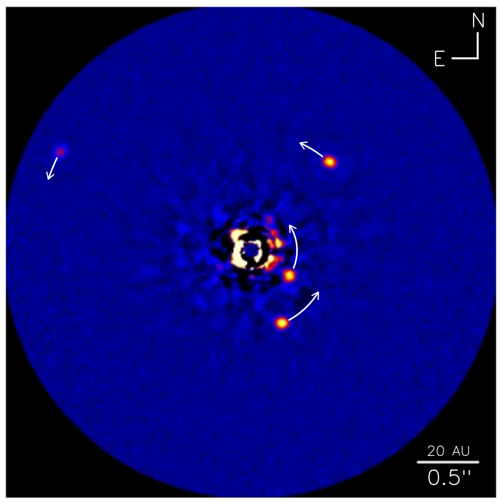
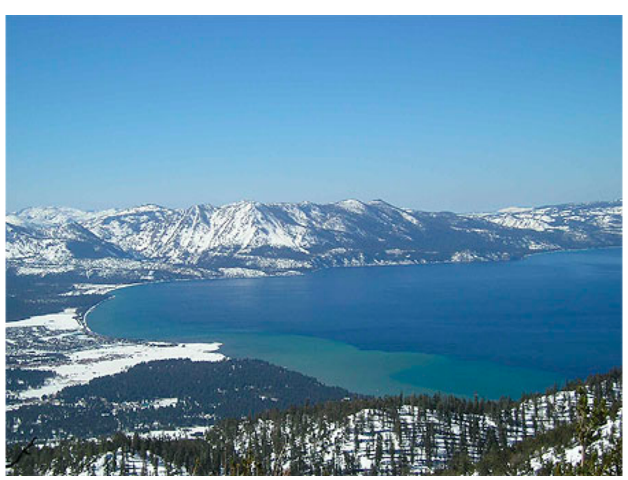


Imaging Exoplanets with ADI & LOCI/SOSIE

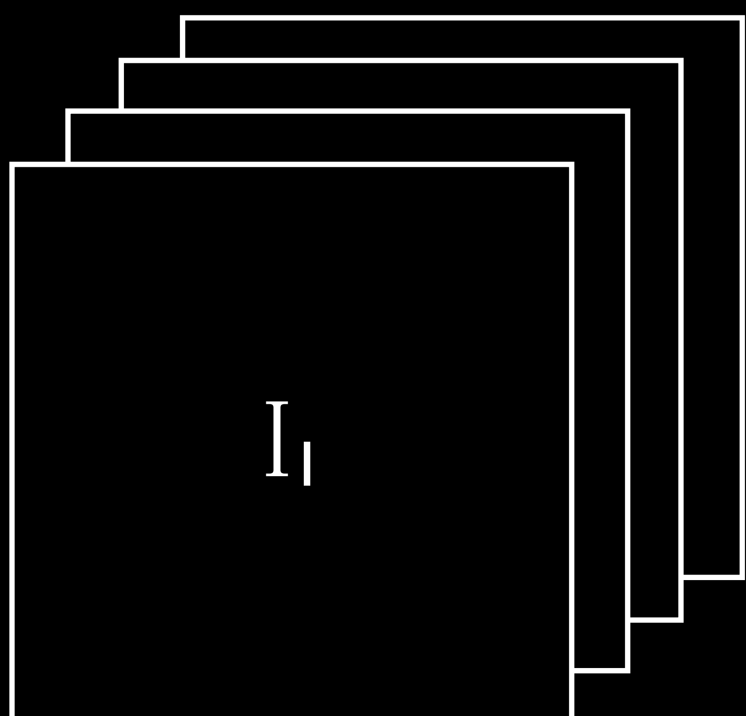
Tahoe March 2012



Christian Marois
Herzberg Institute of Astrophysics

What is ADI/SSDI imaging & LOCI processing?

How to combine a bunch of reference images to subtract the "noise" of an image of interest (while keeping the flux of what we are looking for)?



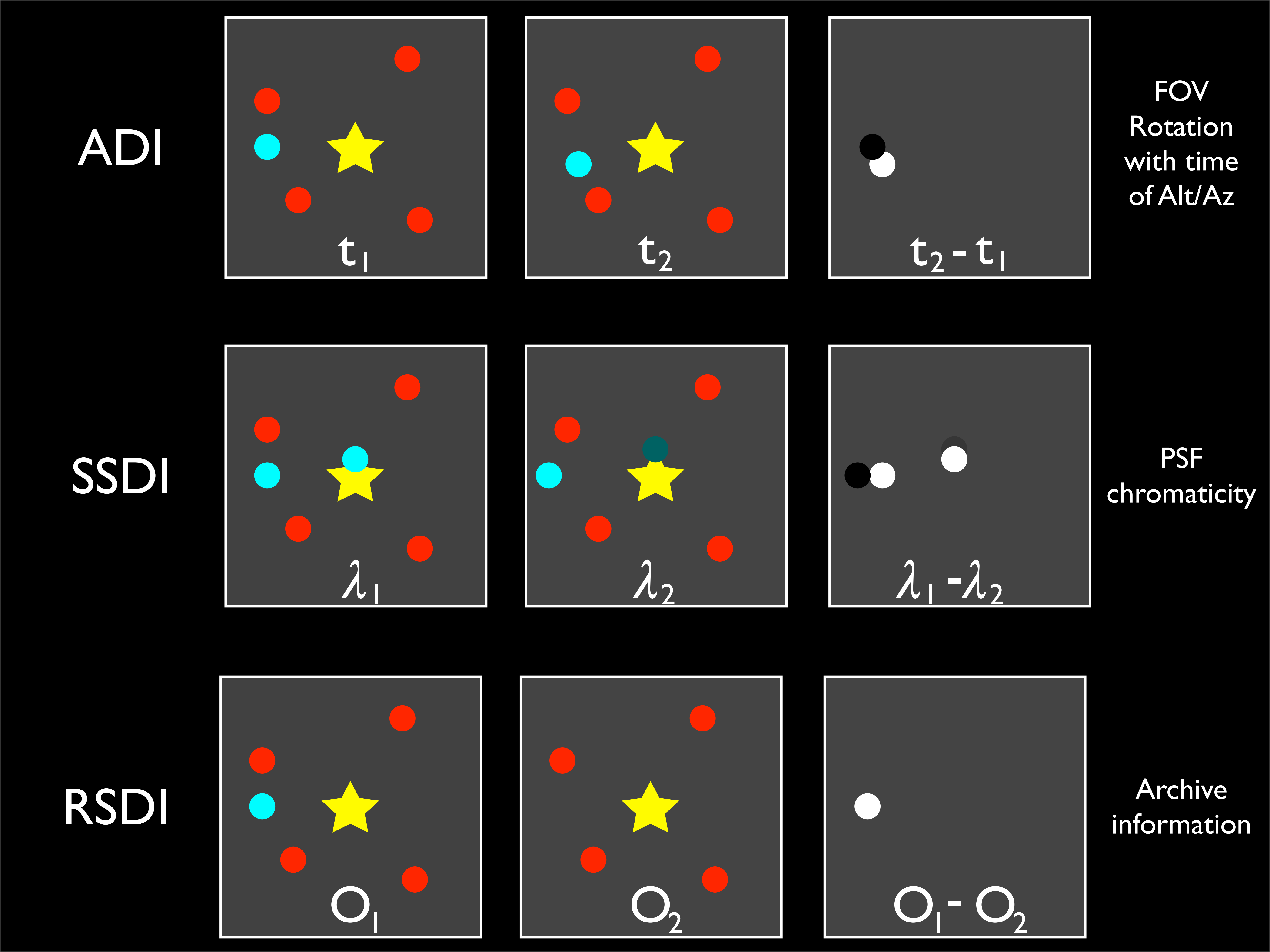
Sources of reference images

Same wavelength, same object, but at different time = ADI

Same object, simultaneous, but at a different wavelength = SSDI

Same wavelength, different time and different object = RSDI

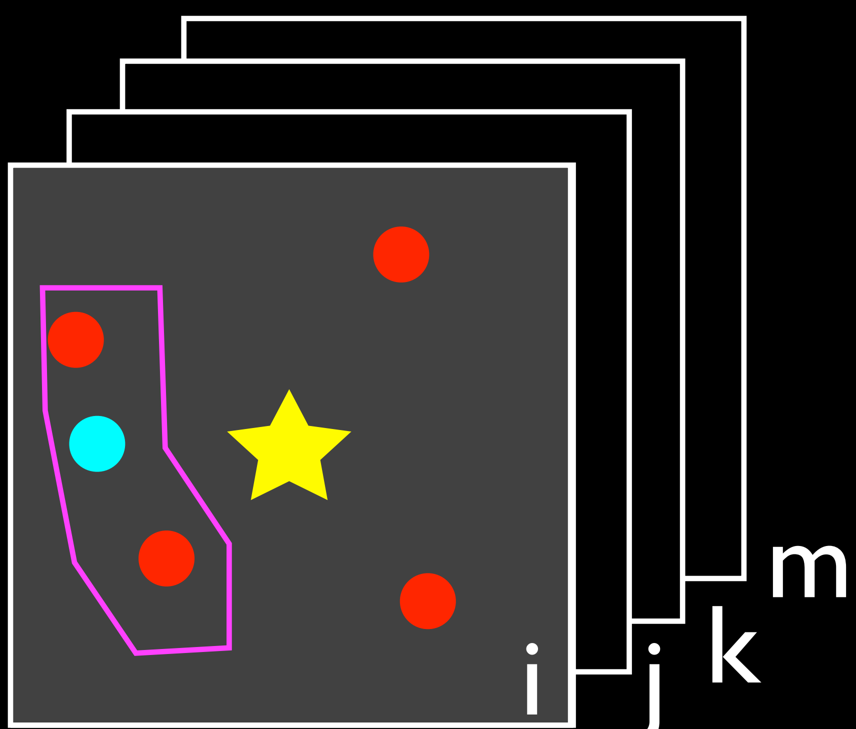
ADI & SSDI may be limited at small separations - Rely on reference stars


ADI
t1
t2
t2 - t1
FOV Rotation with time of Alt/Az
SSDI
λ1
λ2
λ1 - λ2
PSF chromaticity
RSDI
O1
O2
O1 - O2
Archive information

LOCI processing

Trying to remove the "quasi-static" noise of image i using j, k, m, ... while keeping the planet flux

Sequence of images



$$O^R = \sum_{k \in K} c^k O^k,$$

$$\sigma^2 = \sum_i m_i (O_i^T - O_i^R)^2 = \sum_i m_i \left(O_i^T - \sum_k c^k O_i^k\right)^2,$$

$$\frac{\partial \sigma^2}{\partial c^j} = \sum_i -2 m_i O_i^j \left(O_i^T - \sum_k c^k O_i^k\right) = 0, \quad \forall\, j \in K.$$

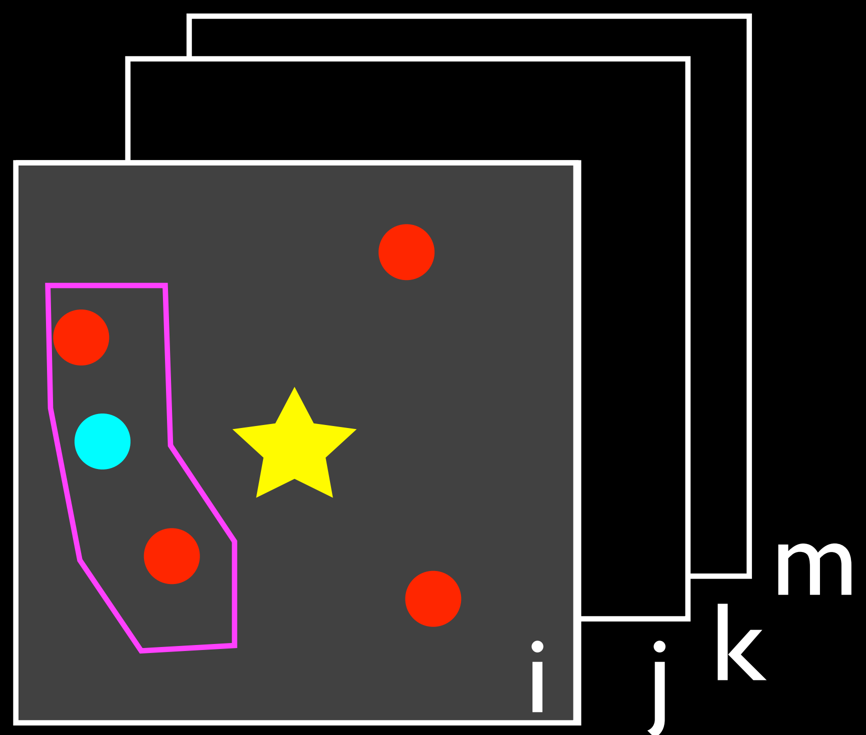
$$\sum_k c^k \left(\sum_i m_i O_i^j O_i^k\right) = \sum_i m_i O_i^j O_i^T, \quad \forall\, j \in K.$$

$$Ax = b$$

$$A_{jk} = \sum_i m_i O_i^j O_i^k, \quad x_k = c^k, \quad b_j = \sum_i m_i O_i^j O_i^T.$$

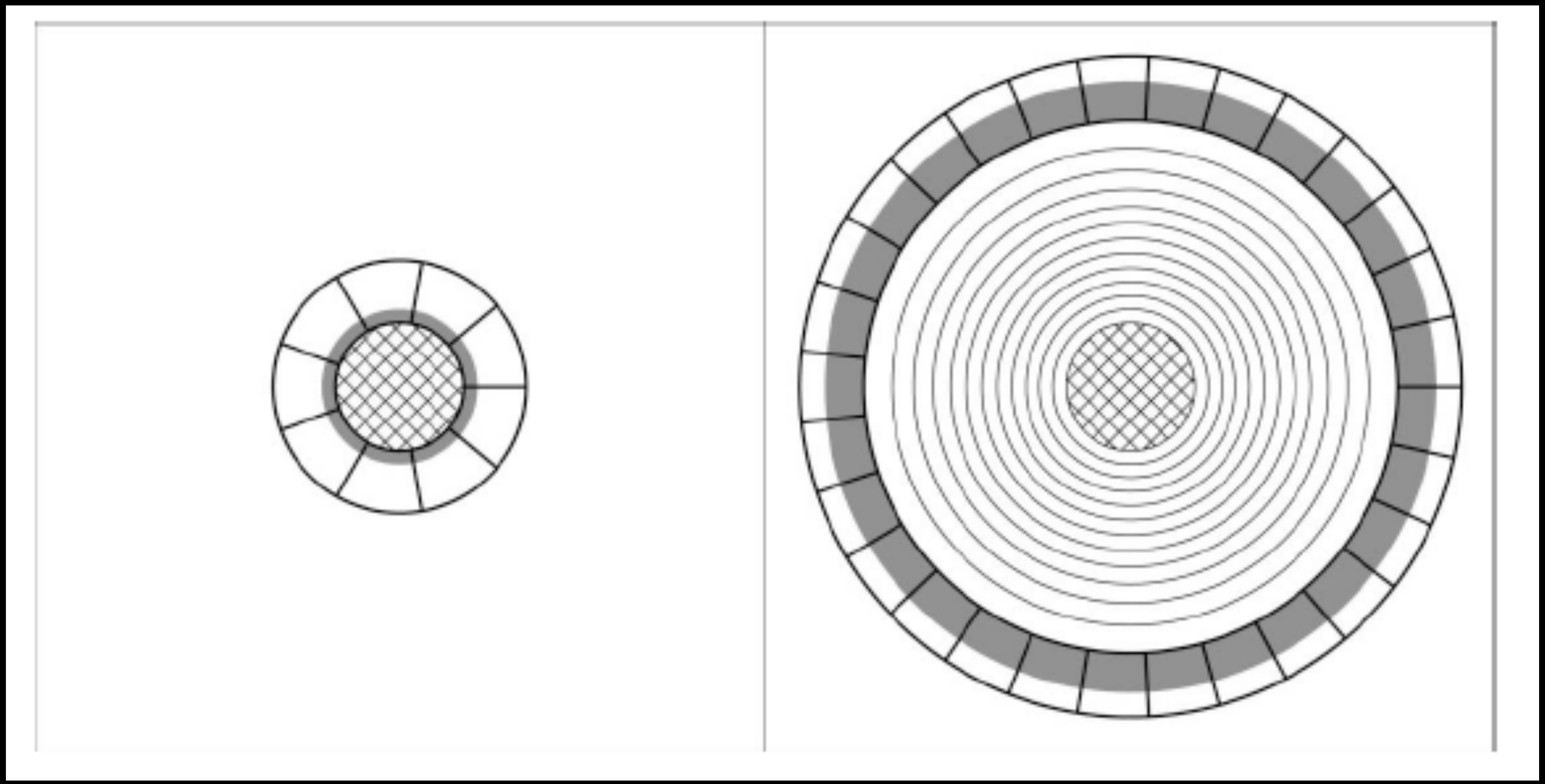
See D. Lafreniere's paper

Sequence of images



- Select a section (purple) on all images.
- Calculate cross-correlation matrix.
- Inverse that matrix.
- Obtain coefficients to multiply j, k, m, ... to minimize the noise in the purple section of i.
- Repeat for many purple sections until all image i has been subtracted.
- Repeat for all images of object of interest.
- Combine all subtracted images of object of interest.
- Find planets/disks/bg objects/...

Slicing an image



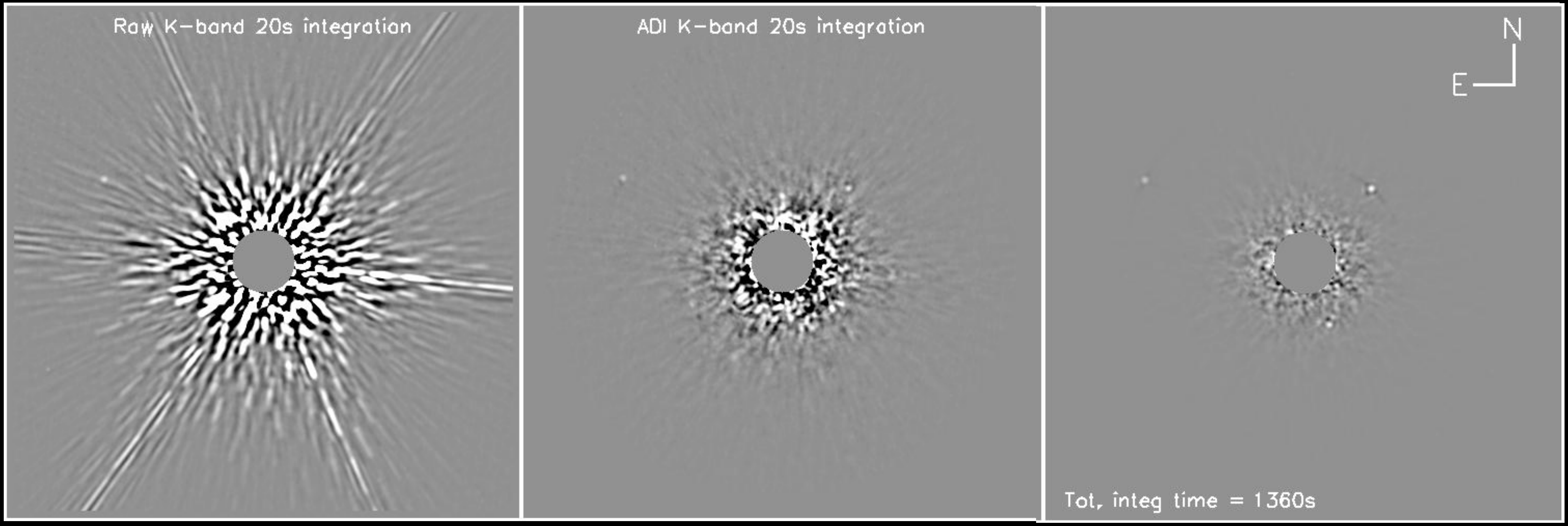
- Section of interest - split the image in azimuth & separation to do “LOCAL” analysis.

- Area to calculate LOCI coefficients may be different than “section of interest”

ADI example

K-band, 10s exposure

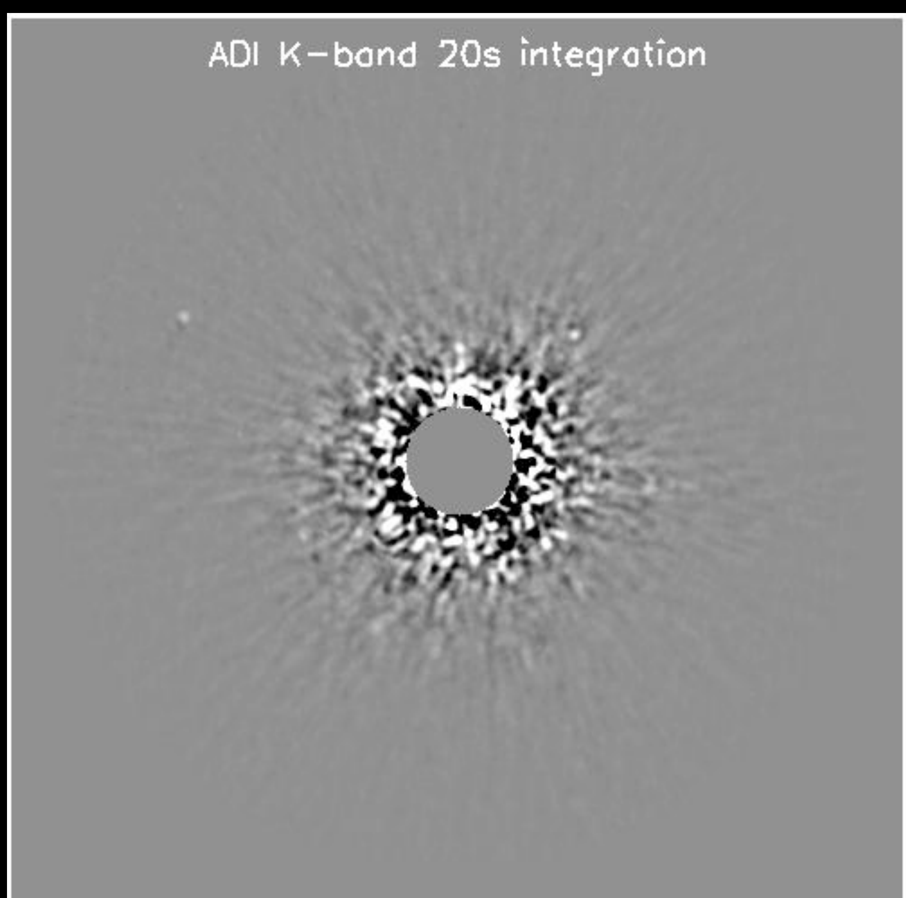
68 coadded



~10x improvement per image, then ~sqrt(n).
For 100 images, gain of the order of 50-100x (5 mag).

Movie...

Finding planets in non-Gaussian statistics



Marois et al. 2008

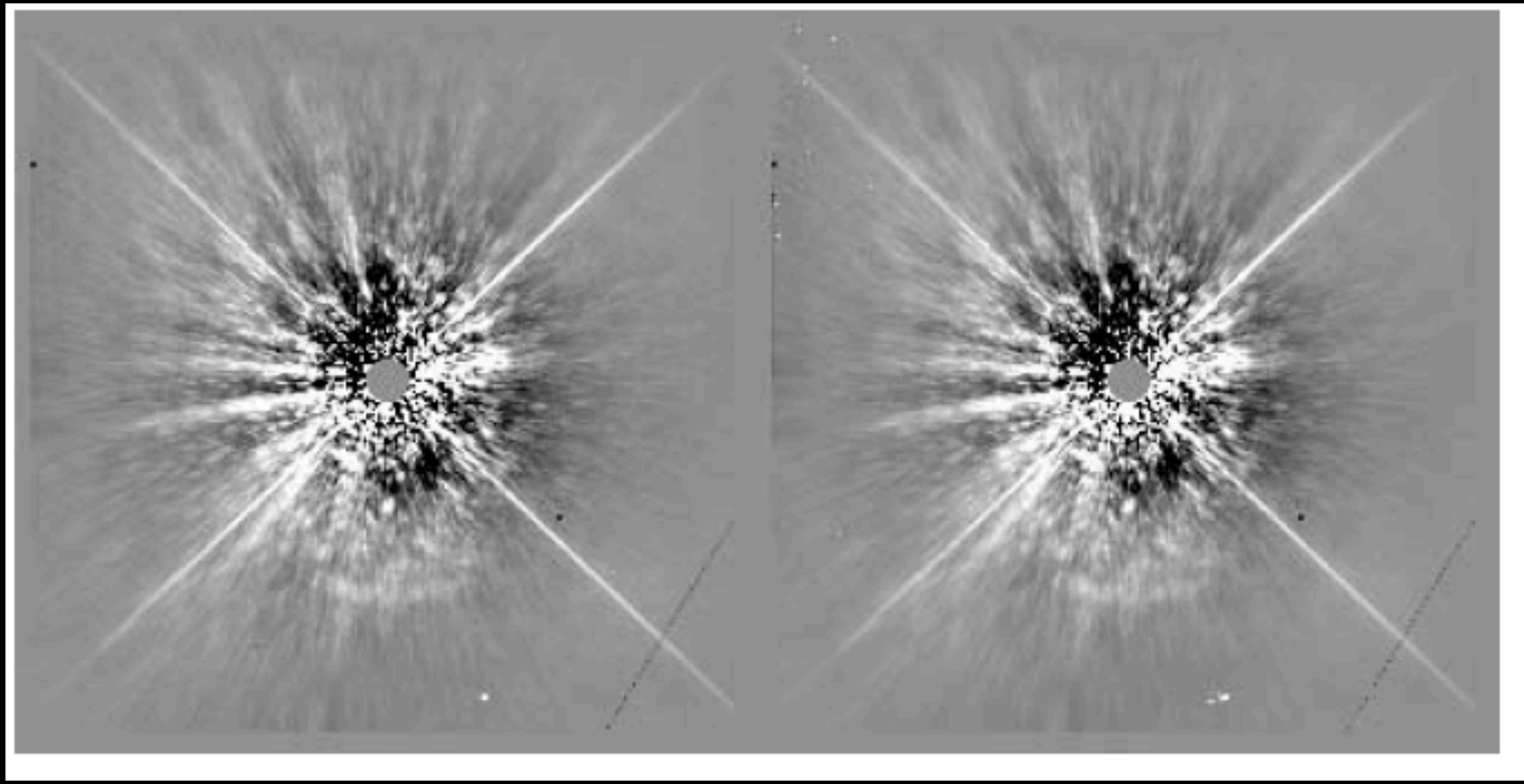
Goodman 1968, Soummer & Aime 2004, Fitzgerald & Graham 2006

- Many images, but with variable statistics as a function of separation and time.

- Initial = Rician statistics for speckle-limited cases and Gaussian for bg limited cases.

- Currently, only simple median-combined. Visual inspection guided with SNR maps/threshold.

A quasi-static limited regime



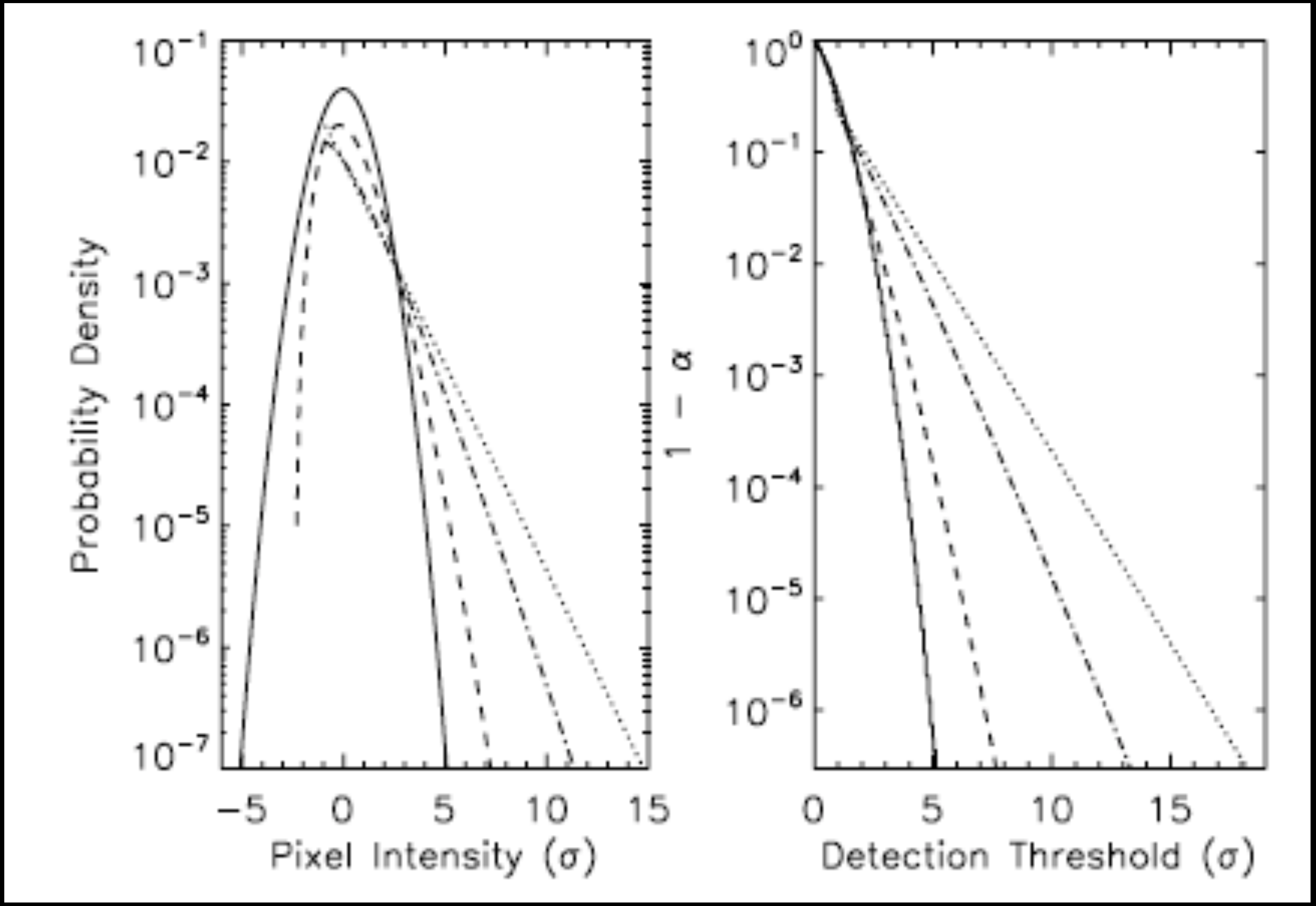
30s Median of 90 30s exposures

PSF intensity

$$p_{\mathrm{MR}}(I) = \frac{1}{I_s} \exp\left(-\frac{I+I_c}{I_s}\right) I_0\left(\frac{2\sqrt{II_c}}{I_s}\right),$$

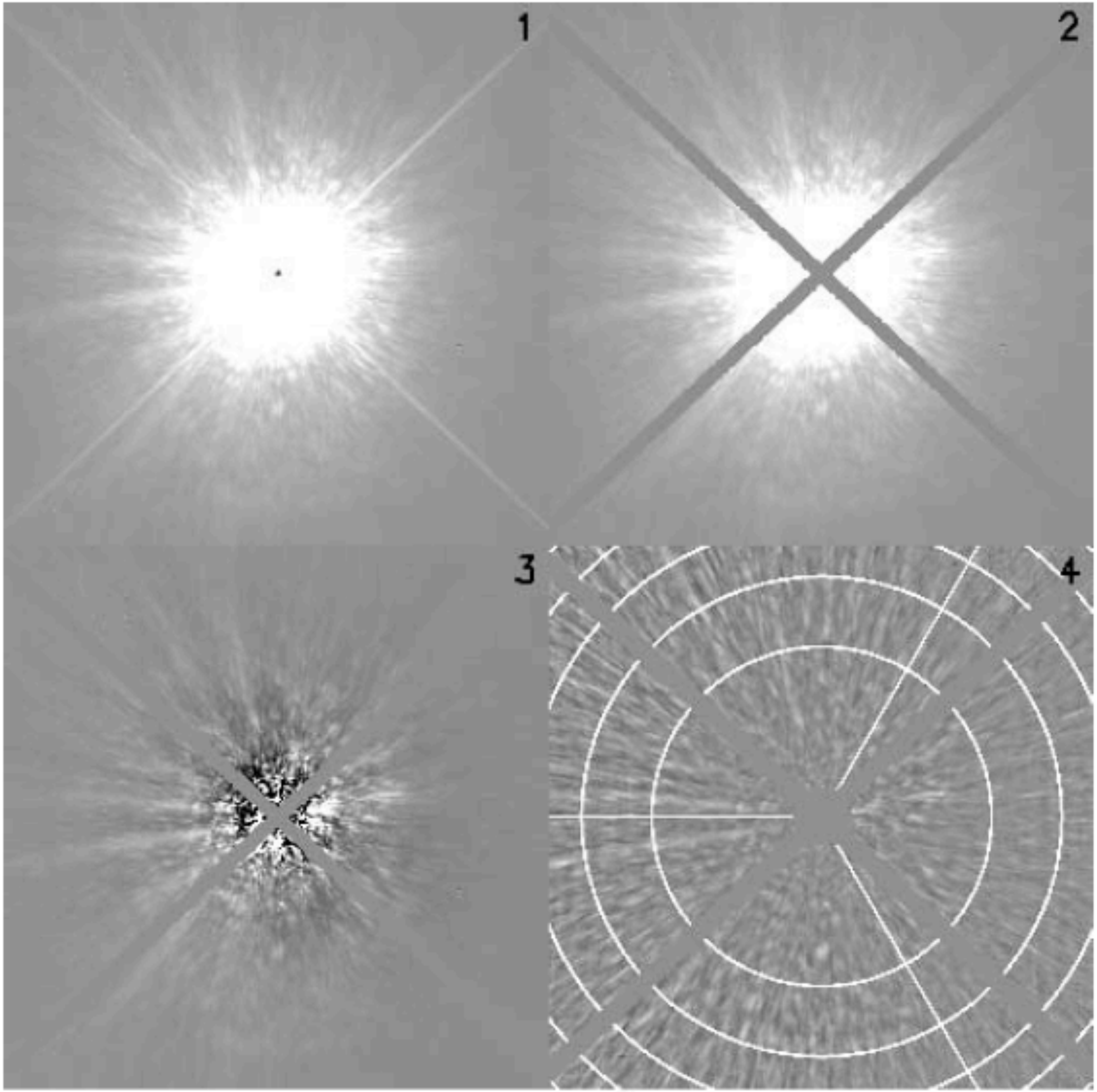
$I = I_c + I_s$

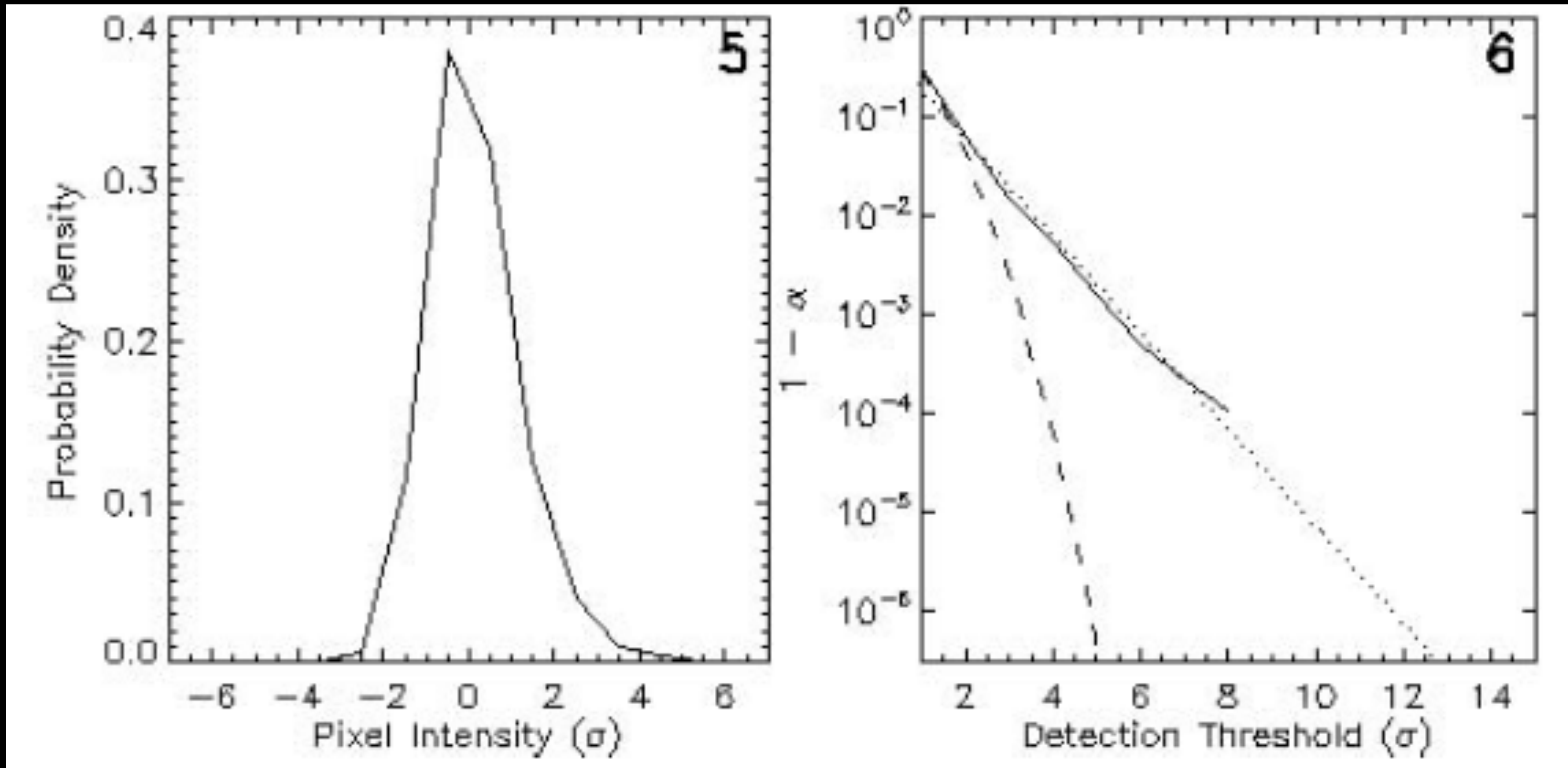
I_0 = Bessel function



Pinned speckles (bright rings; $I_c >> I_s$) = Gaussian-like
Dark rings ($I_c << I_s$) = exponential

"Bright events" (false positives) to be expected

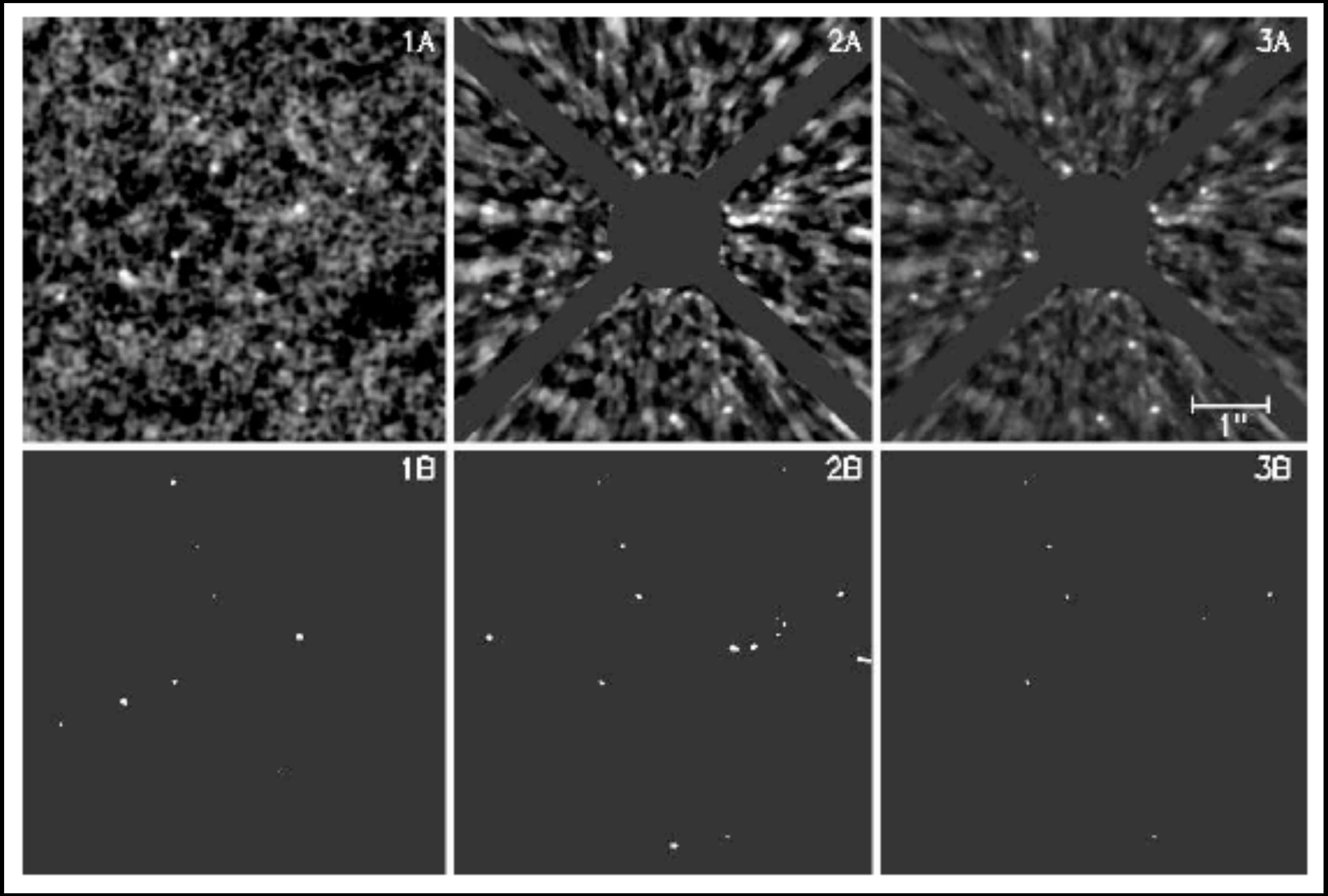

1
2
3
4



Asymmetric distribution

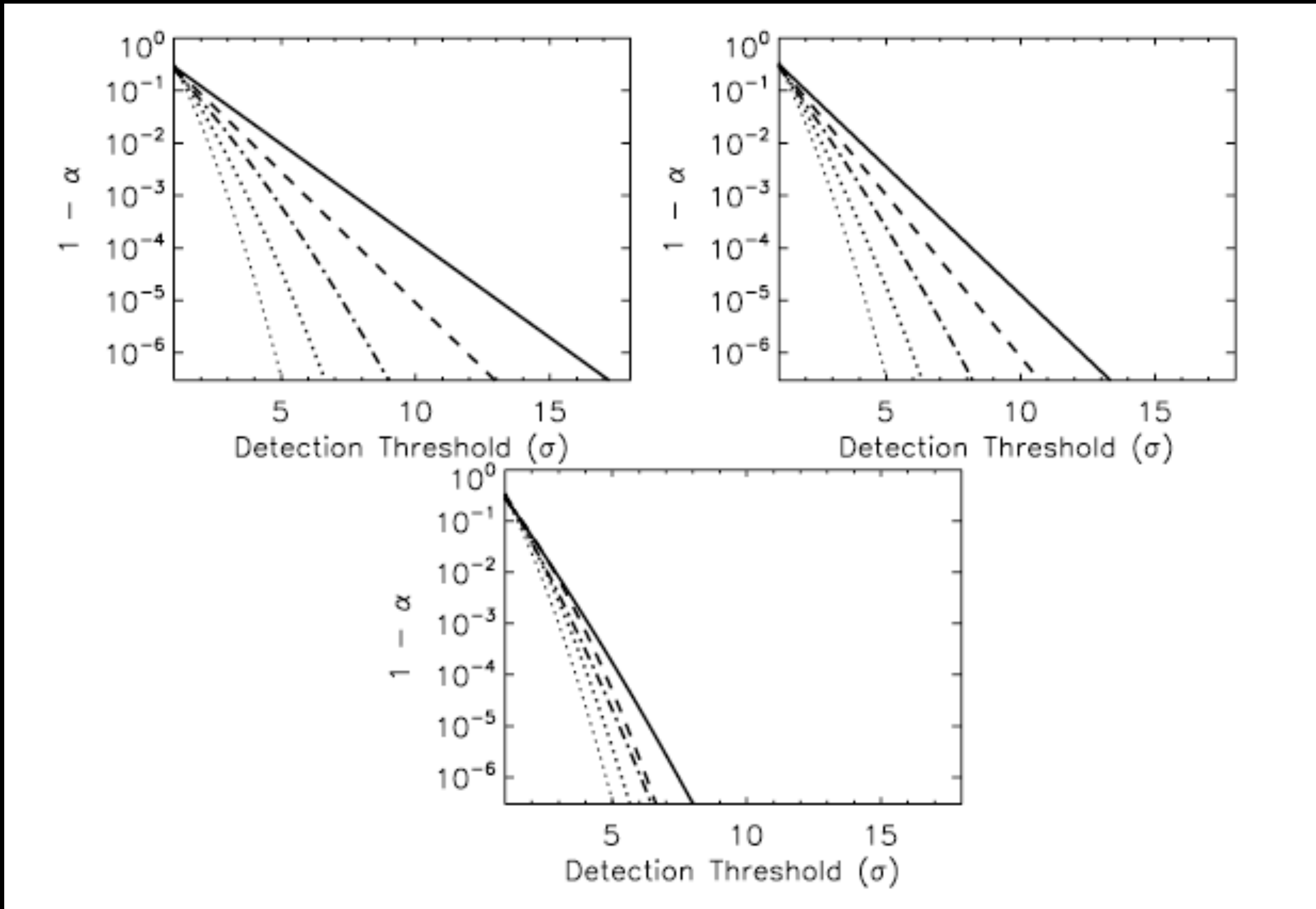
Non-Gaussian noise (~exponential)

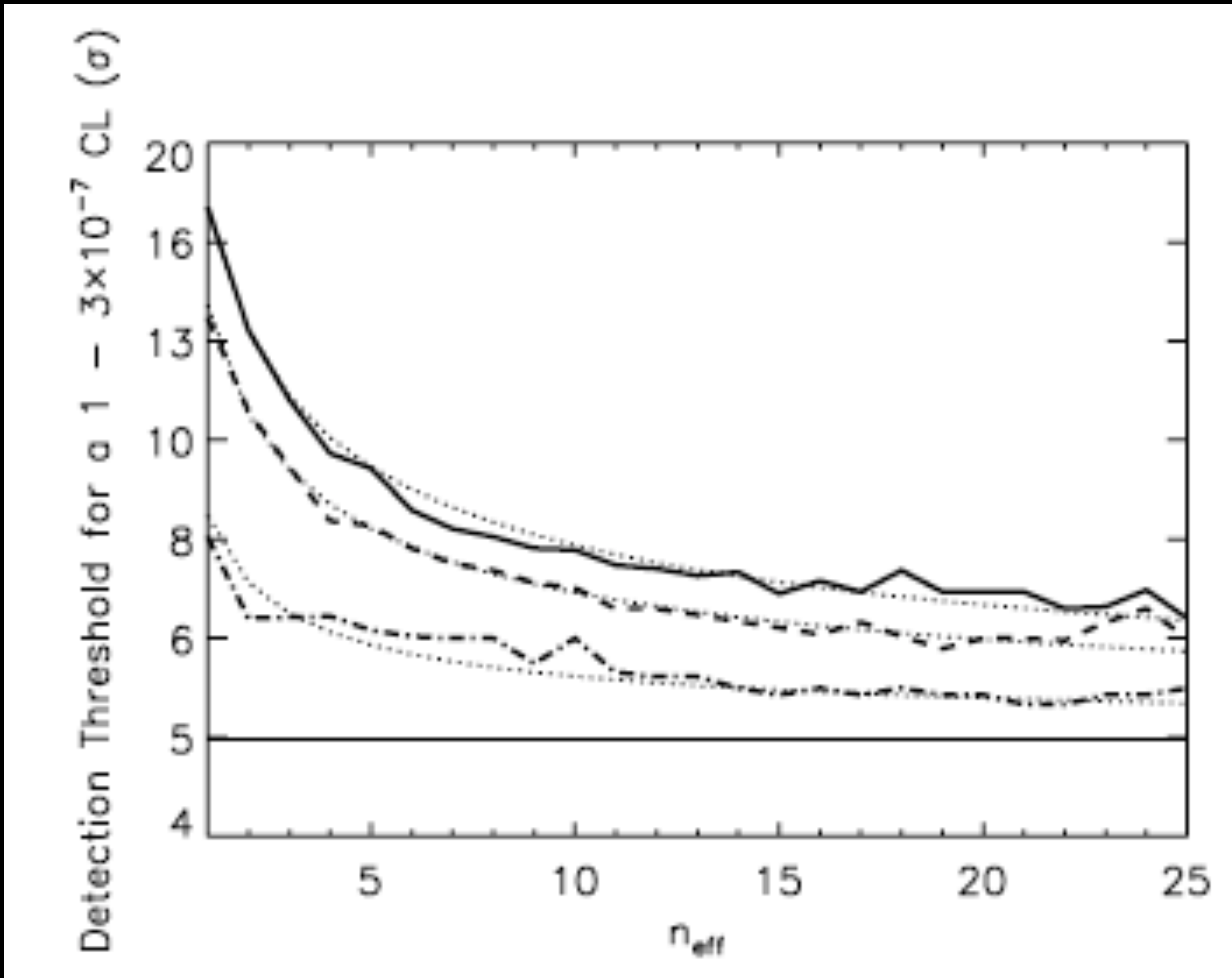
Gaussian | Rician | Rician



5 sigma | 5 sigma | 10 sigma

The Central Limit Theorem @ work with ADI



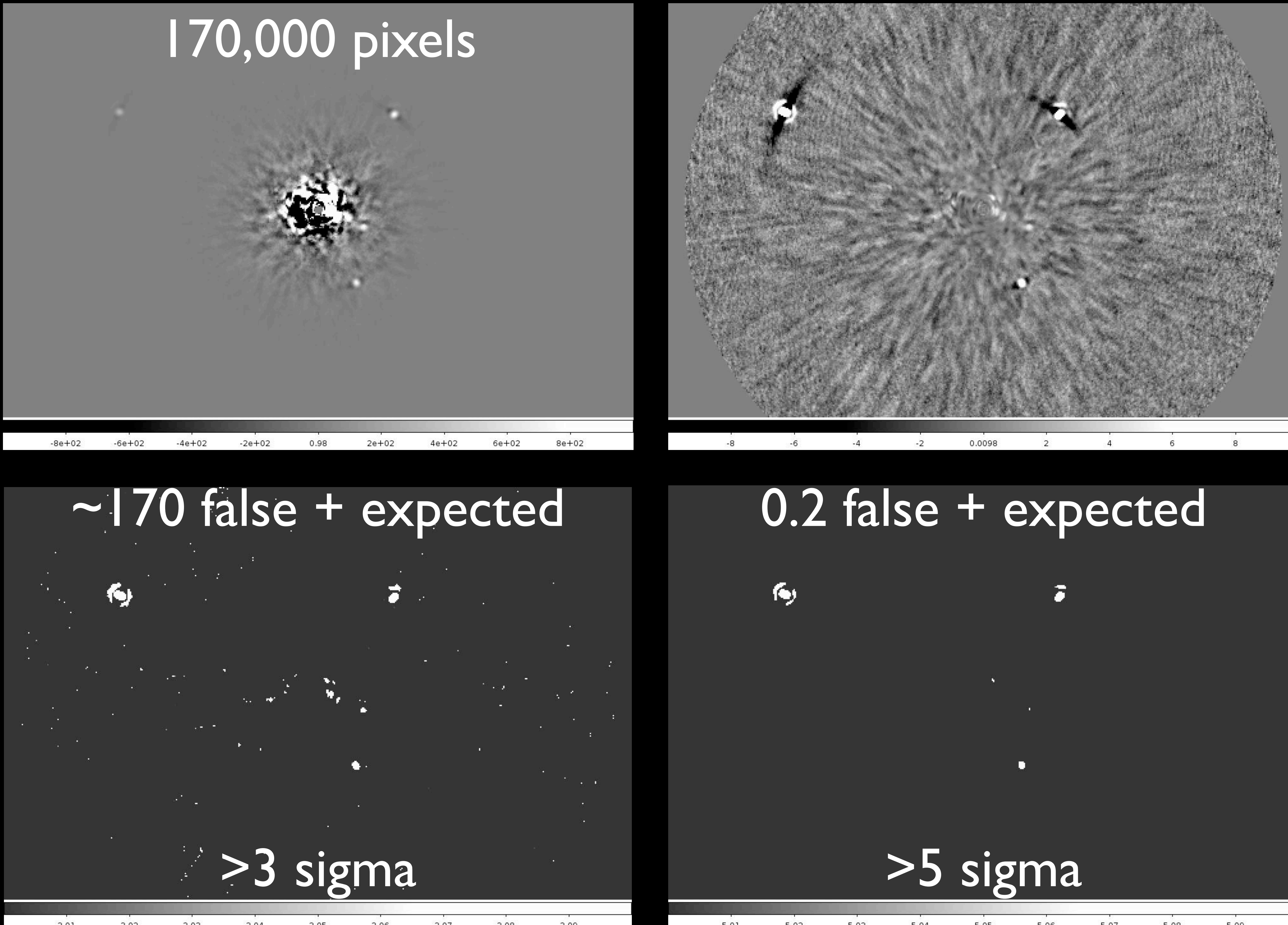


$$n_{\rm eff} = n \frac{t_{\rm exp}}{\tau_{\rm dcorr}},$$

$$d(n) = (d_1 - 5) n_{\rm eff}^{-0.63} + 5,$$

For many “lambda/D” rotation, can consider the noise to be ~Gaussian. May not be the case close to the star.

Candidate ID



GPI development

- Variable threshold as a function of separation (guess from initial image and statistical evolution model).
- Account for PSF expected shape (deconvolution?).
- In the end, track < threshold objects for “in case” situations (having some merit function to evaluate “quality” of detection and follow-up scientific value).

Astrometry & photometry with LOCI

1. "Easy" to make a detection.

2. Harder to optimize & trust the photometry and astrometry (especially if your object transits a few degrees from Zenith...).

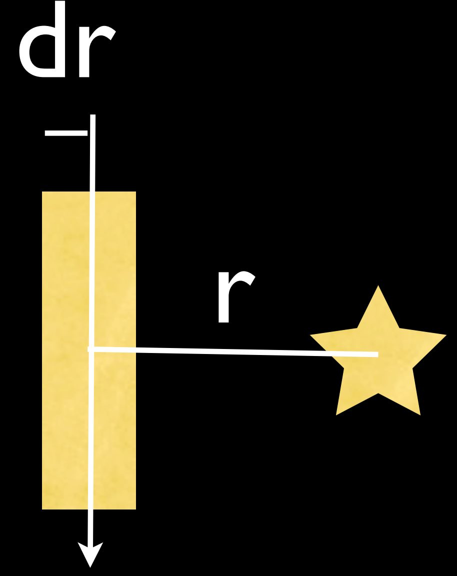
3. Quest for <10% photometry and mas astrometry is not yet a done deal...

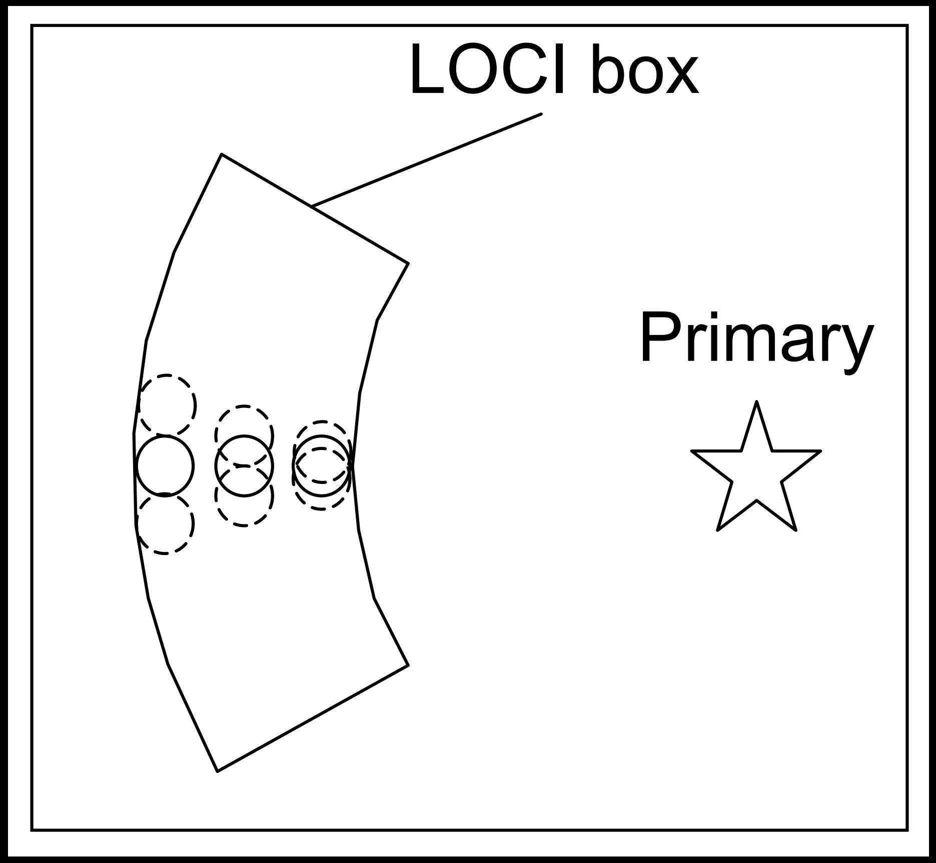
LOCI many biases

- Candidate misalignment: image-to-image, PSF smearing, distortion, rotation axis offset, North angle determination.
- LOCI non-uniform sensitivity (correlation matrix bias).
- LOCI box finite size.
- Non-symmetric dark shadows.

LOCI box finite size

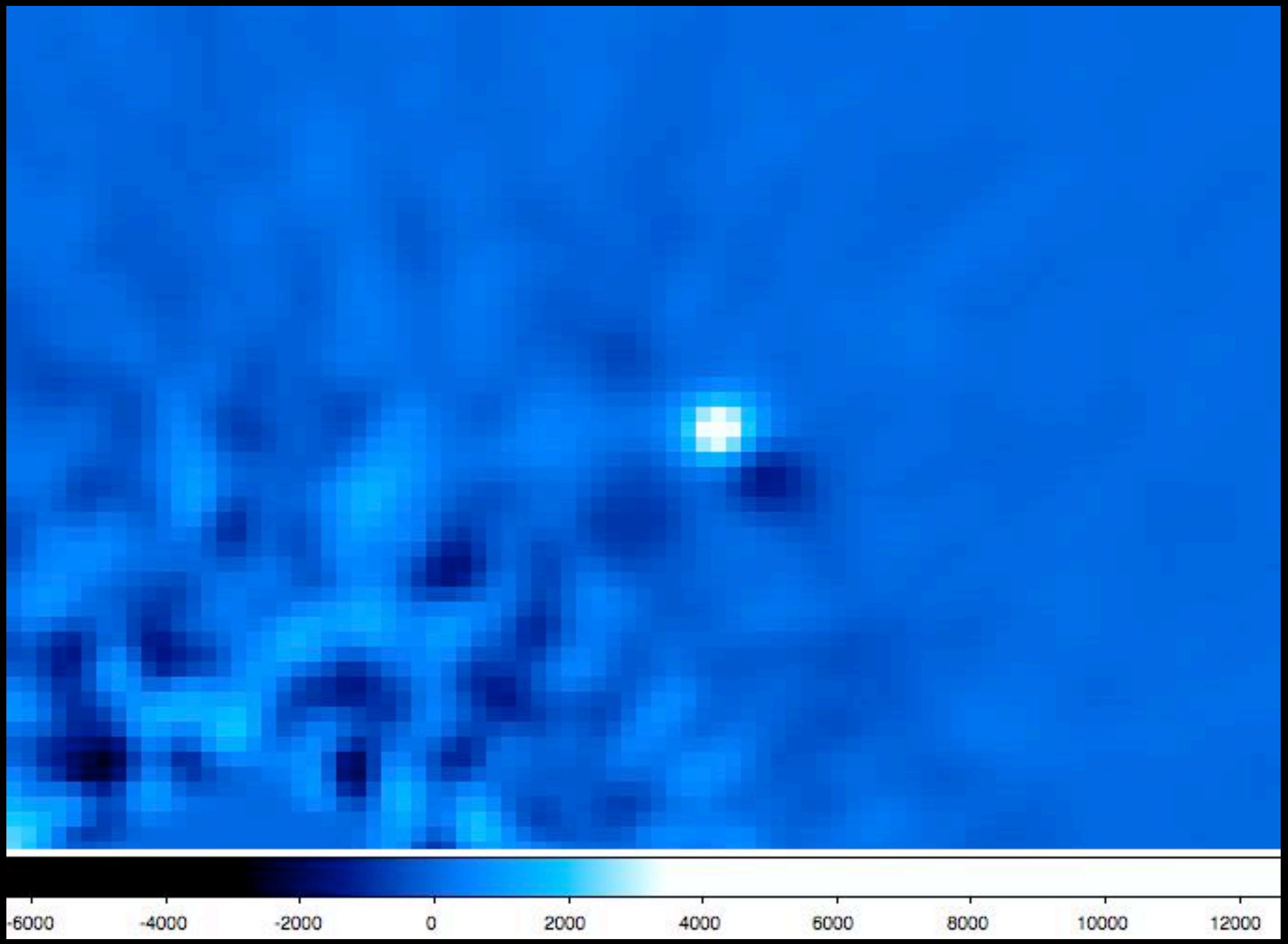
ADI "gap" variations in an optimization box.





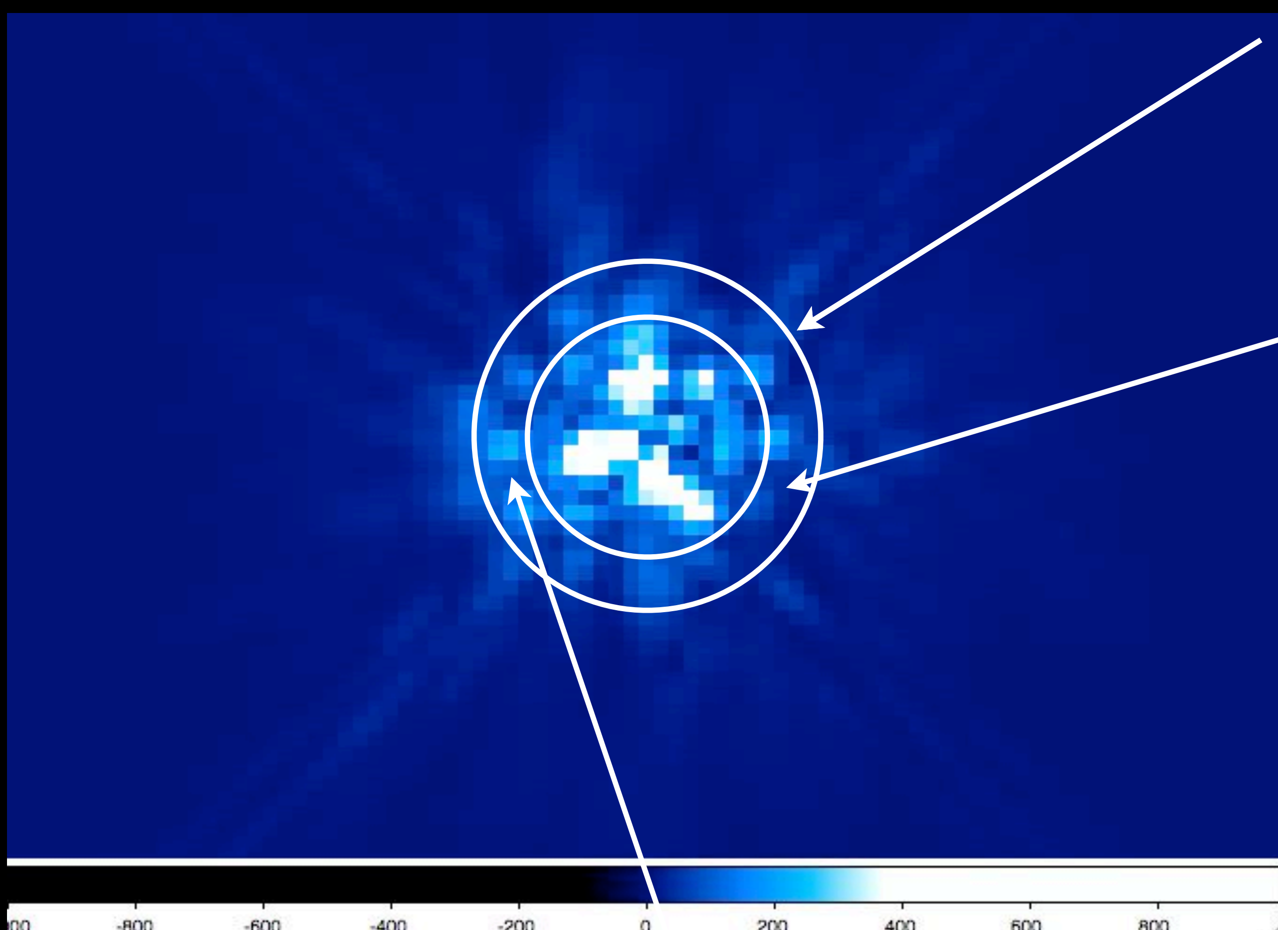
Non-Symmetric Dark Shadows

Occurs in near Zenith transits and with non-symmetric obs. sequences (more data before/after transit).



Non-Uniform Sensitivity

HR8799 HST data



LOCI optimization annulus

Dark

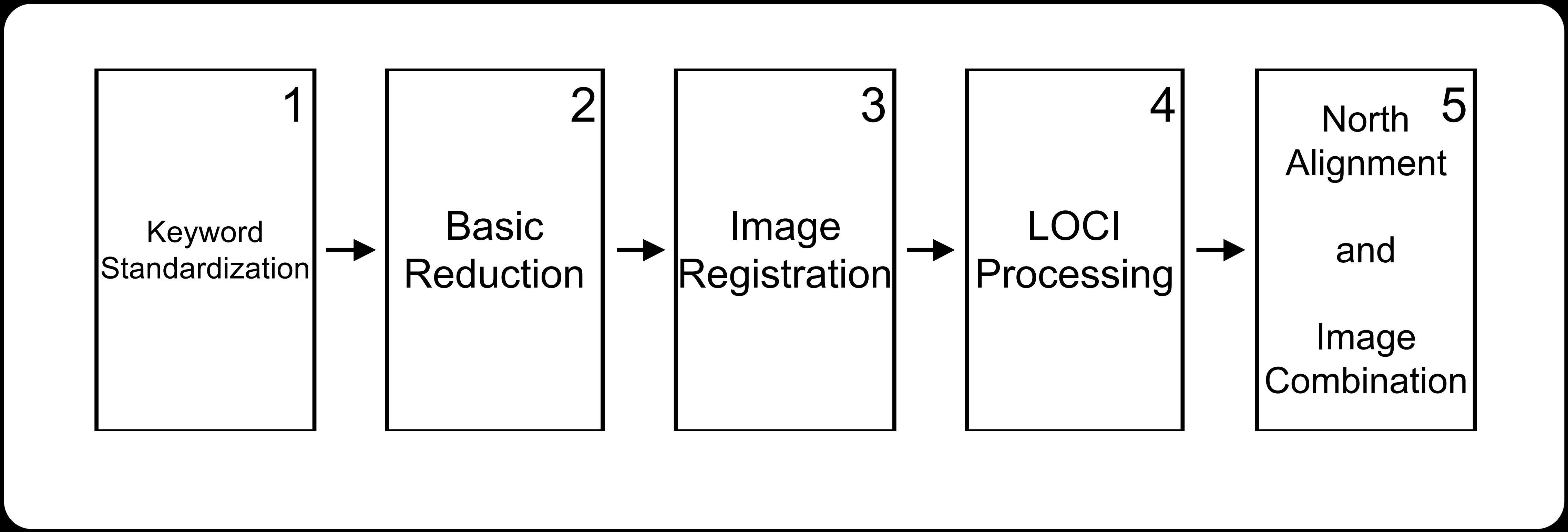
Bright

Regions that are bright have more weight in the LOCI correlation matrix, resulting in more candidate self-subtraction in those areas (lower throughput).

SOSIE Architecture

Marois et al. 2010

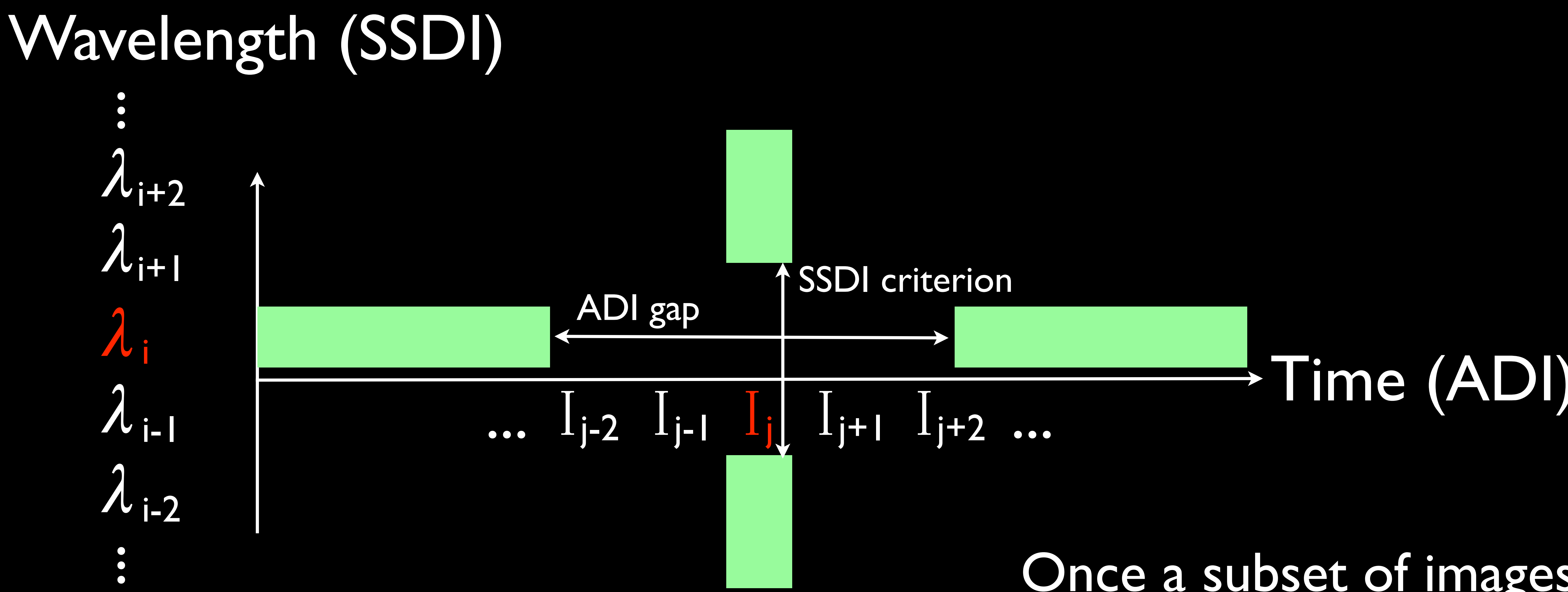
NIRI@GN
NICI@GS
NIRC2@Keck
CONICA@VLT
GPI@GN/S
NICMOS@HST

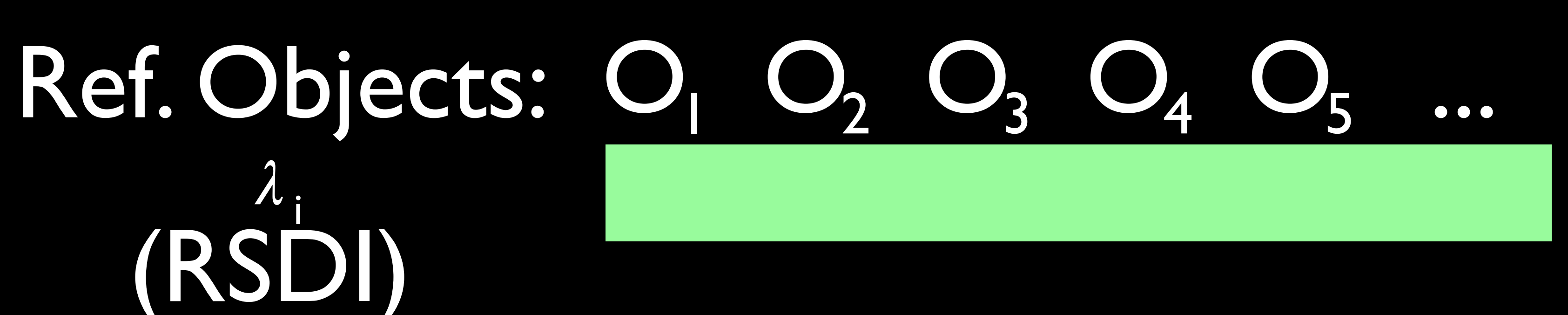


Mainly developed for the (almost finish) IDPS survey.
Future migration to GPI

SOSIE SSDI+ADI+RSDI

For each LOCI box





Once a subset of images has been selected, the best ones are kept for the final LOCI reduction (for speed & stability)

SOSIE

- For each instrument, all reductions are saved in an archive for future use as reference images (planets & disks).

- Multi-wavelengths (SSDI) using “spectrum templates”, followed by an iterative LOCI analysis to recover the real spectrum.

- SSDI, ADI and RSDI PSF subtraction are performed in a single step.

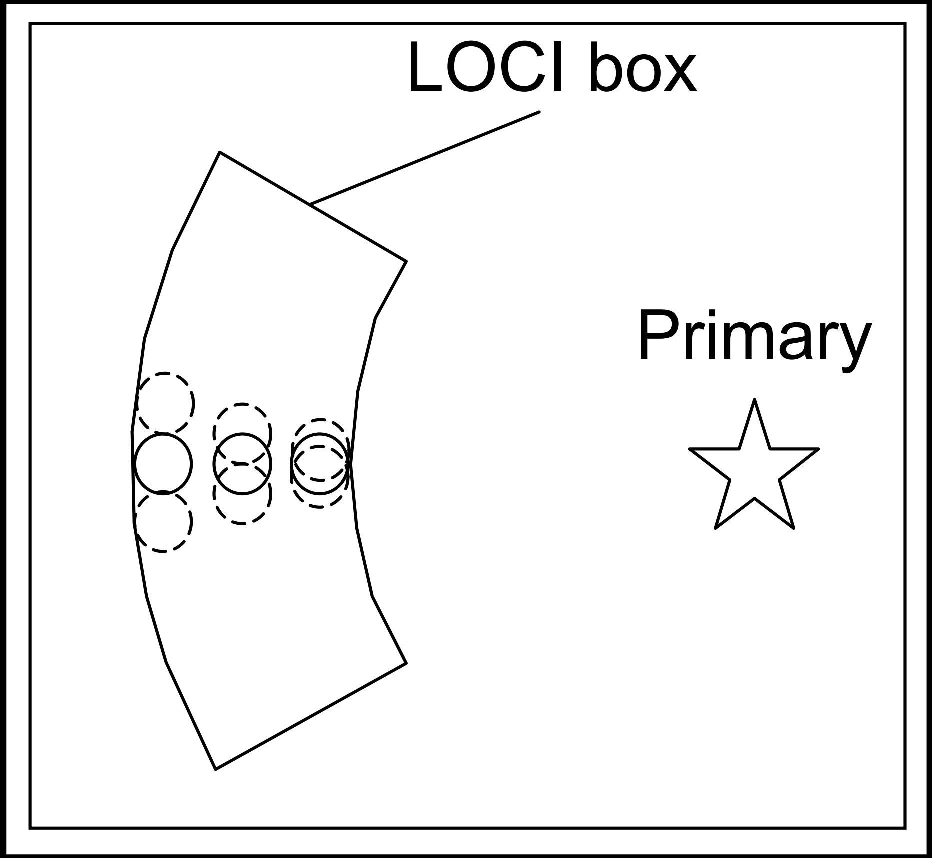
- A masking technique is used to avoid non-uniform sensitivity.

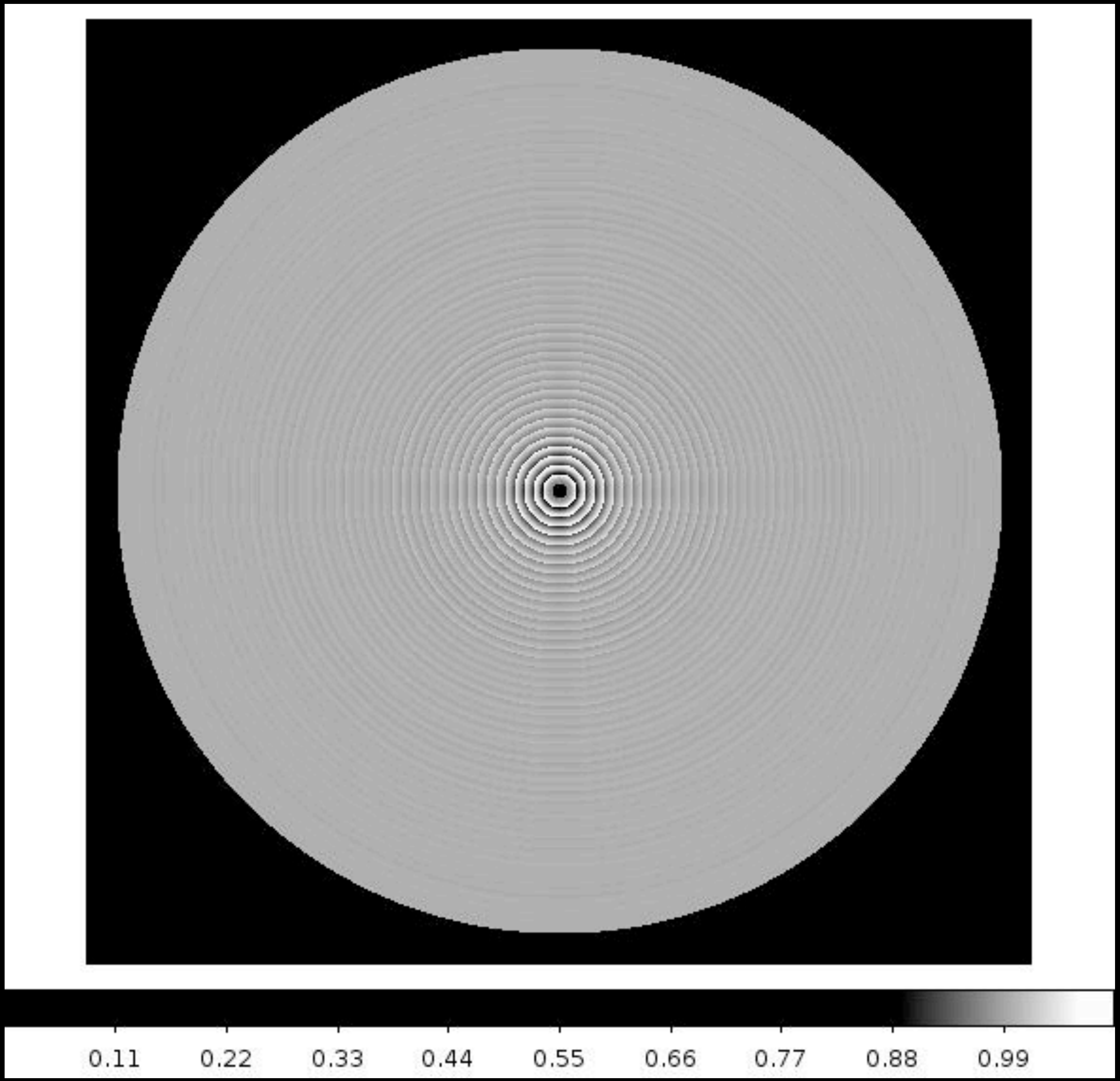
- Astrometry & photometry are derived using PSF fitting with LOCI ADI+SSDI+RSDI template PSFs (remove most of the biases discussed earlier).

- LOCI parameter optimization using Simulated Annealing.

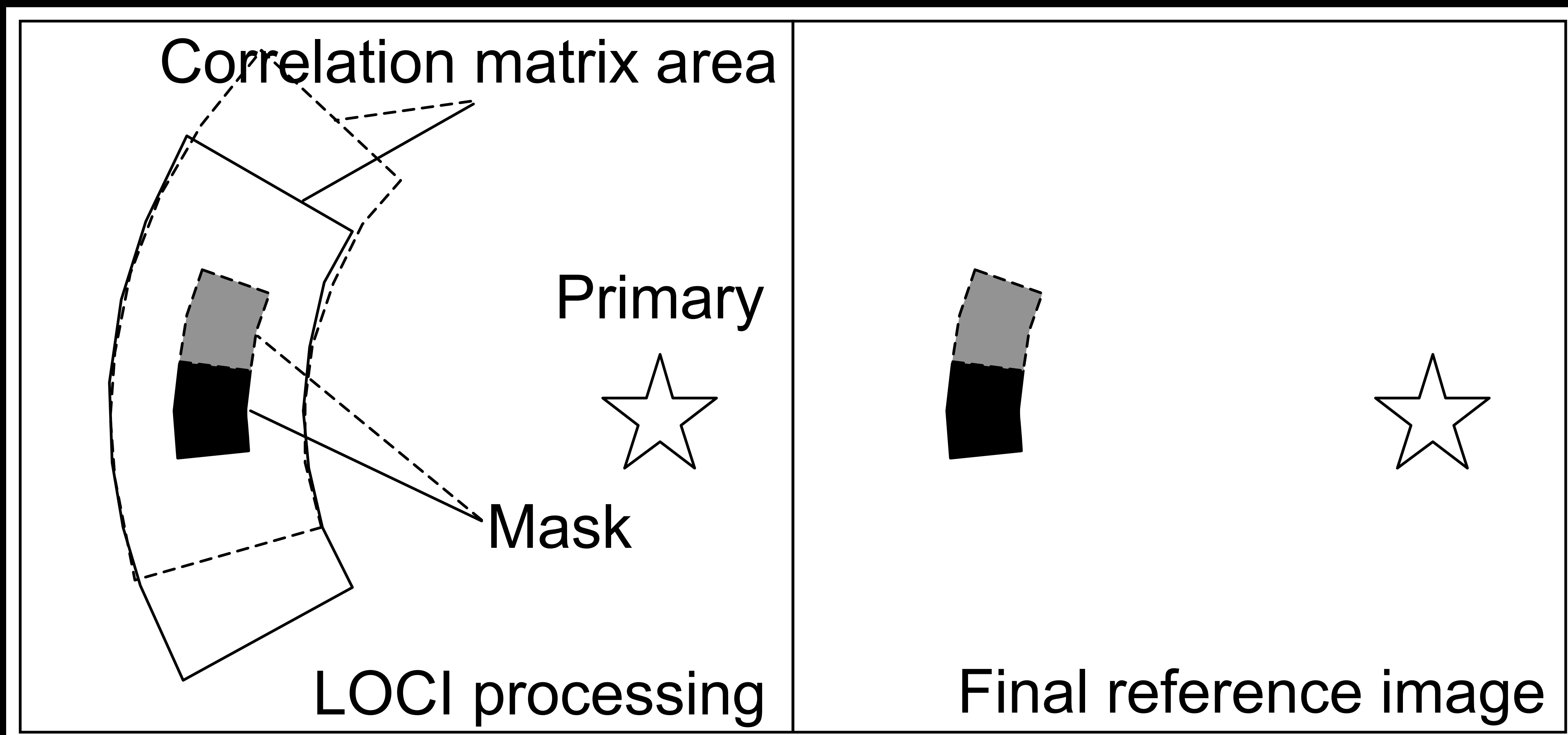
SOSIE "finite size" section bias correction

Run 3 template PSFs: at both edges and section middle to do an image "flat field"

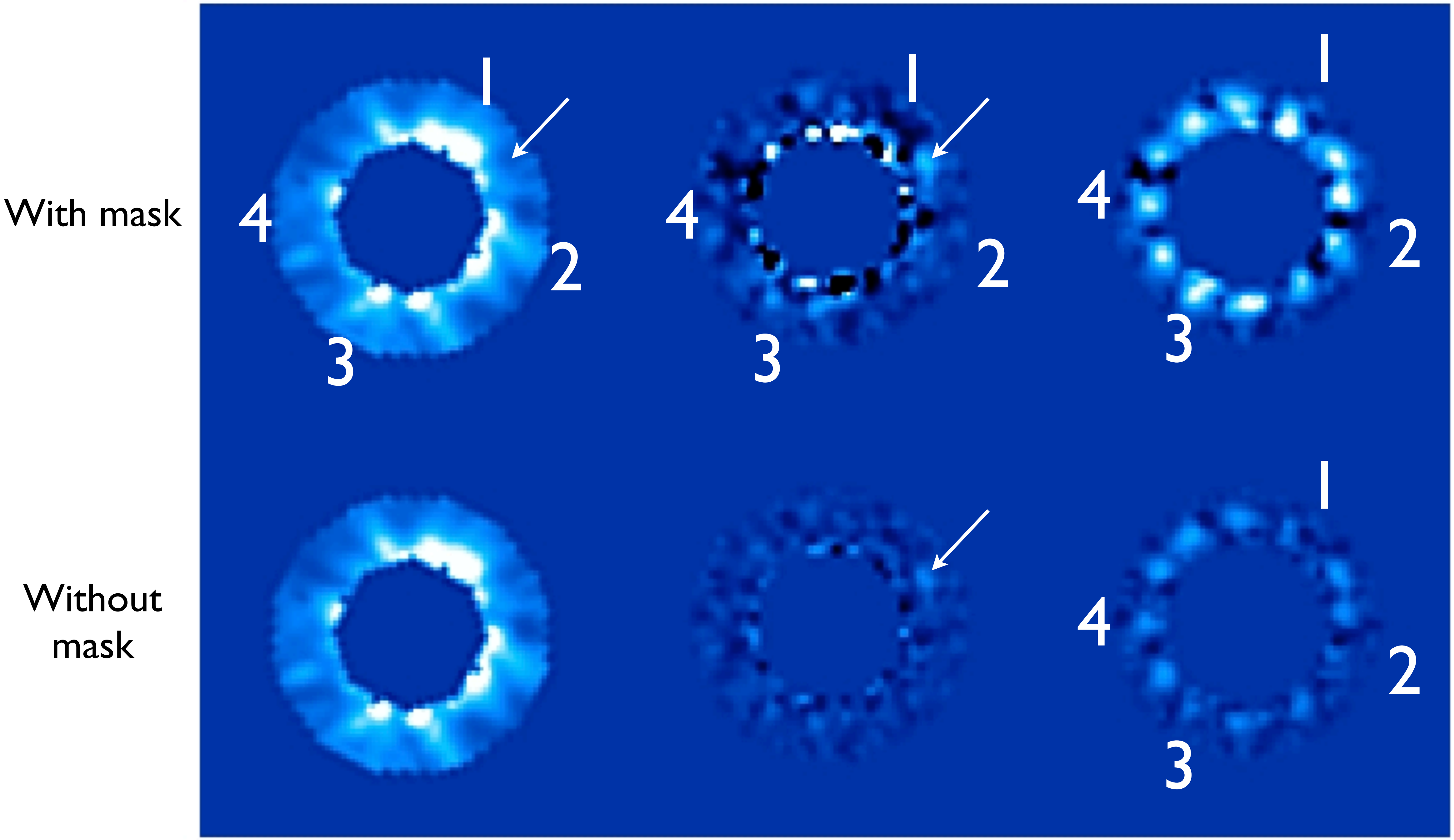




SOSIE Local Masking Technique



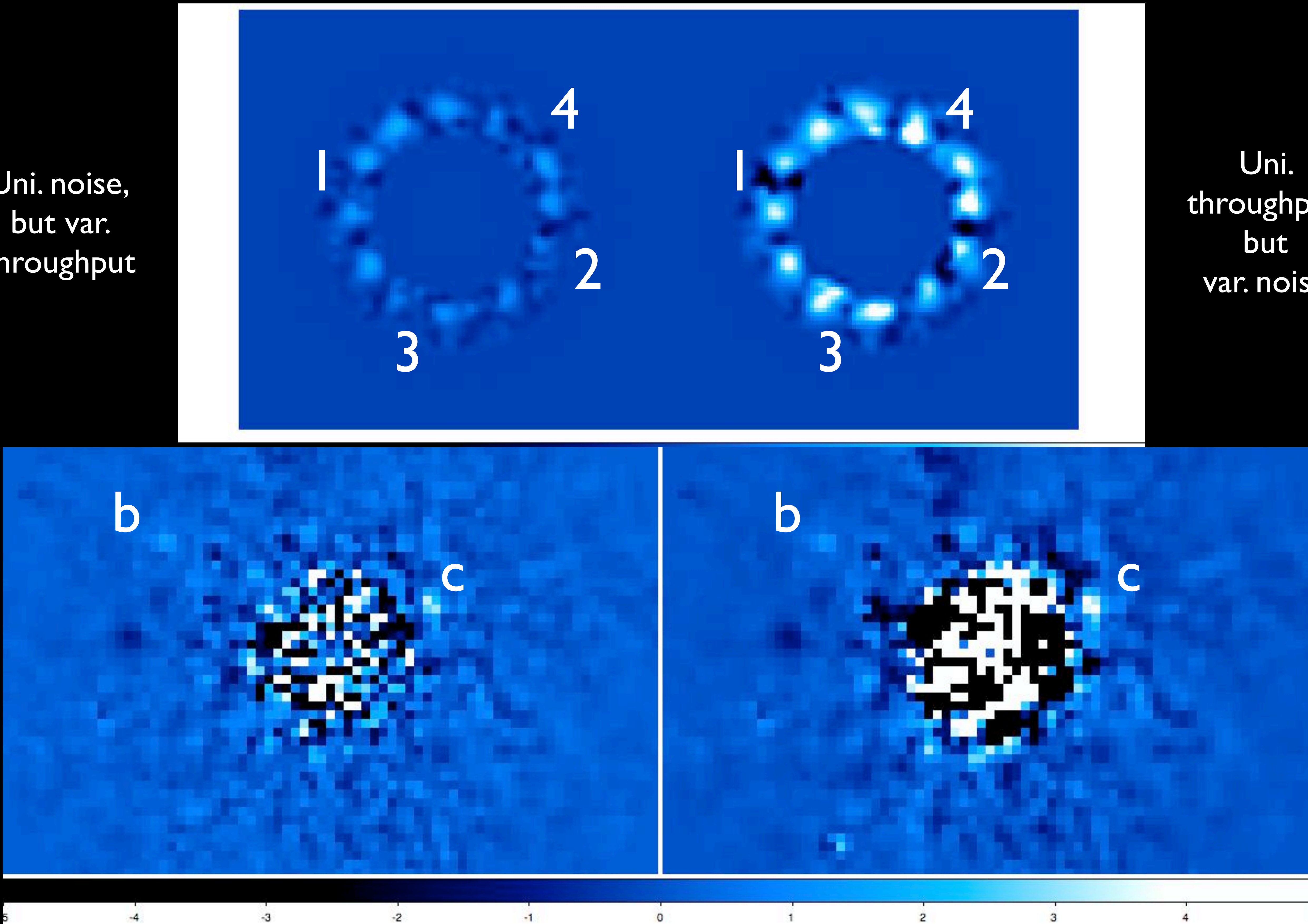
Candidate in optimization section = LOCI is trying to remove candidate.


With mask
Without mask
1
2
3
4

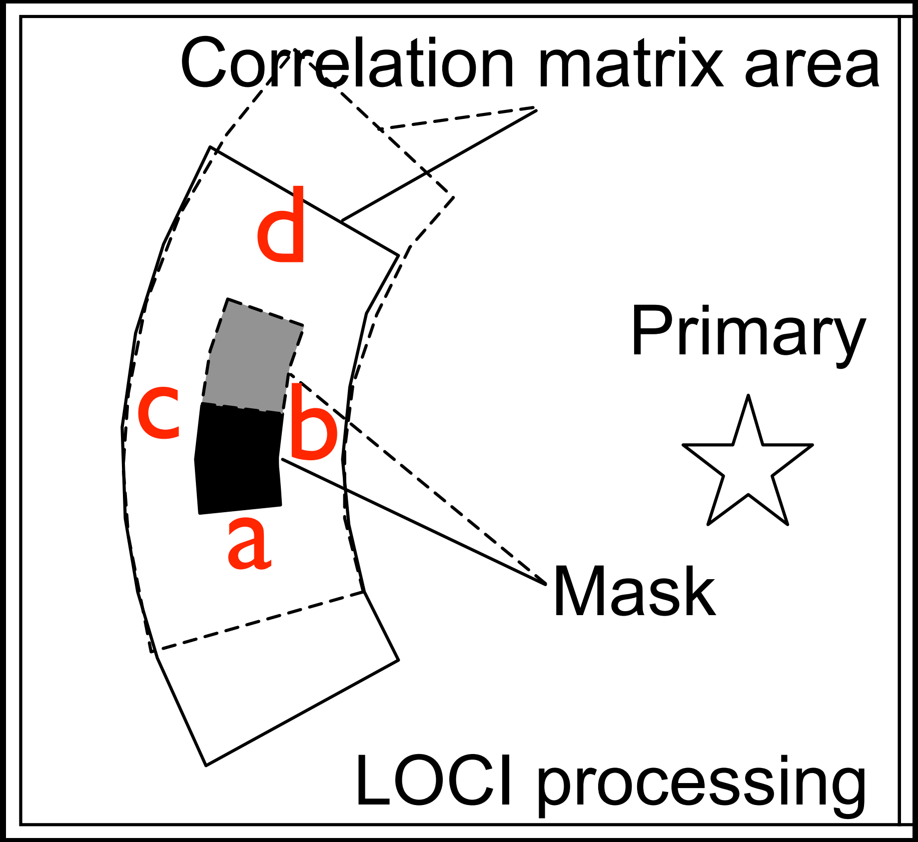
No mask　　With mask

Uni. noise, but var. throughput

Uni. throughput, but var. noise



Opt. SNR with SA Param. Optimization

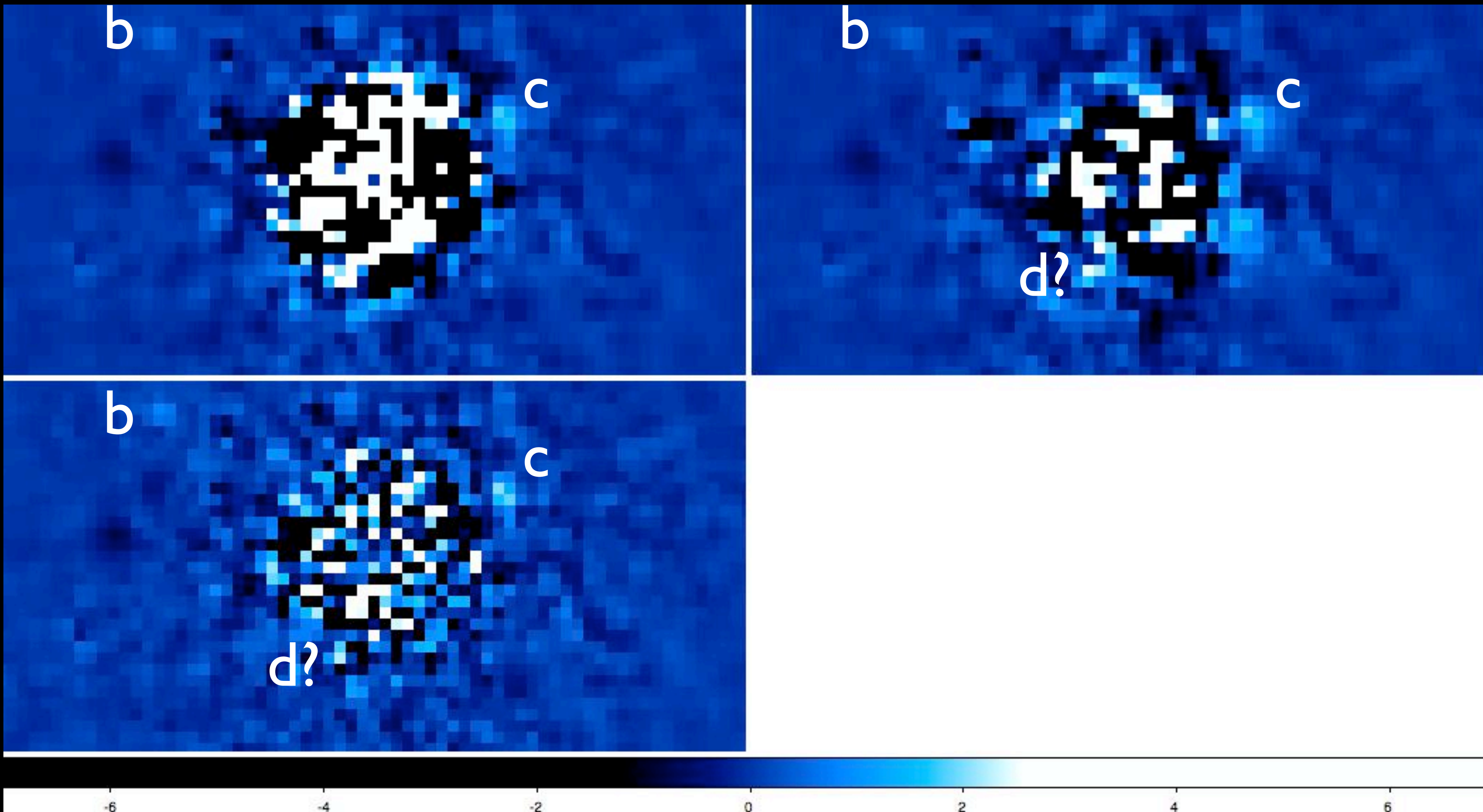


a: Central mask size
b: Cor. matrix inner radius
c: Cor. matrix outer radius
d: Cor. matrix azimuthal radius

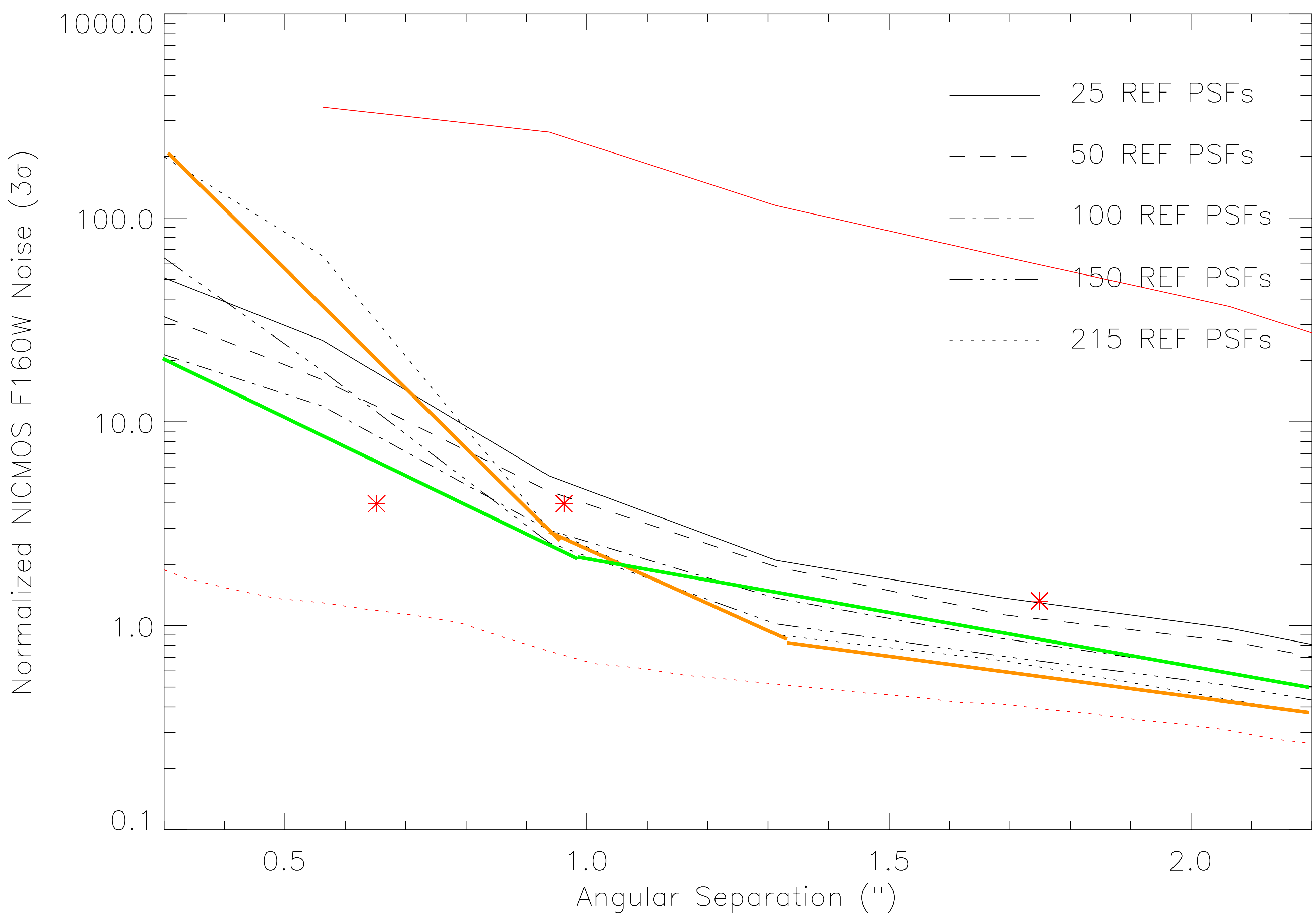
e: ADI motion gap
f: SSDI flux subtraction criterion
g: Nb images to use as ref?

With mask, all ref. images

With mask, not all ref. images

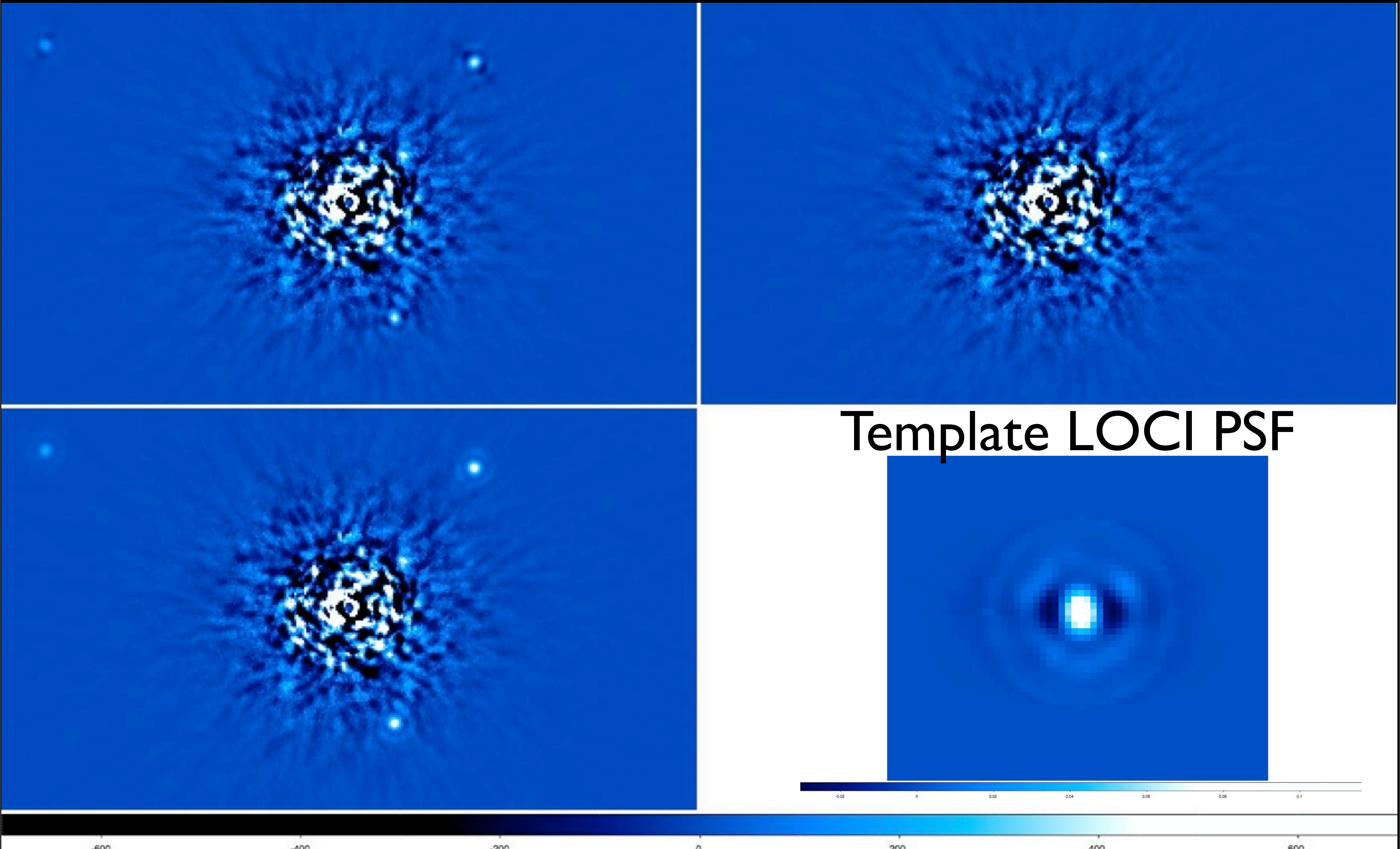


No mask, all ref. images



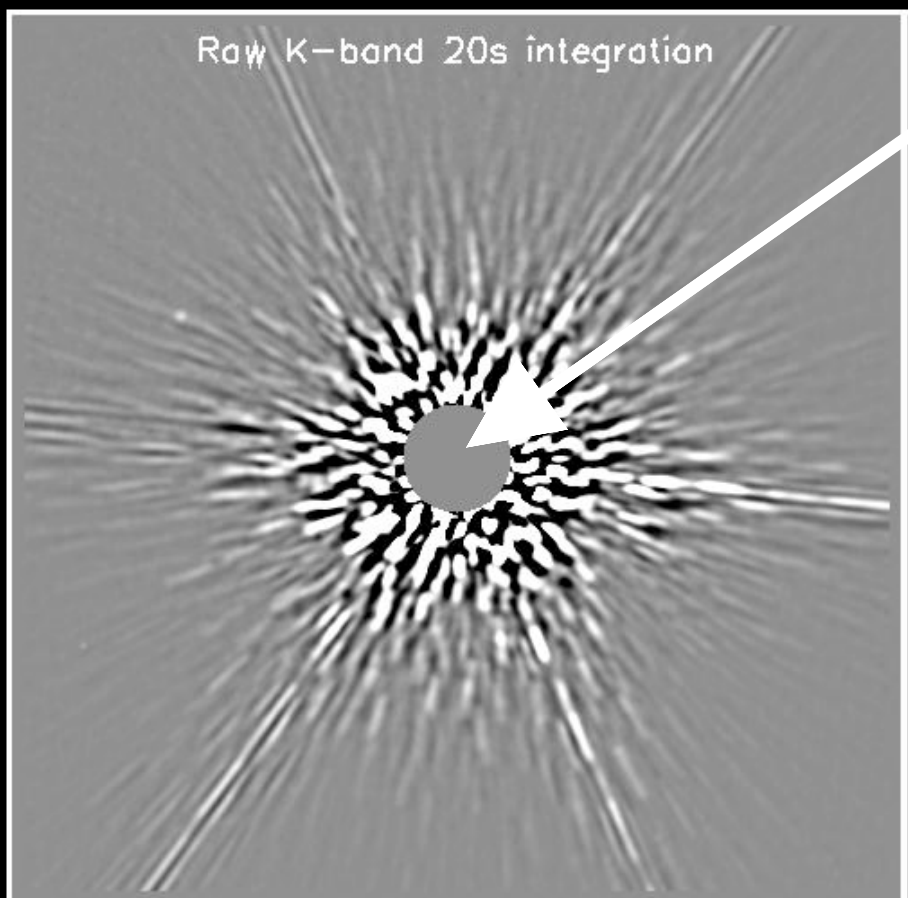
1000.0
100.0
10.0
1.0
0.1
0.5
1.0
1.5
2.0
Normalized NICMOS F160W Noise (3σ)
Angular Separation ('')
25 REF PSFs
50 REF PSFs
100 REF PSFs
150 REF PSFs
215 REF PSFs

SOSIE PSF Fitting



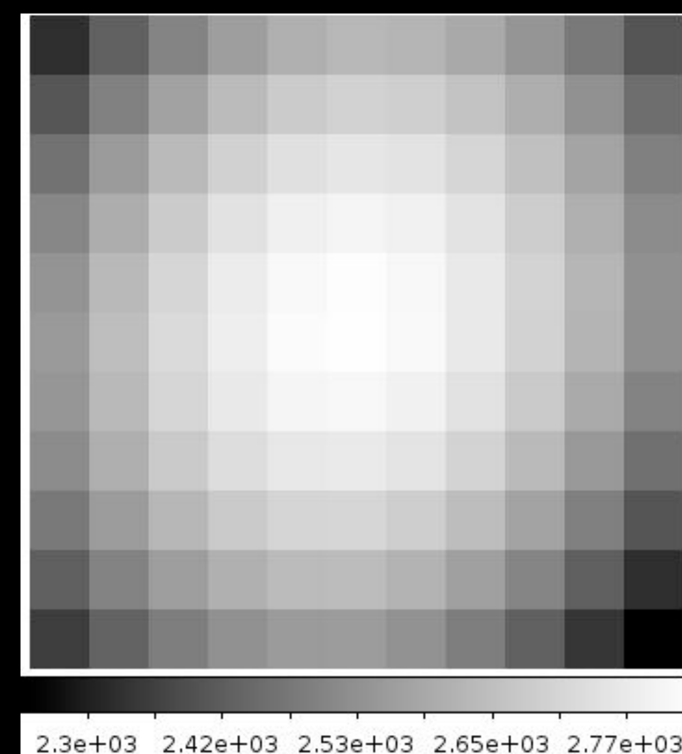
But where is the star?

Saturated or under coronagraph?

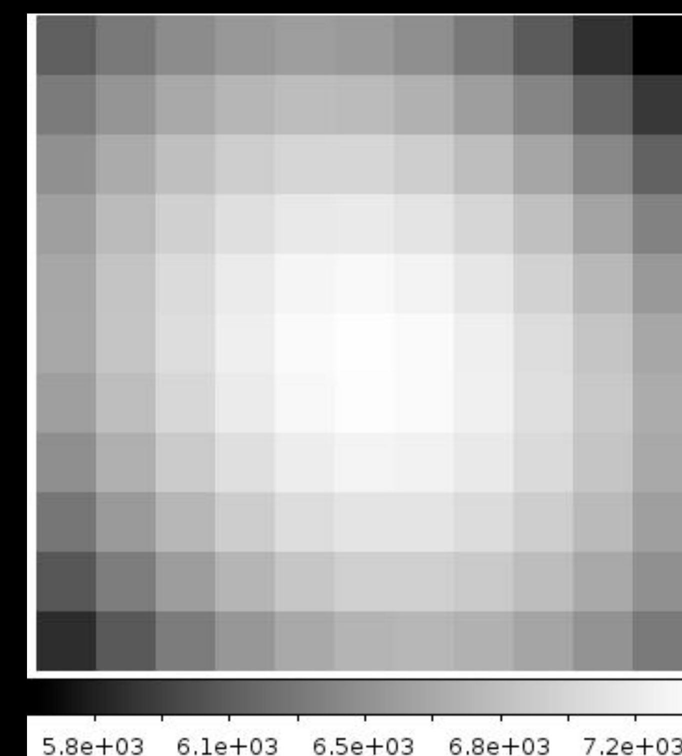


“Rotation axis finder”

HR 8799b



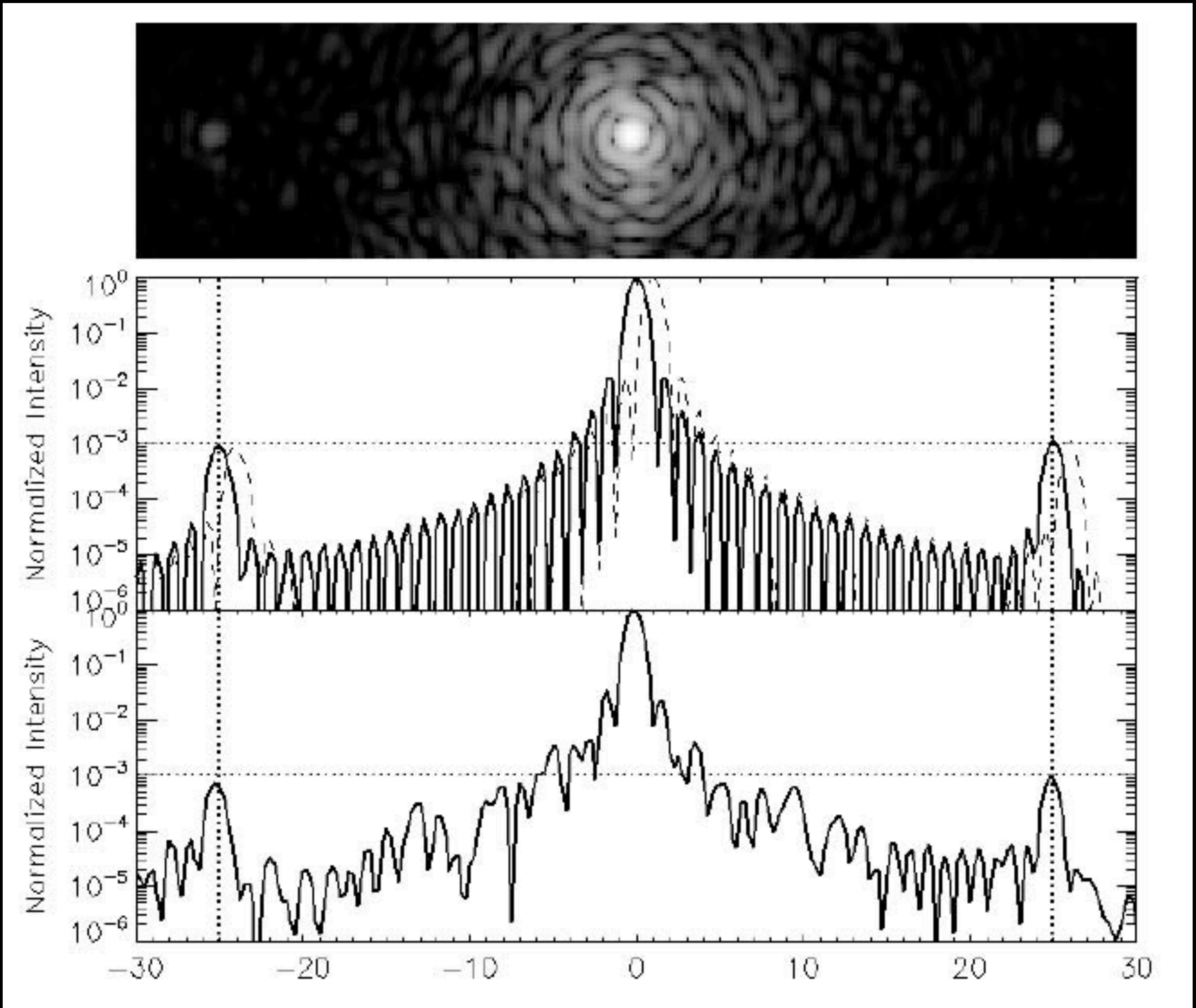
HR 8799c



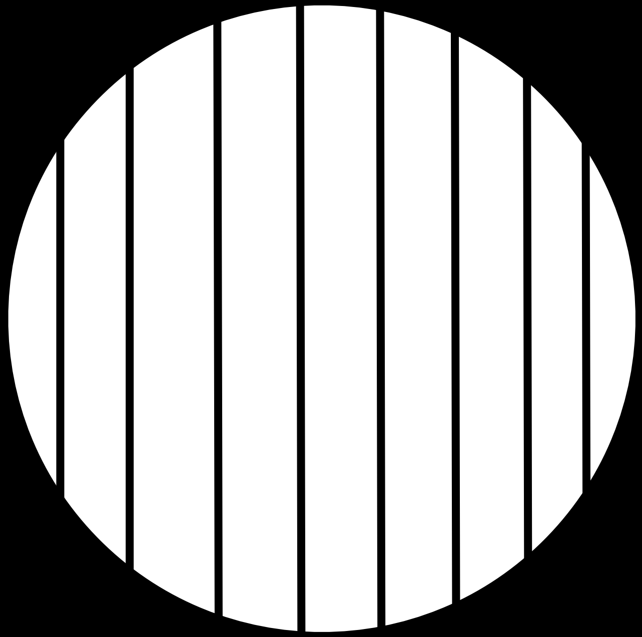
SNR as a function of axis position (2 mas/pixel)

Works for “wide” planets and with significant FOV rotation

GPI solution



Pupil grating

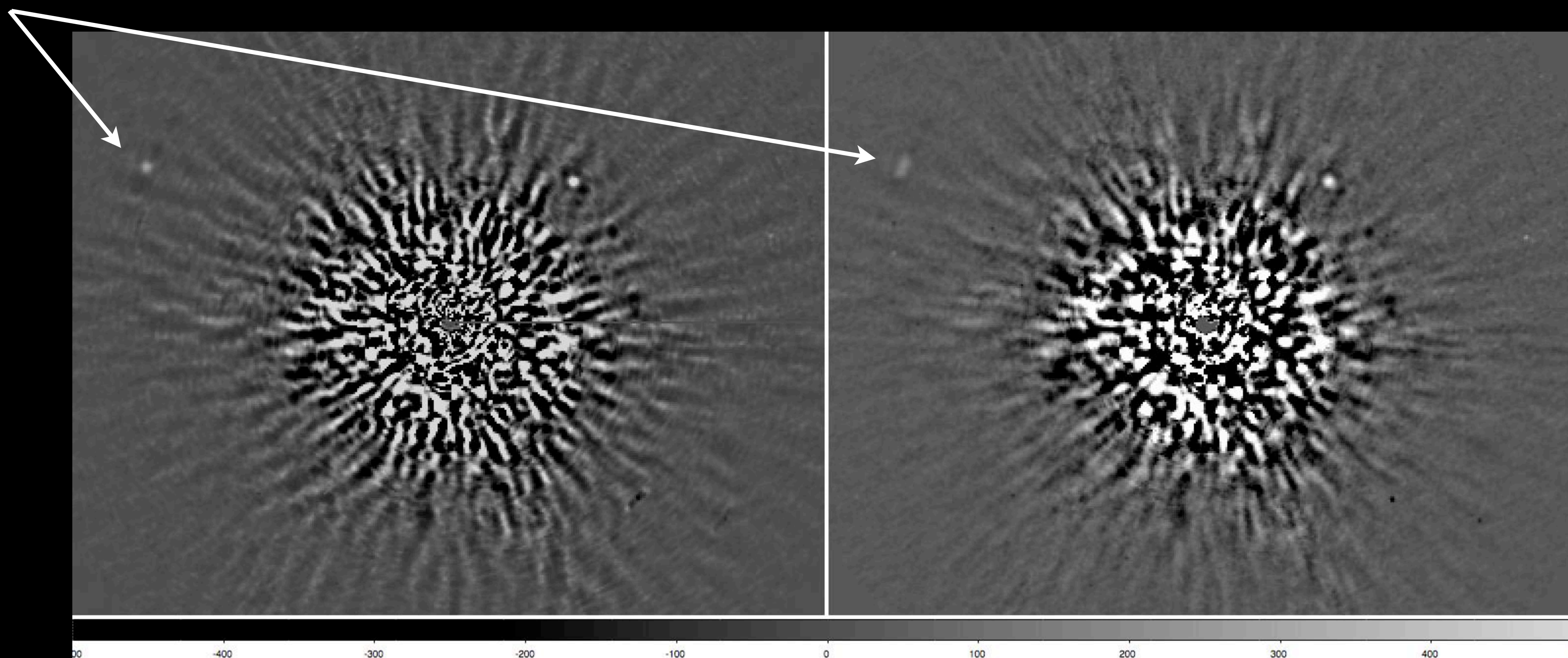


Offaxis “ghosts”
for rel. photometry
& astrometry

Marois et al. 2006

Other Upgrades

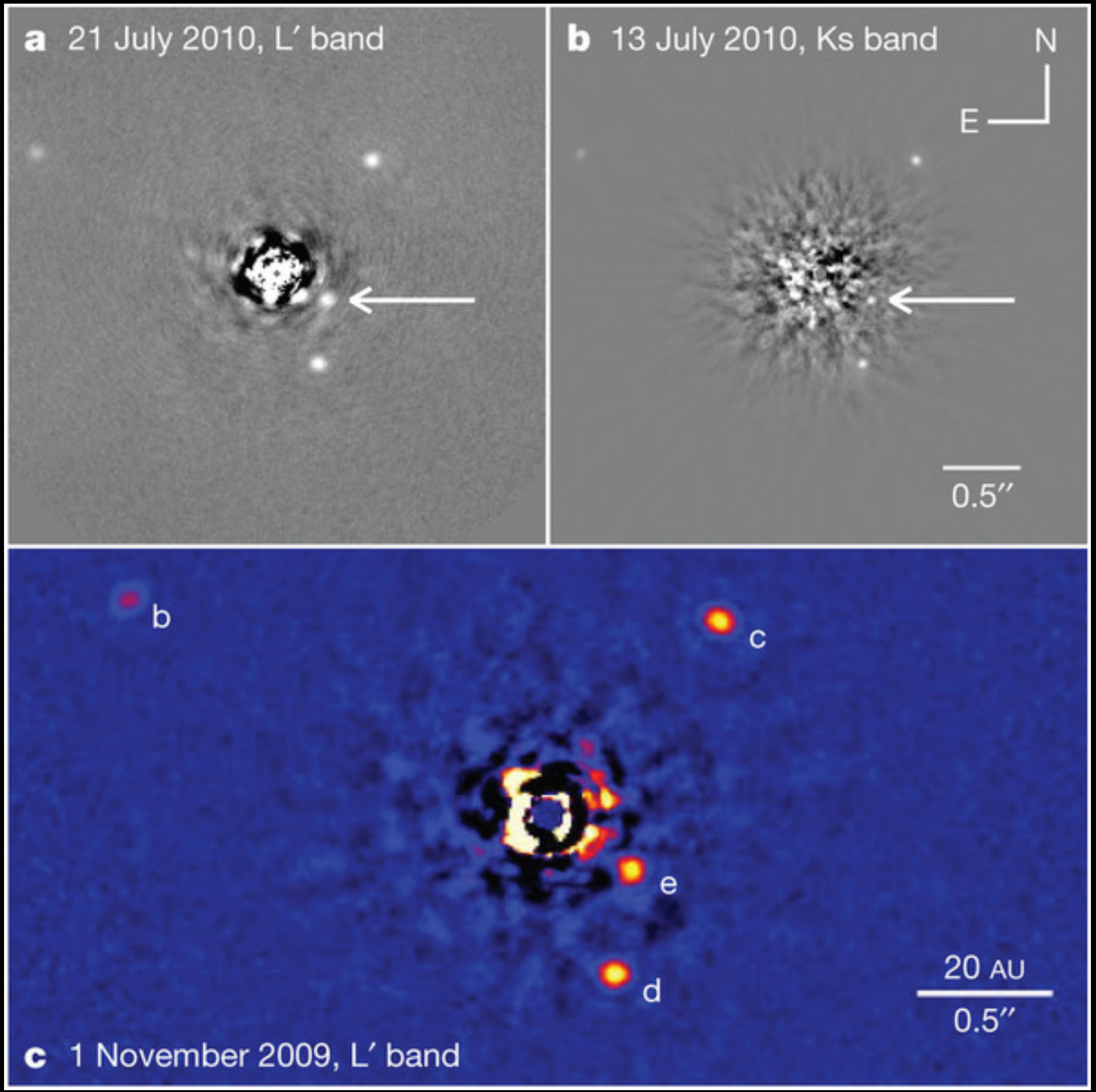
- PSF smearing deconvolution (marginal SNR gain).



- Final image combination: Weighted mean instead of median (similar - sometime worse).
- SVD cutoff for matrix invert (similar perf)
- LOCI MAX SNR instead of min noise (TBD).
- Median-combined - something better (TBD)?

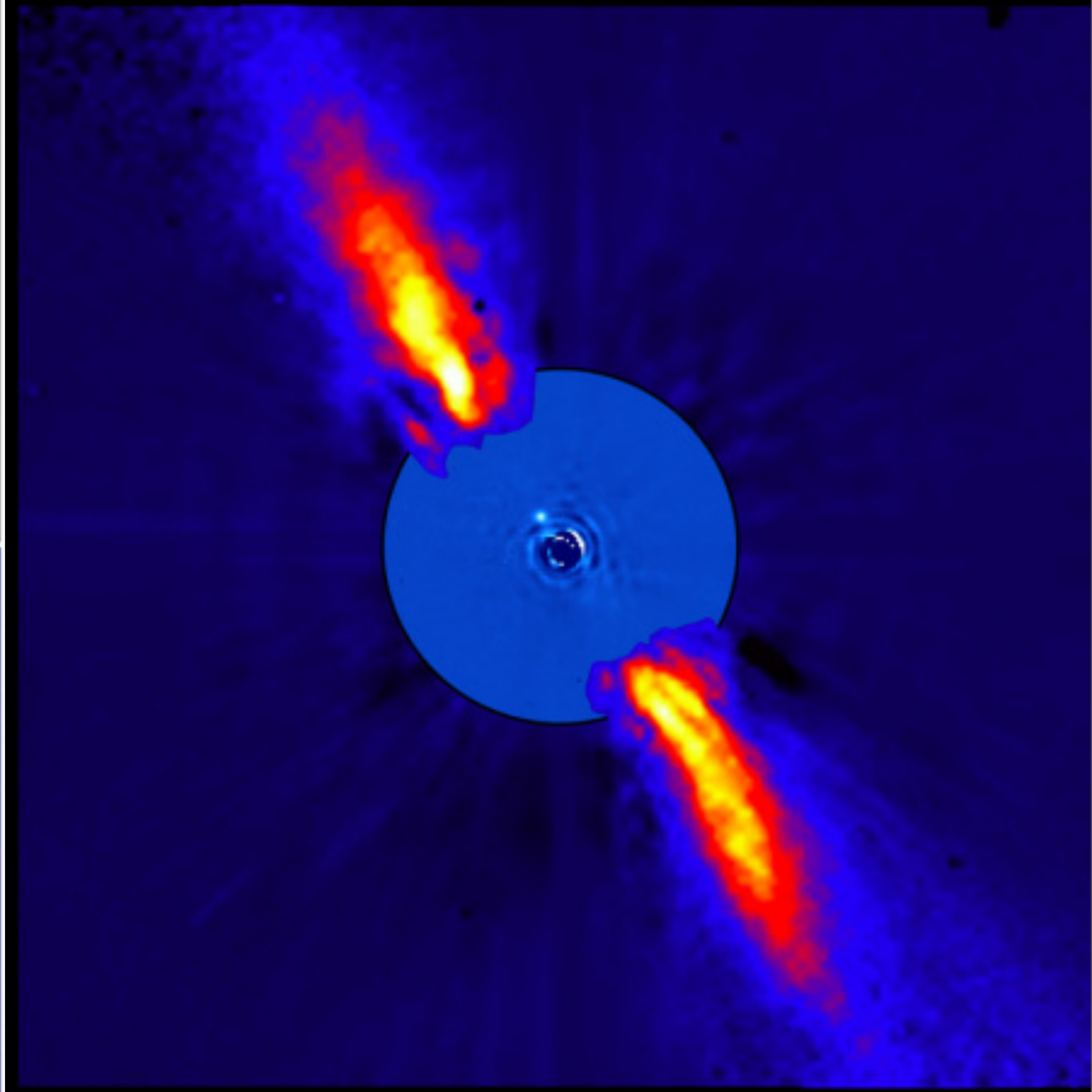
LOCI many applications
ExoPlanet Imaging

HR 8799 bcde



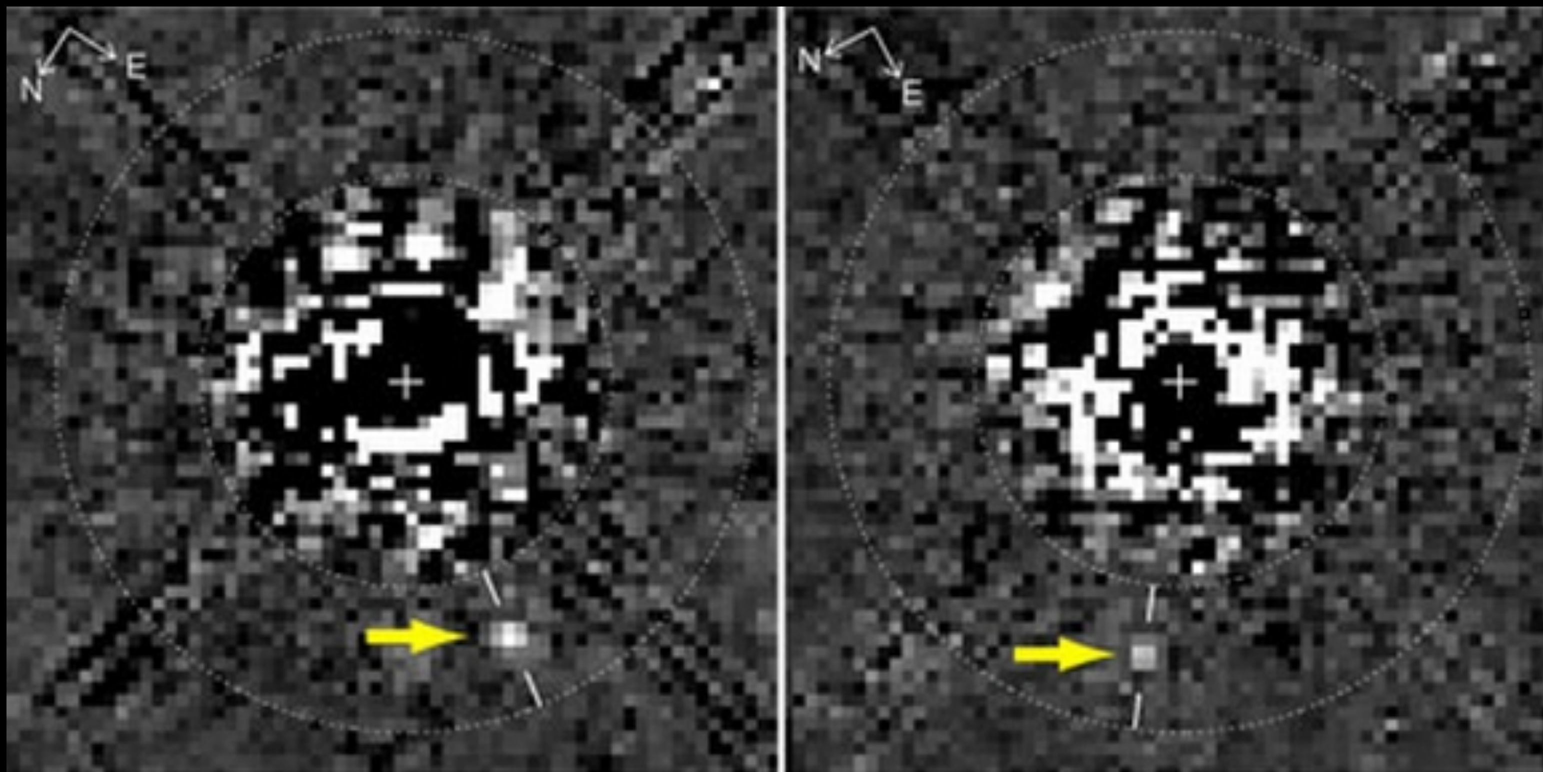
Marois et al. 2008, 2010

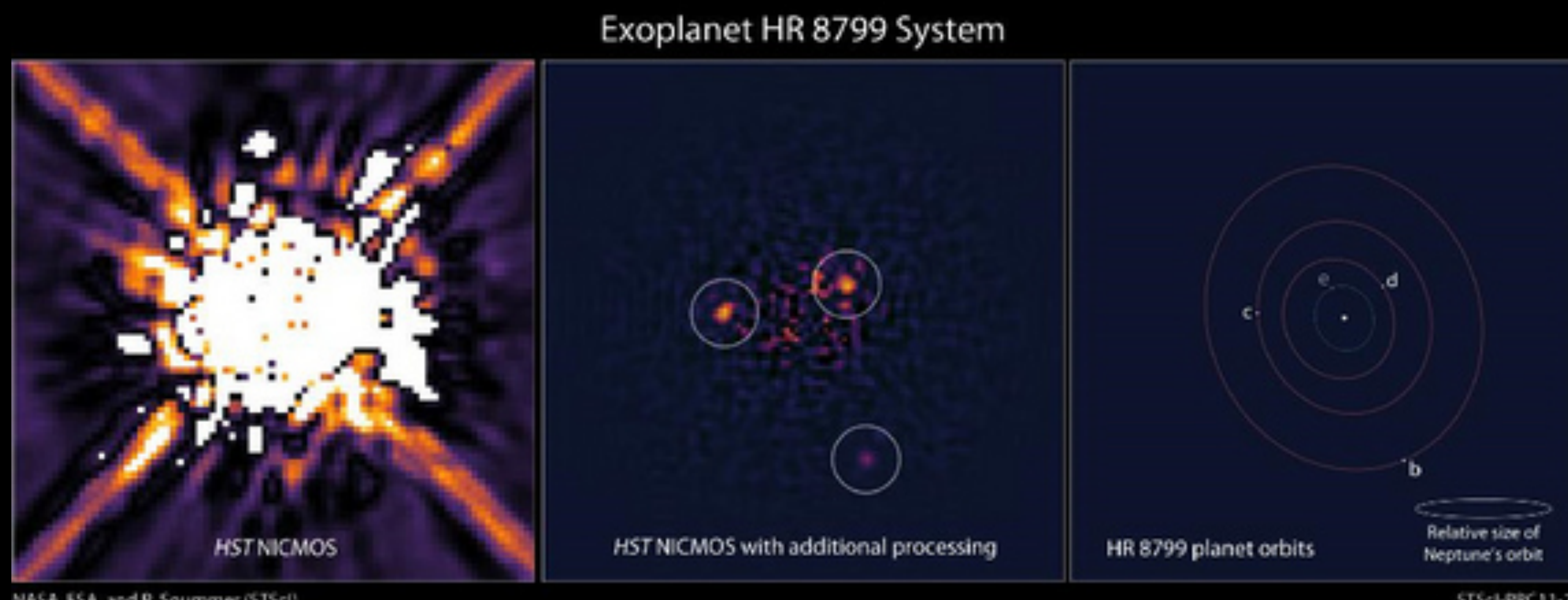
Beta Pic b



Lagrange et al. 2009

HST archive

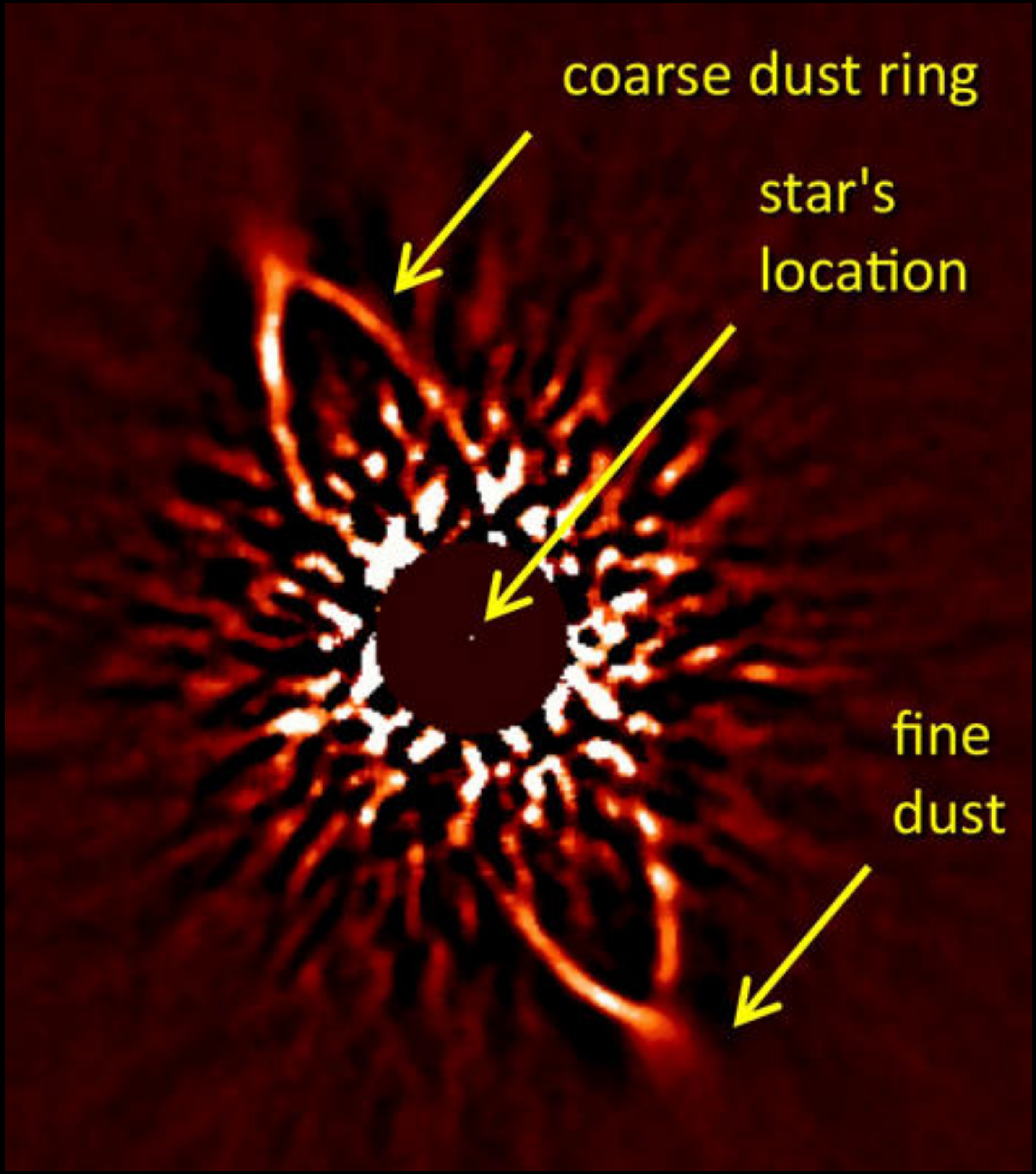




Lafreniere et al. 2009

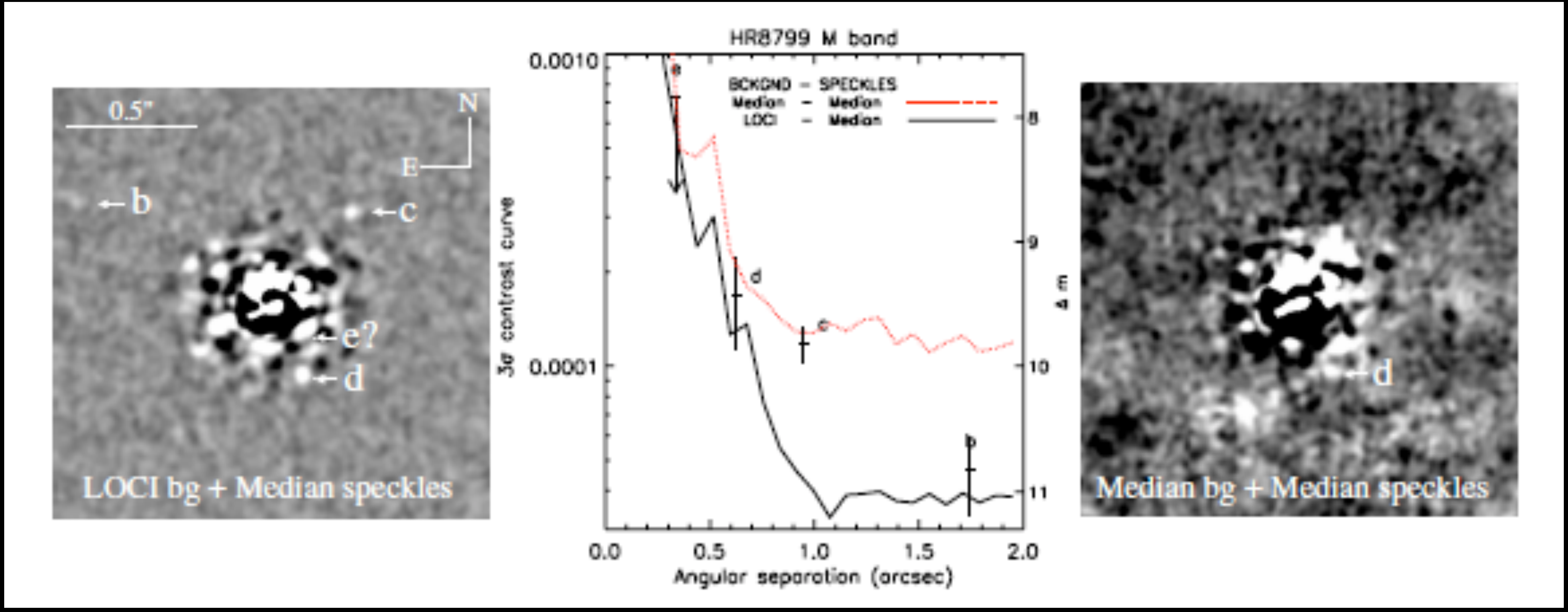
Soummer et al. 2011

Disk imaging



Thalmann et al. 2012

L-/M-band LOCI sky subtraction



Marois et al. 2010
Galicher et al. 2011

Conclusions

- ADI/SSDI has evolved since their original publication. ADI, in combination with LOCI, has achieved 100x gain in contrast.

- LOCI, very powerful tool to remove unwanted quasi-static noise and to keep the signal that we are searching for. Once the noise has been removed, images are combined and candidates are identified by analyzing the residual (mostly Gaussian) noise.

- Once a detection has been made, getting very accurate photometry & astrometry with a non-linear FOV rotation (PSF smearing & various data reduction/LOCI biases) is a challenge.

- New algorithm (SOSIE) uses PSF templates to iterate the position & flux of the candidates (trying to subtract out the candidates before LOCI processing).

- ADI & LOCI, currently the most successful technique so far. LOCI can be used in other applications (ie sky background subtraction).

- Future work: more robust planet ID/better image combination algo, LOCI maximizing SNR instead of minimizing the noise. SSDI implementation.