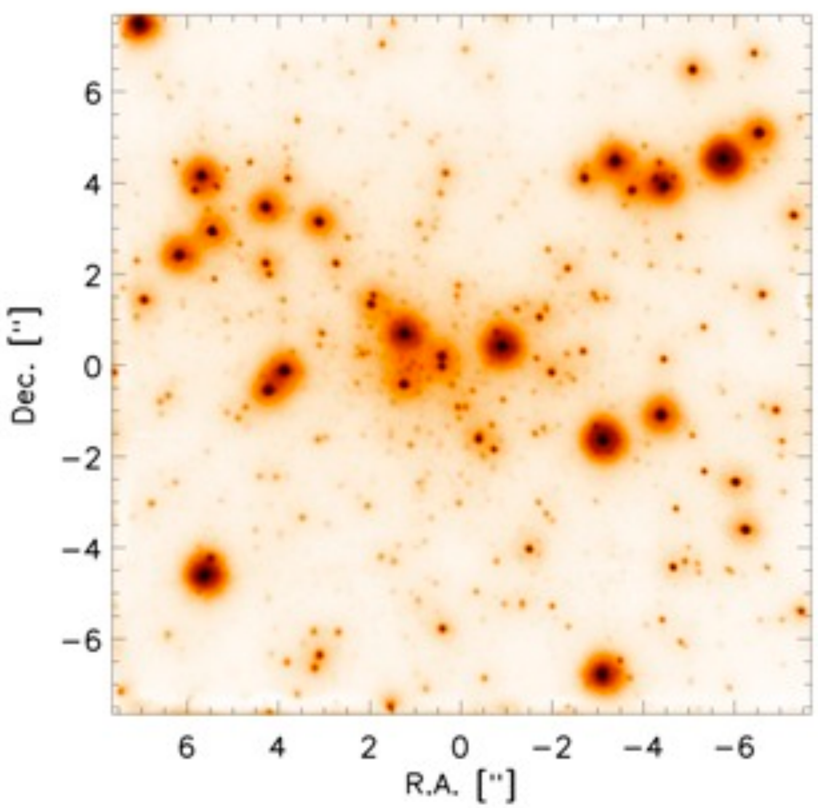
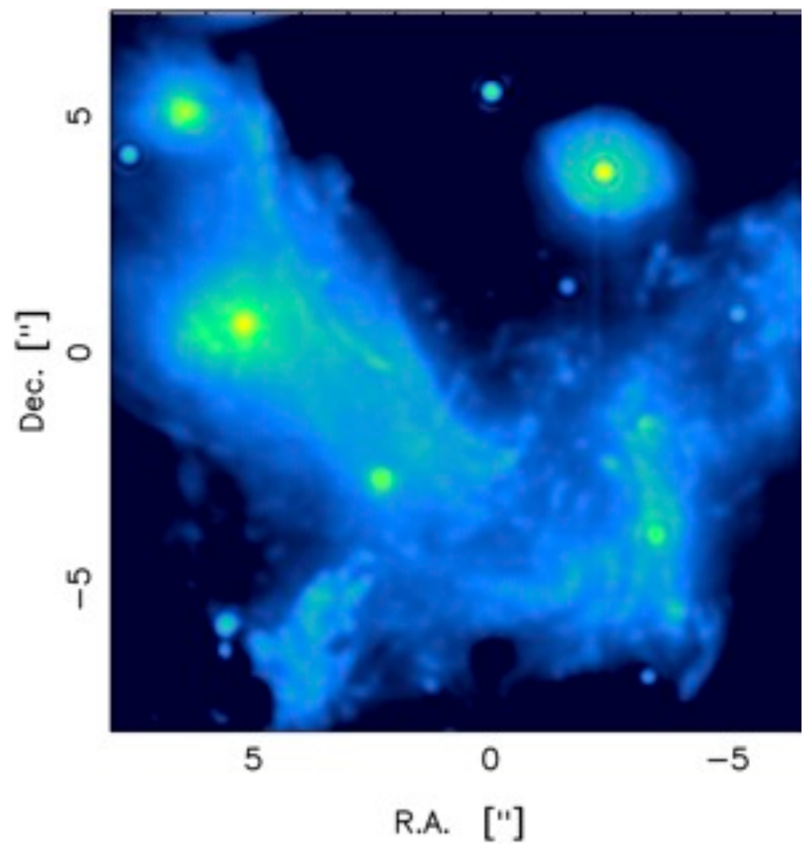
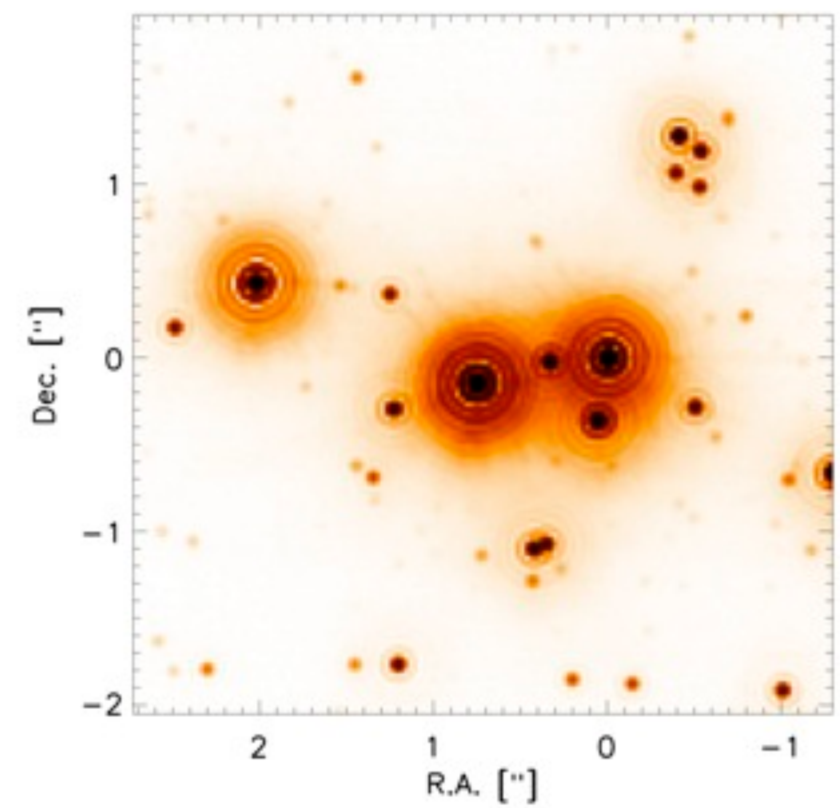
Imaging large fields at high resolution: cheat's MCAO for the CAHA and ORM







Rainer Schödel (IAA-CSIC)
Madrid, 22 March 2012

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

Basic concepts

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

The diffraction limit and atmospheric turbulence

Fried parameter:

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

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

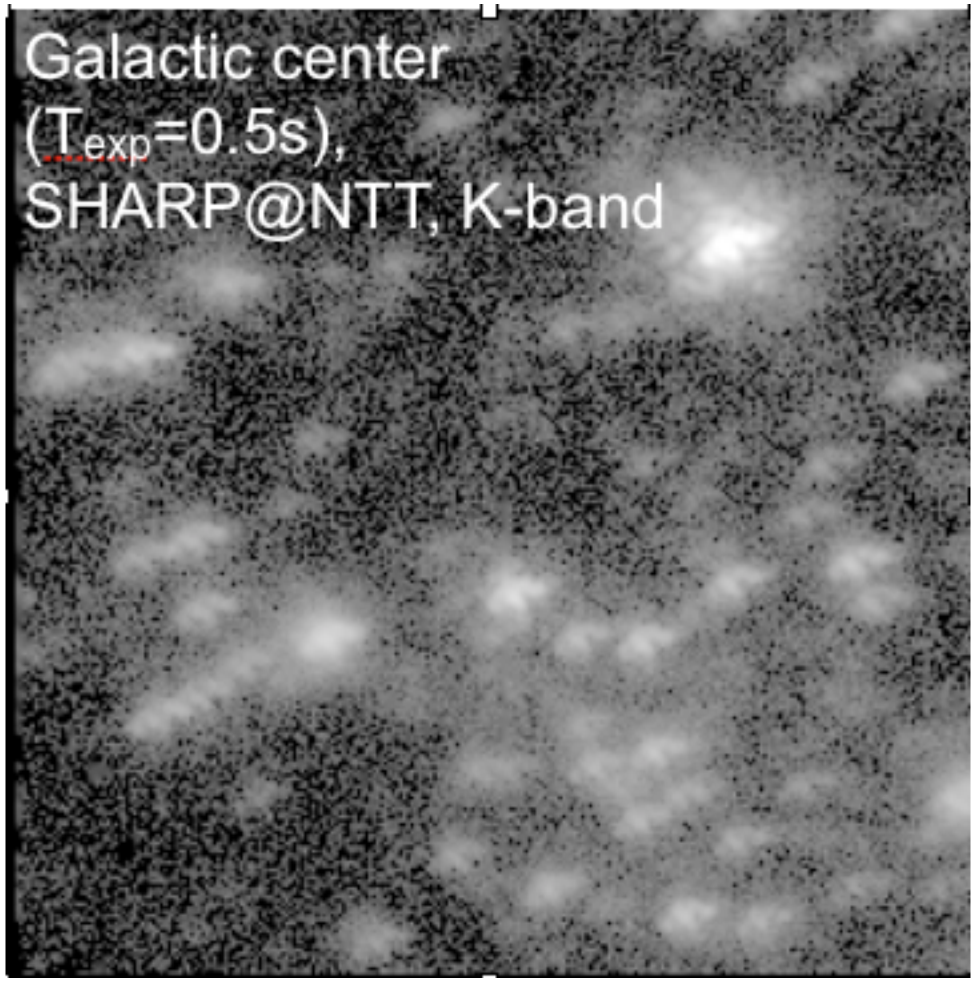
r_0 (0.5μm) ≈ 10 cm

r_0 (2.2μm) ≈ 60 cm

r_0 (10μm) ≈ 360 cm

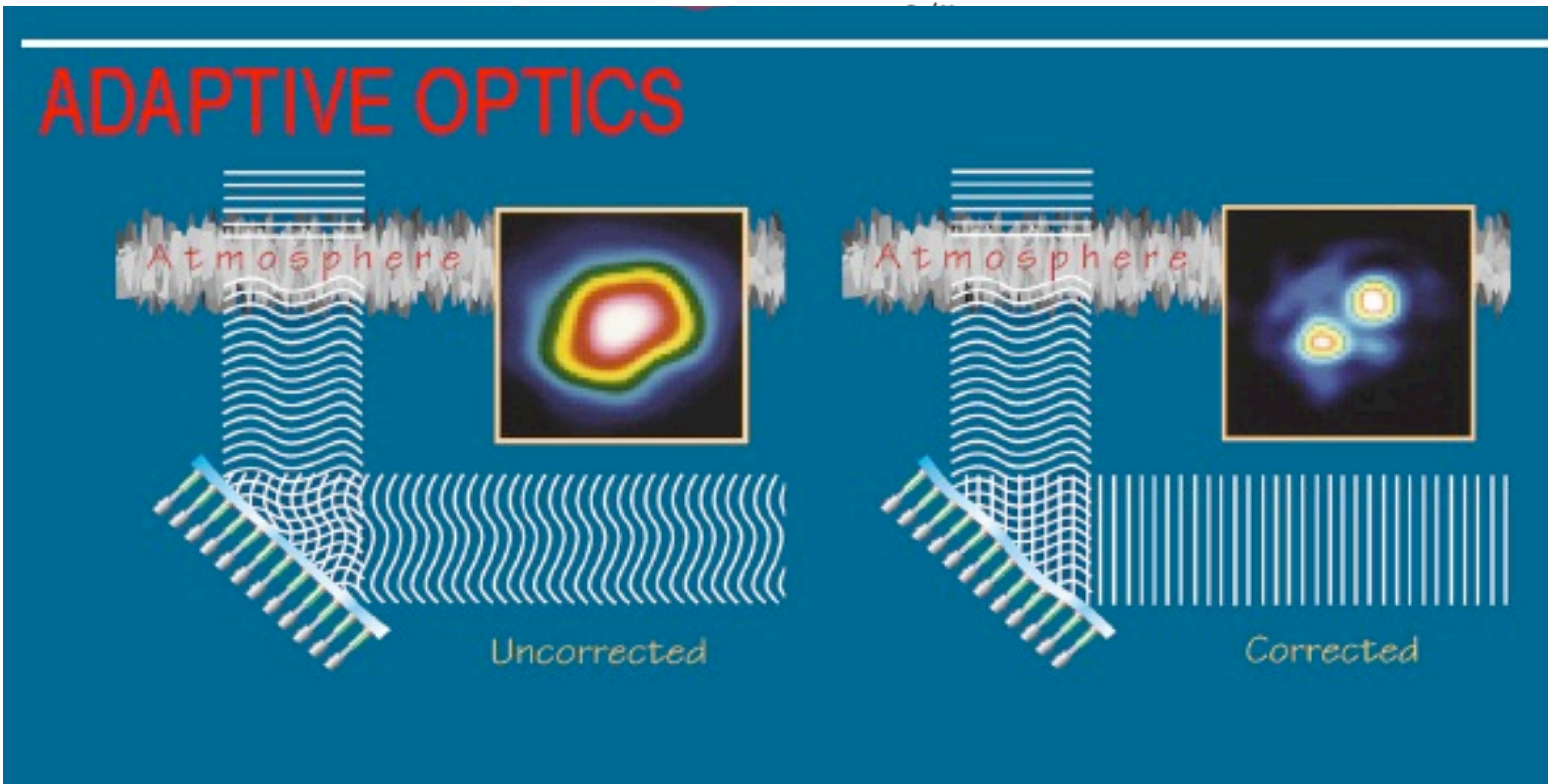
Coherence time:

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



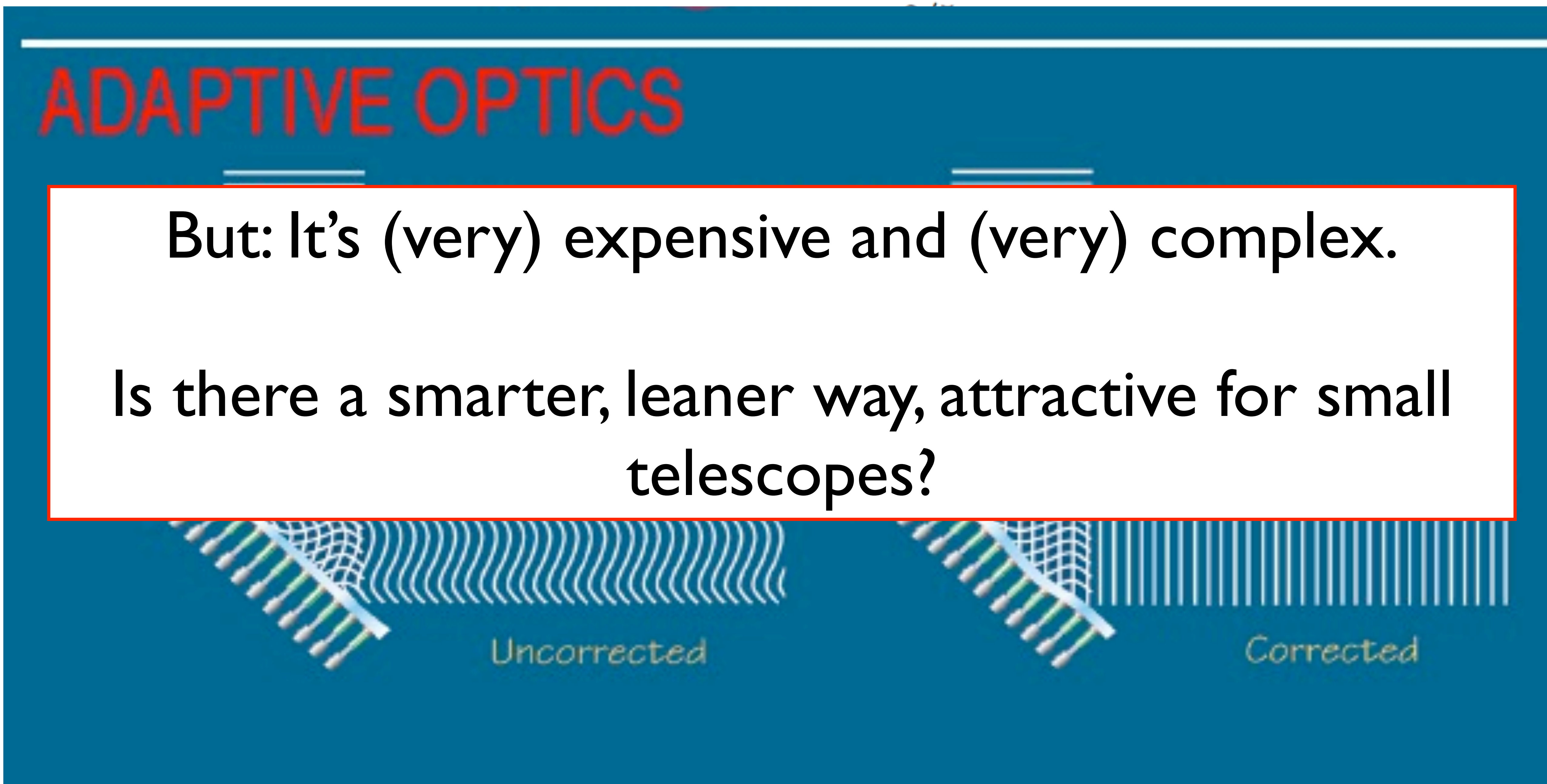
The diffraction limit and atmospheric turbulence

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



The diffraction limit and atmospheric turbulence

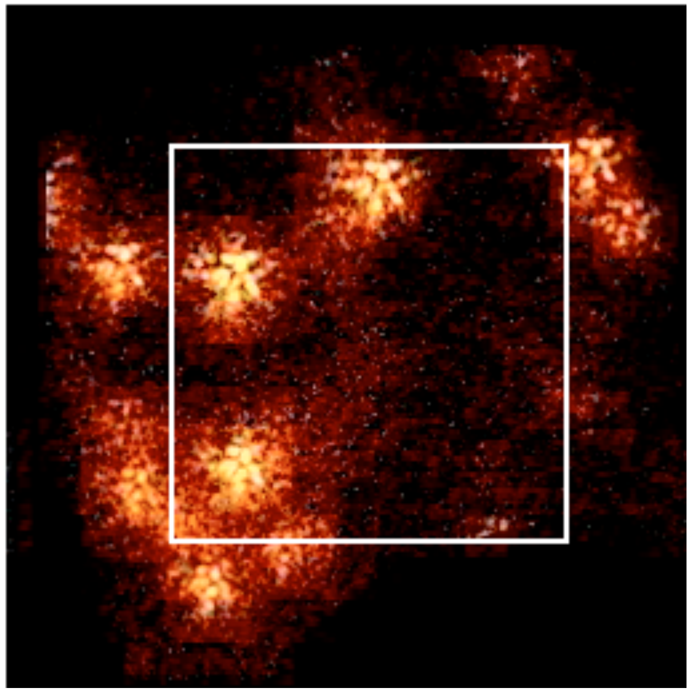
<u>Fried parameter:</u>



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

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

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>

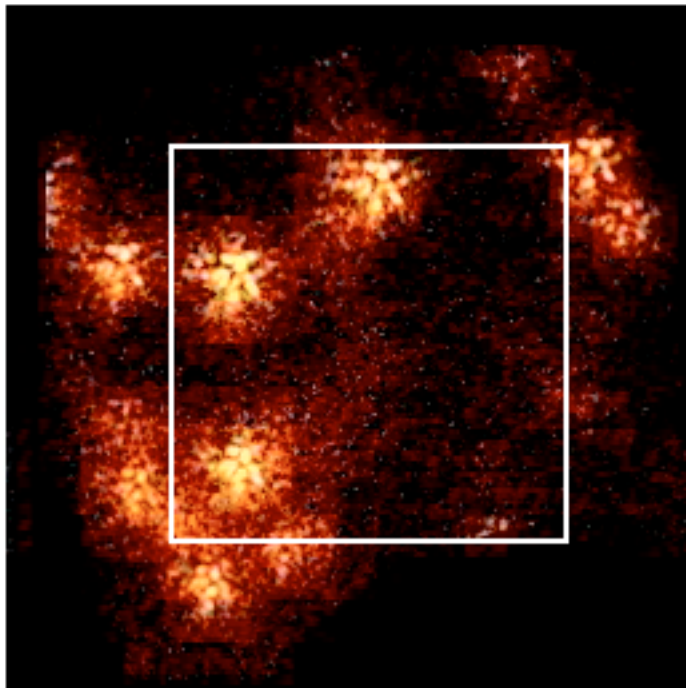
1. choose a reference star and reference pixel
2. shift each image in stack so that brightest speckle of reference star comes to rest on reference pixel
3. average stack

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

Selection of best frames (*lucky imaging*)
⇒ Strehl ratios 10%-30%

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

Speckle imaging



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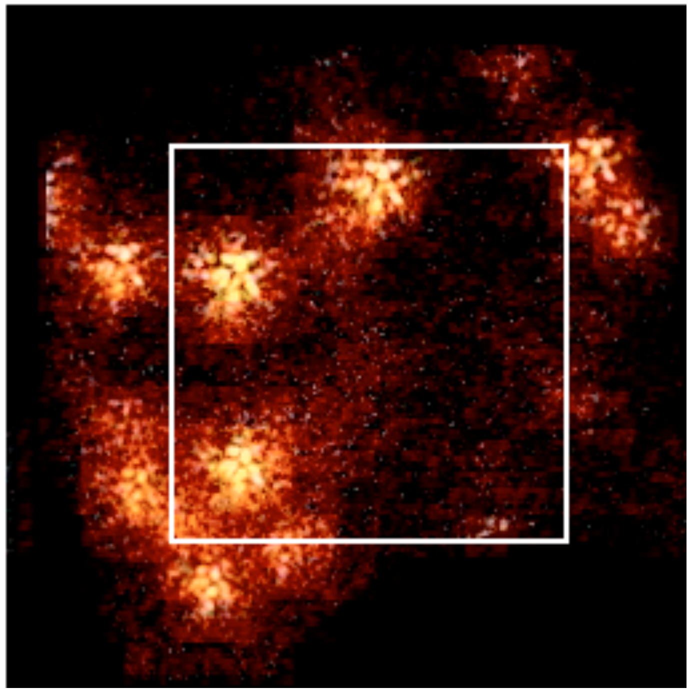

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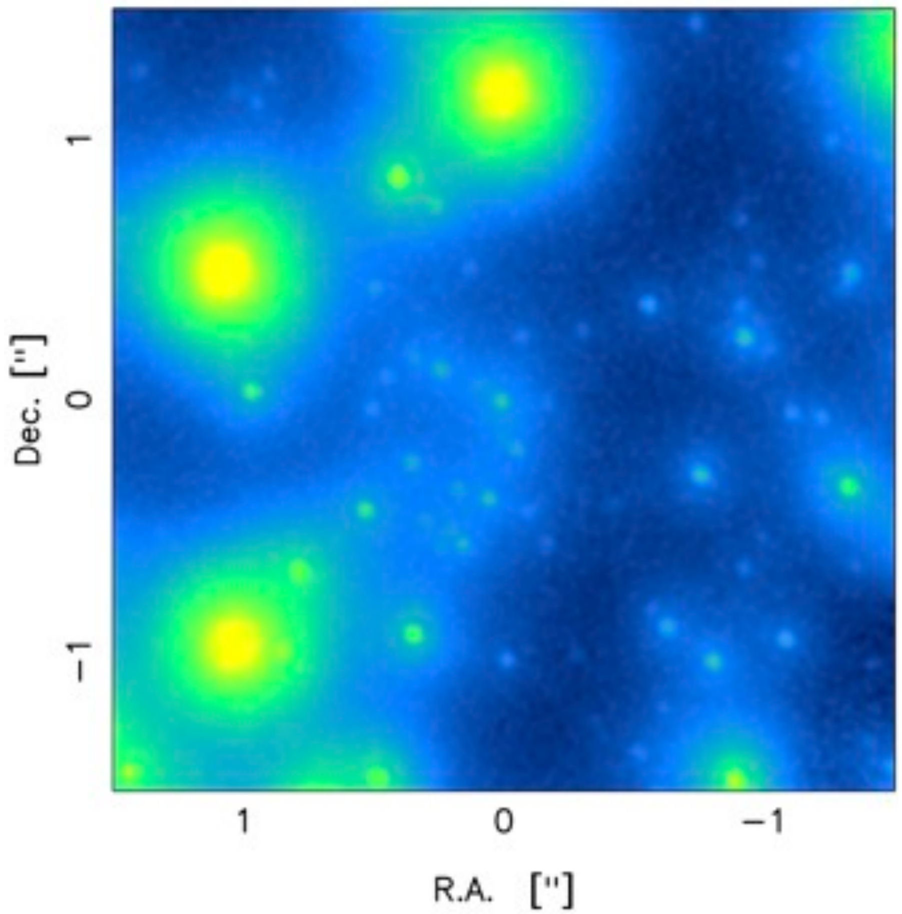

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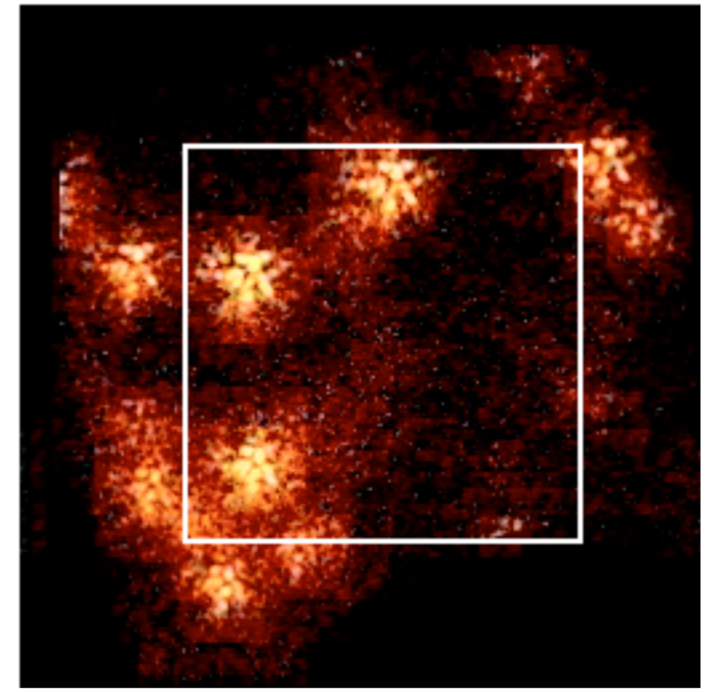
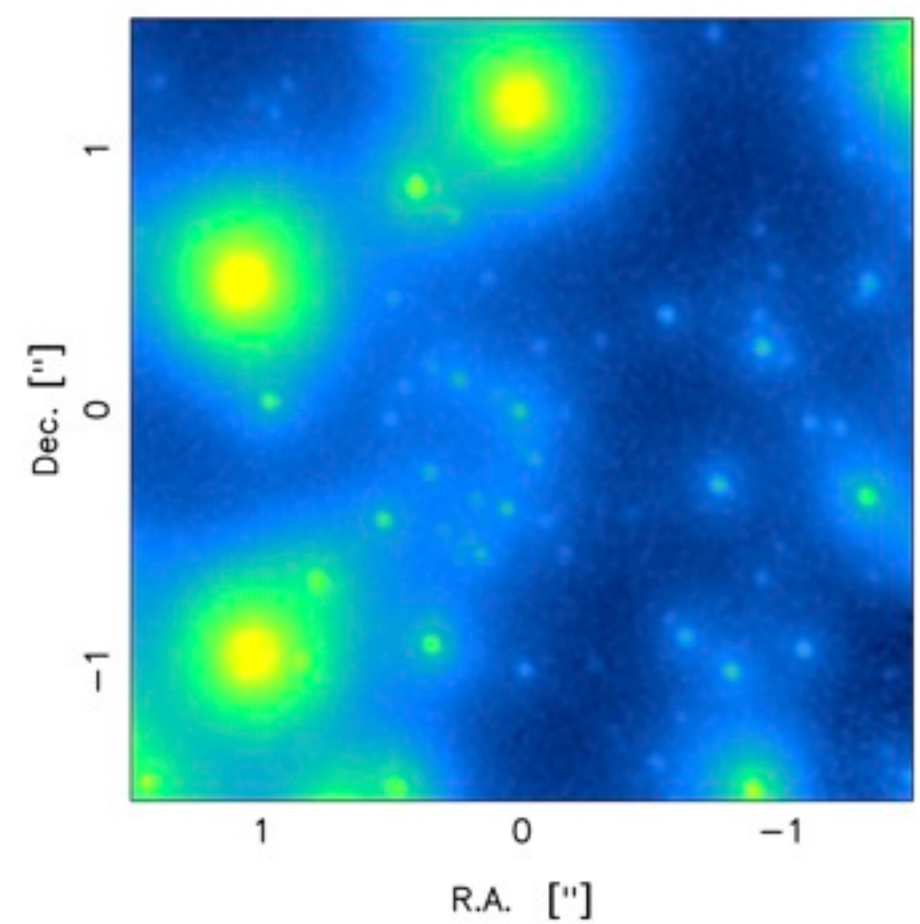


SSA reconstruction



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⇒ Strehl ratios 10%-30%

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

⇒ but: *inefficient and not very sensitive*

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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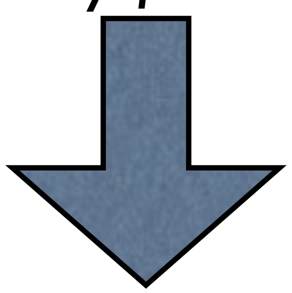

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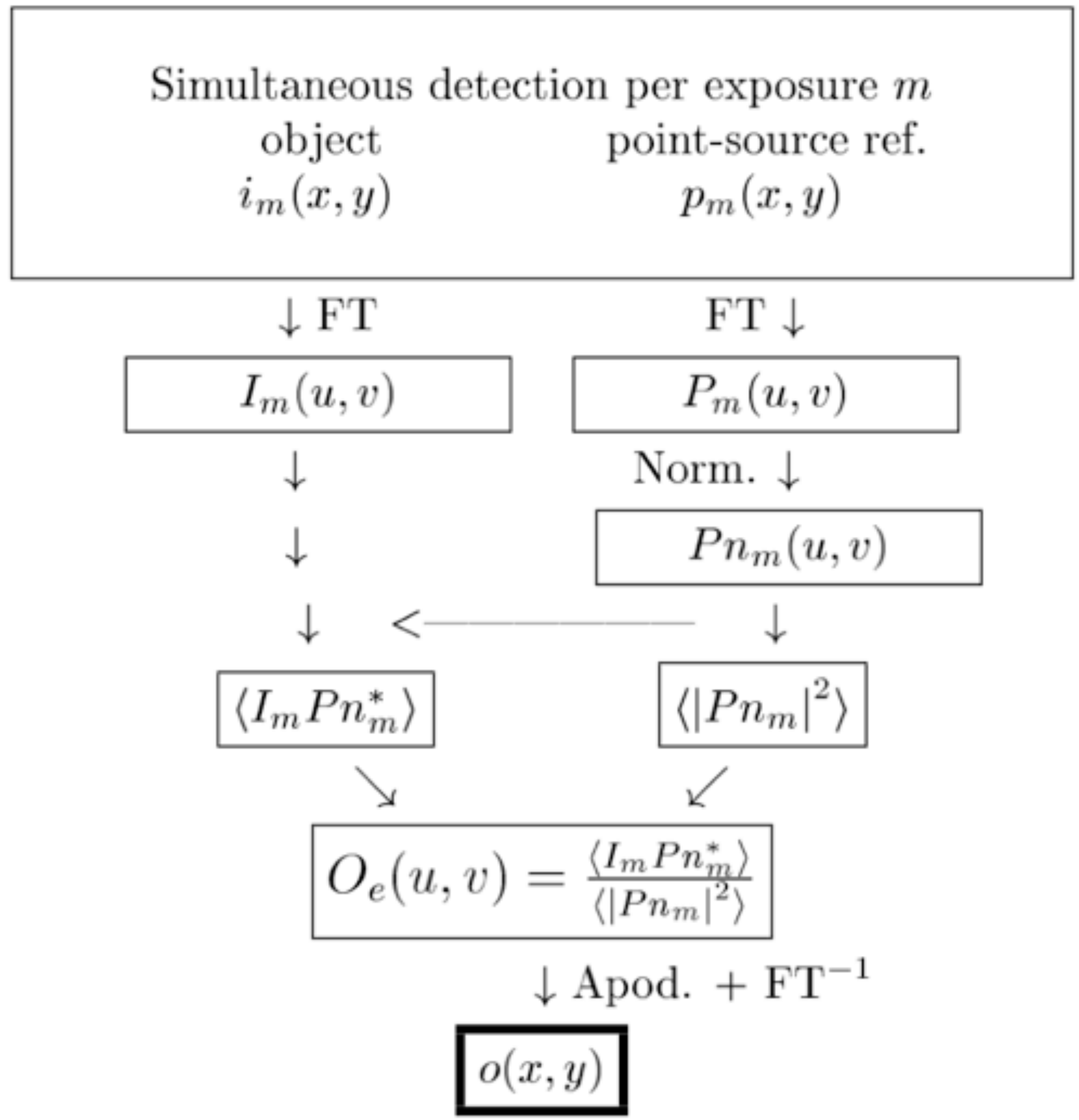


figure from *Petr et al. (1998)*

Speckle holography

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

$$= I_m(u, v)P_m^*(u, v)$$

Simultaneous detection per exposure m

object $i_m(x,y)$ — point-source ref. $p_m(x,y)$

Key is accurate measurement of the instantaneous PSF.

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

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

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

$\langle I_m Pn_m^* \rangle$ ↘ ↙ $\langle |Pn_m|^2 \rangle$

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

↓ Apod. + FT^{-1}

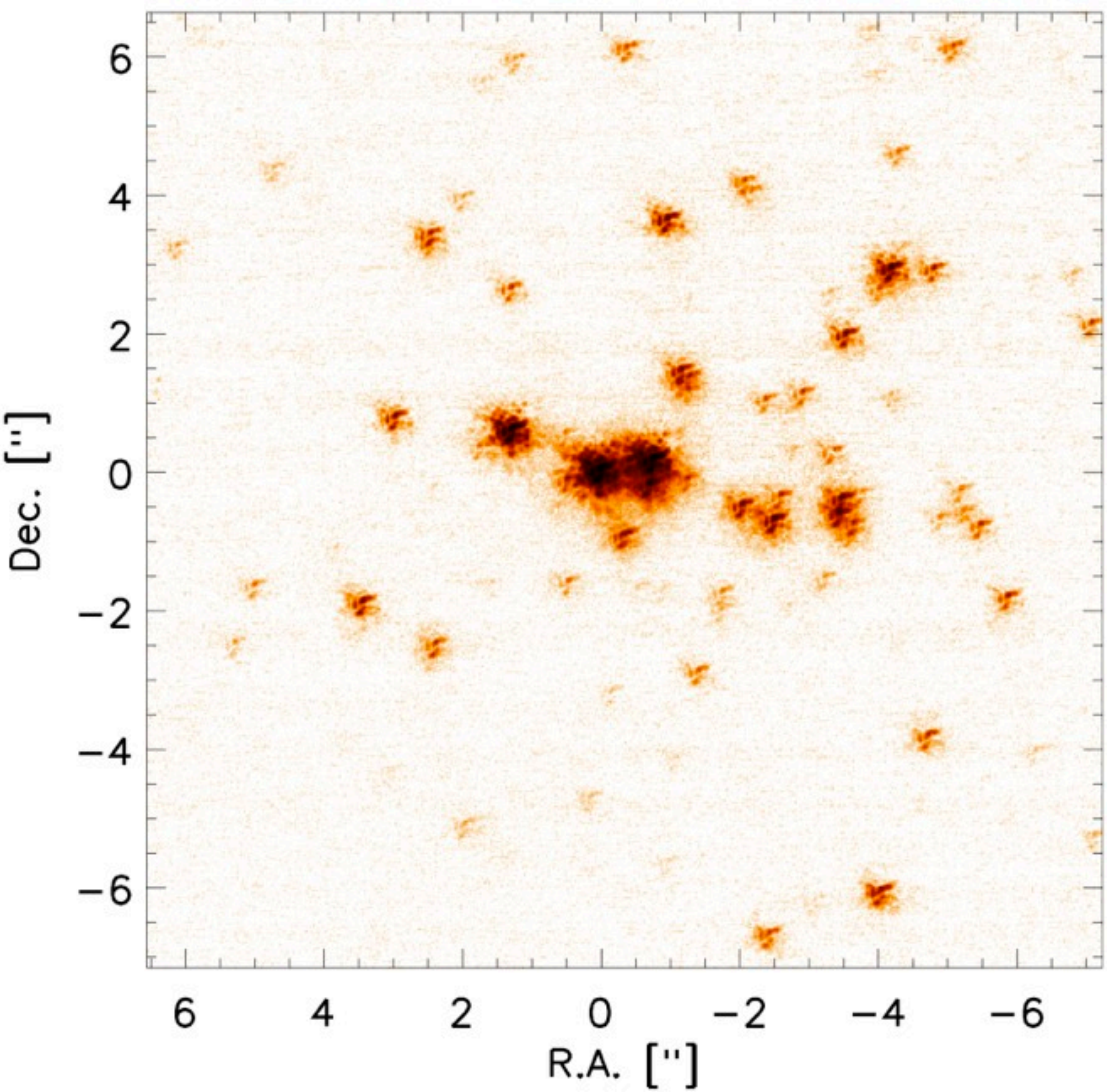
$o(x,y)$

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

figure from *Petr et al. (1998)*

The Test:
Speckle imaging of NGC 3603

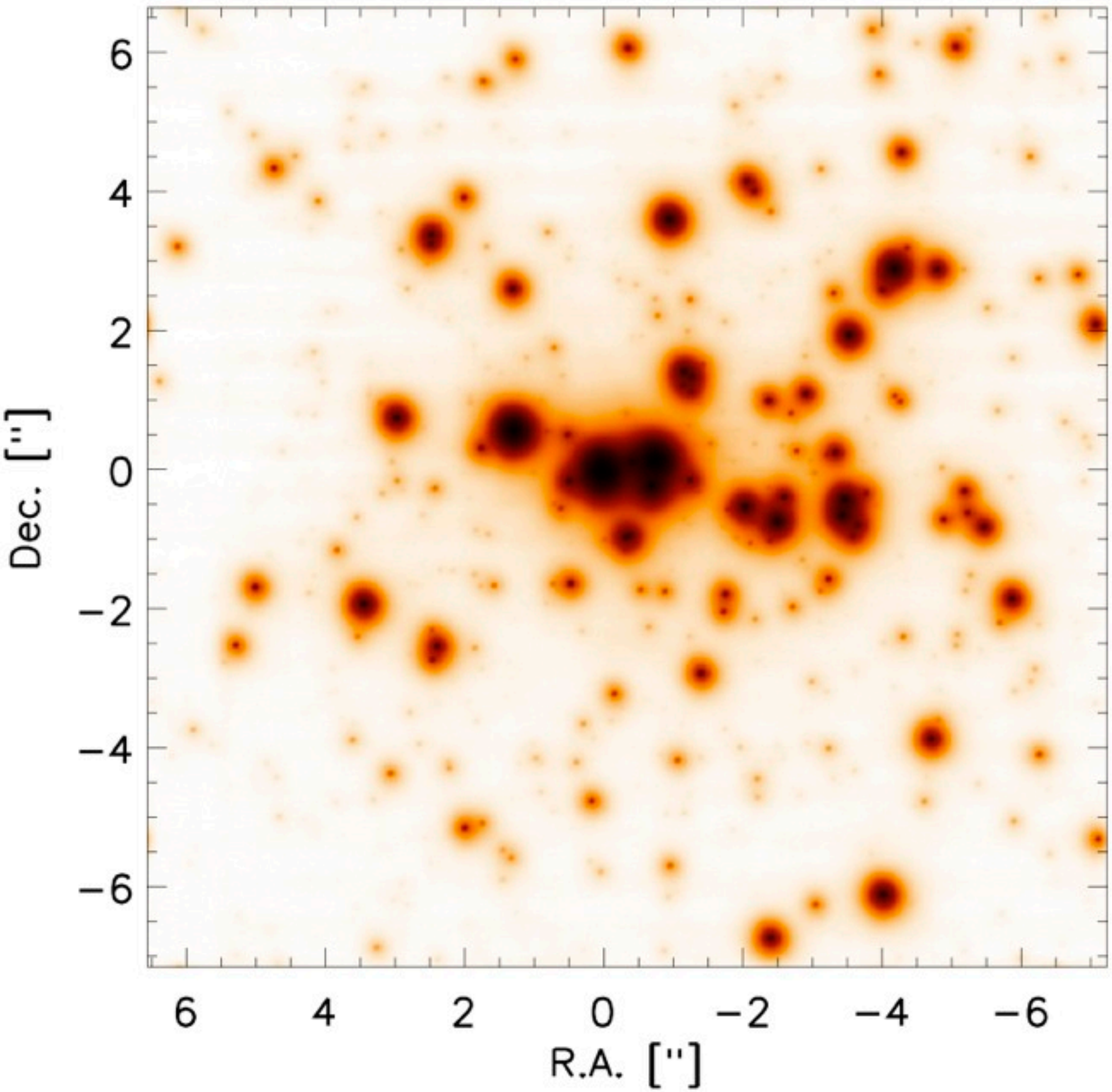
Speckle holography: NGC 3603



NGC 3603
NaCo@VLT, Ks
windowing 512x514
DIT = 0.11s
DIMM~0.5''
4900 frames
$t_{int} \approx 540$s

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

Speckle holography: NGC 3603



- Step 1

Create SSA image

- Step 2

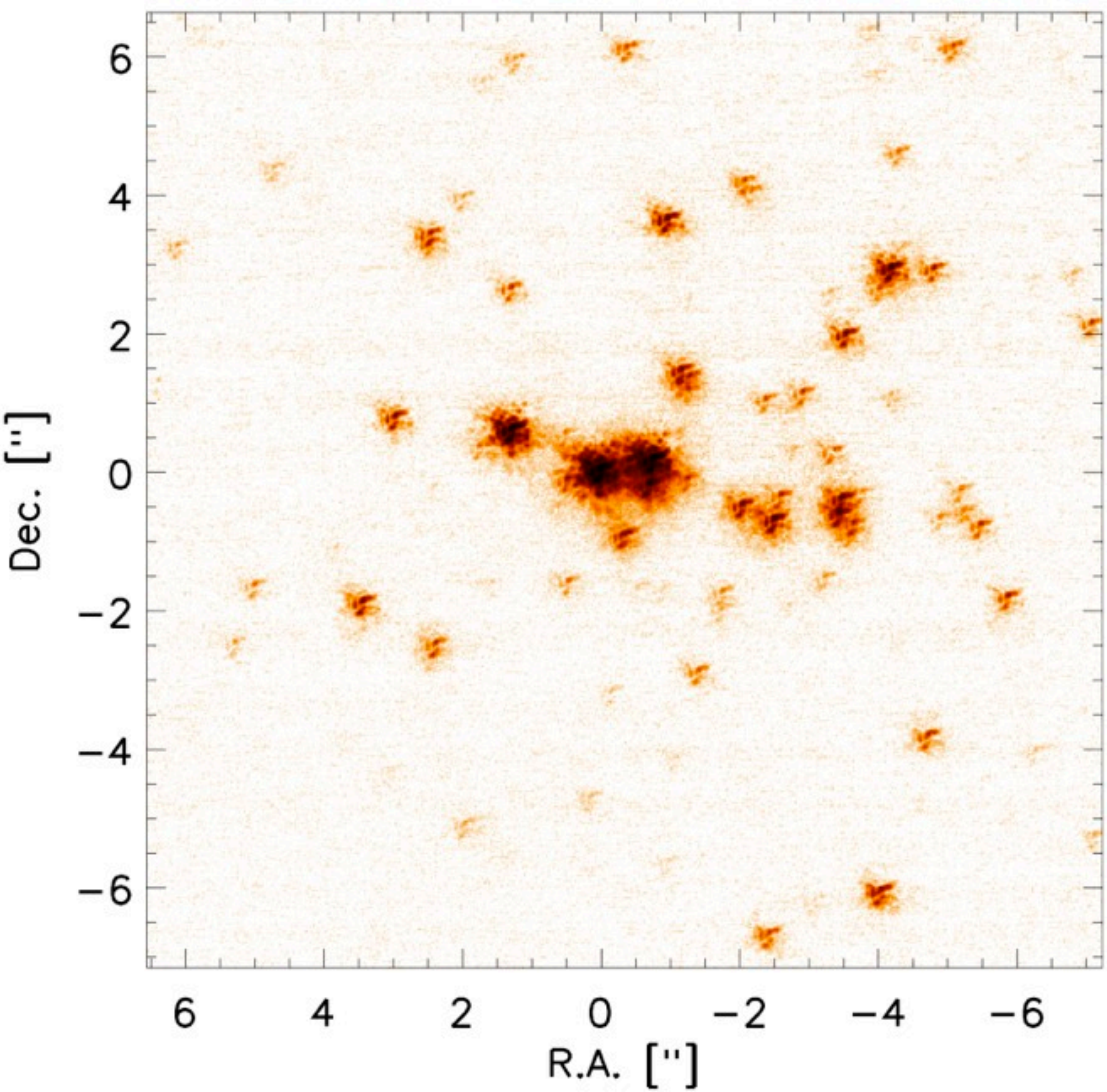
Run StarFinder

- Step 3

Save positions and fluxes of stars

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

Speckle holography: NGC 3603



- Step 4

Select reference + secondary stars

For each frame do...

- Step 5

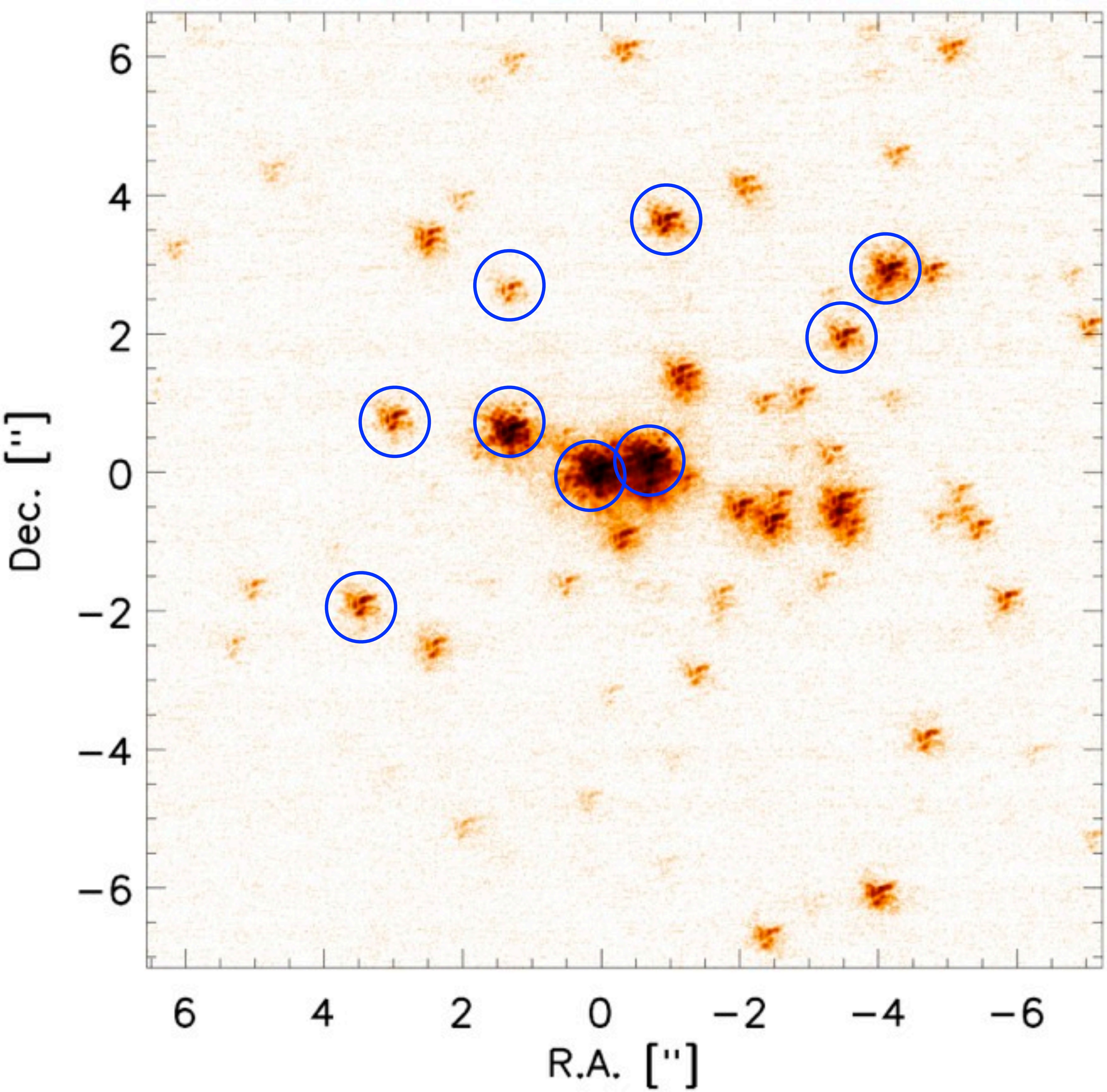
PSF estimate

- Step 6

Improve PSF estimate by subtraction of secondary stars

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

Speckle holography: NGC 3603



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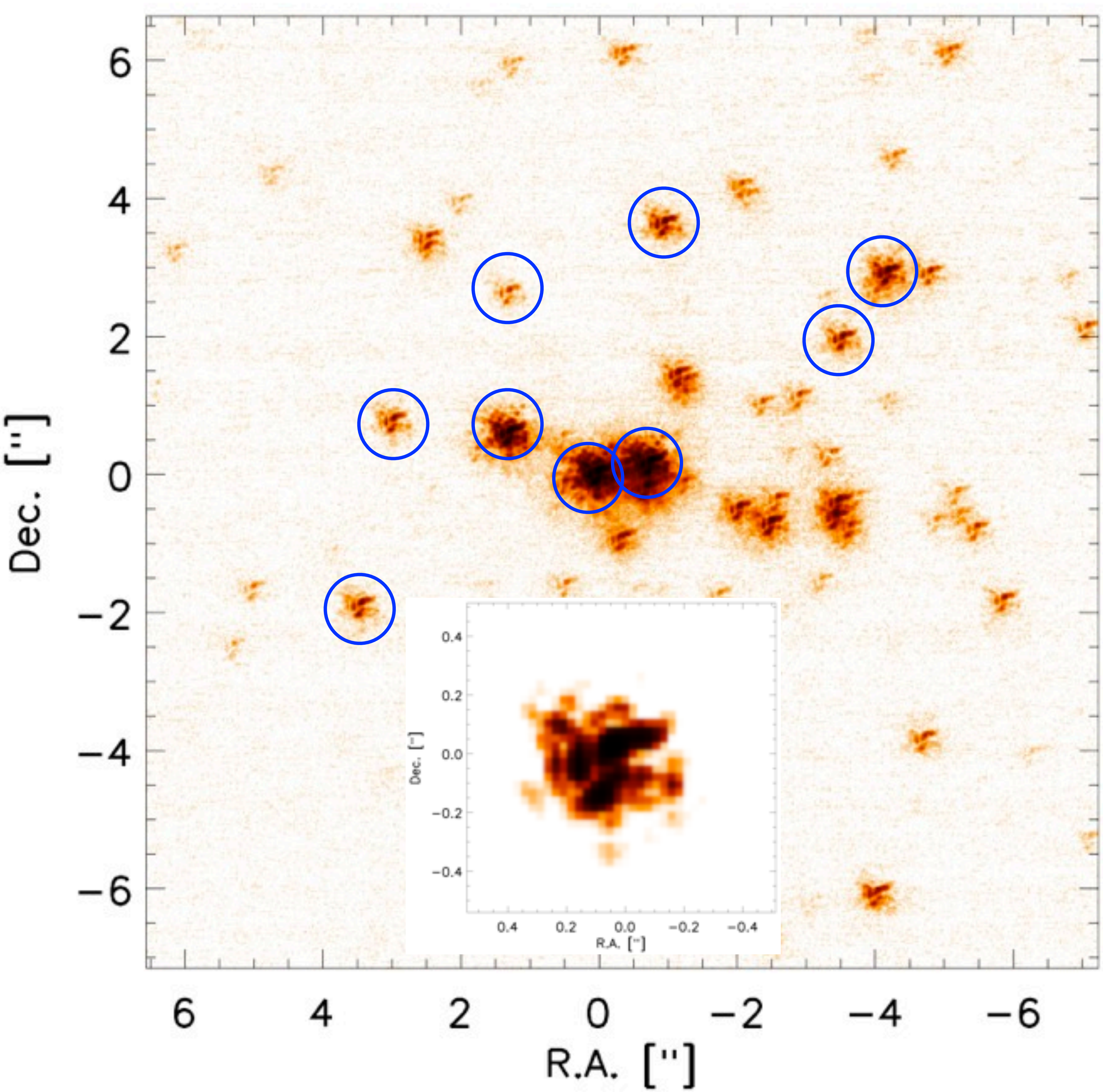

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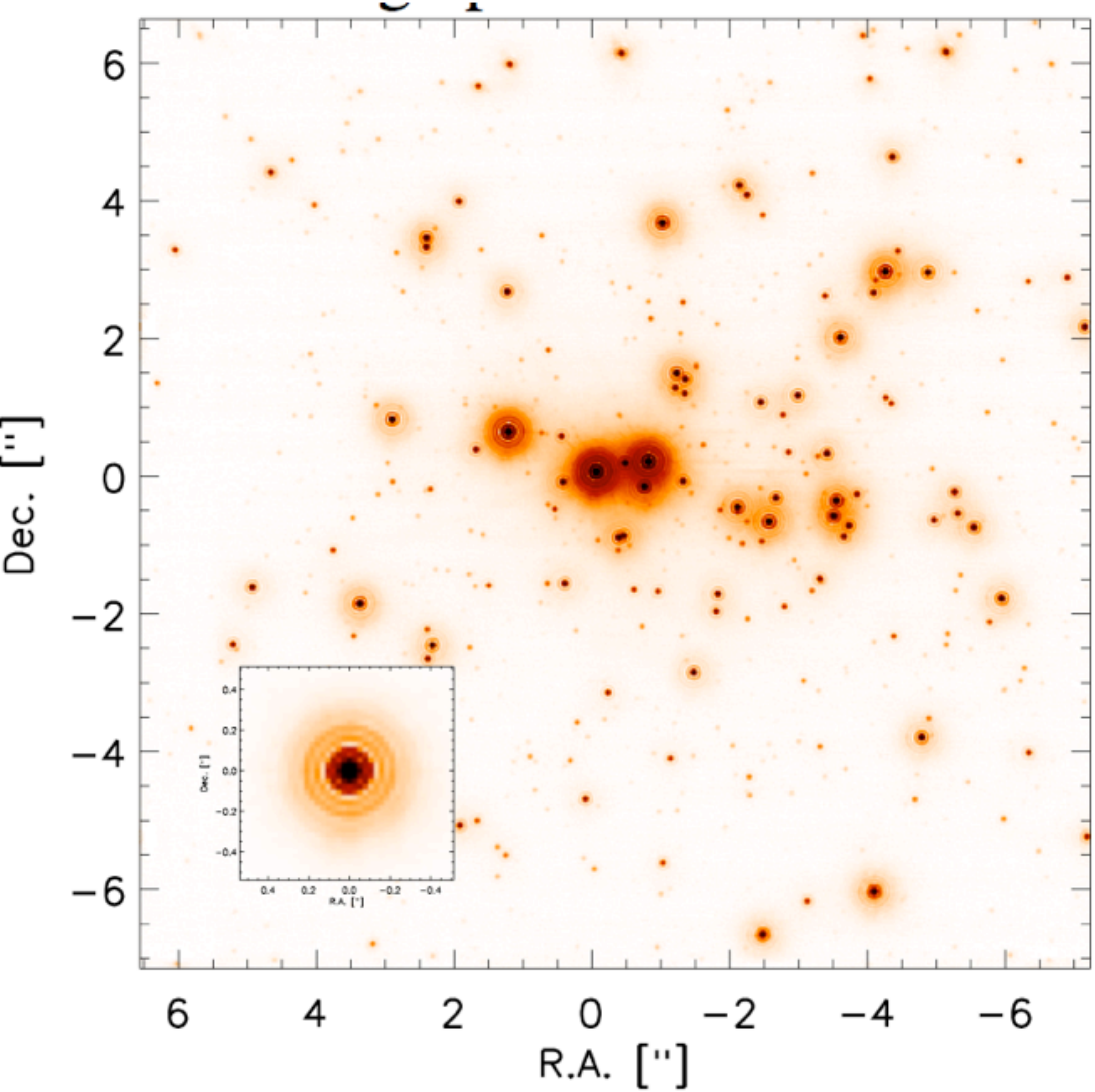


- Step 7

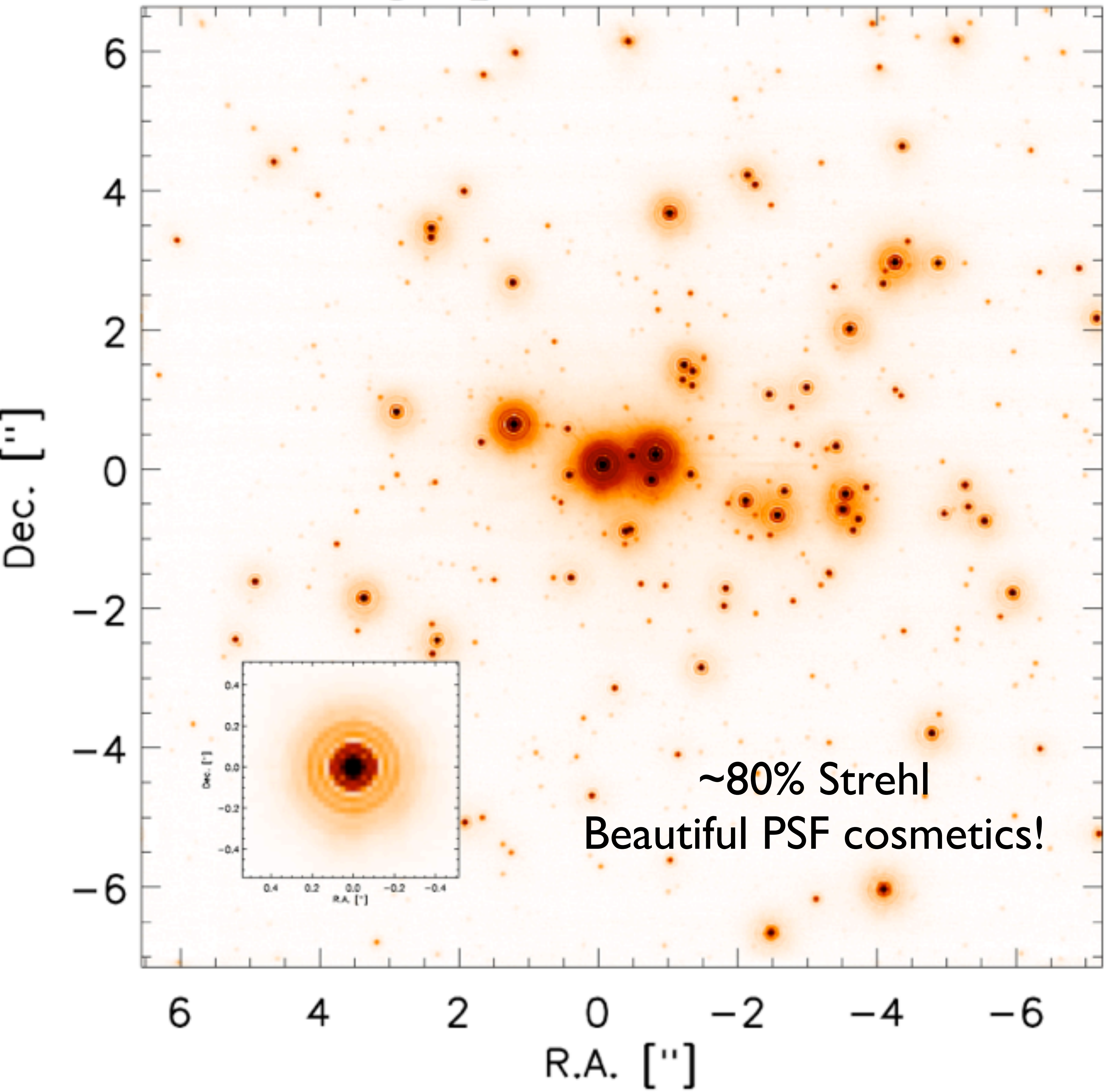
Run holography algorithm

- Step 8 (optional)

Repeat steps 2-7

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

Speckle holography: NGC 3603



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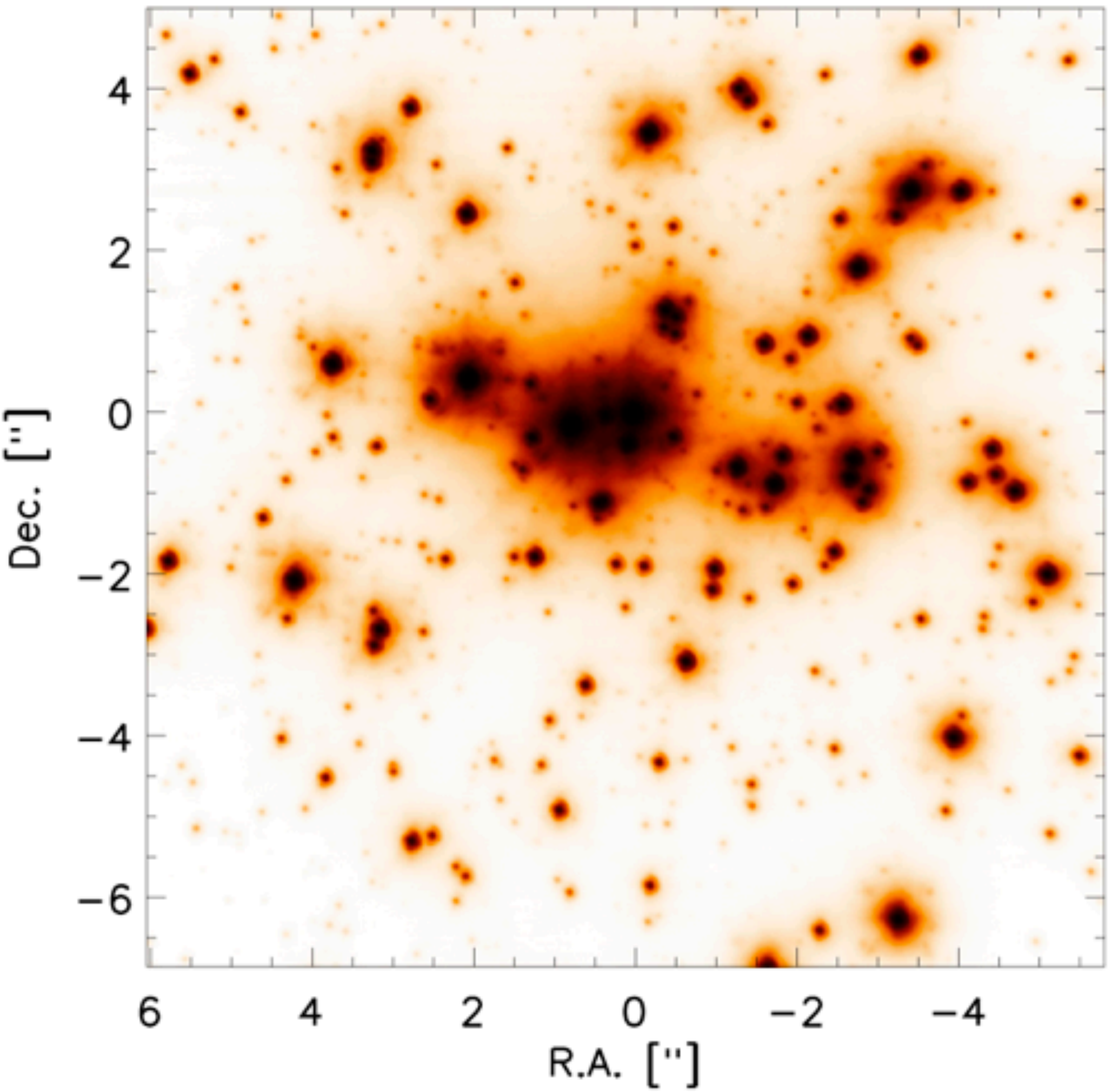
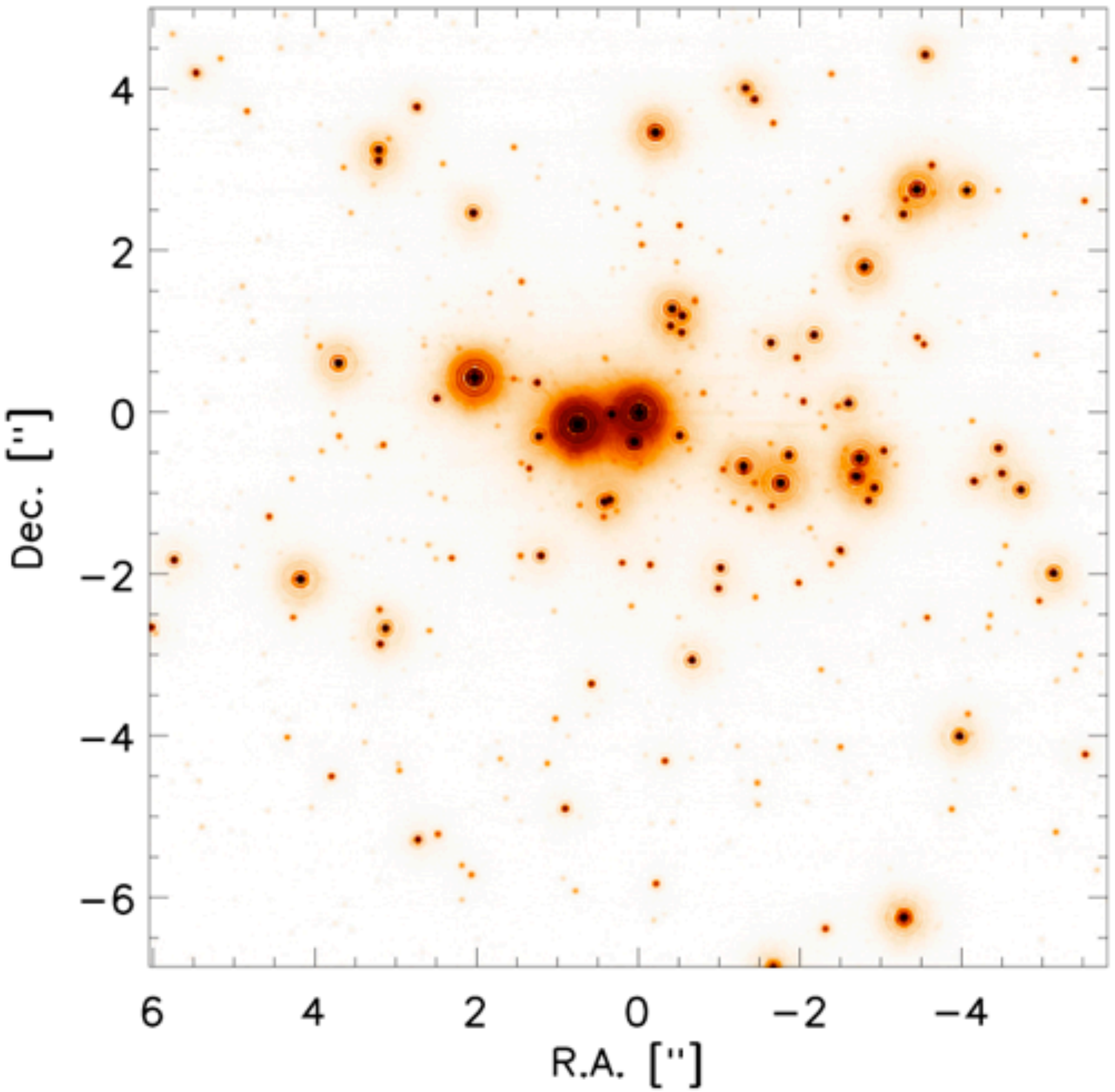
NGC 3603: AO vs. Holography

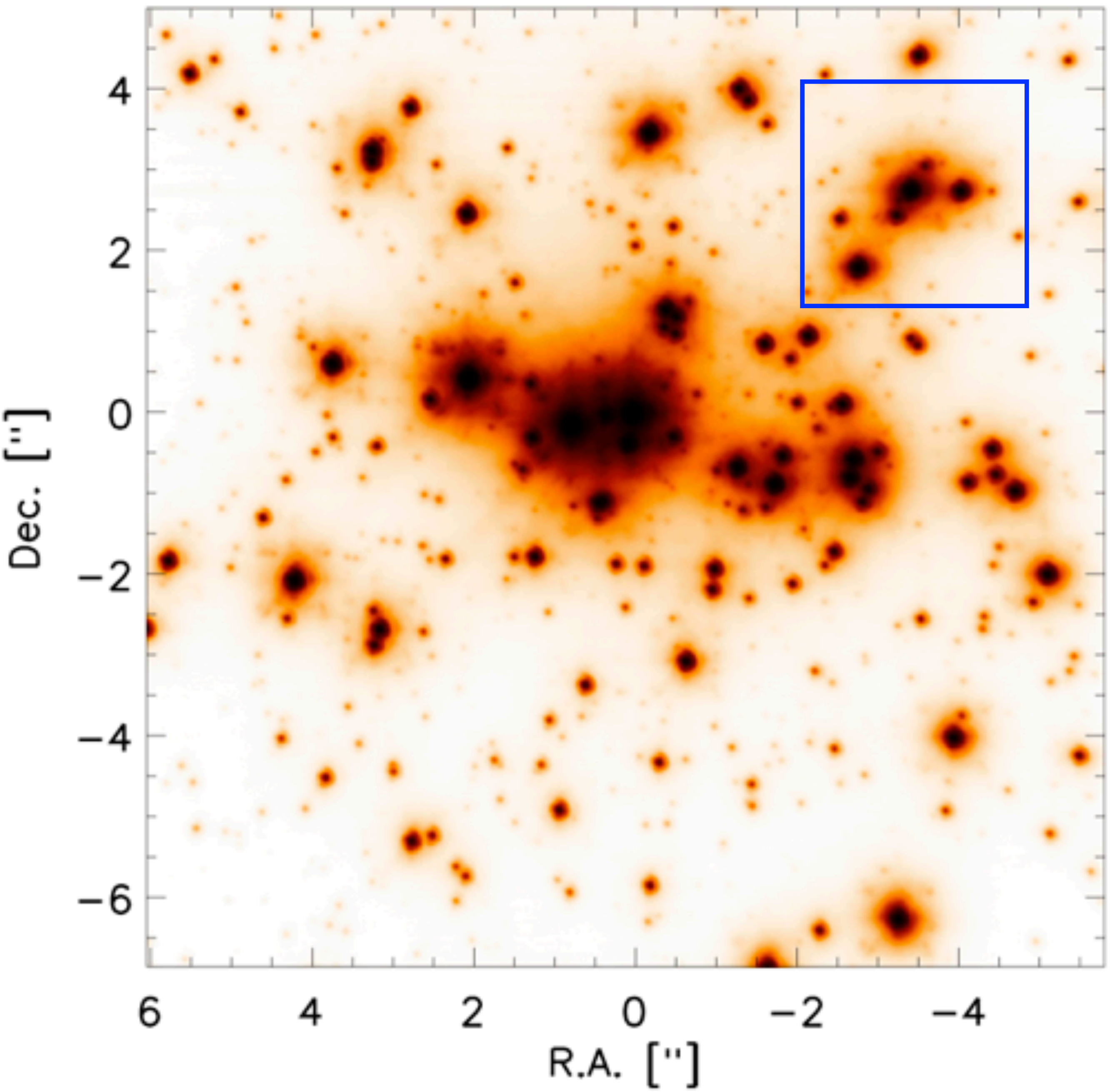


NaCo, AO, 20 April 2008
DIMM≈0.7”
t_{int} = 1320x0.5s = 1320s



NaCo, speckle, 28 Jan 2010
DIMM≈0.5”
t_{int} = 4907x0.11s = 540s

NGC 3603: AO vs. Holography



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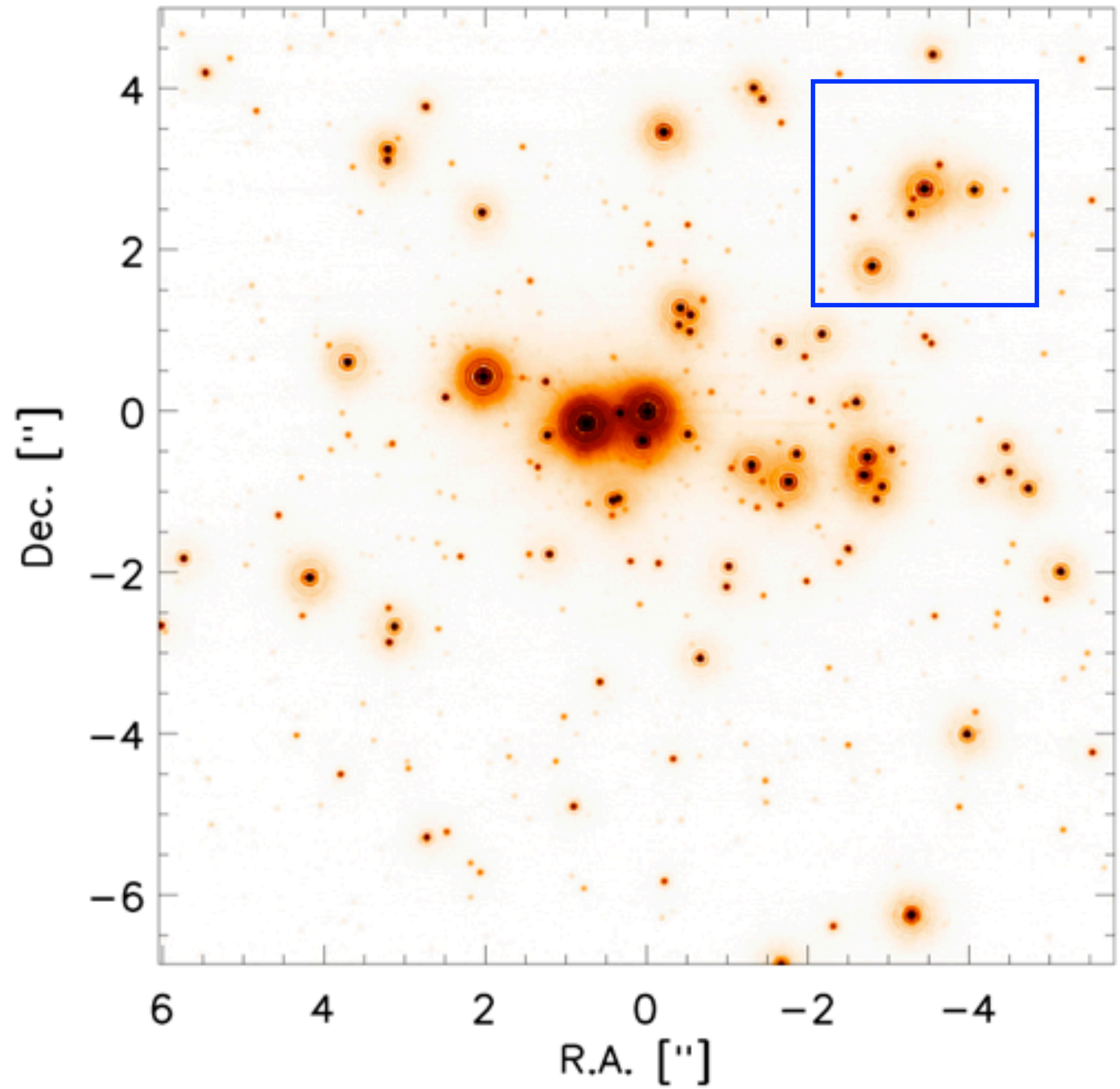

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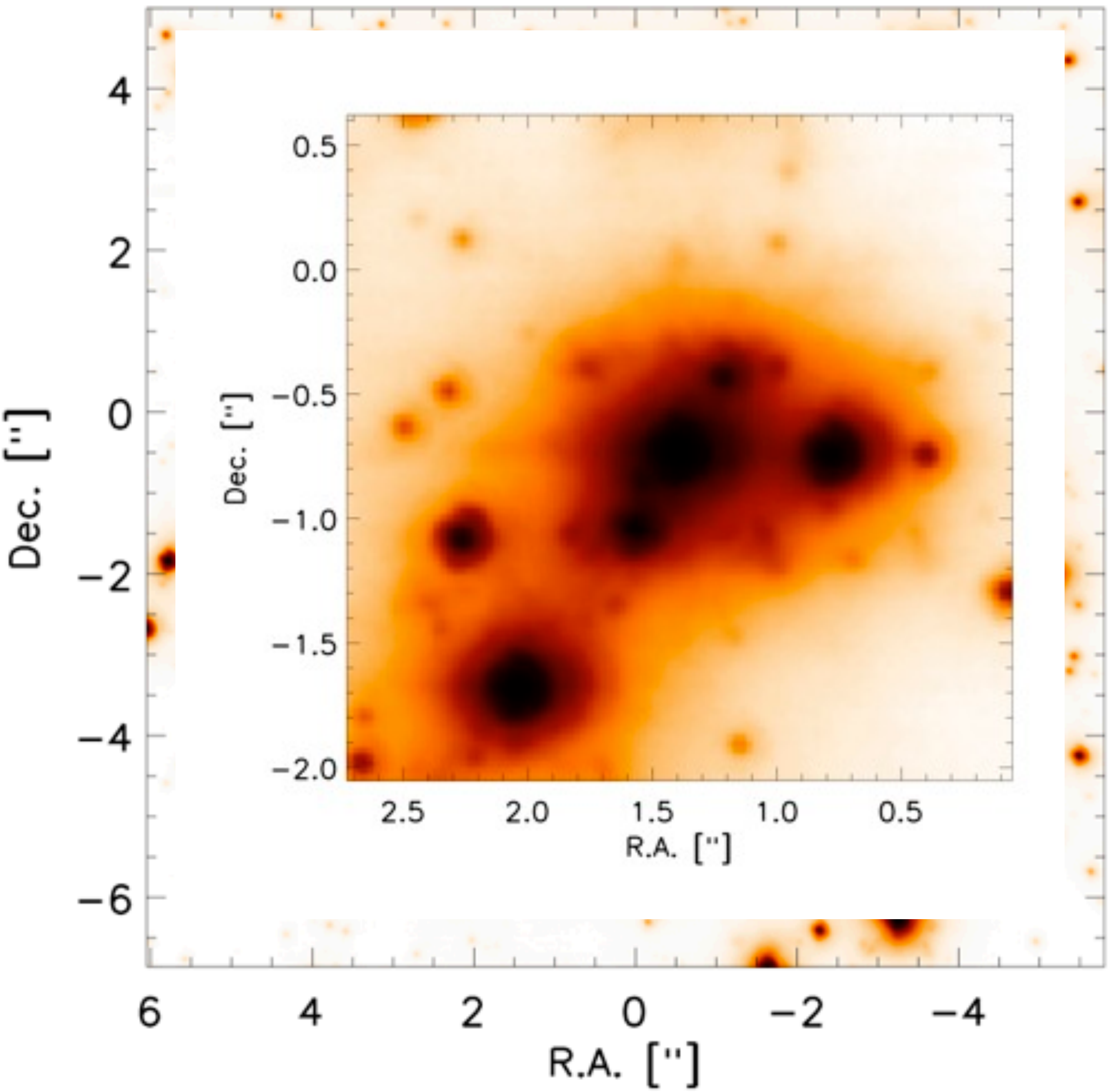

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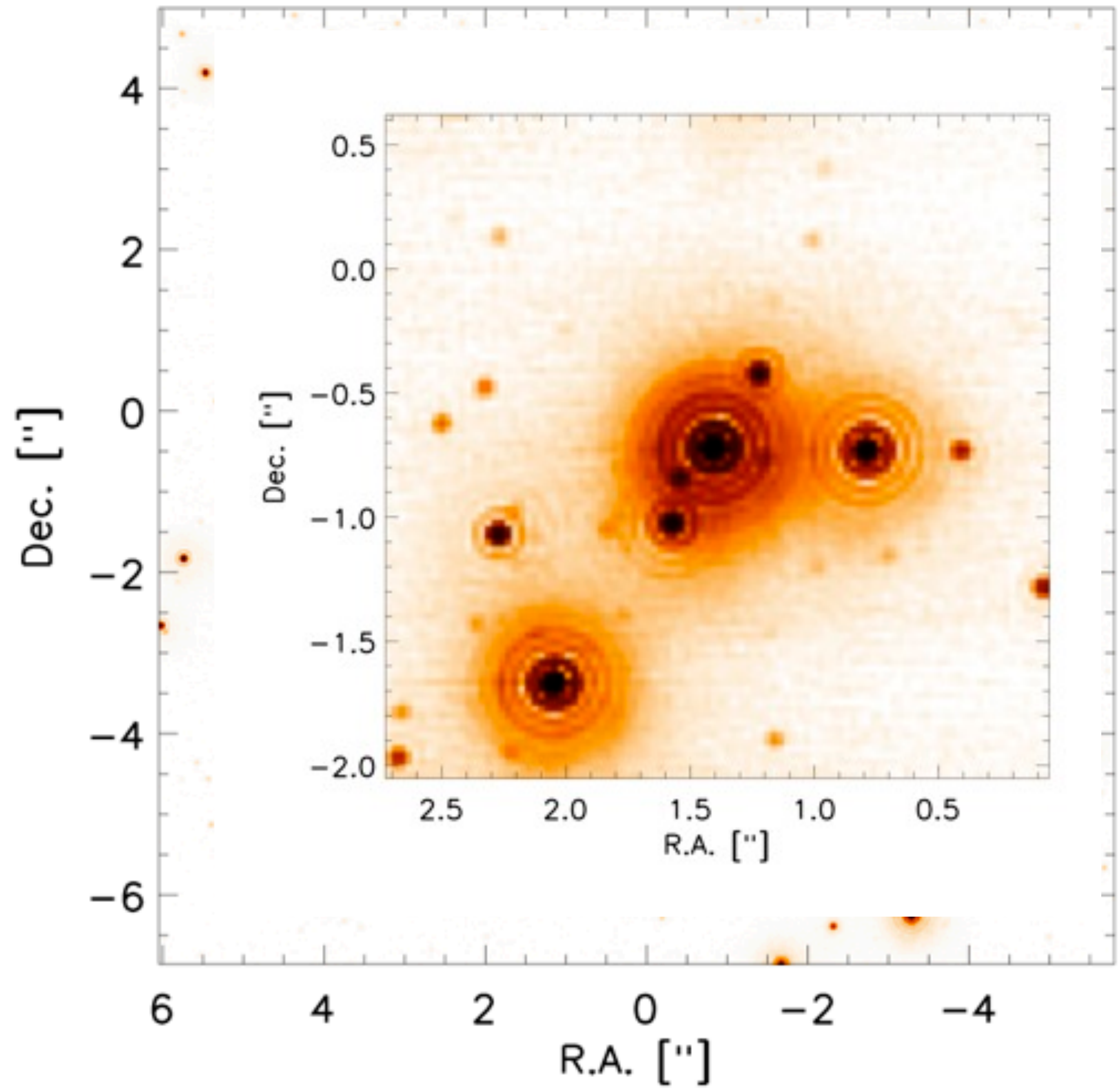

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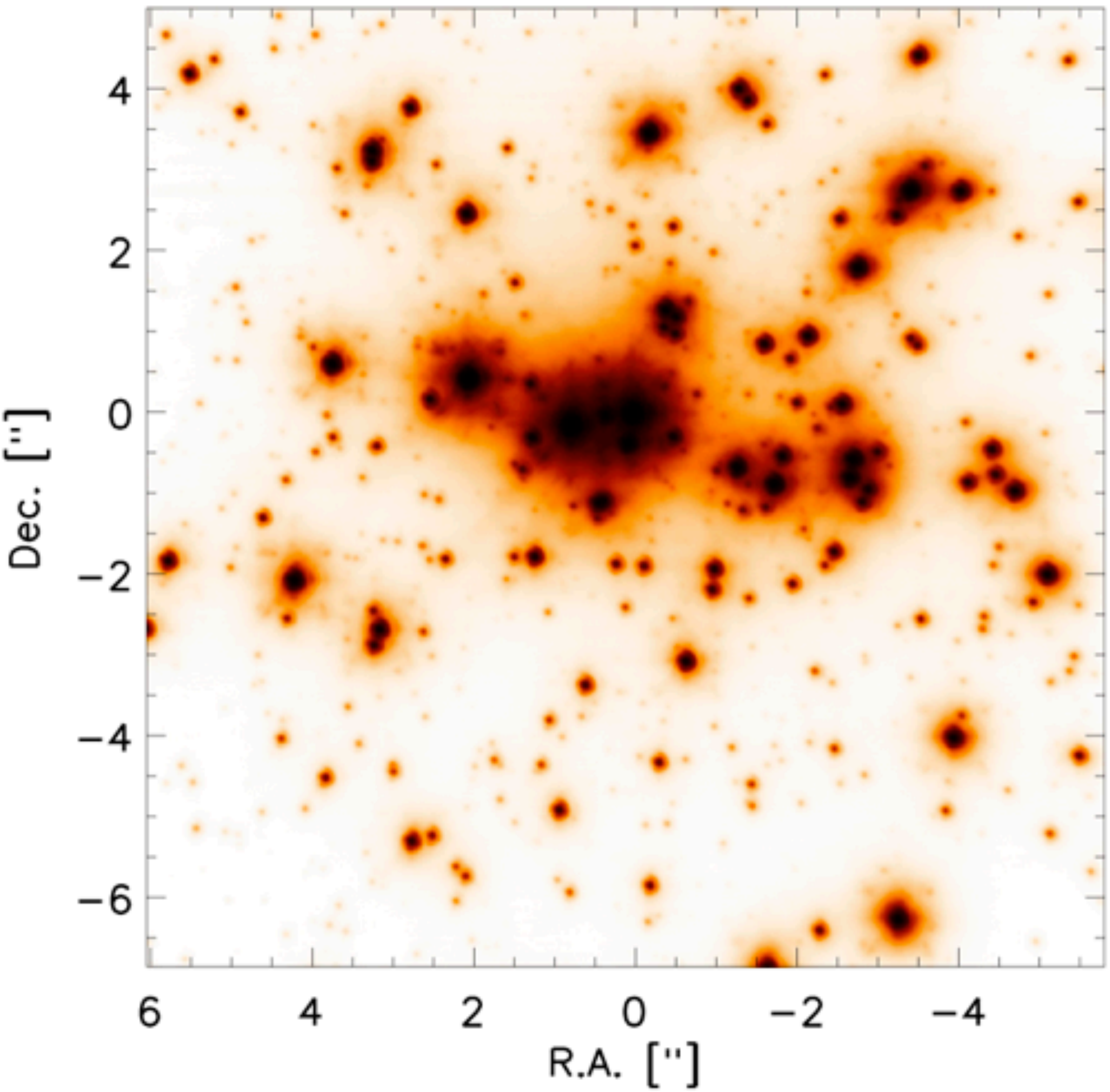

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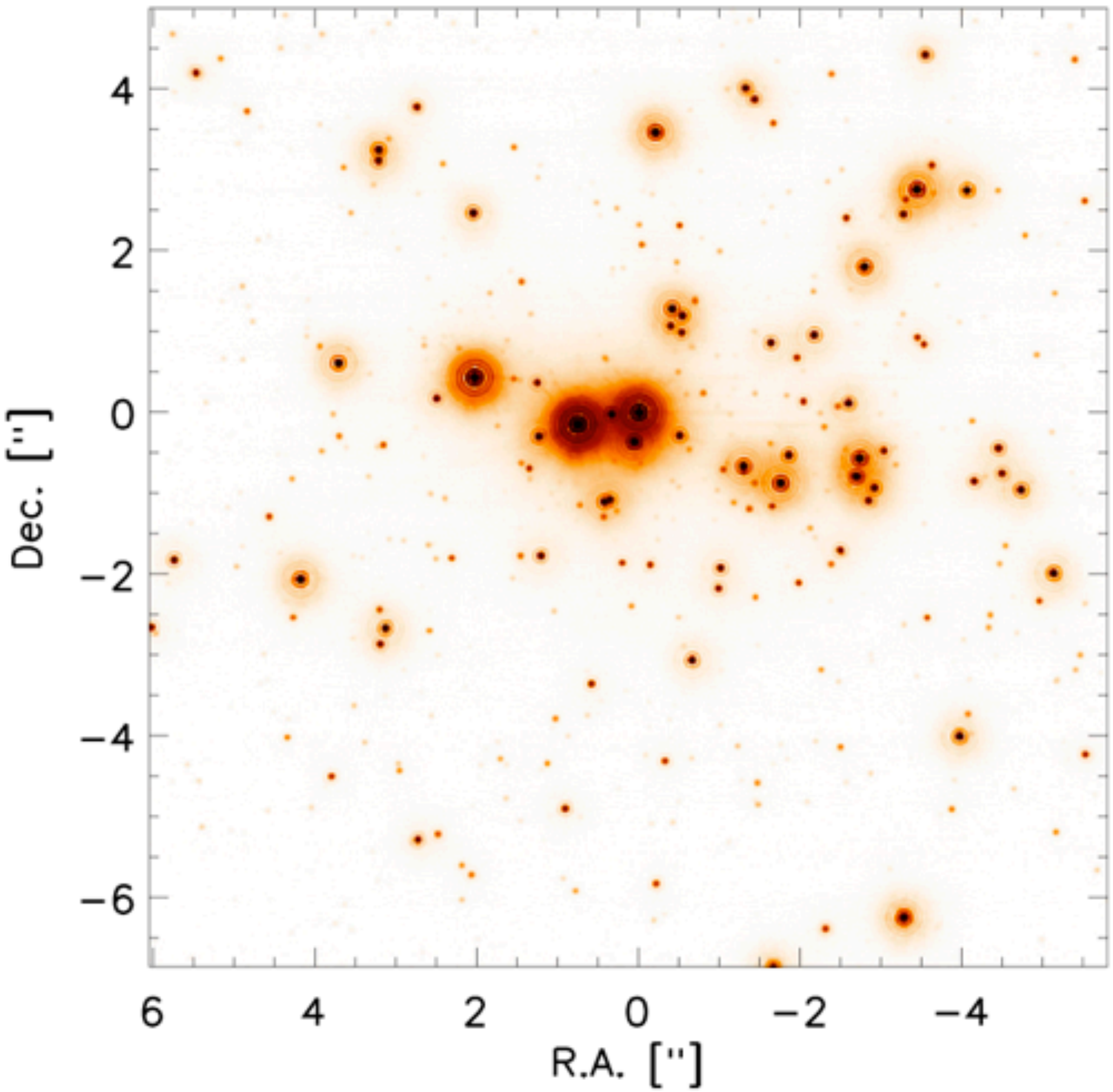

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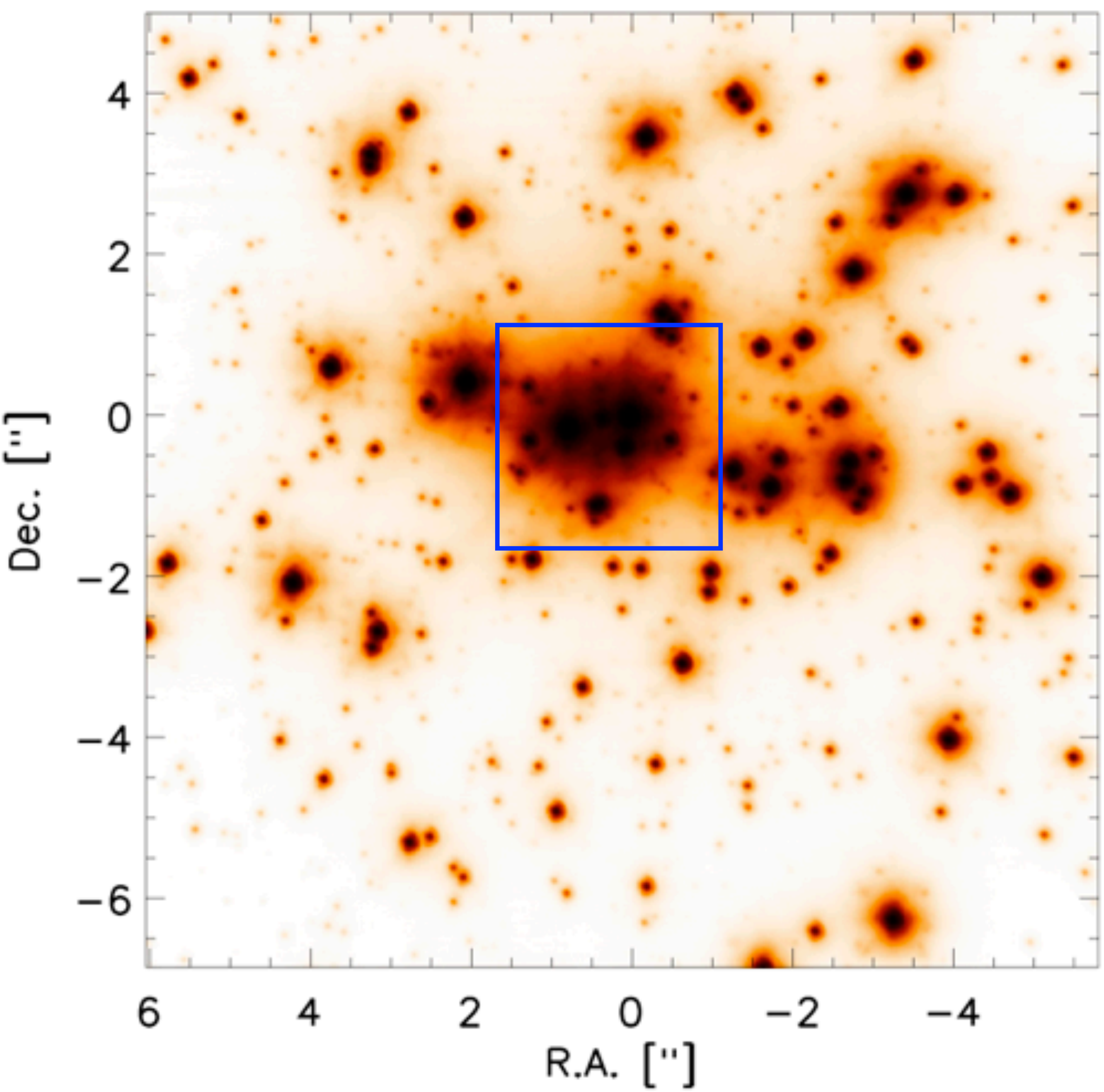

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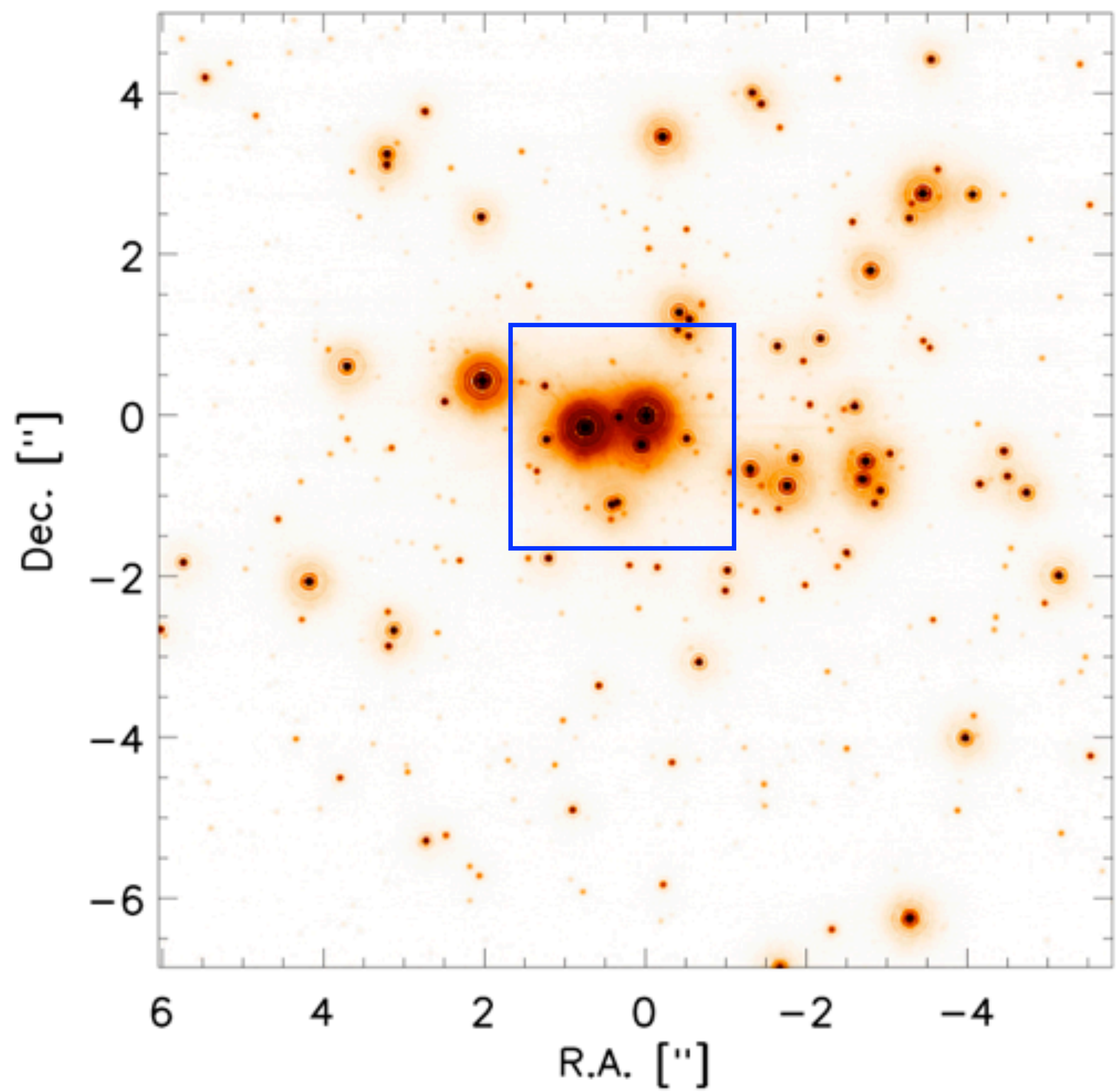

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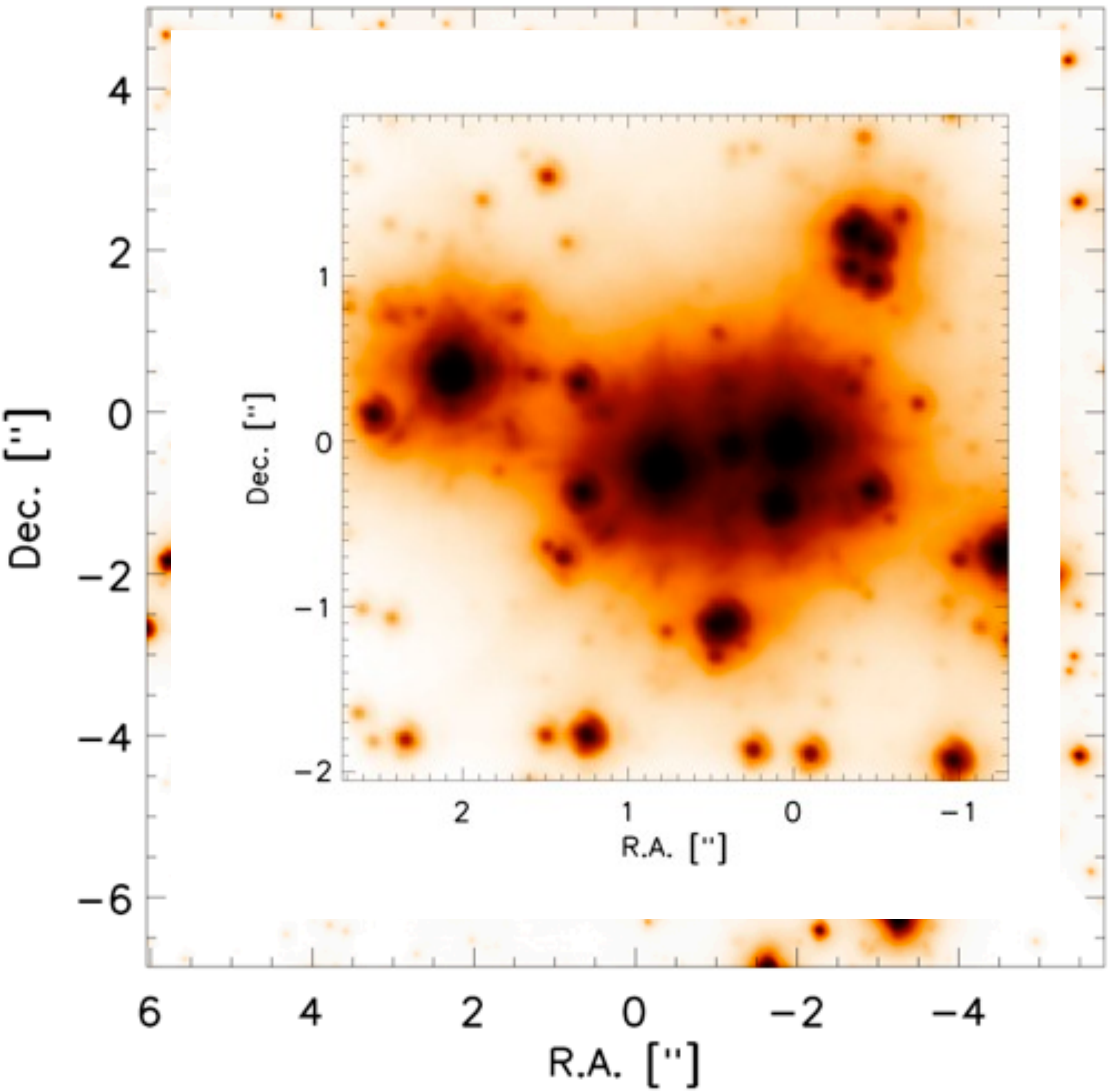

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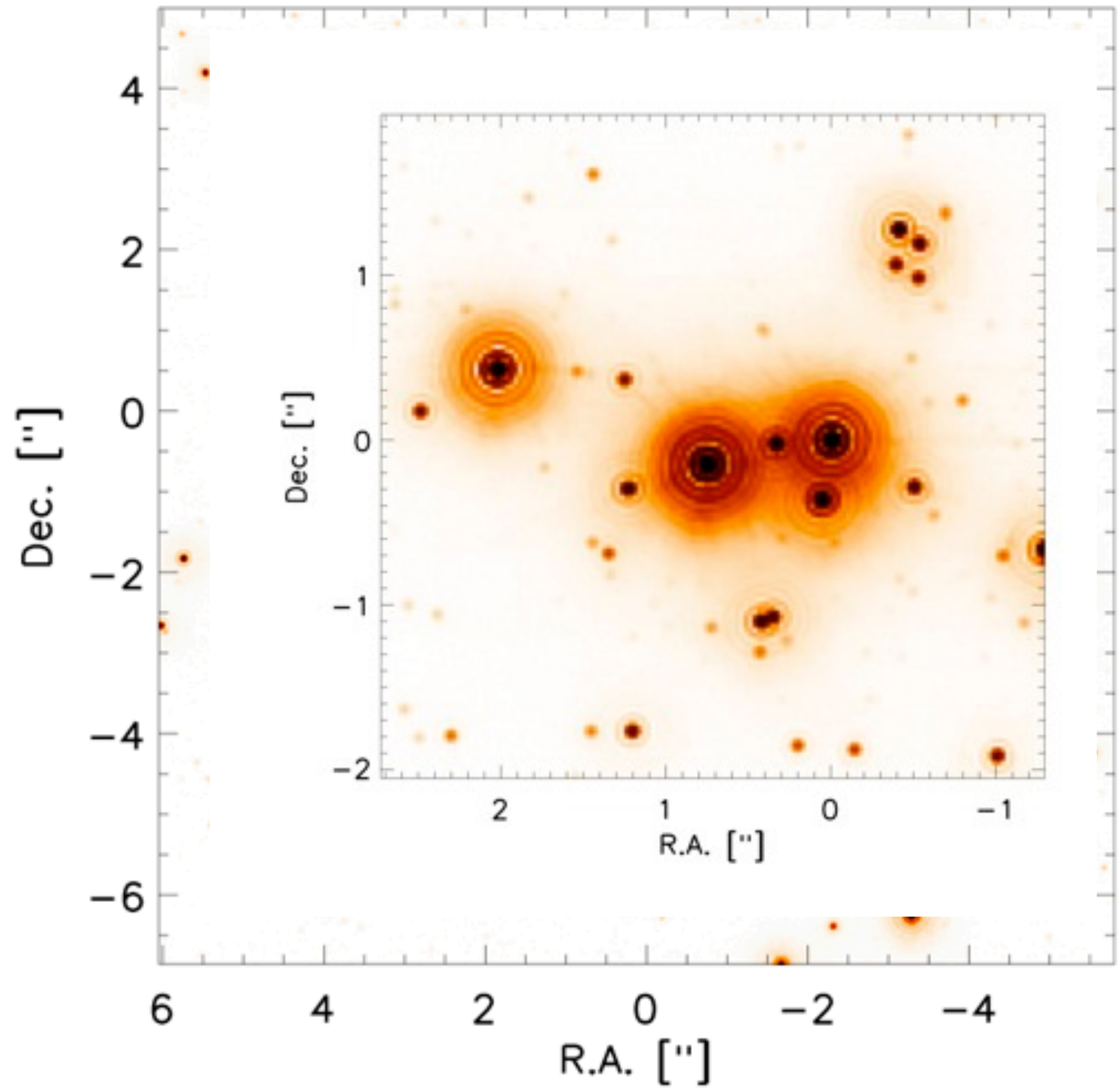

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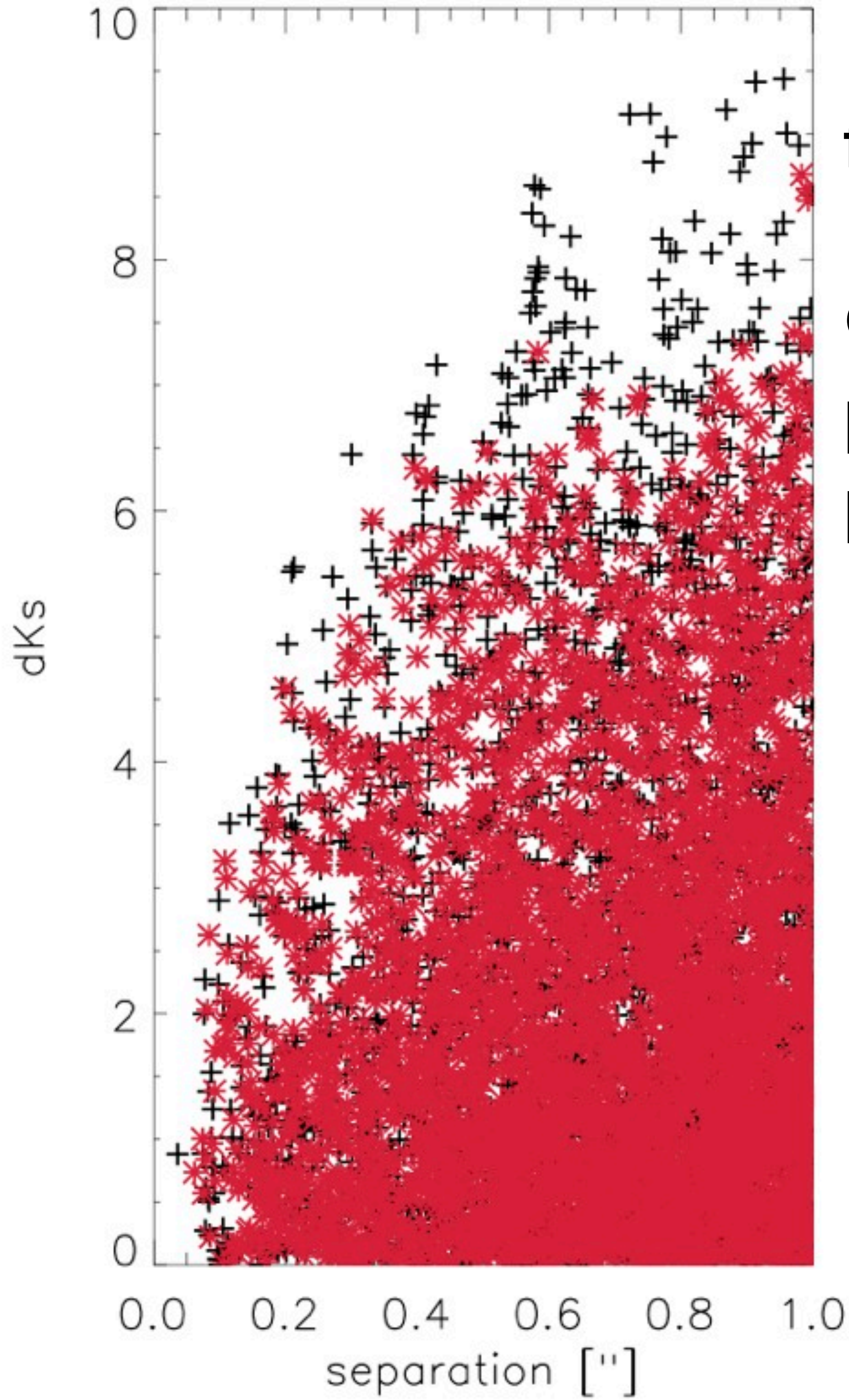


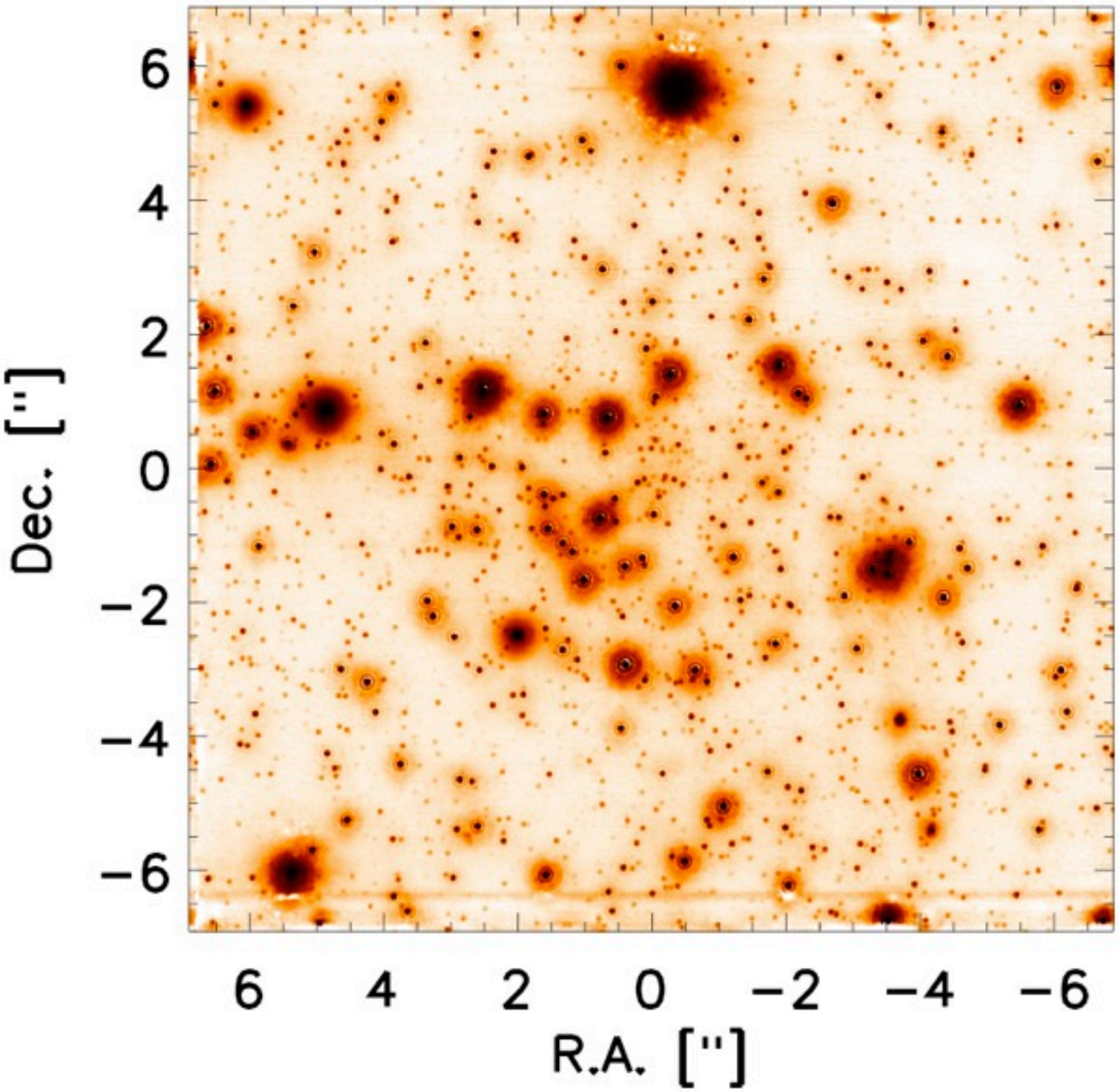
Difference in m_{Ks} vs. separation for all detected pairs of stars

Conservative source selection, performance of holography probably under-estimated.

black: holography
red: AO

More tests…

Multiple, faint reference stars



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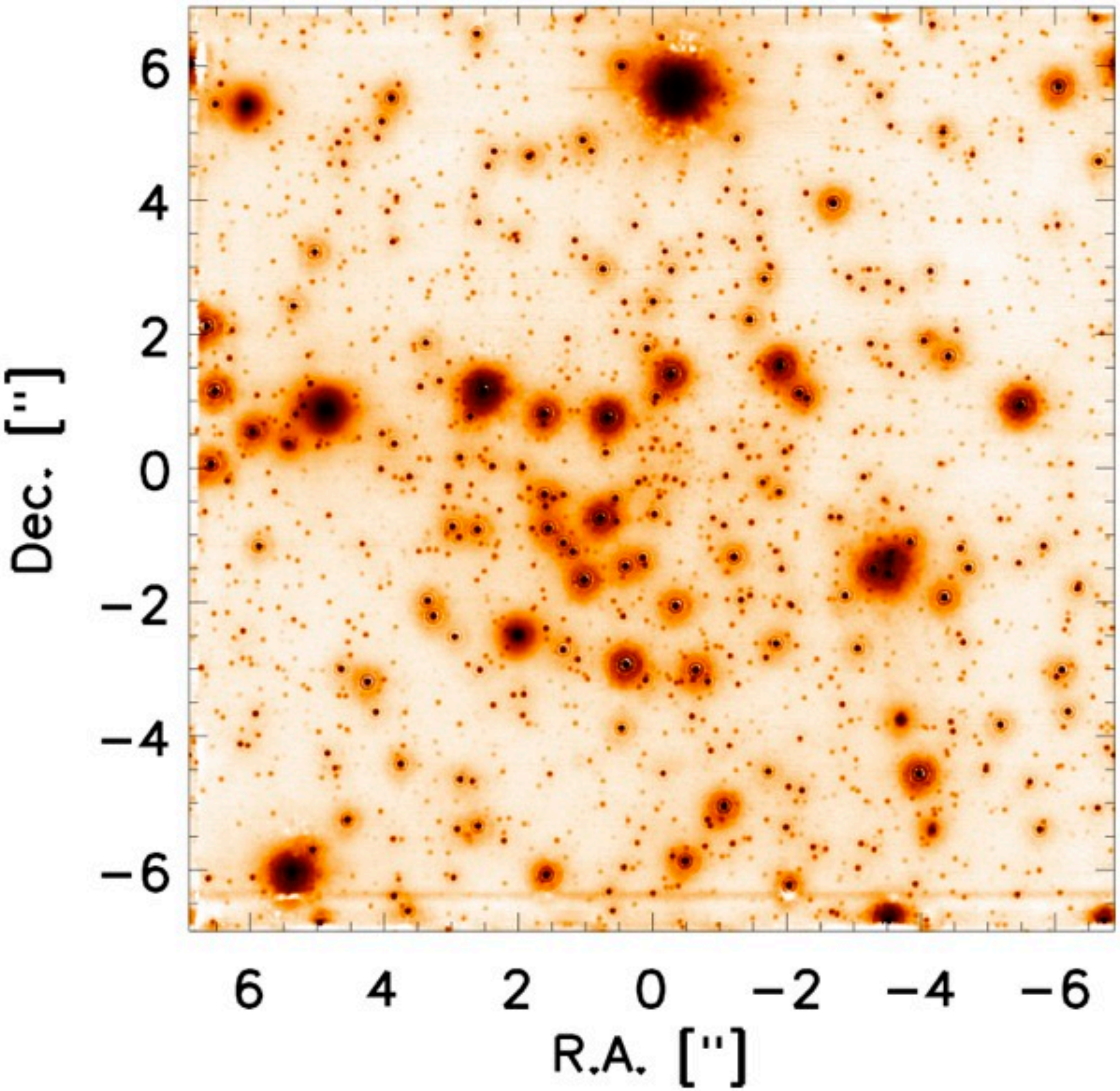
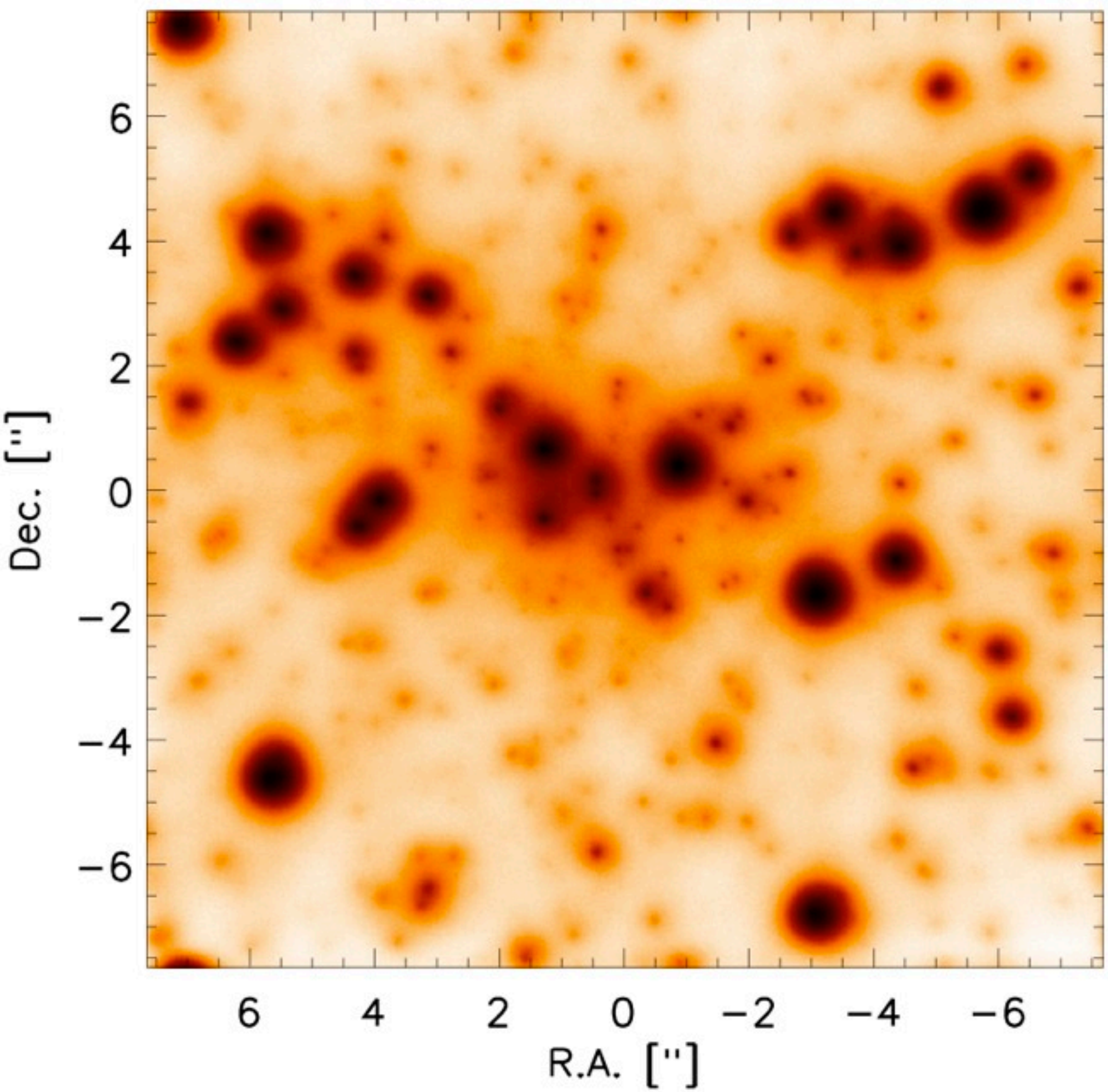


Galactic center, NaCo/VLT
23 Ks≈13 reference stars: Strehl~45%, excellent cosmetics.

⇒ beyond the possibilities of current AO systems

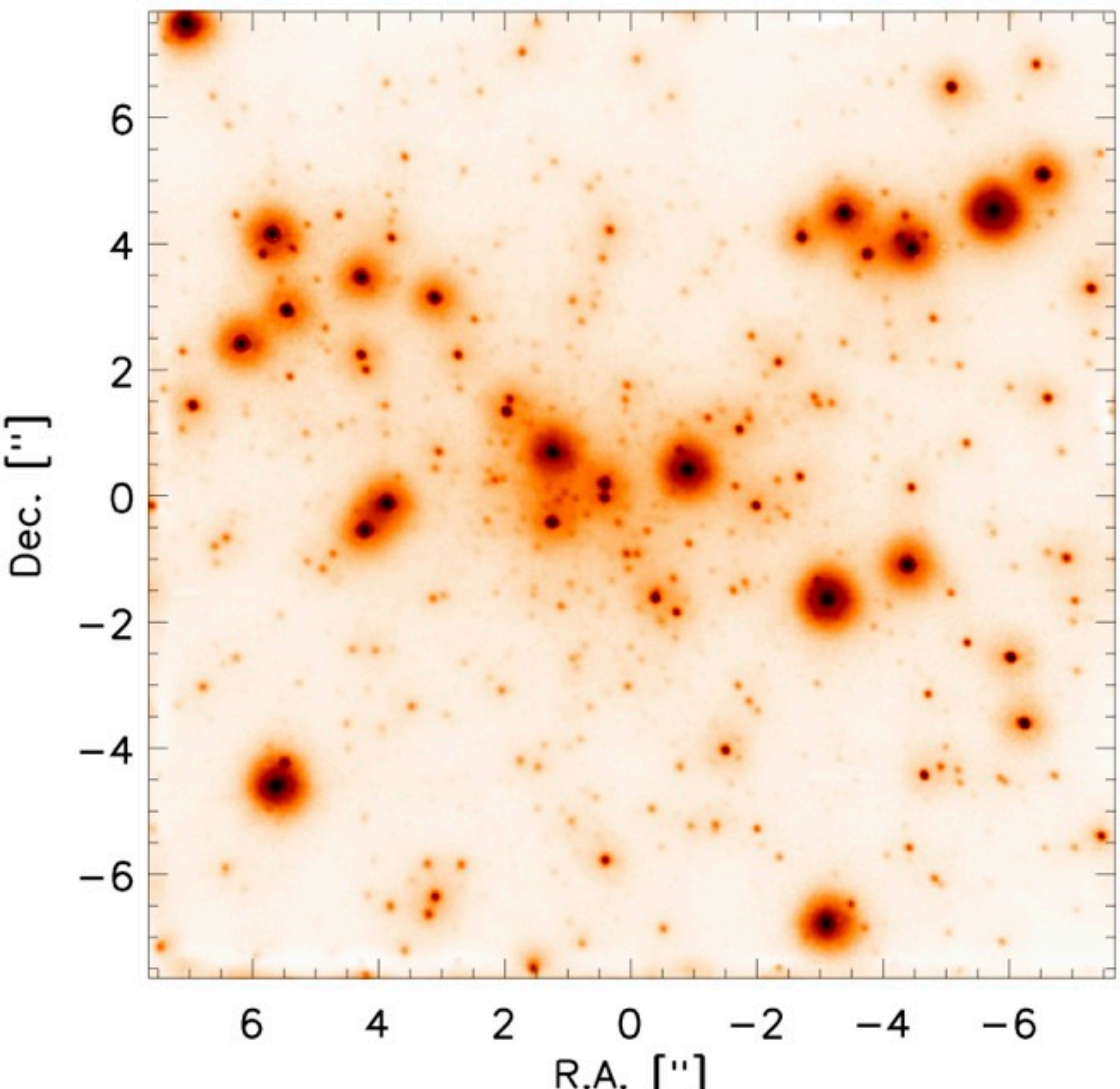
Short wavelengths: I-band



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

Simple shift-and-add with frame selection (8.5%): *lucky imaging*
~7% Strehl, $\Delta m \approx 8$

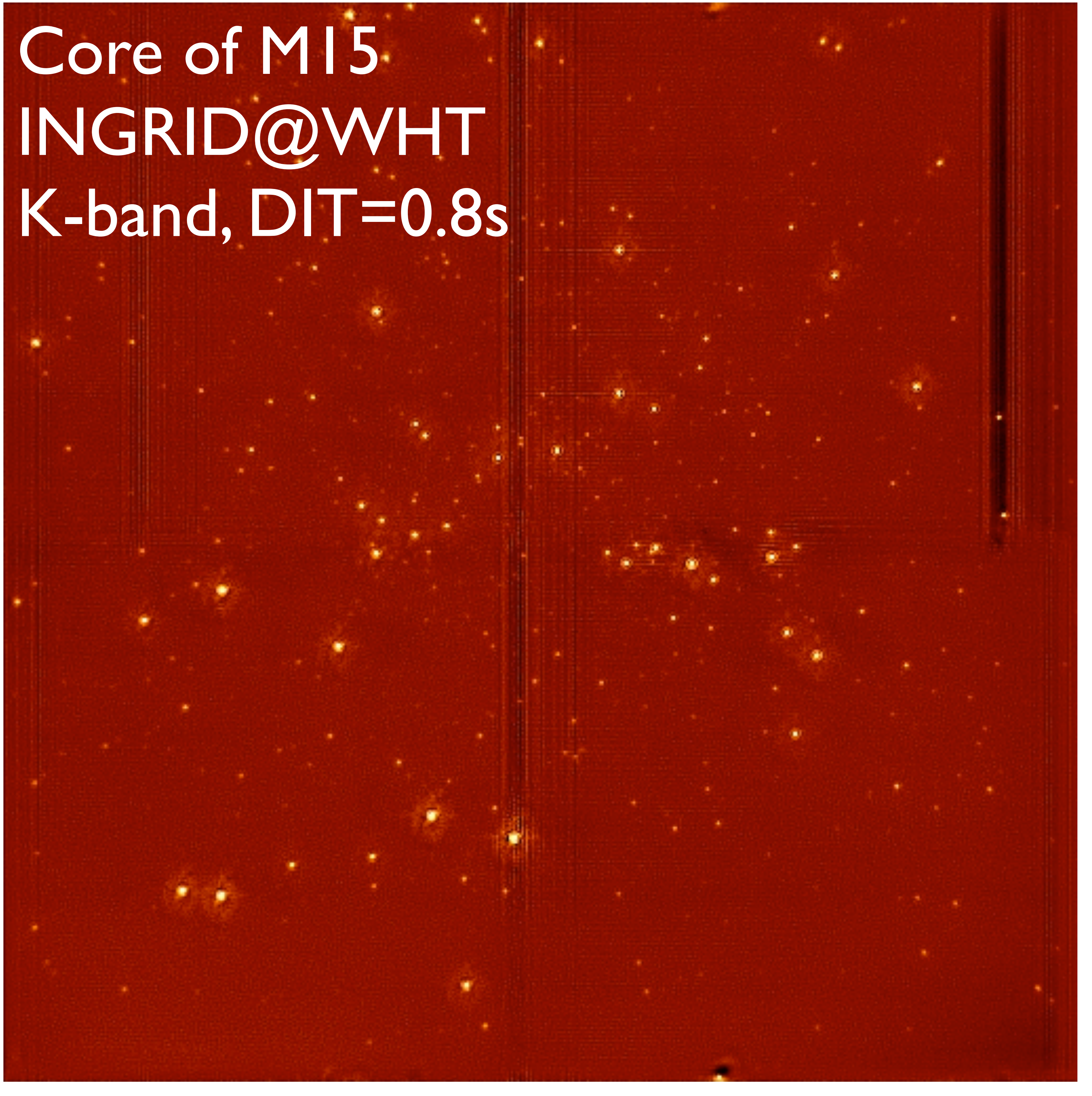
Short wavelengths: I-band



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

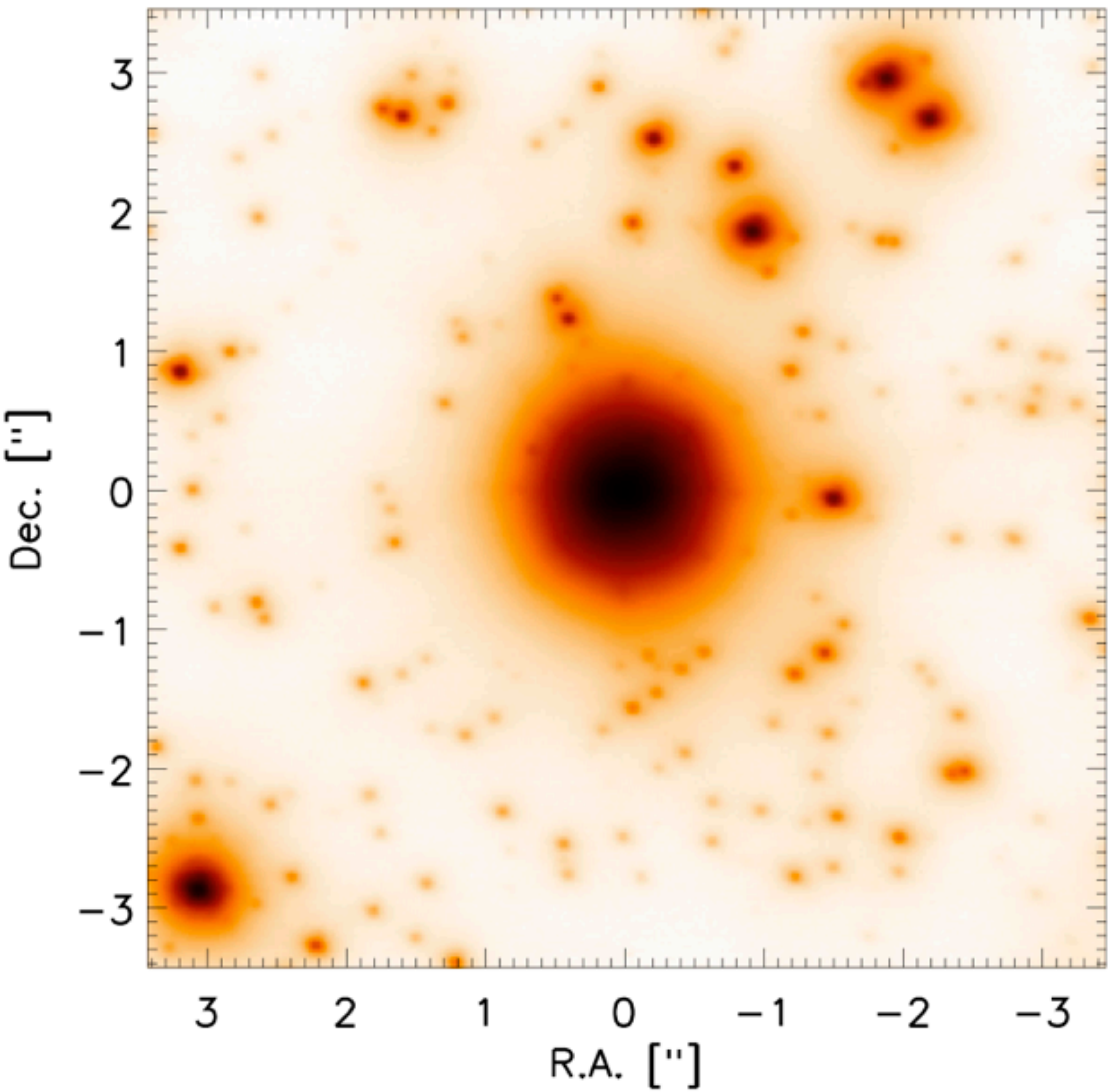
Holography with frame selection (50%), separate reconstruction of subfields to deal with anisoplanatic effects: ~18% Strehl, Δm≈8.5

INGRID@WHT



More applications…

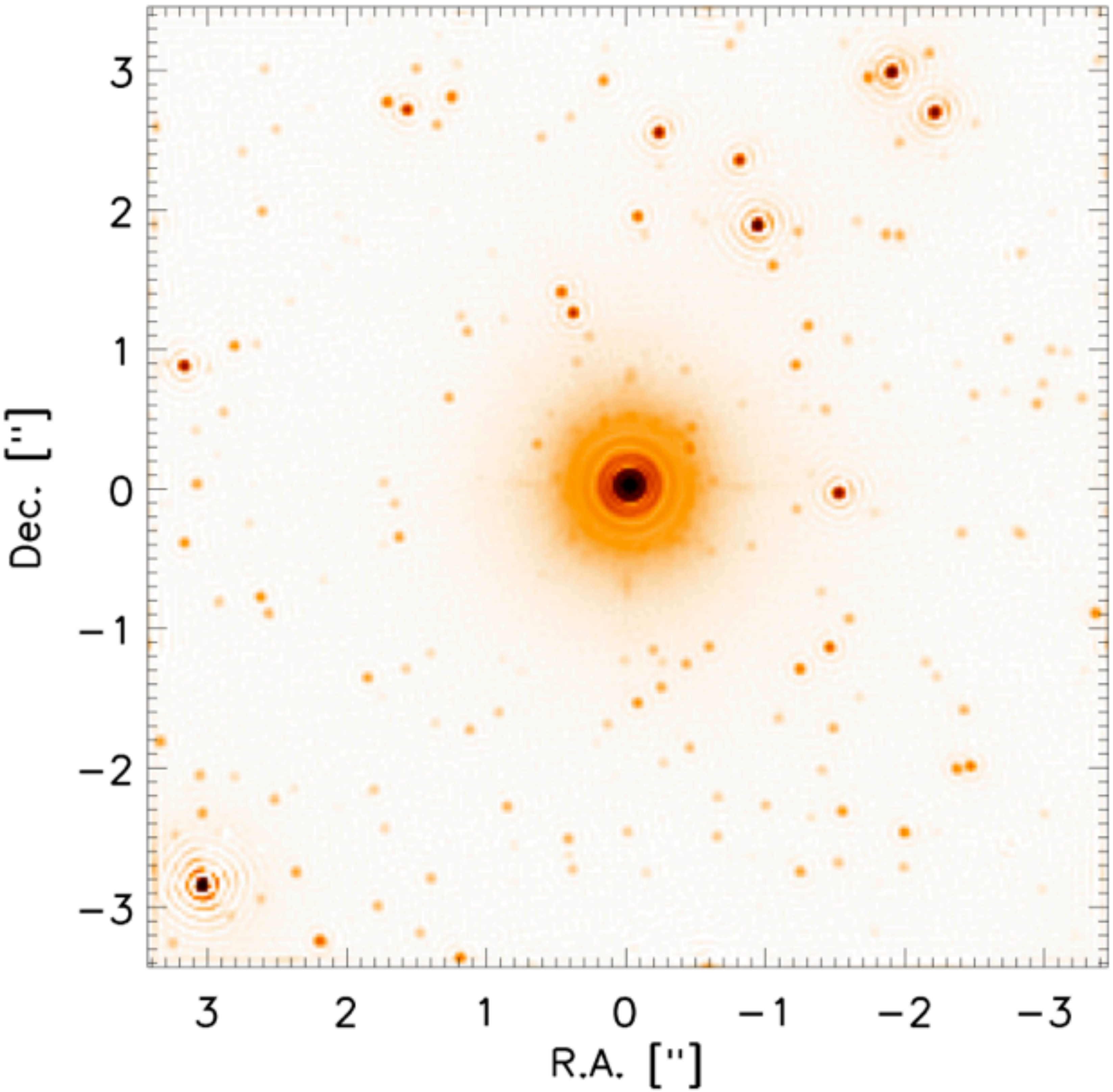
Holography + AO



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



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

"holographic" combination of AO frames

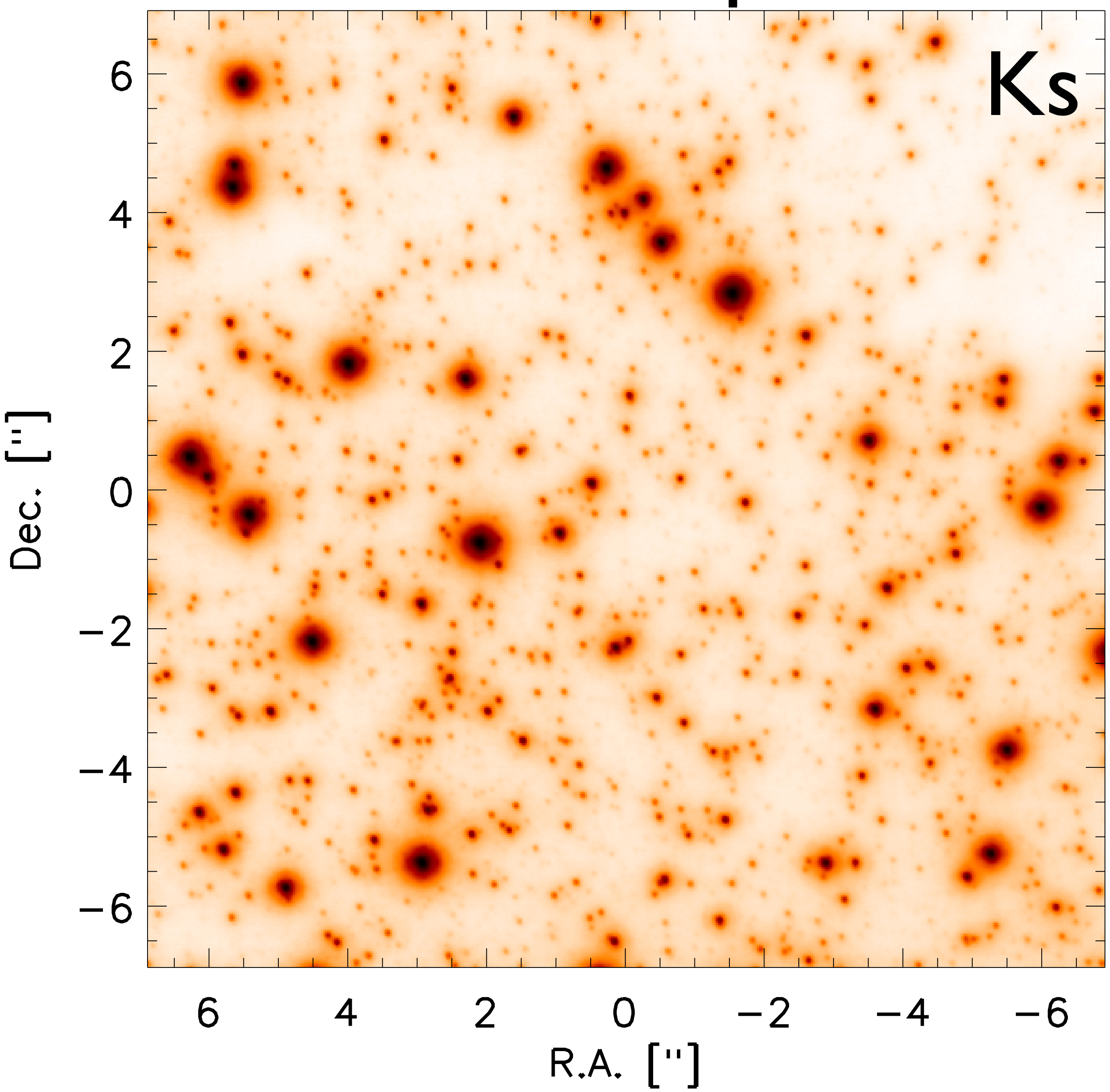
Going wide-field: sub-sampled holography

<u>Idea:</u>
If holography also works when the diffraction limit is *sub-sampled*, then we can trade off *lower angular resolution* for a *larger FOV* and *increased sensitivity*.

Going wide-field: sub-sampled holography

Going wide-field: sub-sampled holography

NACO, 0.027"/pixel scale

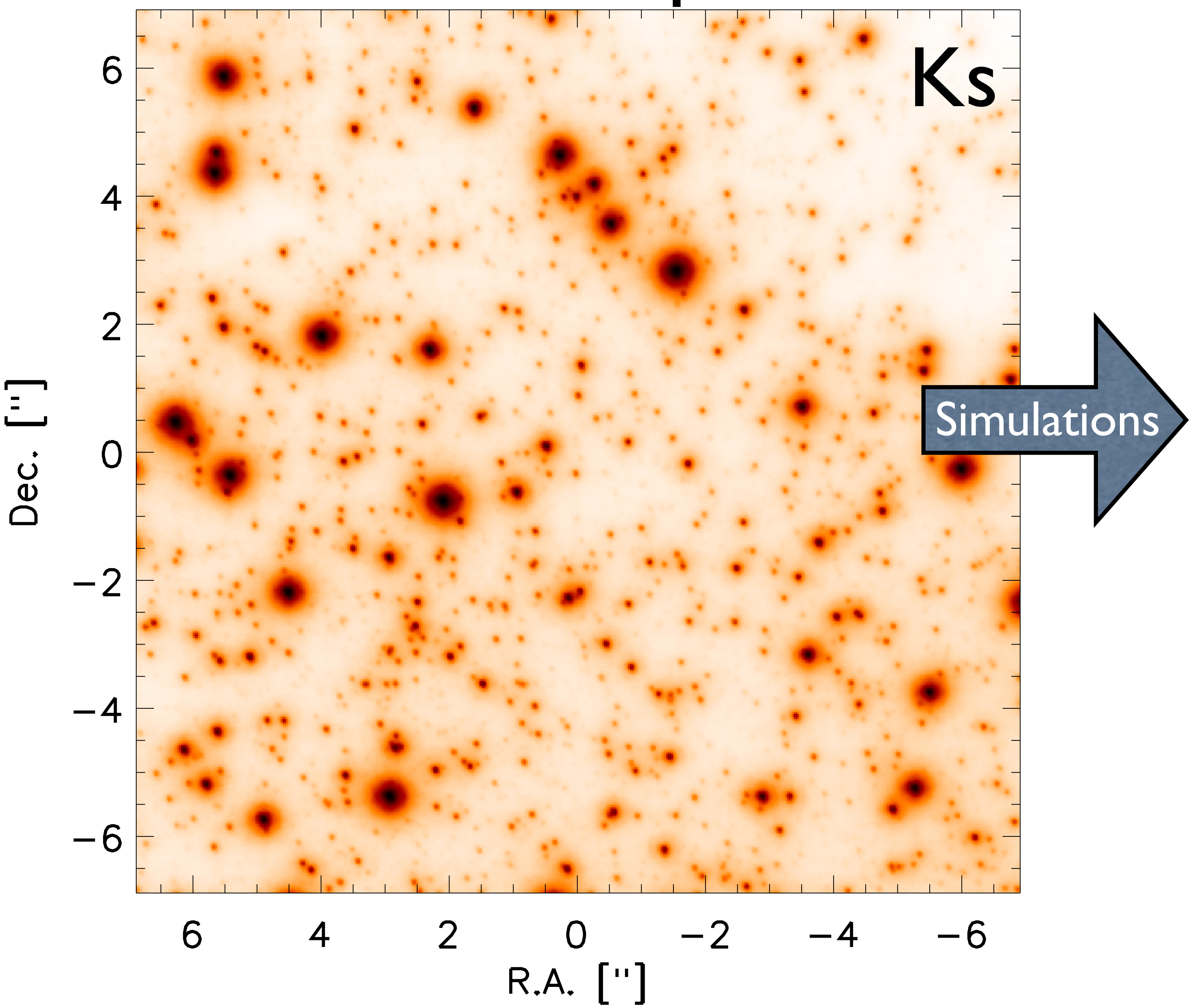


Field 20"NE of SgrA*

(Schödel et al. 2009)

Going wide-field: sub-sampled holography

NACO, 0.027"/pixel scale

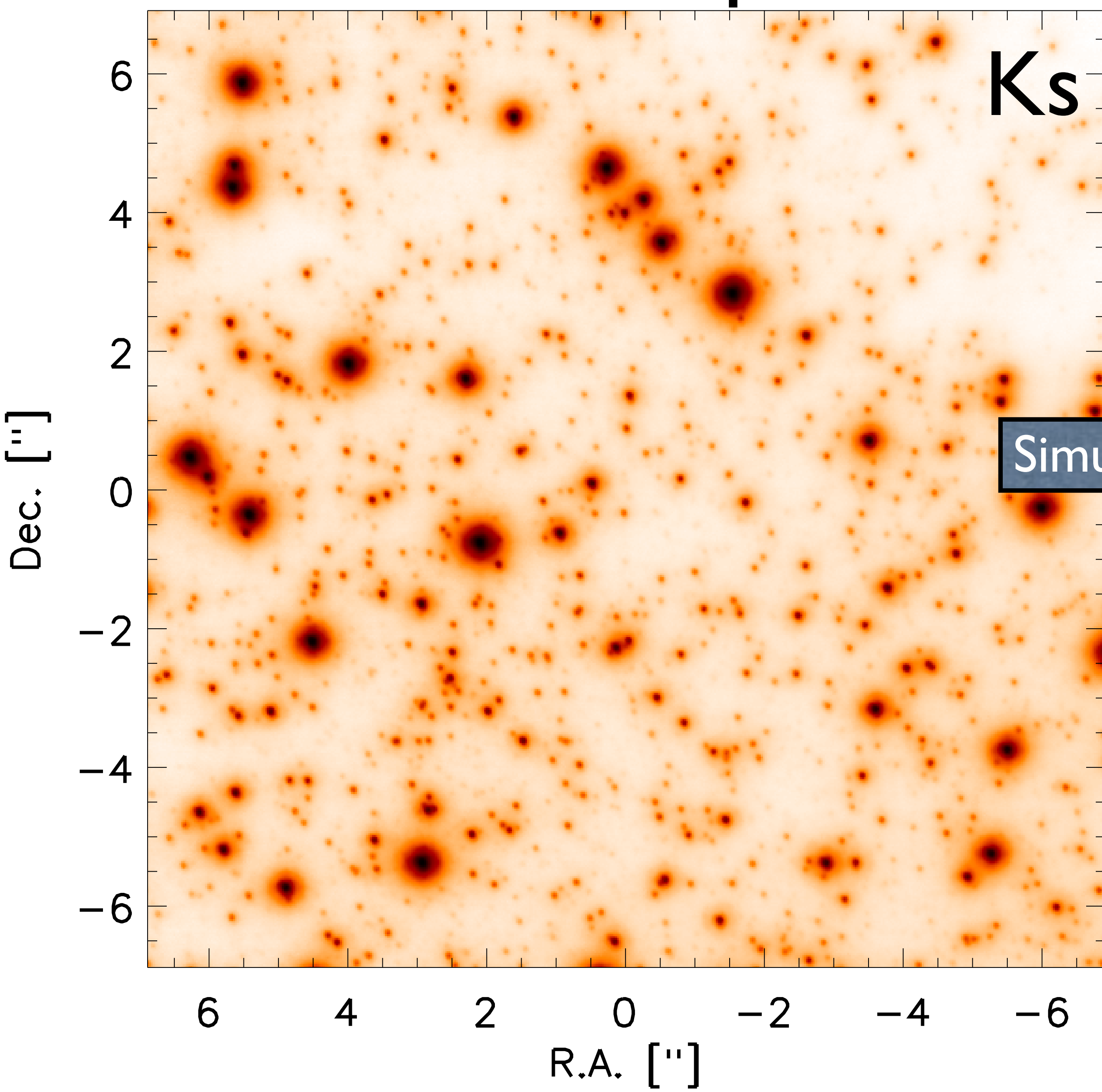


Field 20"NE of SgrA*

(Schödel et al. 2009)

Going wide-field: sub-sampled holography

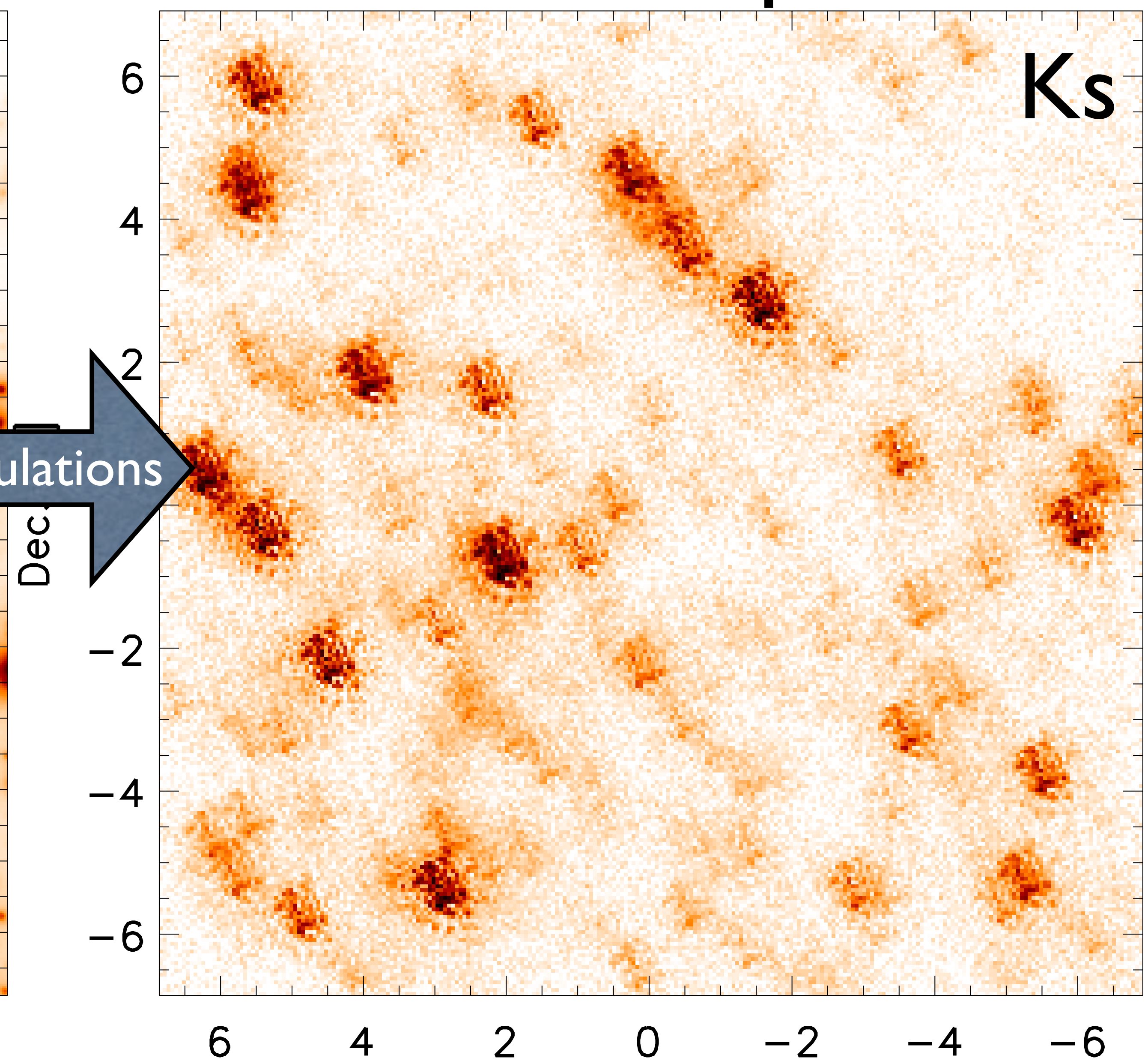
NACO, 0.027''/pixel scale



Field 20''NE of SgrA*

(Schödel et al. 2009)

NACO, 0.054''/pixel scale



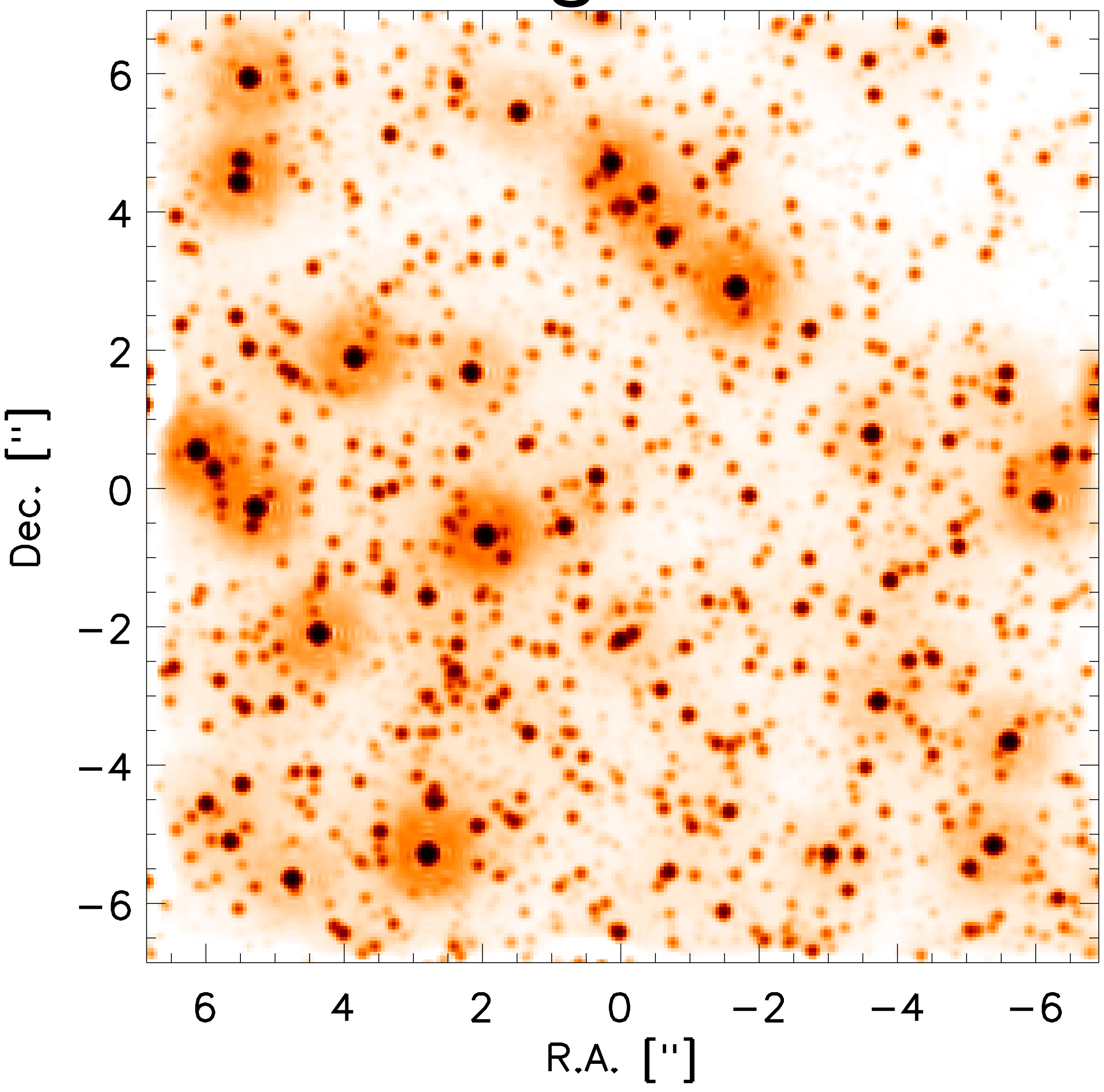
seeing 0.8'', DIT=0.4s, wind speed = 10 m/s, 10,000 frames

speckle code: Rengaswamy et al. 2010)

Going wide-field: sub-sampled holography

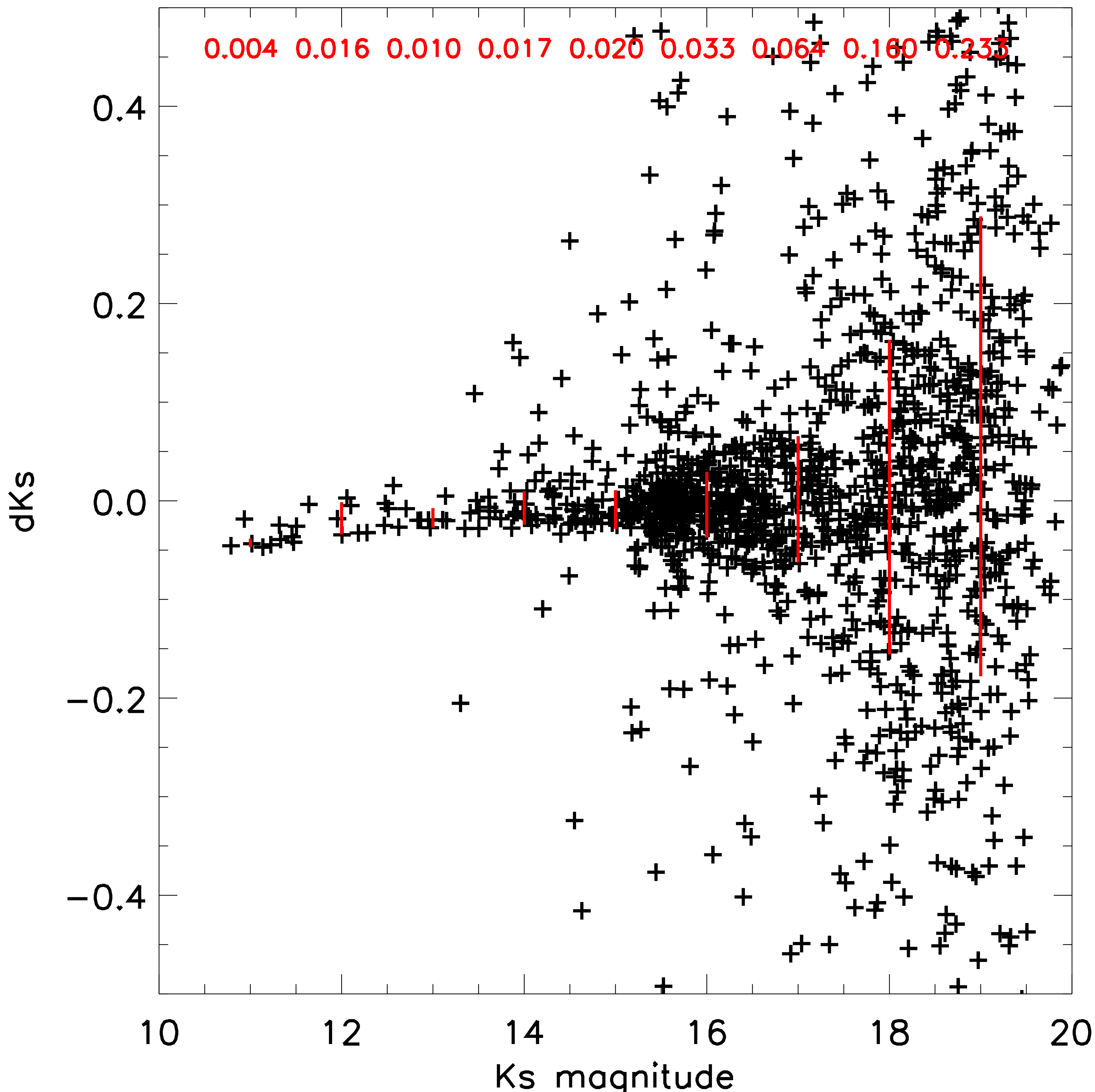
Going wide-field: sub-sampled holography

Reconstructed image, ~0.13" FWHM



Going wide-field: sub-sampled holography

Going wide-field: sub-sampled holography



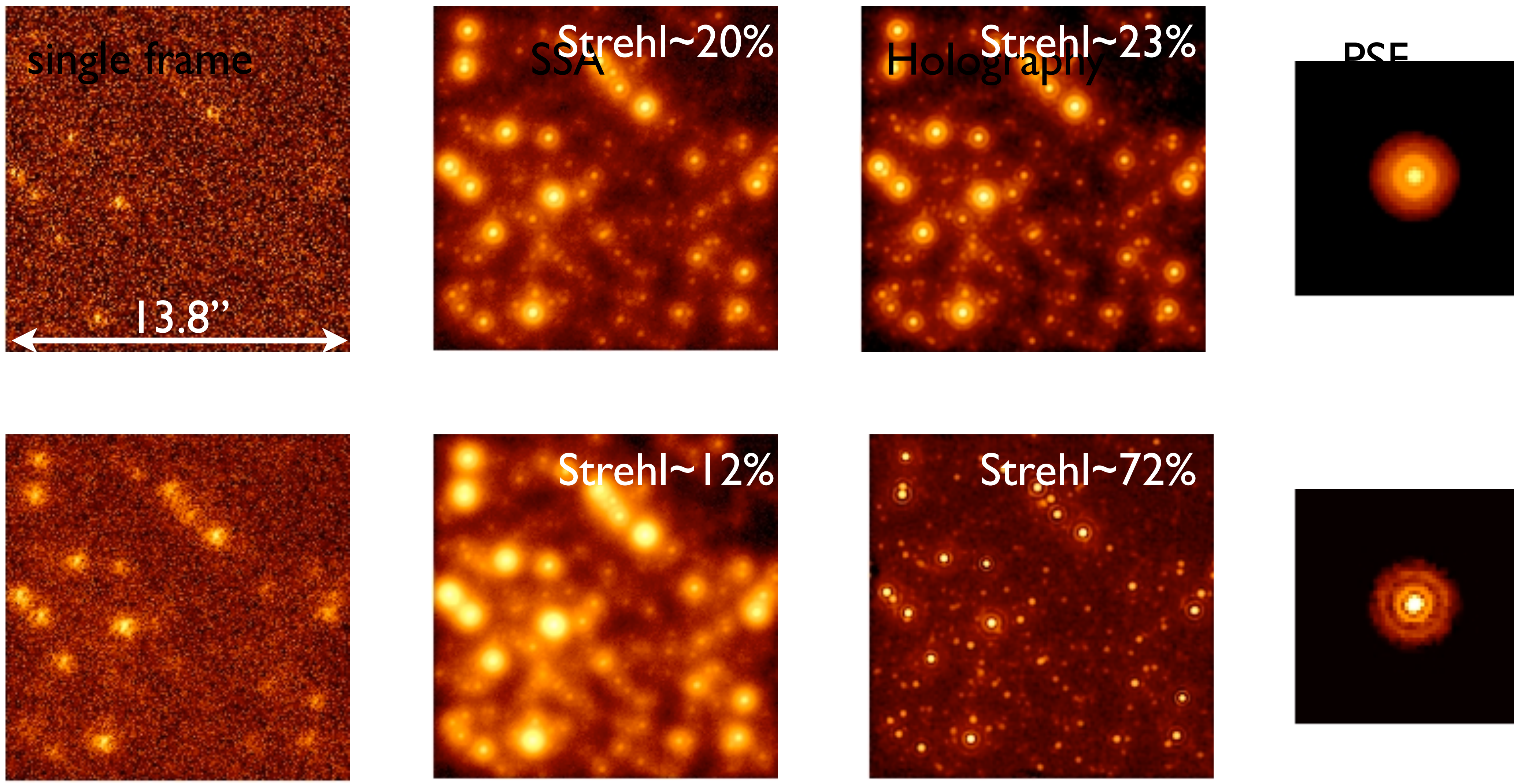
Holography with NOTCAM

80”×80”FOV with **0.078”sampling**, diffraction limit **Ks~0.20”**

Simulation: 0.8” seeing, windspeed 10m/s, airmass 1.2
Gain, Readout noise as in NaCo’s HAWAII - detector

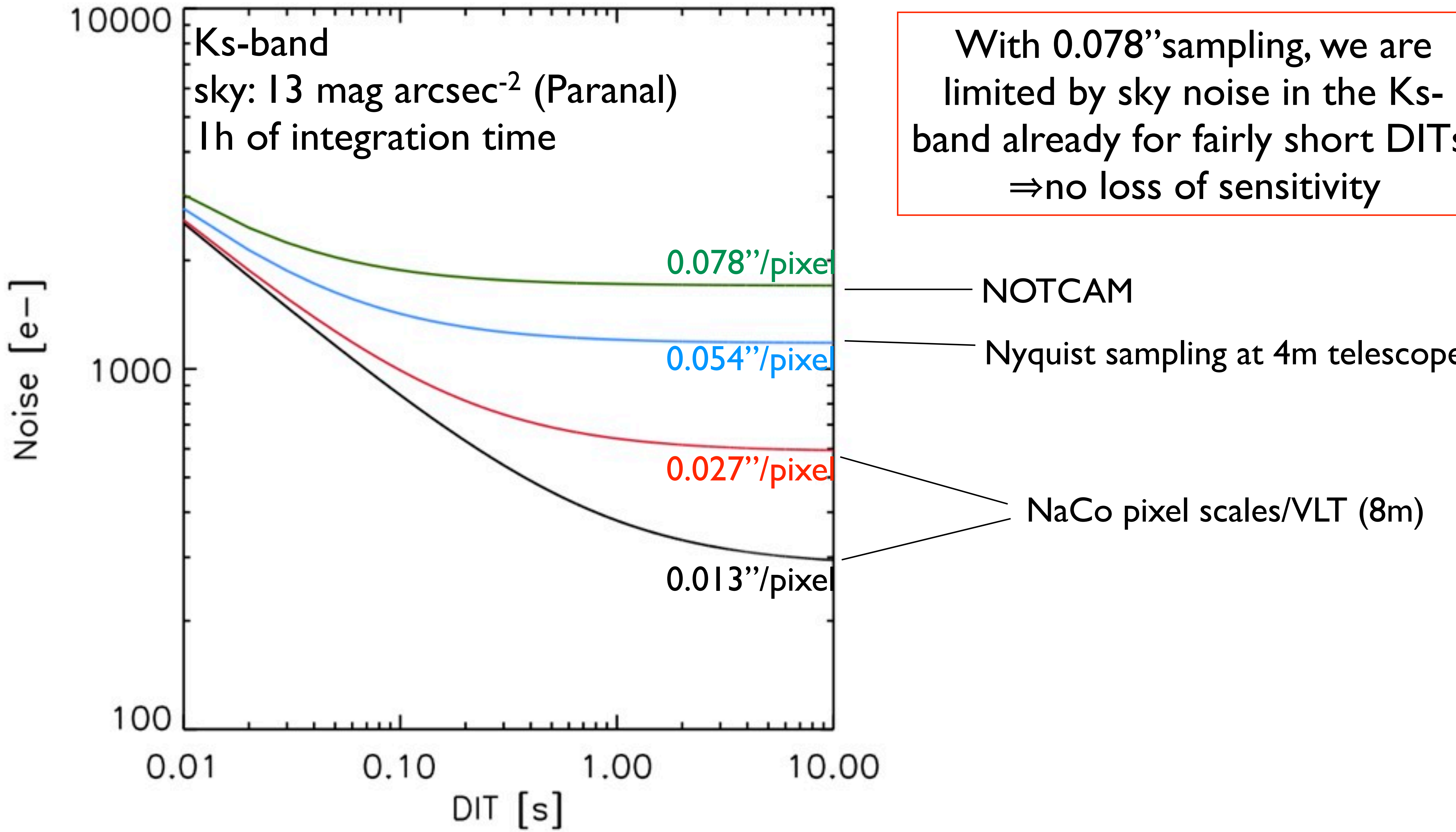
DIT = 0.1s
5000 frames

DIT = 0.5s
1000 frames



Astrometric precision ≤0.001 pixel (~0.1 mas) for Ks≤16 in 1h
⇒ proper motions ≥1 mas/yr can be detected in 1 yr

Holography with NOTCAM



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

Conclusions

The case for a wide angle speckle system - WASPS

Science cases:
High accuracy photometric and astrometric studies of distant (1-10kpc) SFRs, globular clusters, Galactic center, Galactic bulge, multiplicity and orbits of OBstars

Proper motion studies in embedded regions can complement Gaia results.

A speckle camera can provide any telescope within short times and with relatively small investment with MCAO-like capabilities, similar to Gemini's GeMS.

e.g., speckle camera@WHT/CAHA:
2k x 2k detector with Nyquist sampling at K can provide 120''x120'' FOV.

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)**, 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, arXiv:1110. 2261

...and in the future

The ground-based space telescope with "zero noise" NIR detectors... astronomers' dream may actually become true.

Finger et al. (2010): *Development of high speed low noise NIR HgCdTe Avalanche Photo- diode Arrays for Adaptive Optics and Interferometry* (ESO/Selex-Galileo Infrared Ltd)

Figer et al. (2011): *A photon-counting detector for exoplanet missions*

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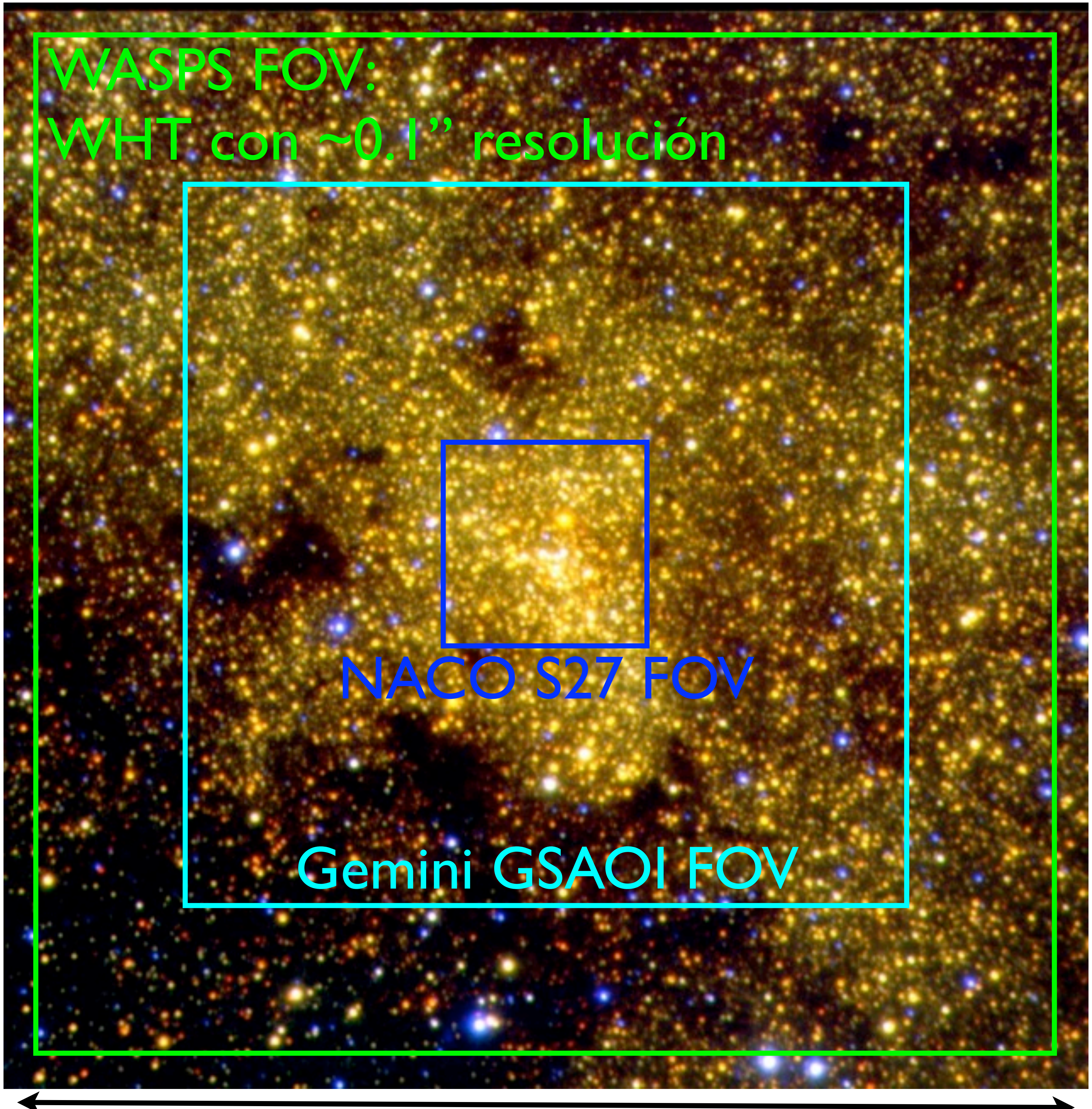
Thank you!


WASPS FOV:
WHT con ~0.1” resolución
NACO S27 FOV
Gemini GSAOI FOV

150”/ 6pc

WASPS: conceptos

dewar + óptica (optimizada para astrometría) + detector

(Sistema de refrigeración opcional)

a) Infrarrojo cercano (sólo J,H,K)

diseño sencillo; desarrollo rápido; costes de material dominados por costes de detector (e.g. Teledyne H2RG: ~350k€)

b) 2 canales: IR/óptico o J-K/L-M

gran utilidad, pero más complejo y caro

Telescopios:
GTC/VLT o NTT/WHT/CAHA

SHARP@ESO NTT: NICMOS
2 256, FOV: 13"×13"

Campo (banda K) con detector 2k x 2k y muestreo del límite de difracción:
~60"x60" en VLT/GTC
~120"x120" en NTT/WHT

con sub-muestreo:
120"x120" en VLT/GTC
240"x240" en NTT/WHT

Lucky imaging

SSA image reconstruction combined with *strong frame selection* (only 1%-10% of frames used).

Special lucky imaging approach, e.g. AstraLux: push into optical domain with electron multiplying high-speed CCDs; off-the-shelf components (low costs!; see, e.g., *Hormuth et al. 2008*)

⇒ HST resolution in i/z-bands on ground-based 2-4m telescopes

Lucky imaging

Core of M15 with AstraLux, Calar Alto 2.2m (Hormuth et al. 2008)

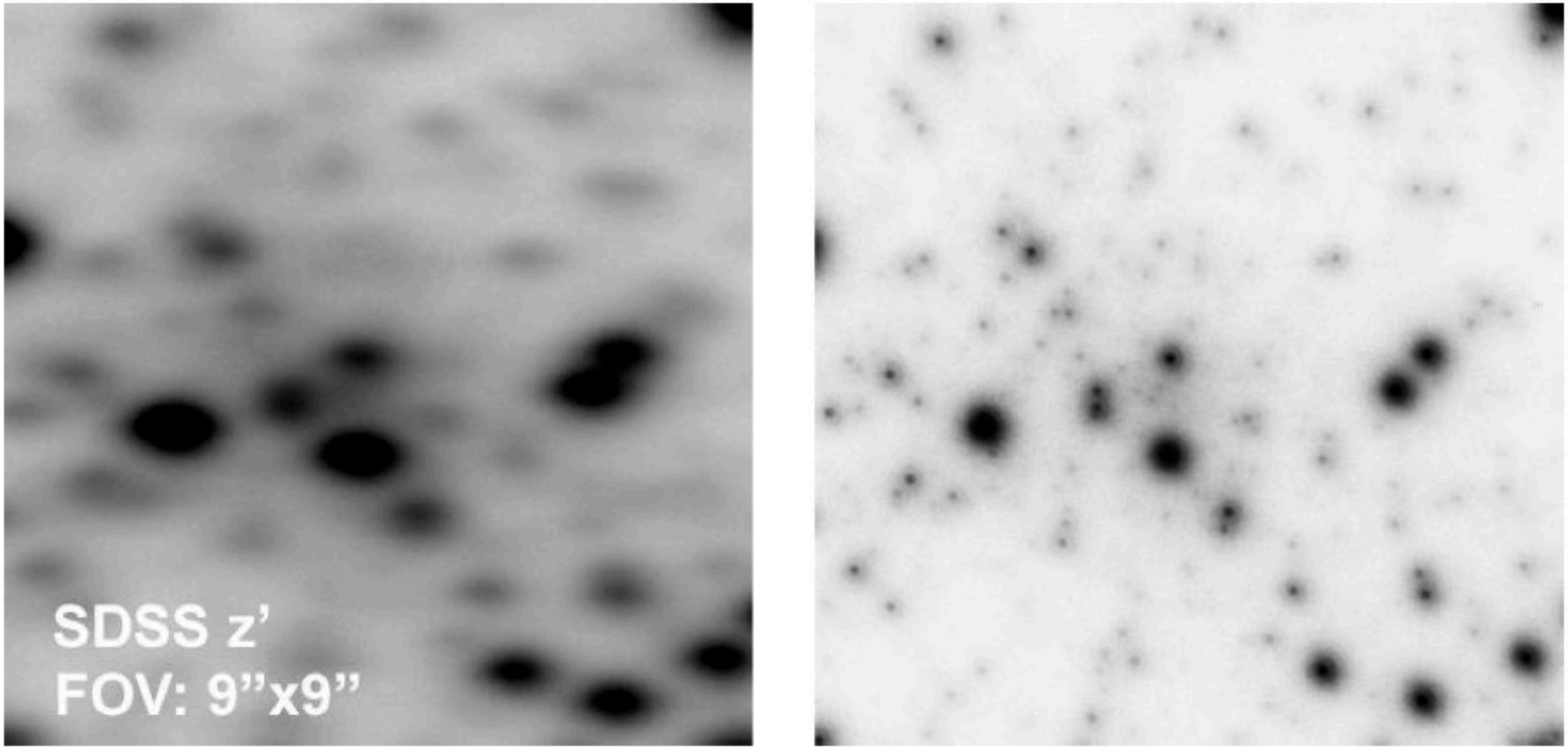


Figure 3. Comparison between seeing limited imaging and the "Lucky" version: The combination of the best 5% of 10000 single frames provided a Strehl ratio of 20% in this observation of the core of the globular cluster M15. Though the conventional result contains 20 times more photons, it is clearly inferior in terms of point source detection limits.