X-ray emission from Isolated Neutron Stars: latest results from XMM-Newton, NICER and eROSITA

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09/07/2024 — Pescara

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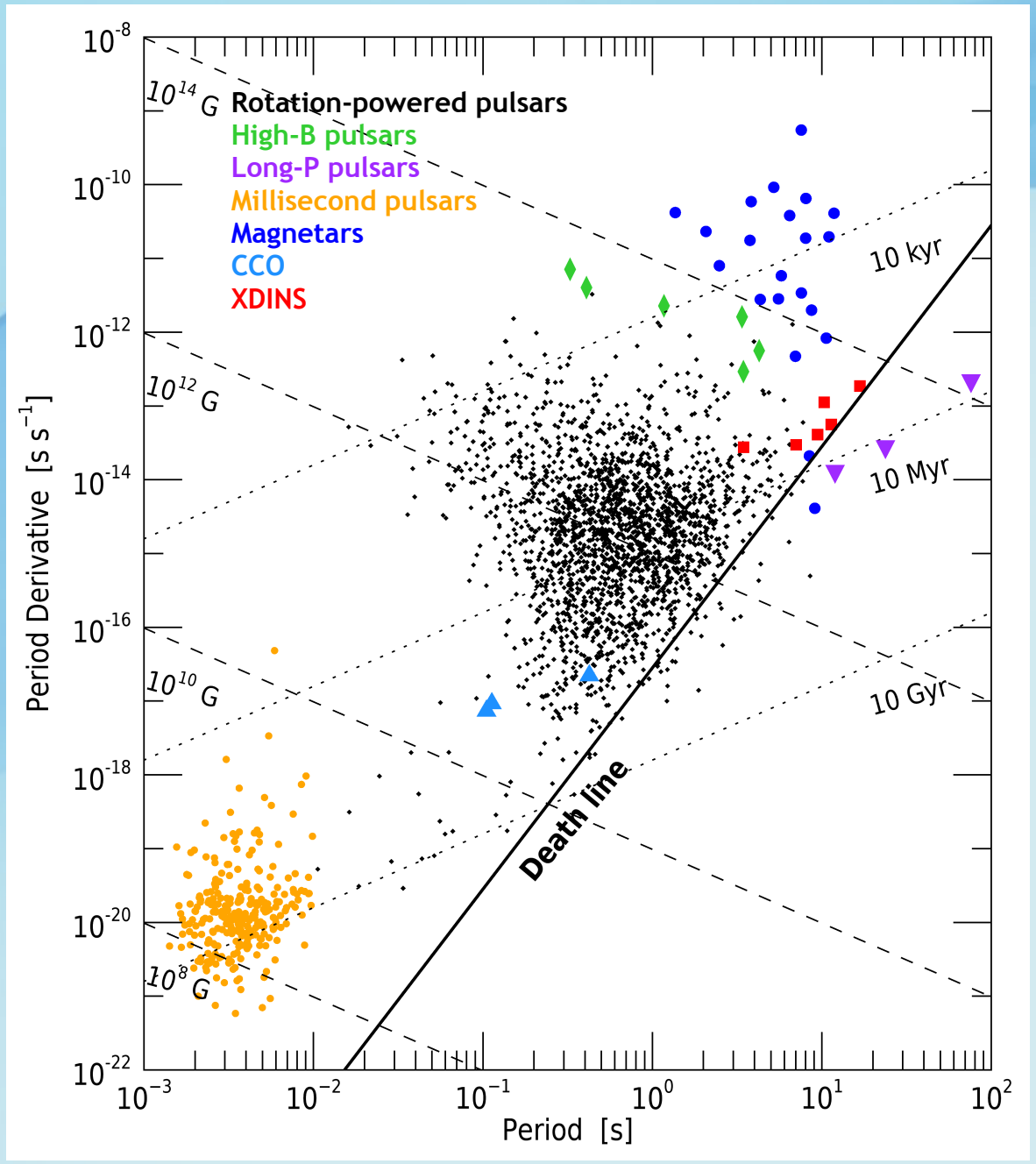
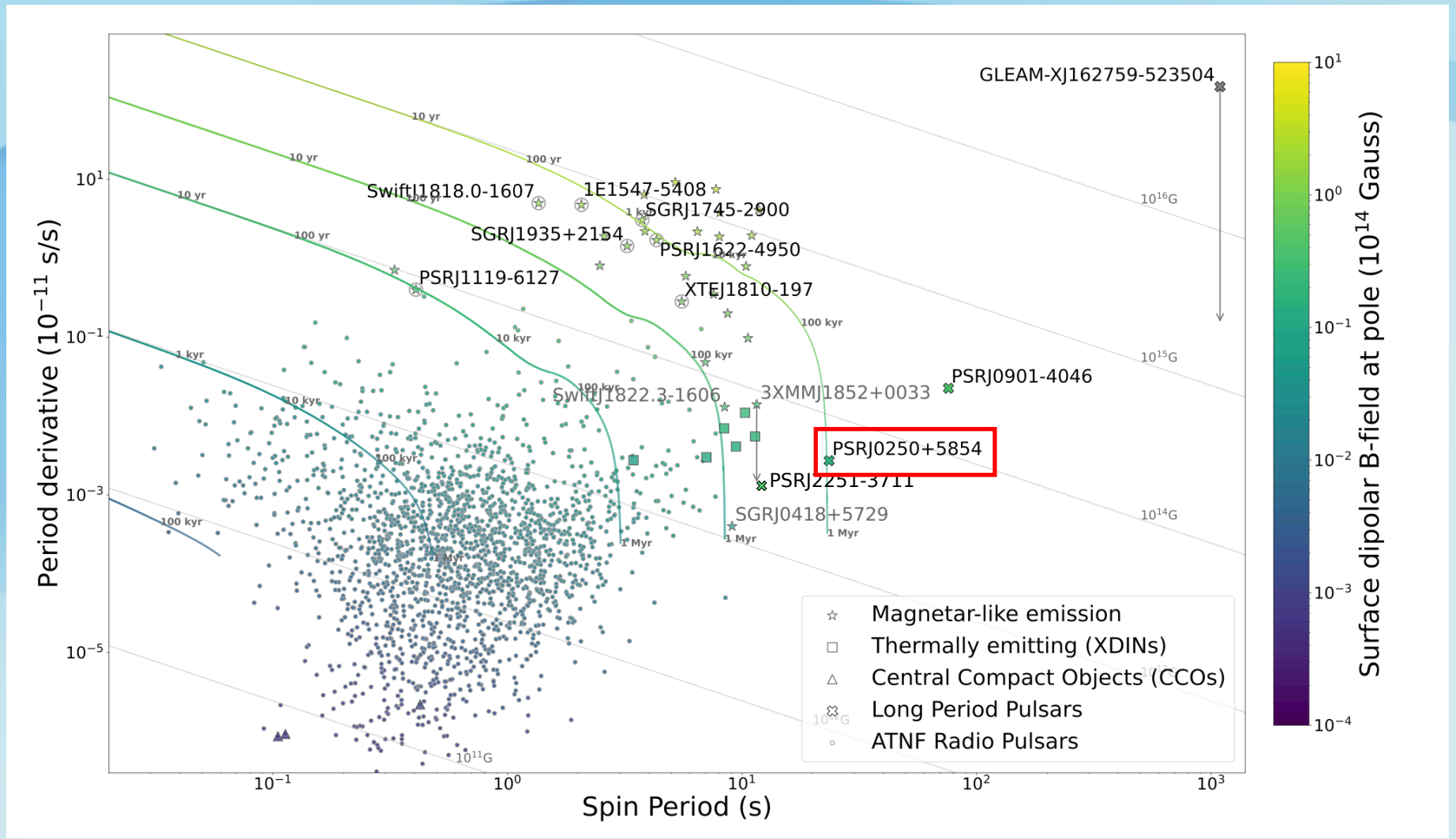
The Isolated Neutron Stars zoology



What's new in the X-rays?

- (Non) detection of long P (>12 sec) pulsars
- Several new thermal-emitting INS canditates
- Link between different classes of INSs
- Non-dipolar B in all INSs

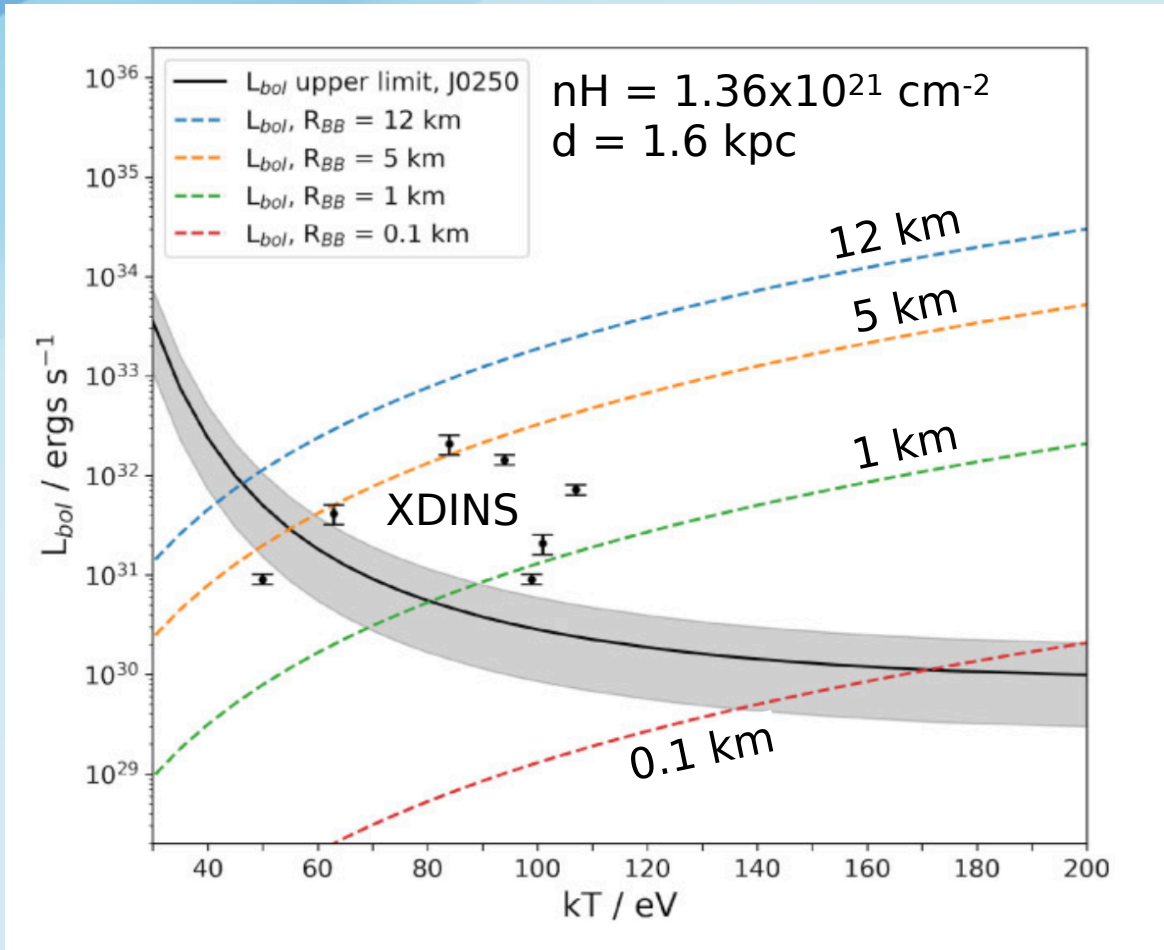
Slowly rotating pulsars: J0250+5854



adapted from Rea+ 2022, ApJ

Slowly rotating pulsars: J0250+5854

- XMM-Newton (~50ks EPIC-pn, ~90ks EPIC-MOS), but no X-ray counterpart
- Either a cold XIDINS (kT<50—80 eV)…
- …or a cold ‘hot’ spot (~SGR J0418+5729 has L_X~10^{31} erg/s and kT~320 eV)



Rea+ 2013, ApJ
Tan, MR+ 2023, MNRAS

Increasing the sample of INS

- How to discover new thermally-emitting INS:
  - Point-like and constant long-term emission

MR+ 2022a, MNRAS
Kurpas+ 2024b, A&A

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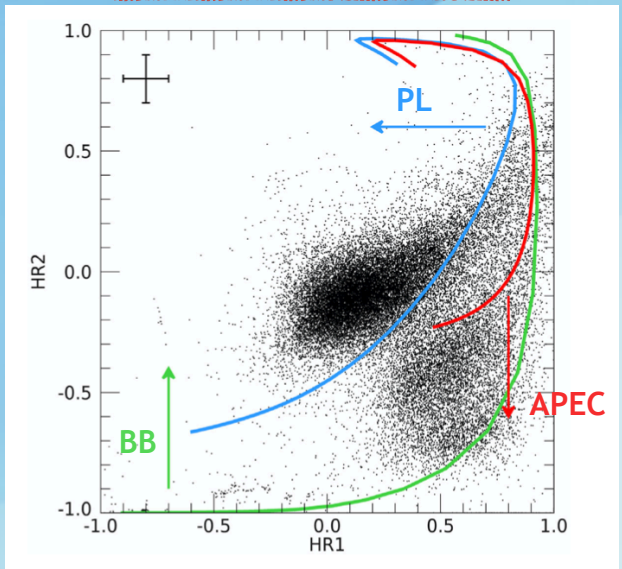
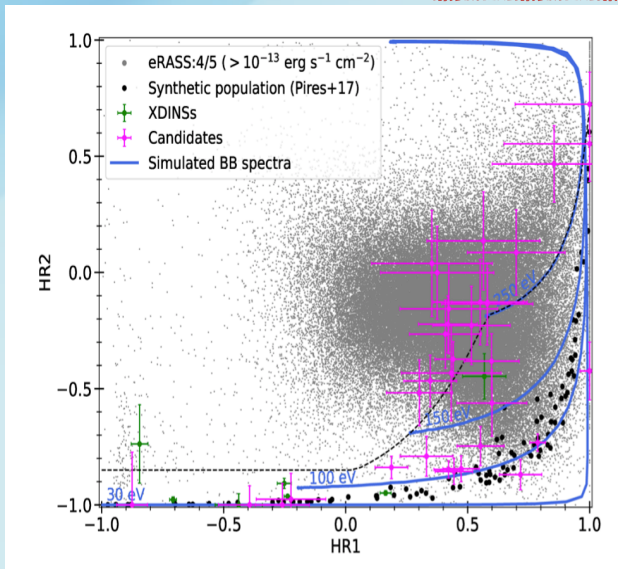
  - Soft X-ray spectrum, thermal emission (it excludes AGNs)

4XMM DR10 catalog



eROSITA DR1 catalog



MR+ 2022a, MNRAS
Kurpas+ 2024b, A&A

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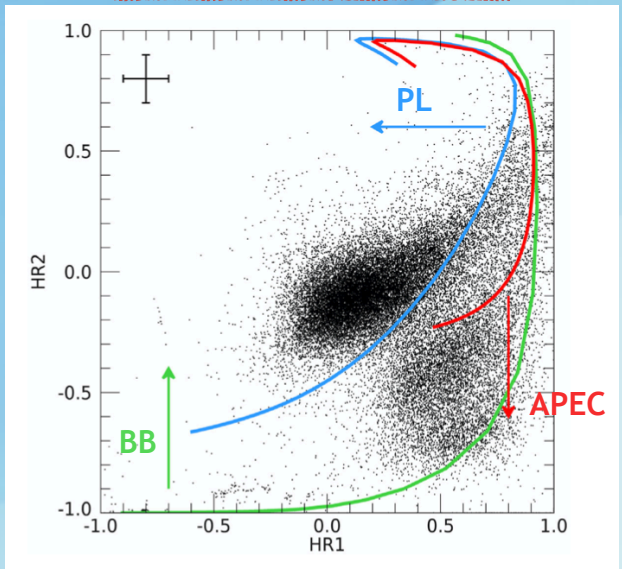
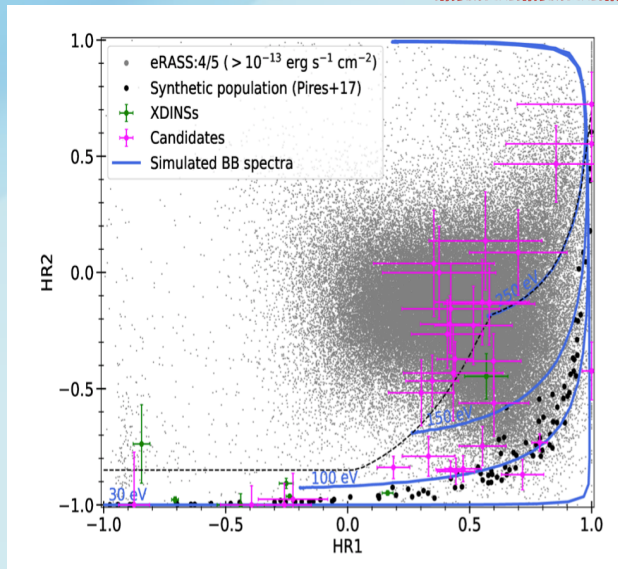
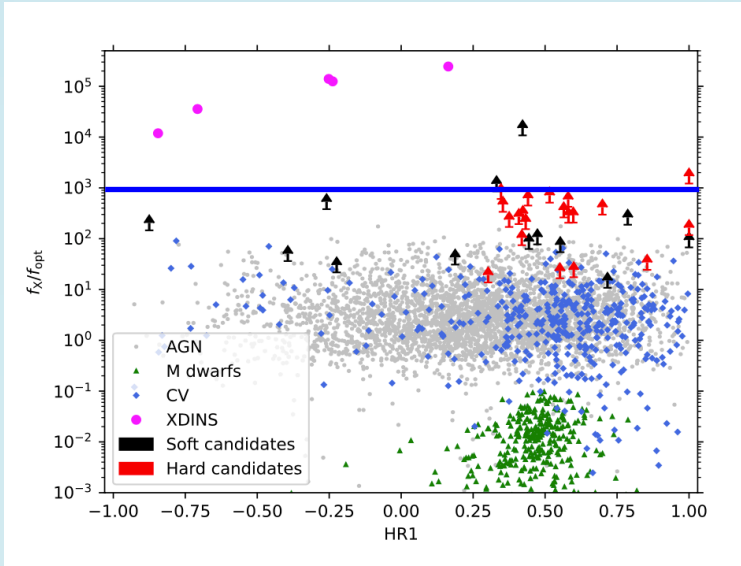


eROSITA DR1 catalog





MR+ 2022a, MNRAS
Kurpas+ 2024b, A&A

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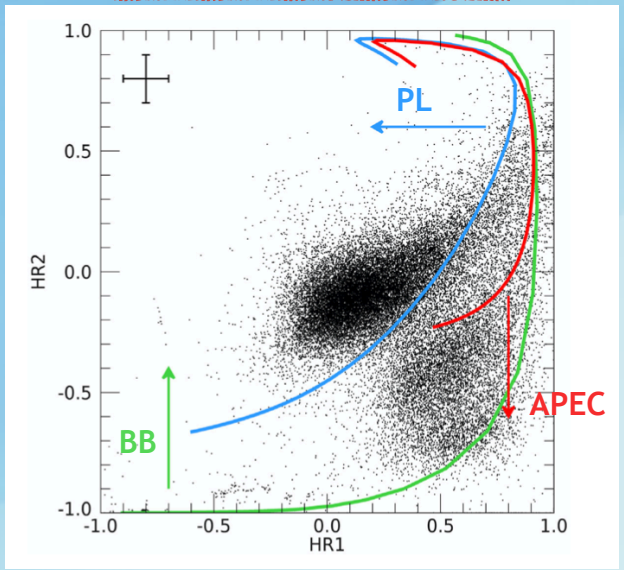

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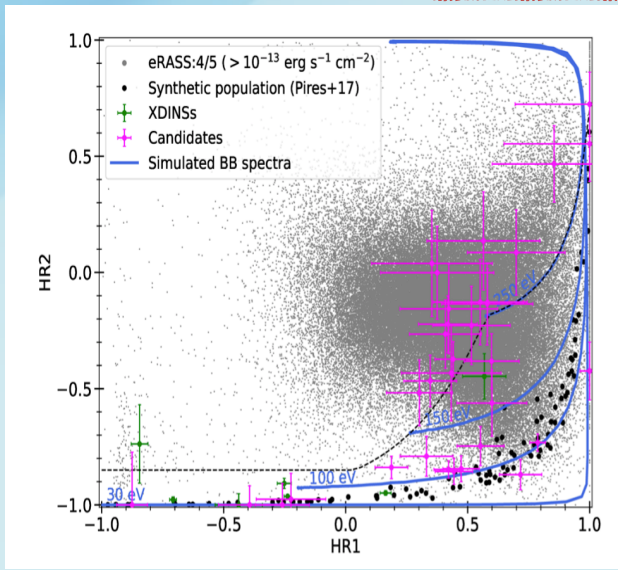
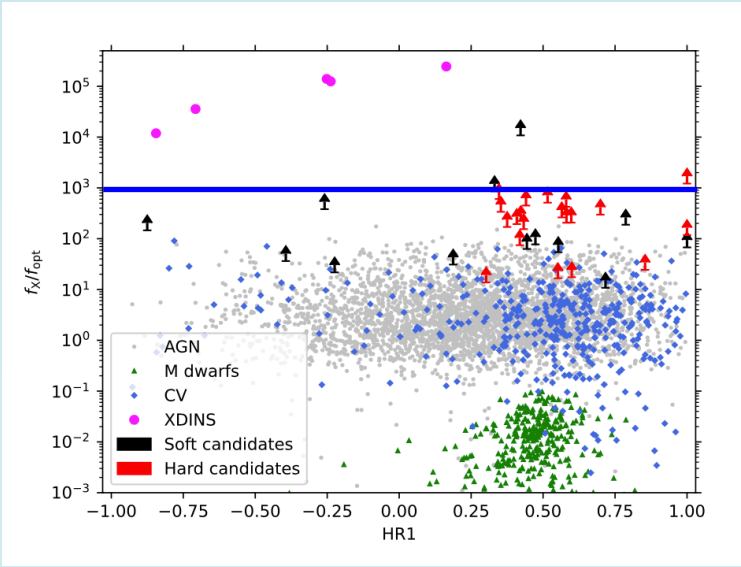


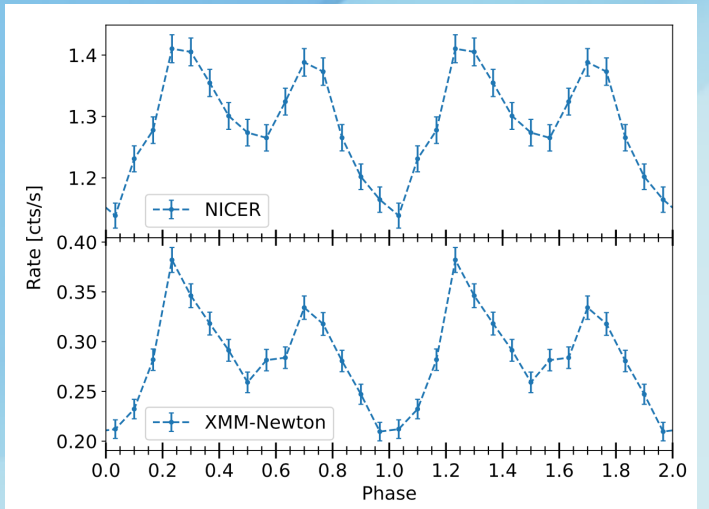


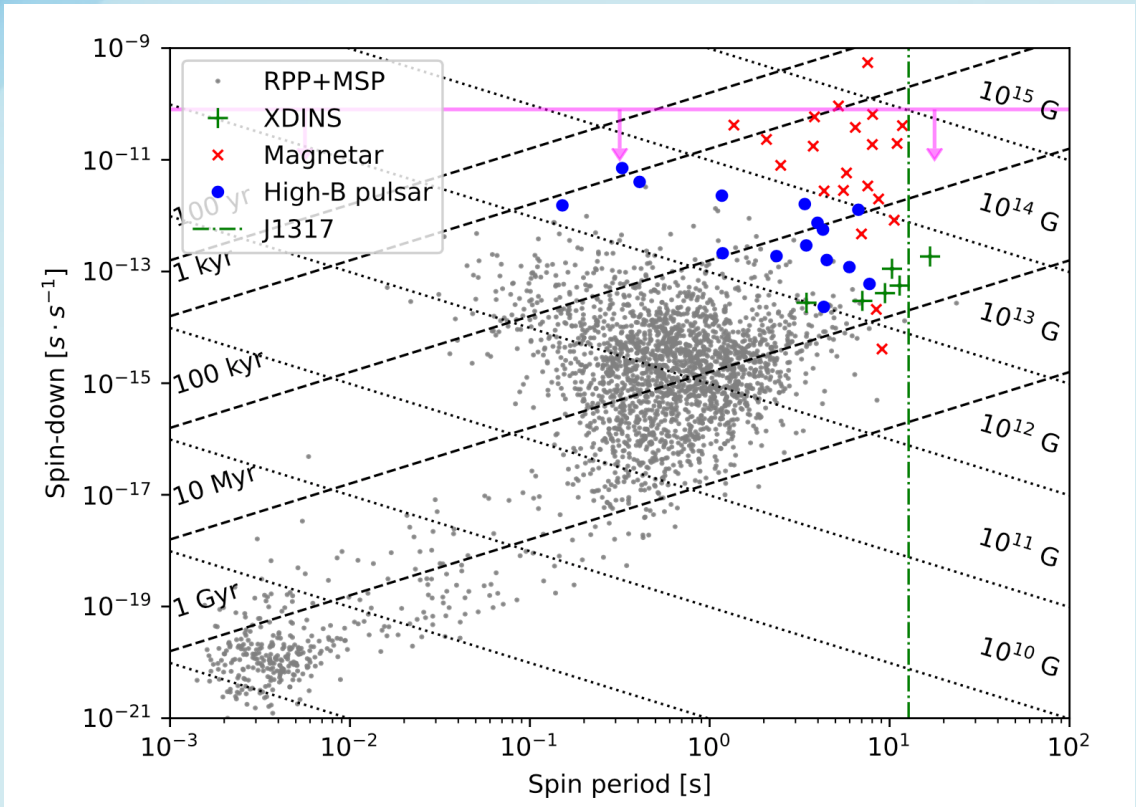
- Most promising candidates:
  - 2XMM J104608.7−594306 (Pires+ 2009, 2015)
  - 4XMM J022141.5−735632 (MR+ 2022a, Pires+ 2022)
  - eRASSU J065715.3+260428 and eRASSU J131716.9−402647 (Kurpas+ 2023)
  - 13 soft and 20 hard eROSITA sources (Kurpas+ 2024b)

MR+ 2022a, MNRAS
Kurpas+ 2024b, A&A

Increasing the sample of INS

- How to <u>confirm</u> the NS nature: The case of eRASSU J131716.9
  - Detection of pulsations: P~12.76 s, Pdot<8×10^{-11} s/s —> B<10^{15} G





Kurpas+ 2024a, A&A

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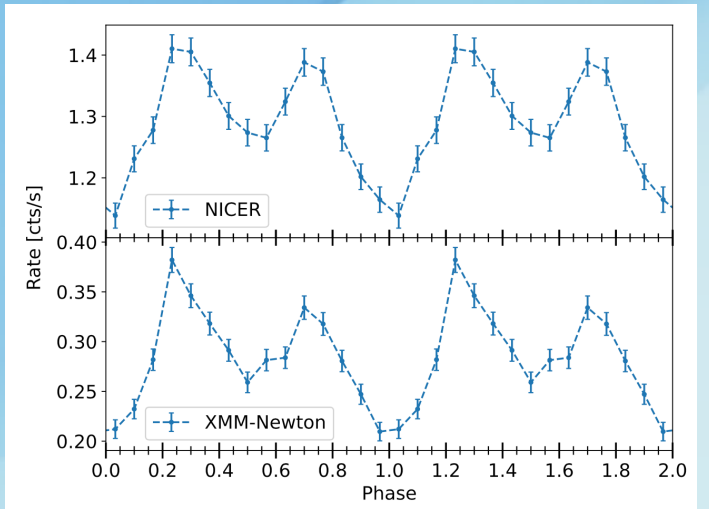
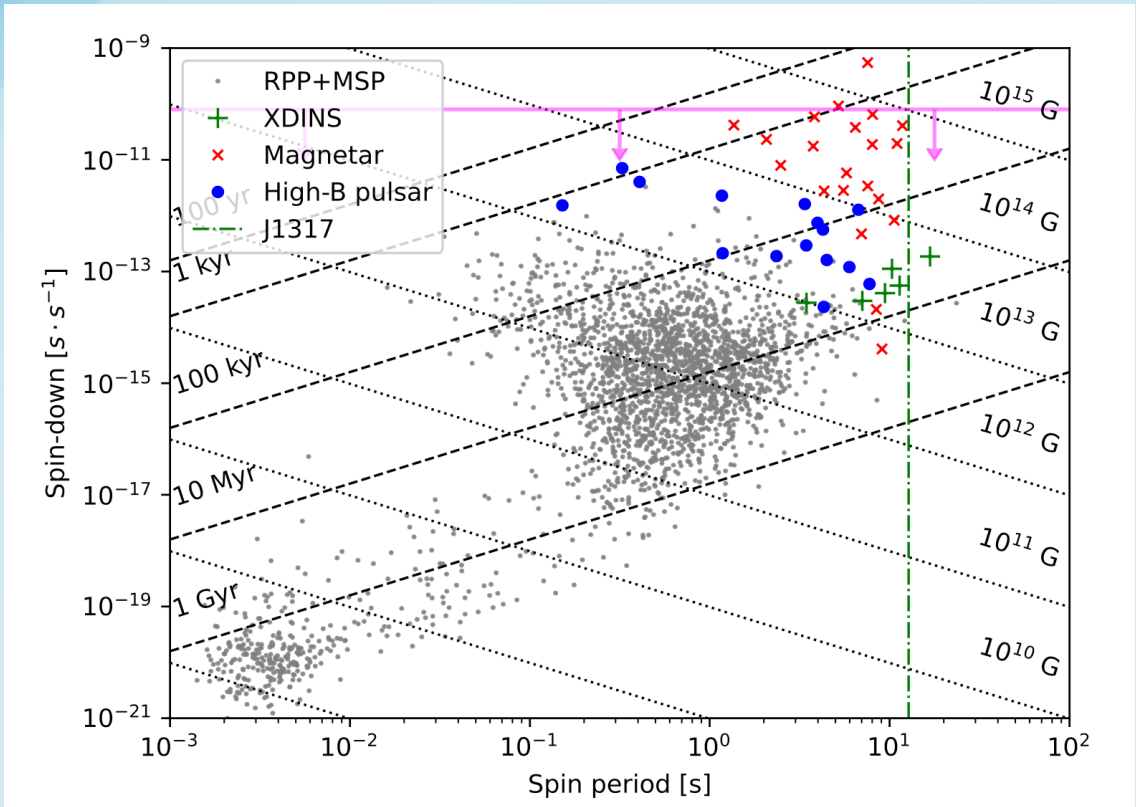
- How to confirm the NS nature: The case of eRASSU J131716.9
  - Detection of pulsations: P~12.76 s, Pdot<8×10^{-11} s/s —> B<10^{15} G
  - Optical counterpart m>27.5 —> F_X/F_O >10^4
  - Absorption features: E_1~350 eV, E_2~590 eV —> B~10^{13}—10^{14} G





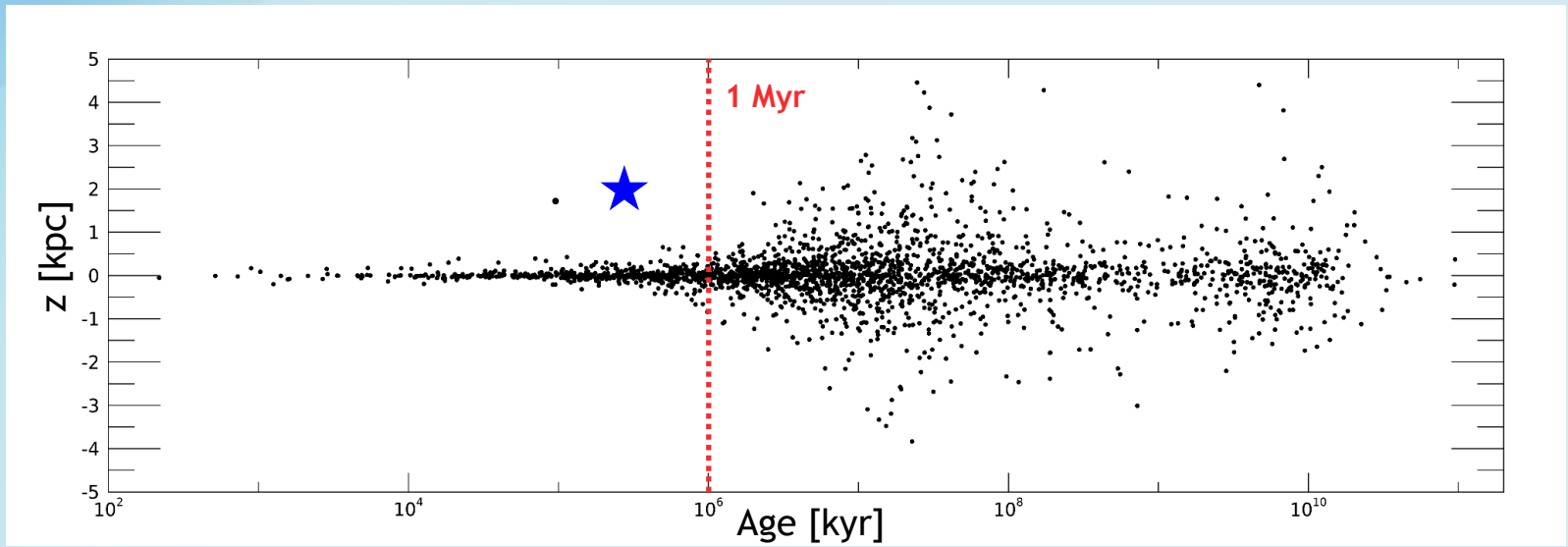
But many more results are coming! Stay tuned!

Kurpas+ 2024a, A&A

A peculiar INS

Calvera is an outlier: thermally-emitting INS detected in 2008 by ROSAT

- X-ray only, spin-down age of 300 kyr
- High b = 37 deg
- Magnetized atmo model: d ~ 3.3 kpc
  —> z ~ 2kpc



Araya 2023, MNRAS
Arias+ 2022, A&A
Bogdanov+ 2019, ApJ
Halpern+ 2013, ApJ
Mereghetti, MR+ 2021, ApJ
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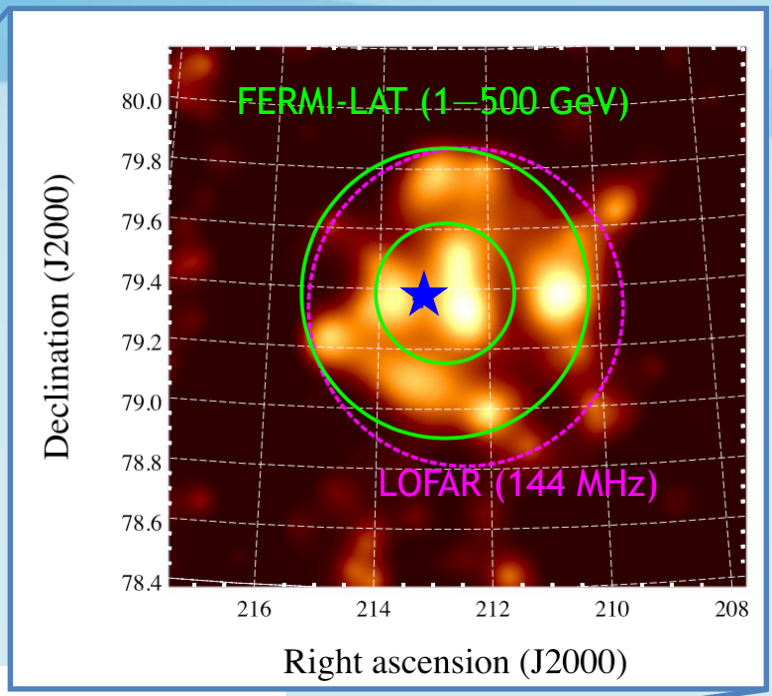
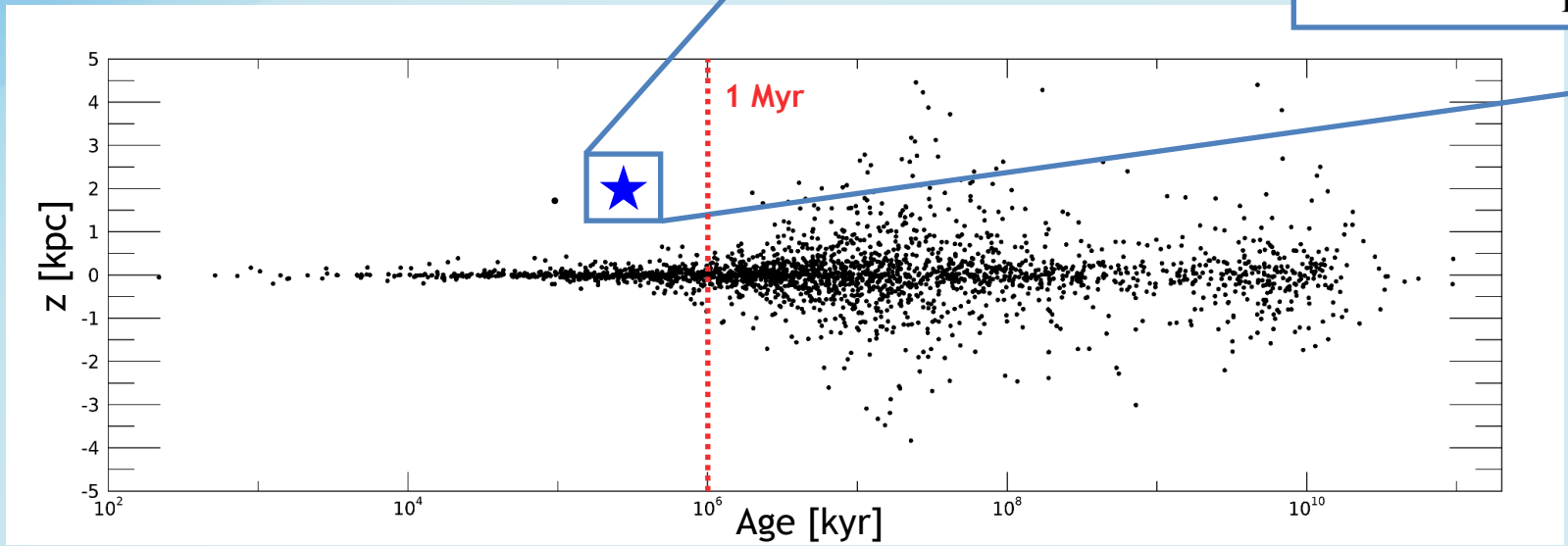
- High b = 37 deg
- Magnetized atmo model: d ~ 3.3 kpc
  —> z ~ 2kpc
- SNR in radio, X-ray and gamma-ray
  —> younger
- First young RPP born in the Galactic halo





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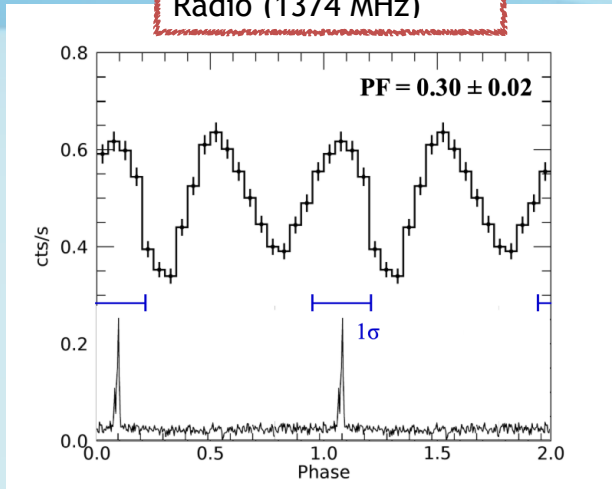
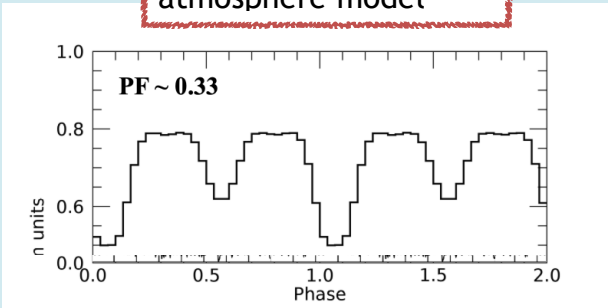
Link between XDINS and RPP

- HB PSR J0726−2612 has an X-ray spectrum 2BB + absorption line at 0.4 keV (= XDINS)
- It also has radio emission (≠ XDINS)
- Magnetized (B~10^{13} G) atmosphere model explains spectrum and pulse profile

Observed data:
X-rays (0.15—1.5 keV)
Radio (1374 MHz)



Simulated data with magnetized (B~10^{13} G) atmosphere model



Burgay+ 2006, MNRAS
Hambaryan+ 2011, A&A
Hambaryan+ 2017, A&A
MR+ 2019a, A&A

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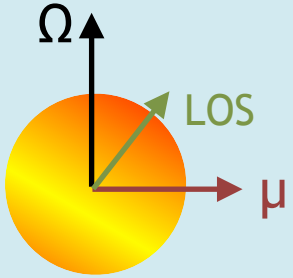
- Inferred geometry:

- XDINSs with similar X-ray pulse profiles have a different geometry, explaing the discrepancy



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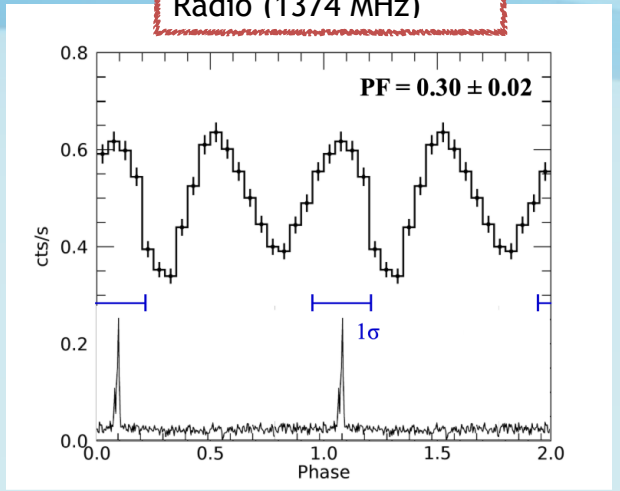

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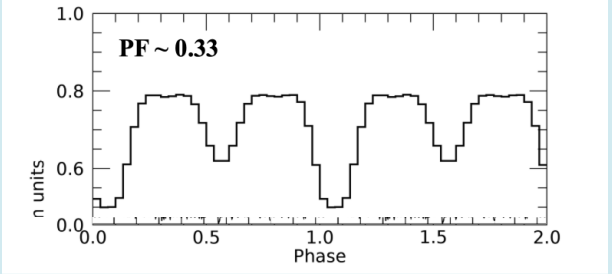

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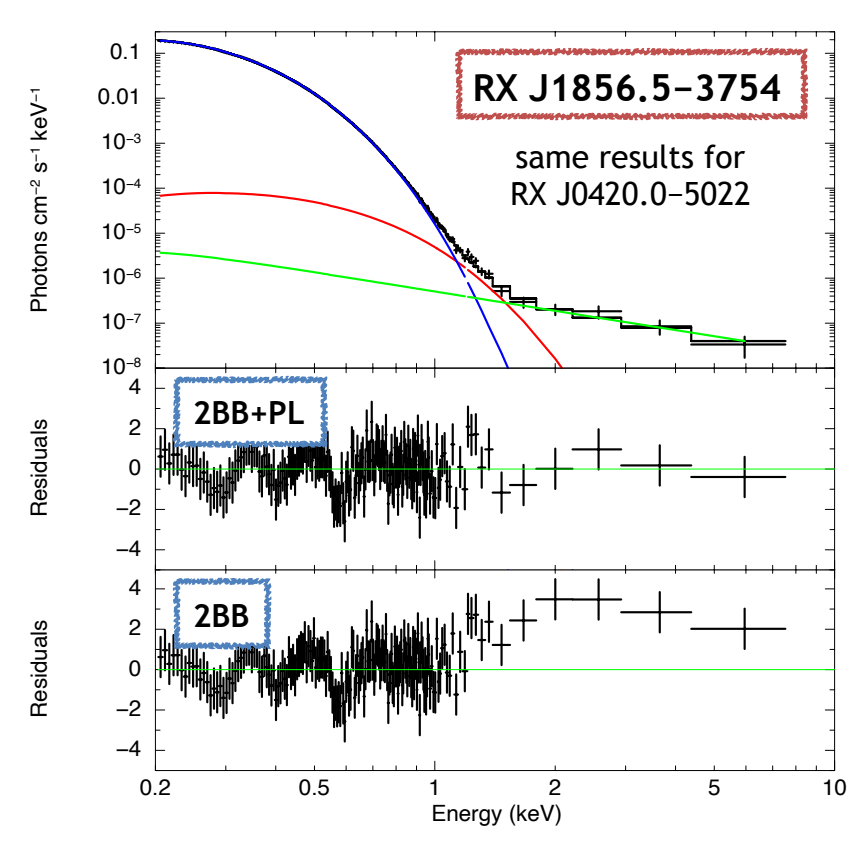
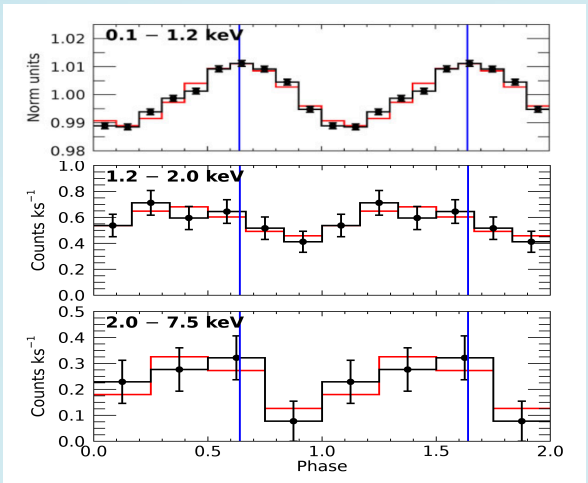




- Two out of seven XDINSs have also an X-ray non-thermal component
- Visible only summing 20 years of *XMM-Newton* data [~Msec]
- Pulsed (magnetospheric origin?) and efficiency $L_{PL}/\dot{E}_{rot} \sim 10^{-3}$ (~RPP)
- Can we detect a similar component in the other XDINS? Expected $F_{PL}<10^{-16}$ erg/cm^2/s…

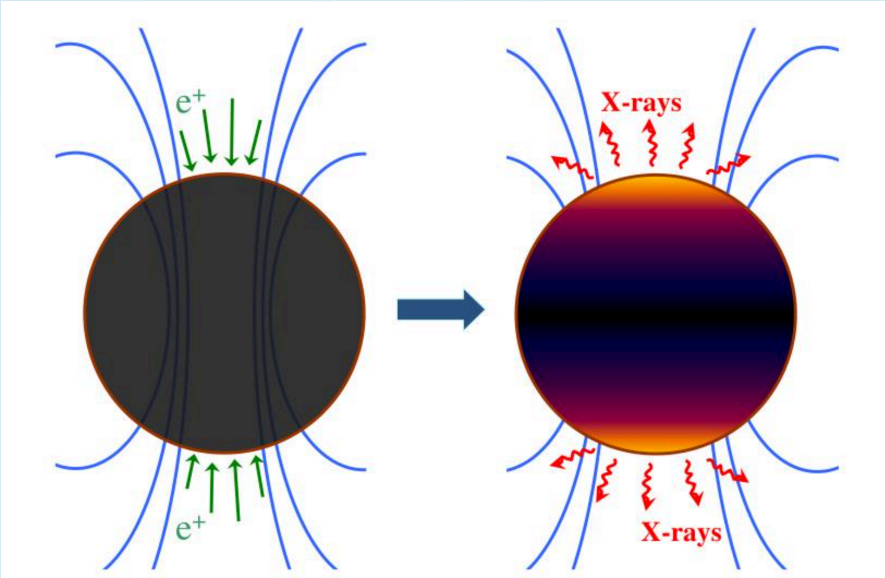
Dessert+ 2020, ApJ
De Grandis, MR+ 2022, MNRAS

Multipolar B

Growing evidences that all INSs (not only magnetars) have complicated (toroidal, multipolar, twisted…) surface and crustal magnetic field:

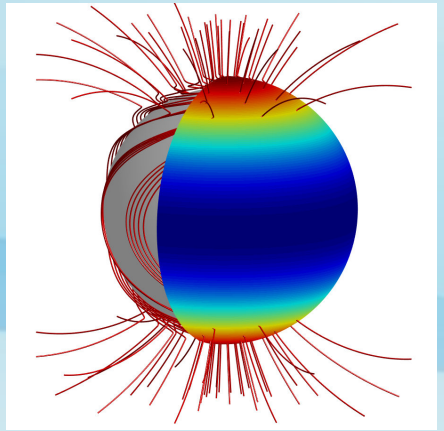
- Presence of absorption lines at ~0.5 keV also in RPPs: $B_{\rm cyc,p} \approx 1.3 \times 10^{14}\, E_{1\,\rm keV}$ G
  (see e.g. Kargaltsev+ 2012, MR & Mereghetti 2018, Arumugasamy+ 2018, MR+ 2022b)

- Polar cap size of RPPs older than 1 Myr (~10^1 m wrt ~10^2 m):
  $B_{\rm PC} = 2 \times 10^{14}\, R_{1,\rm PC}\, P_0^{-1/2} \dot{P}_{-15}^{1/2}$ G
  (see e.g. Gil+ 2003, 2008, MR+ 2019b, Bogdanov+ 2019, Riley+ 2019, Bilous+ 2019)

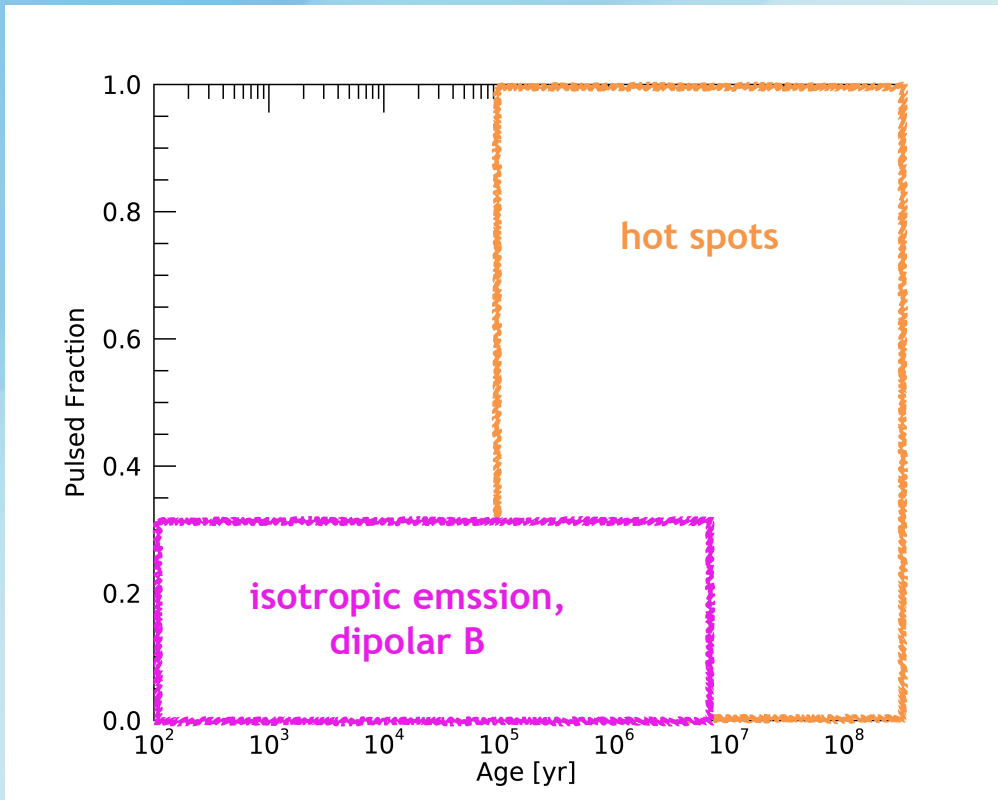


Multipolar B

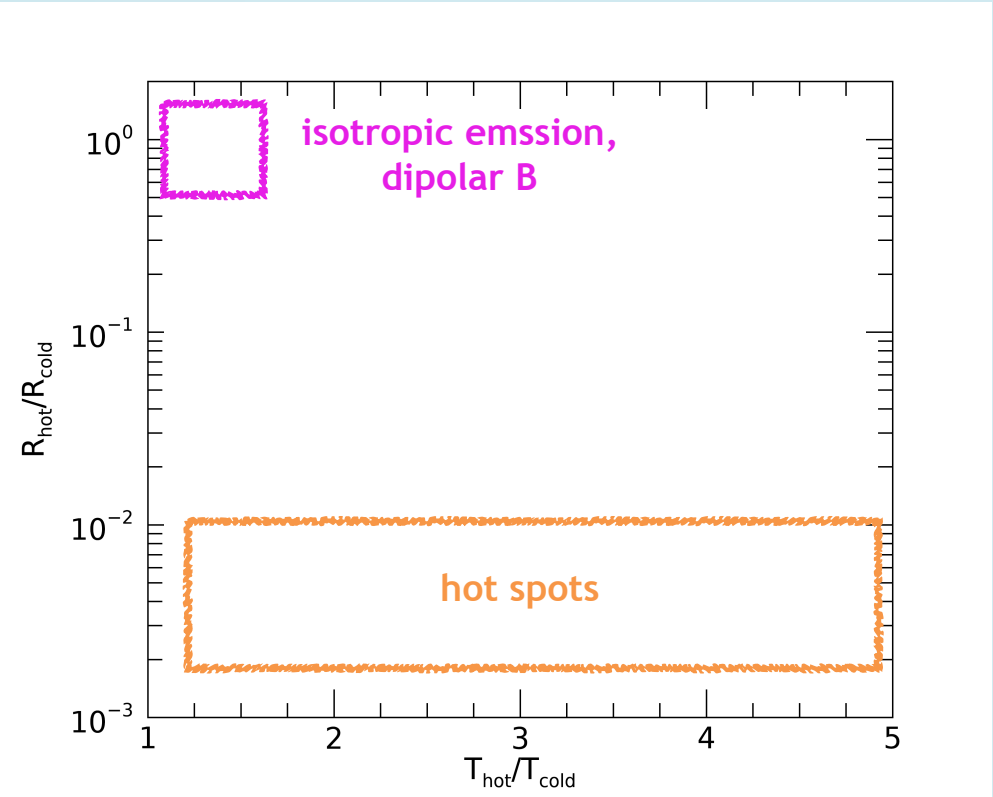
- Steep surface temperature distribution
  (see e.g. Halpern+ 2010, Ng+ 2012, MR+ 2019a, 2021, Yakovlev 2021, Gotthelf+ 2021)



High pulsed fraction



High T contrast



MR+ 2022b, MNRAS

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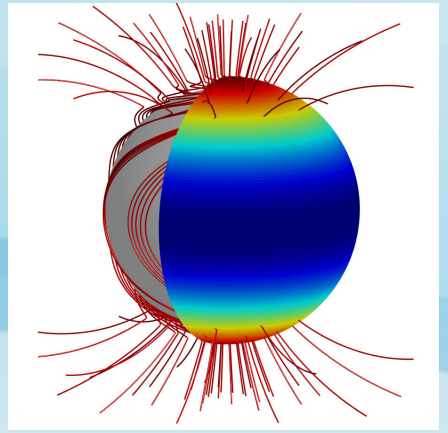

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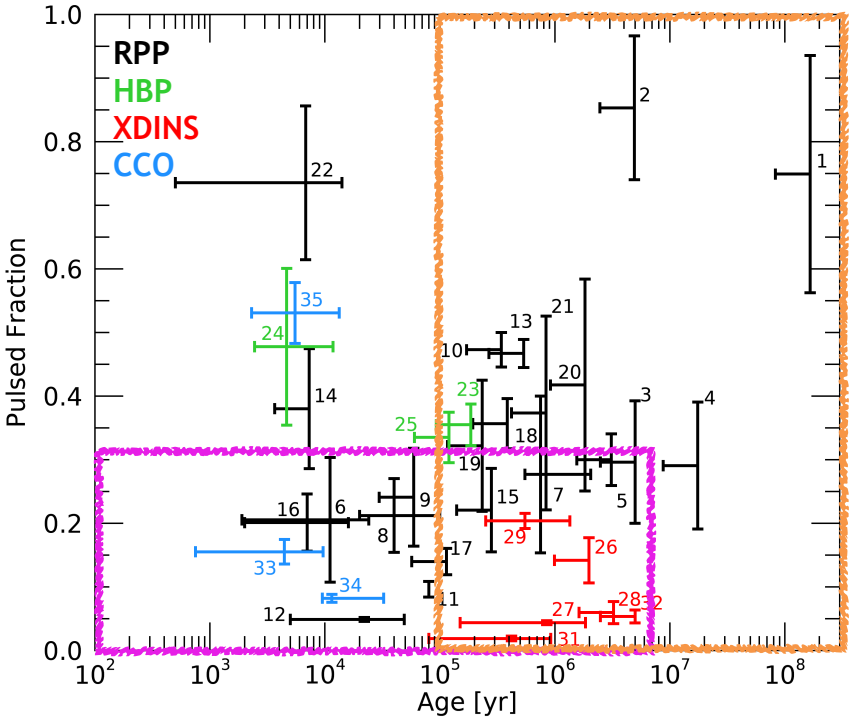

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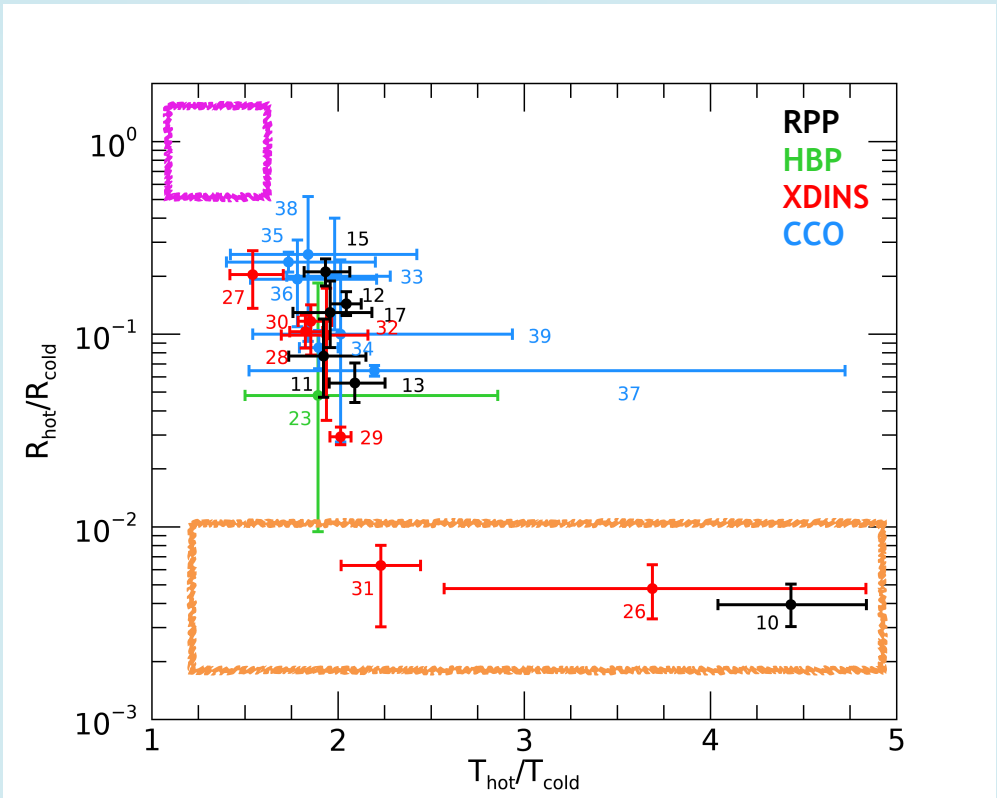


MR+ 2022b, MNRAS

Conclusions

- The XDINS class is probably more variegate than previously thought: they can show non-thermal emission, and the absence of radio emission could be explained by orientation effects.
- Quite all the INS classes share a common T distribution despite a different evolutionary stage.
- Many independent evidences (steep T distribution, abs. lines, small polar caps) for the presence of non-dipolar magnetic fields in all the INS classes.

...see also

- Popov 2023, arXiv:2306.02084
- Esposito, Rea & Israel 2021, arXiv:1803.05716
- Gourgouliatos, Hollerbach & Igoshev 2020, arXiv:2005.02410
- Kaspi 2018, 2018IAUS..337....3K
- De Luca 2017, arXiv:1711.07210
- Igoshev, Popov & Turolla 2014, arXiv:1309.4917
- Harding 2013, arXiv:1302.0869
- Kaspi 2010, arXiv:1005.0876
- Turolla 2009, 2009ASSL..357..141T


Thanks for the attention!

Calvera place of birth

τ = 3x10^5 yr, z = 2 kpc → v = 6700 km/s, unphysically large:

Calvera was born and raised in the Galactic halo

What about its progenitor?

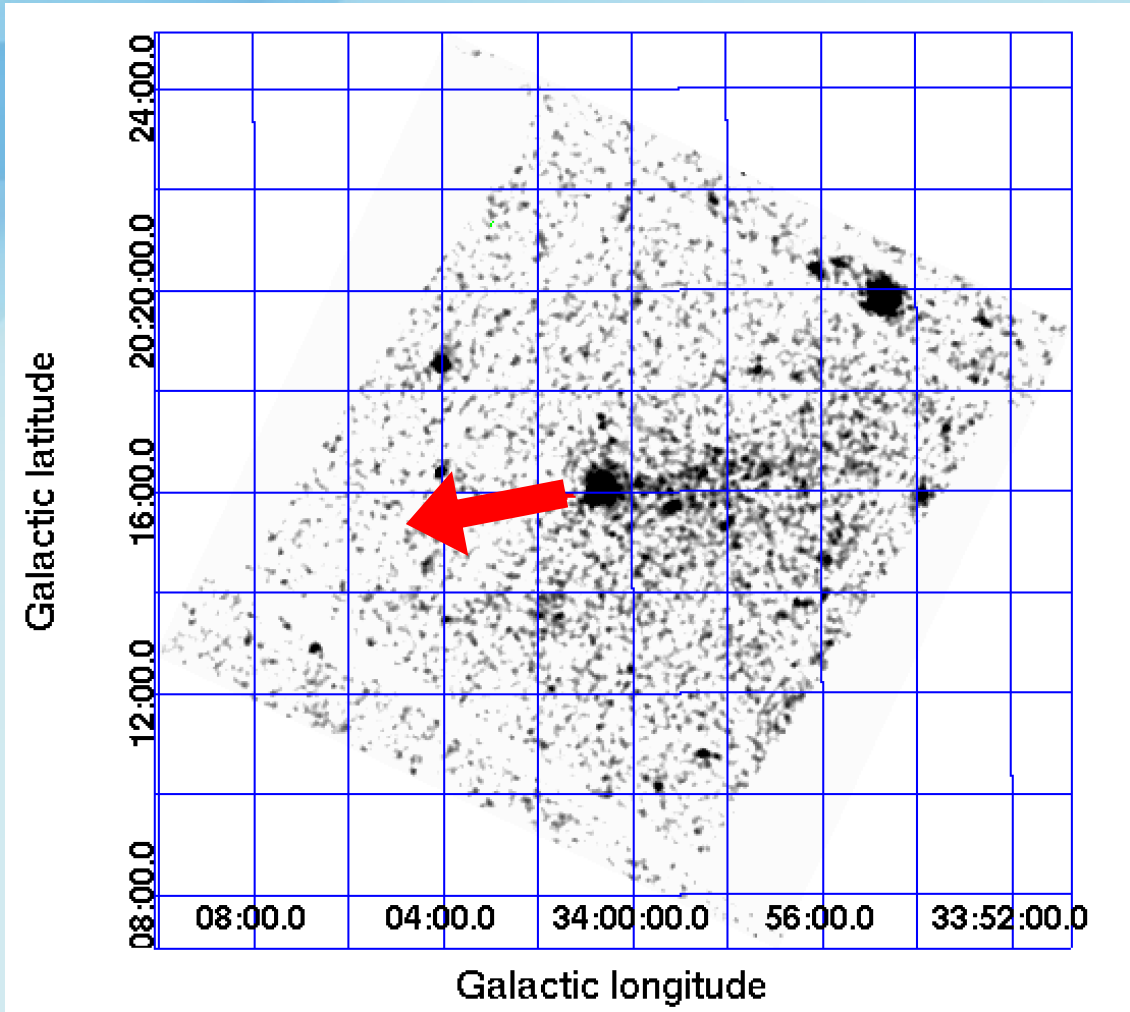
- Was born in the disk, travelled with v ~ 500 km/s and exploded as a SN in the halo (runaway massive star) → large PM
- Was born in the halo from a white dwarf (accretion-induced collapse) → small PM

Current PM = 69±26 mas/yr → 1100±400 km/s, inconclusive

Halpern & Gotthelf 2015, ApJ

PSR J1740+1000

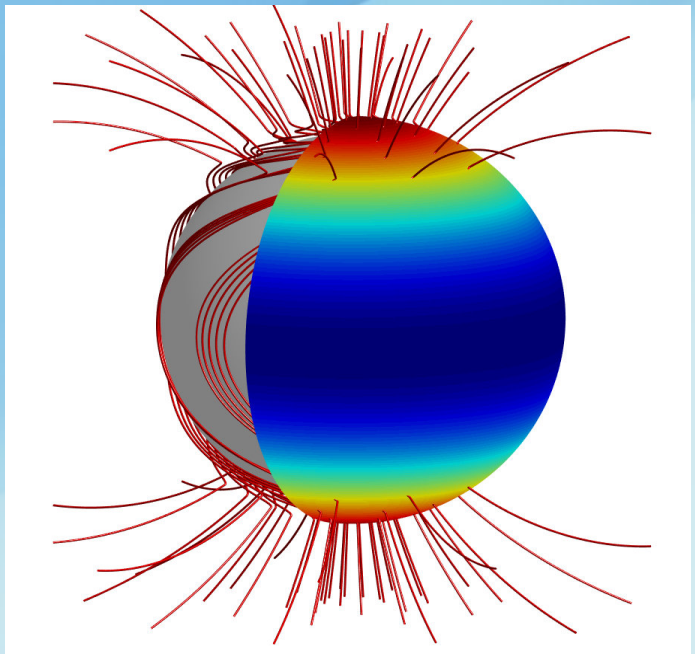
- Age~10^5 yr, b=20 deg
- Distance from DM: 1.2—1.4 kpc
- No proper motion detected:
  <60 mas/yr, i.e.
  <1.67 deg/10^5 yr
- Orientation of the tail implies angle of 7 deg towards the Galactic plane



Benbow+ 2021, ApJ
MR+ 2022b, MNRAS

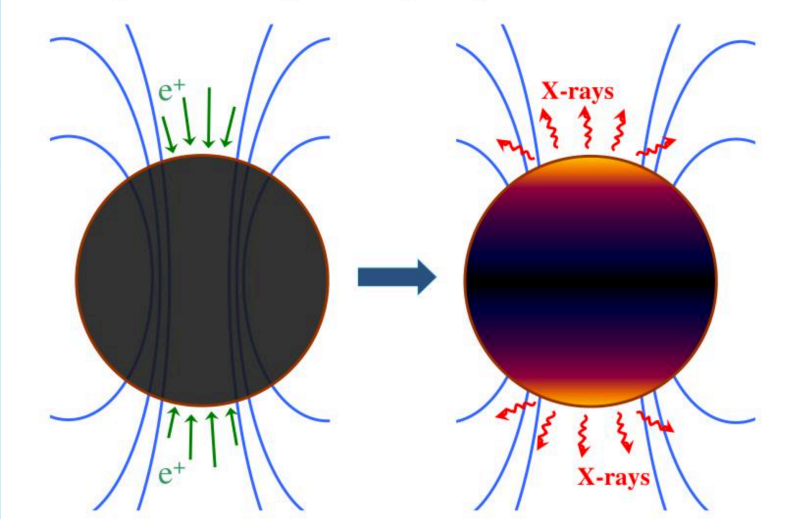
Thermal X-rays from INSs

INTERNAL HEATING



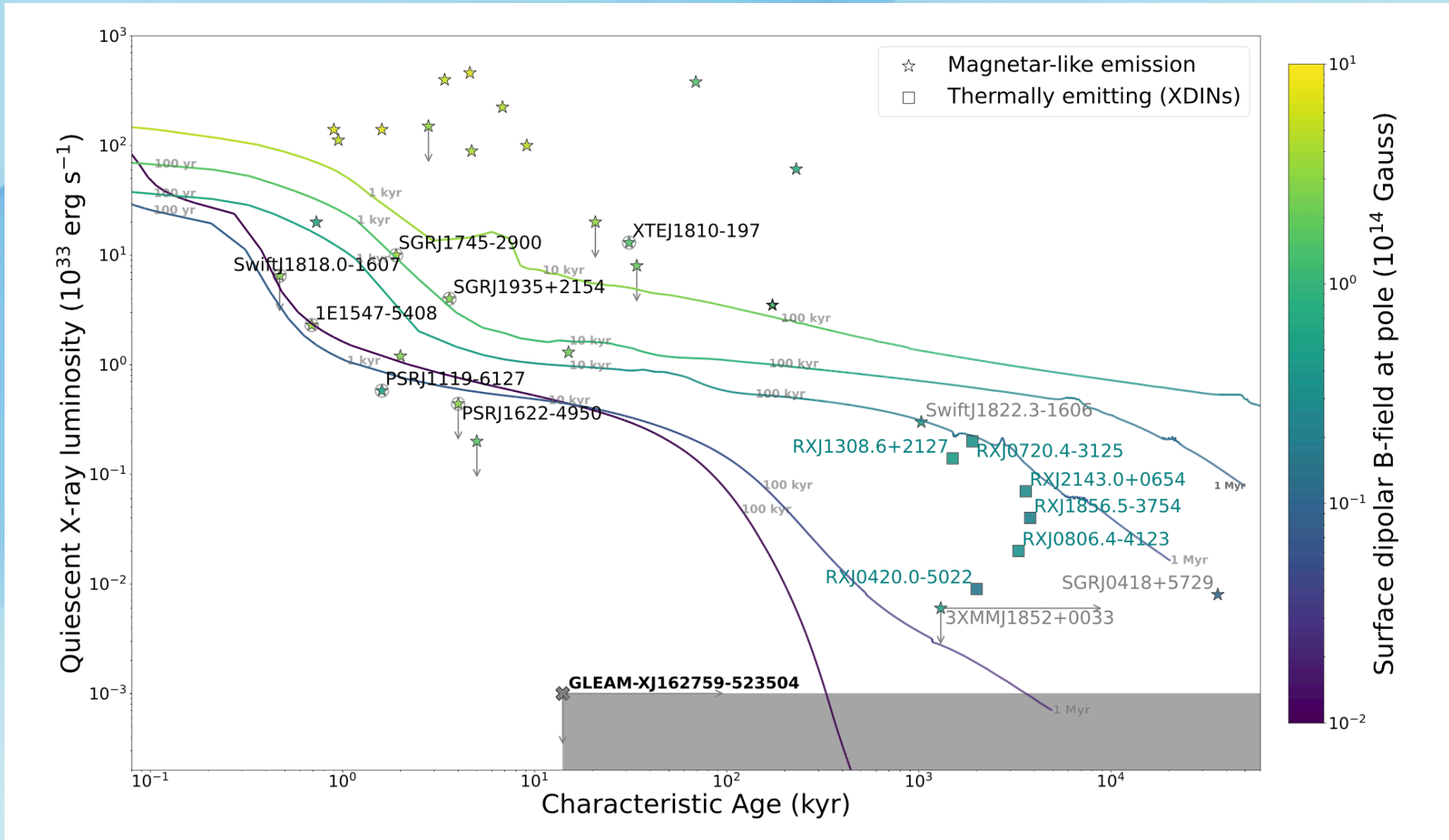
emitting radius ~ R_{NS}
moderately pulsed

EXTERNAL HEATING



emitting radius ~ R_{PC}
strongly pulsed

Slowly rotating pulsars



Rea+ 2022, ApJ