A population of ultra-long period magnetars and its links to fast radio bursts

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ARCO

Astrophysics Research Center
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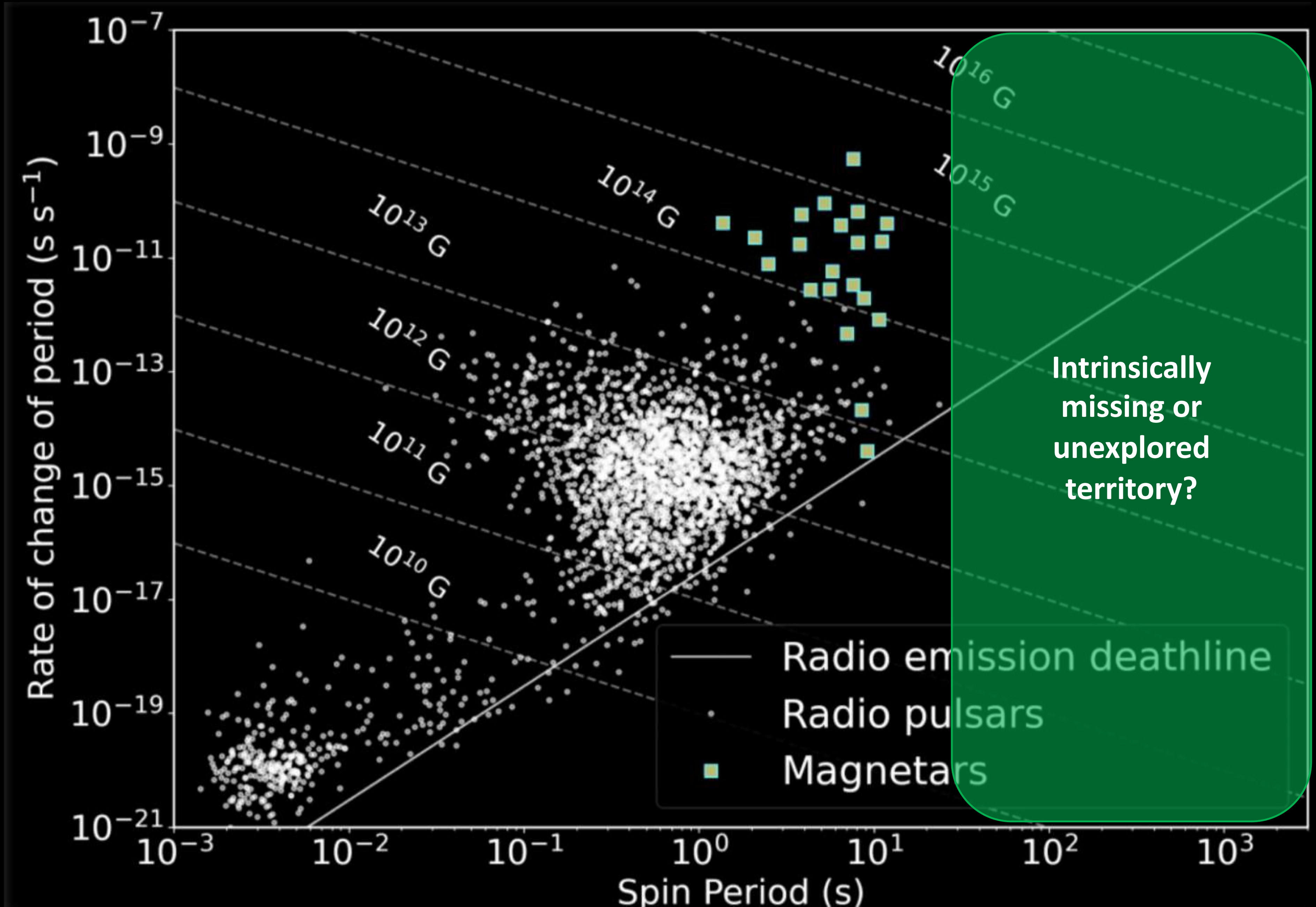
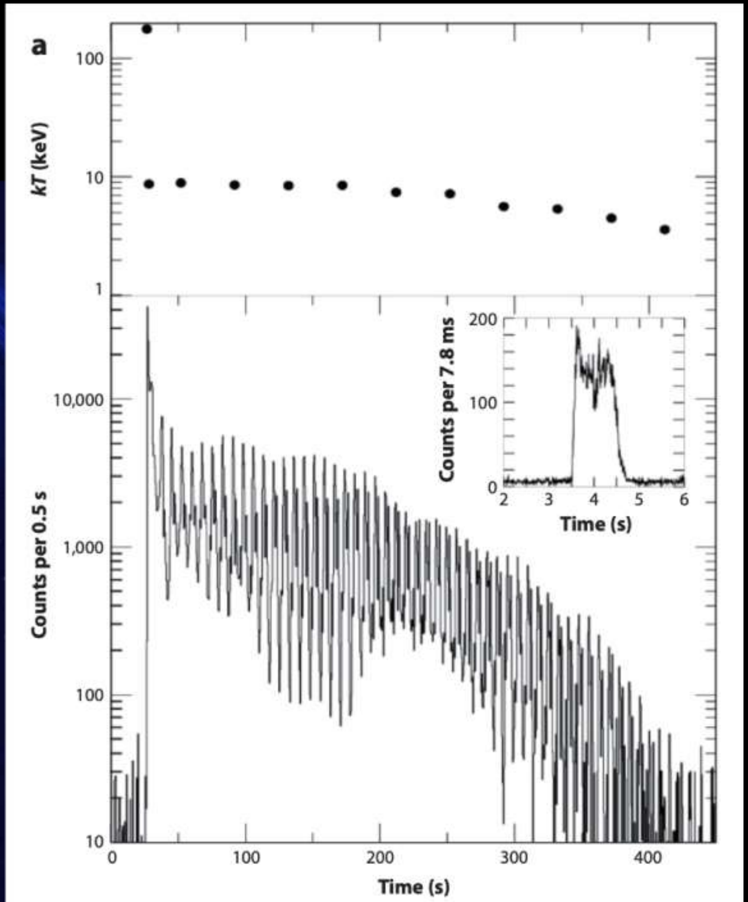
Unexplored parameter space in radio astronomy

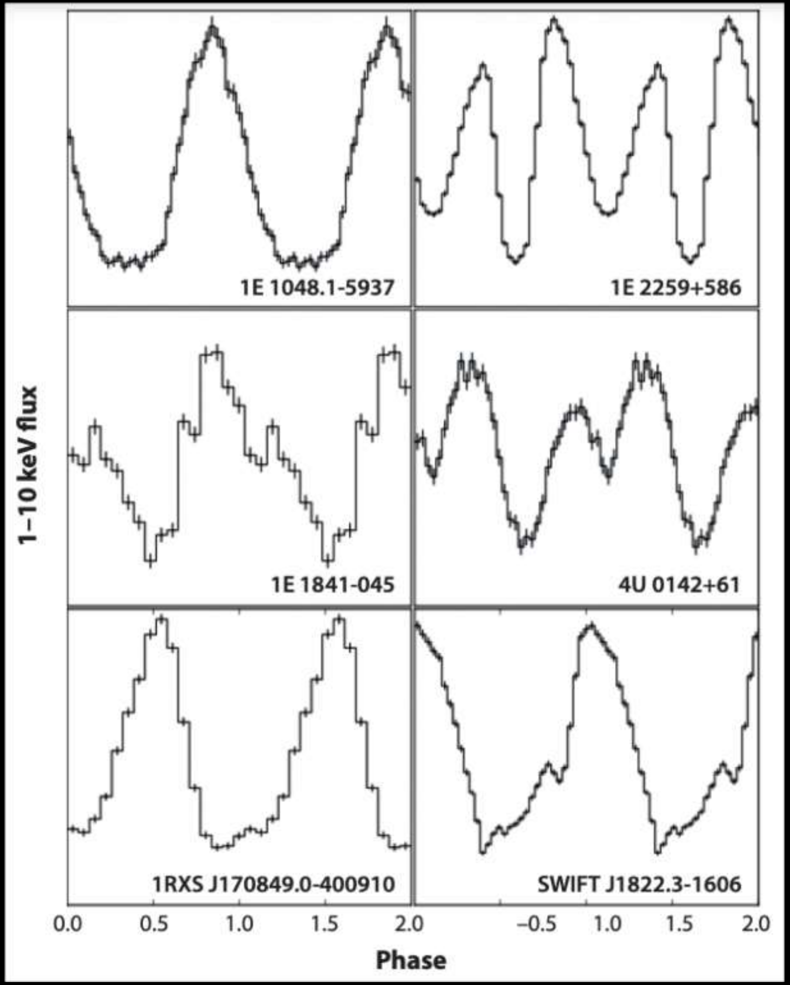


Intrinsically missing or unexplored territory?

Magnetars

- Historically detected as Anomalous X-ray Pulsars or Soft Gamma Repeaters
- Large magnetic field, $B \gtrsim 10^{14} G$ estimated from P and $\dot{P}$
- Persistent and bursting X-ray activity too luminous to be powered by spin-down
- Radiated energy often dominated by most energetic flares with $E \sim 3 \cdot 10^{44} - 3 \cdot 10^{46} erg$
- Magnetic field decay invoked as power source





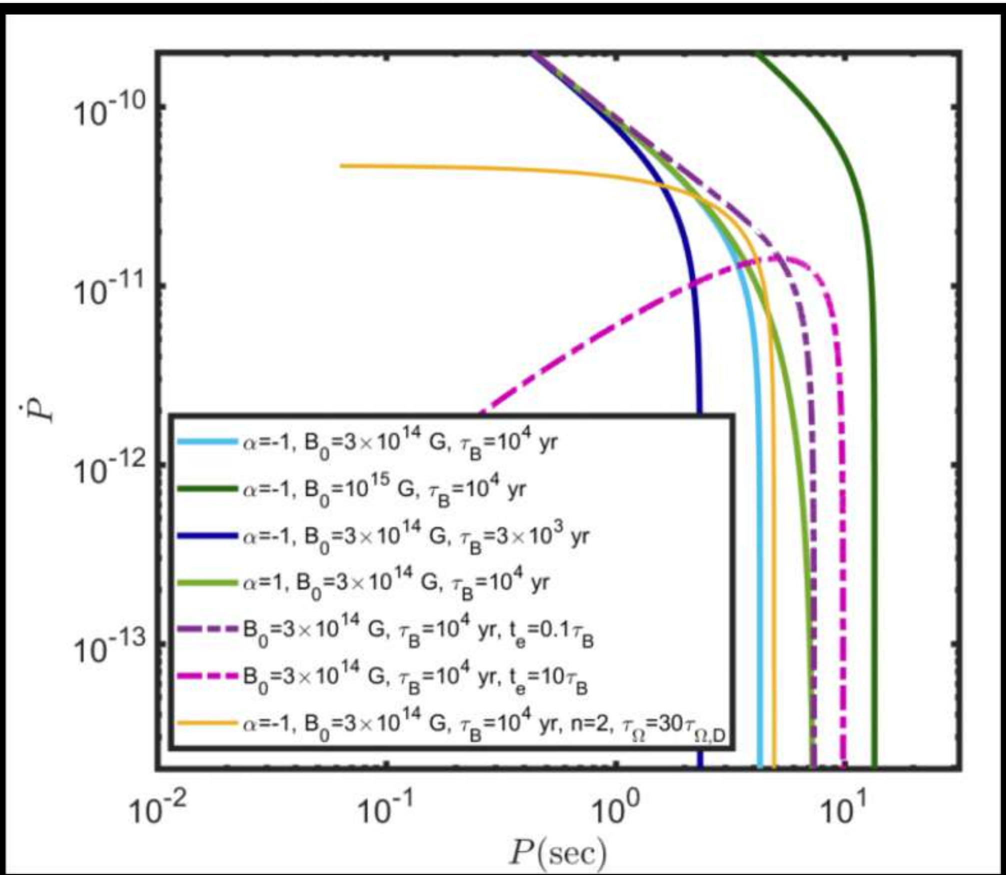
Kaspi & Beloborodov 17

Known Galactic magnetars

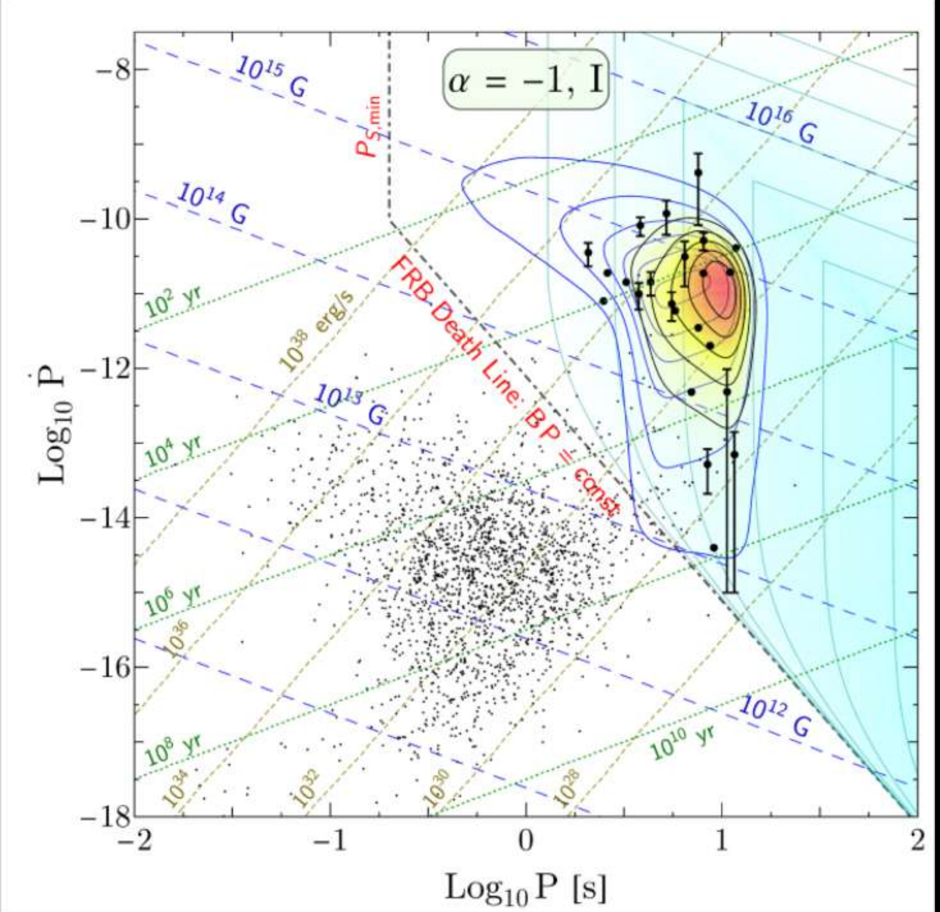
- Confirmed Galactic magnetars have $2 \lesssim P \lesssim 12$ s (regular pulsars have comparable or much lower P)
- P_{max} due to decay of surface field after $\sim 10^3 - 10^4 yr$ (Colpi et al. 00, Dall'Osso et al. 12, Vigano et al. 13, PB et al. 19)

$$\dot{\Omega} \propto \Omega^3 B^2$$

$$\Omega_{\rm min,dip} \approx \sqrt{\frac{3c^3 I(2-\alpha)}{4\tau_B B_0^2 R^6}} \approx 0.5 \left(\frac{10^{15} G}{B_0}\right)\left(\frac{10^4\ {\rm yr}}{\tau_B}\right)^{1/2} {\rm rad\ s}^{-1}$$



PB et al. 19



Wadiasingh, PB, et al. 20

Fast Radio Bursts

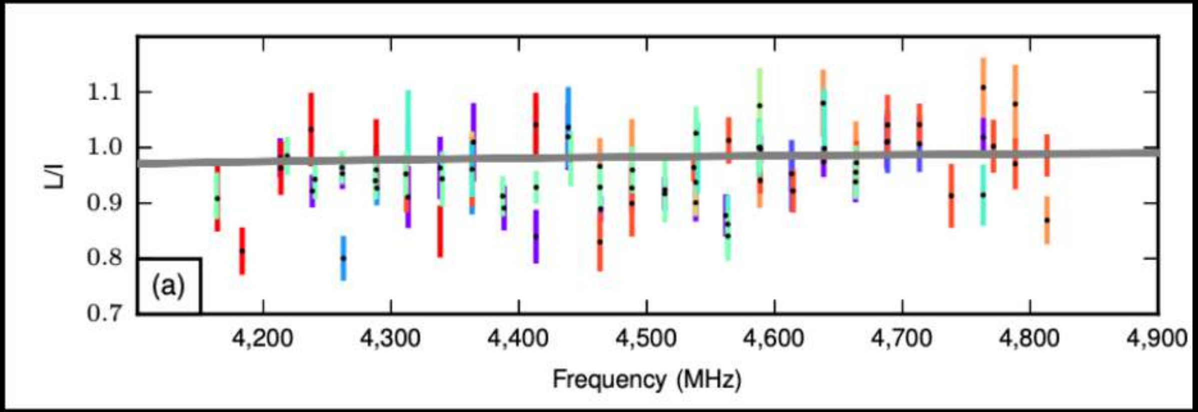
- FRBs are bright, rapid (ms duration) pulses, observed across cosmological distances
- About 50 sources are known to be repeating (non-catastrophic events)

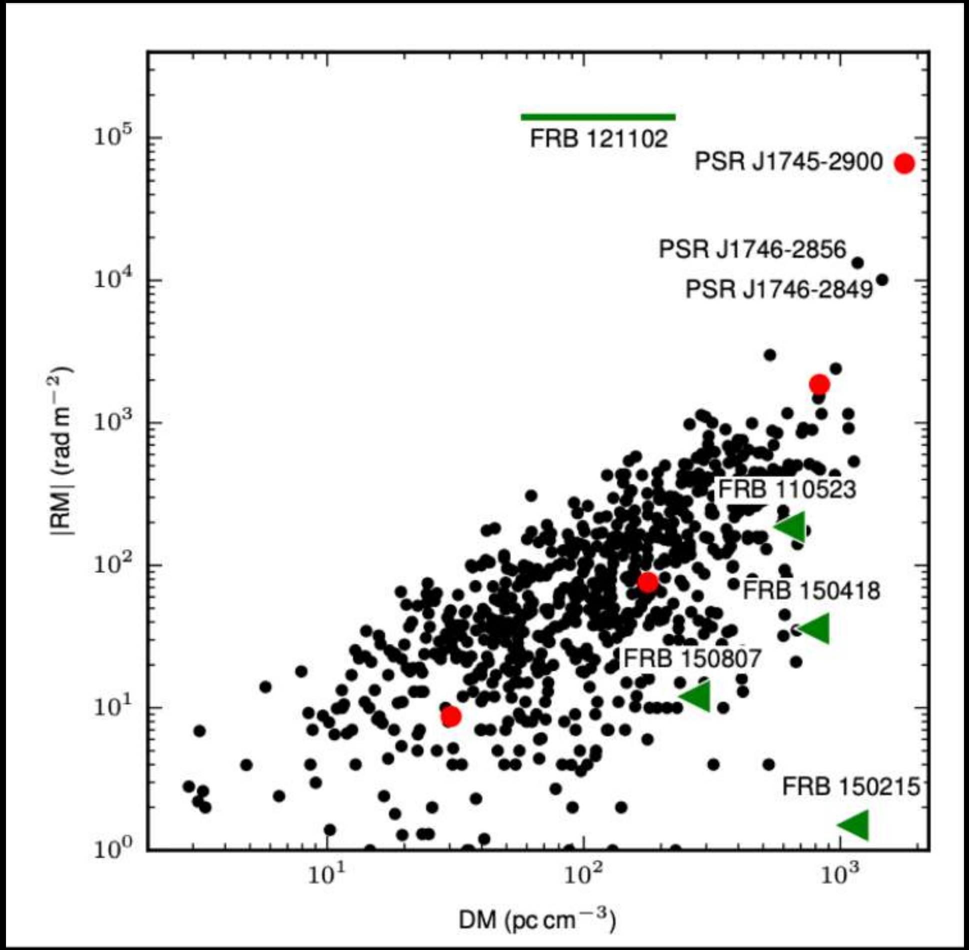
- Many models focus on magnetar central engines, due to:

$$RM \propto \int nB_{\parallel} dl$$

1. High polarization and large rotation measure - > Strongly magnetized engine and environment

(e.g. Masui et al. 15, Michilli et al. 18, Anna-Thomas et al. 23)



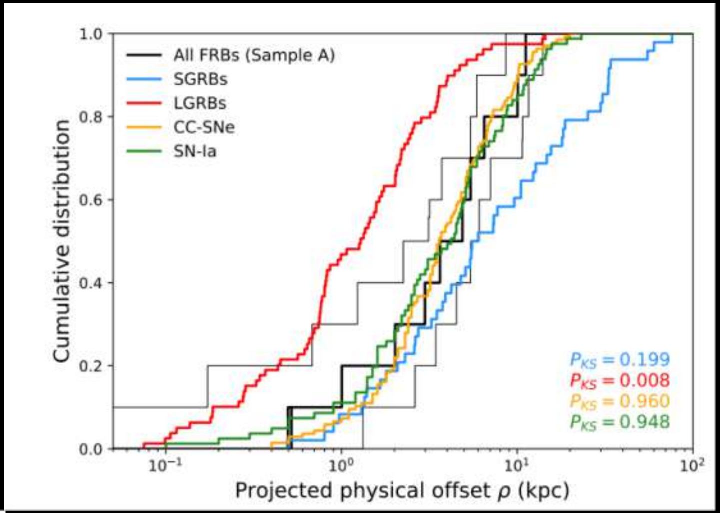


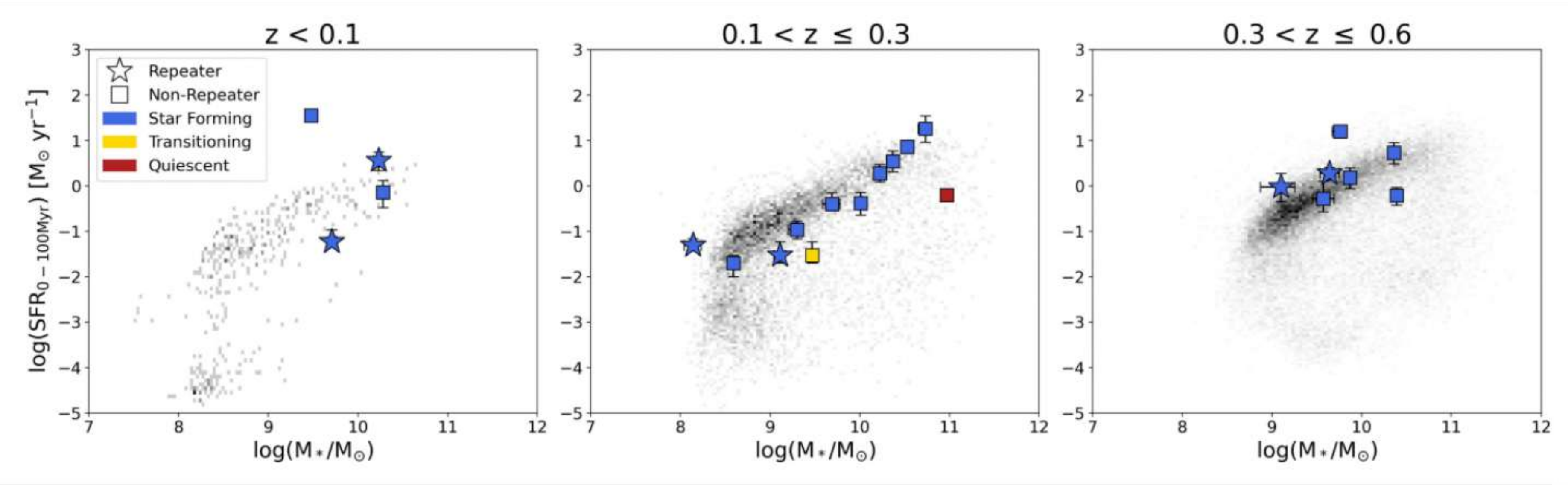
Fast Radio Bursts

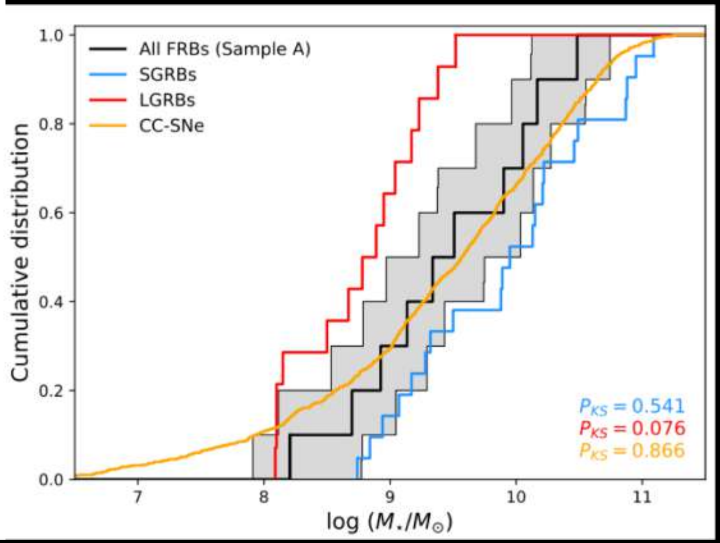
- FRBs are bright, rapid (ms duration) pulses, observed across cosmological distances
- At least some bursts are known to be repeating (non-catastrophic events)

- Many models focus on magnetar central engines, due to:

2. Host galaxies and offsets consistent with core-collapse SNe (e.g. Heintz et al. 20, Bochenek et al. 20, Gordon et al. 23)







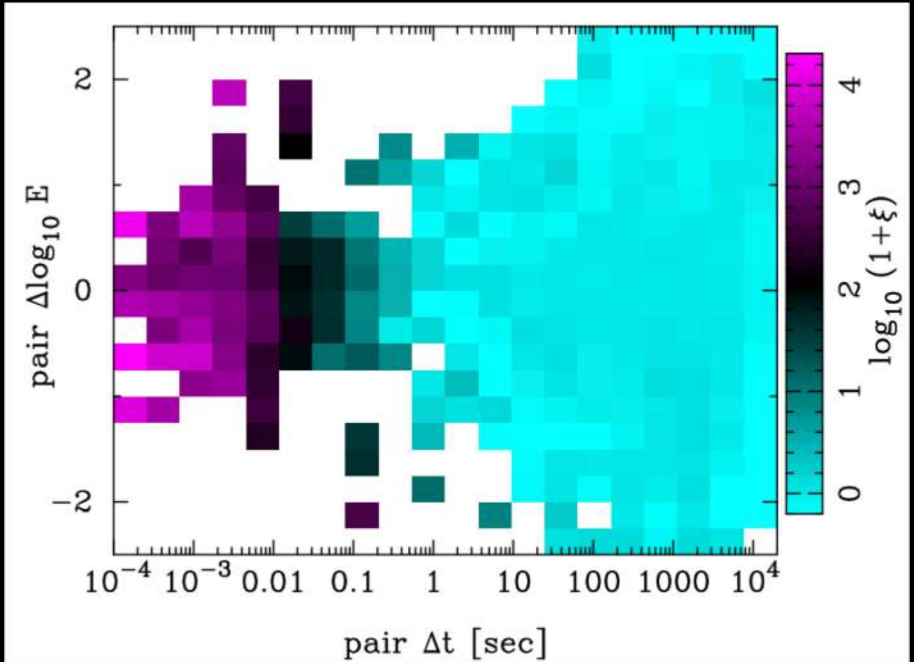
Gordon et al. 23

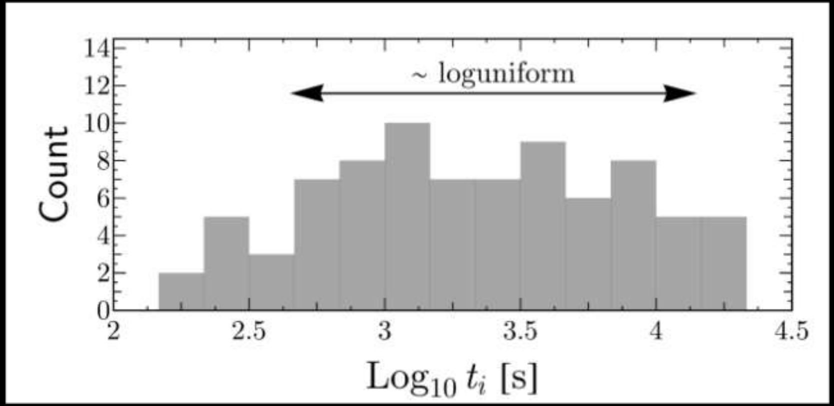
Fast Radio Bursts

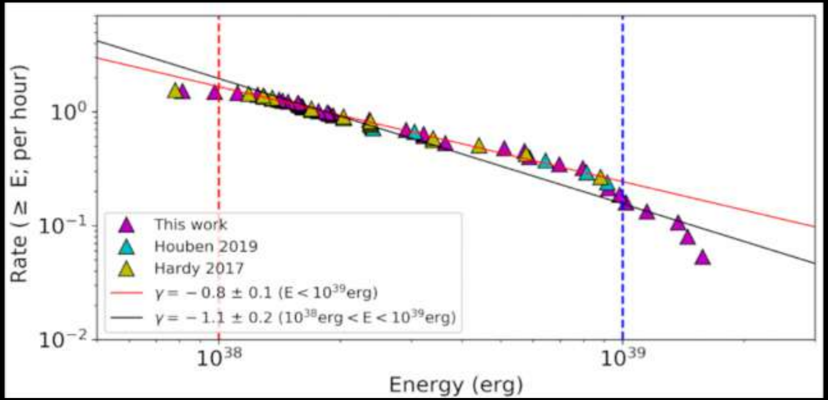
- FRBs are bright, rapid (ms duration) pulses, observed across cosmological distances
- At least some bursts are known to be repeating (non-catastrophic events)

- Many models focus on magnetar central engines, due to:

3. Statistical properties of burst repetitions consistent with magnetar bursts (e.g. Wadiasingh & Timohkin 19, Cheng et al. 20, Cruces et al. 21, Totani & Tsuzuki 23)







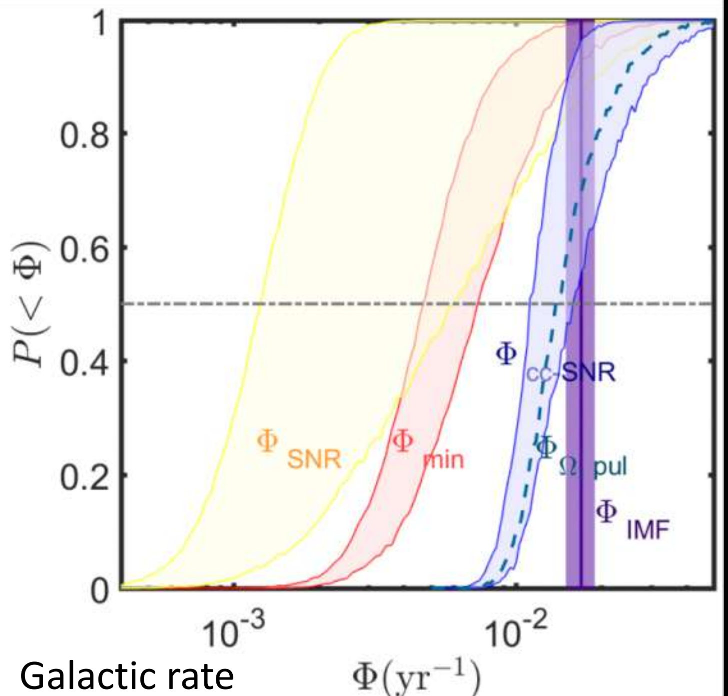
Fast Radio Bursts

- FRBs are bright, rapid (ms duration) pulses, observed across cosmological distances
- At least some bursts are known to be repeating (non-catastrophic events)

- Many models focus on magnetar central engines, due to:

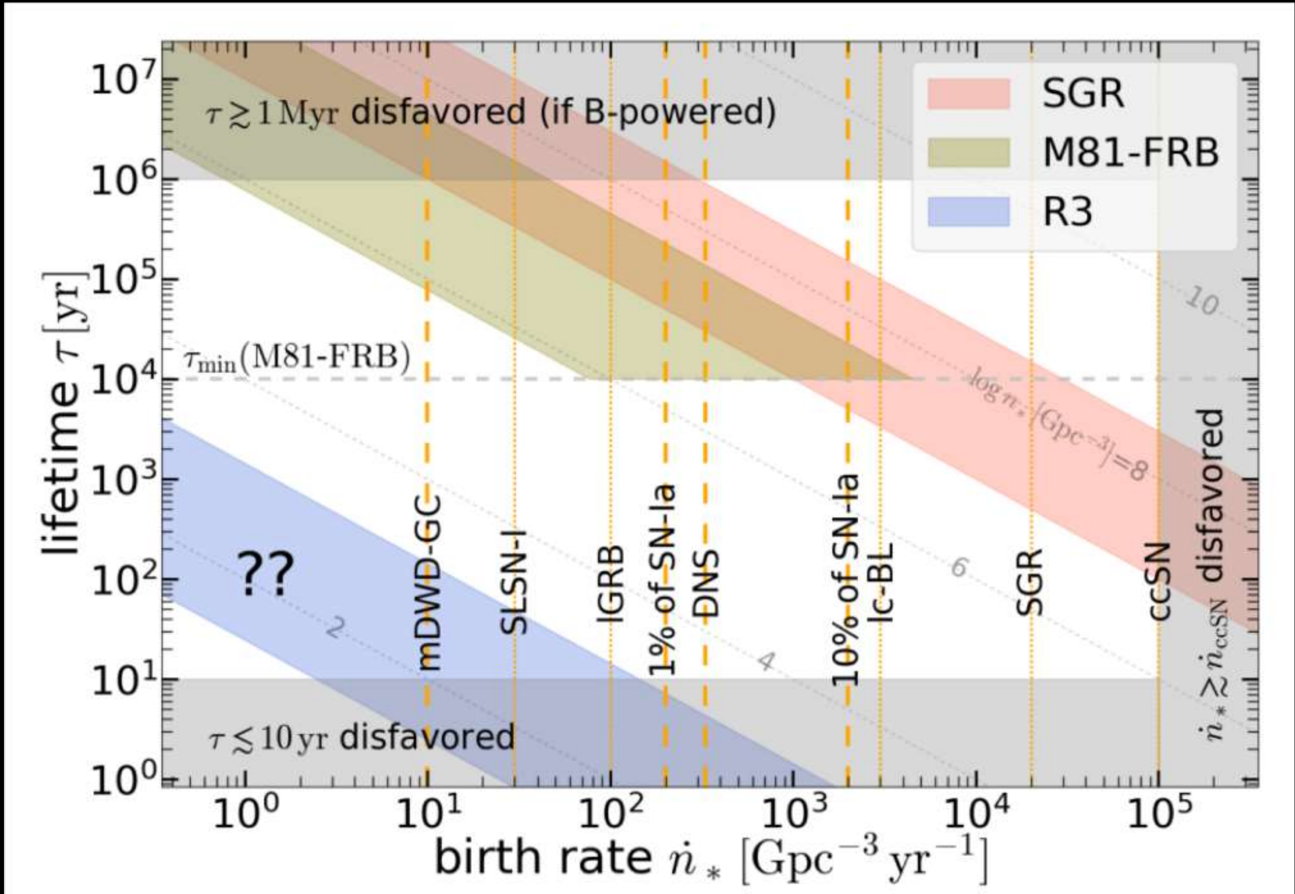
4. Large inferred volumetric rate of repeaters suggests "common" sources (e.g. Lu, PB, Kumar 21)

PB et al. 19



Galactic rate

Magnetar volumetric formation rate $\sim 2 \cdot 10^4 Gpc^{-3} yr^{-1}$

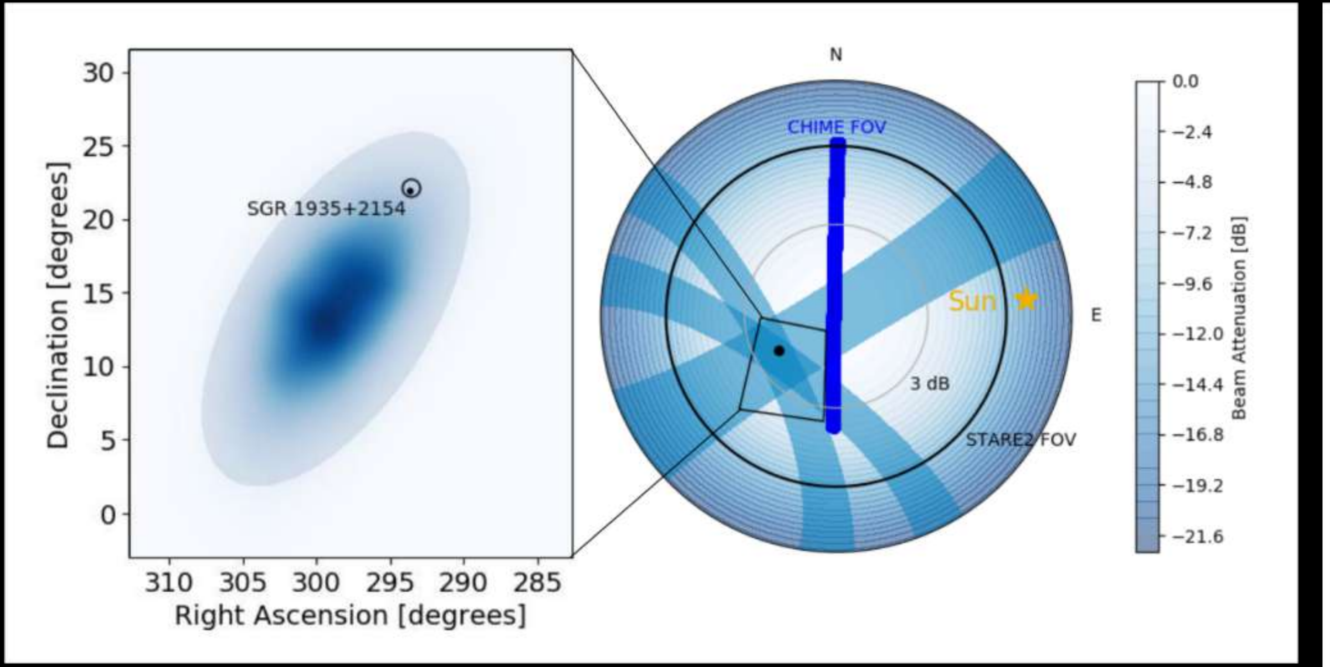


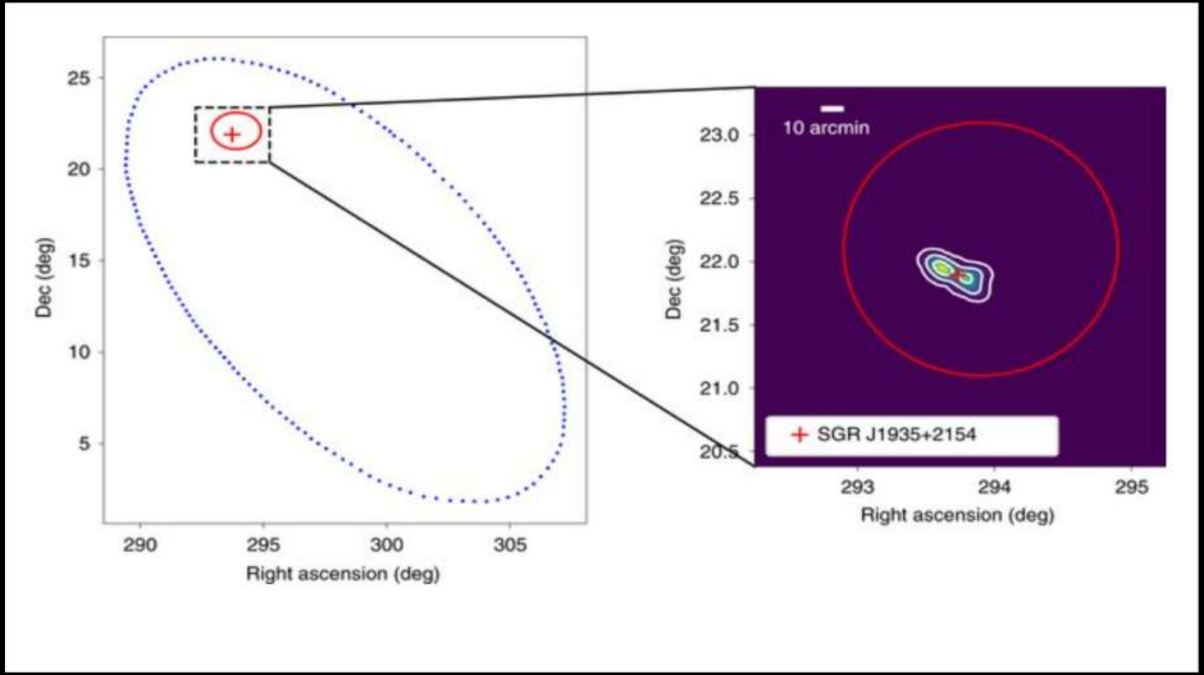
Fast Radio Bursts

- FRBs are bright, rapid (ms duration) pulses, observed across cosmological distances
- At least some bursts are known to be repeating (non-catastrophic events)

- Many models focus on magnetar central engines, due to:

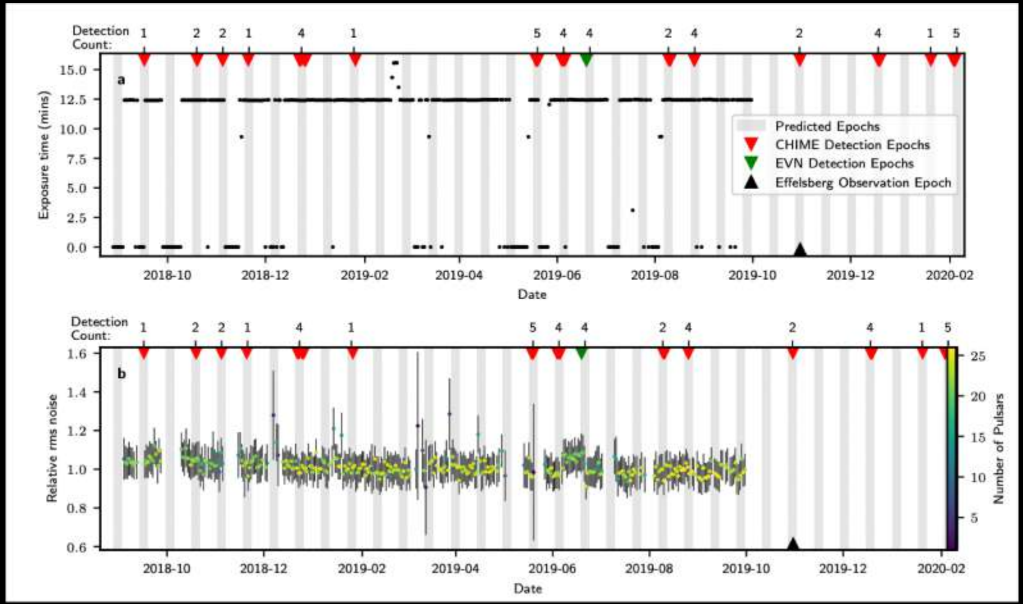
5. FRB 200428 – Association with known Galactic magnetar, SGR 1935+2154 (Chime et al. 20, Bochenek et al. 20, Li et al. 21)





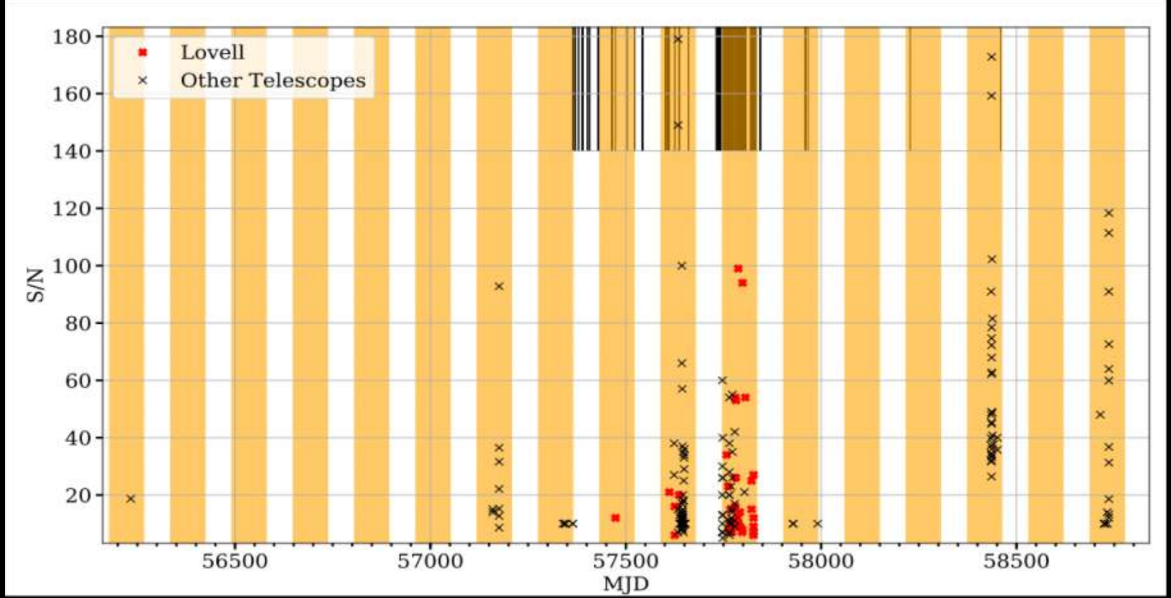
Observed FRB periodicity

- Two prolific repeaters exhibit active phase periodicity



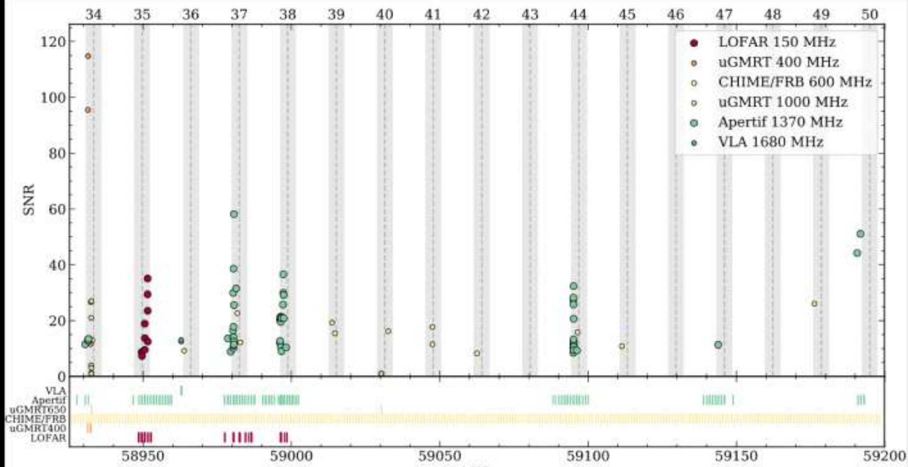
Chime et al. 20

FRB 180916 (R3) – 16.3 day periodicity, ~5 day active



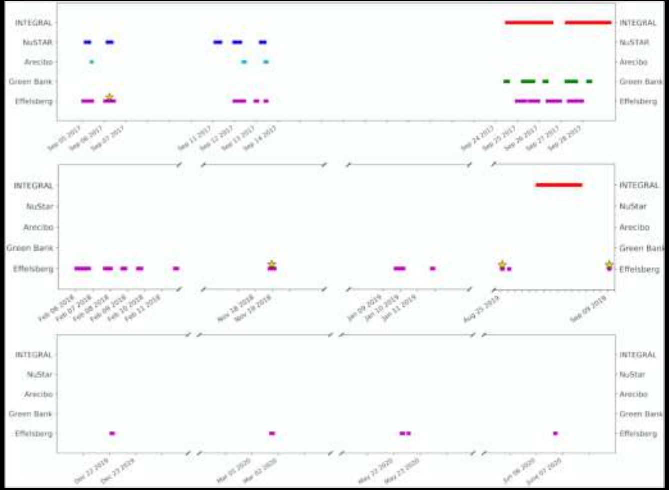
Rajwade et al. 20

FRB 121102 (R1) – 160 day periodicity, ~90 day active



Pastor-Marazuella et al. 20

No aliasing ;
periodicity persists in
continued monitoring /
other bands

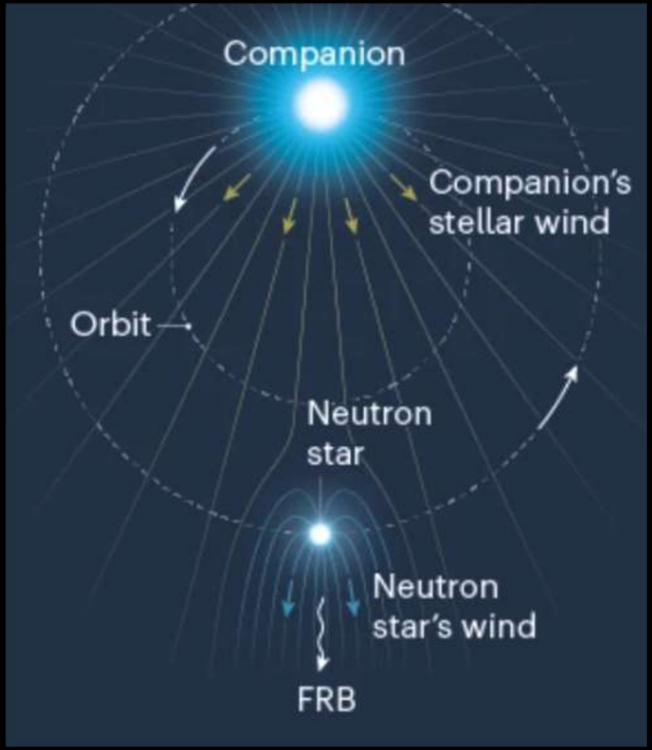


Cruces et al. 21

Potential explanations: binarity, precession, rotation

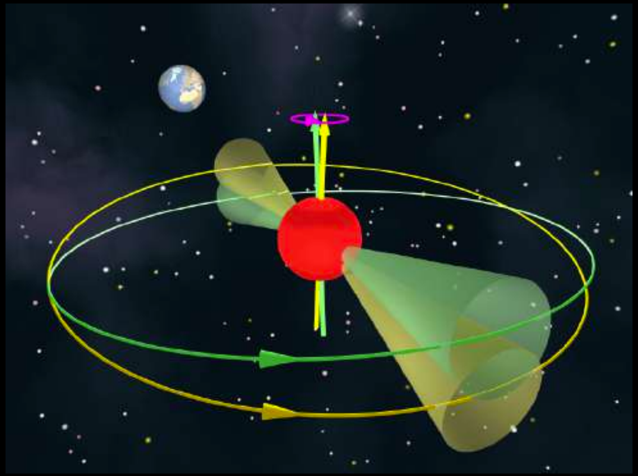
Observed FRB periodicity

Binarity



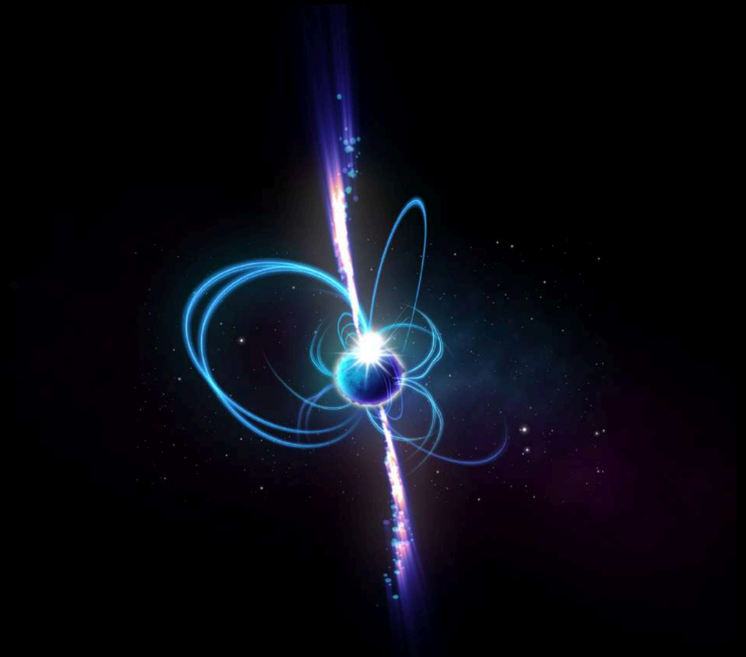
(Lyutikov 2020, Ioka & Zhang 2020)

precession



(Zanazzi & Lai 20, Levin et al. 20, Sridhar et al. 21)

NS rotation



PB, Wadiasingh & Metzger 20

Simplest (most naïve) story – long period magnetars

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Periodicity in recurrent fast radio bursts and the origin of ultralong period magnetars

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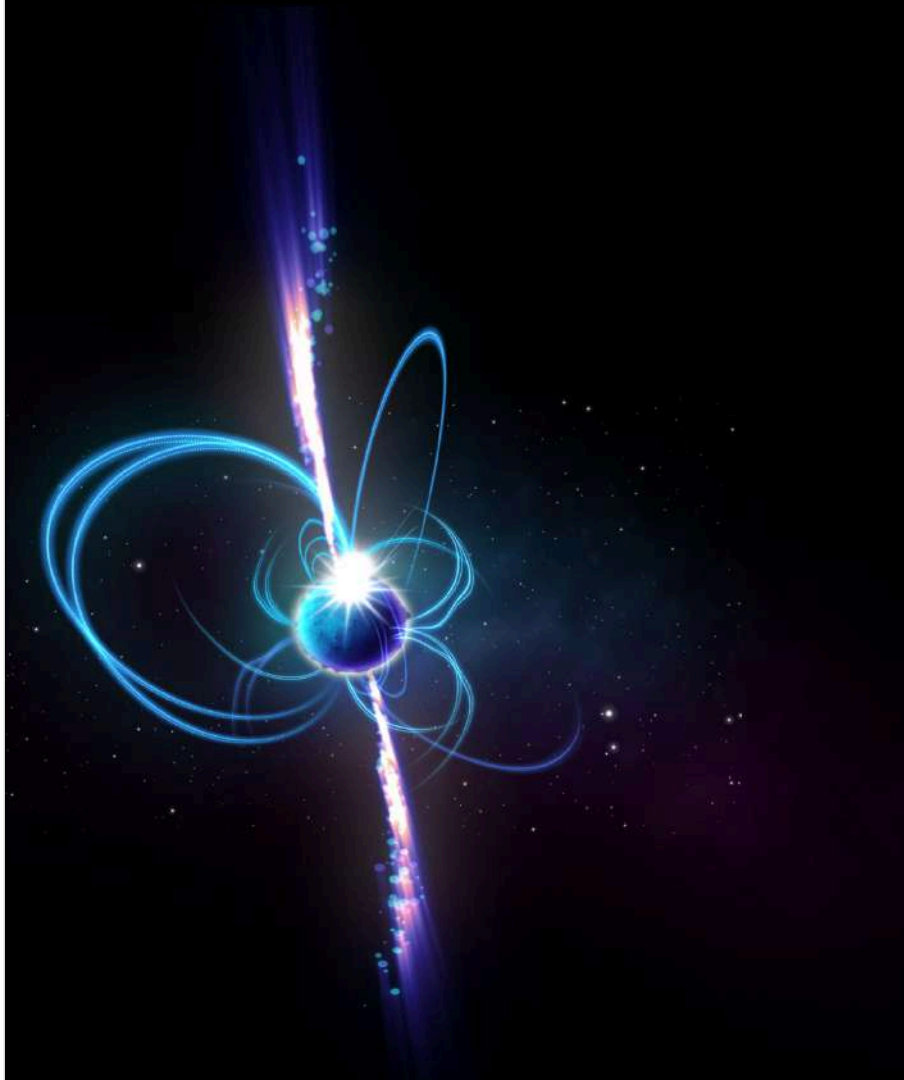
ABSTRACT

The recurrent fast radio burst FRB 180916 was recently shown to exhibit a 16-d period (with possible aliasing) in its bursting activity. Given magnetars as widely considered FRB sources, this period has been attributed to precession of the magnetar spin axis or the orbit of a binary companion. Here, we make the simpler connection to a *rotational period*, an idea observationally motivated by the 6.7-h period of the Galactic magnetar candidate, 1E 161348–5055. We explore three physical mechanisms that could lead to the creation of ultralong period magnetars: (i) enhanced spin-down due to episodic mass-loaded charged particle winds (e.g. as may accompany giant flares), (ii) angular momentum kicks from giant flares, and (iii) fallback leading to long-lasting accretion discs. We show that particle winds and fallback accretion can potentially lead to a sub-set of the magnetar population with ultralong periods, sufficiently long to accommodate FRB 180916 or 1E 161348–5055. If confirmed, such periods implicate magnetars in relatively mature states (ages 1−10 kyr) and which possessed large internal magnetic fields at birth $B_{\rm int} \gtrsim 10^{16}$ G. In the low-twist magnetar model for FRBs, such long period magnetars may dominate FRB production for repeaters at lower isotropic-equivalent energies and broaden the energy distribution beyond that expected for a canonical population of magnetars, which terminate their magnetic activity at shorter periods $P \lesssim 10$ s.



Phenomenological evidence for enhanced NS spin-down

Enhanced spin-down associated with GFs and strong bursting behavior

- SGR 1900+14: $x_p \equiv \frac{\Delta P}{P} \sim 10^{-4}$ after 1998 GF
- SGR 1806-20: Increased $\dot{P}$ since 2004 GF. Up to 2012, P increased by extra 2% compared to pre-GF extrapolation (Younes et al. 15).
- Kinematic age constraints of these magnetars suggest further $\dot{P}$ enhancements in their past (Tendulkar et al. 12)
- 1E 2259+586 : Anti-glitches with $x_p \sim 2\ 10^{-4}$ (Archibaled et al. 20)

Simplest phenomenological model

If $x_p = const$ then $P_f = P_0 \exp\left(N_p x_p\right) \rightarrow P_f \gg P_0$ for $N_p > x_p^{-1}$

- With $E_{GF} \sim 4\ 10^{44} erg$ and $x_p \sim 10^{-4}$, a significant increase of P requires a magnetic energy reservoir of > $4\ 10^{48} erg$ or *internal field* $B_{int} > 5\ 10^{15} G$
- Compare to SGR 1900+14: $B_{dip} = 7\ 10^{14} G$ and recall that B_{int}~10 B_{dip} inferred from X-rays
- Small population of highest B magnetars could plausibly evolve to ULPMs

PB, Wadiasingh, Metzger 20

Physical mechanisms for enhanced spin-down

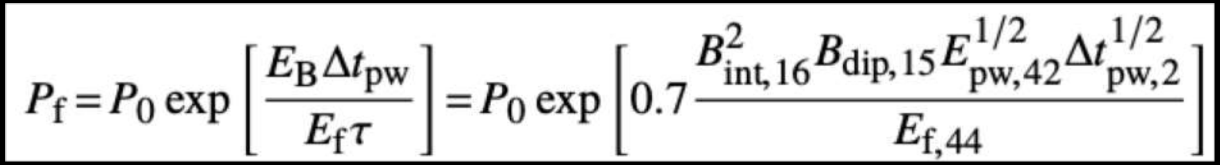
Charged particle winds

- Mass–loaded charged wind with $L_{pw} > L_{dip}$ opens up B lines beyond

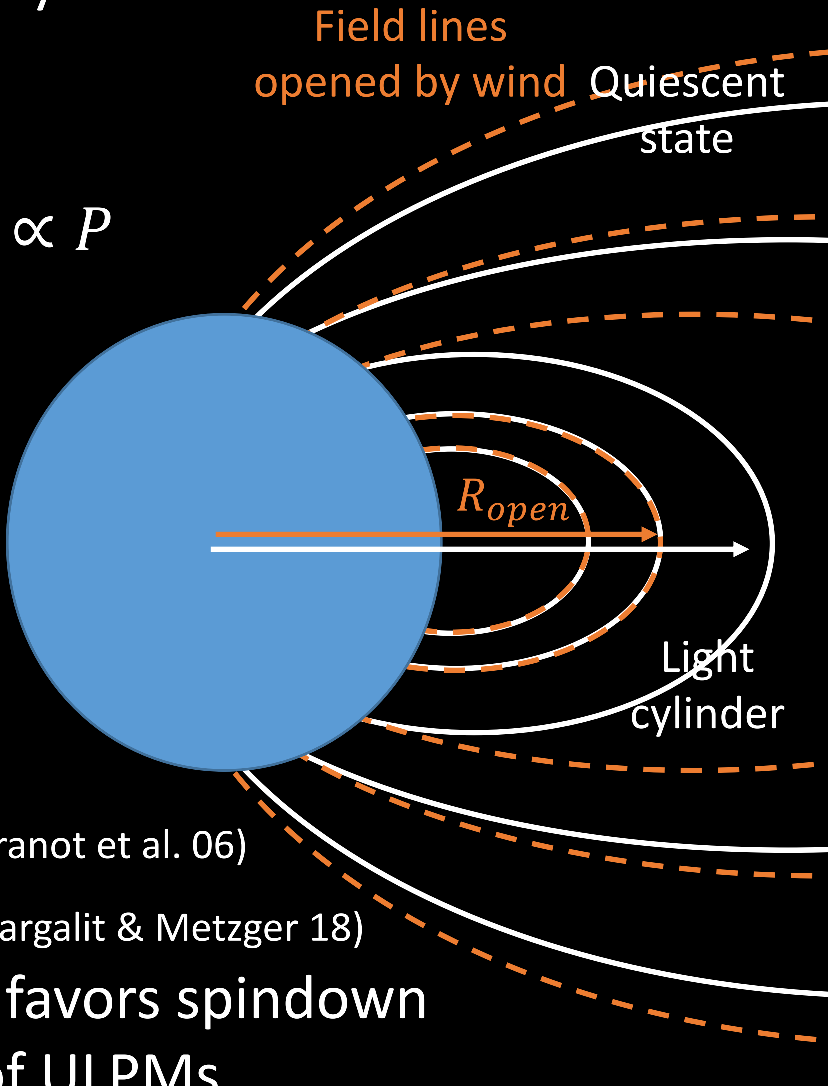
$$R_{open} \sim R_{NS}\left(\frac{B_{dip}^2 R_{NS}^2 c}{L_{pw}}\right)^{1/4}$$

(Thompson & Blaes 98, Harding et al. 00)

- Spindown scales as open flux squared -> Enhanced spindown $\dot{P} \propto P$
- $P_f = P_0 \exp(\frac{t}{\tau})$ with $\tau = \frac{I c R_{open}^2}{B_{dip}^2 R_{NS}^6} \sim 5\ 10^7 B_{dip,15}^{-1} L_{pw,40}^{-1/2}\ s$



$$P_{\mathrm{f}} = P_0 \exp\left[\frac{E_{\mathrm{B}} \Delta t_{\mathrm{pw}}}{E_{\mathrm{f}} \tau}\right] = P_0 \exp\left[0.7 \frac{B_{\mathrm{int},16}^2 B_{\mathrm{dip},15} E_{\mathrm{pw},42}^{1/2} \Delta t_{\mathrm{pw},2}^{1/2}}{E_{\mathrm{f},44}}\right]$$



- Outflows with $E_{kin} \sim E_f$ inferred from 1806-20 GF (Gelfand et al. 05, Granot et al. 06)
- Mass loaded outflows also needed for `far-away’ FRB models (Margalit & Metzger 18)
- Pulsating tail of GF require mass-loaded wind – longer duration favors spindown
- Exponential sensitivity to physical conditions - > small fraction of ULPMs

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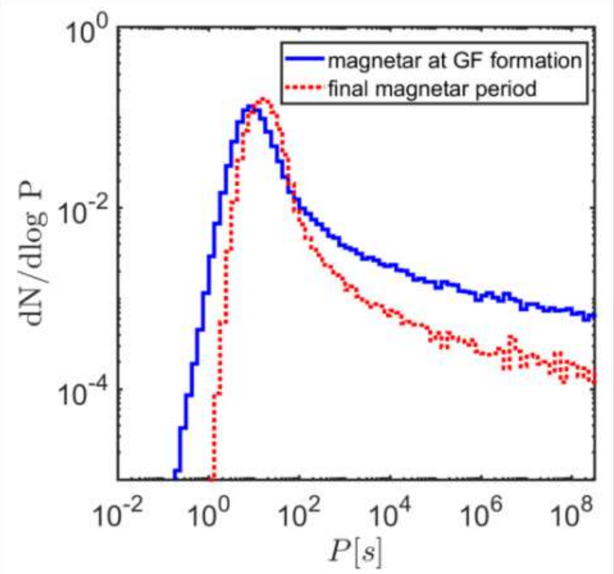
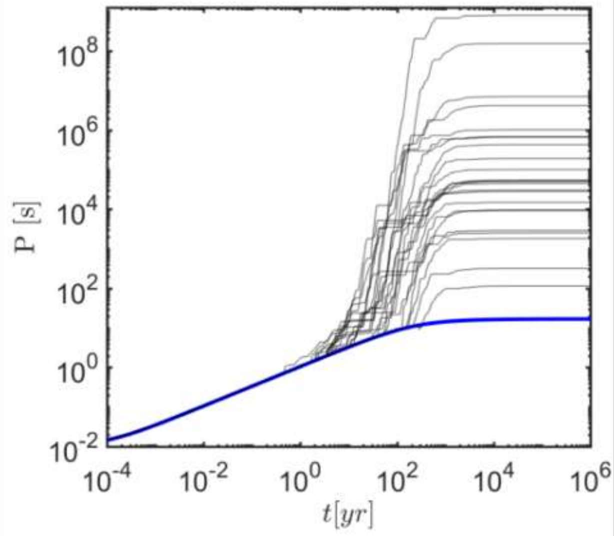
Physical mechanisms for enhanced spin-down

Charged particle winds

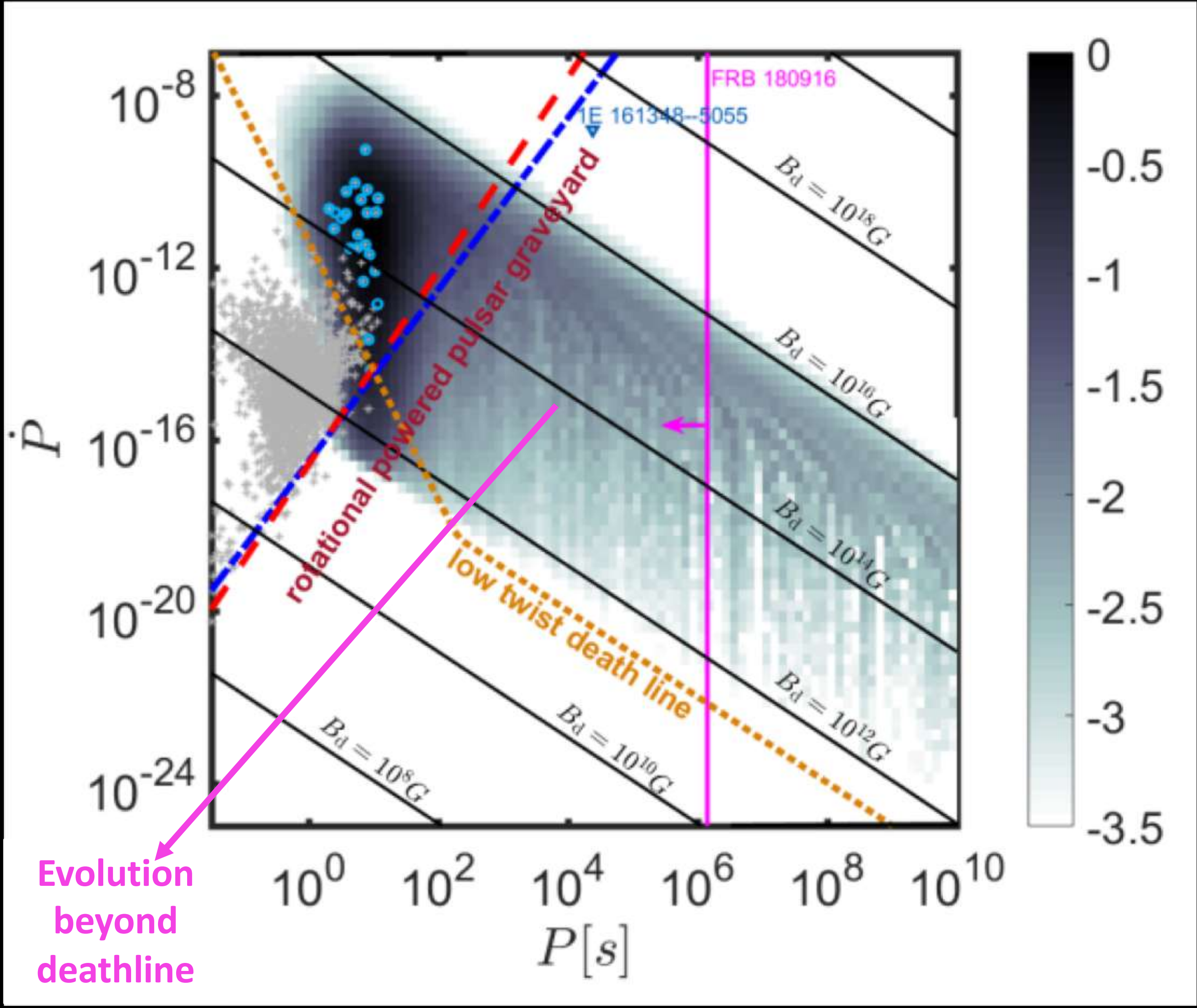
- Monte Carlo proof of concept:



Flat P distribution at large P



Example P evolutions



Evolution beyond deathline

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Galactic Ultra Long Period Magnetar (ULPM) candidates

- Various Galactic objects show magnetar phenomenology

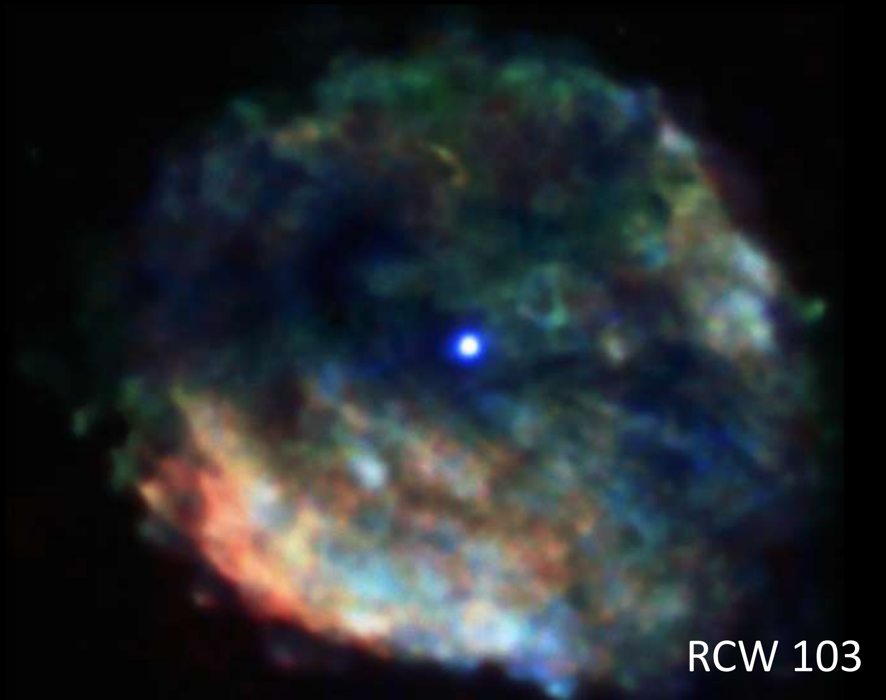
1E 161348–5055

Pulsating ($P\sim 6.7hr \gg P_{max}$) central compact object in SNR RCW 103:

1. $\sim$ms duration short X-ray bursts
2. Long-term outbursts and non-thermal hard X-ray emission

} Magnetar-like phenomenology

3. Proper motion $\sim 170\,\frac{km}{s}$ from CHANDRA imaging – Wide binary would have been disrupted
4. Companion hotter than M7 ruled out by HST observations – close binary should have been detected



RCW 103

Credit: De Luca et al. 06, 08, Esposito et al. 11, D'Ai et al. 16, Rea et al. 16, Tendulkar et al. 17, Borghese et al. 18

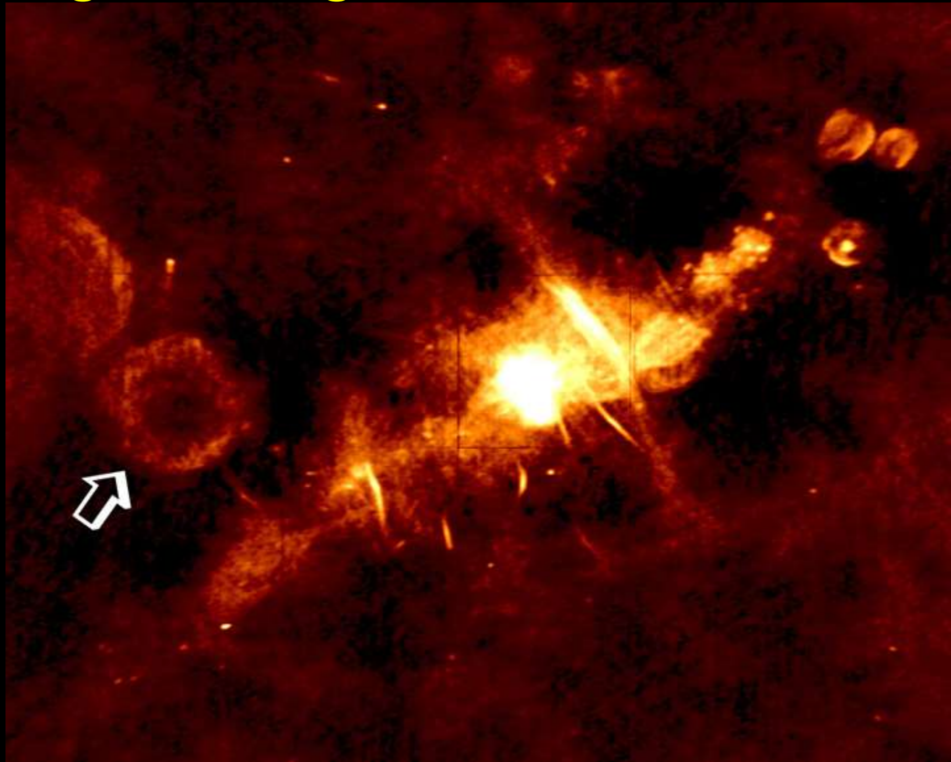
Galactic Ultra Long Period Magnetar (ULPM) candidates

- Various Galactic objects show magnetar phenomenology

GCRT J1745–3009

The Galactic “burper”. A $P \sim 77\ \mathrm{min}$ source discovered serendipitously by VLA

1. 10 minute wide “pulses” -> minute timescale variability implies $T_B \gg 10^{12}\left(\frac{d}{70\ pc}\right)^2 k$
2. Optical observations rule out even M type / brown dwarf nearby counterpart
3. If period is spin – cannot be rotation powered – suggests magnetar origin



Credit: Hyman et al. 05,Kaplan et al. 08, Spreeuw et al. 09

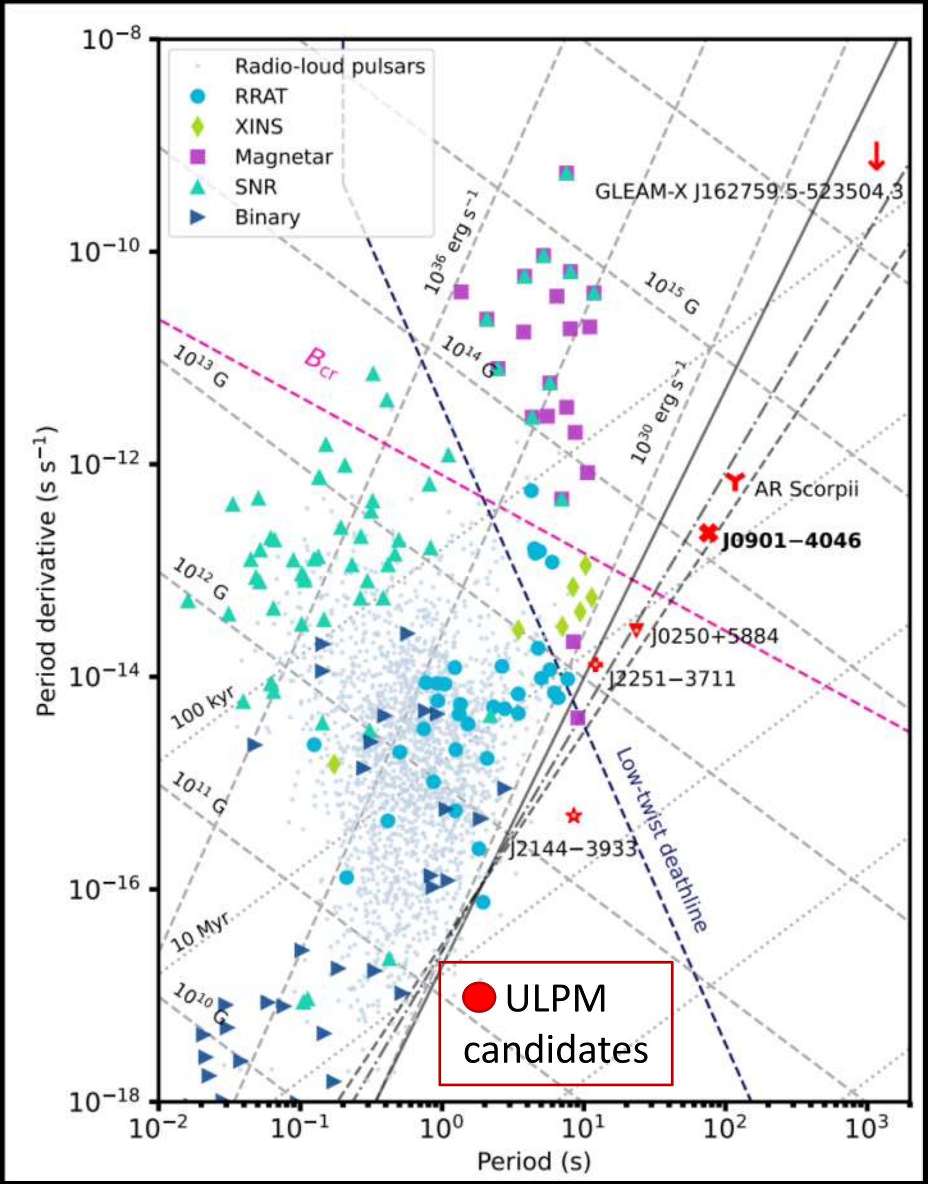
Galactic Ultra Long Period Magnetar (ULPM) candidates

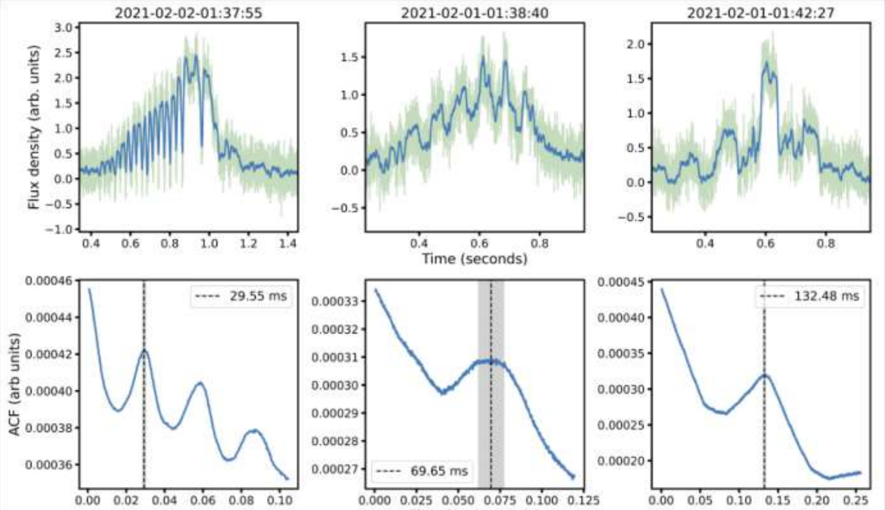
- Various Galactic objects show magnetar phenomenology

PSR J0901–4046 – Meertrap detected pulsar

A $P\sim76\ s, \dot{P}\sim2\ 10^{-13}$ pulsar at a distance of 330 pc → $\boldsymbol{B_d\sim2.6\ 10^{14}G}$

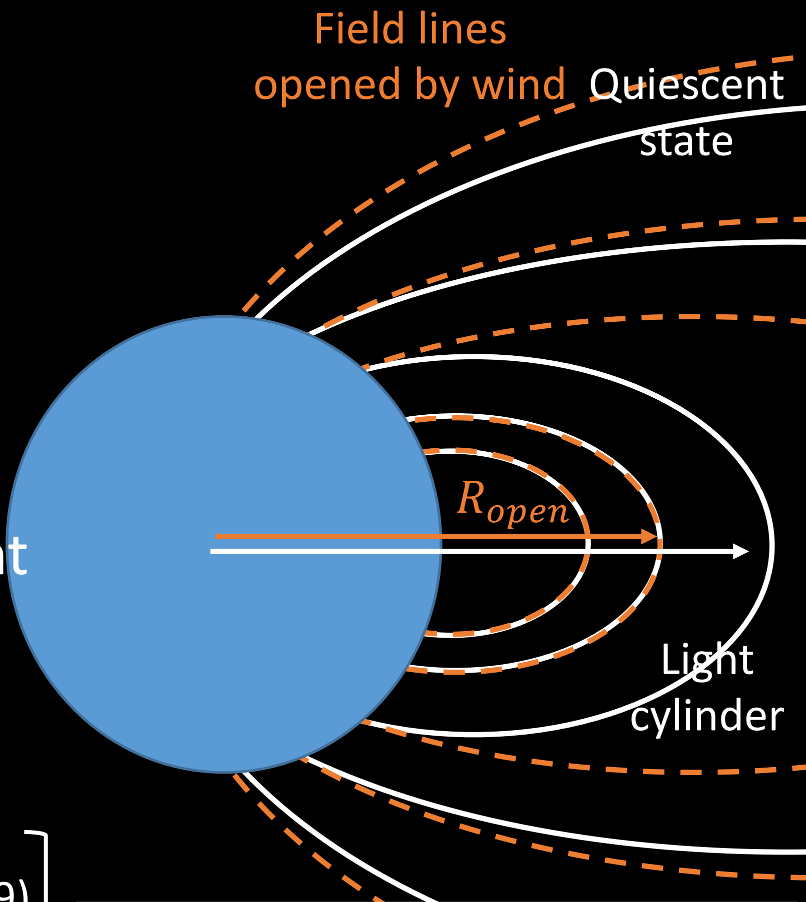
1. Pulsar radio characteristics: high polarization fraction, PPA swings, very large brightness temperature, variability in single pulses of flux and polarization
2. NS spindown cannot power observed radio luminosity
3. Challenges pulsar deathline
4. Tens of ms QPOs – Support existence of NS crust
5. Precise $(\sim10^{-6})$ timing and strong GAIA limits – not in binary





Credit: Caleb et al. 2022

An aside – How confident is the magnetic field estimate?



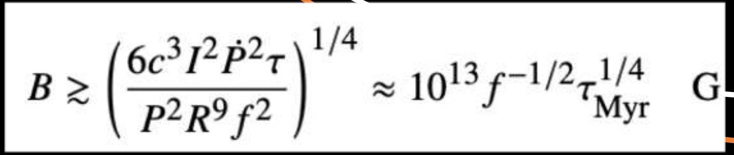
- Multipolar components?

$\mathrm{P}{\sim}80\ \mathrm{s} \rightarrow \mathrm{R_{LC}}{\sim}3 \cdot 10^5 \mathrm{R_{NS}}$ → multipole components sub-dominant

- Particle winds?

1. Hard to reconcile with timing
2. Particle wind luminosity $L_p \sim \frac{B(r_{op})^2 r_{op}^2 C}{2} \sim \frac{6c^3 I^2 \dot{P}^2}{B^2 P^2 R^6}$ (Harding et al. 99)

Powered by magnetic energy: $L_p < E_B/\tau$



$$B \gtrsim \left(\frac{6c^3 I^2 \dot{P}^2 \tau}{P^2 R^9 f^2}\right)^{1/4} \approx 10^{13} f^{-1/2} \tau_{\mathrm{Myr}}^{1/4}\ \mathrm{G}$$

Strong field required even if efficiency of converting magnetic power to radio luminosity is 100%

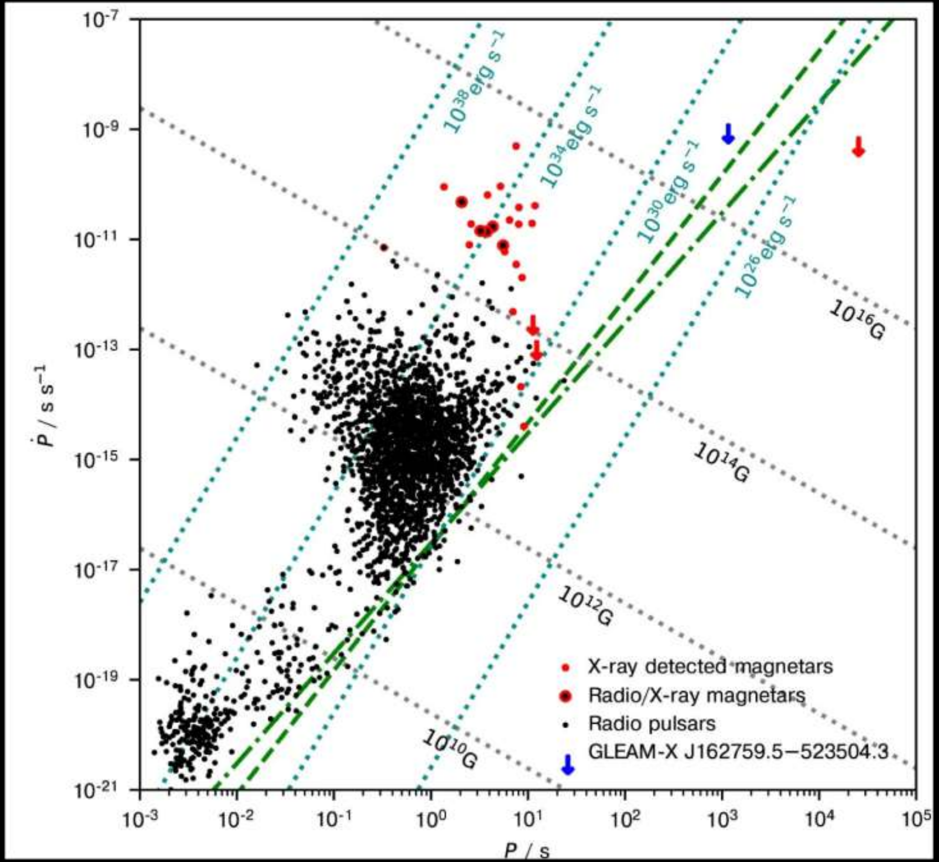
Galactic Ultra Long Period Magnetar (ULPM) candidates

- Various Galactic objects show magnetar phenomenology

GLEAM-X J162759.5–523504.3

A $P{\sim}1091\ s, \dot{P} < 10^{-9}$ persistent radio transient at a distance of 1.3 kpc

1. Close to 100% linear polarization
2. Rapid (~0.5 s) variability suggesting compact object with large brightness temperature $\sim 10^{16} k$
3. Cannot be a rotation powered NS
4. 2% duty cycle – inconsistent with $\Delta\phi \propto P^{-1/2}$ of radio pulsars
5. Beyond pulsar death-line for standard pulsar field strength

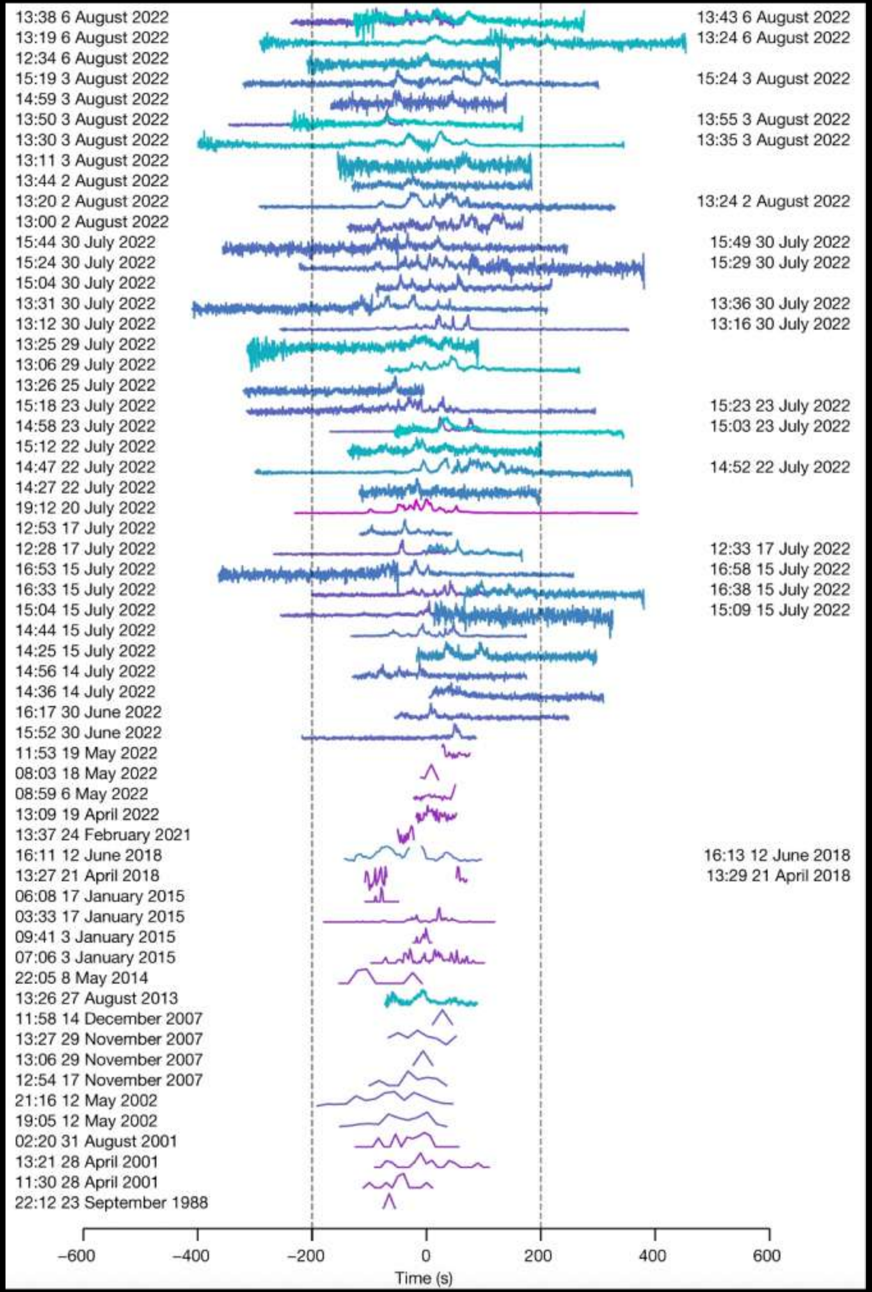


Credit: Hurley Walker et al. 22

Most recent addition to ULPM population

- **GPM J1839-10**

- $P{\sim}1320\ s, \dot{P} < 3.6\ 10^{-13}$ - continuously active for >30 years!
- $d \approx$ 5.7kpc (based on DM)
- High polarization (up to 100% in some bursts)
- Variability as short as 0.2 s over which PA may switch by 90°
- $L_{SD} \ll$ if NS
- 3-10% duty cycle



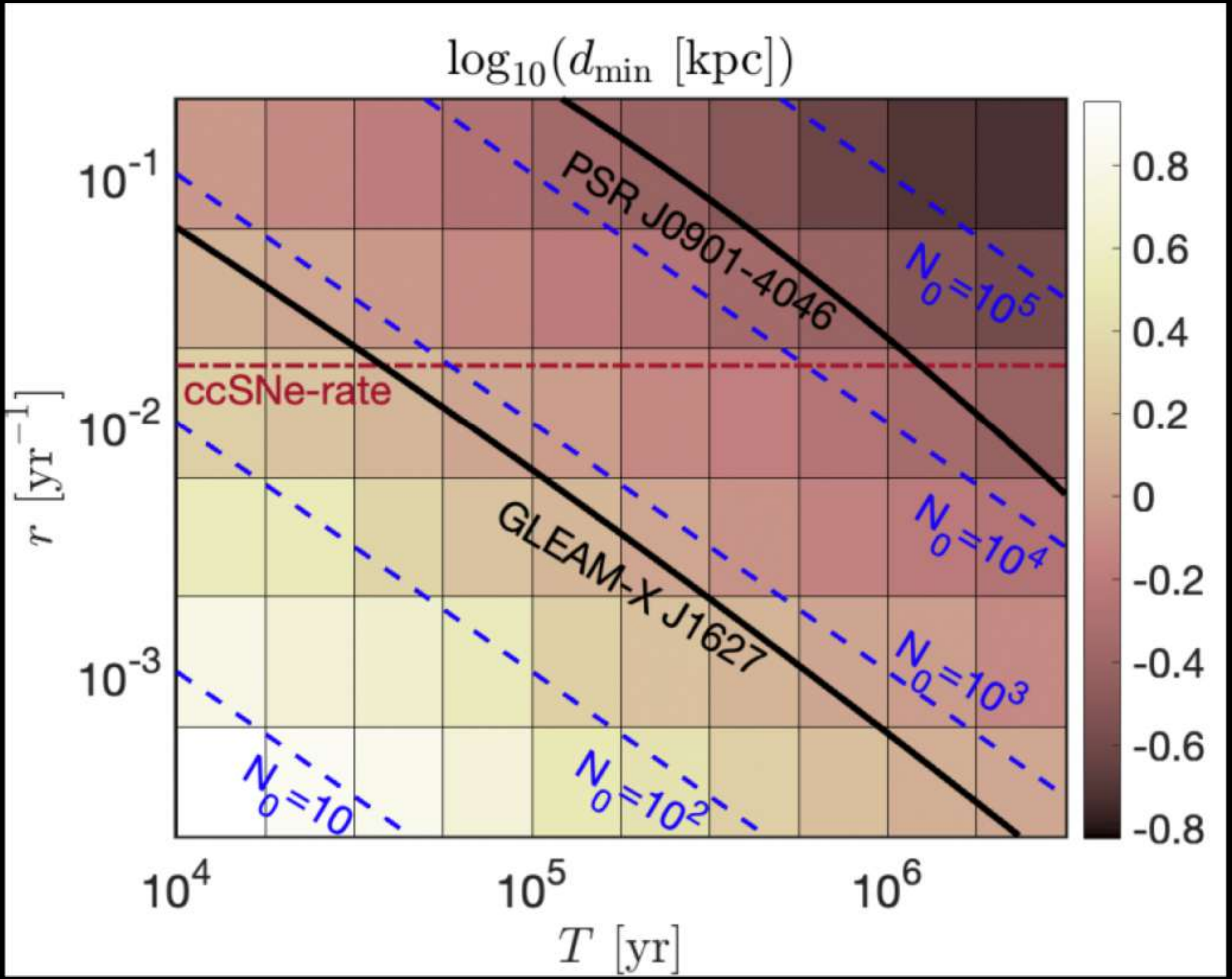
Hurley-Walker et al. 23

ULPM candidates Source densities

- Nearby distances of J0901-4046 and GLEAM-X suggest many more Galactic sources

$3\ 10^{-4}$ volume of Galaxy within 400 pc →
≳3500 similar objects to J0901-4046 in MW

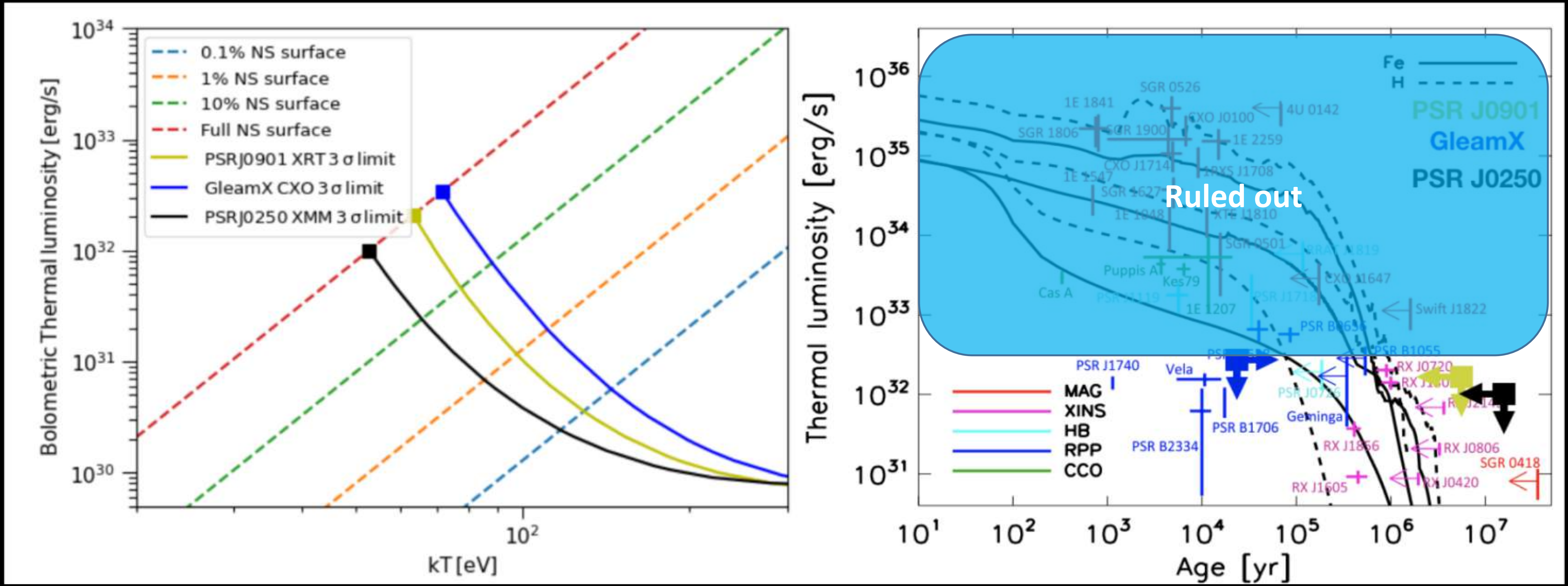
More refined analysis consistent with simple estimate and demonstrates robustness of
$$d_{min} \propto n_s^{-1}$$



PB et al. 23

Age of ULPM candidates

- **Spindown age** provides a rough upper limit $\tau < \tau_{SD} \sim 12Myr$ (J0901-4046)
- **Timing:** ${}^{\Delta\nu}/_{\nu} \lesssim 10^{-6} \rightarrow \tau \gtrsim 100kyr$
- **Source density limits:** $\dot{\mathrm{N}} < \dot{\mathrm{N}}_{\mathrm{ccSNe}} \rightarrow \tau \sim {}^{\mathrm{N}}/_{\dot{\mathrm{N}}} \gtrsim 1.2\mathrm{Myr}$ for J0901-4046 ($\tau \gtrsim 38$kyr for GLEAM-X)
- **Proper motion:** No detected SNR and low offsets from Galactic plane → $\tau \gtrsim 30$kyr
- **Cooling age limits:** Upper limit on X-ray flux → NS must be old and cold, $\tau \gtrsim 100$kyr



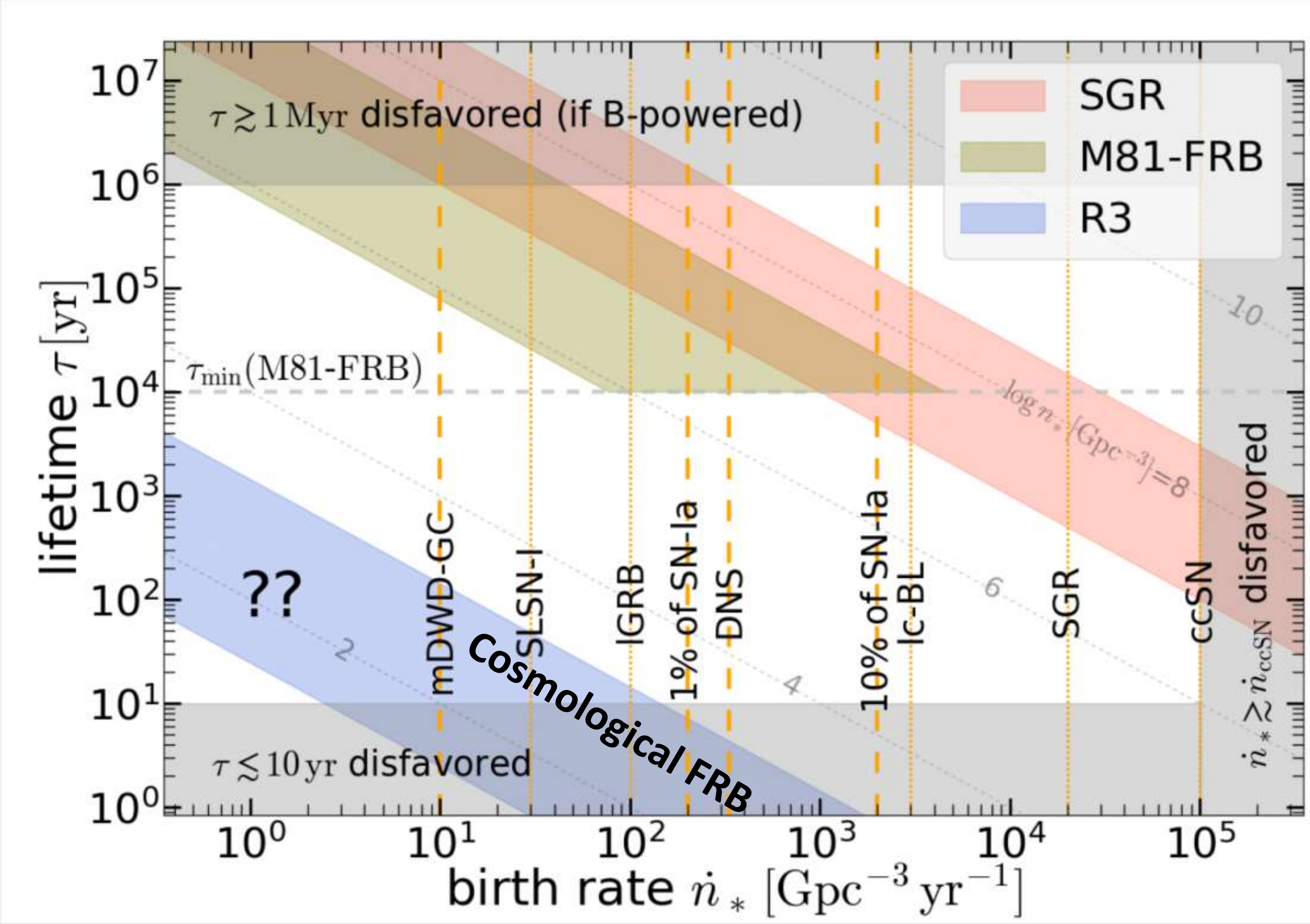
PB et al. 23

Old age suggests unique magnetic field decay channel

Main challenge for FRB association - Source densities

- R3 birth rate $< 10^{-3}$ccSNe rate (Nicholl et al. 16)
- R3 source density $10^{-7} - 10^{-5}$ compared to Galactic magnetars (Lu, PB, Kumar 21)

- Rarity favors ‘exotic’ explanation
- Galactic ULPM source density $\gtrsim 10$ that for Galactic SGRs → Large compared to periodic FRBs



Lu, PB, Kumar 21

Solutions?

- Special conditions required to make FRBs from ULPMs (e.g. B_0)
- FRB more beamed than radio pulses? Requires extremely small inclination angle and beam (polar cap $\theta_c = 10^{-5}$ for 16 d period is such a low inclination natural?)
- Reduction of sources with very large period?

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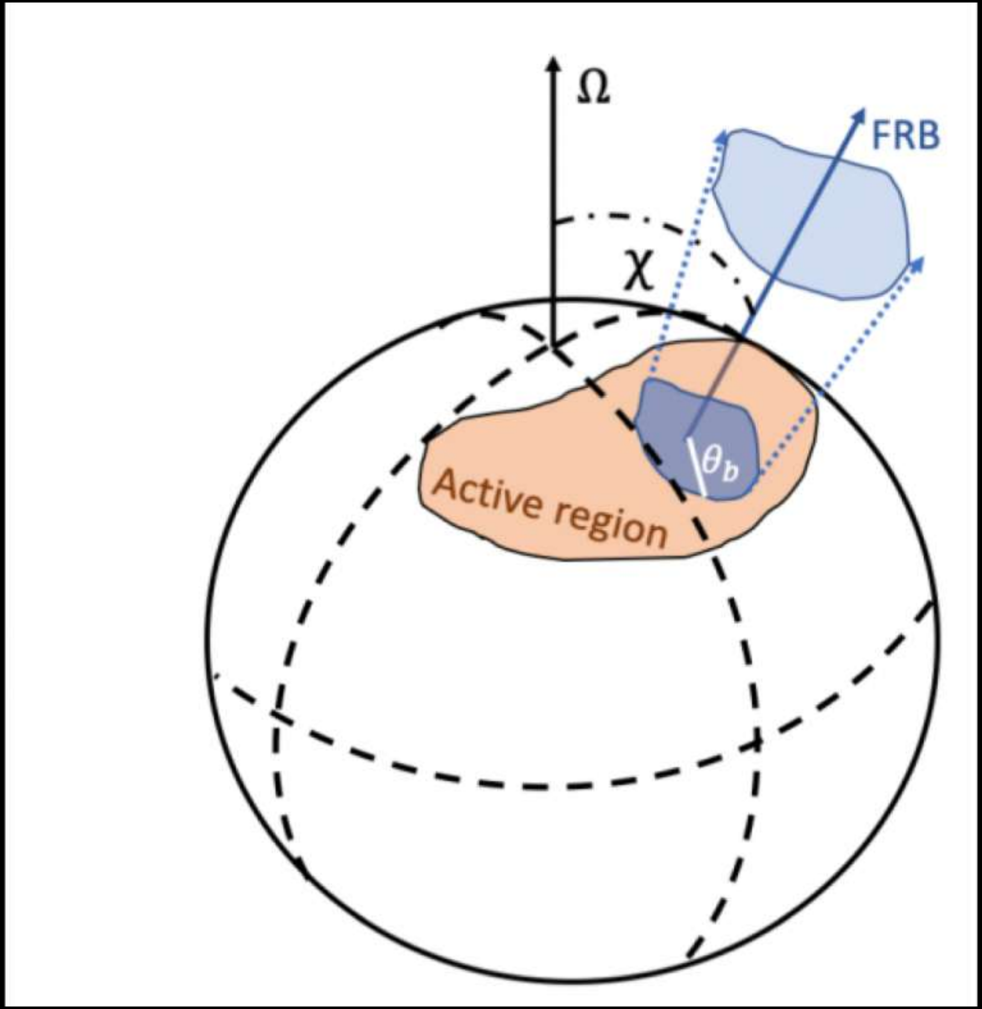


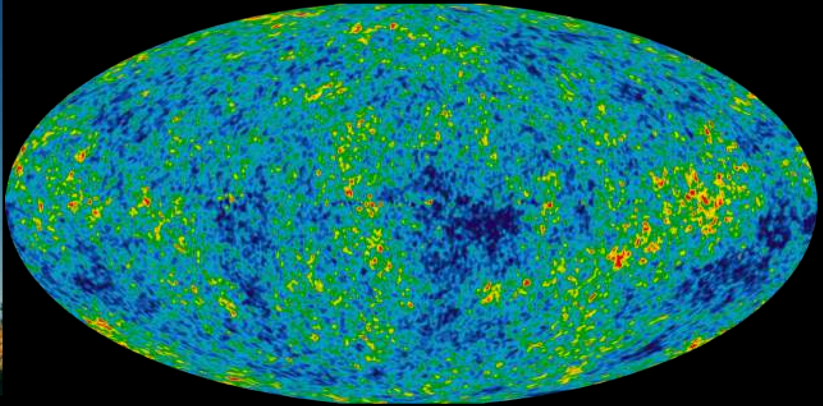
Conclusions

- Newly discovered Galactic long P radio sources: strong ultra-long period magnetar candidates
- Objects close-by → thousands or more in the Galaxy
- Source density, Dipole SD, timing stability, offsets and X-ray limit all suggest old ~ Myr ages
- Evidence for enhanced spin-down also in confirmed Galactic magnetars
- Distinct evolution of magnetic field between magnetars and ULPM candidates
- Possible FRB connection – why is the FRB source density so much smaller?

Thank you!

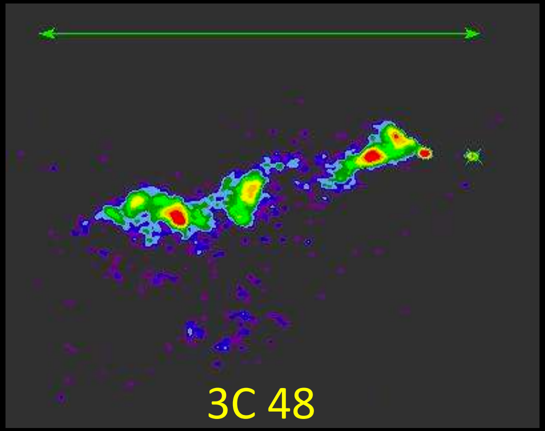
Major astronomical discoveries observed in radio

1933 - Karl Jansky discovers radio waves from Milky Way center



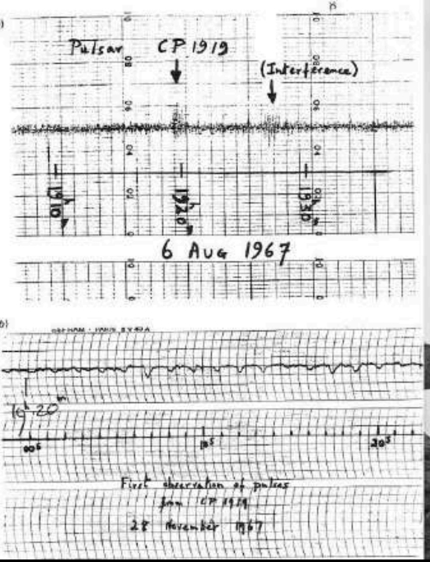
1964 – Penzias and Wilson discover the Cosmic Microwave Background

Sixties – First discoveries of quasars and understanding of them as objects outside Milky Way

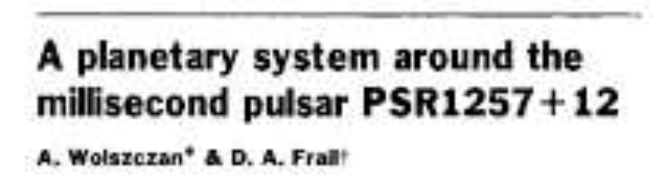


3C 48

1967 – Jocelyn Bell discovers radio pulsars



1992 – First exoplanets discovery, orbiting a pulsar



A planetary system around the millisecond pulsar PSR1257+12

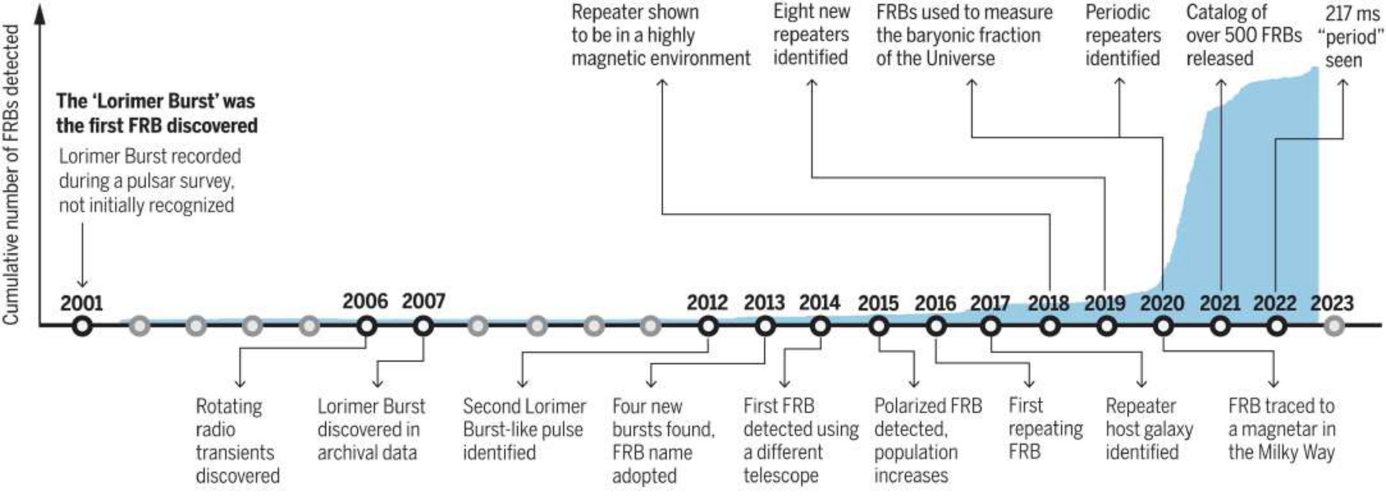
A. Wolszczan* & D. A. Frail†

Unexplored parameter space in radio astronomy

- Radio observations involves trade-offs and compromises:
  - fine spectral or fine temporal resolution
  - Large coverage area or low limiting flux
  - Which bands to observe
  - Storage / computational constraints
  - Etc.

➢ Large unexplored parameter space for radio discoveries

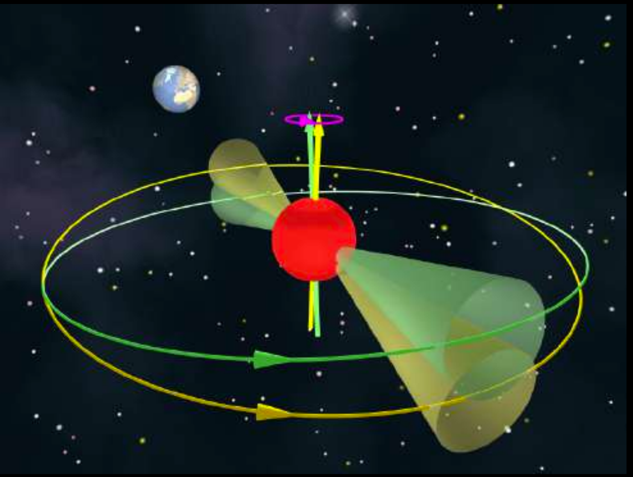
Bailes 22

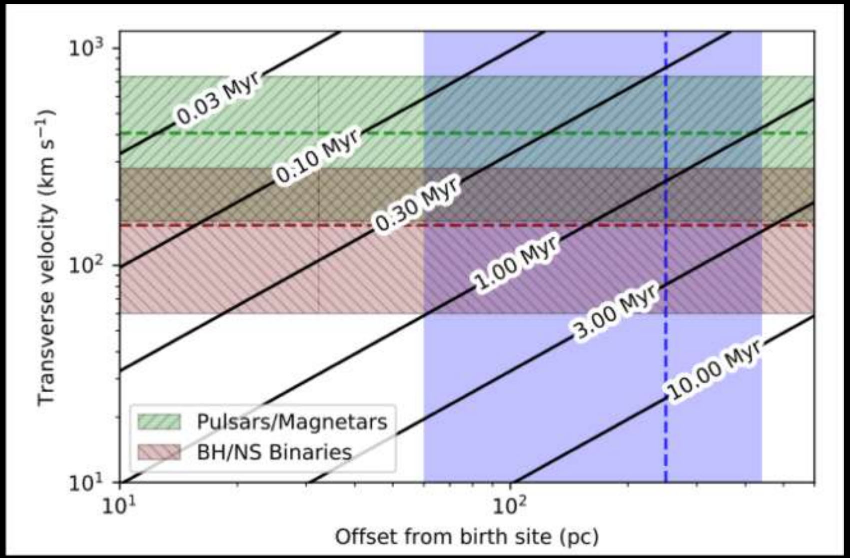


Obstacles for other models

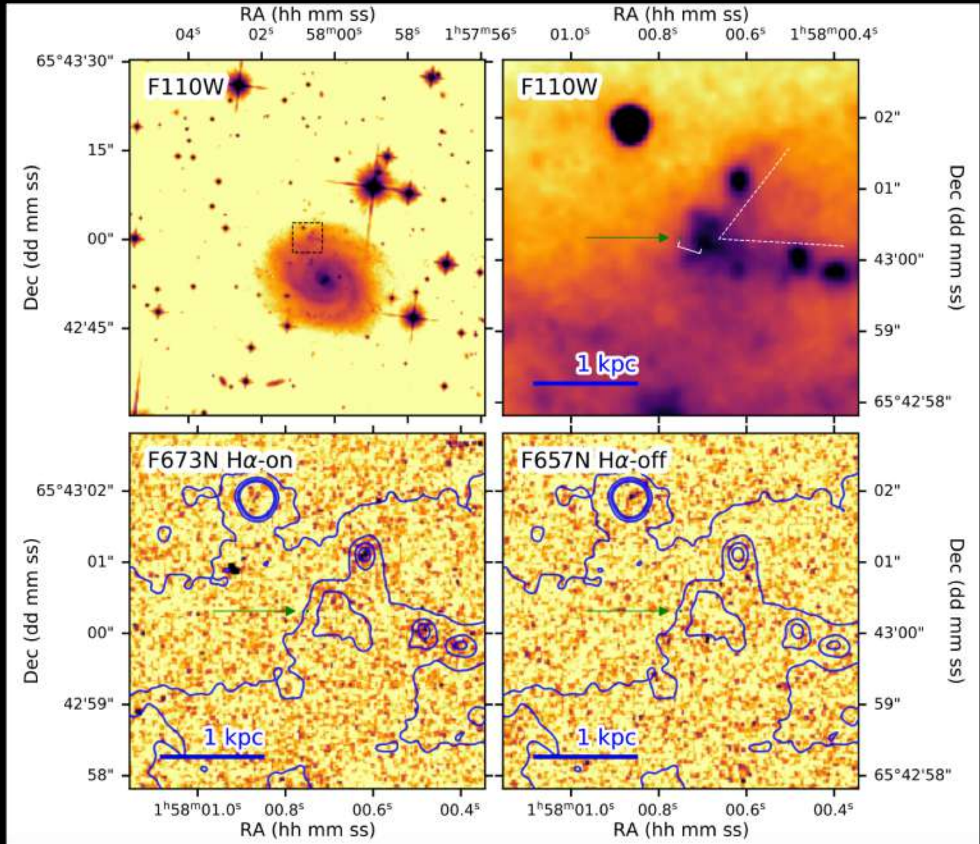
Precession predictions **(Zanazzi & Lai 20, Levin et al. 20)**

- High temperature -> Young age (challenged by non star-forming environment, Tendulkar et al. 21)
- Significant changes in polarization (but R1 polarization quite stable)
- Underlying shorter period (ruled out for R1, Zhang et al. 18)
- Precession inversely related to deformation -> many more FRBs should have longer periods (and activity might anti-correlate with period)



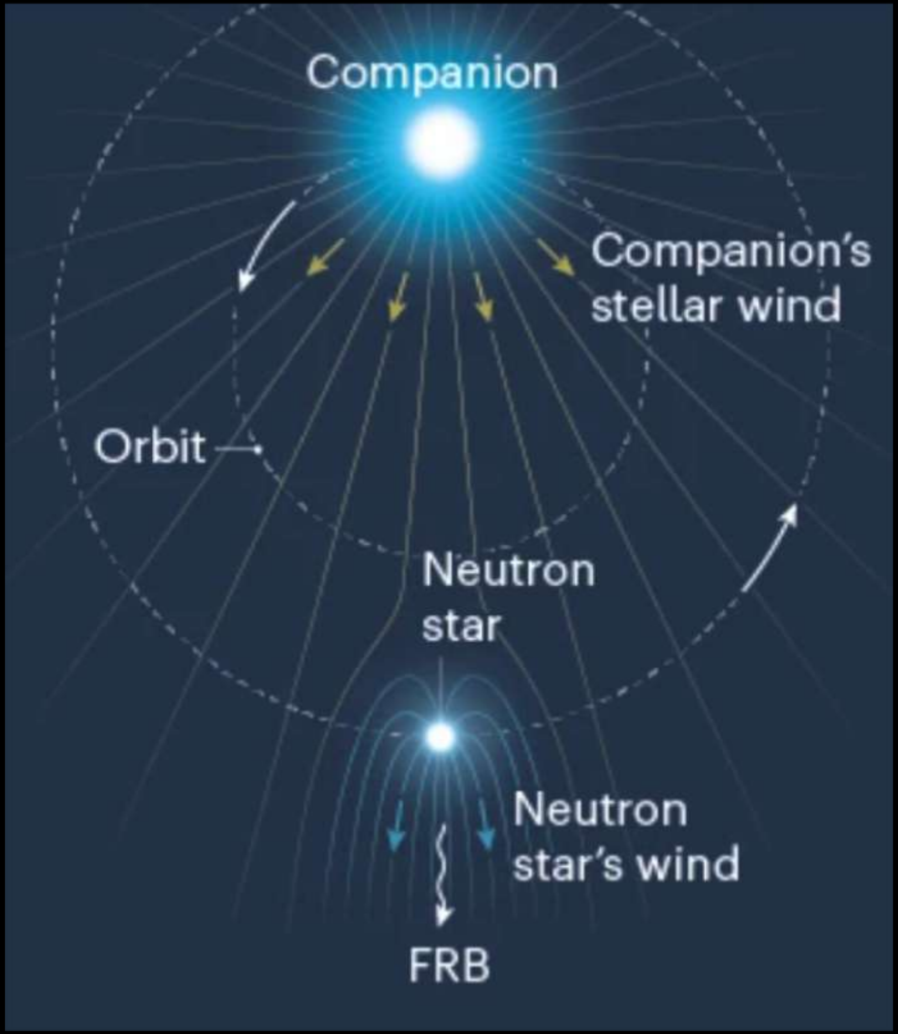


Tendulkar et al. 21



Obstacles for other models

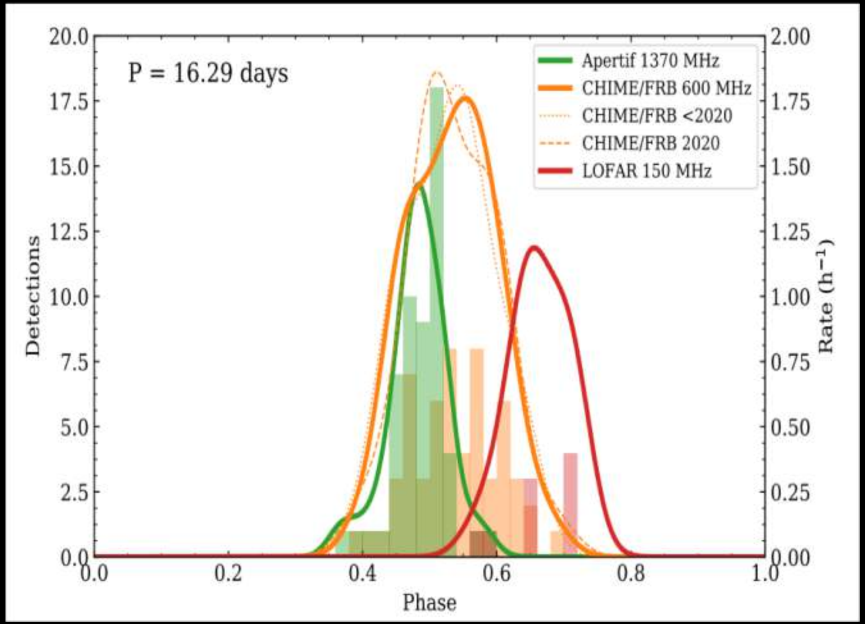
Shrouded binary predictions (Lyutikov 2020, Ioka & Zhang 2020)



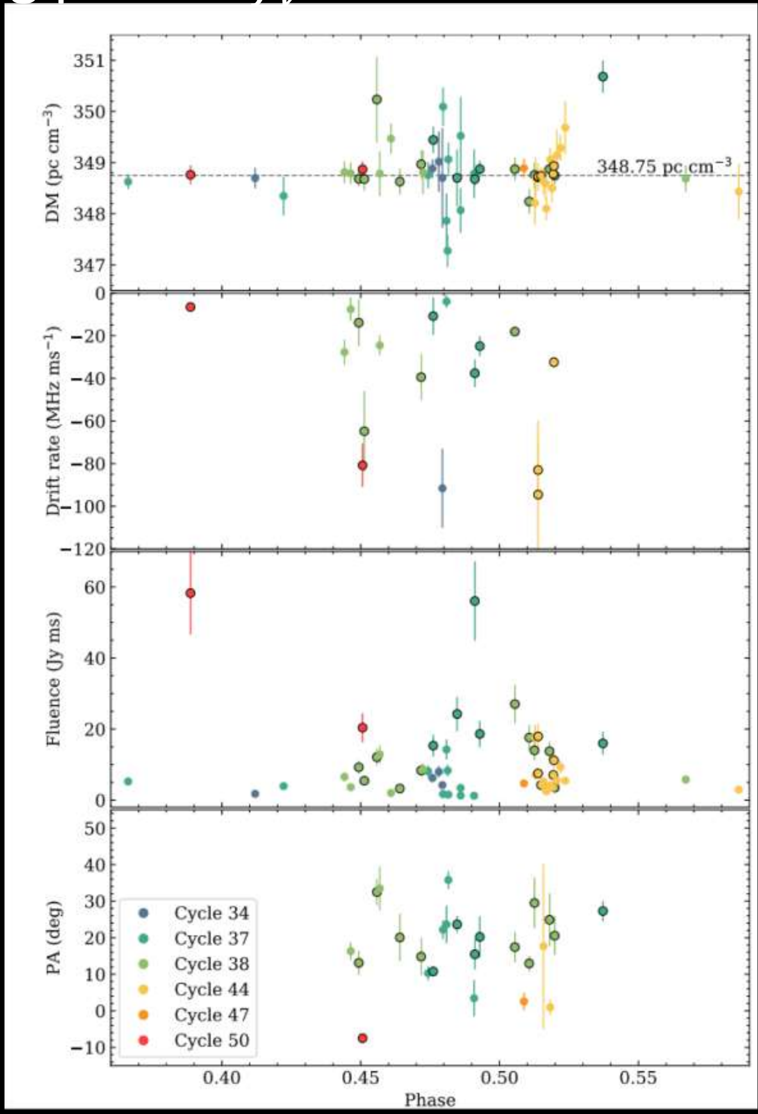
Obstacles for other models

Shrouded binary predictions (Lyutikov 2020, Ioka & Zhang 2020)

- Shrouding preferentially obscures low frequency bursts. In eclipsing pulsars $f_\nu \propto \nu^{-0.4}$ *Opposite is observed!*
- O / B type companion ruled out for R3 (Tendulkar et al. 21)
- DM changes within active phase -> *but* $\Delta DM < 0.1\,\frac{pc}{cm^3}$
- Low frequency spectral cutoff *(unobserved)*
- Flux modulation with phase *(unobserved)*
- Underlying shorter period (ruled out for R1, Zhang et al. 18)
- Large fluctuating RM - significant depolarization at low frequencies and RM sign reversal (PB, Kumar & Narayan 22)

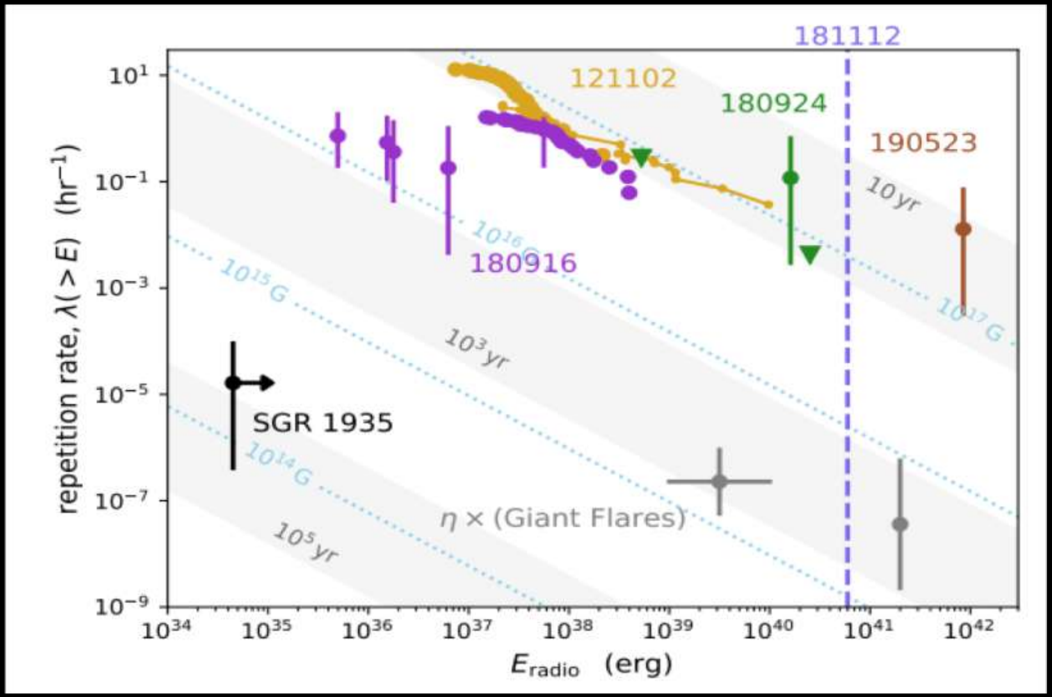


Pastor-Marazuella et al. 20



Simplest (most naïve) story – long period magnetars

- Binarity of FRB progenitors already needed due to Galactic and M81 FRBs



Margalit, PB, Sridhar, Metzger 20

- Existence of ultra-long period magnetar population (probed by persistent radio or X-ray)

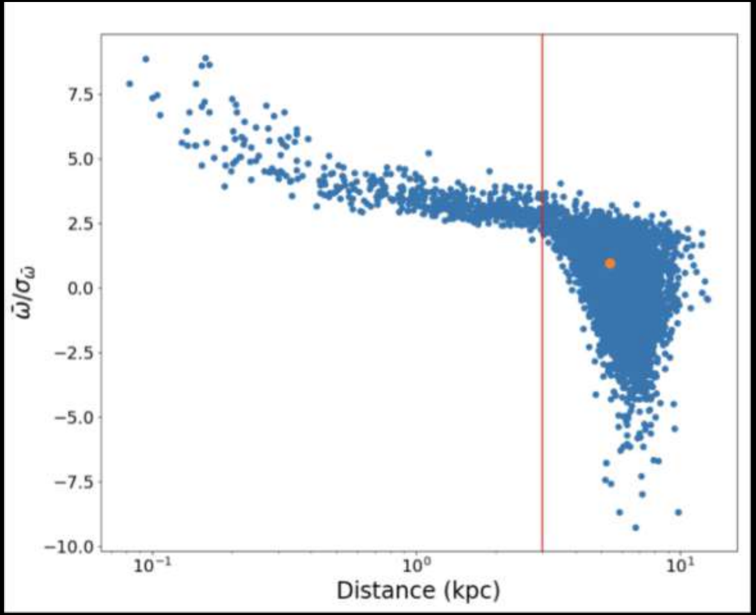
- No underlying shorter period associated with spin

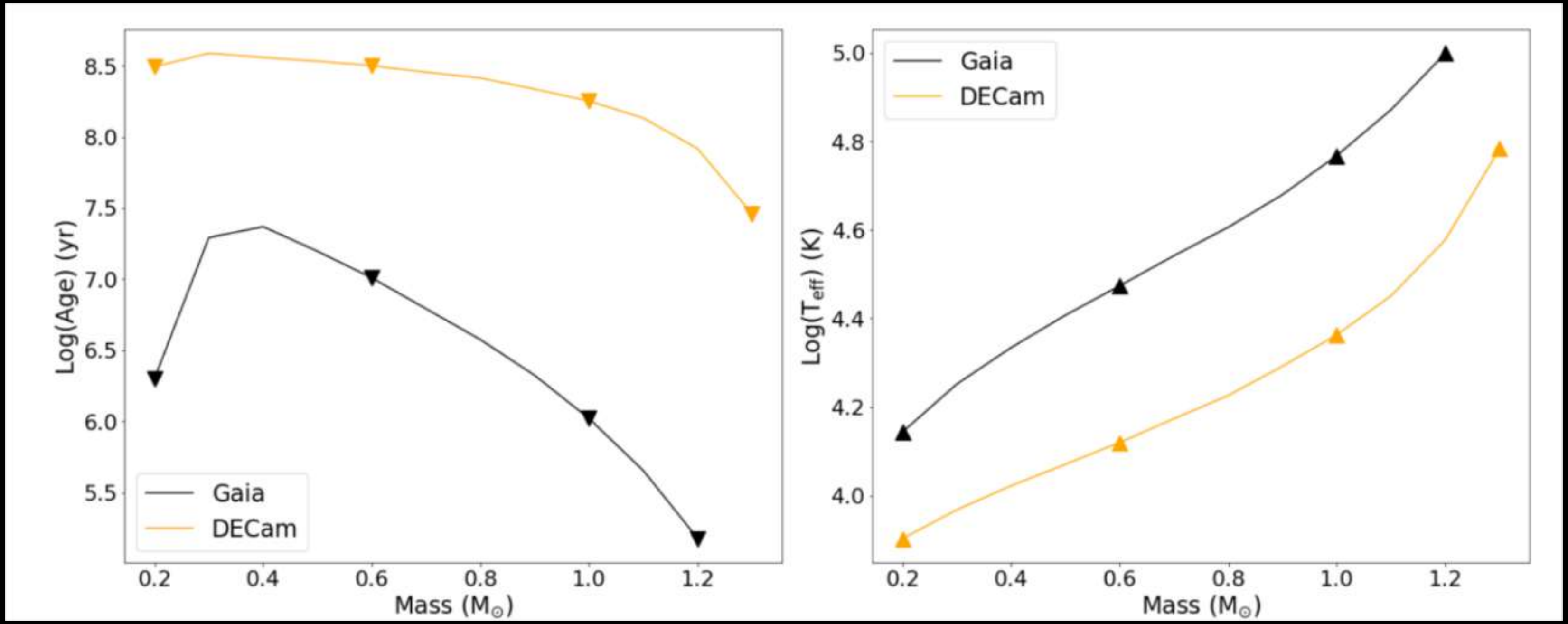
- ΔDM independent of period phase

- If fallback dominates spindown: association with weaker SNe or more massive progenitors

Could GLEAM-X be a WD or part of a stellar binary?

- One potential counterpart detected by GAIA at offset 0.94'' from radio
- *However,* parallax error suggests it is at d>3kpc and unrelated to GLEAM-X





- R and G band limits rule out a WD at radio position unless it is extremely old

PB et al. 23

Could GLEAM-X be a WD or part of a stellar binary?

Magnetic WD?

WD can supply observed radio luminosity only for a very short time

$$\tau_B \lesssim \frac{\eta E_B}{f_\Omega L_R} \sim 50 B_8^2 R_{8.5}^3 \eta f_\Omega^{-1} L_{R,31.5}^{-1} \quad \text{yr},$$

Inconsistent with optical limits and rate of magnetic WD formation

$$\frac{\dot{r}}{\dot{r}_{\rm WD}} \gtrsim 200 B_8^{-2} R_{8.5}^{-3} f_\Omega \eta^{-1} L_{R,31.5}$$

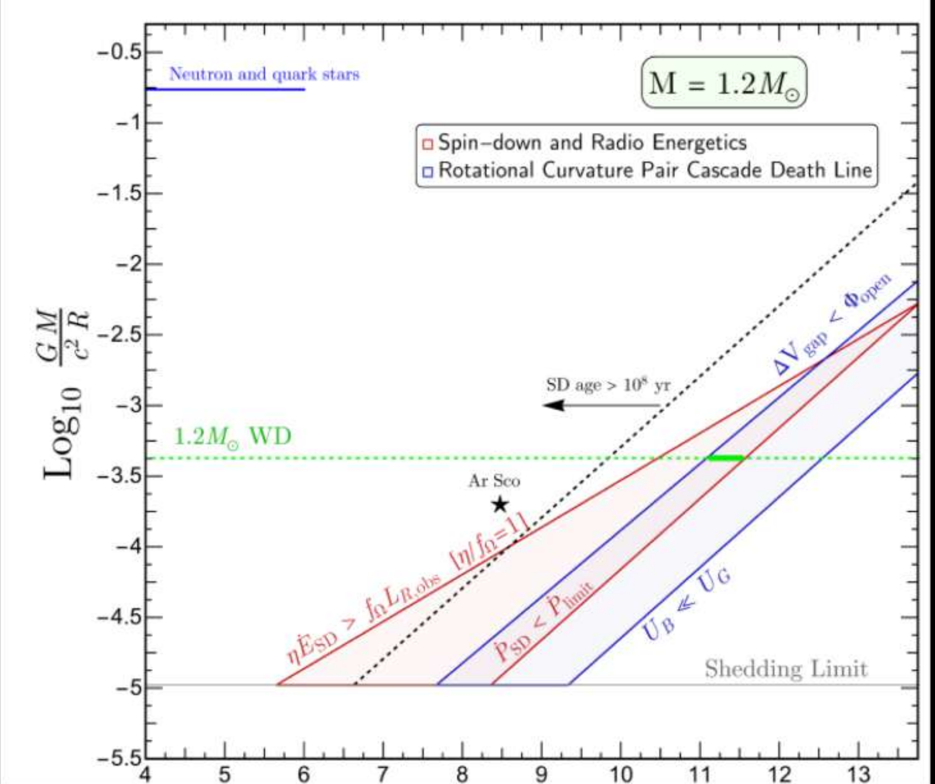
Rotation powered WD?

- Typical $B \sim 10^6 G$ WD has insufficient spindown power $L_{SD} \ll L_R \rightarrow$

one needs $B > 10^{11} G$ → orders of magnitude stronger than most magnetic WD and requires strong Ohmic dissipation → high temperature → high optical luminosity – ruled out by observations

- Small duty cycle → strong beaming → relativistic motion (unnatural from WD surface)

General constraints

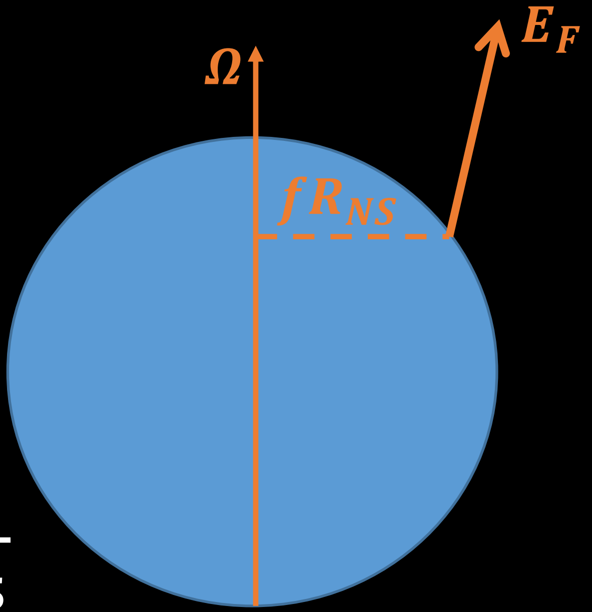


PB et al. 23

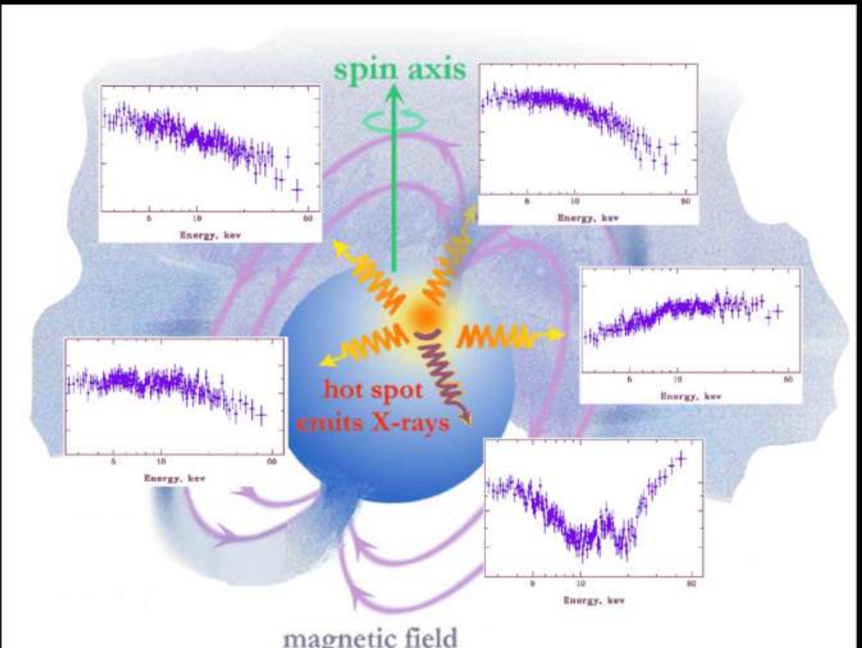
Physical mechanisms for enhanced spin-down

Kicks

- Magnetars have complex field structure near surface
- Energy ejection by Giant Flare may carry angular momentum
- Flare duration << magnetar spin period
- $|\Delta\Omega| \sim \frac{f R_{NS} E_f}{cI} \sim 2.5\ 10^{-5} E_{f,45} f\ s^{-1}$
- Consecutive flares could lead to $\mathrm{P} \propto N$ for favorable geometry
- Followed by small change in linear momentum: $v_{k,N} \sim 3\ 10^{3} E_{f,45} \sqrt{N_5}$

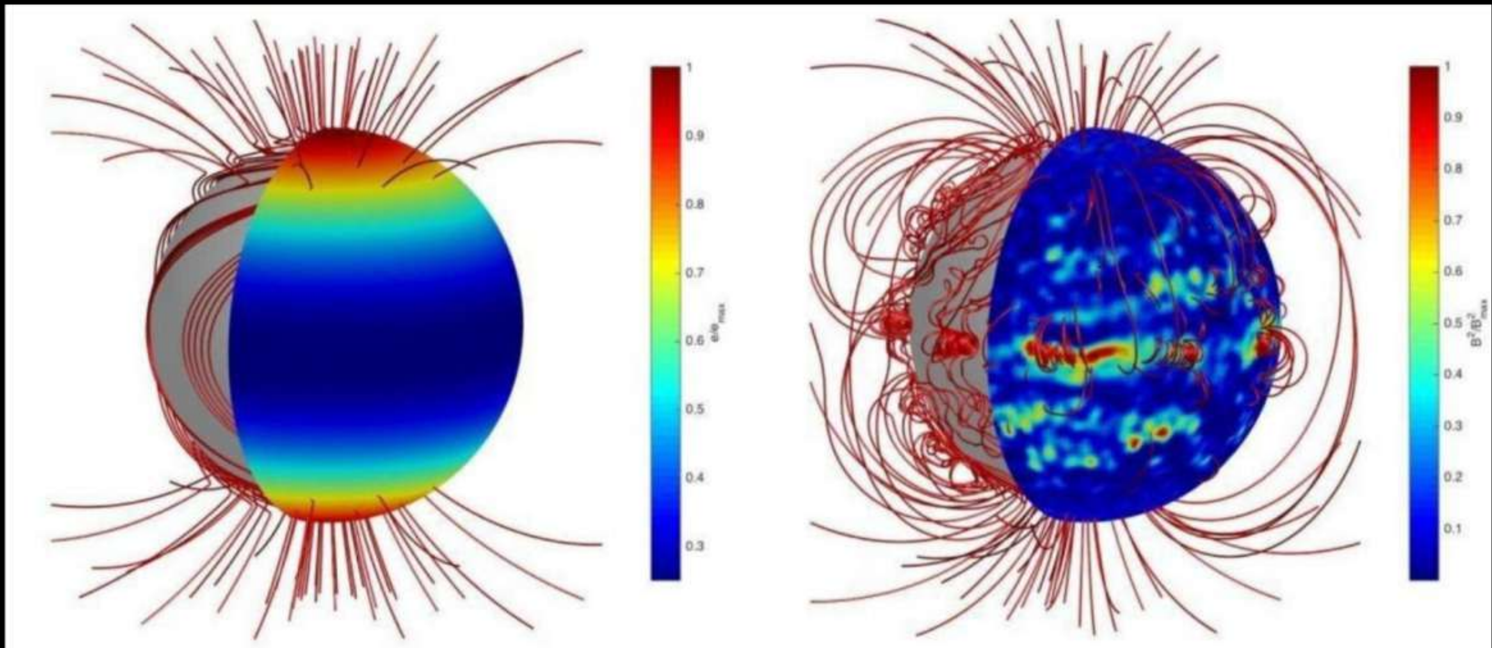


PB, Wadiasingh, Metzger 20



Molkov et al. 22

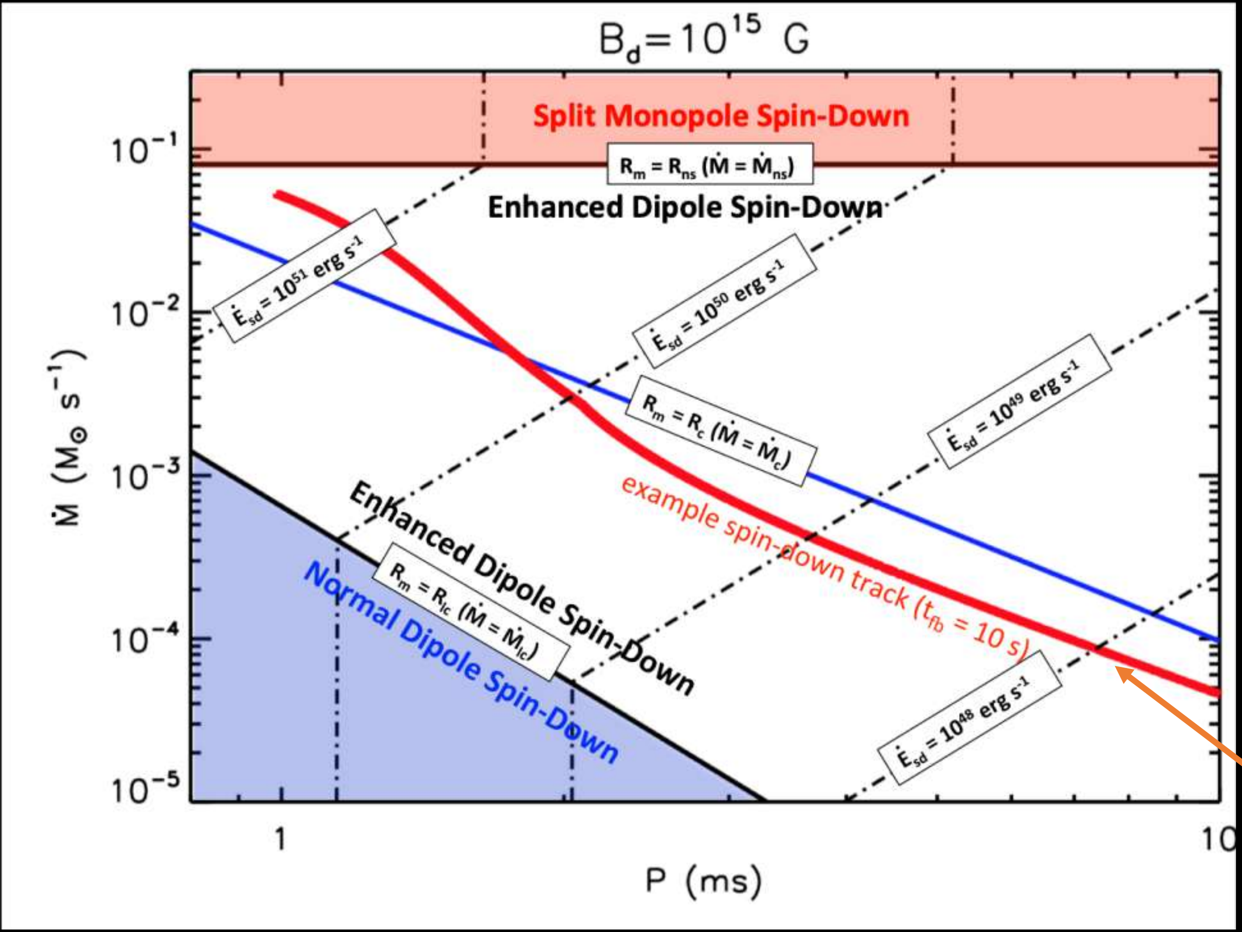
Gourgouliatos et al

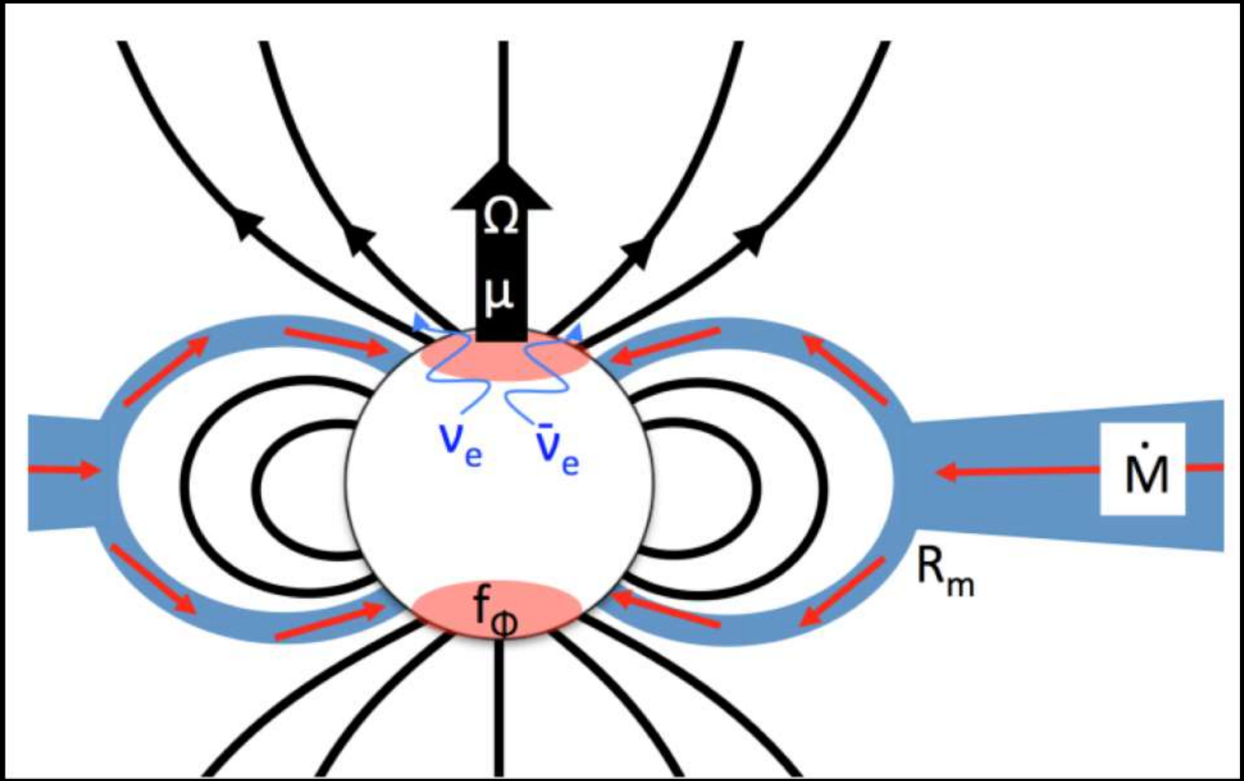


Physical mechanisms for enhanced spin-down

Fallback accretion

- RCW103 – sub-energetic SN remnant: consistent with more fallback
- Fallback accretion alters magnetar evolution by adding rotational energy sink/reservoir and enhancing spindown by opening up field lines





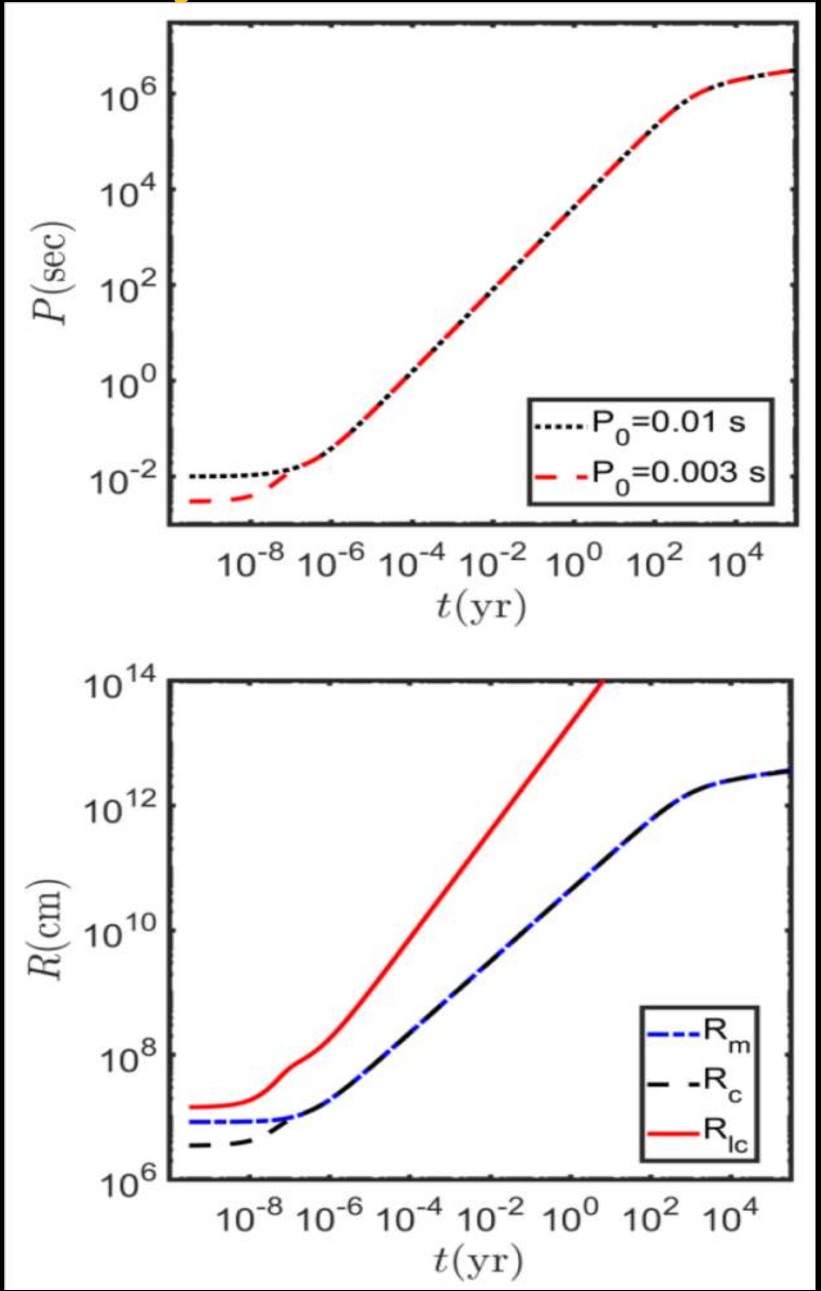
Rough equilibrium between co-rotation and Alfven radius

Metzger, PB, Giannios 18

Physical mechanisms for enhanced spin-down

Fallback accretion

- P exponentially increases until $R_m \sim R_c$ and evolves as $t^{3\zeta/7}$ afterwards, where $\dot{M} \propto t^{-\zeta}$
- Large ζ expected for high $\dot{M}$ RIAFs
- ζ cannot be too large to avoid early disk disruption
- Maximum period set by time it takes magnetic field to decay (relative to initial fallback time)
- Accretion can lead to ULPMs under plausible conditions
- Bimodality of magnetar periods can be related to bimodality in SN properties

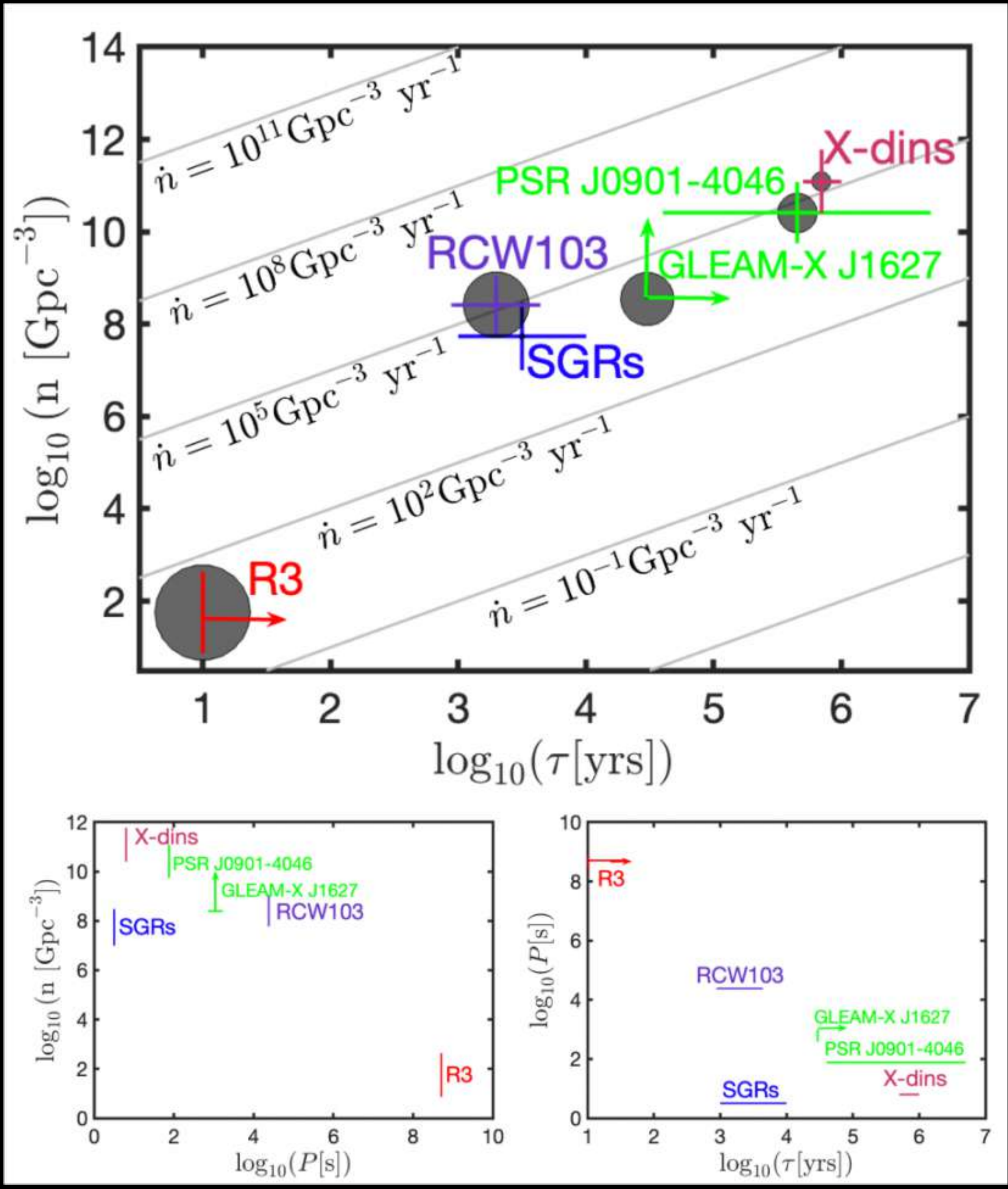


PB, Wadiasingh, Metzger 20

Age of ULPM candidates

PB et al. 23

- Both PSR J0901-4046 and GLEAM-X likely old $0.3Myr \lesssim \tau \lesssim 1Myr$
- Different formation channel to confirmed magnetars , but with similar formation rate
- Parametrizing $\dot{B} \propto B^{1+\alpha}$ (Colpi et al. 2000), normal magnetars require $-1 \lesssim \alpha \lesssim 2$ $10^3yr \lesssim \tau_d \lesssim 10^4yr$
- ULPM candidates require different α and / or τ_d

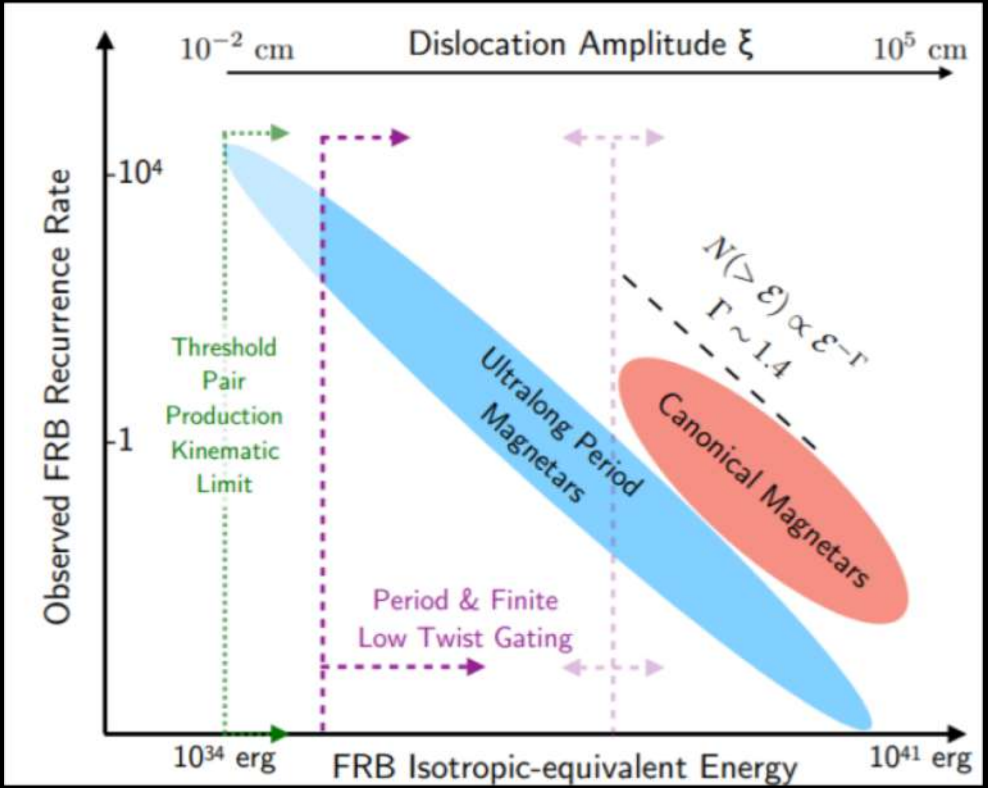


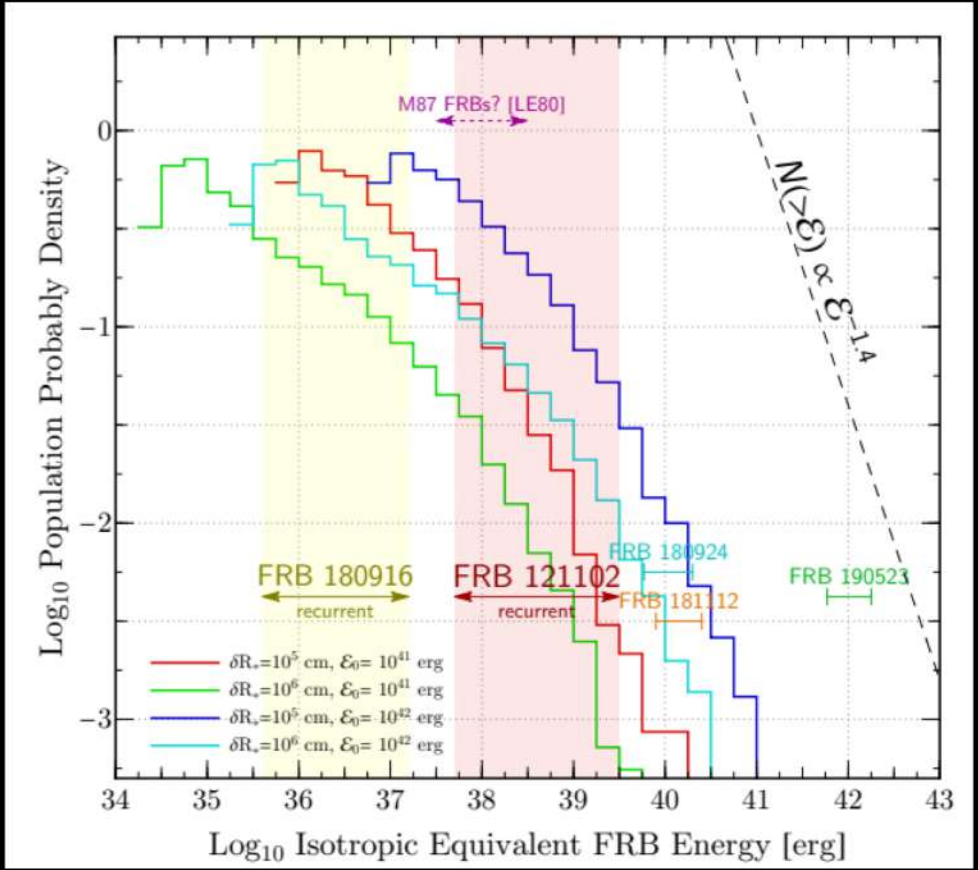
Possible selection effects – ULPMs favor FRB production

Example – low twist model

- The low-twist model of Wadiasingh & Timokhin associates FRBs with avalanche magnetic pair production by local field perturbations
- Minimum dislocation amplitude $\propto P^{-1}$ ->

ULPMs produce more (faint) FRBs than regular magnetars

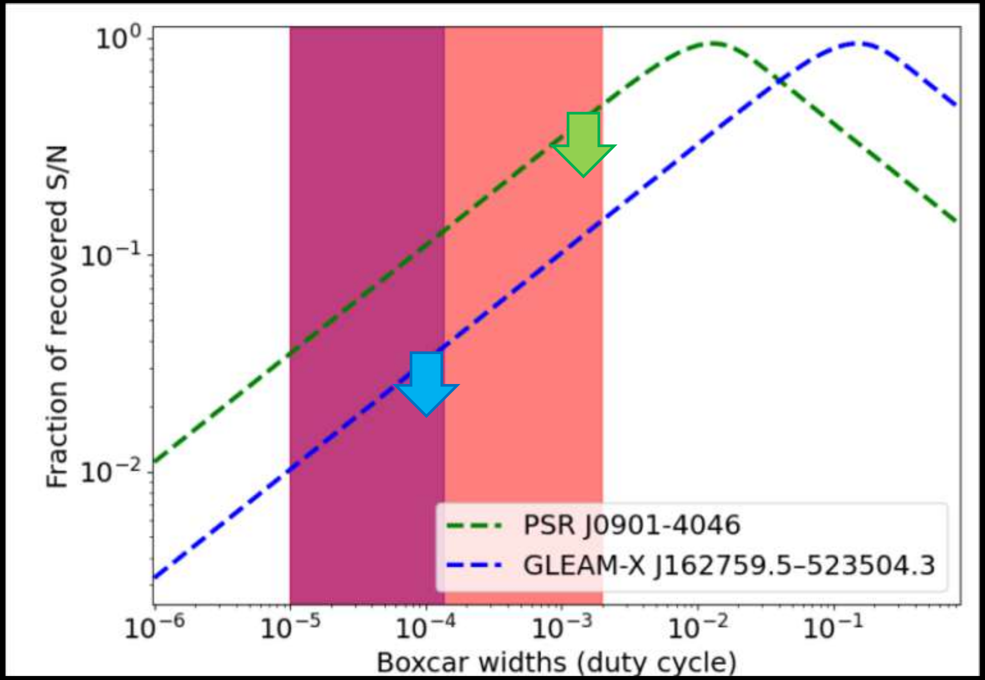


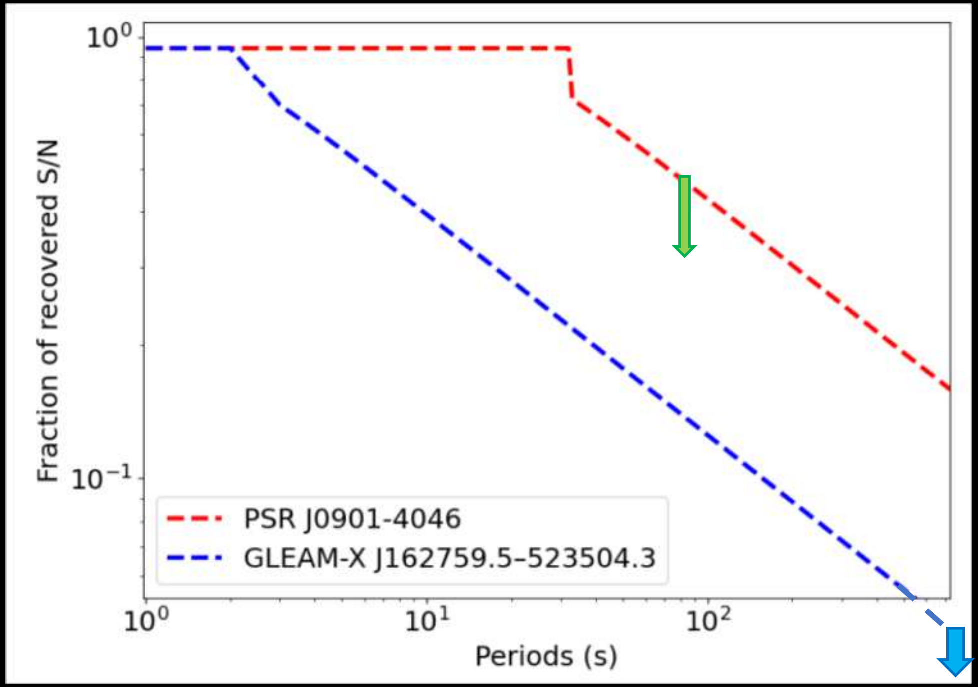


Same population resulting from Monte Carlo simulation corresponds to FRB energy distribution in agreement with periodic FRBs

PB, Wadiasingh, Metzger 20

Why so few sources known so far?





- Time domain surveys spend little time in any one point ($\lesssim 20m$) – inhibits ULPMs detectability prospects
- Current real-time pulse search pipelines recover <0.4 of J0901-4046 SNR (<0.04 for GLEAM-X)

How to correct this?

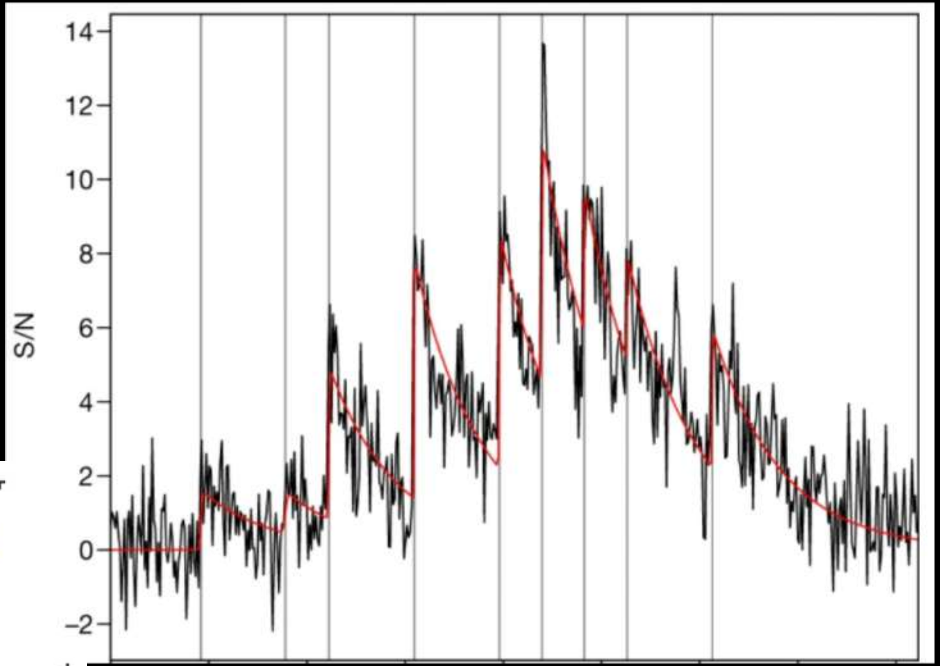
- Phased array feeds – Increase field of view and effective dwell times
- Search in image domain

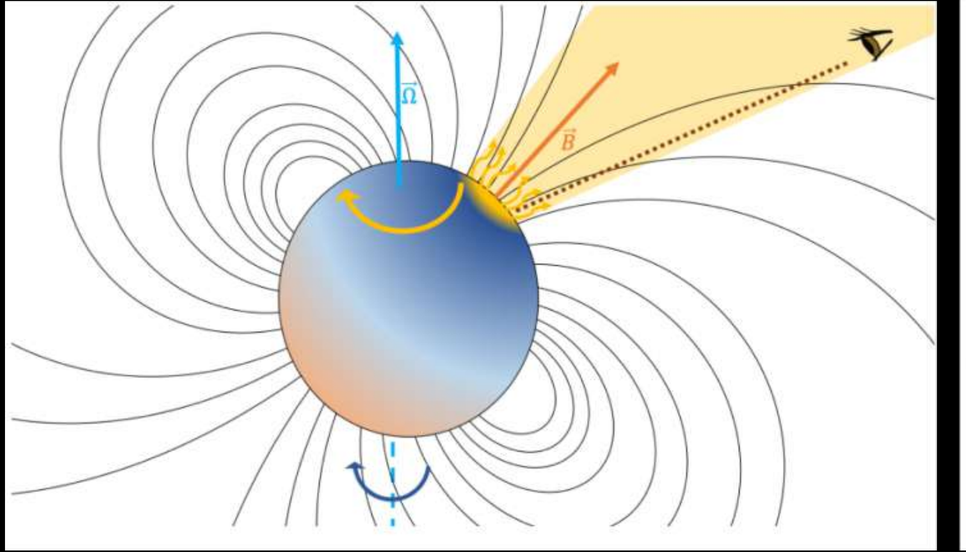
Evidence for hundreds of ms periods in two non-repeaters

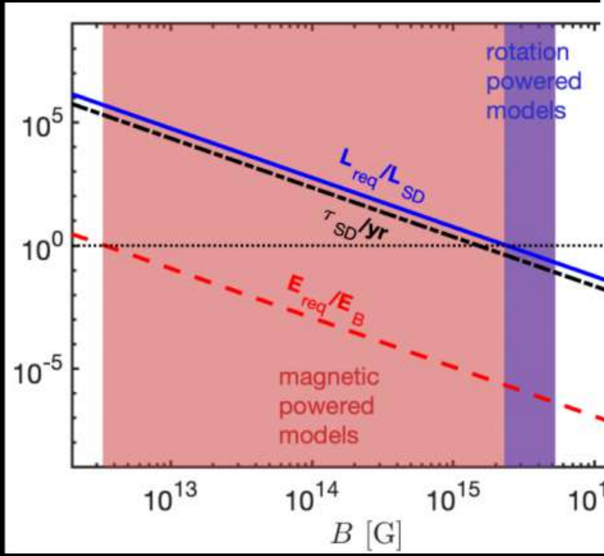
1. FRB 20191221A - Long duration periodic non-repeating FRB

- Long non-repeater with shorter underlying periodicity $P \sim 217ms$
- $\frac{\Delta P}{P} \sim 10^{-4} \rightarrow$ Likely rotational period
- Energetic considerations suggest magnetar scale field
- Rotation powered models practically ruled out

Chime et al. 22







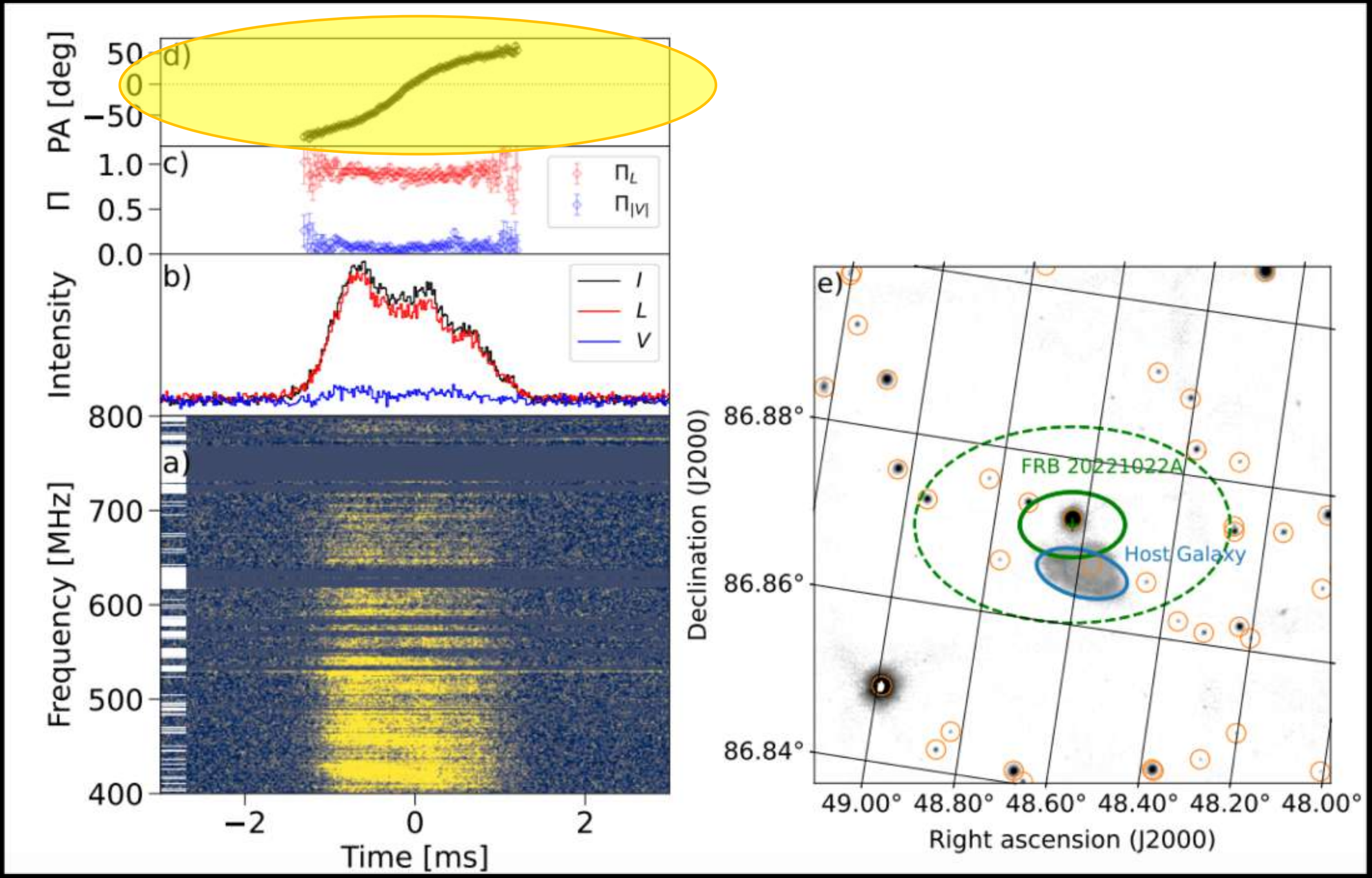
PB & Kumar 23

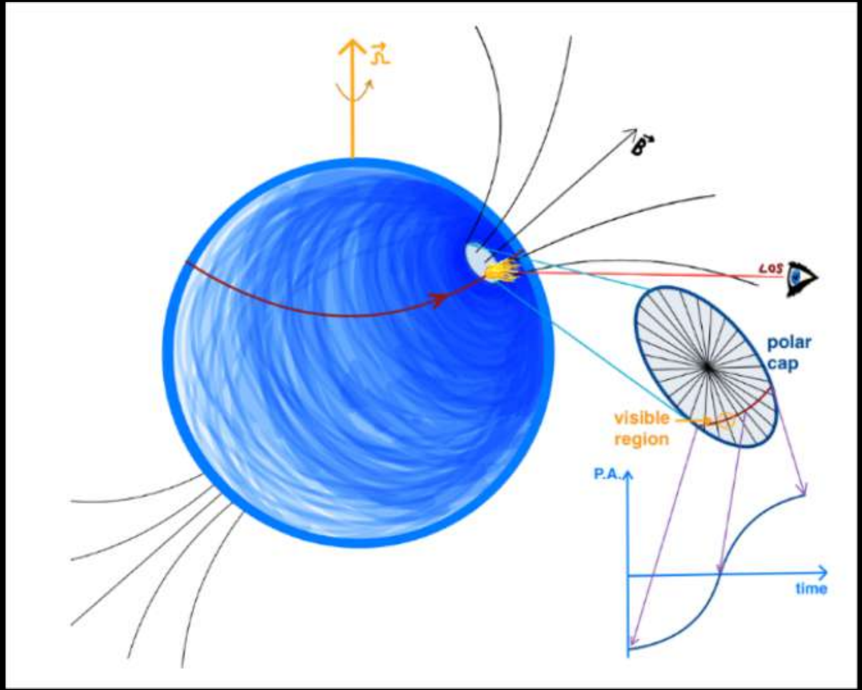
Evidence for hundreds of ms periods in two non-repeaters

2. FRB 20221022A - Magnetospheric emission and polarization angle swing

- Scintillation suggests emission from $R \lesssim 10^9 cm$
- PA swing -> magnetospheric emission from rotating beam
- Radiation from polar cap $\mathrm{P} = \frac{\pi c t_{\mathrm{FRB}}^2}{2r} \sim 0.3\ s$
- Energy source must be magnetic
- Emitting particles have $\Gamma \gtrsim 400$

Mckinven et al. 24

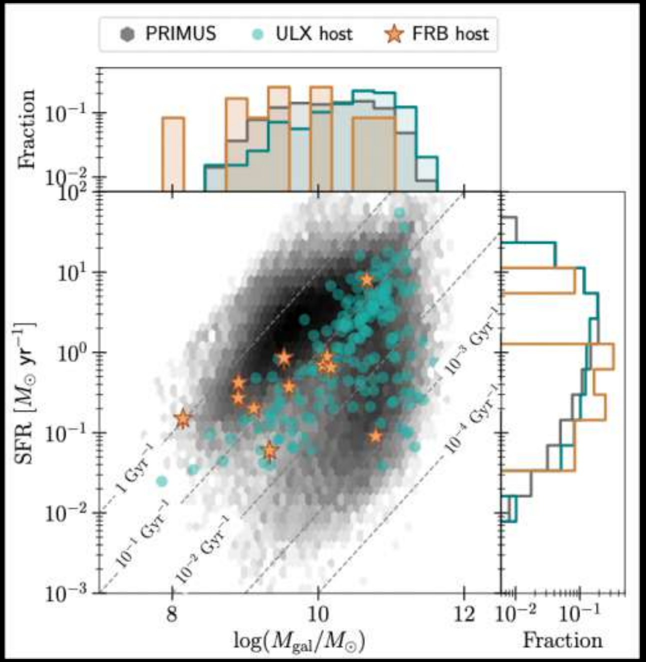




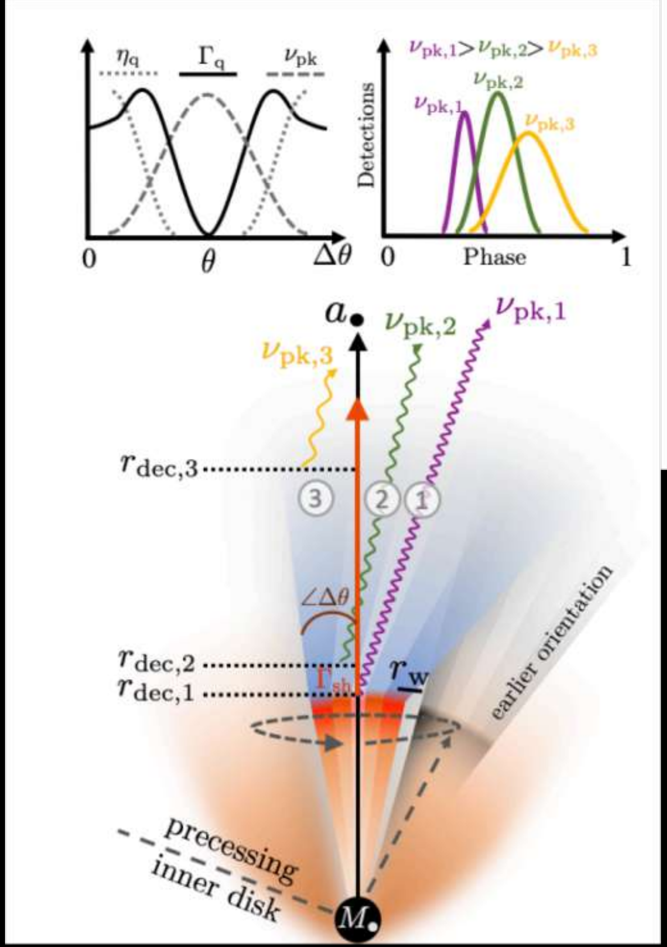
PB et al. in prep.

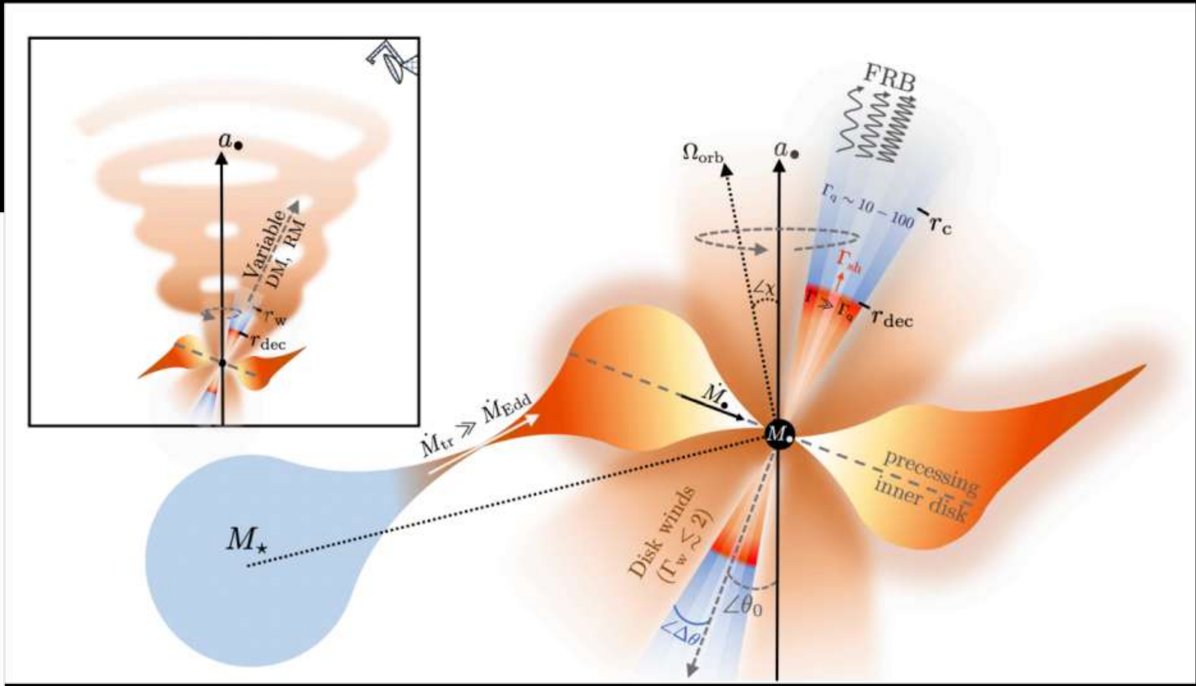
A different binary model: FRBs from X-ray binaries

- Baryonic outflow model requires only relativistic outflow – can be powered by super-Eddington accretion (ULX)
- Requires short stages of unstable mass-transfer
- Host galaxies and spatial offsets consistent
- Period is jet precession



Sridhar, Metzger, PB et al. 21





Predicts

- secular evolution of FRB properties over months / years
- Transient optical/IR counterpart
- Association with ULXs