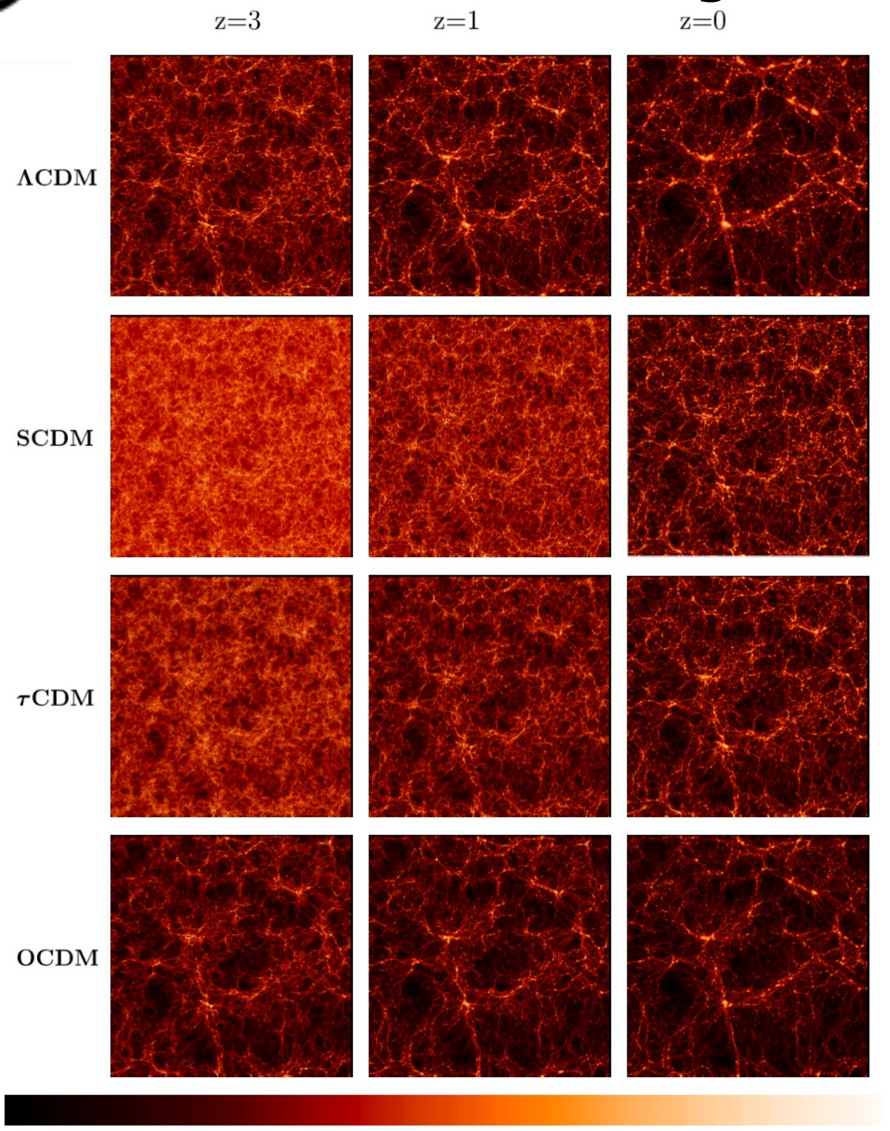
eROSITA on SRG:
Highlights from the all-sky survey

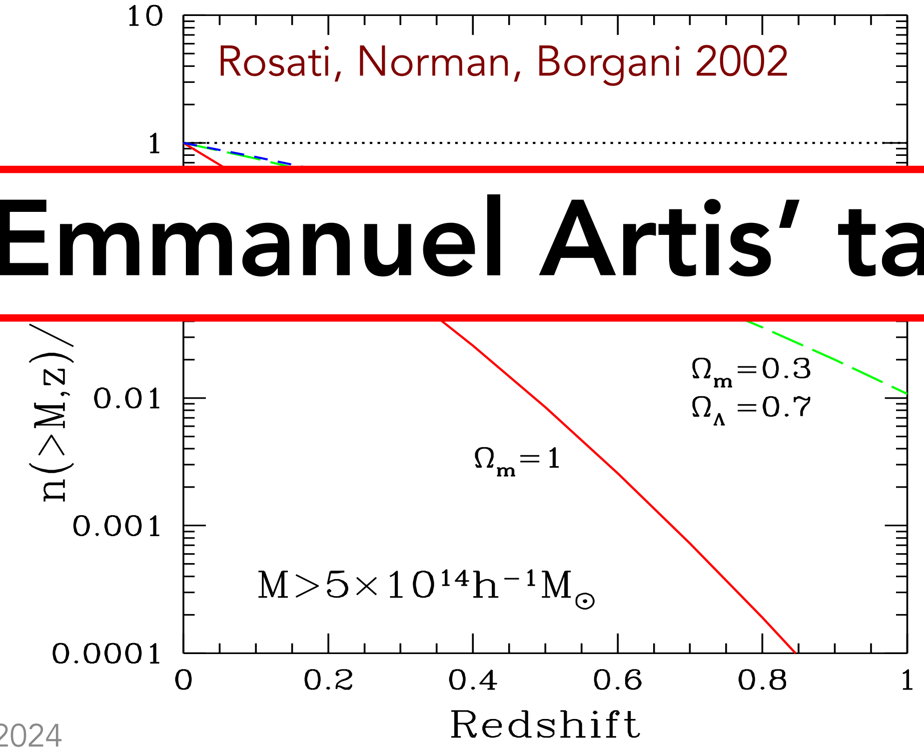
Andrea Merloni (MPE)

(X-ray) Clusters Cosmology



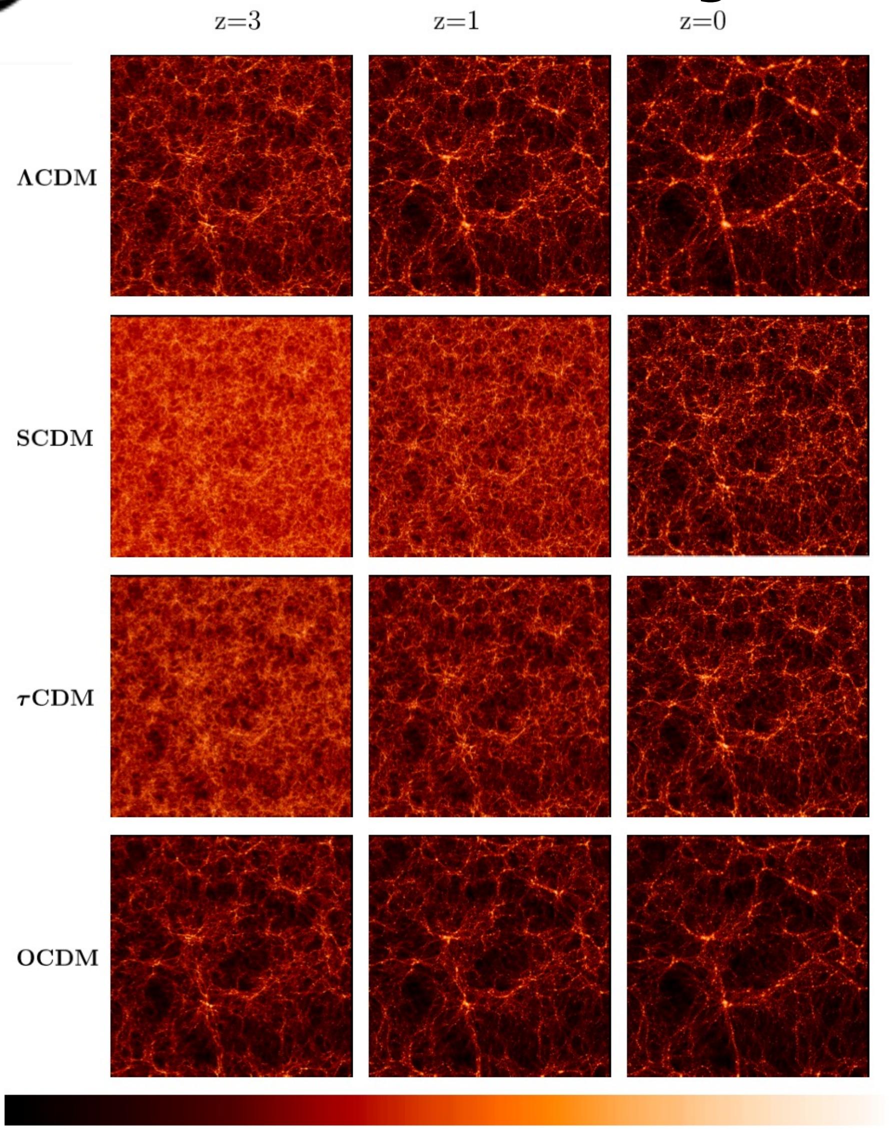
The Virgo Collaboration; Jenkins et al. 1998

- Clusters are *exponentially sensitive* tracers of **growth of structures**
- A signature of clusters is the hot (~10^7 K), extended X-ray ICM
- eROSITA (PSF, sensitivity) was designed to be able to detect >10^5 clusters (Pillepich+ 2018)



See Emmanuel Artis' talk

(X-ray) Clusters Cosmology



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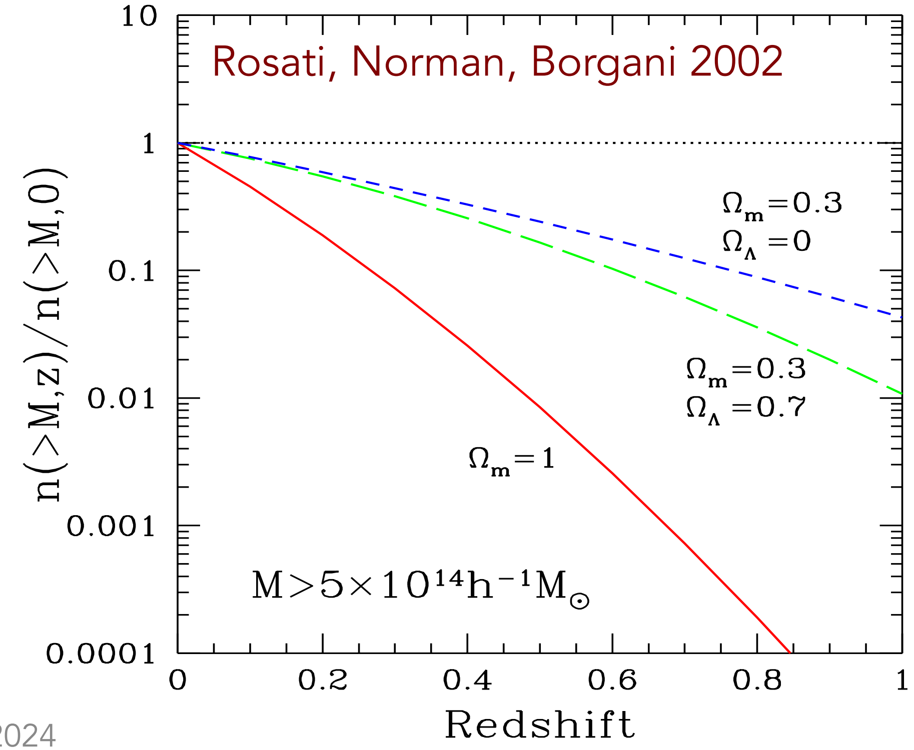
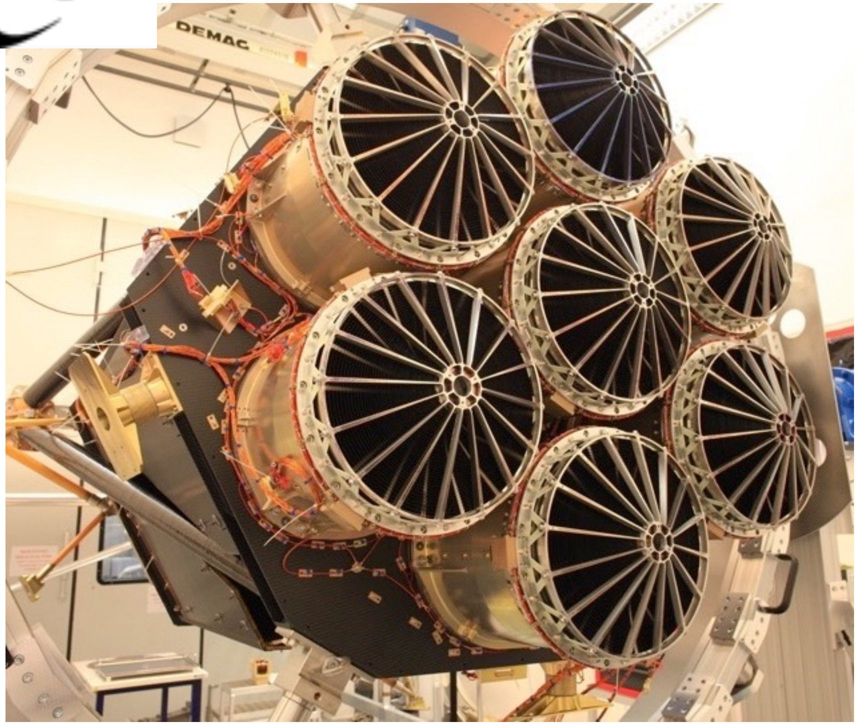
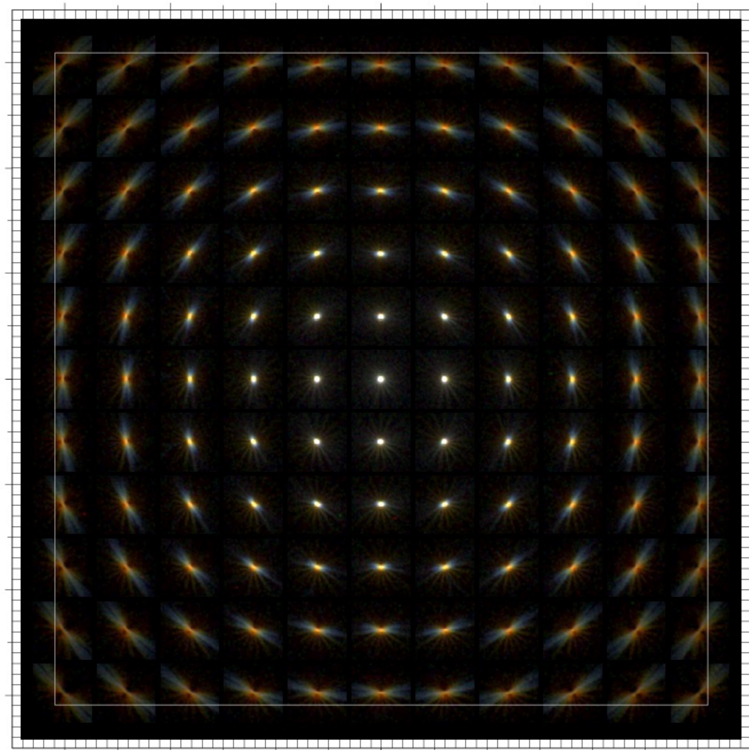
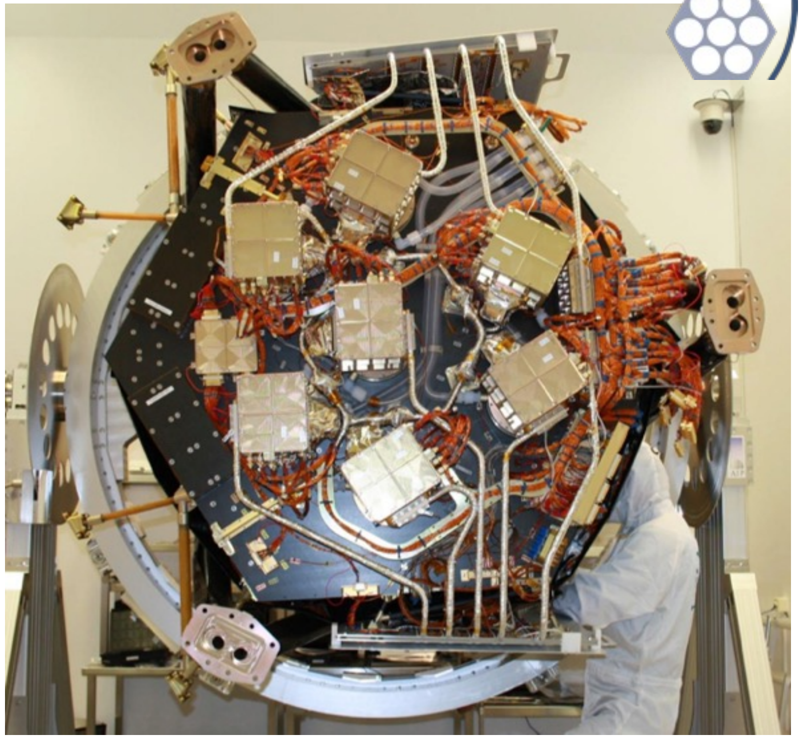


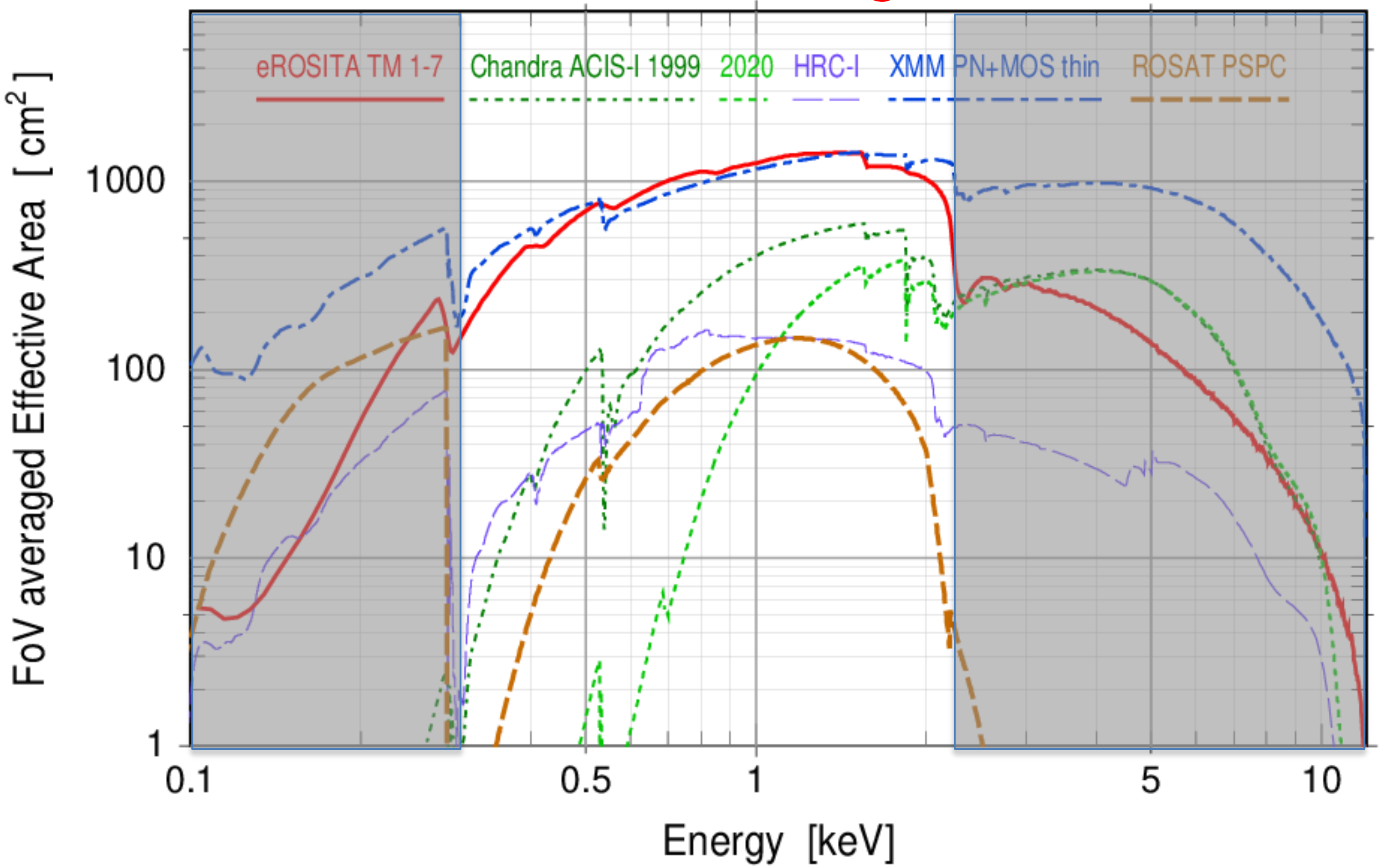
eROSITA on SRG [Predehl et al. 2021]

- Large Effective area (~**1300 cm² @1keV**)
- Large Field of view: **1 degree (diameter)**
- Half-Energy width **(HEW) ~18" (on-axis, point.); ~30" (FoV avg., survey)**
  - **Positional accuracy: ~4.5" (1σ)**
- X-ray baffle: **92% stray light reduction**
- pnCCD with framestore: 384x384x7~10^6 pixels (9.4"), no chip gaps, no 'out of time' events,
- **Spectral resolution** at all measured energies within specs (**~80eV @1.5keV**)

Large Effective Area

~1300 cm^2 (FoV avg. @1keV)



Effective area at 1keV comparable with XMM-Newton

eROSITA's advantage: large Field of View and Grasp

Moon diameter
30 arcmin

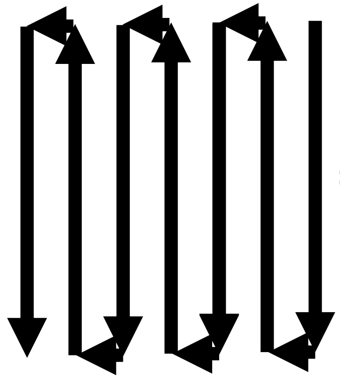
XMM-Newton
Field of view ~ 30 arcmin

Chandra
Field of view ~ 17 arcmin

Grasp (= survey speed)
- 5 x XMM-Newton
- 100 x Chandra (today)

eROSITA
Field of view ~ 62 arcmin

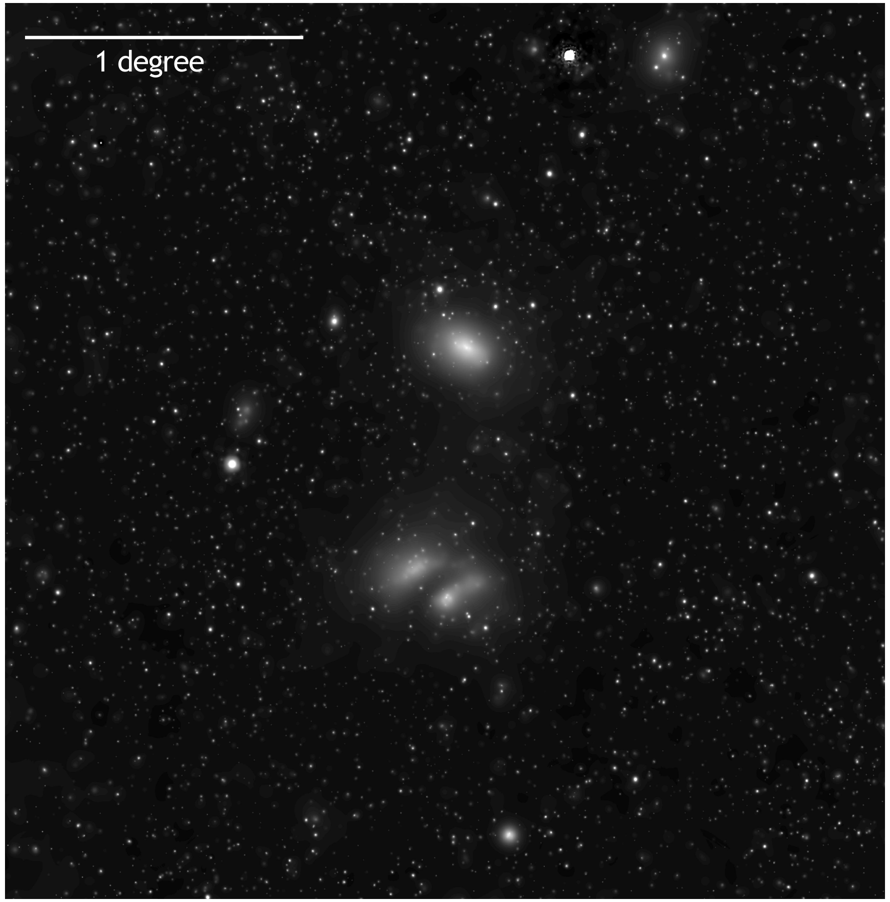
+



Scanning feature

=

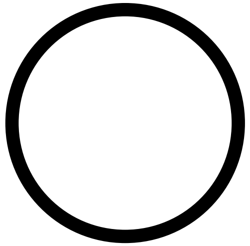
3 Observing modes:
continuous scan (survey), field scan, pointing



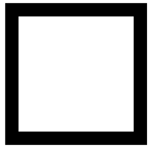
SRG/eROSITA 0.2-2 keV image of A3391/3395
(Reiprich et al. 2021)

Moon diameter
30 arcmin

XMM-Newton
Field of view ~ 30 arcmin



Chandra
Field of view ~ 17 arcmin



Gr

- 5

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3

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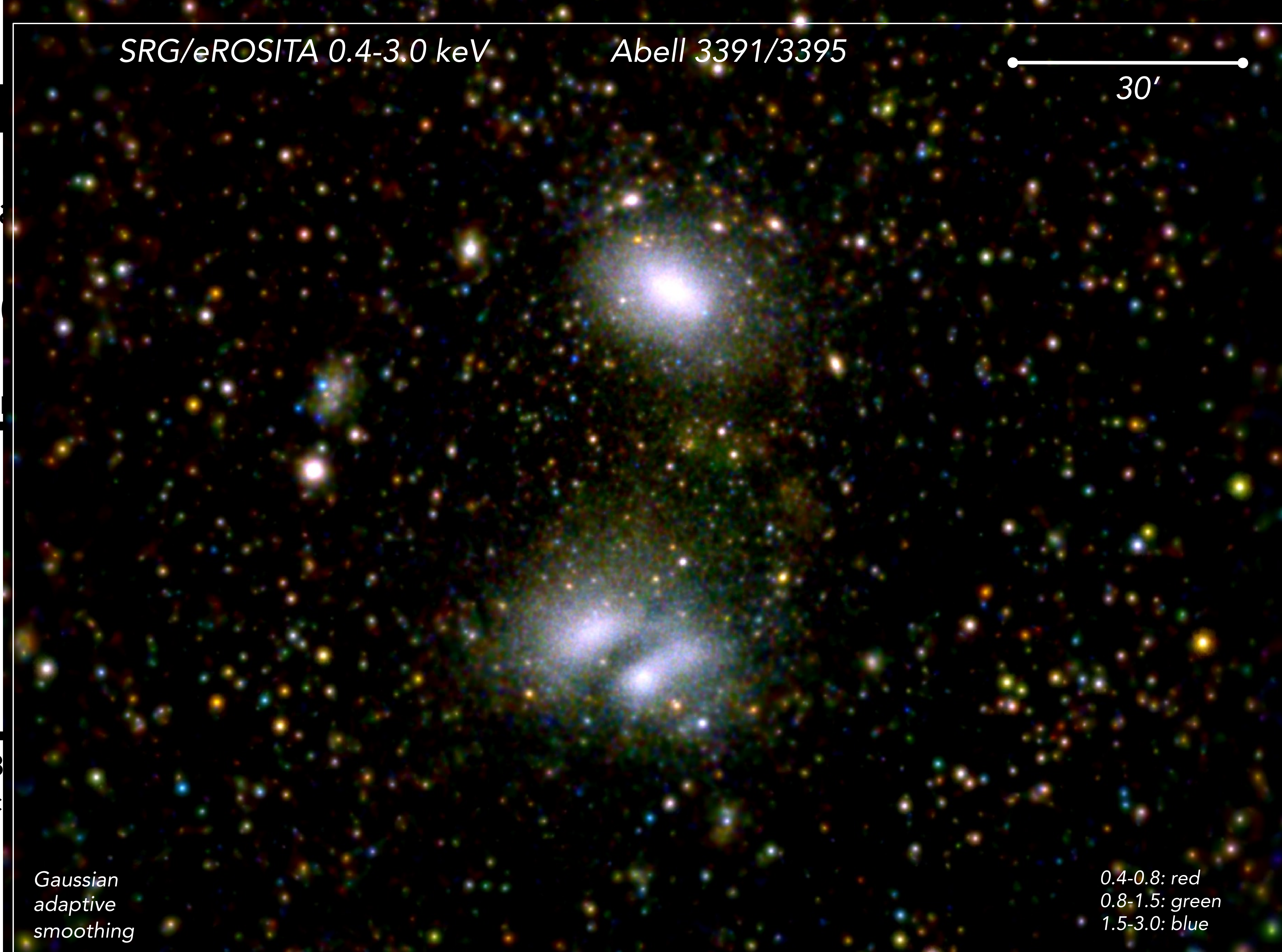
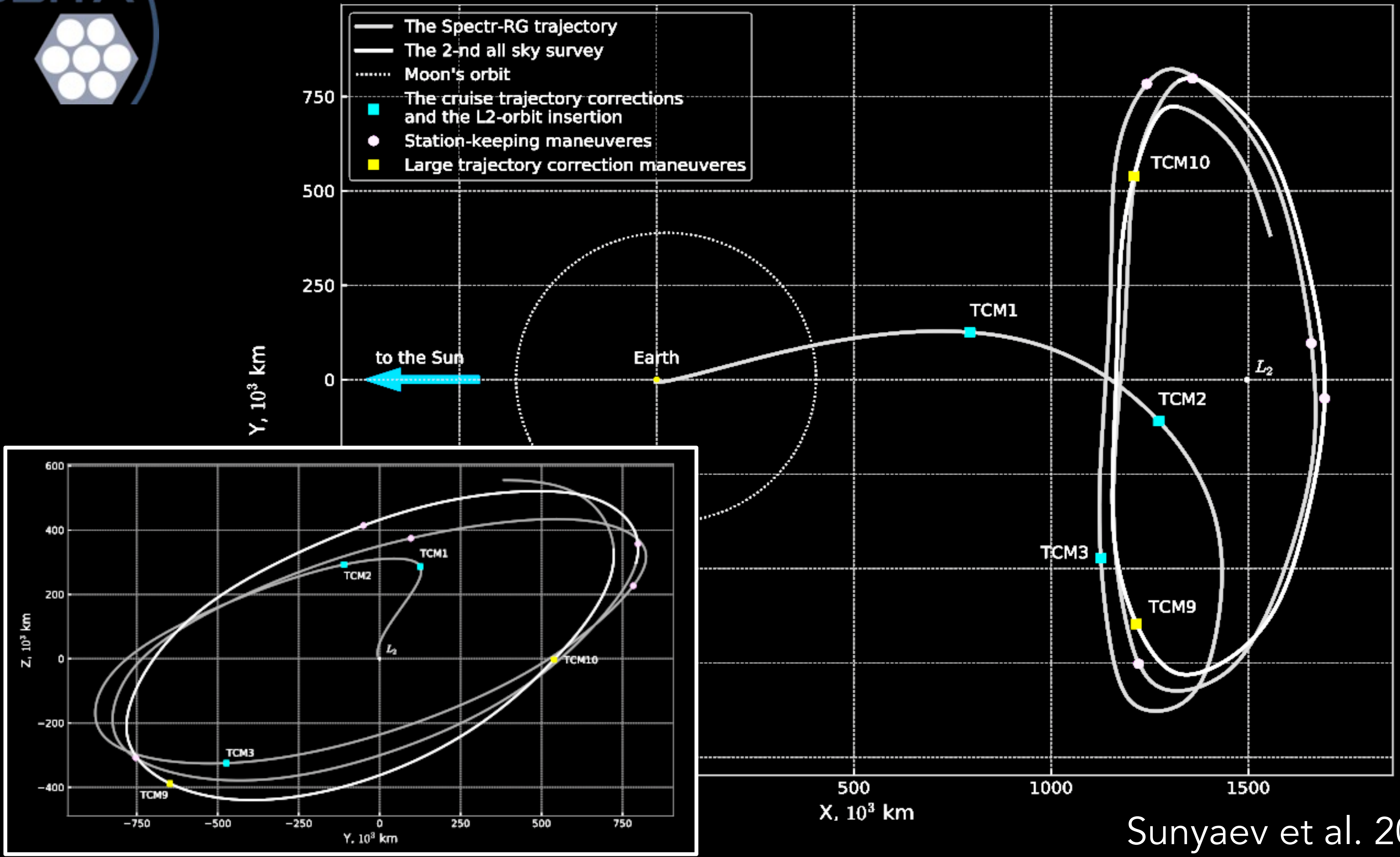
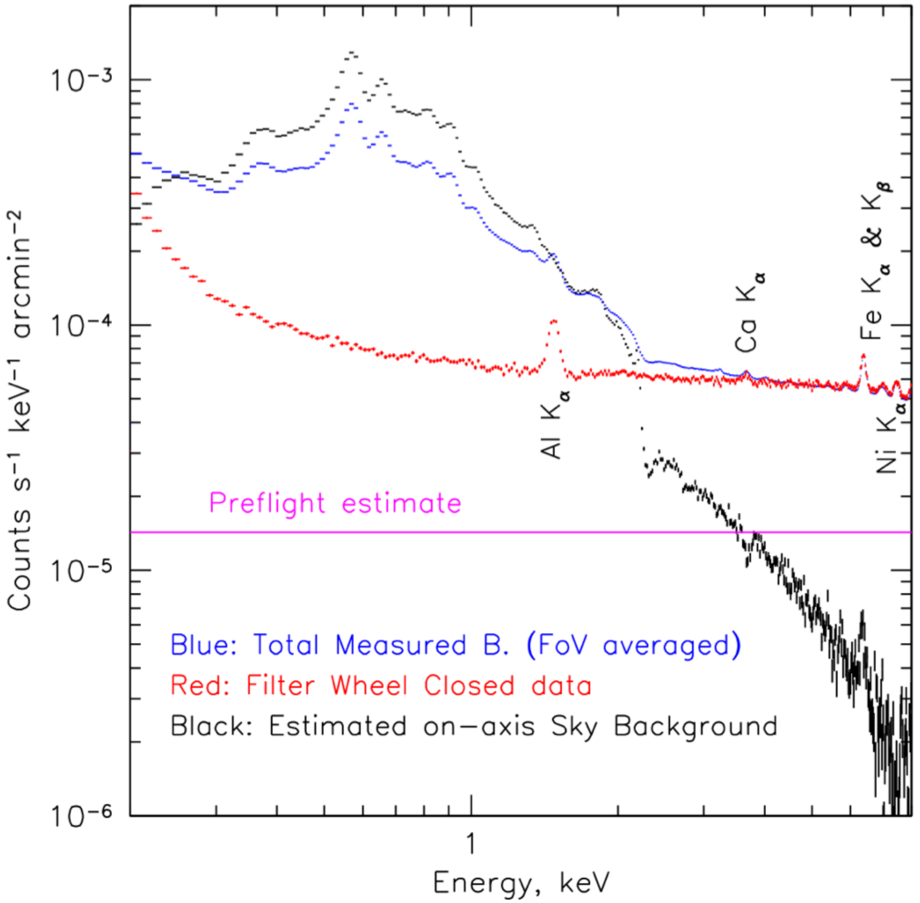


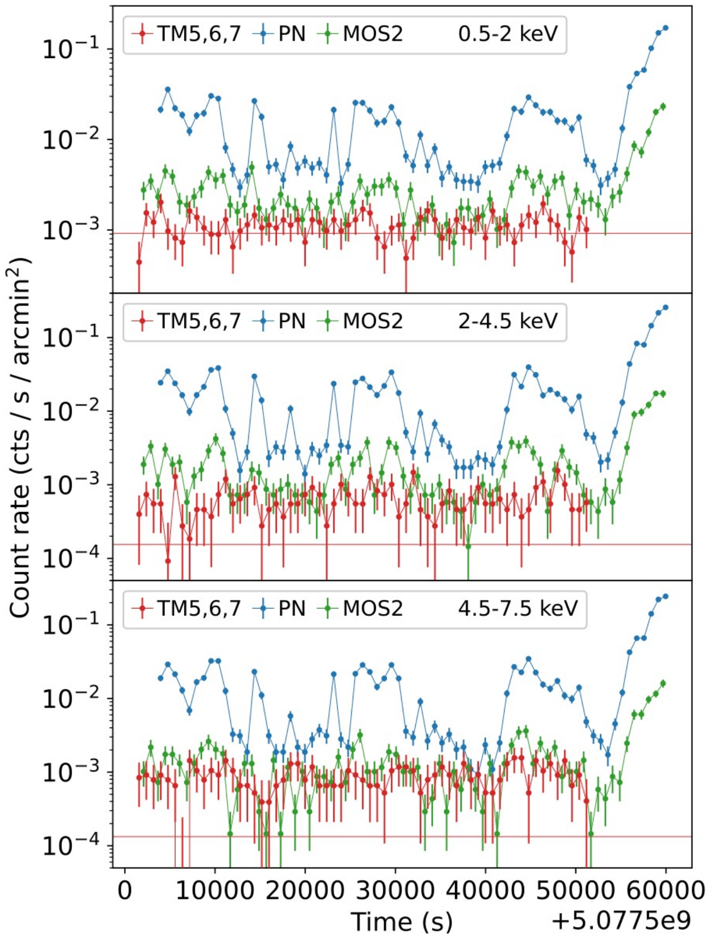
A large Halo L2 orbit



Sunyaev et al. 2021

X-ray Background @ L2

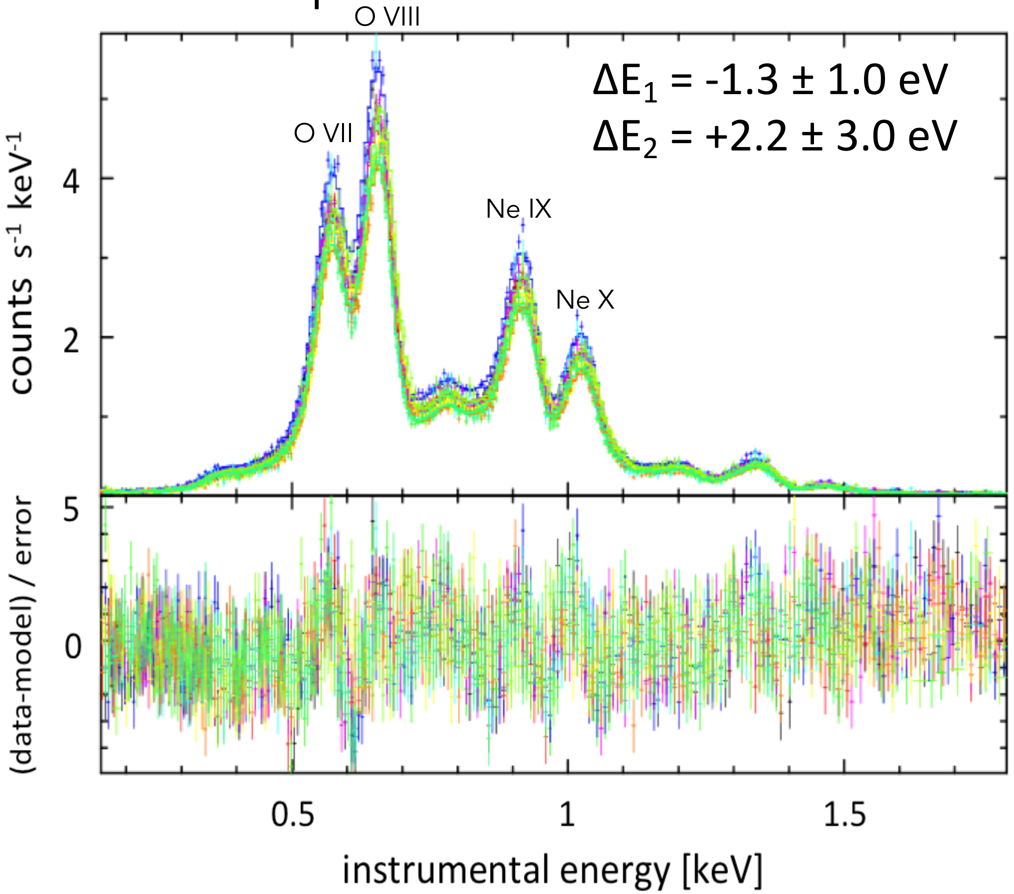




1) Background **much less variable** than in the XMM and Chandra data
2) A factor of **~3 higher** particle bkgnd than predicted in the White Book -> Instrument mass model
3) Less fluorescence lines than EPICpn due to graded shields
4) But: iron line (+others) likely from impurities in the graded shield itself

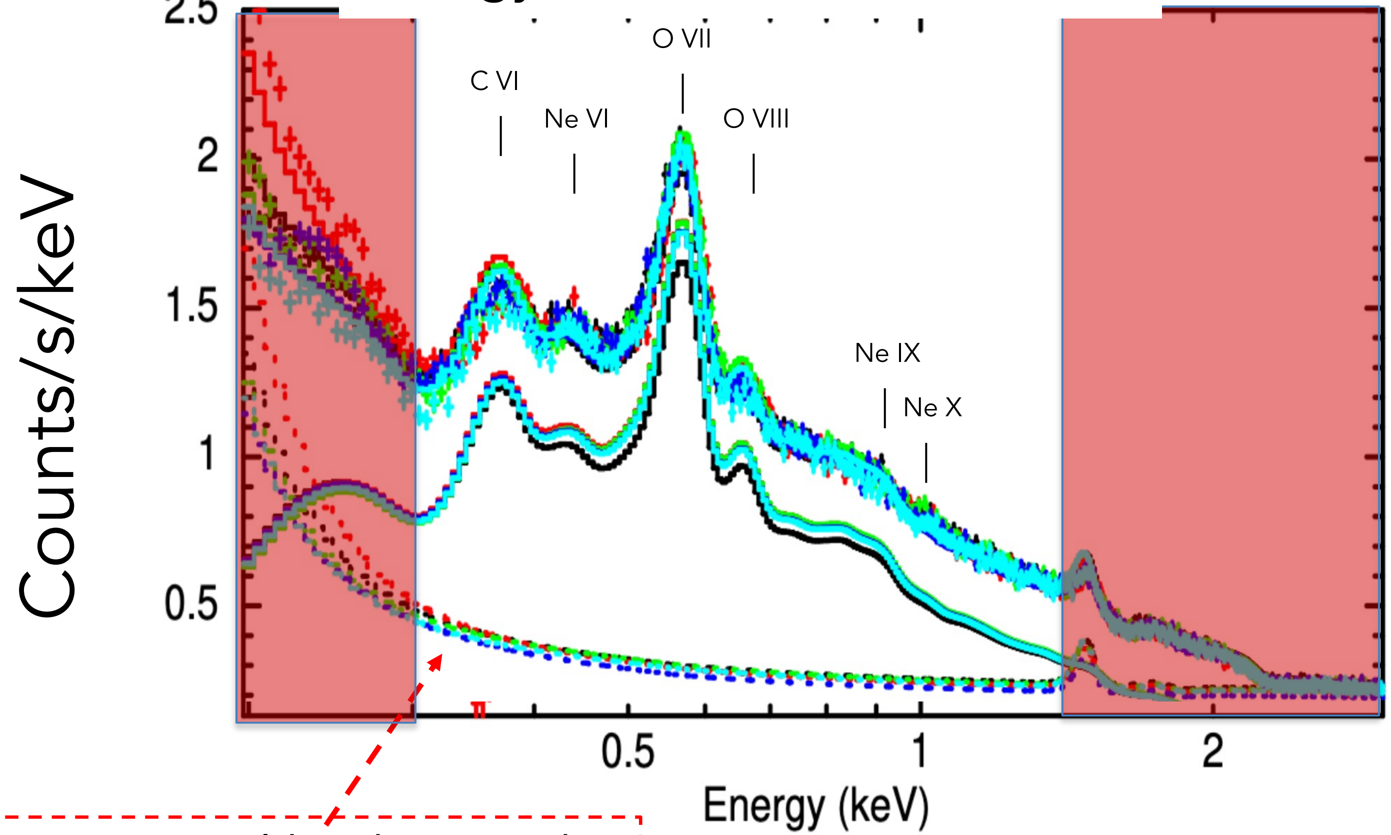
Calibration: Energy scale

eROSITA spectrum of SNR 1E 0102-721



Merloni et al. 2024

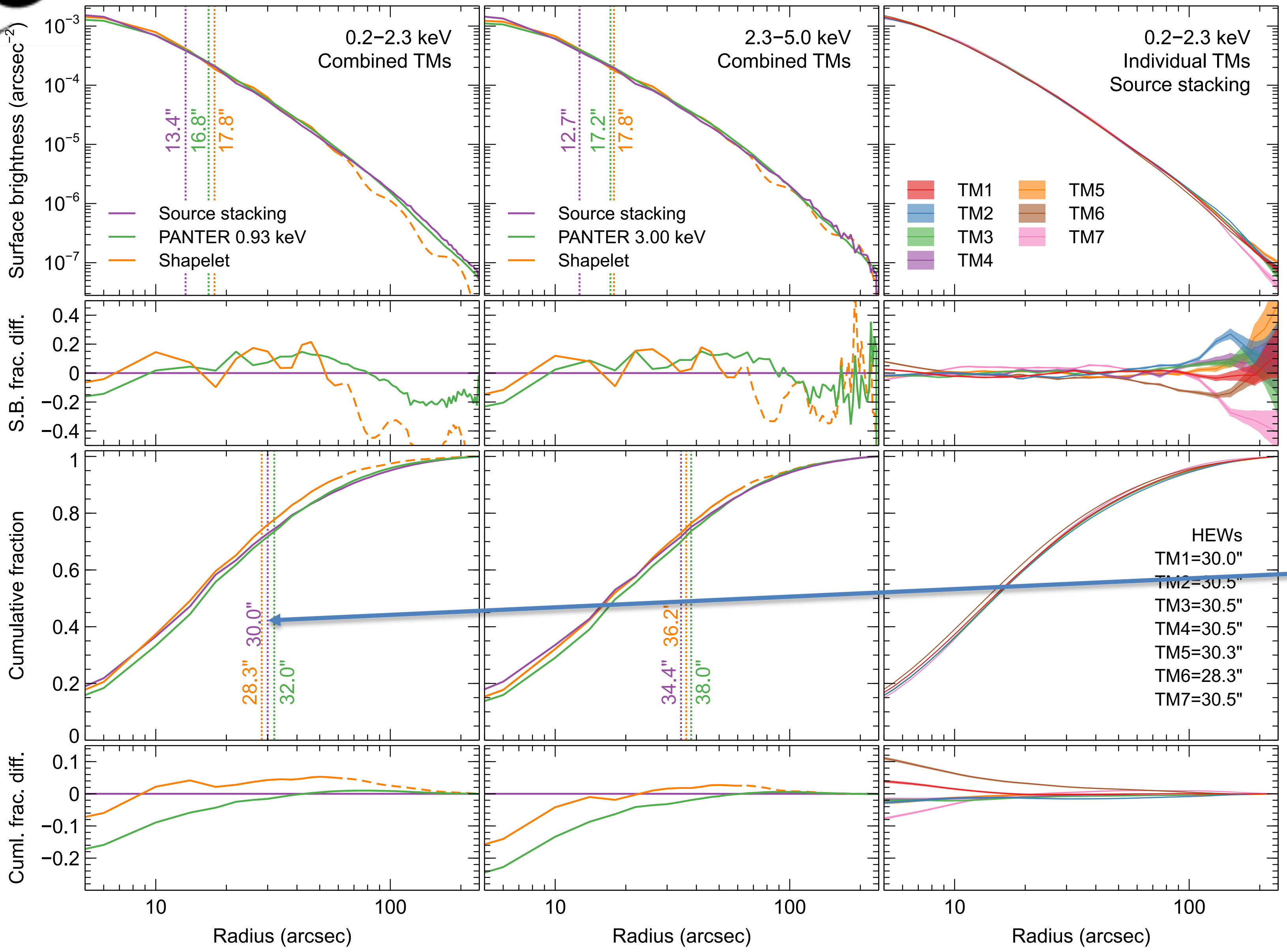
eROSITA spectrum of eFEDS
Energy scale shift factor <3eV



Instrumental background
(particles + detector noise)

G. Ponti, X. Zheng et al. (2022)

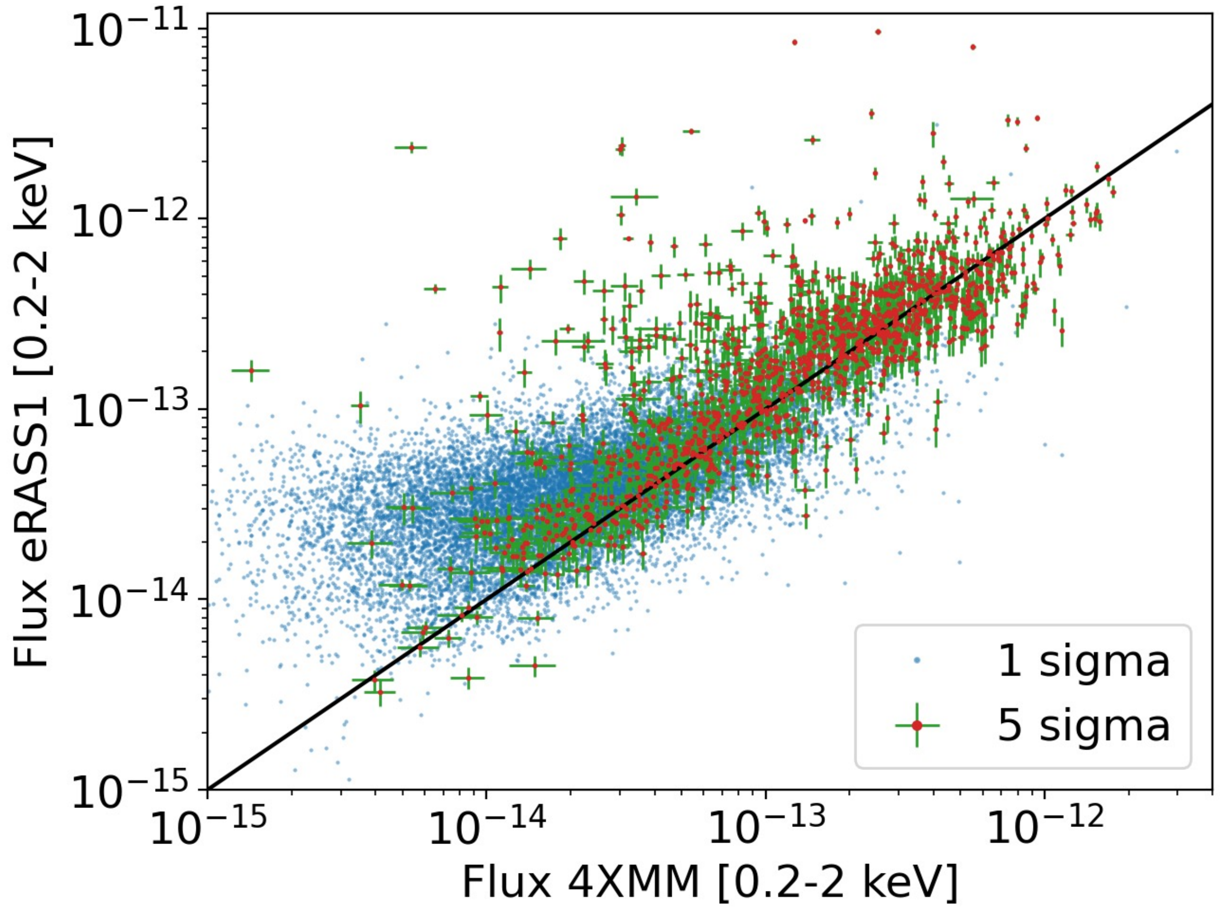
Calibration: PSF

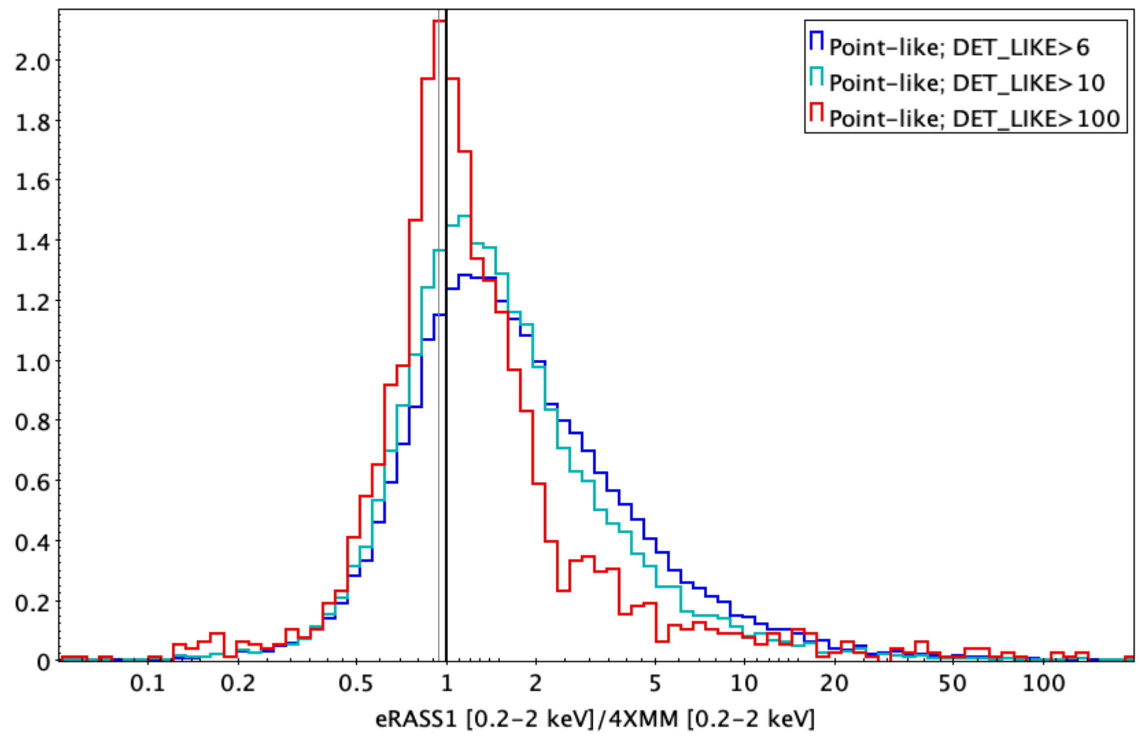


Survey HEW ~30” [0.2-2.3 keV]

Merloni et al. 2024

Flux (ARF) calibration: Comparison with 4XMM

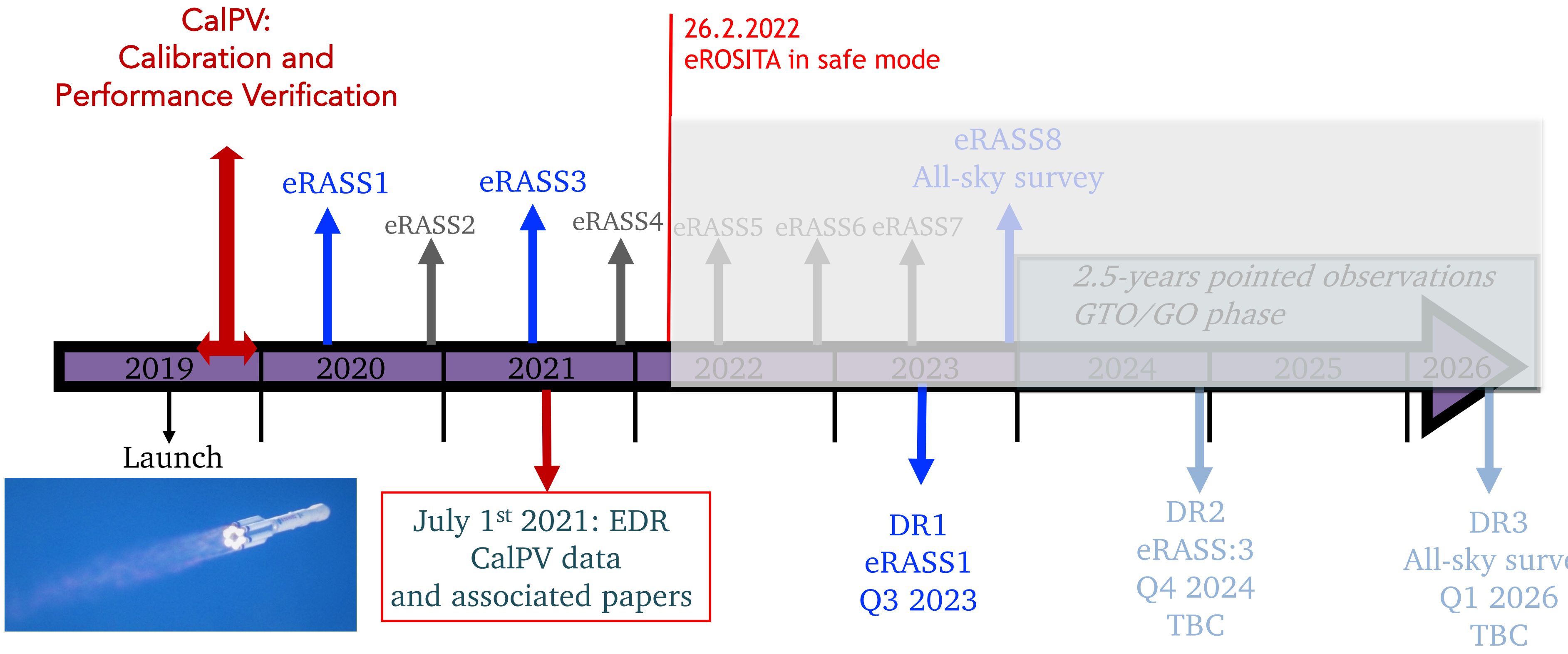




Photometric consistency with 4XMM better than ~10% in 0.2-2 keV [expected mis-calibration ~6%]; much larger offset in 2.3-5 keV (up to 30% Aeff mis-calibration?)

SRG Programmatics

eRASS = eROSITA All-Sky Survey



- Early Data Release (EDR) in 2021: several fields, including eFEDS mini-survey
- DR1 on 31.1.2024
- DR2 (eRASS:4.x) TBD (about two years from now)

The All-Sky Surveys by Numbers

- Completed 4 all-sky survey (12/2019 – 12/2021)
- Uniform exposure, avg.~800s; up to 120ks at the Ecliptic Poles (confusion limited)
- Very few background flares, flexible mission planning: no gaps in exposure
- **~1.6 Billion** 0.2-5keV calibrated photons (~350 Gb telemetry)
- Typical (point-source) sensitivity:
  - Single pass (eRASS1,2,3,4)
    - ~5×10^{-14} erg/s/cm^2 [0.2-2.3 keV]; **4-5x deeper than RASS**
    - ~7×10^{-13} erg/s/cm^2 [2.3-5 keV]
  - Cumulative (eRASS:4)
    - ~2×10^{-14} erg/s/cm^2 [0.2-2.3 keV]
    - ~2×10^{-13} erg/s/cm^2 [2.3-5 keV]
- eRASS1 (half-sky): 0.9M point sources ~doubles the number of known X-ray sources!
- eRASS:4 (half-sky): 2.8M point sources; 87k extended; ~45k confirmed clusters

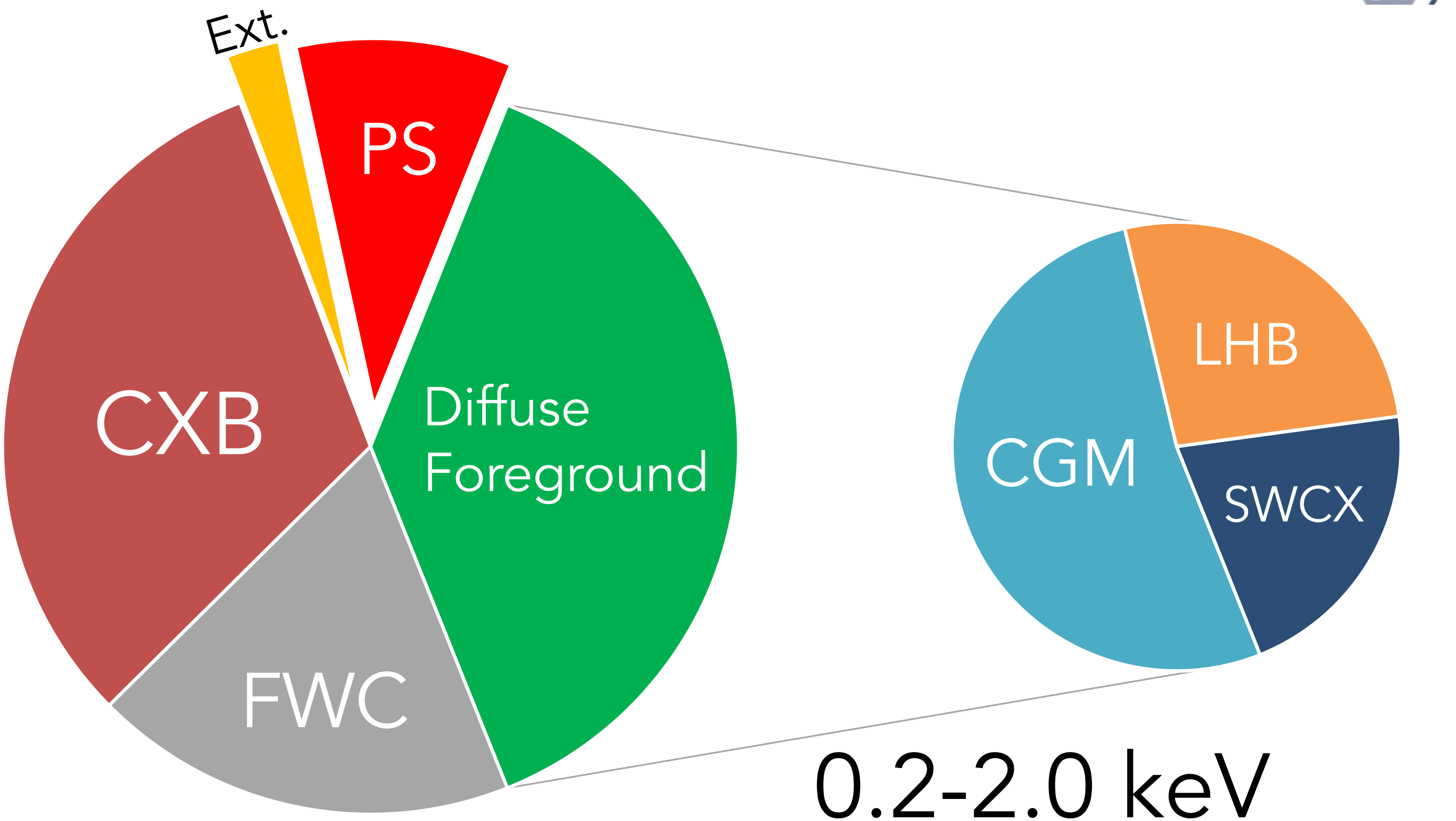
Panning through the eROSITA sky

In this animation, you can enjoy the X-ray sky as seen by eROSITA. The X-ray bands have been colour-coded according to their energy (red for 0.3-0.6 keV, green for 0.6-1 keV, blue for 1-2.3 keV) and a number of prominent sources have been highlighted.

The eRASS1 (soft) photon Pie

~340 Million calibrated events

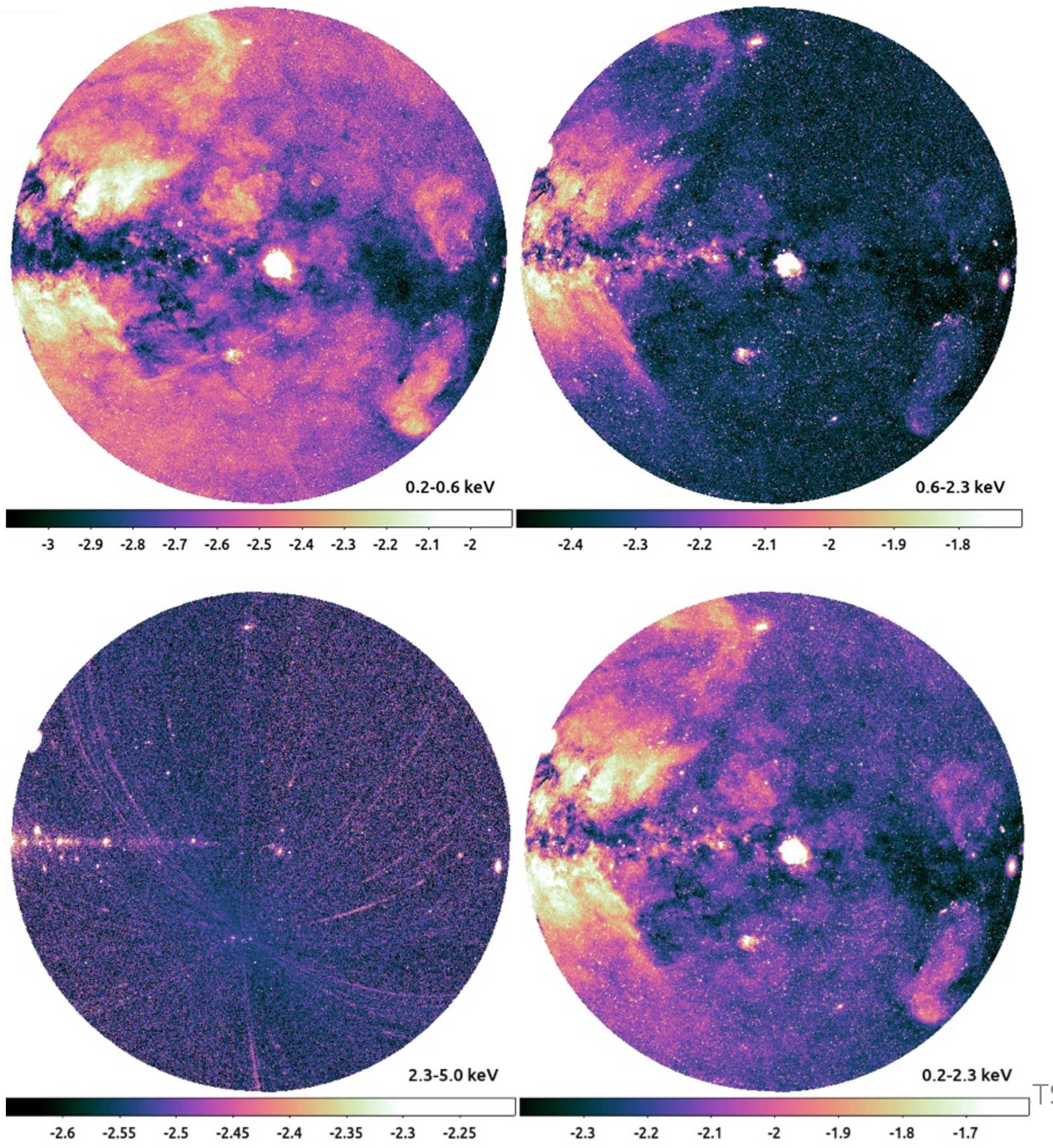
- 107 Million CXB photons
- 67 Million MW Hot CGM photons (58M halo + 9M 'Corona'; Ponti+'23)
- 63 Million Instrumental BKG photons (FWC)
- 34 Million Local Hot Bubble photons
- 27 Million Solar Wind Charge Exchange photons
- 32 Million Point Sources' photons
    - 24 Milllion AGN photons; 8 Million Stars photons
- 8 Million Extended Sources' photons



0.2-2.0 keV

Merloni et al. (2024)

eROSITA-DE Data Release 1 products

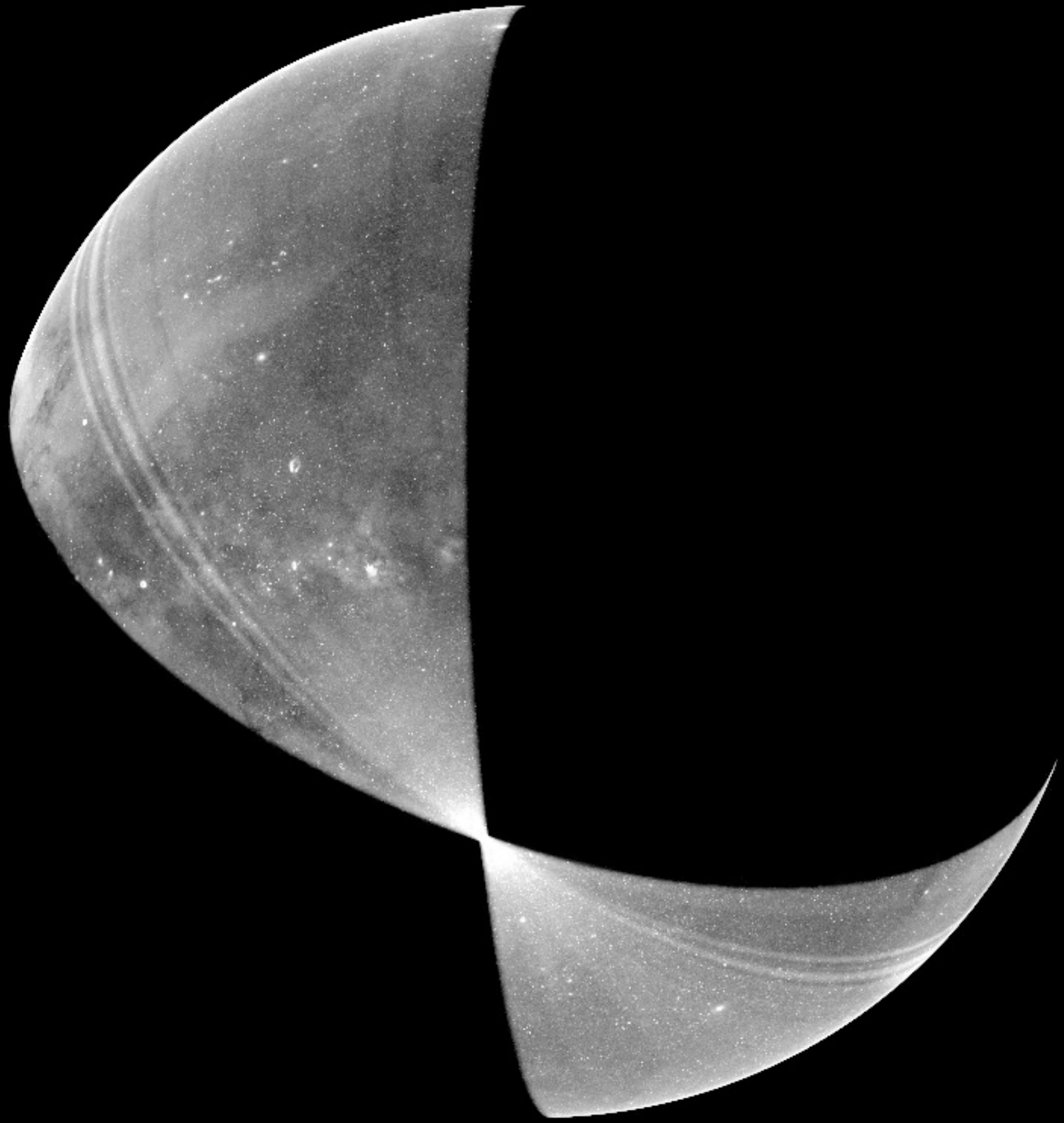


erosita.mpe.mpg.de/dr1/

- Software
- Calibration DB
- Attitude files
- Exposure maps
- Events
- Count rate maps
- Source catalogues
- X-ray Spectra
- Light-curves

Merloni et al. (2024)

eRASS1 in time domain

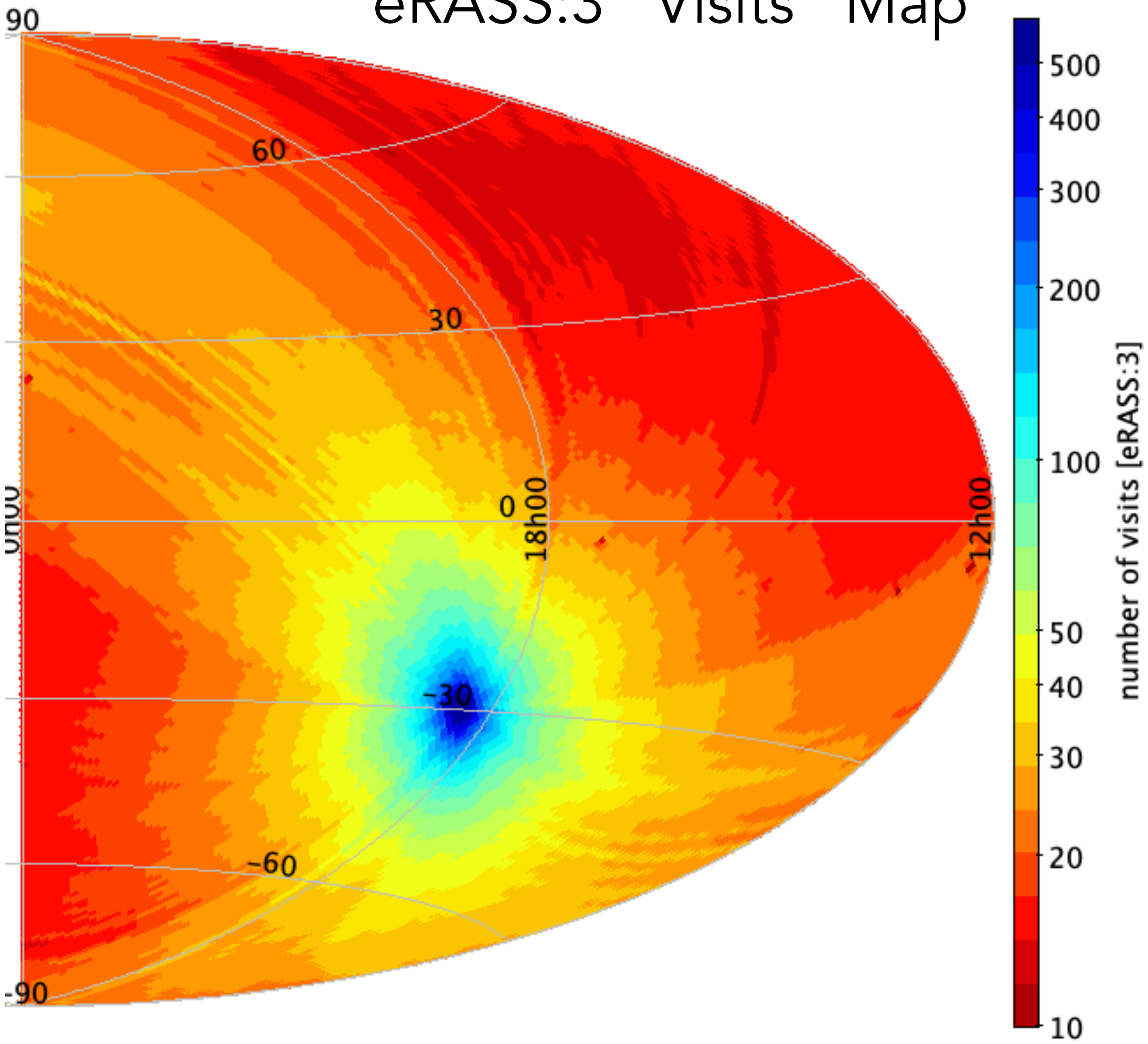


eRASS1 cts rate image
Movie courtesy
of J. Sanders (MPE)

eRASS: Timescales

- **50 msec [Readout]:** Time resolution of each CCD (frame readout cycle)
- **40 sec [Visit]:** Scan speed + 1 deg. FoV (avg effective exposure)
- **4 hours [eRoday]:** Rotation period of SRG (Interval between scans/visits)
- **1 day [Visibility]:** avg. visibility length (~6 visits)
- **6 months [eRASS]:** one complete all-sky survey (revisit period for most of the sky)
- **2 years:** 4 all-sky surveys

eRASS:3 "Visits" Map



eRASS: Timescales

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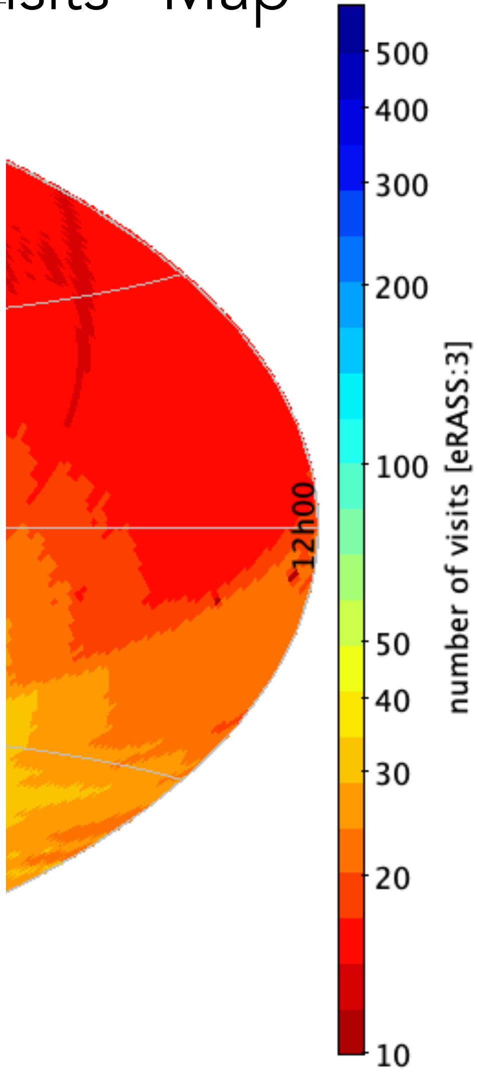

Article

X-ray detection of a nova in the fireball phase

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Novae are caused by runaway thermonuclear burning in the hydrogen-rich envelopes of accreting white dwarfs, which leads to a rapid expansion of the envelope and the ejection of most of its mass[1,2]. Theory has predicted the existence of a 'fireball' phase following directly on from the runaway fusion, which should be observable as a short, bright and soft X-ray flash before the nova becomes visible in the optical[3–5]. Here we report observations of a bright and soft X-ray flash associated with the classical Galactic nova YZ Reticuli 11 h before its 9 mag optical brightening. No X-ray source was detected 4 h before and after the event, constraining the duration of the flash to shorter than 8 h. In agreement with theoretical predictions[4,6–8], the source's spectral shape is consistent with a black-body of $3.27^{+0.11}_{-0.33} \times 10^5$ K ($28.2^{+0.9}_{-2.8}$ eV), or a white dwarf atmosphere, radiating at the Eddington luminosity, with a photosphere that is only slightly larger than a typical white dwarf.

lap

- **50 msec [Readout]:**
each CCD (frame rea
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(avg effective exposu
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- **1 day [Visibility]:** avg
(~6 visits)
- **6 months [eRASS]:** o
survey (revisit period
- **2 years:** 4 all-sky surv

Article

X-ray quasi-periodic eruptions from two previously quiescent galaxies

https://doi.org/10.1038/s41586-021-03394-6

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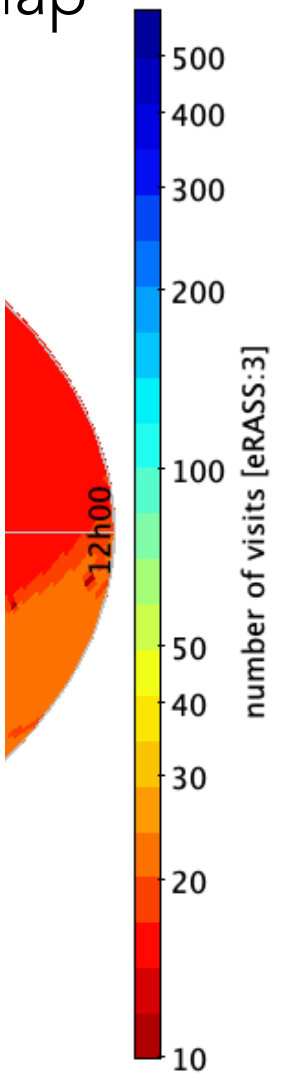
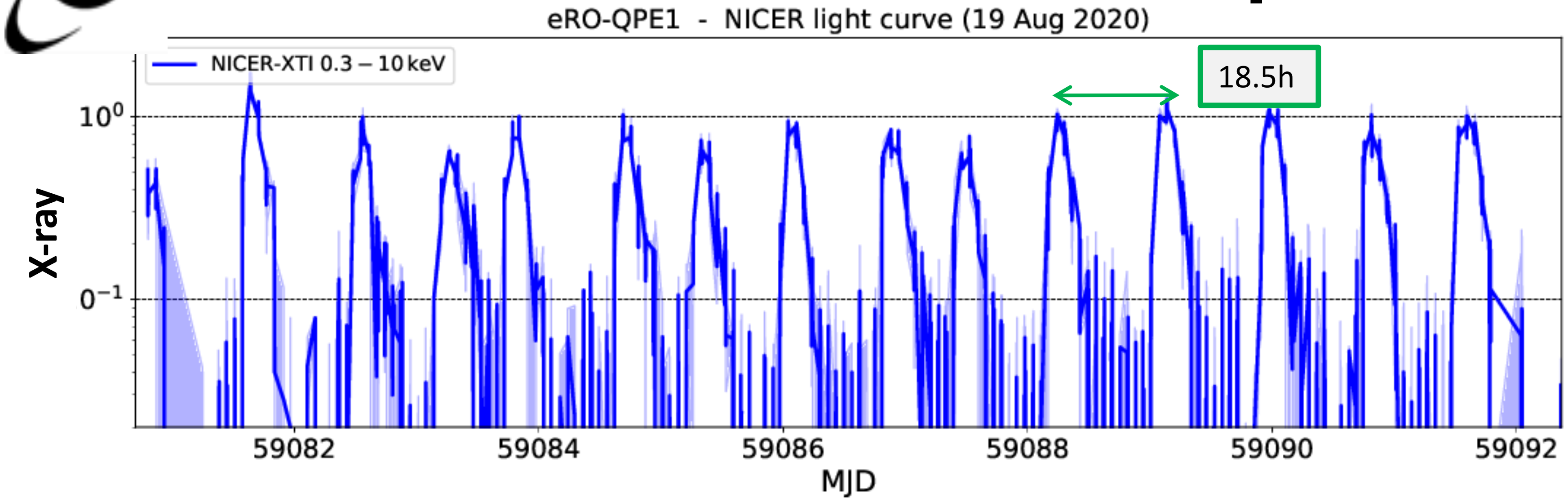
Check for updates

R. Arcodia[1✉], A. Merloni[1], K. Nandra[1], J. Buchner[1], M. Salvato[1], D. Pasham[2], R. Remillard[2], J. Comparat[1], G. Lamer[3], G. Ponti[1,4], A. Malyali[1], J. Wolf[1], Z. Arzoumanian[5], D. Bogensberger[1], D. A. H. Buckley[6], K. Gendreau[5], M. Gromadzki[7], E. Kara[2], M. Krumpe[3], C. Markwardt[5], M. E. Ramos-Ceja[1], A. Rau[1], M. Schramm[8] & A. Schwope[3]

Quasi-periodic eruptions (QPEs) are very-high-amplitude bursts of X-ray radiation recurring every few hours and originating near the central supermassive black holes of galactic nuclei[1,2]. It is currently unknown what triggers these events, how long they last and how they are connected to the physical properties of the inner accretion flows. Previously, only two such sources were known, found either serendipitously or in archival data[1,2], with emission lines in their optical spectra classifying their nuclei as hosting an actively accreting supermassive black hole[3,4]. Here we report observations of QPEs in two further galaxies, obtained with a blind and systematic search of half of the X-ray sky. The optical spectra of these galaxies show no signature of black hole activity, indicating that a pre-existing accretion flow that is typical of active galactic nuclei is not required to trigger these events. Indeed, the periods, amplitudes and profiles of the QPEs reported here are inconsistent with current models that invoke radiation-pressure-driven instabilities in the accretion disk[5–9]. Instead, QPEs might be driven by an orbiting compact object. Furthermore, their observed properties require the mass of the secondary object to be much smaller than that of the main body[10], and future X-ray observations may constrain possible changes in their period owing to orbital evolution. This model could make QPEs a viable candidate for the electromagnetic counterparts of so-called extreme-mass-ratio inspirals[11–13], with considerable implications for multi-messenger astrophysics and cosmology[14,15].



Quasi Periodic Eruptions (QPEs)



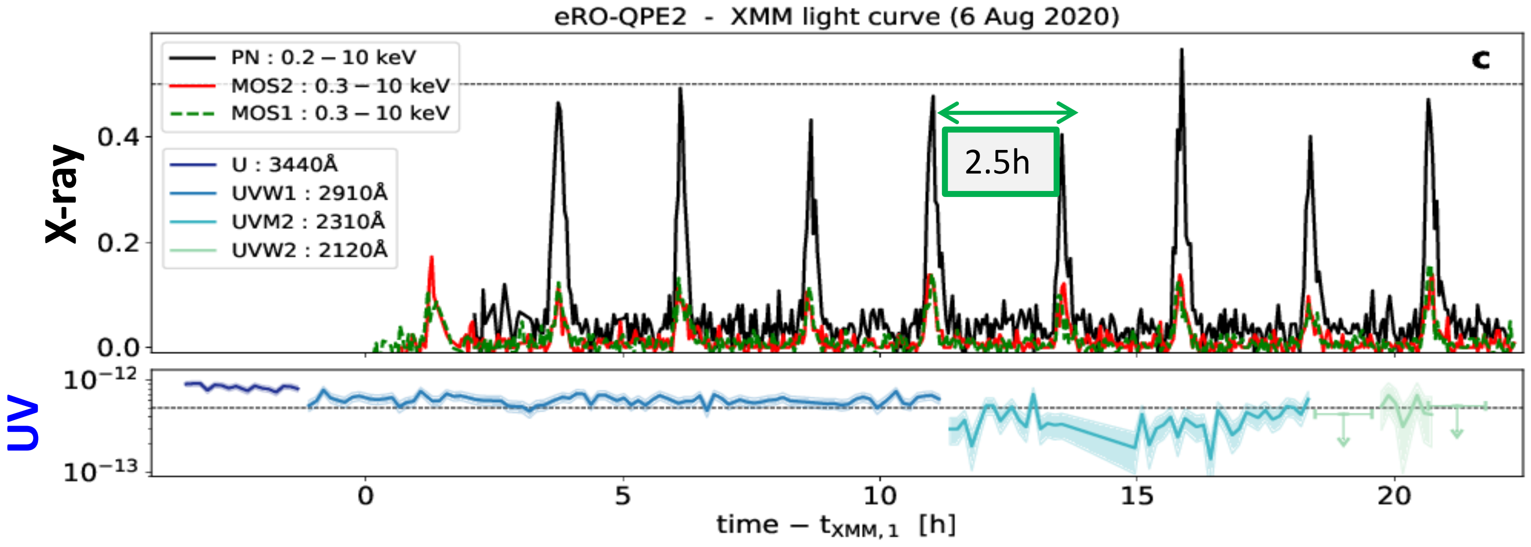
Arcodia+21

QPE1

followed-up with XMM+NICER

$$Lx_{0.5-2keV}^{peak} \approx 1e43\ erg\ s^{-1}$$

11 days!



QPE2

followed-up with XMM-Newton

$$Lx_{0.5-2keV}^{peak} \approx 1e42\ erg\ s^{-1}$$

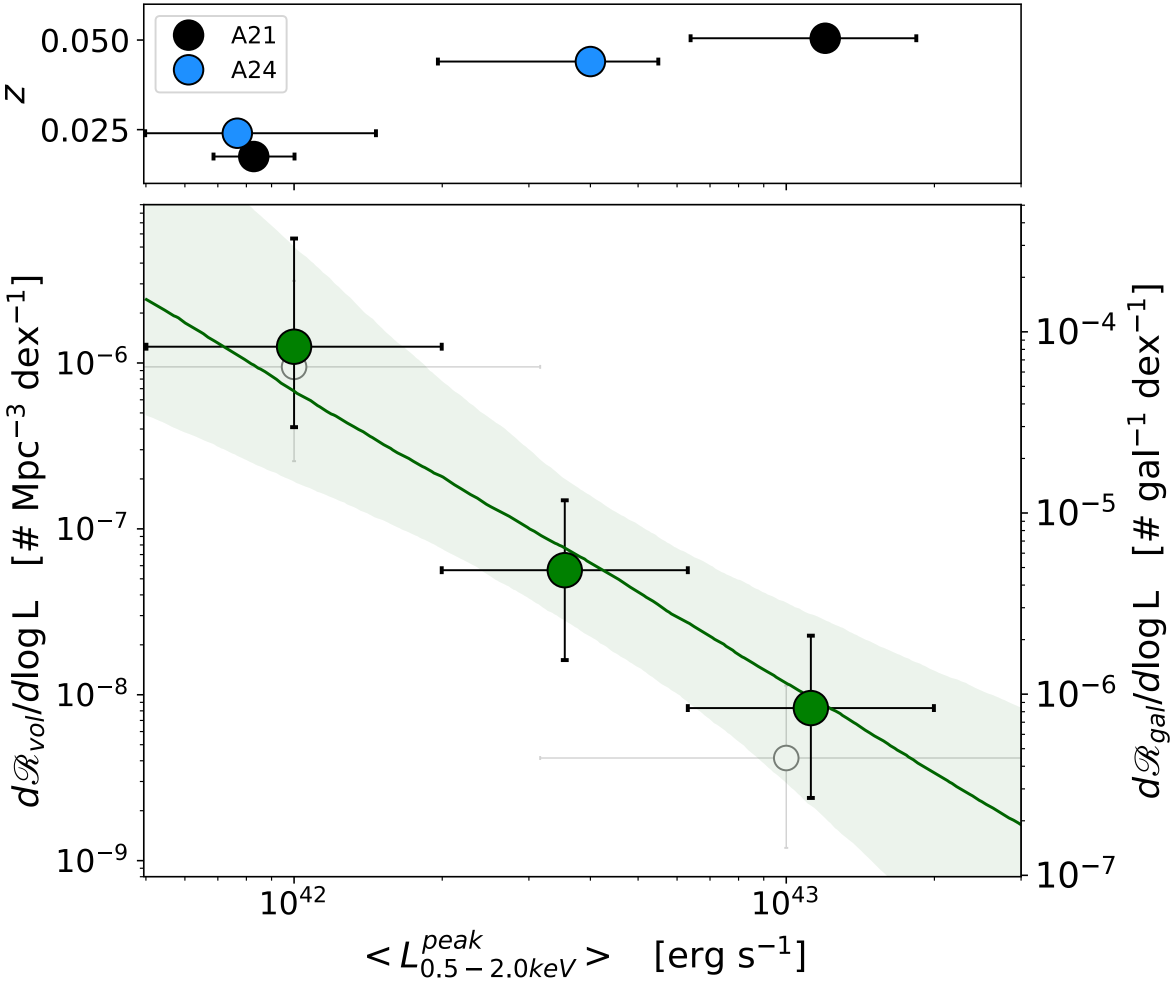
1 day!

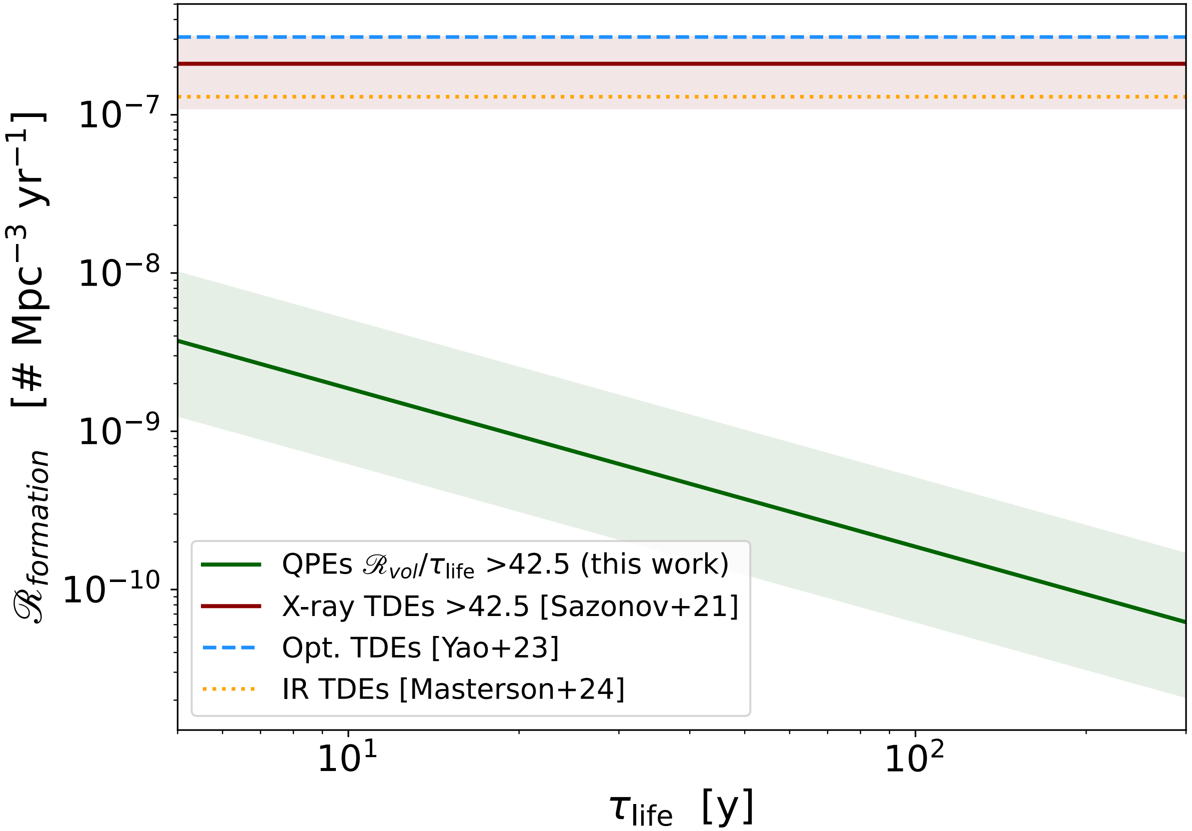
Arcodia et al. 2021, Nature

Arcodia+21

QPE LF and volumetric rate

Arcodia et al., in press (arXiv:2403.17059)

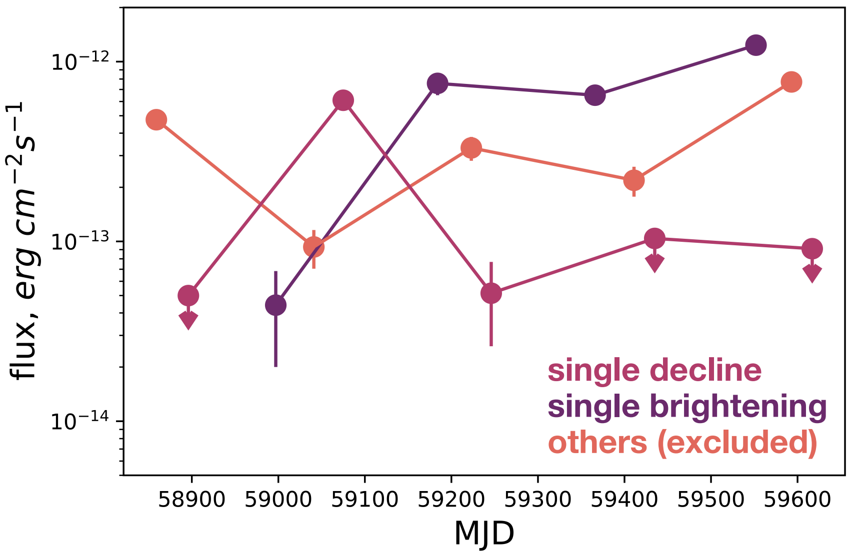


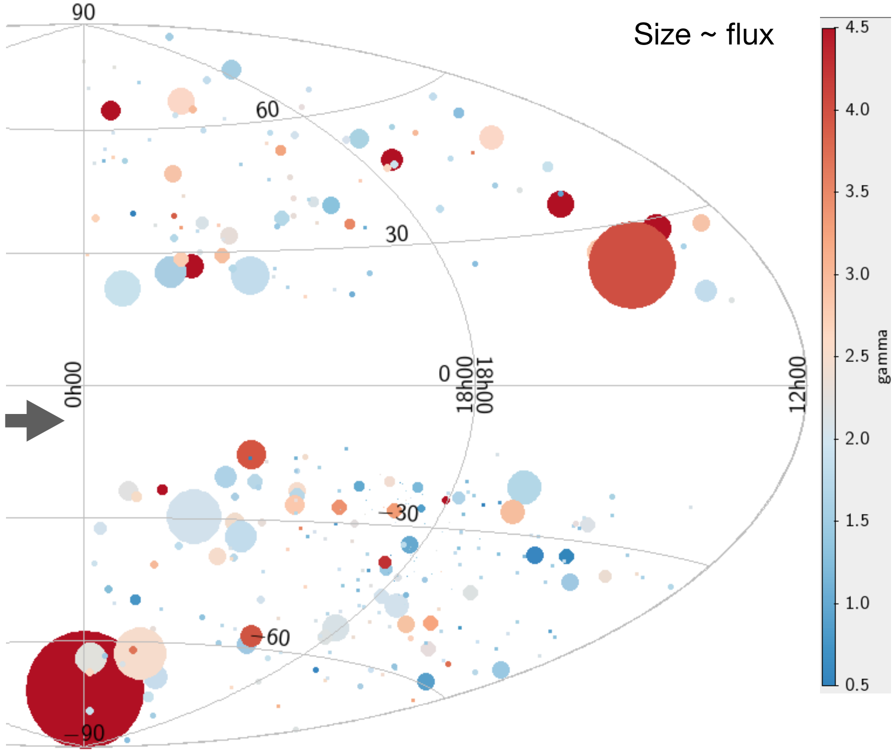


Searching for TDE in eROSITA (eRASS:5 data)

Grotova et al. in prep.

1. **eRASS1 & eRASS2** source catalogues >1 Million each → Variability catalogue **Amplitude,Sig.>4** ~2400
2. **NWAY LS10** counterparts → **Cuts (exclude stars & AGNs)** |BII| > 10, parallax significance < 3, W1 - W2 < 0.5, PSF cut, color cut (STAREX) ~700
3. **Archival X-ray data**
4. **Lightcurves** →
5. **Spectral modelling**
6. **Optical data if available**





~300 TDE candidates

Golden Sample: super-soft X-ray spectra

(Grotova+ in prep)

Grotova et al. in prep.

See also Sazonov et al. 2021

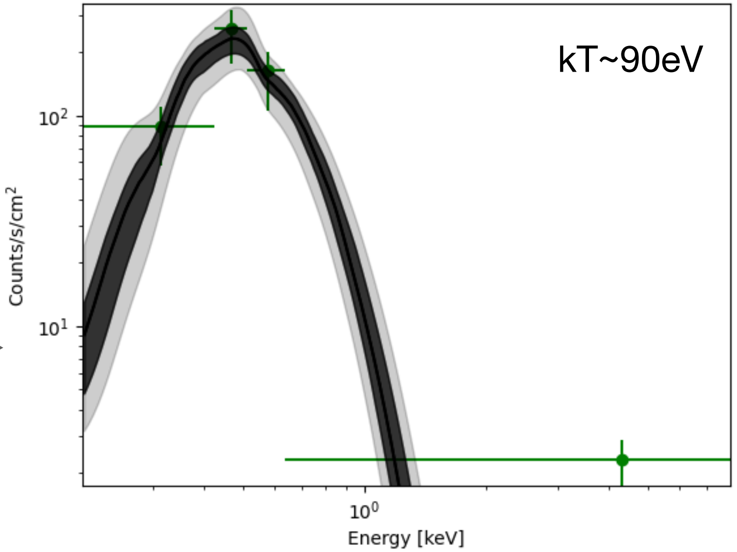
1. **eRASS1 & eRASS2** source catalogues >1 Million each → Variability catalogue **Amplitude,Sig.>4** ~2400

2. **NWAY LS10** counterparts → **Cuts (exclude stars & AGNs)** |BII| > 10, parallax significance < 3, W1 - W2 < 0.5, PSF cut, color cut (STAREX) ~700

3. **Archival X-ray data**

4. **Lightcurves**

5. **Spectral modelling** →



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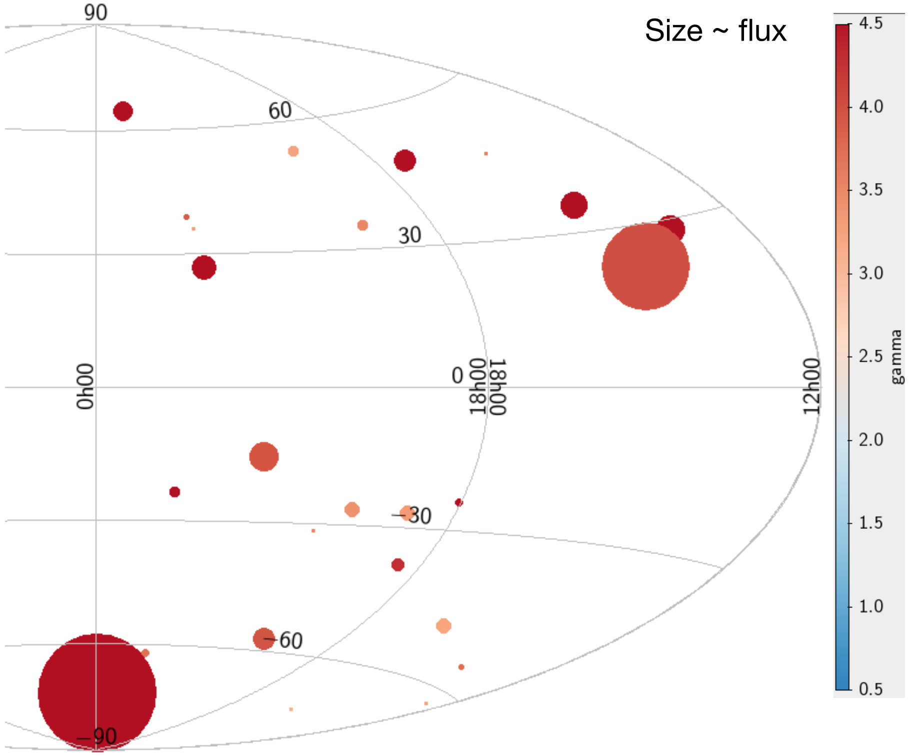
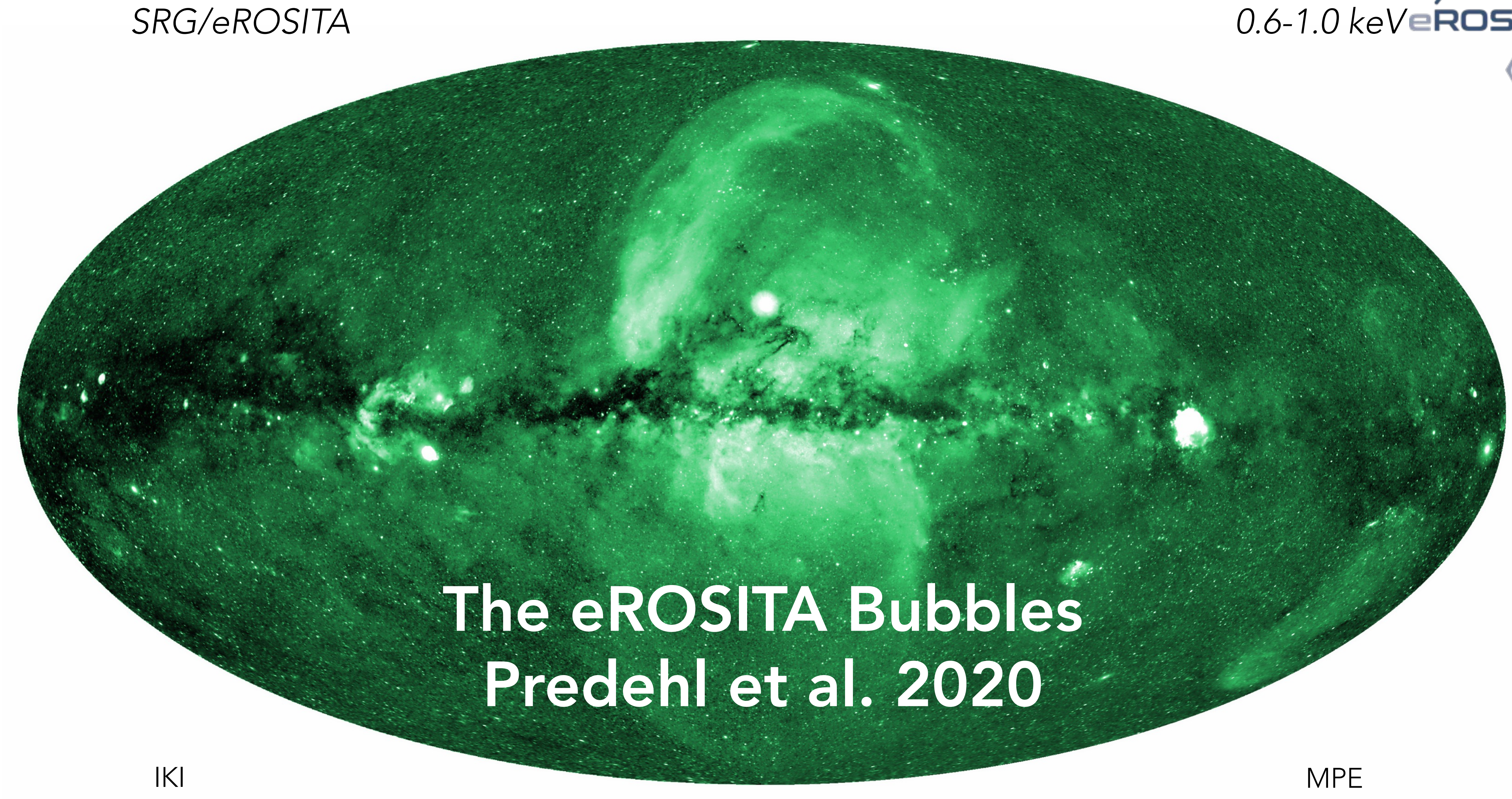


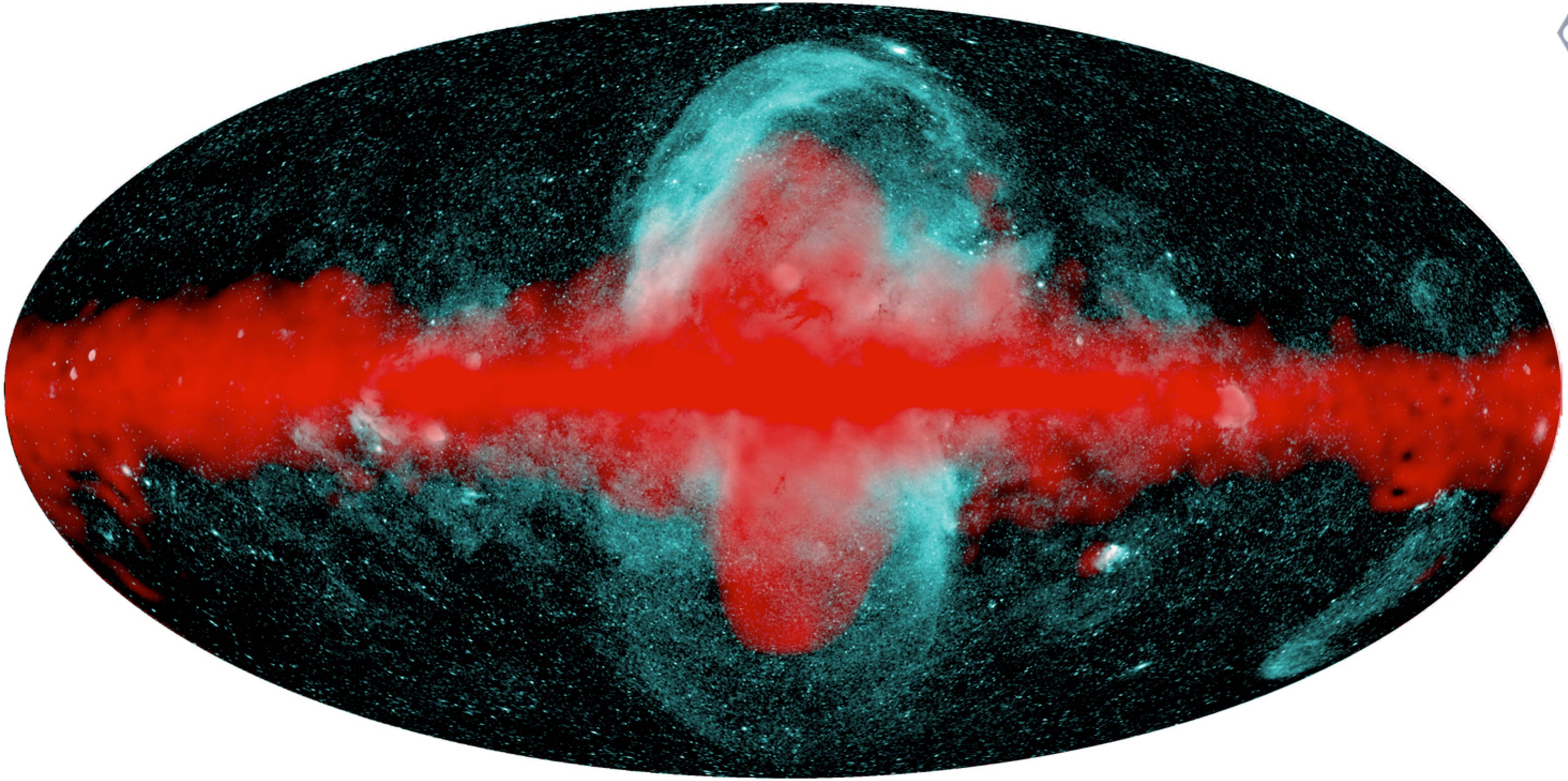
~25 Golden Sample

6. **Optical data if available**



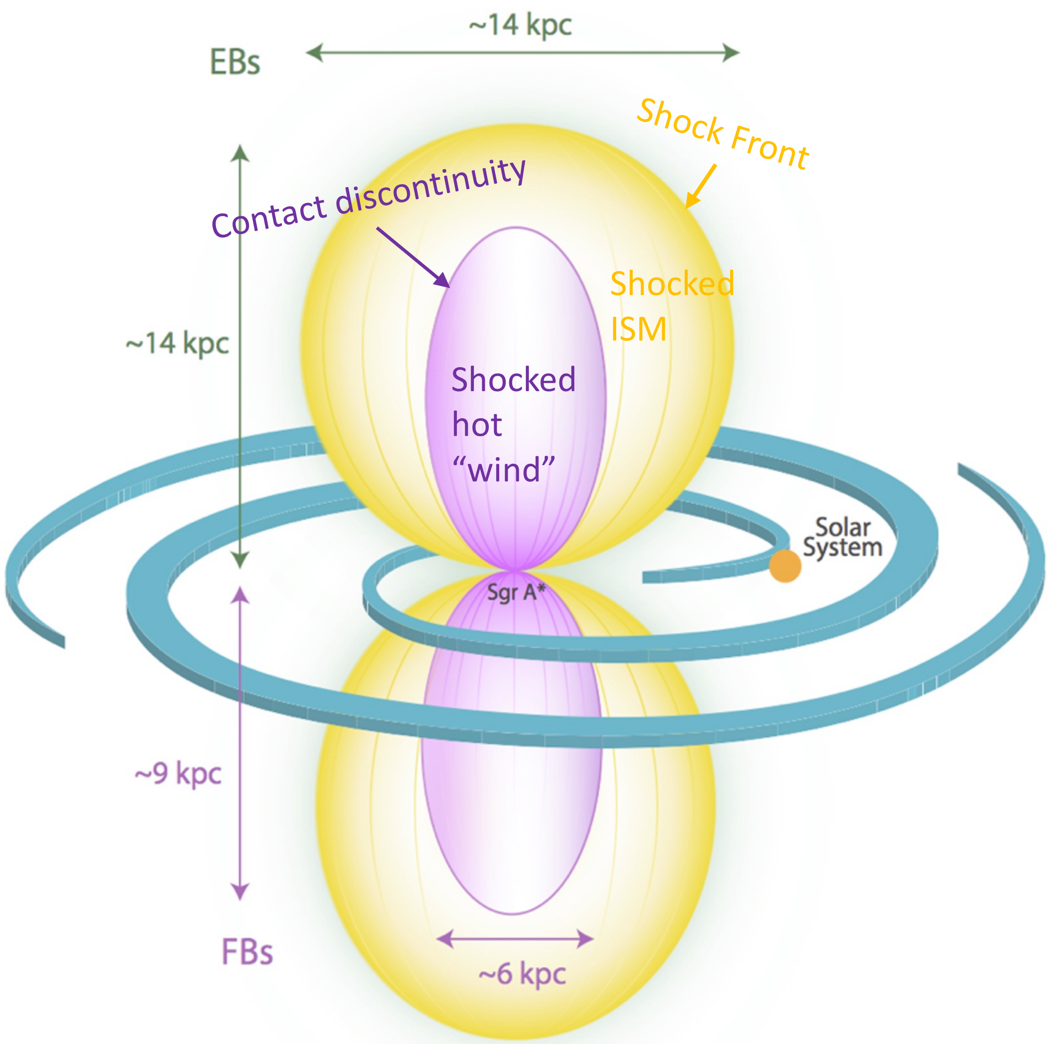
Credit: Sanders, Brunner (MPE); Churazov, Gilfanov (IKI)

Fermi (>1GeV) vs. eRASS1, 0.6-1 keV



Credit: Khabibullin, Selig (MPA)

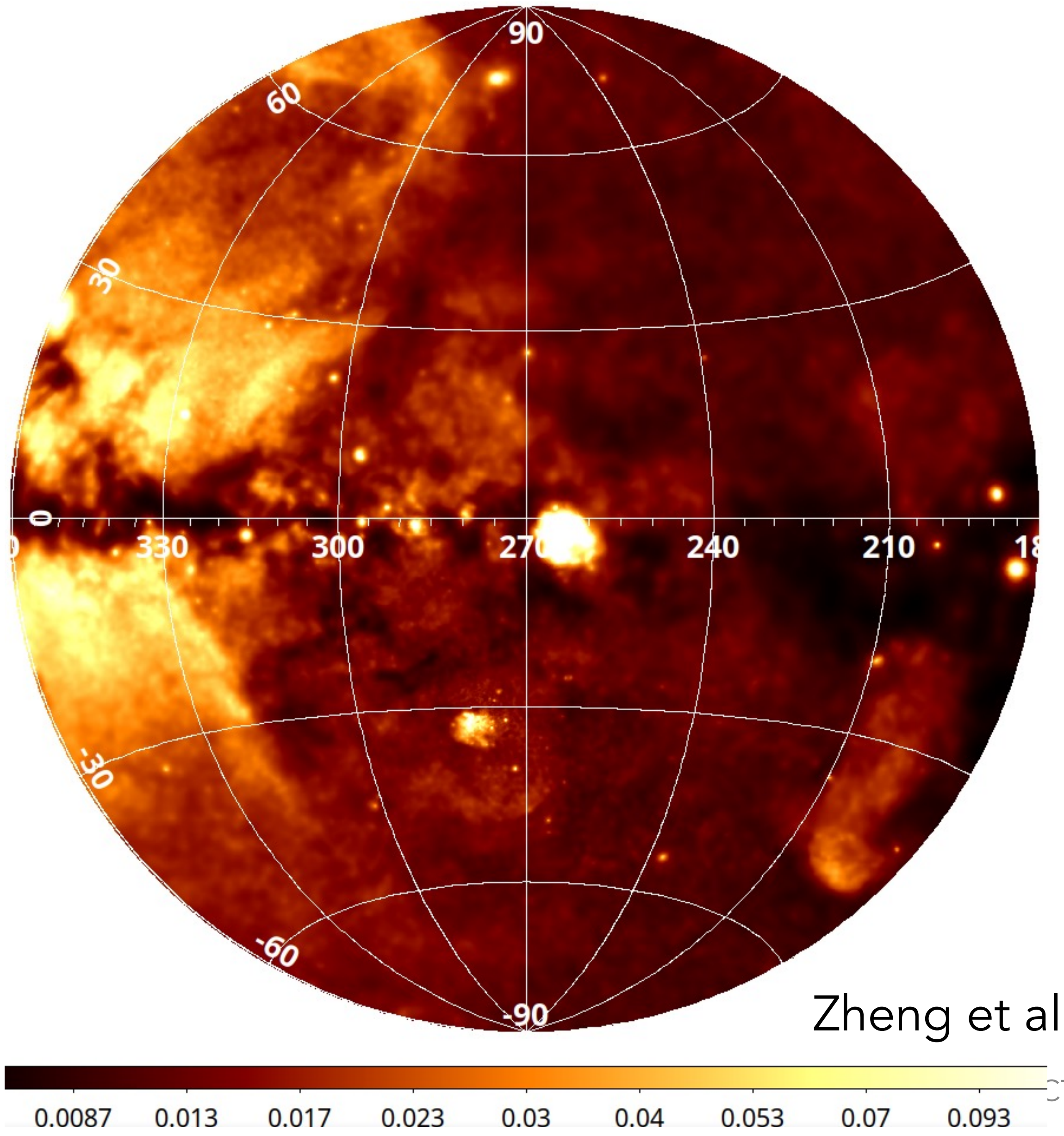
The eROSITA Bubbles

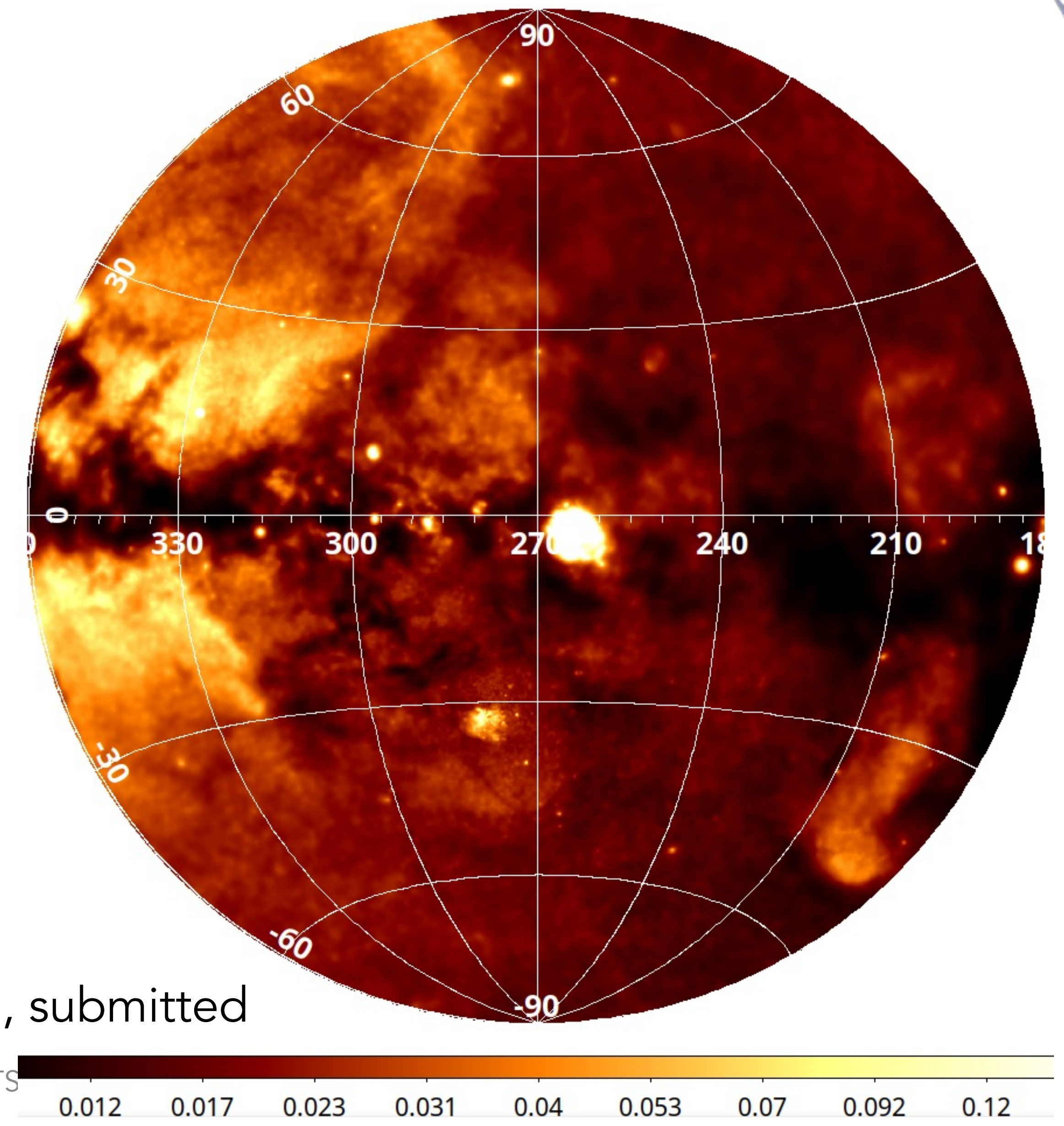


- **$L_{X,tot}$~10^{39} erg/s**
- Energetics:
  - Assume *kT*=0.3 keV and abundances of 0.2 Solar
  - Shock with M~1.5 (from T jump)
- **E_{tot}~10^{56} erg** (~ 10x Fermi bubbles!)
  - **Age~20 Myr**
  - **Energy release rate of ~1-3×10^{41} erg/s**
- Gas Cooling time ~2 x 10^8 years (>> age of bubbles)

Predehl, Sunyaev et al. Nature (2020)

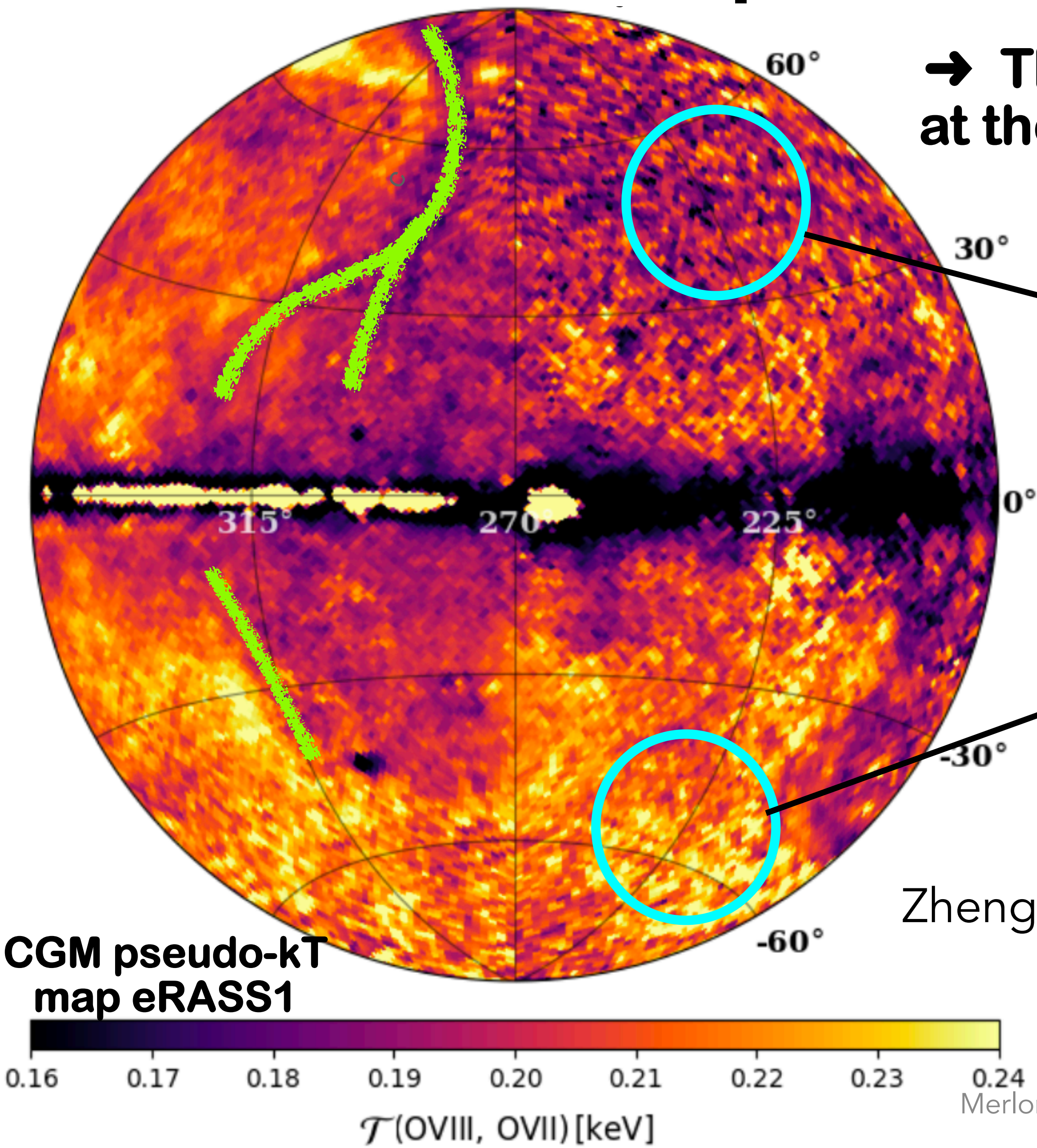
Narrow band maps: OVII and OVIII



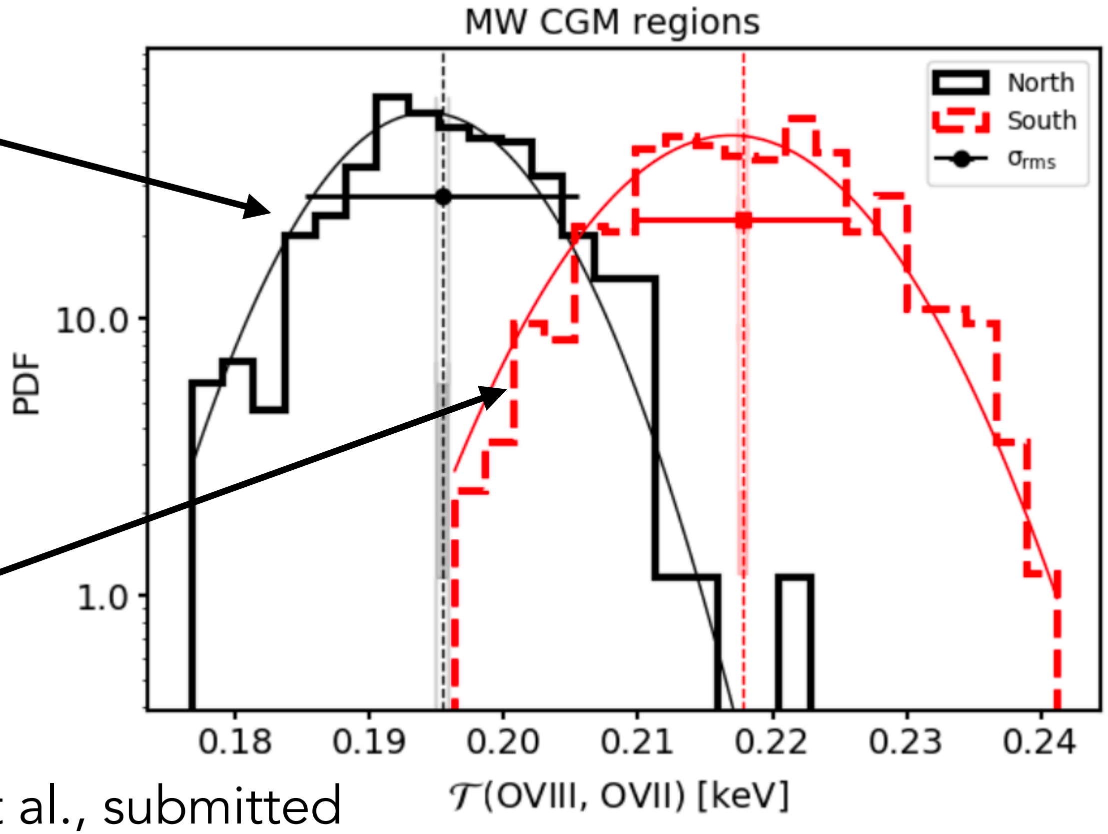


Zheng et al., submitted

Pseudo-temperature map from OVIII/OVII



➜ **Thick (~10°) shell of (colder?) plasma at the interface with the Galactic outflow**

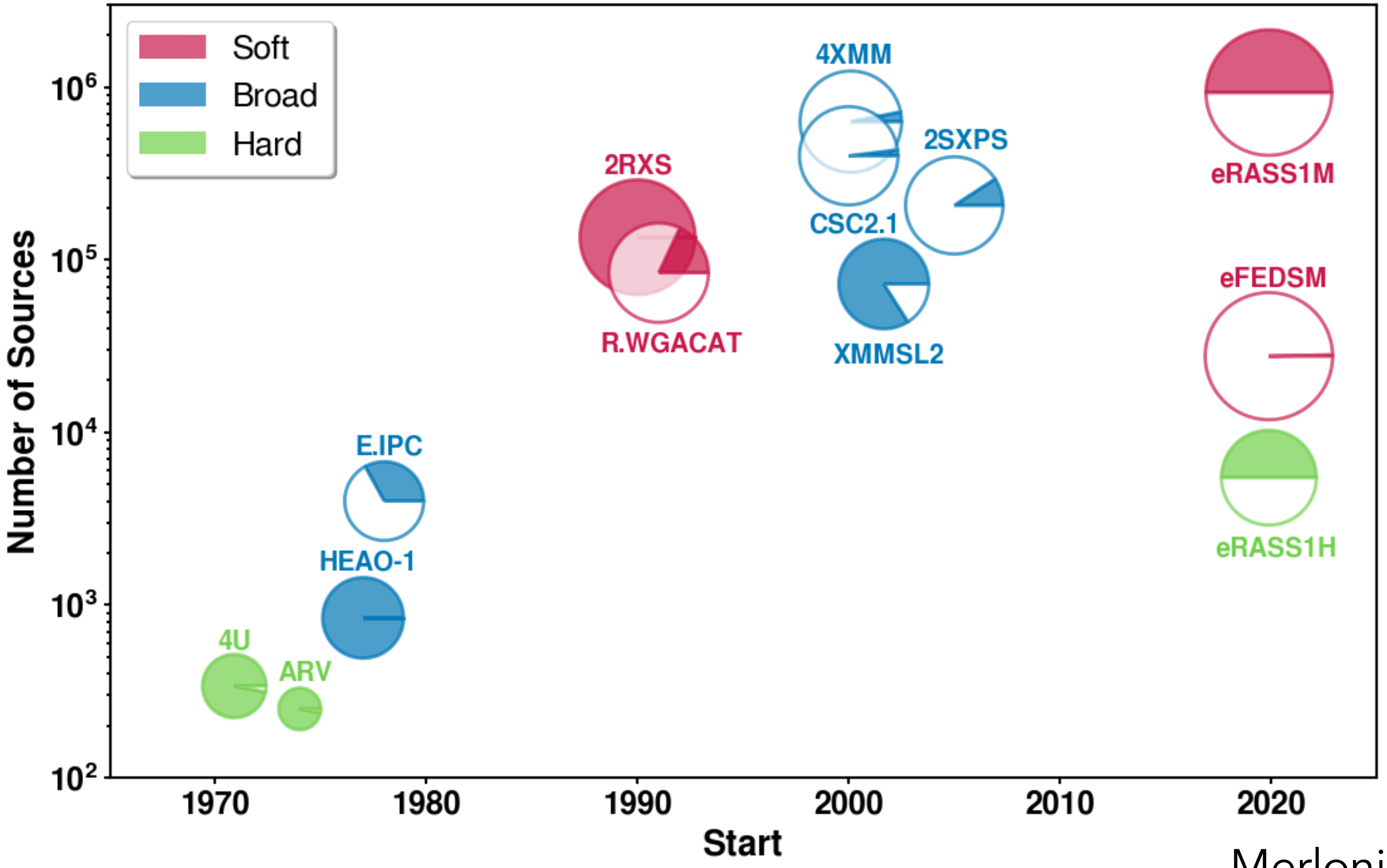


Zheng et al., submitted

➜ **ΔkT_{CGM} ~ 12% between north and south**

➜ **ΔkT_{CGM} < 4% on small (2°-20°) scales**

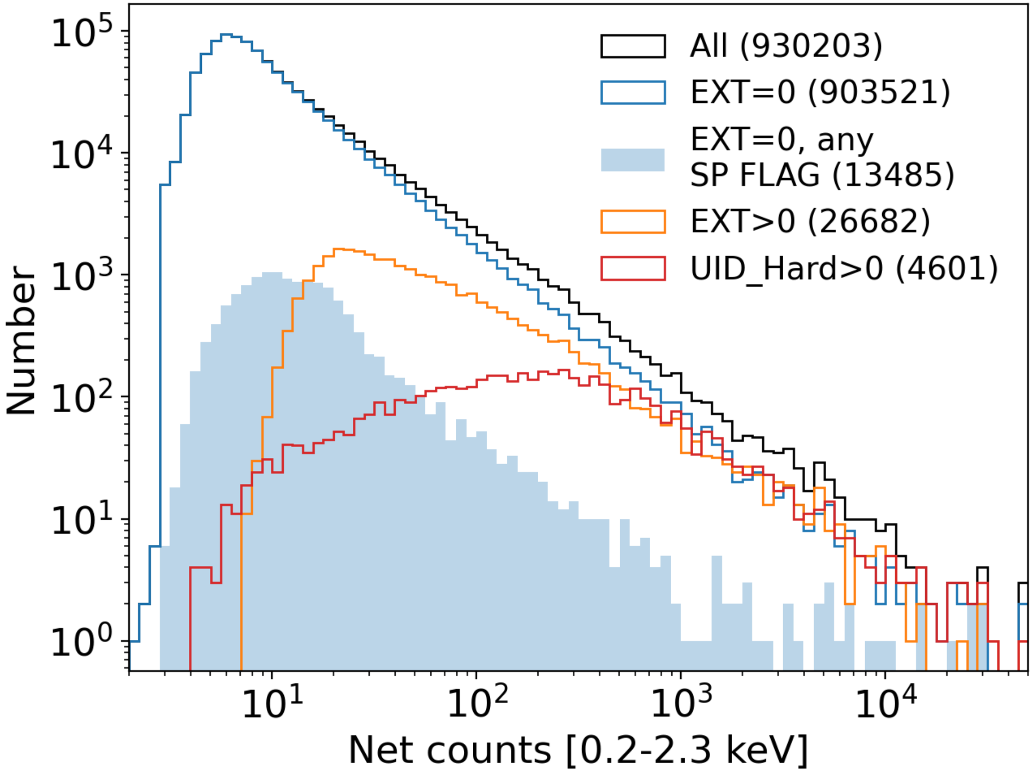
eRASS1 and X-ray catalogues

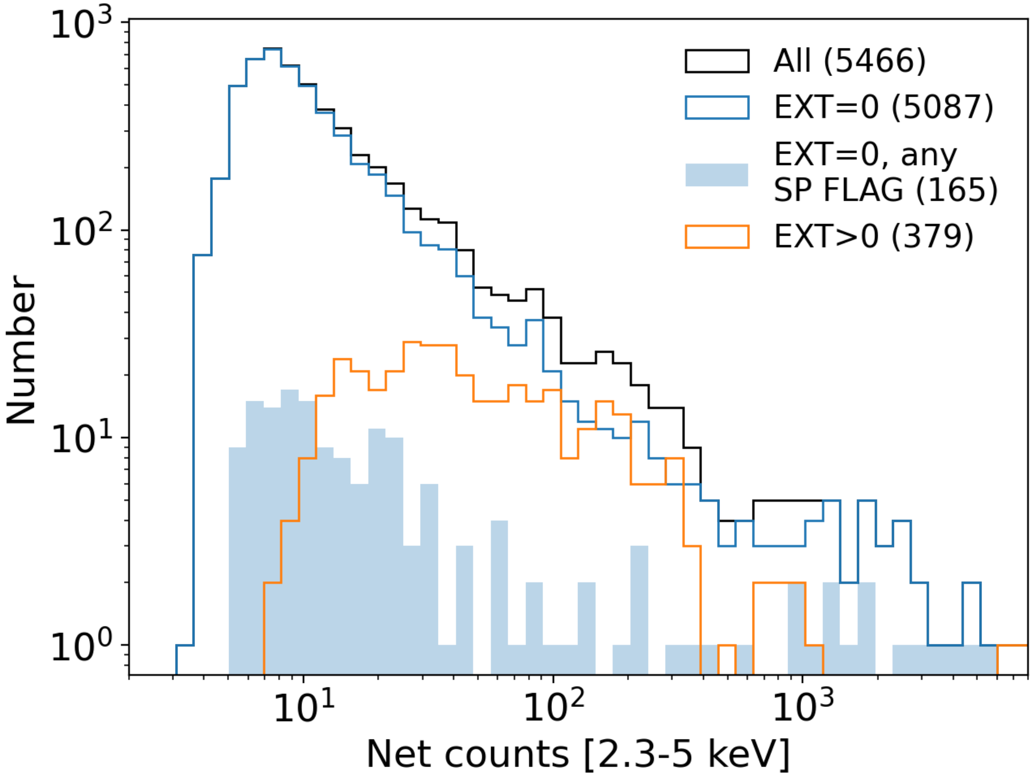


Merloni et al. (2024)

eRASS1 Catalogues

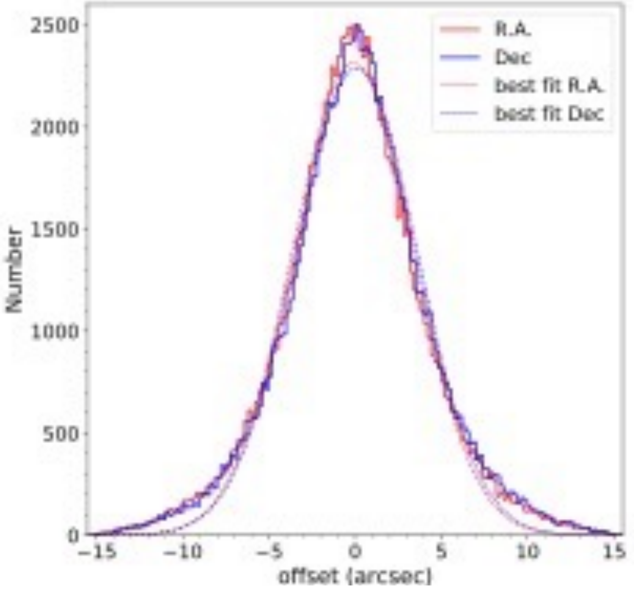
Soft band 0.2-2.3 keV, Point sources: 903k
Soft band 0.2-2.3 keV, extended: 26.6k (of which 12k optically confimred clusters)
Hard band 2.3-5 keV, Point Sources: 5k
Hard band 2.3-5 keV, Extended: 380

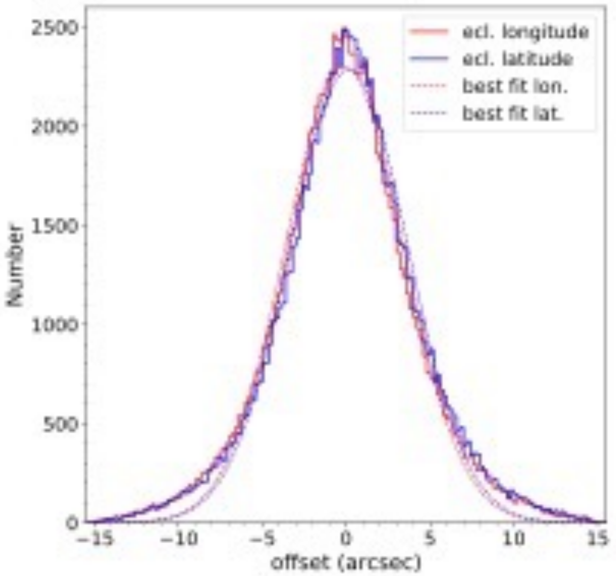




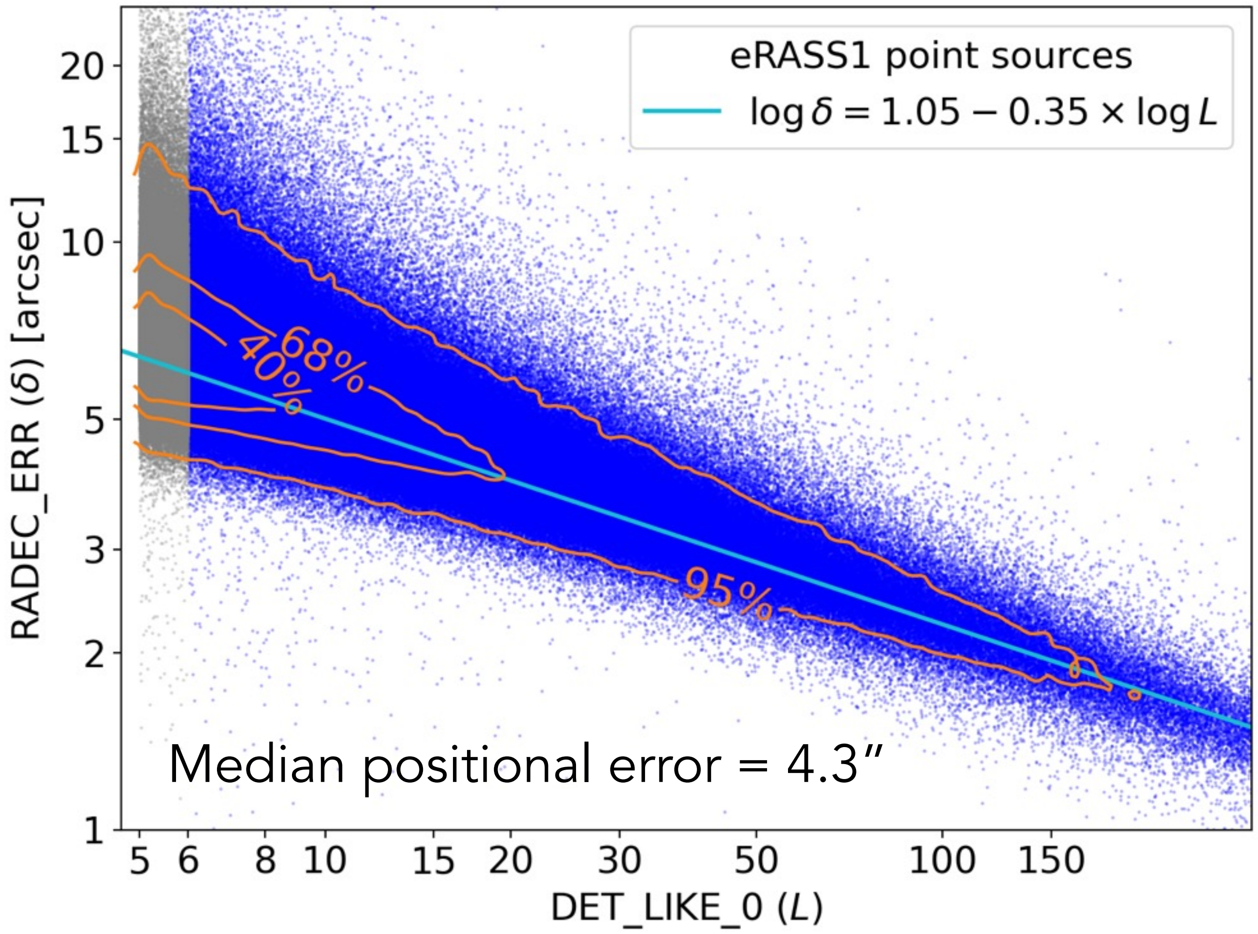
Merloni et al. (2024)

eRASS1 'Main' Catalogue: Astrometry





Point sources astrometric accuracy

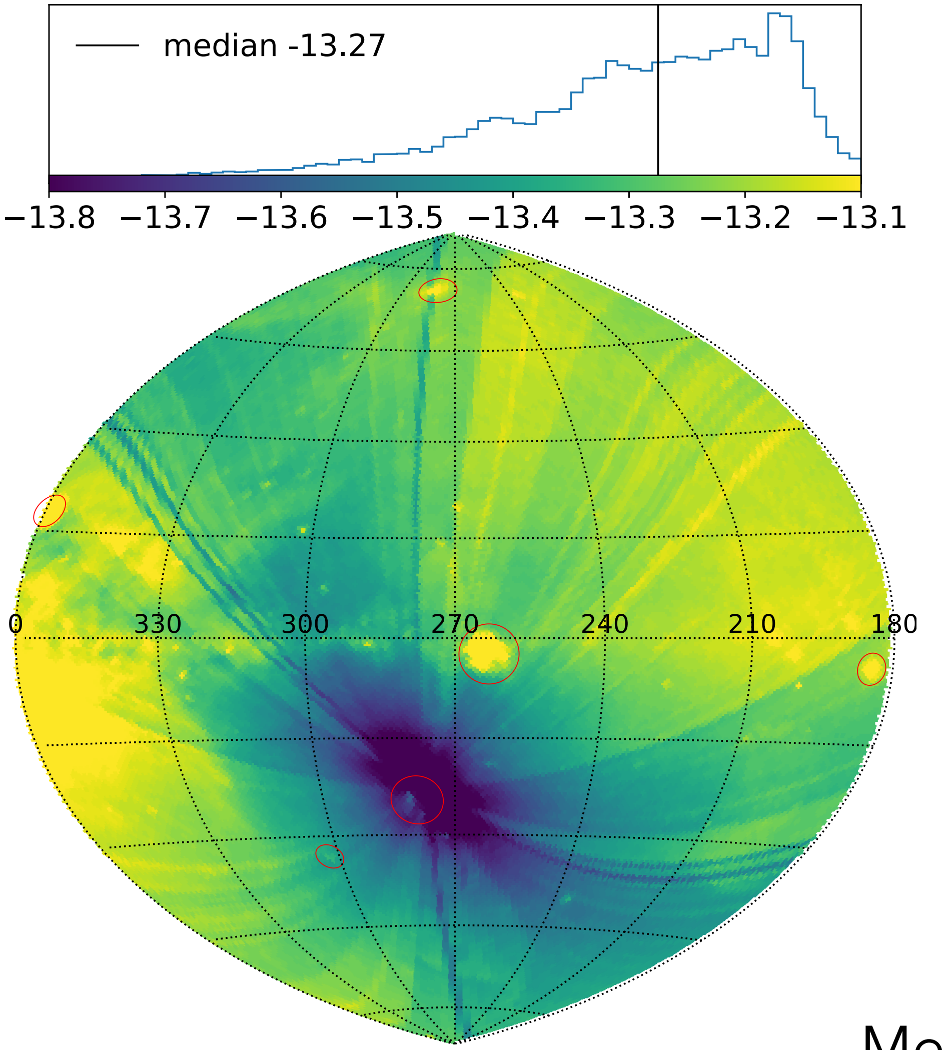


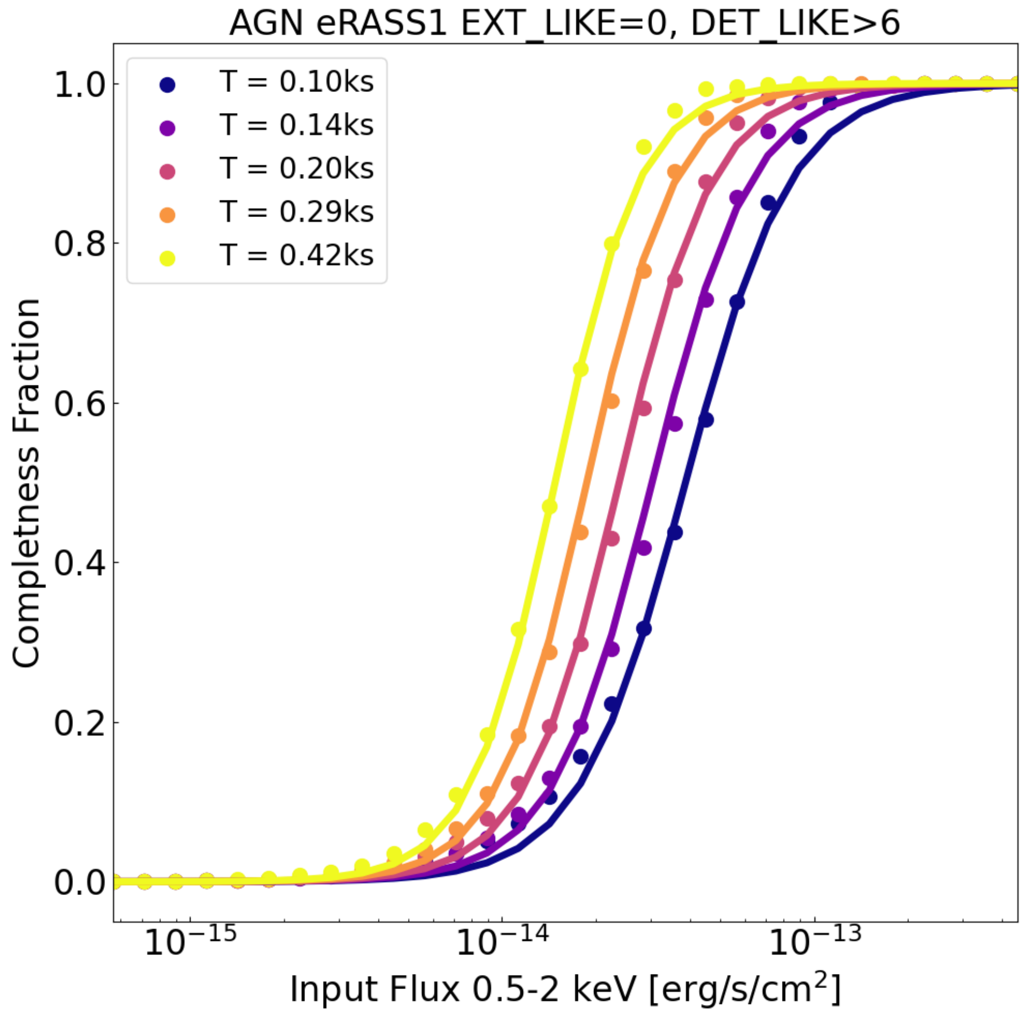
Median positional error = 4.3"

Merloni et al., A&A, in press

eRASS1 Main Catalogue: flux limit

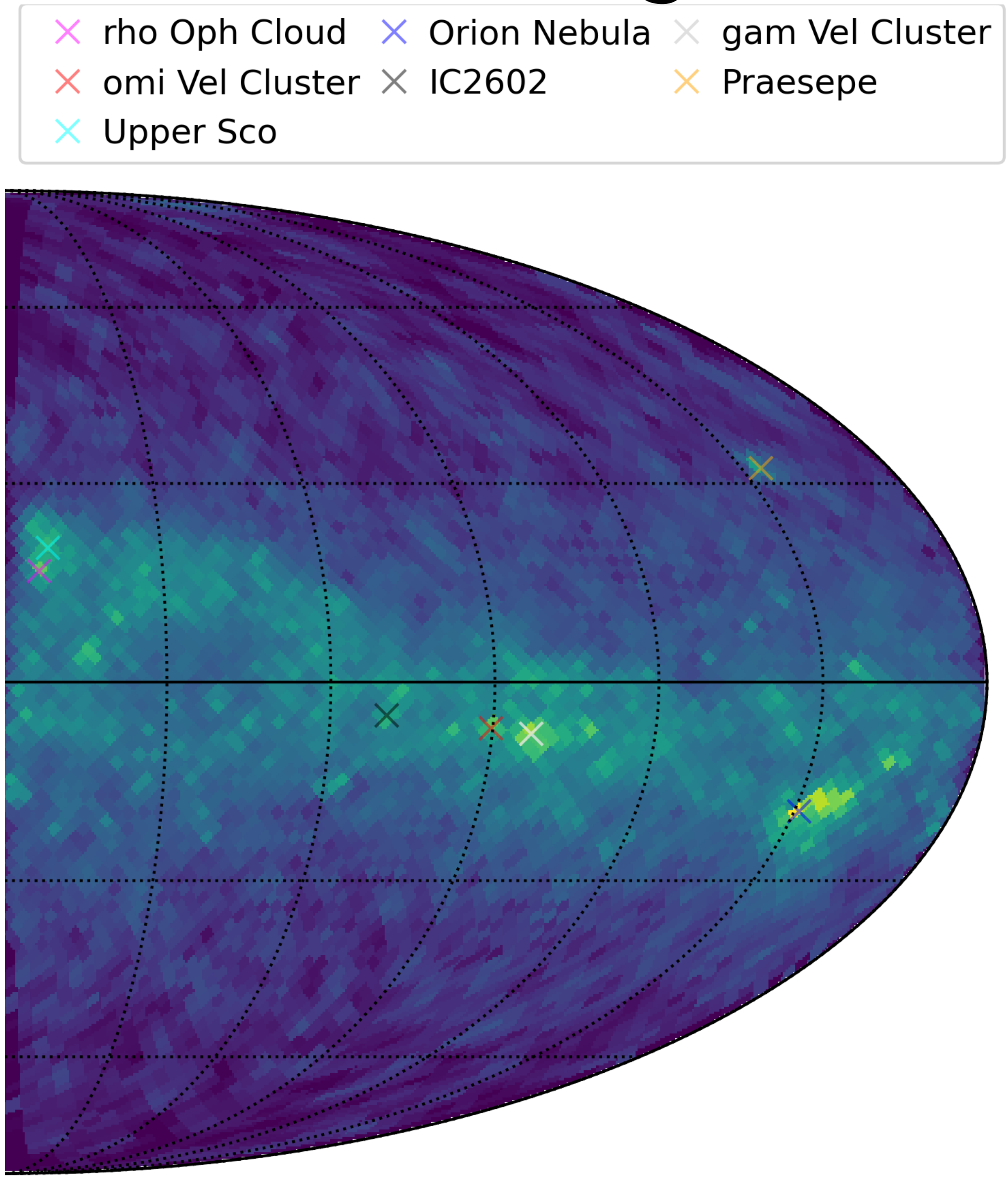
Log of 0.5-2 keV flux limit

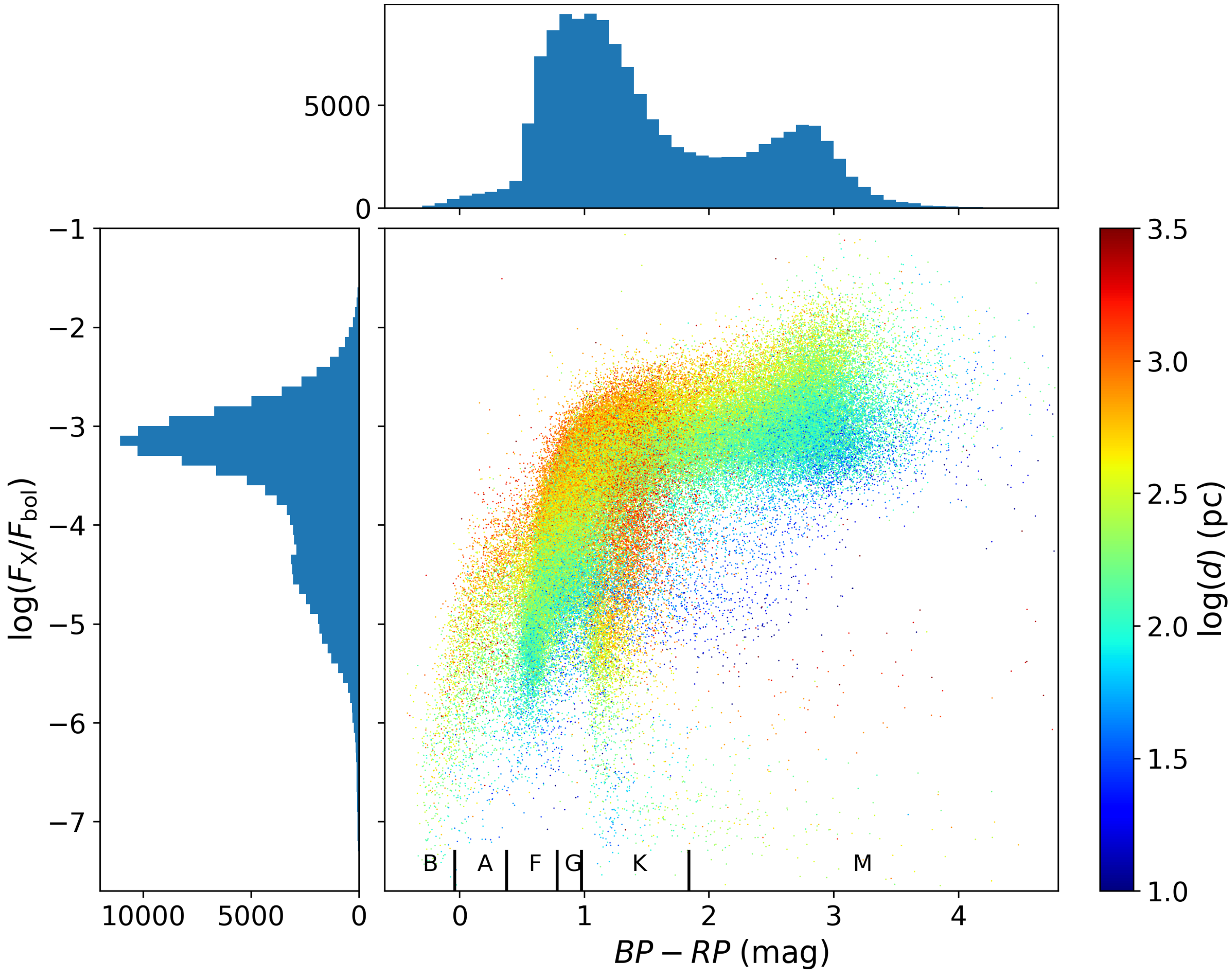




Merloni et al., A&A, in press

The SRG/eROSITA all-sky survey: Identifying ~130k coronal-emitting stars Freund et al. (2024)

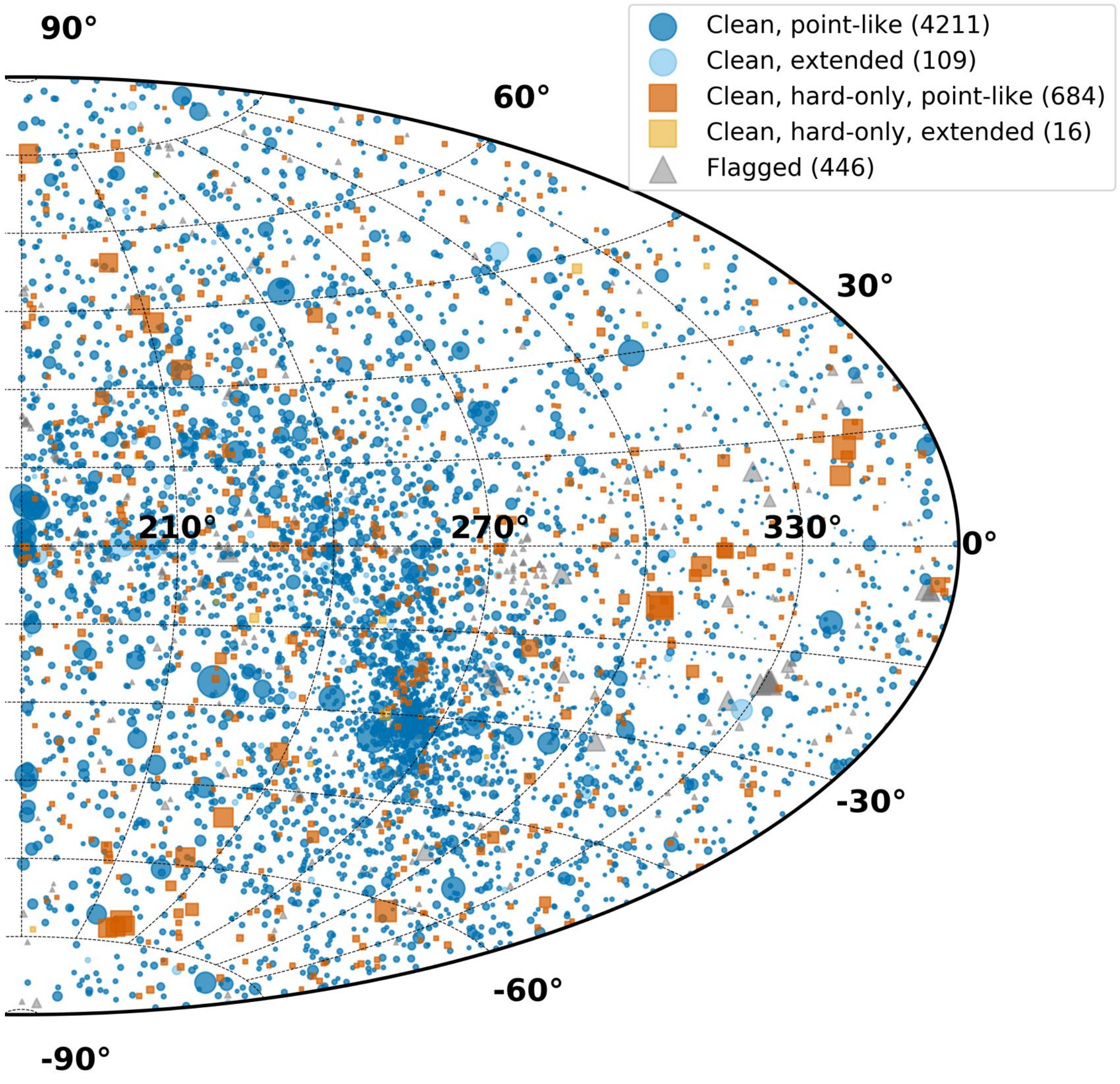




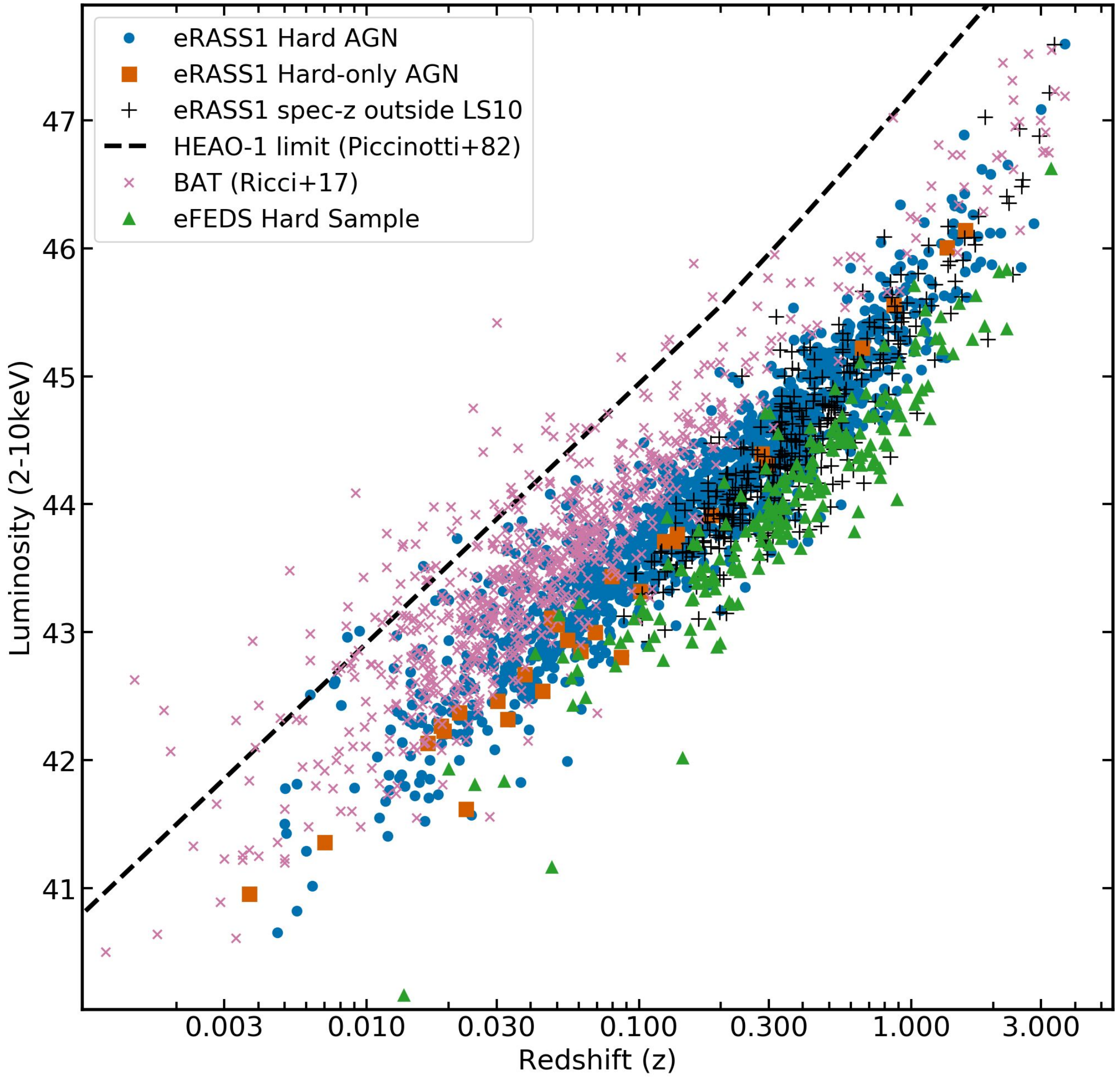
Sophia Waddell et al. arXiv:2401.17306

The eRASS:1 hard (2.3-5keV) sample: **5466 sources**

- 22 times more sources than eFEDS
- Divided into X-ray point-like vs. extended
- Divided into hard + soft detections vs. only above 2.3keV



Luminosity - redshift space

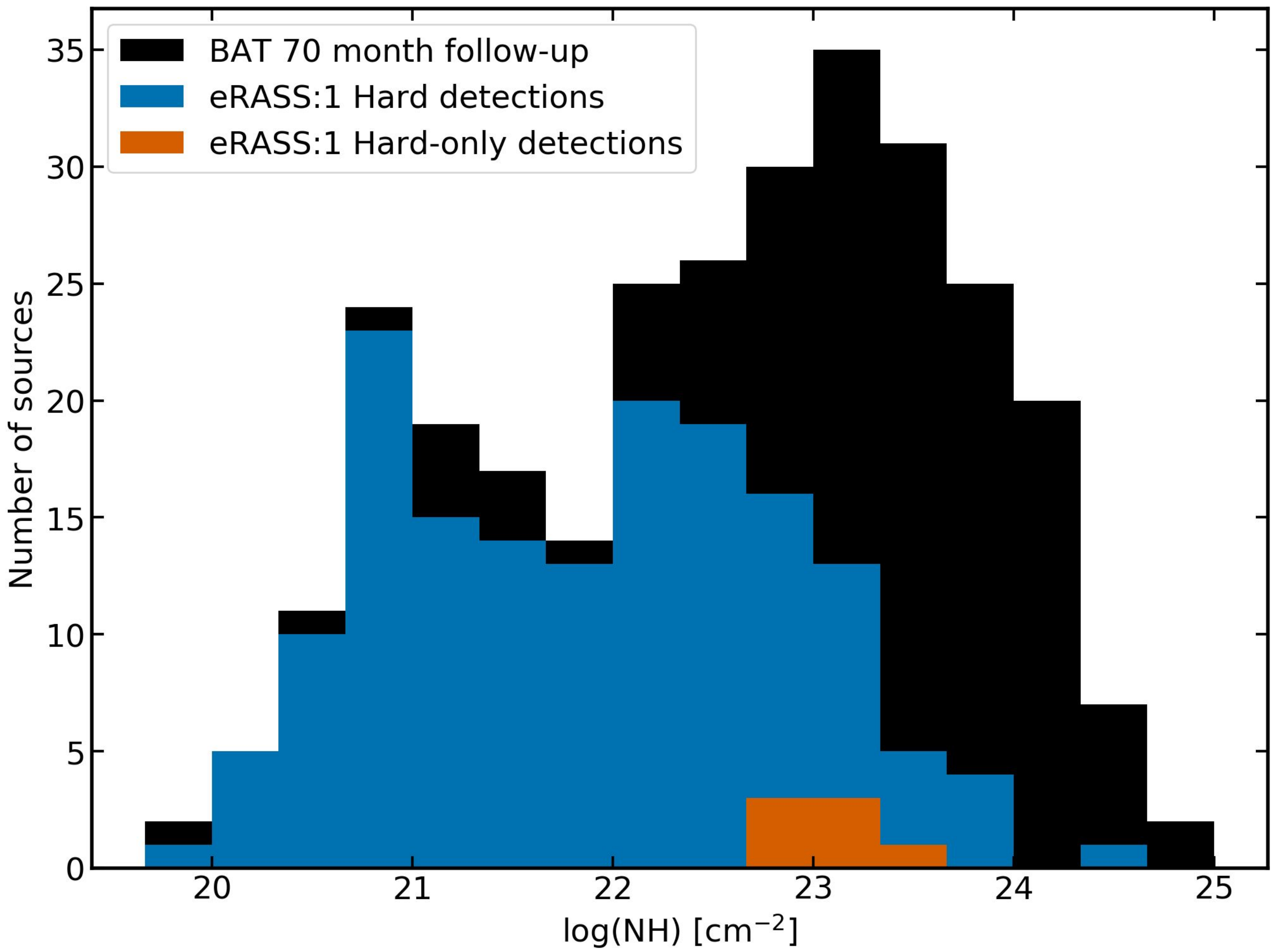


- Luminosity redshift for eRASS1 hard, hard-only, including sources in Galactic plane
- HEAO-1 limit (previous all-sky hard X-ray survey) and BAT AGN also shown
- eRASS1 is deeper, higher redshift than other hard X-ray selected AGN samples
- Redshifts span 3 orders of magnitude, luminosity spans 7

Waddell et al. arXiv:2401.17306

Comparison with Swift-BAT

- Comparison to the Swift-BAT AGN in eROSITA_DE sky (70 month catalog; Ricci et al.)
- NH is measured from spectral fitting using soft X-ray follow up (e.g. with Swift or XMM-Newton)
- Hard-only sources have high NH of log(NH) ~ 23



Waddell et al. arXiv:2401.17306

First results from the SRG/eROSITA All-sky Survey From Stars to Cosmology

RESEARCH CAMPUS, GARCHING, GERMANY

September 15-20, 2024

For information and registration see:

https://events.mpe.mpg.de/event/

Abstract Submission Deadline: May 15, 2024

Conclusions

X-ray astronomy is a key contributor to our exploration of the Universe, as it reveals both fundamental and exotic phenomena

eROSITA on SRG is the most powerful wide-field X-ray telescope to date. It has been in operation since Q3 2019, for more than 2 years, having completed 4.4 all-sky surveys

Thanks to its large Grasp, stable background and observing cadence eROSITA opens up new parameter space for X-ray astronomy

eRASS1 marks the coming of age of clusters cosmology as a Stage IV experiment

Numerous science highlights from DR1!

eRASS1 is now fully public! https://erosita.mpe.mpg.de/dr1/

www.mpe.mpg.de/eROSITA

Thank you