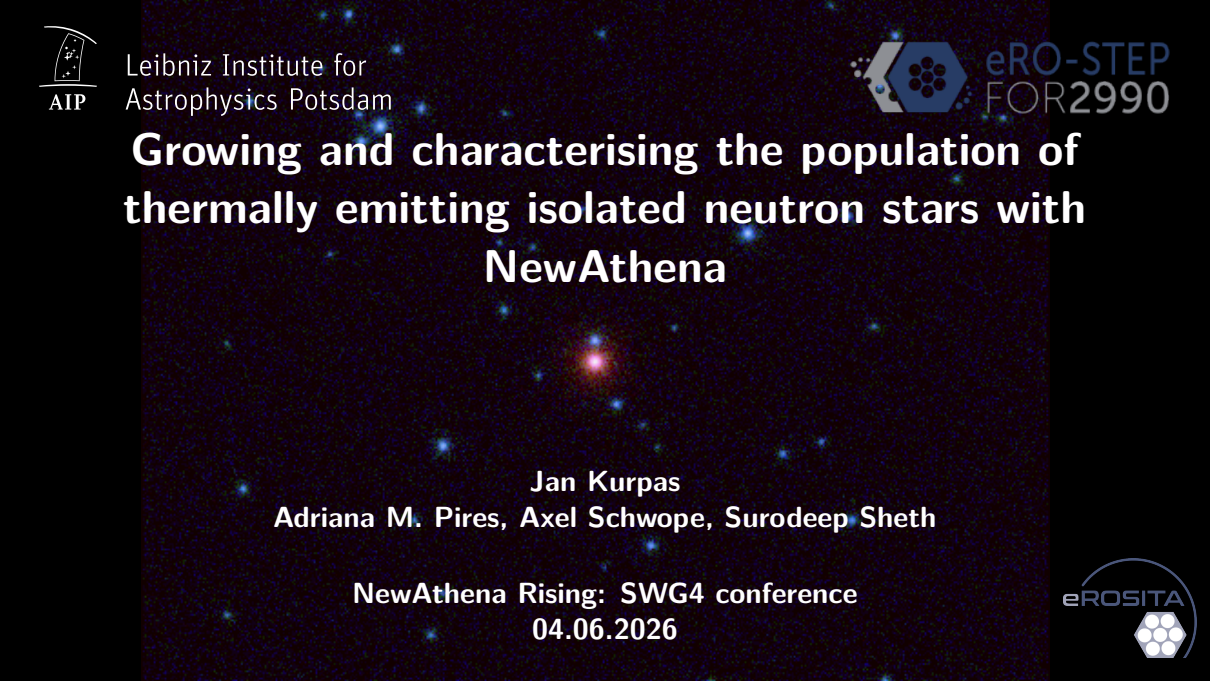


Leibniz Institute for Astrophysics Potsdam

eRO-STEP FOR2990

Growing and characterising the population of thermally emitting isolated neutron stars with NewAthena

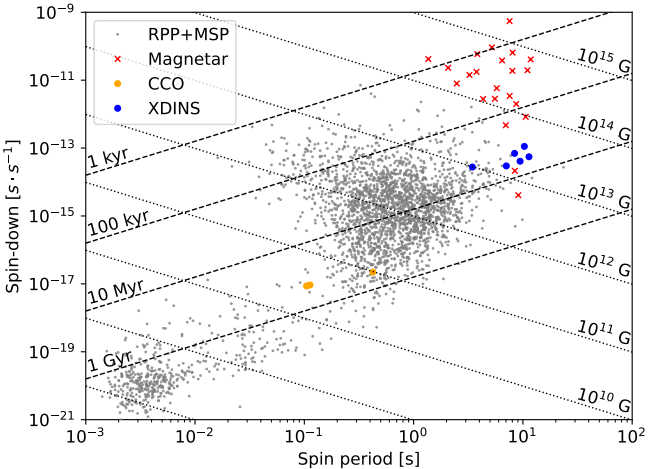
Jan Kurpas
Adriana M. Pires, Axel Schwope, Surodeep Sheth

NewAthena Rising: SWG4 conference
04.06.2026

eROSITA

The known isolated neutron star population

$>$ 4000 isolated neutron stars (INSs) in the ATNF database



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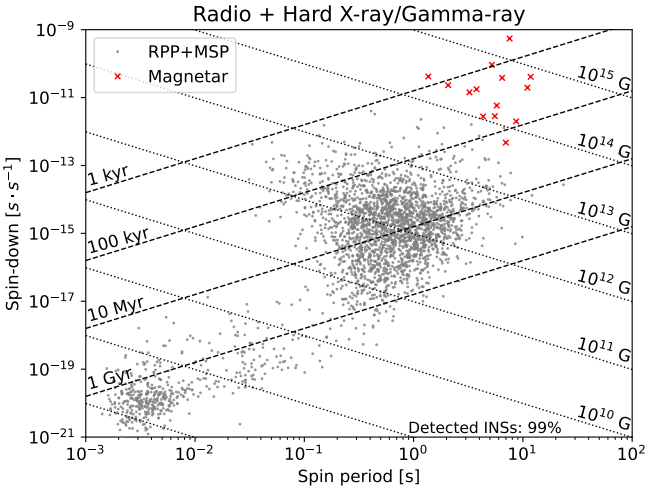

Most INSs discovered in wide-area radio and gamma-ray surveys

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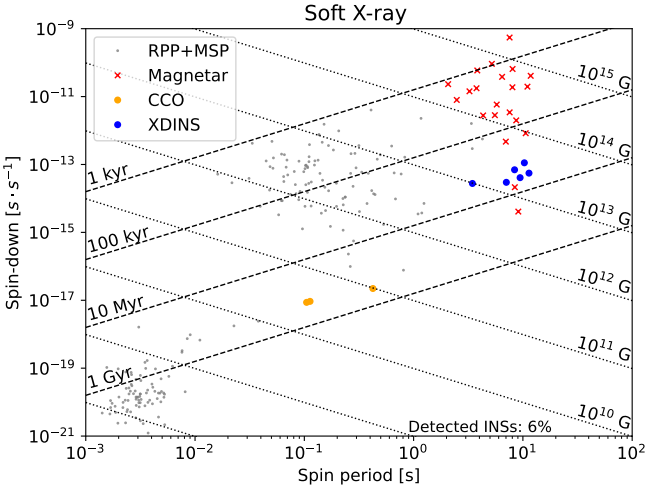

Most INSs discovered in wide-area radio and gamma-ray surveys

Full phenomenology unfolds at soft X-rays

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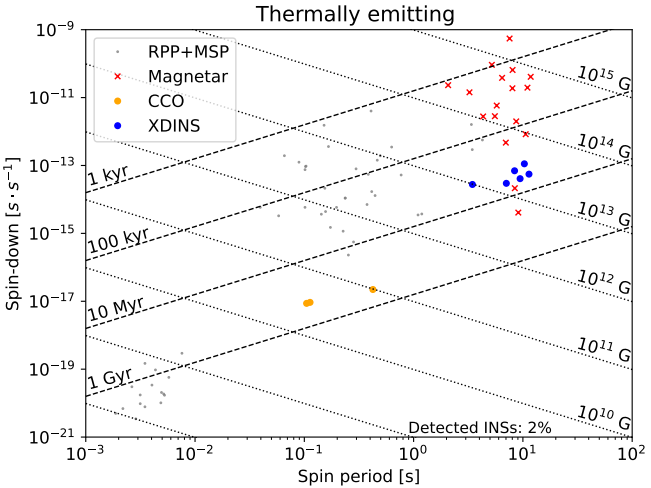
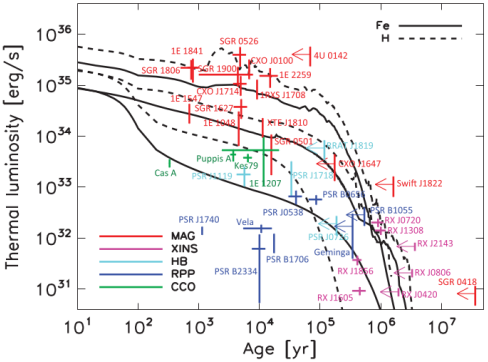


Most INSs discovered in wide-area radio and gamma-ray surveys

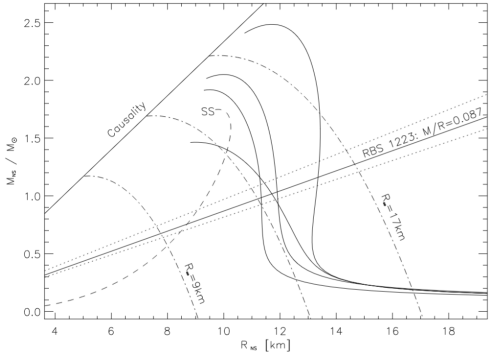
Full phenomenology unfolds at soft X-rays

Only few thermally emitting INSs known

What can be learned from thermally emitting INSs?
Intrinsic properties



Viganò, et al., 2013, MNRAS, 434, 123.

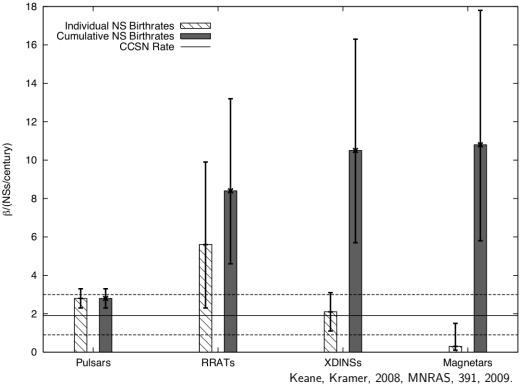


Hambaryan, et al., 2011, A&A, 534, A74.

Direct view on cooling INS surface
- Surface structures/properties
- Absorption features

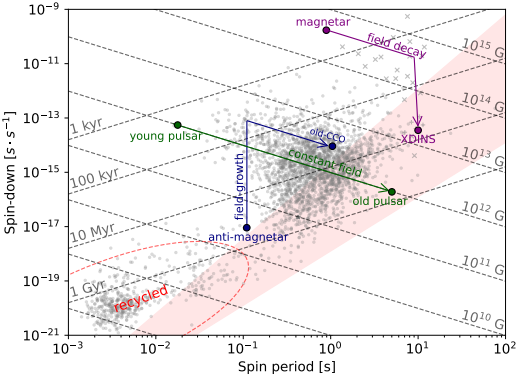
Equation of State constraints
- Cooling evolution
- Pulse/Spectral modeling

What can be learned from thermally emitting INSs?
Population properties



Keane, Kramer, 2008, MNRAS, 391, 2009.

Thermal INSs underrepresented in current population?



Constrain magneto-thermal evolution
- Evolutionary connections?

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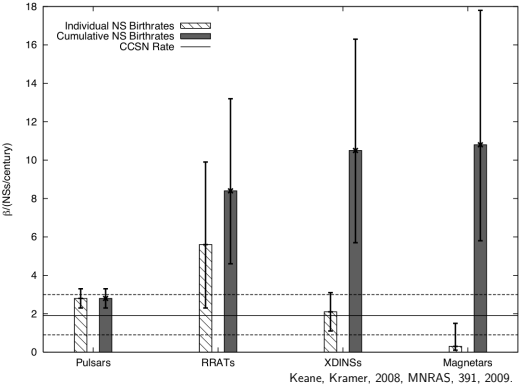

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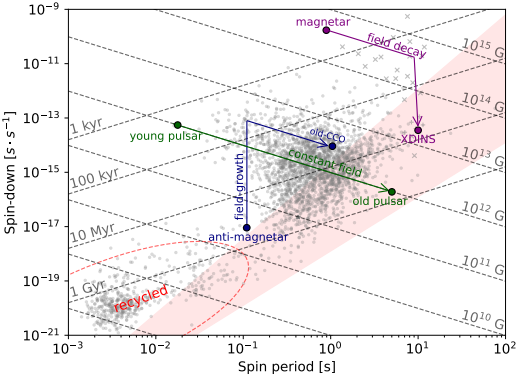

Thermal INSs underrepresented in current population?

Constrain magneto-thermal evolution
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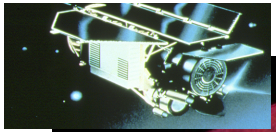
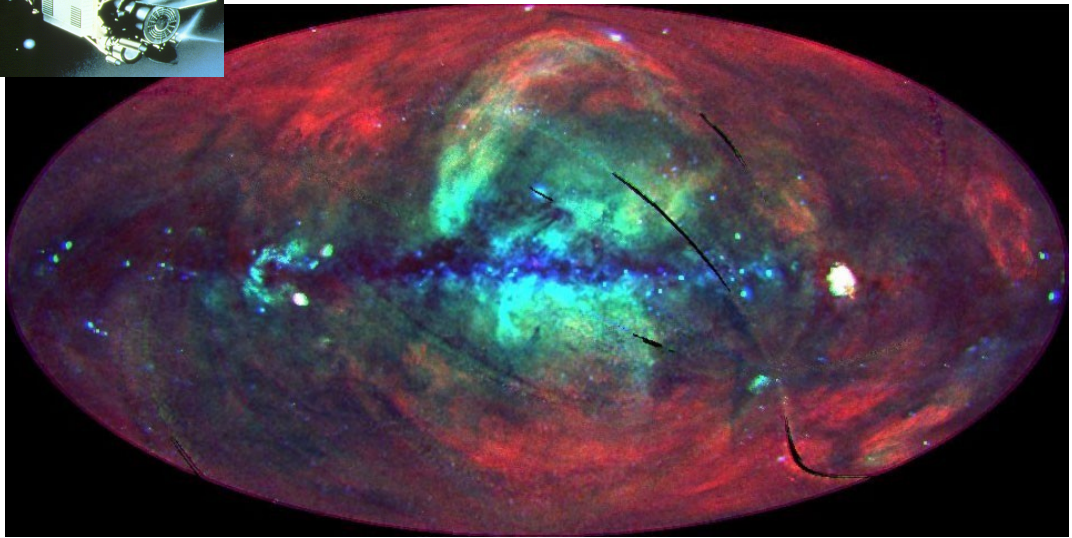
The population must be increased!

The ROSAT All-Sky Survey





MPE

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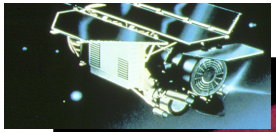
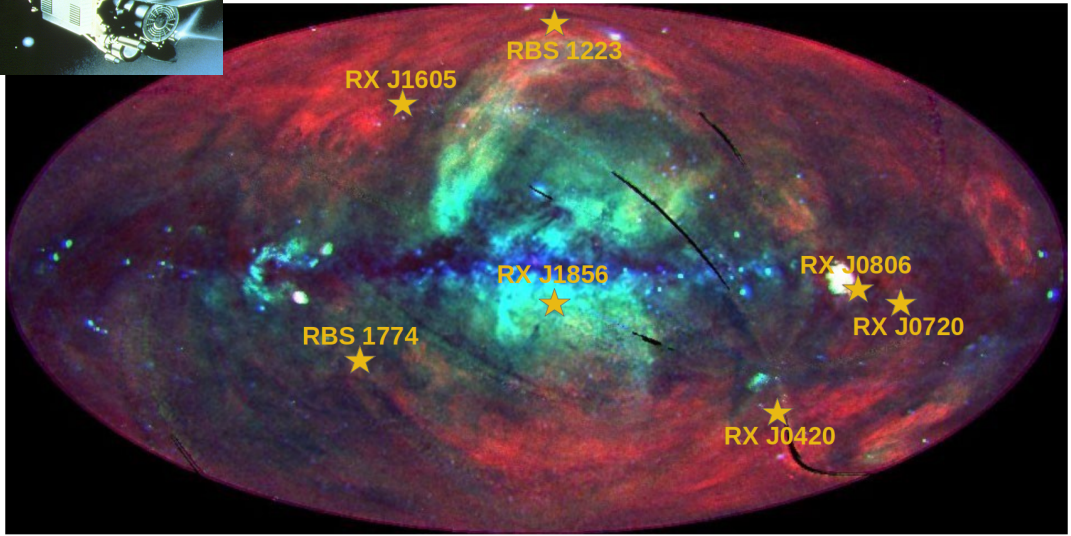




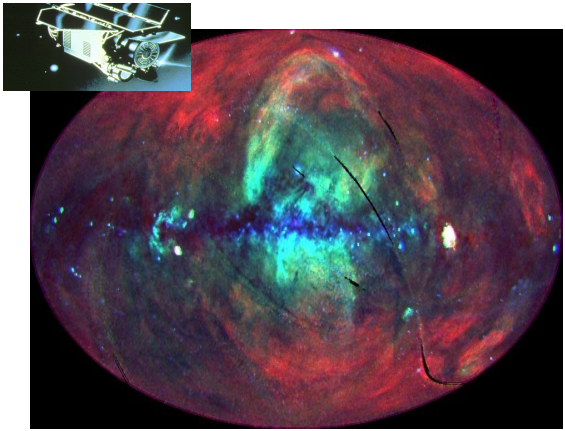
MPE

The quest for additional members

More INSs hiding in ROSAT?

The search is ongoing:
- SWIFT+ROSAT (Rutledge+08): Calvera
- SDSS+ROSAT (Demasi+24): 55 unconfirmed INS candidates

Biggest obstacle:
- Significant source confusion!
- Spectra not well constrained
- Rather shallow; complete up to $\sim 10^{-12}$ erg s^{-1} cm^{-2} (0.2-2 keV)



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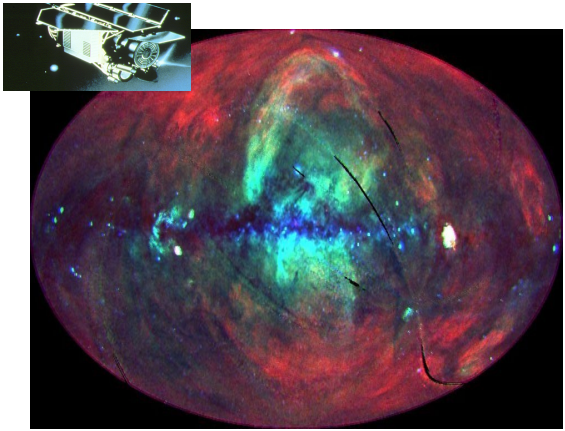
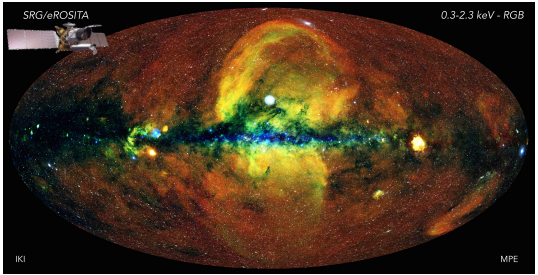


MPE

Need deeper X-ray surveys with "good" positional and spectral accuracy!

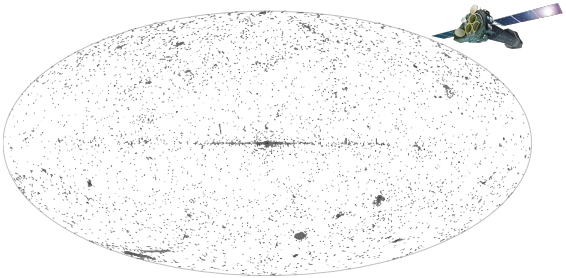
Soft X-ray source catalogues and surveys

SRG/eROSITA All-Sky Survey (eRASS)



4 – 5 all-sky surveys
- Half the sky, short observations, good astrometry for survey mission
- $F_X \gtrsim 10^{-13}$ erg s^{-1} cm^{-2} (0.2 – 2 keV)

XMM-Newton source catalogues



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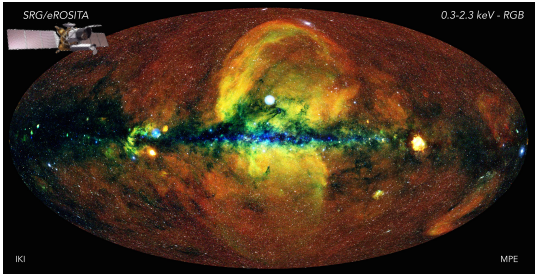

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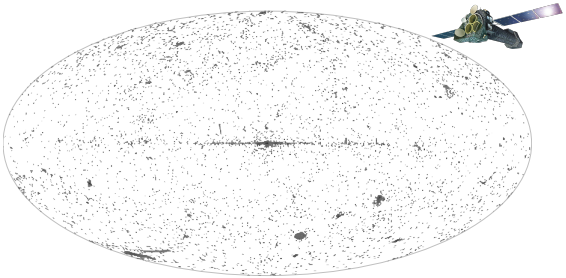

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Build "complete" INS populations

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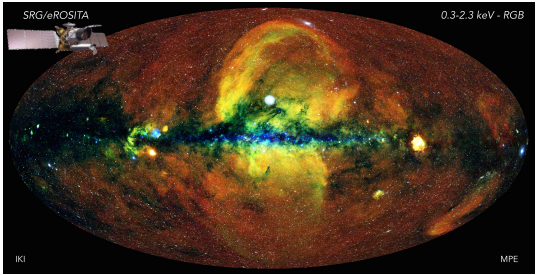

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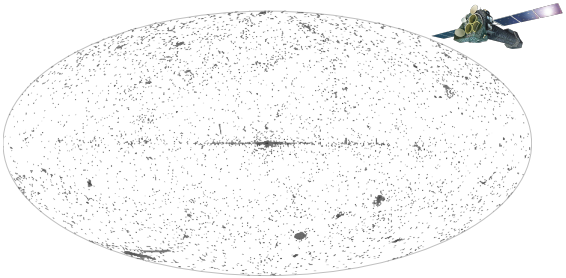

$\sim$ 14000 pointed observations
- "Limited" sky coverage, longer observations, good astrometry
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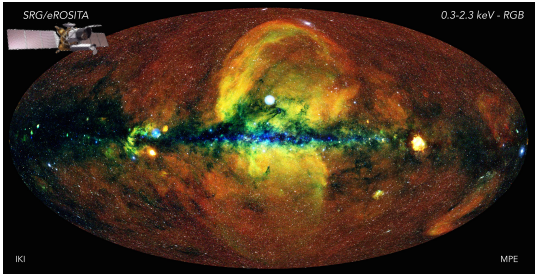

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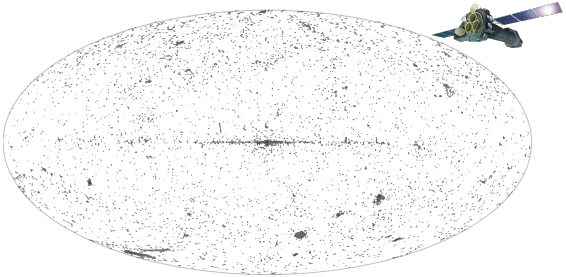

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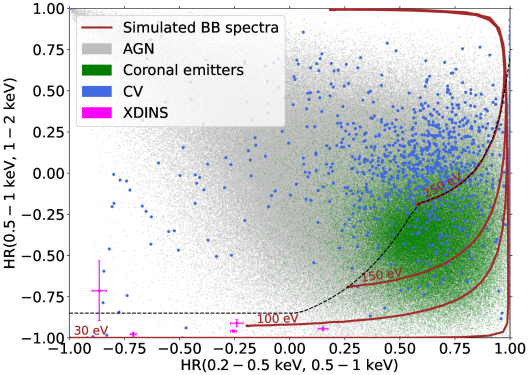
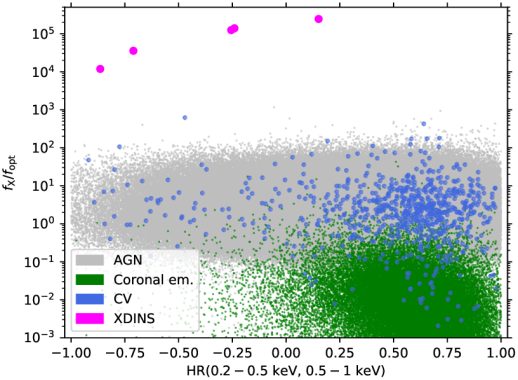
Probe remote INS population

Selecting the needle in the haystack





Soft and steady blackbody-like X-ray emission
→Cut in HR space

(XD)INSs possess $f_X/f_{\rm opt} \gtrsim 10^4$
→ Keep sources without optical/IR counterparts

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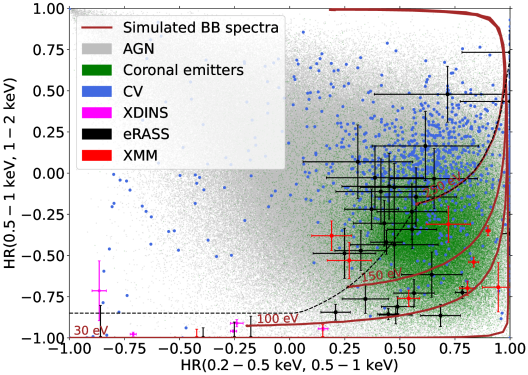

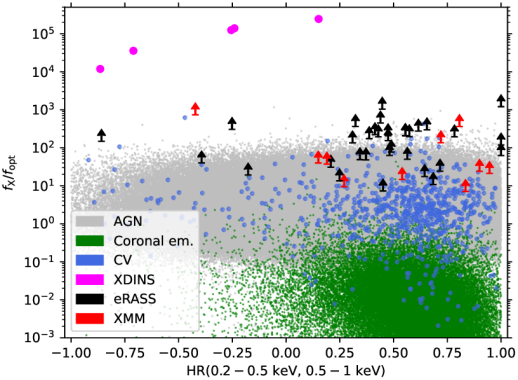

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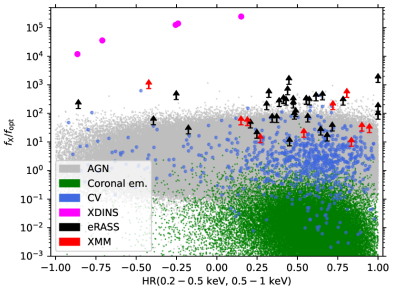
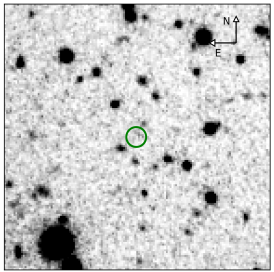
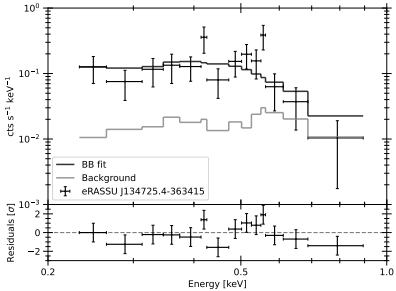
33 (eRASS) + 10 (XMM) candidates were selected!

Limits of the selection I

Archival X-ray and optical data not sufficient to confirm INS nature







Additional follow-up required:

- Optical: $f_{\rm X}/f_{\rm opt}$
- X-ray: position, spectrum, pulsations

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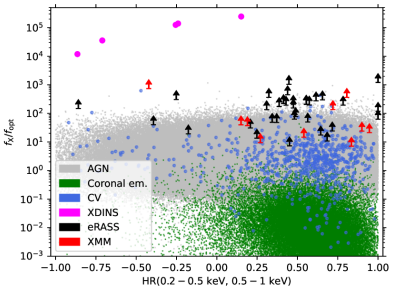

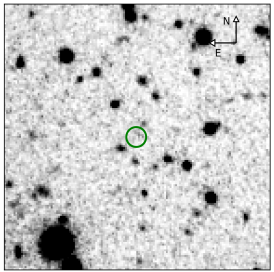

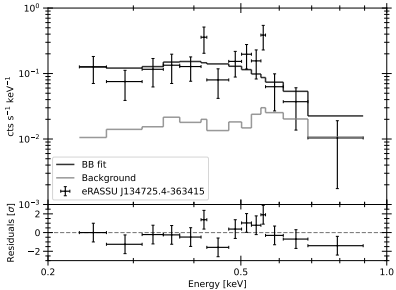

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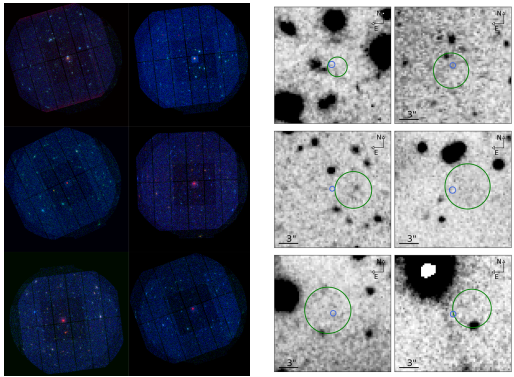
Observing programmes (X-ray $\sim$ 1.5 Ms, Optical $\sim$ 42 hr):

- CXO snapshot survey
- XMM/VLT large program

State of the follow-up programme

eRASS:

- 6 sources well characterised
- $kT \sim 50 - 100$ eV
- Absorption features in four sources:
  $B \sim 10^{13} - 10^{14}$ G



Kurpas, et al., 2026, A&A, 705, A148.

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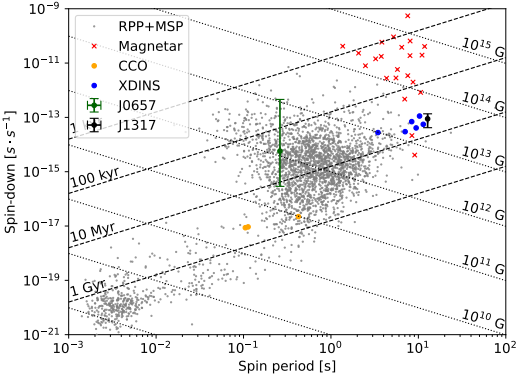

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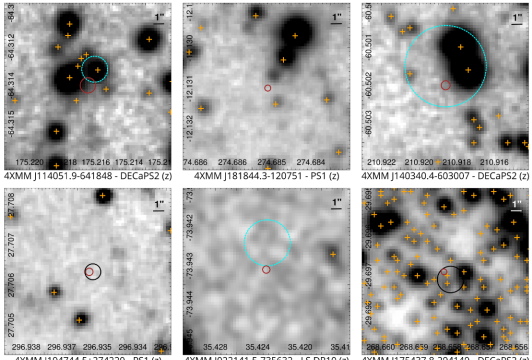

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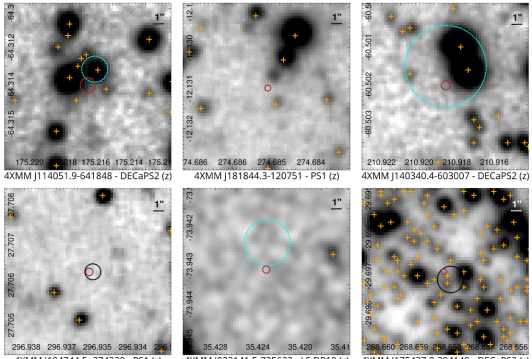
Rare INS classes grow in number!



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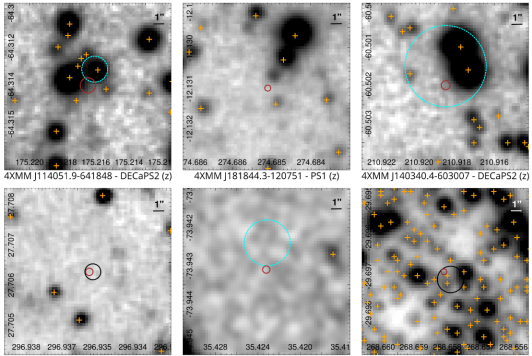
Rare INS classes grow in number!
Requires long observations ...



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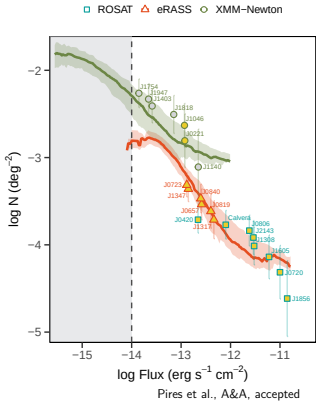
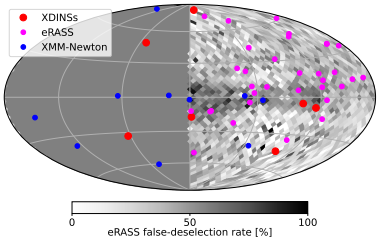
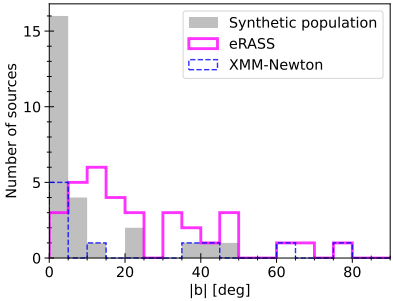
Limits of the selection II



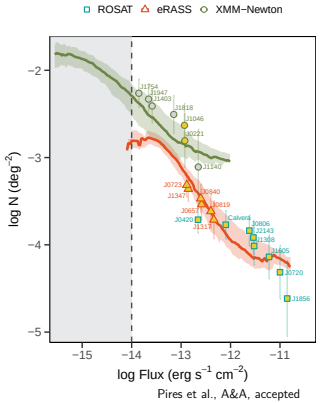


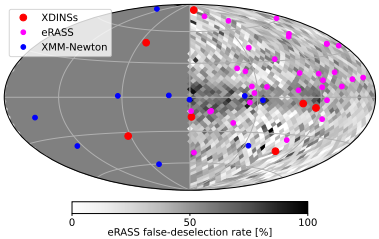


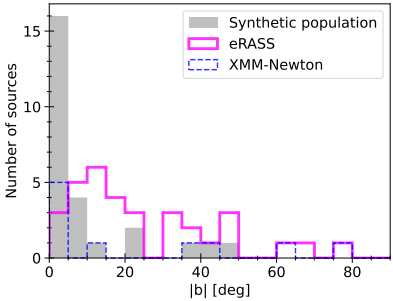
Population synthesis (following Pires+17):
- Fixed cooling rate
- Isotropic emission
- Birthrate $\sim$ 2 INSs/century

Results:
- $\log N - \log S$ follows observed population
- Most INSs below flux limits
- eRASS sources missing in the plane

Limits of the selection II







INS identification challenges:

- Expand search to lower fluxes
- Deal with eROSITA source confusion
- Expansive follow-up required to establish INS nature

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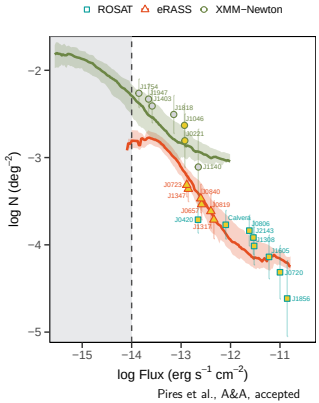

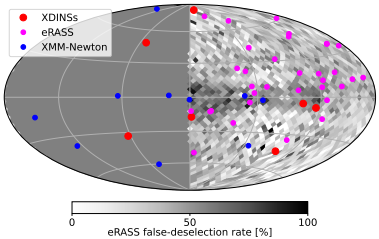

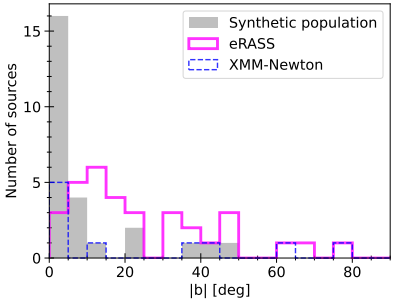

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Need a next generation X-ray observatory!

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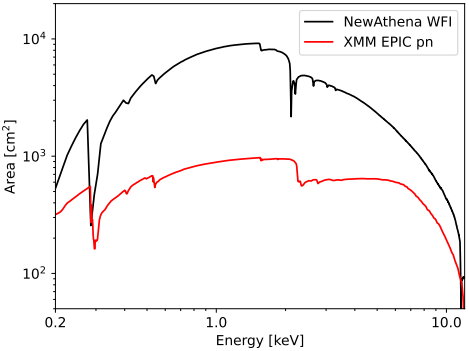
Simulating NewAthena's impact on INS characterisation

NewAthena promises much better constraints on INS parameters

Conducted XSPEC simulations
- WFI LDA: FF mode with filter
- XMM EPIC pn: FF mode with THIN filter

Distinguish two cases:
- J1347: Faintest confirmed INS from eRASS
- J1754: Faintest high-likelihood candidate from XMM



Source	N_H [10^{20} cm^{-2}]	kT [eV]	Flux (0.2–12 keV) [10^{-14} erg s^{-1} cm^{-2}]
J1347	2.2	78	13
J1754	36	110	1.5

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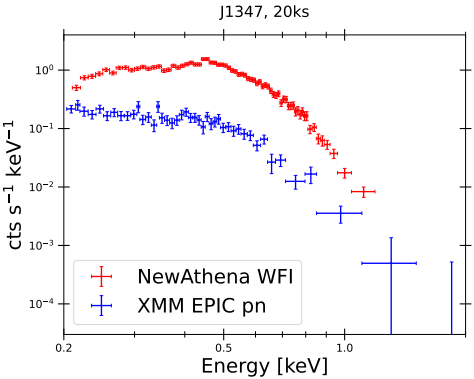

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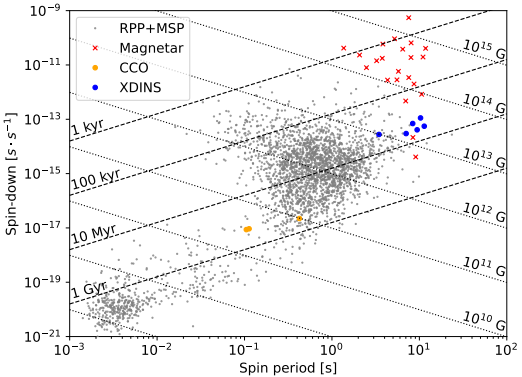
Searching for a pulse

Timing properties crucial to constrain INS nature

Estimated expected pulsed-fraction limits for broad searches
- Sinusoidal pulsation
- 3σ detection significance



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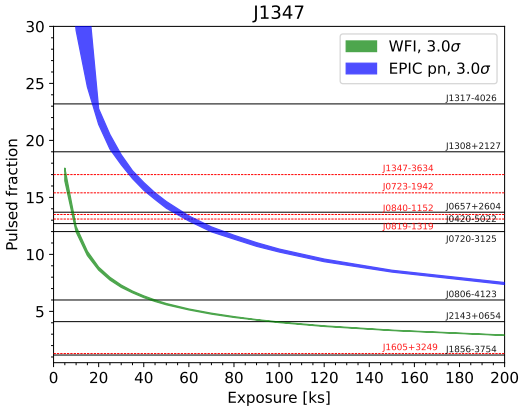

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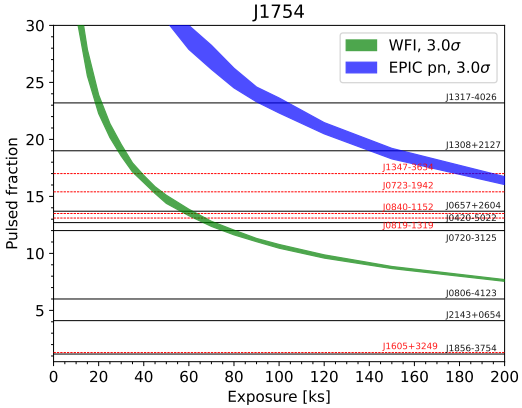
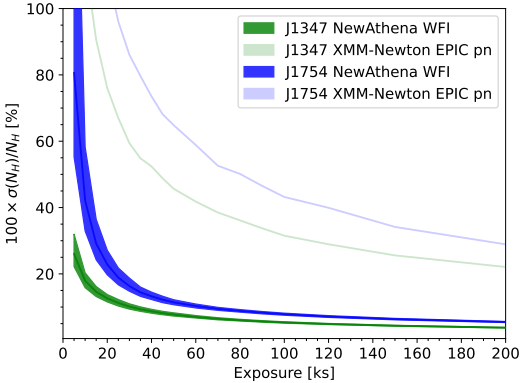


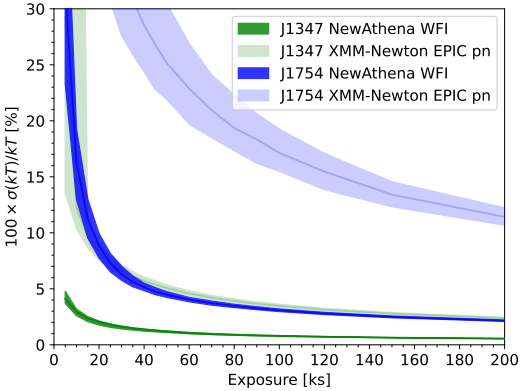
Probing spectral properties - The continuum

N_{H} constraints



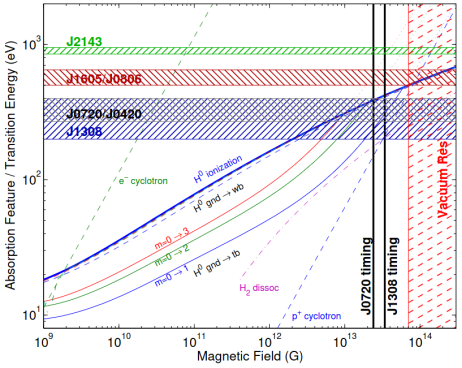
N_{H} and kT both important to measure thermal luminosities

Constraining kT

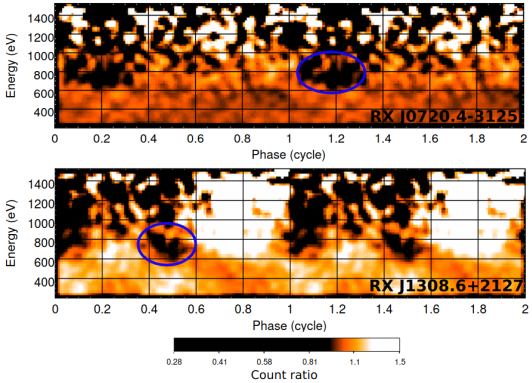


Improvement in respect to XMM
Short exposures measure kT well already

Probing spectral properties - Spectral features



van Kerkwijk, Kaplan, 2007, Ap&SS, 308, 191.



Borghese, et al., 2017, JPhCS, 932, 012007.

Allow to probe:

- B-field
- Surface composition
- INS compactness (M/R)

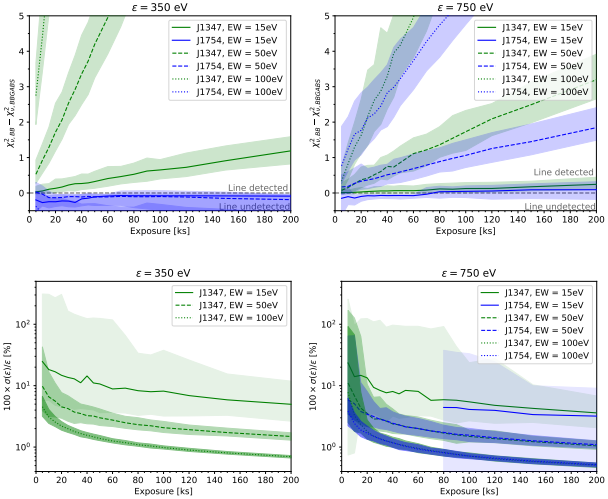
Features detected in many INSs

- Energy range: 200 eV $\lesssim \epsilon \lesssim$ 1000 eV
- EW range: $EW \gtrsim$ 15 eV

Probing spectral properties - Spectral features

Simulated Gaussian lines with
- $\epsilon = 350$ eV, 750 eV
- $EW = 15$ eV, 50 eV, 100 eV
- $\sigma = 40$ eV

- ISM absorption prevents 350 eV line detection for J1754
- Broad features overall well recovered
- Narrow features need long exposures



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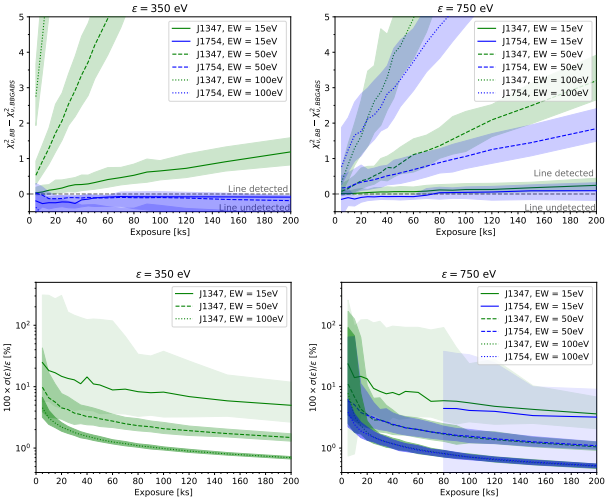
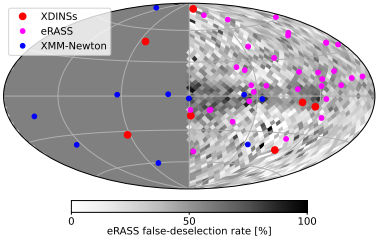


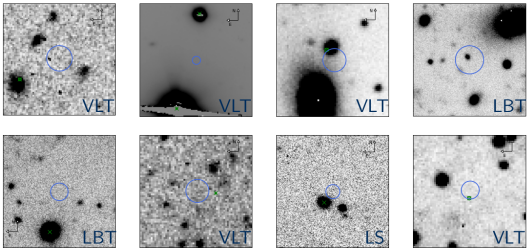
NewAthena will enable much more detailed studies!

Conducting a snapshot survey

Difficult to select INSs at faint fluxes/ in crowded regions
- Follow-up to deselect contaminants

CXO snapshot survey:
- Better positions
- 15 – 30 ks per source





Kurpas, et al., in prep.

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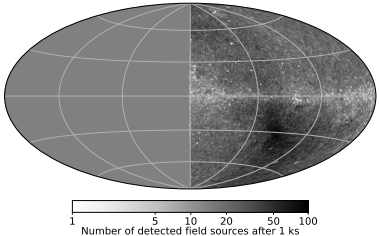
NewAthena snapshot survey:
- sub-arcsecond positional accuracy
- $40' \times 40'$ FoV benefits field source detection
- All eRASS INSs detected after 1 – 3 ks



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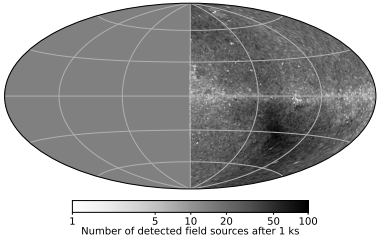
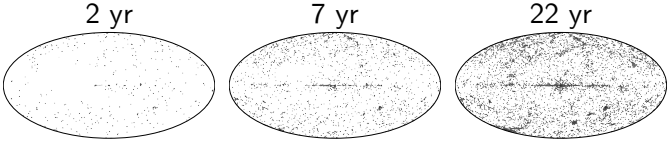
Much faster source characterisation!



Quantifying serendipitous discovery chances!

Assume NewAthena will follow XMM footprint



INSs below 10^{-14} cgs

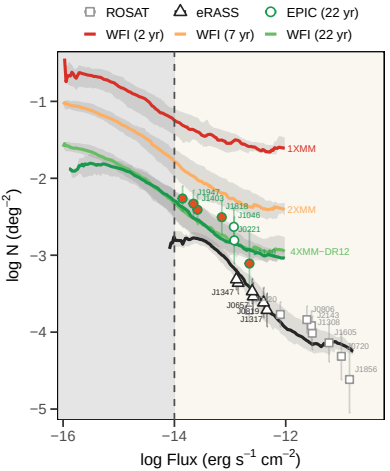
	4XMM-DR12	WFI (2 yr)	WFI (7 yr)	WFI (22 yr)
$N_{\rm XDINS}$	13^{+6}_{-4}	10^{+2}_{-4}	28^{+4}_{-5}	29^{+5}_{-5}
F_X [10^{-15} cgs]	$2.3^{+1.1}_{-0.7}$	$1.1^{+1.4}_{-0.3}$	$0.9^{+0.3}_{-0.2}$	$0.9^{+0.3}_{-0.2}$

Pires, et al., A&A, accepted

2 yr of NewAthena comparable to unprobed XMM population (70% of all INSs)

INSs discovery space stable after 5 – 7 yrs

NewAthena reaches deeper than XMM



Pires, et al., 2017, AN, 338, 213.; A&A, accepted

Conclusions

Thermally emitting INS offer unique insights into neutron star properties and evolution

New INSs are discovered from XMM-Newton/eRASS footprints
- 43 candidates selected so far (Rigoselli+22, Kurpas+24, Pires+26)
- Most INSs hiding at flux limits not probed by current searches
- Long follow-up campaigns required to characterise candidates

NewAthena will much improve INS searches and population-level characterisation
- WFI: Large field of view, very good spectral and timing accuracy
- Pushes INSs studies by an order of magnitude to lower fluxes
- Serendipitous discoveries possible