

Large X-ray galaxy cluster surveys with *e*ROSITA and follow-up programmes

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Journées “Amas France”
10 décembre 2020 – On-line

Thanks to:



Clusters of galaxies in X-rays

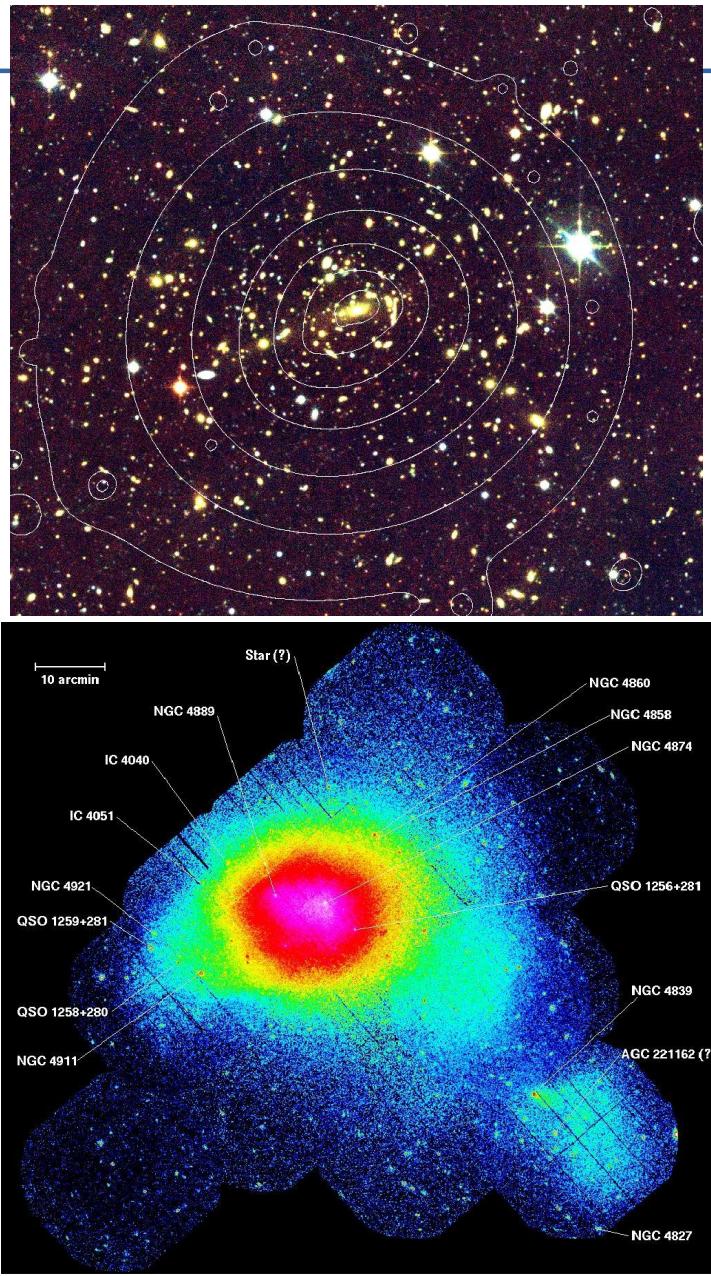
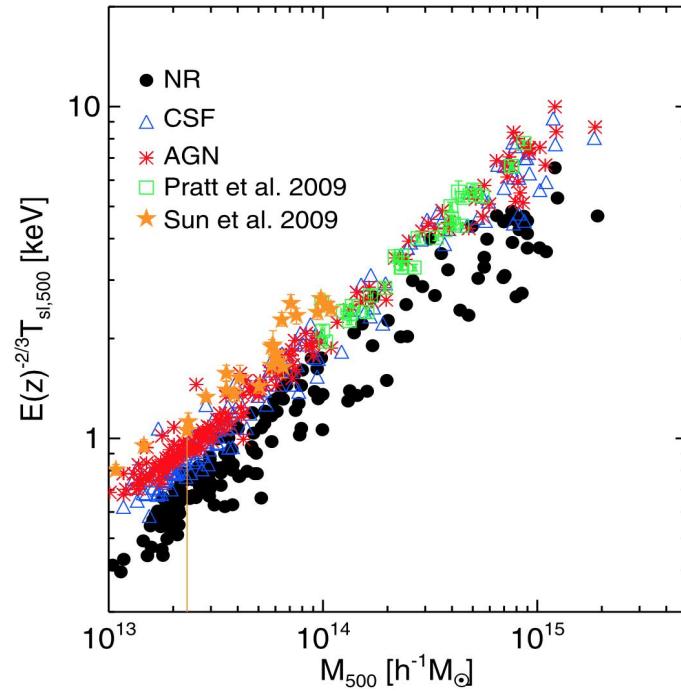


Image courtesy of U. Briel, MPE Garching, Germany

Coma Cluster of galaxies

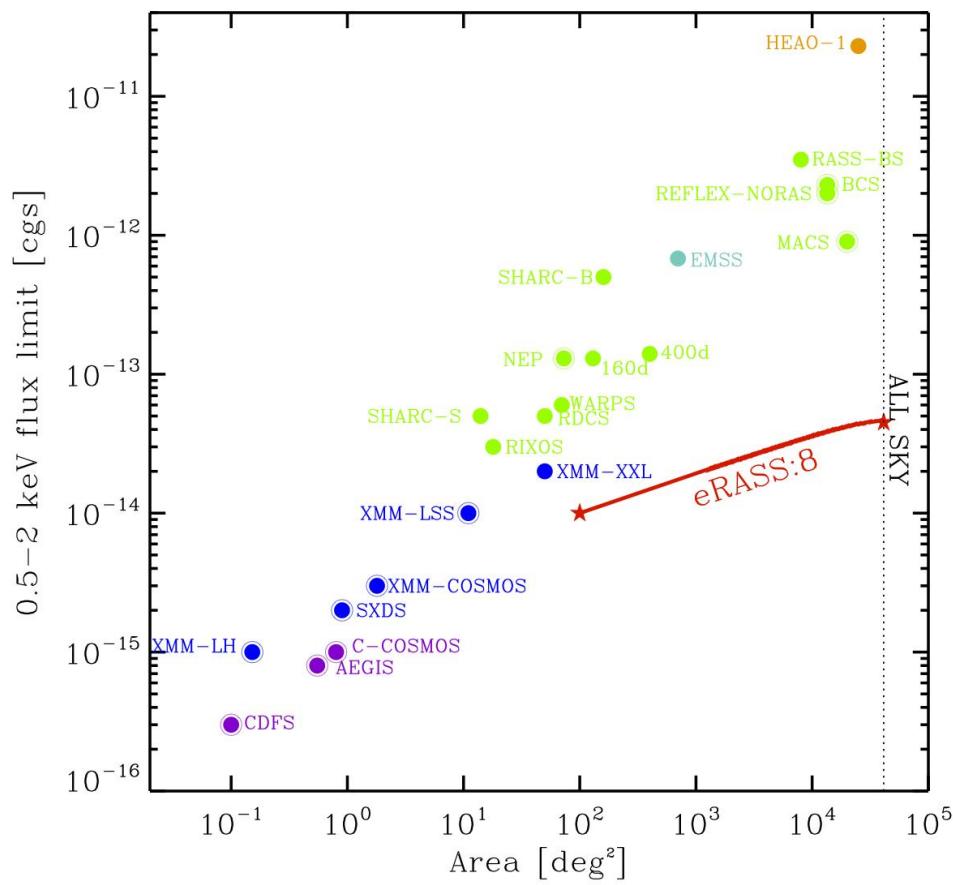
European Space Agency



Data: Pratt et al. 2009 (clusters); Sun et al. 2009 (groups)
Simulations: Planelles et al. 2014

- Hot gas = low-density plasma (15%)
 - Highly ionized (e.g. Fe XXV line)
 - Luminous and extended
- **X-ray: clean and efficient selections**
- **Mass-observable link and evolution**

Large galaxy cluster surveys in (soft) X-rays

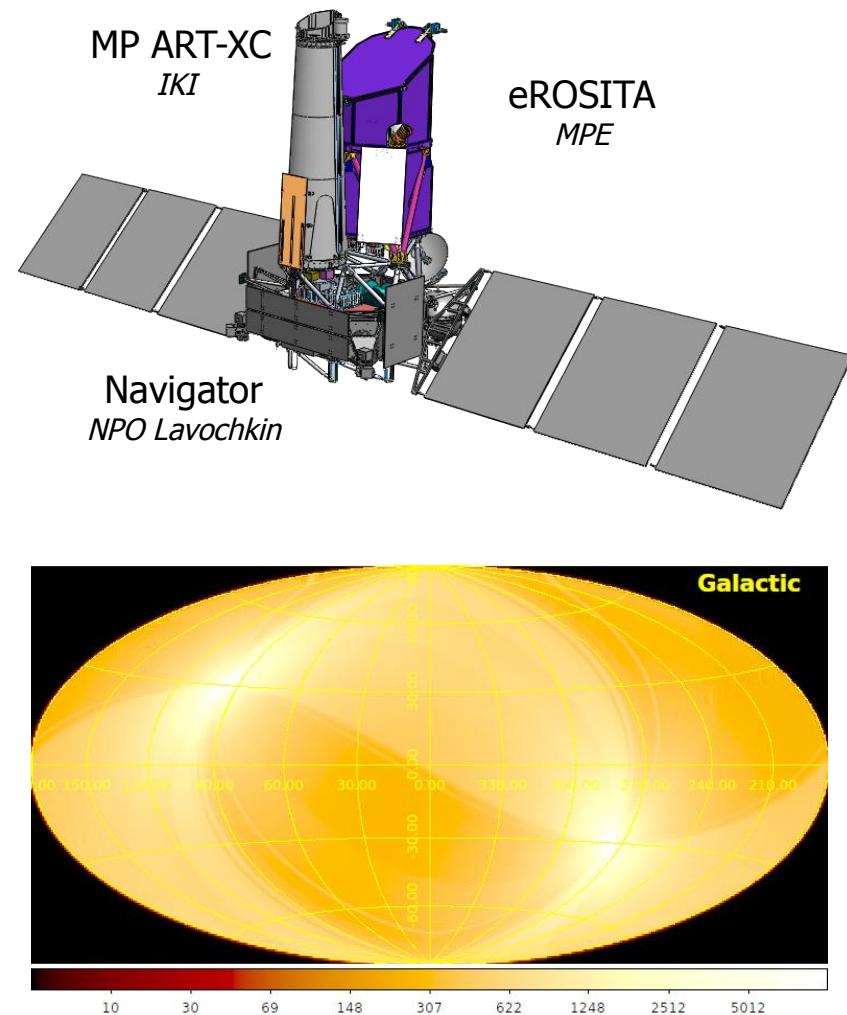


Merloni+12



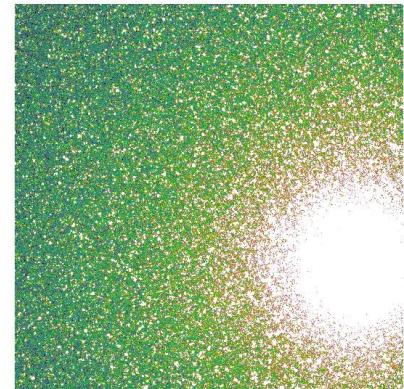
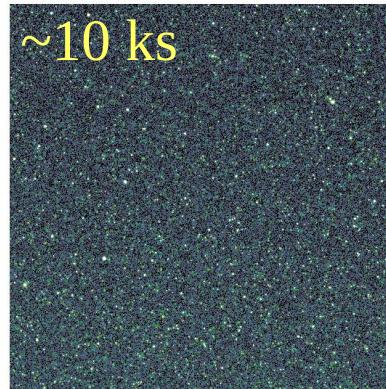
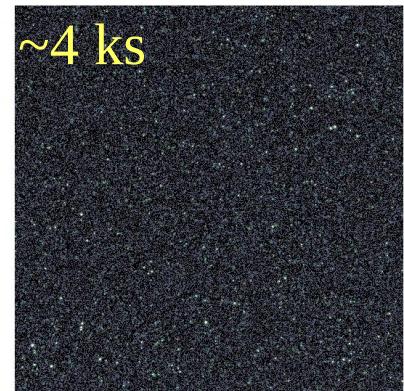
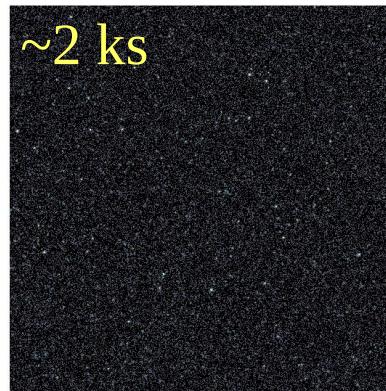
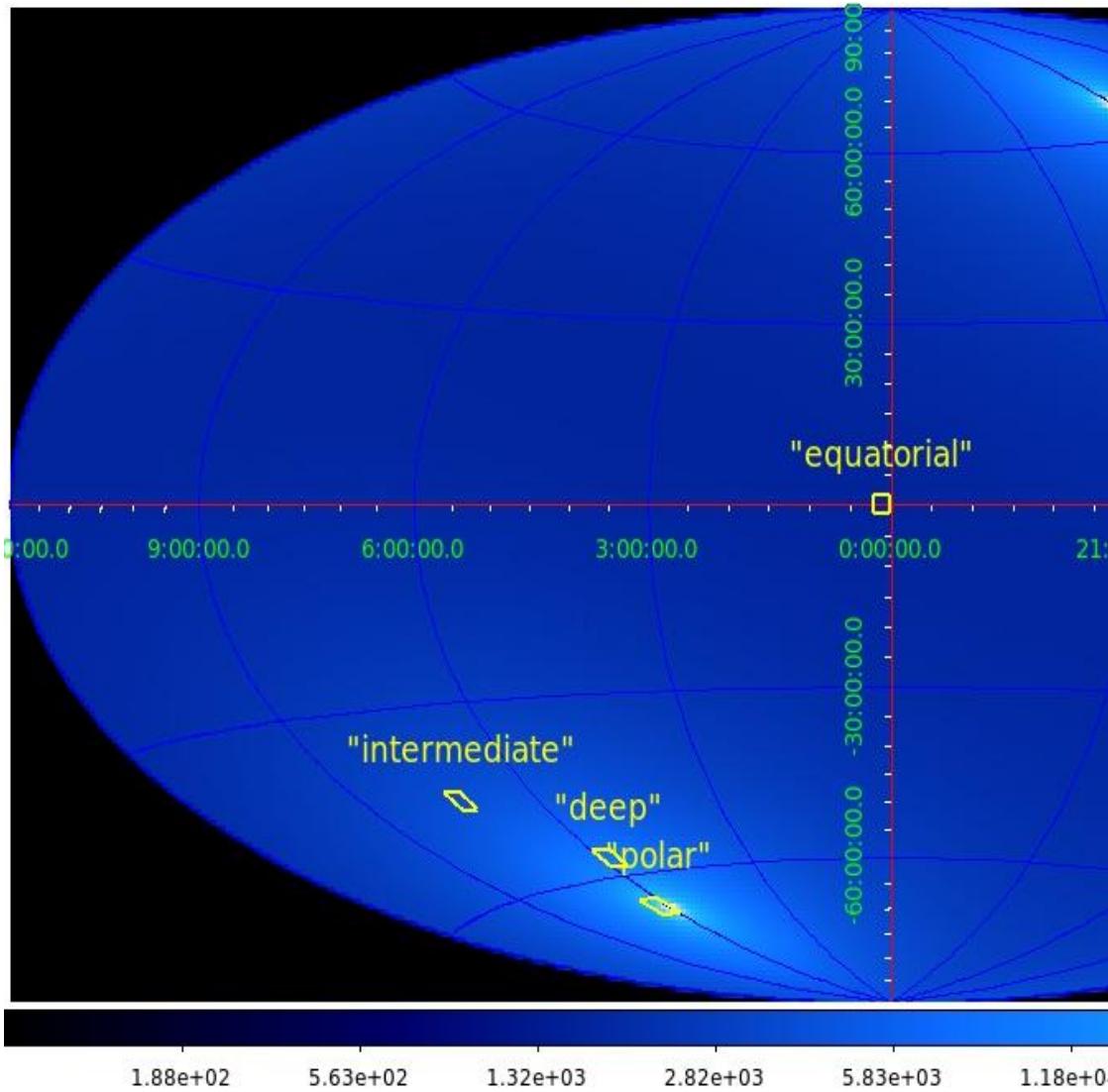
The *e*ROSITA all-sky survey

- **Launched to L2 from Baikonour (13.7.2019)**
 - 3 months flight to L2: *verification, calibration*
 - 4 yrs survey: 8x *all-sky*
 - 2.5 yrs pointed observations ($\sim 20\%$ GTO)
 - Data shared MPE (DE)/IKI (Ru)
 - PI: A. Merloni (MPE)
- **More than the successor of ROSAT!**
 - FoV = 0.8 deg²
 - PSF hew: 26" (survey-averaged) ; 18" (on-axis)
 - $A_{\text{eff}} \sim XMM @ 1 \text{ keV}$
 - 0.3-10 keV ; E/ ΔE $\sim 20-50$ (80 eV @ 1.5 keV)
- ***e*ROSITA just completed the 2nd all-sky map**
 - Excellent performance of the 7 telescopes+cameras. First light images public.



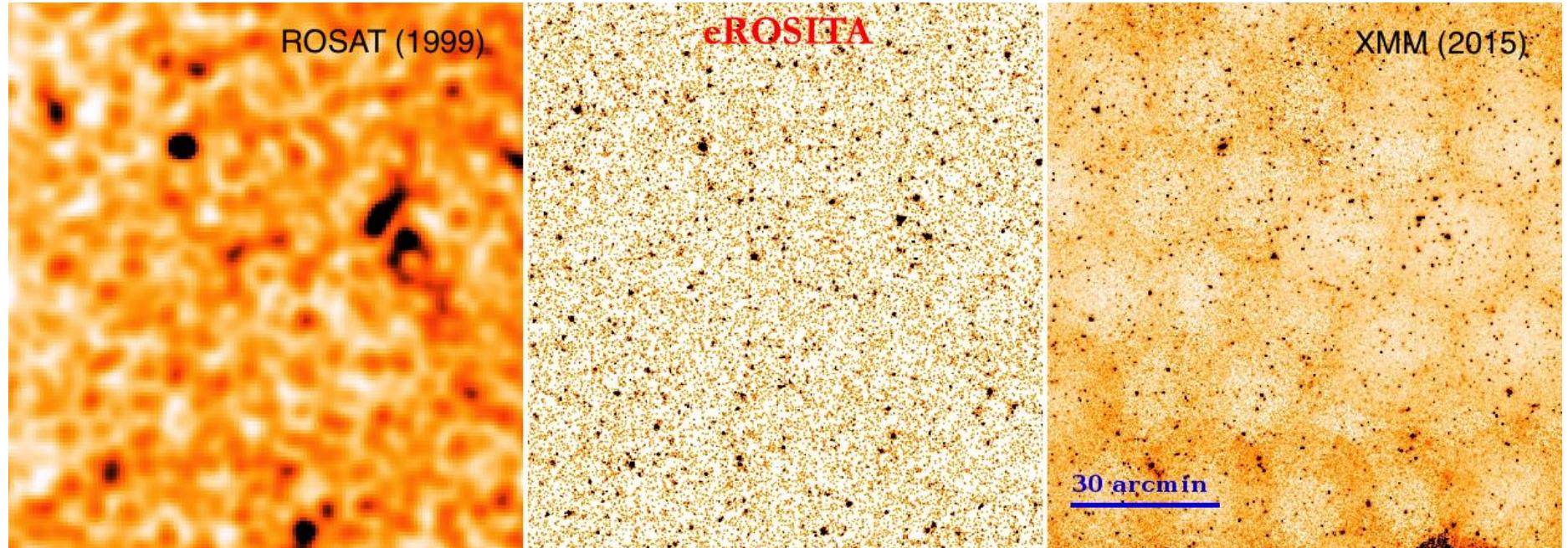
Credit: <https://erosita.hs.uni-hamburg.de/>

Pre-launch “Synthetic” simulations



- ✓ Realistic exposure maps
 - ✓ Representative backgrounds
 - ✓ Ray-tracing PSF/vignetting
 - ✓ Photons → Events transform

The eROSITA all-sky survey (pre-launch simulations)



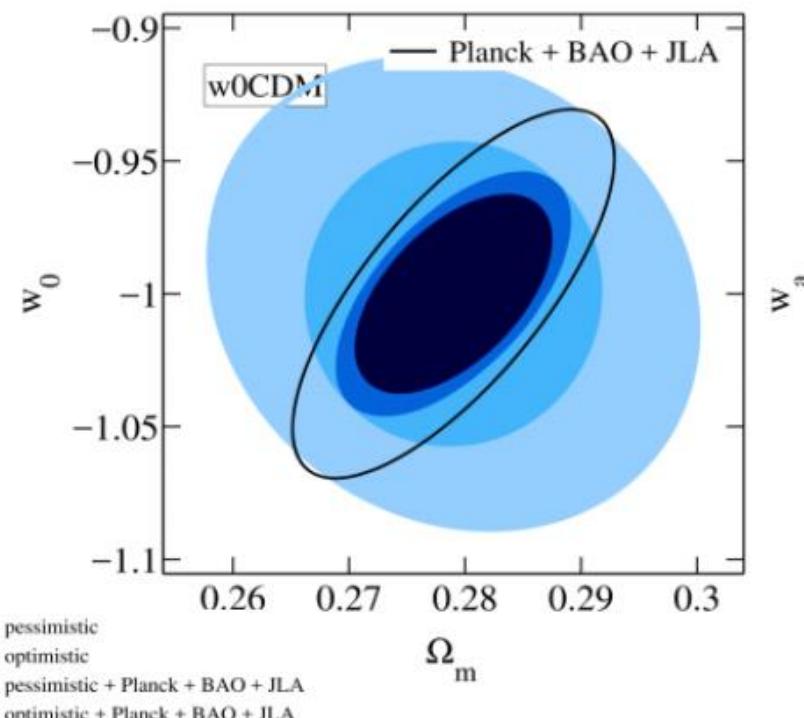
- **Point-source sensitivity:** $\sim 10^{-14}$ (0.5-2 keV) and 2×10^{-13} (2-10 keV) ergs/s/cm²
- **Extended sources sensitivity** $\sim 3\text{-}4 \times 10^{-14}$ ergs/s/cm²
- Wide-area census of galaxy clusters (10^5) and active galactic nuclei (3M) in soft+hard X-rays bands

Merloni et al. 2012 – Image credits: MPE, eROSITA_DE, XMM-XXL

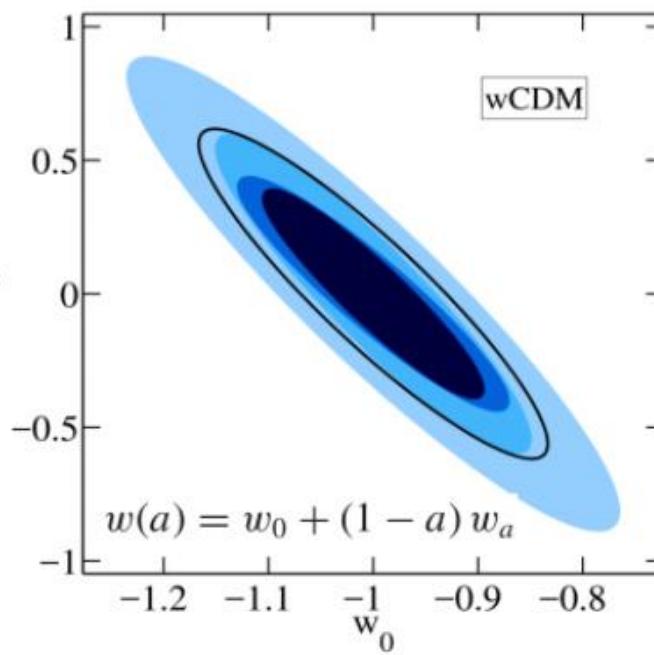
eROSITA forecasts on wCDM

Forecasts on Dark-Energy Models

$eRASS:8 + H_0 + \text{BBN}$
 $\Delta w_0 = 4\text{-}6\%$



$eRASS:8 + H_0 + \text{BBN}$
 $\Delta w_0 = 10\text{-}15\%$
 $\Delta w_a = 0.4\text{-}0.6$



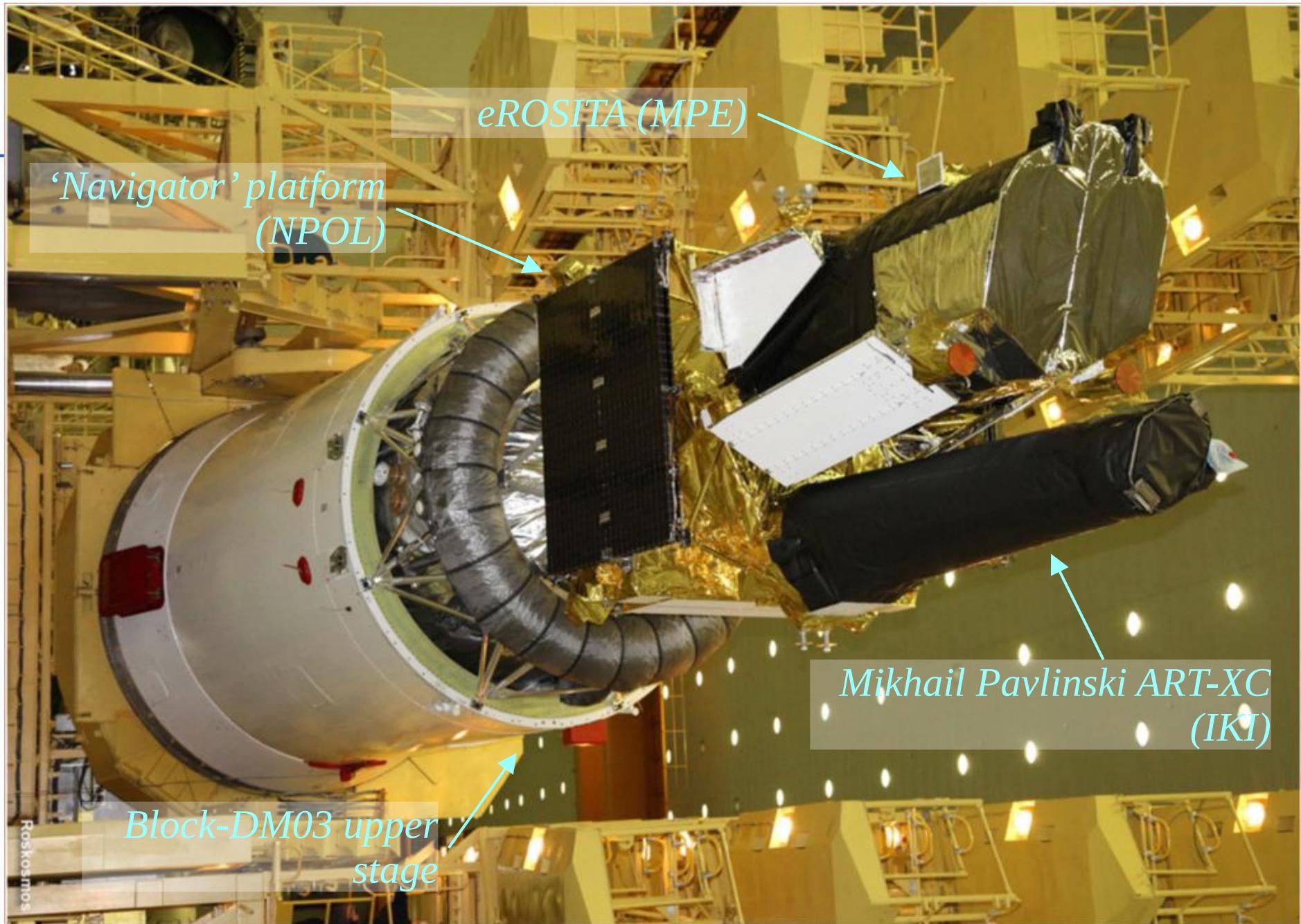
Pillepich et al. 2018

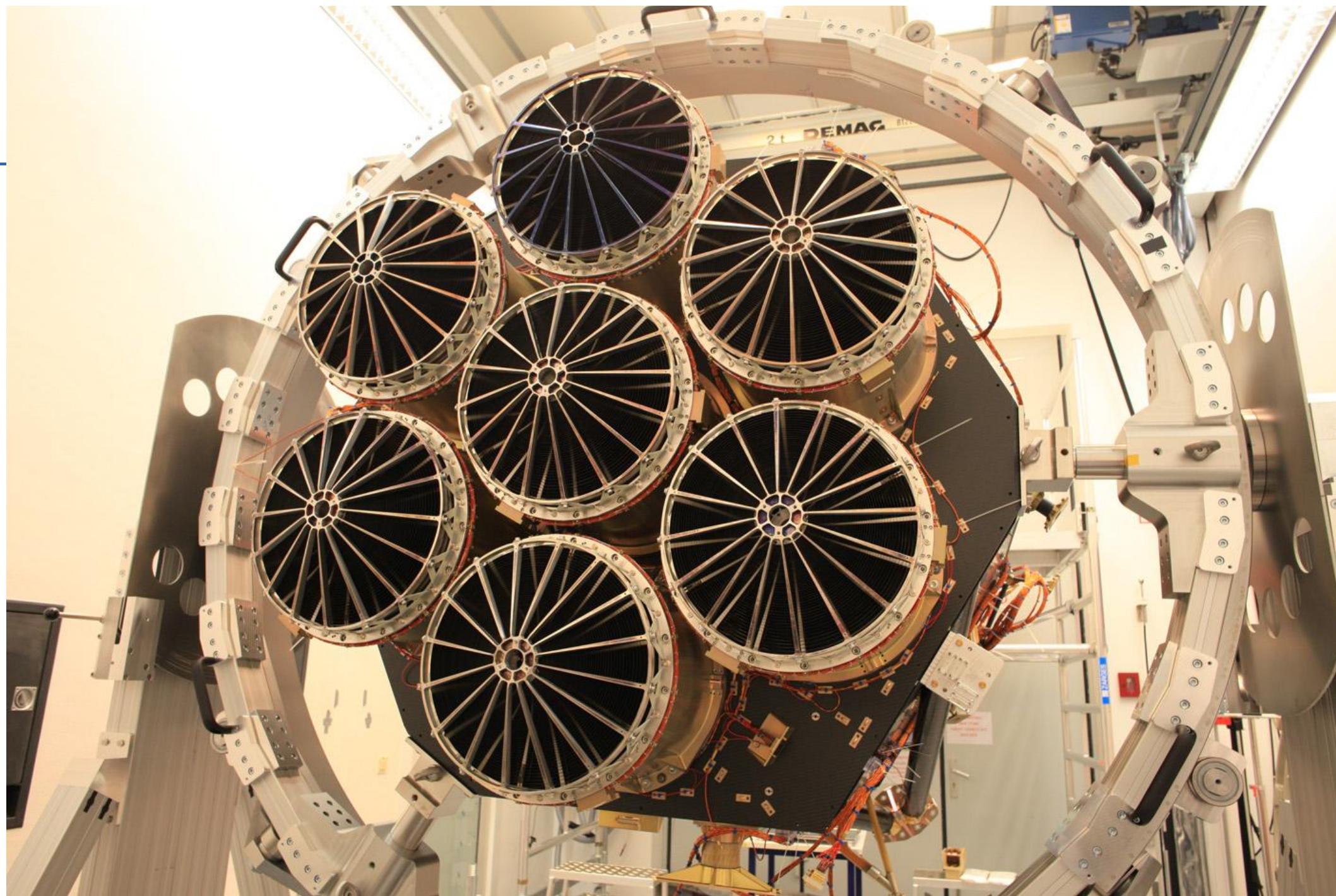
Baikonur, 13. 7. 2019



Quelle: Roscosmos

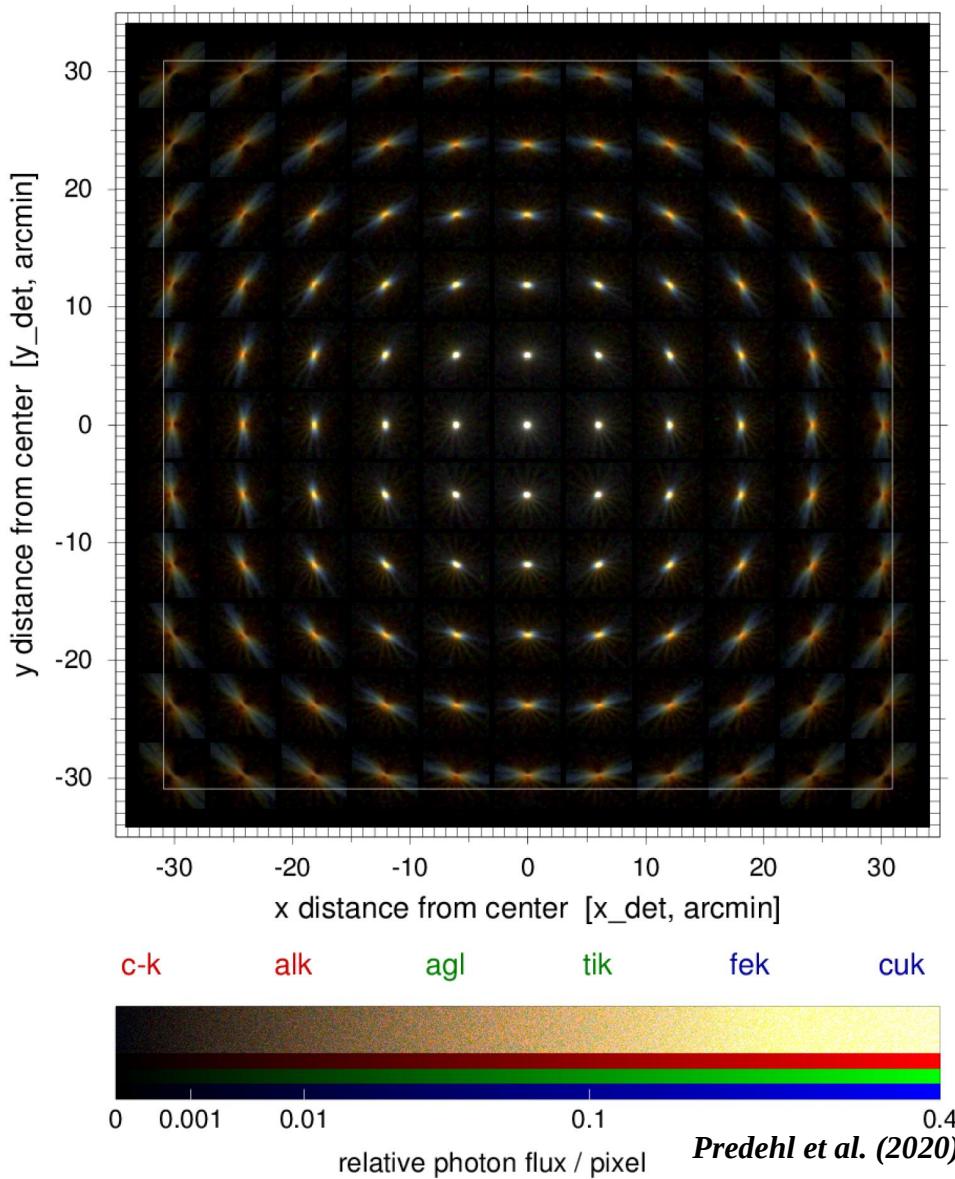
Credits: Roscosmos





Credits: MPE

7 mirrors and 7 ‘pn’ CCDs



- **HEW: 26" (survey), 18" (pointed)**
 - Source location ($1-\sigma$) uncertainty $\sim 3\text{-}5"$
- **X-ray baffle: 92% straylight reduction**
- **Very uniform detectors with little temperature dependence**
- **No chip gaps, no out-of-time events**

Effective area

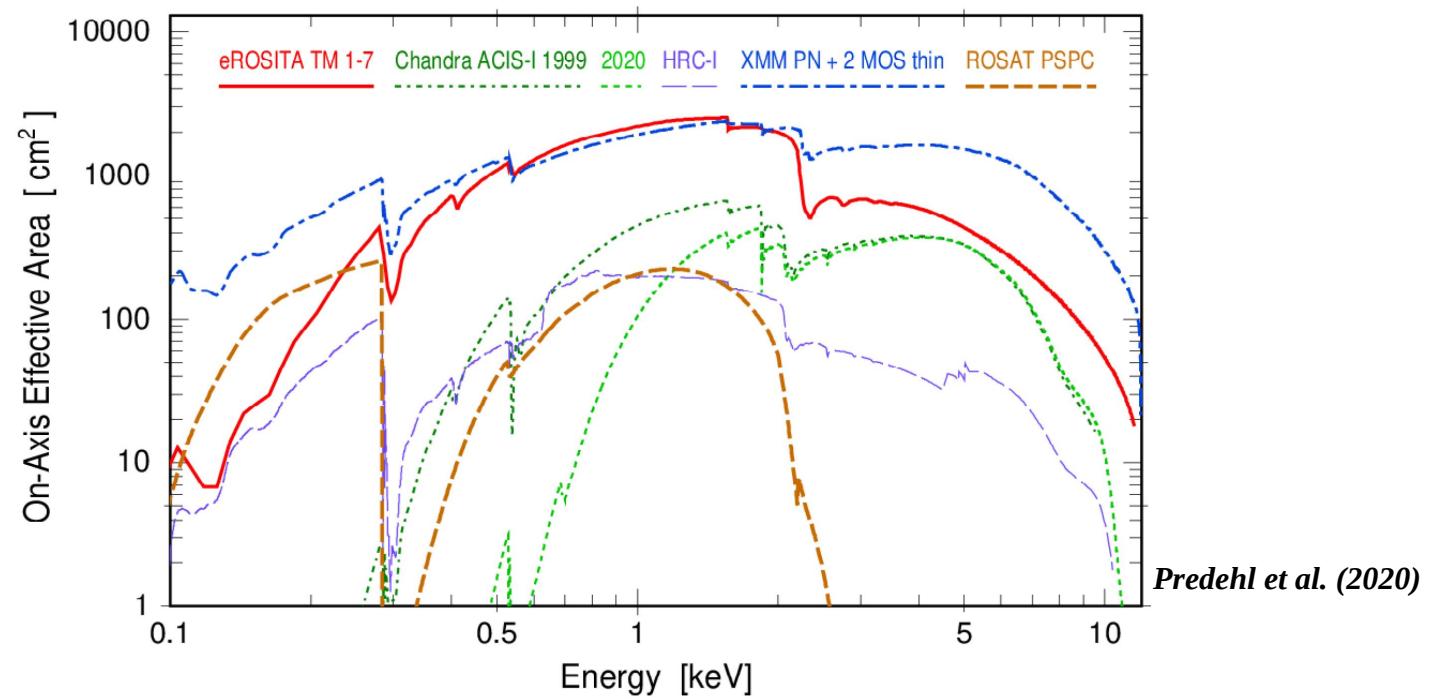
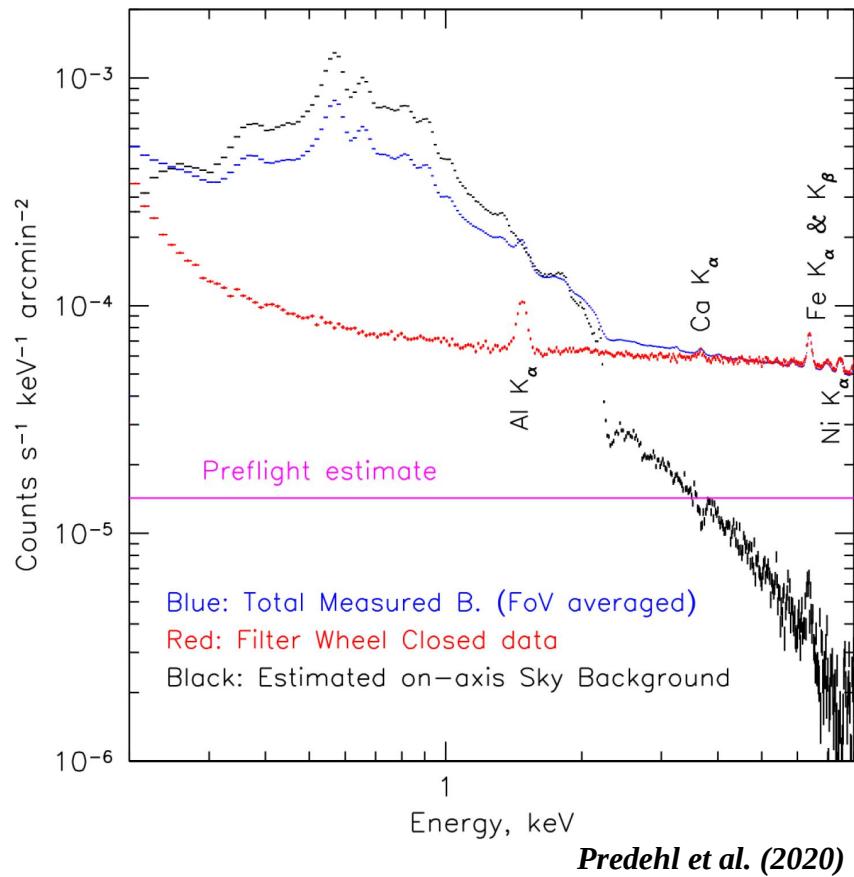
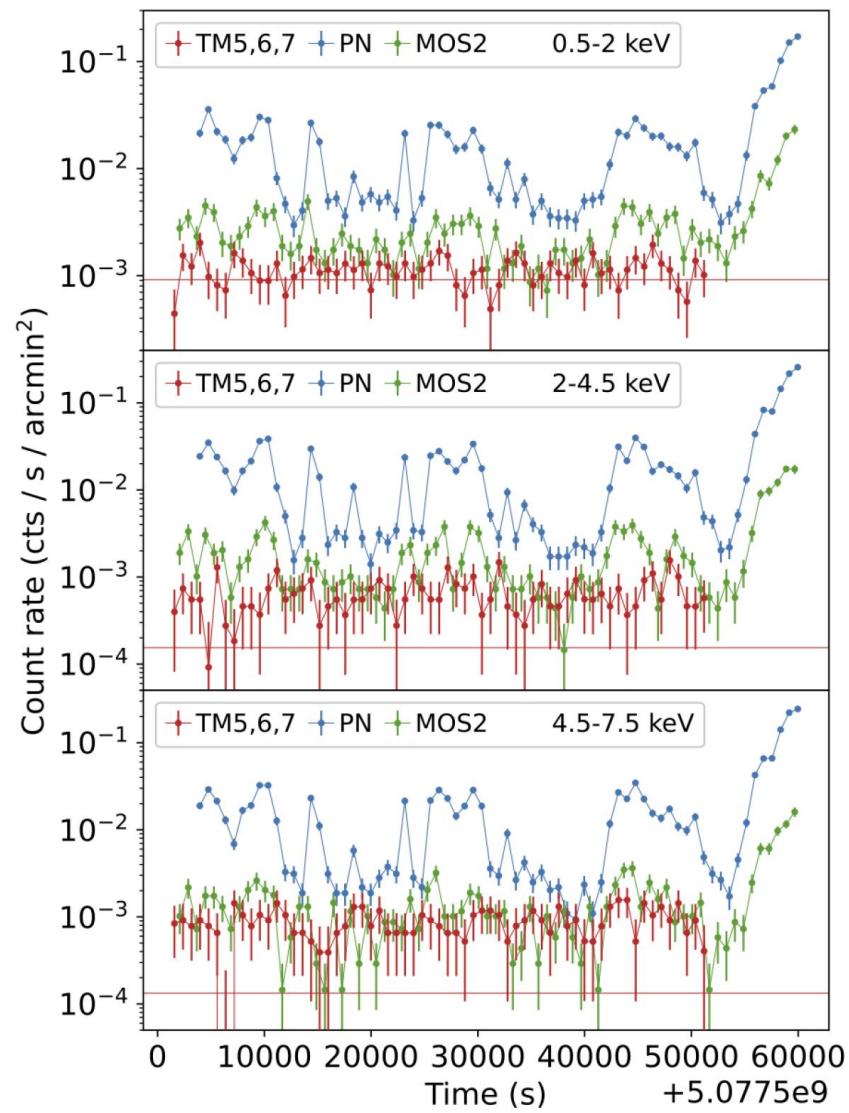


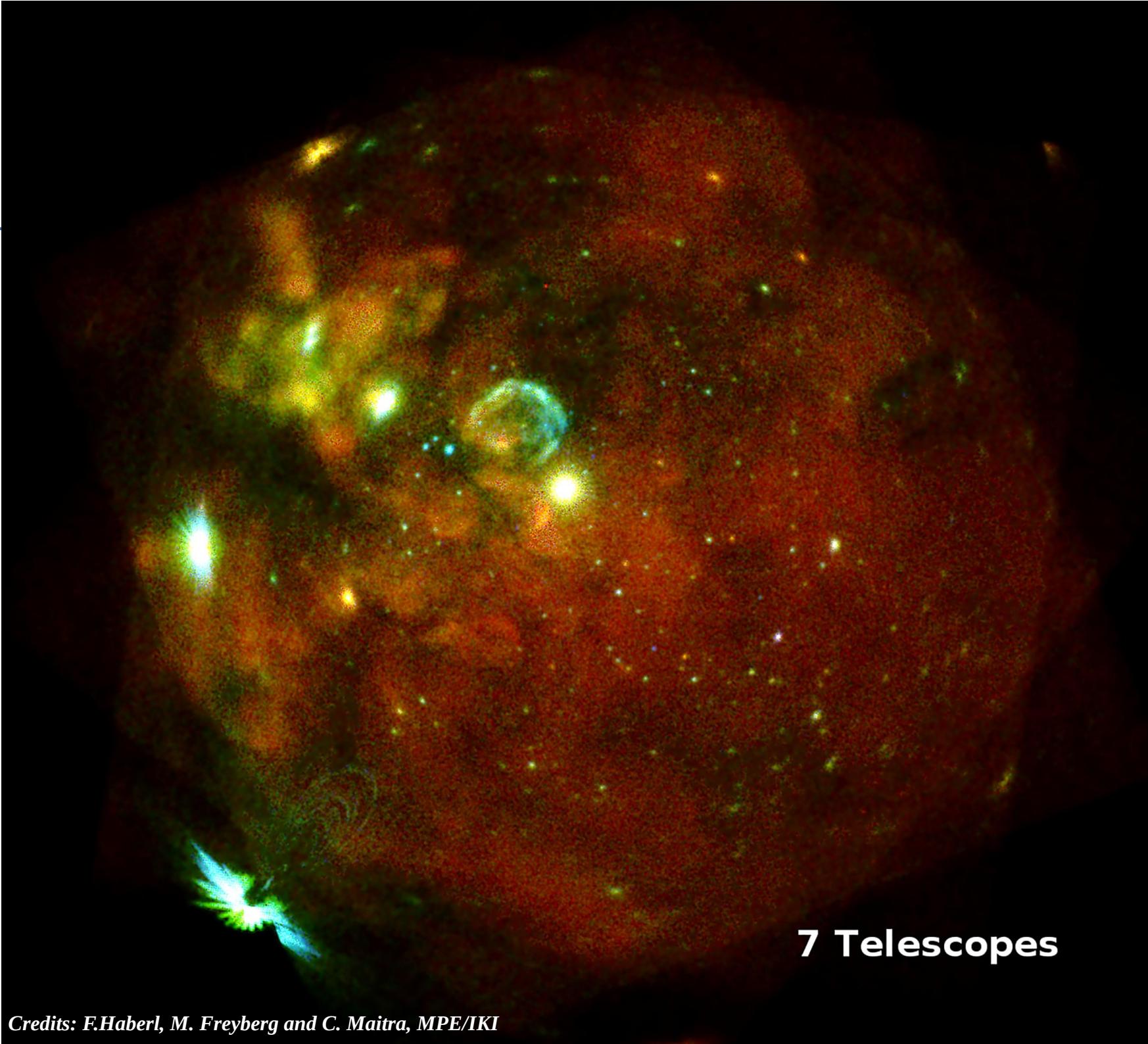
Fig. 9. Comparison of the on-axis effective areas as a function of energy for eROSITA (red), Chandra ACIS-I (in 1999, dark green, and in 2020, light green), Chandra HRC-I (purple), XMM-Newton (blue), and ROSAT (brown).

Background at L2

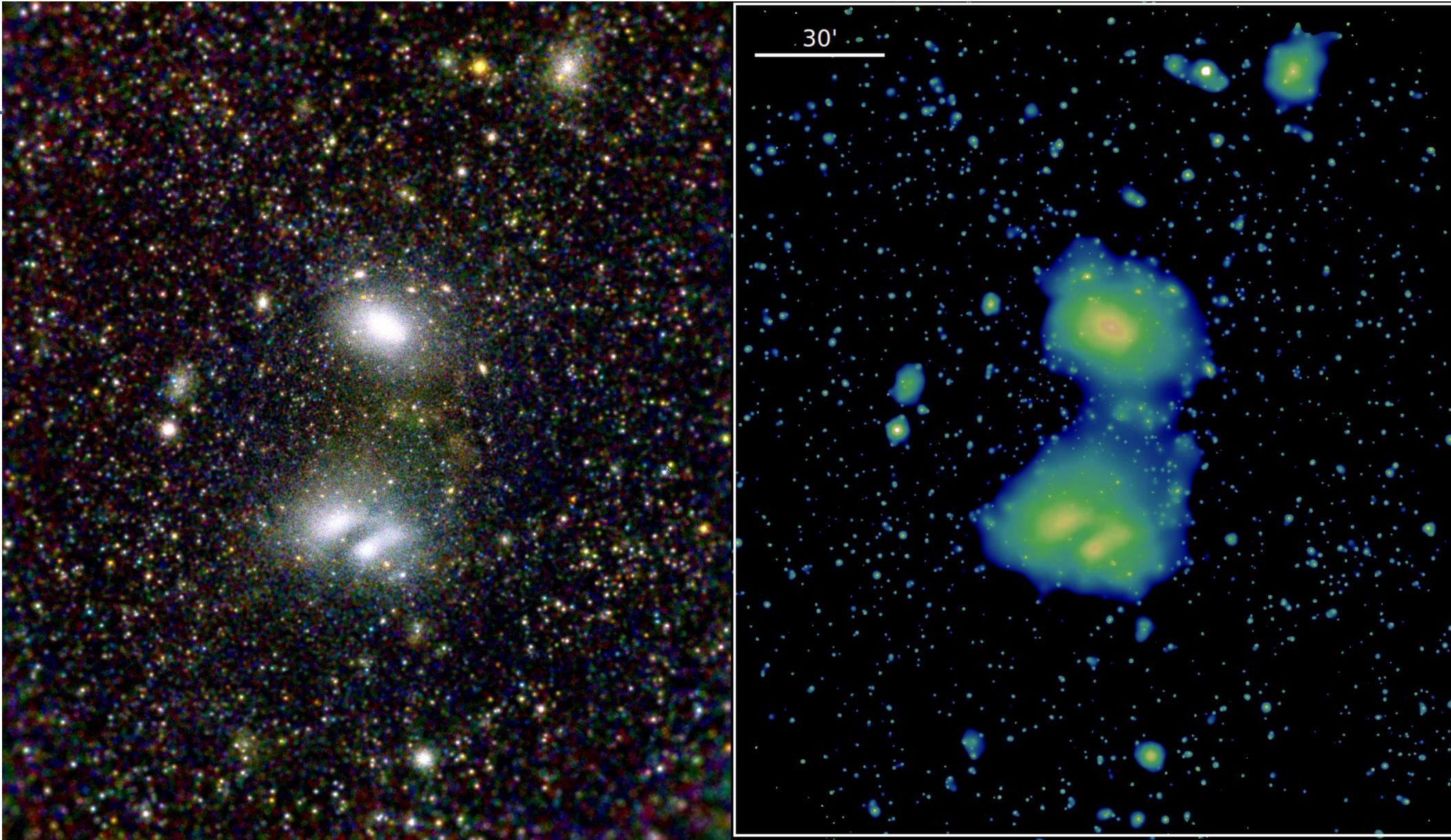


- Less variable background than XMM & Chandra
- 3x higher than predicted in science book
- Fe lines (and others) with yet unclear origin





7 Telescopes

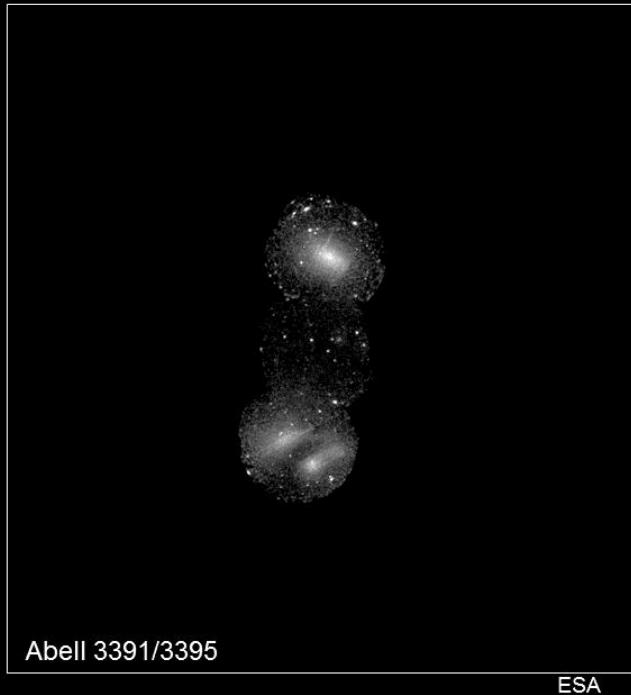


Credits: T. Reiprich (Univ. Bonn), M. Ramos-Ceja (MPE), F. Pacaud (Univ. Bonn), D. Eckert (Univ. Geneva), J. Sanders (MPE), N. Ota (Univ. Bonn), E. Bulbul (MPE), V. Ghirardini (MPE), MPE/IKI

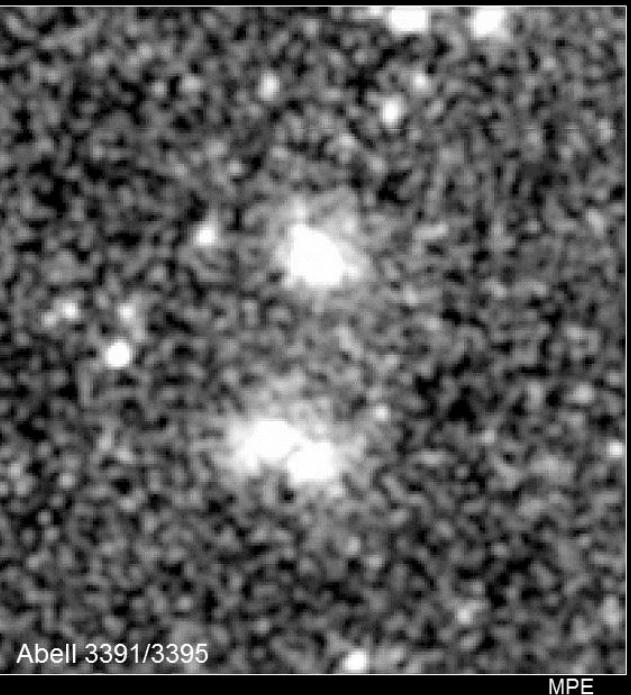
SRG/eROSITA 0.2-2.0 keV



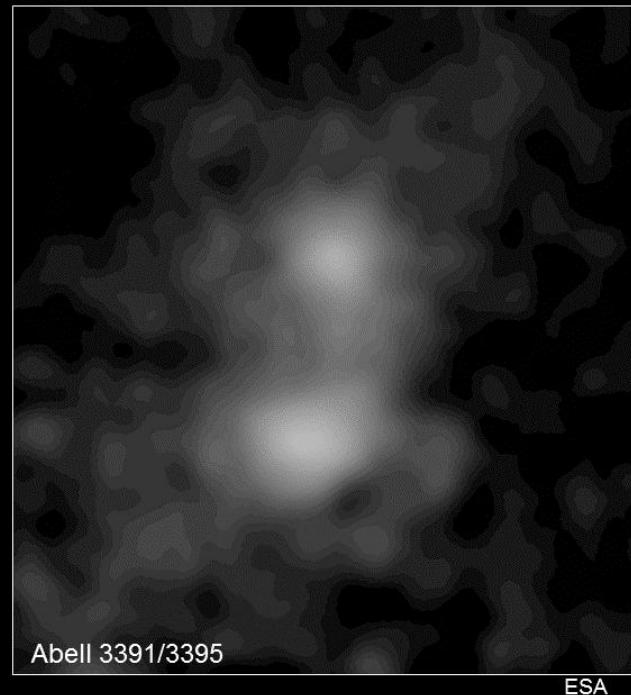
XMM-Newton 0.4-1.25 keV



ROSAT 0.5-2.0 keV

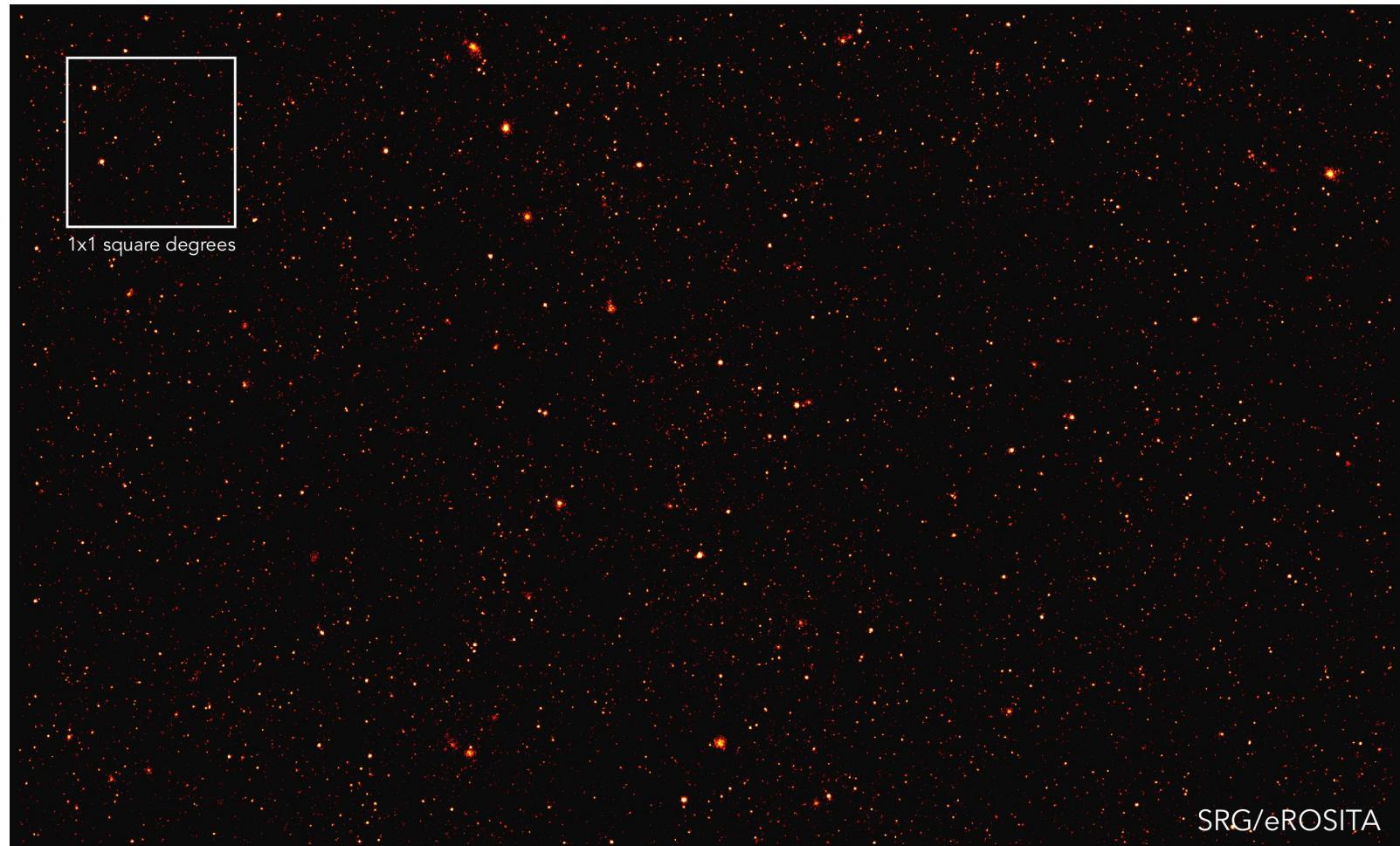


Planck (sub-)mm



Credits: T. Reiprich (Univ. Bonn), M. Ramos-Ceja (MPE), F. Pacaud (Univ. Bonn), D. Eckert (Univ. Geneva), J. Sanders (MPE), N. Ota (Univ. Bonn), E. Bulbul (MPE), V. Ghirardini (MPE), J. Erler (Univ. Bonn), A. Veronica (Univ. Bonn)

eROSITA Final Equatorial Depth Survey

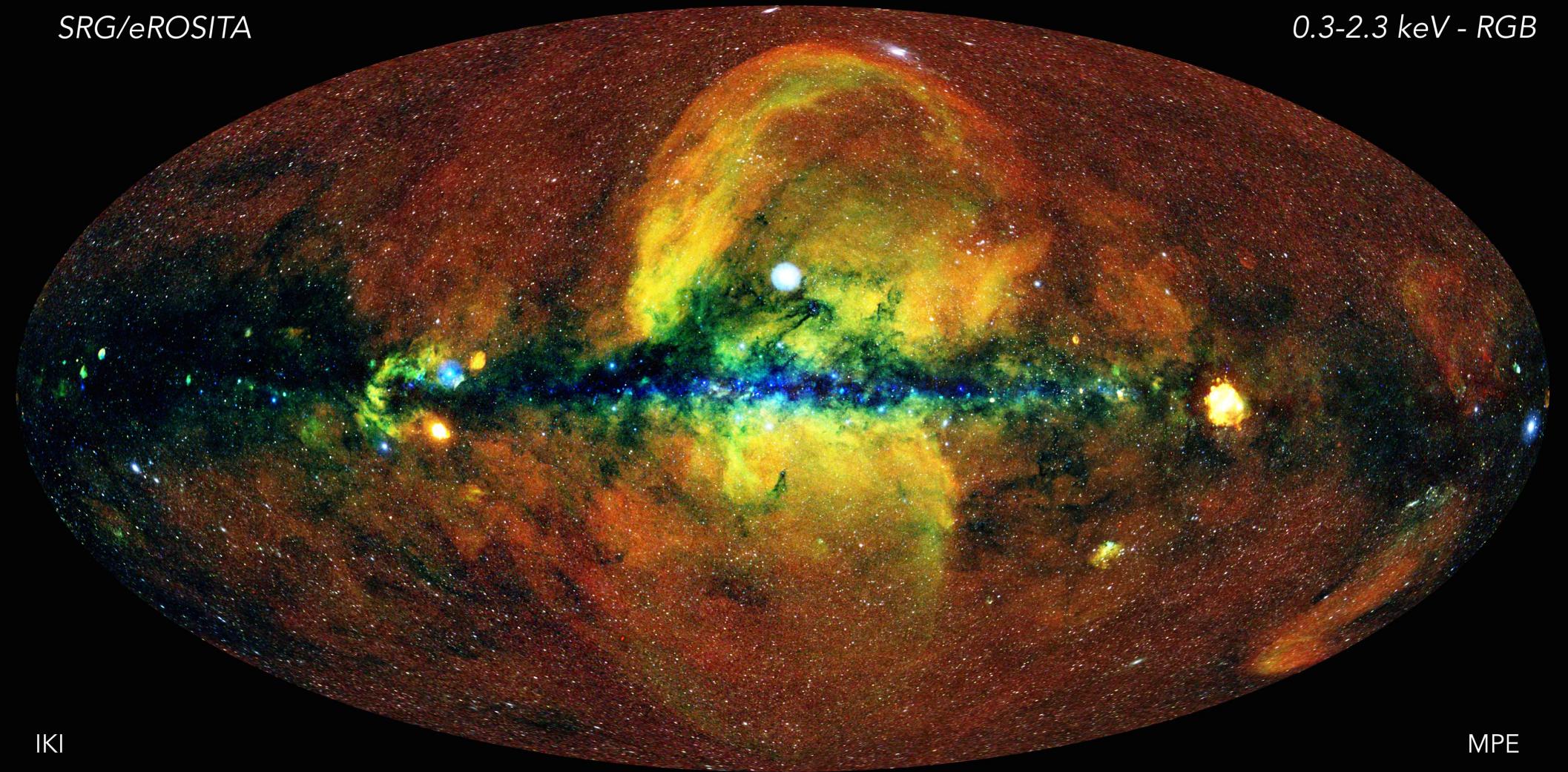


> 3 clusters per deg² (preliminary; Liu et al. In prep.)
370 clusters optically confirmed (Klein et al. In prep.)

Credits: V. Ghirardini, MPE/IKI

SRG/eROSITA

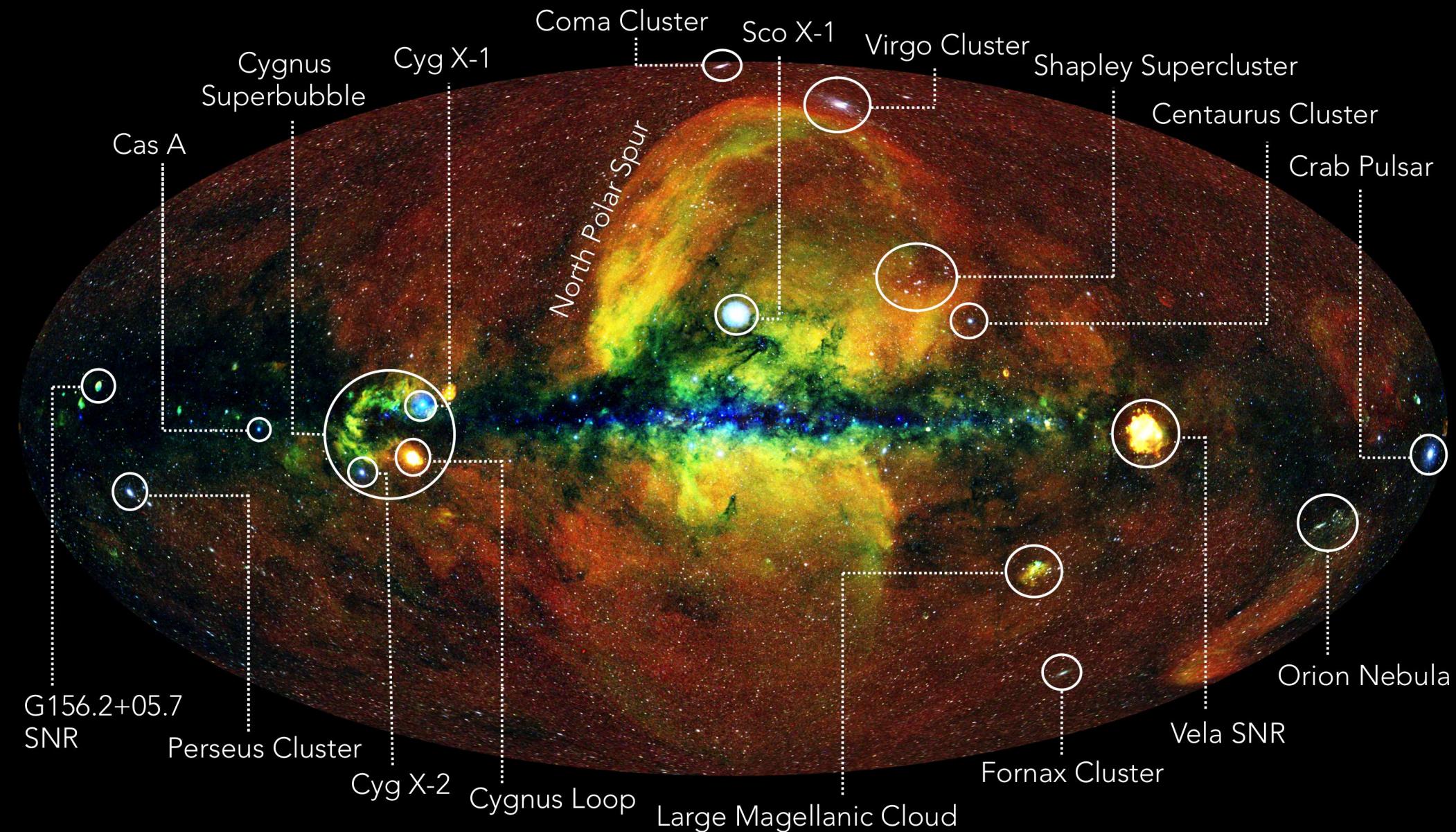
0.3-2.3 keV - RGB



IKI

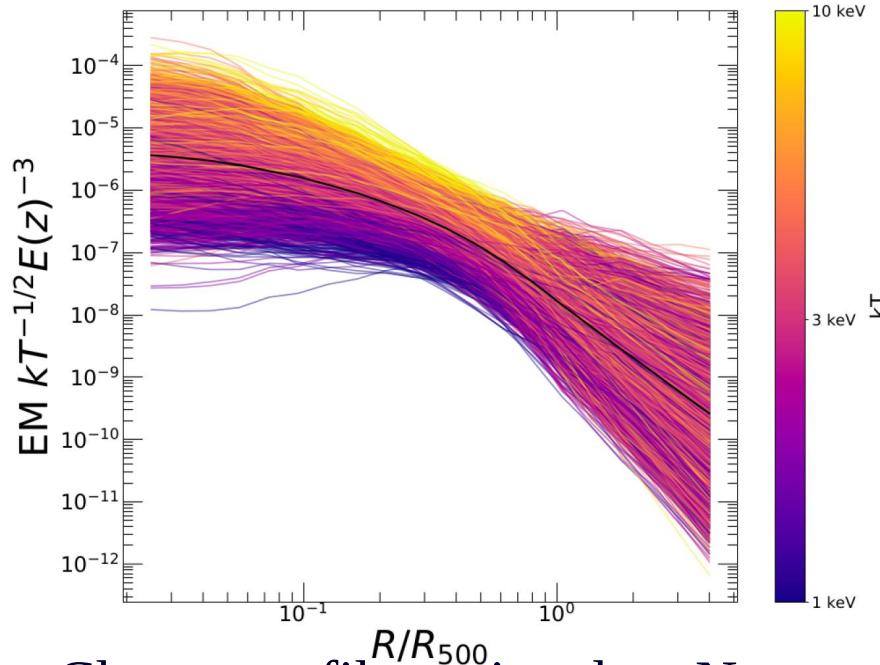
MPE

Navigating the eROSITA X-ray sky

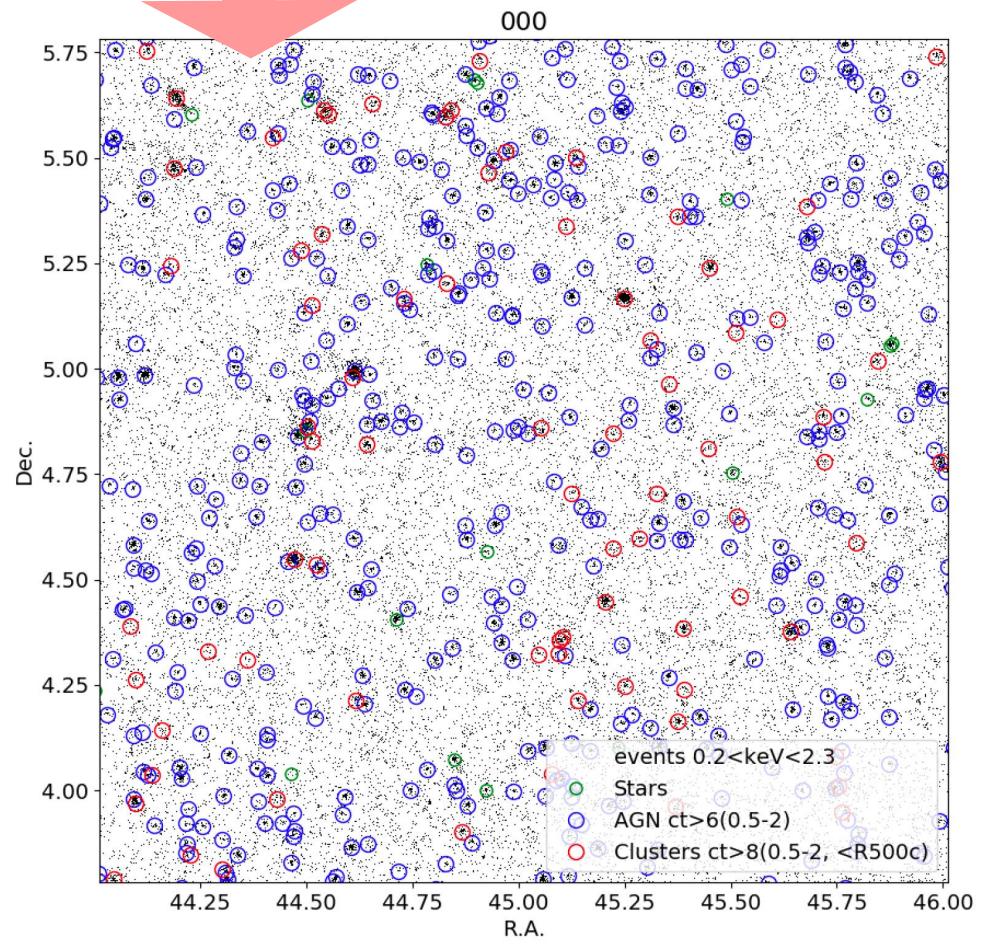


SRG/eROSITA 0.3-2.3 keV - RGB Map

eROSITA full-sky simulations

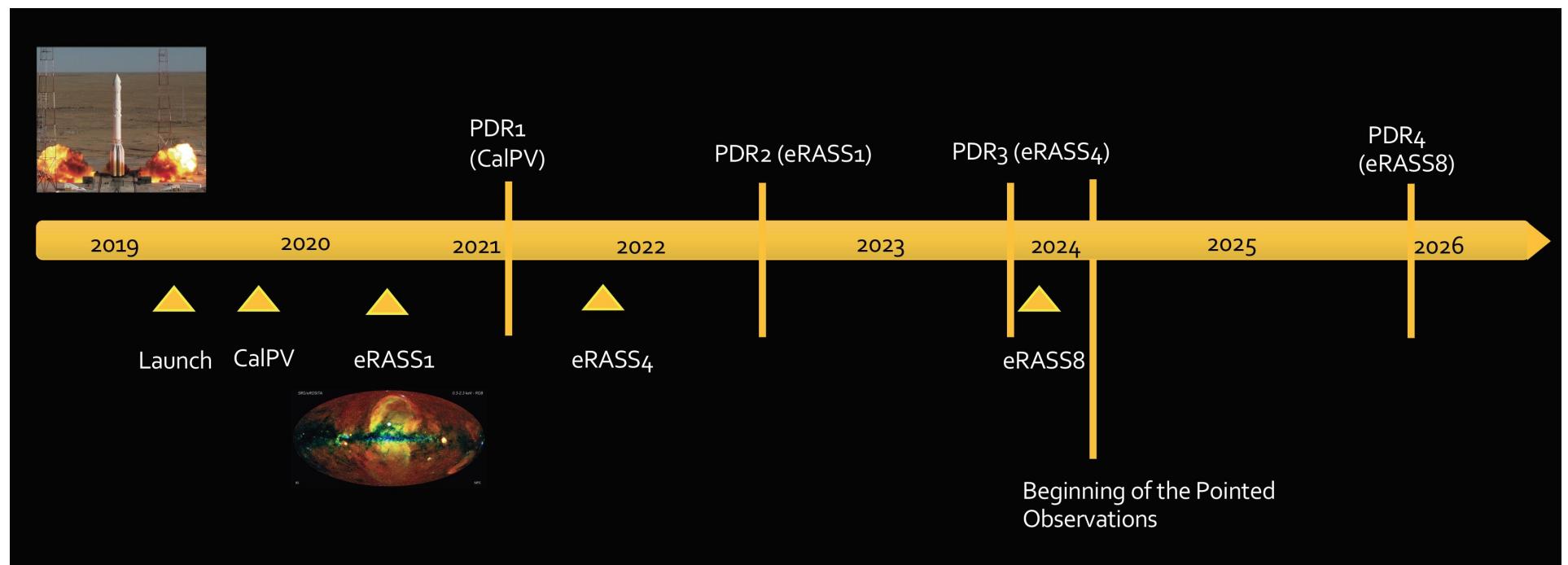


Cluster profiles painted on N-body halos sampled from real measurements (XXL, XCOP, HIFLUGCS, SPT)
Comparat+19, 20



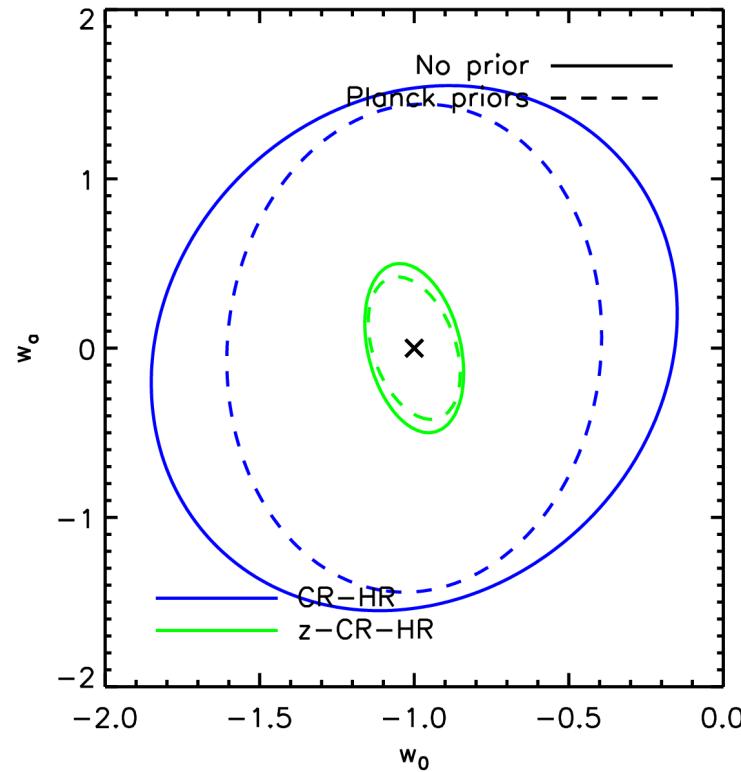
Comparat et al. (2020)

Timeline & collaboration



Interested in collaborating: contact the working groups
https://www.mpe.mpg.de/455860/working_groups

(z)-CR-HR forecasts for eROSITA

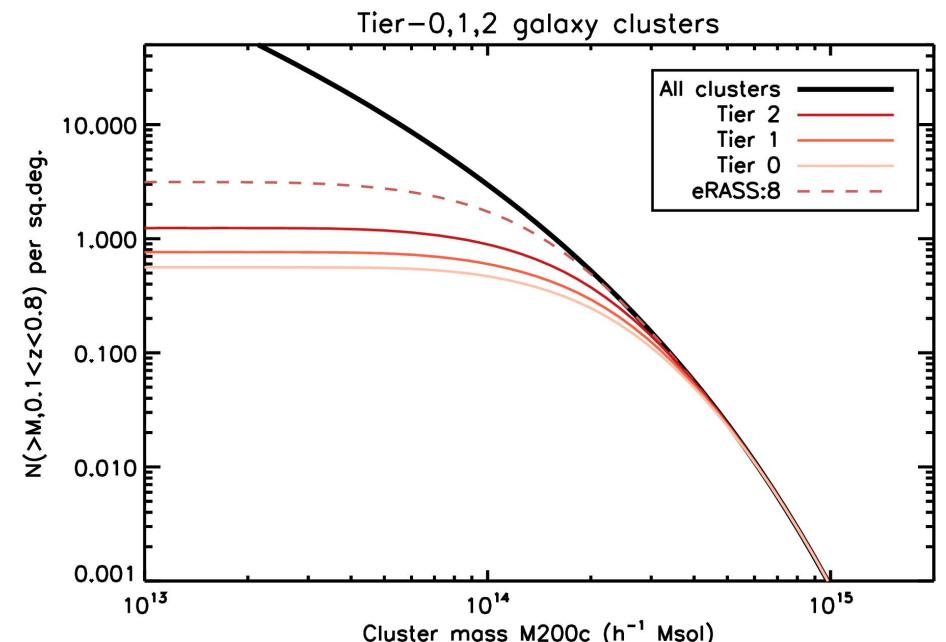


See also talks of
M. Pierre (XXL) and
Christian Garrel
(forward modelling)

	CR-HR		z -CR-HR	
	No prior	Planck priors	No prior	Planck priors
w_0	0.6	0.4	0.1	0.1
w_a	1.0	0.9	0.3	0.3
$\gamma_{z,MT}$	1.3	0.1	0.2	0.05
$\gamma_{z,LT}$	0.8	0.5	0.3	0.1

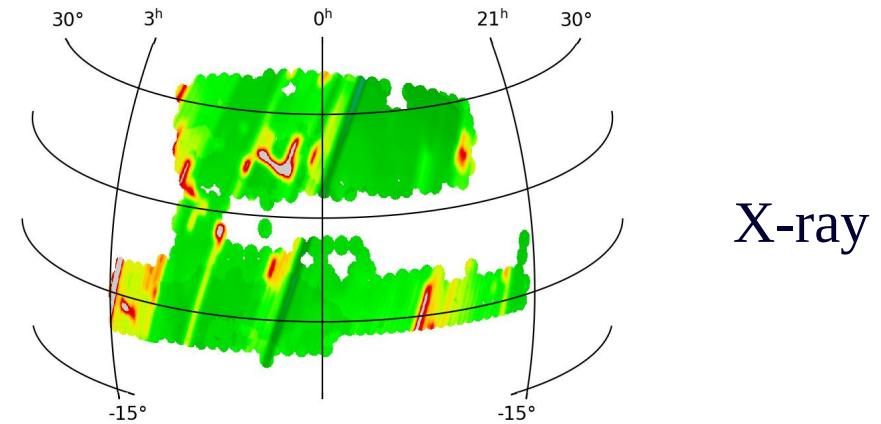
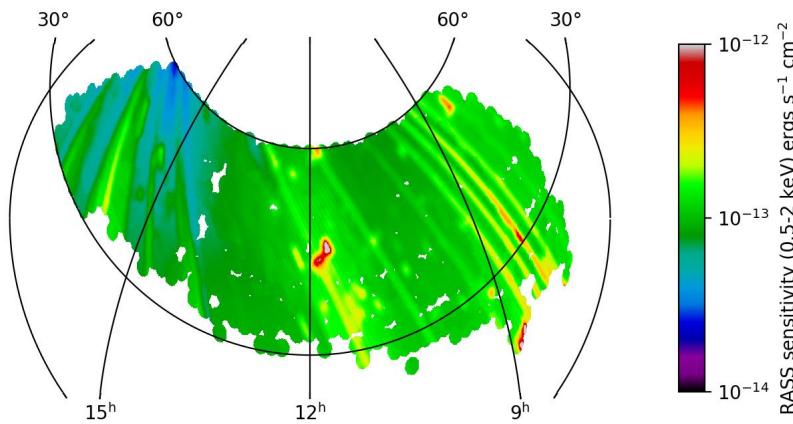
Multi-tiered galaxy cluster optical follow-up

- **Northern hemisphere: SDSS-IV+V**
 - SPIDERS (PI: A. Merloni, K. Nandra)
 - RASS and XMM sources (mainly AGN and clusters)
 - eRASS:2 sources
- **Southern hemisphere:**
ESO/4MOST(+SDSS-V)
 - 4-m VISTA telescope
 - eROSITA AGN and cluster surveys
 - Operations start 2023 (2021)

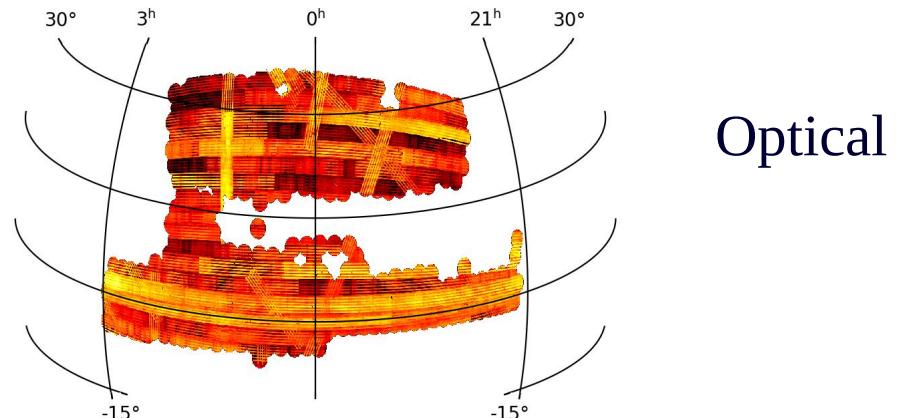
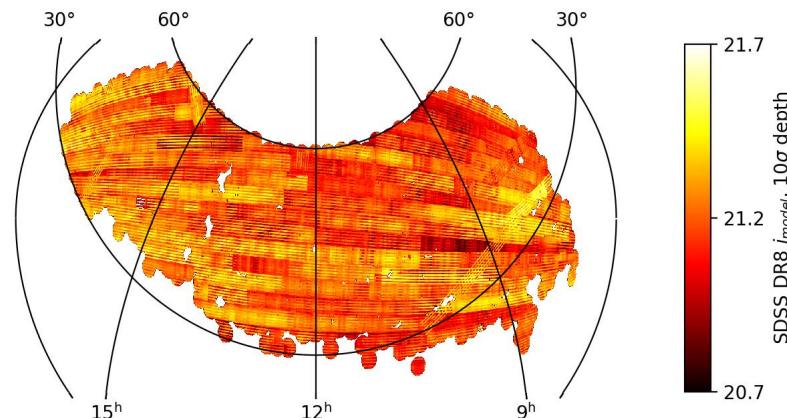


Clerc et al. 2016

SPIDERS galaxy cluster follow-up

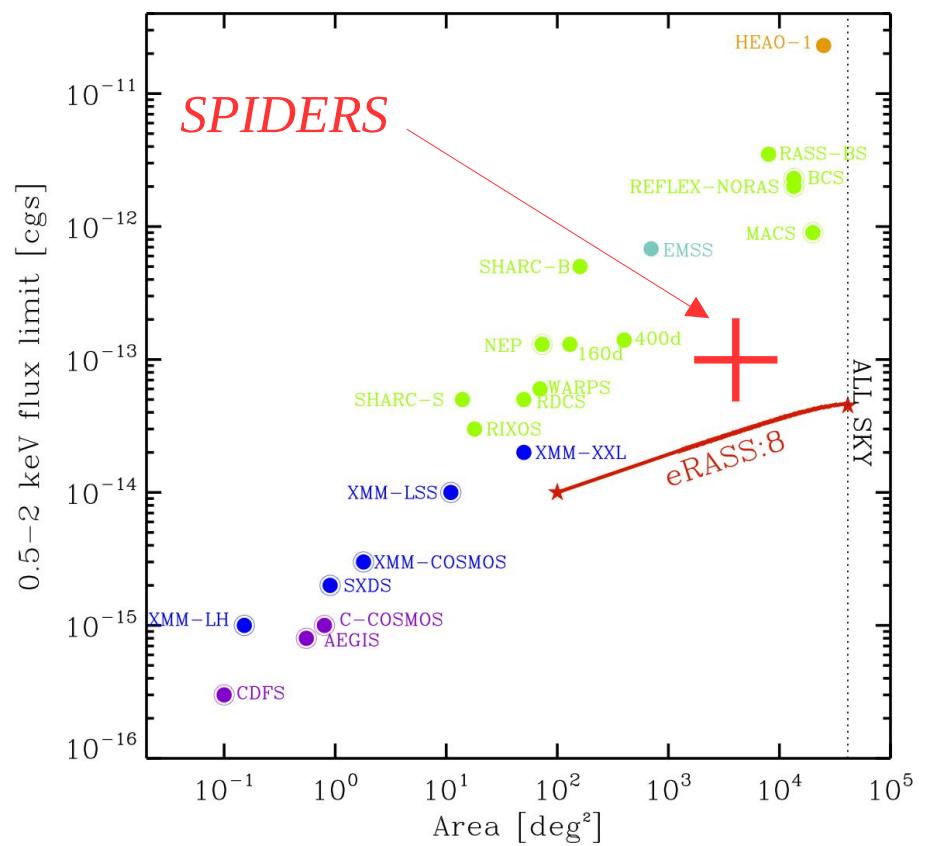


- Uniform, homogeneous X-ray + optical search for clusters in RASS+SDSS
- Uniform, homogeneous spectroscopic confirmation with eBOSS in 5350 deg^2

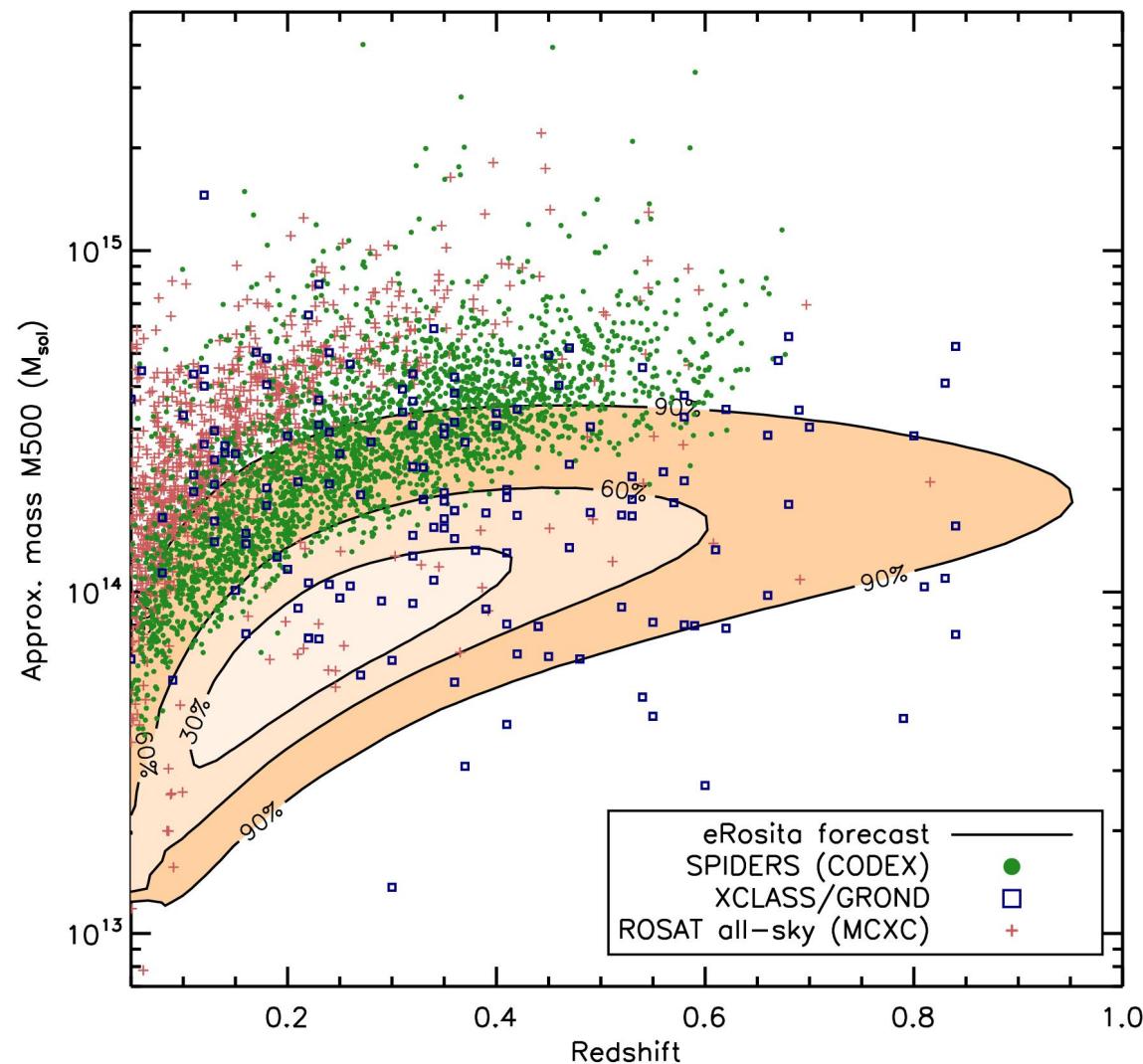


SPIDERS key numbers

- 5 years data collection (2014-2020)
- Initial pool of **4 100 X-ray cluster candidates**
- Volume surveyed about 5 Gpc^3
- **27 000 new spectra** acquired
- 98% redshift success, $\Delta z \sim 20 \text{ km.s}^{-1}$
- **15 600 unique visual inspections**
- Final catalogue of **2 740 clusters**
- Survey relevant papers:
 - *Clerc et al. 2016 ; Clerc et al. 2020*
 - *Kirkpatrick et al. 2020 (subm.)*
 - *Finoguenov et al. 2020*

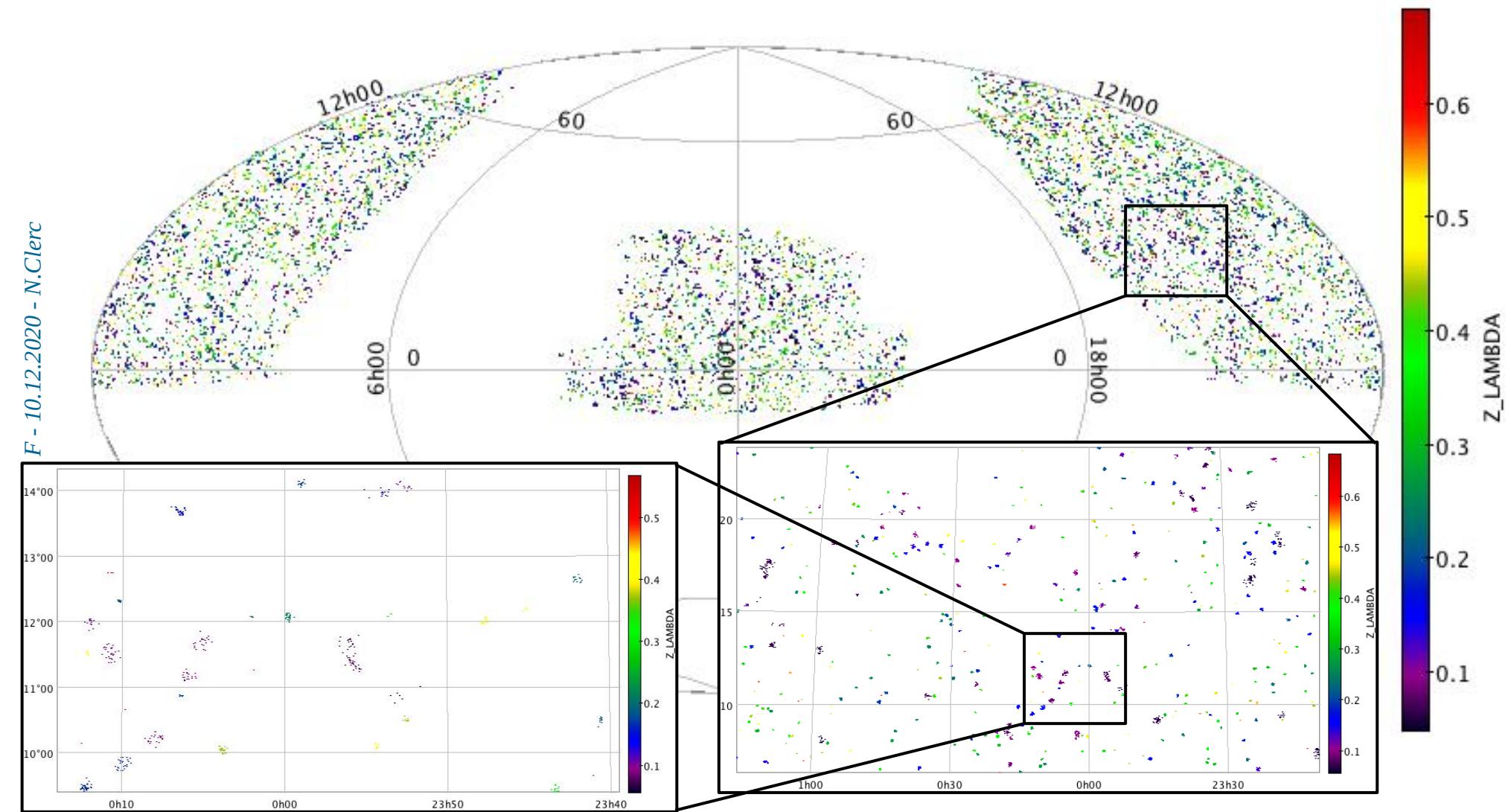


ROSAT, eROSITA, XMM and SPIDERS

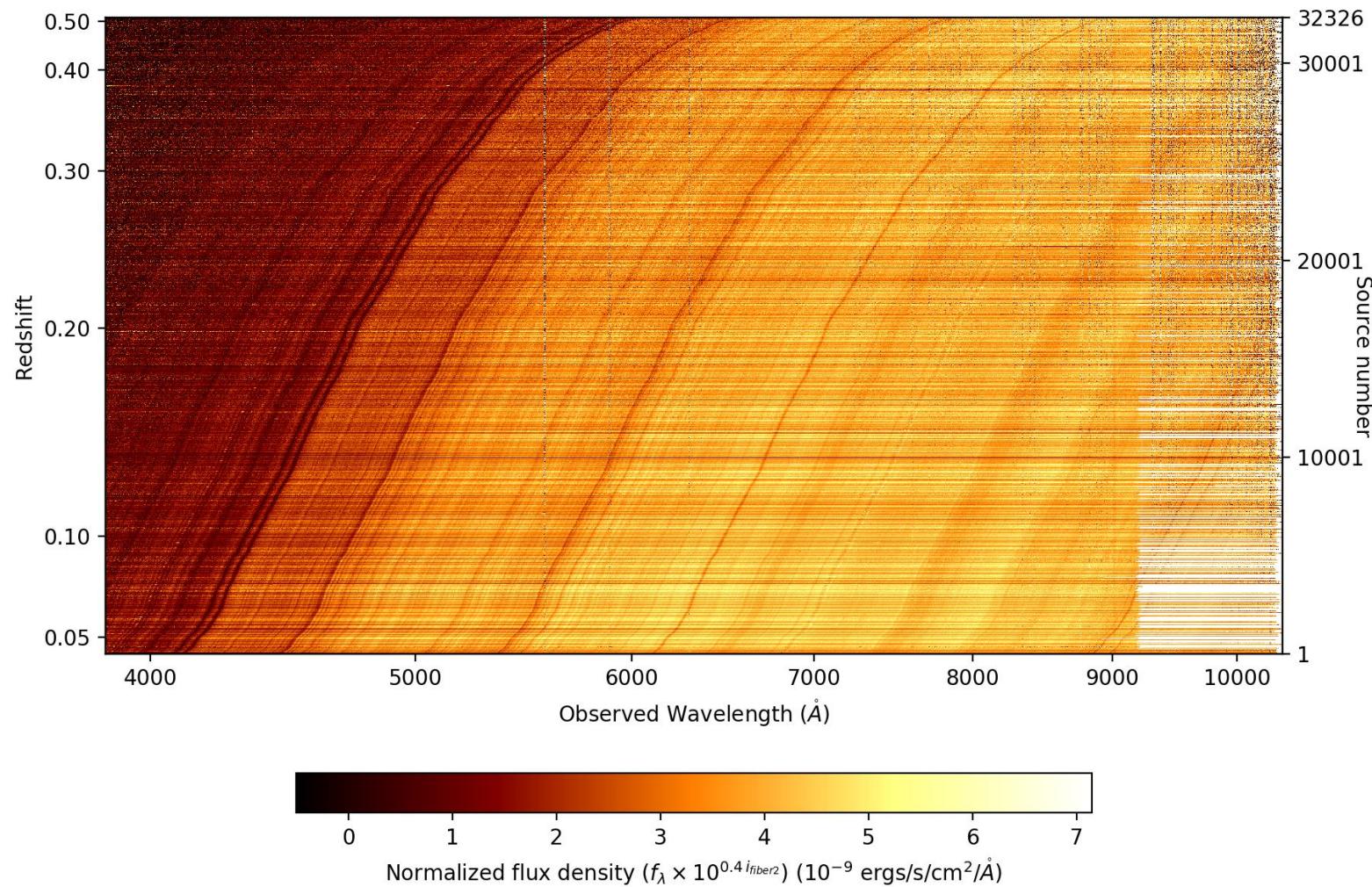


Data points:
Piffaretti+2011
Ridl+2017
Kirkpatrick+2020
Contours: NC+2018

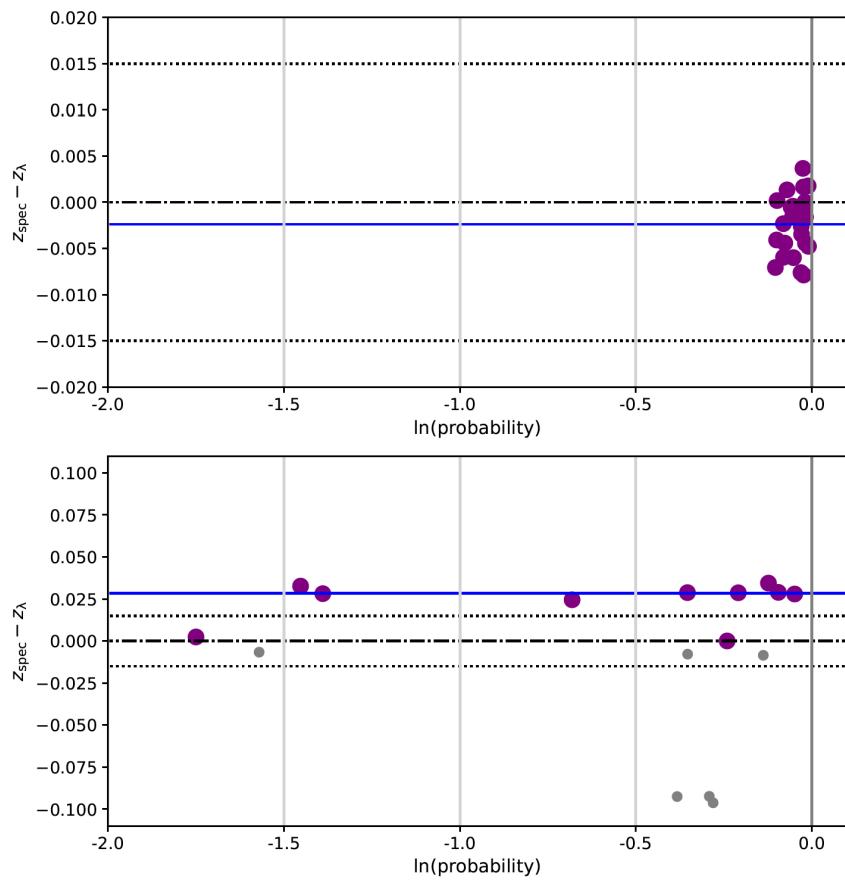
Targeting 50,000 red-sequence galaxies



Collecting 27000 new optical spectra



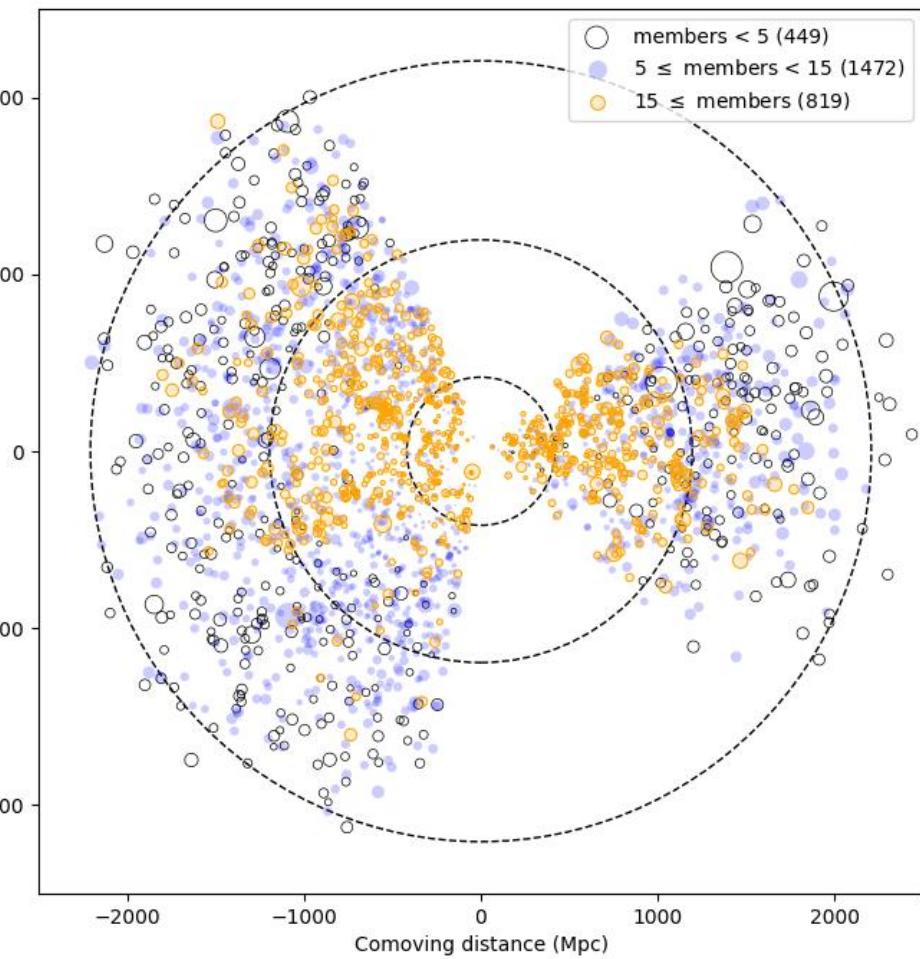
Collaborative inspection



Kirkpatrick et al. (2020)

- **Difficult regime of few members/cluster**
 - Information from X-ray (RASS)
 - Information from red-sequence
 - Typically 12 spectra/red sequence
- **All clusters inspected by 2+ persons**
 - Collaborative interface, 11 inspectors
 - Reconciliation of membership results
 - Assessment of nature and redshift

SPIDERS is finished!

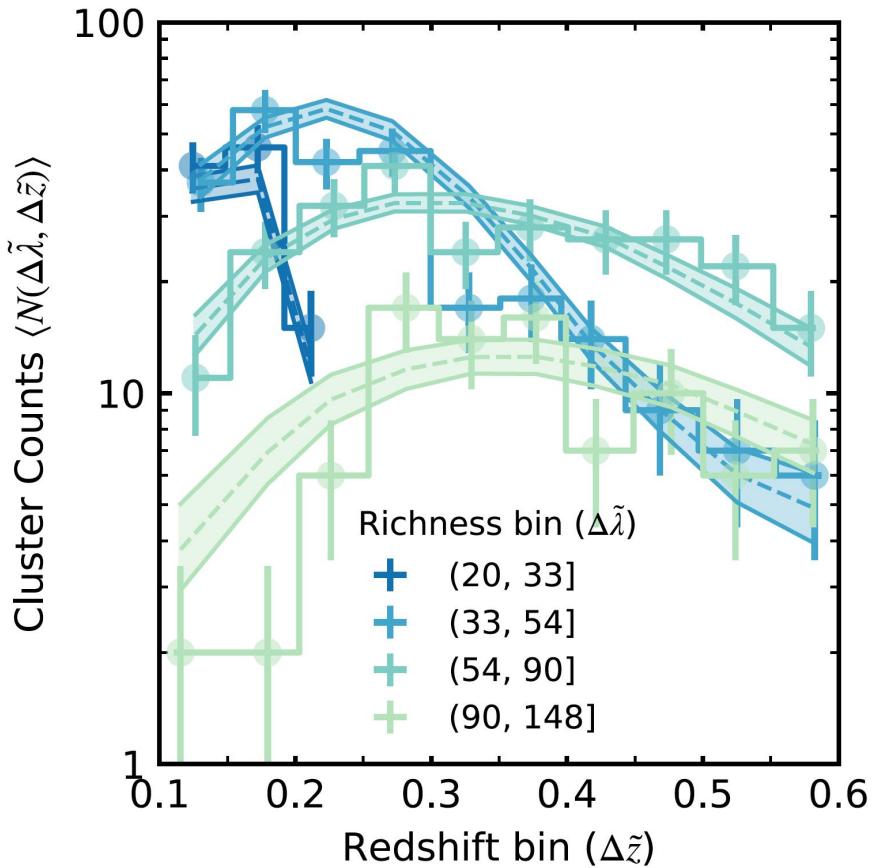


Clerc et al. (2020)

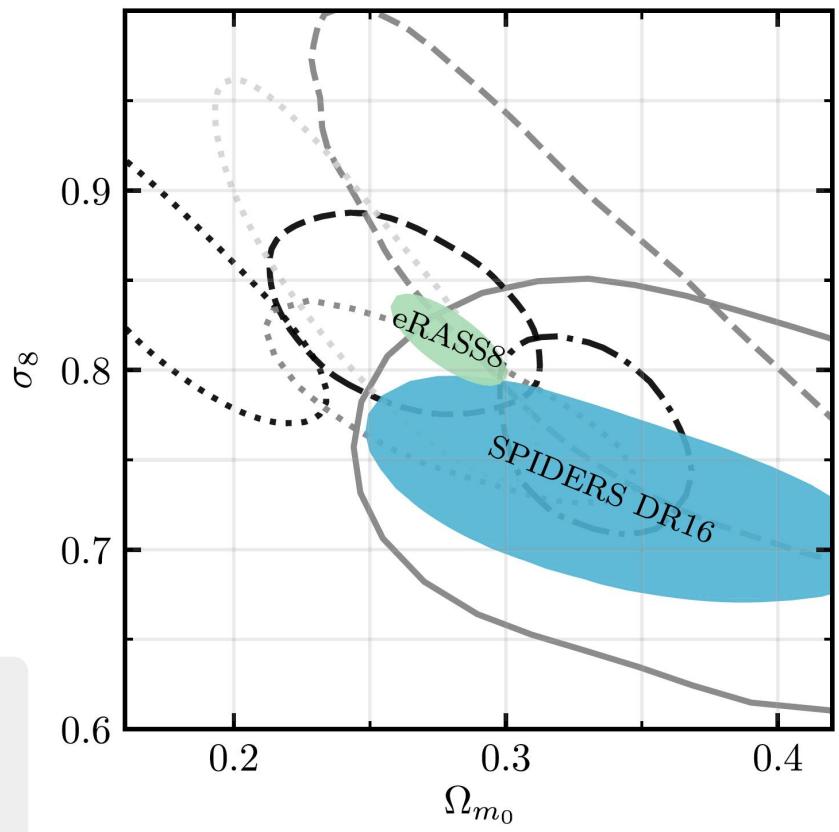
SPIDERS is public along with SDSS Data Release 16

- 2,740 X-ray clusters up to $z \sim 0.6$
- Spectroscopically confirmed
- $> 36k$ members
- $> 27k$ new redshifts
- ~ 5 cGpc³ surveyed volume
- Catalogue: Kirkpatrick et al 2020 (subm.)

Cosmological constraints from counts model



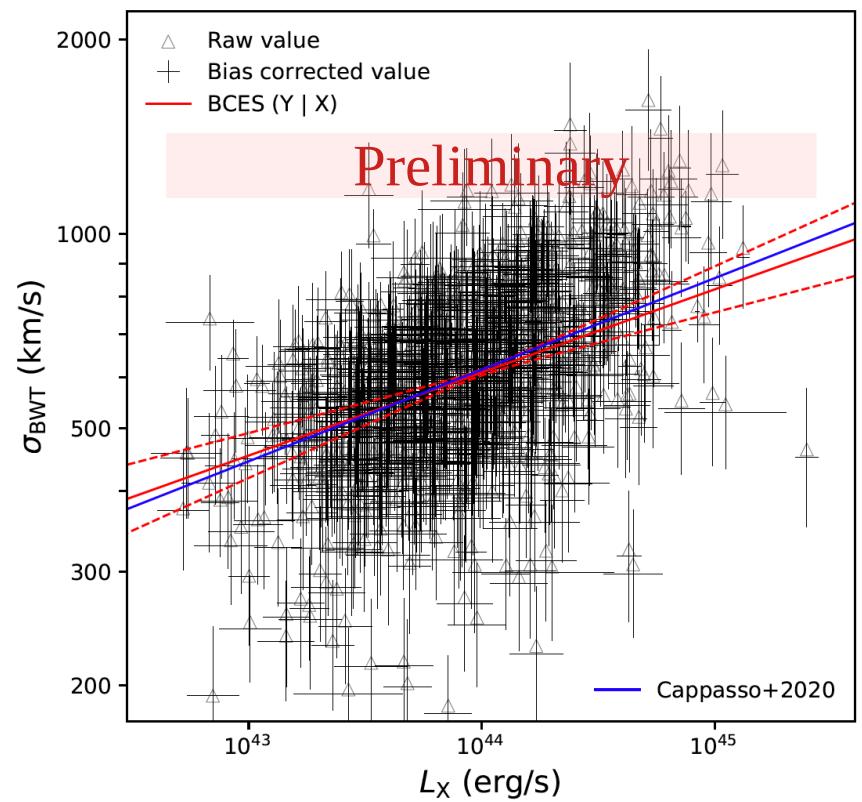
Pillepich+18	DESCollab+20
This work	Zu+14
Zubeldia+19	Mantz+15
Bocquet+19	Pacaud+18
Kirby+19	



- ✓ 691 **SPIDERS** clusters
- ✓ New measurements of richness (**DESI Legacy surveys**)
- ✓ Good knowledge of the cluster selection function

New results from SPIDERS

- Calibration of M_{dyn} - λ and M_{dyn} - L_X
(Capasso et al. 2019; 2020)
- Calibration of σ_v - L_X and σ_v - λ
(Kirkpatrick et al. 2020, subm.)
- Cosmology with $dn/d\sigma_v$
(Kirkpatrick et al. 2020, subm.)
- Detection of gravitational z
(Mpetha et al. 2020, subm.)
- The σ_v - T_X relation in XCLASS
(Clerc, Molham et al. In prep.)



Kirkpatrick et al. (2020, subm.)

Conclusions

- Current and upcoming studies are changing our approach to galaxy cluster surveys:
 - ✓ **Methodology** – self-consistent modeling of the X-ray cluster/group population in a cosmological framework
 - ✓ **Statistics** – new approach to galaxy cluster samples, drawn from a pool of $\sim 10^5$ objects across the entire extra-galactic sky (*eROSITA*)
 - ✓ **Precision measurements** – accurate redshifts enabling precise positions, masses & mapping of the baryonic cosmic web (*SPIDERS*)

Thank you!