Rotating neutron stars as sources of gravitational waves

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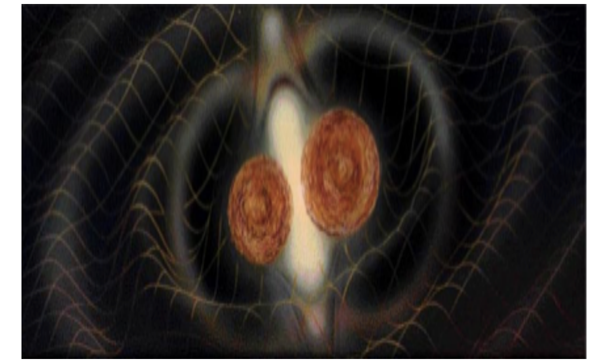
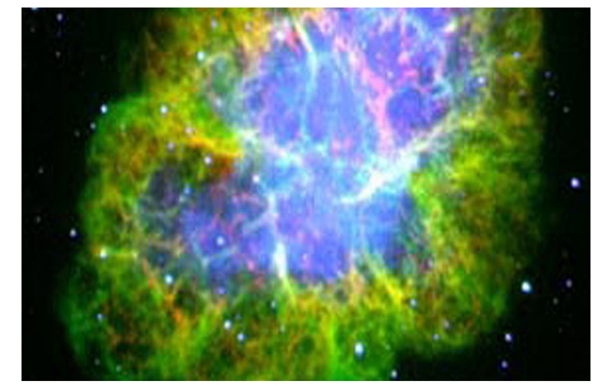
Gravitational wave signals

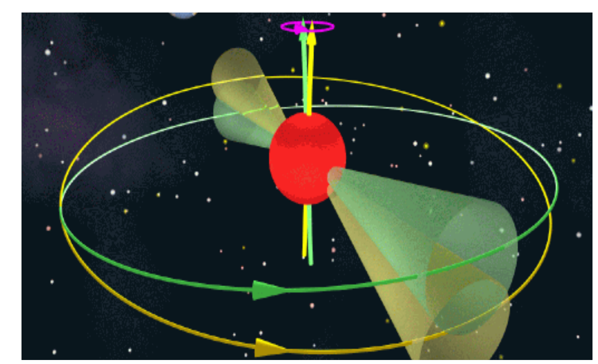
Compact binary inspirals: **"chirps"**



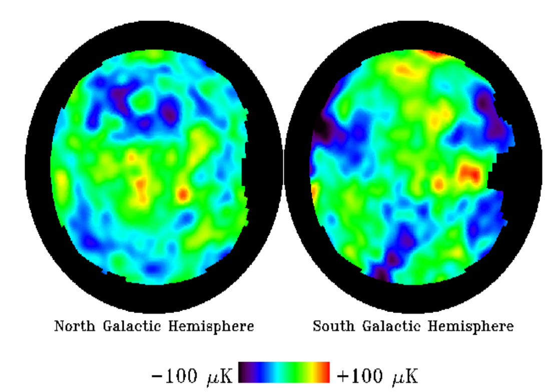
Supernovae, etc.. : **"bursts"**



Pulsars: **"continuous"**



Cosmological signals: **"stochastic"**



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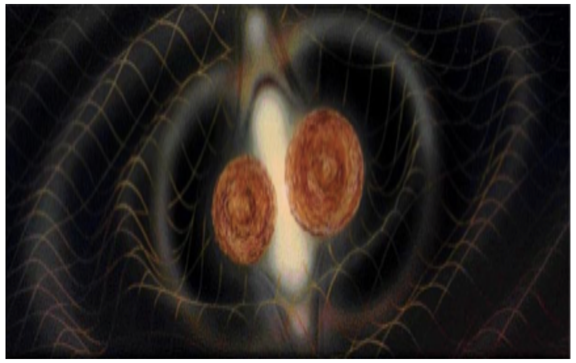

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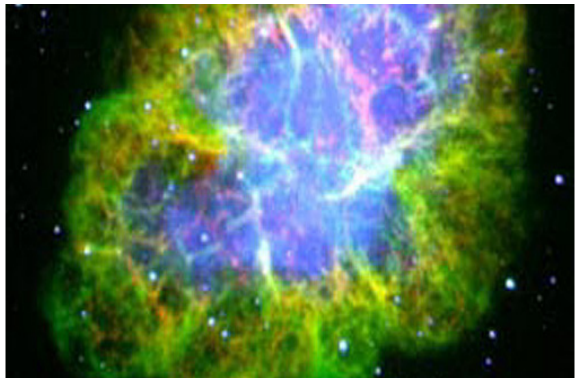

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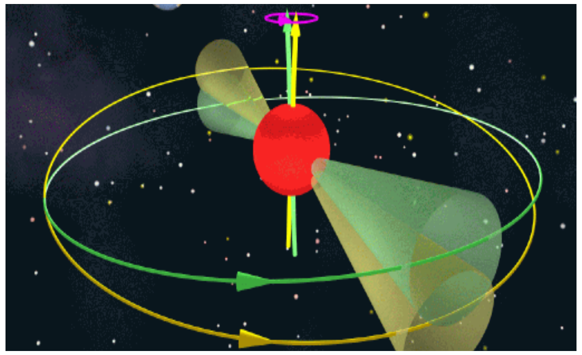

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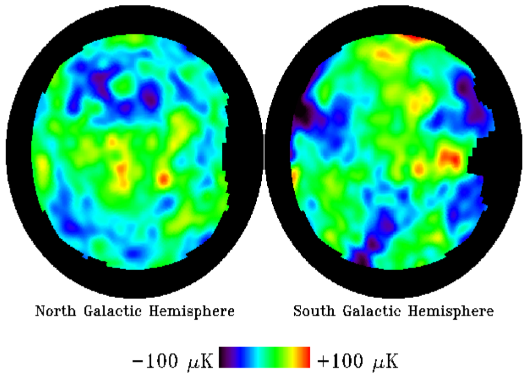
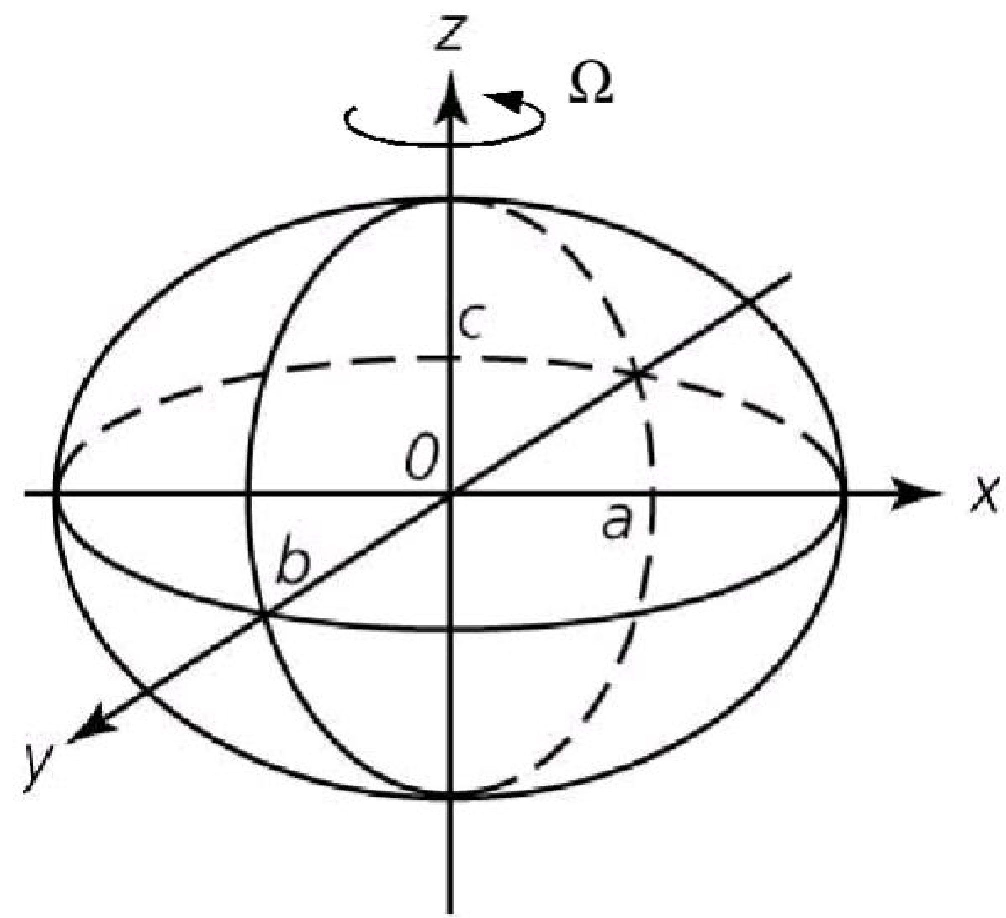


Neutron star mountains

- $\epsilon = \dfrac{I_{xx} - I_{yy}}{I_{zz}}$



- Emission at $\omega = 2\Omega$

- $\dfrac{dE}{dt} \approx \epsilon^2 \Omega^6$

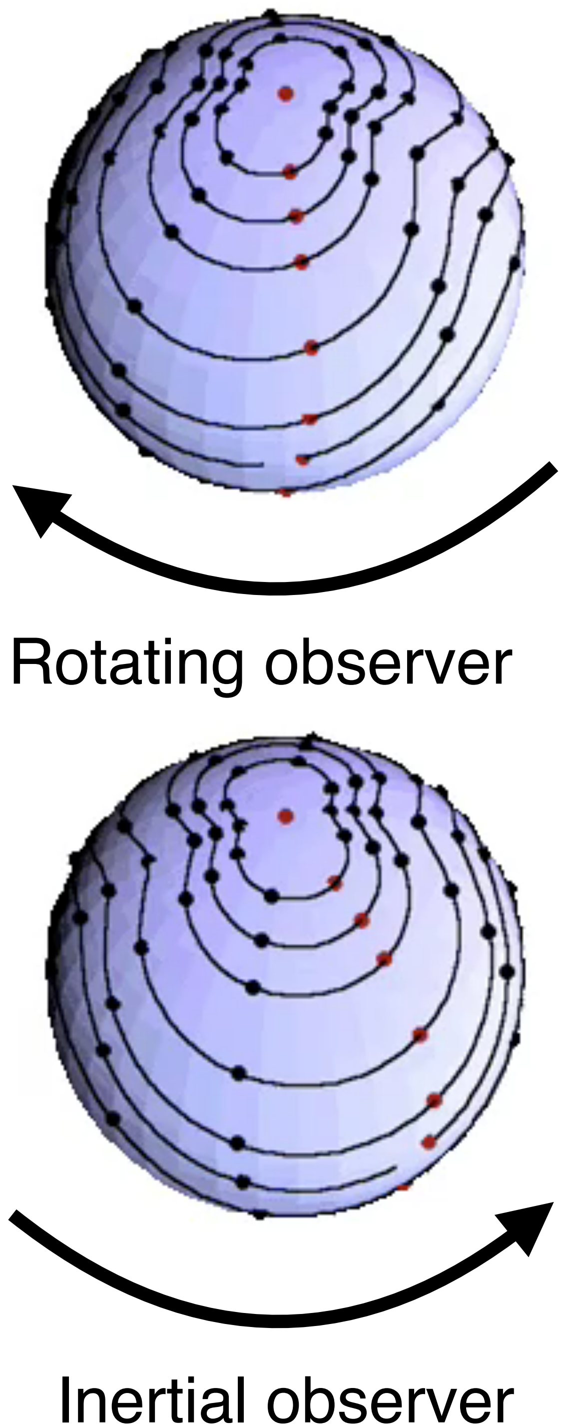
- Supported by crustal elasticity or magnetic fields

- Theoretical (elastic) upper limit $\epsilon \approx 10^{-5}$

(BH, Jones, Andersson 2006, Horowitz & Kadau 2009, Johnson-McDaniel & Owen 2013)

r-mode instability

(Animation by Ben Owen)



$$E_r = E_i - J\Omega$$

- r-mode unstable to GW emission
- Emission at $\omega \approx \frac{4}{3}\Omega$
- Viscosity damps the mode except in a window of temperatures and frequencies

(Andersson 1998, Friedman & Morsink 1998)

r-mode instability

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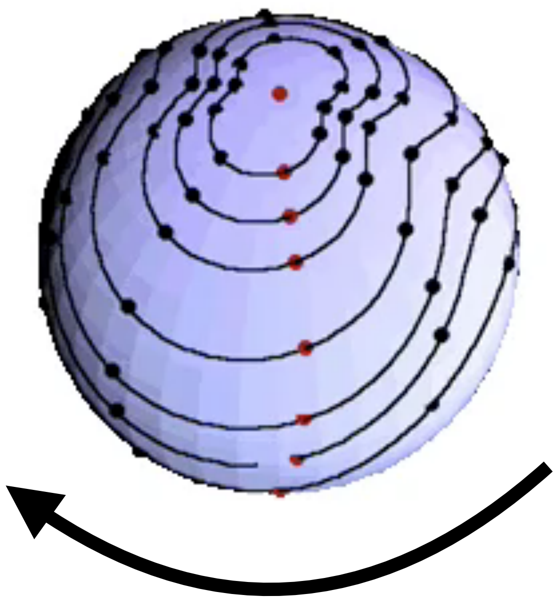
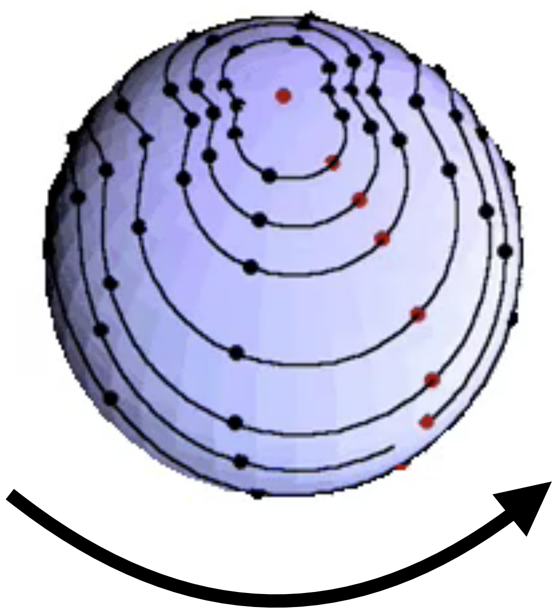


Rotating observer



Inertial observer

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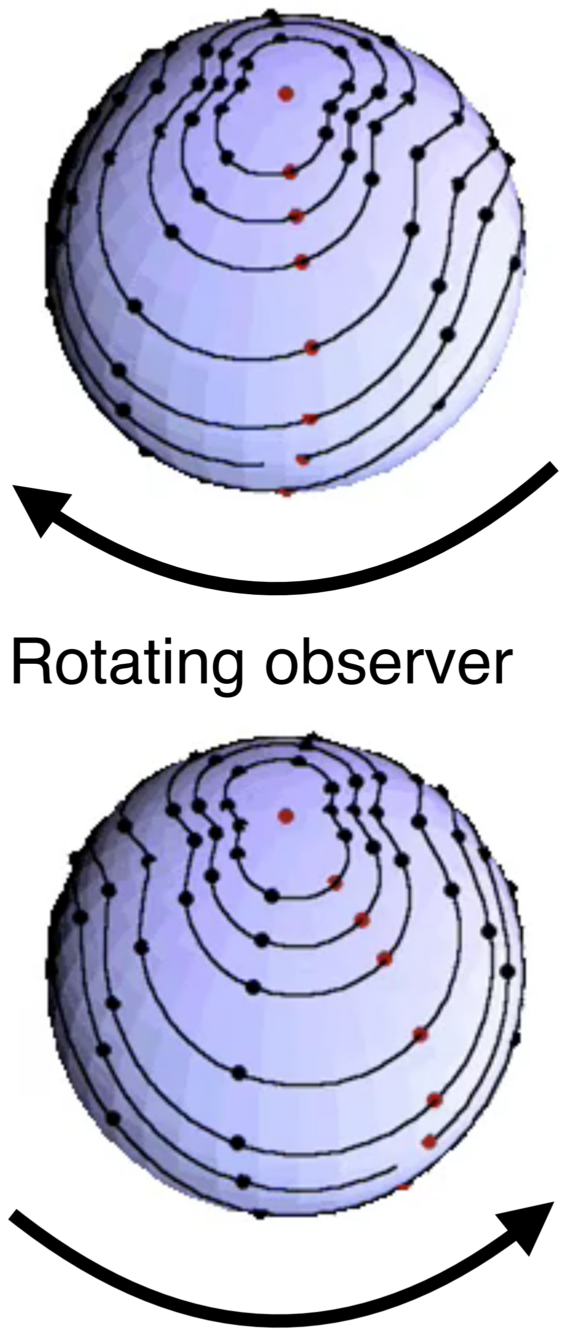

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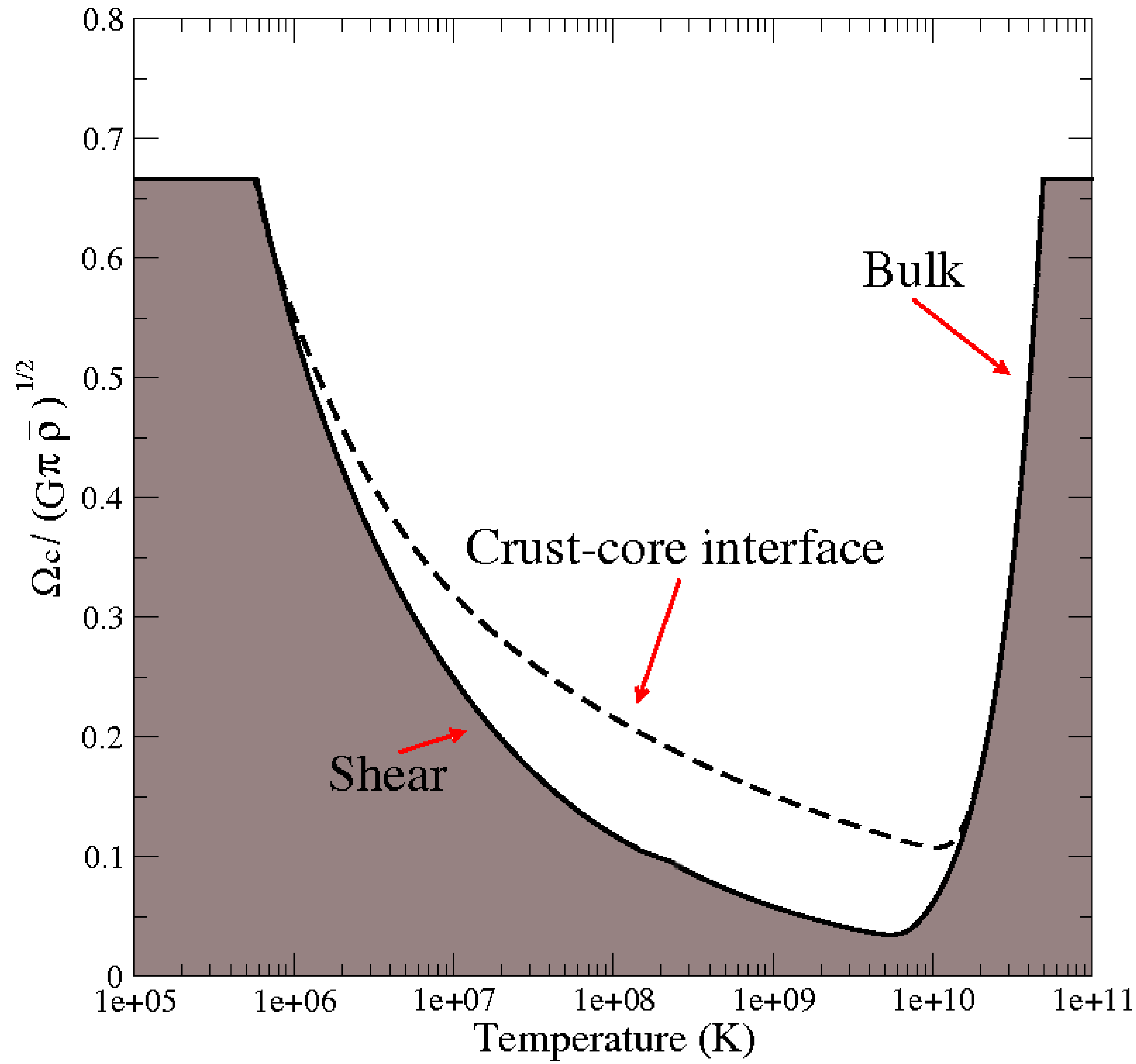

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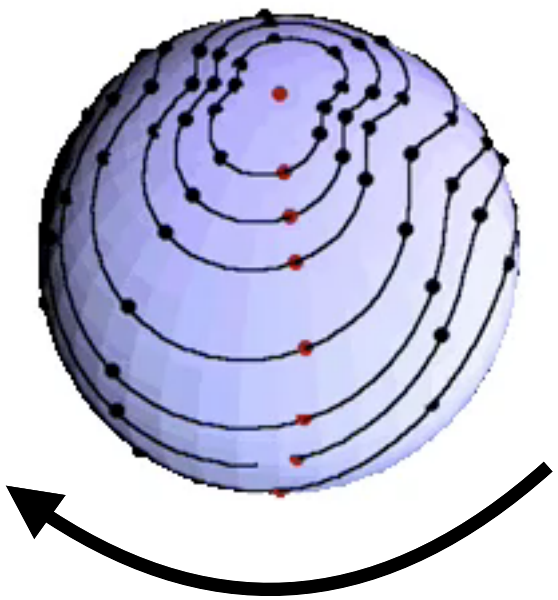

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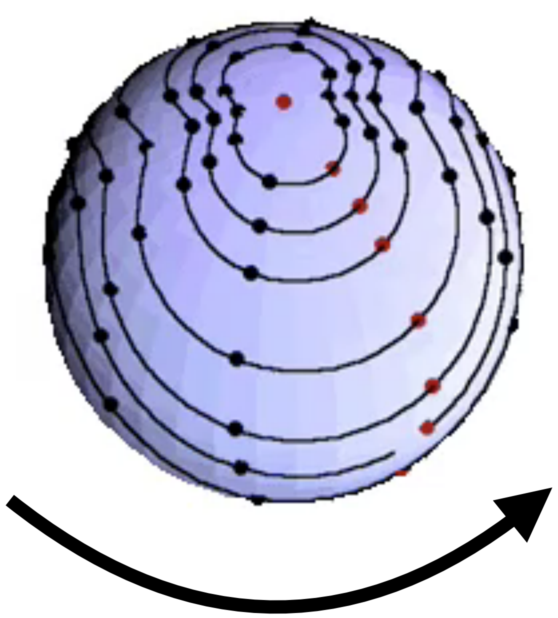

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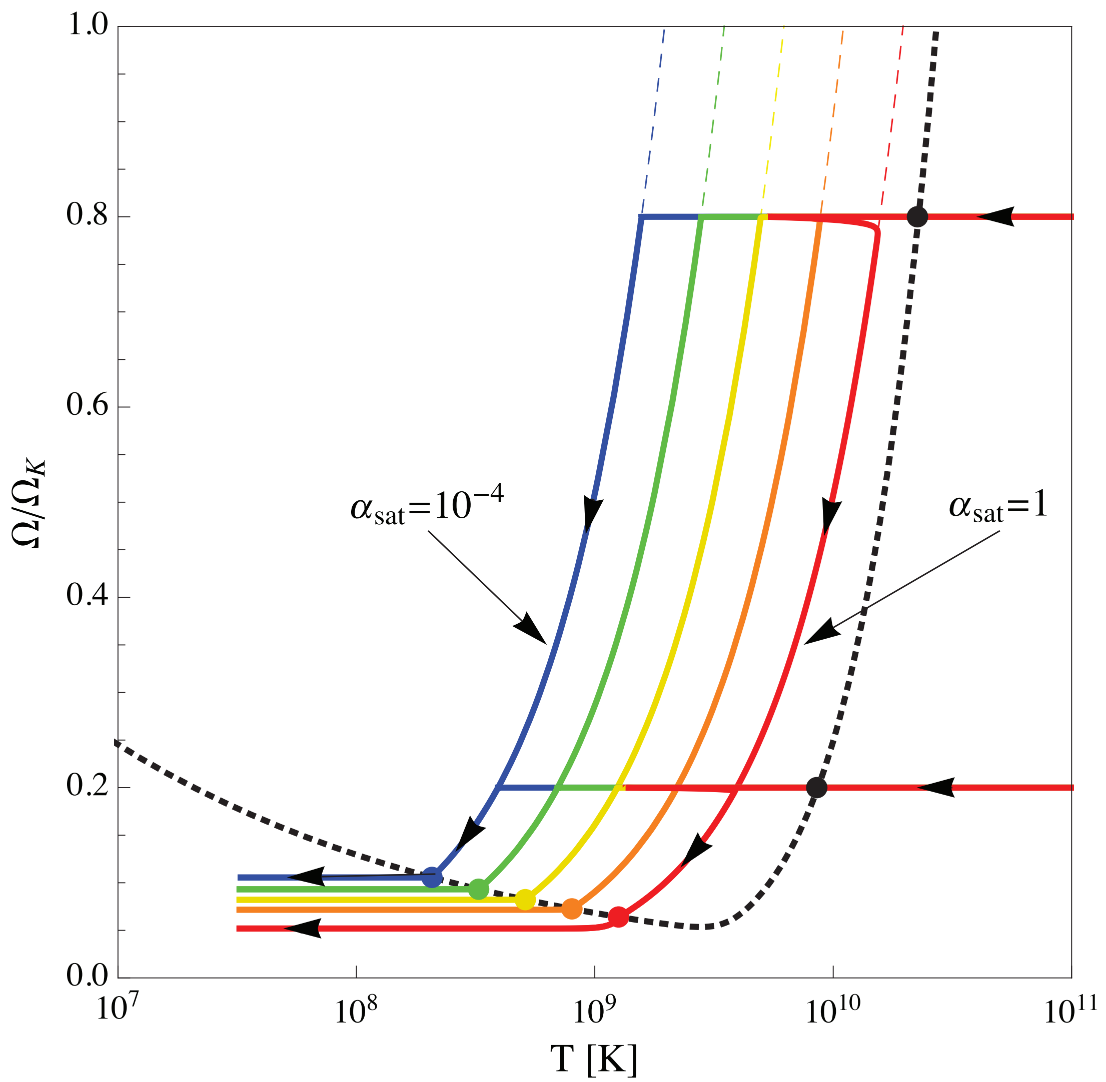
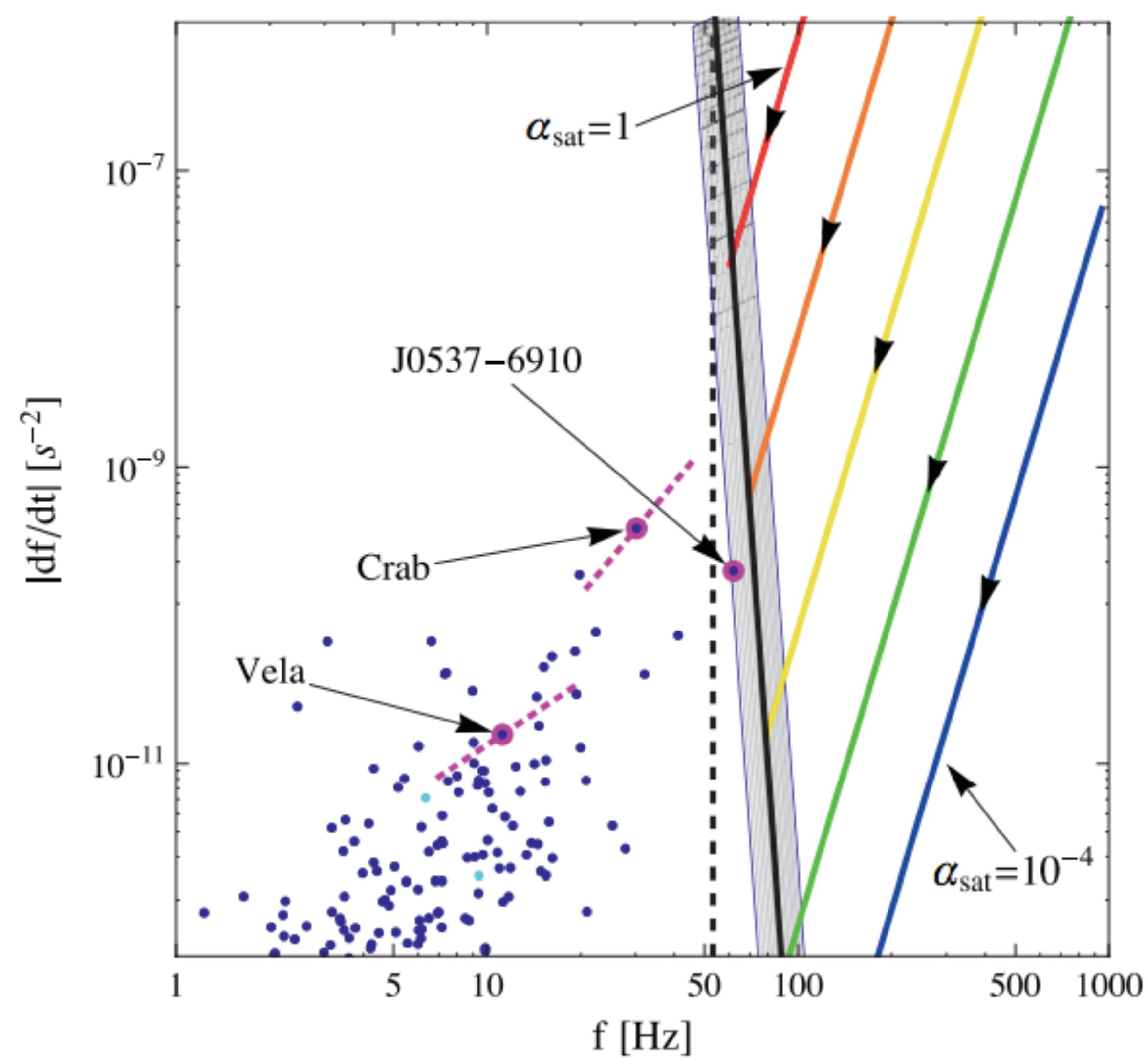
Young neutron stars

- r-modes can spin-down newborn NSs

(Owen et al. 1998, Alford & Schwenzer 2014)





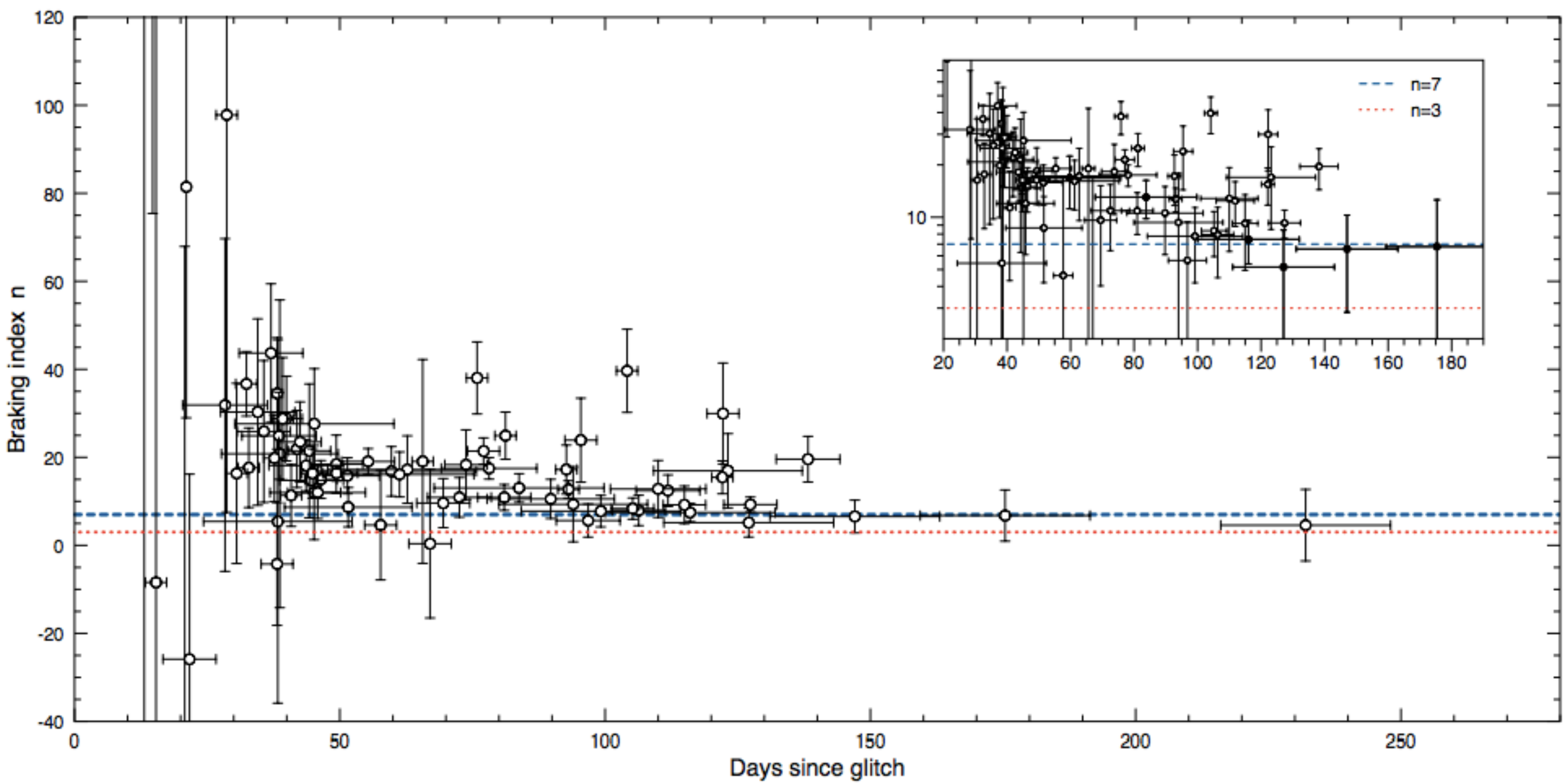
R-modes in J0537?

- Evidence that underlying n=7 for J0537?

(Andersson, Antonopoulou, Espinoza, BH & Ho 2017)

(Ferdman et al. 2018)

$$\dot{\Omega} \propto \Omega^n$$

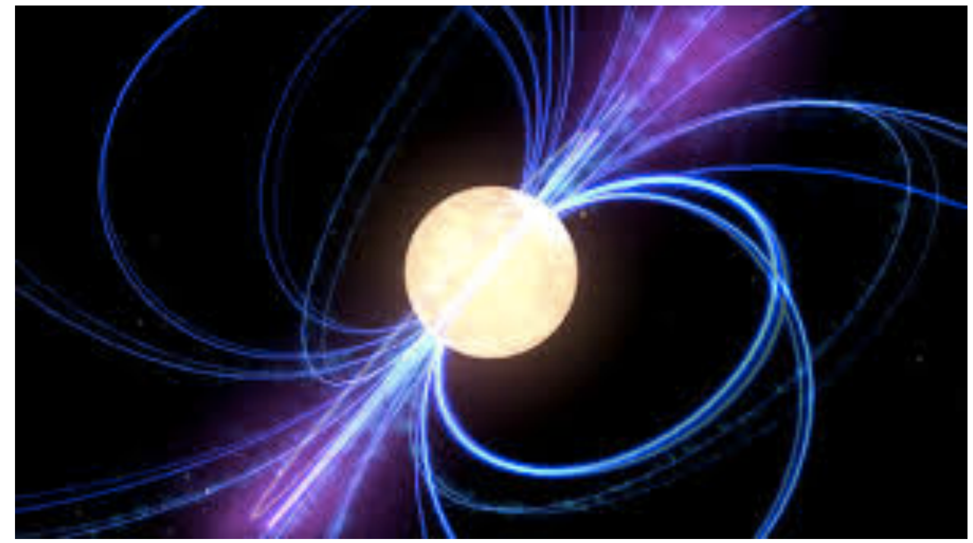


Mature Neutron Stars

- 'standard' radio pulsars

  $B \approx 10^{12}\mathrm{G}$

  $\tau \gtrsim 10^{5}\mathrm{yr}$



- Hall drift can lead to complex magnetic fields and a 'mountain'

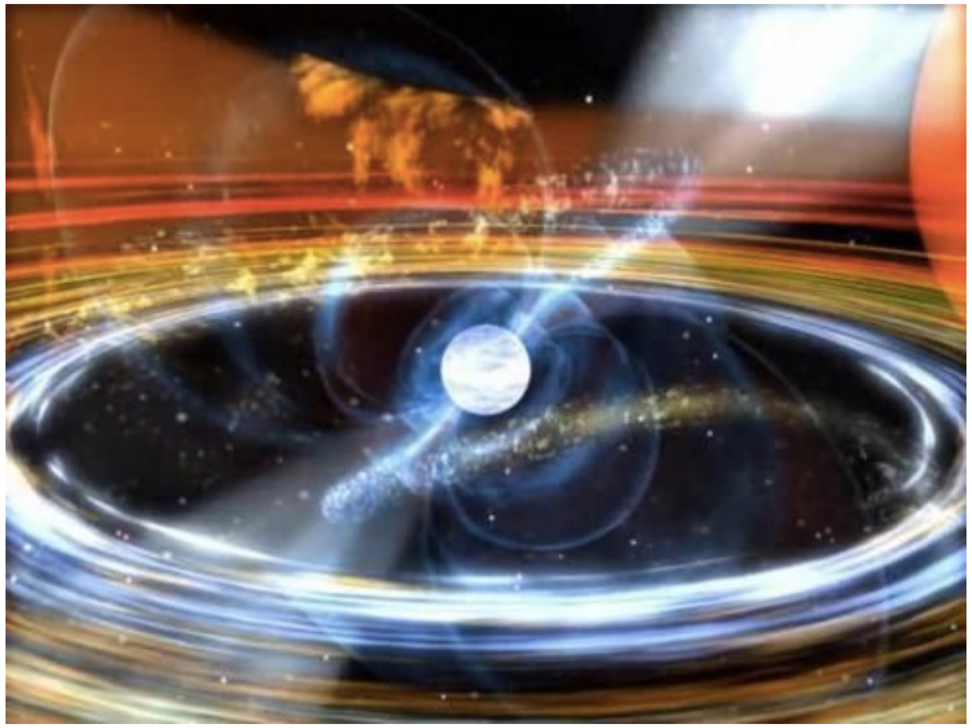
$$\epsilon \approx 10^{-8} - 10^{-6} \quad (\epsilon \approx 10^{-7} \text{ for the Crab})$$

(Suvorov et al 2016)

- For this population current LVC limits $\epsilon \approx 10^{-5} - 10^{-4}$

(Abbott et al. 2019)

Old Recyled Neutron Stars



Fastest Neutron Star: 716 Hz

(Chakrabarty et al 2003, Patruno 2010, Papitto et al. 2014, Patruno, BH and Andersson. 2017)

- Spin up halted well before breakup frequency

(Theoretical lower limit on max breakup f ~1200 Hz - BH et al. 2018)

- Disk/magnetosphere interaction?

(White & Zhang 1997, Andersson, Glampedakis, BH & Watts 2006, BH & Patruno 2011, Patruno, D'Angelo & BH 2012, D'Angelo 2016, Bhattacharya & Chakrabarty 2017)

- GWs!: "mountains", unstable modes, magnetic deformations

$$\epsilon \approx 10^{-7}$$

(Bildsten 1998, Andersson 1998, Cutler 2002, BH et al. 06, BH et al. 08, Payne & Melatos 05)

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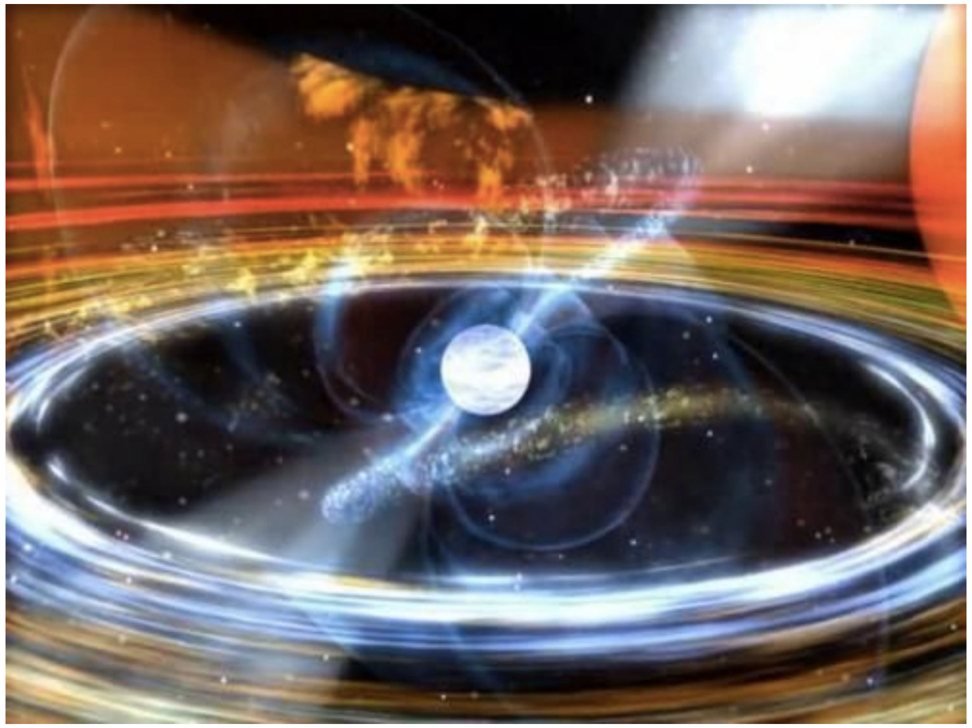

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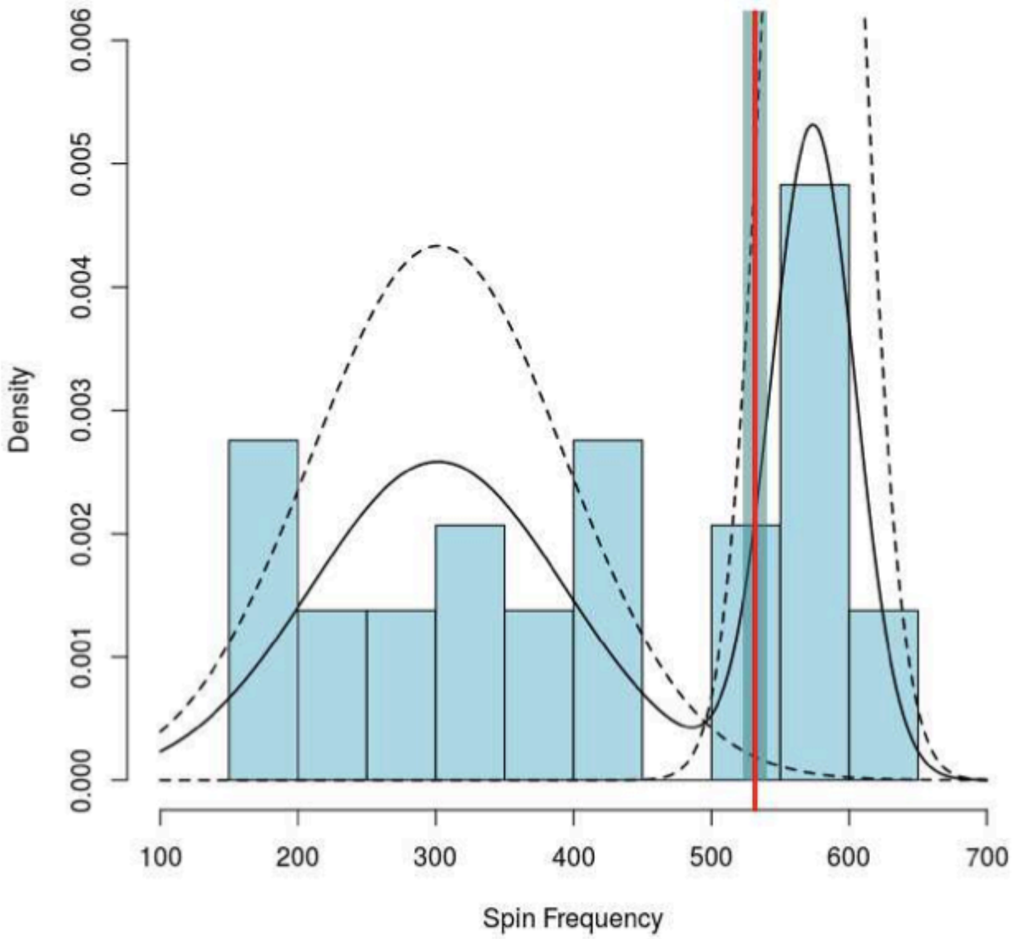
The spin of Low Mass X-ray Binaries



- Spin distribution is bimodal, with a cutoff around 540 Hz
- Slow population widely distributed around 300 Hz

(Patruno, BH & Andersson 2017)

- Ms Radio Pulsar distribution is NOT bimodal, but consistent with the slow population

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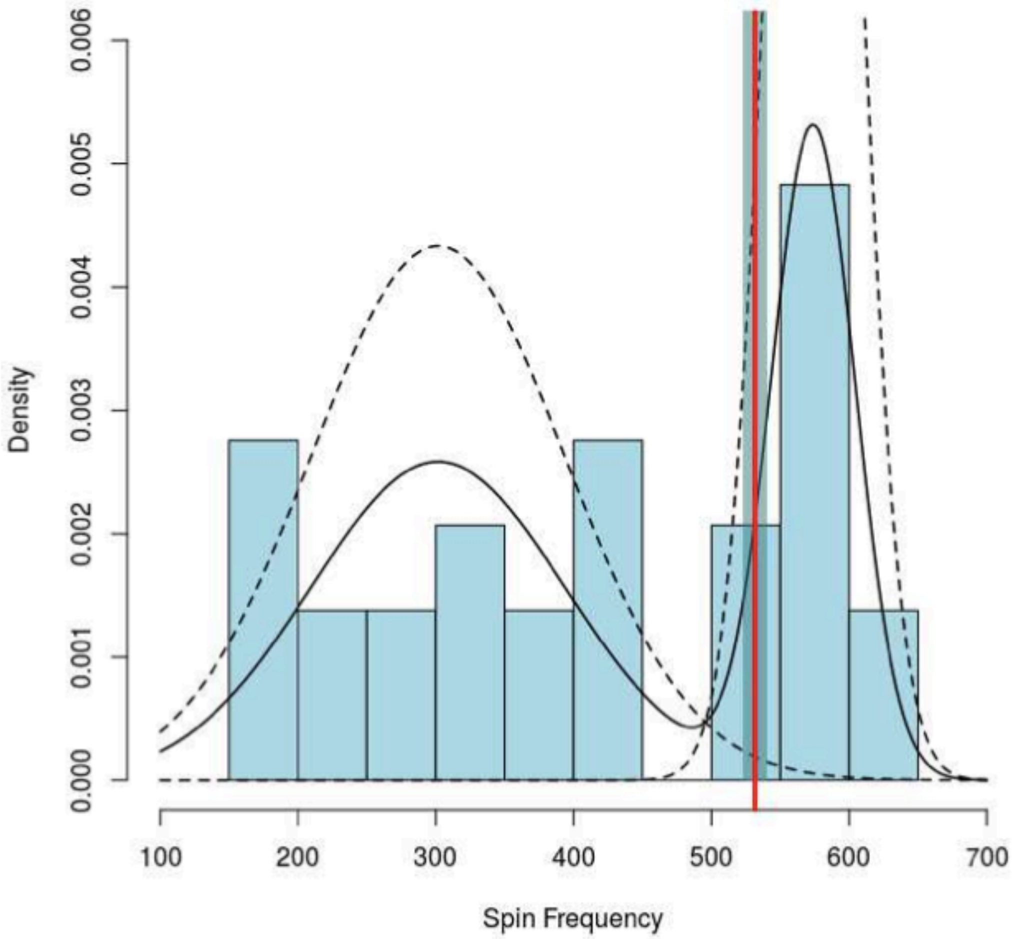

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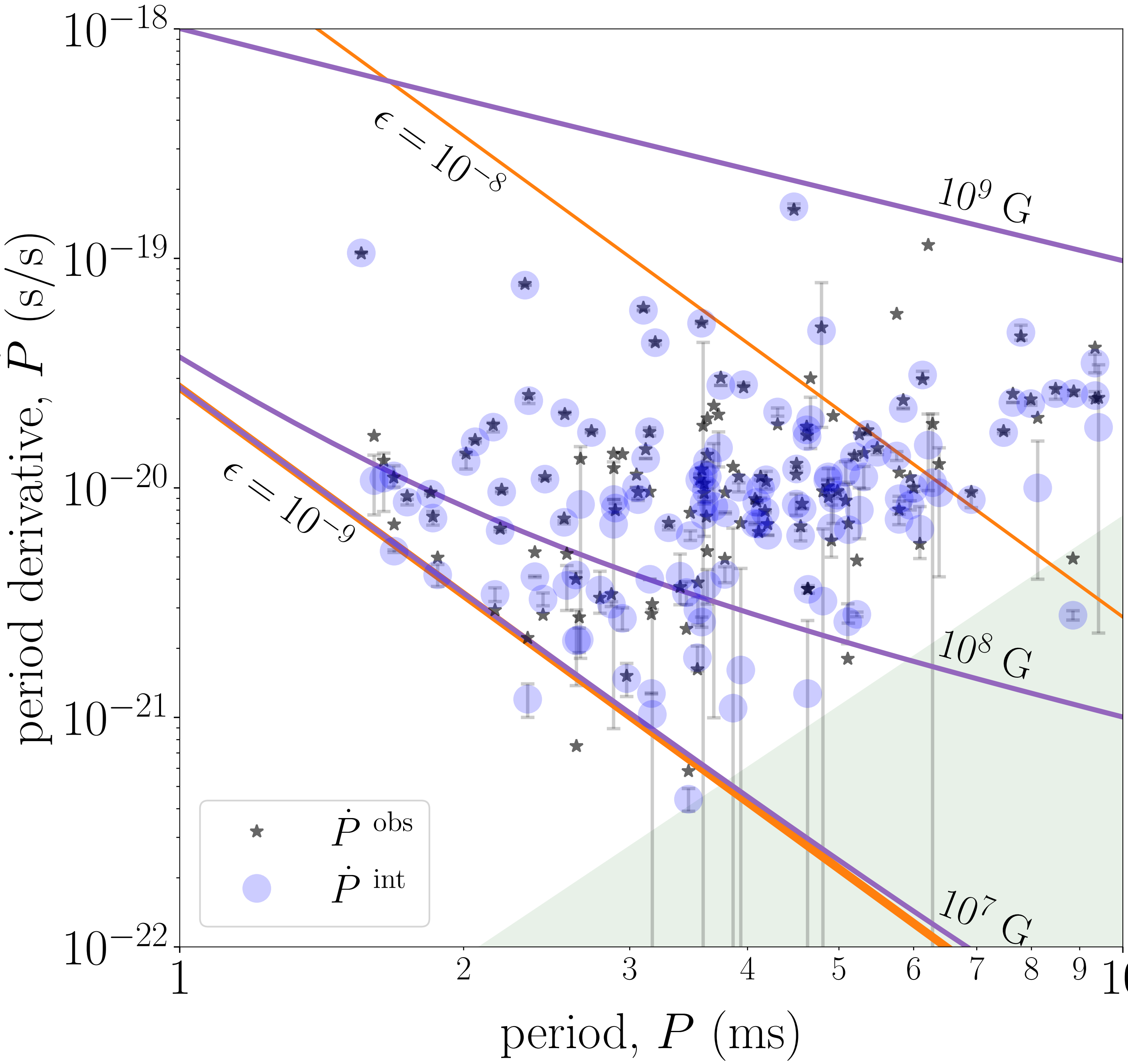
Minimum ellipticity

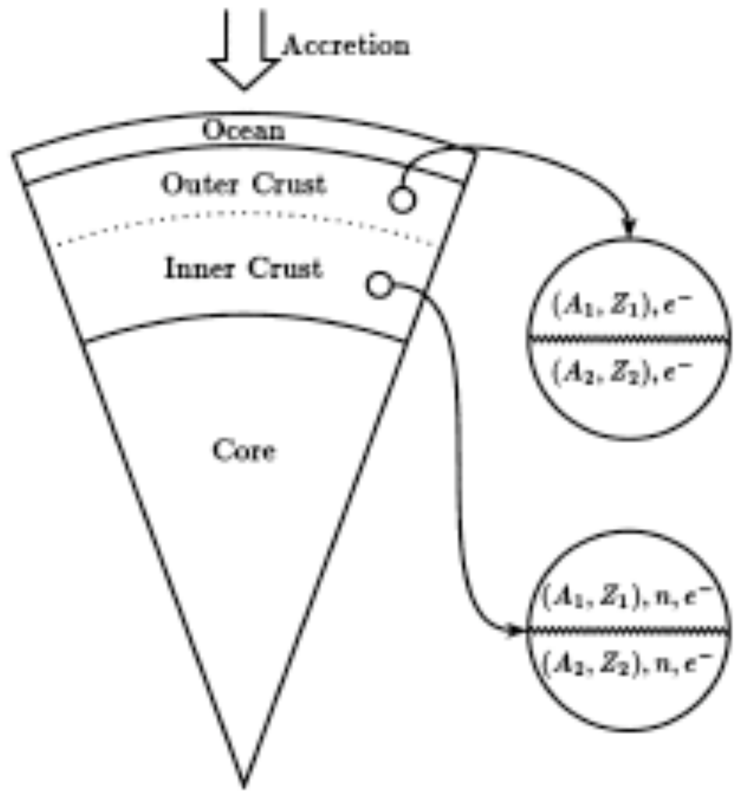


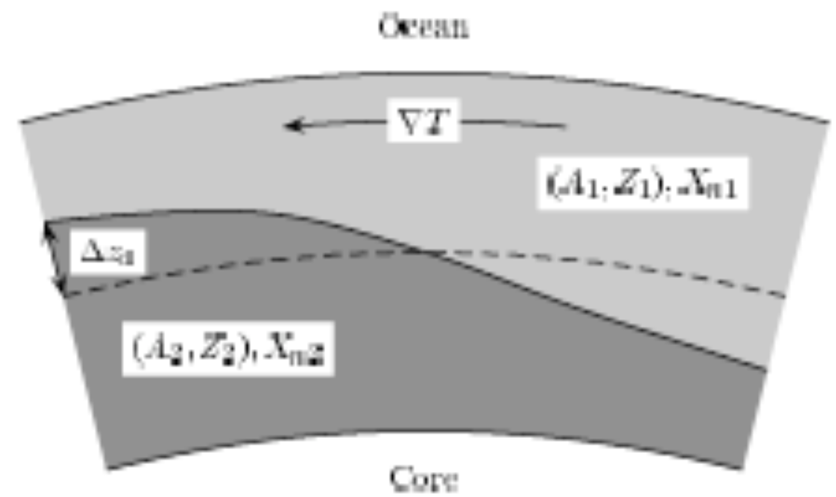
- Evidence for a cutoff in the P-Pdot diagram
- Minimum $\epsilon \approx 10^{-9}$ …. buried magnetic field?

(Woan, Pitkin, BH, Jones & Lasky 2018)

Thermal mountains

- Mountains from 'wavy' capture layers in crust



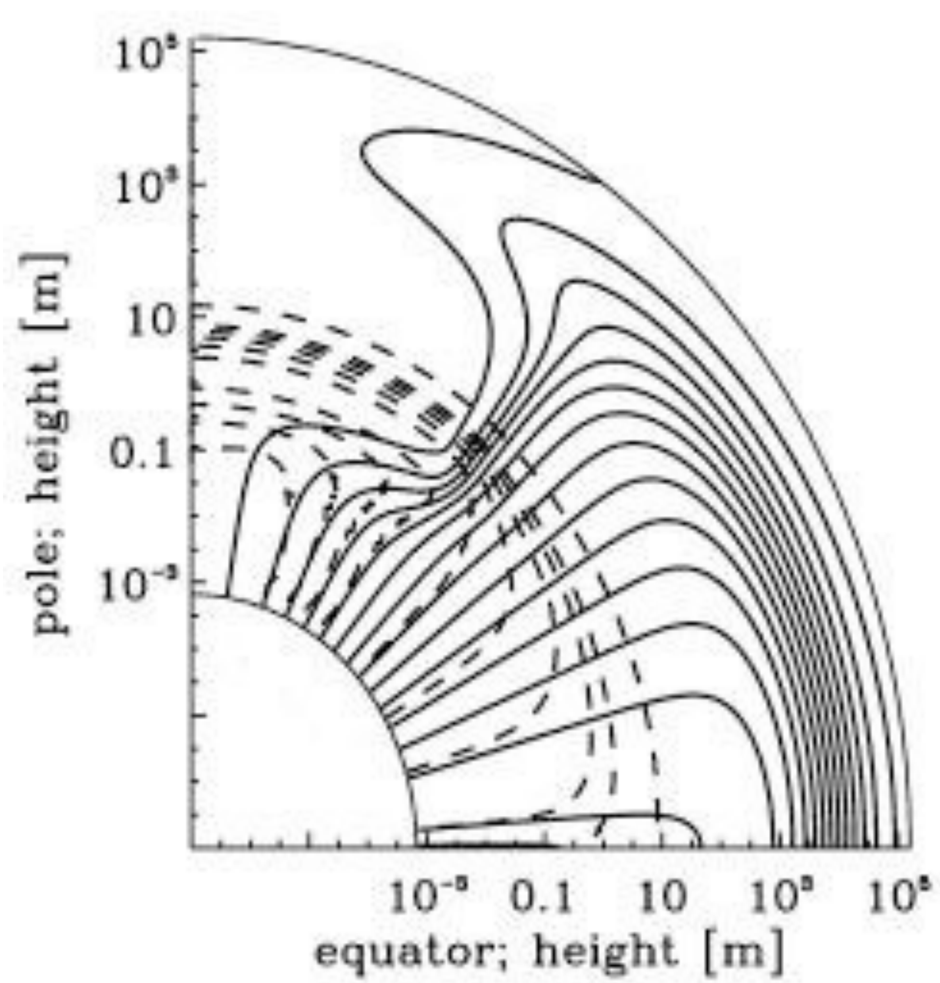


(Ushomirsky, Cutler, Bildsten 2000)

- Deep crustal heating 'consistent' with cooling observations from X-ray transients.

(Haensel & Zdunik 1998, 2008) (Degenaar et al 2015)

Magnetic mountains



- In accreting systems Magnetic field distorted by the accretion flow

- Possibility of confining a 'mountain'

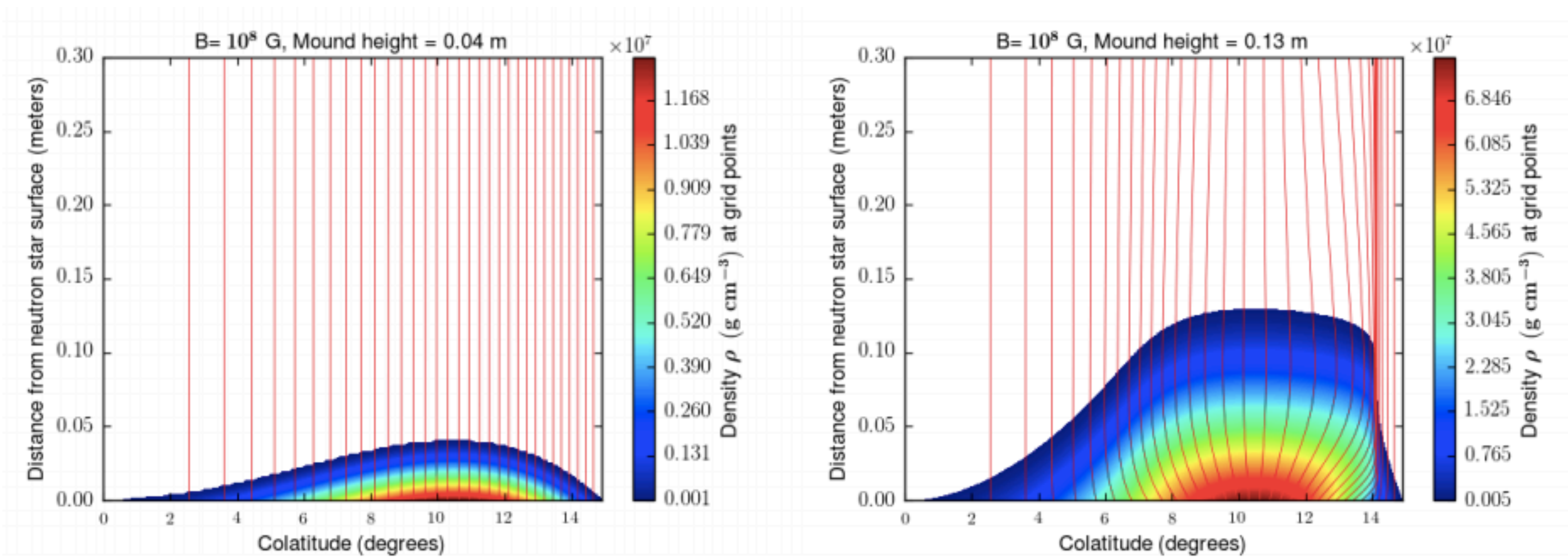
(Payne & Melatos 2005, Priymak et al. 2011, Mukherjee et al. 2012)

- Crustal failure can transfer strain to the quadrupole

(Fattoyev et al. 2018)

Thermal mountains

- Mountains built on magnetised stars during accretion, due both to magnetic support and asymmetric crustal heating due to reactions (BH & Patruno 2017)

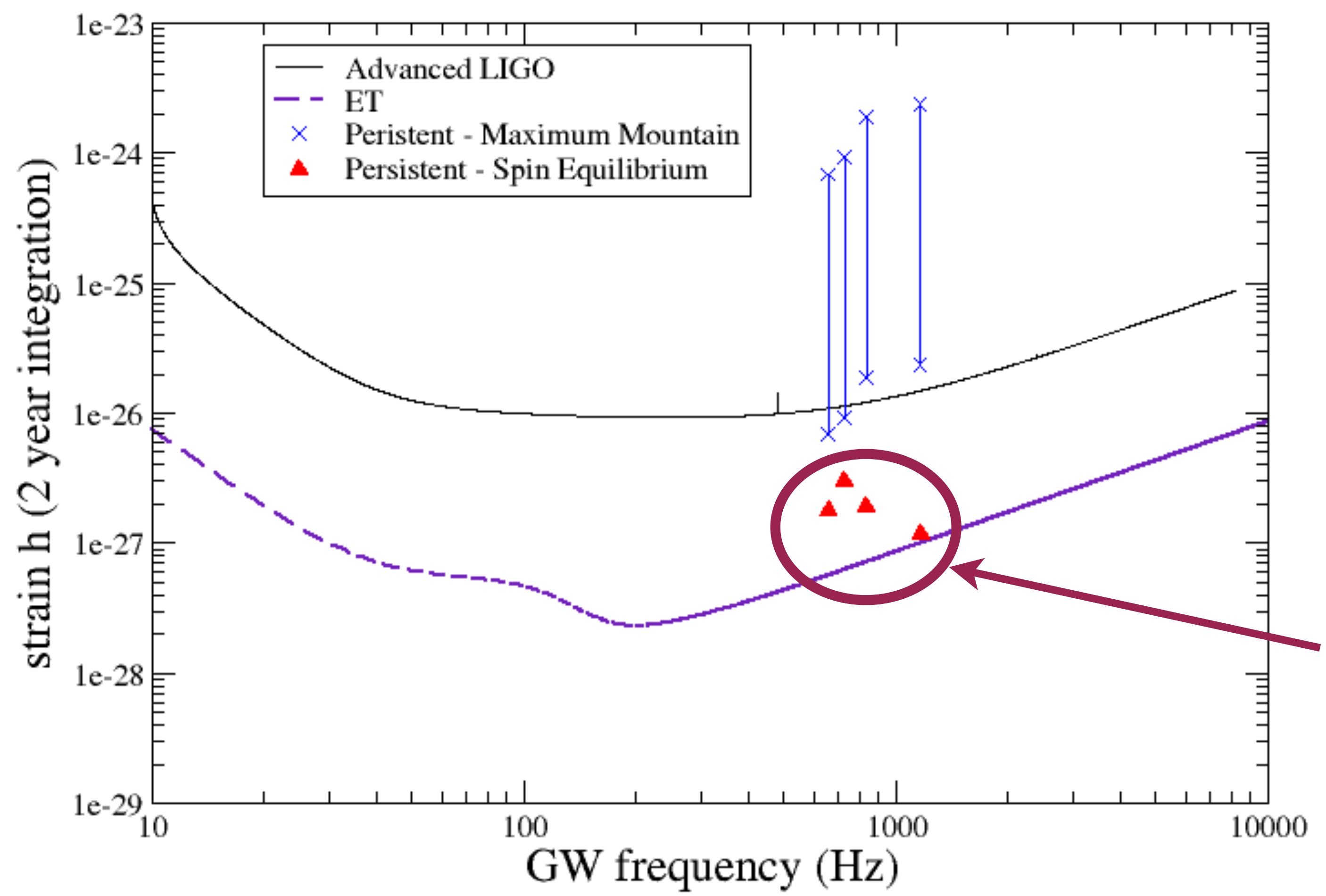


(Singh et al, in preparation)

- To be detectable, mountains need to be built over repeated outbursts - or in persistent sources

Thermal mountains

- Persistent sources promising



Still Tricky!

(Watts et al. 2008)

(BH, Priymak, Melatos, Lasky, Patruno & Oppenoorth, 2015)

Conclusions

- Young pulsars may be spun down by r-modes…evidence for braking index n=7 in J0537?

- Magnetic field sets a minimum ellipticity.

  In mature pulsars $\epsilon \approx 10^{-8} - 10^{-6}$?

- Are gravitational waves setting the speed limit for recycled old pulsars? persistent systems good targets

What about other pulsars?

- Mountain accumulates during outbursts
- Does it dissipate between outbursts?

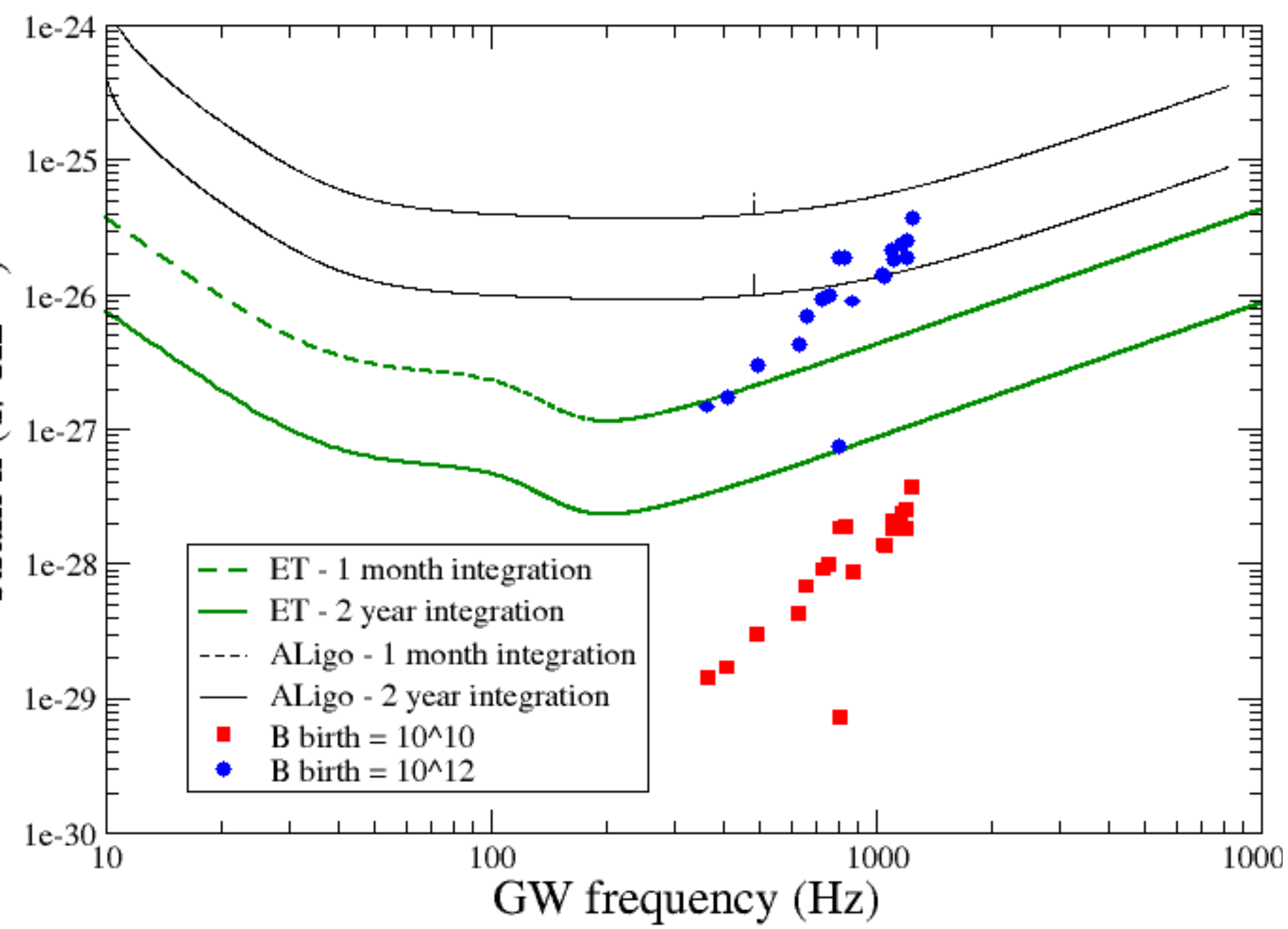
Source	ν (Hz)	d (kpc)	$\langle \dot{M} \rangle$ (10^{-10} M$_{\odot}$ yr^{-1})	Δt (d)	Ref.
SAX J1808.4–3658	401	3.5	4	30	Patruno et al. (2009)
XTE J1751–305	435	7.5	10	10	Miller et al. (2003)
XTE J1814–338	314	8	2	60	this work
IGR J00291+5934	599	5	6	14	Falanga et al. (2005)
HETE J1900.1–2455	377	5	8	3000	Papitto et al. (2013b)
Aql X-1	550	5	10	30	Güngör, Güver & Eksi (2011)
Swift J1756.9–2508	182.1	8	5	10	Krimm et al. (2007)
NGC 6440 X-2	204.8	8.5	1	4	this work
IGR J17511–3057	244.9	6.9	6	24	Falanga et al. (2011)
IGR J17498–2921	400.9	7.6	6	40	Falanga et al. (2012)
Swift J1749.4-2807	518	6.7	2	20	Ferrigno et al. (2011)
EXO 0748–676	552	5.9	3	8760	Degenaar et al. (2011)
4U 1608–52	620	3.6	20	700	Gierlinski & Done (2002)
KS 1731–260	526	7	11	4563	Narita, Grindlay & Barret (2001)
SAX J1750.8–2900	601	6.8	4	100	this work
4U 1636–536	581	5	30	pers.	this work
4U 1728–34	363	5	5	pers.	Egron et al. (2011)
4U 1702–429	329	5.5	23	pers.	this work
4U 0614+091	415	3.2	6	pers.	Piraino et al. (1999)

(BH, Priymak, Patruno, Oppenoorth, Melatos & Lasky 2015)

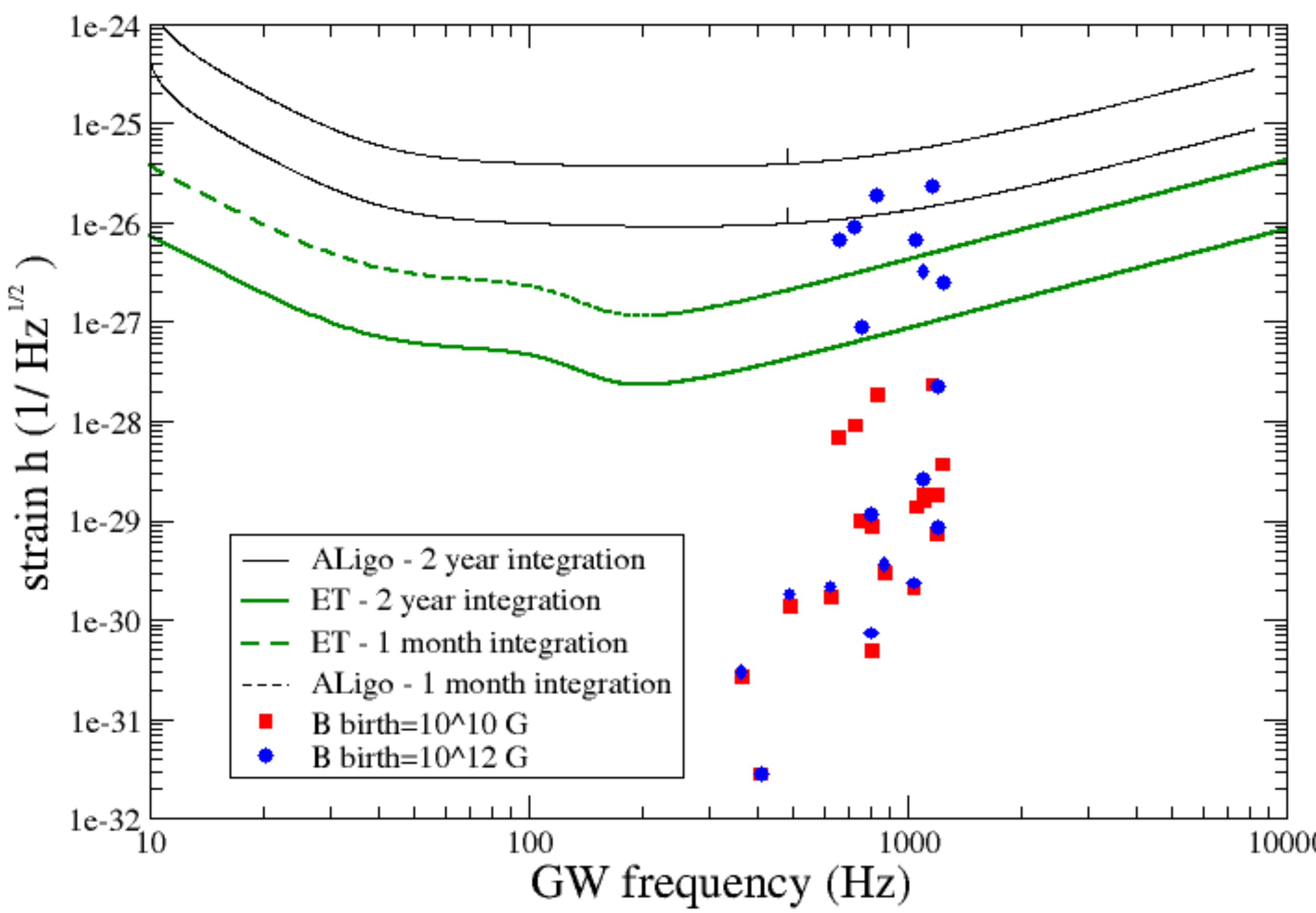
Magnetic mountains

- Only systems with buried fields $B \approx 10^{12}\mathrm{G}$ detectable
- Possible cyclotron features

(BH, Priymak, Patruno, Oppenoorth, Melatos & Lasky 2015)



Maximum



Transient