EPIC astrometry

Long known that astrometry is not as good off-axis

- ✓ Christian Motch's breakthrough
- ✓ Source detection separately for each instrument
- ✓ Aligning MOS to PN
- ✓ PN absolute astrometry

The problem

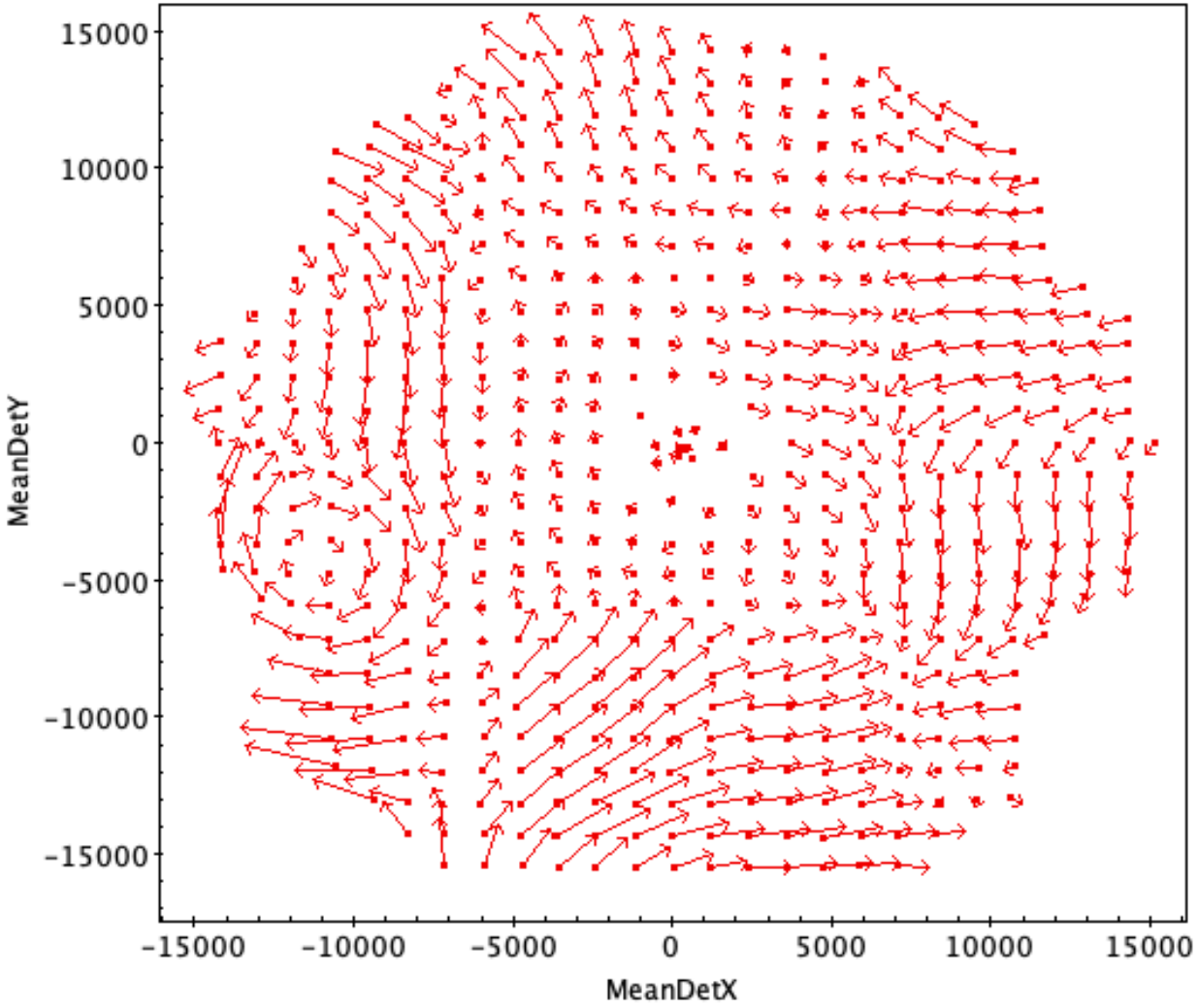
C. Motch (Obs. Strasbourg) at the SSC consortium meeting in October 2021

Average **offsets** between XMM positions and counterparts (amplified)

Follow the structure of the **MOS CCDs**

Implies that **the outer MOS CCDs are not at the right place** in the CCF

Can be used to **correct the astrometry**



The algorithm

1. Extract source positions separately for each camera (PN, MOS1, MOS2)

2. Correlate sources between the cameras. Does not require any catalogue associations (purely internal, any good point source will serve)
3. Compute offsets between MOS1/2 and PN (used as reference)
4. Deduce X/Y shifts and rotation for each MOS CCD

Jean

2. Correlate sources with external counterparts
3. Compute offsets between XMM and counterparts
4. Average offsets over big pixels covering the FOV
5. Deduce correction field for each instrument

Christian

Source selection

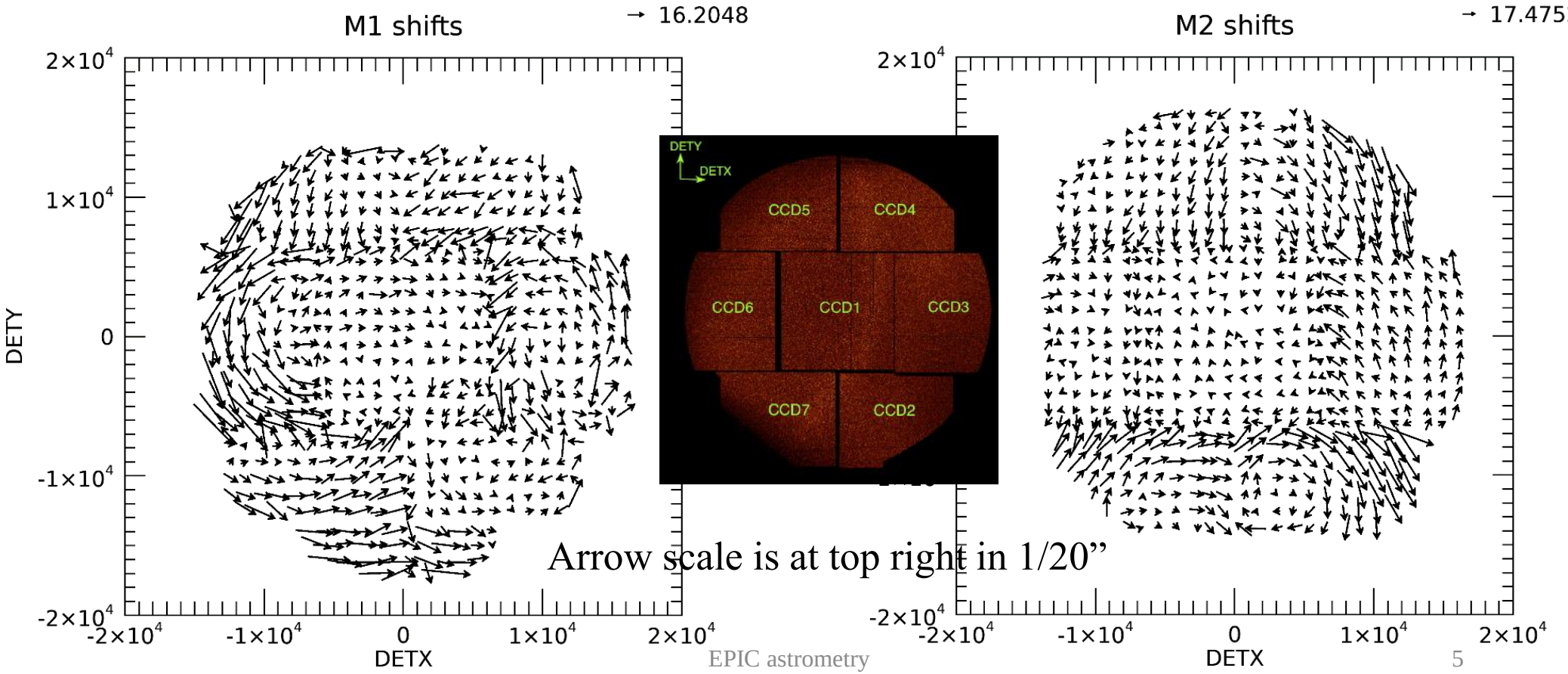
Last year, Iris extracted instrument-specific source lists in her archive of overlapping observations for the stacked catalogue

I obtained from that a list of **45,202 good PN sources** with only one row per source and detector coordinates from each camera.

That list included **33,733 MOS 1** detections (2 CCDs missing now) and **41,207 MOS 2** detections

Detector coordinate shifts

1. Error Δ quadratic sum of PN and MOS error + **1” systematic**
2. **Weight as 1/Δ** (compromise between many sources and good localization)
3. Average shifts over sources in 1x1 arcmin bins, not mixing CCDs

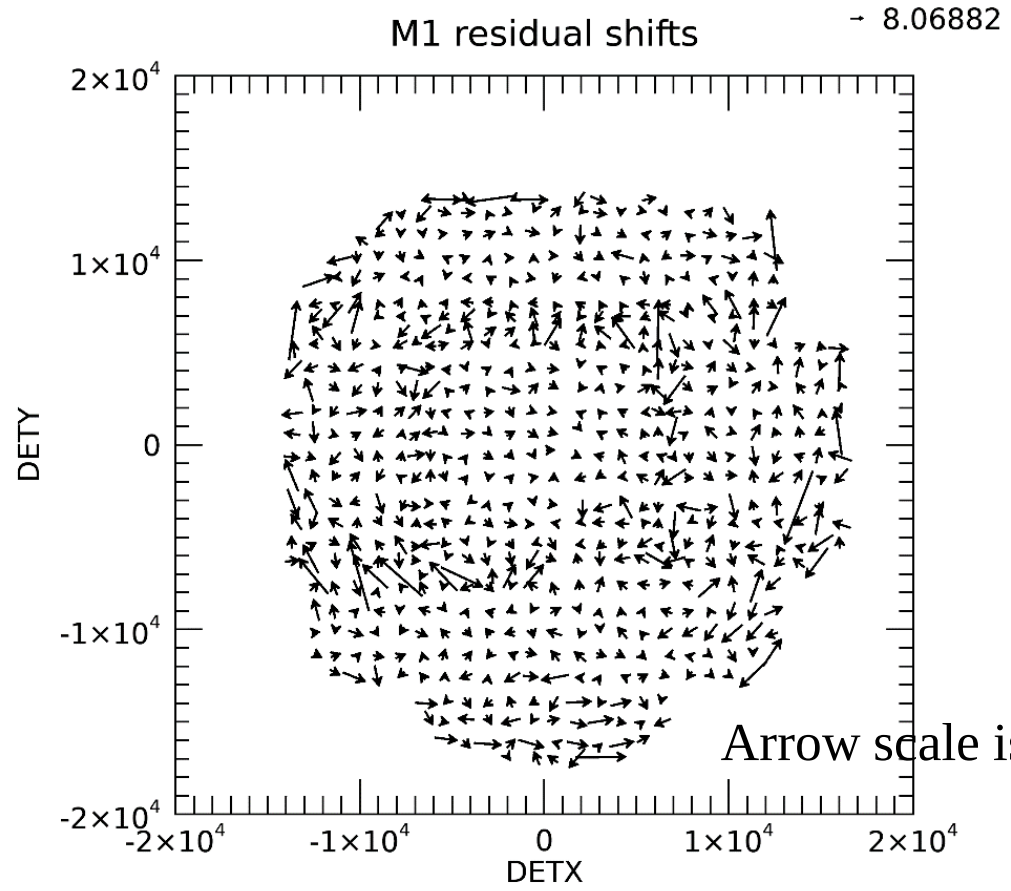


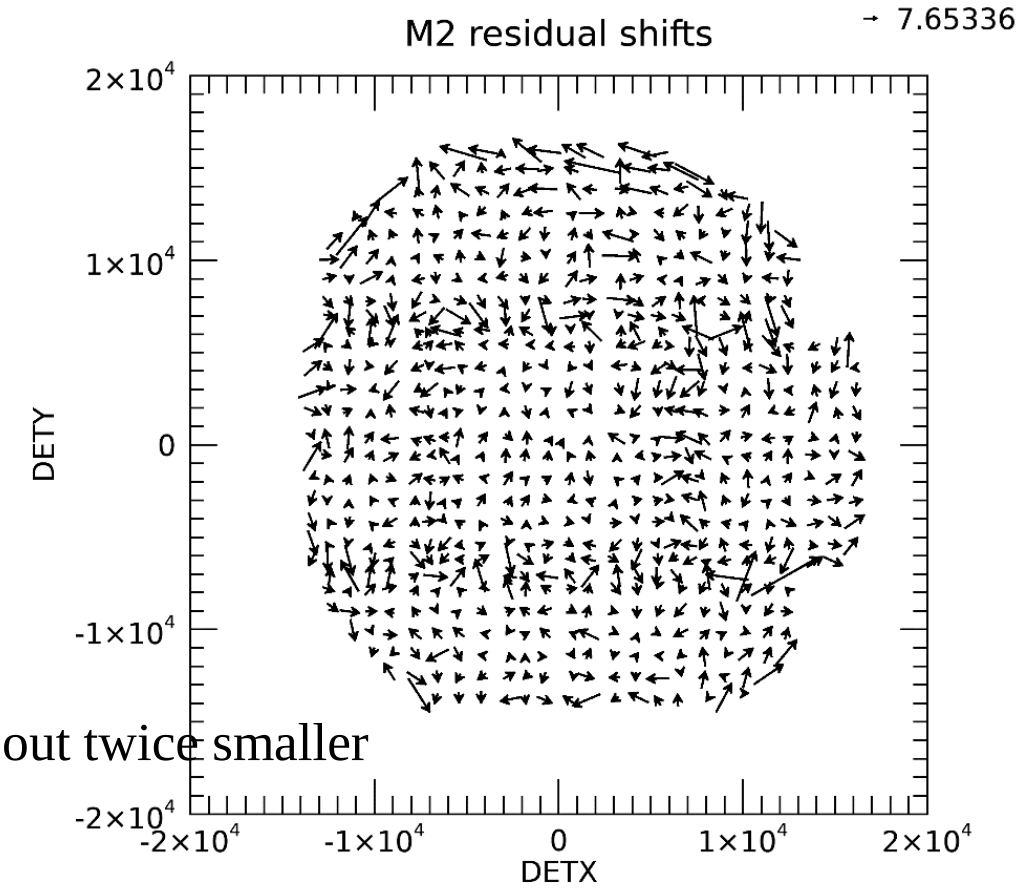
Extract geometric transformation

1. Select sources in one CCD only
2. 4 dof per CCD: scale factor *a*, angle θ, shift $\vec{S} = \begin{pmatrix} SX \\ SY \end{pmatrix}$
3. Remove barycentre $\vec{B}$ from MOS and PN coords: $\vec{D} - \vec{B} = \overrightarrow{DD} = \begin{pmatrix} DX \\ DY \end{pmatrix}$
4. $a = \sum \frac{\overrightarrow{DD_{\mathrm{PN}}} \cdot \left(\overrightarrow{DD_{\mathrm{PN}}} - \overrightarrow{DD_{\mathrm{MOS}}}\right)}{\Delta} / \sum \frac{\mathrm{DD}_{\mathrm{PN}}^2}{\Delta}$
5. $\sin\vartheta = \sum \frac{(DX_{\mathrm{MOS}}\, DY_{\mathrm{PN}} - DY_{\mathrm{MOS}}\, DX_{\mathrm{PN}})}{\Delta} / \sum \frac{\mathrm{DD}_{\mathrm{PN}}^2}{\Delta}$
6. Apply rotation and scaling $\overrightarrow{DR} = (1 + a)\, ROT\left(\vec{D}\right)$
7. Deduce shift (at FOV center) $\vec{S} = \sum \frac{\overrightarrow{D_{\mathrm{PN}}} - \overrightarrow{DR_{\mathrm{MOS}}}}{\Delta} / \sum \frac{1}{\Delta}$

Apply geometric correction

1. Apply transformation to each MOS source
2. New = (1+Scale) x ROT(Old) + Shift





Arrow scale is about twice smaller

Correcting the CCF

Work carried out by **Rebeca Batalha**, postdoc at Saclay

Action at the level of the **LINCOORD** files

In the LINCOORD extension, action on **X0, Y0, Z0** (position of the CCD centre) and **EULER_PHI** (rotation, EULER_PSI would work as well I think)

Since $\overrightarrow{S_0} = (dX_0, dY_0)$ must be provided at the center of the CCD, it is derived from the shift $\vec{S}$ (at FOV centre) and the centre position $\overrightarrow{C_0} = (X_0, Y_0)$ via $\overrightarrow{S_0} = \vec{S} + (1 + a)\, ROT\left(\overrightarrow{C_0}\right) - \overrightarrow{C_0}$

The scale *a* could be related to an offset along the telescope axis via the focal length *F*: $dZ_0 = a\,(F + Z_0)$

Use *ecoordconv* to convert the current det coords to (fractional) CCD coords with the current CCF, then back to det coords using the modified CCF

Check that this procedure actually aligns the sources to PN

SAS-related difficulties

Work carried out by **Rebeca Batalha**, postdoc at Saclay

While proceeding with the actions on the previous slide, Rebeca noticed that:

- The **Z0 entry** in the LINCOORD CCF **changes nothing at all** in the output of *edet2sky* or *ecoordconv*. On the other hand, in *emevents* I explicitly use the Z coordinate returned by CAL_rawXY2mm to compute the angle. Looks like there is an **inconsistency** somewhere.
  Because of that **we did not correct the scale** part of the previous slide.

- Rebeca found a **bug in *ecoordconv*** when converting from fractional CCD to DET coords. For all but the central CCD, the fractional parts of RAWX and RAWY are exchanged, so that (for example) (90.64,30.12) will arrive instead at the DET coords of (90.12,30.64).
  Fortunately this is completely predictable so we could work around it (by inverting the fractional parts) and proceed.

Improvement after correction

Correcting with my original shift, rotation and scale:

1. **Median absolute shift** M1: 14.0 ➔ 6.6 M2: 14.6 ➔ 6.6 det pixels
2. **M1 χ^2** 3724/609 ➔ 861/581 **M2 χ^2** 7154/638 ➔ 1085/610

Correcting via the LINCOORD CCF (without the scale):

1. **Median absolute shift** M1: 14.0 ➔ 7.4 M2: 14.6 ➔ 7.1 det pixels
2. **M1 χ^2** 3724/609 ➔ 1172/581 **M2 χ^2** 7154/638 ➔ 1309/610

Conclusions:

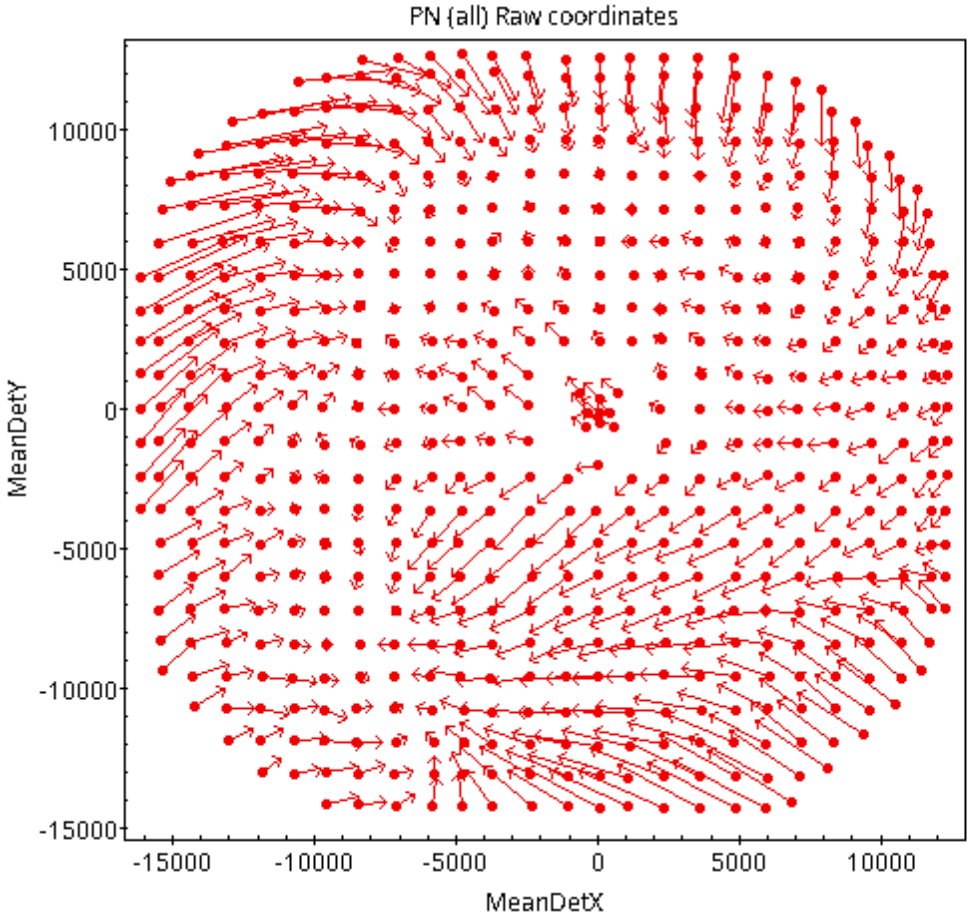
1. **The correction via the CCF works as expected**
2. The scale correction is not critical

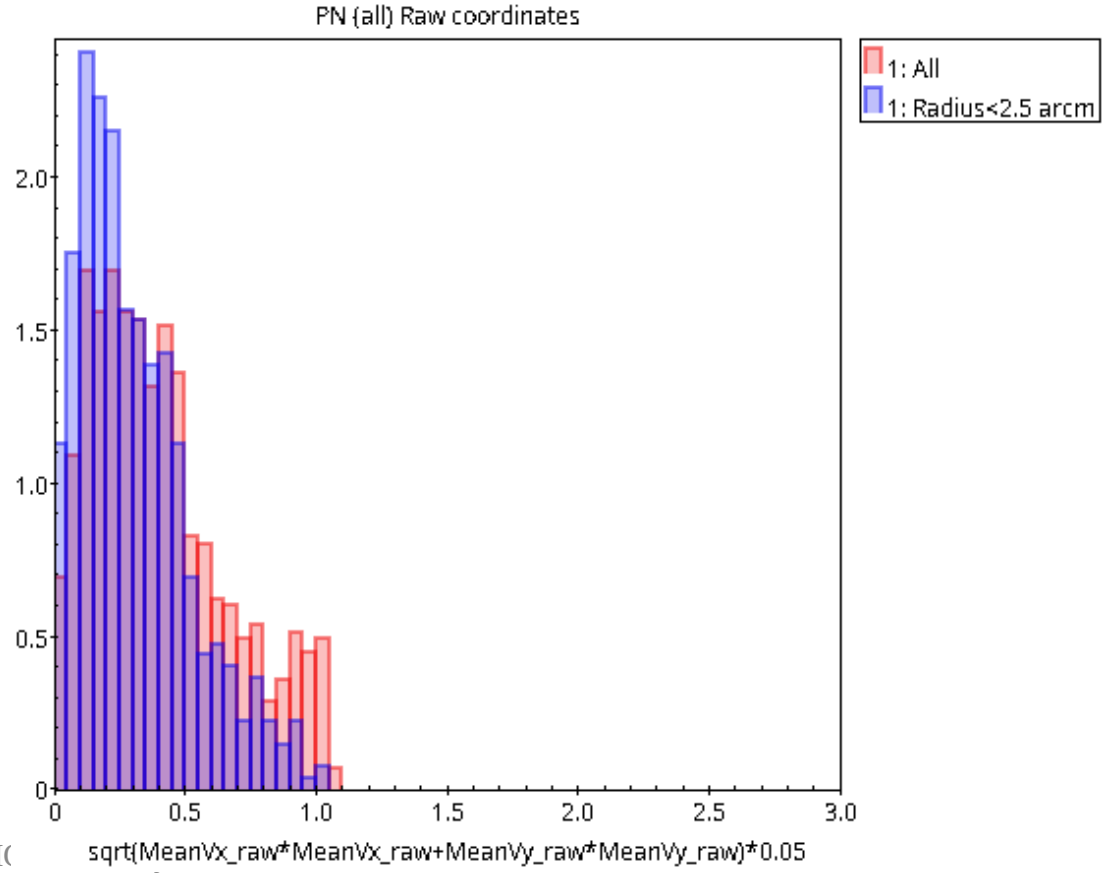
Absolute astrometry (C. Motch)

1. Generated instrument-specific source lists **over entire archive**
2. Cross-match with DR12 to eliminate extended, bad and not well localized (RADEC_ERR > 5”) sources
3. Resulted in list of **493,355** PN-only detections (300k+ MOS detections)
4. Cross-match with best_milliquas.fits (best localised Million quasar positions) up to max(2”,10*POSERR)
5. End up with **58,947** PN matches (45k MOS1 and 56k MOS2)
6. **Difficulty**: The offsets contain the effect of the imperfect pointing of XMM-Newton (rotation and offset), different for every observation. *eposcorr* aligns the sources with the reference, but will tend to minimize the offsets (no way to get the true pointing)
   Hope that this **effect cancels out over large numbers**

Results using raw coords

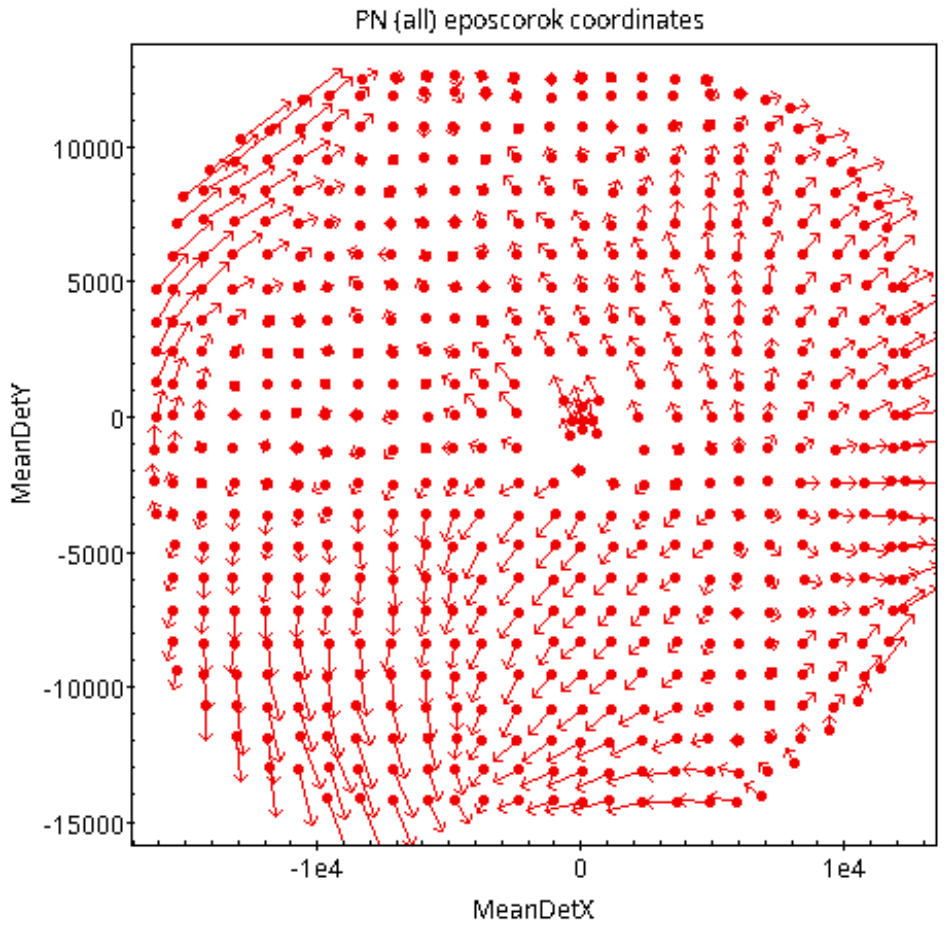
1. Use *ecoordconv* to compute DET coords of the milliquas sources
2. Compare directly with the output of *emldetect* (no *eposcorr*)
3. Similar spatial binning to mine (about 100 sources per point)
4. Offsets by up to 1”

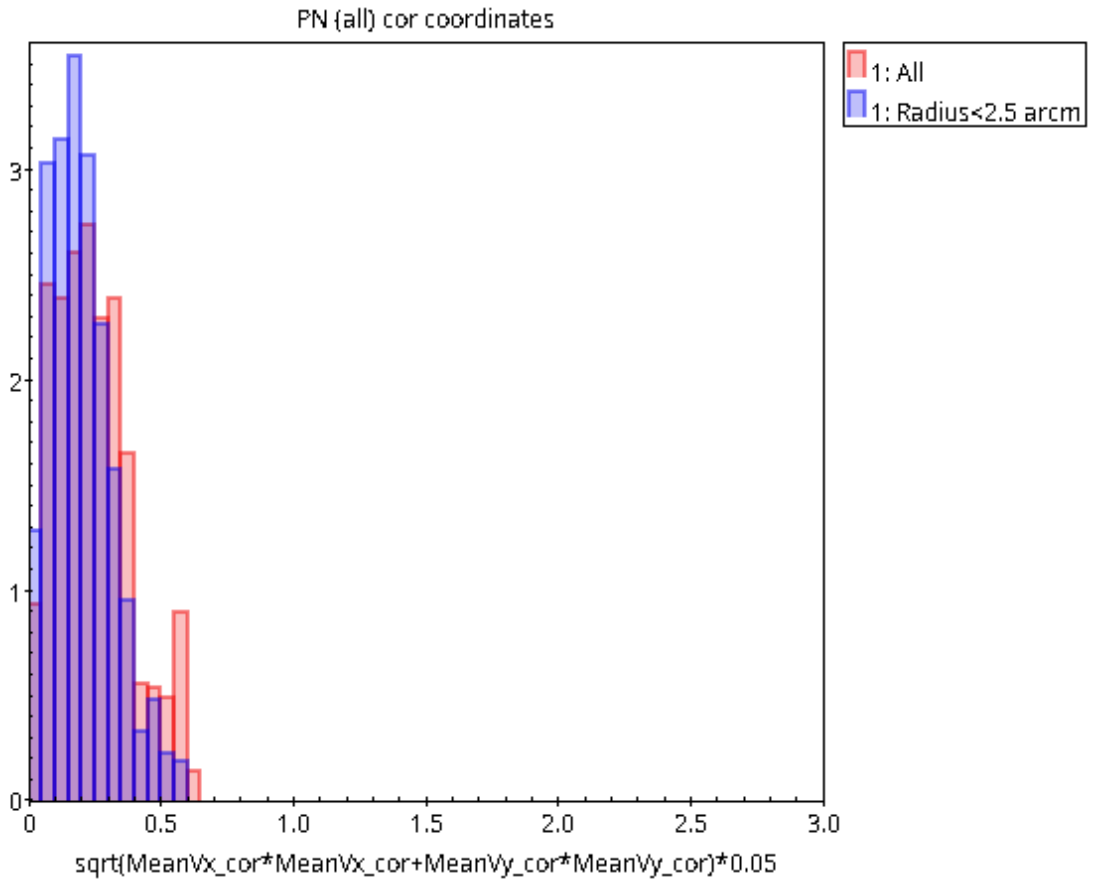




Results after *eposcorr* and *astcor*

1. Use *eposcorr* and *astcor* (3rd degree radial polynomial) to minimize offsets
2. Offsets up to 0.6” **reduced but not eliminated**
3. Better apply average transformation based on the raw positions (unbiased)
4. Unrelated to CCDs (MOS shows the CCD pattern) ➔ **mirror or PSF**





Conclusions

1. Systematic **residual astrometric deviations at the arcsec level**
2. The most obvious effect is that individual external MOS CCDs are not perfectly aligned with PN
3. This can be corrected by **updating the MOS LINCOORD CCF**
4. The PN also shows systematic deviations
5. Correcting this requires defining a **vector field of shifts**

Still to be done

1. Use the corrected CCF to recompute the MOS event lists for (a subset of) Iris' observations; recompute the MOS source lists
2. Check that the resulting MOS source lists are aligned with PN
3. Recompute the source lists from all cameras together and check that the CCD-related patterns have gone away
4. Improve the MOS CCD metrology by using Christian's larger data set
5. Think of the best way to correct the PN distorsion into the SAS
6. Is it important to correct PN before aligning MOS CCDs?