Isolated neutron stars with eROSITA

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Outline

1. Isolated neutron stars in the Milky Way
2. Early results of SRG/eROSITA
   - Deep pointing observations of the *magnificent seven*
   - The all-sky survey: blind searches and promising candidates
3. Follow-up and synergy
   - XMM2ATHENA: 4XMM J022141.5-735632
   - Continuous gravitational waves from Einstein@Home
4. Outlook

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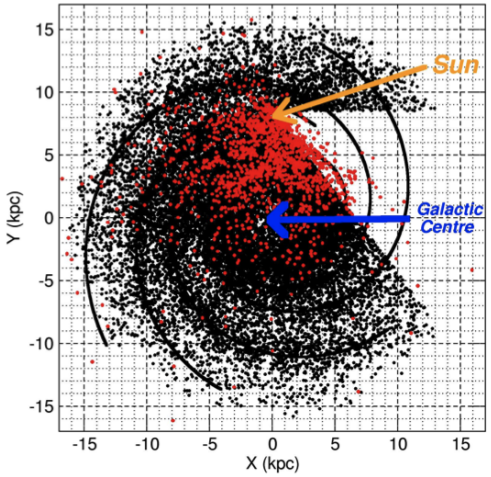

How many neutron stars in the Milky Way?

Today: over 3300 catalogued

(radio; over 310 new FAST additions)

Fermi Pulsar Revolution:

(over 200 LAT detections)

SKA: potentially detect all pulsars beamed towards Earth

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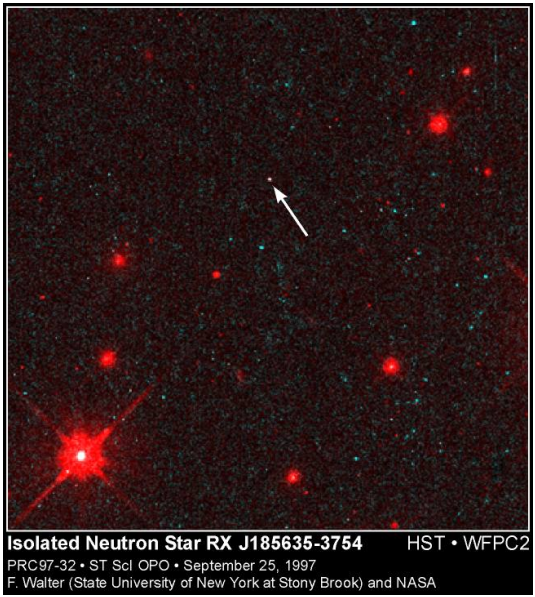

1 : 1000
active pulsar/radio-quiet INS

ROSAT expectations

Detect the slowly moving, old, isolated ISM accretors

- $\gtrsim 10^3$ predicted
- 7 discovered; *"magnificent"*
- no accretors . . . but coolers

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- a legacy of ROSAT
- X-ray bright, soft, purely thermal
- nearby, low absorbed (within 0.5–1 kpc)
- faint optical/UV counterparts
- no accretion, no (?) hard tails, “constant”

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Relevance

- Distance, luminosity, age, undisturbed emission from the stellar surface
- Cooling theory and atmosphere $\rightarrow$ equation of state

M7 as evolved (“waning”) magnetars? $\longrightarrow$ Population and birthrate

- long P, high $L_X/\dot{E}$, high B-field
- Evolution through B-field decay: “normal” pulsars do not tell the whole story

  Viganò, Rea, Pons, Borghese $\longrightarrow$ the Neutron Star Zoo

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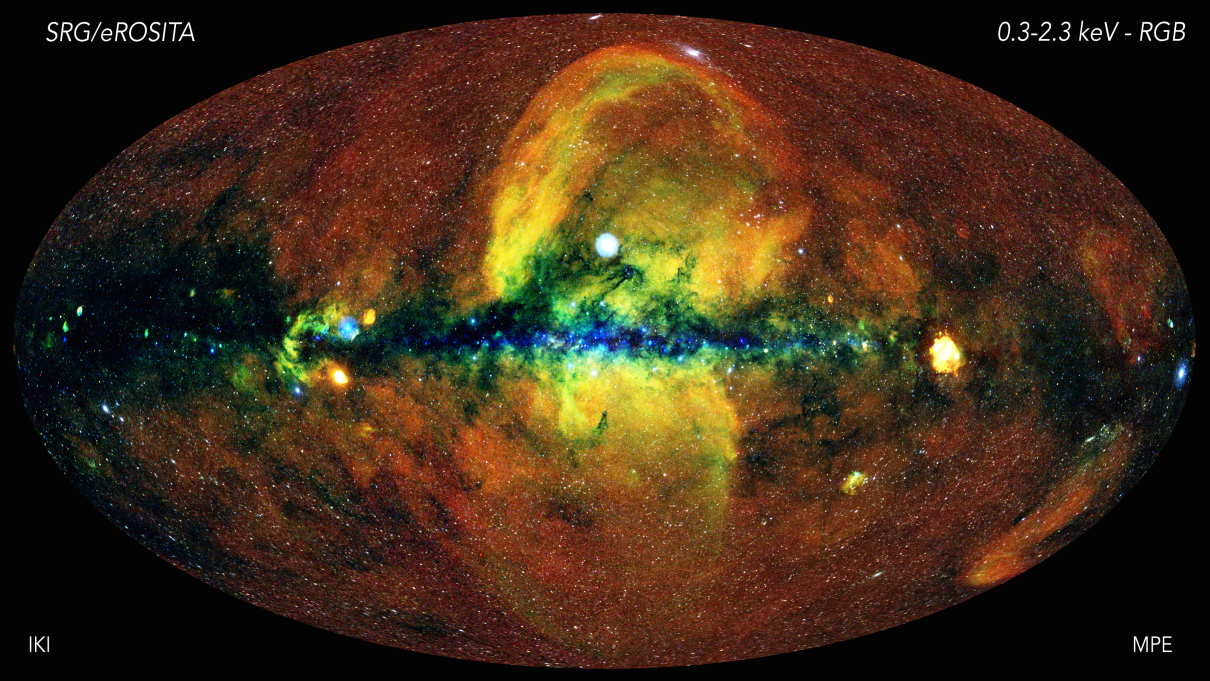
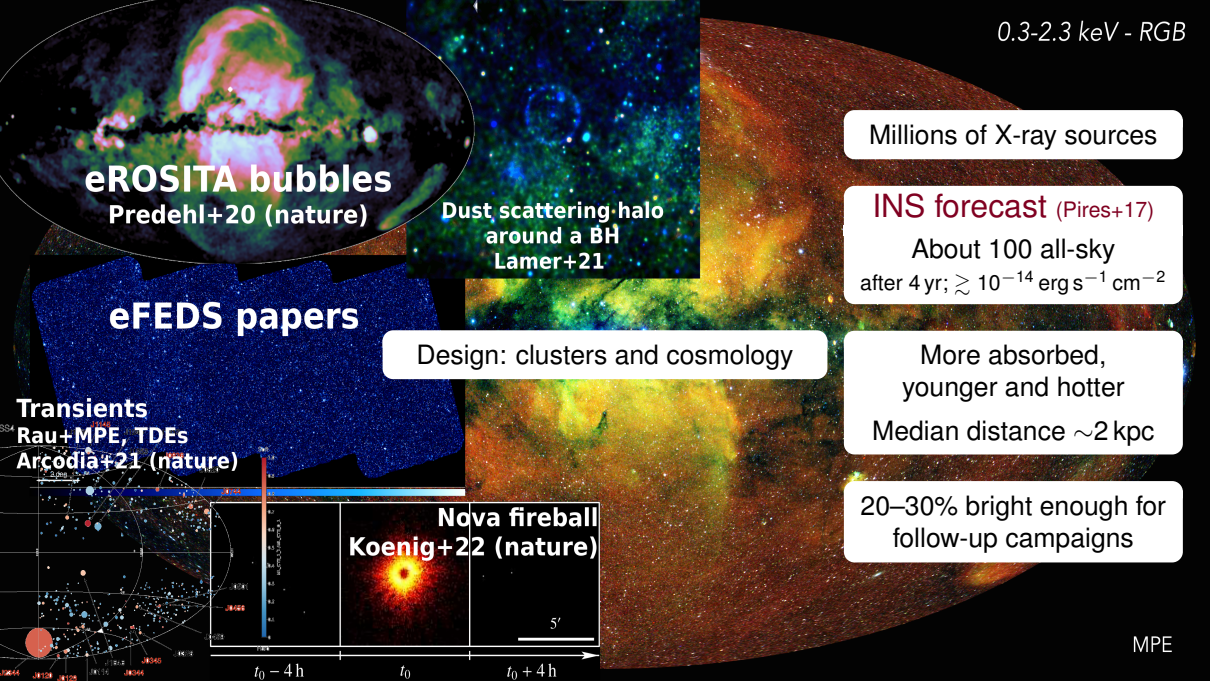

SRG/eROSITA
0.3-2.3 keV - RGB
IKI
MPE


0.3-2.3 keV - RGB
eROSITA bubbles
Predehl+20 (nature)
Dust scattering halo
around a BH
Lamer+21
eFEDS papers
Transients
Rau+MPE, TDEs
Arcodia+21 (nature)
Nova fireball
Koenig+22 (nature)
5′
$t_0 - 4\,\mathrm{h}$
t_0
$t_0 + 4\,\mathrm{h}$
Millions of X-ray sources
INS forecast (Pires+17)
About 100 all-sky
after 4 yr; $\gtrsim 10^{-14}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$
Design: clusters and cosmology
More absorbed,
younger and hotter
Median distance $\sim$2 kpc
20–30% bright enough for
follow-up campaigns
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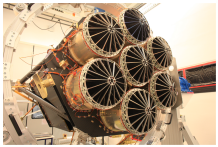
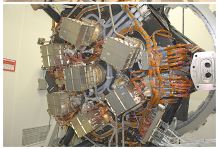
eROSITA on board SRG





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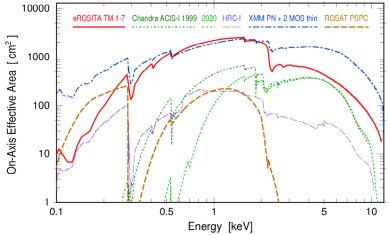
Some specifications

Mirror modules	7
Energy range	0.2–10 keV
Field-of-view	1°
Angular resolution	$< 15''$ on-axis
Energy resolution	60–80 eV
Time resolution	50 ms



	TM1	TM2	TM3	TM4	TM5	TM6	TM7	QE12346	QE57
C-K at 0.277 keV	58±0.3	58±0.3	58±0.4	58±0.3	50±0.2	58±0.4	49±0.2	12.4±1.7 %	31.3±4.4 %
O-K at 0.525 keV	64±0.2	65±0.3	66±0.3	64±0.2	57±0.3	63±0.2	56±0.4	42.2±1.6 %	51.3±2.1 %
Cu-L at 0.93 keV	70±0.3	74±0.3	72±0.3	70±0.3	68±0.3	70±0.3	68±0.3	80.0±4.5 %	83.2±4.7 %
Al-K at 1.49 keV	77±0.3	82±0.3	80±0.3	77±0.3	75±0.3	77±0.3	77±0.2	94.0±4.1 %	94.8±4.2 %

Step up wrt XMM-Newton EPIC!

Comparable effective area (0.3–2 keV), much better energy resolution:
→ better characterisation of spectral lines and ISM absorption

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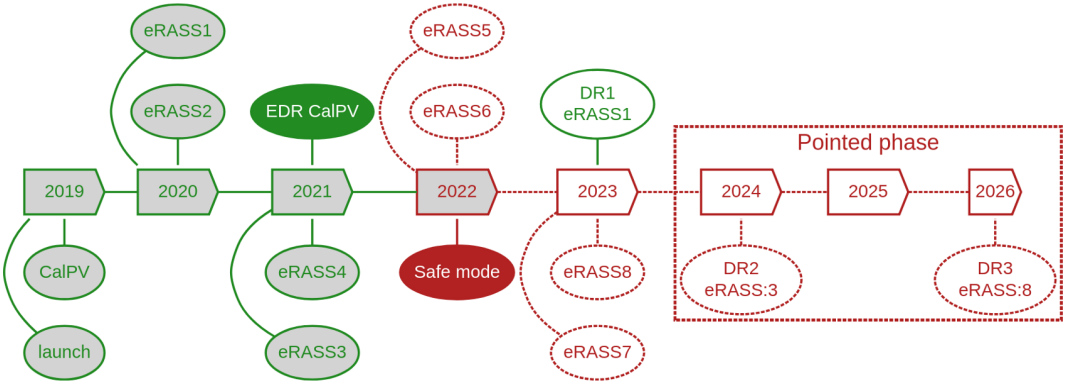
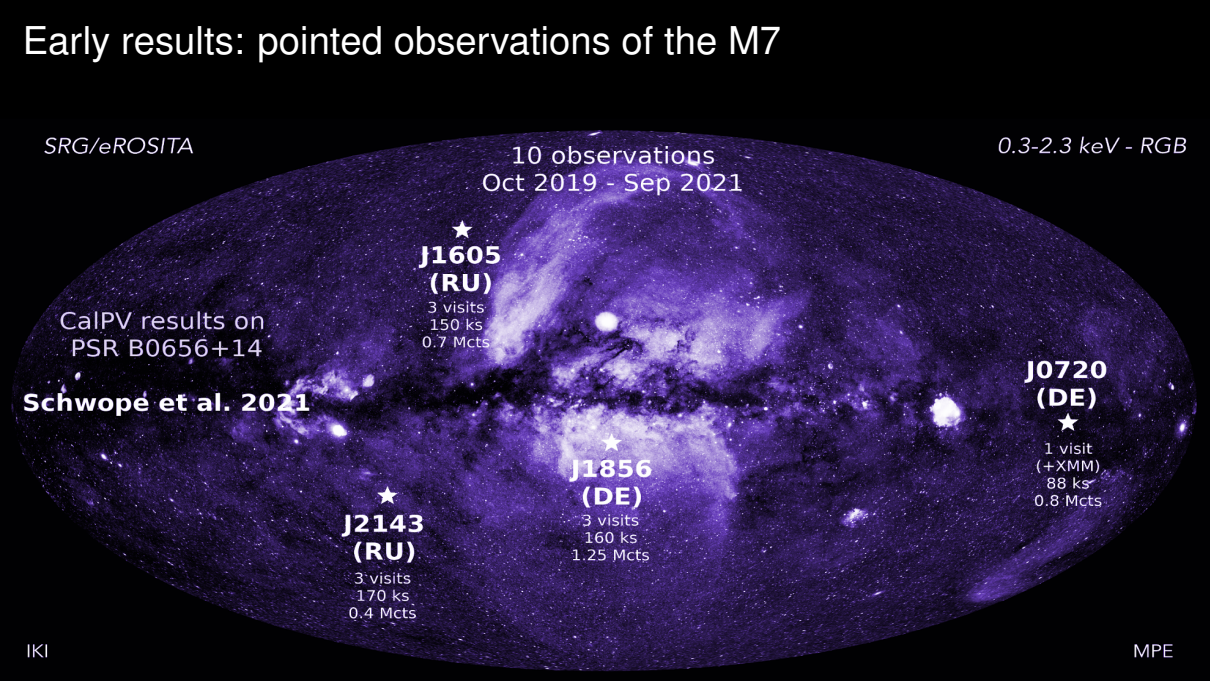
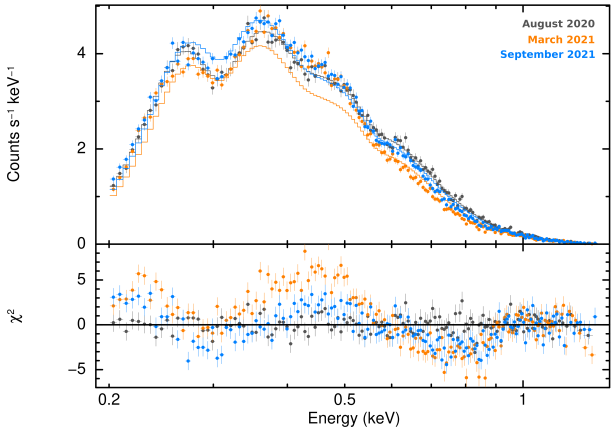
eROSITA timeline



Early results: pointed observations of the M7



RX J1605.3+3249: Long-term spectral and flux variations



First eROSITA epoch (32 ks)

Consistent with AO14 Large Programme 310 ks + 2012 60 ks
(Pires+14, Pires+19; Malacaria+19)

Second eROSITA epoch (59 ks)

Hotter and smaller “spot”, lower flux
additional absorption feature(s)

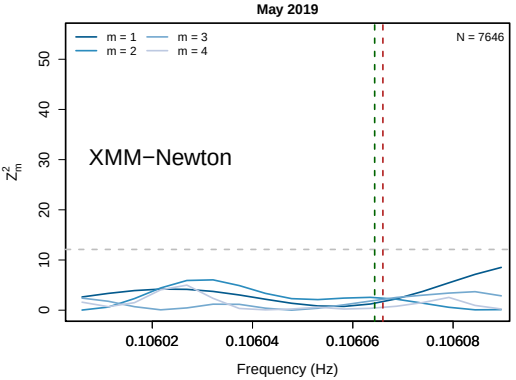
Third eROSITA epoch (55 ks)

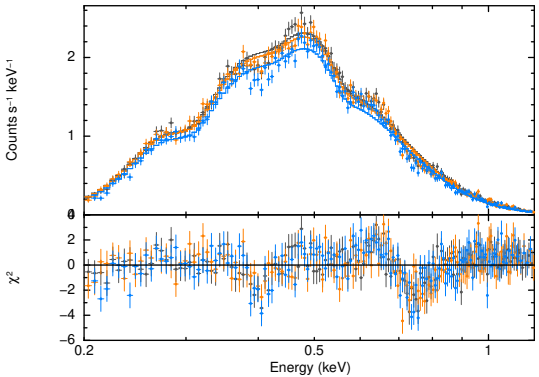
Returning to its original state

$\longrightarrow$ change of spectral state confirmed by XMM-Newton DDT (Frank Haberl; 25 ks, July 2021)

RX J2143.0+0654: spectral complexity, higher spin-down

Zane+04, Kaplan & van Kerkwijk+09, Schwope+09





$\longrightarrow$ NICER campaign in Cycle 4 (PI: Pires)

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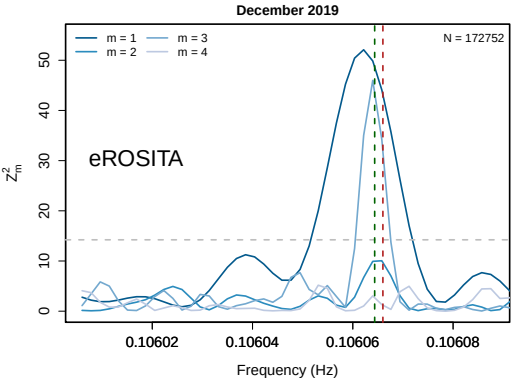

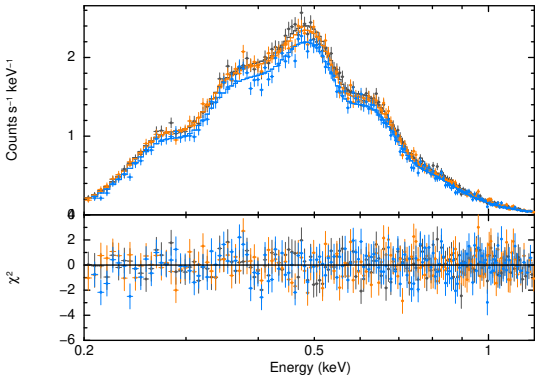

$\longrightarrow$ NICER campaign in Cycle 4 (PI: Pires)

Early results: INS candidates from eRASS

Promising targets starting to emerge (Kurpas et al., in preparation)

Catalogue cross-matching, colour cuts (Pires+09, Rigoselli+22)

- goal: Complete down to $f_X > 10^{-13}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$
- first results: 38 INS candidates picked from over 10^5 sources

Dedicated follow-up

- granted: LBT 21AB, SALT 22AB, XMM AO21, Chandra
- (to be) submitted: NICER, XMM AO22

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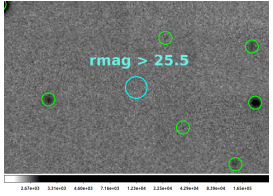
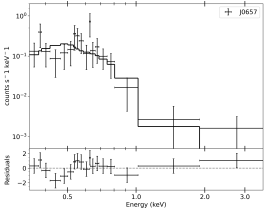
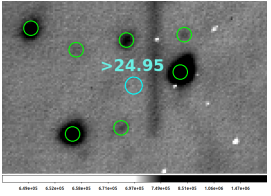
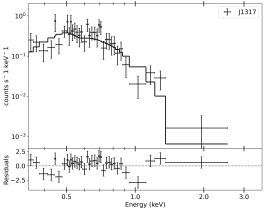


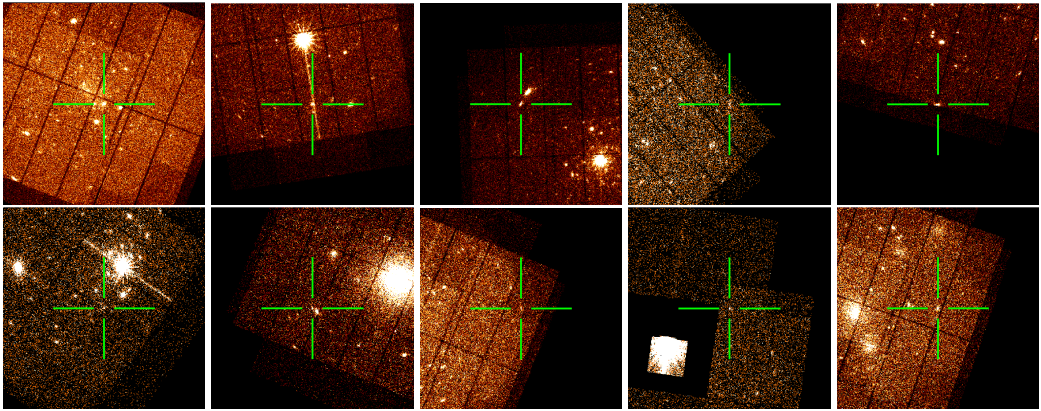






Synergy: 4XMM searches and fulfil programs

Science validation for H2020 XMM2ATHENA

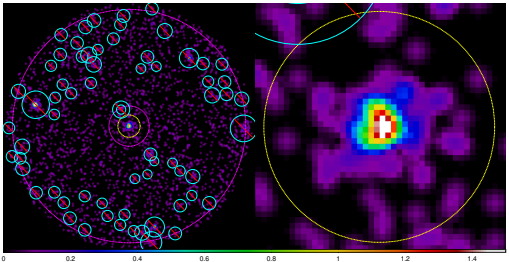


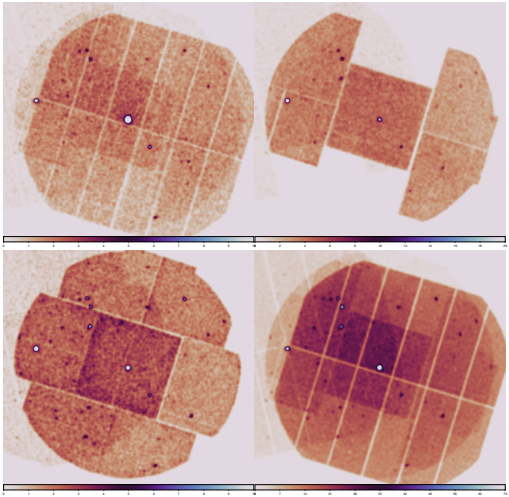
XMM2ATHENA

Synergy: 4XMM J022141.5-735632

Joint analysis XMM/eRASS (6 epochs) + Legacy Survey DR10 (optical/nIR)

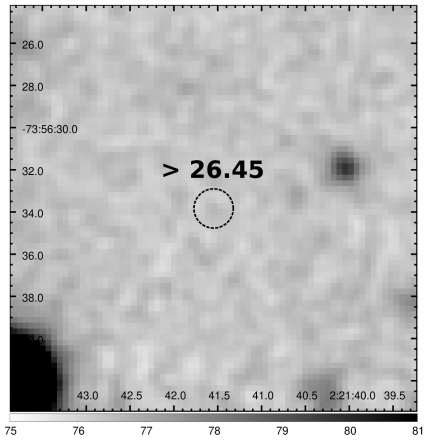
obsid	Date	MJD (days)	Duration (s)	GTI (%)
XMM-Newton				
0674110401 ⋆	2012-02-09	55 967.076	31 915	93
0884190401 †	2021-07-09	59 405.013	41 417	73
eROSITA				
03716501 ‡	2020-04-25	58 970.200	1 008	49
03716502 ‡	2020-10-28	59 155.966	936	47
03716503 ‡	2021-04-28	59 338.242	1 037	43
03716504 ‡	2021-10-30	59 523.091	950	45



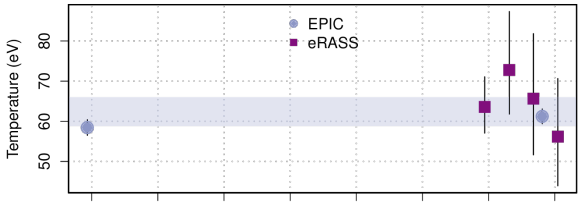


A possible new thermally emitting INS Pires+22, Rigoselli+22

Stacked DECam *ugriz*



- ✓ soft and constant (possibly over ∼30 years)
- ✓ no catalogued source within 13σ
- ✓ high X-ray-to-optical flux ratio (>5000)
- ✓ exclude CVs, AGN, BL Lac, SSS etc
- ? radio limits (nothing in Vizier)
- ? pulsations – upcoming NICER



Synergy: continuous gravitational wave candidates

- spinning neutron stars
- mass asymmetry (cm-high bumps)
- persistent, nearly monochromatic
- at least 4$\times$ weaker than mergers

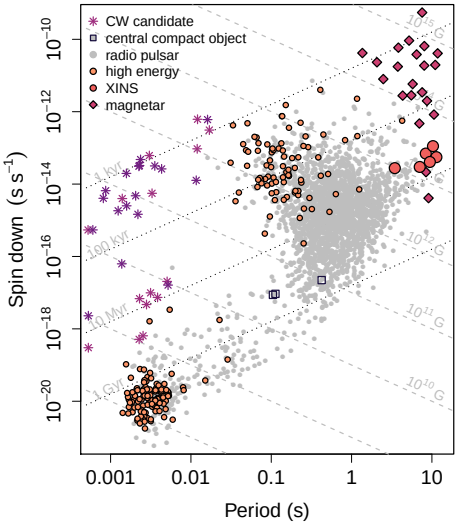
“Louder” candidates

- young (Crab-like) unless atypical

eROSITA follow-up

- 27 CW candidates (ALIGO O1-O3)
- all-sky blind searches, Einstein@Home

$\longrightarrow$ 50 eRASS sources with no counterparts



Summary and outlook

eROSITA is truly a powerful discovery machine

- large grasp, stable background, observing cadence
- eFEDS results: survey design requirements can be met

4.4 all-sky scans were completed; eRASS1 data release Q1 2023

Isolated neutron stars: huge step forward

$\longrightarrow$ promising candidates! population studies, birthrates

$\longrightarrow$ M7: multiple (broad, narrow, phase-dependent) absorption features, spectral complexity, change of spectral state and pulsed fraction

$\longrightarrow$ detailed investigations (neutron star cooling/atmosphere)

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