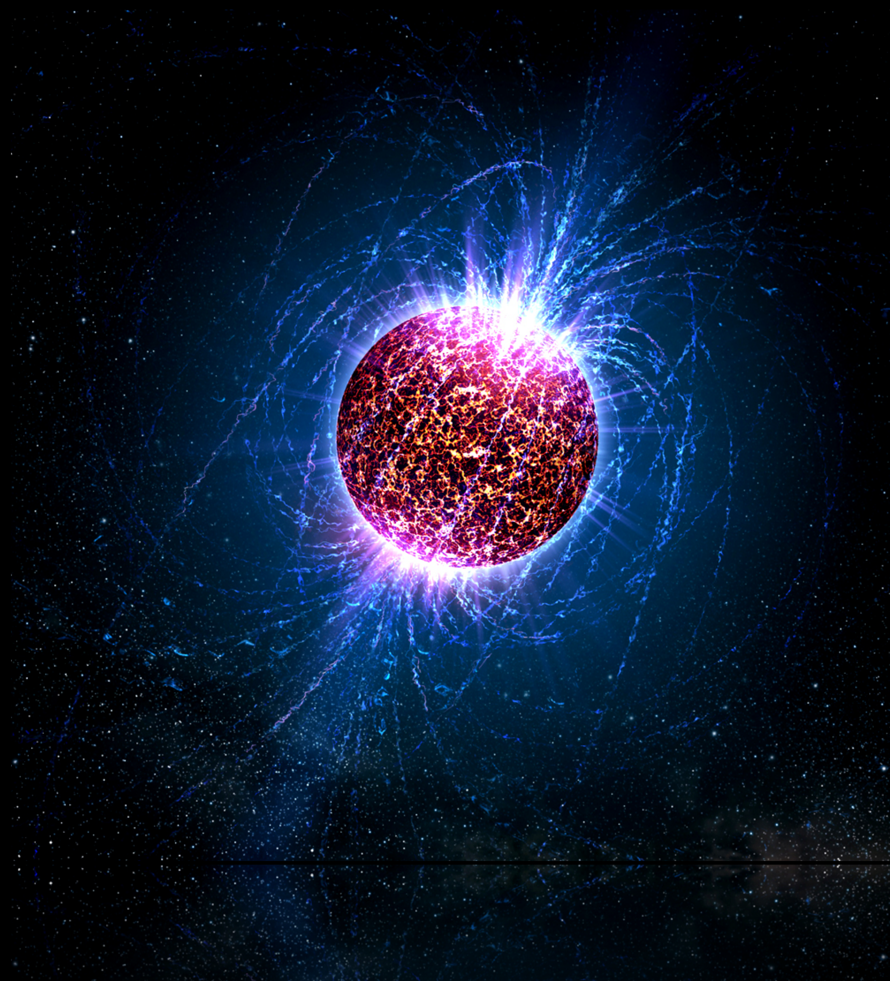
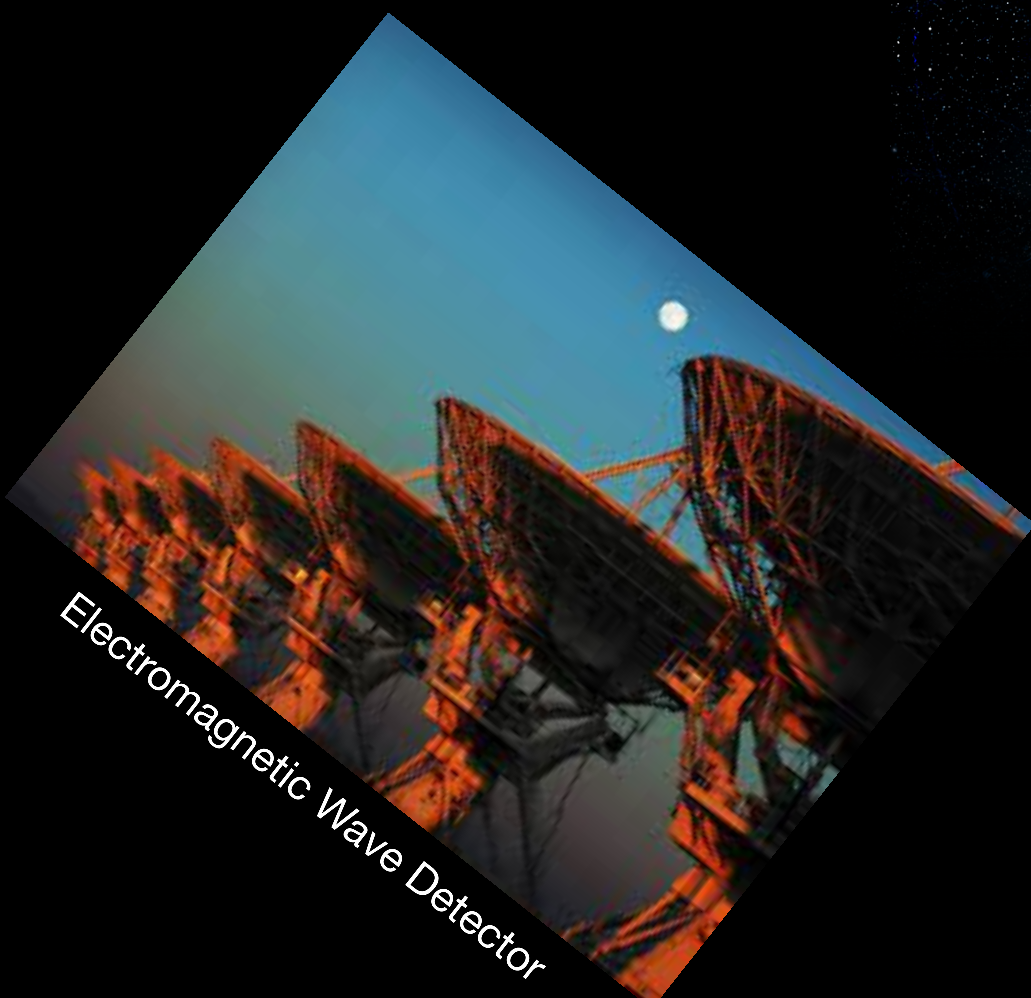


Neutron Star



Electromagnetic Wave Detector

Gravitational Wave Detector

Targeted Searches
For Continuous Gravitational Waves

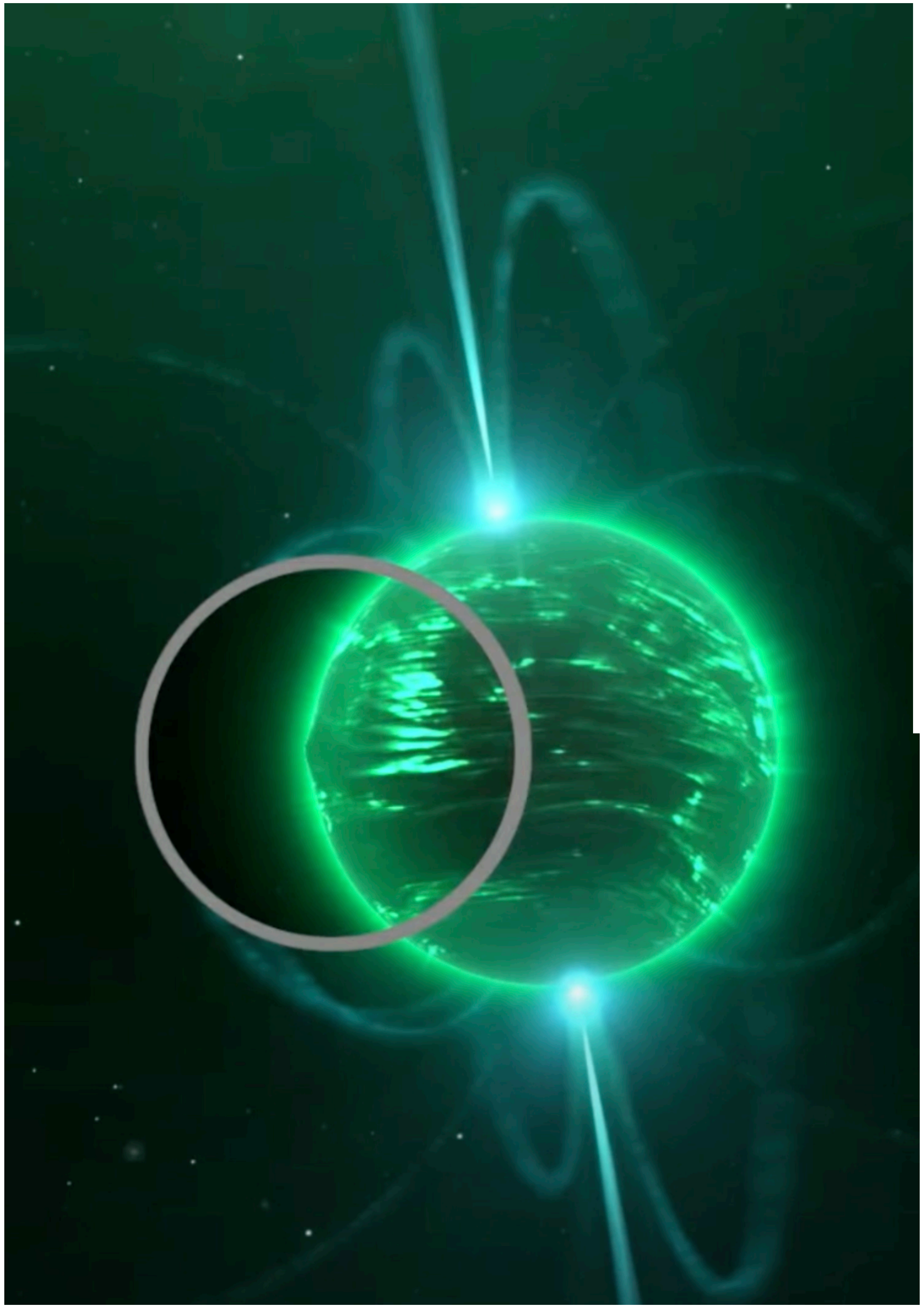
Anjana Ashok
Max Planck Institute for Gravitational Physics, Hannover

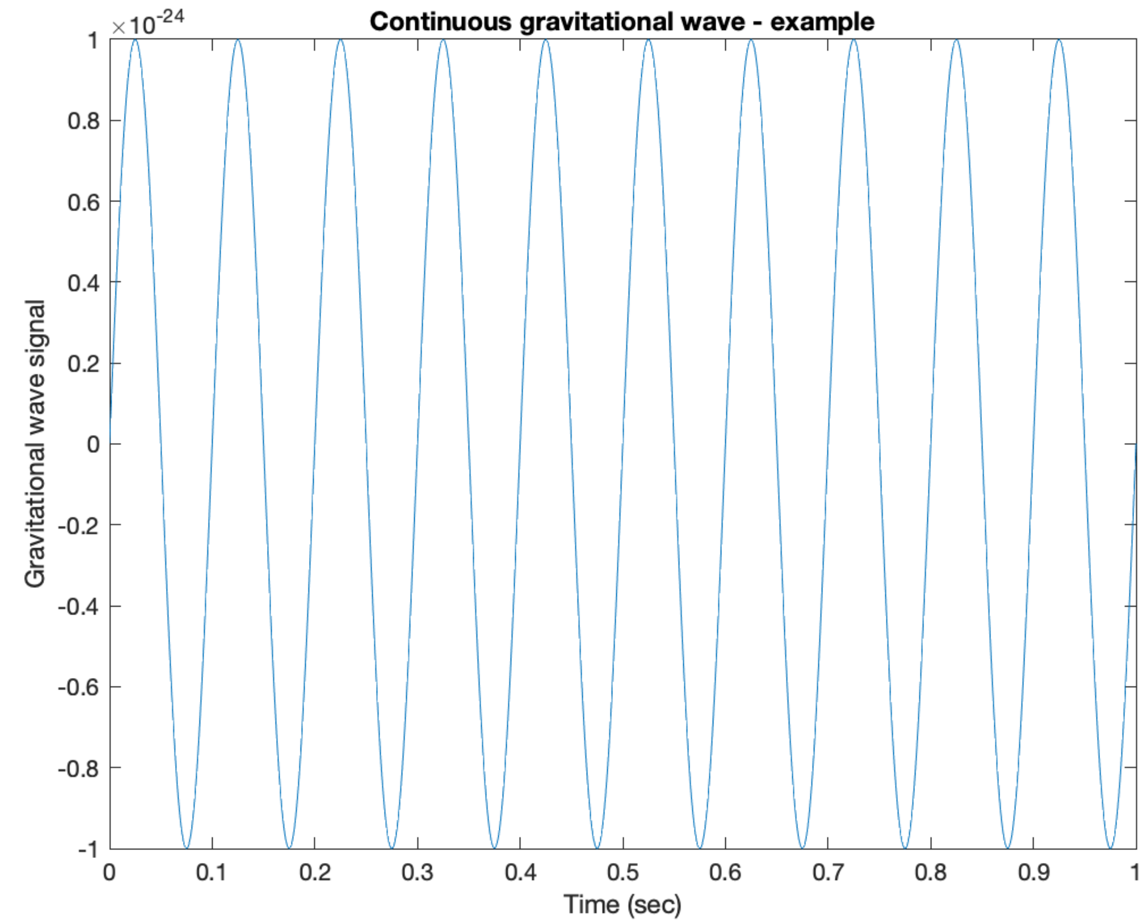
12th July 2023
Multimessenger Continuous Gravitational Wave Workshop
Nikhef/University of Amsterdam

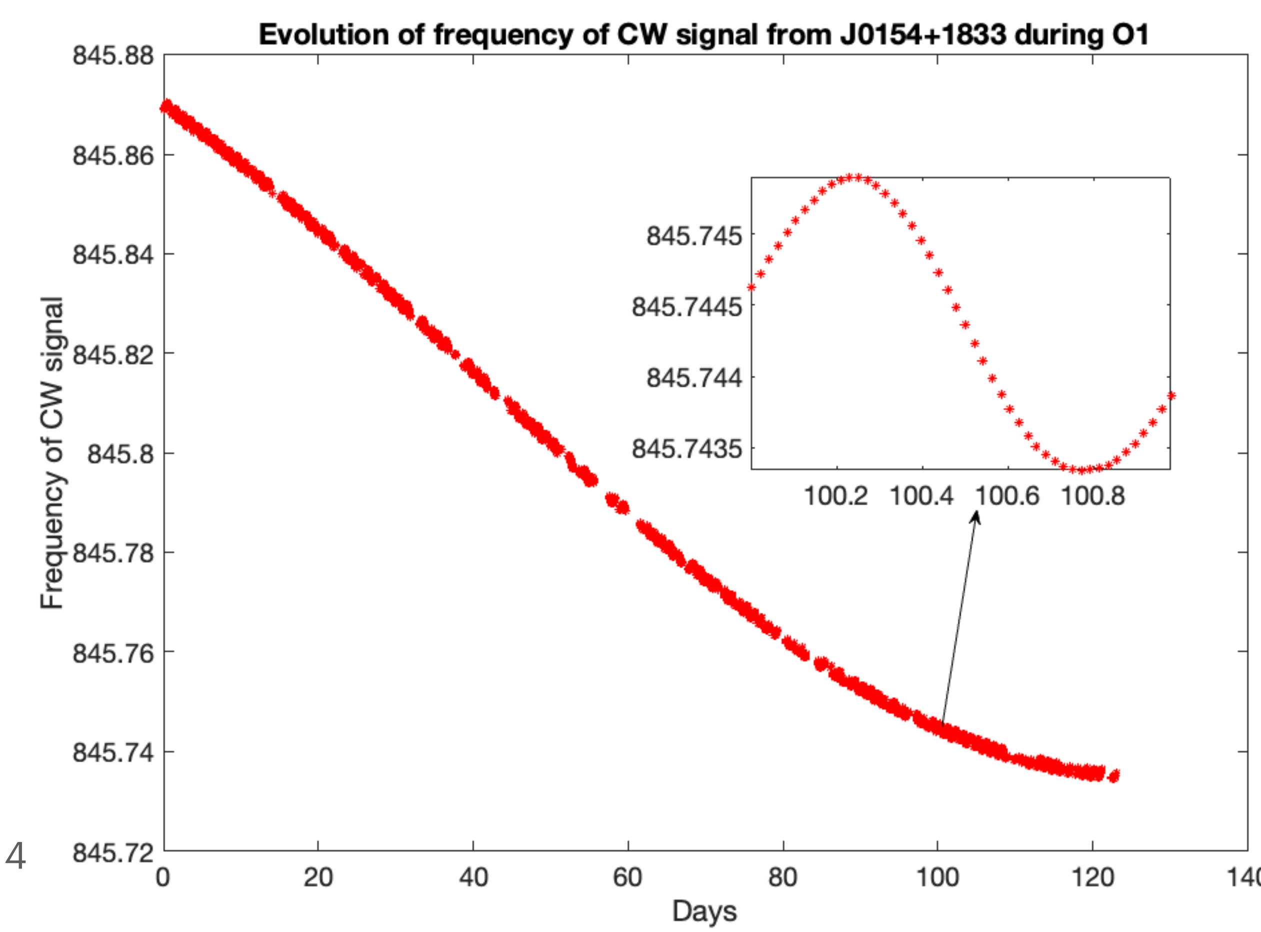
Leibniz Universität Hannover

CONTINUOUS GRAVITATIONAL WAVES


Disputation
sis : 'Targeted Searches for Continuous Gravitational Waves'
Anjana Ashok
23 May 2023
Max Planck Institute for Gravitational Physics,




Continuous gravitational wave - example
×10^-24
Gravitational wave signal
Time (sec)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1


Evolution of frequency of CW signal from J0154+1833 during O1
Frequency of CW signal
Days
845.88
845.86
845.84
845.82
845.8
845.78
845.76
845.74
845.72
0
20
40
60
80
100
120
140
845.745
845.7445
845.744
845.7435
100.2
100.4
100.6
100.8

The Signal is defined by

- Source spin frequency and spin down at a reference time

$$f_{gw} = 2f_{rot}$$

$$\dot{f}_{gw} = 2\dot{f}_{rot}$$

- Source sky position - Right Ascension and Declination (α, δ)

Phase Evolution
λ

- Amplitude - h_0
- Inclination angle - $\cos\iota$
- Initial phase - ϕ_0
- Polarisation angle - ψ

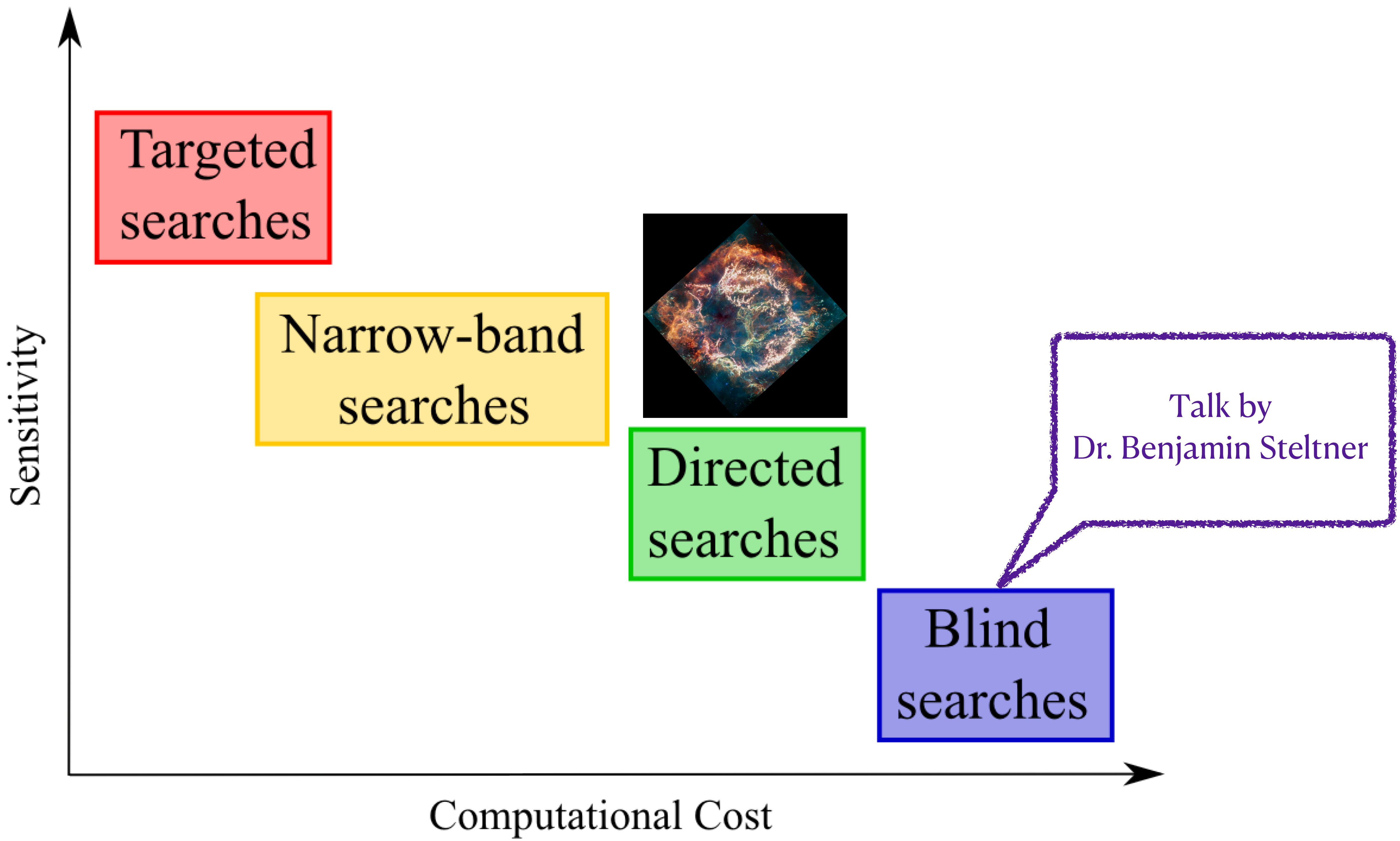
Amplitude
A

..additionally orbital parameters

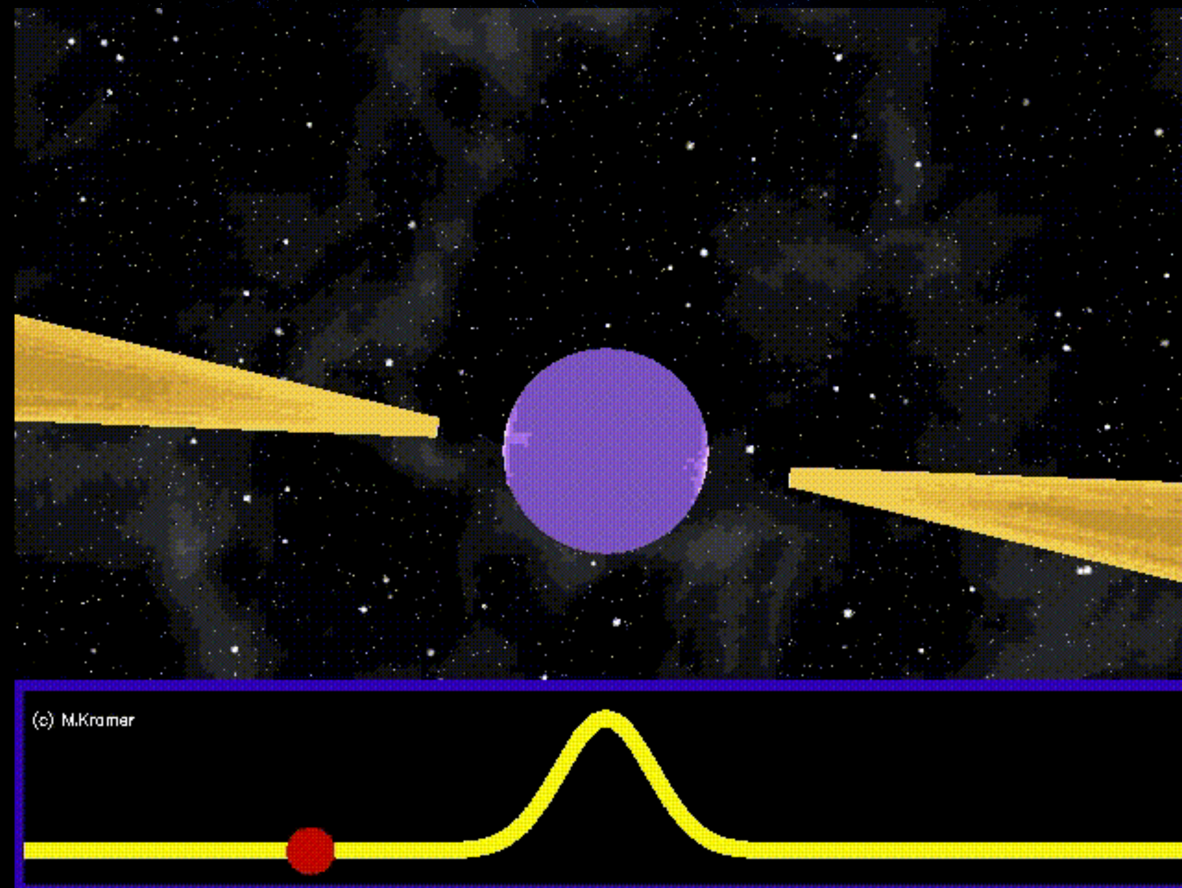
- Orbital Period (P)
- Eccentricity (E)
- Projected semi-major axis ($a \sin \iota$)
- Time of Periapsis (T_p)
- Argument of Periapsis (ω)

Additional
Phase Evolution Parameters
λ

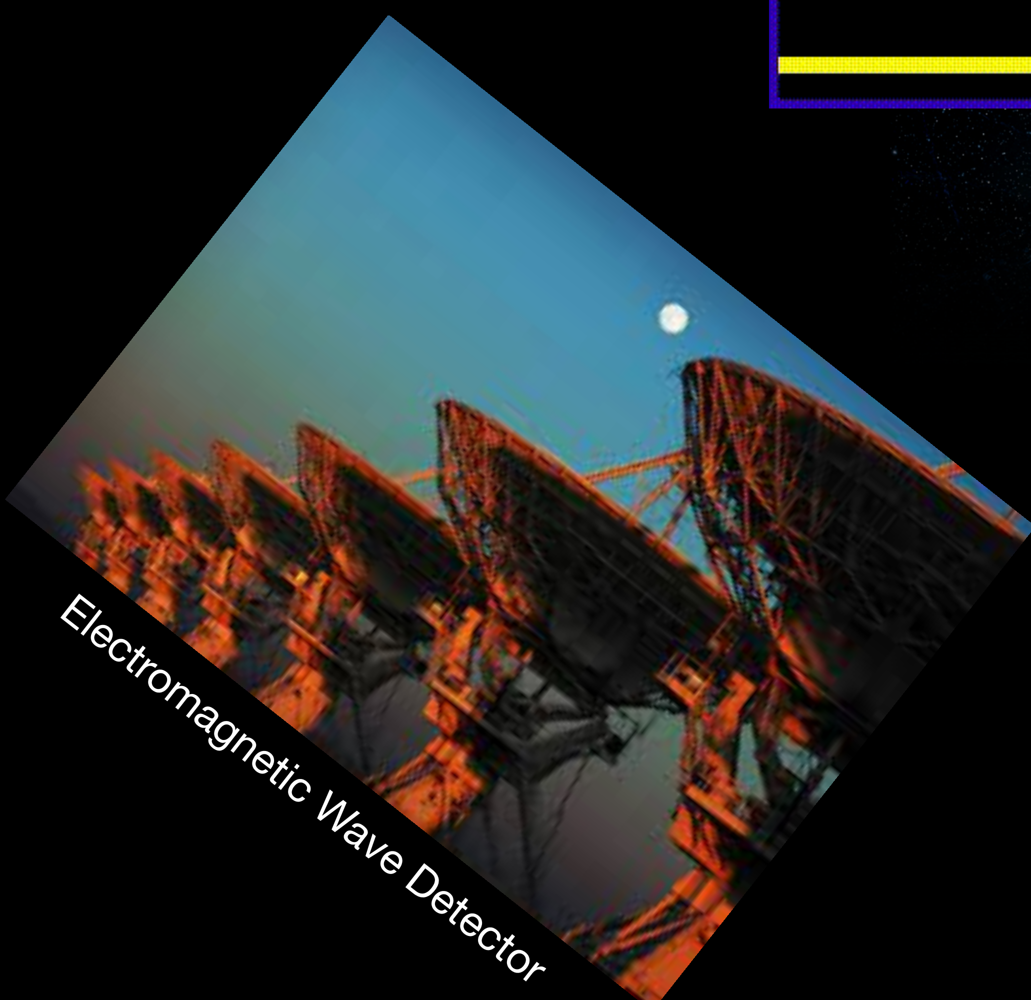
Types of searches for CW Signals



Credit : Sieniawska & Bejger (2019)



Neutron Star



Electromagnetic Wave Detector

Gravitational Wave Detector

Thanks to Pulsar Timing Solutions : Targeted Searches for the CW Signal

$\lambda = \mathrm{known}$

The Signal is defined by

- Source spin frequency and spin down at a reference time

$$f_{gw} = 2f_{rot}$$ ✓

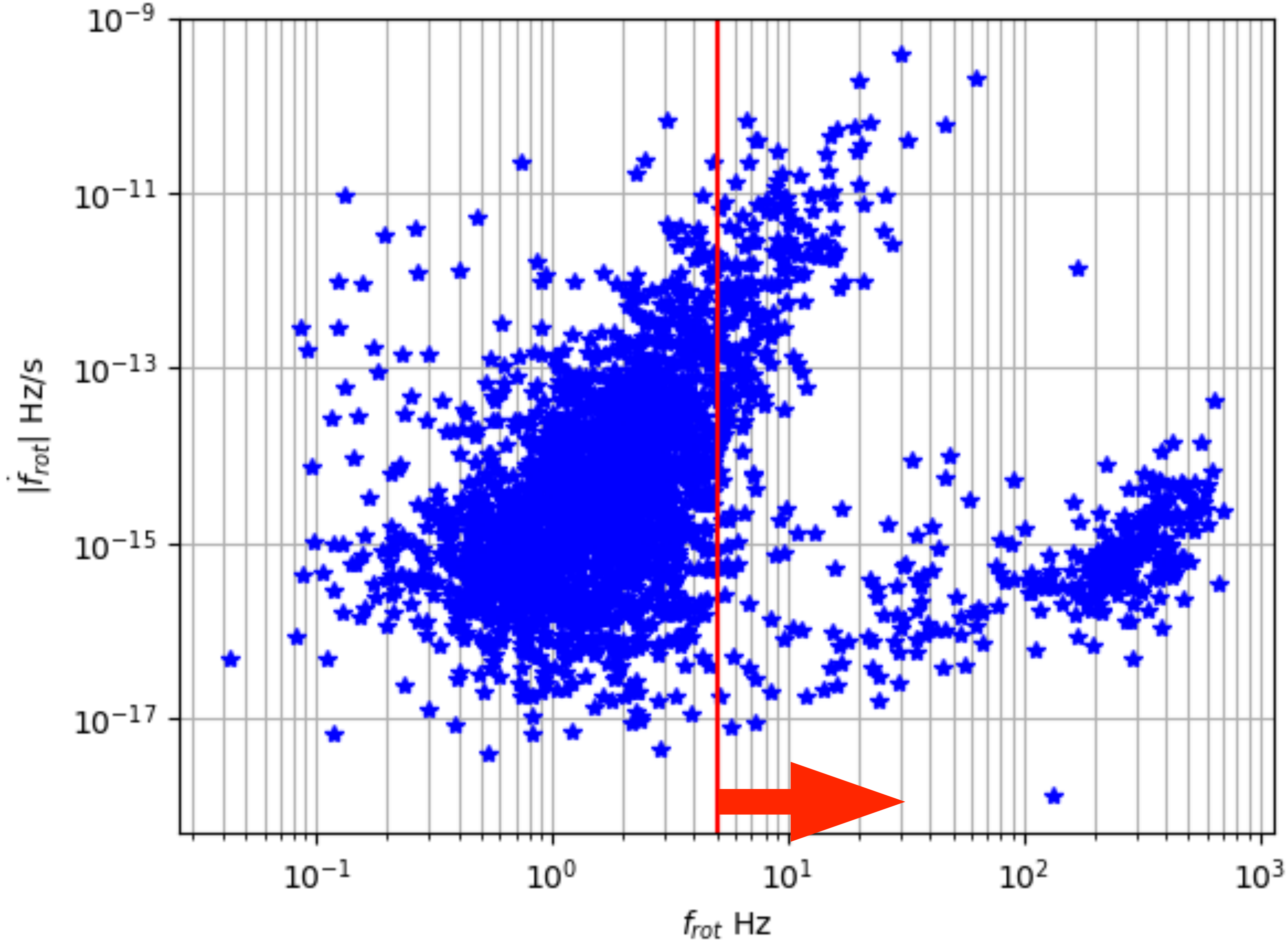
$$\dot{f}_{gw} = 2\dot{f}_{rot}$$ ✓

- Source sky position - Right Ascension and Declination (α, δ) ✓

..additionally orbital parameters

- Orbital Period (P) ✓
- Eccentricity (E) ✓
- Projected semi-major axis $(a \sin \iota)$ ✓
- Time of Ascending Node (T_{asc}) ✓
- Argument of Periapsis (ω) ✓

Population of Pulsars



THE ASTROPHYSICAL JOURNAL

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ARTICLES

GRAVITATIONAL WAVES FROM KNOWN I FROM THE INITIAL DETECTOR ERA

J. Aasi[1], J. Abadie[1], B. P. Abbott[1], R. Abbott[1], T. Abbott[2], M. R. Abern
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THE ASTROPHYSICAL JOURNAL

First Search for Gravitational Waves from Known Pulsars with Advanced LIGO

B. P. Abbott[1], R. Abbott[1], T. D. Abbott[2], M. R. Abernathy[3], F. Acernese[4,5], K. Ackley[6], C. Adams[7], T. Adams[8],
P. Addesso[9], R. X. Adhikari[1], V. B. Adya[10], C. Affeldt[10], M. Agathos[11], K. Agatsuma[11], N. Aggarwal[12], O. D. Aguiar[13]

THE ASTROPHYSI

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N. Arnaud[25,28], S. Ascenzi[29,30], G. As
C. Austin[2], V. Avendano[34], A. Avila-A
S. Bae[37], M. Bailes[38], P. T. Baker[39], F
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G. Cagnoli[22,78], C. Cahillane[1], J. Cald

PHYSICAL REVIEW D **96,** 122006 (2017)

First narrow-band search for continuous gravitational waves from known pulsars in advanced detector data

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 6 October 2017; published 28 December 2017)

Spinning neutron stars asymmetric with respect to their rotation axis are potential sources of

PHYSICAL REVIEW D **99,** 122002 (2019)

Narrow-band search for gravitational waves from known pulsars using the second LIGO observing run

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 22 February 2019; published 27 June 2019)

Isolated spinning neutron stars, asymmetric with respect to their rotation axis, are expected to be sources of continuous gravitational waves. The most sensitive searches for these sources are based on accurate matched filtering techniques that assume the continuous wave to be phase locked with the pulsar beamed

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FOR GRAVITATIONAL PHYSICS
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Home > Observational Relativity and Cosmology > Pulsars

Pulsars

This group's main research aspects are computing-intense searches for and studies of pulsars – rapidly spinning neutron stars – through gamma rays and radio waves in previously inaccessible parameter spaces using efficient data analysis and powerful computing resources.

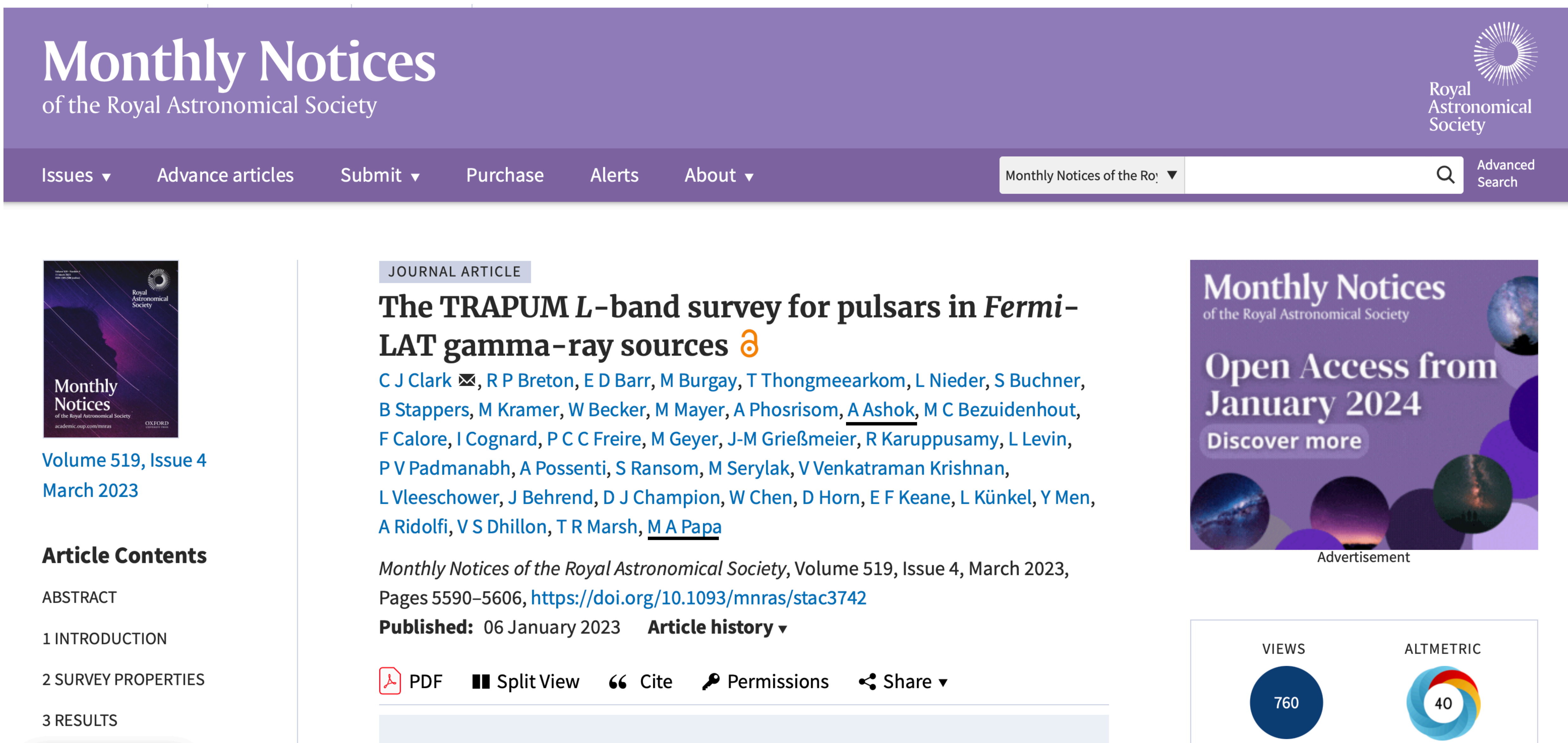
Departure into unexplored lands

Pulsars are some of the most extreme objects in our Universe and important key probes for a wide range of fundamental physics. Yet many aspects are still poorly understood after decades of observations.

We extend neutron star searches to parameter spaces that have been inaccessible before on computational grounds. This requires the development of efficient data analysis methods and the exploitation of powerful computing resources, such as the Einstein@Home volunteer computing project. We adapt and improve methods from gravitational-wave searches for our gamma-ray and radio searches. We also study our discoveries at multiple wavelengths and messengers.

- Atlas computing cluster
- Einstein@Home
- Pulsar Timing Arrays
- Pulsars
- Compact binary coalescence
- Publications
- News
- Student internships
- Cooperations

Method
With the example of
PSR J1526-2744 from



Monthly Notices
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Volume 519, Issue 4
March 2023

Article Contents

JOURNAL ARTICLE

The TRAPUM *L*-band survey for pulsars in *Fermi*-LAT gamma-ray sources

C J Clark ✉, R P Breton, E D Barr, M Burgay, T Thongmeearkom, L Nieder, S Buchner, B Stappers, M Kramer, W Becker, M Mayer, A Phosrisom, A Ashok, M C Bezuidenhout, F Calore, I Cognard, P C C Freire, M Geyer, J-M Grießmeier, R Karuppusamy, L Levin, P V Padmanabh, A Possenti, S Ransom, M Serylak, V Venkatraman Krishnan, L Vleeschower, J Behrend, D J Champion, W Chen, D Horn, E F Keane, L Künkel, Y Men, A Ridolfi, V S Dhillon, T R Marsh, M A Papa

Monthly Notices of the Royal Astronomical Society, Volume 519, Issue 4, March 2023, Pages 5590–5606, https://doi.org/10.1093/mnras/stac3742

Published: 06 January 2023 **Article history** ▾

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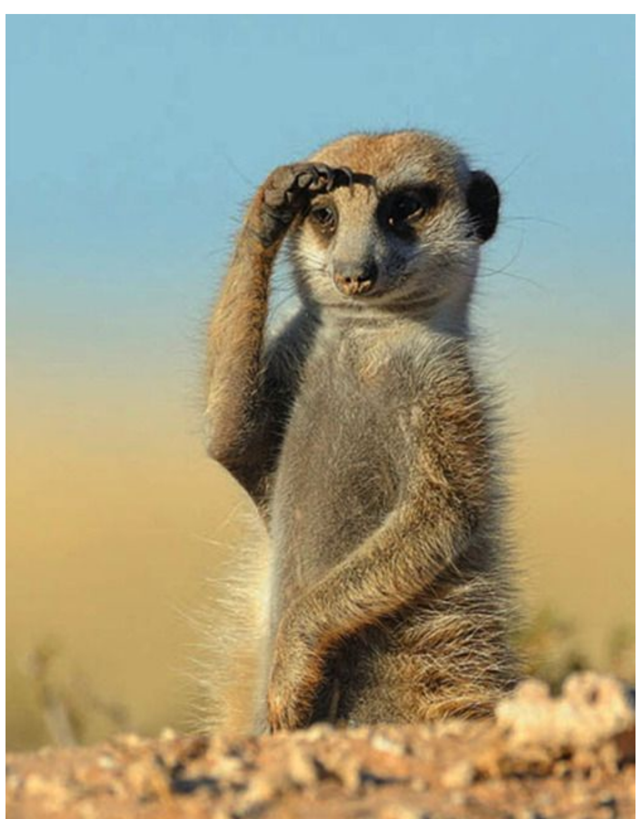
...mentioned by Dr. Colin Clark earlier

PSR J1526-2744



```
PSRJ              J1526-2744
RAJ               15:26:45.103143174773805      1     1.22447858372069e-07
DECJ             -27:44:05.912804593135093      1     3.85234765940031e-07
F0                401.744602097496              1     2.62370693438065e-10
F1               -5.70865795989642e-16          1     1.22993413764598e-18
PEPOCH            59355.468037
BINARY            ELL1
PB                0.202810828455367             1     6.84806307298376e-10
A1                0.224097093580642             1     3.0326078024144e-05
TASC              59303.2059777742              1     9.58144227167222e-06
START             54681.0
FINISH            59476.0
CLK               TT(TAI)
UNITS             TDB
EPHEM             DE405
EPHVER            5
TZRSITE           @
TZRFREQ           0
TZRMJD            59355.468037
CORRECT_TROPOSPHERE N
```

```
PSRJ            J1526-2744
RAJ             15:26:45.103143174773805    1    1.22447858372069e-07
DECJ           -27:44:05.912804593135093    1    3.85234765940031e-07
F0              401.744602097496            1    2.62370693438065e-10
F1             -5.70865795989642e-16        1    1.22993413764598e-18
PEPOCH          59355.468037
BINARY          ELL1
PB              0.202810828455367           1    6.84806307298376e-10
A1              0.224097093580642           1    3.0326078024144e-05
TASC            59303.2059777742            1    9.58144227167222e-06
START           54681.0
FINISH          59476.0
CLK             TT(TAI)
UNITS           TDB
EPHEM           DE405
EPHVER          5
TZRSITE         @
TZRFREQ         0
TZRMJD          59355.468037
CORRECT_TROPOSPHERE N
```

Parameter	Value
f_{gw}	803.5Hz
$\dot{f}_{gw}$	-1.1e-15 Hz/s
RA	4.04 rad
DEC	-0.48 rad
Reference time	59355.5 MJD
Orbital period	5 hours
asini	0.22 lt-s
e	not measured
ω	not measured
Time of Periapsis	59303.2 MJD

Search In O1+O2+O3 data

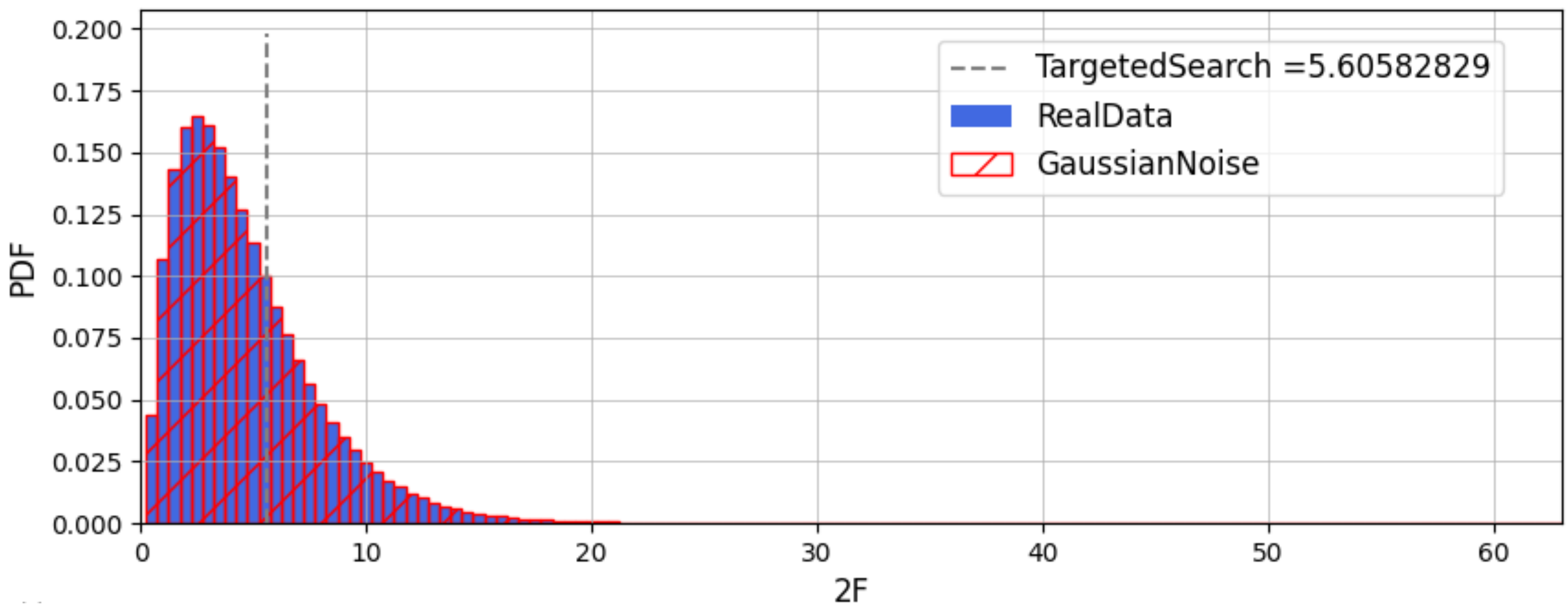
Step I : Single template search

- Hypothesis 0 : The data is $x(t) = n(t)$
- Hypothesis 1 : The data is $x(t) = n(t) + h(t; A, \lambda)$
- Likelihood ratio :

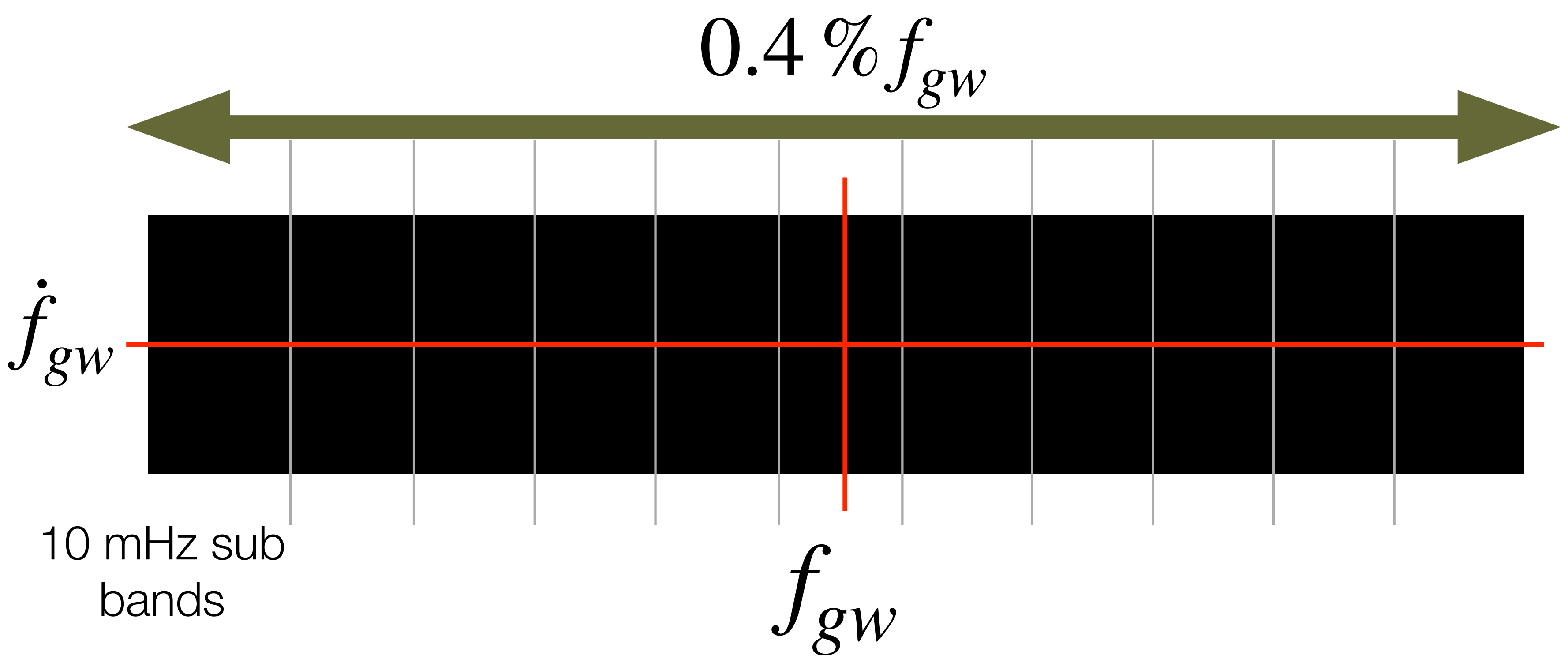
$$\mathscr{L}(x; A, \lambda) \equiv \frac{P(x \,|\, A, \lambda)}{P(x \,|\, 0)}$$

Maximised log-likelihood : $\mathscr{F}$-statistic ($2\mathscr{F}$)

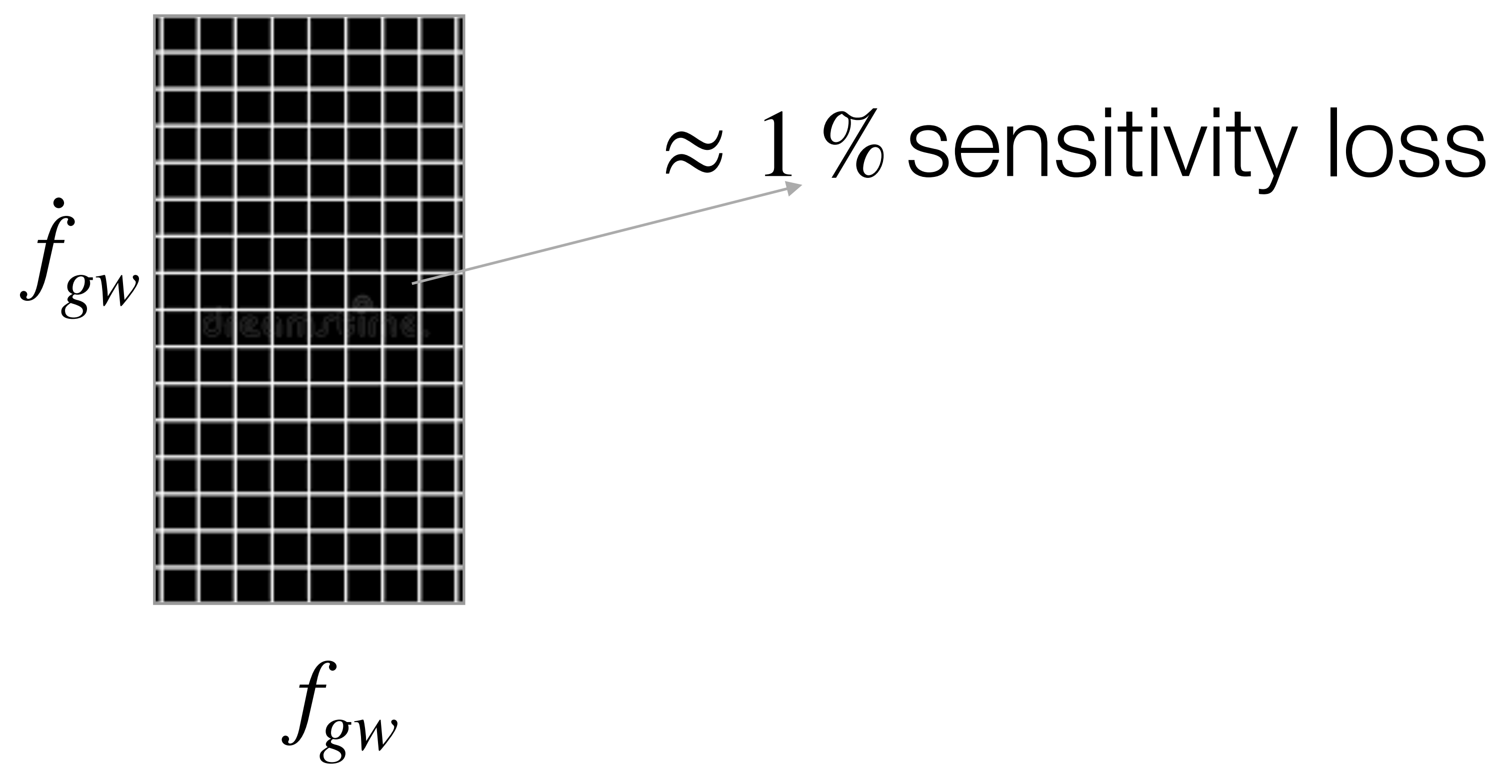
PSR J1526-2744 : Single template search results



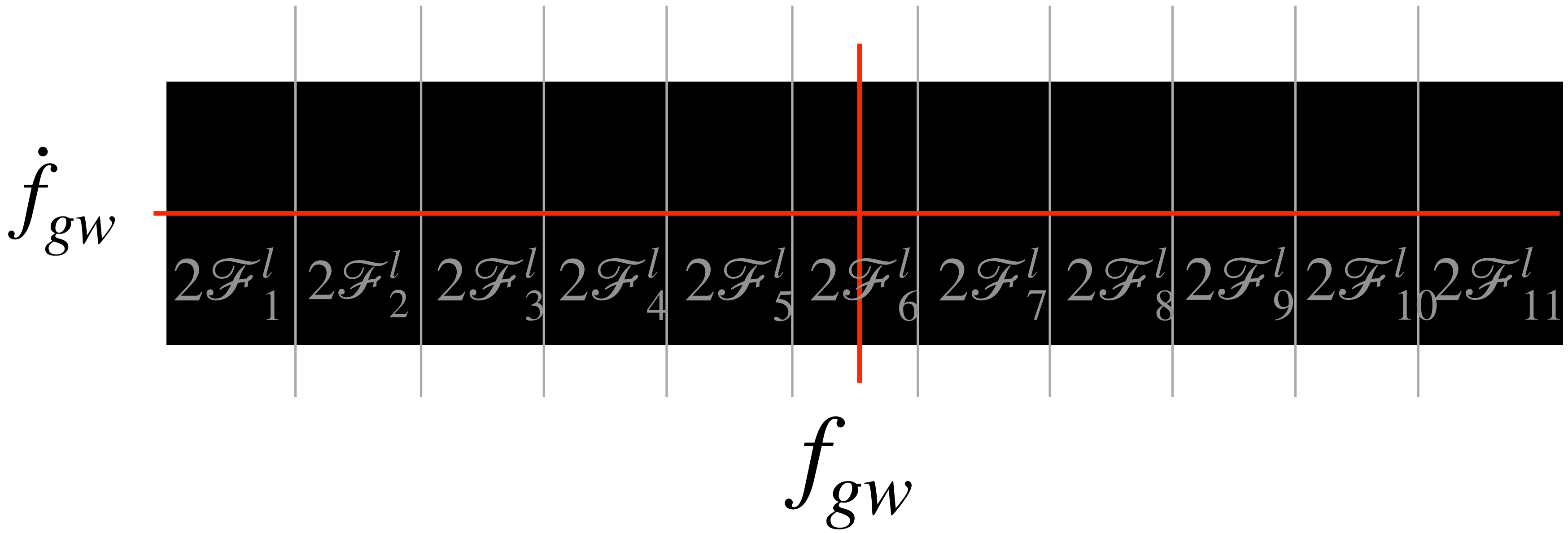
Step II : Band Search in $(f_{gw}, \dot{f}_{gw})$



Band Search in $(f_{gw}, \dot{f}_{gw})$

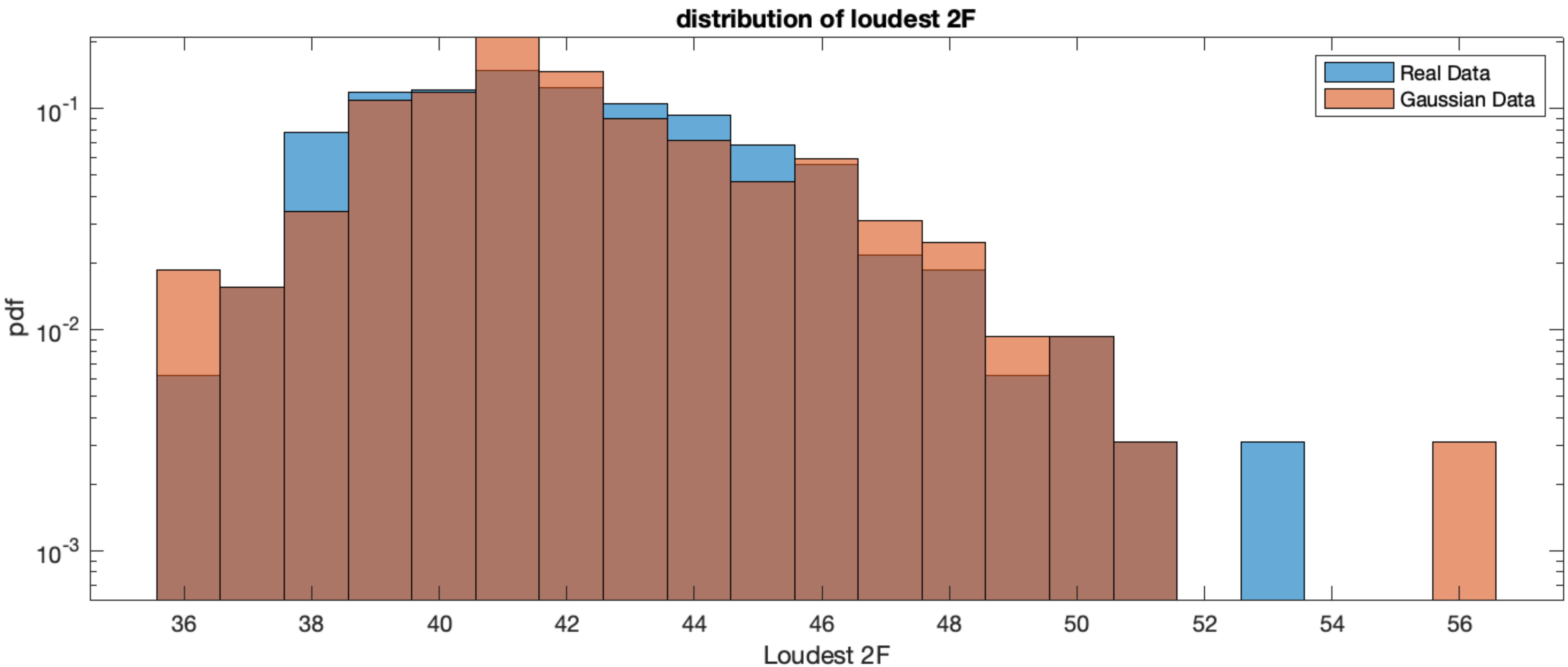


Band Search in $(f_{gw}, \dot{f}_{gw})$



Loudest $2\mathscr{F}$s -> Band Search Results

PSR J1526-2744 : Band search results



Step III : Upper limits on CW emission

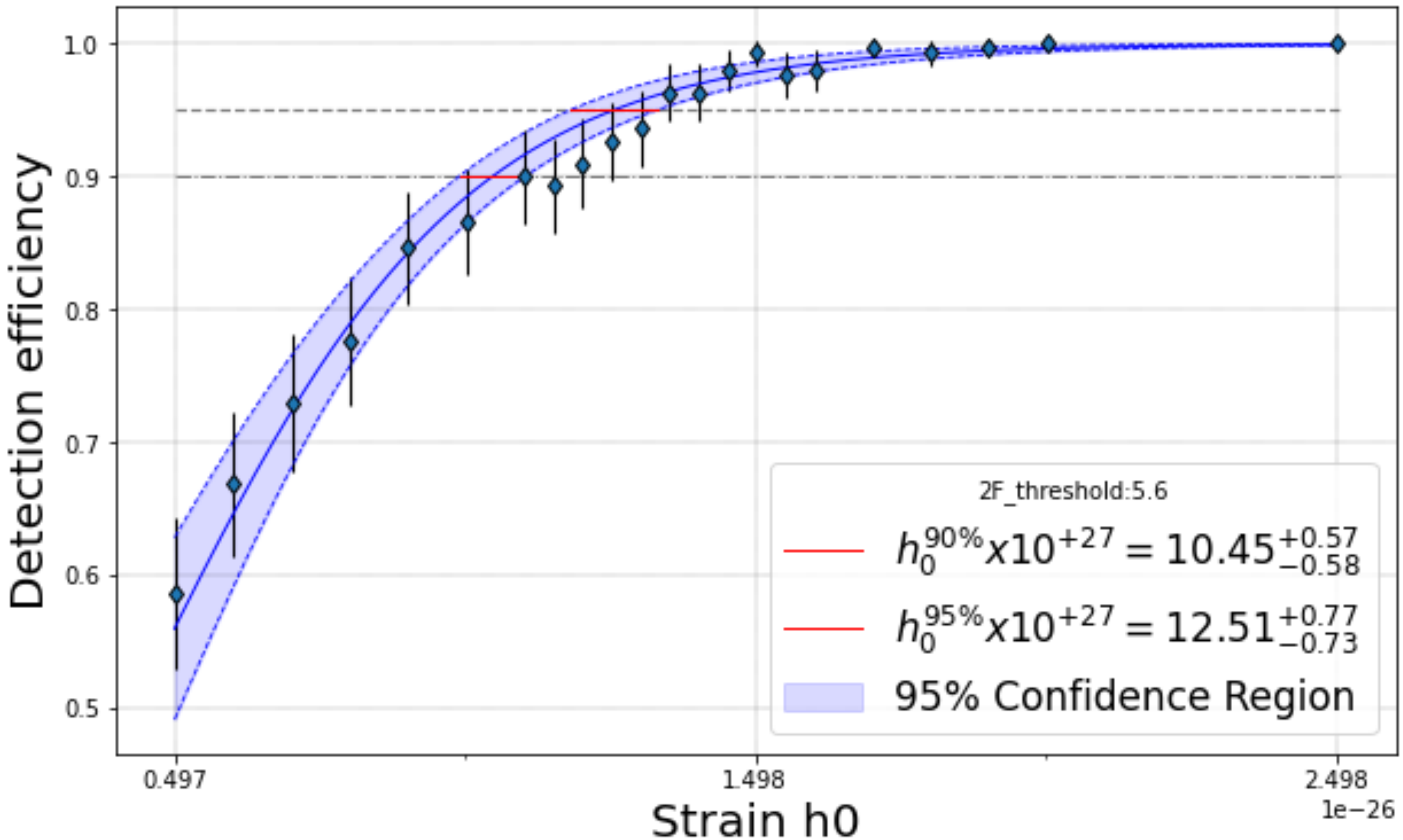
- Based on null results

$$h_0 < h_0^{95\%}$$

Or Else : $2\mathcal{F} > 2\mathcal{F}^{measured}$

PSR J1526-2744 : CW Upper limits

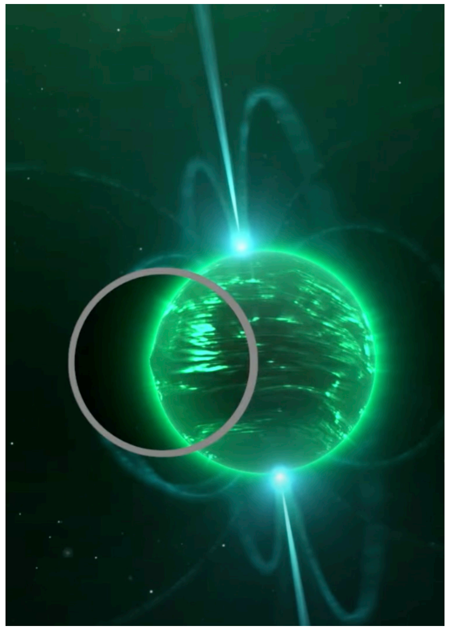
$$h_0^{95} = 1.25 \times 10^{-26}$$



Ellipticity constraints

- Constrain CW → Constrain Ellipticity of pulsar

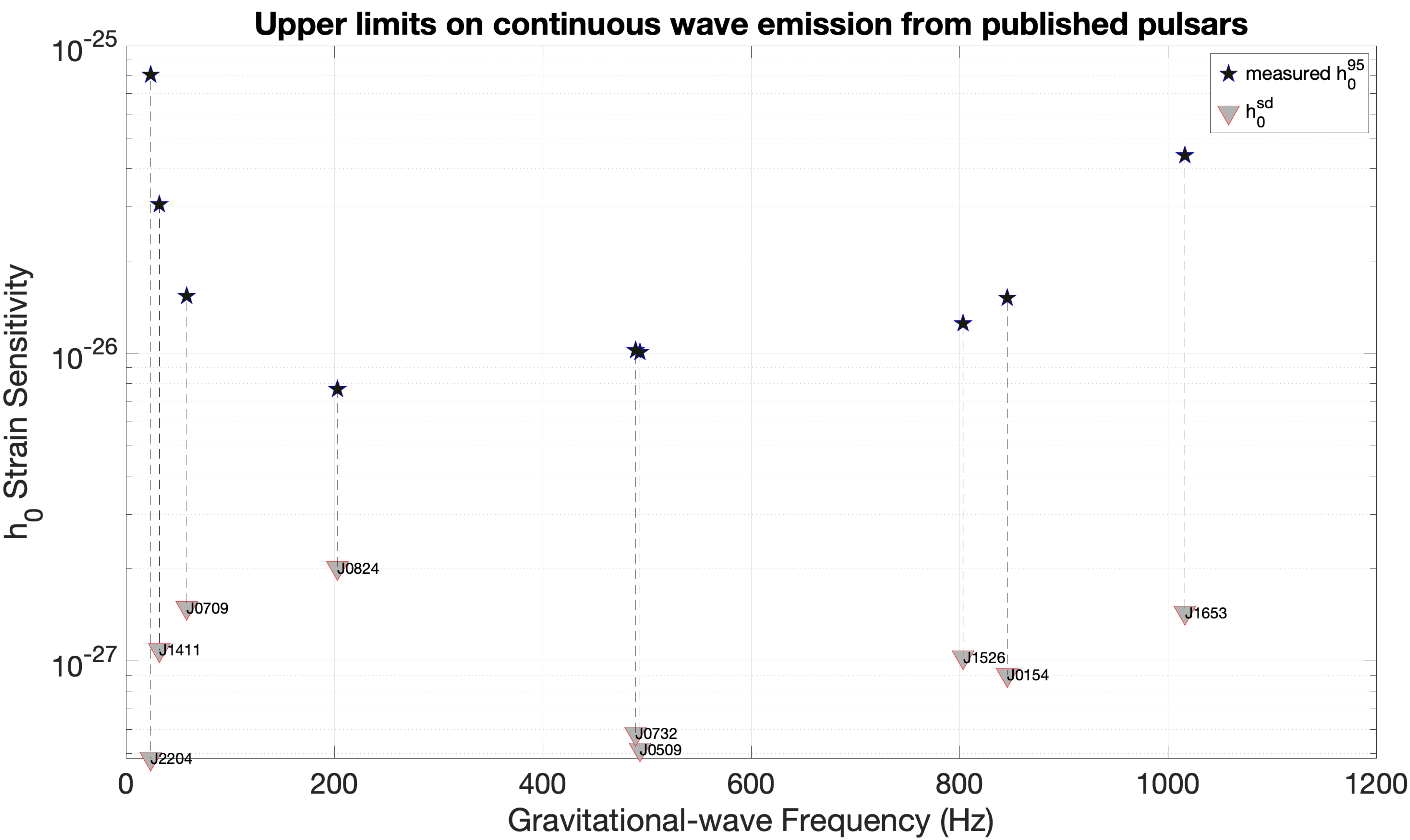
$$\epsilon = 2.4 \times 10^{-7} \left(\frac{h_0}{10^{-26}}\right)\left(\frac{D}{1\ \text{kpc}}\right)\left(\frac{200\text{Hz}}{f}\right)^2\left(\frac{10^{38}\ \text{kg m}^2}{I_{zz}}\right)$$



PSR J1526-2744

$\epsilon^{95} = 2.45 \times 10^{-8}$

General Results - h_0^{95}



Ending Note

- A source is guaranteed to be present : so even a null measurement is informative about the emission.
- High sensitivity ⬆ and low computational expense ⬇
- High value pulsars —
  - nearby,
  - high $\dot{f}_{gw}$,
  - In high sensitivity frequency ranges of Advanced LIGO detectors

Ending Note - II

- New and improved telescopes/strategies are discovering new pulsars
- Ever more known pulsars

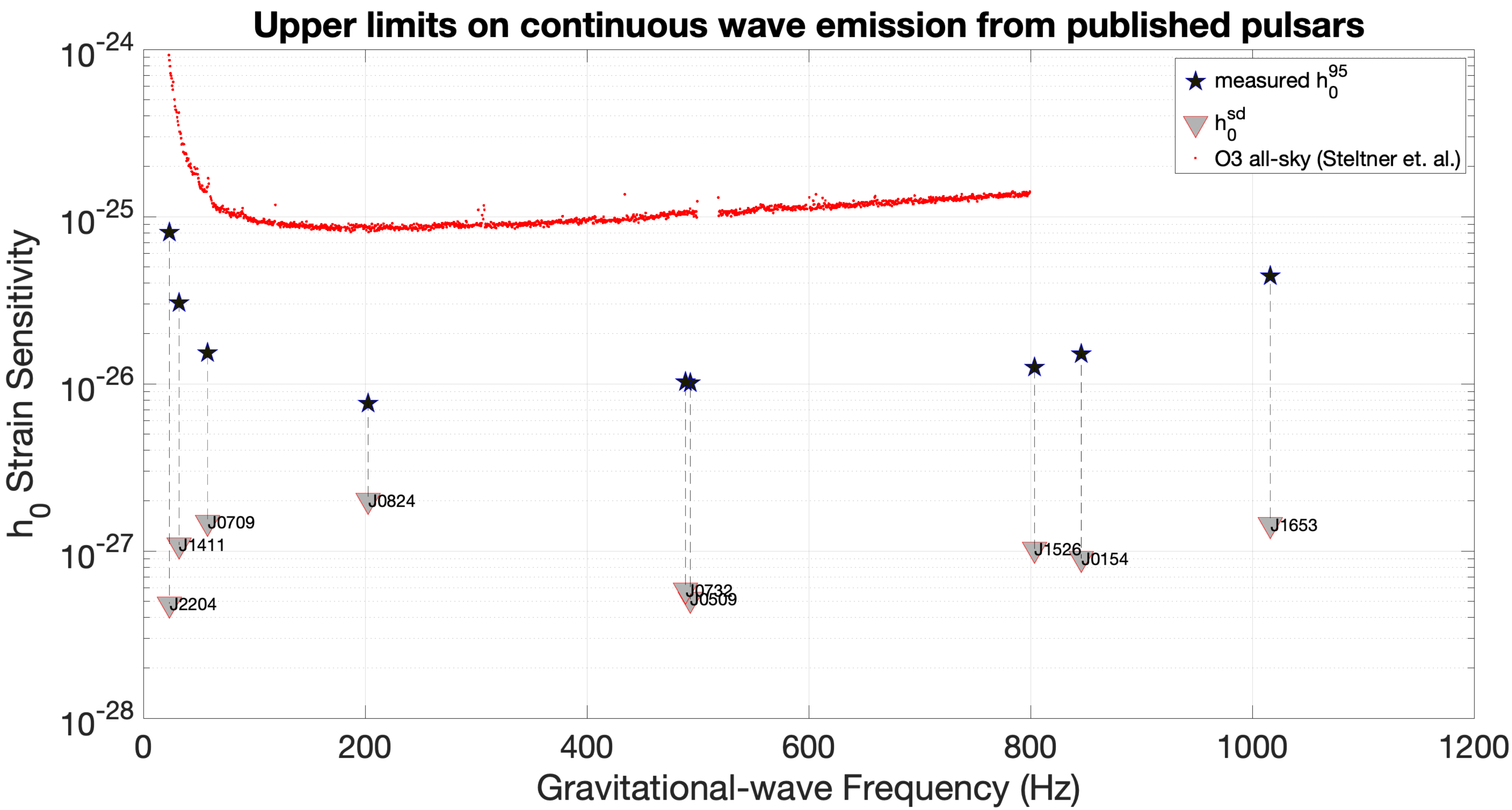
Credits for figures not produced by me

1. M. Sieniawska and M. Bejger. Continuous gravitational waves from neutron stars: current status and prospects. Universe, 5 (11):217, 2019. doi: 10.3390/universe5110217

2. M.A. Papa, Max Planck Institute for Gravitational Physics, Hannover

Additional Slides

Sensitivity Comparison



Spin down upper limit

?

$$h_0^{sd} = \frac{1}{d}\sqrt{\frac{5GI_{zz}}{2c^3}\frac{|\dot{f}_{rot}|}{f_{rot}}}$$

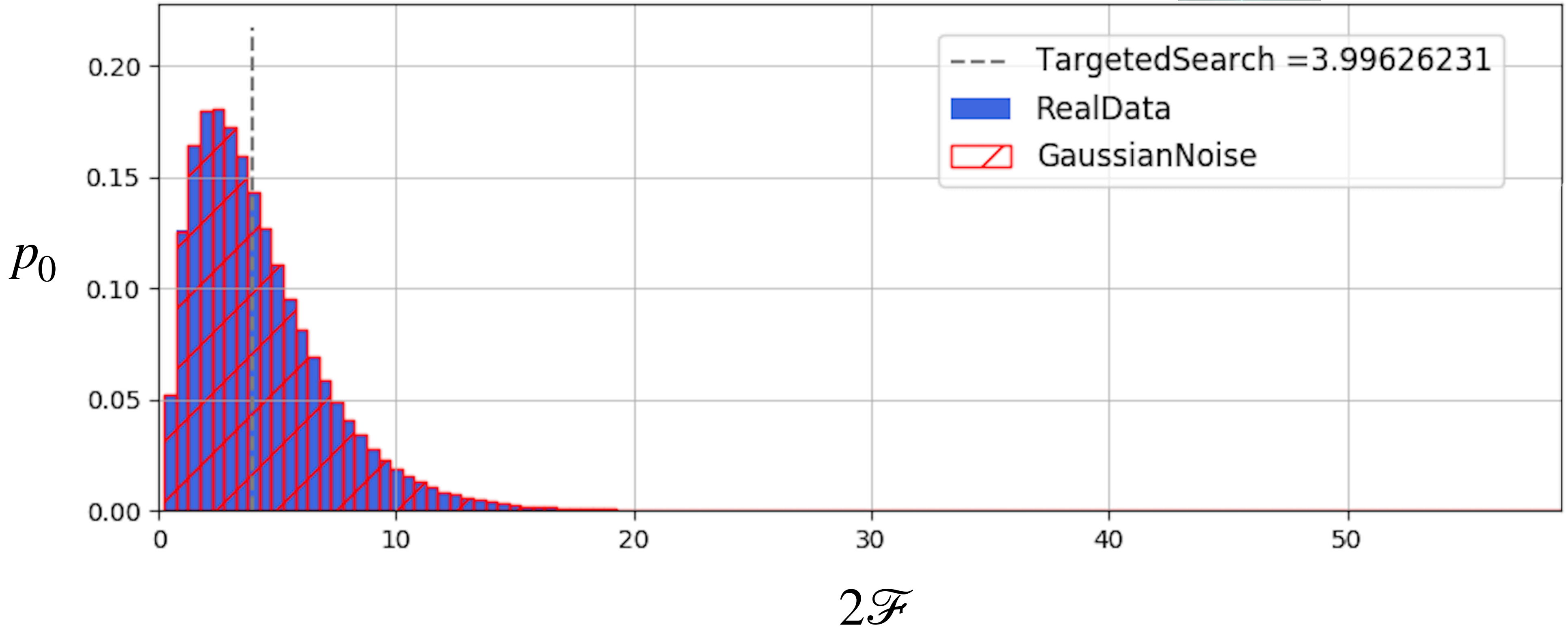
Assuming $M = 1.4M_{\odot}$ and $R = 10$km

$$I_{zz} = 10^{38} kgm^2$$

Significance of search result

- Frequentist p-values
- Search in noise-only
- Find $p_0(2\mathcal{F})$
- $2\mathcal{F}' = 3.99$
- p-value

Targeted search for J0154+1833 



$$\text{p-value}(3.99) = \int_{3.99}^{\infty} p_0(2\mathcal{F})d2\mathcal{F}$$

$$= 41\ \%$$

Targeting Millisecond Pulsars - A good idea

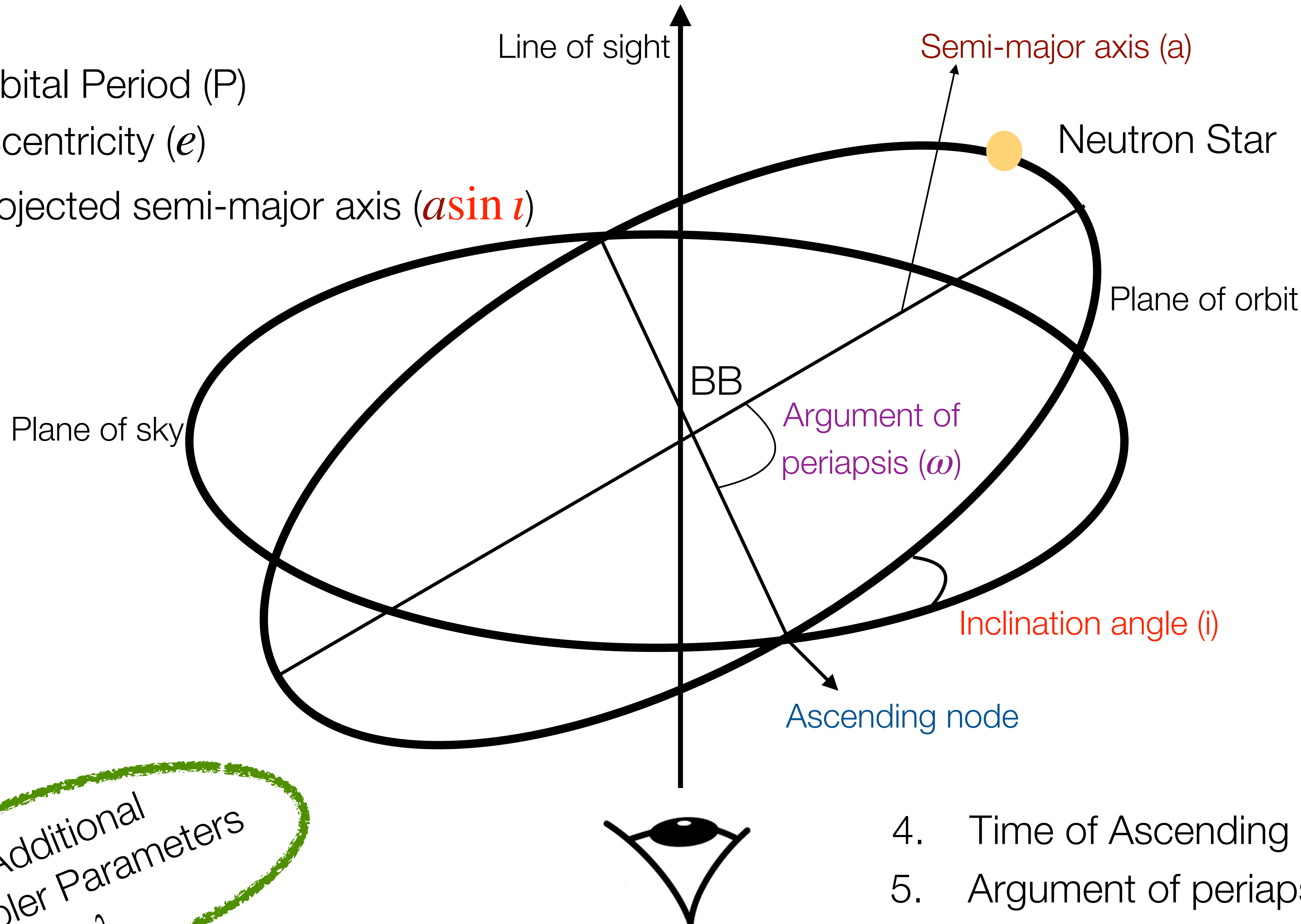
- High frequency, $h_0 \propto f_{gw}^2$, small ϵ is enough for high level of emission
- History of binary interaction - possibility of accreted mountains
- Crossing h_0^{sd} => new regime in terms of physical requirements for a detection

CW Emission : Other modes and sources

- Precessing neutron star -
  - $f_{gw} = f_{rot} + f_{prec}$
  - $f_{gw} = 2(f_{rot} + f_{prec})$
- R-mode emission - current quadrupoles, toroidal fluid oscillations inside the star, 4/3 f_{rot}
- Boson clouds around a black hole - f ~ mass of axion particle

Additionally orbital parameters

1. Orbital Period (P)
2. Eccentricity (e)
3. Projected semi-major axis ($a\sin\iota$)



4. Time of Ascending node (T_{asc})
5. Argument of periapsis (ω)

Additional Doppler Parameters λ