First Multi-messenger Continuous Gravitational-Wave Workshop, NIKHEF Amsterdam

Continuous Gravitational Waves from Galactic Neutron Stars:

Demography, Detectability and Prospects.

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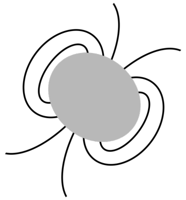
Arxiv:2303.04714, Accepted on ApJ.

Contents

Motivation



ASTROPHYSICS

- What kind of objects?
- How do parameters affect detectability?

SEARCHES

- What latest results tell us?
- Can we better invest the computational budget?

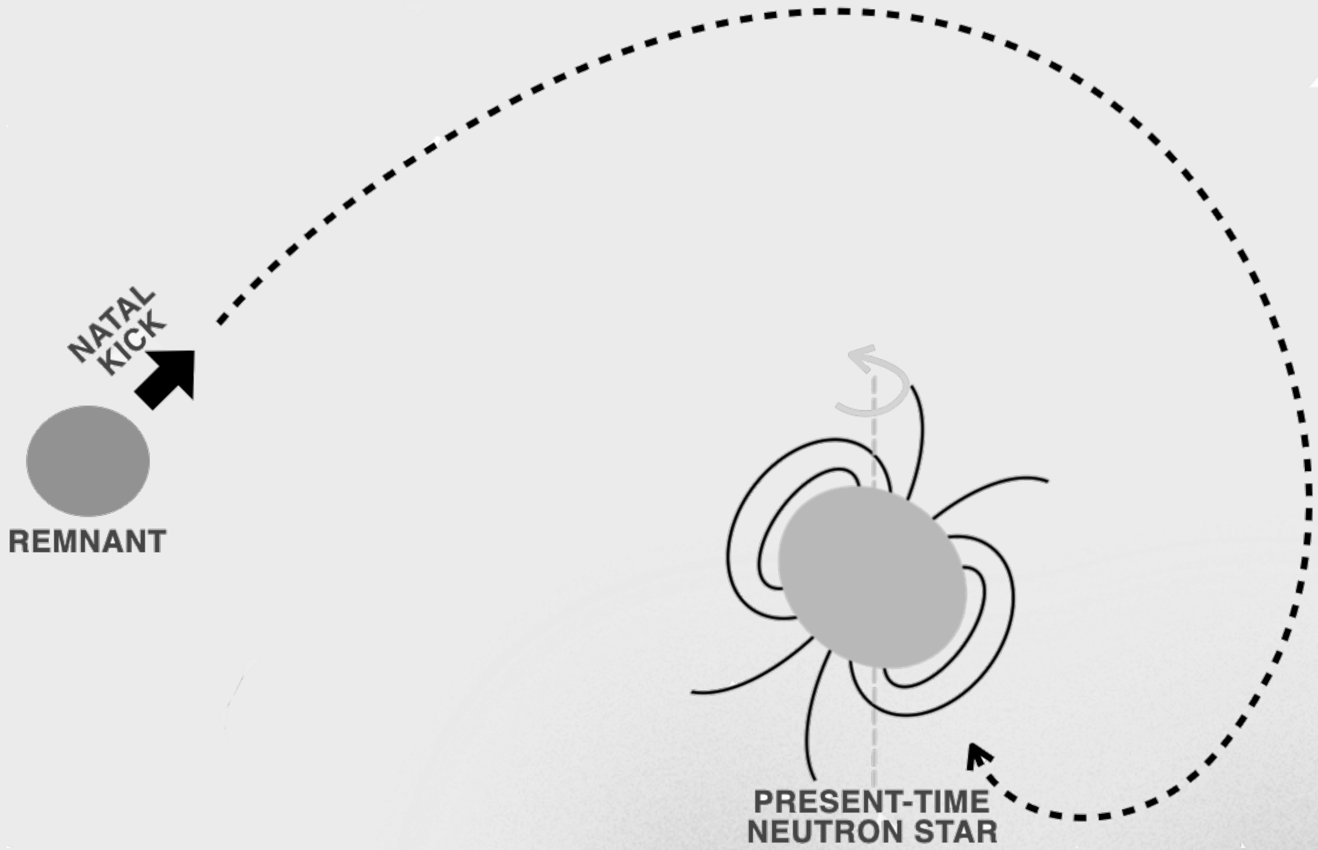
PROSPECTS

- What to expect from upcoming surveys?
- What in view of 3rd generation detectors?

The work in a nutshell

- From remnants to mature NSs
  - Dynamical evolution in the Galaxy
  - Spin evolution due to spin-down torques (EM+GW)

- Detectability assessment
  - Astrophysical characteristics of detectable sources
  - Parameter space of interest



The work in a nutshell

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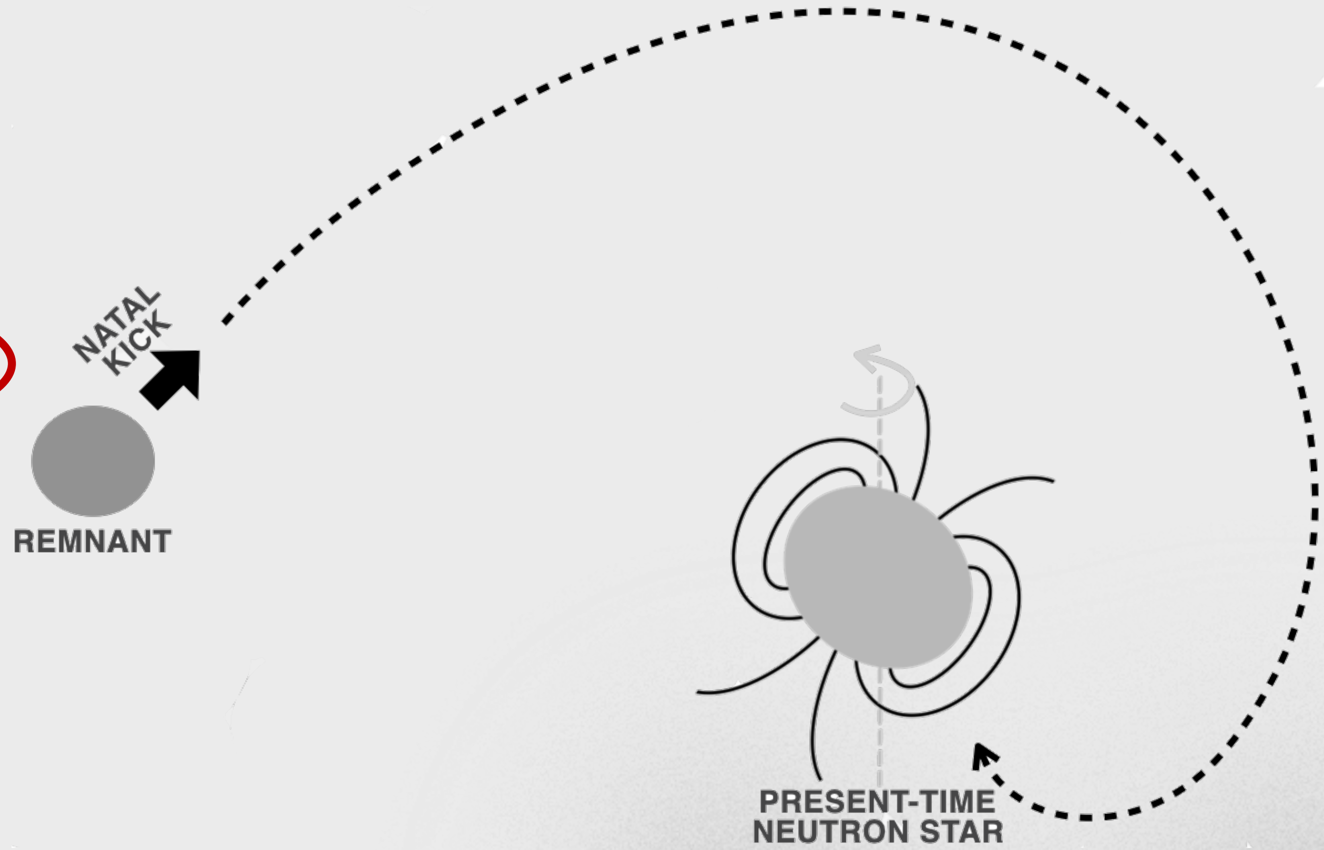

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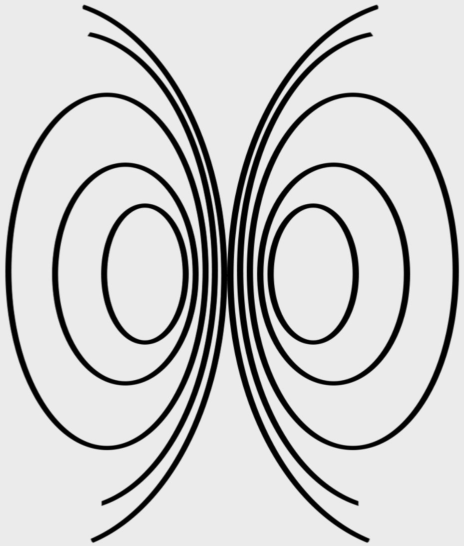
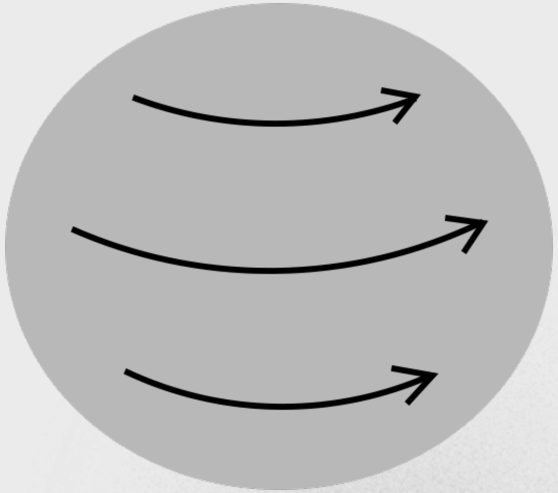
What mostly affects present-time spin frequency:

MAGNETIC FIELDS



BIRTH SPIN FREQUENCY



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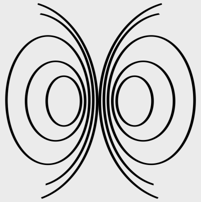
Spin evolution: two main families of models

AGNOSTIC

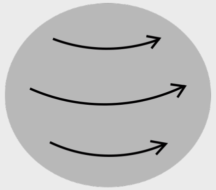
Flat-in-log priors:

MAG FIELD



- $B \in [10^{10}, 10^{15}]G$, no decay

SPIN AT BIRTH



- $f_0 \in [2, 300]Hz$ (Camelio et Al. 2016)
- $f_0 \in [2, 1200]Hz$ (Haskell et Al. 2018)

EMPIRICAL

informed priors consistent with: Popov et Al. (2010), Viganò et Al.(2013), Gullón et Al. (2015)

MAG FIELD

- $p(\log_{10} B/G) = \mathcal{N}(13, 0.8)$

  decay time-scale $\tau = 10^6$yr

SPIN AT BIRTH

- $p(P_0/ms) = \mathcal{N}(300, 200)$
- $p(P_0/ms) = \mathcal{U}(0.8, 500)$

(Gullón et Al. 2014, 2015)
(Gonthier et Al. 2004)

Spin evolution: two main families of models

AGNOSTIC

Flat-in-log priors:

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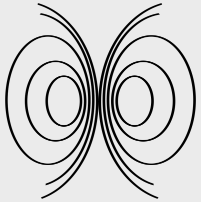

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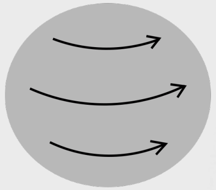

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- $p(\mathrm{P_0/ms}) = \mathcal{U}(0.8, 500)$

(Gullón et Al. 2014, 2015)
(Gonthier et Al. 2004)

and finally…ellipticity

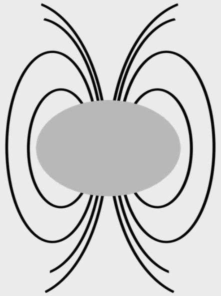
Scenario 1:
MAGNETIC FIELD INDUCED

Mastrano et Al. (2011):

$$\varepsilon(B) \propto B^2\left(1 - \frac{0.4}{\Lambda}\right)$$

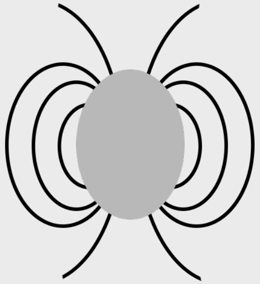
$\Lambda = 0.9$

Ciolfi et Al. (2010), Lasky et Al. (2012), Lander & Jones (2009), Lander et Al. (2021)



$\Lambda = 0.1$

Braithwaite (2009), Akgün et Al. (2013), Ciolfi & Rezzolla (2013)



Scenario 2:
OTHER

Origin of deformation not specified

$$p(\log\varepsilon) = \mathcal{U}(\varepsilon_{min}, \varepsilon_{max})$$

- $\varepsilon_{min} = \varepsilon(B, \Lambda = 0.9)$
- $\varepsilon_{max} = 10^{-5}$

  (Ushomirsky et Al. 2000, Haskell et Al. 2006, Horowitz & Kadau 2009, Morales & Horowitz 2022)

Main results

Current sensitivity: detectable sources

		average no. detectable sources	
		agnostic	empirical
ellipticity	magnetic induced	< 0.01	< 0.01
	other	$\approx 1.4 - 3.6$	0.01

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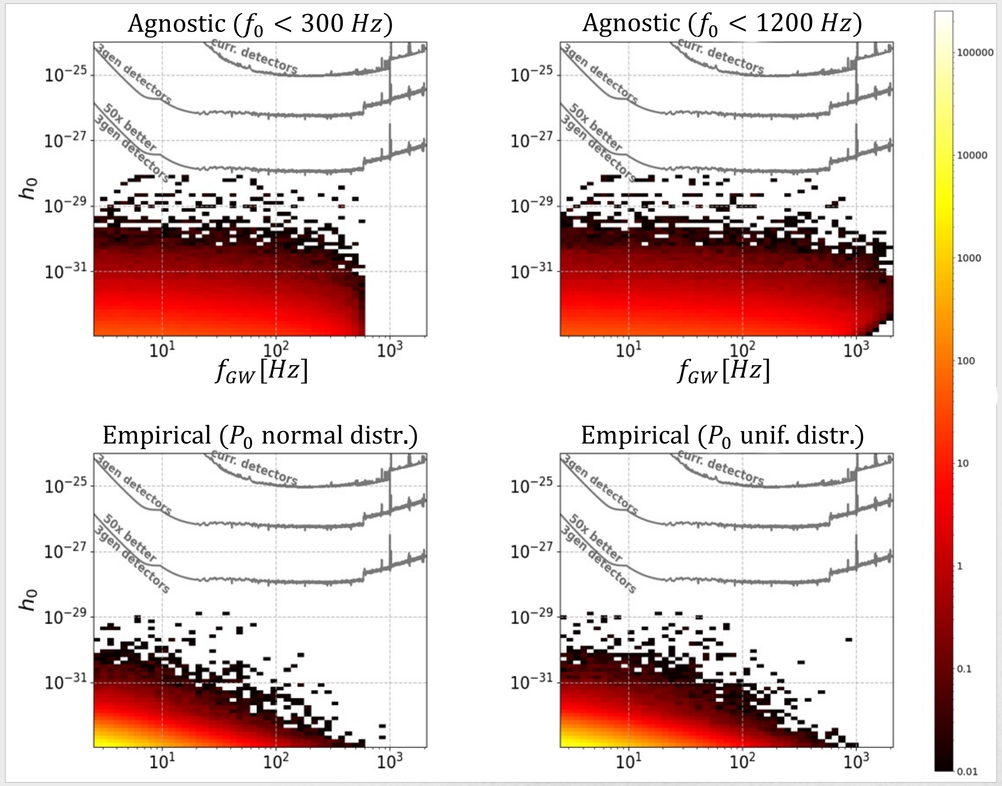

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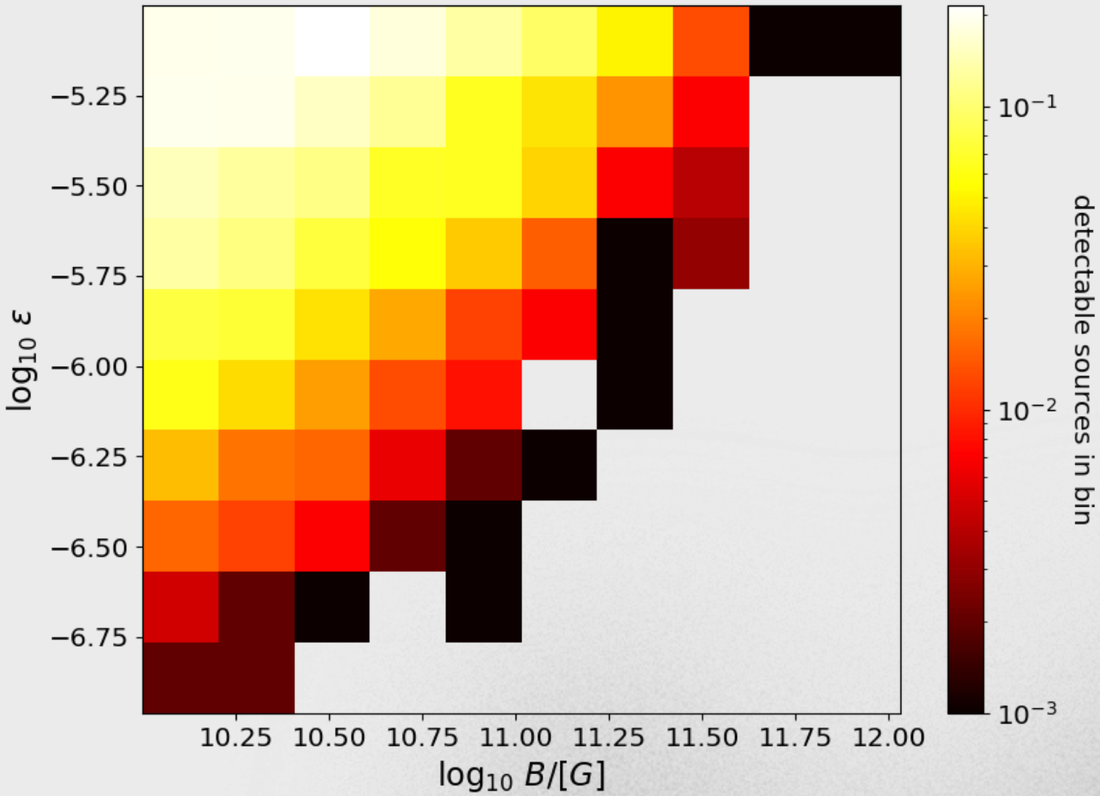
CURRENTLY DETECTABLE SOURCES (agnostic-other)



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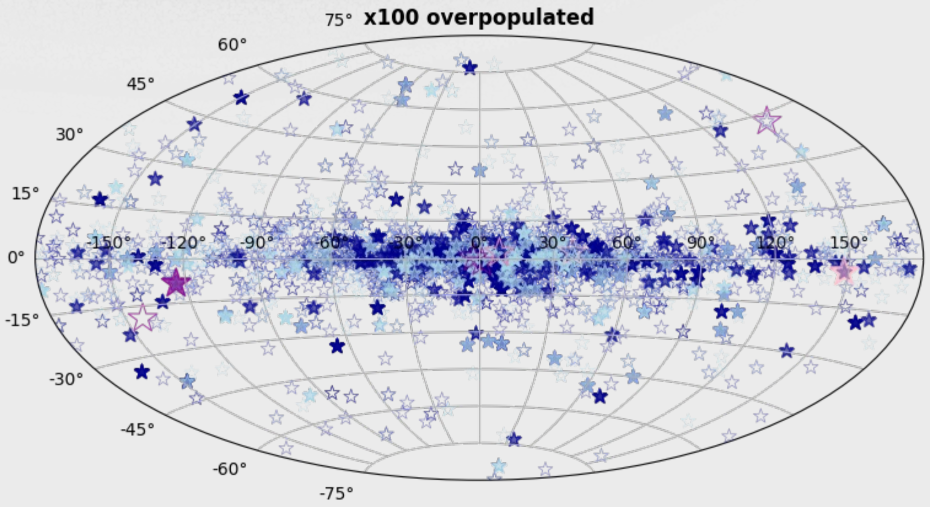
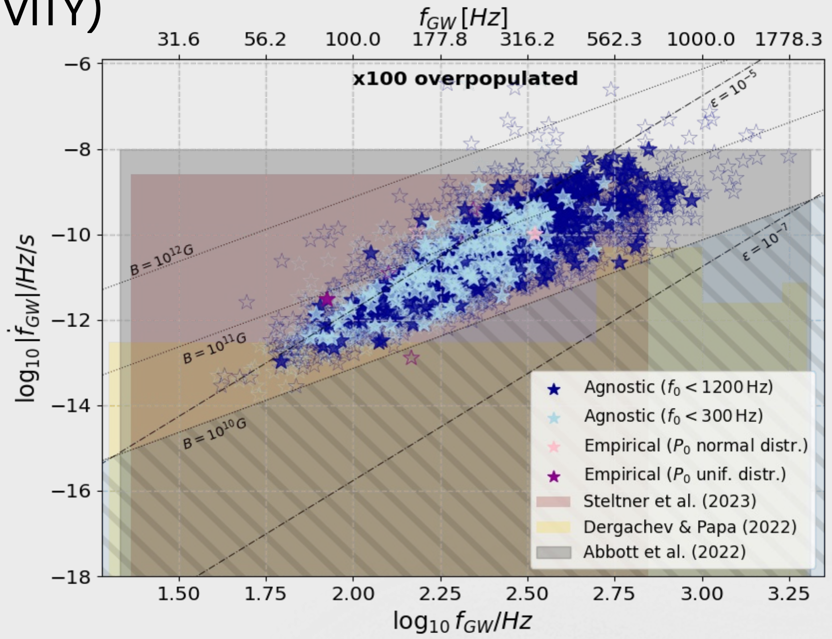
Current sensitivity: parameter space

DETECTABLE AND CLOSE-TO-BE DETECTABLE SOURCES
(CURRENT SENSITIVITY)





Current sensitivity: parameter space

DETECTABLE AND CLOSE-TO-BE DETECTABLE SOURCES
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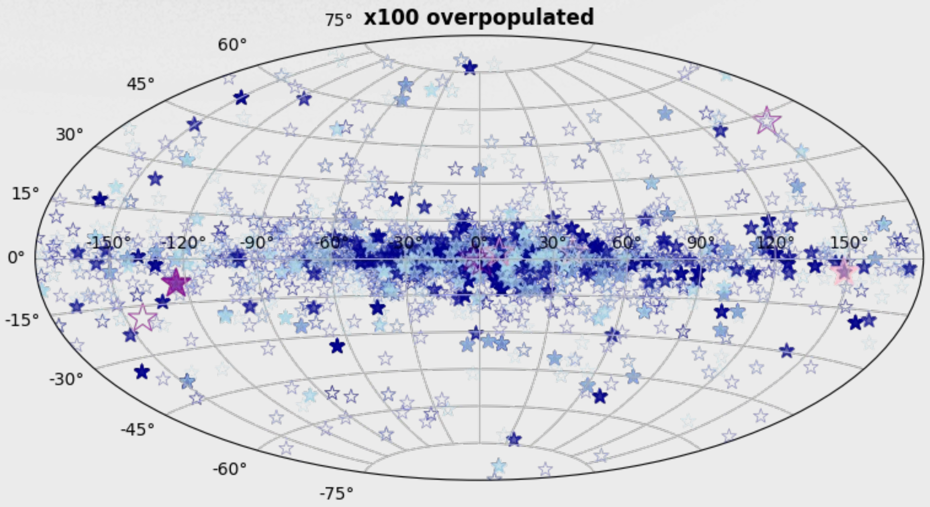

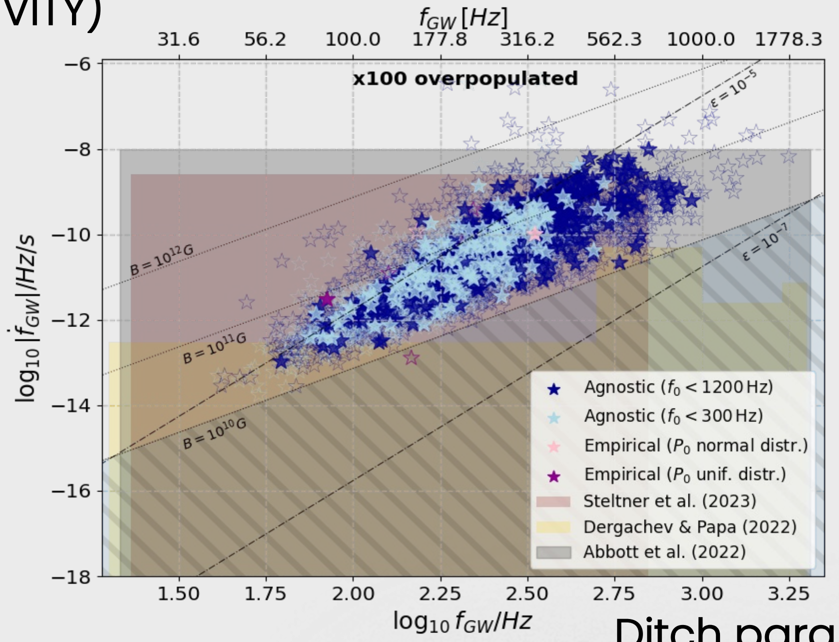

Ditch parameter space portions must be done carefully!
See Ming et Al.(2016,2018)

Current sensitivity: parameter space

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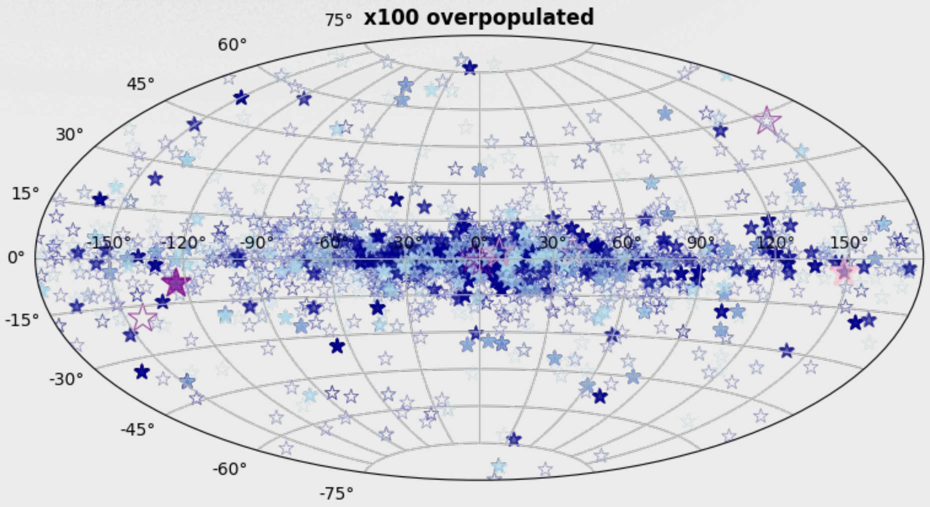

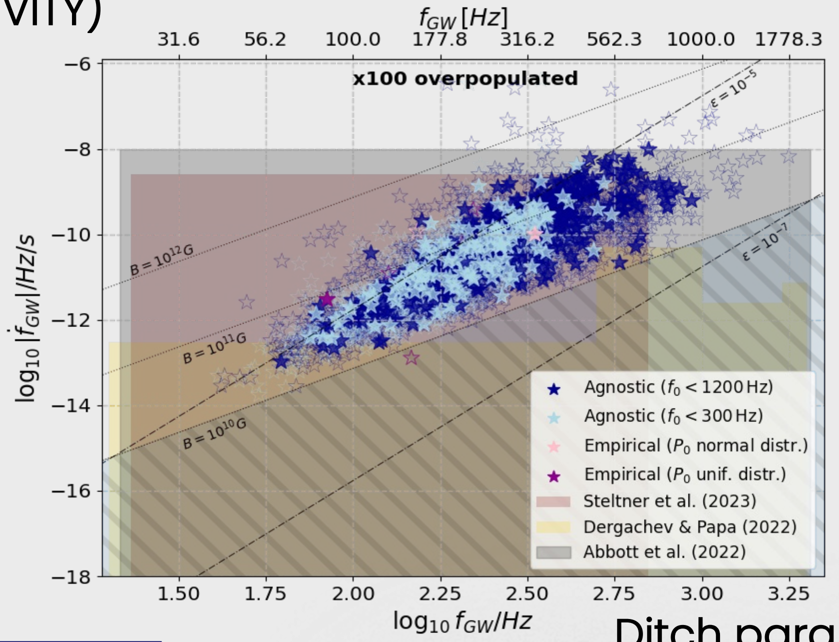

low [20, 100] Hz	*mid* [100, 500] Hz	*high* [500, 2400] Hz	TOTAL
	now		
0.12	3.08	0.42	3.62
	2× **more sensitive**		
0.69	11.26	1.37	13.32
	3× **more sensitive**		
1.79	23.23	2.5	27.52

VS

Ditch parameter space portions must be done carefully!
See Ming et Al.(2016,2018)

3^{rd} gen detectors

EINSTEIN TELESCOPE & COSMIC EXPLORER

NUMBER OF SOURCES IN BAND

	$N_{f_{GW}} > 20$ Hz (%)	$N_{f_{GW}} > 5$ Hz (%)
AGNOSTIC	0.14 - 0.16 %	2.9 - 3 %
EMPIRICAL	0.22 - 0.47 %	6.9 - 8.7 %

3rd gen detectors

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		average no. detectable sources	
		agnostic	empirical
ellipticity	magnetic induced	< 0.01	< 0.01
	other	≈ 350 – 525	≈ 2 – 5

low [20, 100] Hz	*mid* [100, 500] Hz	*high* [500, 2400] Hz	TOTAL
now			
0.12	3.08	0.42	3.62
2× **more sensitive**			
0.69	11.26	1.37	13.32
3× **more sensitive**			
1.79	23.23	2.5	27.52
10× **more sensitive**			
33.77	170.12	9.74	213.63
3rd generation detectors			
[5, 100] Hz	[100, 500] Hz	[500, 2500] Hz	TOTAL
193.2	318.02	15.15	526.37

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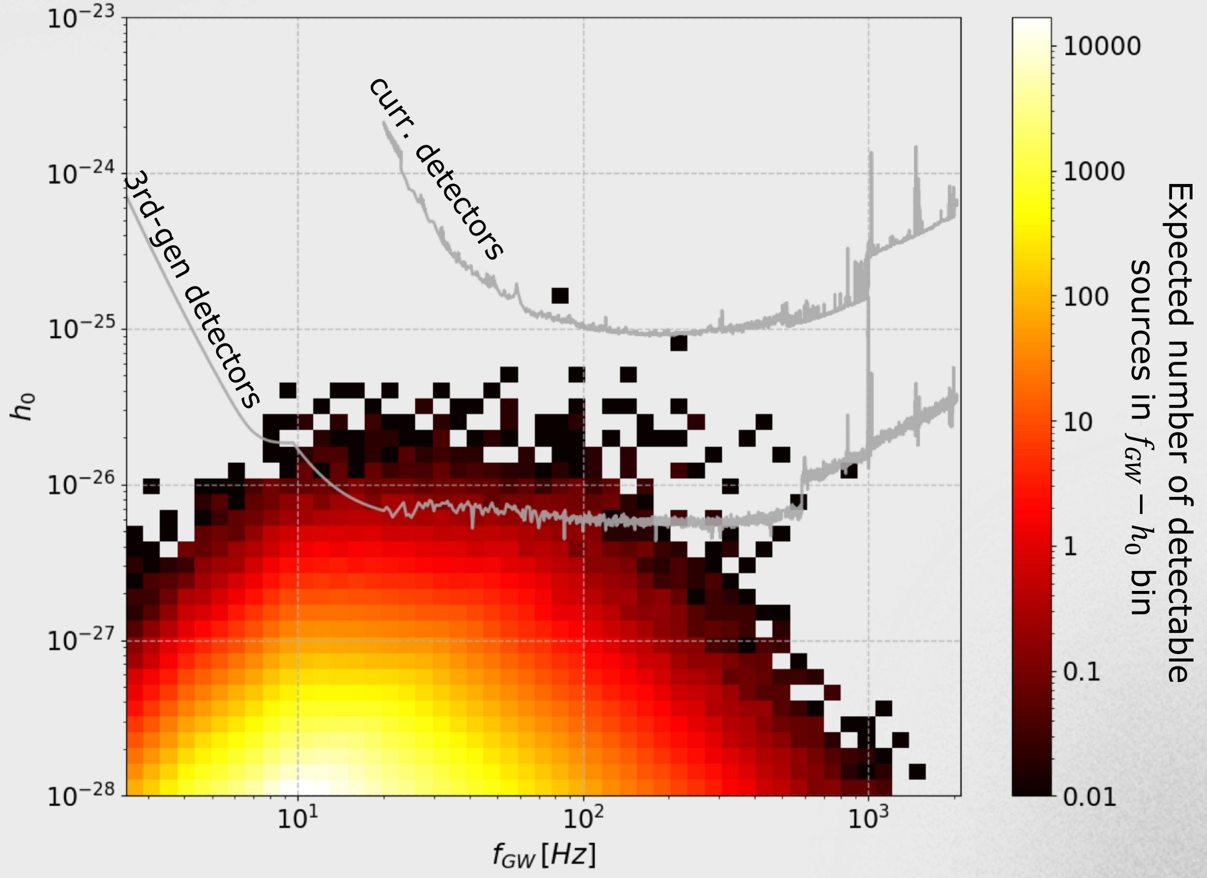
3rd gen detectors

EINSTEIN TELESCOPE & COSMIC EXPLORER

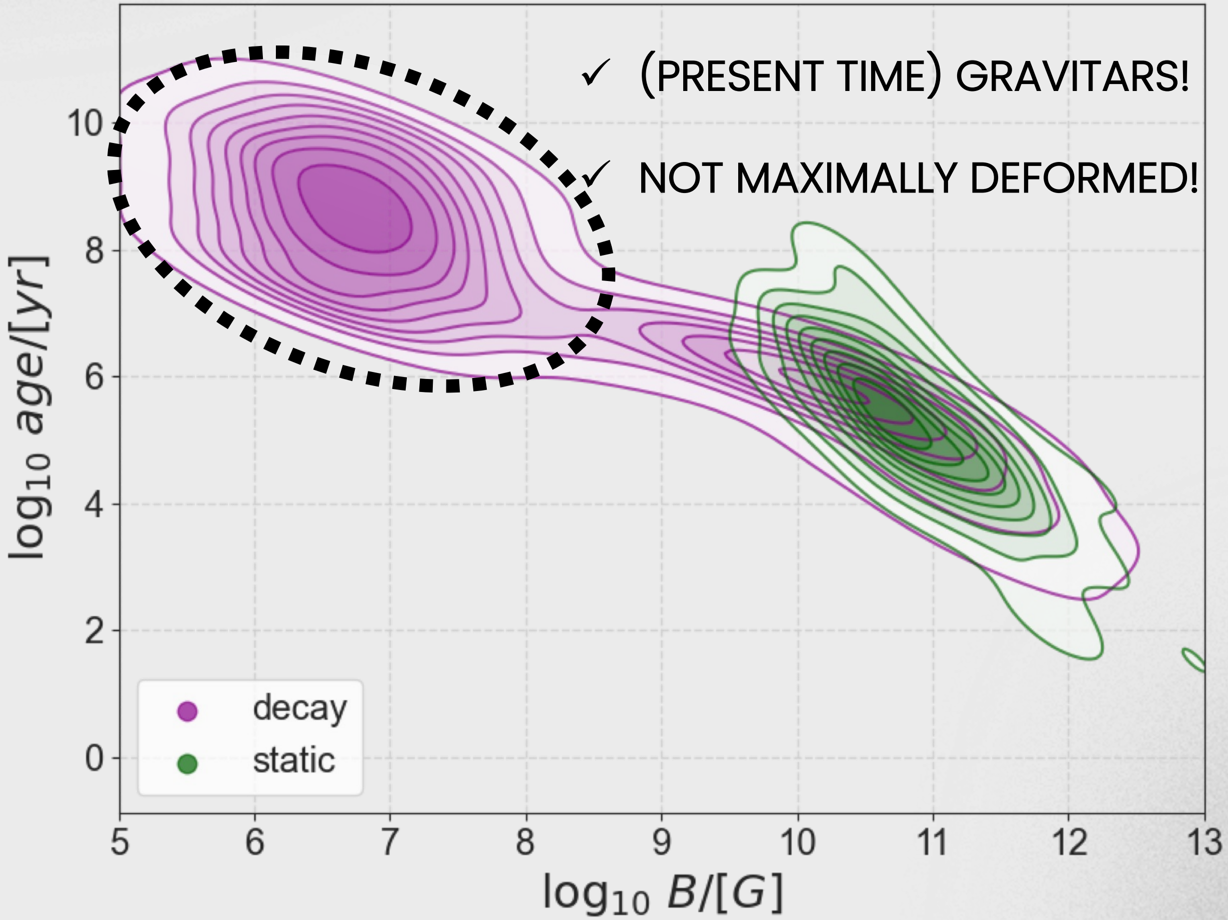
EMPIRICAL MODELS BECOME DETECTABLE!



3^{rd} gen detectors

EINSTEIN TELESCOPE & COSMIC EXPLORER

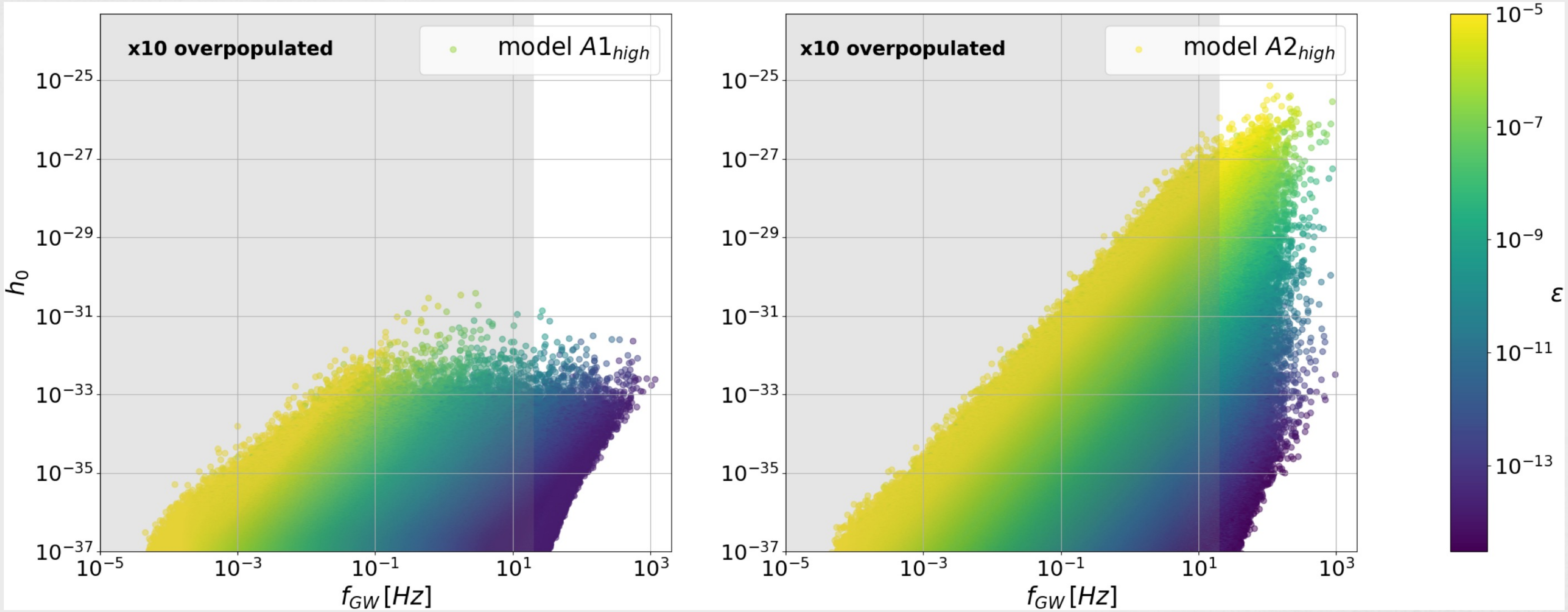
- ✓ DETECTABLE THANKS TO MAGNETIC FIELD DECAY!
- ✓ (PRESENT TIME) GRAVITARS!
- ✓ NOT MAXIMALLY DEFORMED!



Conclusions

- Detection is limited to stars with deformations not just due to magnetic field and is (**currently**) **far from guaranteed**
- Currently detectable sources show a strong correlation between magnetic field and ellipticity: **the larger the magnetic field, the larger the ellipticity needed** for current detectability
- For some of our models, 3rd generation detectors are **able to detect few hundreds more sources** than current ones
- **"Empirical" models become detectable** with 3rd gen. detectors
- For these, it is of fundamental importance to **account for the GW-spin-down contribution** to avoid to overestimate the number of detectable sources
- Feeding our results to optimisation frameworks will help us in **wisely choosing** the parameter space portion to survey

EXTRAS

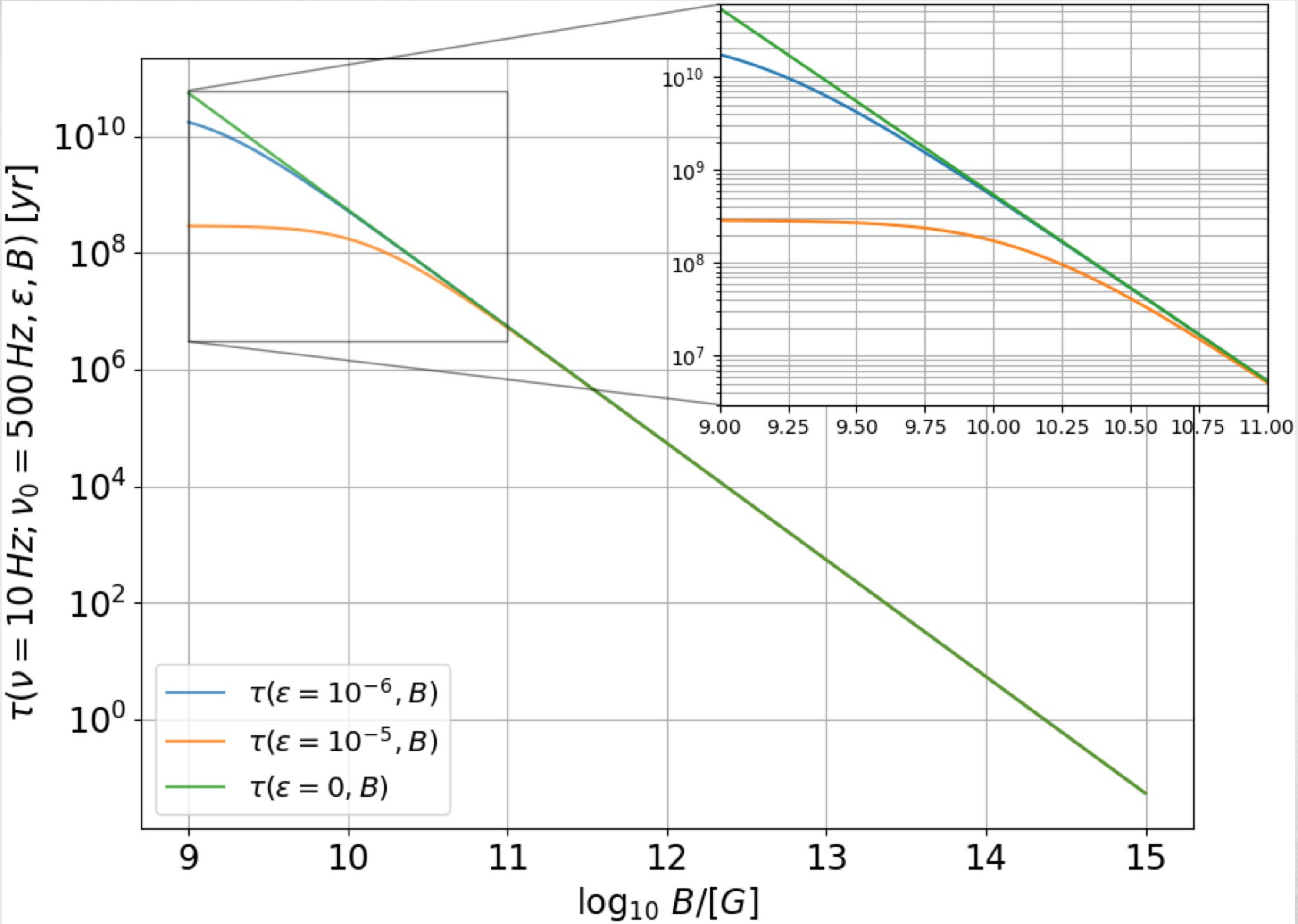

x10 overpopulated
model $A1_{high}$
10^{-25}
10^{-27}
10^{-29}
10^{-31}
10^{-33}
10^{-35}
10^{-37}
h_0
10^{-5}
10^{-3}
10^{-1}
10^{1}
10^{3}
$f_{GW}\,[Hz]$
x10 overpopulated
model $A2_{high}$
$f_{GW}\,[Hz]$
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
ε

EXTRAS

Table 3. Expected number of currently detectable neutron stars, computed as the average $\pm 1\sigma$ over the 100 realisations performed. The last column shows the *percentage probed* with respect to the total number of sources in-band for each model (second column of Tab. 2). The remaining models, here indicated generally as A1 and E1, give no detectable signal in any of the realisations.

Model	$\overline{n}$	% of *in-band*
$A2_{low}$	1.4 ± 1.16	0.0003
$A2_{high}$	3.62 ± 1.91	0.0007
$E2_{norm}$	0.01 ± 0.1	$\approx 10^{-6}$
$E2_{unif}$	0.01 ± 0.1	$\approx 10^{-6}$
A1	< 0.01	–
E1	< 0.01	–

EXTRAS



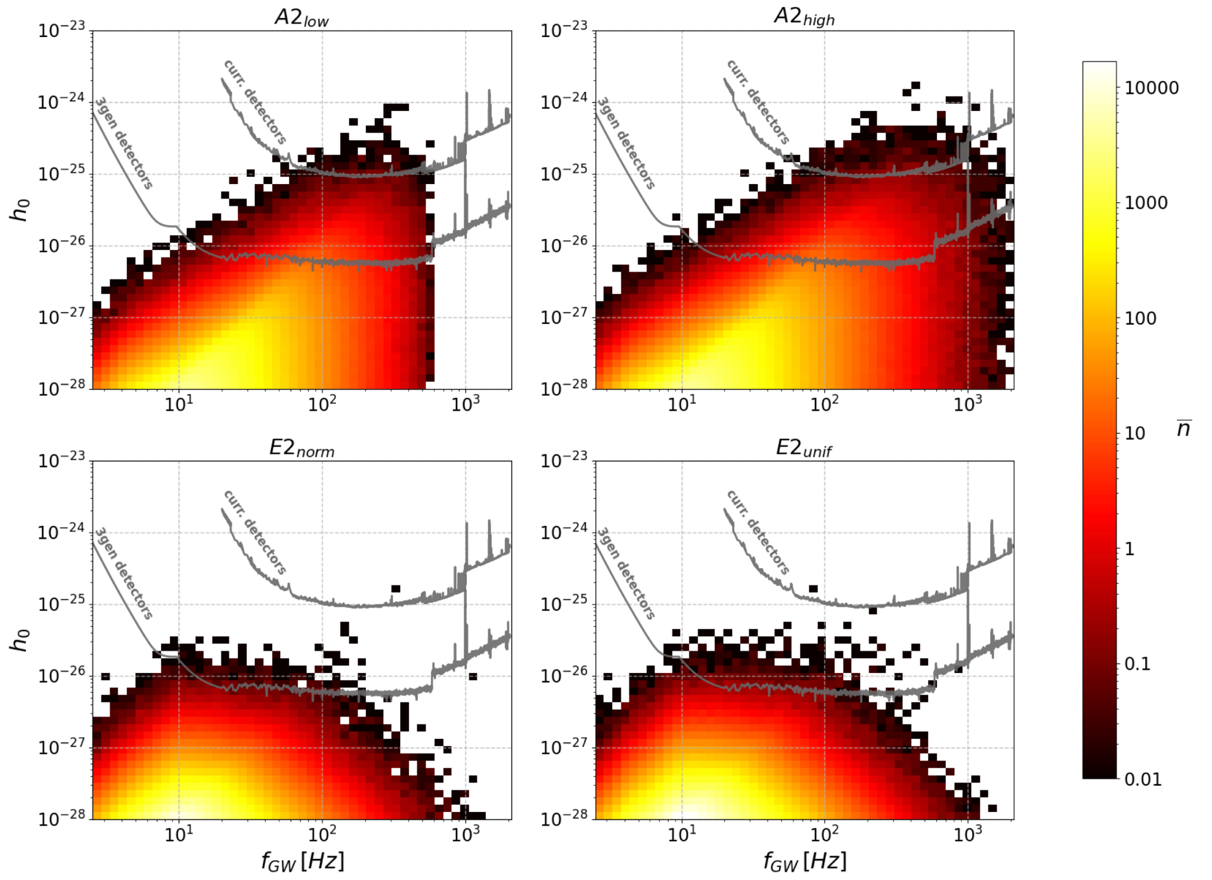
$\tau(\nu = 10\,Hz; \nu_0 = 500\,Hz, \varepsilon, B)$ [yr]
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
9
10
11
12
13
14
15
$\log_{10} B/[G]$
$\tau(\varepsilon = 10^{-6}, B)$
$\tau(\varepsilon = 10^{-5}, B)$
$\tau(\varepsilon = 0, B)$
10^{10}
10^{9}
10^{8}
10^{7}
9.00
9.25
9.50
9.75
10.00
10.25
10.50
10.75
11.00

EXTRAS

Table 7. Average number of detectable sources $\overline{n}$ under different assumptions on the proportions of the number of binary-to-isolated neutron stars. In the mix-model we have assumed 42% isolated objects and 58% in binaries, consistent with the ATNF MSP population. We recall that the total population is 60,000 objects.

	$\overline{n}$ (all binary)	$\overline{n}$ (all isolated)	$\overline{n}$ (mix)
now	< 0.01	0.01 ± 0.1	< 0.01
CE	0.18 ± 0.38	5.8 ± 2.62	3.44
ET	0.09 ± 0.29	4.76 ± 2.32	2.8

EXTRAS



$A2_{low}$
$A2_{high}$
$E2_{norm}$
$E2_{unif}$
curr. detectors
3gen detectors
h_0
$f_{GW}\,[Hz]$
$\overline{n}$
10000
1000
100
10
1
0.1
0.01

EXTRAS

$$\dot{\nu} = -\frac{32\pi^3 R^6}{3Ic^3\mu_0}\left(B(t)\sin\chi\right)^2 \;\; \nu^3 - \frac{512\pi^4 GI}{5c^5}\varepsilon^2\nu^5.$$

EXTRAS

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