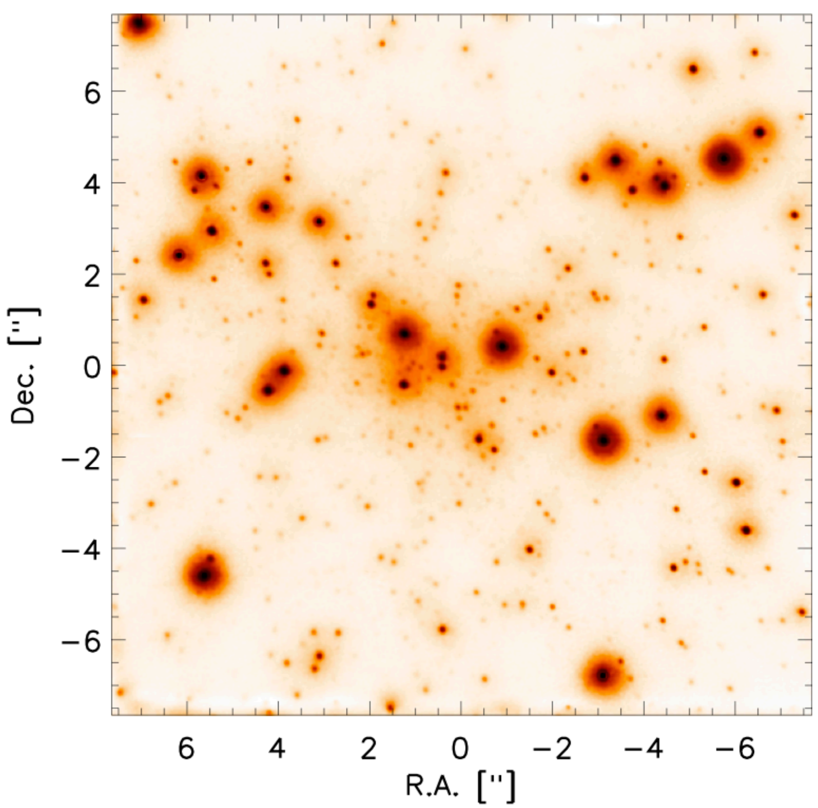
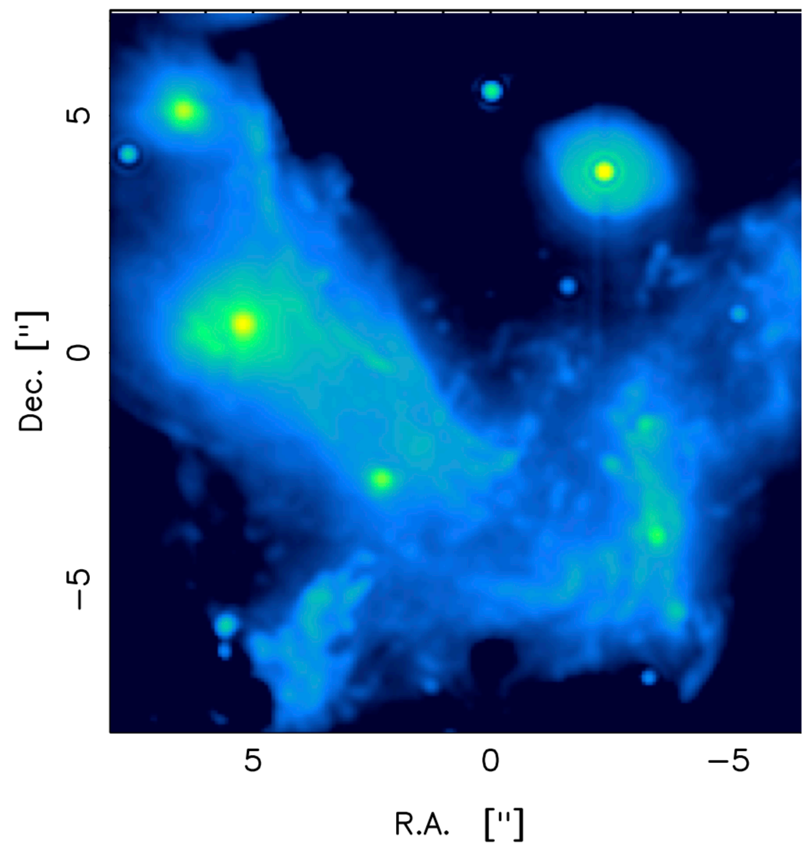
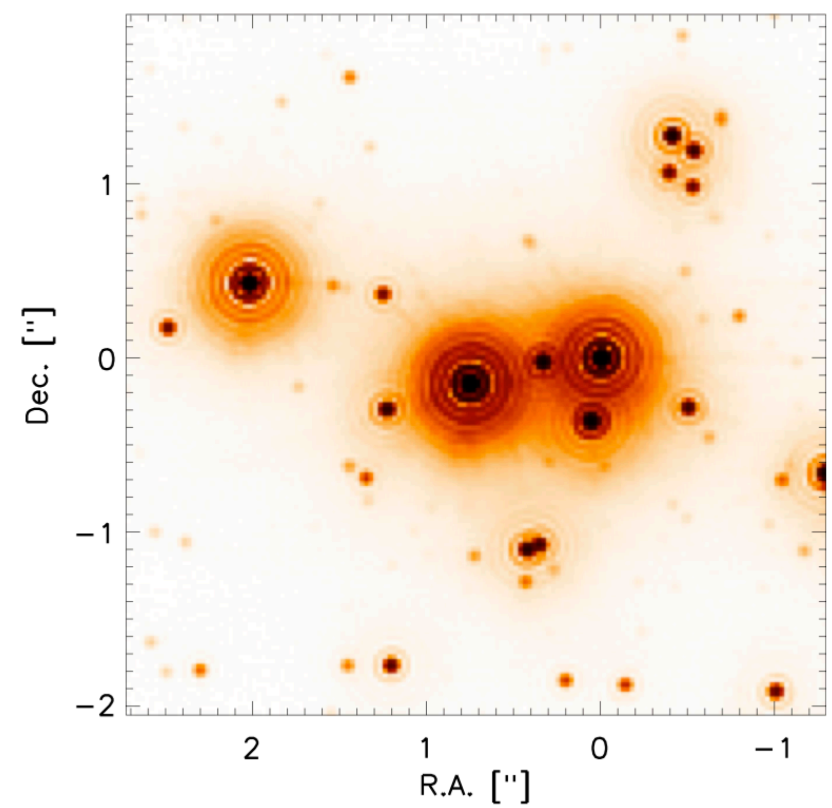
Holographic Imaging: Sharp Images for Everybody







Rainer Schödel (IAA-CSIC)

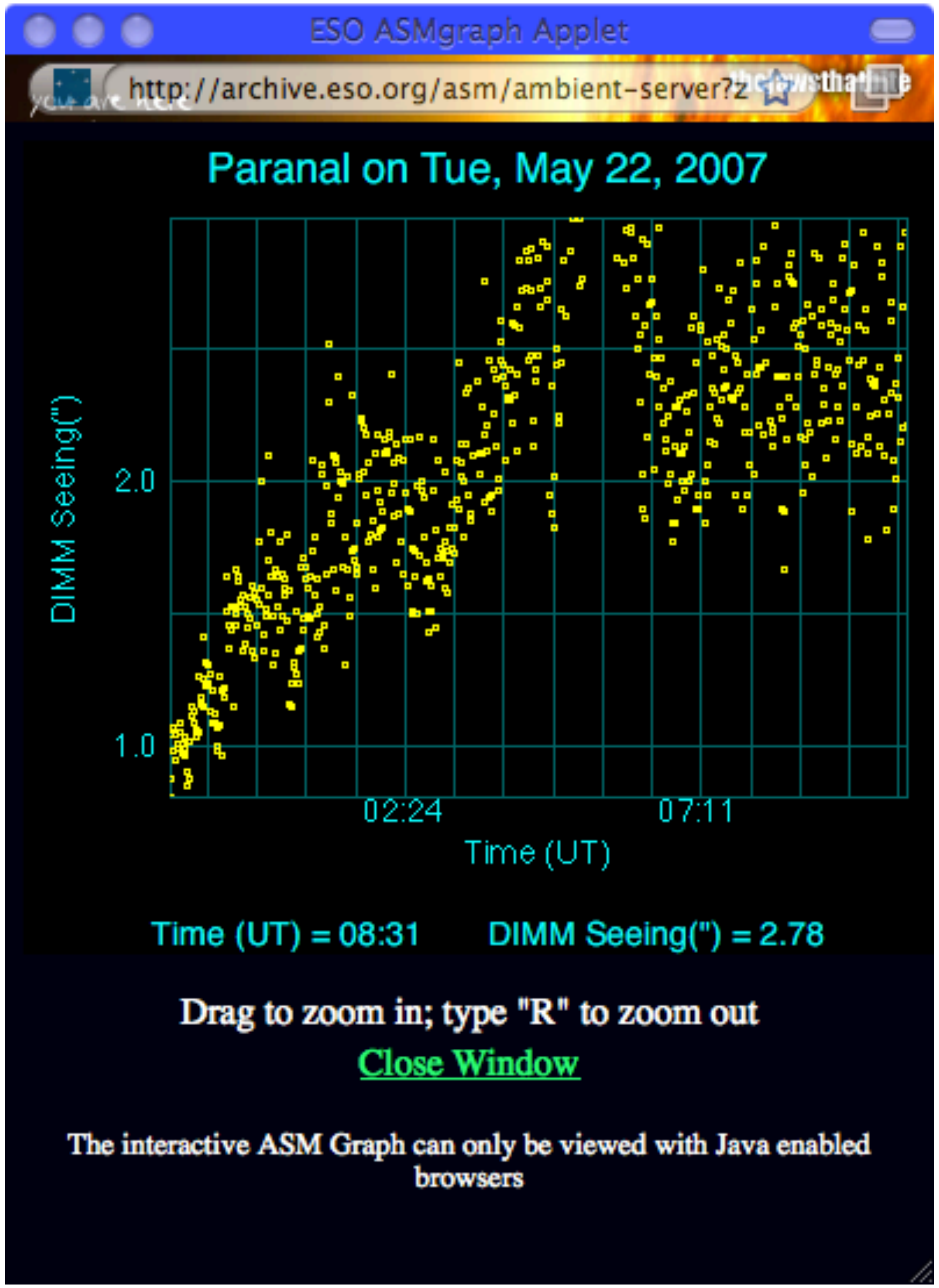
ESAC, Villafranca

15 November 2012

Schödel, Yelda, Ghez, Girard, Labadie, Rebolo, Pérez-Garrido, Morris, 2012, MNRAS, accepted for publication, arXiv:1110.2261

Motivation: no pain, no gain...

The horror...



DIMM seeing ~2” ⇒ predicted FWHM at 8.6 μm ~1”

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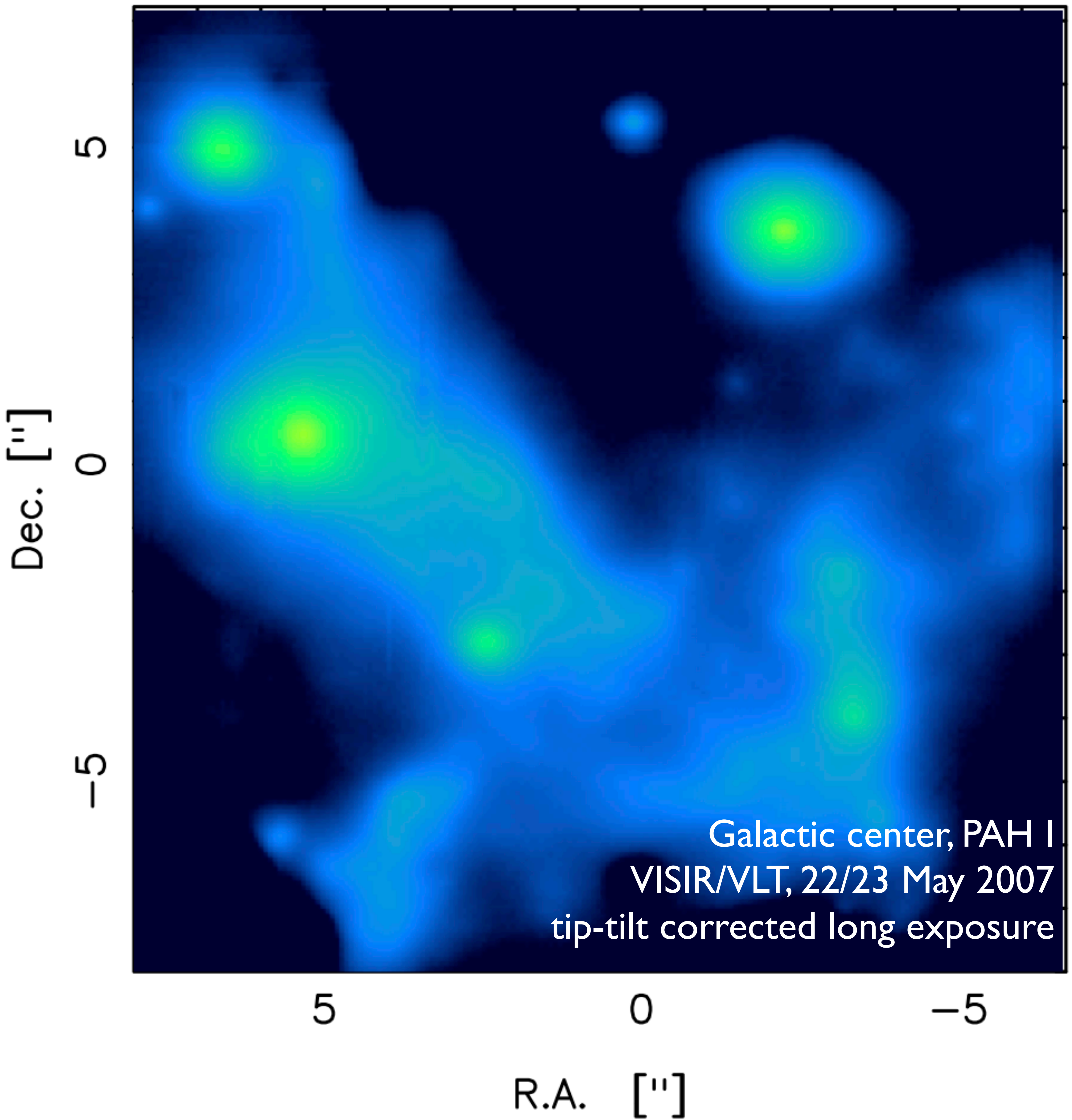

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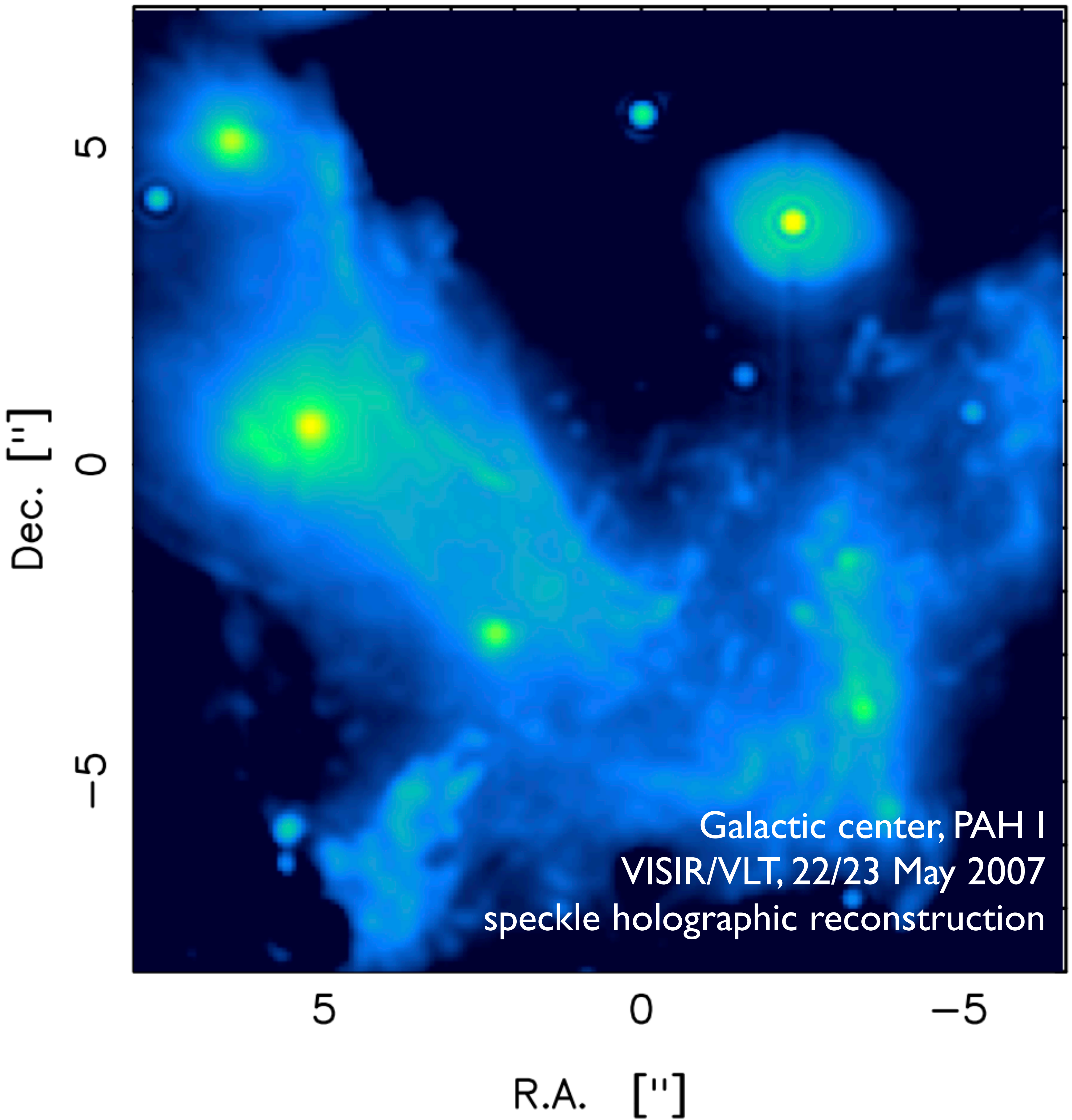


I. Basic concepts

The perfect image from the ground...
an old dream of astronomers.

The diffraction limit and atmospheric turbulence

<u>*Fried parameter:*</u>

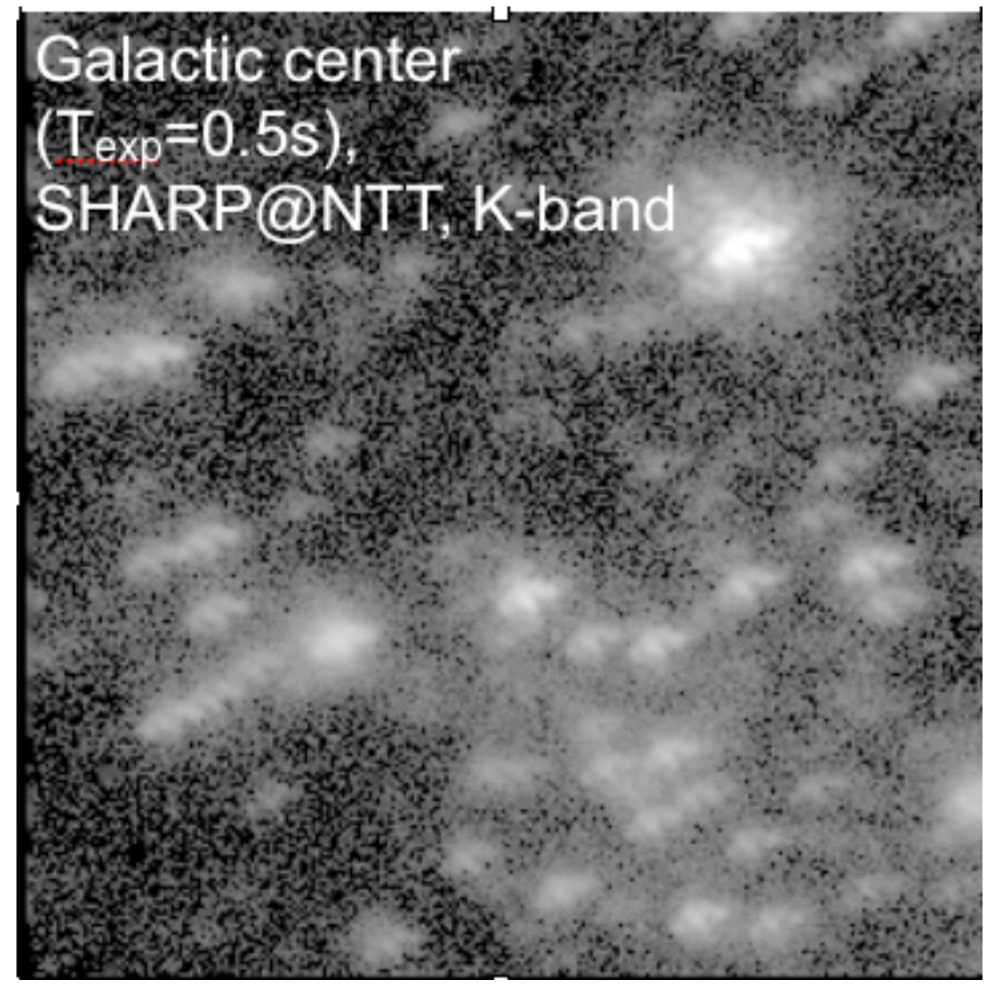
$$r_0 = \left[0.423\left(\frac{2\pi}{\lambda}\right)^2 (\cos\gamma)^{-1} \int_0^\infty C_n^2(h)dh\right]^{-3/5}$$

$r_0 \propto \lambda^{6/5}$

r_0 (0.5µm) ≈ 10 cm

r_0 (2.2µm) ≈ 60 cm

r_0 (10µm) ≈ 360 cm



<u>*Coherence time:*</u>

$\tau_0 = r_0/v_{wind} \approx 60$ ms (2.2µm)

The diffraction limit and atmospheric turbulence

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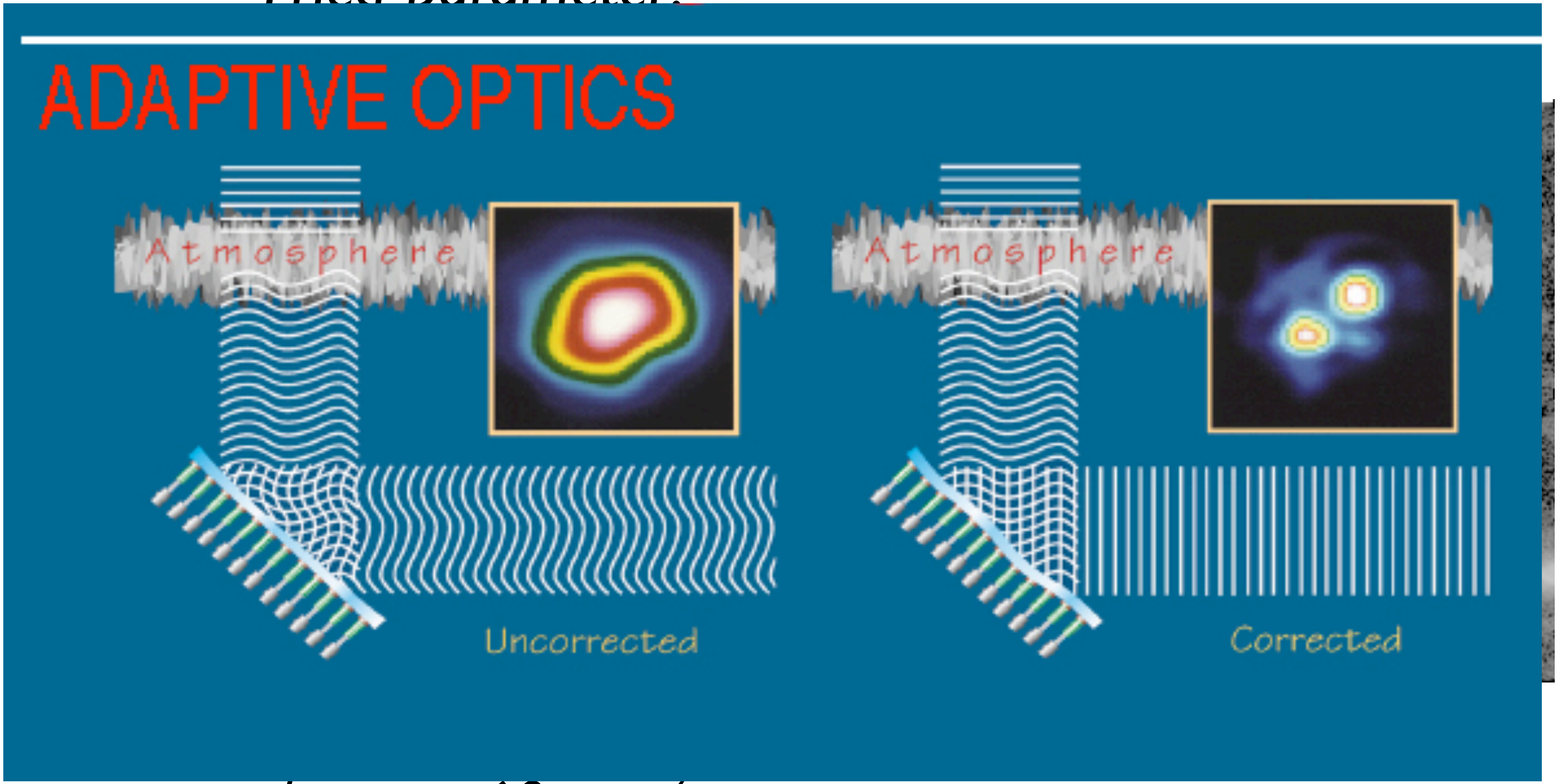

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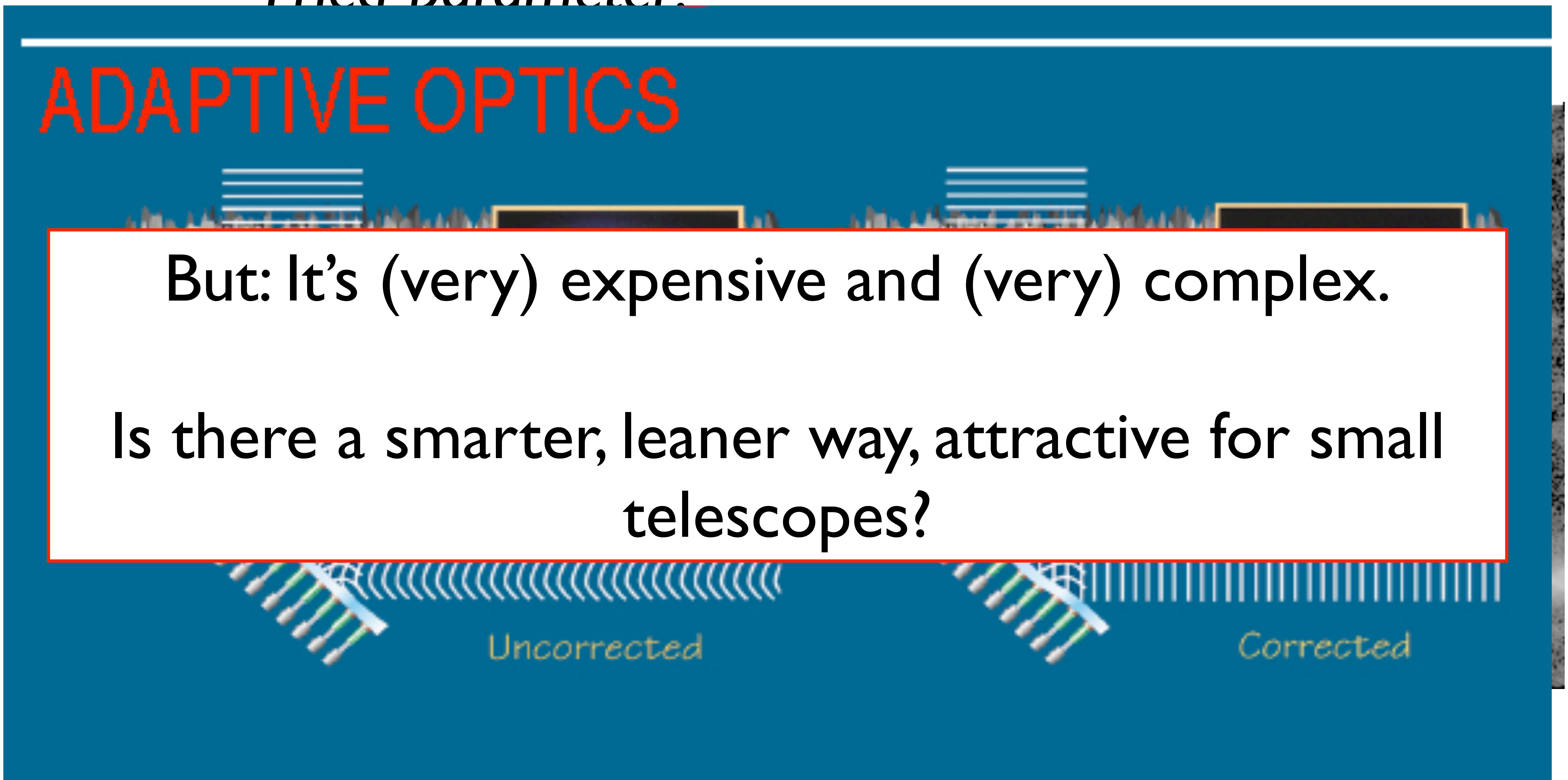

But: It's (very) expensive and (very) complex.

Is there a smarter, leaner way, attractive for small telescopes?

$\tau_0 = r_0/v_{wind} \approx 60$ ms (2.2μm)

Speckle imaging

1) take short exposures with $t_{exp} \sim \tau_0$
2) reconstruct images off-line

<u>Simple Shift-and-Add (SSA) algorithm:</u>

1. choose a reference star and reference pixel
2. shift each image in stack so that brightest speckle of reference star comes to rest on reference pixel
3. average stack

(see, e.g., Christou, 1991; Eckart & Genzel 1996; Ghez et al., 1998)

Selection of best frames
⇒ Strehl ratios 10%-30% in K-band

(4-10m telescopes, Ks-band, e.g. Schoedel et al., 2003; Ghez et al. 2005)

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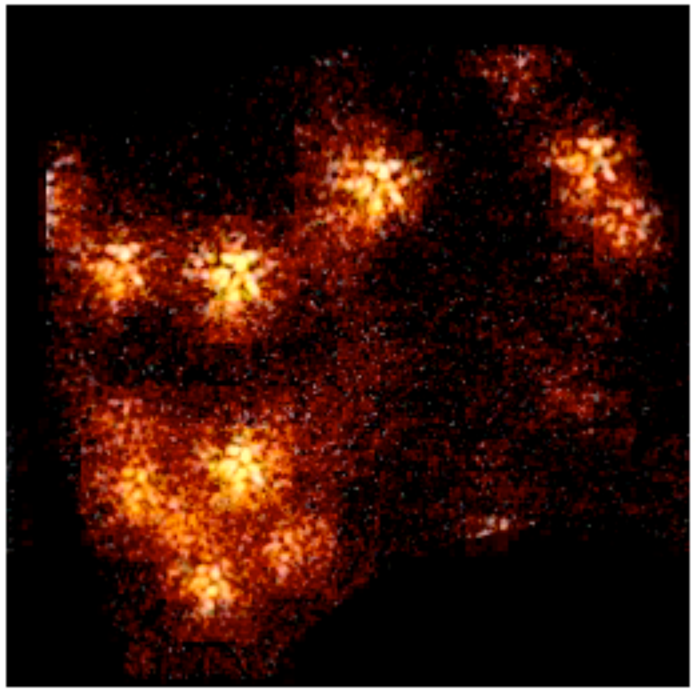

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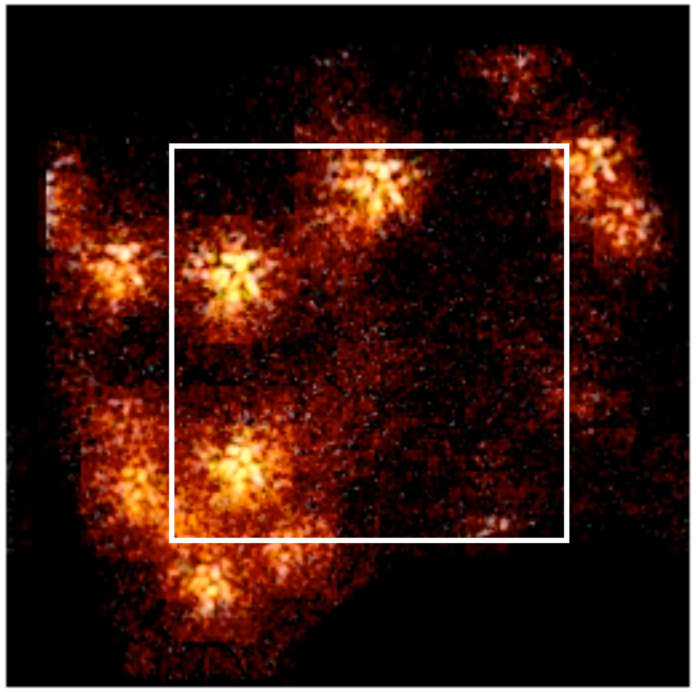

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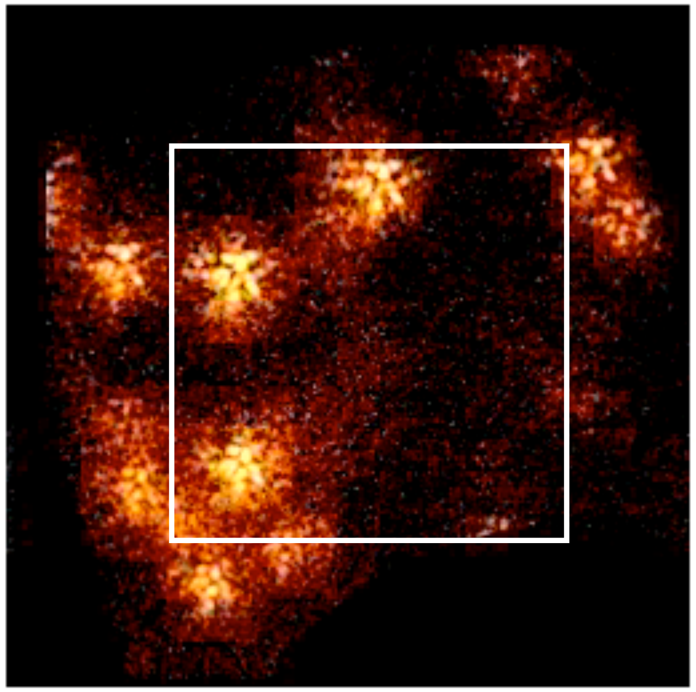

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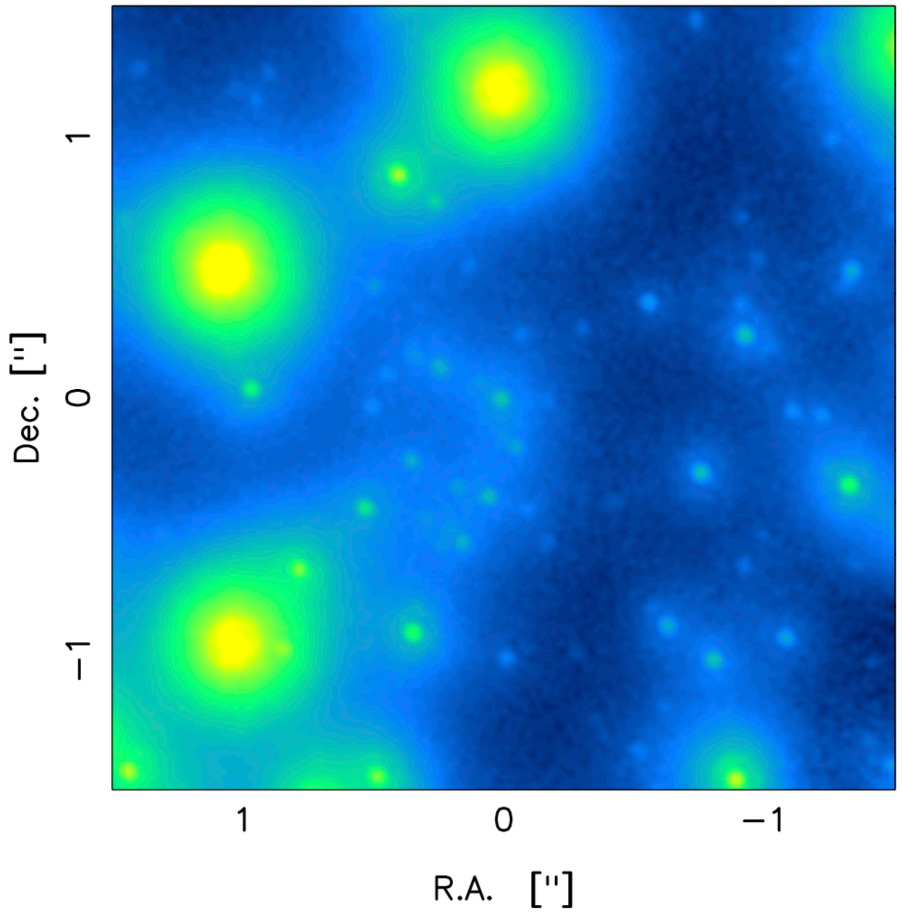

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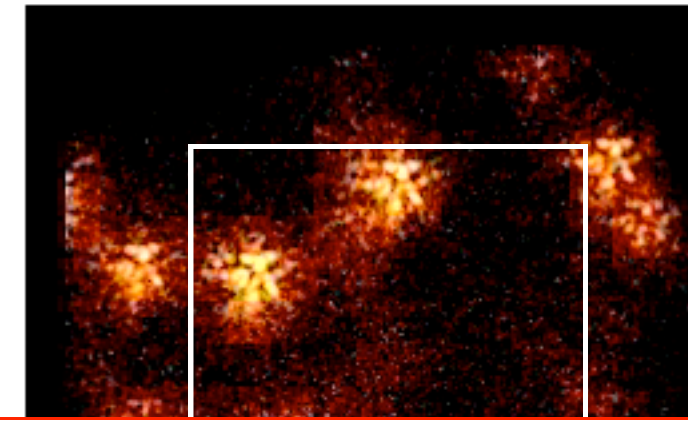


Simp

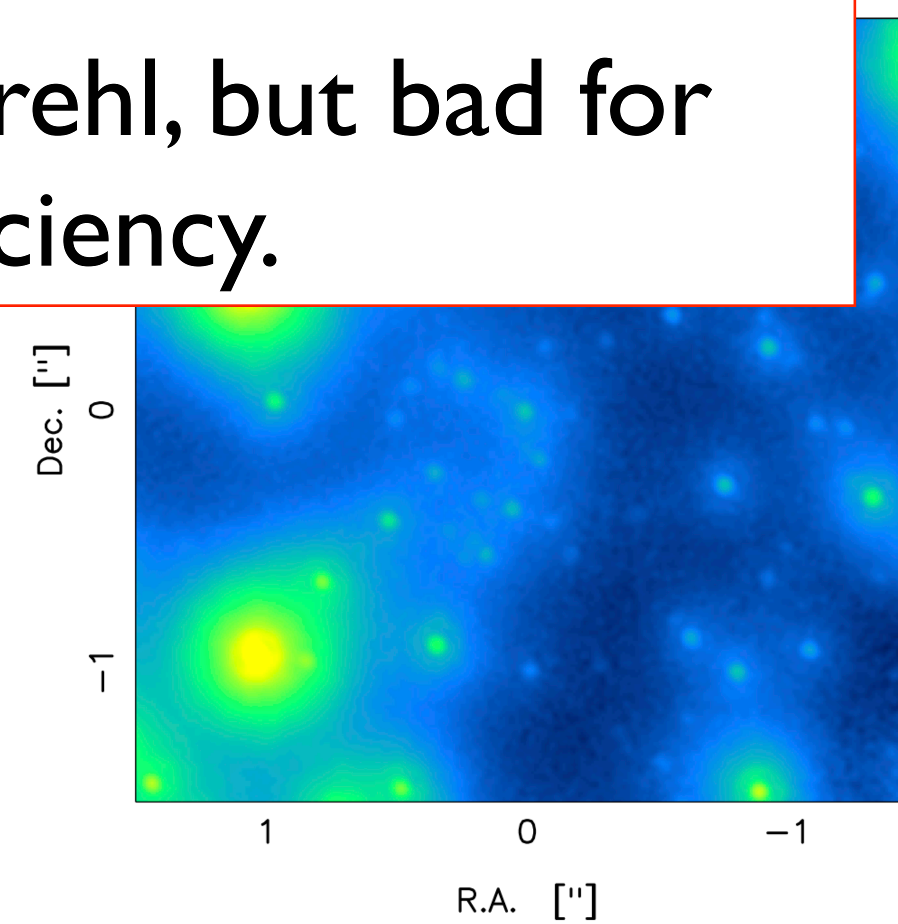
1. choo
2. shift
referen
3. avera
(see, e.g
al., 199

Only moderate Strehl can be achieved with SSA and sensitivity is relatively low.

Lucky imaging is good for Strehl, but bad for sensitivity and efficiency.

Selection of best frames
⇒ Strehl ratios 10%-30% in K-band

(4-10m telescopes, Ks-band, e.g. Schoedel et al., 2003; Ghez et al. 2005)



Speckle holography

$$O(u, v) = \frac{I_m(u, v)}{P_m(u, v)}$$

$$= \frac{I_m(u, v)P_m^*(u, v)}{|P_m(u, v)|^2}$$

many frames

$$O_e(u, v) = \frac{\langle I_m P_m^* \rangle}{\langle |P_m|^2 \rangle} .$$

see, e.g., Primot, Rousset & Fontanella (1990); Petr et al. (1998)

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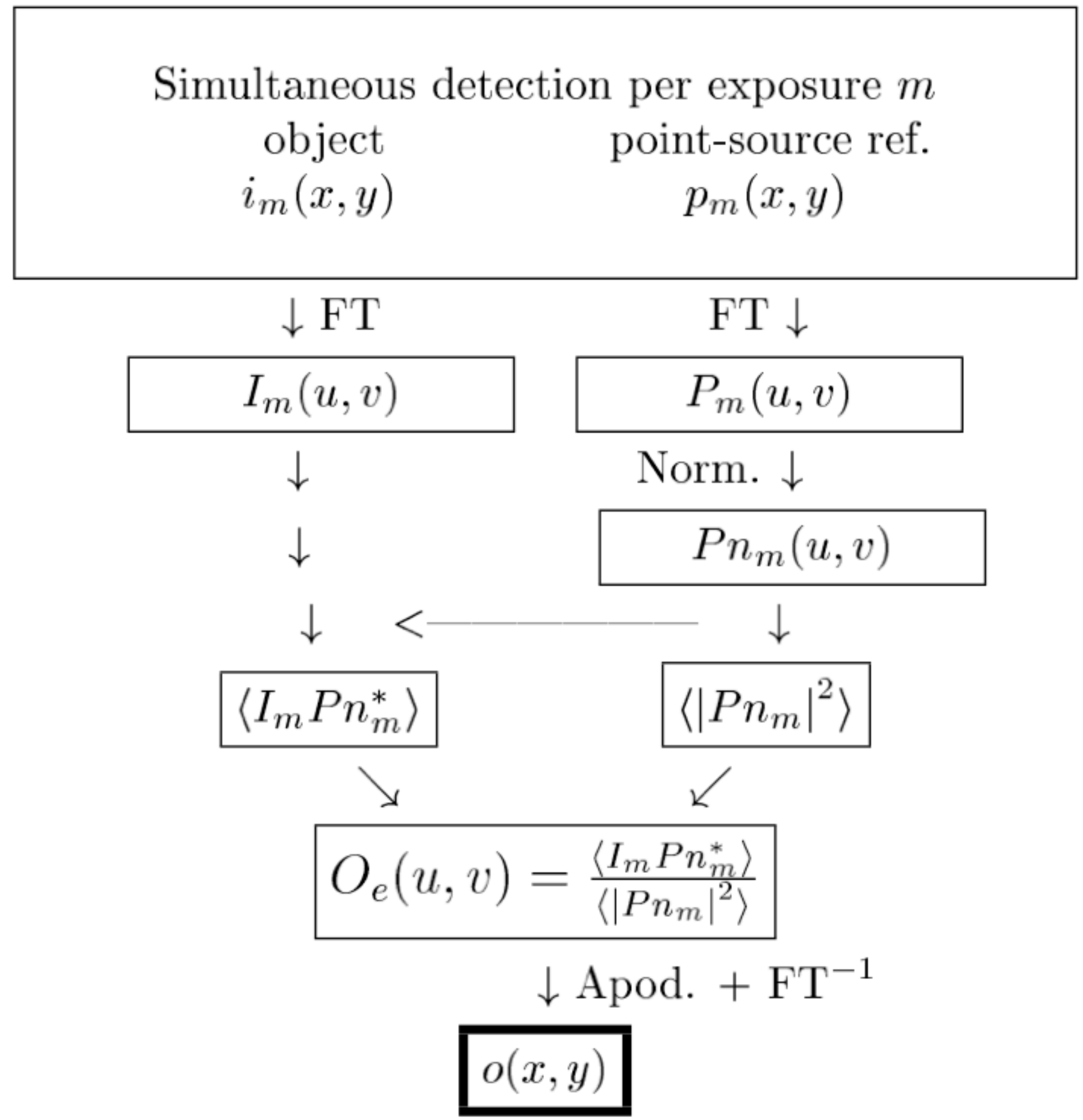

figure from *Petr et al. (1998)*

Speckle holography

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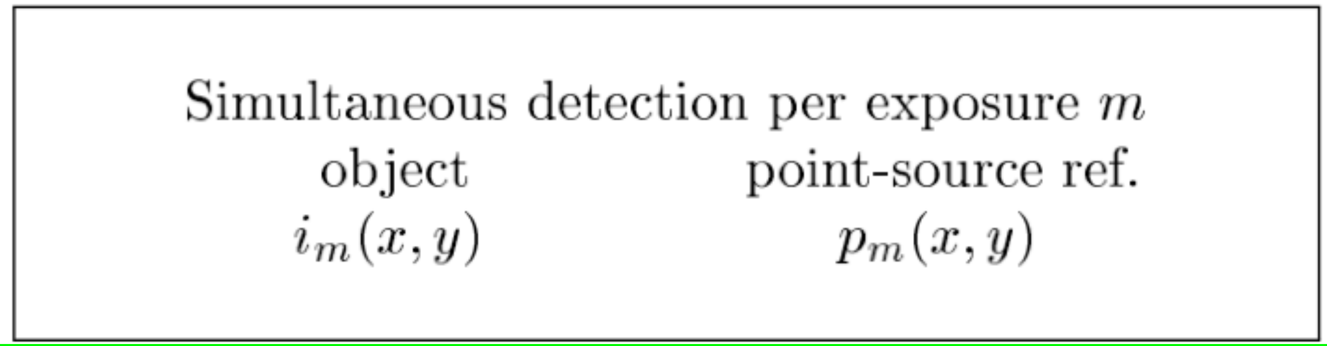
$$= \frac{I_m(u, v)P^*_m(u, v)}{\dots}$$

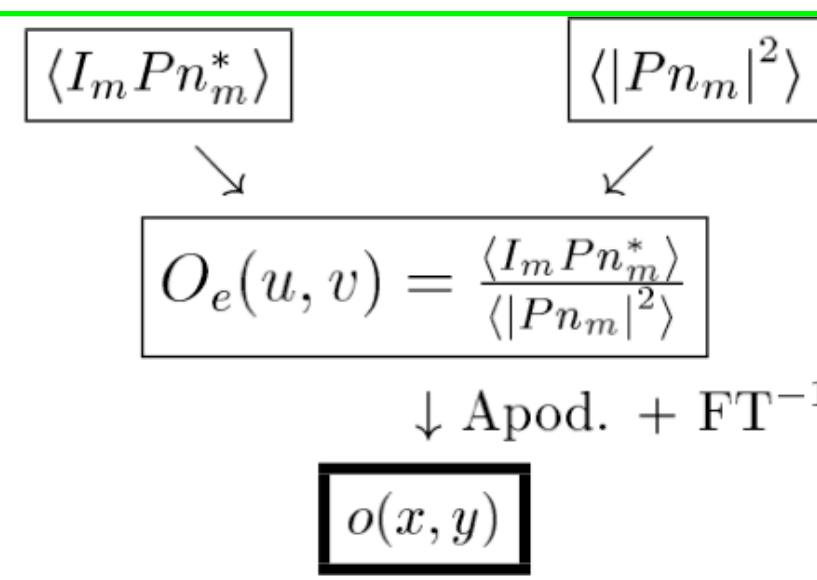


Key is accurate measurement of the instantaneous PSF.

⇒ Isolated, bright point source near target (rare!)

⇒ dense fields: *iterative extraction, use of multiple guide stars*

$$O_e(u, v) = \frac{\langle I_m P^*_m \rangle}{\langle | P_m |^2 \rangle} \cdot$$



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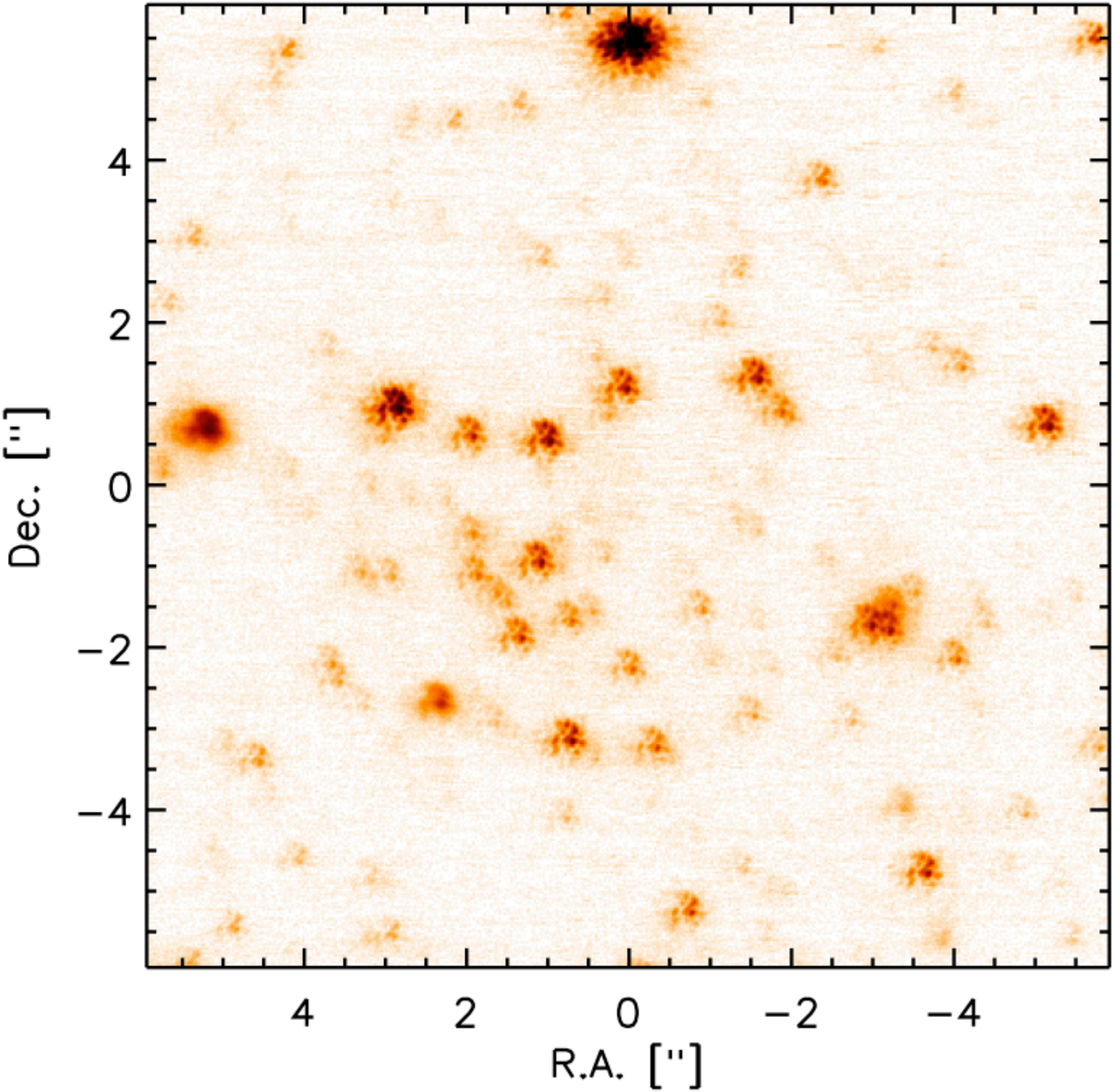
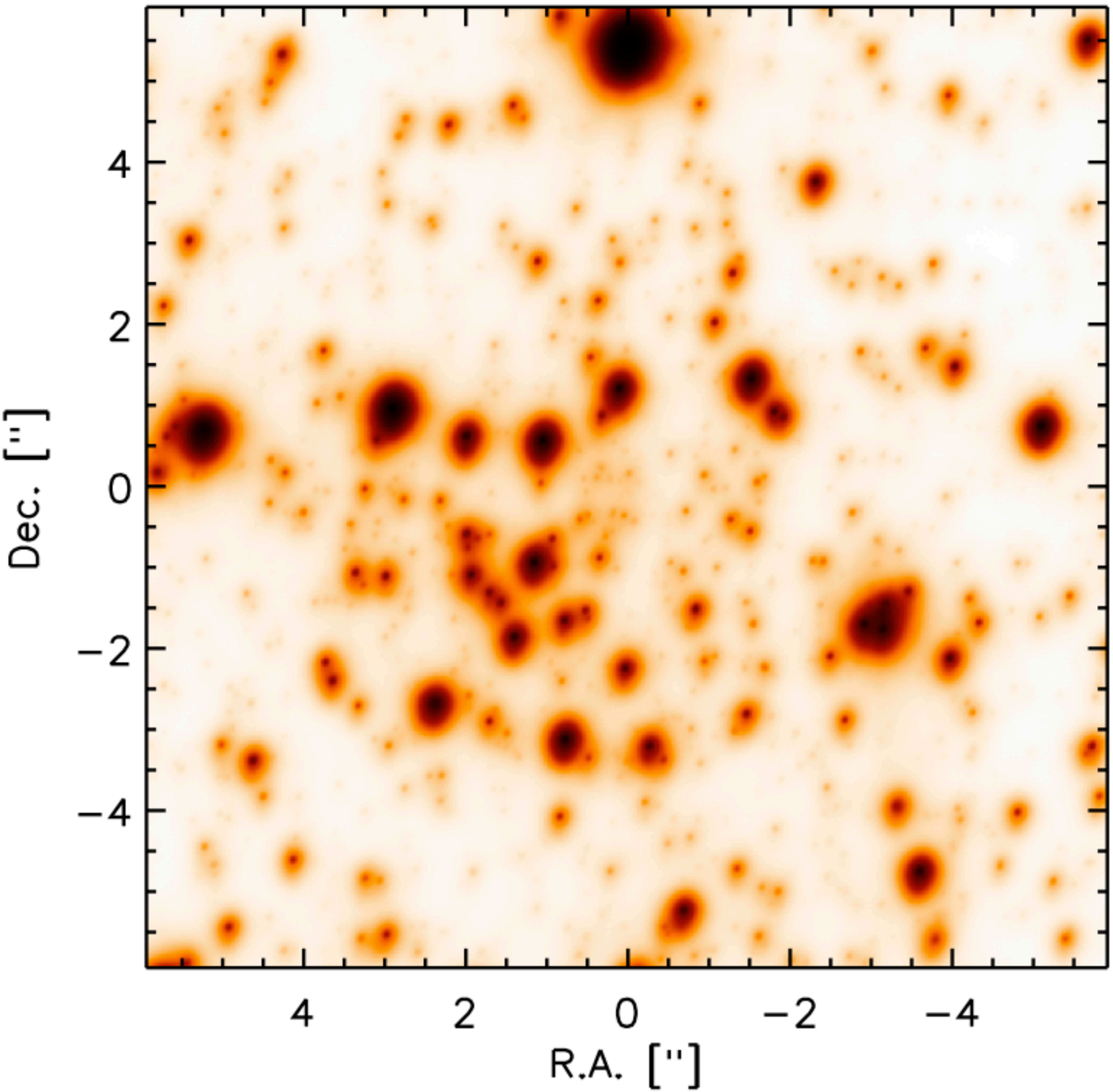
II.Methodology

Data



GC
NACO/VLT, Ks
windowing 512x514
cube mode (Girard et al., 2010)
DIT = 0.15s
DIMM~0.5"
12500 frames
standard reduction

Thanks to J. Girard, S. Rengaswamy, G. Montagnier (ESO)!



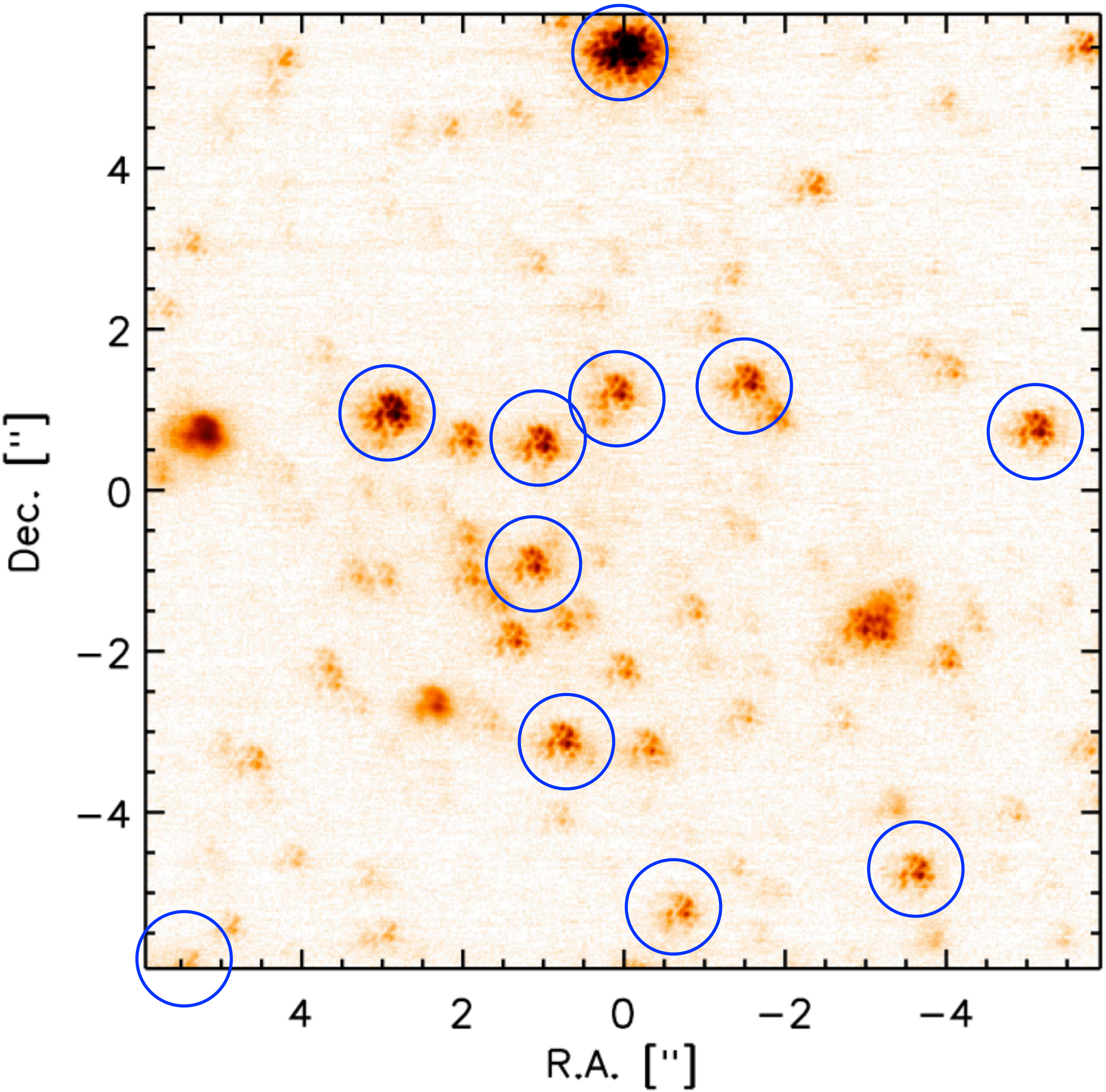
Algorithm

(1) SSA image

(2)PSF fitting

(e.g., StarFinder)
⇒stellar fluxes

and positions



Algorithm

(3) Select reference stars

For each frame do...

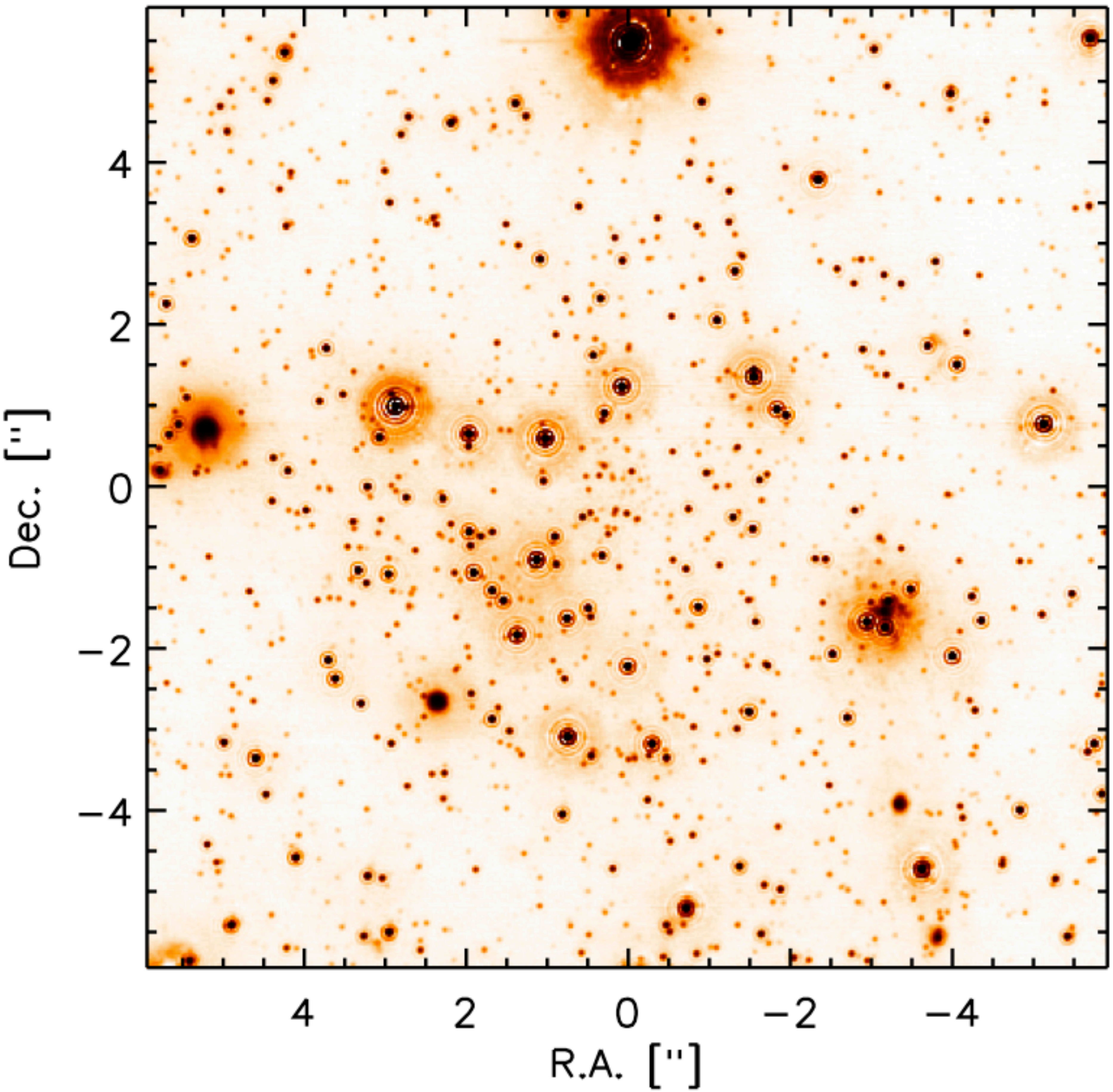
(4) Preliminary PSF estimate

(5) improved PSF estimate (subtraction of secondary stars)

(6) $O = \langle I_m \times P_m^* \rangle / \langle |P_m|^2 \rangle$

(7) Apodization and inverse Fourier transform

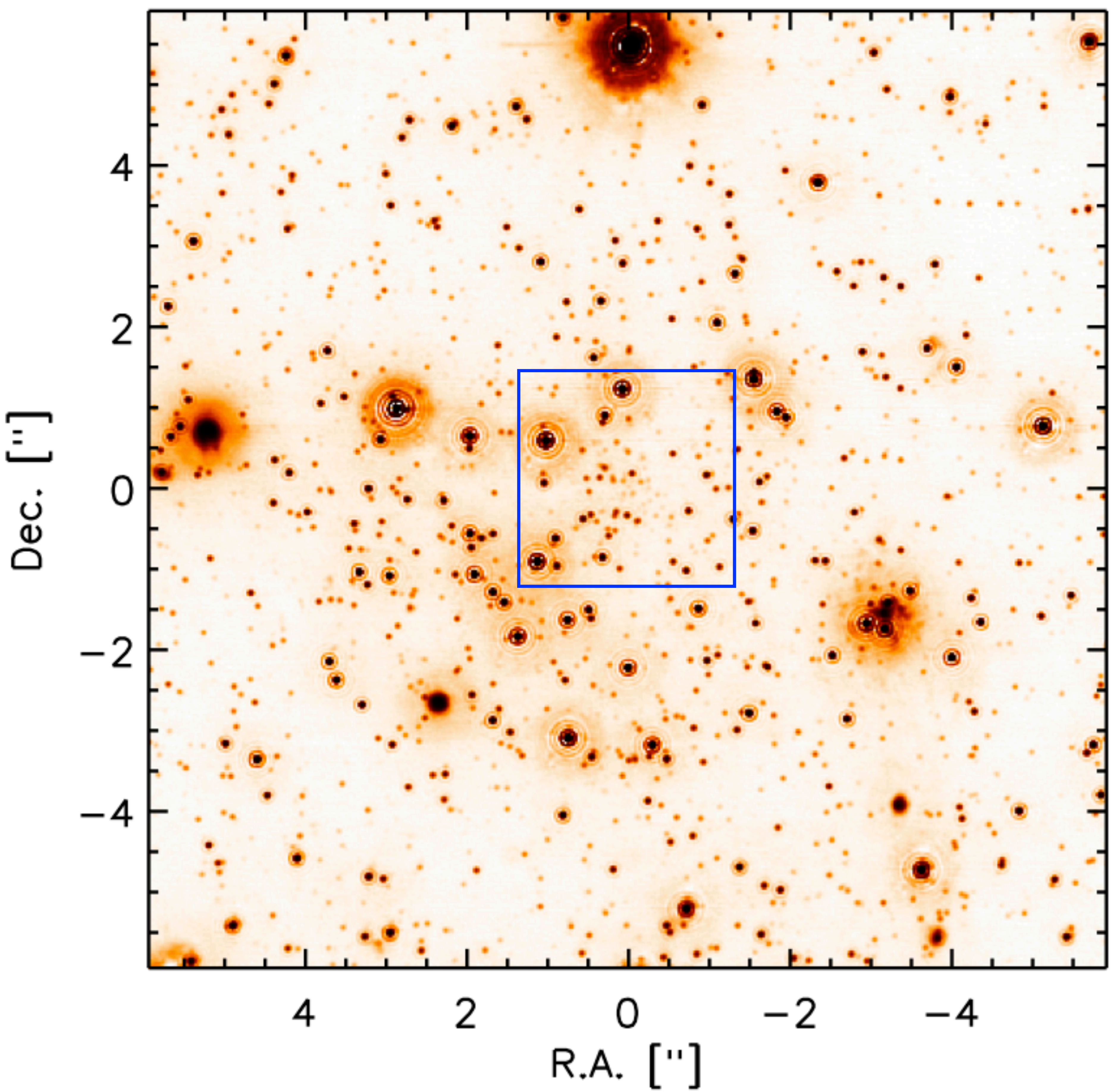
Algorithm



(8) optional: repeat steps 2-7

~80% Strehl

Algorithm



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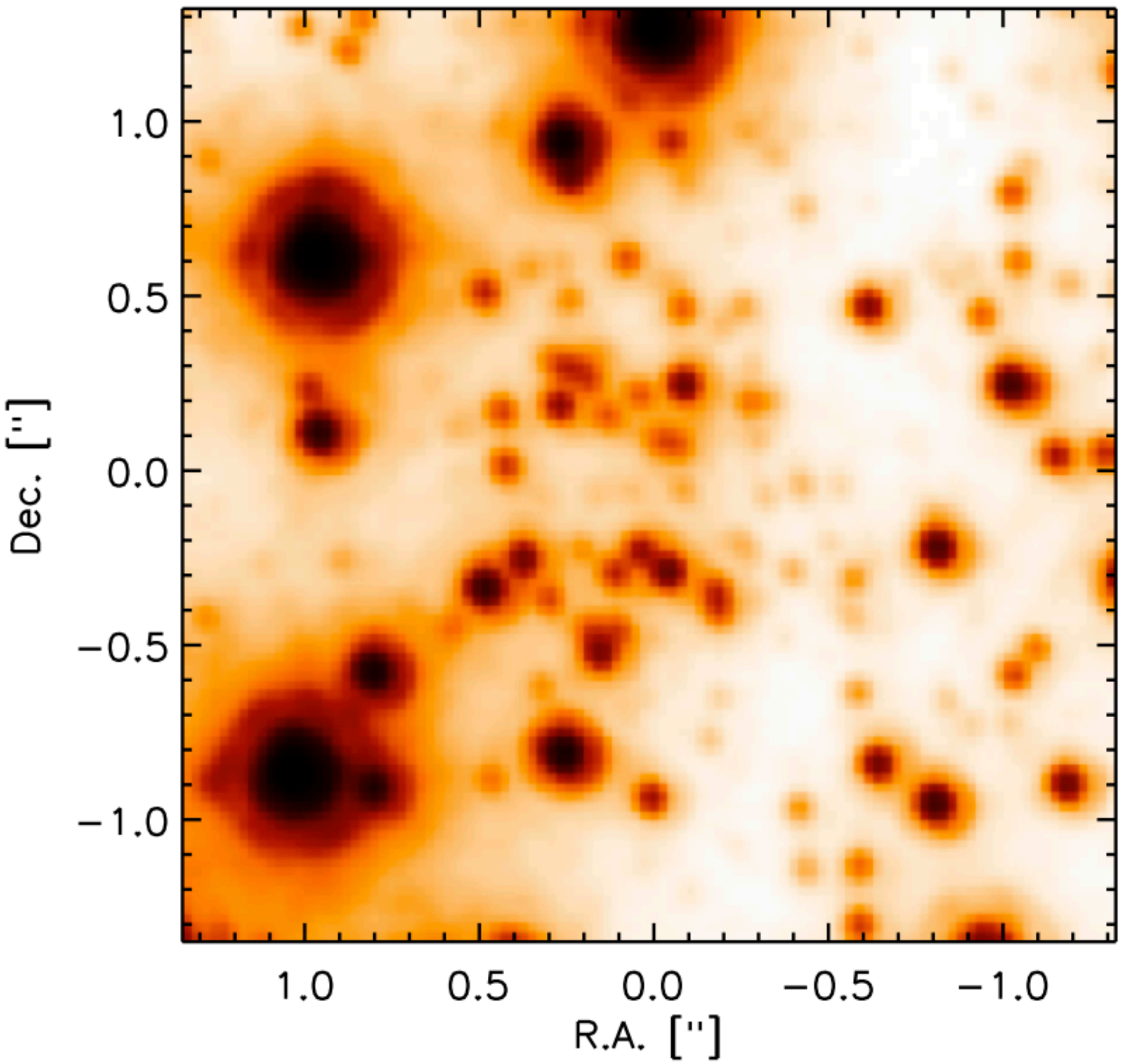
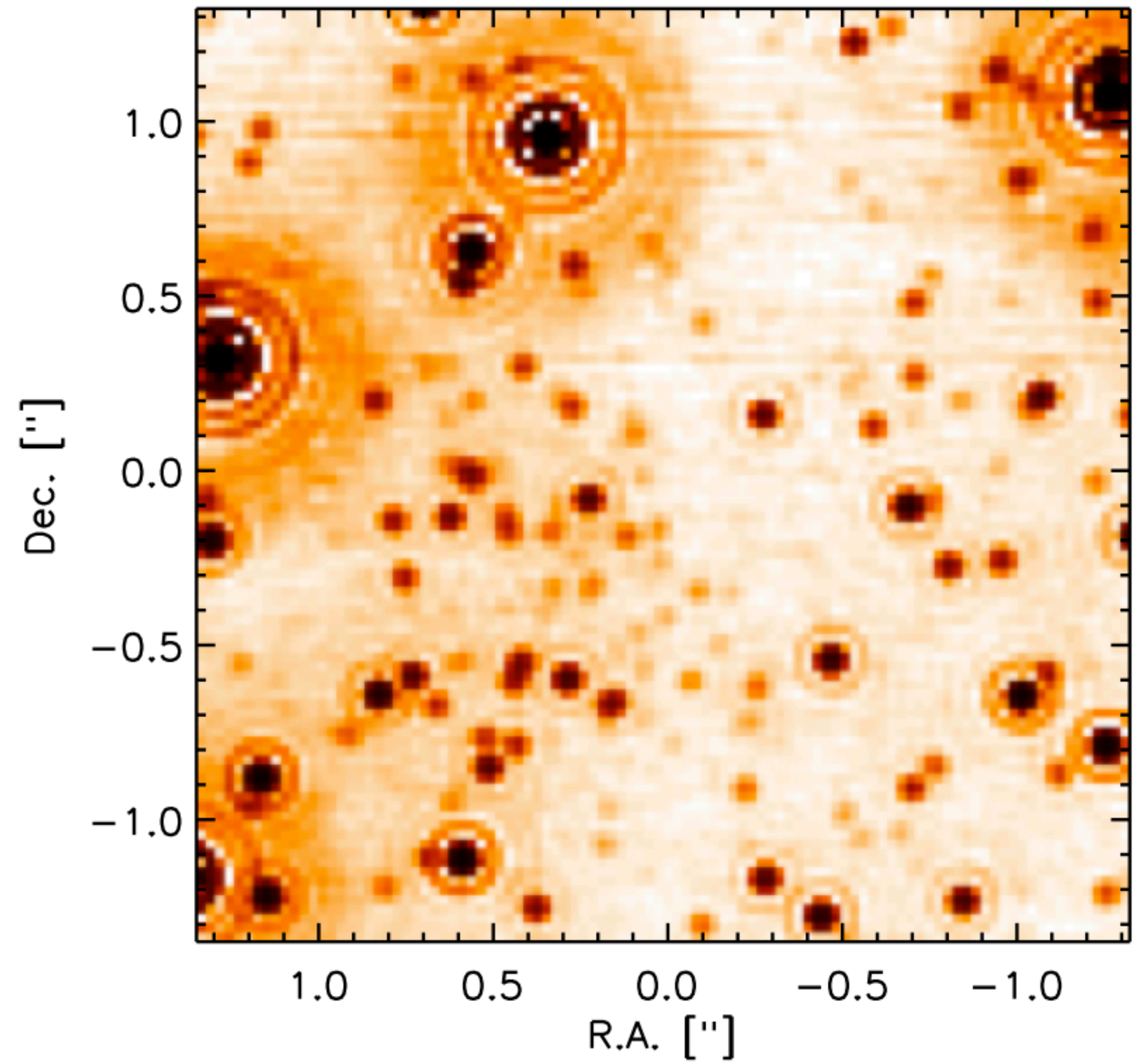
Quality Control: AO vs. Holography

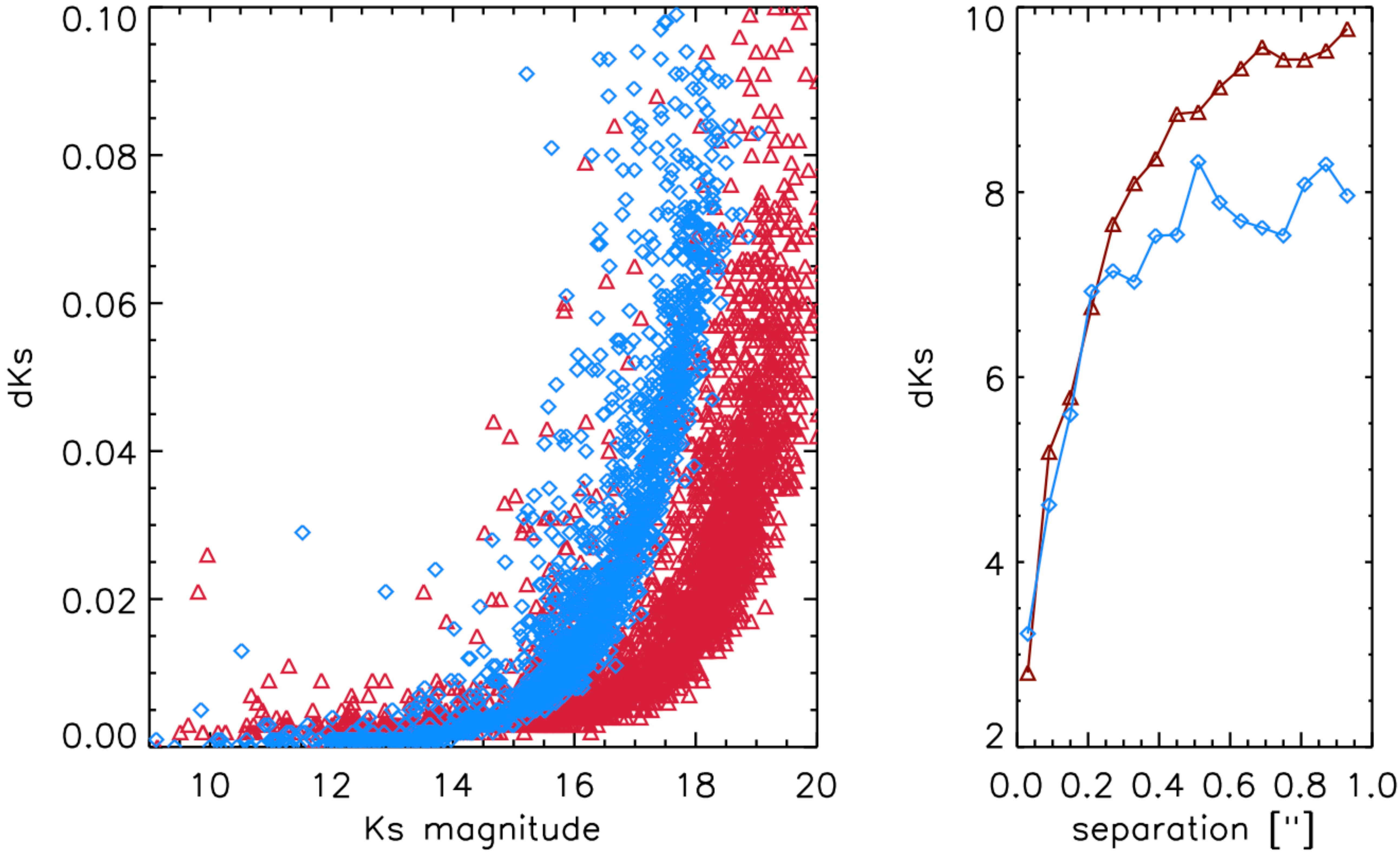


NaCo, AO, 31 March 2009
DIMM≈0.5", $\tau_0 \approx 47$ ms
t_{int} = 1320x0.5s = 1320s



NaCo, holography, 7 Aug 2011
DIMM≈0.5", $\tau_0 \approx 2$ ms
t_{int} = 12,500x0.15s = 1875s

Holography vs. AO



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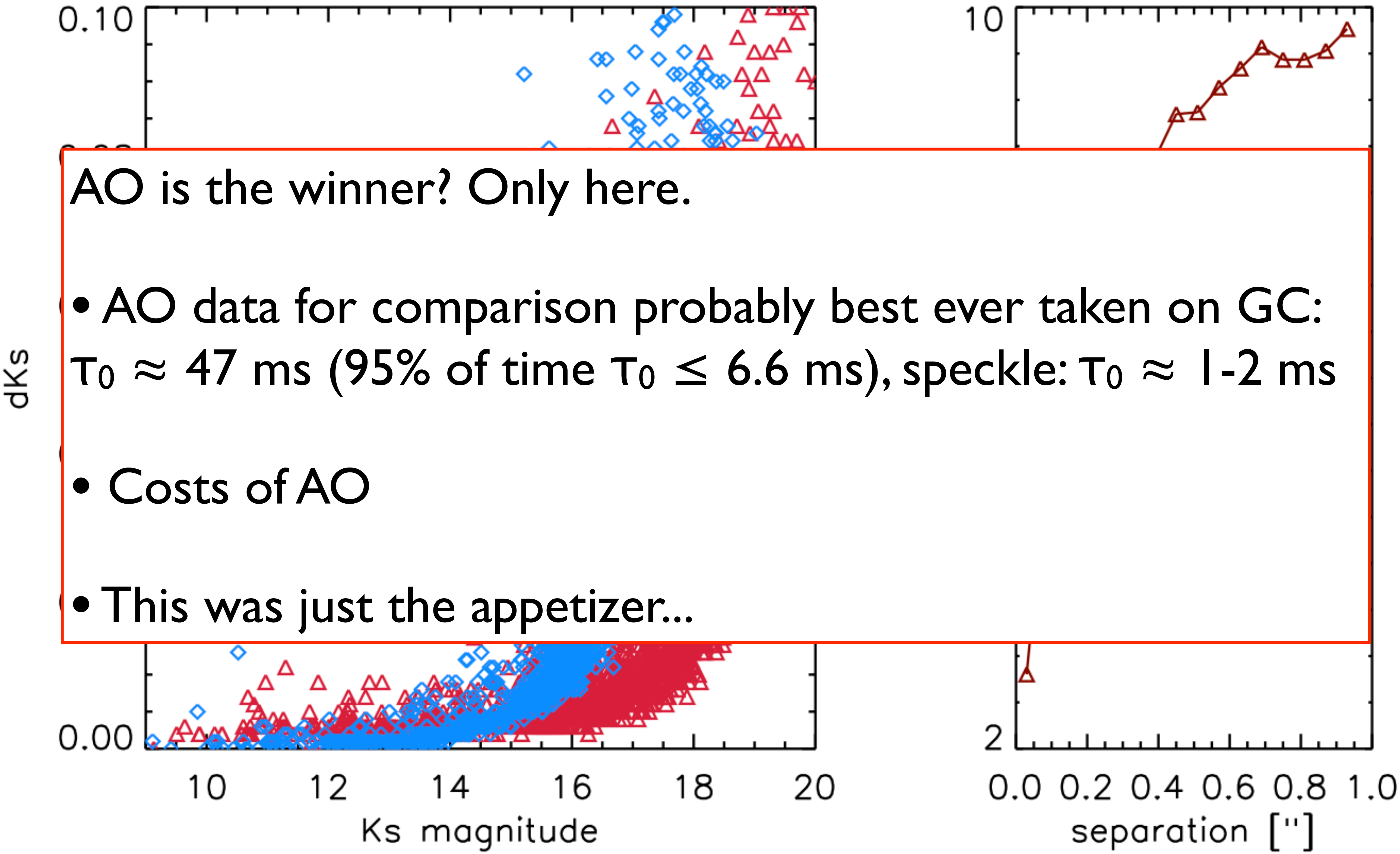


AO is the winner? Only here.

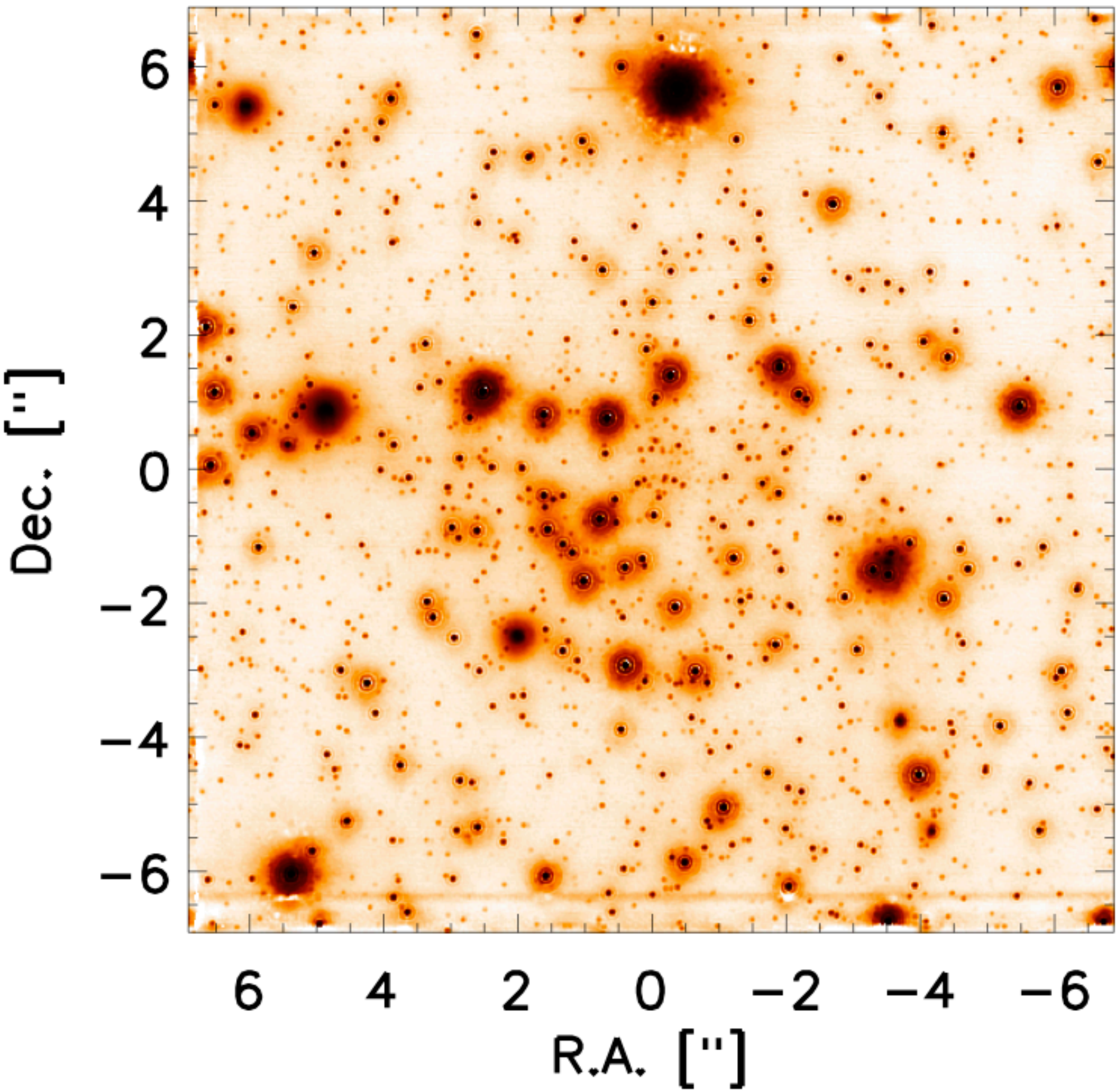
- AO data for comparison probably best ever taken on GC: $\tau_0 \approx$ 47 ms (95% of time $\tau_0 \leq$ 6.6 ms), speckle: $\tau_0 \approx$ 1-2 ms

- Costs of AO

- This was just the appetizer...

III.Holography: under extreme conditions

Faint reference stars



Galactic center, NaCo/VLT, Ks
23 Ks≈13 reference stars:
Strehl~45%, excellent cosmetics

(Strehl ~18% with single, Ks≈12 reference star).

⇒ **beyond the possibilities of current AO systems**

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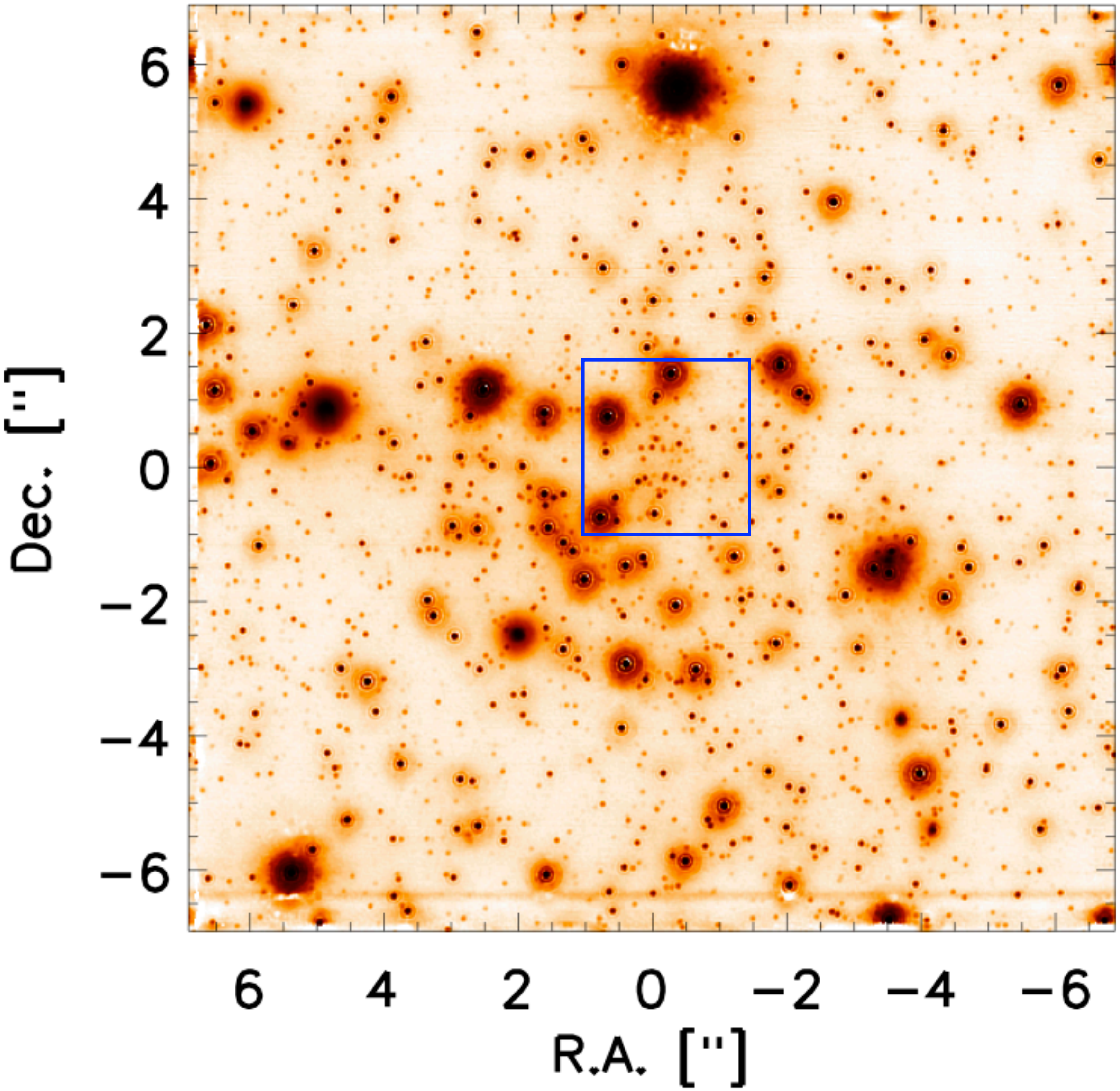

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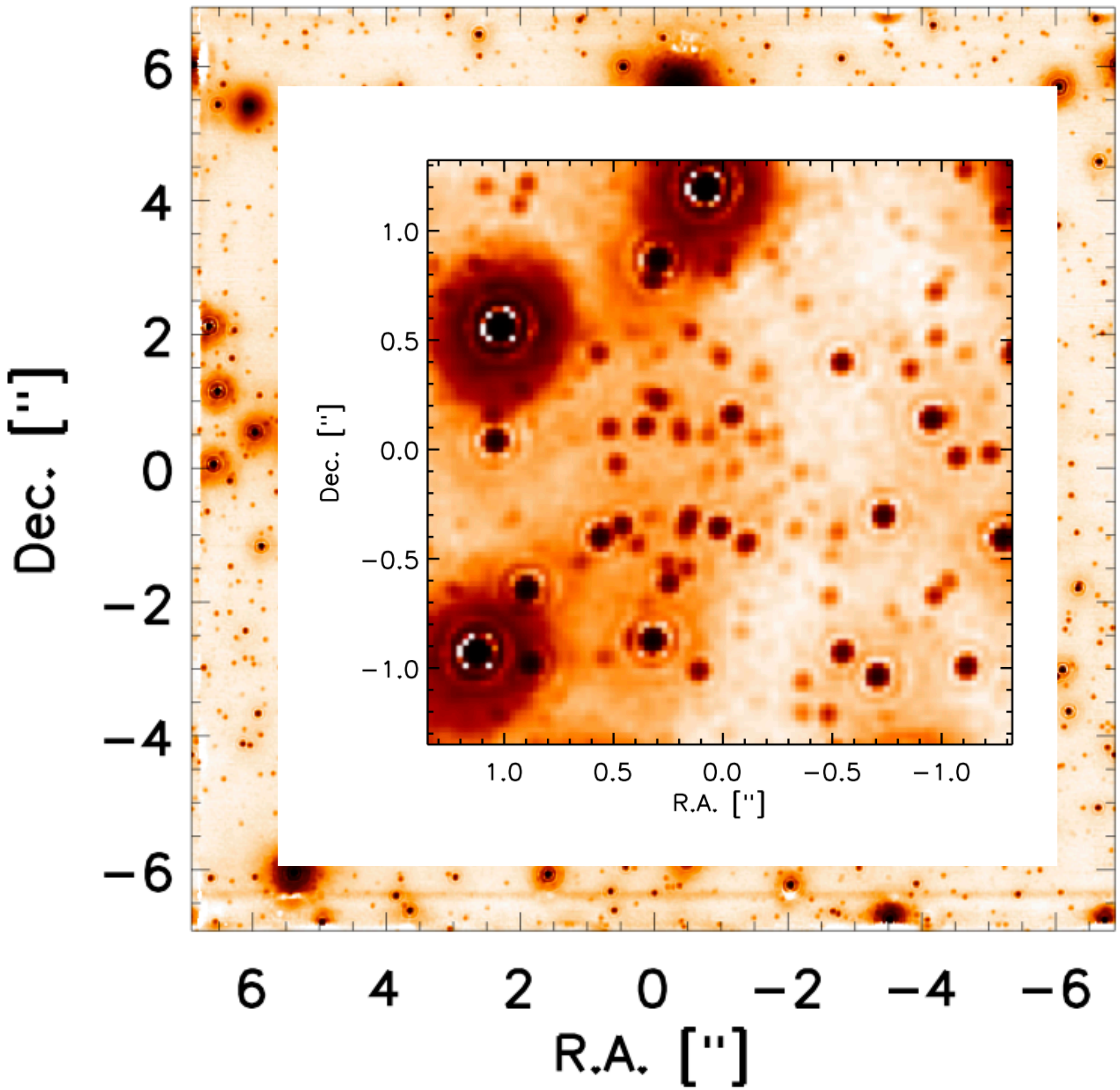

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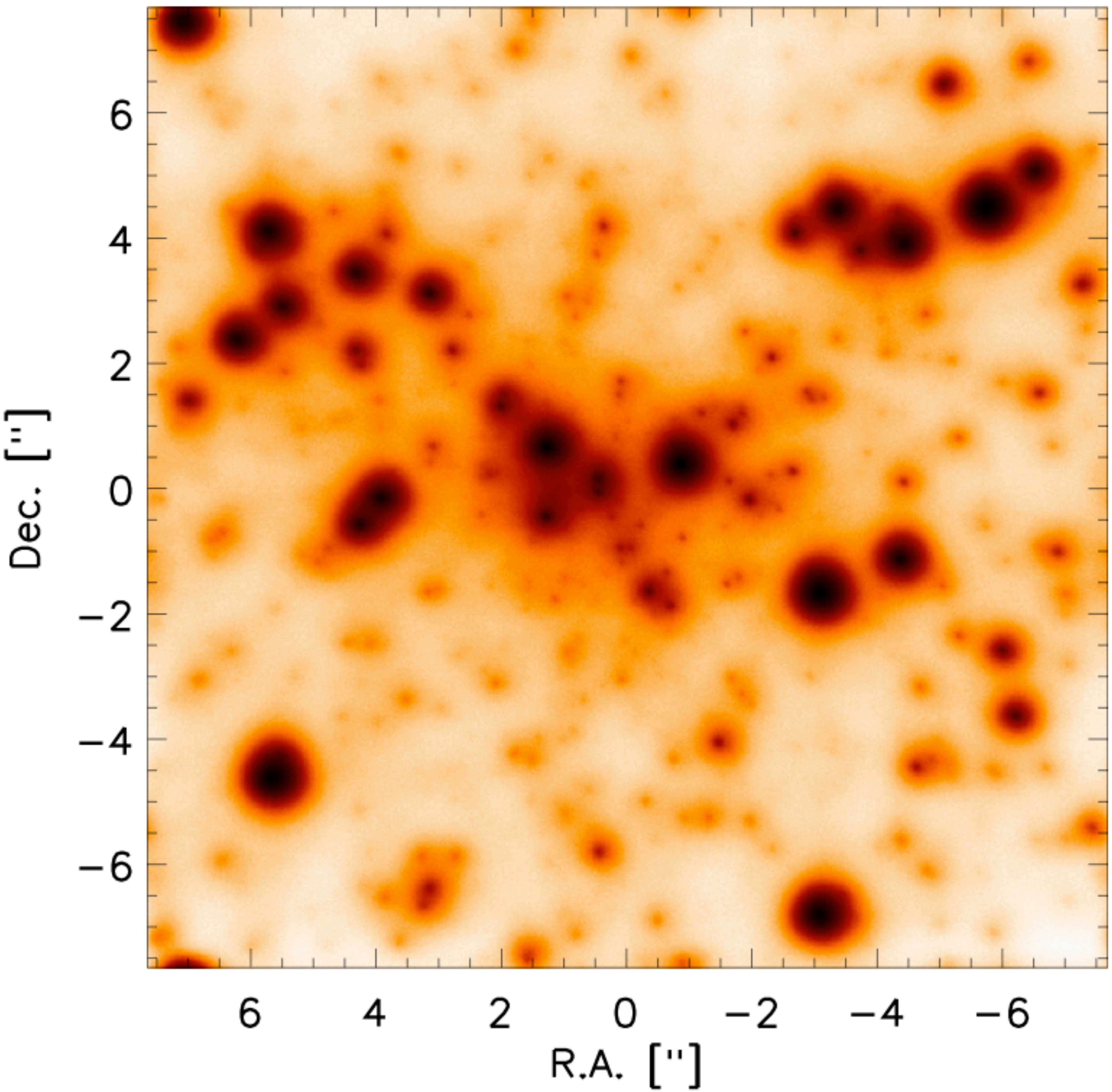
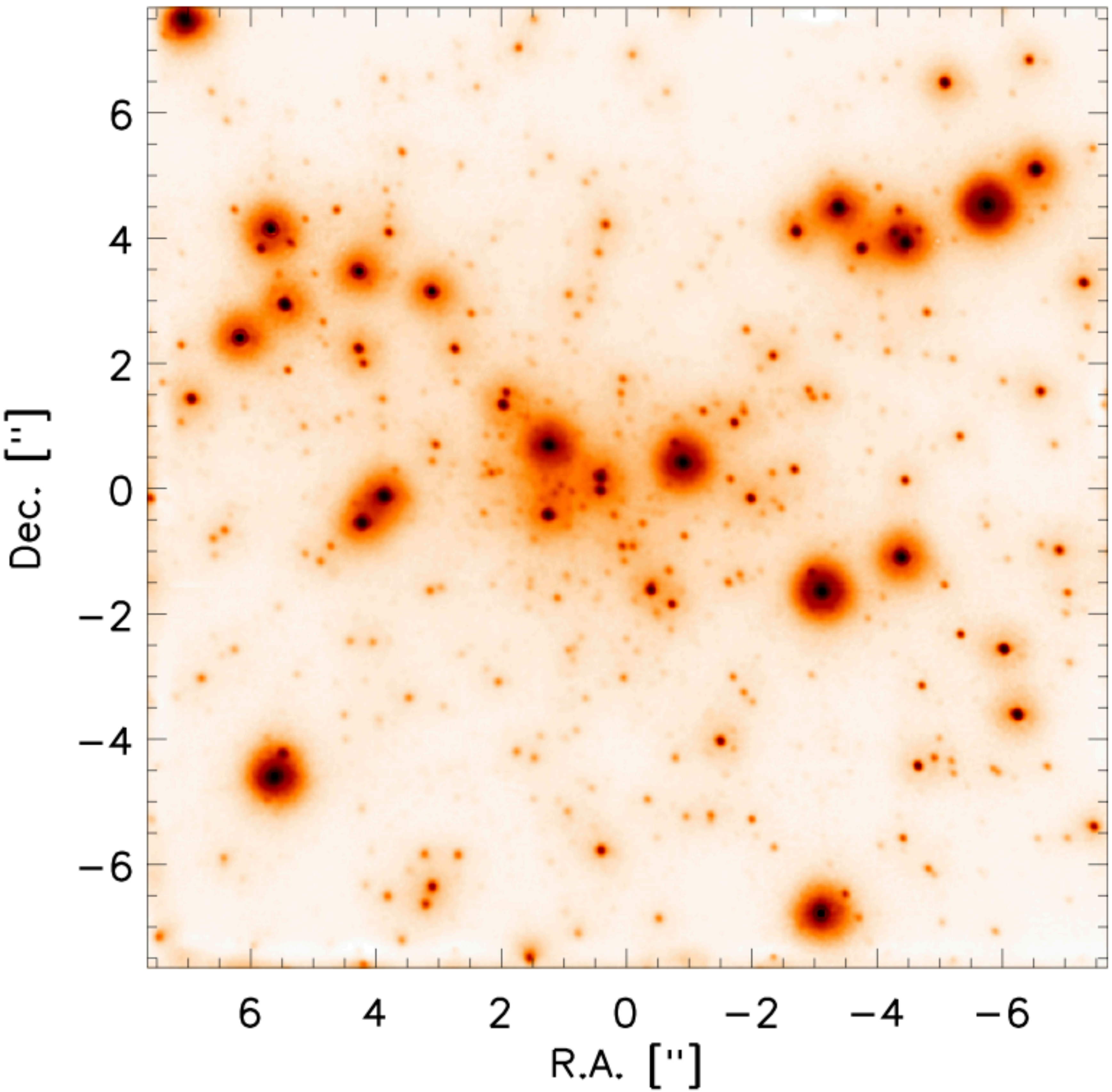
Short wavelengths: I-band



Core of M15
FASTCAM@NOT
I-band, seeing ~1”

Simple shift-and-add with frame selection (1%): *lucky imaging*
~4% Strehl, Δm≈5

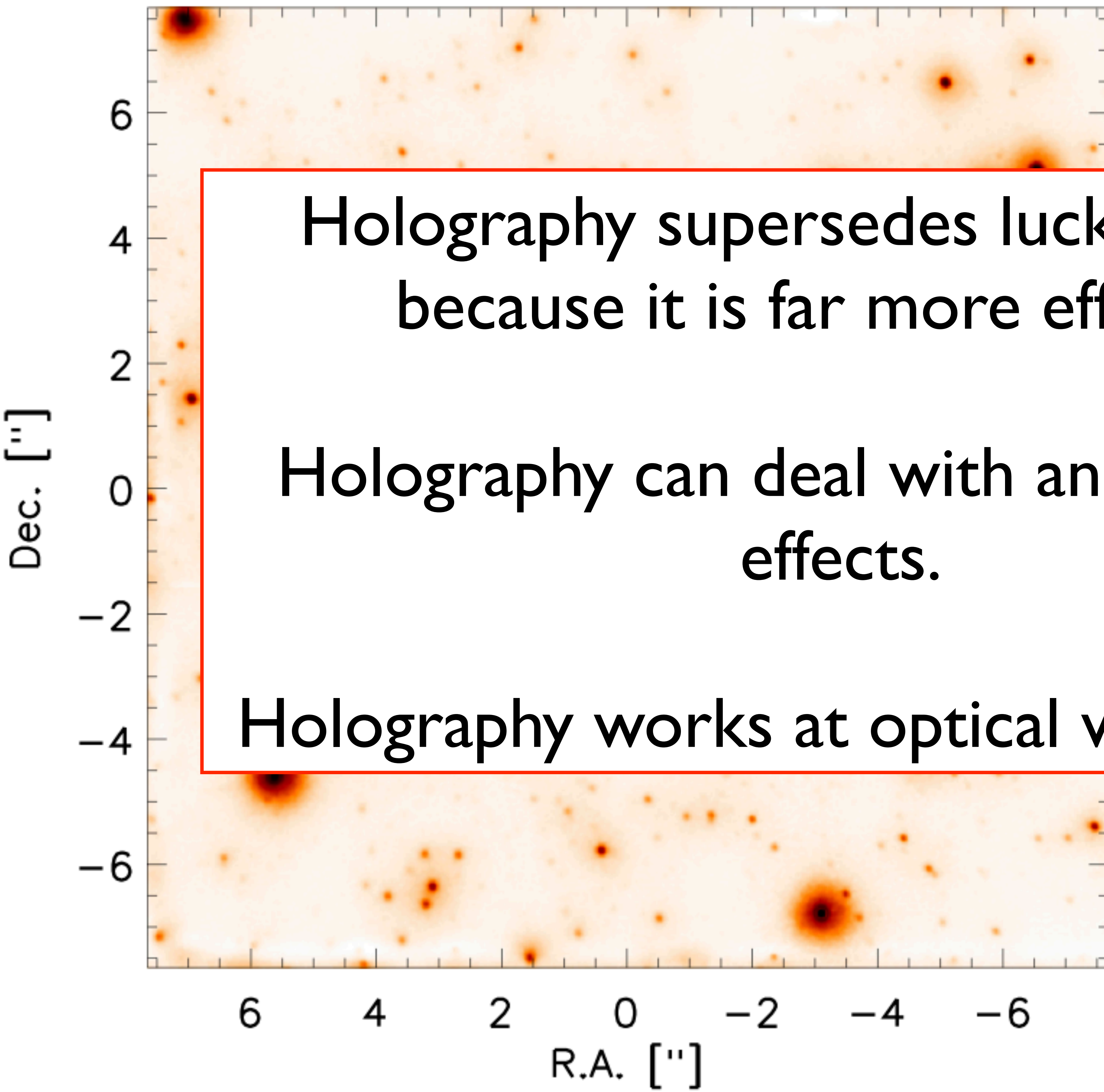
Short wavelengths: I-band



Core of M15
FASTCAM@NOT
I-band, seeing ~1”

Holography with frame selection (50%), **separate reconstruction of subfields to deal with anisoplanatic effects**: ~18% Strehl, Δm≈8.0

Short wavelengths: I-band



Core of M15
FASTCAM@NOT
g ~1”

Holography supersedes lucky imaging because it is far more efficient.

Holography can deal with anisoplanatic effects.

Holography works at optical wavelengths.

e
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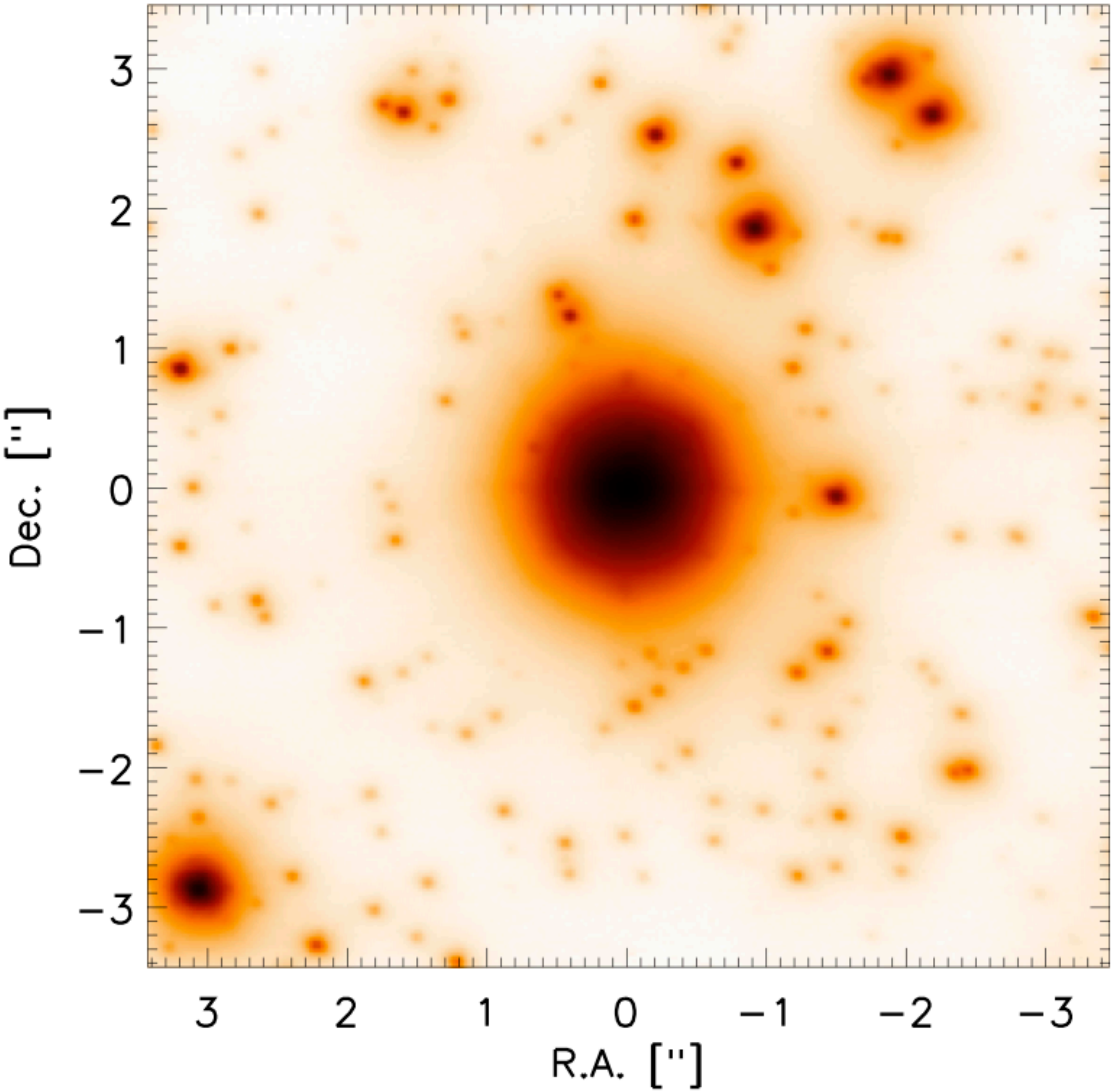
o
deal with anisoplanatic effects: ~18% Strehl, $\Delta m \approx 8.0$

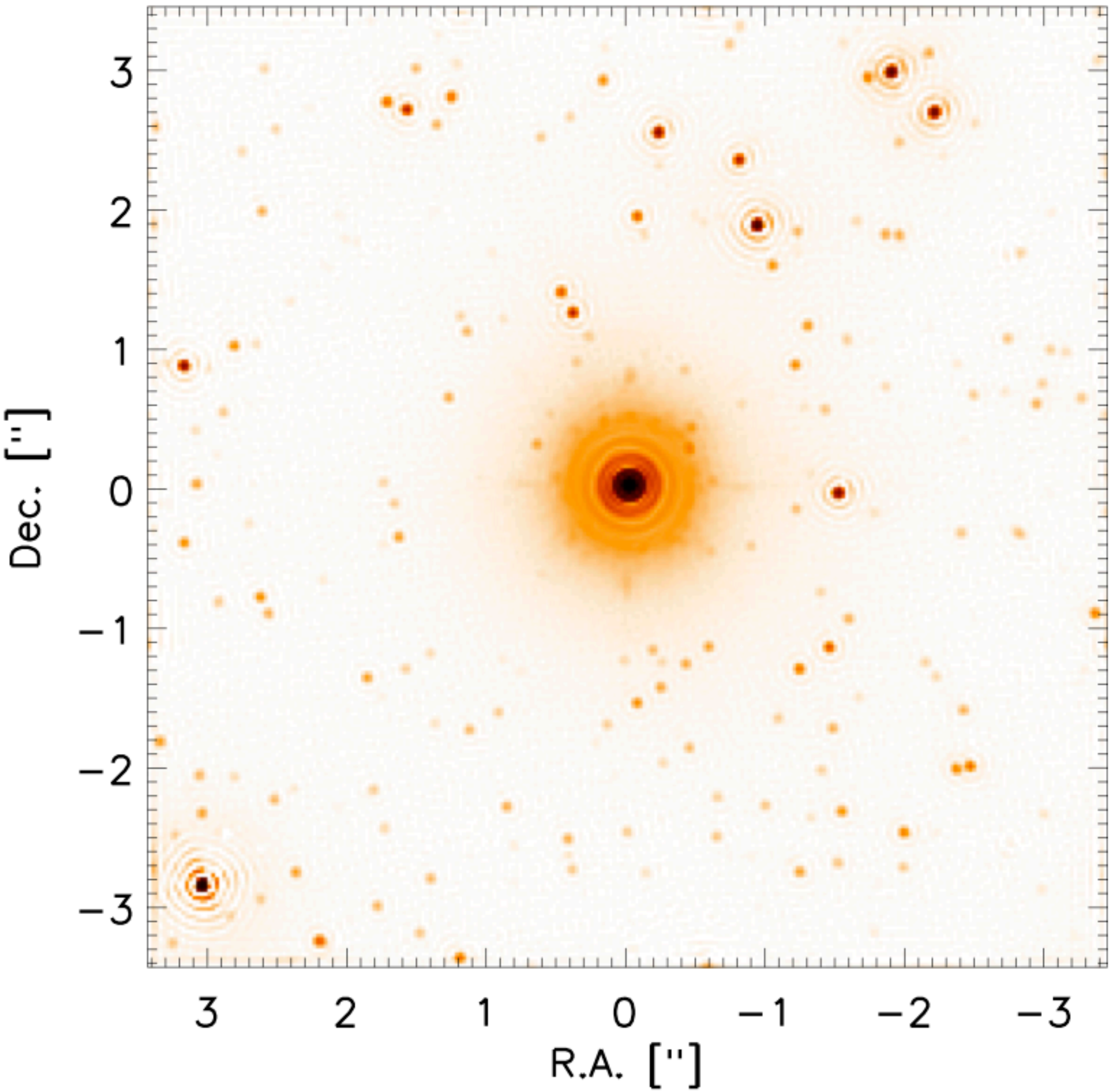
Holography + AO



47 Tuc
NaCO/VLT
Ks
1920×3s = 5760s
τ_0=1-2 ms
AO correction unstable, PSF halo highly variable

SSA combination of AO frames

Holography + AO



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"holographic" combination of AO frames

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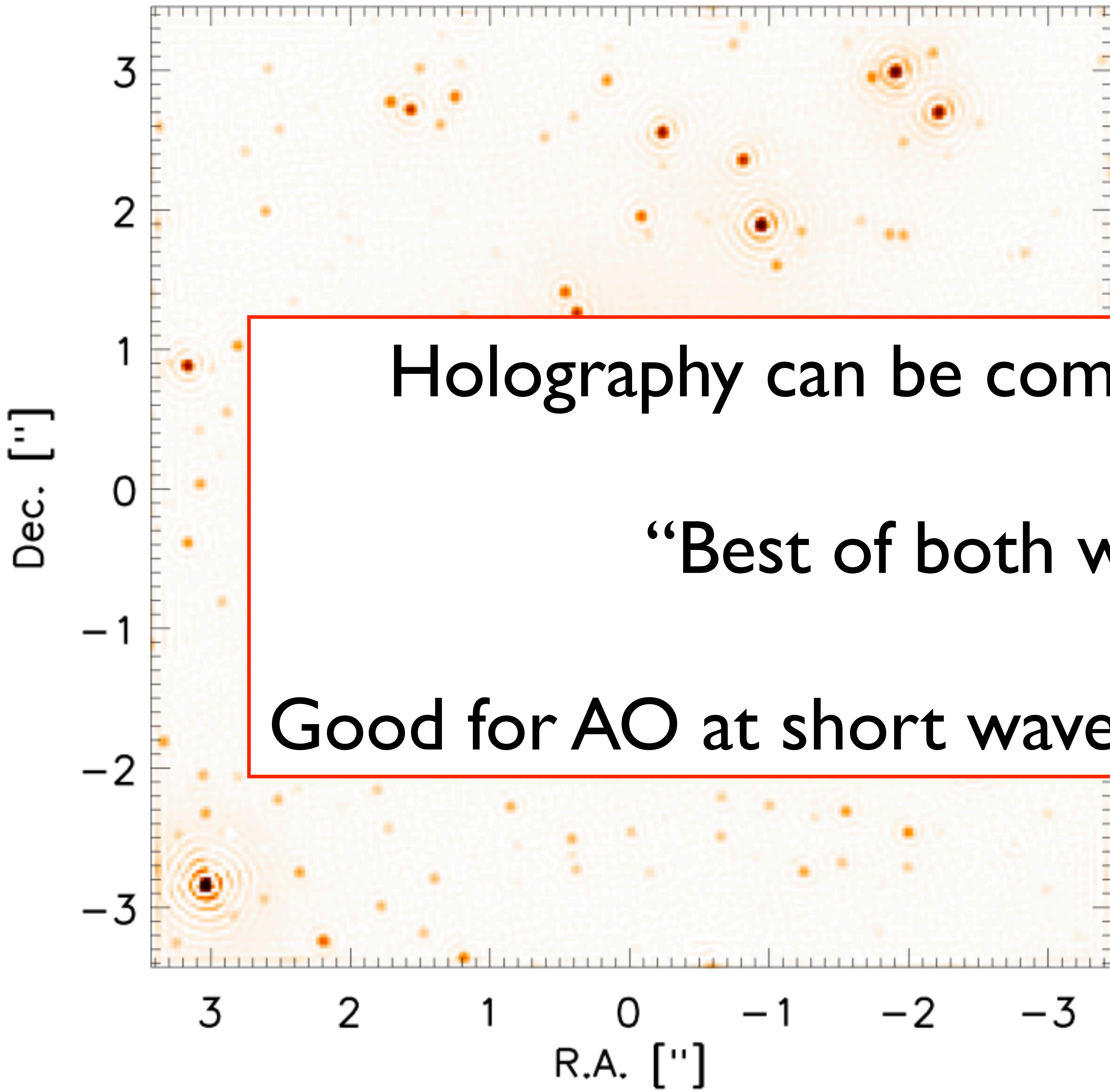

47 Tuc
NaCO/VLT
Ks

Holography can be combined with AO.

"Best of both worlds"

Good for AO at short wavelengths (e.g. AOLI).

"holographic" combination of AO frames

Under-sampling of the diffraction limit

Sensitivity of holography at the diffraction limit with current NIR detectors/electronics: Ks$\approx$19 at 5σ.

Under-sampling: less resolution, but higher sensitivity and larger field-of-view

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Under-sampling: less resolution, but higher sensitivity and larger field-of-view

For example, HAWKI@VLT:

- 0.106”/pixel (0.027”/pixel to sample diffraction limit at VLT)
- Sensitivity Ks≈20 at 5σ with t_{exp}=0.2s and t_{int} = 28s
- FOV: 217”×54”
- Reference stars as faint as Ks≈16 can be used.

Under-sampling of the diffraction limit

Sens rent

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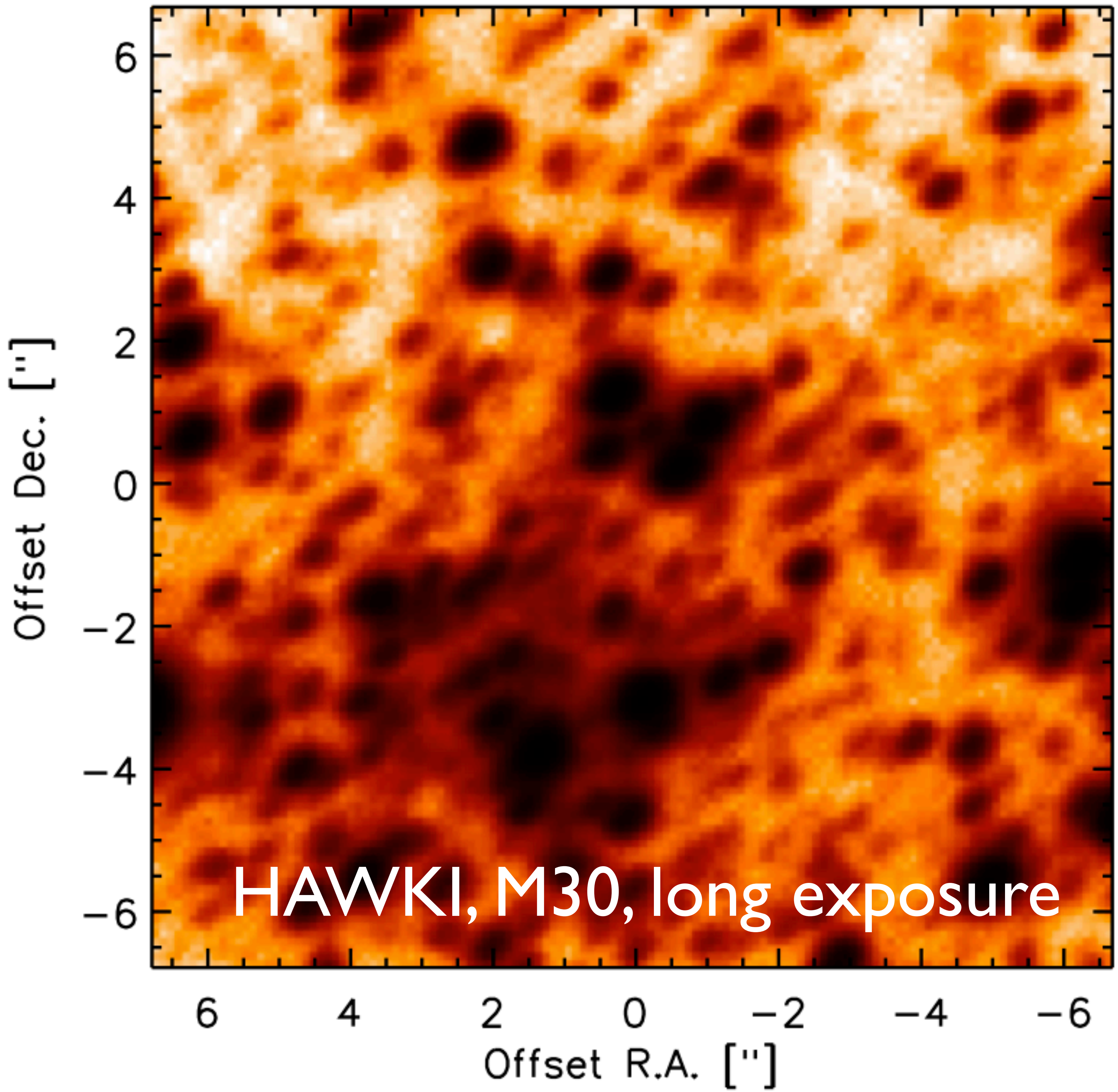
For e

- 0.1 VLT)
- Ser
- FO
- Ref



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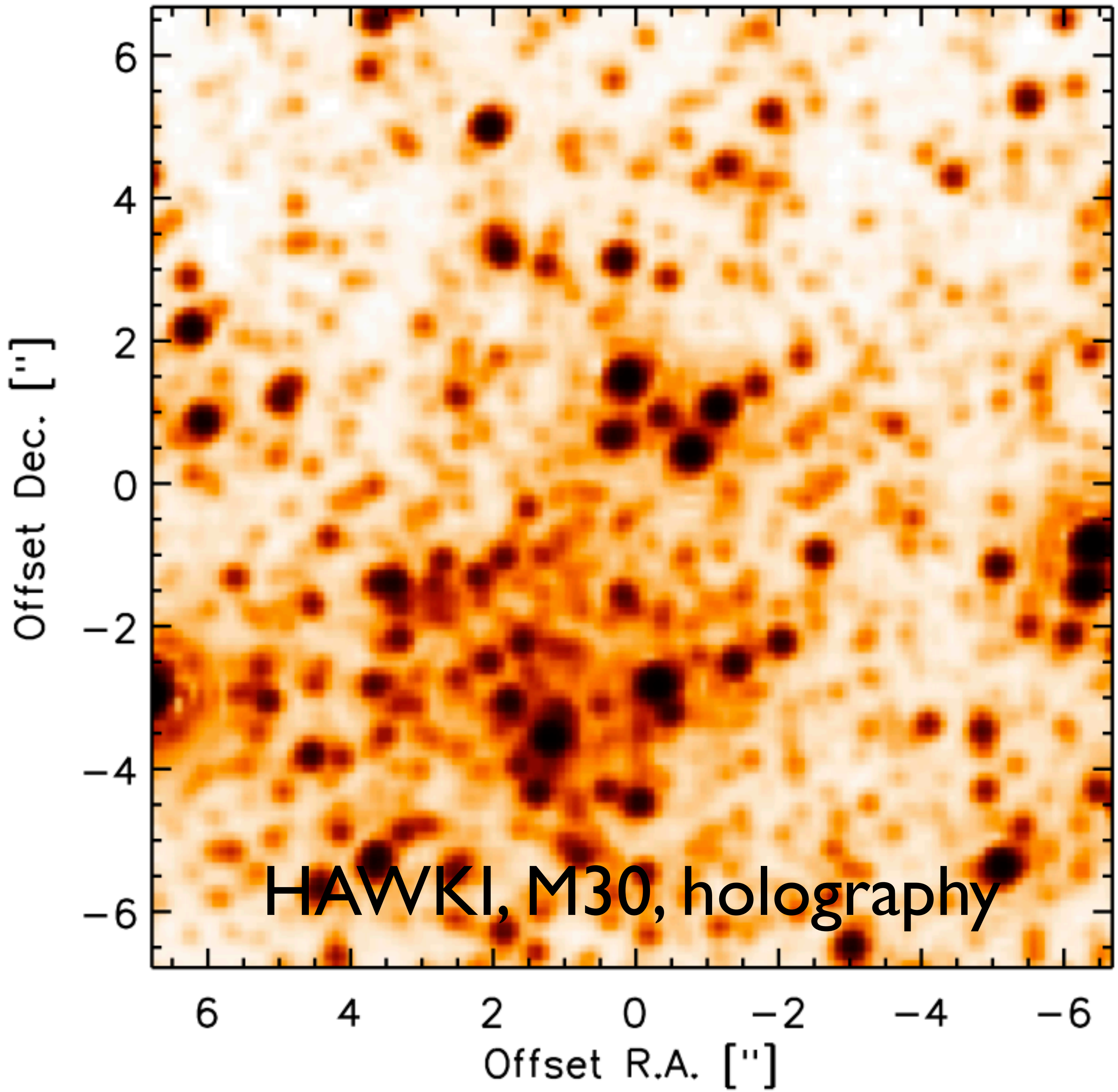

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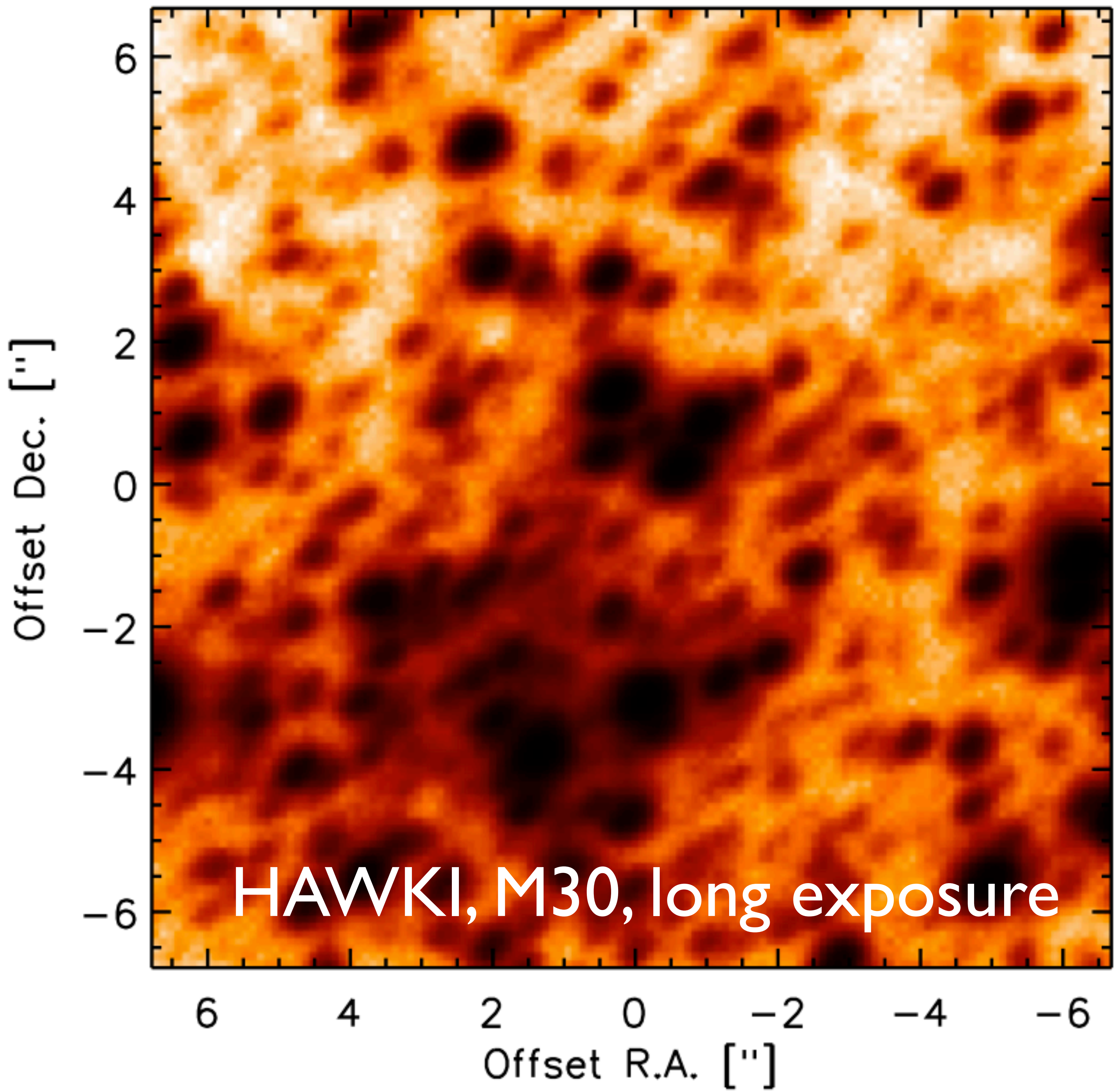

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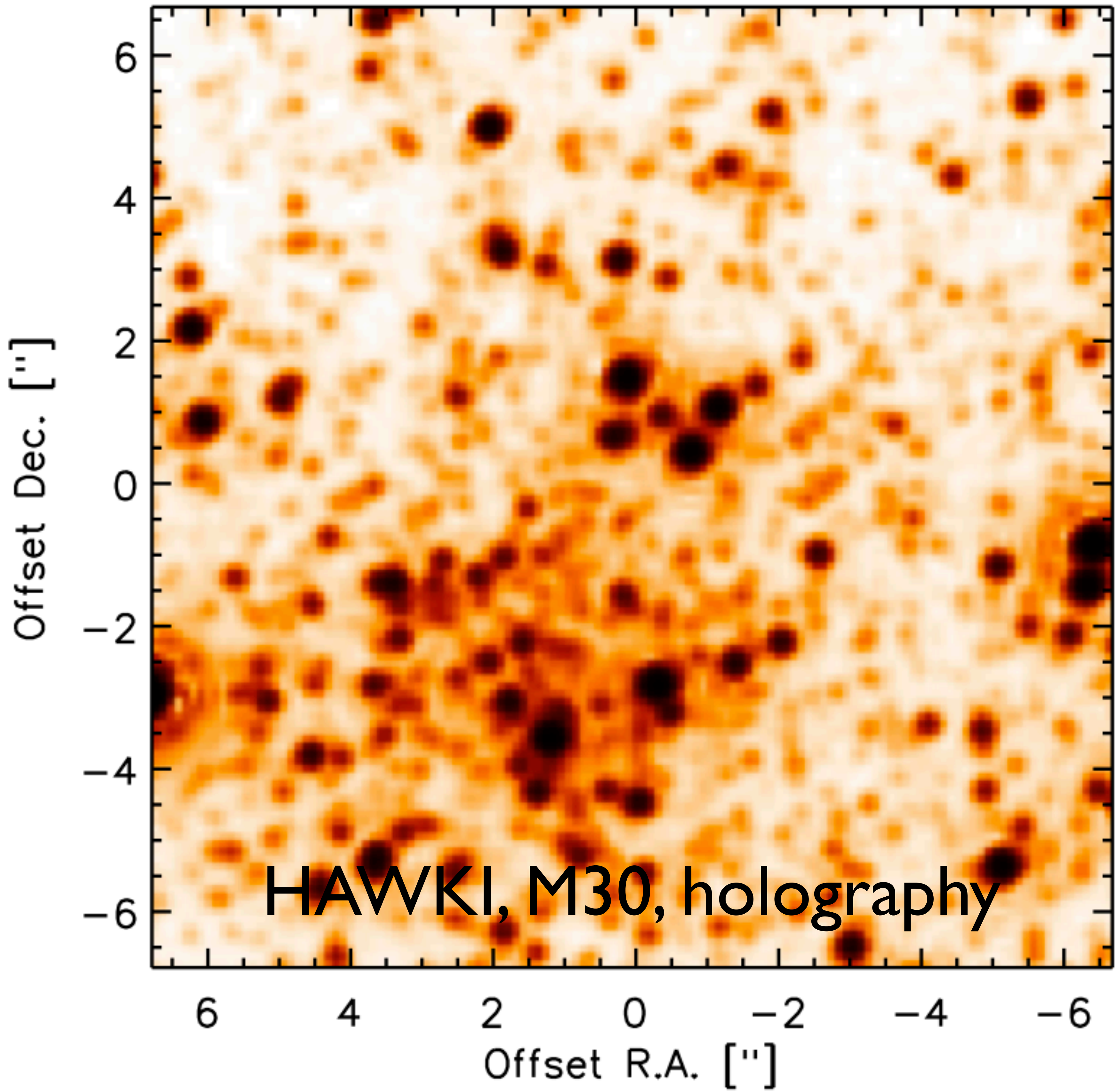
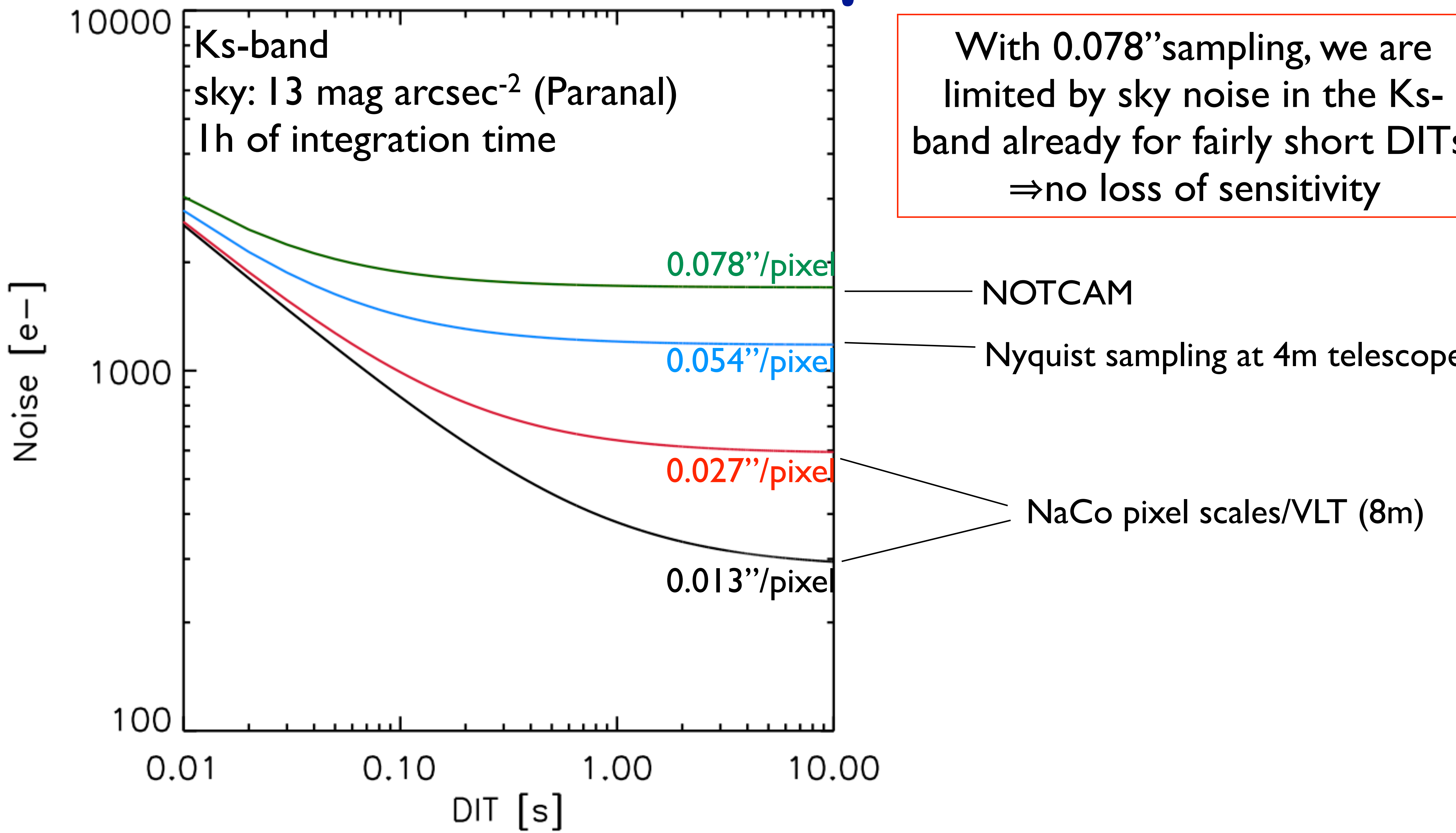


Holography with small telescopes



With 0.078"sampling, we are limited by sky noise in the Ks-band already for fairly short DITs. ⇒no loss of sensitivity

IV.Holography: stellar orbits around Sagittarius A*

Stellar orbits around Sgr A*

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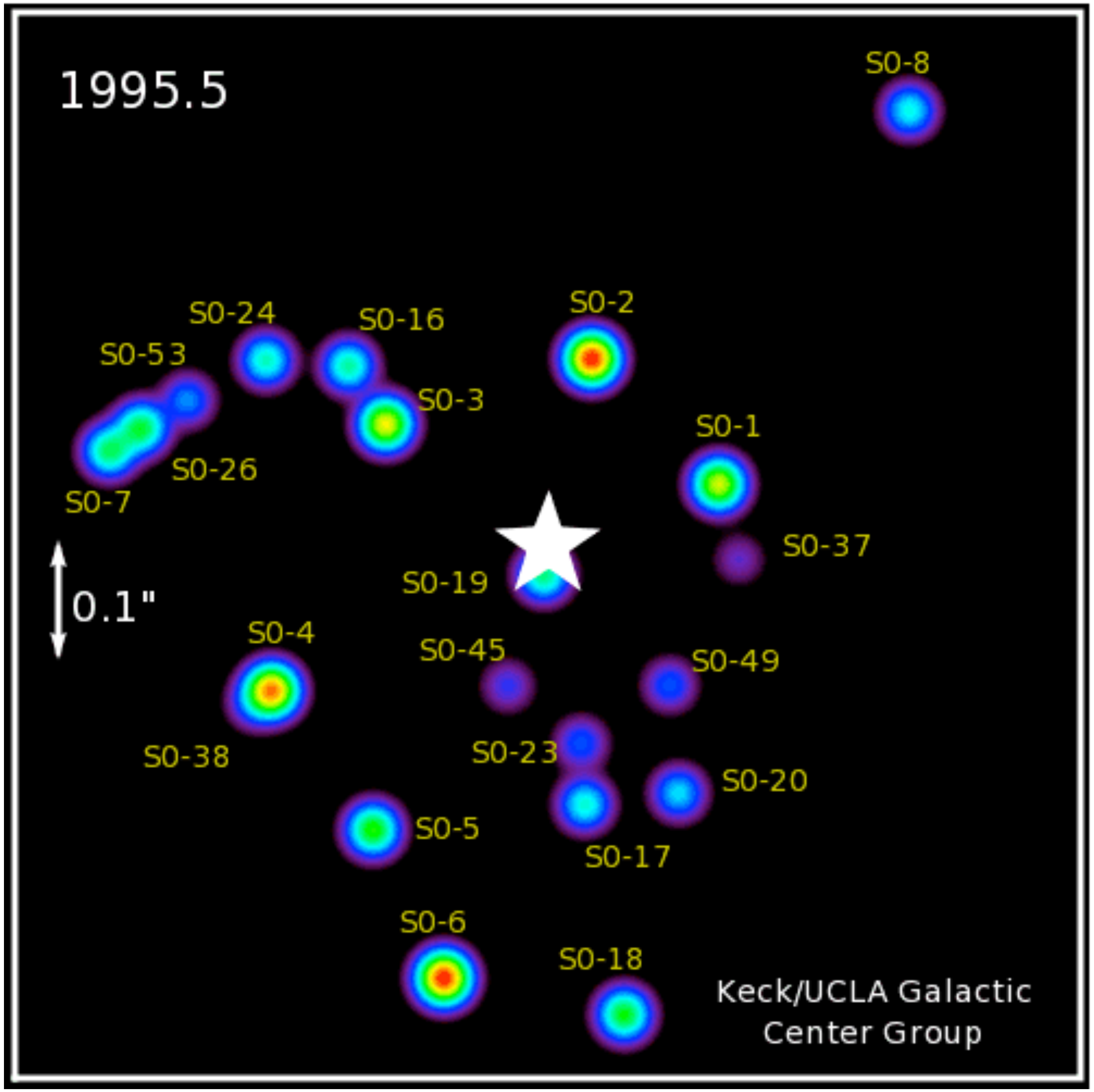

Stellar orbits around Sgr A*

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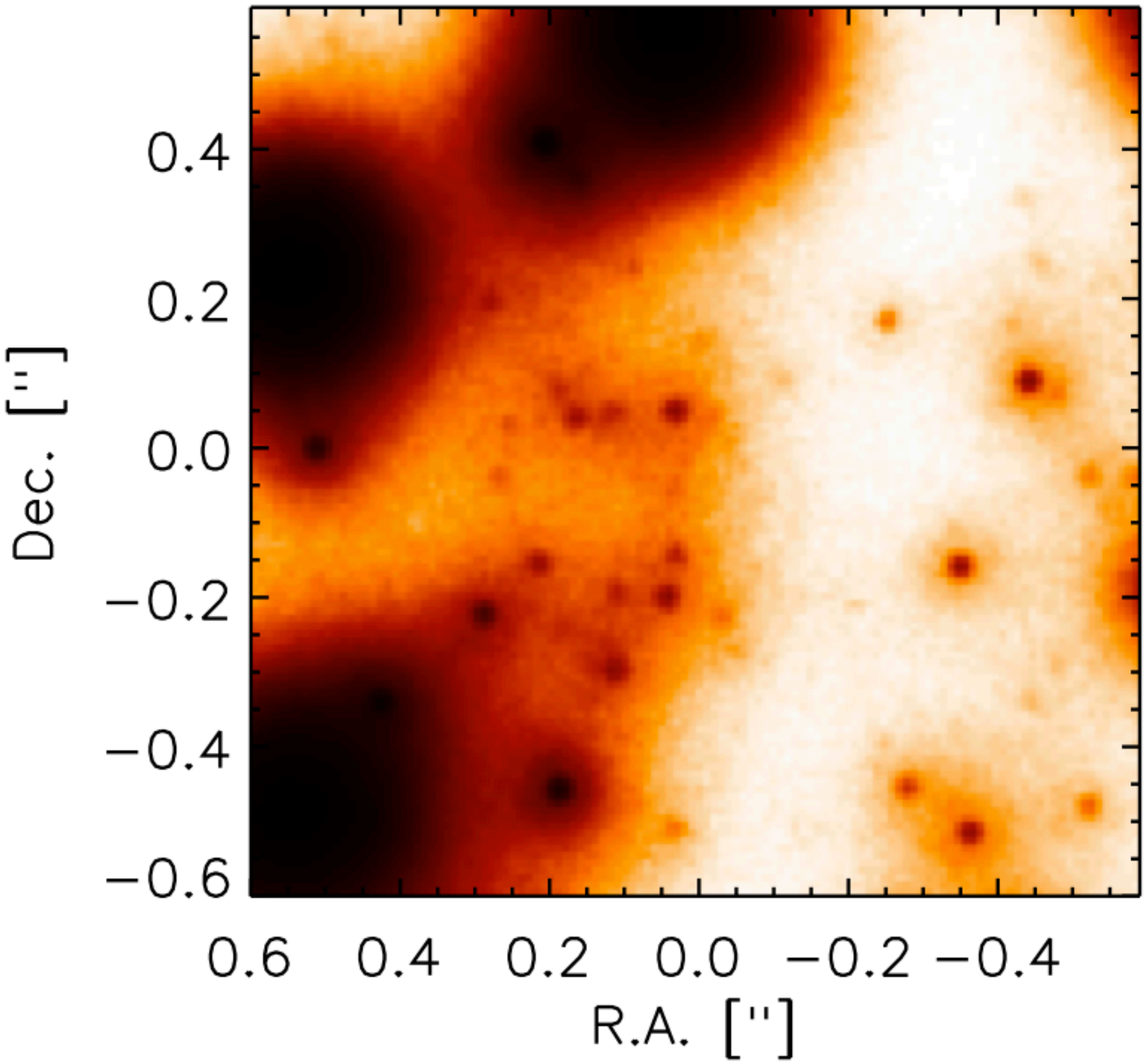
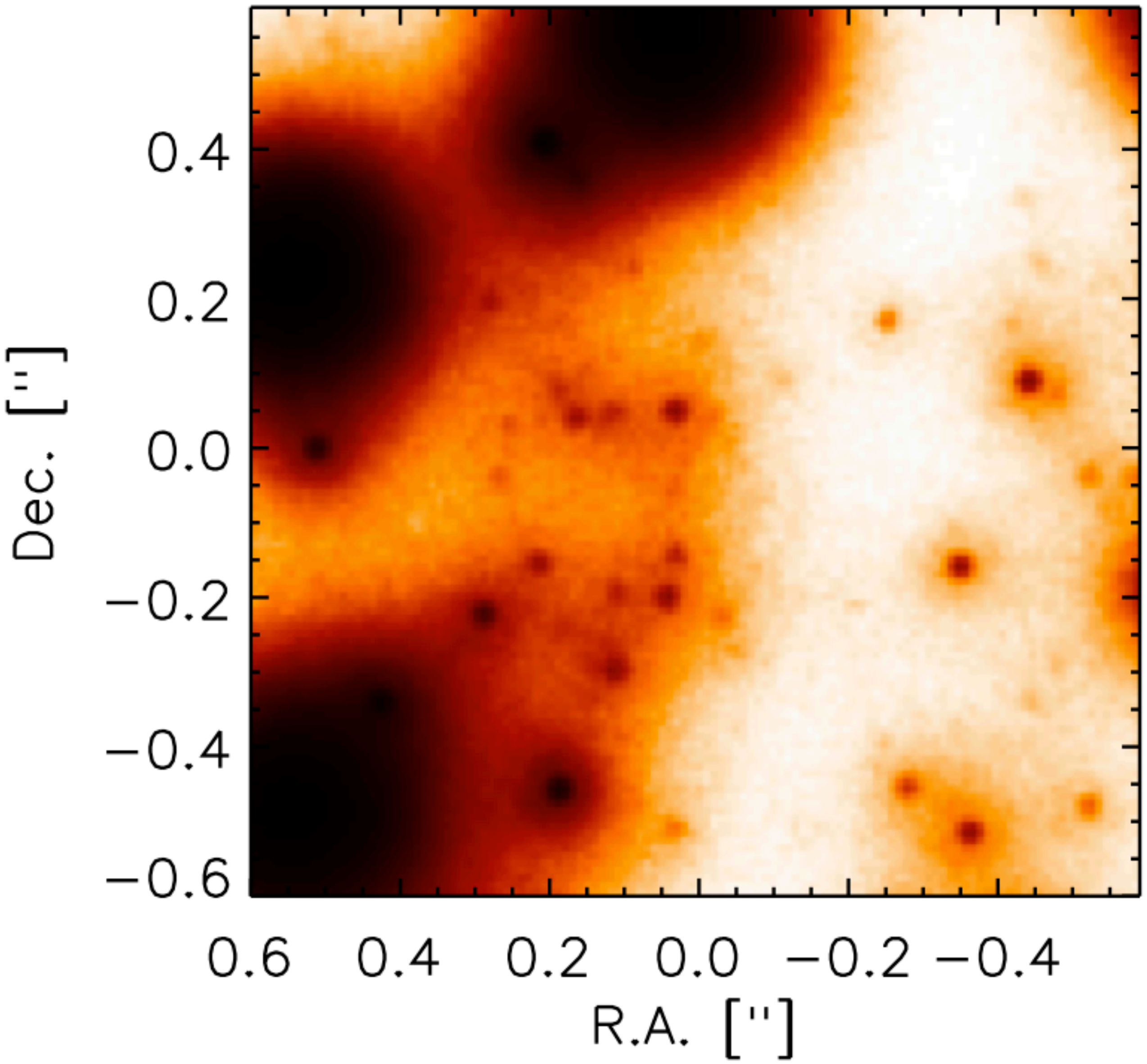
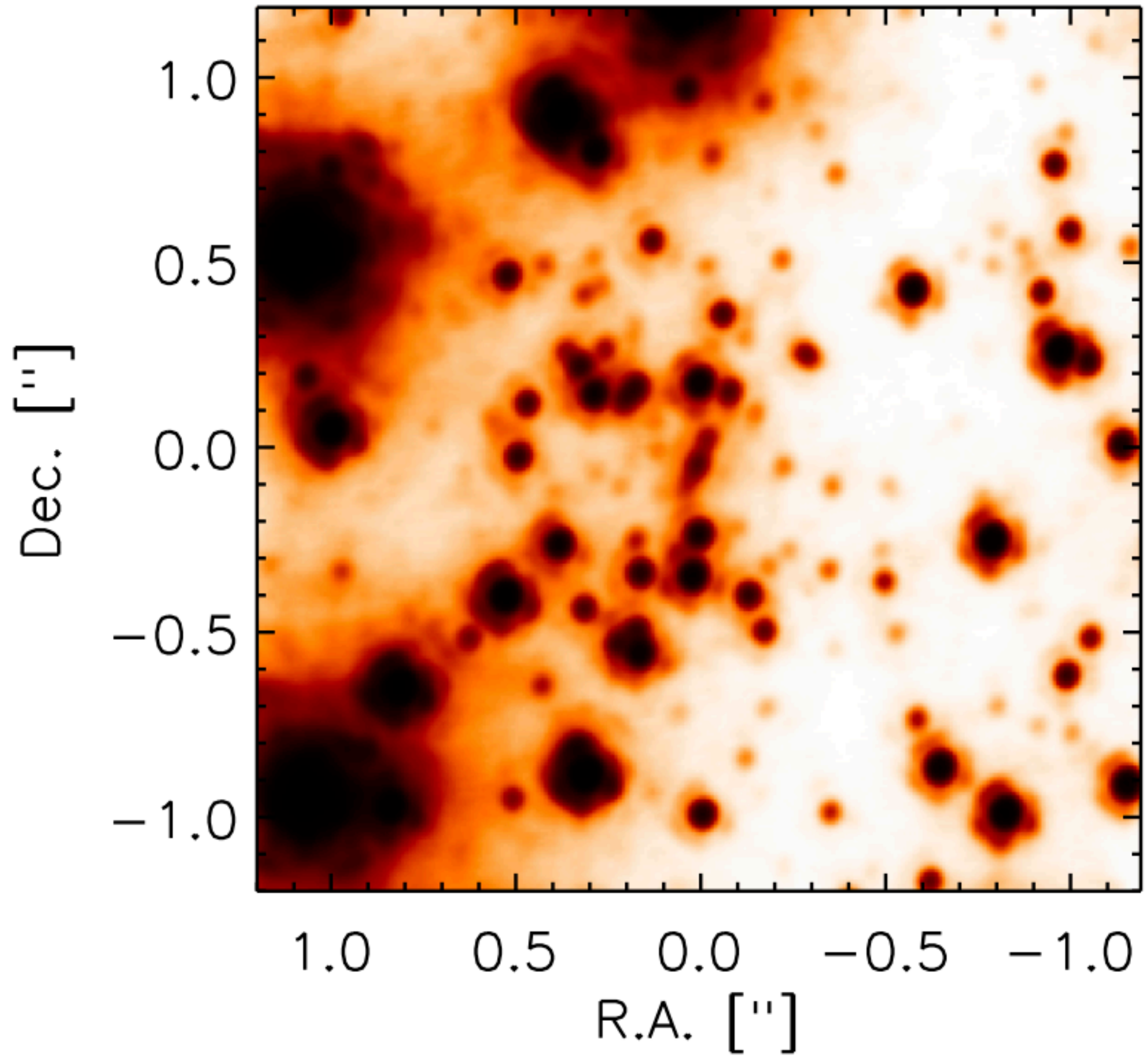


Speckle imaging+SSA
Keck/NIRC, 1995-2005

Stellar orbits around Sgr A*

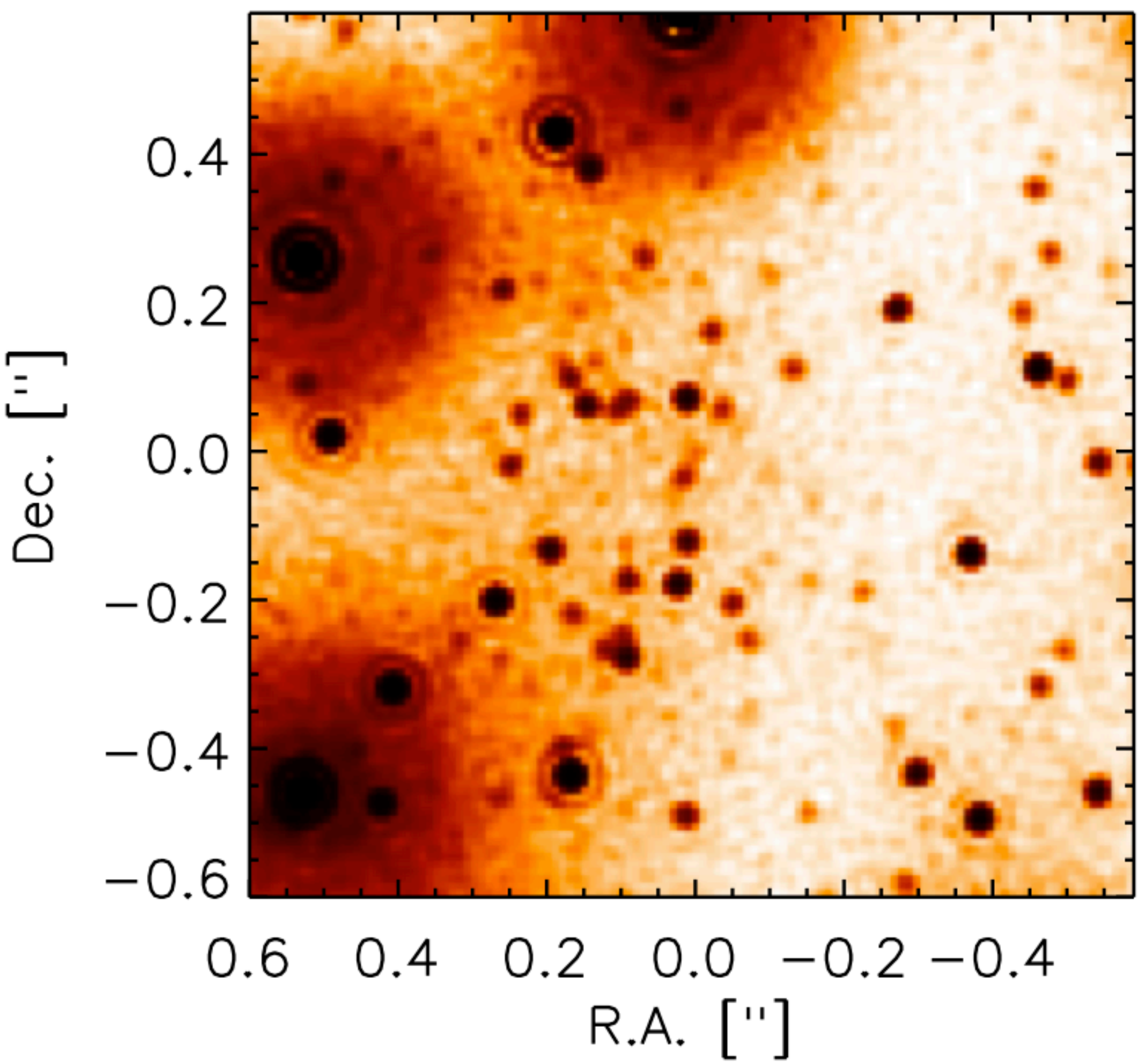


Speckle imaging+SSA
Keck/NIRC, 1995-2005

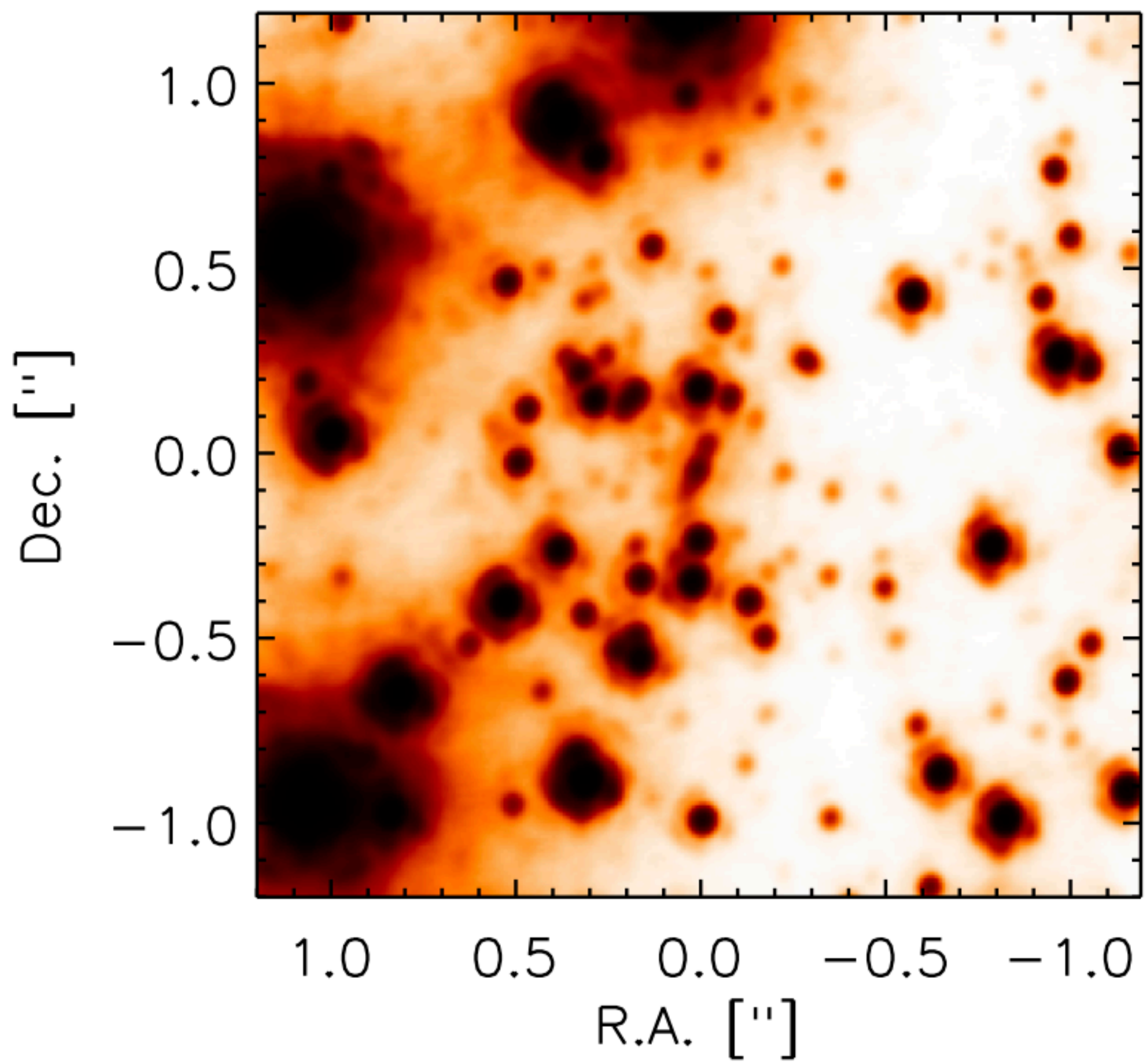


AO + LGS
Keck/NIRC2, since 2005

Stellar orbits around Sgr A*



Speckle imaging+Holography
Keck/NIRC, 1995-2005



AO + LGS
Keck/NIRC2, since 2005

Stellar orbits around Sgr A*

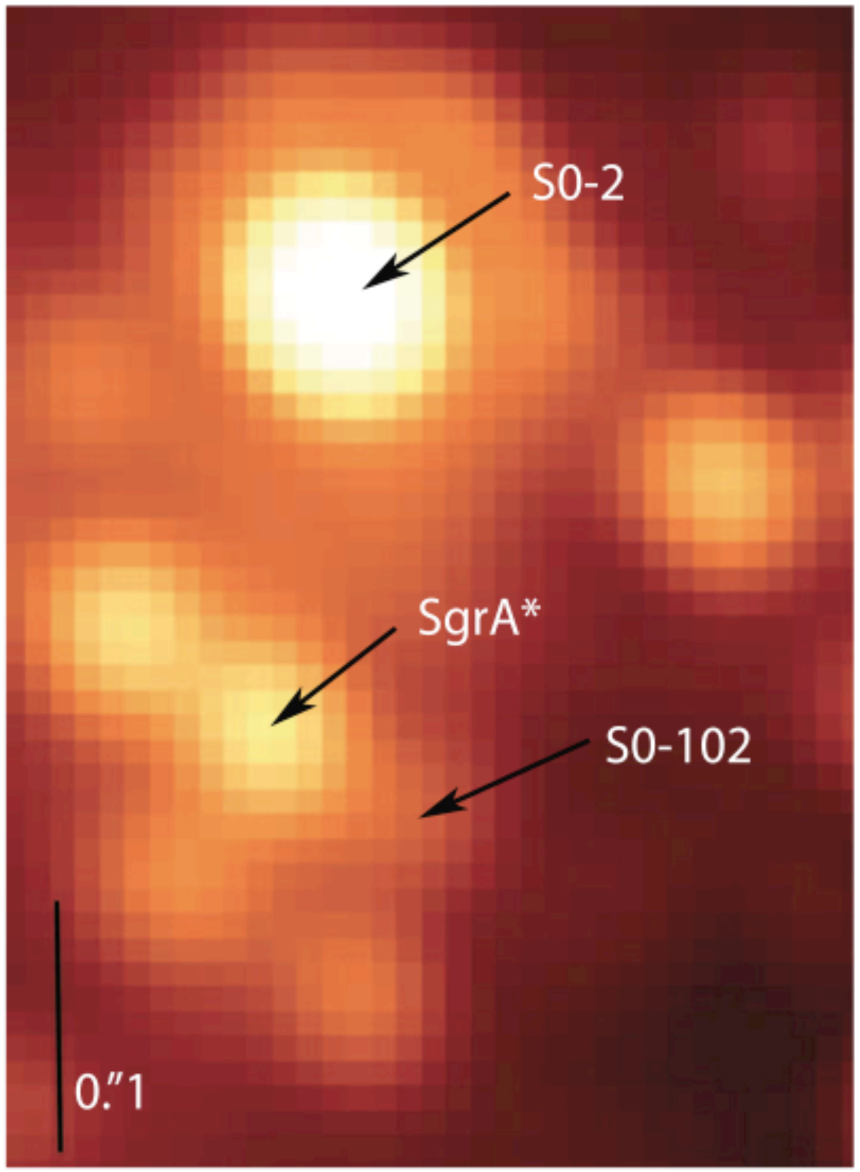
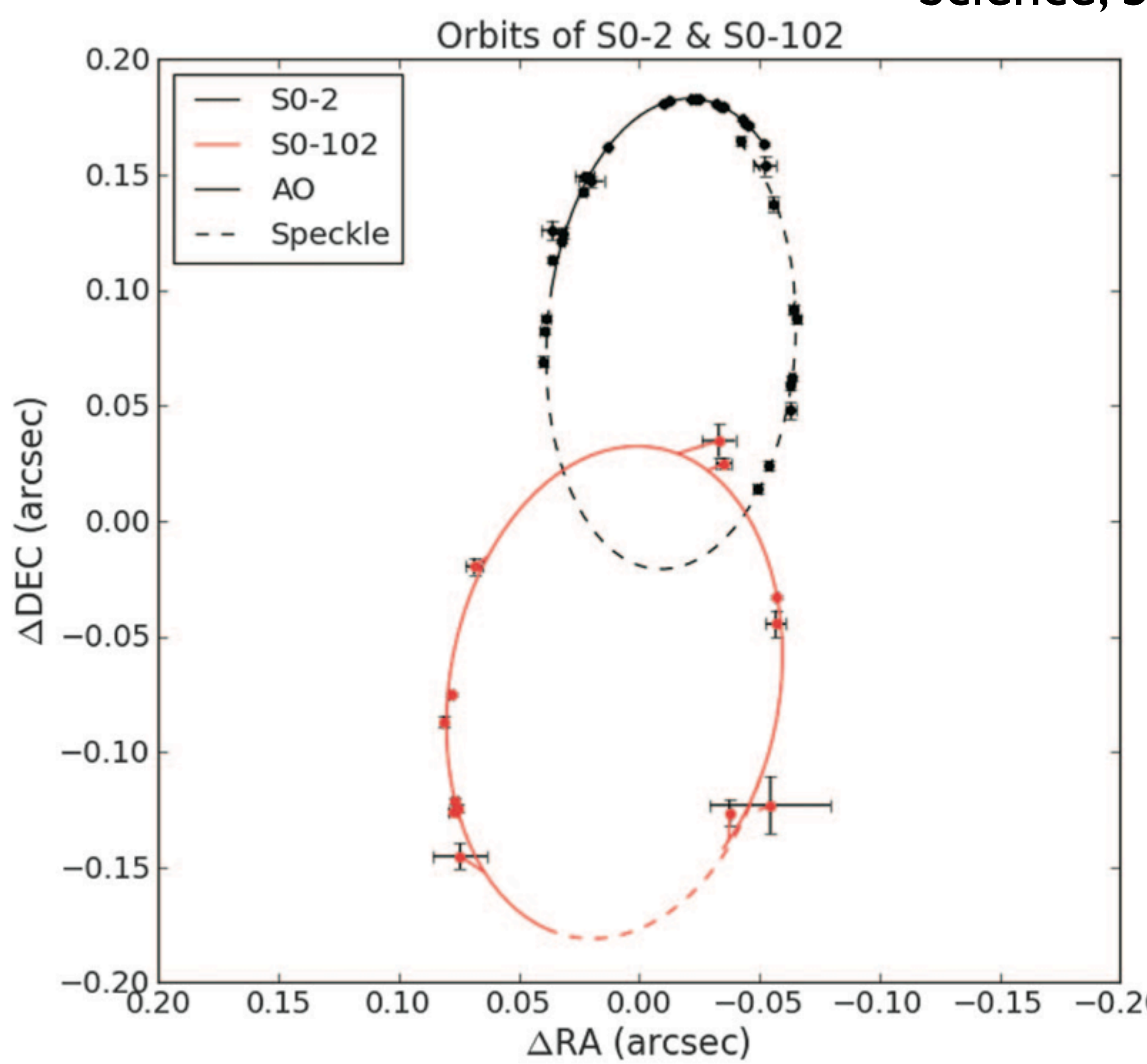


Fig. 1. A Keck/NIRC2 AO image from May 2010 showing the short-period star S0-102, which is, besides S0-2, the only star with full orbital phase coverage, and the electromagnetic counterpart of the black hole, Sgr A*. The image was taken at a wavelength of 2.12 μm and shows the challenge of detecting S0-102, which is 16 times fainter than S0-2 and lies in this crowded region.

The Shortest-Known–Period Star Orbiting Our Galaxy's Supermassive Black Hole

L. Meyer,[1] A. M. Ghez,[1*] R. Schödel,[2] S. Yelda,[1] A. Boehle,[1] J. R. Lu,[3] T. Do,[4,5] M. R. Morris,[1] E. E. Becklin,[1] K. Matthews[6]

Science, 5 Oct 2012



Conclusions

Holography: when to use it

Don't use it for very faint objects or if you need high time resolution, **don't use it** on isolated objects (preferred technique: sparse aperture masking).
Remember: S/N in short-exposures is usually sky-limited.

<u>**Use it in these situations:**</u>

- **Highly extinguished fields** with not optical/IR bright guide or tip-tilt stars

- Dealing with **anisoplanatic effects** in crowded fields

- **No AO** available

- **AO, but unstable correction**

- Sensitive, high angular resolution imaging in the **optical regime**

- **MIR imaging** if there is a sufficiently bright reference object in the field

What to take away...

Holography...

• can be **equivalent to or even superior to AO** and is **(almost always) superior to simple lucky imaging**

• can make **optical diffraction limited imaging** possible **at 10m-telescopes**

• is ***economic, powerful, and easy*** (plug&play)

• is particularly **attractive for small telescopes**

• **works with existing instruments** (INGRID, NOTCAM, ASTRA-LUX,FASTCAM, HAWKI, NACO,VISIR)**, very little or no investment needed** (RO electronics)

• **Fast readout mode** should be made available at all imaging instruments

Schödel, Yelda, Ghez, Girard, Labadie, Rebolo, Pérez-Garrido, Morris, 2012, MNRAS, accepted for publication, arXiv:1110. 2261

Thank you!