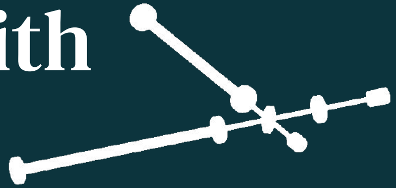
Prospects for detecting transient quasi-monochromatic gravitational waves from glitching pulsars with current and future detectors



Joan Moragues, Luana M. Modafferi, David Keitel

(Universitat de les Illes Balears)

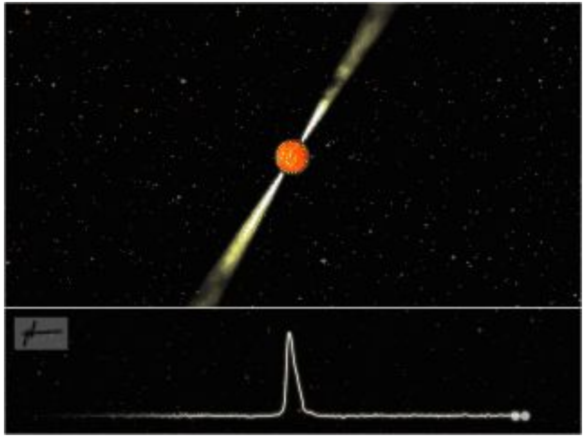
12th Iberian Meeting, June 7, 2022

joan.moragues@uib.cat

DCC: G2200941

Pulsar Glitches

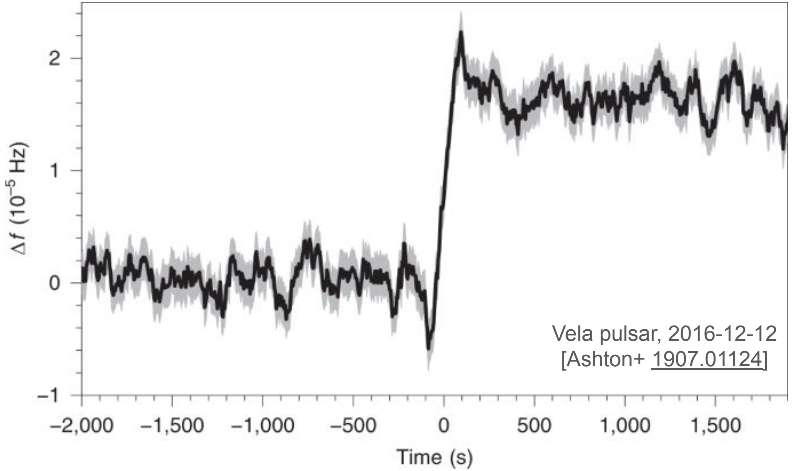
- Pulsars: rapidly rotating neutron stars with strong magnetic fields. We can see some of them if beams intersect the Earth.



[J. van Leeuwen]

$$f_{\mathrm{Taylor}}(t) = \sum_{k=0}^{N} \frac{f^{(k)}(t - T_{\mathrm{ref}})^k}{k!}$$

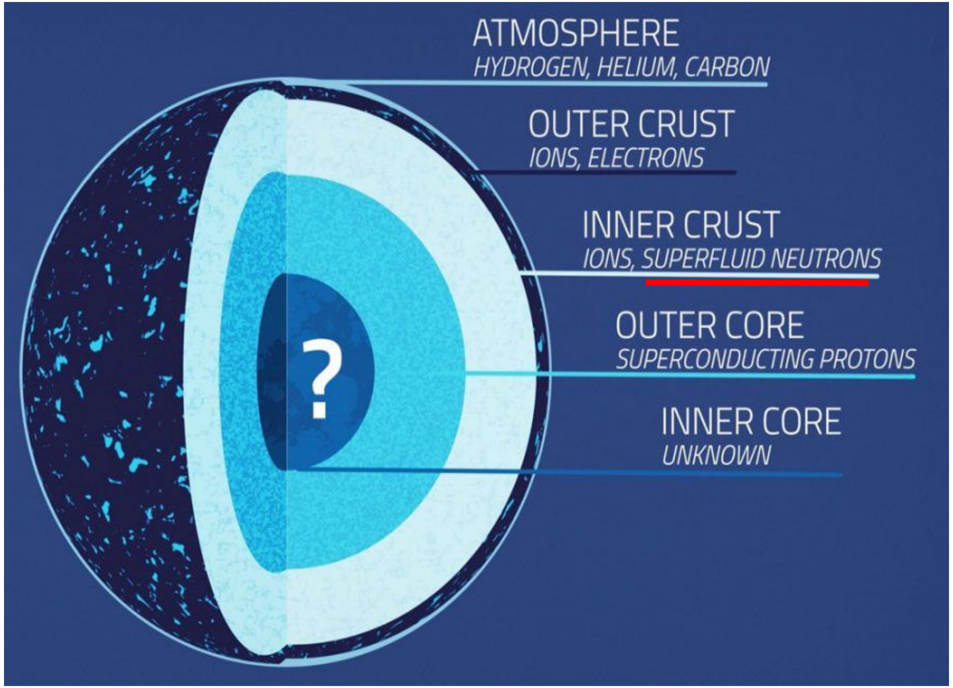
- A glitch takes places when a pulsar’s rotational frequency suddenly spins up; and freq. derivatives can also change.



Vela pulsar, 2016-12-12
[Ashton+ 1907.01124]

$$f_{\mathrm{glitch}}(t) = \Theta(t - T_{\mathrm{gl}}) \left[\sum_{k=0}^{M} \frac{\Delta f_{\mathrm{gl}}^{(k)} (t - T_{\mathrm{gl}})^k}{k!} + \delta f_{\mathrm{R}} e^{-(t - T_{\mathrm{gl}})/\tau_{\mathrm{R}}} \right]$$

Theory of Pulsar Glitches: Two-Fluid Model



Credits: NASA’s Goddard Space Flight Center / Conceptual Image Lab

- Weak coupling between normal component and interior superfluid, spindown leads to → growing “lag” $\Delta\Omega = \Omega_S - \Omega$
- When lag reaches a critical value, some sort of instability occurs: transfer of angular momentum from superfluid to normal component → **spin-up** (i.e. *glitch*)
- Excess of energy is available to potentially produce GWs.
- One model: GWs on the timescale of the after-glitch recovery, through transient mountain formation (e.g. Yim & Jones 2007.05893)

GWs from Pulsar Glitches: Energetics [Prix+ 1104.1704]

- indirect upper limit on emitted GW energy and amplitude: total energy released in glitch
- considering angular momentum conservation between the two fluids but an energy excess of the superfluid

$$E_s = \frac{1}{2} I_s(\Omega_s^2 - \Omega^2) \approx 4\pi^2 I_s \nu \Delta\nu$$

- equate with total energy carried by CW-like GW of amplitude h_0 and frequency f=2ν:

$$\boxed{h_0 = \frac{4\pi^2 G}{c^4}\frac{I_z \epsilon}{d} f^2} \longrightarrow \quad E_{\mathrm{GW}} = \frac{2\pi^2 c^3}{5G} f^2 d^2 \int^T h_0^2(t)\,dt,$$

glitch excess energy upper limit

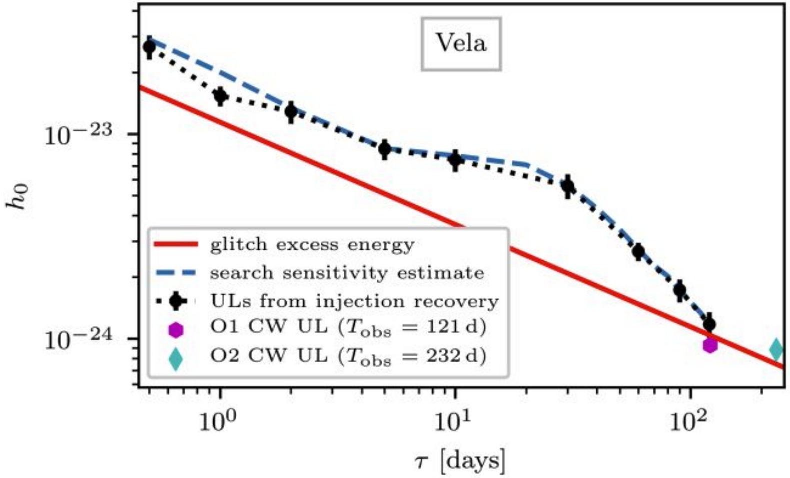
$$\boxed{h_0 \leq \frac{1}{d}\sqrt{\frac{5G}{2c^3}\frac{I_z}{\tau}\frac{|\Delta f|}{f}}}$$

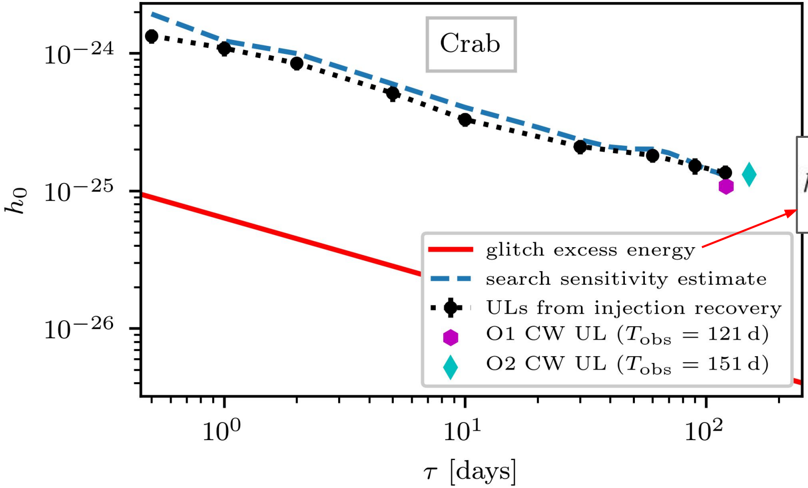
- fixed energy regardless of transient duration τ . SNR increases with same sqrt(τ) as h_0 upper limit → same basic *detectability* for short or long transients

Previous GW glitch searches

- search for ***short**-duration transients* (bursts) from Vela glitch in 2006 [Abadie+ 1011.1357]
- generic all-sky burst searches [e.g. Abbott+ 2107.03701] cover short post-glitch transients (e.g. f-modes)

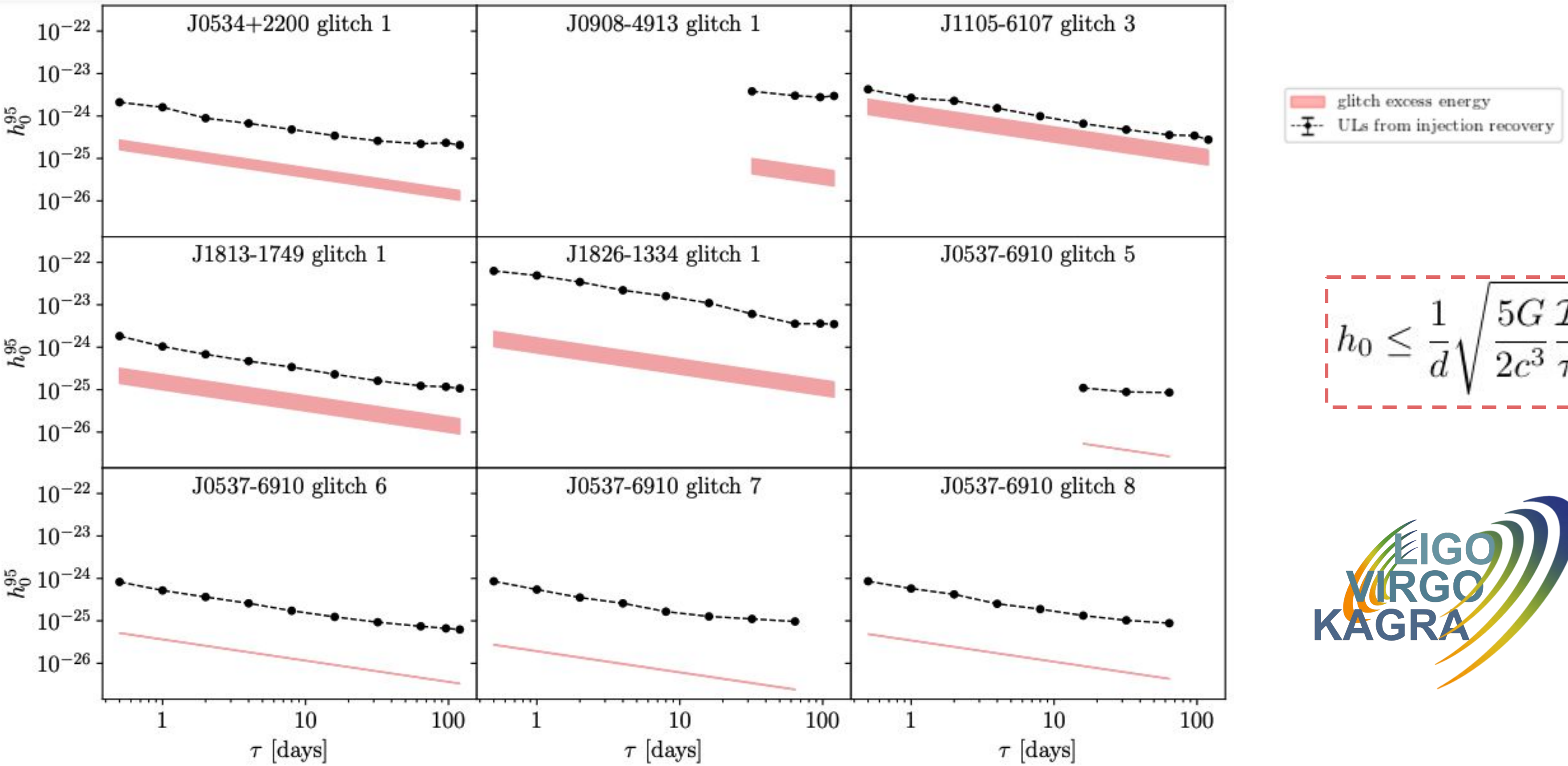
- search for ***long**-duration transients* from Vela & Crab glitches during O2 [Keitel+ 1907.04717] (using Prix+ 1104.1704 method)





$$h_0 \leq \frac{1}{d}\sqrt{\frac{5G}{2c^3}\frac{\mathcal{I}}{\tau}\frac{\Delta f_{\rm gl}}{f}}$$

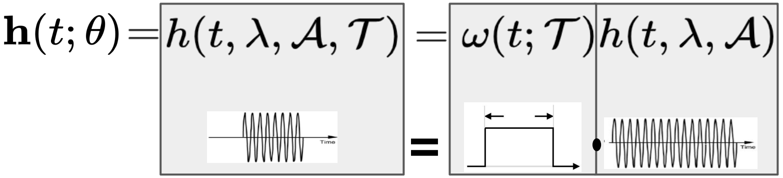
Previous GW glitch searches (O3) [Abbott+ arXiv:2112.10990]



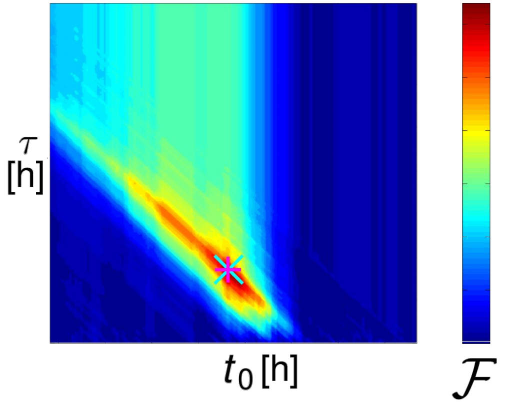
$$h_0 \leq \frac{1}{d}\sqrt{\frac{5G}{2c^3}\frac{\mathcal{I}}{\tau}\frac{\Delta f_{\rm gl}}{f}}$$

Search Methods for Long-Duration Transients

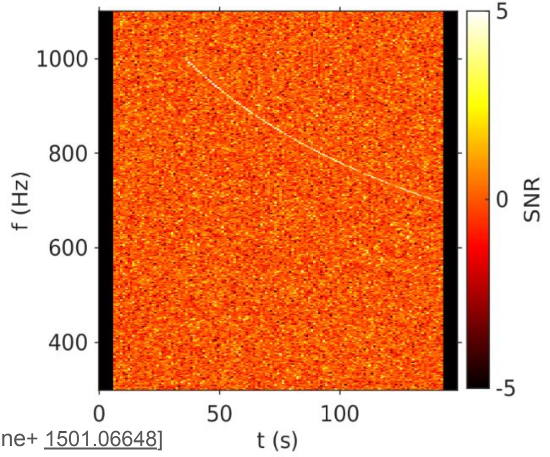
- **Transient $\mathcal{F}$-statistic:** Known sky location, matched filter template grid in freq and spindown, search for peaks over transient map for each point. (used in O2, O3 searches)



$$\mathbf{h}(t;\theta)=\boxed{h(t,\lambda,\mathcal{A},\mathcal{T})}=\boxed{\omega(t;\mathcal{T})}\boxed{h(t,\lambda,\mathcal{A})}$$



- **Others:**
- Semicoherent searches, e.g. Viterbi
- Unmodeled searches, e.g. STAMP
- Machine learning



[Thrane+ 1501.06648]

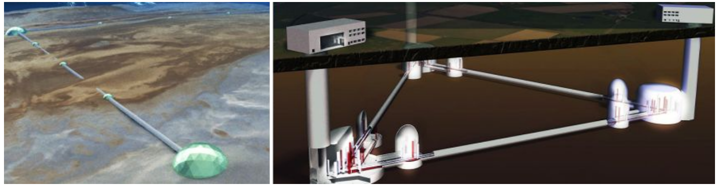
Catalogs of Glitching Neutron Stars

- **EM data**: radio, X- and gamma-ray observations from **Jodrell** and **ATNF** glitch catalogs, combined with data from ATNF pulsar catalog

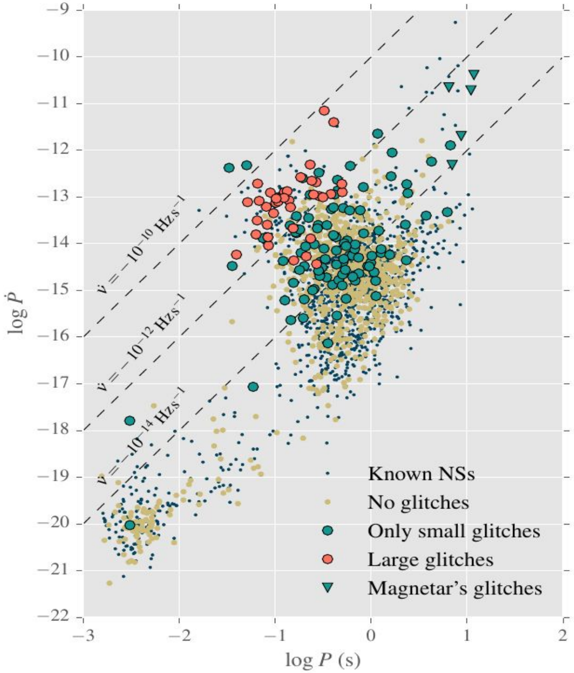
Jodrell catalog

ATNF catalog

- **GW detectors**: Expected sensitivity of current and future detectors (aLIGO, Einstein Telescope and Cosmic Explorer)



- **Population** of glitching pulsars:



[Fuentes+ 1710.00952]

Observed Population of Glitching Pulsars [Ashton+ 1704.00742]

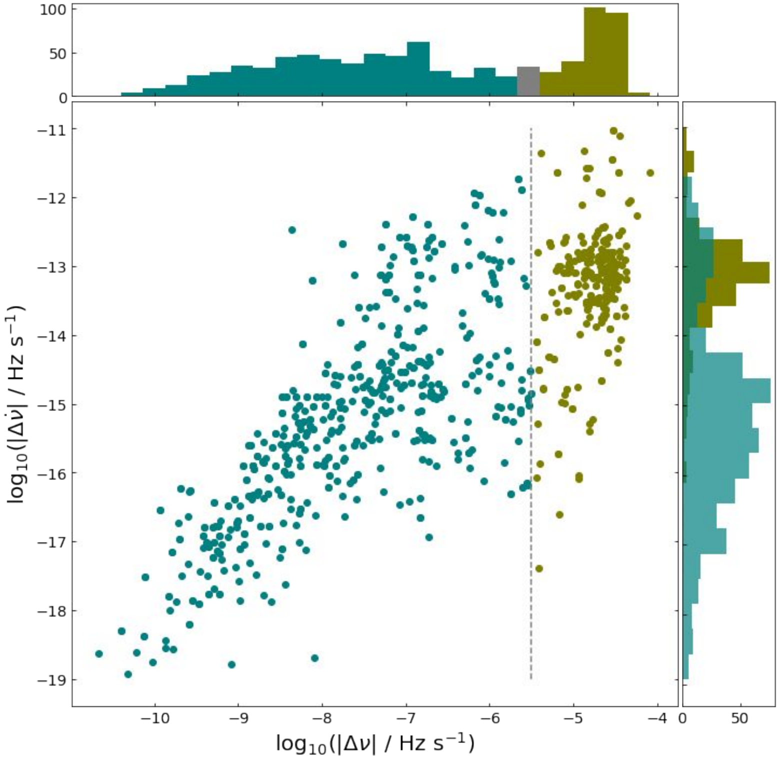
- Two groups of glitching pulsars.

- **Bimodal gaussian distribution** of the glitch sizes: “Crab-like” and “Vela-like” glitches.

- Ashton+2017: **$\Delta\nu = 10^{-5.5}$** as division for both kinds of glitches, from a Gaussian Mixture Model.

- Vela-like glitches have also bigger changes on 1st order spindown than Crab-like pulsars.

- But no relation between original spindown of the pulsar and glitch size or change on spindown.



Prospects of Beating Indirect ULs

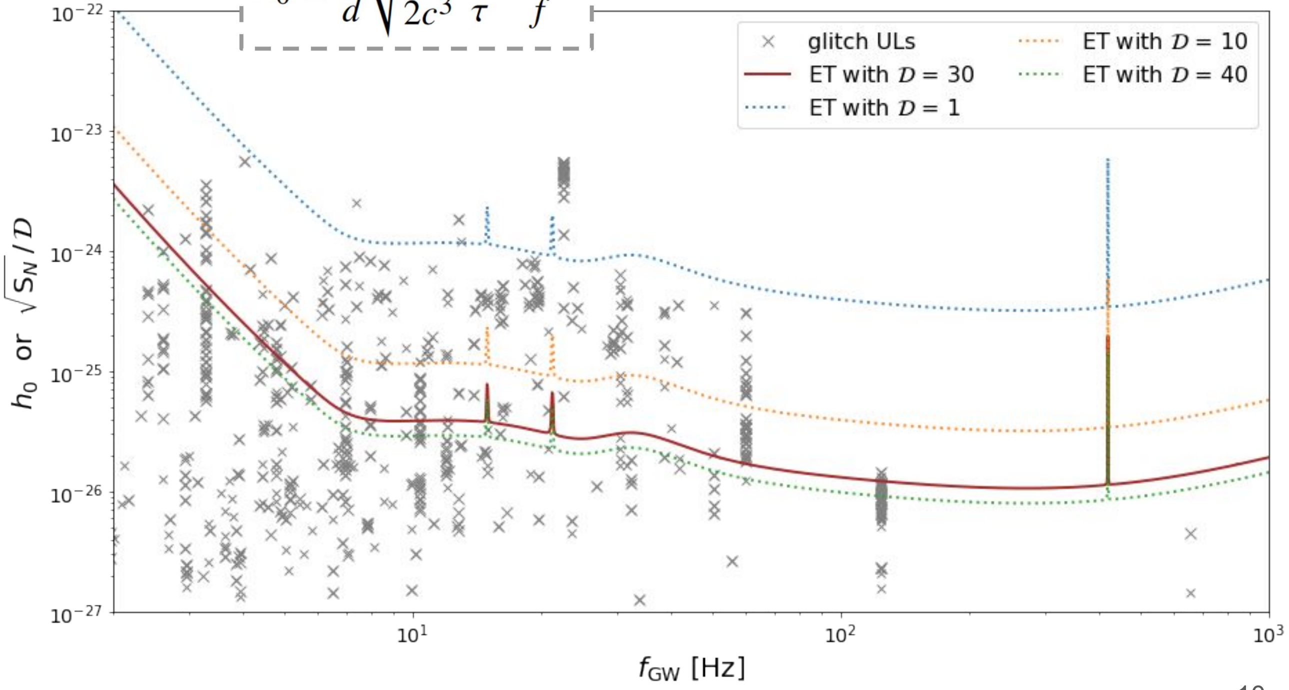
- Sensitivity depth:

$$\mathcal{D} = \frac{\sqrt{S_n}}{h_0}$$

[Dreissigacker+2018]

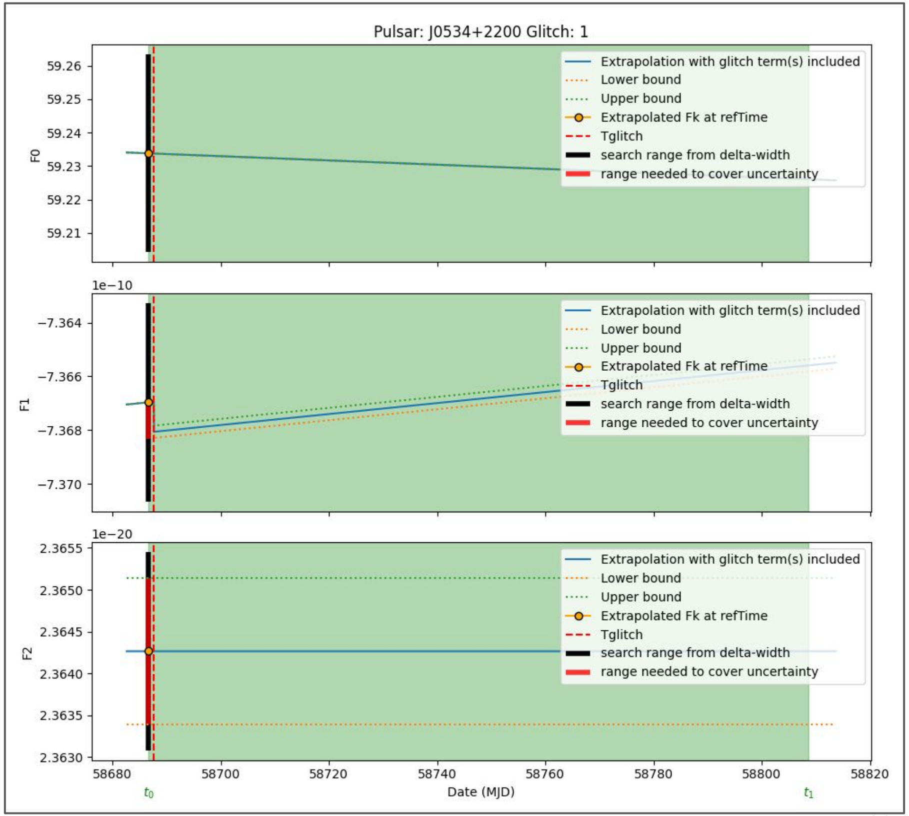
- Depth increases with τ, but also the upper limits of h0 get worse: the whole plot rescales and we achieve the same detectability.

$$h_0 \leq \frac{1}{d}\sqrt{\frac{5G}{2c^3}\frac{I_z}{\tau}\frac{|\Delta f|}{f}}$$



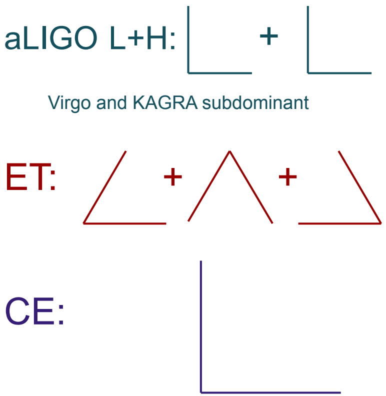
Prospects of Beating Indirect ULs

- Determining the depth factor:
- Find the number of templates for search setup like [arXiv:2112.10990] that both a Crab-like and Vela-like search would need.
- Create fake noise-only distribution with that number of templates.
- Determine the threshold of this distribution with distromax method. [Tenorio+2022].
- Assume a detector network and duty factor of 66% and find sensitivity depth [Dreissigacker+2018].
- H1L1 case: Found 27.5 for Vela, 29 for Crab, use rounded 28.5 for both in plots.



Prospects of Beating Indirect ULs

$$h_0 \leq \frac{1}{d}\sqrt{\frac{5G}{2c^3}\frac{\mathcal{I}}{\tau}\frac{\Delta f_{\mathrm{gl}}}{f}}$$

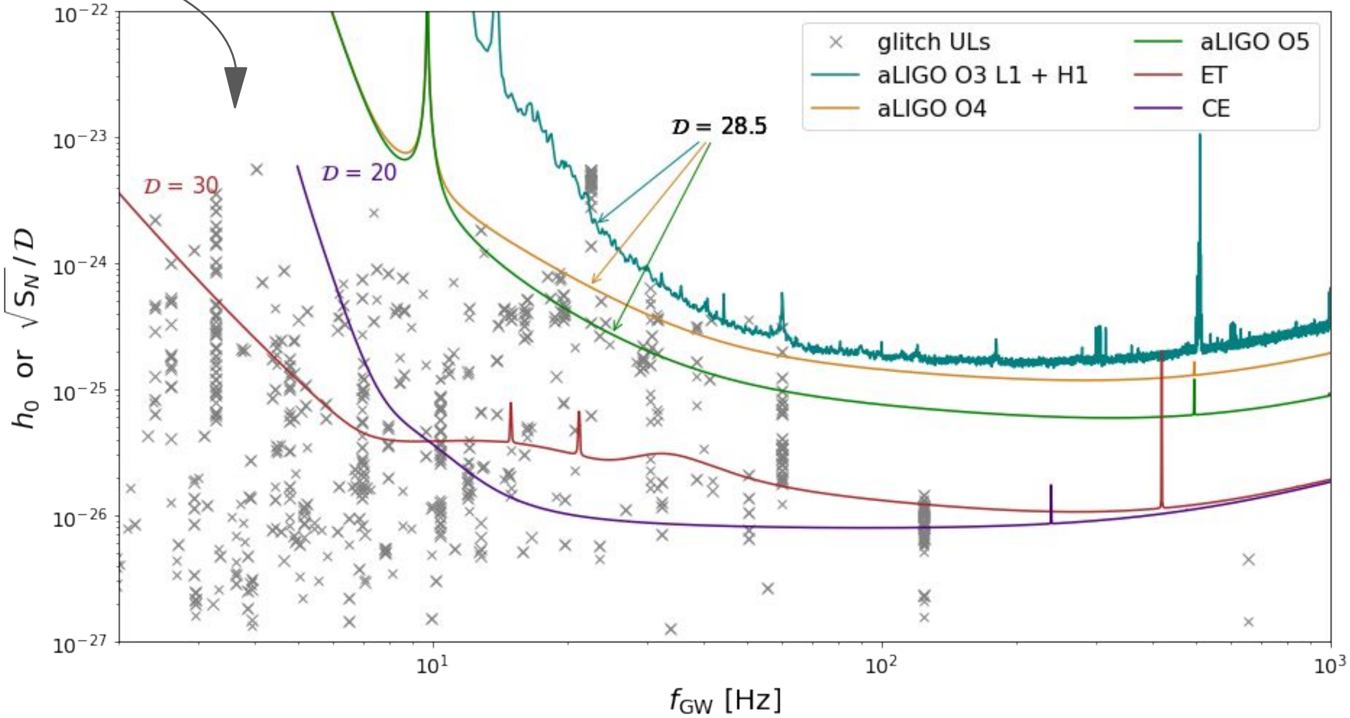


aLIGO L+H:

Virgo and KAGRA subdominant

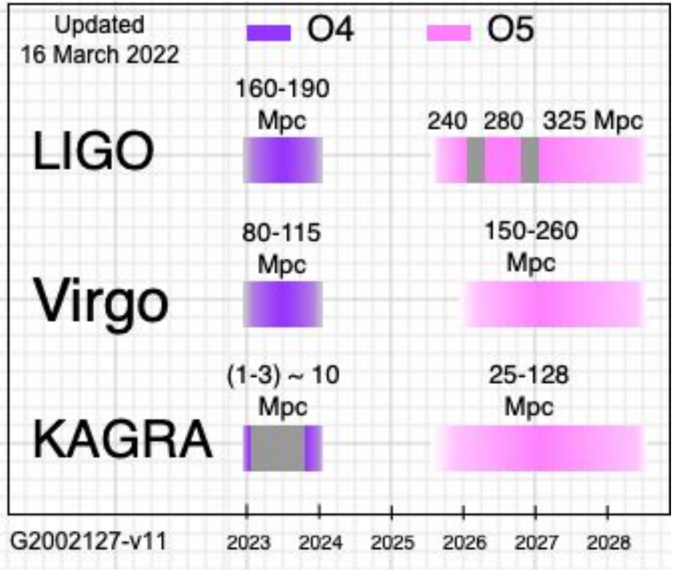
ET:

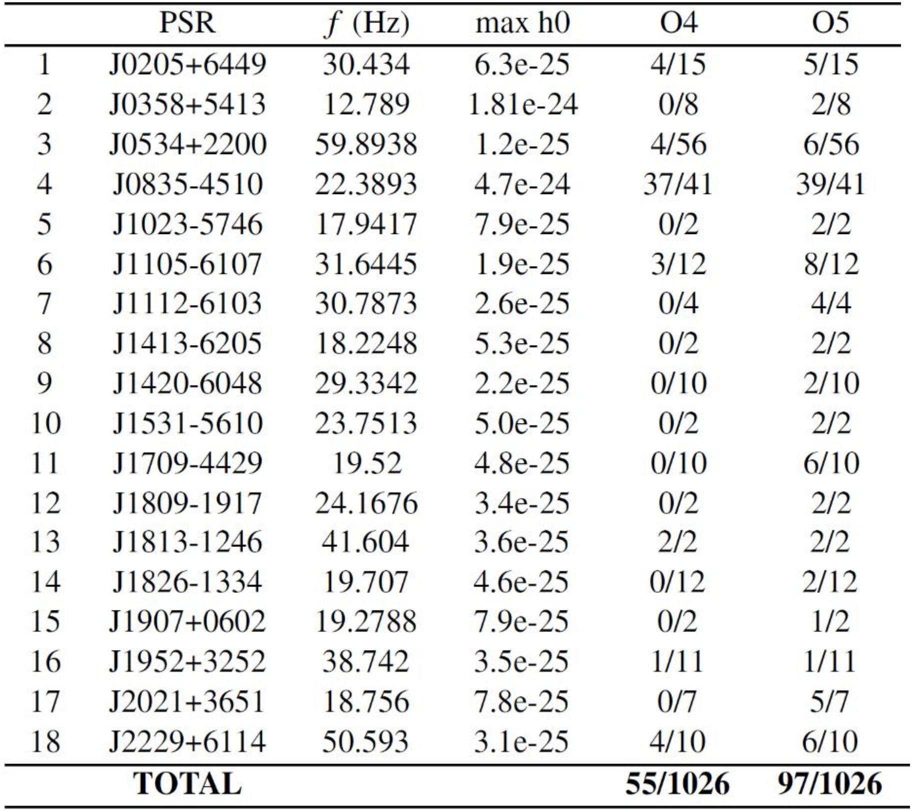
CE:



Prospects of Beating Indirect Glitch ULs

All known pulsars for which indirect glitch ULs could be beaten in future 2G runs.

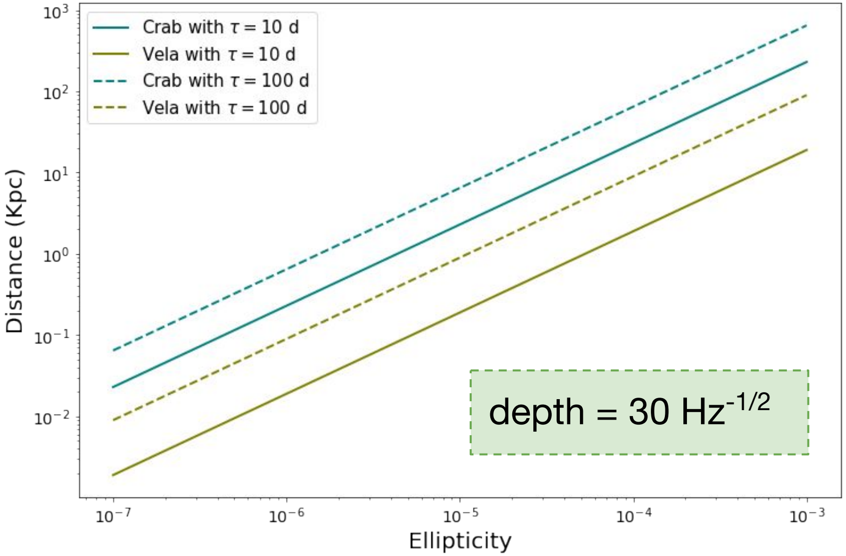


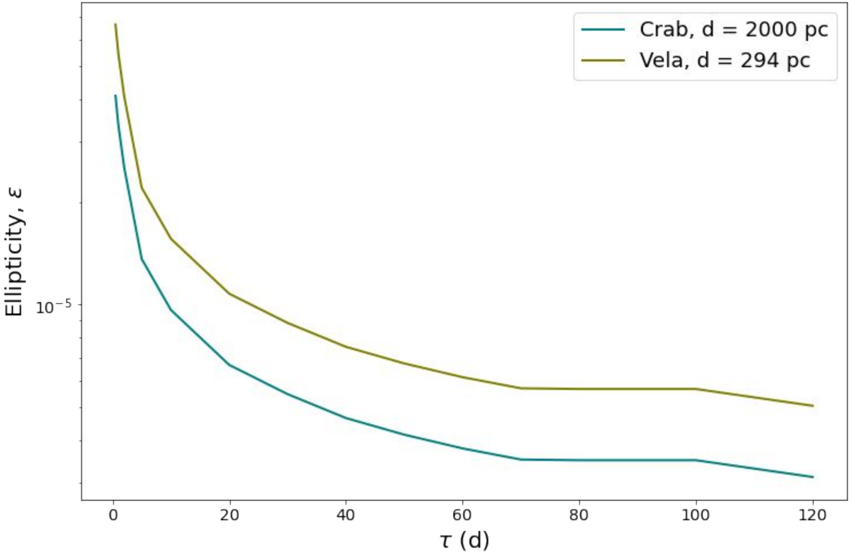


	PSR	f (Hz)	max h0	O4	O5
1	J0205+6449	30.434	6.3e-25	4/15	5/15
2	J0358+5413	12.789	1.81e-24	0/8	2/8
3	J0534+2200	59.8938	1.2e-25	4/56	6/56
4	J0835-4510	22.3893	4.7e-24	37/41	39/41
5	J1023-5746	17.9417	7.9e-25	0/2	2/2
6	J1105-6107	31.6445	1.9e-25	3/12	8/12
7	J1112-6103	30.7873	2.6e-25	0/4	4/4
8	J1413-6205	18.2248	5.3e-25	0/2	2/2
9	J1420-6048	29.3342	2.2e-25	0/10	2/10
10	J1531-5610	23.7513	5.0e-25	0/2	2/2
11	J1709-4429	19.52	4.8e-25	0/10	6/10
12	J1809-1917	24.1676	3.4e-25	0/2	2/2
13	J1813-1246	41.604	3.6e-25	2/2	2/2
14	J1826-1334	19.707	4.6e-25	0/12	2/12
15	J1907+0602	19.2788	7.9e-25	0/2	1/2
16	J1952+3252	38.742	3.5e-25	1/11	1/11
17	J2021+3651	18.756	7.8e-25	0/7	5/7
18	J2229+6114	50.593	3.1e-25	4/10	6/10
	TOTAL			**55/1026**	**97/1026**

Distance and Ellipticity Constraints (ET)

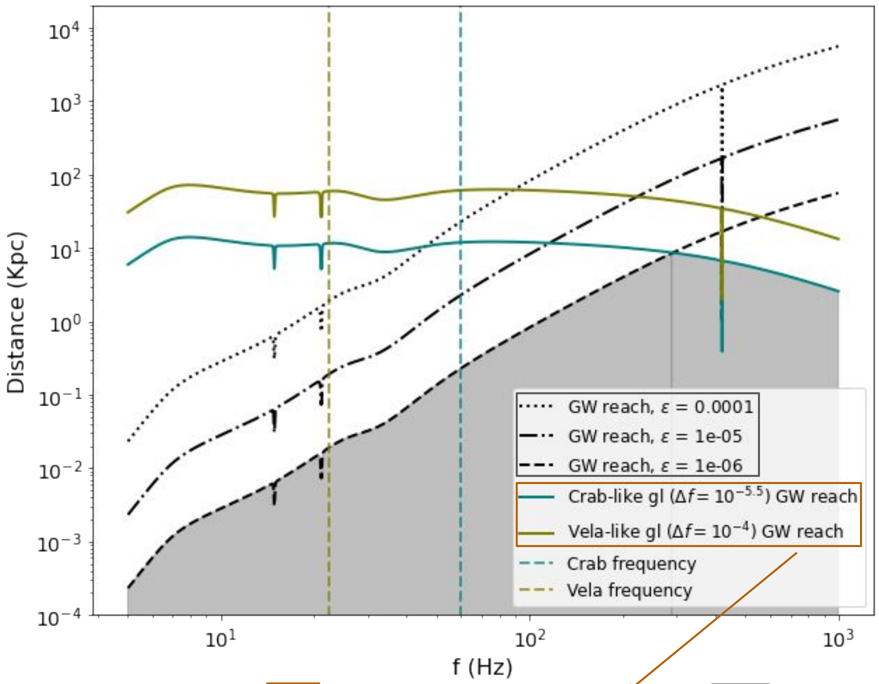
Actual frequencies for Crab and Vela

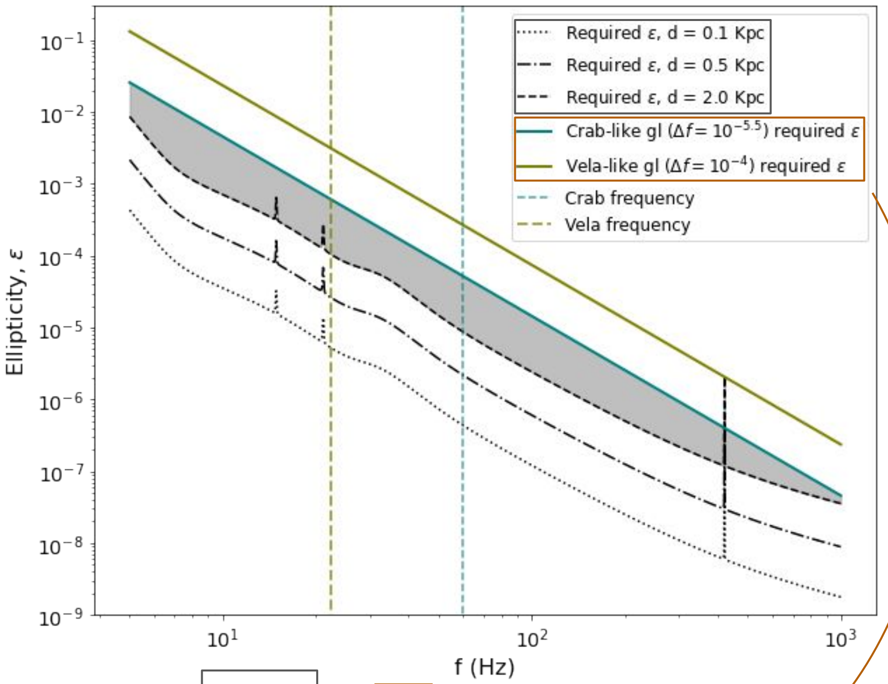




$$h_0(t) = \frac{4\pi^2 G}{c^4} \frac{I f^2}{d} \epsilon(t)$$

Distance and Ellipticity Constraints (ET)





1

$$h_0 \leq \frac{1}{d}\sqrt{\frac{5G}{2c^3}\frac{\mathcal{I}}{\tau}\frac{\Delta f_{\rm gl}}{f}}$$

2

$$h_0(t) = \frac{4\pi^2 G}{c^4}\frac{If^2}{d}\epsilon(t)$$

1 = 2 → **3**

$$\epsilon = \sqrt{\frac{5c^5}{32\pi^4 G I_z \tau}\frac{\Delta f}{f^5}}$$

Acknowledgements

Thank you for listening!

joan.moragues@uib.cat | luana.modafferi@ligo.org | david.keitel@ligo.org

JM and LMM are supported by the Universitat de les Illes Balears.
DK is supported by the Spanish Ministerio de Ciencia, Innovación y Universidades (ref. BEAGAL 18/00148) and cofinanced by the Universitat de les Illes Balears.
We acknowledge support by European Union FEDER funds; the Spanish Ministerio de Ciencia e Innovación and the Spanish Agencia Estatal de Investigación grants No. PID2019-106416GB-I00/AEI/MCIN/10.13039/501100011033, RED2018-102661-T, RED2018-102573-E; the Comunitat Autònoma de les Illes Balears through the Conselleria de Fons Europeus, Universitat i Cultura and the Direcció General de Política Universitaria i Recerca with funds from the Tourist Stay Tax Law ITS 2017-006 (No. PRD2018/24, No. PRD2020/11); the Generalitat Valenciana (No. PROMETEO/2019/071); and EU COST Actions CA18108, CA17137, CA16214, and CA16104.

Unión Europea

Fondo Europeo
de Desarrollo Regional
“Una manera de hacer Europa”

[redacted]

Threshold setting: `distromax` method [Tenorio+ 2111.12032]

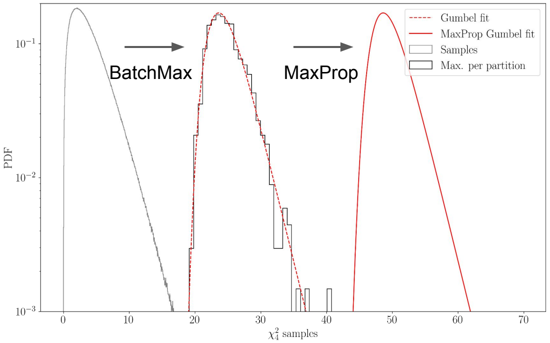
Let us consider the resulting *N* detection-statistic values from evaluating a template bank on a datastream (i.e. what one would call “search results”).

- BatchMax step:
  - Split the *N* results into *B* batches containing *n* elements each. (*N* = *B* * *n*)
  - Retrieve the maximum from each batch and fit a **Gumbel distribution** to the histogram.
  - The resulting distribution is that of the loudest candidate over *n* templates.

$$\mathrm{Gumbel}(\circ; \mu, \sigma) = \frac{1}{\sigma} e^{-(z + e^{-z})}$$

where $z = \frac{\circ - \mu}{\sigma}$

- MaxProp step:
  - The loudest candidate over the *N* (possibly correlated) samples is the loudest candidate over *B* independent BatchMax samples.
  - Let us call the step from *n* to *N* the max-propagation operator (MaxProp).
  - But **Gumbel is max-stable**: Just add two numbers!



$$\mathrm{MaxProp}_B f(x) = B f(x) \left[\int^x \mathrm{d}x' f(x') \right]^{B-1}$$

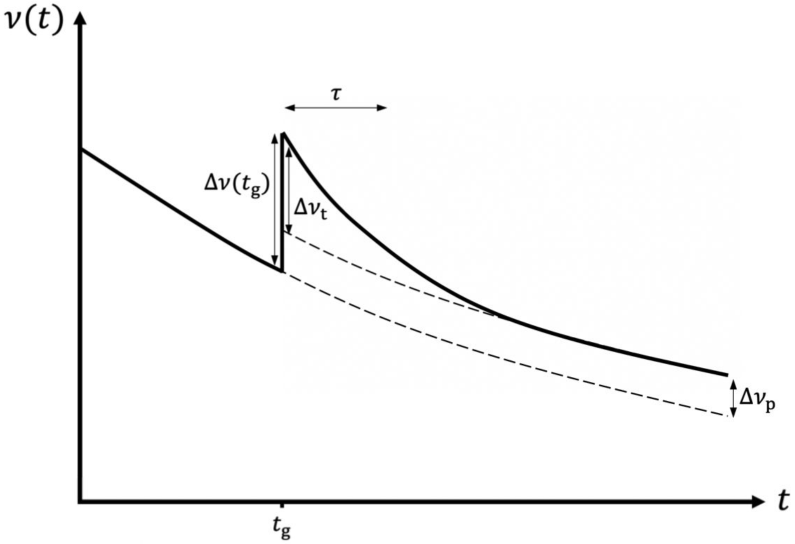
for Gumbel it’s easy:

$$\mathrm{MaxProp}_B \mathrm{Gumbel}(\circ; \mu_n, \sigma_n) = \mathrm{Gumbel}(\circ; \mu_*, \sigma_*)$$

$$\mu_* = \mu_n + \sigma_n \ln B \,,$$

$$\sigma_* = \sigma_n \,.$$

Glitch Recovery and Transient Mountains



Yim & Jones

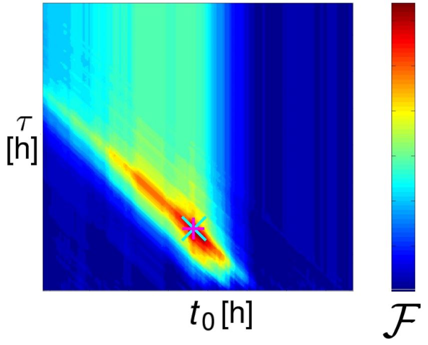
2007.05893

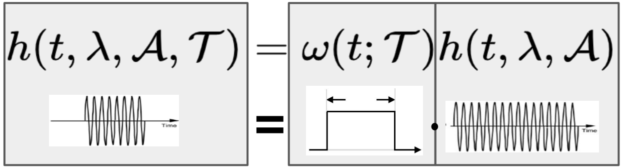
- simple model: mountain forms *at* glitch, causes recovery through external torque, slowly dissipates again
- key parameter: "healing" $Q \equiv \frac{\Delta\nu_t}{\Delta\nu(t_g)}$
- same energy and SNR for large glitches with small recovery or small glitches with large recovery
- GW signal duration linked to EM-observed recovery time: ~24 d for Crab and ~298 d for Vela (exponential decay times)

- If instead buildup of a mountain *causes* the glitch, would expect much shorter signals (e.g. ~400 s for Vela).

Search Methods for Long-Duration Transients

- **Transient $\mathcal{F}$-statistic:** Known sky location, template grid in freq and spindown, search for peaks over transient map for each point.





$$\mathbf{h}(t;\theta) = \boxed{h(t,\lambda,\mathcal{A},\mathcal{T})} = \boxed{\omega(t;\mathcal{T})}\boxed{h(t,\lambda,\mathcal{A})}$$

- **STAMP:** For very long-lived transient GWs. Unmodeled, without imposed fixed starting time nor waveform model. Analyse spectrogram from cross-correlated data of detectors.
- **Viterbi:** Dynamic programming algorithm based on a hidden Markov model (HMM), identifies seed pixels in spectrogram that lay above a threshold, and add neighboring pixels to create contiguous clusters.
- **Others:** Semicoherent searches and machine learning