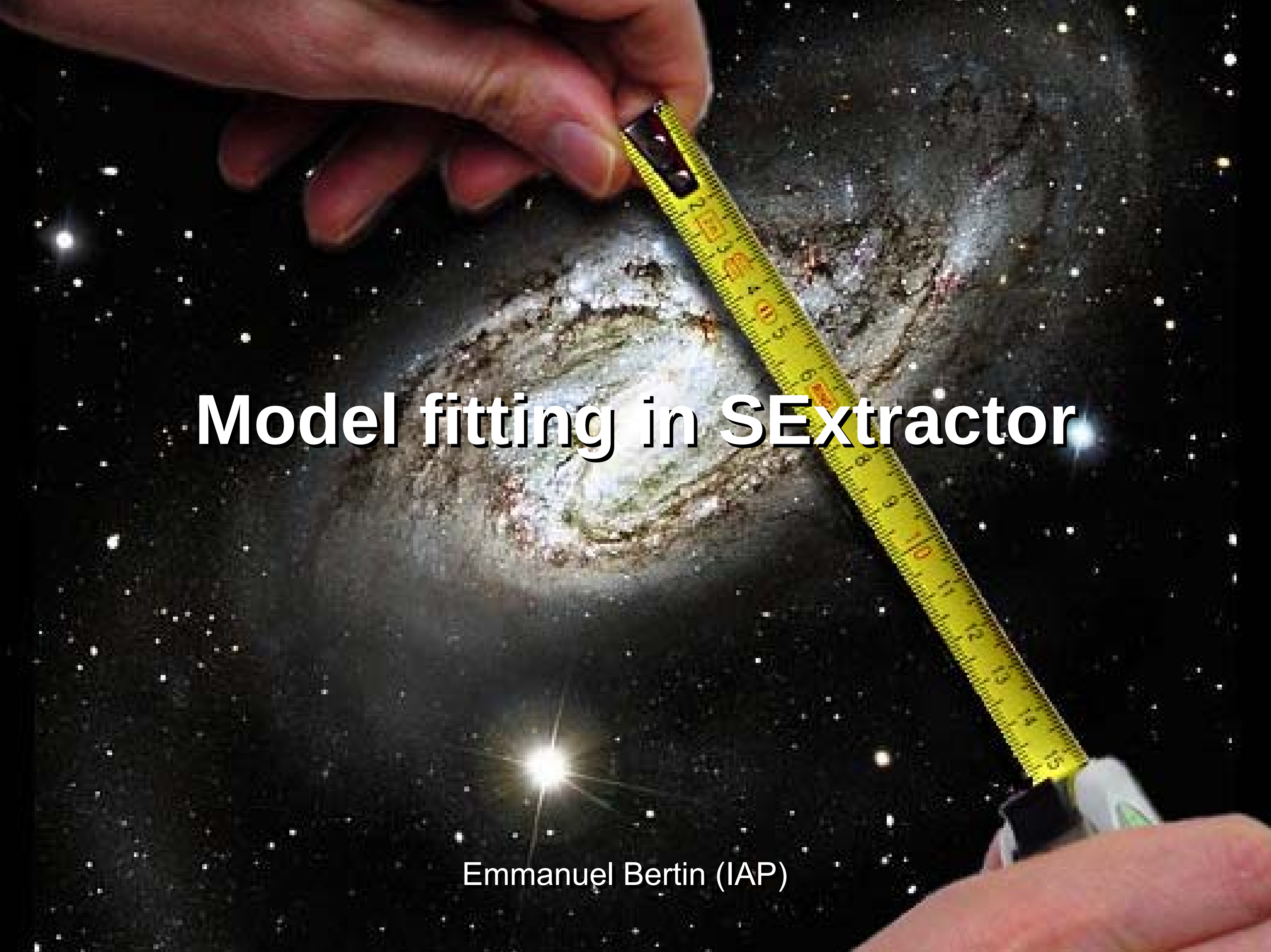


# Model fitting in SExtractor

Emmanuel Bertin (IAP)

# Profile-fitting in SExtractor

- Foreword
- Modelling the PSF
- Implementing profile-fitting in SExtractor
- Results on real data  and image simulations

# Foreword

- The new SExtractor functionalities have been developed in the general framework of the EFIGI project (P.I.: Emmanuel Bertin)
- Profile-fitting process relies on a PSF model which is derived by a companion software called PSFEx
- Improvements and tuning are currently being made to the software.
- The final software will be made public this winter

# What's in an astronomical image?

S/N of sources between -6 and +100dB/pixel

Isophotal footprint of objects: from 1 to $10^6$ pixels

Image artifacts:
Halos
Detector blooming
Diffraction spikes
Cosmic-ray hits

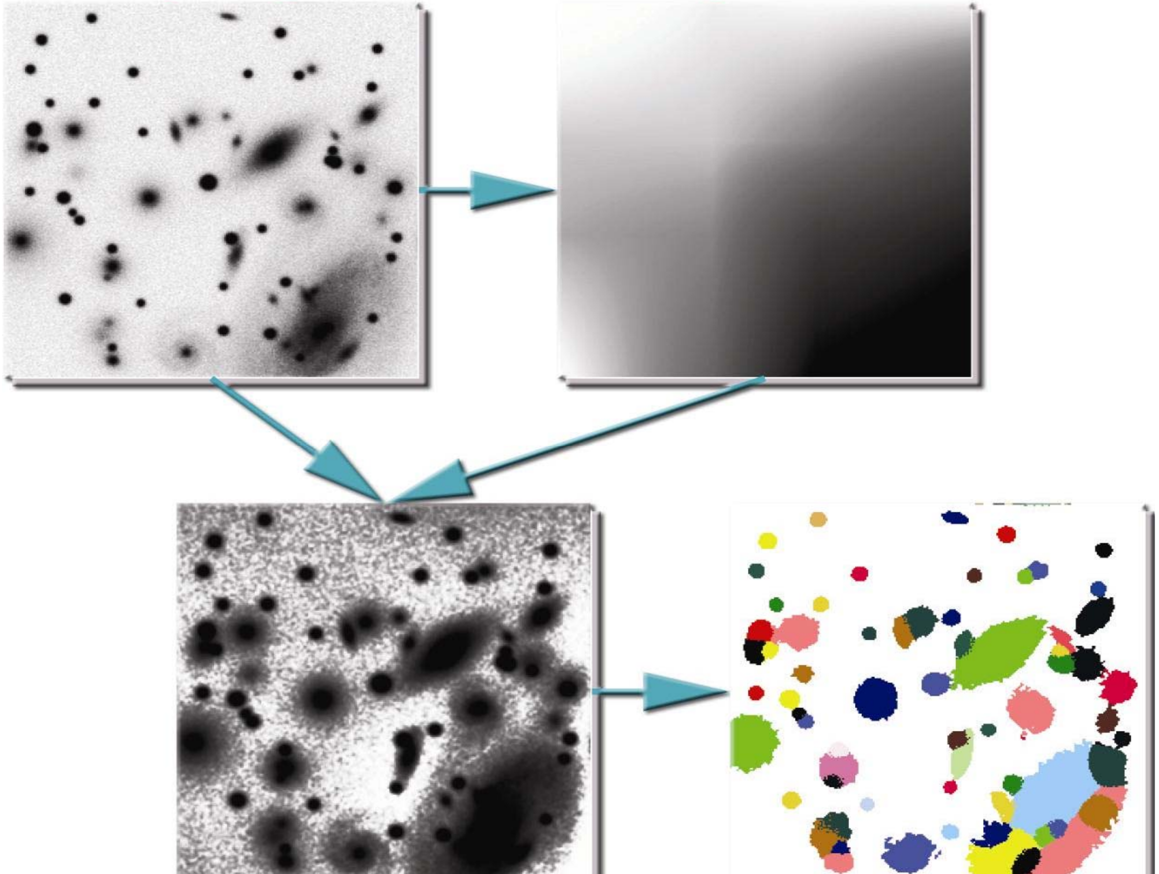
"Almost stationary" Gaussian+Poisson noise correlated on small scales + large scale gradients

Most detectable sources are faint, barely resolved galaxies

Unsaturated stars can be used to map the variable PSF

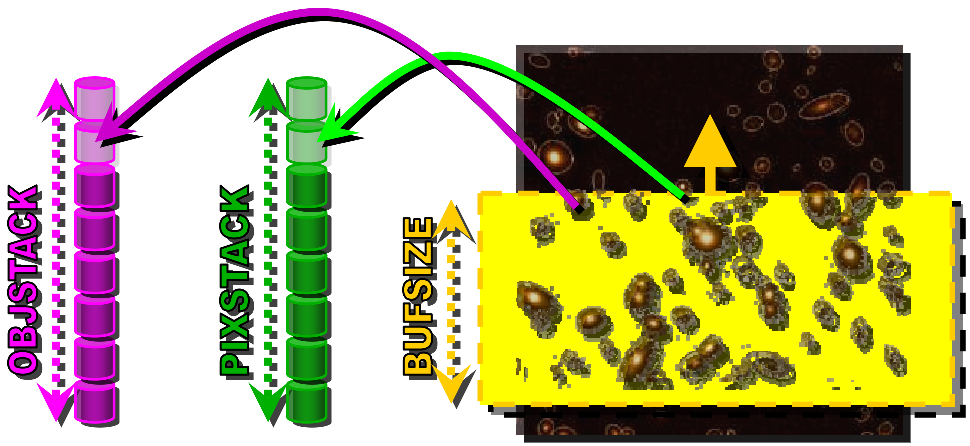
# How sources are detected in SExtractor

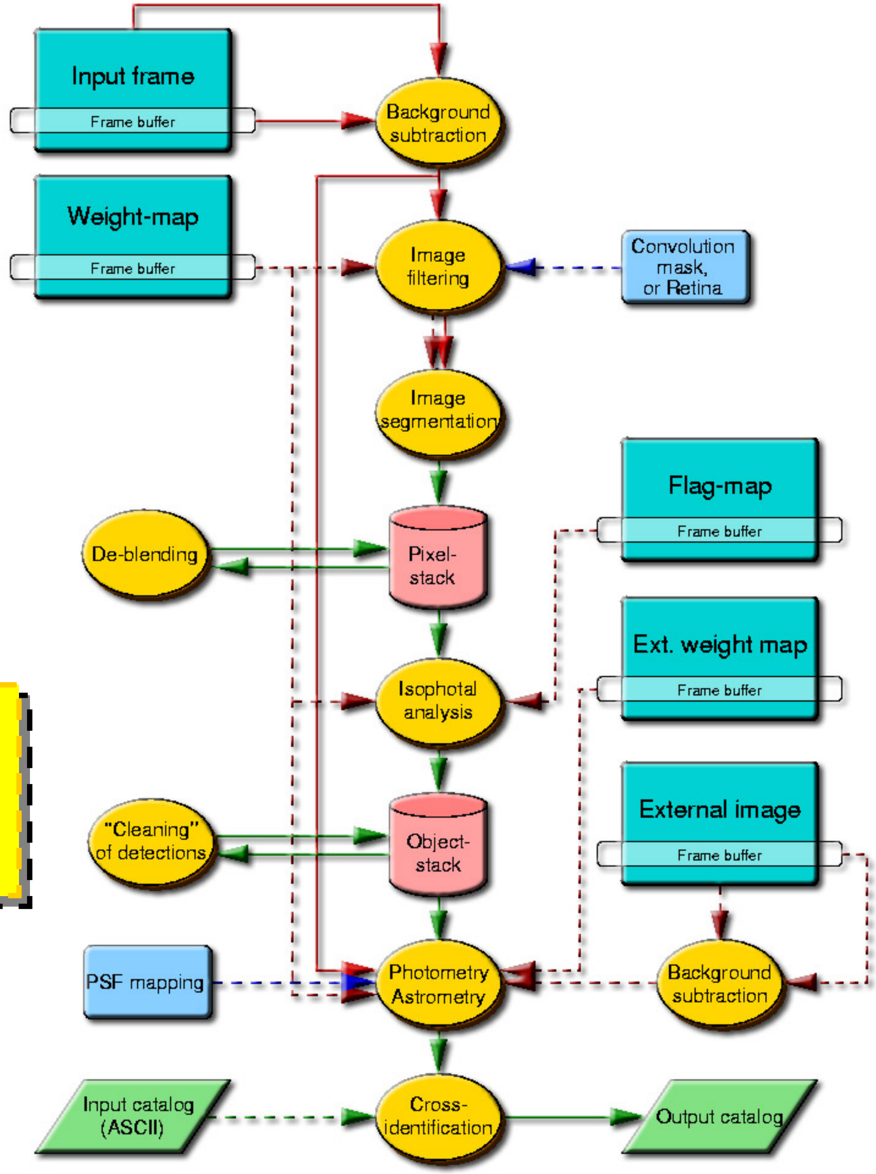
- 4 steps:
  - Sky background modeling and subtraction
  - Image filtering at the PSF scale (matched filter)
  - Thresholding and image segmentation
  - Merging and/or splitting of detections



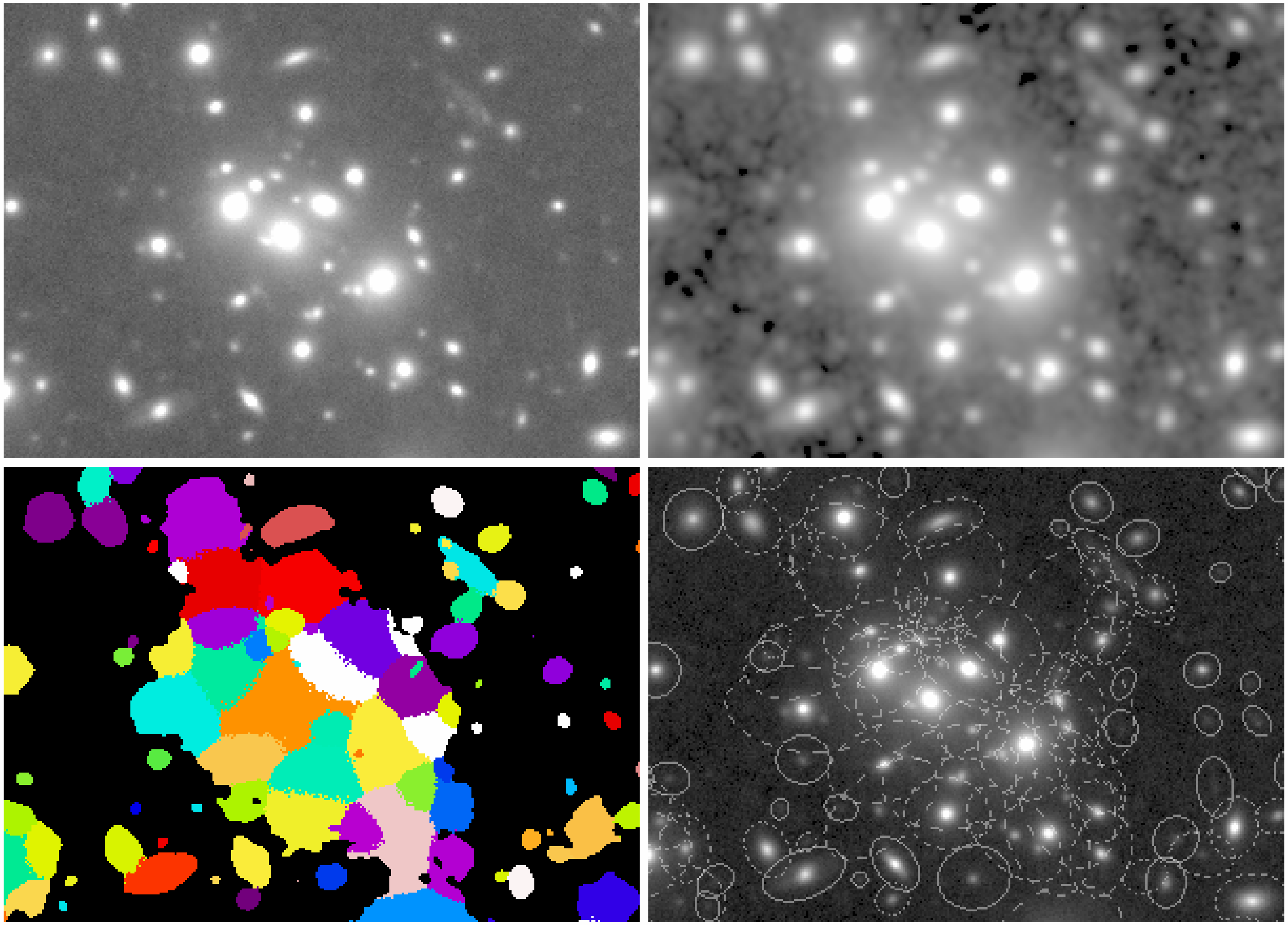
# SExtractor data flow

- The tricky part is the management of all buffers and FIFO stacks:



# Image segmentation



# Model fitting

- The idea is to fit a 2D model of star and galaxy images to the data
  - The point-source model is simply the local Point-Spread-Function with 3 free parameters: $(x,y)_{center}$ and flux (amplitude)
  - The galaxy model contains other free parameters such as size and orientation and must be convolved with the local Point-Spread Function
  - As the image noise is Gaussian, the problem can be expressed as a non-linear least-square minimization problem.
- But the first step is to derive a good model of the local PSF

# PSFEx: Modelling of the PSF

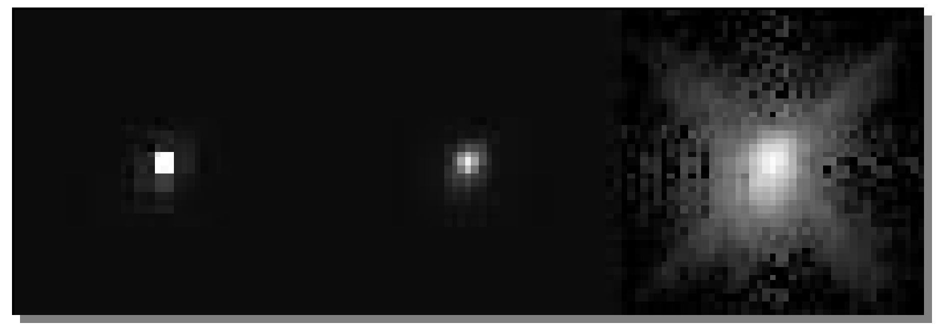
- Knowledge of the Point Spread Function is needed for many image analysis tasks
  - image quality control (FWHM, elongation, asymmetry, distance to best-fitting Moffat)
  - PSF homogenisation
  - matched filtering
  - profile-fitting
  - star/galaxy separation
  - galaxy morphology
  - weak-lensing analyses
- The PSF tool should have the capacity to recover the PSF from aliased images.
- PSFEx
  - works on SExtractor catalogues with thumbnail image content
  - Fully automated
  - originally written in 1998; used in some stellar field studies since (Kalirai et al. 2001, Moraux et al. 2003, Delorme et al. 2007). Large improvements made in the framework of the EFIGI project.
  - Released by December (just a matter of finding the time to document it now)

# PSF modeling: Principle

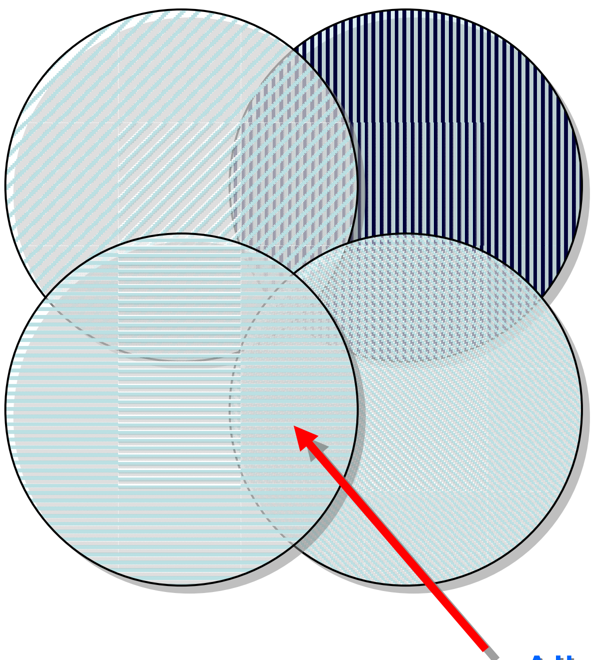
- The PSF is tabulated at a resolution which depends on the stellar FWHM (typically 3 pixels/FWHM)
  - Satisfy the Nyquist criterion + margin for Lanczos interpolation
  - Handle undersampled data by representing the PSF model on a finer grid
  - Minimize redundancy in cases of bad seeing
  - Find the sample values by solving a system using point-sources located at different positions with respect to the pixel grid
- The PSF is modelled as a linear combination of basis functions $\psi_b$
  - "Natural" pixel basis $\psi_b(\mathbf{x}) = \delta(\mathbf{x}-\mathbf{x}_b)$
    - Work with any diffraction-limited image (images are bandwidth-limited by the autocorrelation of the pupil)
  - Gauss-Hermite or Gauss-Laguerre basis functions (aka polar *Shapelets*)
    - Scale parameter ($\beta$) adjusted to provide proper sampling
    - Provide a more robust model for data with low S/N
  - One might use PCA components of the theoretical PSF aberrations for diffraction-limited instruments.

# Solving in Fourier space

Reconstructed NICMOS PSF



Lauer 1999



Aliased portion of the spectrum

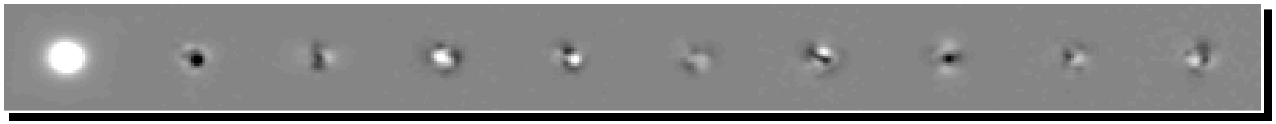
# PSFEx: solving in direct space

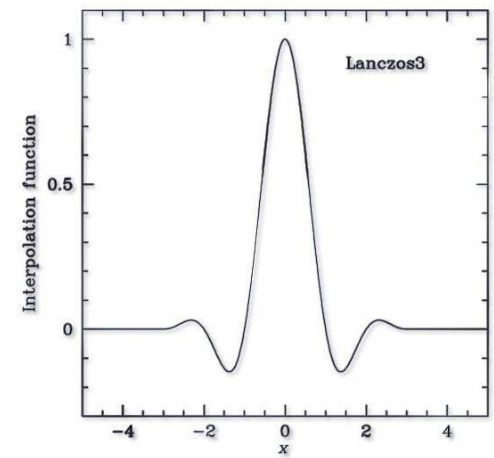
- A resampling kernel *h*, based on a compact interpolating function (*Lanczos3*), links the “super-tabulated” PSF to the real data: the pixel *j* of star *i* can be written as

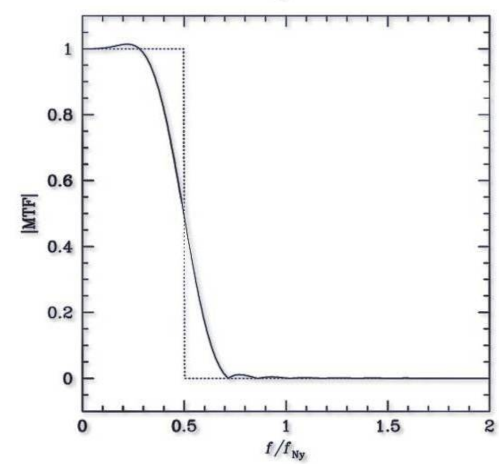
$$P_{ij} = a_i \sum_b \sum_k h_i\left(\mathbf{x}_k - \mathbf{x}_j\right) c_b \psi_{bk}$$

- The $c_b$’s are derived using a weighted $\chi^2$ minimization.
- The $a_i$’s are obtained from “cleaned” aperture magnitude measurements
- No regularisation required in practice with real PSFs
- PSF variations are assumed to be a smooth function of object coordinates
  - The variations can be decomposed on a polynomial basis $X_l$

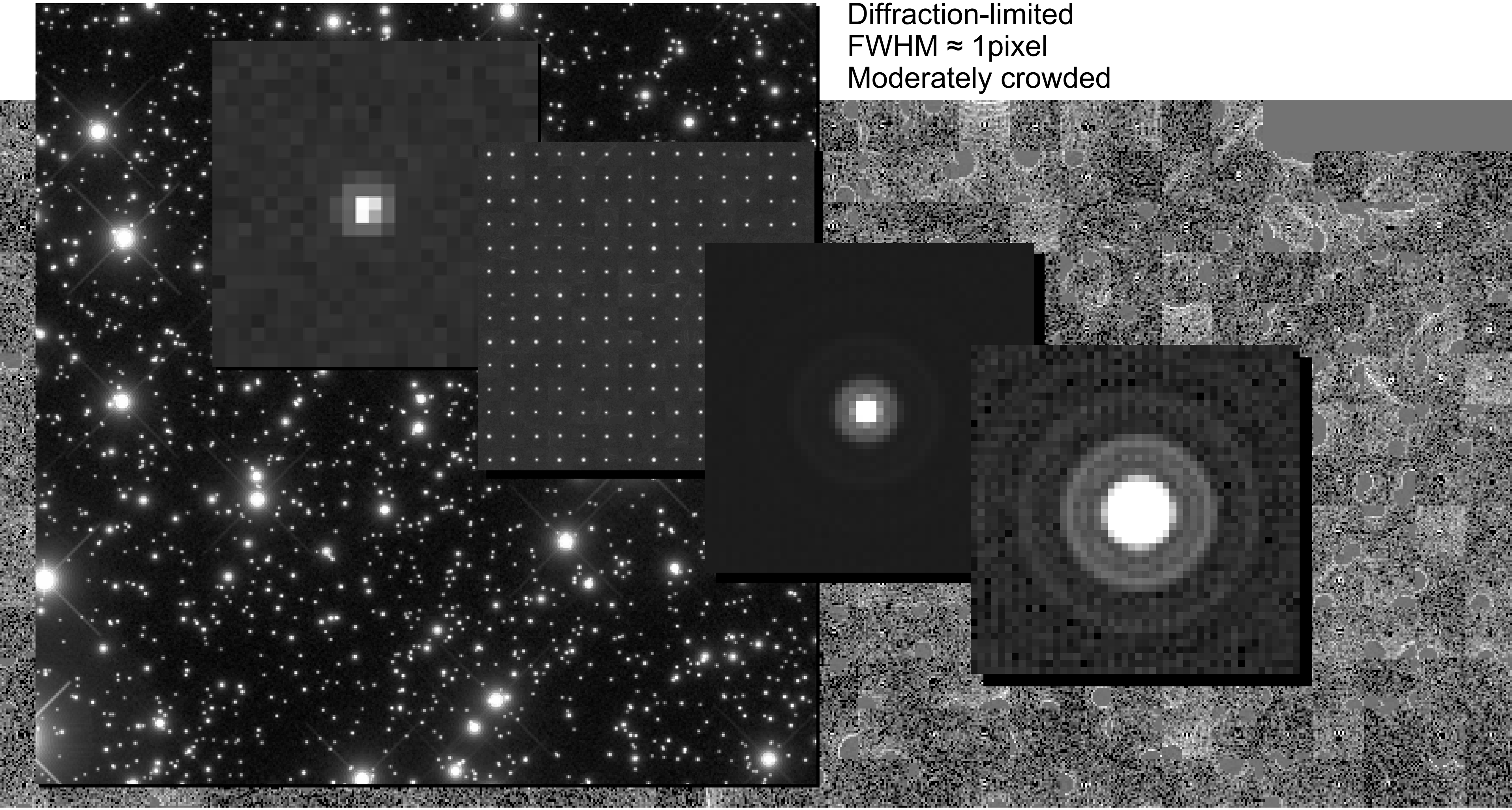
$$P_{ij} = a_i \sum_l X_l \sum_b \sum_k h_i\left(\mathbf{x}_k - \mathbf{x}_j\right) c_b \psi_{lbk}$$



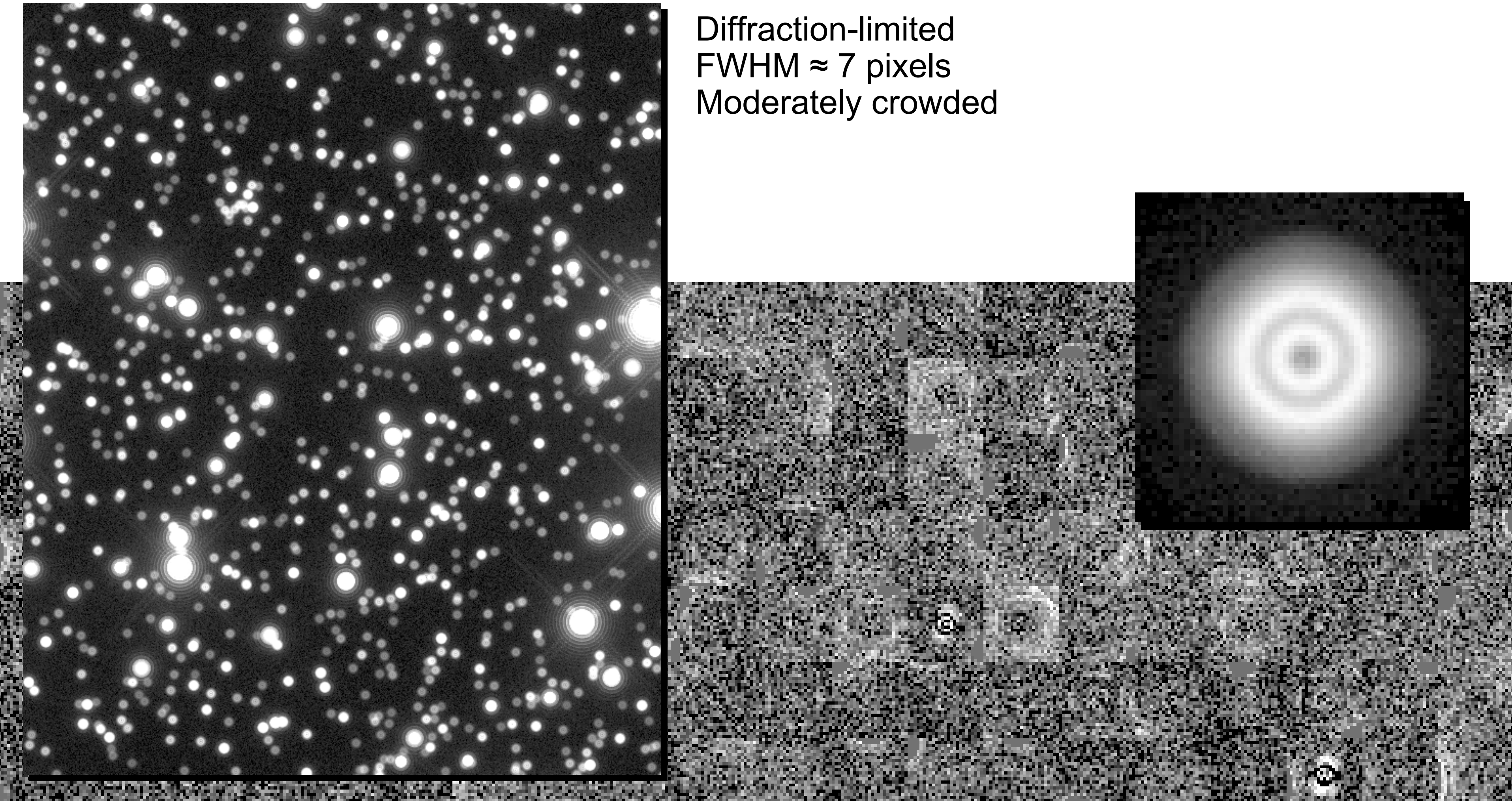



# Recovered PSF with simulated, undersampled data



Diffraction-limited
FWHM ≈ 1pixel
Moderately crowded

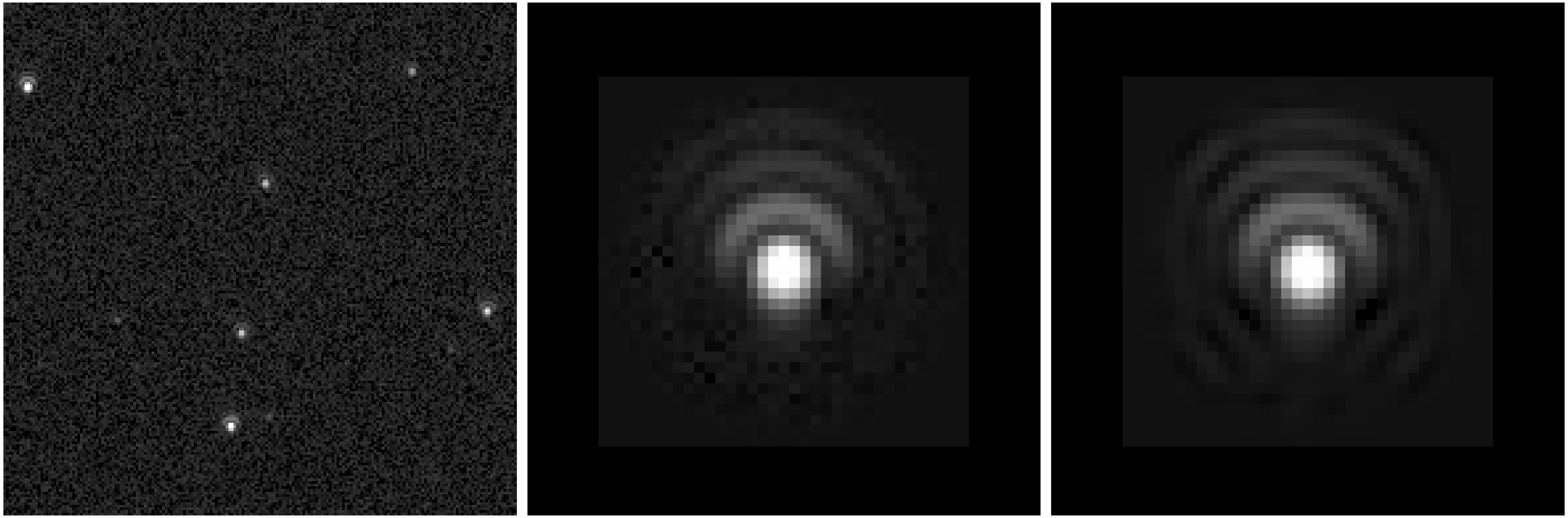
# Simulated, defocused data



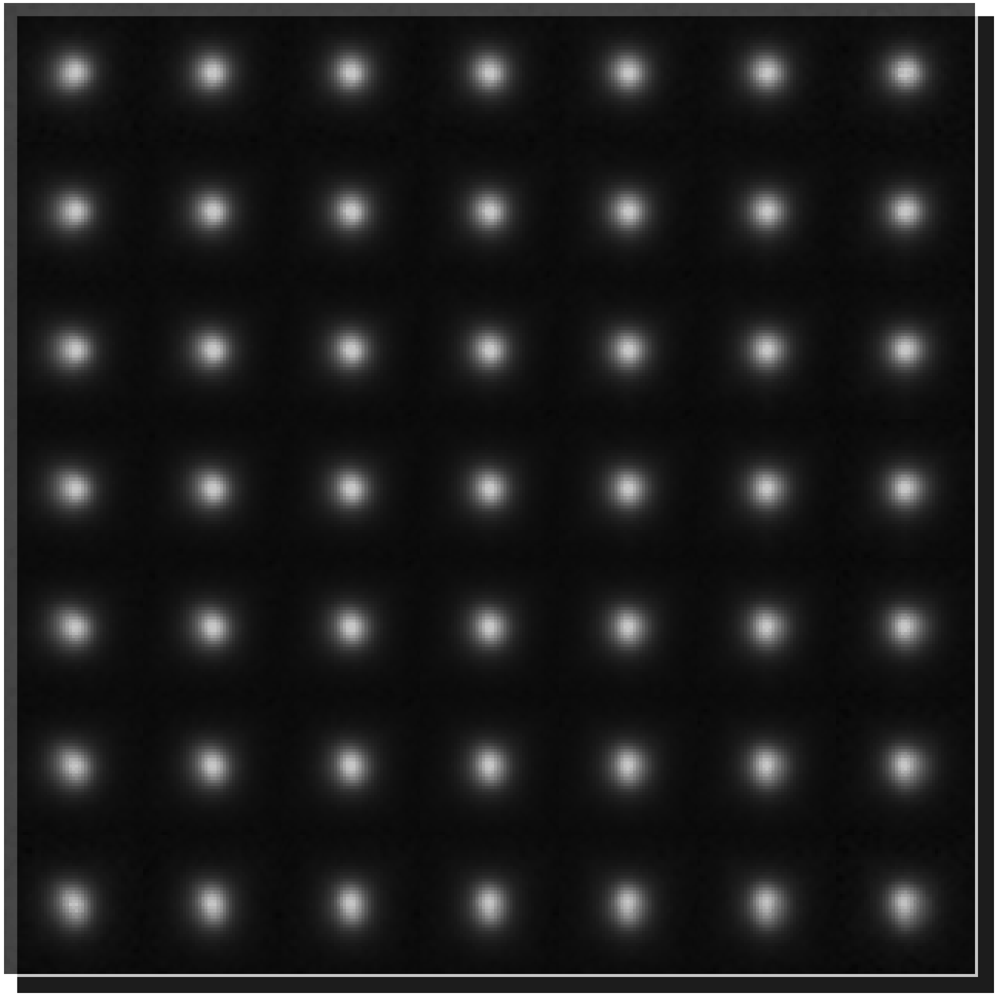
Diffraction-limited
FWHM ≈ 7 pixels
Moderately crowded

# Gauss-Laguerre basis vs pixel basis

- Except for the simplest PSF profiles, shapelet decomposition does not seem to be more efficient than simple tabulation for precise modeling.
  - Typically a few hundred free parameters required in each case.

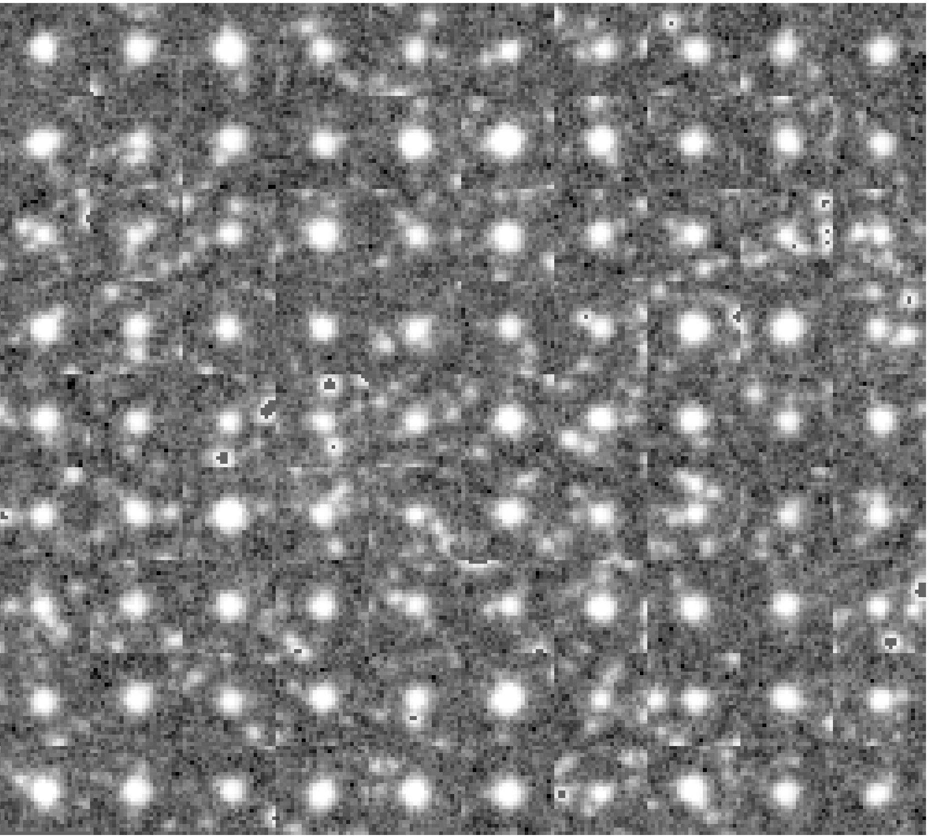


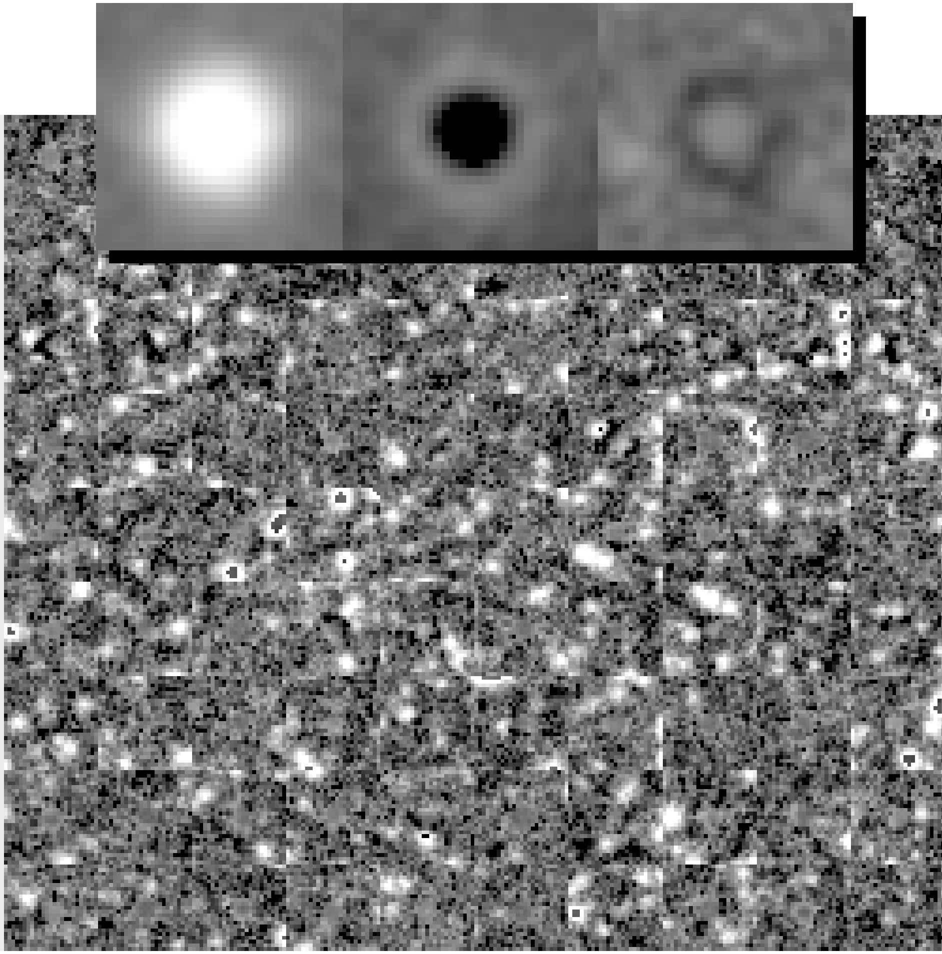
# Modelling PSF variations: Reconstructed UH8k PSF



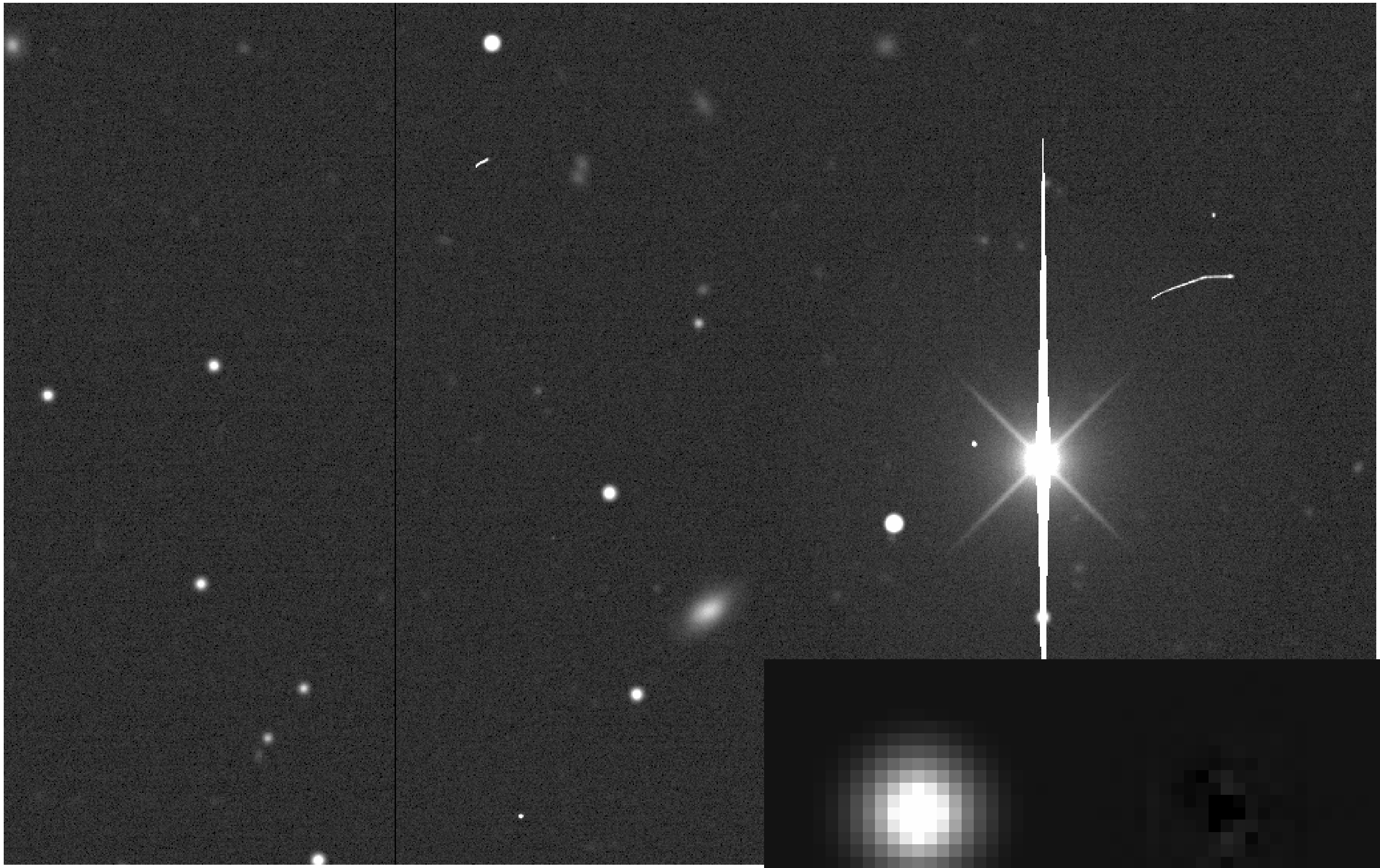
# Testing on real, non-linear data

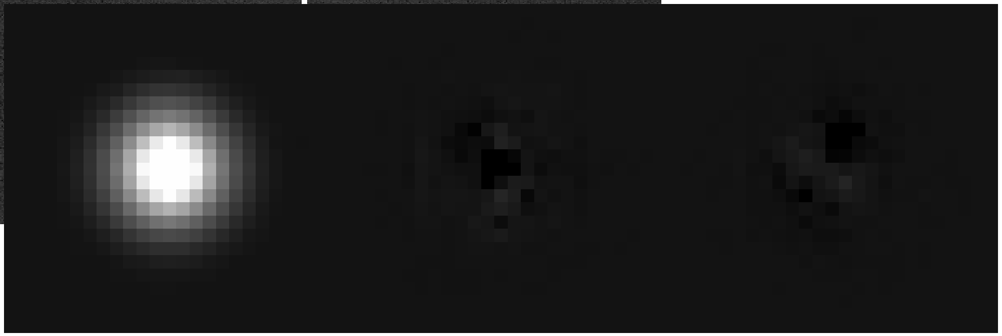
Schmidt-plate exposures in the galactic plane
FWHM ≈ 3pixel
Second order polynomial in FLUX_AUTO



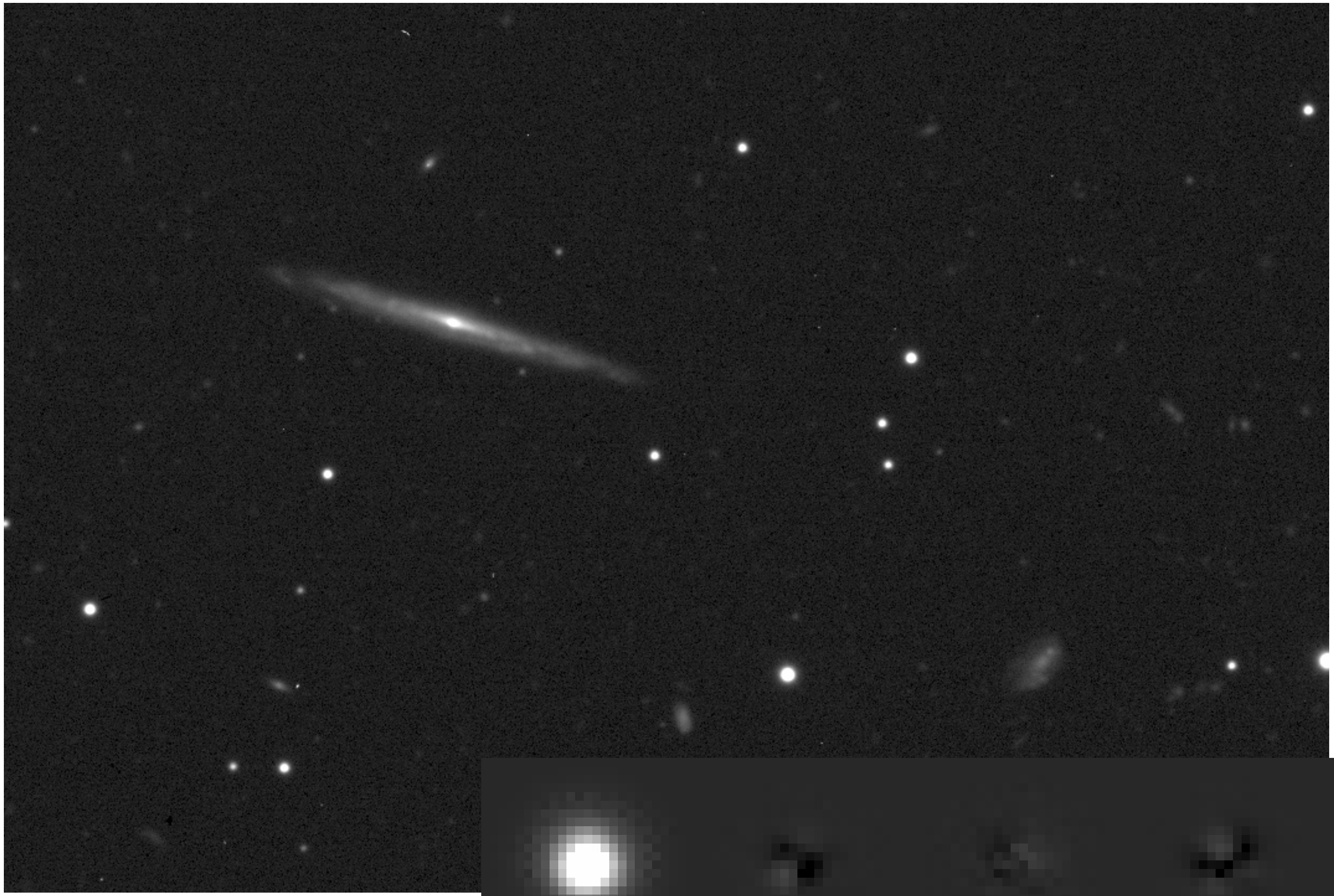


# DES simulations

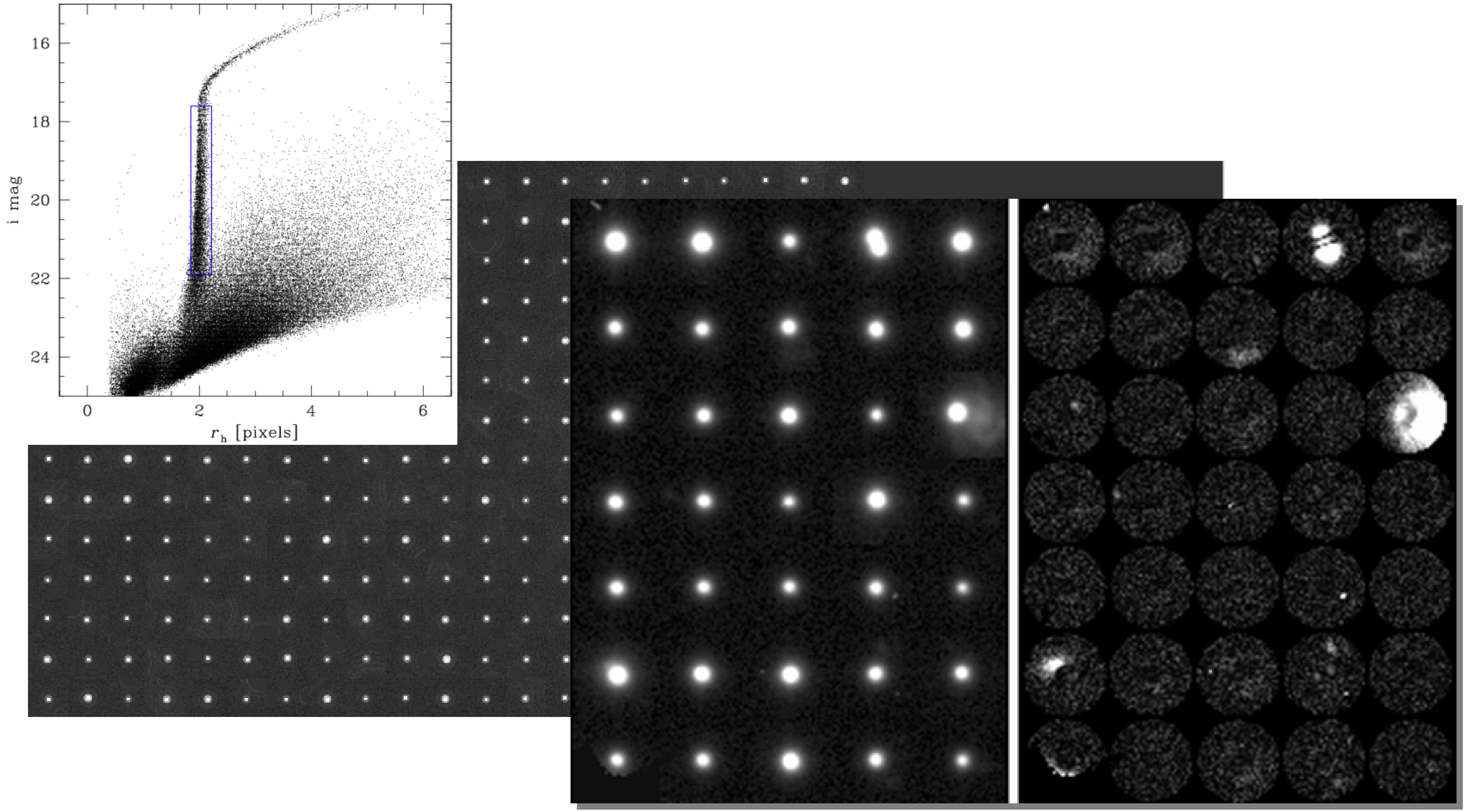




# BCS data

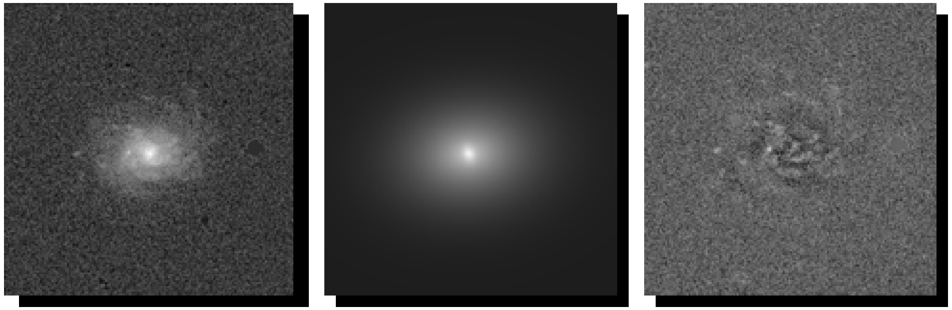


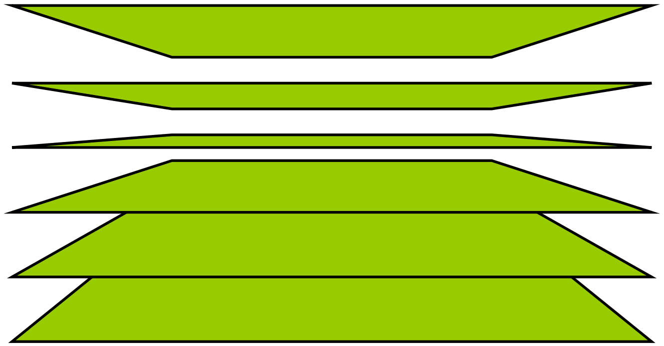
# Automatic point-source selection



# Sextractor's approach to model fitting

- The current fitting algorithm came out as a « Plan B » triggered because of difficulties with the linear decomposition approach in the EFIGI experiment.
- Implementation within ***SExtractor*** (http://terapix.iap.fr/soft/sextractor/) started by the end of 2006
- The main issue with general 2D model-fitting is **speed**: at least a few s per core for a « small » galaxy with current software.
- The original idea was to fit only tabulated models:
  - with « regular » math libraries, mathematical functions such as **`pow()`** are generally slower than a bi-linear interpolation.
    - It is often faster to regrid « on the fly » some precomputed 2D profiles
    - Unfortunately, interpolating variations of morphological parameters such as the Sersic index would prove unpractical.
  - With efficient math libraries such as INTEL's, pre-computing the profiles is not necessary anymore.



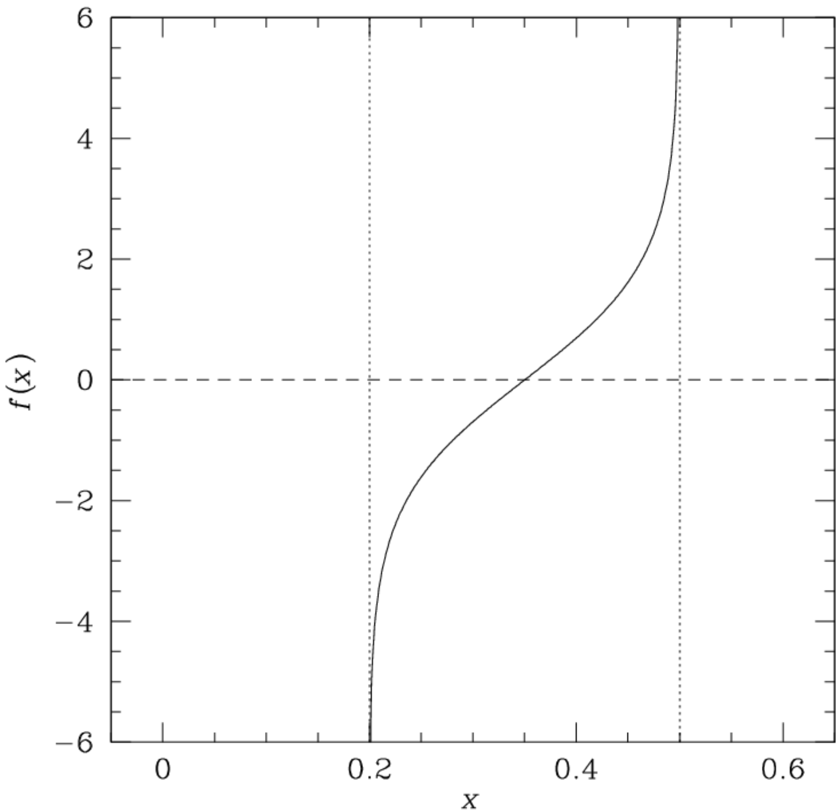


# Model-fitting: implementation

- PSF modeled using ***PSFEx***
  - Sampling automatically adjusted depending on image
  - Several improvements and bugfixes done over the past months
- Profile models are computed with a grid size that depends on the object.
- Automatic sharing of component parameters (e.g. *x*,*y*,…)
- Several profile components currently available:
  - Background level
  - Sersic (2 + 5 free parameters)
  - De Vaucouleurs (2 + 4 free parameters)
  - Exponential (2 + 4 free parameters)
  - others currently in development
- Minimisation:
  - Two C implementations of the Levenberg-Marquardt algorithm:
    - ***lmfit*** by J.Wuttke
    - ***LevMar*** by M.Lourakis
  - Initial parameter guesses made from isophotal measurements and half-light radius.
  - Bright pixels from neighbours automatically masked by SExtractor.
  - Robust fitting

# Model-fitting: fighting degeneracies

- It is mandatory to include some implicit prior in the $\chi^2$:
  - positivity constraints for fluxes
  - ellipticity constraints for the bulge
- Implementation of the box-constrained algorithm by Kanzow, N. Yamashita and M. Fukushima (2004) in levmar does not seem to work as intended.
- House-made trick: map free parameters from a bounded space to an unbounded space
  - A sigmoid function works fine!
  - In some rares cases a free parameter can get stuck at one of the boundaries



# Robust profile-fitting (cont.)

- The sky around galaxies is not « clean » because of overlapping stars, galaxies or defects. Possible solutions:
  - Use nFIGI: fast and efficient for images of individual objects.
  - The old SExtractor « CLEANer » masks out the pixels from bright neighbours, but it is not efficient enough
- The « perfect fit » does not exist, except may be for some ellipticals and spheroidals
  - dust, star formation regions, overlapping objects,…
- Minimizing <u>fractional</u> errors instead of absolute ones is more appropriate for bright parts of the profile
- Proposition: replace the usual residual in

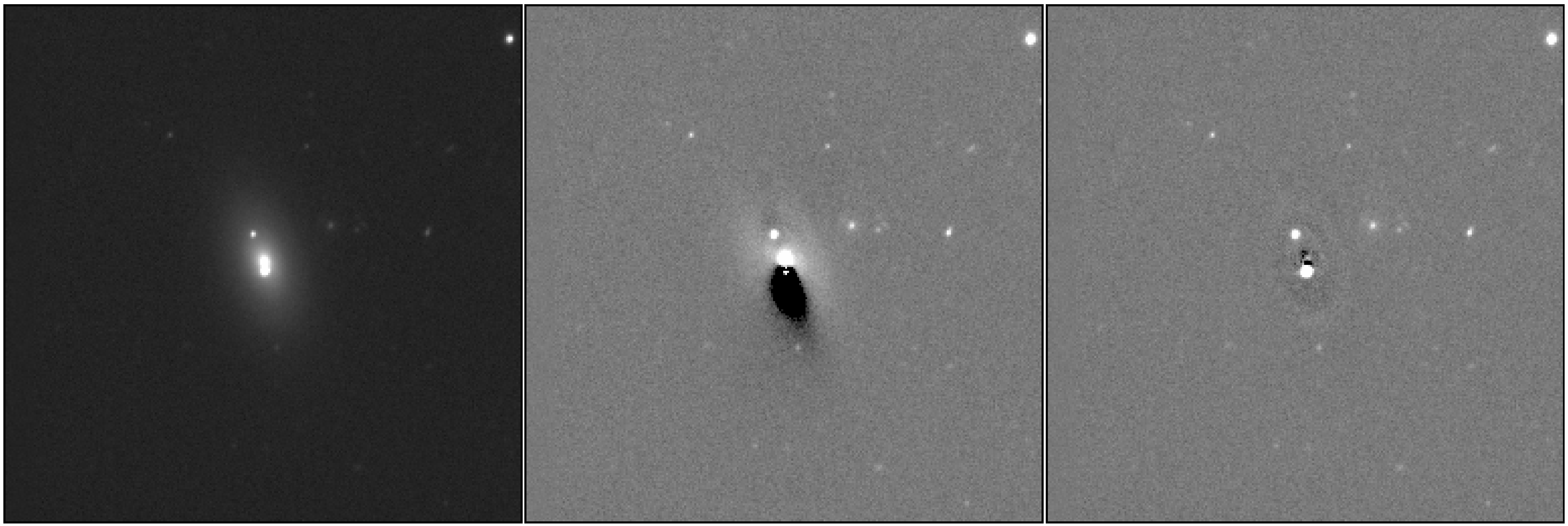
$$\chi^2 = \sum_i \frac{I_i - f(x_i)}{\sigma^2}$$

with

$$\chi^2 = \sum_i g\left(\frac{I_i - f(x_i)}{\sigma}\right)^2 \quad \text{where } g(u) = \begin{cases} \log(1+\kappa u) & \text{if } u \geq 0 \\ -\log(1-\kappa u) & \text{otherwise} \end{cases}$$

- $\kappa$~1: linear close to the noise and continuously derivable
- Possibility to additionally weight pixels according to their distance to the center

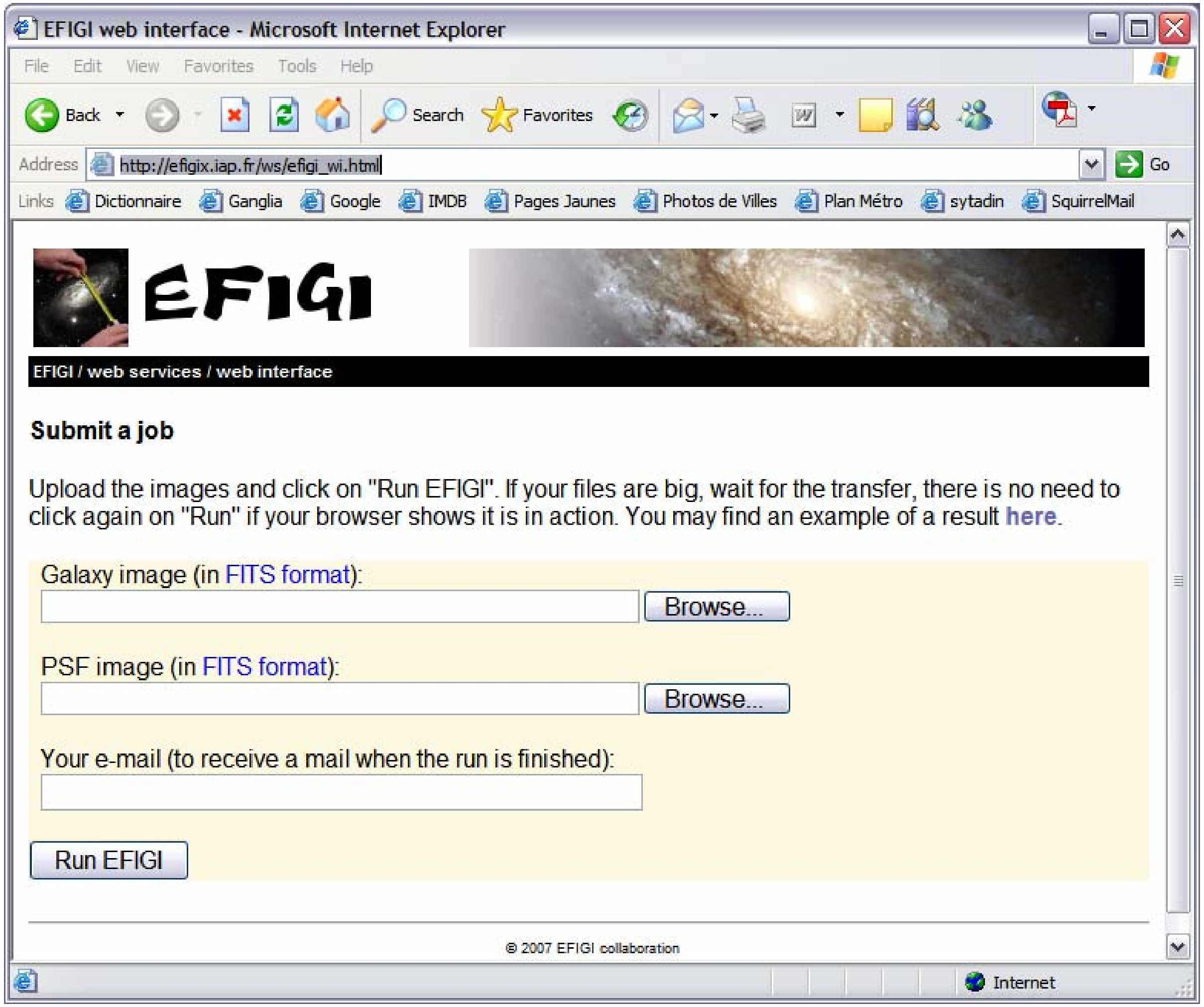
# Robust profile-fitting



Galaxy | Linear weighting | Non-linear weighting

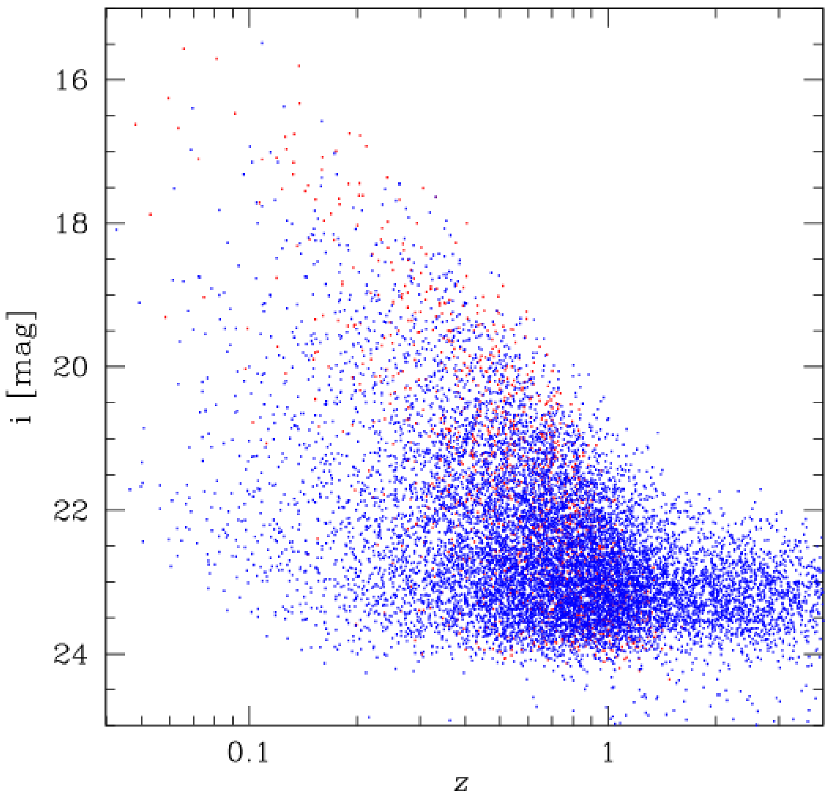
- More robust towards bright interlopers
- In rare cases, the minimization algorithm may accidentally “lock” on some bright, non-galaxy feature

# Demo on BCS data



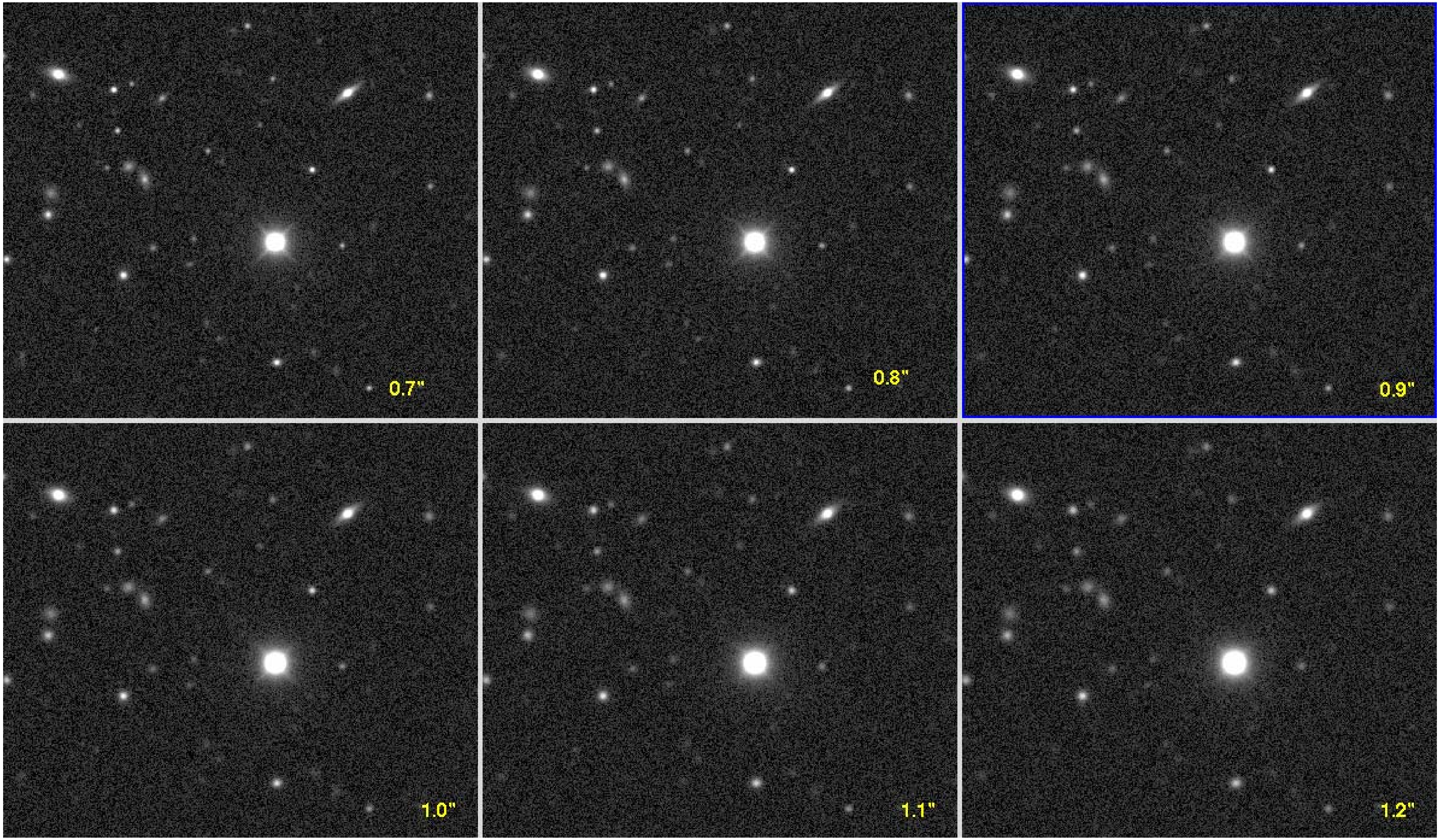
# House-made DES simulations

- Catalog simulated with Stuff
  - 6 galaxy “types”: E, S0, Sab,Sbc,Scd,Sd/Im
  - LF parameters from Madgwick et al. 2002 (2dFGRS)
    - Evolution of $\phi^*$ and $M^*$ consistent with Gabasch et al. 2004, Ilbert et al. 2005, and Zucca et al. 2005.
  - Empirical internal absorption law from the RC3.
  - Empirical bulge and disk scaling laws follow Sandage 1970, Bingelli et al. 1987, and de Jong & Lacey 2000
- Images created with SkyMaker
  - i band, 4m M1 with 1.5m diameter circular obscuration, 40% total throughput
  - exposure time 100-1200s, 50% comp.limit i~24
  - seeing FWHM=0.7”-1.2”, pixel=0.27”
  - Bulge+disk galaxies with deVaucouleurs and exponential profiles, respectively.
- ~10,000 detected galaxies per simulation
- PSF model derived from stars in the image

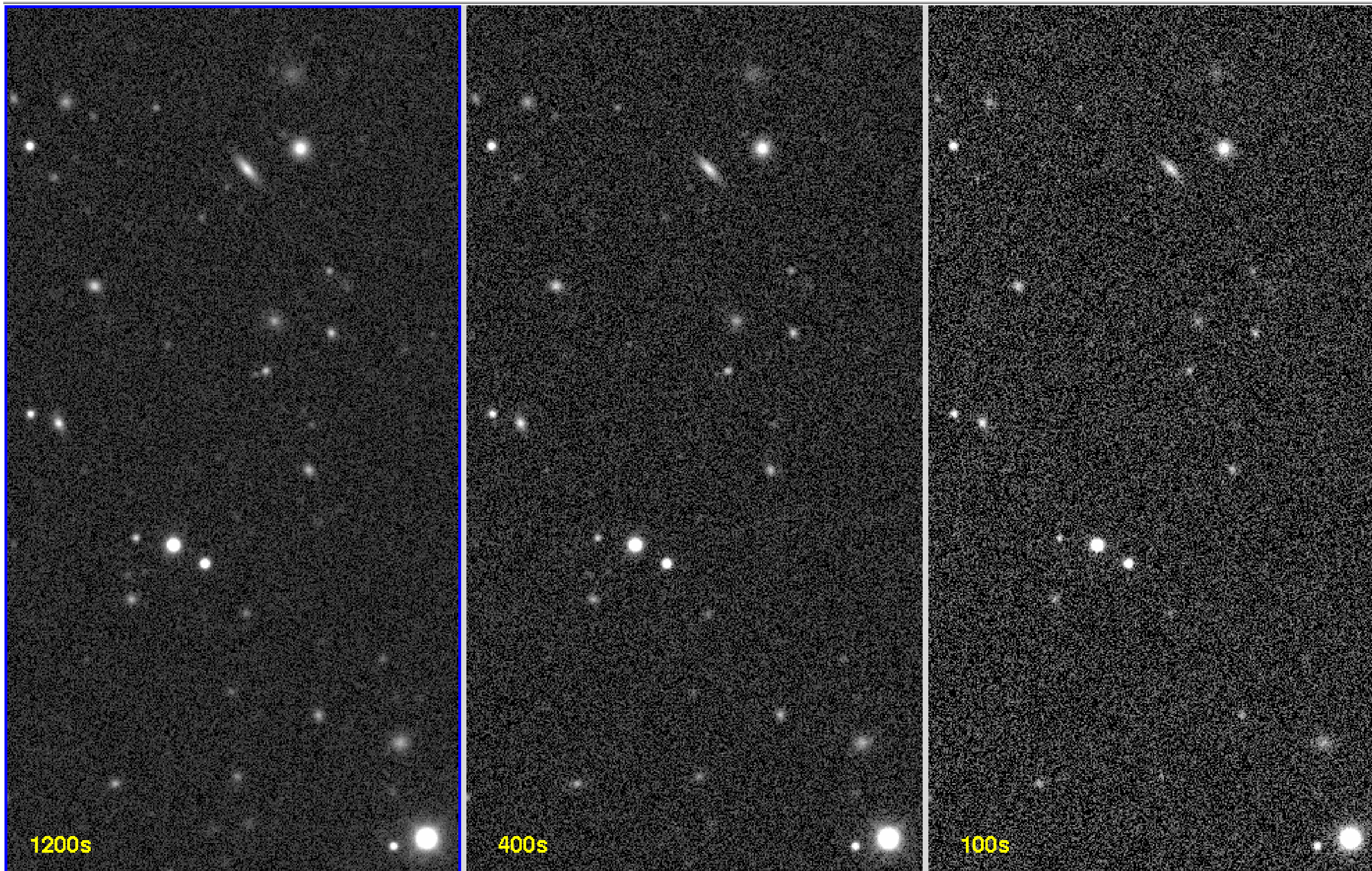



Hubble diagram of the simulation

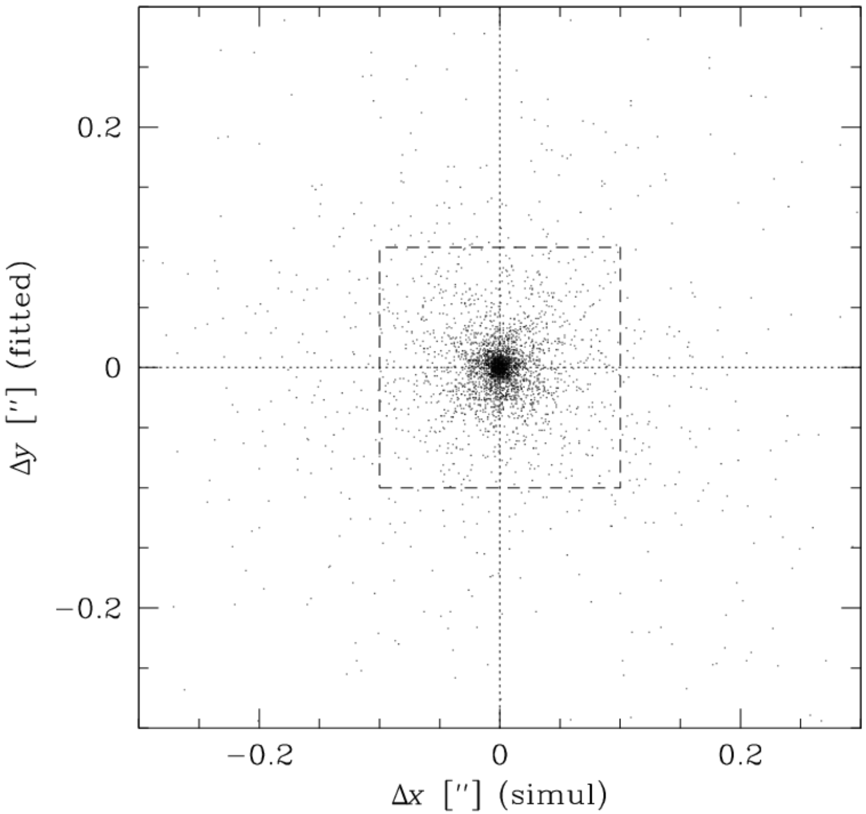
# DES simulations: variable seeing



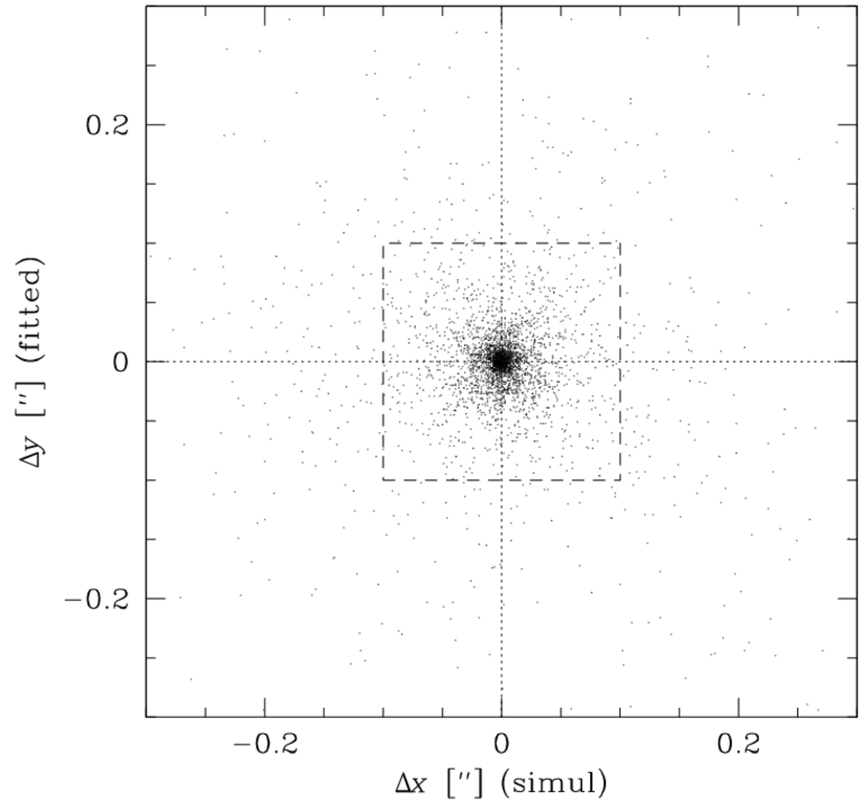
# DES simulations: variable depth



# Positional accuracy

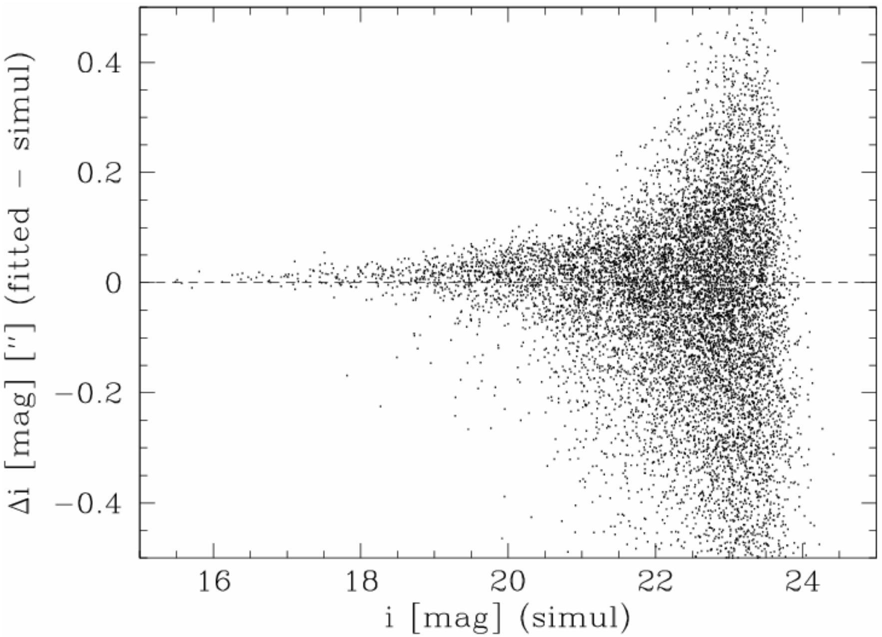



Sersic + Exponential fit (i<22)

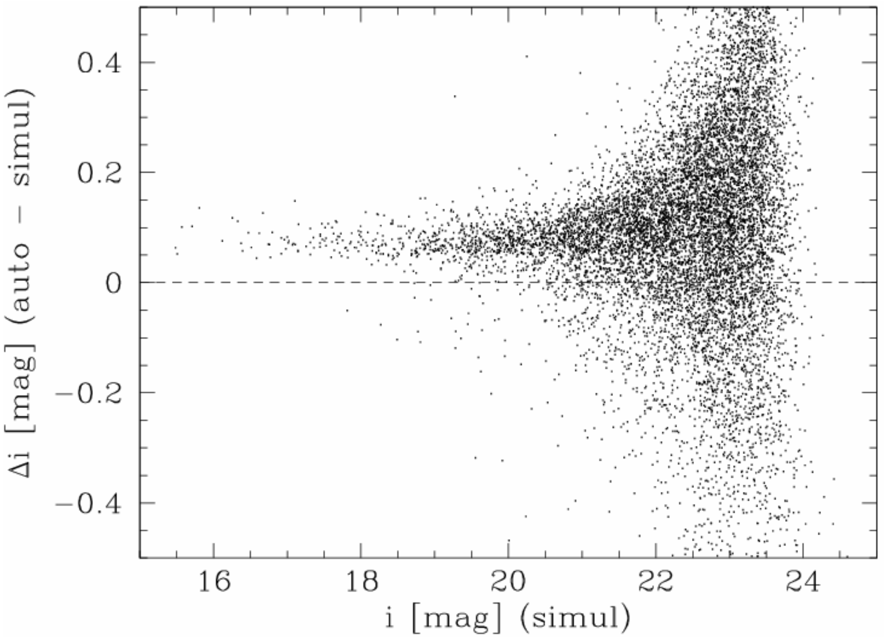



X/YWIN (i<22)

# “Total” magnitudes

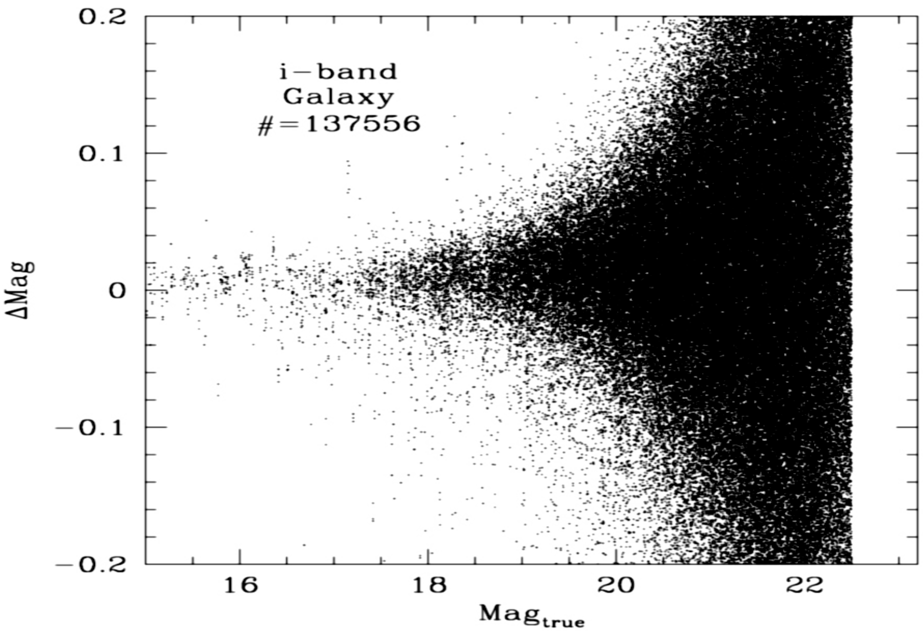


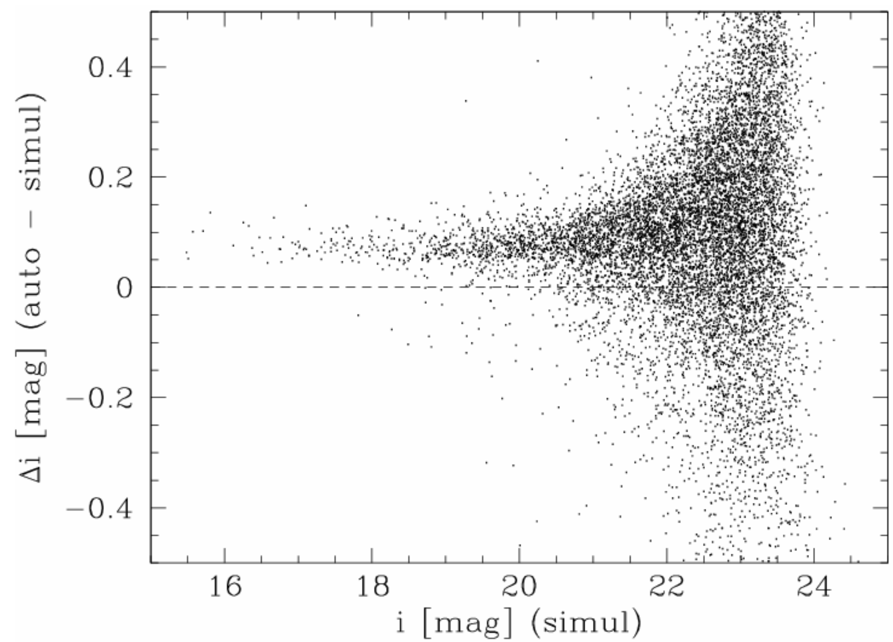

Asymptotic from Sersic+Exponential fit




MAG_AUTO (Kron-like)

# “Total” magnitudes

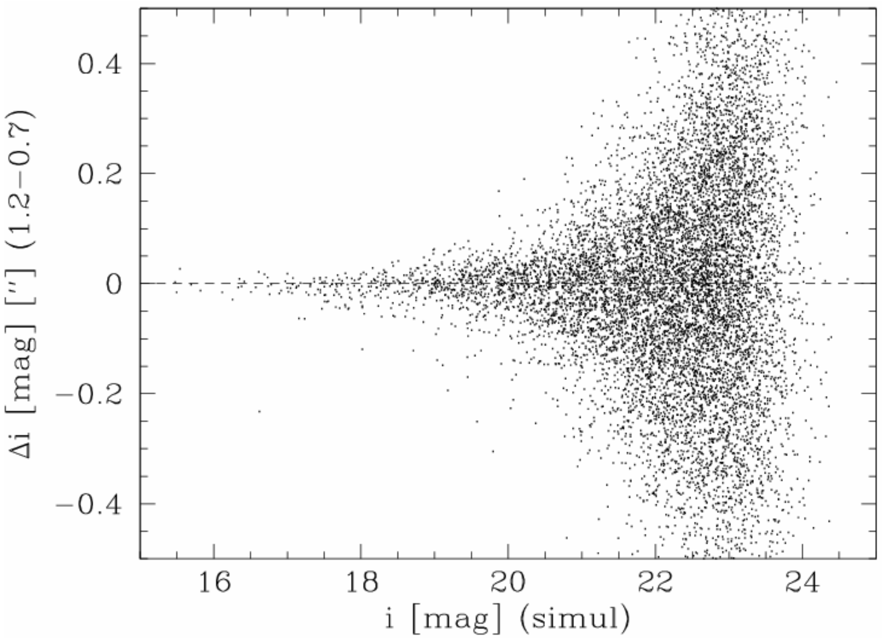


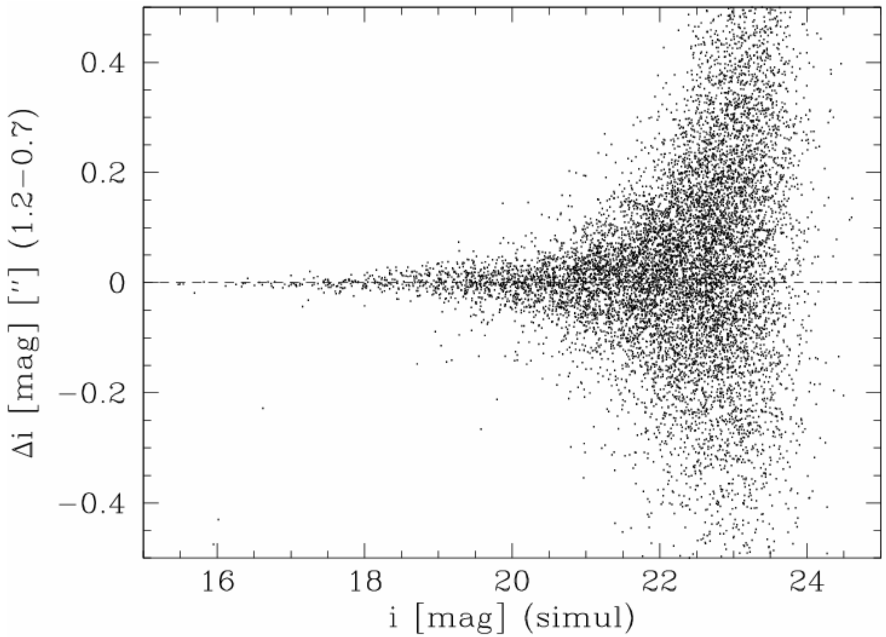

MAG_AUTO on GSN-lite (J.Mohr)

MAG_AUTO (Kron-like)

# "Total" magnitudes: seeing dependence

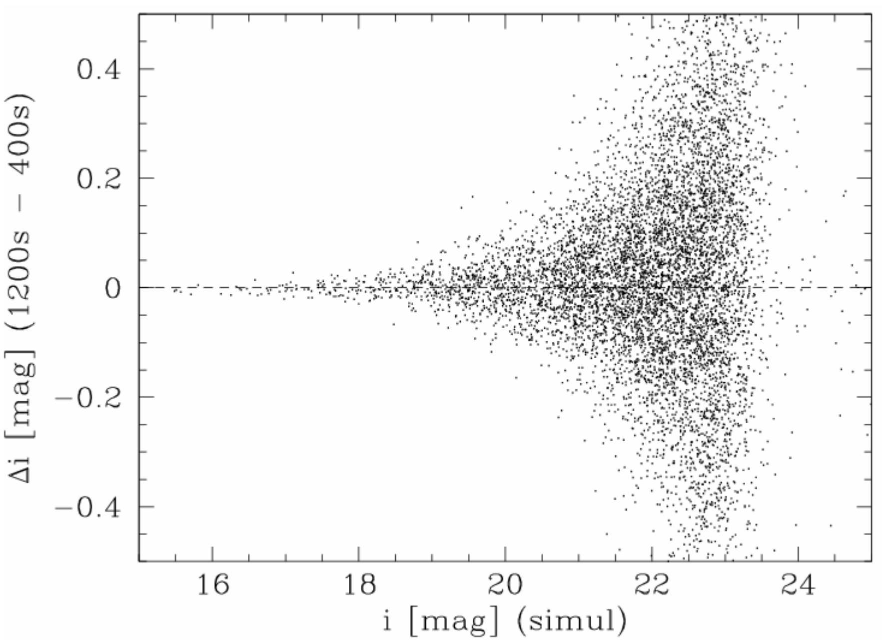



Asymptotic from Sersic+Exponential fit

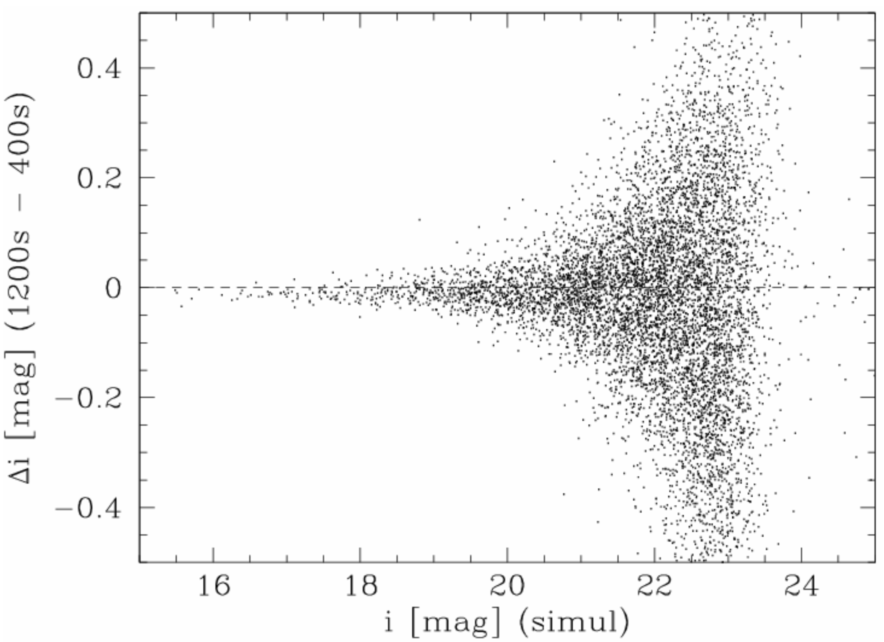



MAG_AUTO (Kron-like)

# "Total" magnitudes: dependence with depth: 1200 *vs* 400s

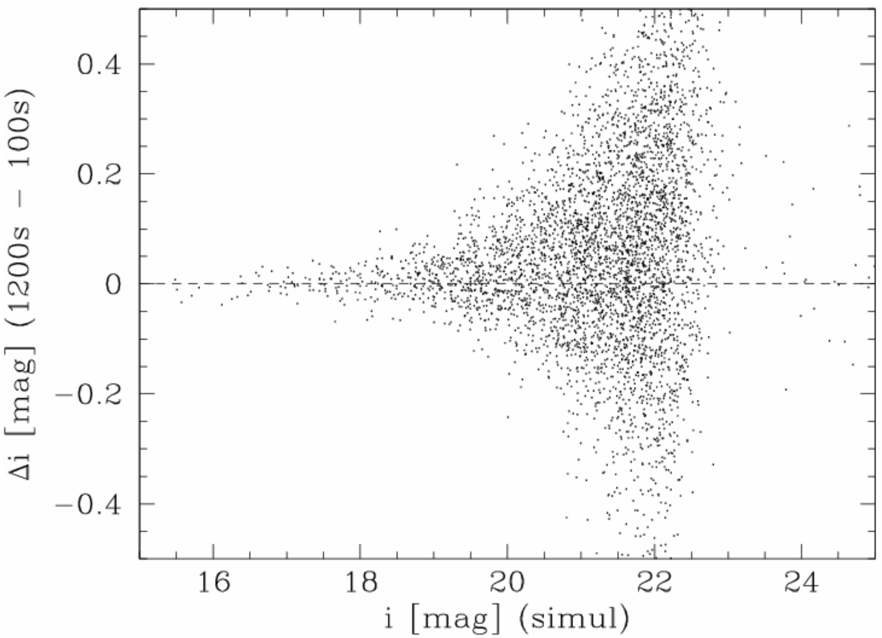



Asymptotic from Sersic+Exponential fit

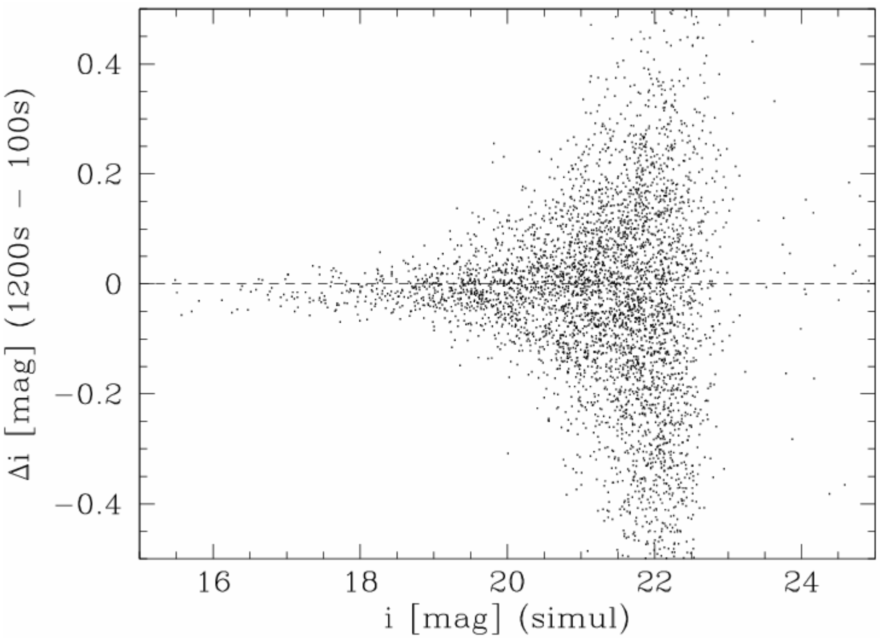



MAG_AUTO (Kron-like)

# “Total” magnitudes: dependence with depth: 1200 *vs* 100s

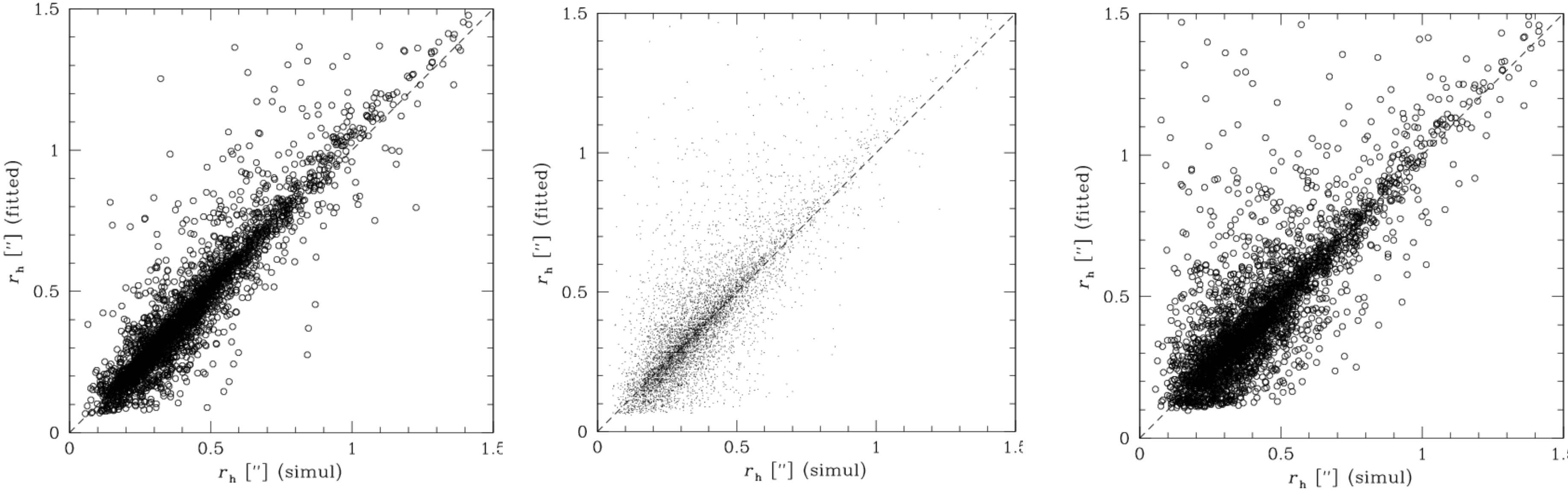



Asymptotic from Sersic+Exponential fit




MAG_AUTO (Kron-like)

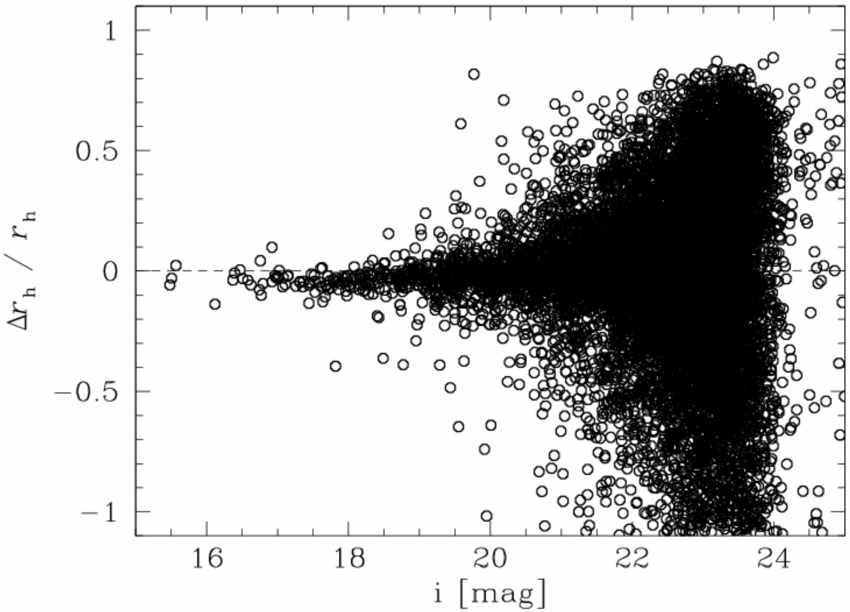
# Disk scalelengths

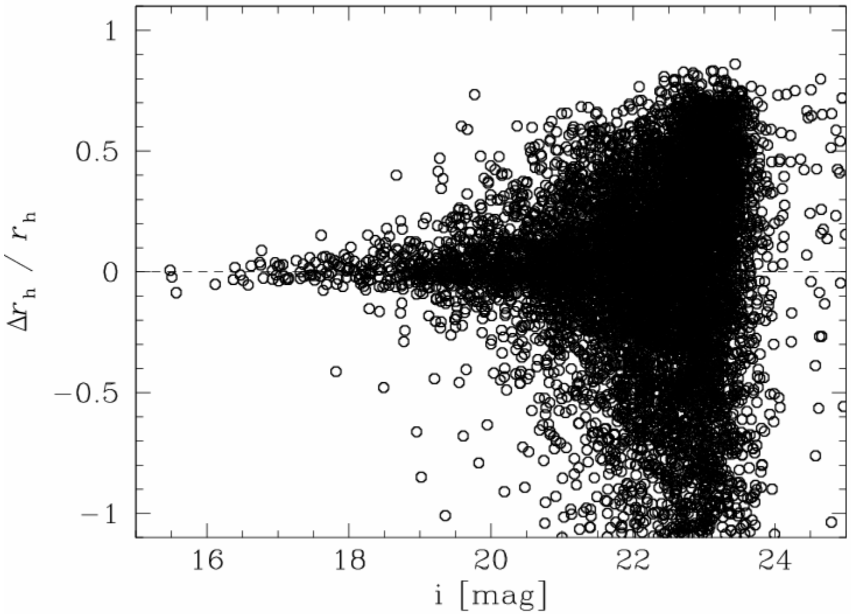



FWHM = 0.7”    FWHM=0.9”    FWHM=1.2”

Sersic + exponential fit (i<22)

# Disk scalelengths (cont.)



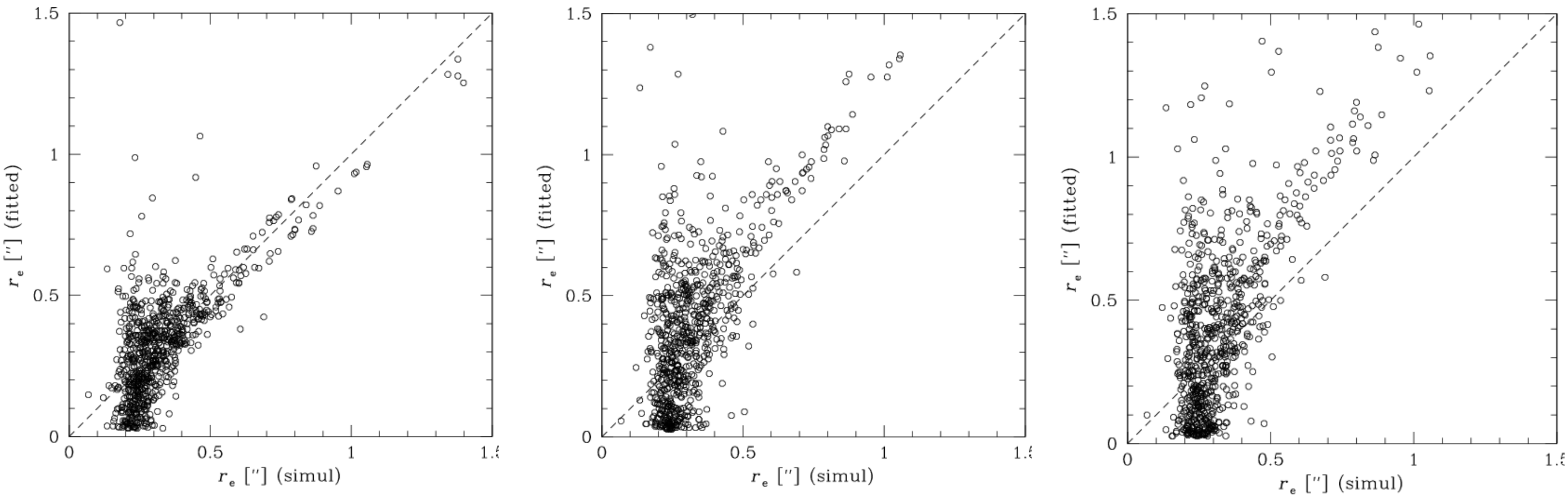




FWHM = 0.7”

FWHM=1.2”

Fractional error as a function of magnitude

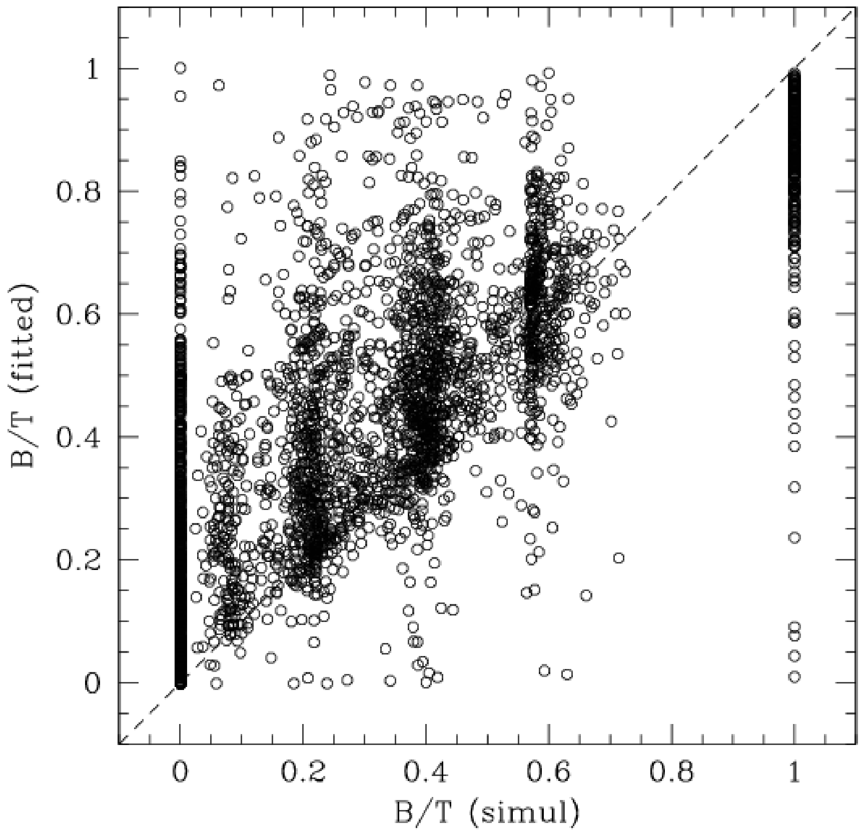
# Bulge effective radii



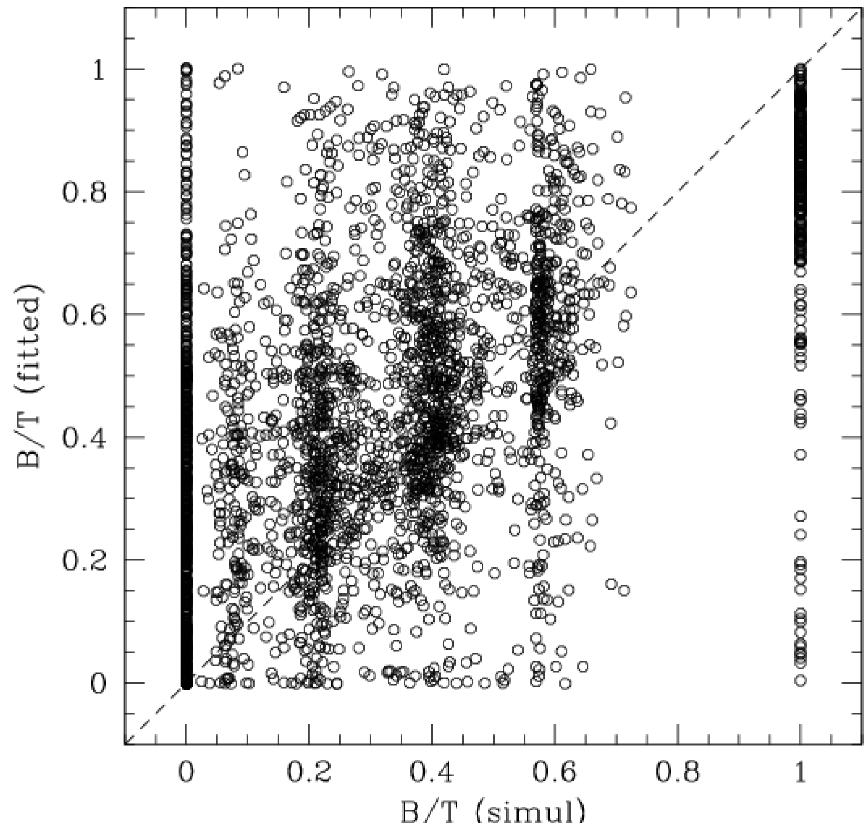

FWHM = 0.7”　　FWHM=0.9”　　FWHM=1.2”

Sersic + exponential fit (i<22 && B/T>0.2)

# Bulge-to-Total ratio



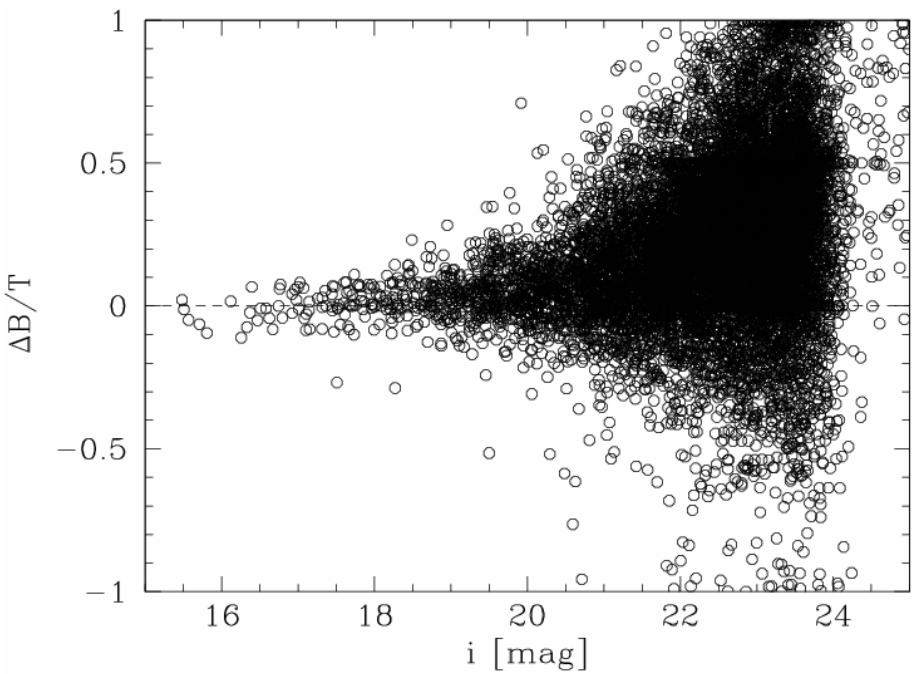

FWHM = 0.7”



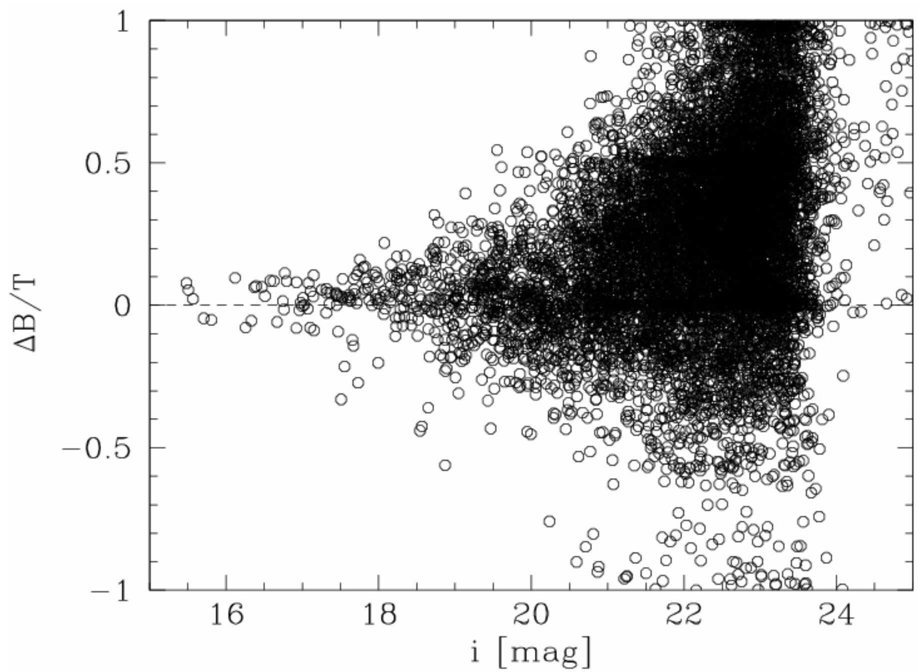

FWHM=1.2”

Sersic + exponential fit (i<22)

# Bulge-to-Total ratio (cont.)



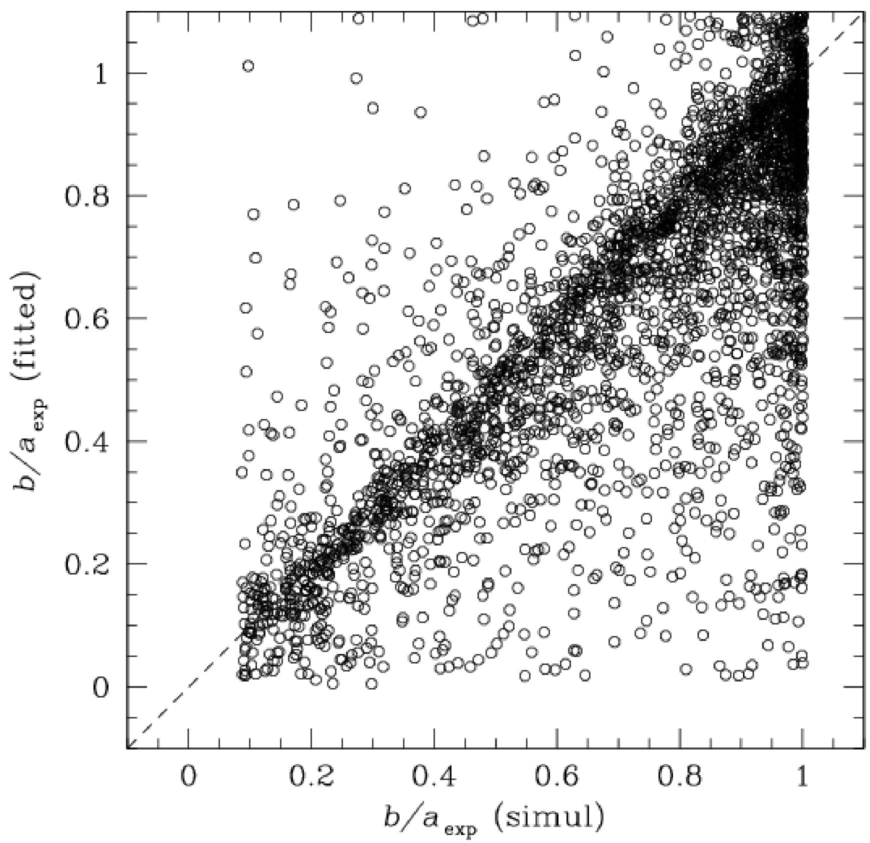

FWHM = 0.7”



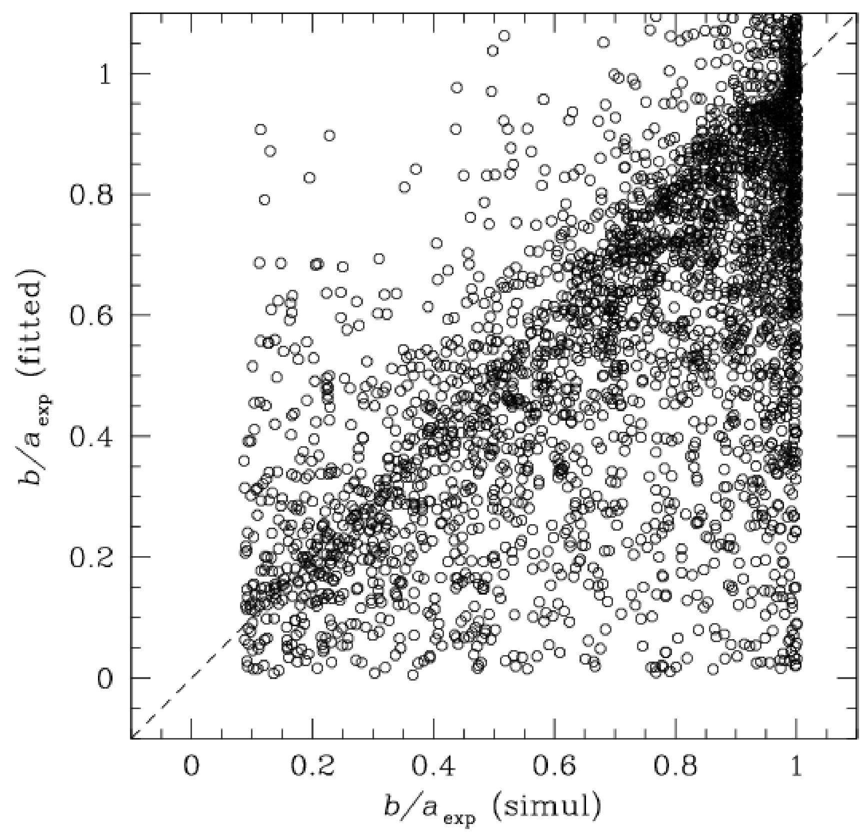

FWHM=1.2”

Fractional error as a function of magnitude

# Disk aspect ratio



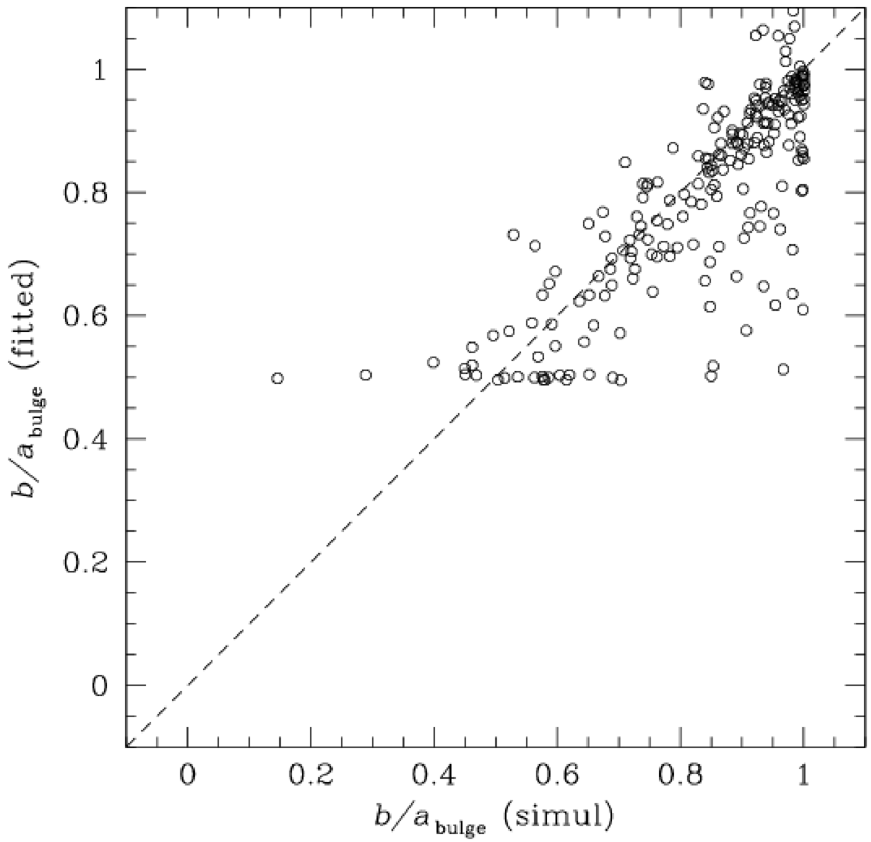

FWHM = 0.7”



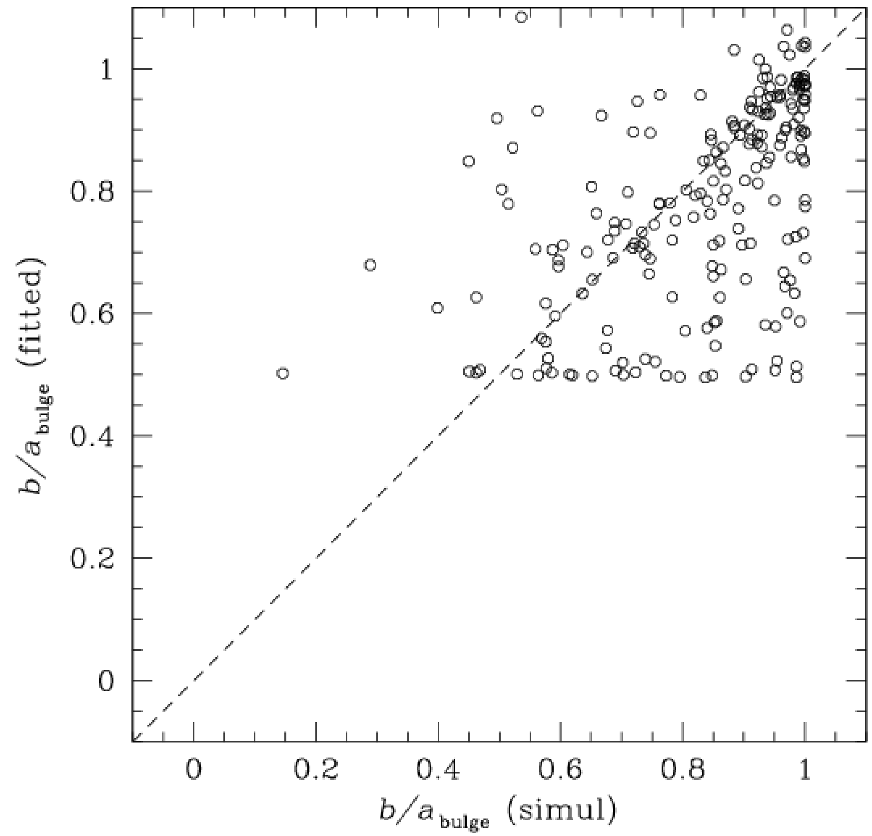

FWHM=1.2”

Sersic + exponential fit (i<22 && B/T<0.9)

# Bulge aspect ratio



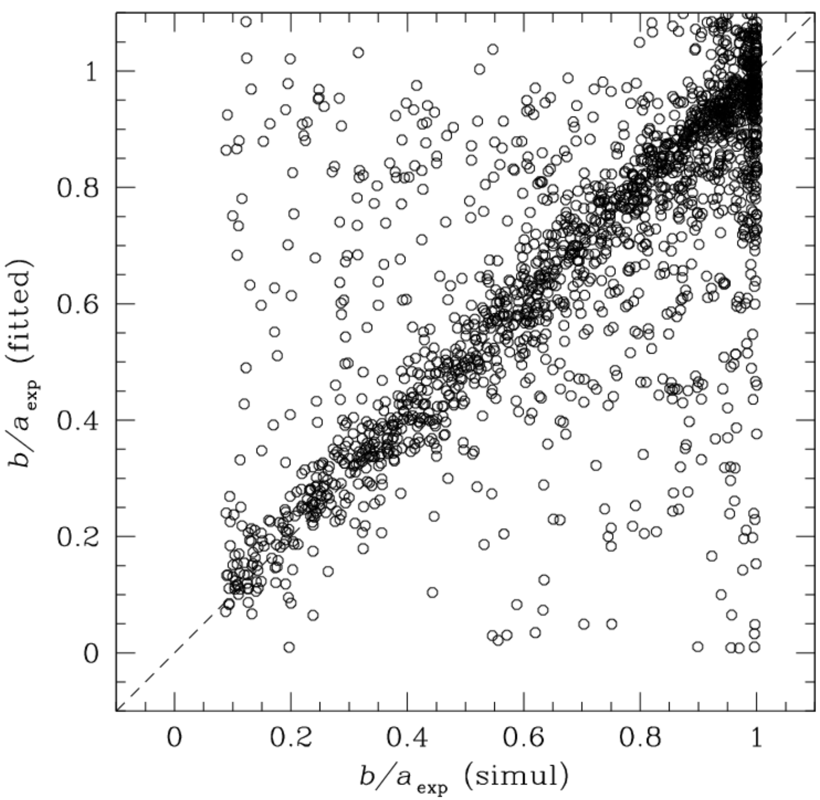

FWHM = 0.7”

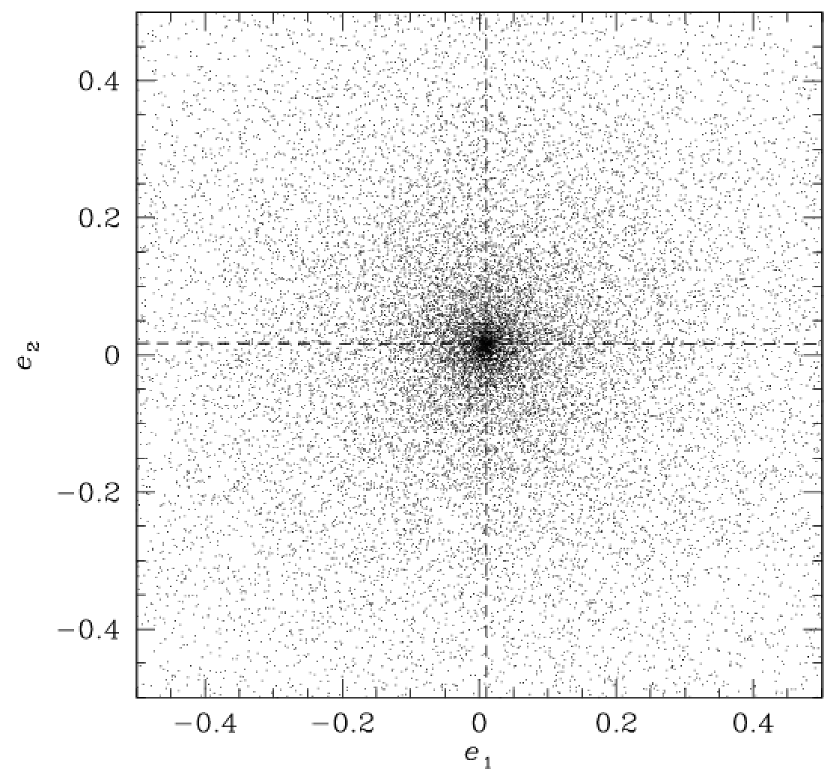



FWHM=1.2”

Sersic + exponential fit (i<22 && B/T>0.3)

# Applicable to shear measurements?




i<22

Sersic + exponential fit

# Comments and future plans

- Sersic + exponential model-fitting is now operational in SExtractor.
- On a typical ground-based 4m-class telescope, basic morphological classification (early/late) based on bulge+disk decomposition rate should be possible with a >80% success rate for M* galaxies up to z~0.7 (assuming a seeing <1.0'')
- No significant biases are seen in the recovery of disk parameters
- Some biases remain in bulge size parameters
- « Total profile magnitude » provides a dispersion similar to MAG_AUTO.
  - current systematics are about 50% lower (less than 2% for bright galaxies): should improve with a more clever sampling
  - more checks needed on real overlapping exposures with different seeings
  - Background as a free parameter makes measurements noisier unless areas far enough from the galaxy are sampled
- There is a hint that current GSN-lite simulated galaxy images miss light in their wings
- The typical processing speed is 1-10 Sersic+exponential fits/s for not-too-large galaxies on a single 2GHz core.
  - Optimization of model and residual calculations not node yet: a gain of at least a factor of 2 in speed should be possible.
- TODO
  - Cleaning up of the interface to parameters
  - Investigate
    - Suitability for seeing-corrected weak-shear measurements
    - simultaneous fitting of two+ overlapping profiles
    - simultaneous bulge+disk fitting in two bands
    - Merged star/galaxy fitting process
  - Comparison with GalFit and GIM2D