Einstein@Home Search For Continuous Gravitational Waves From Vela Jr, Cas A and G347.3 in O3 data

Draft in Progress

June. 18, 2024 @ AEI Hannover

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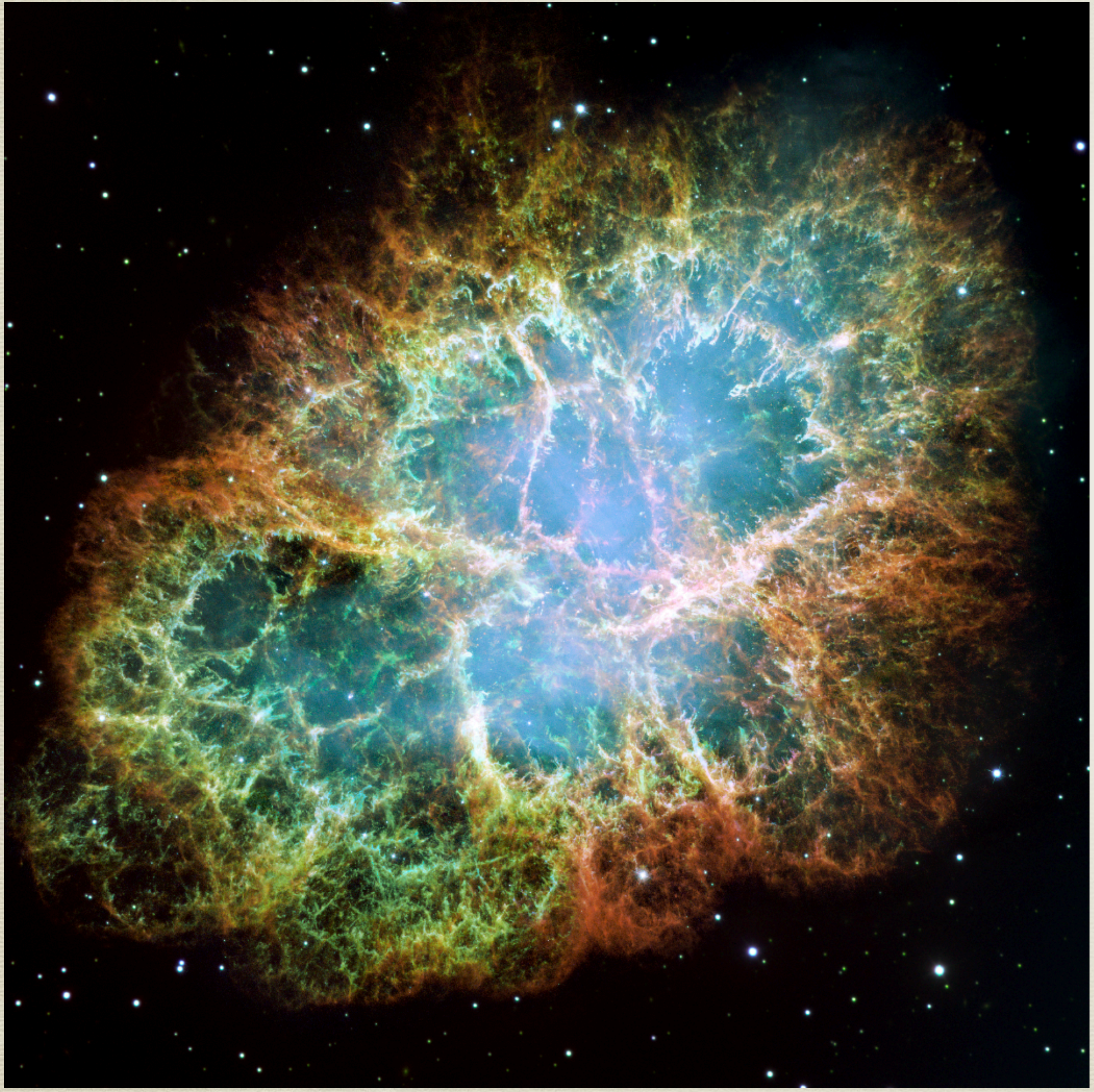
AEI, Hannover (Max Planck Institute for Gravitational Physics)

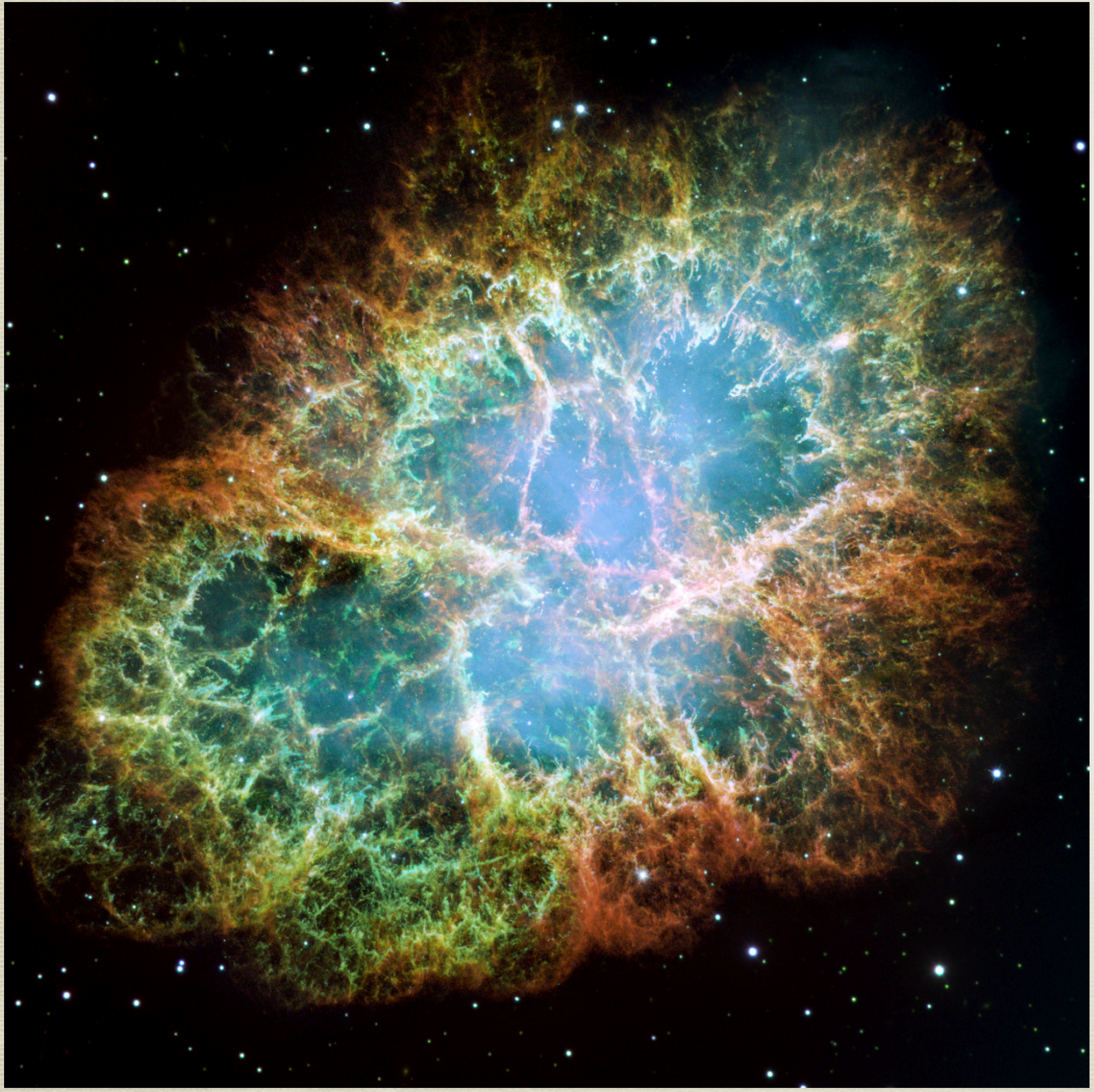
On behalf of Einstein@Home Group

CW candidates: Young SNRs



$$h_0^{spdwn} = \frac{1}{d}\sqrt{\frac{nGI}{8c^3\tau}}$$

CW candidates:Young SNRs



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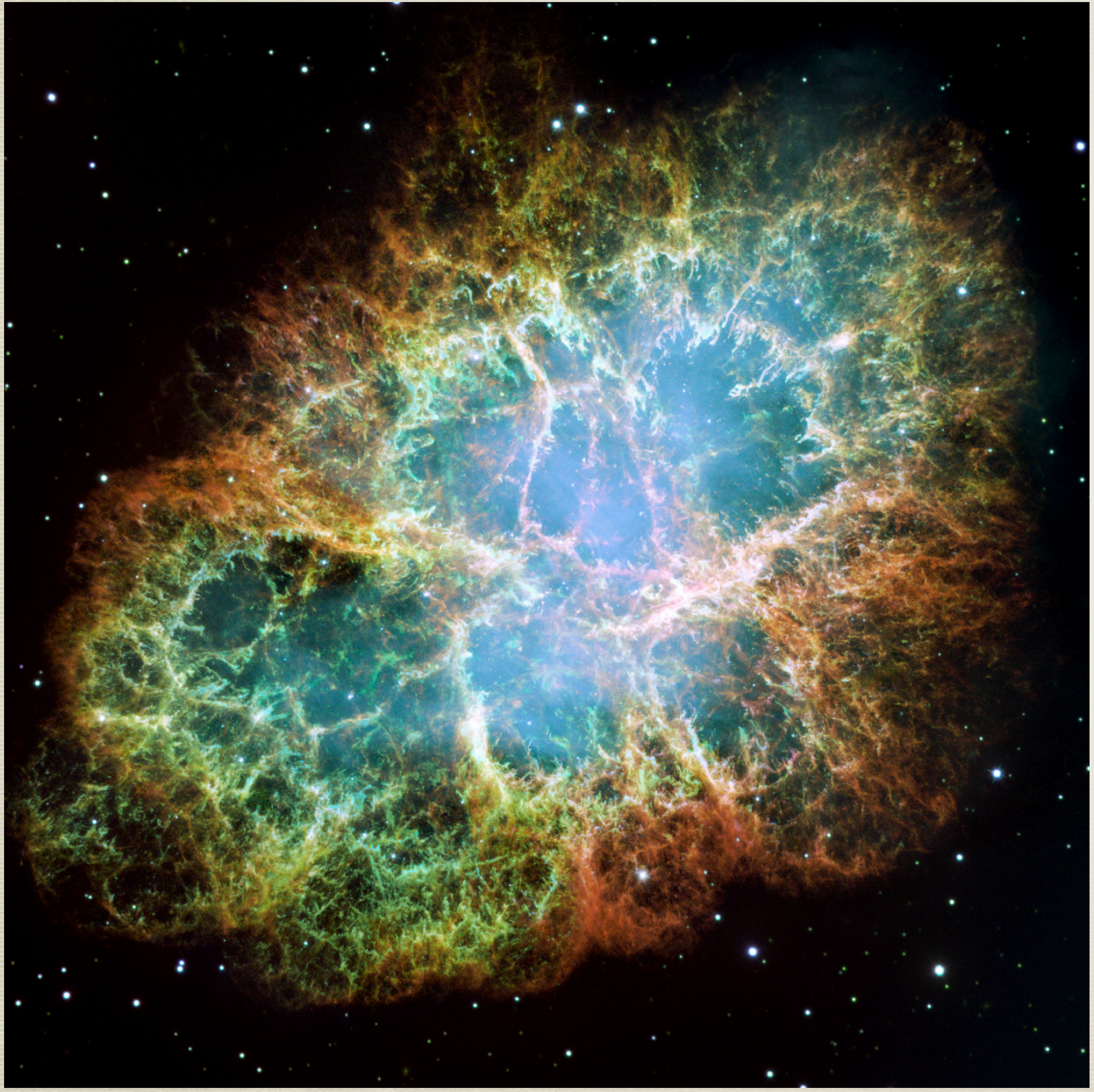
$$h_0^{spdwn} = \frac{1}{d}\sqrt{\frac{nGI}{8c^3\boxed{\tau}}}$$

CW candidates: Young SNRs



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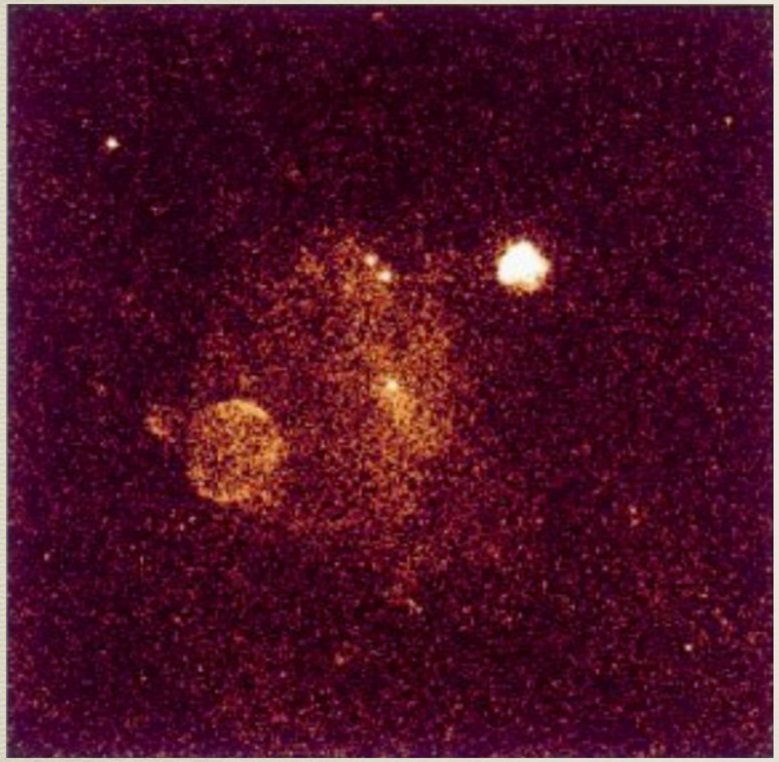
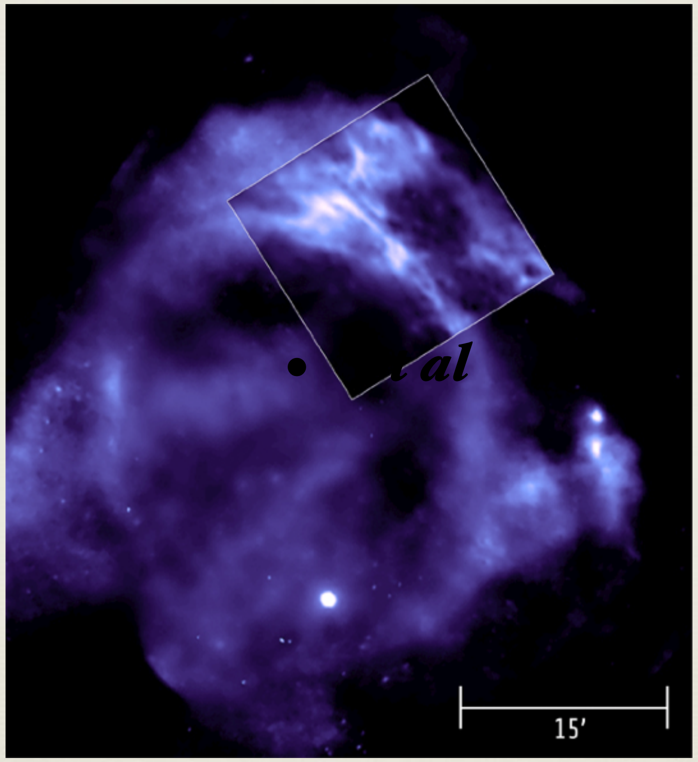
$$h_0^{spdwn} = \frac{1}{\boxed{d}}\sqrt{\frac{nGI}{8c^3\boxed{\tau}}}$$

Directed search

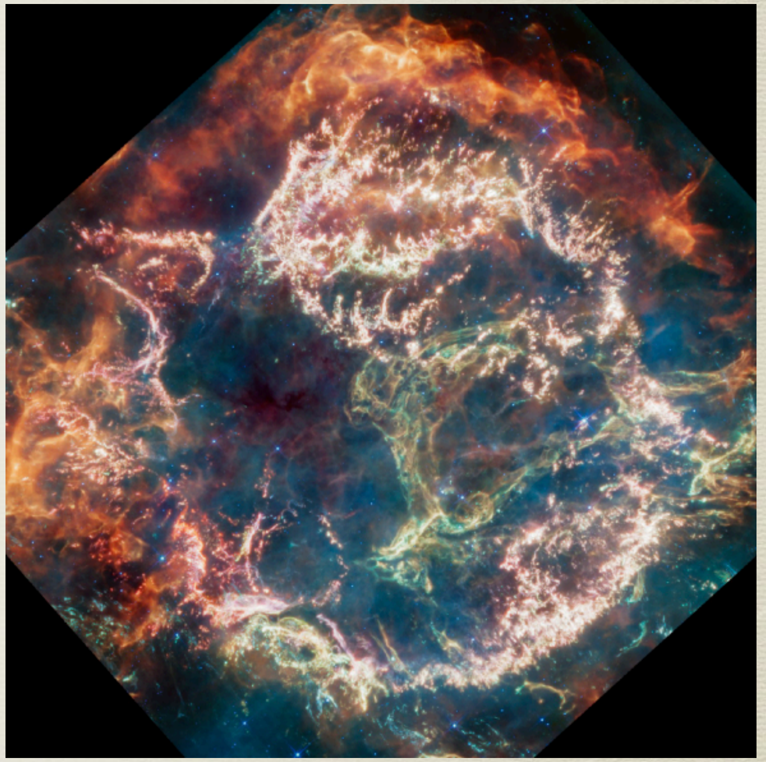
known sky position
unknown frequency, fdot and f2dot …



Vela Jr
Nature 396, 141-142(1998)



G347.3
Credit: Chandra&XMM-Newton



Cas A
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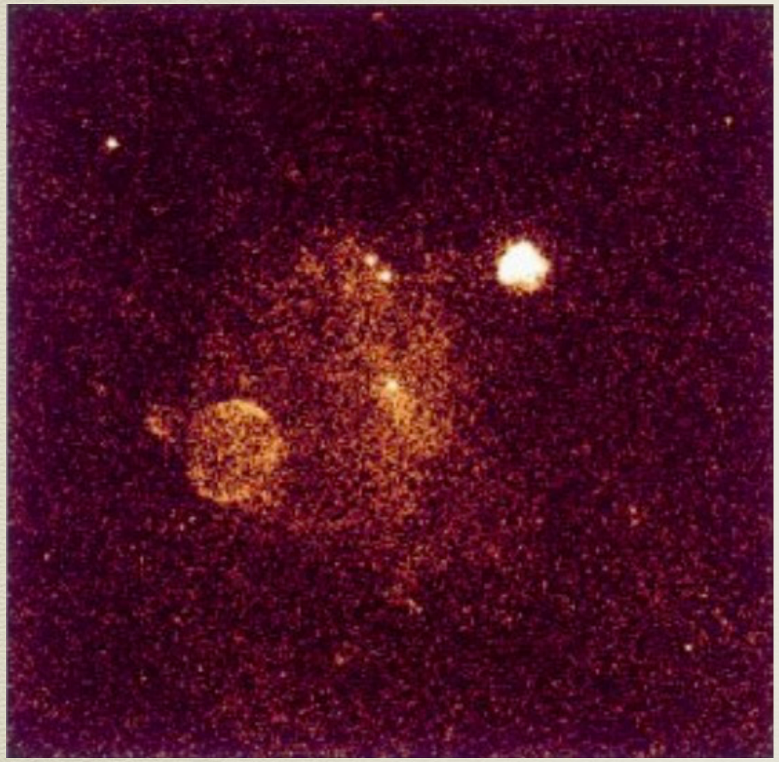
- To maximise the detection probability : ***PRD 2016, Ming et al***

Directed search

known sky position
unknown frequency, fdot and f2dot ...

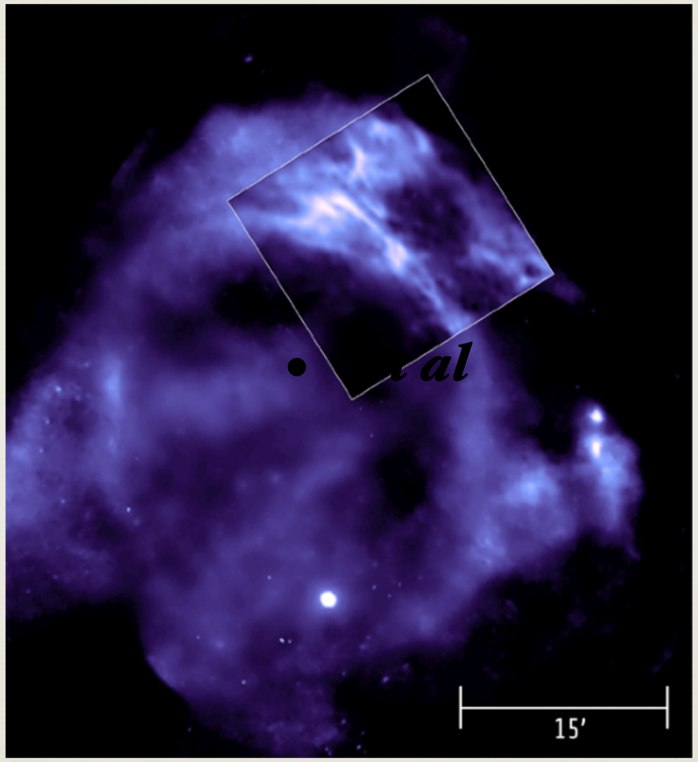


Vela Jr

Nature 396, 141-142(1998)

700-5000 yrs

200-900 pc

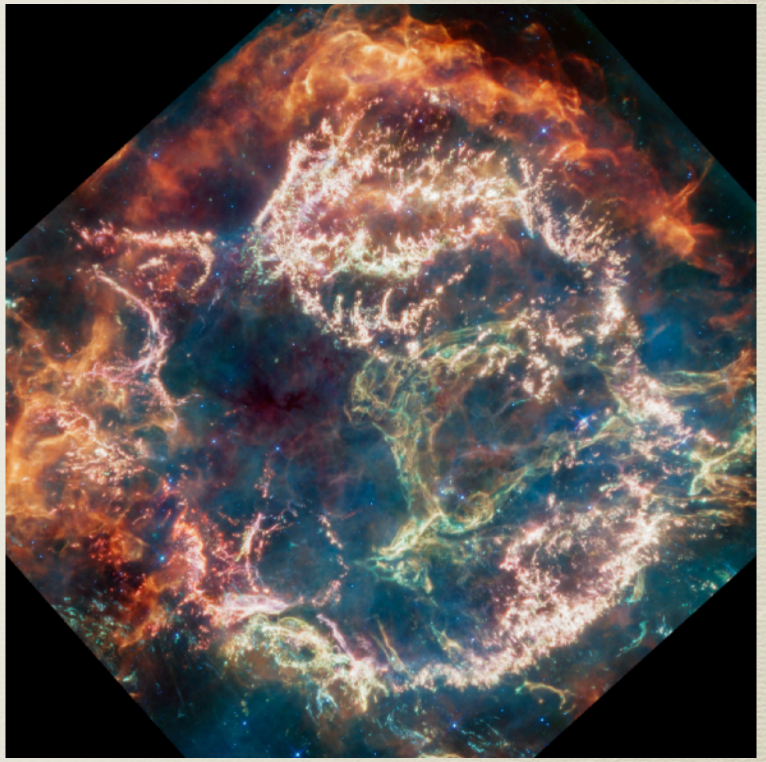


G347.3

Credit: Chandra&XMM-Newton

1600 yrs

1.3 kpc



Cas A

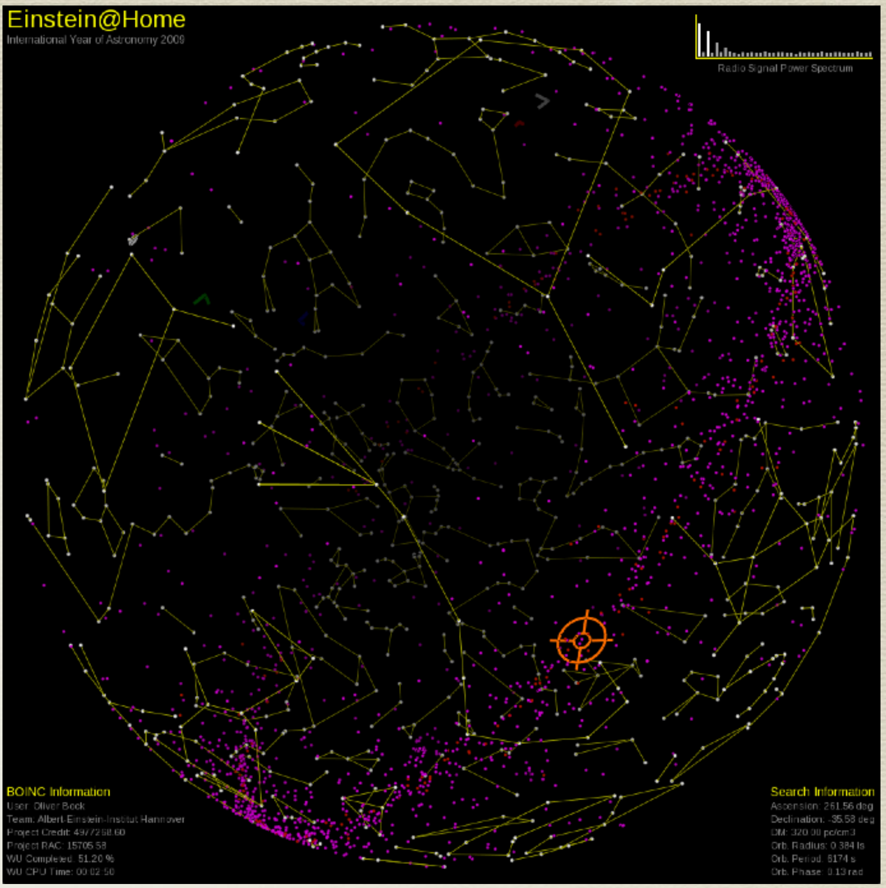
copyright@NASA/JWST

330 yrs

3.4 kpc

Einstein@home

https://einsteinathome.org/



BOINC Information
User: Oliver Bock
Team: Albert-Einstein-Institut Hannover
Project Credit: 4977258.60
Project RAC: 15705.58
WU Completed: 51.20 %
WU CPU Time: 00:02:50

Search Information
Ascension: 261.56 deg
Declination: -35.58 deg
DM: 320.00 pc/cm3
Orb. Radius: 0.384 ls
Orb. Period: 6174 s
Orb. Phase: 0.13 rad

Einstein@Home uses your computer's idle time to search for weak astrophysical signals from spinning neutron stars using data from the LIGO gravitational-wave detectors, the MeerKAT radio telescope, the Fermi gamma-ray satellite, as well as archival data from the Arecibo radio telescope.

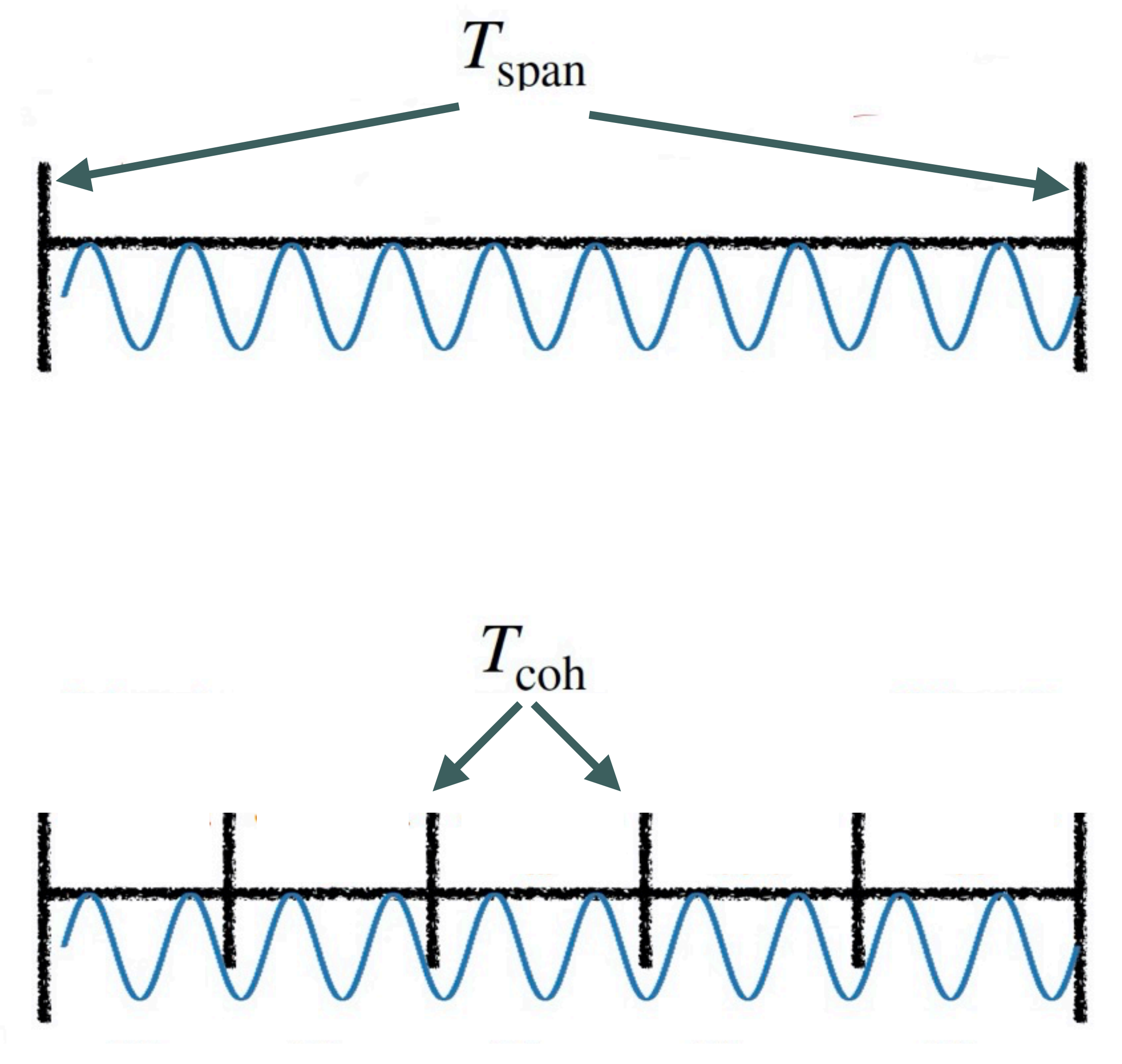
Active users: >500,000
Computing power: >50,000 CPU cores
(taken into account GPU)

EM means Einstein@Home-month.

Semi-Coherent method

Coherent search: computationally limited:
necessary templates $\propto T_{span}^{6}$

Semi-coherent search:
Divide T_{span} in N segments of T_{coh}
Less sensitive
Computational cost $\propto N \times T_{coh}^{6}$



Search

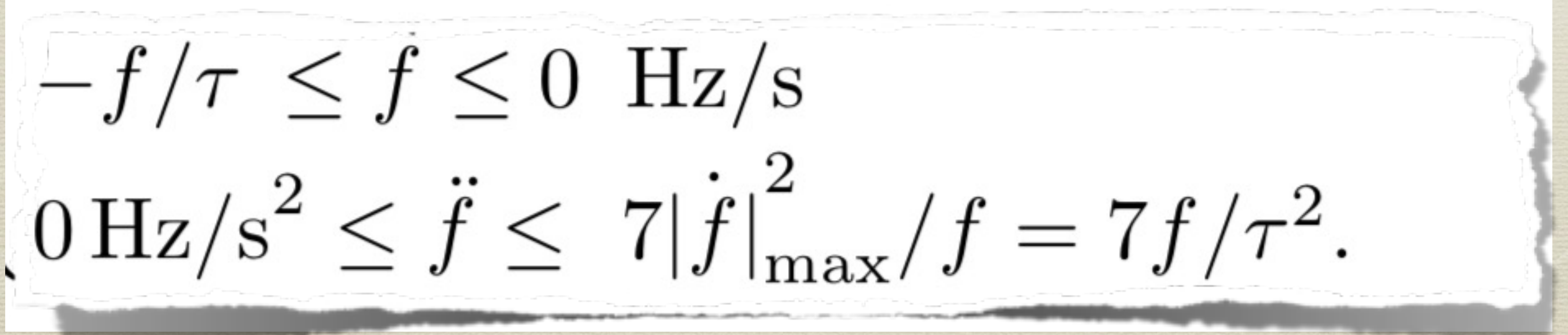
- O3 first half data (~180 days)

- running on Einstein@Home for 7 months (GPU and CPU)

- Two bands: < 500 Hz and 500- 1500 Hz for three sources

- frequency second time derivative included

- Maximum possible ranges for f, fdot and f2dot:



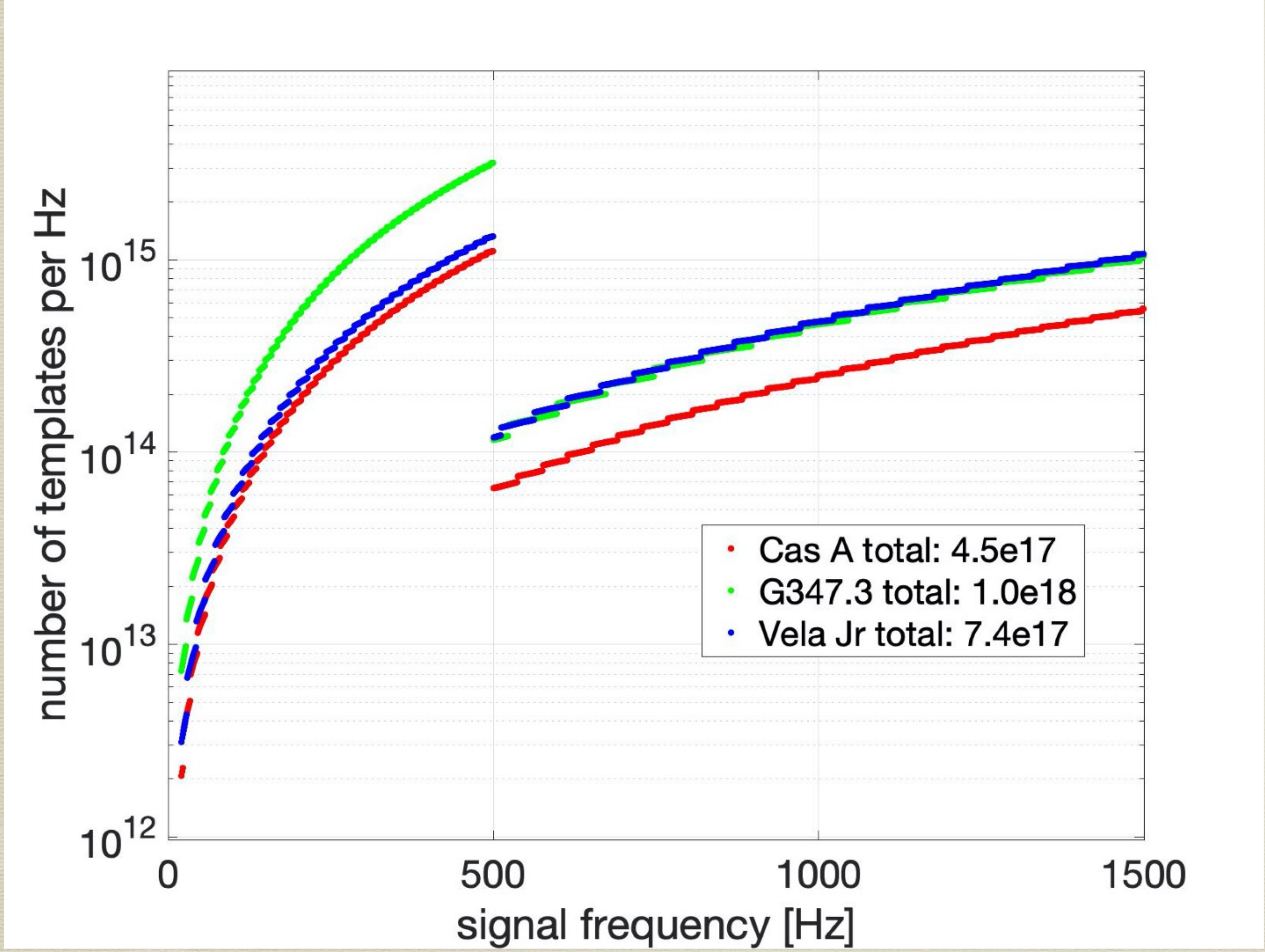
$$-f/\tau \leq \dot{f} \leq 0 \ \mathrm{Hz/s}$$

$$0\,\mathrm{Hz/s^2} \leq \ddot{f} \leq 7|\dot{f}|^2_{\mathrm{max}}/f = 7f/\tau^2 .$$

Search Setups

20 - 500 Hz 500 - 1500 Hz	Vela Jr	G347.3	Cas A
Number of seg X Tcoh (days)	6 x 30D 12 x 15D	**3 x 60D** 6 x 30D	12 x 15D 18 x 10D
frequency spacing(Hz)	1.9e-7 4.7e-7	**6.7e-8** 1.9e-7	4.7e-7 7.0e-7
Mismatch	22% 17%	5% 22%	17% 33%
Number of Templates (fine)	2.3e17 5.2e17	5.4e17 5.0e17	1.9e17 2.7e17

Number of templates per Hz

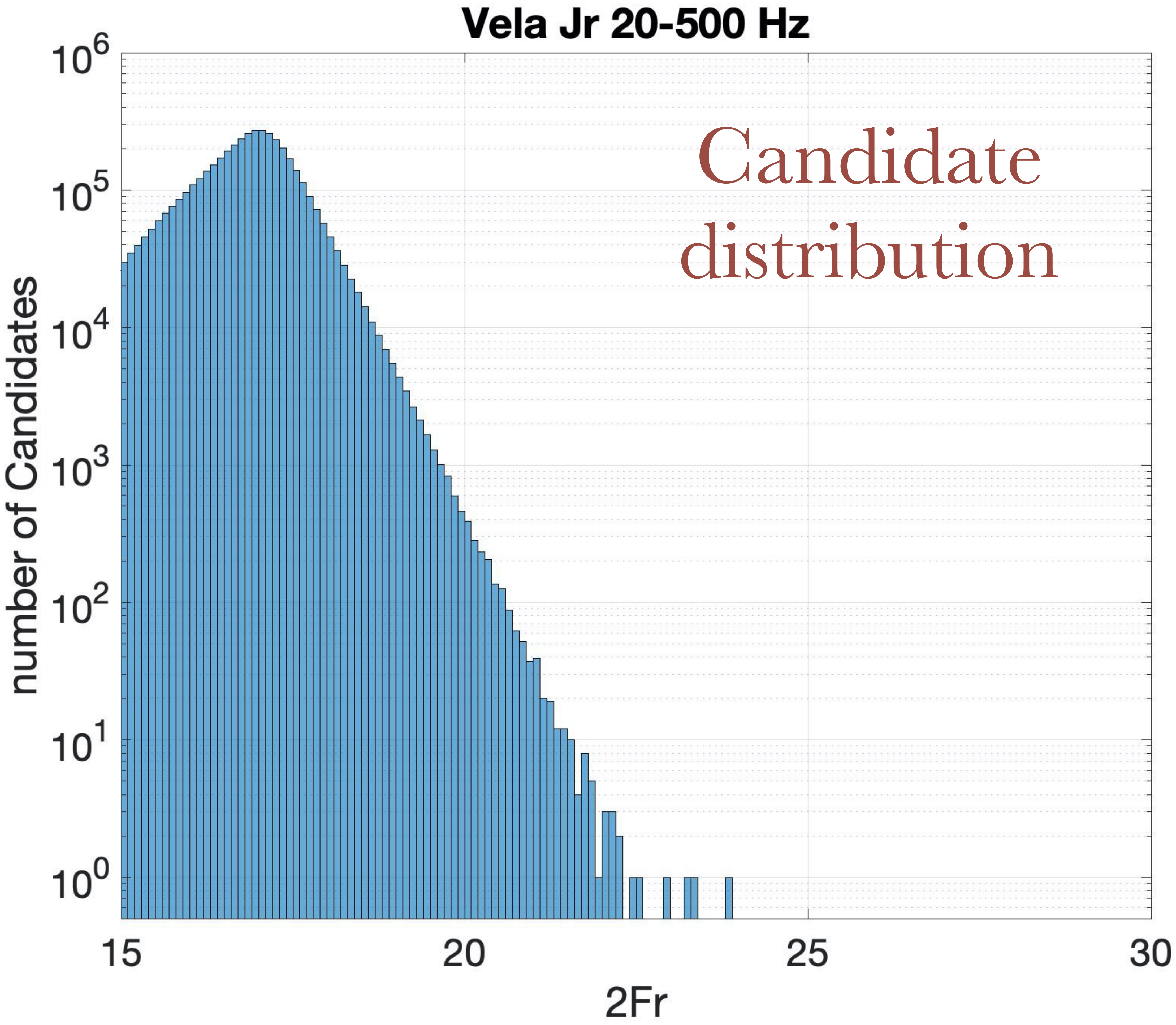


Total:

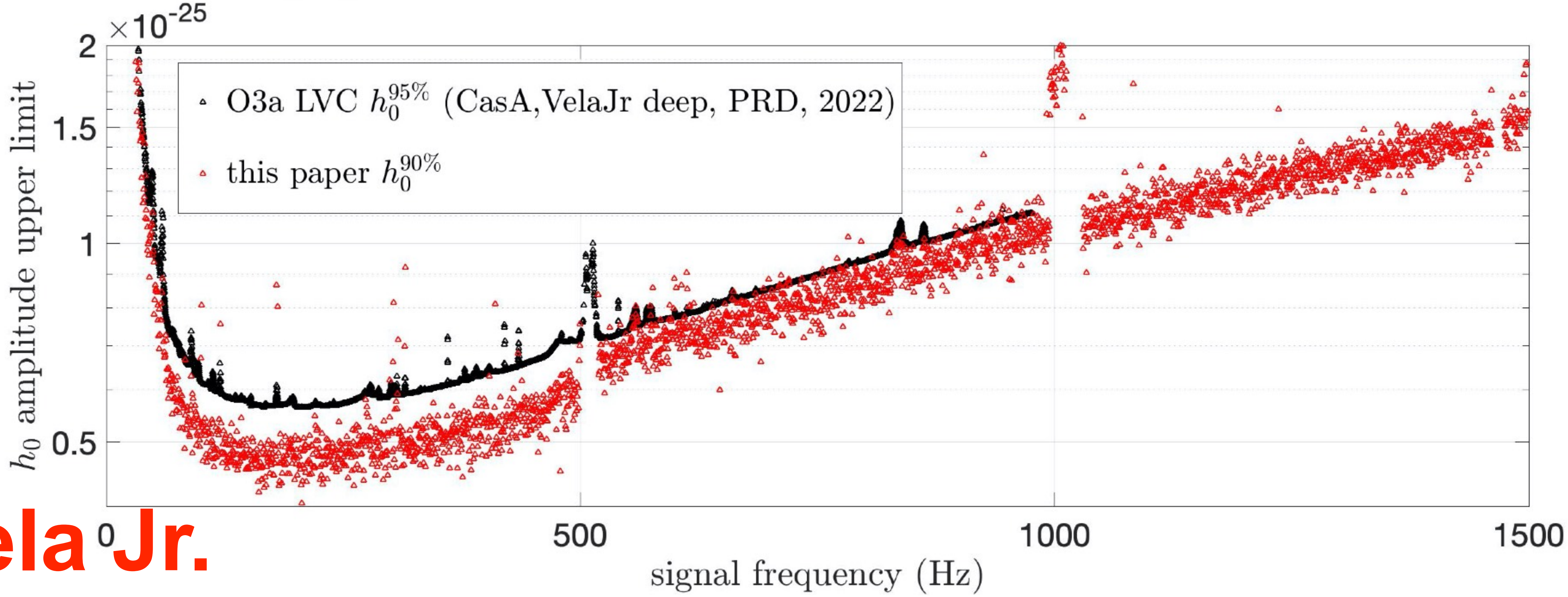
$$2.2 \times 10^{18}$$

- **8 million WU Each for 8 hours on host's CPU**
- **Each WU keeps top 50,000 candi and returned to E@H server**

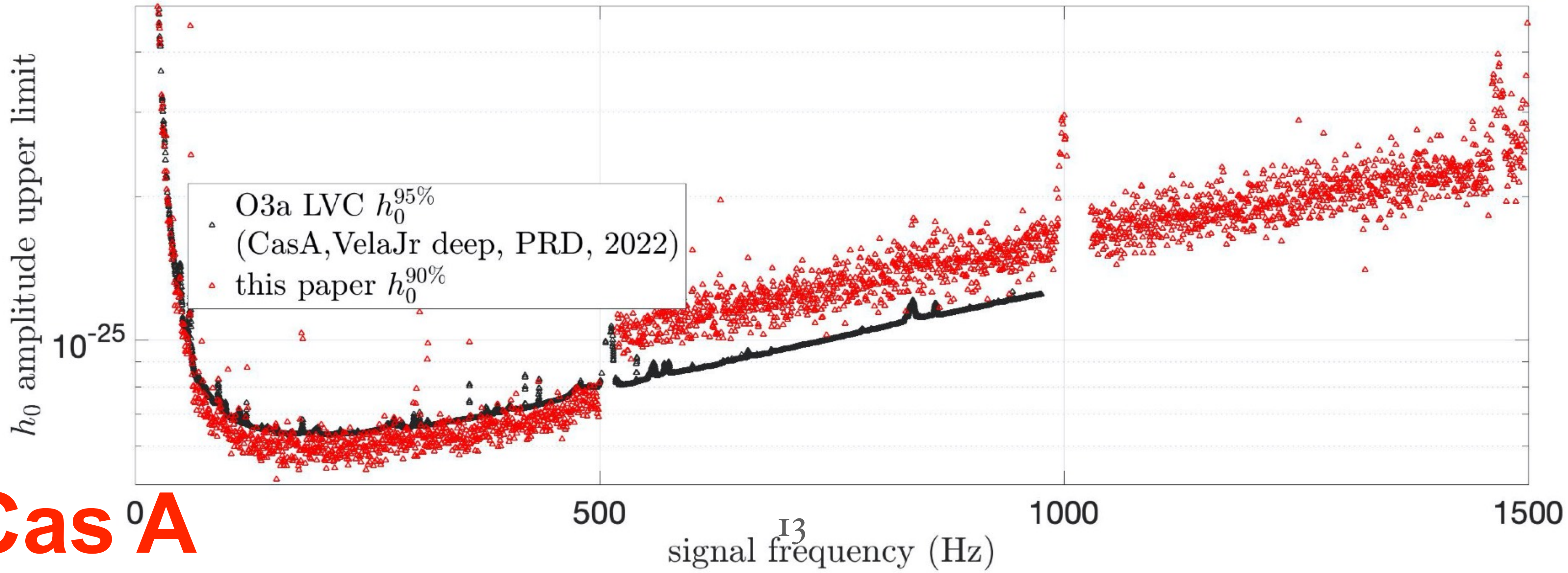
Candidate distribution



h0 Upper Limit: Vela Jr. and Cas A

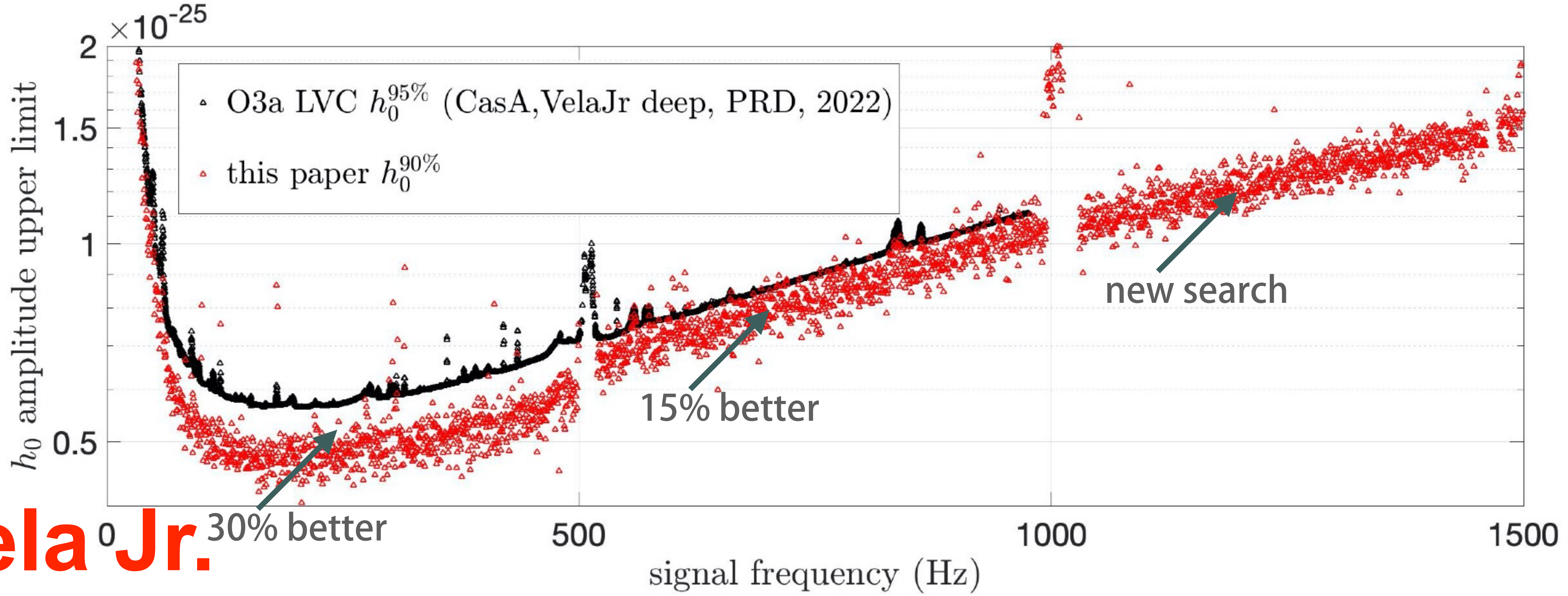


Vela Jr.



Cas A

h_0 Upper Limit: Vela Jr. and Cas A

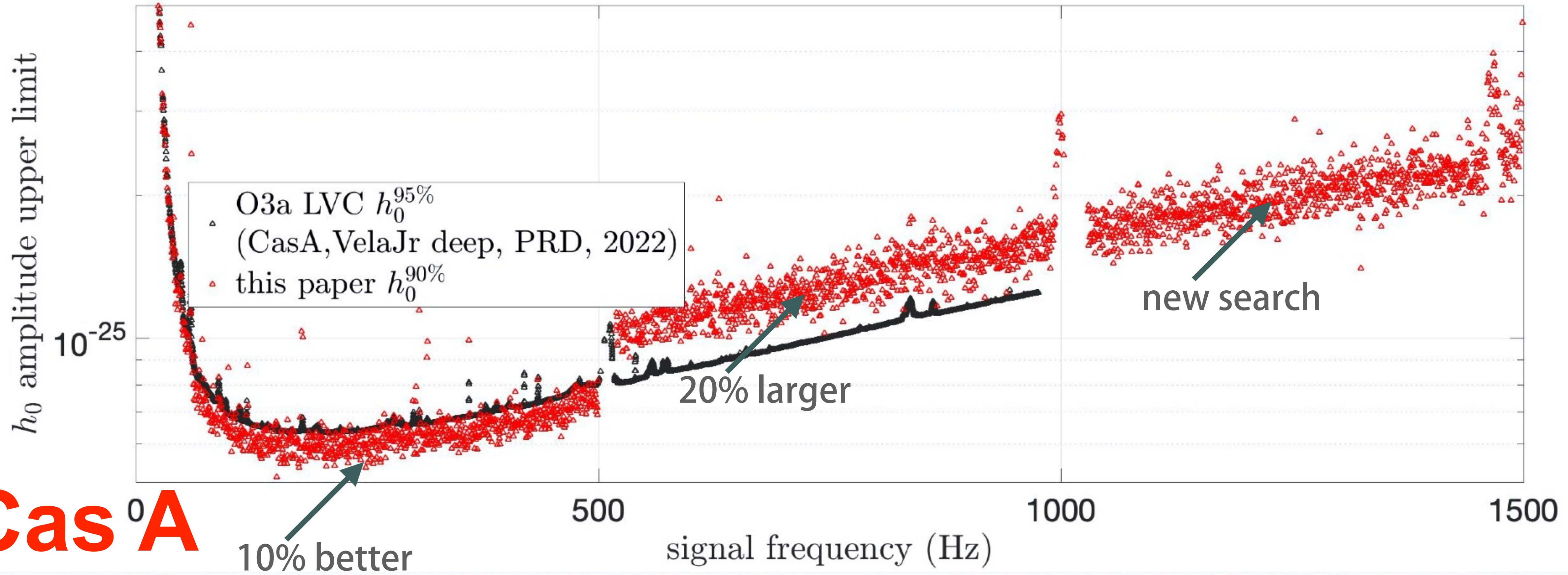


Vela Jr.

30% better

15% better

new search



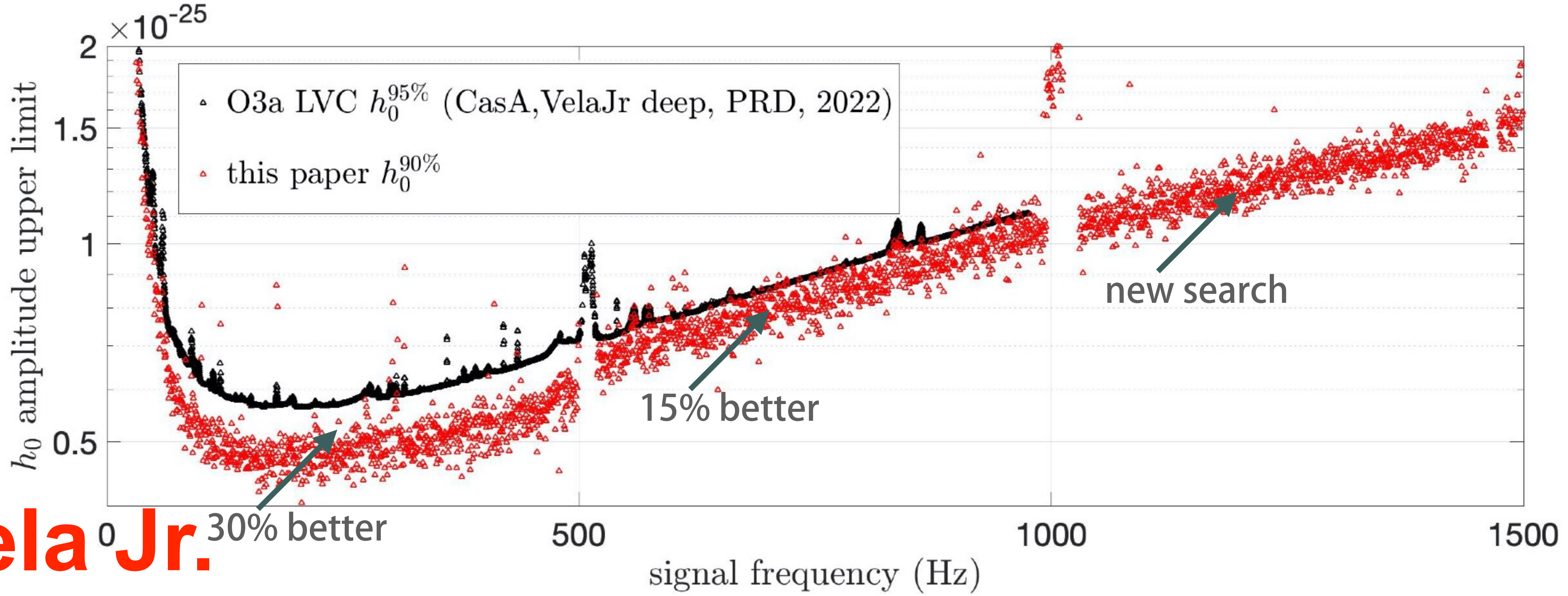
Cas A

10% better

20% larger

new search

h0 Upper Limit: Vela Jr. and Cas A

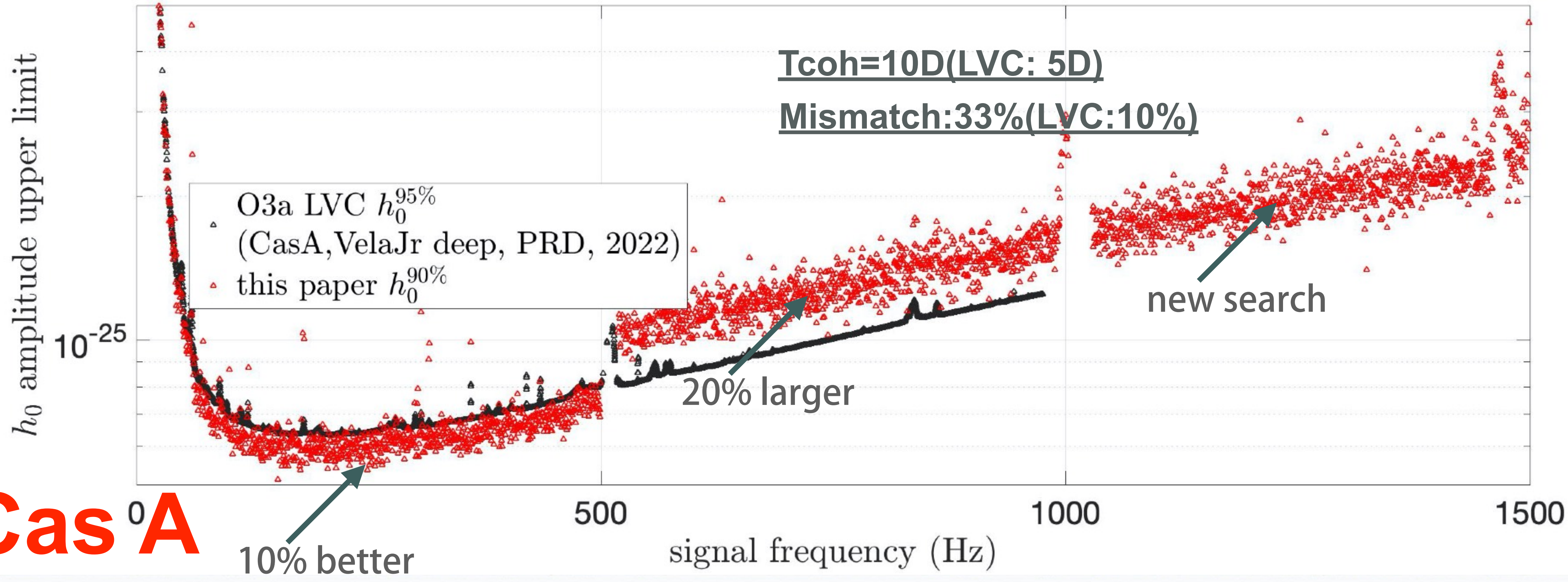


Vela Jr.

30% better

15% better

new search



Tcoh=10D(LVC: 5D)

Mismatch:33%(LVC:10%)

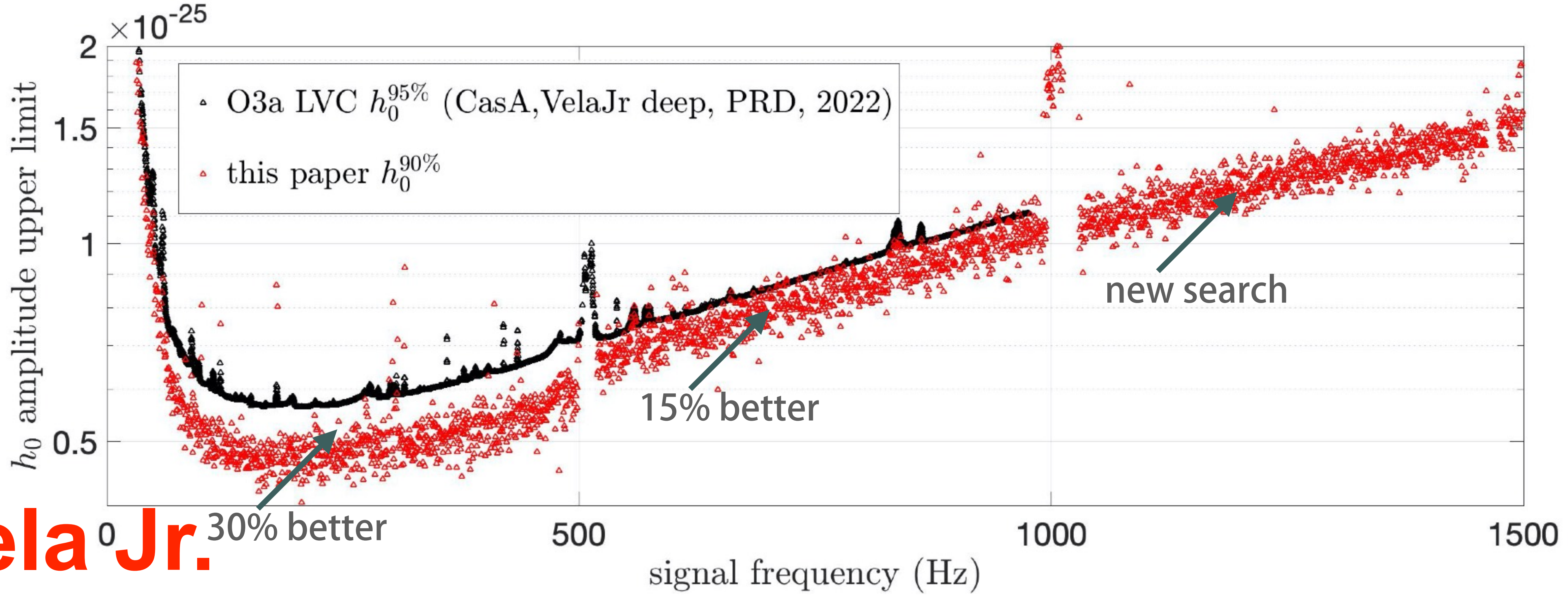
Cas A

10% better

20% larger

new search

h0 Upper Limit: Vela Jr. and Cas A

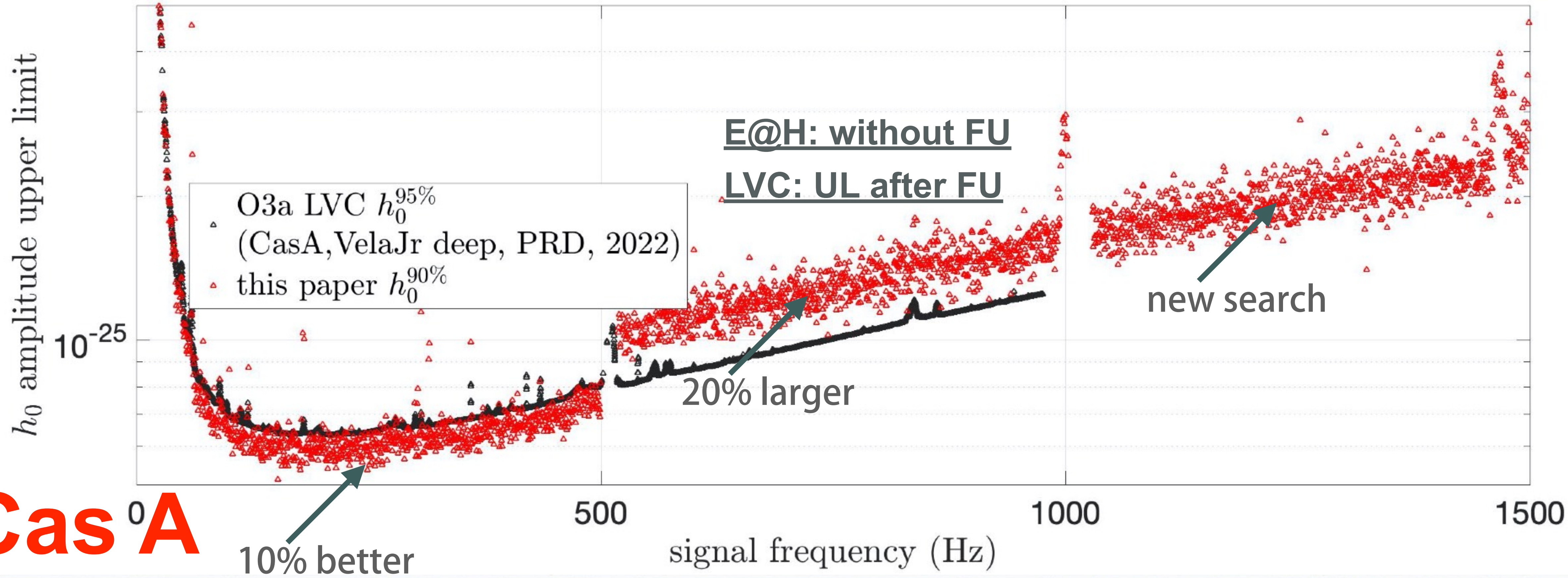


Vela Jr.

30% better

15% better

new search



E@H: without FU

LVC: UL after FU

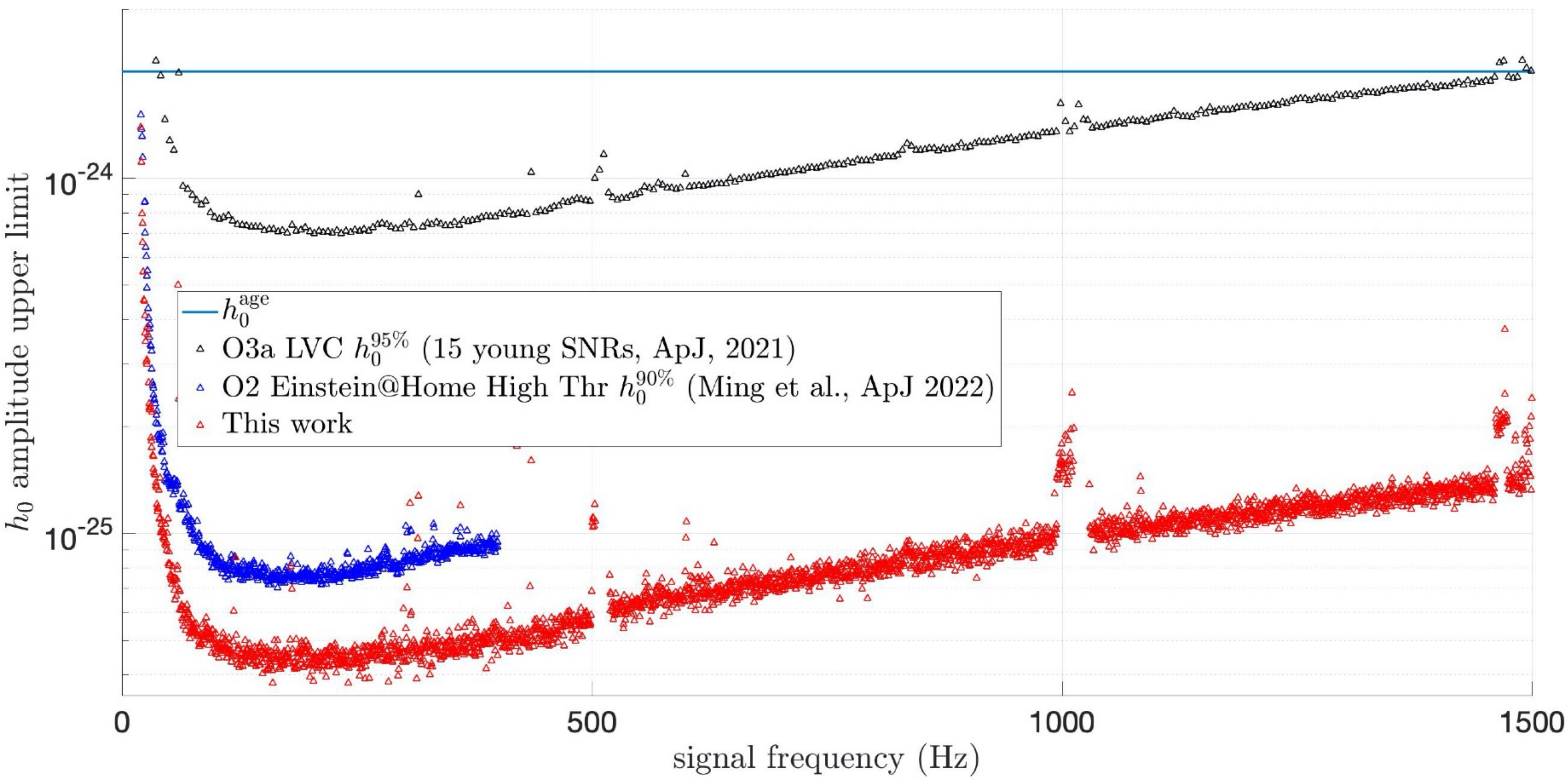
20% larger

new search

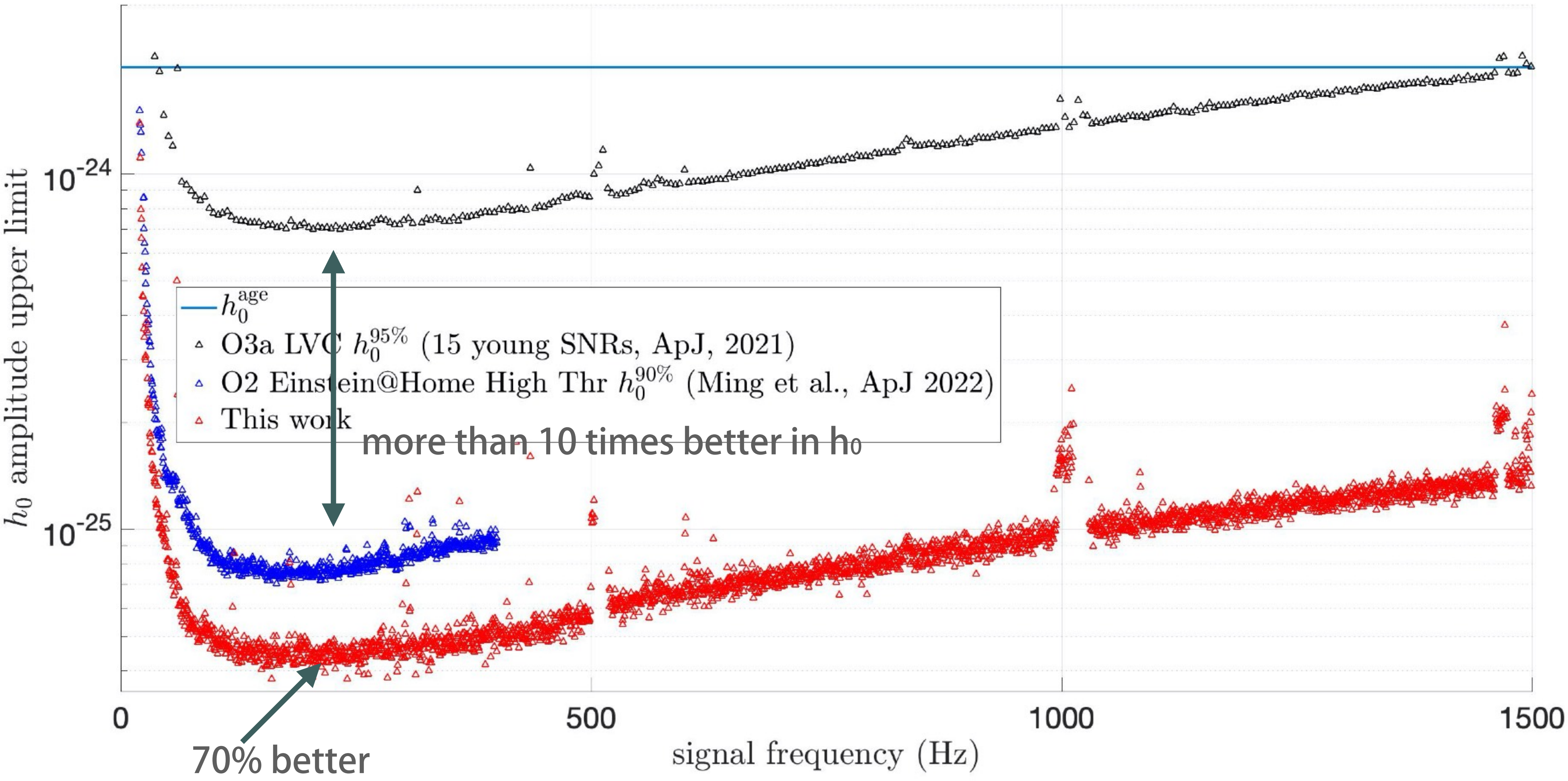
10% better

Cas A

h_0 Upper Limit: G347.3



h_0 Upper Limit: G347.3

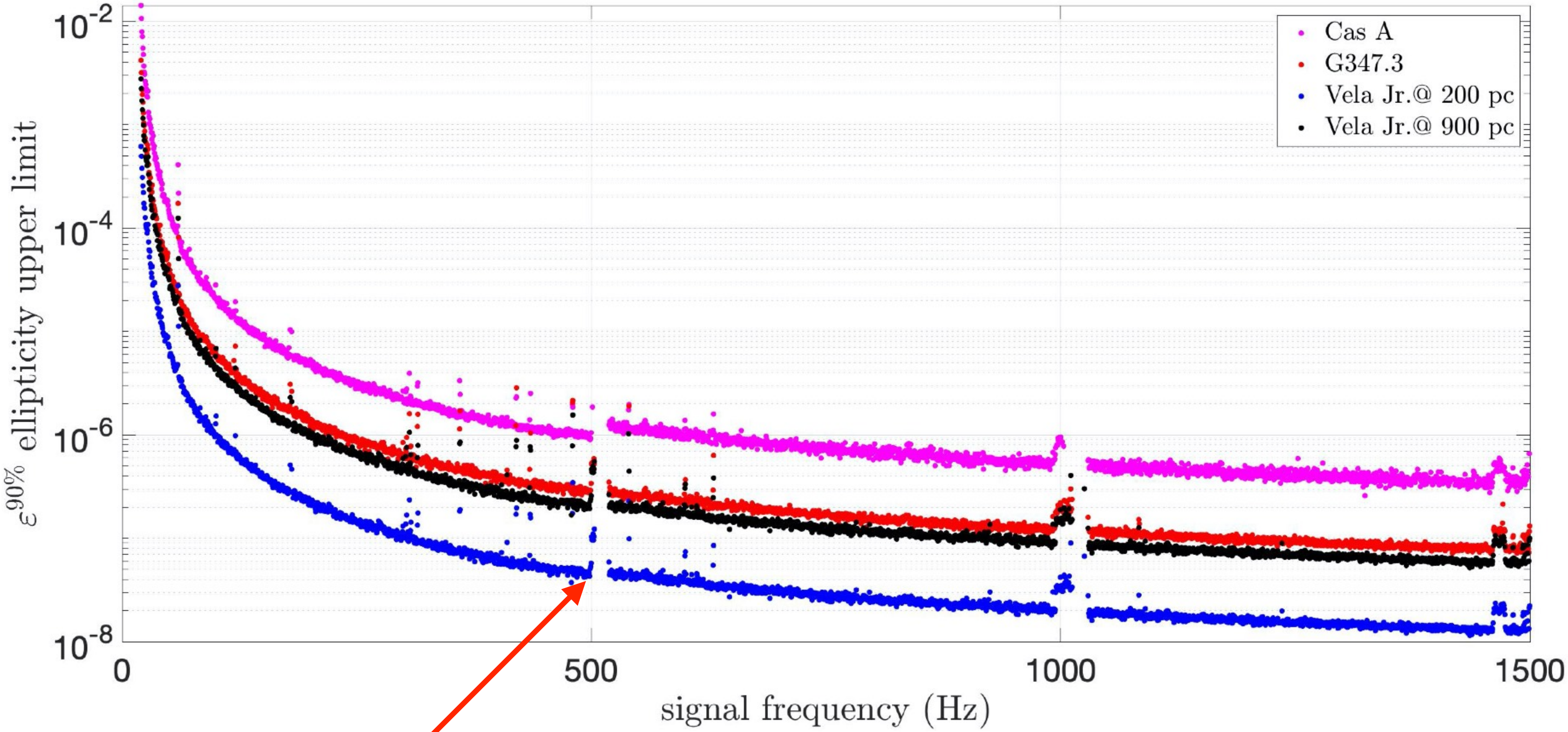


more than 10 times better in h_0

70% better

Upper limits on the NS ellipticity

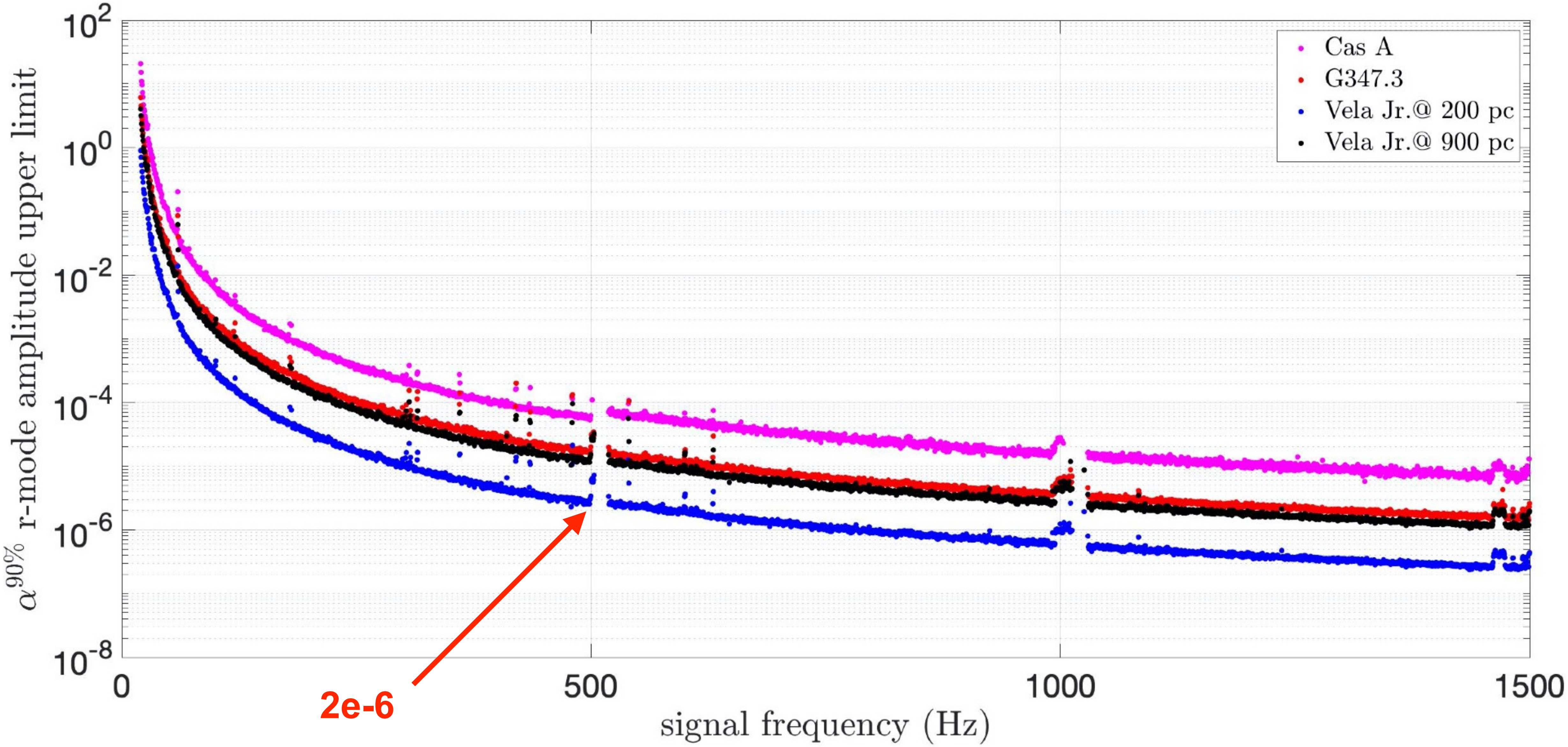
$$\varepsilon = \frac{c^4}{4\pi^2 G} \frac{h_0 D}{I f^2}$$



0.4 mm of 10km NS radius

Upper limits on r-mode amplitude

$$\alpha = 0.028 \left(\frac{h_0}{10^{-24}}\right) \left(\frac{D}{1\ \mathrm{kpc}}\right) \left(\frac{100\ \mathrm{Hz}}{f}\right)^3$$



2e-6

Summary

- no detection of CW, but set most constraint upper-limits
- widest search range for all three sources (f, fdot and f2dot)
- Follow-ups on top candidates are on going.

  might be signals?

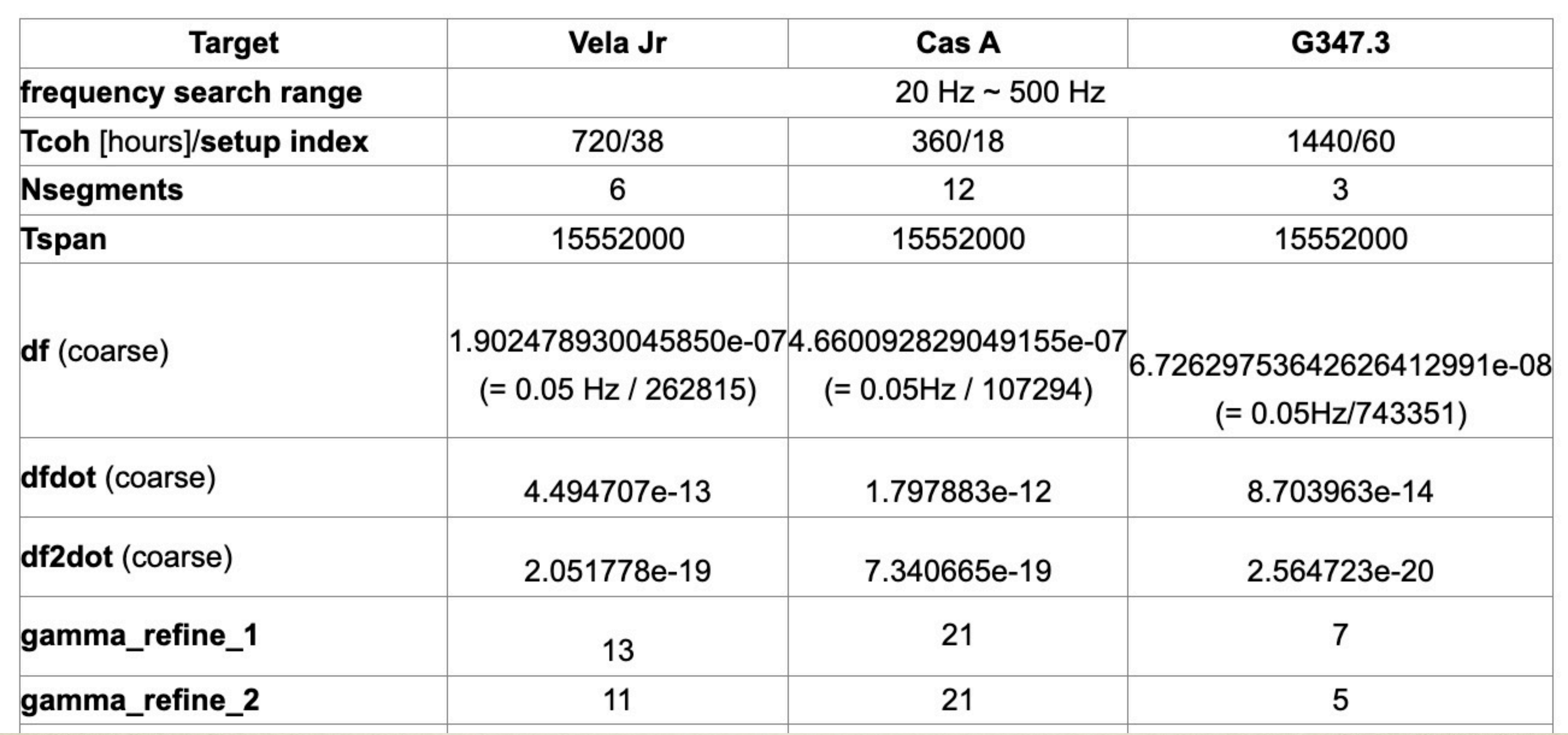
  If not: Upper-limits will be further improved by ~20%.

Thank you

Search Setups

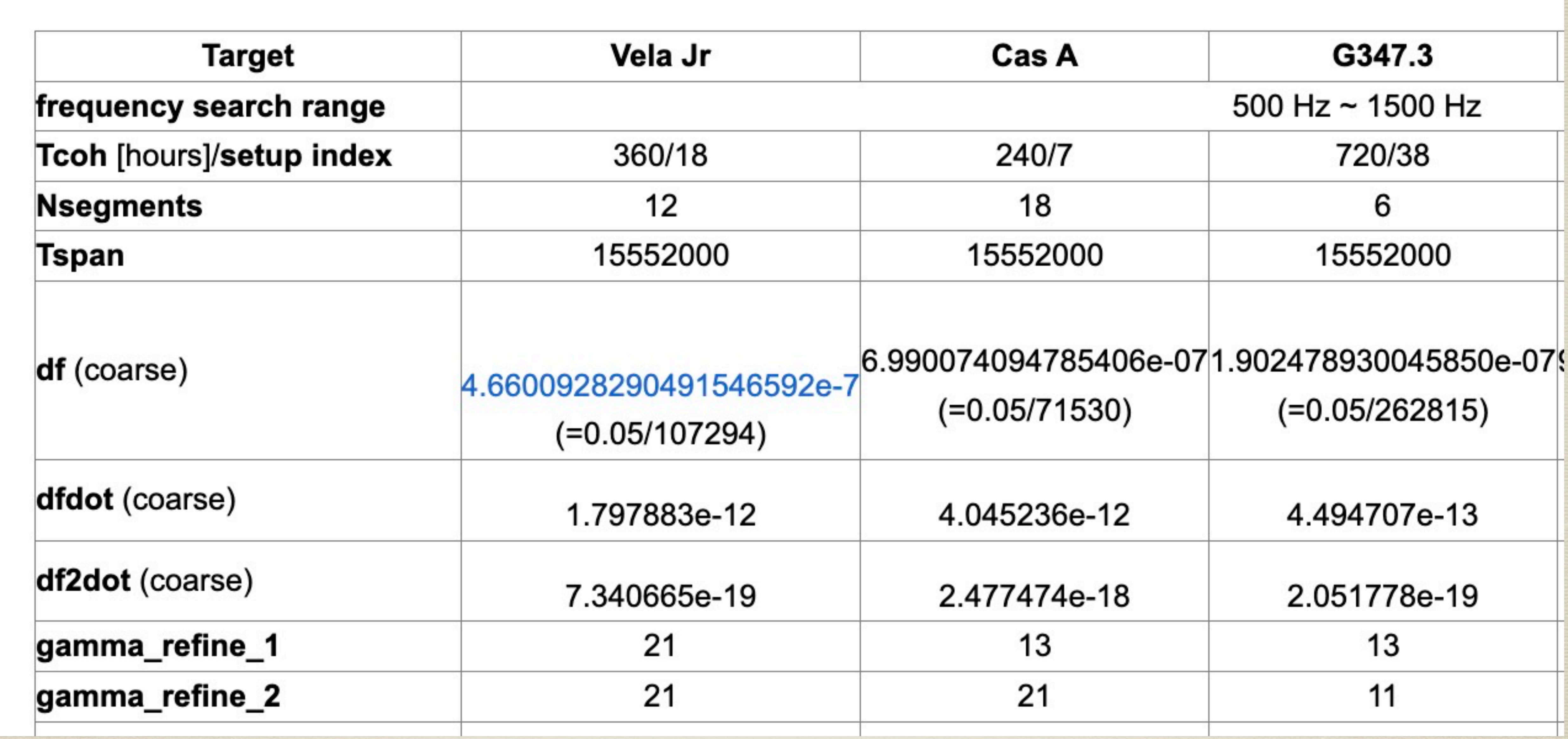
20 - 500 Hz 500 - 1500 Hz	Vela Jr	G347.3	Cas A
Number of seg X Tcoh (days)	6 x 30D 12 x 15D	**3 x 60D** ***(Depth:124)*** 6 x 30D	12 x 15D 18 x 10D ***(Depth:90)***
frequency spacing(Hz)	1.9e-7 4.7e-7	**6.7e-8** 1.9e-7	4.7e-7 7.0e-7
Mismatch	22% 17%	5% 22%	17% 33%
Number of Templates (fine)	2.3e17 5.2e17	5.4e17 5.0e17	1.9e17 2.7e17

S0 set-up <500 Hz



Target	**Vela Jr**	**Cas A**	**G347.3**
frequency search range	20 Hz ~ 500 Hz		
Tcoh [hours]/**setup index**	720/38	360/18	1440/60
Nsegments	6	12	3
Tspan	15552000	15552000	15552000
df (coarse)	1.902478930045850e-07 (= 0.05 Hz / 262815)	4.660092829049155e-07 (= 0.05Hz / 107294)	6.72629753642626412991e-08 (= 0.05Hz/743351)
dfdot (coarse)	4.494707e-13	1.797883e-12	8.703963e-14
df2dot (coarse)	2.051778e-19	7.340665e-19	2.564723e-20
gamma_refine_1	13	21	7
gamma_refine_2	11	21	5

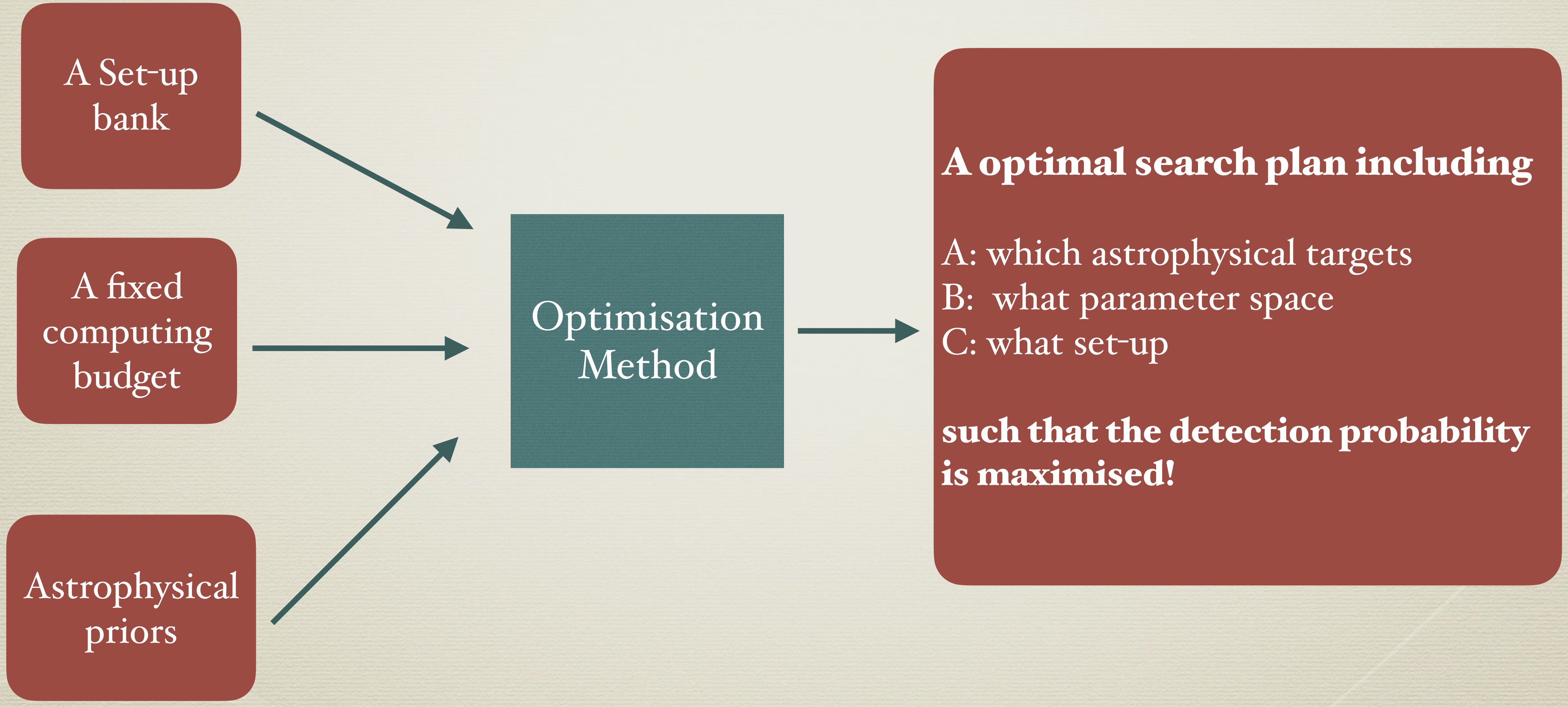
S0 set-up >500 Hz



Target	**Vela Jr**	**Cas A**	**G347.3**
frequency search range			500 Hz ~ 1500 Hz
Tcoh [hours]/**setup index**	360/18	240/7	720/38
Nsegments	12	18	6
Tspan	15552000	15552000	15552000
df (coarse)	4.6600928290491546592e-7 (=0.05/107294)	6.9900740947854 06e-07 (=0.05/71530)	1.902478930045850e-07 (=0.05/262815)
dfdot (coarse)	1.797883e-12	4.045236e-12	4.494707e-13
df2dot (coarse)	7.340665e-19	2.477474e-18	2.051778e-19
gamma_refine_1	21	13	13
gamma_refine_2	21	21	11

The optimisation method

- Optimisation method paper: ***PRD 93, 064011 (2016)***



A Set-up bank

A fixed computing budget

Astrophysical priors

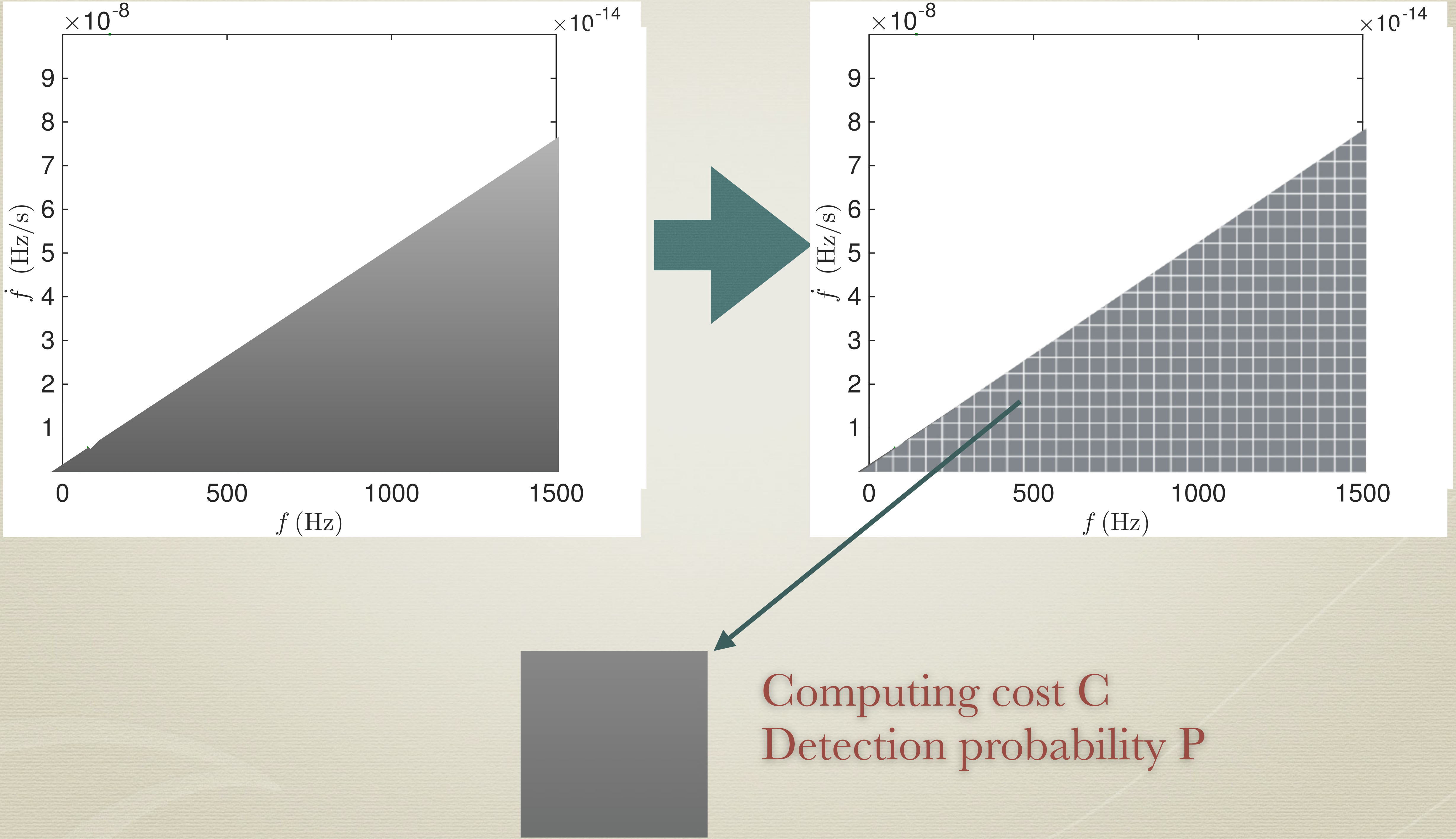
Optimisation Method

A optimal search plan including

A: which astrophysical targets
B: what parameter space
C: what set-up

such that the detection probability is maximised!

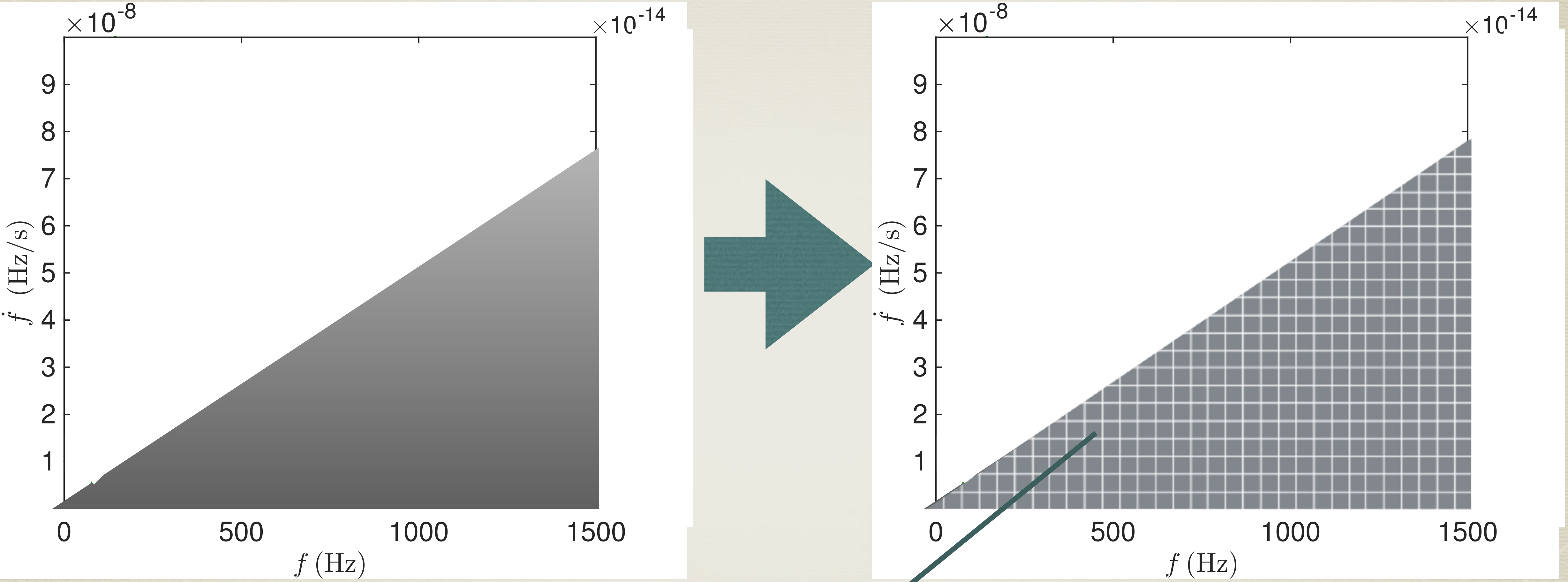
Optimisation scheme



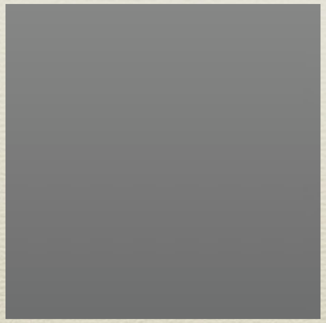
Computing cost C
Detection probability P

Optimization method

(J. Ming, B. Krishnan, M. A. Papa, C. Aulbert, and H. Fehrmann. Physical Review D, 93(6):064011, Mar. 2016.)



Restrict set-ups to be same across cells (single set-up):
rank the cells by efficiency and
pick cells in order of descending efficiency



Computing cost C
Detection probability P
Efficiency e = P/C

Allow different set-ups across cells (multiple set-ups):
same cells from same source with different set-ups shouldn't be picked twice, this ranking doesn't work.

Background info of CW

- **Template searches need lots of computing power**
  - ✶ $\mathcal{F}$-statistic: detection statistic based on matched filtering filtering
  - ✶ Computing power needed in CW searches:

Search template waveform = $(\alpha, \delta, f, \dot{f}, \ddot{f}, \ldots)$

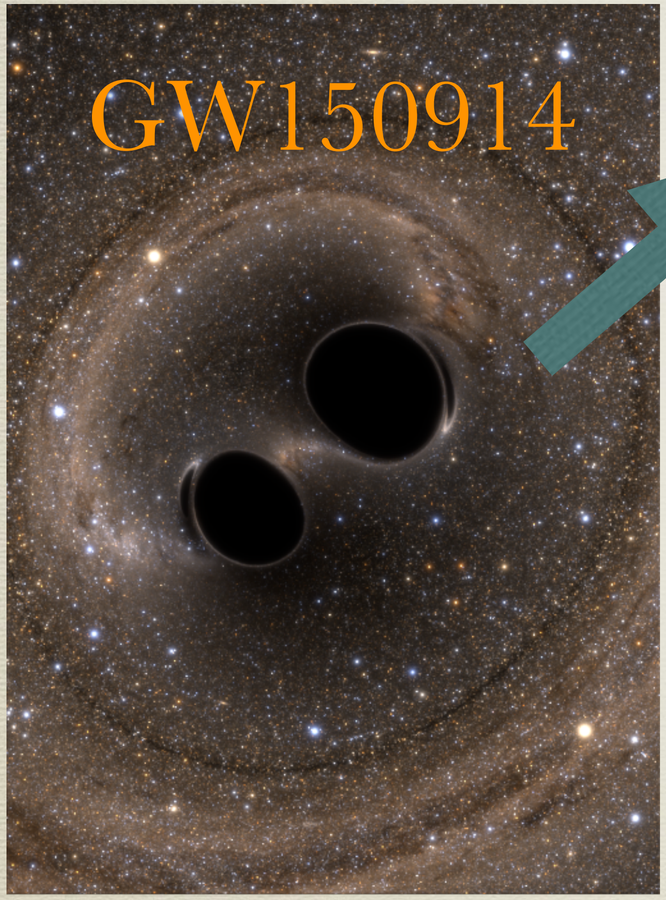
Spacing between templates:

$$\begin{aligned} \delta f &\propto 1/T_{\rm obs} \\ \delta \dot{f} &\propto 1/T_{\rm obs}^2 \\ \delta \ddot{f} &\propto 1/T_{\rm obs}^3 \\ \delta\alpha &\propto 1/T_{\rm obs} \\ \delta\delta &\propto 1/T_{\rm obs} \end{aligned}$$

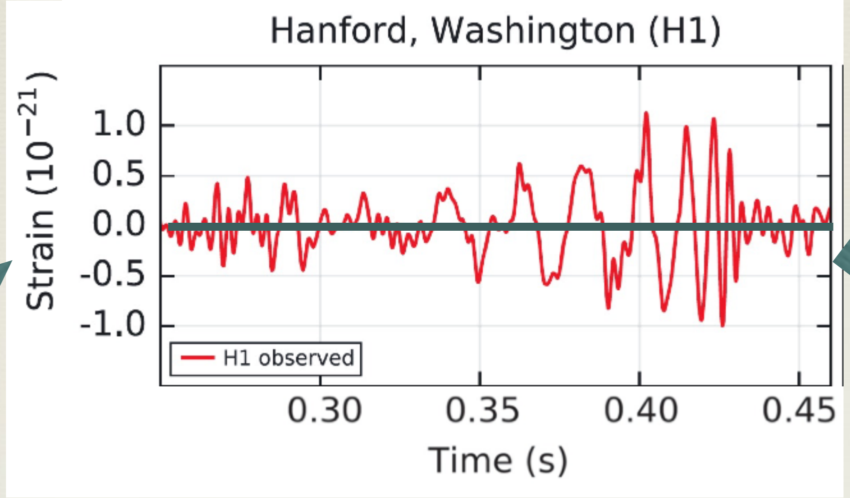
→ **>10^17**

Background info of CW

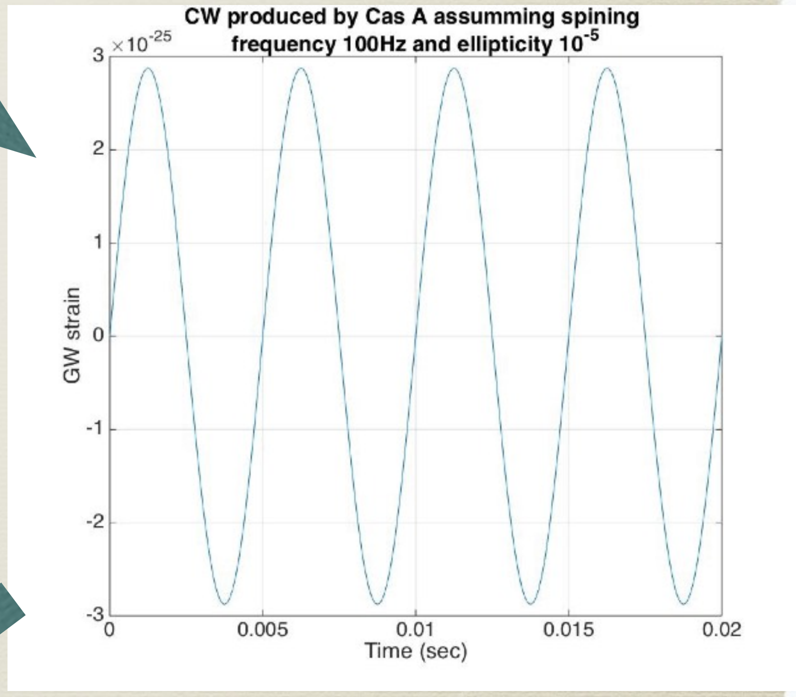
- **Very weak GWs from isolated spinning neutron star**

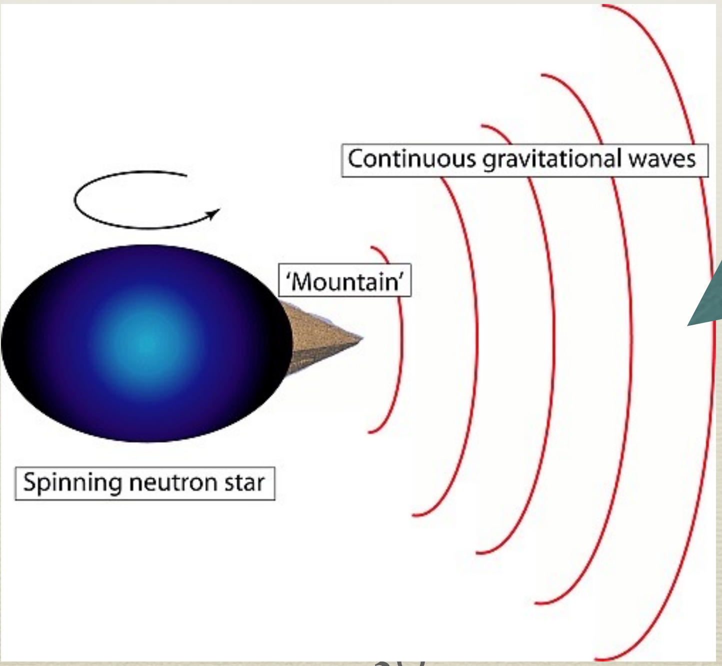


Credit: LSC



PRL 116 (6): 061102(2016)





Background info of CW

- Making detection or not depends on:

    1: sensitivity of detectors (data)

    2: sensitivity of the search (what we do)
        - A: computing budget (Einstein@Home)
        - B: how wisely we spend the budget
          (method can maximise detection probability)

Results: injection and recovery

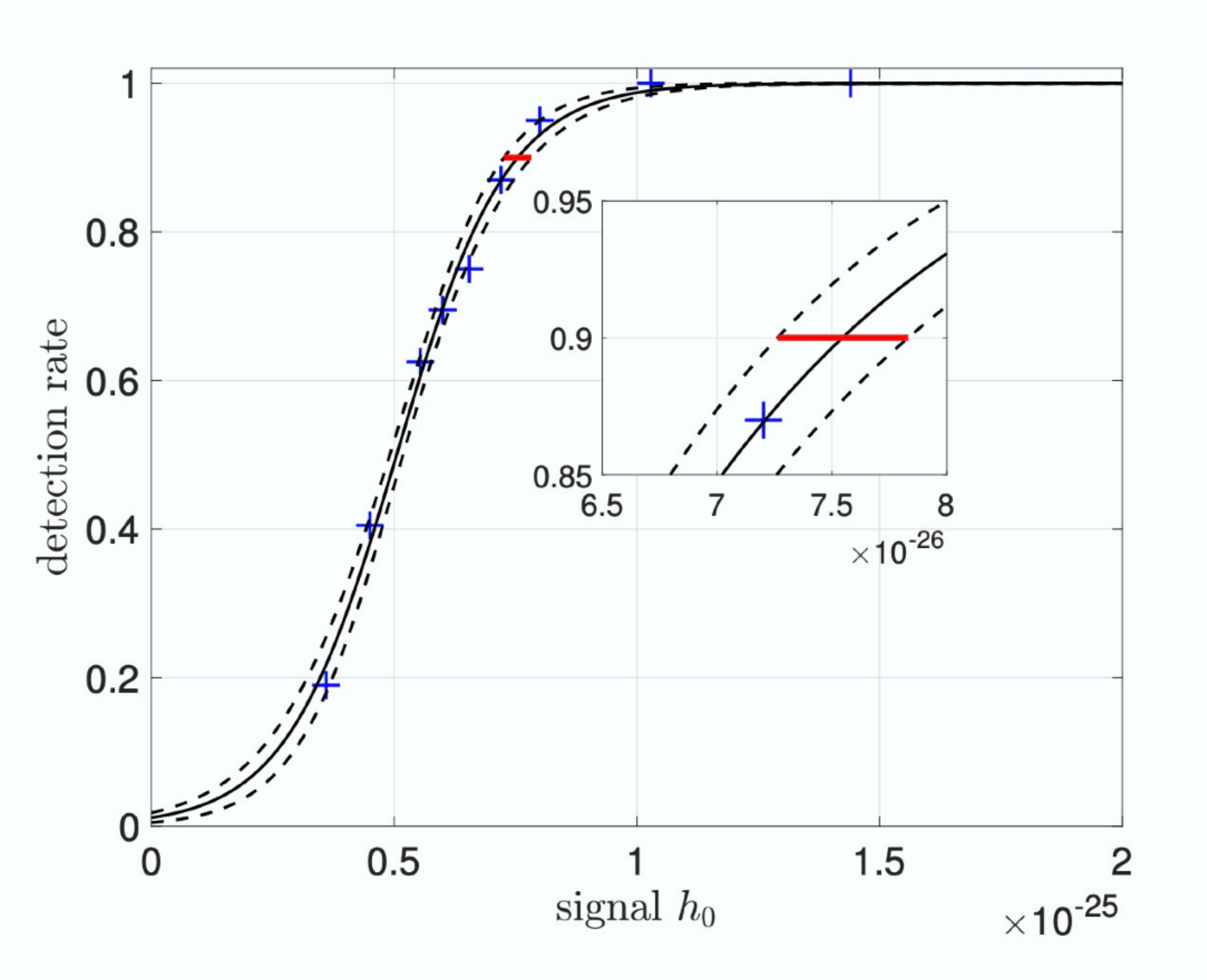
Considering 7 values of h0, spanning the range [4e−26 ~ 5e−25].

A search is performed with the same grids and set-up as the original E@H search, in the neighbourhood of the fake signal parameters.

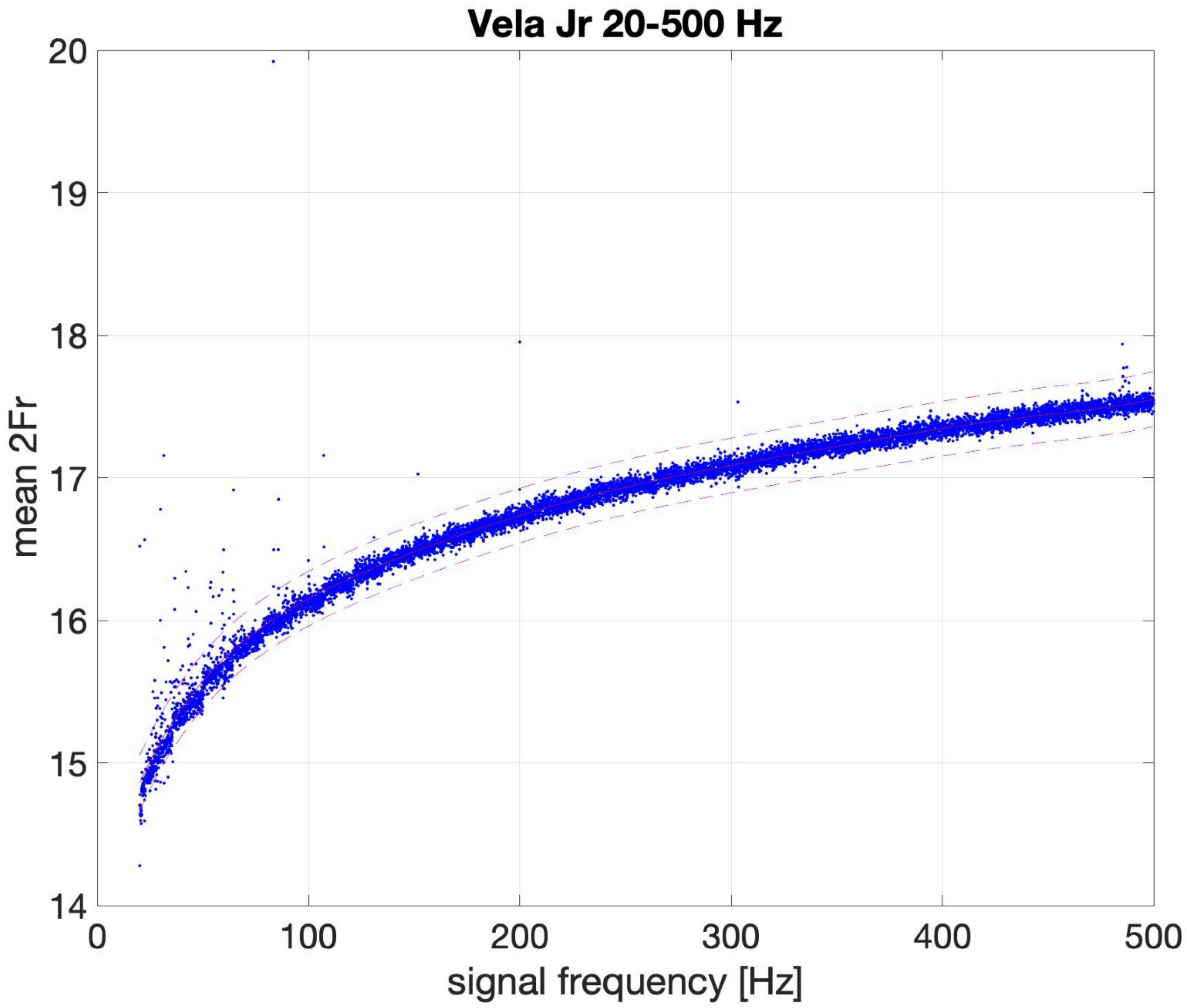
Counting the fraction of recovered signals out of the total 1000.

The h0 versus confidence data is fit with a sigmoid of the form

$$C(h_0) = \frac{1}{1 + \exp(\frac{\mathrm{a} - h_0}{\mathrm{b}})}$$

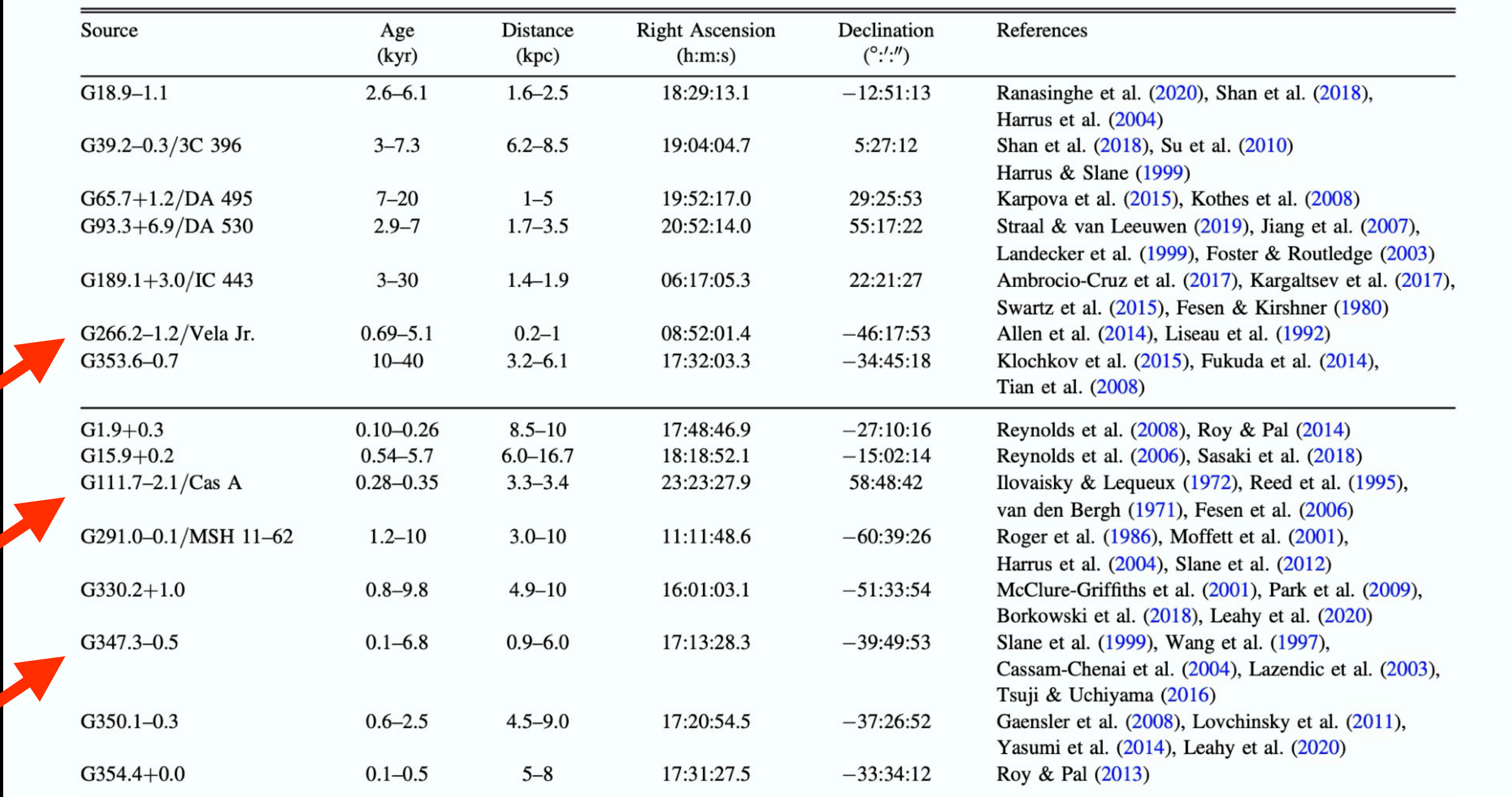


disturbed band Identification



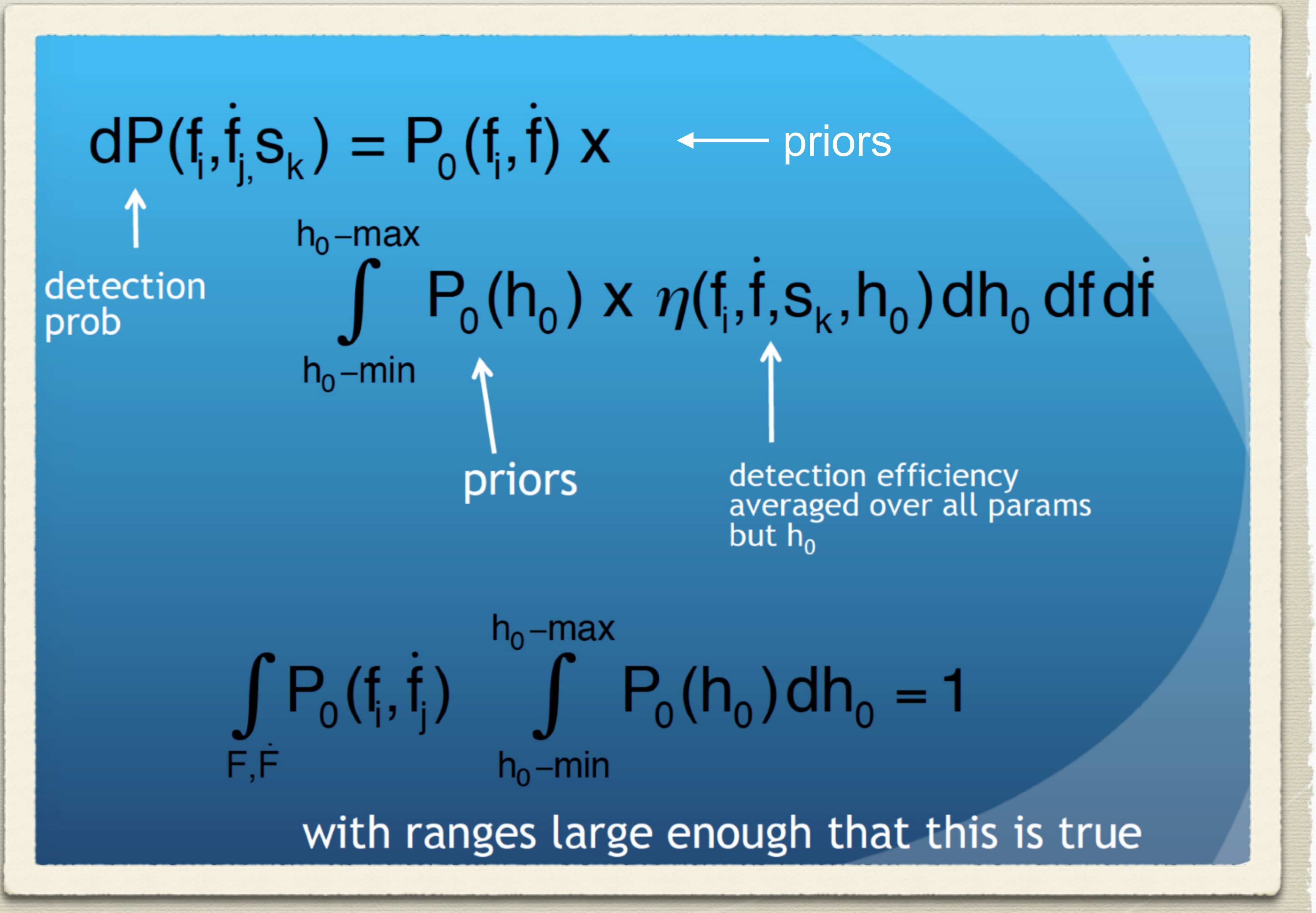
OPTIMISE A SEARCH

Maximize the detection probability at fixed computing budget by choosing appropriately:
1:the search set-up
2: the parameter space, including which targets to search
Ming+2016



Source	Age (kyr)	Distance (kpc)	Right Ascension (h:m:s)	Declination (°:′:″)	References
G18.9–1.1	2.6–6.1	1.6–2.5	18:29:13.1	−12:51:13	Ranasinghe et al. (2020), Shan et al. (2018), Harrus et al. (2004)
G39.2–0.3/3C 396	3–7.3	6.2–8.5	19:04:04.7	5:27:12	Shan et al. (2018), Su et al. (2010) Harrus & Slane (1999)
G65.7+1.2/DA 495	7–20	1–5	19:52:17.0	29:25:53	Karpova et al. (2015), Kothes et al. (2008)
G93.3+6.9/DA 530	2.9–7	1.7–3.5	20:52:14.0	55:17:22	Straal & van Leeuwen (2019), Jiang et al. (2007), Landecker et al. (1999), Foster & Routledge (2003)
G189.1+3.0/IC 443	3–30	1.4–1.9	06:17:05.3	22:21:27	Ambrocio-Cruz et al. (2017), Kargaltsev et al. (2017), Swartz et al. (2015), Fesen & Kirshner (1980)
G266.2–1.2/Vela Jr.	0.69–5.1	0.2–1	08:52:01.4	−46:17:53	Allen et al. (2014), Liseau et al. (1992)
G353.6–0.7	10–40	3.2–6.1	17:32:03.3	−34:45:18	Klochkov et al. (2015), Fukuda et al. (2014), Tian et al. (2008)
G1.9+0.3	0.10–0.26	8.5–10	17:48:46.9	−27:10:16	Reynolds et al. (2008), Roy & Pal (2014)
G15.9+0.2	0.54–5.7	6.0–16.7	18:18:52.1	−15:02:14	Reynolds et al. (2006), Sasaki et al. (2018)
G111.7–2.1/Cas A	0.28–0.35	3.3–3.4	23:23:27.9	58:48:42	Ilovaisky & Lequeux (1972), Reed et al. (1995), van den Bergh (1971), Fesen et al. (2006)
G291.0–0.1/MSH 11–62	1.2–10	3.0–10	11:11:48.6	−60:39:26	Roger et al. (1986), Moffett et al. (2001), Harrus et al. (2004), Slane et al. (2012)
G330.2+1.0	0.8–9.8	4.9–10	16:01:03.1	−51:33:54	McClure-Griffiths et al. (2001), Park et al. (2009), Borkowski et al. (2018), Leahy et al. (2020)
G347.3–0.5	0.1–6.8	0.9–6.0	17:13:28.3	−39:49:53	Slane et al. (1999), Wang et al. (1997), Cassam-Chenai et al. (2004), Lazendic et al. (2003), Tsuji & Uchiyama (2016)
G350.1–0.3	0.6–2.5	4.5–9.0	17:20:54.5	−37:26:52	Gaensler et al. (2008), Lovchinsky et al. (2011), Yasumi et al. (2014), Leahy et al. (2020)
G354.4+0.0	0.1–0.5	5–8	17:31:27.5	−33:34:12	Roy & Pal (2013)

The detection probability



$$dP(f_i,\dot{f}_{j,}s_k) = P_0(f_i,\dot{f}) \text{ x}$$

priors

detection prob

$$\int_{h_0-\min}^{h_0-\max} P_0(h_0) \text{ x } \eta(f_i,\dot{f},s_k,h_0)\,dh_0\,df\,d\dot{f}$$

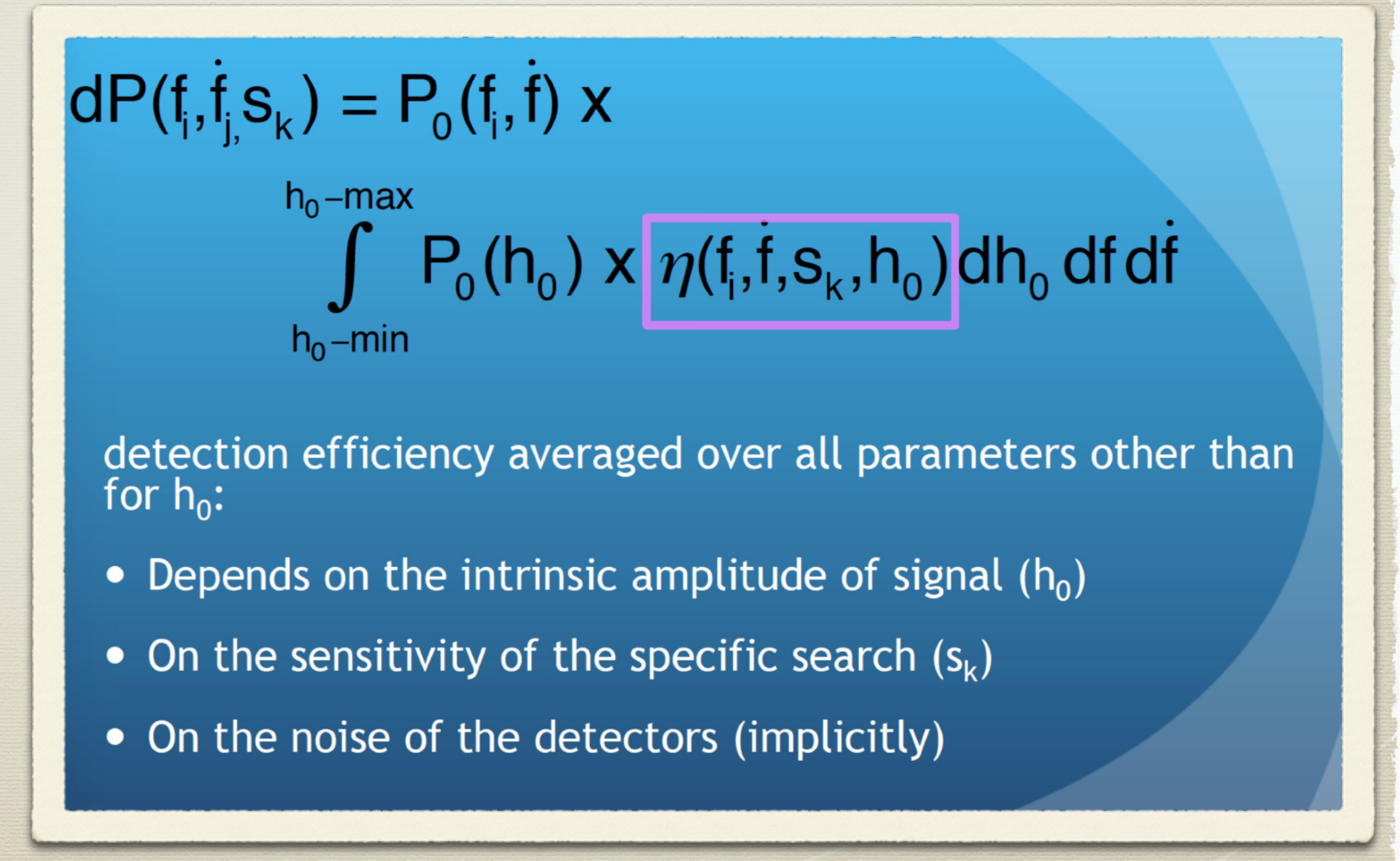
priors

detection efficiency averaged over all params but h_0

$$\int_{F,\dot{F}} P_0(f_i,\dot{f}_j) \int_{h_0-\min}^{h_0-\max} P_0(h_0)\,dh_0 = 1$$

with ranges large enough that this is true

The detection probability

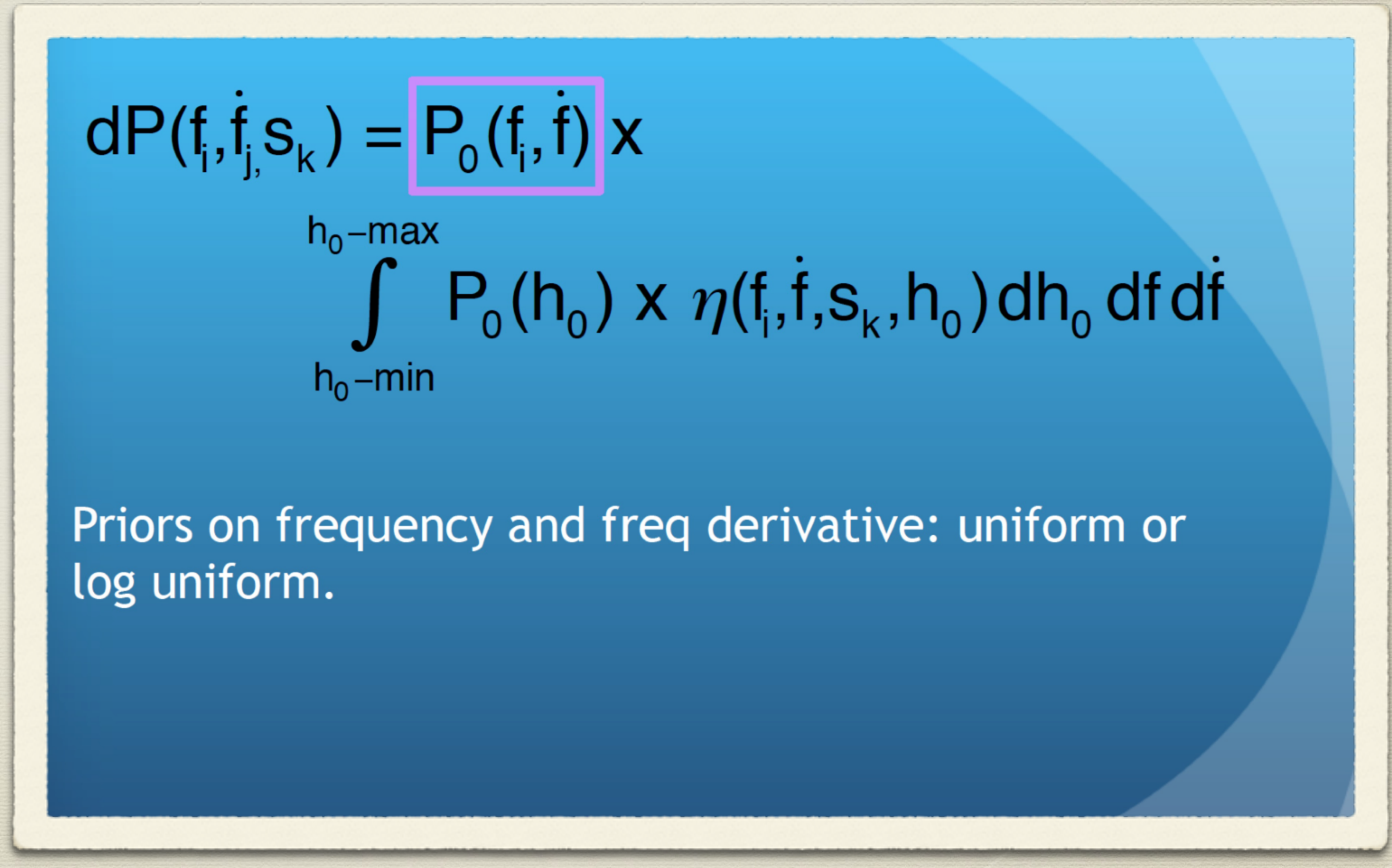


$$dP(f_i,\dot{f}_{j,}s_k) = P_0(f_i,\dot{f}) \text{ x } \int_{h_0-\min}^{h_0-\max} P_0(h_0) \text{ x } \boxed{\eta(f_i,\dot{f},s_k,h_0)}\, dh_0\, df\, d\dot{f}$$

detection efficiency averaged over all parameters other than for h_0:

- Depends on the intrinsic amplitude of signal (h_0)
- On the sensitivity of the specific search (s_k)
- On the noise of the detectors (implicitly)

The detection probability

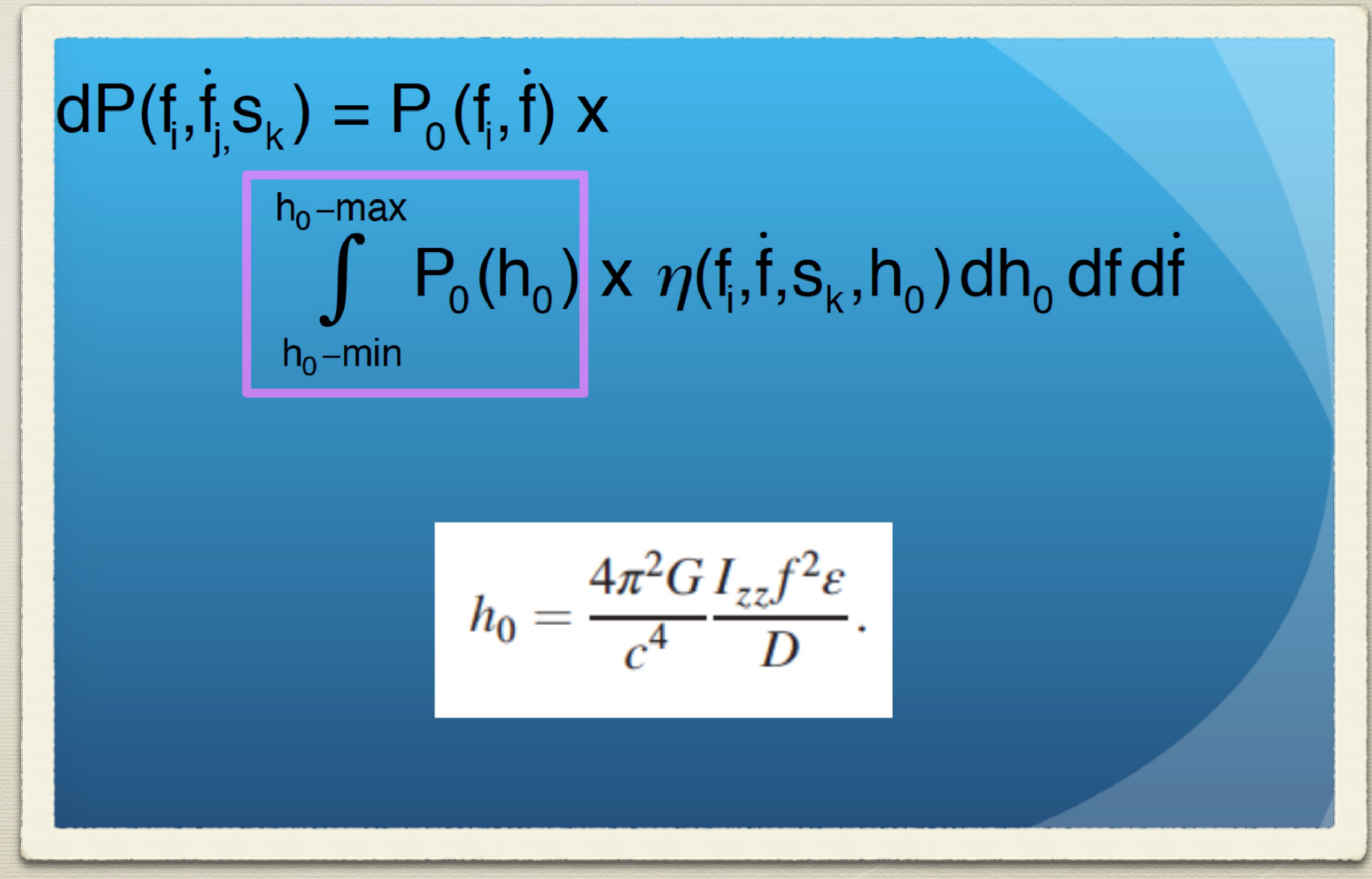


$$dP(f_i,\dot{f}_{j,}s_k) = \boxed{P_0(f_i,\dot{f})}\ x$$

$$\int_{h_0-min}^{h_0-max} P_0(h_0)\ x\ \eta(f_i,\dot{f},s_k,h_0)\,dh_0\,df\,d\dot{f}$$

Priors on frequency and freq derivative: uniform or log uniform.

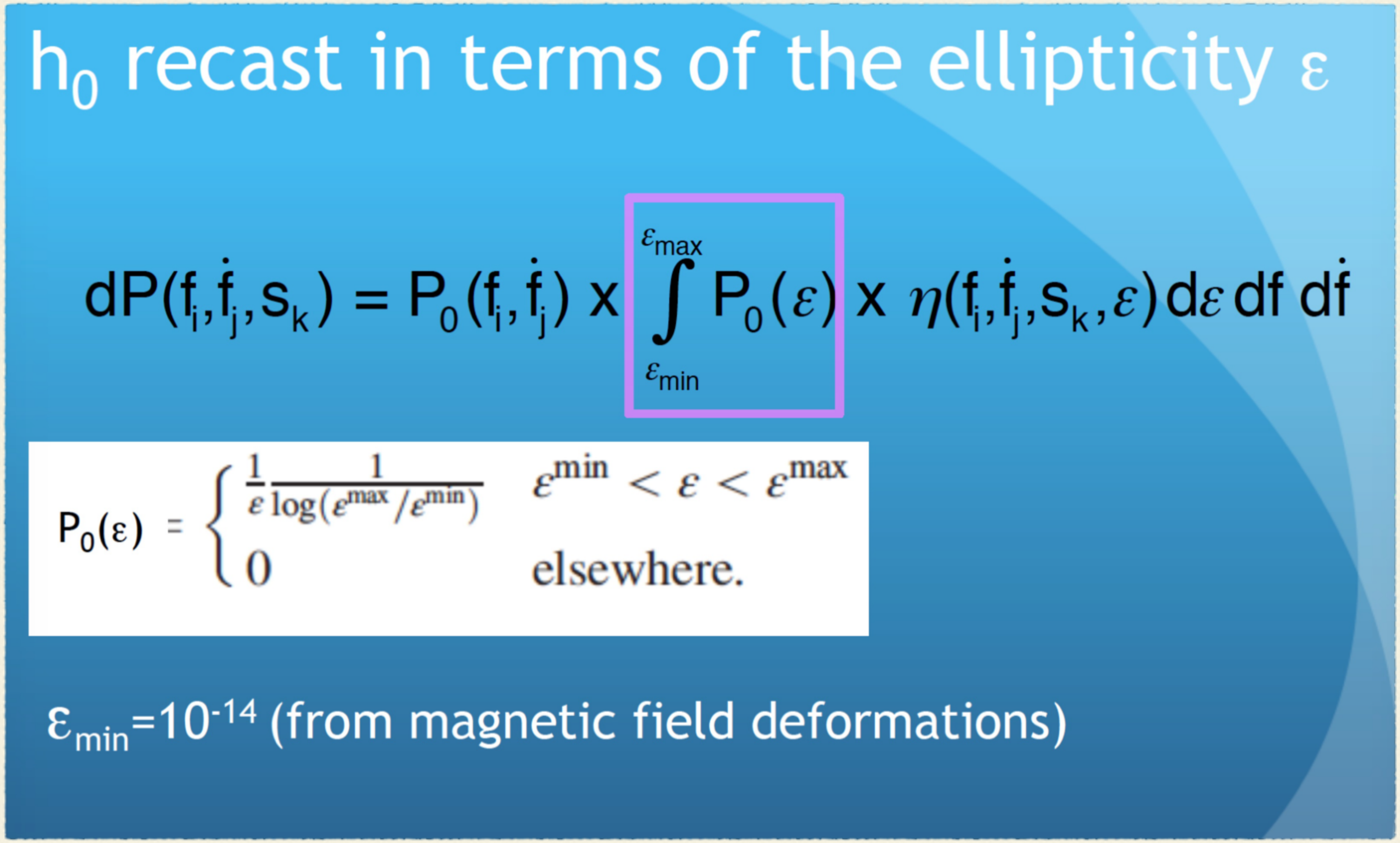
The detection probability



$$dP(f_i,\dot{f}_{j,}s_k) = P_0(f_i,\dot{f}) \text{ x } \boxed{\int_{h_0-\text{min}}^{h_0-\text{max}} P_0(h_0)} \text{ x } \eta(f_i,\dot{f},s_k,h_0)\, dh_0\, df\, d\dot{f}$$

$$h_0 = \frac{4\pi^2 G}{c^4}\frac{I_{zz} f^2 \varepsilon}{D}.$$

The detection probability



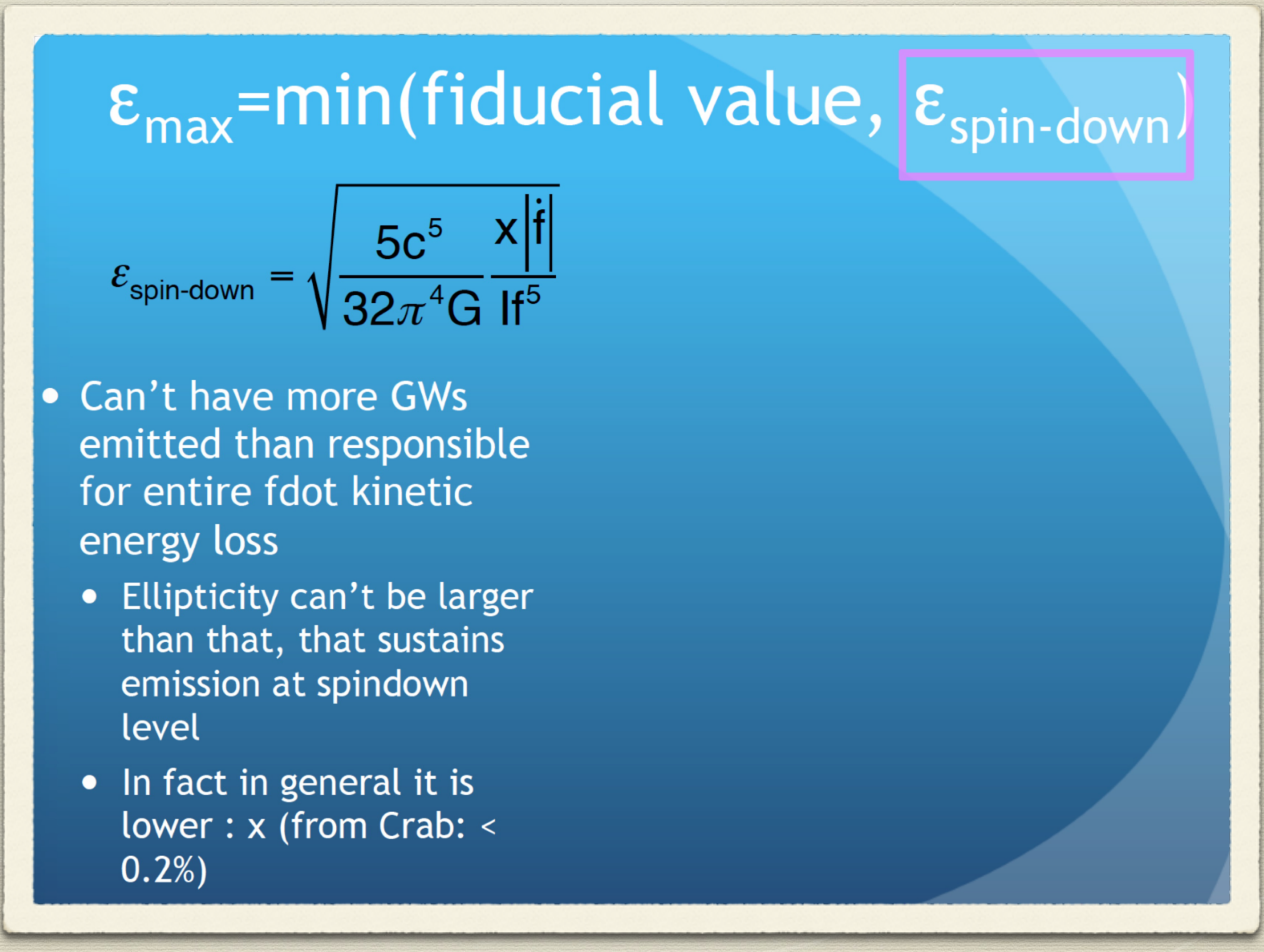
h_0 recast in terms of the ellipticity ε

$$dP(f_i,\dot{f}_j,s_k) = P_0(f_i,\dot{f}_j) \text{ x } \boxed{\int_{\varepsilon_{min}}^{\varepsilon_{max}} P_0(\varepsilon)} \text{ x } \eta(f_i,\dot{f}_j,s_k,\varepsilon)\, d\varepsilon\, df\, d\dot{f}$$

$$P_0(\varepsilon) = \begin{cases} \frac{1}{\varepsilon}\frac{1}{\log(\varepsilon^{\max}/\varepsilon^{\min})} & \varepsilon^{\min} < \varepsilon < \varepsilon^{\max} \\ 0 & \text{elsewhere.} \end{cases}$$

$\varepsilon_{min}=10^{-14}$ (from magnetic field deformations)

The detection probability



ε_{max}=min(fiducial value, $\boxed{\varepsilon_{\text{spin-down}}}$)

$$\varepsilon_{\text{spin-down}} = \sqrt{\frac{5c^5}{32\pi^4 G}\frac{x\left|\dot{f}\right|}{If^5}}$$

- Can't have more GWs emitted than responsible for entire fdot kinetic energy loss
  - Ellipticity can't be larger than that, that sustains emission at spindown level
  - In fact in general it is lower : x (from Crab: < 0.2%)