Search for long-duration GWs from glitching pulsars during LIGO-Virgo third observing run

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for the LIGO Scientific Collaboration, Virgo Collaboration and KAGRA Collaboration

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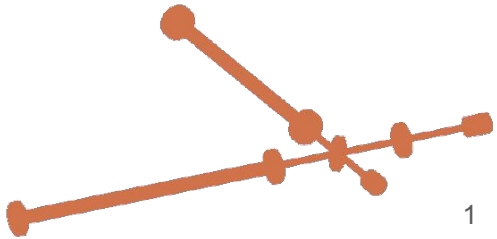

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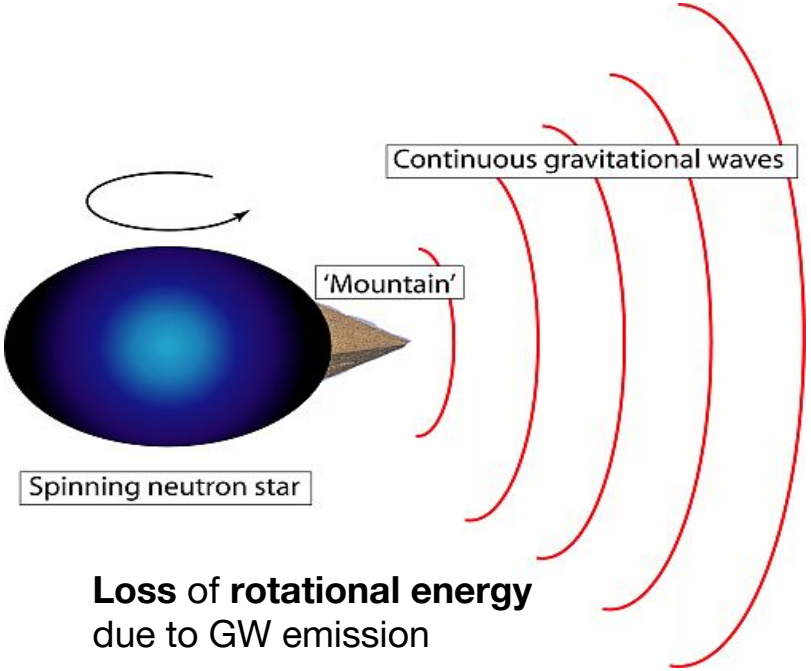
Different Sources of Gravitational Waves

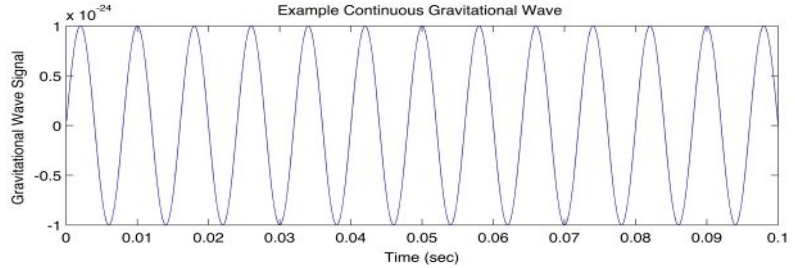
First detection of gravitational waves from a **BBH coalescence** in 2015

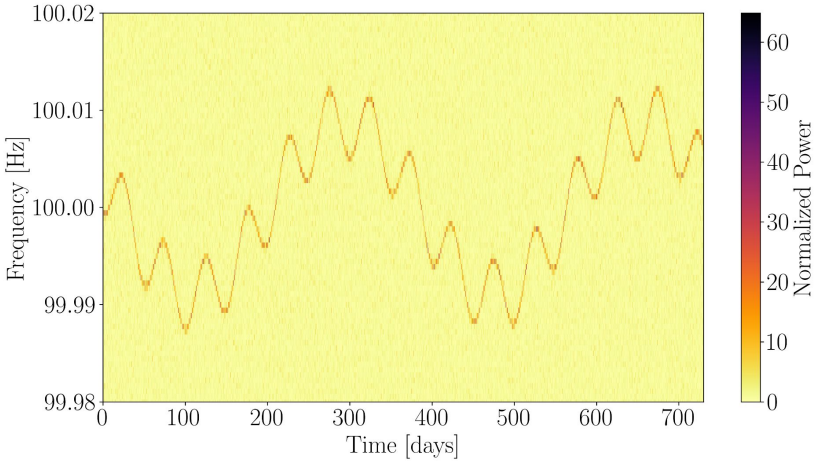
Gravitational waves from **spinning neutron stars**: not yet detected

Gravitational Waves from Pulsars

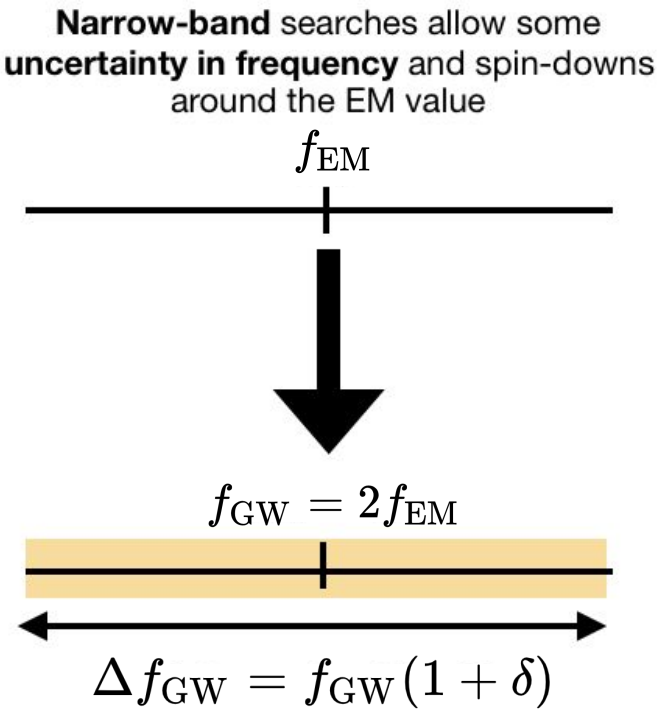


Loss of **rotational energy** due to GW emission





Narrow-band Searches



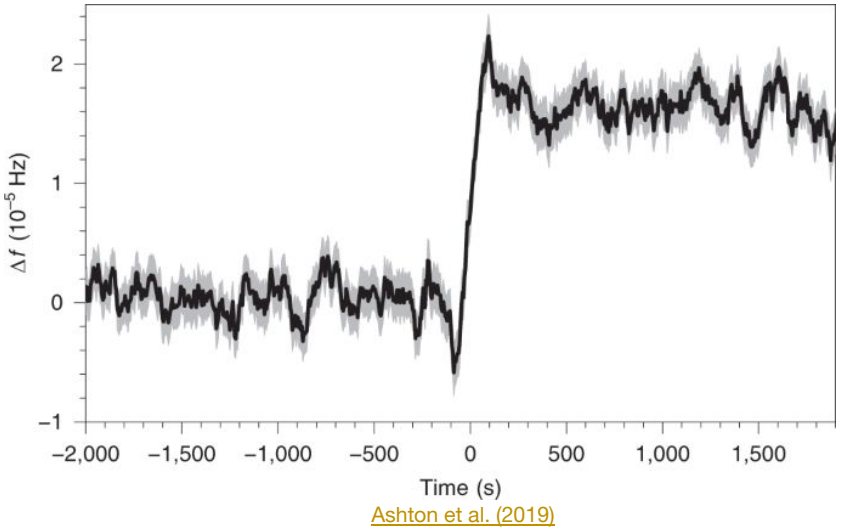
2 main pipelines:

- 5-vector search (used for O2)
  Abbott et at. 2019 [PRD99,122002]
- search using $\mathcal{F}$-stat (new!)

Our contribution to the LVC:

search for ***long-duration transient continuous waves,*** with duration O(hours-months) i.e. in the gap between the burst-like *O(*ms*)* and truly continuous *O(∞)* waves

Astrophysical Motivation: Glitching Neutron Stars

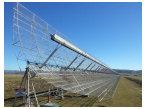


Ashton et al. (2019)

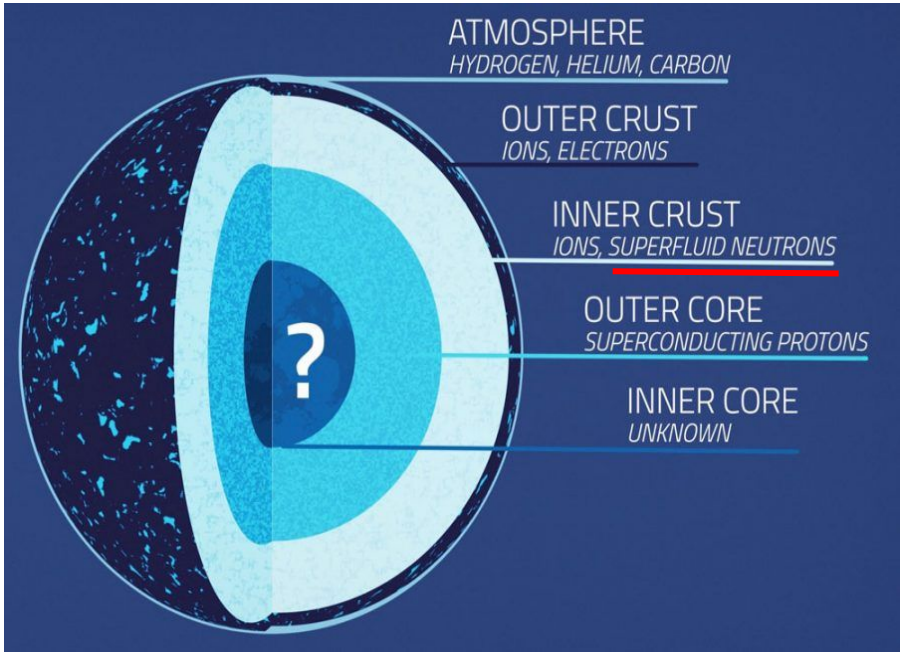
TARGETS (during O3)

J0534+2200 f_{GW} ~ 60 Hz glitched on 2019/07/23	**J0537-6910** f_{GW} ~ 123 Hz 3 glitches in 2019, 1 glitch in 2020	**J0908-4913** f_{GW} ~ 19 Hz glitched ~ 2019/10/09
J1105-6107 f_{GW} ~ 31 Hz glitched ~ 2019/04/09	**J1813-1749** f_{GW} ~ 45 Hz glitched ~ 2019/08/03	**J1826-1334** f_{GW} ~ 20 Hz glitched on 2020/01/31

- **EM data**: radio and X-ray observations from **Jodrell, the ATNF, NICER, UTMOST**
- **GW data**: full **3rd observing run** from the 3 detectors (2 Advanced **LIGO** detectors and **Virgo**), from April 2019 to March 2020, with a break in October 2019

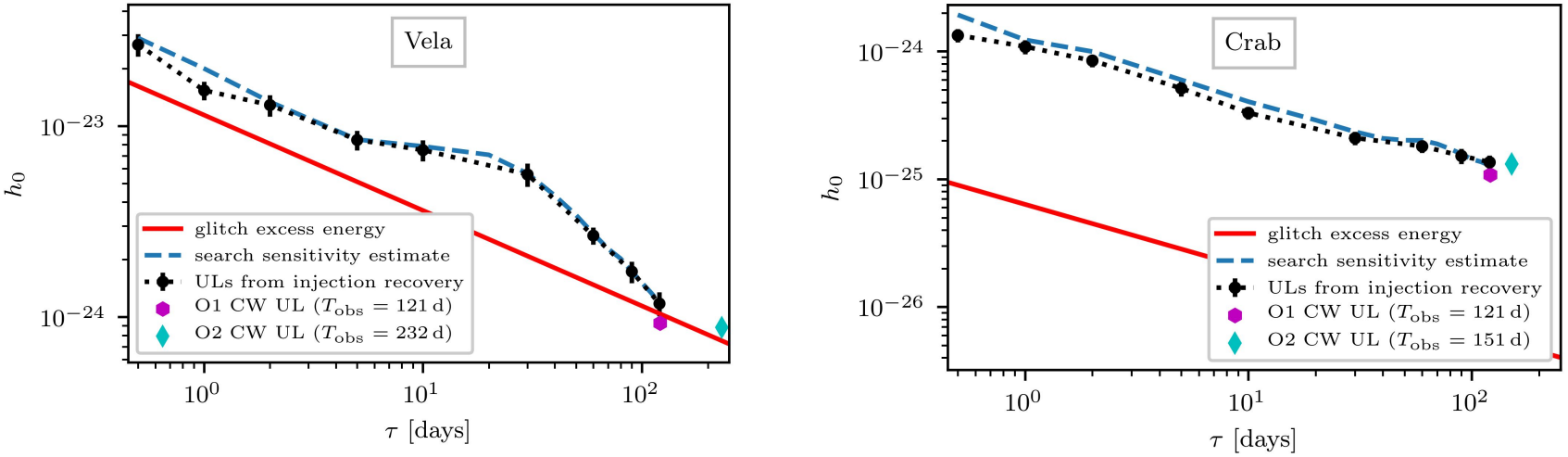
Theory of Pulsar Glitches: Two-Fluid Model



- observed pulses with angular velocity $\boldsymbol{\Omega}$, associated to NS magnetic field and which gradually decreases
- interior neutrons are **superfluid**, forming an independent component that rotates at angular velocity $\boldsymbol{\Omega}_S$
- weak coupling between the two components → growing "lag" $\boldsymbol{\Delta\Omega} = \boldsymbol{\Omega}_S - \boldsymbol{\Omega}$
- when lag reaches a critical value, some sort of instability occurs
- transfer of angular momentum from superfluid to normal fluid → **spin-up** (i.e. *glitch*)
- change in quadrupole moment can cause GWs

Previous GW Glitch Searches

- search for ***short***-*duration transients* (bursts) from Vela's glitch in 2006 Abadie et al. 2010
- search for ***long***-*duration transients* from Vela & Crab glitches during O2 Keitel et al. 2019



We will be using the same procedure as Keitel et al. (2019)

Transient Continuous Waves Model [Prix et al. (2011)]

Similar to CW standard model, but in addition to the **phase** and **amplitude parameters**:

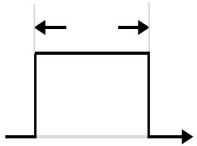
$$\lambda = \{\alpha, \delta, f, \dot{f}, \ddot{f} \dots\}$$
$$\mathcal{A} = \{h_0, \cos\iota, \psi, \phi_o\}$$

we consider a set of **transient parameters**:

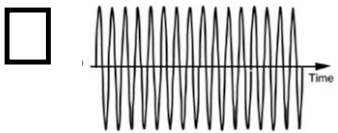
$$\mathcal{T} = \{t_0, \tau\}$$

$$\mathbf{h}(t;\theta)$$

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

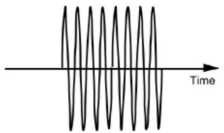


window function



standard CW signal model

=



transient CW!

How Do We Detect These Signals? Prix et al. (2011)

Based on observed data $\mathbf{x}$, we want to decide between 2 hypotheses:

$$\begin{cases} \mathcal{H}_{\mathrm{G}} : \mathbf{x}(t) = \mathbf{n}(t) & \text{data contains only gaussian noise} \\ \mathcal{H}_{\mathrm{S}} : \mathbf{x}(t) = \mathbf{n}(t) + \mathbf{h}(t;\theta) & \text{data contains signal too!} \end{cases}$$

define the likelihoods for each hypothesis… and their ratio

$$\frac{P(\mathbf{x}|\mathcal{H}_{\mathrm{S}},\theta)}{P(\mathbf{x}|\mathcal{H}_{\mathrm{G}})}$$

maximize the likelihood ratio over the parameters θ

$$\ln \mathcal{L}_{\mathrm{ML}}(\mathbf{x}) = \max_{\{\lambda,\mathcal{T}\}} \mathcal{F}(\mathbf{x};\lambda,\mathcal{T})$$

The "$\mathcal{F}$- statistic"

Search Method

- **select target** of known sky coordinates
- place a **template grid** in $f, \dot{f}, \ddot{f} \ldots$ space
- compute $\mathcal{F}$-statistic map for each point in the space:

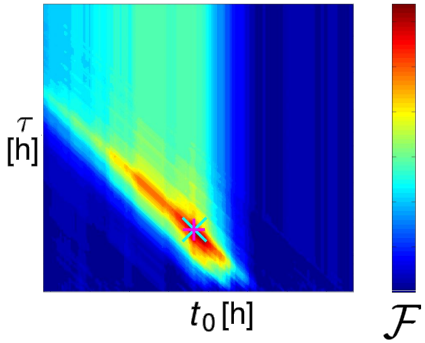
$$\mathcal{F}_{mn} = \mathcal{F}(\lambda, t_{0m}, \tau_n)$$

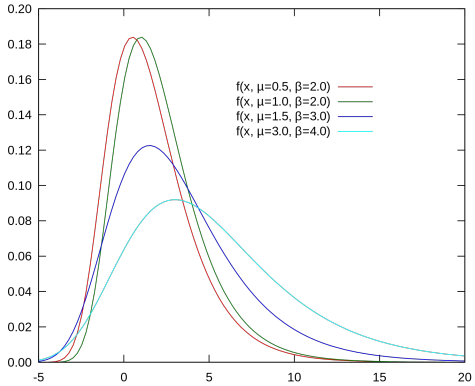
- search for **peaks** over the $(f, \dot{f}, \ddot{f}, \mathcal{T})$ space
- get **detection threshold** from the Gumbel distribution, the expected distribution in the absence of a signal:

used in Generalized Extreme Value Theory to model the **distribution of the maximum** of a number of samples: exactly what we need!

$$p(\max_{\{\lambda, \mathcal{T}\}} \mathcal{F}; \mu, \beta) = \frac{1}{\beta} e^{-(z+e^{-z})}$$

where $z = \dfrac{\max \mathcal{F} - \mu}{\beta}$





Tenorio, Keitel & Sintes, 2021
Tenorio, Modafferi, Keitel & Sintes, in prep

Search Setup

$(f, \dot{f}, \ddot{f} \ldots)$

- **narrow-band approach**: allow mismatch between the true GW and its nominal value
- **frequency band** Δf = maximum between glitch size, frequency uncertainty and $f \cdot 10^{-3}$
- **template bank**: square grid in $(f, \dot{f}, \ddot{f} \ldots)$ where the number of spindowns depends on the ephemerides

$\mathcal{T} = t_0, \tau$

- search for transients **starting** in a window centered at the glitch time with width ΔT_{glitch}
- **duration** of transients up to **4 months**
- window function: rectangular

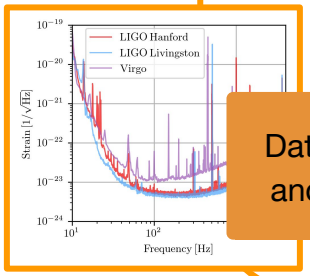
Search Procedure

For each target

Split data into 1800s long Short Fourier transforms (SFTs)

Grid Setup

Data quality studies and cleaning stage

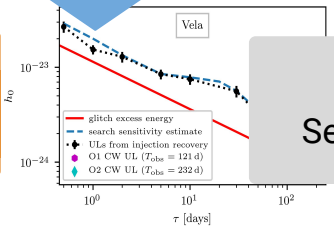


Run F-stat search

Interesting outliers?

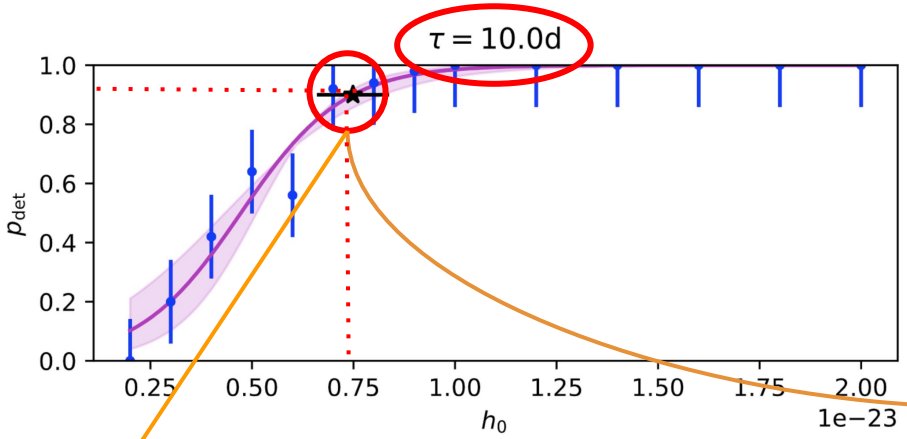
Yes: Follow-up

No: Set Upper Limits

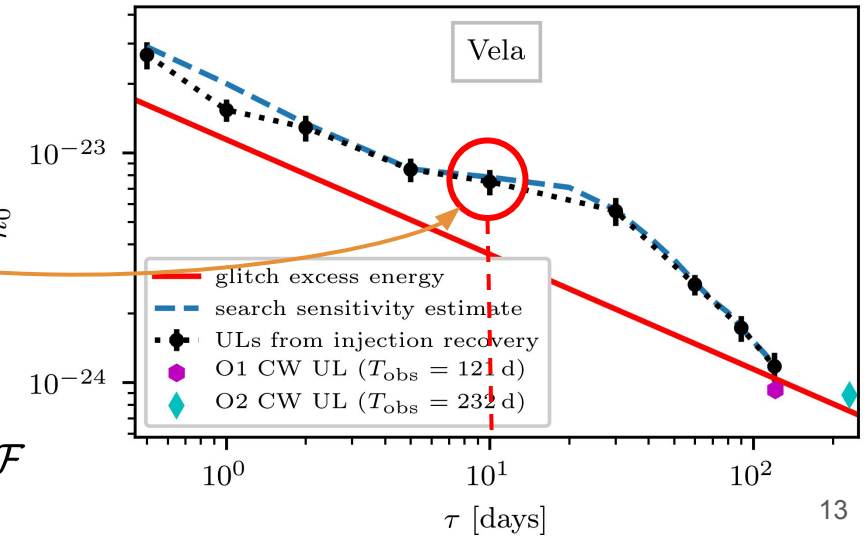


Upper Limits Procedure (example from O2)

- Software injections of simulated signals at different durations τ



repeat for multiple τ



h_0^{90} = required scale of the strain at which 90% of the signals are recovered above the threshold on $\mathcal{F}$

Acknowledgements

Thank you for listening!

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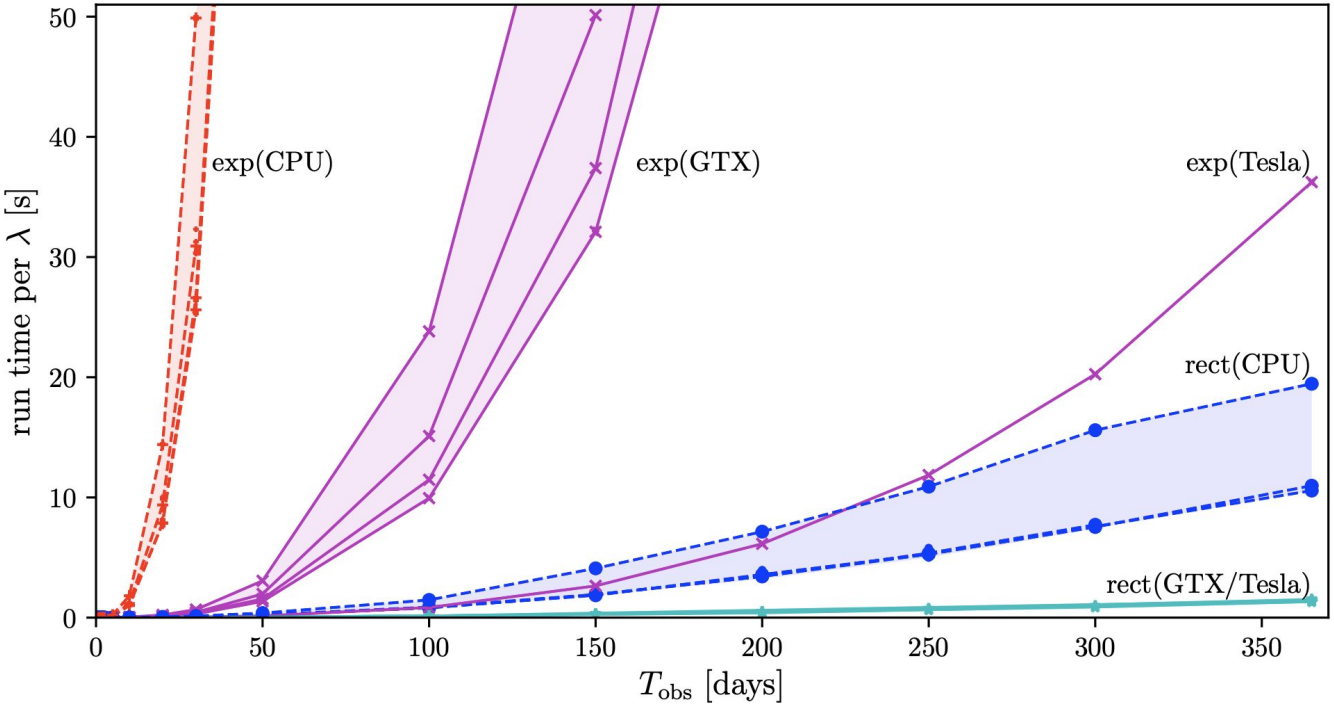
Rectangular vs Exponential Window



Timing results for both rectangular and exponential transient windows, from CPU and GPU implementations on various devices.

Keitel & Ashton, 2018