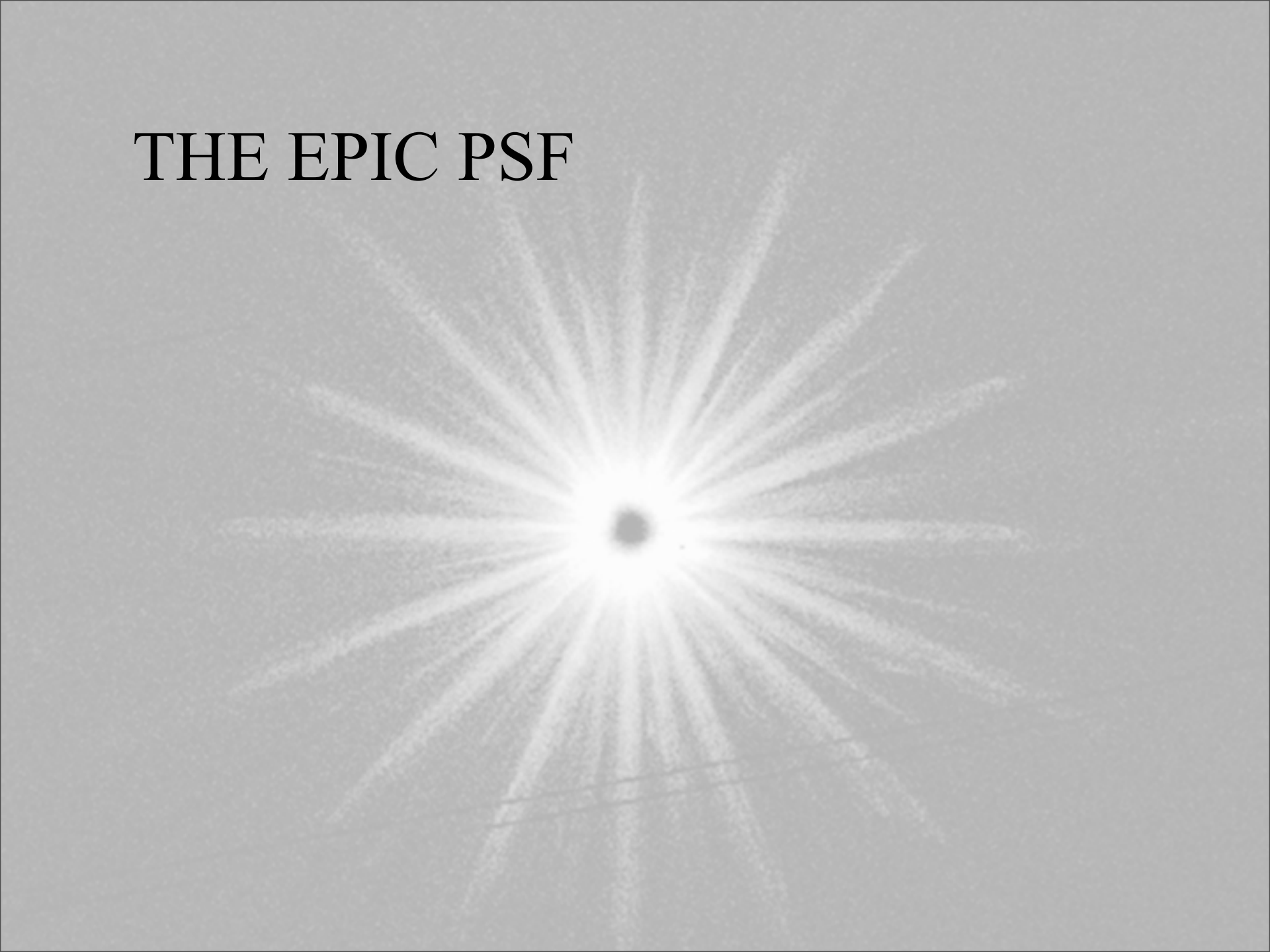
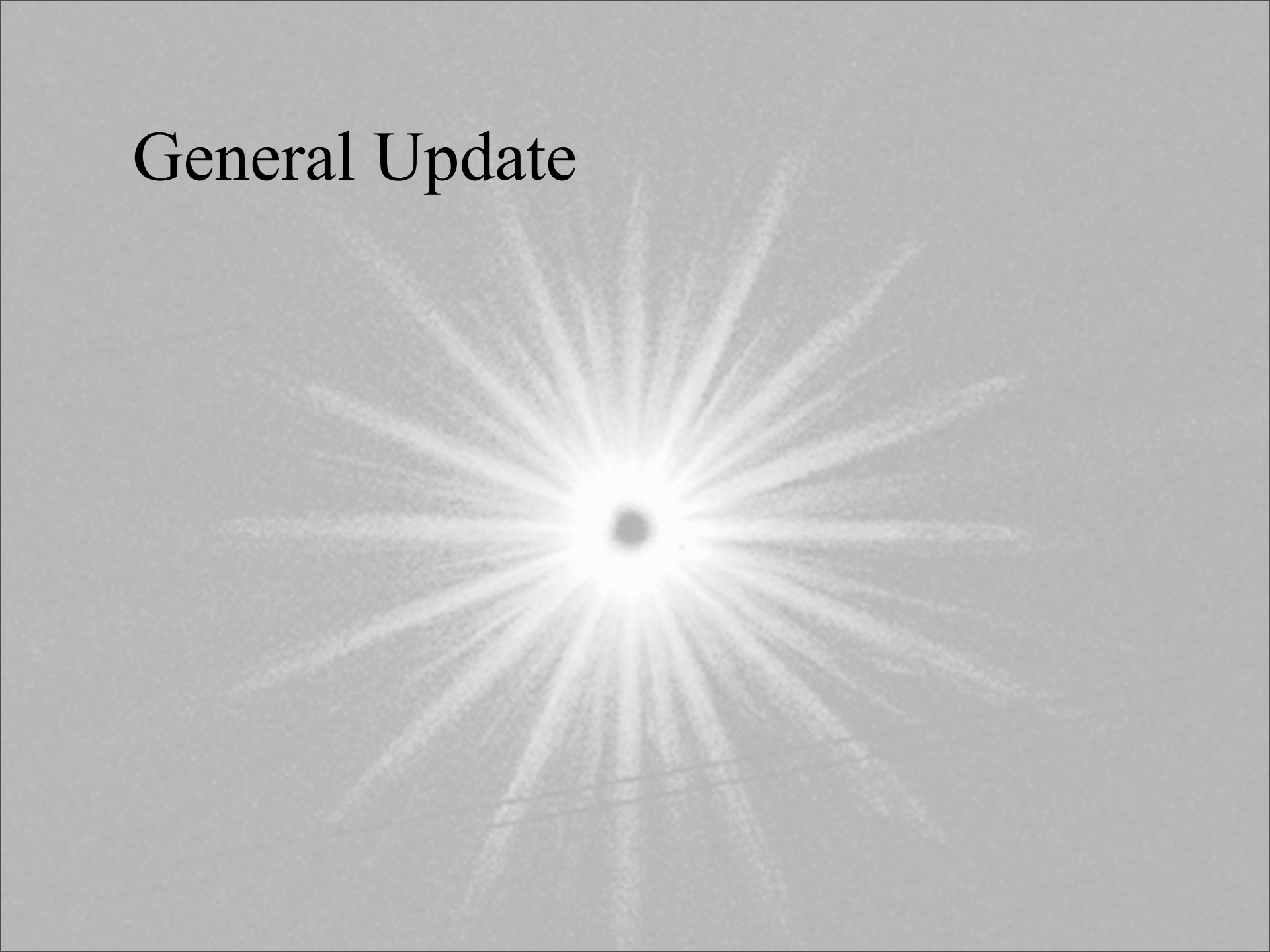
THE EPIC PSF



General Update



A&A 534, A34 (2011)
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Astronomy & Astrophysics

A new comprehensive 2D model of the point spread functions of the *XMM-Newton* EPIC telescopes: spurious source suppression and improved positional accuracy

A. M. Read[1], S. R. Rosen[1], R. D. Saxton[2], and J. Ramirez[3]

[1] Dept. of Physics and Astronomy, Leicester University, Leicester LE1 7RH, UK
e-mail: amr30@star.le.ac.uk
[2] XMM SOC, ESAC, Apartado 78, 28691 Villanueva de la Cañada, Madrid, Spain
[3] Leibniz-Institut für Astrophysik Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany

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ABSTRACT

Aims. We describe here a new full 2D parameterization of the PSFs of the three *XMM-Newton* EPIC telescopes as a function of instrument, energy, off-axis angle and azimuthal angle, covering the whole field-of-view (FoV) of the three EPIC detectors. It models the general PSF envelopes, the primary and secondary spokes, their radial dependencies, and the large-scale azimuthal variations.
Methods. This PSF model has been constructed via the stacking and centering of a large number of bright, but not significantly piled-up point sources from the full FoV of each EPIC detector, and azimuthally filtering the resultant PSF envelopes to form the spoke structures and the gross azimuthal shapes observed.
Results. This PSF model is available for use within the *XMM-Newton* science analysis system via the usage of current calibration files XRT*i*_XPSF_0011.CCF and later versions. Initial source-searching tests showed substantial reductions in the numbers of spurious sources being detected in the wings of bright point sources. Furthermore, we have uncovered a systematic error in the previous PSF system, affecting the entire mission to date, whereby returned source RA and Dec values are seen to vary sinusoidally about the true position (amplitude $\approx 0.8''$) with source azimuthal position.
Conclusions. The new PSF system is now available and is seen as a major improvement with regard to the detection of spurious sources. The new PSF also largely removes the discovered astrometry error and is seen to improve the positional accuracy of EPIC. The modular nature of the PSF system allows for further refinements in the future.

Key words. X-rays: general – instrumentation: miscellaneous – telescopes

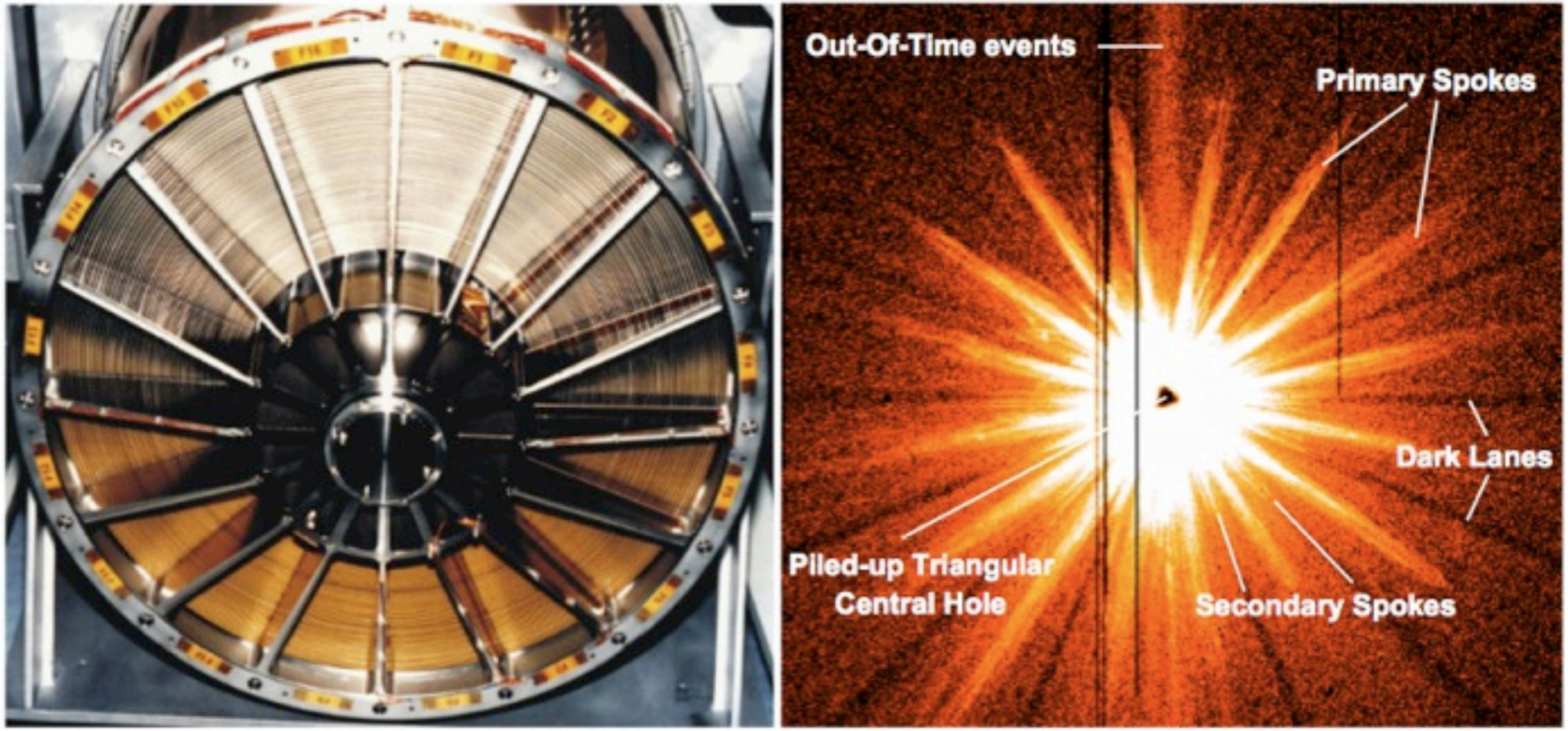


Fig. 2. (*Left*) a front-end view of one of the EPIC mirror modules containing the 58 co-axial mirrors shells, and the spider support structure used to hold the shells. (*Right*) the MOS2 PSF of the severely piled-up source GX 339-4 (ObsID 0204730301, revolution 783), showing the various PSF and other features (see text) – bad columns on the CCD are also visible as dark vertical lines.

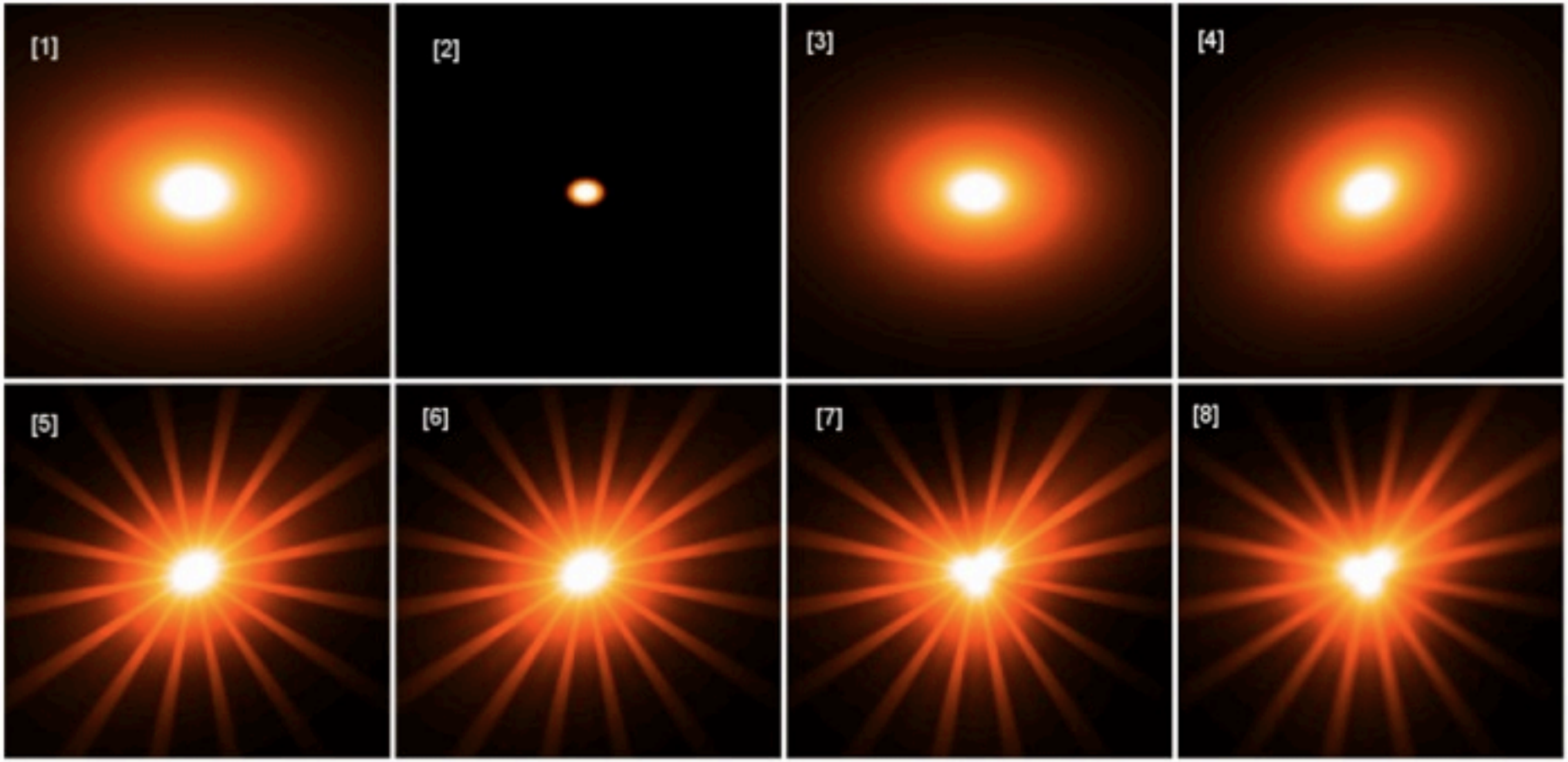


Fig. 6. The eight main steps in the formation of the full 2D PSF for a source in a given instrument, of a given energy and at a given off-axis and azimuthal angle: the King (`beta2d`) component [1] is constructed, then the Gaussian (`gaus2d`) core [2] is constructed, and these are added [3] in the correct ratio (the CCF parameters in steps 1–3 are all functions of instrument, energy and off-axis angle). Then this is rotated [4] according to the azimuthal position of the source on the detector, and only then are the radially-dependent primary [5] and secondary [6] spoke structures azimuthally filtered in, using a flat-topped triangular function. Finally, the large-scale azimuthal modulation (a function of EPIC instrument) is filtered in [7], and the very light radially-dependent smoothing applied [8]. The example shown is for MOS2, at an energy of 1.5 keV, an off-axis angle of 9′, and a source azimuthal position of 30°.

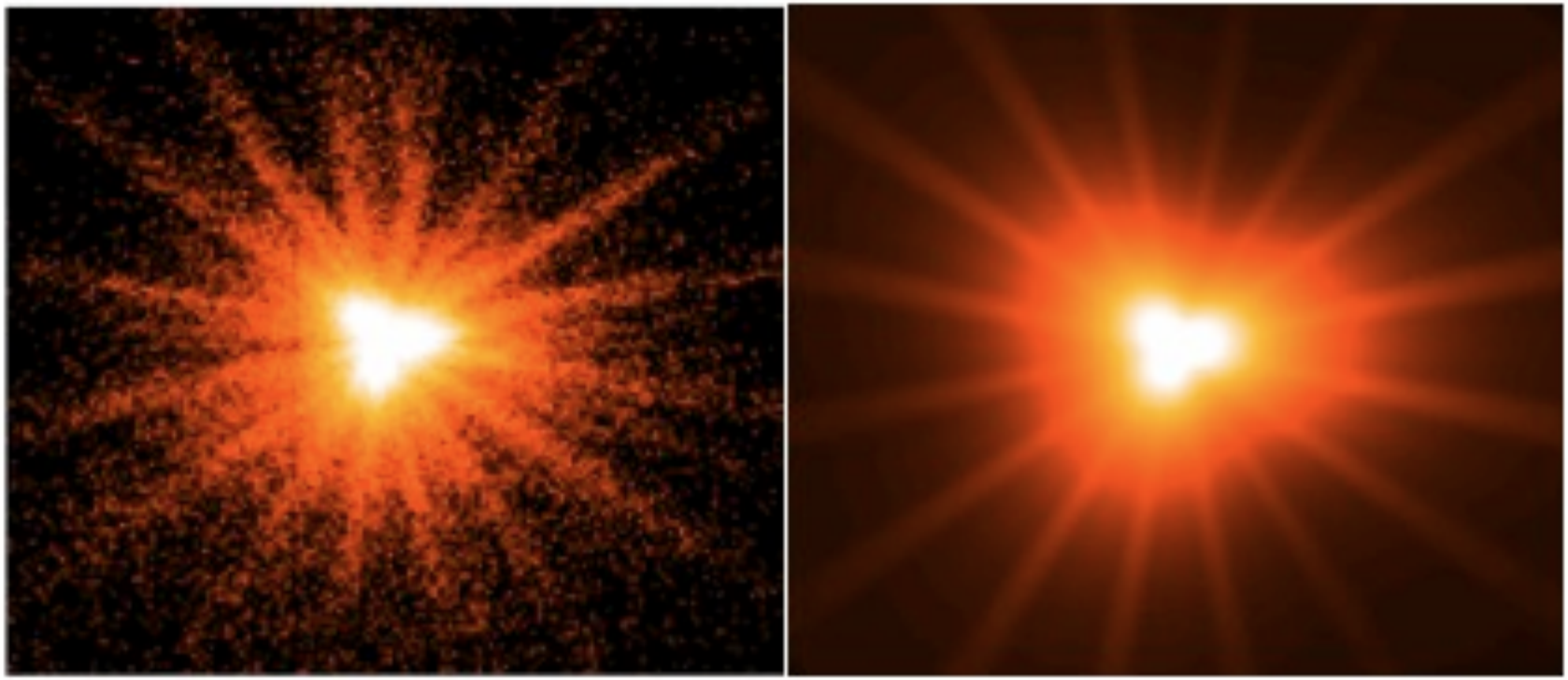


Fig. 7. A very bright, slightly piled-up, ≈4′ off-axis angle MOS2 point source and the equivalent PSF model at a similar off-axis and the appropriate source azimuthal position.

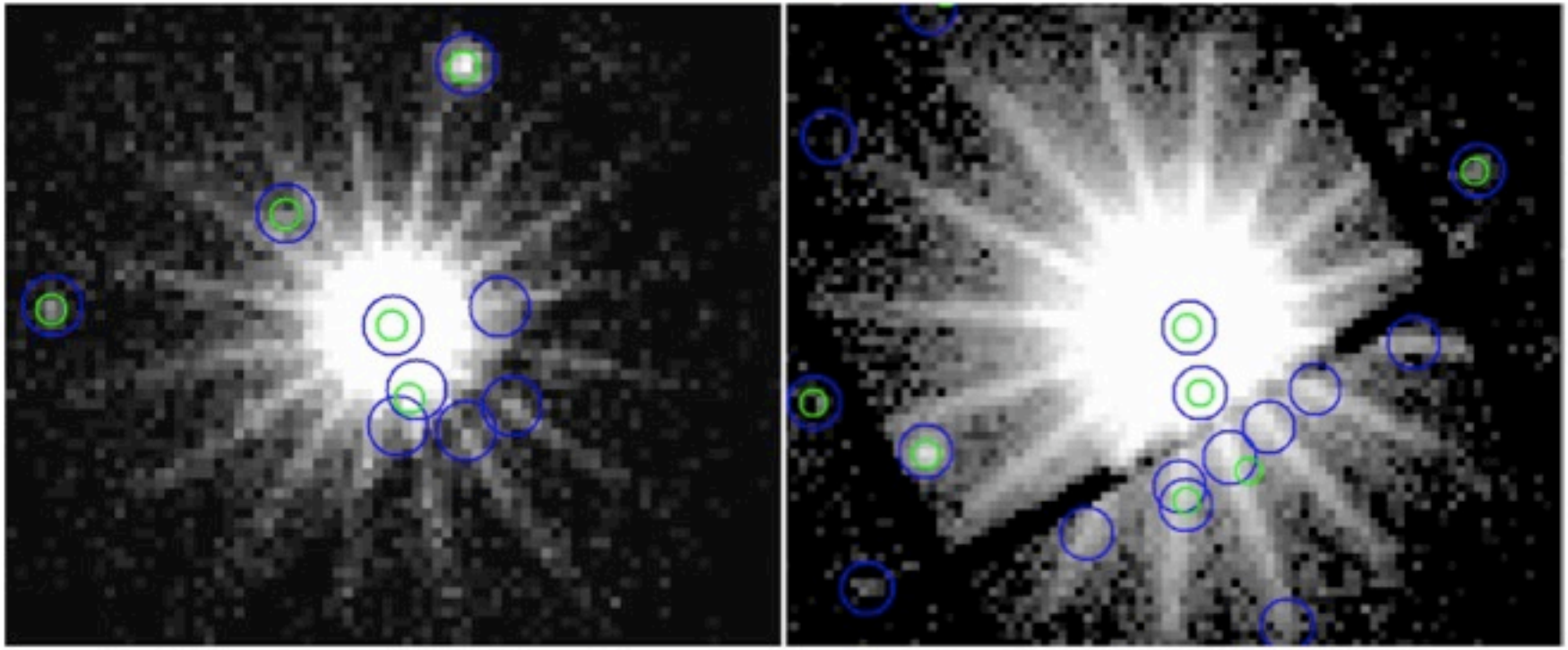
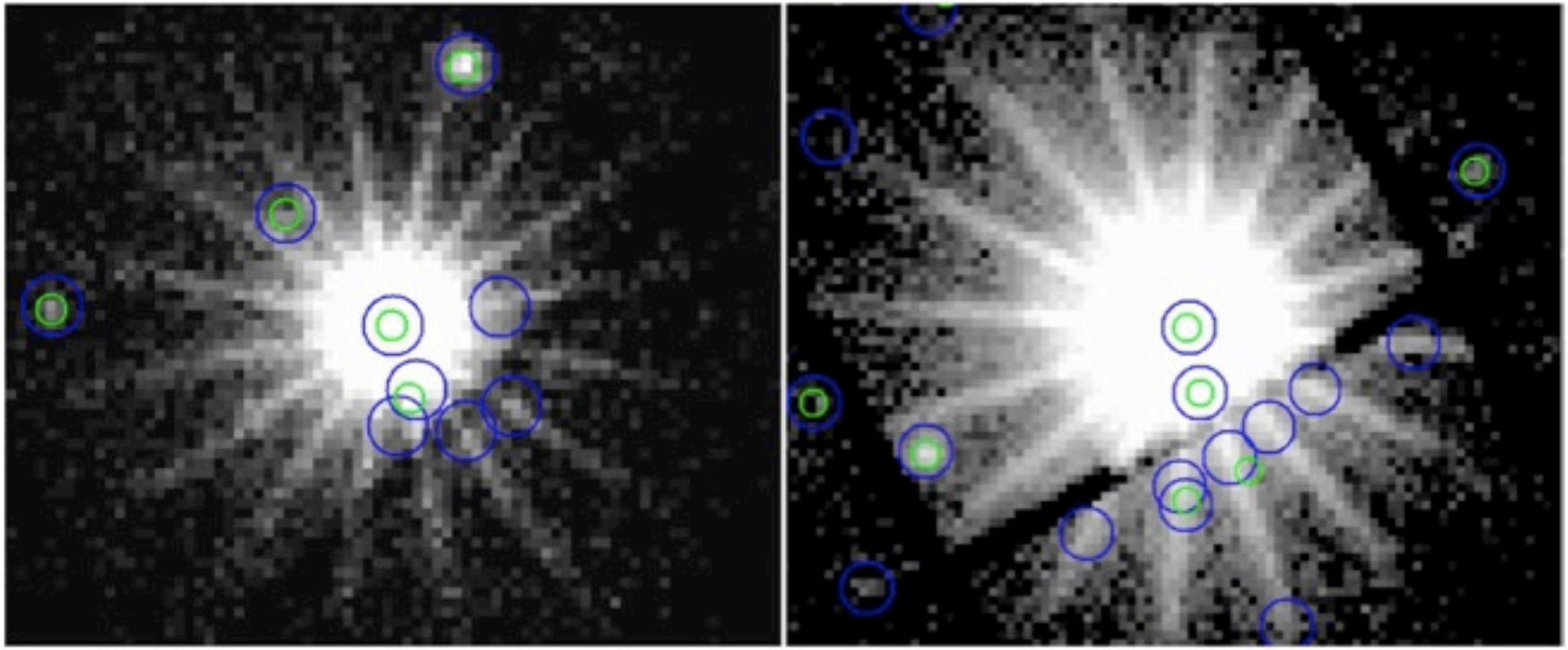


Fig. 9. Example output from a full all-EPIC source-detection analysis of ObsIDs 0107660201 (*left*) and 0302850201 (*right*). The blue circles show the sources detected using the default PSF and the yellow circles show the sources detected using the 2D PSF. Many spurious sources previously detected by the default PSF in the spokes of the central bright source are now not detected by the 2D PSF.



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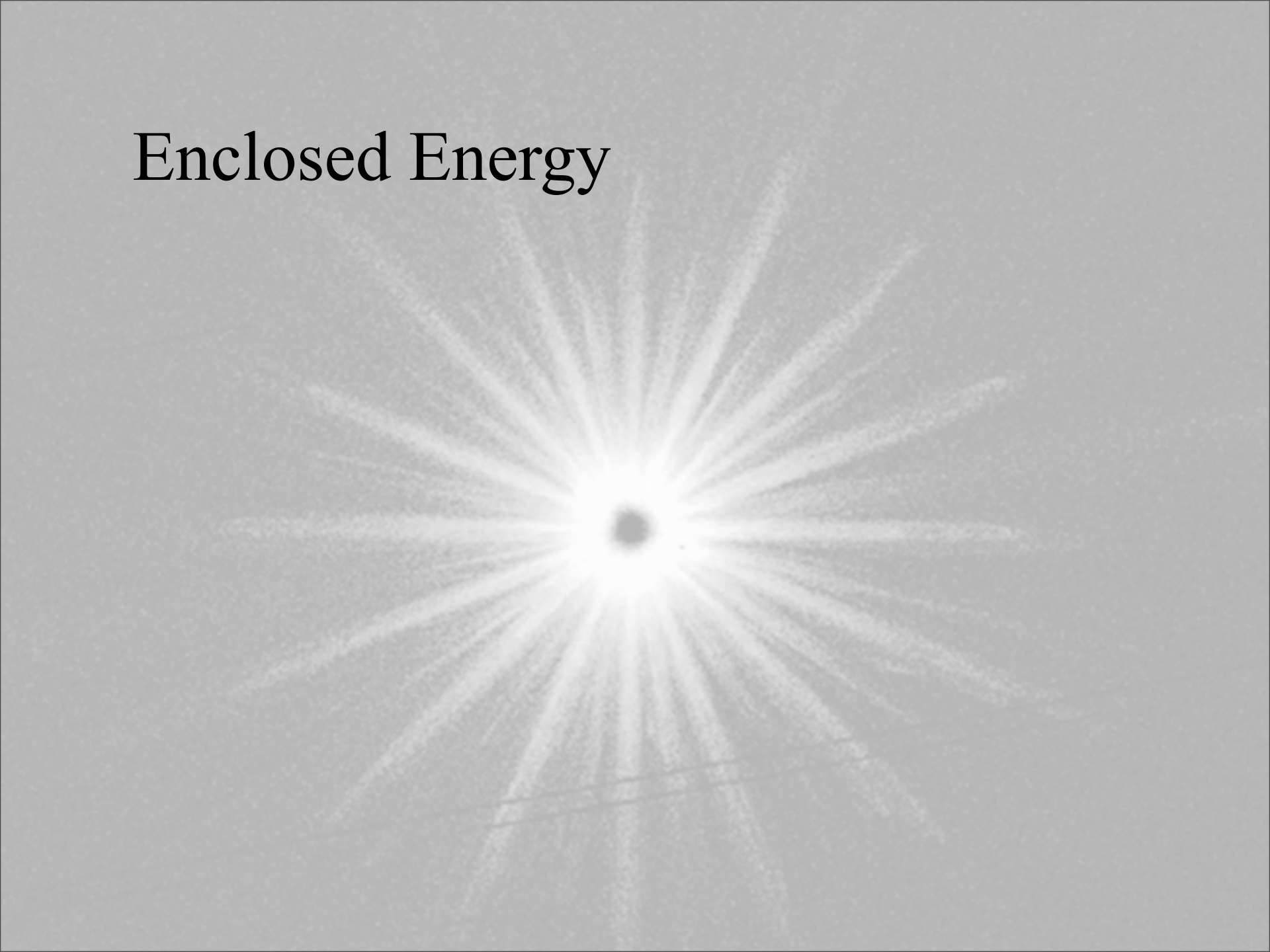
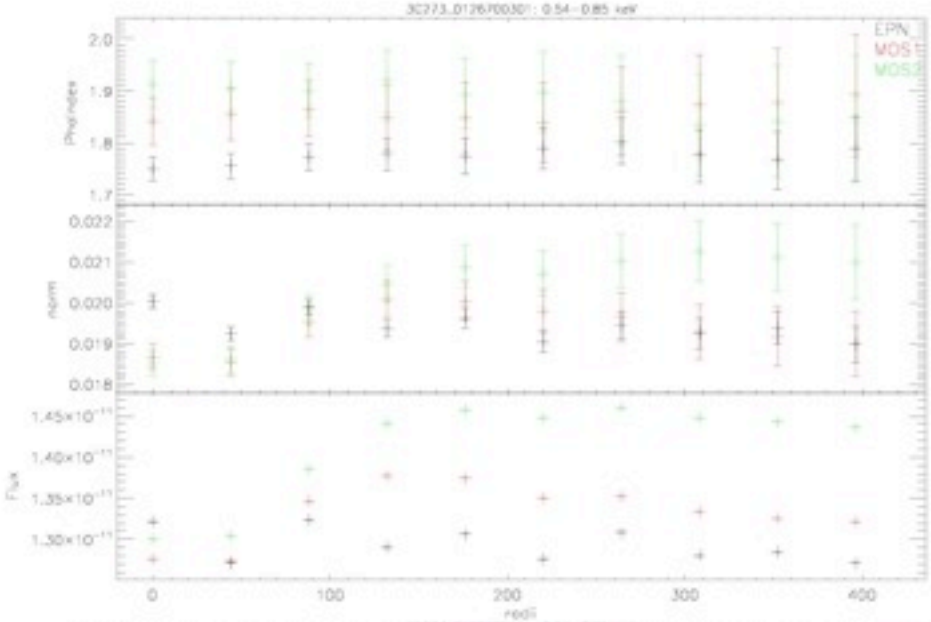
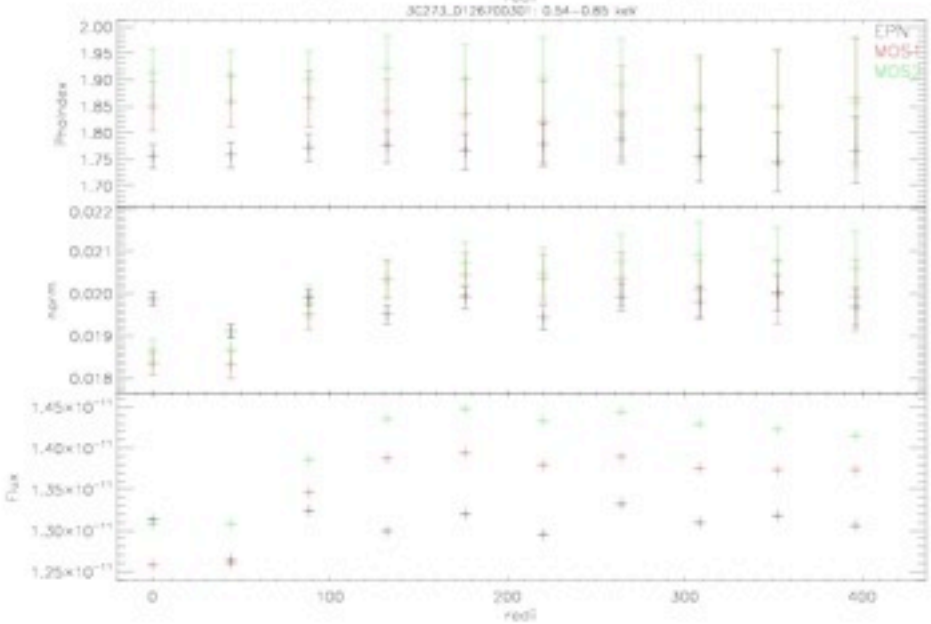
- Better characterization of cores, spokes and polygonal structures
- Reduction of spurious source detections by ~30% around 'problem' sources
- Sensitivity improved – increase in likelihoods (though no 'new' detections… ebox, BG)
- Extensive testing performed – unresolved issues mainly 'non-PSF'…
- In pipeline – non-default at present – intended as default, and to be used for 3XMM

Enclosed Energy




3C273_0126700301: 0.54–0.85 keV
EPN
MOS1
MOS2
Phoindex
Norm
Flux
0
100
200
300
400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EPN
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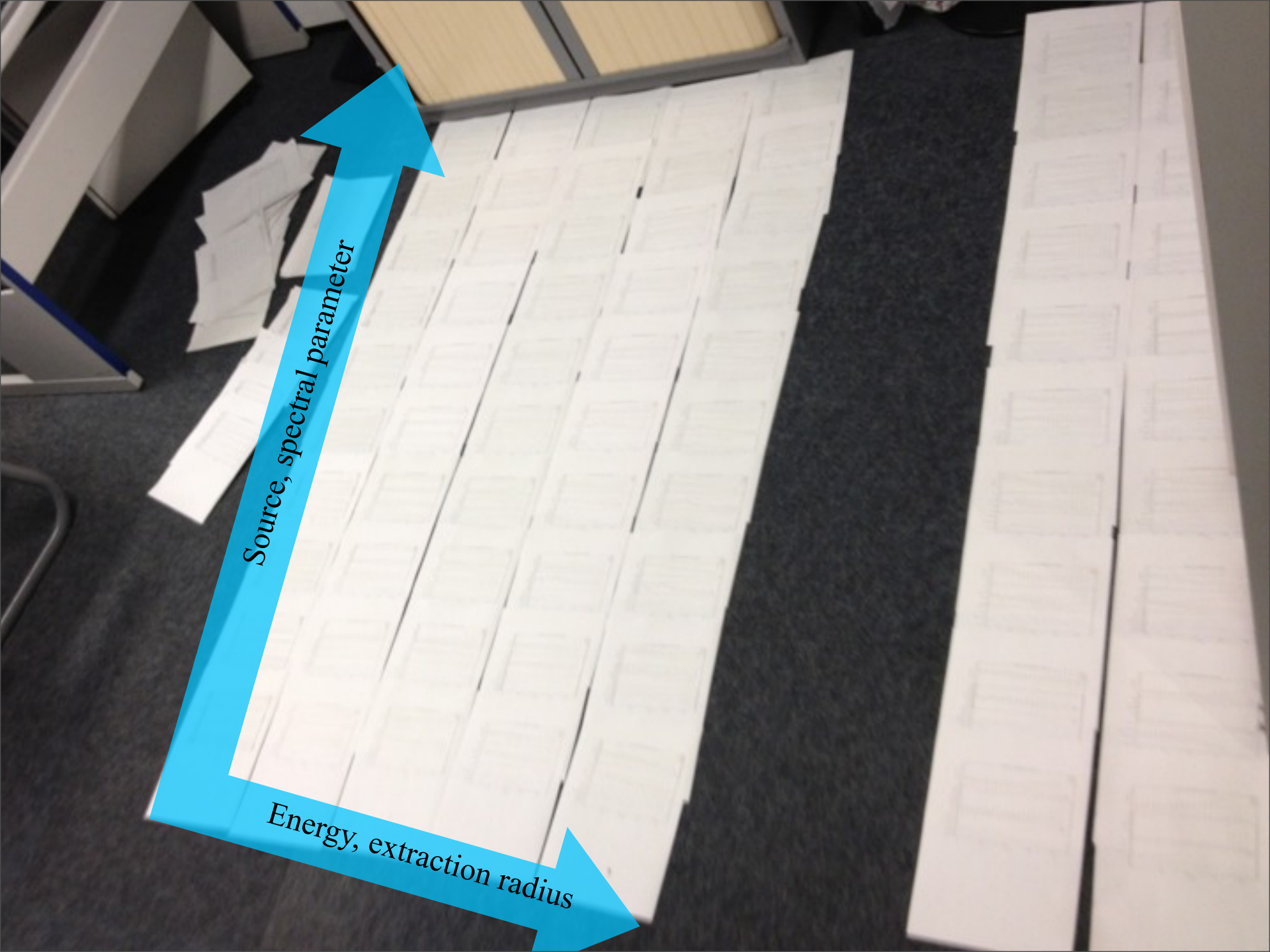
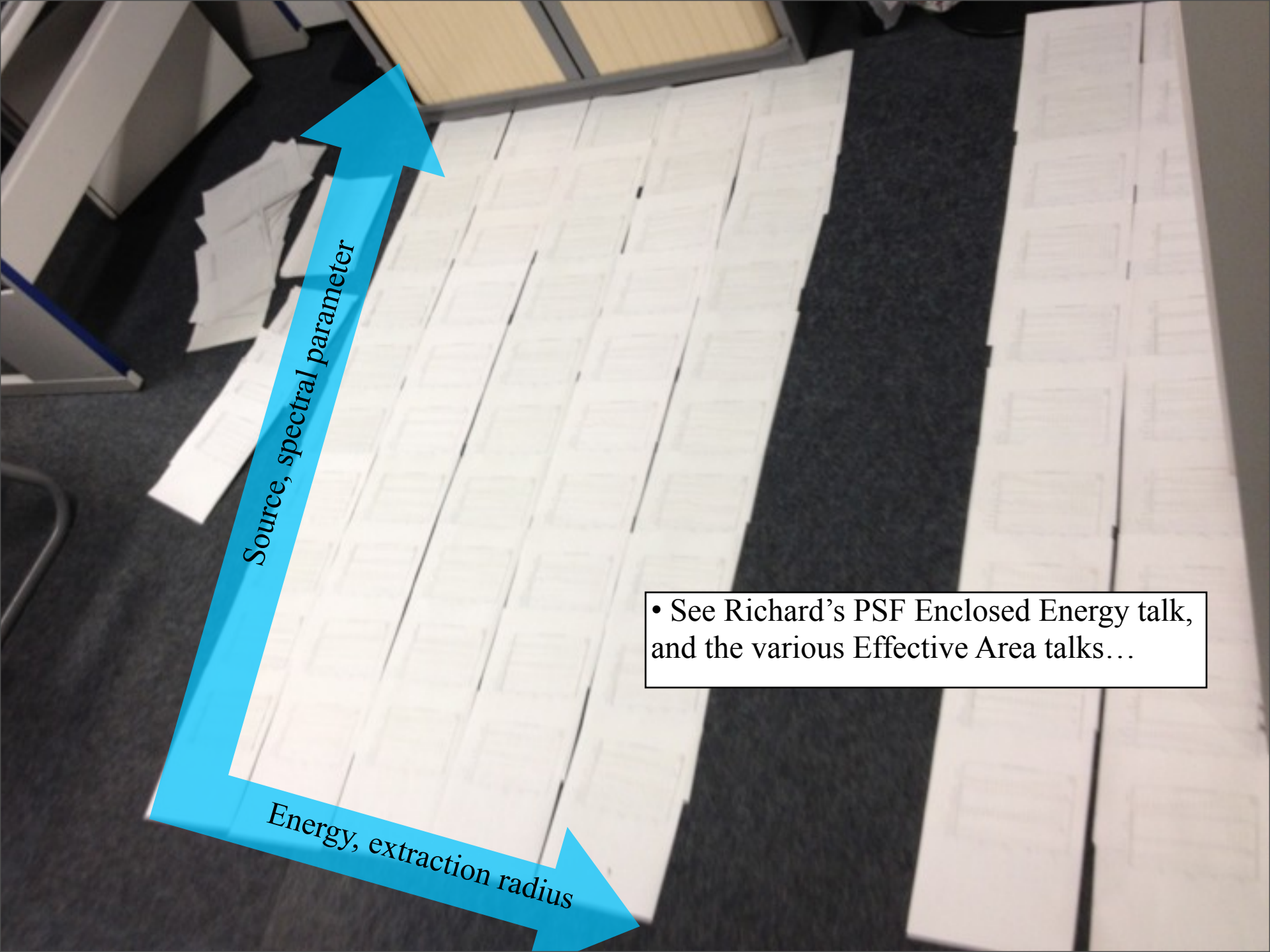
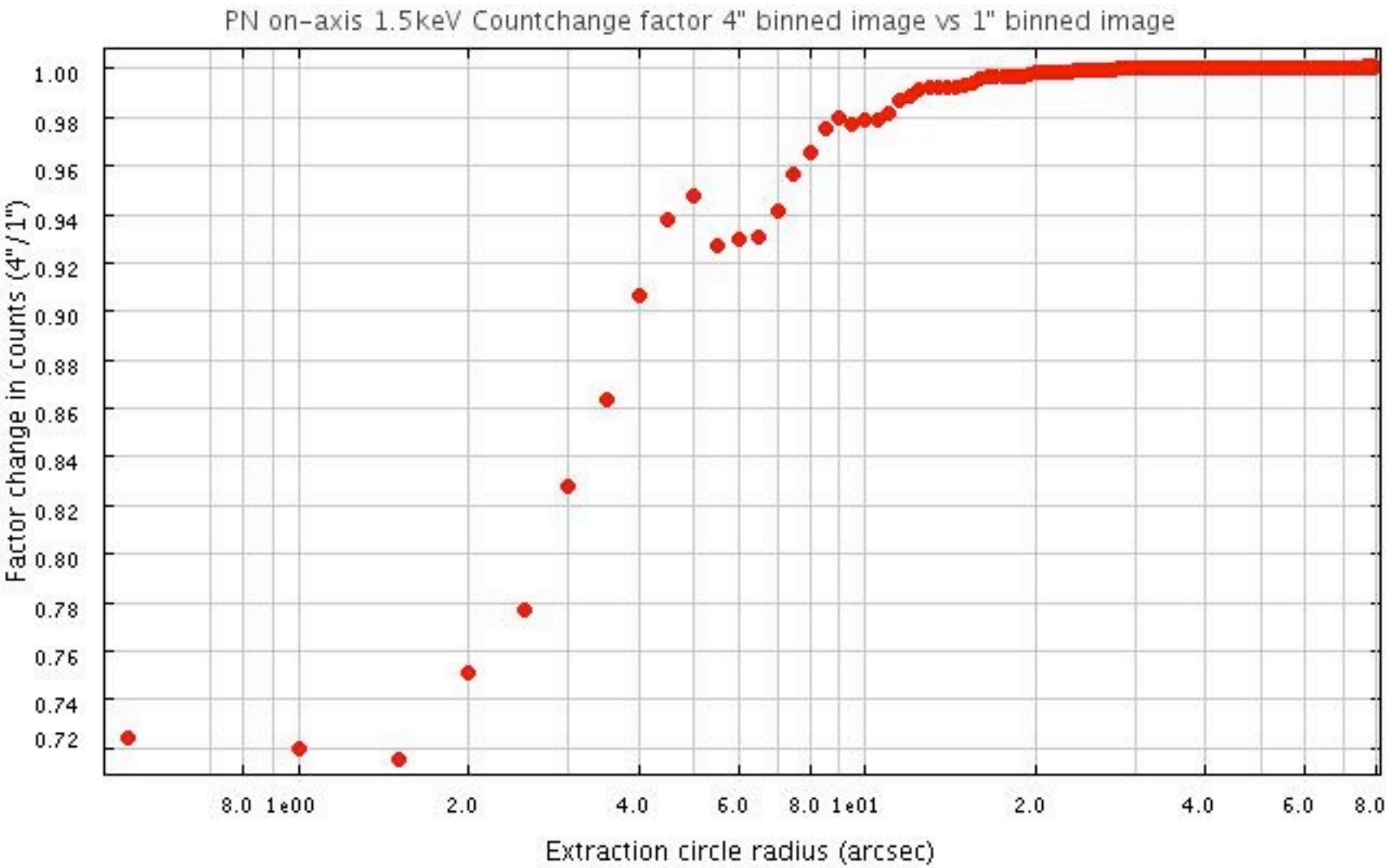
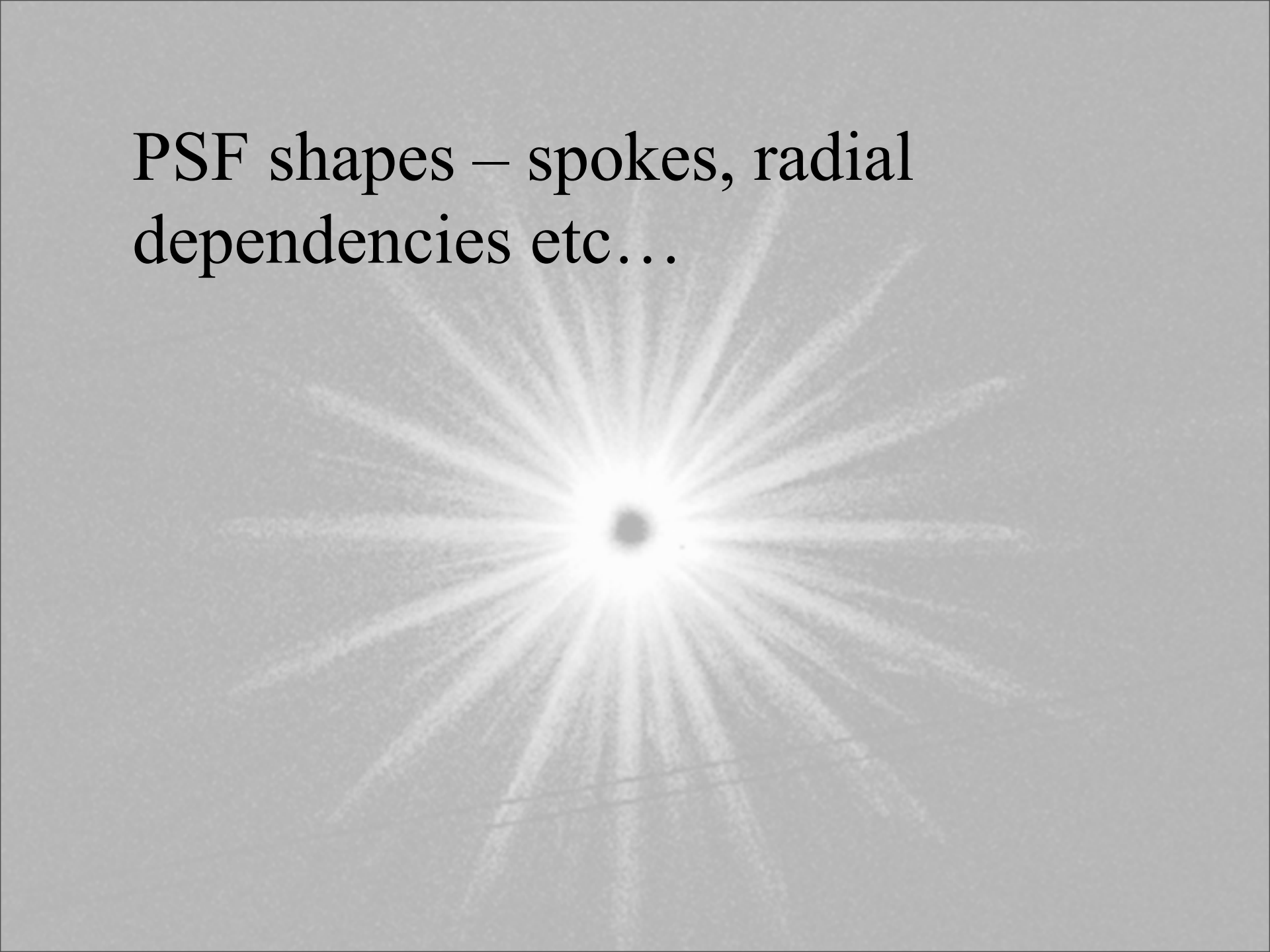

Source, spectral parameter
Energy, extraction radius



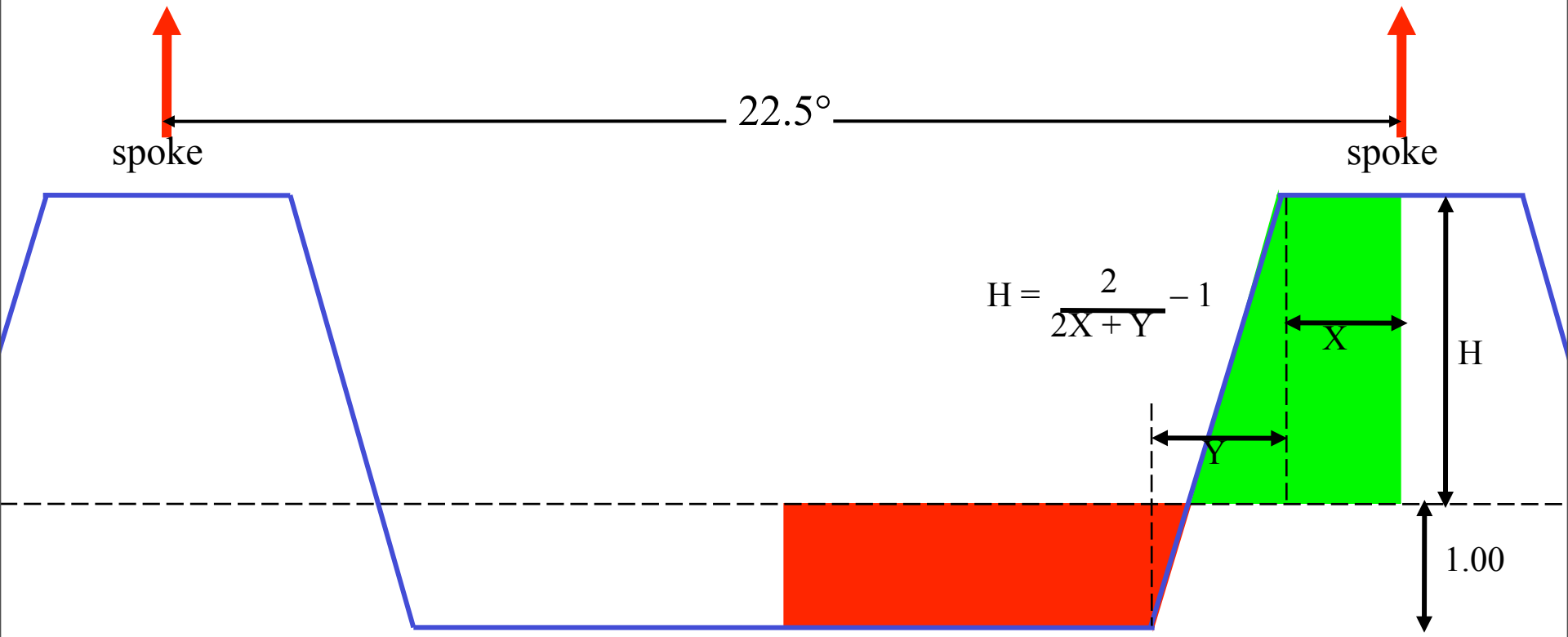
• See Richard's PSF Enclosed Energy talk, and the various Effective Area talks…


PN on-axis 1.5keV Countchange factor 4" binned image vs 1" binned image
Factor change in counts (4"/1")
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
0.84
0.82
0.80
0.78
0.76
0.74
0.72
8.0 1e00
2.0
4.0
6.0
8.0 1e01
2.0
4.0
6.0
8.0
Extraction circle radius (arcsec)

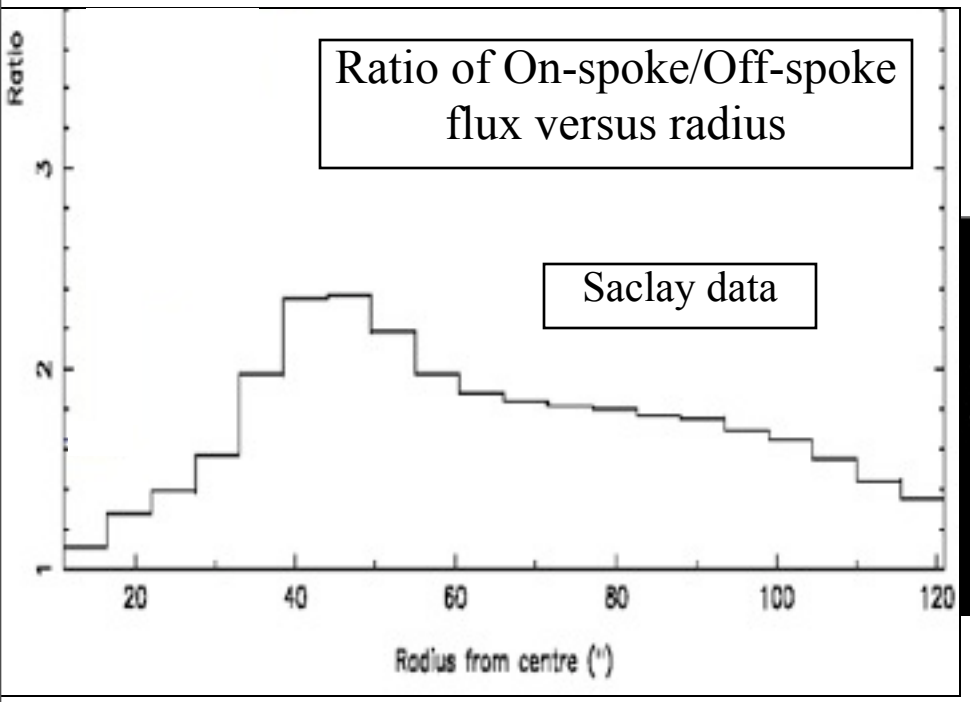
PSF shapes – spokes, radial dependencies etc…



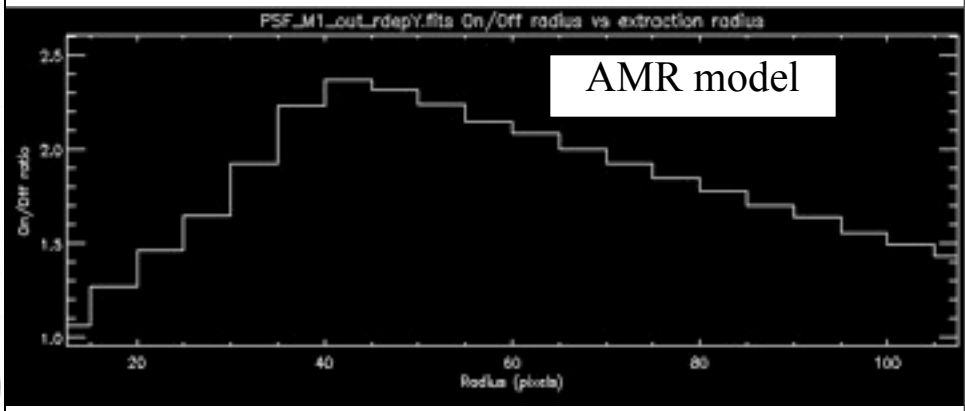
Spokes modelled by a Flat-Topped Triangular Function



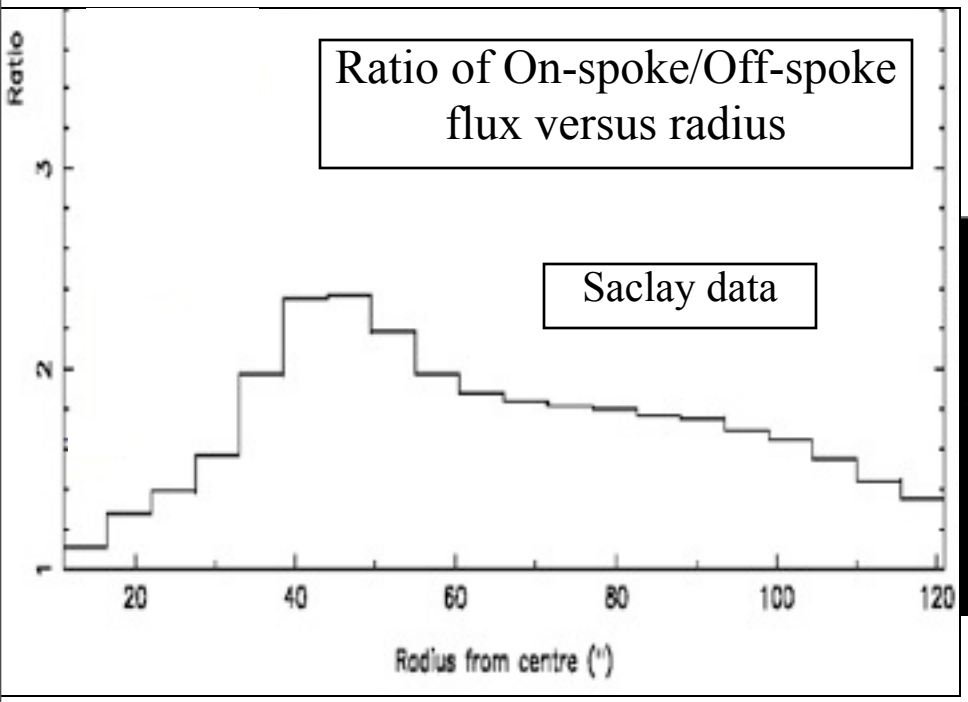
Model OK, but inaccuracy found in variation of effect strength with radius



- Radial dependence of spoking designed to match Saclay MOS work on heavily piled-up sources



- Code incorporated into SAS



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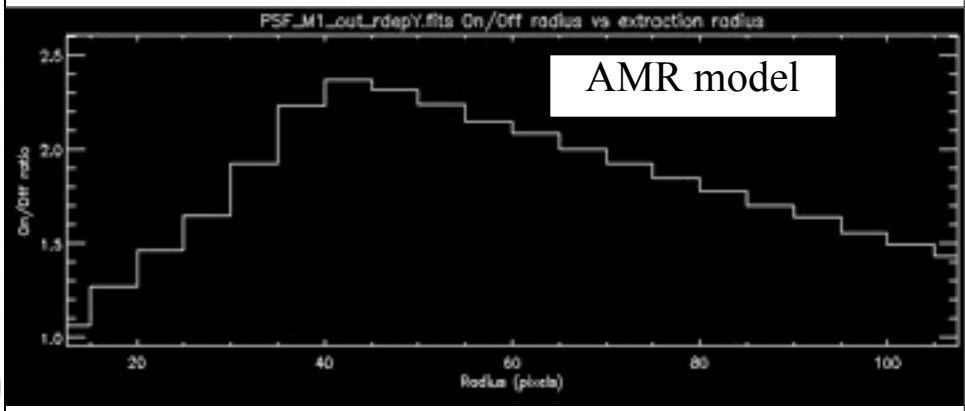
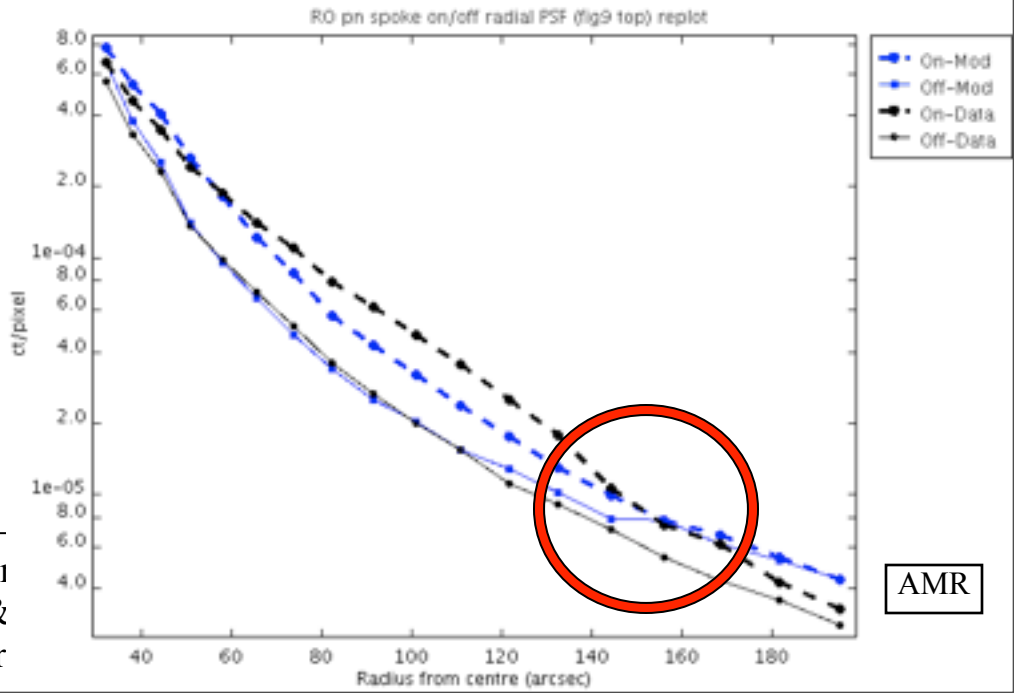


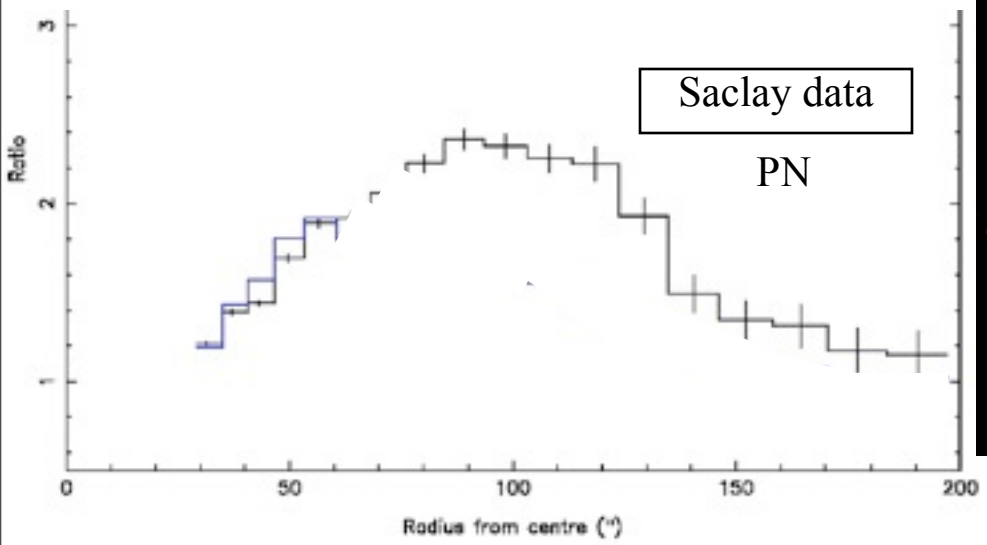
- Code incorporated into SAS

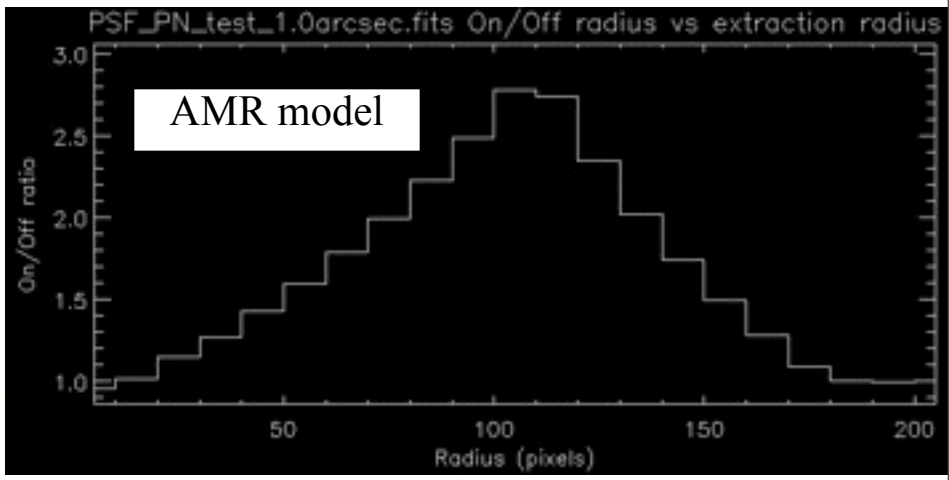
- But, errors found in Saclay work…
- Also their data had been contaminated with a Galactic scattering halo…
- Had to redo…



- Corrected Saclay results quite different from original (surprising…)
- Suggestion of differences between pn and MOS (MOS1 similar to MOS2)
- New model coded and delivered – incorporated into SAS
- Currently modelled to be same for all EPIC
- (R Owen has left Saclay [and astronomy] – currently no testing of SAS/new CCFs at Saclay)

Ratio of On-spoke/Off-spoke flux versus radius





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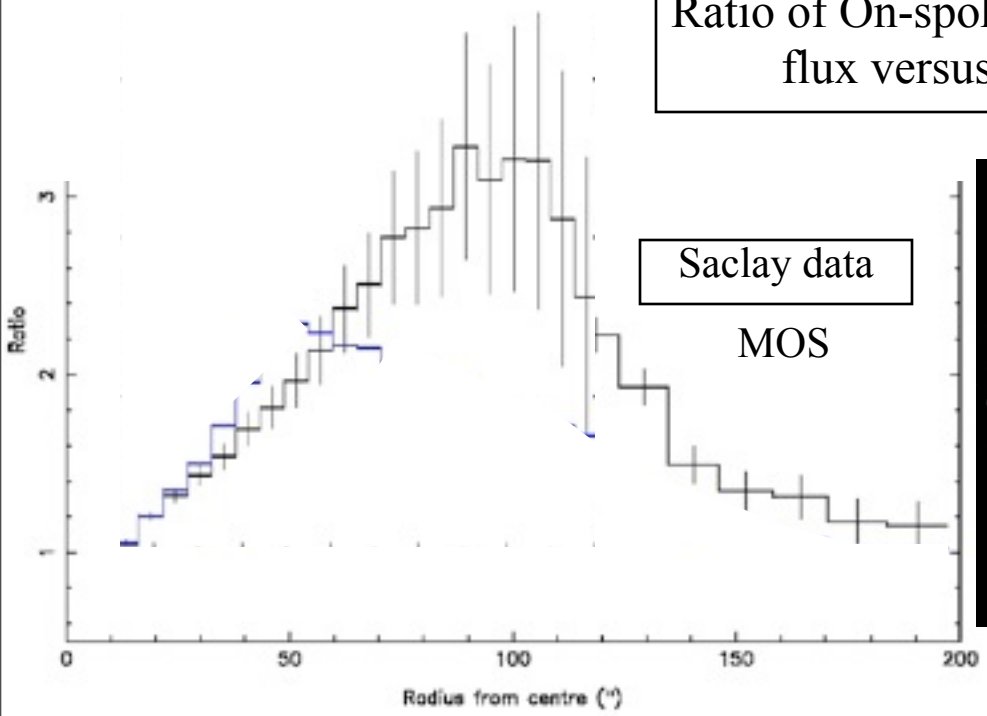
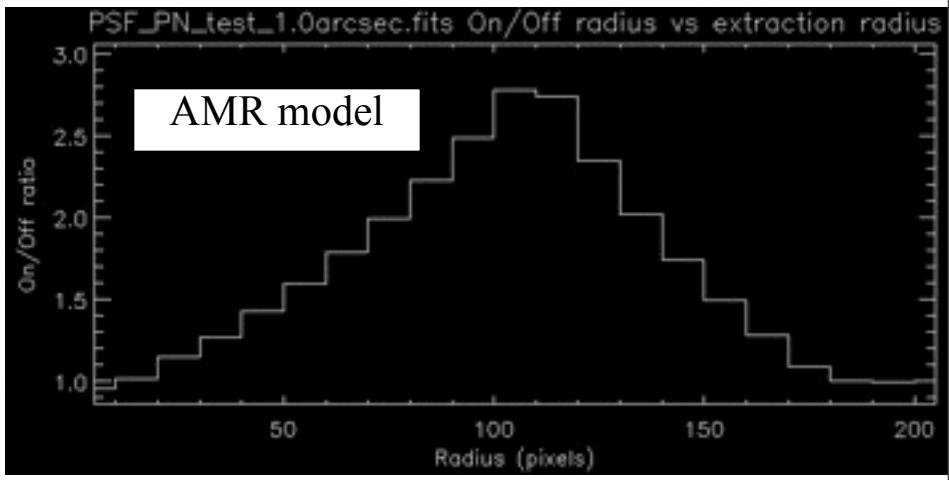




CCF release note to accompany 0013 PSF CCFs (radial dependence of spokes tuned to match the original Saclay work)

XMM-Newton CCF Release Note

XMM-CCF-REL-277

2-D PSF spoke parameterization

A. M. Read & R. Saxton

December 1, 2011

1 CCF components

Name of CCF	VALDATE	List of Blocks changed	Change in CAL HB
XRT1_XPSF_0013.CCF	2000-01-01	ELLBETA_PARAMS	YES
XRT2_XPSF_0013.CCF	2000-01-01	ELLBETA_PARAMS	YES
XRT3_XPSF_0013.CCF	2000-01-01	ELLBETA_PARAMS	YES

CCF release note to accompany 0014 PSF CCFs (radial dependence of spokes tuned to match the corrected Saclay work, plus new PSF ELLBETA paramaterization from enclosed energy [annuli + spectra] work)

XMM-Newton CCF Release Note

XMM-CCF-REL-XXX

2-D PSF spoke parameterization

A. M. Read & R. Saxton

February 15, 2012

1 CCF components

Name of CCF	VALDATE	List of Blocks changed	Change in CAL HB
XRT1_XPSF_0014.CCF	2000-01-01	ELLBETA_PARAMS	YES
XRT2_XPSF_0014.CCF	2000-01-01	ELLBETA_PARAMS	YES
XRT3_XPSF_0014.CCF	2000-01-01	ELLBETA_PARAMS	YES

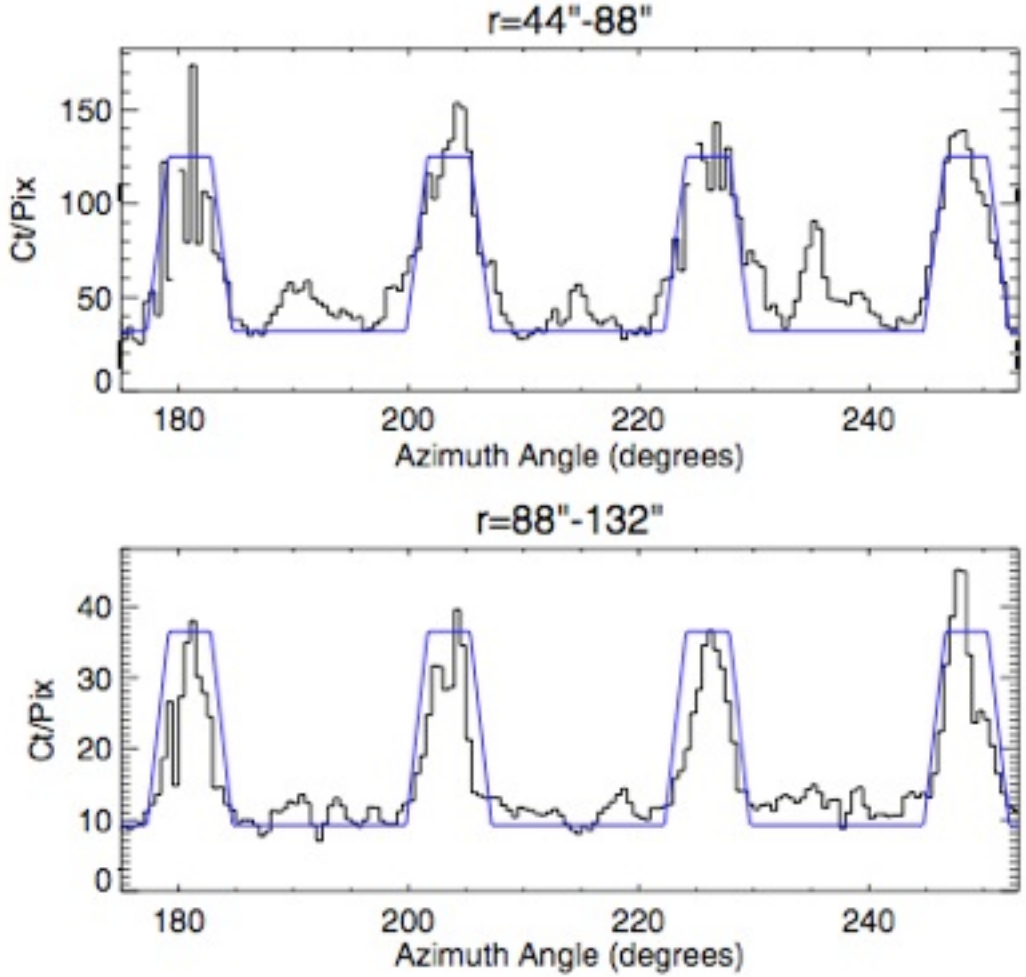
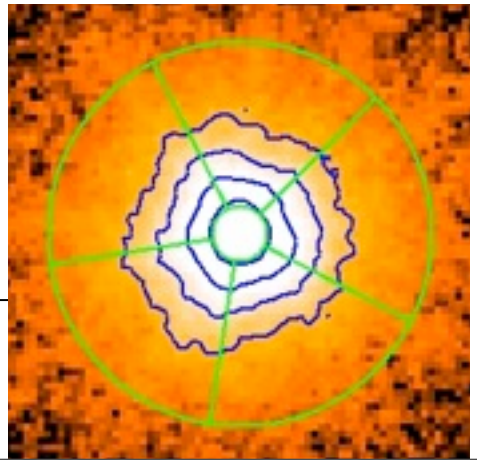


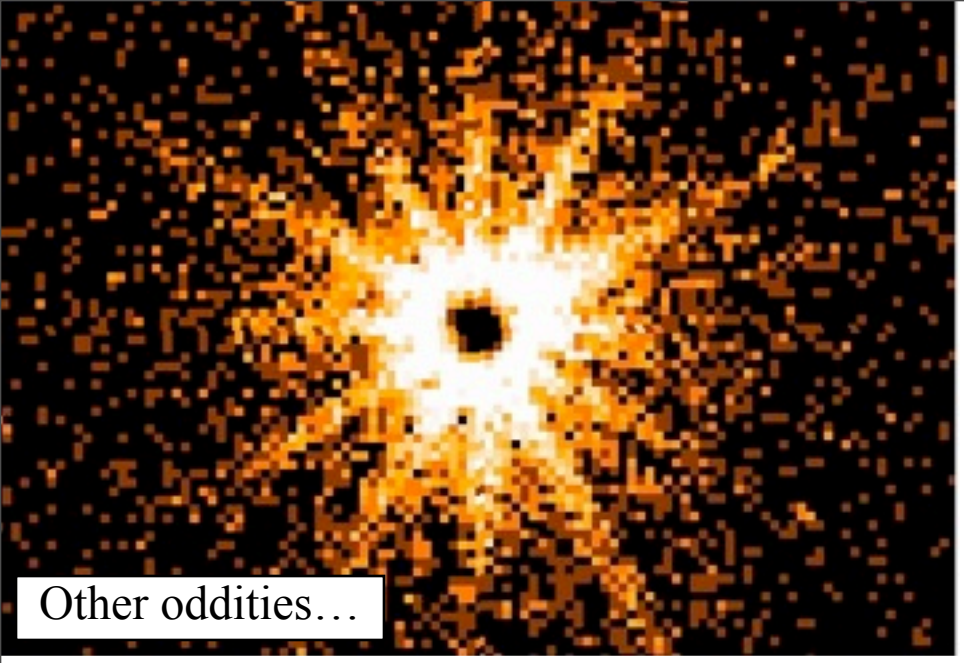
Fig. 5. A section of the azimuthal profile (black line) from GX 339-4 (ObsID 0204730301) (MOS1, 0.2–12 keV) in annular extractions of (*top*) 44″–88″ and (*bottom*) 88″–132″. The current (CCF 0013) flat-topped triangular function for the primary spokes at maximum strength (i.e., at a radius of 110″) is shown in blue (see text).

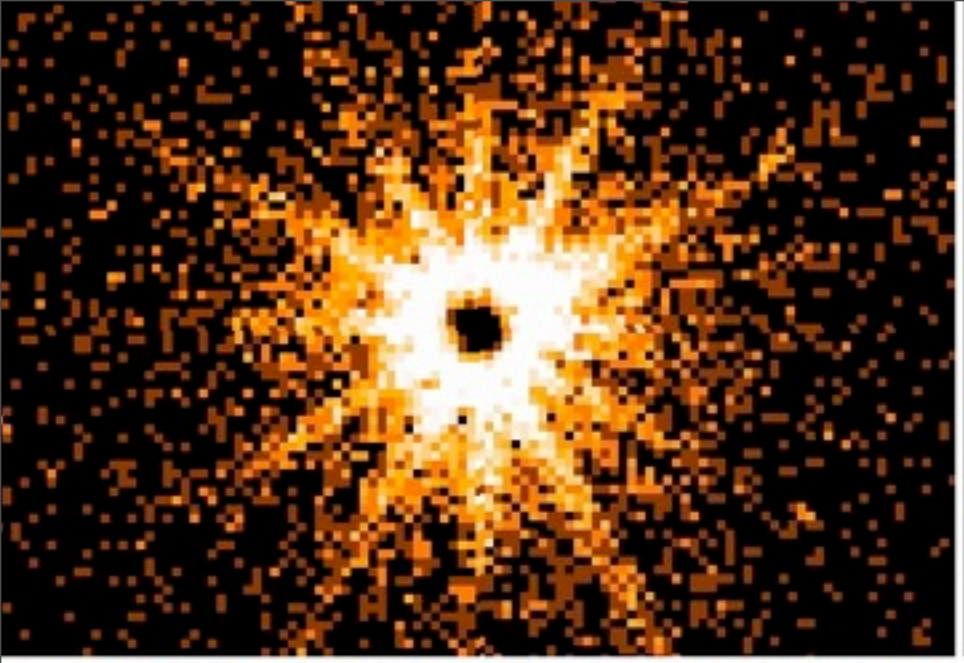
- True spoke-to-spoke (primary & secondary) variations
- u & v may vary with radius – spokes are thinner at larger r
- Radial dependence of secondary spokes different from that of primary spokes
- Impinges on on-spoke-off-spoke results – secondary spokes are relatively stronger at small r than at large r

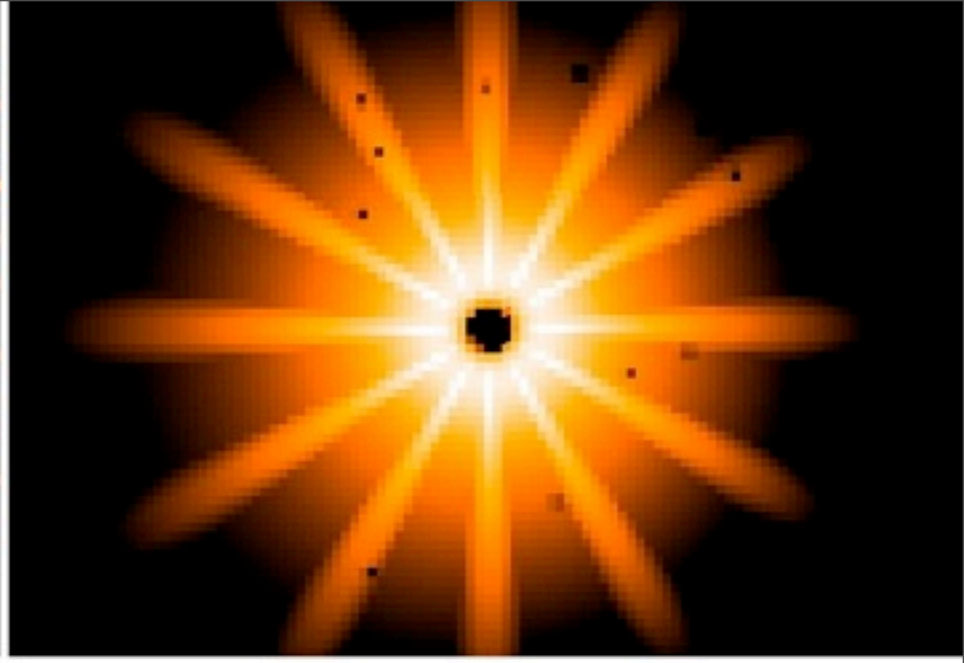
The full 2-D PSF? – possible futures

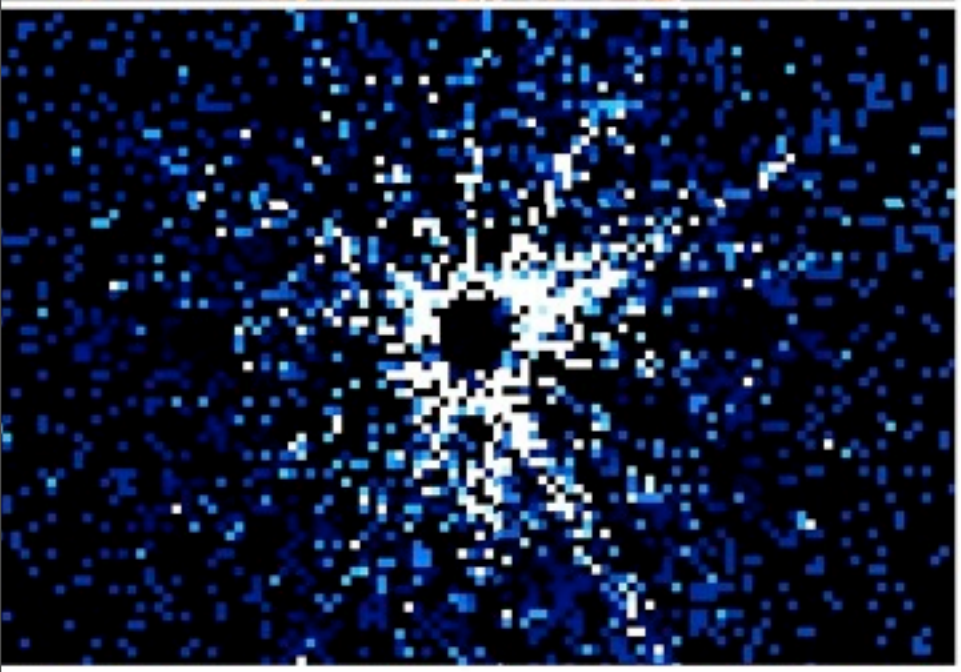
- Spoke (primary & secondary) and polygonal structure tuning: radial-dependencies, energy-dependencies, differences between instruments…
- More clean data could improve PSF parameterization, especially at high energies and large off-axis angle
- Ongoing testing possible – spectrally, with varying extraction annuli etc. – also detect chain output - likelihoods, rates, fluxes, extents, spurious sources, sources close to bright sources etc.
- Proper handling of the Sagittal-Meridional effect (off-axis and energy dependent) - not yet included
- (MOS events spread across the RGS dispersion axis – Is this a PSF issue?)
- (Out-of-time events - Is this a PSF/emldetect issue? MOS/pn?)
- Azimuthal phi-dependence of the Ellbeta parameters, e.g. RGA obscuration, individual chip-to-chip height variations (MOS)
- Pentagon in pn - calibration and azimuthal filtering
- Dark lanes due to electron deflector - not yet included
- ...




Other oddities…

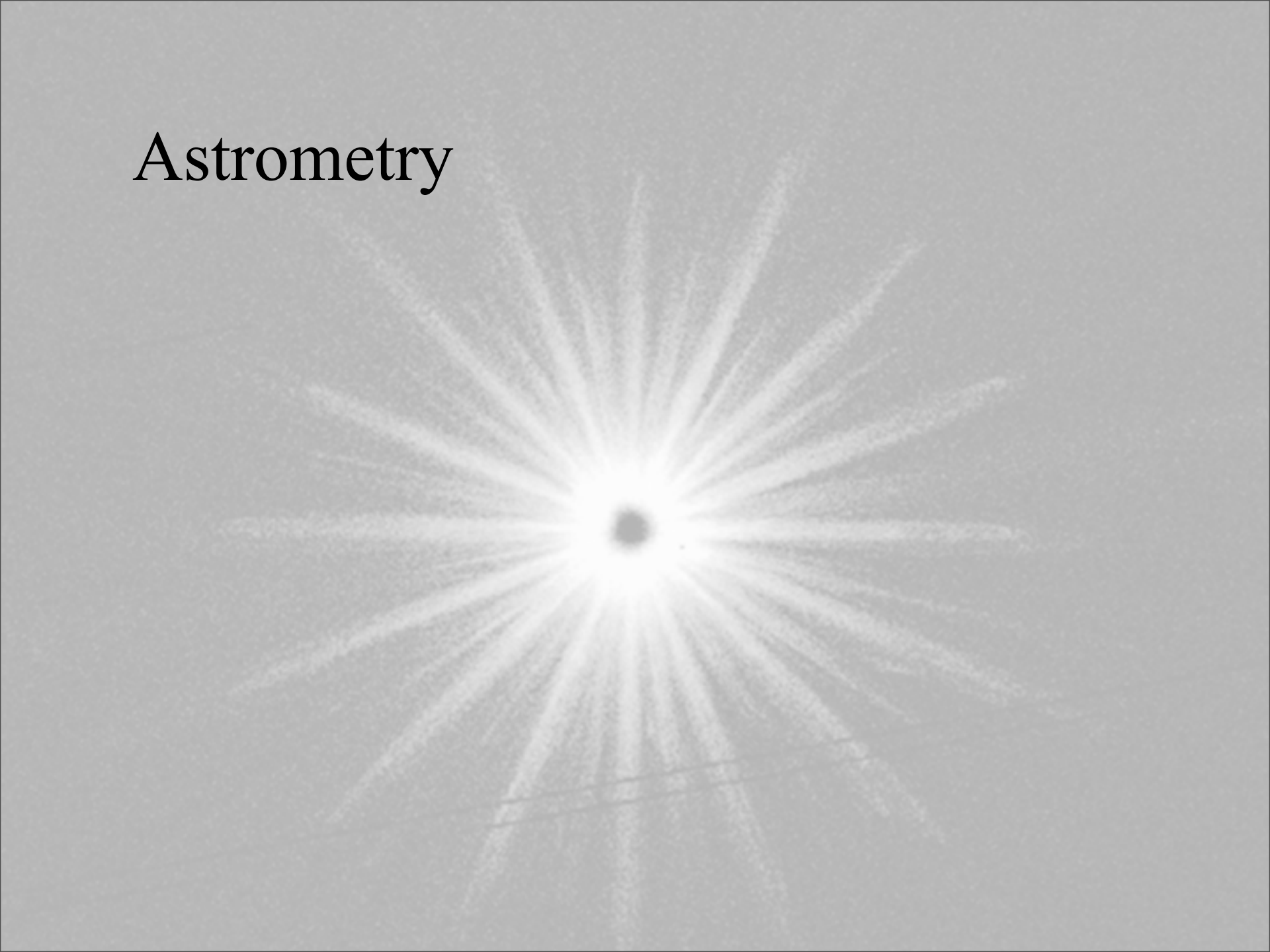






- Swift XRT PSF (Phil Evans/AMR)
- Image of bright (piled-up) point source
- Fitted with AMR EPIC PSF model, including beta function, 12 (not 16) spokes (flat-topped triangular function plus radial dependency) – different model parameters are obtained.
- Residuals show triangular MOS2-like structure

Astrometry



The original problem :

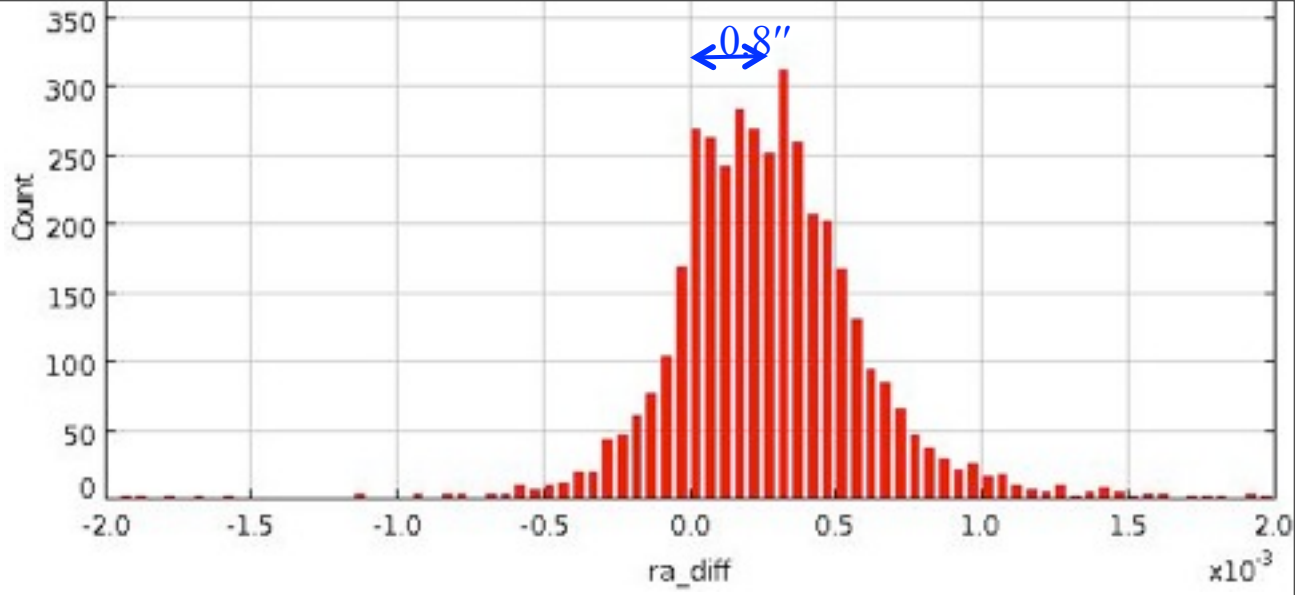
Positions obtained from 2D PSF and default PSF runs are different.

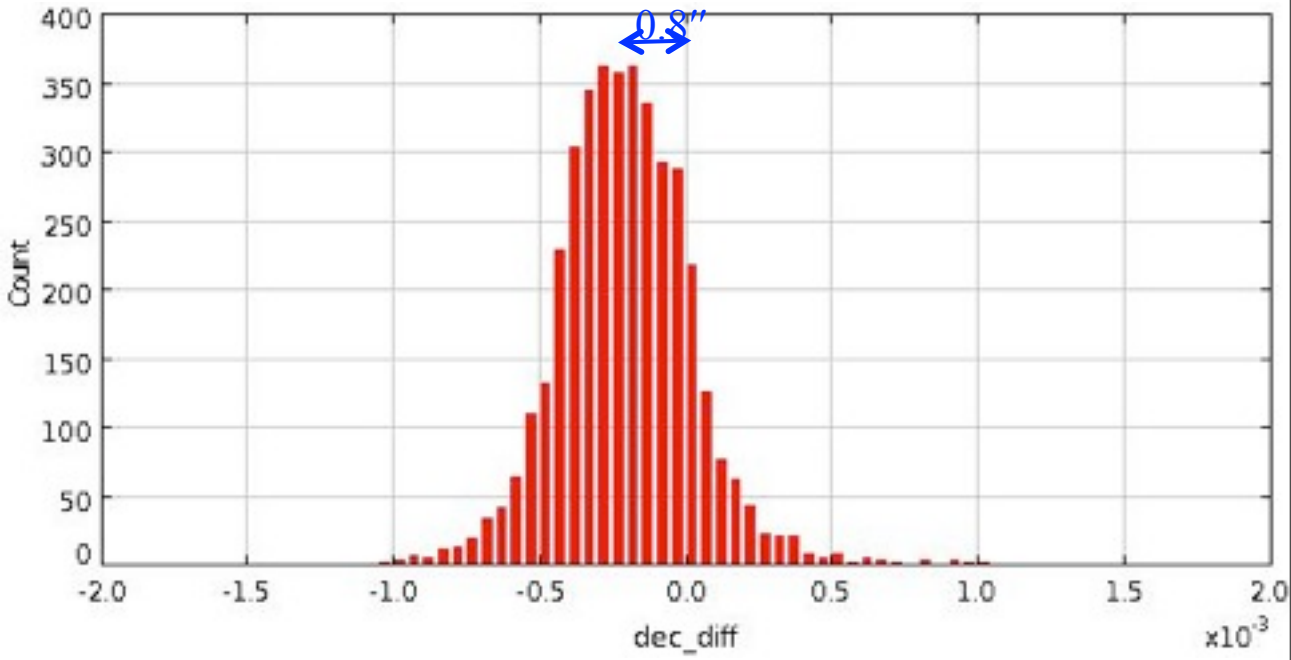
Positional shifts seen:

~+0.8” in RA

~-0.8” in Dec

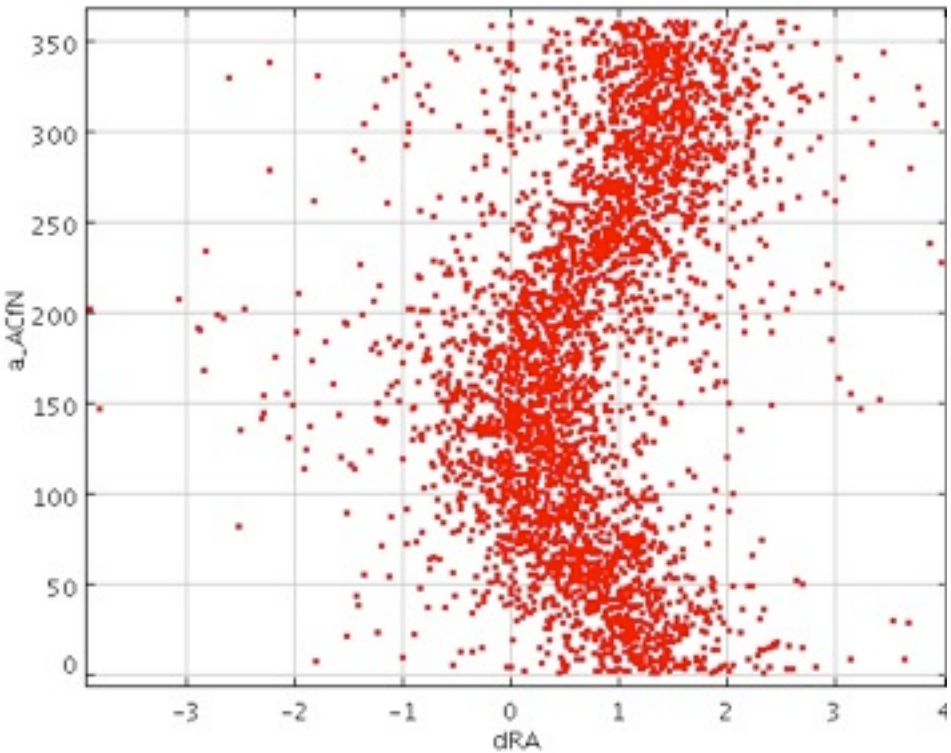
(2D minus default)

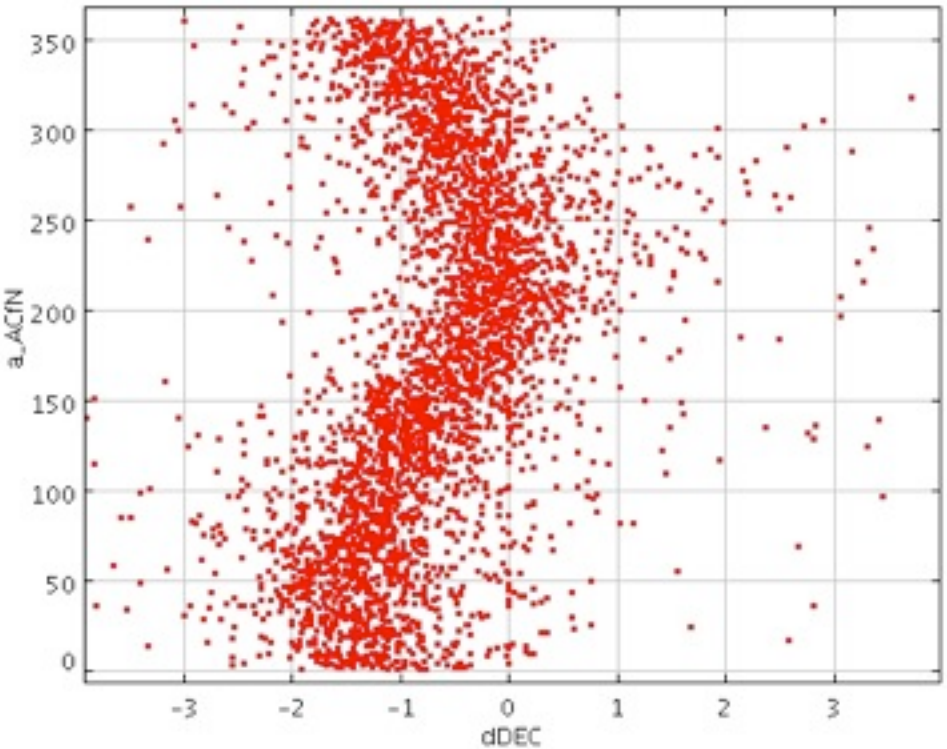




deltaRA (2D – def, arcsec) and deltaDec (2D – def, arcsec) versus sky phi (angle anti-clockwise from North, degrees)

Sinusoidal variation seen - Is it due to the 2D PSF or the default PSF?...





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versus sky phi (angle anti-clockwise from North, degrees)

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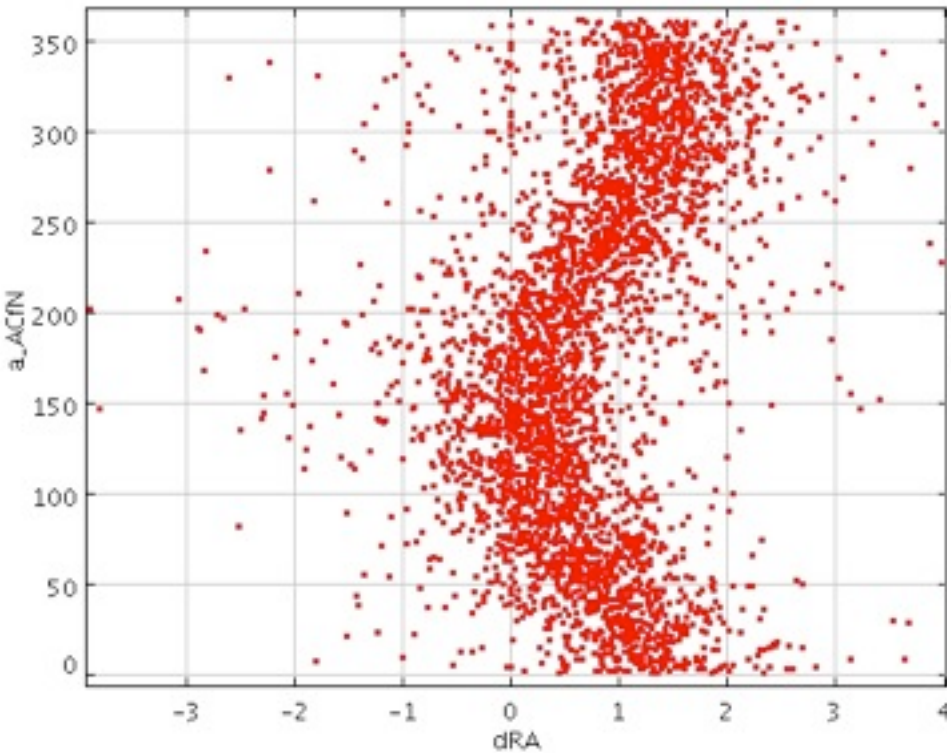
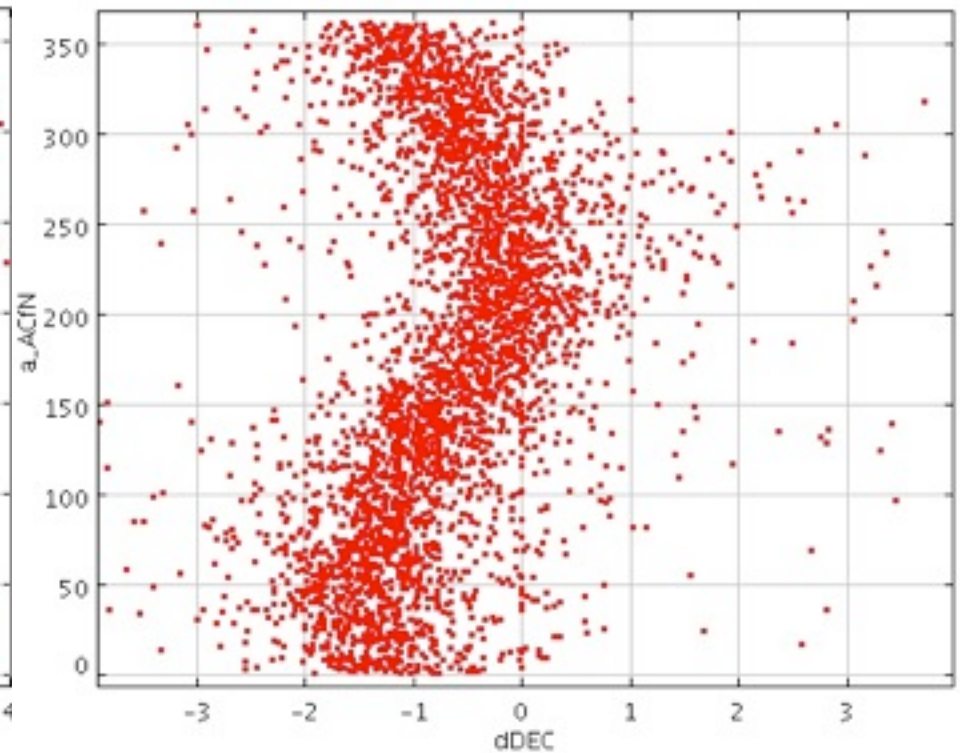
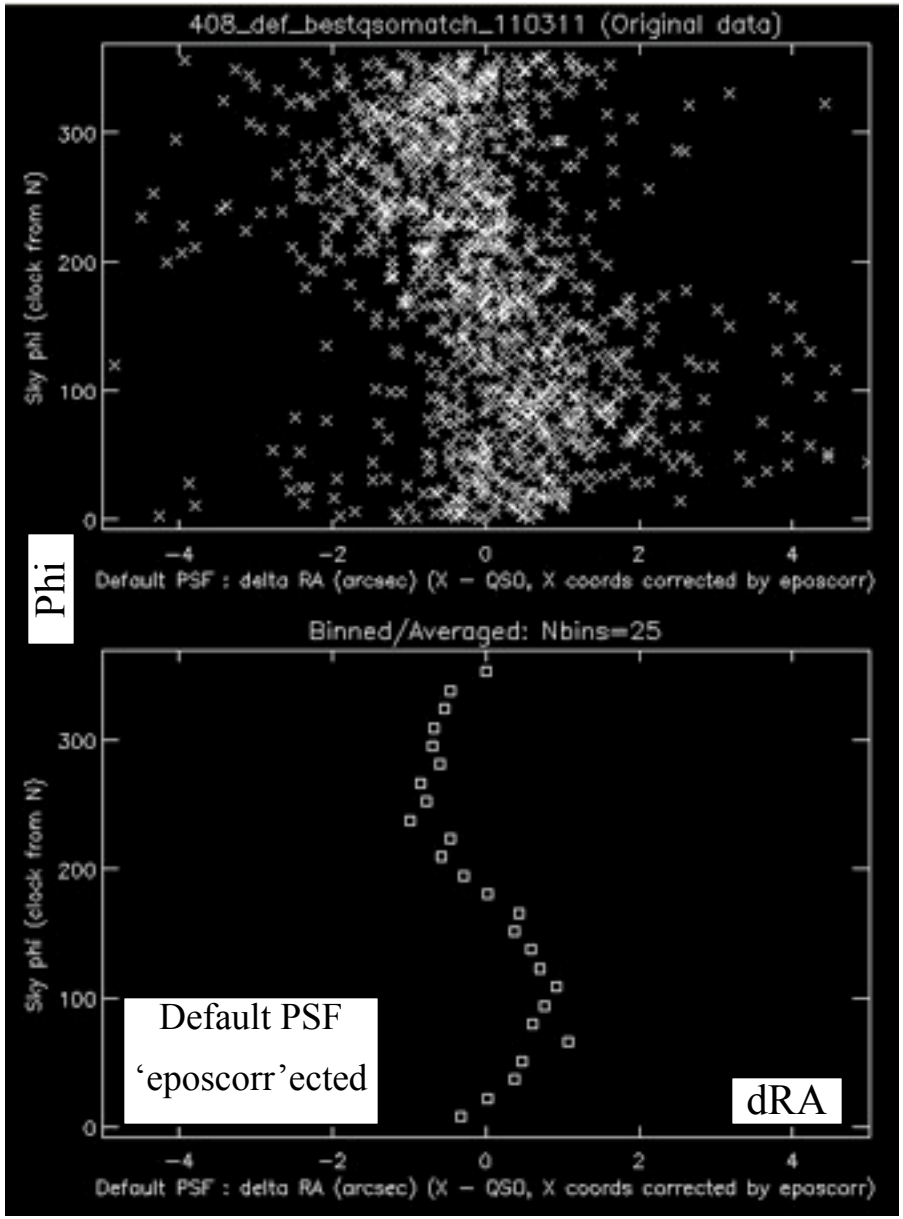
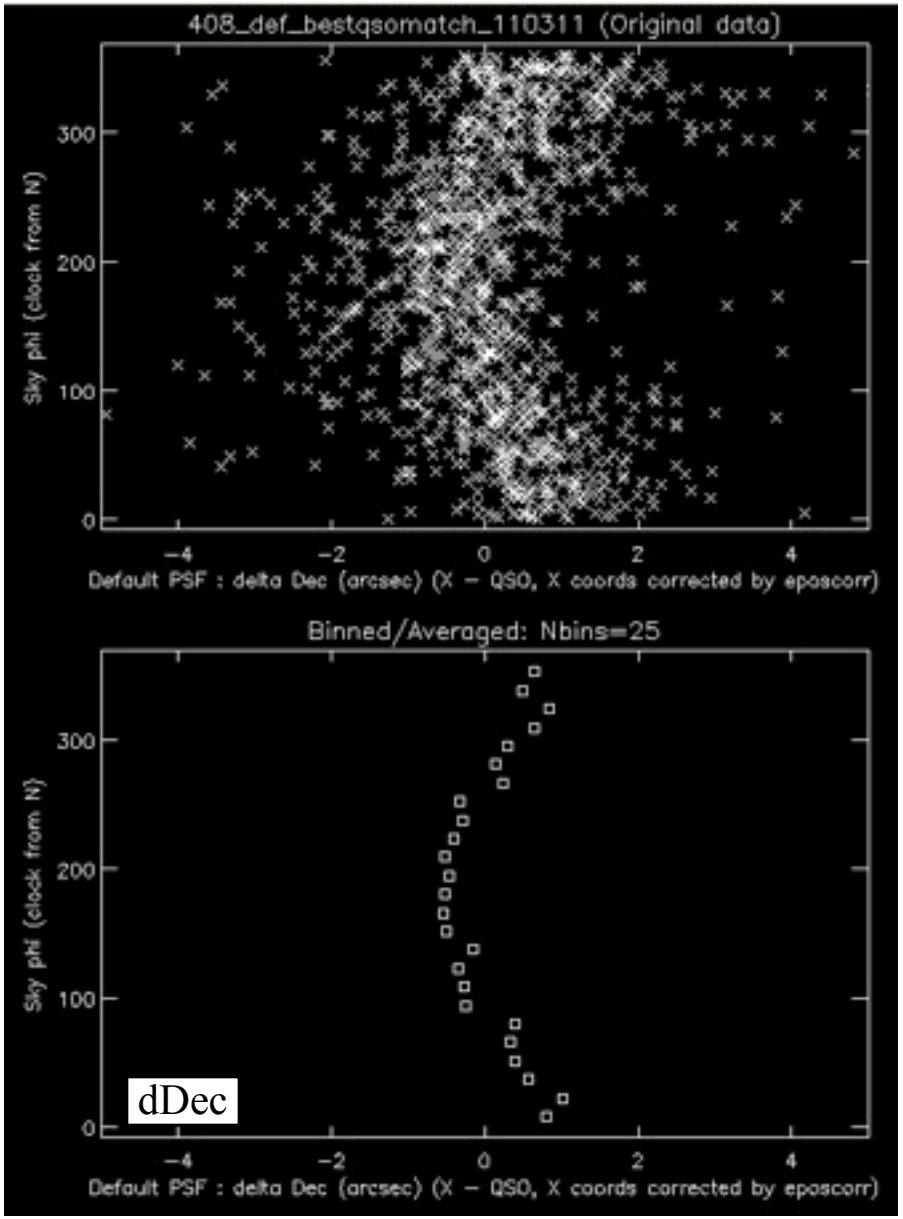


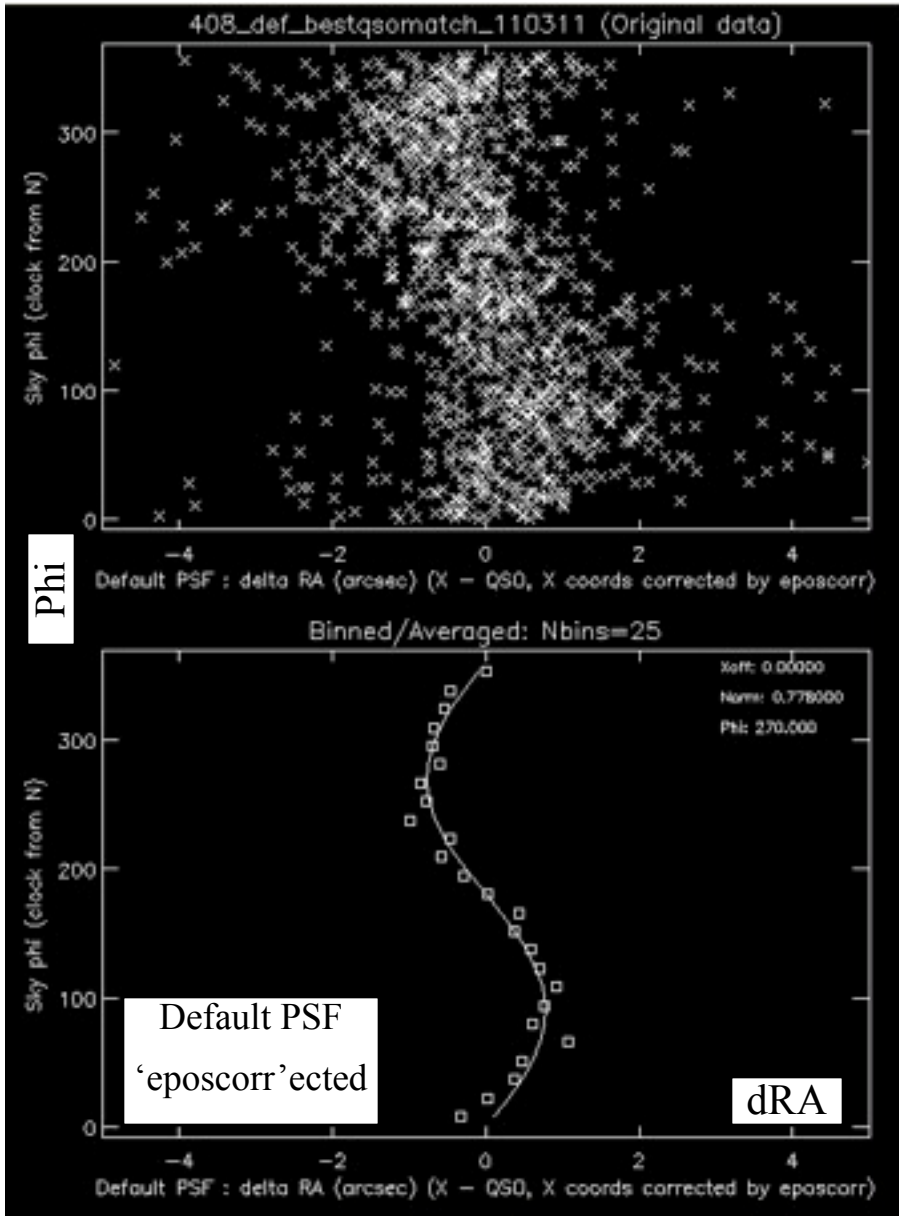


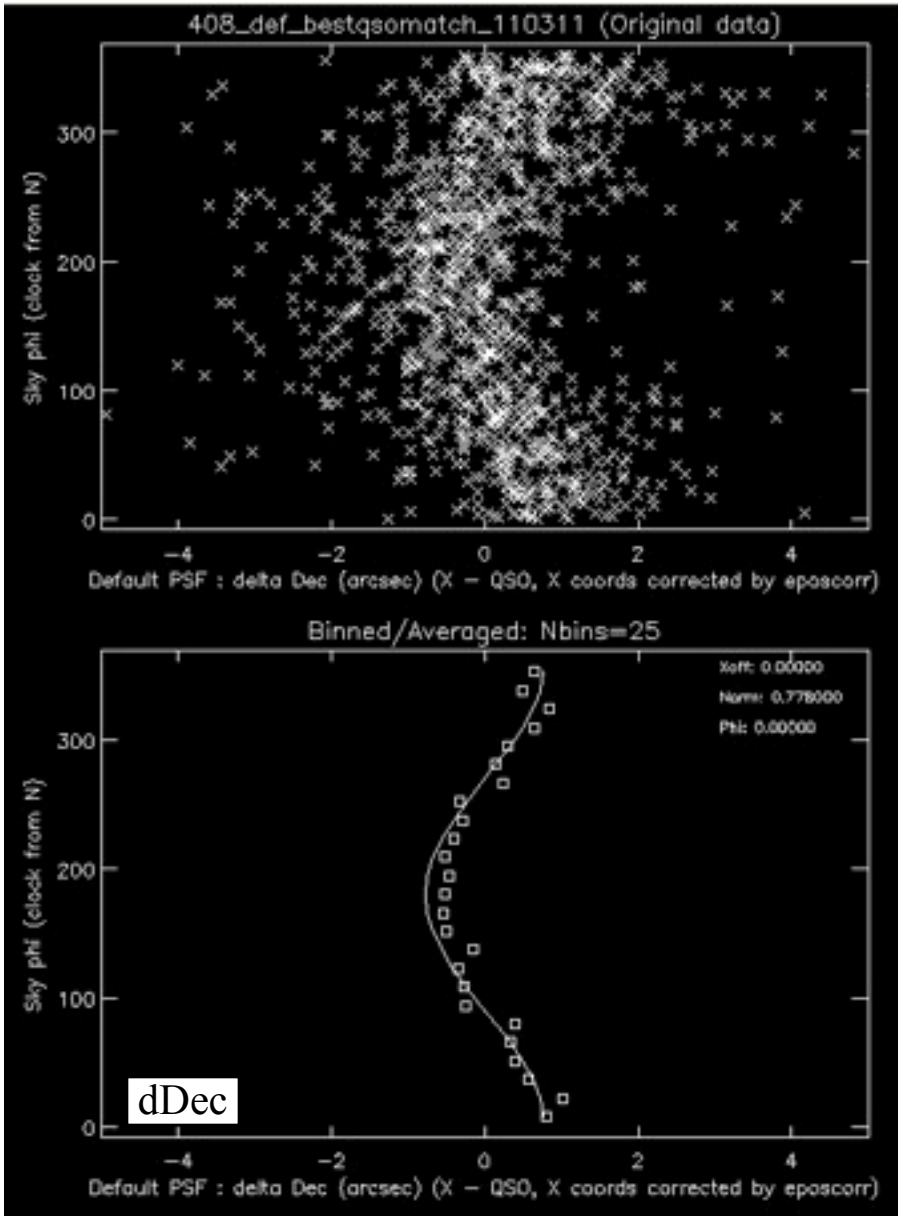
1st Astrometry Issue – The 'S'

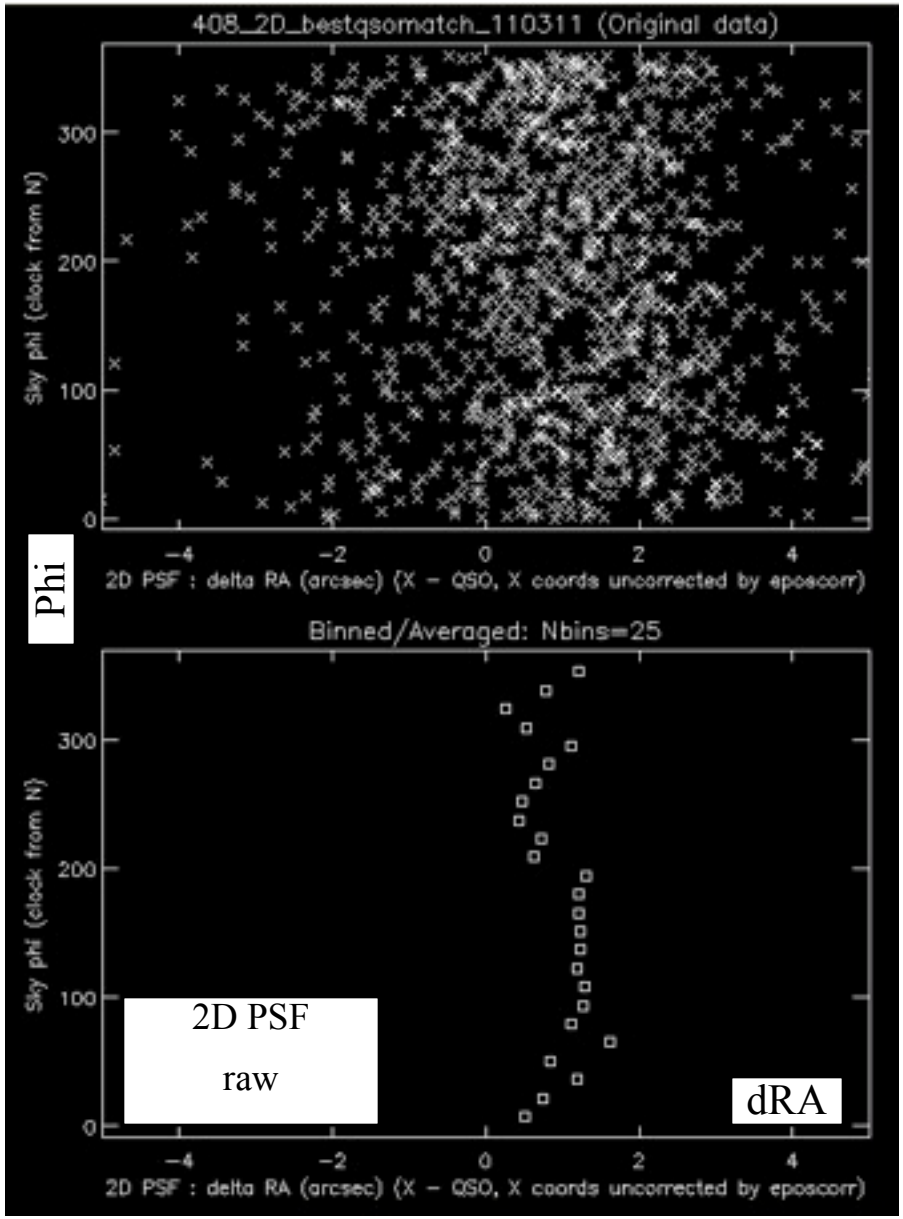
Last meeting: Look at X-QSO offsets - It's due to the default PSF…

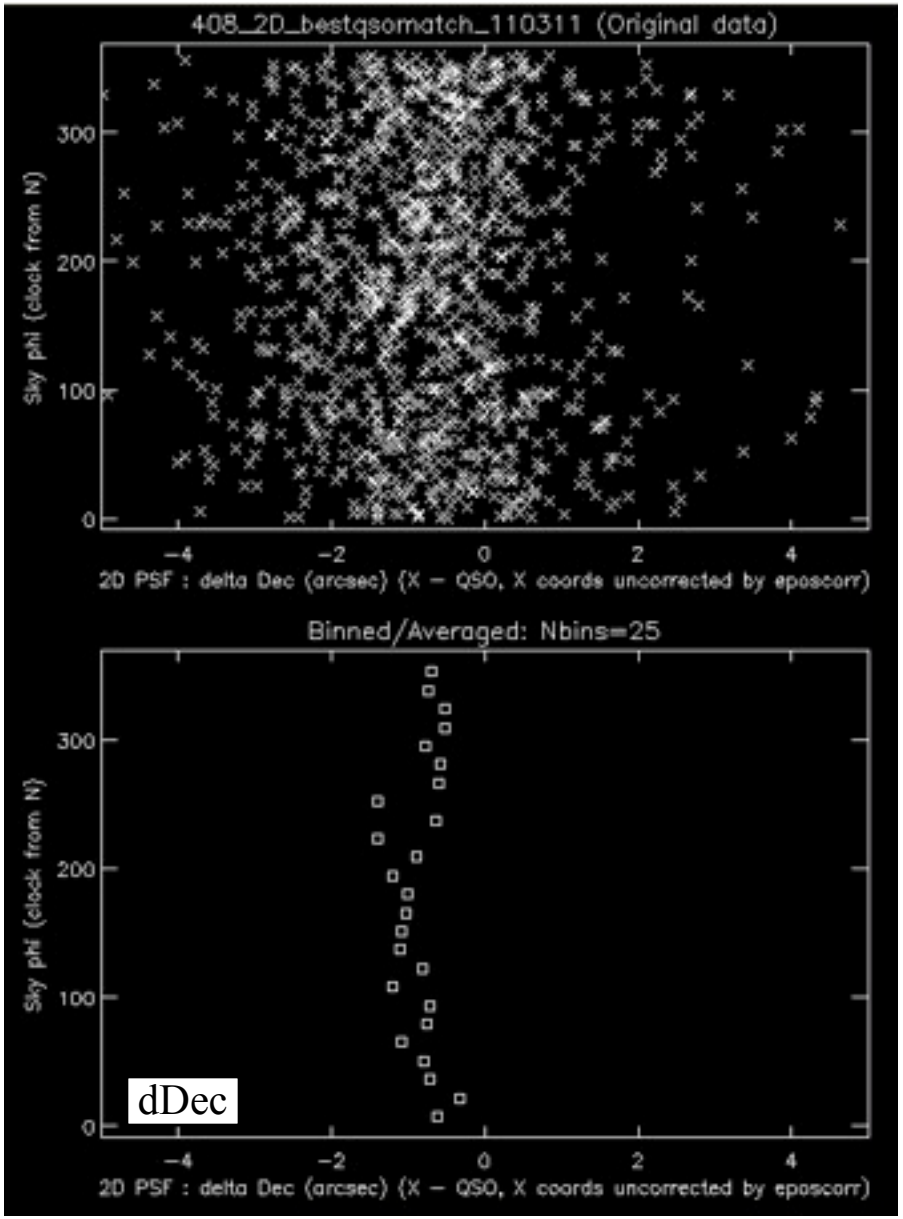

408_def_bestqsomatch_110311 (Original data)
Sky phi (clock from N)
Default PSF : delta RA (arcsec) (X – QSO, X coords corrected by eposcorr)
Phi
Binned/Averaged: Nbins=25
Default PSF
'eposcorr'ected
dRA


408_def_bestqsomatch_110311 (Original data)
Sky phi (clock from N)
Default PSF : delta Dec (arcsec) (X – QSO, X coords corrected by eposcorr)
Binned/Averaged: Nbins=25
dDec


408_def_bestqsomatch_110311 (Original data)
Sky phi (clock from N)
Default PSF : delta RA (arcsec) (X – QSO, X coords corrected by eposcorr)
Phi
Binned/Averaged: Nbins=25
Xoff: 0.00000
Norm: 0.778000
Phi: 270.000
Default PSF
'eposcorr'ected
dRA

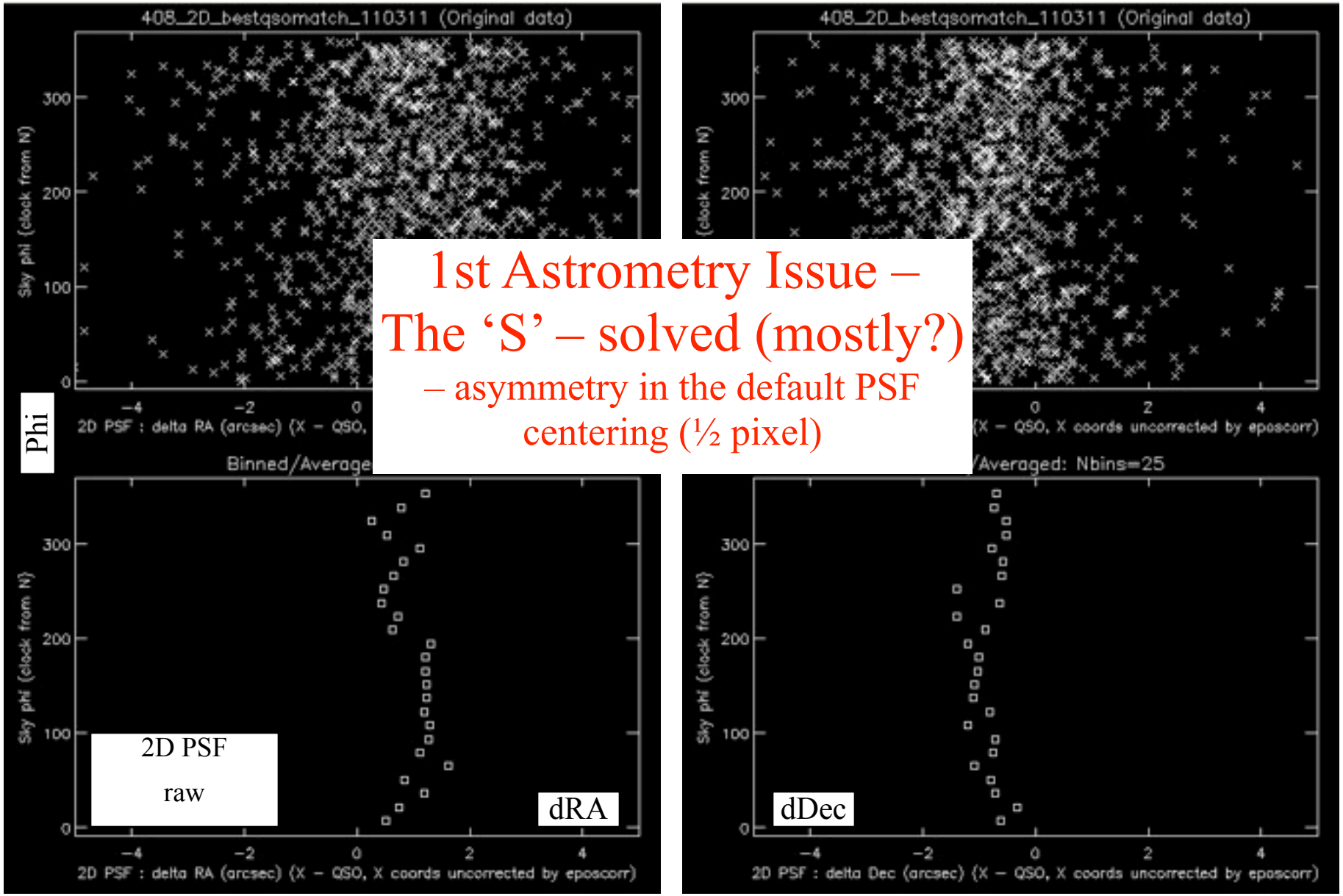

408_def_bestqsomatch_110311 (Original data)
Sky phi (clock from N)
Default PSF : delta Dec (arcsec) (X – QSO, X coords corrected by eposcorr)
Binned/Averaged: Nbins=25
Xoff: 0.00000
Norm: 0.778000
Phi: 0.00000
dDec

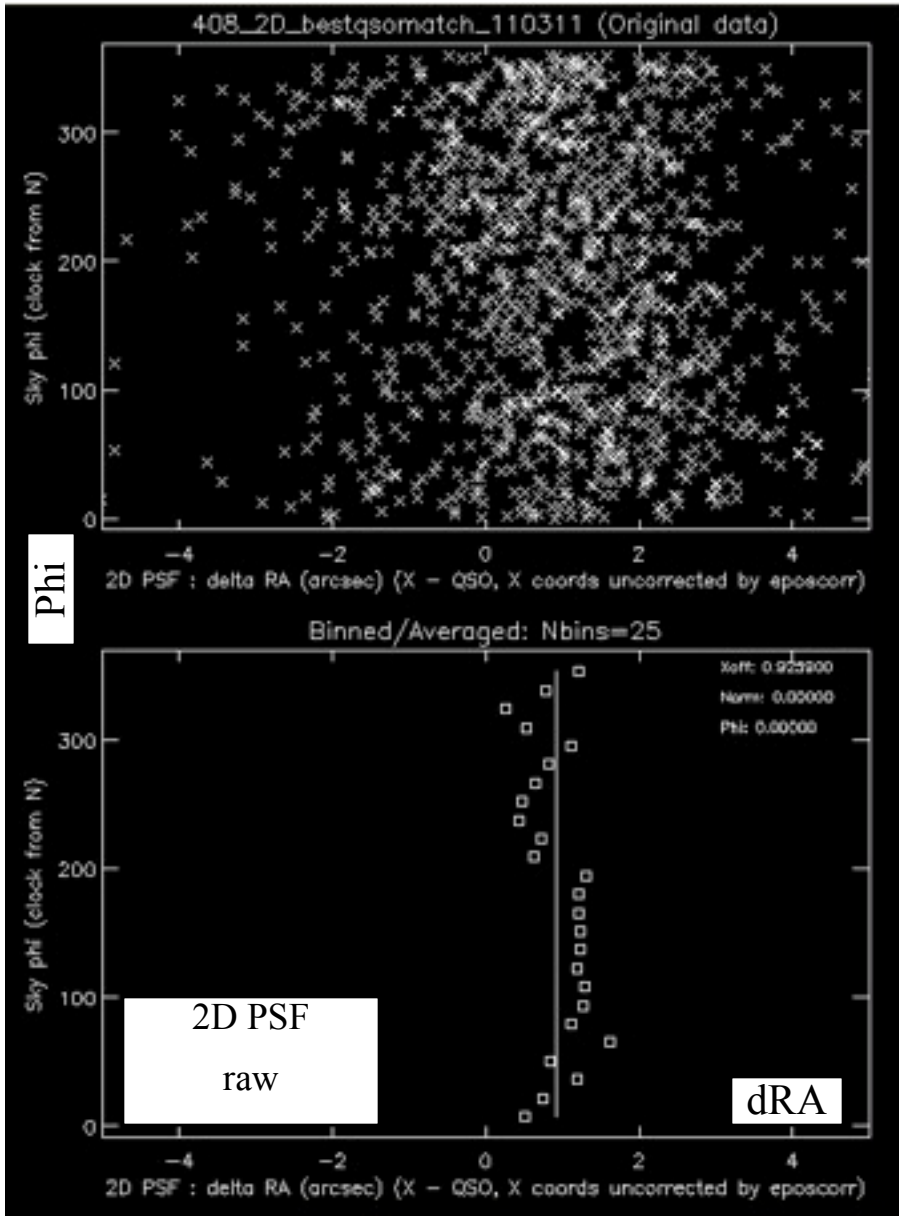

408_2D_bestqsomatch_110311 (Original data)
Sky phi (clock from N)
2D PSF : delta RA (arcsec) (X – QSO, X coords uncorrected by eposcorr)
Phi
Binned/Averaged: Nbins=25
2D PSF
raw
dRA

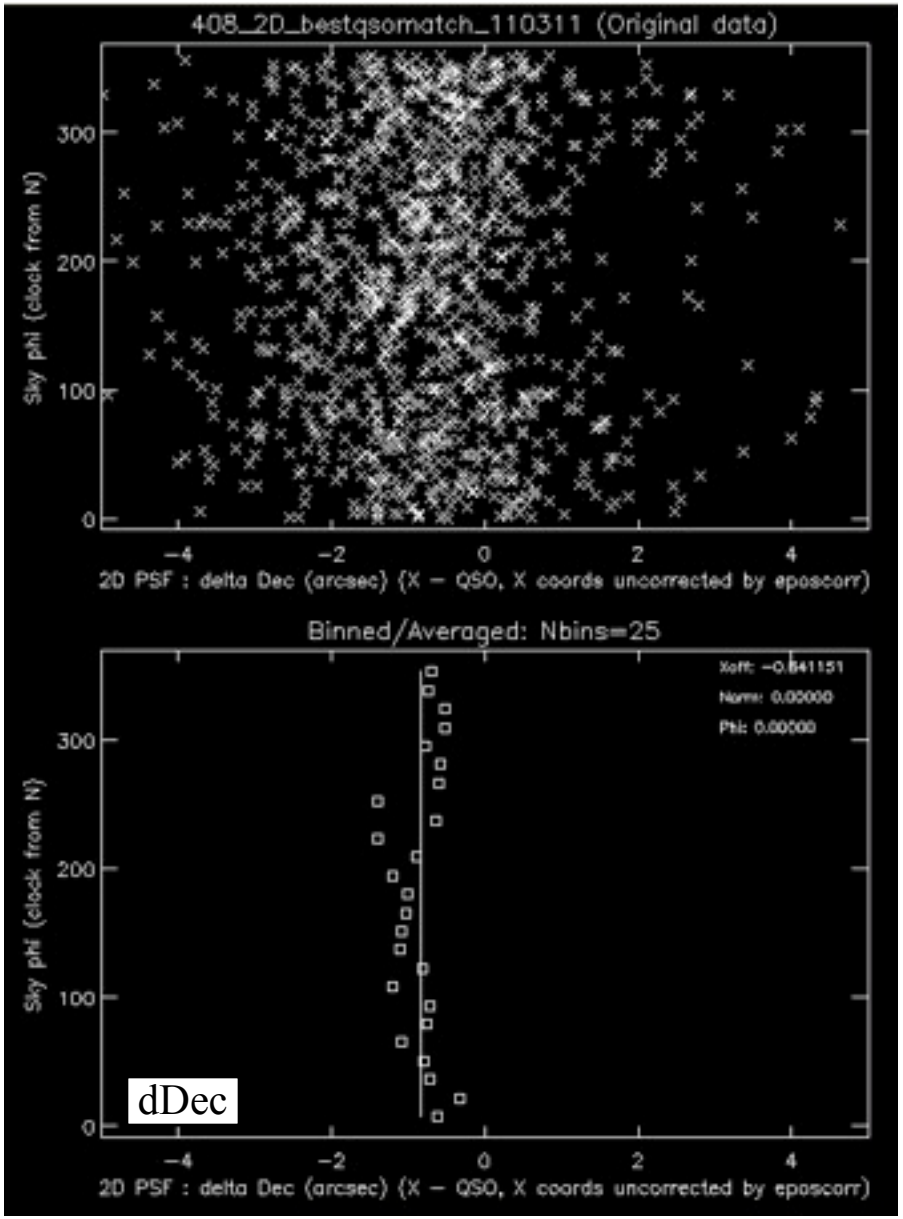

408_2D_bestqsomatch_110311 (Original data)
Sky phi (clock from N)
2D PSF : delta Dec (arcsec) (X – QSO, X coords uncorrected by eposcorr)
Binned/Averaged: Nbins=25
dDec

1st Astrometry Issue – The ‘S’ – solved (mostly?)

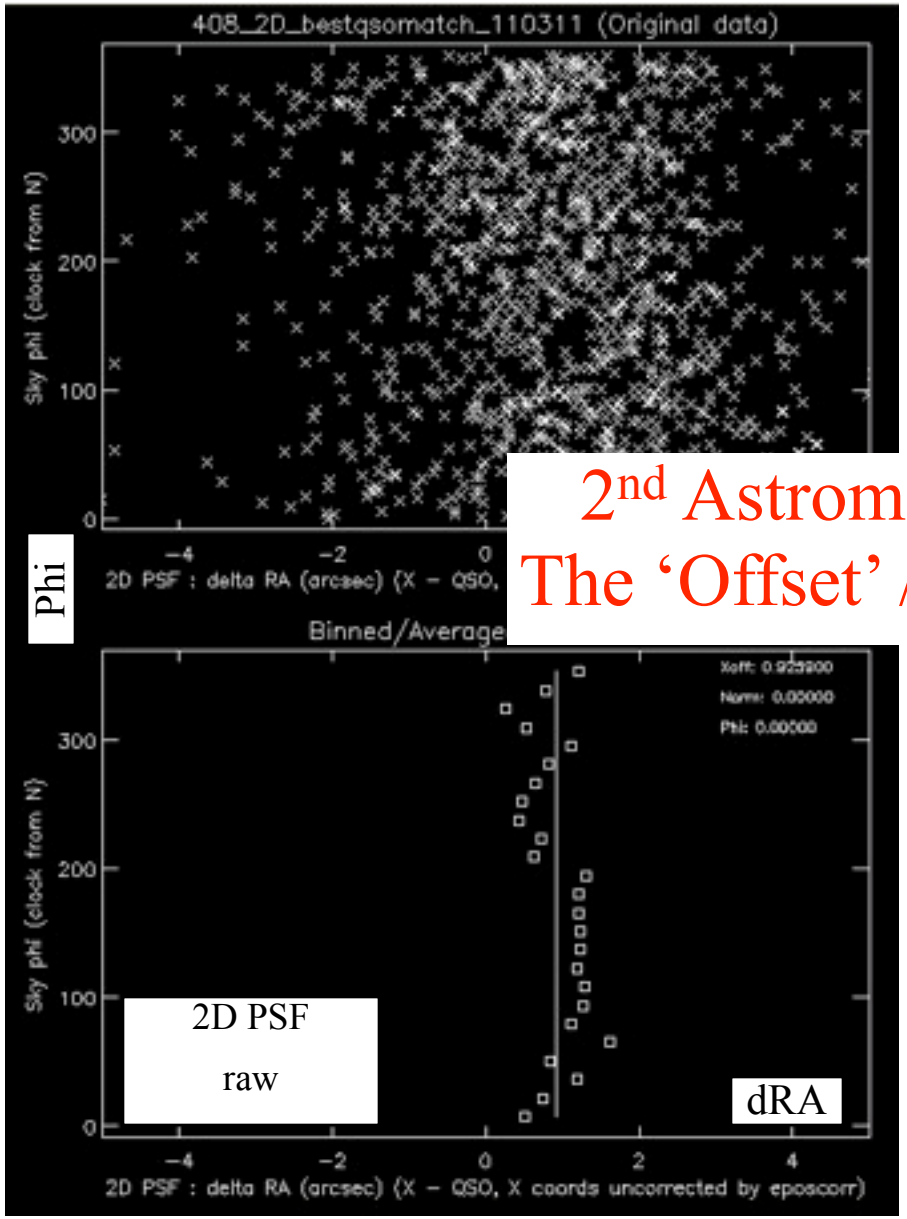
– asymmetry in the default PSF centering (½ pixel)

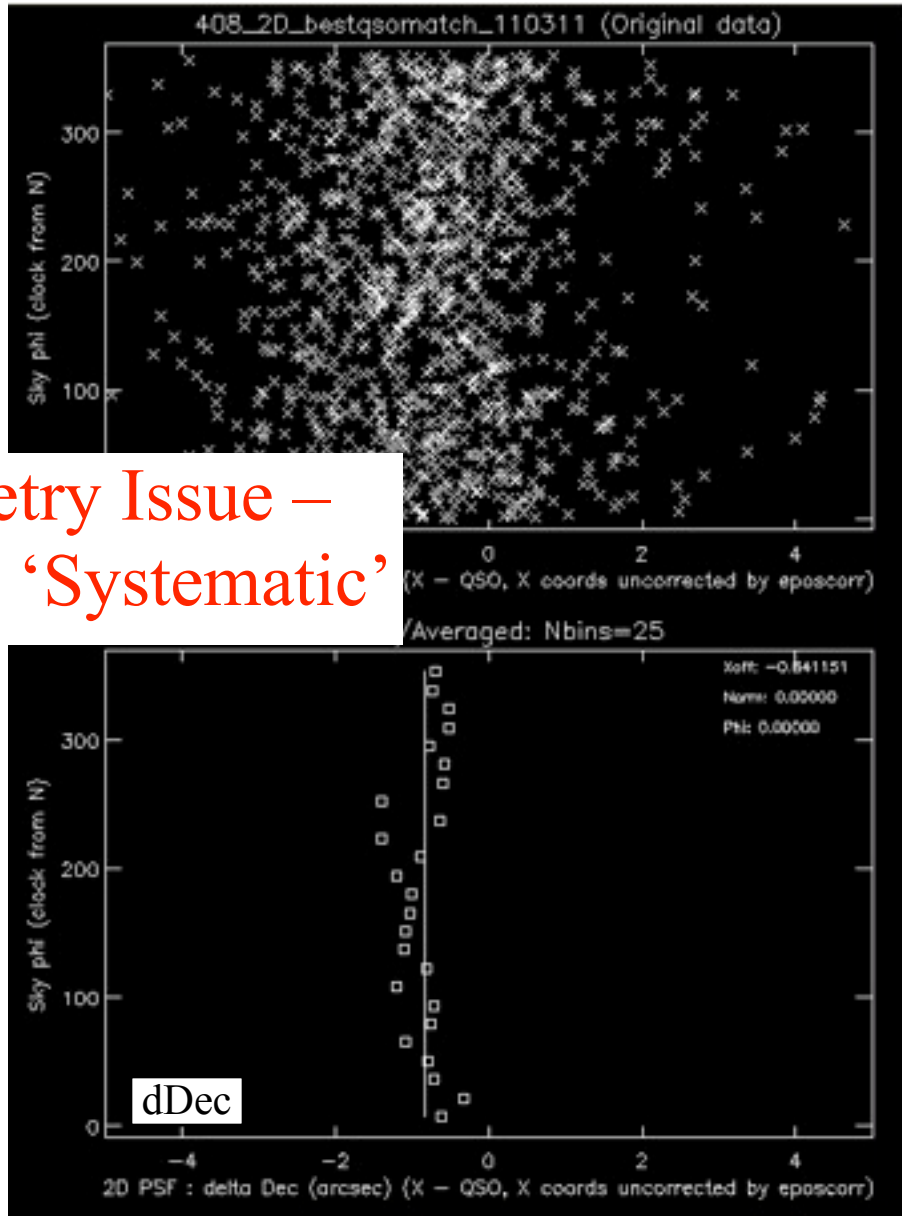


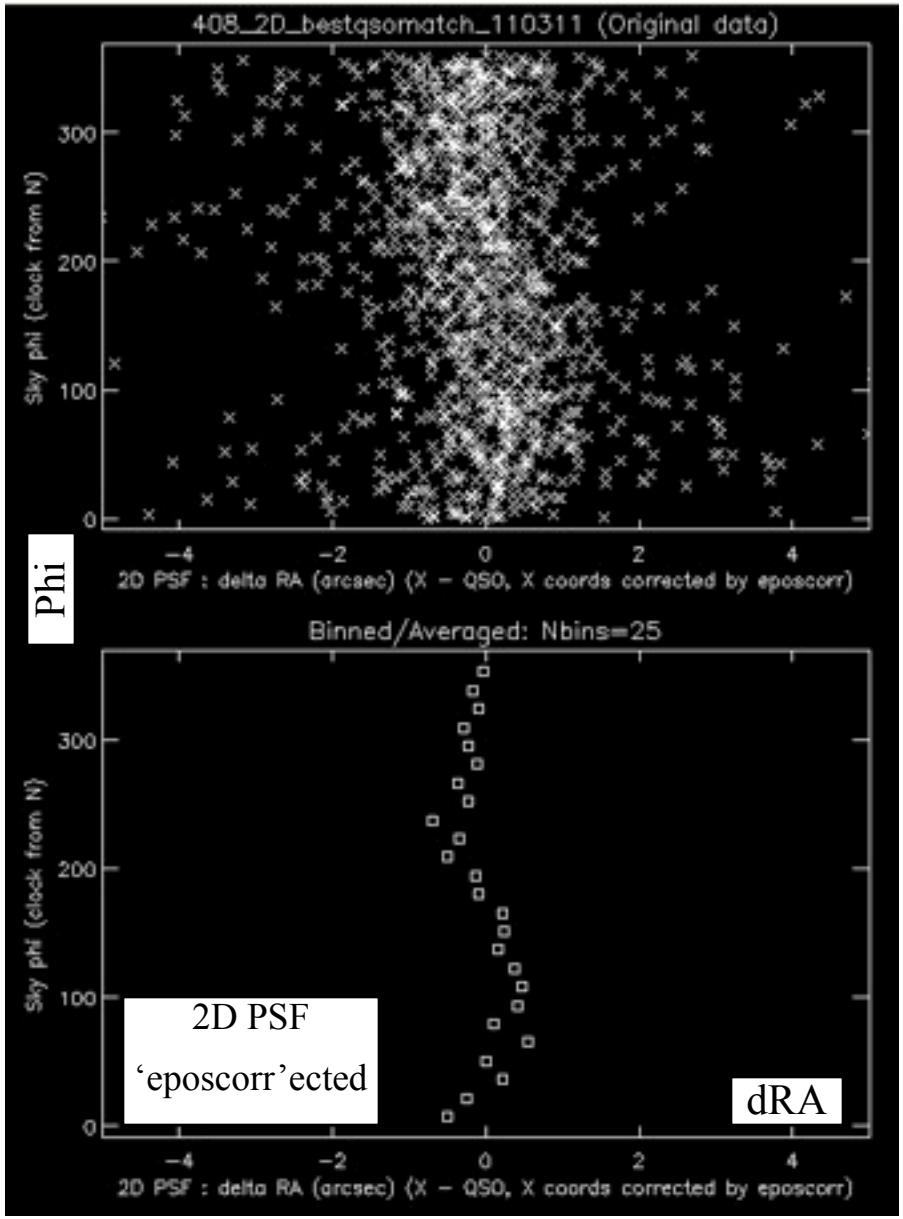

408_2D_bestqsomatch_110311 (Original data)
Sky phi (clock from N)
2D PSF : delta RA (arcsec) (X – QSO, X coords uncorrected by eposcorr)
Phi
Binned/Averaged: Nbins=25
Xoff: 0.929900
Norm: 0.00000
Phi: 0.00000
2D PSF
raw
dRA

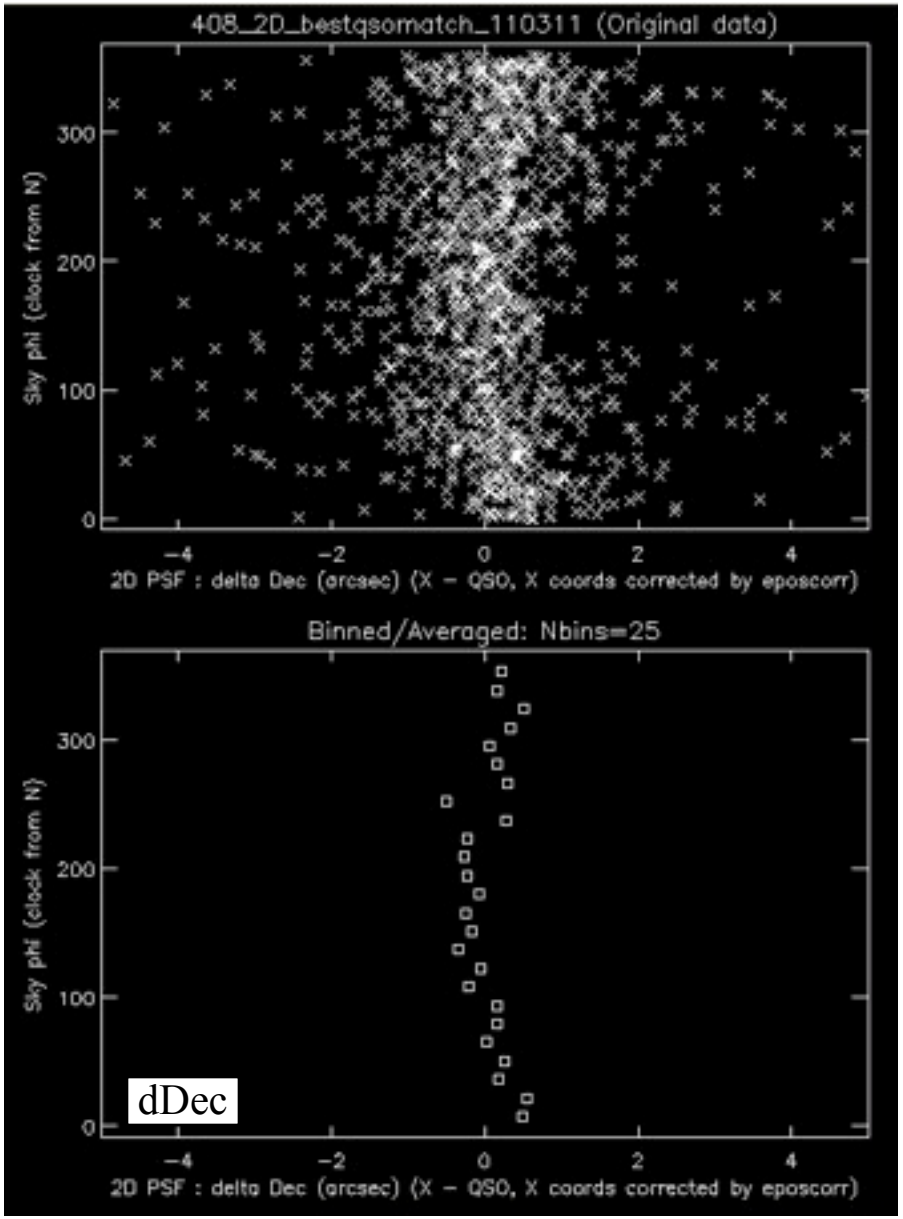

408_2D_bestqsomatch_110311 (Original data)
Sky phi (clock from N)
2D PSF : delta Dec (arcsec) (X – QSO, X coords uncorrected by eposcorr)
Binned/Averaged: Nbins=25
Xoff: −0.841151
Norm: 0.00000
Phi: 0.00000
dDec

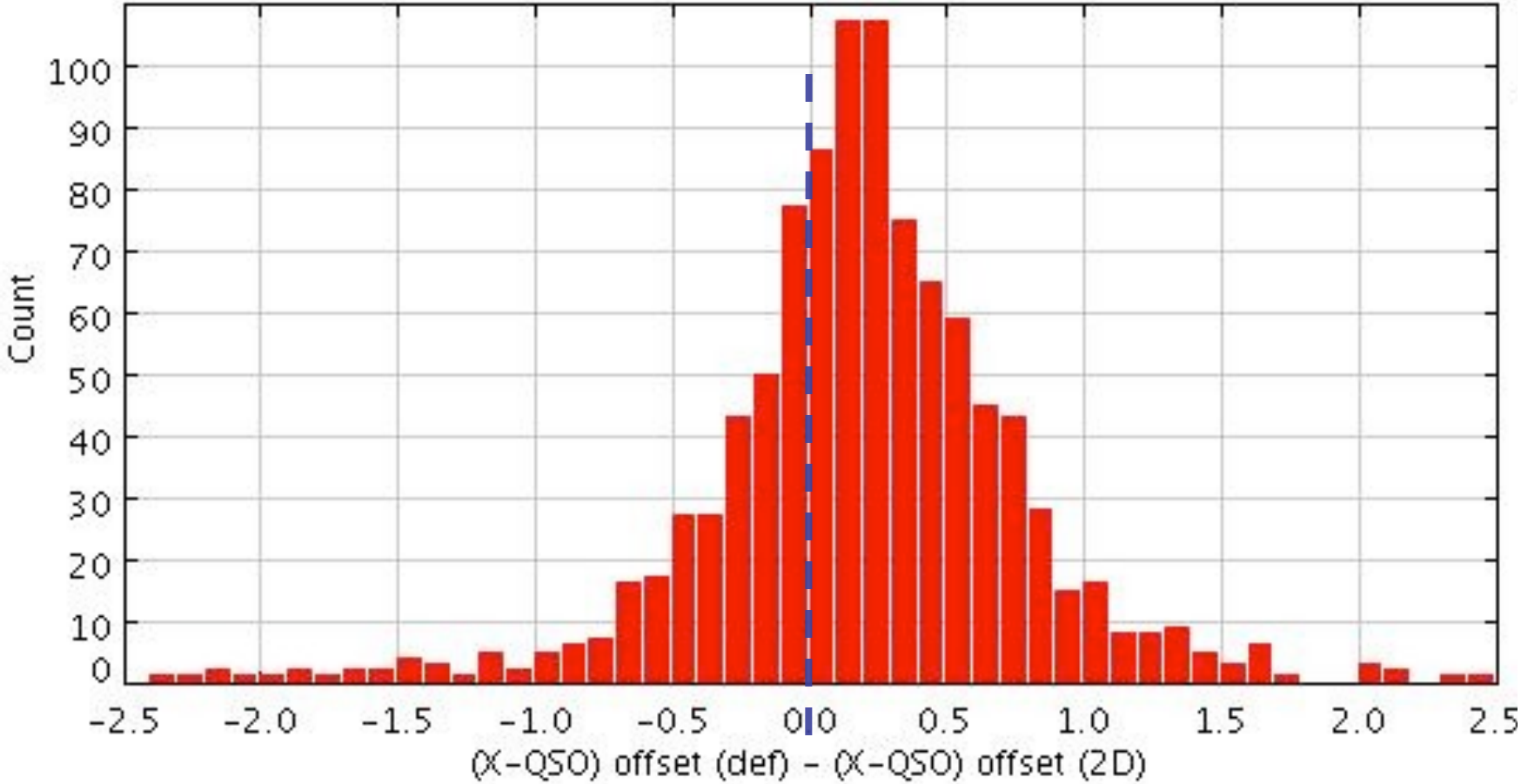
2nd Astrometry Issue – The 'Offset' / 'Systematic'






408_2D_bestqsomatch_110311 (Original data)
Sky phi (clock from N)
2D PSF : delta RA (arcsec) (X – QSO, X coords corrected by eposcorr)
Phi
Binned/Averaged: Nbins=25
2D PSF
'eposcorr'ected
dRA

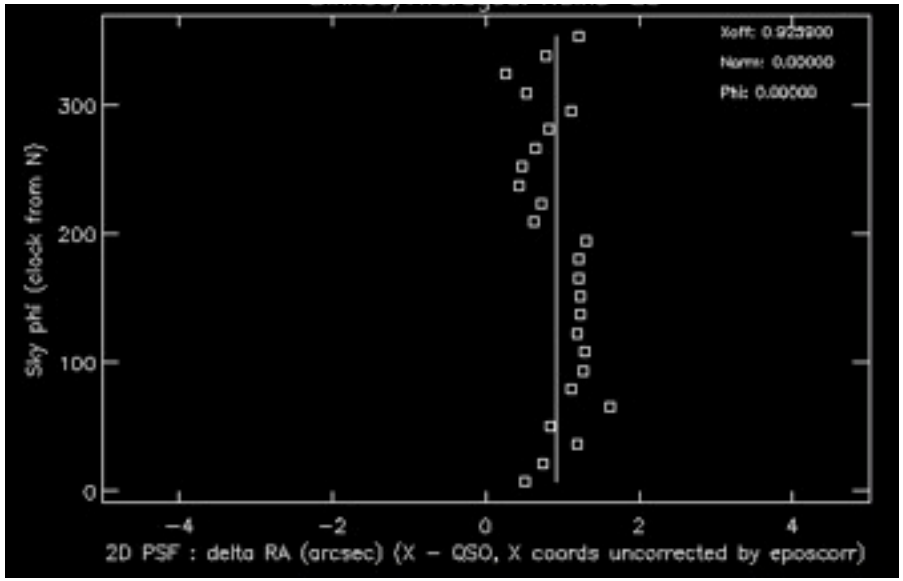

408_2D_bestqsomatch_110311 (Original data)
Sky phi (clock from N)
2D PSF : delta Dec (arcsec) (X – QSO, X coords corrected by eposcorr)
Binned/Averaged: Nbins=25
dDec

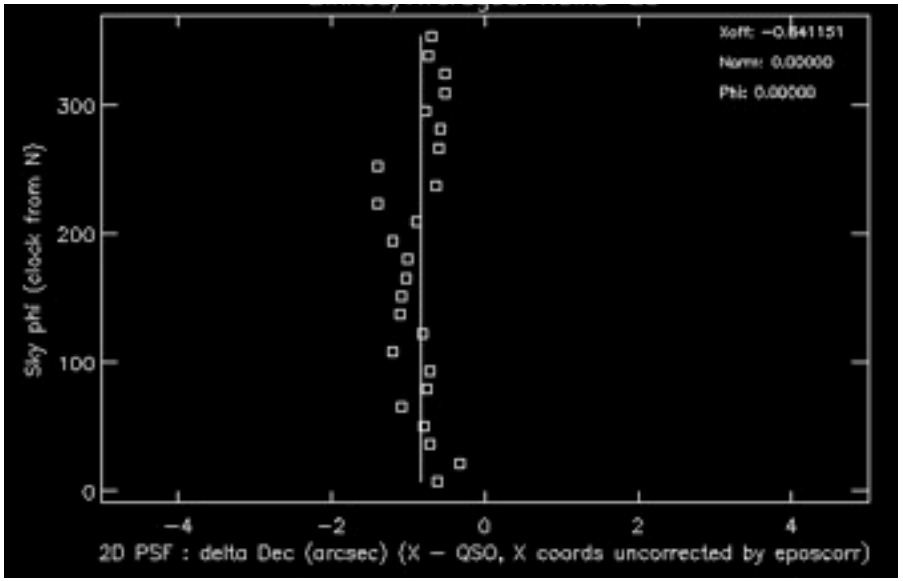


%age of cases where the 2D position is the closest to the QSO position : 70%

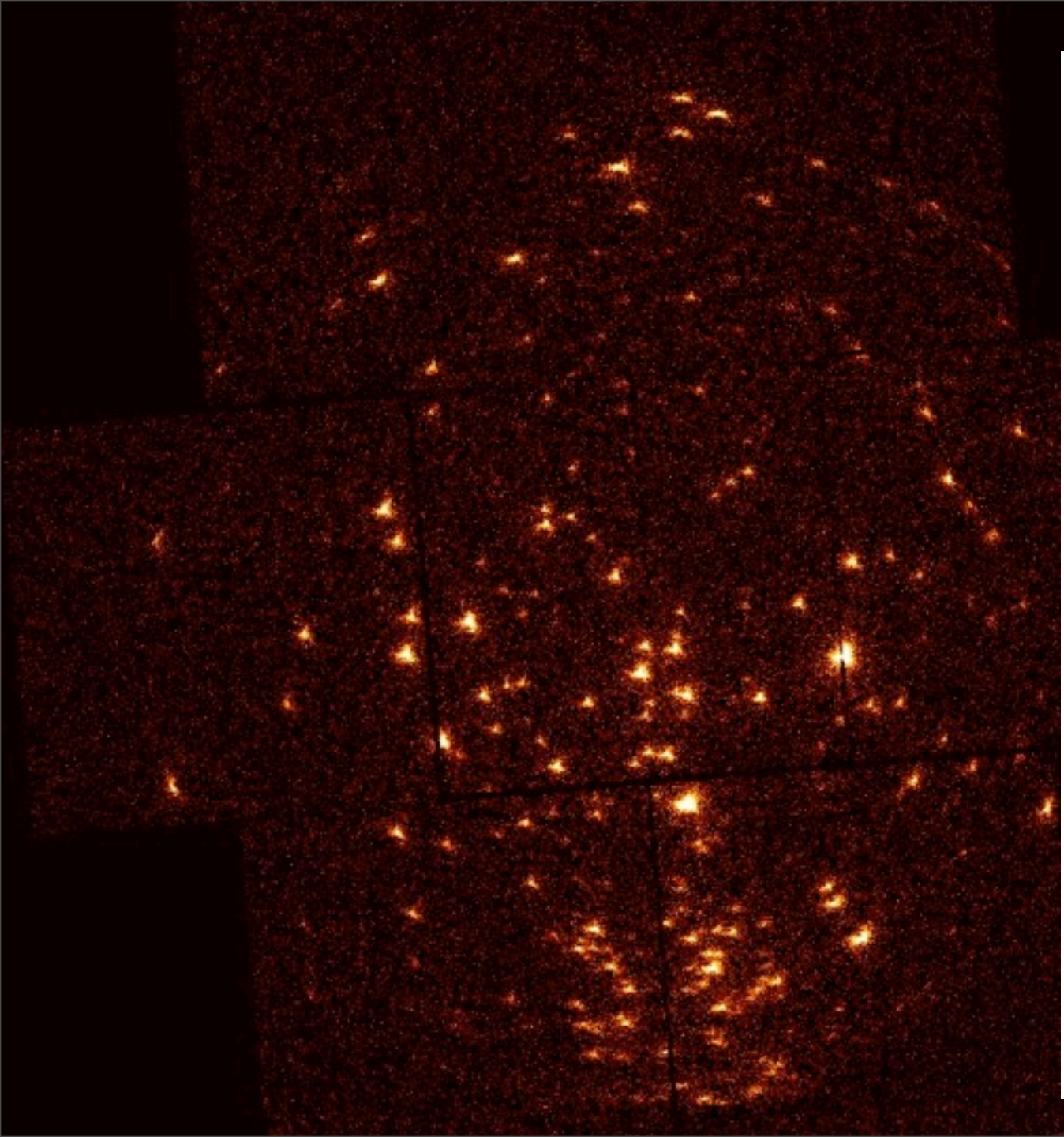
Solved the 1st Astrometry Issue – the 'S' – via using the 2-D PSF ('S' is due to the default PSF) – improved the astrometry of EPIC over the whole mission

The 2nd Astrometry Issue – the 'Offset'



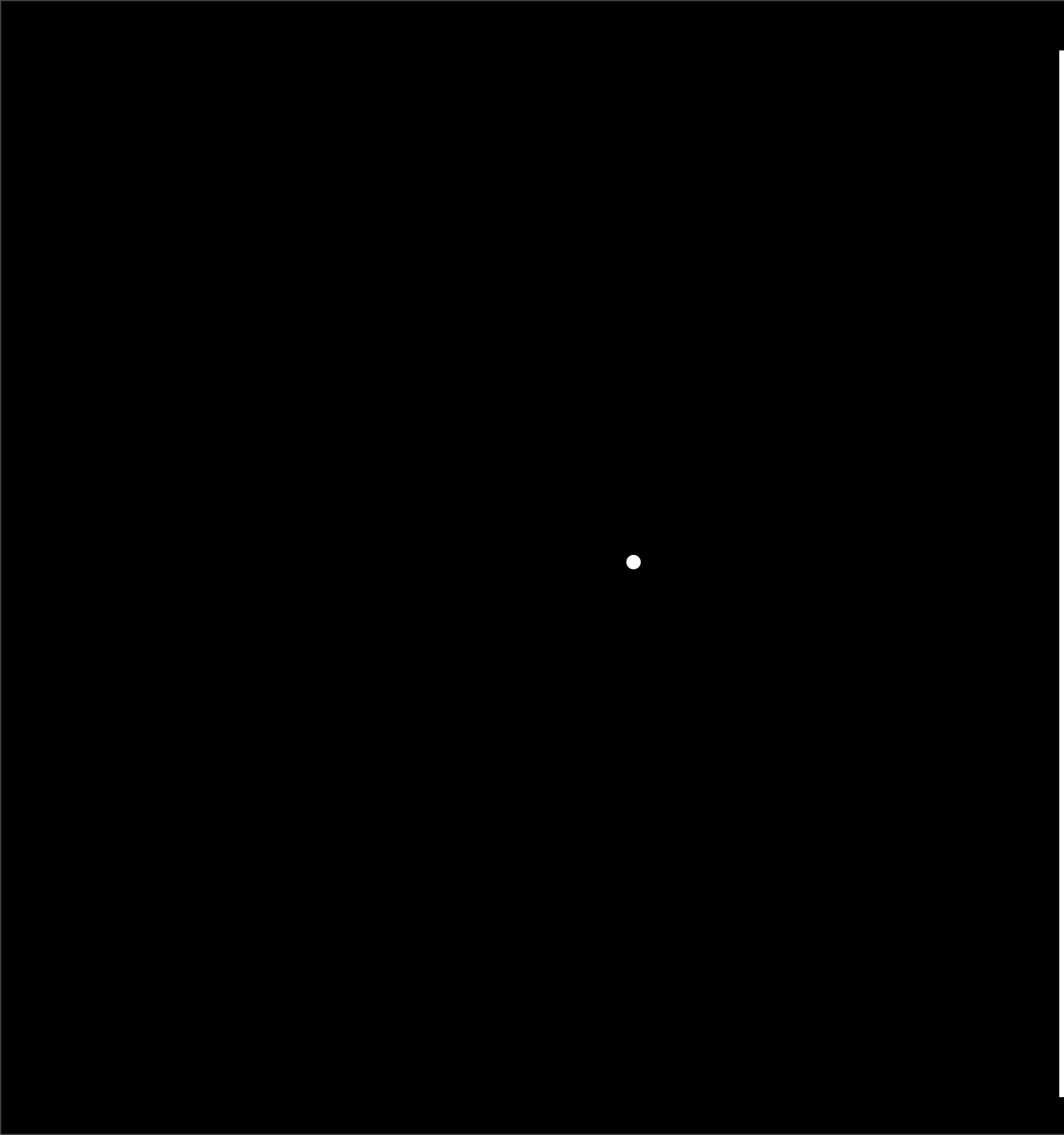


- Several attempts at correcting this, but all unsuccessful, but these did uncover the 3rd Astrometry Issue (see later)
- Fact that an RA/Dec shift is seen when the only thing that is changed is the PSF (Def to 2D) suggests that something is different/wrong in the software when extracting/forming the PSF 'image' from the CAL and placing it in the emldetect sky frame (PSF systems are very different [default-images, 2D-analytic]).
- However, needed to look at this in more detail to convince people…



Method

- Simplify everything as much as possible
- Take a typical event file and force all events to be at the same X/Y – create image of a ‘perfect’ ‘delta’ point source, where the position is precisely known
- Run full detection chain, with simplifying exposure maps, masks etc
- Test usage of both PSFs and at several points across the detector and using different image binnings



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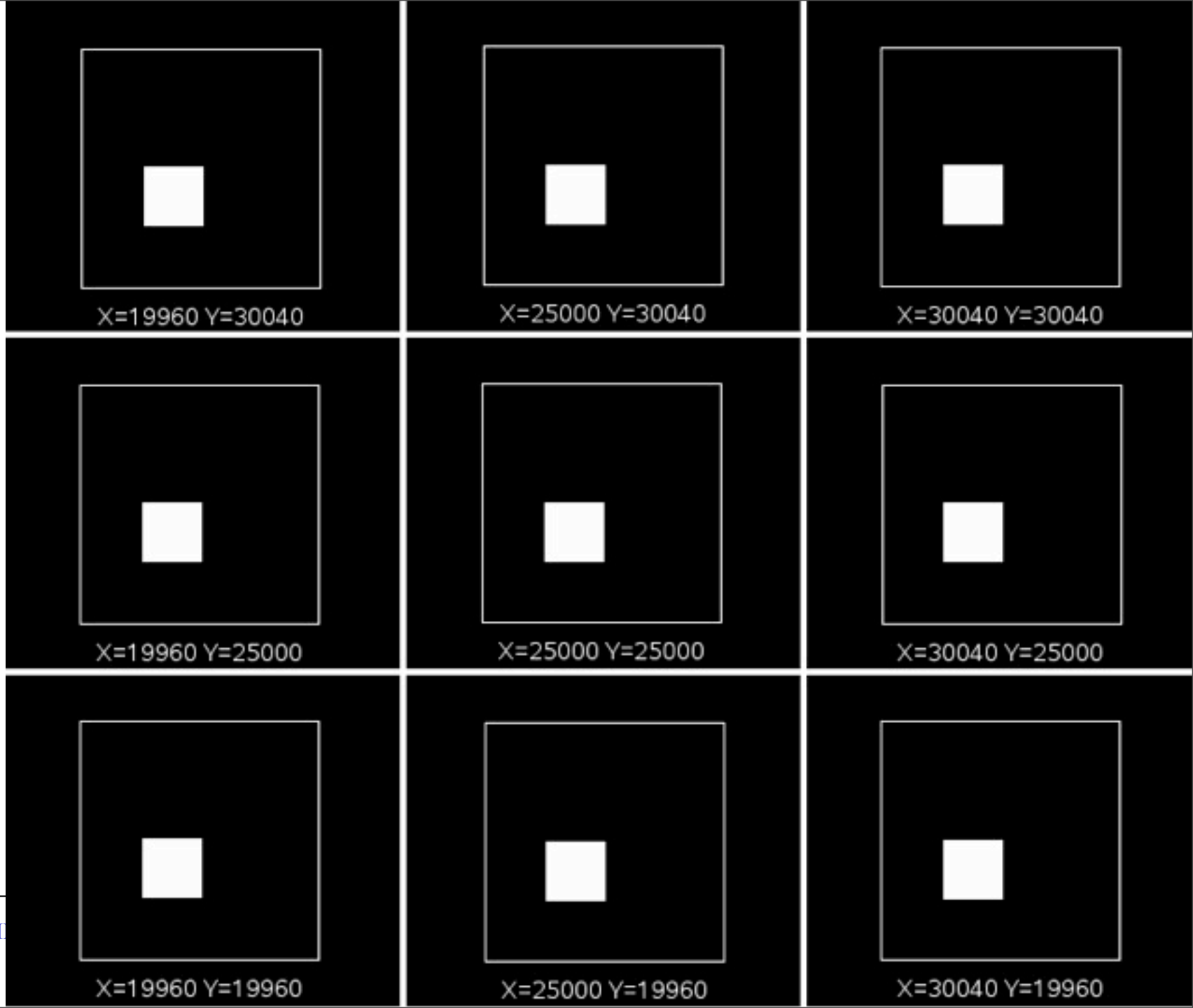
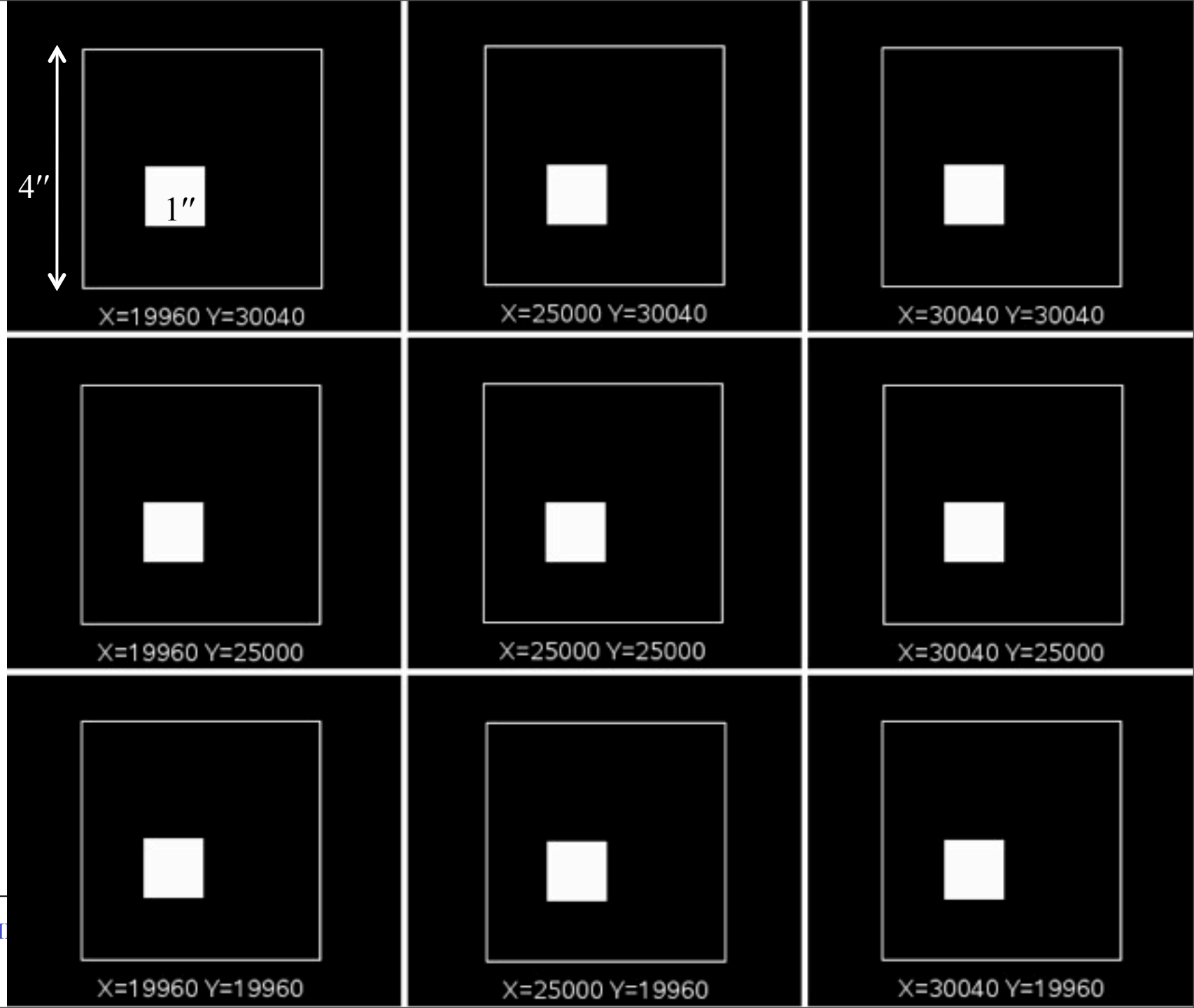

X=19960 Y=30040
X=25000 Y=30040
X=30040 Y=30040
X=19960 Y=25000
X=25000 Y=25000
X=30040 Y=25000
X=19960 Y=19960
X=25000 Y=19960
X=30040 Y=19960

XM

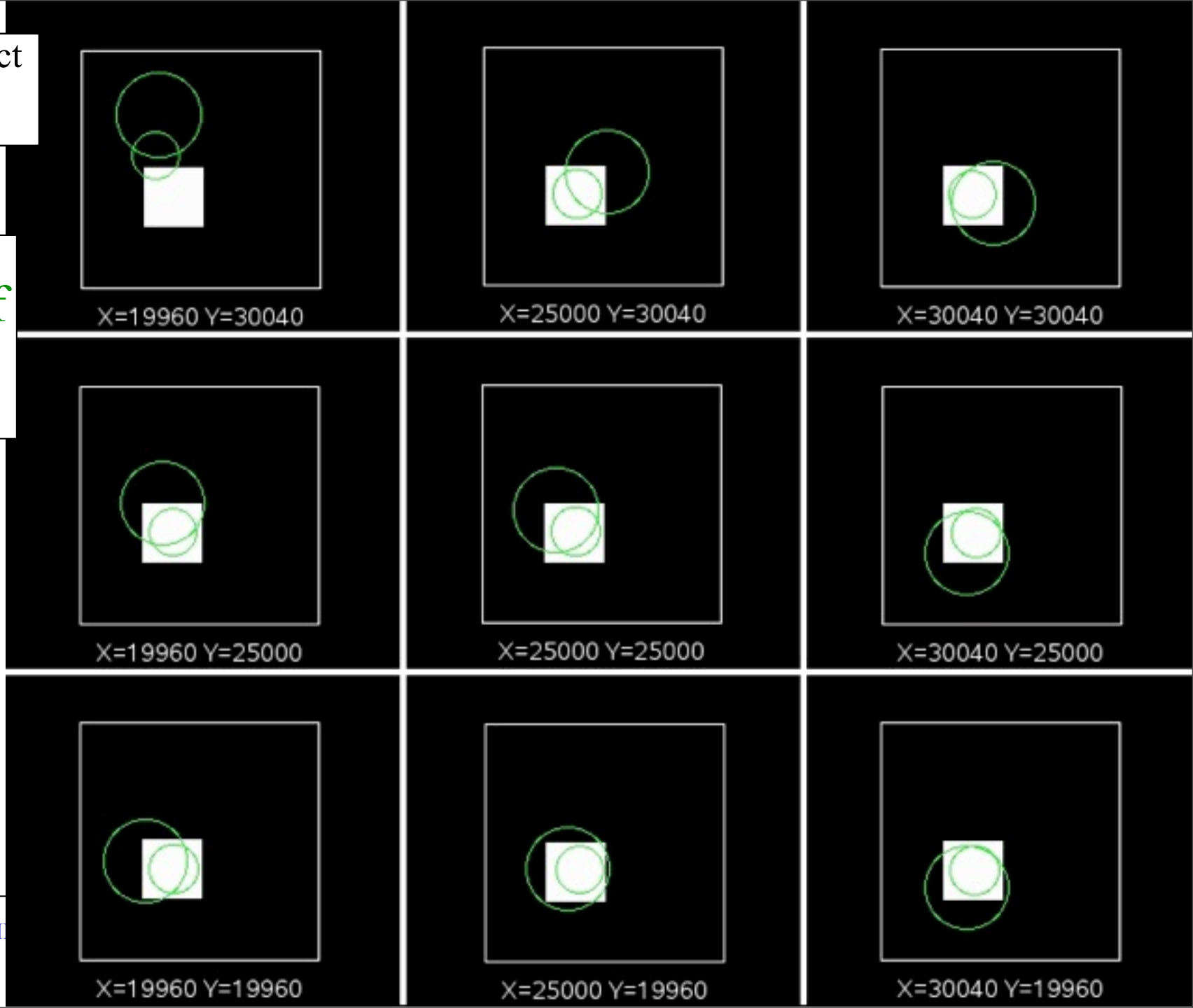

4″
1″
X=19960 Y=30040
X=25000 Y=30040
X=30040 Y=30040
X=19960 Y=25000
X=25000 Y=25000
X=30040 Y=25000
X=19960 Y=19960
X=25000 Y=19960
X=30040 Y=19960

XMI

emldetect
5.15.2

4” def

4” 2-D

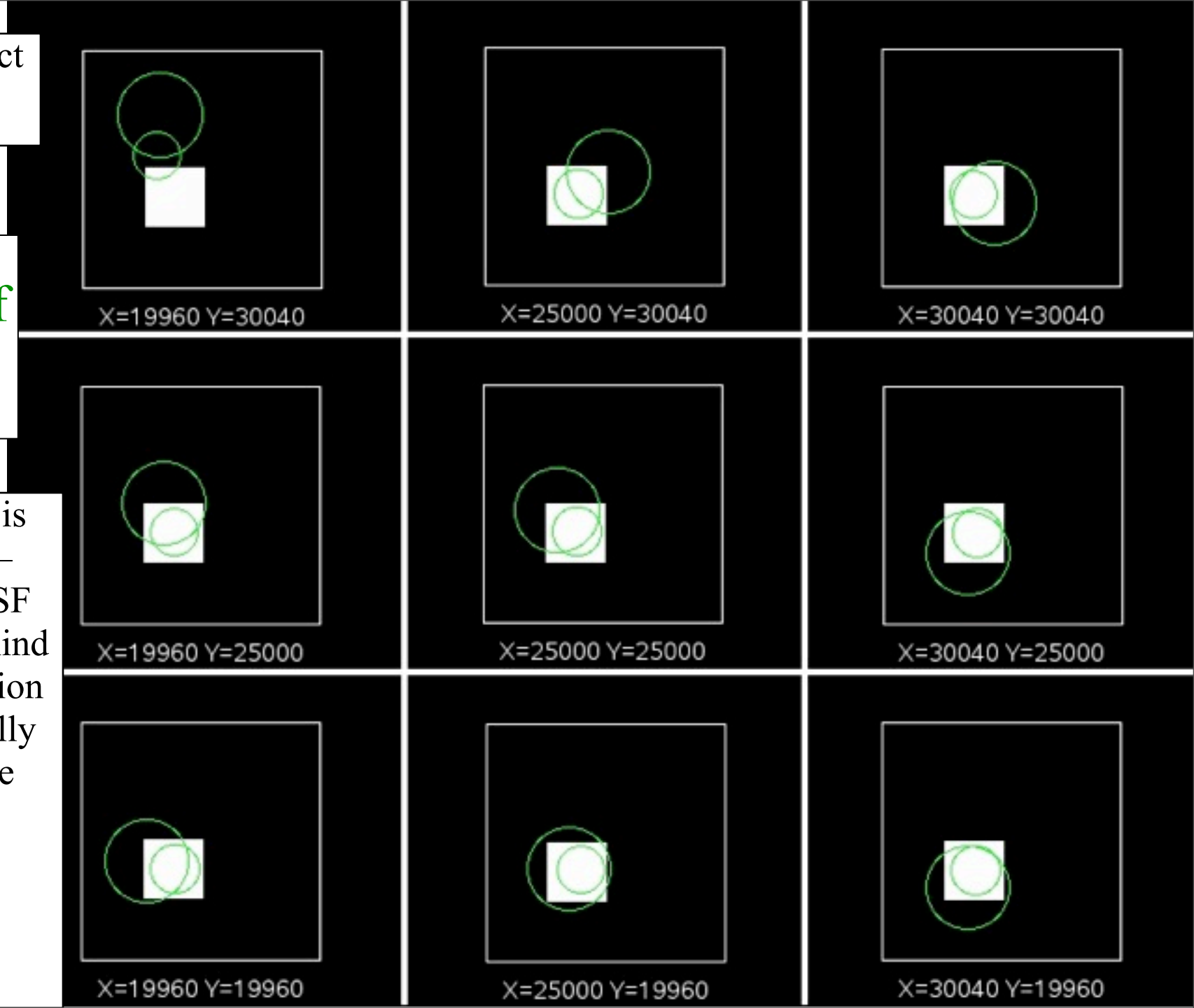


emldetect
5.15.2

4” def

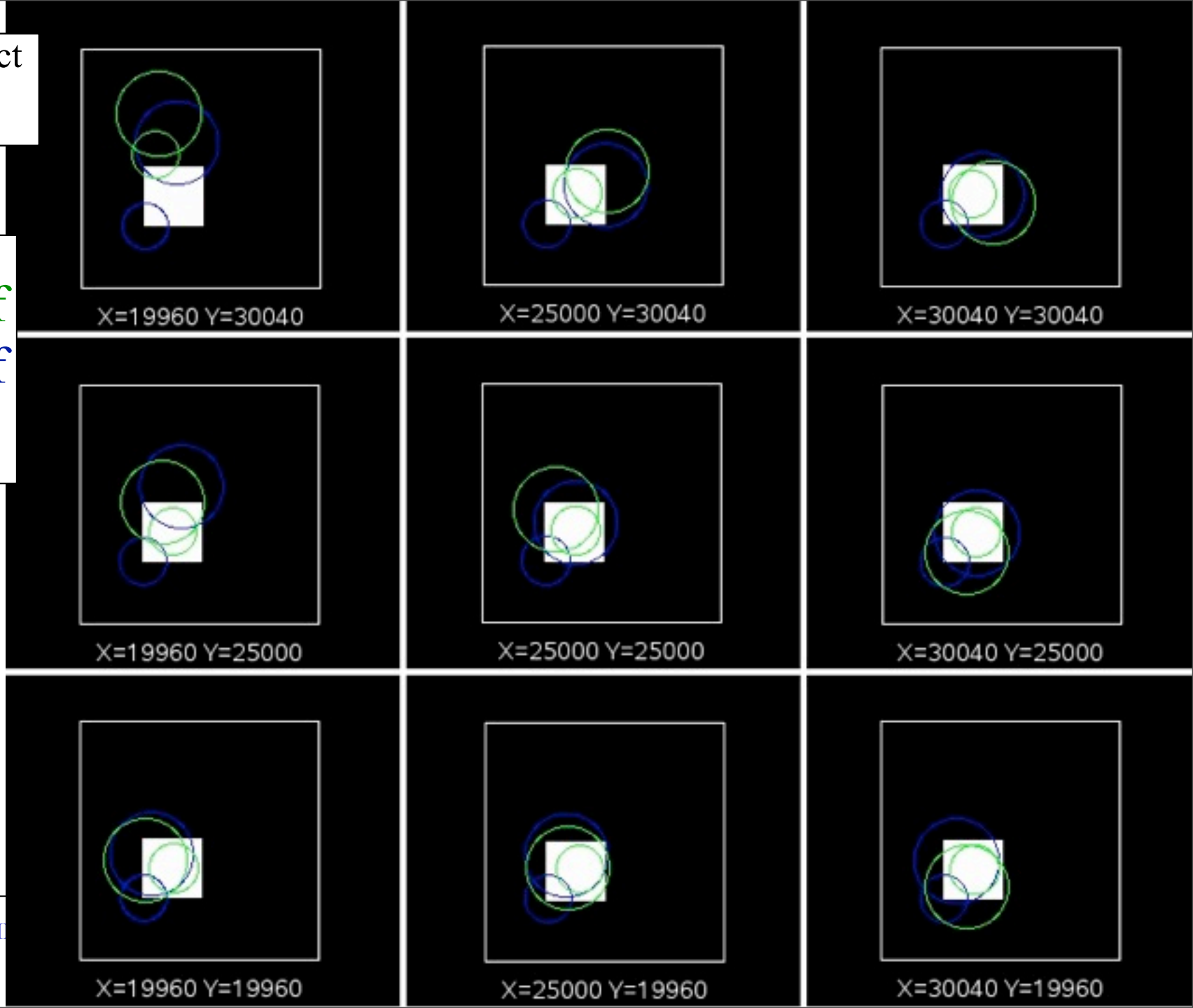
4” 2-D

‘S’ effect is apparent – default PSF ‘lags’ behind 2-D position sinusoidally around the detector



emldetect
5.15.2

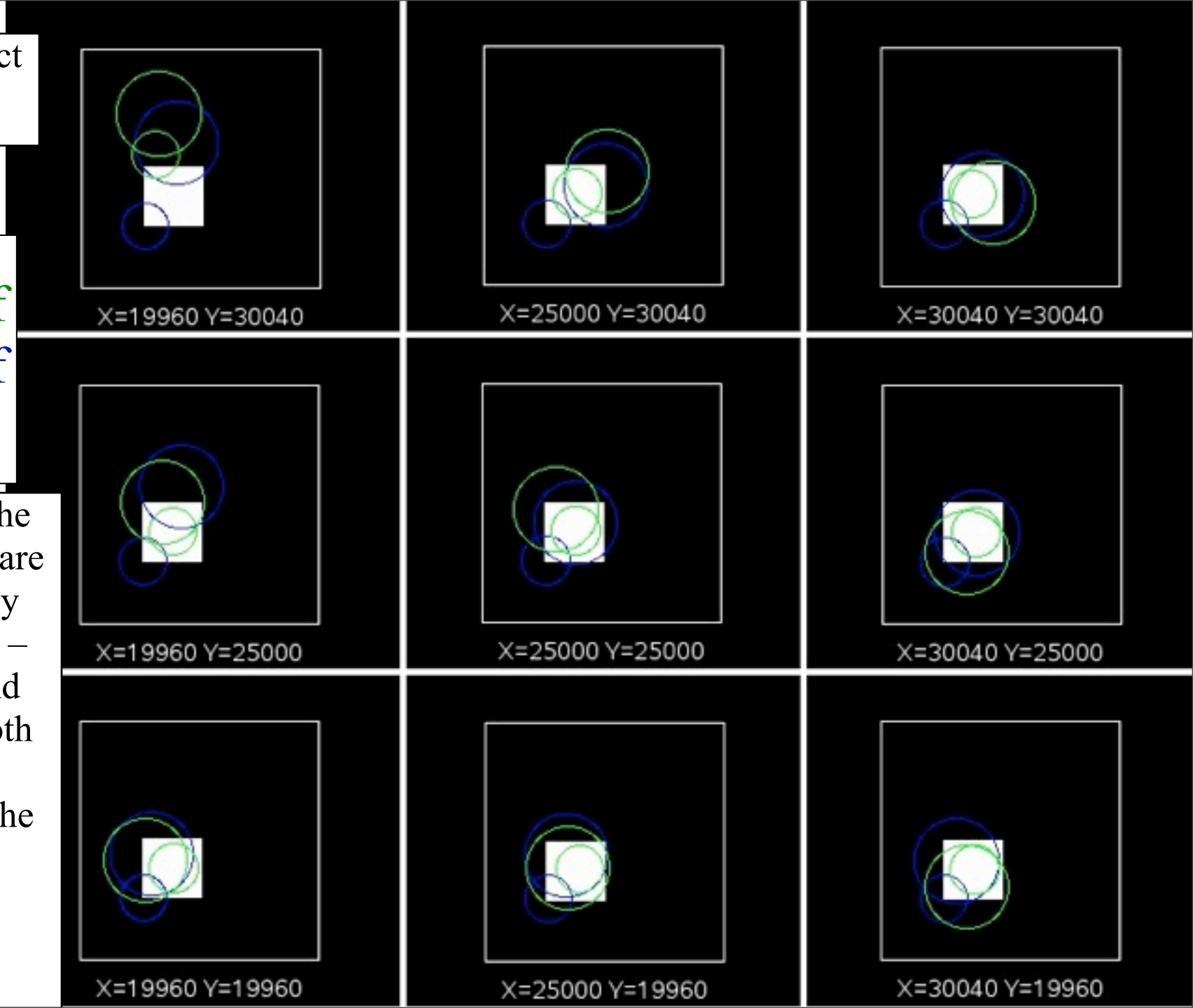
4” def
1” def
4” 2-D
1” 2-D



emldetect
5.15.2

4” def
1” def
4” 2-D
1” 2-D

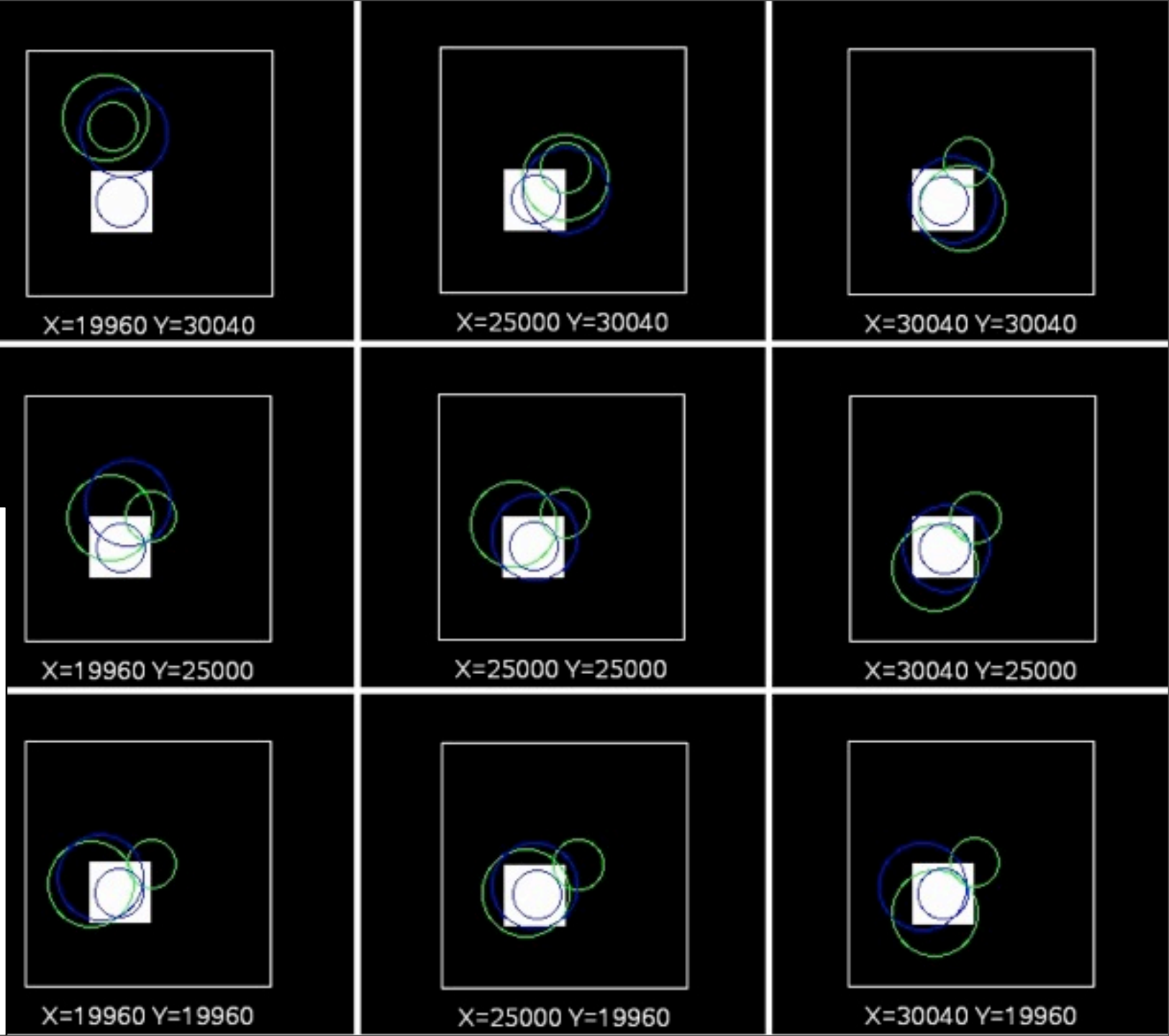
None of the positions are where they should be – 4” 2-D and 1” 2-D both should be ~0.5” to the right and ~0.5” up.



emldetect
5.15.4

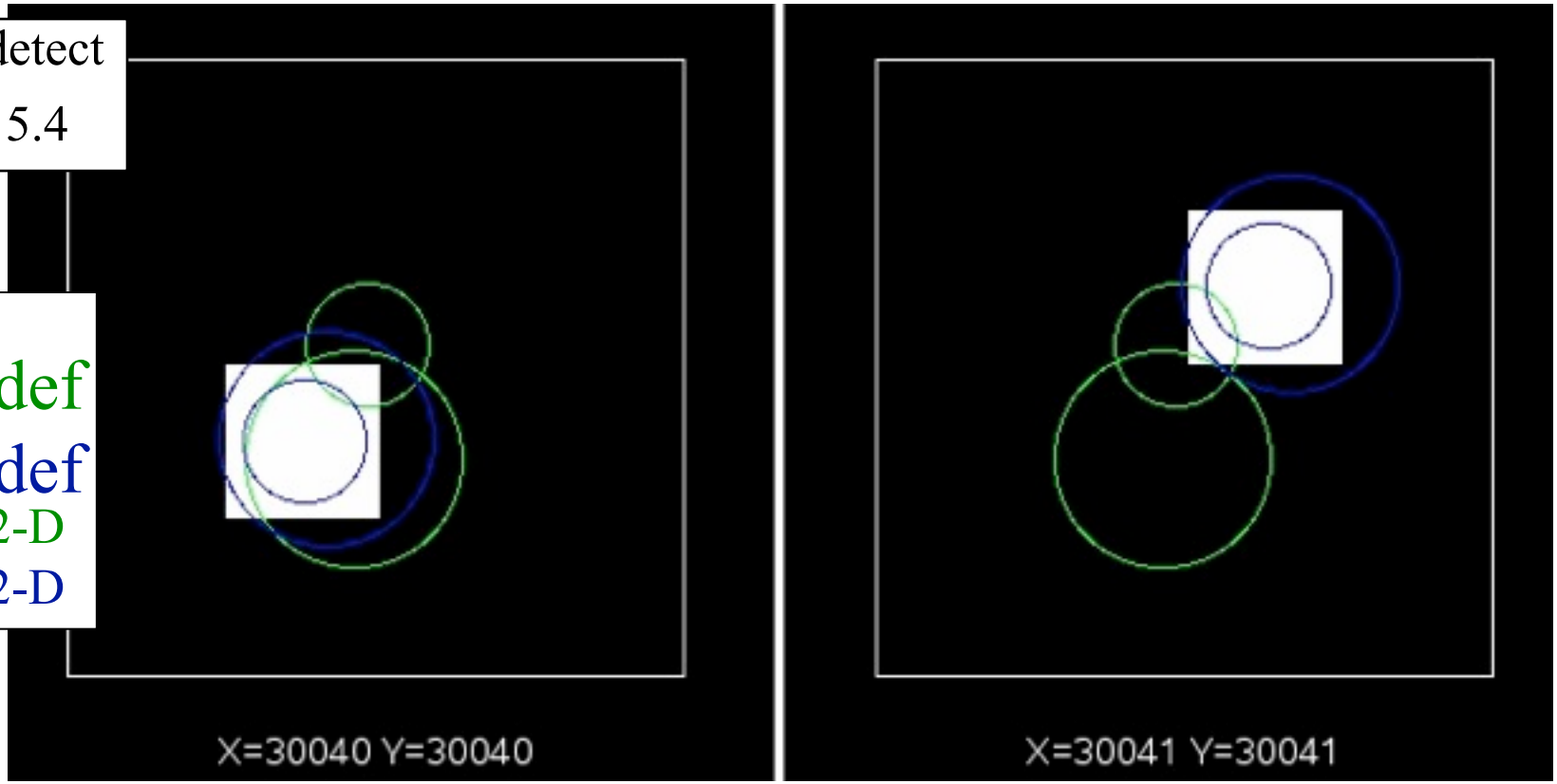
4” def
1” def
4” 2-D
1” 2-D

New (2-D) emldetect – 2-D positions are now a lot closer to where they should be.



emldetect
5.15.4

4” def
1” def
4” 2-D
1” 2-D

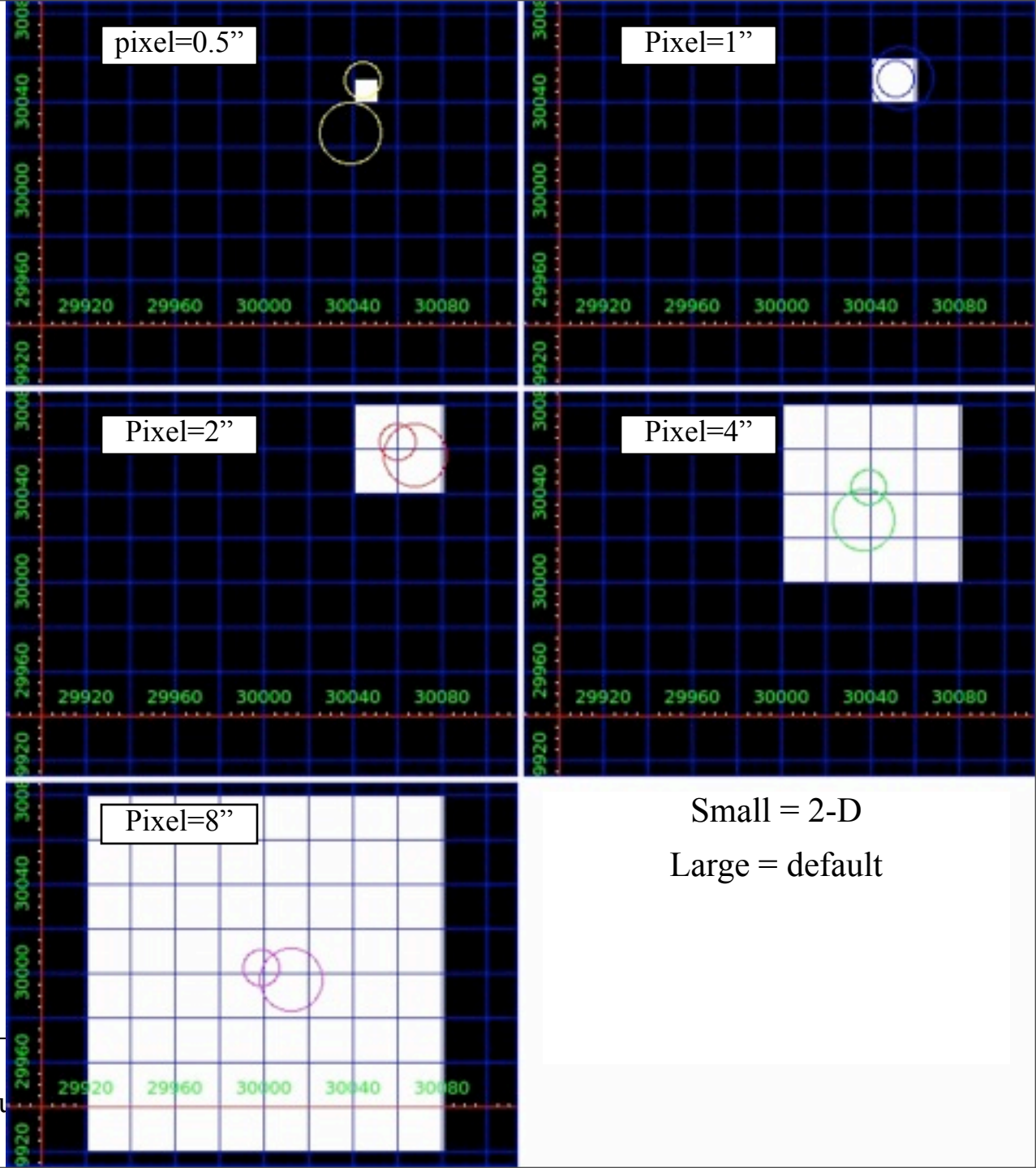


- Detailed look at situation when we shift event X/Y values by 1 sky pixel (0.05”).
- Situation looks sensible – new emldetect 2-D positions are where they should be.
- Potsdam believe there to be a different, separate error in the default PSF (which is already problematic [last AMR BOC talk]) – many reasons to ditch default PSF…

emldetect
5.15.4

Detailed look over several binning scales (at X=30040, Y=30040)

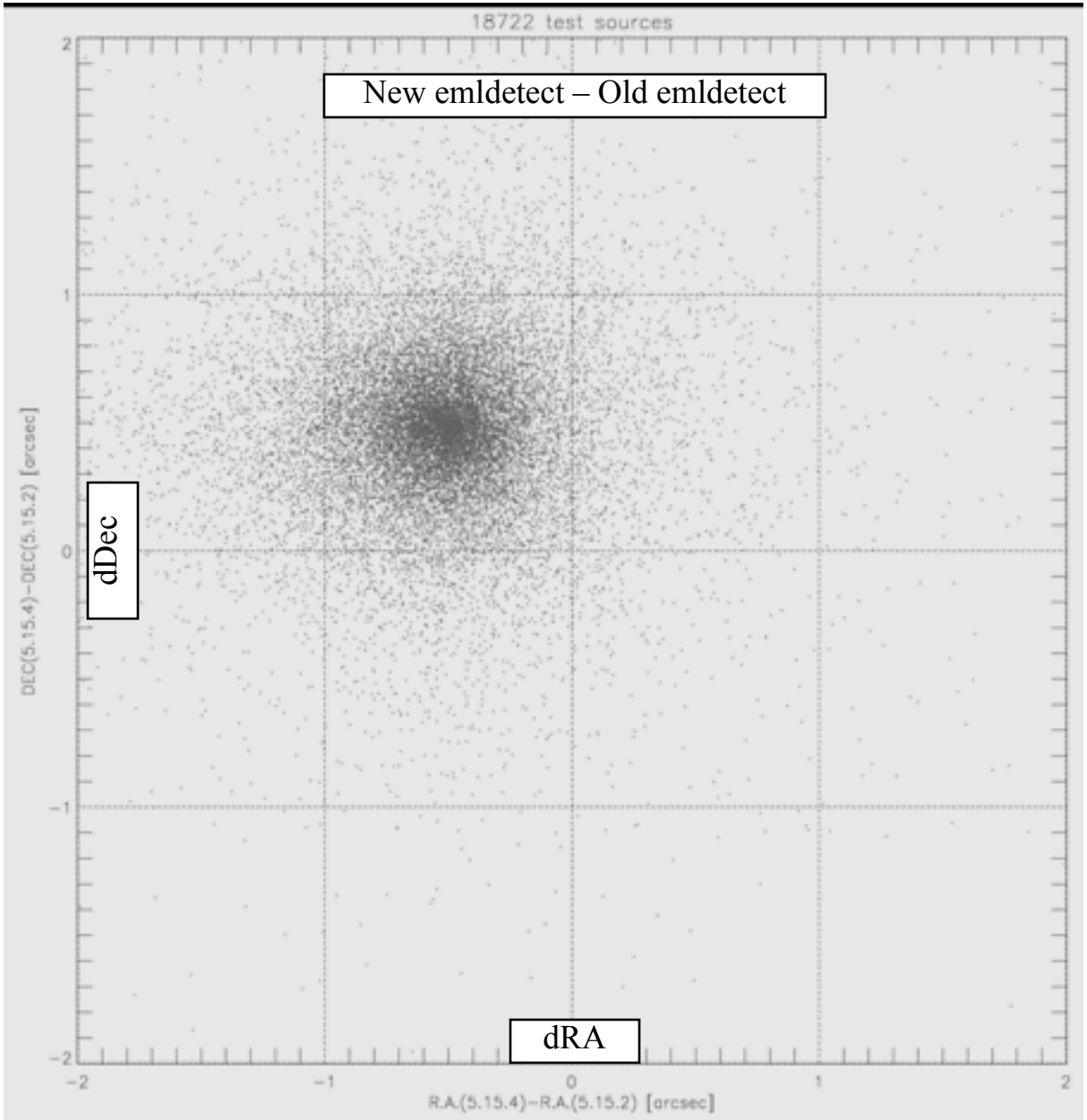
New emldetect (2-D) situation looks sensible



Small = 2-D

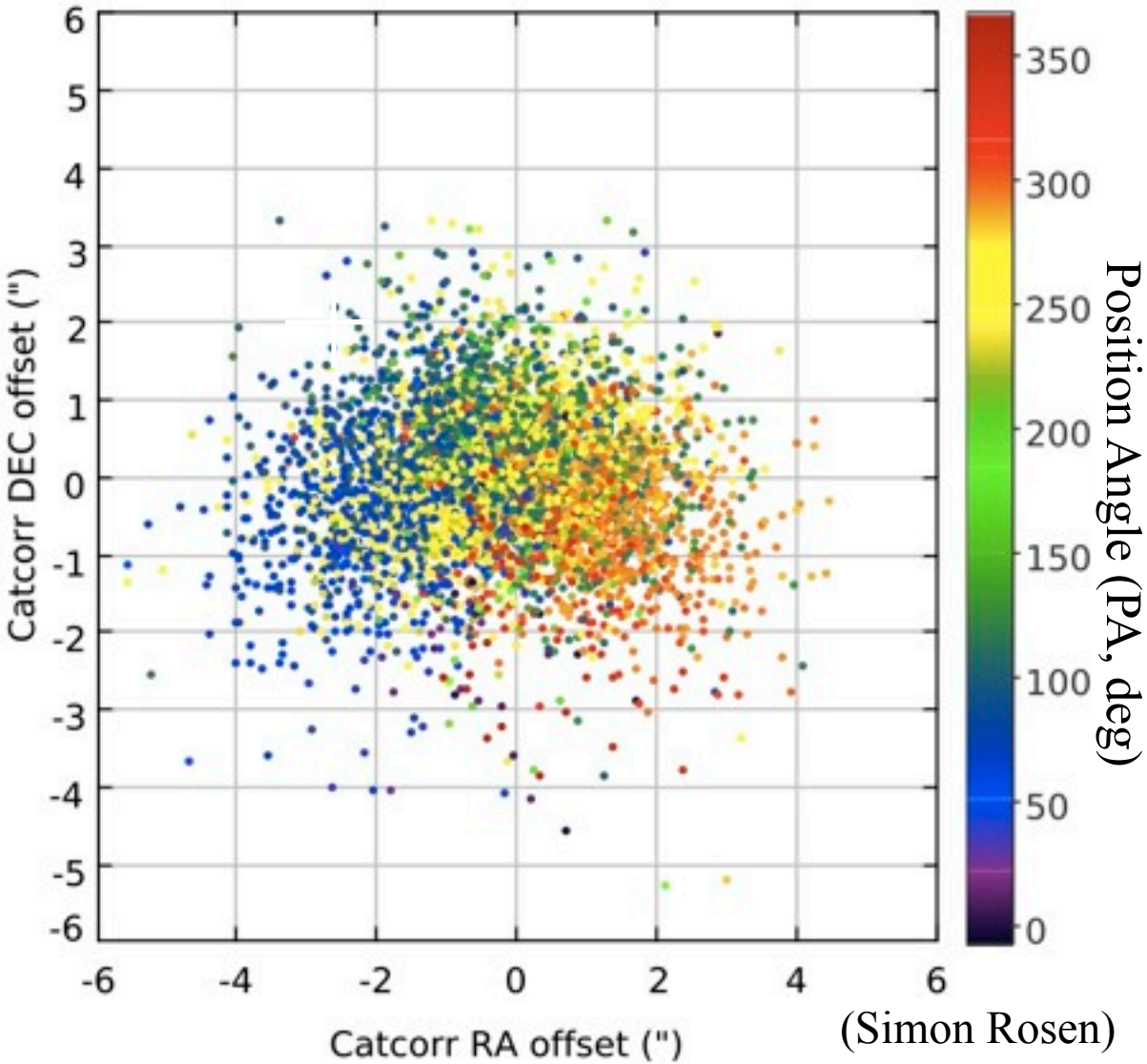
Large = default

- New emldetect ran on several datasets.
- Plot shows RA & Dec shifts (new emldetect minus old emldetect) for 18722 sources.
- Mean shift is approx -0.5” in RA and +0.5” in Dec
- As expected from ‘delta’ source work
- Accounts for some, but not all of the offset (2nd AI).



The 3rd Astrometry Issue – the 'PA Effect'

- During attempts to correct the offset, 3rd Astrometry Issue – the 'PA effect' was uncovered.
- Strong PA dependence on catcorr EPIC field offsets (SDSS QSO analysis shows same behaviour)
- Example is for default PSF – The 2D PSF shows same behaviour but with the 'offset' (2nd AI) in addition – The 'PA effect' is not due to the PSFs
- This effect has been present over the whole mission
- catcorr/eposcorr rectification can correct majority of EPIC sources



(Simon Rosen)

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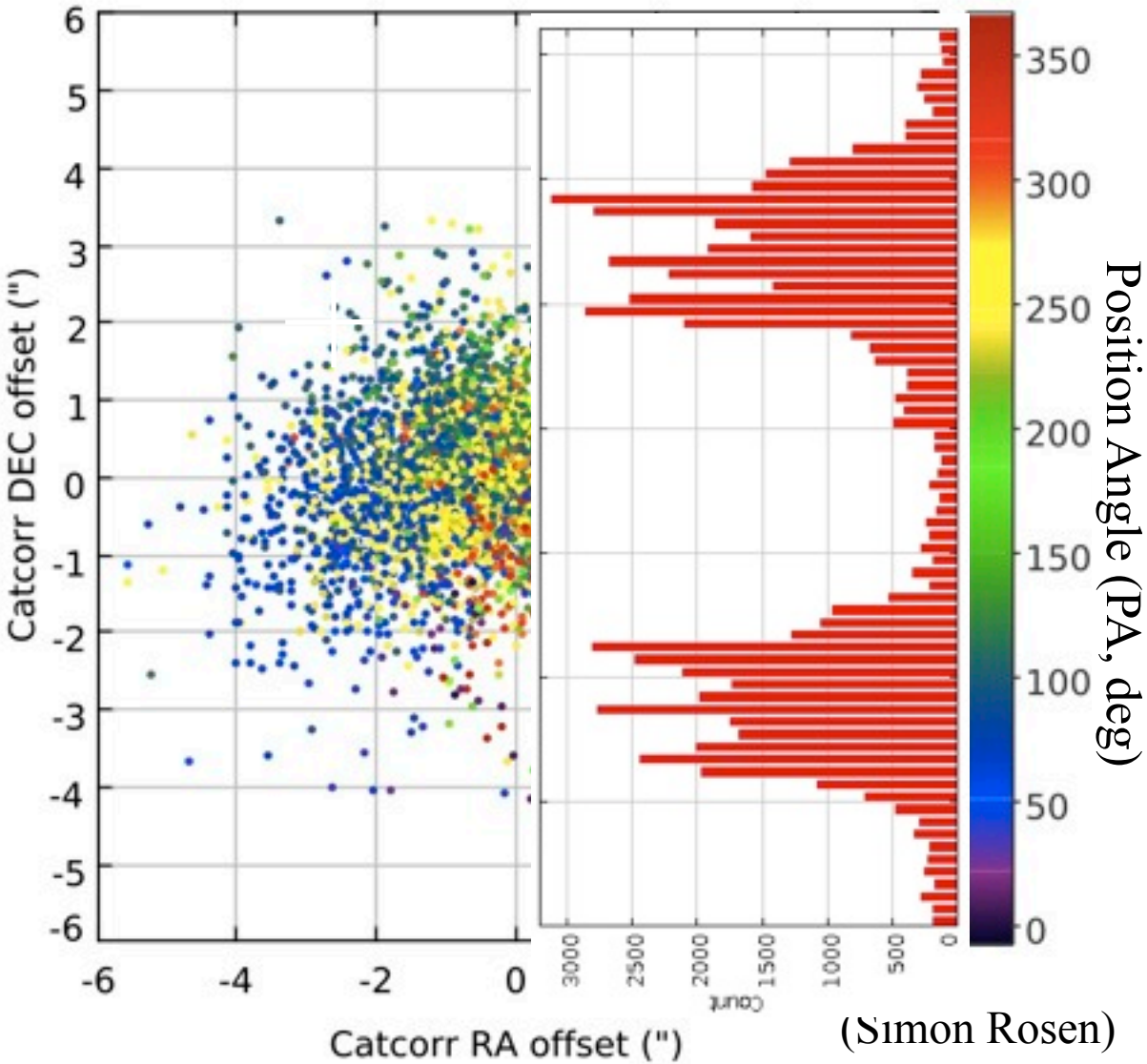
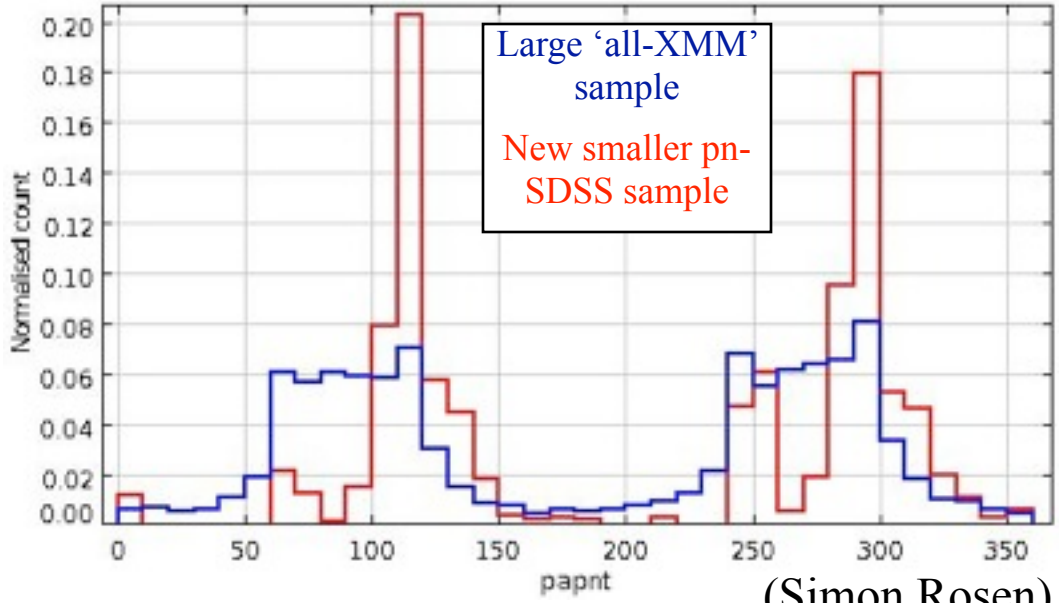


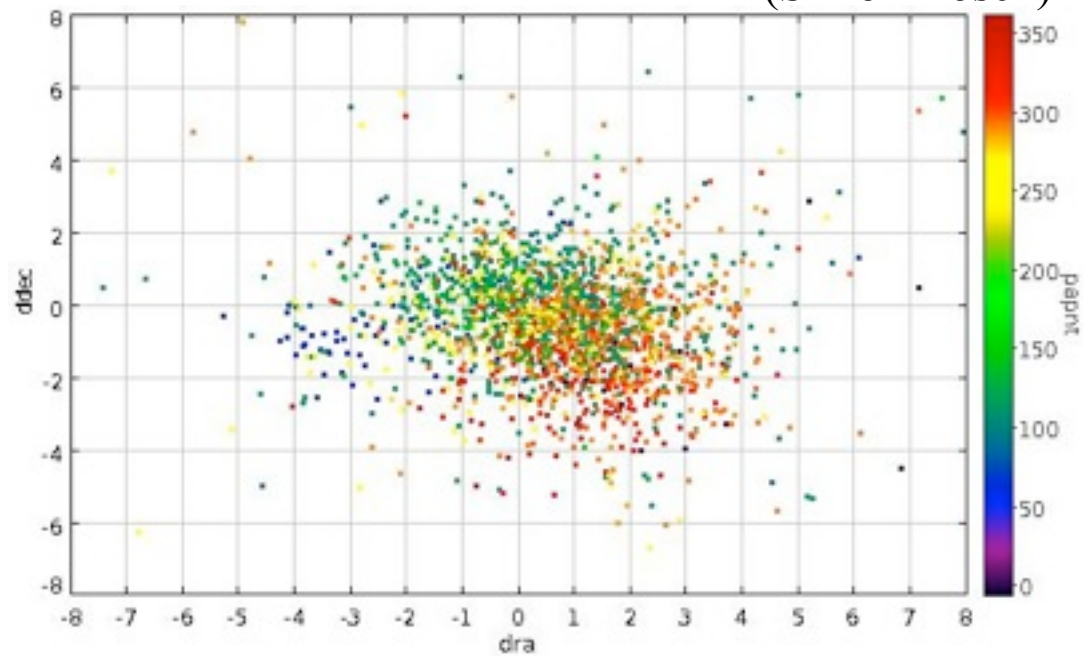
(Simon Rosen)

PA Sampling Biases

- Means that PA range sampled will bias the results obtained
- e.g. in verifying absolutely the shifts introduced by the new emldetect (to correct 2nd AI), we get different (mean) X-SDSS shifts depending on the PA distribution(s) sampled
- Need to be careful in our conclusions – take care in matching PA samplings

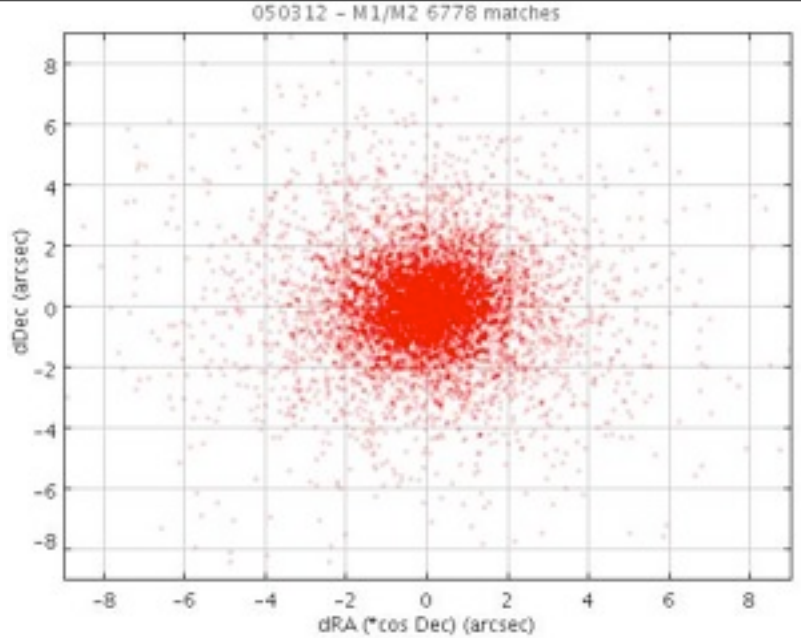


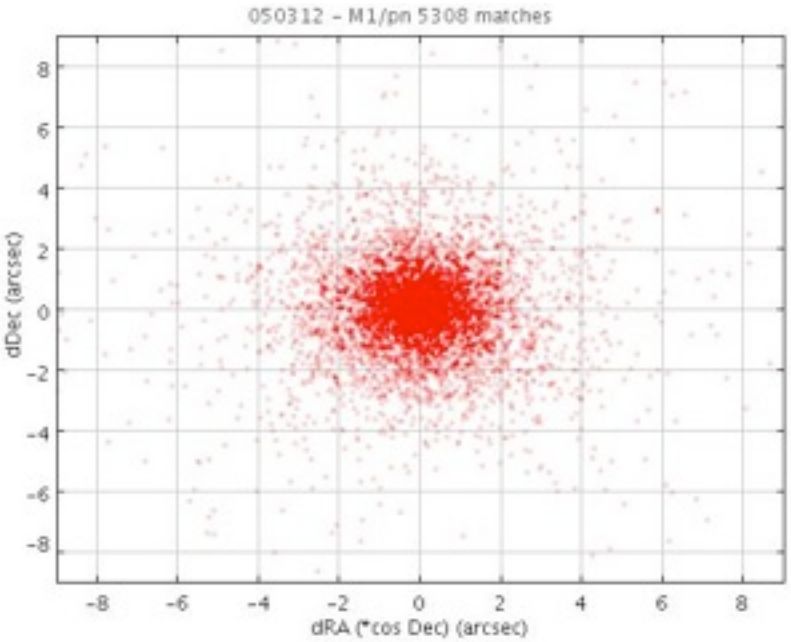
(Simon Rosen)

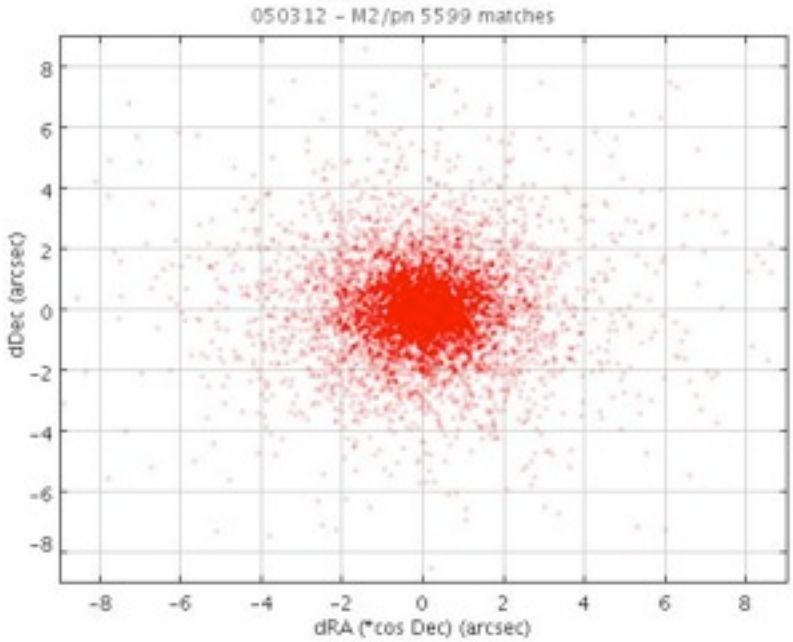


Offsets between EPIC instruments are very small. (New emldetect, new 2-D PSFs [0014], separate band-8 runs per EPIC instrument 409/426/426 pn/ MOS1/MOS2 fields successfully processed)

Instrument		dRA	dDec
MOS1	MOS2	-0.002”	-0.021”
MOS1	pn	-0.018”	-0.017”
MOS2	pn	-0.019”	-0.005”

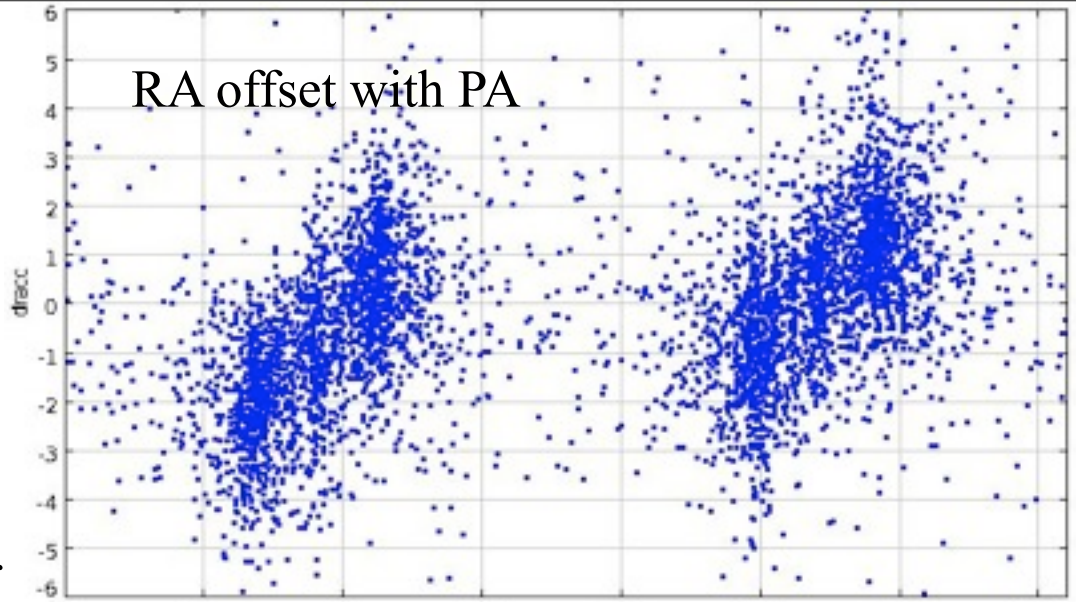


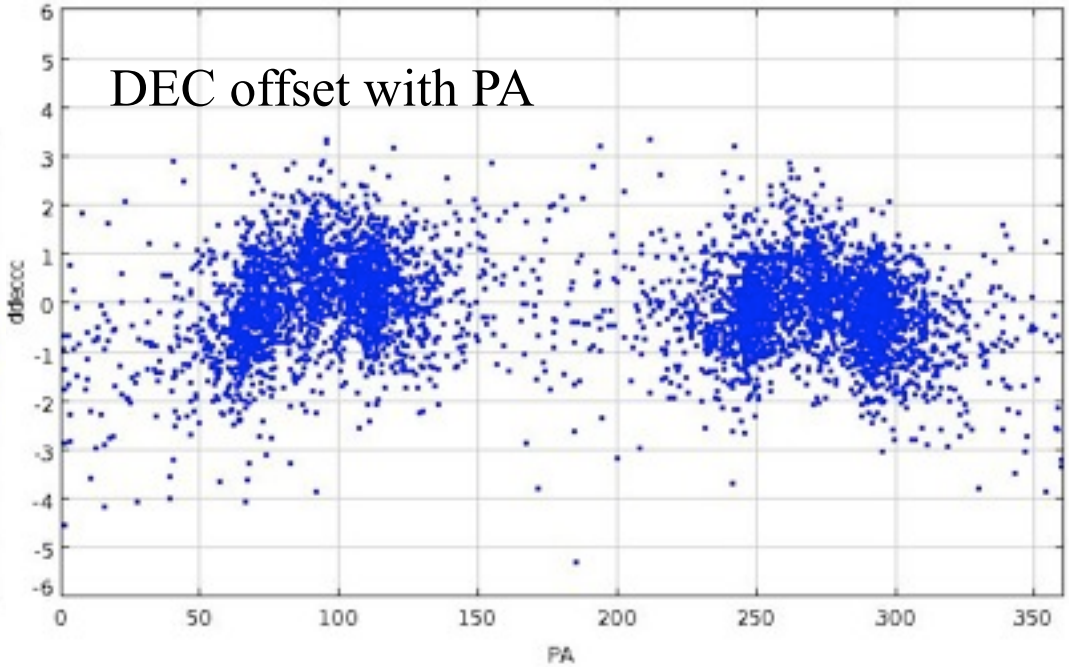


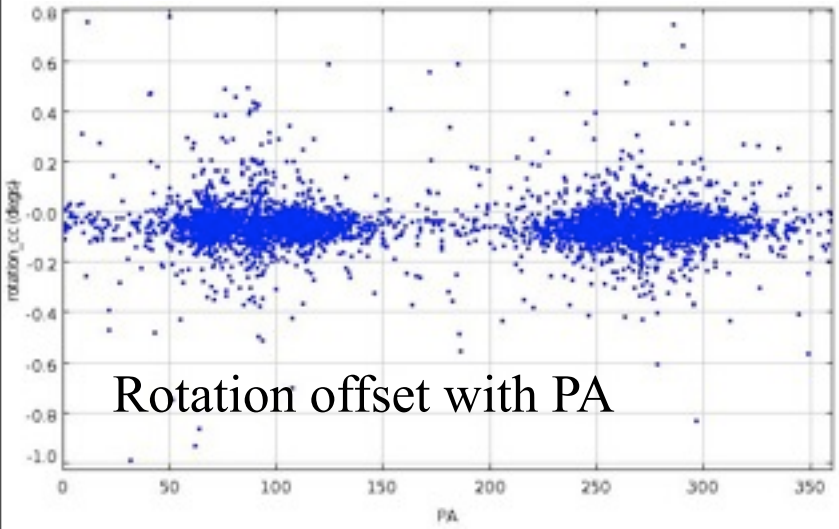


3rd AI – The 'PA' Effect

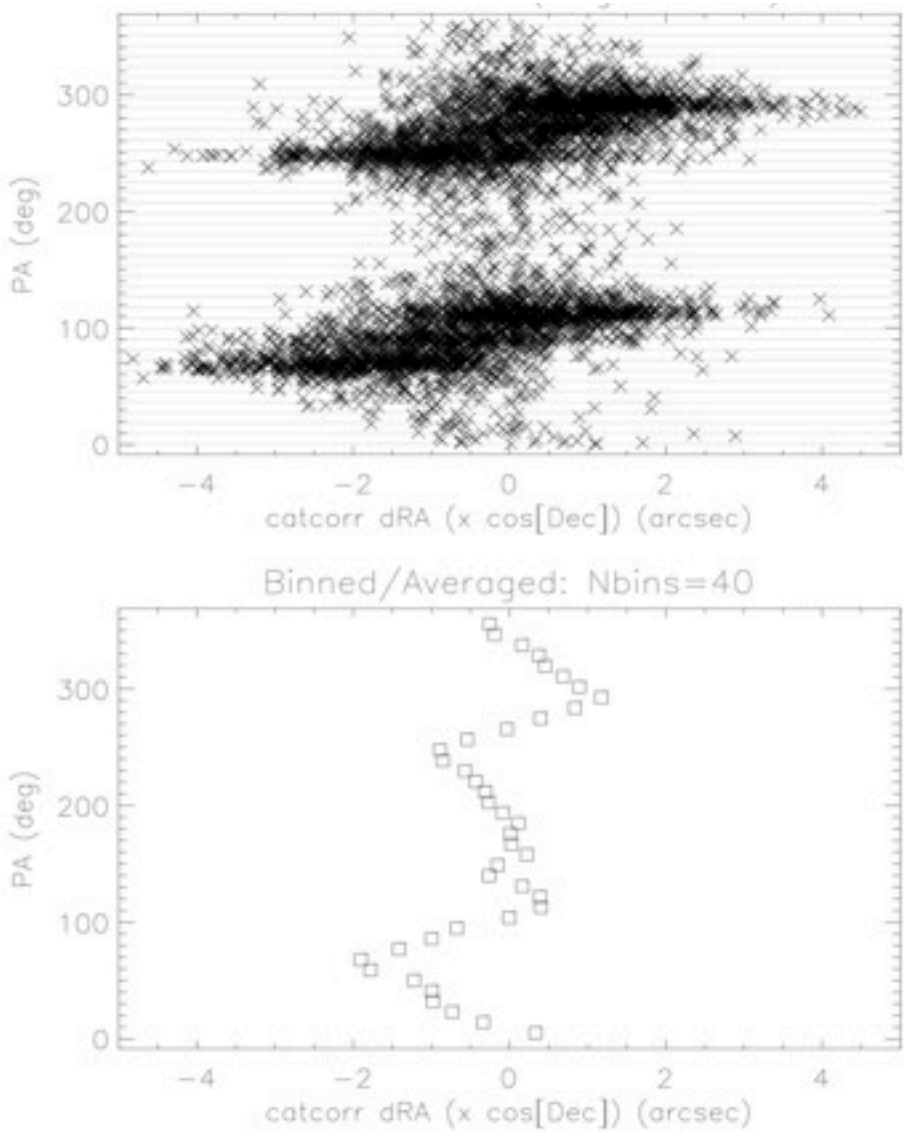
- RA & Dec offsets show 2 strong cycles over PA range
- Not easily characterised by simple trig function
- Correlations between many (sets of) parameters (e.g. RA-PA), such that underlying origin not clear (error in code? e.g. attcalc?)



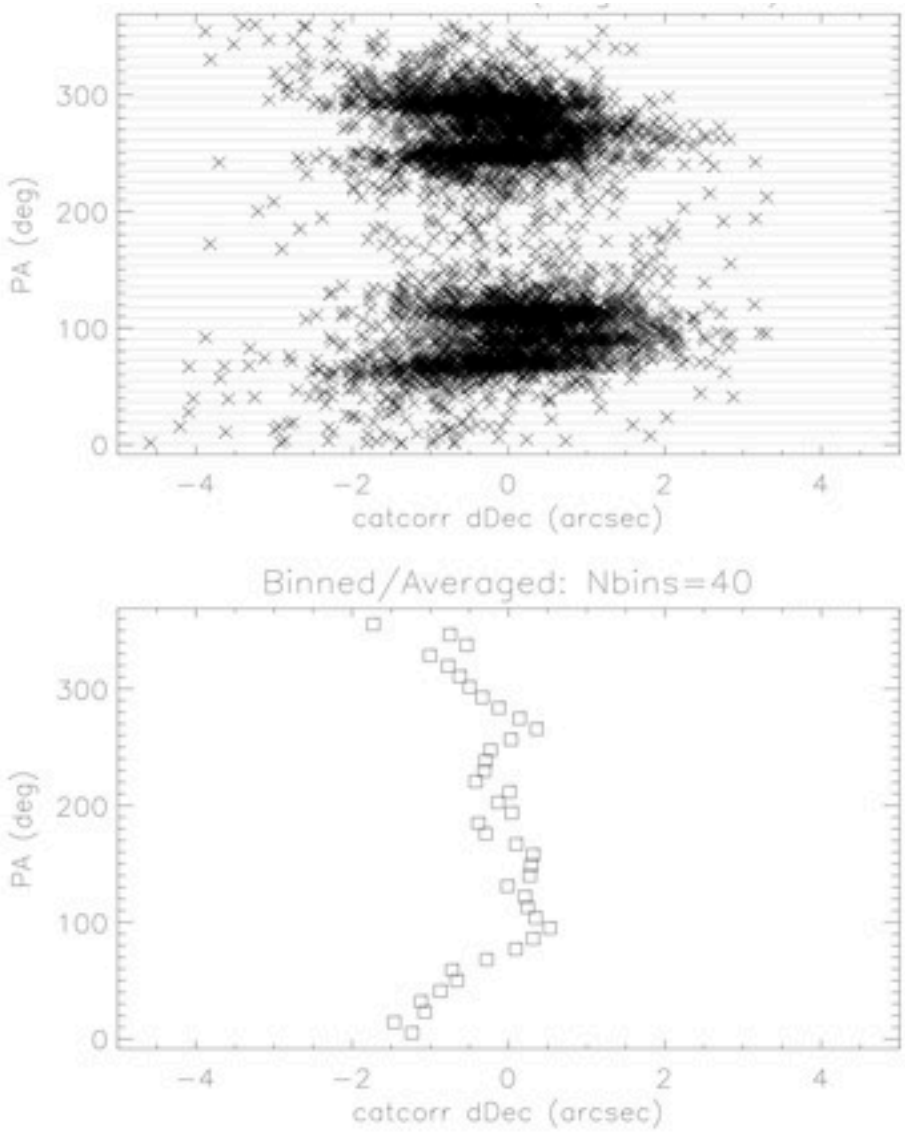




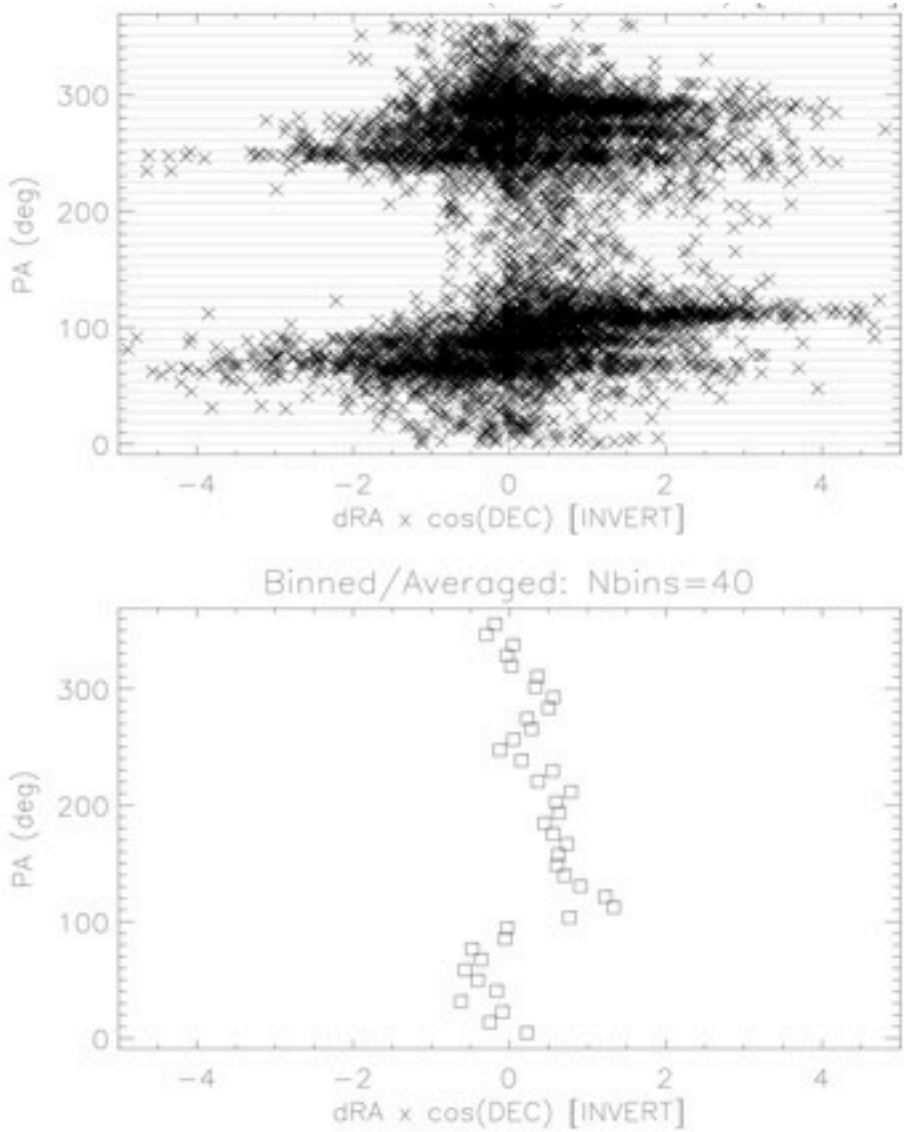
EPIC dRA v PA



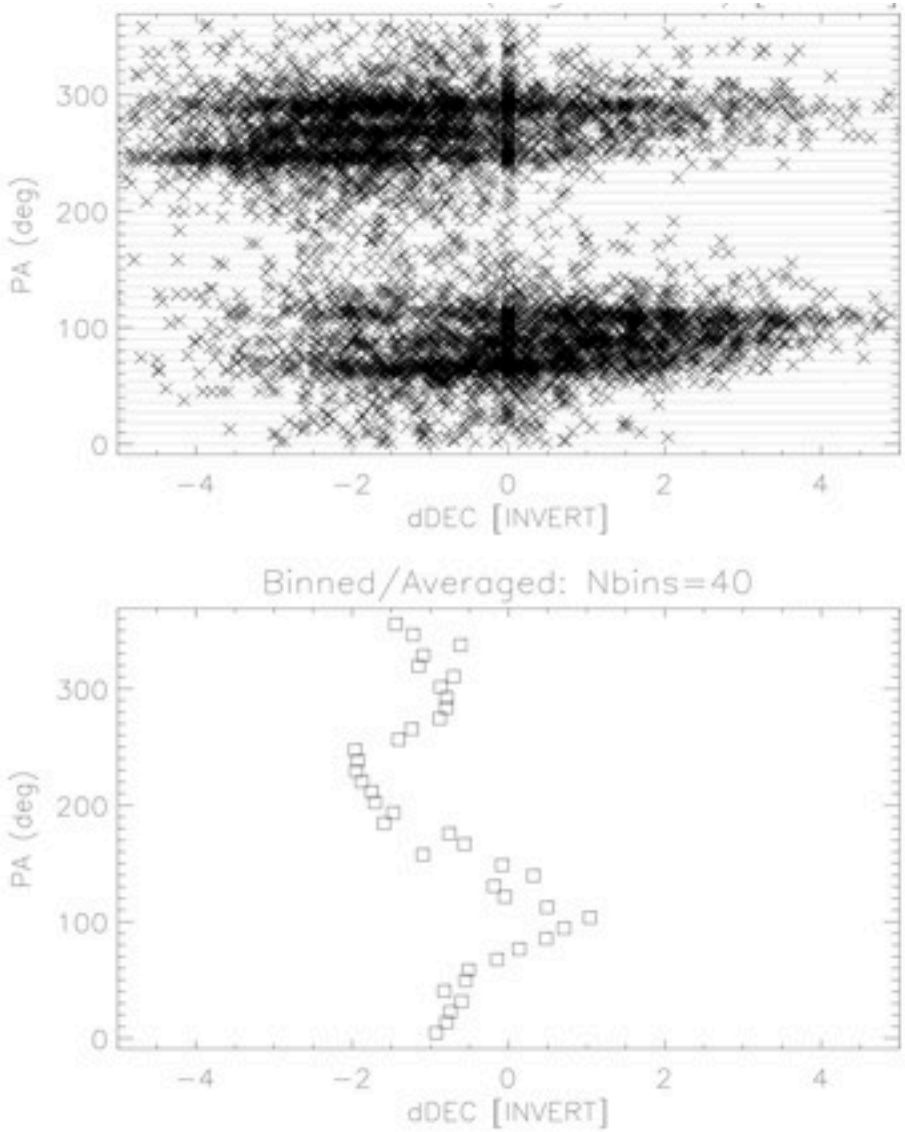
EPIC dDEC v PA



OM dRA v PA

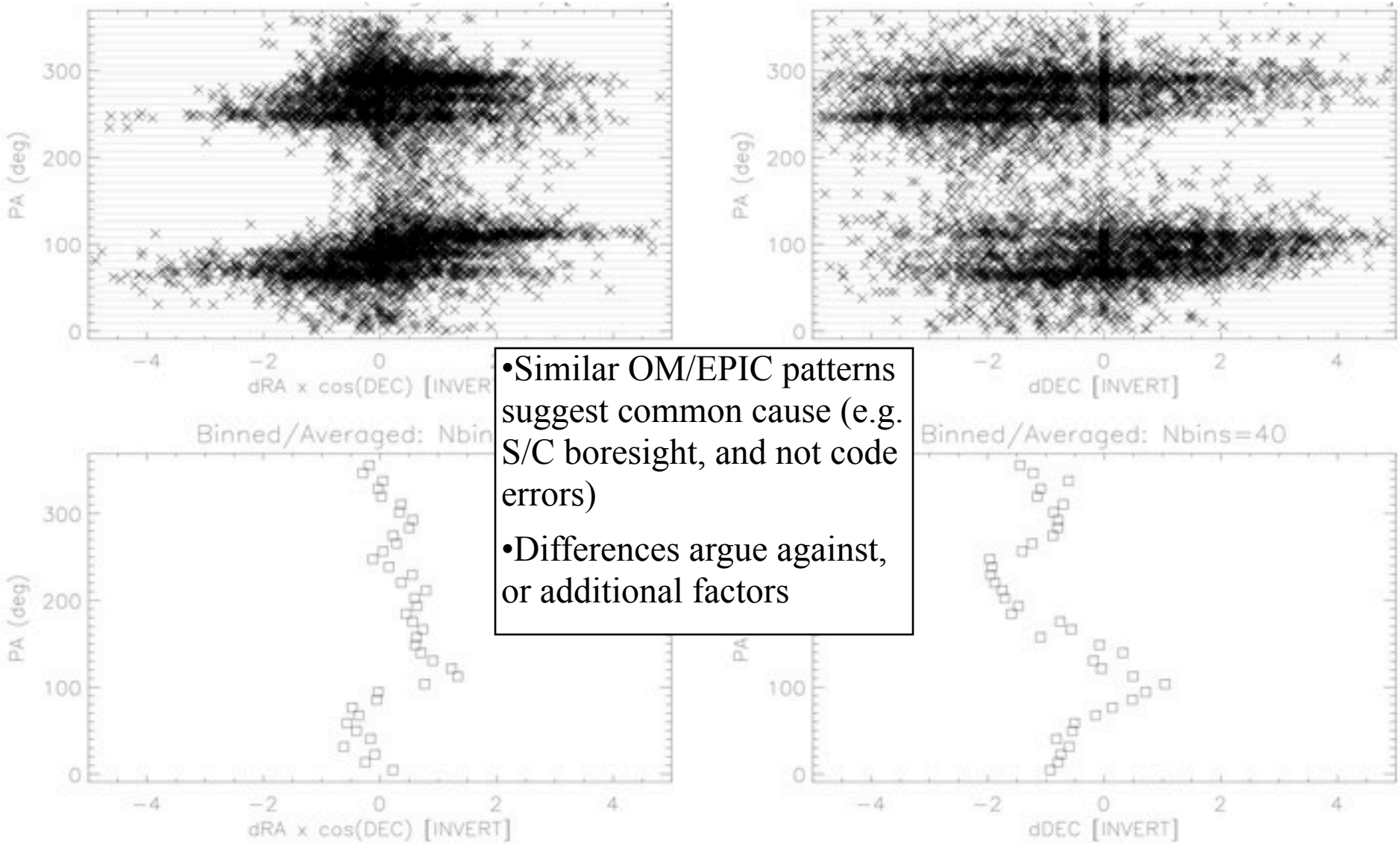


OM dDEC v PA



OM dRA v PA

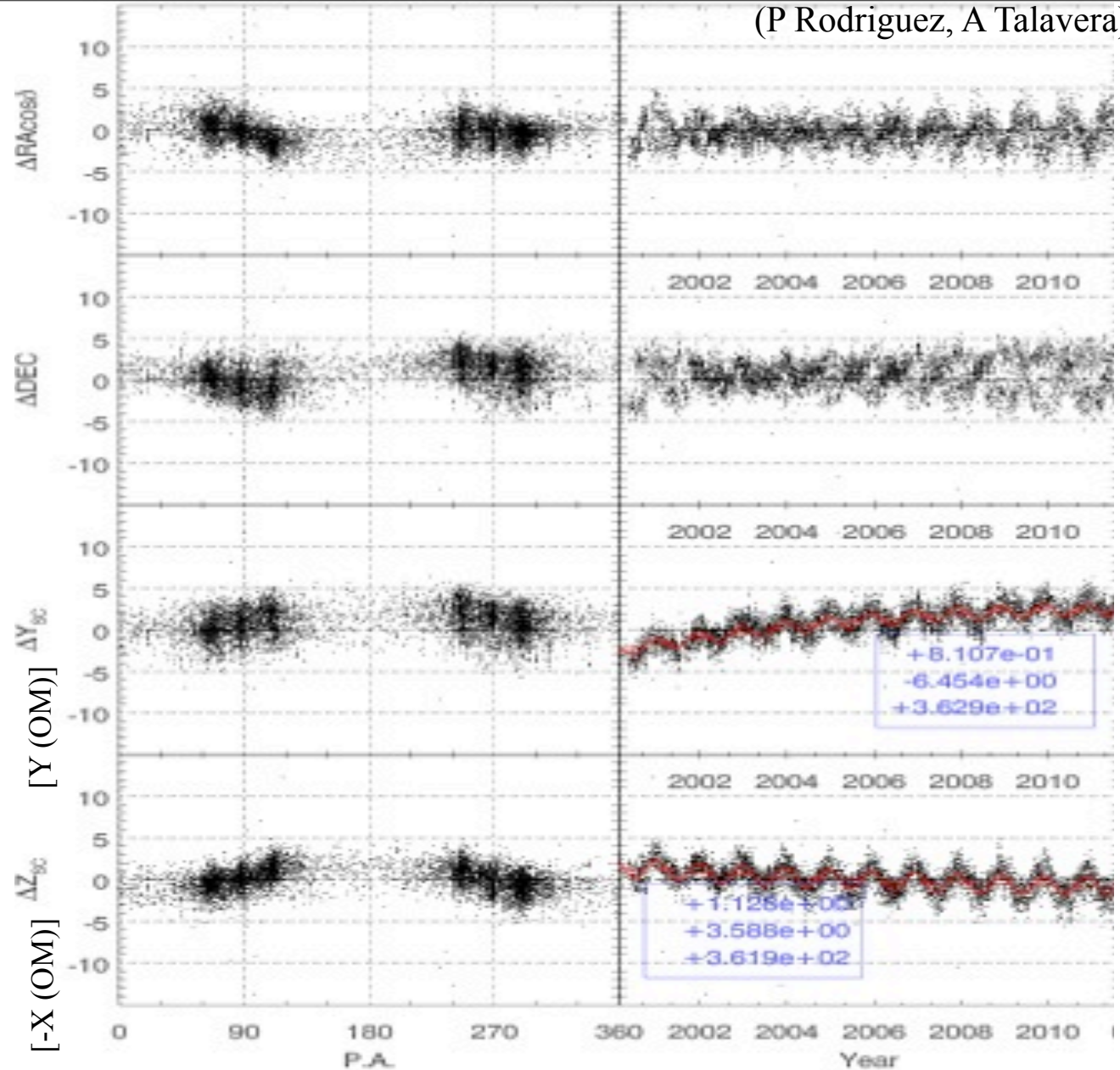
OM dDEC v PA



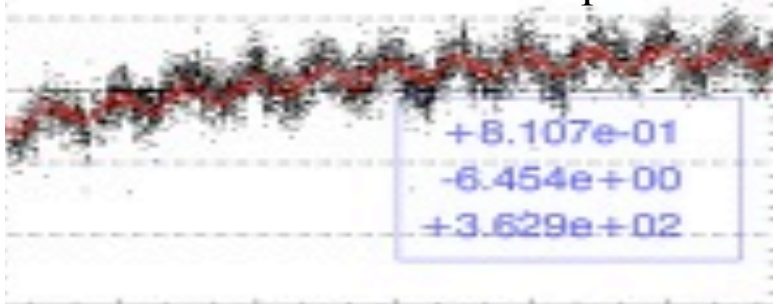
- Similar OM/EPIC patterns suggest common cause (e.g. S/C boresight, and not code errors)
- Differences argue against, or additional factors

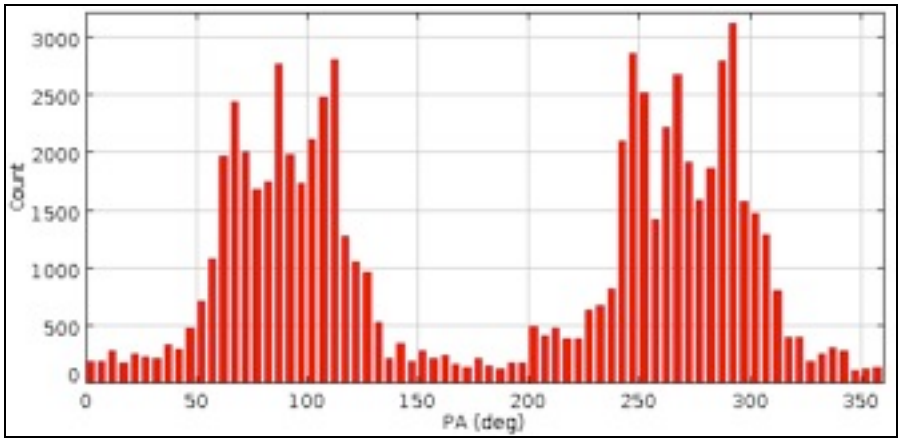
(P Rodriguez, A Talavera)

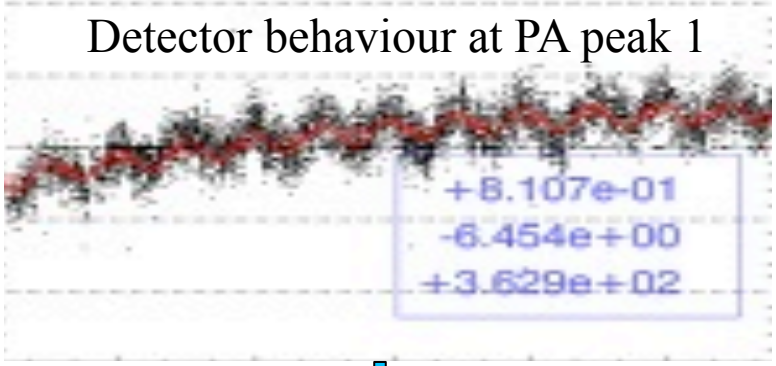
- OM boresight [offset of FAQ stars / OM-catalogue positions] shows strong seasonal (~year) variation plus trend over mission
- EPIC (3-combined) shows similar seasonal variation, but no apparent drift over the mission

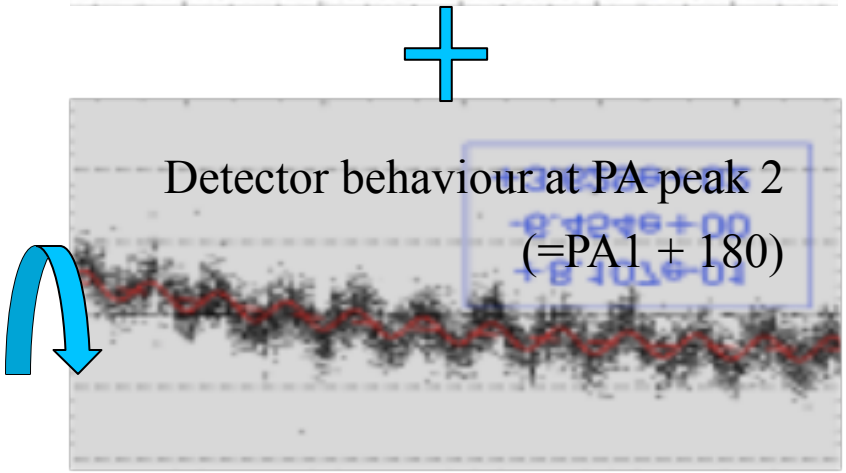


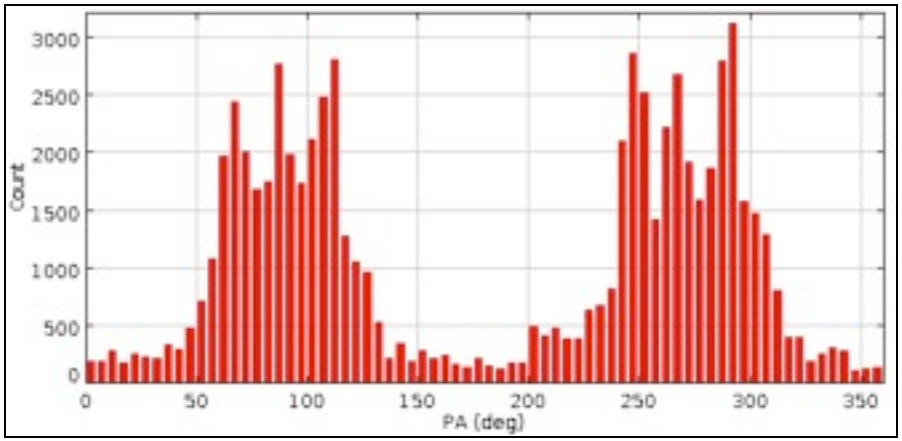
Detector behaviour at PA peak 1

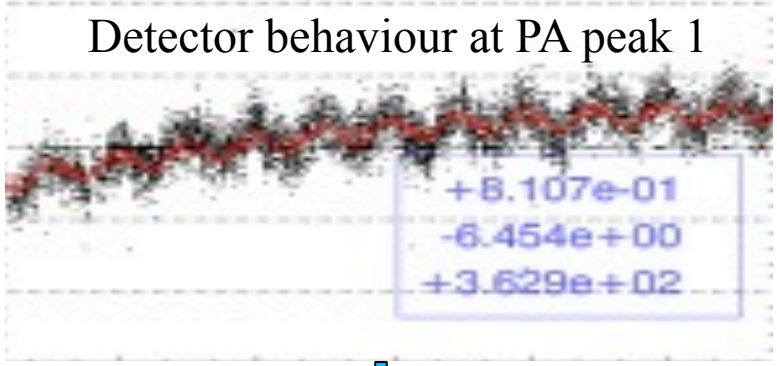




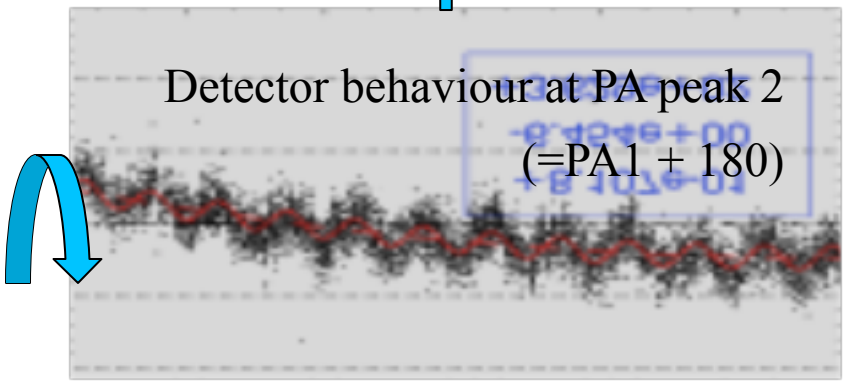

Detector behaviour at PA peak 1
+8.107e-01
-6.454e+00
+3.629e+02


Detector behaviour at PA peak 2
(=PA1 + 180)

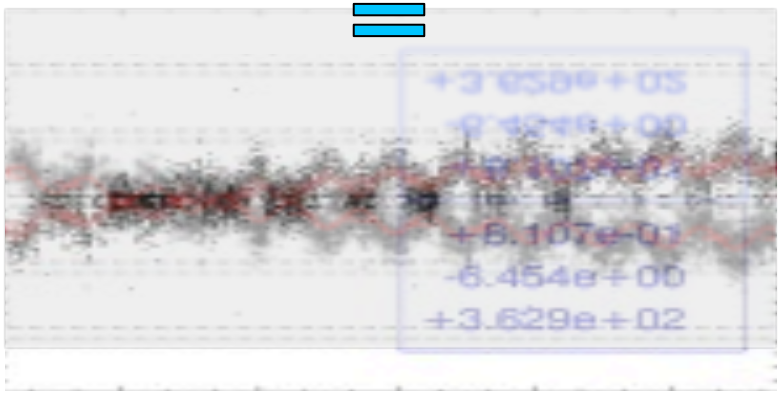

Count
PA (deg)
0
500
1000
1500
2000
2500
3000
0
50
100
150
200
250
300
350

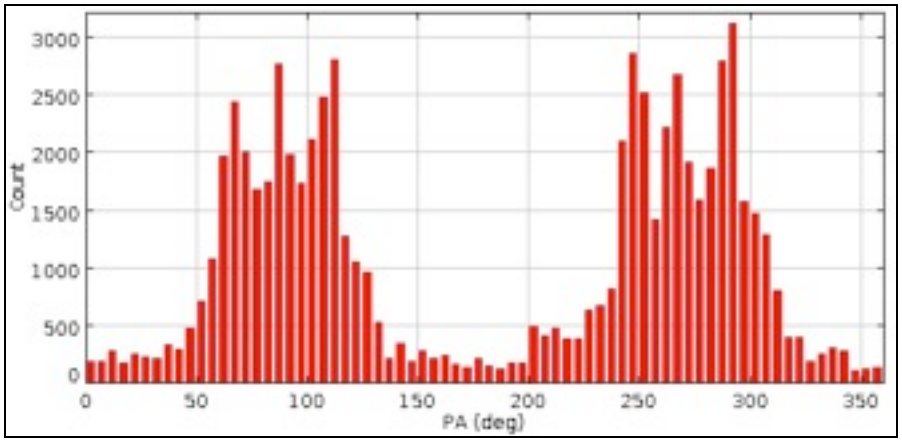

Detector behaviour at PA peak 1
+8.107e-01
-6.454e+00
+3.629e+02

+

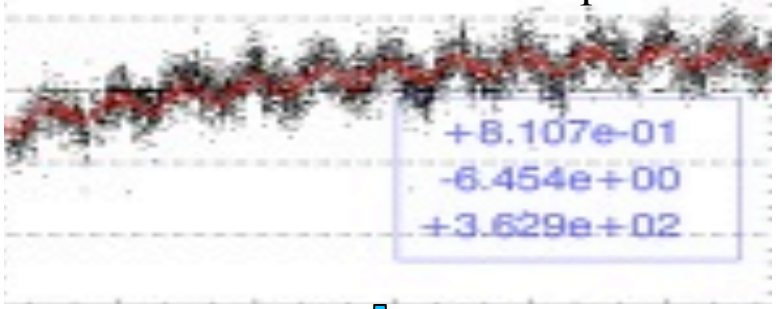

Detector behaviour at PA peak 2
(=PA1 + 180)

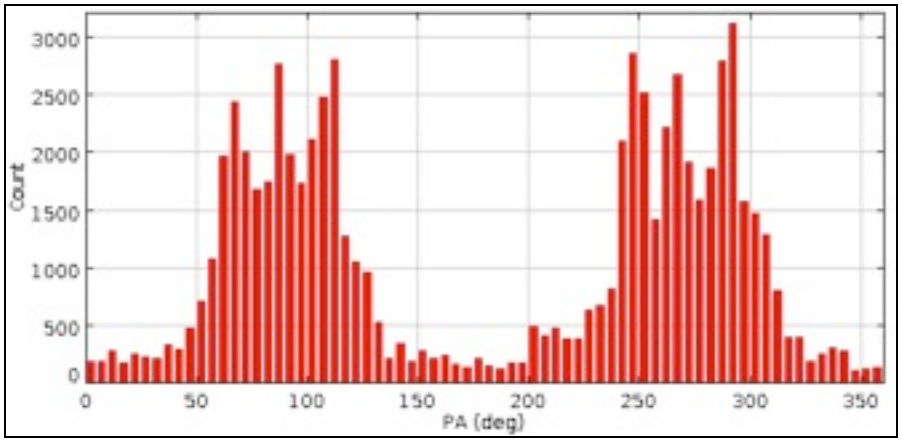
=


+8.107e-01
-6.454e+00
+3.629e+02


Count
PA (deg)
0
500
1000
1500
2000
2500
3000
0
50
100
150
200
250
300
350

Detector behaviour at PA peak 1





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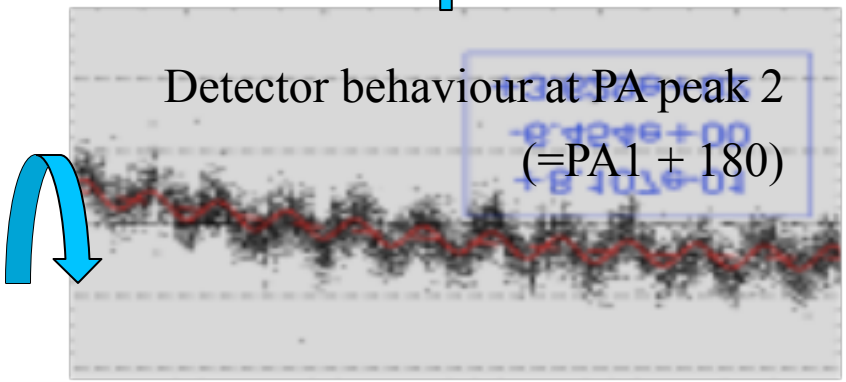
Detector behaviour at PA peak 2
(=PA1 + 180)



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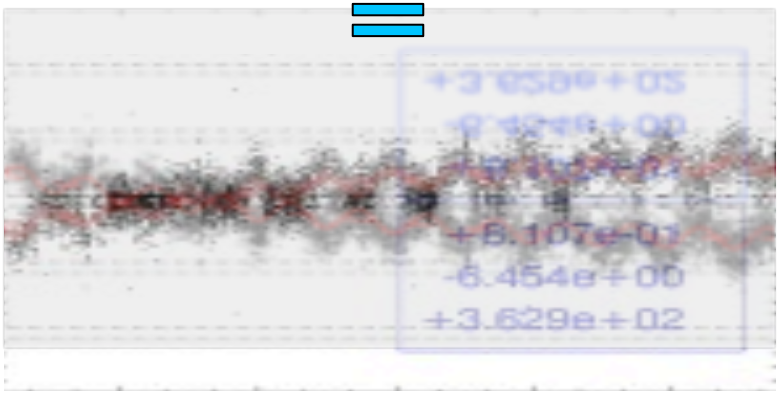

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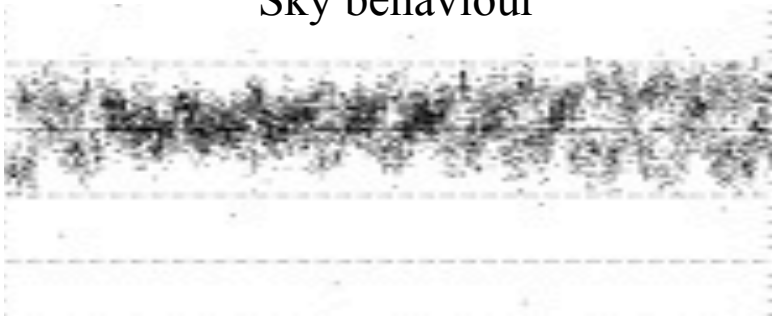
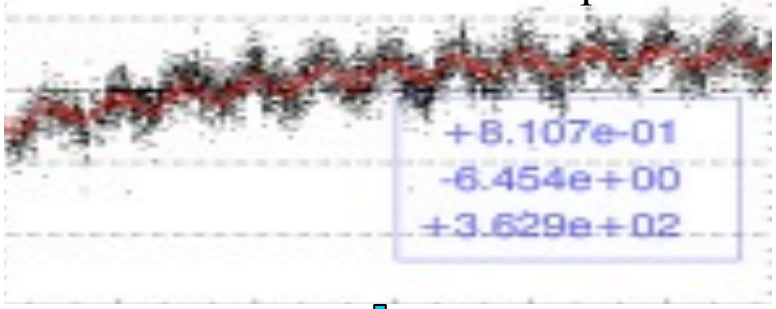
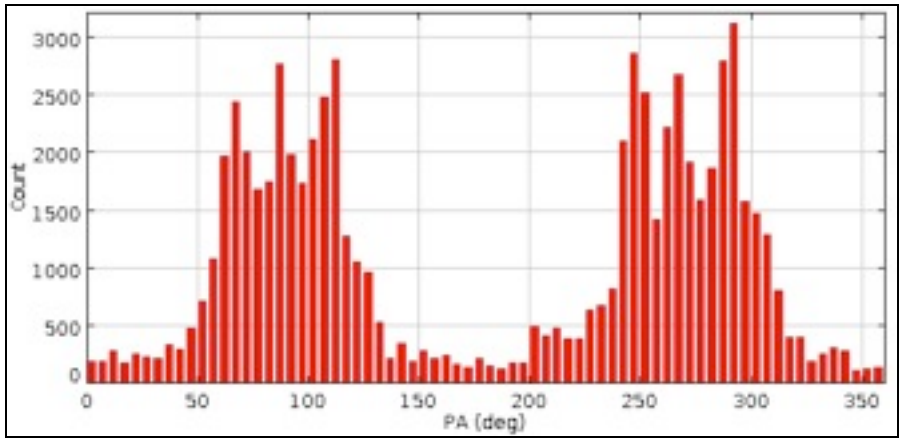
Sky behaviour



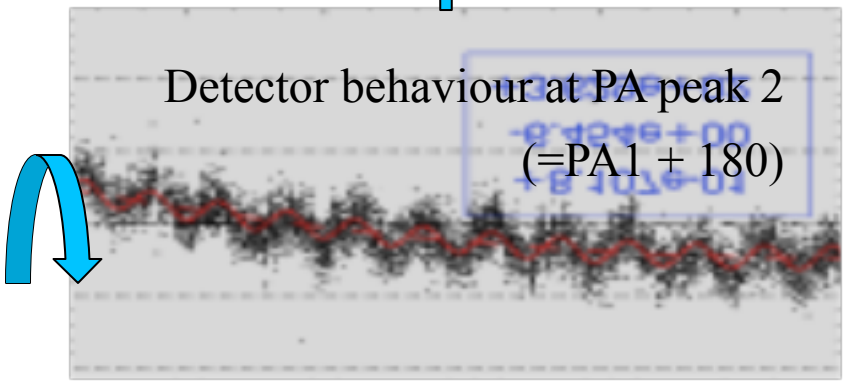
Detector behaviour at PA peak 1





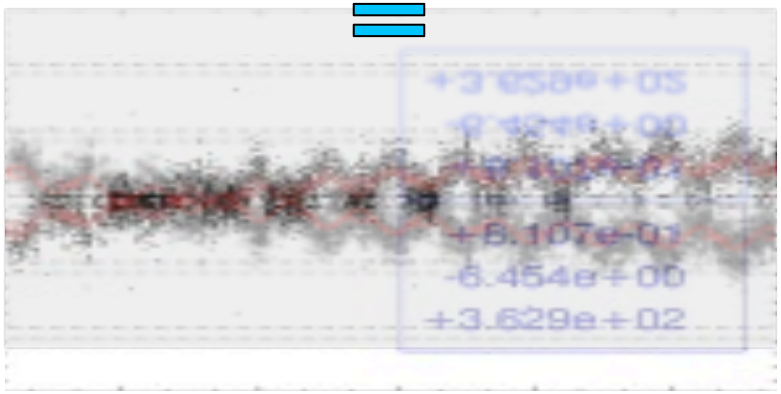
+

Detector behaviour at PA peak 2
(=PA1 + 180)



- Can correct OM in the SAS – tabulate variations every ~5 days – new CCF format, new CAL code. Technically feasible, TBD
- EPIC should have a similar system, TBD
- EPIC, OM, …?

=



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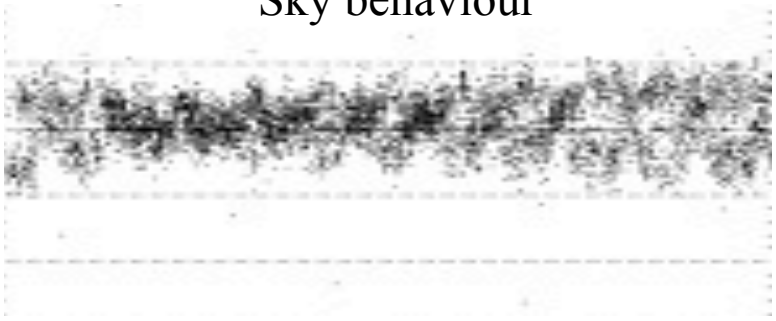
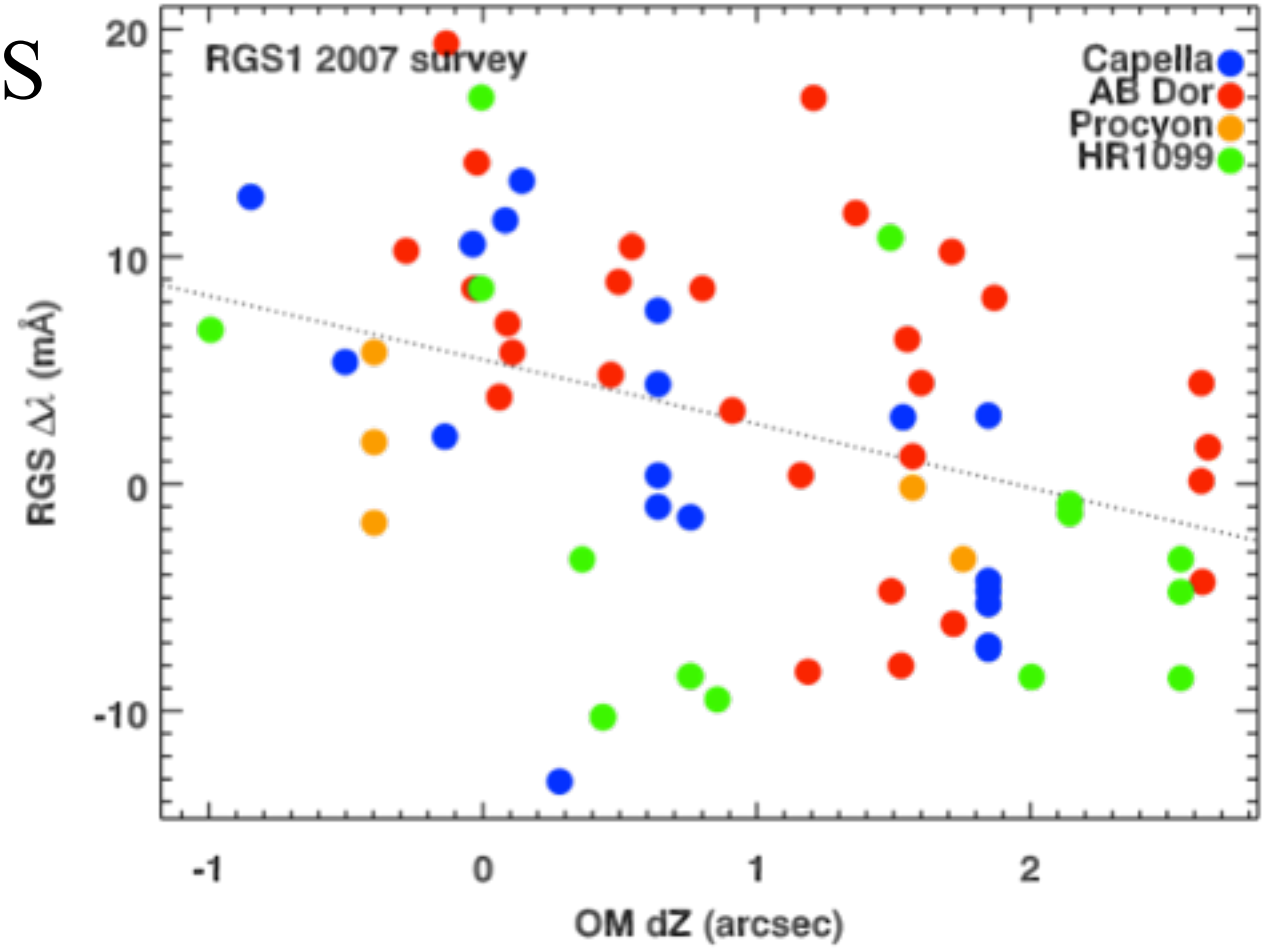
Sky behaviour



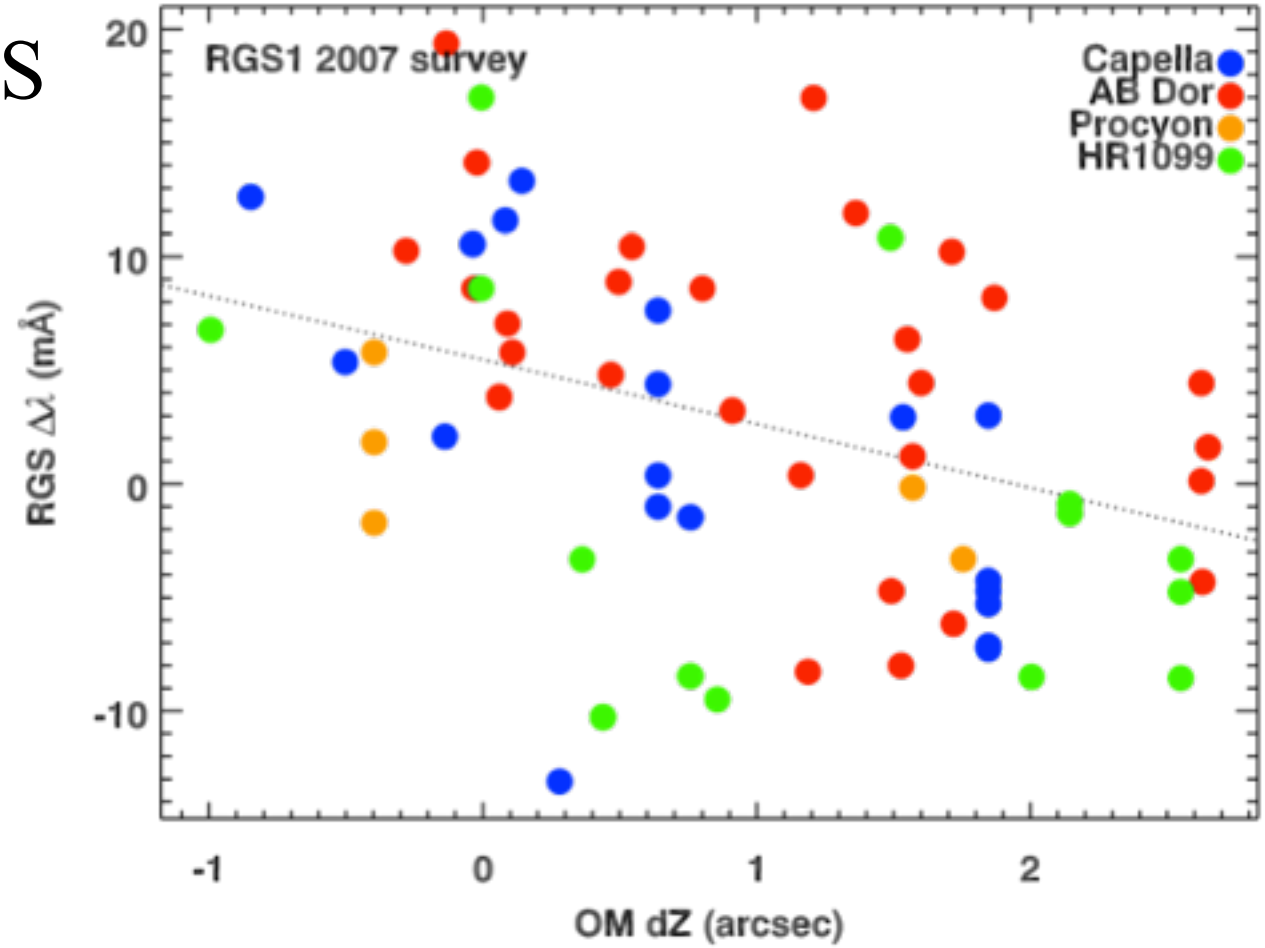
RGS



(Andy Pollock)

• Mean RGS1 wavelength shift in sample of coronal spectra plotted against median OM dZ within 20 days of the RGS observation (OM often off during RGS observations)

RGS



(Andy Pollock)

- Mean RGS1 wavelength shift in sample of coronal spectra plotted against median OM dZ within 20 days of the RGS observation (OM often off during RGS observations)
- Dotted line – linear regression – astrometric PA effect (3rd AI) errors could account for ~half+ of the systematic errors in RGS wavelengths

Astrometry – 1st AI (the ‘S’)

- Essentially solved via usage of the 2D PSF over the default PSF – problem/ asymmetry in the default PSF (½ pixel) centering giving rise to the azimuthal ‘S’ effect in the field
- ‘S’ effect has affected entire mission and all catalogues (e.g. 2XMM) to date
- EPIC positional accuracy has been improved with 2D PSF
- Note that if there is any residual similar issue with the 2D PSF (or indeed any system), it too will manifest itself as an ‘S’-type effect, as may be seen at the 0.2-0.3” level.

Astrometry – 2nd AI (the ‘offset’)

- Appears to be ~two-thirds solved through ‘delta’ source analysis & via usage of the 2D PSF with the new 5.15.4+ emldetect – previous emldetect+2D PSF had ½-pixel error w.r.t. obtaining PSF image from CCF (via CAL) and placing it in the emldetect sky image frame.
- Still have shift of +/- 0.3-0.4” to contend with – could be due to:
    - Error in code
    - S/C boresight systematic error
    - Biases in PA and the 3rd AI - See next slide

Astrometry – 3rd AI (the 'PA effect')

- Seeing similar dRA & dDec seasonal variations with PA in both EPIC and OM (with a mission-trend in OM not seen so far in EPIC)
- Lots of similarities point to (a) common cause(s), however differences argue (partially) against.
- Effect also accounts for half+ of RGS wavelength-scale systematic error.
- Has affected entire mission to date
- PA biases make comparisons problematic – offsets/shifts calculated depend strongly on the PA/time distribution(s) of the sample(s) analysed
- Causes (single, or combination):
    - Errors in code (however, OM shows same general behaviour)
    - PA-dependent systematics in S/C boresight (FD doubt there is S/C problem)
    - Real physical effect, e.g. seasonal (PA-dependent) thermal flexing (though no evidence so far of correlation of RA/Dec offsets with telescope temperatures…)
- To Do
    - Calibrating out the OM PA effect via 5-day cadence table and new CAL/CCF
    - Aiming to produce similar correction for the (similar, though not identical) EPIC PA effect – can fold in the remnants of the 2nd AI effect into this

End