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

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Sandro Mereghetti[2], Roberto Turolla[3,4], Roberto Taverna[3], Davide De Grandis[5], Silvia Zane[4], Alexander Y. Potekhin[6], Valery Suleimanov[7], George Younes[8], Fabio Pintore[9], Paolo Esposito[2,10], Andrea Tiengo[2,10]

08/07/2024 — Pescara

MG17PESCARA 7-12 JULY 2024
SEVENTEENTH MARCEL GROSSMANN MEETING
ON RECENT DEVELOPMENTS IN THEORETICAL AND EXPERIMENTAL GENERAL RELATIVITY, ASTROPHYSICS AND RELATIVISTIC FIELD THEORIES

1 INAF-OA Brera
2 INAF-IASF Milano
3 Dipartimento di Fisica e Astronomia, Università di Padova
4 MSSL, University College London
5 ICE-CSIC & IEEC, Barcelona
6 Ioffe Institute, St. Petersburg
7 Institut für Astronomie und Astrophysik, Tübingen
8 Department of Physics, The George Washington University
9 INAF-IASF Palermo
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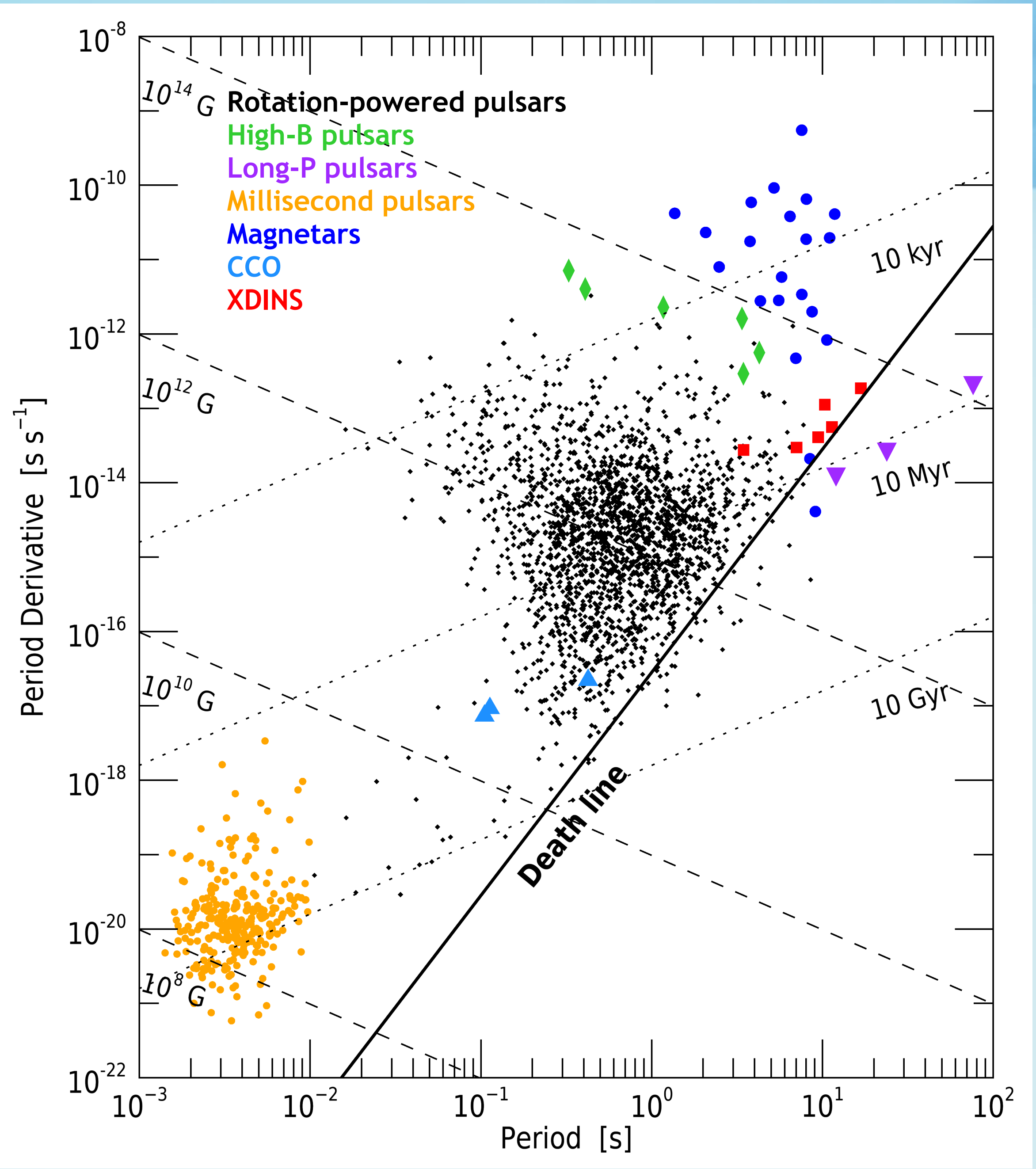
The Isolated Neutron Stars zoology



Isolated —> non-accreting

Under some very simple assumptions:

$$\dot{E}_{\rm rot} = 4\pi^2 I_{\rm NS} \dot{P} P^{-3}$$

$$B_{\rm dip} \approx 3.2 \times 10^{19} (P\dot{P})^{1/2} \text{ G}$$

$$\tau_c = \frac{P}{2\dot{P}}$$

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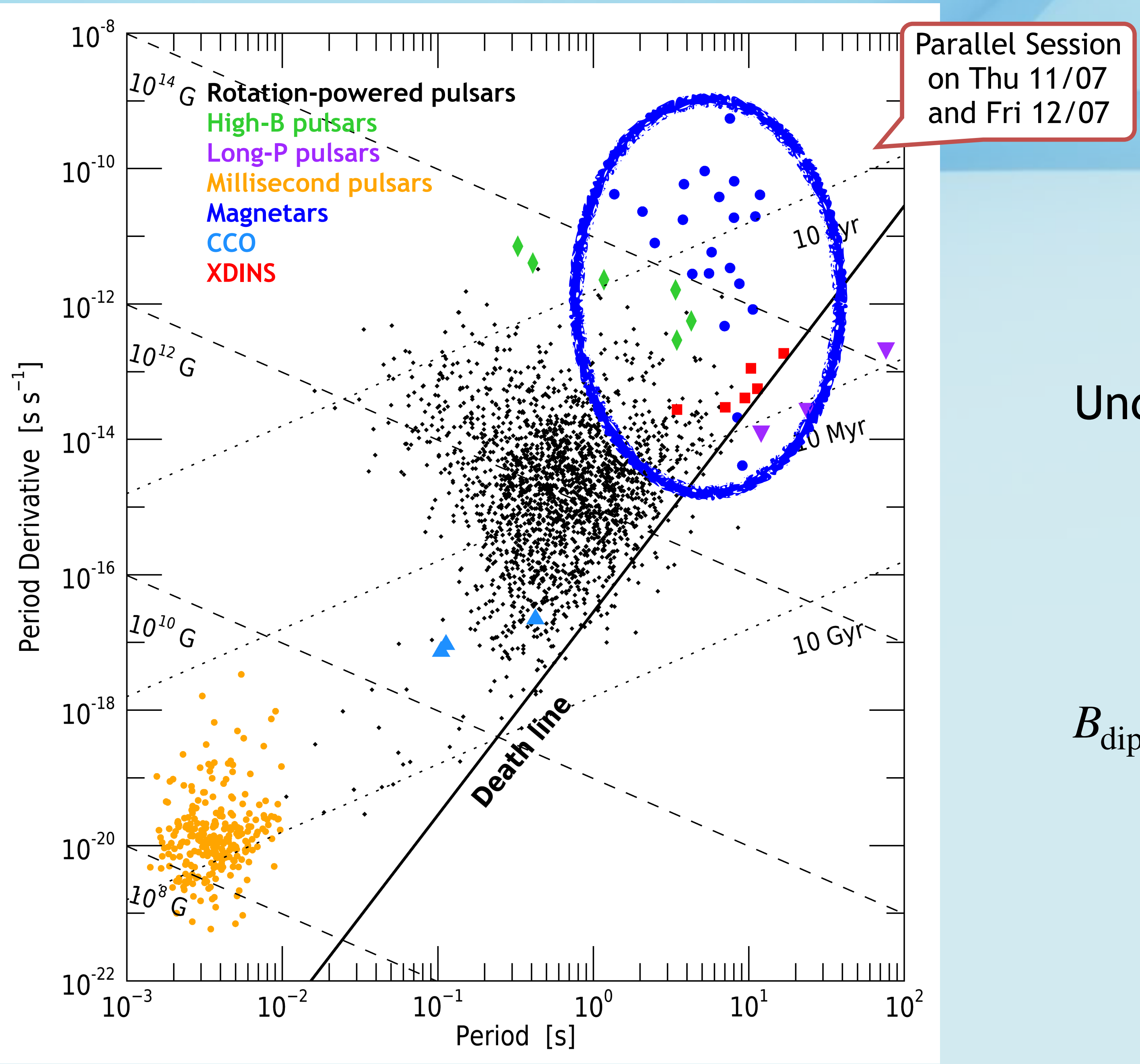

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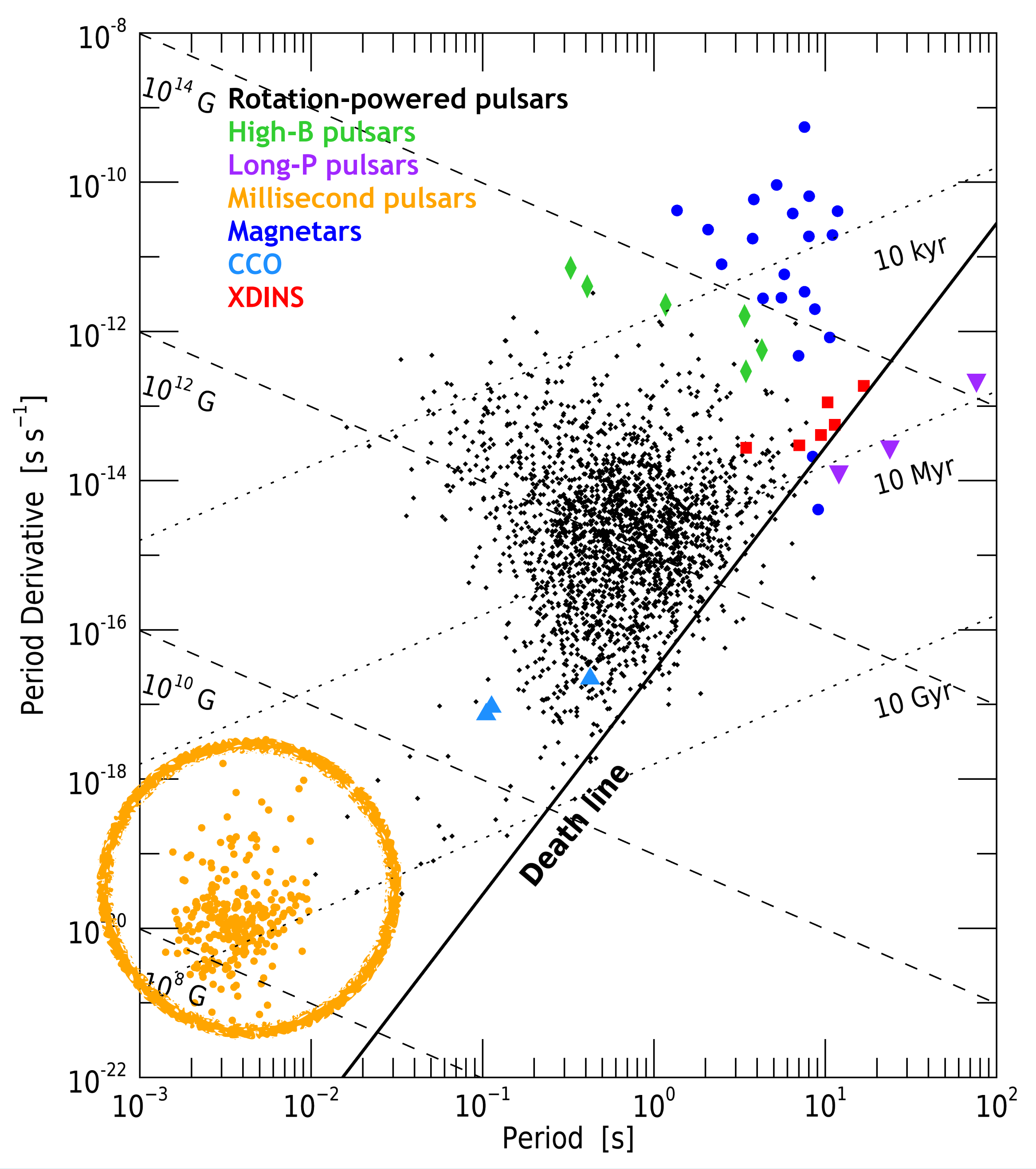

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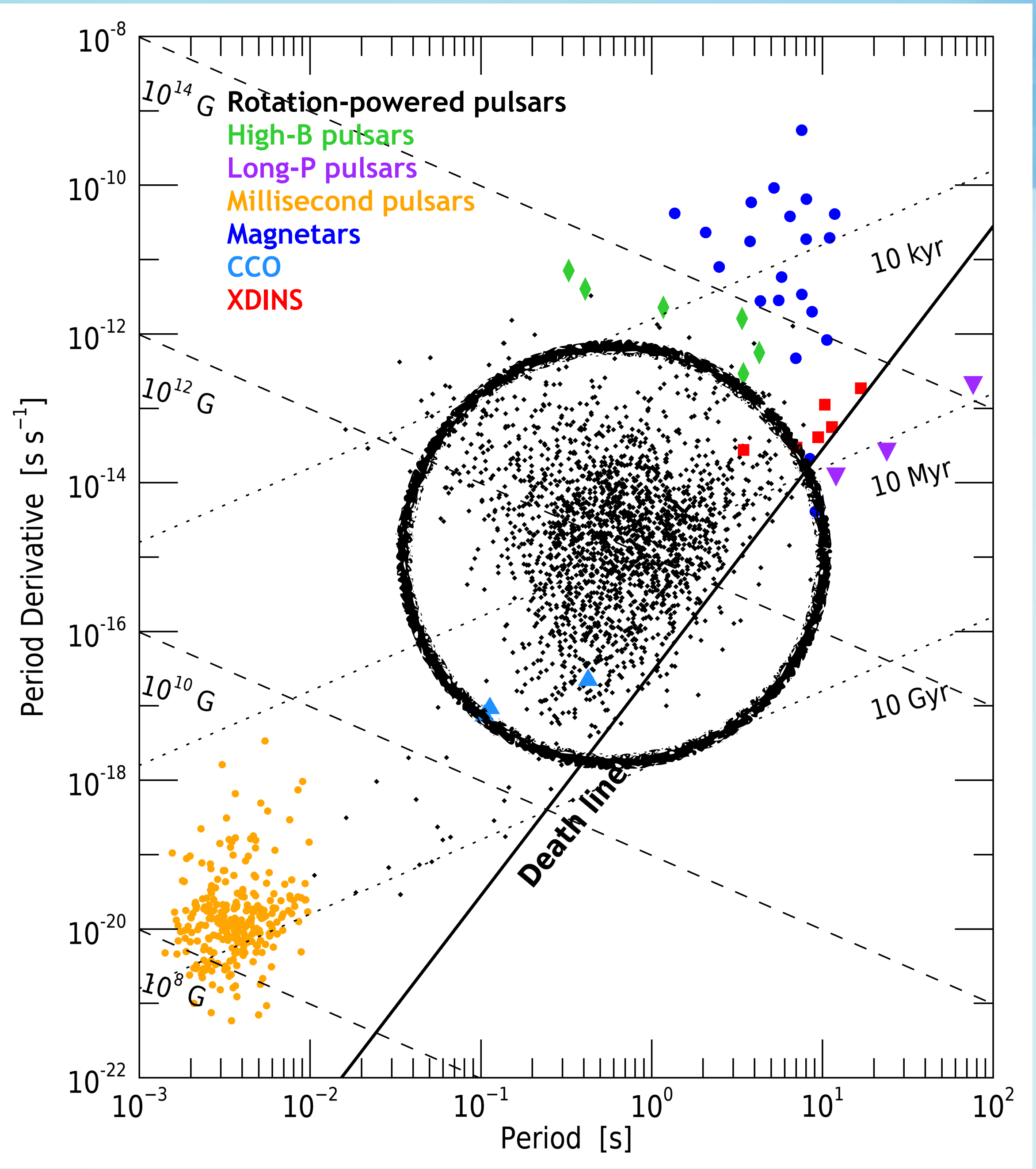
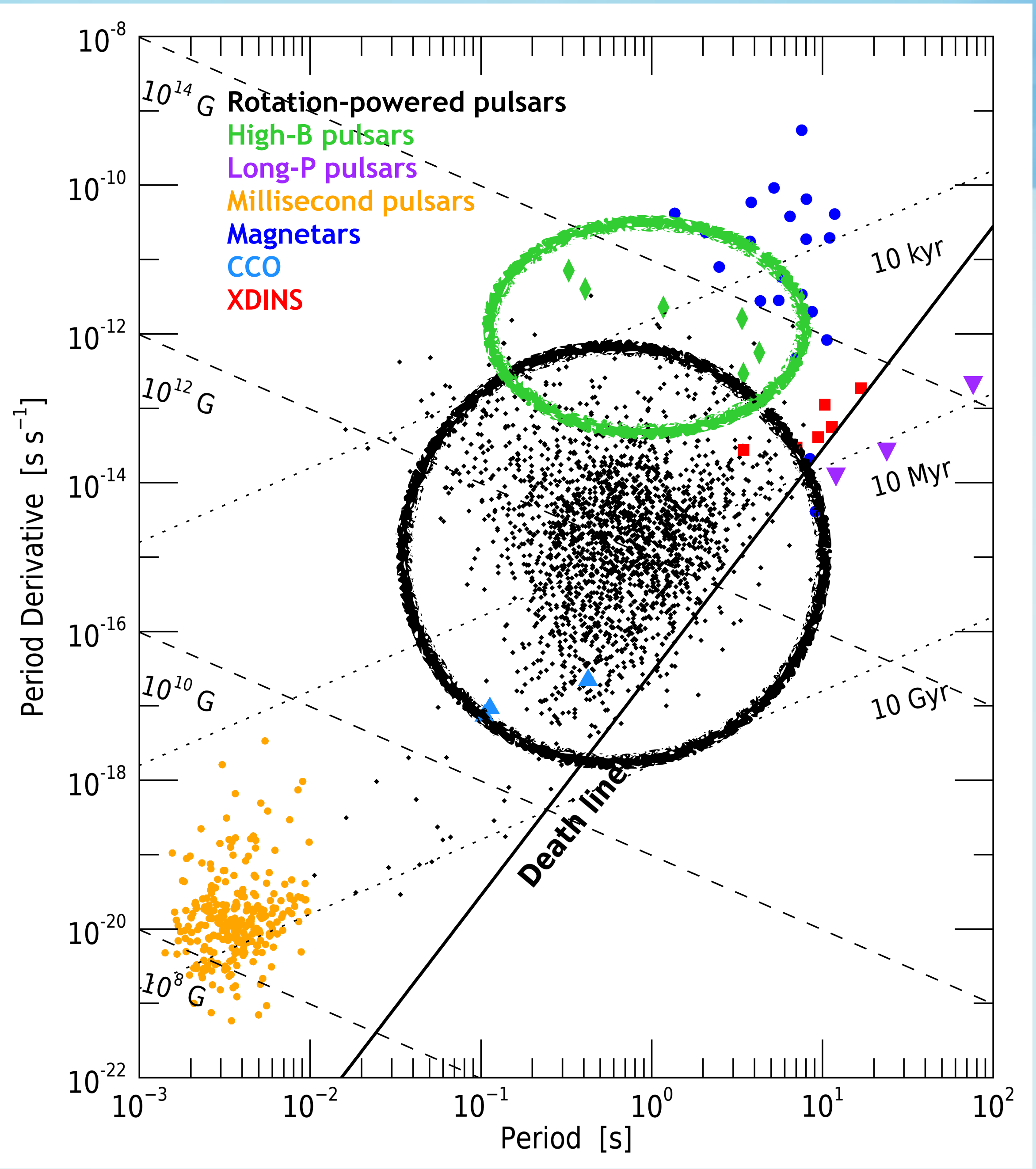


Rotation-powered pulsars

- The bulk of INS (~3000)
- Discovered by pulsating non-thermal emission, mainly in radio and gamma
- They also show Optical/UV/X-ray thermal emission from cooling surface and heated hot spots

The Isolated Neutron Stars zoology



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- With B ~ $B_{cr} = 4.4\times10^{13}$ G
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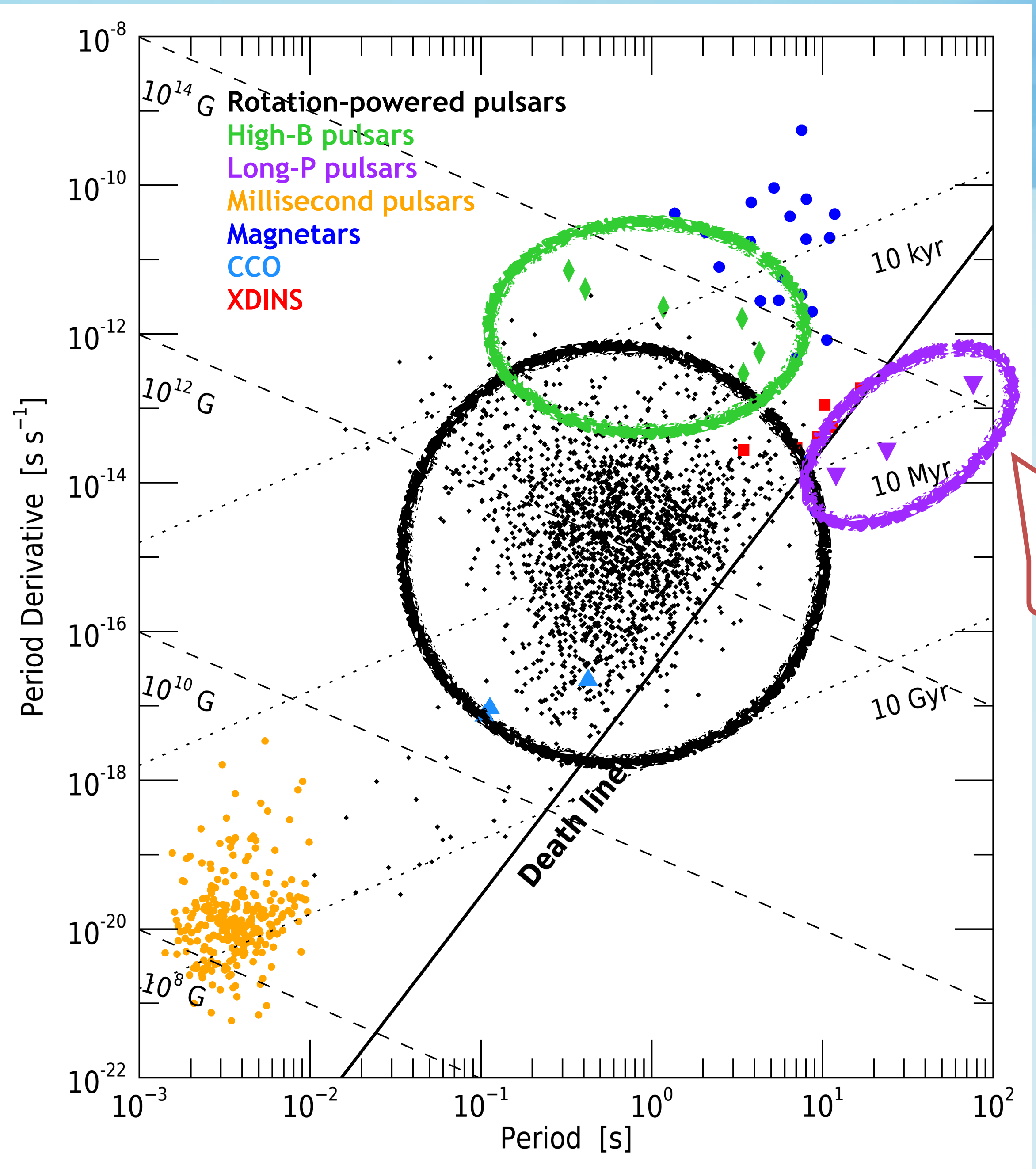

Parallel Session on Tue 09/07

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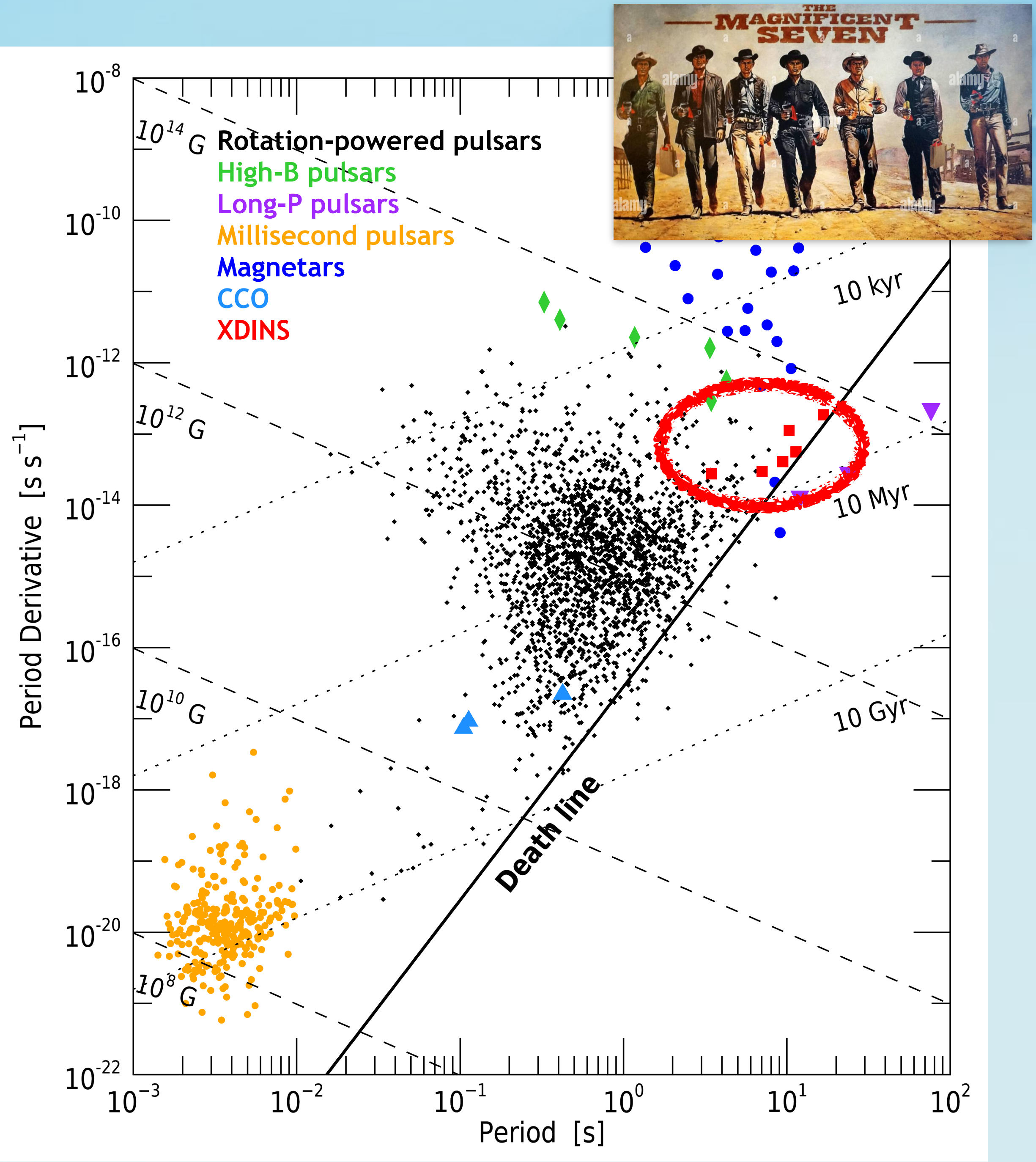
Long-P pulsars

- Beyond 'death line'
- Fall-back accretion models to slow down

The Isolated Neutron Stars zoology



➡ powered by cooling and not by rotation

XDINS

- Discovered as ROSAT bright sources, with high F_X/F_O
- Optical/UV/X-ray multi-T thermal spectrum that peaks in the X-rays
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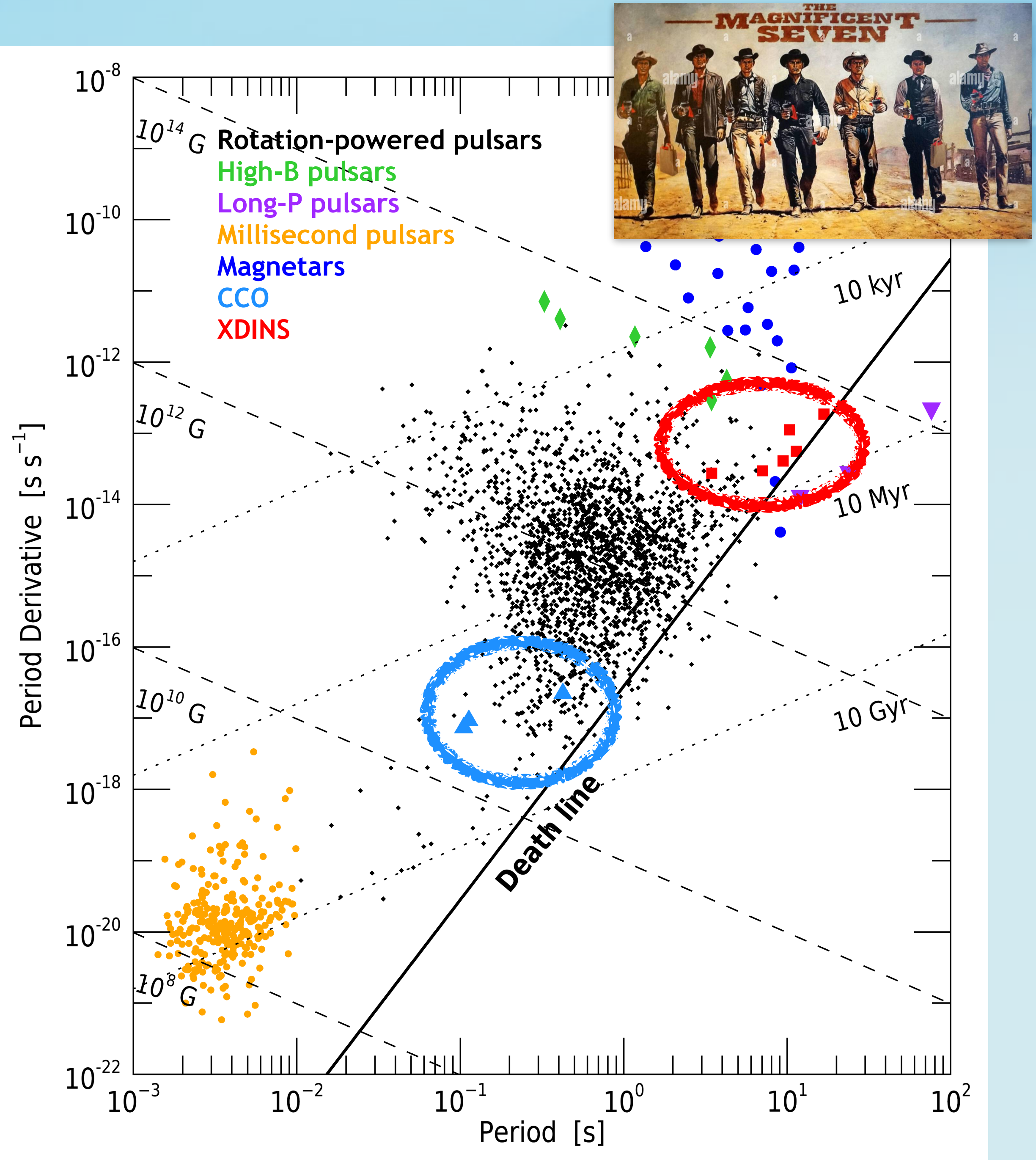

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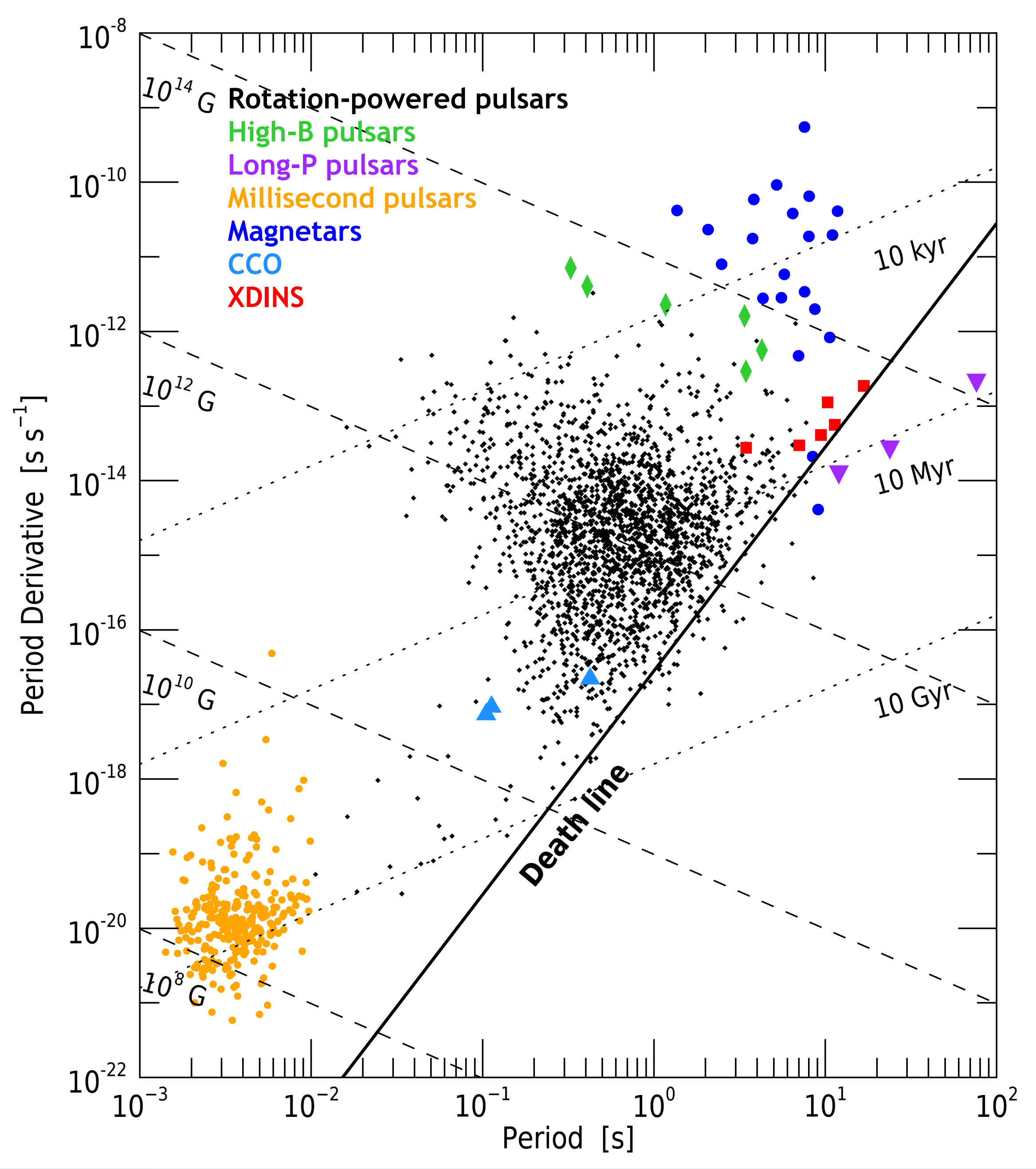
CCO

- Discovered as Central Compact Objects of SNRs
- Soft X-ray thermal spectrum

The Isolated Neutron Stars zoology



What's new in the X-rays?

- Several new thermal-emitting INS canditates
- Link between different classes of INSs
- Non-dipolar B in all INSs

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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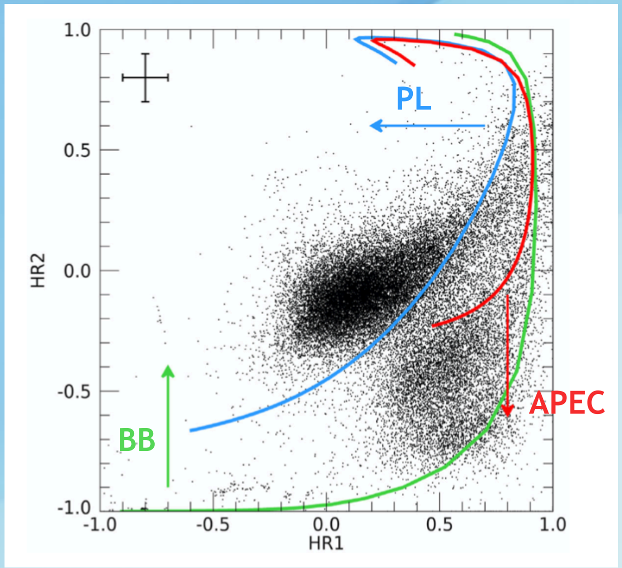
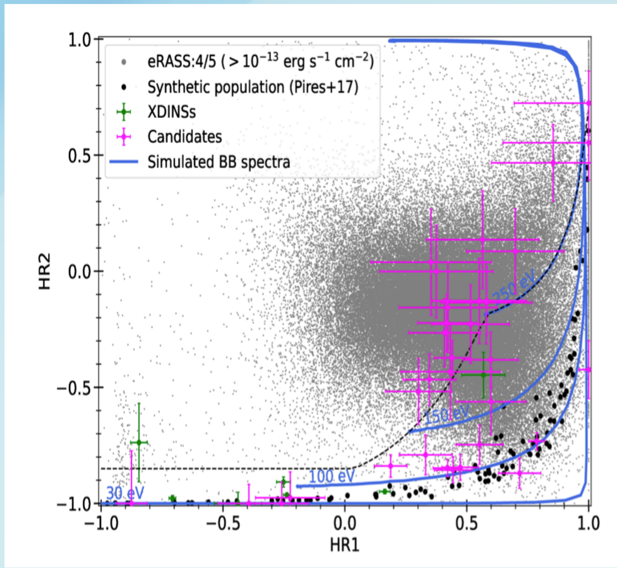
4XMM DR10 catalog



eROSITA DR1 catalog



MR+ 2022a, MNRAS
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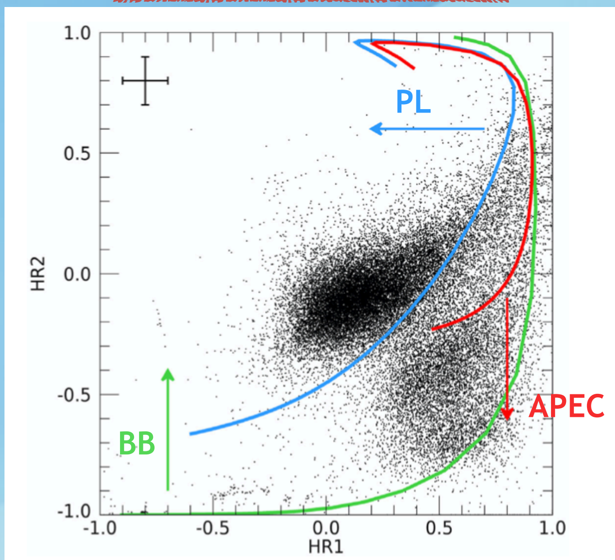

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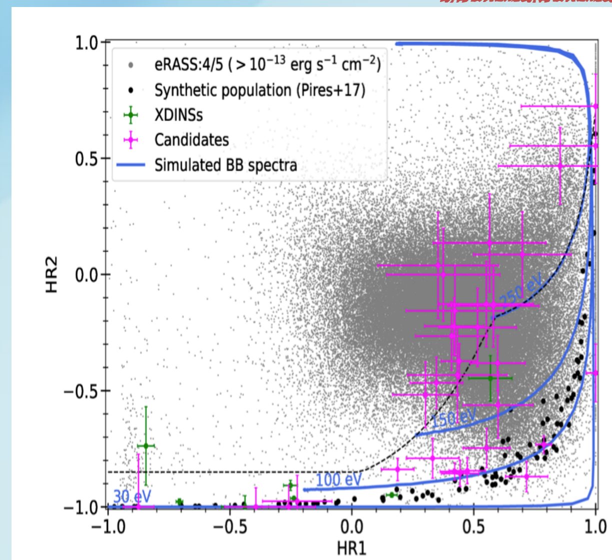

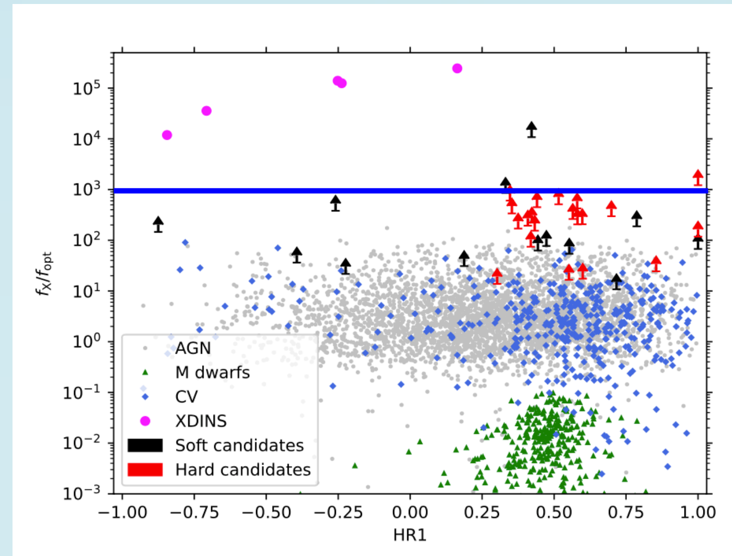

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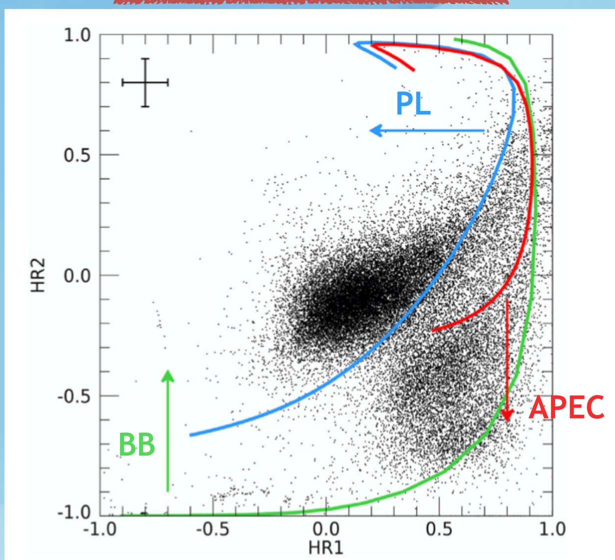

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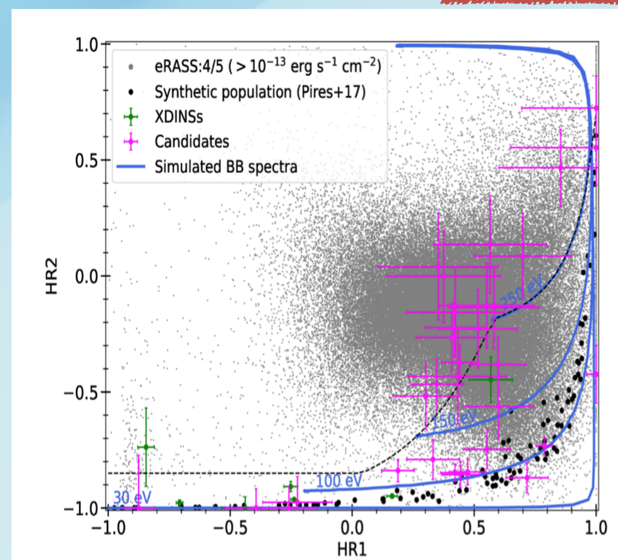
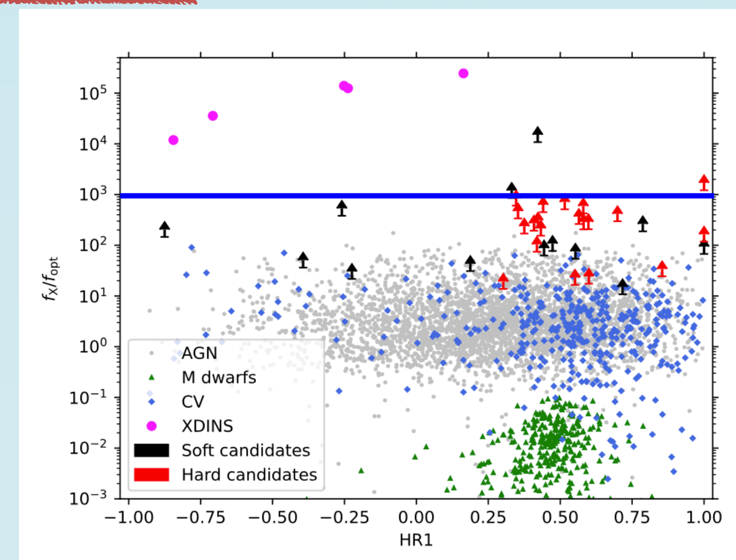


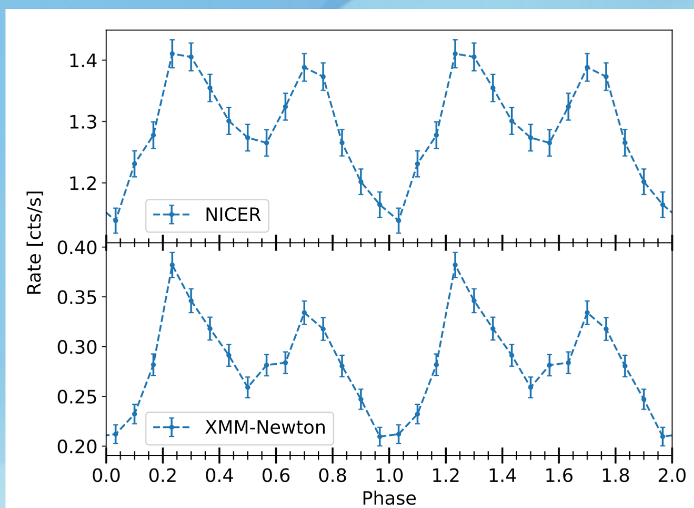


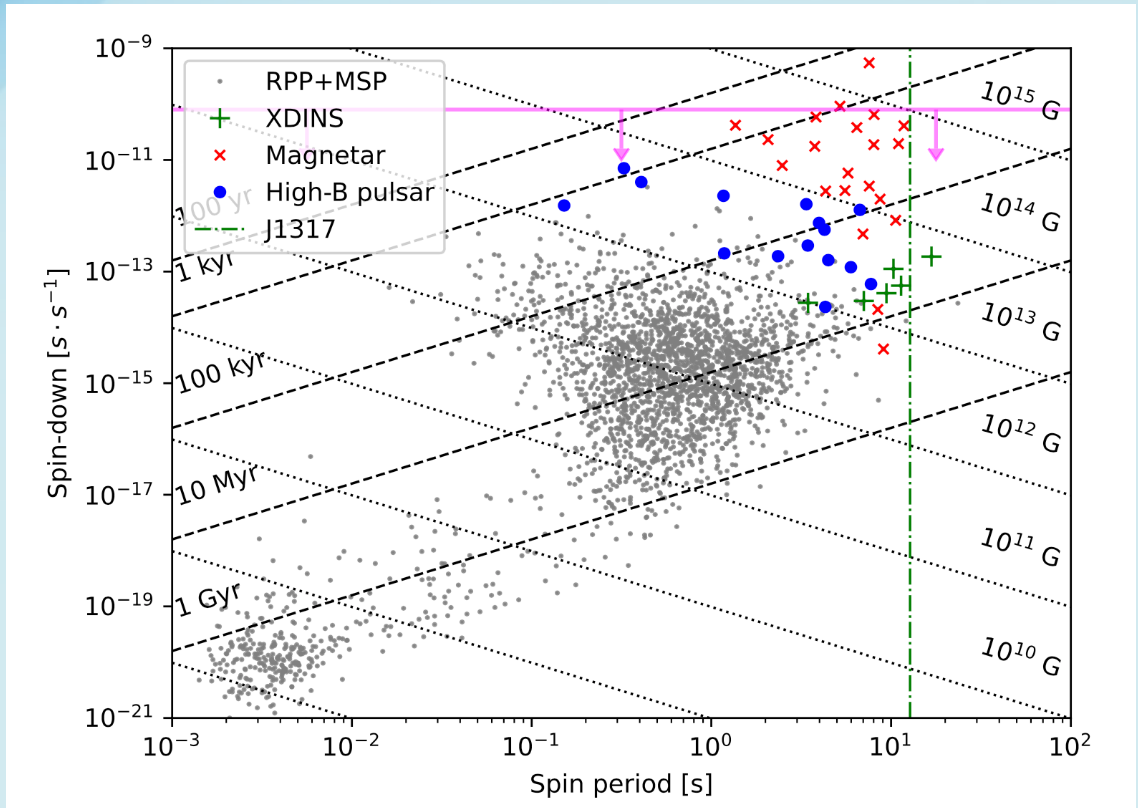
- Most promising candidates:
  - 2XMM J104608.7−594306 (Pires+ 2009, 2015)
  - 4XMM J022141.5−735632 (MR+ 2022a, Pires+ 2022)
  - eRASSU J065715.3+260428 and eRASSU J131716.9−402647 (Kurpas+ 2023)
  - 13 soft and 20 hard eROSITA sources (Kurpas+ 2024b)

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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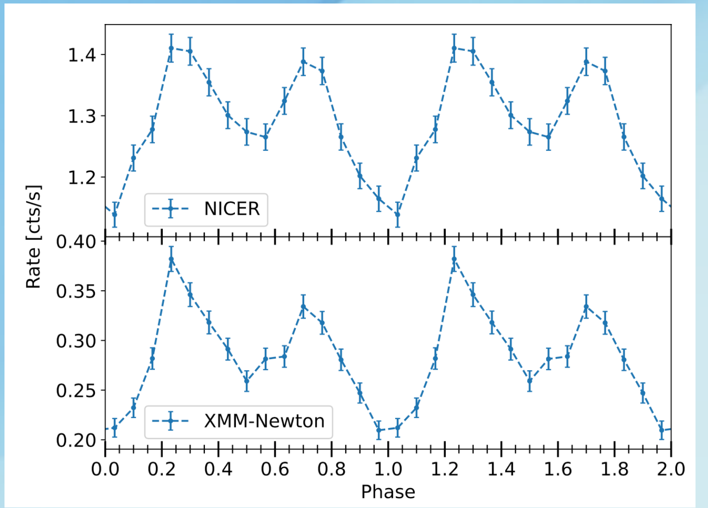
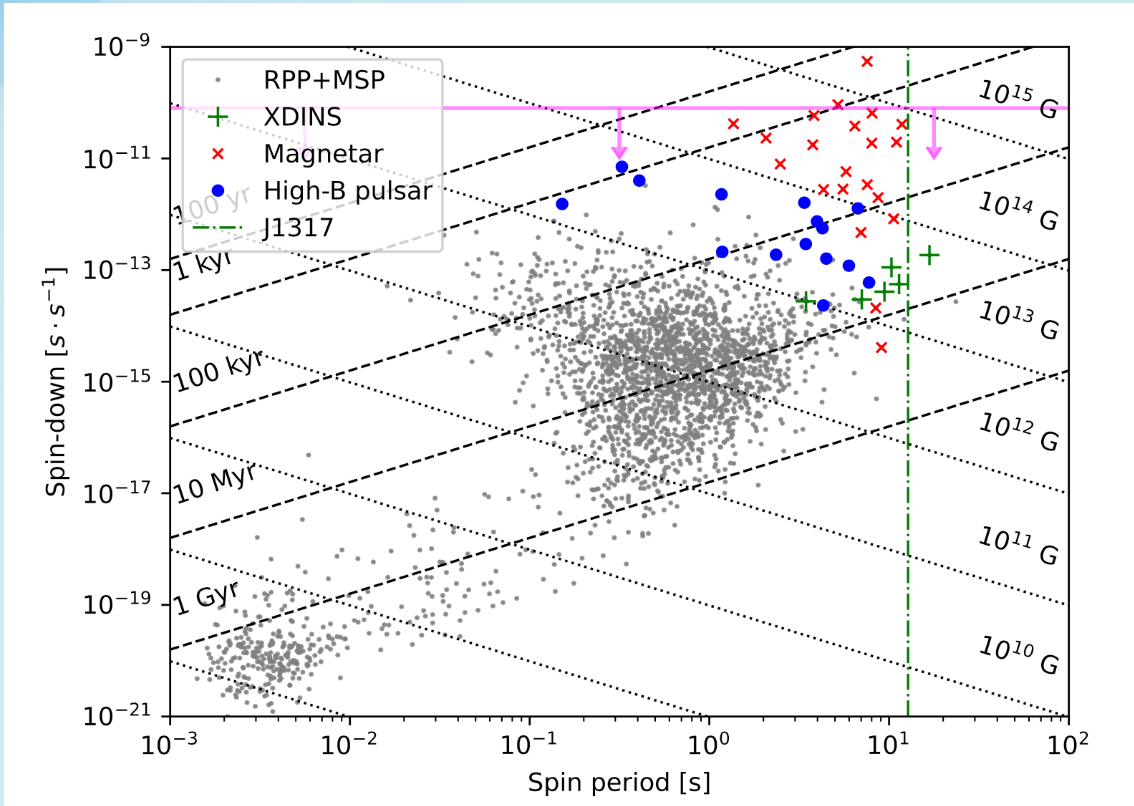
  - Optical counterpart m>27.5 —> $F_X/F_O > 10^4$
  - Absorption features: E_1~350 eV, E_2~590 eV —> B~10^{13}—10^{14} G





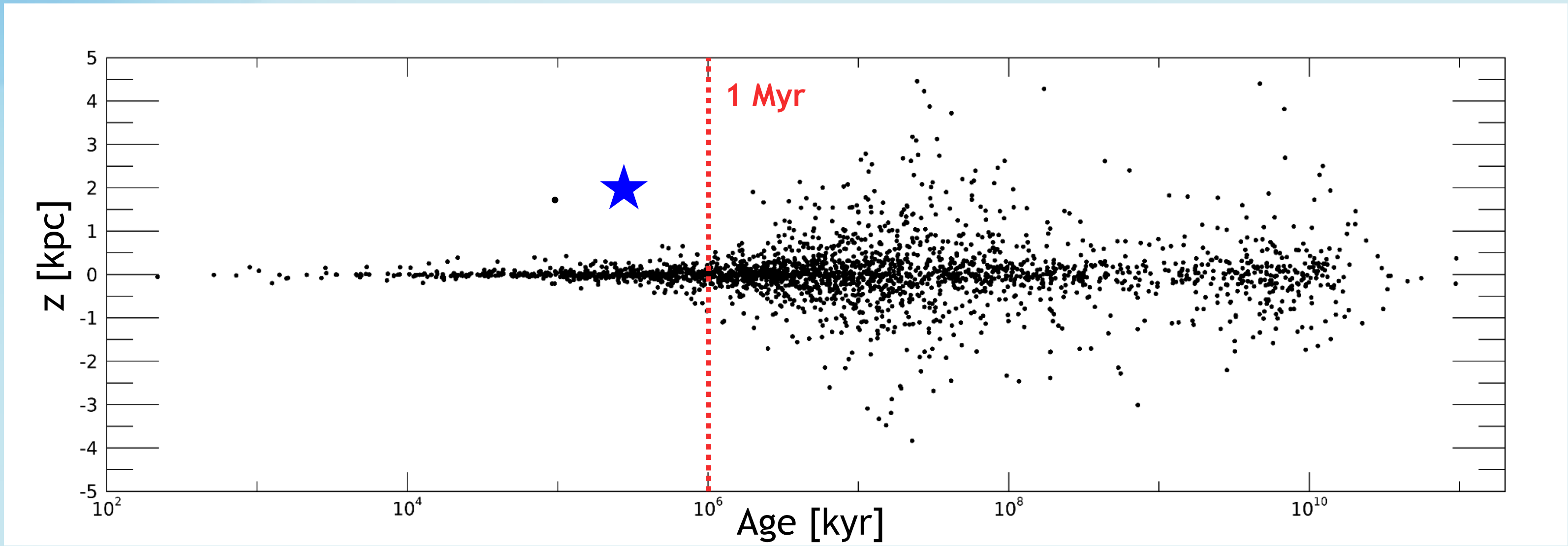
But many more results are coming! Stay tuned!

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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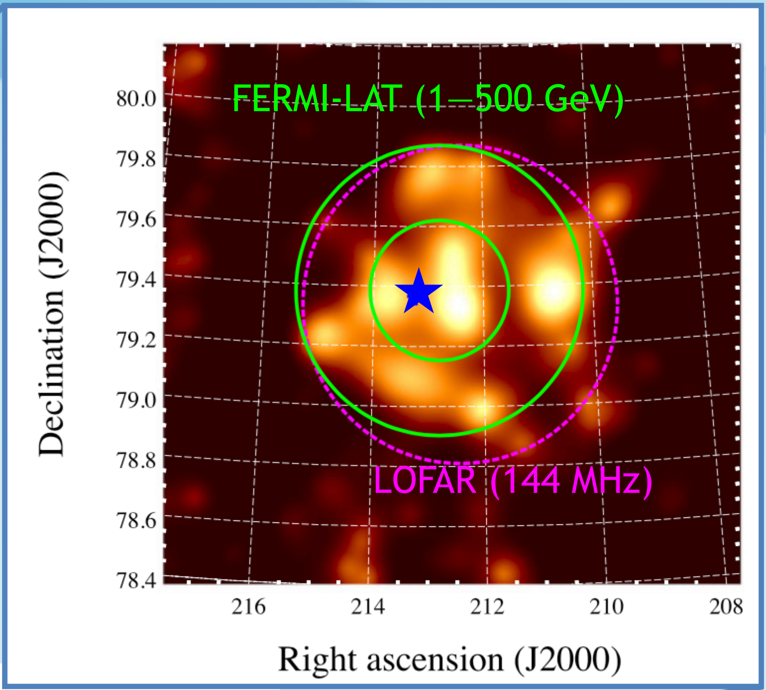
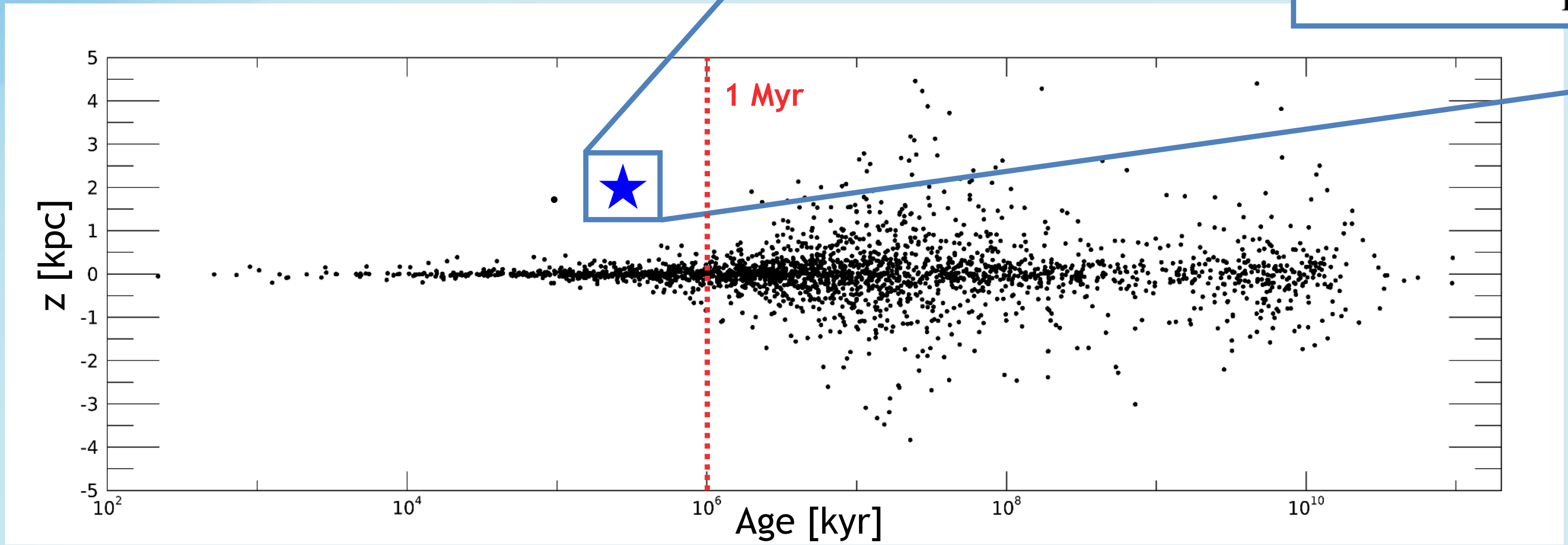
- SNR in radio, X-ray and gamma-ray —> younger
- First young RPP born in the Galactic halo





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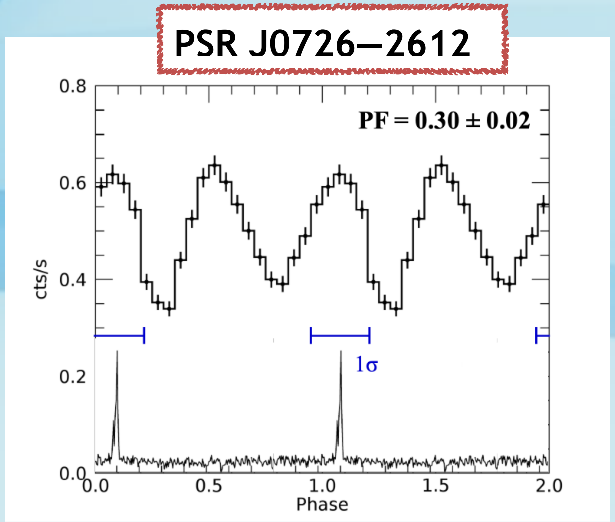
Link between XDINS and RPP



- PSR J0726−2612 has an X-ray spectrum 2BB + absorption line at 0.4 keV (= XDINS)
- It also has radio emission (≠ XDINS)
- Spectrum and pulse profile fit —> inferred geometry can explain this discrepancy

Burgay+ 2006, MNRAS
Hambaryan+ 2011, A&A
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Dessert+ 2020, ApJ
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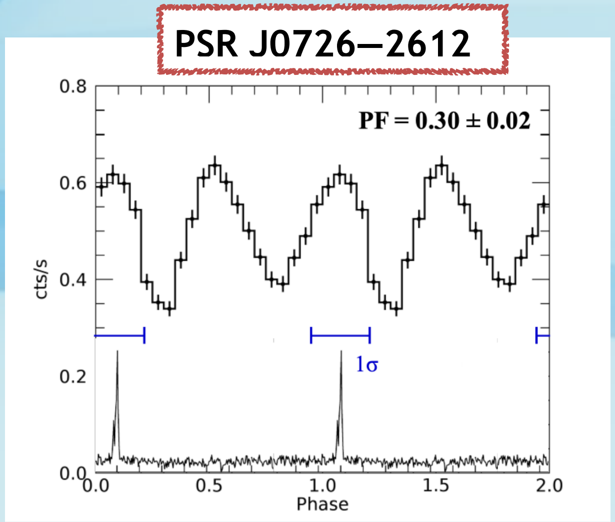
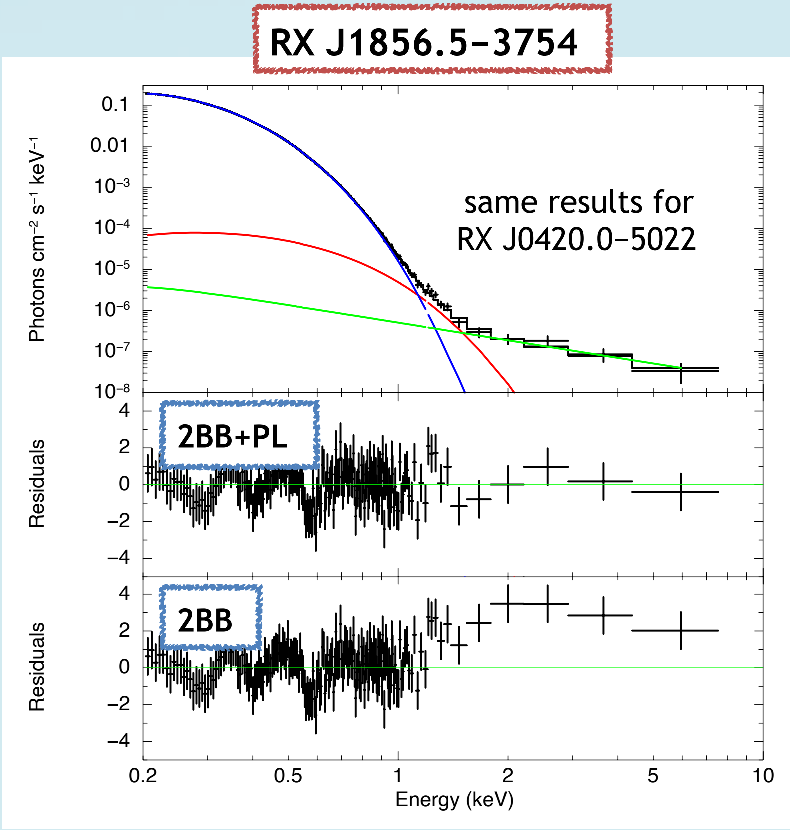


- Two out of seven XDINSs have also a non-thermal component
- Pulsed (magnetospheric origin?) and efficiency $L_{PL}/\dot{E}_{rot}$ ~ 10^{-3} (~RPP)
- Can we detect a similar component in the other XDINS? Expected $F_{PL}<10^{-16}$ erg/cm^2/s…



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Multipolar B of RPP

Growing evidences that all INSs (<u>not only magnetars</u>) have complicated (toroidal, multipolar, twisted…) crustal magnetic field:

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- 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)

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- Steep surface temperature distribution:
  high PF and kT2~2 x kT1
  (see e.g. Yakovlev 2021, Gotthelf+ 2021, MR+ 2022b)

More details on
Tue 09/07

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?

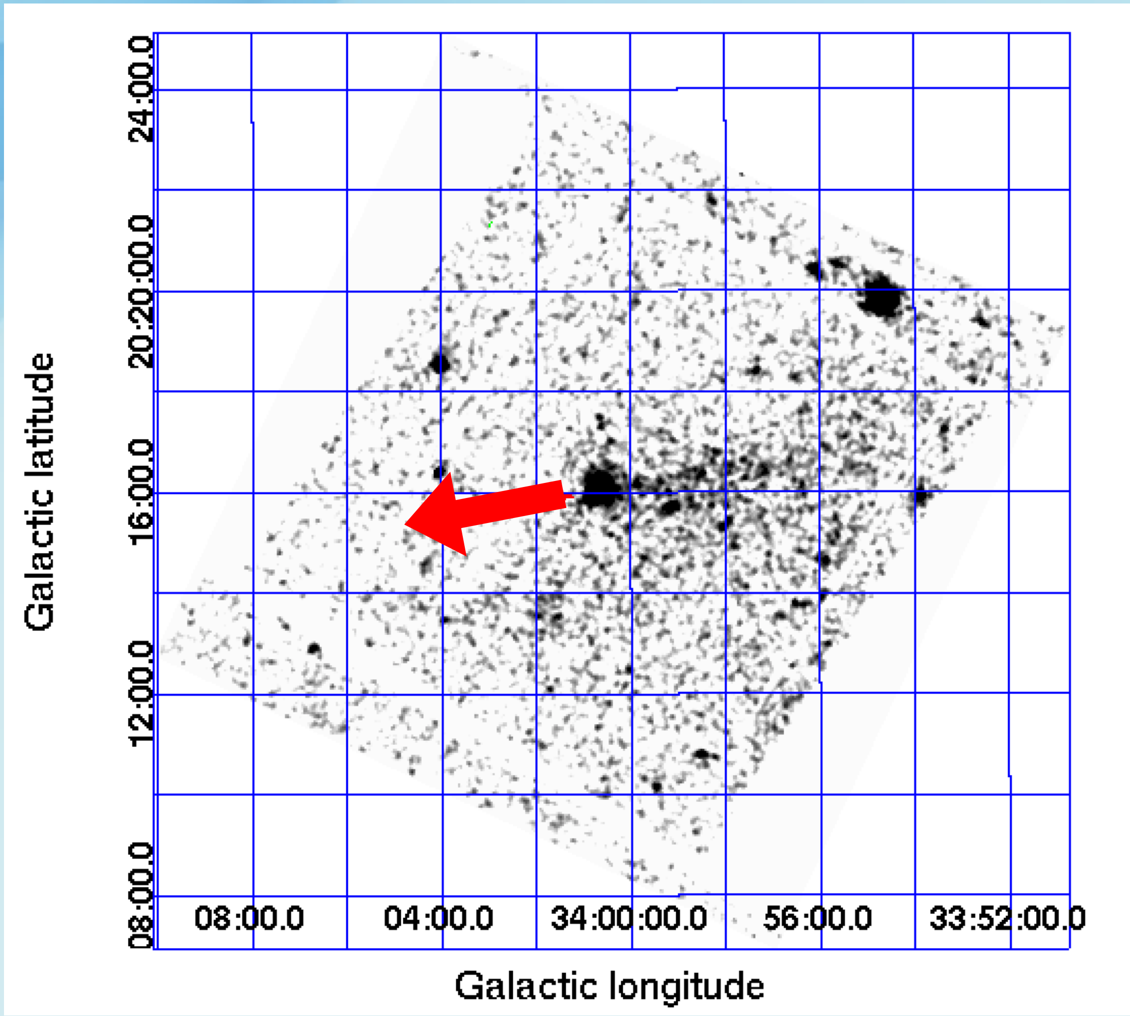
- Was born in the disk, travelled with v ~ 500 km/s and exploded as a SN in the halo (runaway massive star) → large PM
- Was born in the halo from a white dwarf (accretion-induced collapse) → small PM

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

Halpern & Gotthelf 2015, ApJ

PSR J1740+1000

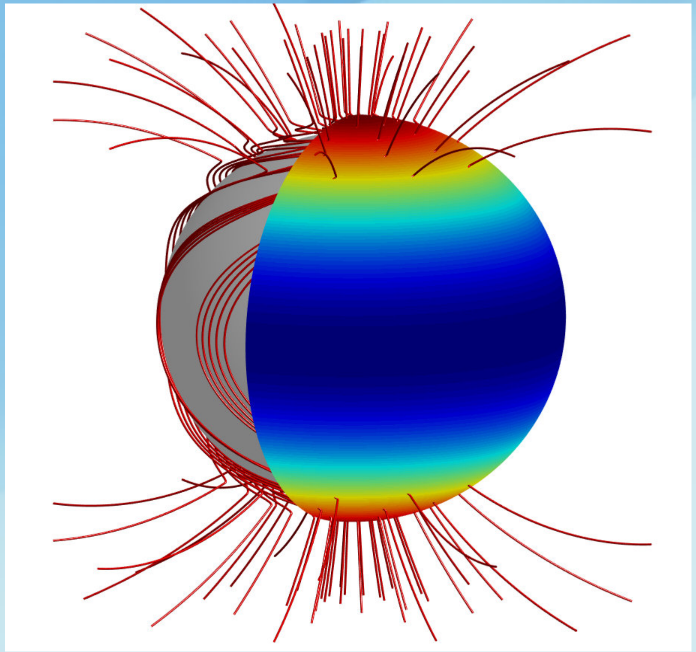
- Age~10^5 yr, b=20 deg
- Distance from DM: 1.2—1.4 kpc
- No proper motion detected:
  <60 mas/yr, i.e.
  <1.67 deg/10^5 yr
- Orientation of the tail implies angle of 7 deg towards the Galactic plane



Benbow+ 2021, ApJ
MR+ 2022b, MNRAS

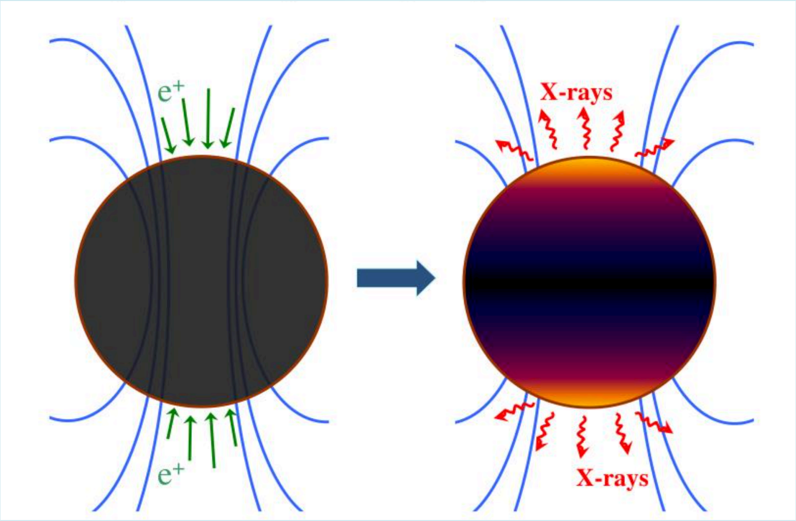
Thermal X-rays from INSs

INTERNAL HEATING



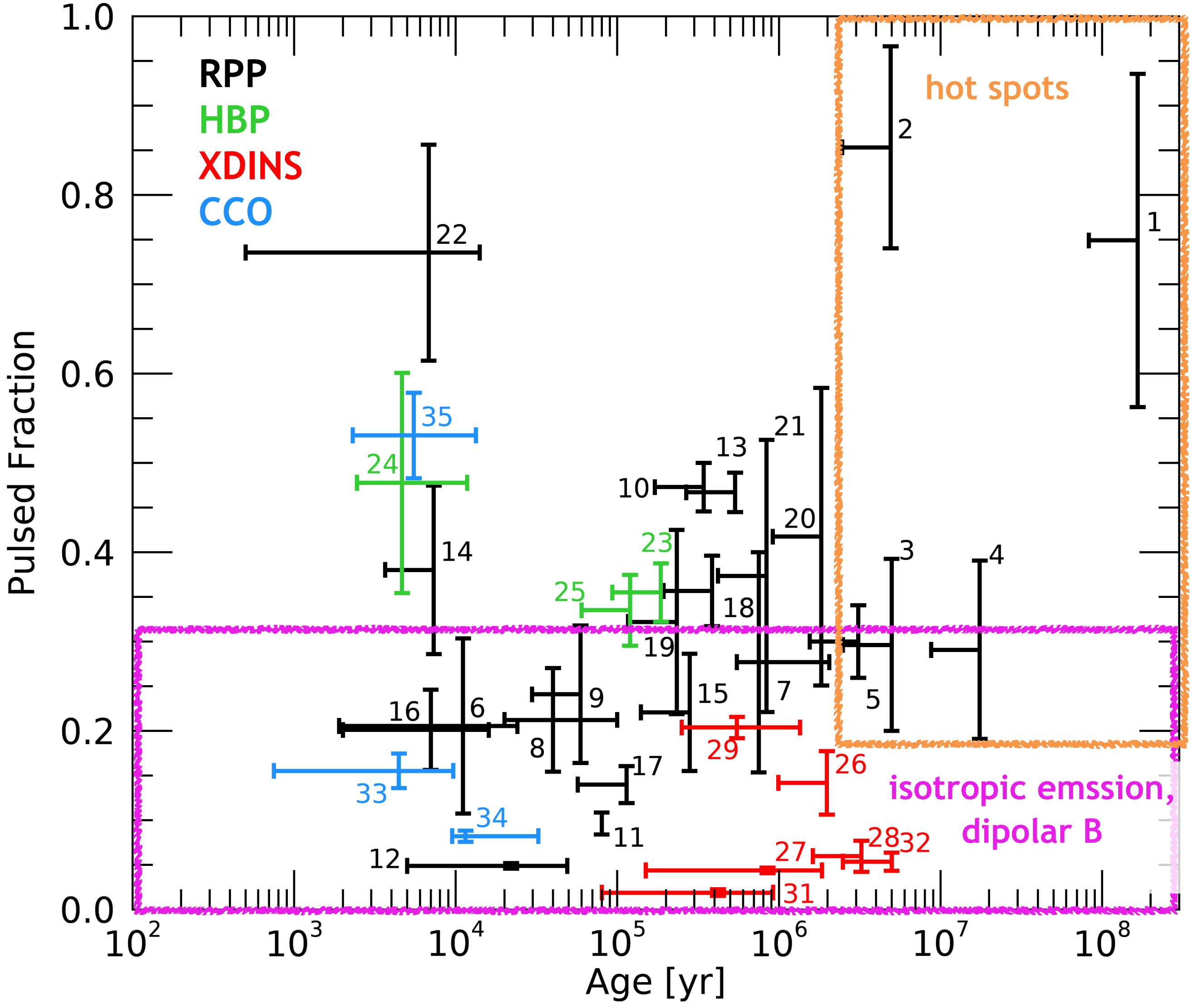
emitting radius ~ R_{NS}
moderately pulsed

EXTERNAL HEATING



emitting radius ~ R_{PC}
strongly pulsed

Multipolar B



MR+ 2022b, MNRAS

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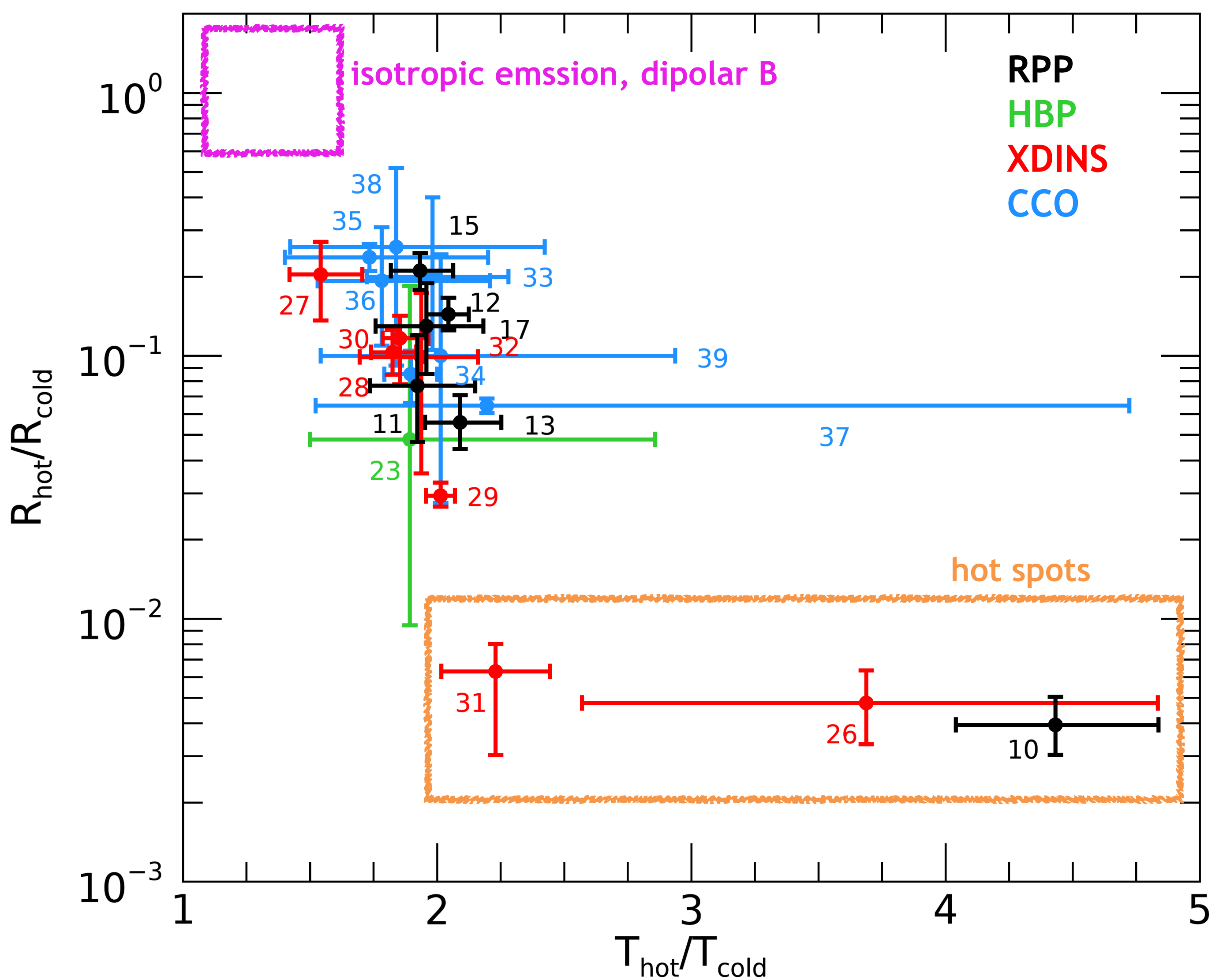

MR+ 2022b, MNRAS