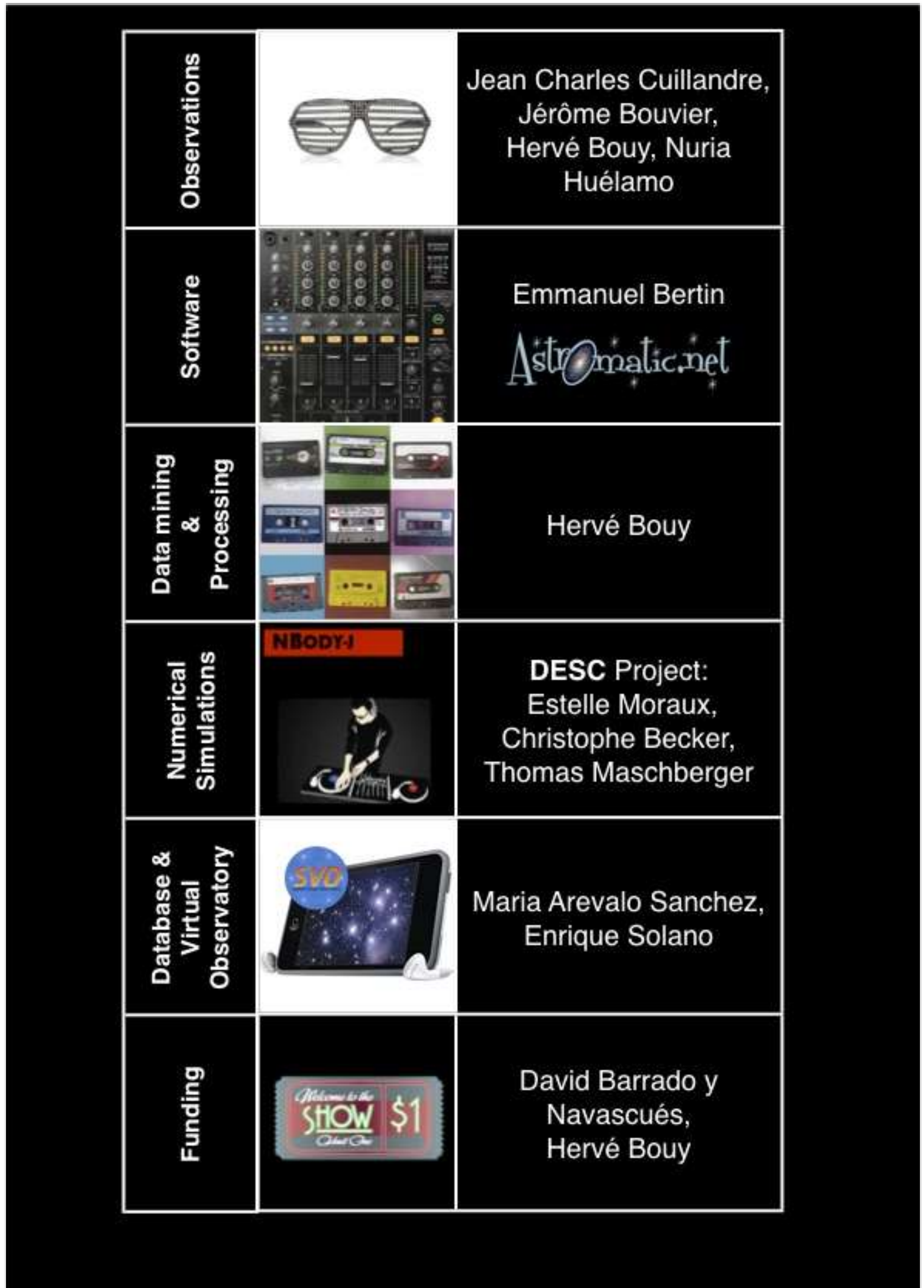
# Dynamical Analysis of Nearby ClustErs

Emmanuel Bertin (IAP)
for the DANCe collaboration

# DANCeRS



| | | |
|---|---|---|
| Observations | | Jean Charles Cuillandre, Jérôme Bouvier, Hervé Bouy, Nuria Huélamo |
| Software | | Emmanuel Bertin<br>Astromatic.net |
| Data mining & Processing | | Hervé Bouy |
| Numerical Simulations | NBODY-I | **DESC** Project:<br>Estelle Moraux, Christophe Becker, Thomas Maschberger |
| Database & Virtual Observatory | SVO | Maria Arevalo Sanchez, Enrique Solano |
| Funding | Welcome to the SHOW $1 | David Barrado y Navascués, Hervé Bouy |

# DANCe

## Main Objectives

Derive high precision astrometry over entire associations down to the substellar and planetary mass regimes

## Scientific goals

1. Detailed census of an association (identifying co-moving members and rejecting contaminants)
2. Study of internal dynamics and dynamical evolution as a function of mass, age, environment.
3. Compare with numerical simulation

## Requirements

1. astrometric accuracy better than 1 km/s for comparison with numerical simulations
2. cover large areas of the sky including entire associations

## Challenge

1 km/s at 200 pc = 1 mas/yr

## Strategy

Retrieval of wide field observations performed over the past 15 years from public archives

New observations

Fully automated multi-epoch, multi-instrument, multi-wavelength analysis

# Dancefloor: The Pleiades

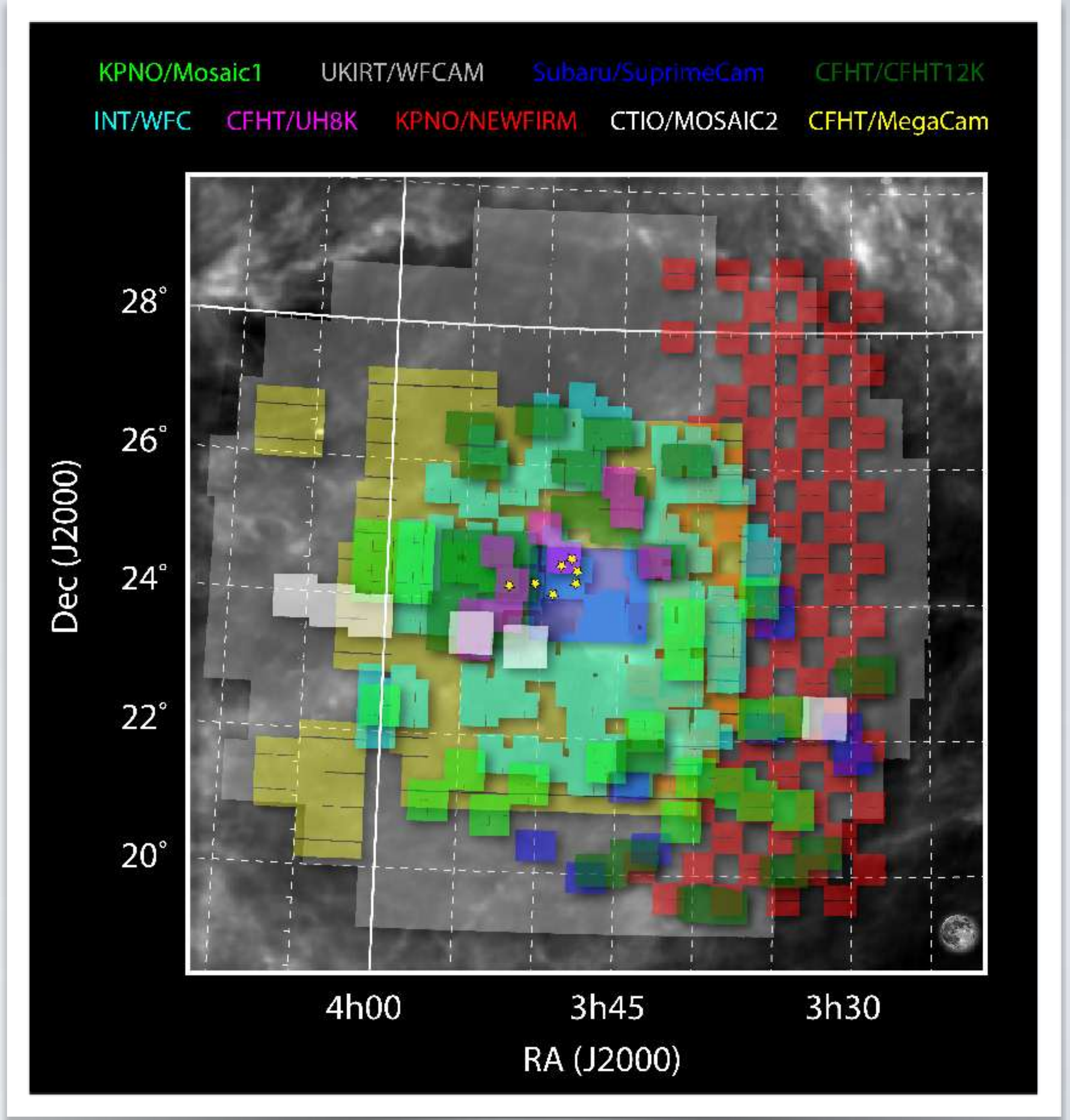
~17,000 images

~$10^{12}$ pixels

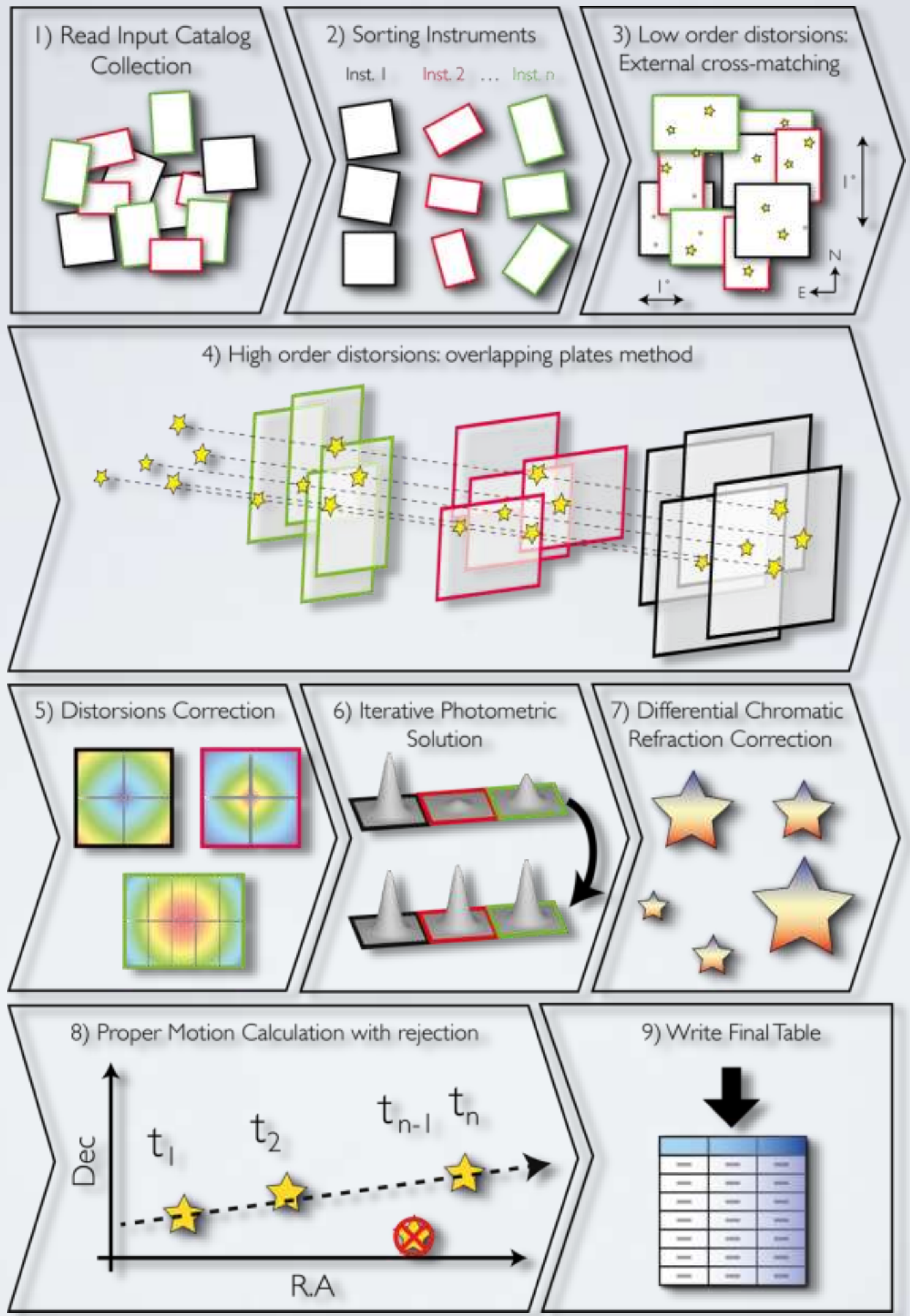
~5TB

~$10^{8}$ detections

~$10^{7}$ sources

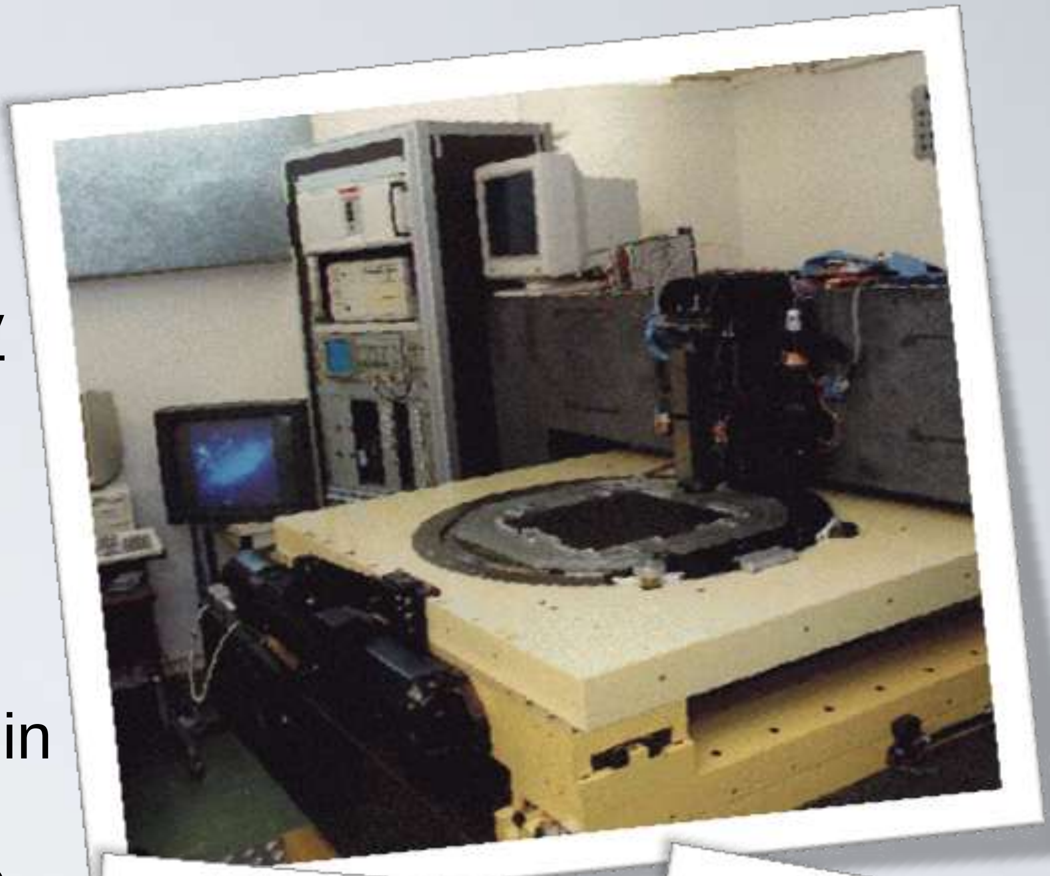


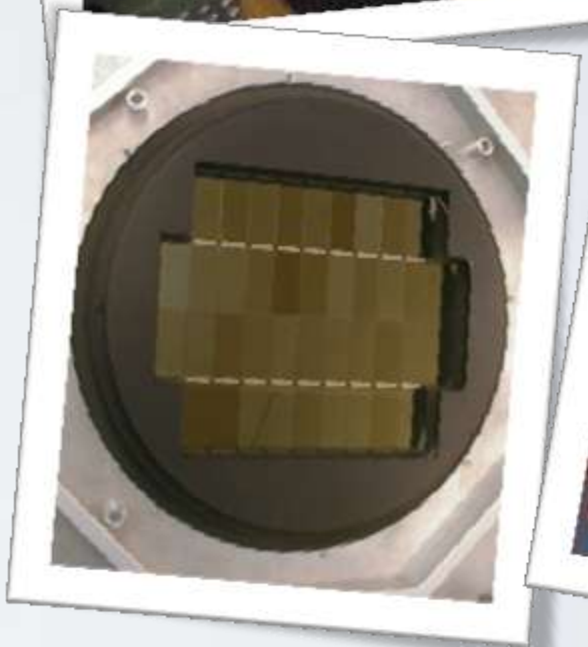
# Processing using AstrOmatic software



# SExtractor: source extraction

- SExtractor program originally developed to extract sources from Schmidt plate scans (MAMA microdensitometer at the Paris observatory) in a fully automated way
  - Allow to process very large images (up to 2GB) on a regular workstation (16MB of memory!) in one go.
  - Soon modified to allow processing of CCD data
  - First public SExtractor release in **1994**
- **1995** and onward: software developed and released in the framework of various wide-field digital data processing projects (LDAC, EIS, **TERAPIX**, DESDM)
  - Surveys set technical requirements
  - Public, « open » approach and user feedback:
    - Large user base helps improve software portability and robustness
    - Give precious hints in choosing generic algorithms that will work with most kinds of wide-field image data.
- **1998:** SExtractor 2
- **2009**: Astr*O*matic website online
  - All the code mentioned here is open source and available for download at `astromatic.net`
- **2012**: SExtractor 3



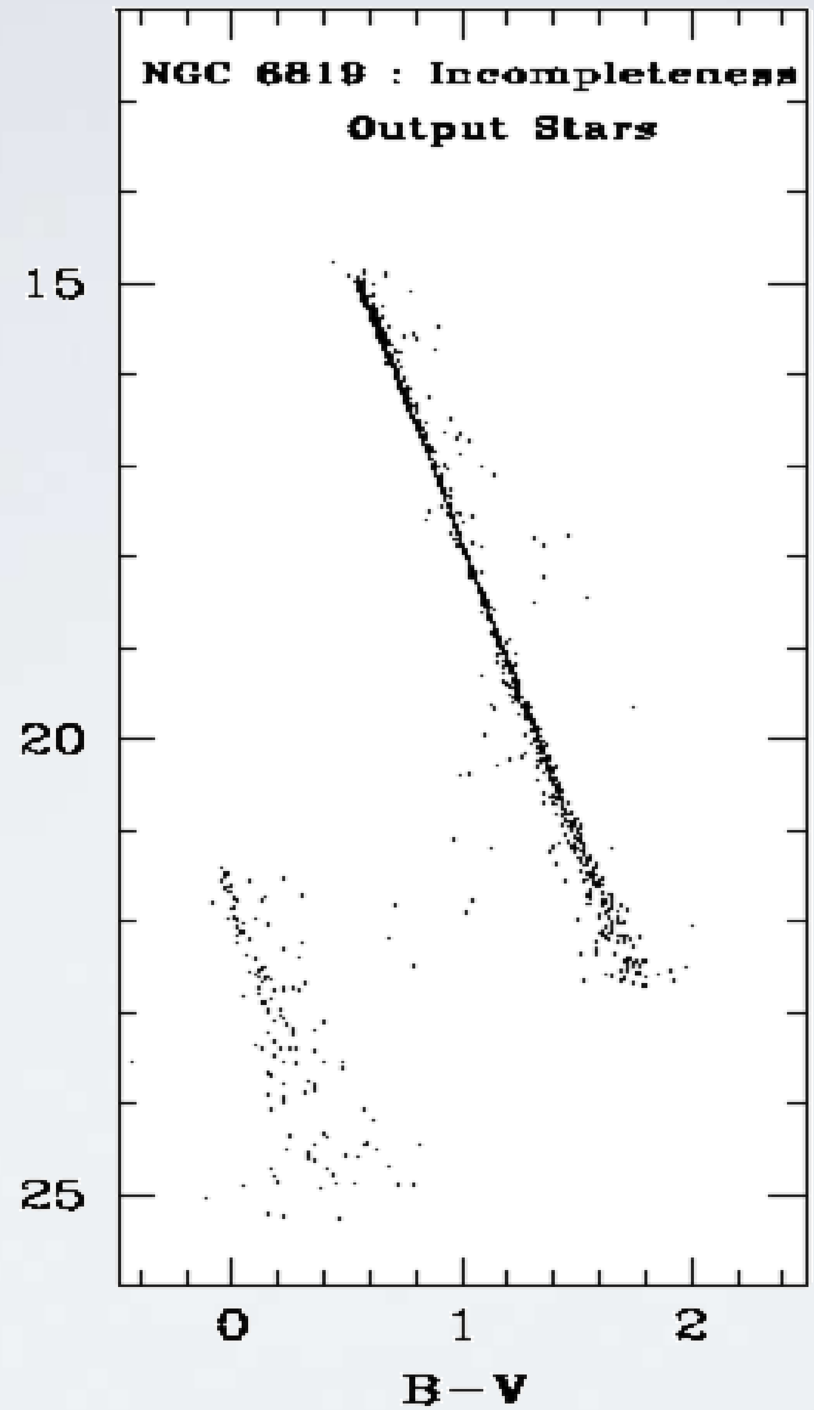


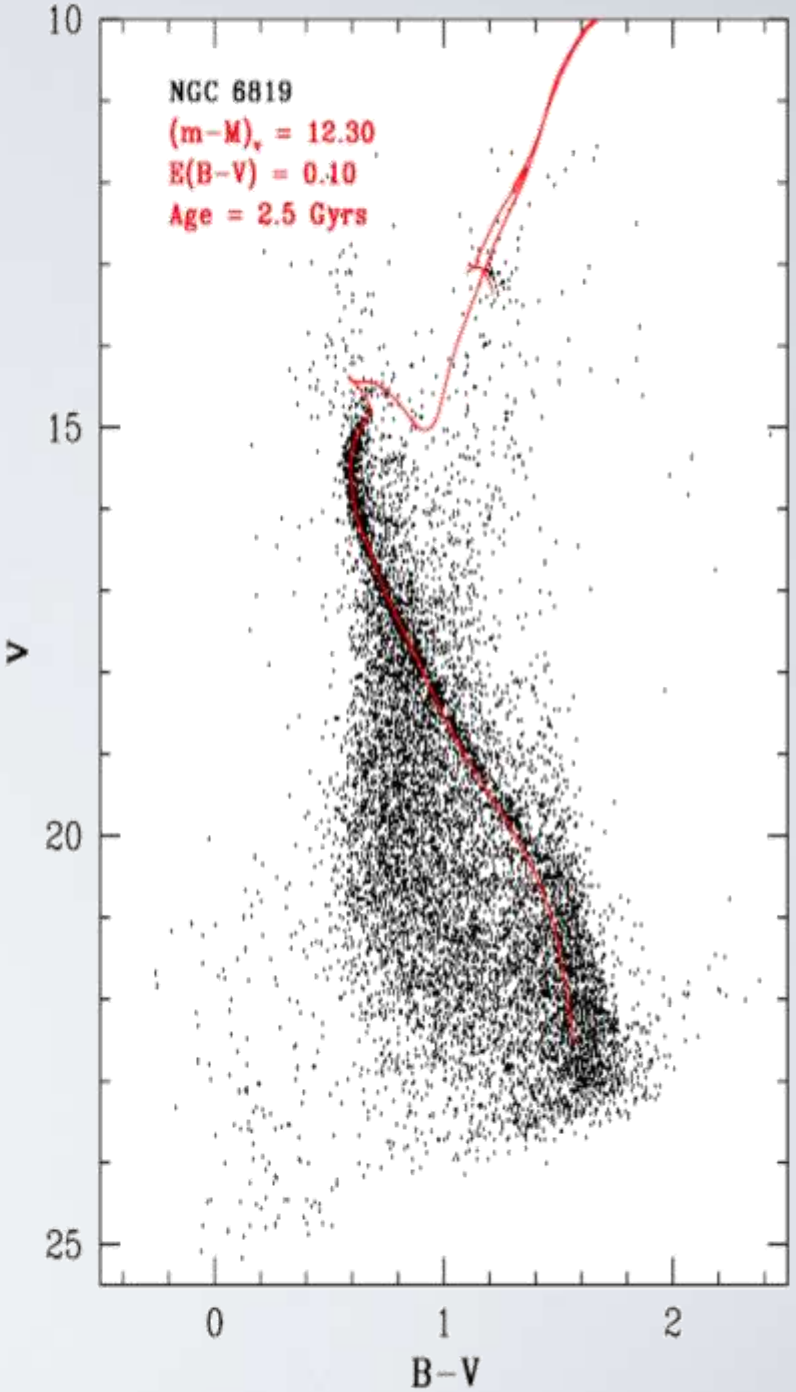
Megacam 350 Mpixel camera

Decam 520 Mpixel camera

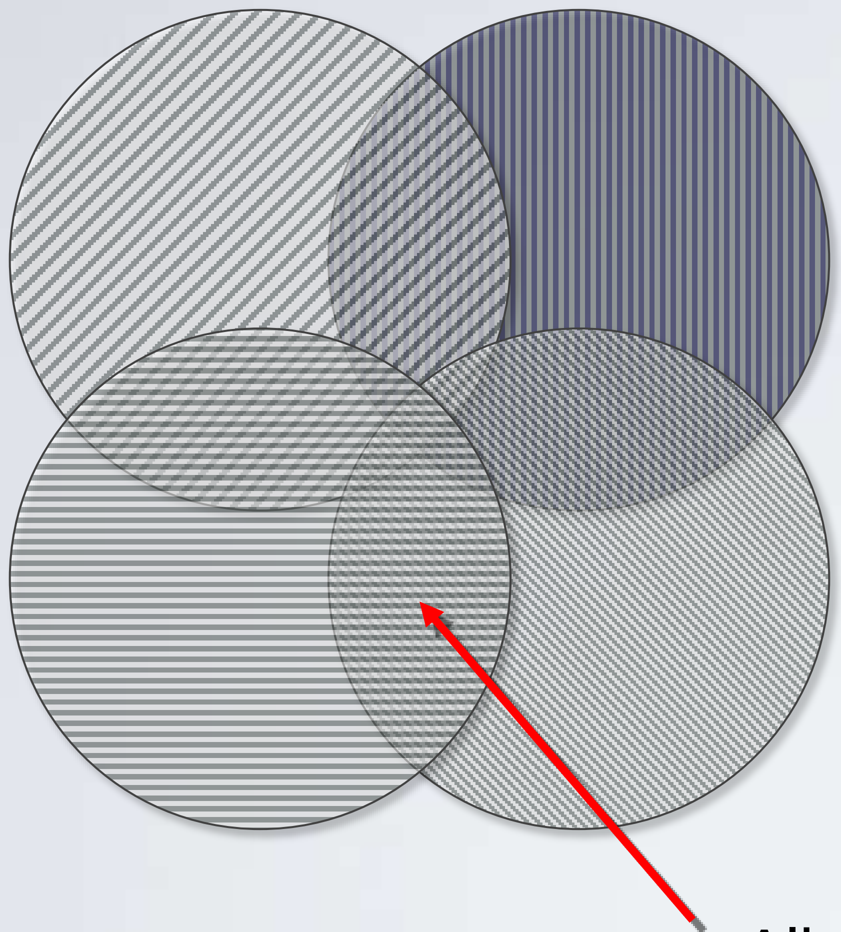
# PSF modeling and fitting

- PSF modeling and fitting in SExtractor operating in an experimental way since 2001 (Cuillandre et al. 2001, Kalirai et al. 2001)
- Fitting routine can fit groups of blended stars
- Much work went into handling arbitrary PSFs and undersampled data.



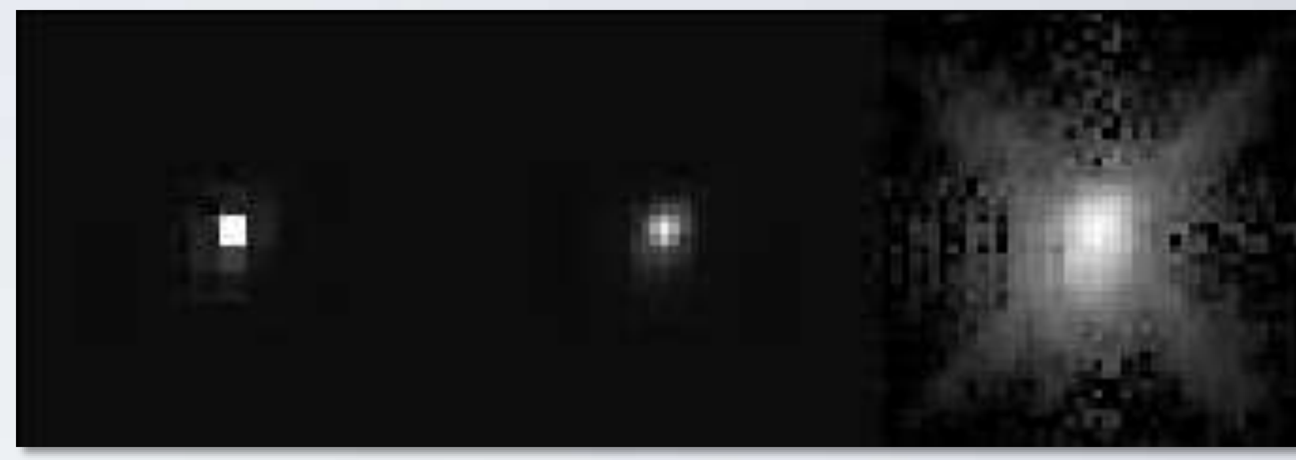



# Modeling undersampled PSFs



Aliased portion of
the image spectrum

Reconstructing the NICMOS PSF by solving in Fourier space *(**Lauer 1999**)*



Problem: noise is seldom stationary on astronomical images!

# PSFEx: solving in direct space

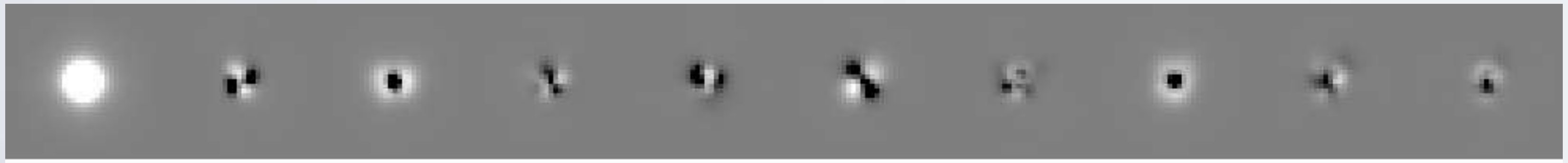
- A resampling kernel $h$, based on a compact interpolating function (*Lanczos3*), links the “super-tabulated” PSF to the real data: the pixel $j$ of star $i$ can be written as

$$P_{ij} = a_i \sum_b \sum_k h_i\left(\boldsymbol{x}_k - \boldsymbol{x}_j\right) c_b \psi_{bk}$$

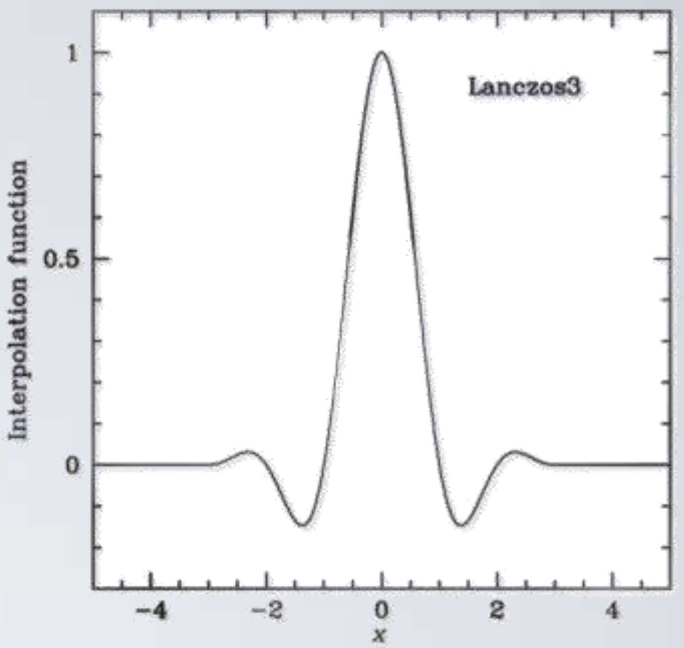
- The $c_b$’s are derived using a <u>weighted</u> $\chi^2$ minimization.
- The $a_i$’s are obtained from “cleaned” aperture magnitude measurements
- Regularisation required for highly undersampled PSFs (FWHM <1.5 pixel)
  - $\ell^2$ norm (Tikhonov)
- PSF variations are assumed to be a smooth function of object coordinates
  - ☞ The variations can be decomposed on a polynomial basis $X_l$

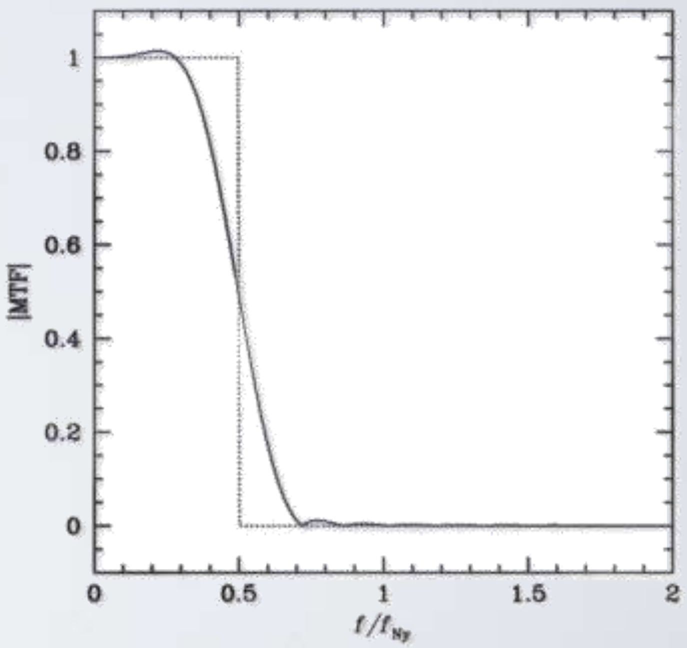
$$P_{ij} = a_i \sum_l X_l(\boldsymbol{x}_i) \sum_b \sum_k h_i\left(\boldsymbol{x}_k - \boldsymbol{x}_j\right) c_b \psi_{lbk}$$

$\psi_b$



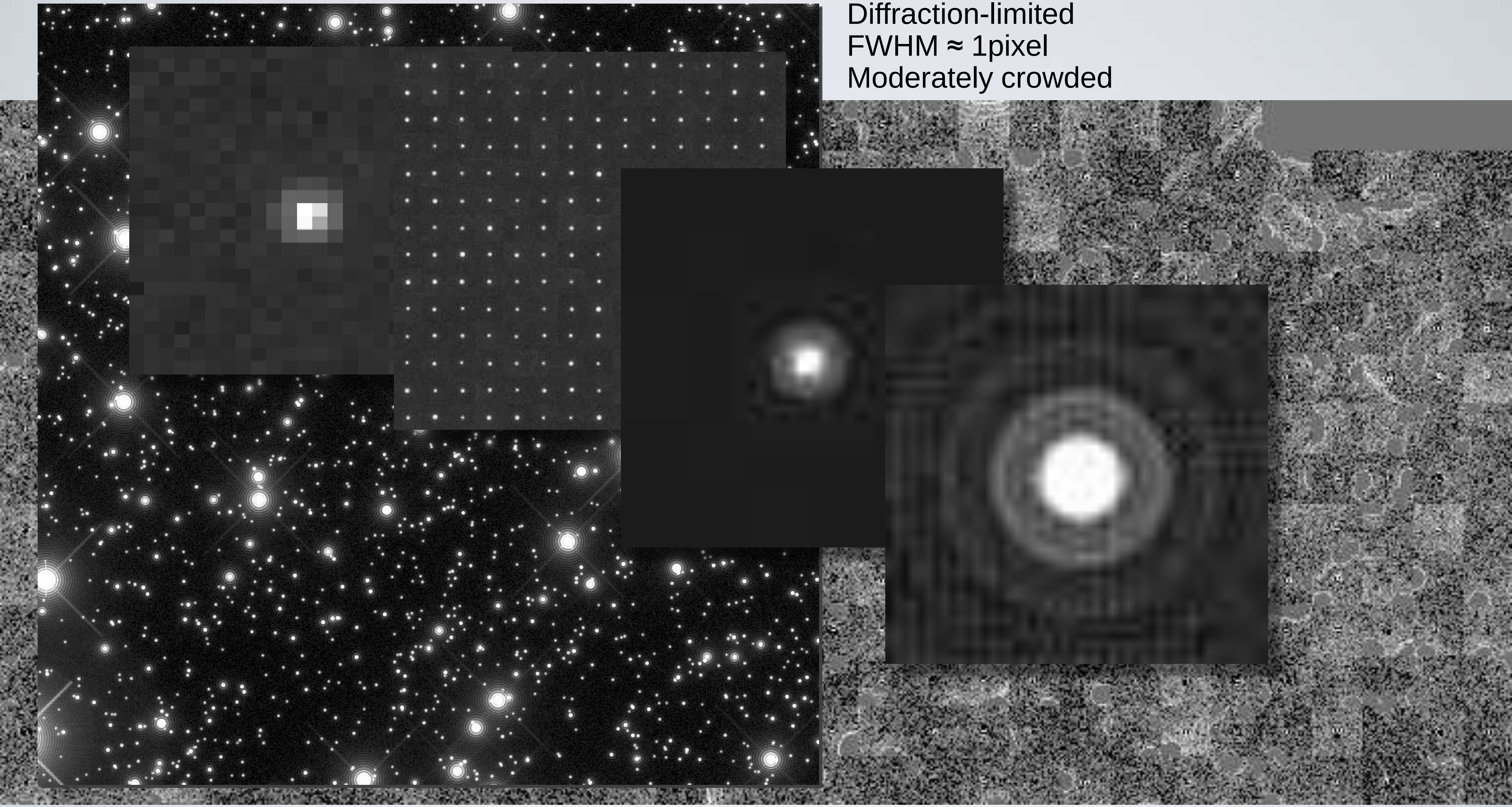
| $X_l =$ | cste | $x$ | $x^2$ | $x^3$ | $y$ | $xy$ | $x^2y$ | $y^2$ | $xy^2$ | $y^3$ |
|---|---|---|---|---|---|---|---|---|---|---|



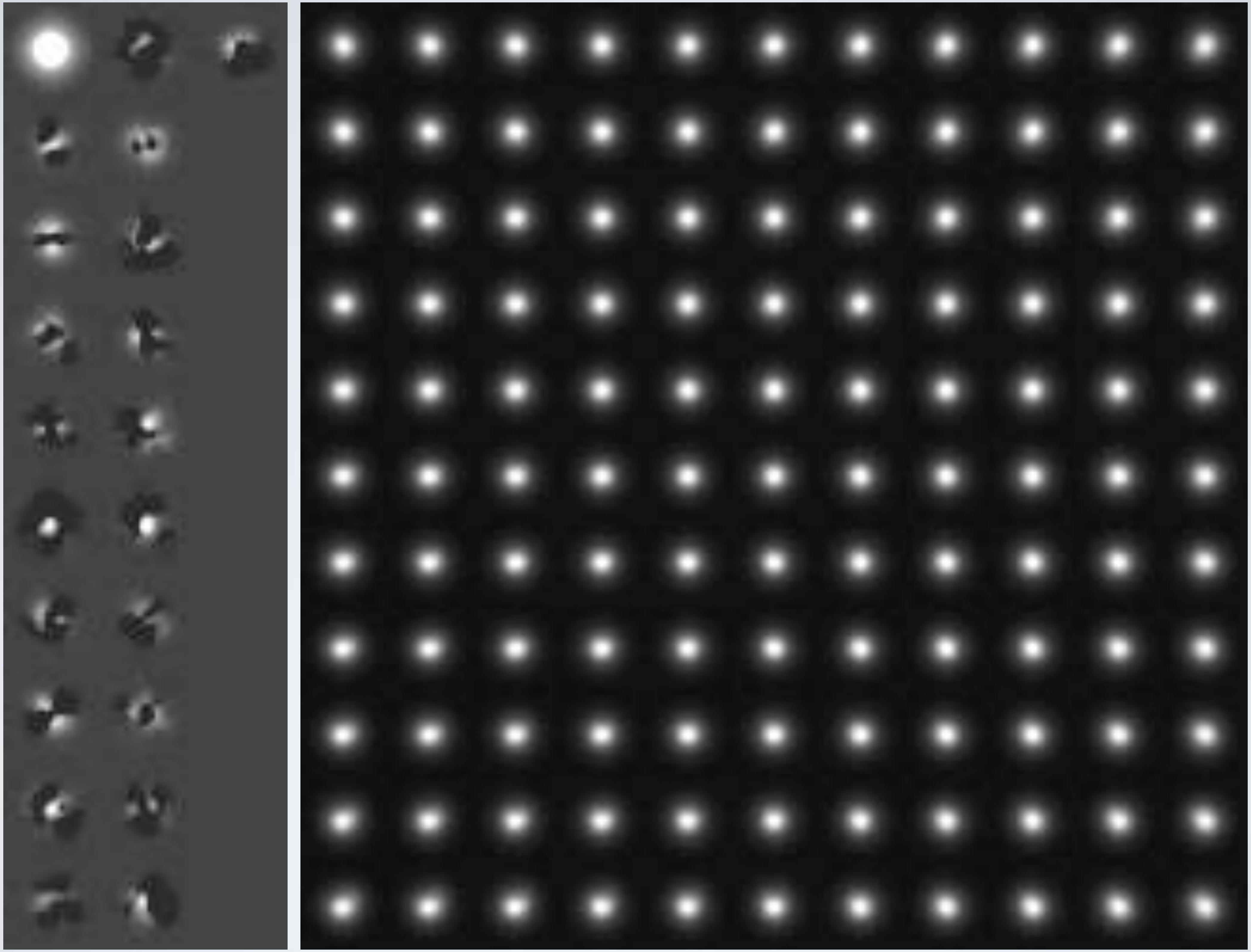



# Recovered PSF with simulated, undersampled data

Diffraction-limited
FWHM ≈ 1pixel
Moderately crowded



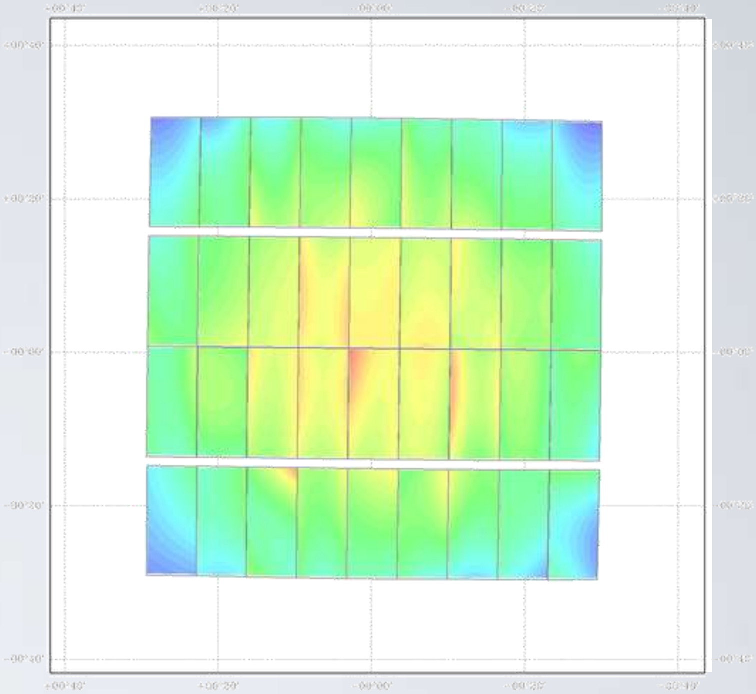
# Example of a reconstructed MEGACAM average PSF in the i band

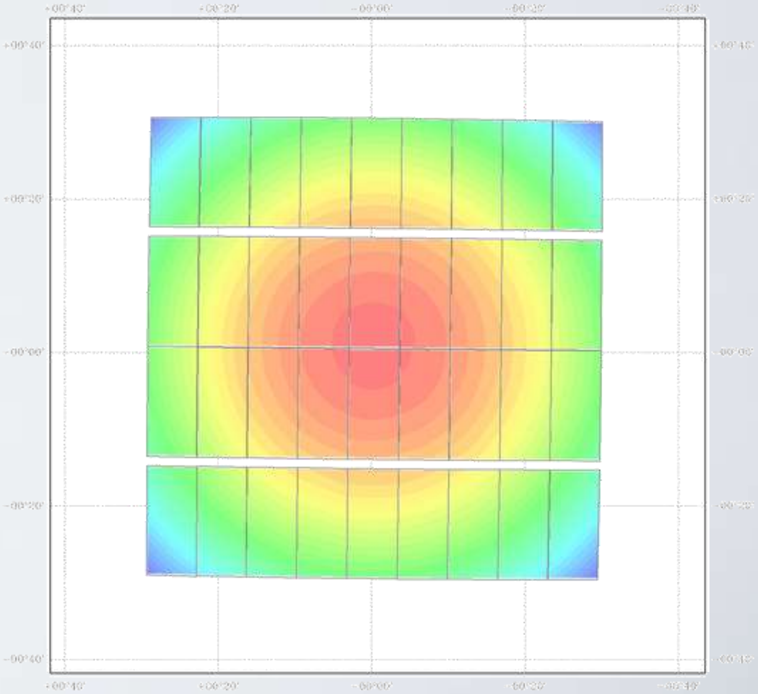


# "Blind'', global astrometric solutions

- The mapping of astrometric distortions typically requires a $4^{th}$ degree polynomial in projected coordinates $\xi$
  - 30 free parameters per CCD, written to FITS headers using the "TPV" convention
  - Approaches that won't work here:
    - "physical" modeling (CCD geometry, optical distortions, atmospheric refraction)
      - Too many different instruments
      - Information missing
    - fit the distortion coefficients for each exposure using a reference catalog (GSC, USNO,…)
      - Simple and fast but too sensitive to inaccuracies in the reference catalog, especially when a little more than 20 stars are cross-identified on a CCD.
  - Global solution: fit the distorsion coefficients by additionally minimizing the distances between the projected coordinates of overlapping detections.
    - Approach taken for many astrometric reduction problems (e.g. ***Eichhorn 1960***, ***Deul et al. 1995***, ***Kaiser et al. 1999***, ***Radovich et al. 2004***)
    - For every source s on overlapping exposures *a* and *b* minimize

$$\chi^2 = \sum_s \sum_a \sum_b w_{sab} \left\| \xi_a(\mathbf{x}_{sa}) - \xi_b(\mathbf{x}_{sb}) \right\|^2$$



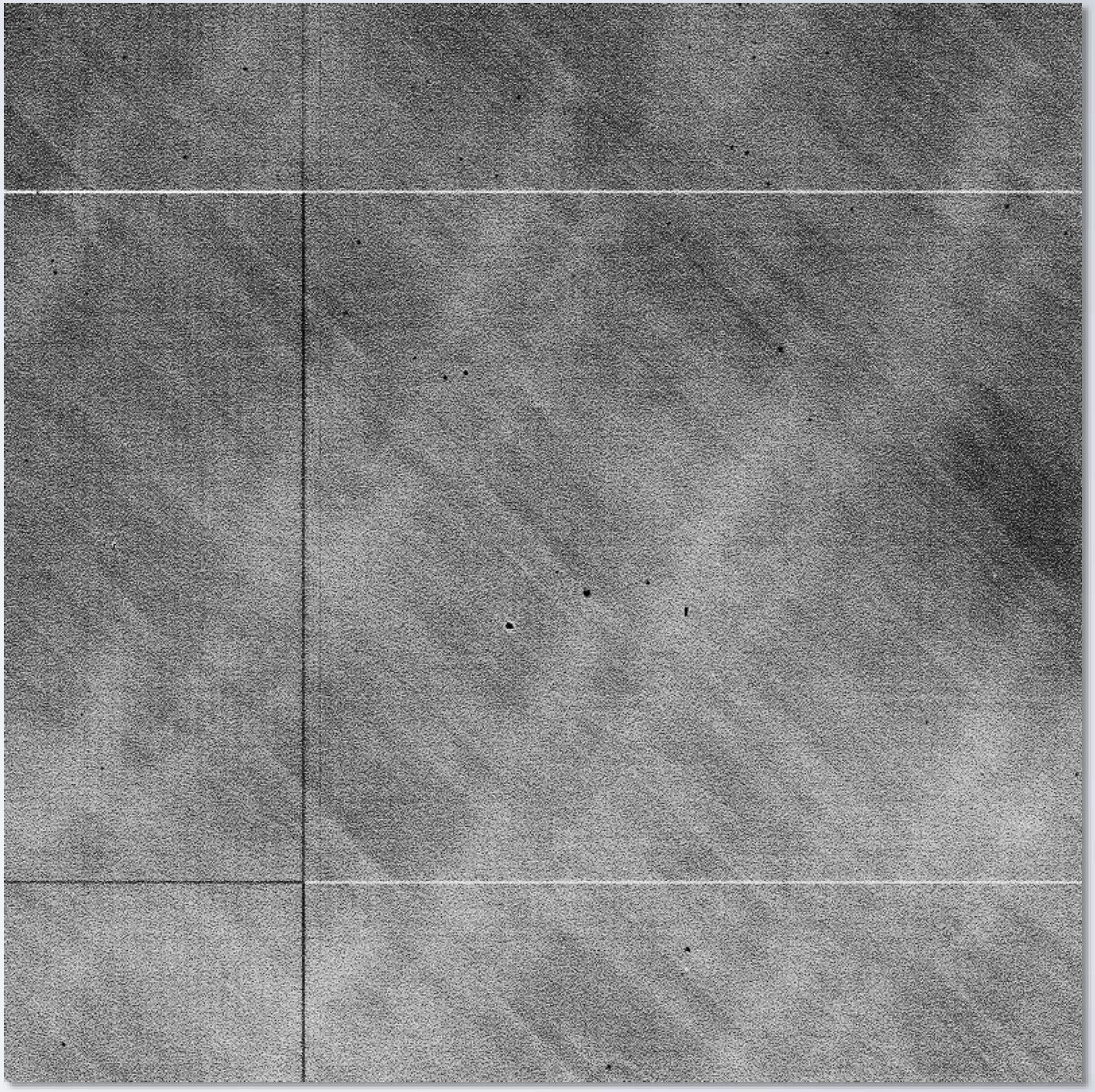


# Minimising the number of free parameters

- Mosaic cameras: $n_{\rm chip}\times 30$ = hundreds of free parameters per exposure for a 4th degree polynomial per chip!
  - Too many free parameters: robustness problems arise because of a lack of sources or confusion in some fields
  - Slow, iterative approach necessary
- For a given instrument (and a given filter combination), one may assume that the distortion pattern does not vary measurably over some period of time (observing run)
  - Use FITS keywords to automatize the process of grouping exposures per instrumental "context"
- One must still allow the lower orders of the distorsion pattern to vary globally from exposure to exposure because of atmospheric refraction and flexures
  - $n_{\rm chip}\times n_{\rm instru}\times 30 + 12\times(n_{\rm exp} - n_{\rm instru})$ free parameters
  - Requires an intermediary transformation to a common re-projection
    - Deal with the Jacobians of individual re-projections

# Factors limiting astrometric precision

- Photon noise: 3 – 200 mas on individual exposures depending on SNR and seeing
- “Frozen” atmospheric turbulence on short exposures (~5-20 mas for t<30s)
- Source crowding and confusion noise
- Differential Chromatic Refraction (wide filters)
  - Atmospheric
  - Chromatic aberrations
- Variability of the intra-pixel response profile from pixel to pixel
  - Mostly affect IR arrays
  - On modern CCDs, repeatability of centroiding with properly sampled stars is ~ 1/300$^{th}$ of a pixel over the array (e.g. ***Yano et al. 2004***)
  - Step-and-repeat pixel size error on some generations of large CCDs (***Shaklan & Pravdo 1994***): typically 0.5$\mu$m (a few hundredth of a pixel) each 512 or 1024 pixel
- Proper motions
- Trigonometric parallaxes

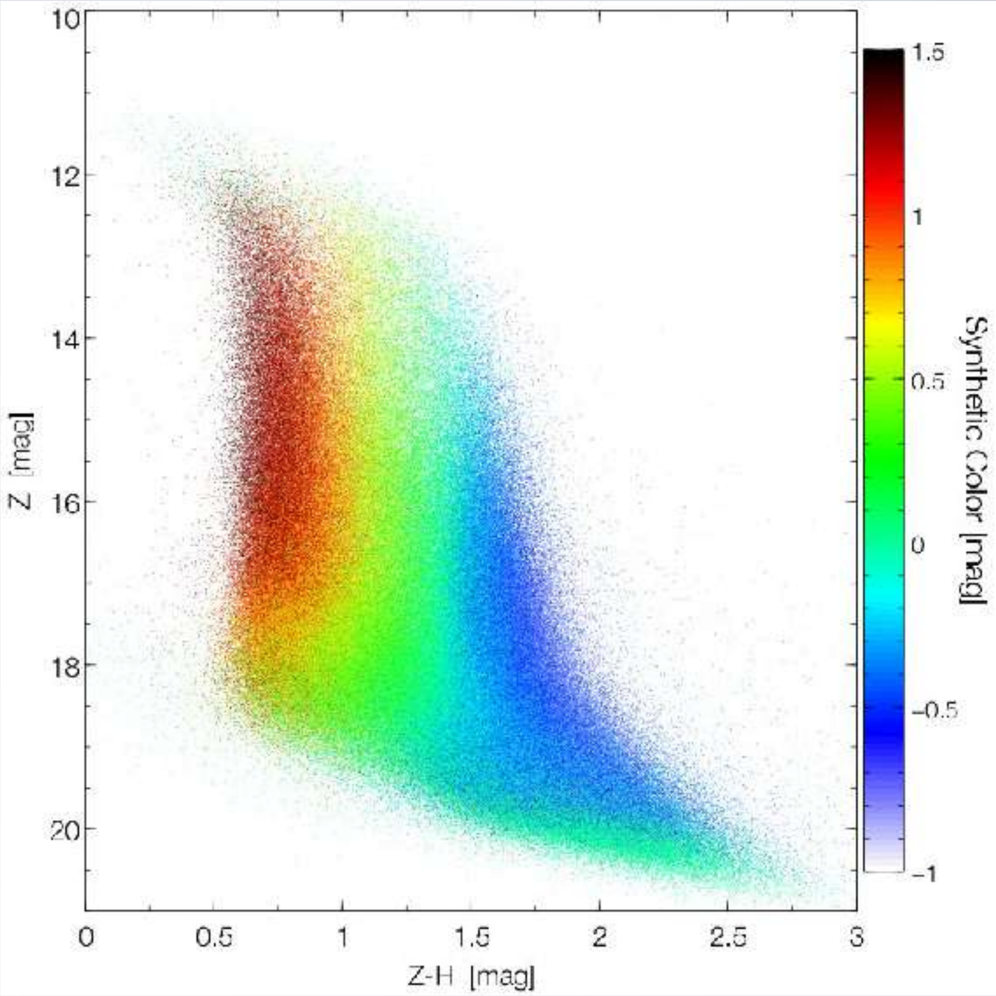


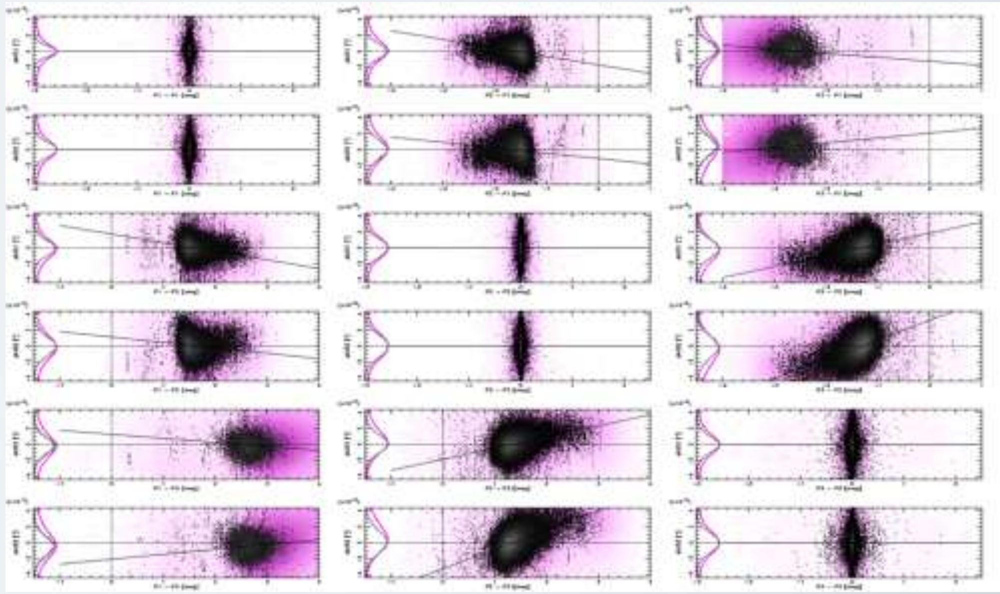
# Correcting differential chromatic refraction

- For a star with spectral index $\alpha$, observed at zenithal distance *z* in a filter of bandwidth *w* (in microns) centered on wavelength $\lambda_0$ (in arcsec):

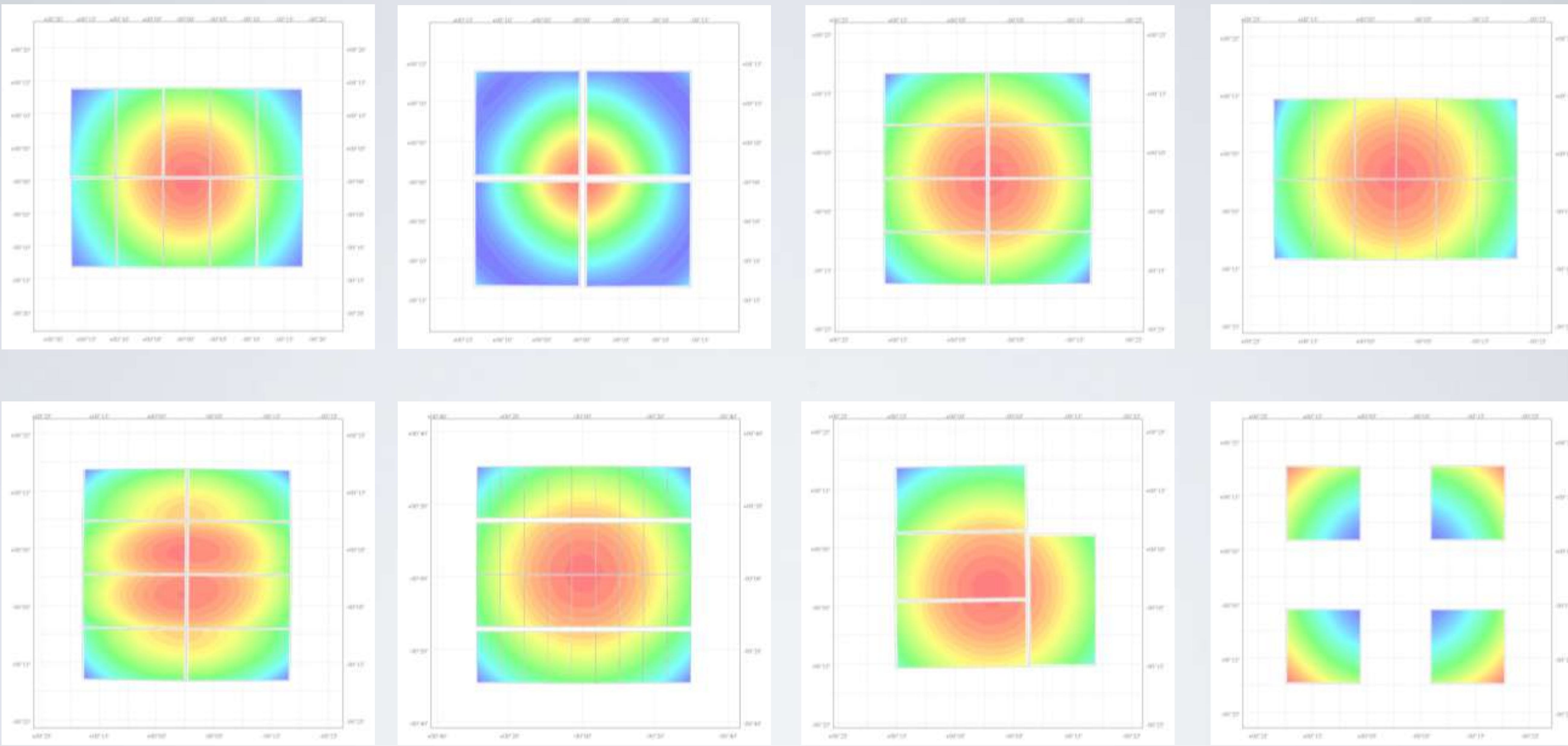
$$\Delta z_{\lambda_0,w} \approx 23750 \left(\frac{dn}{d\lambda}\right)_{\lambda_0} \tan z \;\; w^2 \alpha$$

- w≈0.1μm for the u,g,r,i,z photometric system (SDSS,MEGACAM,…)
    - At *z*=45 deg, $\Delta z$ varies from ~20mas (z band) to ~150mas (u band).
- Most ground-based catalogues are not corrected for DCR!
- We create a synthetic, global color index by assuming linear dependency between "true" color indices and correct relative position assuming that shift in position is proportional to color index.



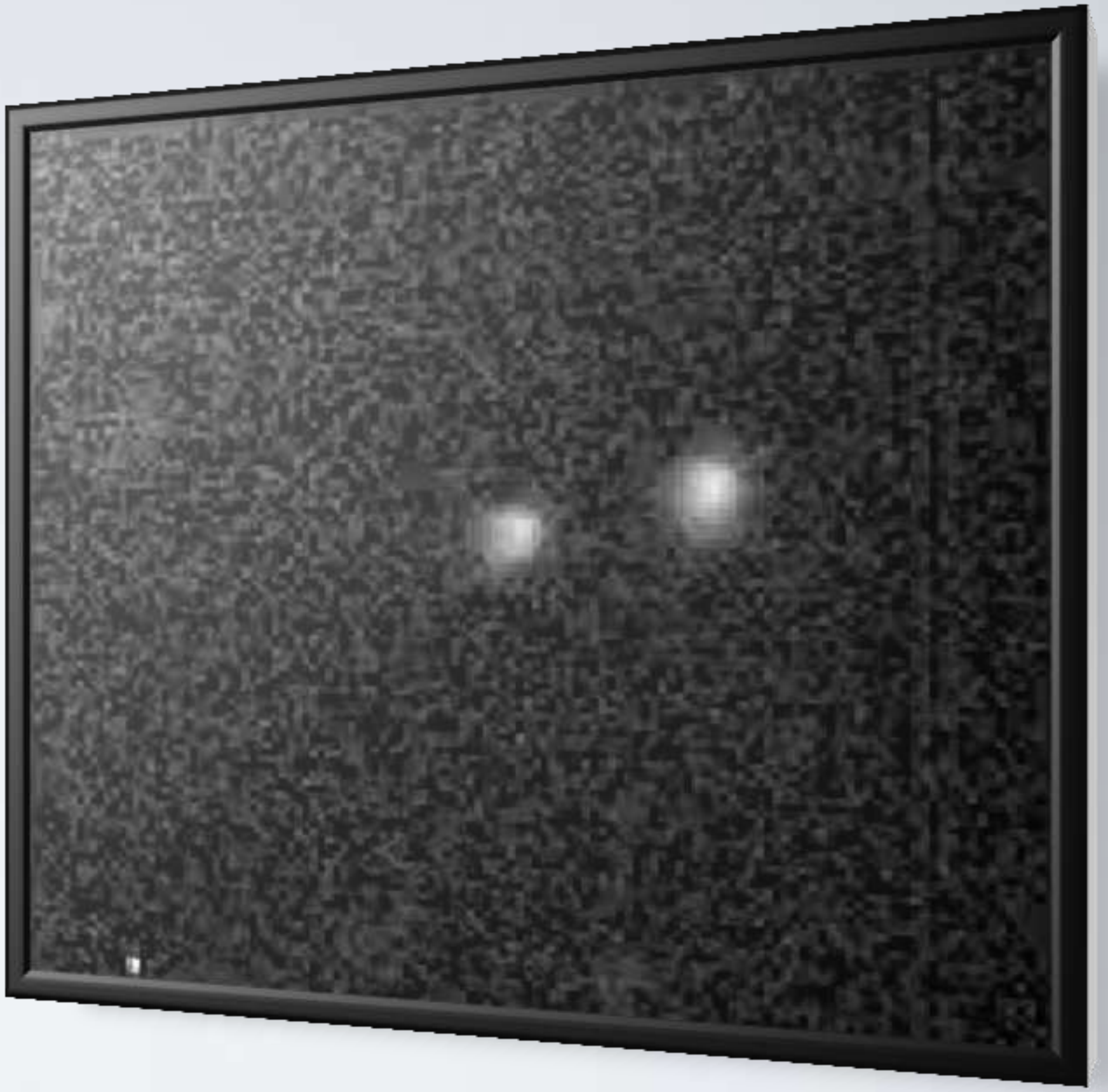



# Some of the distorted plate solutions coming out of the system

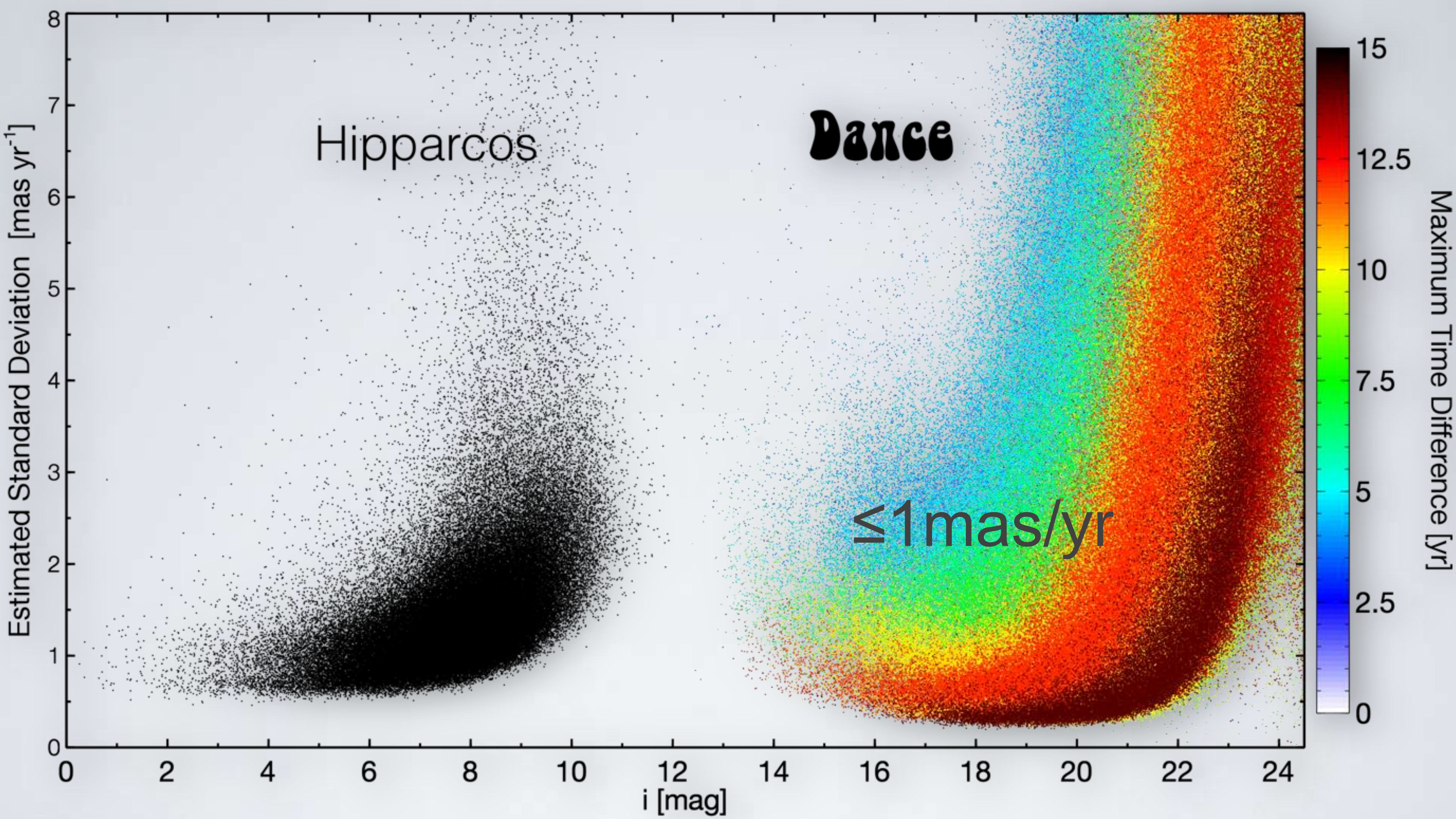


# Computing individual proper motions

- Iterative clipping on global solution
- Proper motions computed from deviations to the global solution
- Iterative rejection of outliers in time sequence for each object.
- Trigonometric parallaxes are ignored

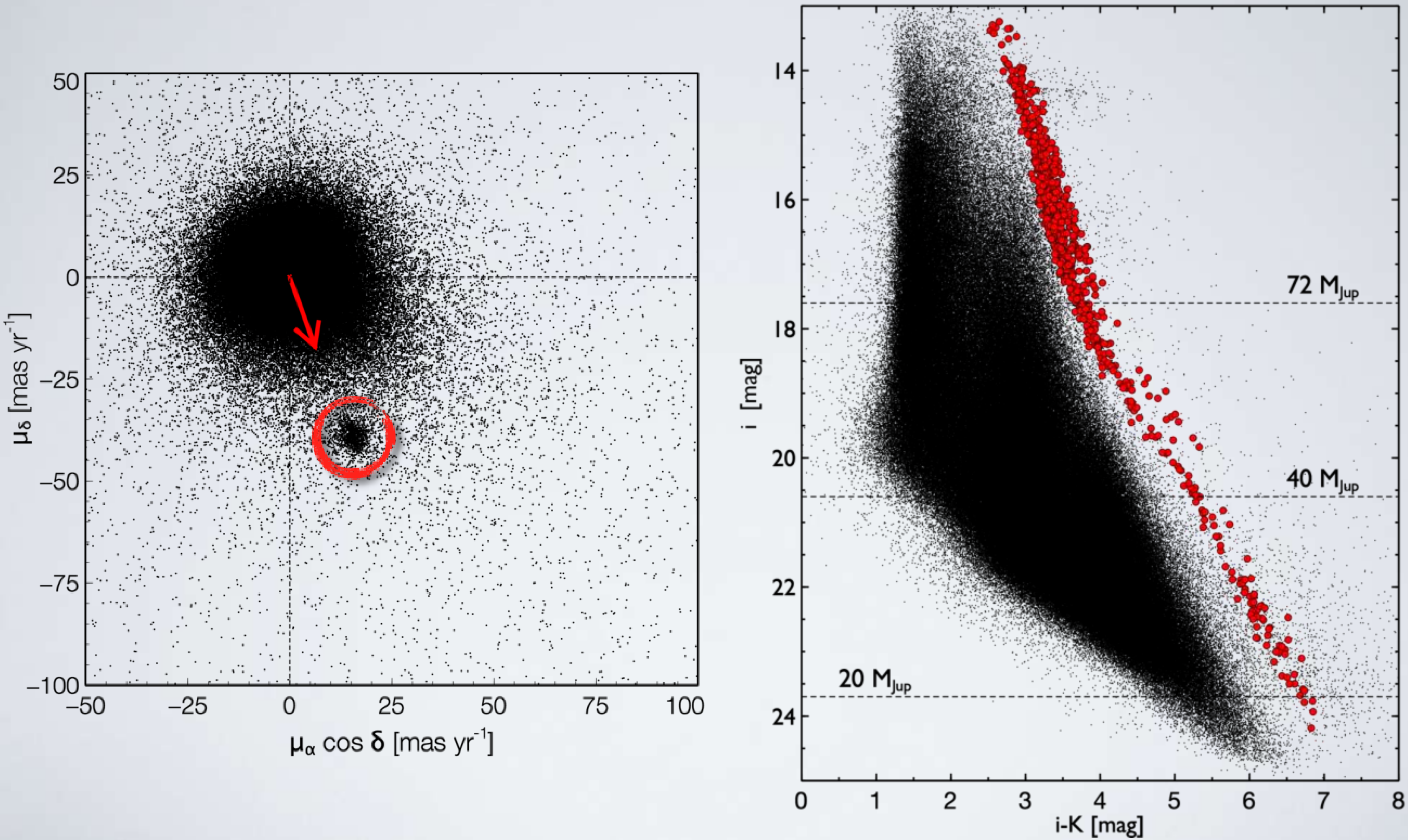


# Results

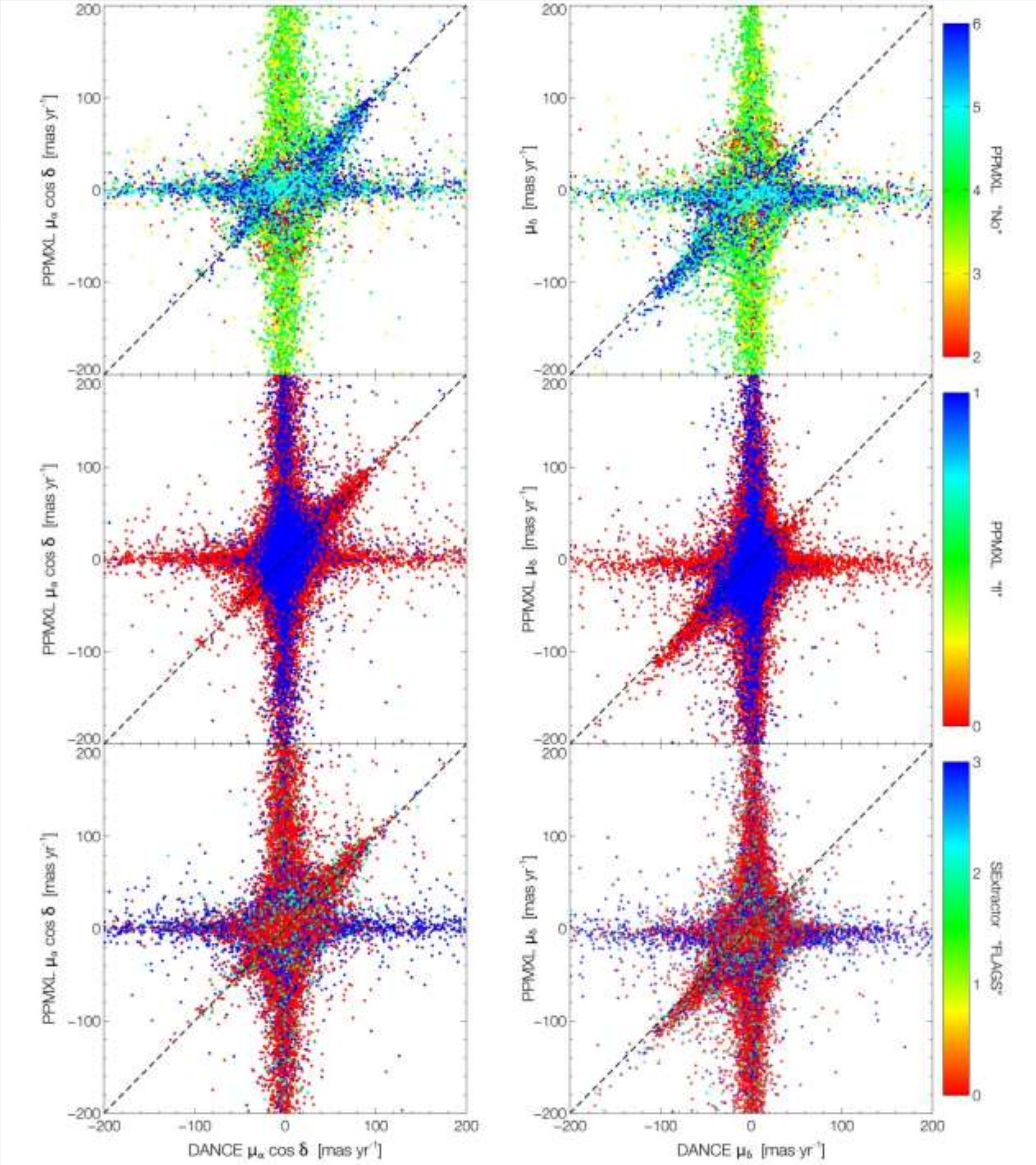


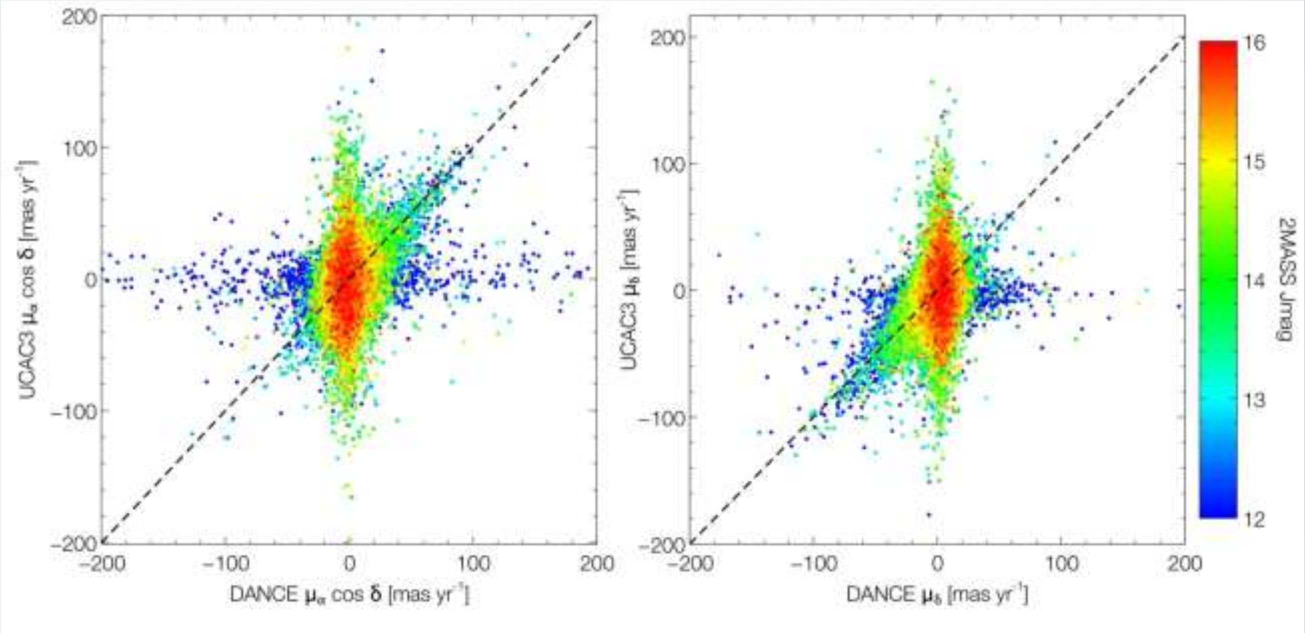
Hipparcos
Dance
≤1mas/yr
Estimated Standard Deviation [mas yr$^{-1}$]
i [mag]
Maximum Time Difference [yr]
0
2
4
6
8
10
12
14
16
18
20
22
24
0
1
2
3
4
5
6
7
8
0
2.5
5
7.5
10
12.5
15

# Results


50
25
0
−25
−50
−75
−100
−50
−25
0
25
50
75
100
μδ [mas yr⁻¹]
μα cos δ [mas yr⁻¹]
14
16
18
20
22
24
0
1
2
3
4
5
6
7
8
i [mag]
i-K [mag]
72 MJup
40 MJup
20 MJup

# Comparison with independent proper motion measurements

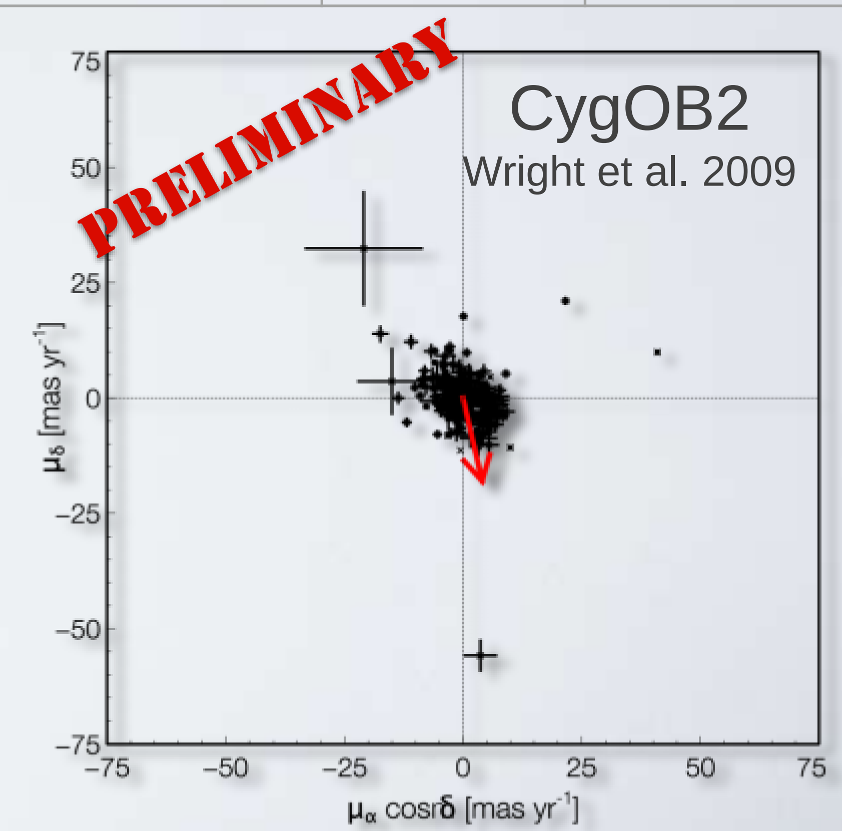


# Perspectives / Plans

| "Fast" Associations | | | | |
|---|---|---|---|---|
| **Association** | **Age [Myr]** | **Distance [pc]** | **μRA [mas/yr]** | **μDec [mas/yr]** |
| Pleiades | 120 | 120 | -35 | -15 |
| CrA | 1 | 130 | -35 | 51 |
| η Cha | 9 | 100 | -30 | 28 |
| Upper Sco | 5 | 125 | -9 | -24 |
| α Per | 50 | 180 | 24 | -26 |
| IC2391 | 55 | 155 | -25 | 23 |
| IC2602 | 50 | 145 | -22 | 10 |
| Lupus | 3 | 140 | -17 | -27 |
| IC348 | 3 | 350 | 7 | -9 |
| NGC1333 | 1 | 350 | 7 | -9 |
| Praesepe | 650 | 180 | -36 | -13 |
| Ophiuchus | 1 | 145 | -10 | -25 |
| Taurus | 3 | 140 | -8 | -25 |
| Blanco 1 | 100 | 210 | 19 | 4 |
| Hyades | 625 | 40 | ~100 | |

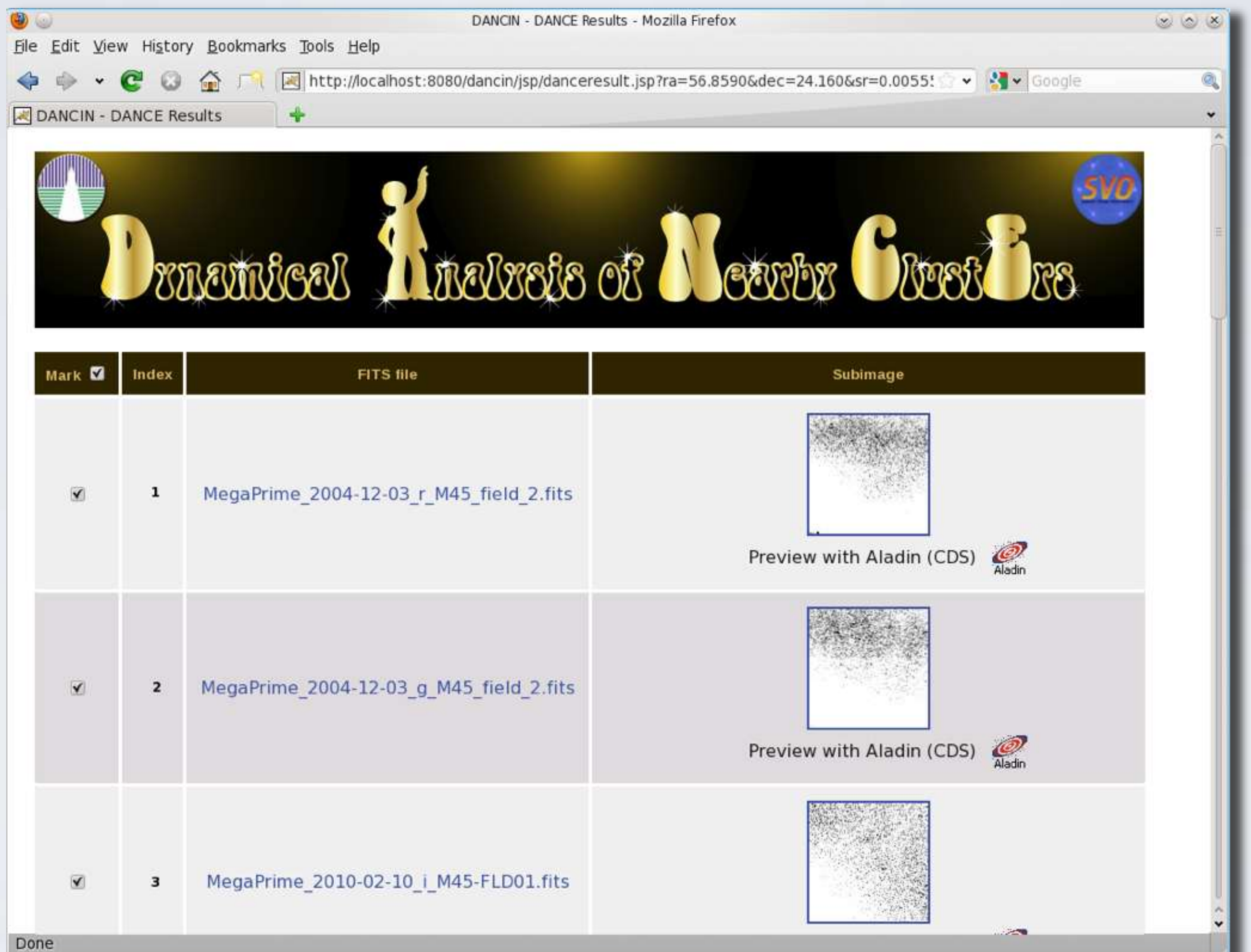
| "Slow Associations" | | |
|---|---|---|
| **Association** | **Age [Myr]** | **Distance [pc]** |
| Cygnus OB2 | | 2000 |
| IC348 | 3 | 350 |
| NGC1333 | 1 | 350 |
| Serpens | 3 | 450 |
| Orion | 1-10 | 400 |



# DANCIN'

## DANCE over the INternet

- Entire photometric and astrometric catalogues will be available on the internet in V.O format

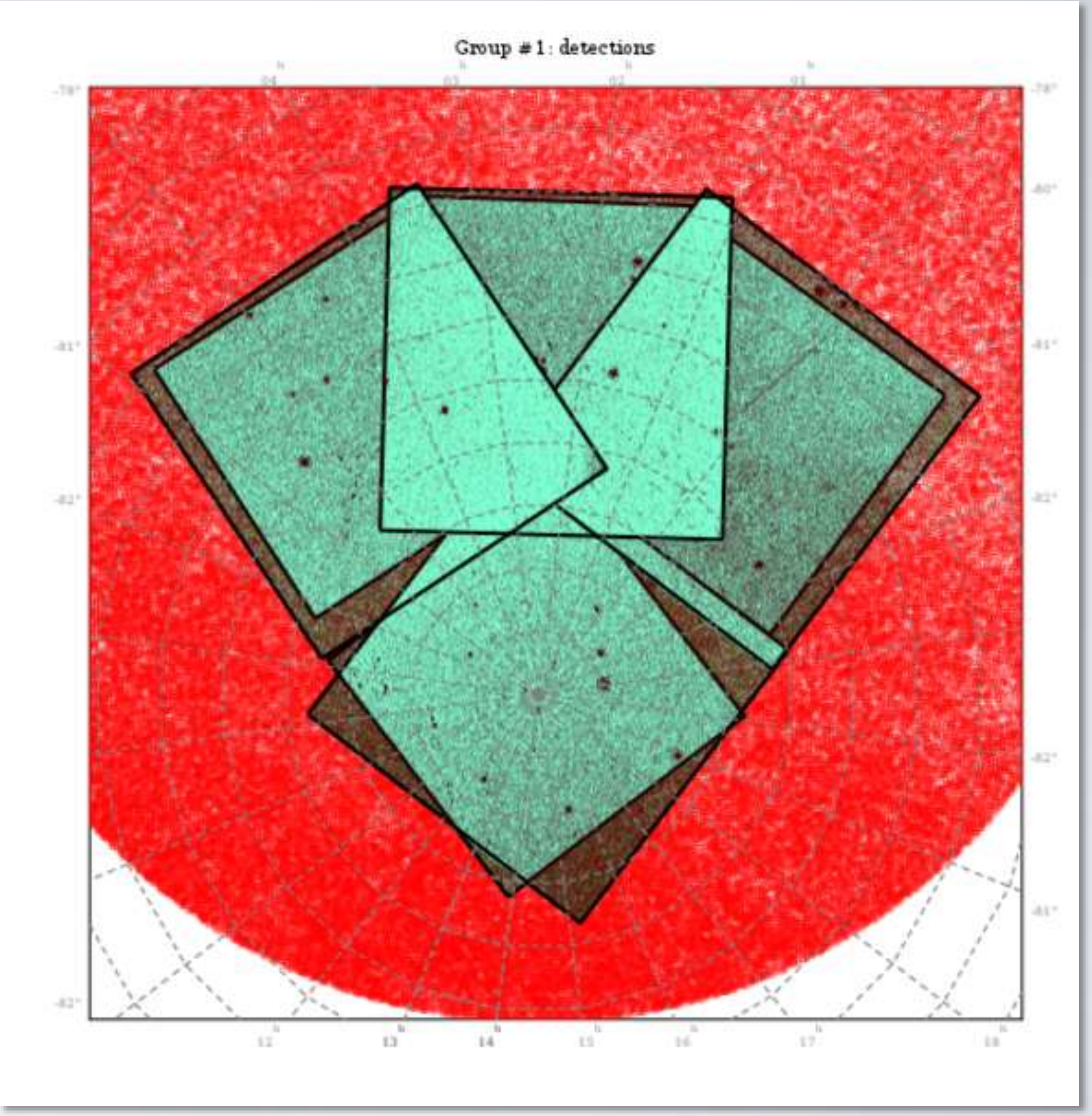


# Lessons learned

- The most time-consuming issues we faced were related to the quality of data and metadata
  - “Funny PSFs”
    - Automated PSF modeling and diagnostic
  - metadata inconsistency in image headers
    - Incorrect values (e.g. saturation level)
    - Basic WCS information sometimes missing
    - Different header keywords used for representing the same information (e.g. DATE-OBS, MJD-OBS, MJDSTART, EPOCH, etc.)
- Don’t trust proper motion measurements obtained from less than ~half-a-dozen distinct epochs

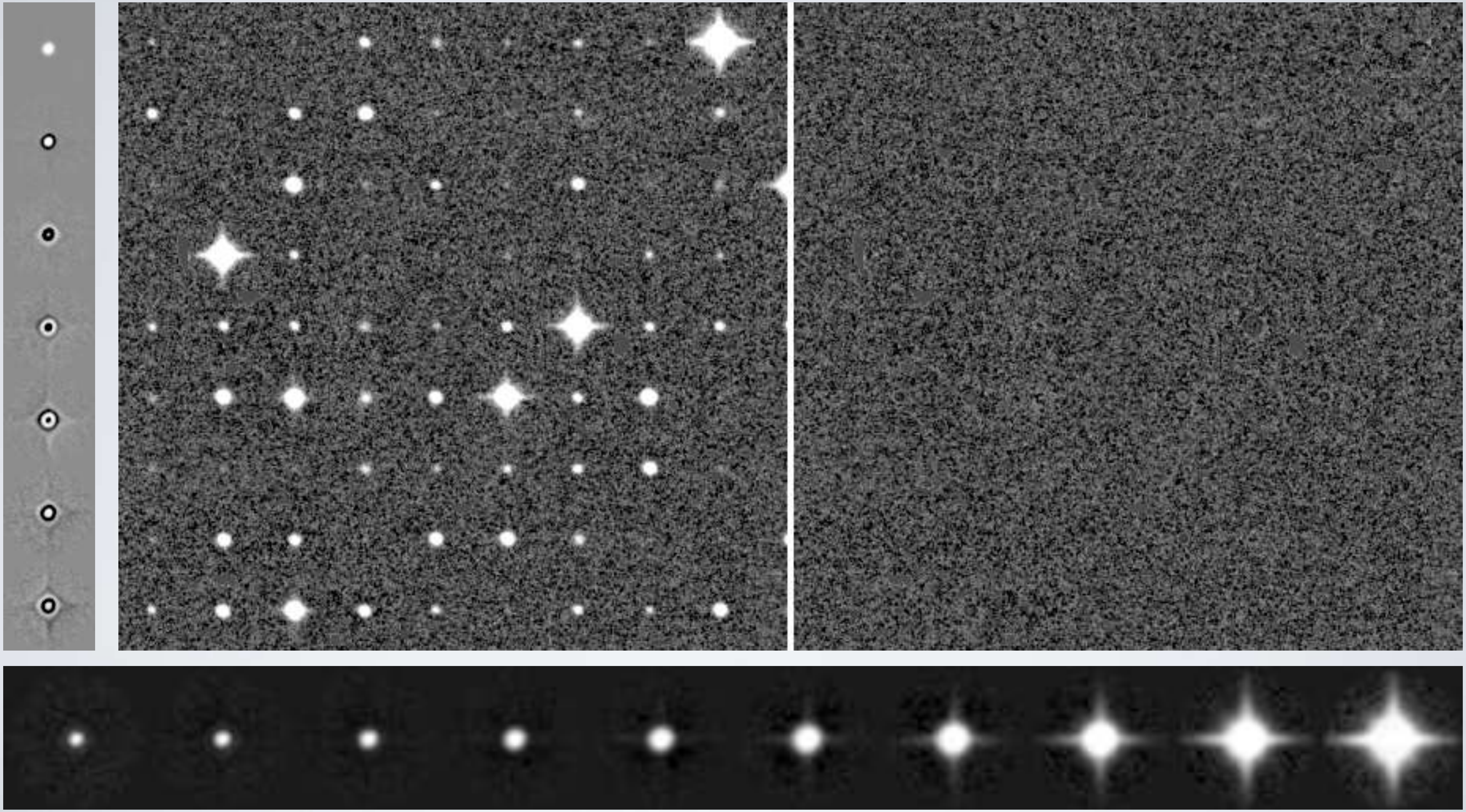
# Schmidt plate time!

- Small test with 8 partially overlapping Schmidt plates (4 ESO-R + 4 SERC-J) around the south celestial pole.
  - 1976-1990
- Digitized in density mode with the MAMA plate scanner and downloaded from the VO-Paris southern atlas repository
- Trimmed to exclude calibration wedges
- UCAC-3 used as reference catalog

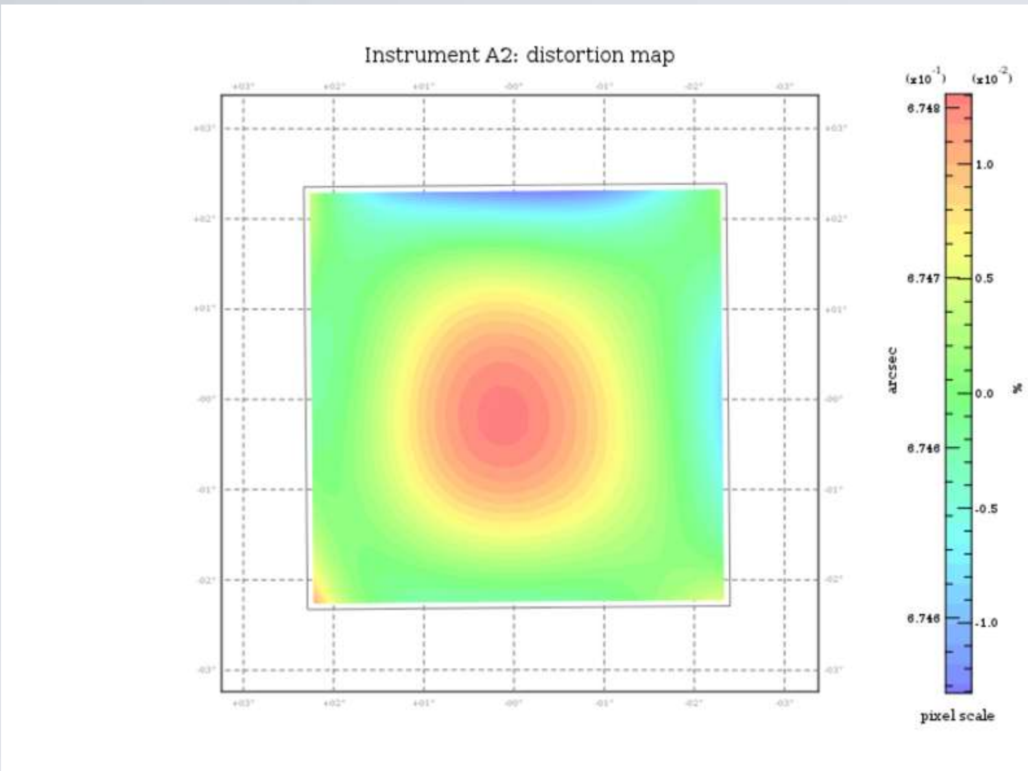


# PSF modeling

- 6th degree polynomial in MAG_AUTO

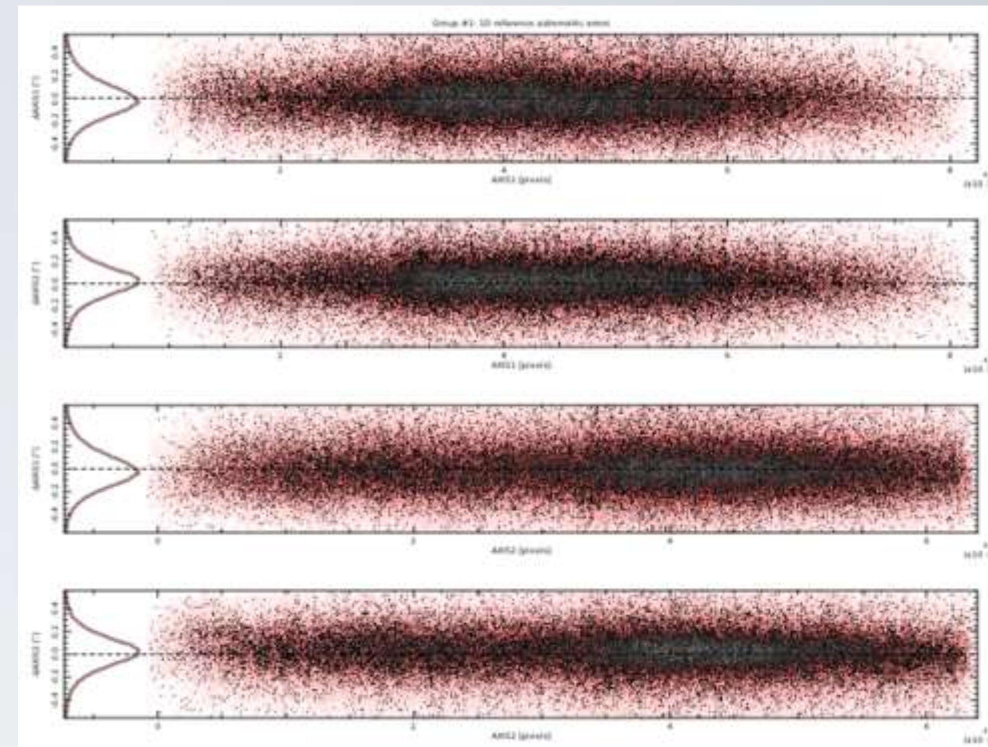


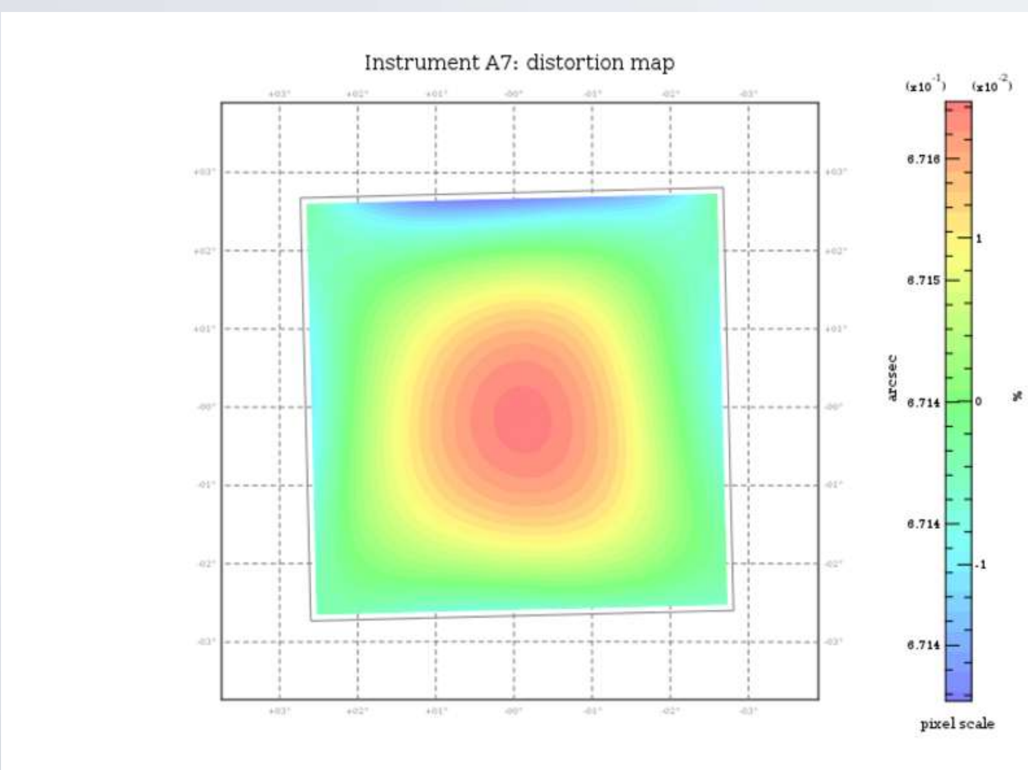
# Astrometric calibration




ESO-R

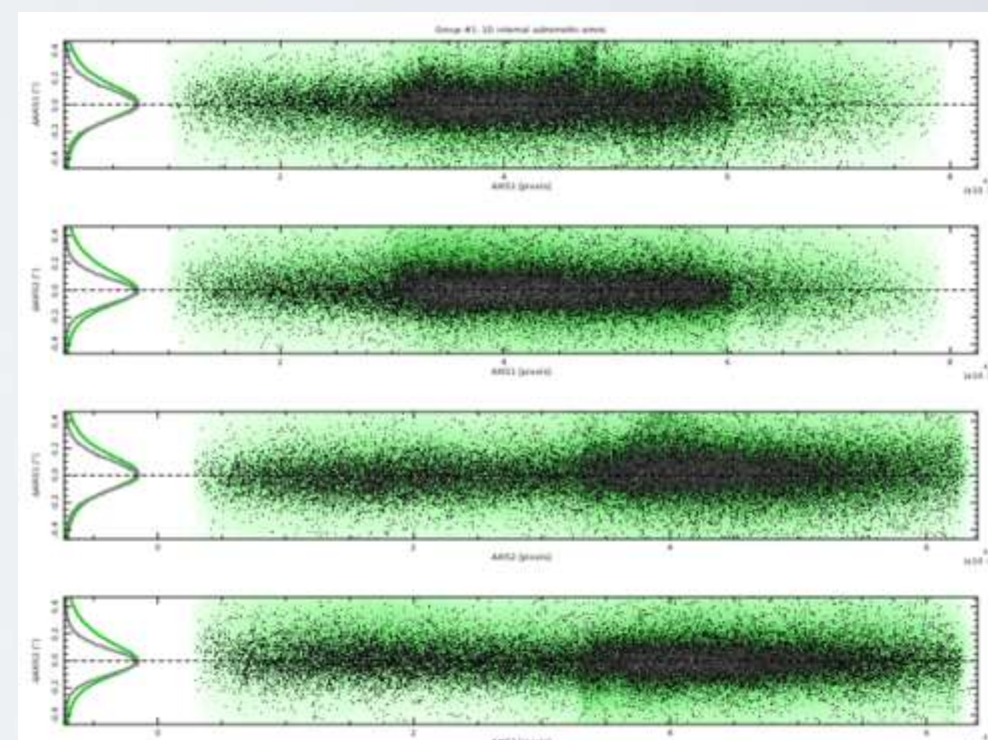
Residuals w.r.t. reference $\sigma$=0.17”



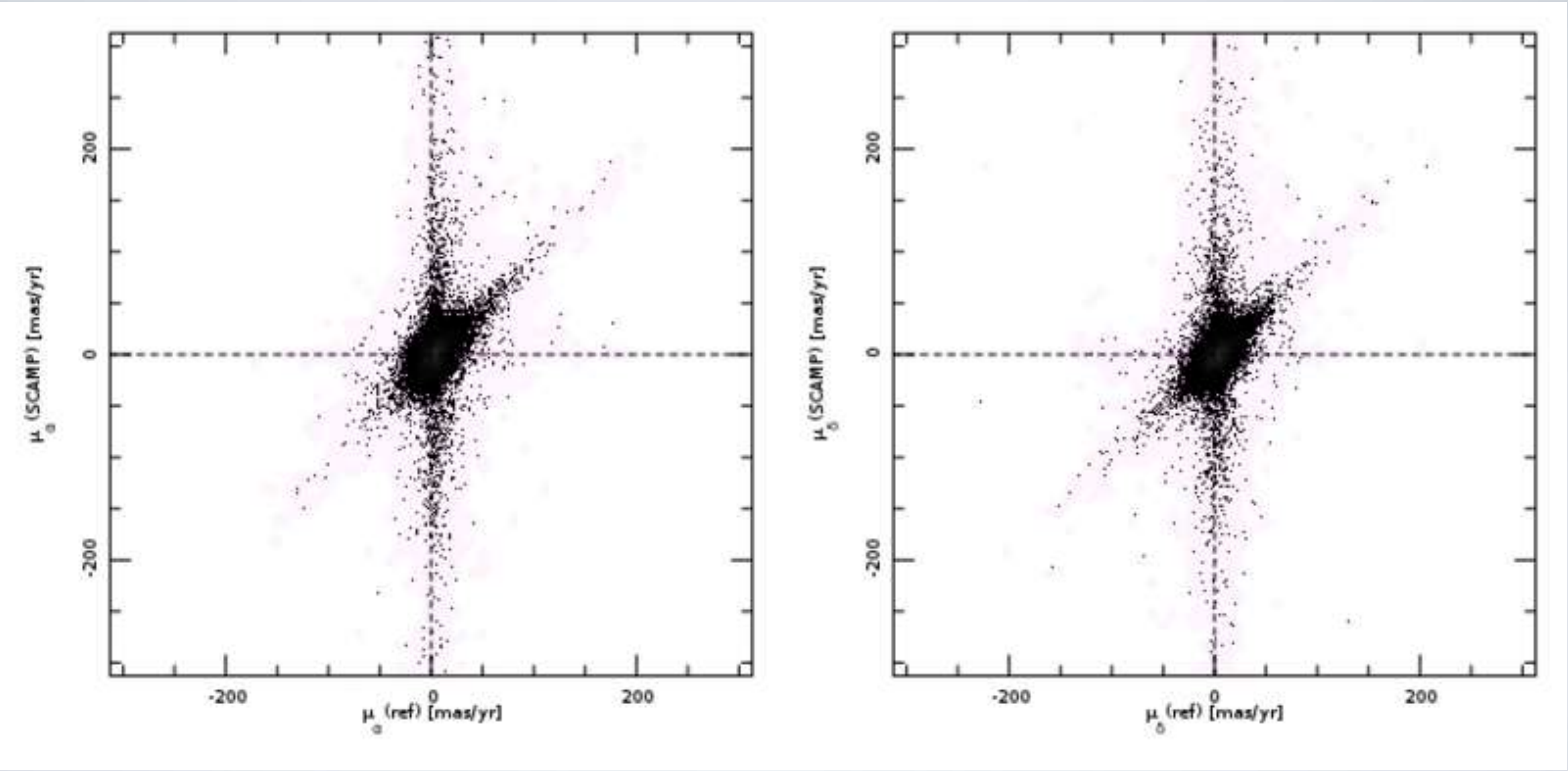



SERC-J

Internal (pairwise) residuals: $\sigma$=0.10”



# Quick PM comparison with UCAC-3 (all detections)



# Future improvements

- Astrometric calibration
  - Need to improve the solver
    - Explicit handling of proper motions and trigonometric parallaxes
    - Parallelize parts of the code which are not yet multithreaded
  - Include `astrometric.net` client in SCAMP
- Image measurements
  - Automatize further image diagnostic tools
  - Implement a “dash model” (and a “planet disk” model?) among models fitted in SExtractor

# Dynamical Analysis of Nearby ClustErs

Thank you