

# HSC Astrometry (and photometry)

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# What is astrometry ?

- In principle, anything that has to do with measuring positions of astrophysical objects
- In practice, defining the reference frame is now provided by GAIA
- LSST will improve over GAIA only for faint ( $m > \sim 20$ ) objects.
- We are then concerned about **relative astrometry**
- It boils down to mapping position measurements in sensors coordinates on a global reference frame, **possibly using objects not in the reference catalog.**

# What for?

- In the context of “repeated imaging”, relating positions measured in different images is mandatory:
  - Prior to co-adding (!)
  - Prior to subtracting
  - For all sorts of measurements carried out on individual images, e.g. lightcurve extraction, shape measurement, ...

# Astrometric residuals for photometry and shape measurement

- Forced photometry: astrometric offsets cause a photometric bias:

$$E[\hat{f}] = f \left( 1 - \frac{(\delta X)^2}{R_{PSF}^2} \right)$$

- Second moments are sensitive to the position:

Second moments matrix

$$M = \frac{\int (X - X_0)(X - X_0)^T W(X - X_0) I(X) d^2 X}{\int W(X - X_0) I(X) d^2 X}$$

centroid      Some weight function      image

In both cases, the measured quantity depends quadratically on position. Hence, astrometric residuals do not average out.

# Astrometric solution

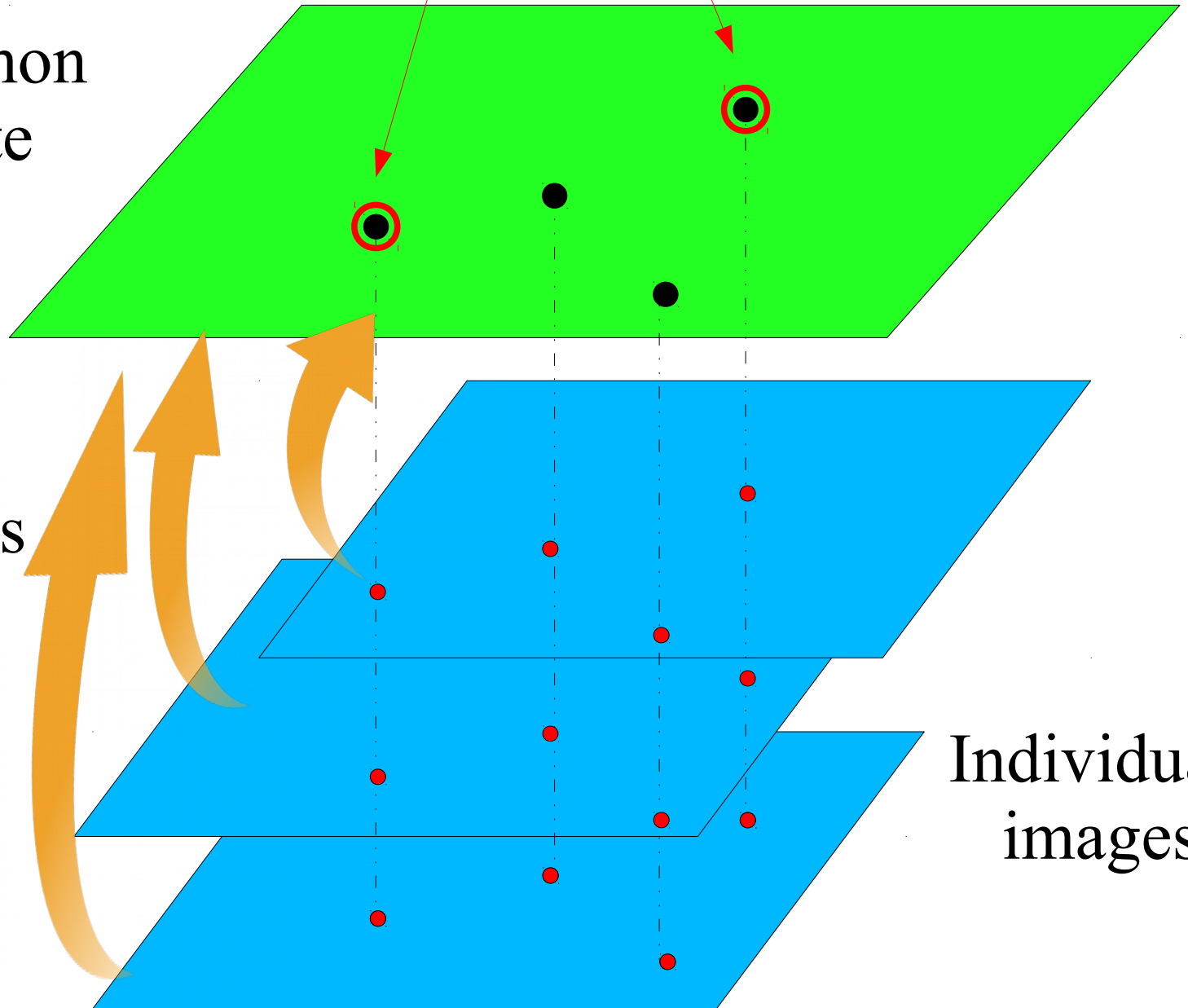
- The goal is to map the pixel space of every image to some common frame (e.g. sidereal)
- Much lighter than determining all image-to-image mappings ( $n(n+1)/2$ )
- Mappings to some undistorted space (e.g. tangent plane) allows one to remove the effects of optical distortions (important for shape measurements)

External catalog constraints

Some common  
coordinate  
frame

Mappings

Individual  
images



# Fitting the (distorted) WCS

- Means fitting the mapping from pixel coordinates to e.g. tangent plane.
- It is less trivial than it seems, because we are fitting polynomials.
- One *has* to fit in “reduced” coordinates, and re-express the resulting polynomial.
- Best linear system solving methods :
  - SVD on the Jacobian (and check for degeneracies).
  - $\text{LDL}^T$  on the Hessian (rather than  $\text{LL}^T$ , i.e. Cholesky)

# Combinatorial matching: HSC

- HSC is challenging for combinatorial astrometric matching, because of huge optical distortions.
- We have to rely on an “instrument model”, in order to project all catalogs from an exposure on some “undistorted” plane.
- A successful recipe to get this instrument model:
  - Find a set of exposures where each CCD of the mosaic was successfully matched (stand-alone) at least once.
  - Run the simultaneous astrometric fit on those matched images.
  - Use the output instrument model to combinatorial match whole exposures. This works(!)
  - Rerun the simultaneous astrometry on the whole sample



# Three implementations of the simultaneous fitter

- SCAMP (Emmanuel Bertin 2008 ?)
  - The reference and the largest user base.
- WcsFit (Garry Bernstein, 2016)
  - Developed to fit a detailed instrument model for DECam.
- Jointcal (LSST-DM & co, ~2015-)
  - Just entered into the DM stack.

# Jointcal (1)

- Developed for DM, from a precursor written for SNLS (“gastro”, still used on HSC).
- Fits both mappings and common objects positions, possibly using reference objects:

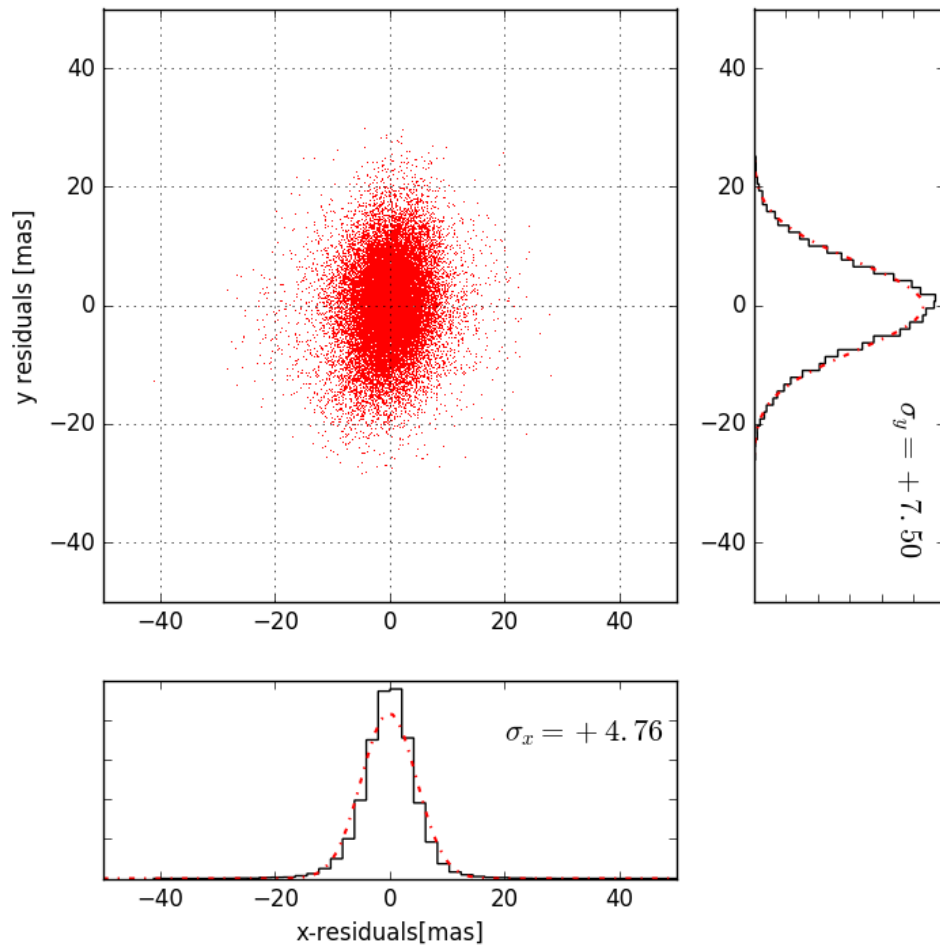
$$\chi^2 = \sum_{\gamma,i} [M_{\gamma}(X_{\gamma,i}) - P_{\gamma}(F_k)]^T W_{\gamma,i} [M_{\gamma}(X_{\gamma,i}) - P_{\gamma}(F_k)] \quad (\text{meas. terms})$$
$$+ \sum_j [P(F_j) - P(R_j)]^T W_j [P(F_j) - P(R_j)] \quad (\text{ref. terms})$$

- Relies on sparse linear algebra for expressing and solving the system, using the LDL<sup>T</sup> factorization of *cholmod*, using its “factorization update” capability (for outlier removal).
- The fitted model is abstract for the fitter.

## Jointcal (2)

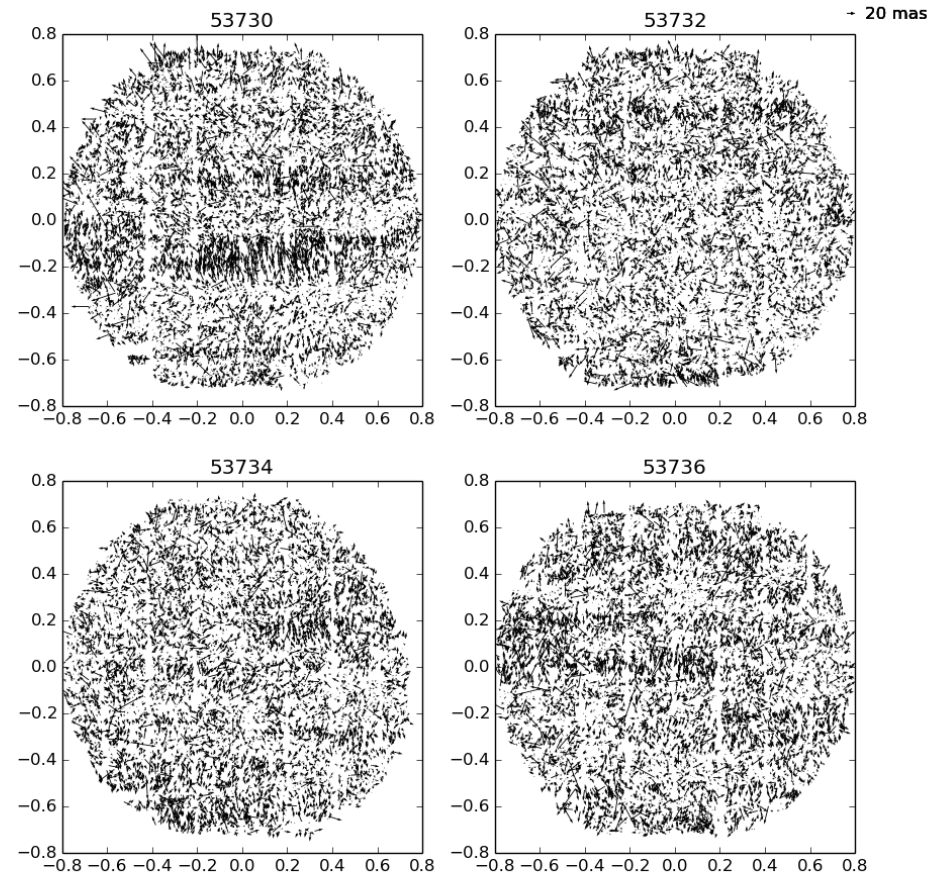
- So far, the code only contains two models:
  - Images are mapped independently  $T_{\text{expo,CCD}}(X)$  .
  - Images are mapped as  $T_{\text{expo}}(T_{\text{CCD}})(X)$  (ConstrainedModel)
    - $T_{\text{expo}}$  = Identity for one exposure.
  - In both instances mappings are polynomials.
- Results that follow come from reductions of HSC data on Cosmos. We<sup>(\*)</sup> have been only using the ConstrainedModel (very similar to what SCAMP does). Uses Gaussian-Weighted positions.

(\*) LPNHE LSST team



All residuals ( $m < \sim 20$ )

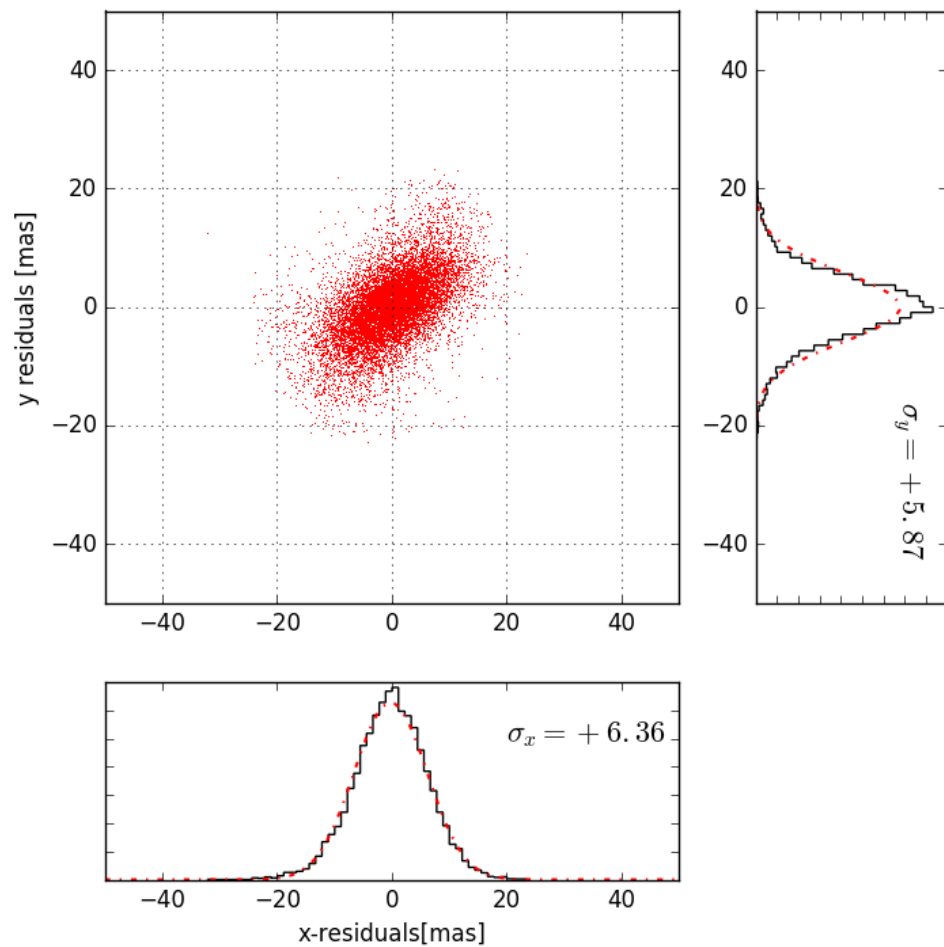
Residuals per exposure  
As a function of position  
In the focal plane



Night 57402, z band.

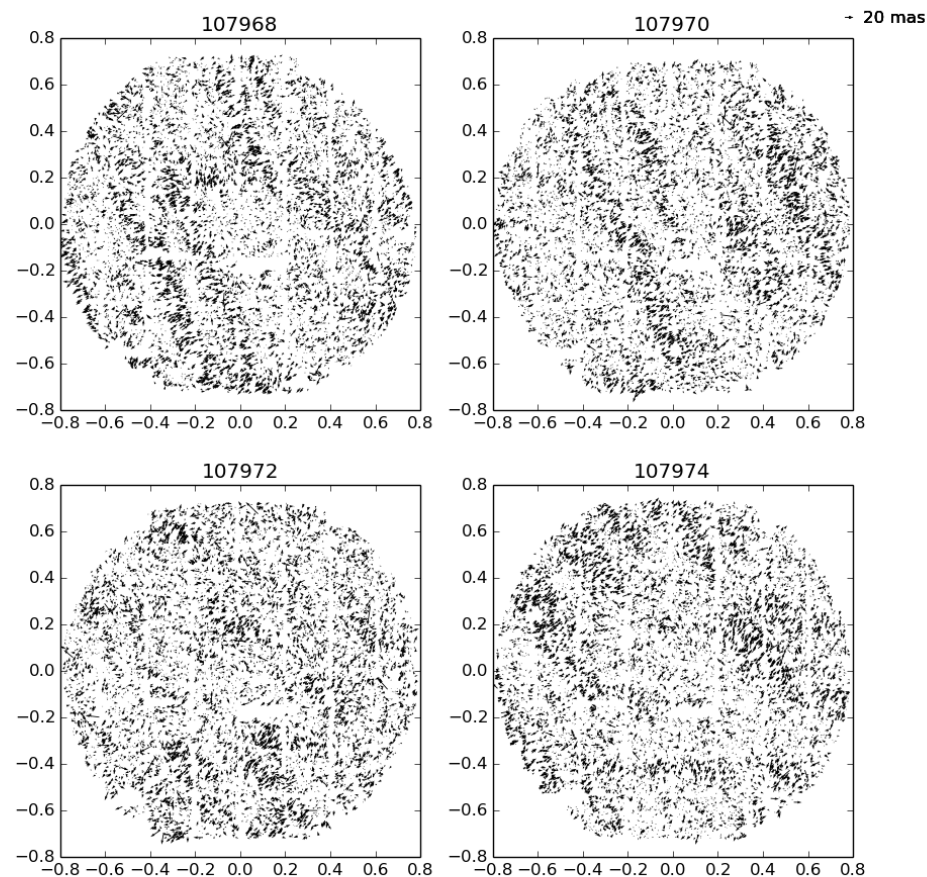
17 exposures on Cosmos

- $\sim 400$  s of wall time (1 core)
- 509 k 2d-measurements, 138 k parameters
- Computing derivatives: 1 s
- “squaring”: 5 s
- Factorize-solve : 6 s
- Computing uncertainties 12 s



All residuals ( $m < \sim 20$ )

Residuals per exposure



Night 57841, z band.  
11 exposures.

# Source of these residual patterns

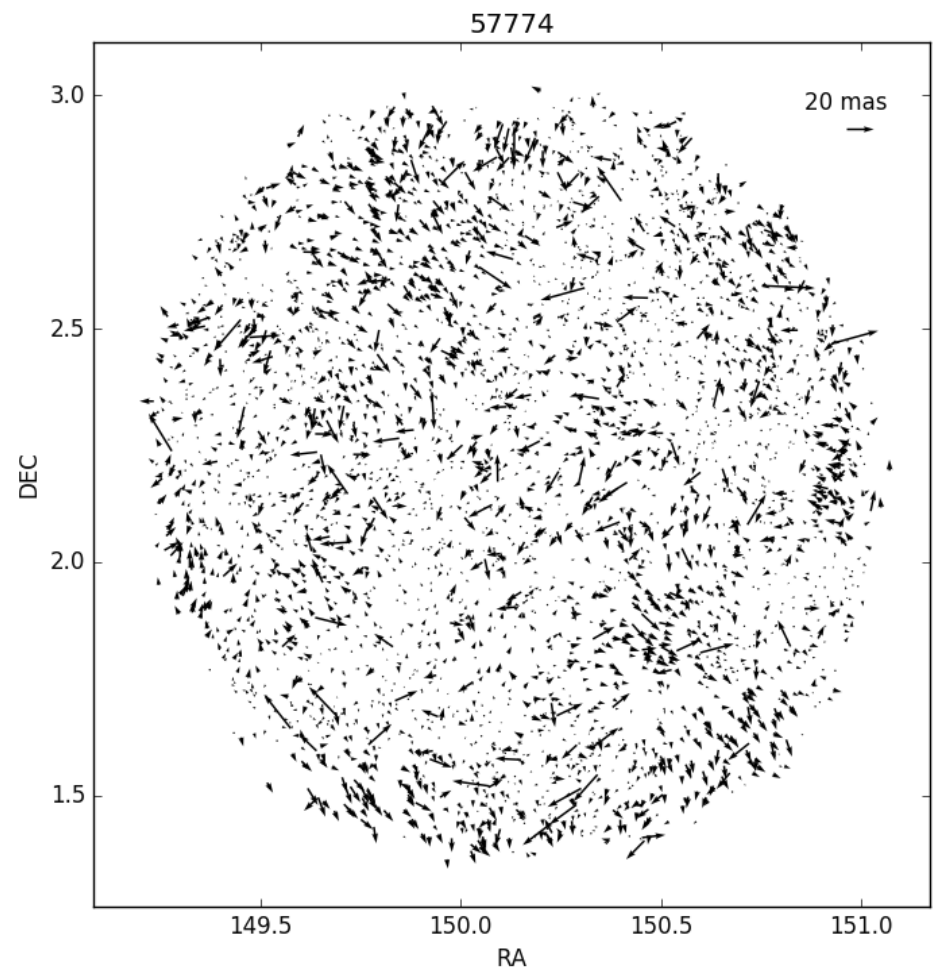
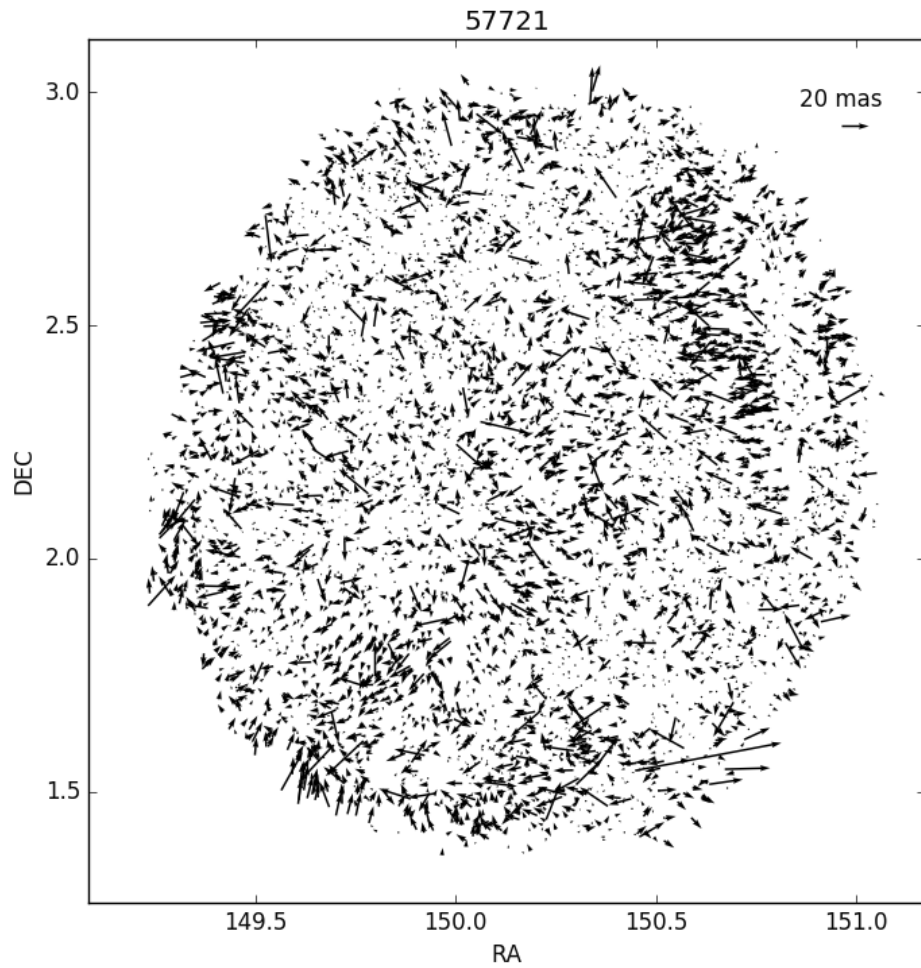
- Their variability from exposure to exposure points towards the atmosphere
- This kind of pattern is expected from high altitude refraction index variations.
- Then, the displacements are the gradient of a scalar field. G. Bernstein checks that.
- Getting rid of those residuals at scales  $>$  a few arcmin, means several hundred parameters per exposure. This is a lot.

# Our reduction strategy for the Subaru SN program

- Fit each night/band separately, using Gaia as a reference. We only use the output catalog.
- Average output catalogs from different epochs, detecting and fitting proper motions.
- Redo the above steps after removal of moving stars from the Gaia catalog (temporary...).
- Refit separately all WCS's, using the (average) catalog at the date of observation.
  - Accommodates atmospheric turbulence (20 parameters/chip) and proper motions.

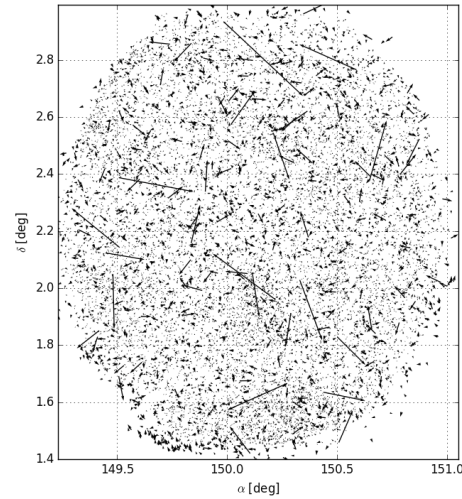
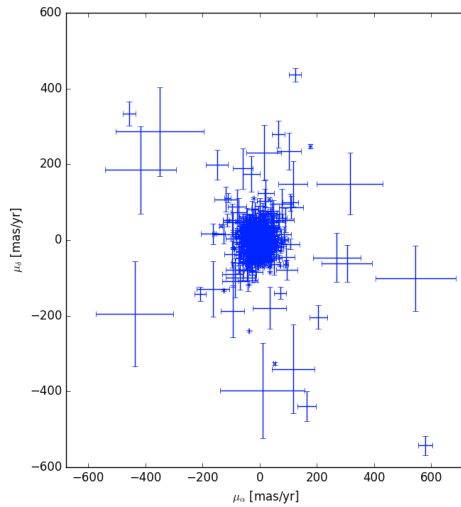


# Residuals between epochs

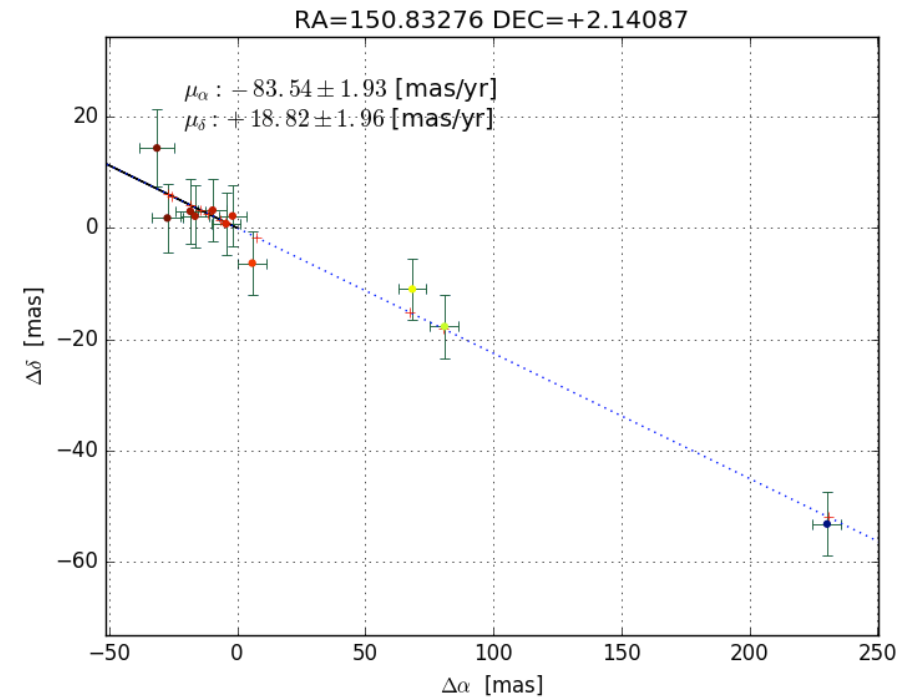




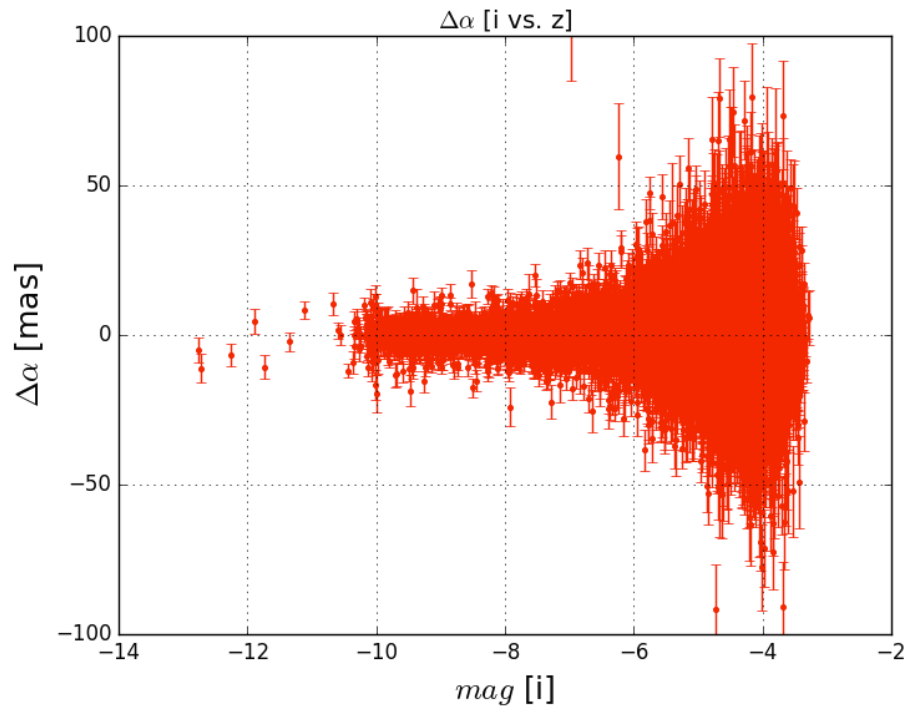
# Proper motions



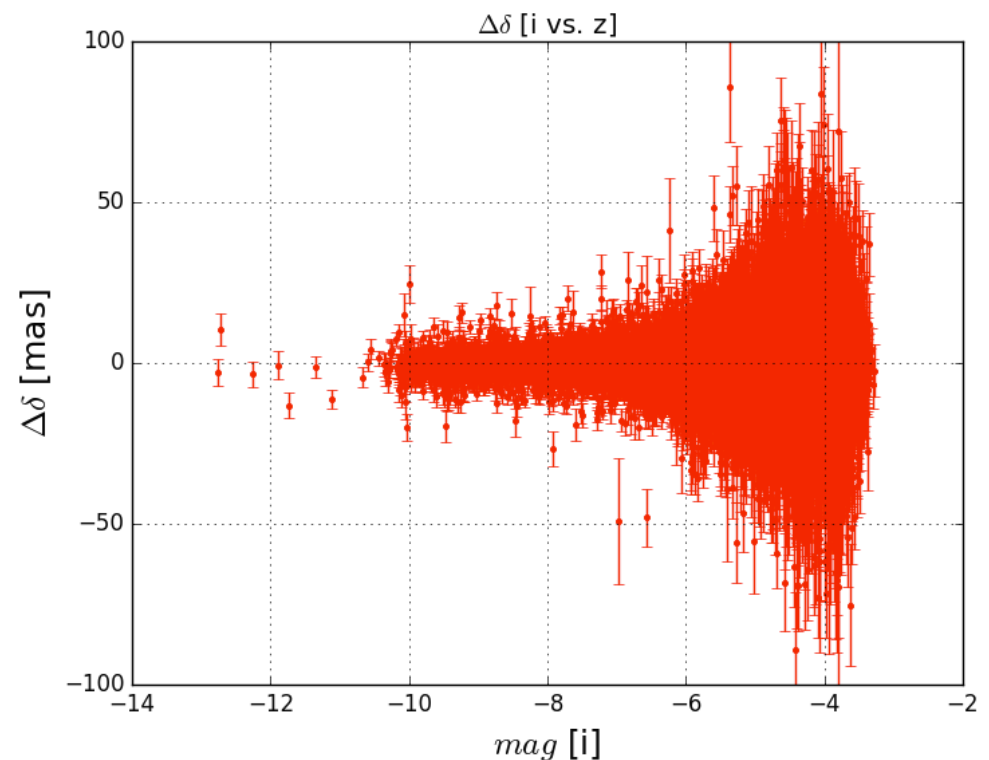
Baseline:  $\sim 2 +$  years



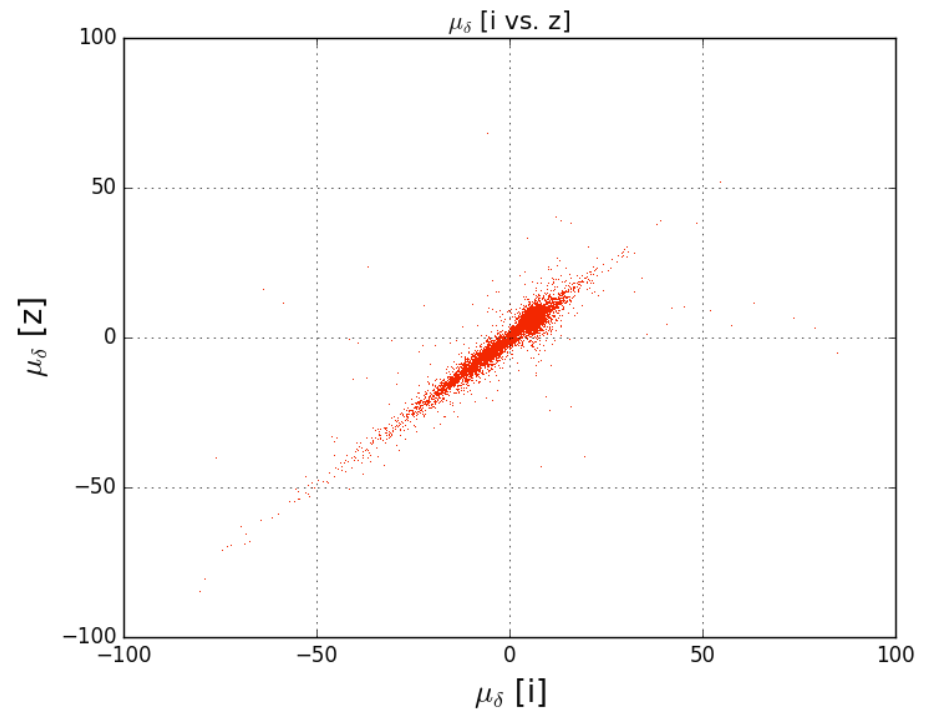
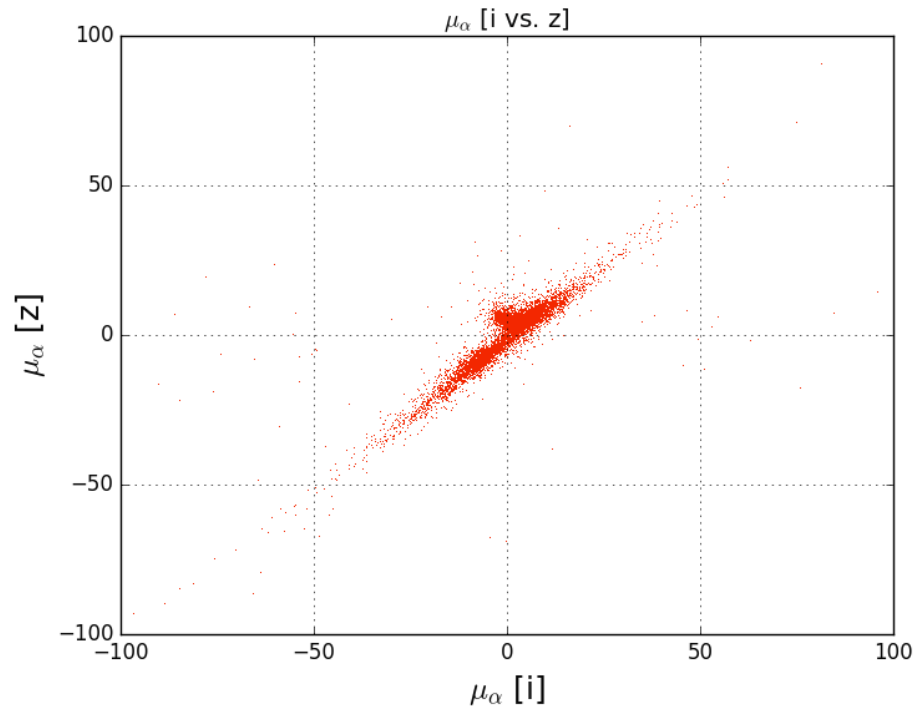
# Residuals between bands : i vs z



Residual:  $\sim 5$  mas rms



# Proper motions: i vs z



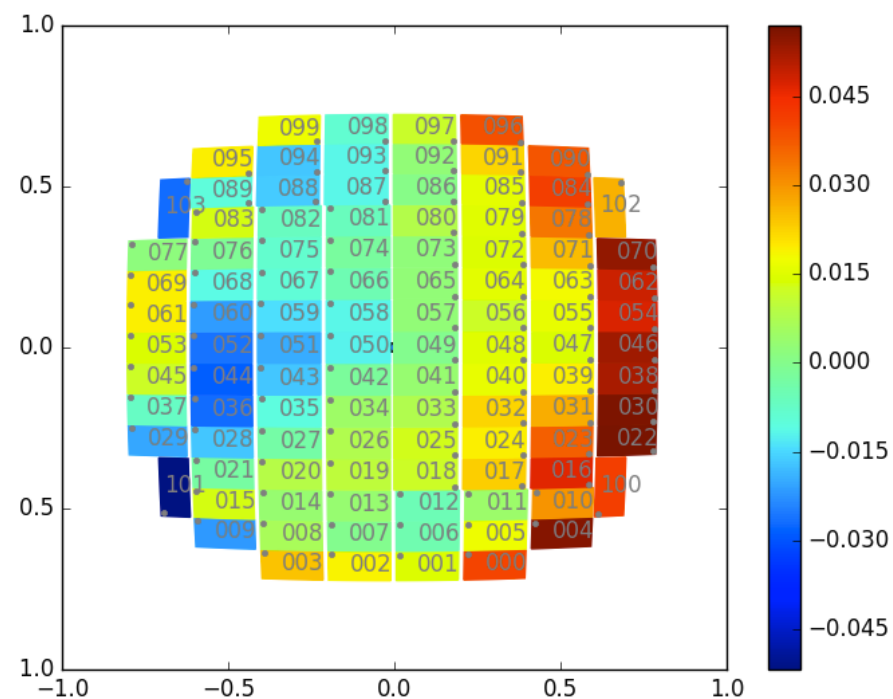
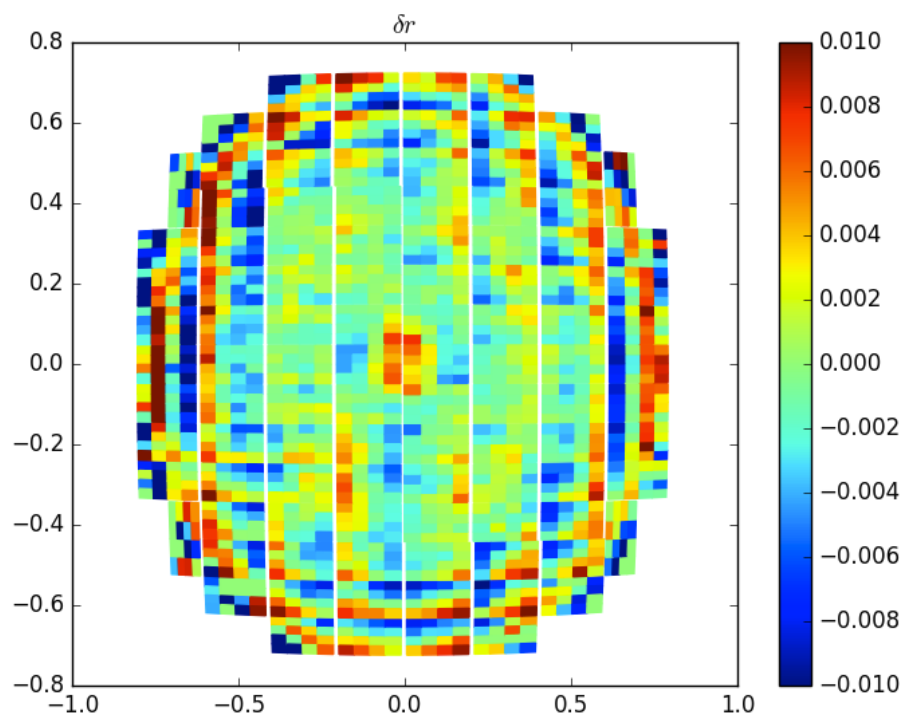
# Photometric uniformity (1)

- Flat-fielded images do not provide uniform photometry:
  - Plate scale (pixel size) variations affect flat-fields
  - Vignetting is not accurately mapped by dome flats
  - Flat-fields contain ghosts due to the corrector.
  - Band-passes may vary with position.
  - ....
- → All images should be rescaled by a position-dependent function prior to stacking (or subtraction).

# Photometric uniformity (2)

- Model:
  - Instrumental distortion (on top of the astrometric Jacobian)
  - One distortion per visit.
  - Model expressed in mags: totally linear.
- Parameters:
  - Distortion parameters.
  - Magnitude of stars.
- Constraint:
  - External catalog: D2 field from SNLS (smaller than Cosmos with HSC...)

## Residuals



Average  
offset per chip  
(w.r.t dome flats)

# To Be Done

- Fit several instrumental configurations at the same time.
- Detect and fit proper motions within jointcal
- Accommodate reference catalogs with (accurate) proper motions.
- Switch the photometric fit to mags ?
- ....

# More slides

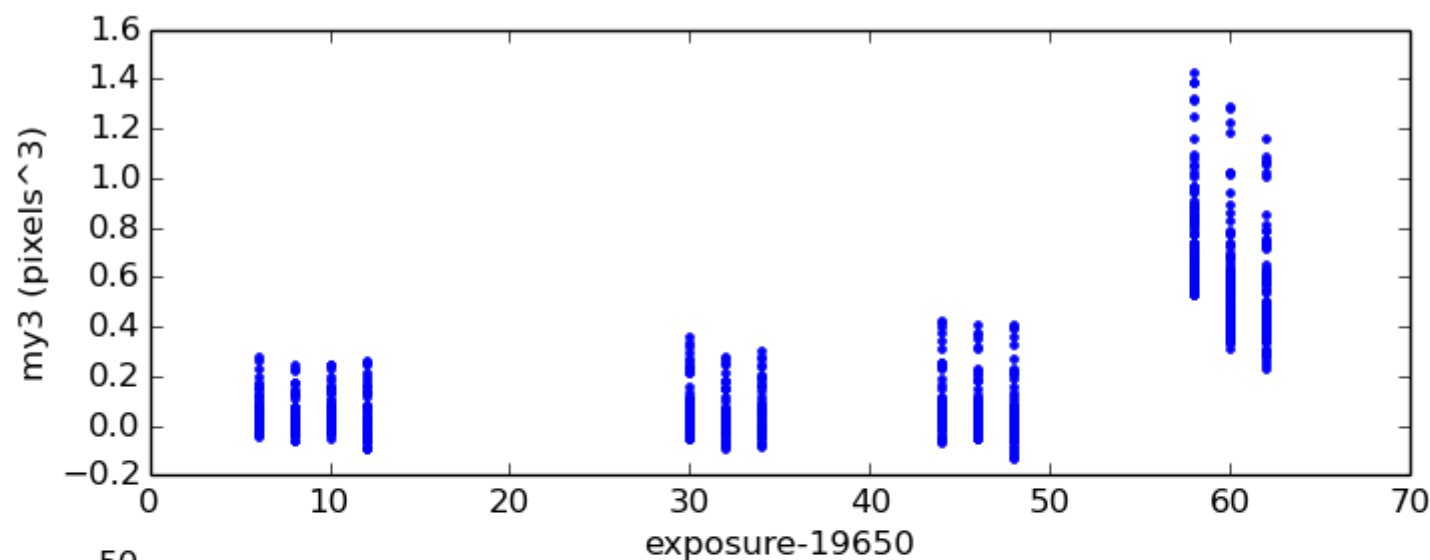


# Odd PSF terms

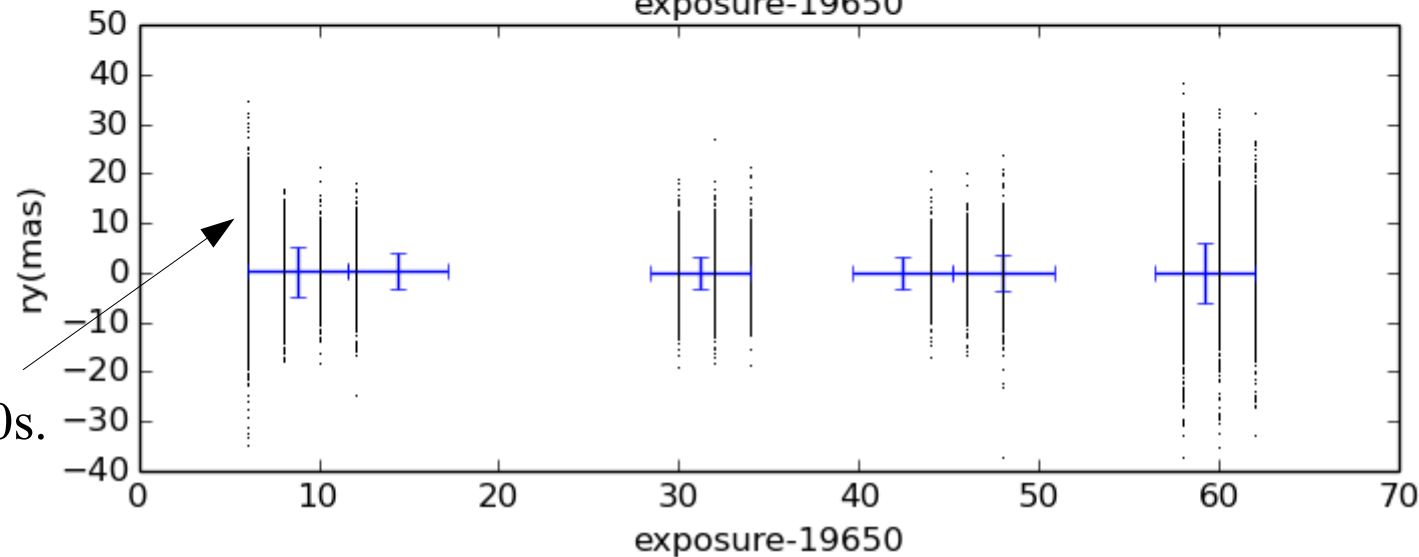
Skewed PSFs



3<sup>rd</sup> Gaussian  
moments ( $y^3$ )  
of stars



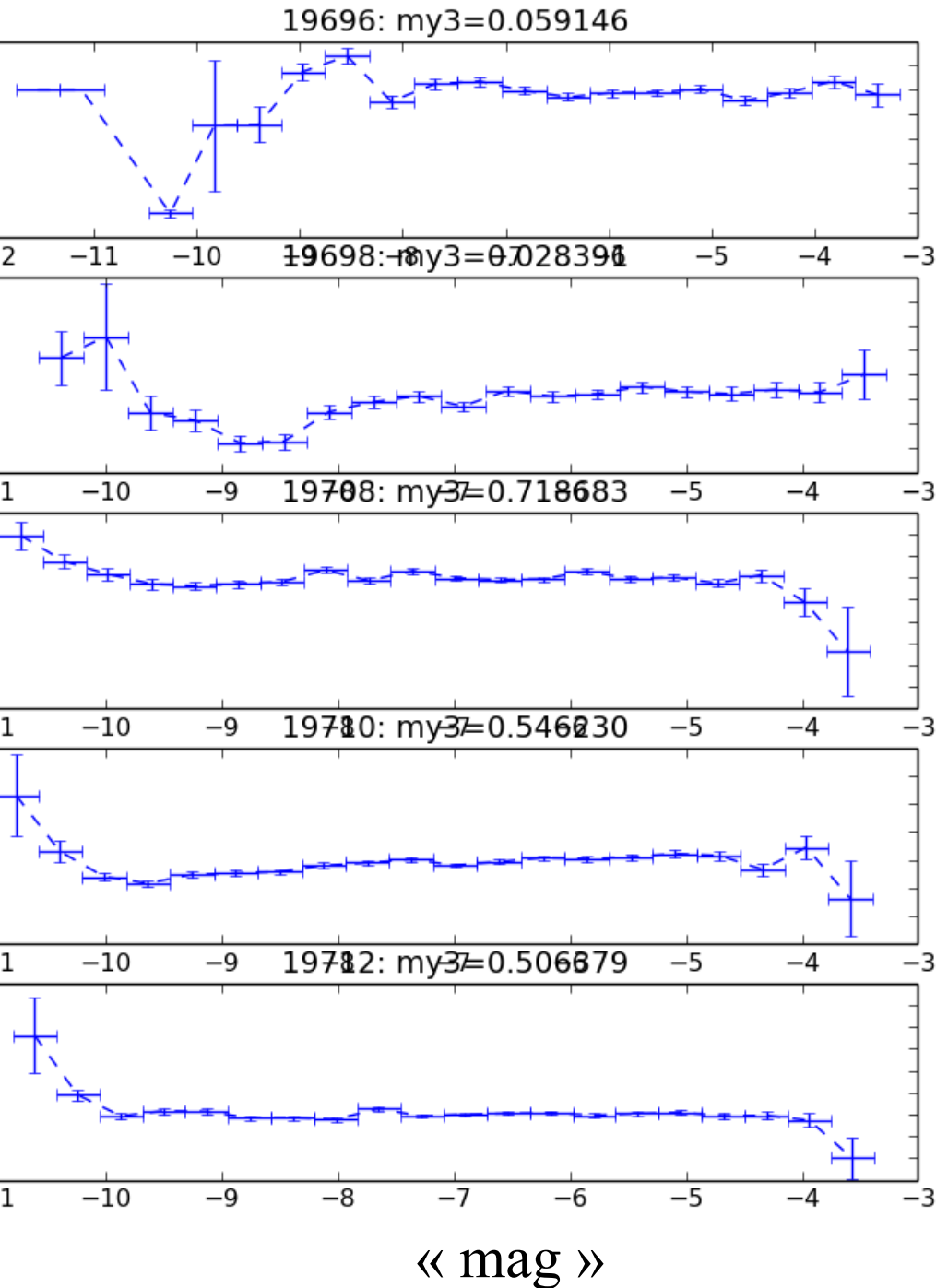
Residuals  
along  $y$   
( $m > \sim 20$ )



Night 57043, i band,  
300s exposures, first is 30s.

3362\_57043\_0\_i

# Odd PSF terms



Astrometric residuals  
To the night average

Exposures  
with poor  
residuals  
(and large 3<sup>rd</sup> moments)

# Jointcal status (1)

Diff. Atm. Refraction	→	One parameter per Band. What about HSC ???
Atm. Refraction	→	Per exposure Mosaic-wide anamorphisms
Flexure of the corrector	→	
Atmospheric turbulence	→	?? per exposure
Optical distortions	→	Per “run”(TBD)/band CCD → tang. plane mapping
Mechanics of the mosaic	→	
Tree rings	→	Fixed after determination from a specific Fitter (to be done)
Side shifts	→	
Chromatic aberrations	→	

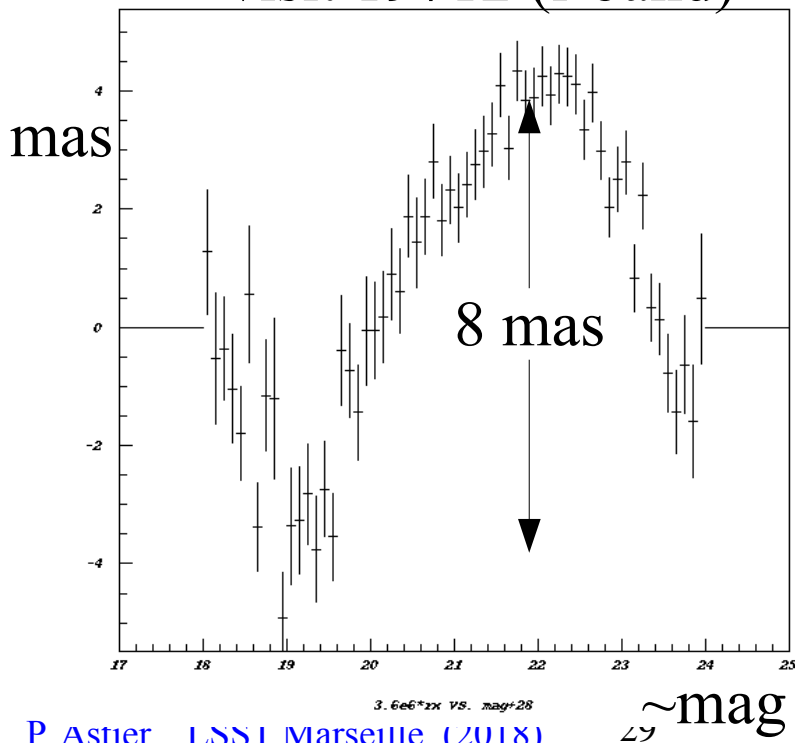
## Jointcal status/future (2)

- Any layer added to the model should come with a scheme to lift the added degeneracies.
- For some reason (guiding?), odd PSF components probably compromise the astrometric solution.
- Atmospheric turbulence requires a lot of parameters per exposure to be modeled. Some sort of post-processing would be welcome.
- Depending on the fit size, some parallelism could be needed.
- .... Proper motions, .....

# HSC: effect of PSF skewness

- Position estimation: SDSS-like coordinates, i.e Gaussian fit.

Residual( $r_x$ ) vs mag,  
visit 19712 (i-band)



- The average residual depends on how extended the object is, and hence on magnitude.
- The skewness of stars is consistent across the mosaic.
- Current fix: exclude skewed-PSF exposures from stacking.
- Is there a general way to measure positions, accounting for PSF skewness?

# Why do we care about positions when measuring fluxes ?

- When measuring the light-curve of a point source there is a benefit at using the best possible (common) position estimator.
- This requires to map the coordinate systems of the involved images one on the other.

## However....

- If  $\delta X$  is due to inaccuracies of image-to-image mappings (i.e. the floor of astrometric residuals)
- The flux bias vanishes in flux ratios
- .... which are actually used when considering the photometric calibration phase.
- So, the astrometric accuracy floor is not a first order issue when measuring lightcurves.

# Why do we care about positions when measuring shapes ?

$$M = \frac{\int (X - X_0)(X - X_0)^T W(X - X_0) I(X) d^2 X}{\int W(X - X_0) I(X) d^2 X}$$

Second moments matrix      centroid      Some weight function      image

Again, a shift of  $X_0$  will alter  $M$ , independently of the sign of the shift  
→ the  $X_0$  uncertainty causes a bias of  $M$ .

But this time, both the statistical (shot noise) and systematic (astrometric floor) contributions remain, because of the absence of a “calibration”.



# Various steps towards the astrometric solution

- Initial match (not part of the fitter but worth mentioning rapidly)
- Reading/filtering the catalogs
- Association (cross-id)
- Fit, iterations, outlier removal
  - Possibly re-associate
- Output : average catalog, WCS's, diagnostic ntuples, plots....

# Initial combinatorial match

- Problem: matching a “reference catalog” to the one of an image.
- 4-parameter space: e.g. 2 offsets, rotation, scale.
- In practice, scale is often known to  $< 1\%$  rotation angle to  $< 1^\circ$ , location on the sky to  $< 1'$ . But not always.
- There is a handful of good algorithms:
  - See e.g. Scamp doc. and astro-ph/9907229, astrometry.net
- All work properly, **provided the two catalogs overlap enough (!)**.
- The robustness of an algorithm primarily depends on how many times the right match could be found.

# SCAMP (1)

$$\chi^2 = \sum_s \sum_a \sum_{b>a} w_{s,a,b} \|\xi_a(\mathbf{x}_{s,a}) - \xi_b(\mathbf{x}_{s,b})\|^2, \quad (13)$$

where  $w_{s,a,b}$  is the non-zero weight for the pair of detections in fields  $a$  and  $b$  related to source  $s$ :

$$w_{s,a,b} = \frac{1}{\sigma_{s,a}^2 + \sigma_{s,b}^2}. \quad (14)$$

$\sigma_{s,f}$  is the positional uncertainty for source  $s$  in field  $f$ .

- Scamp minimizes the difference between mapped coordinates of measurement pairs.
- This is not exactly a maximum likelihood.

# SCAMP (2)

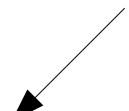
- The default fitted model combines an instrument-specific mapping and an exposure anamorphism (atmosphere+...)
- Scamp incorporates the mechanics for combinatorial matching (possibly at the array level, using an embedded instrument layout).
- Can handle dozens of different reference catalogs.
- Parallaxes and proper motions (fitted separately...)
- Outputs the “average” catalog and WCS fits headers.
- Also outputs a lot of diagnostic plots.
- Any contender should provide at least these functionalities....

# WcsFit (1703.01679)

- Written by G. Bernstein to finely map the instrumental distortions of Decam, from dithered exposures of dense stellar fields.
- Actually fits positions of common objects.
- Does not rely on sparse linear algebra, thanks to a trick:

$$\begin{aligned}\chi^2 &\approx \chi^2(\boldsymbol{\pi}_0) + 2\mathbf{b} \cdot \Delta\boldsymbol{\pi} + \Delta\boldsymbol{\pi} \cdot \mathbf{A} \cdot \Delta\boldsymbol{\pi}, \\ b_\mu &\equiv \frac{1}{2} \frac{\partial \chi^2}{\partial \pi_\mu} = \sum_i w_i (\mathbf{x}^w(\mathbf{x}_i^p, \boldsymbol{\pi}_0) - \bar{\mathbf{x}}_{\alpha_i}) \cdot \left( \frac{\partial \mathbf{x}^w(\mathbf{x}_i^p, \boldsymbol{\pi})}{\partial \pi_\mu} - \frac{\partial \bar{\mathbf{x}}_{\alpha_i}}{\partial \pi_\mu} \right) \\ A_{\mu\nu} &\equiv \left( \frac{\partial \mathbf{x}^w(\mathbf{x}_i^p, \boldsymbol{\pi})}{\partial \pi_\mu} - \frac{\partial \bar{\mathbf{x}}_{\alpha_i}}{\partial \pi_\mu} \right) \cdot \left( \frac{\partial \mathbf{x}^w(\mathbf{x}_i^p, \boldsymbol{\pi})}{\partial \pi_\nu} - \frac{\partial \bar{\mathbf{x}}_{\alpha_i}}{\partial \pi_\nu} \right).\end{aligned}$$

Position of sources  
treated as the  
average of  
transformed  
measurements



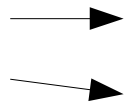
# WcsFit (2)

- The user provides the fitted model at run time, by specifying a combination of transformations.
- The code does its best to eliminate degeneracies, but there is no failsafe algorithm.
- An example of the fitted components:

Table 2. Components of the DECam astrometric model

Description	Name	Type	Max. Size
Tree ring distortion	$\langle band \rangle / \langle device \rangle / rings$	Template (radial)	$\approx 0''.05$
Serial edge distortion	$\langle band \rangle / \langle device \rangle / lowedge$	Template (X)	$0''.03$
Serial edge distortion	$\langle band \rangle / \langle device \rangle / highedge$	Template (X)	$0''.03$
Optics	$\langle band \rangle / \langle device \rangle / poly$	Polynomial (order= 4)	$\gg 1''$
Lateral color <sup>a</sup>	$\langle band \rangle / \langle device \rangle / color$	Color×Linear	$\approx 0''.04$
CCD shift	$\langle epoch \rangle / \langle device \rangle / ccdshift$	Linear	$\approx 0''.1$
Exposure	$\langle exposure \rangle$	Linear	$\gg 1''$
Differential chromatic refraction	$\langle exposure \rangle / dcr$	Color×Constant	$\approx 0''.05$

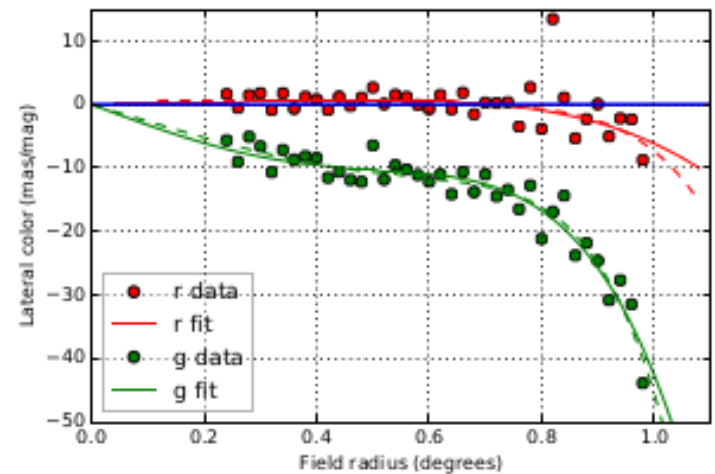
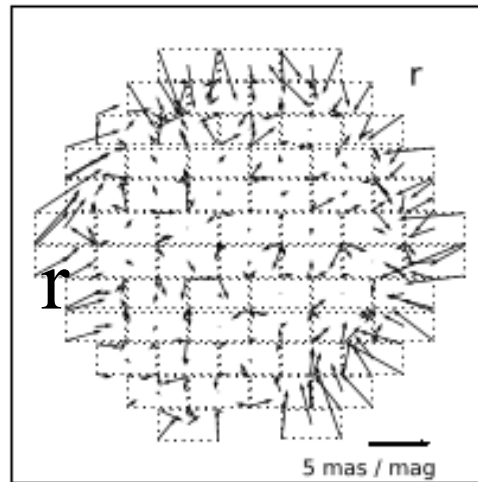
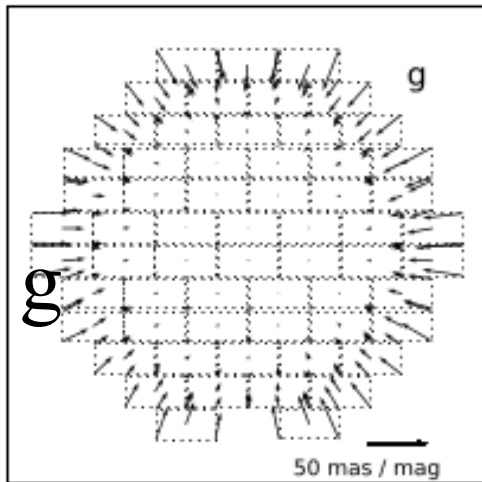
Degeneracy ?



Next slide  
Not sufficient  
for  
refraction

# WcsFit for Decam

Chromatic terms (per chip/band) for g-i color



Large chromaticity of the Decam corrector.  
It can (will?) eventually become a static part of the instrument model