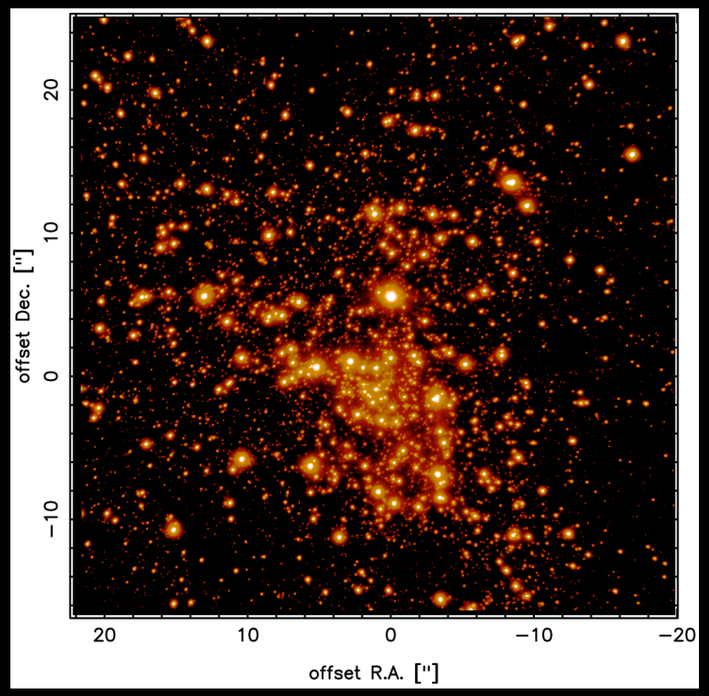
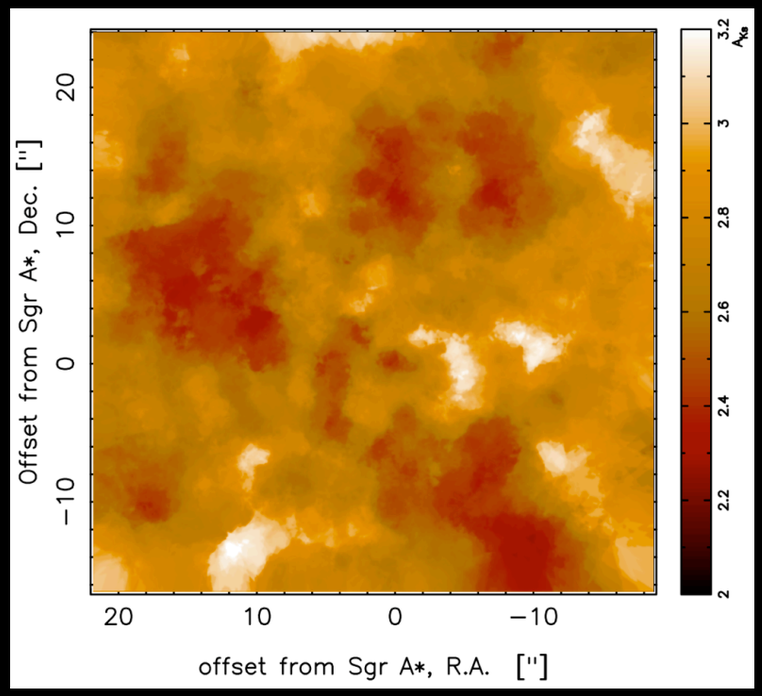
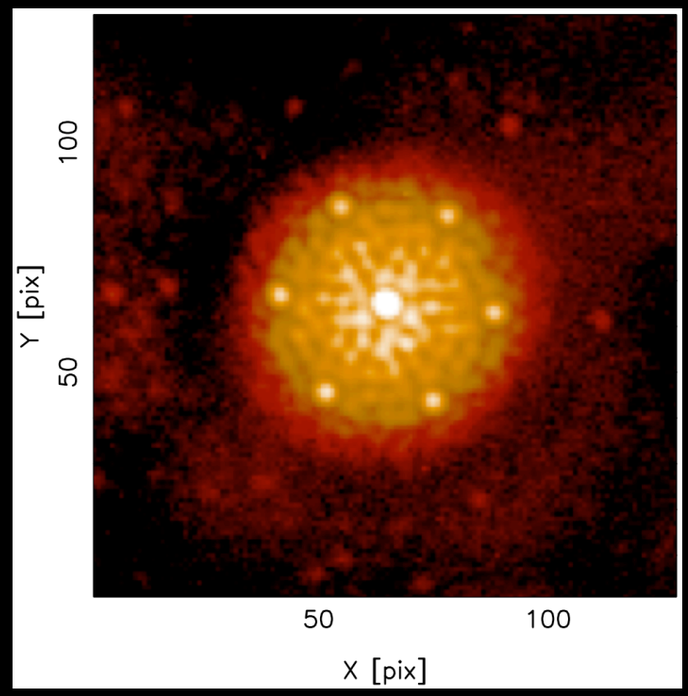
Observations of the Galactic Center with VLT/NACO







Rainer Schödel, IAA (CSIC)

Jornada ESO 2009, Madrid, 22 September 2009

NACO in a Nutshell

- NAOS + CONICA = NACO
- NIR camera plus adaptive optics system (144 actuators)
- VLT UT 4 (Yepun)
- Diffraction limited imaging at 1-5 μm ~40 -110 milli-arcsec
- Unique feature: IR WFS
- Numerous (or rather : innumerable) modes: spectroscopy, SDI, polarization, coronagraphy, cube mode, many(!) filters...

The black hole at the Galactic center

50 light days

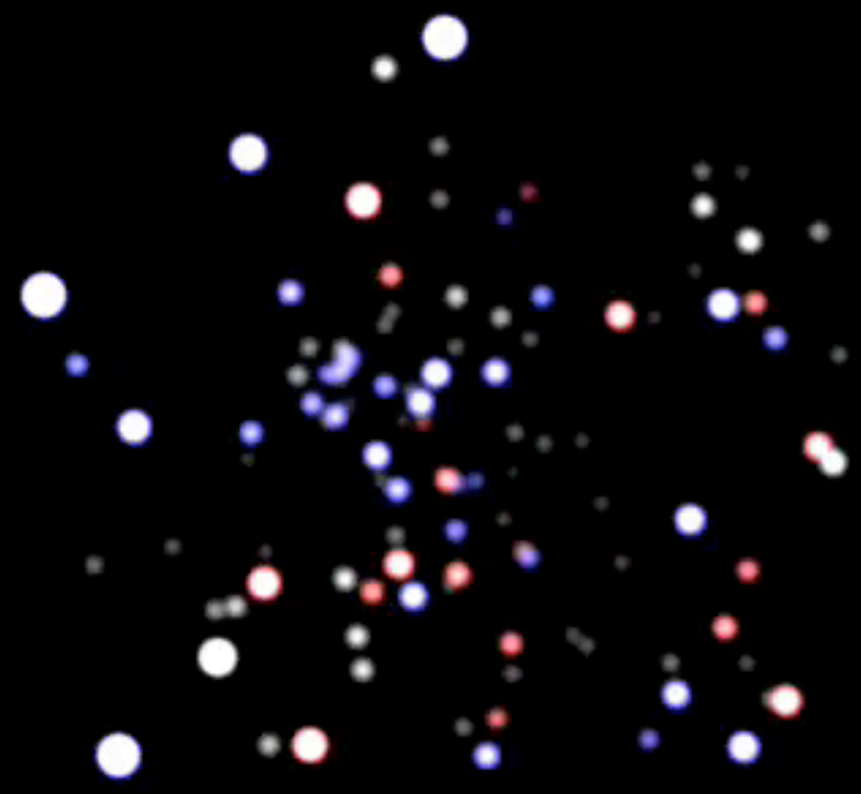
14 light days

MPE/ESO

UCLA/Keck

The black hole at the Galactic center

50 light days



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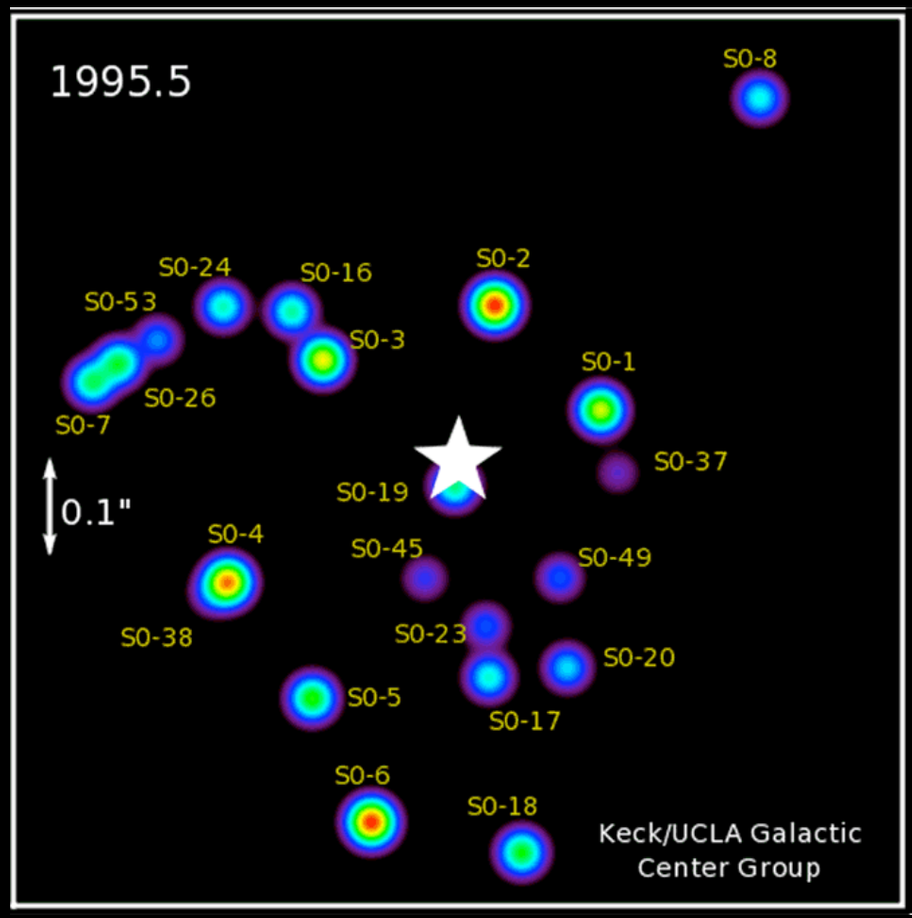

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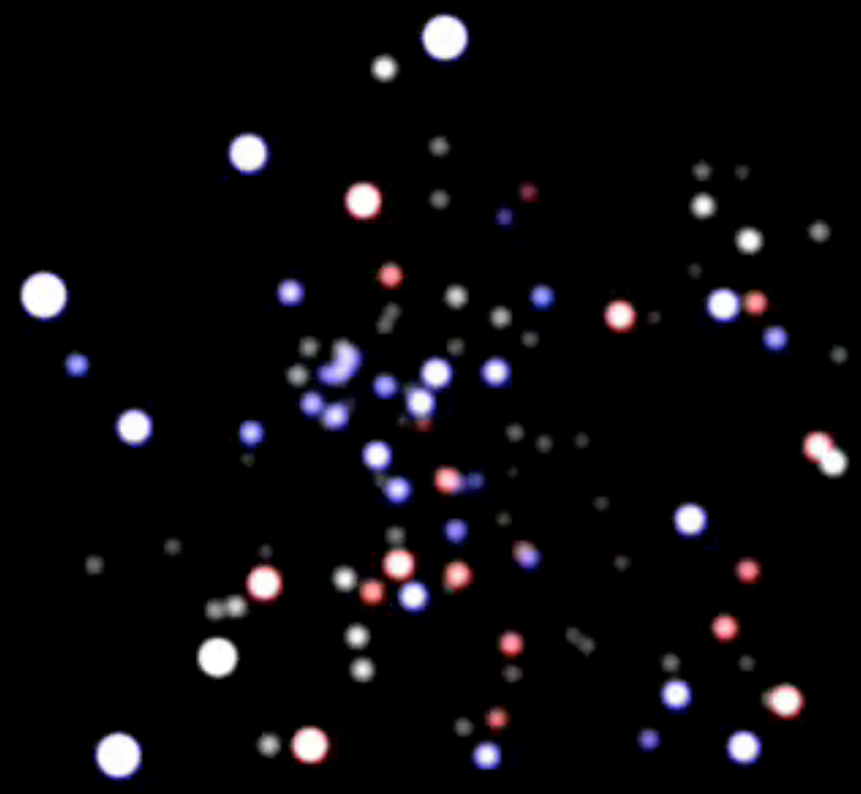
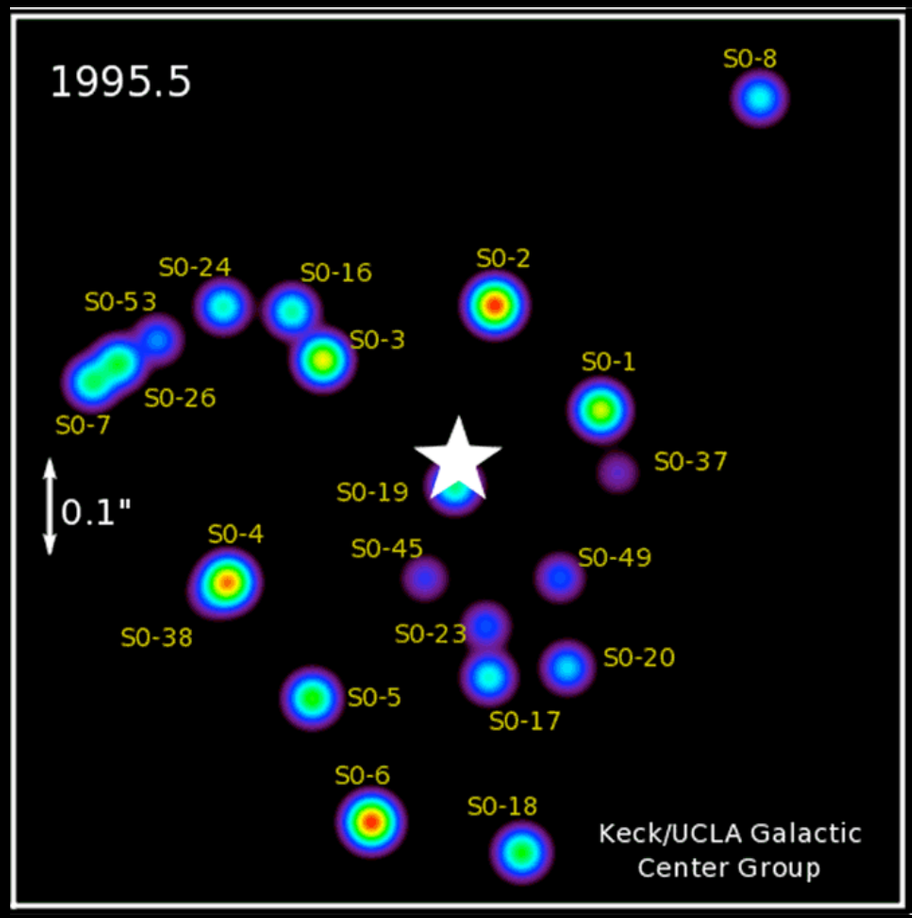


MPE/ESO

14 light days



UCLA/Keck

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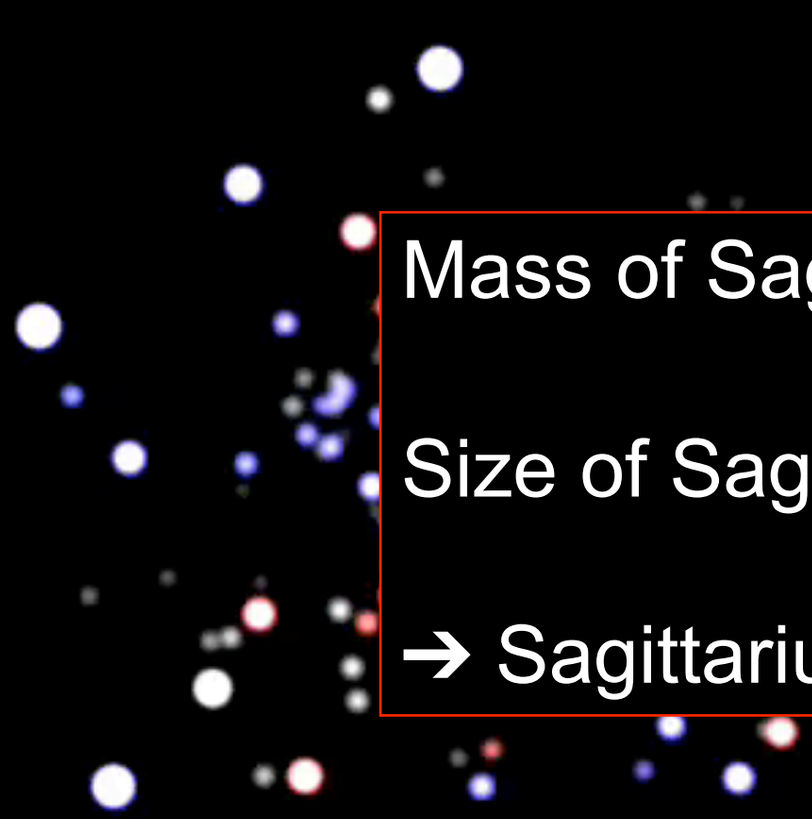

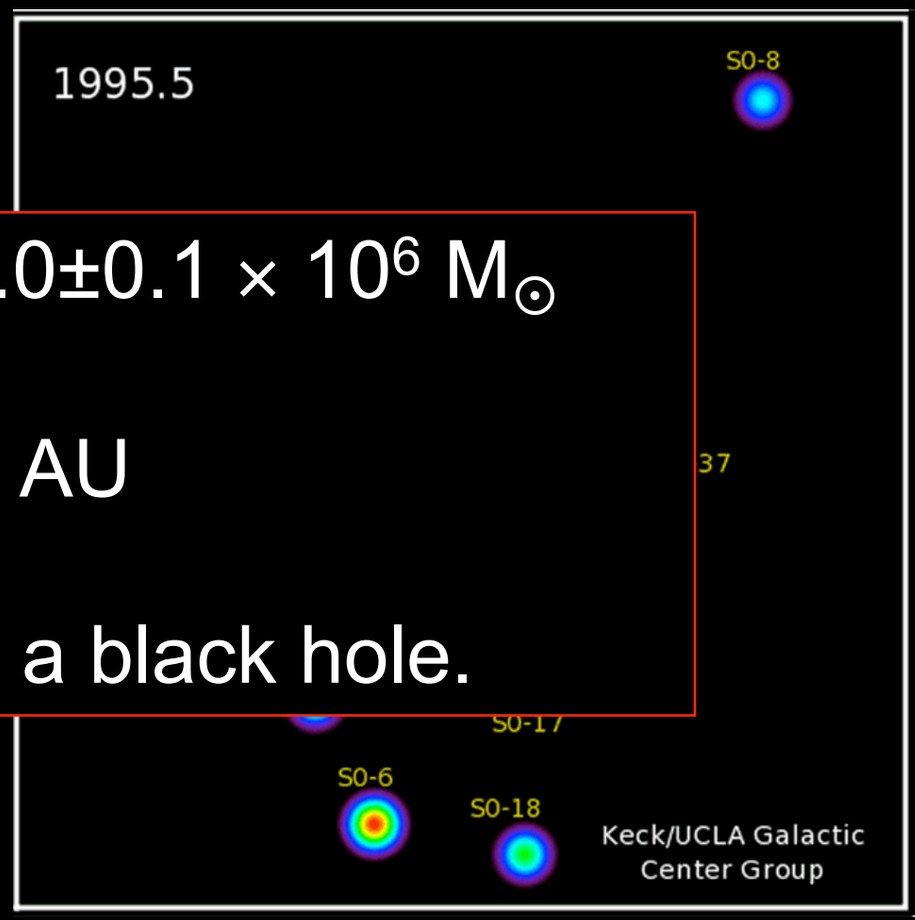

Mass of Sagittarius A*: $4.0 \pm 0.1 \times 10^6\ M_\odot$

Size of Sagittarius A* < 1 AU

➔ Sagittarius A* must be a black hole.

MPE/ESO

UCLA/Keck

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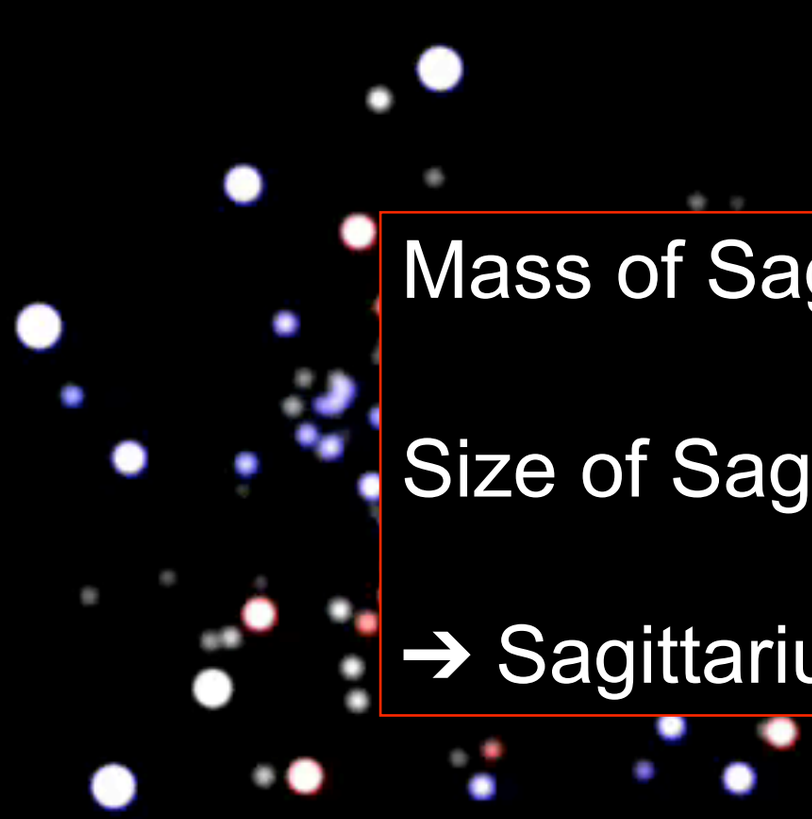

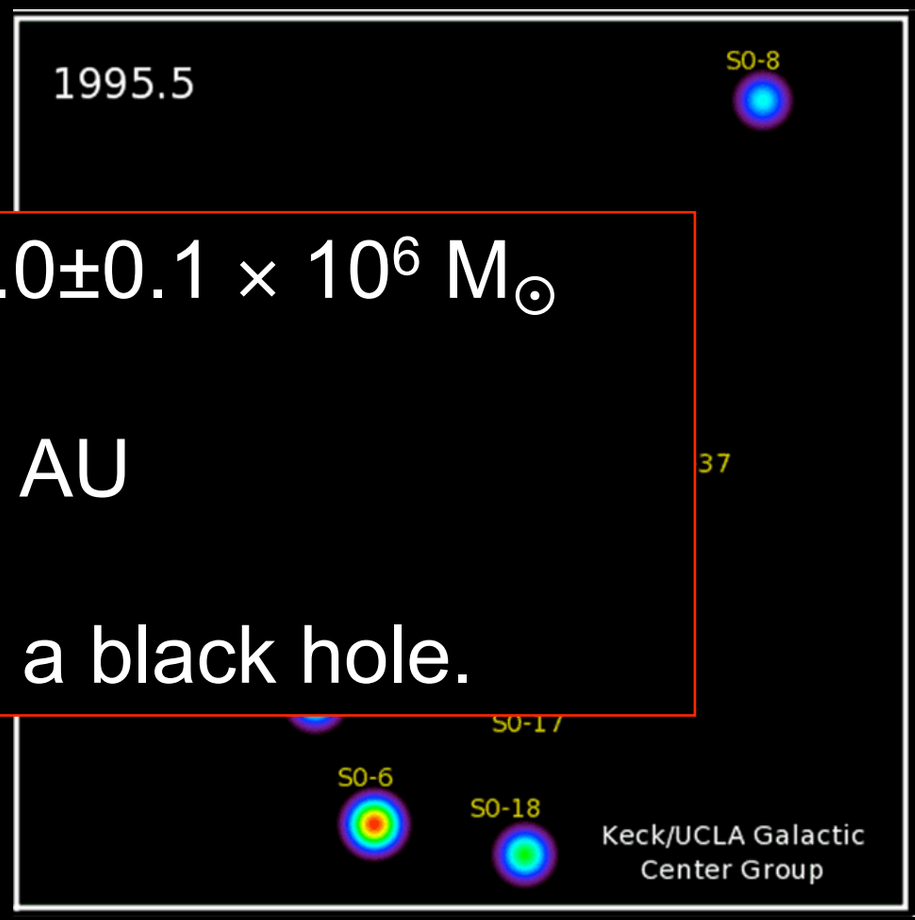

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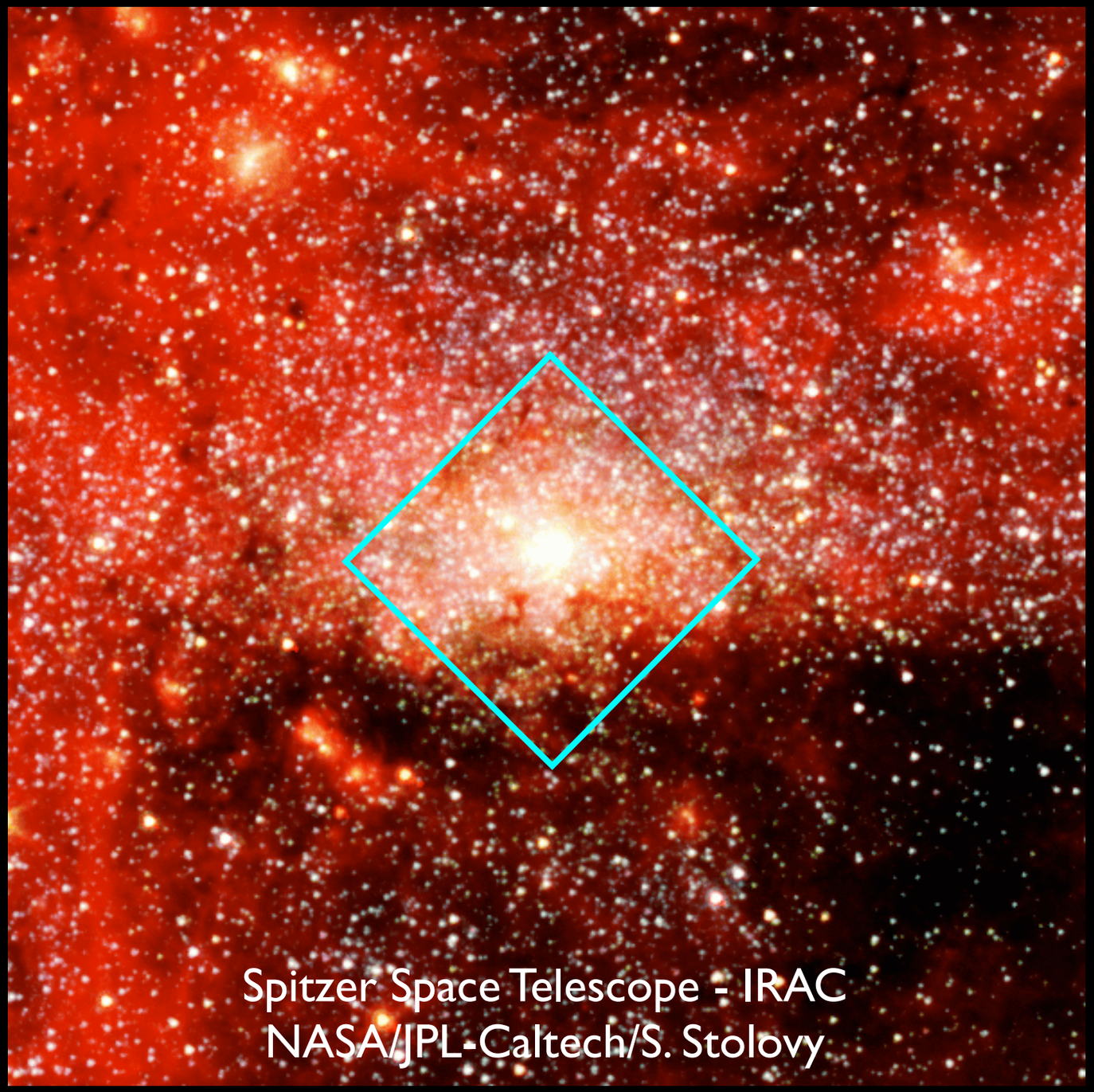
e.g. Eckart & Genzel (1996); Ghez et al. (1998, 2003,2008); Genzel et al. (2000); Eckart et al. (2002); Schödel et al. (2002, 2003, 2009); Reid et al. (2004); Eisenhauer et al. (2003, 2005); Gillessen et al. (2009); Doeleman et al. (2008) etc.

The Nuclear Star Cluster of the Milky Way

e.g. Launhardt et al. (2002), Schoedel et al., (2007), Graham & Spitler (2009)

The Nuclear Star Cluster of the Milky Way



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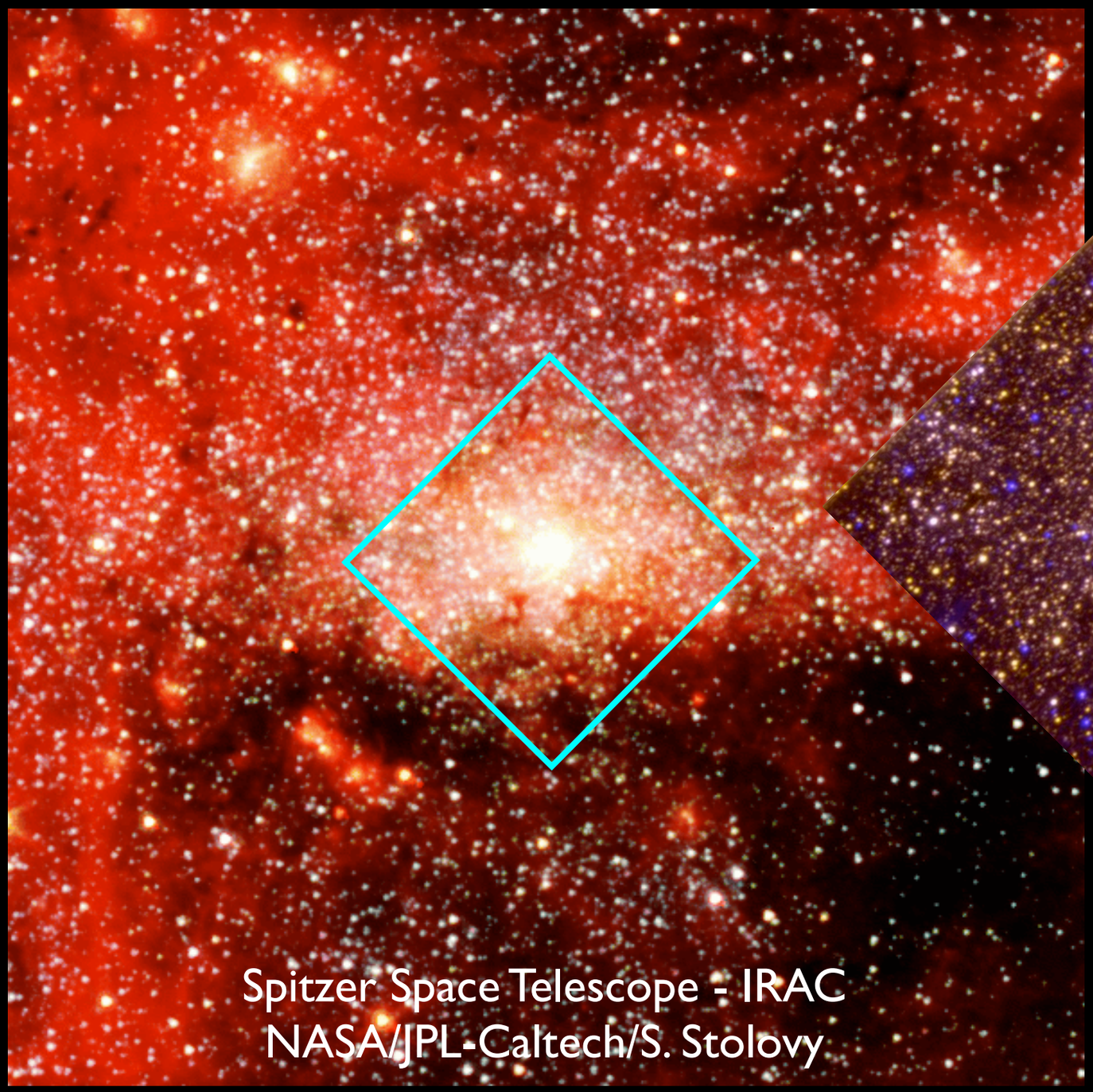
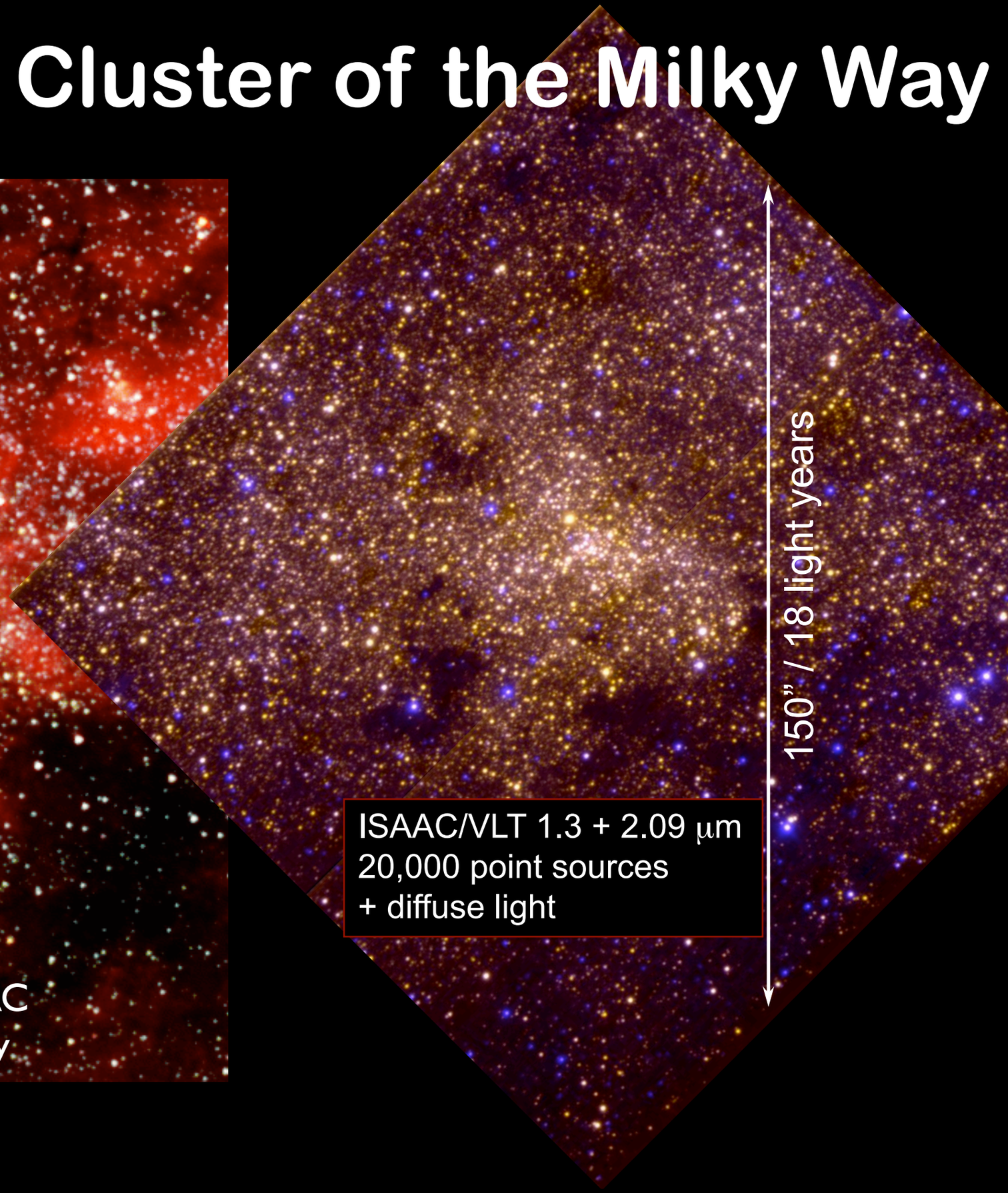
The Nuclear Star Cluster of the Milky Way





e.g. Launhardt et al. (2002), Schoedel et al., (2007), Graham & Spitler (2009)

1. Stellar population in the central parsec of the Milky Way: multi-band imaging with NACO

Classifying stars in the GC

NSC population is mixed old/young. Components must be separated in order to understand cluster structure.
➔ Is there a density cusp around the BH or not?

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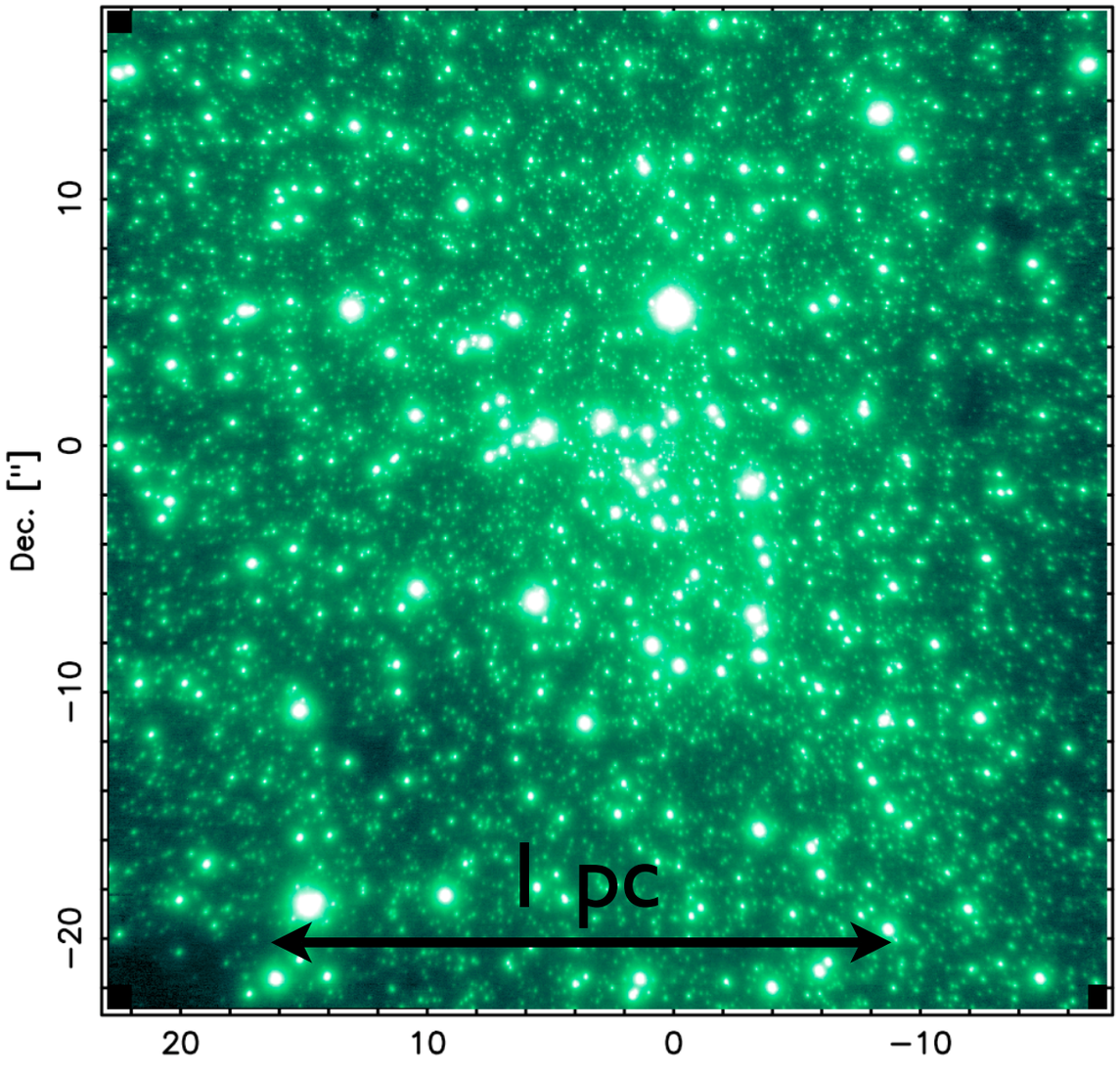

NACO/VLT, 2.2 μm
adaptive optics, ~0.06” FWHM

10,000 point sources ($mag_K \leq 17.5$)

Classifying stars in the GC

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Classifying stars in the GC

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➔ Is there a density cusp around the BH or not?

Main difficulties for classification of stars:

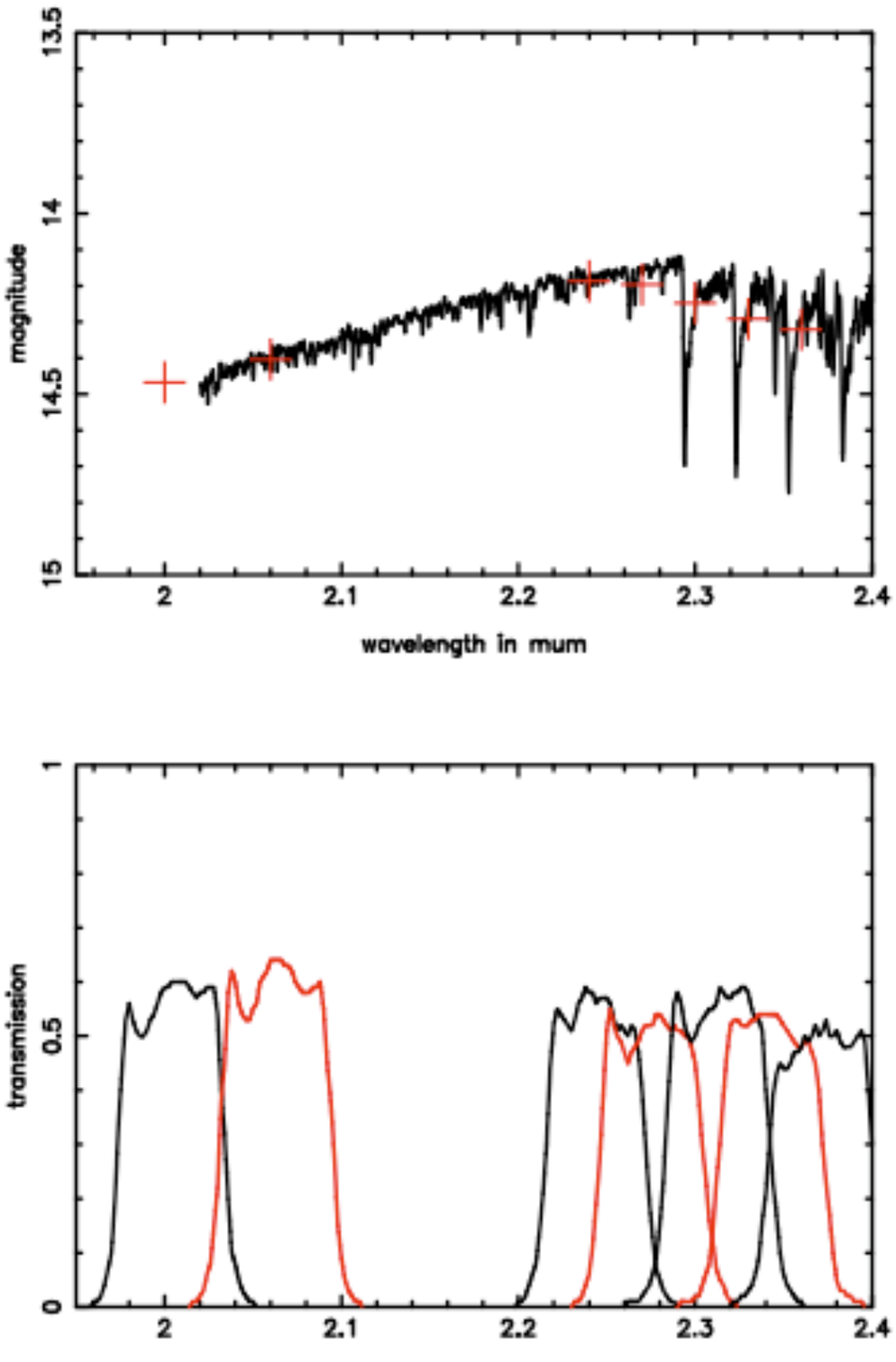
- high and variable extinction

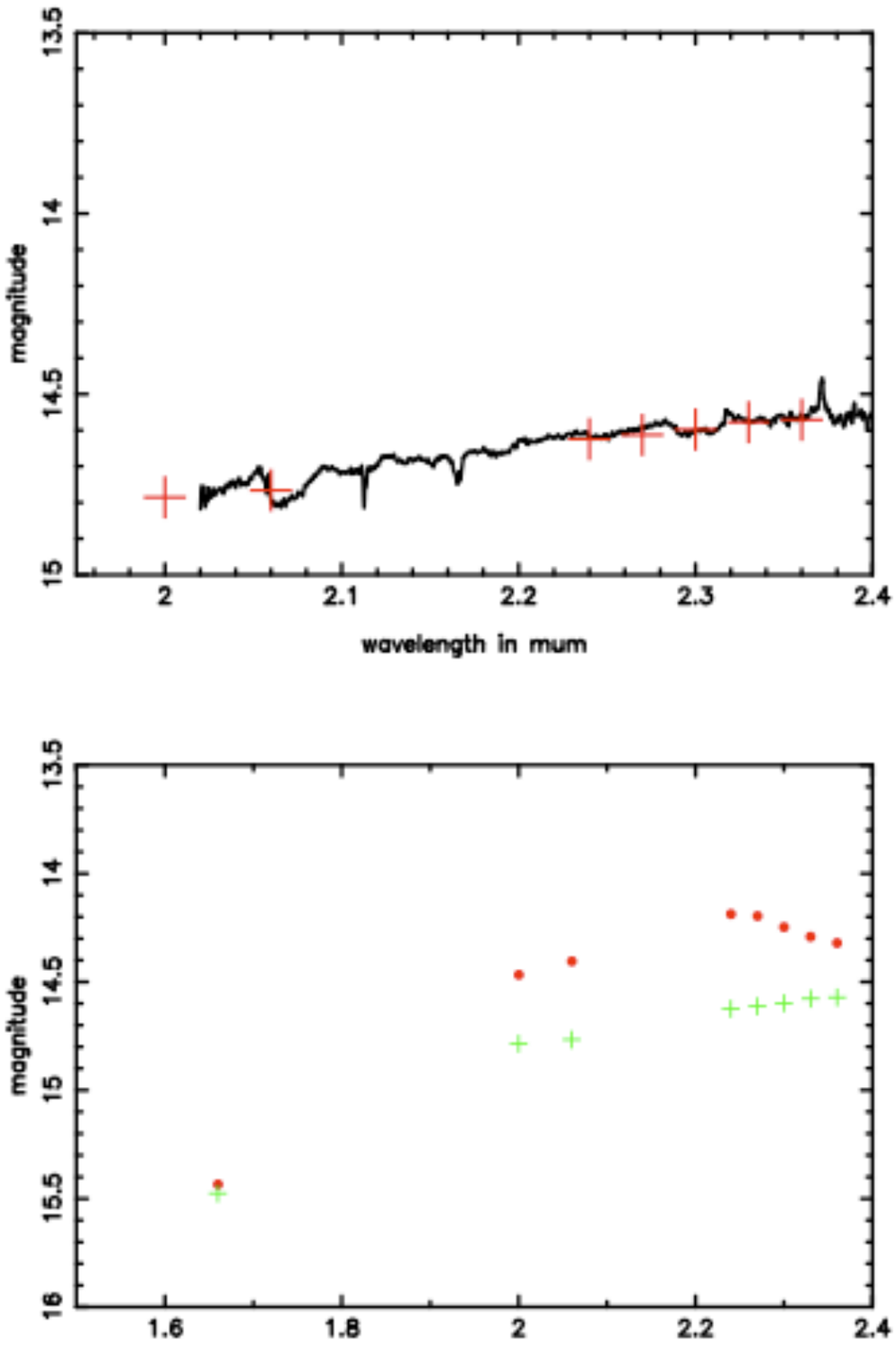
- only H,K,L observations (narrow range of stellar colors)

- anisoplanatic effects make photometric accuracy better than 0.05 mag extremely challenging

- FOV of spectroscopy very small

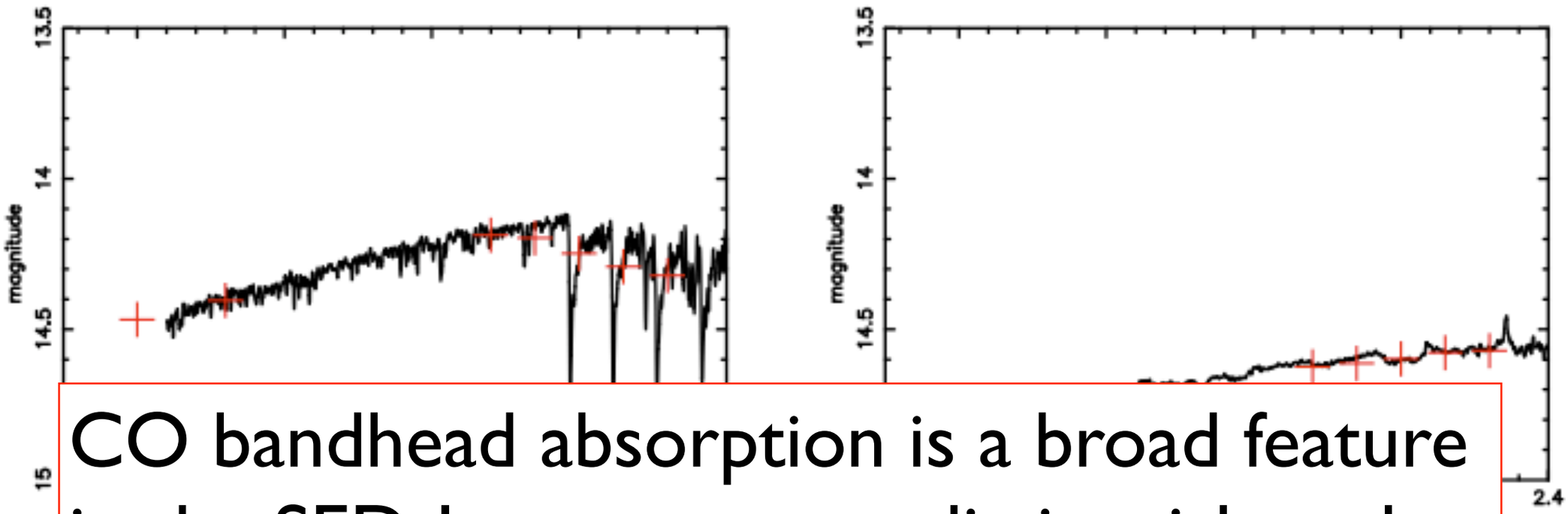
Classifying stars in the GC



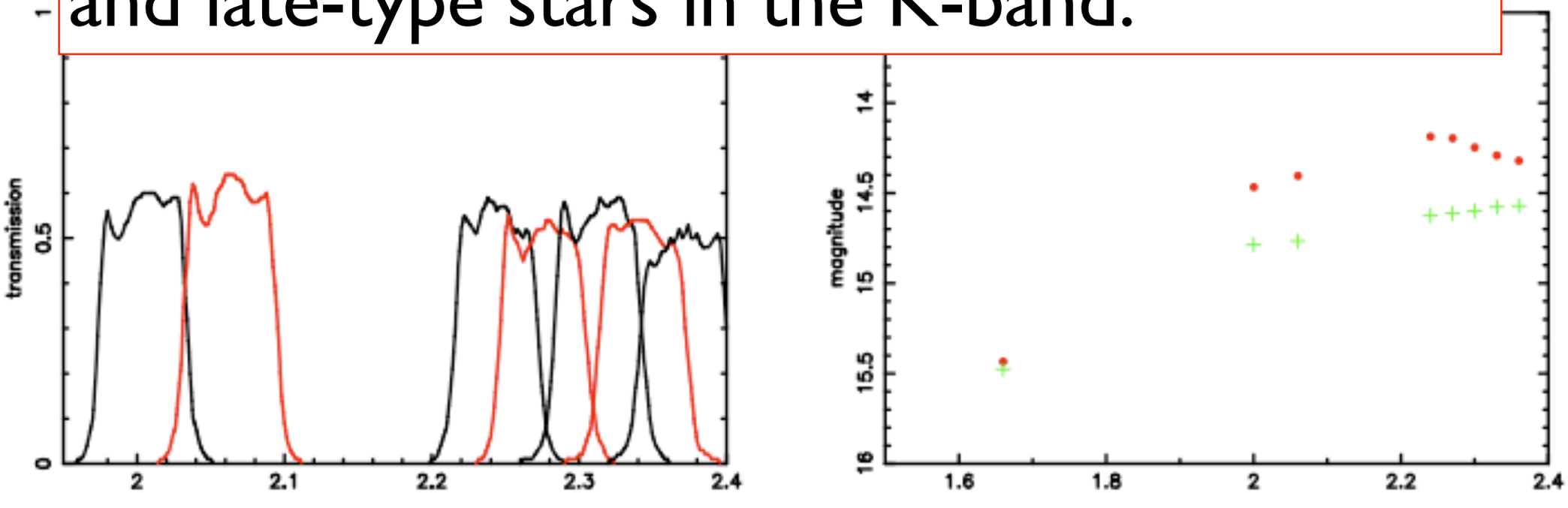


Buchholz, Schödel, & Eckart (2009, A&A)

Classifying stars in the GC

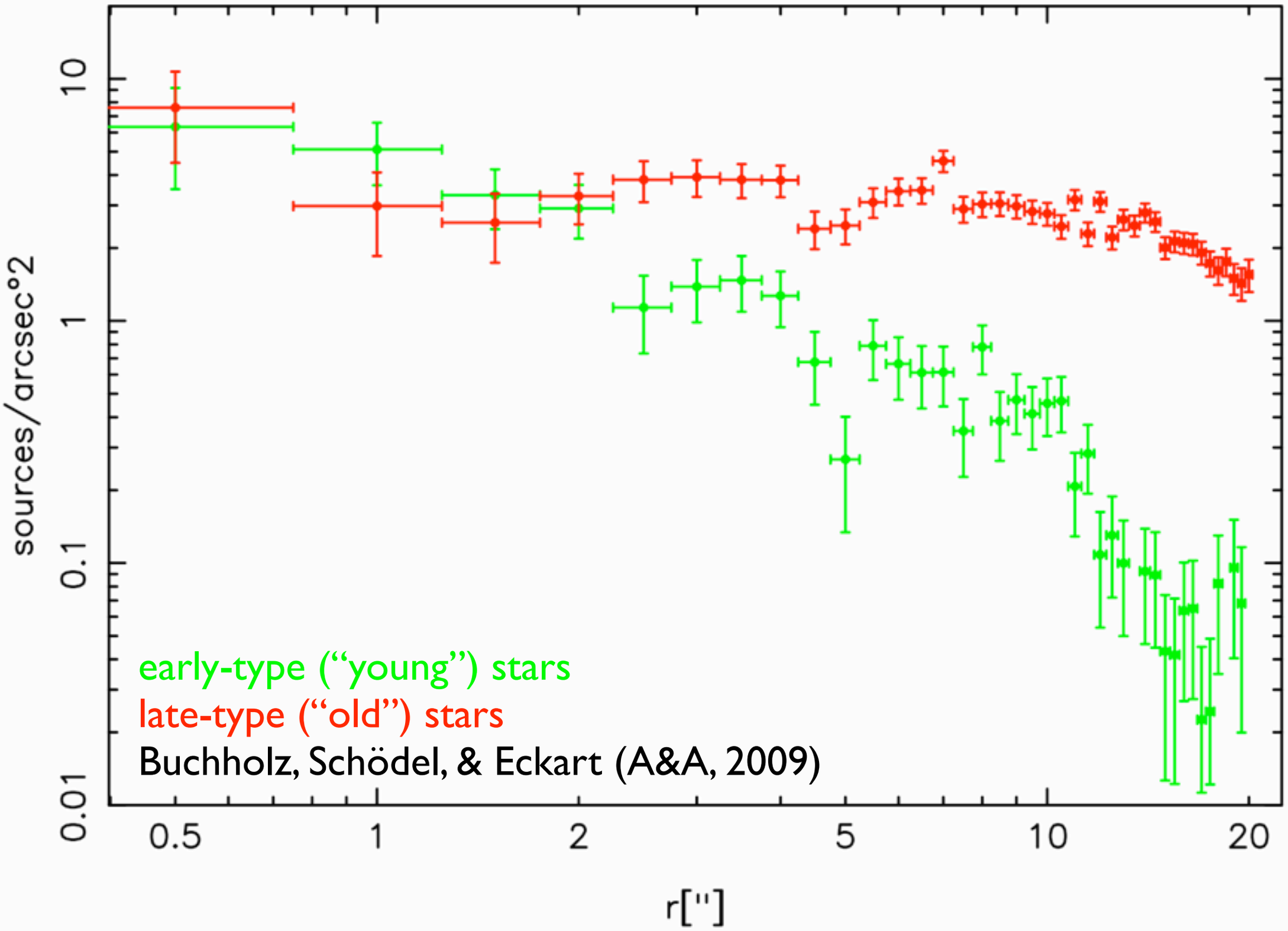


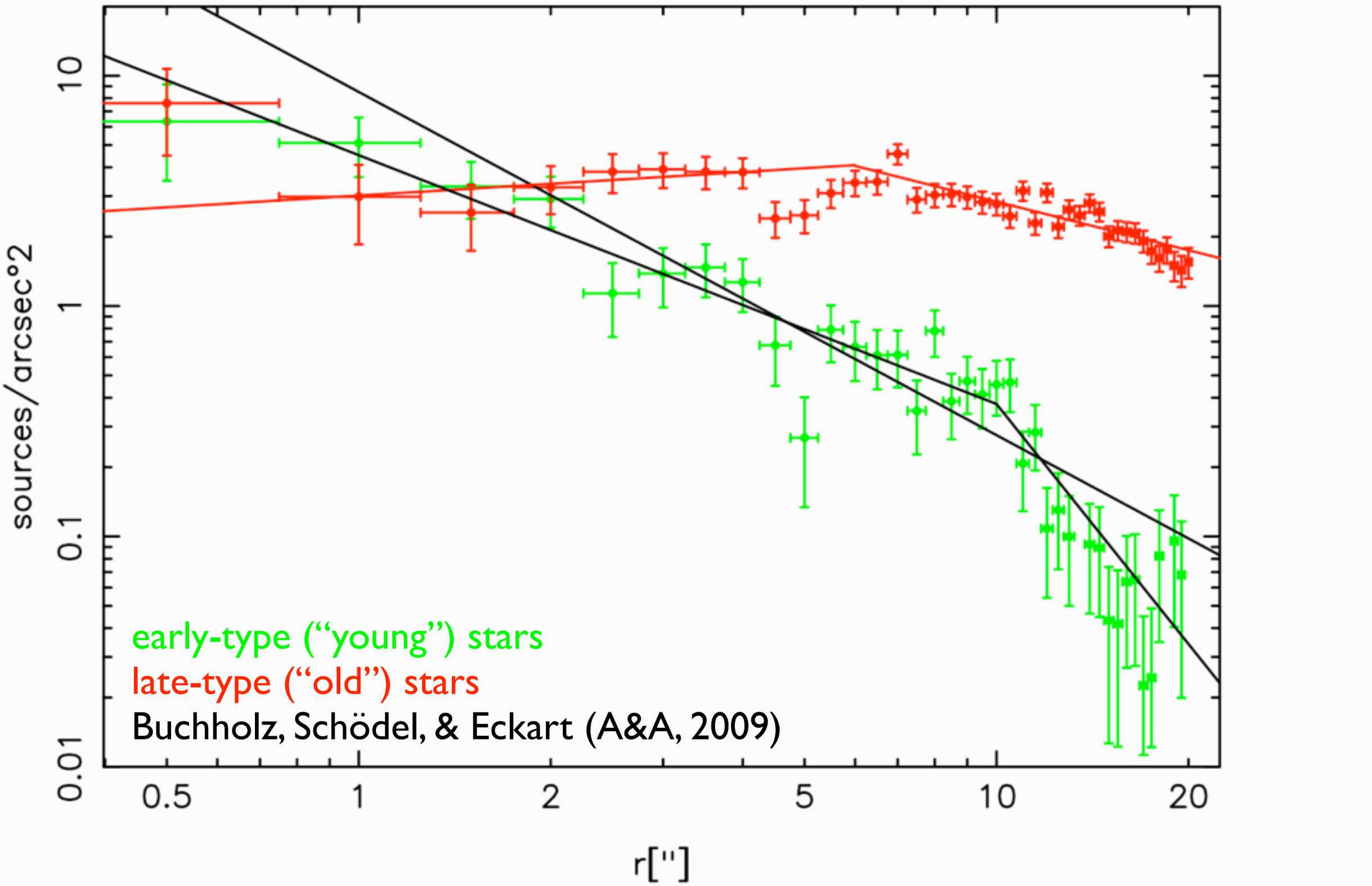
CO bandhead absorption is a broad feature in the SED. It can serve to distinguish early- and late-type stars in the K-band.

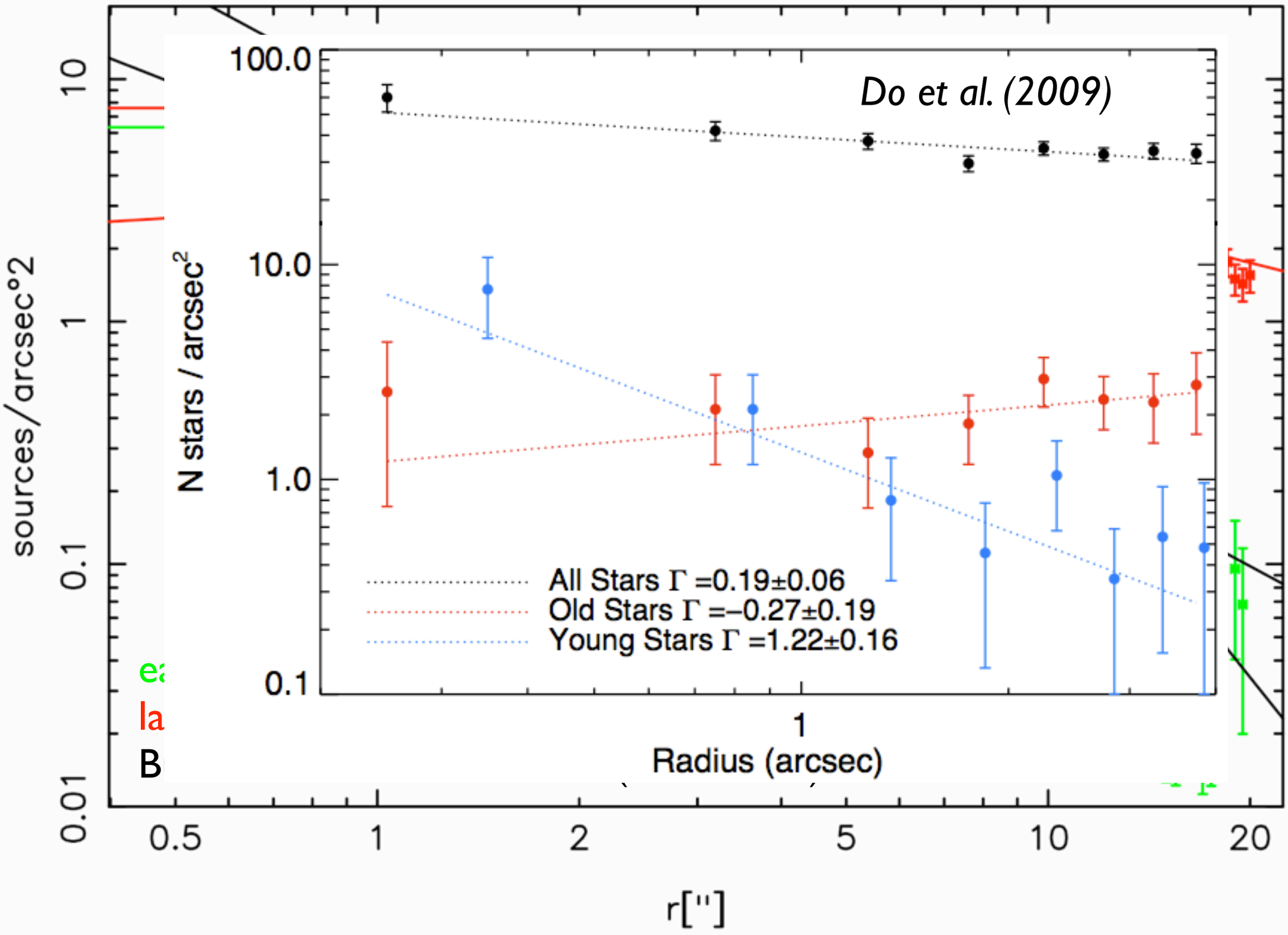


Buchholz, Schödel, & Eckart (2009, A&A)

n(r) of old stars ≠ n(r) of young stars




sources/arcsec°2
10
1
0.1
0.01
0.5
1
2
5
10
20
r["]
early-type ("young") stars
late-type ("old") stars
Buchholz, Schödel, & Eckart (A&A, 2009)


Do et al. (2009)
N stars / arcsec²
Radius (arcsec)
All Stars Γ =0.19±0.06
Old Stars Γ =–0.27±0.19
Young Stars Γ =1.22±0.16
sources/arcsec°2
r['']
0.01
0.1
1
10
0.5
1
2
5
10
20
100.0
10.0
1.0
0.1

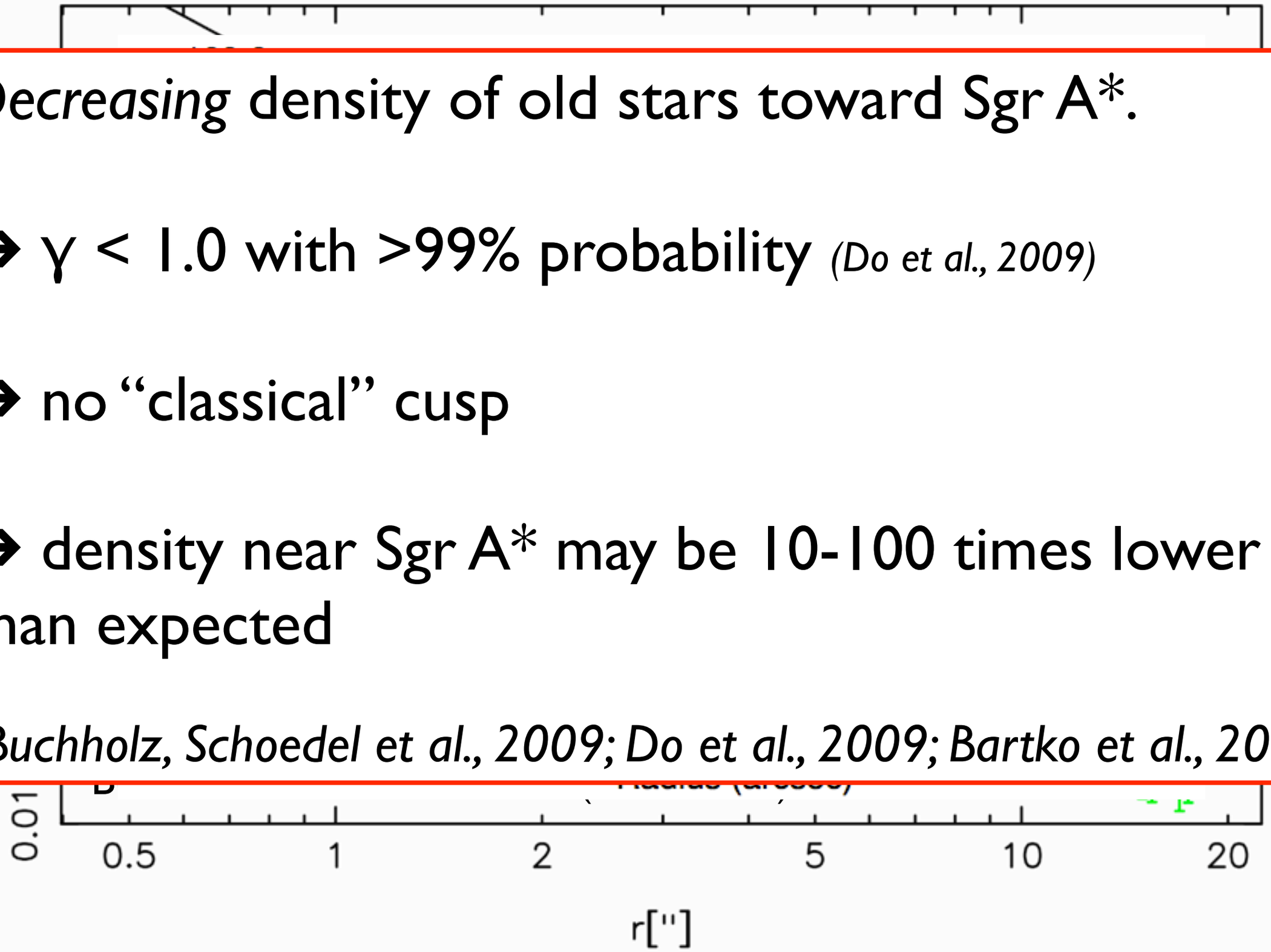
Decreasing density of old stars toward Sgr A*.

➔ γ < 1.0 with >99% probability *(Do et al., 2009)*

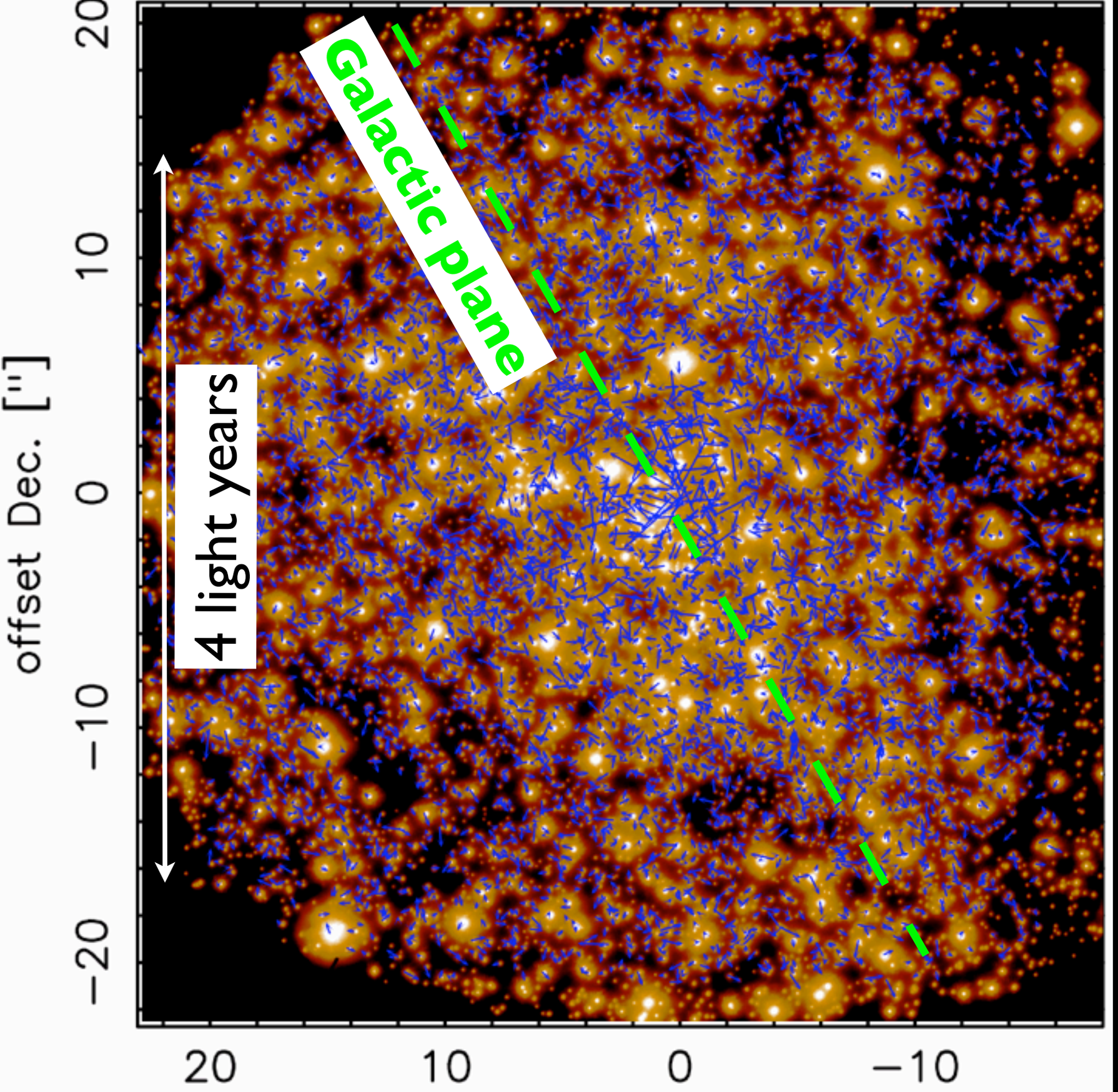
➔ no "classical" cusp

➔ density near Sgr A* may be 10-100 times lower than expected

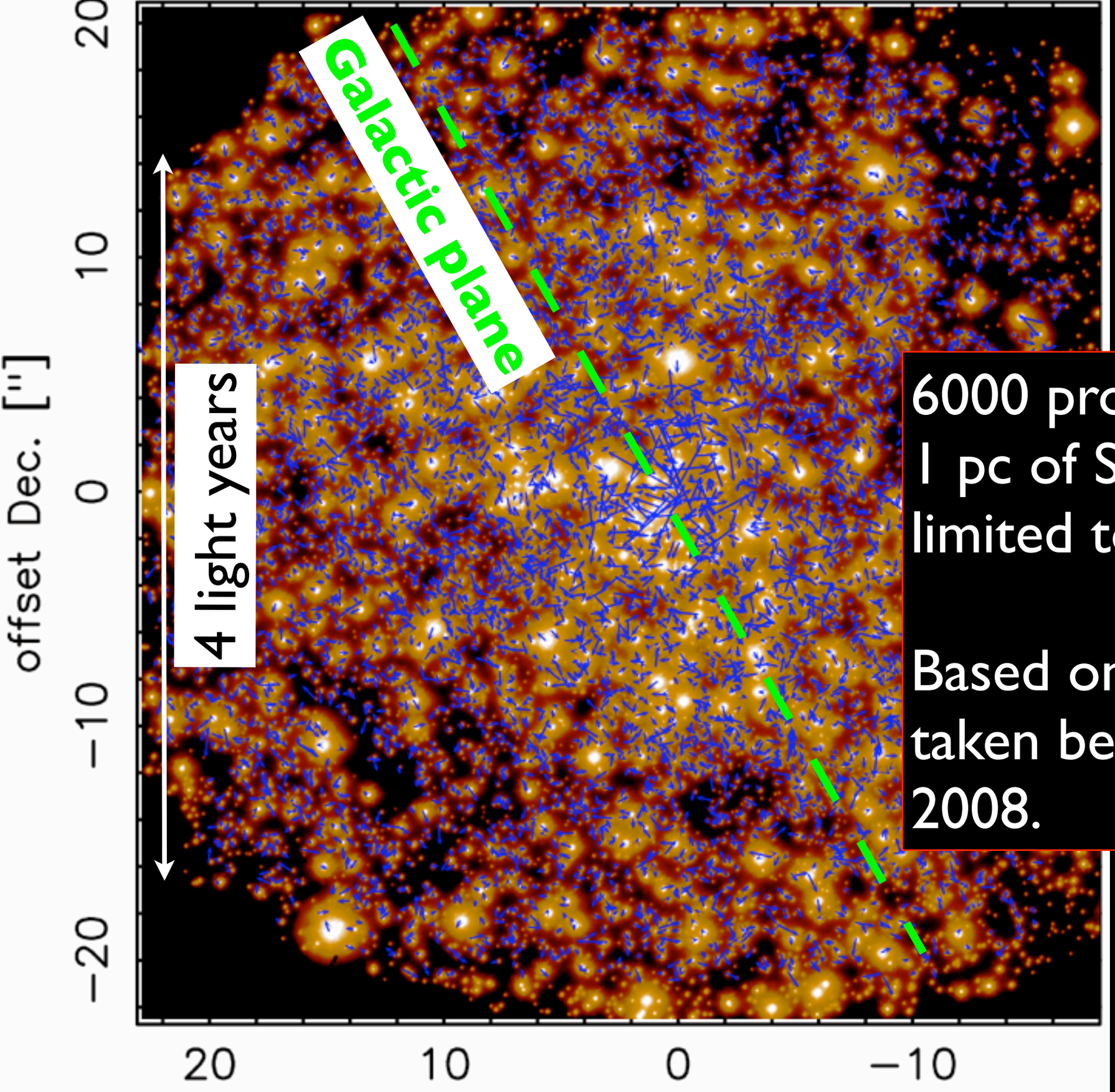
(Buchholz, Schoedel et al., 2009; Do et al., 2009; Bartko et al., 2009)



2. Kinematics and mass of the nuclear star cluster of the Milky Way: high precision astrometry with NACO



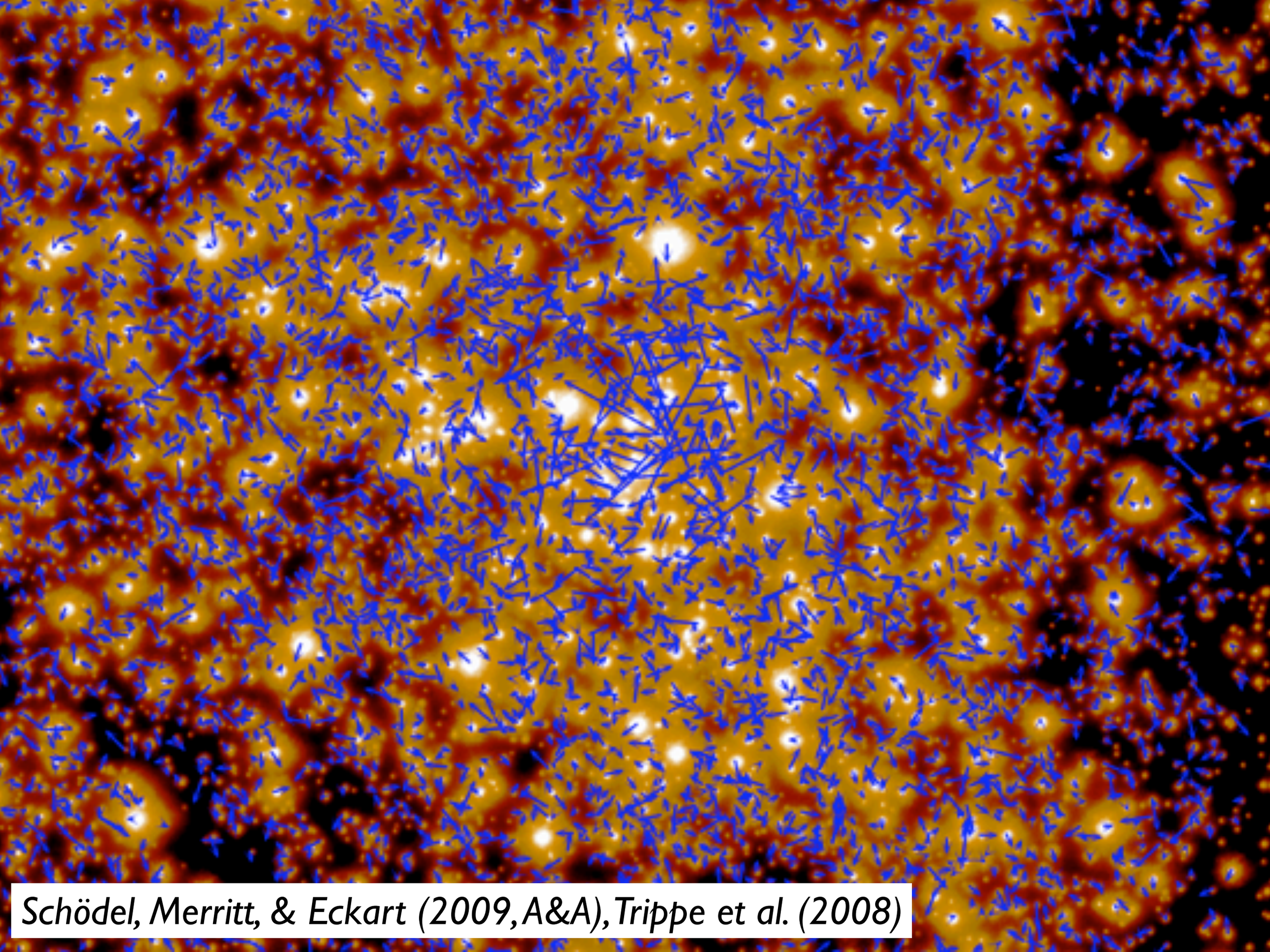
Schödel, Merritt, & Eckart (2009, A&A), Trippe et al. (2008)



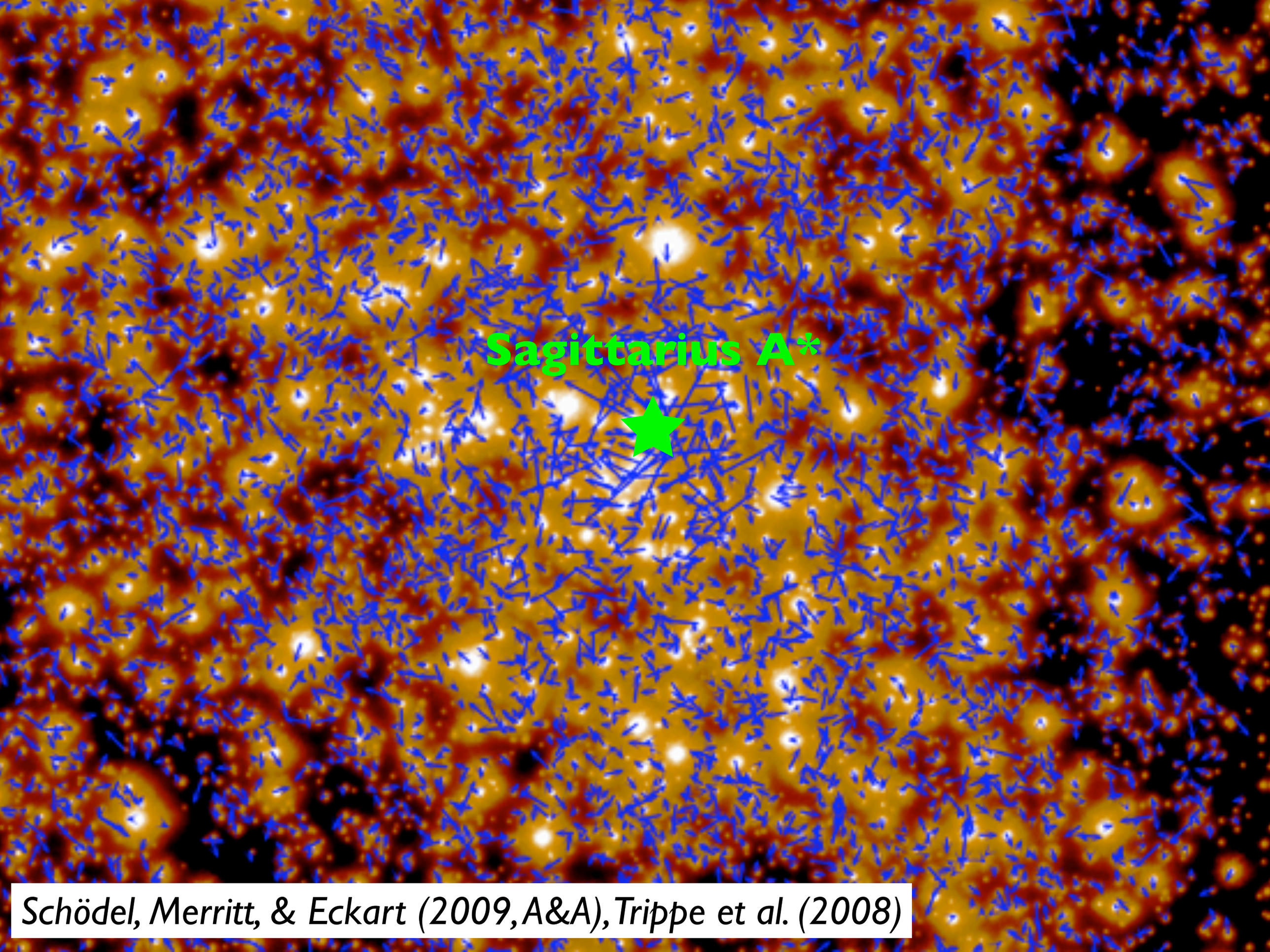
6000 proper motions within 1 pc of Sgr A* (previously limited to <0.5 pc).

Based on 10 NACO images taken between 2002 and 2008.

Schödel, Merritt, & Eckart (2009, A&A), Trippe et al. (2008)

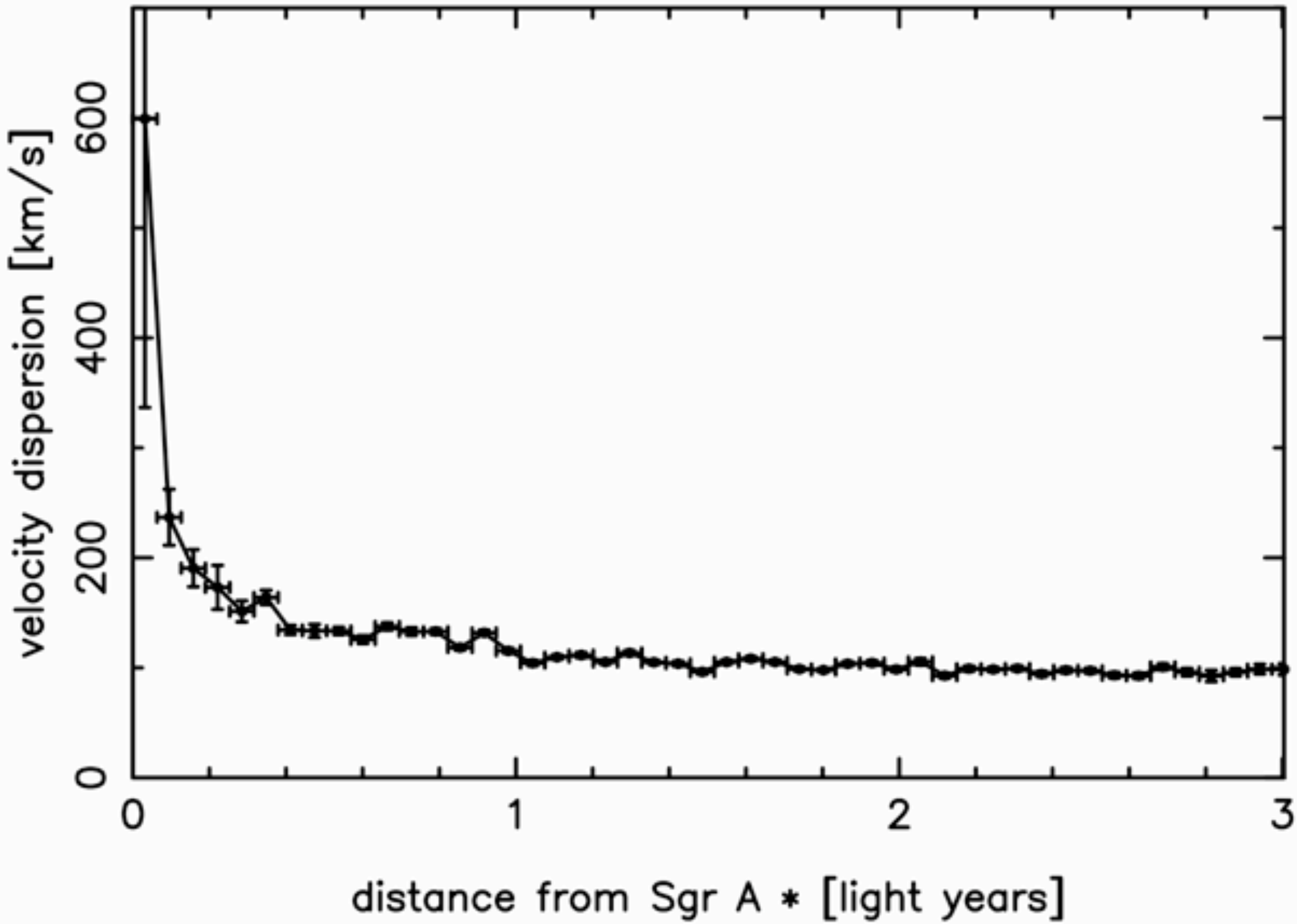


Schödel, Merritt, & Eckart (2009, A&A), Trippe et al. (2008)



Schödel, Merritt, & Eckart (2009, A&A), Trippe et al. (2008)

Velocity dispersion at the Galactic Center



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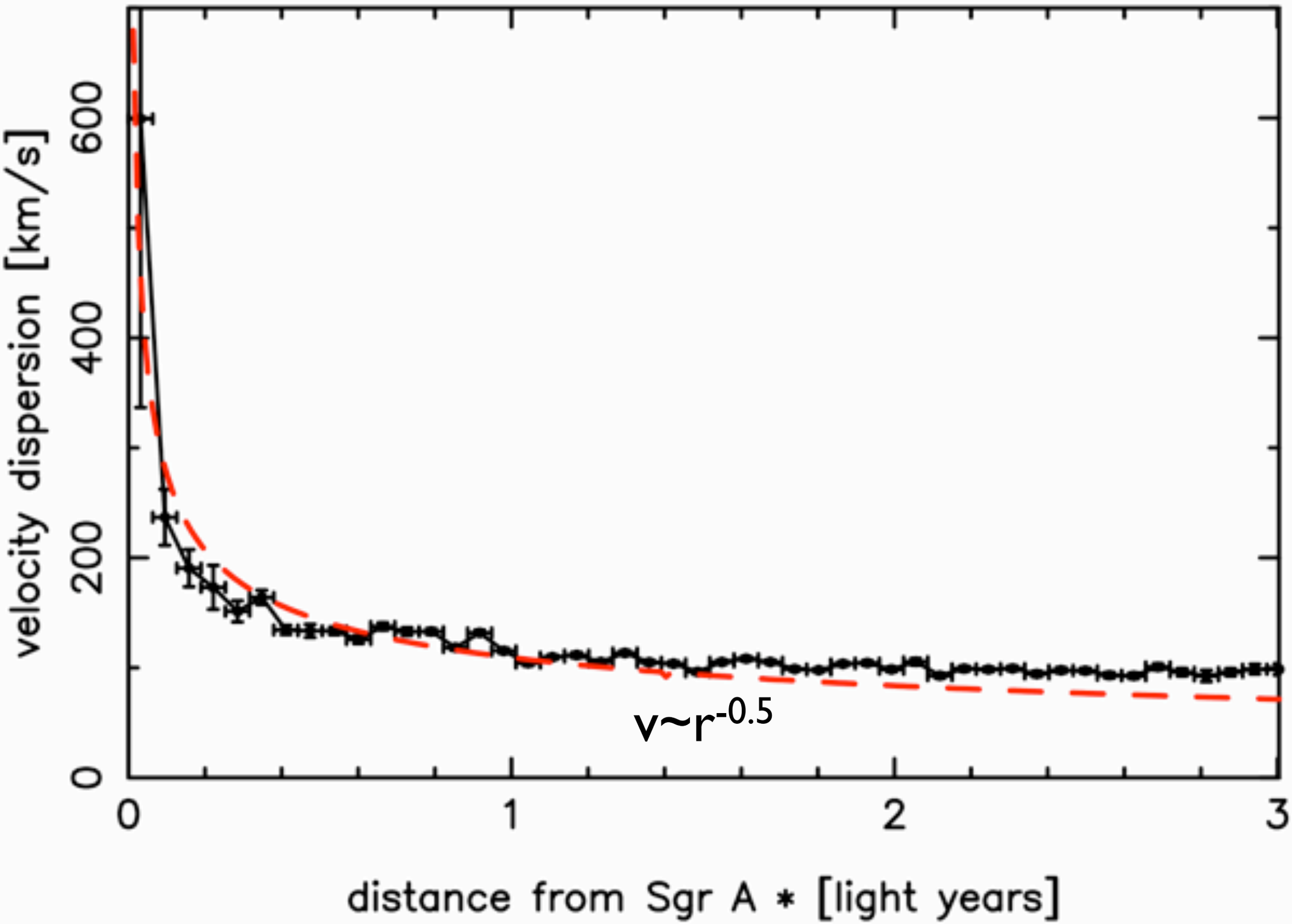

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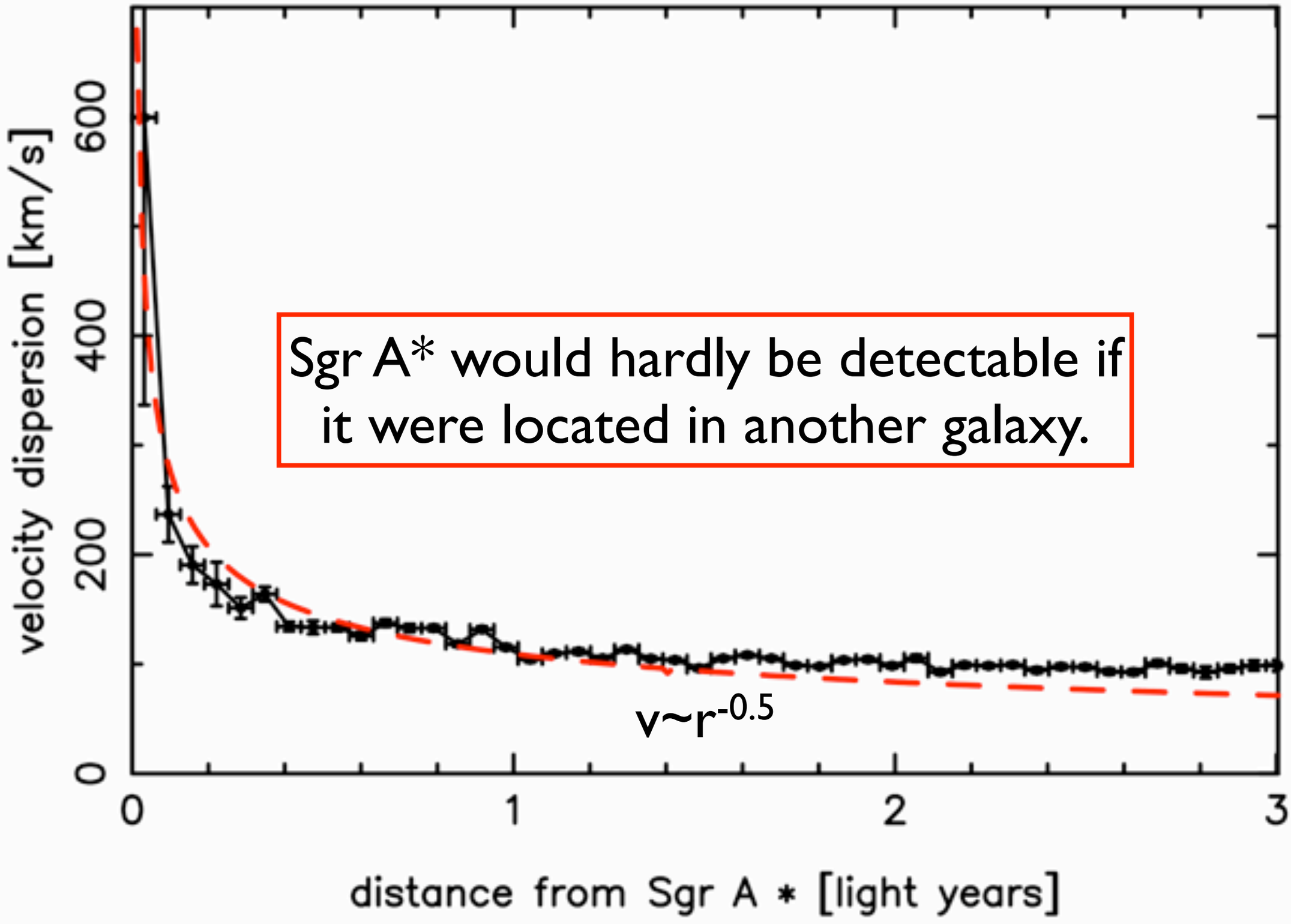


Modeling the enclosed mass

- **Extended mass** is detected for the first time **unambiguously** from the stellar dynamics in the central parsec.

- **Cluster rotation** confirmed

- **Extended mass in central parsec:**
  $M_\star(r<1\,pc) = 1.5\times10^6\ M_\odot$ for M/L = const.

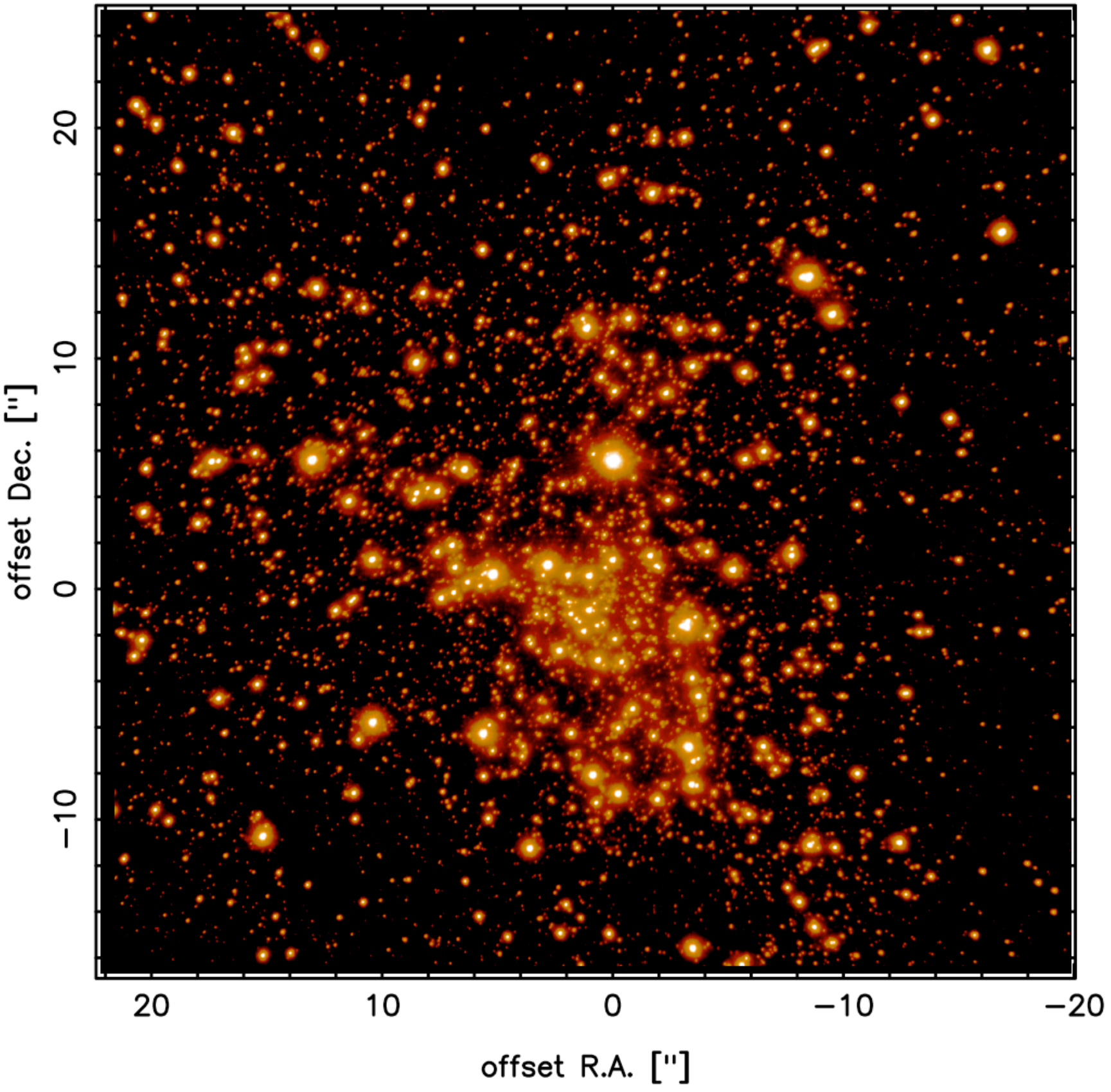
  Consistent with normal stars.

Schödel, Merritt & Eckart (2009, A&A)

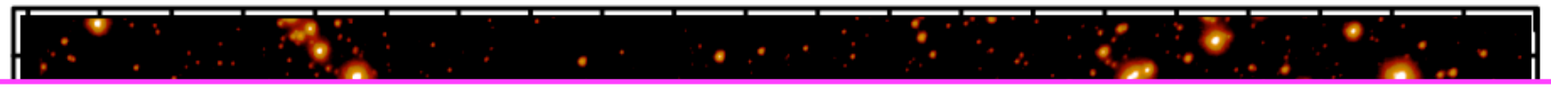
3. Extinction toward the Galactic Center

precision photometry with NACO

Extinction toward the GC



Extinction toward the GC



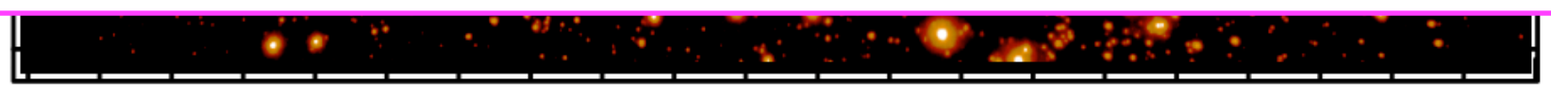
- Precision photometry (<5%) with AO over large and crowded FOV

- Red clump stars used to constrain absolute extinction and NIR extinction law.

- $A_\lambda \propto \lambda^{-\alpha}$, with $\alpha = 2.22 \pm 0.23$

→ significantly steeper than previously assumed
in agreement with other recent work
(e.g. Nishiyama et al., 2009; Gosling et al., 2009; Stead & Hoare 2009)

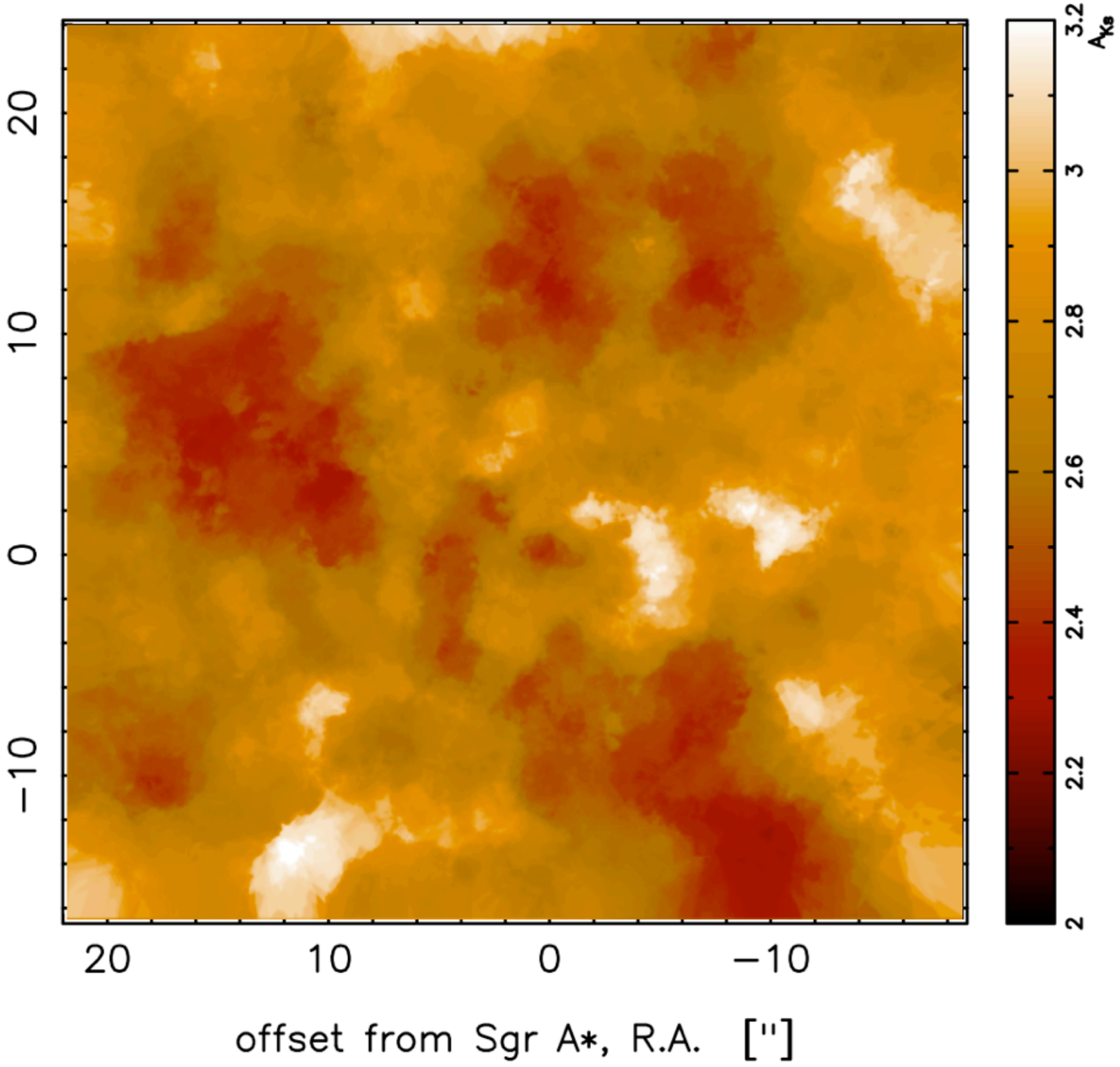
- High resolution extinction map for the central parsec



Schoedel 2009 & Schoedel et al., 2009, submitted to A&A

Extinction toward the GC

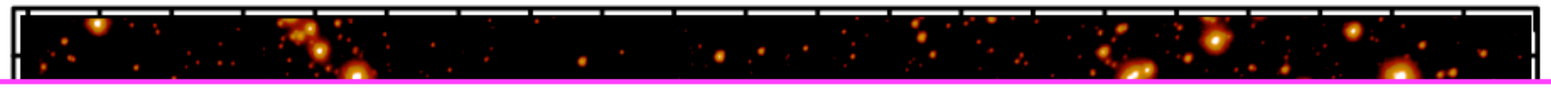
- Precisio … owded FOV
- Red clu … and NIR extinctior
- $A_\lambda \propto \lambda$ … → signific … in agre … *(e.g. Ni… 2009)*
- High re…



Hoare

Schoedel 2009 & Schoedel et al., 2009, submitted to A&A

Extinction toward the GC



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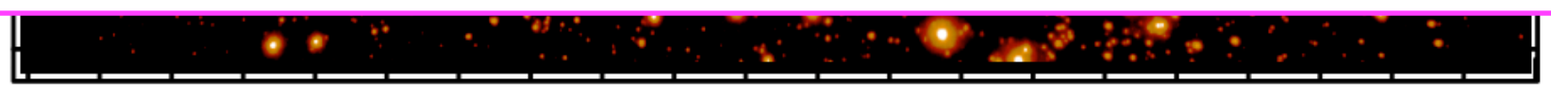
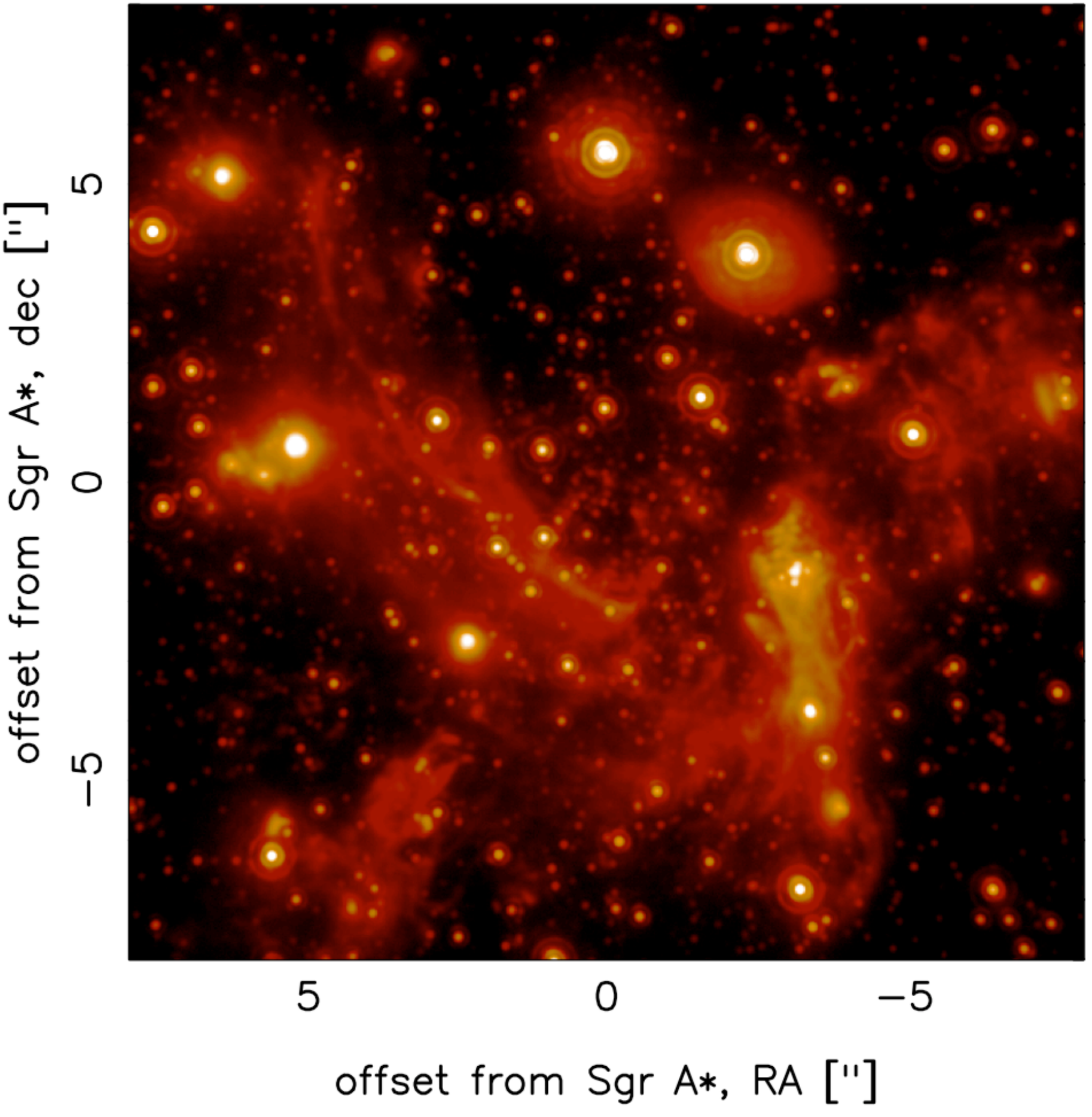


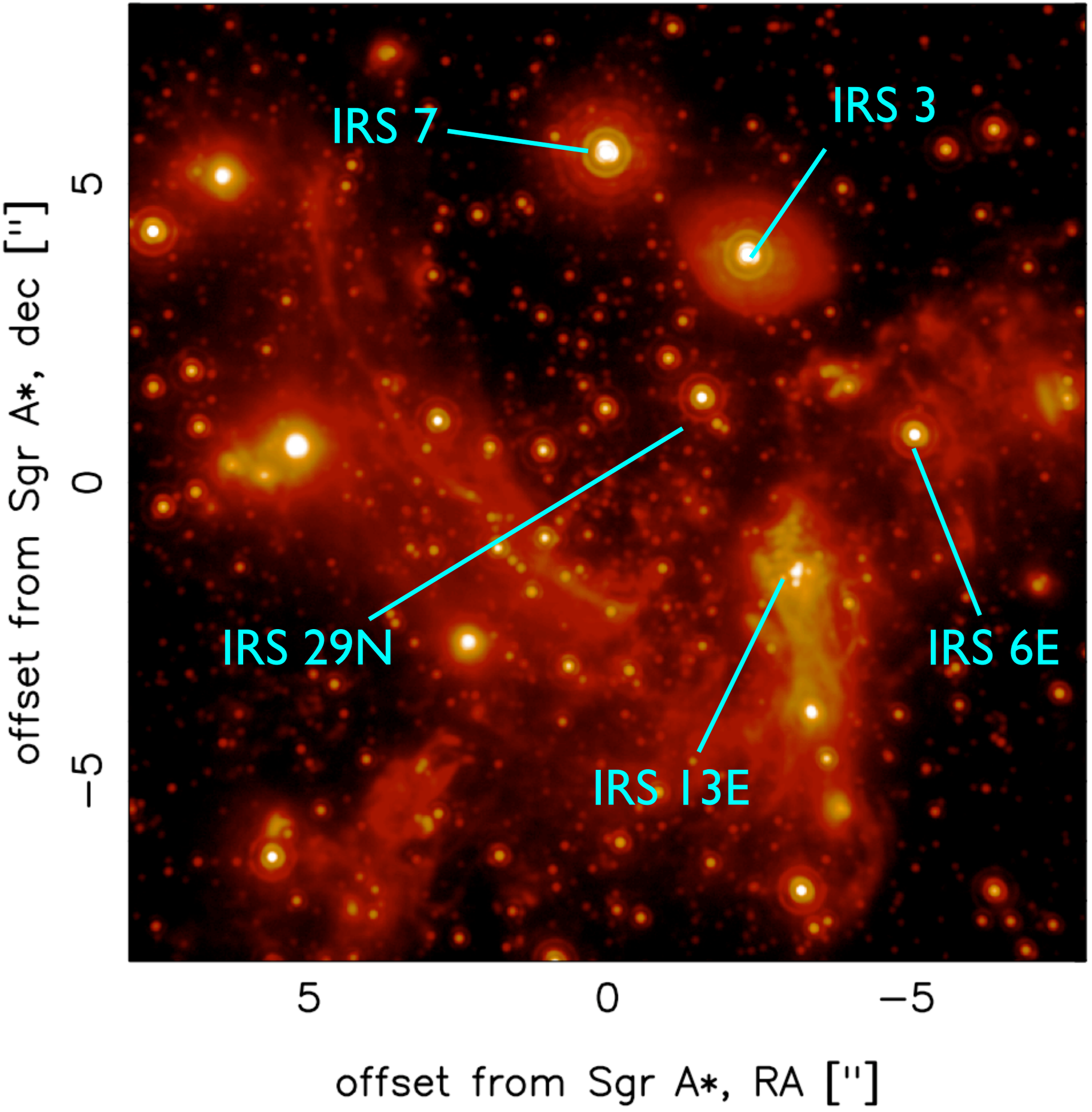
Schoedel 2009 & Schoedel et al., 2009, submitted to A&A

4. Extreme stars in an extreme environment

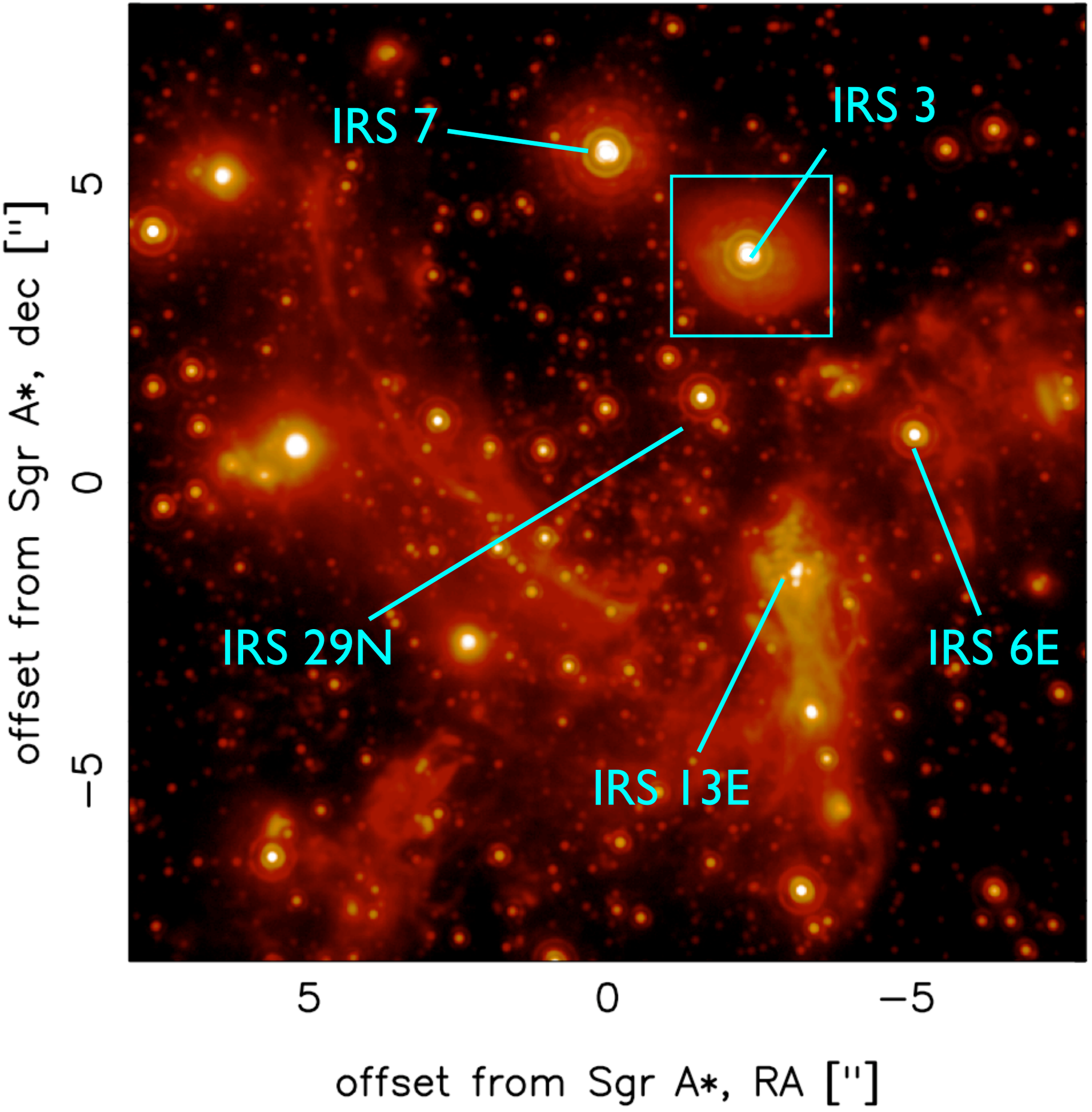
sparse aperture masking interferometry with NACO



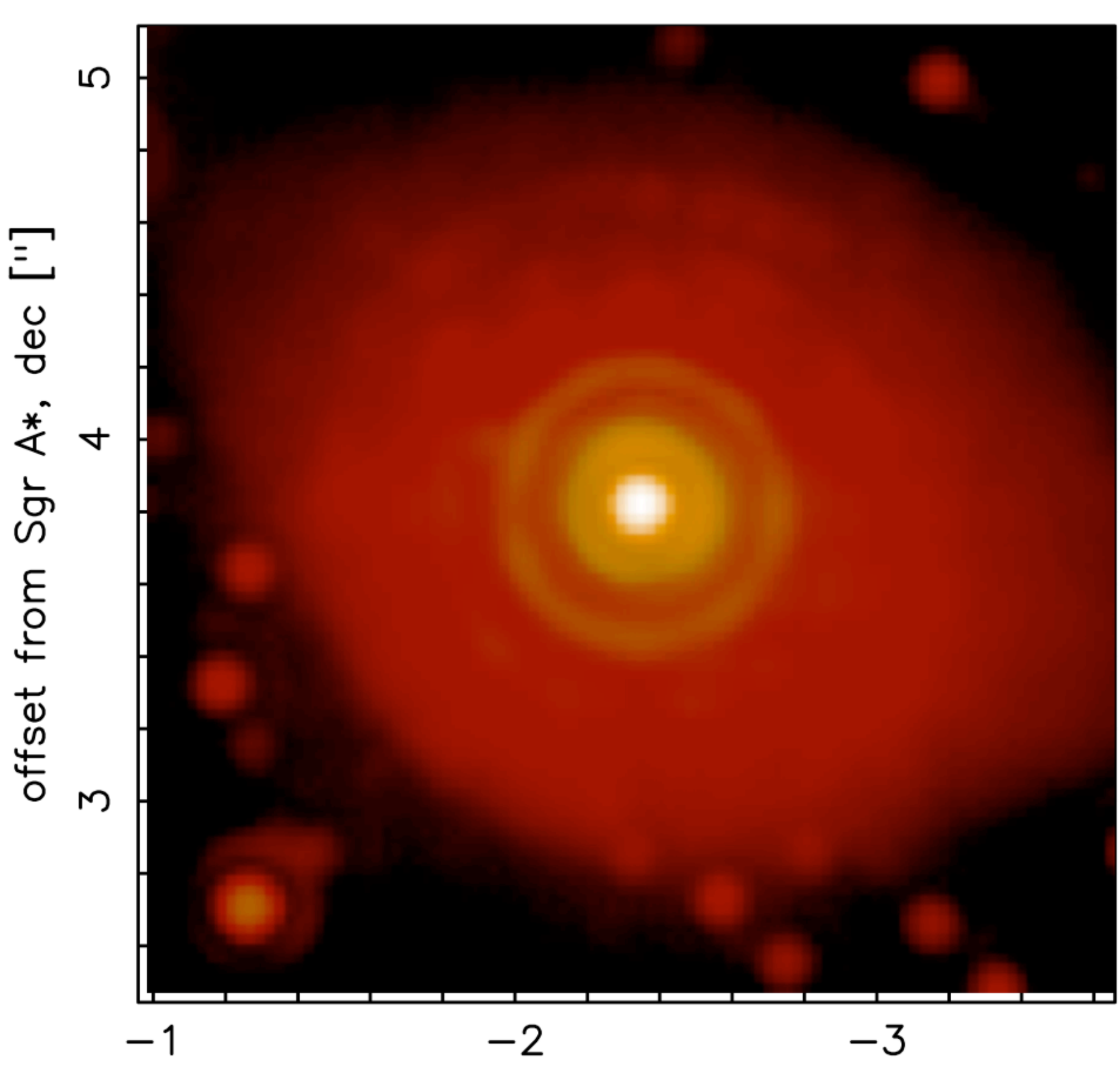
Galactic center
NACO/VLT
L’



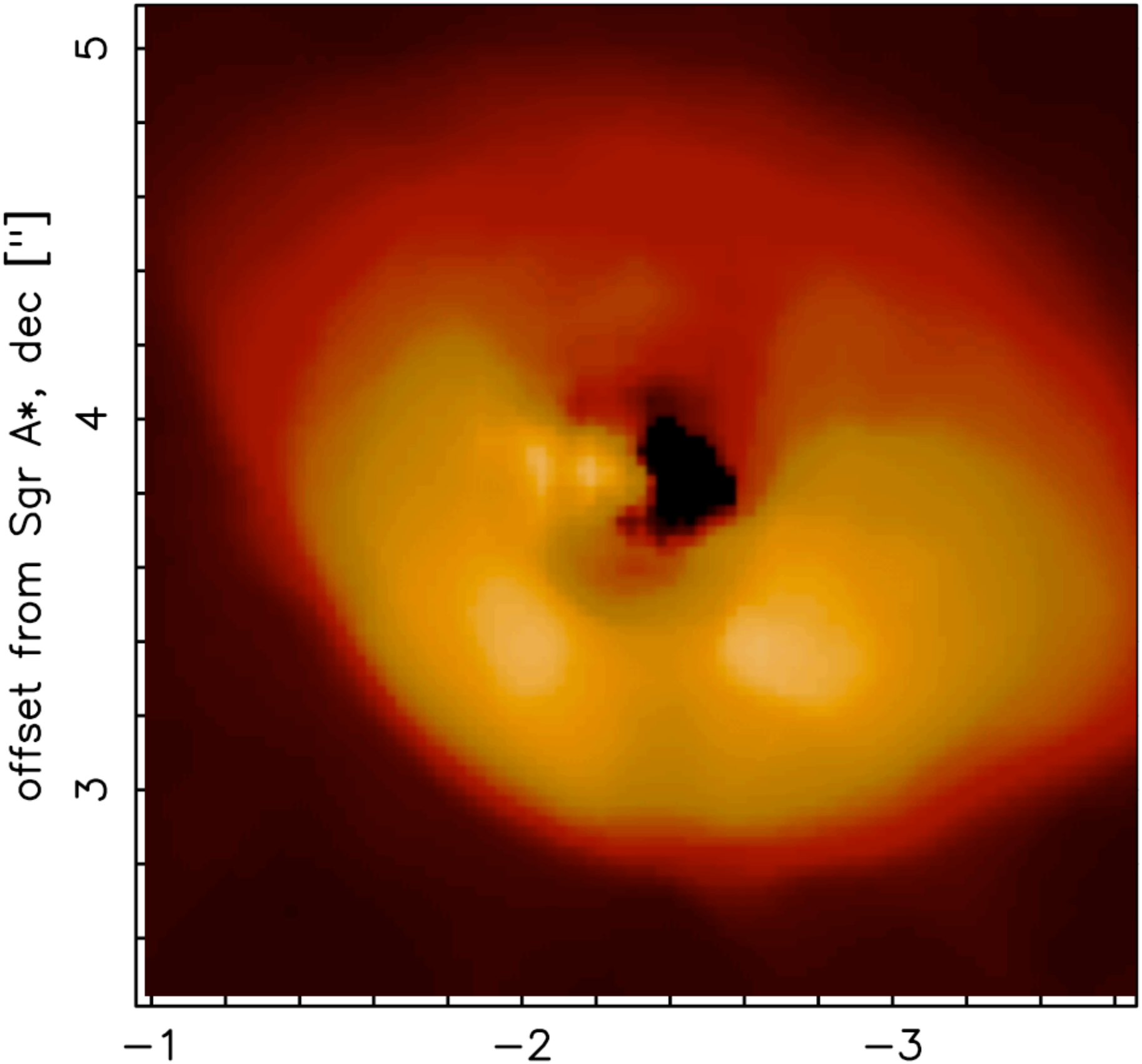
Galactic center
NACO/VLT
L’



Galactic center
NACO/VLT
L'



Galactic center
NACO/VLT
L’



Galactic center
NACO/VLT
L’

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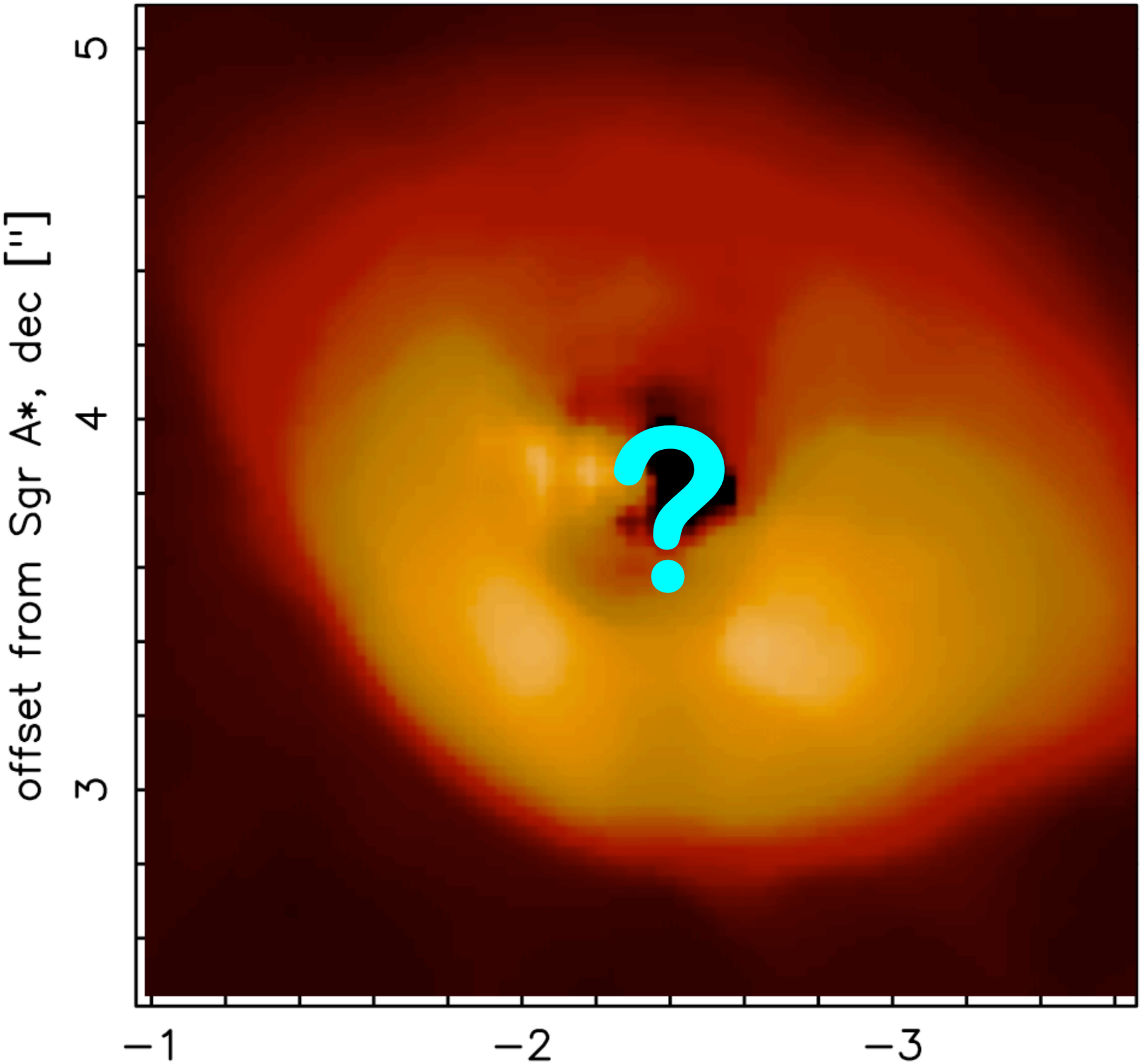
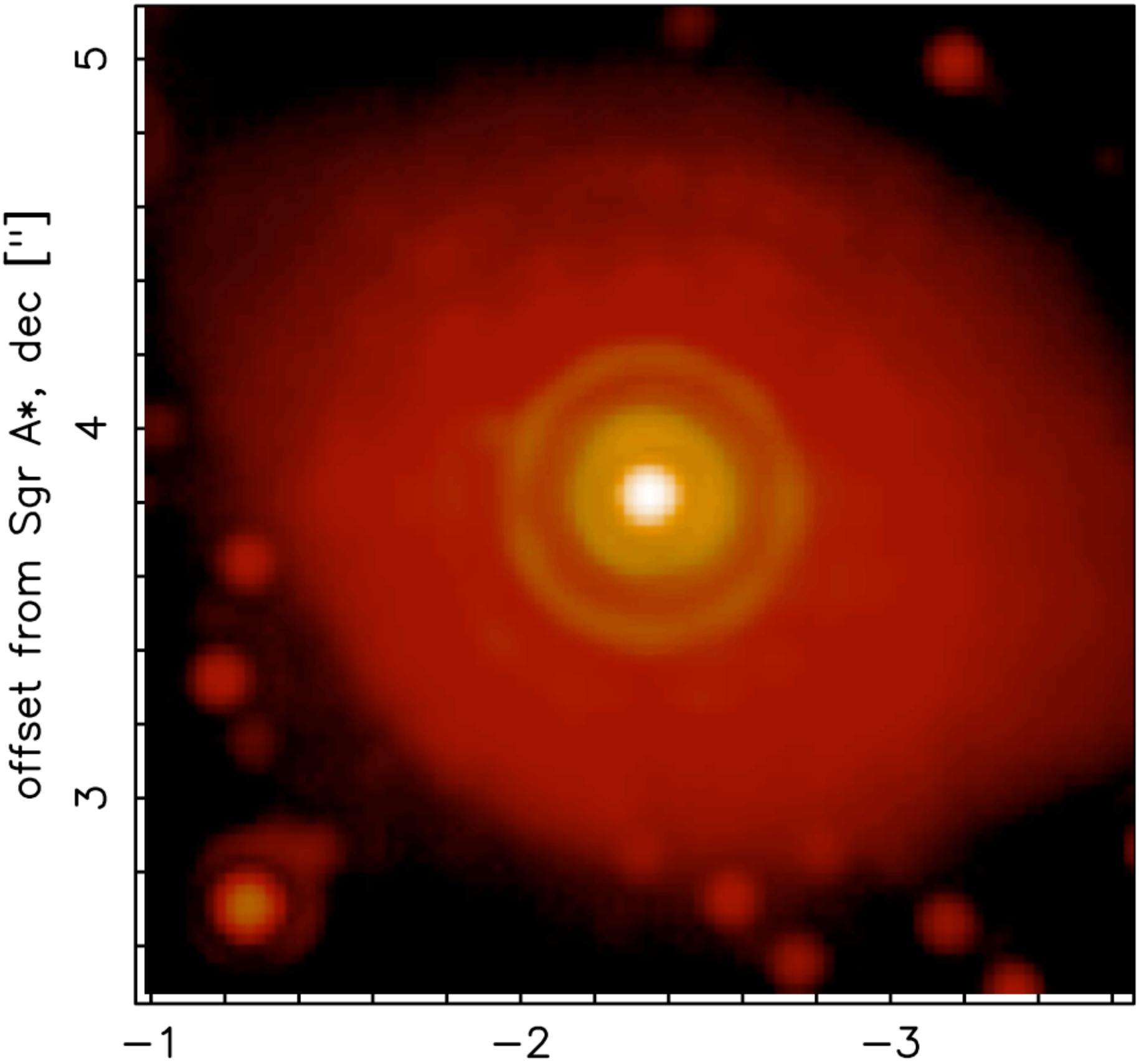
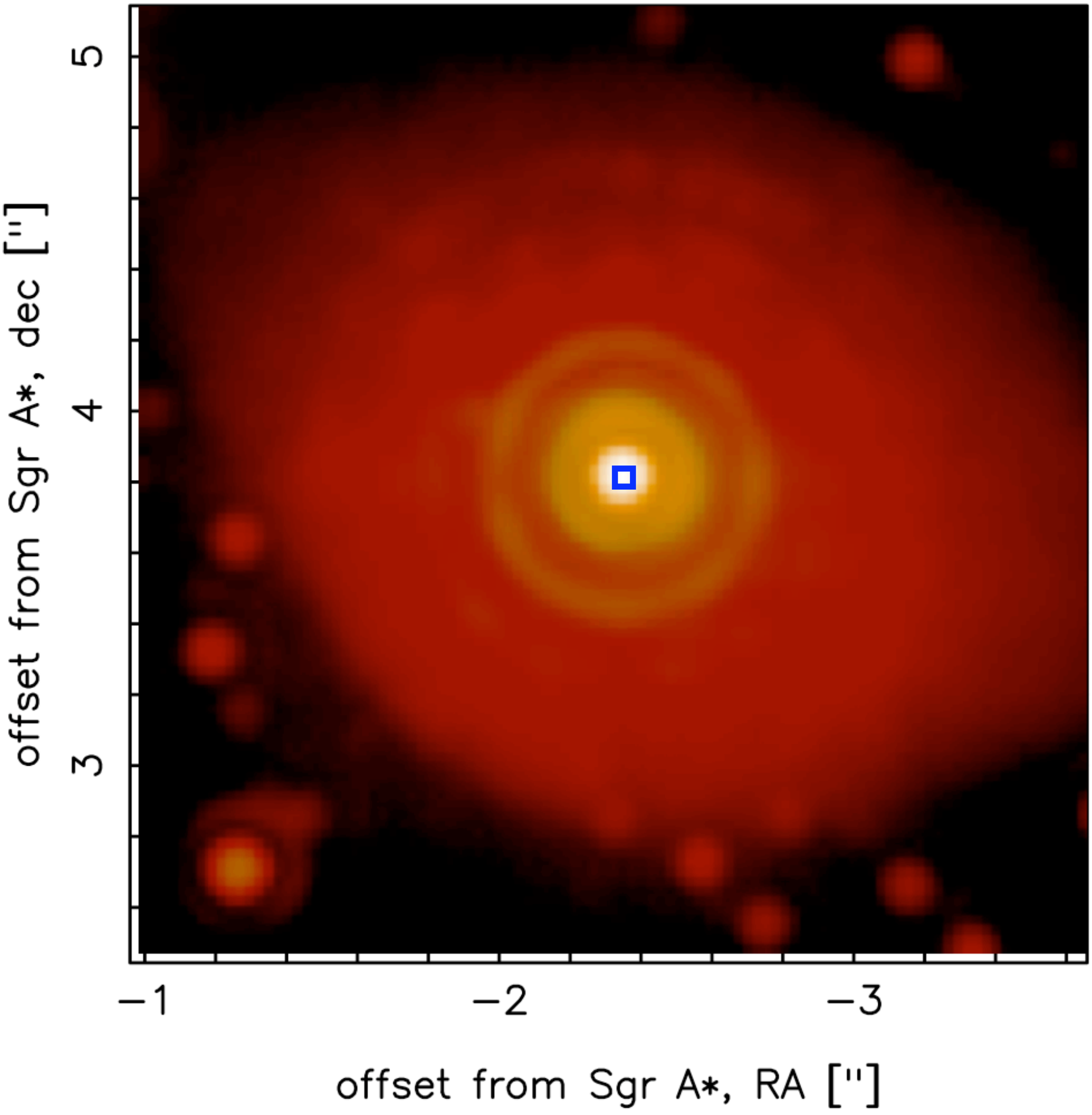
NACO/VLT
L’




offset from Sgr A*, dec ['']
5
4
3
−1
−2
−3
offset from Sgr A*, RA ['']


offset from Sgr A*, dec ['']
5
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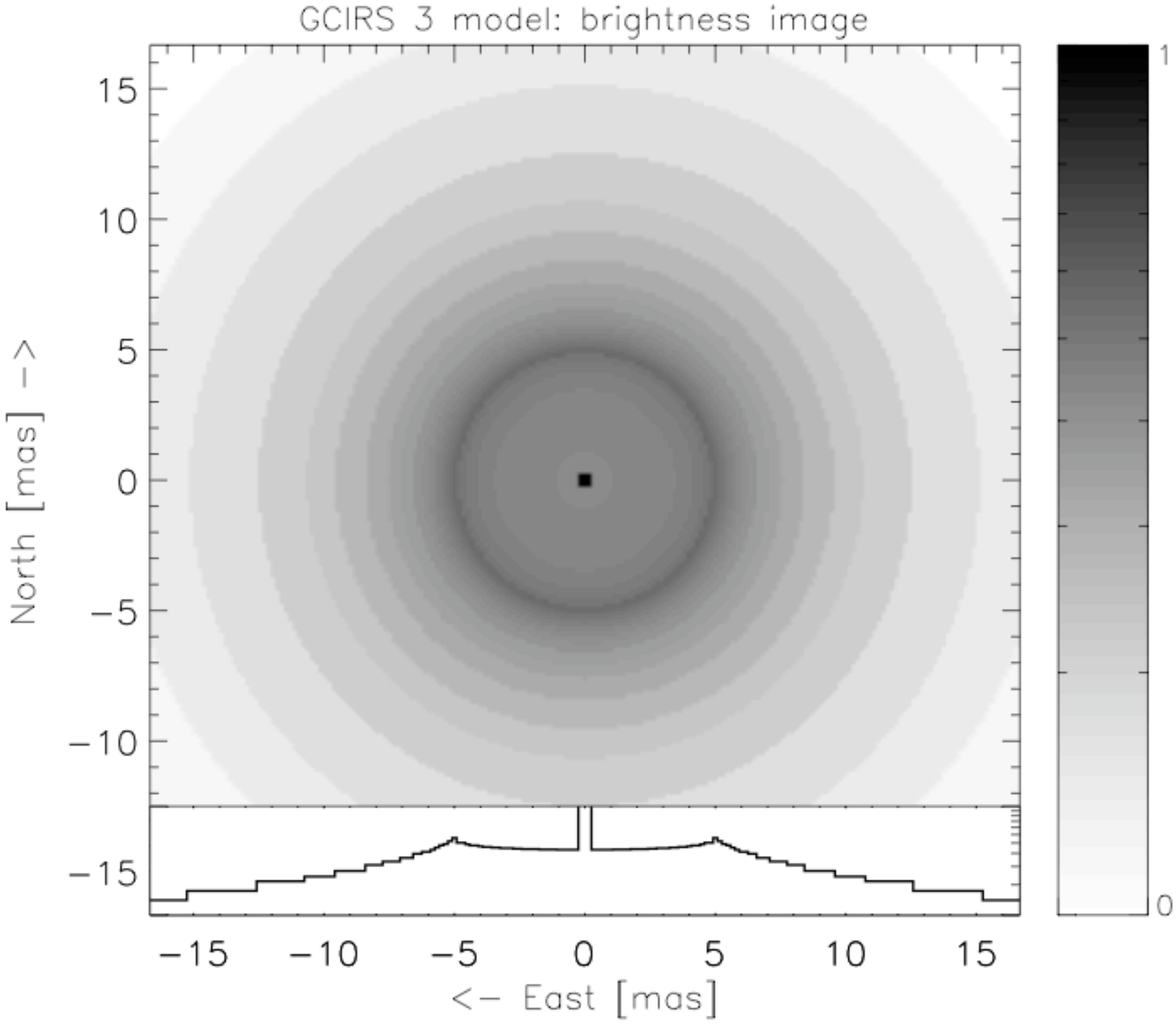
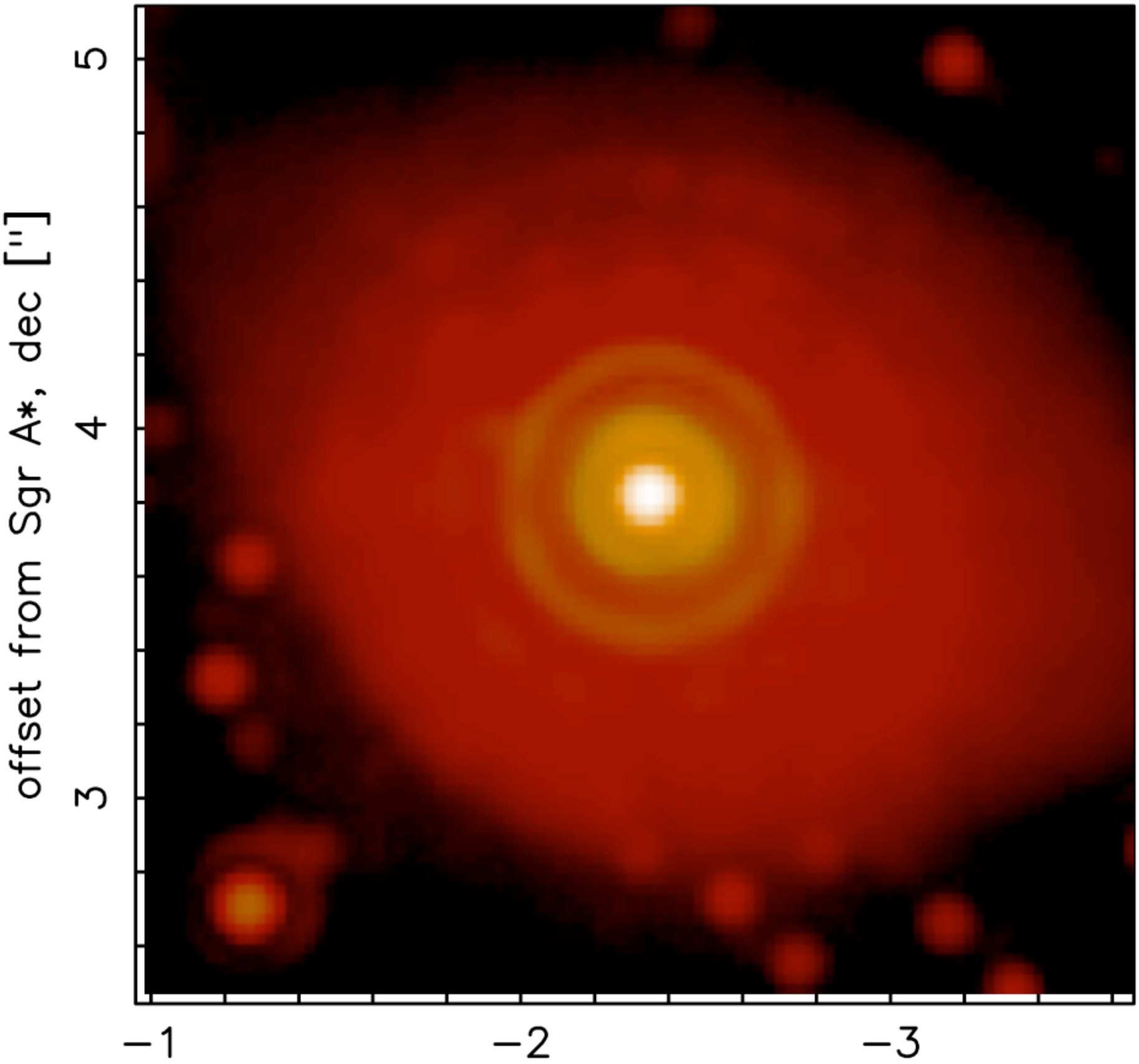
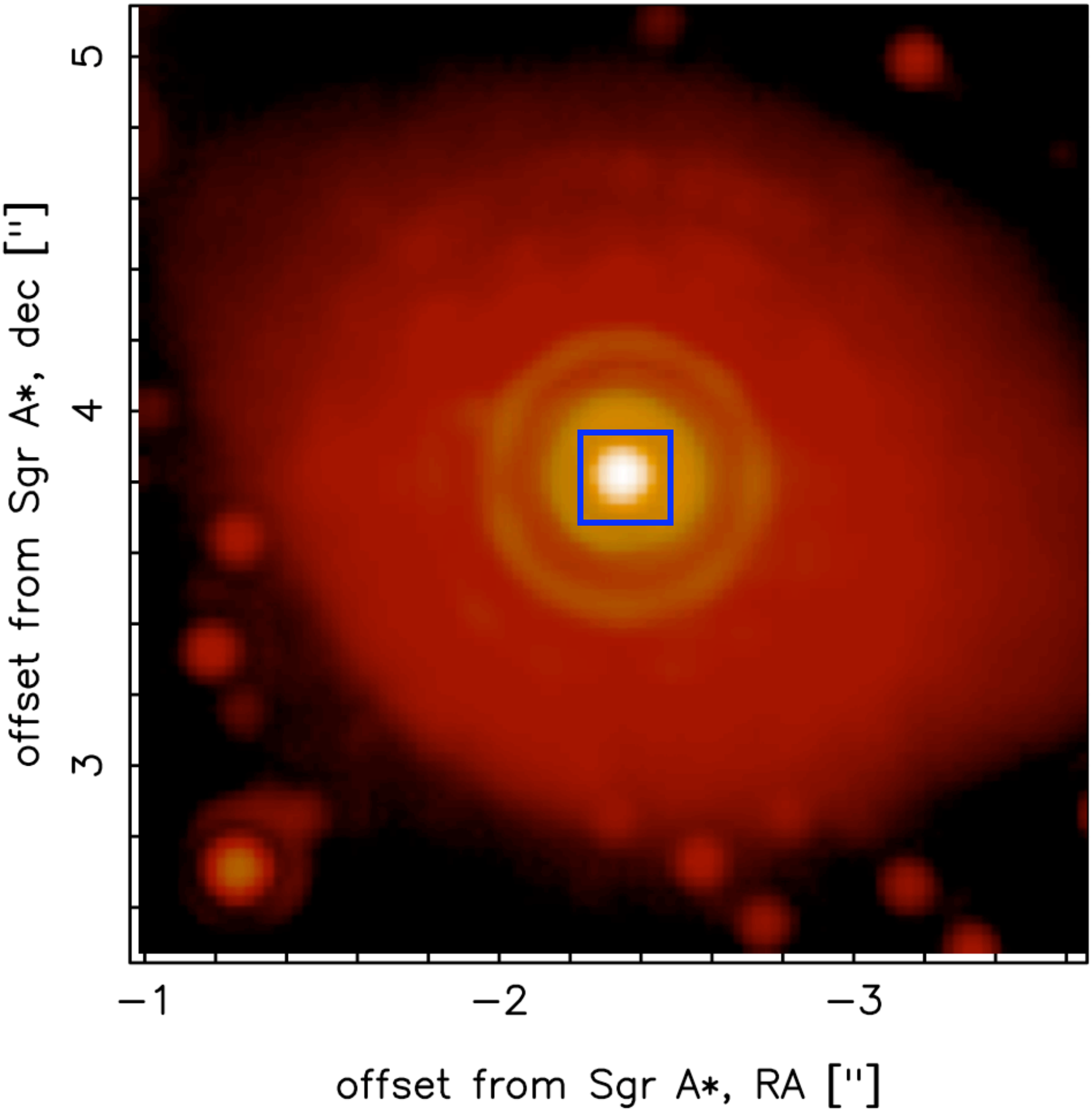
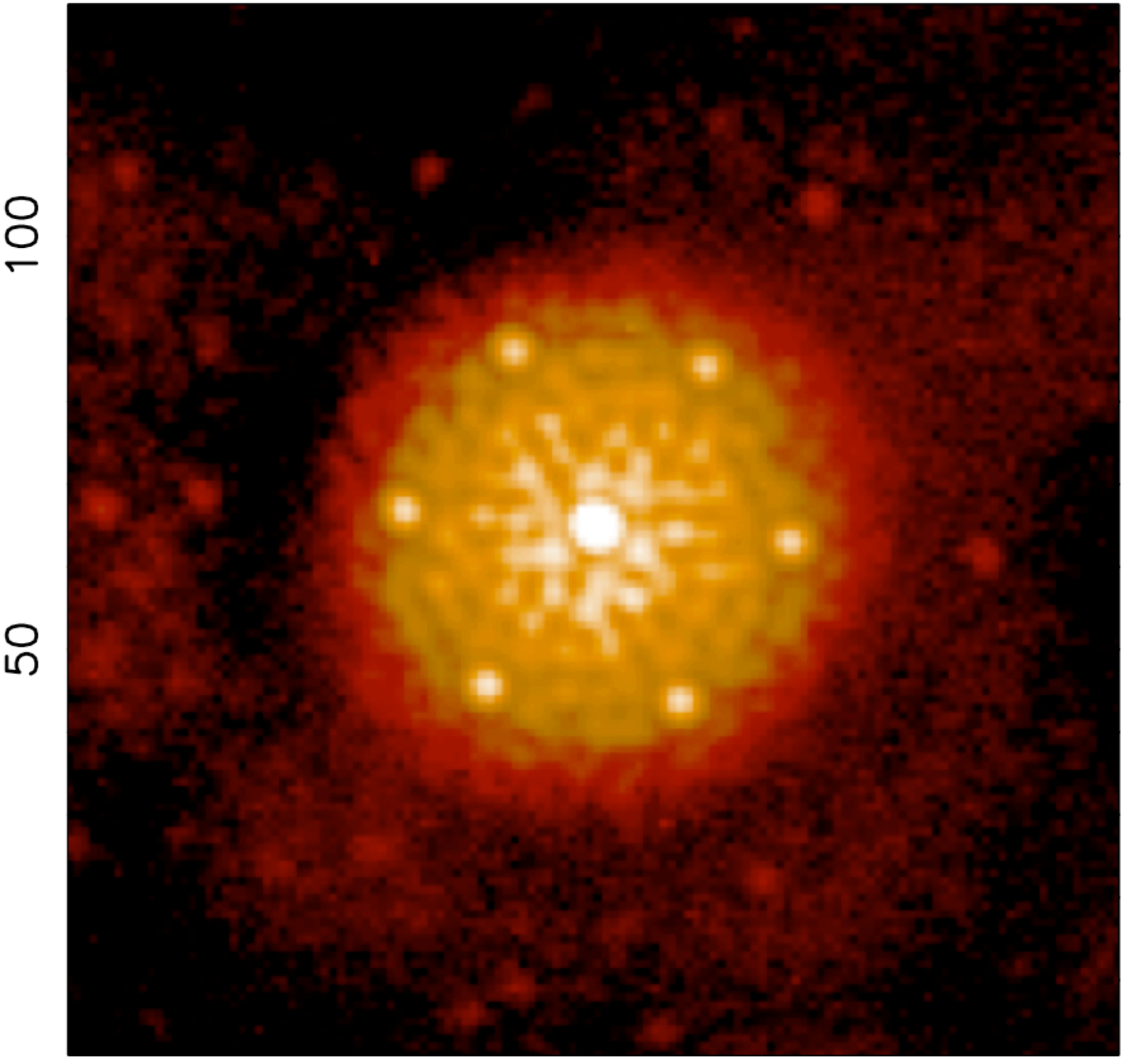
offset from Sgr A*, RA ['']

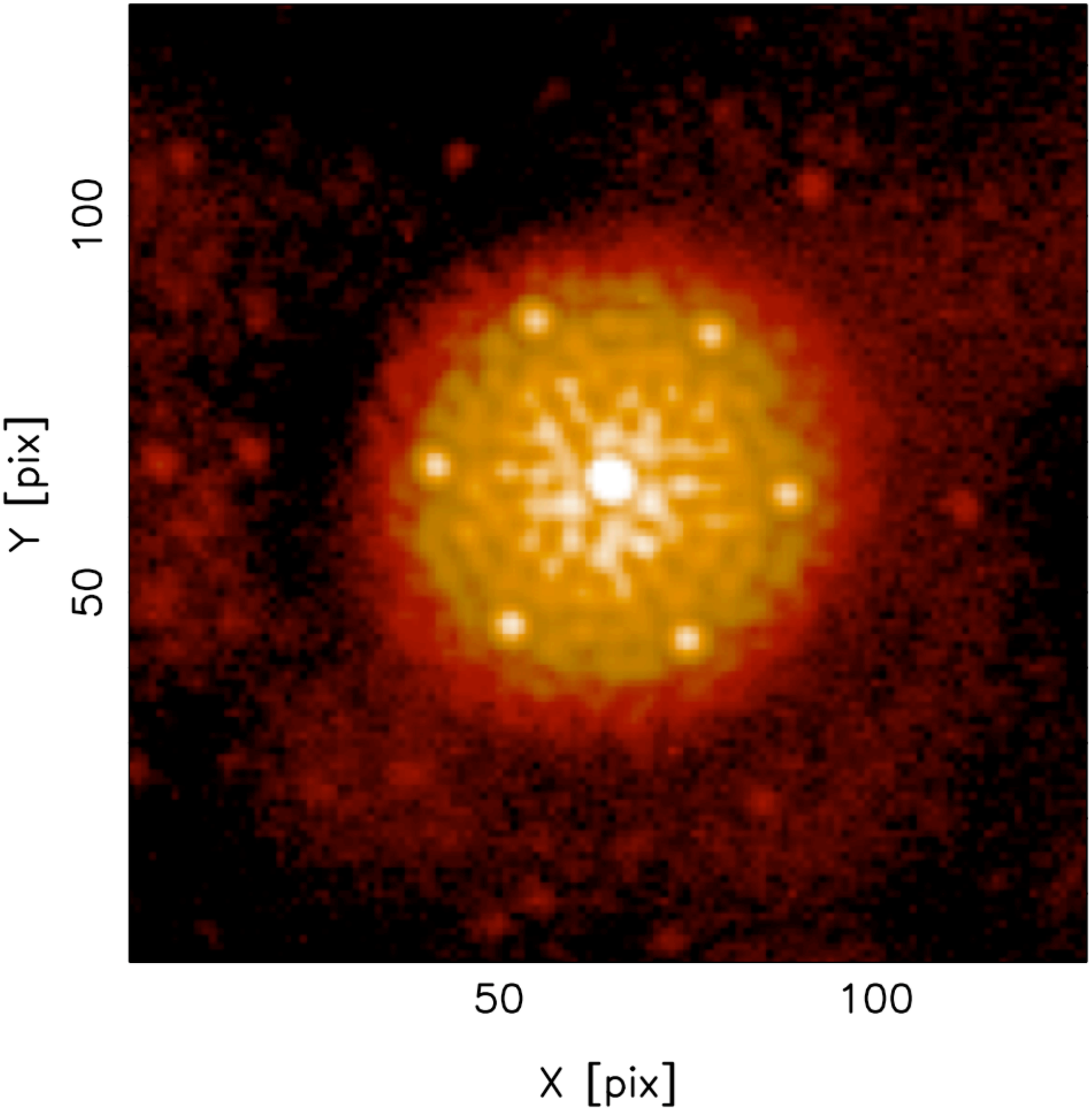


VLTI (MIDI) observations:
dust formation zone resolved (Pott et al. , 2008)


offset from Sgr A*, dec ['']
5
4
3
−1
−2
−3
offset from Sgr A*, RA ['']


offset from Sgr A*, dec ['']
5
4
3
−1
−2
−3
offset from Sgr A*, RA ['']

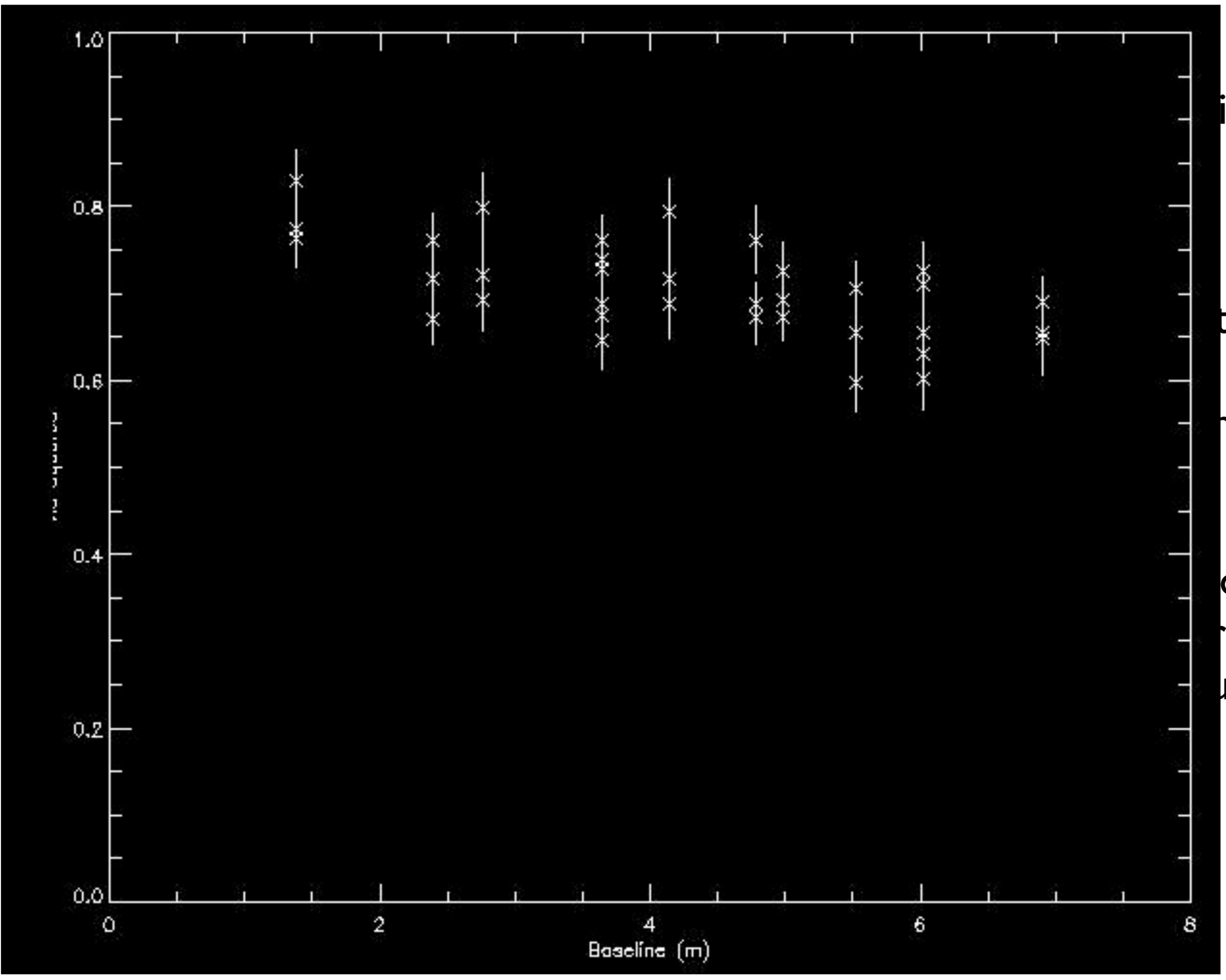

Y [pix]
50
100
50
100
X [pix]



NACO sparse aperture masking (SAM)
9 Holes mask

2 nights of visitor mode observations in July 2009

80% loss due to bad weather (re-submission), but nevertheless some success



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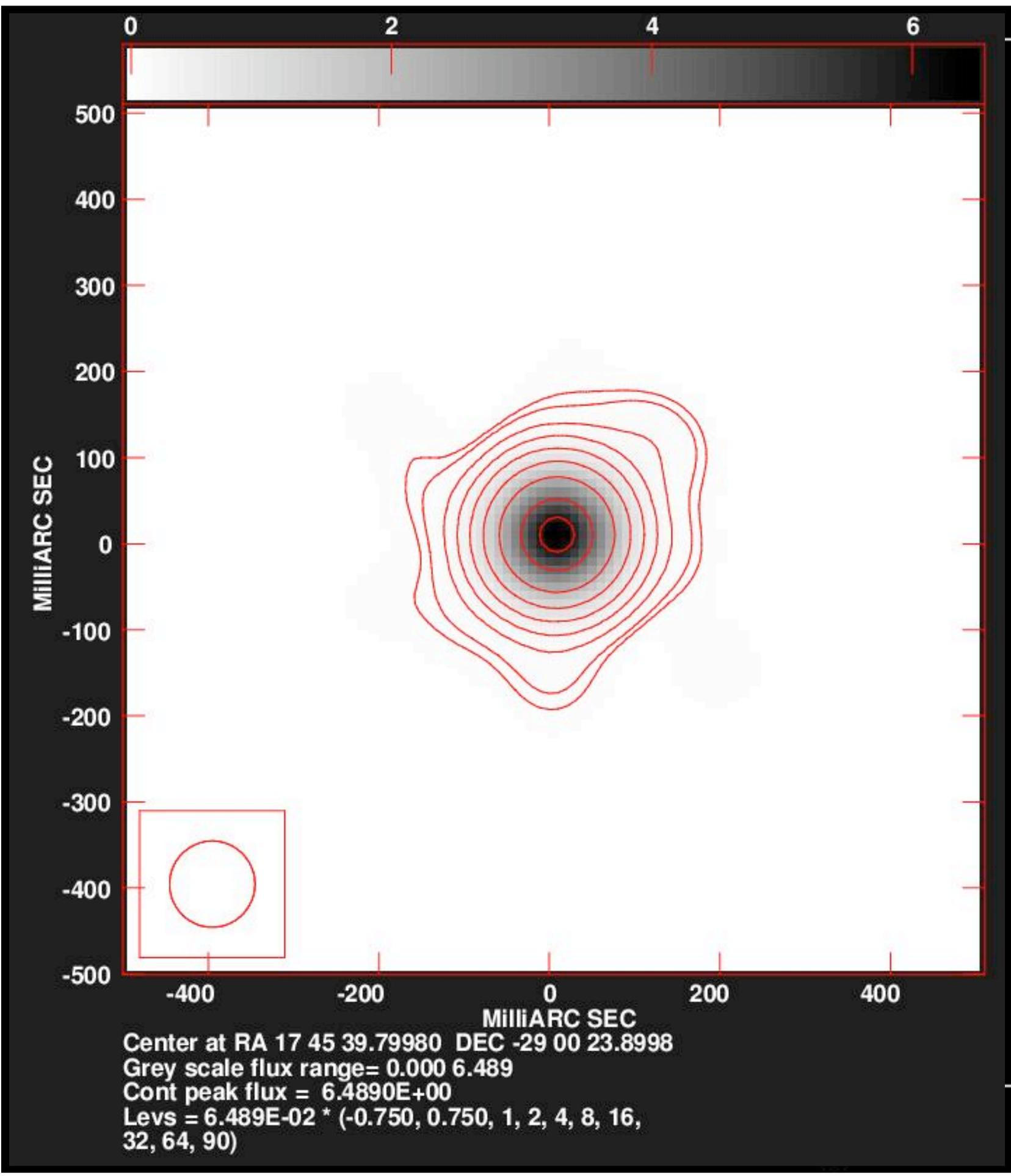

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IRS 3 resolved on ~100 mas scale diffraction limit of VLT in L' fully reached.

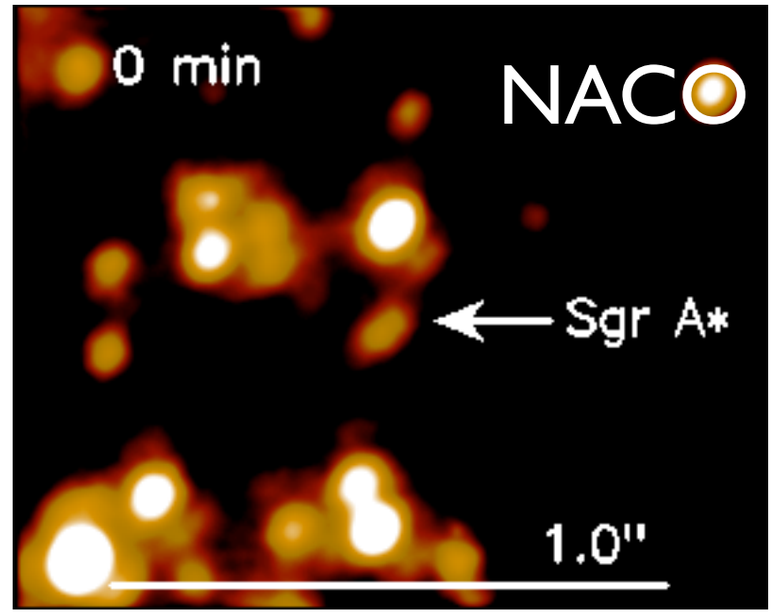
More observations needed ➔ proposal re-submission

(Schödel, Alberdi et al.)

5. Sagittarius A*

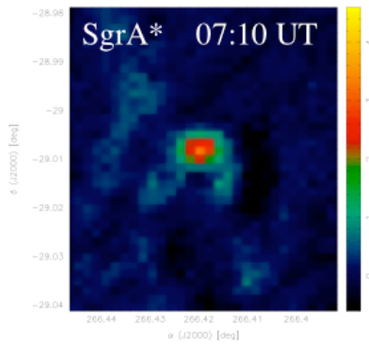
Sagittarius A*: IR/multiwavelength observations

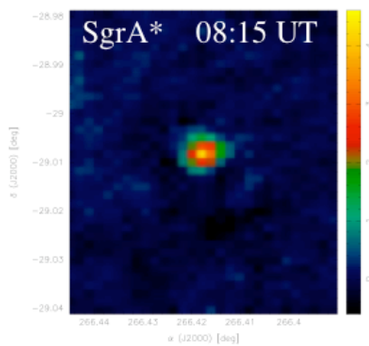
- since 2004 yearly ~3-5 full nights at NaCo/VLT
- PI: A. Eckart (University of Cologne)
- Goals: understand Sgr A* variability: BH spin, accretion disk/outflow

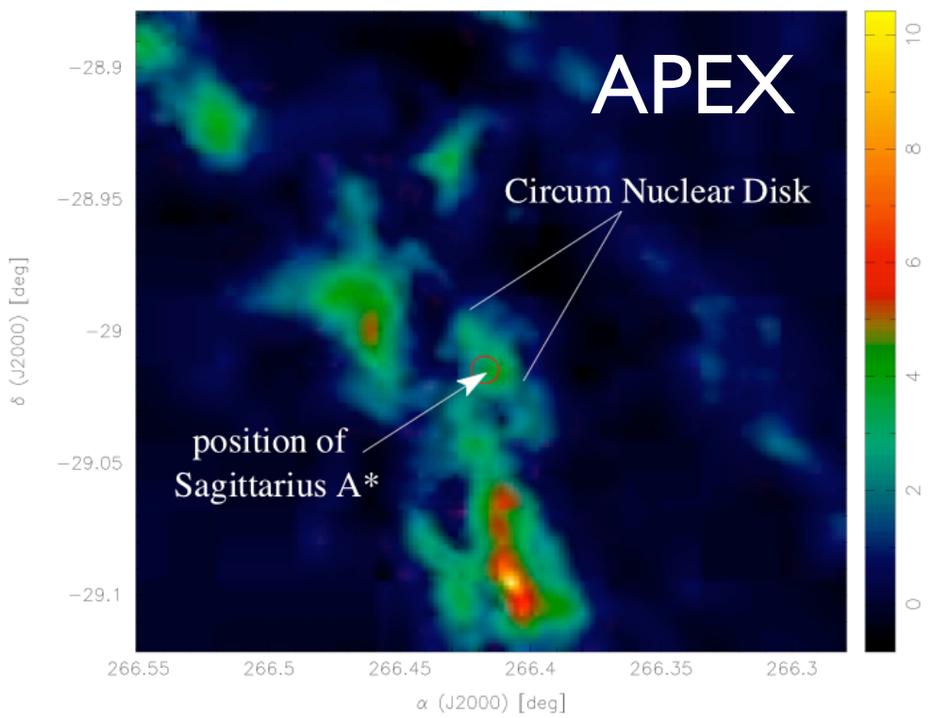


Recent publications:

Meyer et al. (2007), Schödel et al. (2007), Eckart et al. (2008), Meyer (2008, 2009), Eckart et al. (2009)...







Thank you!

...for questions contact the ESO USD

...and also rainer@iaa.es