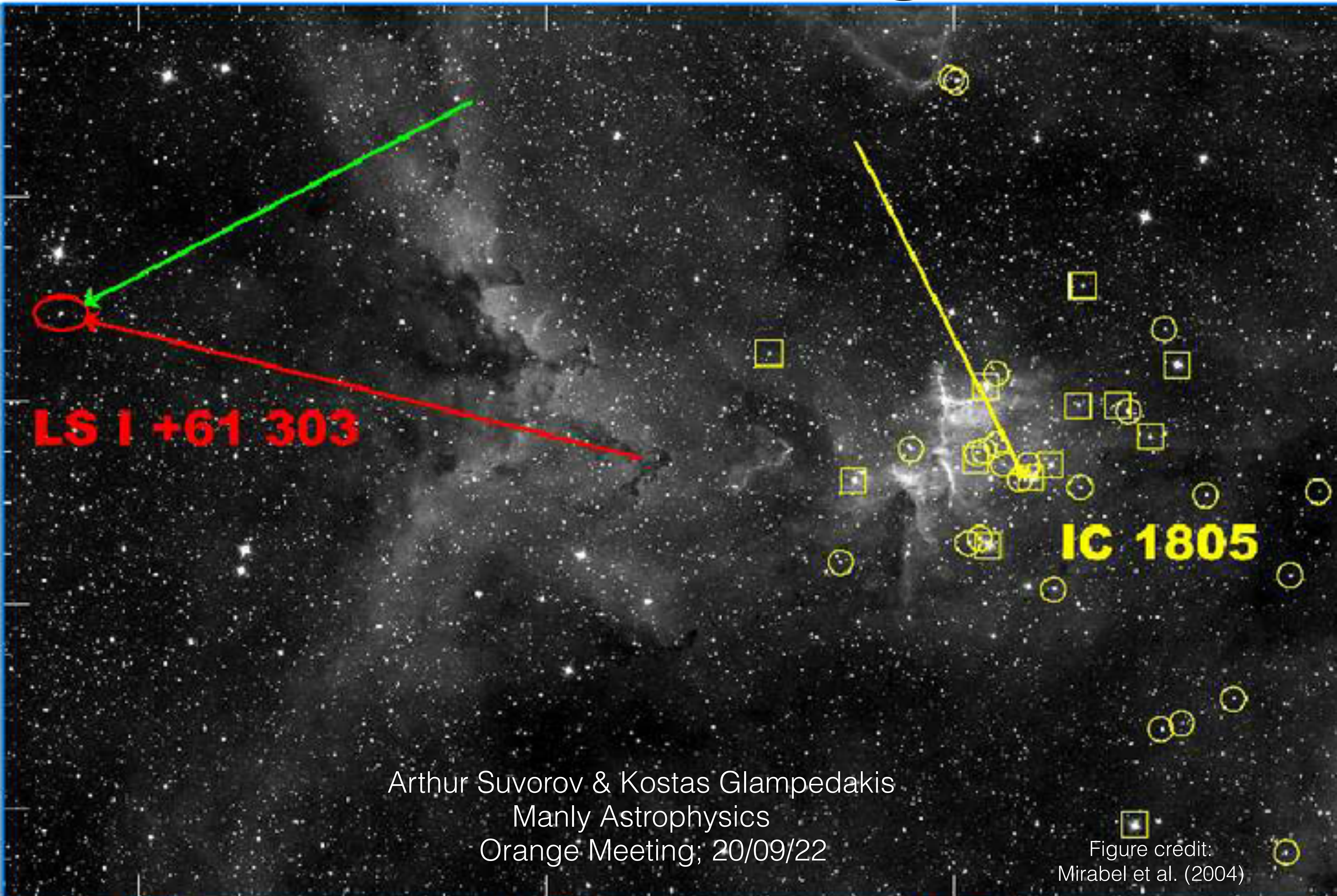
LSI +61°303: Magnetar?



Arthur Suvorov & Kostas Glampedakis

Manly Astrophysics

Orange Meeting; 20/09/22

Figure credit:
Mirabel et al. (2004)

A brief history of the source

1959 — Luminous Stars in the Northern Milky Way catalog Kodak IIa-0 photographic plates taken with the Curtis Schmidt Telescope and UV-transmitting objective prism at the Cerro Tololo Inter-American Observatory; Hardrop et al (1959)

1977 — gamma rays ESA gamma-ray satellite COS B (2CG) catalog Hermsen et al. (1977)

1978 — Highly variable radio source (also outbursts with period 26.5 days); NRAO 91-m transit telescope Gregory & Taylor (1978)

1995 — ROSAT Satellite discovers orbitally-modulated X-rays; Goldoni & Mereghetii (1995)

1999 — VLBI astrometry of the source (Effelsberg, …) determine proper motions (Lestrade et al. 1999); Mirabel et al. (2004) suggest it came from IC 1805 (Heart nebula)

2007 — ~ks long X-ray bursts (~1e35 erg/s; Swift; Esposito et al. 2007)

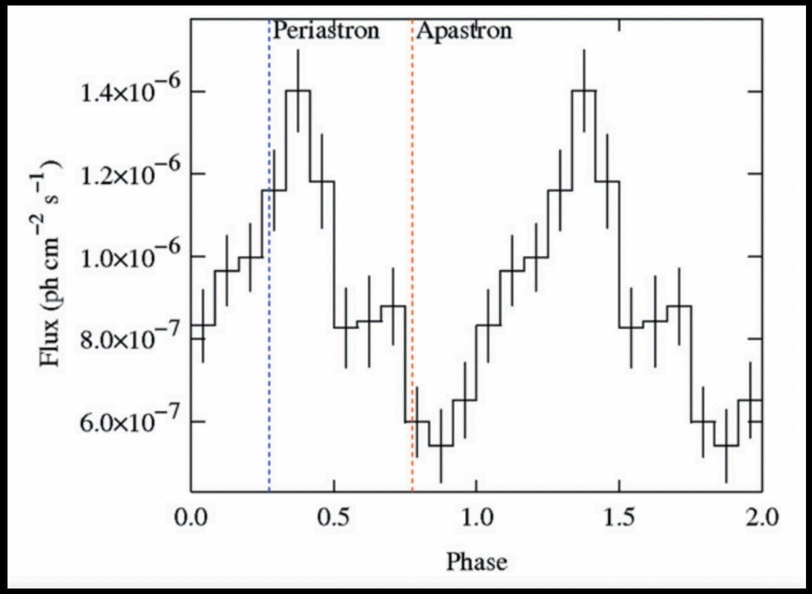
2008 — ~0.1s long soft-gamma flare (~1e37 erg/s; detected by Swift also ; Dubus & Giebels 2008)

2009 — Fermi; first detection of orbitally modulated outbursts at >TeV photon energies (Abdo et al 2009)

2012 — Another ~0.1 long soft-gamma flare (~1e37 erg/s; Burrows et al. 2012)

2022 — Radio pulsations at ~0.269s (FAST; Weng et al. 2022)

Abdo et al 2009 (Fermi)

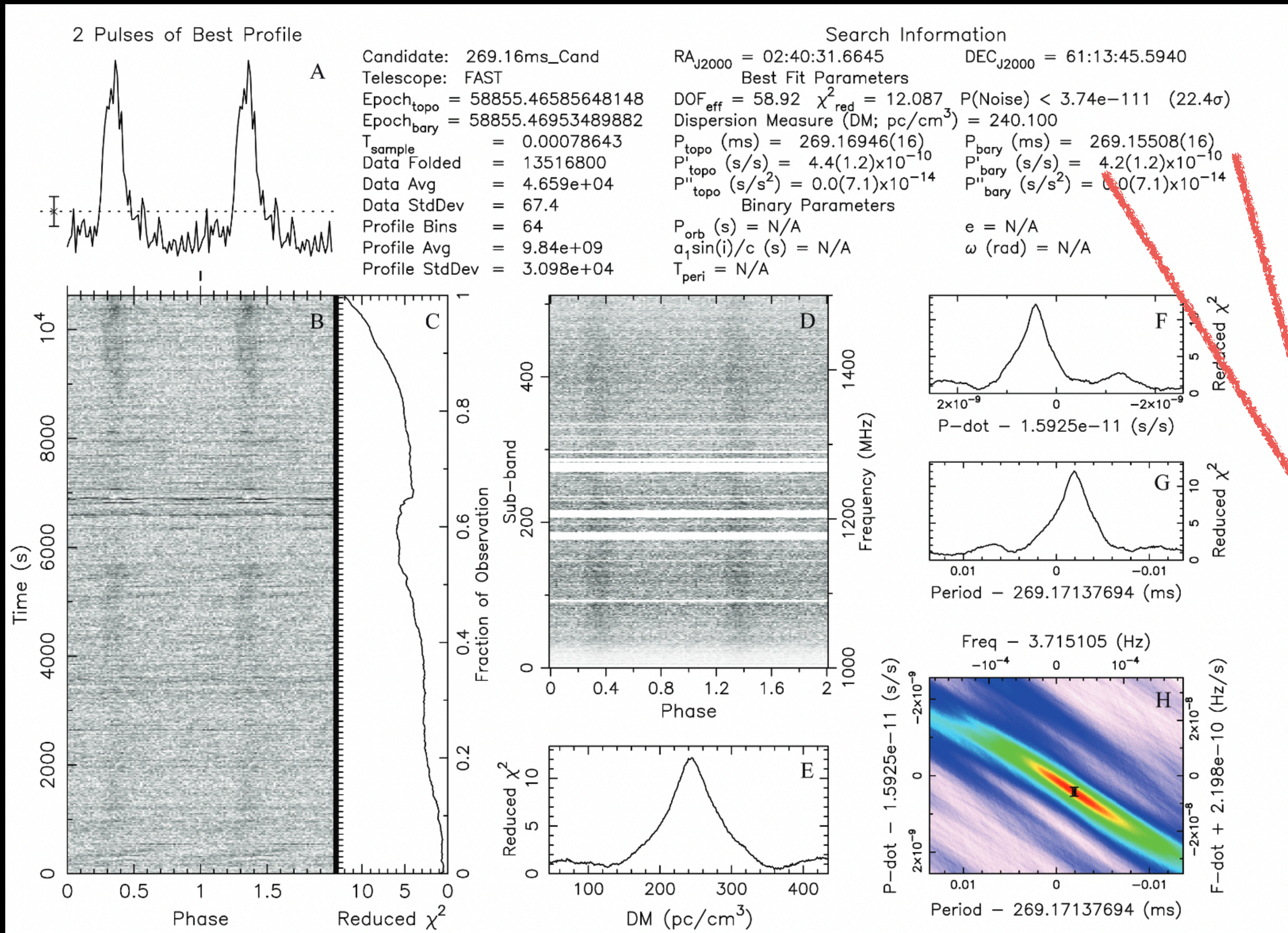


Papitto et al. 2012 (Swift/BAT)

Table 1
Bursts Observed by *Swift*-BAT from LS I +61°303

	Burst No. I[a]	Burst No. II[b]
Date	2008 Sep 10	2012 Feb 5
Position uncertainty	2′.1	3′
Angular separation	0′.60	1′.07
T_{100} (s)	0.31	0.044
Fluence (10^{-8} erg cm^{-2})	1.4 ± 0.6	0.58 ± 0.14
Γ	2.0 ± 0.3	3.9 ± 0.4
Luminosity (10^{37} erg s^{-1})	2.1	6.3

Radio pulsations with FAST



Output from Presto pipeline

Weng et al. (2022)

Bp ~ 7e14G?!

This was obtained by folding data to maximise the signal-to-noise ratio using the prepfold pipeline within the PulsaR Exploration and Search TOolkit (PRESTO) package (Ransom et al. 2002).

Period derivative and its uncertainties are **not** obtained from direct timing. Only 3 hours worth of observations spanning a tight orbital phase (~ 0.58) were taken — unable to recover the Doppler-shift. (THOUGH they say: a preliminary analysis reveals several single pulses on 2021 November 2nd, corresponding to an orbital phase of ~ 0.69. These single pulses share similar properties to those reported here in more detail andfurther support their origin in LS I +61 303).

Acceleration from the binary motion may leave a significant imprint on Pdot that cannot be corrected for with the existing data.

Orbital sol of Casares et al. (2005):

$$|(\Delta\dot{\nu})_{\rm Doppler}| \lesssim \left(\frac{2\pi}{P_{\rm orb}}\right)^2 \times a \times \nu$$

$\sim 2 \times 10^{-9}$ Hz s^{-1} **(Periastron)** $\sim 6 \times 10^{-9}$ Hz s^{-1} **(apastron)**

$$|(\dot{\nu})_{\rm FAST}| = \dot{P}/P^2 \sim (6.1 \pm 1.7) \times 10^{-9}$$

Radio emissions: Death valley physics

- In addition to the primary source of charges plucked from the stellar surface, it is generally put forth that pair production in the magnetosphere is essential for radio emissions in pulsars (& magnetars; Rea++ 2012) $\rho_0 = \nabla \cdot \left(\frac{(\boldsymbol{\Omega} \times \boldsymbol{r}) \times \boldsymbol{B}}{4\pi c} \right) \approx -\frac{\boldsymbol{\Omega} \cdot \boldsymbol{B}}{2\pi c}$

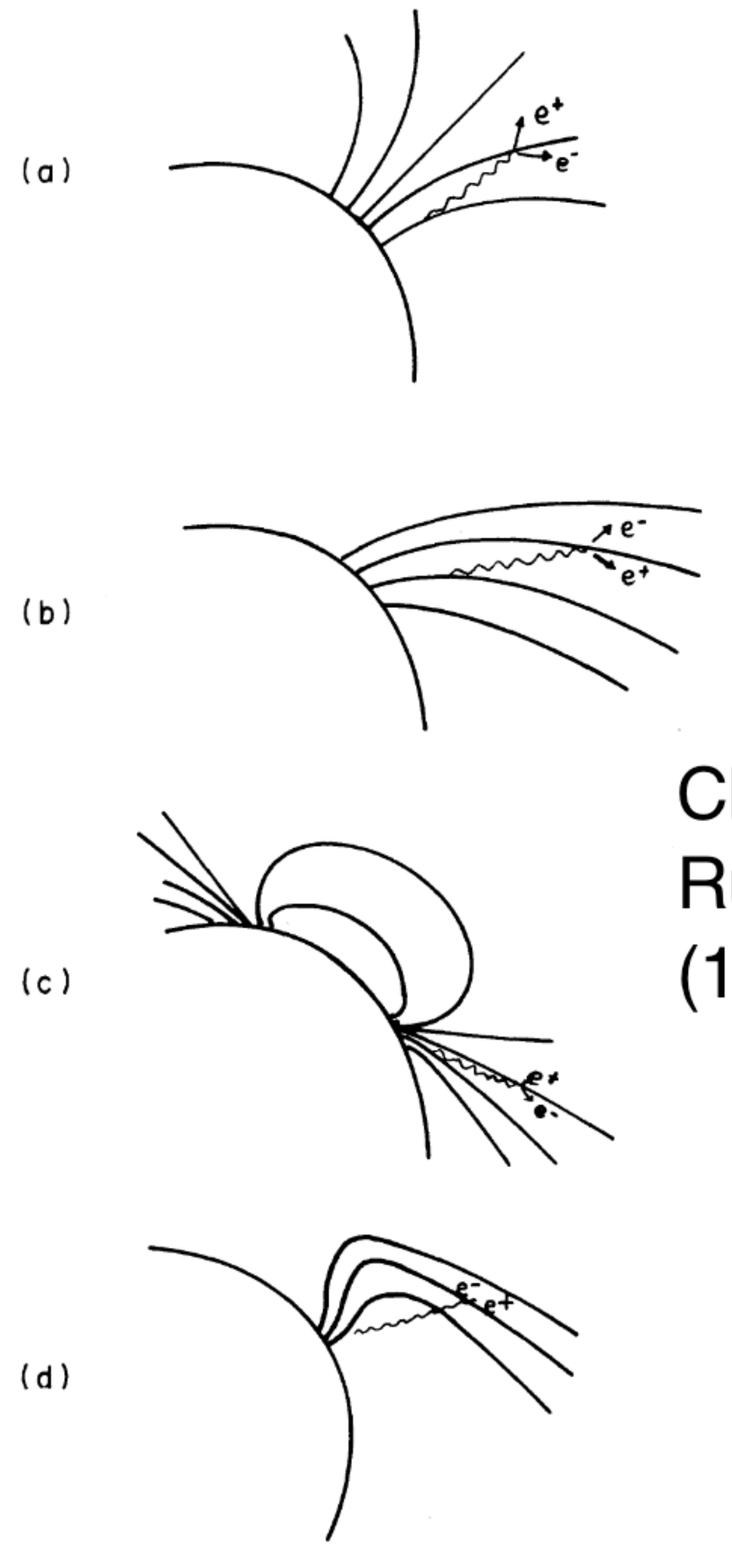
- General picture (though still unsolved in reality; cf. Melrose++ 2021):

- Vacuum/partially-screened gaps form in regions where ρ~0 -> electric fields along magnetic fields in there are strong -> accelerated charges beget photons beget charges -> pair fountain (cf. photon splitting) -> beam instabilities (free energy associated with relative streaming motion transferred to waves) leads to radio emission.

$$\gamma^3 \frac{\hbar c / r_c}{2mc^2} \frac{B_\perp}{B_g} \approx \frac{1}{15}$$

- Key point: one must satisfy

$$\left(\frac{e\Delta V}{mc^2} \right)^3 \frac{\hbar}{2mcr_c} \frac{h}{r_c} \frac{B_s}{B_g} \approx \frac{1}{15}$$



Chen & Ruderman (1993)

FIG. 3.—Several categories of the surface magnetic field structure at the (open field line) polar cap region of pulsars: (*a*) a pure central dipole; (*b*) a very twisted dipole with curvature radius $r_c \sim R$ and $B_s \sim B_p$; (*c*) a sunspot configuration with $r_c \sim R$ and a fixed B_s; and (*d*) an extreme case of twisted surface magnetic field.

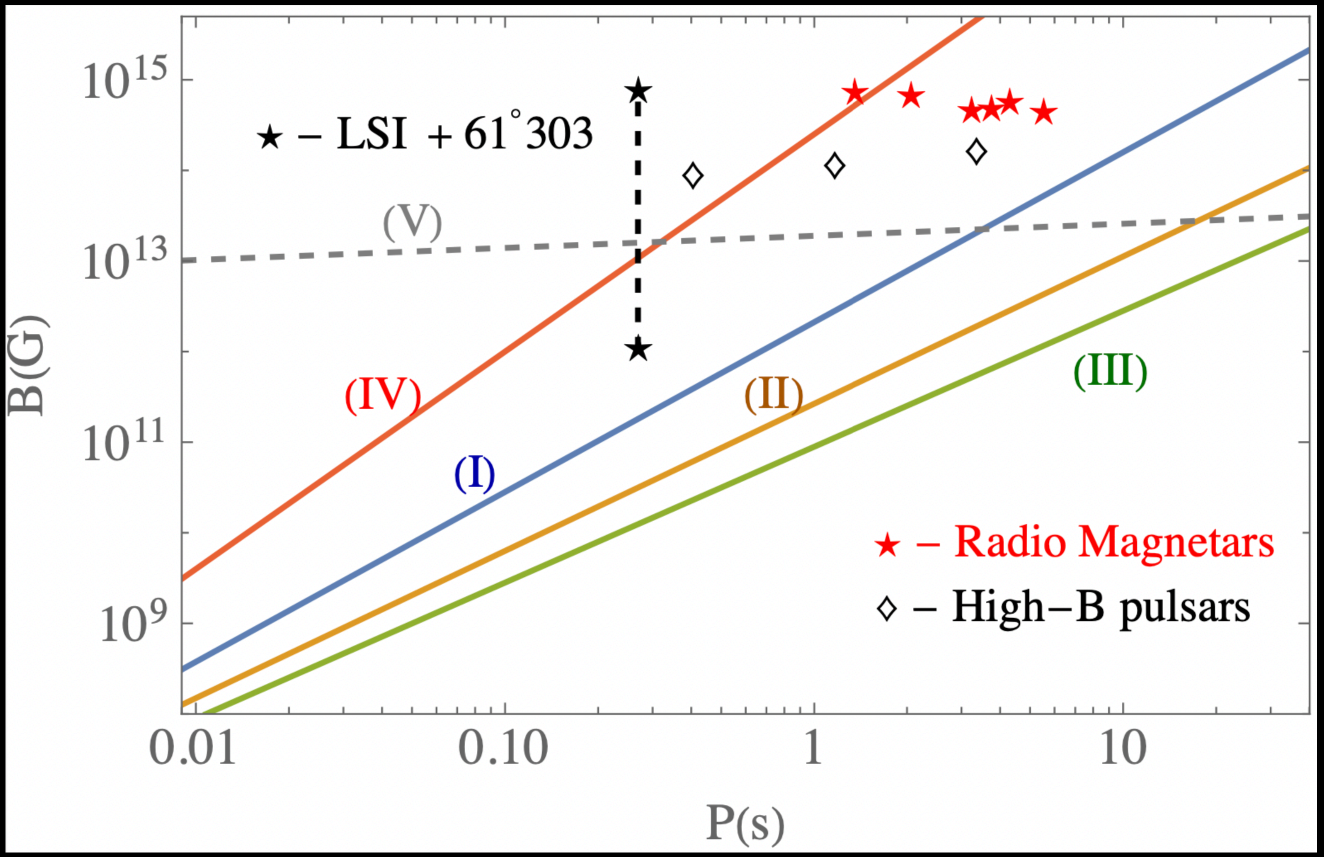
Easy for the source?

- Based on the previous conventional wisdom, it should be easy for the source to “switch on” generically. So why are pulsations only seen now, ~60 years after discovery? Maybe:

- 1) One may argue that magnetic substructures atop the crust (‘starspots’; Zhang, Gil & Dyks 2007) or in the magnetosphere (‘twists’; Beloborodov 2009) may have only recently developed or (Hall-)drifted into regions that are conducive to radio activity; has been observed in other radio magnetars.

- 2) The ram pressure of infalling material may temporarily subside, allowing for the source to activate as a radio pulsar, similar to what is thought to happen for the ‘swinging’ pulsars PSR J1023+0038 and IGR J18245–2452 (Bogdanov et al. 2015; though no X-ray pulses).

- 3) The pulsar beam is most often directed through the wind from the companion, and is regularly quenched because the region is optically thick to free-free absorption; PSR B1259-63 switches off at periastron (Zdziarski, Neronov & Chernyakova 2010)



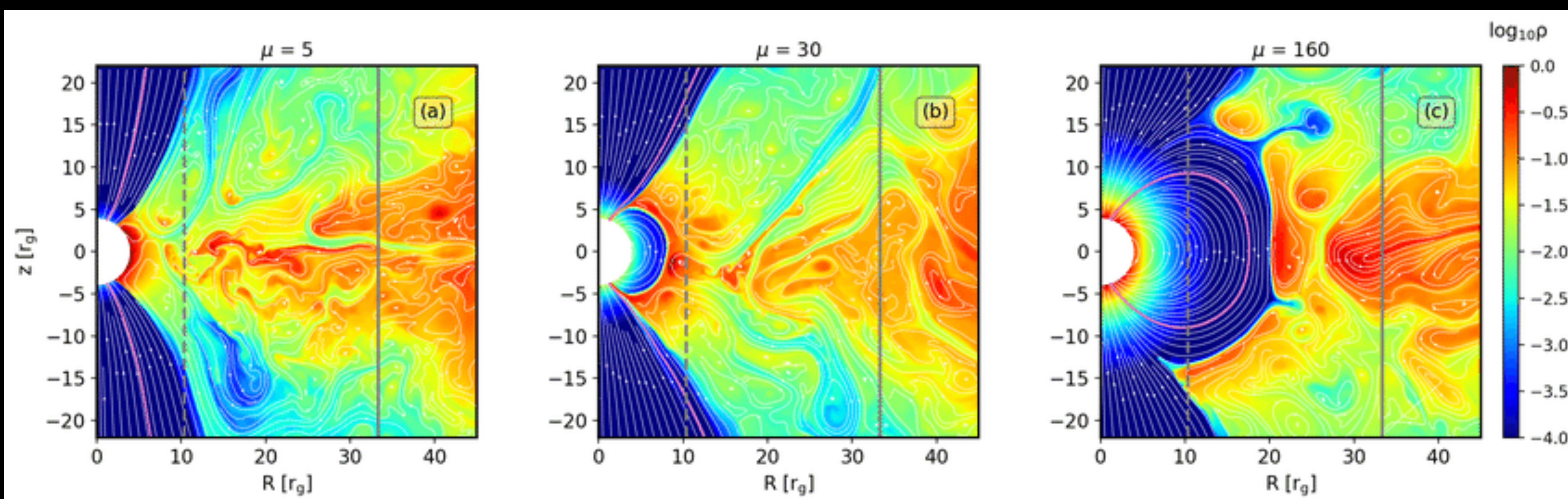
B-P line with radio-loud magnetars and “High-B pulsars” (standard n=3 torque model; Death lines (I)-(III) are inner gap models from Ruderman & Sutherland (1975) and Chen & Ruderman (1994); (IV) is an outer-gap model, and (V) is the photon-splitting threshold from Baring & Harding (2000)

$$\tau_{\rm w,ff} \simeq 5\times10^3 \left(\frac{\dot{M}_{\rm w}}{10^{-8}\,{\rm M}_\odot\,{\rm yr}^{-1}}\right)^2 \left(\frac{v_\infty}{10^8\,{\rm cm\,s}^{-1}}\right)^{-2} \left(\frac{f}{0.1}\right)^{-1} \times \left(\frac{\nu}{1\,{\rm GHz}}\right)^{-2} \left(\frac{T}{10^5\,{\rm K}}\right)^{-3/2} \left(\frac{D}{3\times10^{12}\,{\rm cm}}\right)^{-3}, \quad (13)$$

X-rays: accretion modes

- Depending on the relationship between the accretion rate (i.e., X-ray luminosity), the spin of the neutron star and its magnetic field strength, the mode of accretion could be either:

- (a) boundary layer accreted; (b) pole-channeled, or (c) propeller.



Das et al. (2022)

Matter is force-stopped at the magnetospheric boundary, but if Rco < Rm, the rotating magnetosphere will ‘propeller’ plasma back beyond the capture radius (Illarionov & Sunyaev 1975)

$$\frac{R_{\rm A}}{R_{\rm co}} \approx 289\,\xi\,\frac{R_6^{12/7}B_{14}^{4/7}}{M_{1.4}^{10/21}\dot{M}_{-10}^{2/7}P_{-1}^{2/3}}$$

X-rays: torque models II

- Something of a review for torque models (+some new ones that solve a problem mentioned by Andersson+ +2014 for J00291) is in Glampedakis & AGS (2021) — the truncation of the disc at r ≈ R_A is associated with a material Alfvén torque at the "lever-arm", but:

$$N_{\rm A} = \dot{M} R_{\rm A}^2 \Omega_{\rm K}(R_{\rm A}) = \dot{M}\sqrt{GM_\star R_{\rm A}}$$

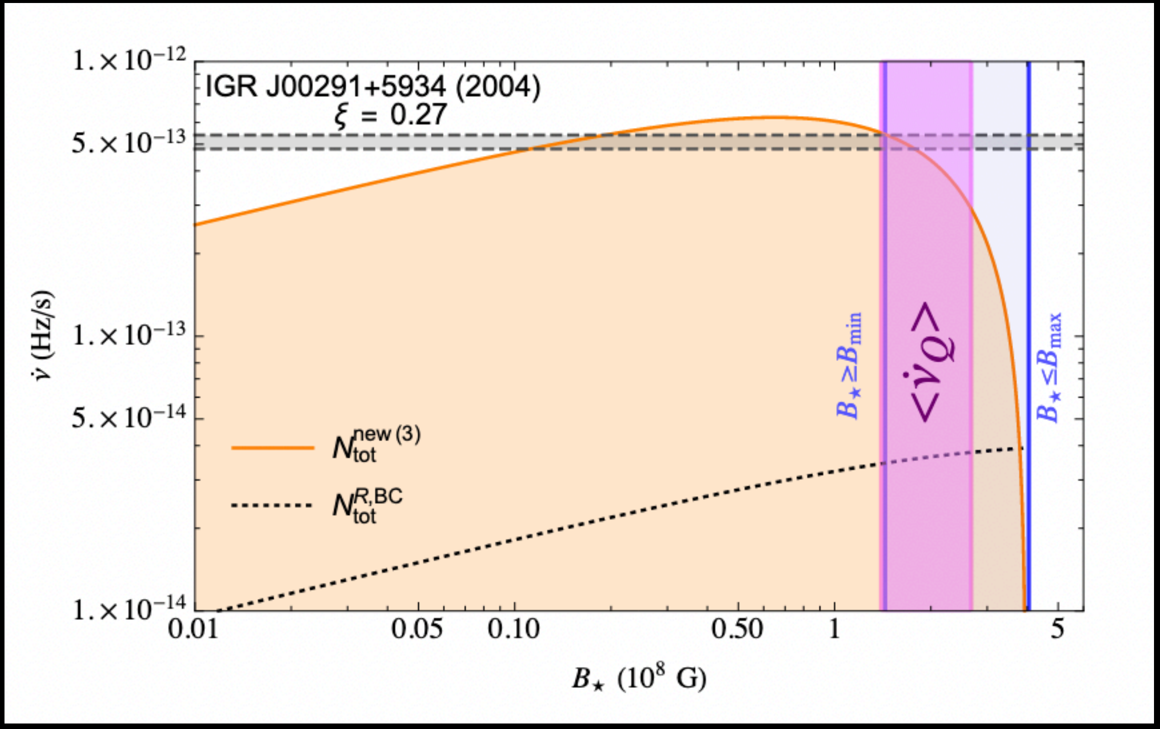
Torque symbol	Functional form	Reference(s)
$N_{\rm A}$	$\dot{M}\sqrt{GM_\star R_{\rm A}}$	(Pringle & Rees 1972)
$N_{\rm m}$	$N_{\rm A}(1-\omega_{\rm A})$	[cf. Andersson et al. (2005)]
$N_{\rm tot}^{\rm W(2)}$	$\frac{1}{3}N_{\rm A}(7/2-4\omega)(1-\omega)^{-6/7}$	(Wang 1995)
$N_{\rm tot}^{\rm W(3)}$	$\frac{1}{3}N_{\rm A}(7/2-4\omega+\omega^2/3)(1-\omega)^{-6/7}$	(Wang 1995)
$N_{\rm tot}^{\rm R,BC}$	$\frac{2}{3}N_{\rm A}(2-\omega_{\rm A}+\frac{1}{3}\omega_{\rm A}^2)$	(Rappaport, Fregeau & Spruit 2004) (Bhattacharyya & Chakrabarty 2017)
$N_{\rm tot}^{\rm A}$	$\frac{1}{3}N_{\rm A}(7/2-7\omega+3\omega^2)(1-\omega)^{-6/7}$	(Andersson et al. 2005)
$N_{\rm tot}^{\rm new(3)}$	$\frac{2}{3}\xi^{-7/2}N_{\rm A}\left[\frac{1}{2}(1+3\xi^{7/2})-\omega_{\rm A}+\frac{1}{3}\omega_{\rm A}^2\right]$	This paper
$N_{\rm tot}^{\rm new(2)}$	$\frac{1}{3}\xi^{-7/2}N_{\rm A}(1+3\xi^{7/2}-2\omega_{\rm A})$	This paper

- Induction-generated toroidal fields imply that the magnetic field lines threading the disc generate an additional accretion torque N_{disc} exerted on teutron star: depends on the "fastness" controlling Rco/Rm.

$$\partial_t B_\varphi = |\nabla \times (\mathbf{v}\times\mathbf{B})|_\varphi$$

$$N_{\rm disc} = -\int_{R_{\rm m}}^{\infty} dr r^2 B_\varphi B_z .$$

- Depending on boundary-layer assumptions, N can be large.

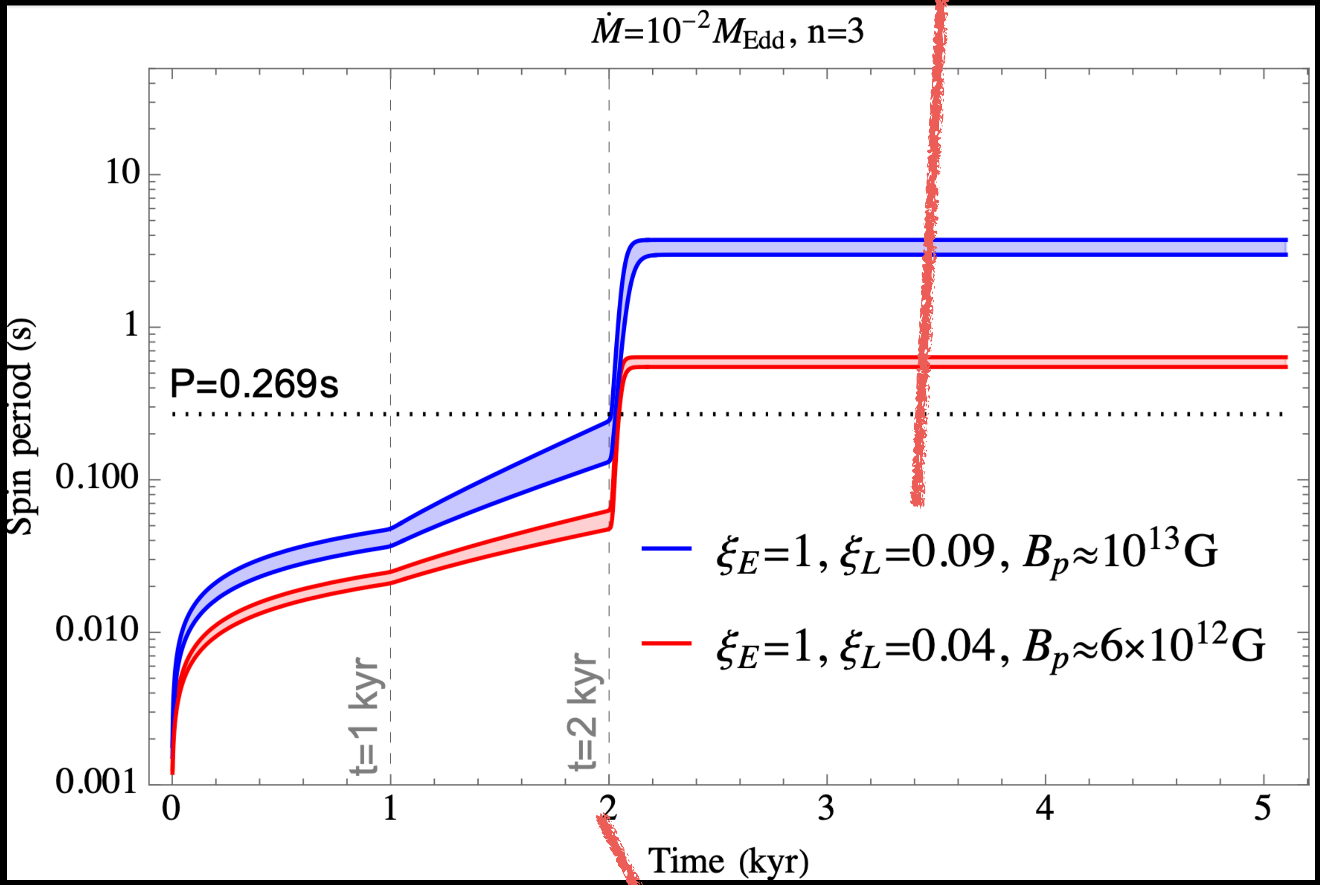


Glampedakis & AGS (2021)

Even with large Pdot...

- Rather in a reverse fashion, since the torques can be substantially larger depending on what complicated physics is taking place near the boundary layer, the propeller torque can also be large.
- This implies that even if we accept such a large Pdot, it is possible that a propeller torque makes up for the bulk of the observed spin down -> non-magnetar.
- Such a situation is complicated if the system switches between propeller and accreting often, but just considering one such “switch” at a fiducial time of ~5kyr, a large Pdot could be explained, especially if we allow for a non-dipole intrinsic torque

Depends critically on the size of the magnetospheric radius



AGS & Glampedakis (2022; in prep).

Switching time

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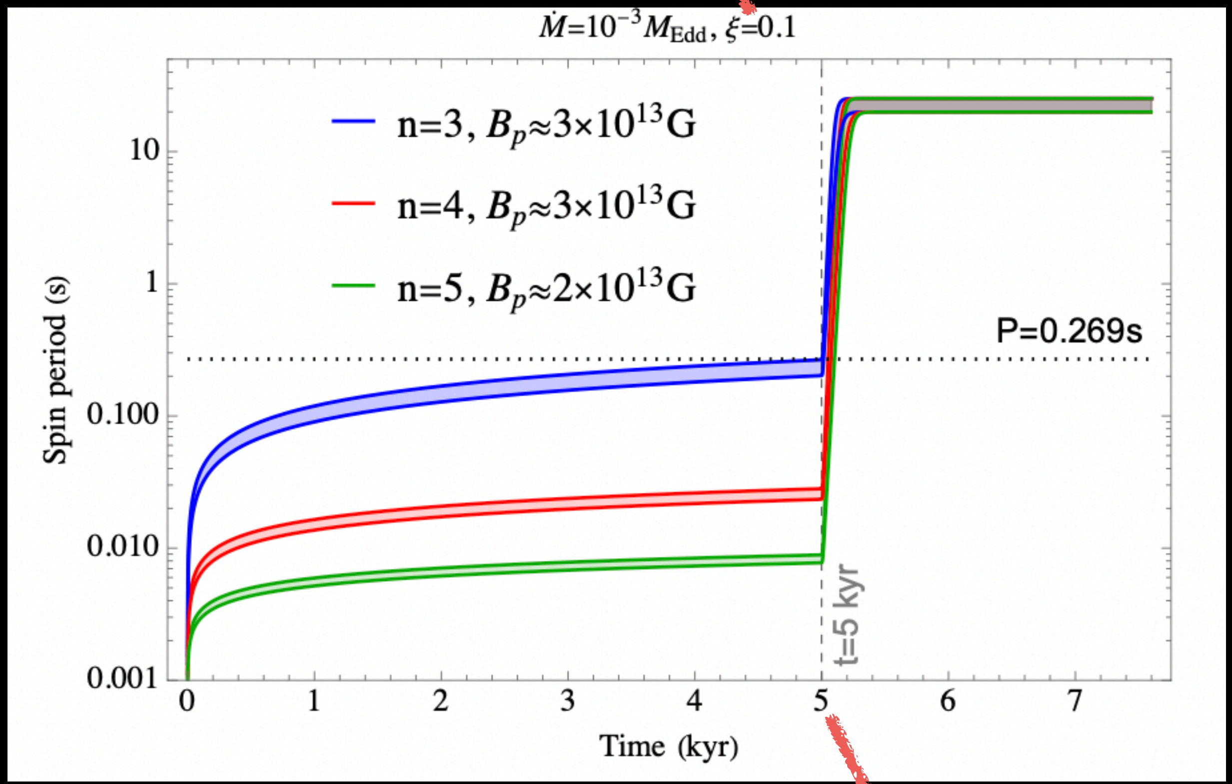


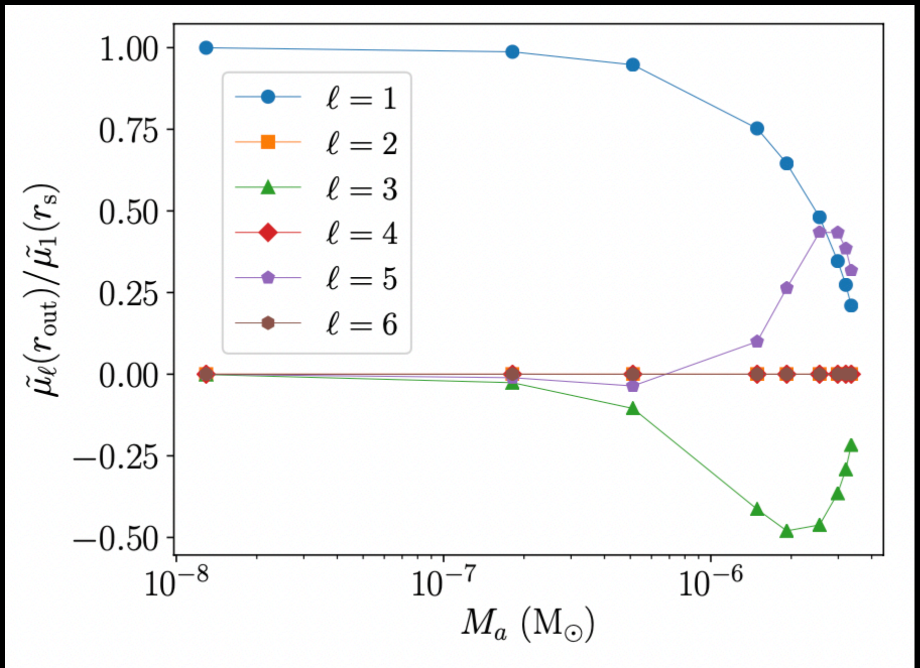
AGS & Glampedakis (2022; in prep).

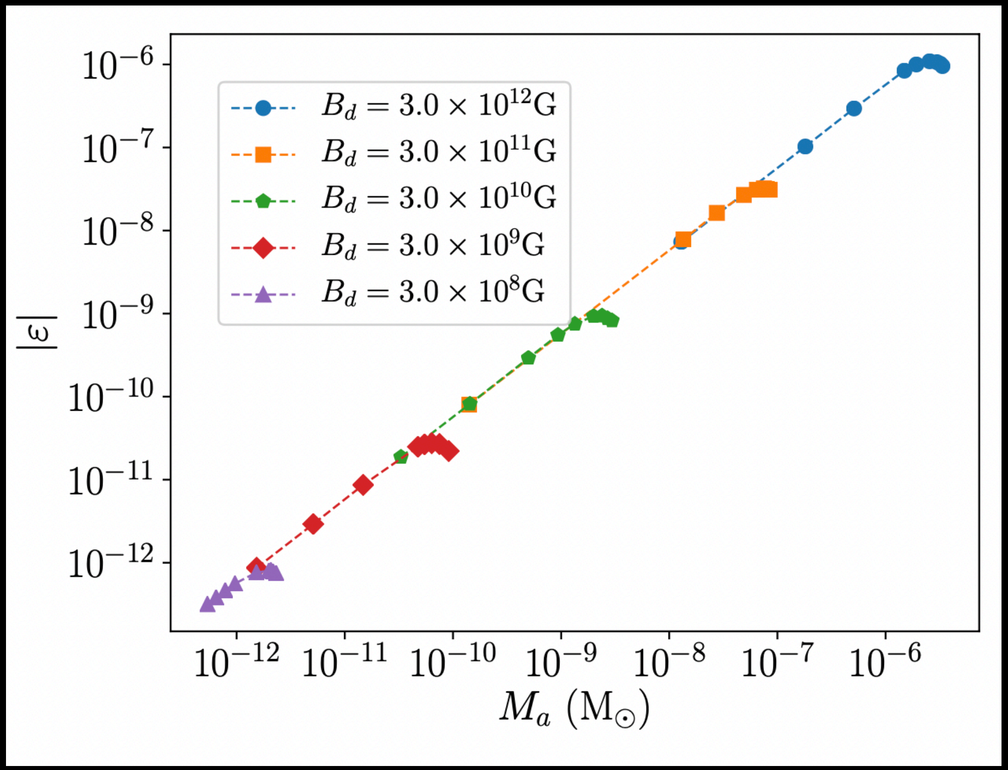
Switching time

What about magnetars in binaries, generally?

- King & Lasota (2019) argue that magnetars in binaries should be rare: the most natural evolutionary scenario involves one member from a binary star (e.g., of class OB) undergoing core collapse and, eventually, leaving behind an X-ray binary with a magnetar primary. Large angular momentum reserves may be necessary to entice dynamo activity in the proto-star to generate internal magnetic fields exceeding ~ 1e15 G (Thompson & Duncan 1993). In this case the supernova will be especially powerful, likely destroying the companion, leaving only an isolated magnetar.

- Magnetic burial is another consideration: if the system accretes matter, the magnetic field will reduce as field lines are "buried" under the infalling matter (e.g., AGS & Melatos 2019,2020). If the system was forever in propeller its hard to explain a large age, while if it often accretes then it is very difficult to sustain a large dipole moment (cf. gravitational waves also).

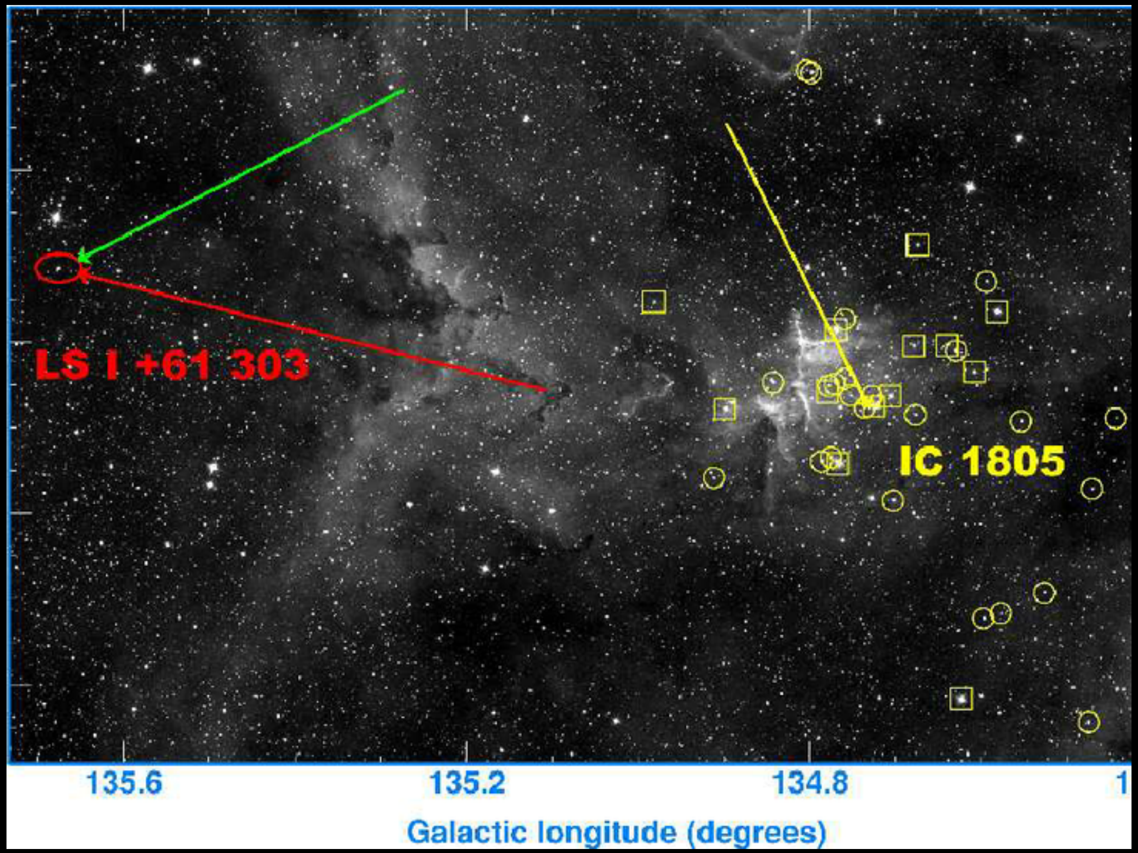




Fujisawa et al. 2022

Age limits on source?

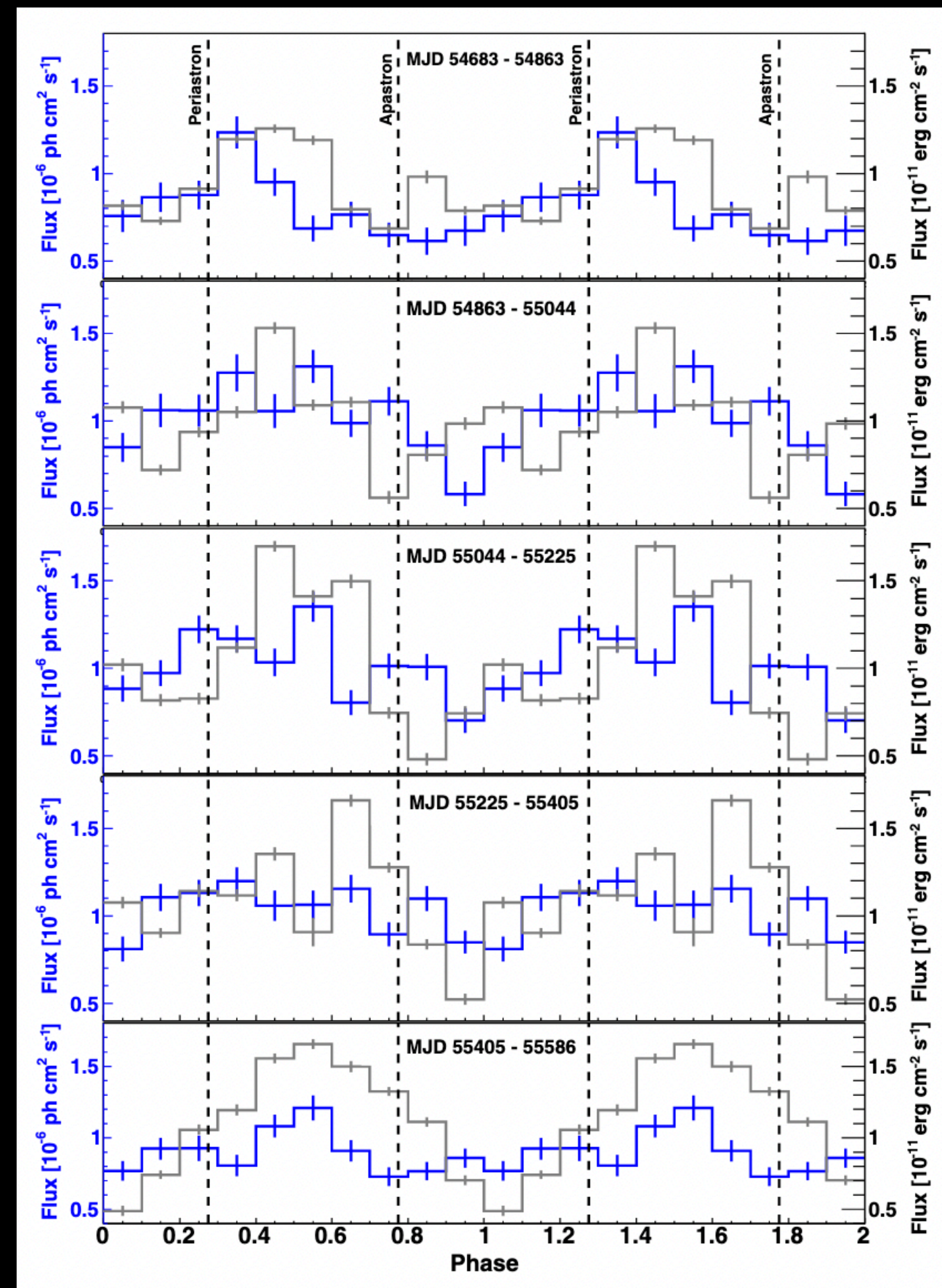
- The lack of an associated supernova remnant for LSI implies a likely age > **few kyr** (Papitto et al. 2012).
- Based on its kinematic velocity relative to the Heart Nebula cluster IC 1805, Mirabel et al. (2004) argue that LSI was ejected from there ≈ **1.7 ± 0.7 Myr** ago. Such an age is not unusual for binaries involving neutron stars, though is virtually impossible to accommodate with a (present-day) sub-second magnetar scenario, as spindown and field decay prevent old objects from being both fast and strongly magnetised simultaneously.



Mirabel et al. (2004)

Gamma-rays: observations

- Correlations between X-rays (black) and gamma-rays (blue) show complicated, quasi-periodic modulations (overlaid with super orbital variabilities).
- Explanations for the observed X-ray luminosity, varying between ~1e33 and ~1e34 erg/s, is relatively straightforward with standard models
- The gamma-rays, on the other hand, require something a bit different: what causes this unusual feature?



Hadasch et al. (2012)

Gamma-rays: Fermi processes?

- Fermi processes are a possible candidate: As put forth by Bednarek (2009a,b), electrons can be accelerated in the turbulent, transition region near the boundary of the Alfve´n surface through stochastic “bouncing” events

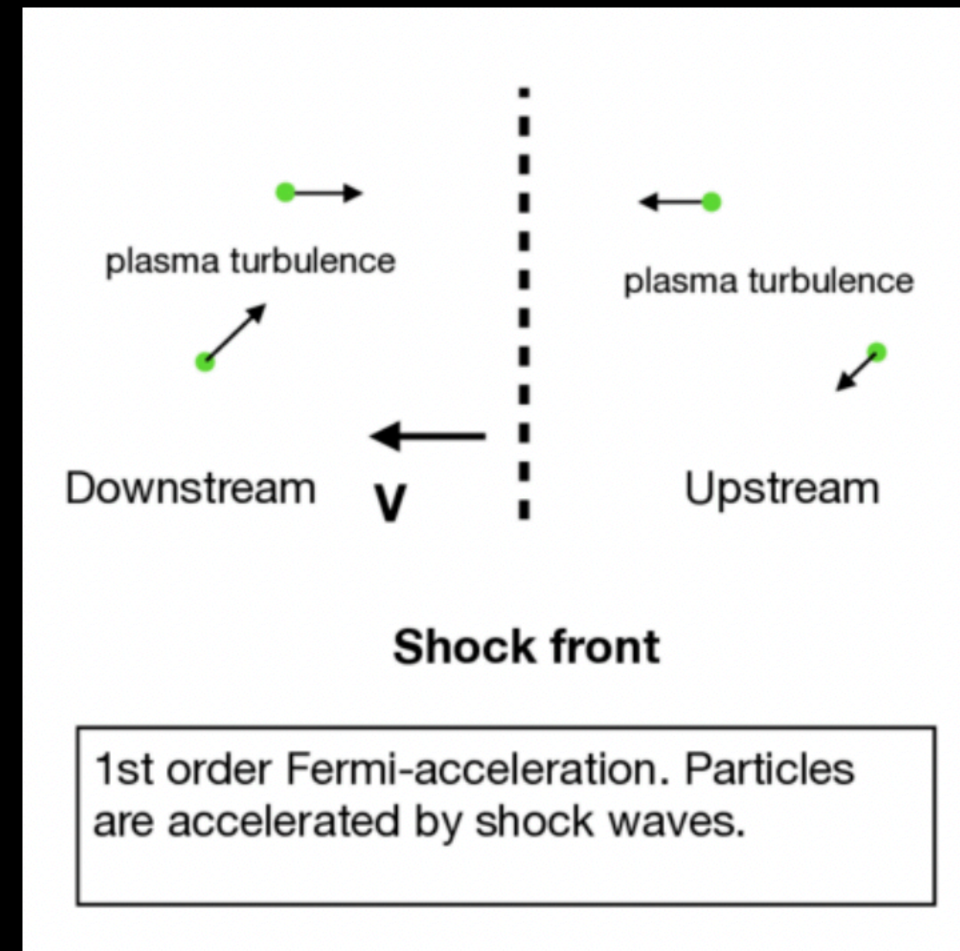
$$\dot{P}_{\rm syn} \approx \frac{4c\sigma_T \rho_A \gamma^2}{3},$$

$$\dot{P}_{\rm acc} = \zeta c E / R_{\rm Lar} = \zeta c e B$$

- Energy is lost through Synchrotron processes, implying a maximum Lorentz factor for the particles.

In general, the relativistic electron energy, $E = \gamma m_e c^2$ for mass m_e, acquires a $\sim$ TeV value for $\gamma_{\rm TEV} \sim 2 \times 10^6$. Demanding that $\gamma_{\rm max} \gtrsim \gamma_{\rm TEV}$, we obtain the inequality

$$B_{14} \gtrsim 0.15 \left(\frac{M_{1.4}^{3/14} \dot{M}_{10}^{3/7}}{R_6^{15/14} \zeta_{-1}^{1/2} \xi^{3/2}} \right)^{14/5} \left(\frac{\gamma_{\rm TEV}}{2 \times 10^6} \right)^{14/5}.$$

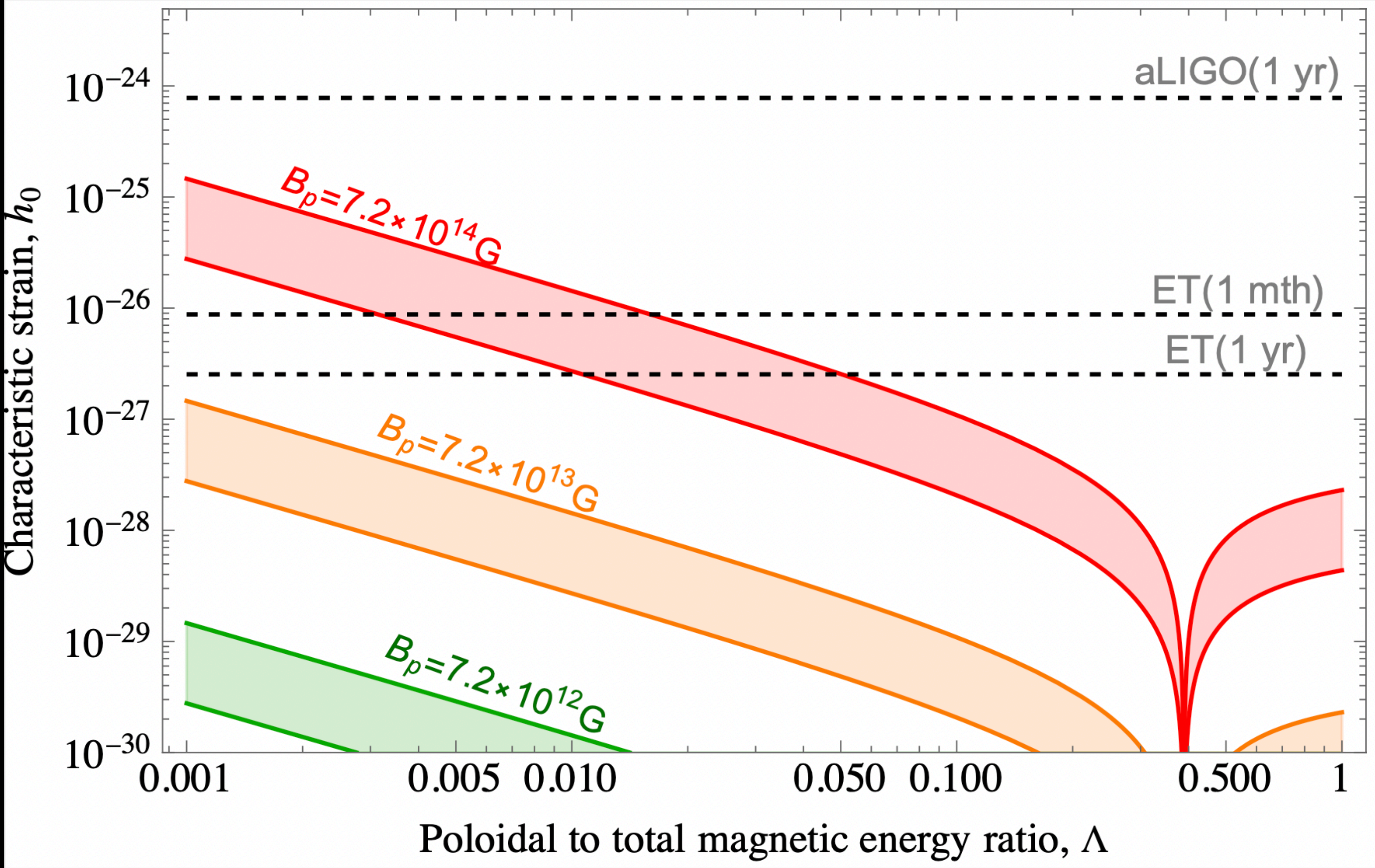


Punchline: if ξ is too small, synchrotron losses prevent the system from emitting high energy particles, while if it is too large the system cannot spin down fast enough. Overall, therefore, polar field strengths of order ~1e13 or larger seem to be required for LSI. If relativistic shocks dominate the acceleration process at the magnetospheric radius however (i.e., if ζ « 1; Khangulyan et al. 2007) then magnetar-level fields appear to be necessary.

Gravitational waves

- If indeed a sub-second magnetar, or even with a strong toroidal field in order to explain the short bursts, the source could be bright in GWs.
- With aLIGO or ET though, phase-coherent search still seems unlikely to detect them, unless core is superconducting (boost the lines up by ~an order of magnitude).
- Future upper limits would go a long way to probing the toroidal field, which could be responsible for the soft-gamma flares (Perna & Pons 2011).

$$\epsilon \approx 6 \times 10^{-6} B_{p15}^2 R_6^4 M_{1.4}^{-2} \left(1 - \frac{0.389}{\Lambda}\right)$$

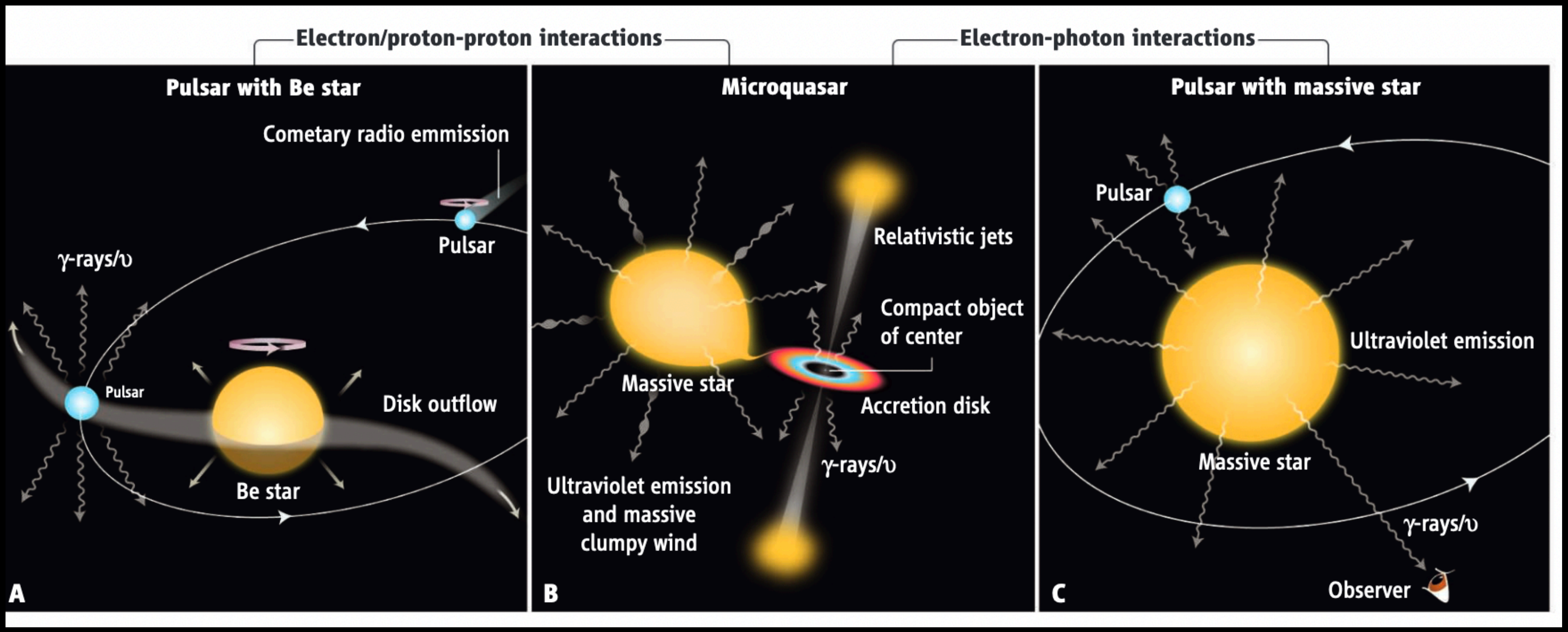


AGS & Glampedakis (2022; in prep).

If there is an accreted mountain also, could be visible to ET!

Summary

- What can we actually say? That a neutron star is there!
- Conventional wisdom suggests radio switch-on is easy: likely impeded by free-free absorption by the companion wind blocks the beam, but if its “intrinsic” it could be related to magnetic field evolution in a magnetar
- Even huge Pdots cannot point to magnetar necessarily — situation is complicated by age considerations, both suggesting magnetar unlikely
- Whence the TeV outbursts? Efficient Fermi acceleration can match predictions, again if Pdot is much smaller; this also matches observations of PSR J2032+4127 and PSR B1259– 63
- Soft-gamma flares? Toroidal field could be responsible, since its decay can be much slower if it penetrates into the core (am bipolar diffusion)



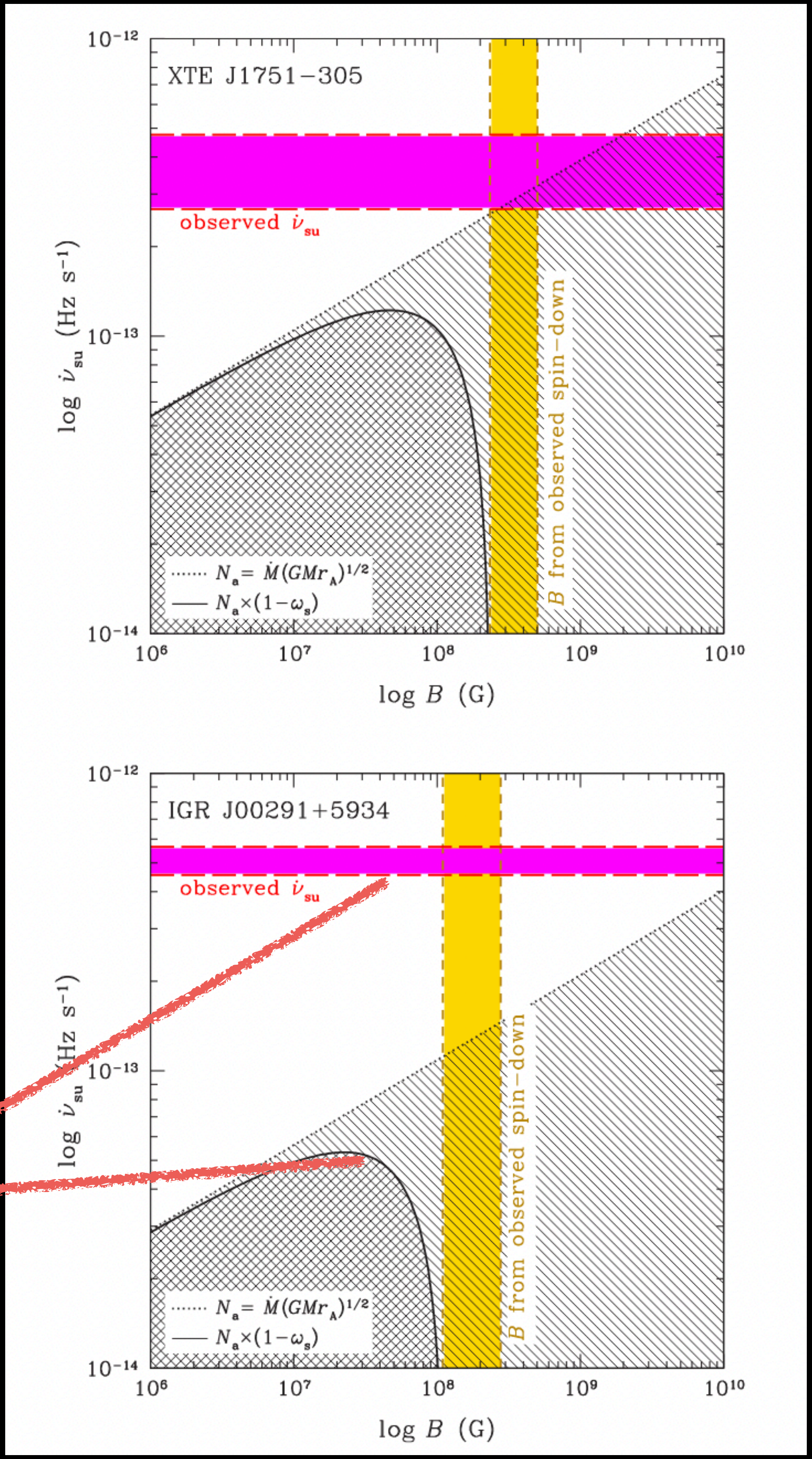
Mirabel (2012) — the first picture!

X-rays: torque models

- Andersson et al. (2014) noted that contemporary accretion models could not account for spin-up of IGR J00291+5934 (v = 599 Hz) which, in 2004, went into outburst. A mean spin-up of vdot ~ 5e-13 Hz/s, was recorded with a mean X-ray luminosity L~3e36erg/s.

- Standard expressions imply an implausibly large (surface!) magnetic field (B ~ 1e11G), inconsistent with the field inferred from quiescent spin-down and other observations.

Can't match!



Andersson et al. (2014) — contemporary spin-up models could not account for the observed spin period