High priority transient continuous gravitational wave targets from glitching pulsars

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Contents

Motivation:
- O4 run is underway
- Not yet observed a continuous gravitational wave (CW) signal

Objectives:
- Compare different pulsar glitch models
- Create a list of high priority targets

Part I - Energy budgets from pulsar glitches

Part II - Gravitational wave signal analysis

Part III - Results

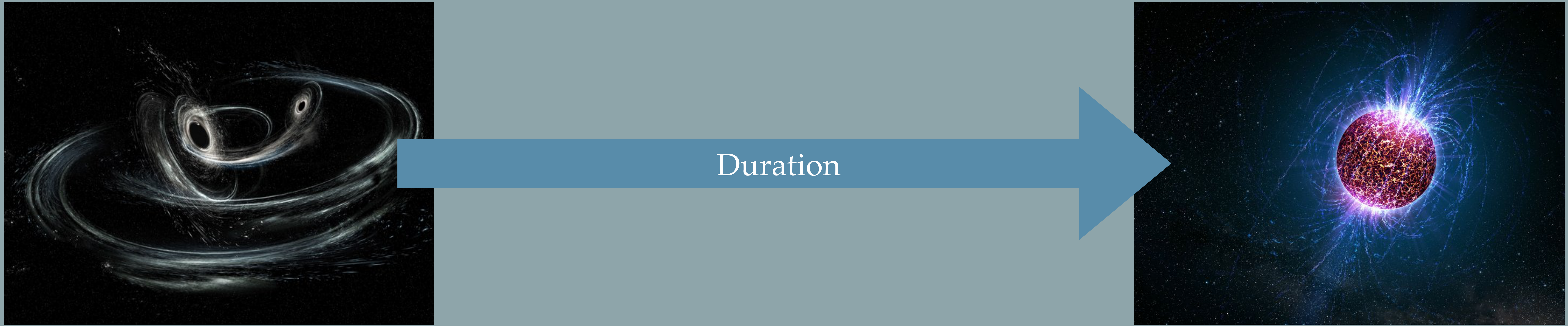
Part IV - Summary

Part I - Energy budgets from pulsar glitches

Transient continuous waves

Duration = $\mathcal{O}$(Minutes)

Duration $\gg$ Observation time



Transient continuous waves

Transient Continuous Waves

$$h(t) = \varpi(t; t_0, T_{GW}) h_{CW}(t)$$

$\mathcal{O}$(Minutes) < Duration < $\mathcal{O}$(Months)

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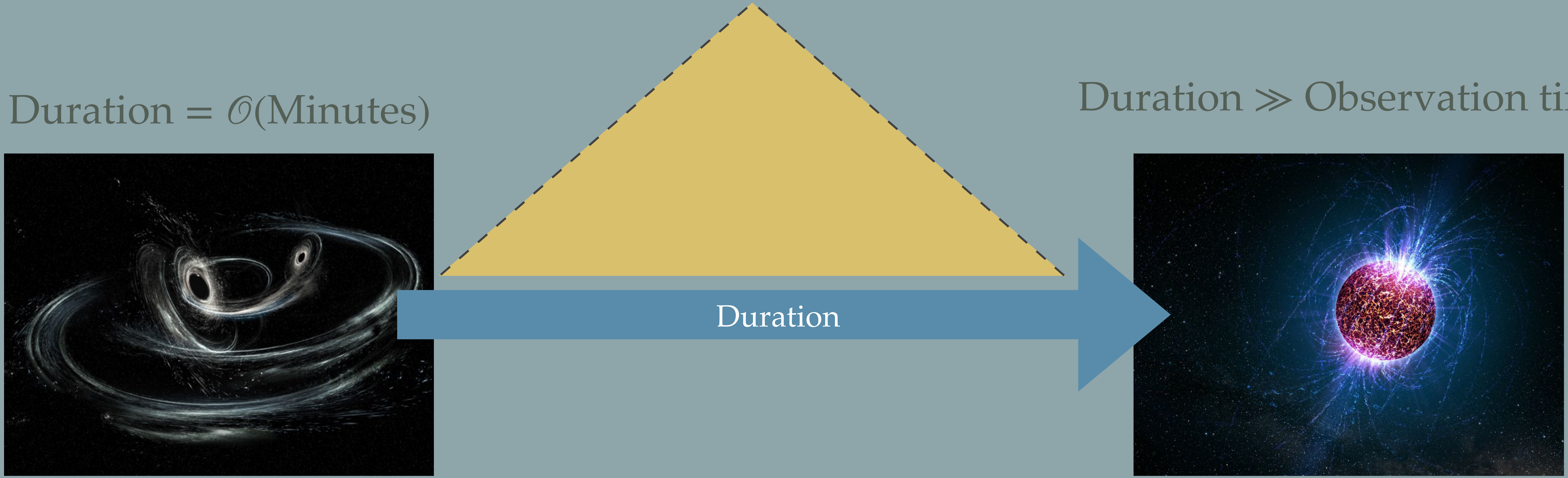
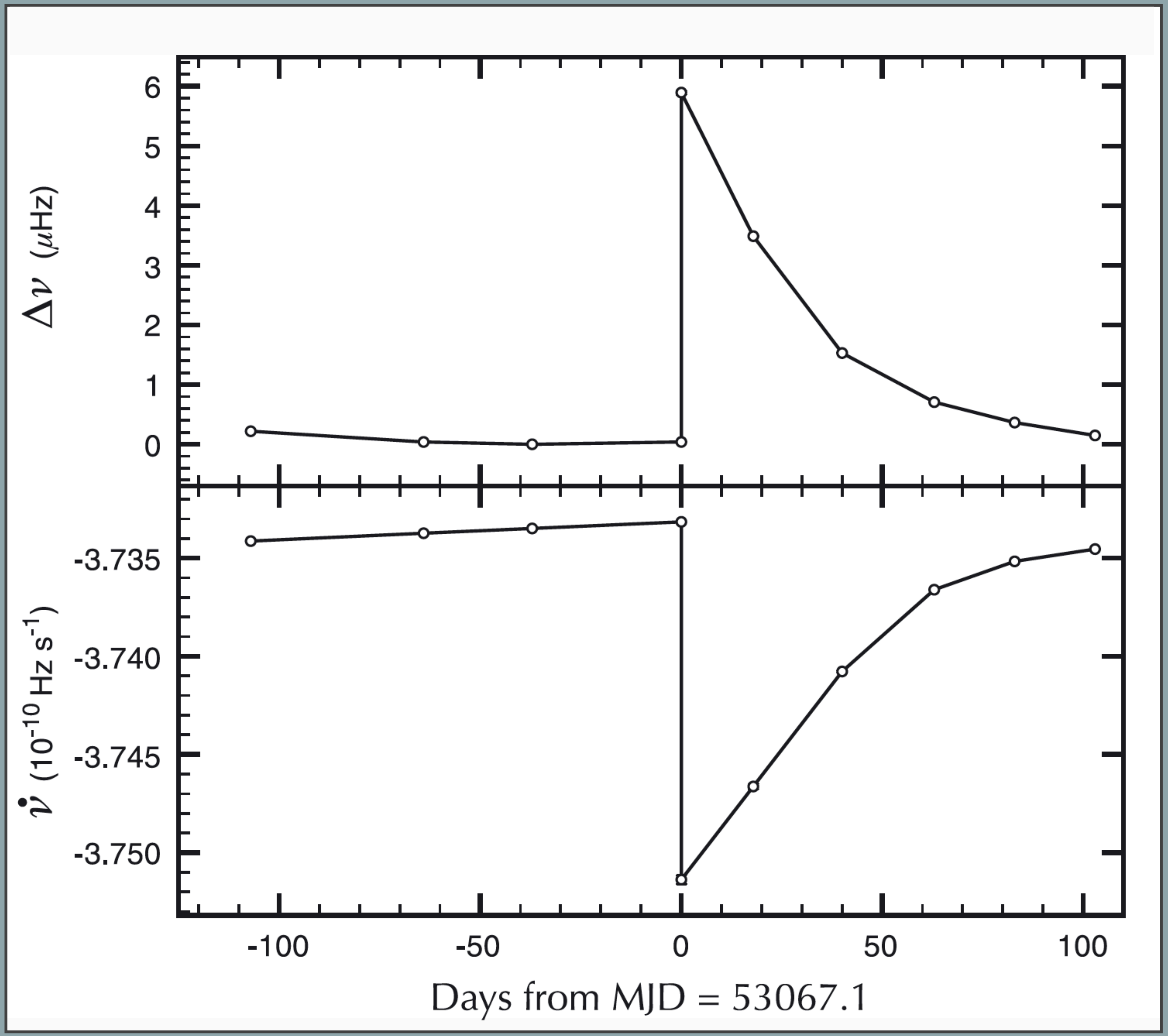
Duration $\gg$ Observation time



Pulsar glitches



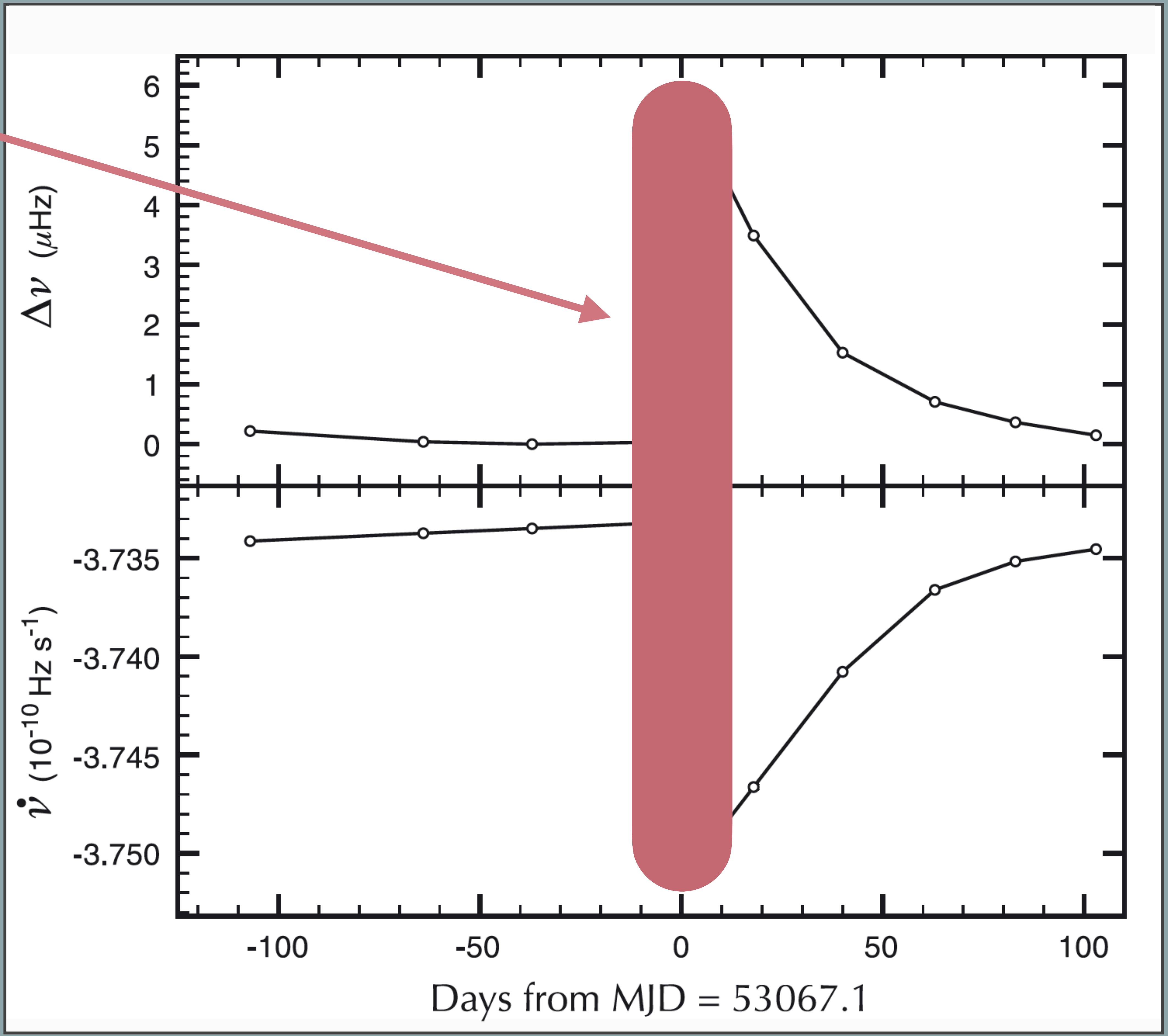
Credit: Espinoza et al. (2011)

Pulsar glitches

"Glitch rise" models

Model 1: Starquake (one component)

Model 2: Superfluid vortex unpinning (two components)



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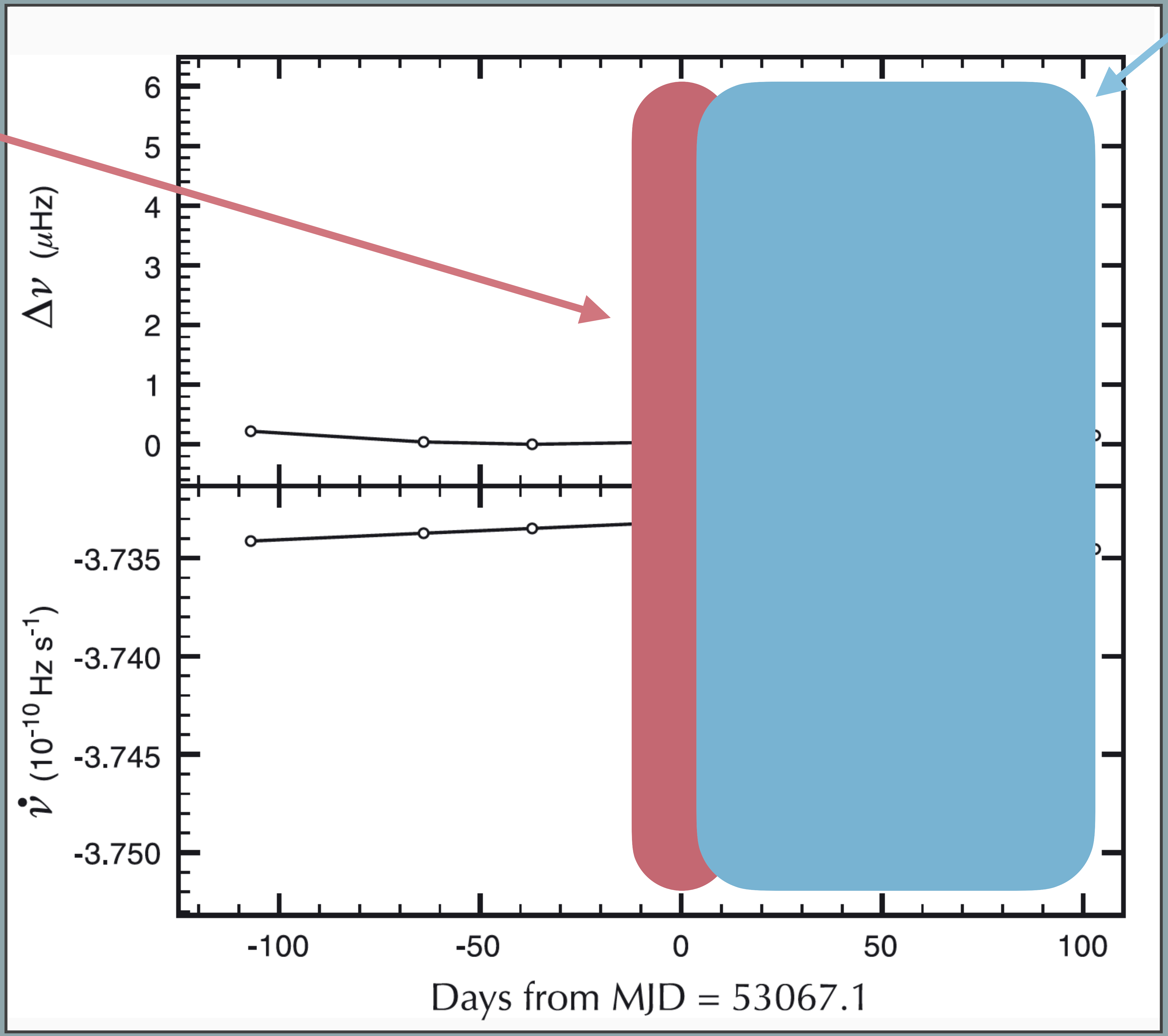

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"Postglitch" models

Model 3: Transient mountain

Model 4: Ekman pumping

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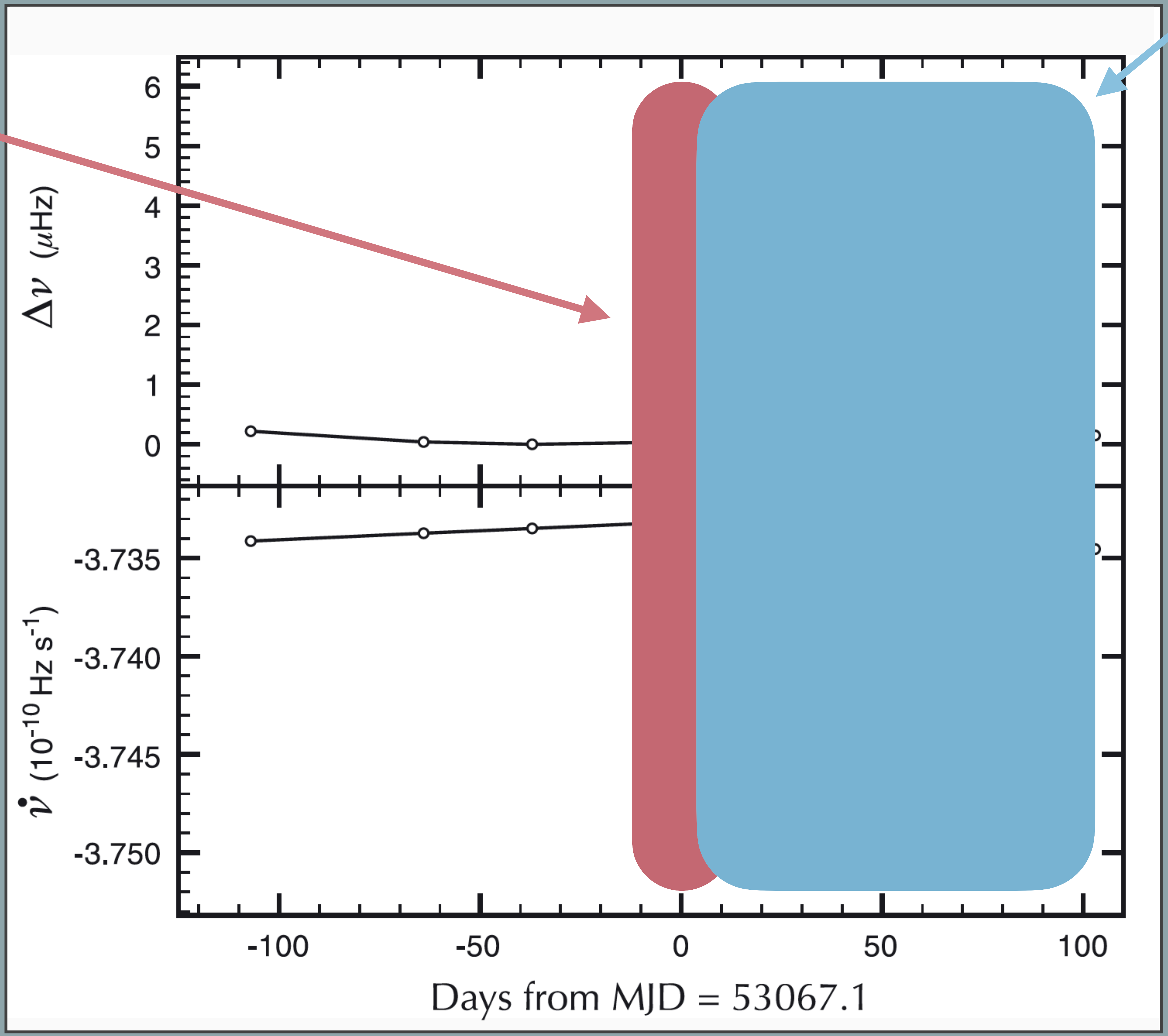

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Postglitch models are agnostic to what causes the spin-up. Glitch models attempt to explain the spin-up.

Pulsar glitches

+2 "naïve" models, one each for one- and two- component neutron stars

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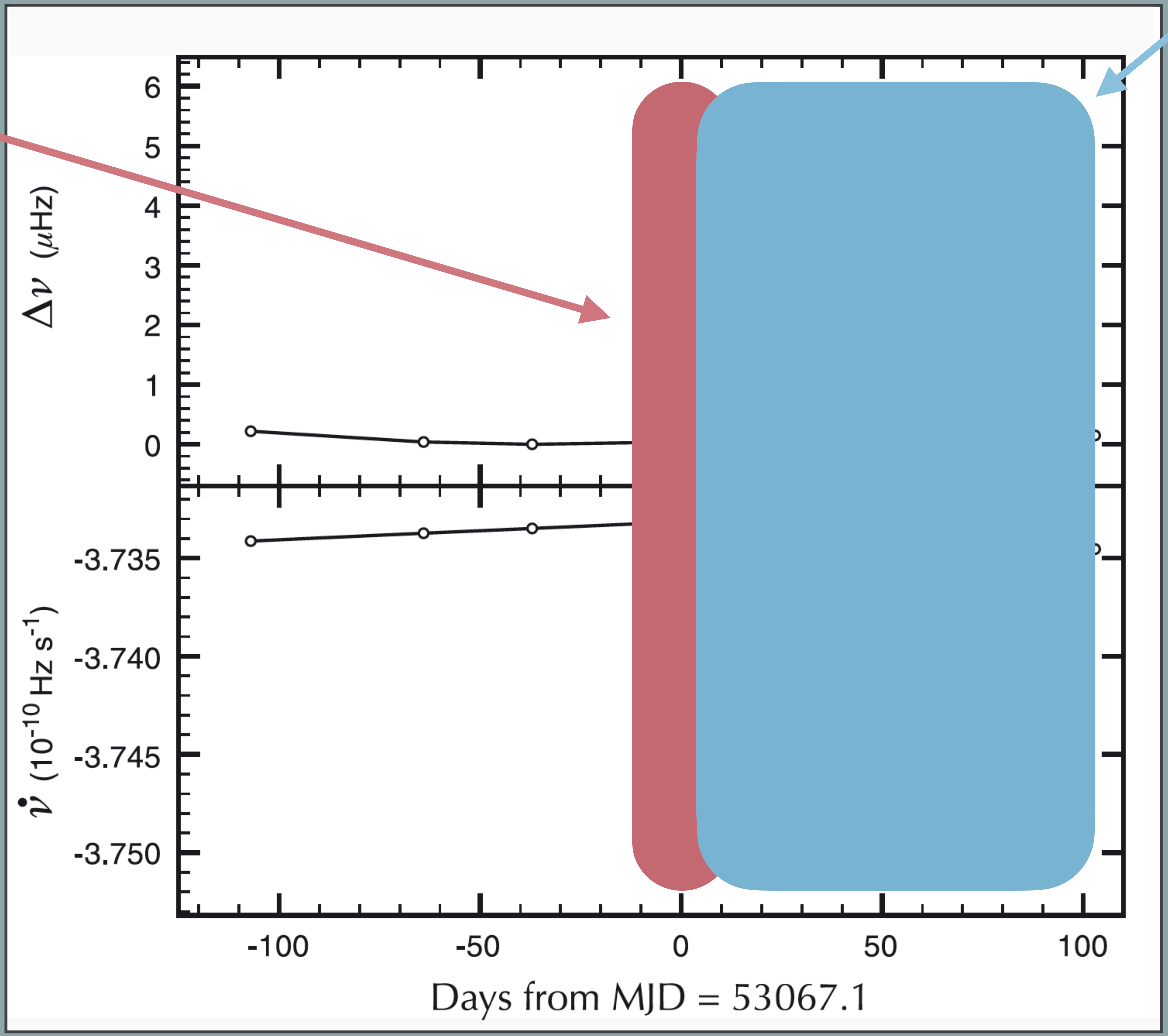

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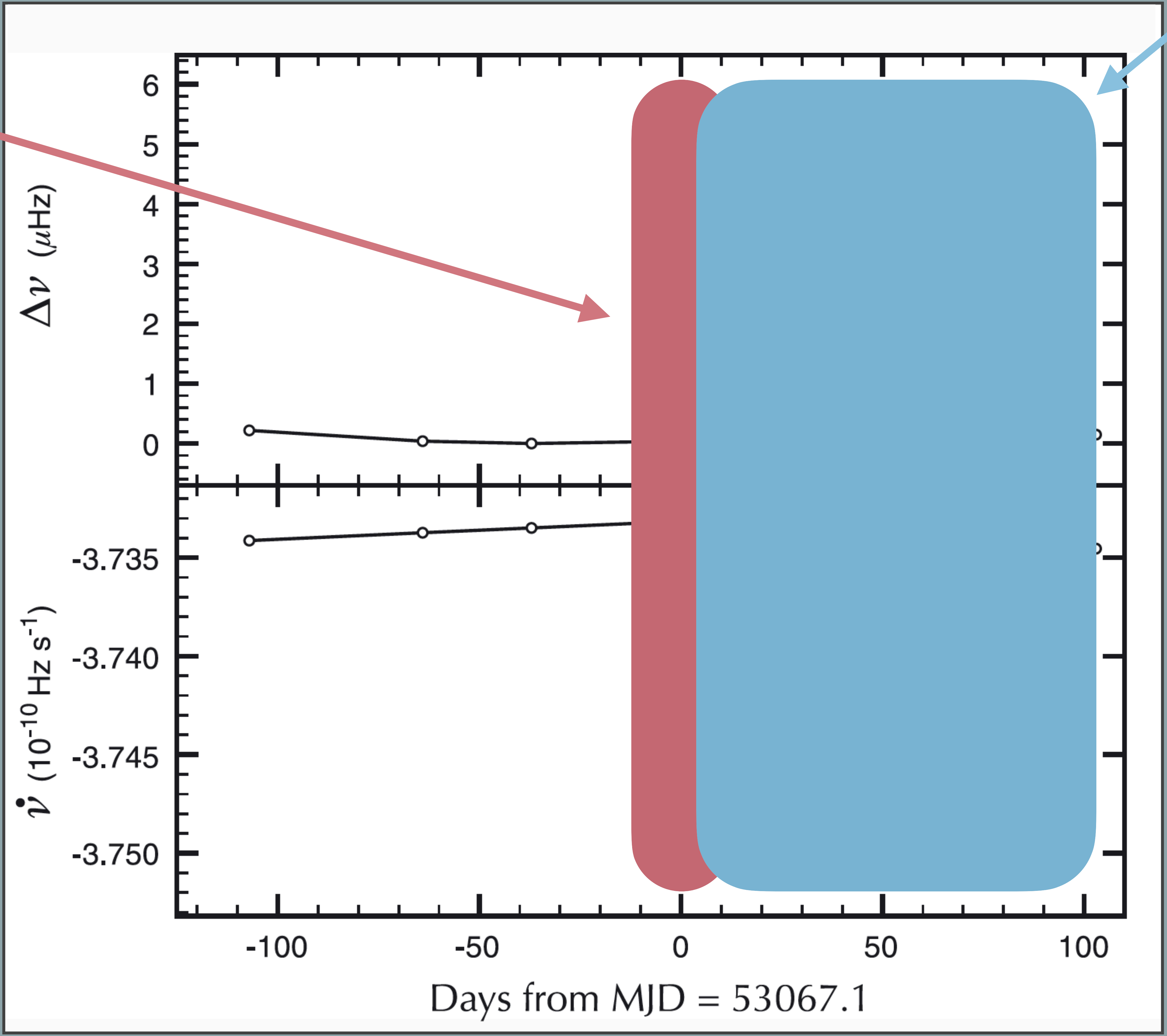
Concerned mostly about the energy available for GW emission, E_{GW}



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- Imagine a sudden decrease in the moment of inertia ΔI, i.e. a starquake.
- We must conserve angular momentum so $\Delta J \approx (\Delta I)\Omega + I\Delta\Omega = 0$
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- Assuming $E_{GW} = \Delta E_{rot}$ this means: $E_{GW} = \frac{1}{2}I\Omega\Delta\Omega$

Model 2: Vortex unpinning (two component) model

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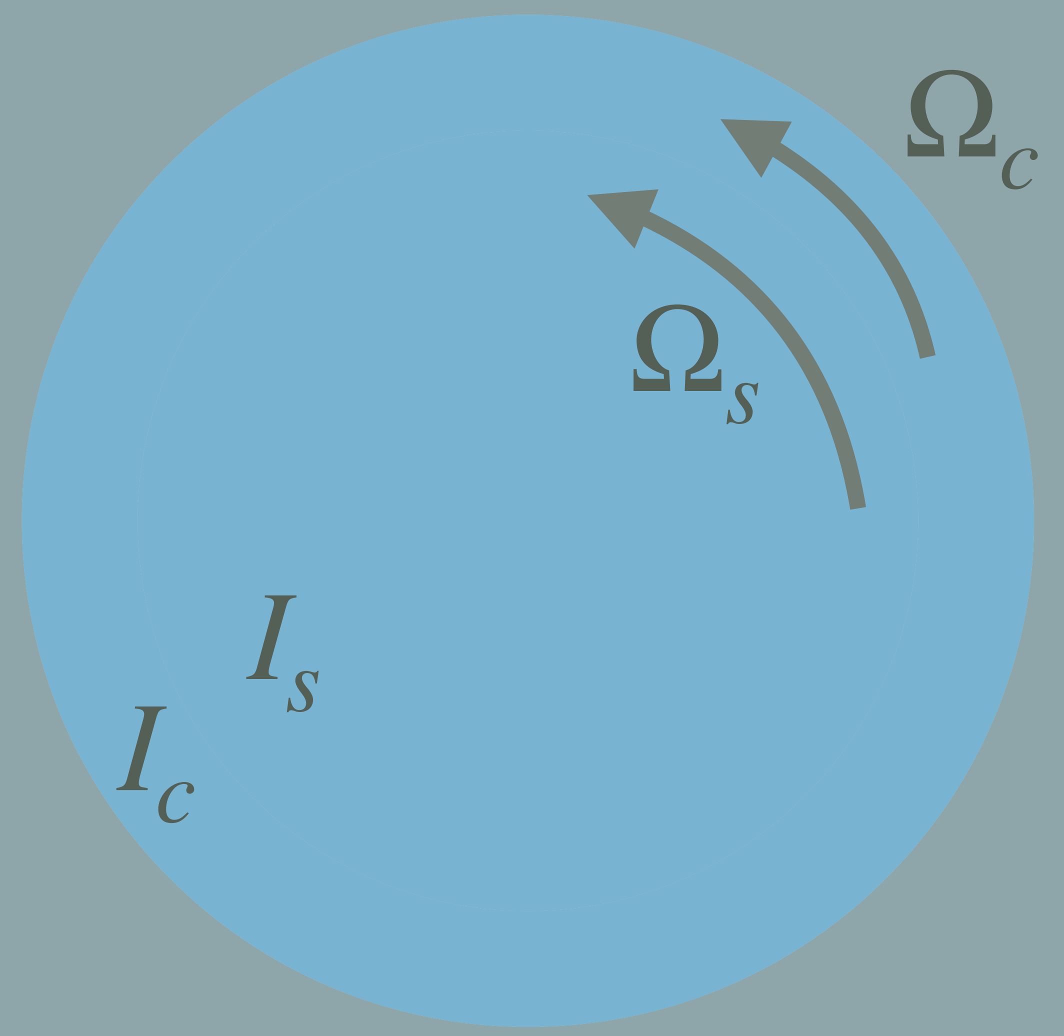

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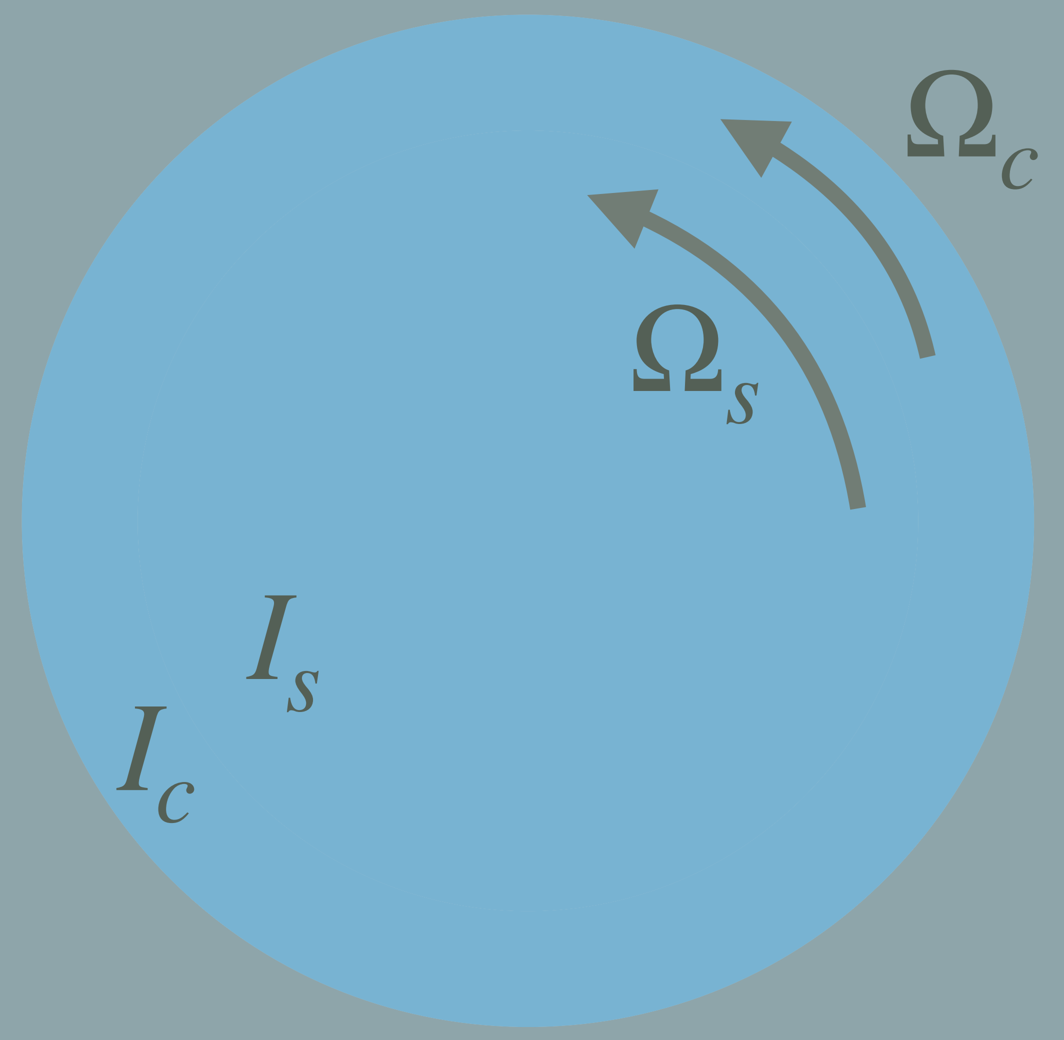
- External torque (e.g. magnetic dipole radiation) acts only on the crust component, so lag develops between the two components: $\omega \equiv \Omega_s - \Omega_c > 0$



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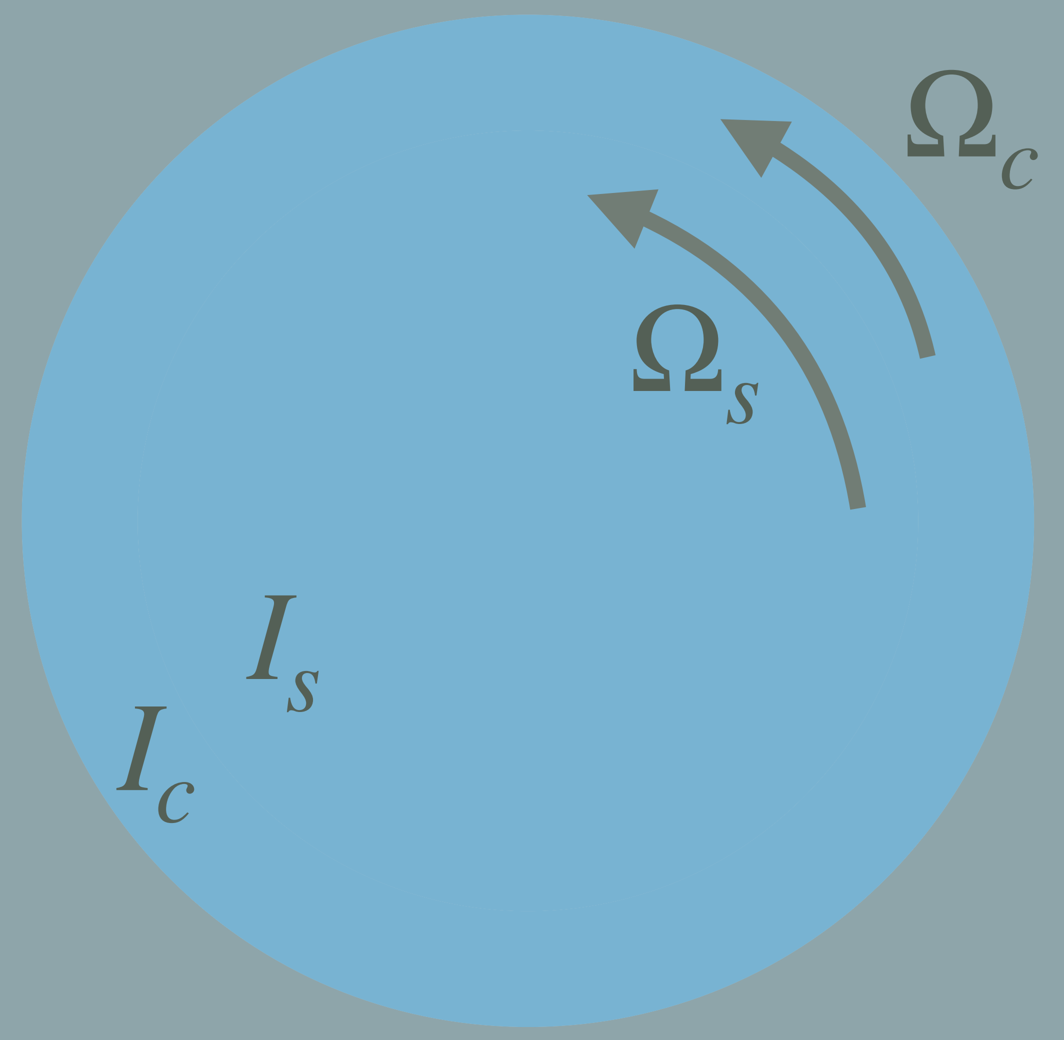
- At a glitch, the components couple and the superfluid component transfers angular momentum to the crustal component, leading to an observed glitch



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Summary: Excess rotational kinetic energy of two components → E_{GW}

- The superfluid component spins-down as the crustal component spins-up

$$\Delta J = I_s \Delta\Omega_s + I_c \Delta\Omega_c = 0$$

and they co-rotate after the glitch at $\Omega_{co} = \Omega_{0,i} + \Delta\Omega_i$ for $i = s, c$.

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- We can calculate the resultant change in energy for each component

$$\Delta E_{rot,i} = \frac{1}{2} I_i [\Omega_{co}^2 - (\Omega_{co} - \Delta\Omega_i)^2]$$

and when we sum the two components together, we get an excess energy of:

$$E_{GW} = \frac{1}{2} I (\Delta\Omega)^2 \left(\left(\frac{I_s}{I} \right)^{-1} - 1 \right)$$ where $I = I_s + I_c$

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Summary: Increase in $|\dot{\nu}|$ due to mountain, present until $|\dot{\nu}|$ recovers

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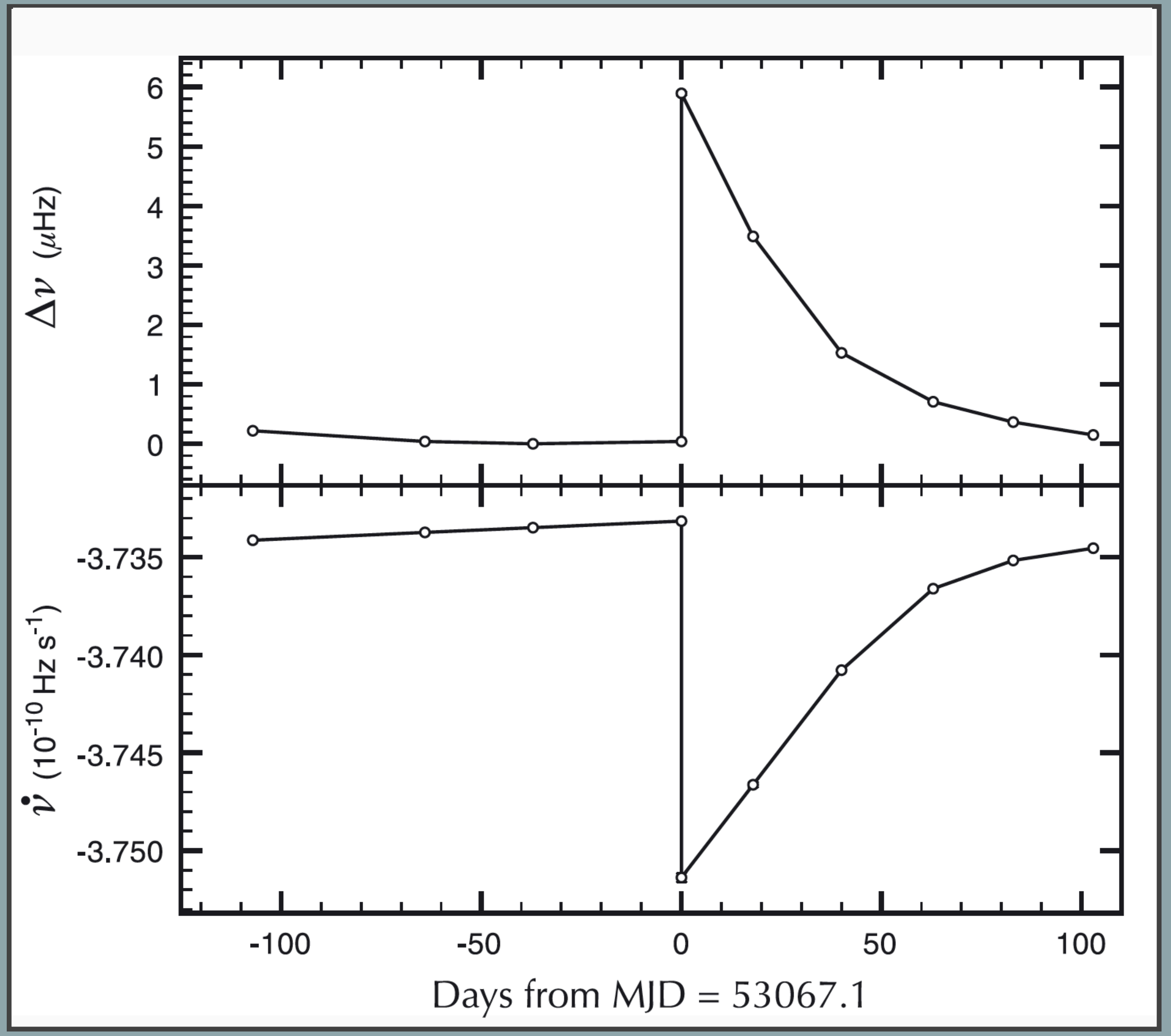
- Considers angular momentum conservation
  - Glitch: $\Delta\dot{\Omega}(t) = \Delta\dot{\Omega}_p + \Delta\dot{\Omega}_t(t) = \Delta\dot{\Omega}_p + \Delta\dot{\Omega}_t e^{-\frac{t}{\tau_{EM}}}$



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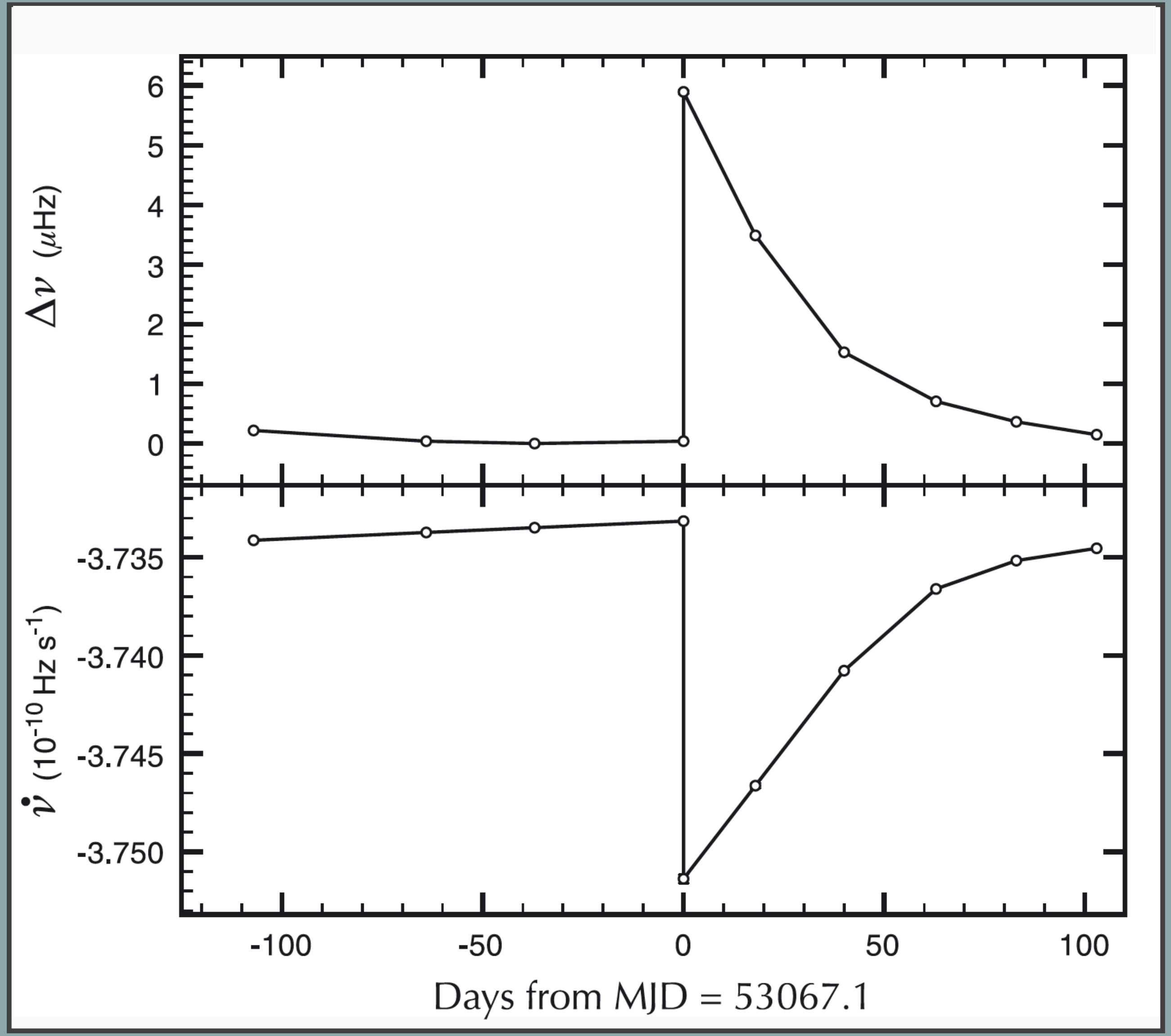
  - Attribute the transient part to a transient mountain

$$I\Delta\dot{\Omega}_t(t) = -\frac{32}{5}\frac{G}{c^5}I^2\Omega^5\varepsilon^2(t)$$



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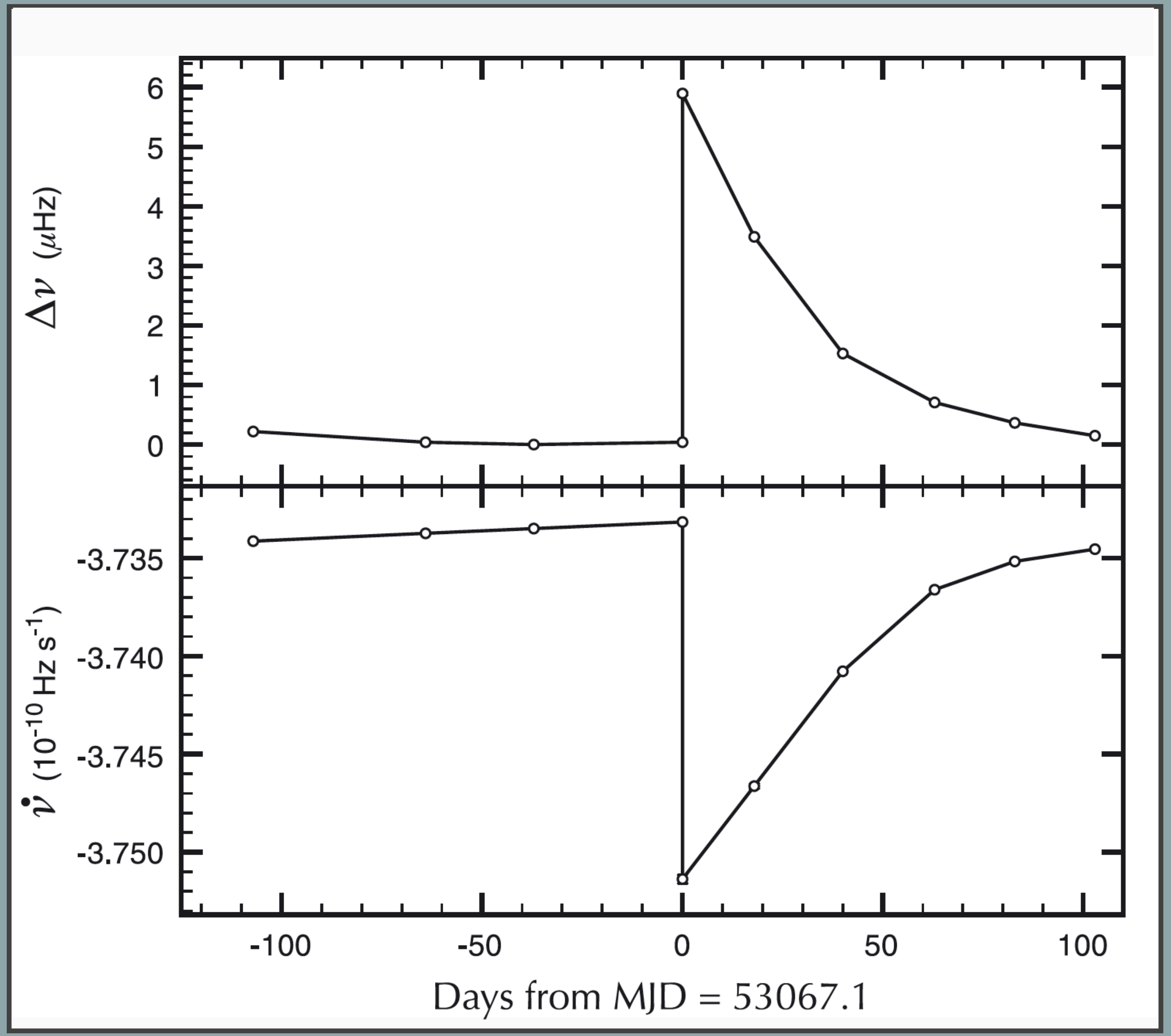
$$I\Delta\dot{\Omega}_t(t) = -\frac{32}{5}\frac{G}{c^5}I^2\Omega^5\varepsilon^2(t) \quad \rightarrow \quad \varepsilon(t) = \sqrt{-\frac{5}{32}\frac{c^5}{G}\frac{1}{I}\frac{\Delta\dot{\Omega}_t}{\Omega^5}}e^{-\frac{t}{2\tau_{EM}}}$$



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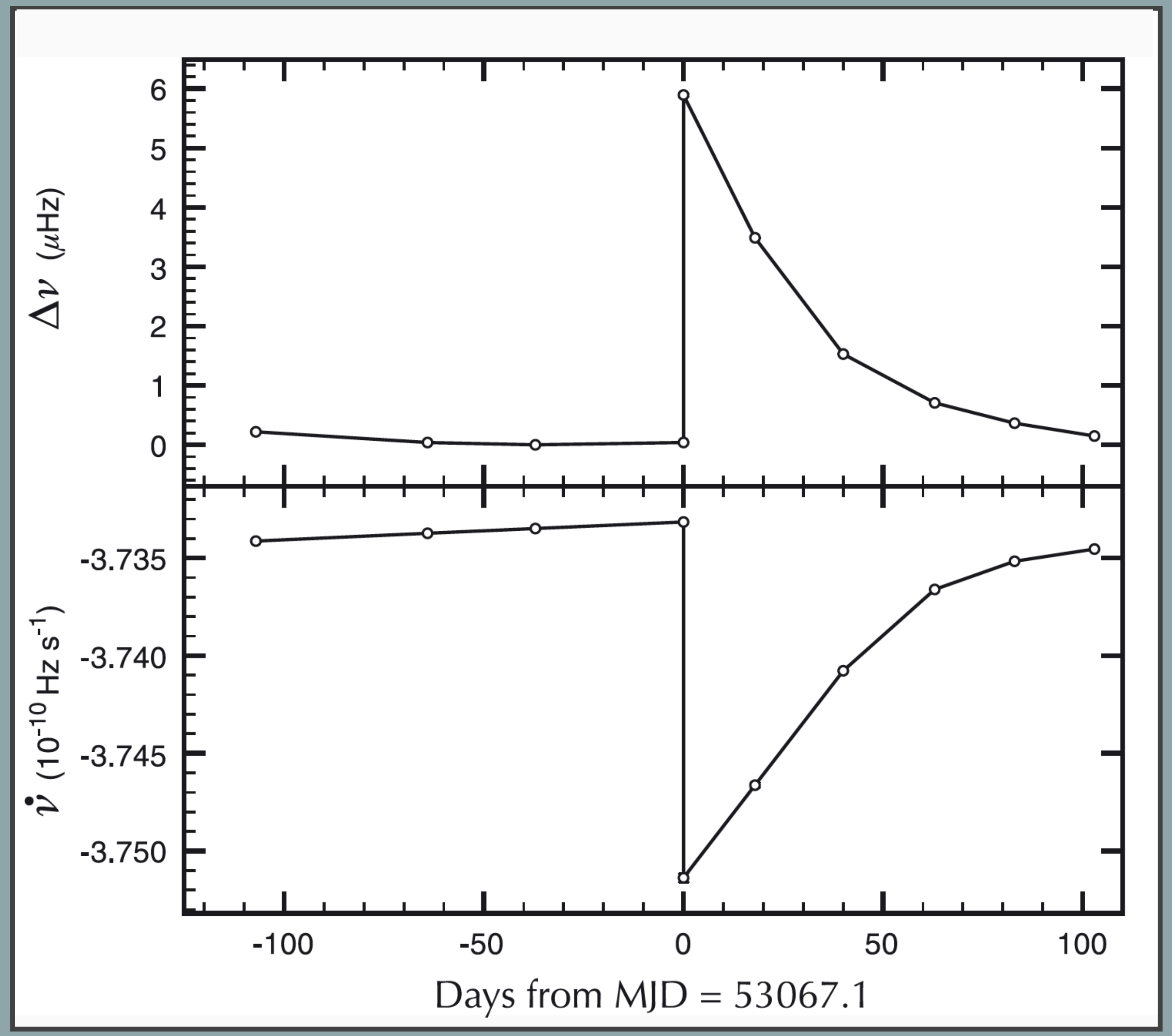

Note: $h_0(t) \propto \varepsilon(t)$ so if $h_0(t) \equiv h_0 e^{-\frac{t}{\tau_{GW}}}$ then $\tau_{GW} = 2\tau_{EM}$

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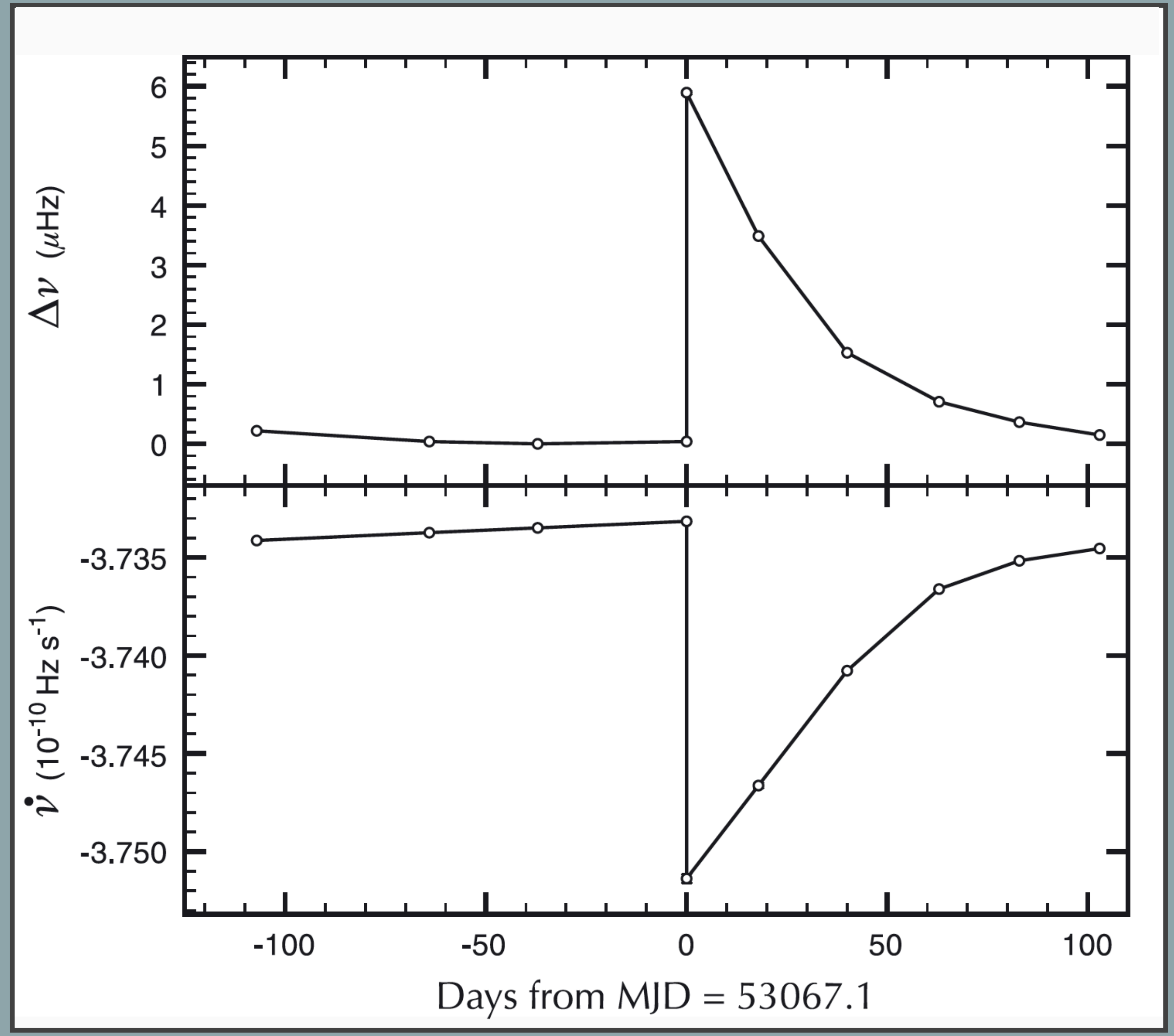
- Once $\varepsilon(t)$ is obtained from torque balance, can substitute into GW luminosity

$$L_{GW} = \frac{1}{10}\frac{G}{c^5} I^2 \Omega^6 \varepsilon^2(t)$$

and integrate between $t = 0$ and $t \to \infty$ to find

$$E_{GW} = QI\Omega\Delta\Omega$$

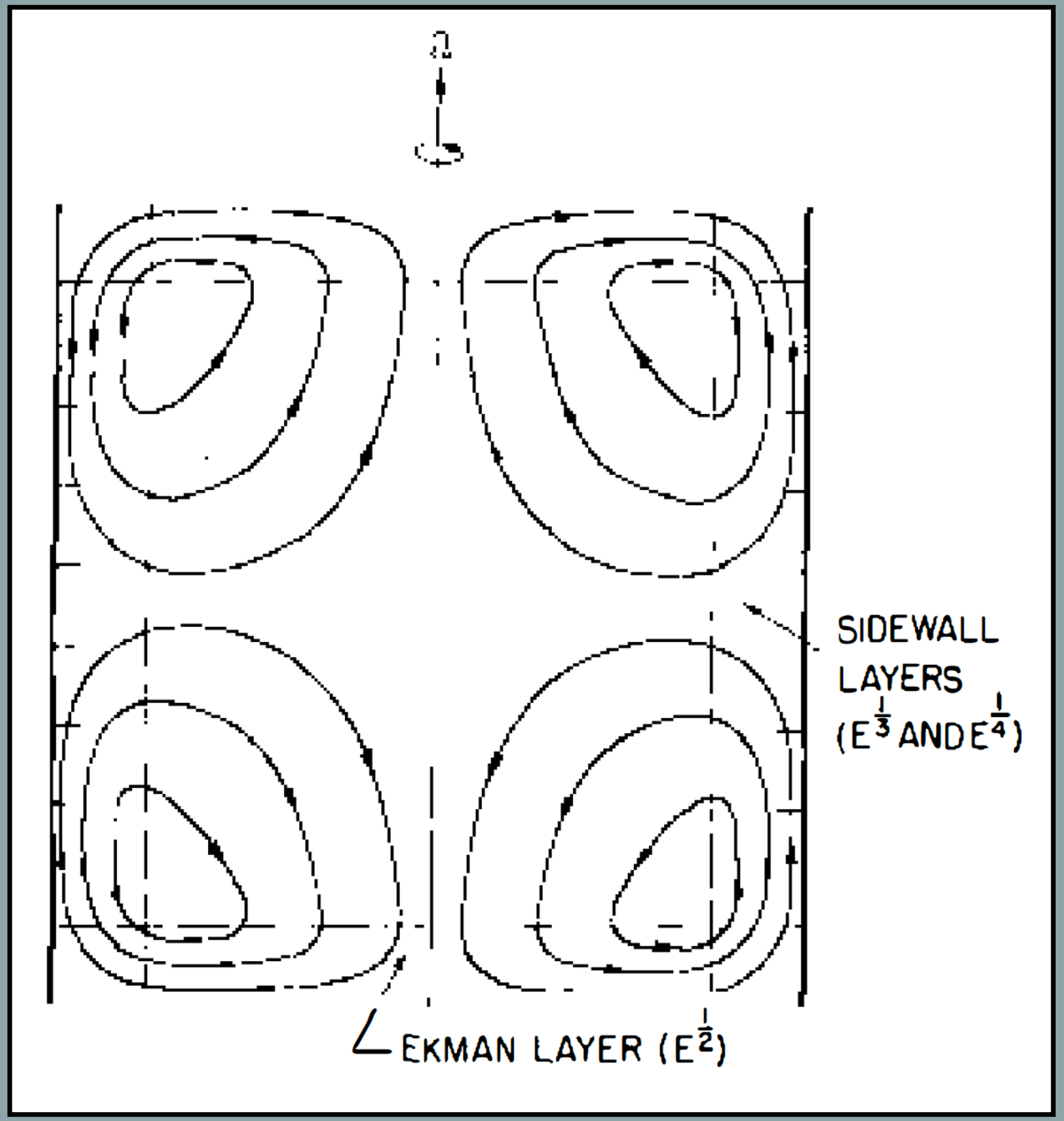
where $Q = \frac{\Delta\Omega_t}{\Delta\Omega} = -\frac{\Delta\dot{\Omega}_t}{\tau_{EM}\Delta\Omega}$.



Model 4: Ekman pumping model

[van Eysden & Melatos 2008, Bennett et al. 2010, Singh 2017]

Summary: Tangential forces at a boundary of a viscous fluid causes (non-axisymmetric) meridional flows, sets up mass and current multipoles



Credit: Benton & Clark (1974)

$$E_{GW} = \eta I_{crust} \Omega \Delta\Omega$$

$\eta = 10^{-7} - 10^{-5}$ from simulations (Singh 2017)

Model 5: Naïve (one component) model [Ho et al. 2020]

Summary: 100% rotational kinetic energy from glitch → E_{GW}

$$E_{GW} = I\Omega\Delta\Omega$$

(Assumes $\Delta I = 0$, unlike starquake model)

Model 6: Naïve (two component) model [Prix et al. 2011, Moragues et al. 2023]

Summary: Reservoir of rotational kinetic energy in superfluid component if $\Omega_s > \Omega_c$

$$E_{GW} = \frac{1}{2} I_s (\Omega_s^2 - \Omega_c^2) \quad \rightarrow \quad E_{GW} = I\Omega\Delta\Omega$$

Analogous to "CW spin-down limit" but for glitches!

Summary table

	Glitch rise		Post-glitch		Naïve	
	Starquake	Vortex unpinning	Transient mountain	Ekman pumping	One component	Two components
E_{GW}	$\frac{1}{2}I\Omega\Delta\Omega$	$\frac{1}{2}I(\Delta\Omega)^2\left(\frac{I}{I_{\mathrm{p}}}-1\right)$	$QI\Omega\Delta\Omega$	$2\pi\rho_0\Gamma L^5\eta\Omega\Delta\Omega$	$I\Omega\Delta\Omega$	$I\Omega\Delta\Omega$
κ	$\frac{1}{2}$	$\frac{1}{2}\left(\frac{\Delta\Omega}{\Omega}\right)\left(\frac{I}{I_{\mathrm{p}}}-1\right)$	Q	$\eta\frac{I_{\mathrm{crust}}}{I}$	1	1

where κ is defined as $E_{GW} = \kappa I\Omega^2\left(\frac{\Delta\Omega}{\Omega}\right)$

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κ	$\frac{1}{2}$	$\frac{1}{2}\left(\frac{\Delta\Omega}{\Omega}\right)\left(\frac{I}{I_{\rm p}}-1\right)$	Q	$\eta\frac{I_{\rm crust}}{I}$	1	1

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Part II - Gravitational wave signal analysis

Signal-to-noise ratio in terms of E_{GW} [Prix et al. 2011]

- Now that we have E_{GW} for different models, we need to find a way to express the signal-to-noise ratio (SNR) ρ in terms of E_{GW}.
- The SNR is defined as: $\rho = \sqrt{(h|h)}$ where $(a|b) = 4\mathrm{Re}\left(\int_0^\infty \frac{\tilde{a}(f)\tilde{b}^*(f)}{S_n(f)} df\right)$

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- Polarisation: $h(t) = F_+(t)h_+(t) + F_\times(t)h_\times(t)$ where $h_{+,\times}(t) = h_0(t)\, f_{+,\times}(\theta, \iota; t)$

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$$\rightarrow \quad \rho^2 = \beta \frac{1}{S_n(f)} \int_0^{T_{obs}} h_0^2(t)dt$$

$\beta = 1$ if $F_{+,\times} = \frac{1}{\sqrt{2}}$ (constant), $\theta = \frac{\pi}{2}$ and $\iota = 0$

$\beta = \frac{4}{25}$ if sky and orientation averaged [Jarankowski, Królak & Schutz 1998]

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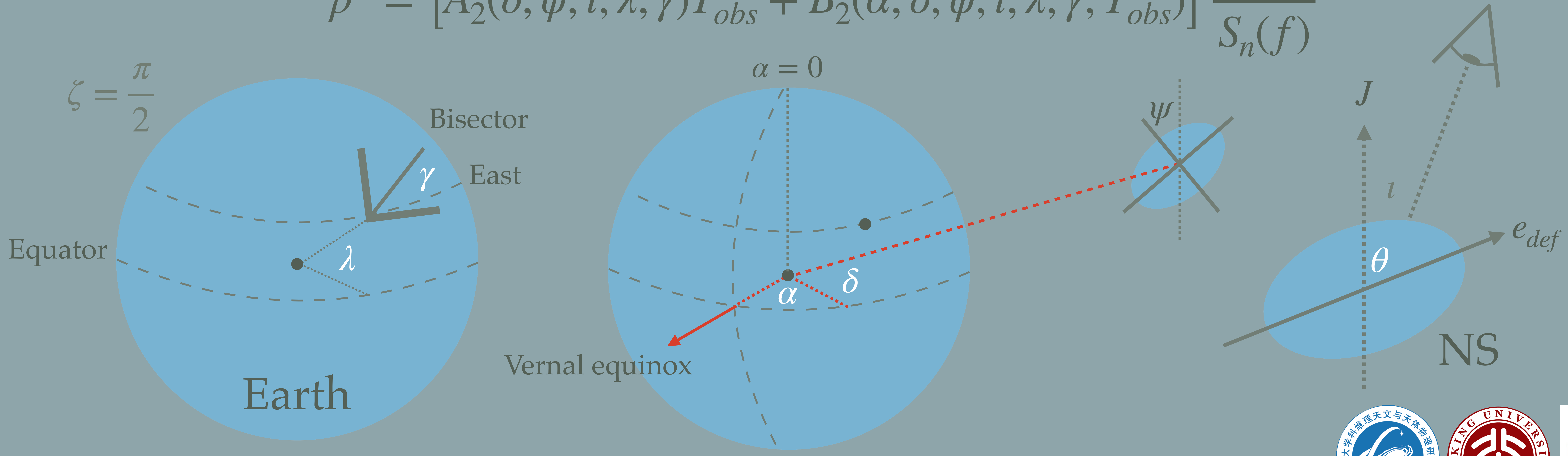
Signal-to-noise ratio from JKS [Jaranowski, Królak & Schutz 1998]

- We will now alter the assumptions to allow us to find a more suitable β. We will focus on the $f = 2\nu$ gravitational wave radiation only. Here, $h_0(t) = h_0$.
- From Jaranowski, Królak & Schutz (1998), we write down the SNR for $f = 2\nu$:

$$\rho^2 = \left[A_2(\delta, \psi, \iota, \lambda, \gamma)T_{obs} + B_2(\alpha, \delta, \psi, \iota, \lambda, \gamma; T_{obs})\right] \frac{h_0^2}{S_n(f)}$$



Transient CW approximation

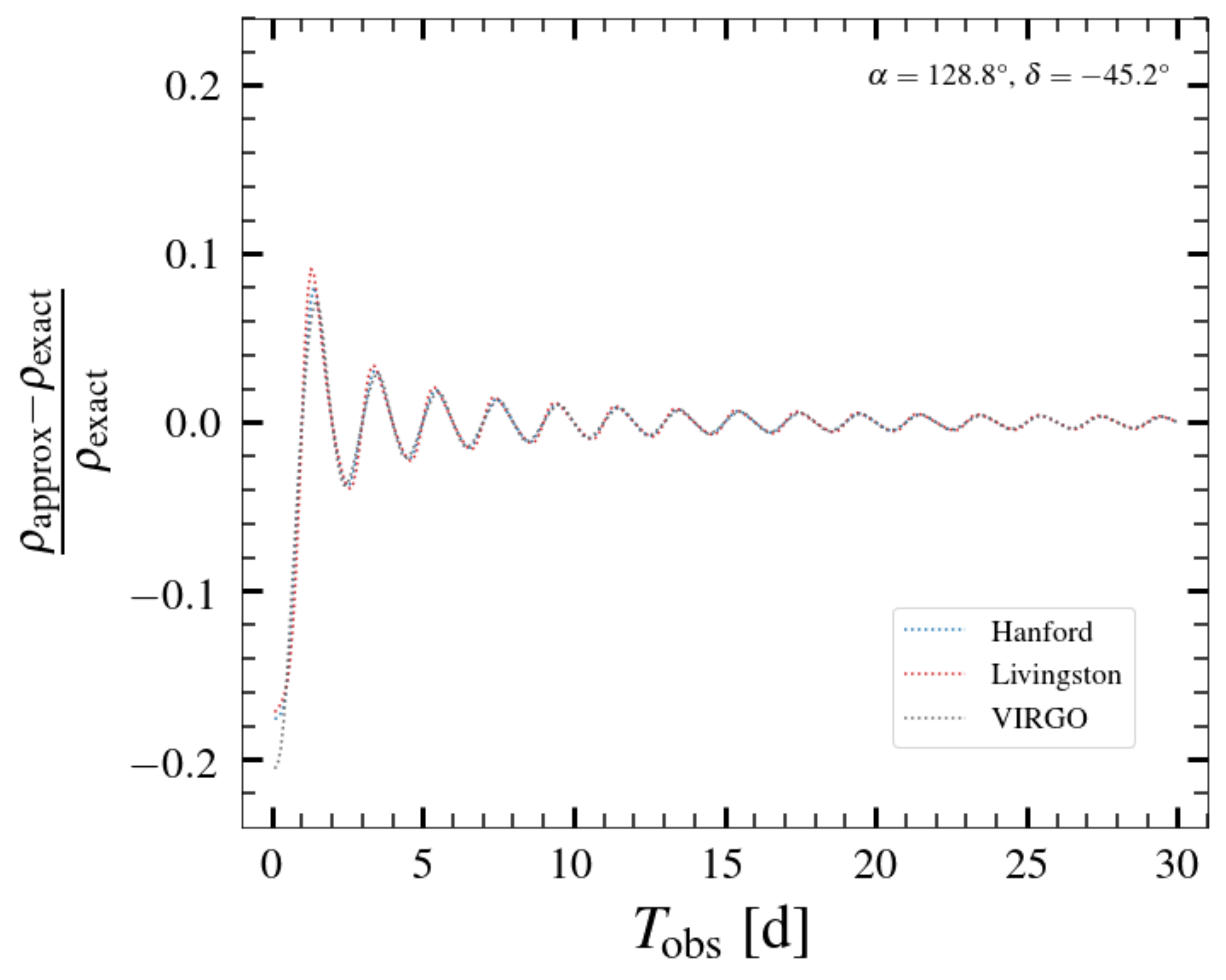
$$\rho^2 = \left[A_2(\delta, \psi, \iota, \lambda, \gamma) T_{obs} + B_2(\alpha, \delta, \psi, \iota, \lambda, \gamma; T_{obs})\right] \frac{h_0^2}{S_n(f)}$$

- Ideally, we want to discard the B_2 term. One could do so by averaging over α, which was done in JKS.
- Here, we note that for sufficiently long T_{obs}, the $A_2 T_{obs}$ term will dominate:

$$\rightarrow \quad \rho^2 = A_2(\delta, \psi, \iota, \lambda, \gamma) \frac{h_0^2 T_{obs}}{S_n(f)}$$

- Comparing to our earlier expression, we find: $\beta = A_2(\delta, \psi, \iota, \lambda, \gamma)$

Quantifying the error



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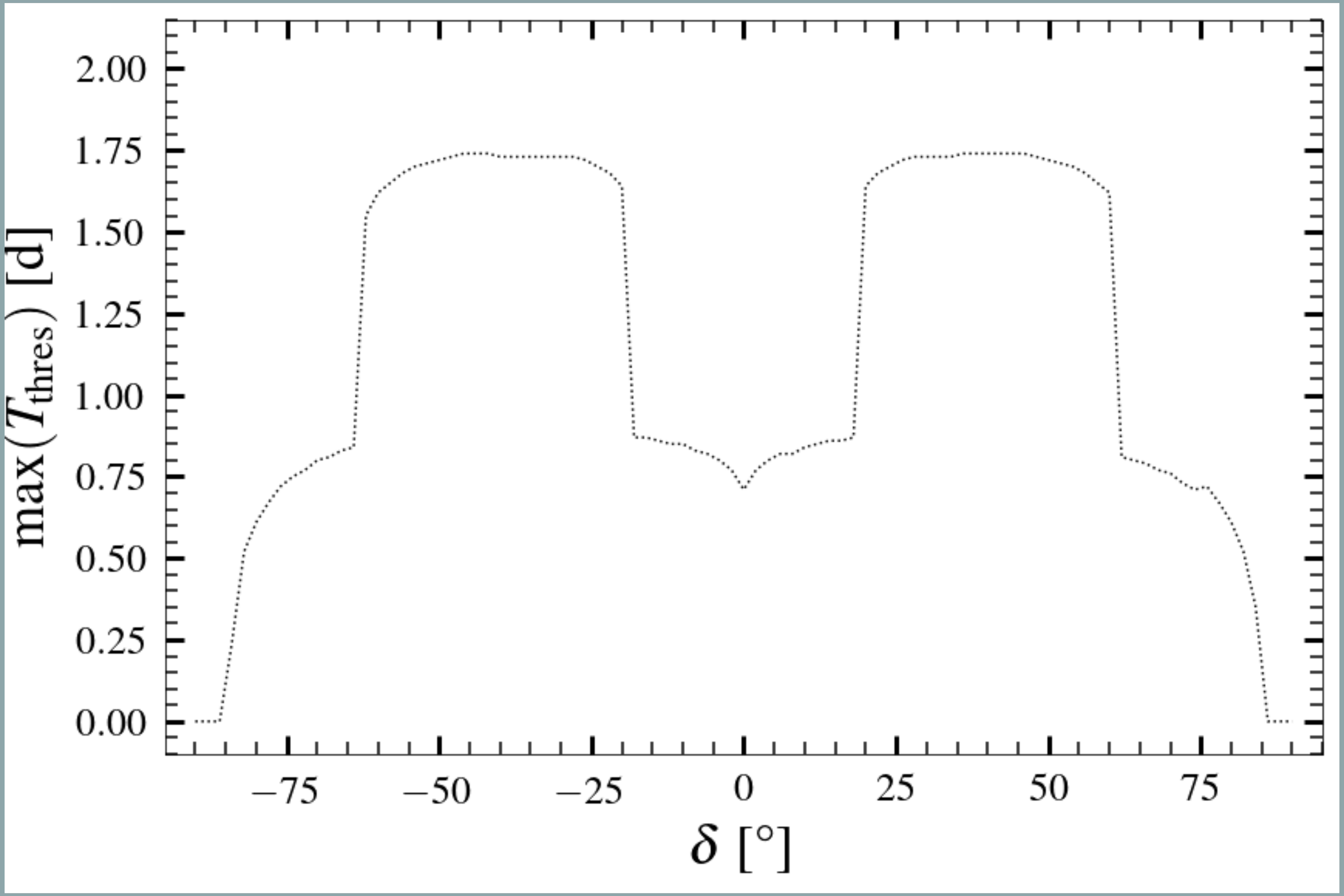
T_{thres} is the minimum observation time such that the SNR error is less than 10%

$$T_{thres} = 0.77 \text{ d}$$

max(T_{thres}) as a function of δ



Error in SNR will be less than 10% for all (α, δ) so long as $T_{obs} > 1.74$ d

Part III - Results

Data information

- We can now analytically approximate the SNR from the different models (naïve, vortex unpinning, transient mountain).

$$E_{GW} \rightarrow \frac{\Delta\Omega}{\Omega}, Q, \frac{I_s}{I}$$

$$\rho \rightarrow \Omega, d, S_n(f)$$

$$\rho^2 = \frac{5A_2}{2\pi^2}\frac{G}{c^3}\frac{1}{S_n(f)}\frac{E_{GW}}{f^2d^2}$$

$S_n(f) =$ Hanford, Livingston and VIRGO in O4

JBCA Glitch Catalogue: $\frac{\Delta\Omega}{\Omega}$

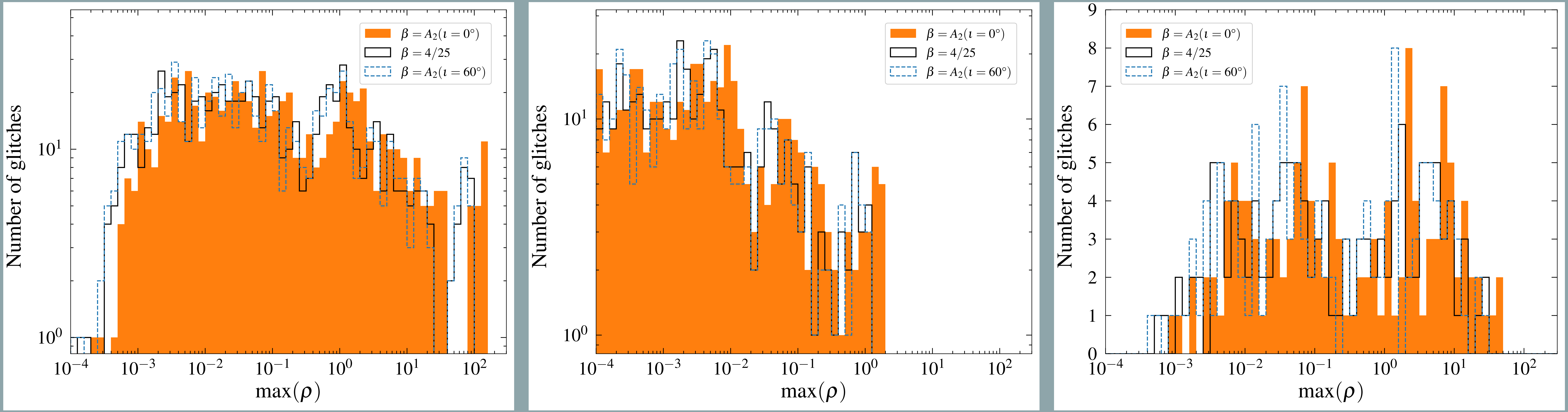
ATNF Glitch Table: $\frac{\Delta\Omega}{\Omega}, Q$

ATNF Pulsar Catalogue: Ω, d

$\left(\frac{\Delta\Omega}{\Omega}, d\right)$: 686 glitches from 219 pulsars

$\left(\frac{\Delta\Omega}{\Omega}, Q, d\right)$: 132 glitches from 57 pulsars

SNR histograms



Naïve

Vortex unpinning

Transient mountain

Top 15 targets for naïve models

Naïve models										
Pulsar J-name	α [°]	δ [°]	ν [Hz]	$\dot{\nu}$ [Hz s$^-$1]	d [kpc]	N_g	$\Delta\nu/\nu$ [10^{-9}]	$\Delta\dot{\nu}/\dot{\nu}$ [10^{-3}]	E_{GW} [erg]	max(ρ)
J0835−4510	128.84	−45.18	11.195	-1.57×10^{-11}	0.280	24	3100	148	1.53×10^{43}	156.3
J0940−5428	145.24	−54.48	11.423	-4.29×10^{-12}	0.377	2	1573.9	11	8.11×10^{42}	95.9
J1952+3252	298.24	32.88	25.296	-3.74×10^{-12}	3.000	6	1489.9	5.4	3.76×10^{43}	38.5
J0205+6449	31.41	64.83	15.217	-4.49×10^{-11}	3.200	9	3800	12	3.47×10^{43}	36.6
J1813−1246	273.35	−12.77	20.802	-7.60×10^{-12}	2.635	1	1166	6.4	1.99×10^{43}	34.3
J2229+6114	337.27	61.24	19.362	-2.90×10^{-11}	3.000	9	1223.6	13	1.81×10^{43}	30.9
J1105−6107	166.36	−61.13	15.822	-3.97×10^{-12}	2.360	5	971.7	0.1	9.60×10^{42}	26.1
J0534+2200	83.63	22.01	29.947	-3.78×10^{-10}	2.000	30	516.37	6.969	1.83×10^{43}	24.0
J1028−5819	157.12	−58.32	10.941	-1.93×10^{-12}	1.423	1	2296.5	35	1.09×10^{43}	23.9
J1524−5625	231.21	−56.42	12.785	-6.37×10^{-12}	3.378	1	2977	15.5	1.92×10^{43}	22.5
J1531−5610	232.87	−56.18	11.876	-1.95×10^{-12}	2.841	1	2637	25	1.47×10^{43}	20.0
J1112−6103	168.06	−61.06	15.394	-7.45×10^{-12}	4.464	4	1825	4.7	1.71×10^{43}	18.3
J1617−5055	244.37	−50.92	14.418	-2.81×10^{-11}	4.743	6	2068	13.2	1.70×10^{43}	16.0
J1420−6048	215.03	−60.80	14.667	-1.79×10^{-11}	5.632	7	2019	6.6	1.71×10^{43}	13.9
J1809−1917	272.43	−19.29	12.084	-3.73×10^{-12}	3.268	1	1625.1	7.8	9.37×10^{42}	13.6

Top 15 targets for vortex unpinning model

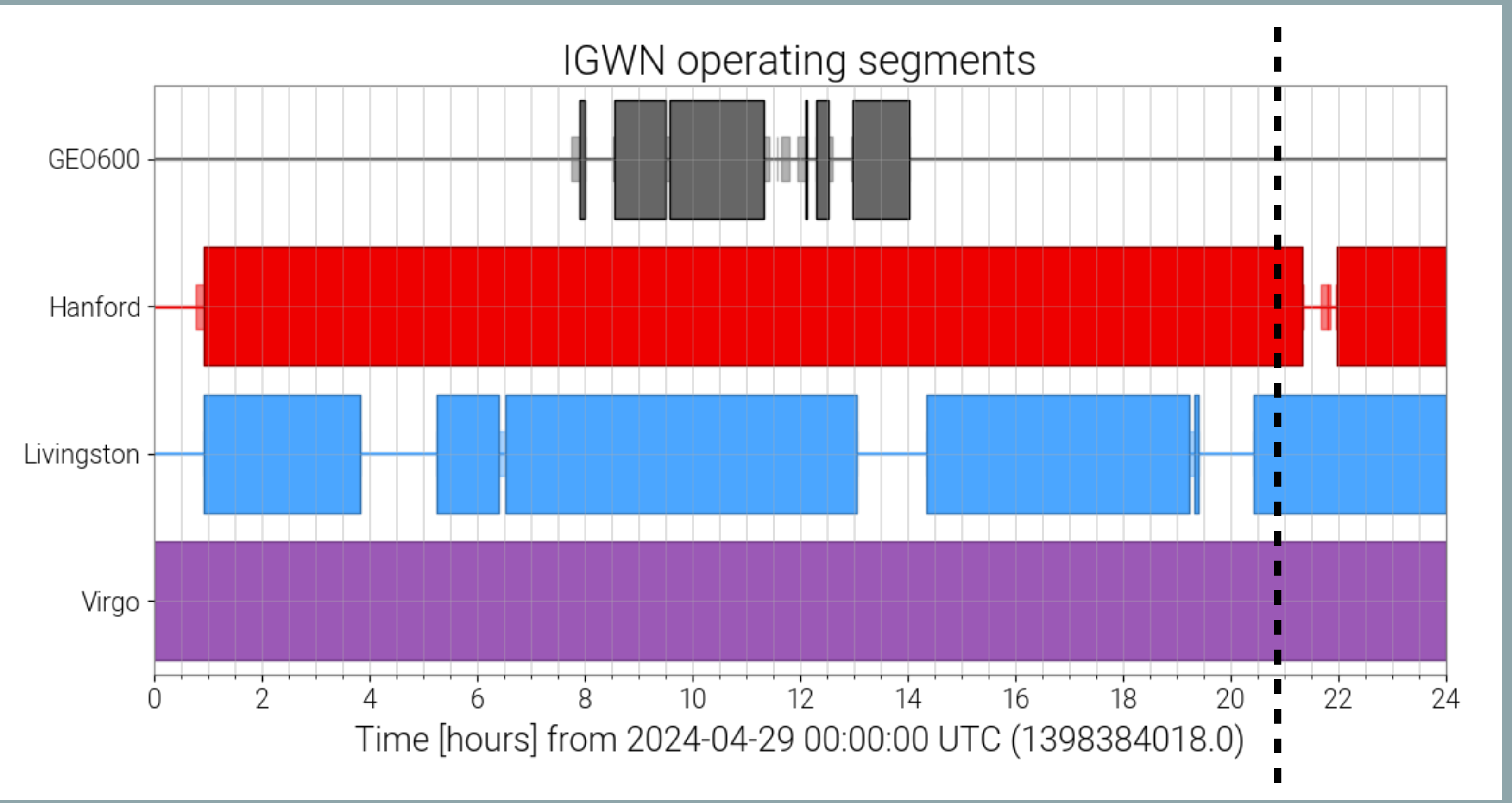
Vortex unpinning model										
Pulsar J-name	α [°]	δ [°]	ν [Hz]	$\dot{\nu}$ [Hz s$^-1$]	d [kpc]	N_g	$\Delta\nu/\nu$ [10^{-9}]	$\Delta\dot{\nu}/\dot{\nu}$ [10^{-3}]	E_{GW} [erg]	max(ρ)
J0835−4510	128.84	−45.18	11.195	-1.57×10^{-11}	0.280	24	3100	148	2.35×10^{39}	1.94
J0940−5428	145.24	−54.48	11.423	-4.29×10^{-12}	0.377	2	1573.9	11	6.32×10^{38}	0.85
J0205+6449	31.41	64.83	15.217	-4.49×10^{-11}	3.200	9	3800	12	6.53×10^{39}	0.50
J1952+3252	298.24	32.88	25.296	-3.74×10^{-12}	3.000	6	1489.9	5.4	2.78×10^{39}	0.33
J1524−5625	231.21	−56.42	12.785	-6.37×10^{-12}	3.378	1	2977	15.5	2.83×10^{39}	0.27
J1813−1246	273.35	−12.77	20.802	-7.60×10^{-12}	2.635	1	1166	6.4	1.15×10^{39}	0.26
J1028−5819	157.12	−58.32	10.941	-1.93×10^{-12}	1.423	1	2296.5	35	1.23×10^{39}	0.25
J2229+6114	337.27	61.24	19.362	-2.90×10^{-11}	3.000	9	1223.6	13	1.10×10^{39}	0.24
J1531−5610	232.87	−56.18	11.876	-1.95×10^{-12}	2.841	1	2637	25	1.92×10^{39}	0.23
J1105−6107	166.36	−61.13	15.822	-3.97×10^{-12}	2.360	5	971.7	0.1	4.62×10^{38}	0.18
J1112−6103	168.06	−61.06	15.394	-7.45×10^{-12}	4.464	4	1825	4.7	1.54×10^{39}	0.17
J1617−5055	244.37	−50.92	14.418	-2.81×10^{-11}	4.743	6	2068	13.2	1.74×10^{39}	0.16
J1420−6048	215.03	−60.80	14.667	-1.79×10^{-11}	5.632	7	2019	6.6	1.71×10^{39}	0.14
J1809−1917	272.43	−19.29	12.084	-3.73×10^{-12}	3.268	1	1625.1	7.8	7.54×10^{38}	0.12
J0534+2200	83.63	22.01	29.947	-3.78×10^{-10}	2.000	30	516.37	6.969	4.67×10^{38}	0.12

Top 15 targets for transient mountain model

Transient mountain model											
Pulsar J-name	α [°]	δ [°]	ν [Hz]	$\dot{\nu}$ [Hz s^{-}1]	d [kpc]	N_{g}	$\Delta\nu/\nu$ [10^{-9}]	$\Delta\dot{\nu}/\dot{\nu}$ [10^{-3}]	Q	E_{GW} [erg]	max(ρ)
J0835−4510	128.84	−45.18	11.195	-1.57×10^{-11}	0.280	24	1805.2	77	0.1684	1.50×10^{42}	48.9
J0205+6449	31.41	64.83	15.217	-4.49×10^{-11}	3.200	9	5400	52	0.77	3.80×10^{43}	38.3
J0534+2200	83.63	22.01	29.947	-3.78×10^{-10}	2.000	30	81	3.4	0.894	2.56×10^{42}	9.0
J0940−5428	145.24	−54.48	11.423	-4.29×10^{-12}	0.377	2	1573.9	11	0.0068	5.51×10^{40}	7.9
J1617−5055	244.37	−50.92	14.418	-2.81×10^{-11}	4.743	6	334	13	0.975	2.67×10^{42}	6.4
J1028−5819	157.12	−58.32	10.941	-1.93×10^{-12}	1.423	1	2296.5	35	0.0114	1.24×10^{41}	2.6
J1112−6103	168.06	−61.06	15.394	-7.45×10^{-12}	4.464	4	1202	7	0.022	2.47×10^{41}	2.2
J1524−5625	231.21	−56.42	12.785	-6.37×10^{-12}	3.378	1	2977.1	15.6	0.0058	1.11×10^{41}	1.7
J1531−5610	232.87	−56.18	11.876	-1.95×10^{-12}	2.841	1	2637	25	0.007	1.03×10^{41}	1.7
J1420−6048	215.03	−60.80	14.667	-1.79×10^{-11}	5.632	7	2019	6.6	0.008	1.37×10^{41}	1.2
J1809−1917	272.43	−19.29	12.084	-3.73×10^{-12}	3.268	1	1625.1	7.8	0.00602	5.64×10^{40}	1.1
J1302−6350	195.70	−63.84	20.937	-9.99×10^{-13}	2.632	1	2.3	...	0.36	1.43×10^{40}	1.0
J1837−0604	279.43	−6.08	10.383	-4.84×10^{-12}	4.779	3	1376	8	0.06	3.51×10^{41}	0.9
J1709−4429	257.43	−44.49	9.760	-8.86×10^{-12}	2.600	5	2872	8	0.0129	1.39×10^{41}	0.8
J1826−1334	276.55	−13.58	9.853	-7.31×10^{-12}	3.606	7	3581	9.6	0.0066	9.06×10^{40}	0.5

Breaking news: Vela glitched on 29th April 2024!

- ATel: 16608 (2nd May), 16610, 16611, 16615, 16619
- Glitch time: Between 20:52:11.4 and 20:52:18.1
- ~7 second uncertainty
- $\Delta\Omega/\Omega \approx 2.4 \times 10^{-6}$
- Hanford, Livingston, VIRGO all observing during glitch



	Naïve	Vortex unpinning	Transient mountain
E_{GW} [erg]	1.2×10^{43}	1.4×10^{39}	2.4×10^{42}
$\max(\rho)$	137.8	1.5	61.6

f-mode calculation (Yim & Jones 2023) gives: $\rho = 50,\ 25,\ 7,$ for Livingston, Hanford and VIRGO (but using $\beta = 1$)

Part IV - Summary

Summary

- The SNR of a transient CW source can be estimated by obtaining E_{GW}.
- We explored 6 different models associated with pulsar glitches.
- For a sufficiently long transient CW, we can make a better estimate of the SNR by including the pulsar's sky position information.
- In O4, we will start putting upper limits on some of these models. As shown, this can already be done with Vela's latest glitch!
- Must start considering what physics can be learnt from a (non-)detection: superfluidity, elasticity/plastic flow, viscosity, magnetic diffusion, temperature gradients, etc...

Continuous Waves School at KIAA, PKU

- 7th - 11th July (FPS13/SPSS2024 begins on 12th)
- Invited lecturers:
  - Prof. Maria Alessandra Papa (Albert Einstein Institute)
  - Prof. Ian Jones (University of Southampton)
  - Dr. David Keitel (University of the Balearic Islands)
  - Dr. Lilli Sun (Australian National University)
  - Plus 6 guest speakers
- Speak with me if you are interested - spaces are limited!
- Email: g.yim@pku.edu.cn
- Website (needs VPN): https://garvinyim.wixsite.com/home/cw-school-at-kiaa
- Website (accessible): https://cwschool2024.kiaa-pku.cn/