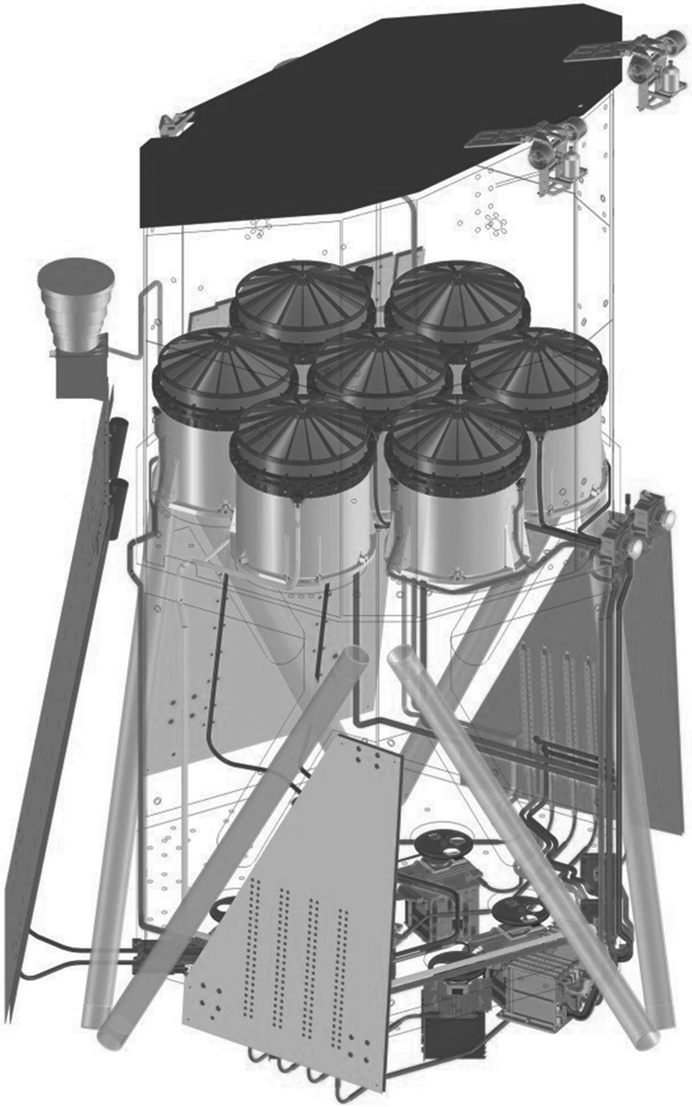
eROSITA in-orbit calibration – and monitoring: from theory to science (i.e.: do the work)

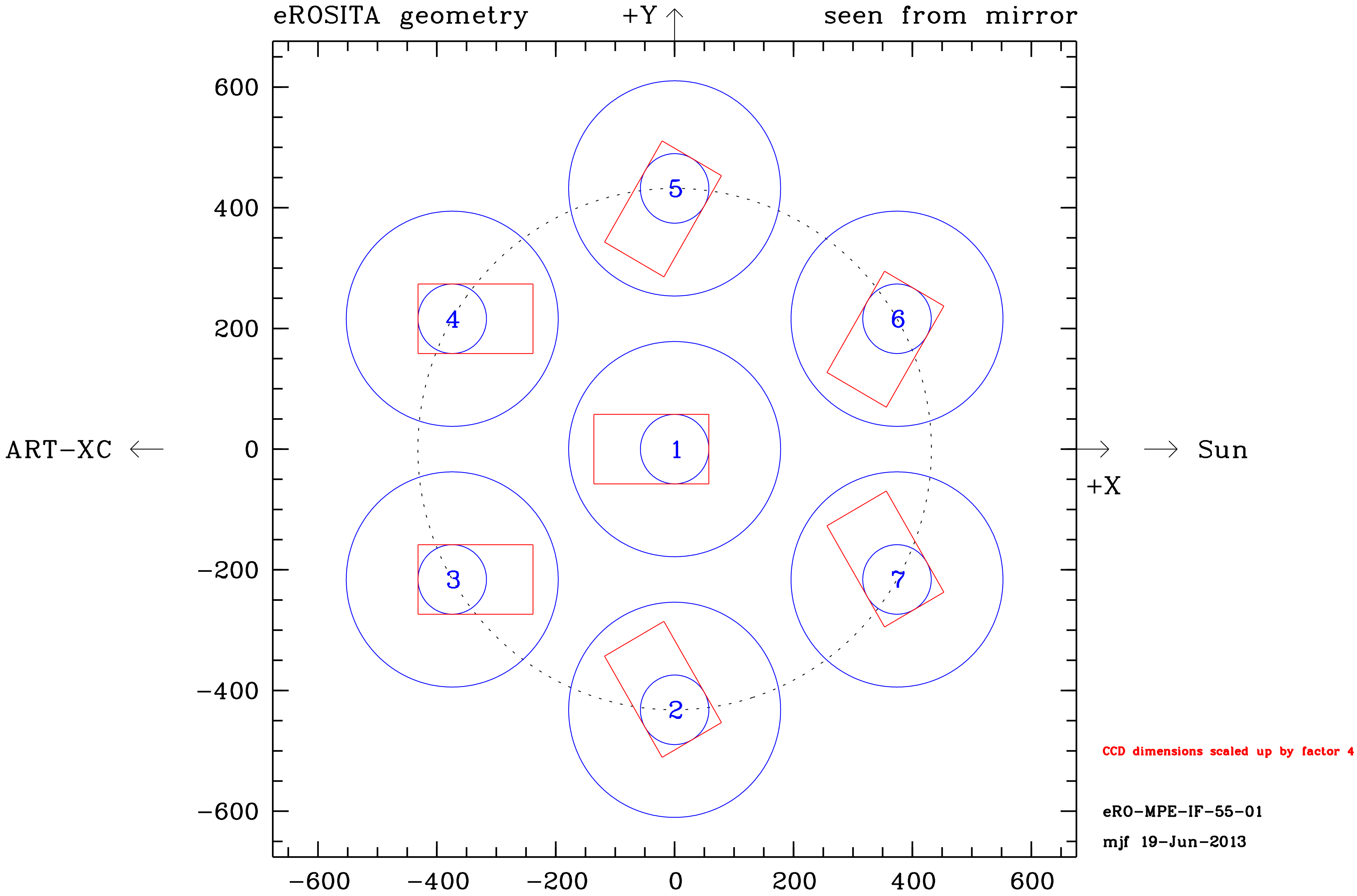


Predehl (2017)

eROSITA aboard SRG: summary

- 7 cameras (pnCCD) with 7 filter wheels and 7 mirror modules with 7 X-ray baffles
- only 1 mode (frame-store, 50 ms), "standard candles" are too bright (pile-up)!
- Fe-55 source (+ Al + Ti): on filter wheel, strong enough for later mission phases
- Schedule: use ~105 d (15 wk) transfer phase to L2 for initial measurements, then start survey phase (90°/h)... (after 7 weeks SRG at "about L2")
- Launch, satellite checkout,
  4 wk outgassing + 4 wk commissioning (1 + 2 + 2 + 2 cameras per week),
  4 wk in-orbit calibration phase interleaved with 3 wk performance verification,
  4 yr all-sky survey(s) interleaved with monitoring, 3 yr guest observer programme ...
- Why: ground calibration: individual modules (mirrors + X-ray baffle) → PANTER,
  ground calibration: individual cameras (including filter wheel, electronics) → PUMA,
  but: no full system calibration, "only" end-to-end test → PANTER,
  but: assembly (eROSITA + SRG), shipping, and launch may change performance,
  but: operational environment is different from ground (background, ...),
  but: changes expected due to radiation damage,
  but: changes not excluded due to contamination,
  → cross-calibration (+ with ART-XC and other missions (XMM-Newton, Chandra)
- CalPV: not only "launch date" matters, but also "success date" of commissioning !
- CalPV will be performed with fixed optimized set-up

eROSITA geometry: mirror modules and cameras

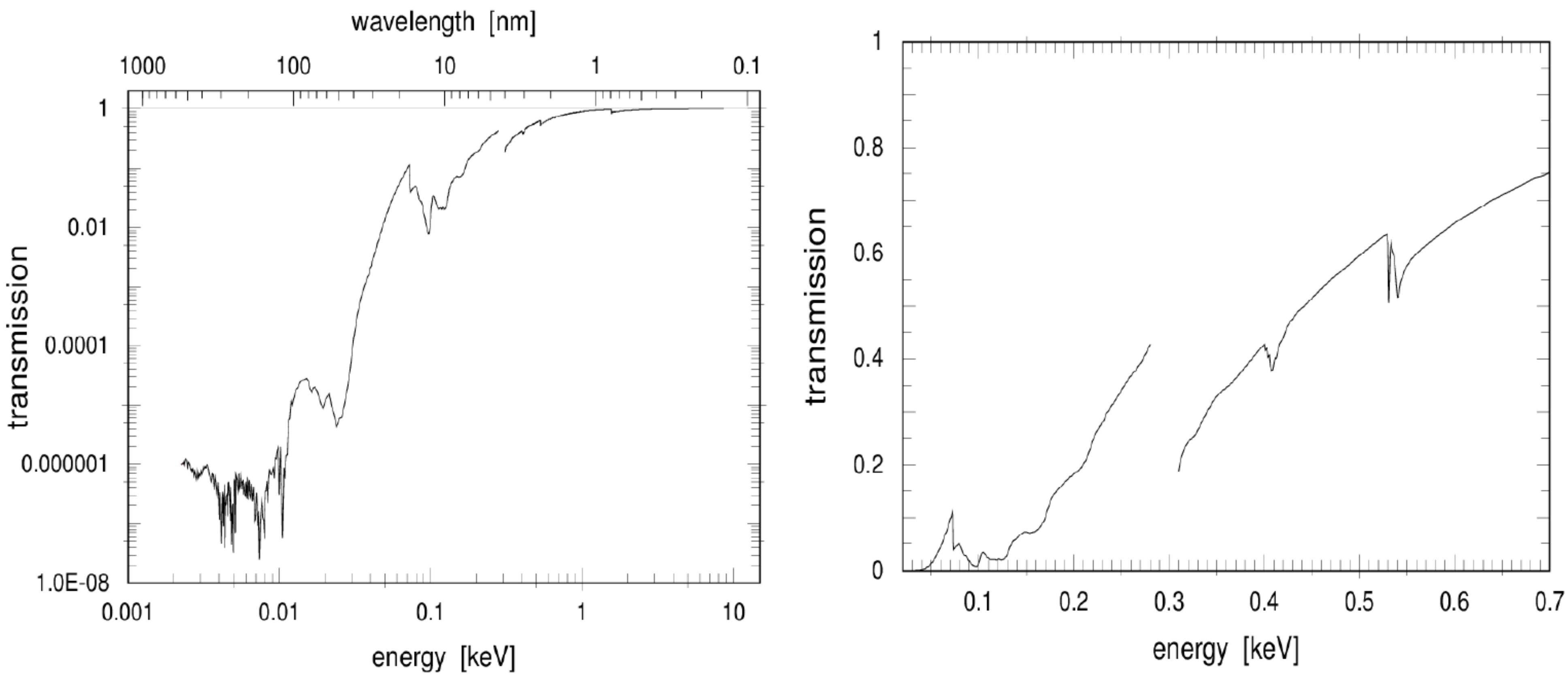


eROSITA geometry: FM Assembly and Position

Telescope Module (pos.)	1	2	3	4	5	6	7
Mirror Assembly (FM)	2	3	5	4	6	7	1
Camera Assembly (FM)	3	2	7	4	5	6	1
ext. Filter (frame #)	23	10	7	24	20	1	19
ext. Filter (PI) [nm]	205.0	207.7	209.9	204.5	219.5	212.5	203.1
ext. Filter (Al) [nm]					103.3		102.3

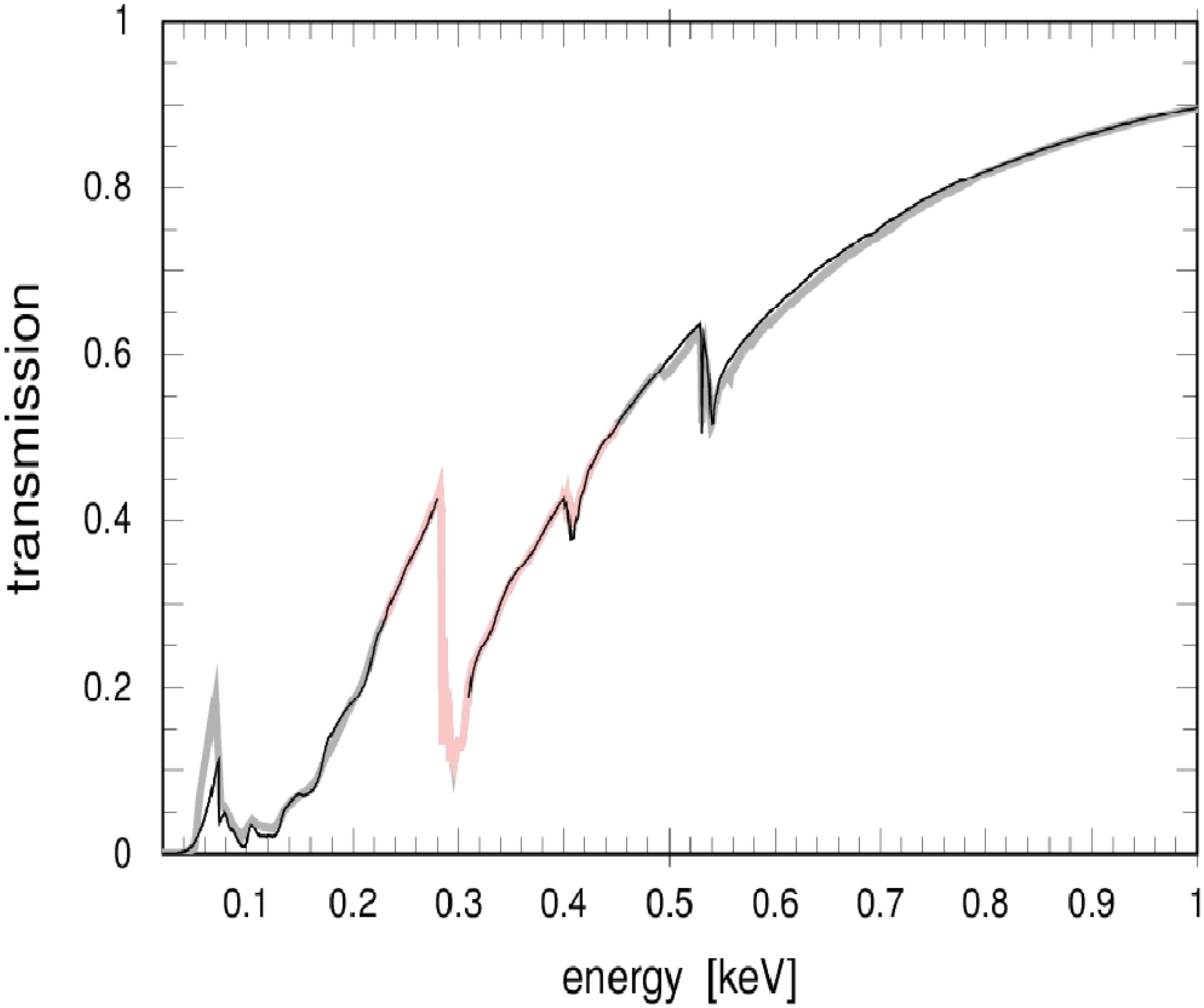
On-chip filter: 200 nm Al + external 200 nm PI (nominal)
Off-chip filter: external 200 nm PI + 100 nm Al (nominal)
All (will be) handled consistently
in calibration files and software
baseline: always use external filter (CalPV + surveys)
introduces small carbon edge:
smaller than EPIC, much smaller than PSPC
filters measured at BESSY in 2015: 5, 11, 16, 21
problems at BESSY around C-edge
model gap with extrapolation from EPIC thin/medium filters

Optical light blocking filter transmission recovery (K. Dennerl)



BESSY measurements:
degraded performance suspected around C-K edge
$\rightarrow$ no data delivered, gap

Optical light blocking filter transmission recovery (K. Dennerl)



→ **fill the gap by rescaling EPIC Thin/Medium filter transmission (PI/Al)**

Ground calibration: mirror assemblies (MA)

Key performance parameter	FM1	FM2	FM3	FM4	FM5	FM6	FM7	FM8
HEW @ Al-Kα (1.49 keV) [arcsec]	17.0	16.0	15.5	15.9	16.5	16.1	15.6	17.1
HEW @ Cu-Kα (8.04 keV) [arcsec]	14.7	14.5	15.1	16.3	15.6	15.1	16.2	17.8
Effective area @ Al-Kα [cm^2]	392	391	393	369	388	378	392	390
Effective area @ Cu-Kα [cm^2]	24.8	24.8	25.1	23.8	24.1	25.1	25.0	24.2
Scattering @ Cu-Kα [%]	10.2	11.1	11.0	12.1	13.2	11.2	12.8	12.3

On-axis in-focus values, FM8 is flight spare

Measured at PANTER using target source in 2016

Requirement: HEW 15 arcsec @ Al-Kα, 20 arcsec @ Cu-Kα

intentionally integrated $\sim$0.4 mm intra-focal

Ground calibration: camera assemblies (CA)

Key performance parameter	FM1	FM2	FM3	FM4	FM5	FM6	FM7	QE [%]
FWHM @ C-Kα (0.277 keV) [eV]	49	58	58	58	50	59	58	16
FWHM @ O-Kα (0.525 keV) [eV]	56	65	64	64	57	69	66	53
FWHM @ Cu-L (0.93 keV) [eV]	68	74	70	70	68	71	72	89
FWHM @ Al-Kα (1.49 keV) [eV]	77	82	77	77	75	77	72	85
FWHM @ Ti-Kα (4.51 keV) [eV]	117	125	118	118	116	120	122	98
FWHM @ Fe-Kα (6.40 keV) [eV]	136	145	138	138	135	141	142	99
FWHM @ Cu-Kα (8.04 keV) [eV]	156	167	158	158	155	159	163	100
FWHM @ Ge-Kα (9.89 keV) [eV]	175	204	178	173	170	180	182	98

mean quantum efficiency including optical light-blocking filter

measured at PUMA using target source in 2016

In-orbit calibration subjects

- **Commissioning**
- **Background (graded shield, calibration and monitoring, "Closed", etc.)**

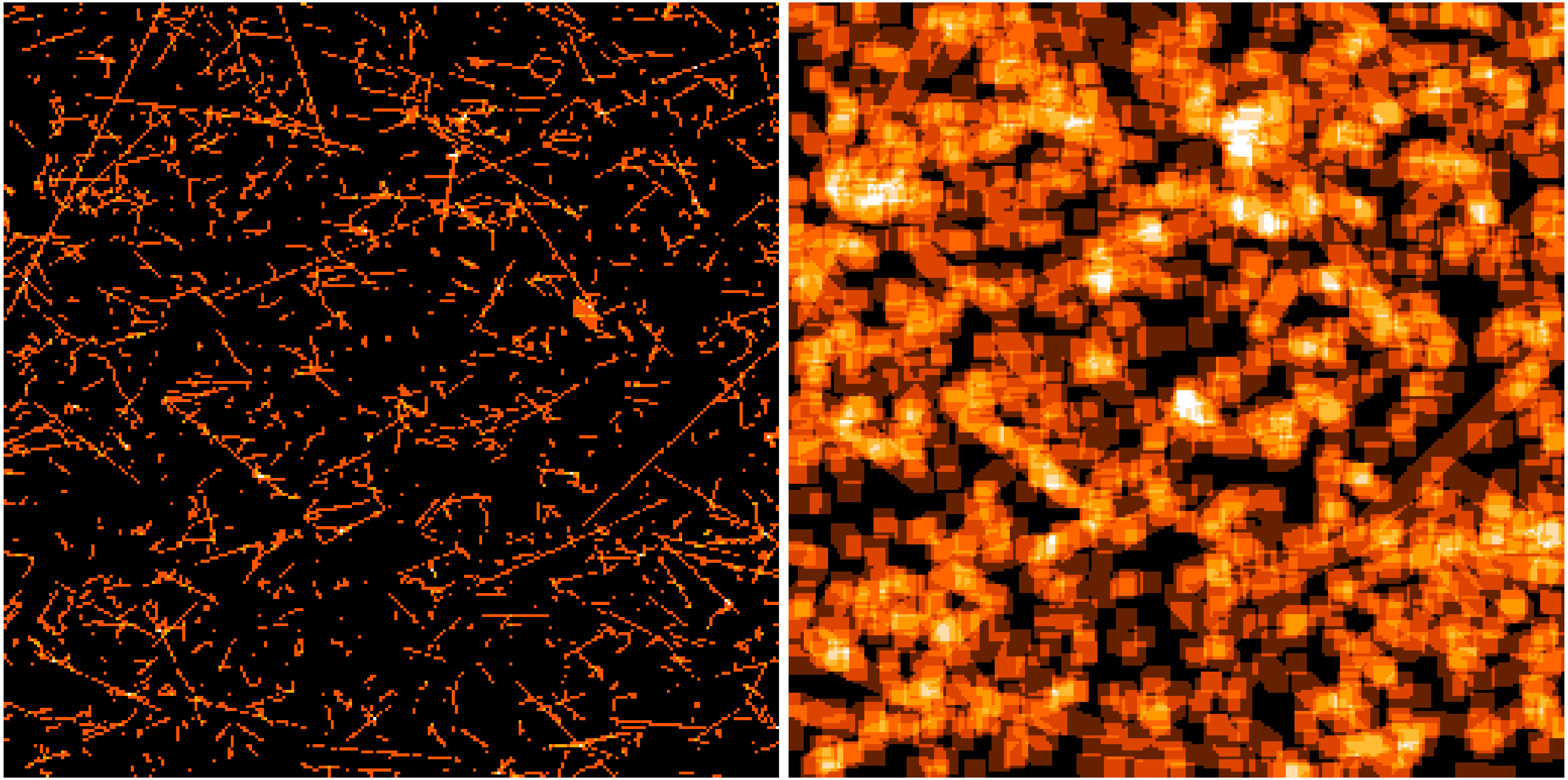
- **Plate scale and boresight of the 7 modules (star-trackers vs. mirror assembly)**
- **Filter integrity (launch, micrometeorites)**
- **Soft X-ray response and contamination monitoring**
- **Gain and CTI (calibration and monitoring, "CalClosed" Fe-55)**
- **PSF (on-axis, off-axis, survey)**
- **Power-law type spectrum (cross-calibration)**
- **Effective area, flat-fielding, and vignetting**
- **Optical loading by point sources**
- **X-ray baffle (mosaic, mini-survey in great circles)**
- **Absolute and relative timing (and operational tests like "mini-survey" in great circles for time-delays between star tracker and X-ray cameras, attitude reconstruction)**
- **XUV response and contamination monitoring**
- **Masked mode, etc.**

- **Performance verification / "early science" (interleaved with calibration observations)**

Operational constraints:

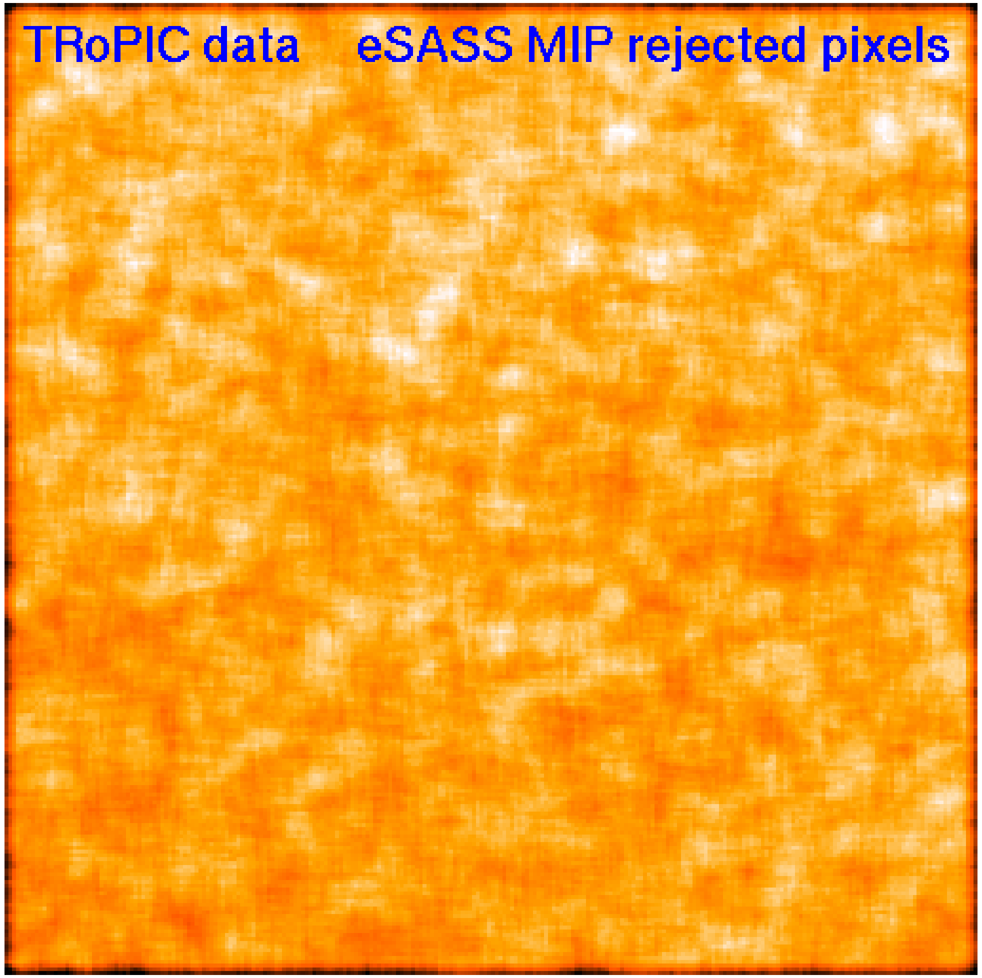
- Data handling rate inside camera (buffers)
- Data downlink rate limited
- Only short commanding period during ground contacts
- Number of time-tagged commands to be stored very limited
- response time of manual commanding to L2: $\sim$12 s
- Pile-up and pseudo-MIPs (for bright sources, see below)
- Visibility (ecliptic coordinates), depends on launch date and switch-on date
- Closed/CalClosed: only 1 module at a time
  (i.e., 6/7 of exposure to avoid dark regions)
- Monitor health and calibration validity regularly, but do not stop surveys too long:
  after each all-sky survey (6 months): 1 day Cal/monitoring campaign:
  1E0102 and RXJ1856
- cross-calibration with other operational X-ray missions,
  depends then also on other (external) constraints, e.g. for 3C 273

Background: Minimum ionizing particles (I)



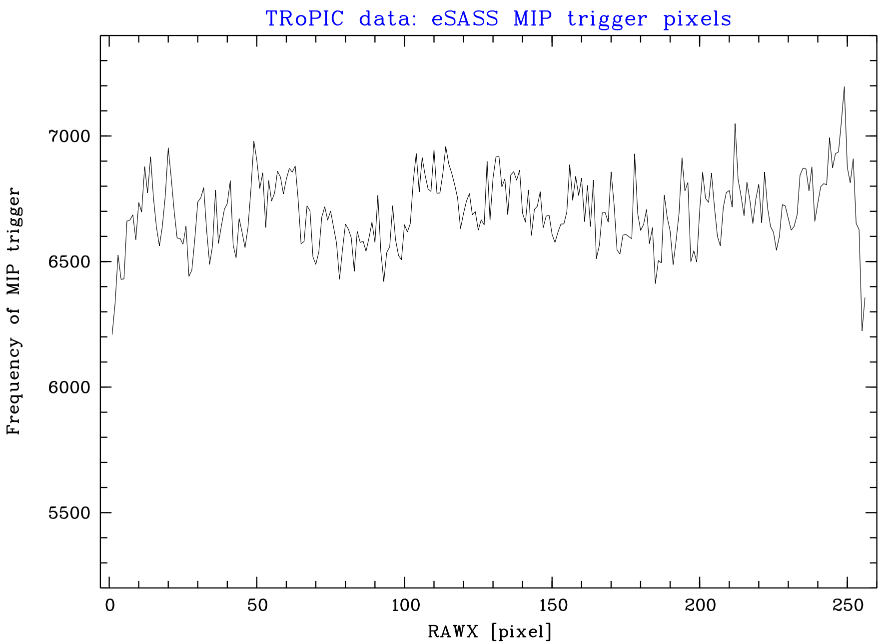
pixels above trigger threshold → pixels rejected by 2D algorithm
here: 3 pixels width in each X and Y semi-axis

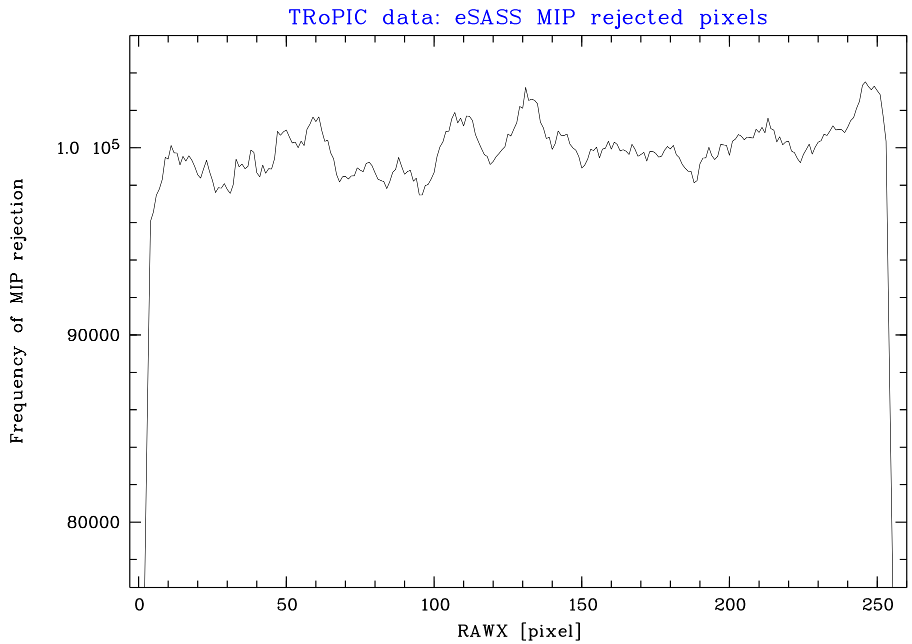
Background: Minimum ionizing particles (II)



pixels above trigger threshold → pixels rejected by 2D algorithm
here: 3 pixels width in each X and Y semi-axis

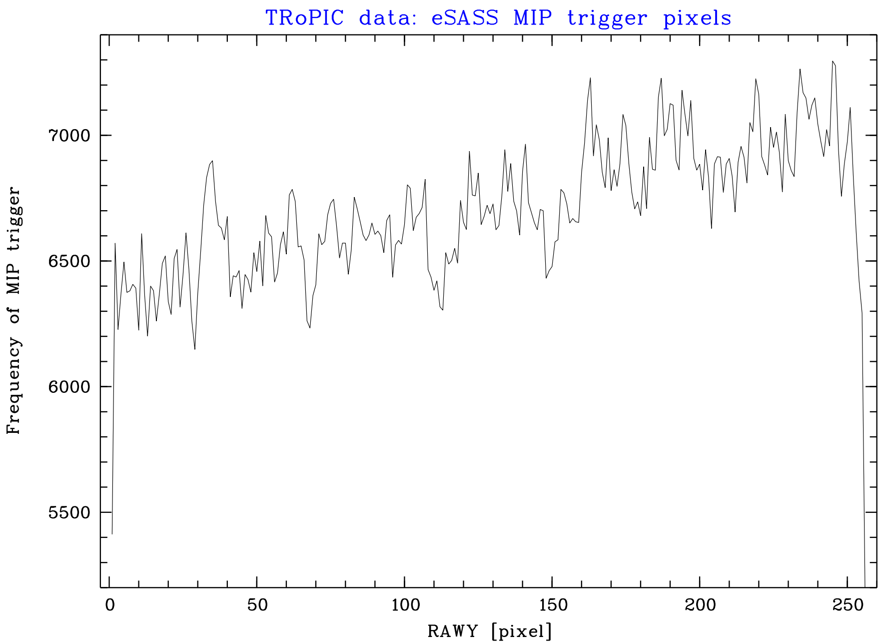
Background: Minimum ionizing particles (III)

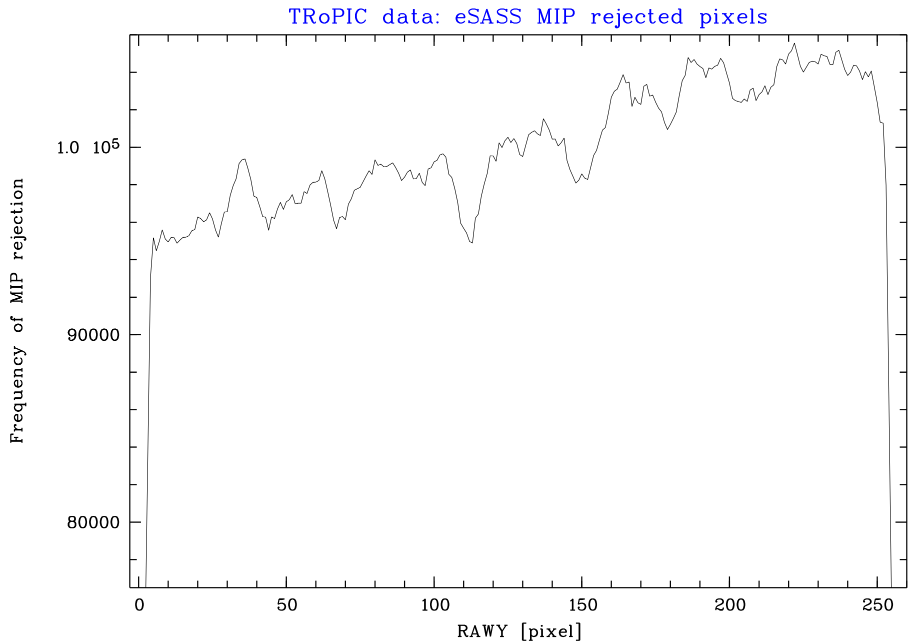




pixels above trigger threshold → pixels rejected by 2D algorithm
here: projected on X-axis

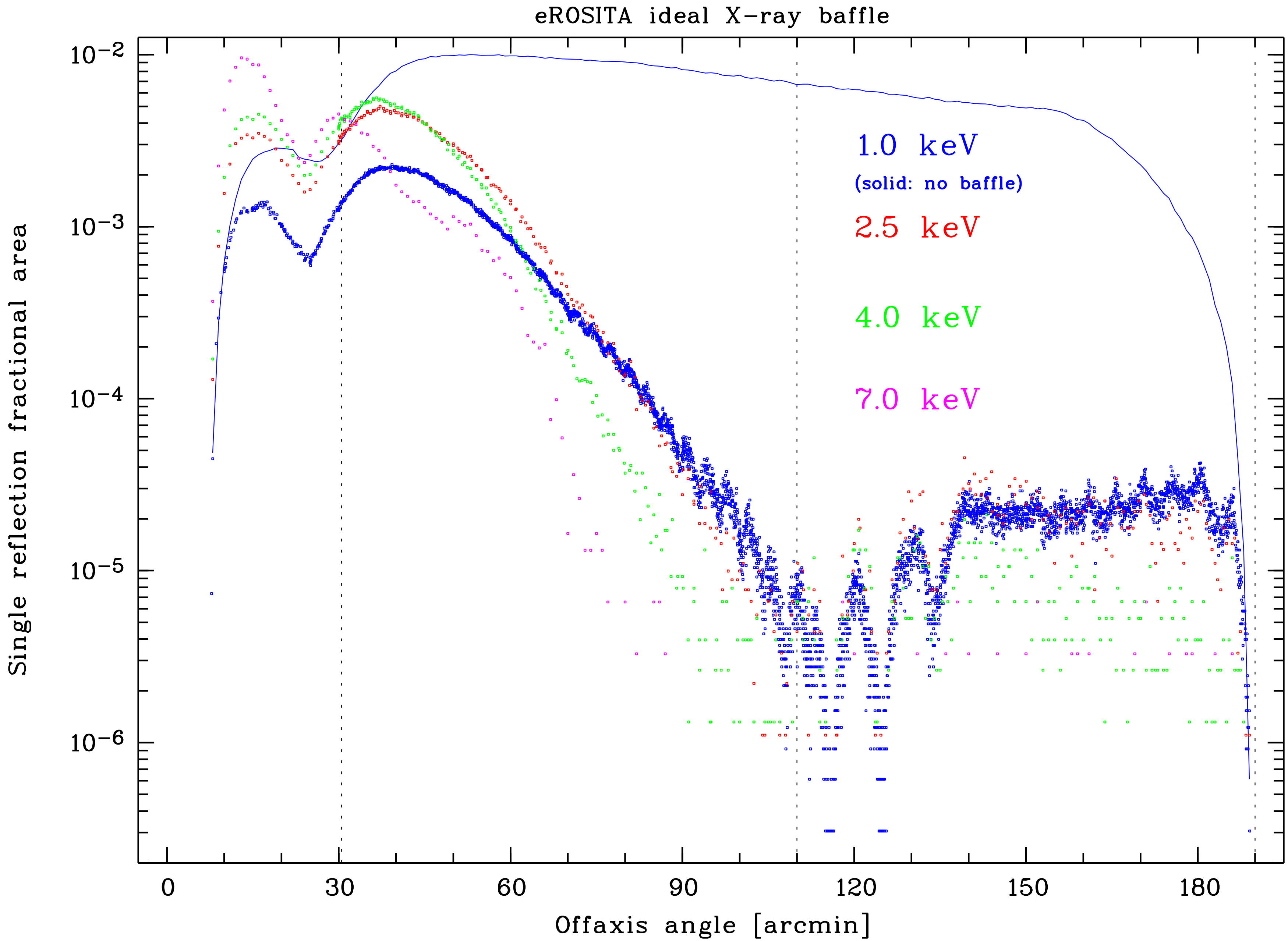
Background: Minimum ionizing particles (IV)



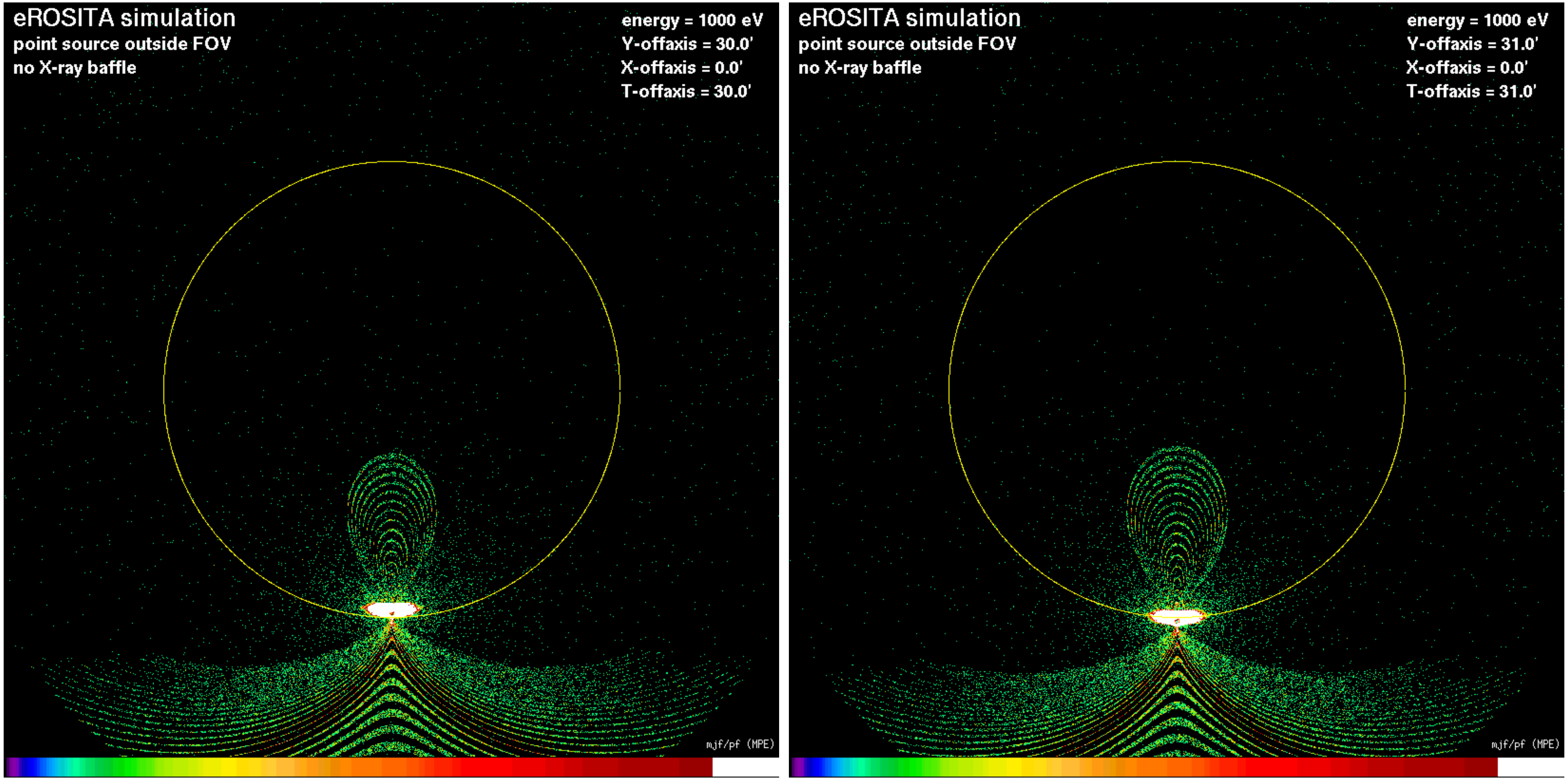


pixels above trigger threshold → pixels rejected by 2D algorithm
here: projected on Y-axis
Origin of slope: framestore area
Soft protons cause another spatial inhomogeneity
(estimator for soft proton content)
X/Y projections used for spatial exposure correction
total number used for temporal exposure correction

eROSITA simulations: out-of-FOV PSF (P.Friedrich + MF)

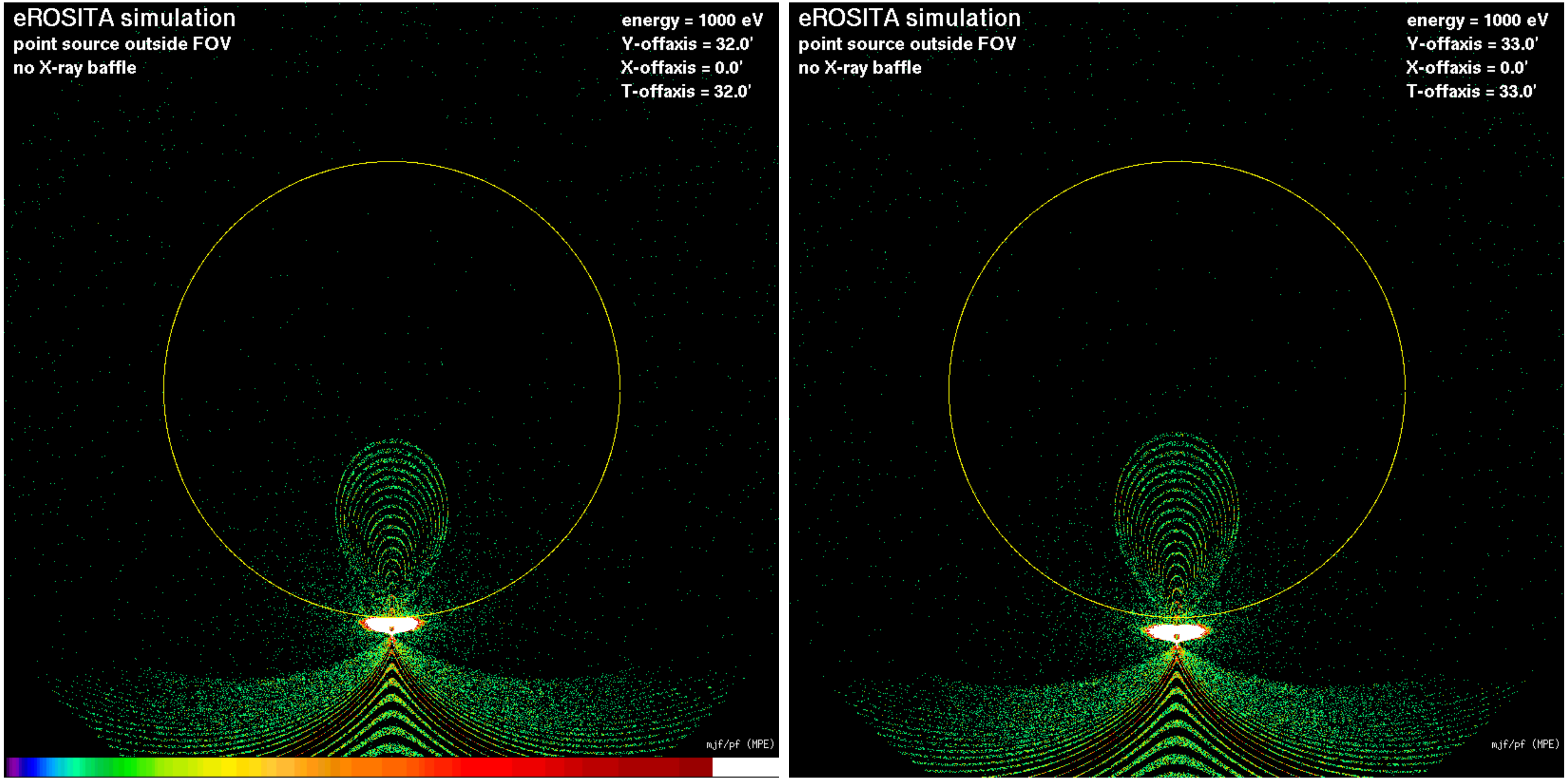


eROSITA simulations: out-of-FOV PSF (P.Friedrich + MF)



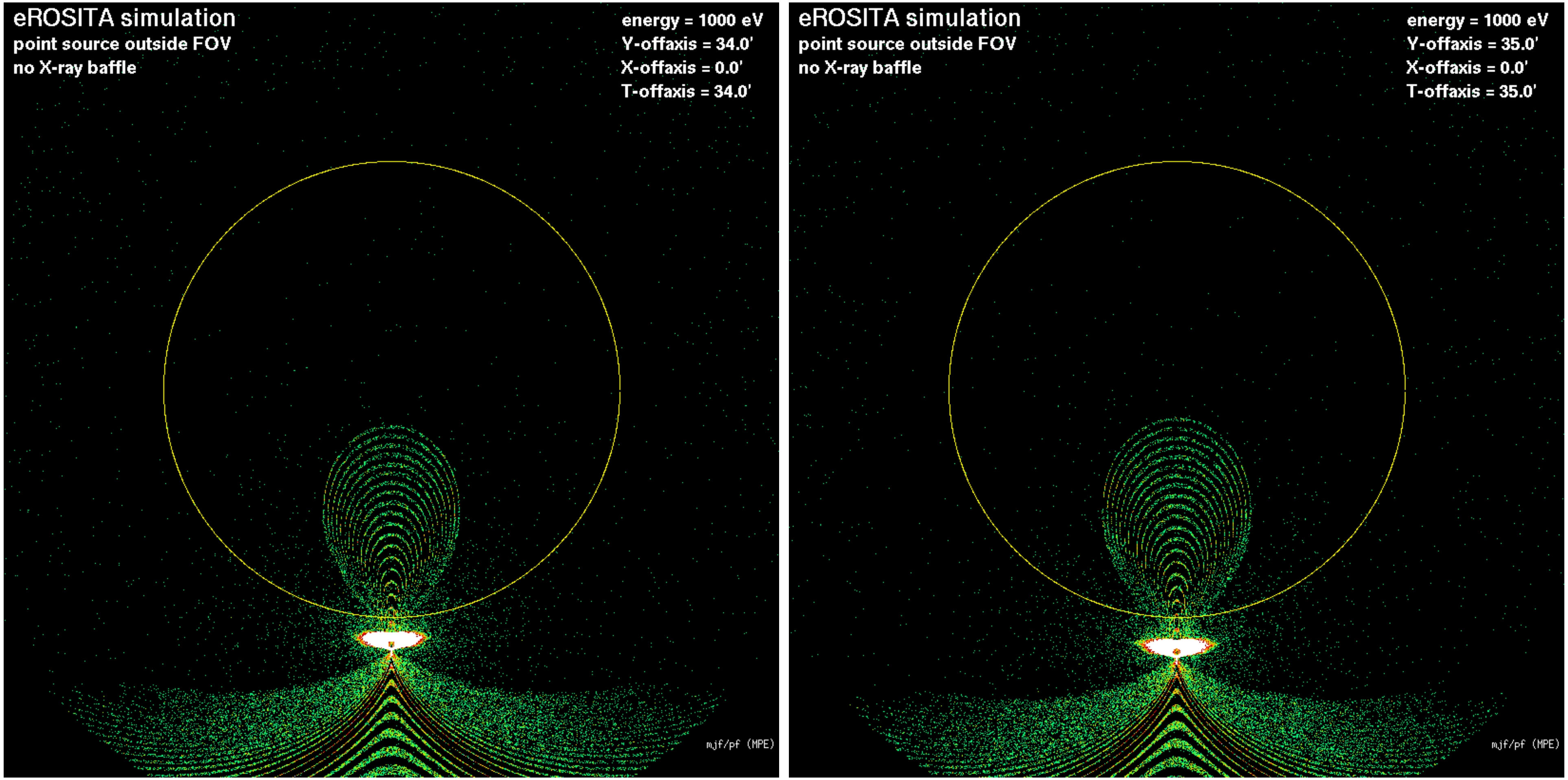
no baffle, no pile-up: bright source off-axis: 30 arcmin (left), 31 arcmin (right)

eROSITA simulations: out-of-FOV PSF (P.Friedrich + MF)



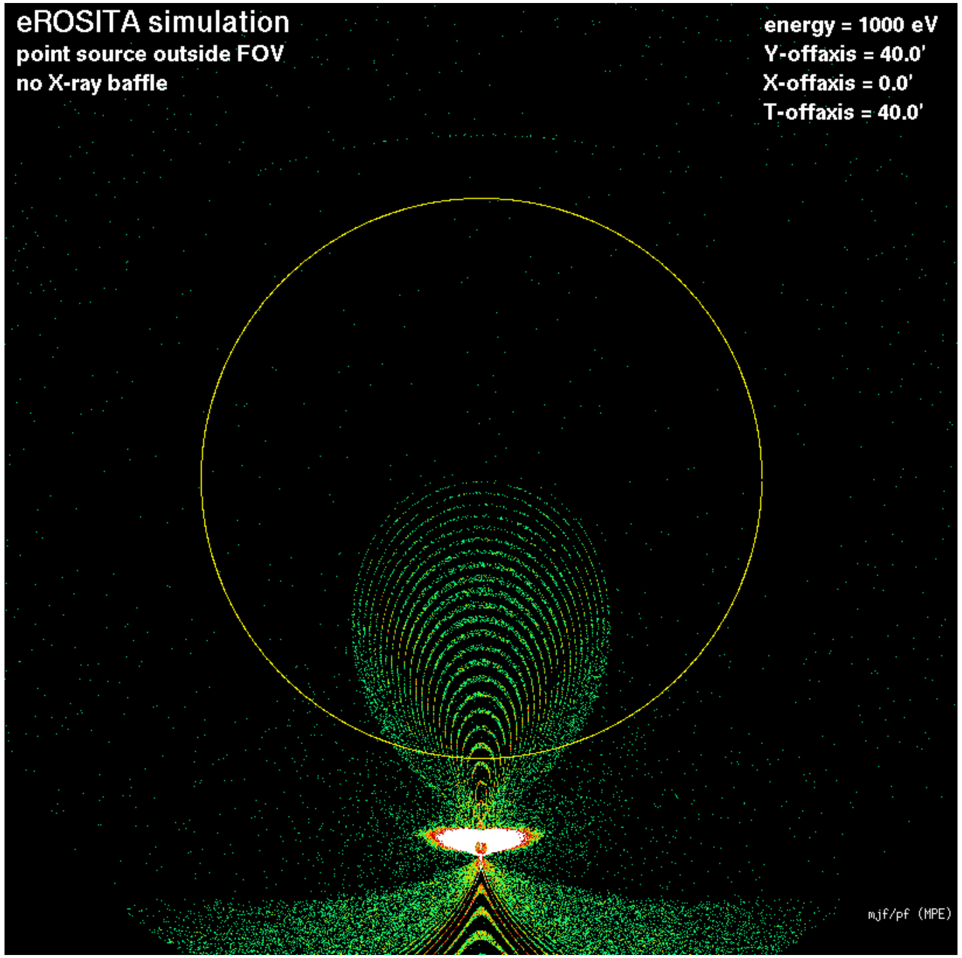
no baffle, no pile-up: bright source off-axis: 32 arcmin (left), 33 arcmin (right)

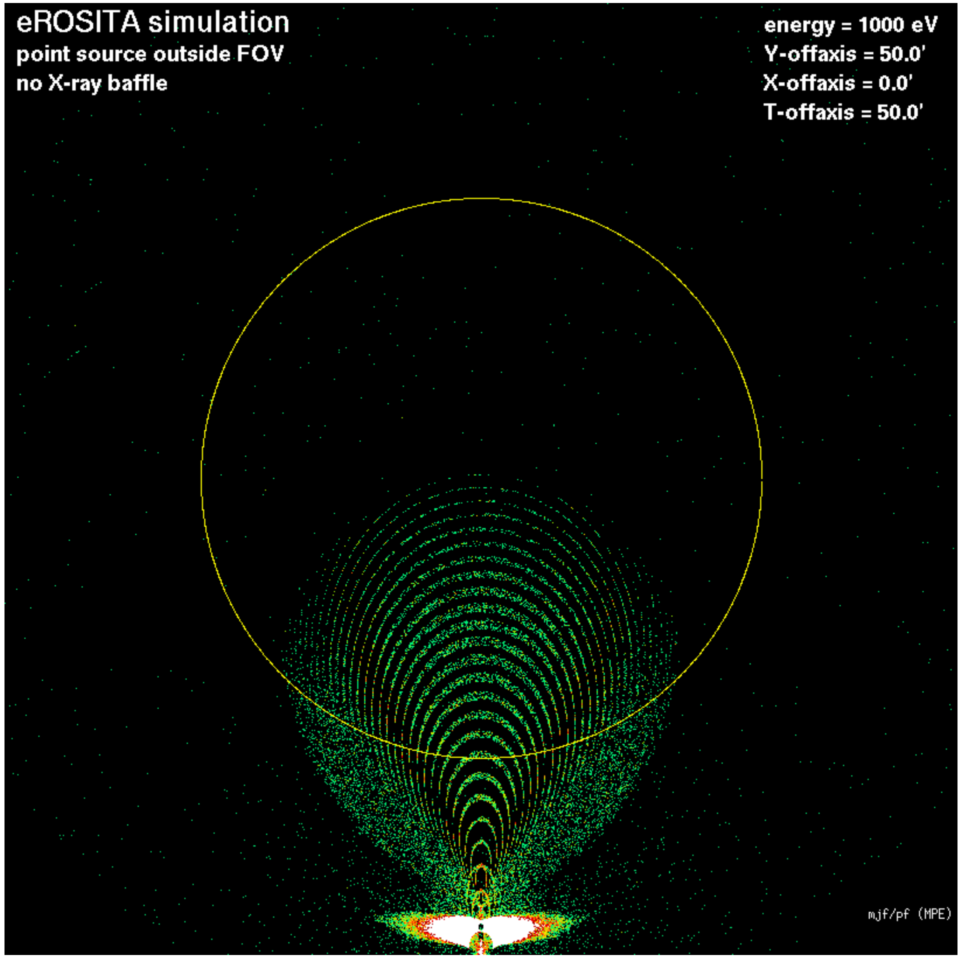
eROSITA simulations: out-of-FOV PSF (P.Friedrich + MF)



no baffle, no pile-up: bright source off-axis: 34 arcmin (left), 35 arcmin (right)

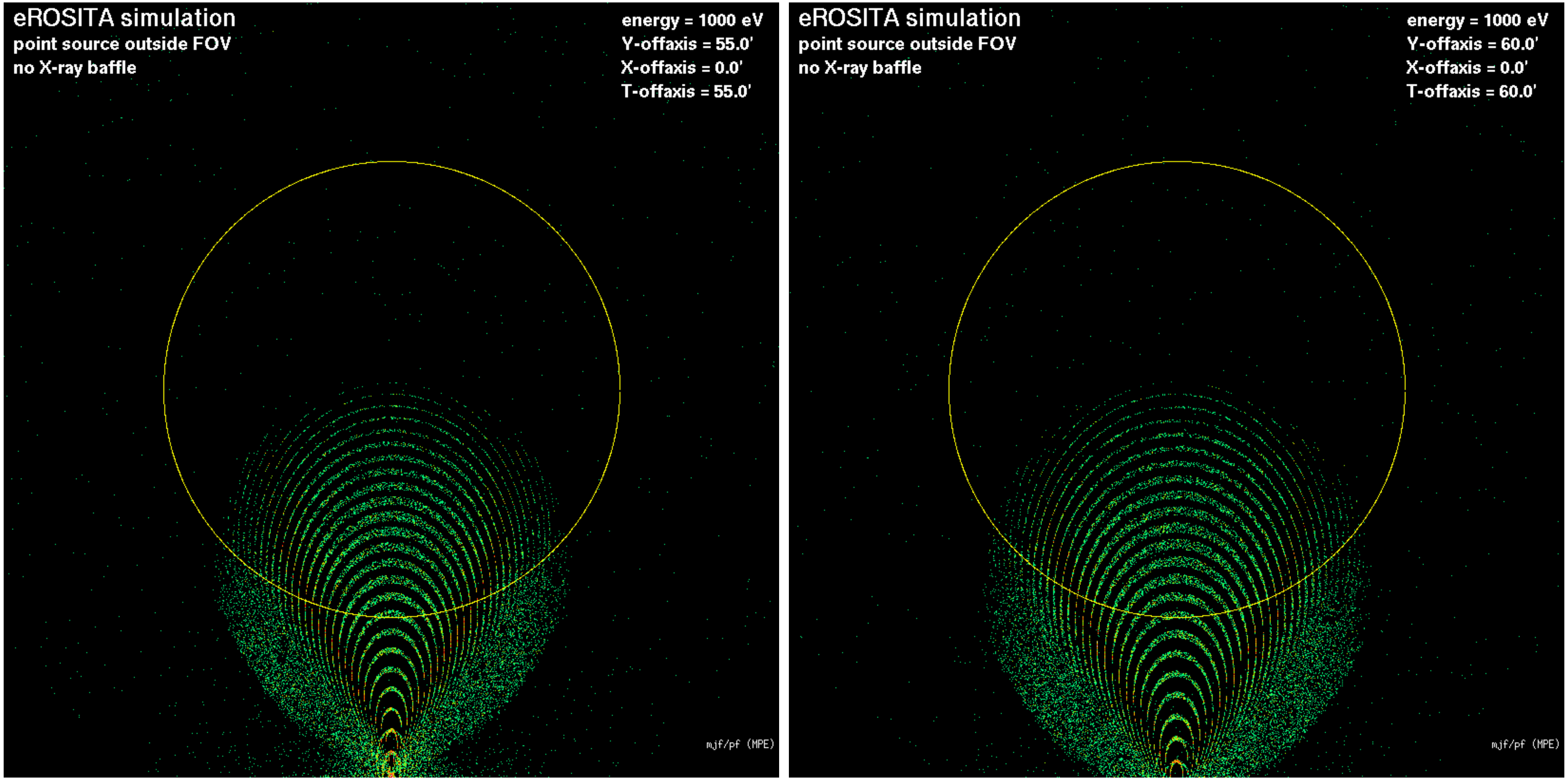
eROSITA simulations: out-of-FOV PSF (P.Friedrich + MF)





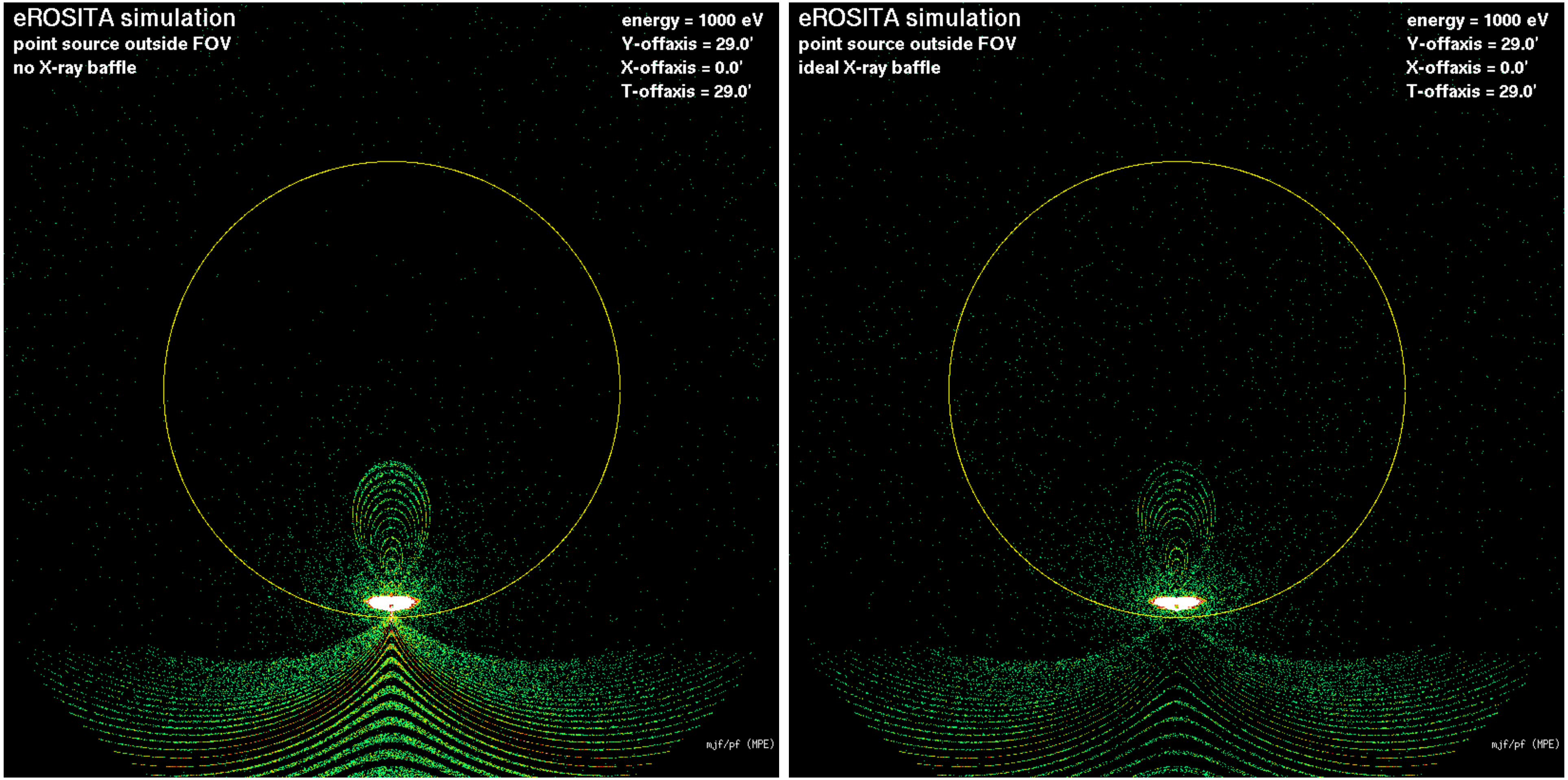
no baffle, no pile-up: bright source off-axis: 40 arcmin (left), 50 arcmin (right)

eROSITA simulations: out-of-FOV PSF (P.Friedrich + MF)

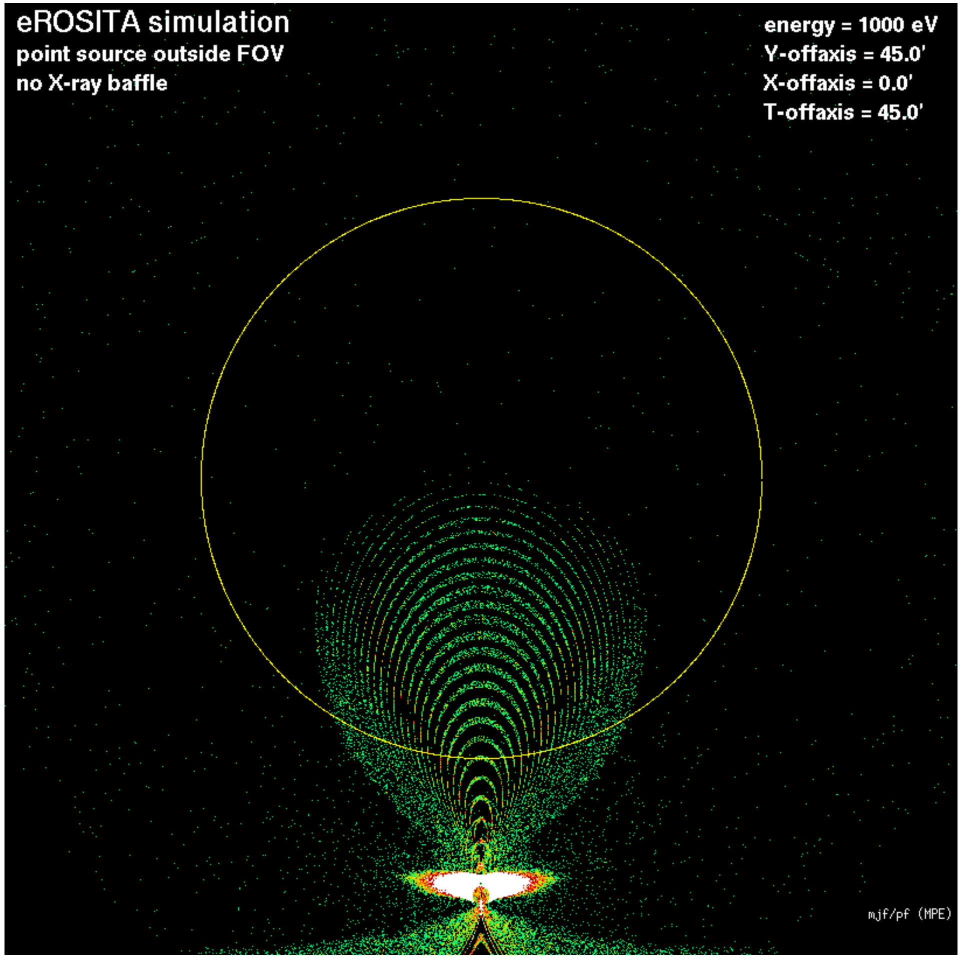


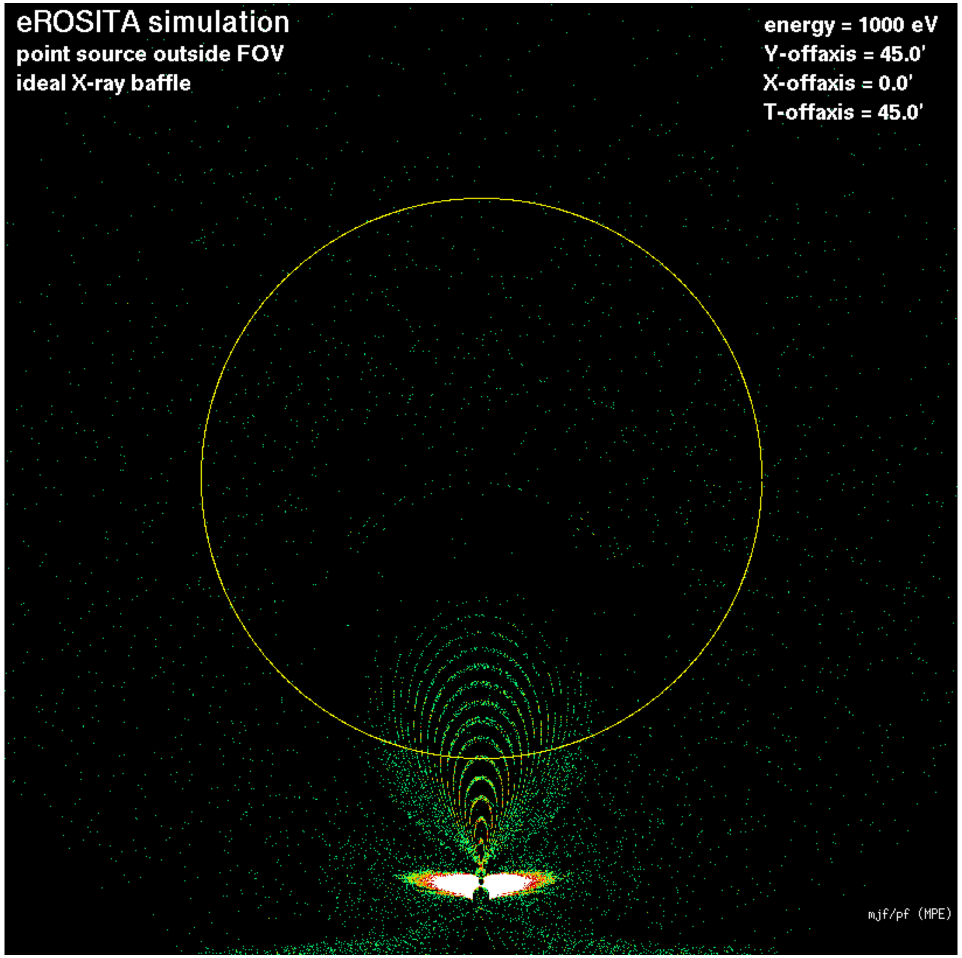
no baffle, no pile-up: bright source off-axis: 55 arcmin (left), 60 arcmin (right)

eROSITA simulations: out-of-FOV PSF (P.Friedrich + MF)

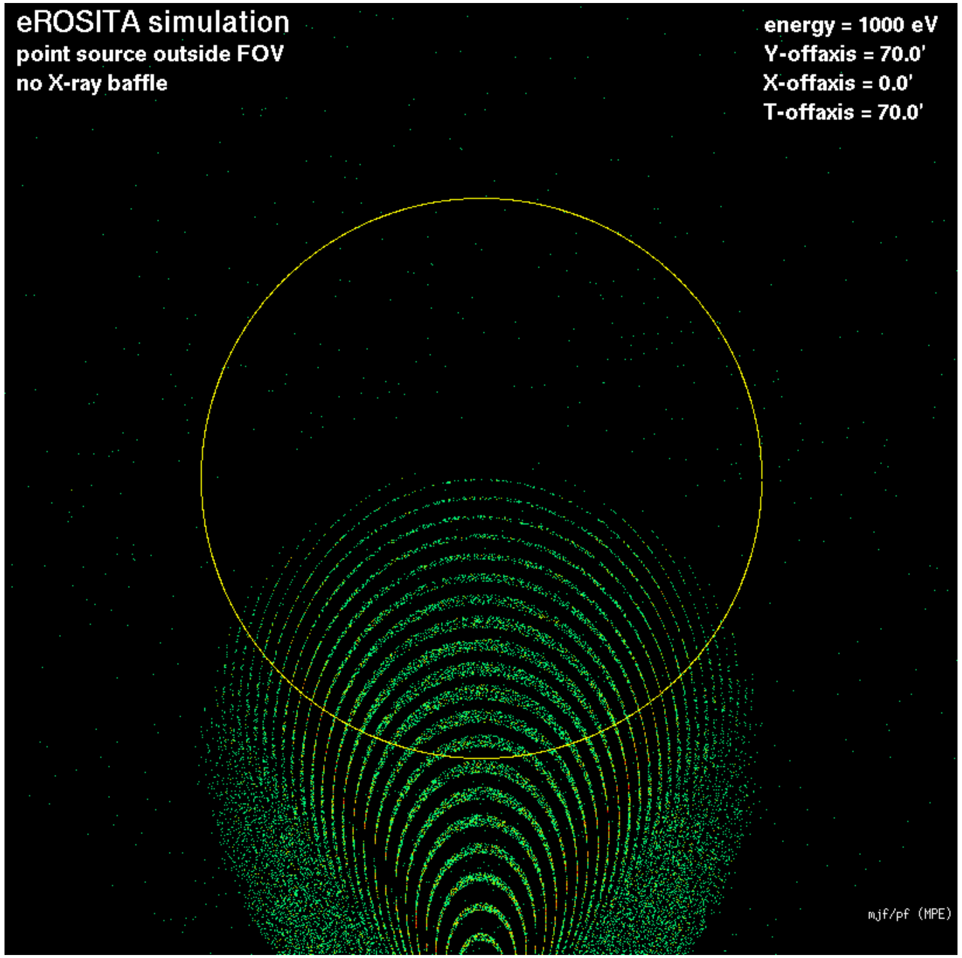


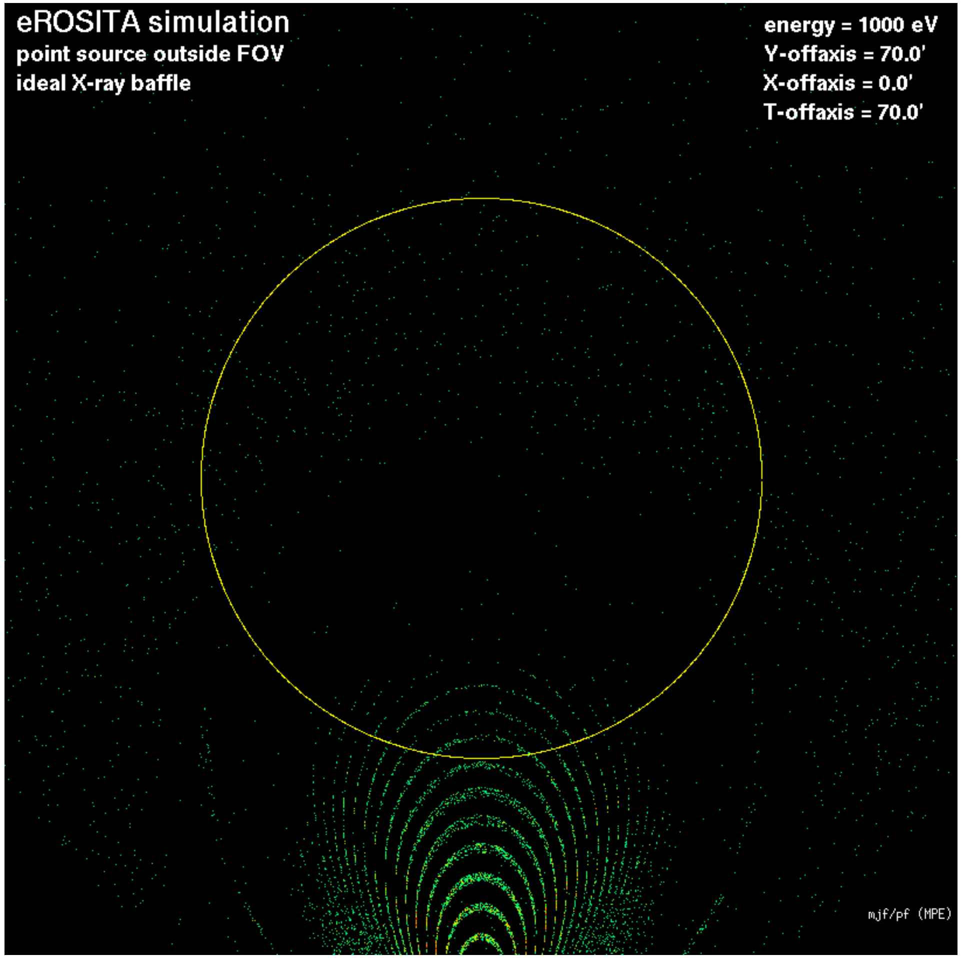
eROSITA simulations: out-of-FOV PSF (P.Friedrich + MF)



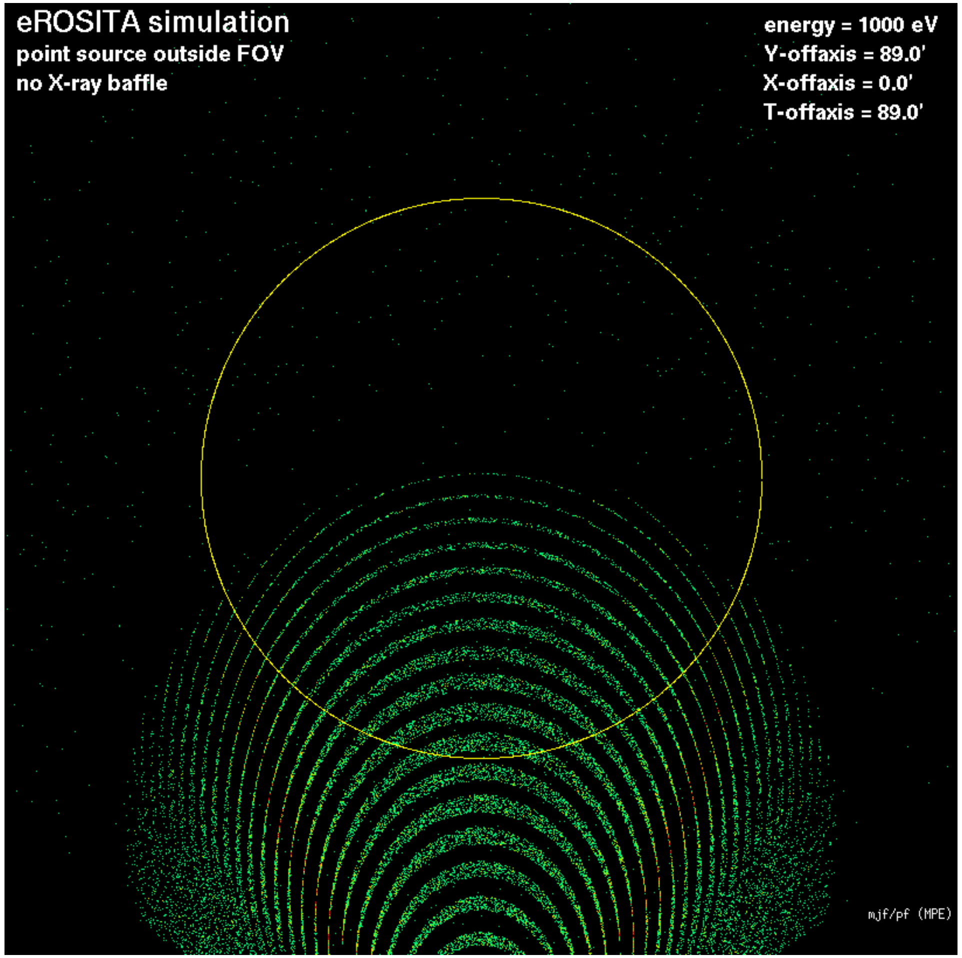


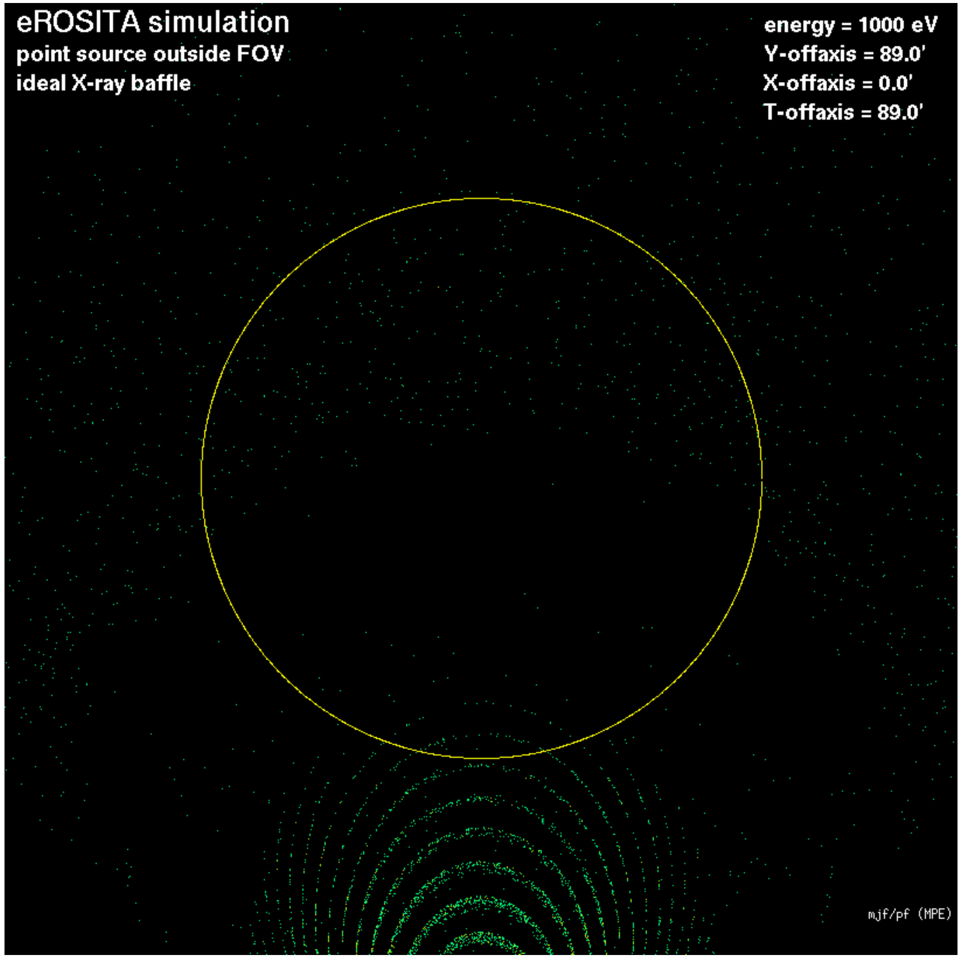
eROSITA simulations: out-of-FOV PSF (P.Friedrich + MF)





eROSITA simulations: out-of-FOV PSF (P.Friedrich + MF)





Commissioning: 4wk

- During/after commissioning of camera:
  closed, calclosed, low-gain closed, low-gain open, "open" (i.e., filter): "Comm. Light"
- Why as soon as possible: immediate quicklook of :
  background (soft protons !)
  filter integrity, optical loading,
  mirror module health, PSF,
  baffle performance, single-reflections, bore-sight, ...
- helps to optimize set-up for following "open" (filter) scientific CalPV observations
  (save weeks of time to possibly adapt on-board software, but also eSASS)
- Preferred target: LMC: 30 Dor region / SN1987A (observable at any time)
- Details TBD: what shall be observed during commissioning of other cameras?
  all the time "Comm. Light", same or different position ?
  follow ART-XC and return to "Comm. Light" with next camera ??
- Commissioning phase determines and fixes set-up for CalPV (and survey) phase

Background: 1d

- During/after commissioning of all cameras:
  defined mixture of cameras with closed and (open) filter, high and low gain (TBC)
- as predefined set of commands (macro)
- similar to calibration source: one after another CLOSED filter during survey
- joint SRG background study for L2: eROSITA + ART-XC

Clusters of galaxies: 2d

- Are more subject of cross-calibration with other missions
  than actual eROSITA calibration (scientific like cluster T, not gain/CTI)
- eROSITA advantage: no chip gaps, large FOV!
- Preferred targets (1 low-T, 1 high-T): IACHEC recommendation
  A1795, A2029 (Coma (center to be defined), A1835, A2052, A2199)
- work to be expected, e.g.: derive T for eROSITA
  (7 temperatures should be the same within errors), XMM, Chandra
  determine differences and re-iterate (effective area, vignetting, EEF, RMF),...
  contribute to calibration parameters

In-orbit Calibration Plan (see CalPlan document)

- **Commissioning**

Target name	RA (2000)	Dec (2000)	l (deg)	β (deg)	Remark	Duration (ks)
LMC (30 Dor)	05 38 42.4	−69 01 02	279.37	−86.827	**for each camera**	**40**

- **Filter integrity**

Target name	RA (2000)	Dec (2000)	l (deg)	β (deg)	Remark	Duration (ks)
Omega Cen	13 26 47.2	−47 28 46	309.103	−35.228	**d=10' V=3.7**	**80**
M4 (NGC 6121)	16 23 35.2	−26 31 32	350.974	−4.869	**d=8.5' V=5.6**	**80**
M22 (NGC 6656)	18 36 23.9	−23 54 17	9.893	−0.728	**d=6.5' V=5.1**	**80**
47 Tuc (NGC 104)	00 24 05.6	−72 04 52	305.896	−62.353	**d=6' V=4**	**80**
NGC 6752	19 10 52.1	−59 59 04	336.494	−37.221	**d=3.8' V=5.4**	**80**
M5 (NGC 5904)	15 18 33.2	+02 04 51	3.860	+19.646	**d=3.5' V=5.7**	**80**
M71 (NGC 6838)	19 53 46.4	+18 46 45	56.747	+38.792	**d=3.3' V=8.2**	**80**
M2 (NGC 7089)	21 33 27.0	−00 49 23	55.045	+14.509	**d=2' V=6.5**	**80**
NGC 1261	03 12 16.2	−55 12 58	270.540	−67.273	**d=1.4' V=8.3**	**80**
(total)						**80**

In-orbit Calibration Plan (see CalPlan document)

Target name	RA (2000)	Dec (2000)	l (deg)	β (deg)	Remark	Duration (ks)
NGC 2516	07 58 20.0	−60 52 13	273.940	−75.890	**mosaic** $\pm 25'$	4×20
Hyades	04 31 60.0	+18 10 00	178.972	−3.691	**mosaic** $\pm 25'$	4×20
Pleiades	03 47 00.0	+24 07 00	166.572	+4.086	**mosaic** $\pm 25'$	4×20
NGC 6475	17 53 30.0	−34 49 12	355.802	−11.388	**mosaic** $\pm 25'$	4×20
NGC 752	01 57 41.0	+37 47 06	137.126	+24.061	**mosaic** $\pm 25'$	4×20
(Cal I)						**80**
(Cal II)						**80**
(survey)						**80**

Observe one field with all 7 cameras simultaneously, in 4 positions (square with length 25'). Coordination with ART-XC could be checked (would however require different targets)

Run (full) pipeline. Perform source detection for each camera separately. Identify the detected sources by position correlation with other source catalogues. Determine the centers of the FOVs and relative pointing offsets for each camera, and update the corresponding calibration file entries.

Determine the plate scale for each camera (and update the corresponding calibration file entries). For the brightest point sources also a PSF analysis (as function of off-axis angle) shall be performed.

Filter integrity (launch and micrometeorites): 1d

- objects with extended optical emission
- Preferred targets: the more extended the better:
  Omega Cen (NGC 5139) (M4 (NGC 6121), M22 (NGC 6656), 47 Tuc,
  NGC 6752, M5, M71, M2, M15, NGC 1261)

Boresight (and plate scale) of the 7 modules: 2d + 1d + 1d

- 2 star trackers attached to eROSITA, 1 to ART-XC
- Fields with many sources with well-known positions
- Preferred targets (repeat once in CalPV + after 1/2 yr):
  NGC 2516 (Hyades, Pleiades, NGC 6475, NGC 7520)

Gain and CTI: 4d

- line positions and line widths
- Preferred targets:
  1ES 0102-72 (repeat every 6 months !),
  Vela SNR, 3C 58 (Puppis-A, SNR G021.5-00.9, LHA 120-N 132D)
- in addition: CalClosed (Fe-55): cameras one by one (also during survey)

Soft X-ray response and contamination monitoring: 2d + 1d

- Verify filter transmission in soft X-rays, constant source, time dependent
- Preferred targets: Isolated neutron stars (Magnificent Seven):
  1RXS J185635.1−375433, 1RXS J080623.0−412233, 1RXS J160518.8+324907, 1RXS J130848.6+212708,
  1RXS J042003.1−502300, 1RXS J214303.7+065419,
  1RXS J072025.1−312554;
  repeat the one selected target every 6 months !

XUV response and contamination monitoring: 1d

- White dwarfs, supersoft sources, counts below lower threshold:
- Preferred targets:
  HZ 43, GD 153, PG 1658+441, PG 0136+251, ...

Power-law type spectrum: 1d

- Preferred targets (one or two): 1ES 1553+11.3, Mkn 3,
  PKS 0558−304, MS0419.3+1943, MS0317.0+1834, MS0737.9+7441, ...
  (pile-up: 3C 273, PKS 2155−304, Mkn 421)

Effective area, vignetting, flatfield: 4d

- Preferred targets: supernova remnants, clusters of galaxies
- Out-of-focus not possible in-orbit (to avoid pile-up)

PSF (core and wings): 7d

- Use ground calibration and few verification observations:
- Preferred targets: point-like 3XMM 3-10 cts/s (pile-up limit!)
- Actual PSF in-orbit calibration: stacked data from first all-sky survey
- Use point-like sources from first eROSITA catalog

Stars (optical loading): 1d

- Bright optical stars will move through FOV during survey
- will shift X-ray energies and cause spurious events
- Calibrate effect by observing bright optical X-ray dark stars
- Preferred targets: single A-type stars (ROSAT non-detections)
- Procedure: offset map calculation + short exposure)

General Schedule: start of commissioning:

- **Main question: when will Spectrum-Roentgen-Gamma be ready such that eROSITA can start its schedule ?**
- **Power to prevent from excessive cooling**
- **SRG orbit correction maneuvers (after about 10d, 20d, 30d): propellant may cause contamination (telescope door ? ART-XC ?)**
- **Open telescope cover for outgassing of mirror system**
- **Open filter wheels for outgassing of cameras**
- **Check-out of electronics**
- **Open valve to cool cameras (irreversible !)**

Performance Verification vs. Calibration: 21d

- **visibility of certain targets during Cal-PV: depends on launch date + successful commissioning + ART-XC + ...**
- **full calibration may not be available at the time of PV observation**
- **PV requires Cal, but can in turn also improve in-flight Cal (e.g., PSF)**

In-orbit calibration subjects

- Commissioning
- Background (graded shield, calibration and monitoring, "Closed", etc.)

- Plate scale and boresight of the 7 modules (star-trackers vs. mirror assembly)
- Filter integrity (launch, micrometeorites)
- Soft X-ray response and contamination monitoring
- Gain and CTI (calibration and monitoring, "CalClosed" Fe-55)
- PSF (on-axis, off-axis, survey)
- Power-law type spectrum (cross-calibration)
- Effective area, flat-fielding, and vignetting
- Optical loading by point sources
- X-ray baffle (mosaic, mini-survey in great circles)
- Absolute and relative timing (and operational tests like "mini-survey" in great circles for time-delays between star tracker and X-ray cameras, attitude reconstruction)
- XUV response and contamination monitoring
- Masked mode, etc.

- Performance verification / "early science" (interleaved with calibration observations)