How astrophysical priors can inform the GW searches

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https://dcc.ligo.org/G1800792

priors on astrophysical objects

How ~~astrophysical priors~~ can inform the GW searches

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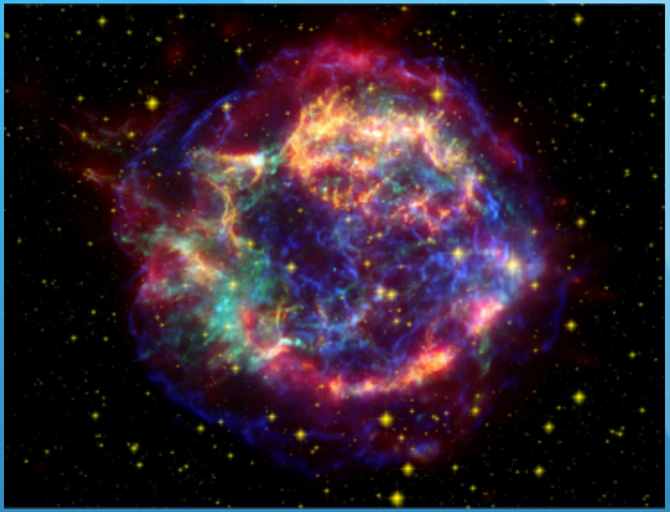
Different types of searches

Targeted (e.g. Crab)



Directed (e.g. CasA)

All-sky

einstein@home

https://einsteinathome.org/

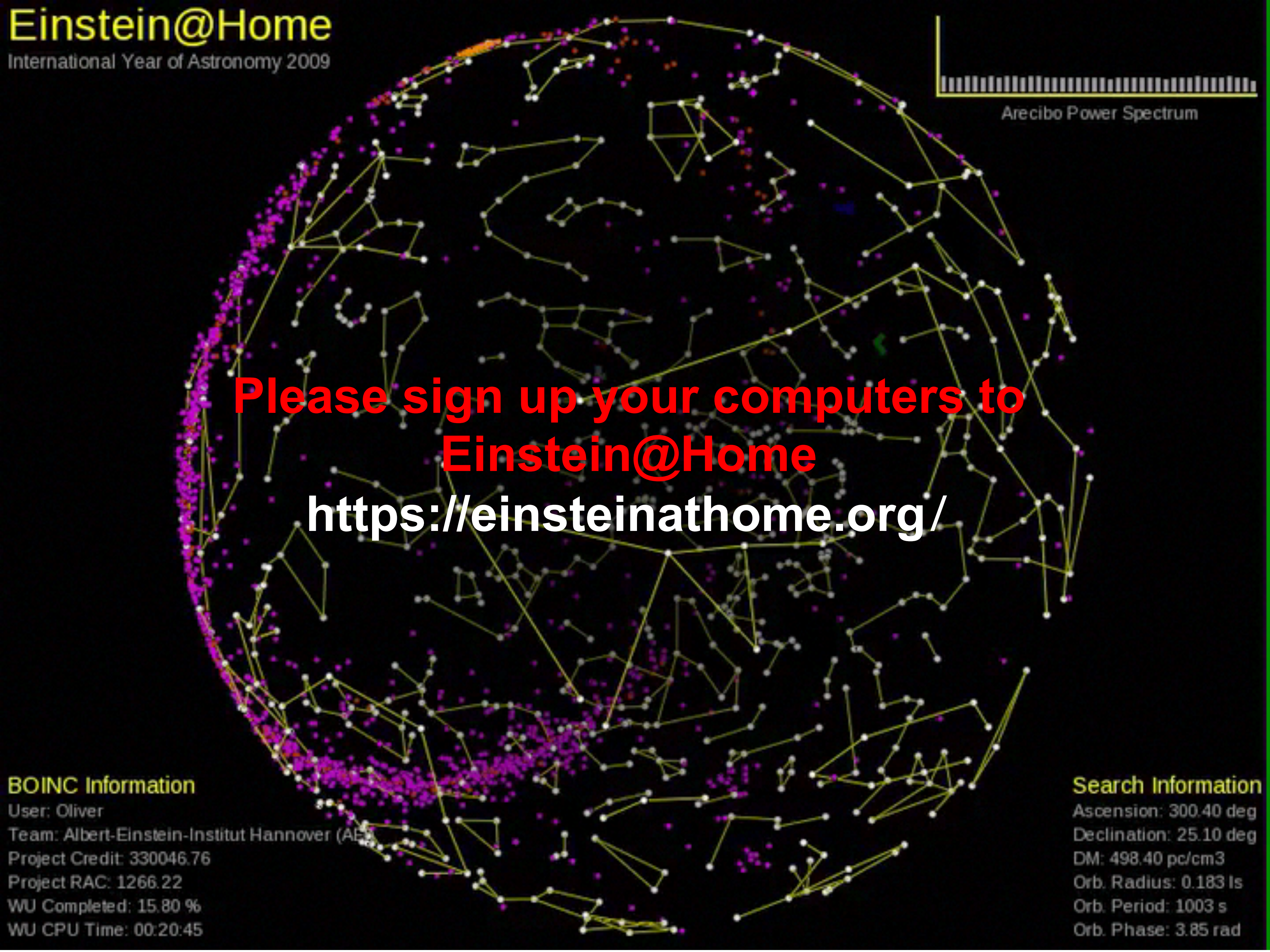
- Public distributed computing project: people donate idle cycles of their machines to some scientific project.
  - Public get a screensaver and get to take part in research
  - We get their compute cycles

- Like SETI@home, but for GW data and EM data.

- APS has publicized this as part of World Year of Physics 2005 activities.

- Use infrastructure and help from SETI@home developers for the distributed computing parts (BOINC).

- Support for Windows, Mac OSX, Linux clients.



BOINC Information

User: Oliver

Team: Albert-Einstein-Institut Hannover (AE

Project Credit: 330046.76

Project RAC: 1266.22

WU Completed: 15.80 %

WU CPU Time: 00:20:45

Search Information

Ascension: 300.40 deg

Declination: 25.10 deg

DM: 498.40 pc/cm3

Orb. Radius: 0.183 ls

Orb. Period: 1003 s

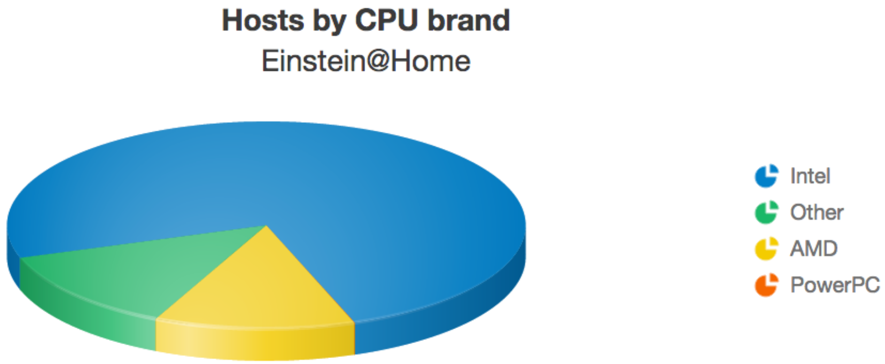
Orb. Phase: 3.85 rad

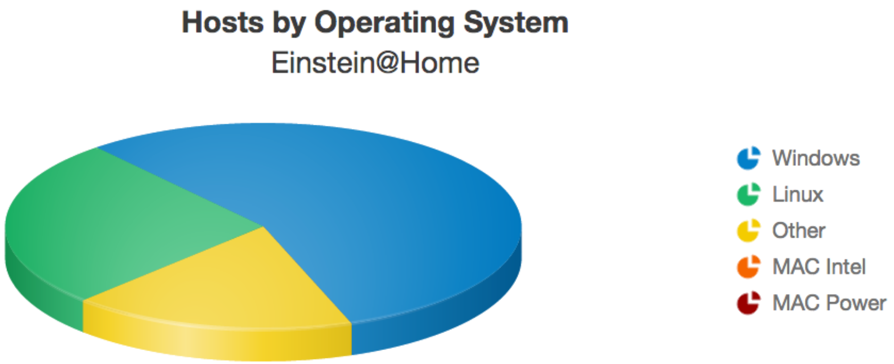
Please sign up your computers to Einstein@Home

https://einsteinathome.org/

https://einsteinathome.org/

- Over 1.6 million hosts and 1 million participants have done work for E@H
- ~ 50 000 hosts (33 000 participants) active
- > 5 Pflops sustained 24 x 7
- Would be in the top-500 list

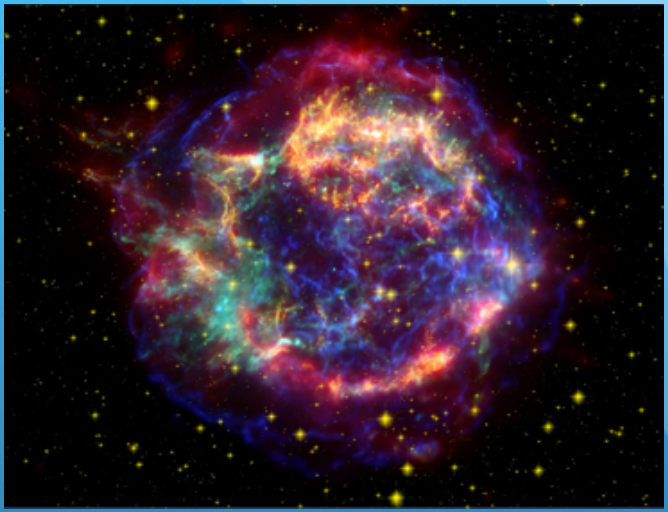




“heavy lifting” machine

Different types of searches

Targeted (e.g. Crab)

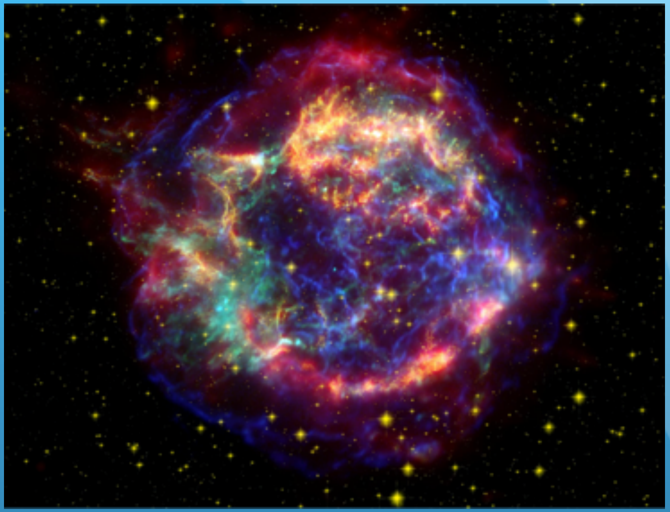


Directed (e.g. CasA)

All-sky

Different types of searches

Targeted (e.g. Crab)



Directed (e.g. CasA)

All-sky

Young objects might be promising

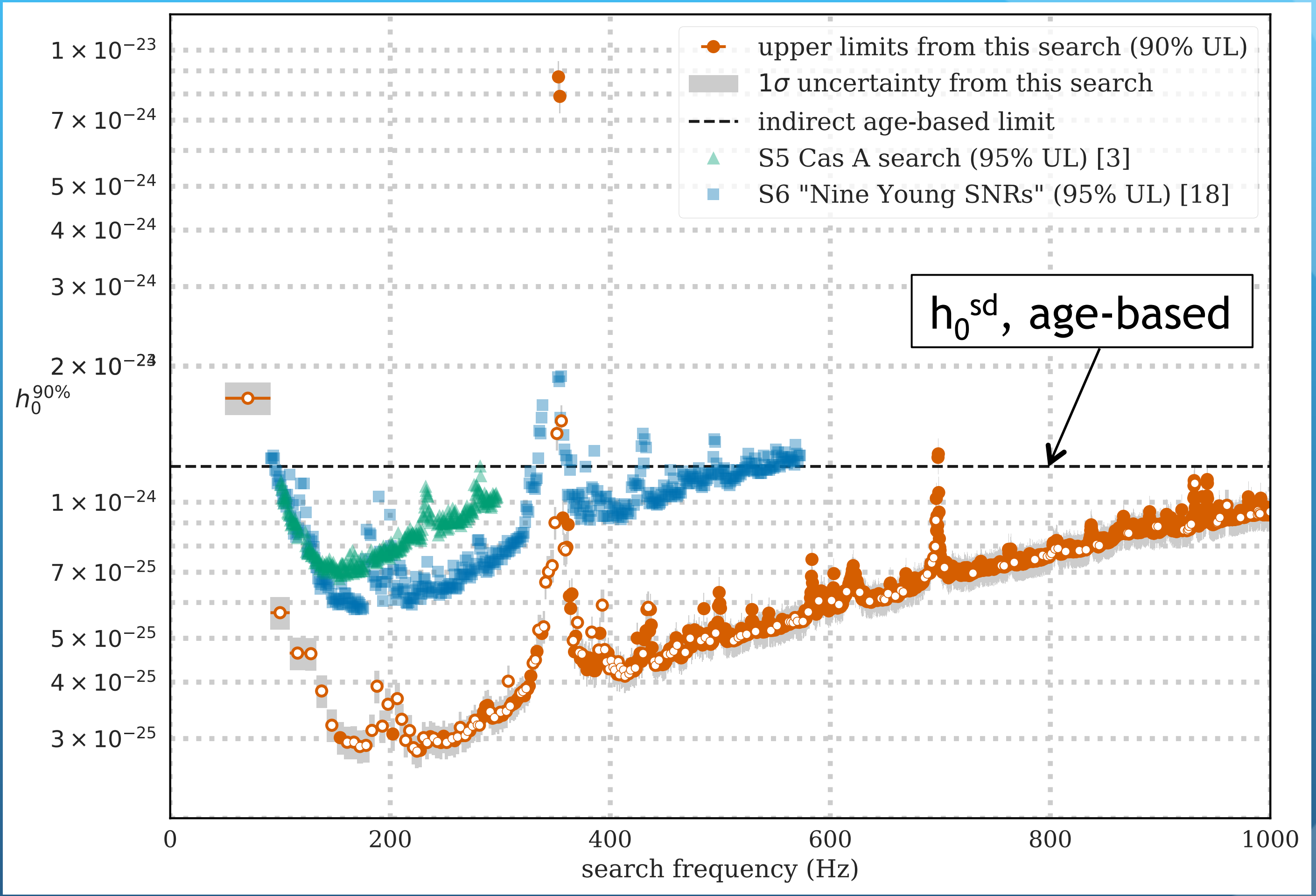
Pulsar spin decreases, so the younger the object, the higher the spindown, i.e. the kinetic energy loss, a fraction of which, might go in GWs

$\dot{f} \propto f^n$ n, braking index

$$\tau_c = \frac{1}{n-1}\frac{f}{\dot{f}}$$ characteristic age of object

$$h_0^{spindown} = \frac{1}{D}\sqrt{\frac{5GI}{2c^3}\frac{|\dot{f}|}{f}} \Rightarrow \frac{1}{D}\sqrt{\frac{5GI}{8c^3}\frac{1}{\tau_c}}$$ (age-based upper limit)

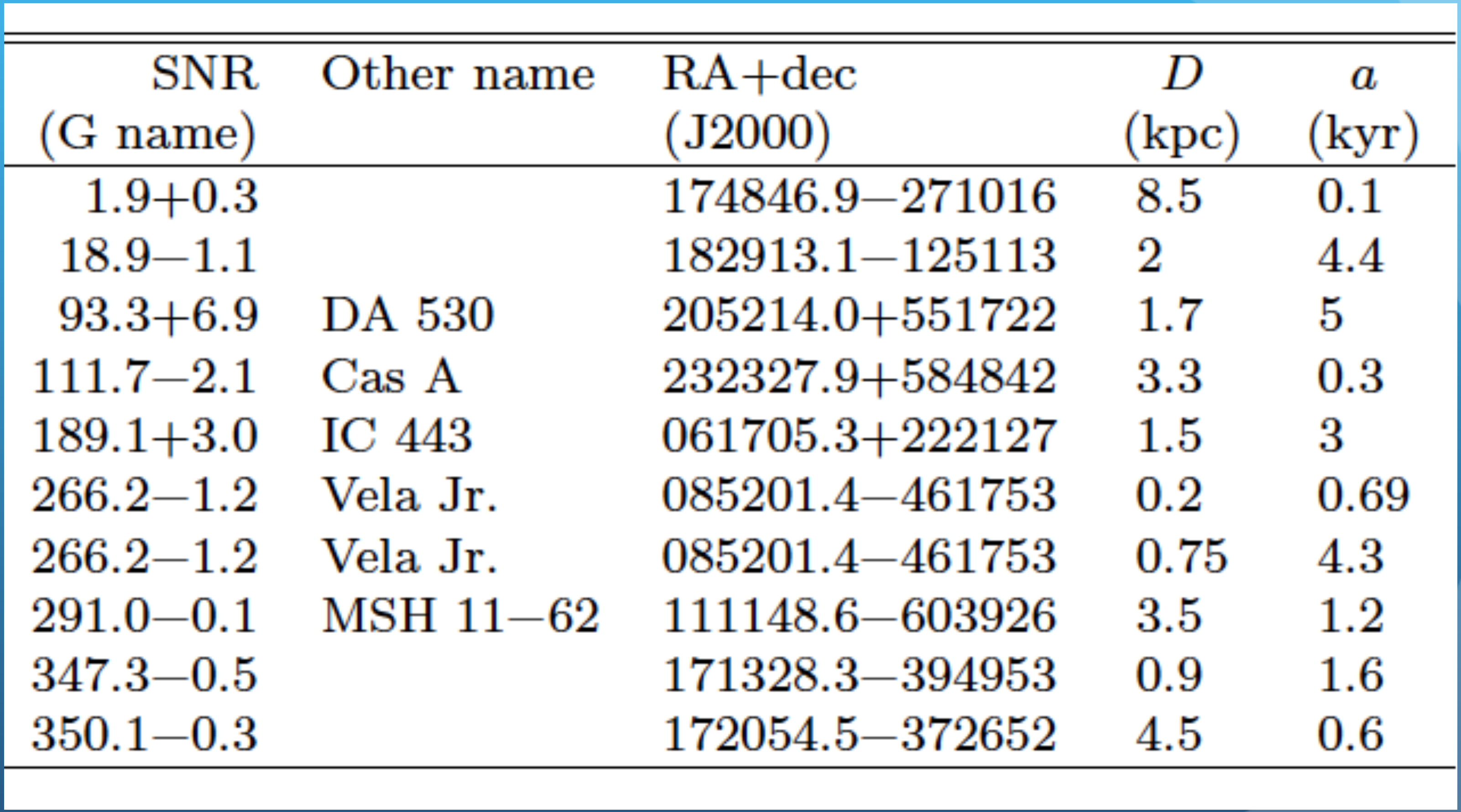
CasA example



h_0^{sd}, age-based

Zhu, Papa, Eggenstein, Prix et al., Results of the deepest Einstein@Home search for continuous gravitational waves from CasA from the S6 LIGO Science Run, Phys. Rev. D 94, 082008 (2016)

Targets used in S6 (Ben Owen led the search)



SNR (G name)	Other name	RA+dec (J2000)	*D* (kpc)	*a* (kyr)
1.9+0.3		174846.9−271016	8.5	0.1
18.9−1.1		182913.1−125113	2	4.4
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
266.2−1.2	Vela Jr.	085201.4−461753	0.2	0.69
266.2−1.2	Vela Jr.	085201.4−461753	0.75	4.3
291.0−0.1	MSH 11−62	111148.6−603926	3.5	1.2
347.3−0.5		171328.3−394953	0.9	1.6
350.1−0.3		172054.5−372652	4.5	0.6

Aasi et al, Astrophys.J. 813 (2015) no.1, 39

Decisions, decisions …

- Which ones ?
  - Youngest ?
  - Closest ?
- What frequency range ?
- What spindown range ?

- Search
  - What frequency and frequency-derivative grid spacings ?
  - What search set-up ?

Optimisation scheme

$P_{s,i,k}$ probability of detecting a signal from source s, with parameters i and with search set-up k

Pick $\{s,i,k\}^*$ such that the total detection probability

$$P_{tot} = \Sigma_{\{s,i,k\}^*} P_{\{s,i,k\}^*}$$

is maximized, at fixed computing cost.

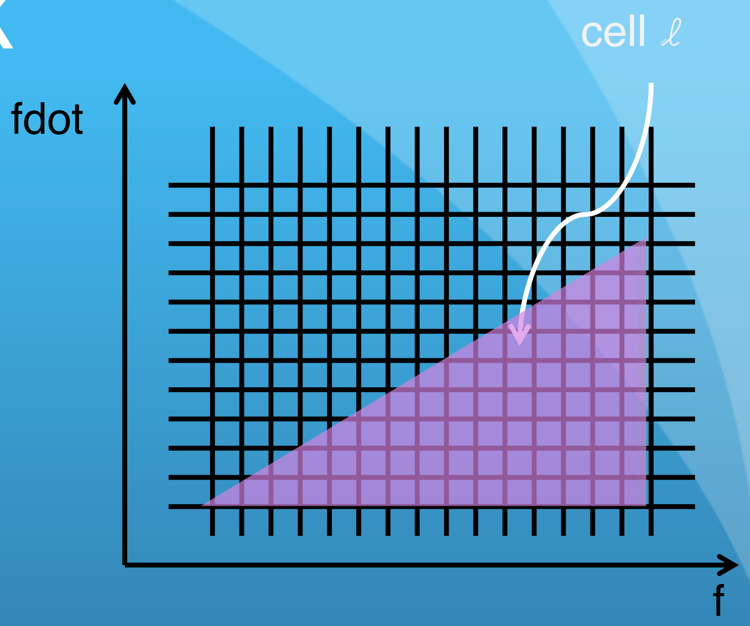
Ming et al, Phys. Rev. D 97, 024051 (2018)
Ming et al, Phys. Rev. D 93, 064011 (2016)

General framework

For every possible target we consider a very broad range of f values, such that the signal is expected to take one of those values (e.g. 0-2 kHz)

The freq derivative ranges are determined allowing the broadest possible range

For every freq cell (ℓ) we determine the computational cost C_ℓ to search for a signal with parameters within that cell, with a given search set-up, and the associated detection probability.

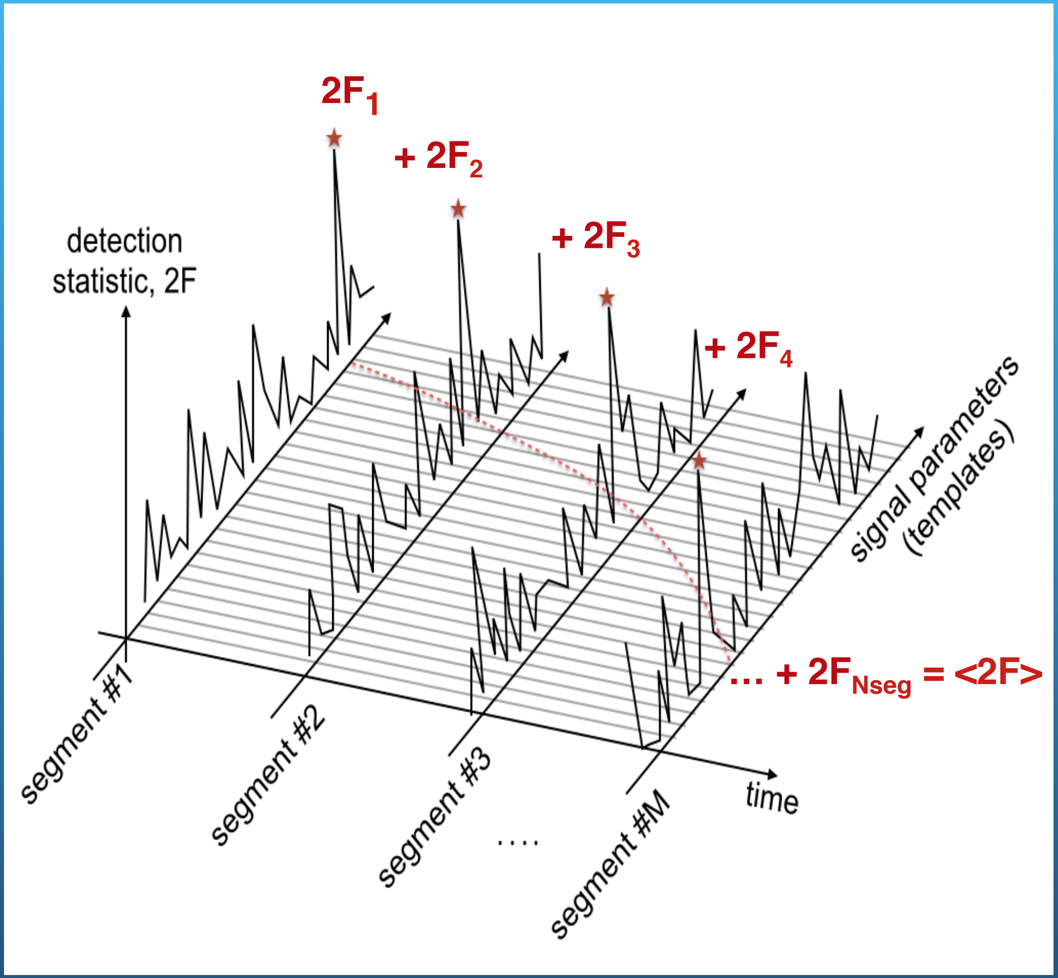


$$20\text{ Hz} \le f \le 1500\text{ Hz}$$

$$-\frac{f}{\tau} \le \dot{f} \le 0\text{ Hz/s}$$

$$0\text{ Hz/s}^2 \le \ddot{f} \le \frac{5\dot{f}^2}{f}$$

Semi-coherent searches



One needs to decide:

- Length of segments
- Grid spacings

Both impact sensitivity and computing cost.

The detection probability

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

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

detection prob

priors

detection efficiency averaged over all params but h_0

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

with ranges large enough that this is true

The detection probability

$$dP(f_i,\dot{f}_j,s_k) = \boxed{P_0(f_i,\dot{f})} \times \int_{h_0-\mathrm{min}}^{h_0-\mathrm{max}} P_0(h_0) \times \eta(f_i,\dot{f},s_k,h_0)\, dh_0\, df\, d\dot{f}$$

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

The detection probability

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

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

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

$$dP(f_i,\dot{f}_j,s_k) = P_0(f_i,\dot{f}) \times$$

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

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

h_0 recast in terms of the ellipticity ε

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

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

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

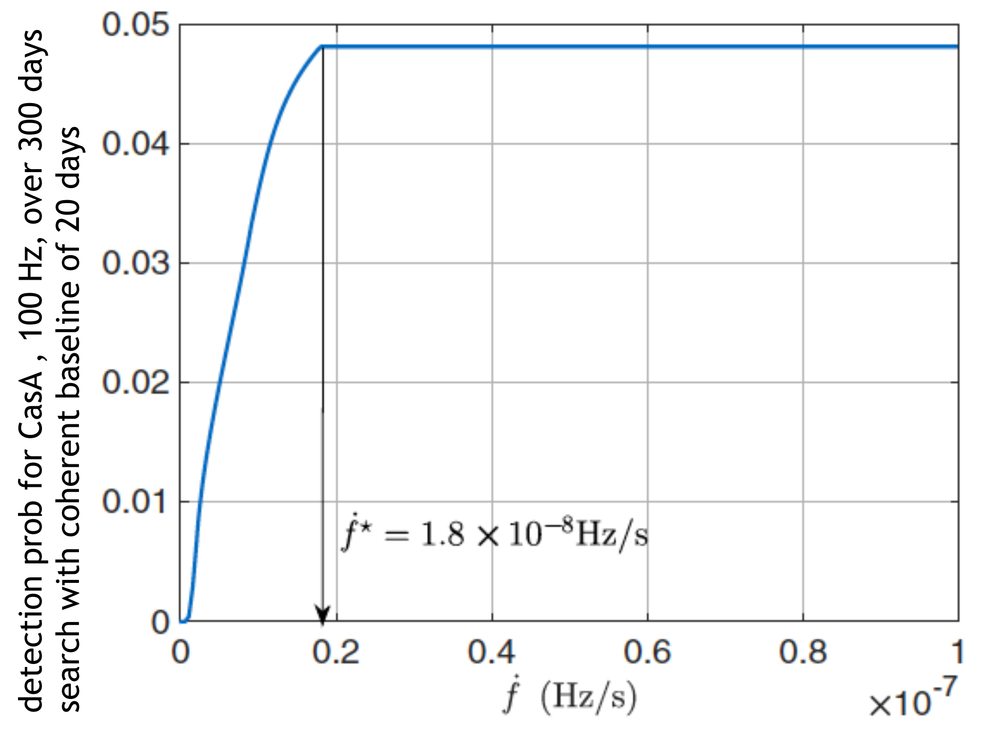
ε_{max}=min(fiducial value, $\boxed{\varepsilon_{spin\text{-}down}}$)

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

- 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%)

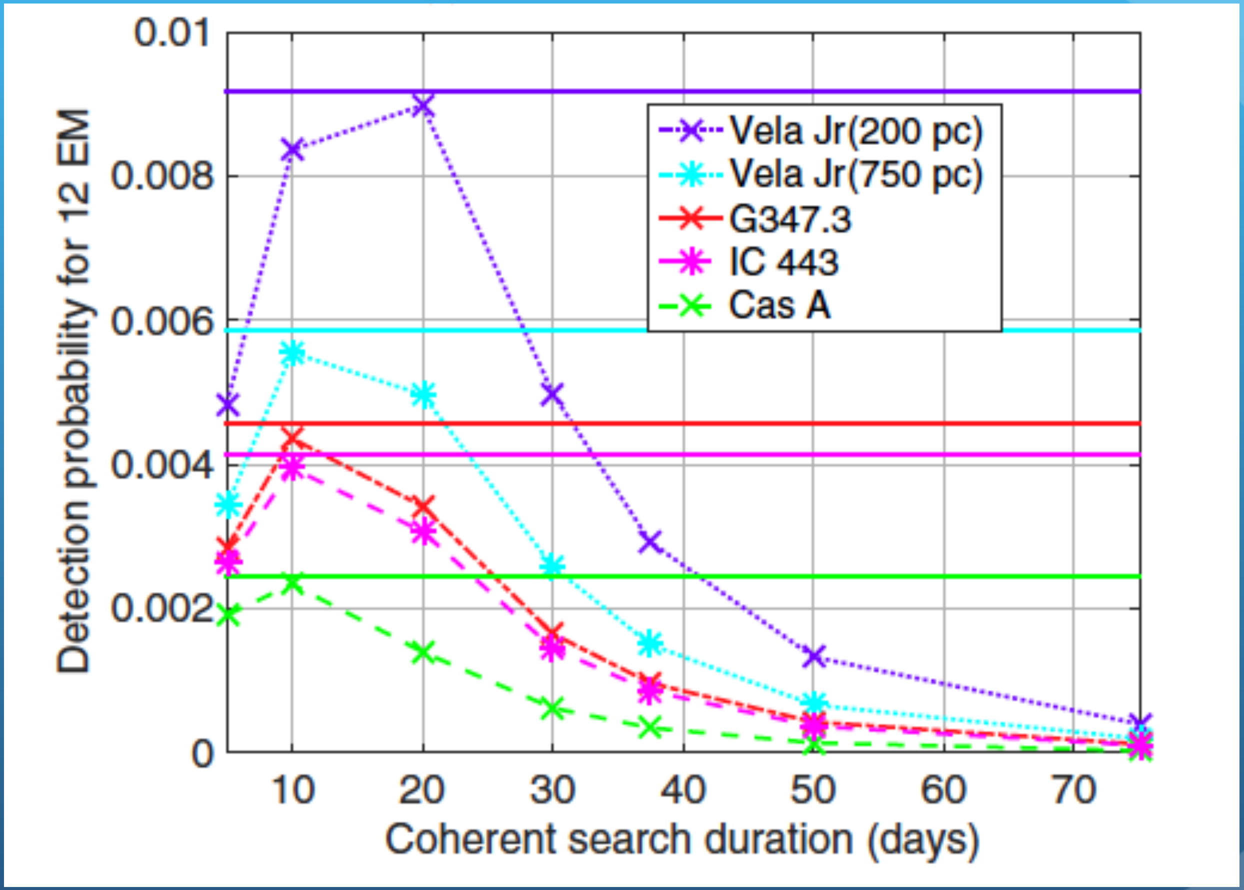
ε_{max}=min(fiducial value, $\varepsilon_{spin\text{-}down}$)

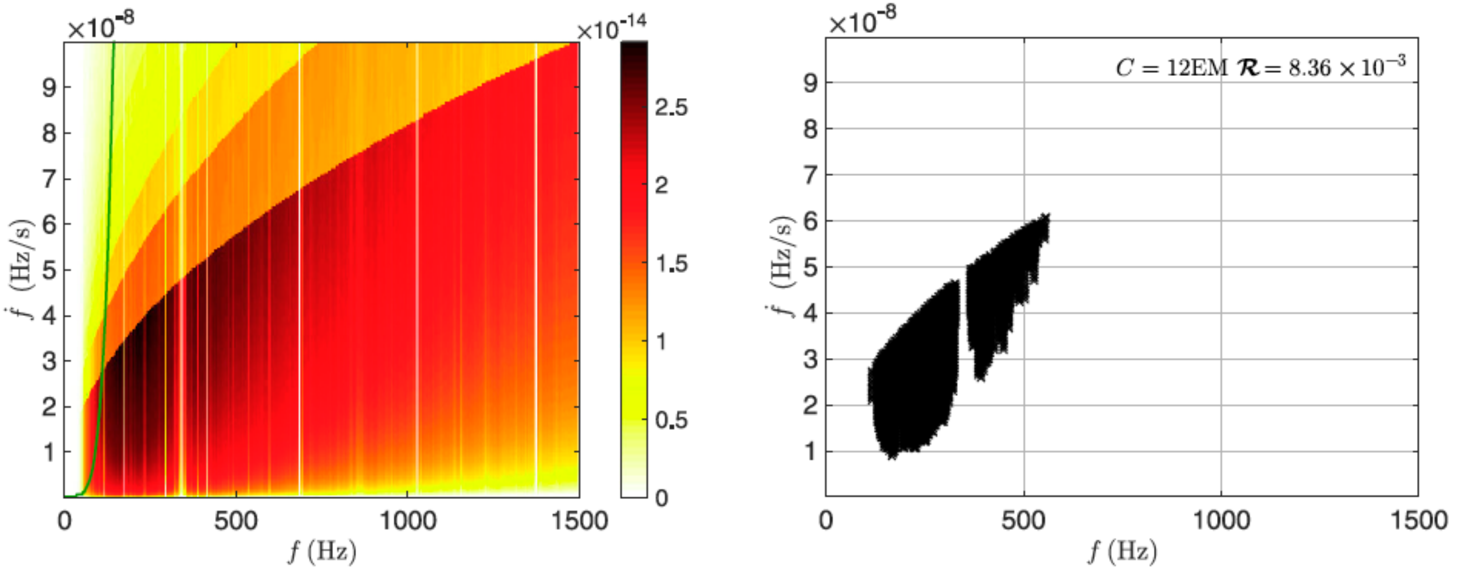
- On general grounds we simply do not believe that ellipticities can be larger than some value fiducial values.



When fdot yields fiducial max ellipticity, the detection prob stops growing.
Here it was 10^{-4}.

Some examples

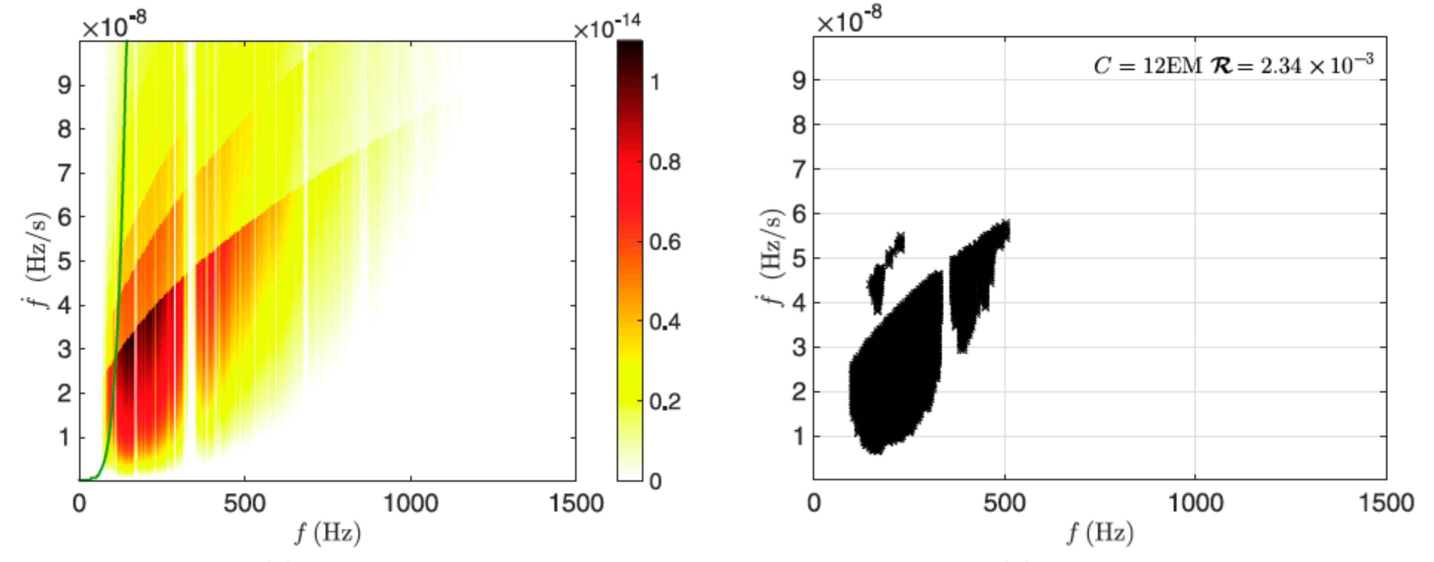

0.01
0.008
0.006
0.004
0.002
0
Detection probability for 12 EM
10
20
30
40
50
60
70
Coherent search duration (days)
Vela Jr(200 pc)
Vela Jr(750 pc)
G347.3
IC 443
Cas A



(a) Efficiency (b) Coverage

Vela Jr

Total detection prob 8x 10^{-3}



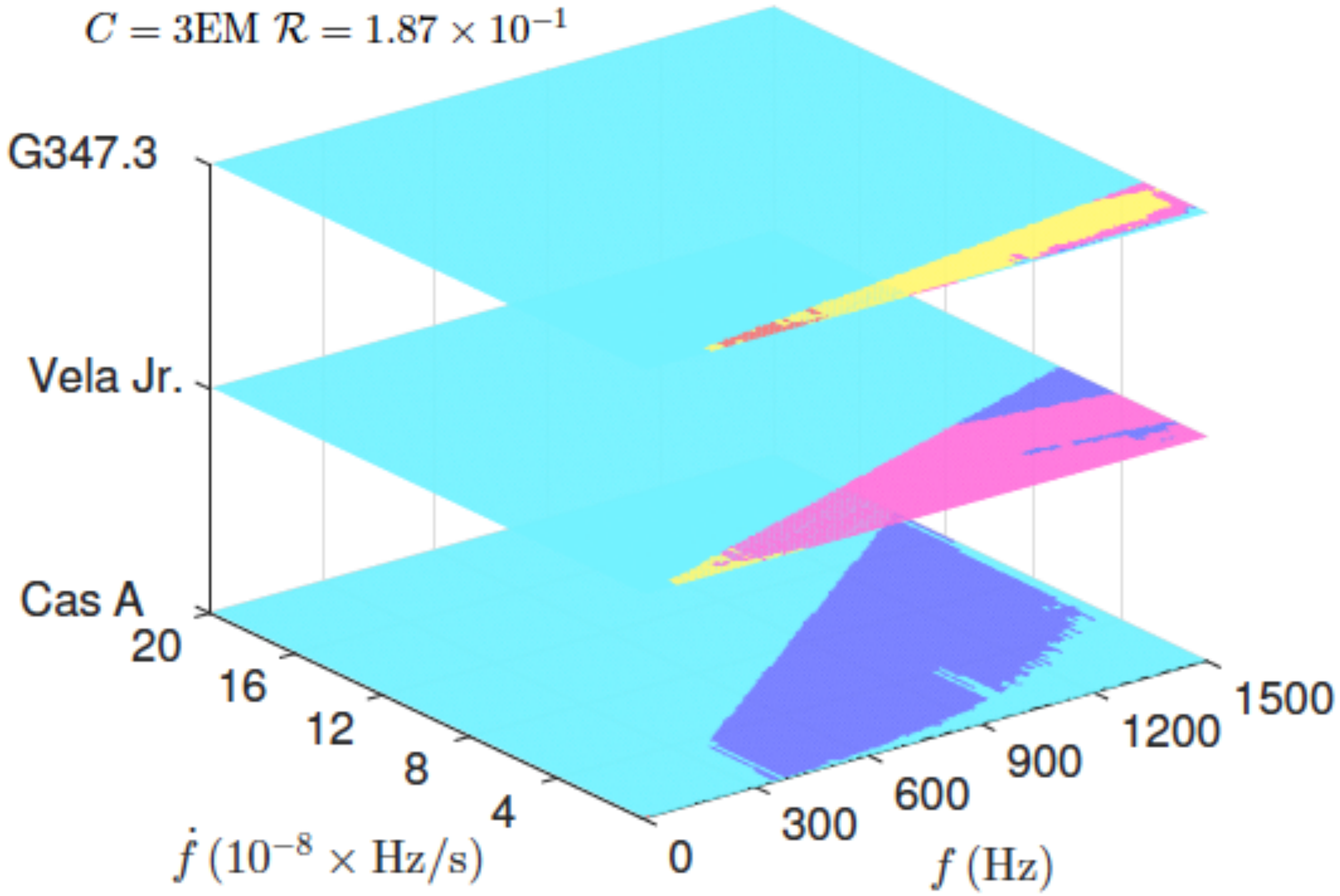
(a) Efficiency (b) Coverage

CasA

Total detection prob 2x 10^{-3}

MONTHS on Einstein@Home 300 days of data, S6 level

Optimising also over set-up and targets



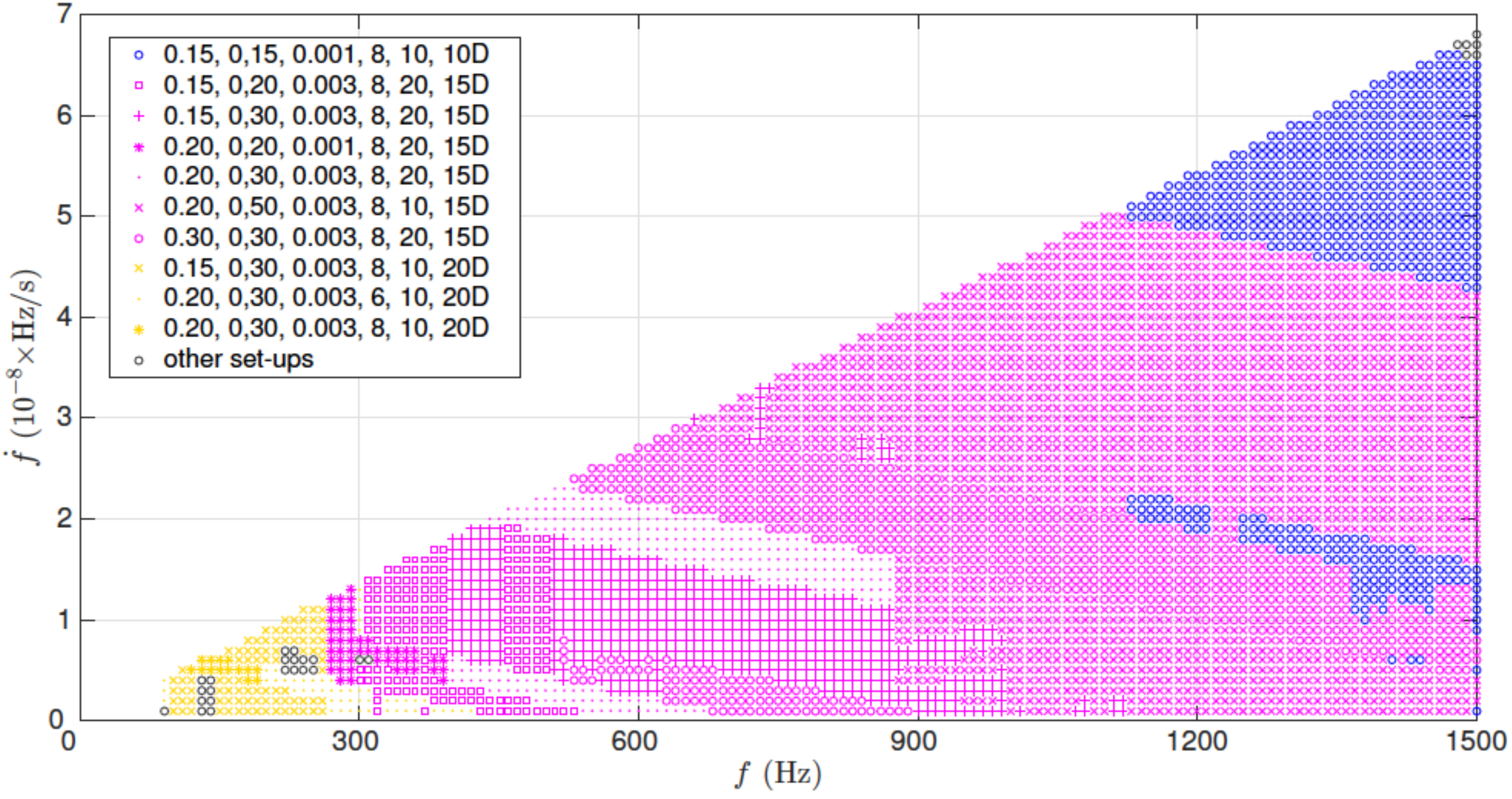
Blue: 10 Days

Magenta: 15 Days

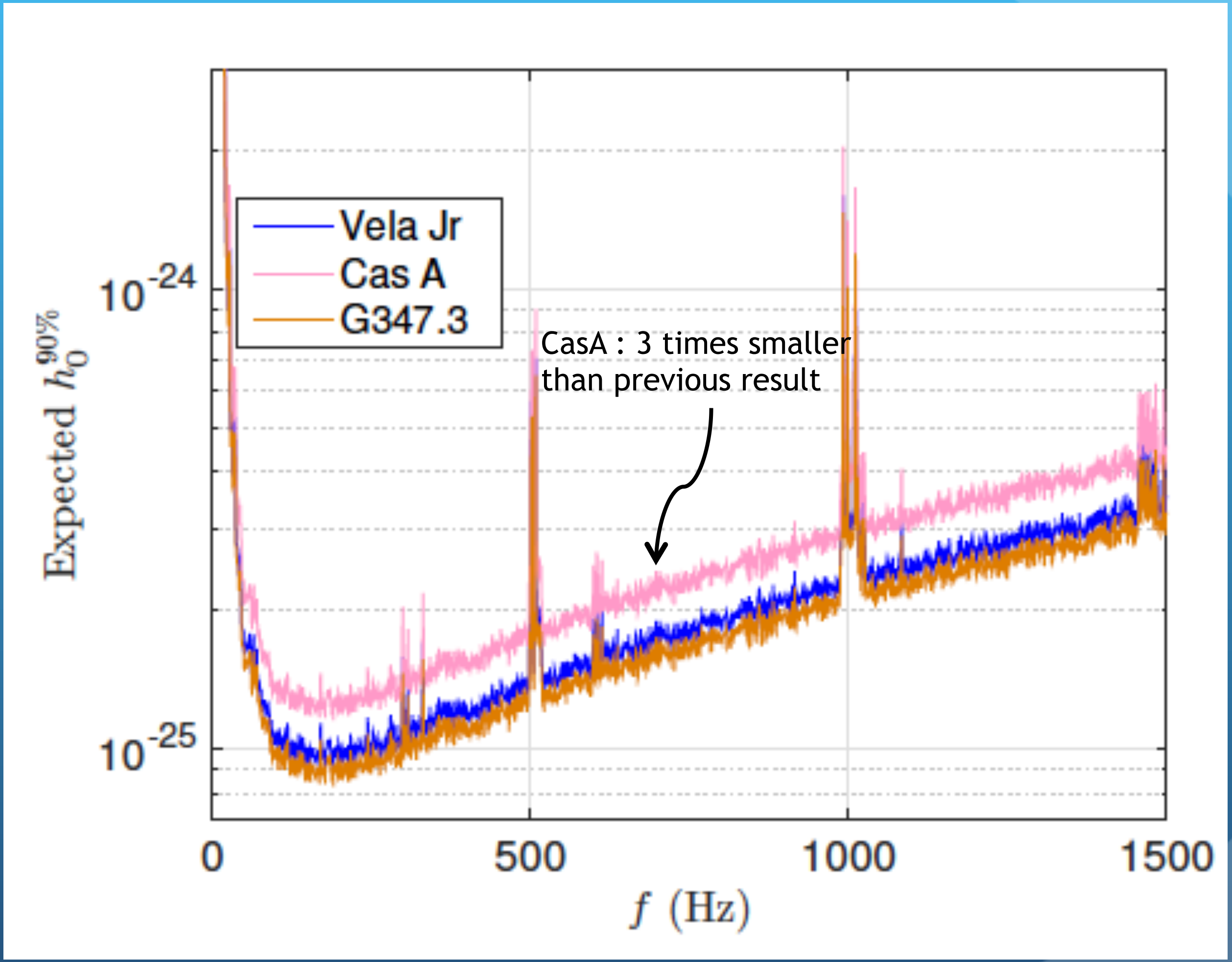
Yellow: 10

Red: 5 Days

Zooming in on Vela Jr



Expected sensitivity



CasA : 3 times smaller than previous result

Bring-home message:

- We have a scheme to fold-in priors on the source parameters and ensure an optimal search set-up
  - Caveat: there are many uncertainties. This scheme is utilized for deep searches.
- Any prior on the maximum ellipticity and/or ellipticity distribution of a specific object, or a population of objects, is most welcome
- Important are also possible dependencies with frequency and/or frequency derivatives
- Priors on frequency, frequency derivatives and the ranges of the latter in relation to frequency and age.
- Would like to use this sort of approach to determine parameter space and search set-up for blind surveys: additional search parameter, sky position

Thank you!