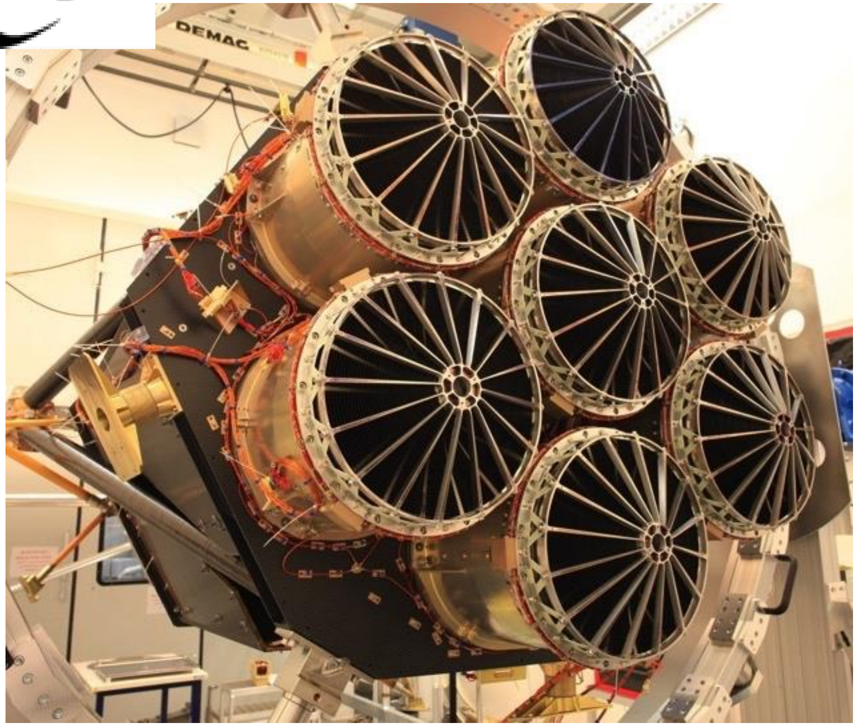
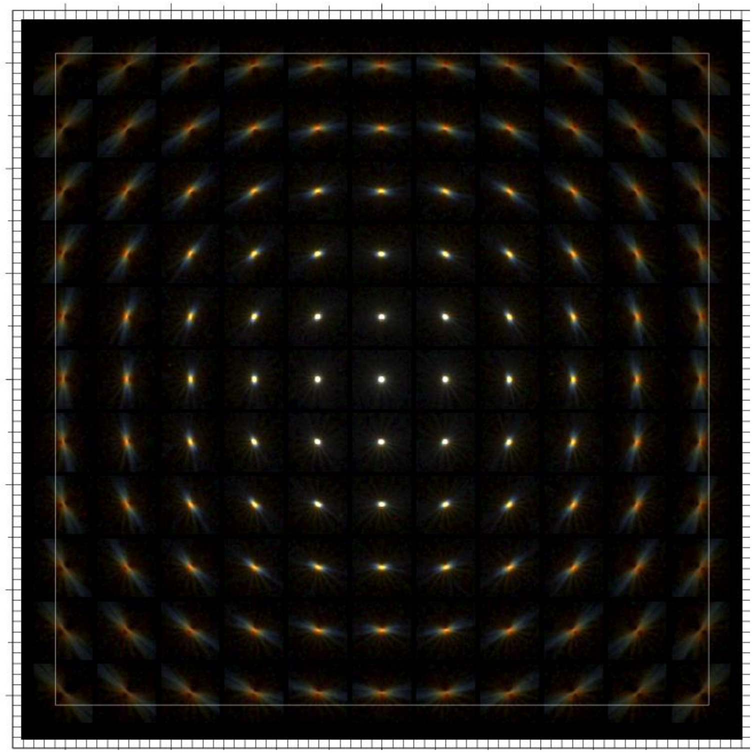
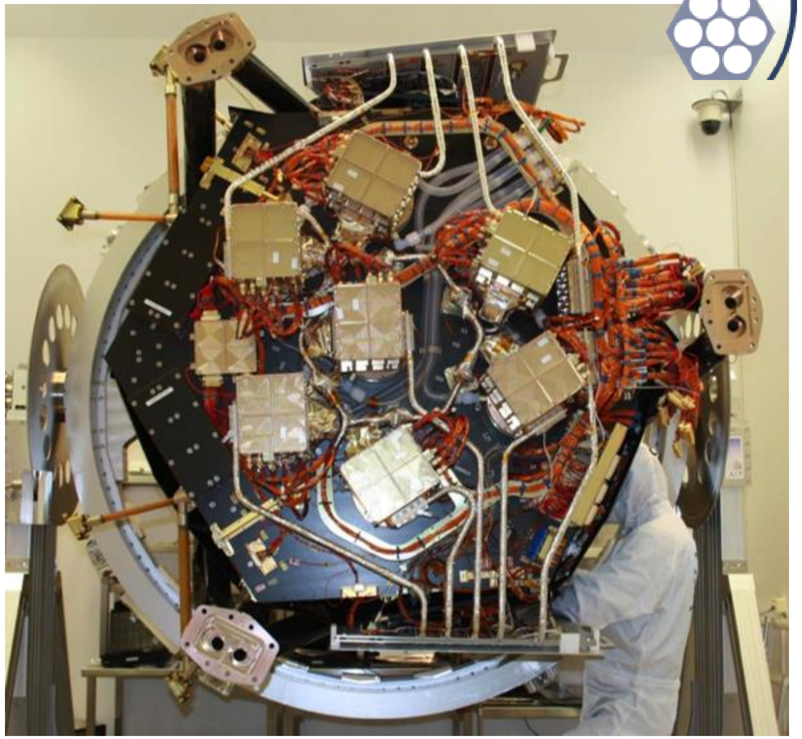
SRG/eROSITA:
Highlights from the all-sky survey DR1

Andrea Merloni (MPE)

eROSITA on SRG [Predehl et al. 2021]



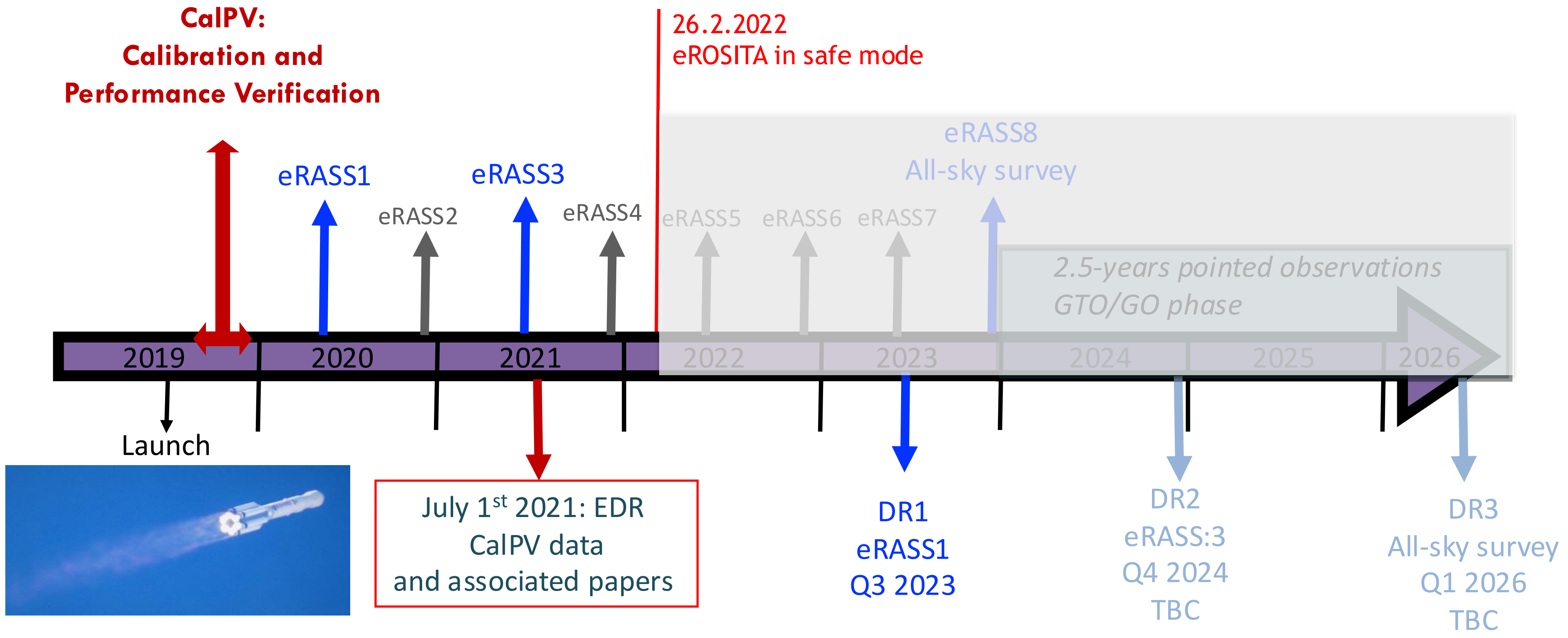




- Large Effective area (~**1300 cm^2 @1keV**, ~XMM-Newton)
- Large Field of view: 1 degree (diameter)
- Half-Energy width (HEW) ~18” (on-axis, point.); ~30” (FoV avg., survey)
  - Positional accuracy: ~4.5” (1σ)
- X-ray baffle: 92% stray light reduction
- pnCCD with framestore: 384x384x7~10^6 pixels (9.4”), no chip gaps, no ‘out of time’ events,
- **Spectral resolution** at all measured energies within specs (~80eV @1.5keV)

SRG Programmatics

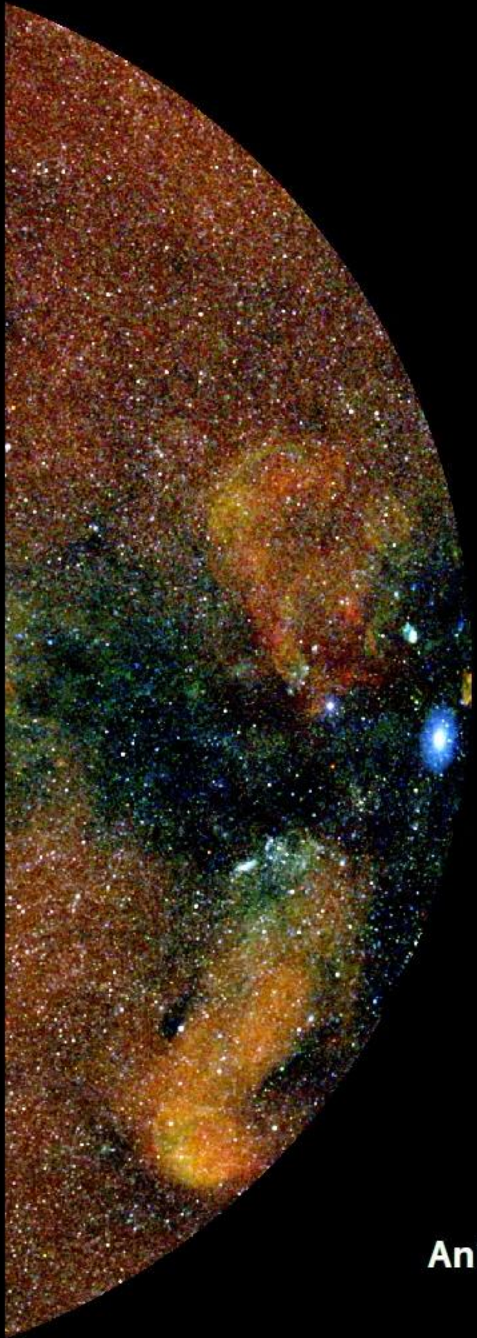
eRASS = eROSITA All-Sky Survey



- Early Data Release (EDR) in 2021: several fields, including eFEDS mini-survey
- DR1 on 31.1.2024
- DR2 (eRASS:3 catalogue only) Q3 2026
- DR3 (eRASS:4.4, all products) Q3 2028

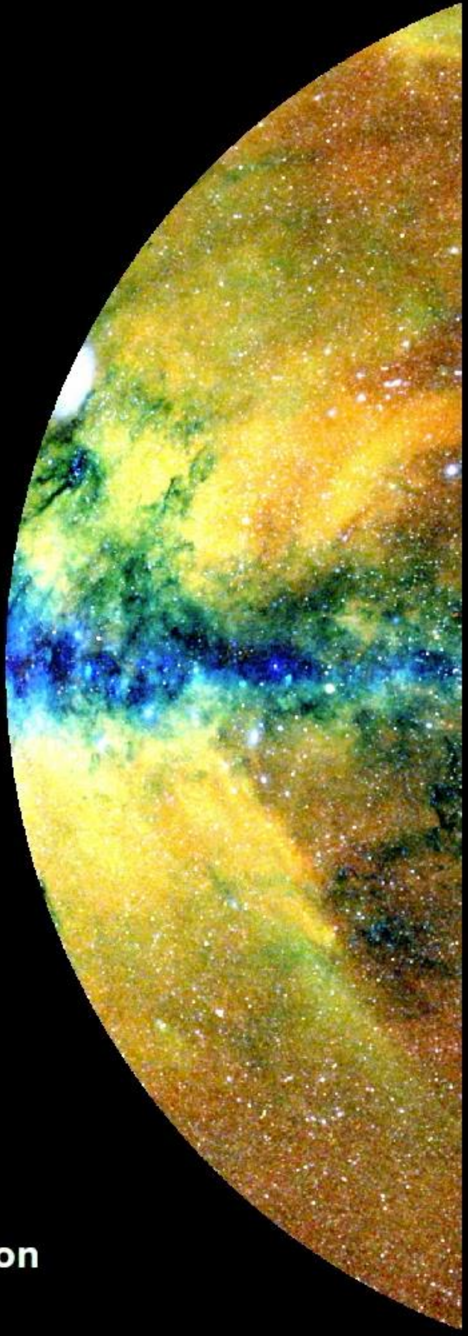
The All-Sky Surveys by Numbers

- 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



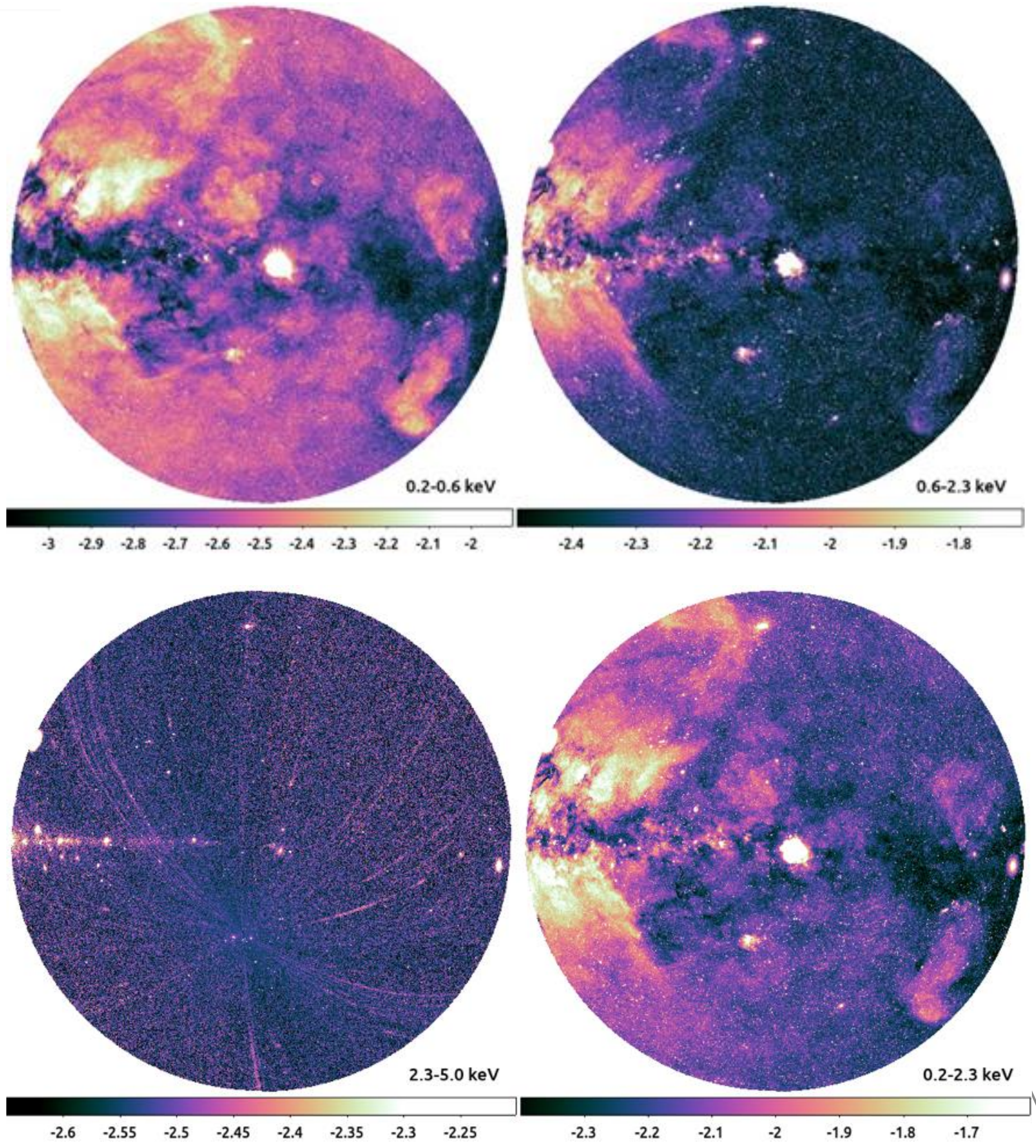
eROSITA

A tour of the western galactic hemisphere in eRASS1



Orthographic projection
Animation: J. Sanders for the MPE/eROSITA-DE collaboration
Music: Tonic by Torus

eROSITA-DE Data Release 1 products



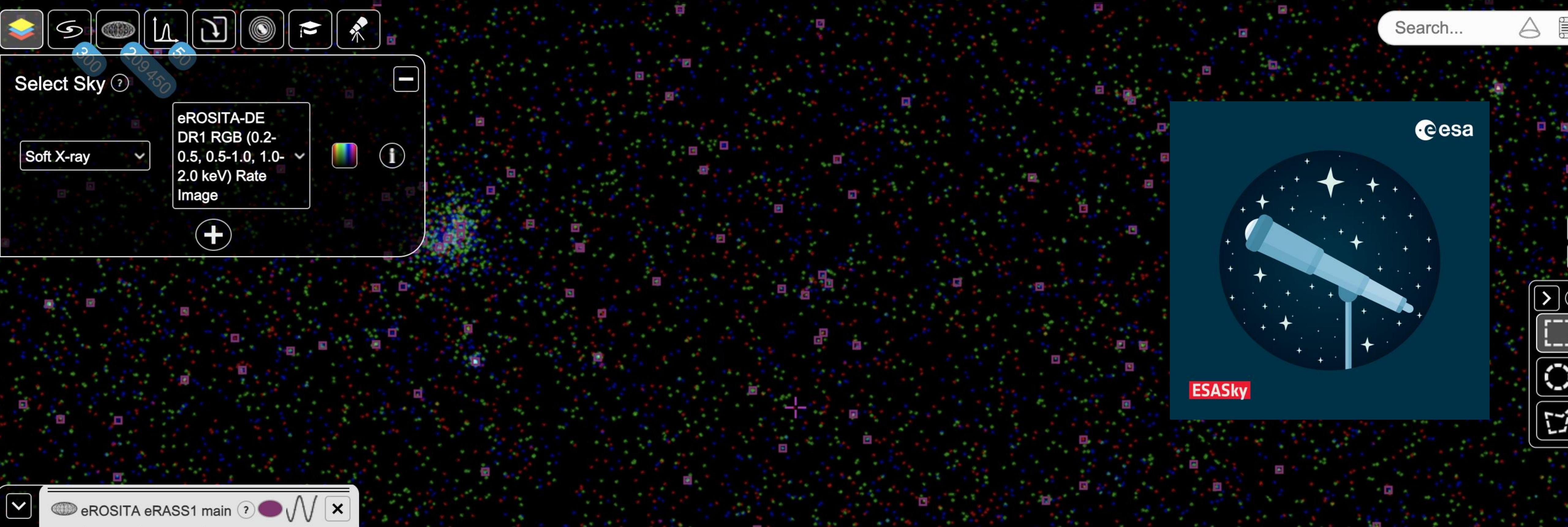
erosita.mpe.mpg.de/dr1/

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

Merloni et al. (2024)

J2000 11 27 25.082 -14 55 05.49 FoV: 3.3° X 1.8° eROSITA-DE DR1 RGB (0.2-0.5, 0.5-1.0, 1.0-2.0 keV) Rate Image

Sci. Mode En Feedback

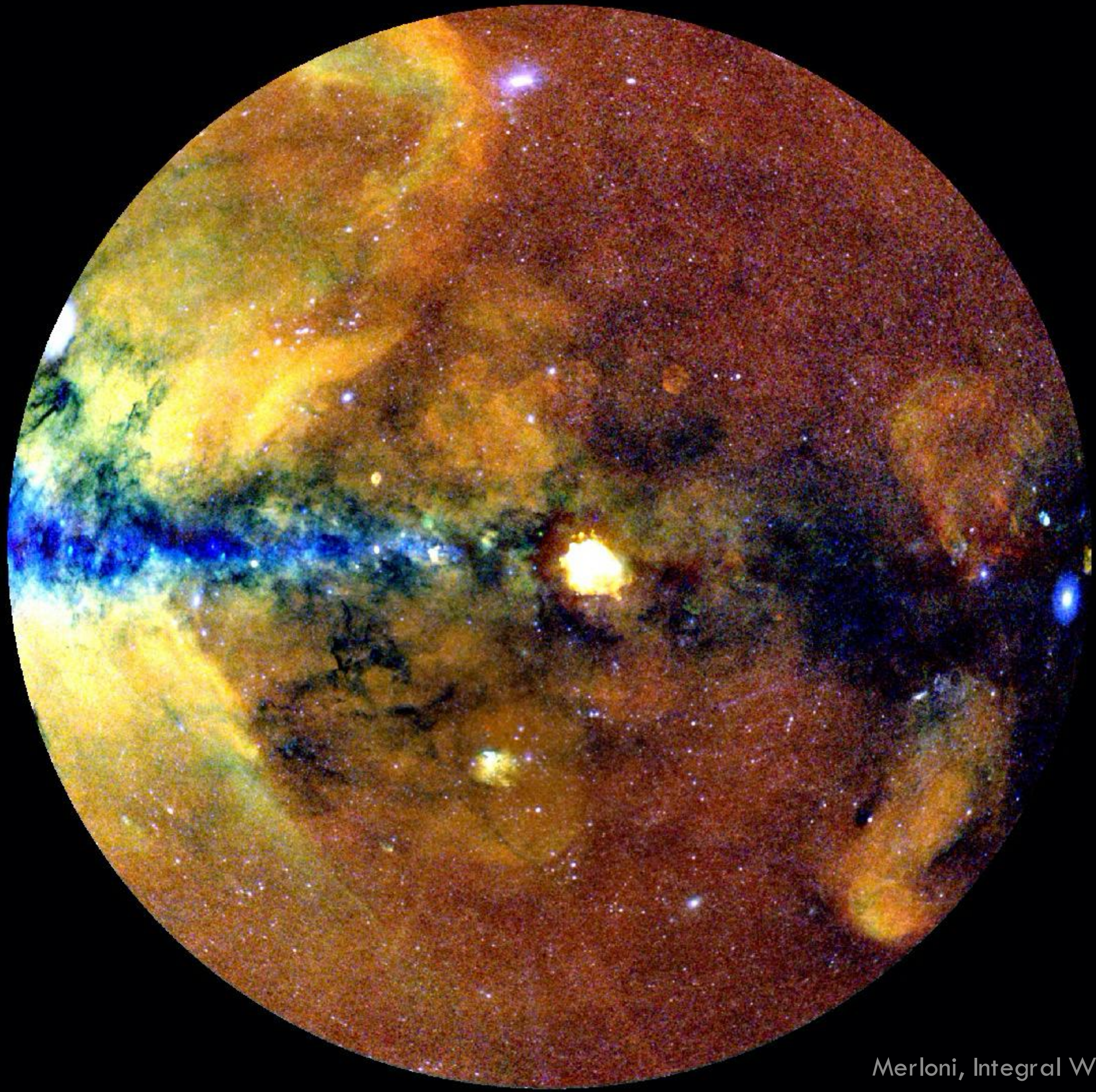


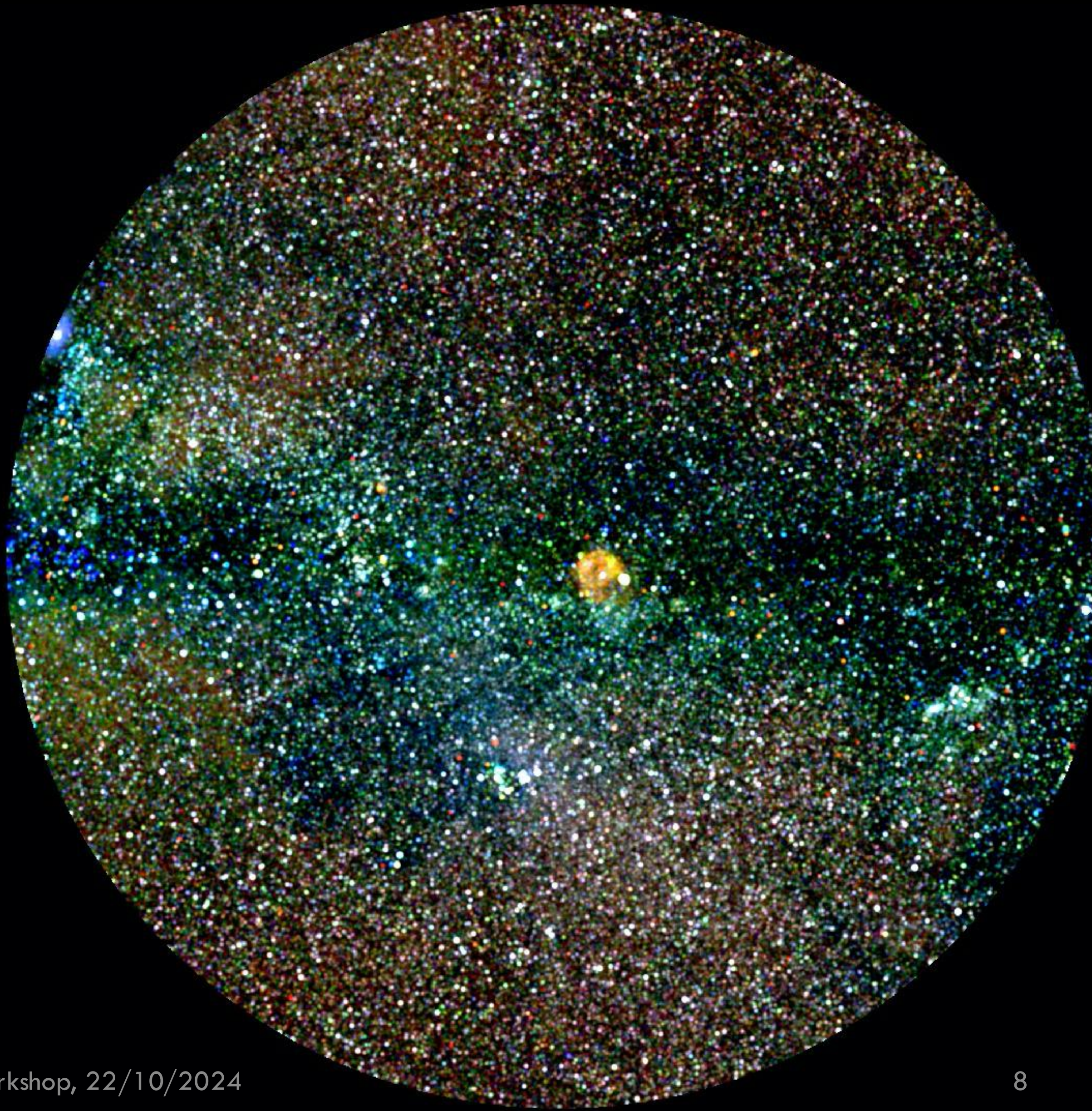
eROSITA eRASS1 main

	Go to	Archive	IAUNAME	UID Hard	RA [deg]	DEC [deg]	ML CTS 1 [count]	ML FLUX 1 [erg s-1 cm-2]	ML CTS P1 [count]	ML FLUX P1 [erg s-1 cm-2]	ML CTS P2 [count]	ML FLUX [erg s-1 cr
			1eRASS J113007.0-144926	217410500008	11h 30m 07.062s	-14° 49' 26.78"	126.7935	1.1505E-12	5.7864	6.0287E-14	45.6895	3.2202E-1
			1eRASS J112047.2-141639	0	11h 20m 47.275s	-14° 16' 39.18"	77.8598	7.032E-13	7.7978	8.1012E-14	37.5667	2.6358E-1
			1eRASS J112129.4-141542	0	11h 21m 29.475s	-14° 15' 42.53"	52.5244	4.7087E-13	14.6249	1.5056E-13	21.7688	1.5151E-1
			1eRASS J112222.3-145110	0	11h 22m 22.313s	-14° 51' 10.84"	33.8453	3.152E-13	6.1663	6.5875E-14	20.6594	1.4939E-1
			1eRASS J112904.9-144856	0	11h 29m 04.958s	-14° 48' 56.58"	31.5837	2.8423E-13	3.0111	3.1119E-14	17.0191	1.1889E-1
			1eRASS J112055.4-142028	0	11h 20m 55.419s	-14° 20' 28.10"	27.8536	2.6134E-13	2.1907	2.3621E-14	8.005	5.8312E-1
			1eRASS J112655.7-145556	0	11h 26m 55.750s	-14° 55' 56.51"	15.5465	1.4698E-13	3.5586	3.8631E-14	3.7665	2.7672E-1

Rows: 222

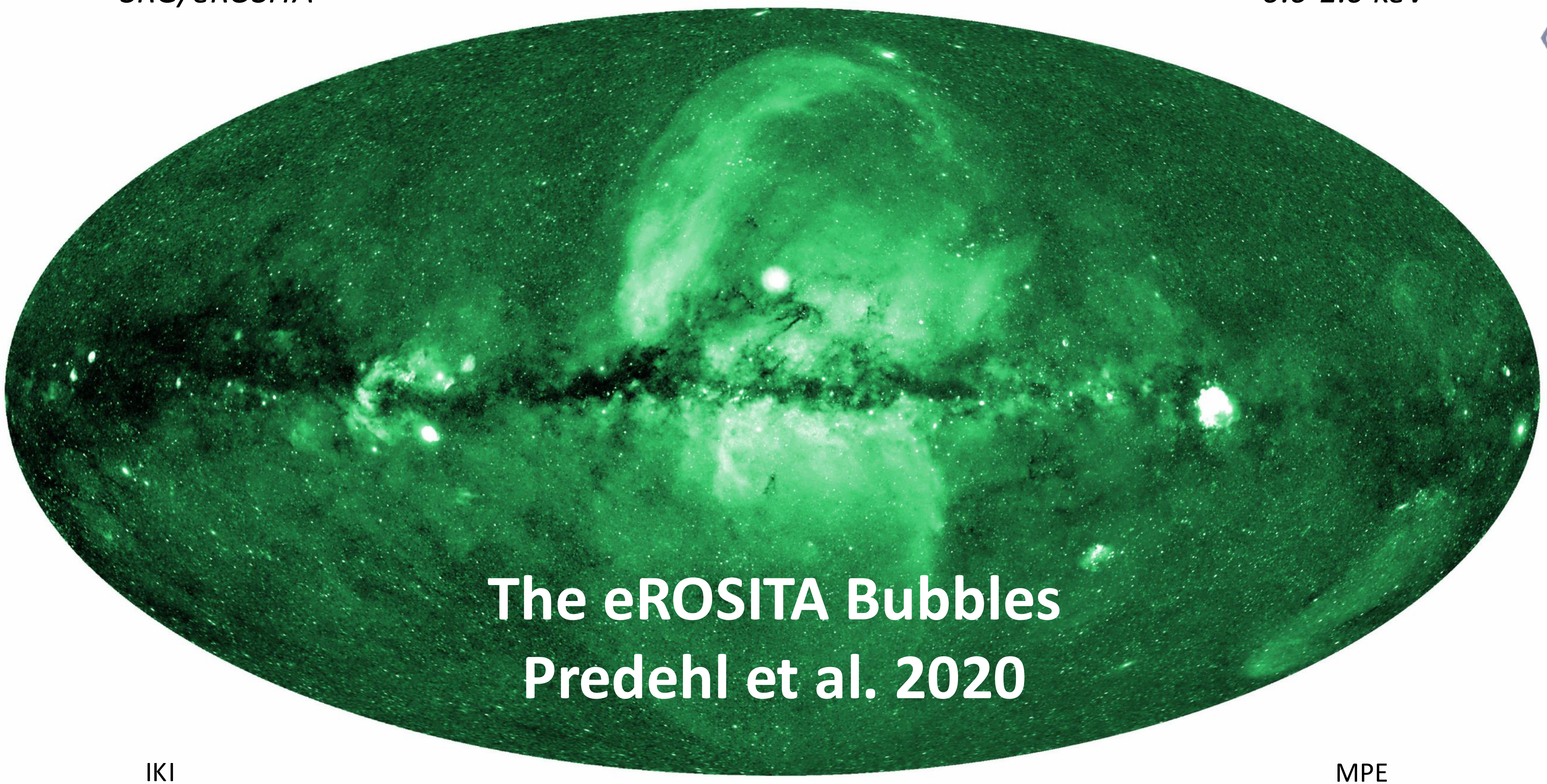
Selected Science highlights from DR1





SRG/eROSITA

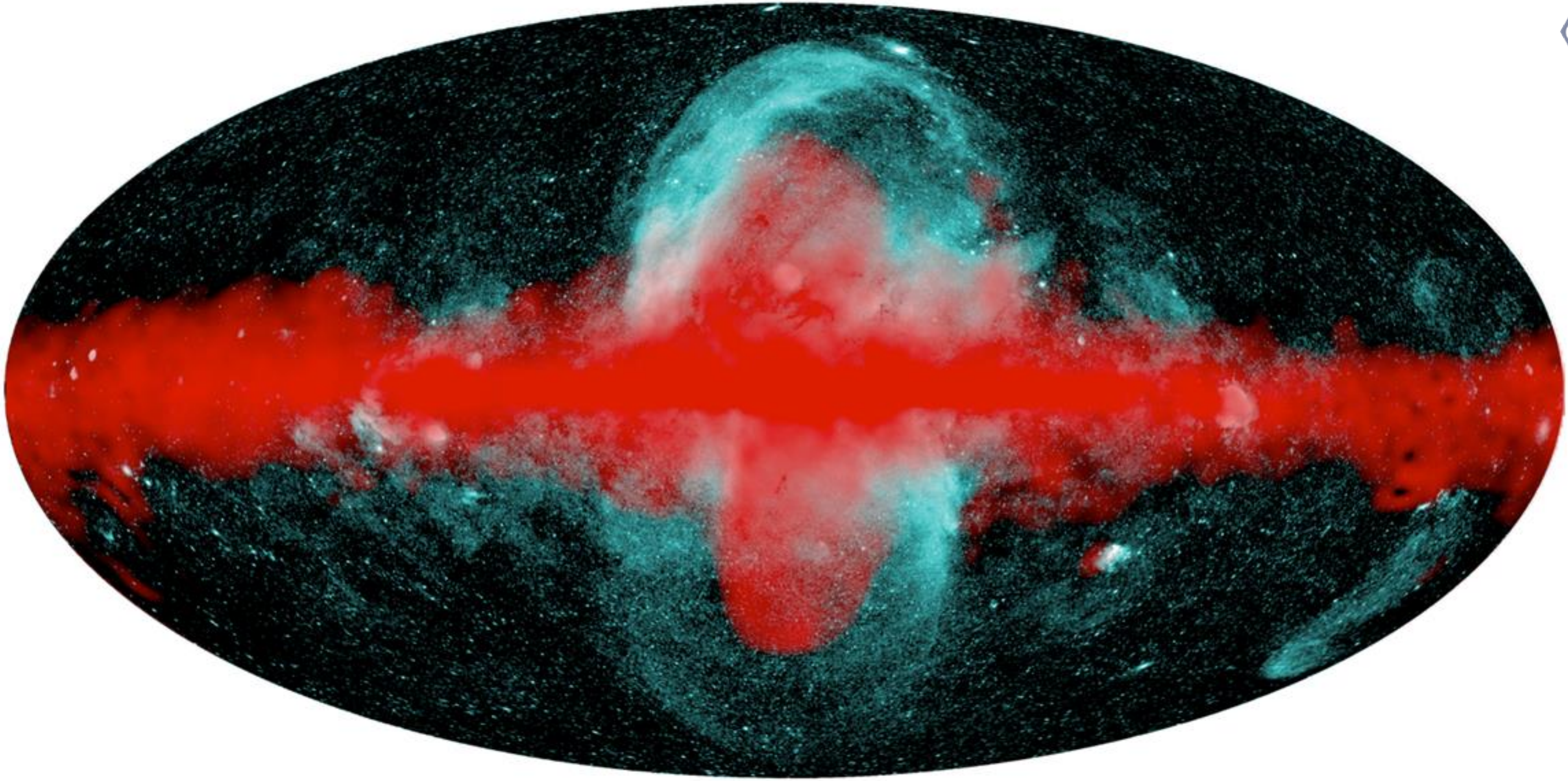
0.6-1.0 keV



The eROSITA Bubbles
Predehl et al. 2020

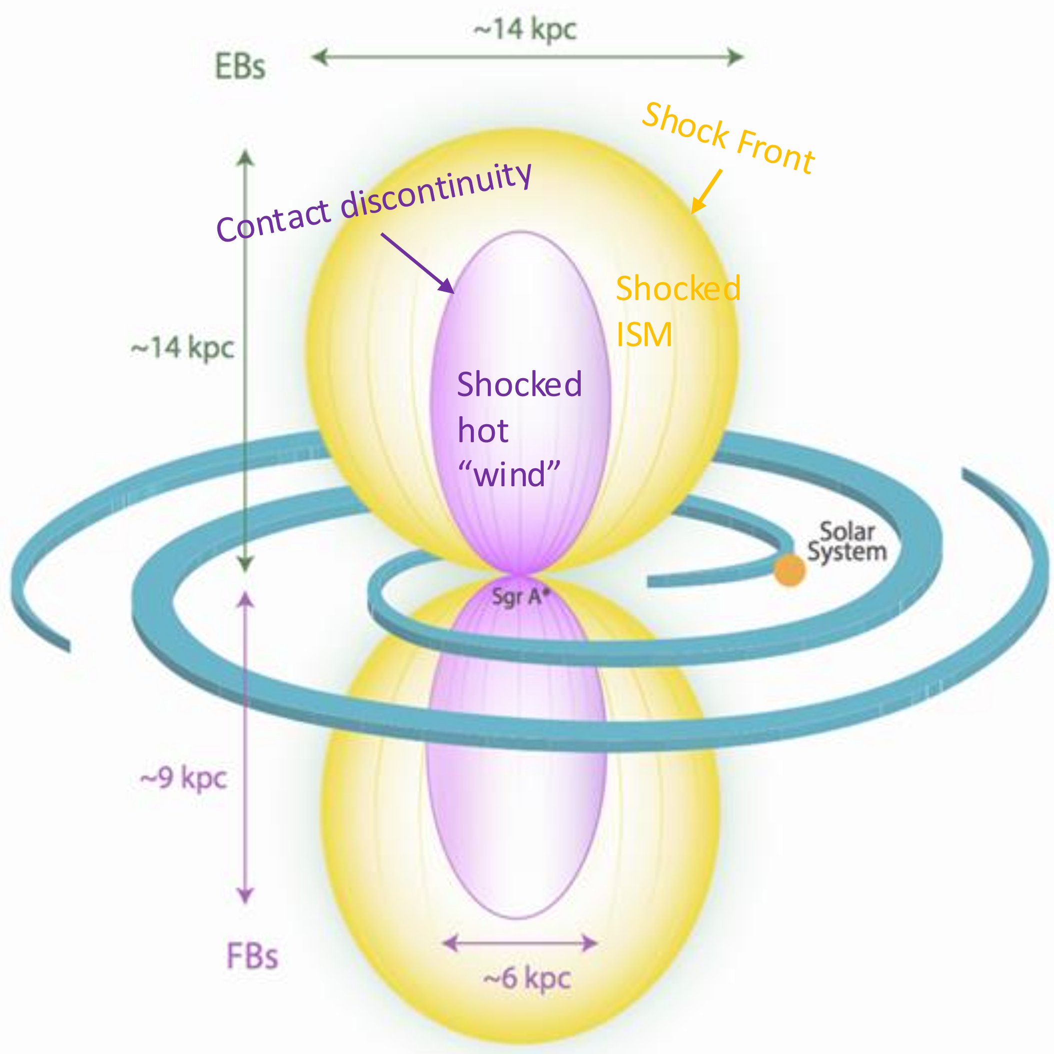
Credit: Sanders, Brunner (MPE); Churazov, Gilfanov (IKI)

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



Credit: Khabibullin, Selig (MPA)

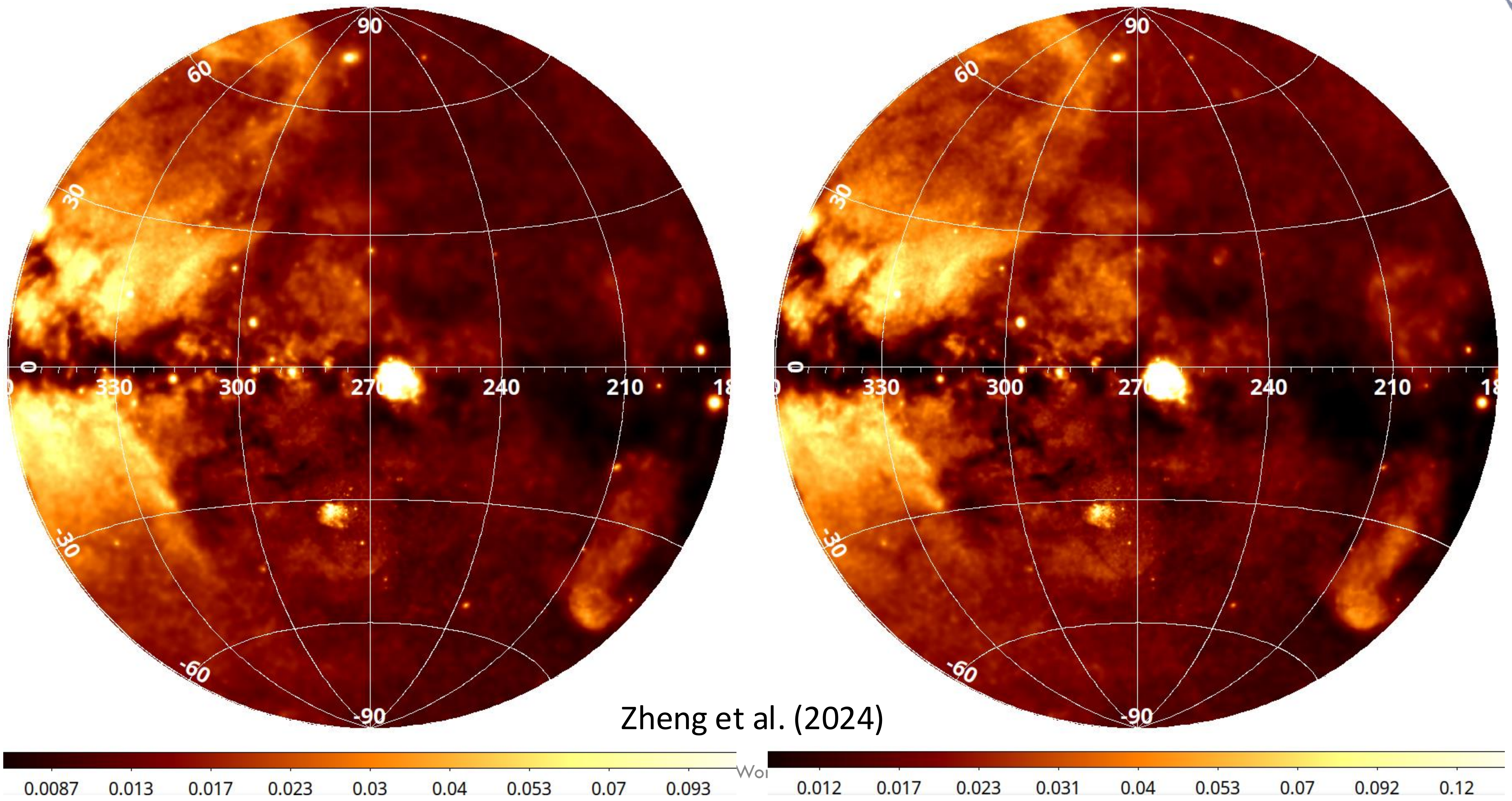
The eROSITA Bubbles



- $L_{X,tot}$~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)

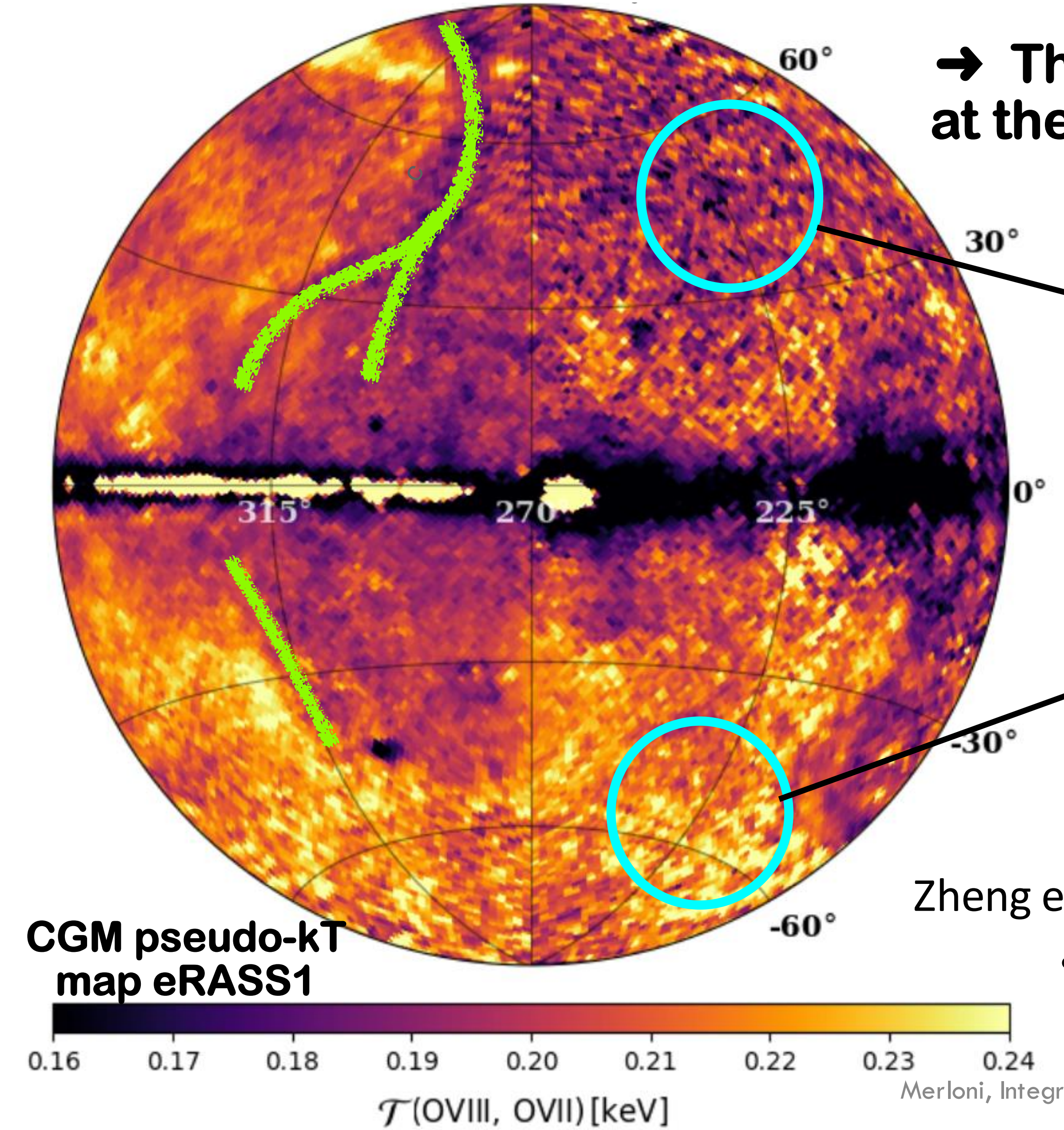
Predehl, Sunyaev et al. Nature (2020)

Narrow band maps: OVII and OVIII

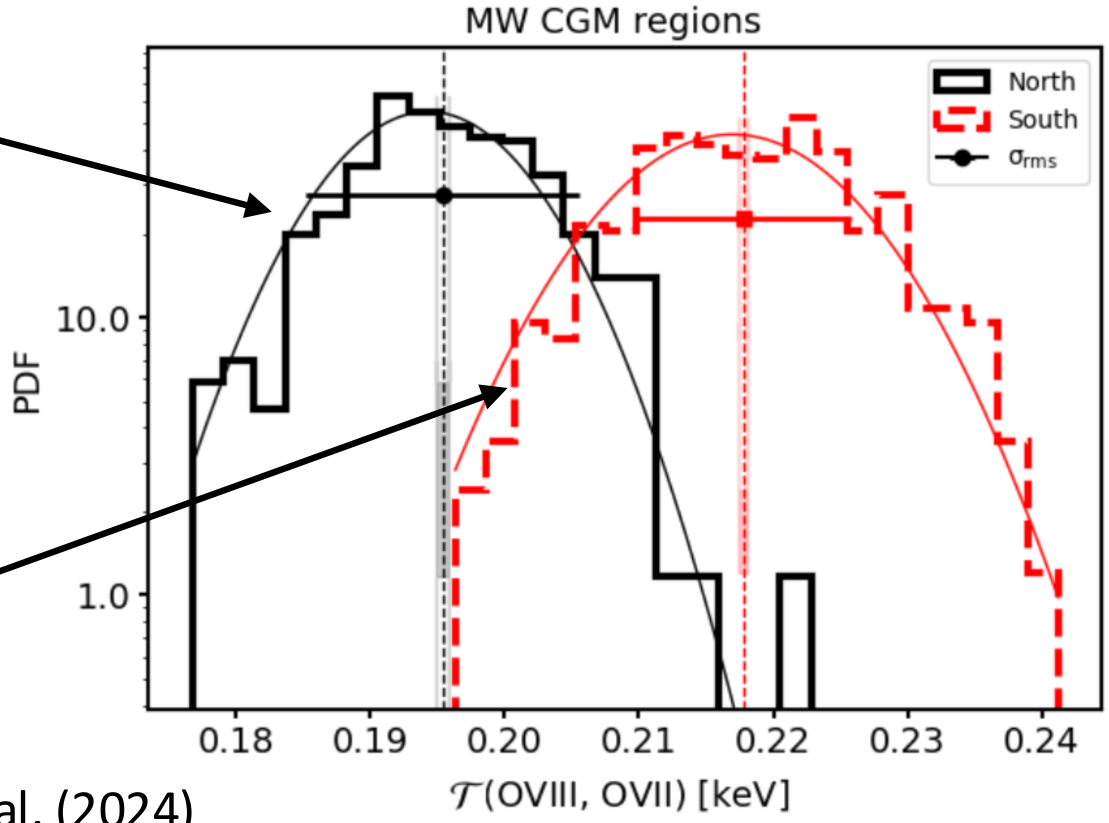


Zheng et al. (2024)

Pseudo-temperature map from OVIII/OVII



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



Zheng et al. (2024)

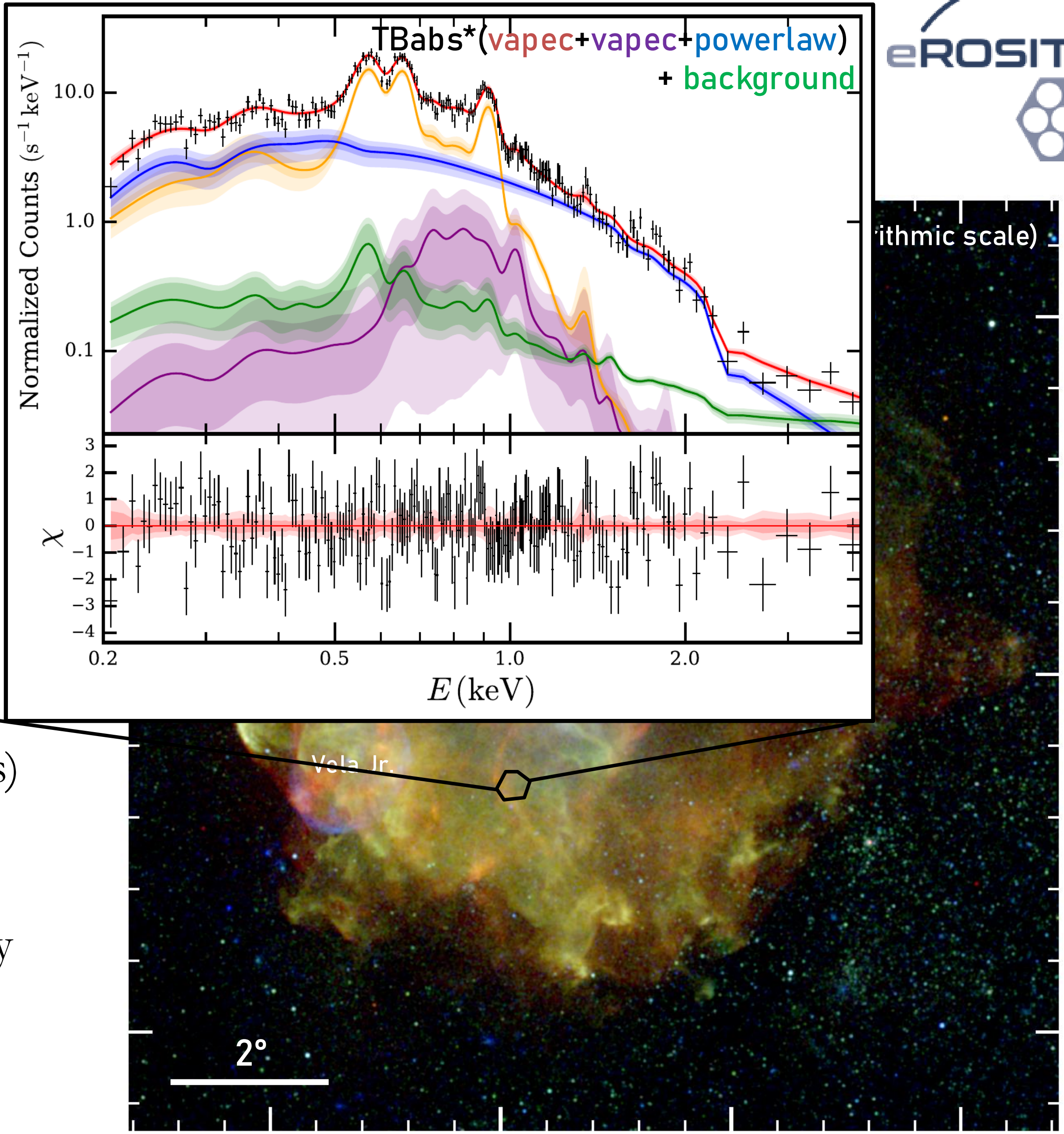
➜ ΔkT_{CGM} ~ 12% between north and south

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

The Vela Supe

- Very extended X-ray-bright core-collapse SNR
  - Central energetic pulsar PSR B0833-45 & pulsar wind nebula (Vela X)
  - Nearby (~ 290 pc; *Dodson+03*)
  - Age ~ 11 – 30 kyr (*Manchester+05, Espinoza+17*)

➢eRASS:4 data provide opportunity to study
  - Foreground absorption (➢ Local ISM properties)
  - Ejecta distribution & composition (➢ SN nucleosynthesis)
  - Synchrotron emission from PWN (➢ Cosmic ray acceleration)

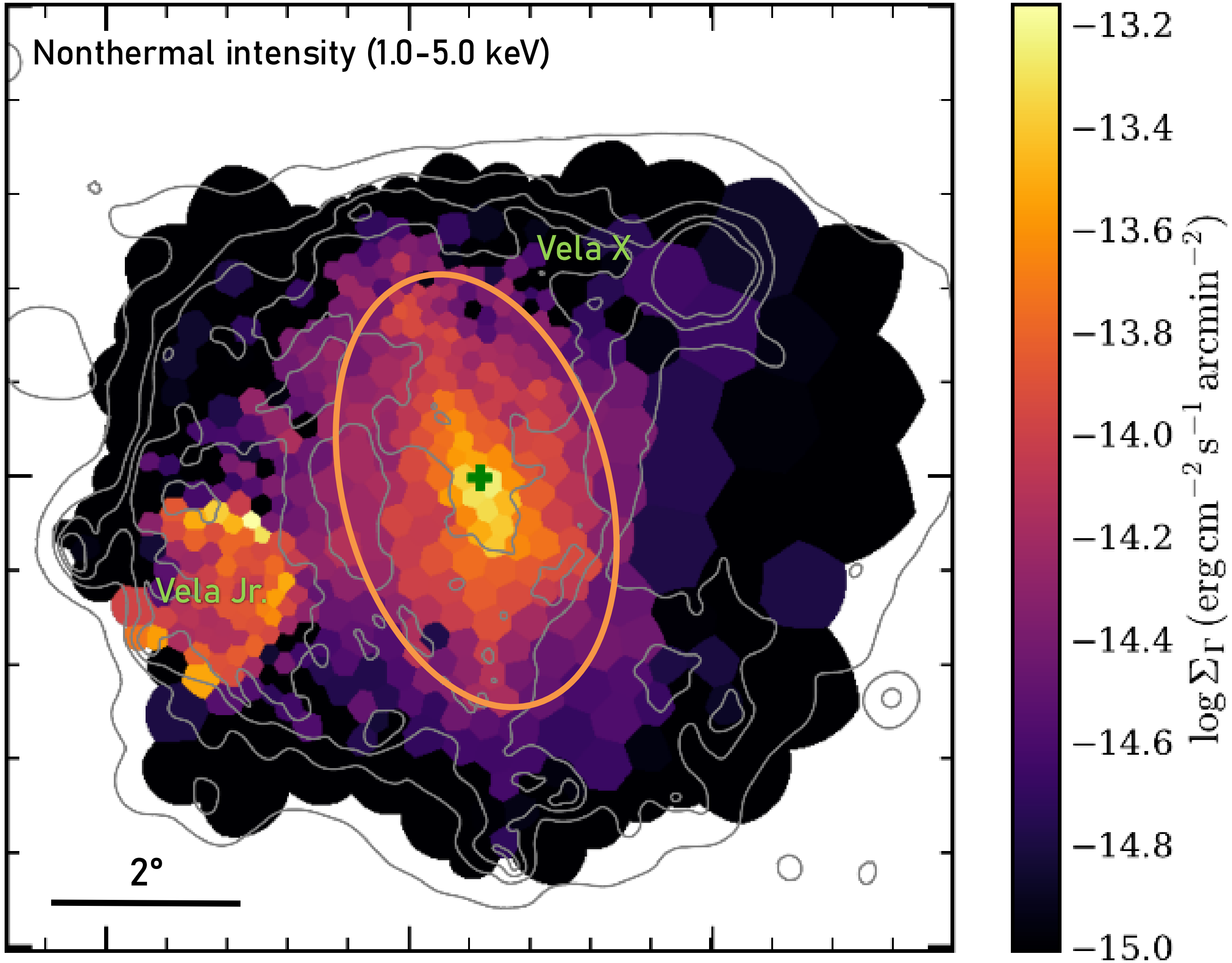


Mayer, Becker et al. (2023)

Vela SNR: Non-thermal Emission

- Vela X, prior to eROSITA:
  - Synchrotron emission in „Cocoon“ visible with ROSAT & XMM (*e.g. Slane+2018*)

➢With eROSITA, observe much larger size of pulsar‘s diffuse X-ray nebula, with a radial extent of 2° - 3°



Mayer, Becker et al. (2023)

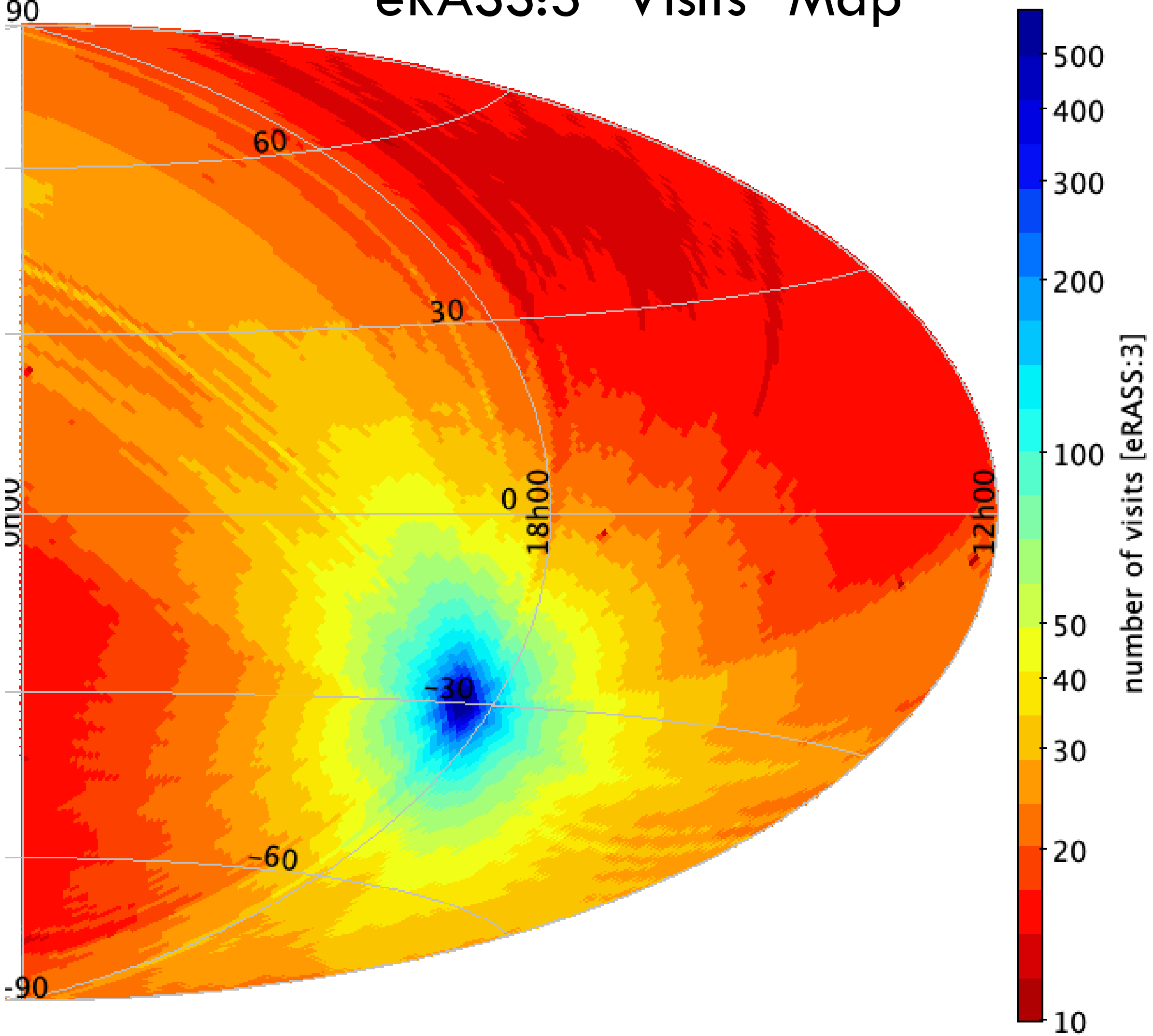
eRASS1 in time domain

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

- **50 msec [**
  CCD (fram
- **40 sec [Vi**
  effective
- **4 hours**
  (Interva
- **1 day [V**
  visits)
- **6 month**
  survey (
- **2 years:**

its” Map

Article

X-ray detection of a nova in the fireball phase

https://doi.org/10.1038/s41586-022-04635-y

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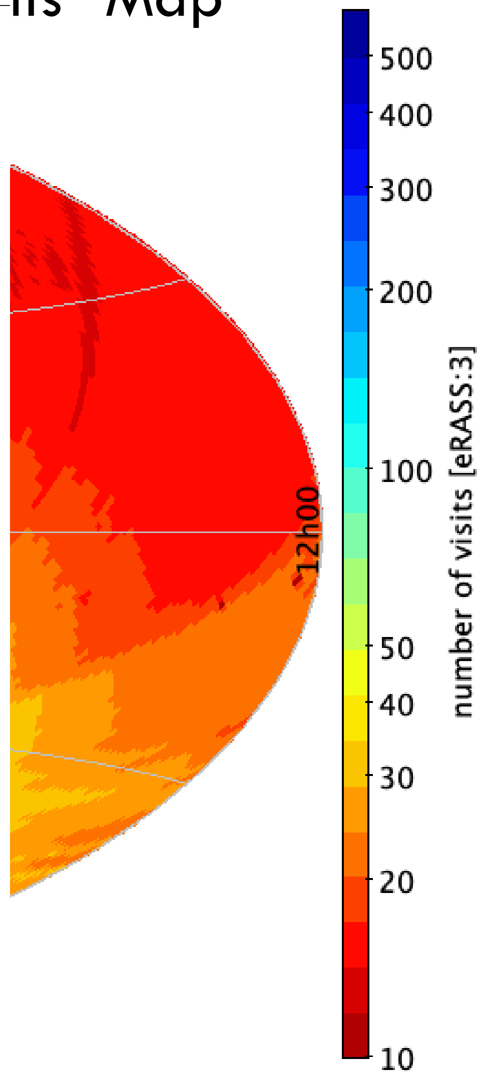
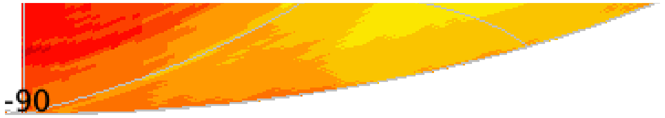
Accepted: 14 March 2022

Ole König[1✉], Jörn Wilms[1✉], Riccardo Arcodia[2], Thomas Dauser[1], Konrad Dennerl[2], Victor Doroshenko[3], Frank Haberl[2], Steven Hämmerich[1], Christian Kirsch[1], Ingo Kreykenbohm[1], Maximilian Lorenz[1], Adam Malyali[2], Andrea Merloni[2], Arne Rau[2], Thomas Rauch[3], Gloria Sala[4,5], Axel Schwope[6], Valery Suleimanov[3], Philipp Weber[1] & Klaus Werner[3]

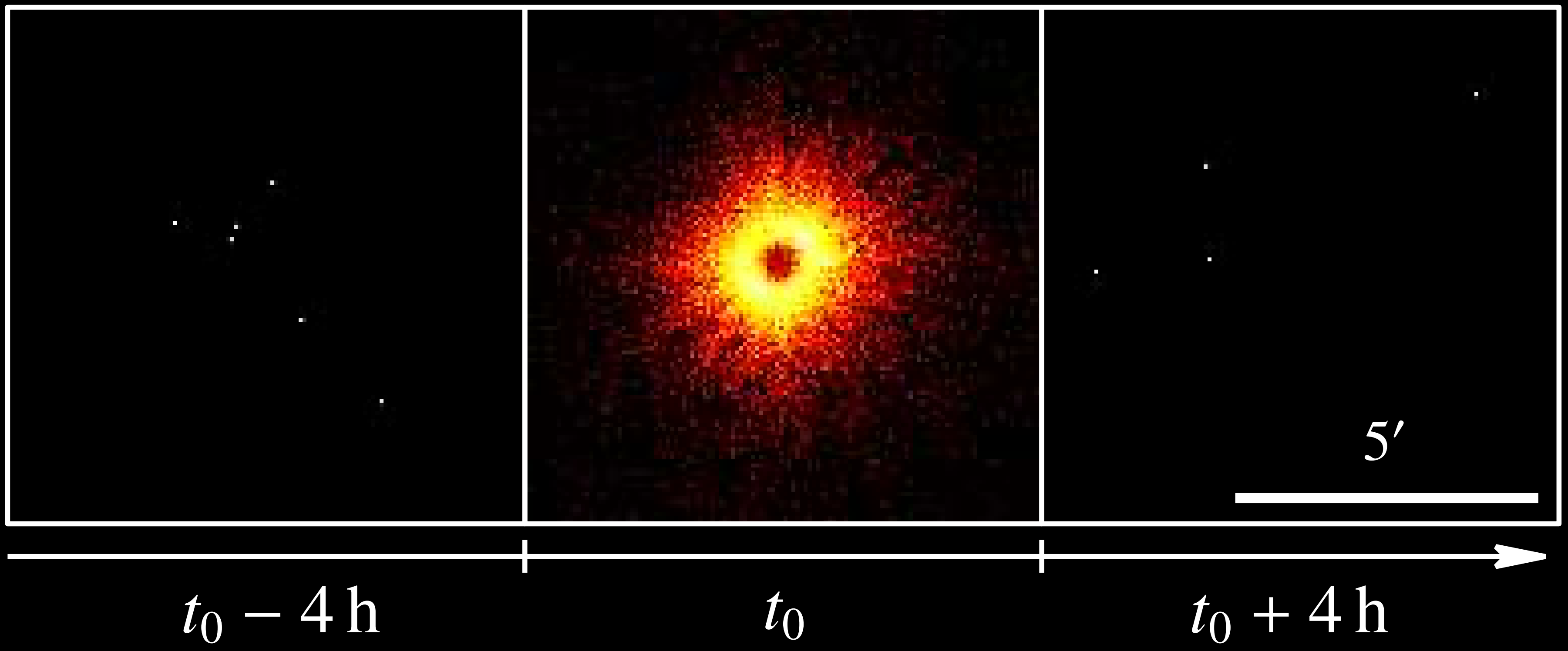
Novae are caused by runaway thermonuclear burning in the hydrogen-rich envelopes of accreting white dwarfs, which leads to a rapid expansion of the envelope and the ejection of most of its mass[1,2]. Theory has predicted the existence of a ‘fireball’ phase following directly on from the runaway fusion, 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.



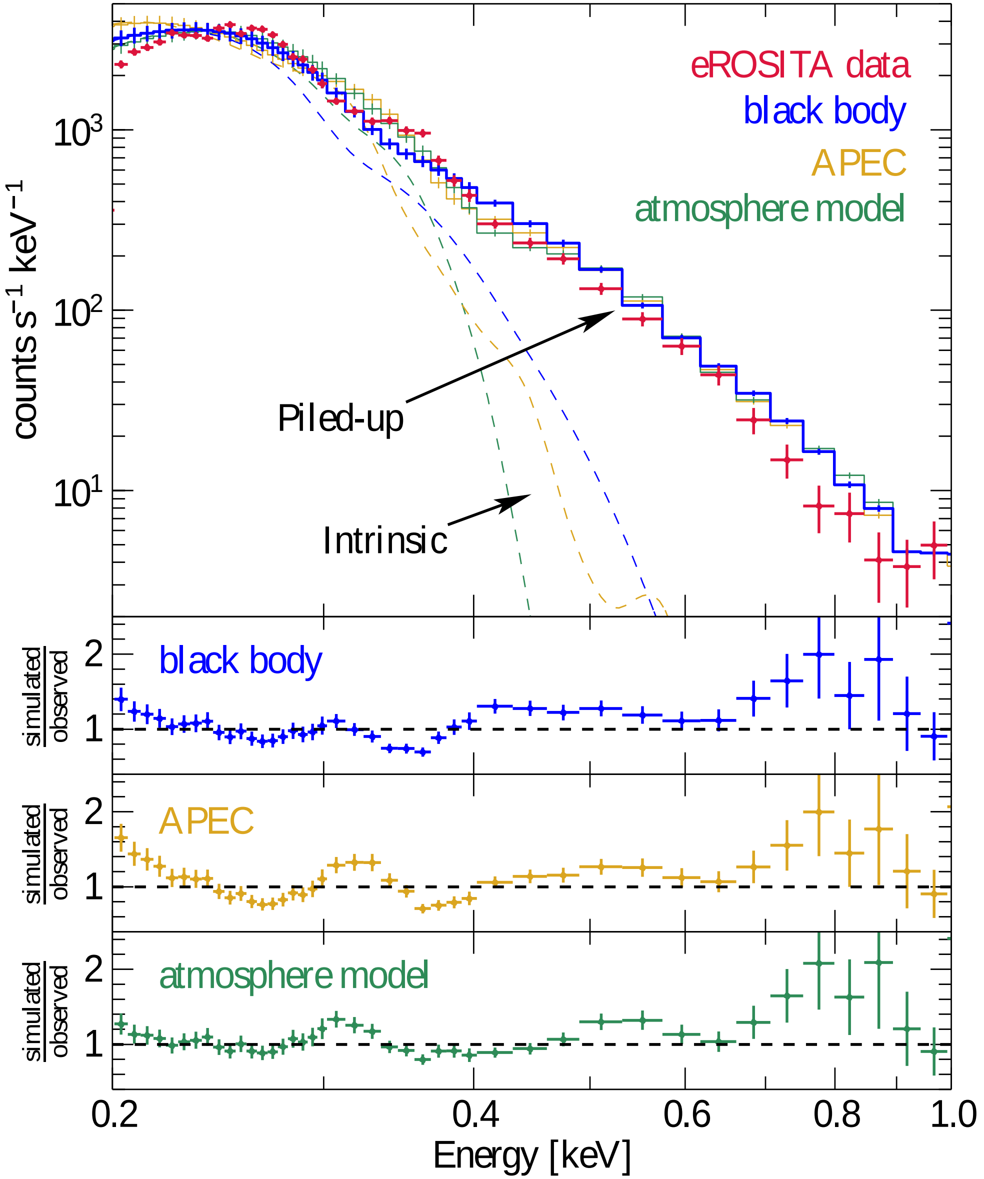


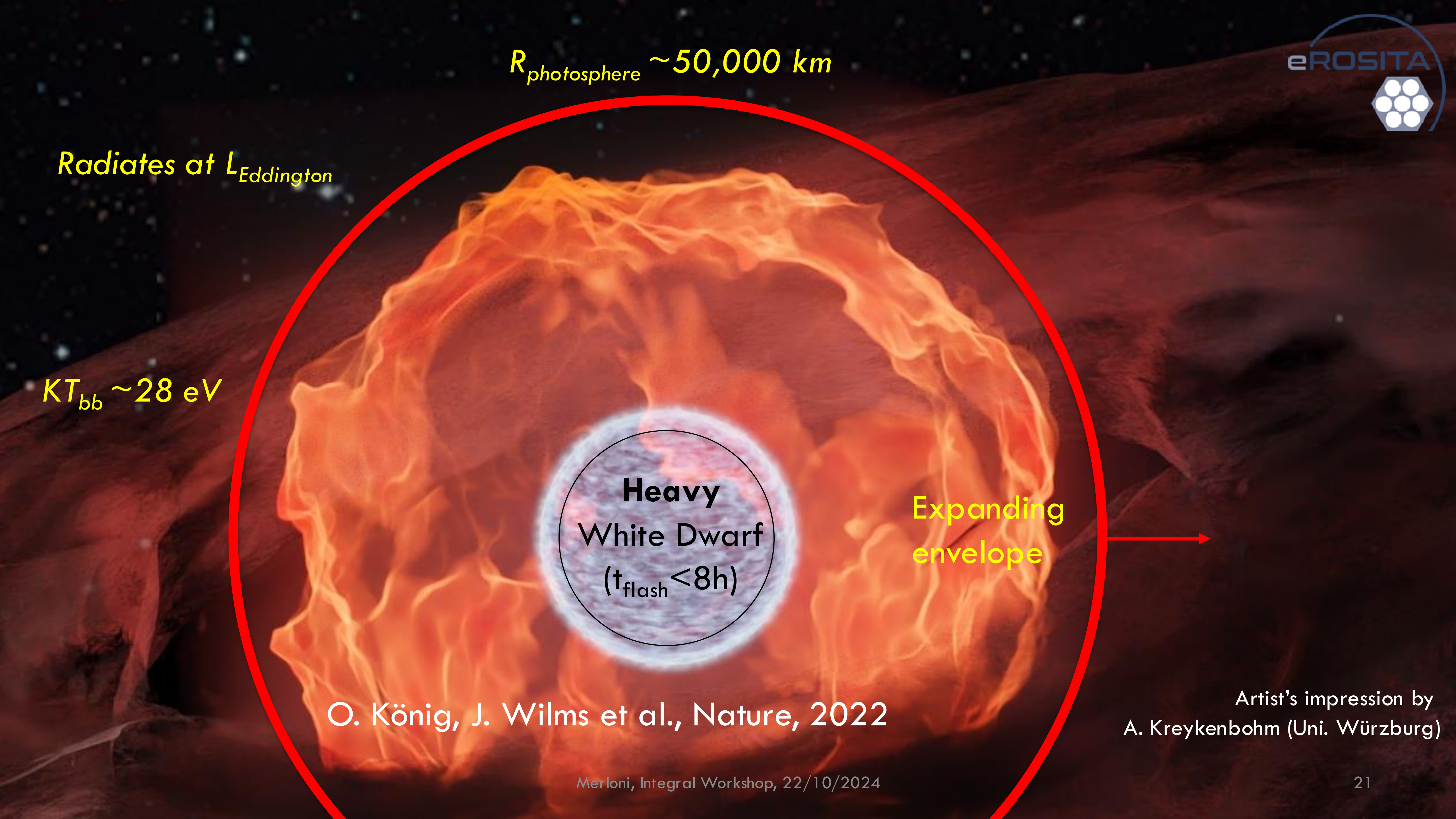
Discovery of a Nova ignition flash

O. König, J. Wilms et al., Nature, 2022



Dealing with pileup: SIXTE simulation





O. König, J. Wilms et al., Nature, 2022

Artist's impression by
A. Kreykenbohm (Uni. Würzburg)

- **50 msec [Readout]:** Tin
CCD (frame readout cyc
- **40 sec [Visit]:** Scan spe
effective exposure)
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(Interval between scans,
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- **6 months [eRASS]:** one
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- **2 years: 4** all-sky survey

Article

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

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

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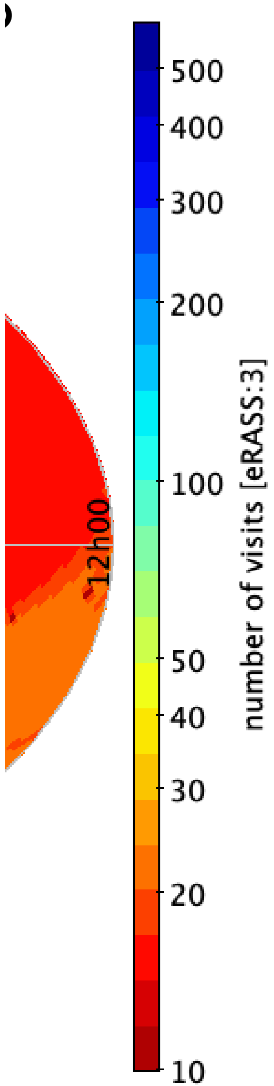
Check for updates

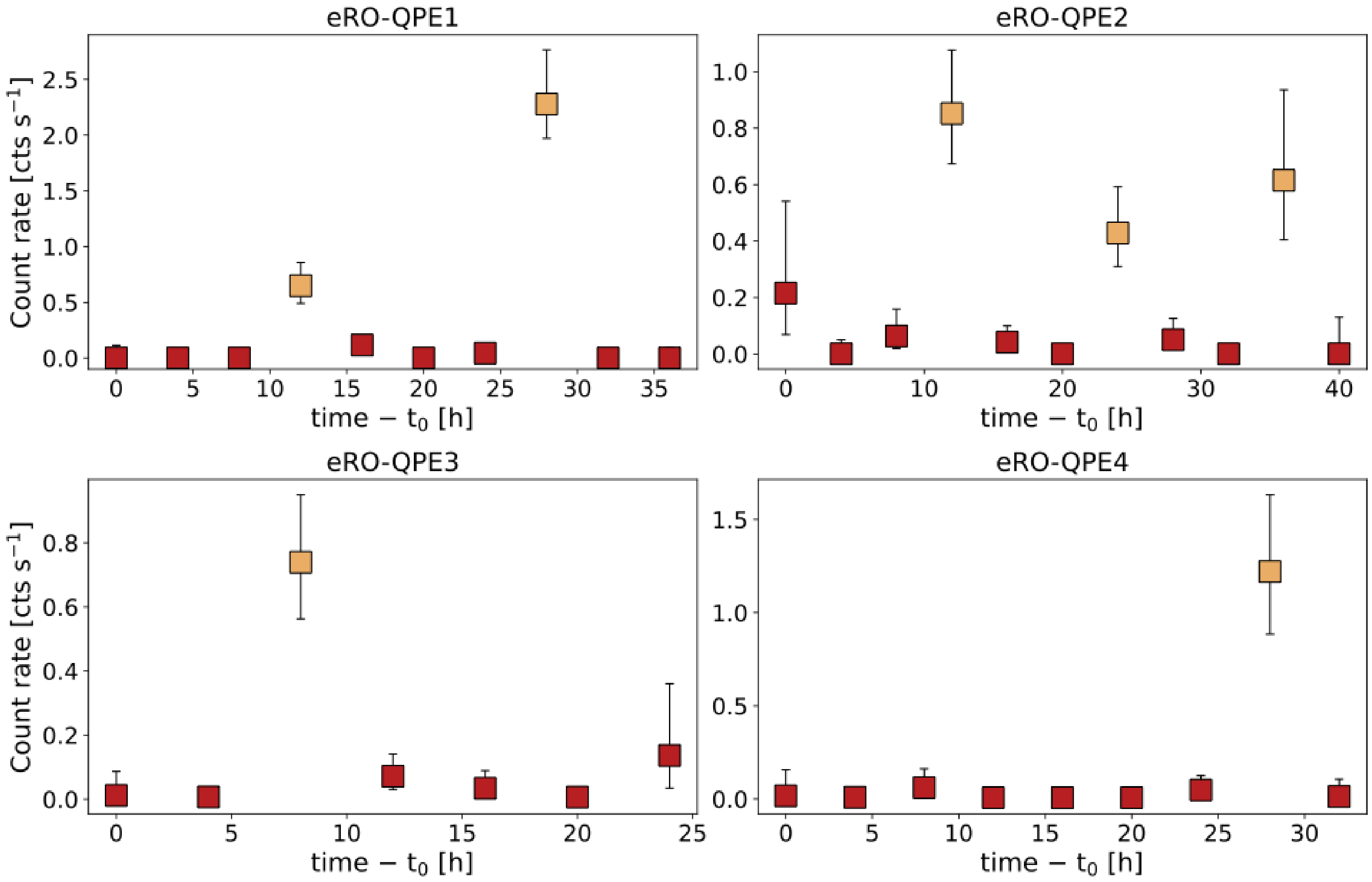
R. Arcodia[1✉], A. Merloni[1], K. Nandra[1], J. Buchner[1], M. Salvato[1], D. Pasham[2], R. Remillard[2], J. Comparat[1], G. Lamer[3], G. Ponti[1,4], A. Malyali[1], J. Wolf[1], Z. Arzoumanian[5], D. Bogensberger[1], D. A. H. Buckley[6], K. Gendreau[5], M. Gromadzki[7], E. Kara[2], M. Krumpe[3], C. Markwardt[5],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

QPE: Large-amplitude, periodic outbursts from MBH discovered by Miniutti+2019 & Giustini+2020



From well-understood eROSITA selection function ->

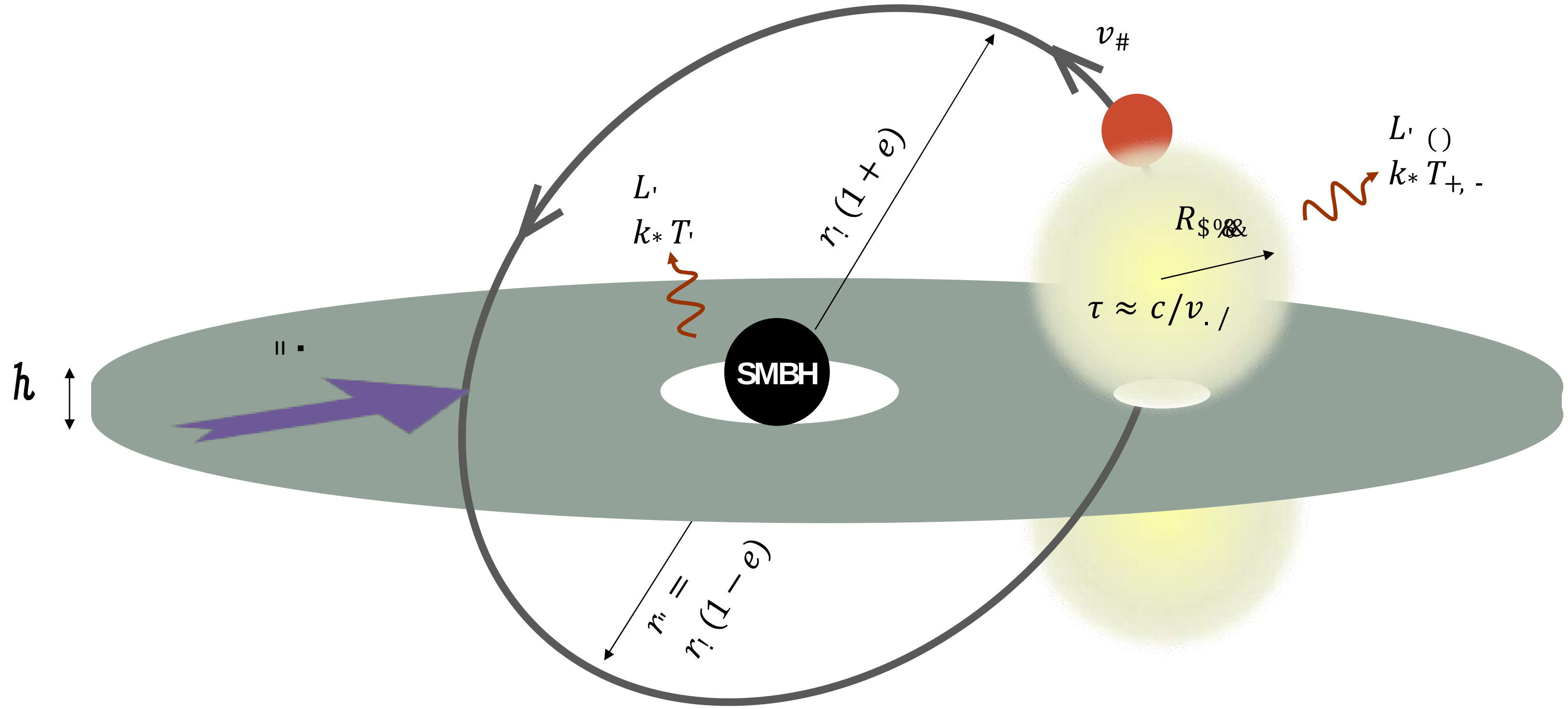
Volumetric rate etimates

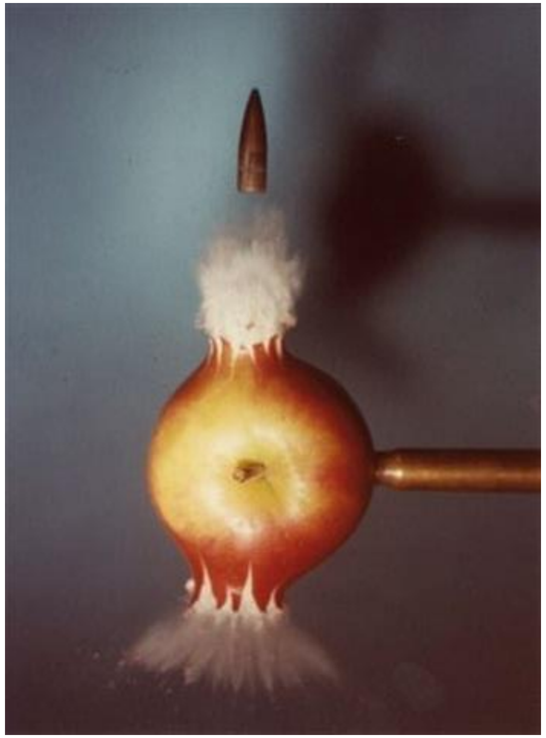
About ~1/10x TDE rate (depending on uncertain lifetime of QPE)

Arcodia+21
Arcodia+24a
Arcodia+24b

Arcodia+21

EMRI+TDE=QPE?
Linial & Metzger (2023)

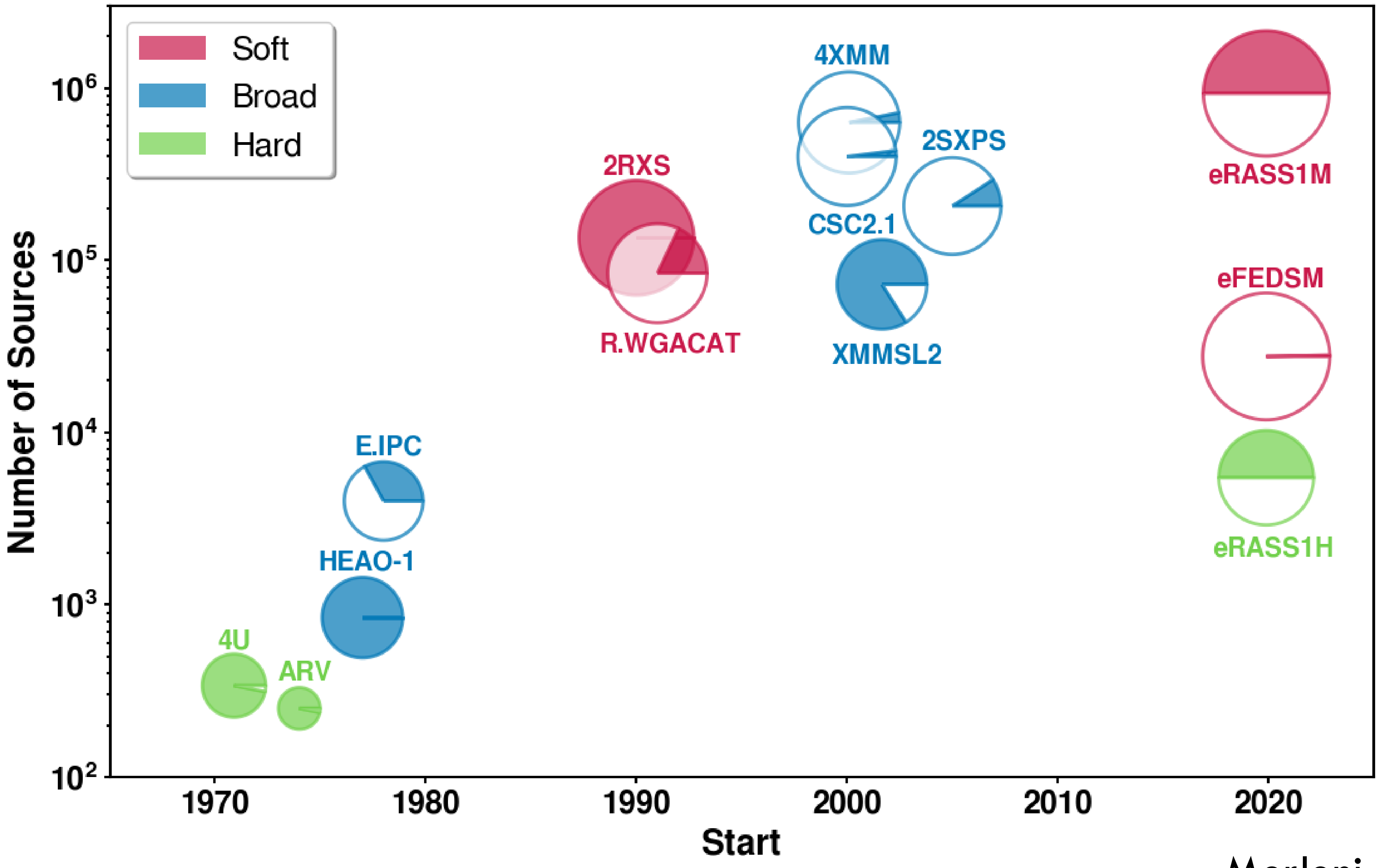




QPE may be produced by EMRIs, revealed by a TDE!

See also Xian+21; Sukova+21; Franchini,Bonetti+23; Tagawa&Haiman23; Zhou+24

eRASS1 and X-ray catalogues

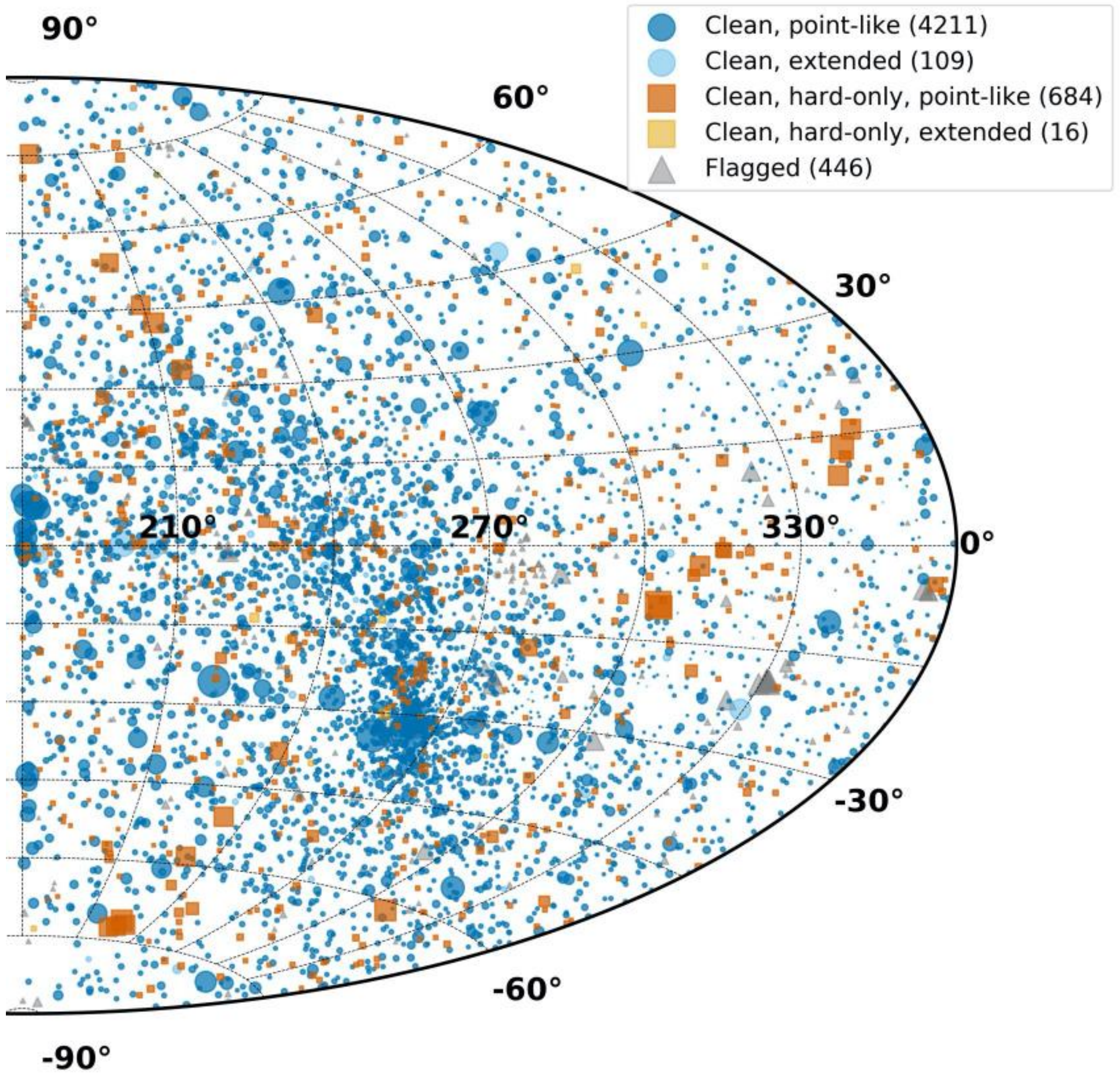


Merloni et al. (2024)

Sophia Waddell et al. arXiv:2401.17306

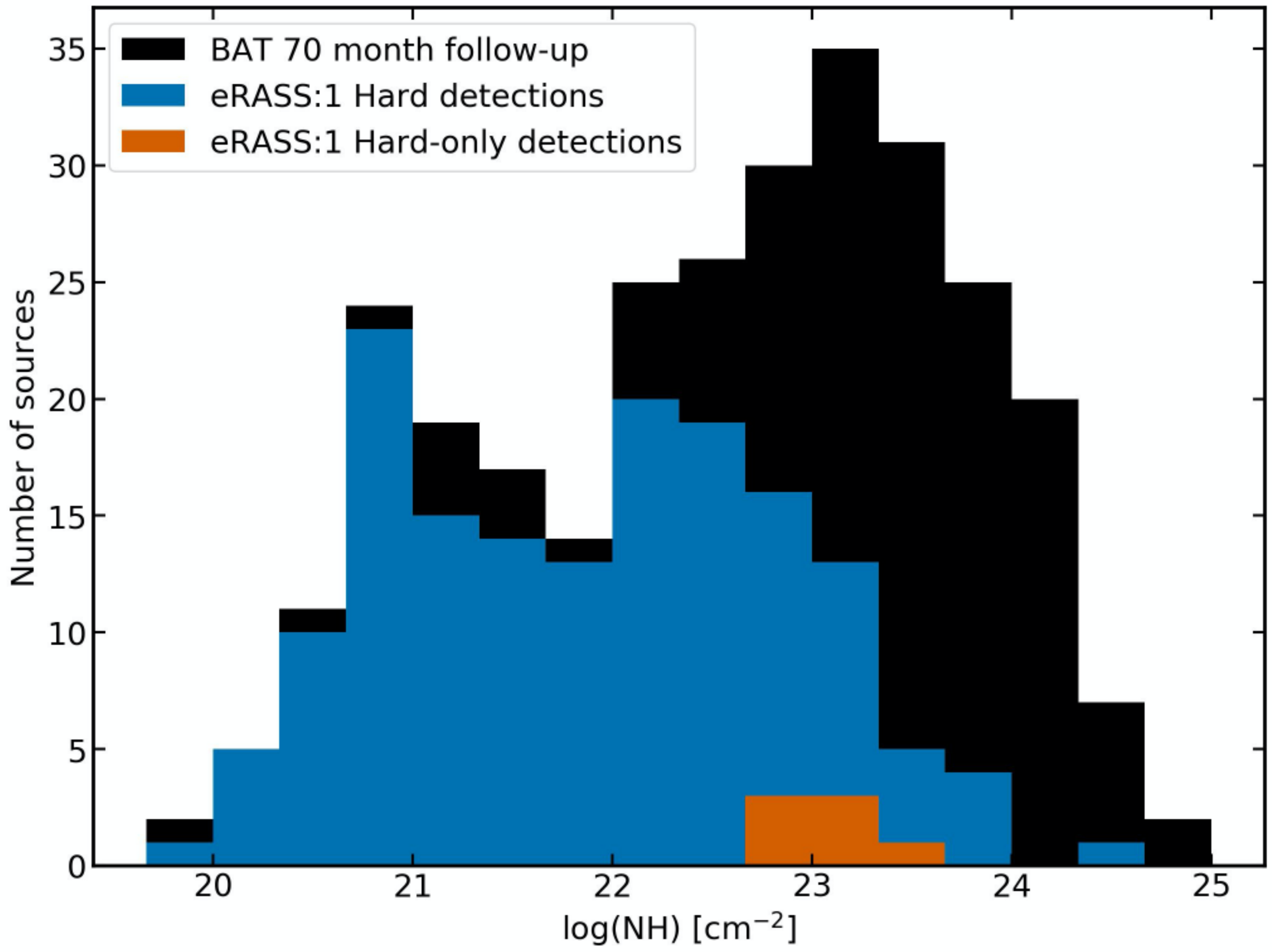
The eRASS:1 hard (2.3-5keV) sample: **5466 sources**

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



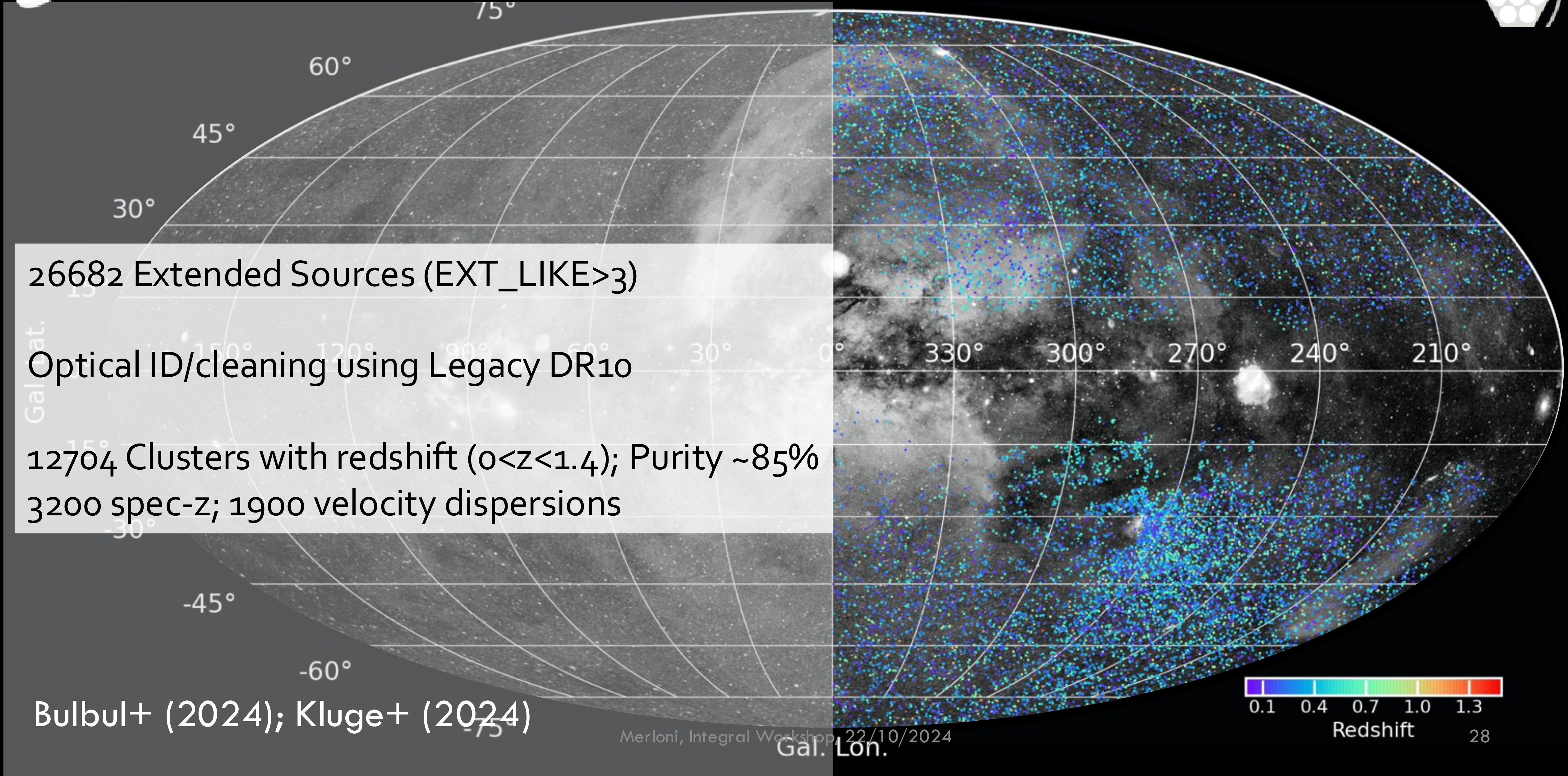
Comparison with Swift-BAT

- 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

Clusters and Groups in eRASS1

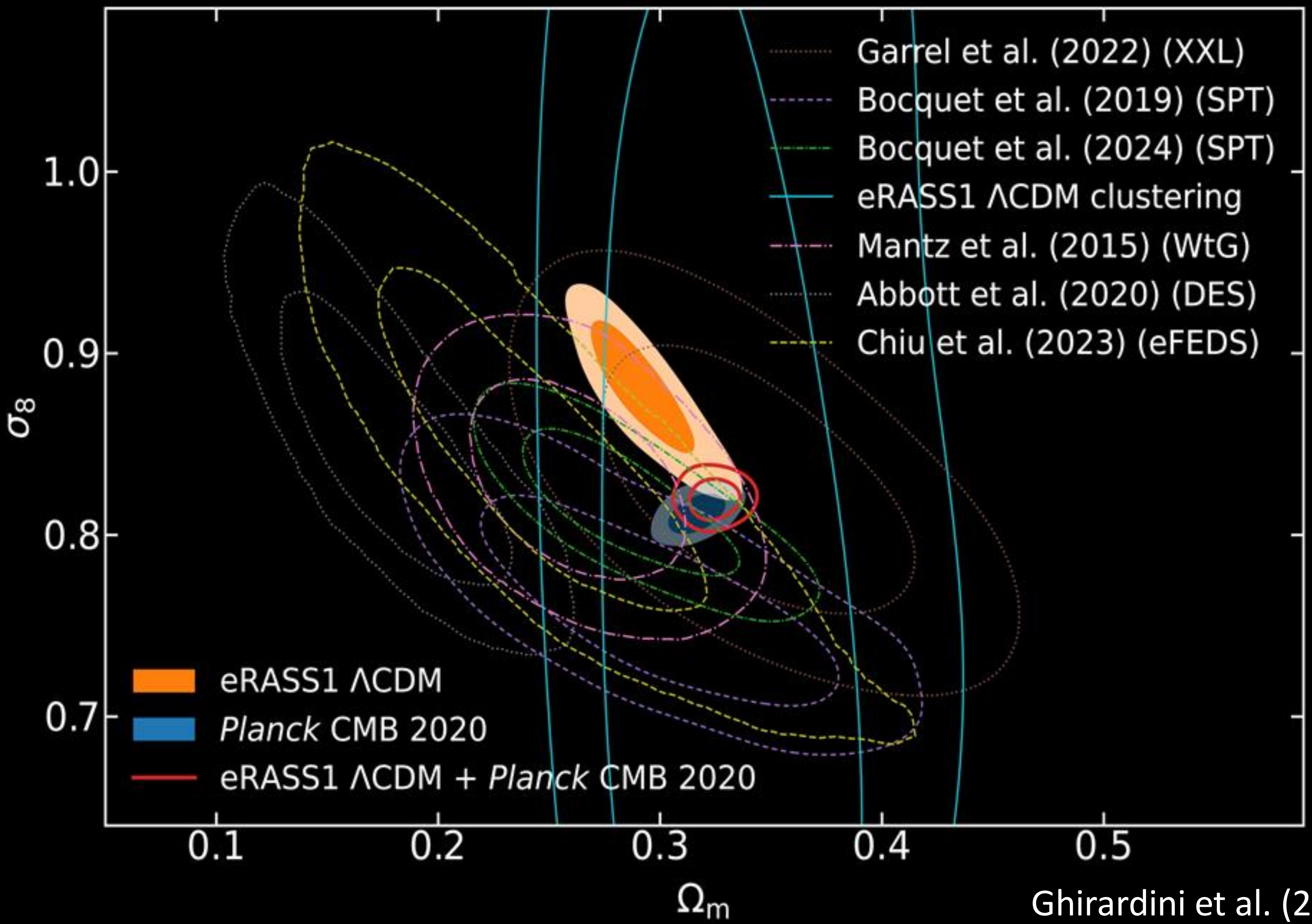


26682 Extended Sources (EXT_LIKE>3)

Optical ID/cleaning using Legacy DR10

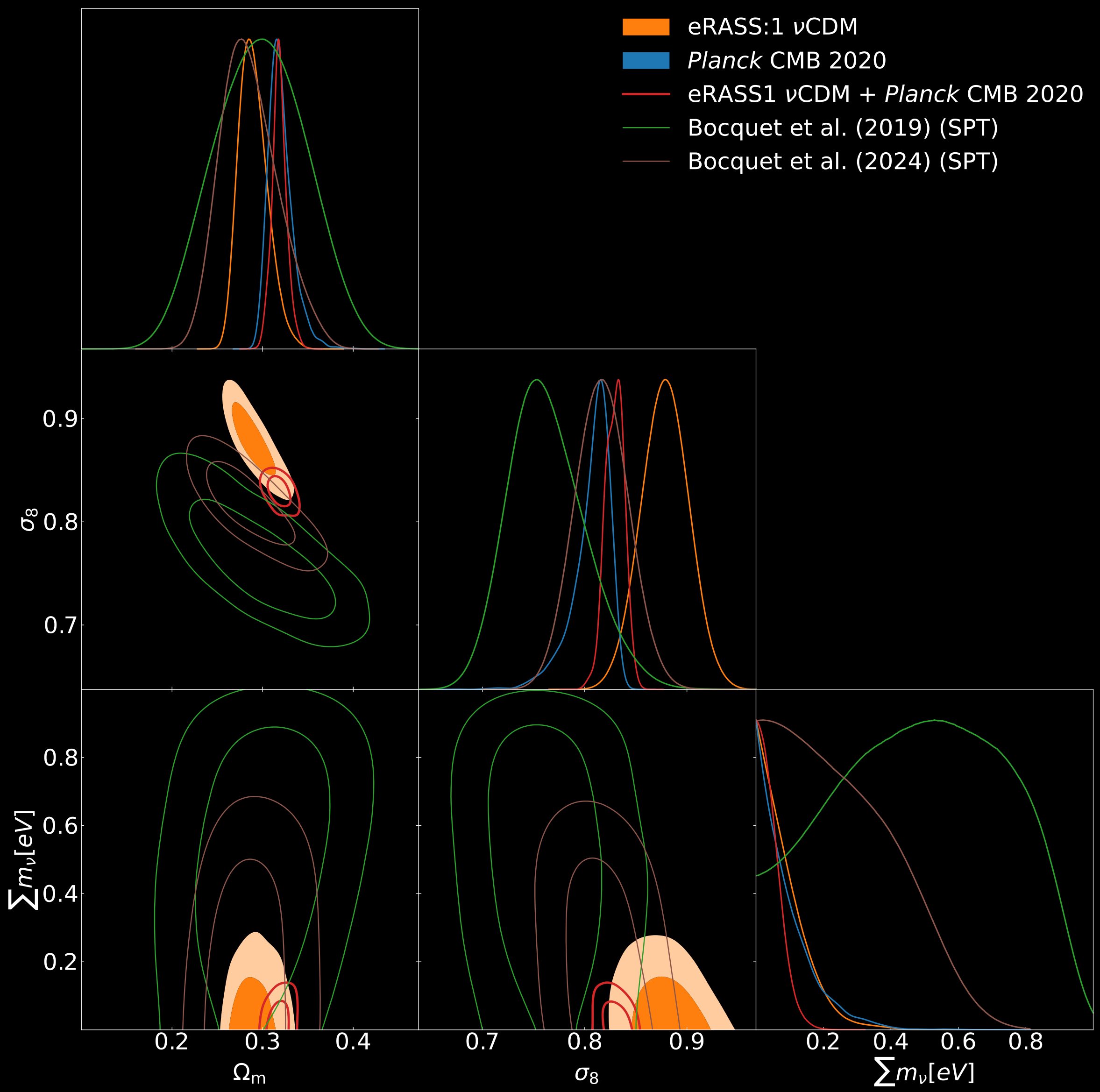
12704 Clusters with redshift (0<z<1.4); Purity ~85%
3200 spec-z; 1900 velocity dispersions

Bulbul+ (2024); Kluge+ (2024)

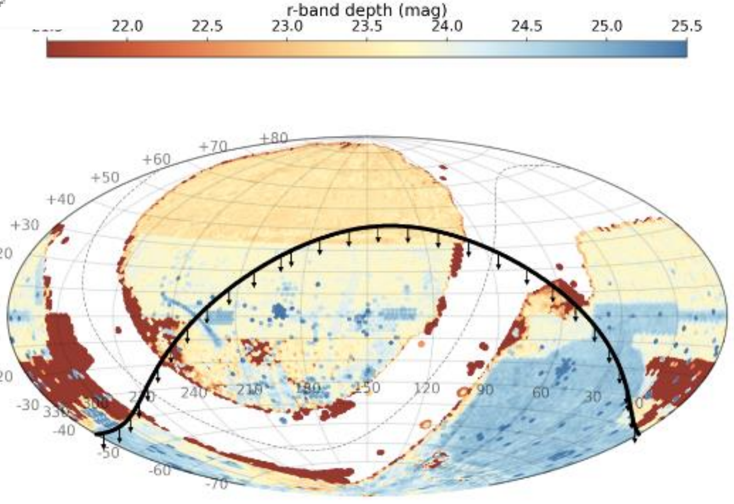


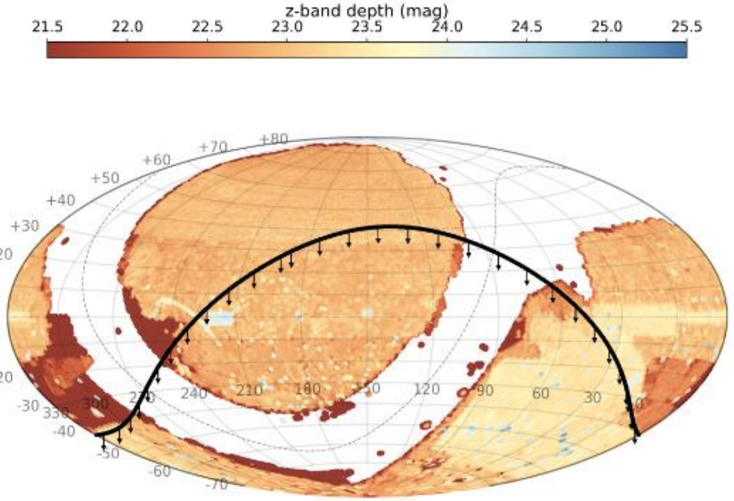
Ghirardini et al. (2024)

Neutrino sector

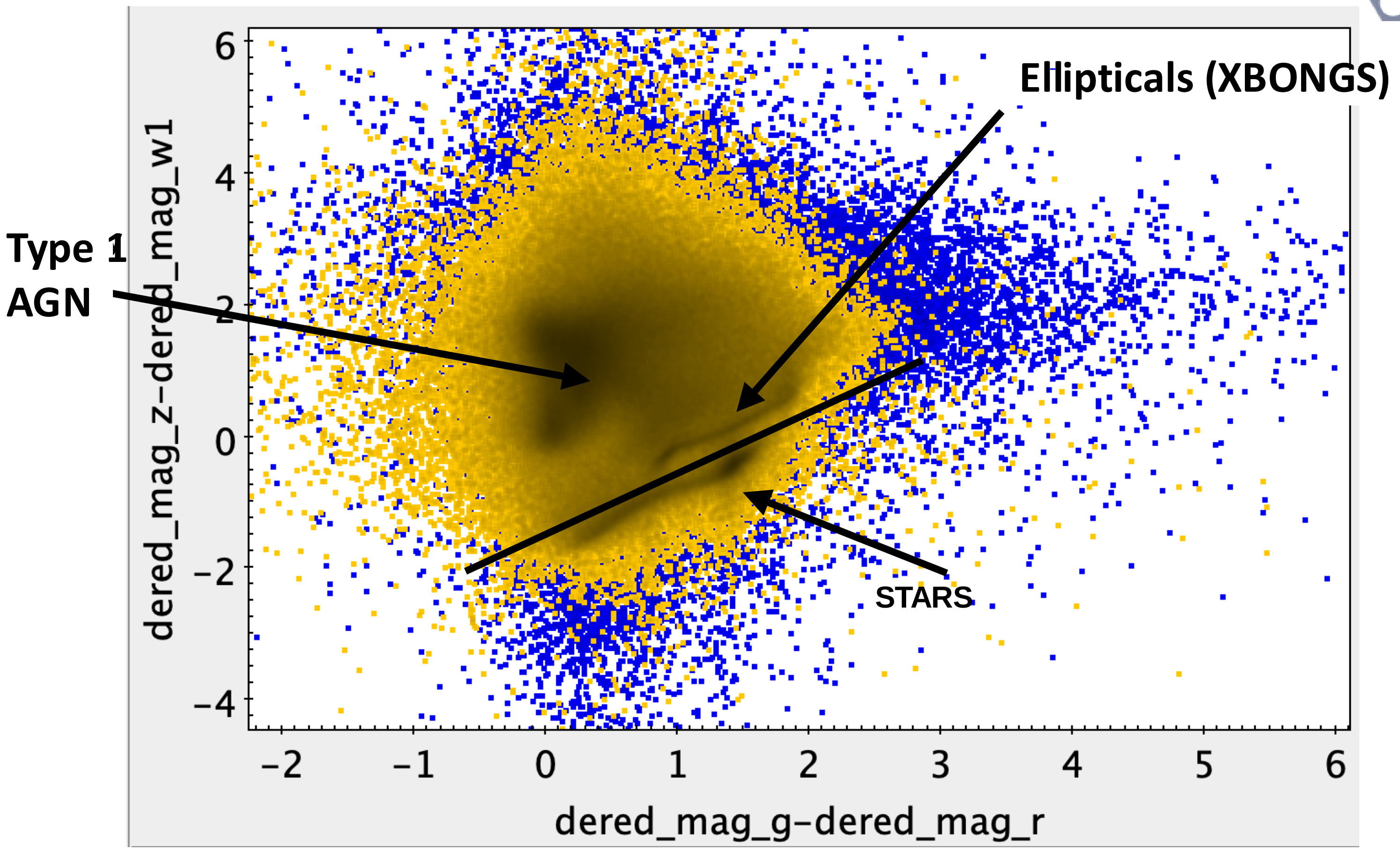


The AGN content of eRASS1



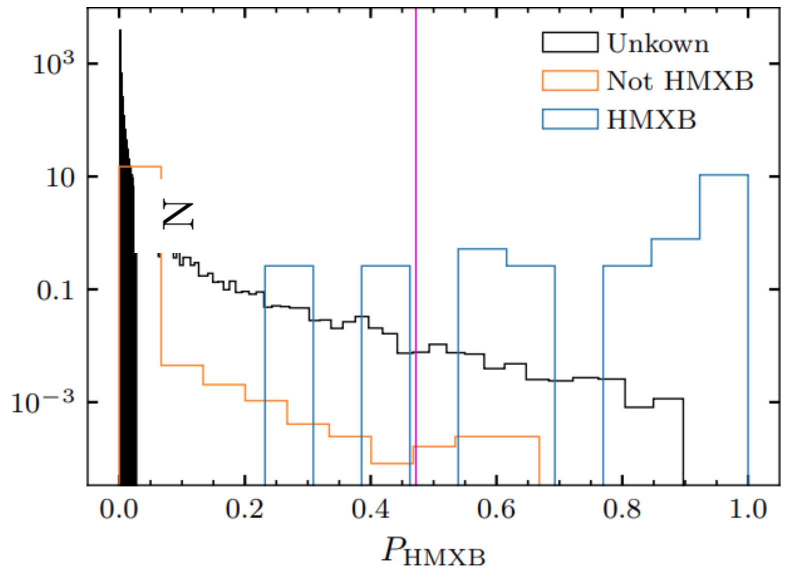


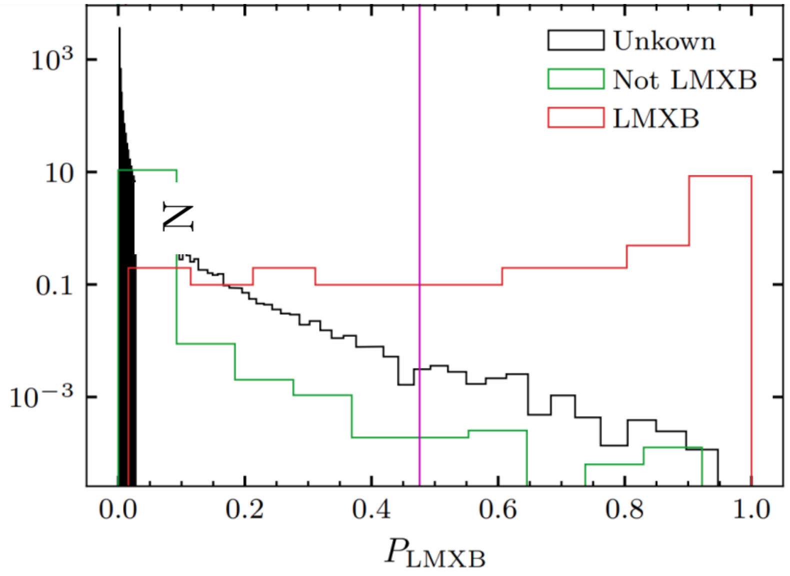
Optical ctp identification: Legacy DR10



CLASSIFICATION:
Using optical/IR photometry, astrometry (LS10, WISE, Gaia)
At least 550k AGN

A needle in a haystack problem for XRB: ML classification results



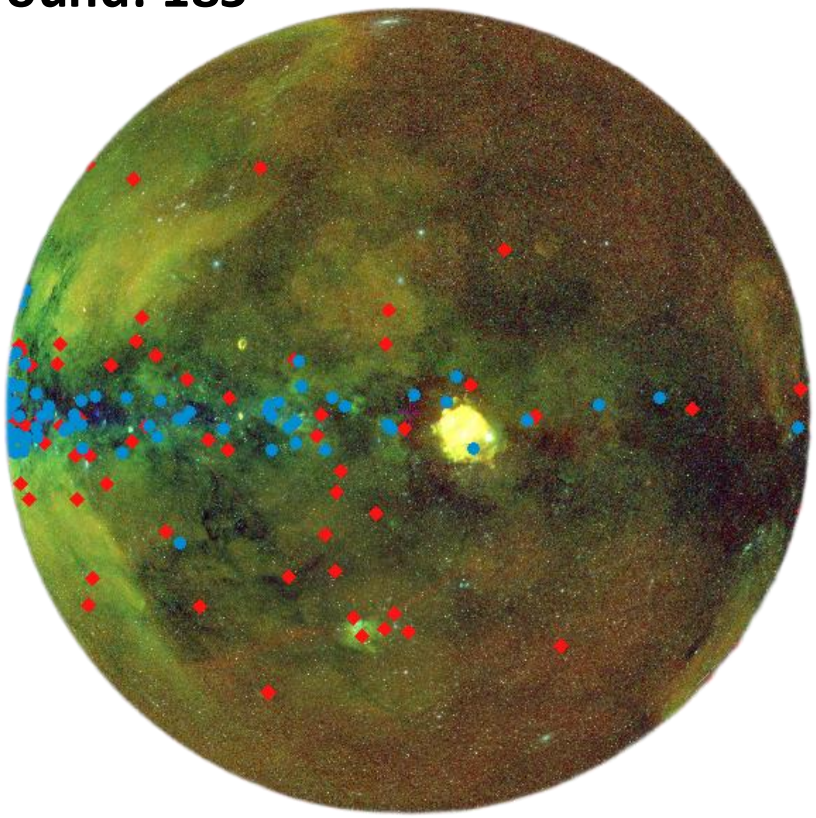


Completeness = 0.7 Purity = 0.83

Prob_cut = 0.472

XRB Candidates found: 185

Avakyan et al (in prep.)

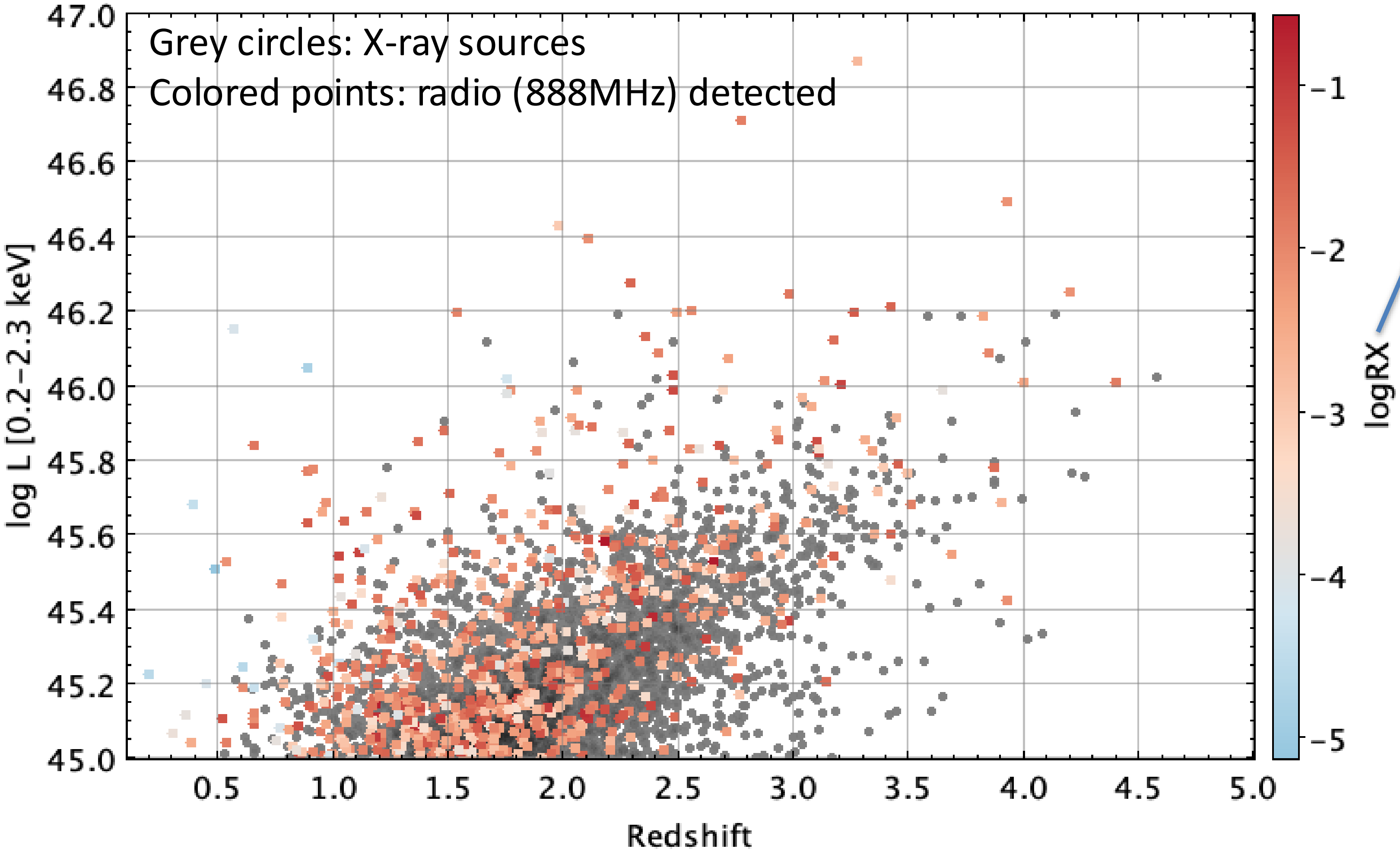


HMXB (blue) and LMXB (red) candidates.

eRASS DR1 map view

The most luminous (Radio Loud) QSOs

Out of ~40k eRASS AGN with SDSS-V spectra, Here 4555 QSO with $\log L_X > 45$
With ASKAP 888MHz coverage from RACS (730 radio detections S>2mJy)

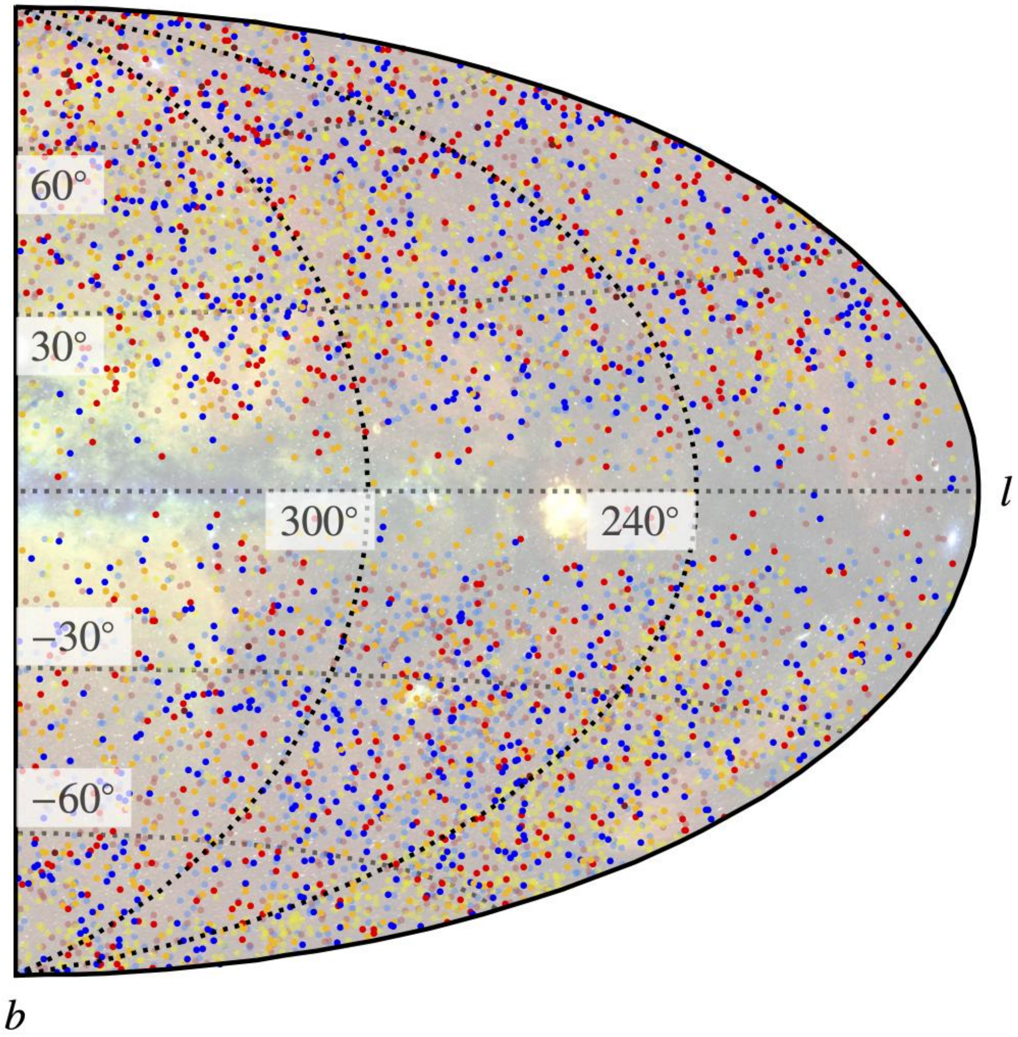


$R_X = \nu L\nu / L_X$
(Terashima & Wilson 2003
Panessa 2007)

(red: more radio loud)

BlazEr1 - matches

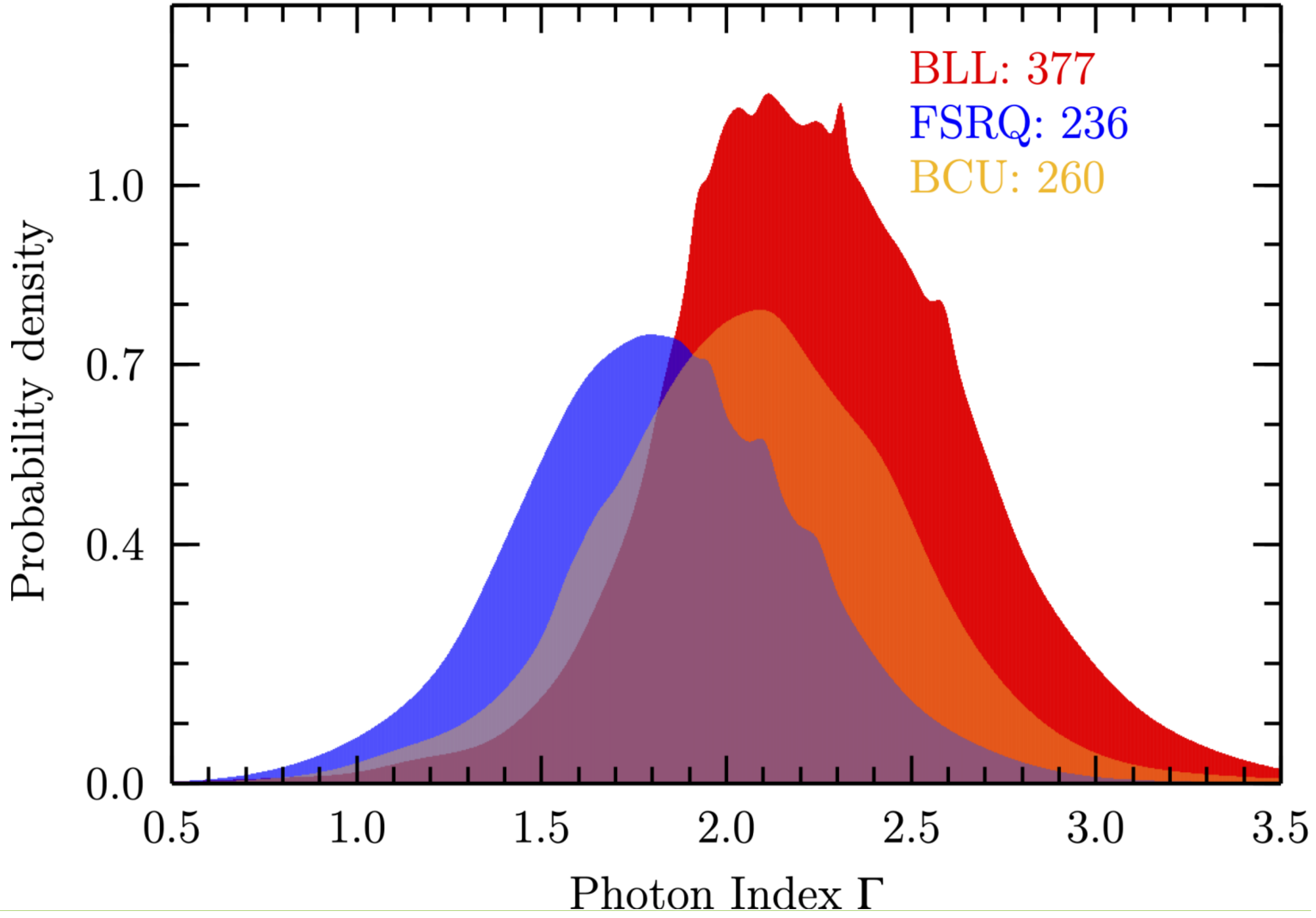
total matches: 6421
within 8.0″
and with detection likelihood of 10.0 or higher
uncertain blazar type: 735
BL Lac-galaxy dominated: 32
BL Lac candidates: 1054
FSRQ candidates: 1076
BL Lac: 639
uncertain blazar type candidates: 2079
FSRQ: 806



Courtesy of Steven Hämmerich (FAU)

BlazEr1 - properties

- More than 1400 sources have enough counts for a spectral analysis
- BLLs have softer spectra than FSRQs, while BCUs are in-between
- The populations of blazars and blazar candidates are studied
- Extensive use of MWL data to get a detailed picture



Courtesy of Steven Hämmerich (FAU)

Conclusions

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/

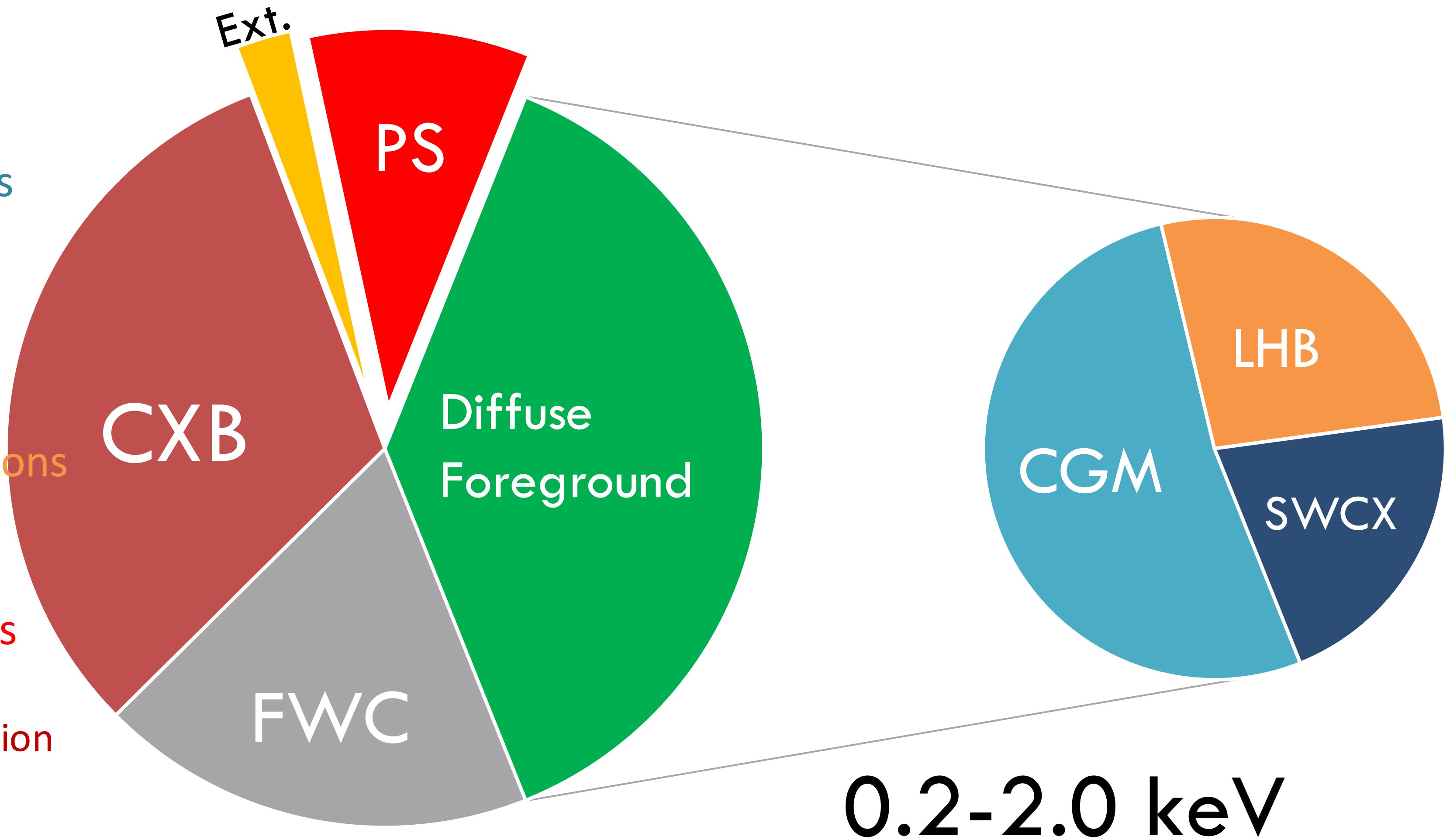
www.mpe.mpg.de/eROSITA

Thank you

The eRASS1 (soft) photon Pie

~340 Million calibrated events

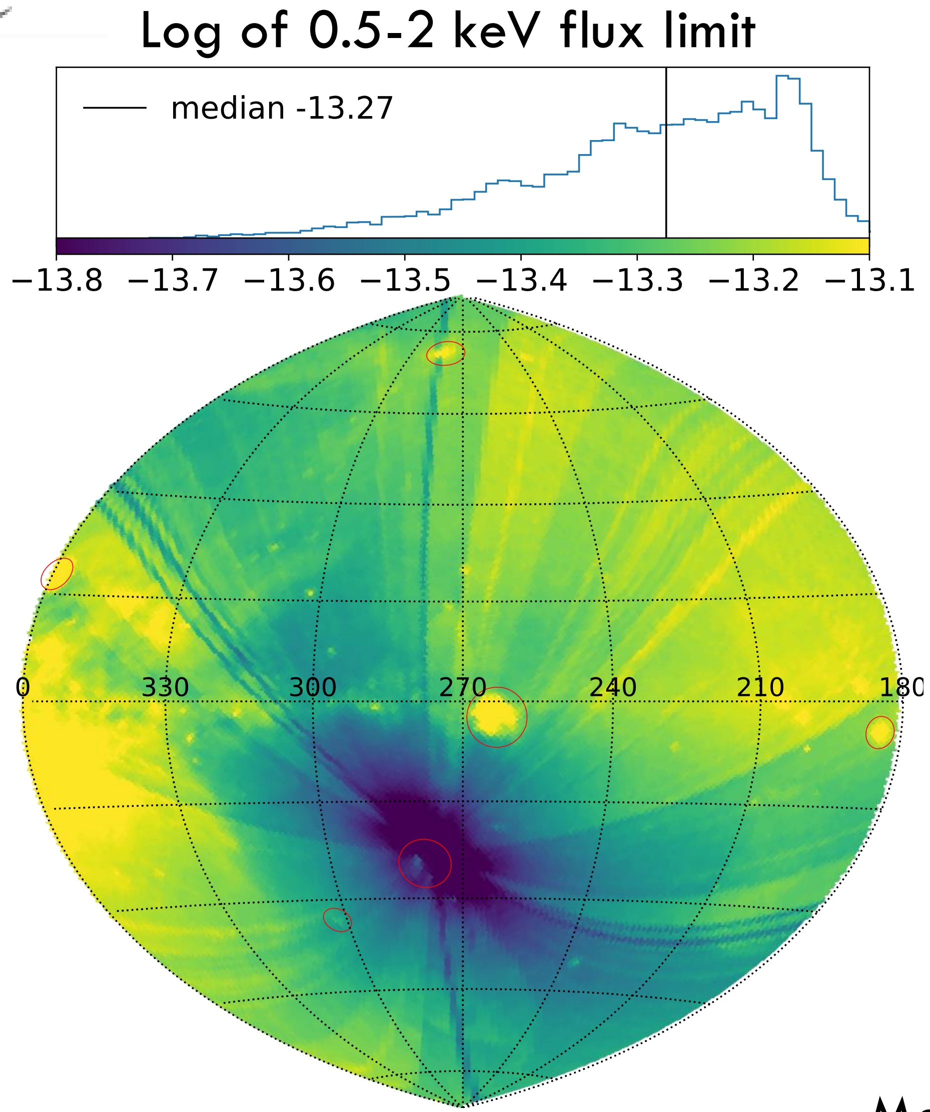
- 107 Million CXB photons
- 67 Million MW Hot CGM photons (58M halo + 9M ‘Corona’; Ponti+’23)
- 63 Million Instrumental BKG photons (FWC)
- 34 Million Local Hot Bubble photons
- 27 Million Solar Wind Charge Exchange photons
- 32 Million Point Sources’ photons
    - 24 Milllion AGN photons; 8 Million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

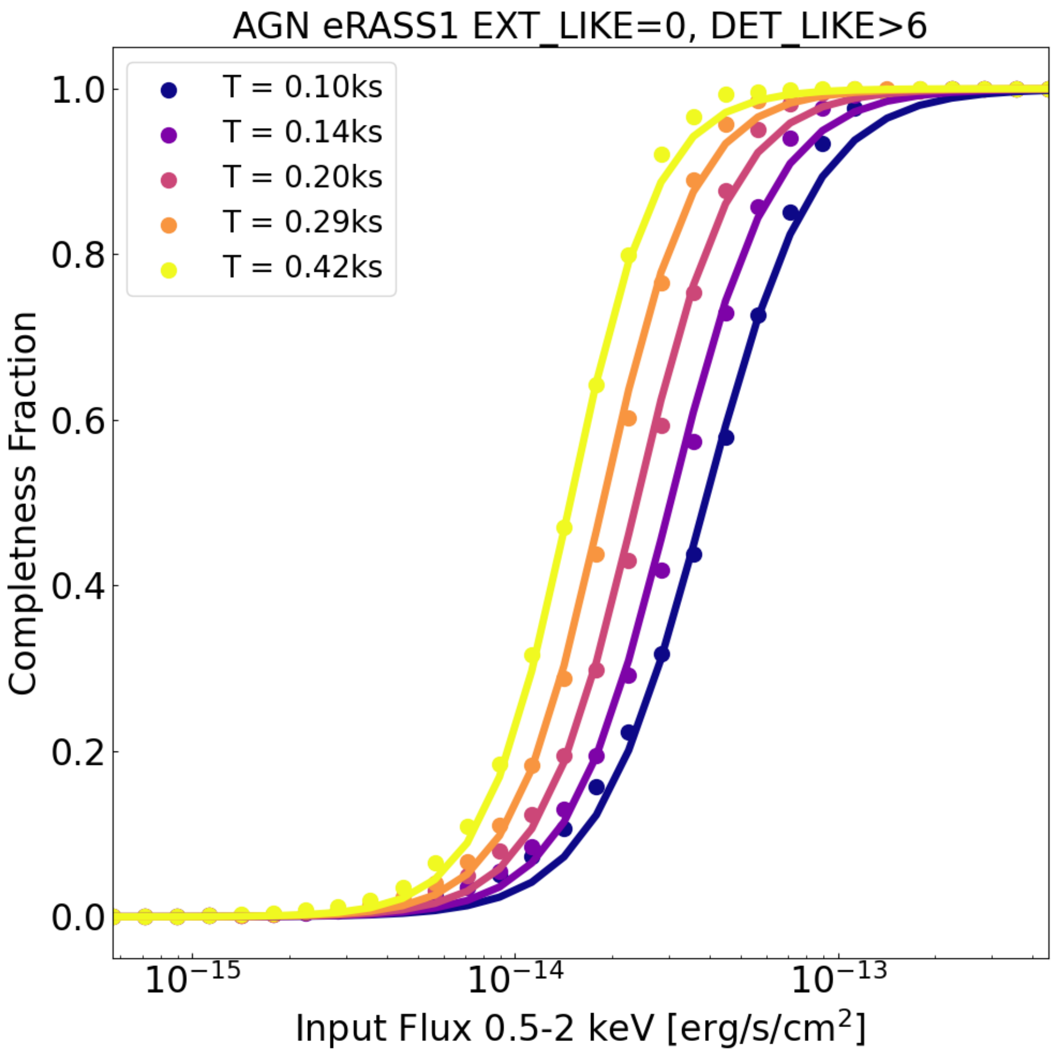


0.2-2.0 keV

Merloni et al. (2024)

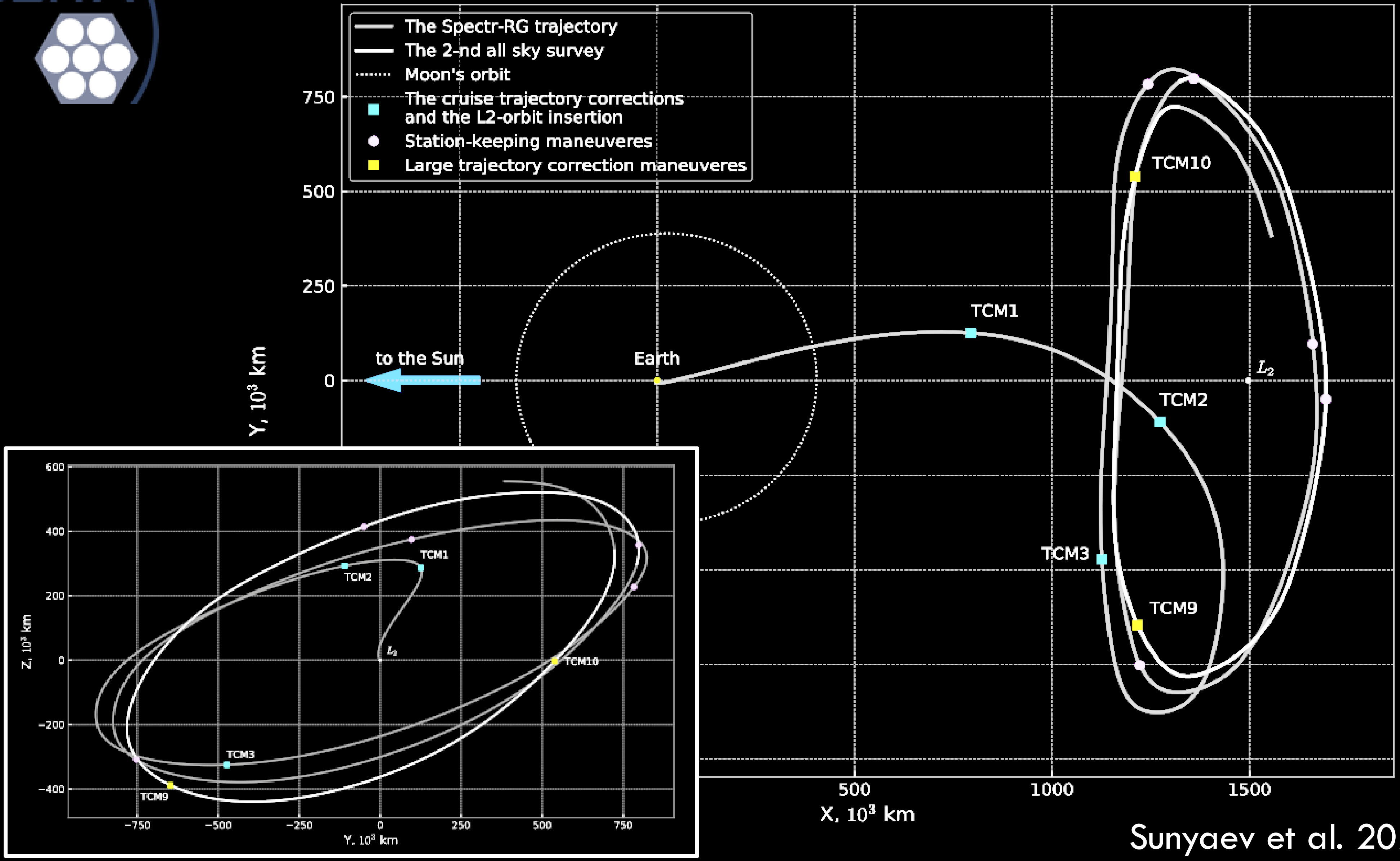
eRASS1 Main Catalogue: flux limit





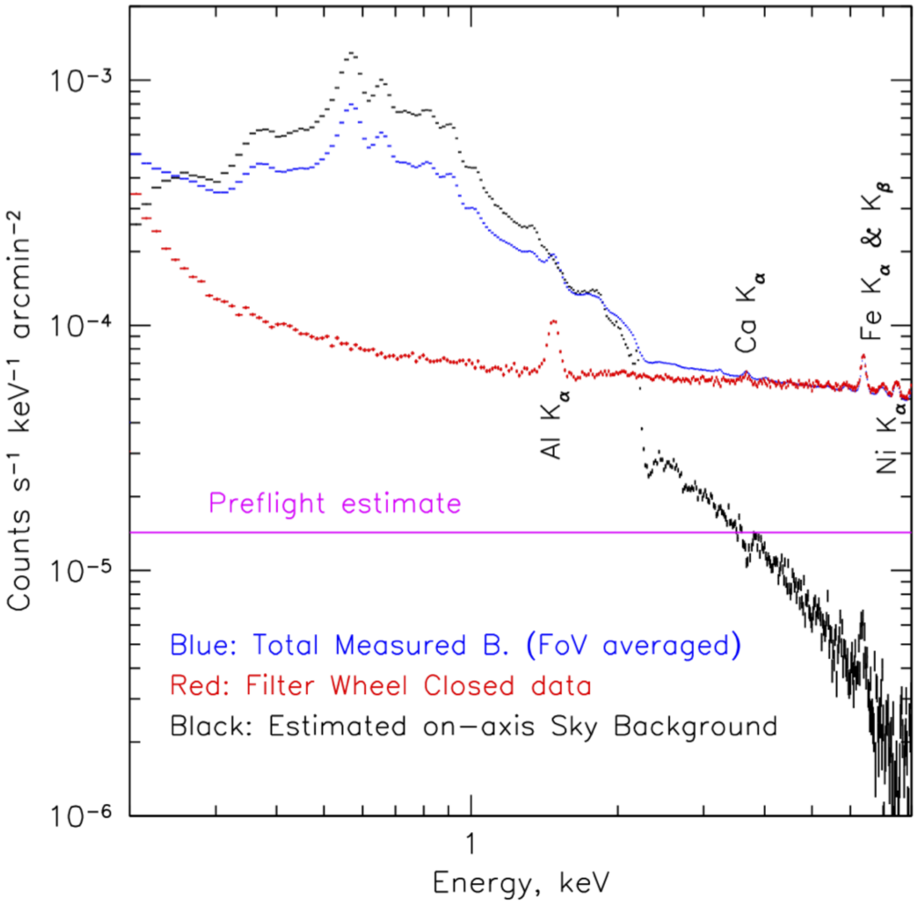
Merloni et al., 2024

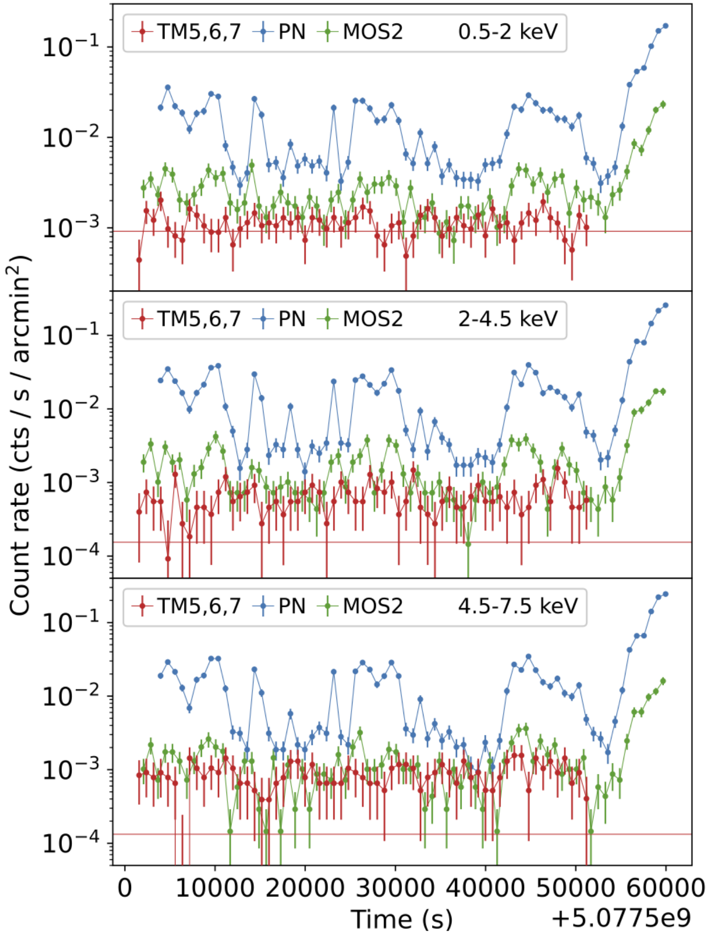
A large Halo L2 orbit



Sunyaev et al. 2021

X-ray Background @ L2

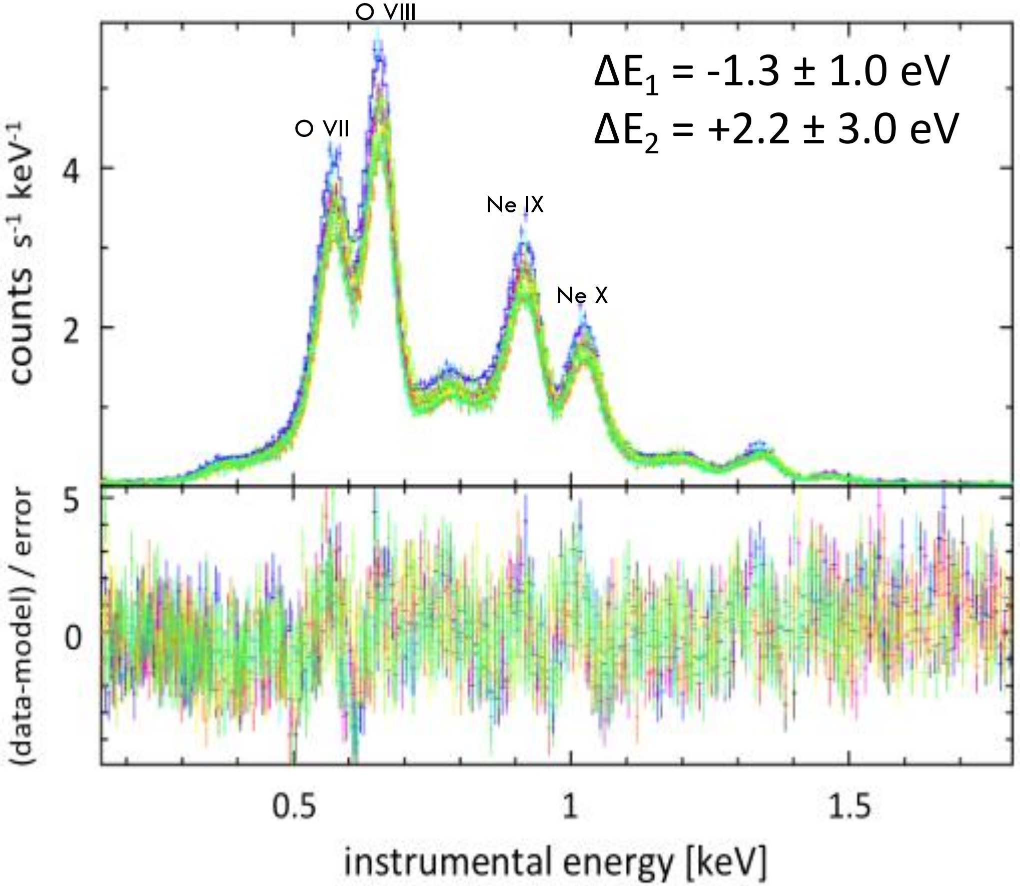




1) Background much less variable than in the XMM and Chandra data
2) A factor of ~3 higher particle bkgnd than predicted in the White Book -> Instrument mass model
3) Less fluorescence lines than EPICpn due to graded shields
4) But: iron line (+others) likely from impurities in the graded shield itself

Calibration: Energy scale

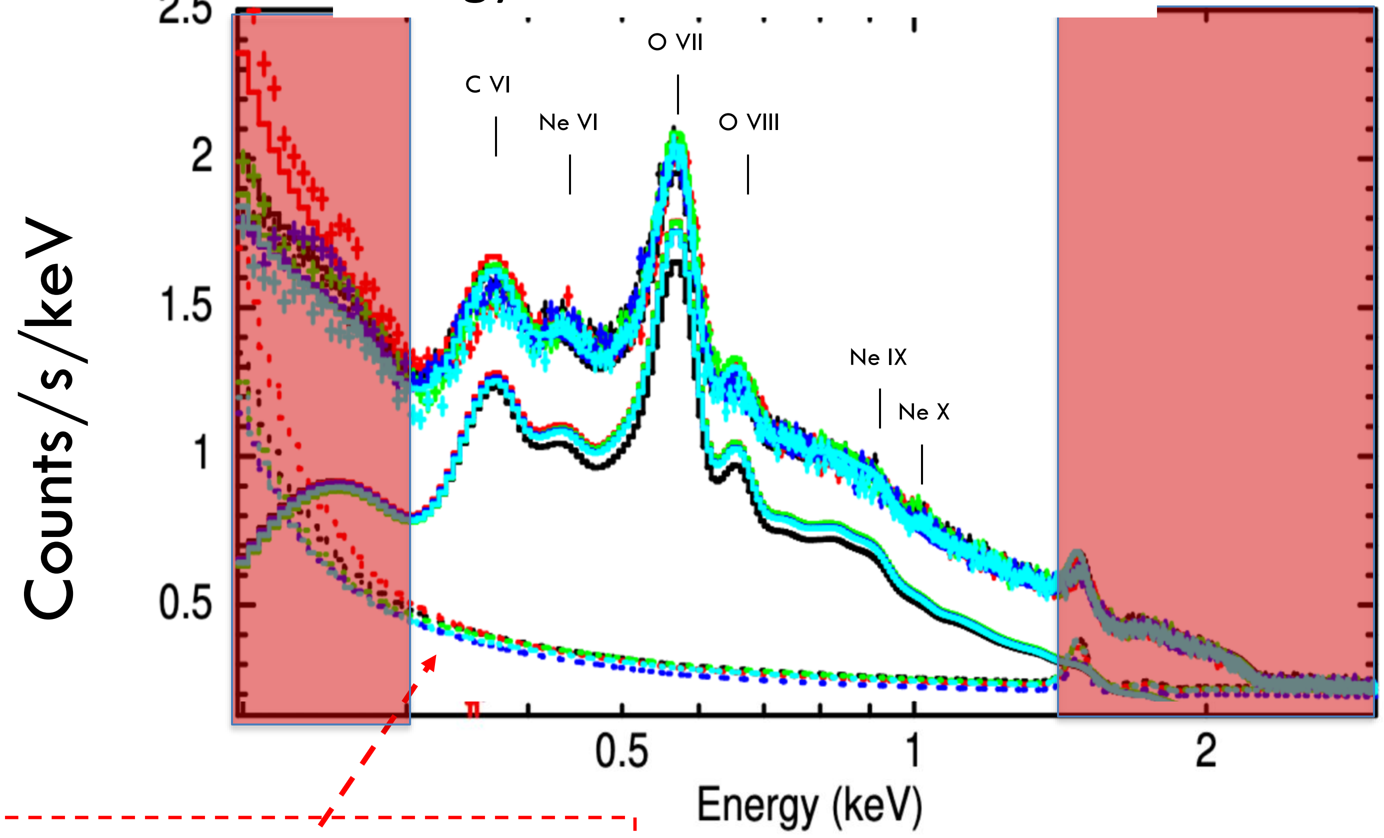
eROSITA spectrum of SNR 1E 0102-7219



Merloni et al. 2024

eROSITA spectrum of eFEDS

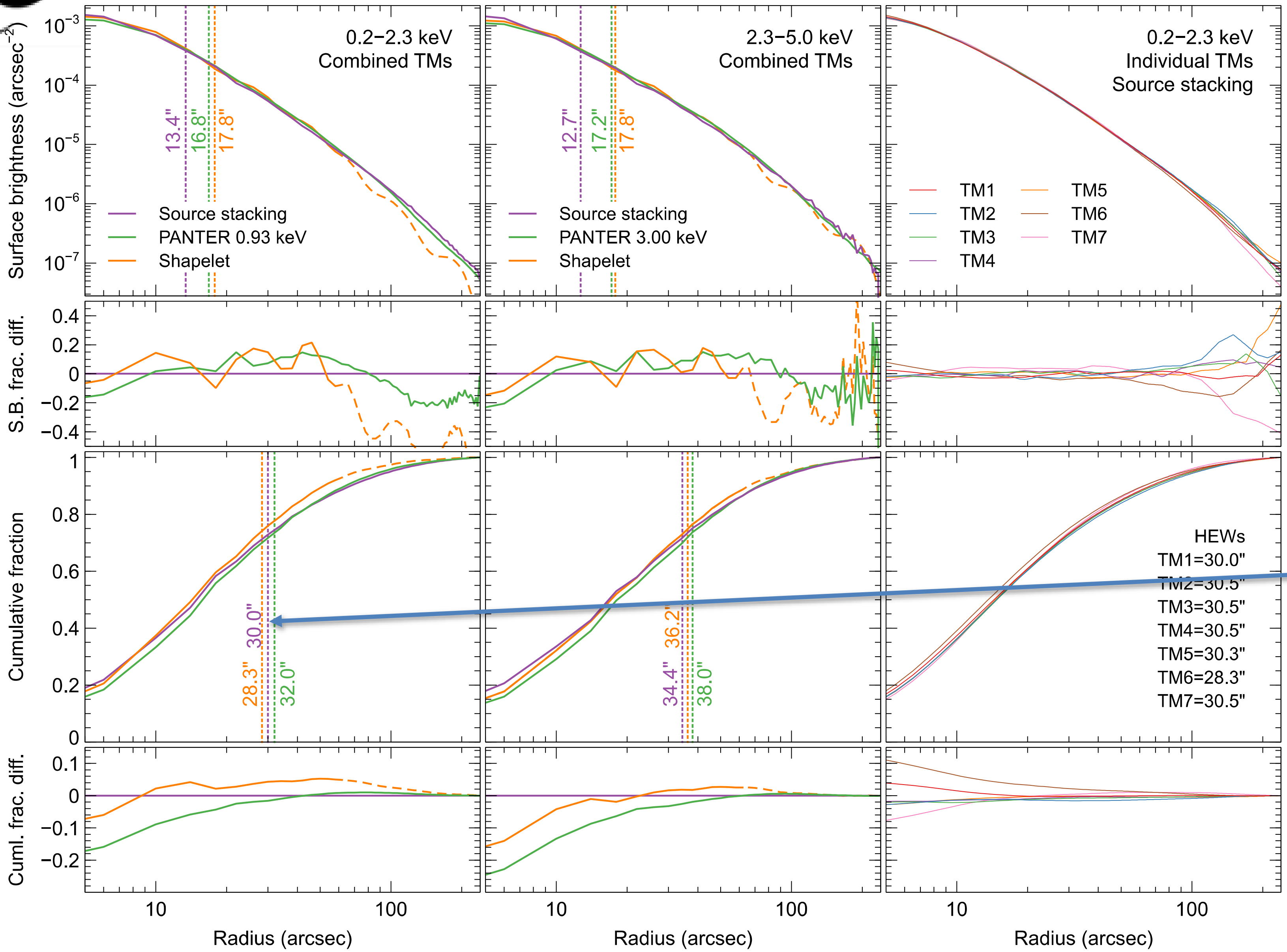
Energy scale shift factor <3eV



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