Continually Evolving: Our Understanding of the Galactic center

Rainer Schödel, IAA-CSIC

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I. The massive black hole Sagittarius A*

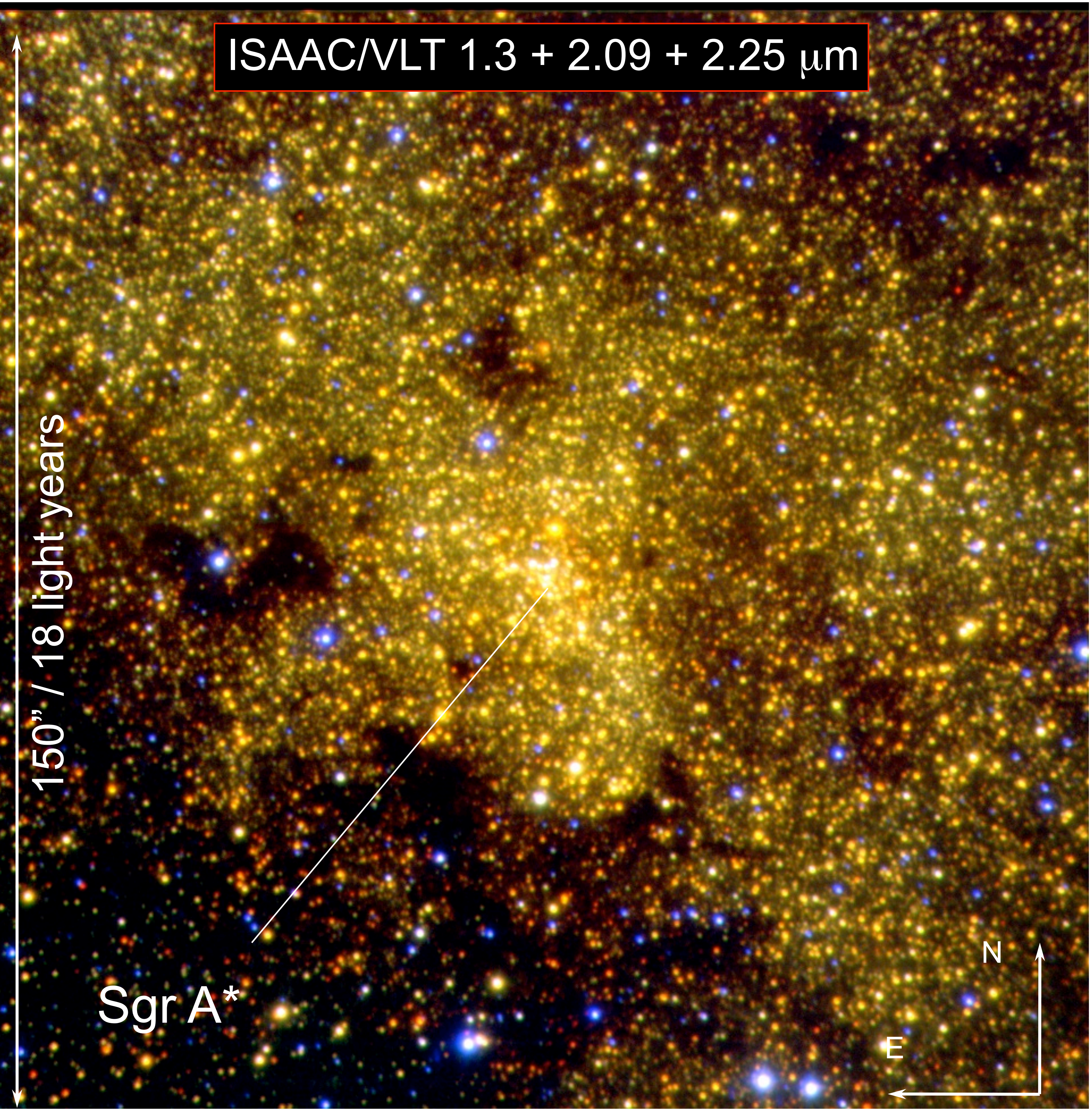
II. The nuclear stellar cluster of the Milky Way

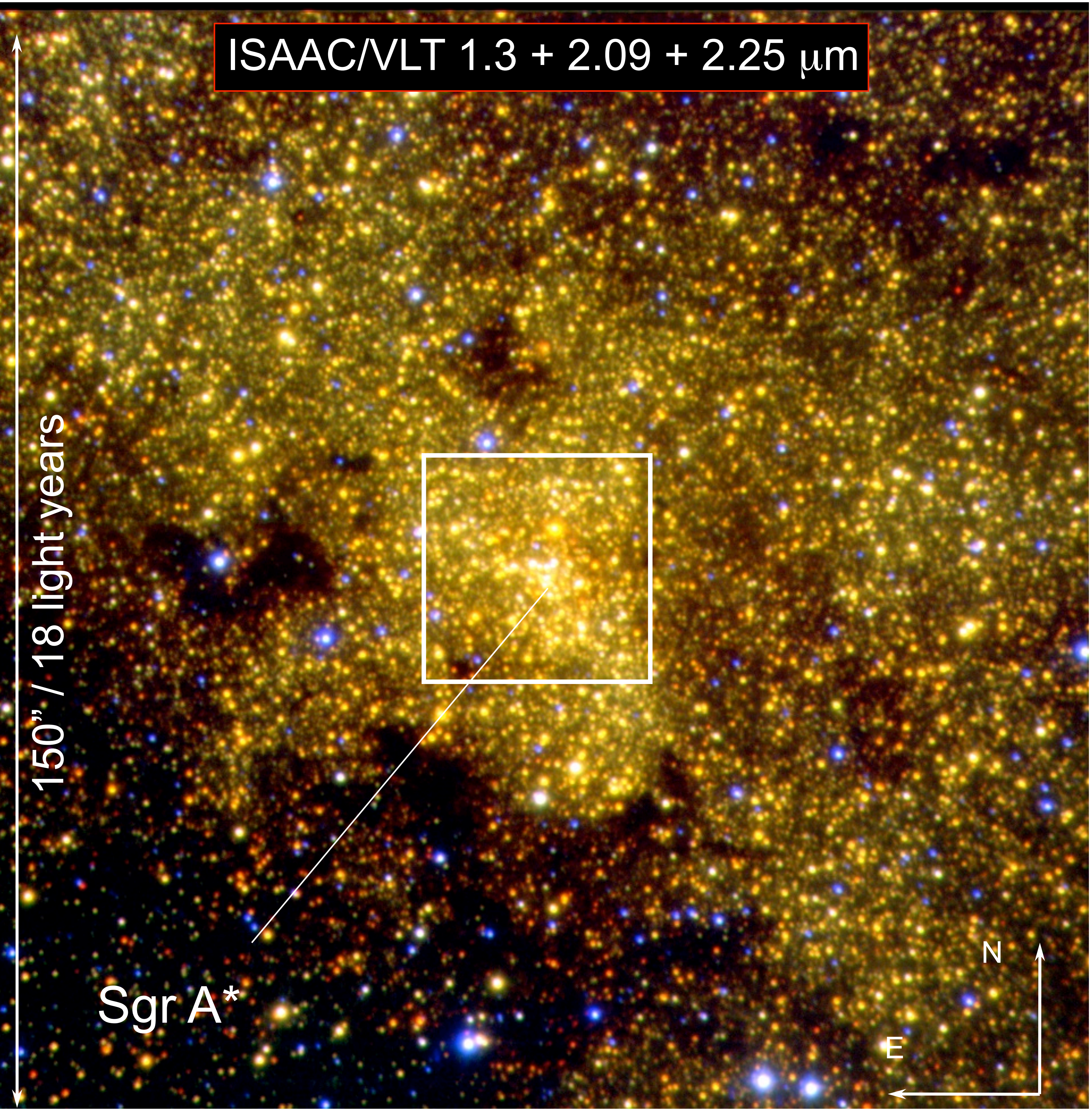
III. Star Formation at the Galactic Center

IV. The missing stellar cusp around Sagittarius A*

V. Kinematics and Mass in the Central Parsec

The massive black hole Sagittarius A*


ISAAC/VLT 1.3 + 2.09 + 2.25 μm
150" / 18 light years
Sgr A*
N
E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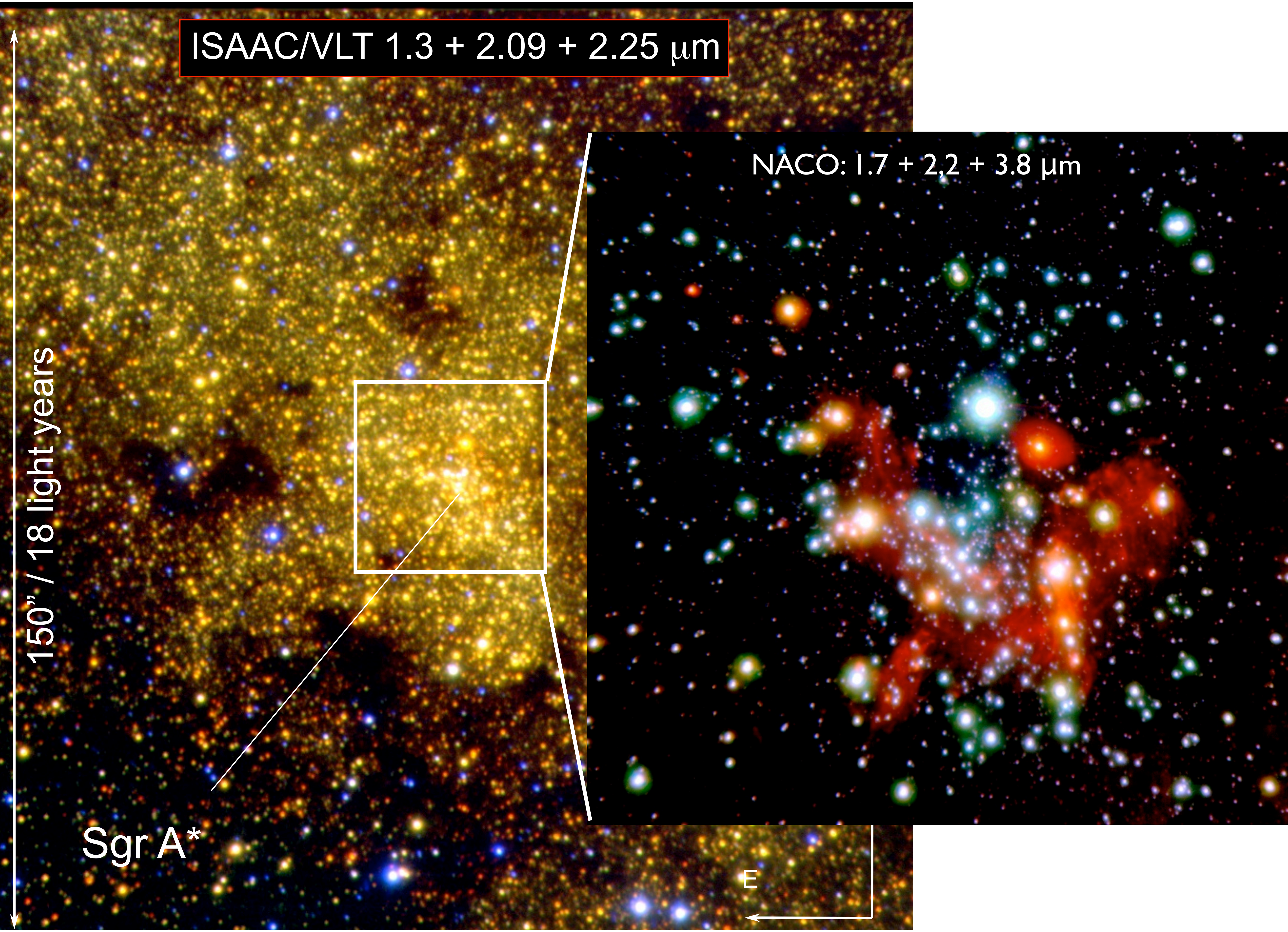
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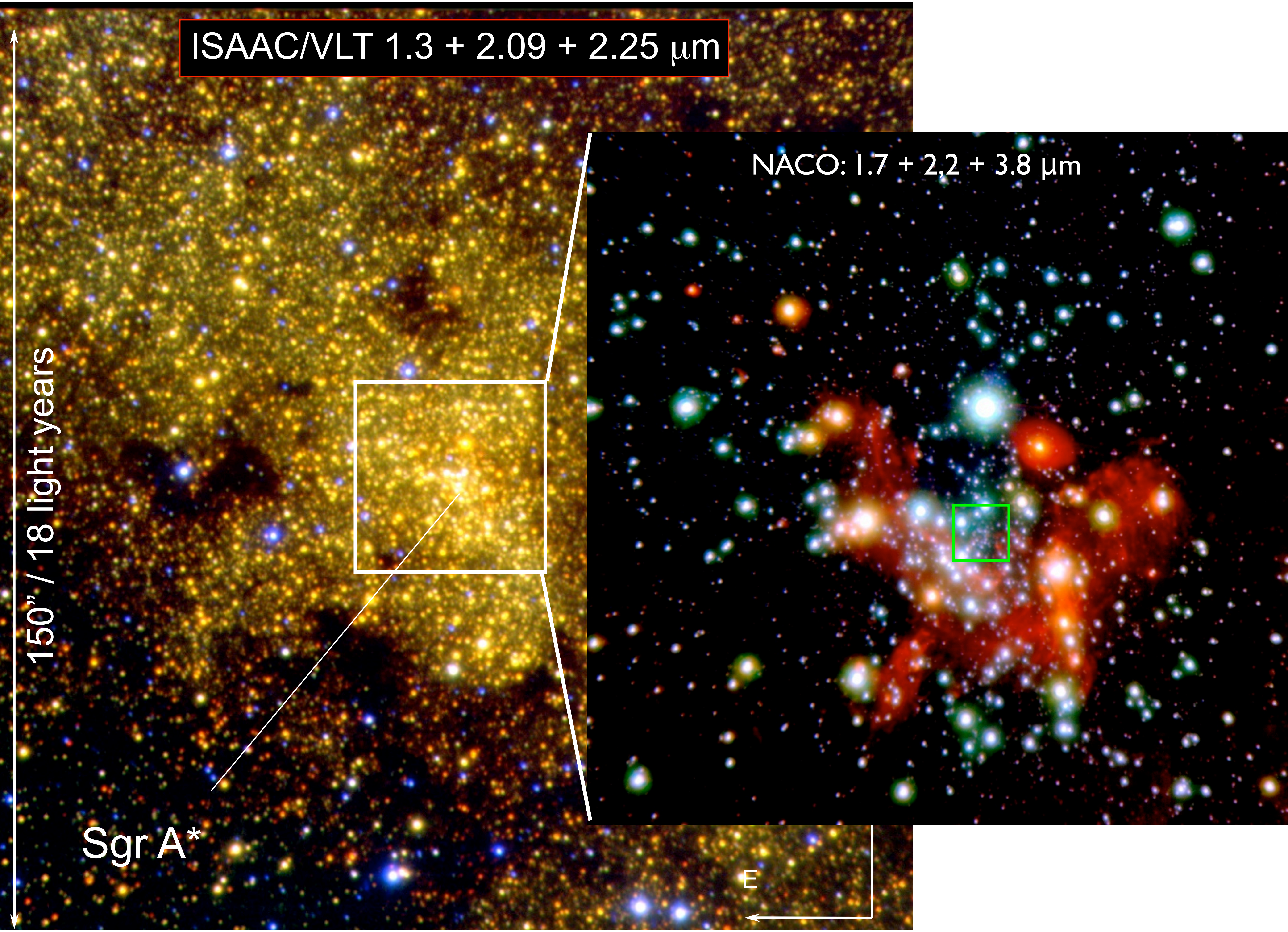
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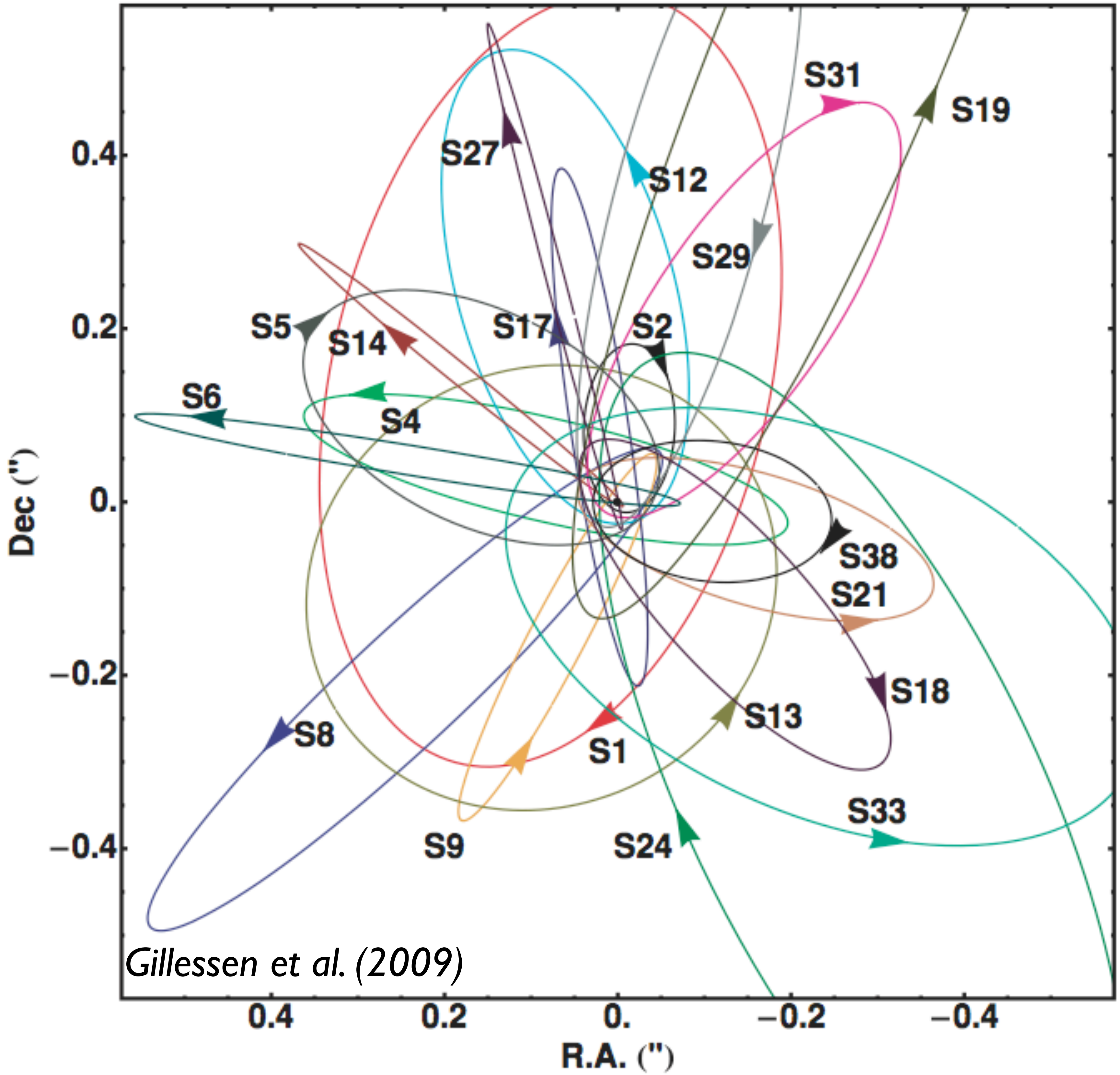
Orbits around Sagittarius A*



Gillessen et al. (2009)

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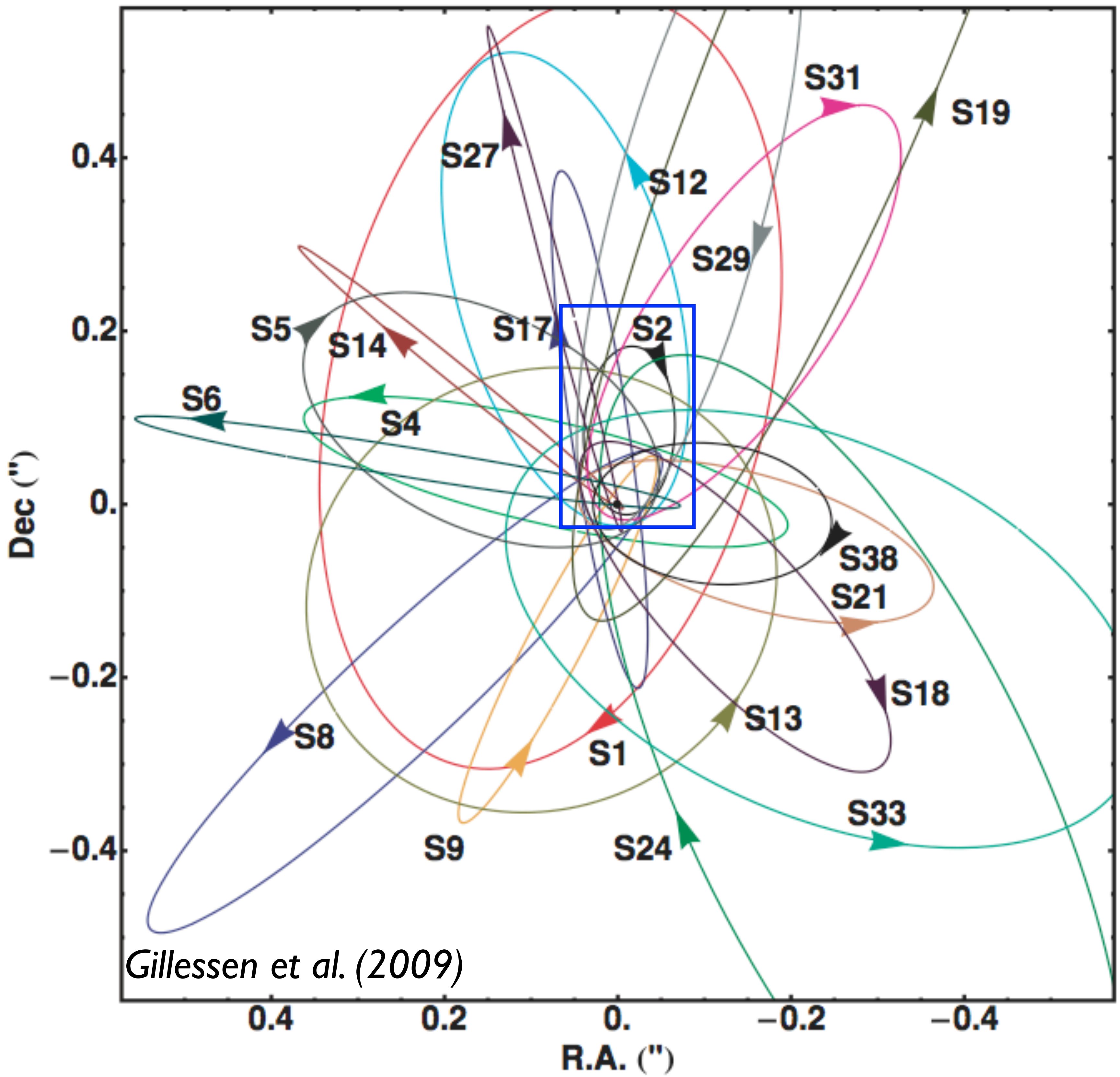

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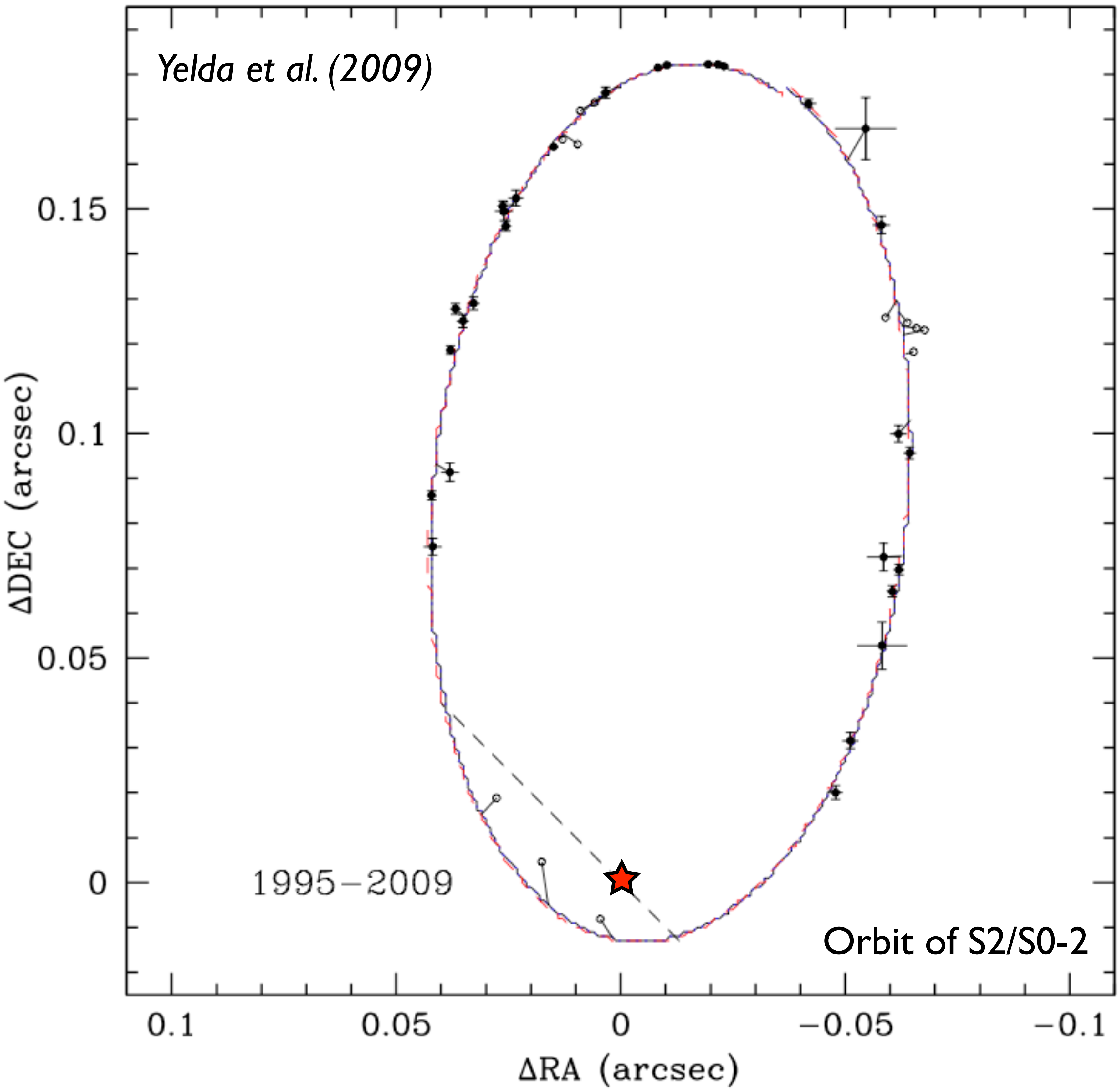

50 light days

14 light days

MPE/ESO

UCLA/Keck

e.g. Eckart & Genzel (1996); Ghez et al. (1998, 2003,2008); Genzel et al. (2000); Eckart et al. (2002); Schödel et al. (2002, 2003); Reid et al. (2004); Eisenhauer et al. (2003, 2005); Gillessen et al. (2009); Yelda et al. (2010)

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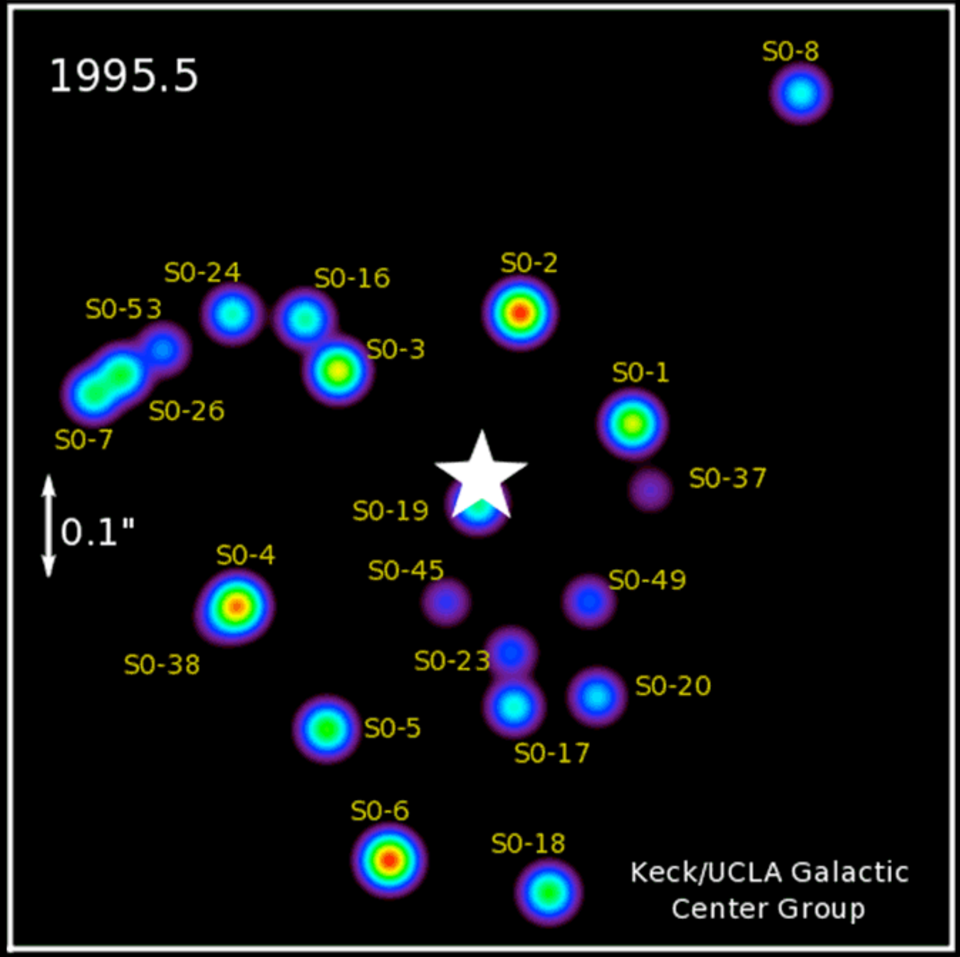

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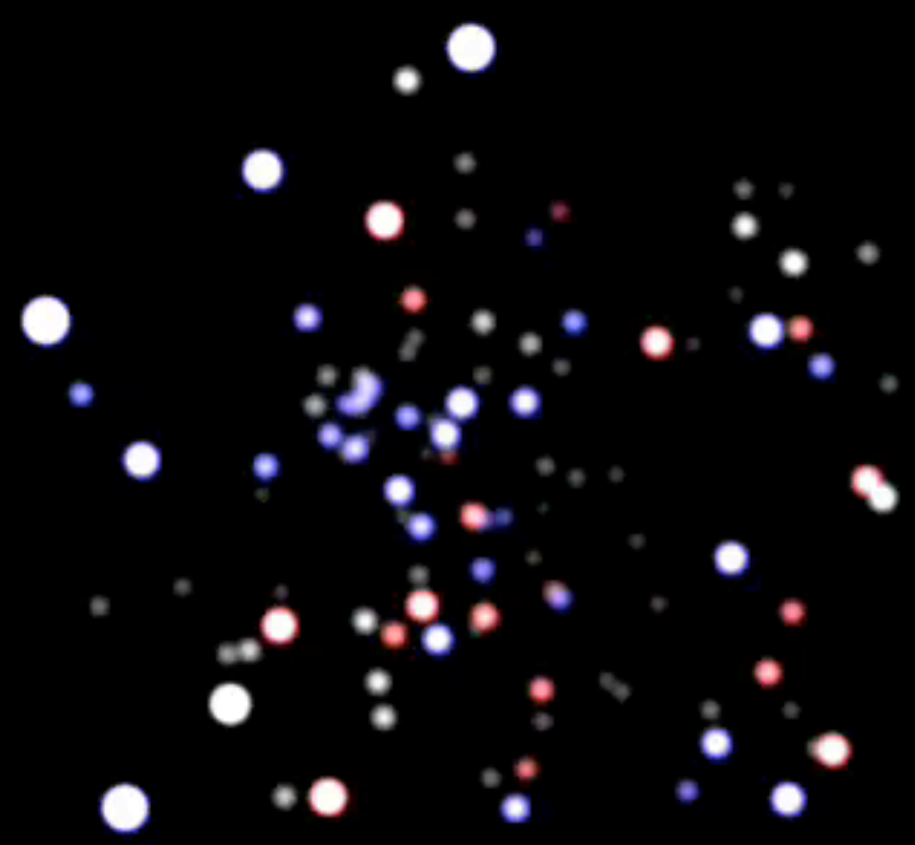

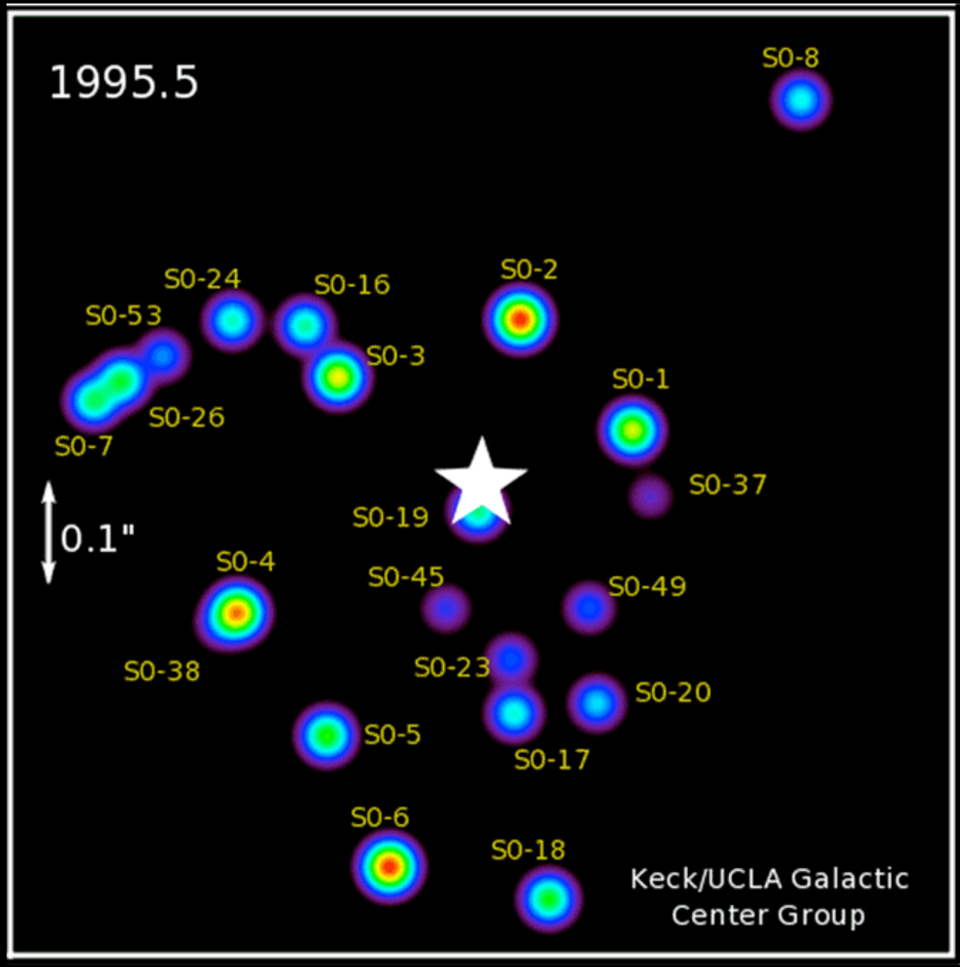

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Some numbers...

- Distance of Sagittarius A*:
  - 8.0 ± 0.3 kpc *(Yelda, Ghez+ 2010)*
  - 8.3 ± 0.3 kpc *(Gillessen+ 2009)*
  - 8.1 ± 0.3 (0.15) kpc *(average of 2006-2009 measurements; Schödel+ 2010)*

- Mass of Sagittarius A* from stellar dynamics:
  - $4.1 \pm 0.3 \times 10^6\ M_\odot$ *(Yelda, Ghez+ 2010)*
  - $4.3 \pm 0.3 \times 10^6\ M_\odot$ *(Gillessen et al., 2009)*

⇒ angular size of $R_{Schwarzschild} \approx 10\ \mu as$ (with M87 largest one on the sky)

compare:

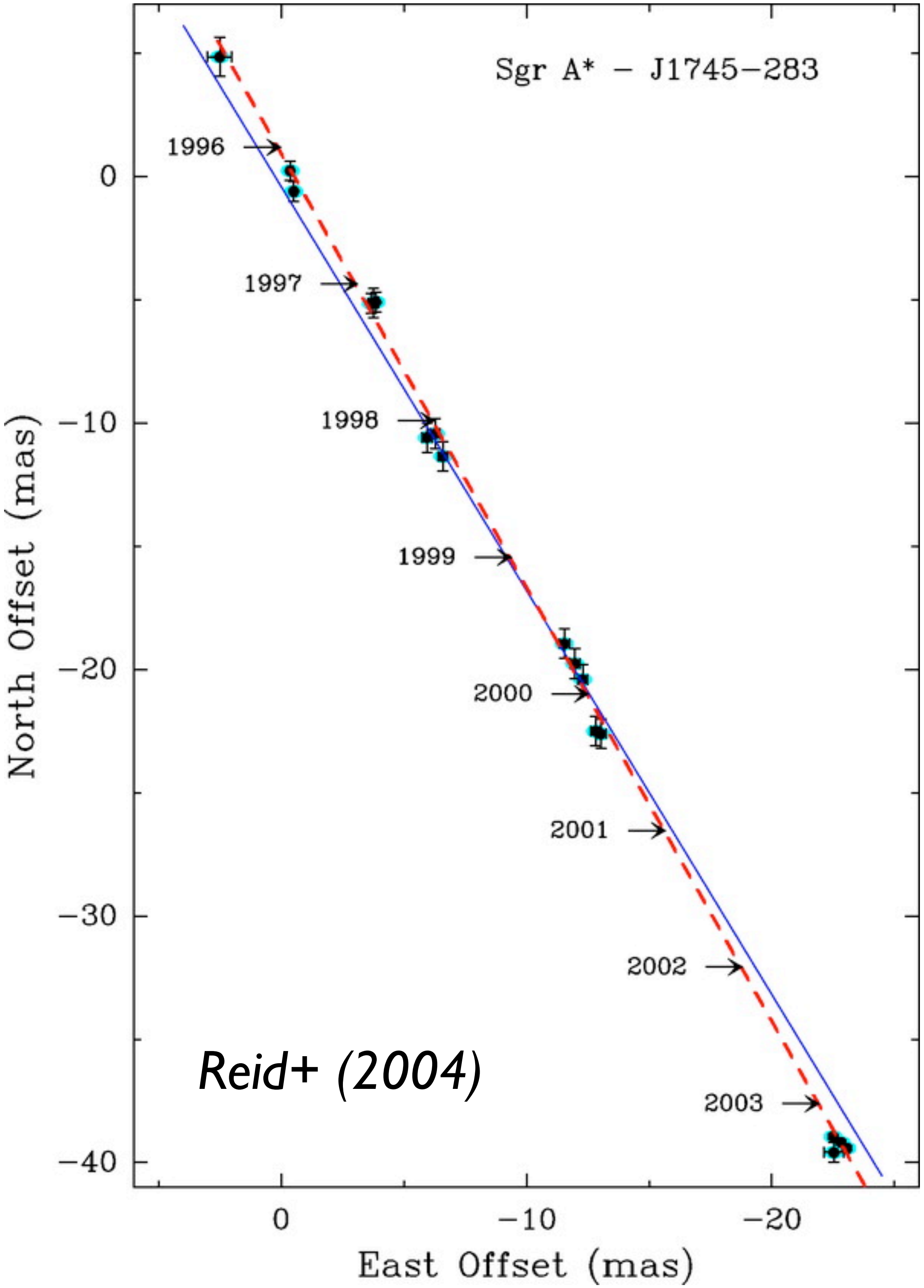
- 8m telescope, NIR: FWHM ~60 mas, astrometric accuracy ~1 mas
- Resolution element inter-continental VLBI 345GHz ~20 μas

Is Sagittarius A* at rest?

Sgr A* should show some reflex motion because of its interaction with the (much lighter) stars in its surroundings.

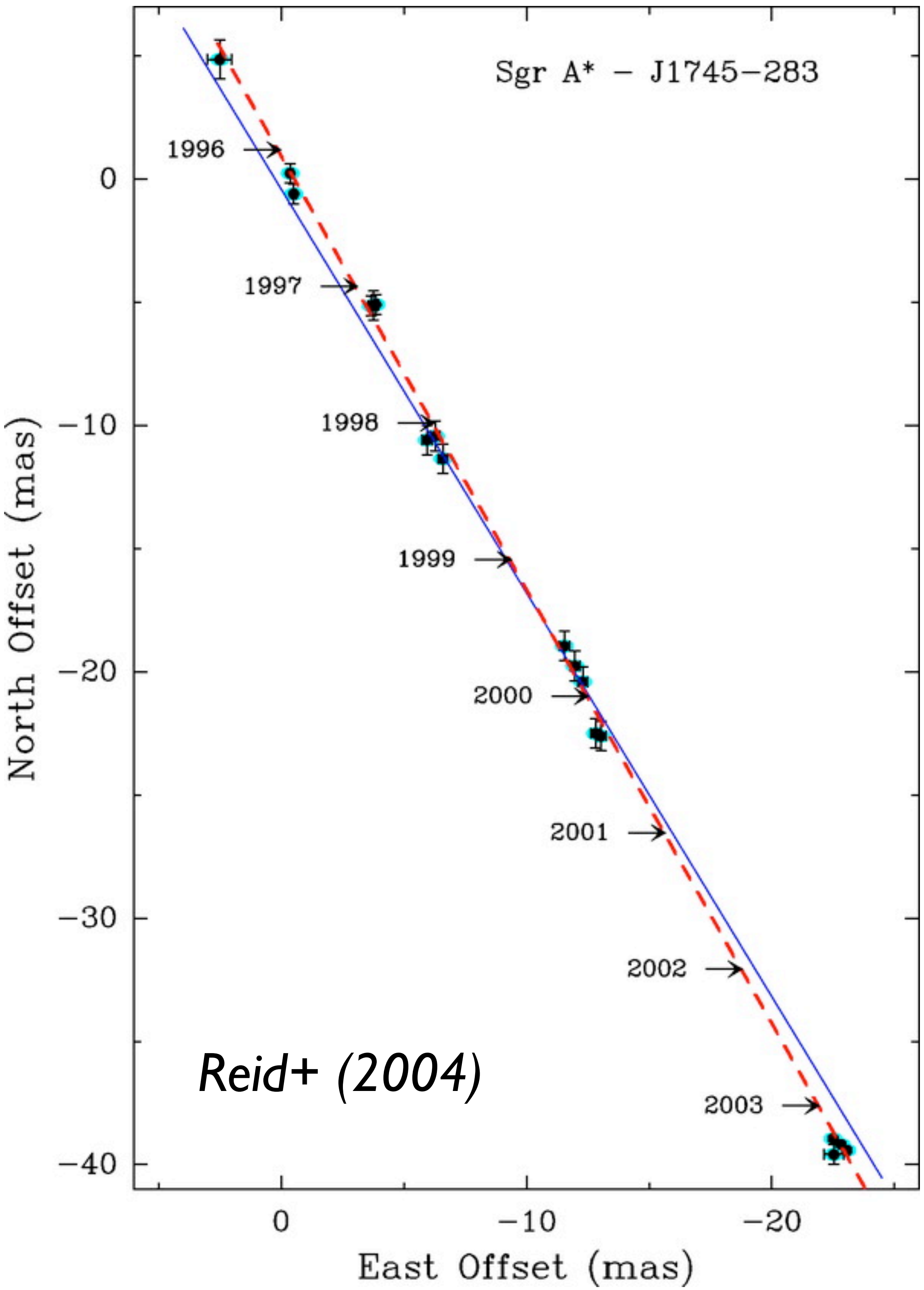
⇒ ***“Brownian Motion”***

Is Sagittarius A* at rest?



Reid+ (2004)

Is Sagittarius A* at rest?



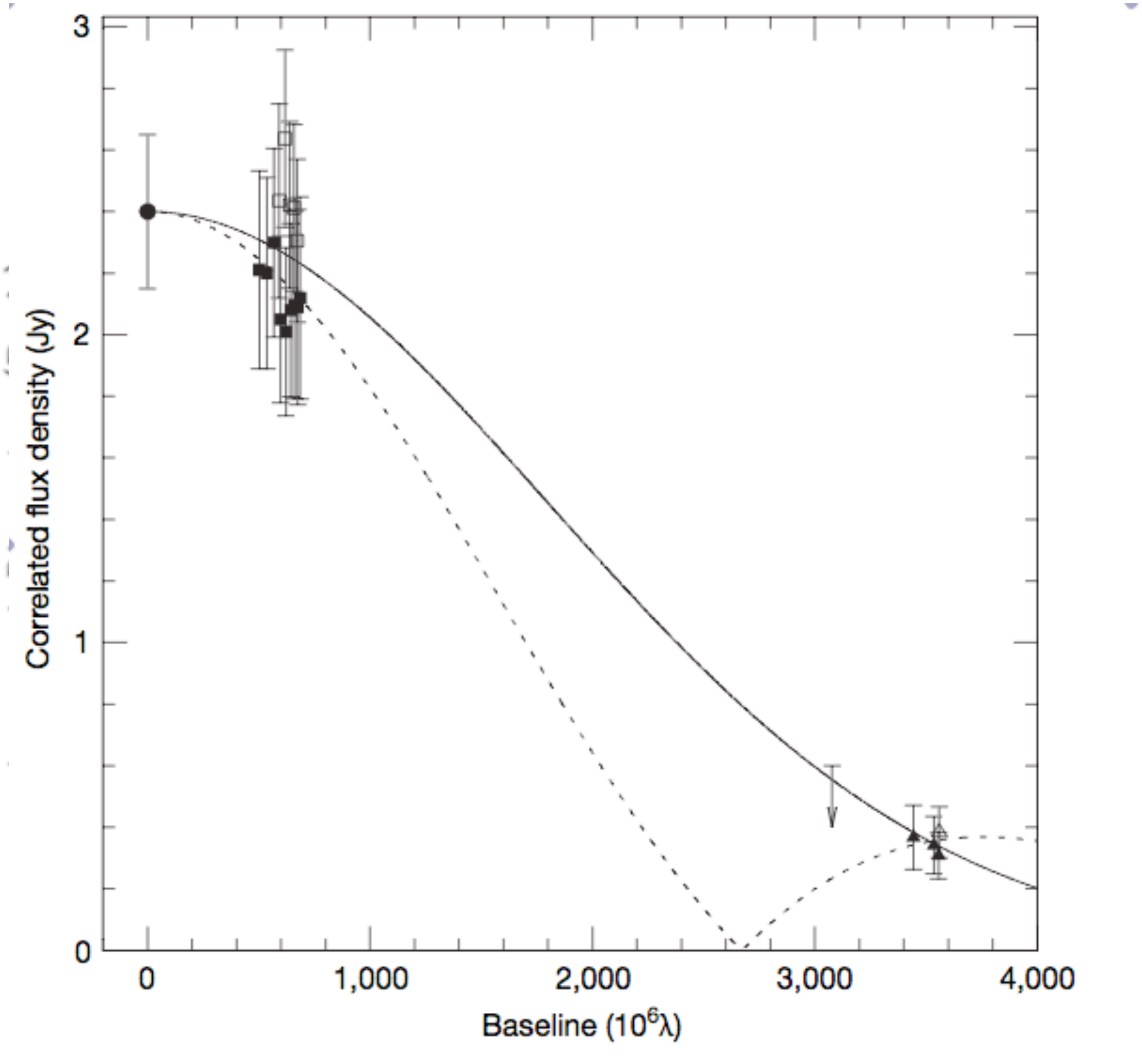
Detectable proper motion of Sgr A* relative to a quasar is consistent with its expected apparent motion because of the Sun's Galactic orbit.

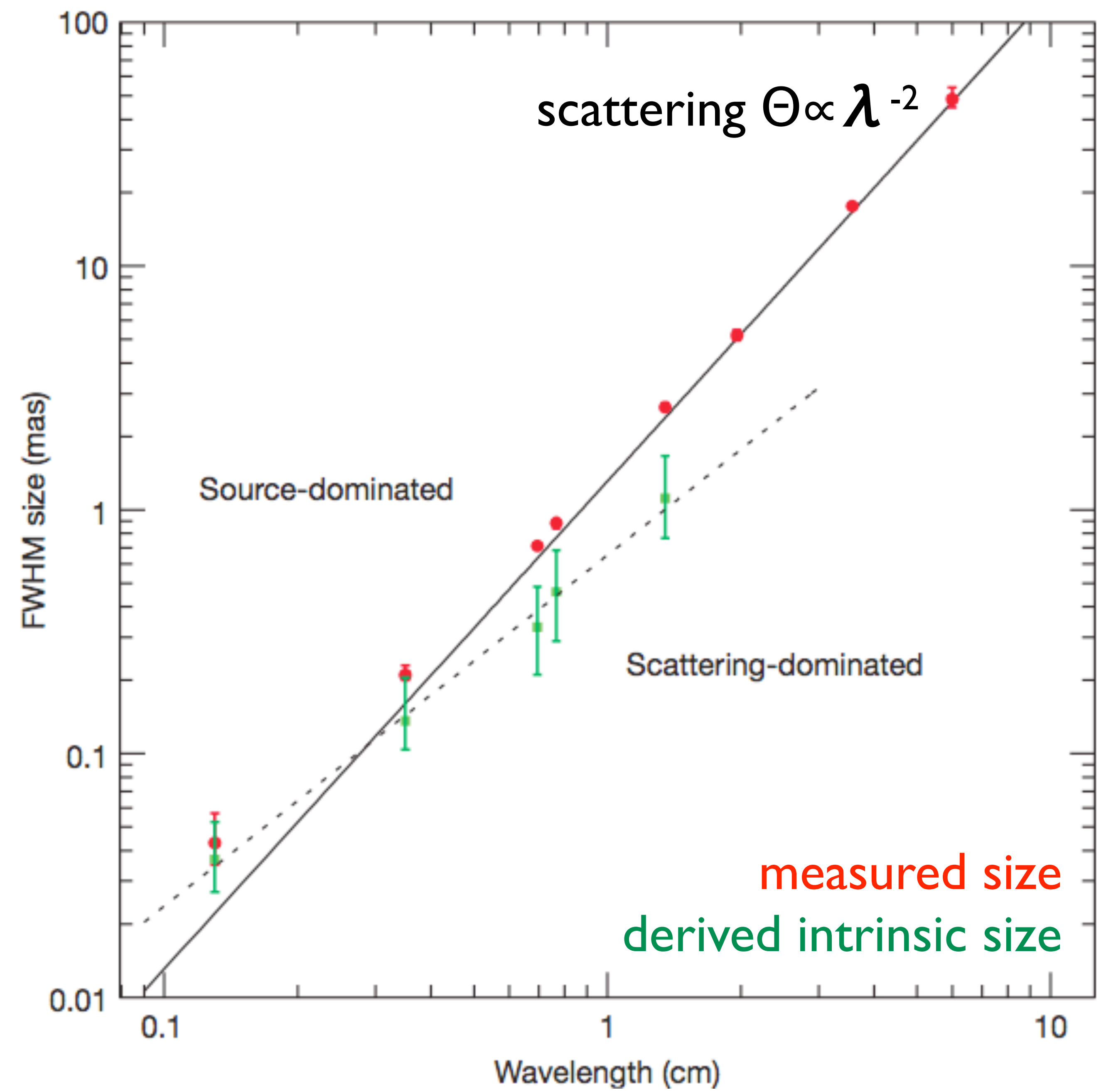
⇒ $> 4\times10^5\ M_\odot$

must be **directly** related to the radio source Sgr A*

⇒ Sgr A* must be a black hole.

VLBI observations of Sgr A*

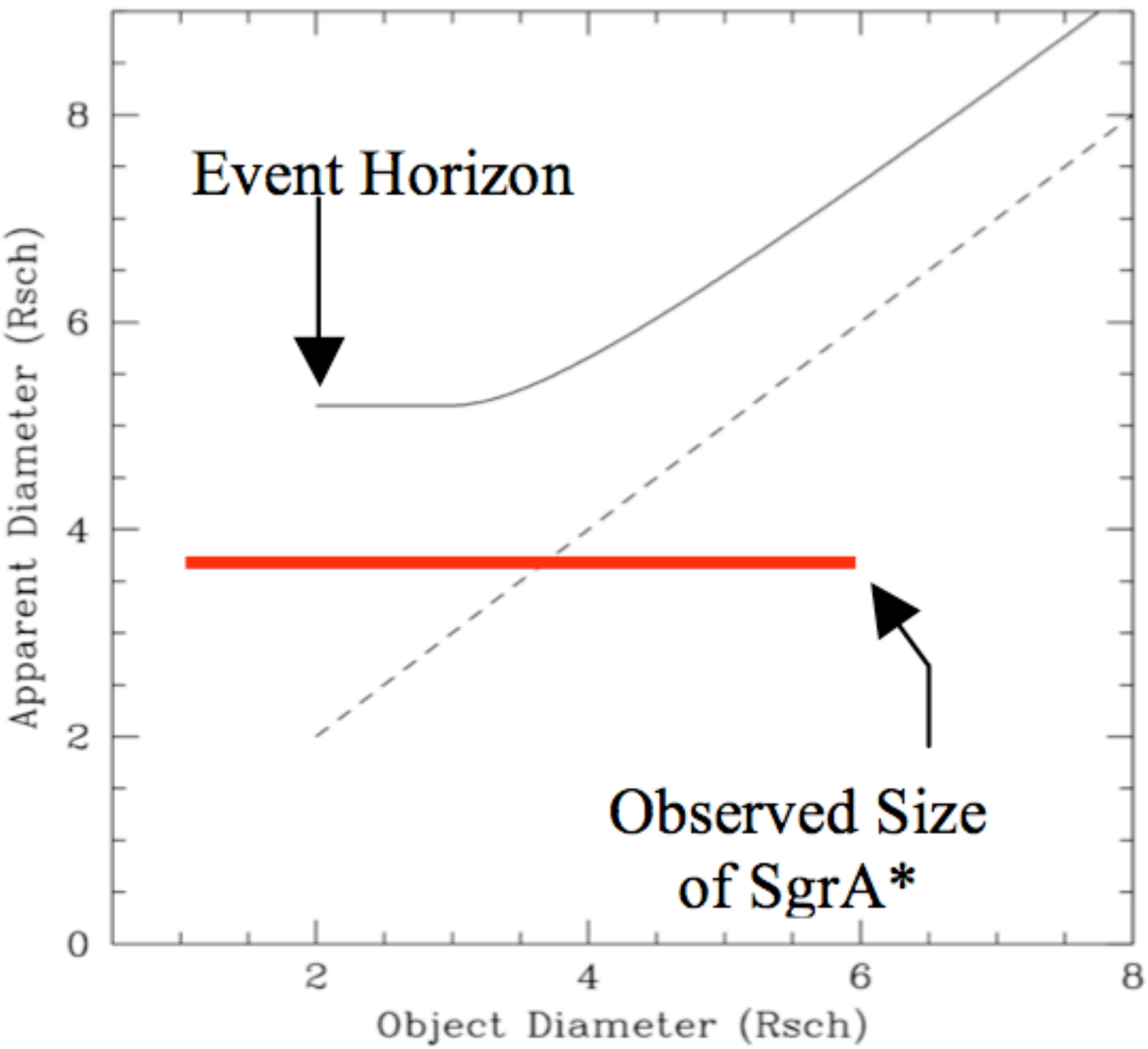


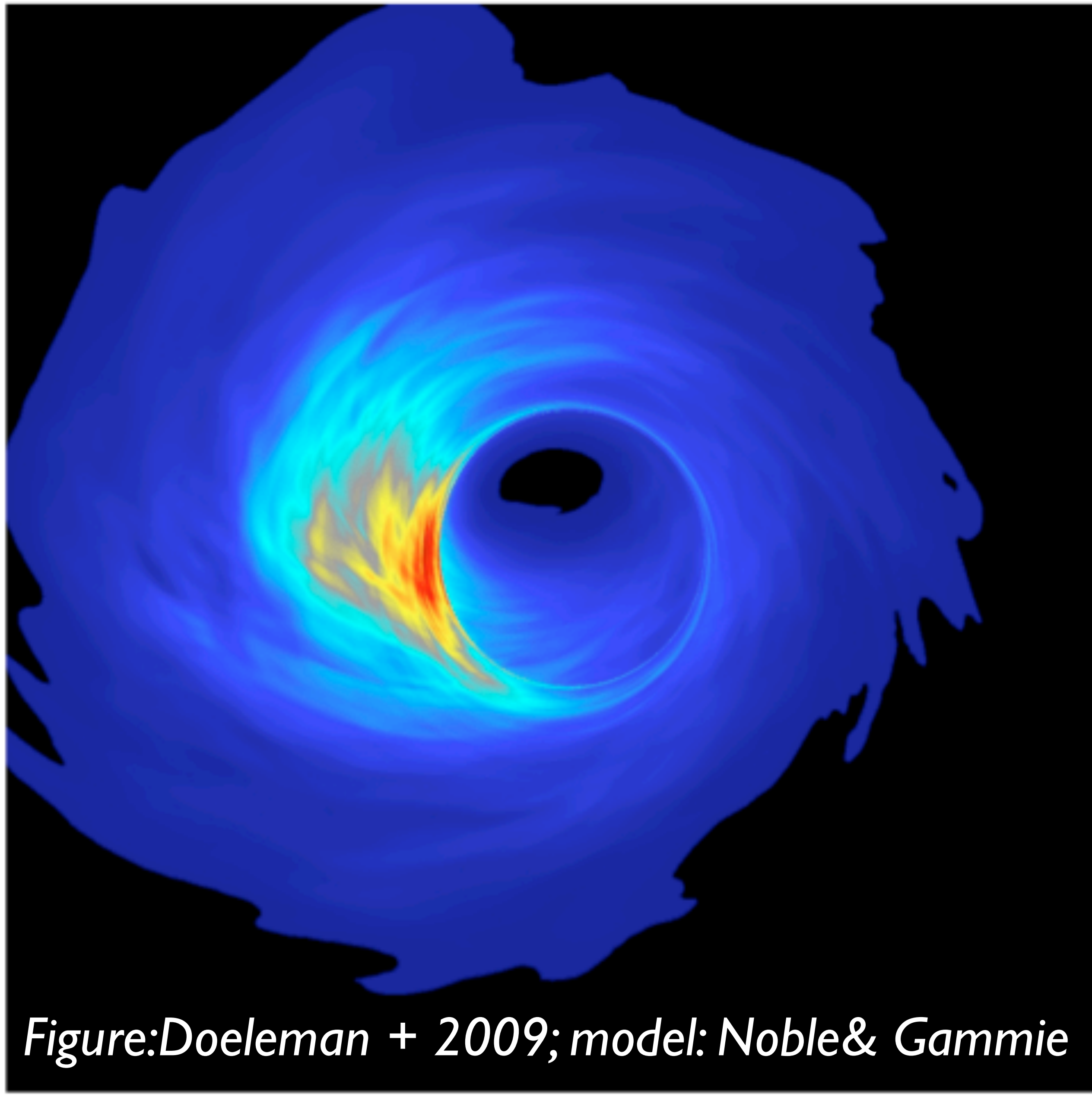


Doeleman+ (Nature, 2008)

Observed size larger than expected apparent size of event horizon.
⇒emission probably not centered on Sgr A* (relativistic flow, jet)

VLBI observations of Sgr A*





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Sgr A* : Outflow/Jet

Available material from stellar winds for accretion near Bondi radius ~10^{-5} -10^{-6} $M_\odot$ yr^{-1} *(e.g., Baganoff + 2003; Quataert 2004)*

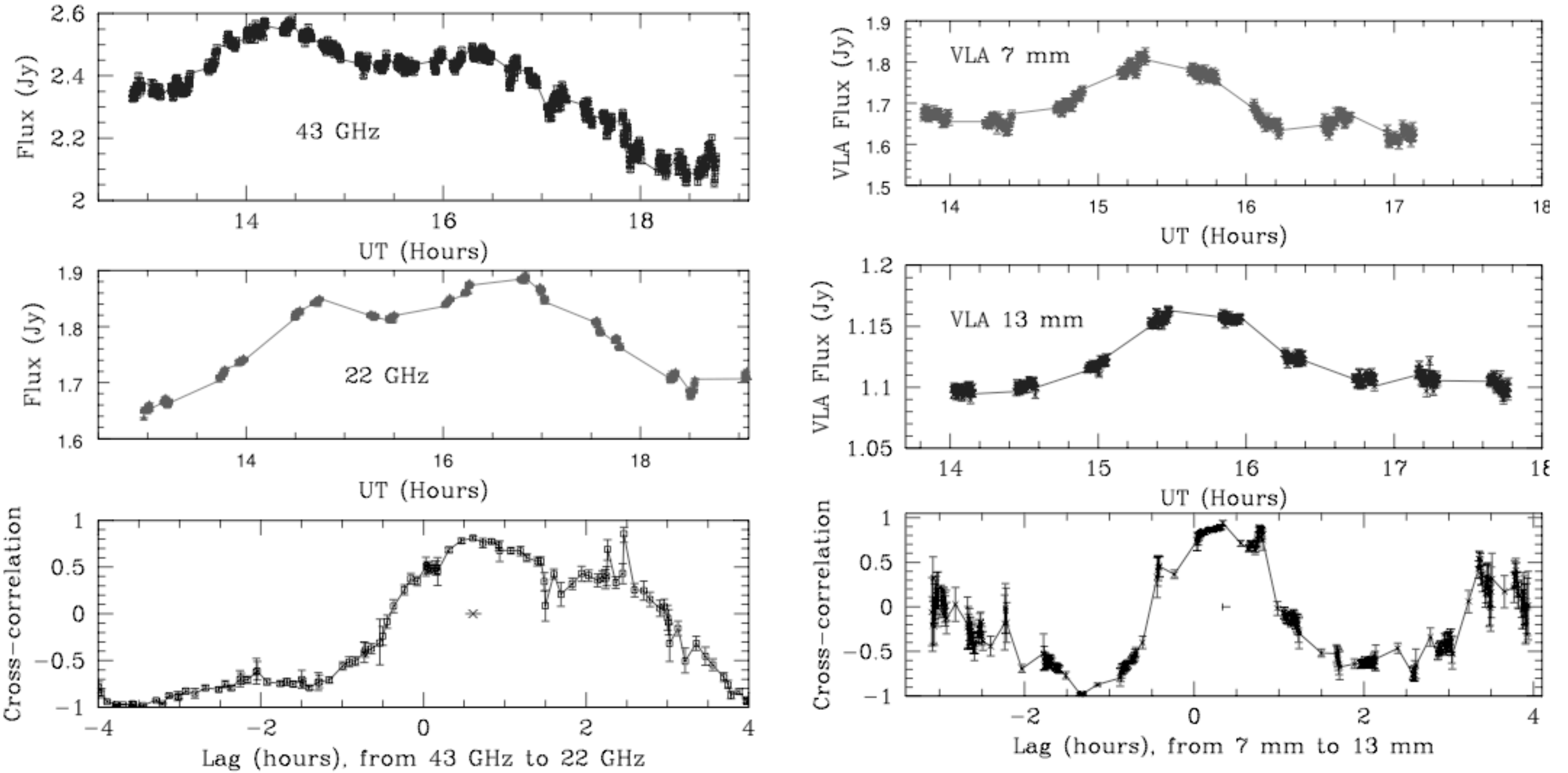
Actual accretion rate <10^{-7} $M_\odot$ yr^{-1} *(Marone+ 2009)*

⇒ outflow must exist

Outflow also predicted by theoretical models *(e.g., Blandford & Begelman, 1999; Markoff & Falcke, 2003;Yuan 2006; Shcherbakov & Baganoff, 2010)* and required to explain radio SED of Sgr A*

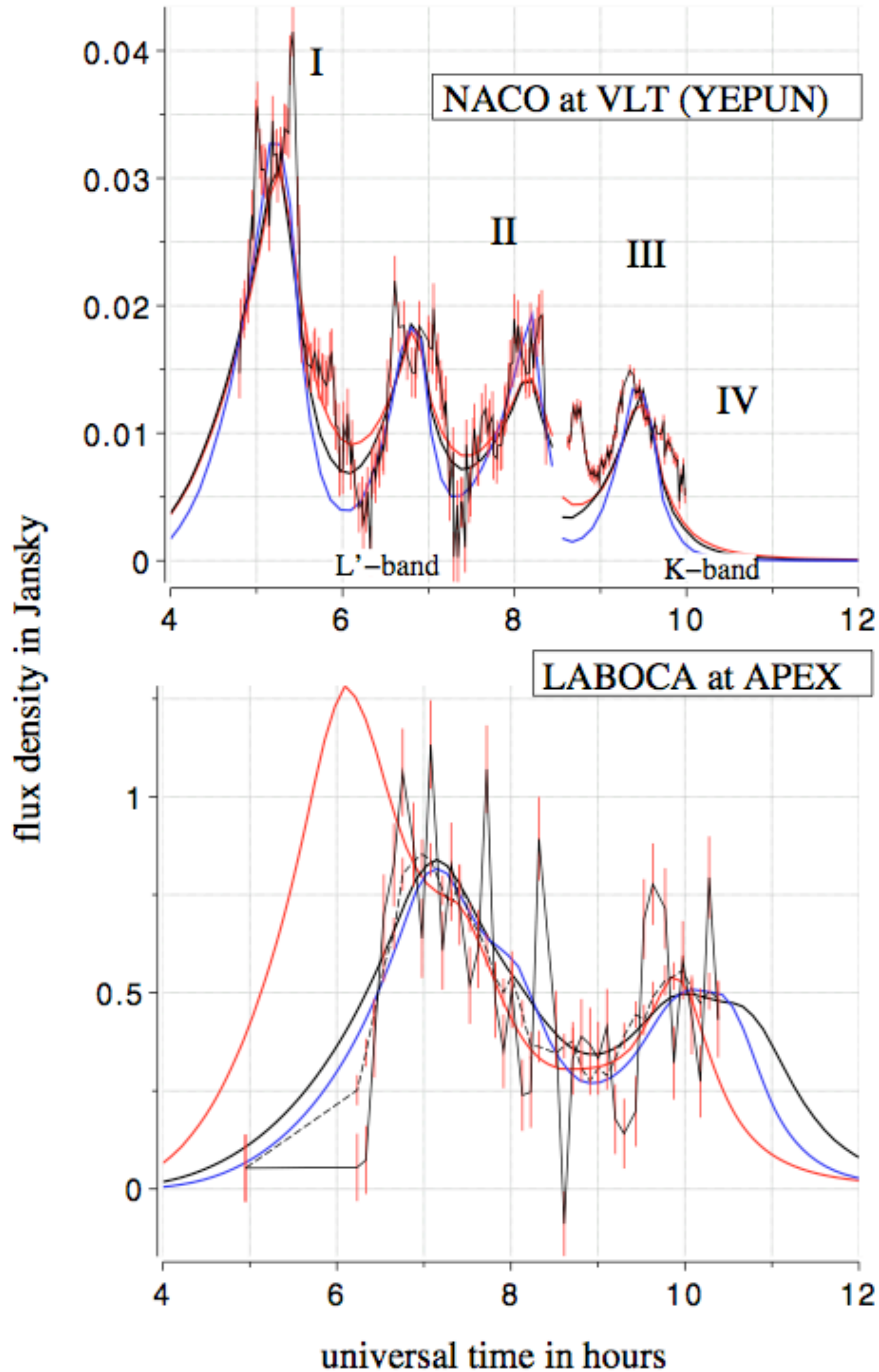
Sgr A* : Outflow/Jet

Yusef-Zadeh et al. (2008)



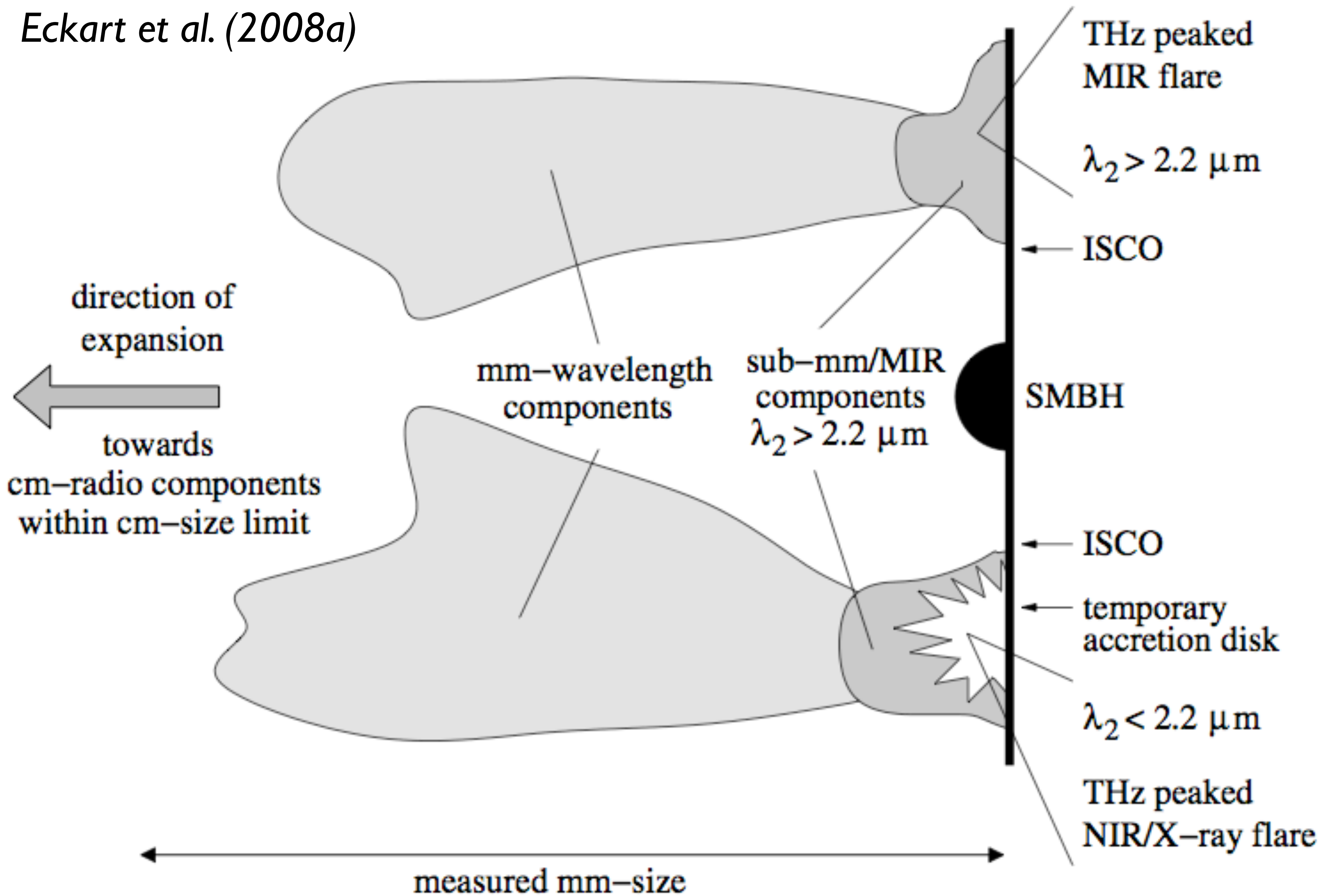
Sgr A* : Outflow/Jet

Eckart et al. (2008b)



Sgr A* : Outflow/Jet

Eckart et al. (2008a)



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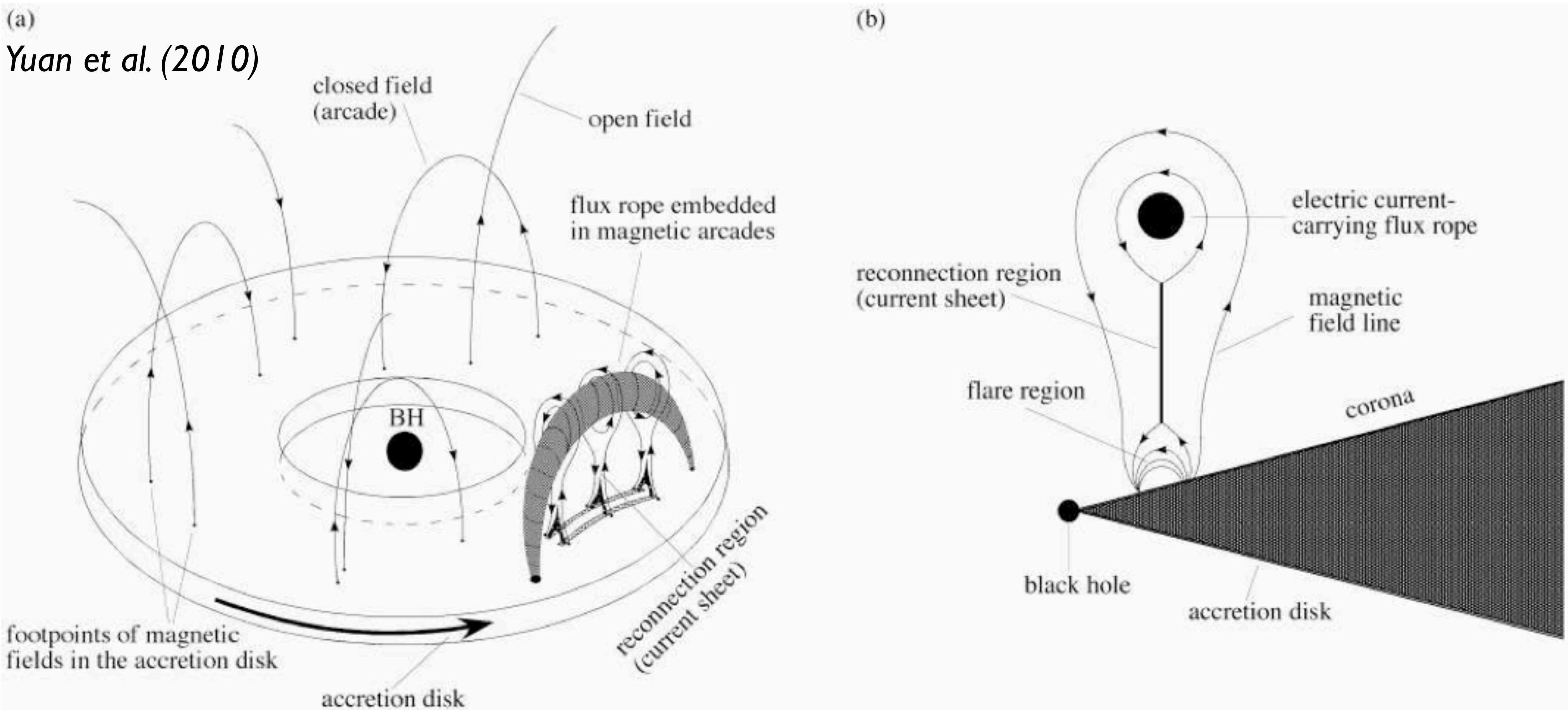
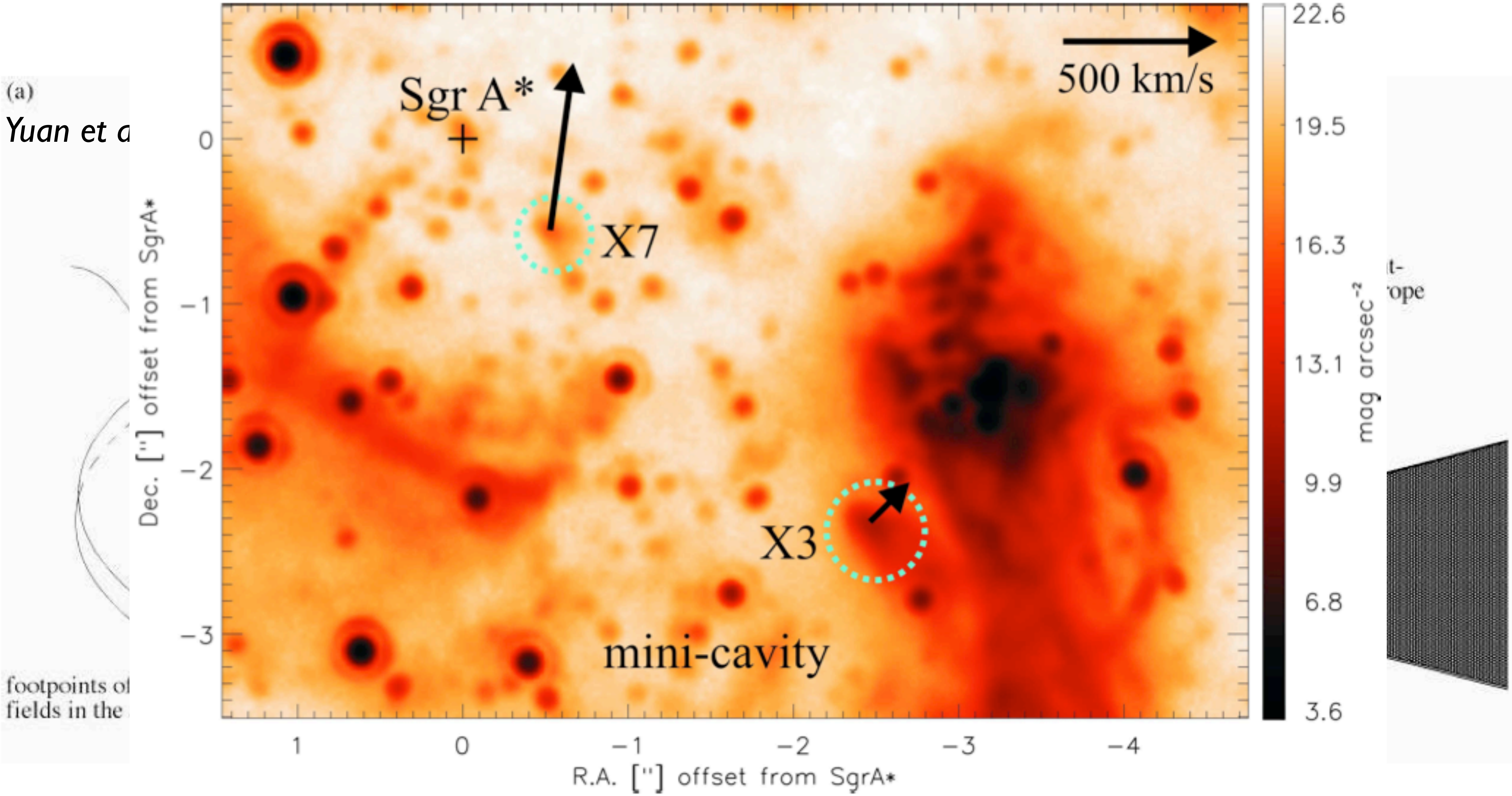


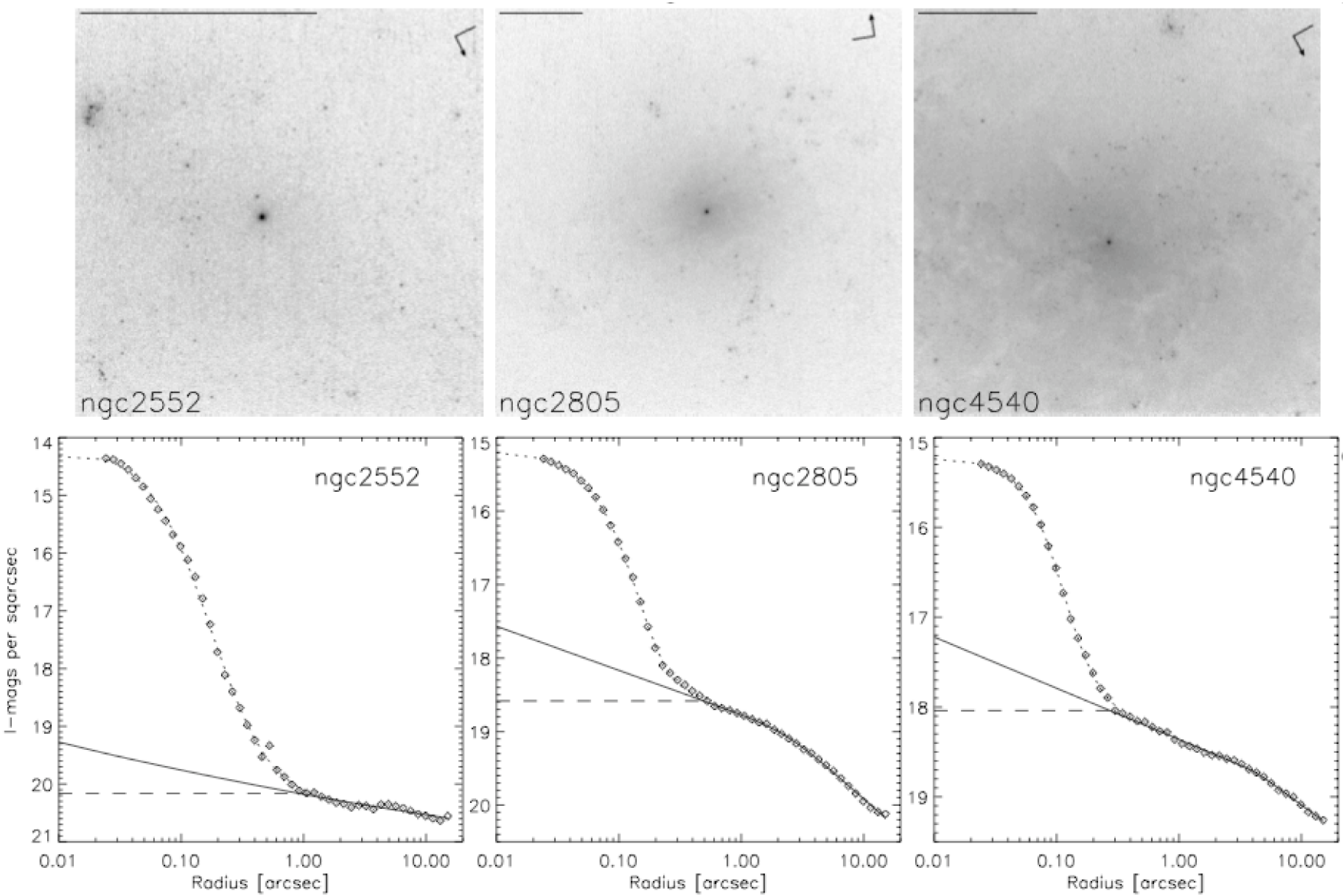
Sgr A* : Outflow/Jet



Muzic et al. (2009)

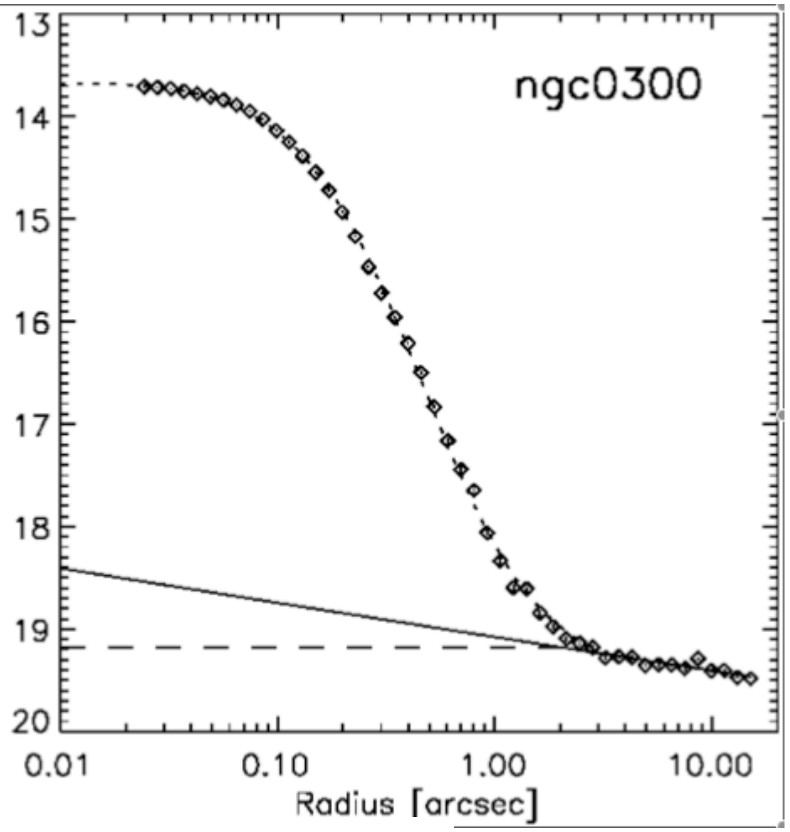
The nuclear stellar cluster of the Milky Way

Nuclear Star Clusters (NSCs)



Böker et al. (2002)

Nuclear Star Clusters (NSCs)



van der Marel et al. (2007), image from the observations of Bresolin et a. (2005)

Nuclear Star Clusters (NSCs)

NSCs are detected *unambiguously* in 50%-75% of spiral, spheroids (“dwarf ellipticals”), and S0 galaxies. Their actual rate of occurrence in these galaxies may be close to 100%.

NSCs appear to be absent in elliptical galaxies (i.e. products of major mergers: coreless and extra-light ellipticals).

see also, e.g., Phillips+ 1996; Carollo+ 1998; Matthews+ 1999; Böker+ 2002, 2004; Balcells+ 2003; Ferrarese+ 2006; Kormendy+ 2009

Nuclear star clusters

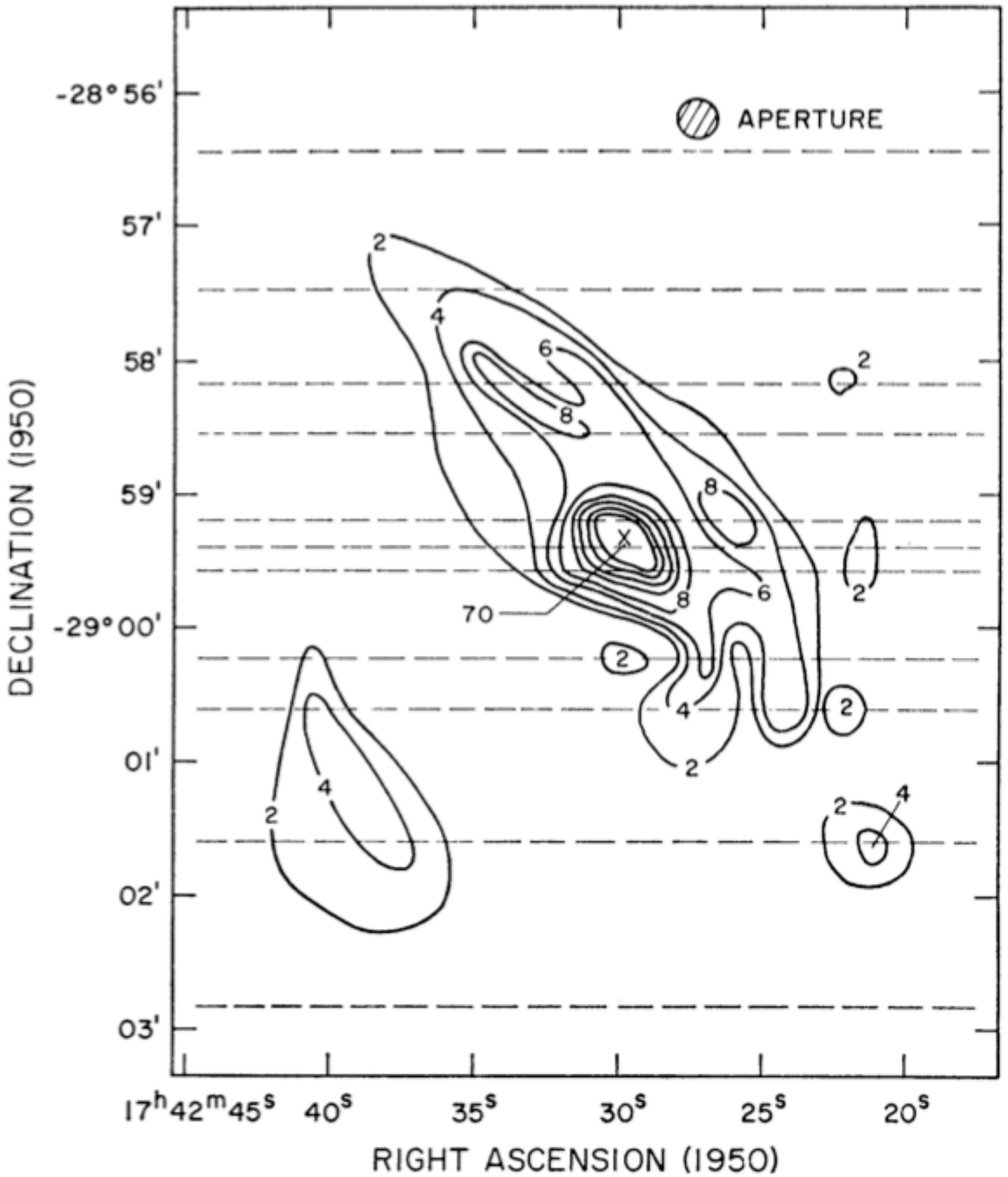
- **Half-light radii** typically 2-5 pc
- **Masses** of 10^6 - 10^7 $M_\odot$
- **Complex star formation histories**: evidence for frequent and repetitive star formation episodes, most recent generation often younger than 10^8 yr
- NSCs may obey similar **scaling relationships with properties of host galaxies** as do massive black holes

see, e.g., review by *T. Böker (2008)*

First observations of the NSC

2.2 μm observations from Becklin & Neugebauer 1968:

0.5 × 0.5mm PbS cell IR photometer on 200 inch telescope on Mt. Palomar



- dominant extended, elongated source of 3'- 5'FWHM
- surface brightness proportional $R^{-0.8}$
- dense stellar cluster with $\rho \propto r^{-1.8}$
- density in central parsec 10^7 times the one in the solar neighborhood
- mass in central pc ~3×10^6 M☉

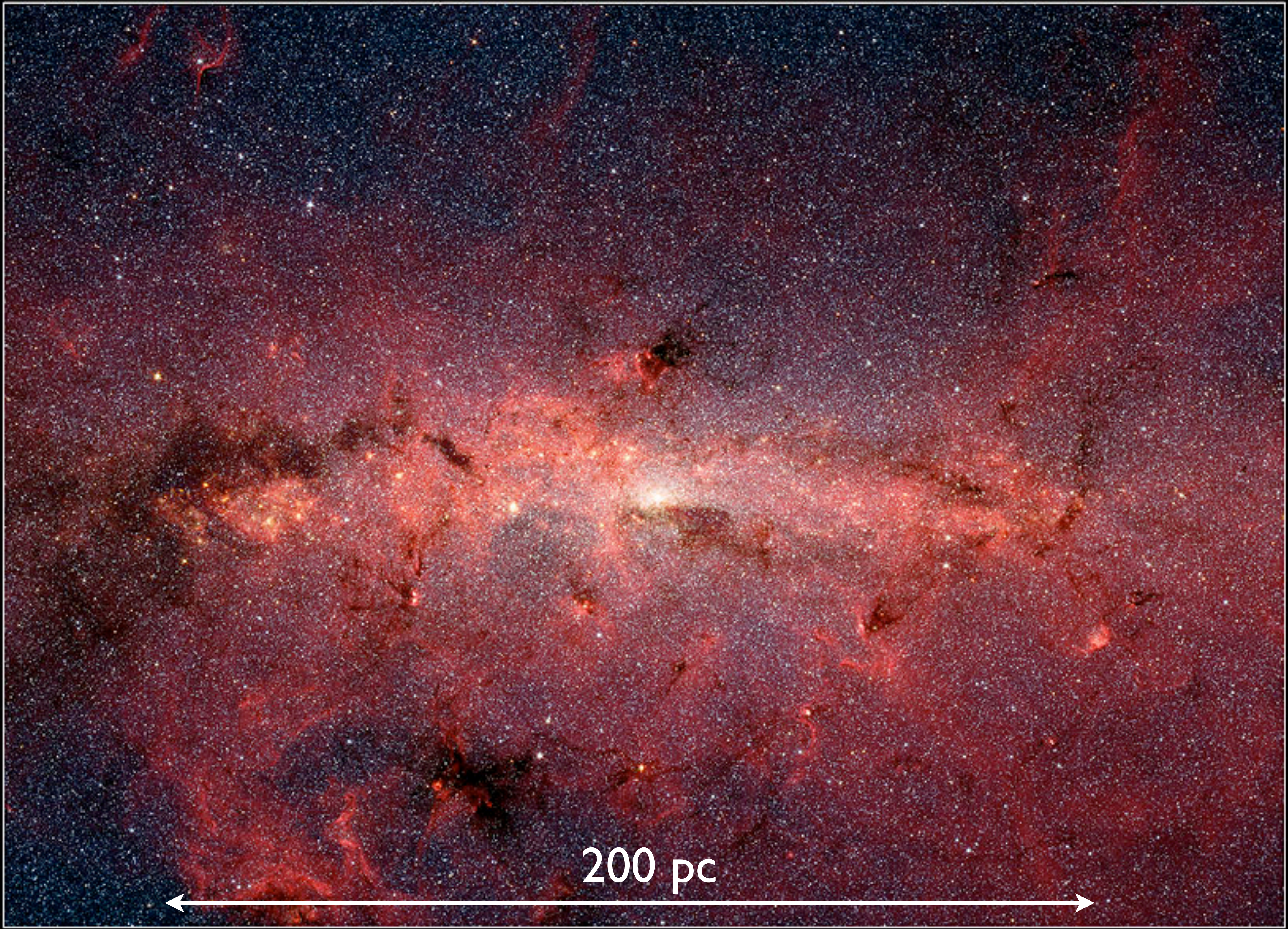
TABLE 7

Calculated Intrinsic Physical Properties

Diameter (pc)	Mean Intrinsic 2 2-μ Surface Brightness (10^{-18} W m^{-2} Hz^{-1} $sterad^{-1}$)	Intrinsic Luminosity (10^6 $L_\odot$)*	Mass (10^6 $M_\odot$)†
1	78	1	3
2	45	2	6
5	21	7	20
10	12	15	45
20	7	35	100
40	4	80	230
60	3	130	370

* $L_\odot = 4 \times 10^{26}$ watts. † $M_\odot = 2 \times 10^{30}$ kg

Contemporary view of the Galactic Center



The Center of the Milky Way Galaxy
NASA / JPL-Caltech / S. Stolovy (Spitzer Science Center/Caltech)

Spitzer Space Telescope • IRAC
ssc2006-02a

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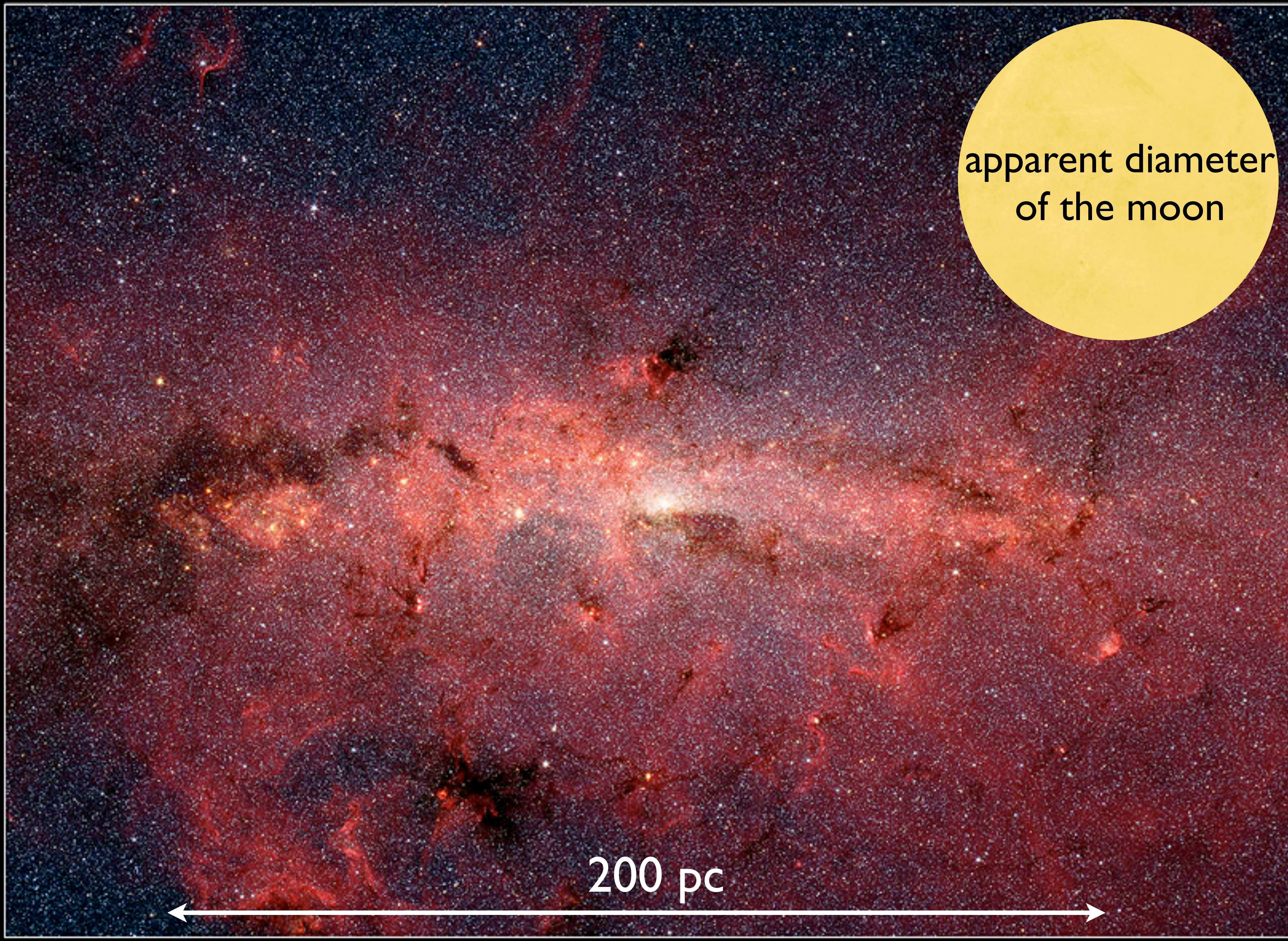

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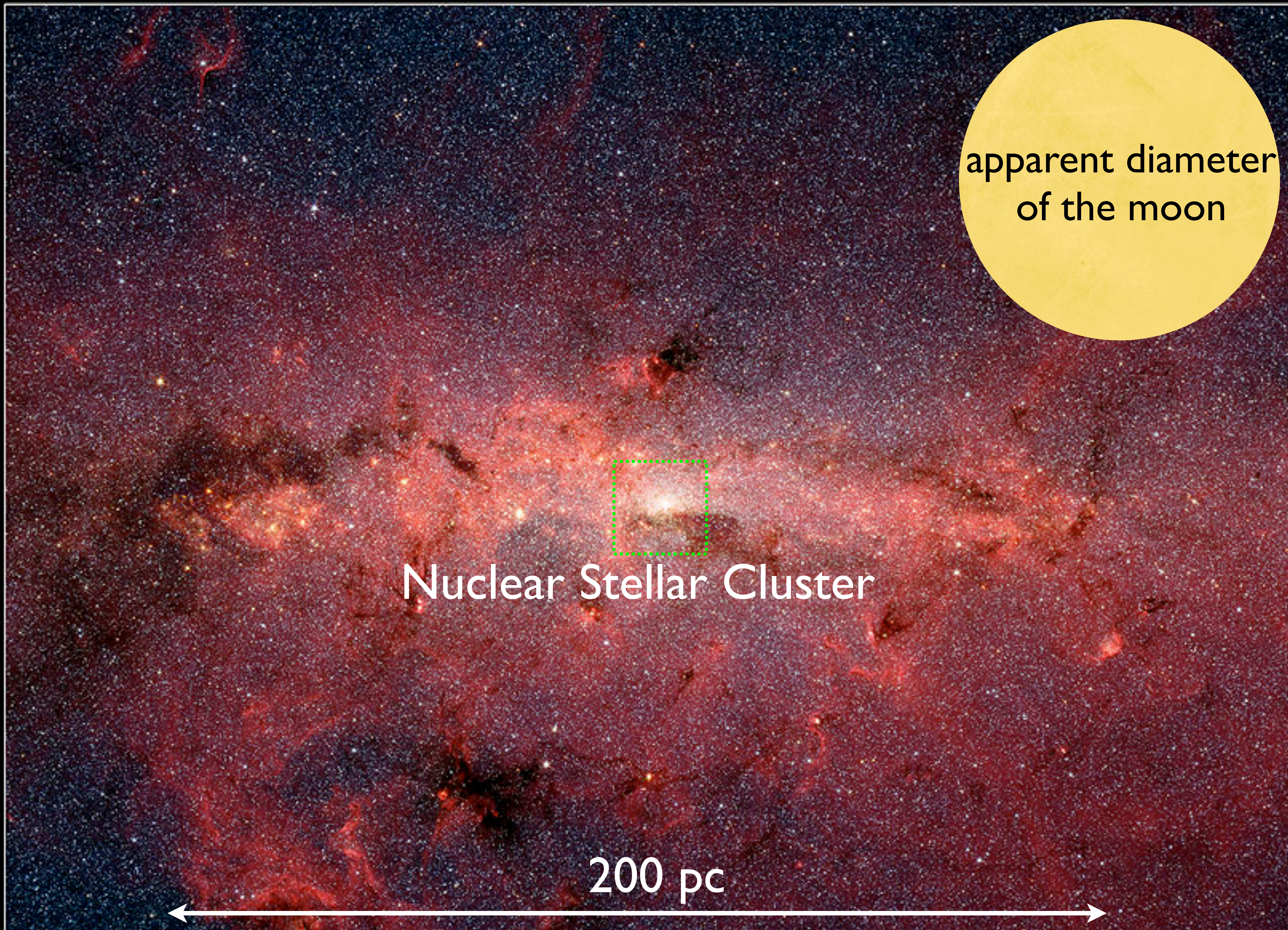

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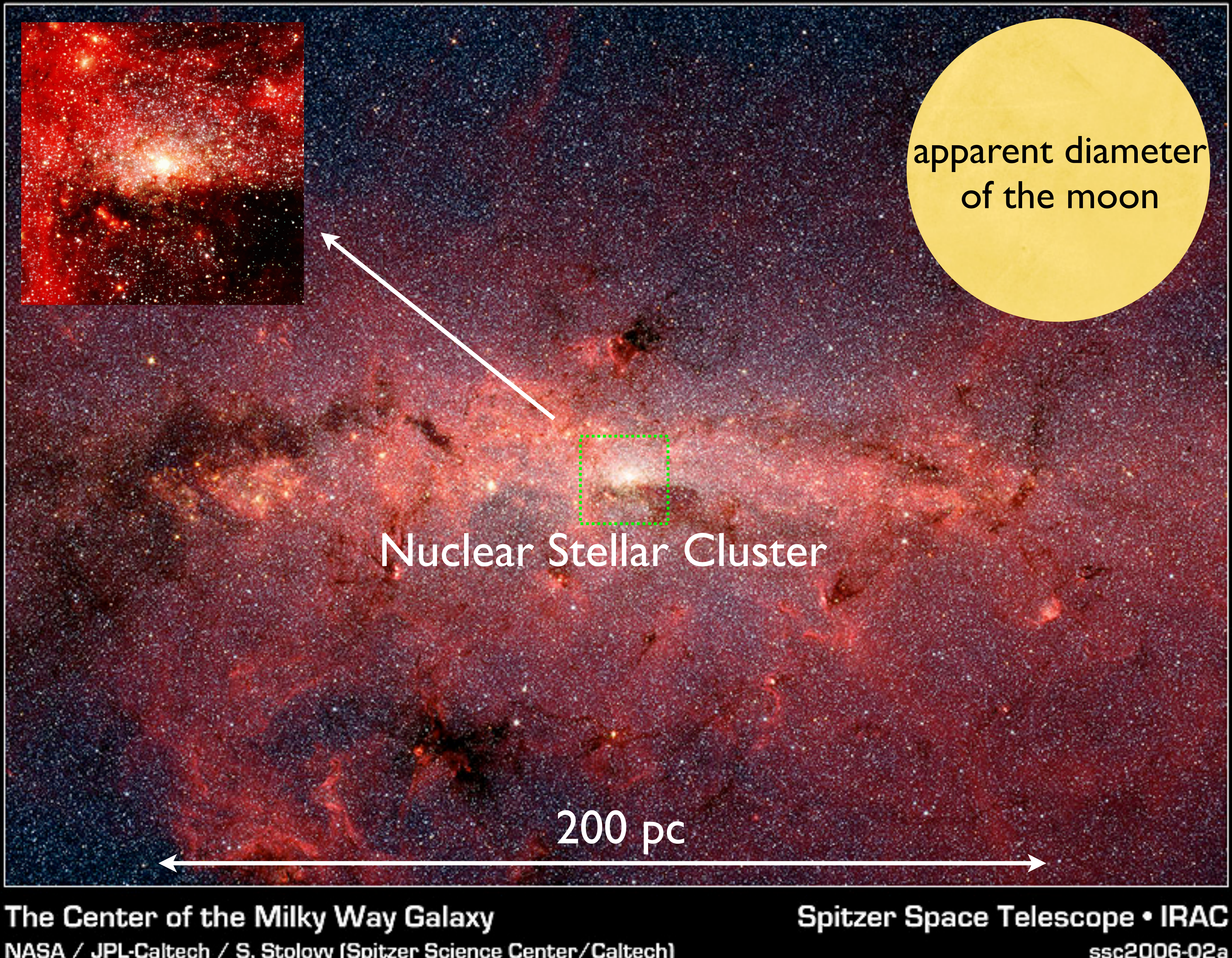
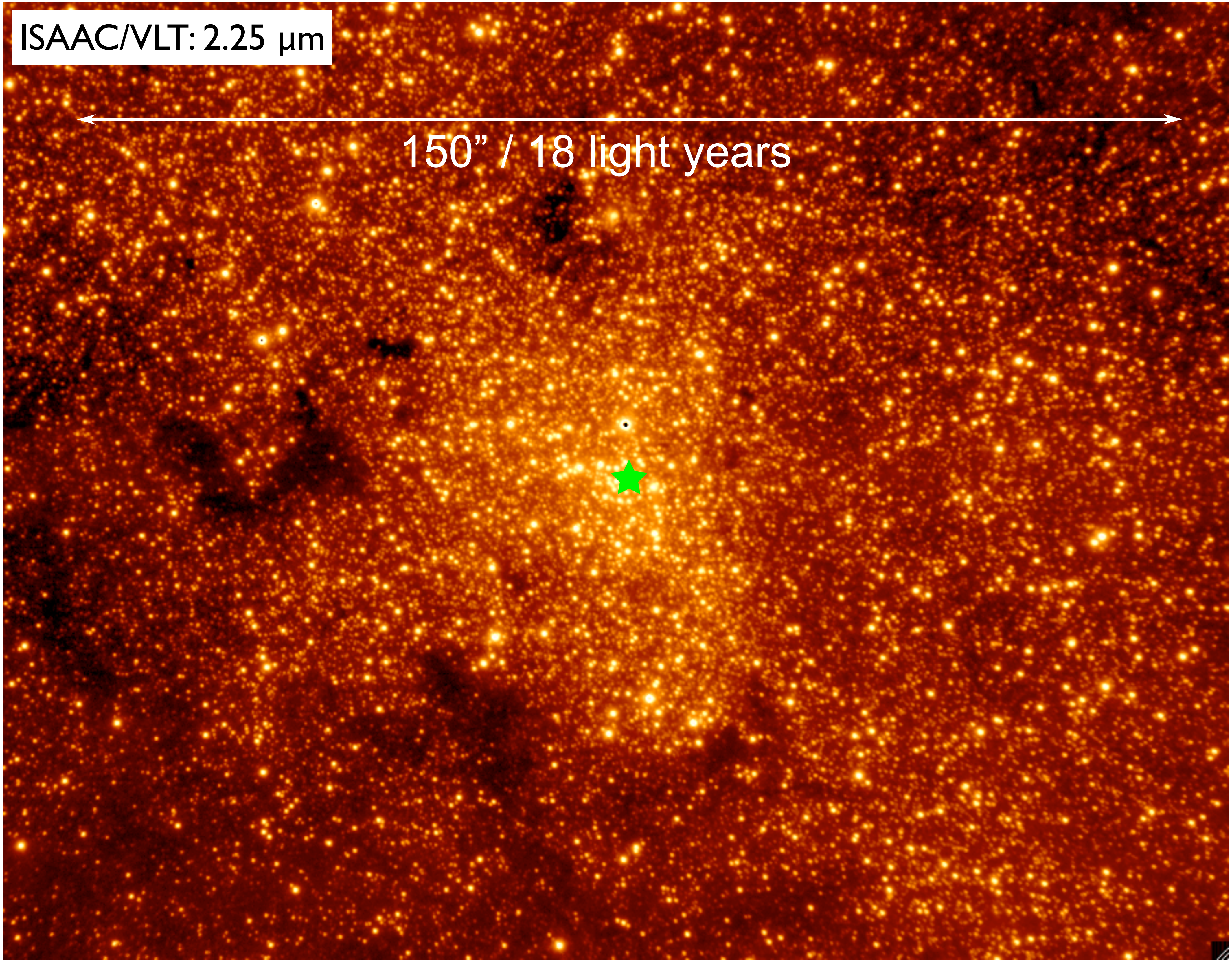


A Word about Extinction…



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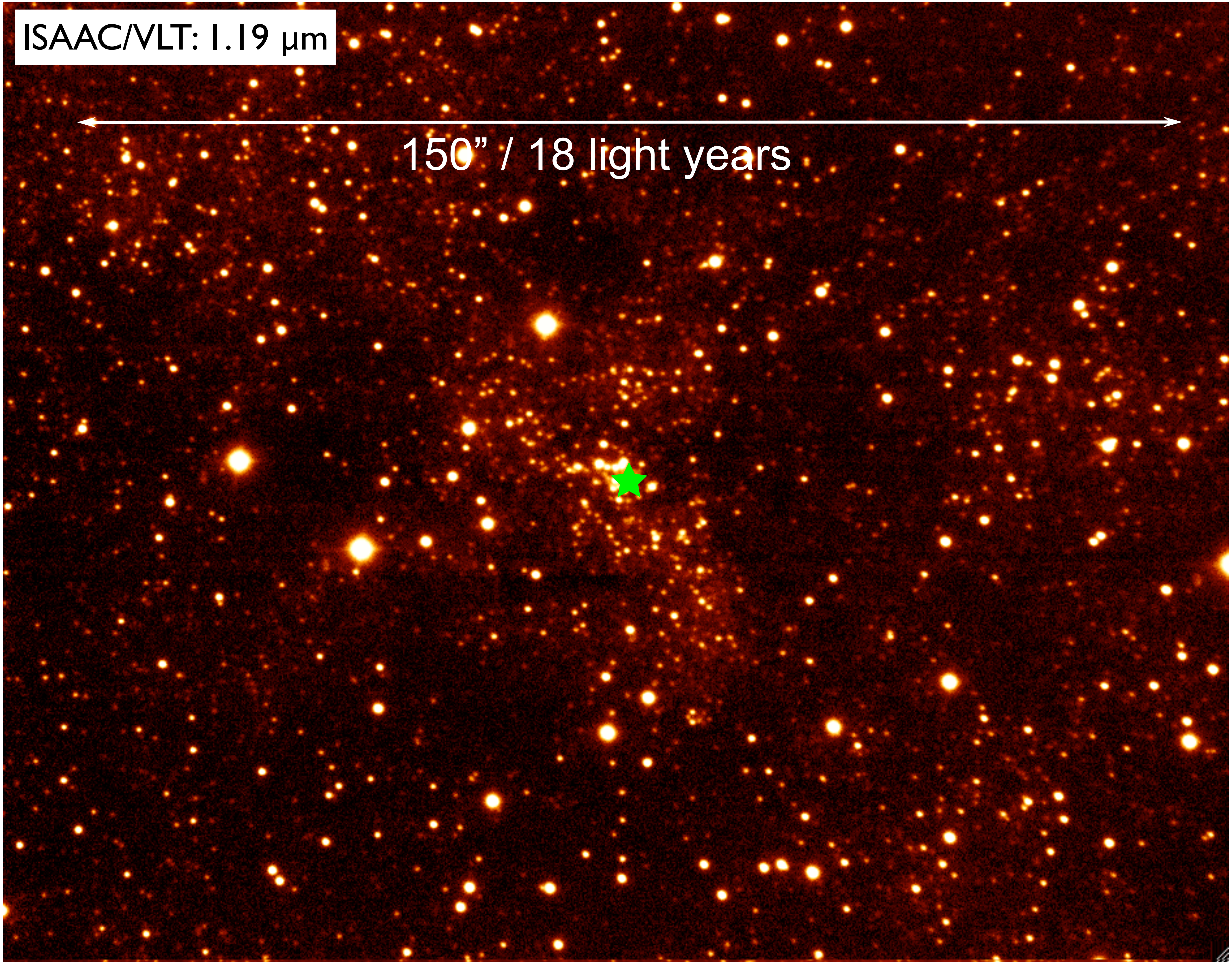

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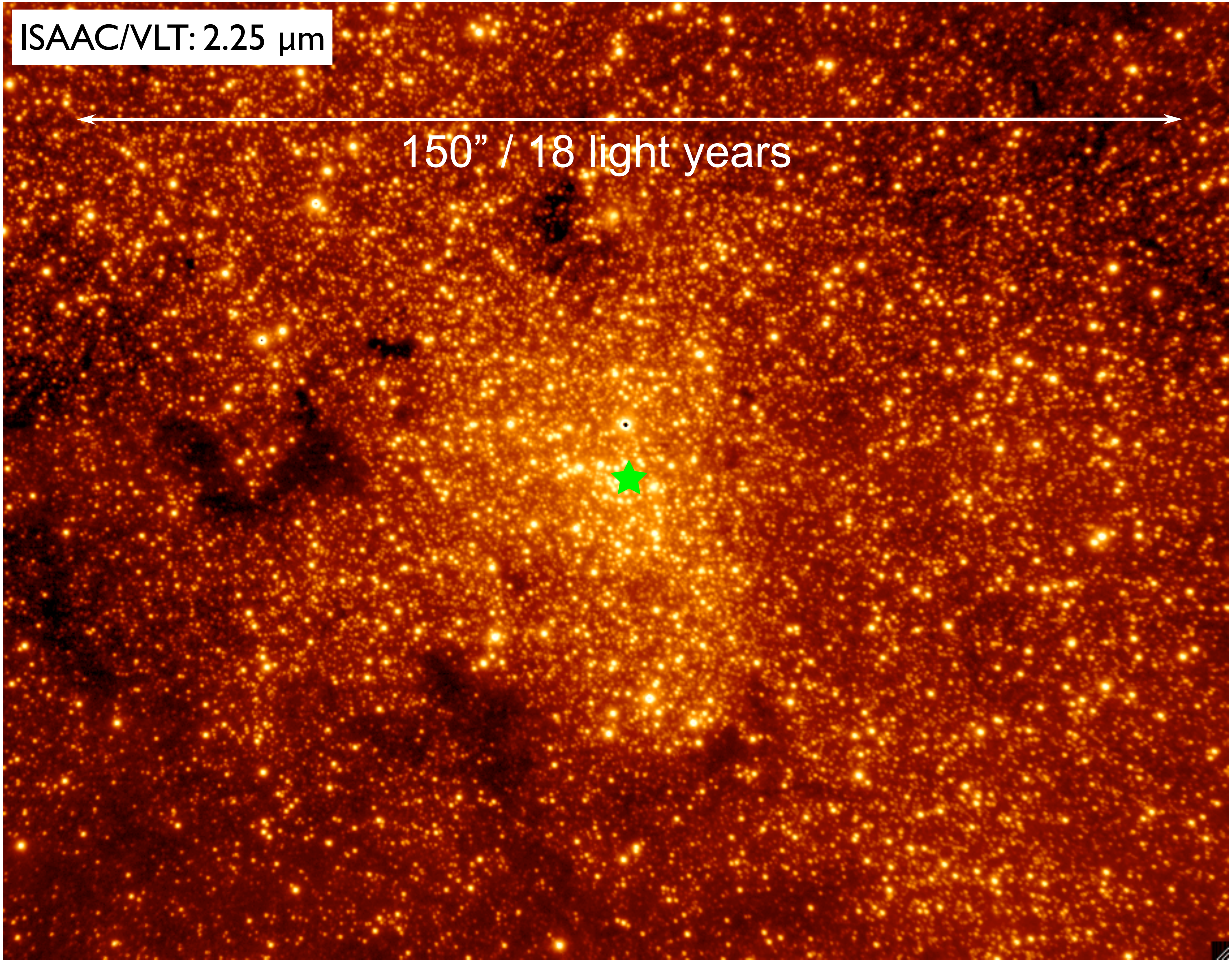

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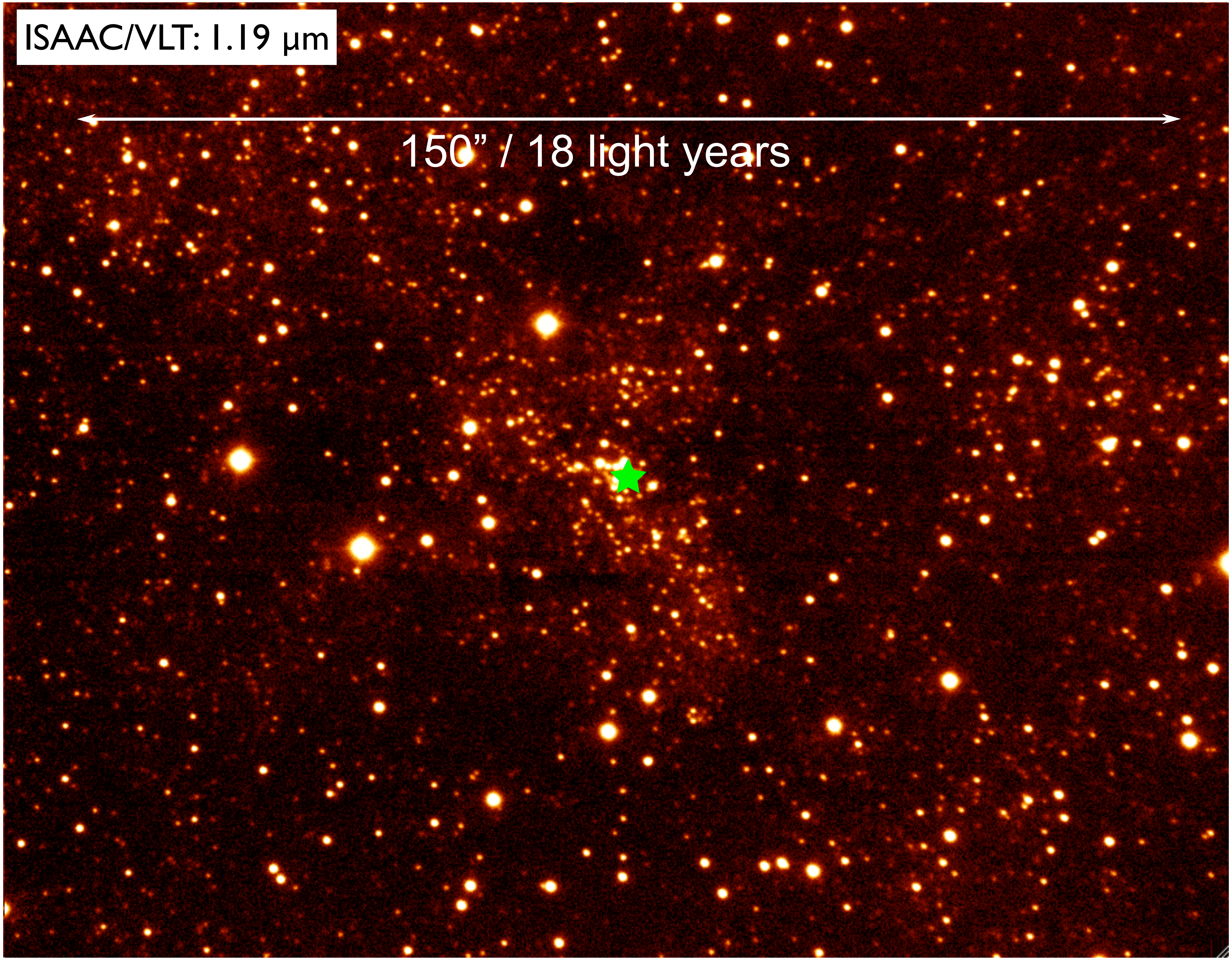

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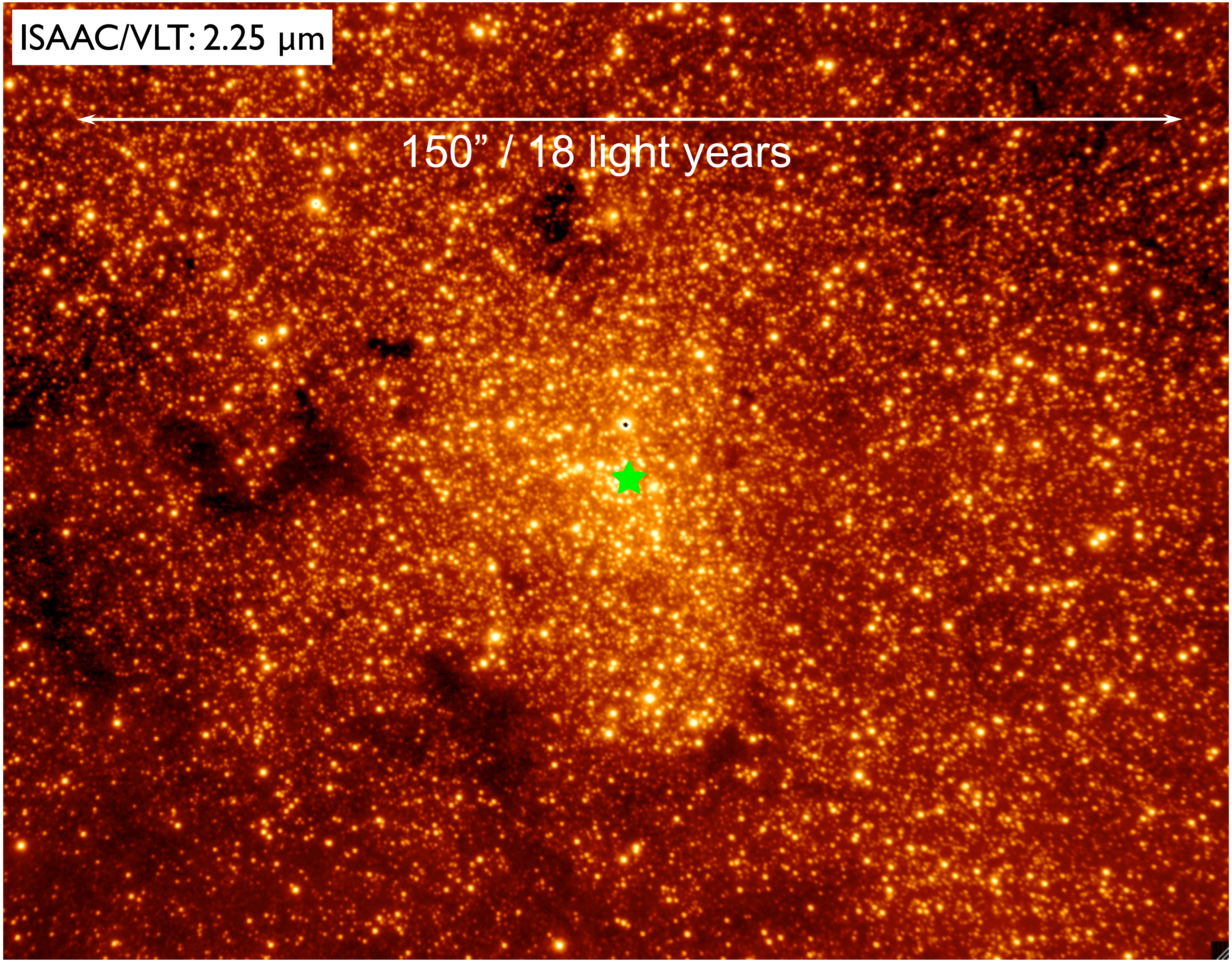

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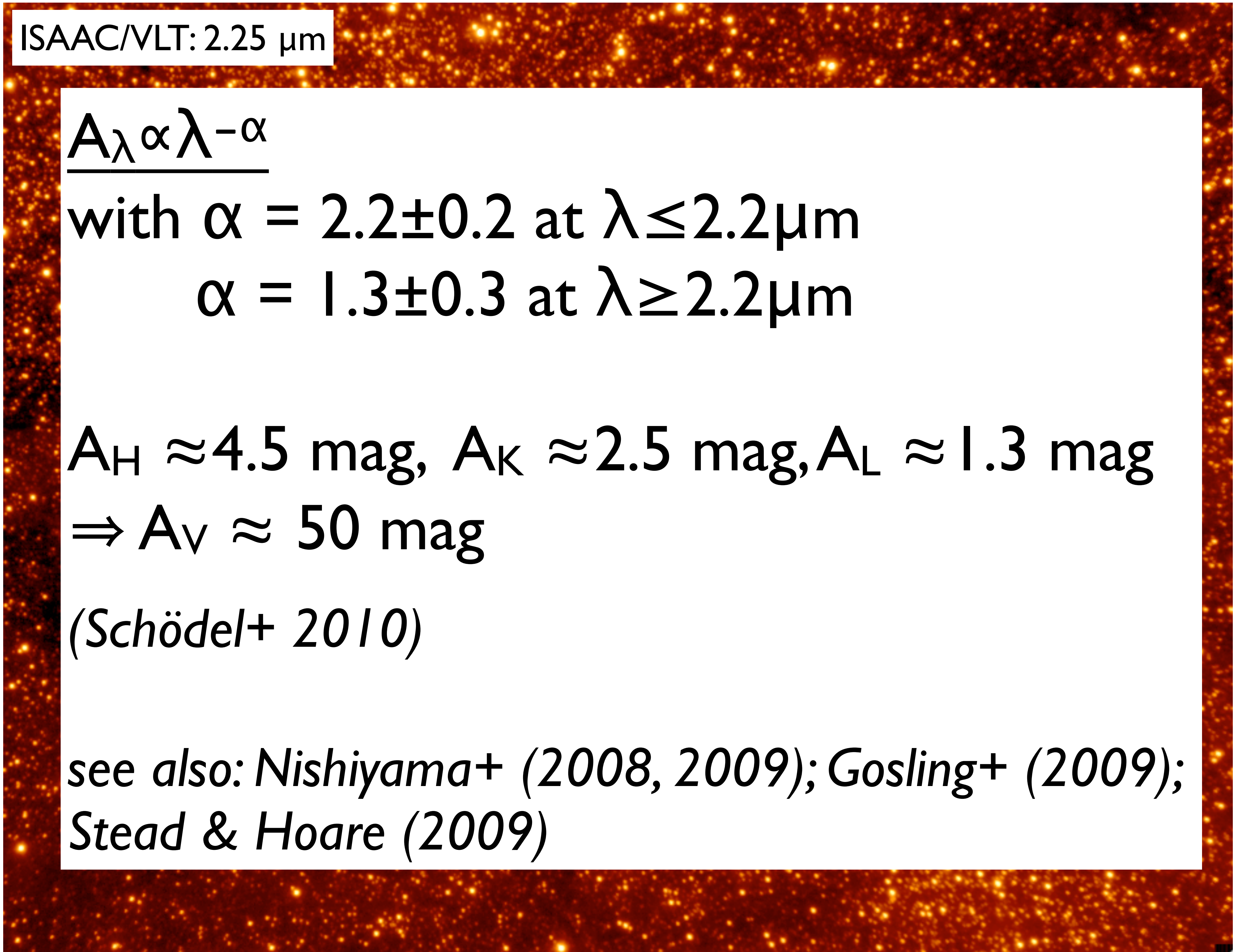


$\underline{A_\lambda \propto \lambda^{-\alpha}}$

with $\alpha = 2.2 \pm 0.2$ at $\lambda \leq 2.2 \mu m$

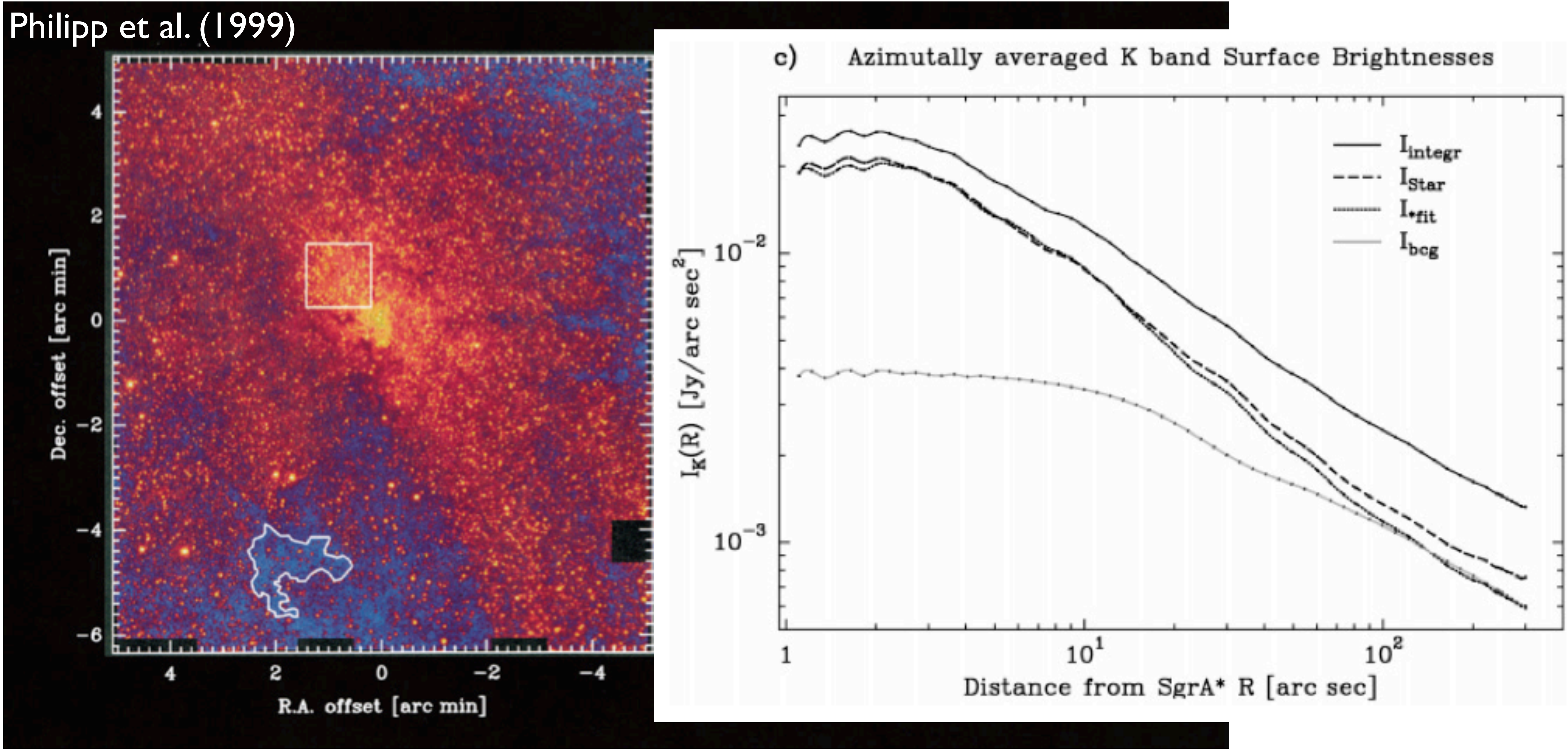
$\alpha = 1.3 \pm 0.3$ at $\lambda \geq 2.2 \mu m$

$A_H \approx 4.5$ mag, $A_K \approx 2.5$ mag, $A_L \approx 1.3$ mag

$\Rightarrow A_V \approx 50$ mag

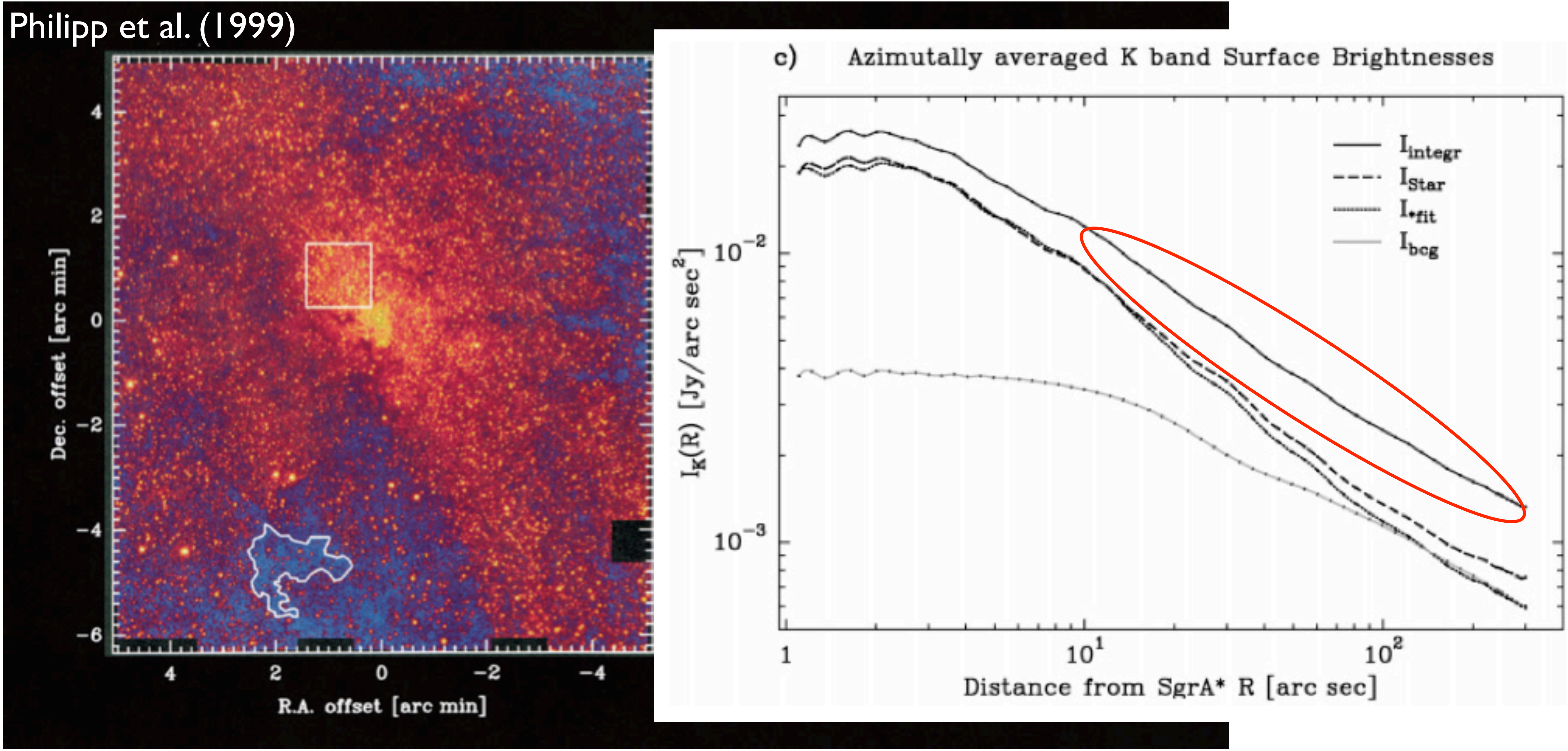
(Schödel+ 2010)

see also: Nishiyama+ (2008, 2009); Gosling+ (2009); Stead & Hoare (2009)



Studies on stellar number and/or light surface density of NSC find $\rho(r) \propto r^{-1.5...-2}$ at distances $r \geq 1$ *pc (~25")*

e.g., *Becklin & Neugebauer, 1968* - $\rho \propto r^{-1.8}$ (bulge reference field subtracted); *Catchpole+, 1990; Eckart+ ,1993* - $\rho \propto r^{-1.8}$ (SHARP source counts, inner 15"); *Genzel+, 1996* - $\rho \propto r^{-1.8}$ (inner 20", late-type stars); *Haller+ 1996; Genzel+, 2003; Schoedel+, 2007* - $\rho \propto r^{-1.75}$ (ISAAC+NACO, no bulge correction); *Graham & Spitler, 2009* - $\rho \propto r^{-2.0...2,7}$ (2MASS light density, bulge correction); *Oh +, 2009* - $\rho \propto r^{-1.5}$ *(various models and data)*



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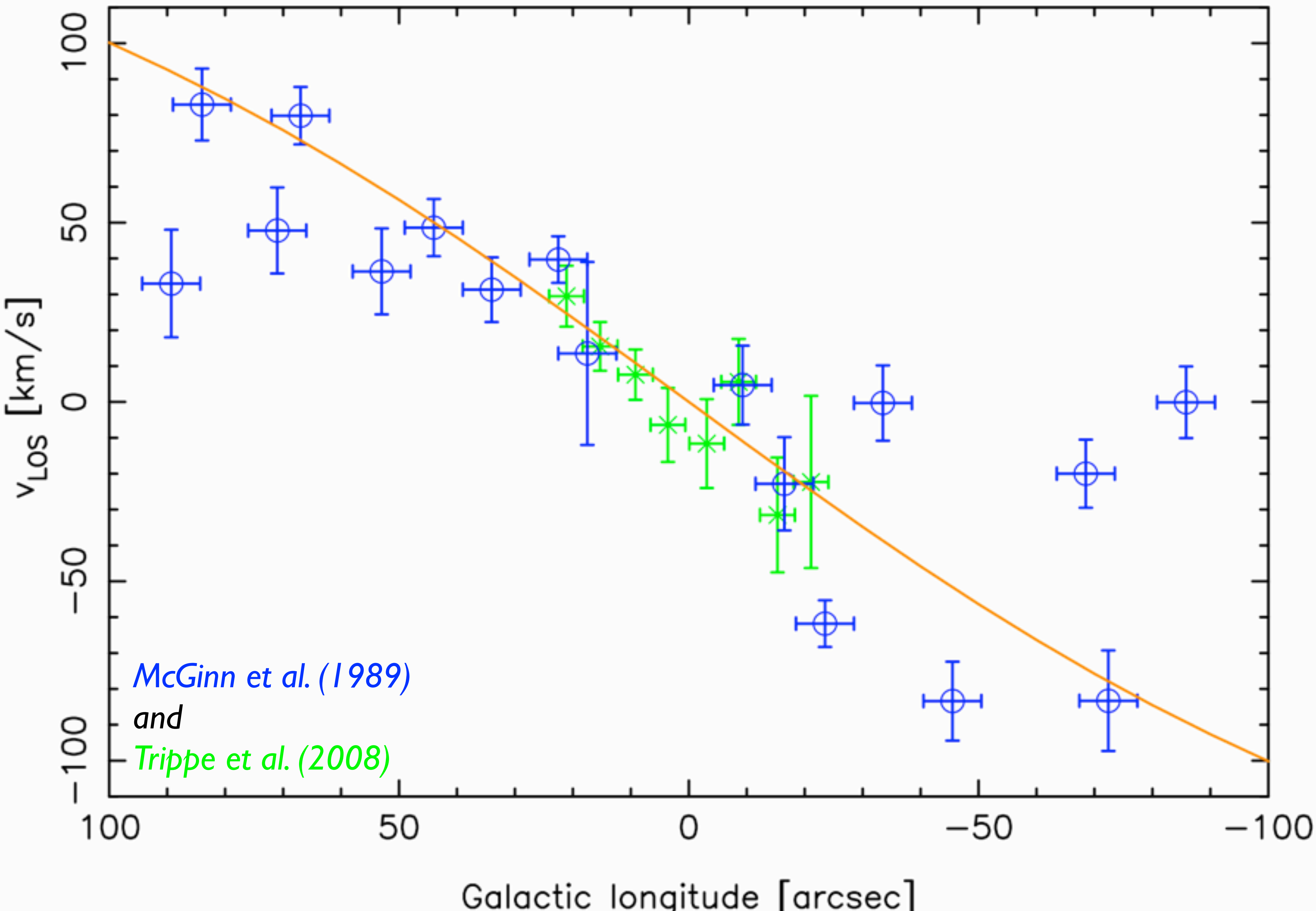
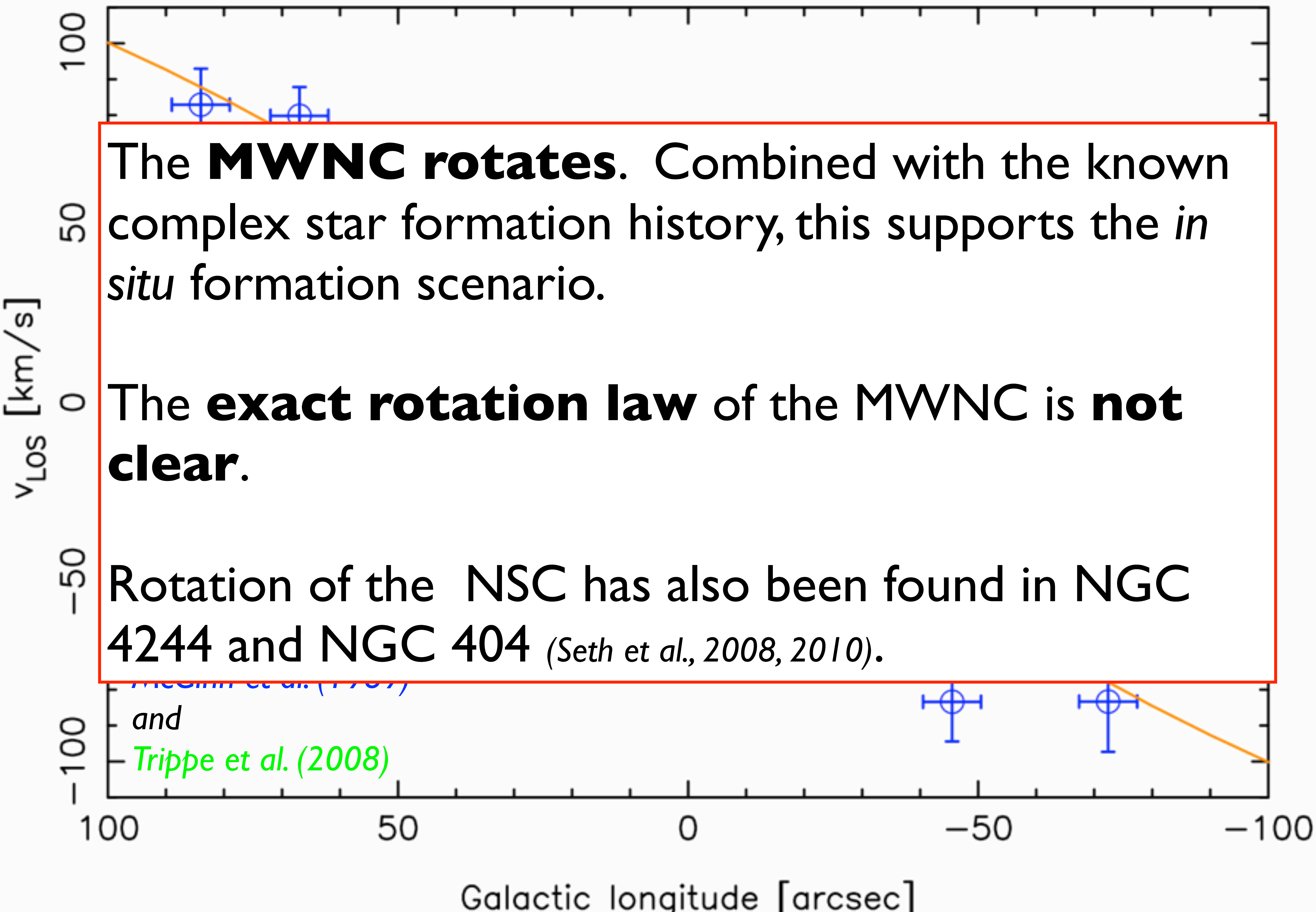
Rotation of the NSC



Schödel, Merritt, & Eckart (2009)

Rotation of the NSC



The **MWNC rotates**. Combined with the known complex star formation history, this supports the *in situ* formation scenario.

The **exact rotation law** of the MWNC is **not clear**.

Rotation of the NSC has also been found in NGC 4244 and NGC 404 *(Seth et al., 2008, 2010)*.

Schödel, Merritt, & Eckart (2009)

Overall properties of the Milky Way's NSC

Shape:
- both King and Sérsic models have been used
- spherically symmetric (probably slightly flattened)?
- ρ (light, number density) $\propto r^{-2}$ at r > 0.5-1pc

Star formation:
- significant overabundance of supergiants and bright giants as well as presence of young massive stars
- starburst-like activity in the central 1 pc about 4-6 Myr ago

Mass: $3 \pm 1.5 \times 10^7\ M_\odot$ *(Launhardt+ 2002)*
Size: half light radius of 3-5 pc (large uncertainties)
Density: $\sim 1.5\times 10^5\ M_\odot\ pc^{-3}$ at $r=1\ pc$, $\sim 10^7\ M_\odot\ pc^{-3}$ at $r=0.1\ pc$
Rotation: The NSC rotates.

Overall properties of the Milky Way's NSC

Shape:

-
-
-

In general, the properties of MW NSC are similar to extragalactic ones.

Difficult to determine exact parameters of MW NSC because of strong and variable extinction.

St

-

as

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Size: half light radius of 3-5 pc (large uncertainties)

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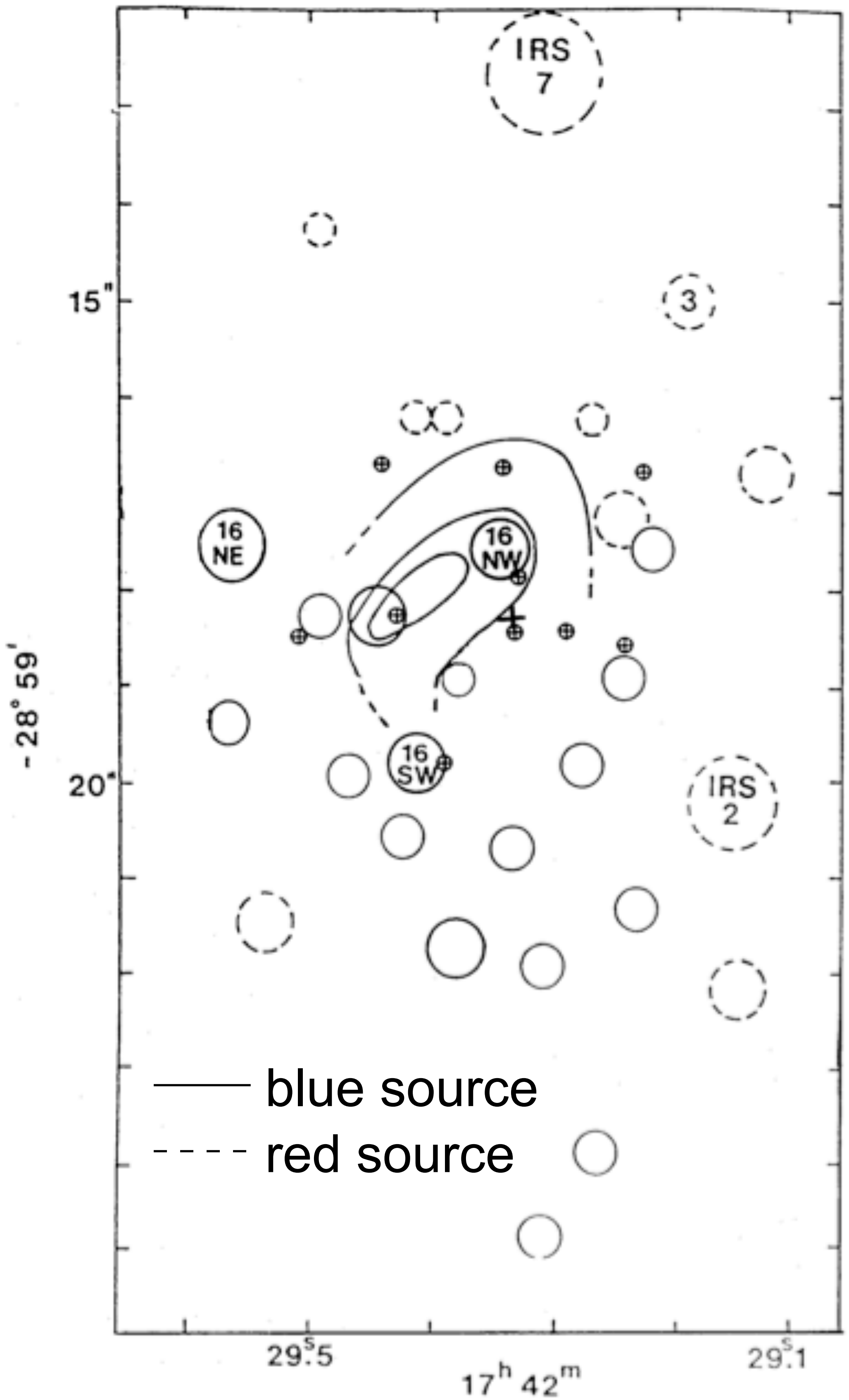
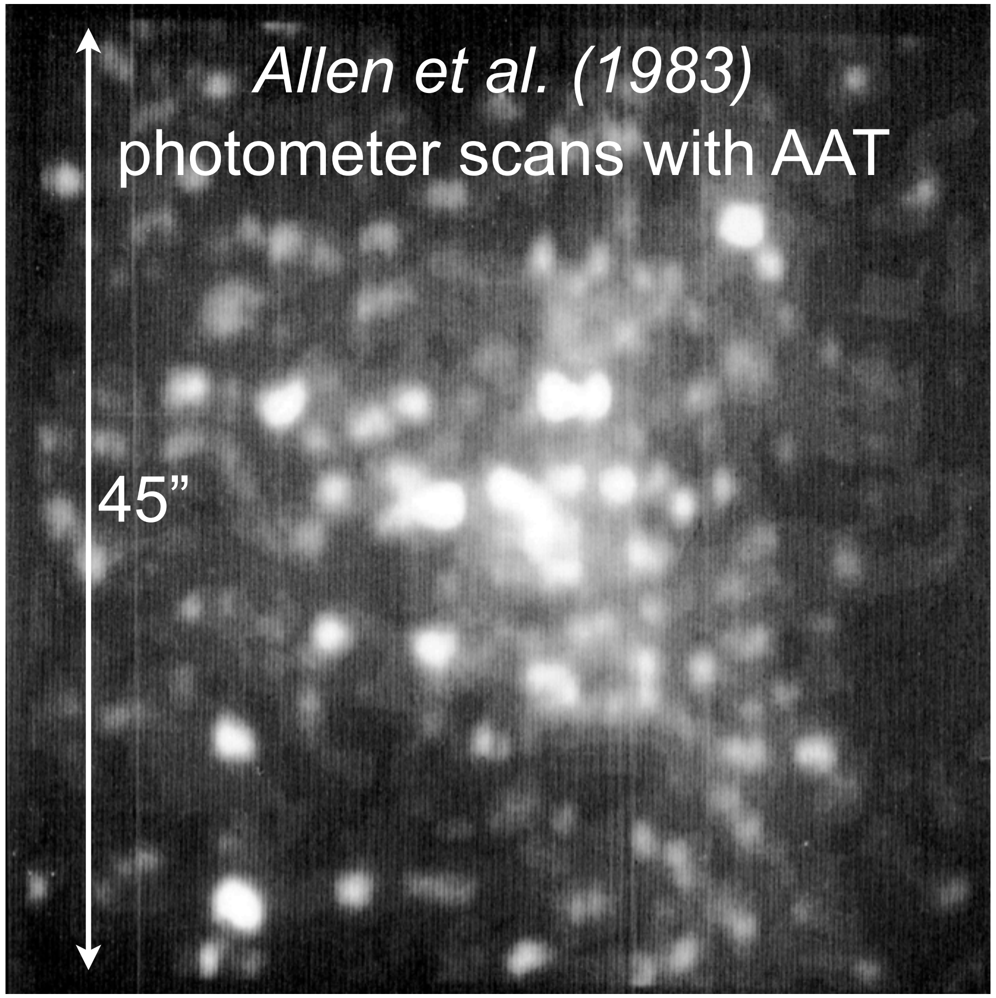
Rotation: The NSC rotates.

Star Formation at the Galactic Center

WN9 & Ofpe stars in central parsec



schematic map,
Allen et al. (1990)



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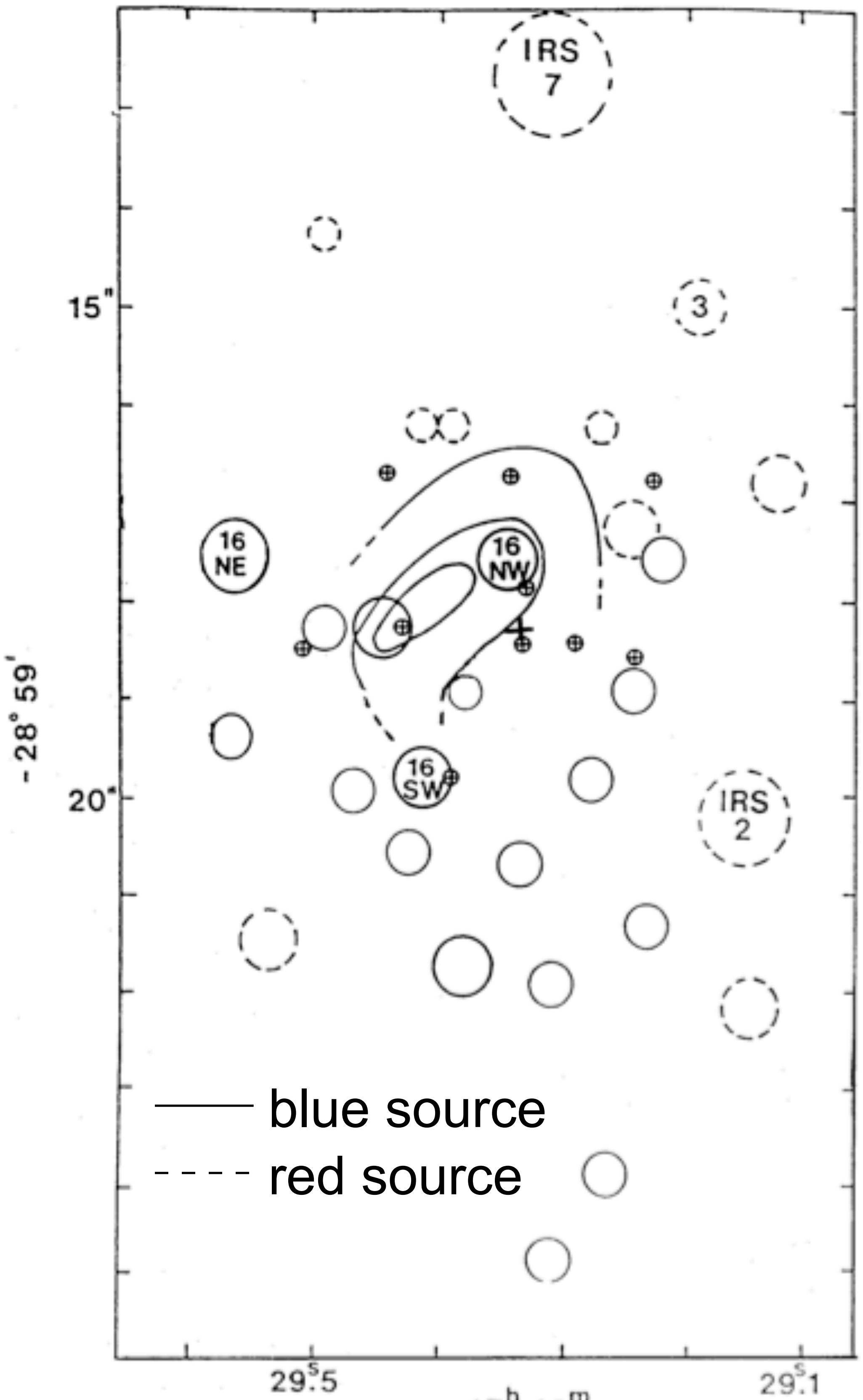

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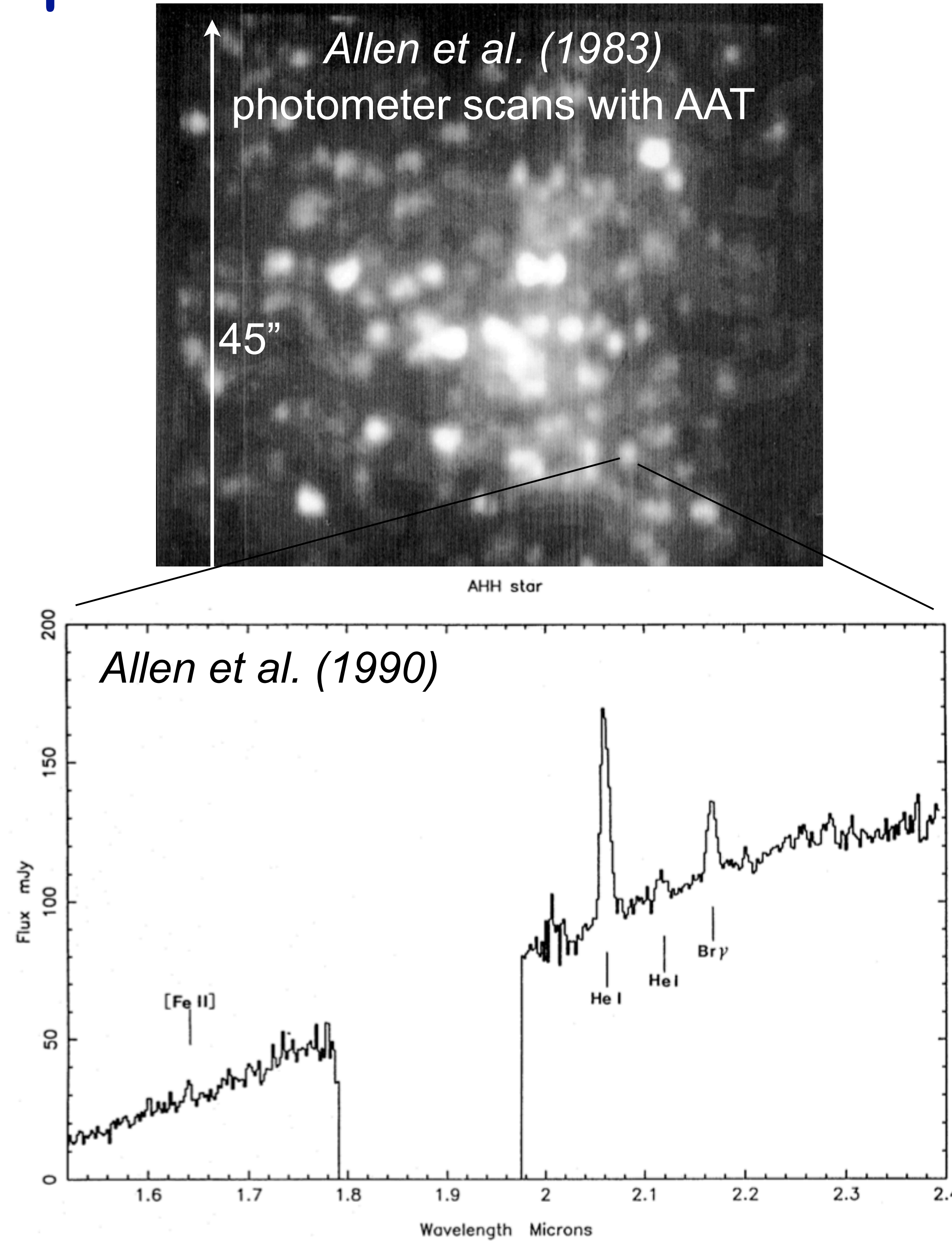
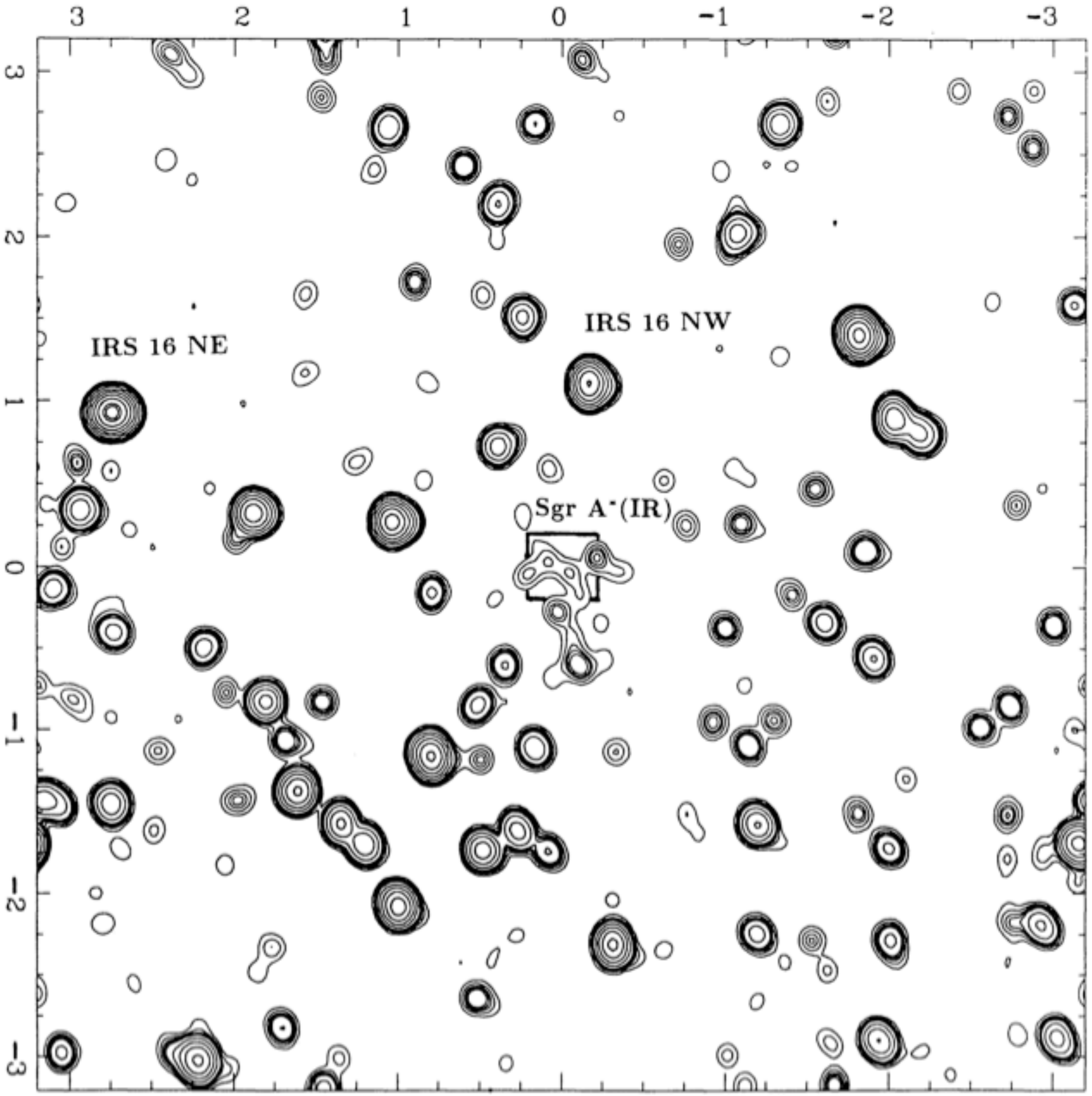


Figure 4. Low-dispersion spectrum of the AHH star, uncorrected for reddening.

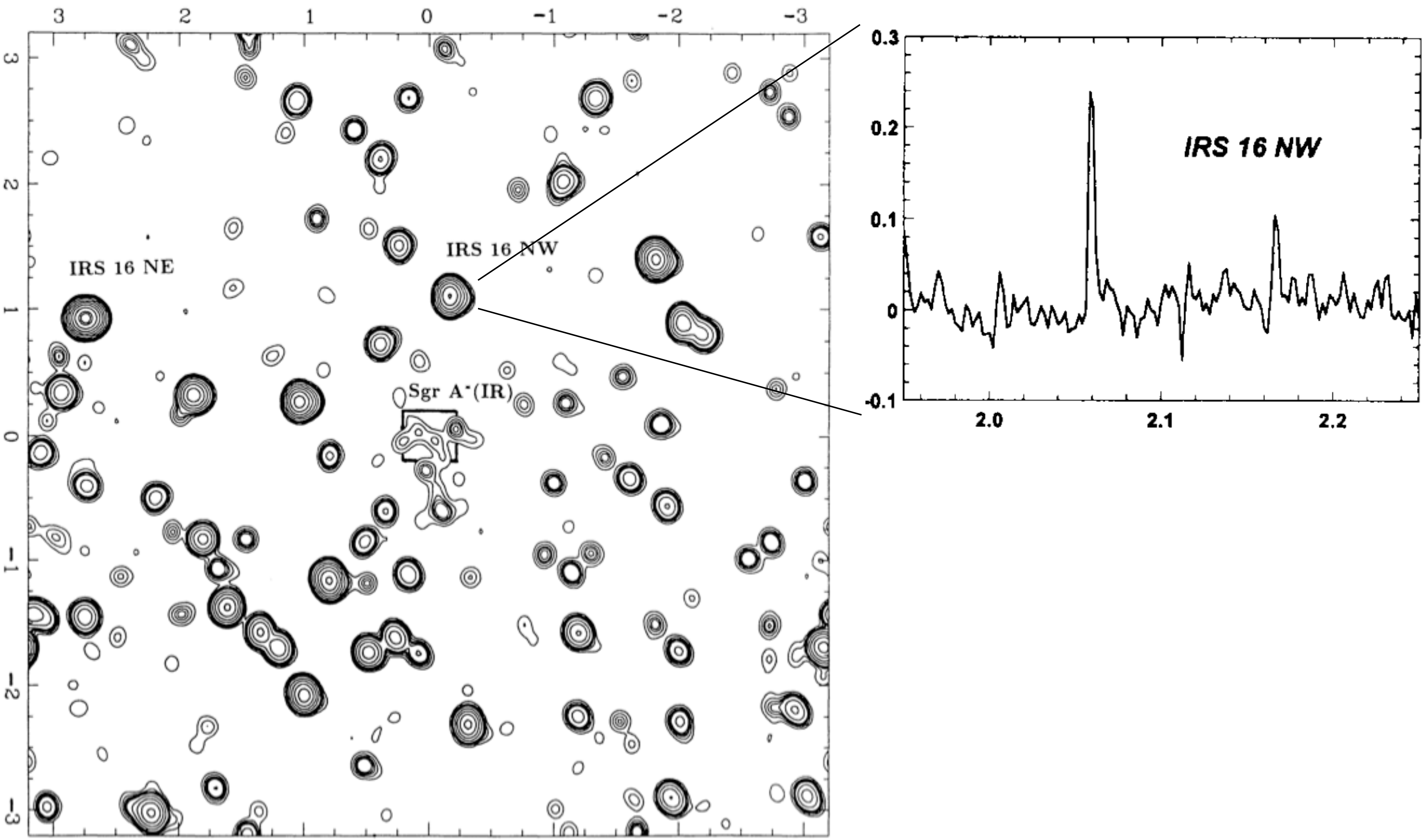
“HeI-stars” and Wolf-Rayet stars



simple shift-and-add map from speckle imaging with SHARP/NTT *(Eckart et al.,1995)*

e.g., Krabbe et al. (1995); Genzel et al. (1996); Najarro et al. (1997); Haller et al. (1996)

“HeI-stars” and Wolf-Rayet stars



simple shift-and-add map from speckle imaging with SHARP/NTT *(Eckart et al.,1995)*

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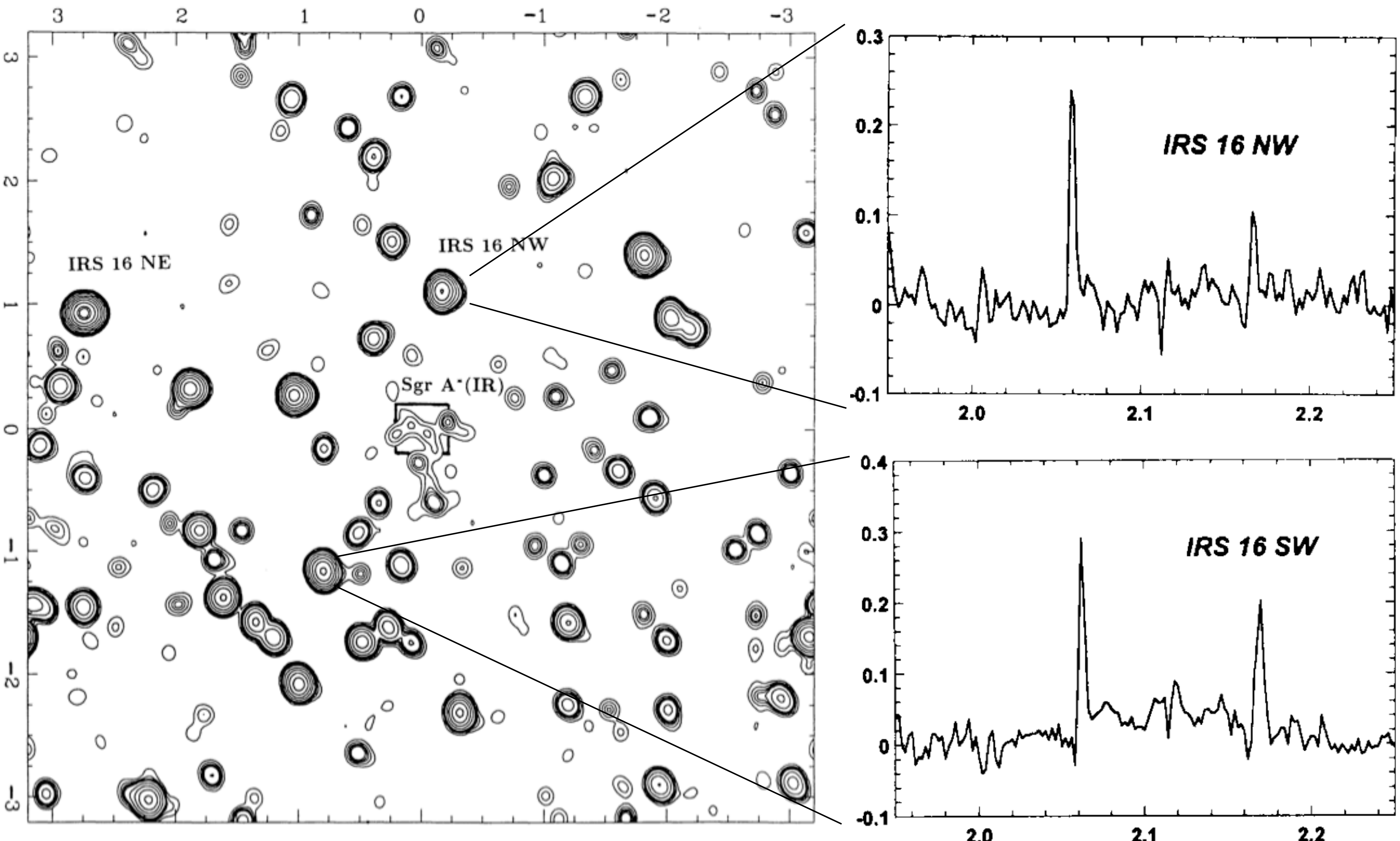

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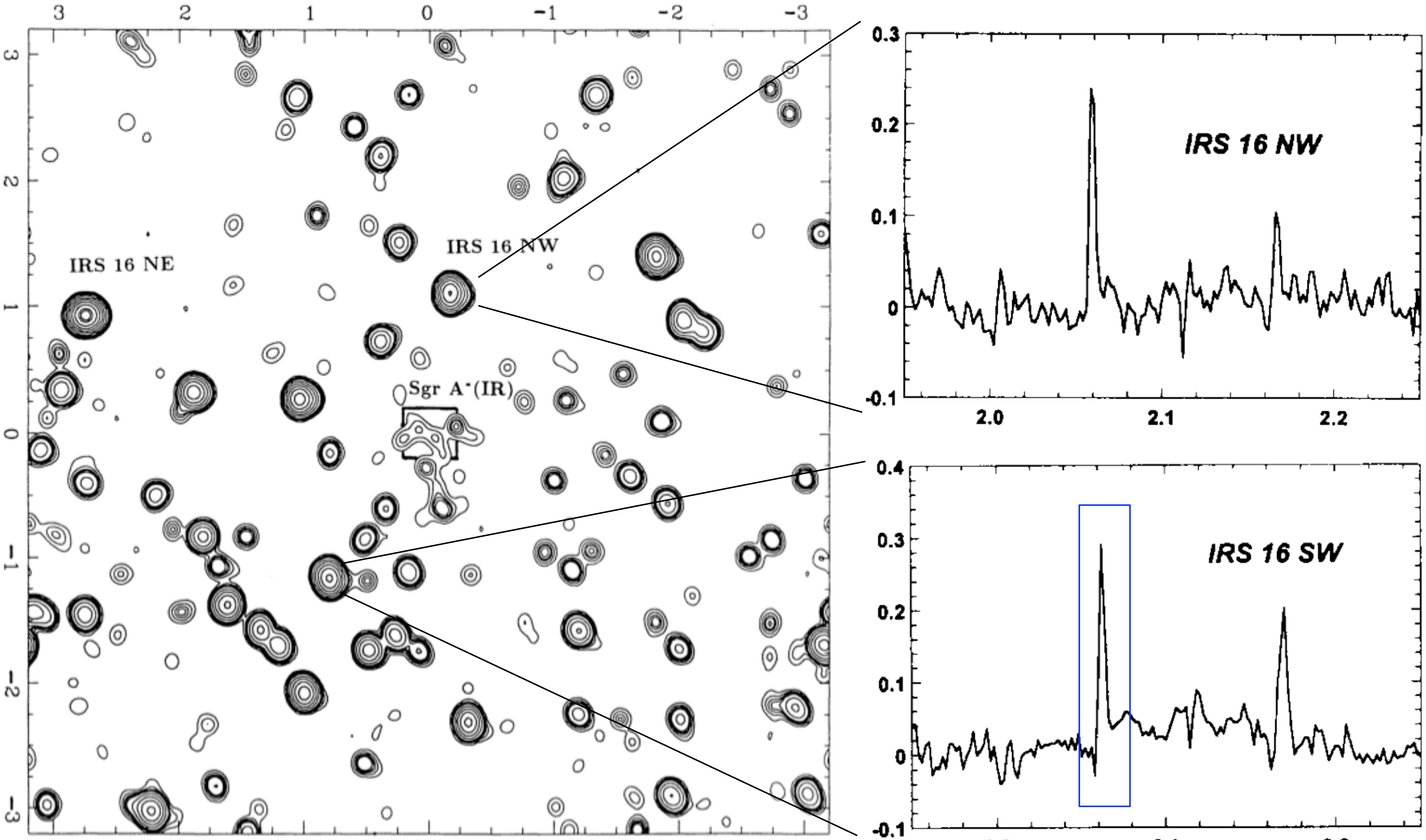

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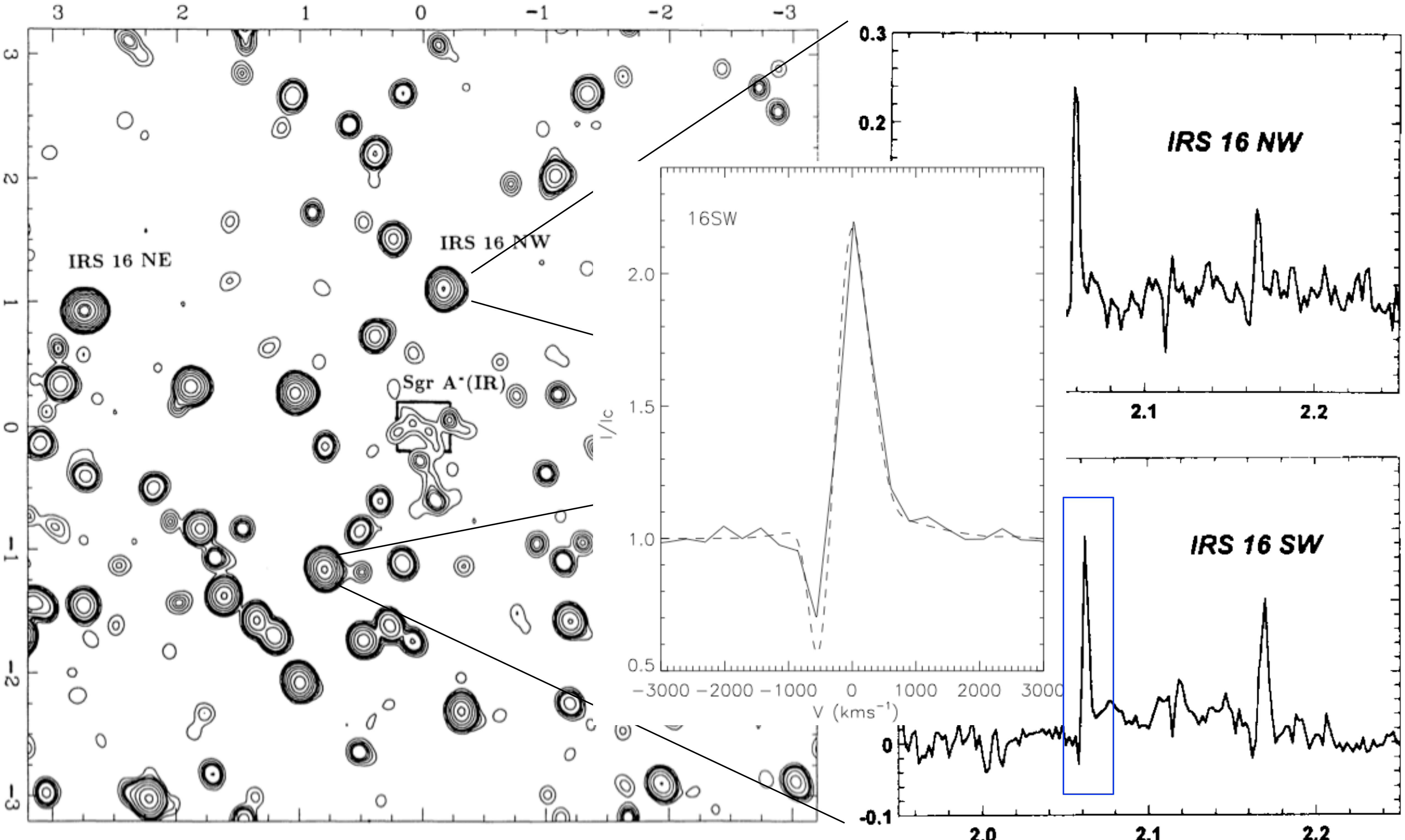

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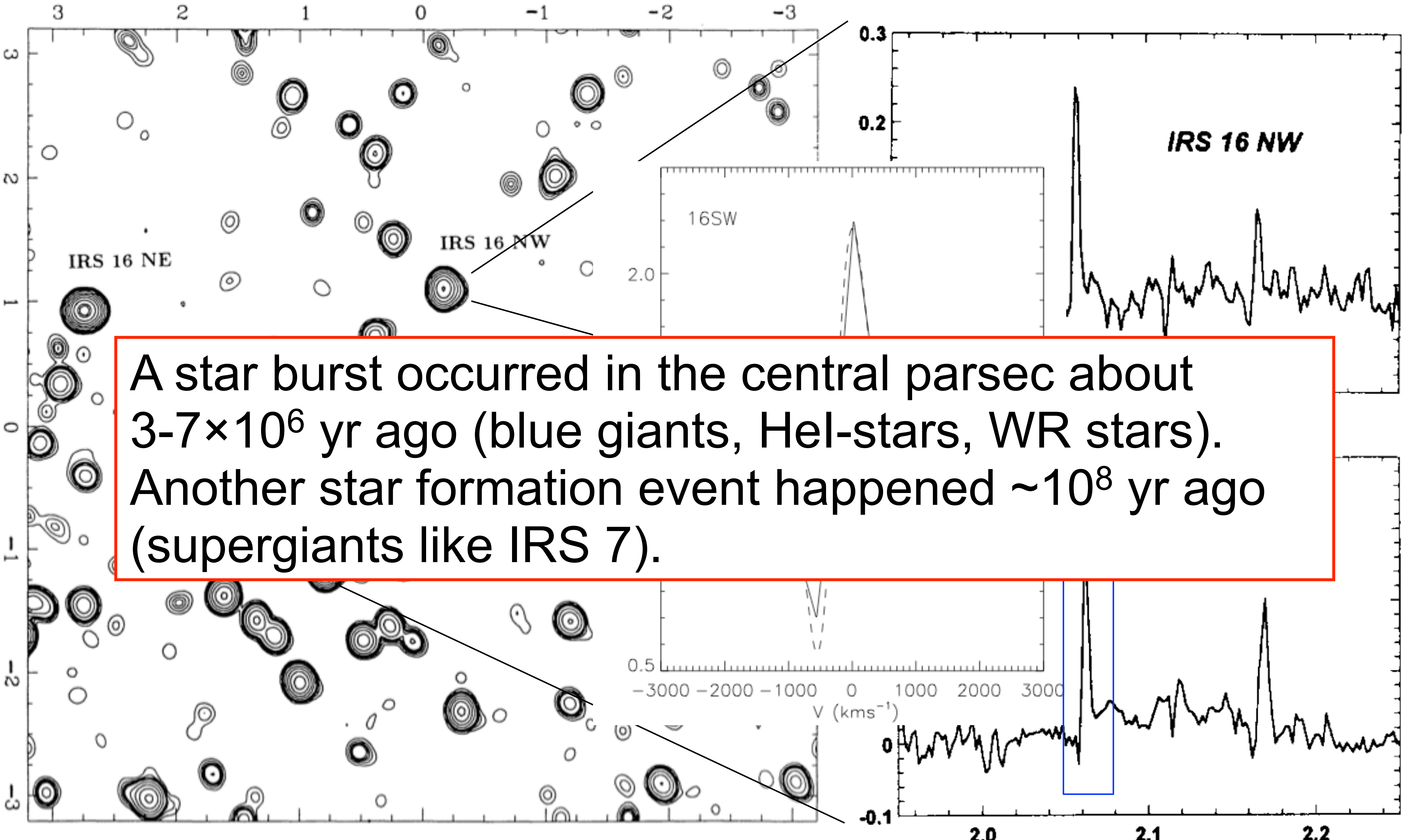


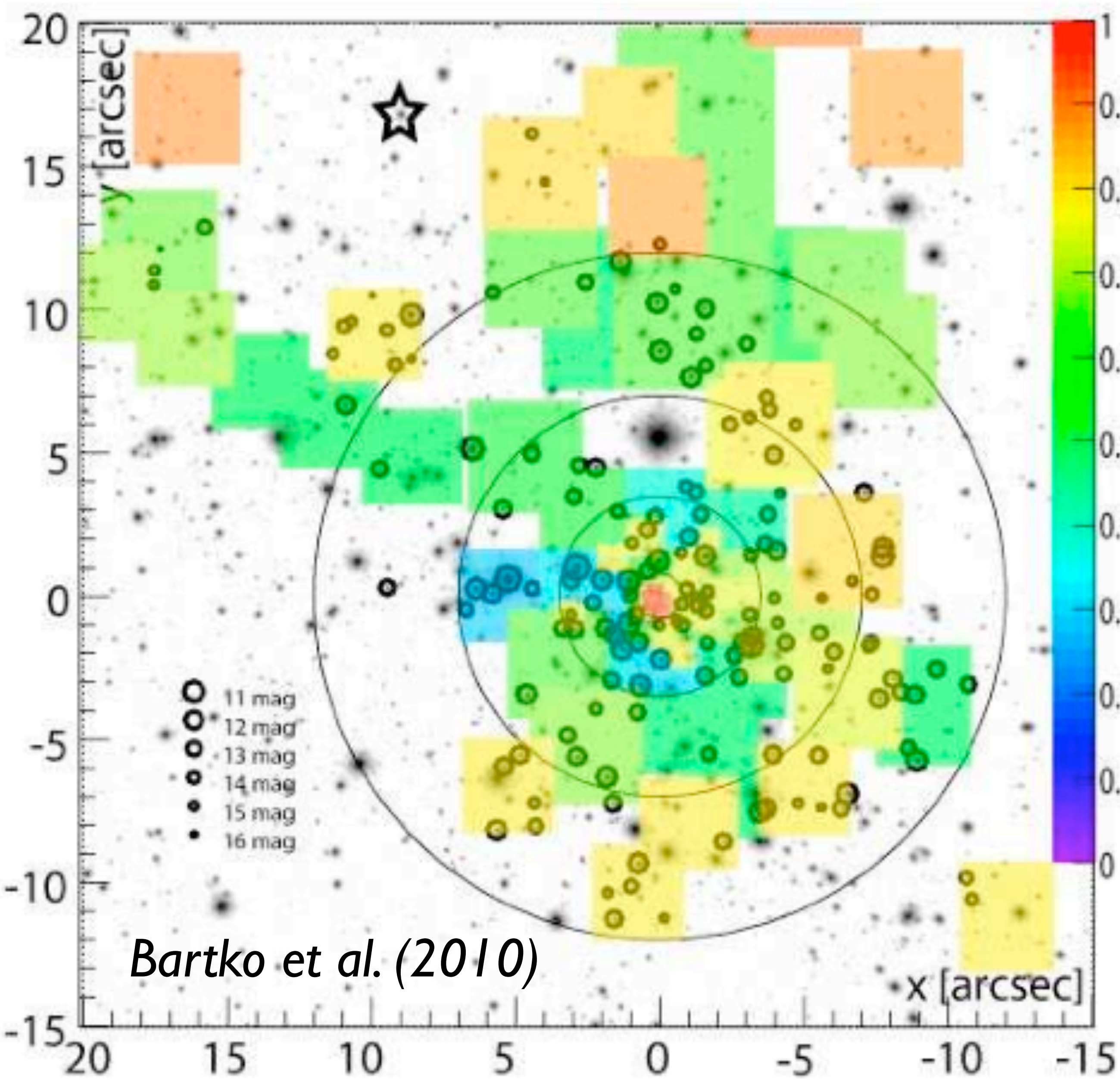
A star burst occurred in the central parsec about 3-7×10^6 yr ago (blue giants, HeI-stars, WR stars). Another star formation event happened ~10^8 yr ago (supergiants like IRS 7).

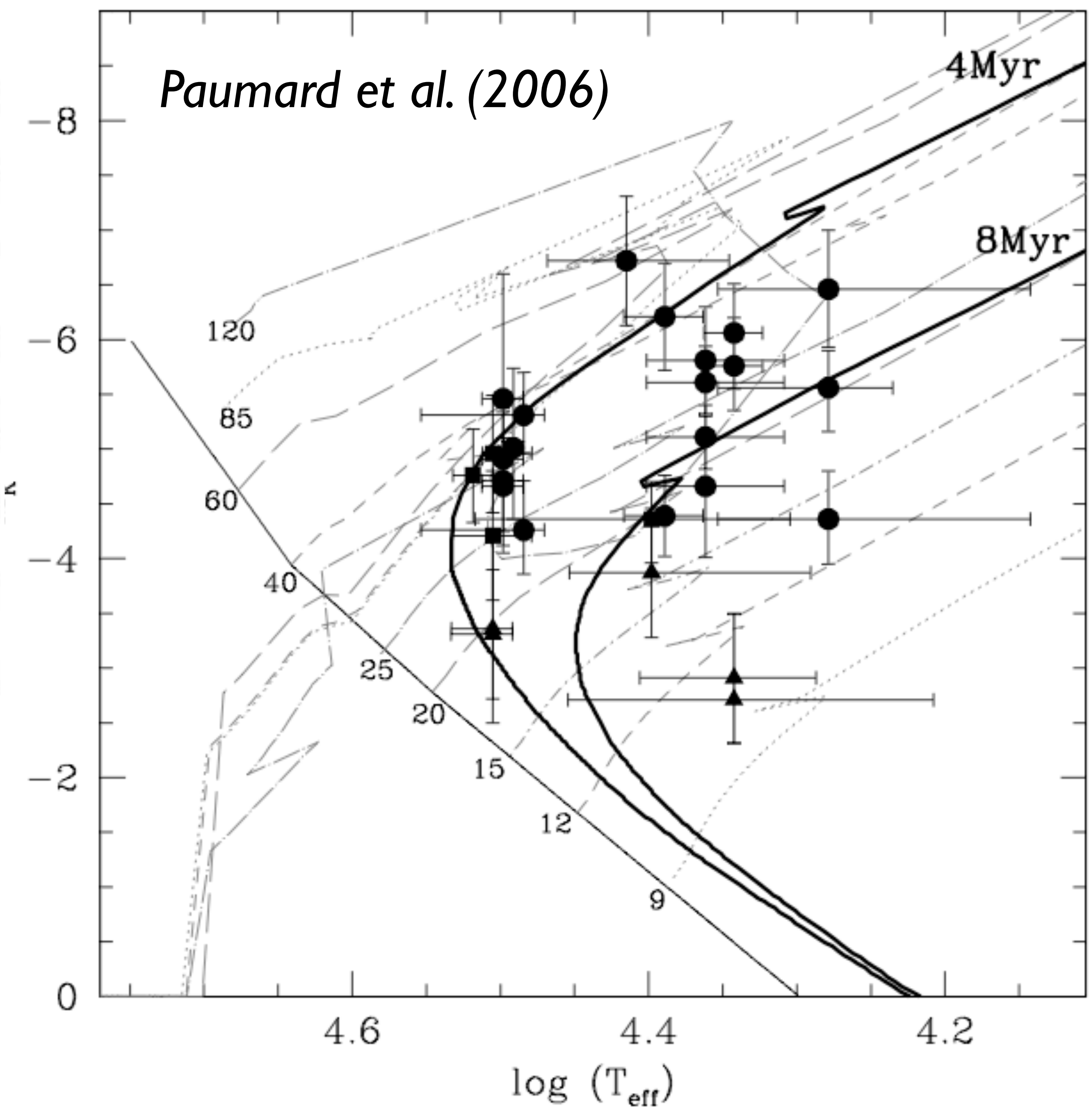
simple shift-and-add map from speckle imaging with SHARP/NTT *(Eckart et al.,1995)*

e.g., Krabbe et al. (1995); Genzel et al. (1996); Najarro et al. (1997); Haller et al. (1996)

The recent star burst in the GC

IF-spectroscopy with SINFONI/VLT





The recent star burst in the GC

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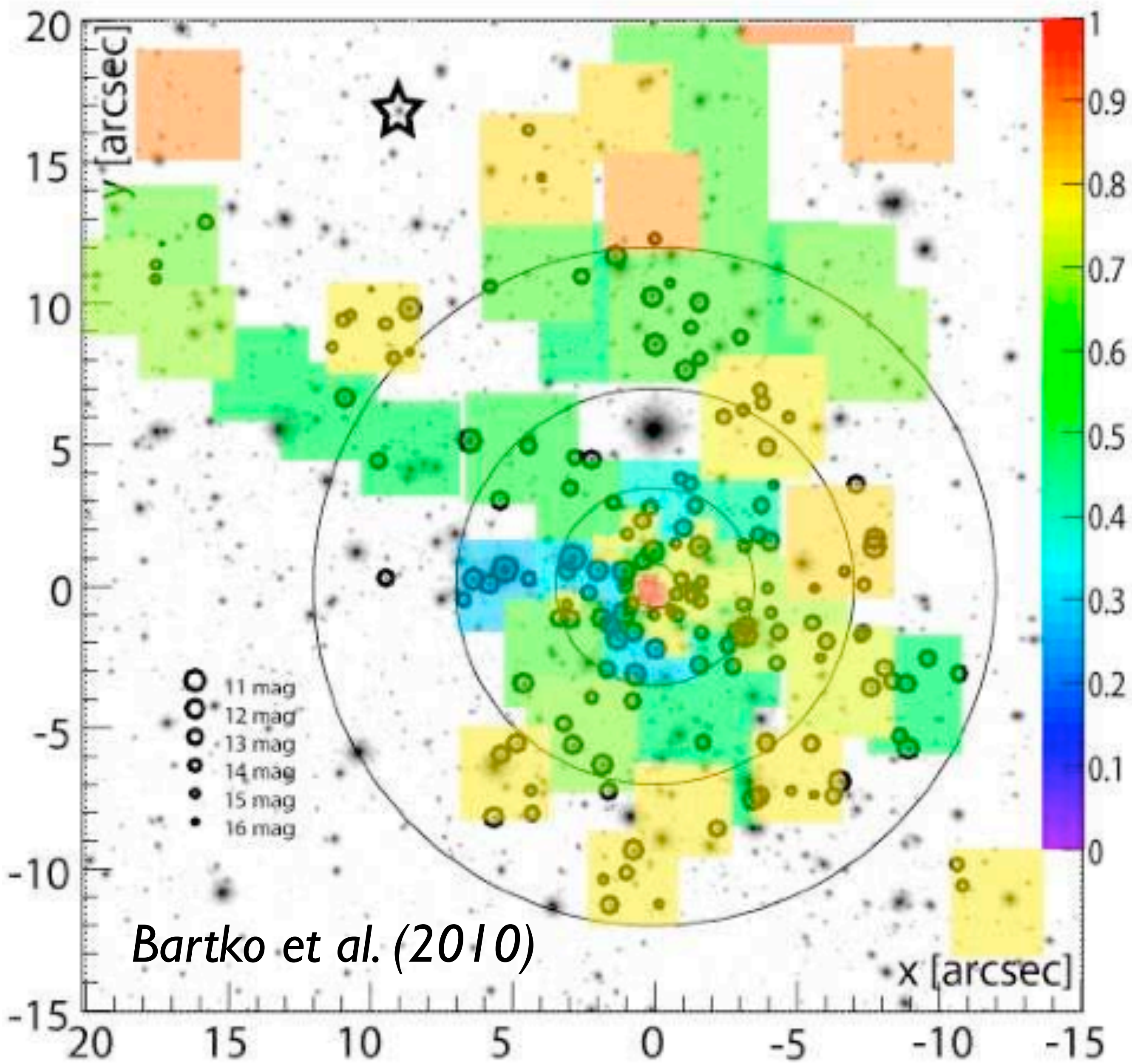
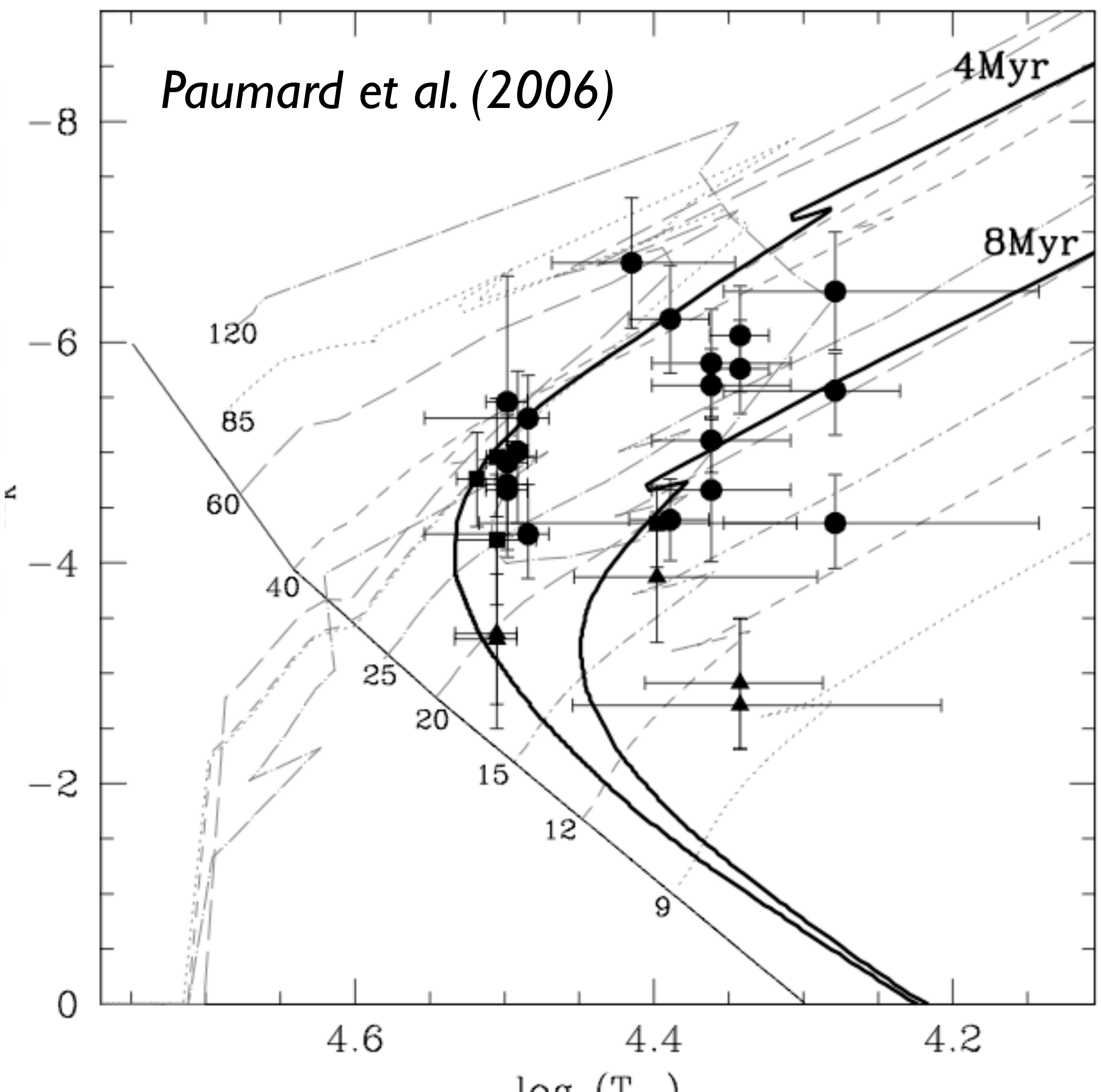
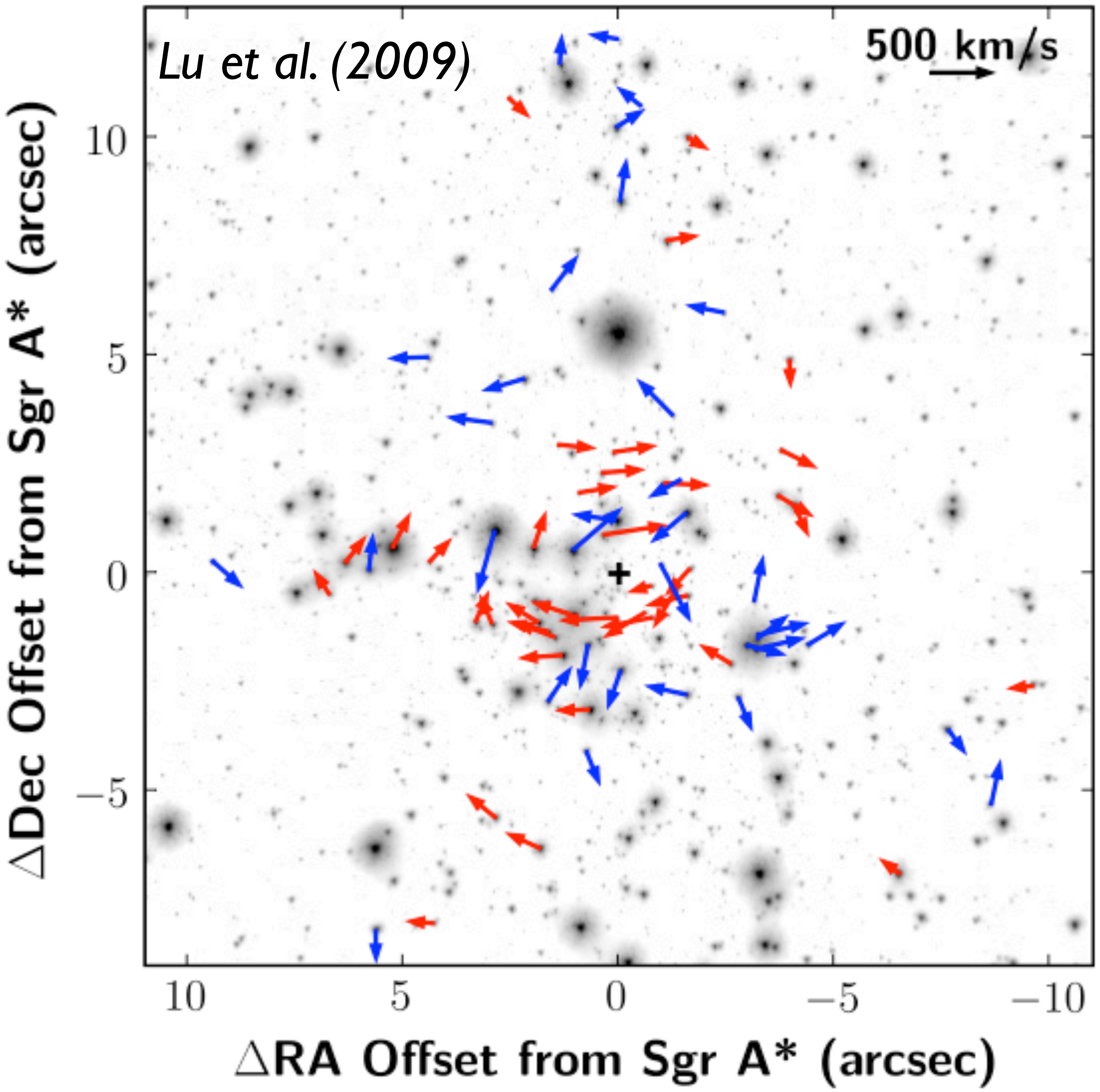
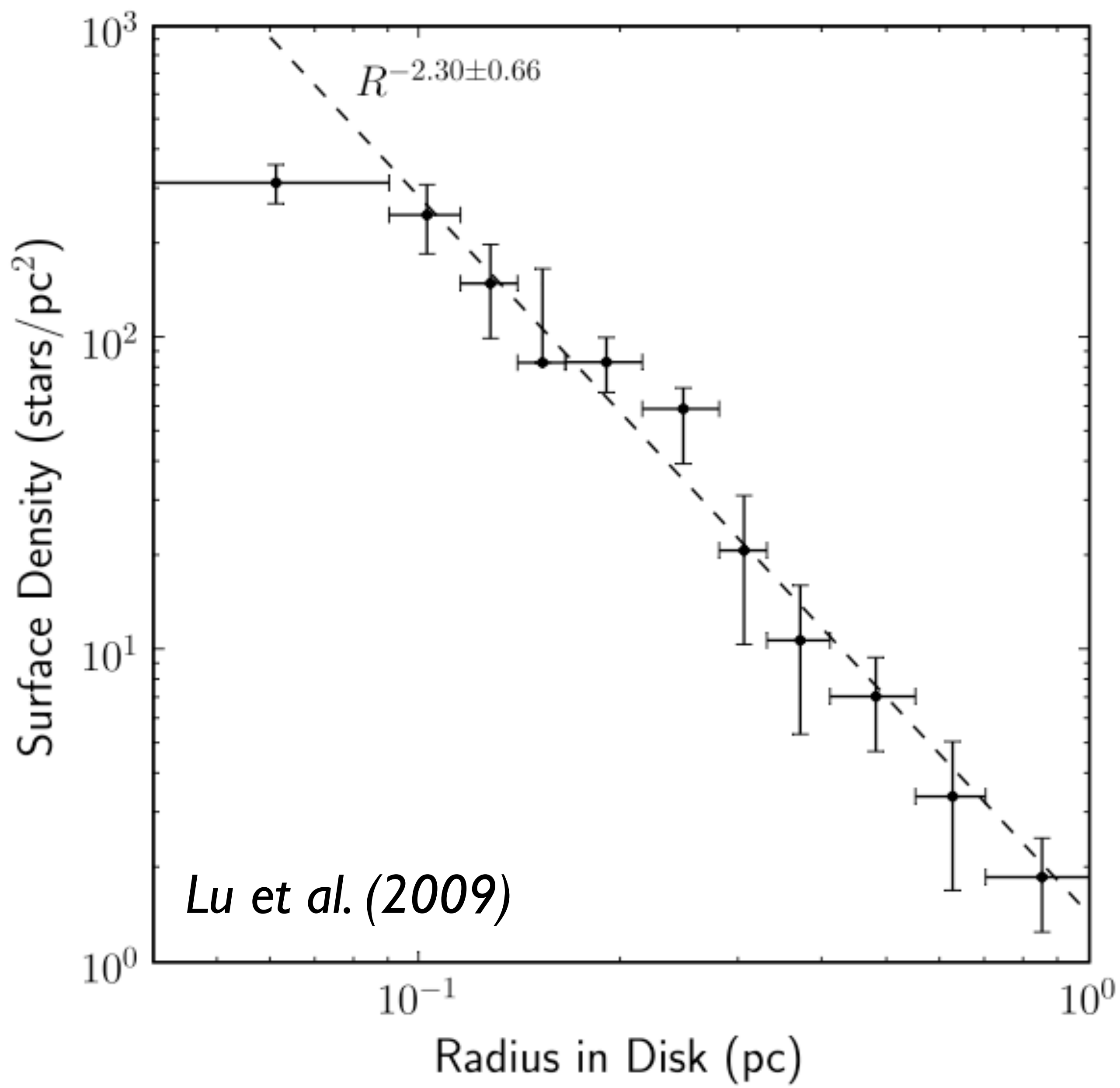




About 180 reliably detected massive, early type stars (O/B giants and main sequence stars, WR stars); total mass of star burst ~1.5×10^4 $M_\odot$; age ~6 Myr.

The star burst happened in a disk (or 2)





see also, e.g., *Genzel et al. (2000), Levin & Beloborodov (2003), Paumard et al. (2006), Tanner et al. (2006);*

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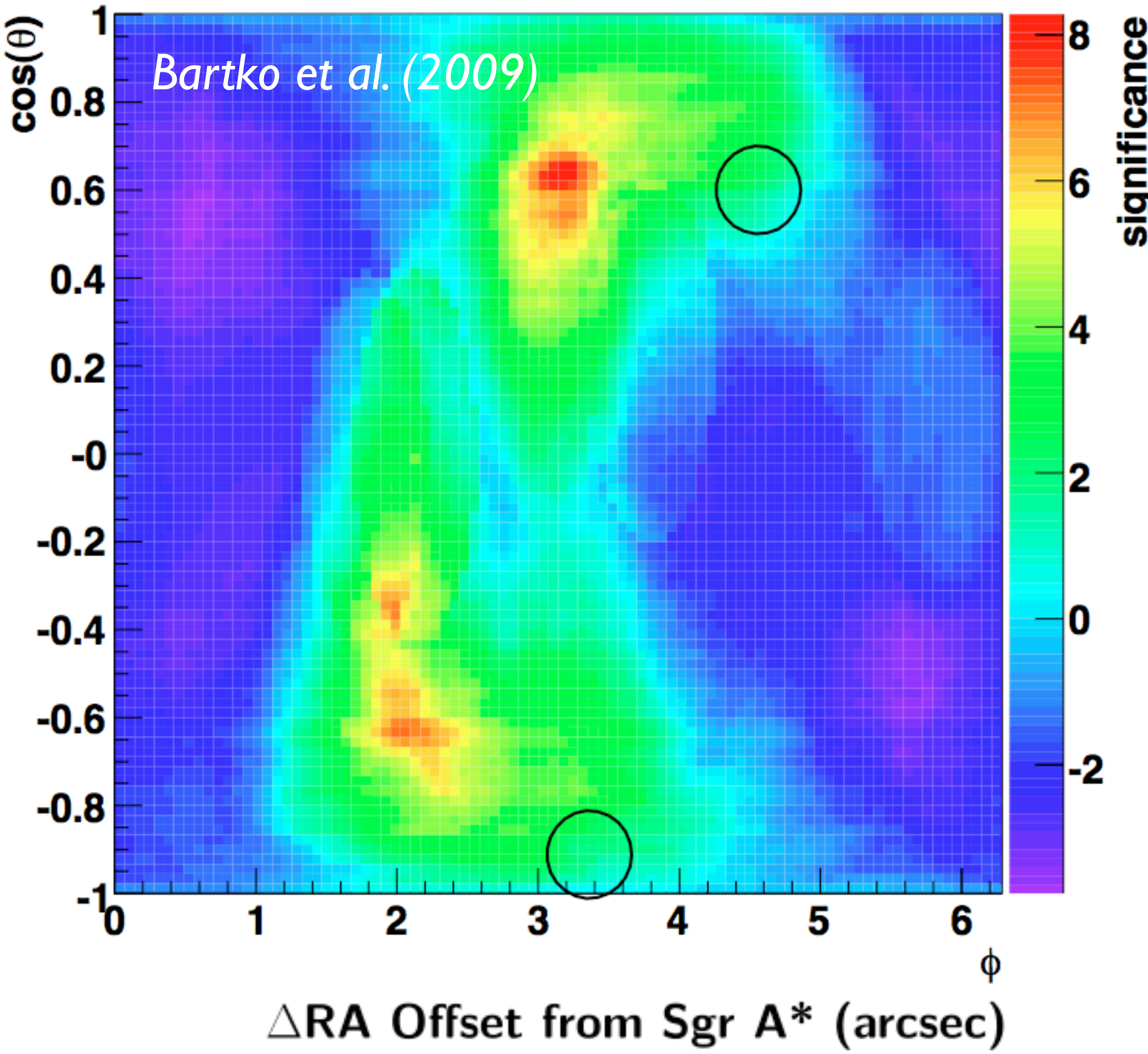
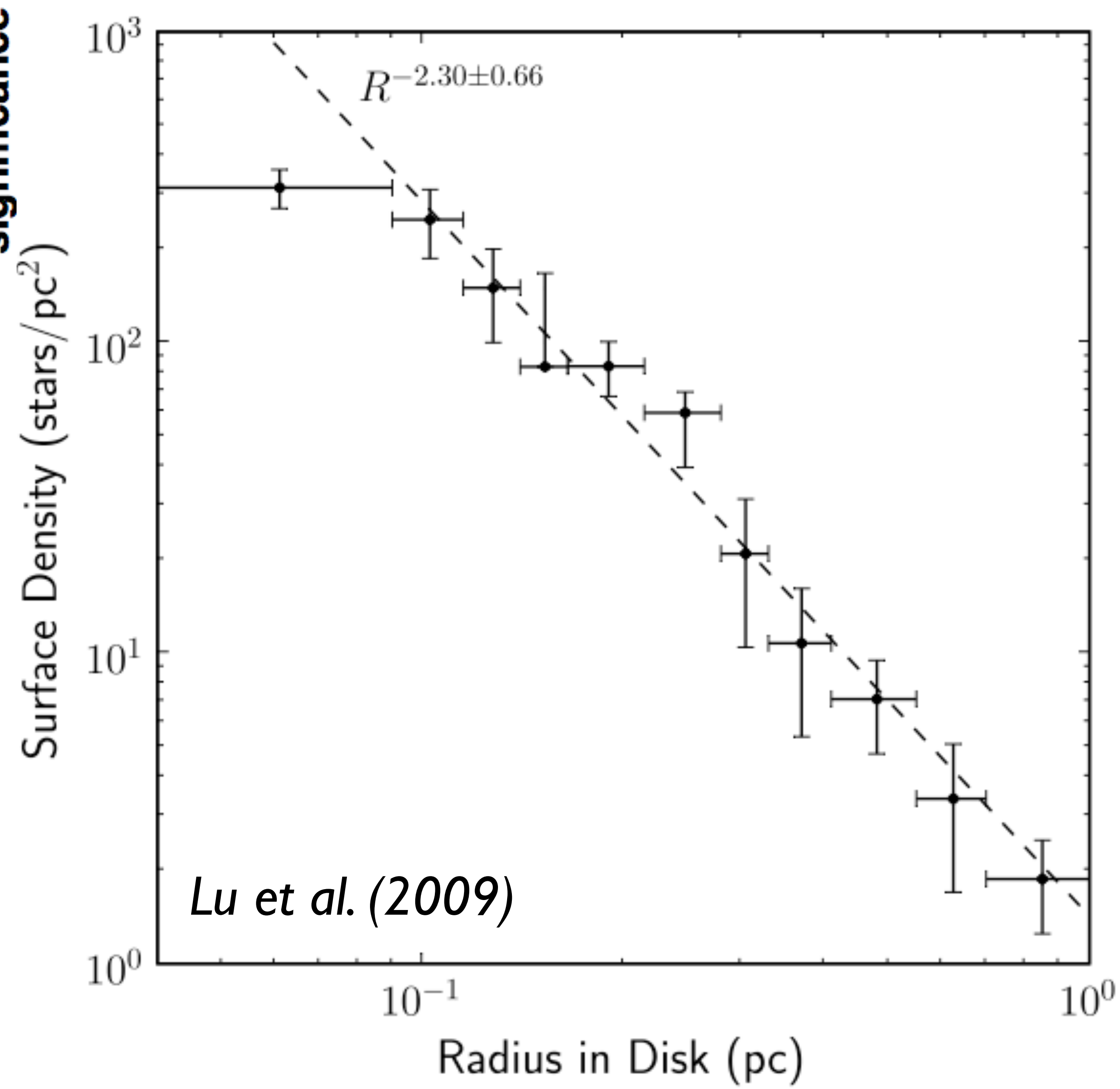
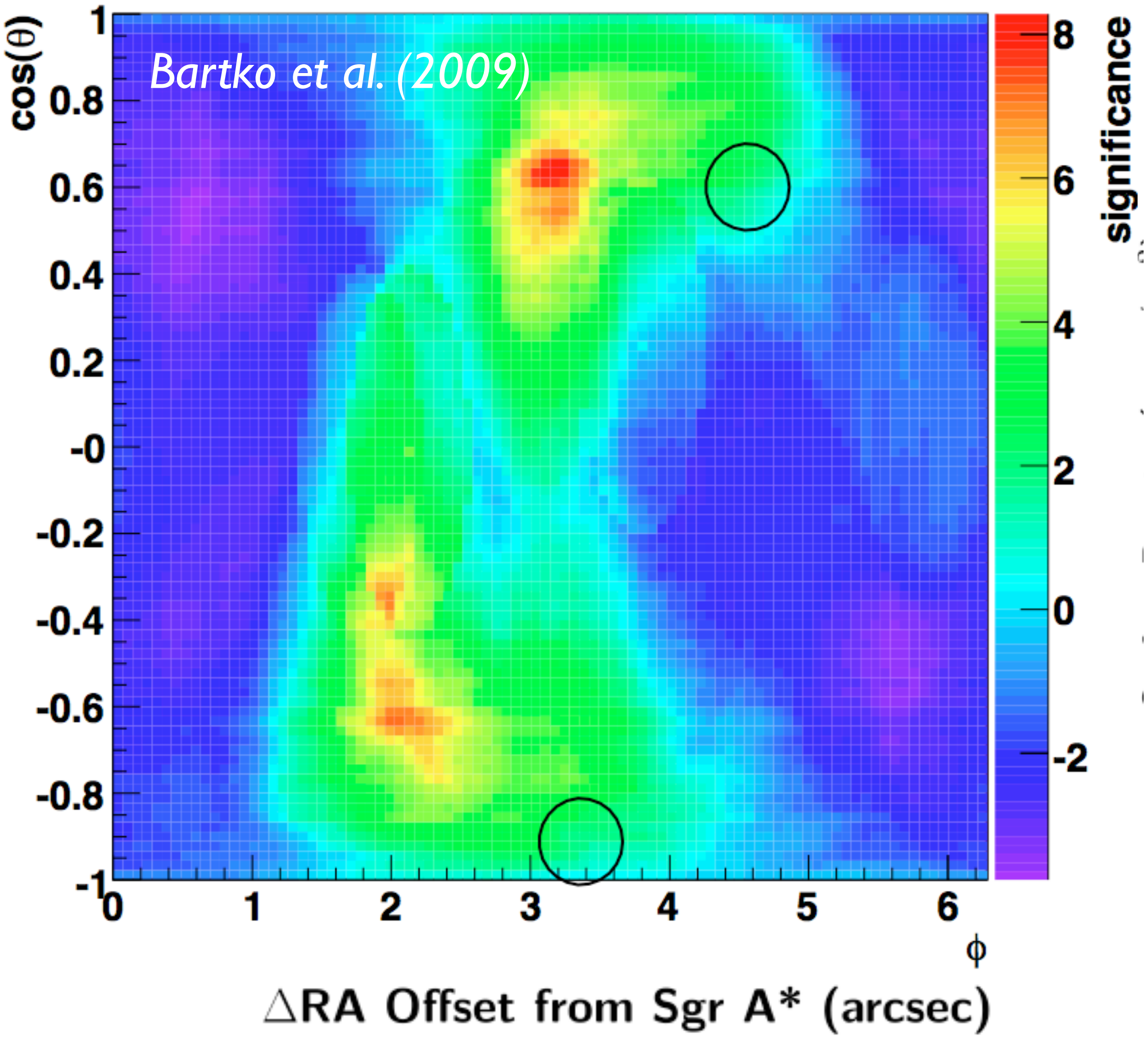
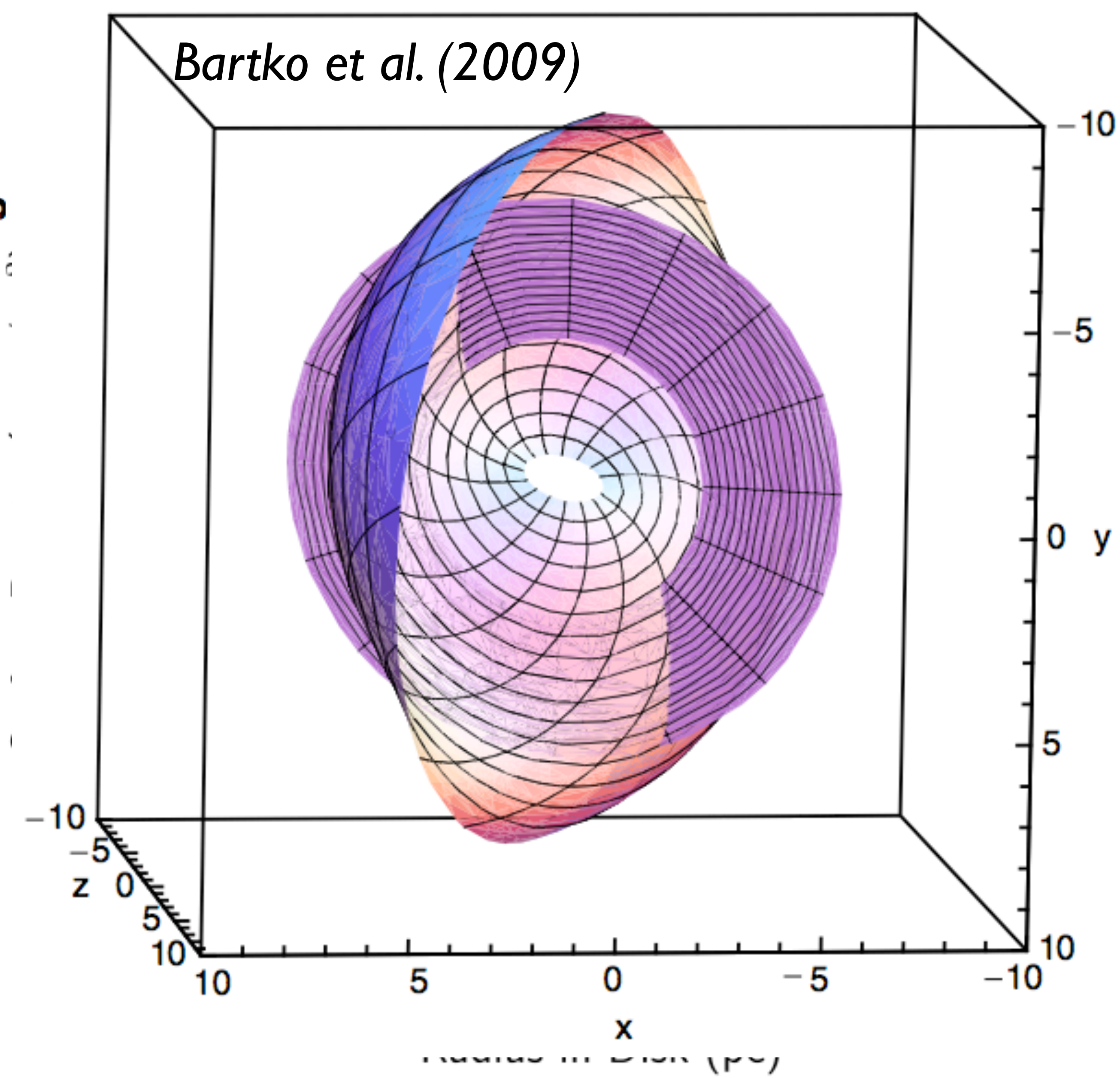




see also, e.g., *Genzel et al. (2000), Levin & Beloborodov (2003), Paumard et al. (2006), Tanner et al. (2006);*

The star burst happened in a disk (or 2)





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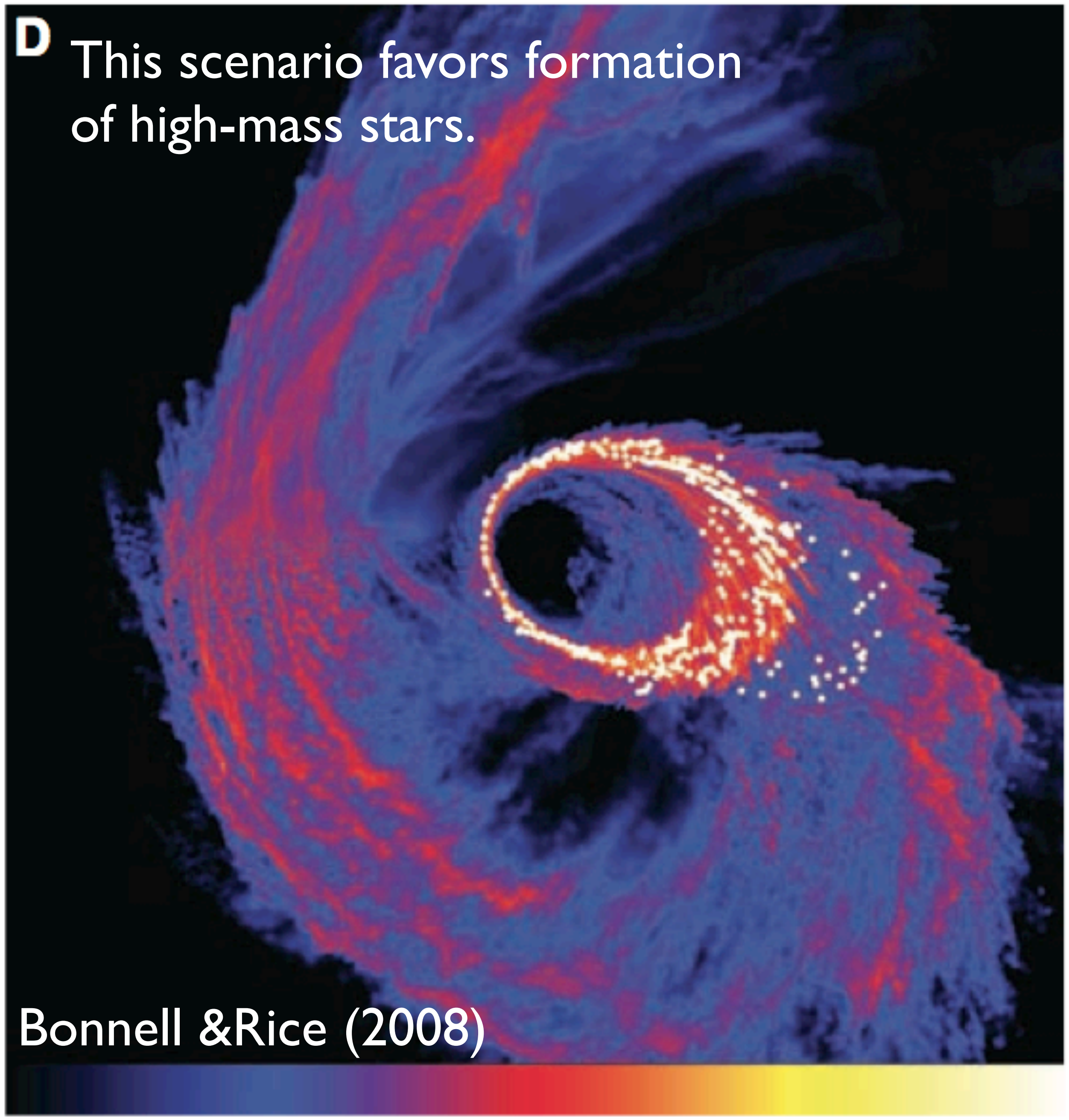
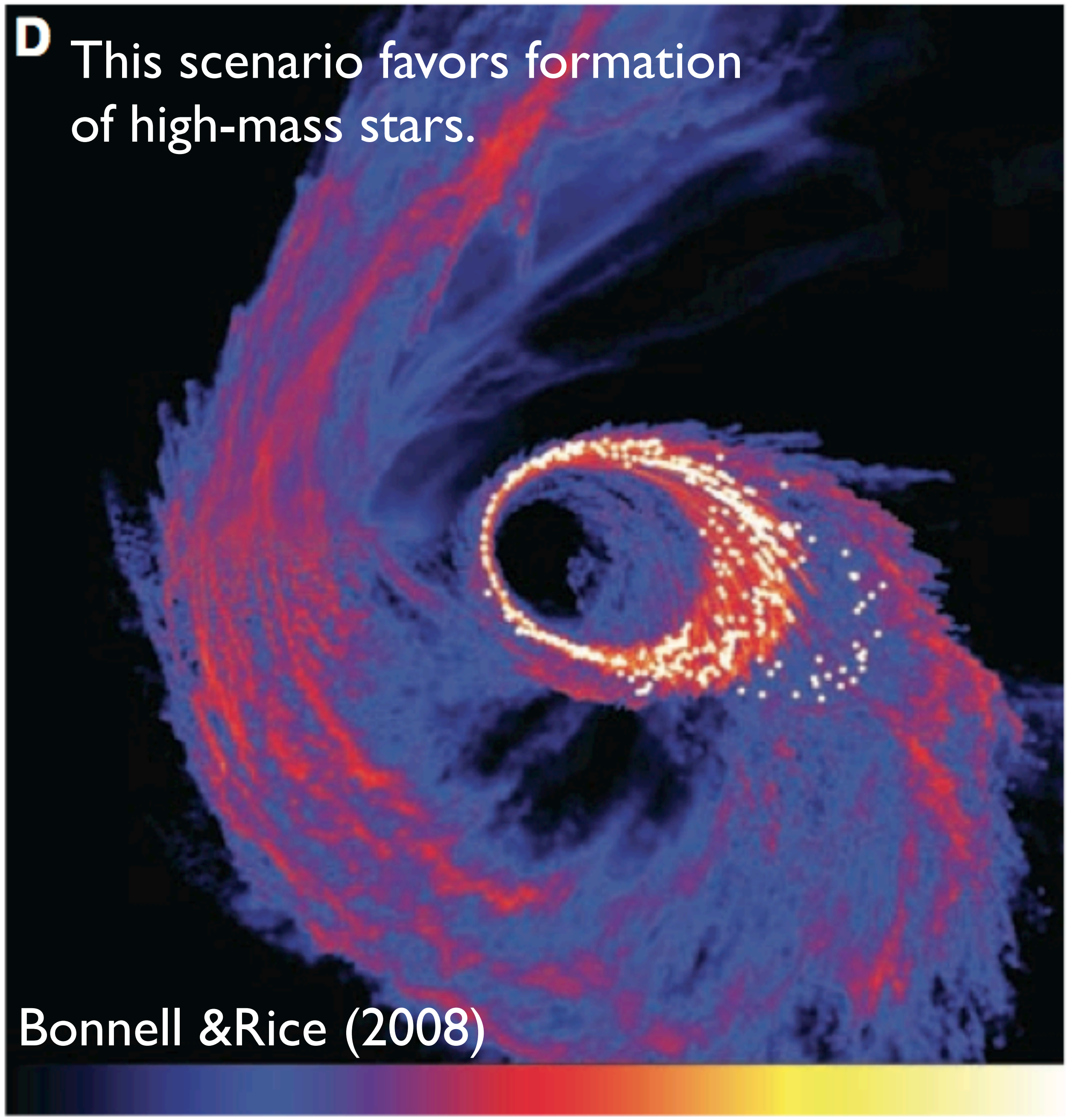


see also *Hobbs & Nayakshin (2009)*

The star burst happened in a disk (or 2)



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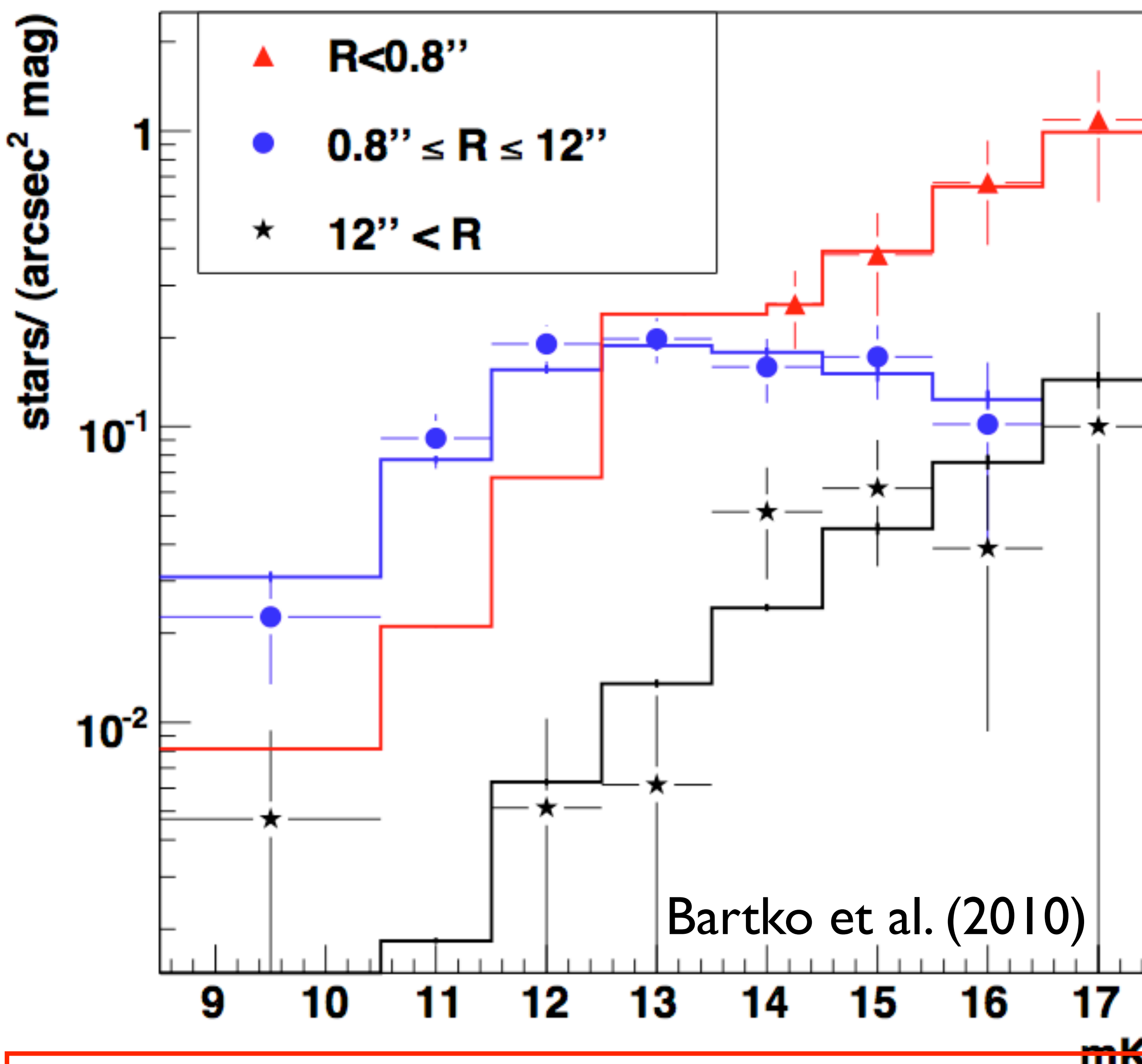
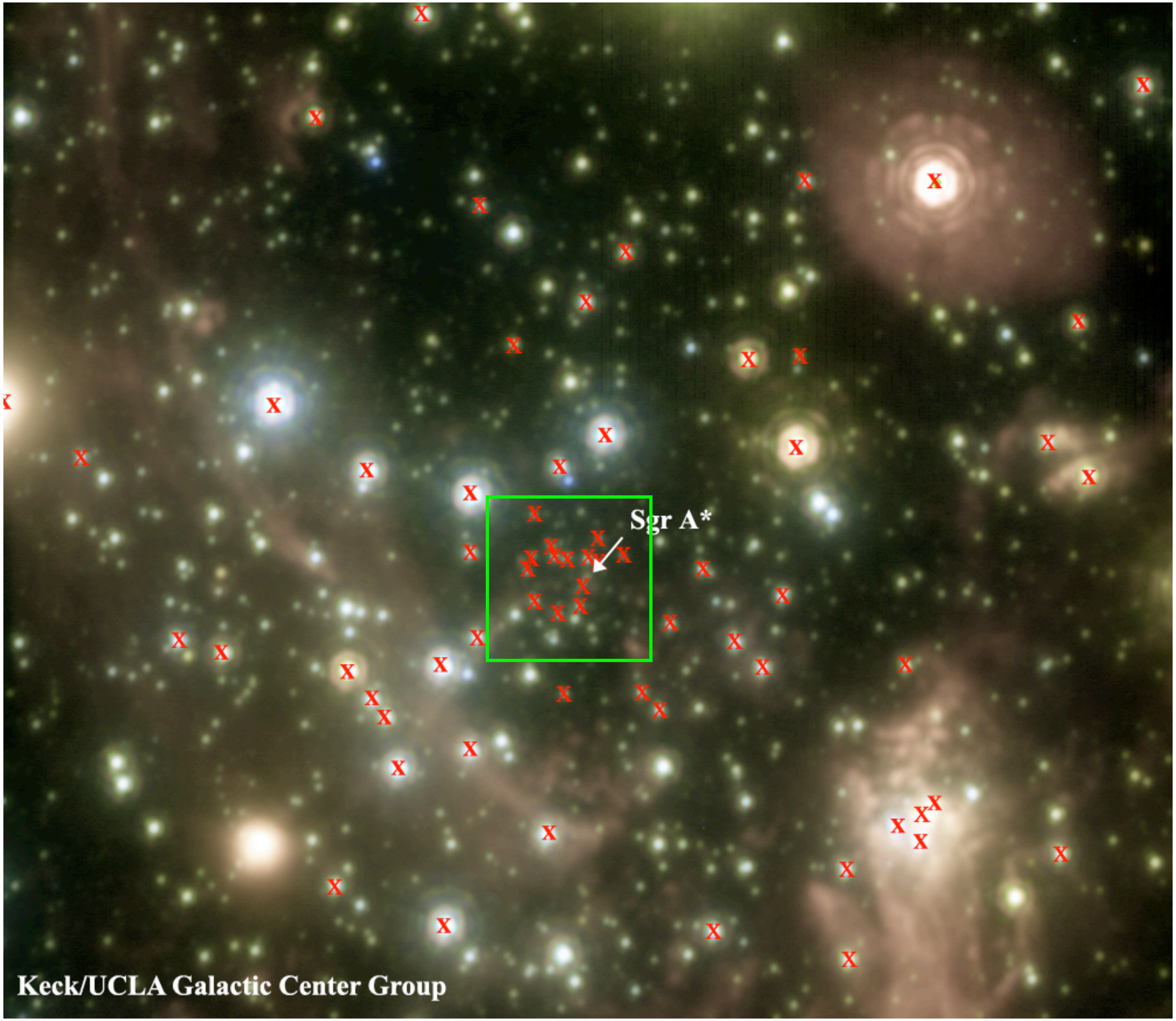


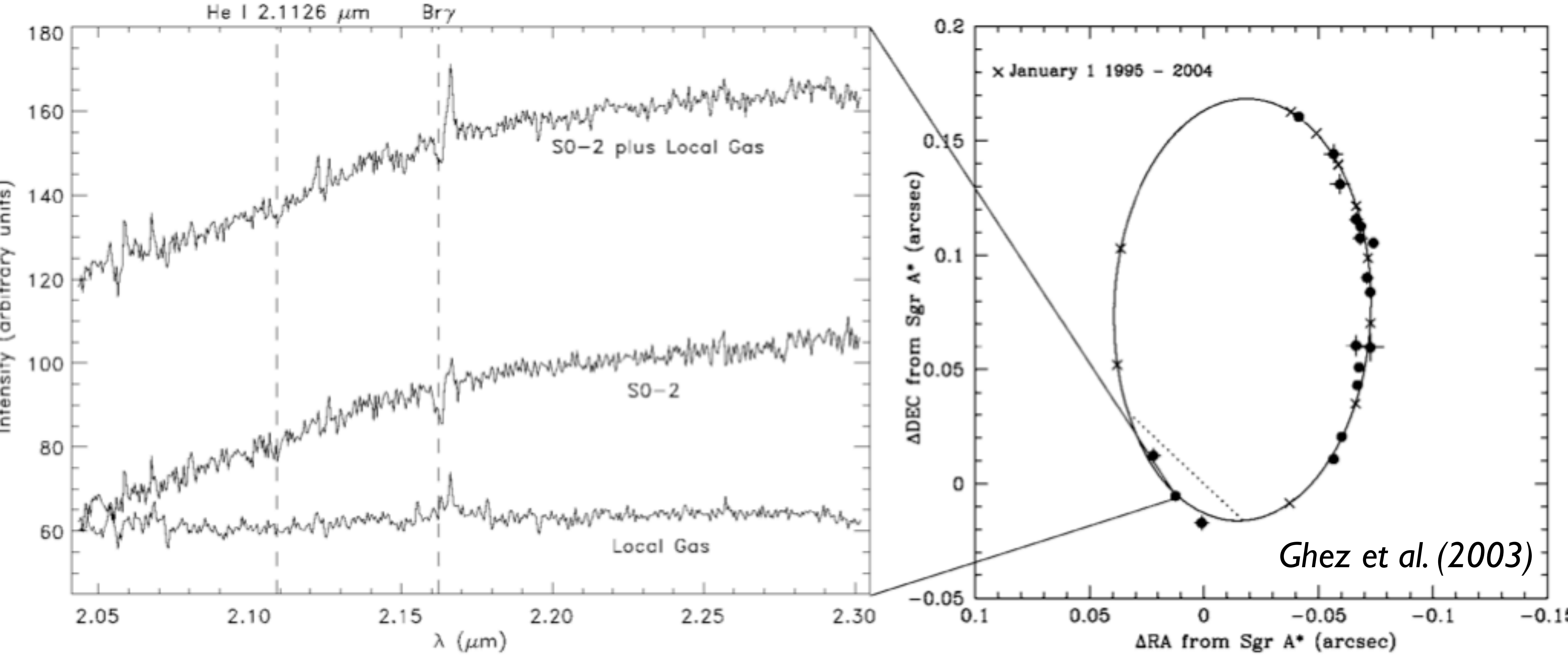
The IMF in the disks of young stars was probably top-heavy.

see also *Nayakshin & Sunyaev (2005)*

The S-stars: B-dwarfs near Sgr A*

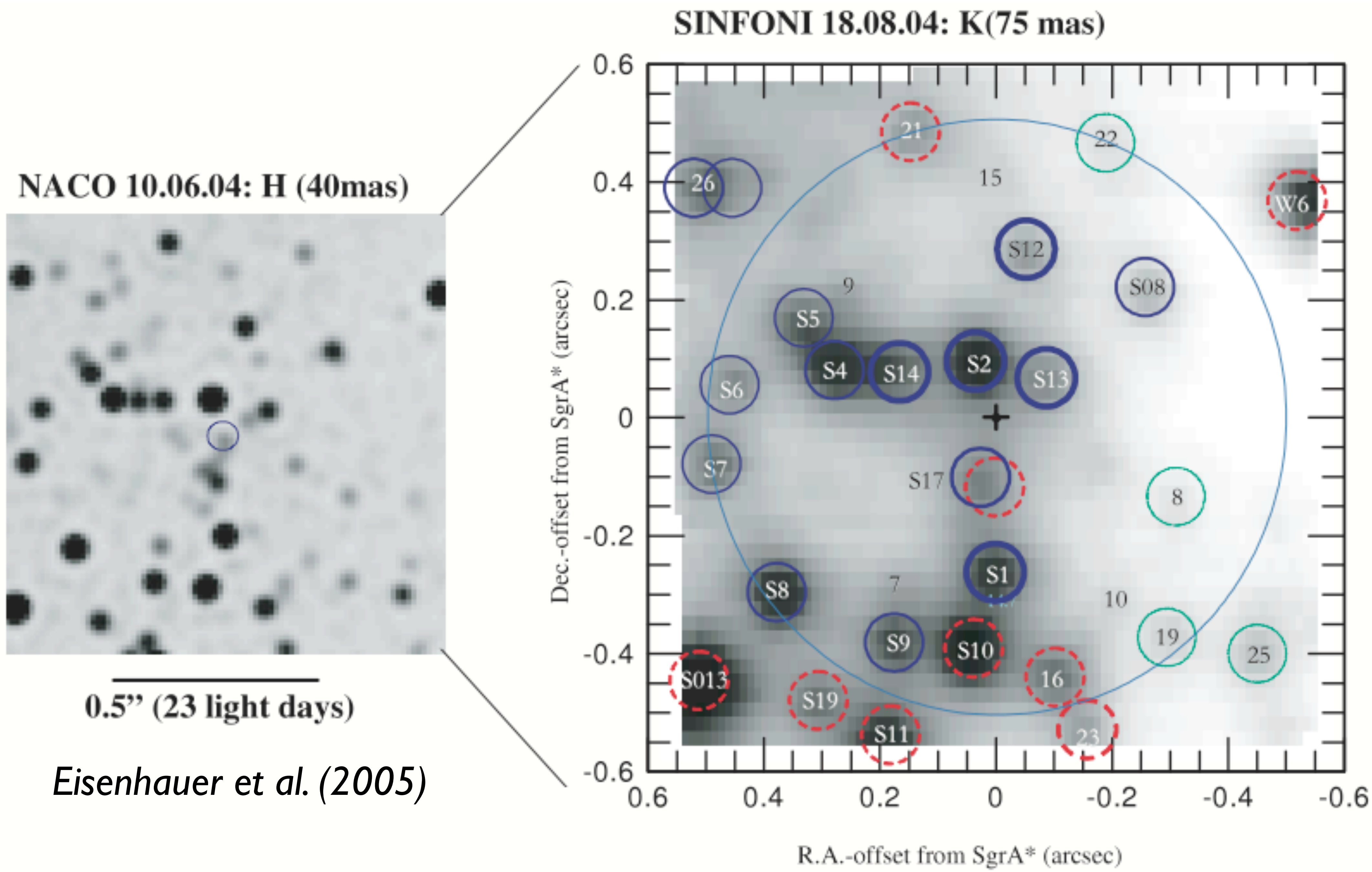


The S-stars: B-dwarfs near Sgr A*



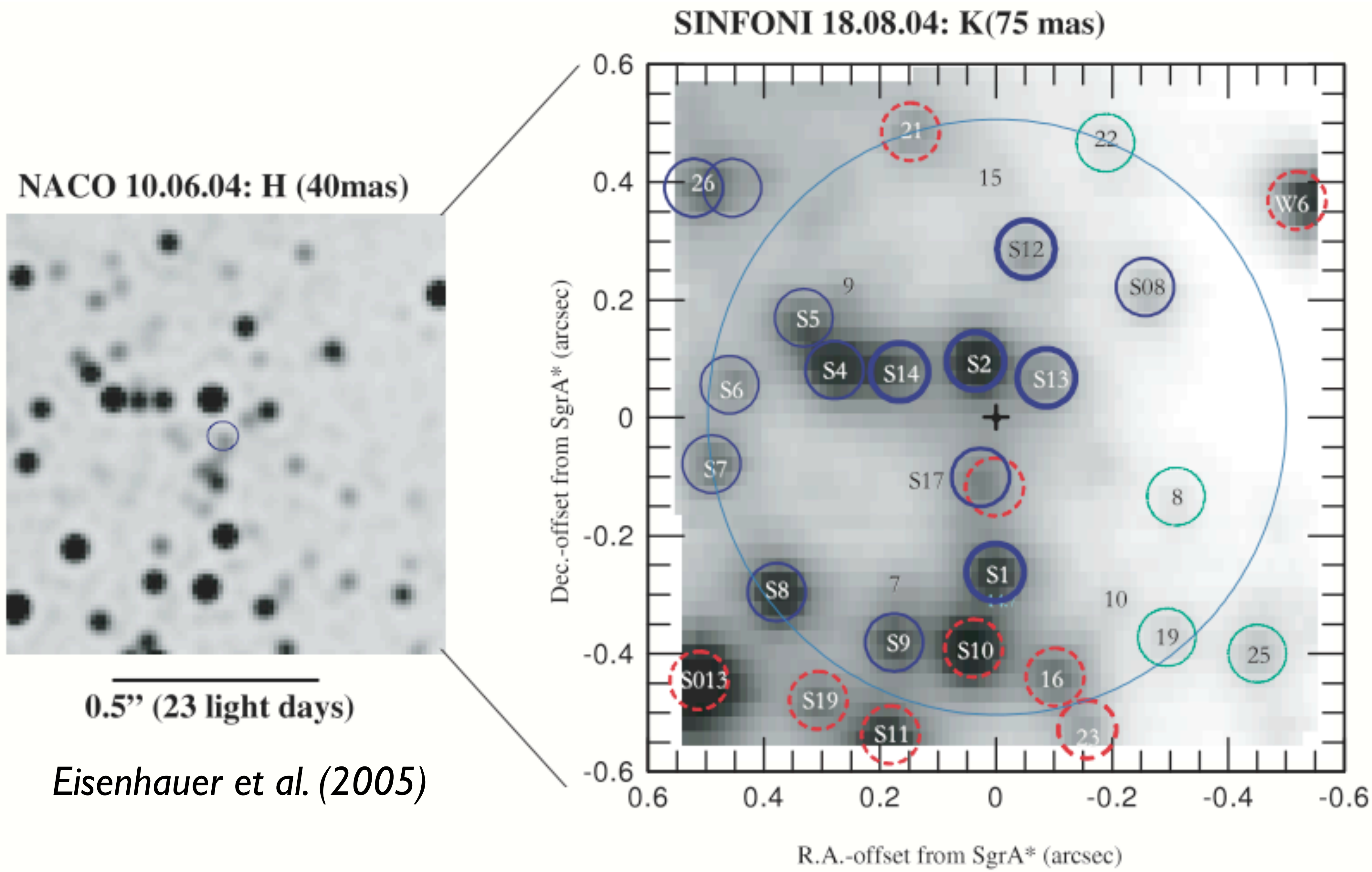
Ghez et al. (2003)

The S-stars: B-dwarfs near Sgr A*



Eisenhauer et al. (2005)

The S-stars: B-dwarfs near Sgr A*



Eisenhauer et al. (2005)

> 75% of the K=14-16 stars within ~1"of Sgr A* are B-dwarfs. They cannot have formed there nor migrated there via dynamical friction from larger distances during their lifetime ($\leq 10^8$ yr).

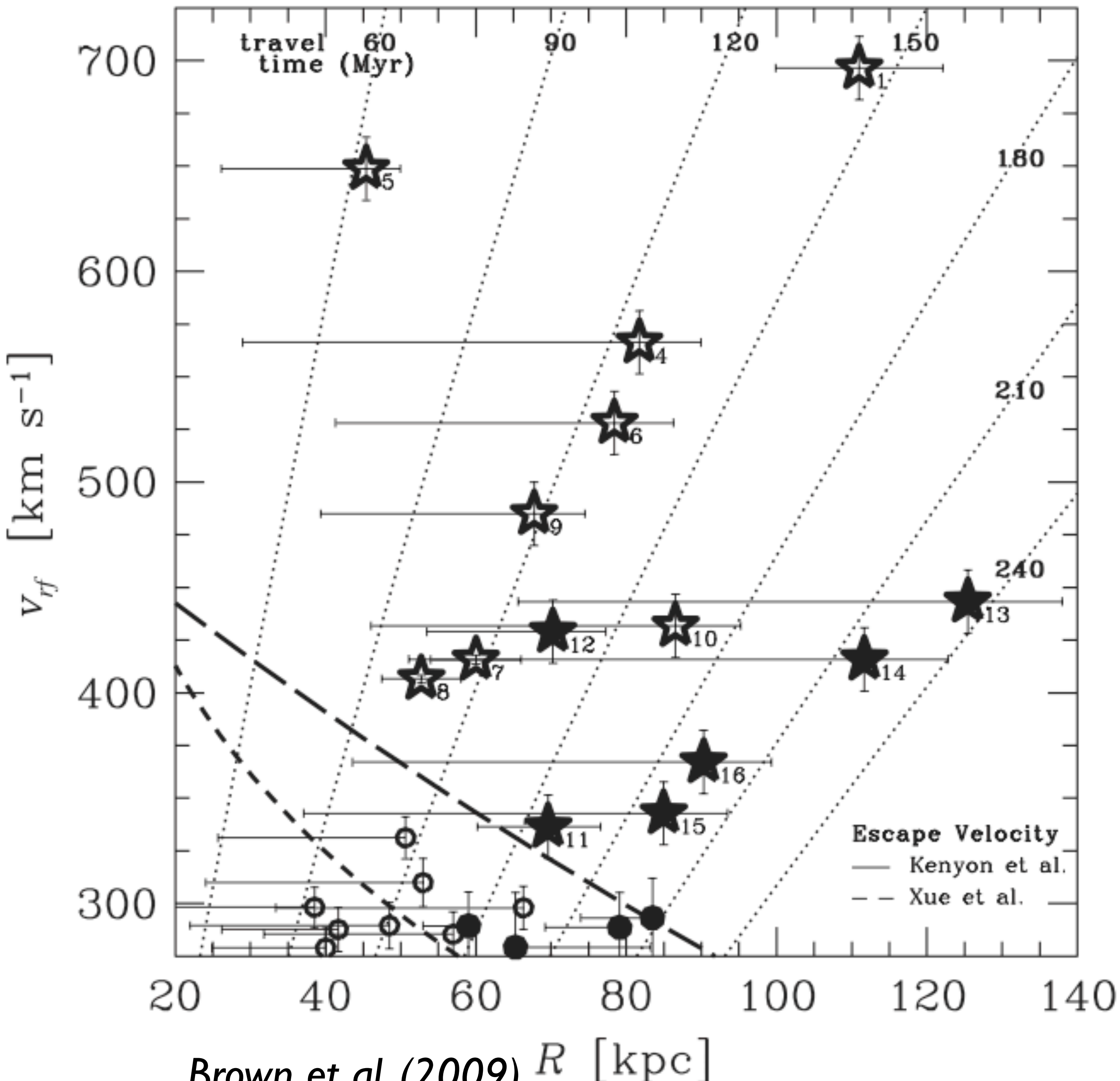
Origin of S-stars

Close encounters between binary stars and massive BH

→

one stars remains tightly bound, the other one is ejected as hypervelocity star (Hills 1988)

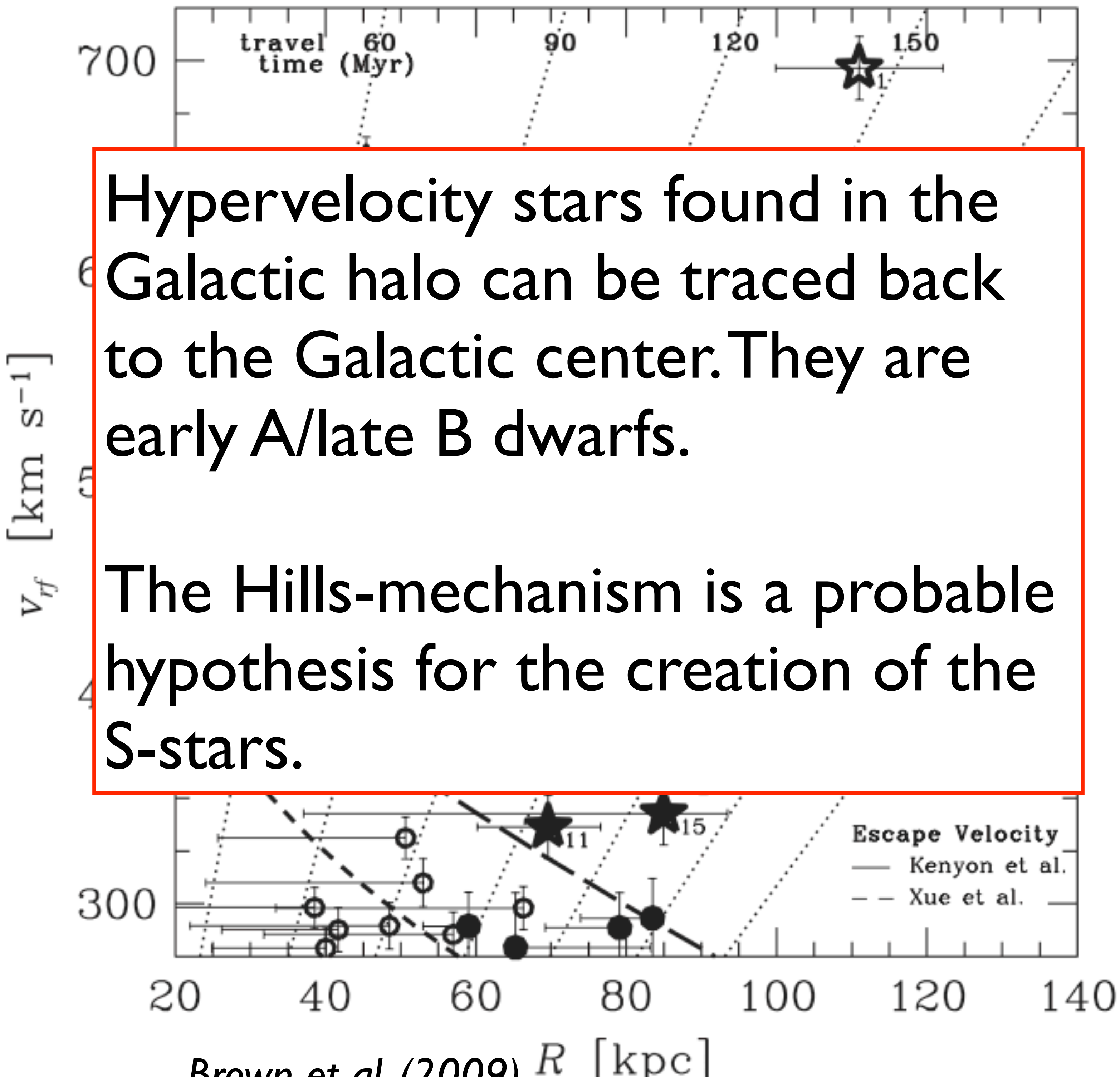
Origin of S-stars



Brown et al. (2009)

Close encounters between binary stars and massive BH
➔
one stars remains tightly bound, the other one is ejected as hypervelocity star (Hills 1988)

Origin of S-stars



Hypervelocity stars found in the Galactic halo can be traced back to the Galactic center. They are early A/late B dwarfs.

The Hills-mechanism is a probable hypothesis for the creation of the S-stars.

Brown et al. (2009)

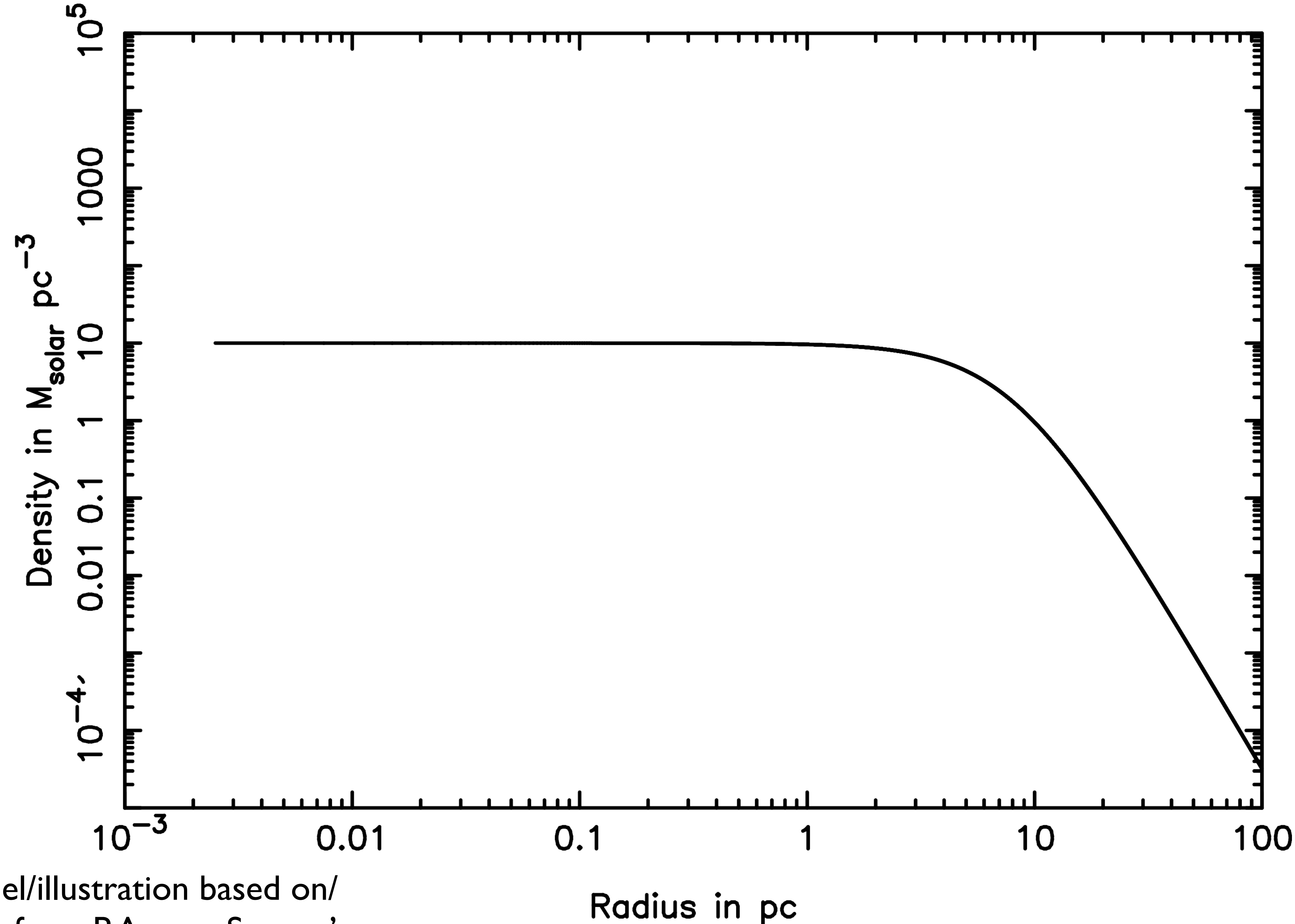
Close encounters between binary stars and massive BH

➔

one stars remains tightly bound, the other one is ejected as hypervelocity star (Hills 1988)

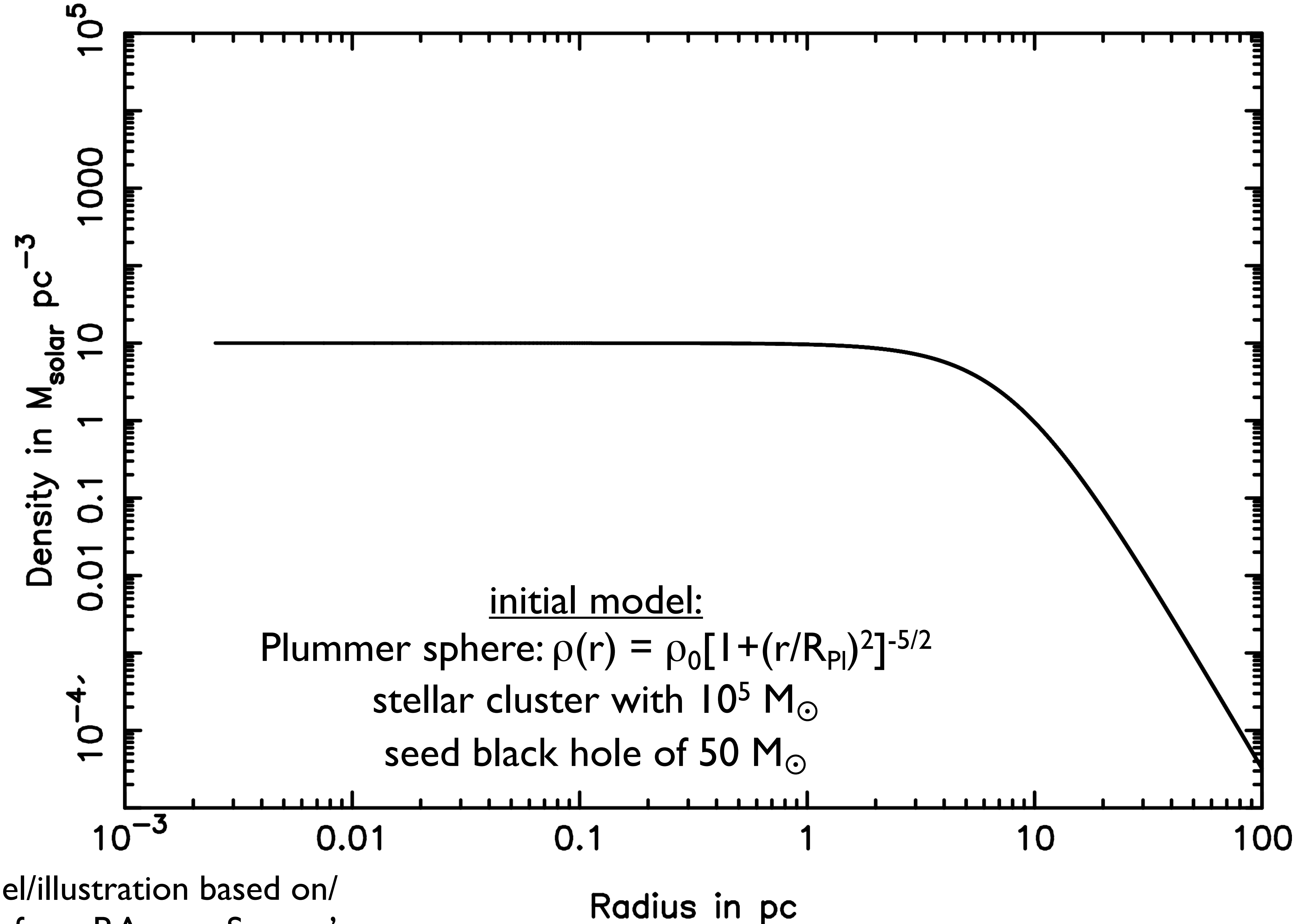
The missing stellar cusp Sagittarius A*?

Formation of a stellar cusp



Model/illustration based on/
taken from P. Amaro-Seoane's
PhD Thesis (2004).

Formation of a stellar cusp



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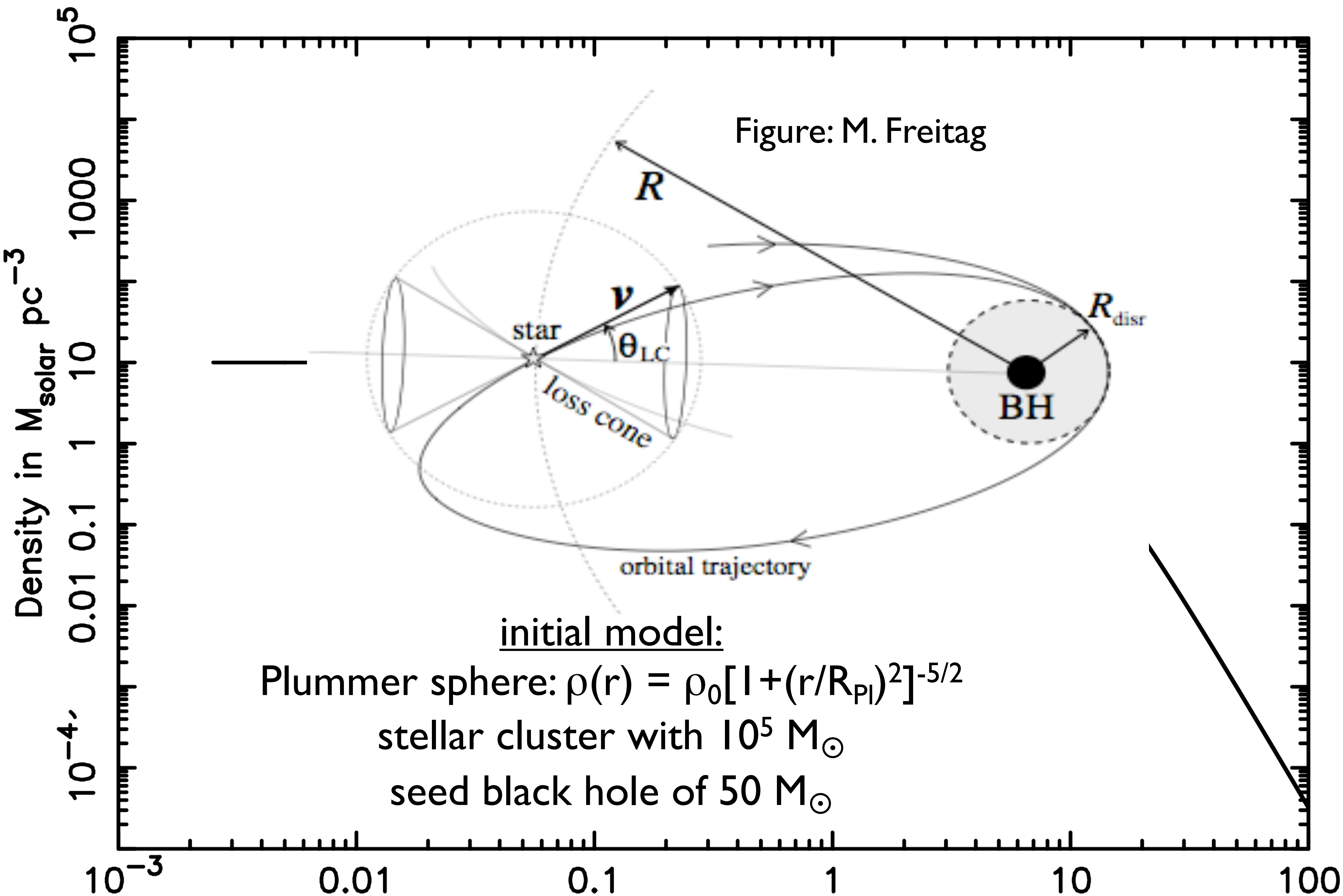


initial model:

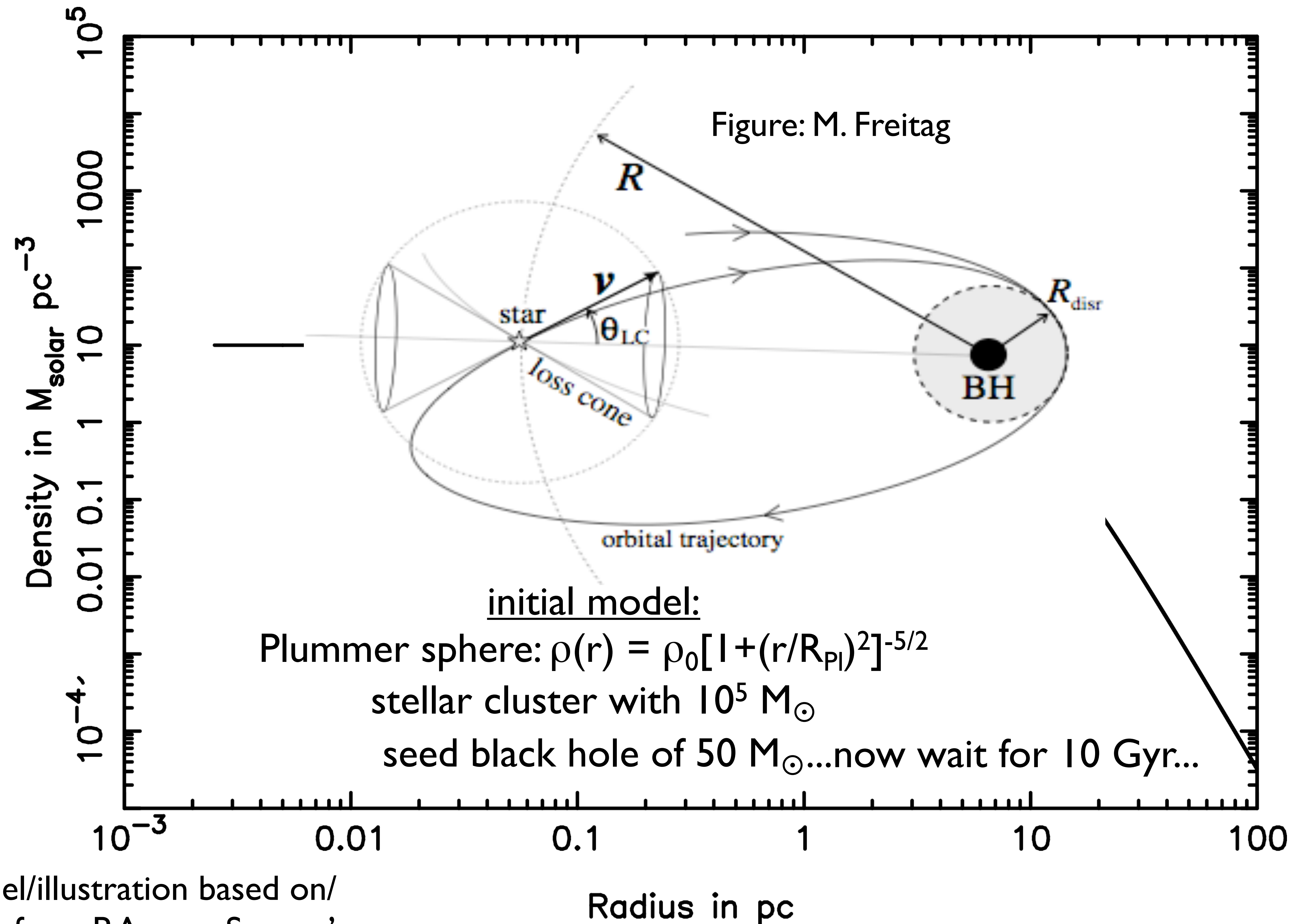
Plummer sphere: $\rho(r) = \rho_0[1+(r/R_{Pl})^2]^{-5/2}$

stellar cluster with 10^5 $M_\odot$

seed black hole of 50 $M_\odot$

Model/illustration based on/ taken from P. Amaro-Seoane's PhD Thesis (2004).

Formation of a stellar cusp



initial model:

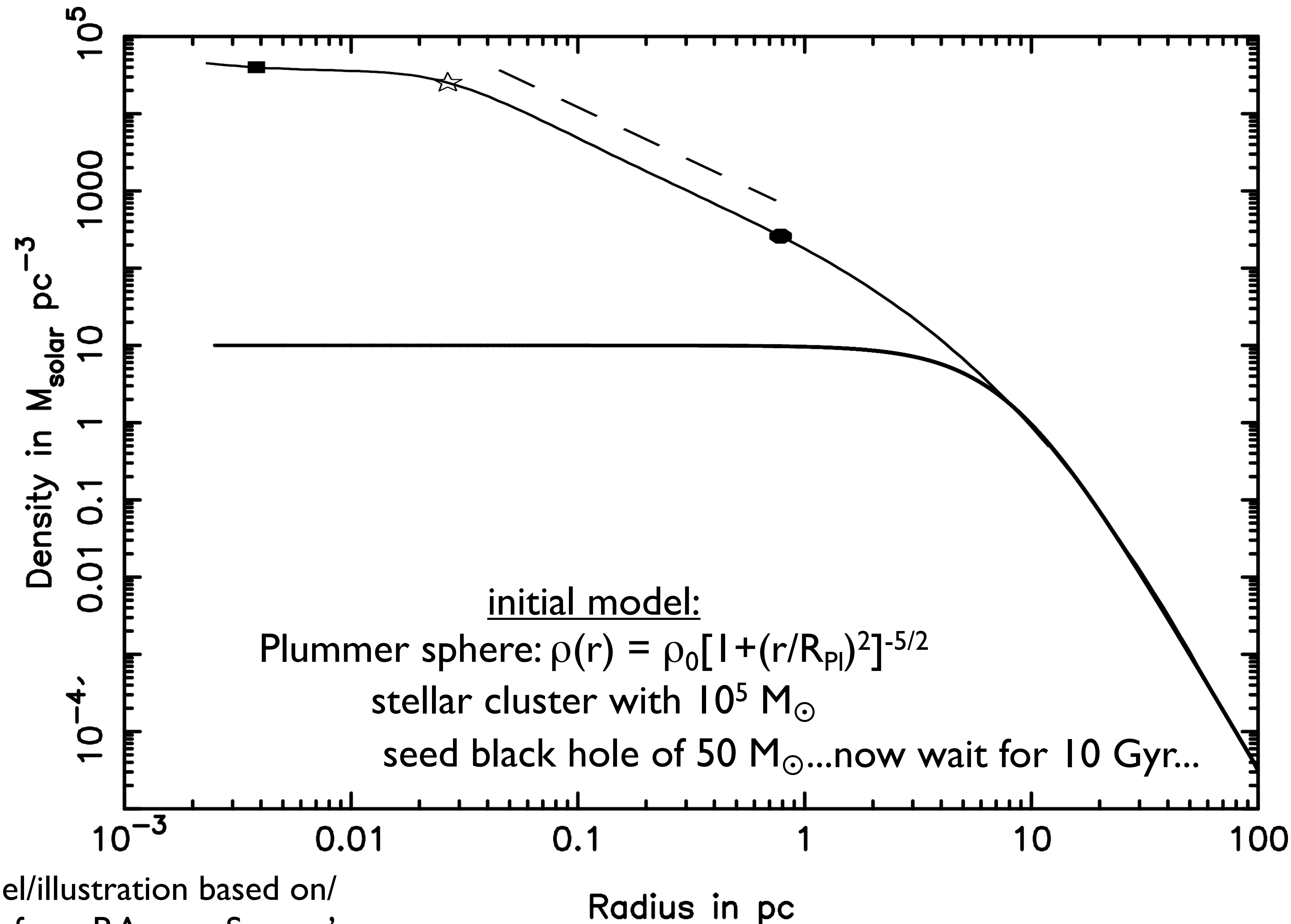
Plummer sphere: $\rho(r) = \rho_0[1+(r/R_{Pl})^2]^{-5/2}$

stellar cluster with 10^5 $M_\odot$

seed black hole of 50 $M_\odot$...now wait for 10 Gyr...

Model/illustration based on/ taken from P. Amaro-Seoane's PhD Thesis (2004).

Formation of a stellar cusp



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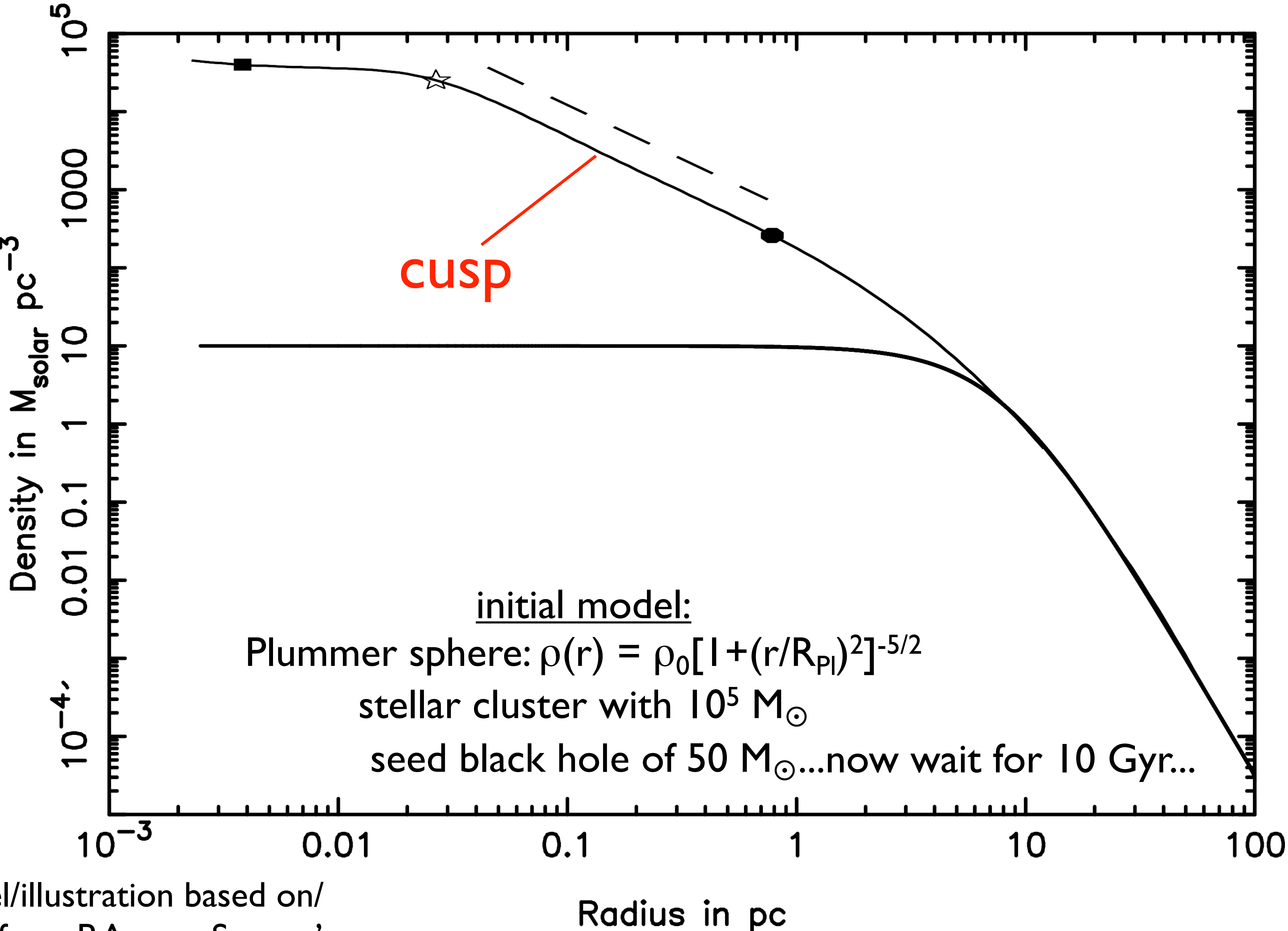

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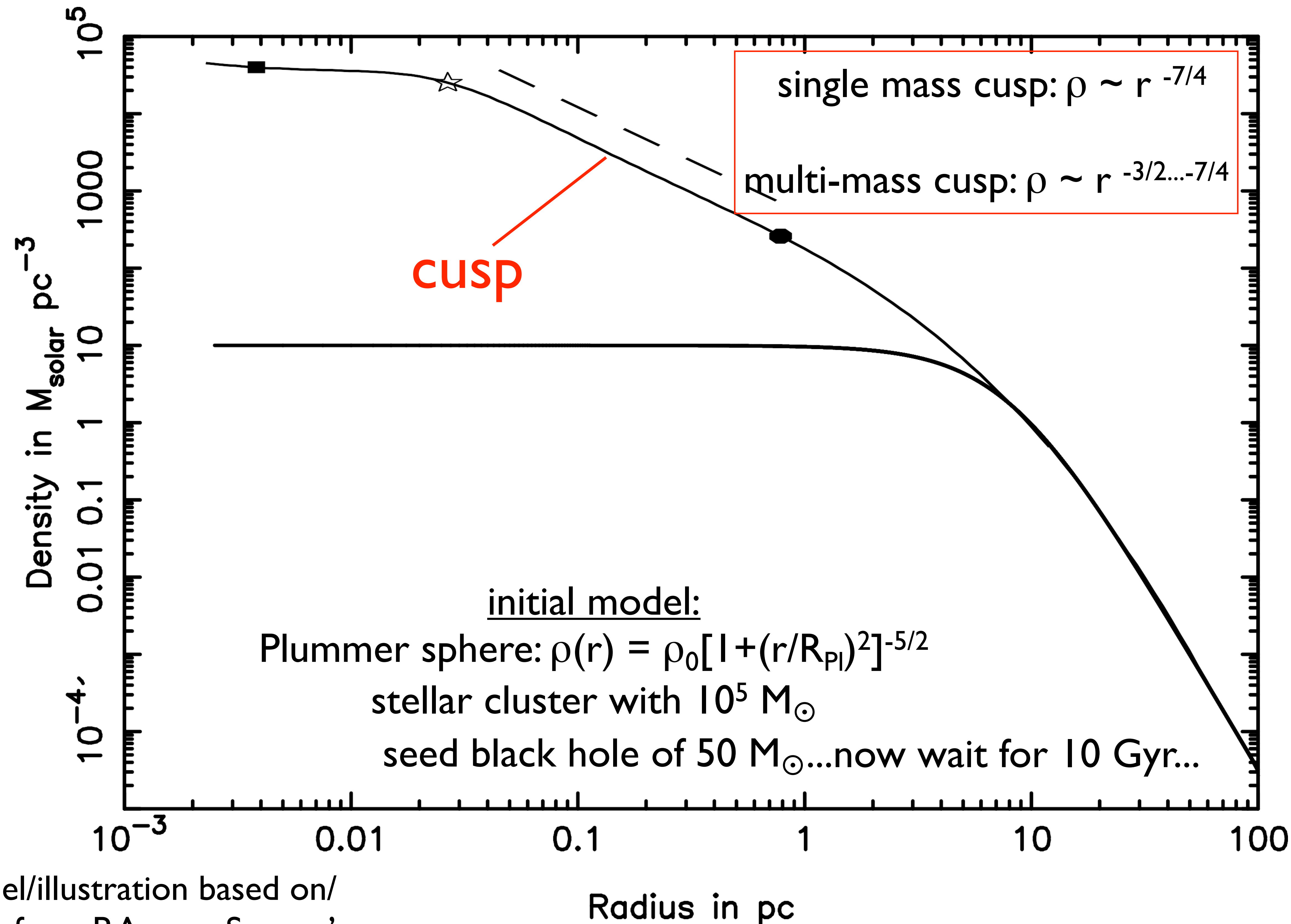

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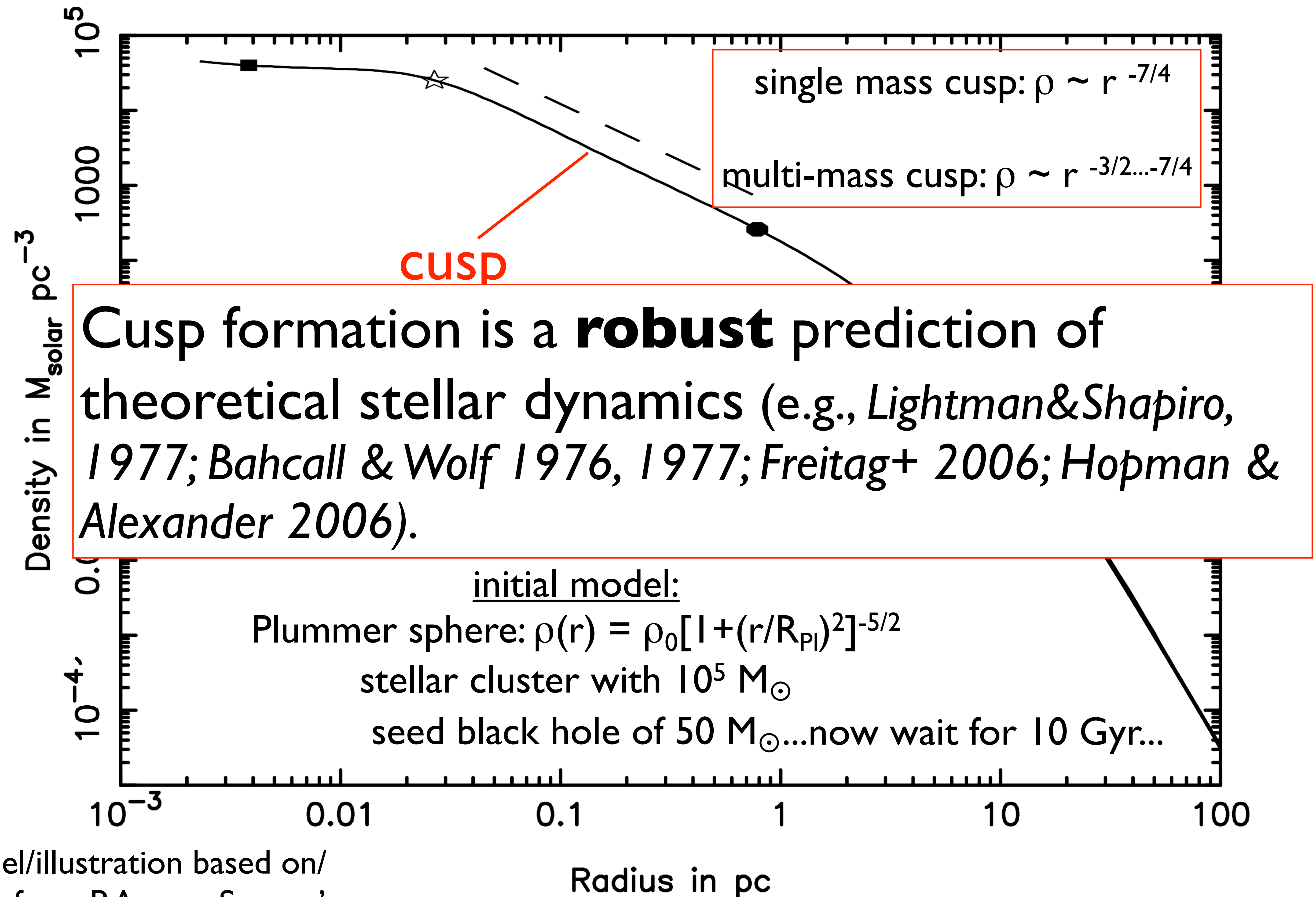
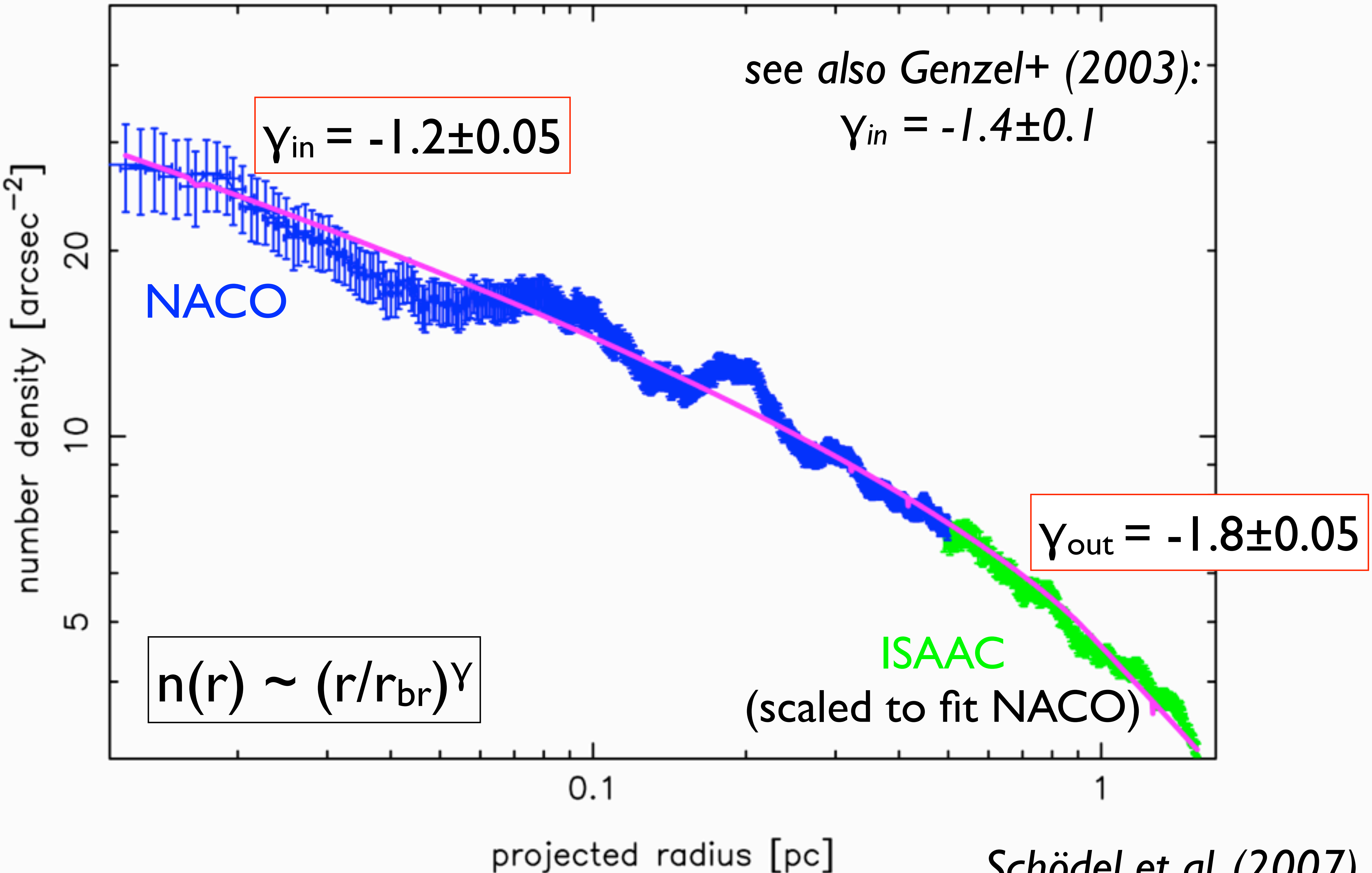


Cusp formation is a **robust** prediction of theoretical stellar dynamics (e.g., *Lightman&Shapiro, 1977; Bahcall & Wolf 1976, 1977; Freitag+ 2006; Hopman & Alexander 2006*).

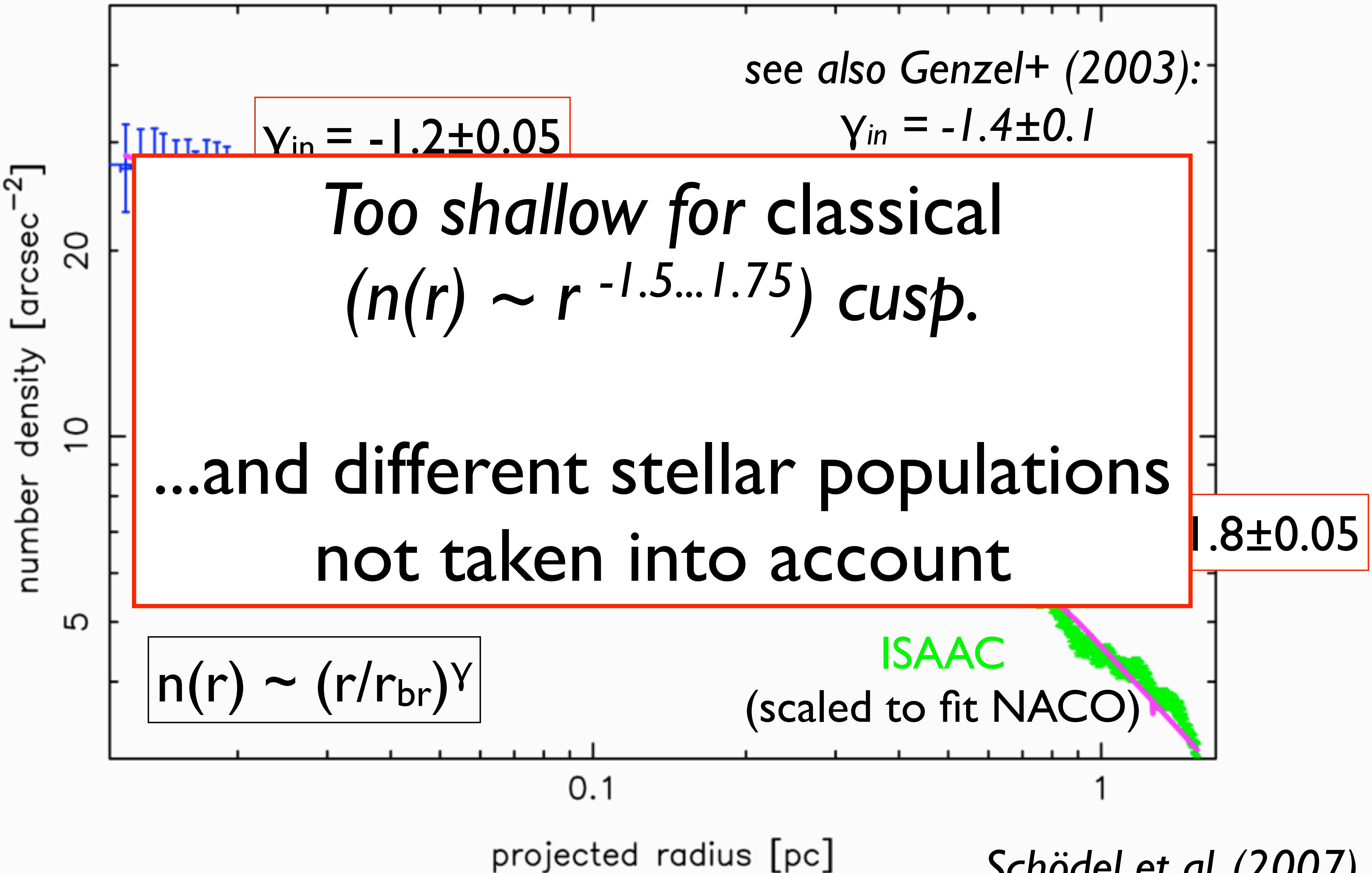
Model/illustration based on/ taken from P. Amaro-Seoane's PhD Thesis (2004).

Stellar surface number density



Schödel et al. (2007)

Stellar surface number density



Too shallow for classical
(n(r) ~ r $^{-1.5...1.75}$*) cusp.*

...and different stellar populations
not taken into account

Schödel et al. (2007)

Classifying stars at the GC: Broad-band

main problems:

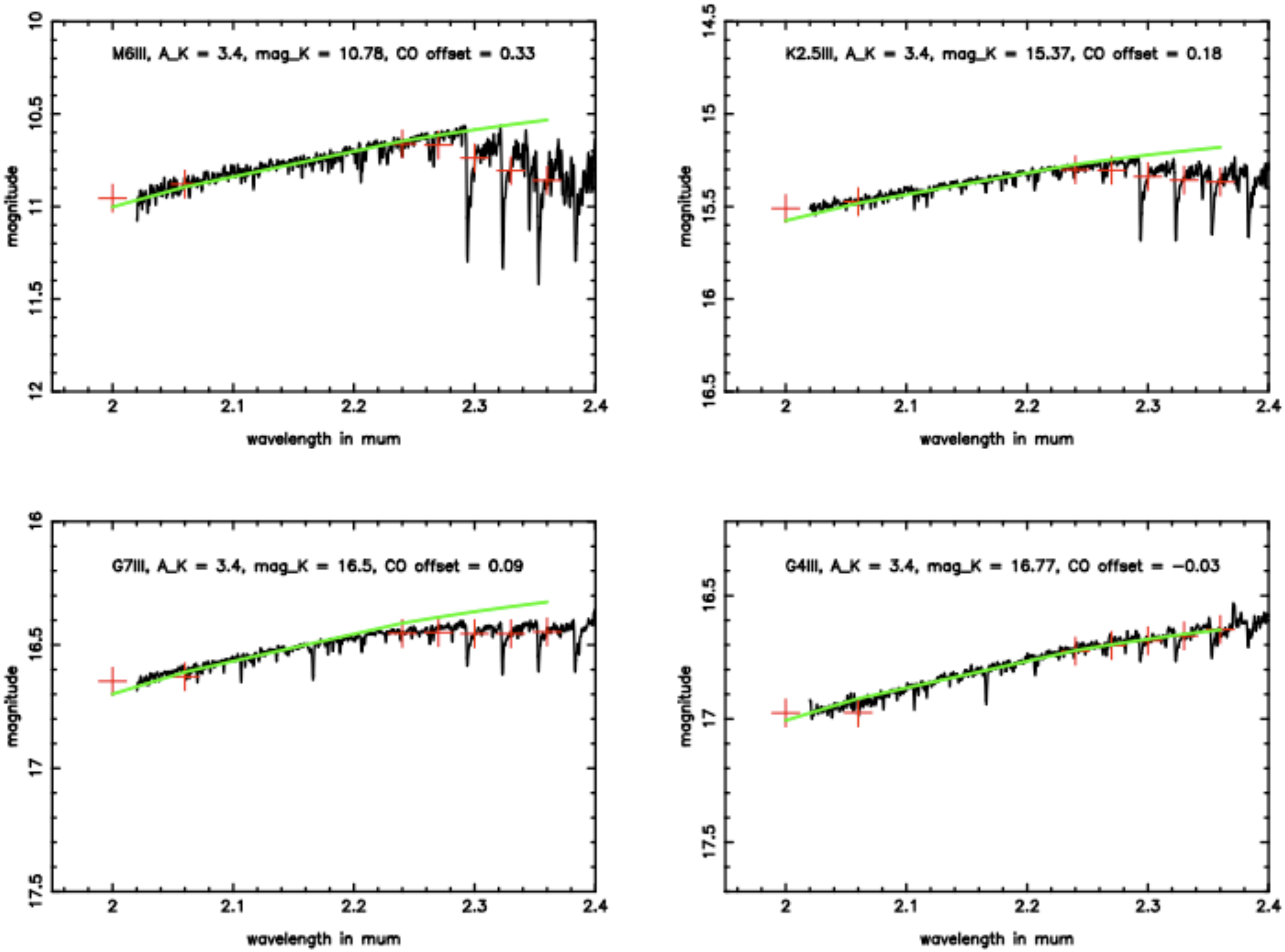
- high and variable extinction
- only H,K,L observations (narrow range of stellar colors)
- FOV of spectroscopy very small

see Schödel et al. (2010, A&A)

Classifying stars at the GC: Broad-band

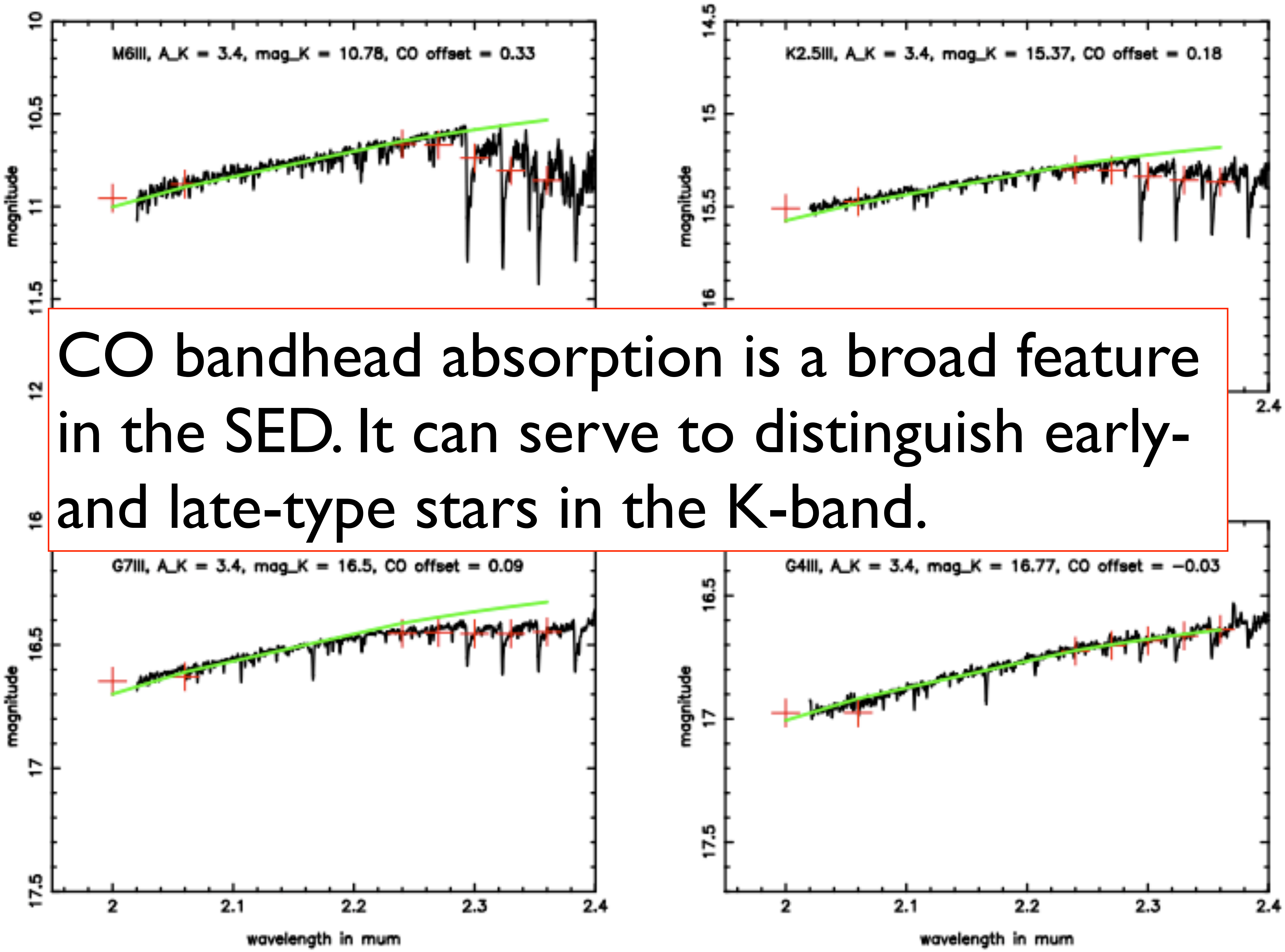
see Schödel et al. (2010, A&A)

Classifying stars at the GC: Narrow band



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

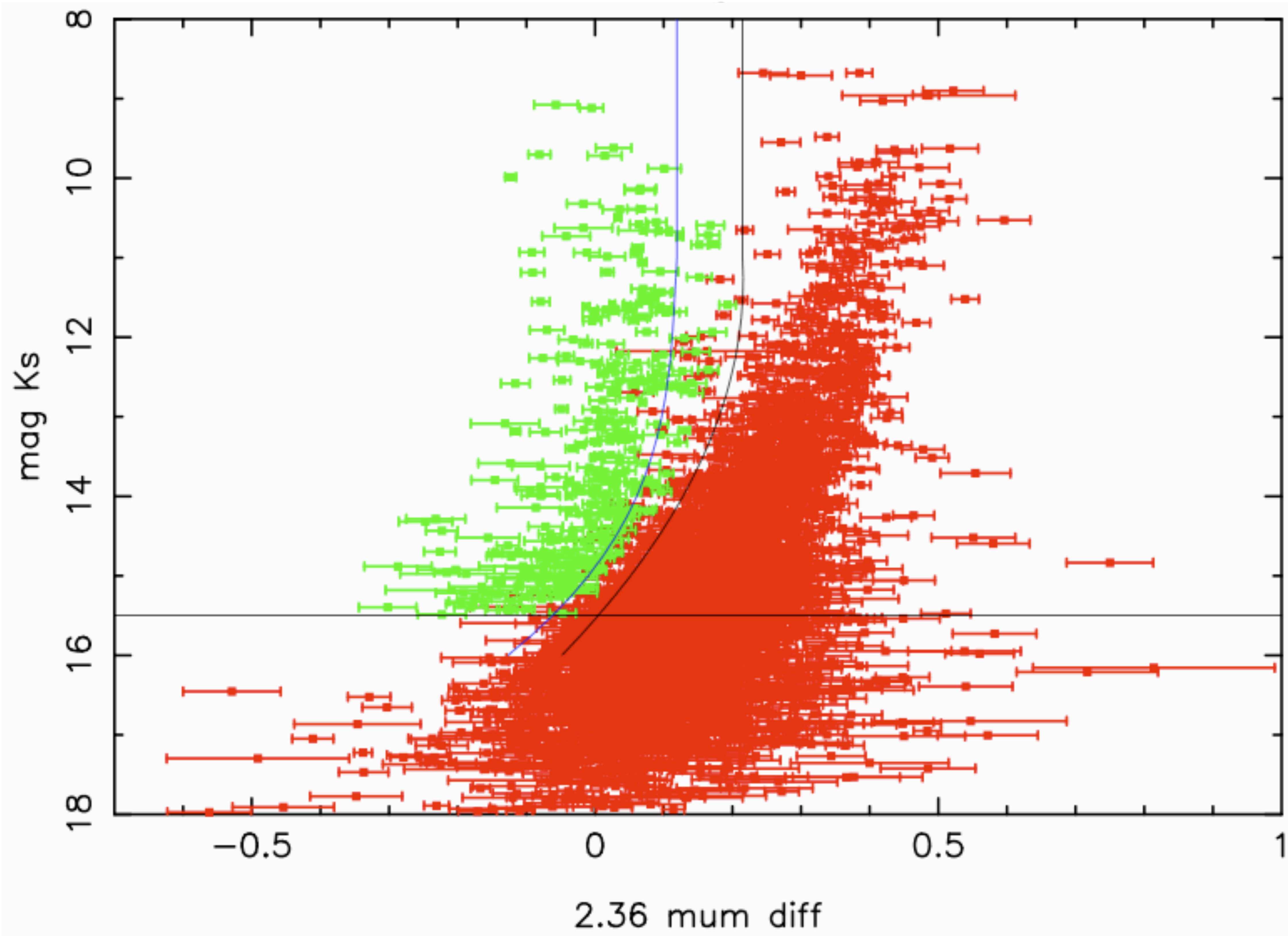
Classifying stars at the GC: Narrow band



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

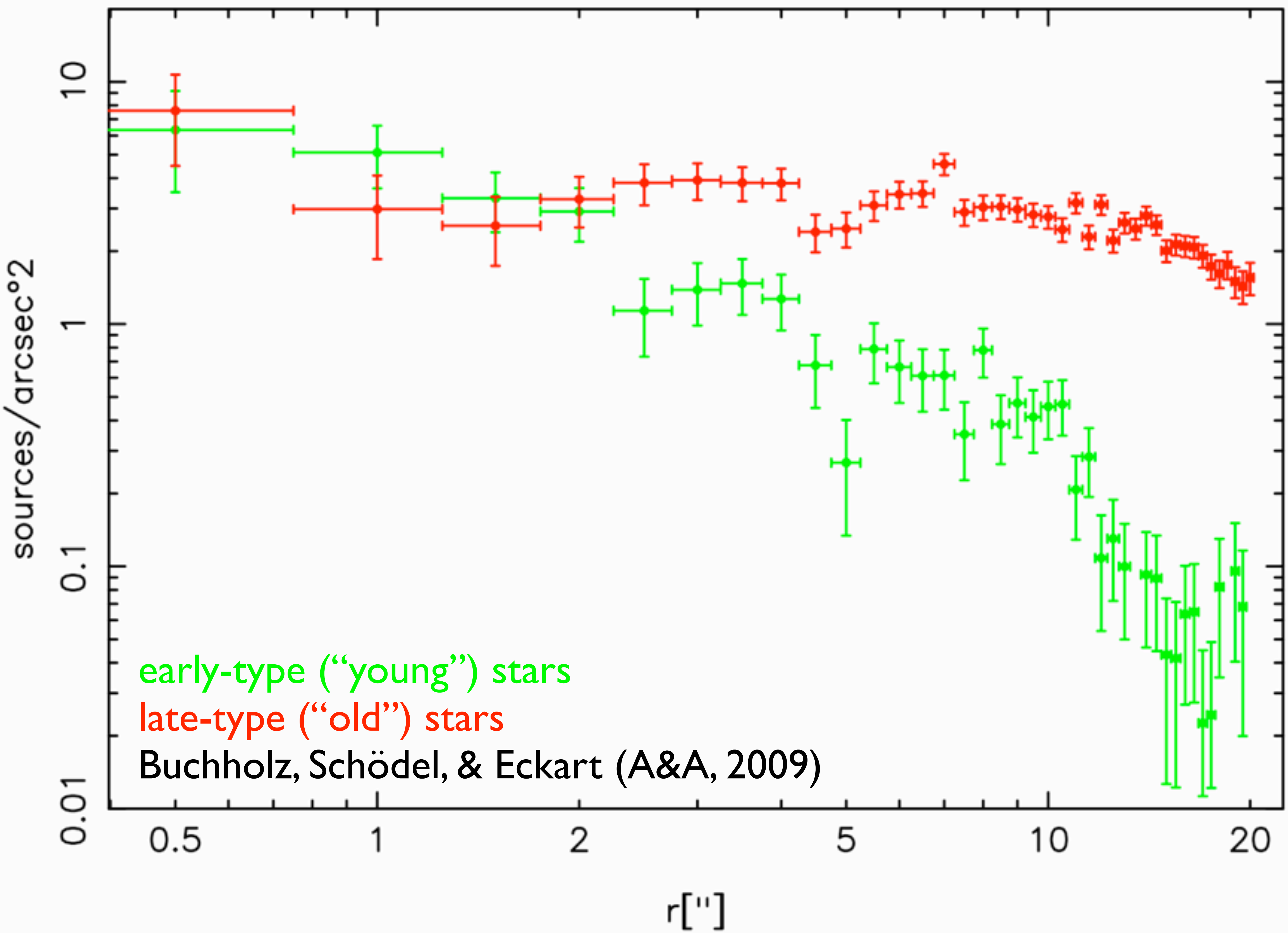
Buchholz, Schödel, & Eckart (2009, A&A)

Classifying stars at the GC: Narrow band

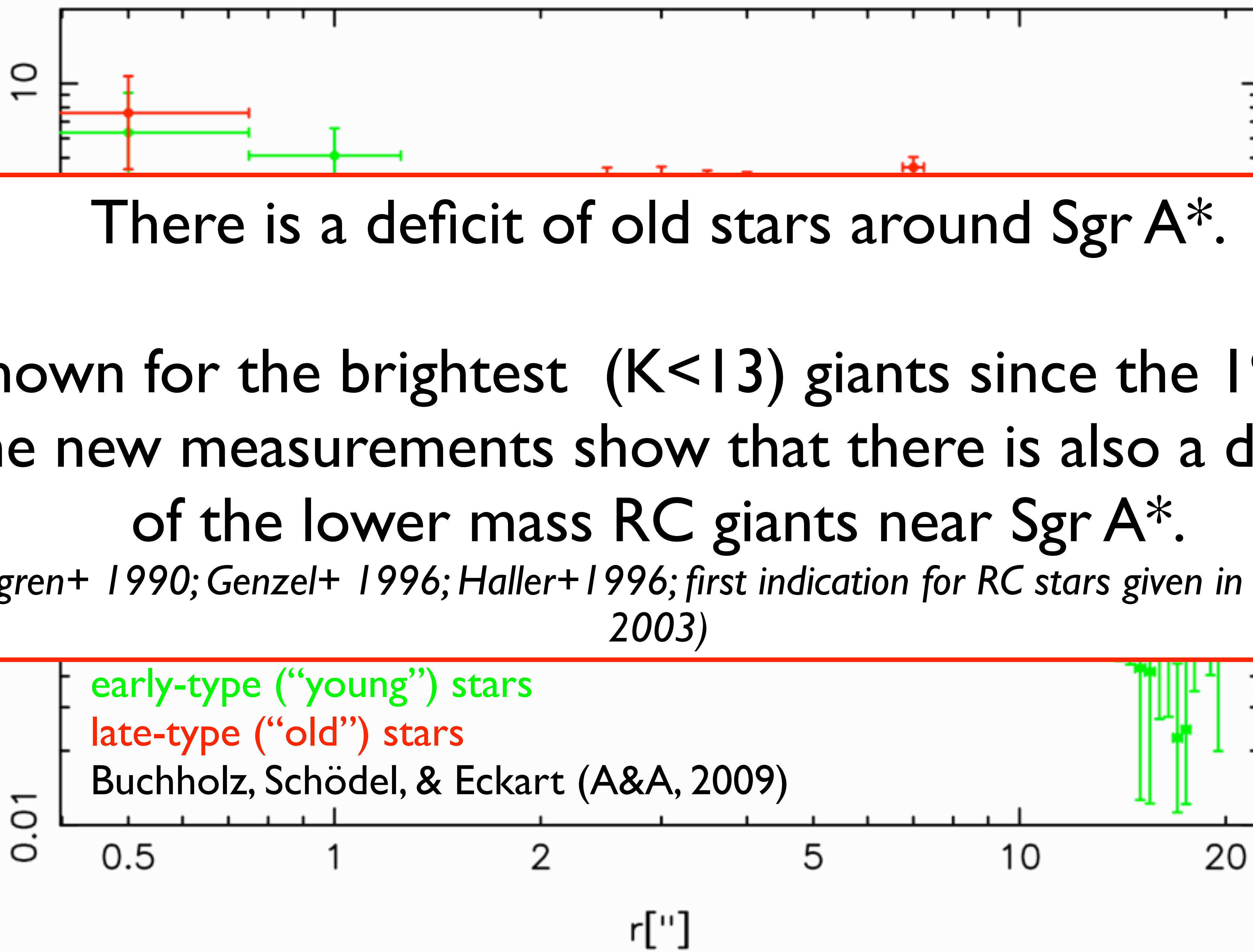


Buchholz, Schödel, & Eckart (2009, A&A)

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



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

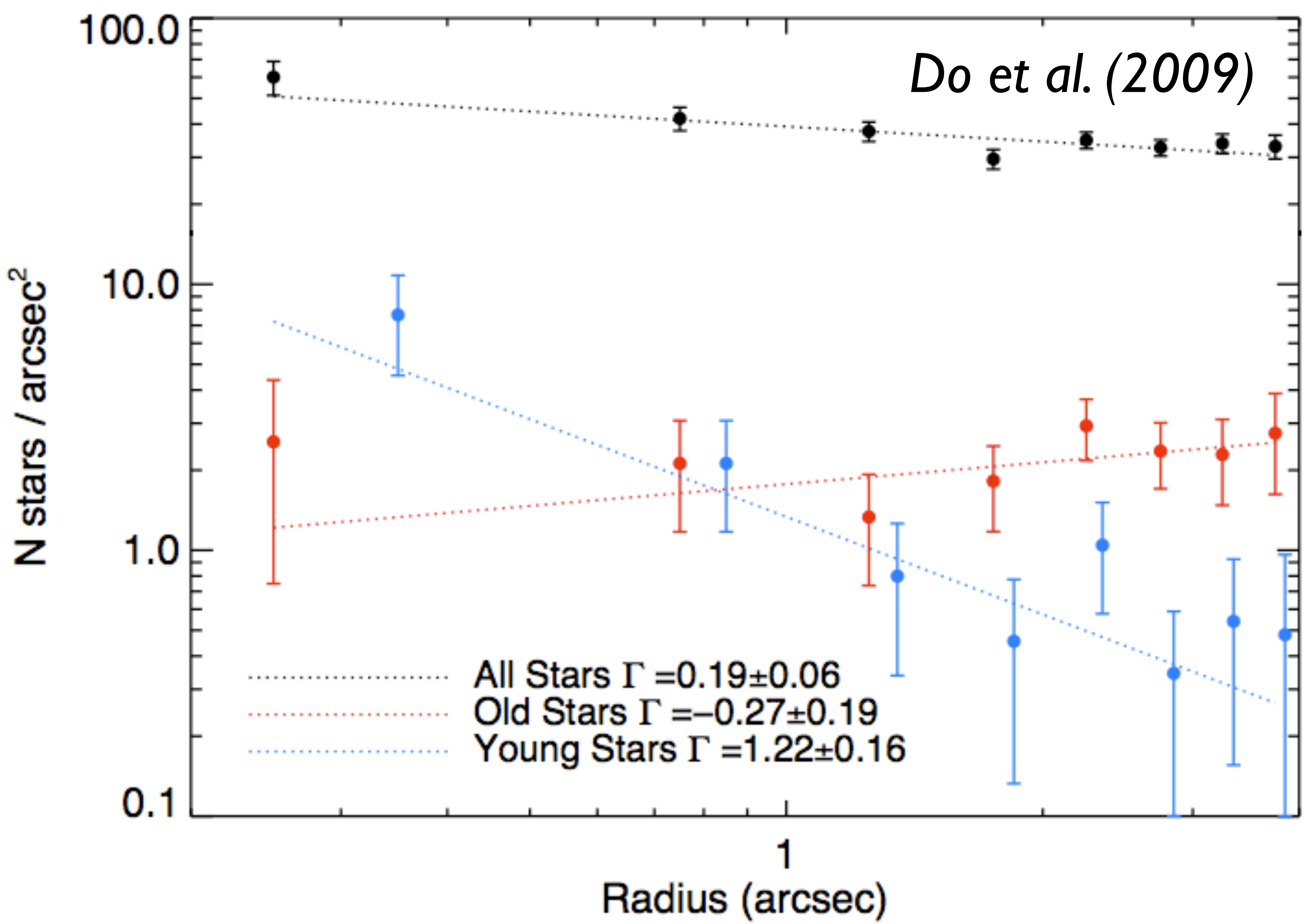


There is a deficit of old stars around Sgr A*.

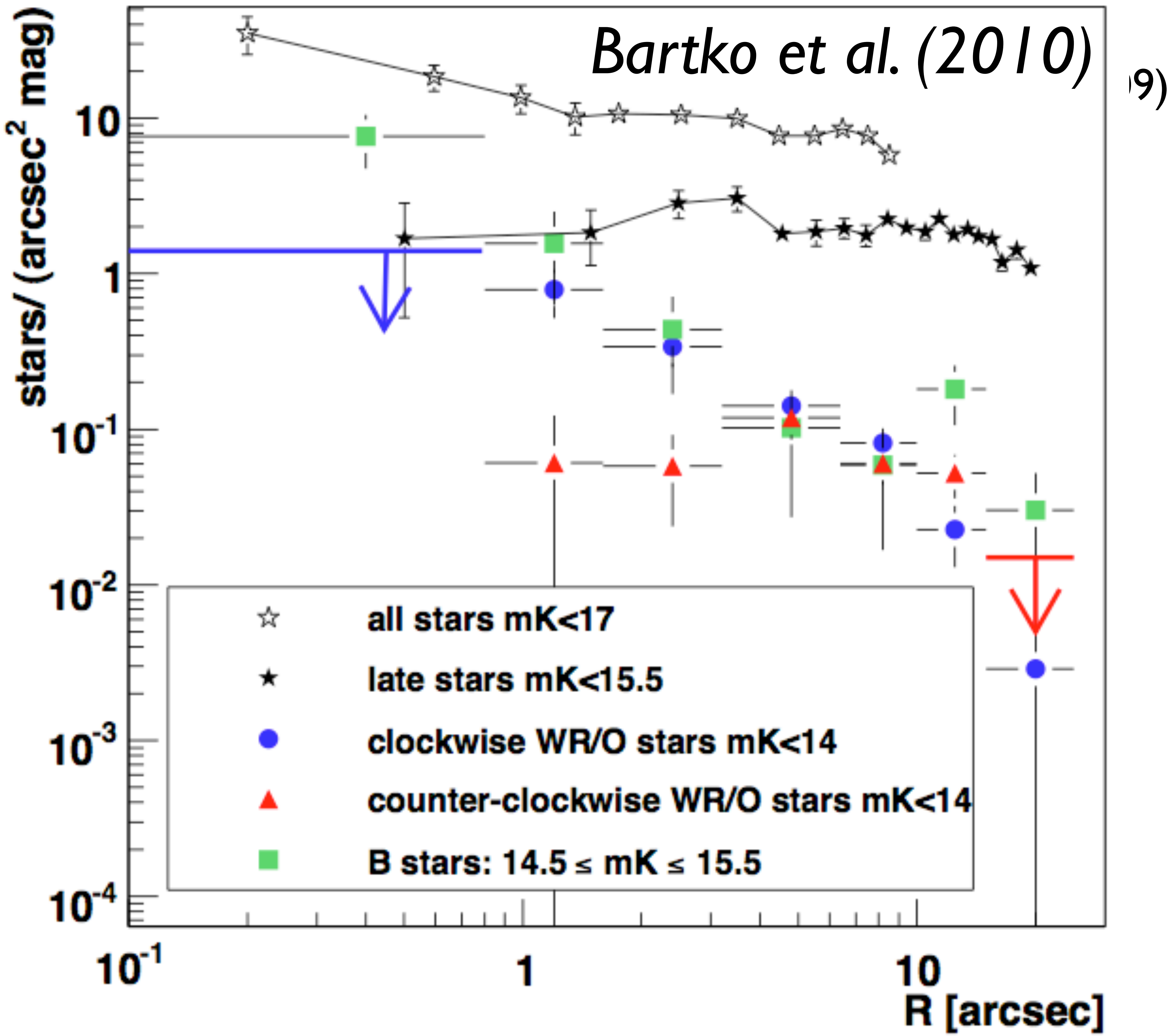
Known for the brightest (K<13) giants since the 1990s. The new measurements show that there is also a deficit of the lower mass RC giants near Sgr A*.

(Sellgren+ 1990; Genzel+ 1996; Haller+1996; first indication for RC stars given in Genzel+ 2003)

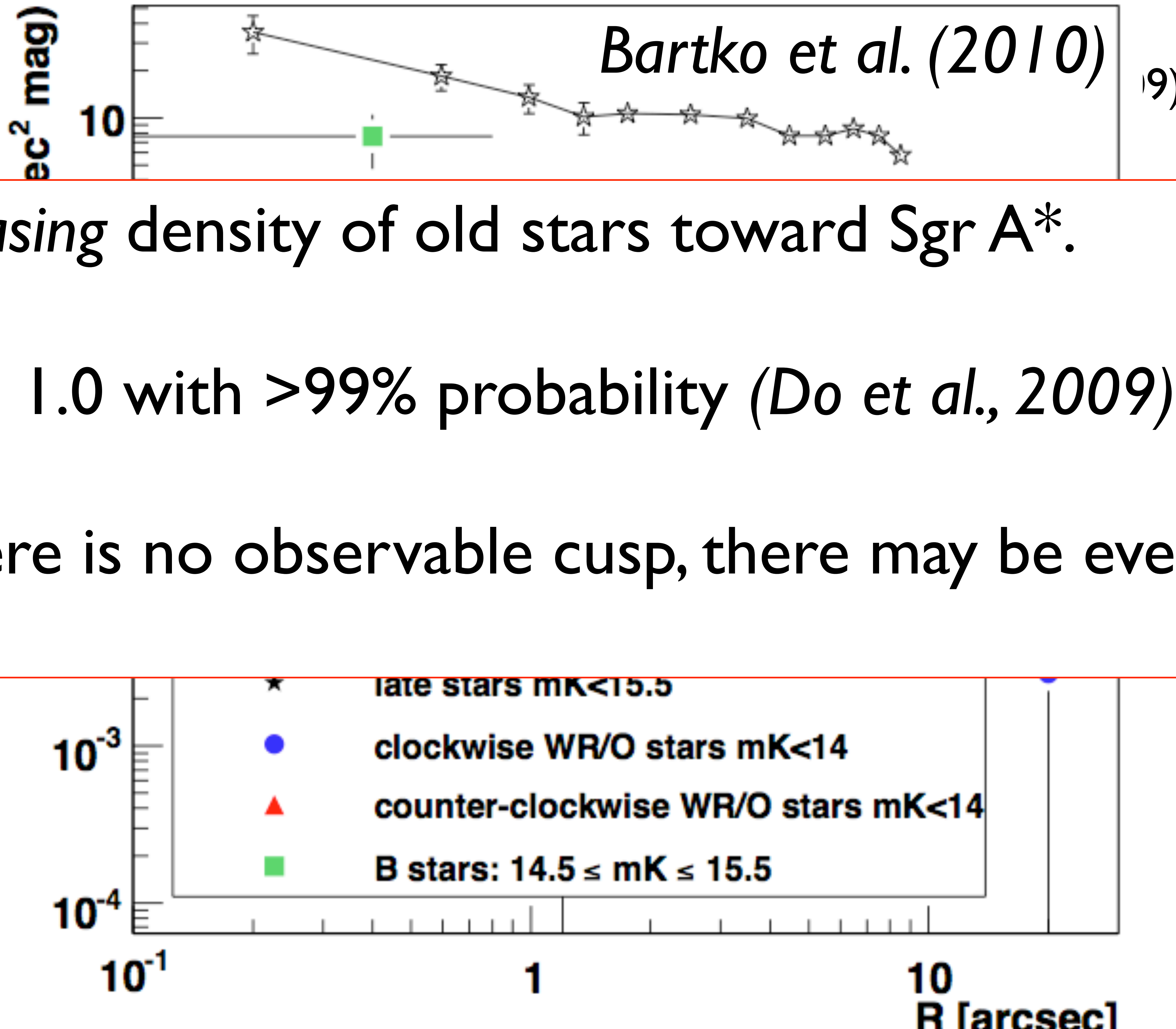
Spectroscopic studies of late-type stars at the GC



Spectroscopic studies of late-type stars at the GC



Spectroscopic studies of late-type stars at the GC



Decreasing density of old stars toward Sgr A*.

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

➔ There is no observable cusp, there may be even a hole.

Where is the stellar cusp at the GC?

- Destroyed:
  e.g., by infall of IMBH up to a few 10^9 yr ago

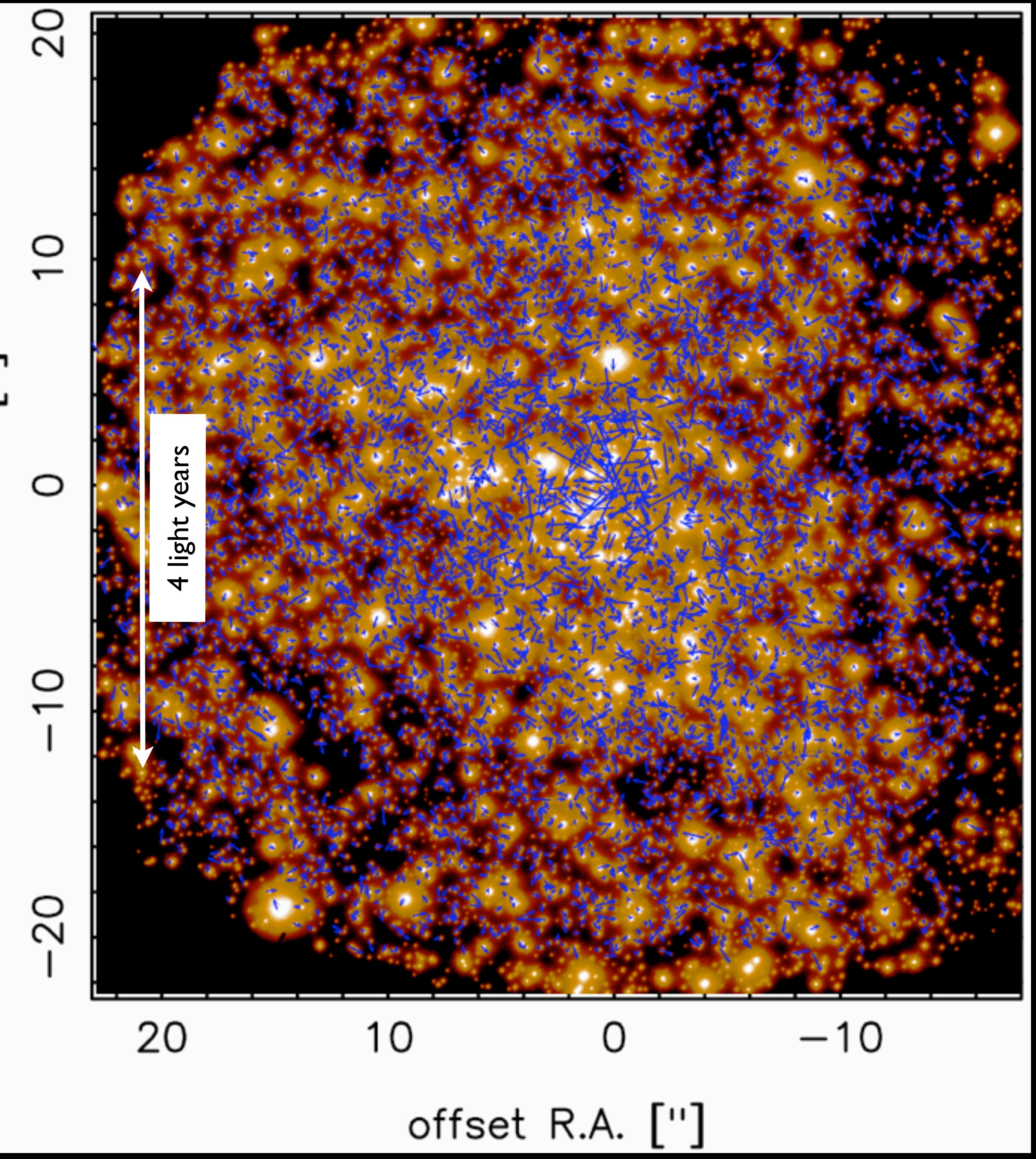
- Not yet formed:
  necessary time scale may be longer than ~10^{10} yr *(Merritt 2009)*

- Invisible:
  giants could be destroyed by collisions with MS stars and BHs in dense cluster center; however, mechanism probably not effective enough *(Dale+ 2009)*

- Are our assumptions correct?
  Continuous star formation, cluster not old enough?, cluster embedded in nuclear bulge, fraction of disrupted star accreted onto BH?, etc.

Kinematics and Mass in the Central Parsec

Kinematics

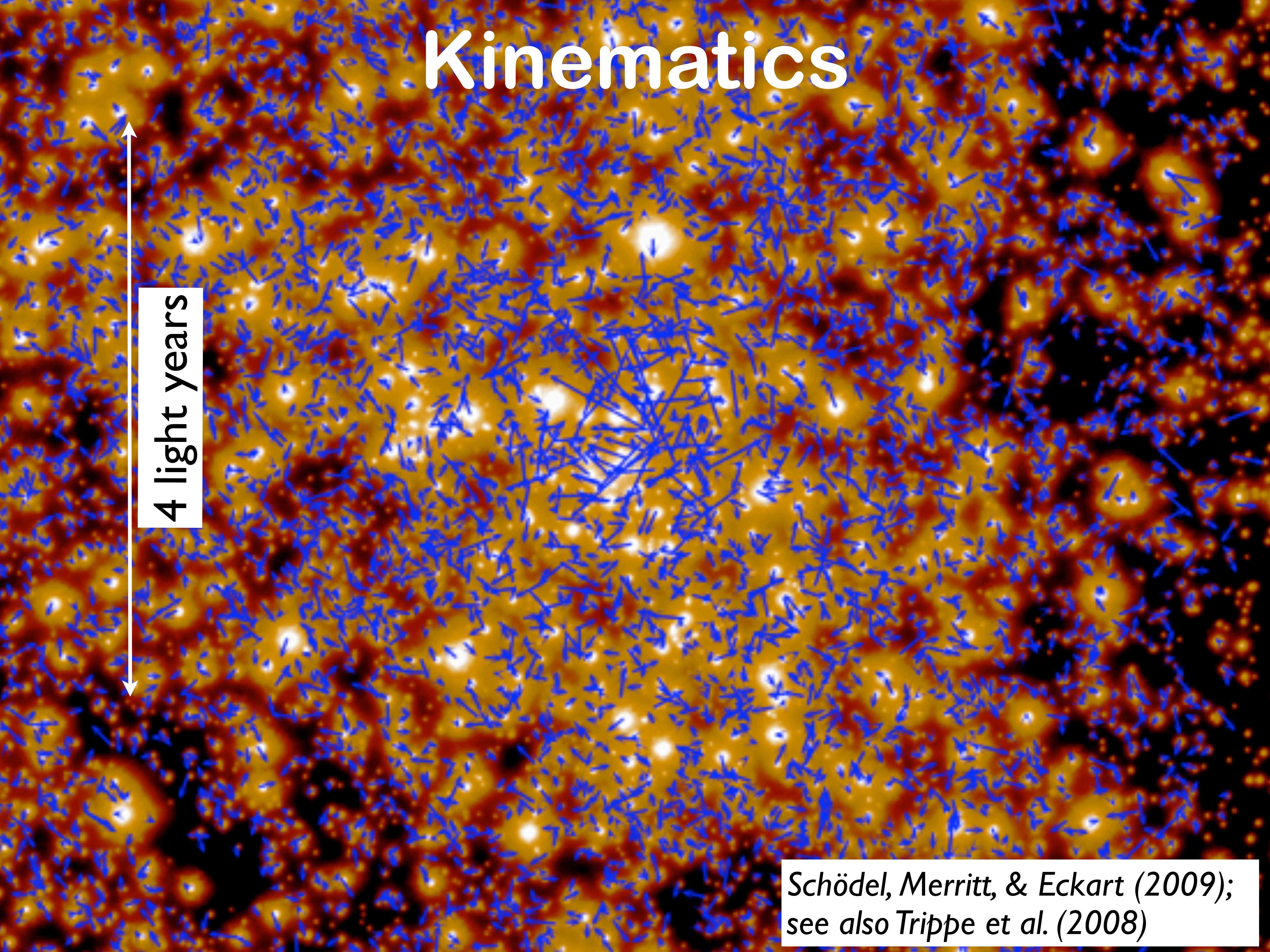


6000 proper motions within 1 pc of Sgr A*, data from Schoedel+ (2009) publicly available.

Based on10 images taken between 2002 and 2008.

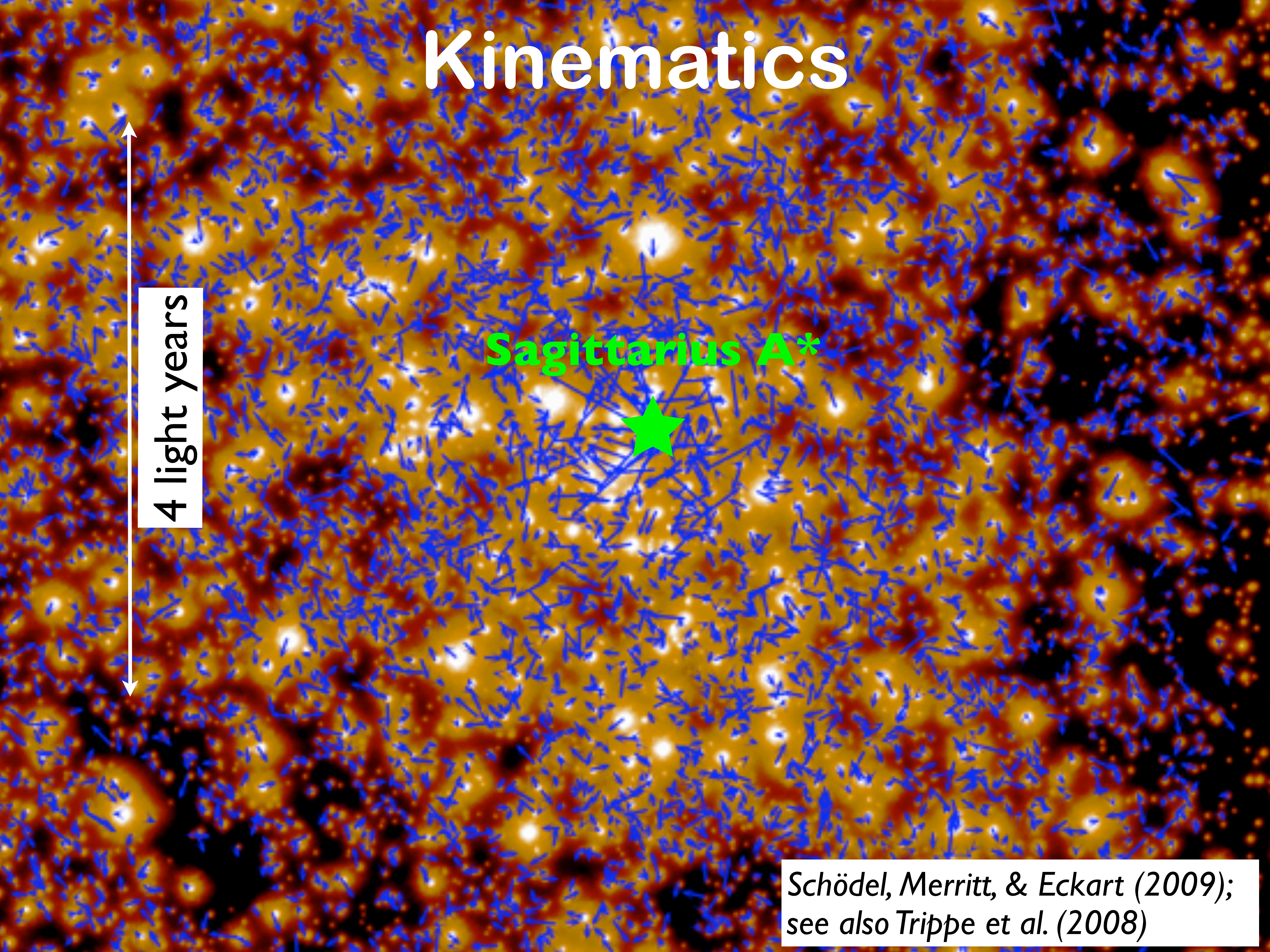
Schödel, Merritt, & Eckart (2009); see also Trippe et al. (2008)

Kinematics

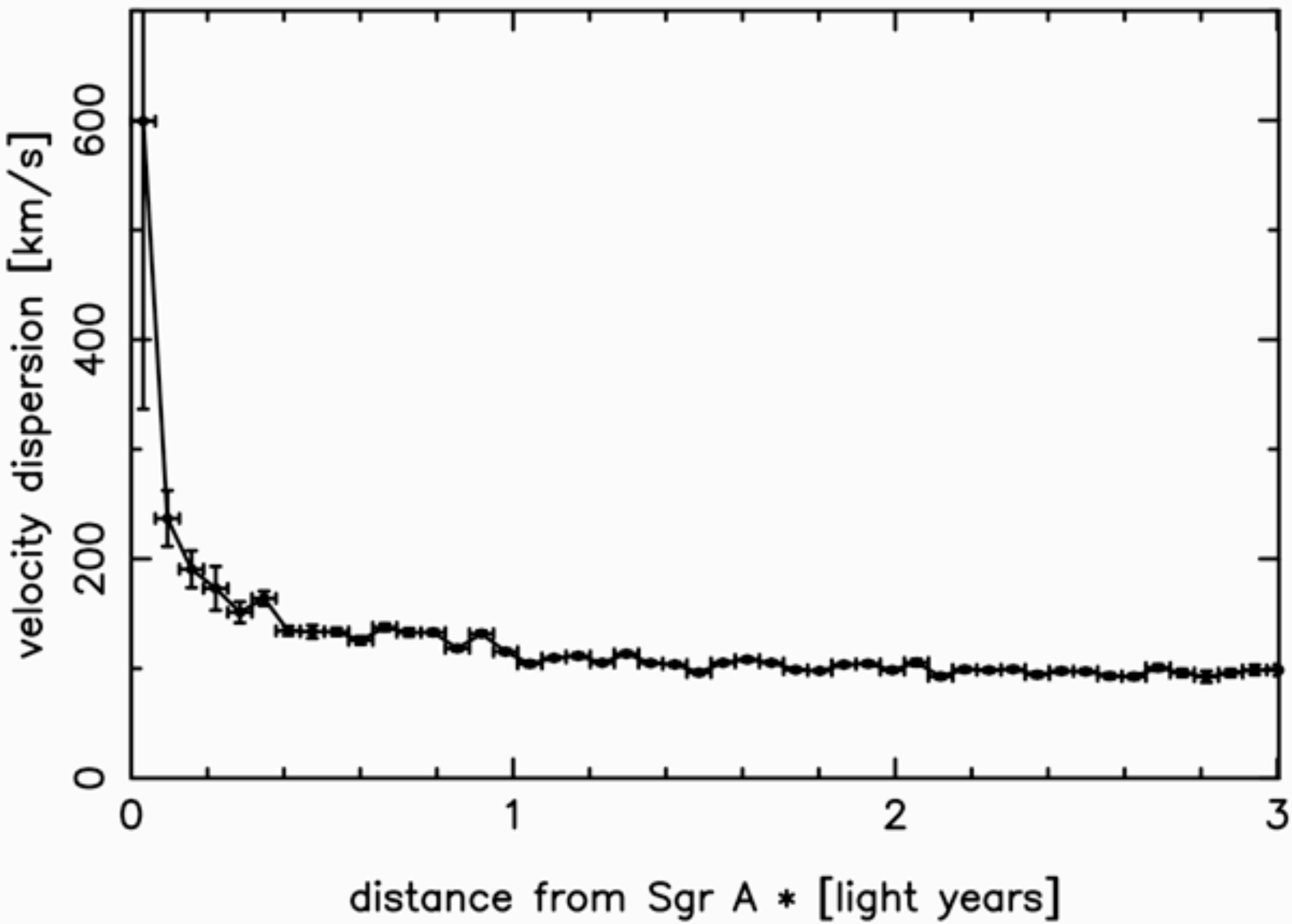


Schödel, Merritt, & Eckart (2009); see also Trippe et al. (2008)

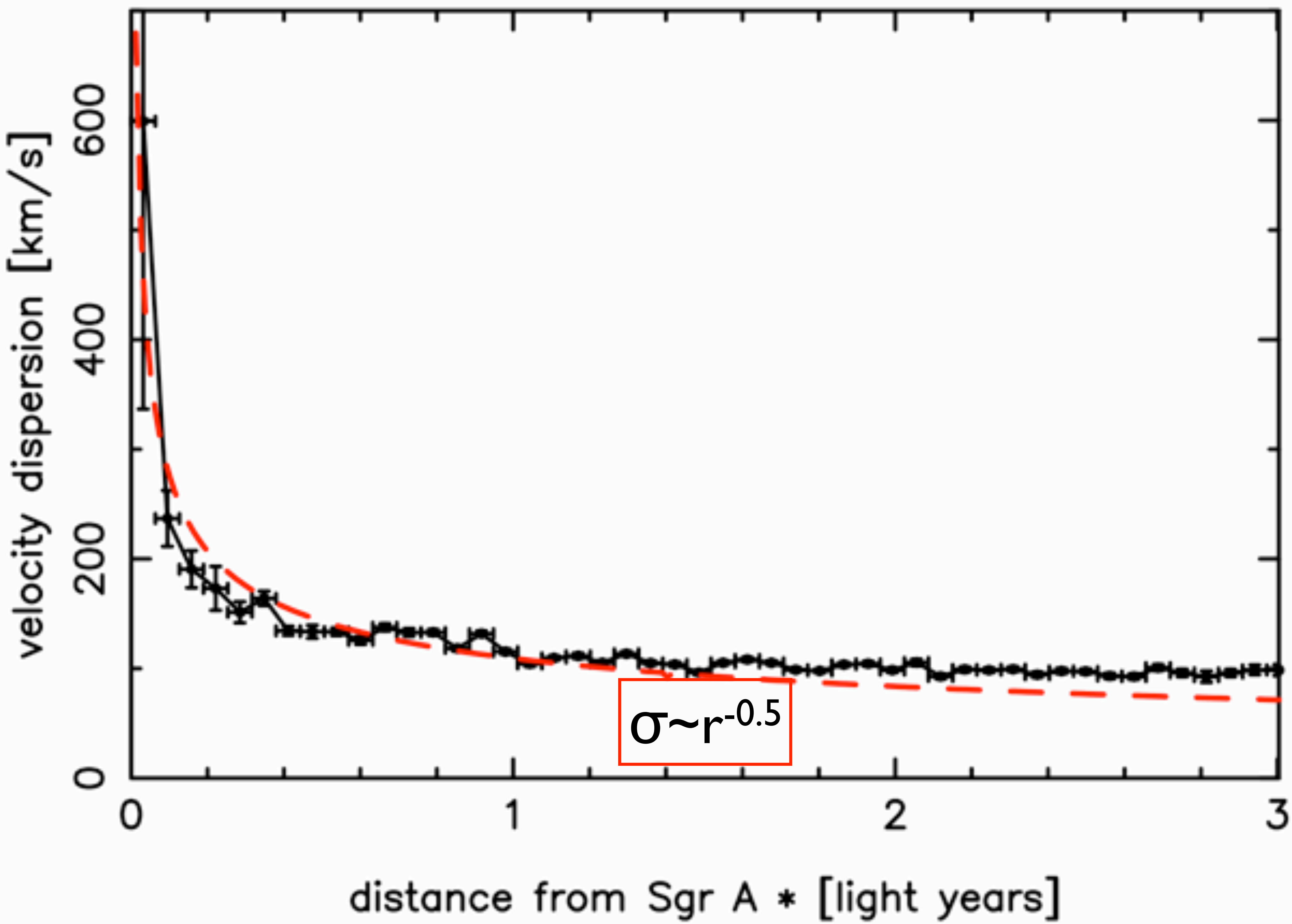
Kinematics


4 light years
Sagittarius A*
Schödel, Merritt, & Eckart (2009); see also Trippe et al. (2008)

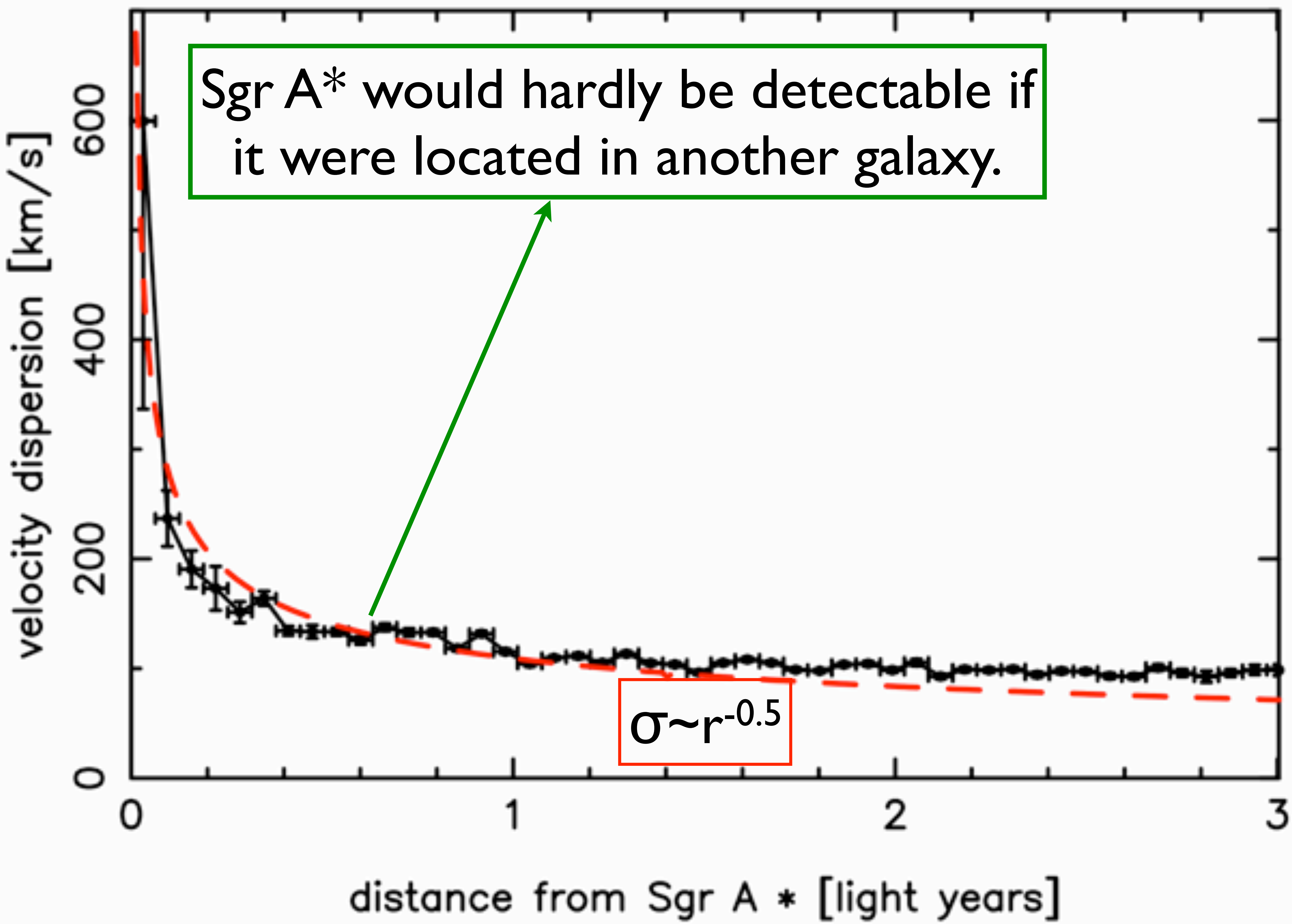
Velocity dispersion at the Galactic Center



Velocity dispersion at the Galactic Center



Velocity dispersion at the Galactic Center



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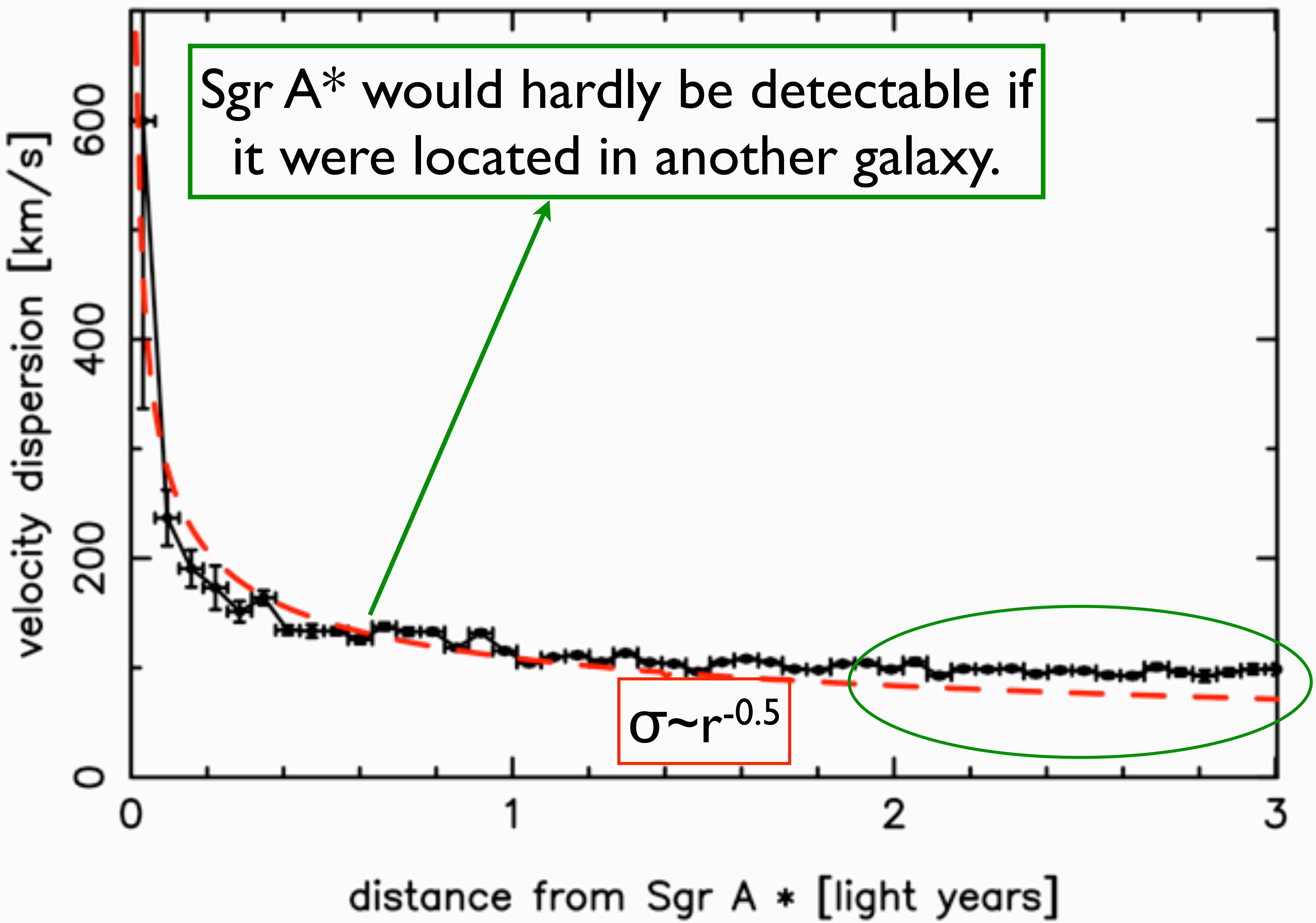
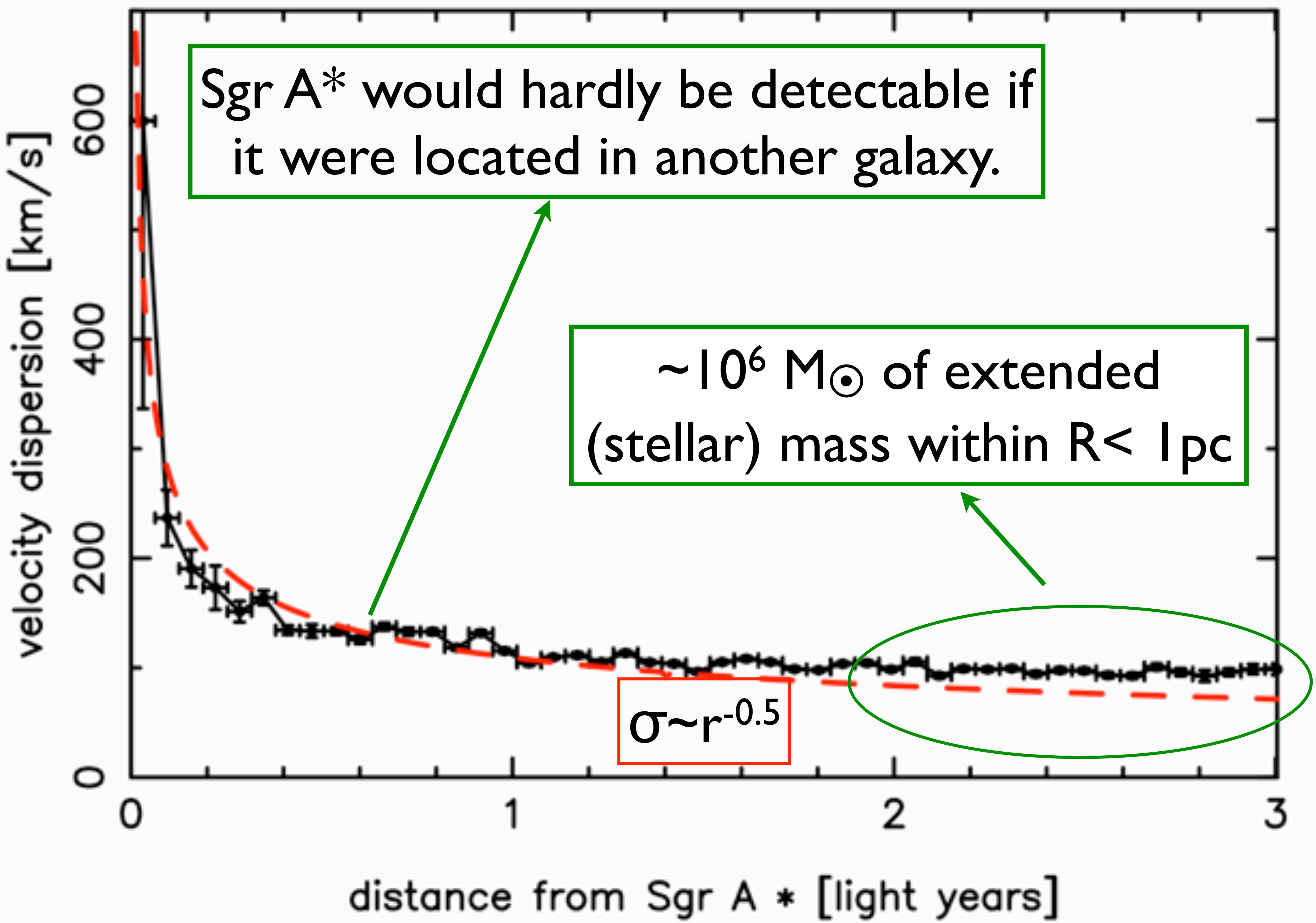


Velocity dispersion at the Galactic Center



Enclosed mass at R < 1 pc

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

- **Mass *distribution* hardly constrained**: Models allow even a decrease toward Sgr A*.

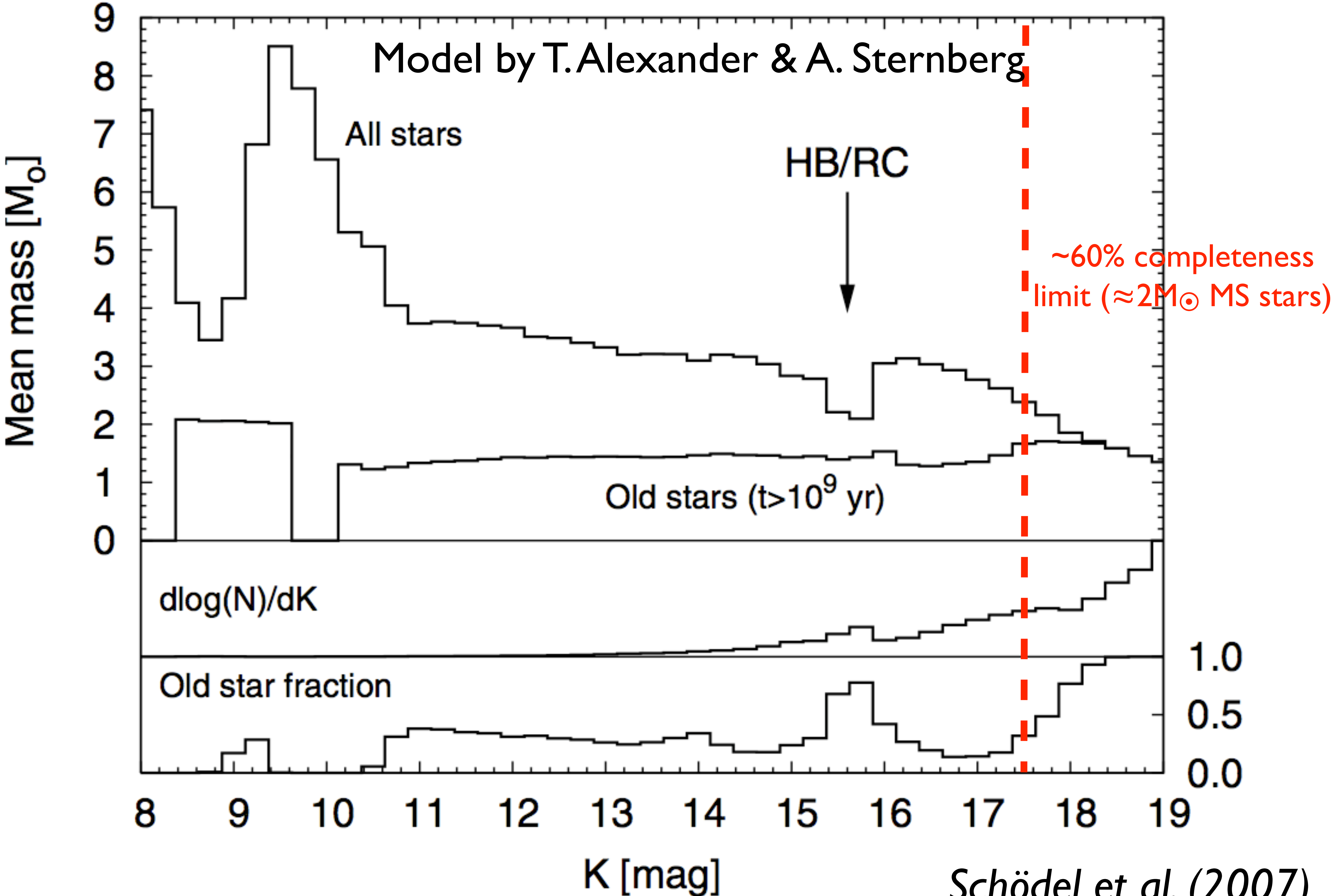
- If mass density rises toward the black hole, then $M_\star(r<1pc) > 0.5\times10^6\ M_\odot$

- If M/L = const then $M_\star(r<1pc) \approx 1.5\times10^6\ M_\odot$

- Major sources of uncertainty:
cluster structure on large scales, symmetry and isotropy of cluster, mass *distribution* in central parsec

see Schödel, Merritt, & Eckart (2009, A&A)
see also, but note differences with, Trippe+ 2008

What do we observe at the GC?



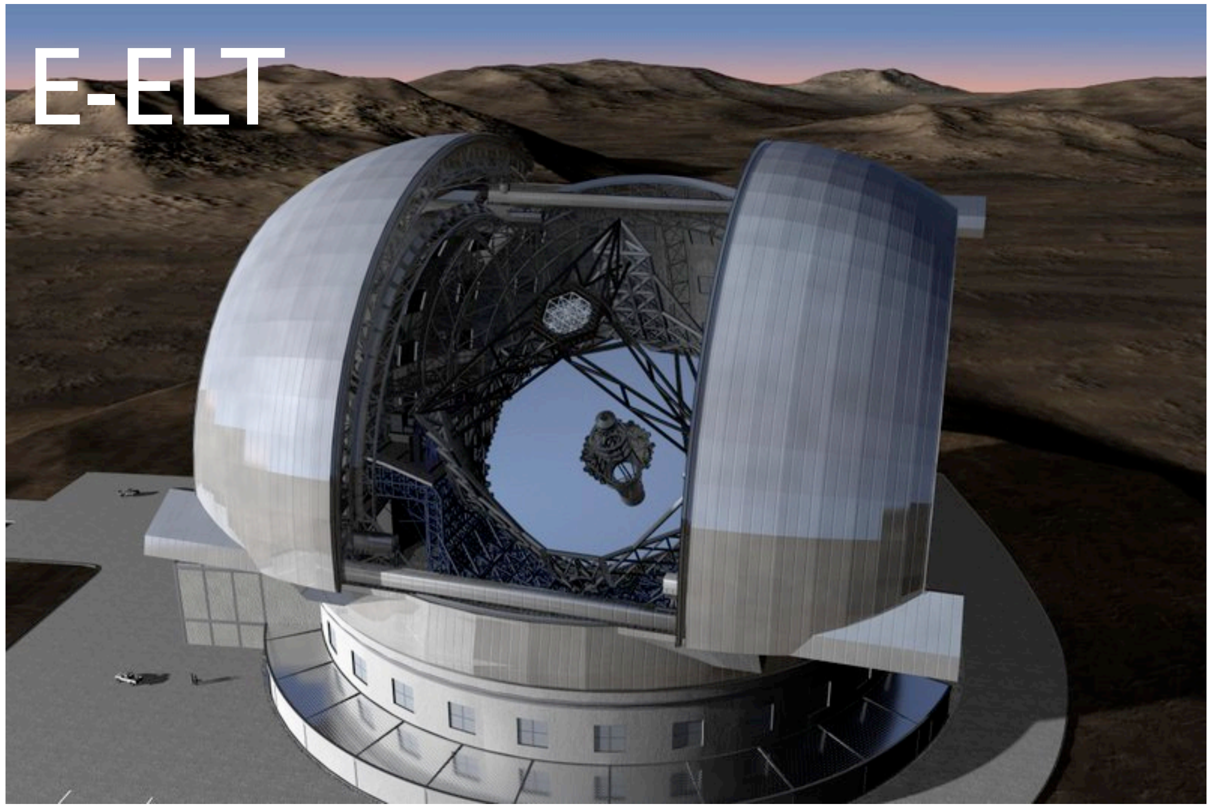
Schödel et al. (2007)

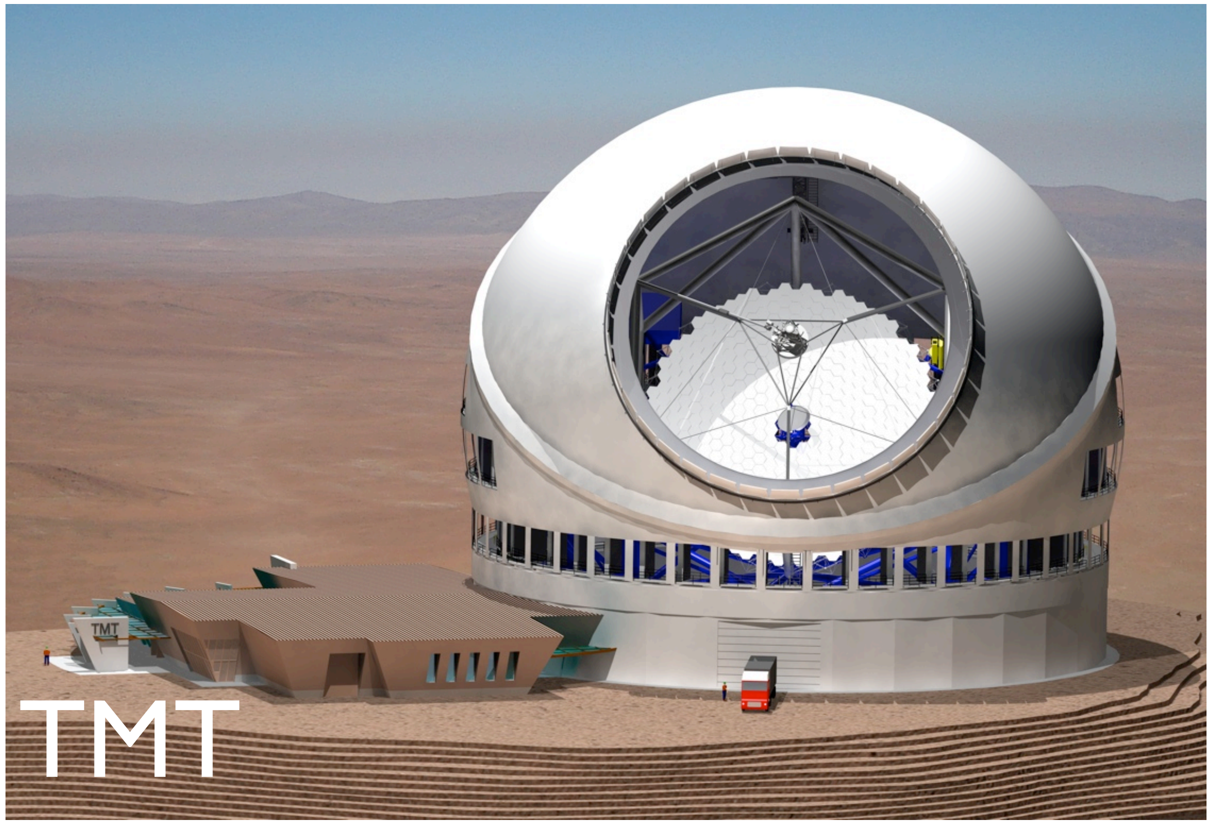
What do we observe at the GC?

Source:Wikipedia
Created by Uwe Kils (iceberg) and User:Wiska Bodo (sky).

A Look into the Future…

...in the near-infrared...





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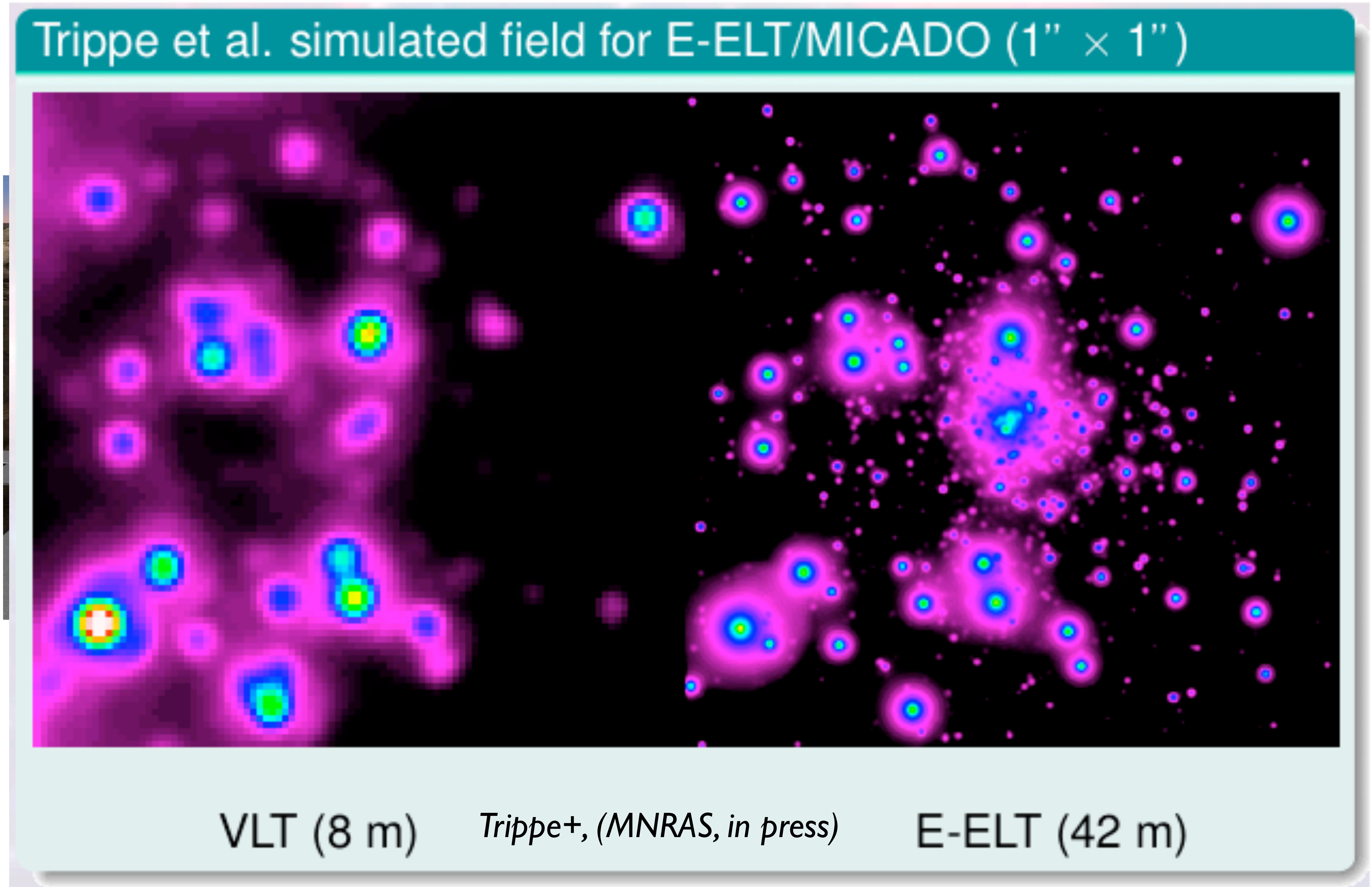

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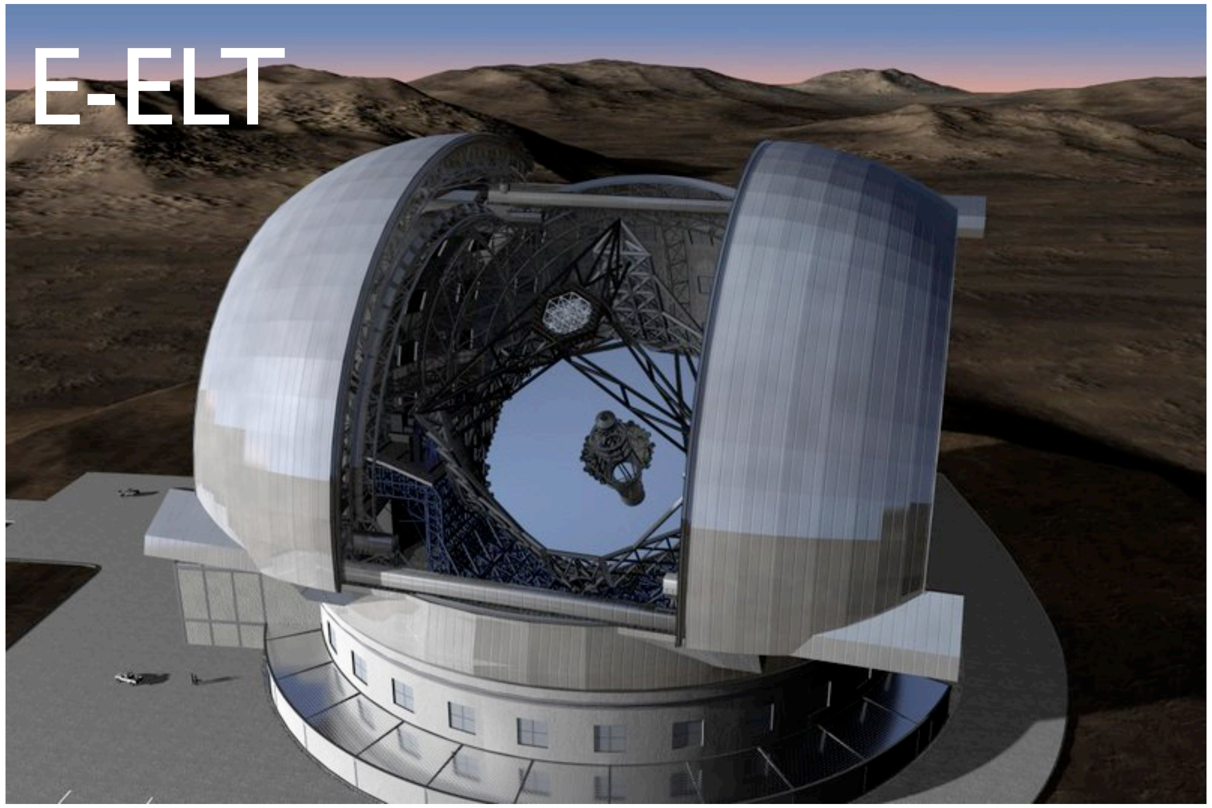

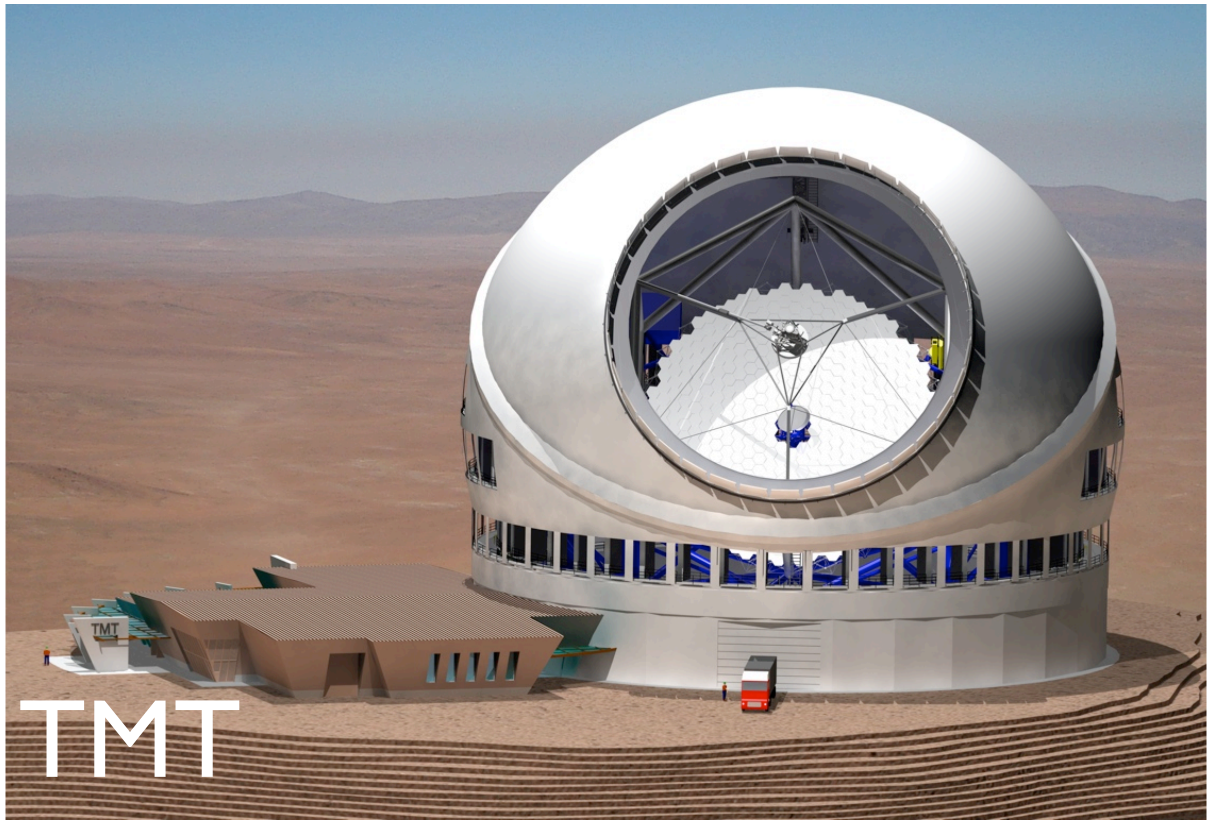

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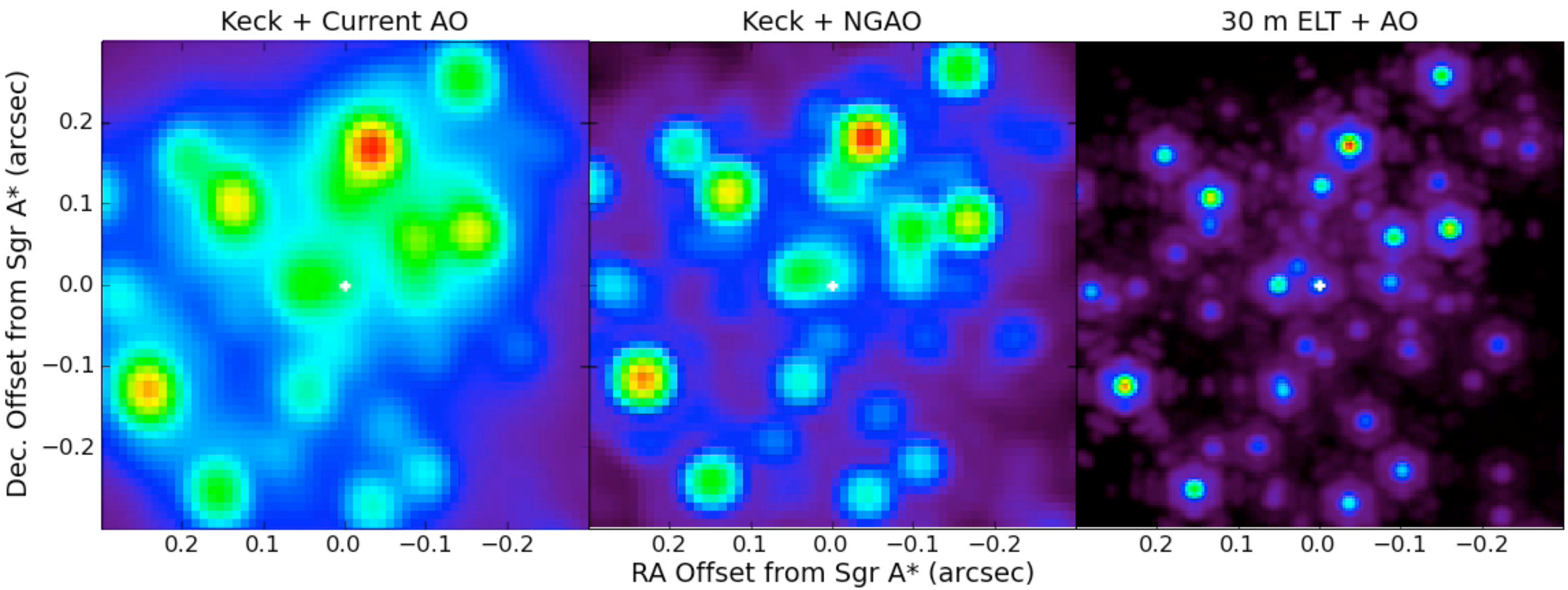

http://www.astro.ucla.edu/~ghezgroup/gc/pictures/Future_GCorbits.shtml

Thank you!