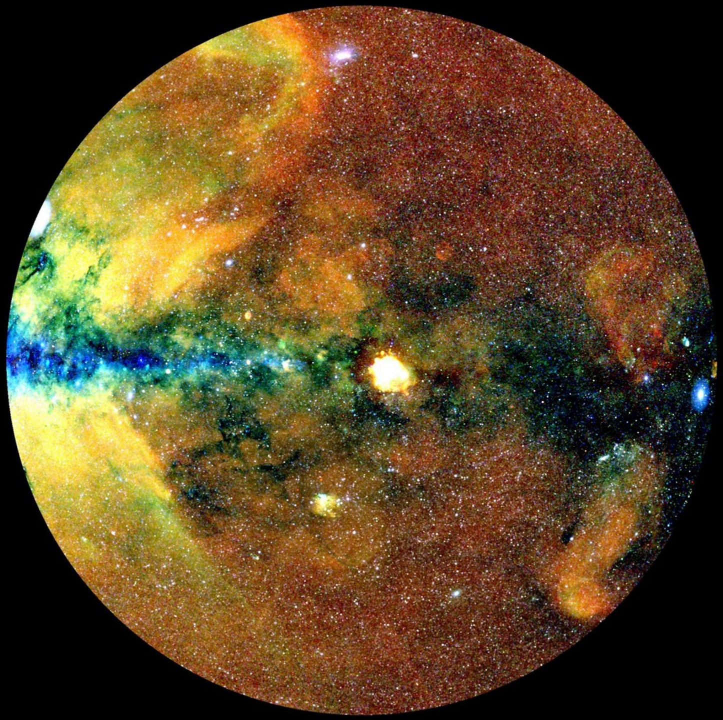
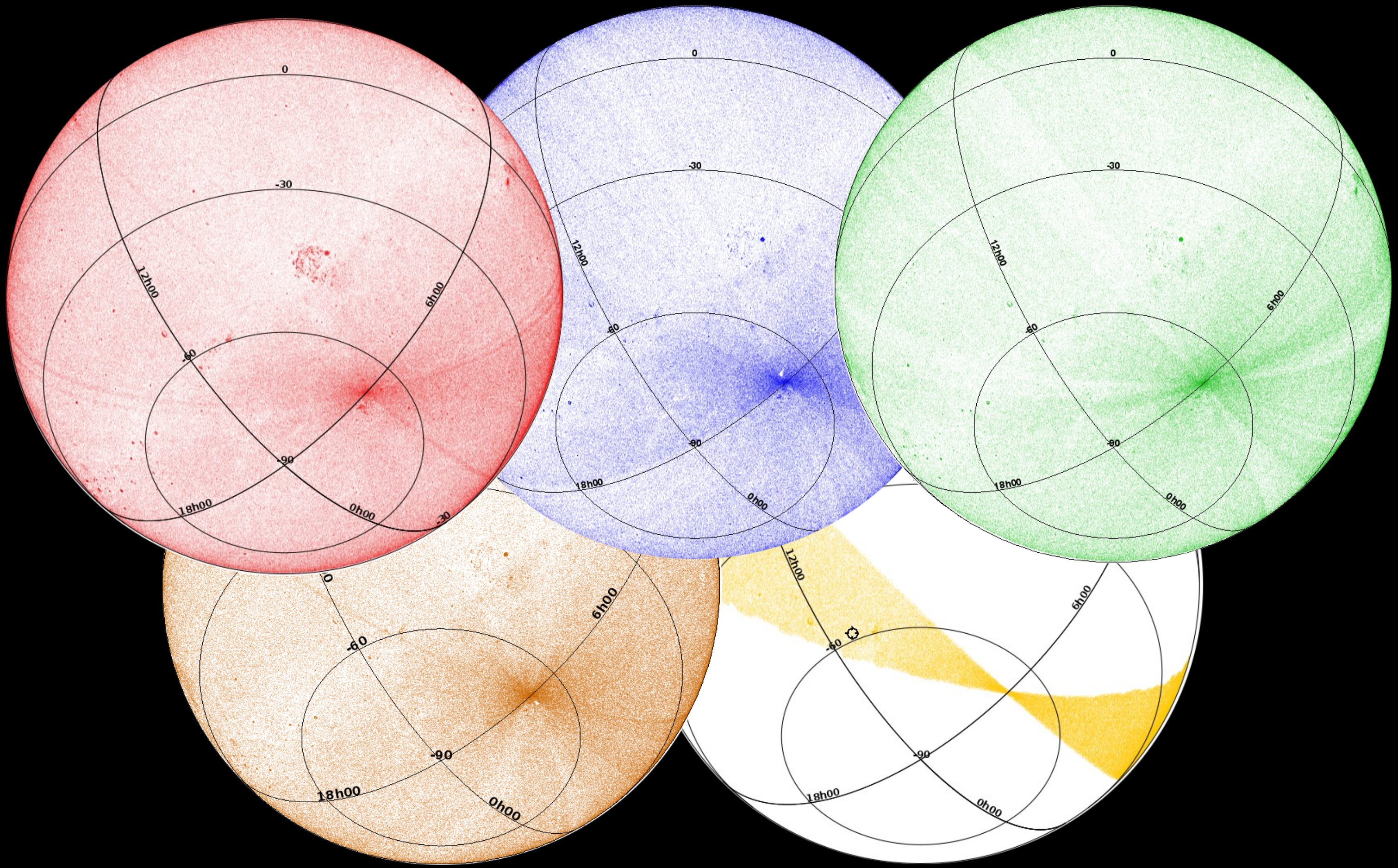
The eROSITA data analysis and catalogue pipeline



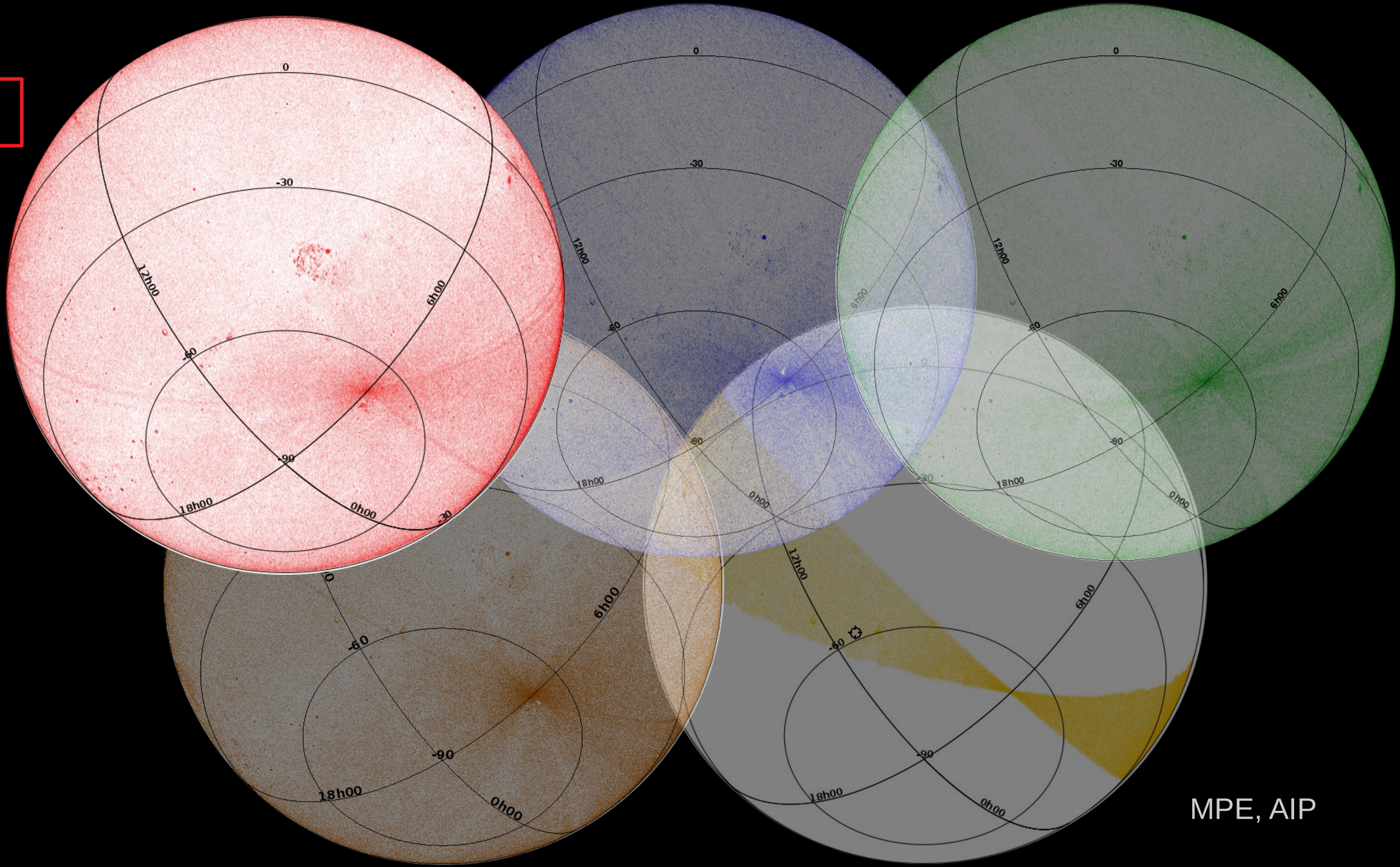
Georg Lamer (AIP), *XMM survey legacy for Athena and beyond*, Toulouse, 26 Feb 2024

First eROSITA data release 31 Jan 2024



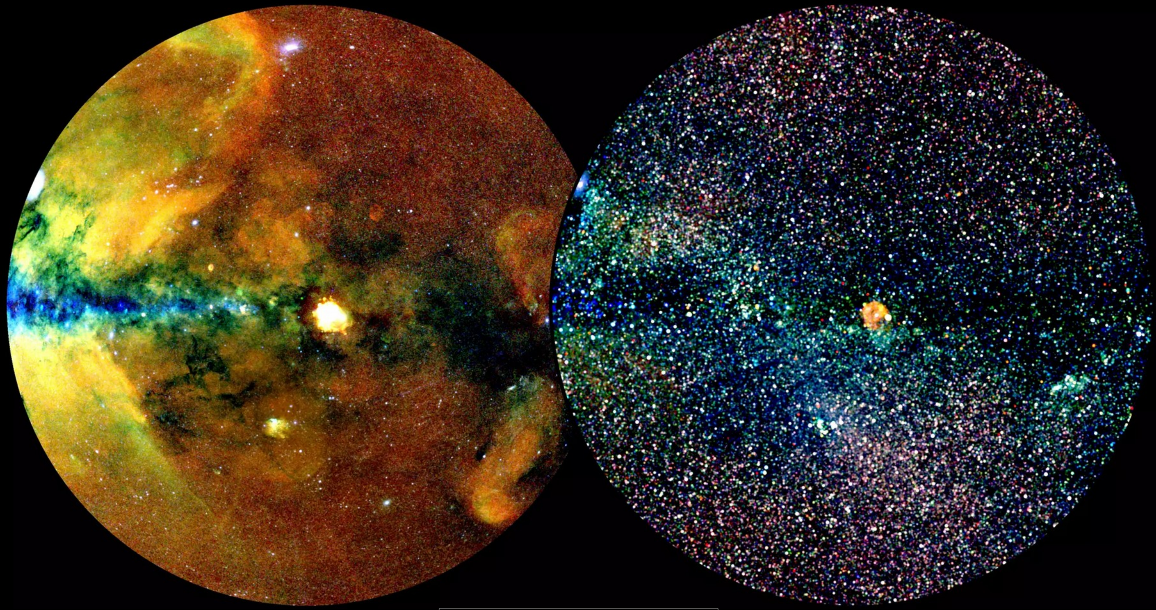
First eROSITA data release

eRASS1



MPE, AIP

First eROSITA data release



MPE, J. Sanders

eRASS1:

6 month: Dec 2019 – Jun 2020

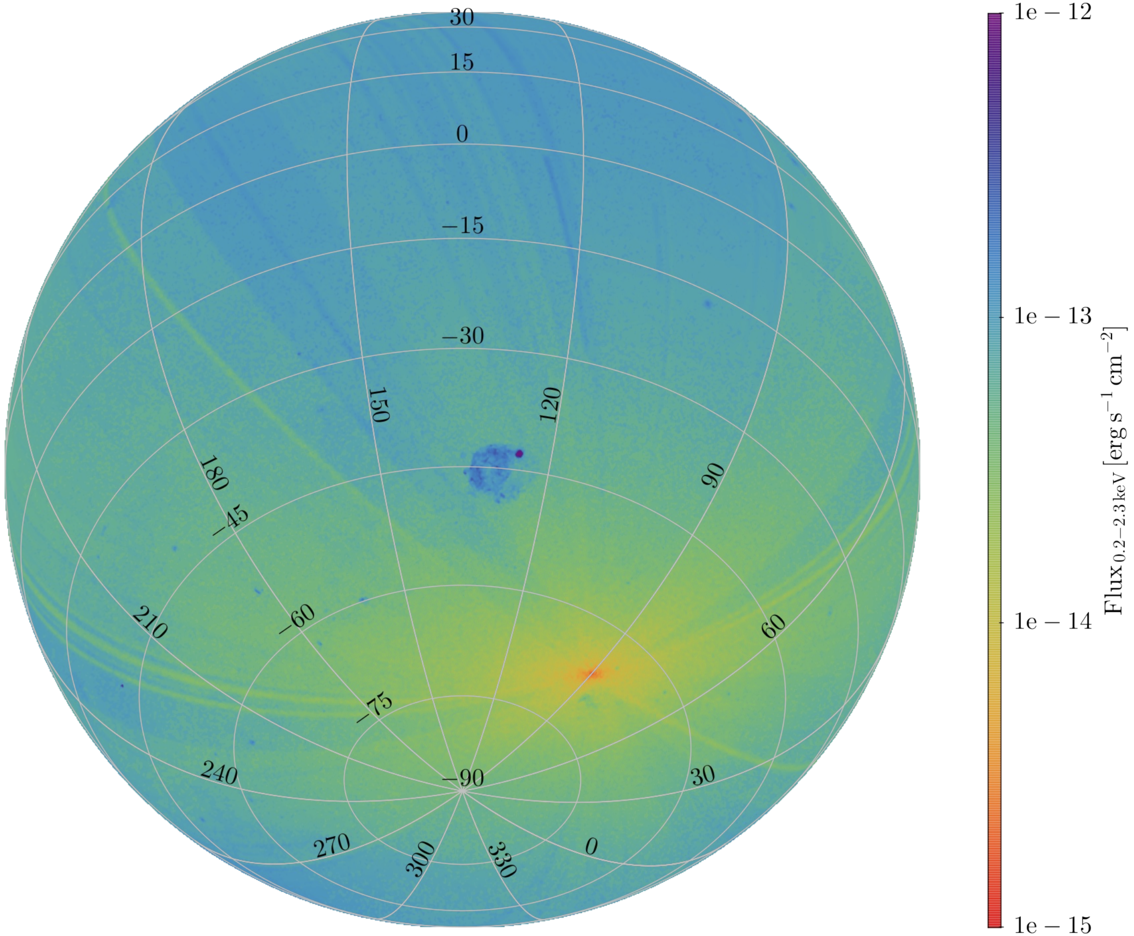
900 000 catalogue sources

~710000 AGN
~180000 stars
~ 12000 galaxy clusters

200 000 spectra / light curves

170 Million photon events

Upper limit server



Tubín-Arenas et al. 2024

Provides upper limits based on

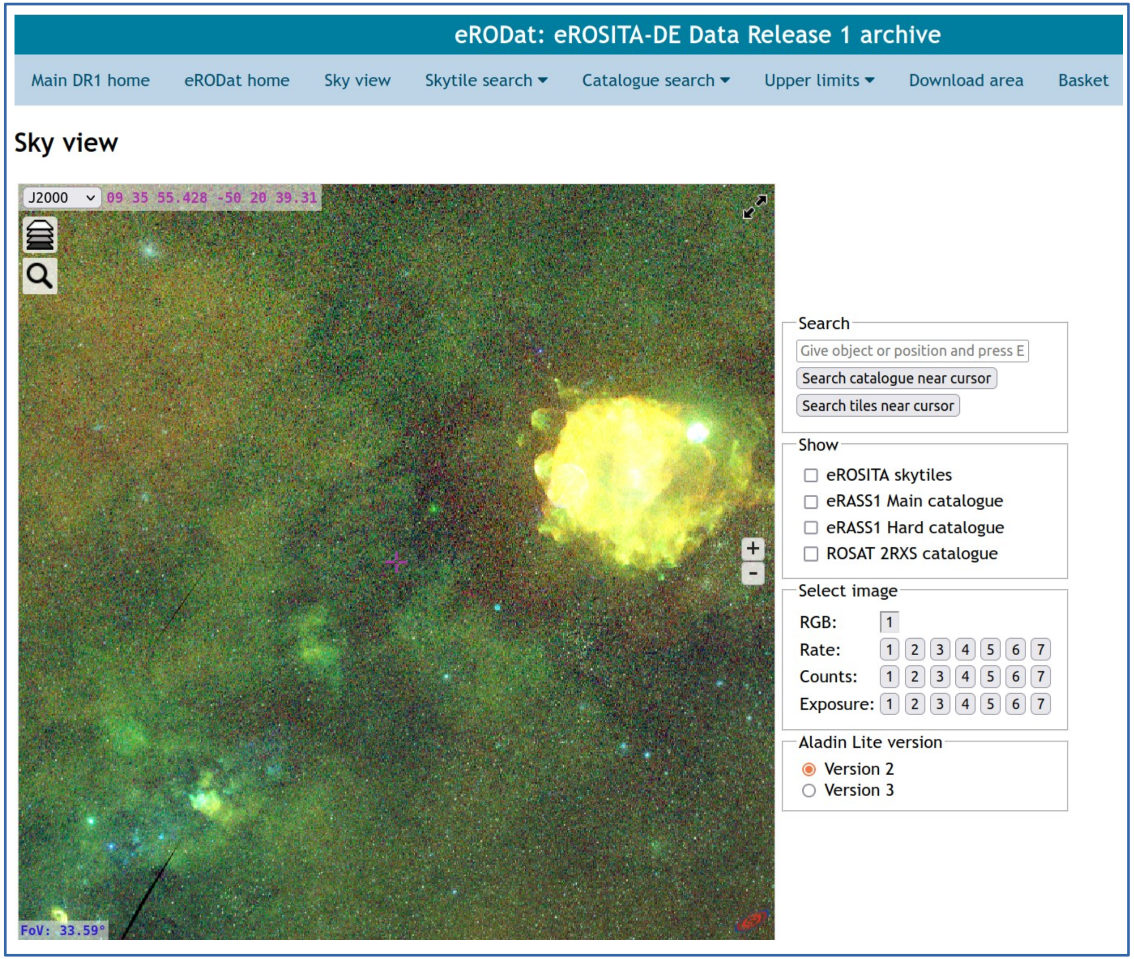
- exposure
- background
- nearby detected sources

Where can I find all this?

erosita.mpe.mpg.de/dr1/

Various search options:

- cone search
- list uploads
- APIs for cone search and upper limits
- sky view



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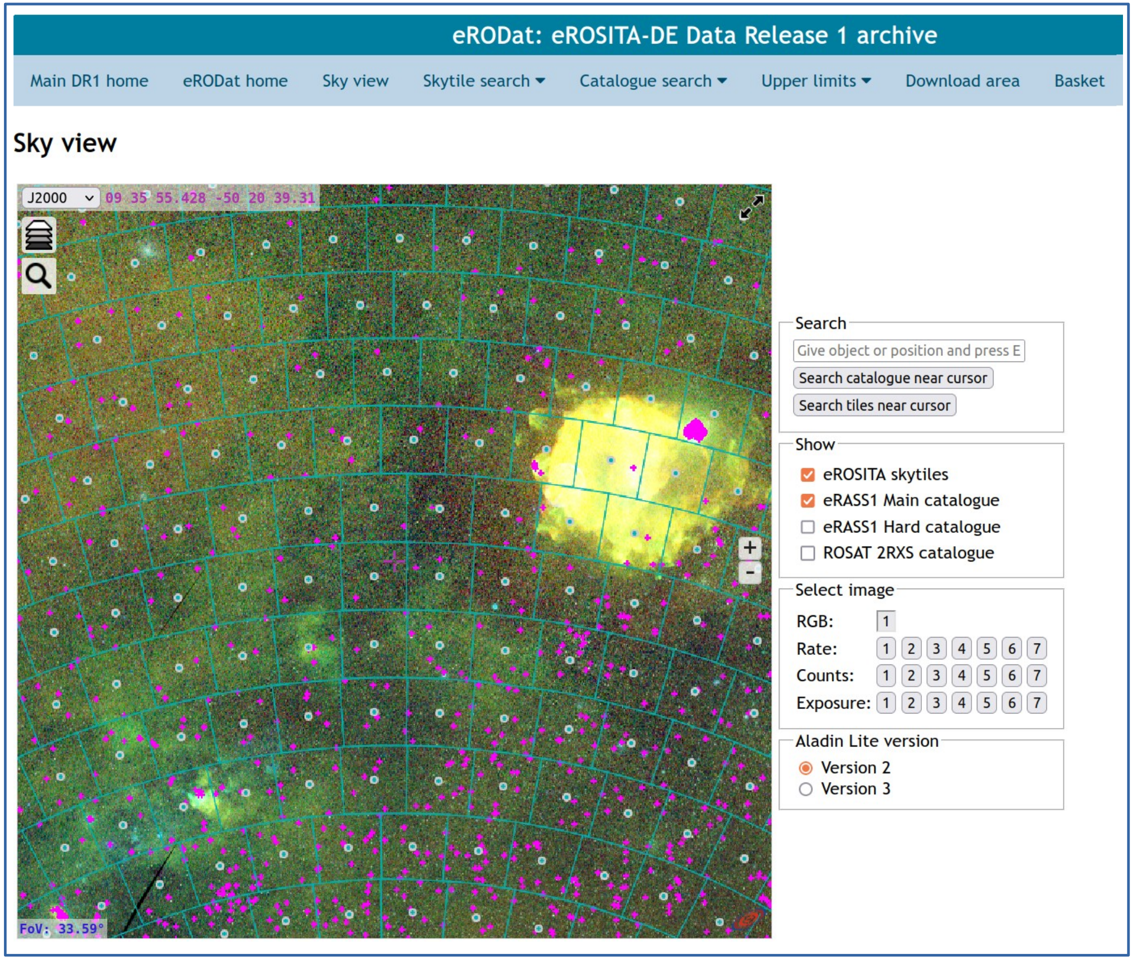


eROSITA Standard Analysis Software System (eSASS)

eROSITA Standard Analysis Software System (eSASS)

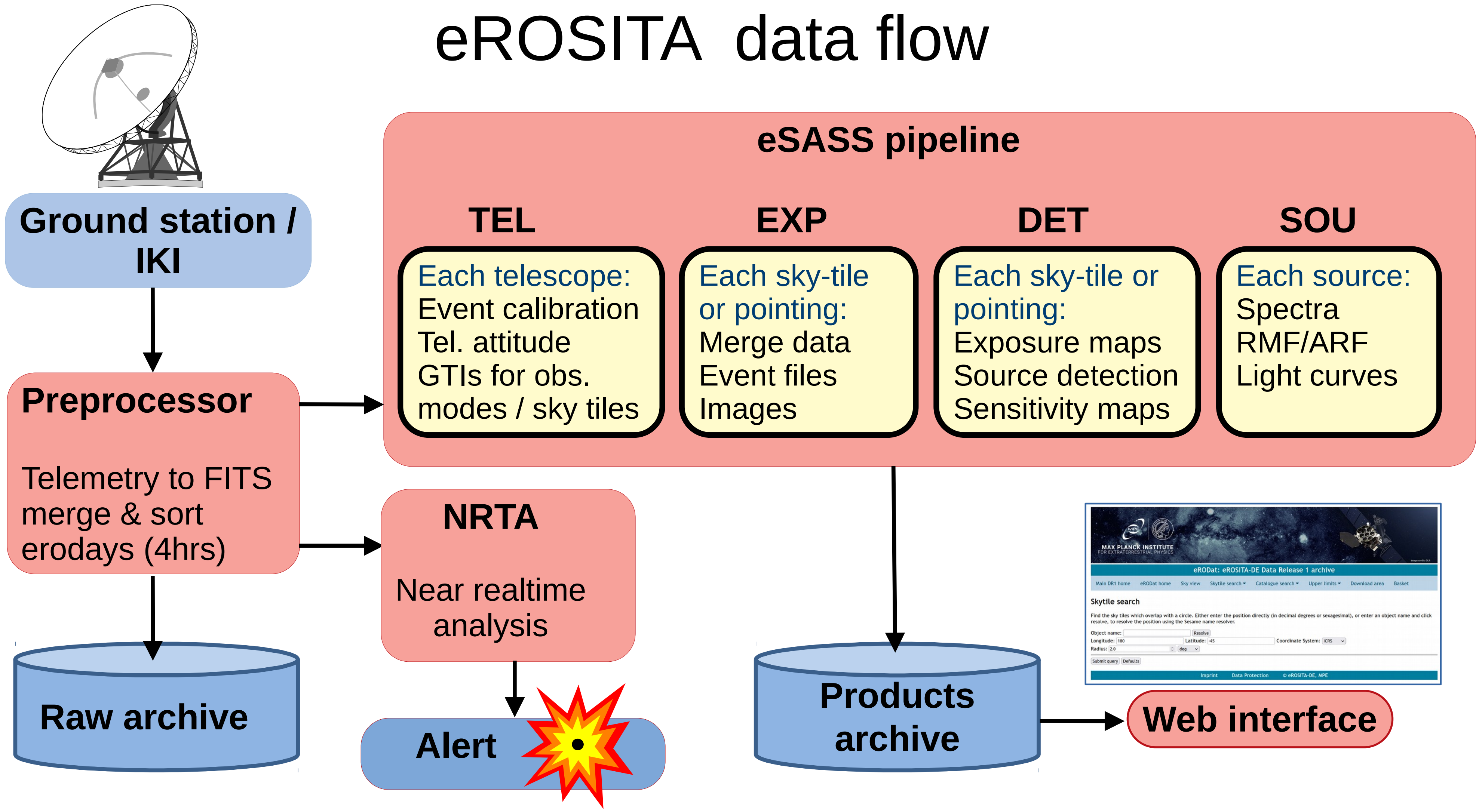
eSASS task authors:

Hermann Brunner
Konrad Dennerl
Tom Dwelly
Antonis Georgakakis
Christoph Großberger
Ingo Kreykenbohm
Georg Lamer
Adriana Pires
Jeremy Sanders
Ian Stewart

Pipeline, calibration, etc.:

Michael Freyberg
Alain Guenguen
Chandreyee Maitra
Sabine Osterhage
Miriam Ramos
Jan Robrade

* former team members


eROSITA data flow
Ground station / IKI
Preprocessor
Telemetry to FITS
merge & sort
erodays (4hrs)
eSASS pipeline
TEL
Each telescope:
Event calibration
Tel. attitude
GTIs for obs.
modes / sky tiles
EXP
Each sky-tile
or pointing:
Merge data
Event files
Images
DET
Each sky-tile or
pointing:
Exposure maps
Source detection
Sensitivity maps
SOU
Each source:
Spectra
RMF/ARF
Light curves
NRTA
Near realtime
analysis
Alert
Raw archive
Products
archive
MAX PLANCK INSTITUTE
FOR EXTRATERRESTRIAL PHYSICS
eRODat: eROSITA-DE Data Release 1 archive
Skytile search
Web interface

eROSITA Standard Analysis Software System (eSASS) users release

Subset of eSASS tasks for interactive analysis

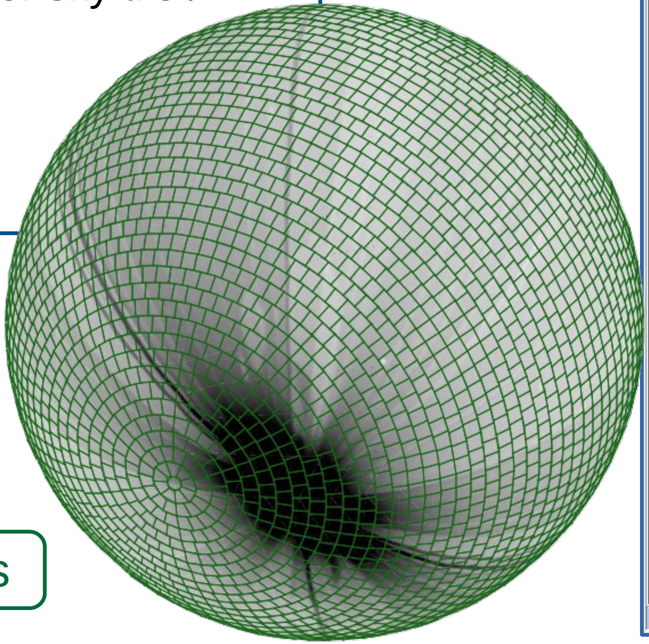
Full event calibration not foreseen in the users release

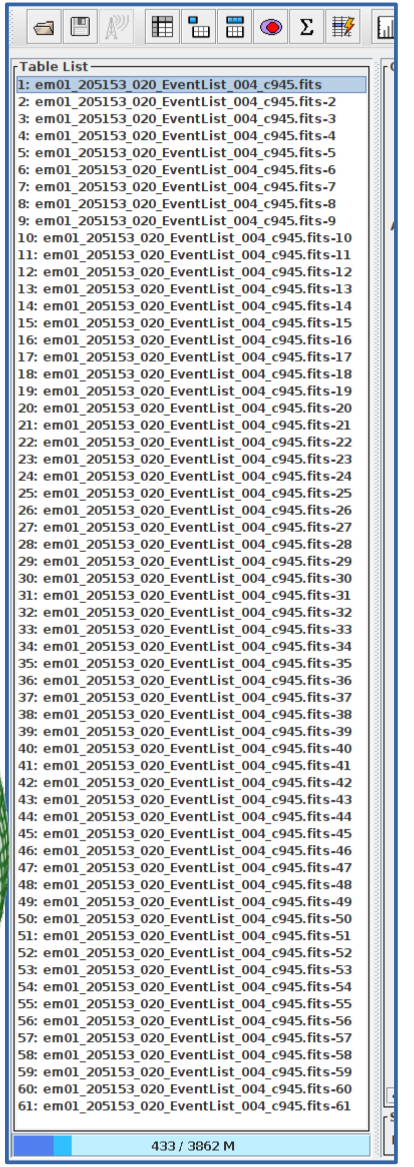
Changes in calibration applied by re-processing of the data archive

Interactive analysis starts with calibrated event file per sky tile / pointing

- Contains extensions for attitude, bad pixels, GTIs, dead-time, house-keeping (x 7 telescopes)

3°x3° sky tiles





eROSITA Standard Analysis Software System (eSASS) users release

Subset of eSASS task for interactive analysis

Preparatory (optional)	
evatt	Calculate events equatorial positions
radec2xy	Calculate sky coordinates from RA, DEC
flaregti	Create flare filtering GTIs
ebarycen	Apply barycentric correction to event times

Event manipulation	
evtool	Filter events (GTI, flag, pattern), image binning

eROSITA Standard Analysis Software System (eSASS) users release

Source detection and characterisation	
expmap	Compute exposure maps (survey or pointing)
ermask	Calculate detection mask based on exposure map
erbox	Search sources im mage (with or w/o background map)
erbackmap	Calculate background map (masking and adaptive smoothing)
ermldet	Calculate source parameters using PSF fitting
ersensmap	Calculate maps with expected detection sensitivity
catprep	Re-format ermldet output

eROSITA Standard Analysis Software System (eSASS) users release

Source specific products	
apetool	Perform aperture photometry and create sensitivity maps
srctool	Extract spectra (with ARFs, RMFs) and light curves

The current eSASS users release is **eSASS4DR1**

https://erosita.mpe.mpg.de/dr1/eSASS4DR1/

eSASS detection chain

expmap:

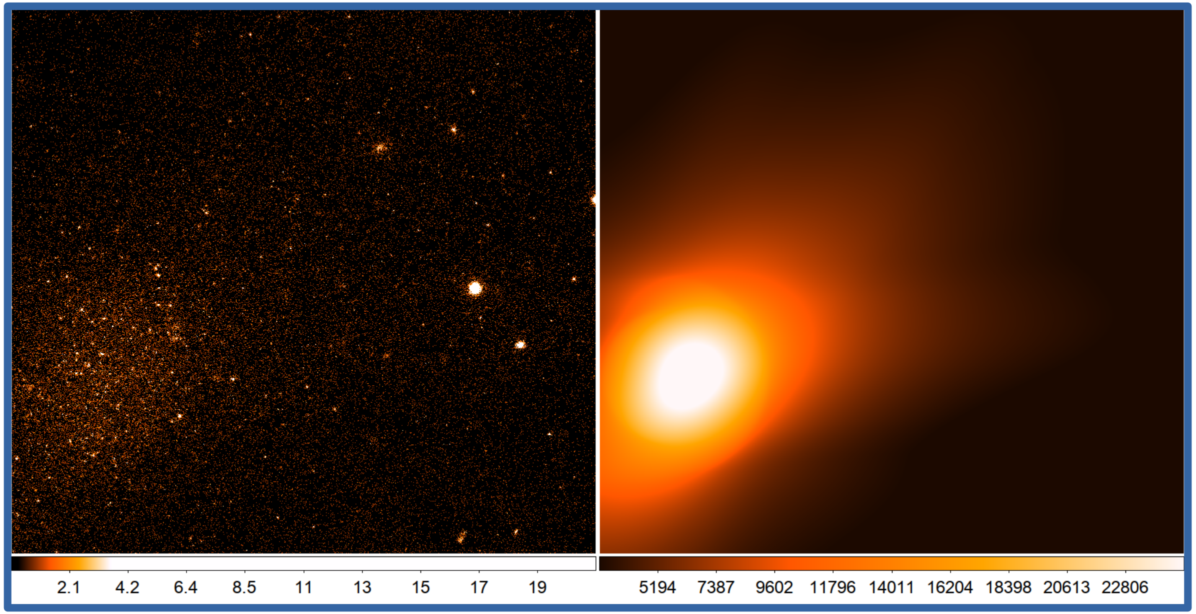
Creates exposure maps by projecting instrument map to sky and integrating over attitude.

Attitude bins: 1 sec for survey

emask:

Creates logical detection masks based on relative exposure and/or exposure gradients

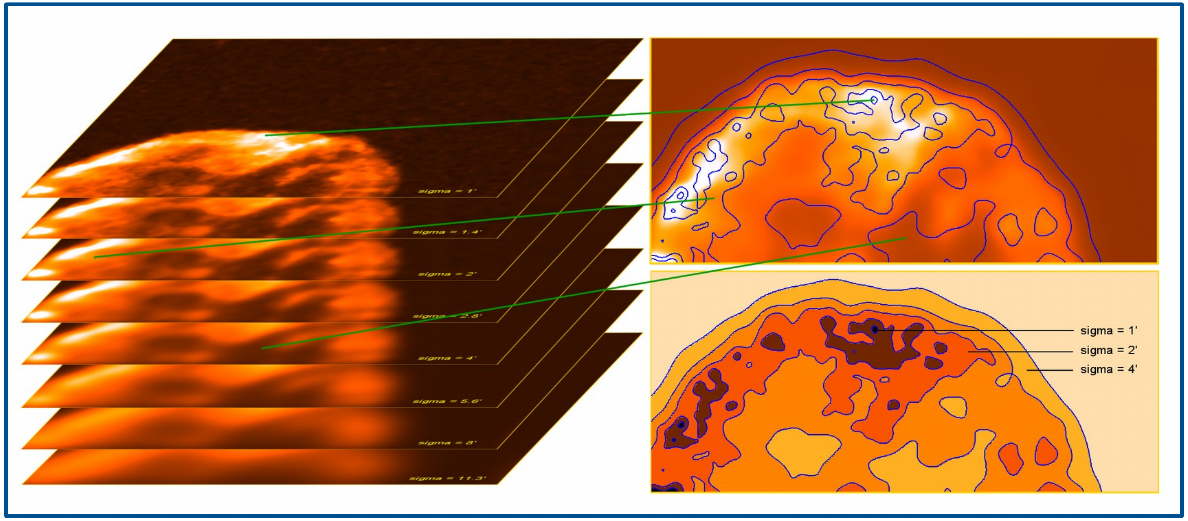
See Brunner et al. 2022 for full description



eRASS1 image and exposure map at SEP

eSASS detection chain

erbox:
Sliding box detection
with smoothing kernel



erbackmap:

Calculates background maps using source masking and adaptive smoothing

Pipeline iterates erbox and erbackmap 3 times for final background map

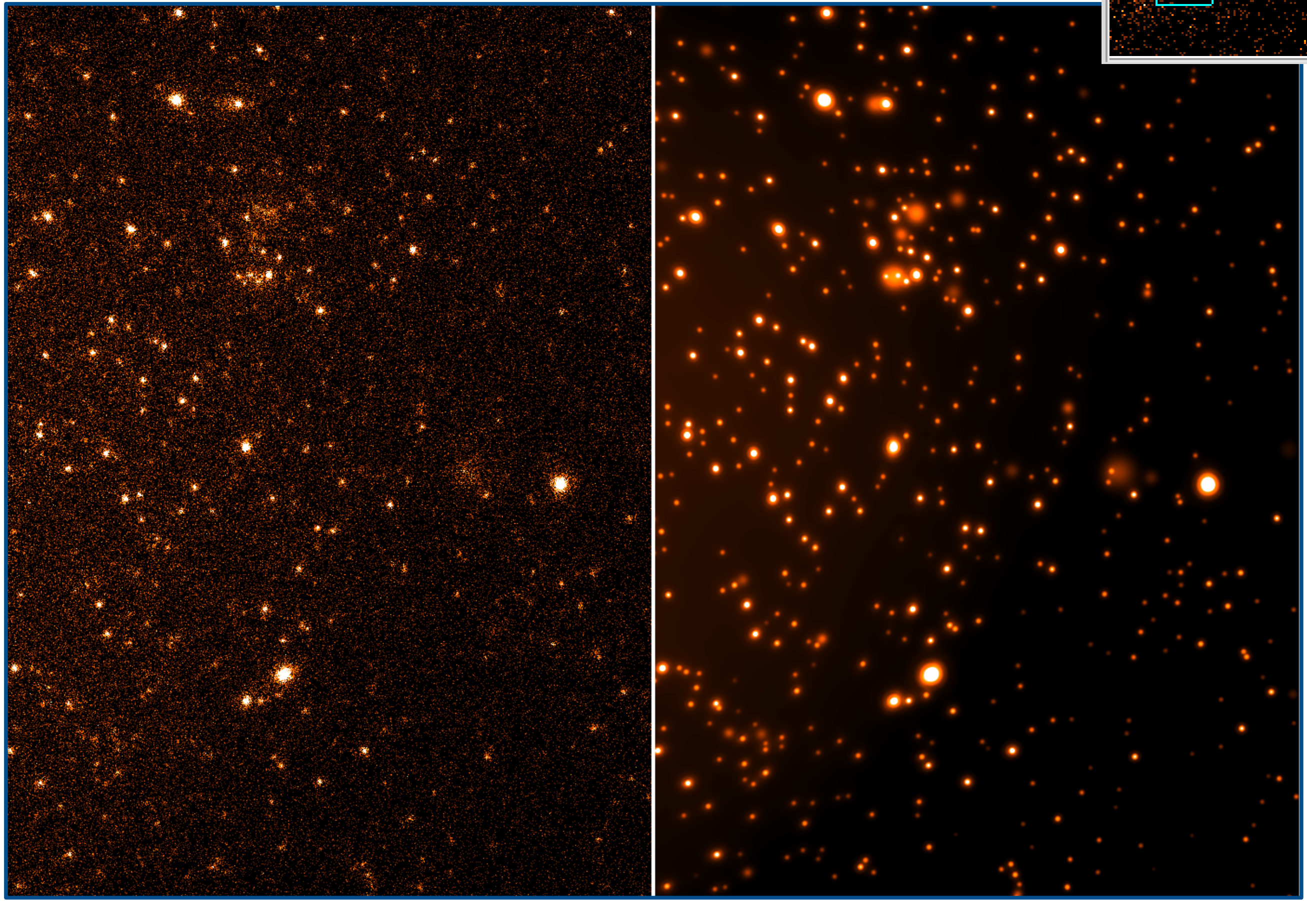
eSASS detection chain

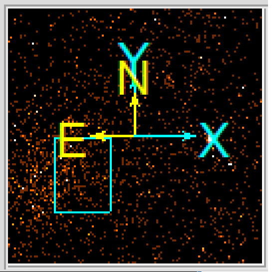
ermldet:

PSF fitting using maximum likelihood ratios (Cash 1979)

Modelling of extended sources with beta model

Multi PSF fitting in crowded areas





eSASS detection chain

ermldet PSF modes:

significant PSF variation over FOV:

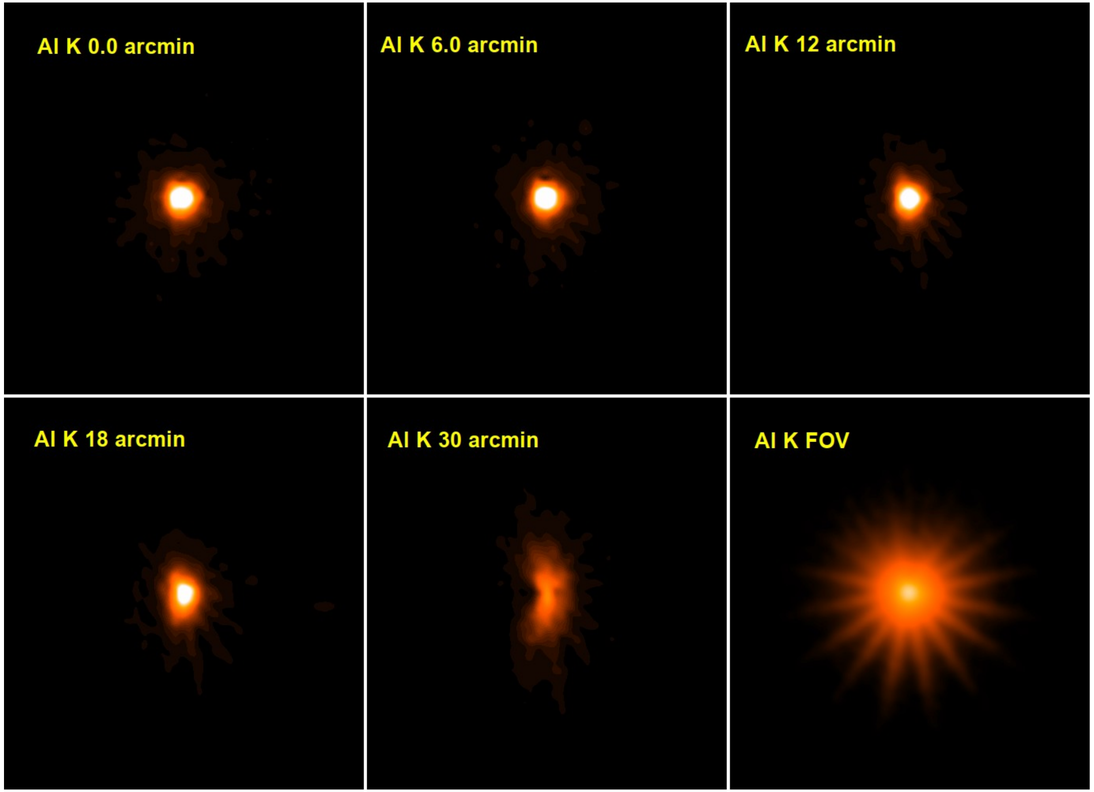
On axis HEW: ~18 arcsec
Survey HEW : ~26 arcsec

3 PSF modes:

1) 2D PSF image

2) Shapelet PSF model

3) Event based fitting (unbinned likelihoods with shapelet PSF)

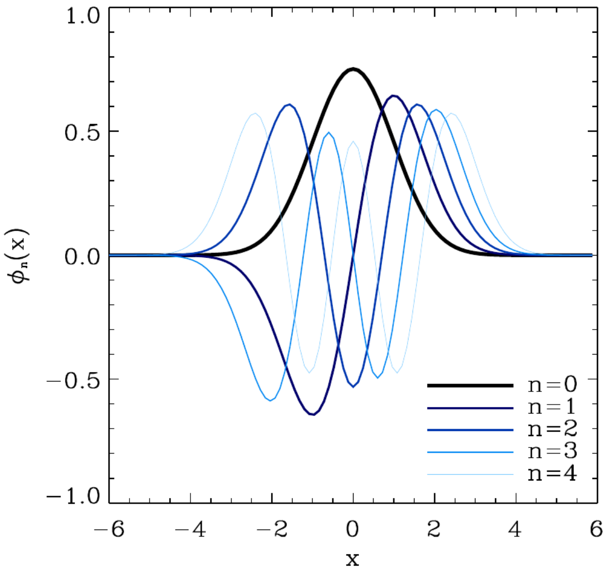


eROSITA PSF, Panter measurements at 1.5 keV

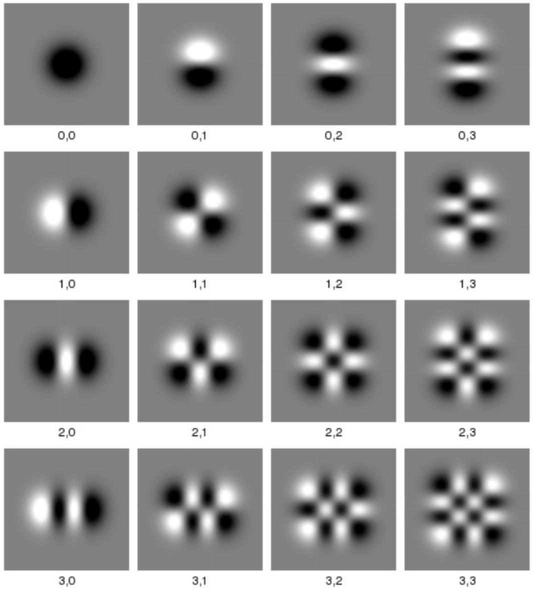
PSF modelling with shapelets

Decomposition of (suitable) distributions into orthonormal basis functions:

Refregier (2001), Refregier & Bacon (2001)



$$\phi_n(x) \equiv \left[2^n \pi^{\frac{1}{2}} n!\right]^{-\frac{1}{2}} H_n(x) e^{-\frac{x^2}{2}}$$



2D basis functions

eSASS detection chain

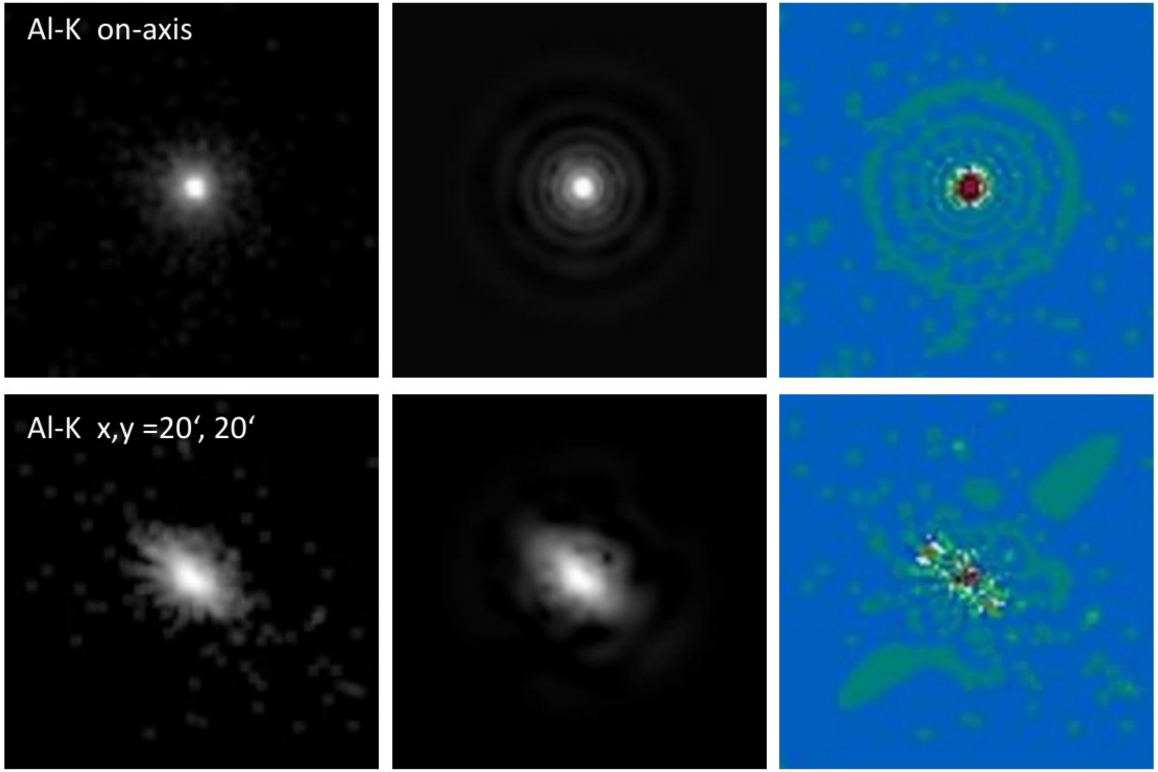
Shapelet PSF

Implemented in eSASS library `shapelib` (A. Georgakakis)

Fits to Panter PSF stored in calibration files:
3 shapelet scales with up to 66 coefficients
6 energies, 13x13 FOV positions.

Averaging or interpolation of PSF can be performed on shapelet coefficients.

Called by `ermldet` to provide source averaged PSF or event specific PSF (event based fitting)



Panter | shapelet reconstruction | residuals

eSASS detection chain

Event based PSF fitting

PSFs reconstructed for each photon event

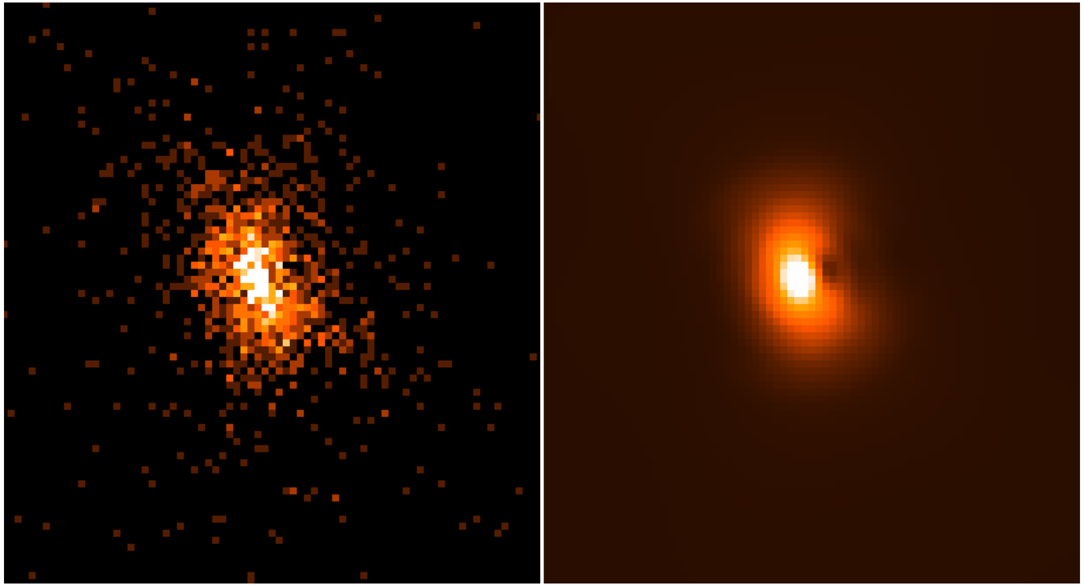
Optionally convolved with extent model

Likelihoods are calculated for each source event separately:

$$C = 2\sum_{i=1}^{N}(e_i - n_i \ln e_i)$$

Pro:
Make full use of smaller on-axis PSF

Contra:
CPU intensive, execution times scales with number of events



PSF reconstruction in single off-axis survey scan

eSASS detection chain

Event based PSF fitting

Standard mode for survey pipeline

PSFs reconstructed for each photon event

Optionally convolved with extent model

Likelihoods are calculated for each source event separately

$$C = 2\sum_{i=1}^{N}(e_i - n_i \ln e_i)$$

Pro:

Makes full use of narrower on-axis PSF

Contra:

CPU intensive, execution time scales with number of events

```
** Shapelet (photon) **
Matched pts:       897809 ( +0.0%)      Point in both eRASS1 and :4
Matched exts:       10628 ( +0.0%)      Extended in both eRASS1 and :4
Mismatched pts:     22164 ( +0.0%)      Point in eRASS1, extended in :4
Mismatched exts:     6815 ( +0.0%)      Extended in eRASS1, point in :4
Unmatched pts:     347164 ( +0.0%)      Point in eRASS1, none in :4
Unmatched exts:      7246 ( +0.0%)      Extended in eRASS1, none in :4

** Shapelet (image) **                  ** PANTER (image) **
Matched pts:       853707 ( -4.9%)      Matched pts:       845167 ( -5.9%)
Matched exts:        9744 ( -8.3%)      Matched exts:        9107 (-14.3%)
Mismatched pts:     23162 ( +4.5%)      Mismatched pts:     23495 ( +6.0%)
Mismatched exts:     5359 (-21.4%)      Mismatched exts:     4173 (-38.8%)
Unmatched pts:     331582 ( -4.5%)      Unmatched pts:     319308 ( -8.0%)
Unmatched exts:      7516 ( +3.7%)      Unmatched exts:      6642 ( -8.3%)
```

Comparison of PSF modes (eRASS1; refererence: eRASS:4)
J. Sanders (MPE)

Compiling the final catalogues

Merged catalogues:

Merging all sky tiles

Matching with WISE counterparts (QSO colours)

Calculate median offsets in ecl. lon, ecl. lat in 1 deg latitude strips

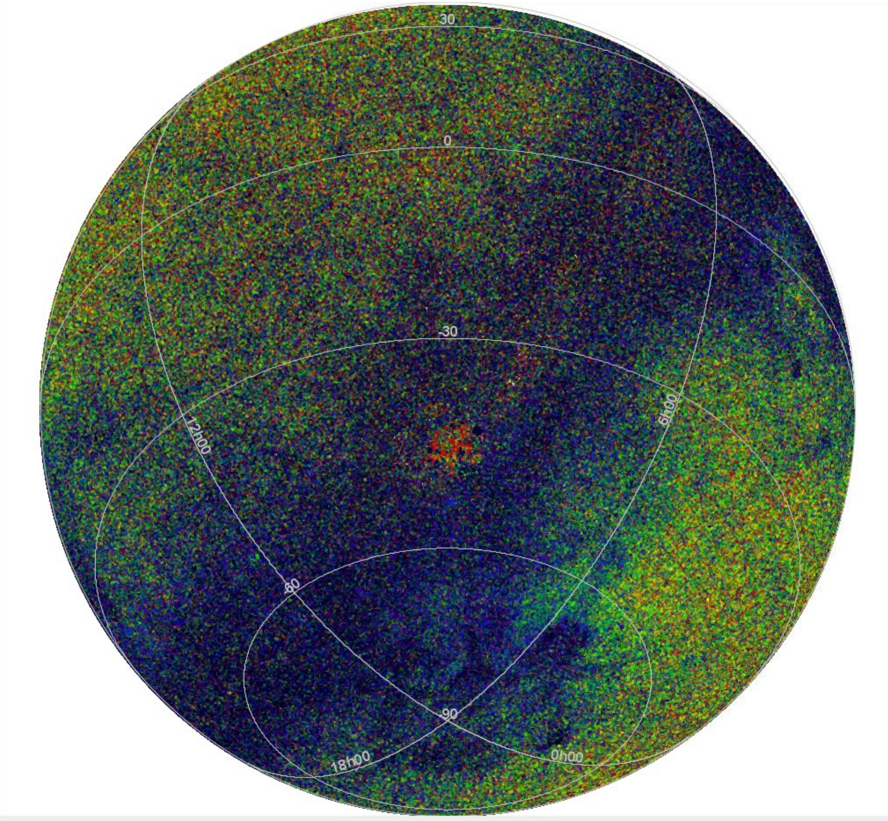
Apply astrometric correction

Clean overlaps between sky tiles

Filter for eROSITA.DE sky area

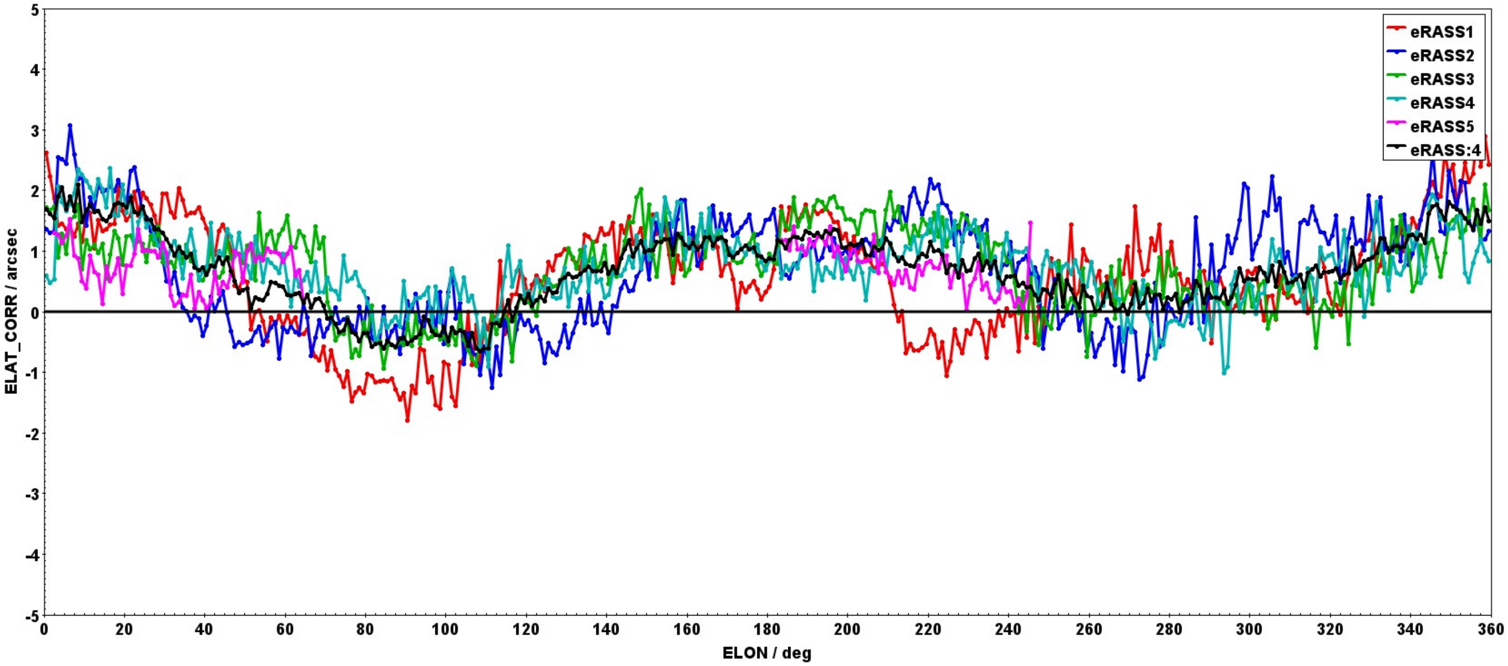
Add rates/fluxes from forced photometry

For eRASS:4 : calculate variability parameters



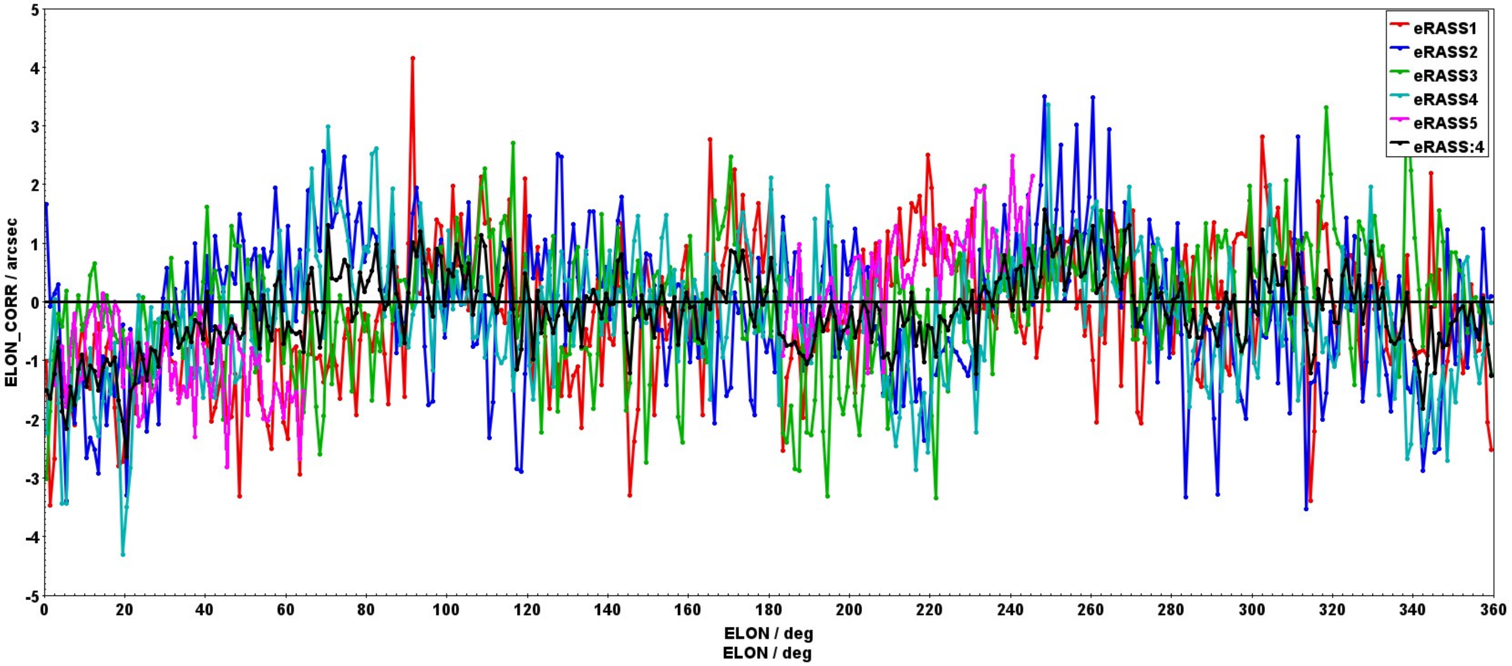
Hardness ratios beween forced photometry bands (0.2-0.5, 0.5-1.0 keV)

Astrometric corrections



Corrections in ecl. latitude (scan direction) as function of longitude

Astrometric corrections



Corrections in ecl. longitude as function of longitude

eRASS:4 variability catalogue

VAR_CHI2:

chi-square calculated from columns ML_RATE_1,ML_RATE_ERR_1

VAR_PROB:

probability for variability based on VAR_CHI2 and the ndof (n_epochs-1)

FRATIO:

max(ML_RATE_1)/min(ML_RATE_1)

FRATIO_ERR:

error of parameter FRATIO

FLUXVAR:

maximum of error normalised differences in ML_RATE_1

Variability parameter as used in 2RXS (Boller et al 2016):

AMPMAX_NORM:

error normalised maximum variability amplitude (Boller et al 2016):

$$\mathrm{VAR\_CHI2} = \frac{1}{n-1}\sum_{k=1}^{n}\left(\frac{F_k - F_{\mathrm{EPIC}}}{\sigma_k}\right)^2, \tag{1}$$

the associated cumulative chi-square probability of the flux measurements being consistent with constant flux

$$\mathrm{VAR\_PROB} = \int_{\chi^2}^{\infty} \frac{x^{\nu/2-1}e^{-x/2}}{2^{\nu/2}\Gamma(\nu/2)}\mathrm{d}x, \tag{2}$$

where smaller values indicate a higher chance that the source is variable and Γ denotes the gamma function, the ratio between the highest and lowest observation-level flux

$$\mathrm{FRATIO} = F_{\max}/F_{\min}, \tag{3}$$

the associated 1σ error

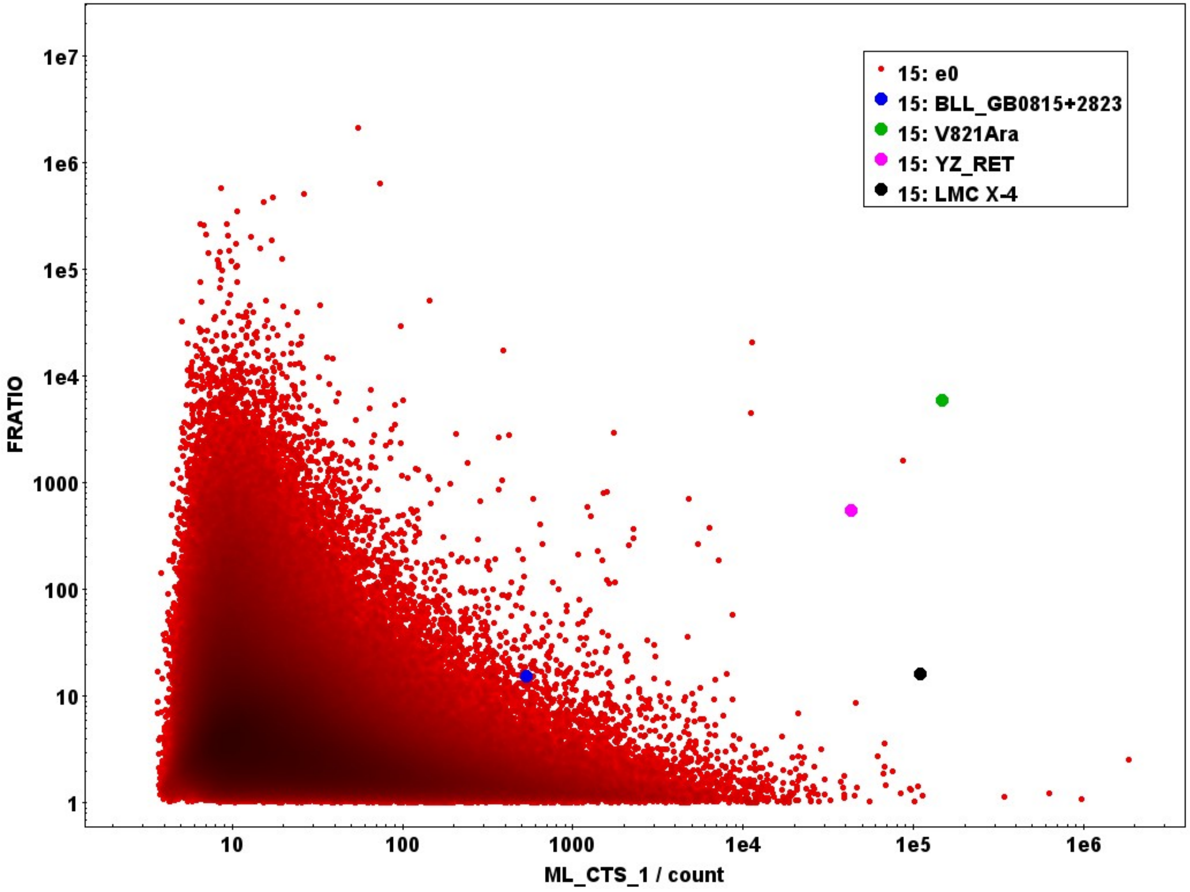
$$\mathrm{FRATIO\_ERR} = \left(\frac{\sigma^2_{F\min}}{F^2_{\min}} + \frac{\sigma^2_{F\max}}{F^2_{\max}}\right)^{0.5}\frac{F_{\max}}{F_{\min}}, \tag{4}$$

and the largest flux difference between any combination of the observation-level fluxes in terms of σ

$$\mathrm{FLUXVAR} = \max_{k,l\in[1,n]} \frac{|F_k - F_l|}{\sqrt{\sigma_k^2 + \sigma_l^2}} \tag{5}$$

Traulsen et al. 2019

eRASS:4 variability catalogue



Outlook

eROSITA:

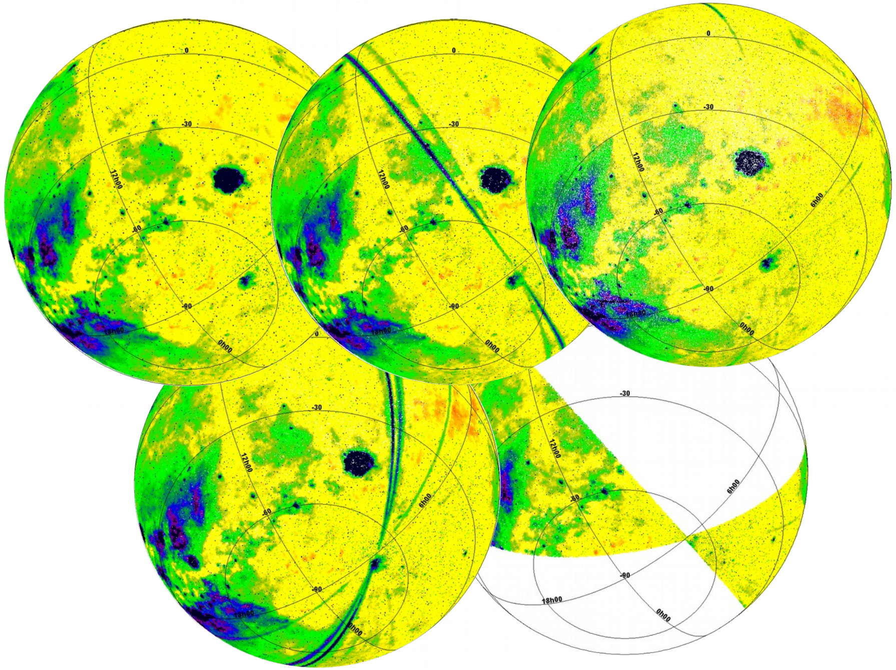
Ongoing reprocessing:

- Improved event calibration
- Flare screening
- Time dependent boresight correction
- Improved astrometry

Future missions:

New detection algorithms?

Machine learning?



eRASS1 - eRASS5
0.2-2.3 keV background rate