A mechanism for coherent radio emission from ultra-long period magnetars

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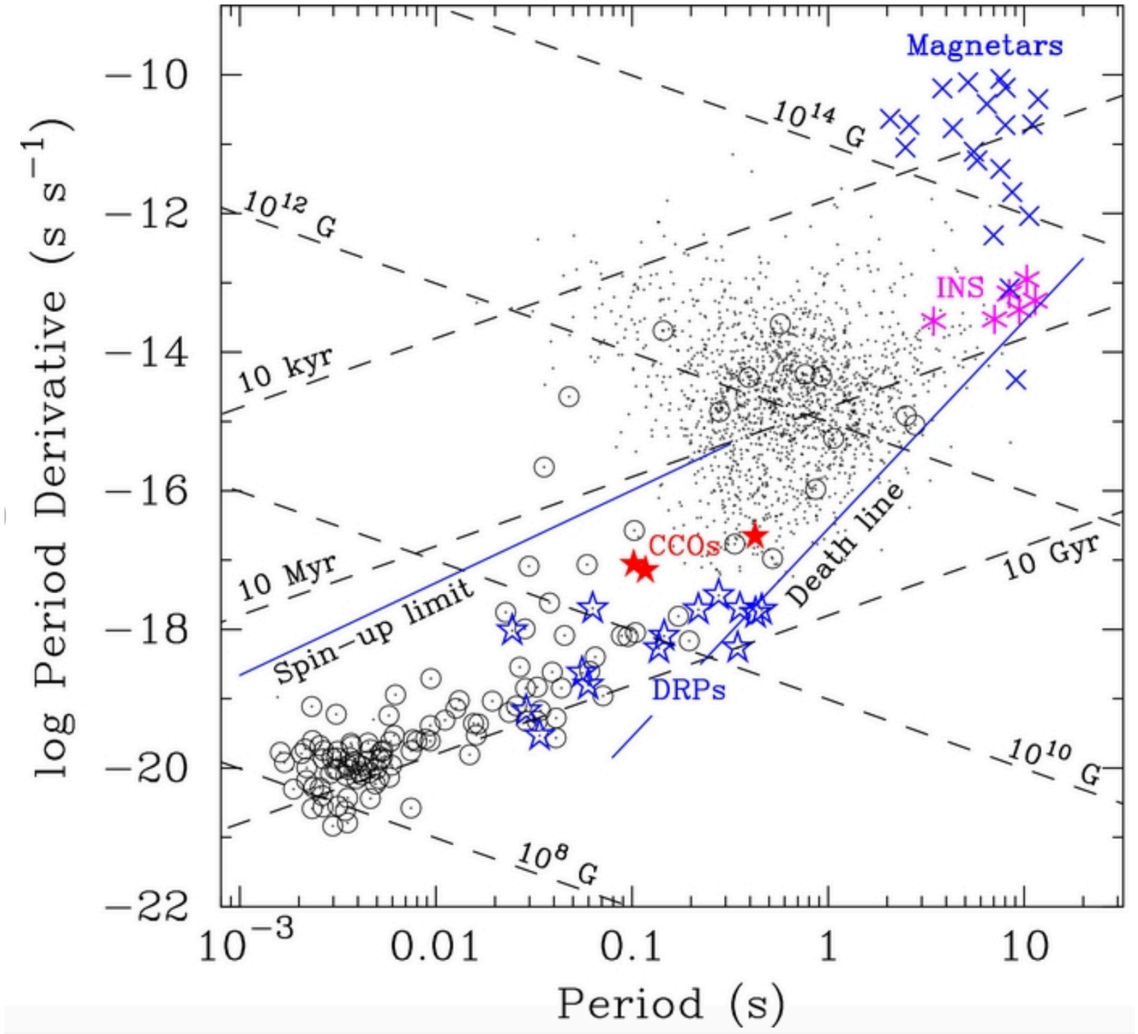
DDF24

In collaboration with Zorawar Wadiasingh (UMD/NASA Goddard)

UNIVERSITY OF OXFORD

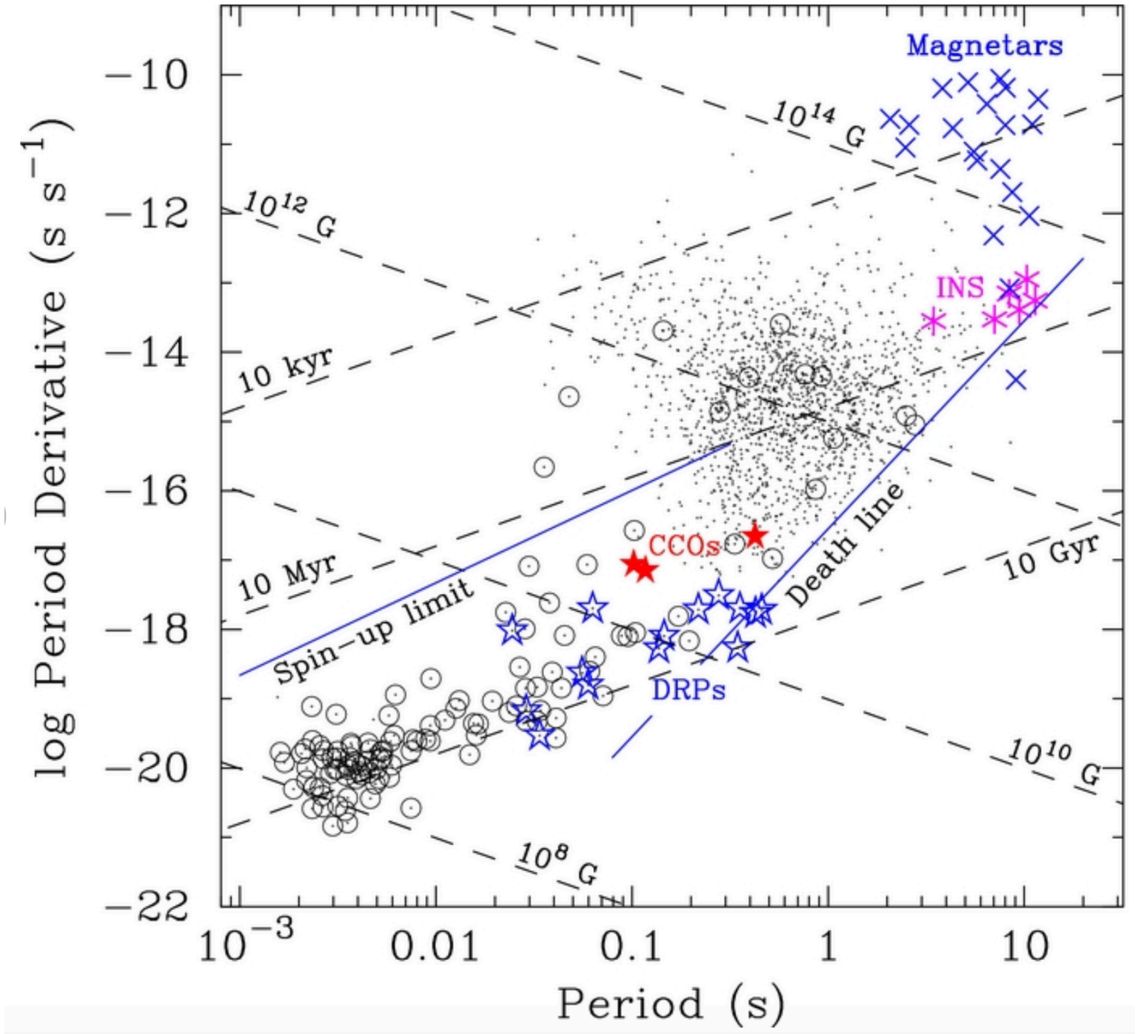
Big Picture



Cooper & Wadiasingh, in review

Big Picture

Neutron star break up



Cooper & Wadiasingh, in review

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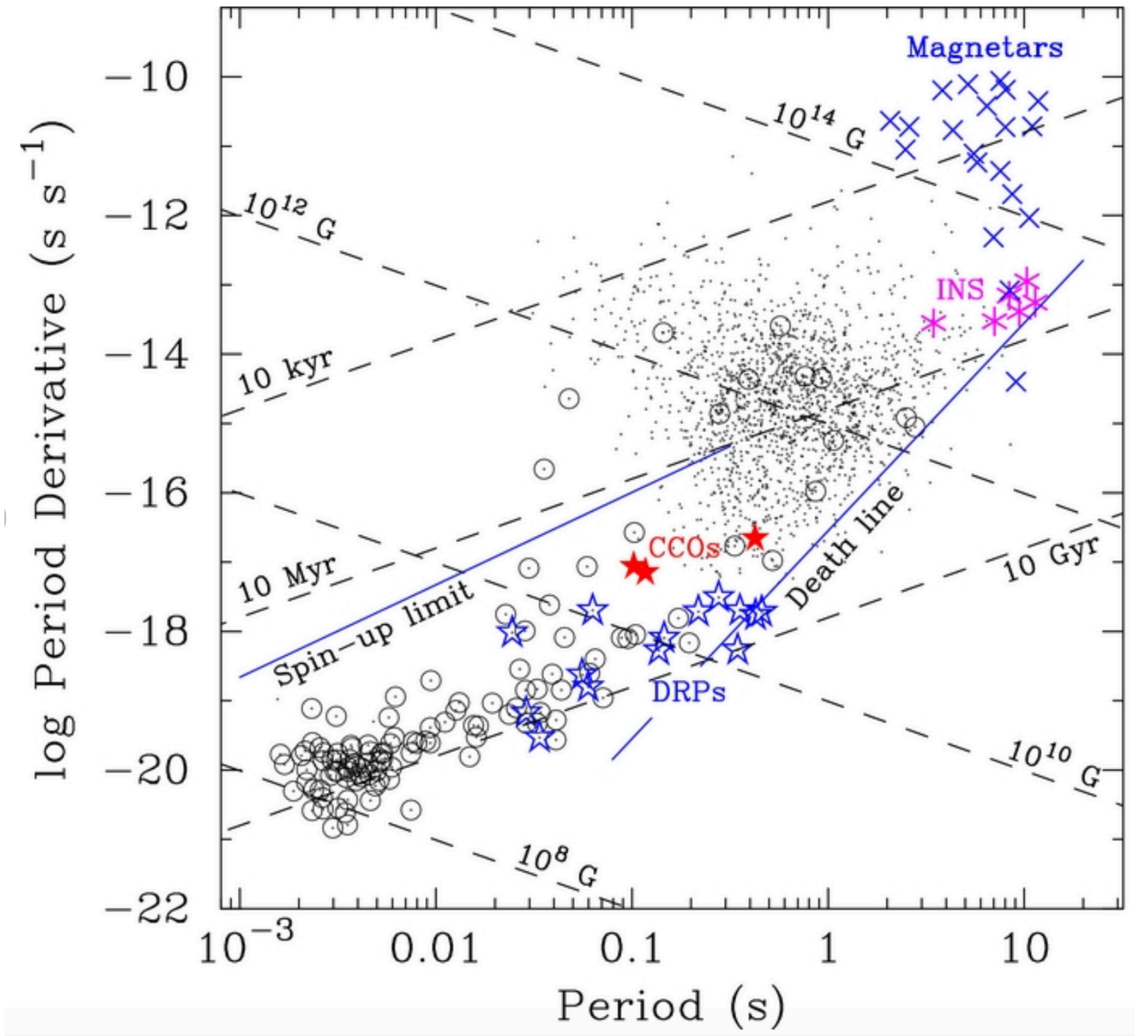

Unrealistic magnetic field: B >$10^{16\text{-}17}$ G

Neutron star break up

Cooper & Wadiasingh, in review

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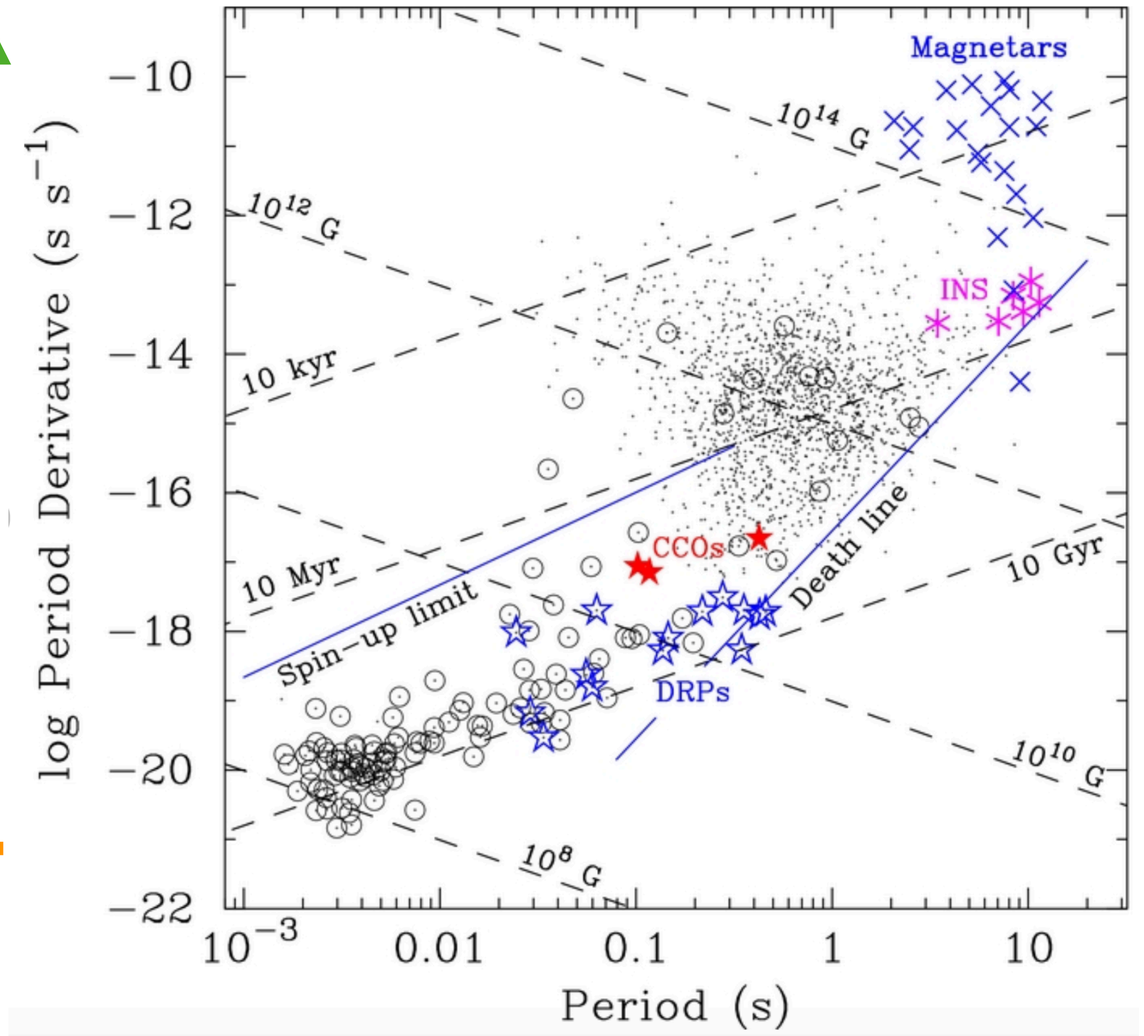
Short-lived Magnetar engine transients

e.g. talks by Bing Zhang/Yunwei Yu



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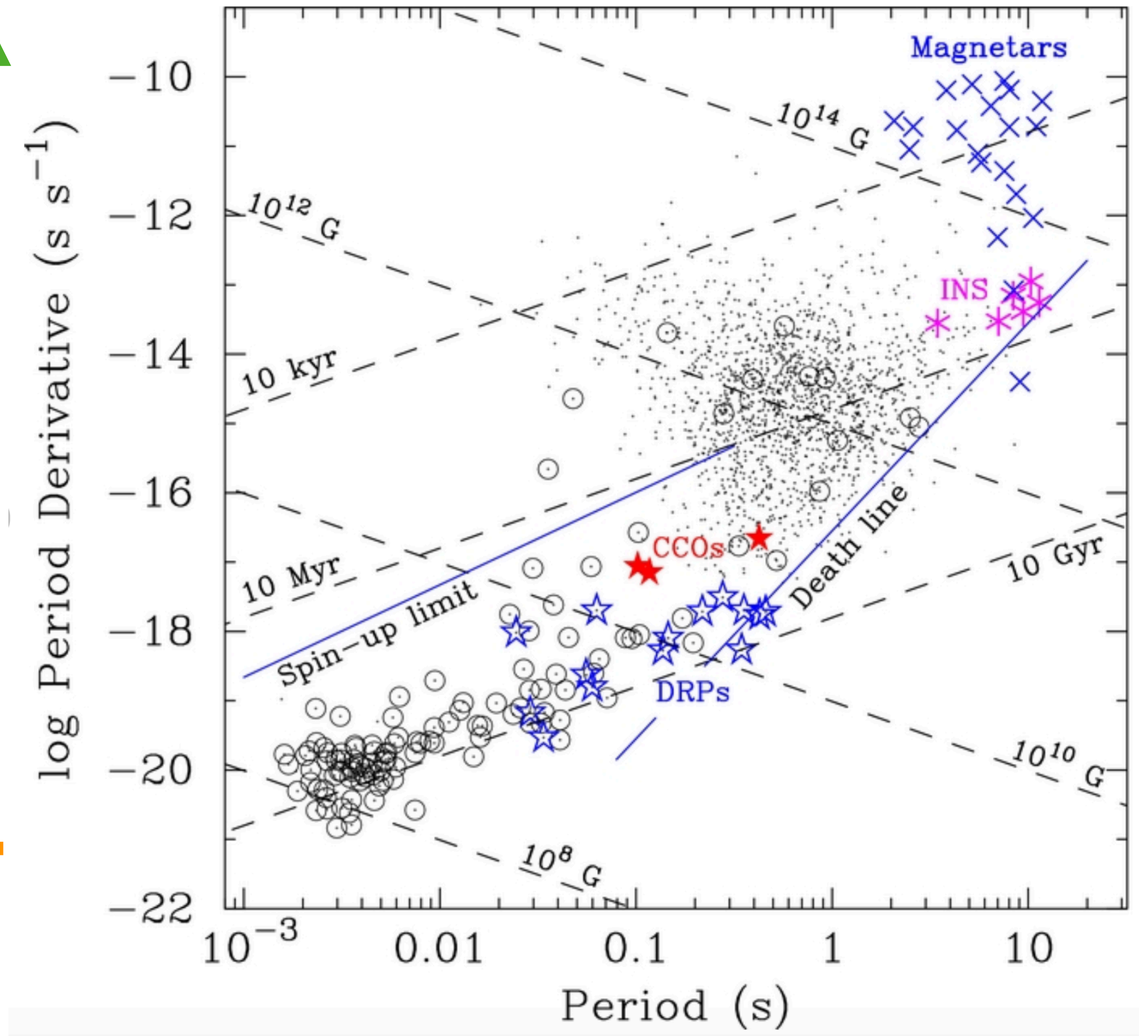

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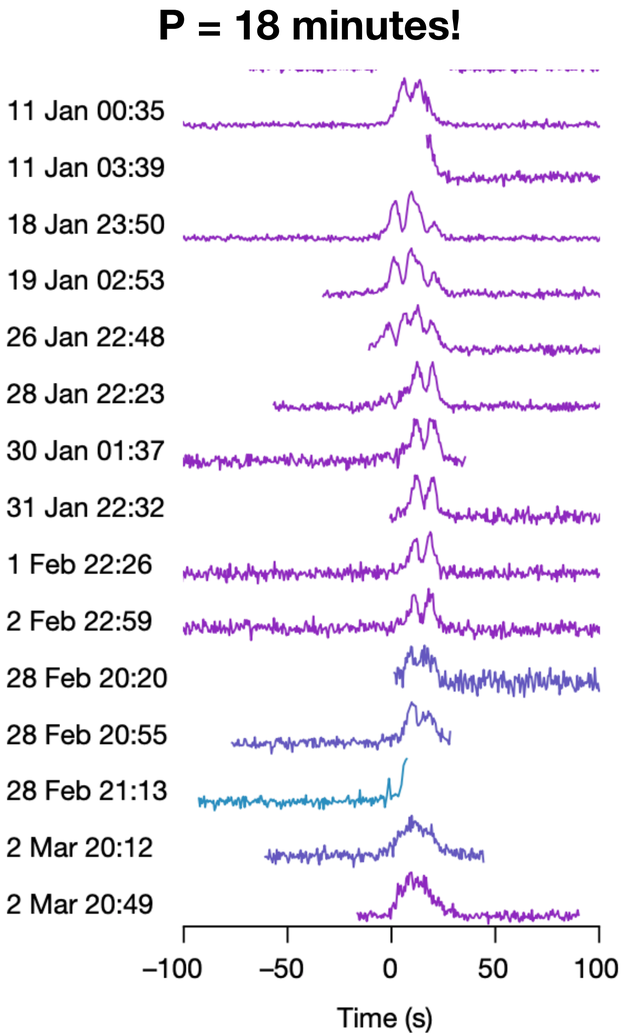
Beyond rotational Deathline?

Neutron star break up

Cooper & Wadiasingh, in review

Observations

- We have now detected multiple coherent radio transients with P>1000s



Hurley-Walker et al., 2022

Cooper & Wadiasingh, in review

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- Minute-long Jy pulses with $L_{radio} > L_{spin\text{-}down,\ max}$

Source	GLEAM-X J1627	GPM J1839-10	GCRT J1745
P [min]	18.18	21	77
$\dot{P}$	$< 1.2 \times 10^{-9}$	$< 4.6 \times 10^{-13}$	n/a
Pulse [s]	30-60	30-300	~600
Distance [kpc]	1.3±0.5	5.7±2.9	~ 8
$F_{\nu,\mathrm{radio}}$ [Jy]	5-40	0.1-10	~1
L_{radio} [erg/s]	$\approx 10^{28-31}$	$\approx 10^{28}$	$\sim 10^{30}$
$L_{\mathrm{spin-down}}$ [erg/s]	$\lesssim 1.2 \times 10^{28}$	$\lesssim 10^{25}$	n/a
$L_{\mathrm{X},0.3-10\mathrm{keV}}$ [erg/s]	$< 10^{32}$	$< 1.5 \times 10^{32}$	$\lesssim 3 \times 10^{35}$
Duty cycle	≈ 2 months	≳ 33 years	~7 hours

Cooper & Wadiasingh, in review

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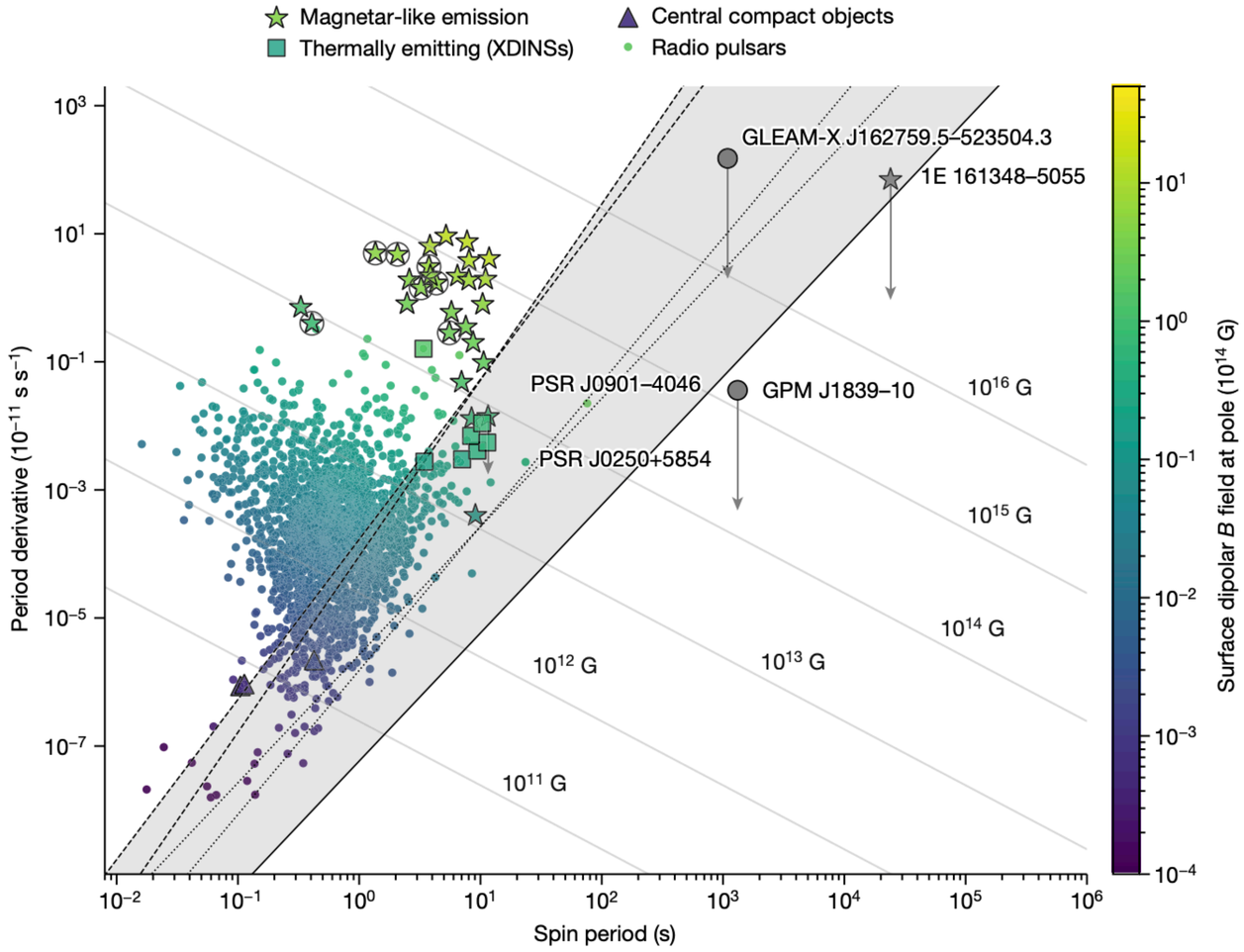

Cooper & Wadiasingh, in review

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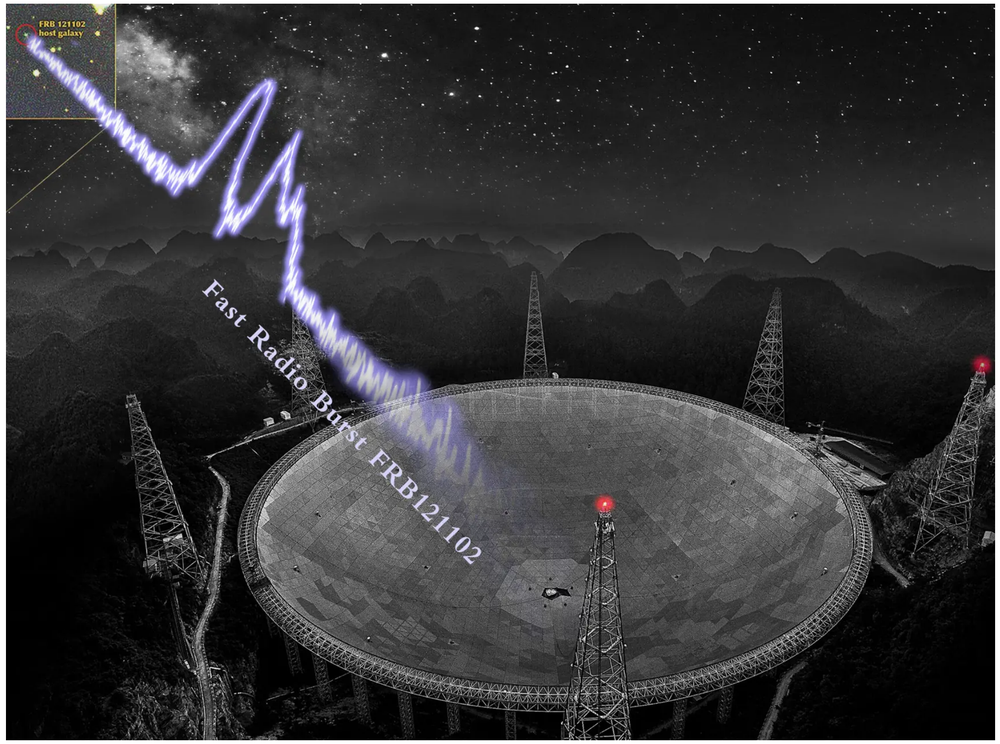
- Possible connection to repeating FRBs (See talk by Paz)



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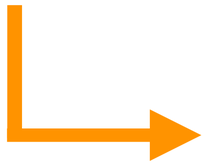

Idea: **Magnetically-powered** radio emission from motivated crustal phenomena and radiation mechanism

Cooper & Wadiasingh, in review

Background

- Magnetar activity (bursts, giant flares, persistent emission, FRBs?) is most readily explained by crustal displacements

  See talk by Tomonori Totani

Cooper & Wadiasingh, in review

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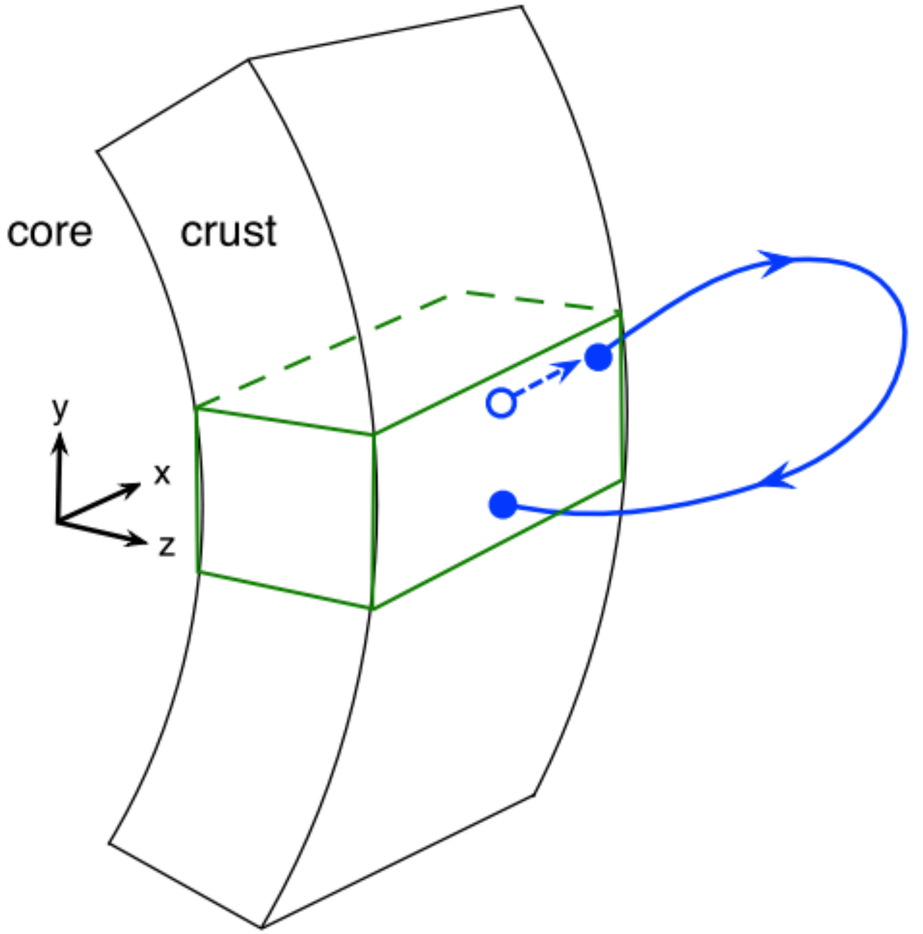
- Crustal displacements impart a twist into the magnetosphere:

$$E_{\rm tw} = \int \frac{B_\phi^2}{8\pi} dV \qquad \psi \equiv \frac{B_\phi}{B_{\rm dp}} < 1$$



Lander, 2019

Cooper & Wadiasingh, in review

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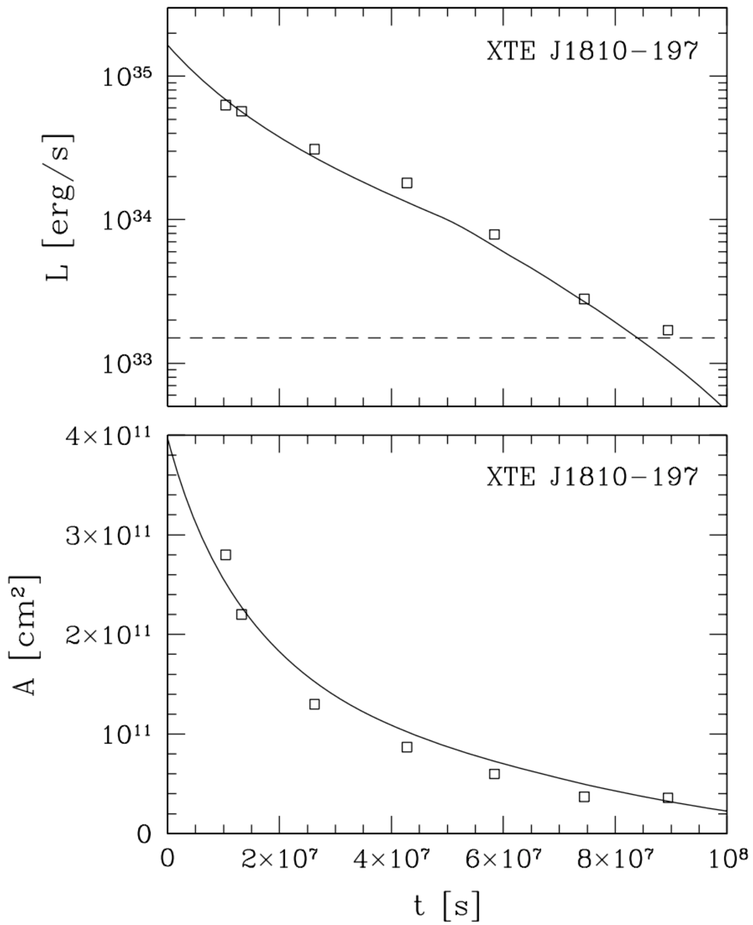
- Persistent, decaying X-ray pulses have been successfully modelled as untwisting magnetic field lines.

- This occurs on timescales of decades, modulated by **pair production** along field lines

See also Wang et al., 2019



Beloborodov, 2013

Cooper & Wadiasingh, in review

Background

- These twists require current in the same way as rotation does:

$$j_\Psi \approx \frac{cB\sin^2(\theta_{\rm fp})\Psi}{4\pi R_{\rm NS}}$$

- If these requirements are not met, acceleration gaps form dissipating twist and **producing pairs**

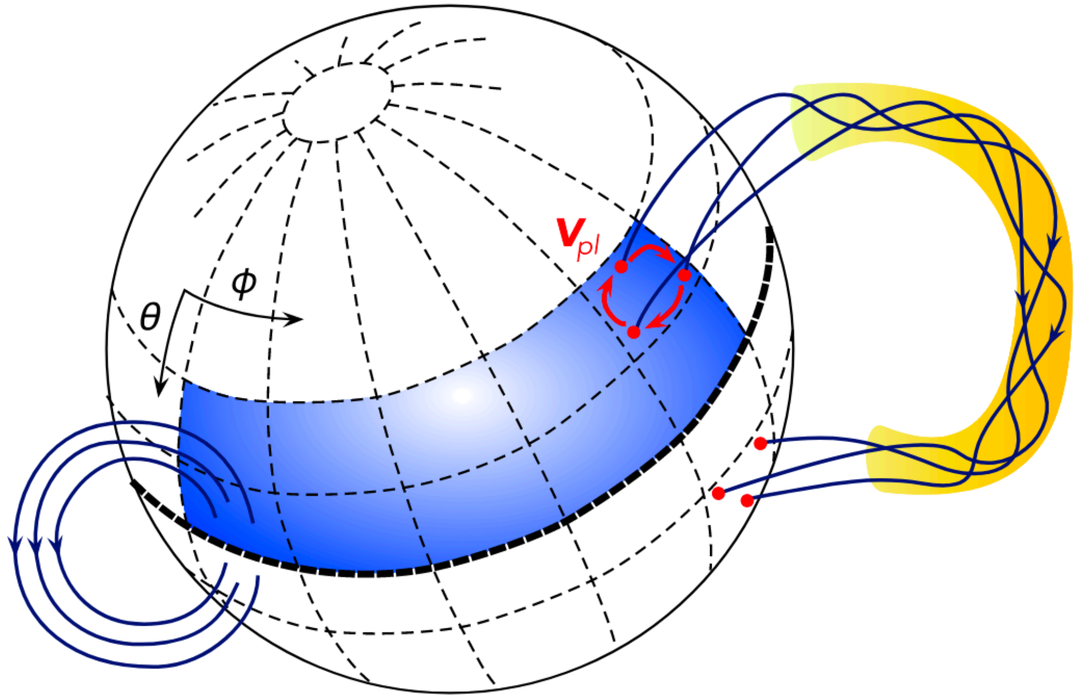
$$\rho_\psi > \rho_{GJ} \propto B/P$$

Necessary and sufficient for broadband coherent radio emission
(Timokhin & Arons, 2015)

Cooper & Wadiasingh, in review

Plastic flow

- At B > 10^{15} G **plastic flow** likely dominates crustal evolution, akin to ‘continental drift’, and can twist the magnetic field



Lander et al., 2019

Cooper & Wadiasingh, in review

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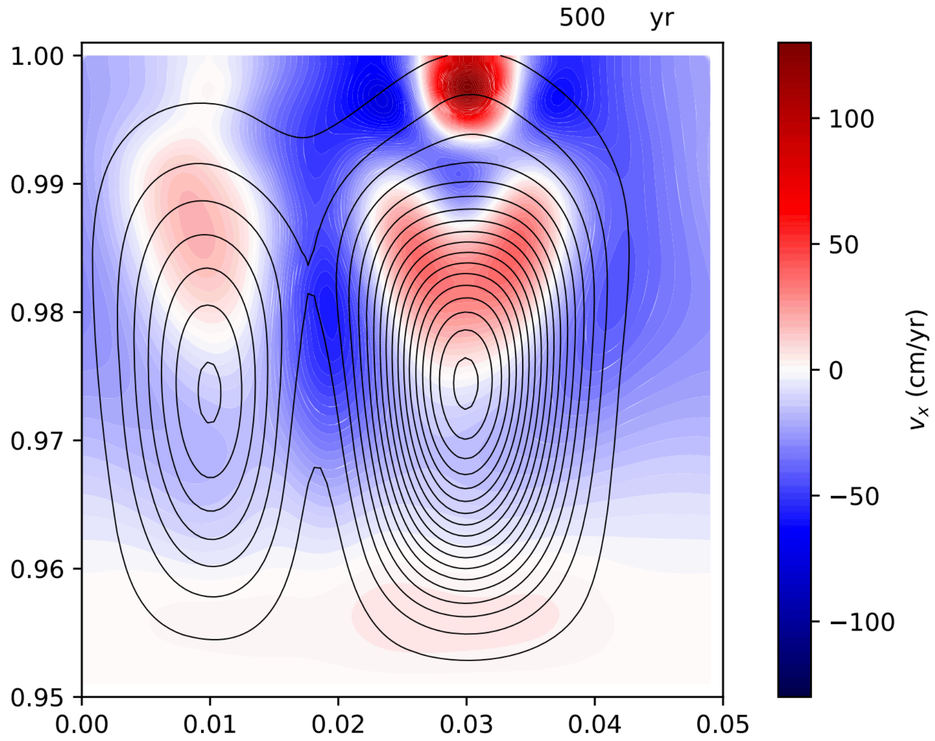
- Lander et al (2019) show that plastic flow of 1km^2 patches has velocities of **1-100 cm/yr** for months to decades

- Similar twists can also be powered by thermoelectric gradients



Lander, 2023

Cooper & Wadiasingh, in review

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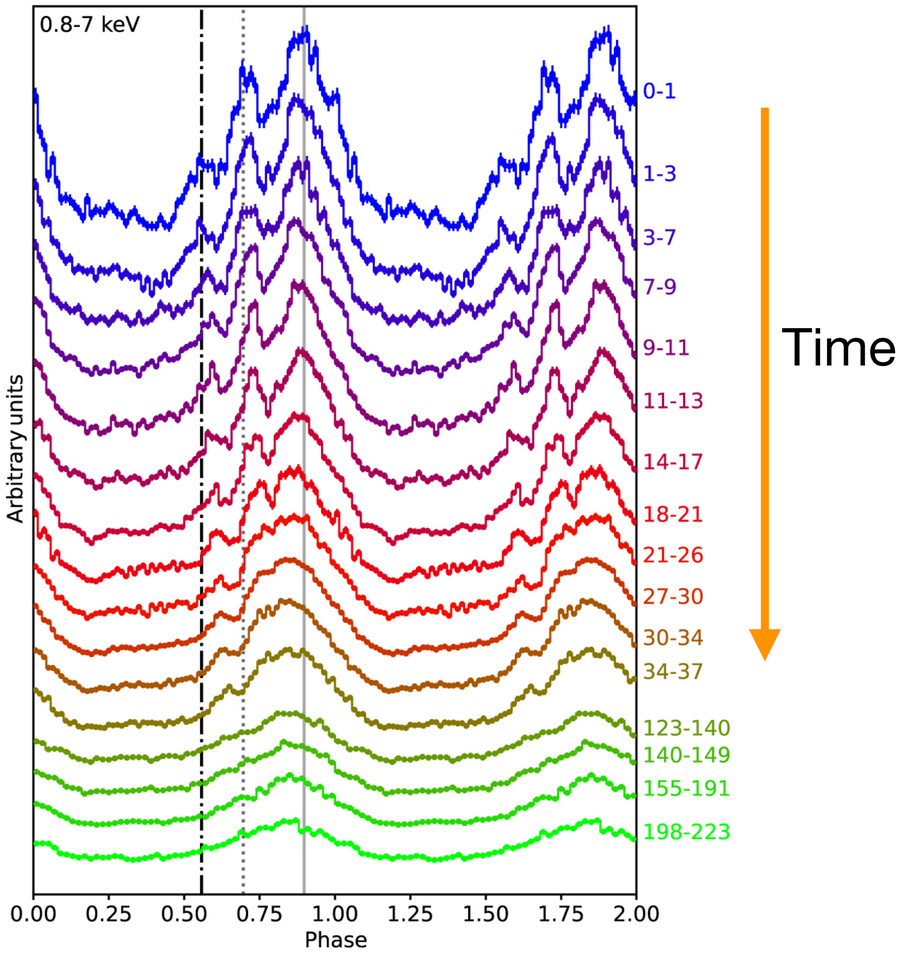
- Similar twists can also be powered by thermoelectric gradients
- Younes et al., 2022 attribute pulse peak migration to plastic flow, requiring higher values of 10^6 cm/yr

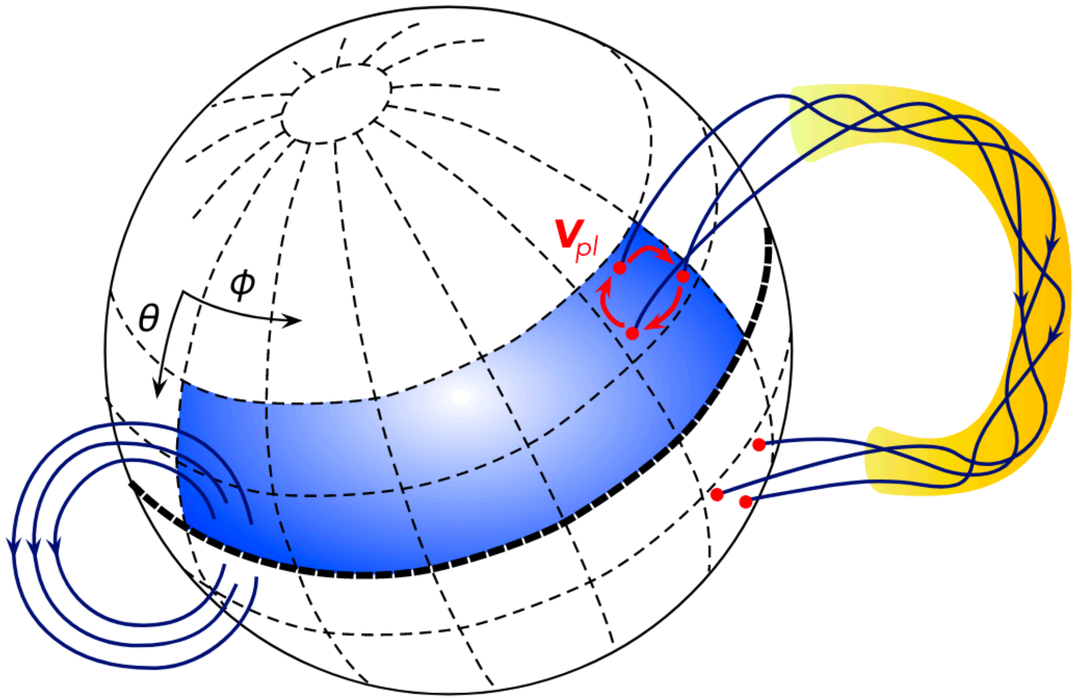


Younes+ 2022

Cooper & Wadiasingh, in review

Model: Six steps

(1) Plastic motion twists field lines in ~km^2 patches



Lander et al., 2019

$$\Psi = \frac{B_\phi}{B_0}$$

$\dot{\Psi} \propto v_{pl}$

Time

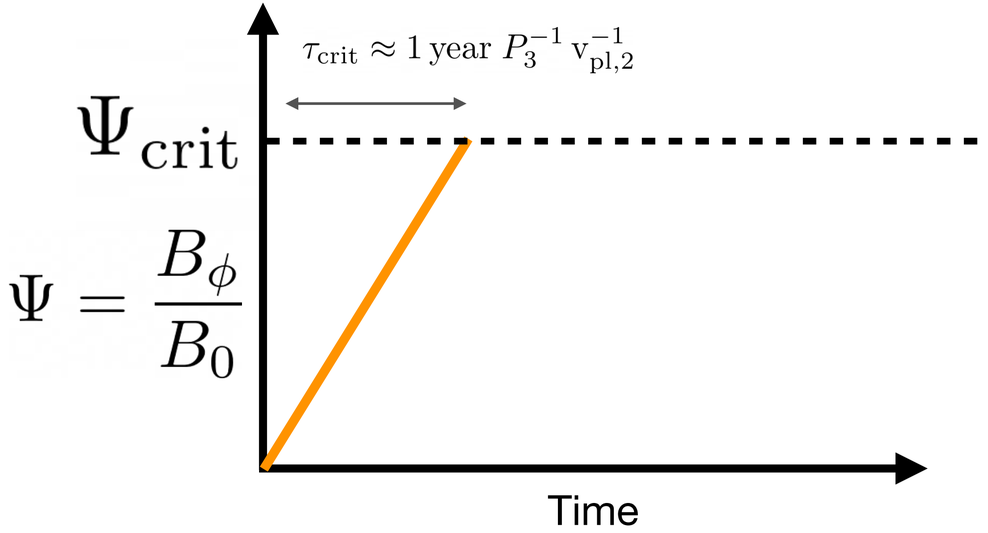
Cooper & Wadiasingh, in review

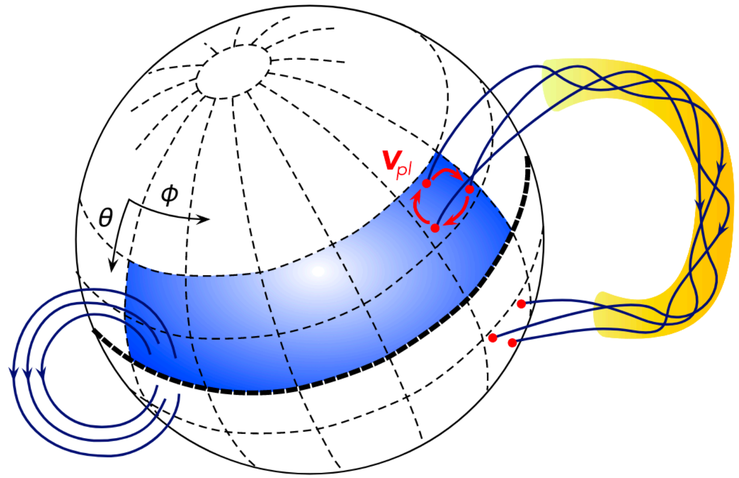
Model: Six steps

(1) Plastic motion twists field lines in ~km^2 patches

(2) Twist current requirements exceed GJ current

$$\Psi_{\rm crit} = \frac{8\pi R_*}{cP\sin^2(\theta_{\rm fp})} \approx 10^{-4}\, P_{\rm NS,3}^{-1}\, \theta_{\rm fp,-1}$$





Cooper & Wadiasingh, in review

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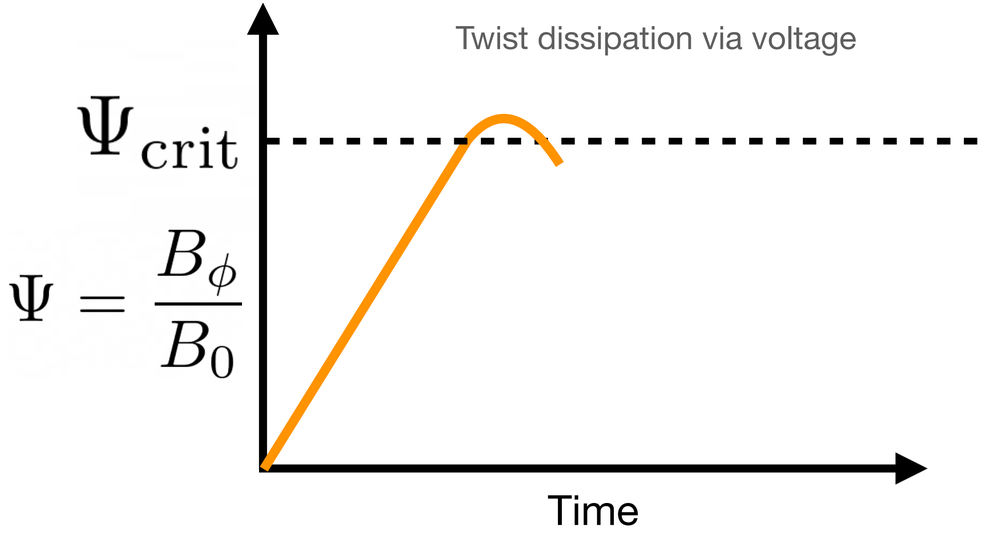
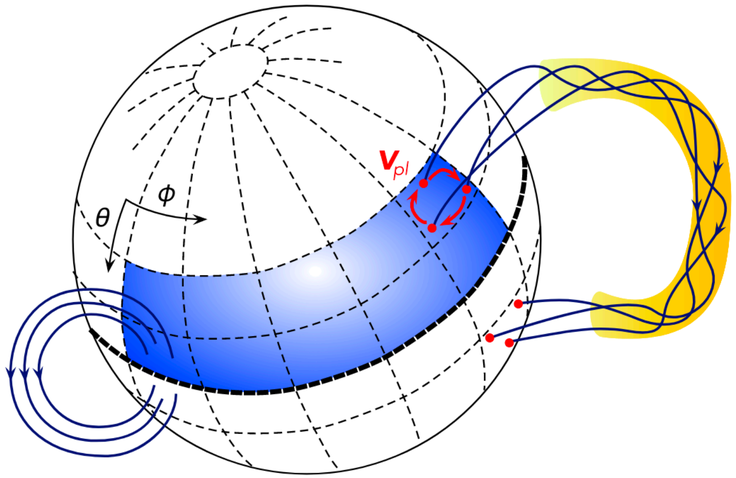
   (a) Particles bombard surface producing thermal UV/X-ray counterpart





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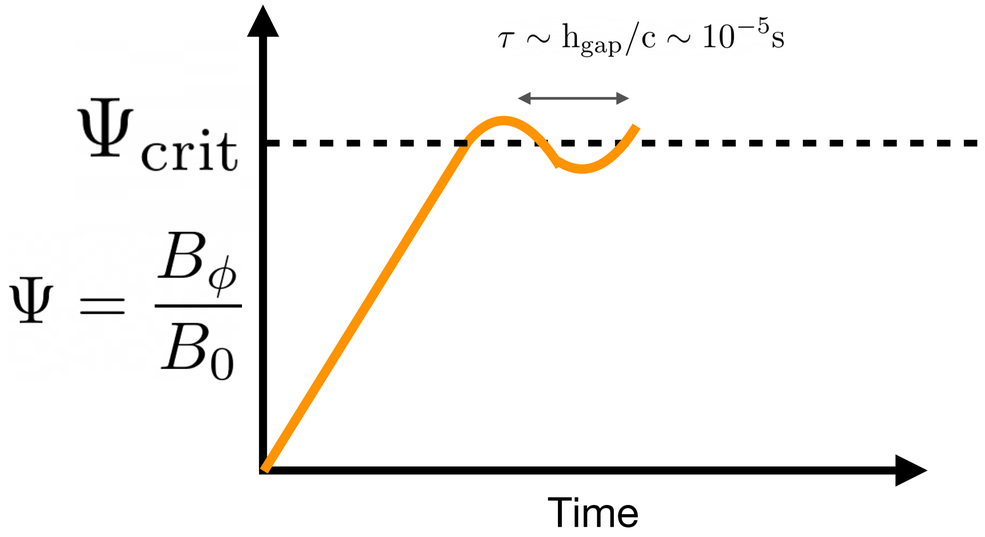

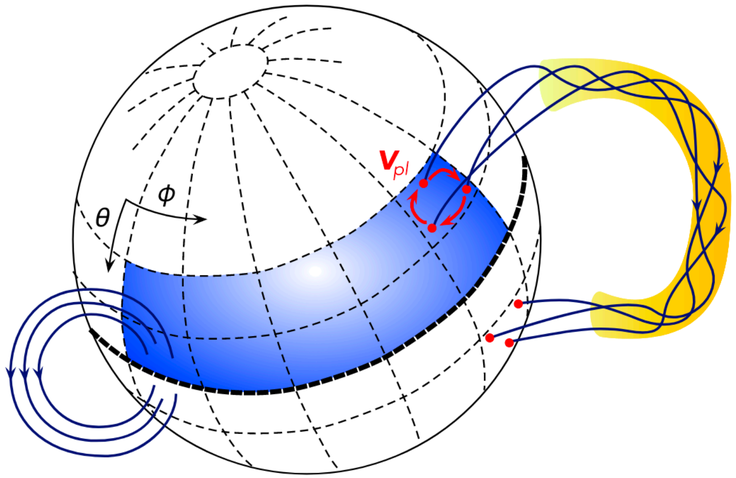

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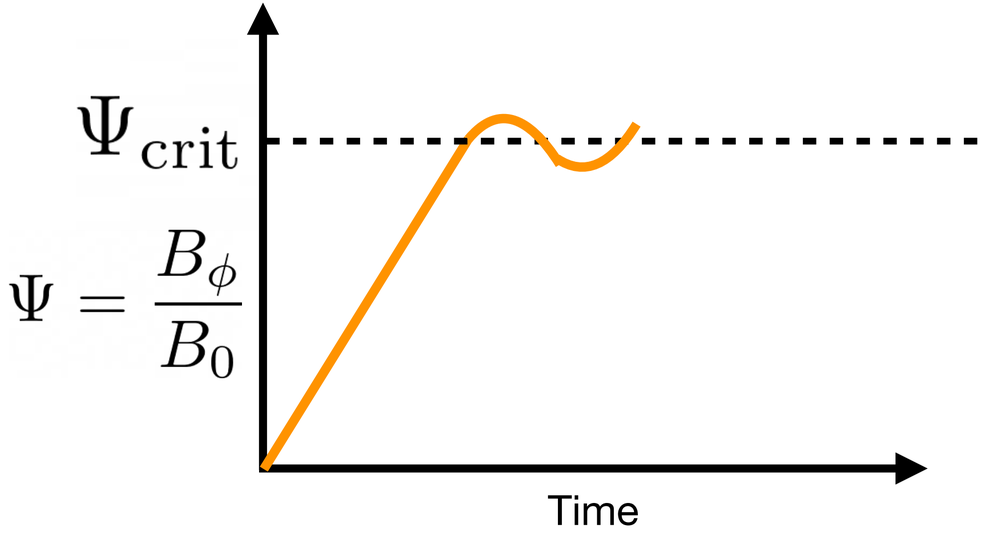

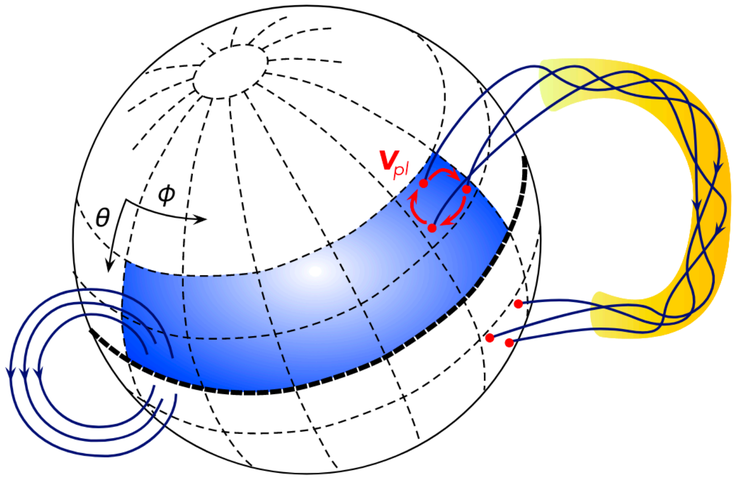

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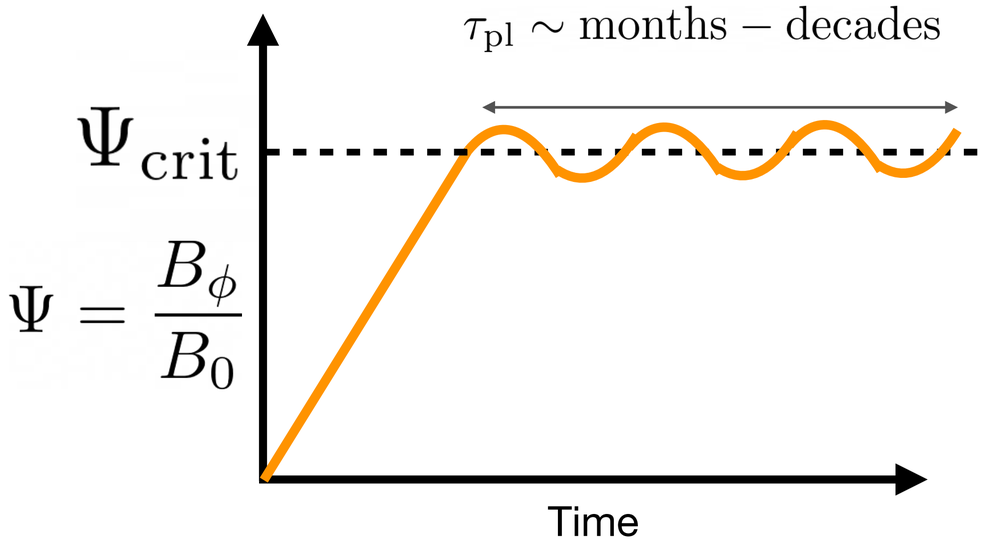
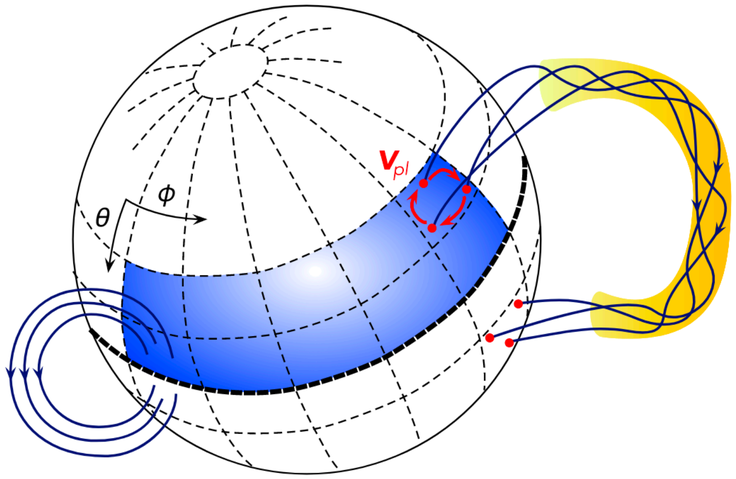
(6) Twist hovers around critical value, with stable dissipation plastic motion duration if $\dot{\Psi}_{\rm pl} < \dot{\Psi}_{\rm diss}$





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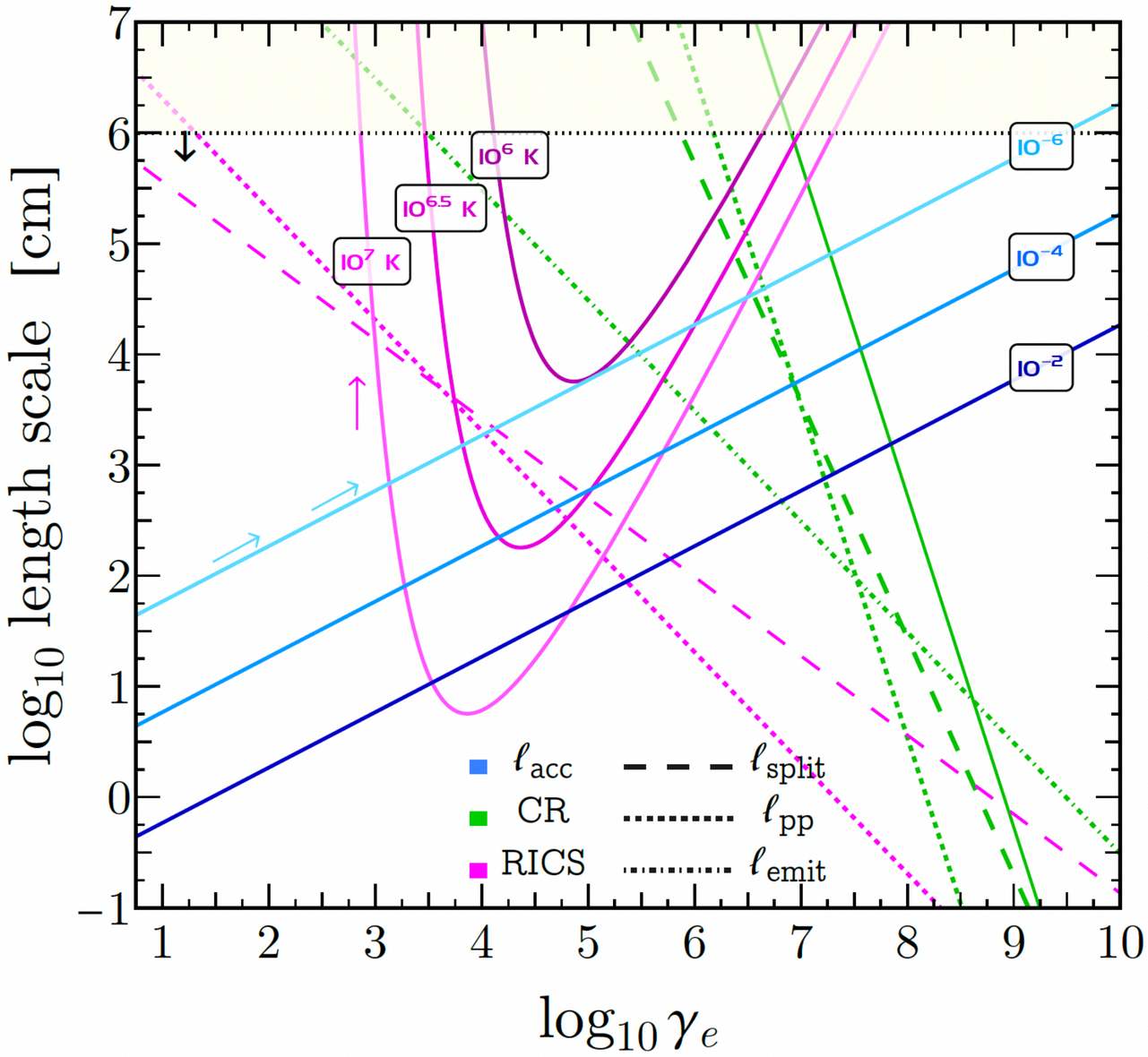
Cooper & Wadiasingh, in review

Microphysics



Particles accelerated as they cross gap height

Cooper & Wadiasingh, in review

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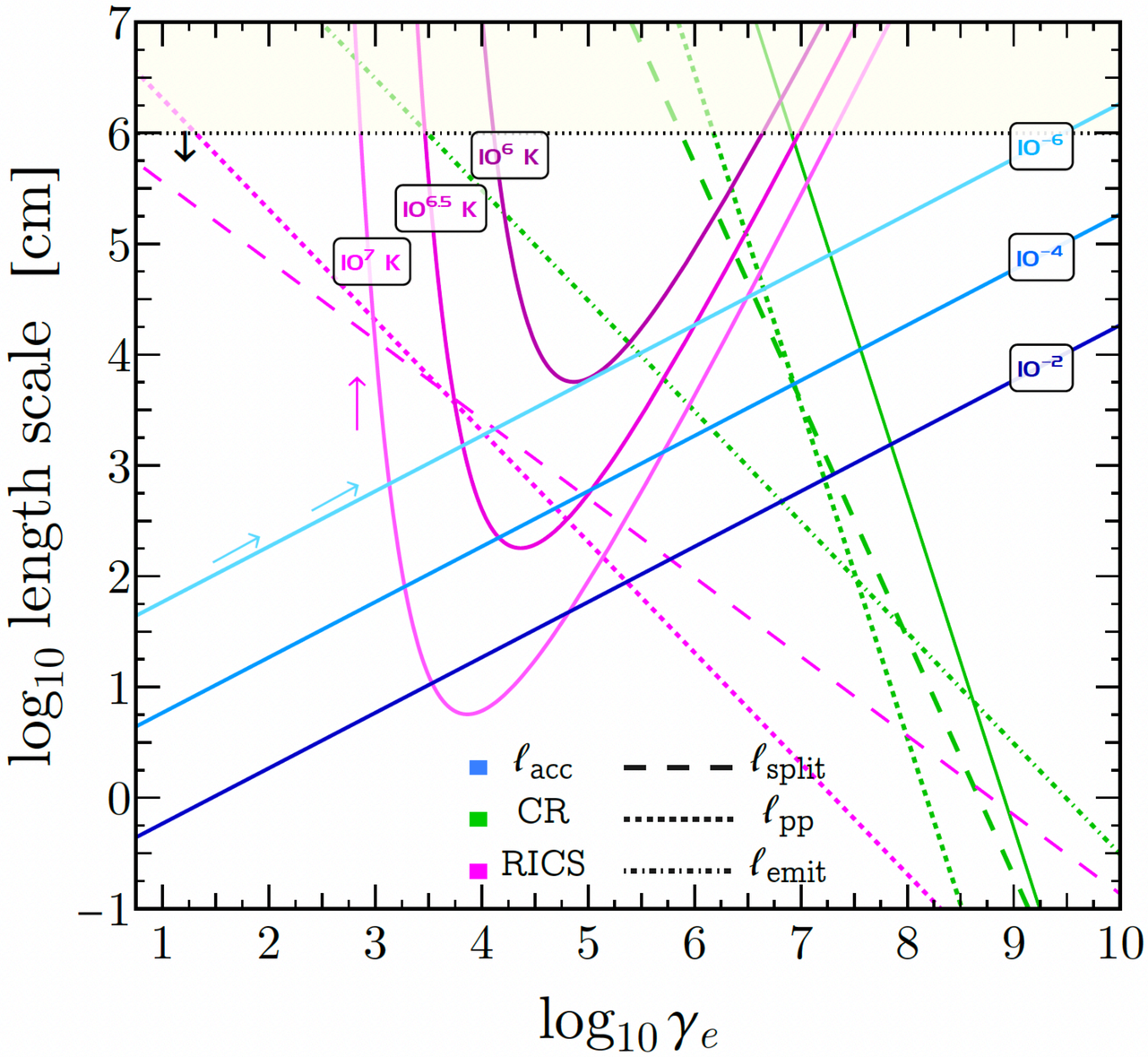
For high temperatures they produce gamma-rays via RICS of thermal photons, which produces pairs



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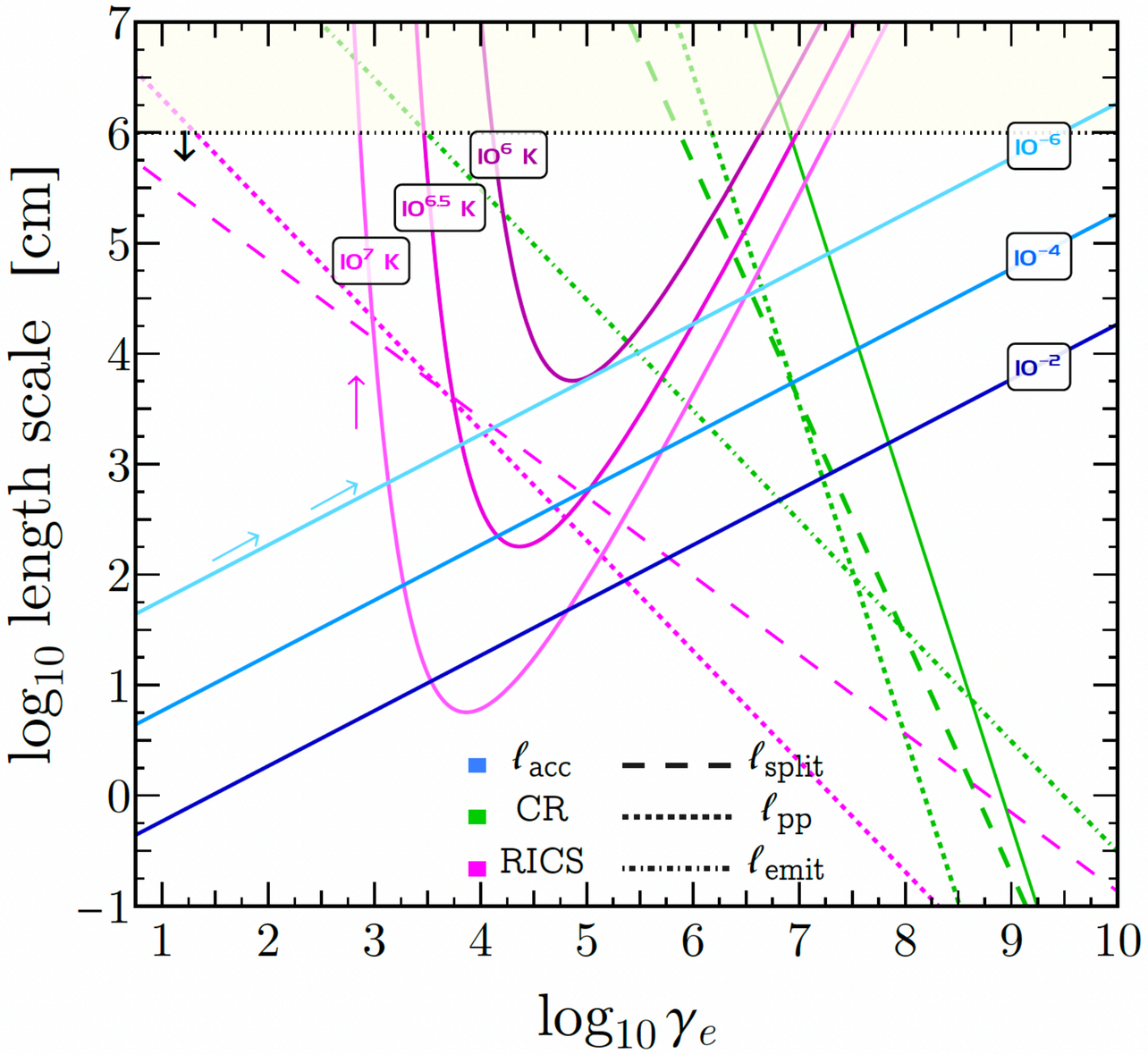


Particles accelerated as they cross gap height

If they ‘miss’ RICS tail, they produce gamma-ray curvature photons which produces pairs

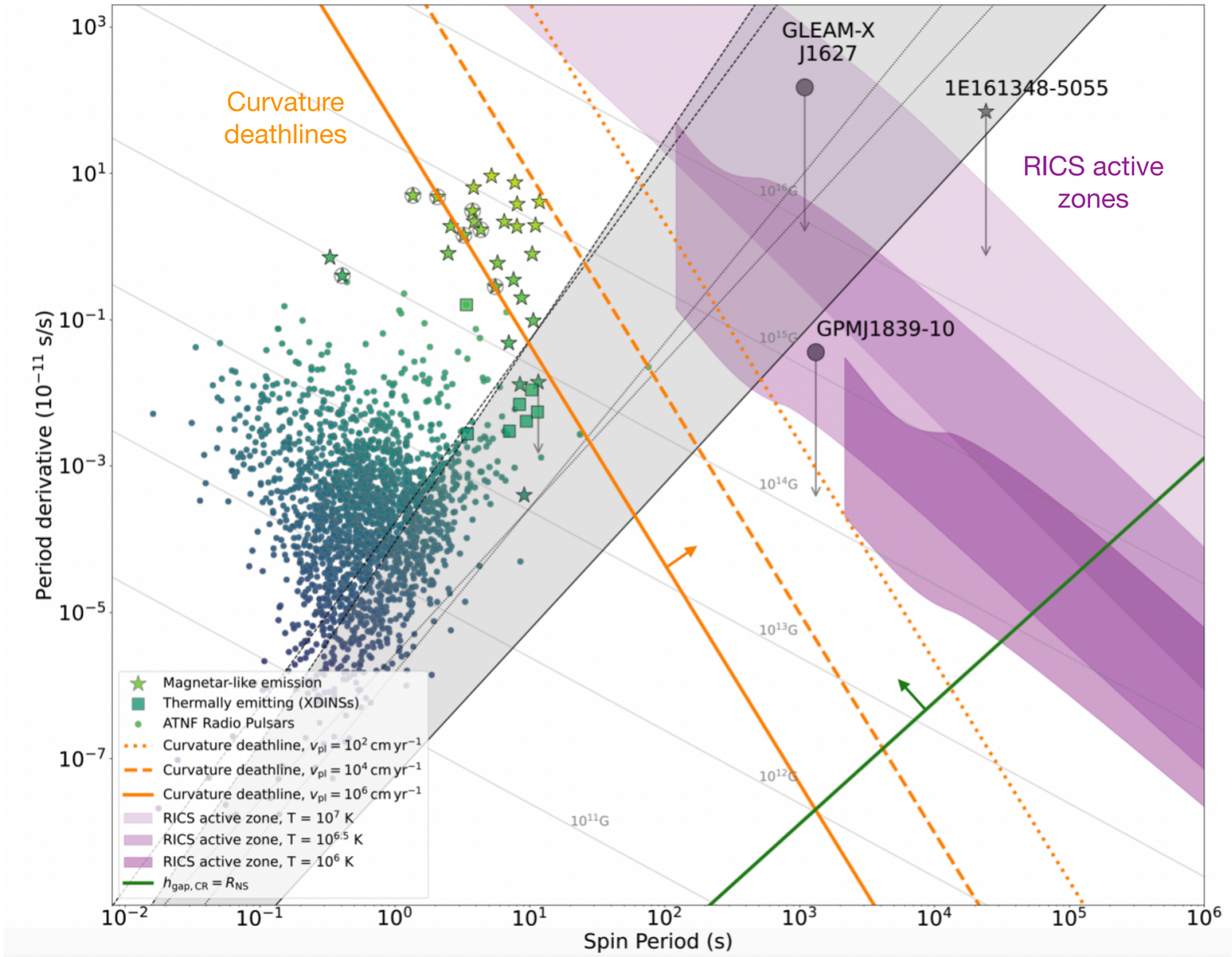
Cooper & Wadiasingh, in review

Results

- Deathlines from: $L_{pair} < L_{diss}$
- Further considerations for RICS: multiplicity & viable intersection

$$L_{\rm pair} \sim 2\pi\rho_{\rm twist}^2 h_{\rm gap}^2 A_{\rm fp} c$$

$$L_{\rm diss} \sim \dot{\Psi}_{\rm pl} B_\Psi^2 R_{\rm NS} A_{\rm fp}/8\pi$$



Cooper & Wadiasingh, in review

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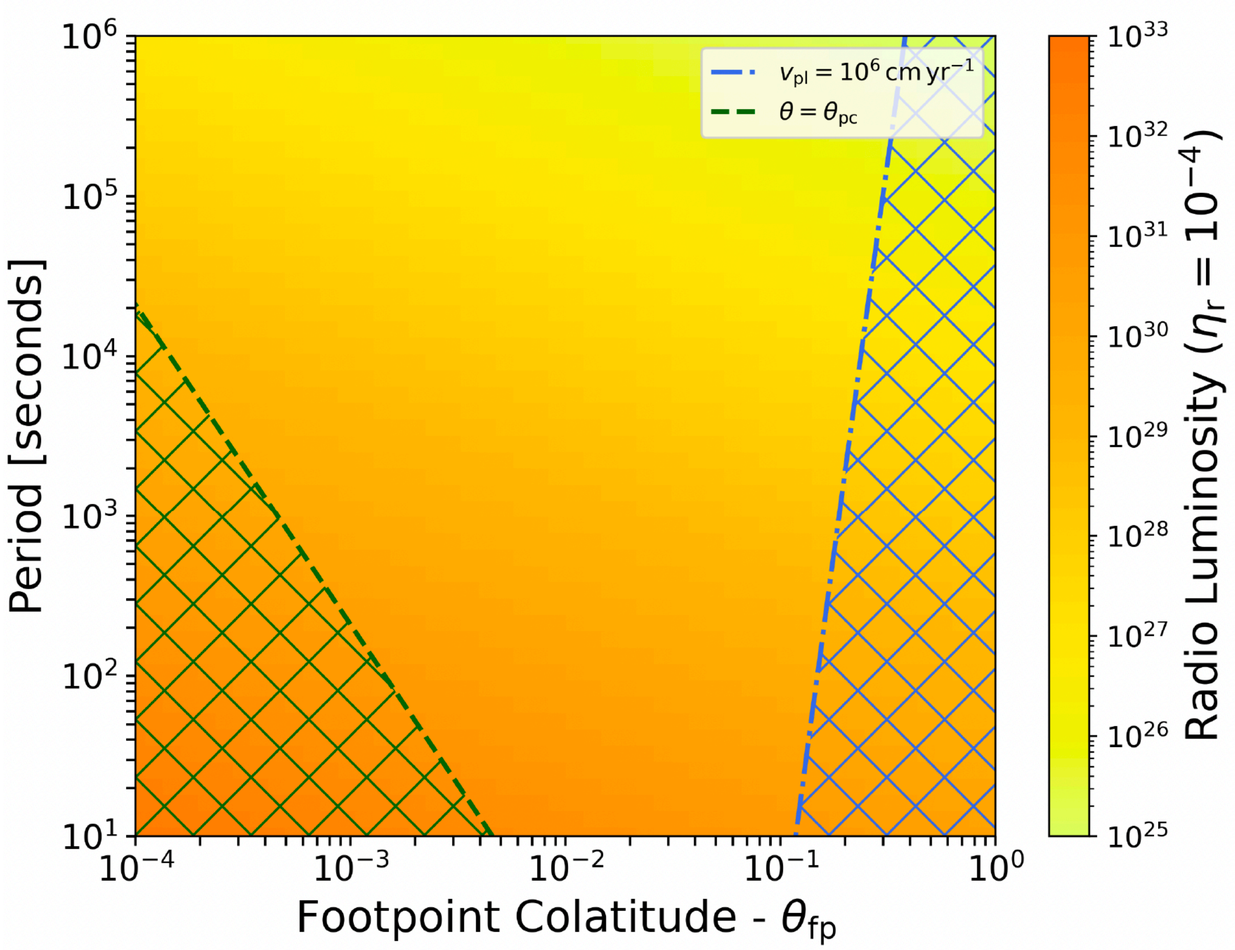
- Expect more longer period (weaker) transients



Cooper & Wadiasingh, in review

Predictions

- Minimum period depending on v_{pl} or T

$$P_{\rm RICS} \gtrsim 120\ (T/10^{6.5}{\rm K})^{-5}\ {\rm sec}$$

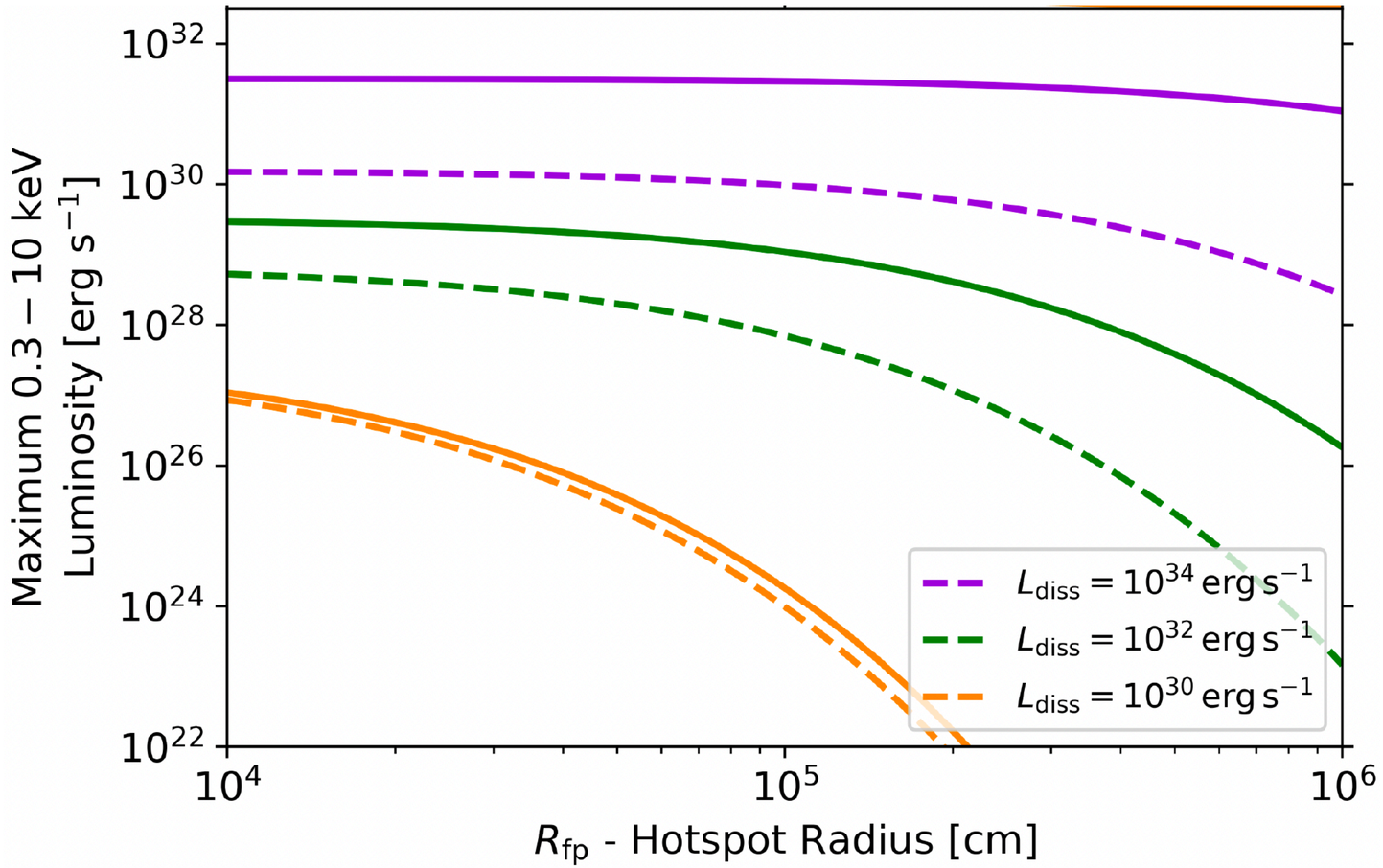
$$P_{\rm curv} \gtrsim 150\ ({\rm v_{pl}}/10^{3}\ {\rm cm\ yr^{-1}})^{-7/6}\ {\rm sec}$$

Cooper & Wadiasingh, in review

Predictions

- Minimum period depending on v_{pl} or T

- Pulsed X-ray/UV counterpart due to return current bombardment



Cooper & Wadiasingh, in review

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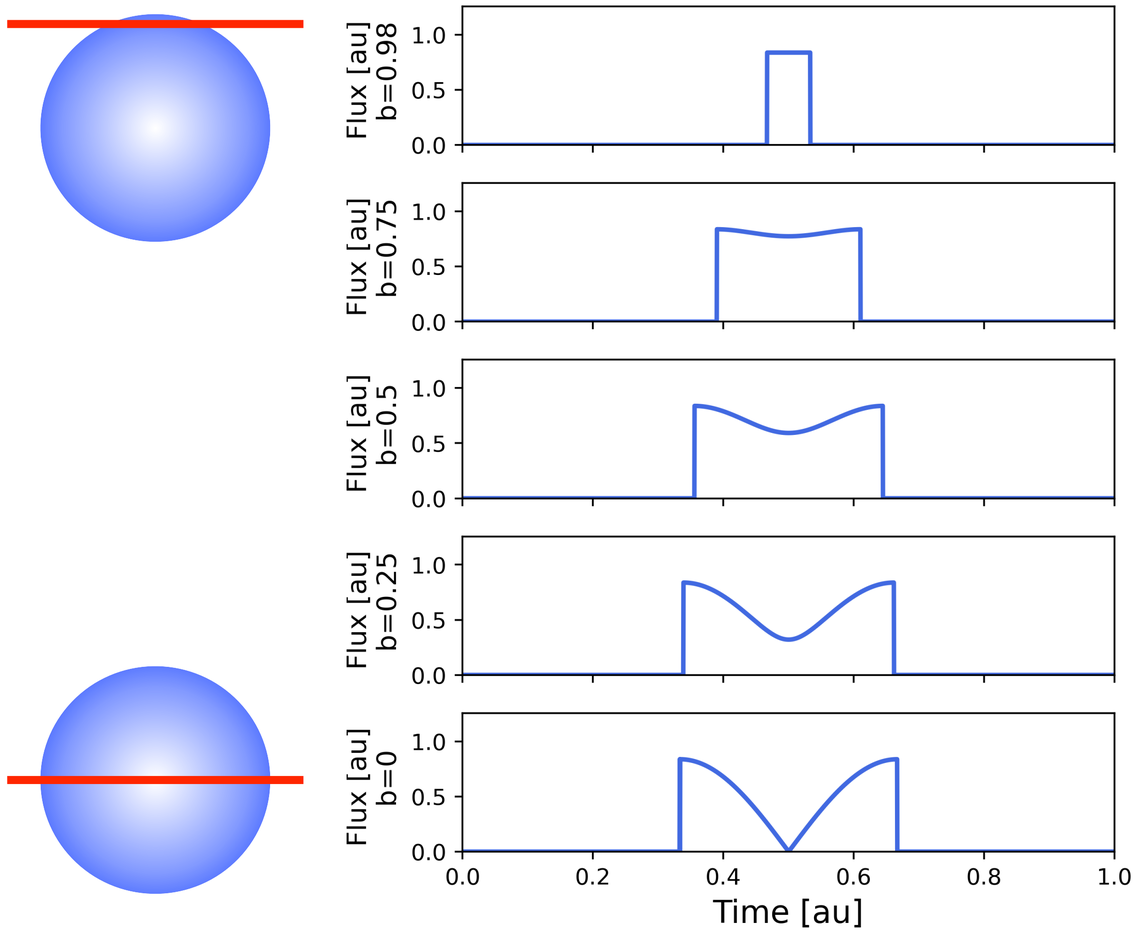
- Generically 2 pulse peaks per patch



Cooper & Wadiasingh, in review

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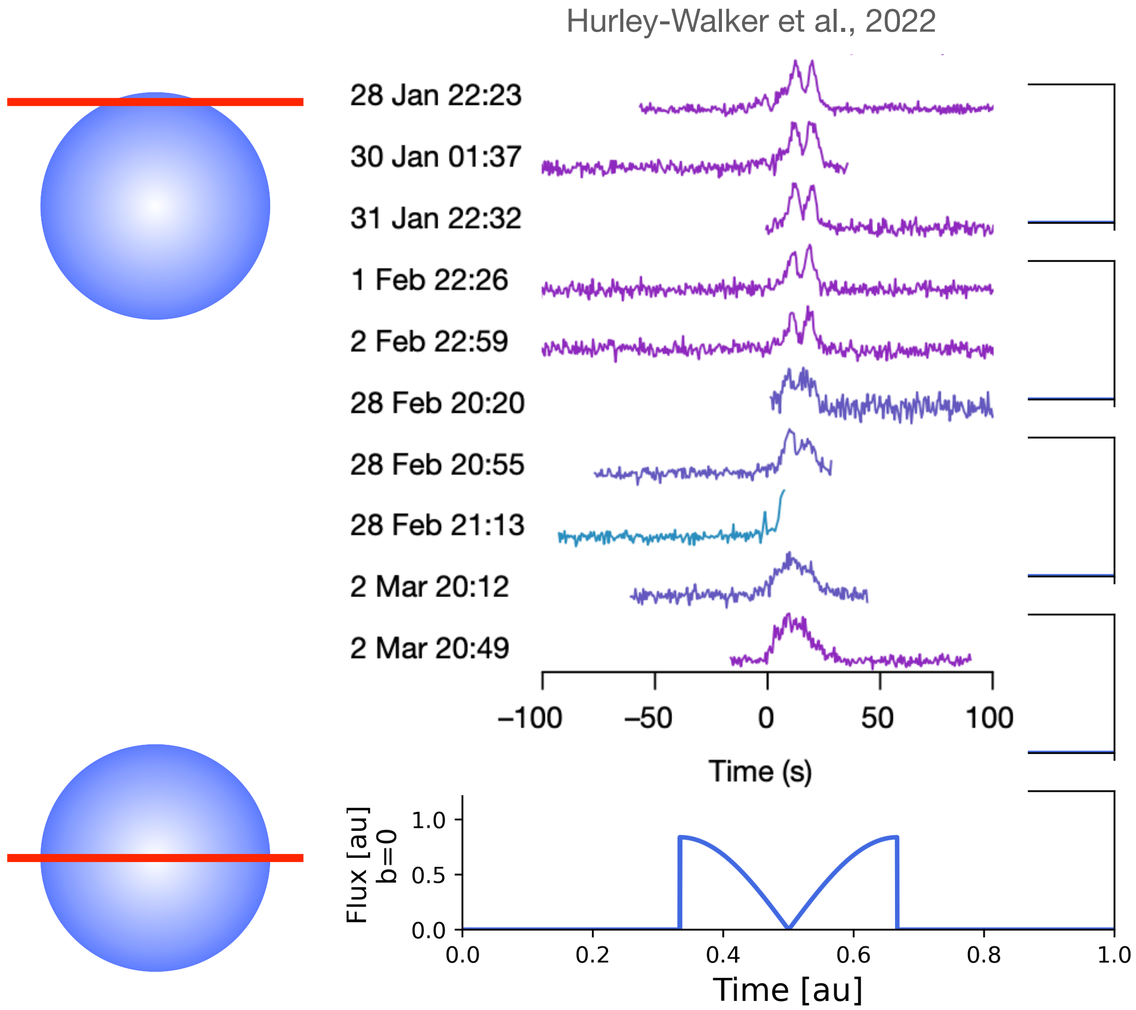

Cooper & Wadiasingh, in review

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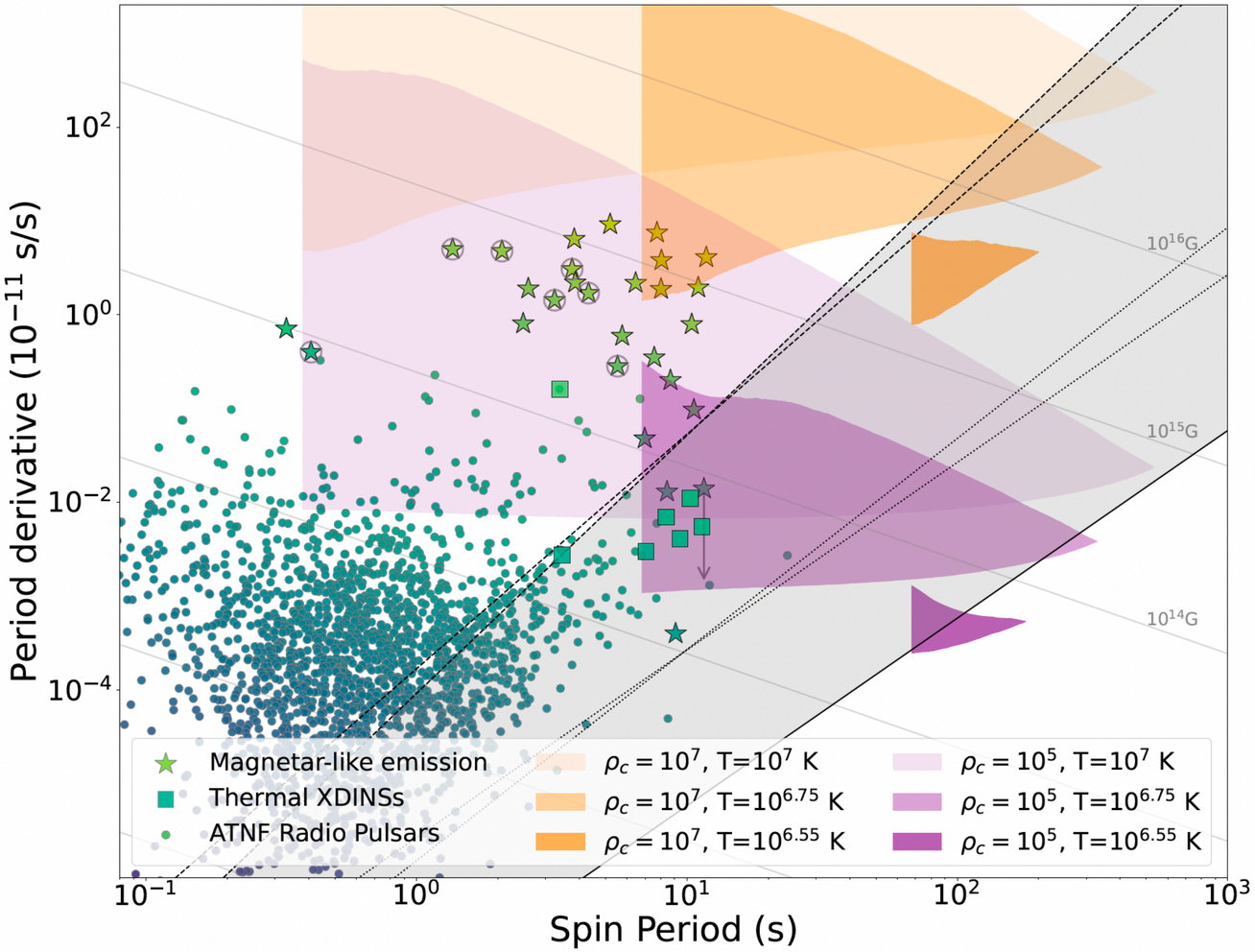

Cooper & Wadiasingh, in review

See also: Zhang, Harding & Muslimov (2000), Medin & Lai (2007)

Predictions

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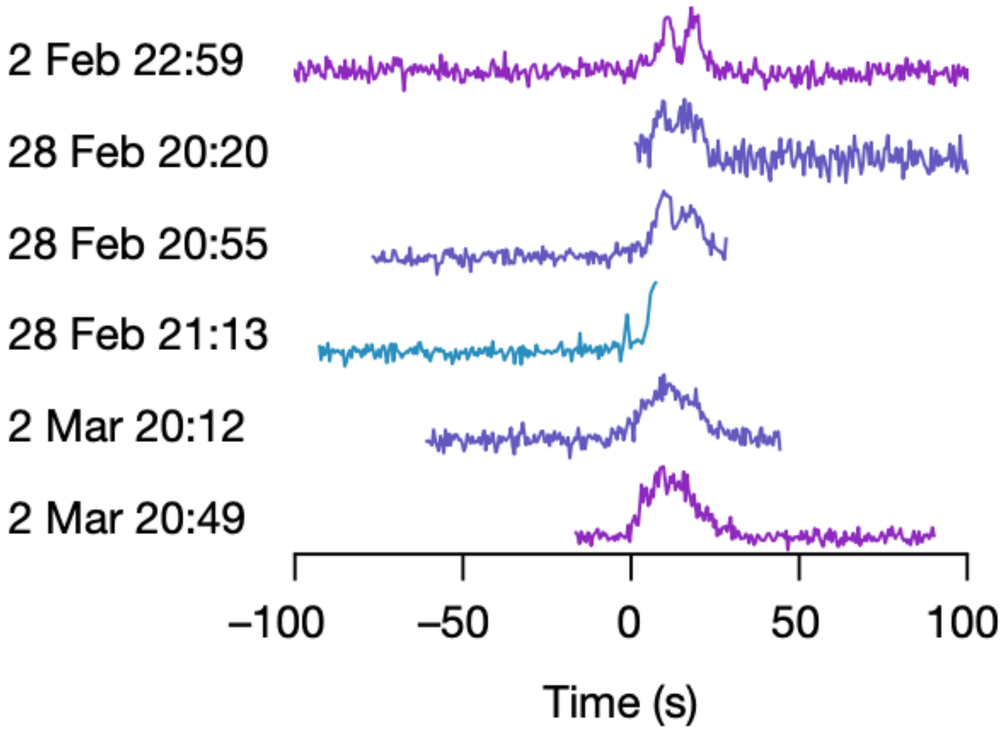
- Generically 2 pulse peaks per patch
- RICS pair production also occurs for rotationally powered E-fields
- Sensitive observations (e.g. FAST) may probe magnetospheric ‘weather’



Hurley-Walker et al., 2022

Cooper & Wadiasingh, in review

Summary

- Plastic motion can impart twist which produces magnetic coherent radio emission
- This occurs via RICS or CR only for long period, highly magnetised neutron stars
- Deep soft X-ray/UV observations may confirm this picture

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