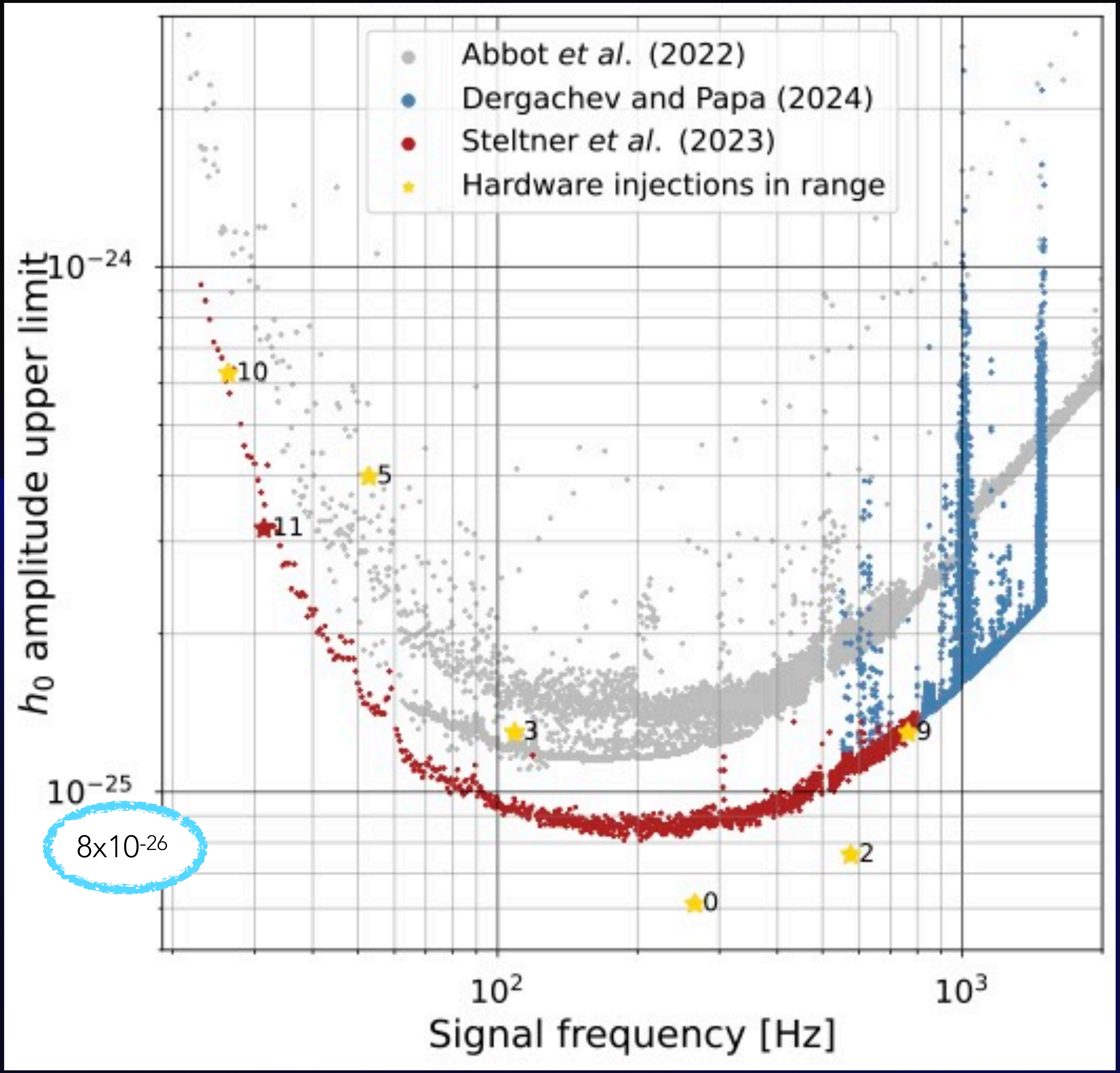
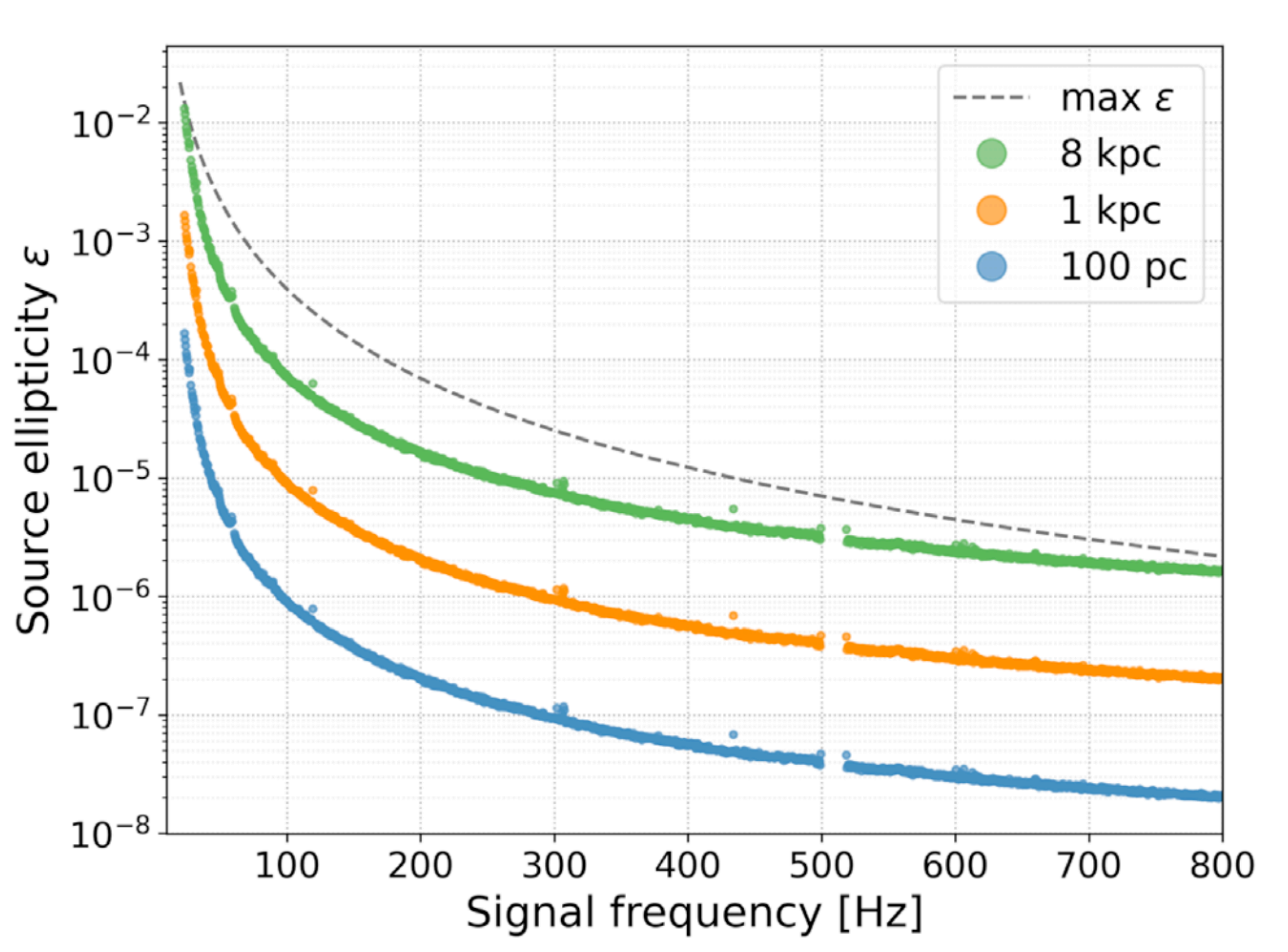
If something is detected how does it make sense to inspect that spot in the sky ?

O3 data



Abbot et al. (2022)
Dergachev and Papa (2024)
Steltner et al. (2023)
Hardware injections in range
h_0 amplitude upper limit
10^{-24}
10^{-25}
8x10-26
10^2
10^3
Signal frequency [Hz]
10
5
11
3
9
2
0

ELLIPTICITY UPPER LIMITS



FIRST STAGE IS THE MOST EXPENSIVE

Einstein@Home volunteer distributed computing project, tens of thousands of machines 24 x 7.

FIRST STAGE IS THE MOST EXPENSIVE

Einstein@Home volunteer distributed computing project, tens of thousands of machines 24 x 7.

Sign-up and help us find CWs !

https://einsteinathome.org/

BUT NOT ALL SEARCHES NEED EINSTEIN@HOME …

Expanded atlas of the sky in continuous gravitational waves

Vladimir Dergachev[1, a] and Maria Alessandra Papa[1, 2, b]

[1] *Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Callinstrasse 38, 30167 Hannover, Germany*
[2] *Leibniz Universität Hannover, D-30167 Hannover, Germany*

We present the full release of the atlas of continuous gravitational waves, covering frequencies from 20 Hz to 1700 Hz and spindowns from -5×10^{-10} to 5×10^{-10} Hz/s. Compared to the early atlas release, we have extended the frequency range and have performed follow-up on the outliers. Conducting continuous wave searches is computationally intensive and time-consuming. The atlas facilitates the execution of new searches with relatively minimal computing resources.

BUT NOT ALL SEARCHES NEED EINSTEIN@HOME …

arXiv:2503.11512v2 [gr-qc] 6 Apr 2025

Expanded a … **tional waves**

Vlad … 1, 2, b

[1] *Max Planck Institute for Gravita* … *sse 38, 30167 Hannover, Germany*

[2] *Leib* … *many*

We present the full … s, covering frequencies
from 20 Hz to 1700 Hz … Compared to the early
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Conducting continuous … -consuming. The atlas
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SYNTHETIC POPULATIONS AND CHANCES OF DETECTION

- must be lucky to see a signal from a non-recycled neutron star now
- Much better prospects with next generation detectors:

Model	expected # of detectable signals	
	ET	CE
$A2_{low}$	231.9 ± 14.6	338.1 ± 16.8
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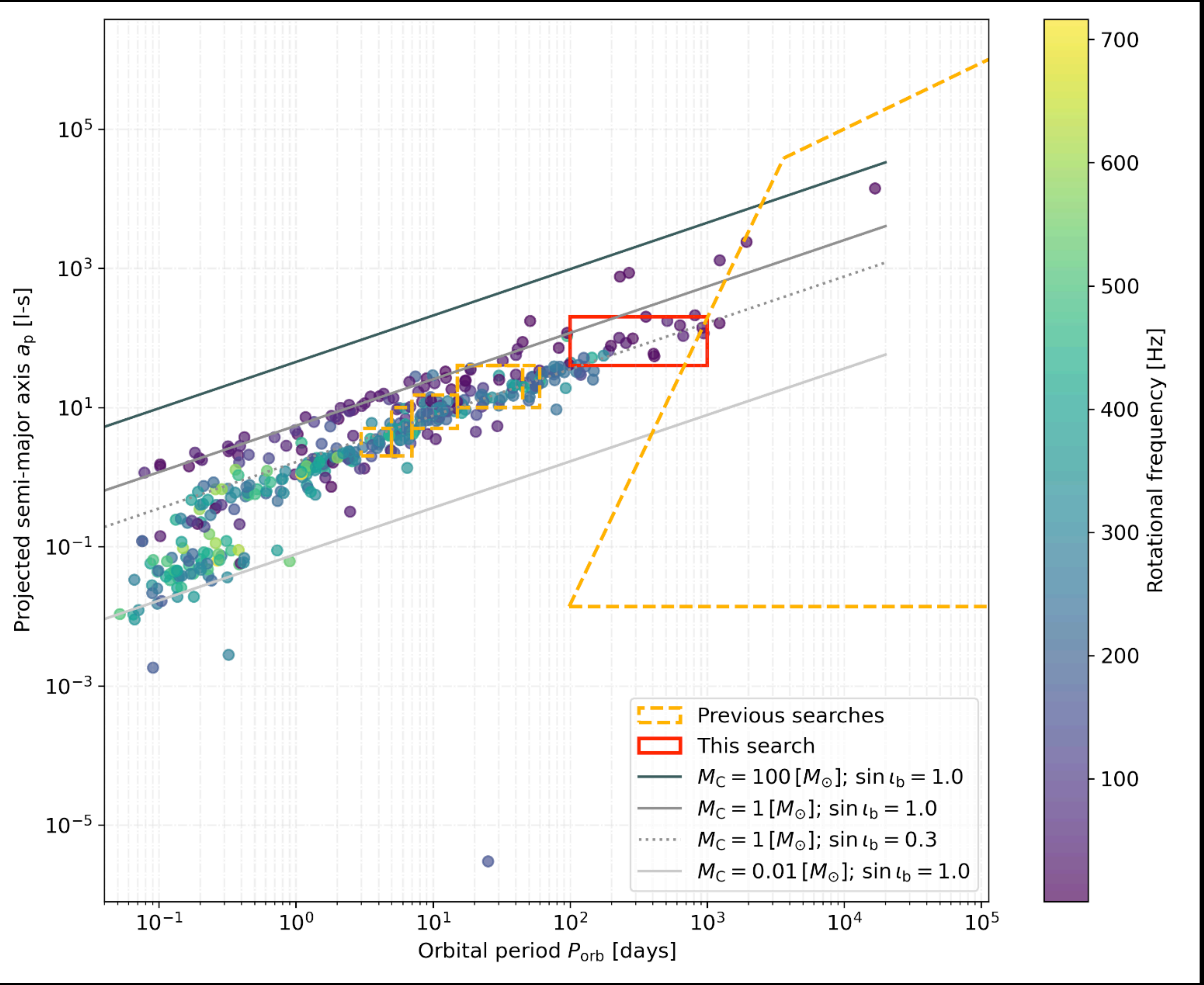
Pagliaro et al, ApJ 952 (2023)

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

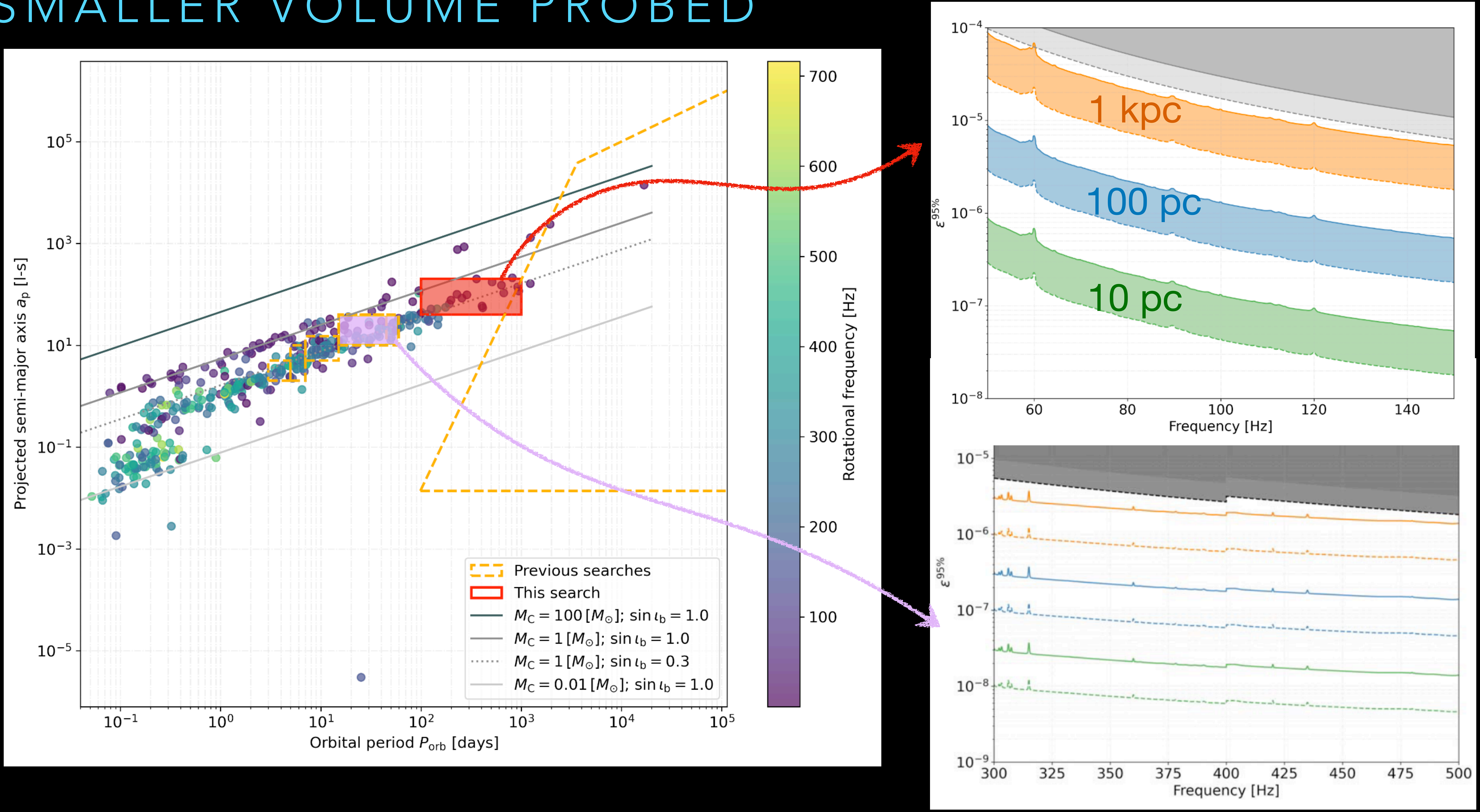
SIGNAL FROM NEUTRON STARS IN BINARY SYSTEM



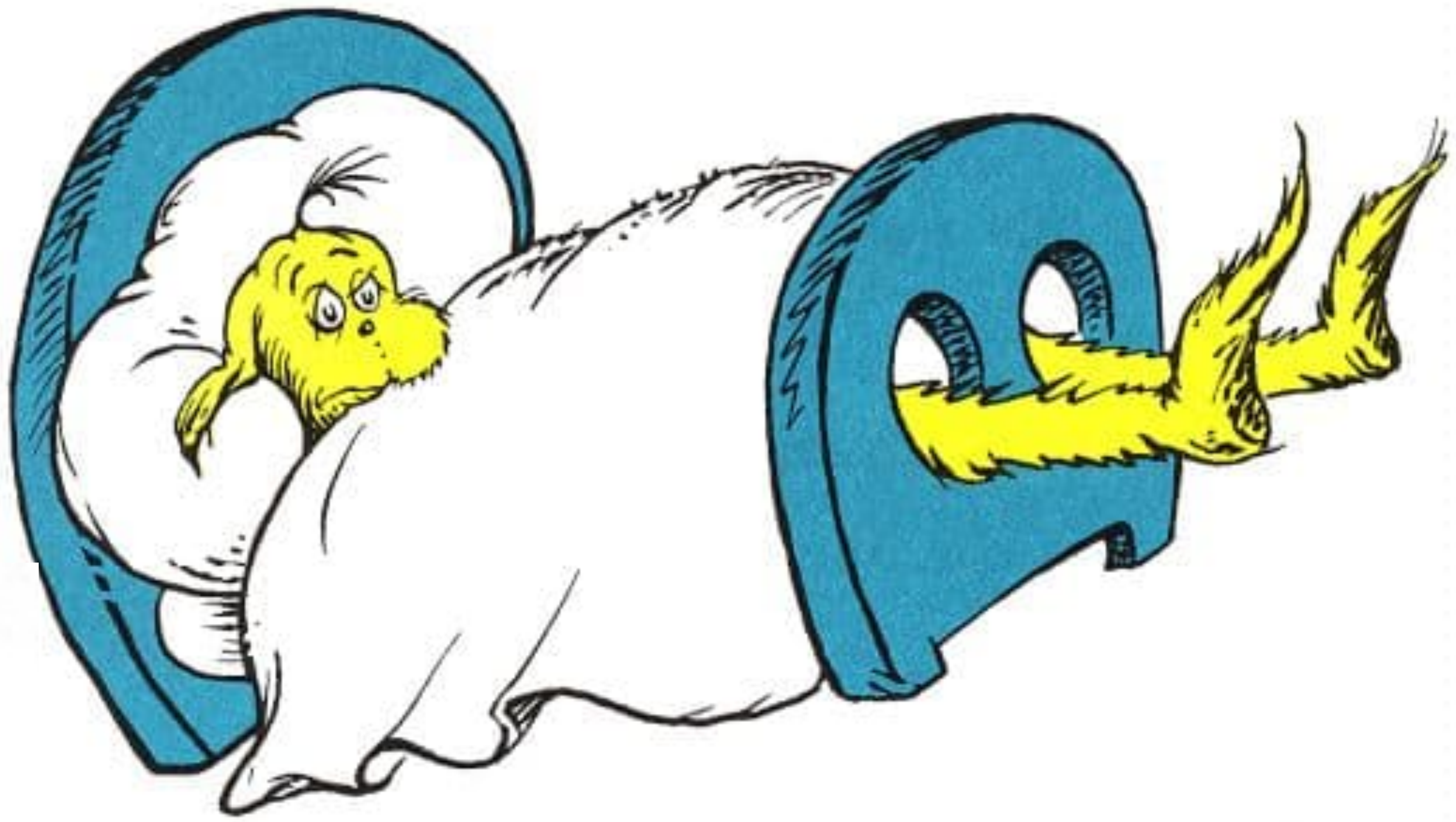
Covas et al, arxiv:2409.16196, to appear in ApJ

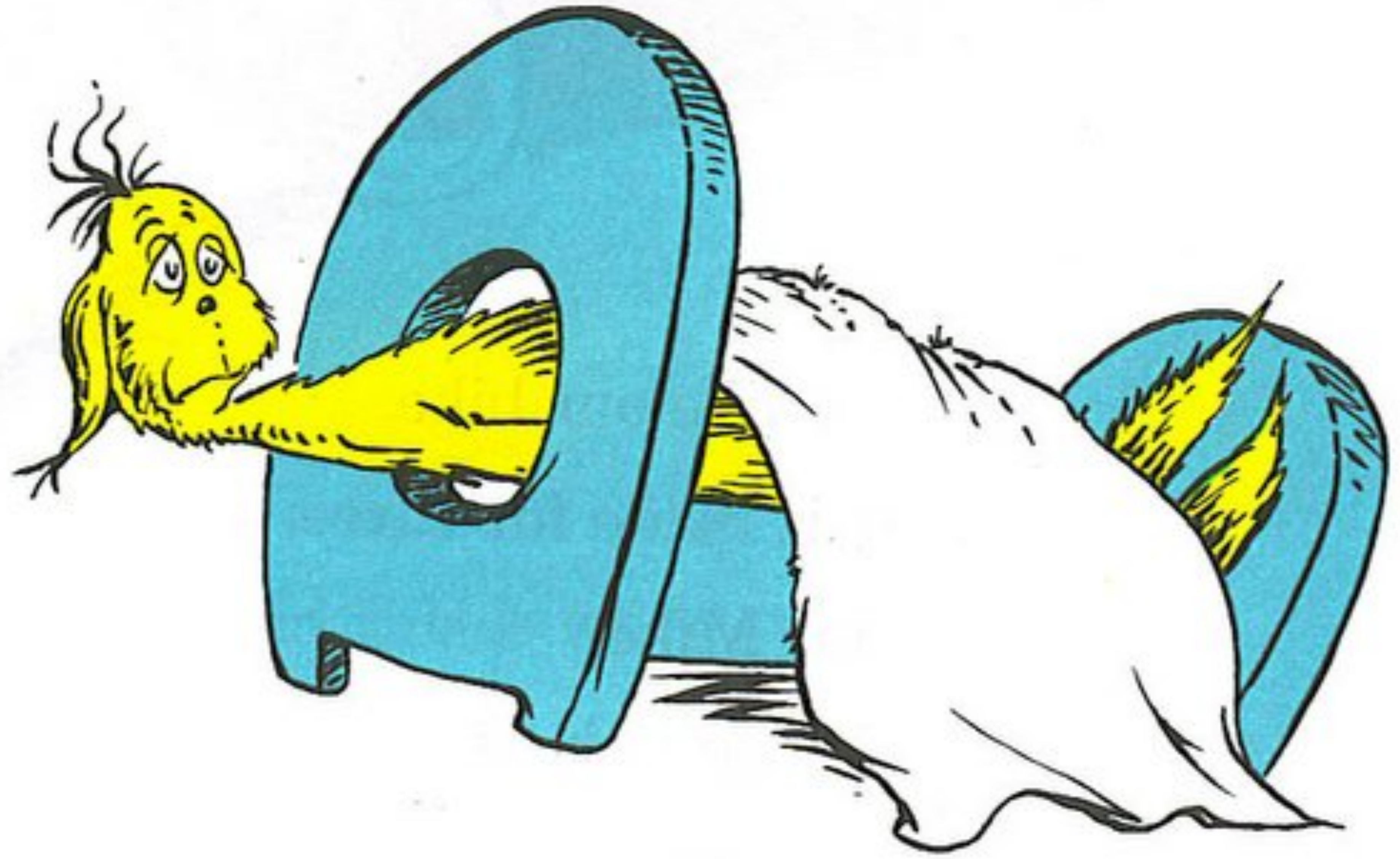
SMALLER VOLUME PROBED

Covas et al, arxiv:2409.16196



NEED FOR NEW AND CLEVER METHODS





...SUMMARISING

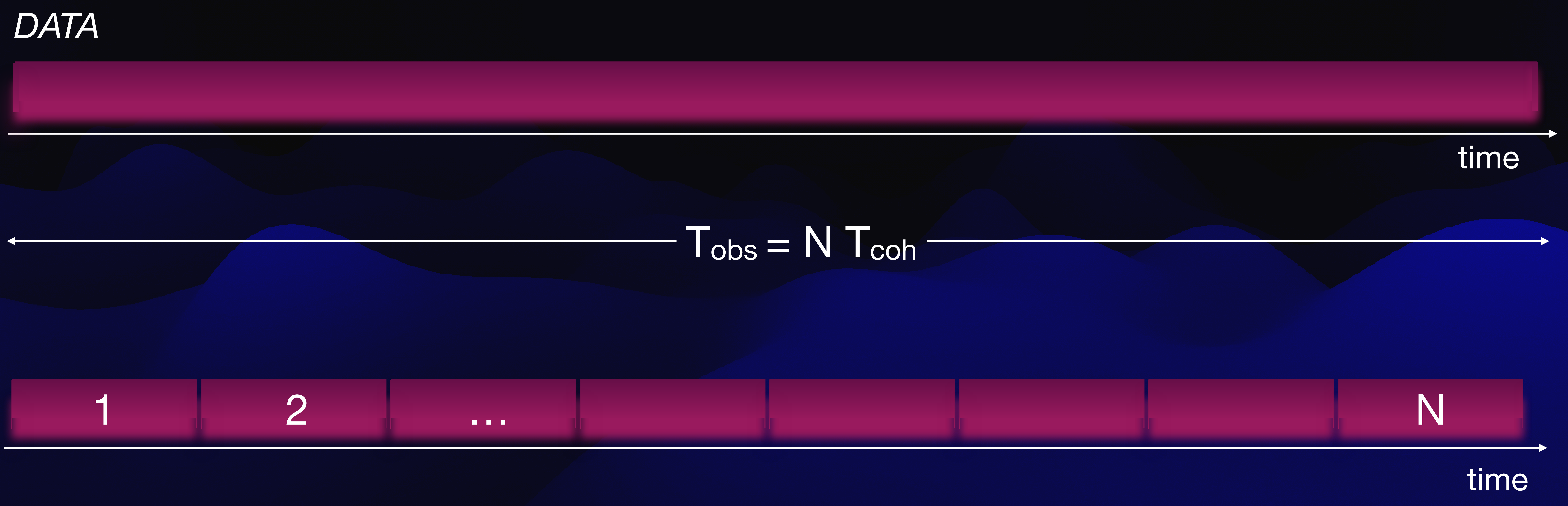
- the first detection of a continuous GW from a neutron star will open the field of GW-pulsar-astronomy
- now probing interesting source parameter-range
- broad surveys are hard and require significant computing
- trade-offs necessary: different approaches ma different choices
- many open problems
- auxiliary observations and modelling useful now and after first detection
- high-risk/high-gain enterprise, but remember the history of GWs...

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

–JOHN C. MAXWELL

THANK YOU !

Semi-coherent searches



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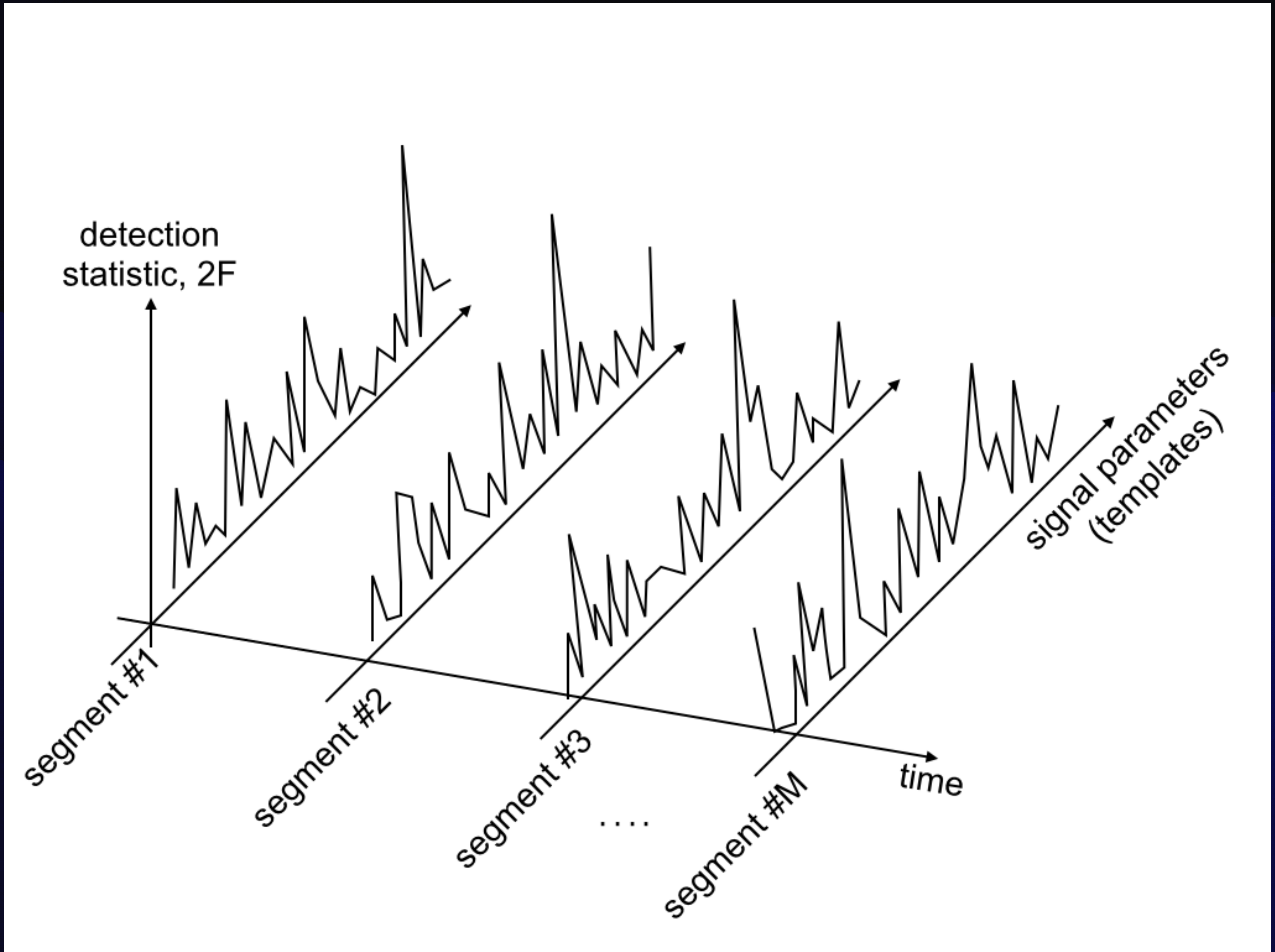
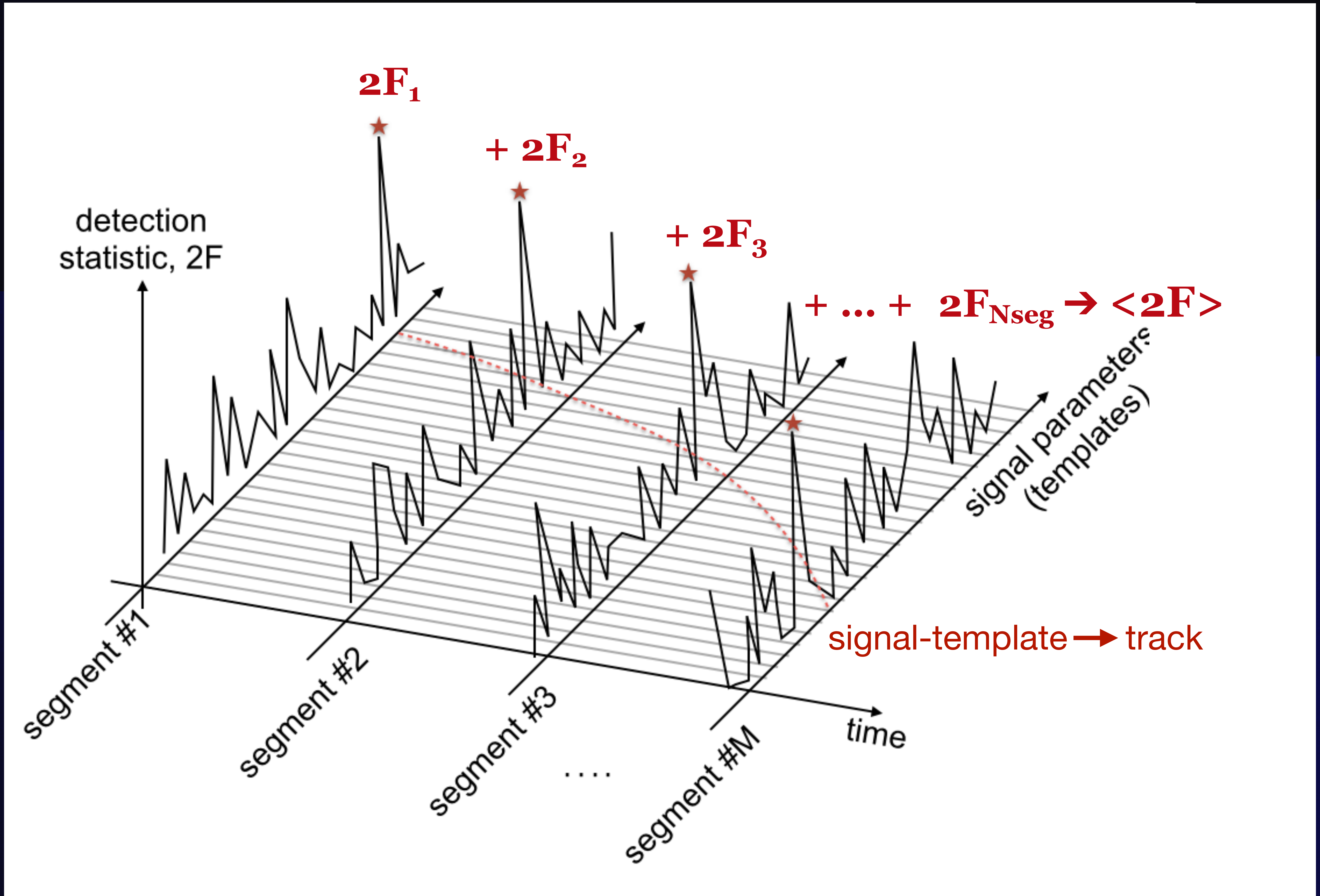
combination of per-segment results



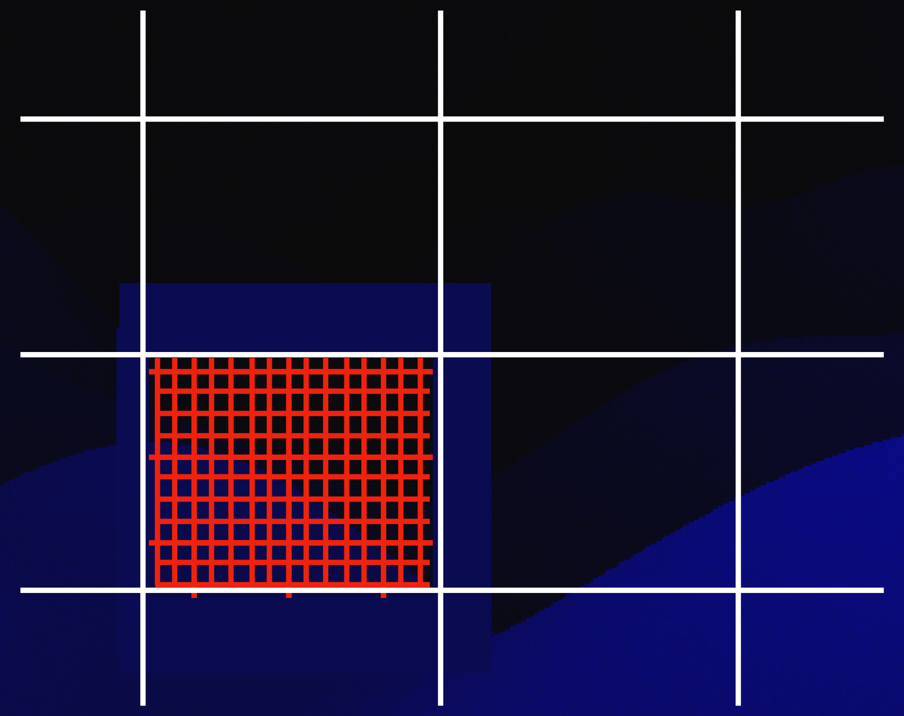
- divide the data set in segments
- perform a coherent (F-stat) search on each segment
- combine the results from the segments, by adding the $\mathscr{F}$-stat values, one per segment

$$\frac{1}{N_{seg}} \sum_{i=1}^{N_{seg}} 2\mathscr{F}_i$$

Combination of the single-segment results



- per-segment search uses coarse template grid



- sum-track uses finer grid

WHAT ARE THE CHANCES OF DETECTION?

S_h(freq) ⟶ search-sensitivity(freq)

age

$\mathcal{E}$

Distance

Magnetic field

Spin frequency, now

Spin frequency at birth

Position

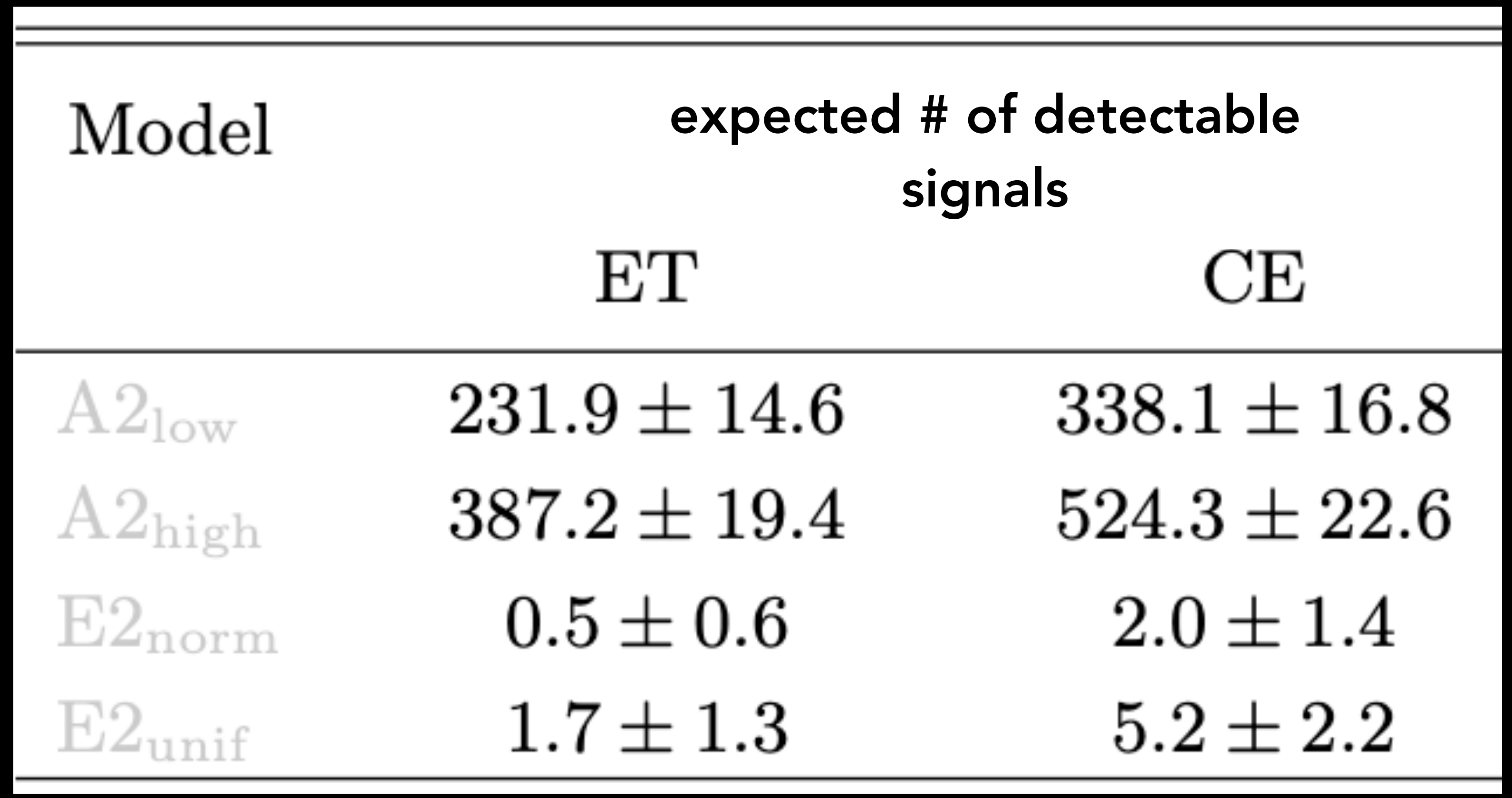
Kick velocity at birth

Convolve together all these effects by building a synthetic population of neutron stars

Pagliaro et al, ApJ 952 (2023)

Convolve together all these effects by building a synthetic population of neutron stars

- must be lucky to see a signal from a non-recycled neutron star now
- Much better prospects with next generation detectors:



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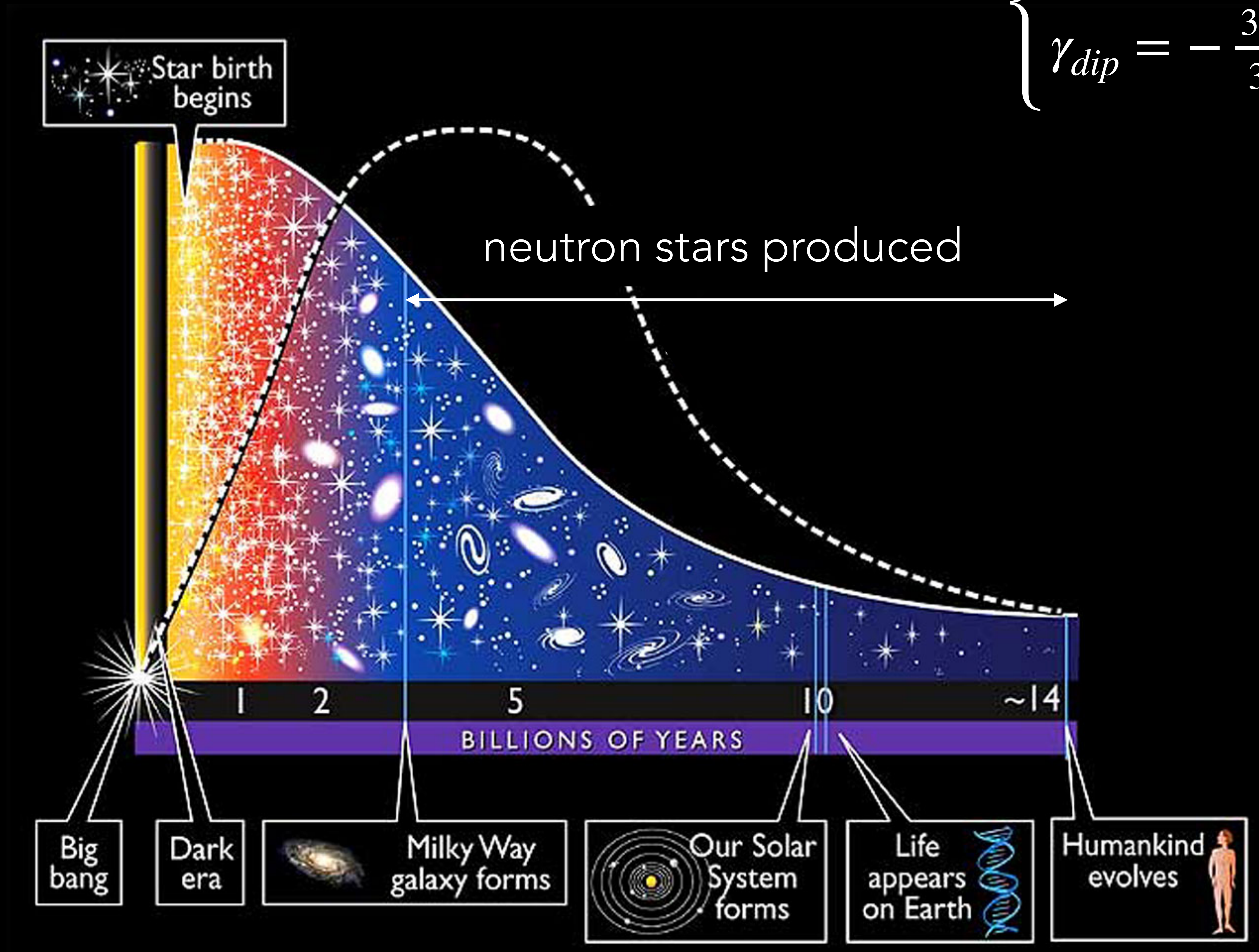
Pagliaro et al, ApJ 952 (2023)

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
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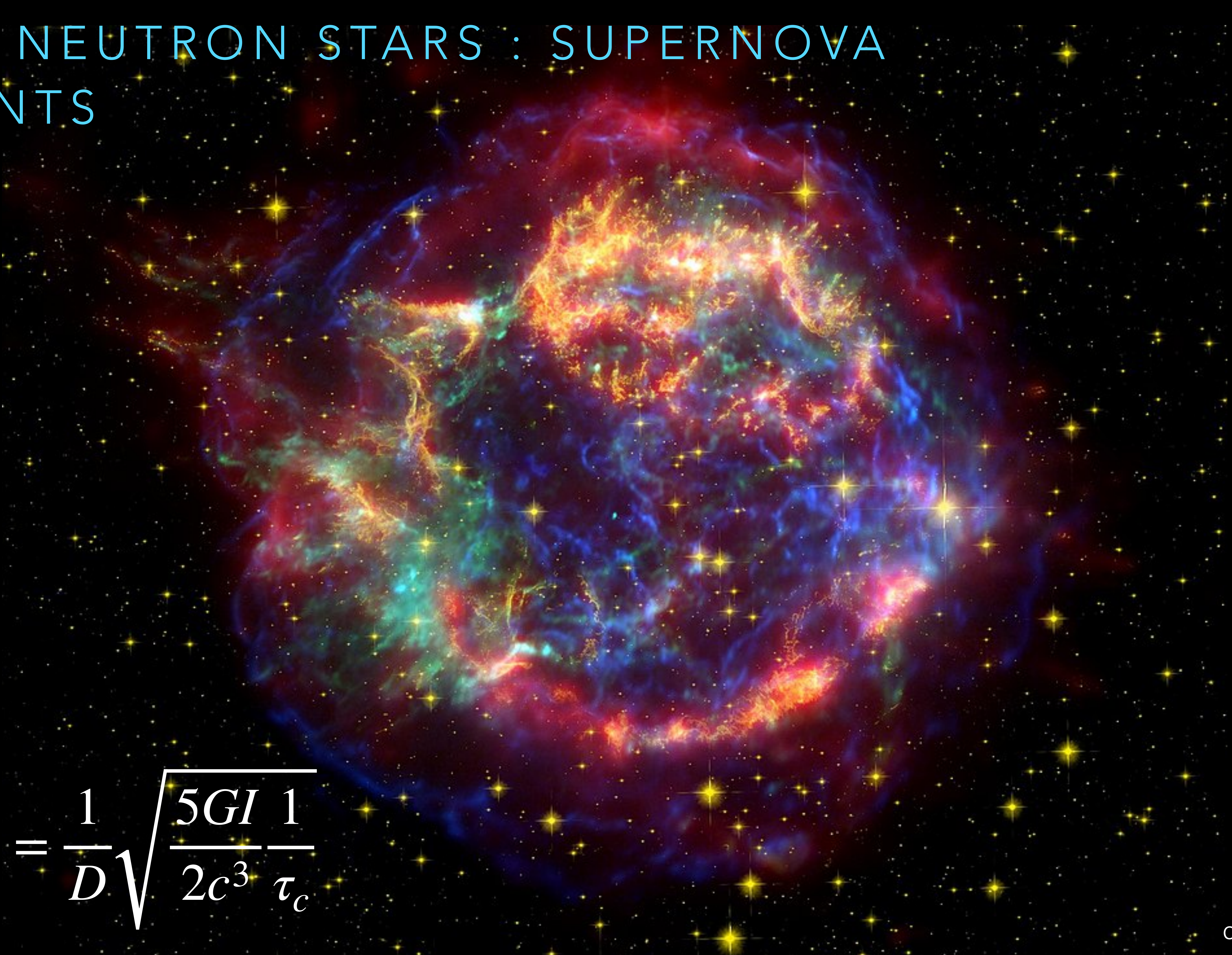
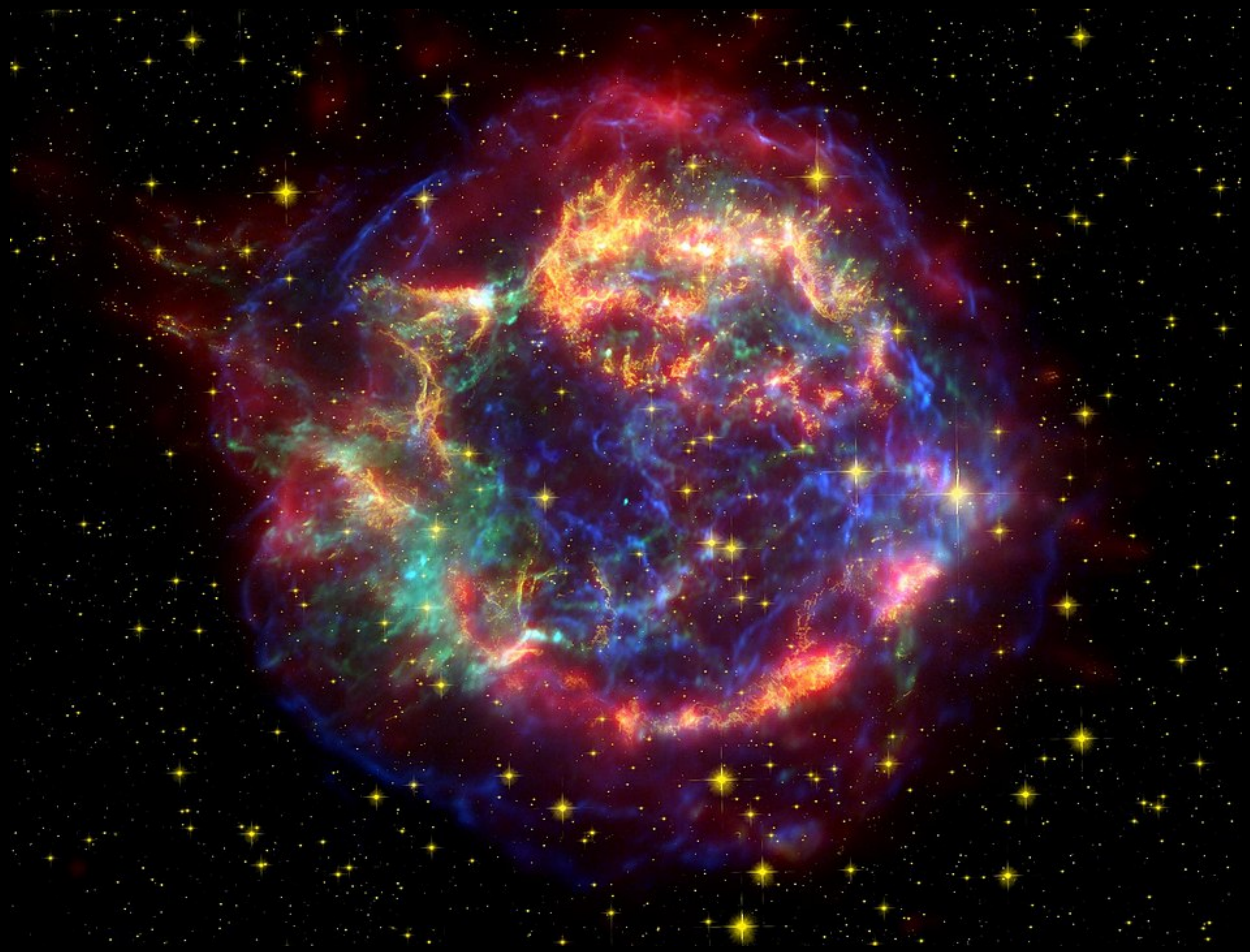


$$h_0 \leq h_0^{age} = \frac{1}{D}\sqrt{\frac{5GI}{2c^3}\frac{1}{\tau_c}}$$

Courtesy NASA/JPL-Caltech

Cassiopeia A (Cas A)



- 330 ± 20 yrs old
- 3.5 ± 0.2 kpc away

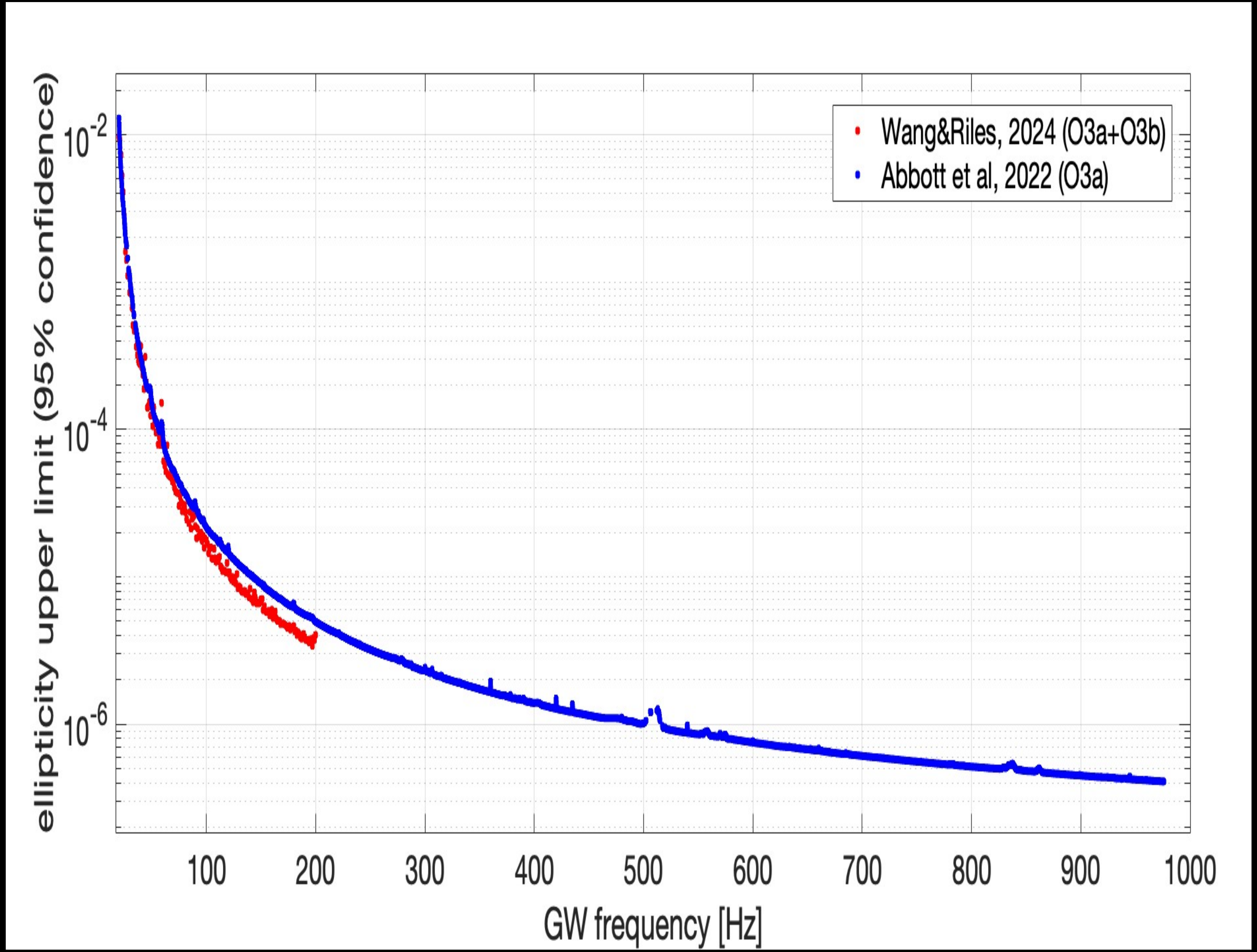
Vela Jr

- 700 yrs old
- 200 pc away

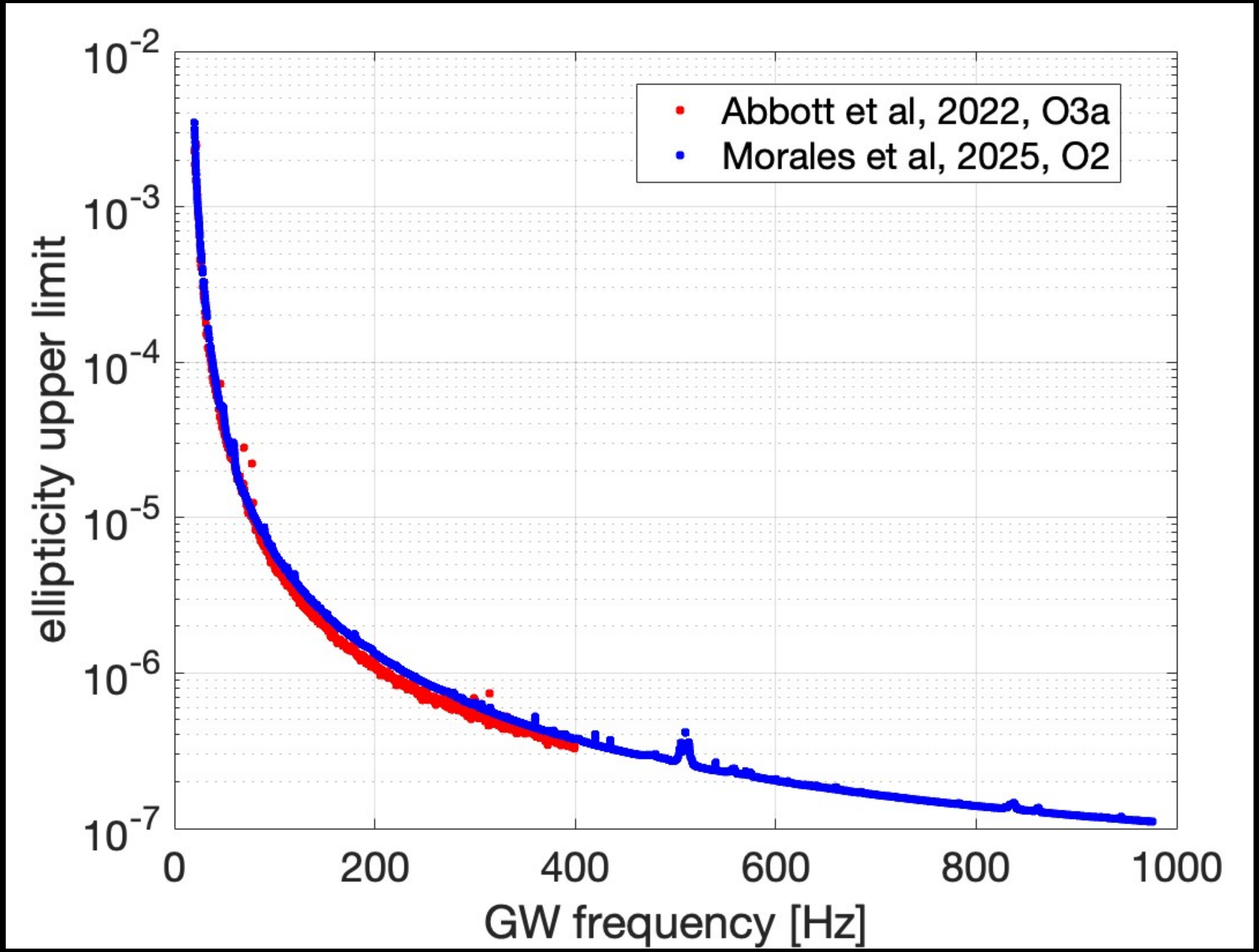
- 4300yrs old
- 750 pc away

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

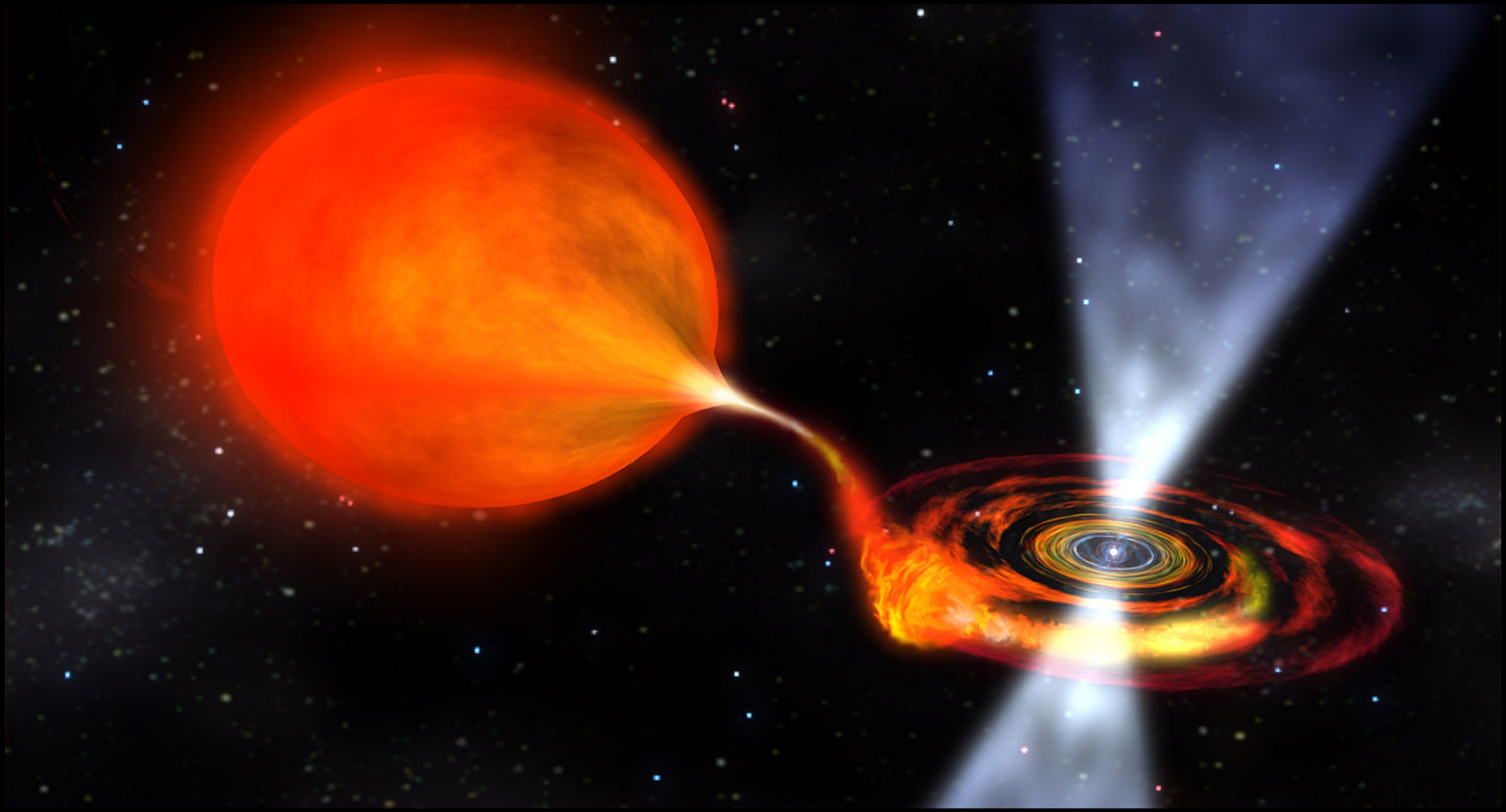
Cassiopeia A (Cas A)



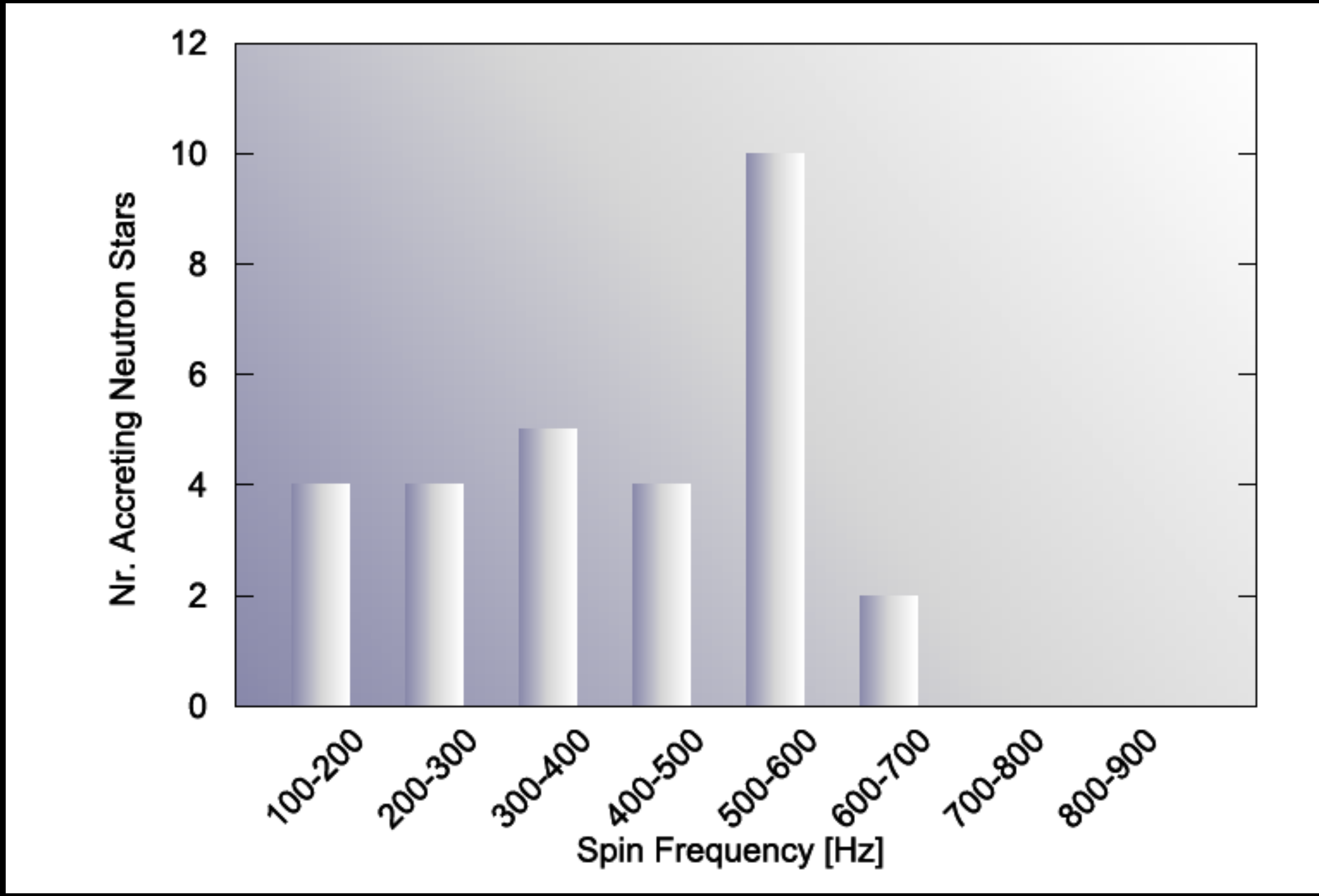
Vela Jr



ACCRETING NEUTRON STARS



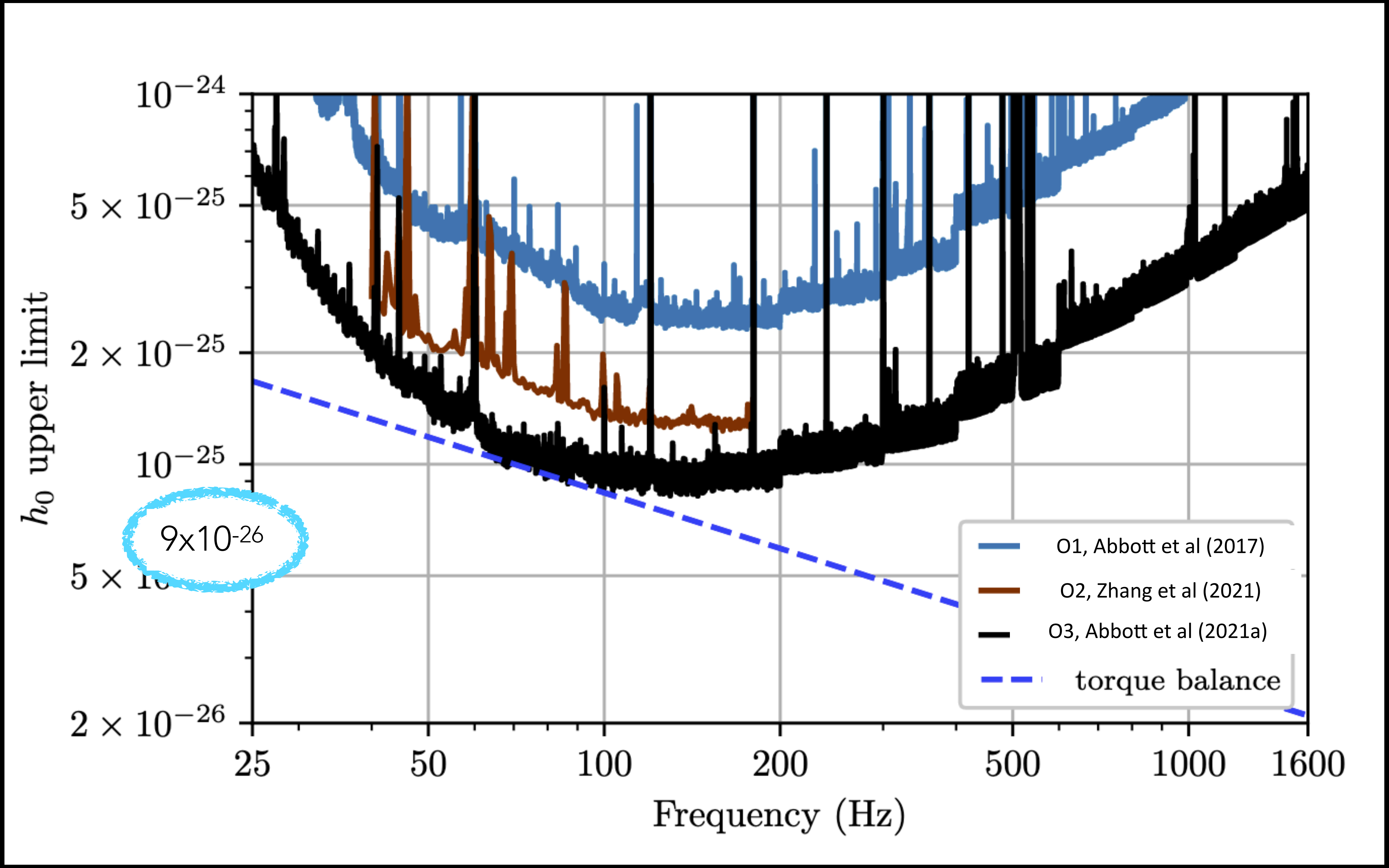
SPINS OF ACCRETING NEUTRON STARS



Patruno Haskell Andersson, ApJ 850 (2017)

IDEA: TORQUE BALANCE, GW EMISSION BALANCING ACCRETION TORQUE

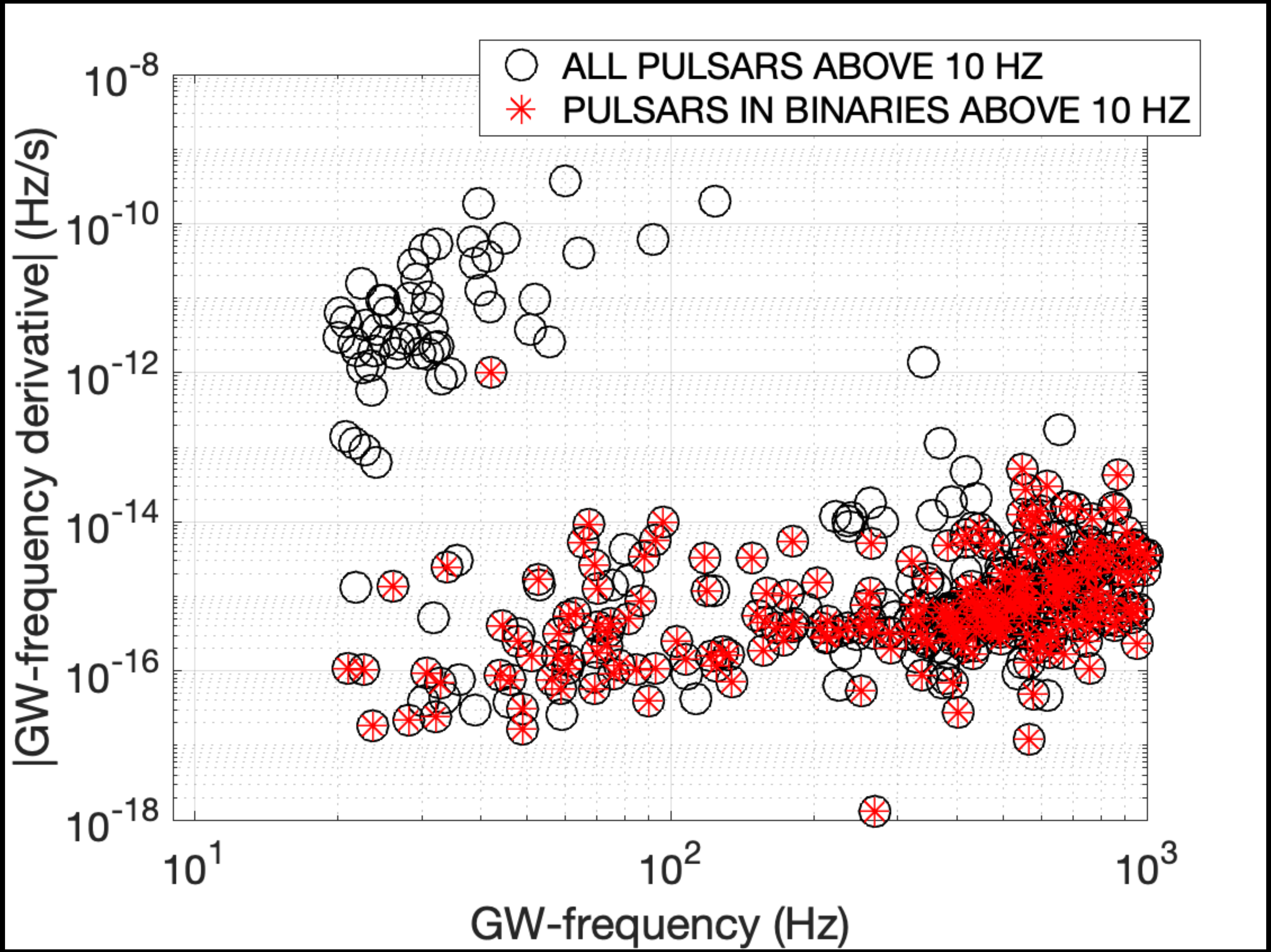
SCORPIUS X-1
BRIGHTEST X-RAY SOURCE (AFTER SUN)



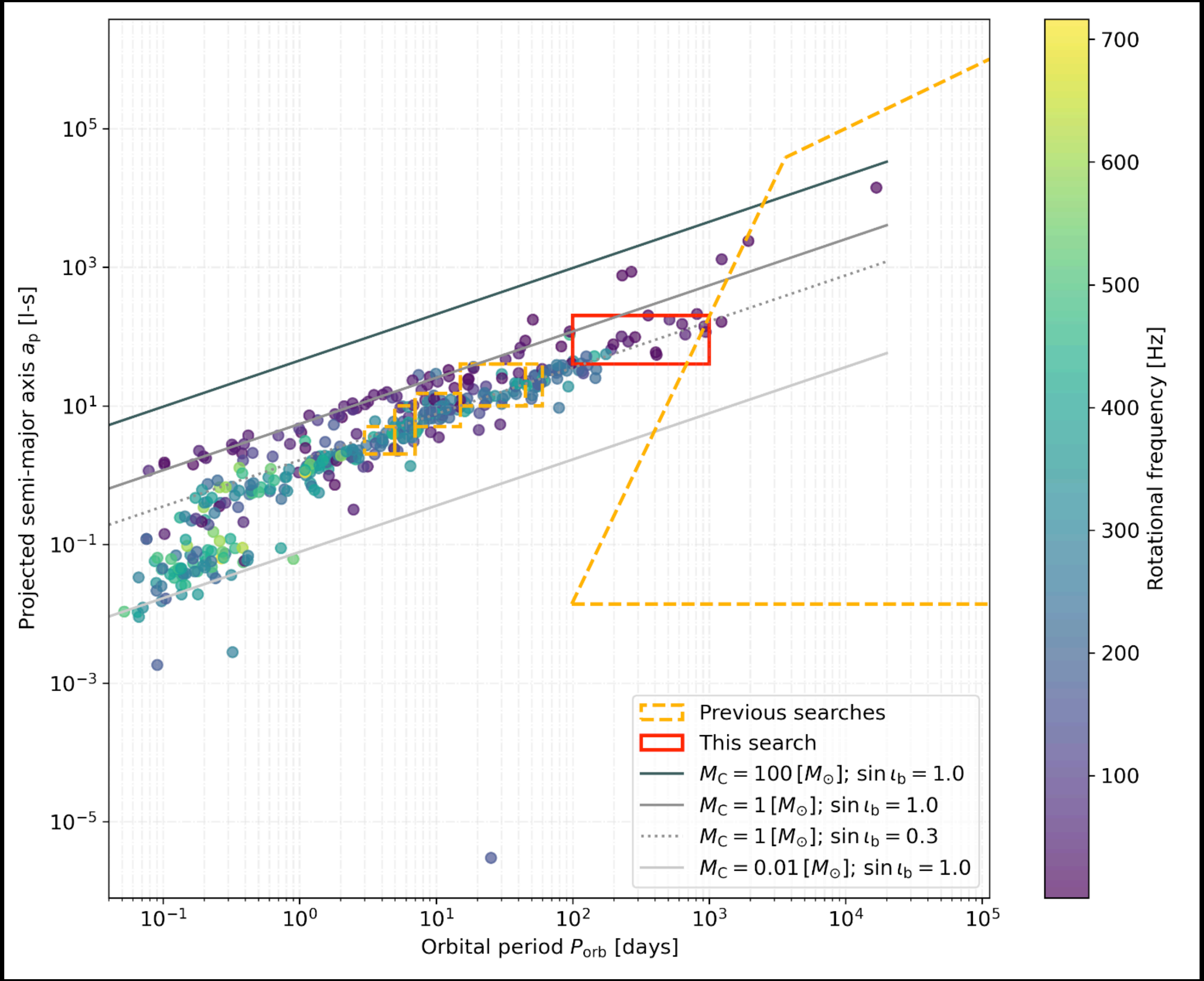
Abbott et al, *Astrophys.J.Lett.* 941 (2022) 2, L30, Whelan et al, *Astrophys.J.* 949 (2023) 2, 117

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

50% OF PULSARS ROTATING ABOVE 10 HZ ARE IN BINARIES



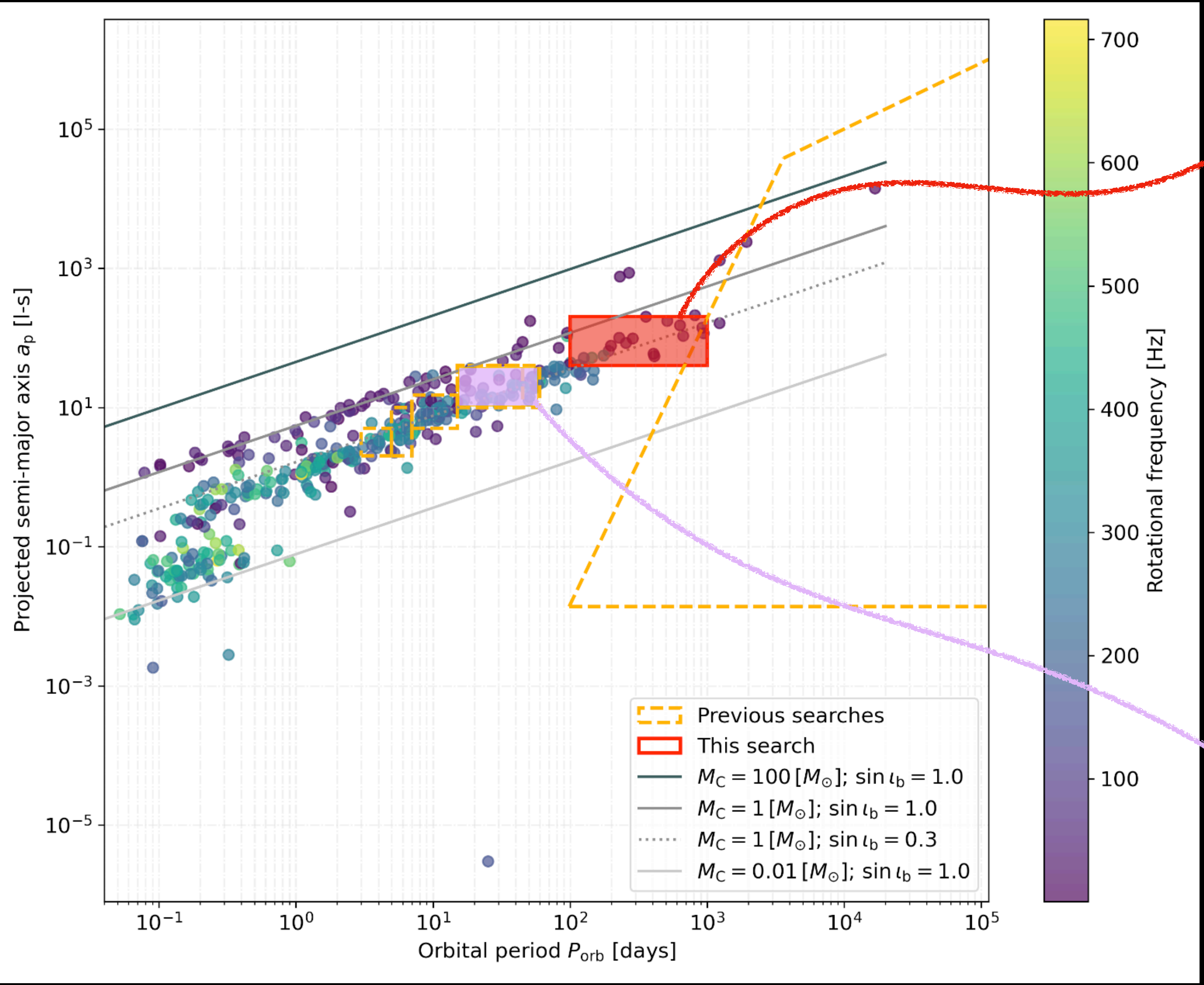
SIGNAL FROM NEUTRON STAR IN BINARY SYSTEM

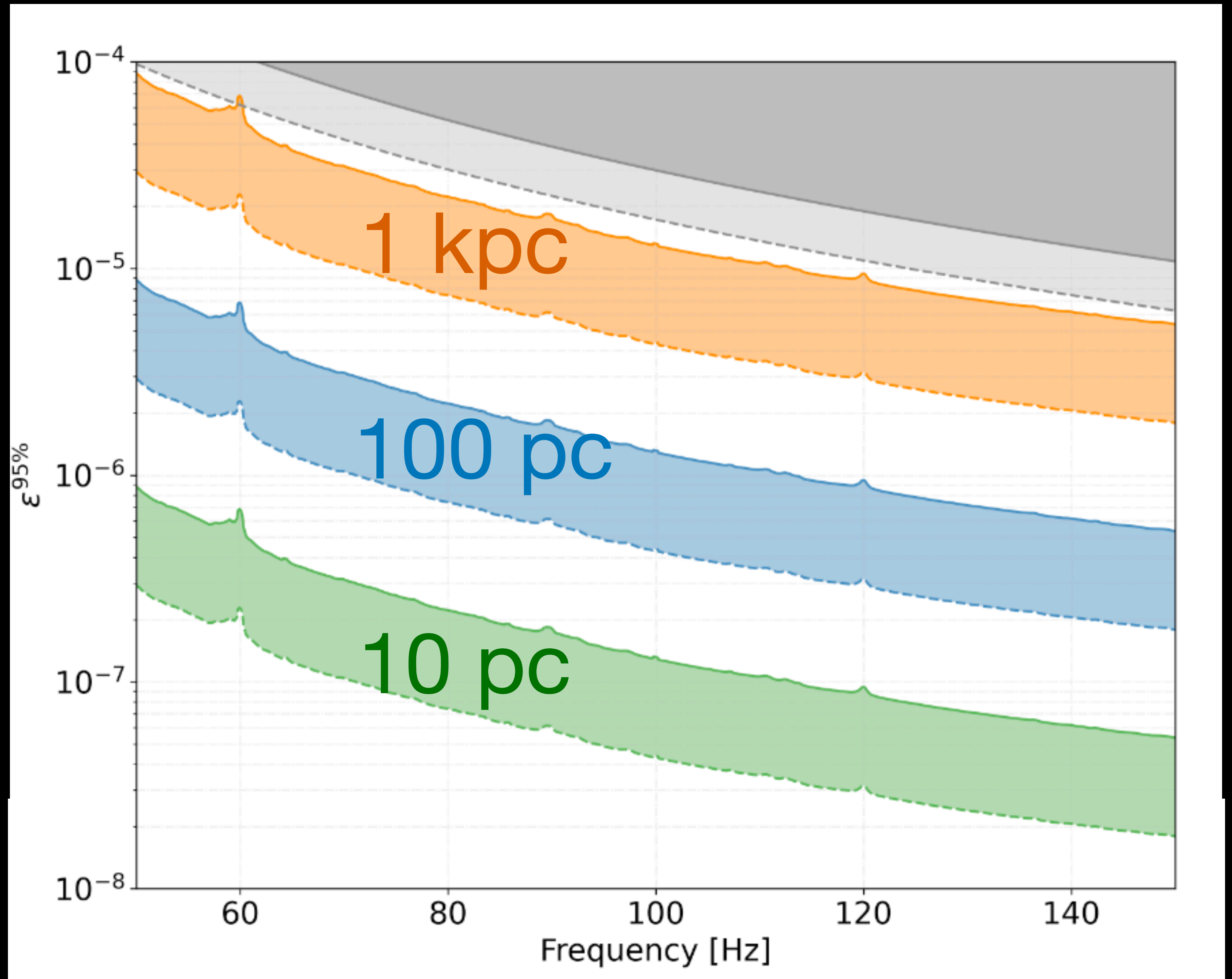


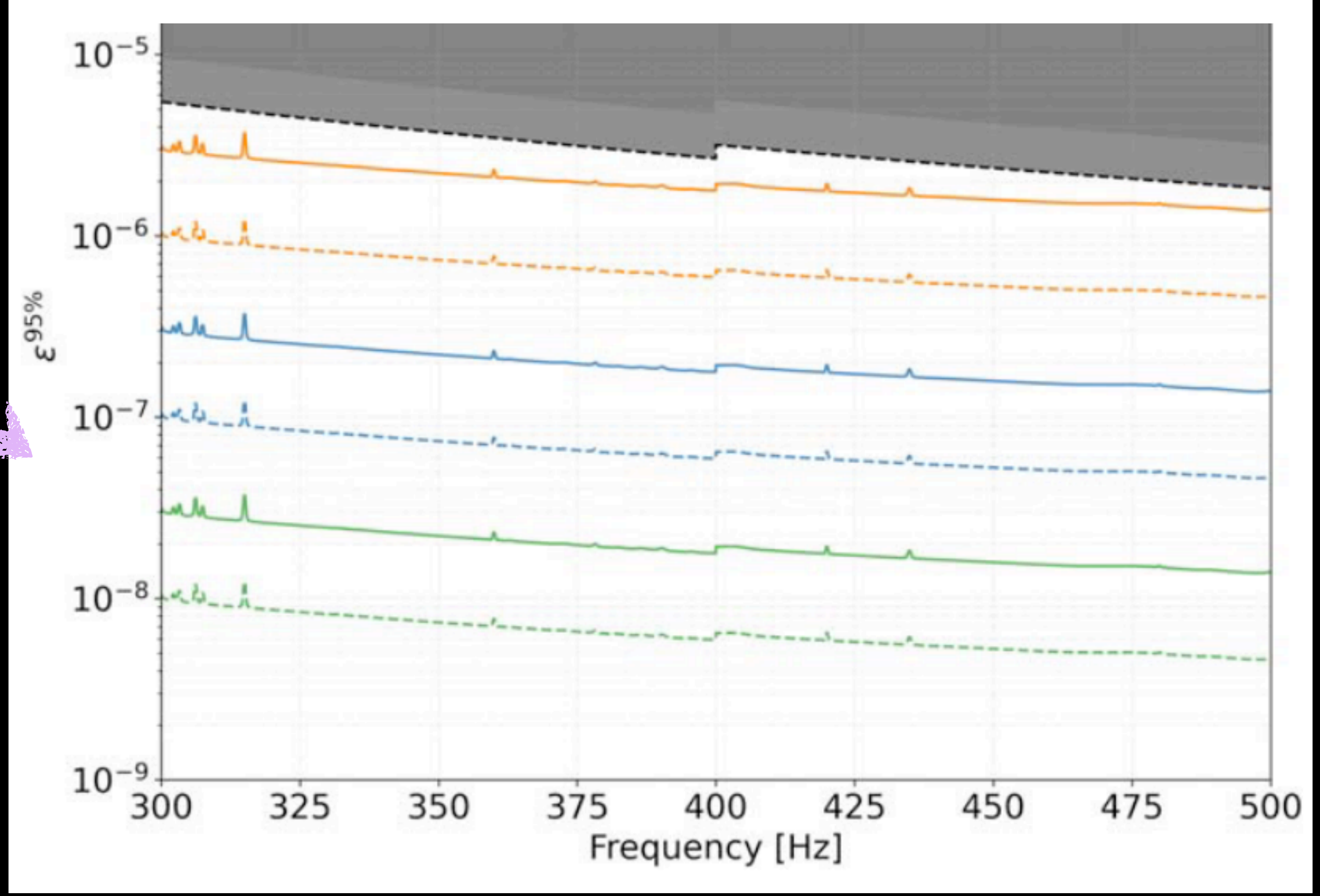
Covas et al, arxiv:2409.16196, to appear in ApJ

PREVIOUS SEARCHES

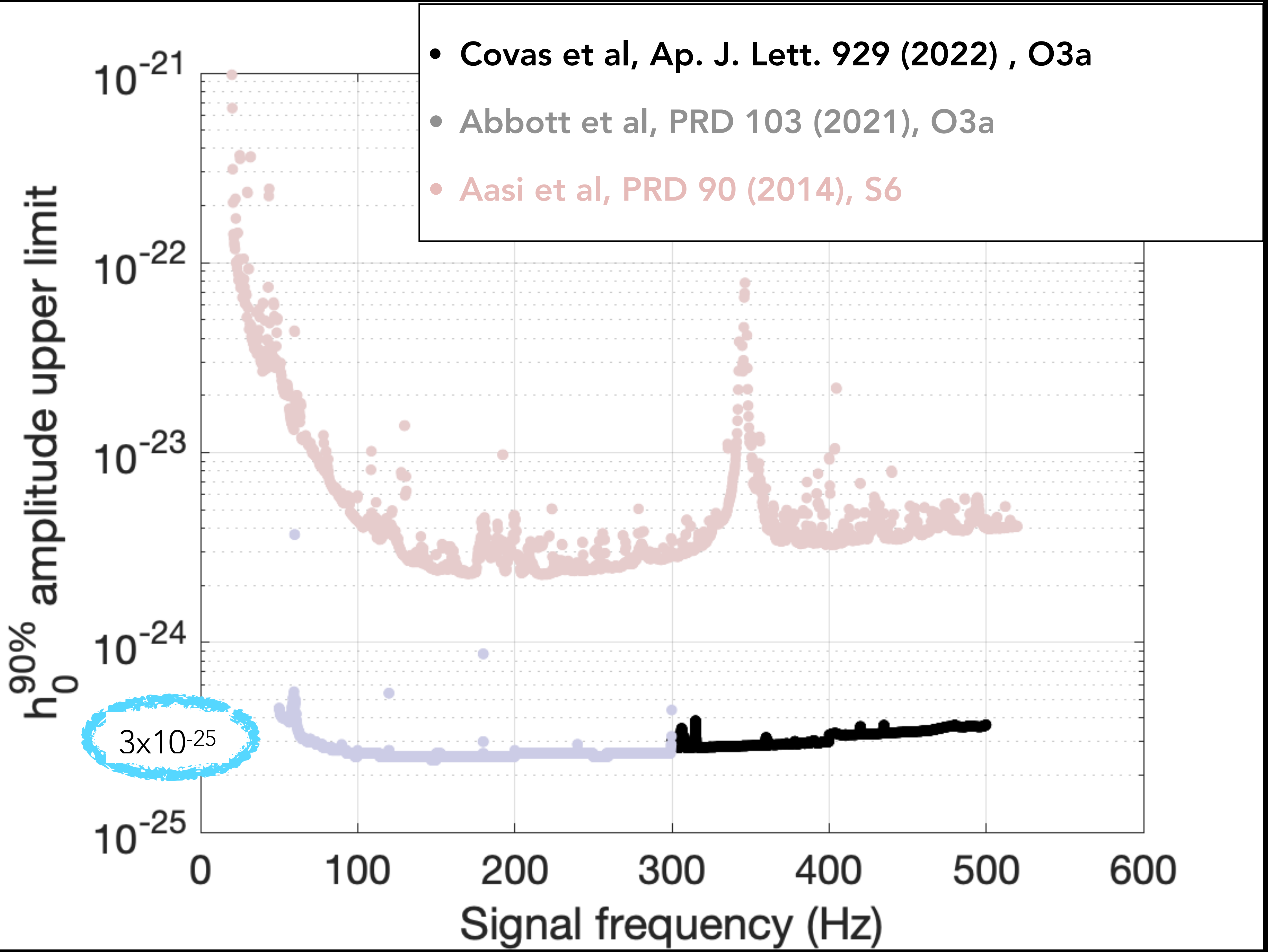
Covas et al, arxiv:2409.16196







A FEW DETAILS OF ALL-SKY SEARCH FOR EMISSION FROM NEUTRON STARS IN BINARY SYSTEMS



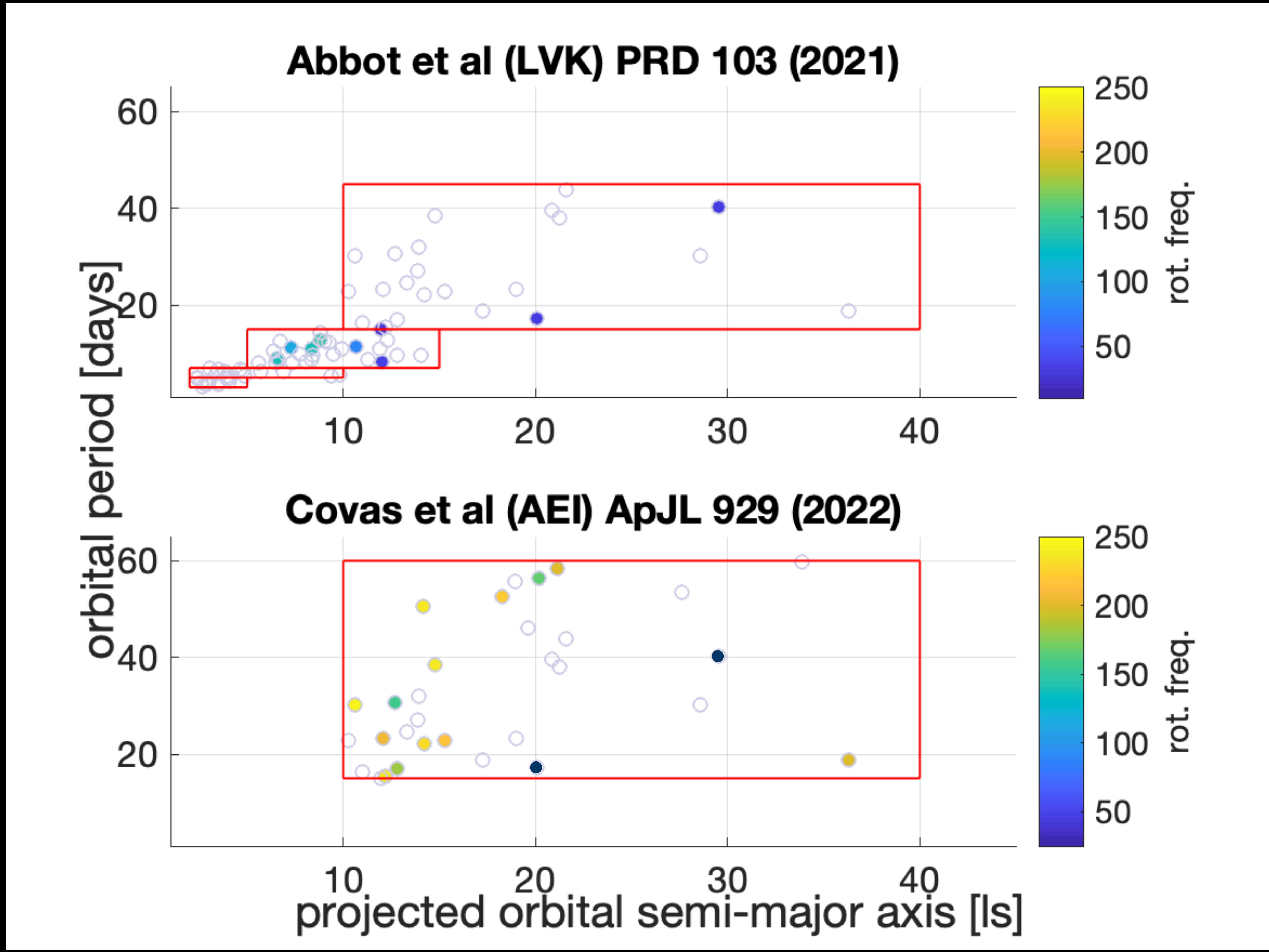
Parameter	Range
f_0 : Frequency [Hz]	300–500
$\lvert\dot{f}_0\rvert$: Frequency deriv. [Hz/s]	$<4 \times 10^{-10}$
a_p : Projected semimajor axis [lt-s]	10–40
P : Orbital period [days]	15–60
t_{asc} : Time of ascension [s]	$t_m \pm P/2$
e : Orbital eccentricity	$<5.7 \times 10^{-3}\left[\frac{500\text{ Hz}}{f_0}\right]$
α : Right ascension [rad]	0–2π
δ : decl. [rad]	$-\pi/2$–$\pi/2$

Resolution	Frequency Range [300, 400)	Frequency Range [400, 500)
δf_0 [mHz]	1.1	1.1
δa_p [l-s] $\left[\frac{P}{37\text{days}}\right]$	$2.7\left[\frac{400\text{ Hz}}{f_0}\right]$	$3.1\left[\frac{500\text{ Hz}}{f_0}\right]$
$\delta\Omega[10^{-8}\text{ rad}]\left[\frac{P}{37\text{days}}\right]\left[\frac{25\text{ l}-\text{s}}{a_p}\right]$	$2.4\left[\frac{400\text{ Hz}}{f_0}\right]$	$2.7\left[\frac{500\text{ Hz}}{f_0}\right]$
$\delta t_{asc}[10^4\text{ s}]\left[\frac{P}{37\text{days}}\right]^2\left[\frac{25\text{ l}-\text{s}}{a_p}\right]$	$5.5\left[\frac{400\text{ Hz}}{f_0}\right]$	$6.2\left[\frac{500\text{ Hz}}{f_0}\right]$
$\delta\alpha = \delta\delta[10^{-2}\text{ rad}]$	$4.3\left[\frac{400\text{ Hz}}{f_0}\right]$	$4.0\left[\frac{500\text{ Hz}}{f_0}\right]$

Note. $\Omega = 2\pi/P$ is the average angular orbital velocity.

- $\lvert\dot{f}_{GW}\rvert \leq$ a few 10^{-10} Hz/s
- Orbital eccentricity $e \leq 5.7 \times 10^{-3}\left[\frac{500\text{Hz}}{f_{GW}}\right]$
- Orbital parameters additionally searched
- Less sensitive search than for isolated objects

TRADE-OFFS



50-300 Hz: covered parameters of 12% of known PSRS

300-500 Hz: covered parameters of 42% of known PSRS

DEEP NEURAL NETWORKS ?

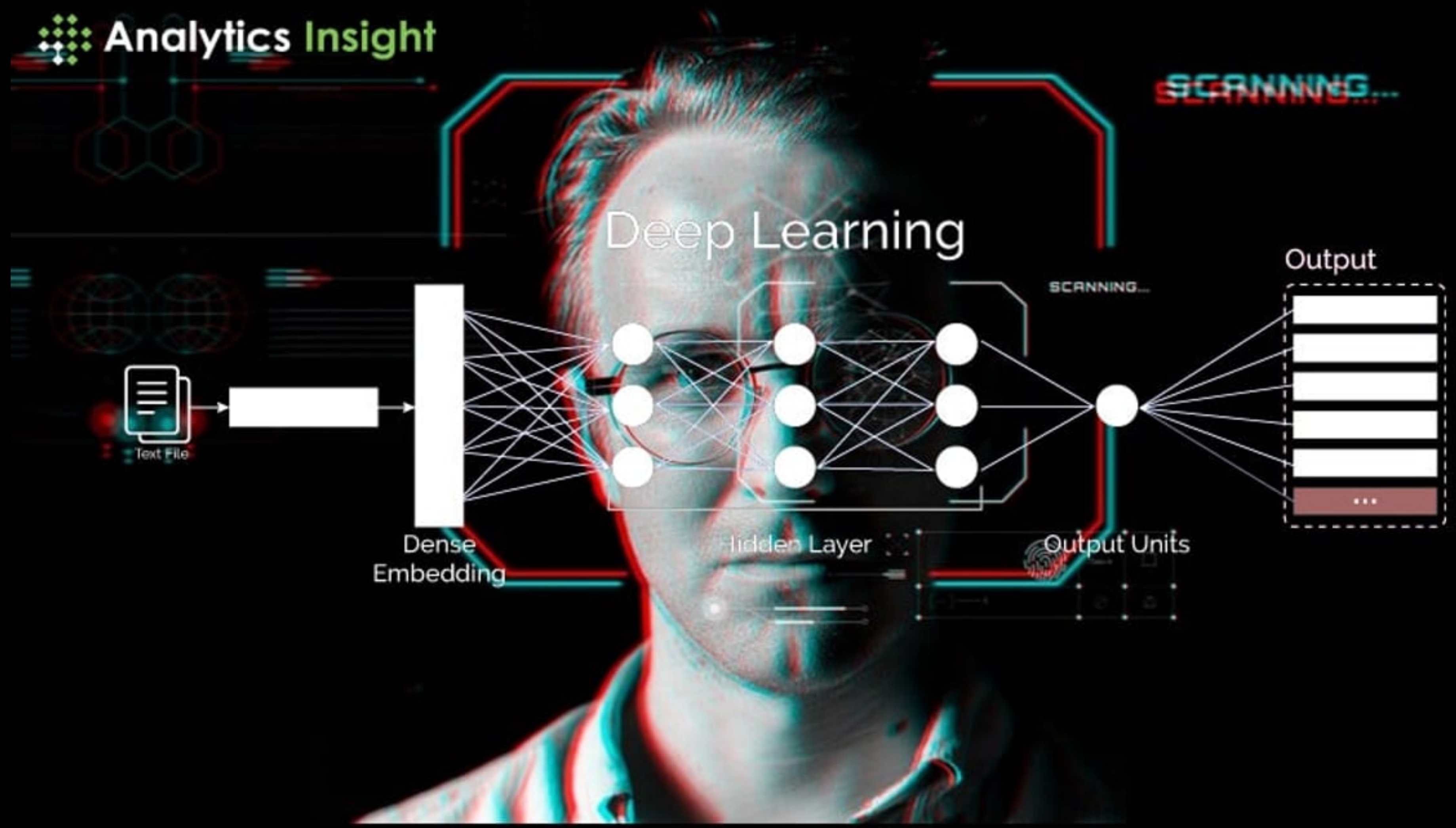
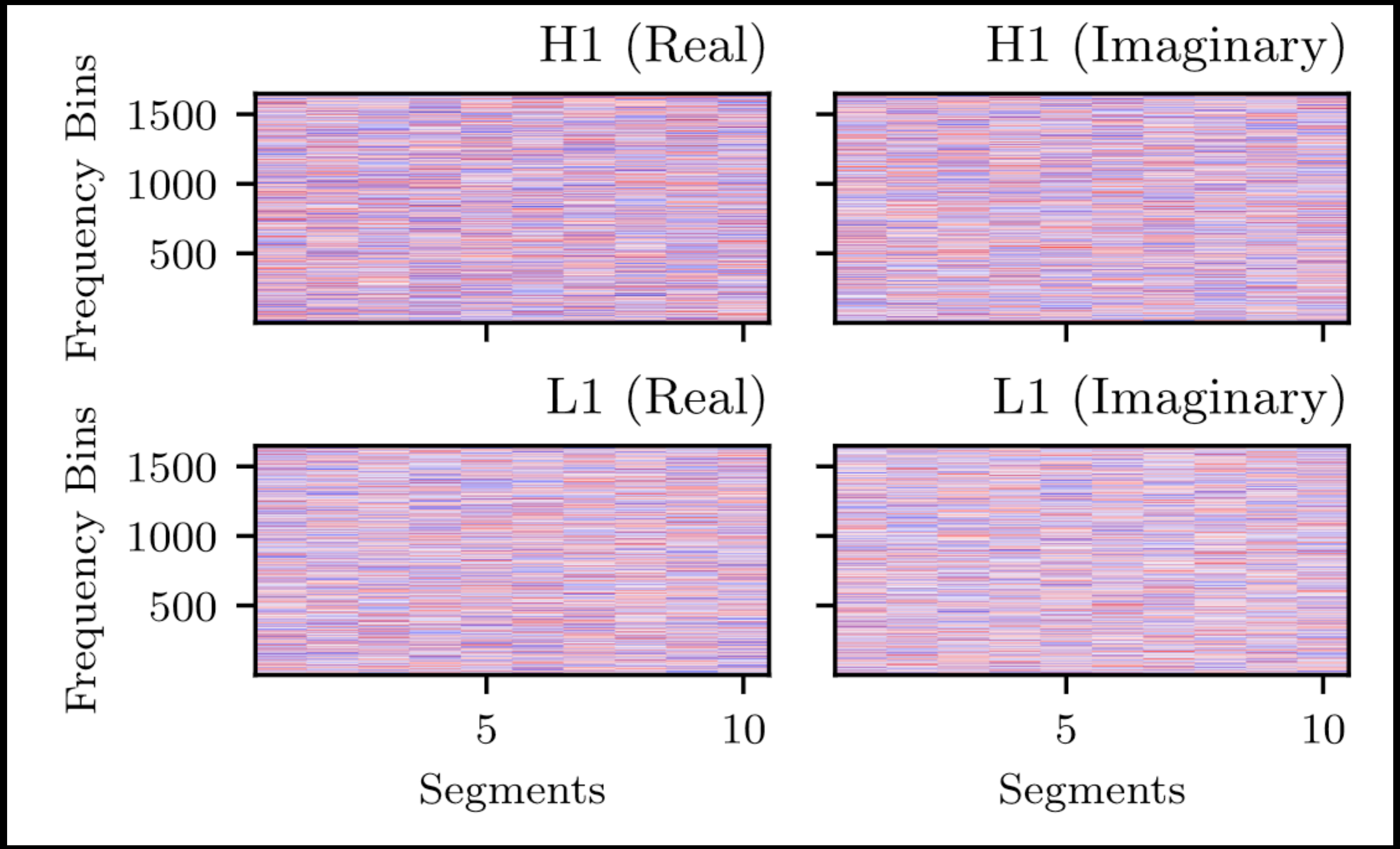


Image:Analytics Insight, Parvin Mohmad



Joshi et al, PRD 108, 2023

NEURAL NETWORKS: DIFFERENT THAN STANDARD USE-CASE

- Poor performance of DNN (standard image recognition convolutional networks)
  - Different regime than usually assumed: here we have weak and “delocalised” features
  - Prospects for use in the incoherent combination step are perhaps better
- Only recently a custom-designed DNN* could match optimal detection statistic performance for Tcoh ~ 10 days
  - MUCH work to do

*Joshi et al, (Joshi and Prix, “Novel neural-network architecture for continuous gravitational waves” PRD 108 (2023)
Dreissigacker et al, “Deep-Learning Continuous Gravitational Waves: Multiple detectors and realistic noise", PRD 102 (2020)
Dreissigacker et al, “Deep-Learning Continuous Gravitational Waves", PRD 100 (2019)
Bayley et al, “Robust machine learning algorithm to search for continuous gravitational waves”, PRD 102 (2020)

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

FEW DETAILS ON BOSON CLOUD MODEL

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

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

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

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

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

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

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

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

As the boson annihilate the cloud is depleted so:

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

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

Cloud mass decreases, grav. 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

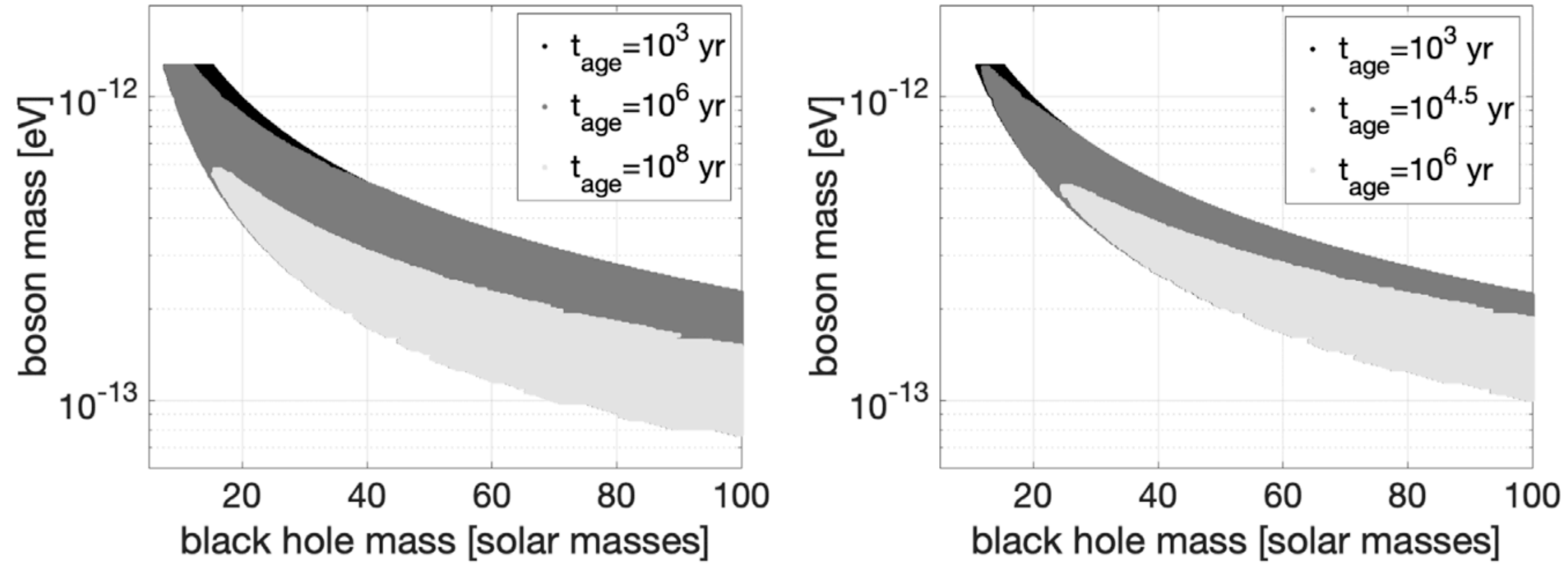


FIG. 6. Exclusion regions in the boson mass (m_b) and black hole mass ($M_{\rm BH}$) plane for an assumed distance of $D = 1$ kpc (left) and $D = 15$ kpc (right), and an initial black hole dimensionless spin $\chi_i = 0.9$. For $D = 1$ kpc, three possible values of the black hole age, $t_{\rm age} =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

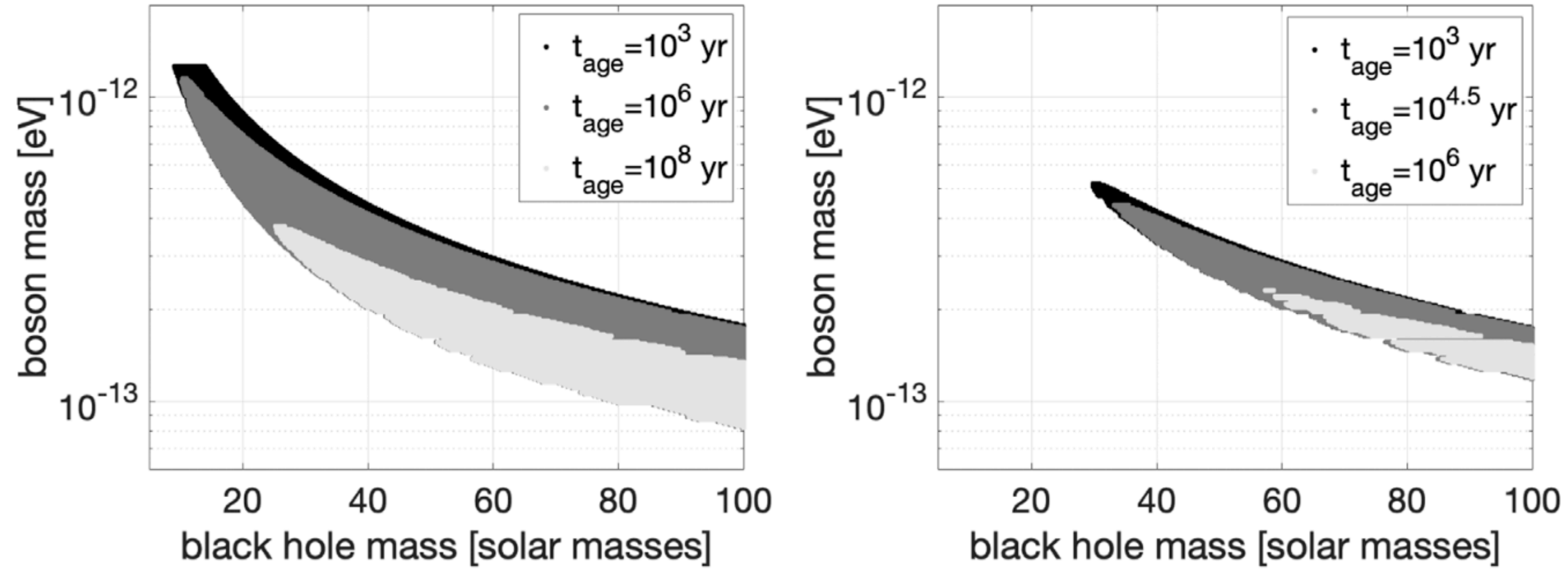
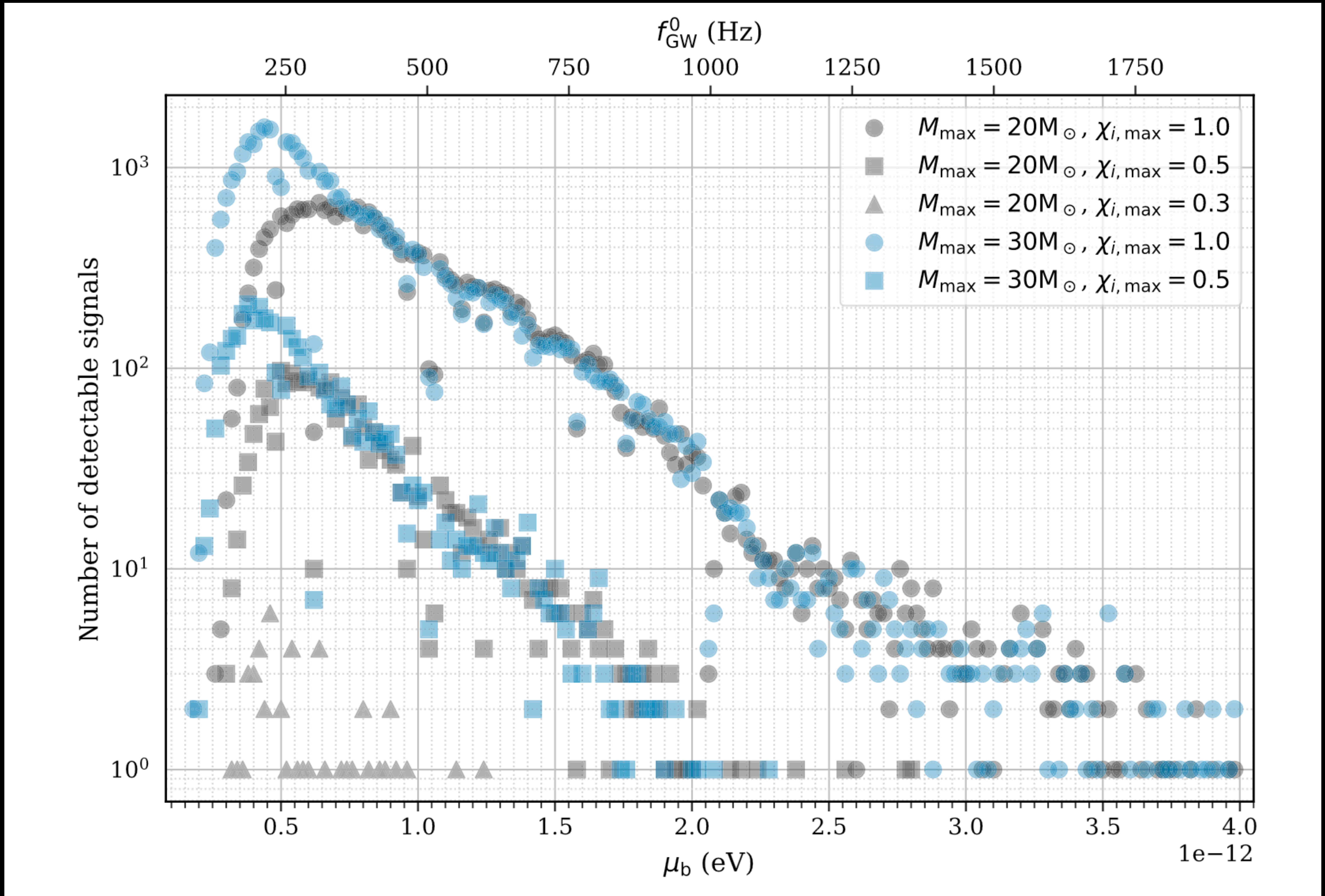


FIG. 7. Same as Fig. 6 but for black hole initial spin $\chi_i = 0.5$. The assumed distance is $D = 1$ kpc (left), and $D = 15$ kpc (right).

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

- 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

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 $= 0$

Sco X-1 searches

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

Sky position known

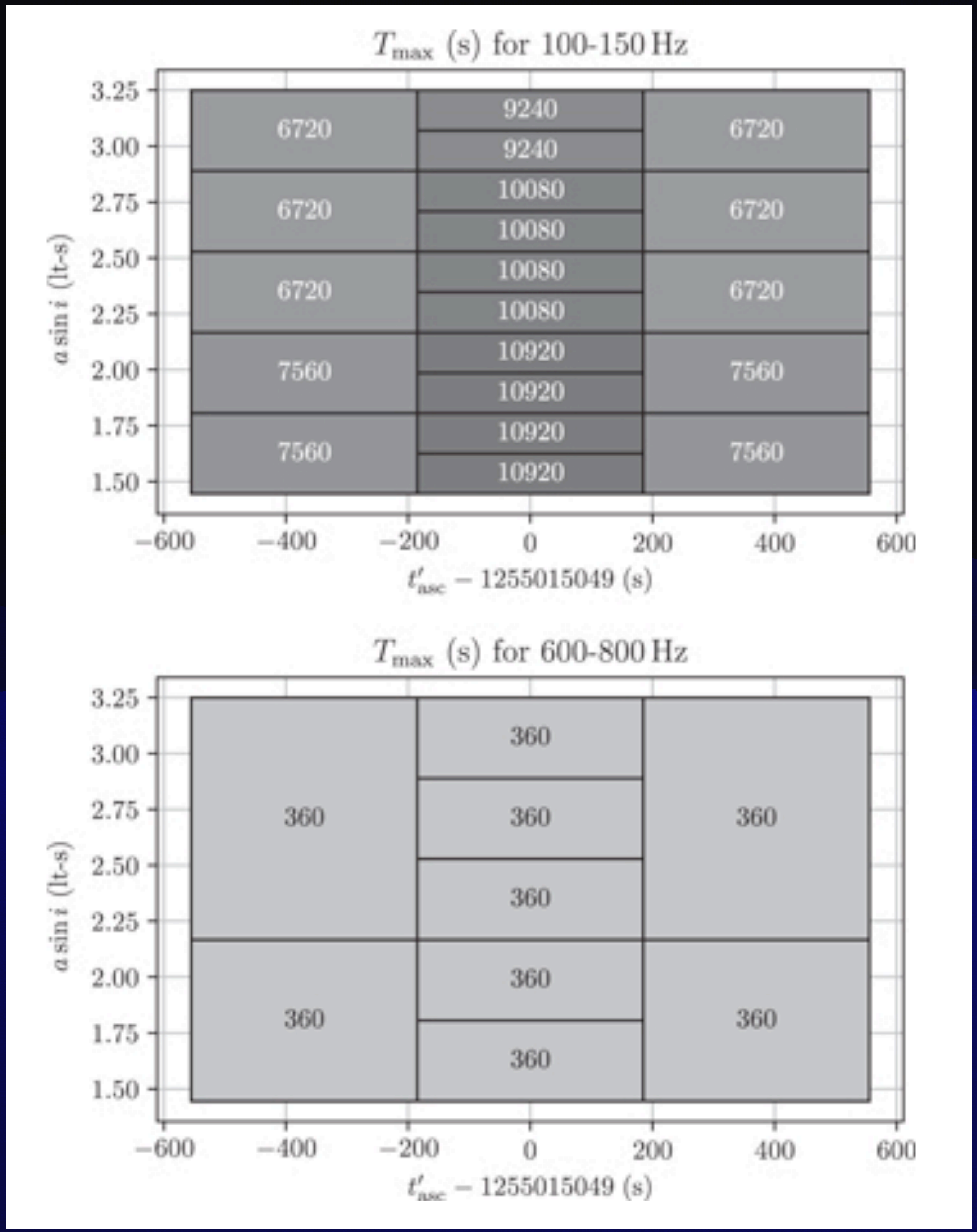
$\dot{f}_{GW}$ assumed $= 0$

Parameter	Range	Grid spacing
f_{GW} (Hz)	$[40, 180]$	$\sim 2 \times 10^{-6}$
$a \sin i$ (lt-s)	$[1.45, 3.25]$	$\sim \frac{0.17\ [\text{lt-s Hz}]}{f_{\mathrm{GW}}}$
T_{asc} (GPS s)[a]	$1178556229 \pm 3 \times 139$	$\sim \frac{1576\ [\text{lt-s}]}{f_{\mathrm{GW}}\, a \sin i}$
P_{orb} (s)	$68023.86 \pm 3 \times 0.04$	$\sim \frac{18\ [\text{lt-s}]}{f_{\mathrm{GW}}\, a \sin i}$

Zhang et al, ApJ Lett 906 (2021)

40 Hz $\leq f_{GW} \leq 180$ Hz

T$_{coh} = 19$ hrs

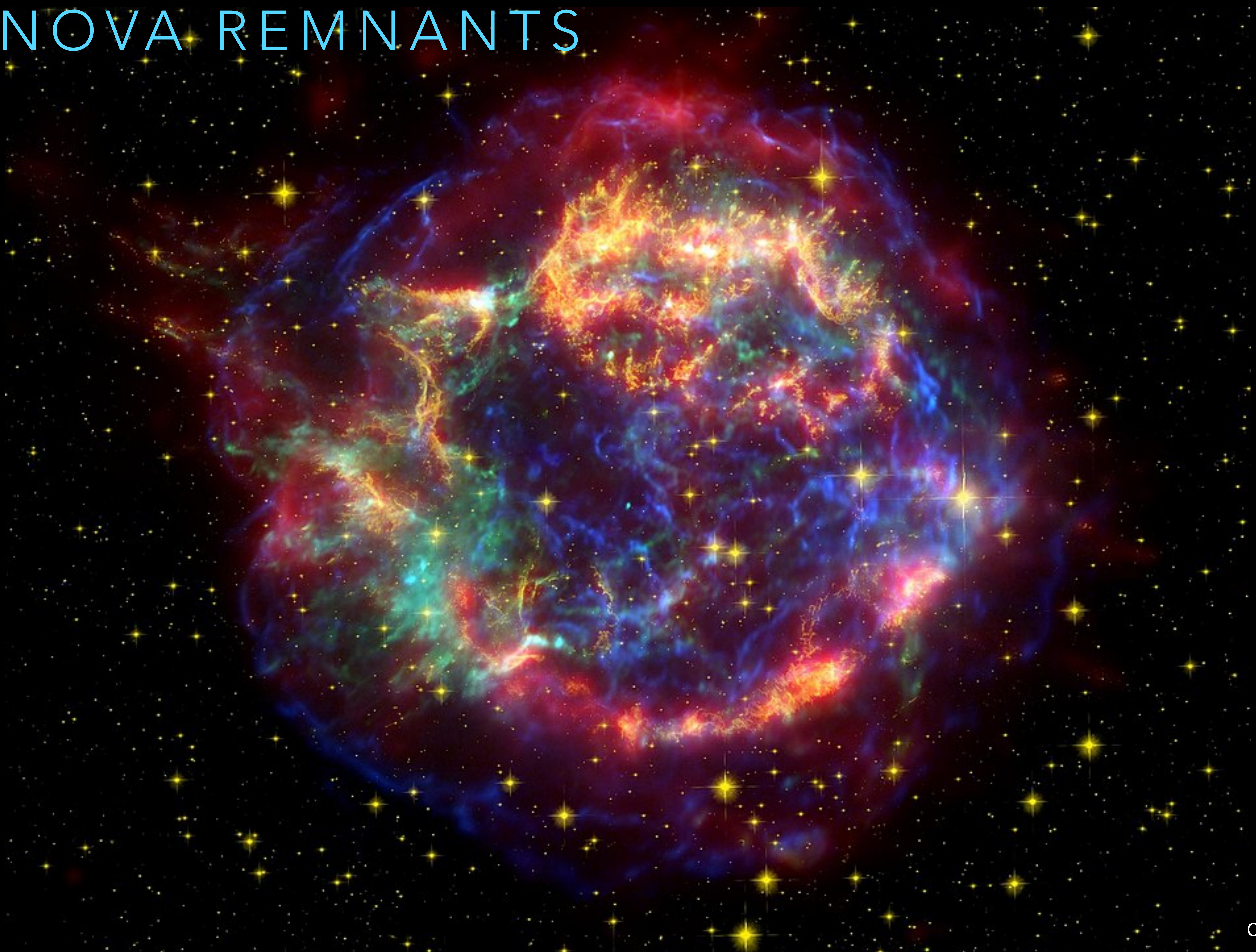


Whelan et al, ApJ 949 (2023)

25 Hz $\leq f_{GW} \leq 1600$ Hz

4 min $\leq$ T$_{coh} \leq 2.8$ hrs

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

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

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

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

when n=2 this is the smallest.

EMISSION FROM NEUTRON STARS IN YOUNG SUPERNOVA REMNANTS: PARAMETER SPACE

Assume frequency. Characteristic age

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

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

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

when n=7 this is the largest.

EMISSION FROM NEUTRON STARS IN YOUNG SUPERNOVA REMNANTS: PARAMETER SPACE

Assume frequency. Characteristic age

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

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

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

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

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

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

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

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

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

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

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

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

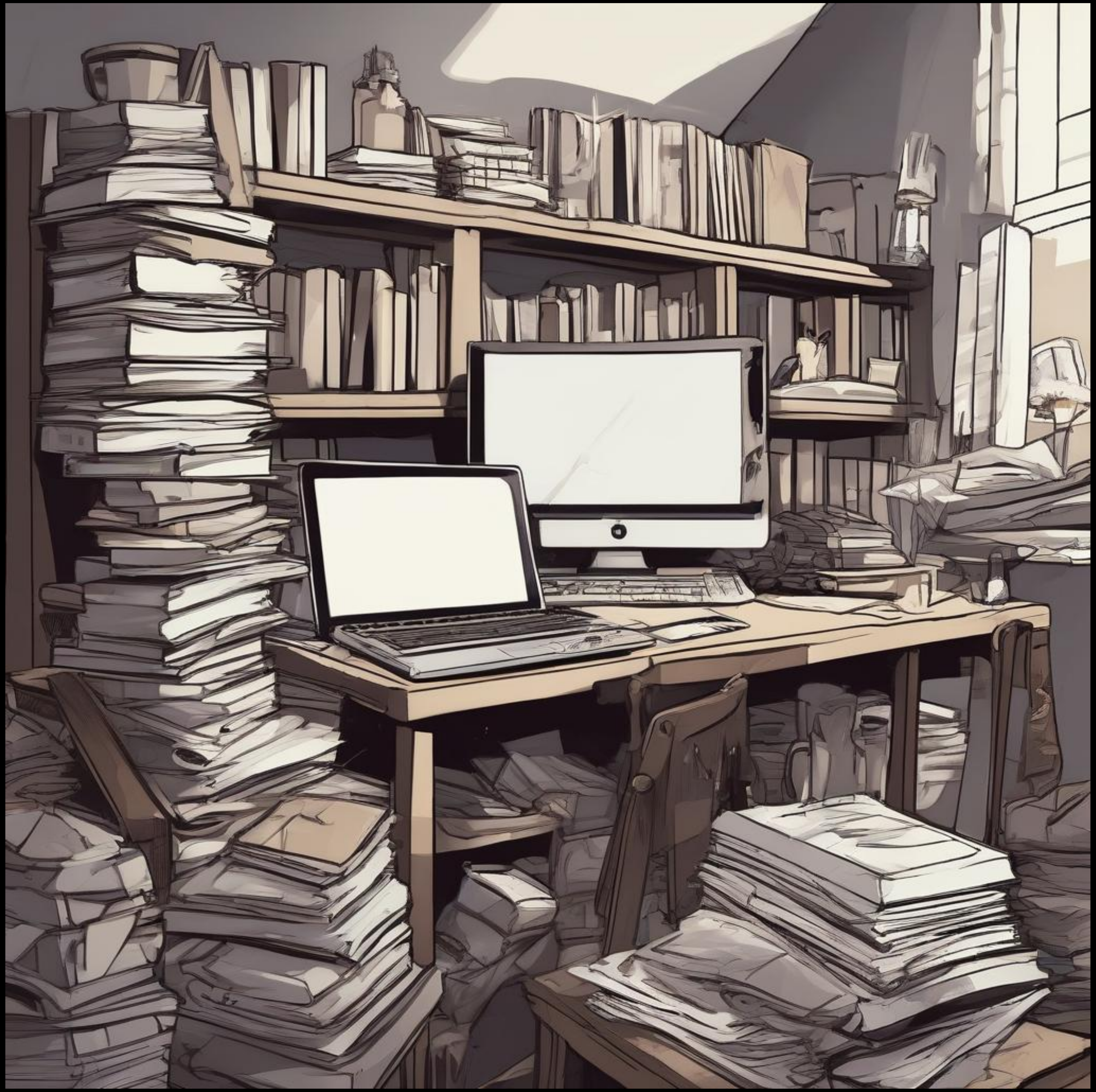
DECISIONS…

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
189.1+3.0	IC 443	061705.3+222127	1.5	20
266.2−1.2	Vela Jr.	085201.4−461753	0.2	0.69
266.2−1.2	Vela Jr.	085201.4−461753	0.9	5.1
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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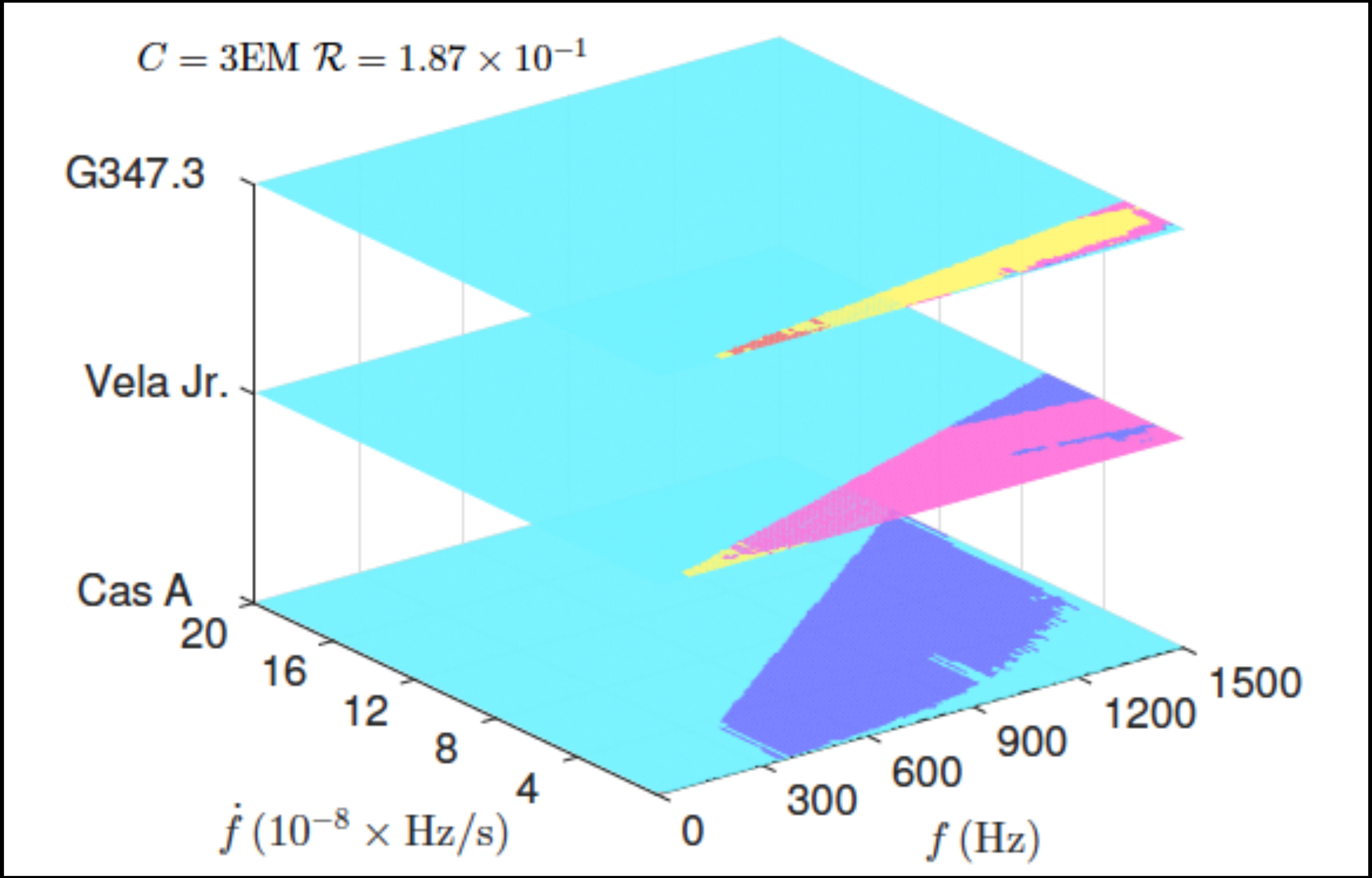
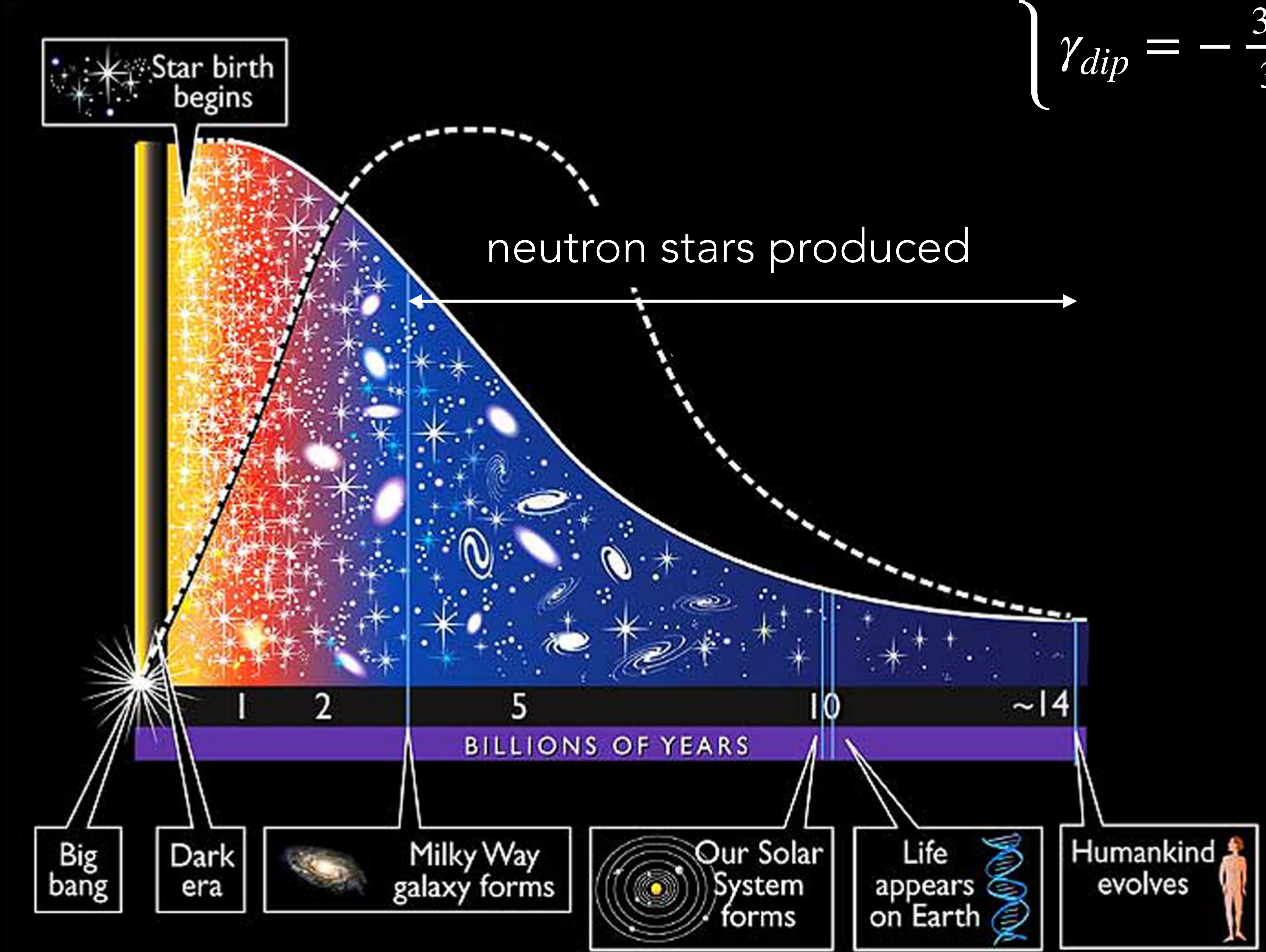
SUPERNOVA REMNANTS TO TARGET:



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)

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

Bells and monochromatic signal

from Prof. Andrew Yao’s Basic Science Lecture, on Monday: