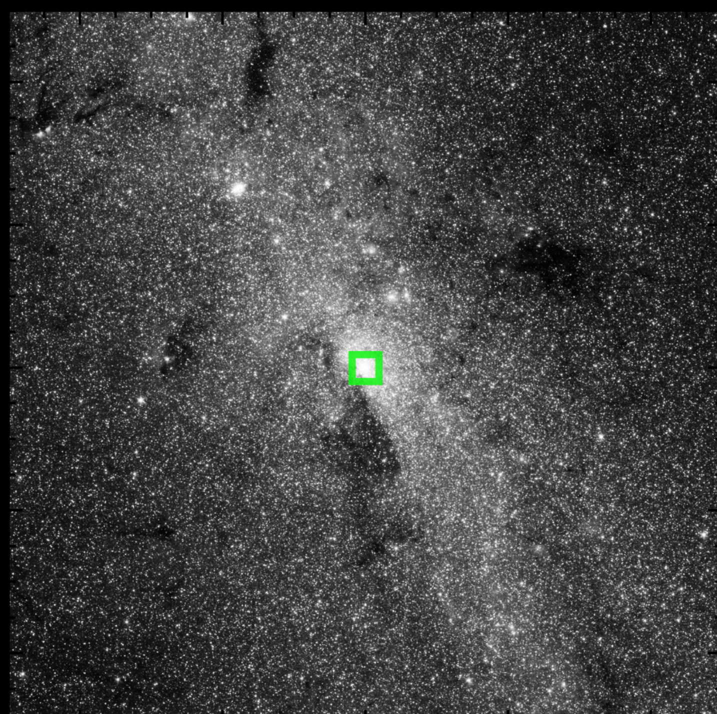
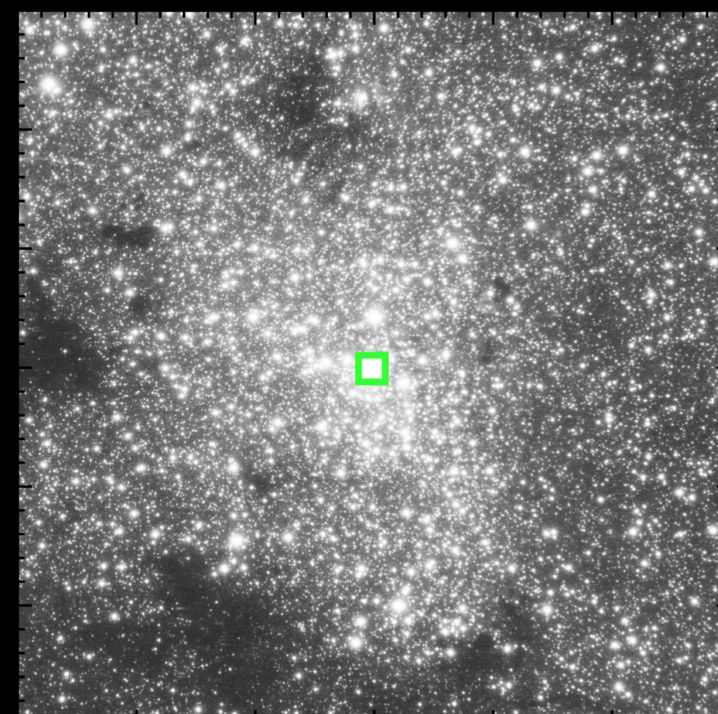
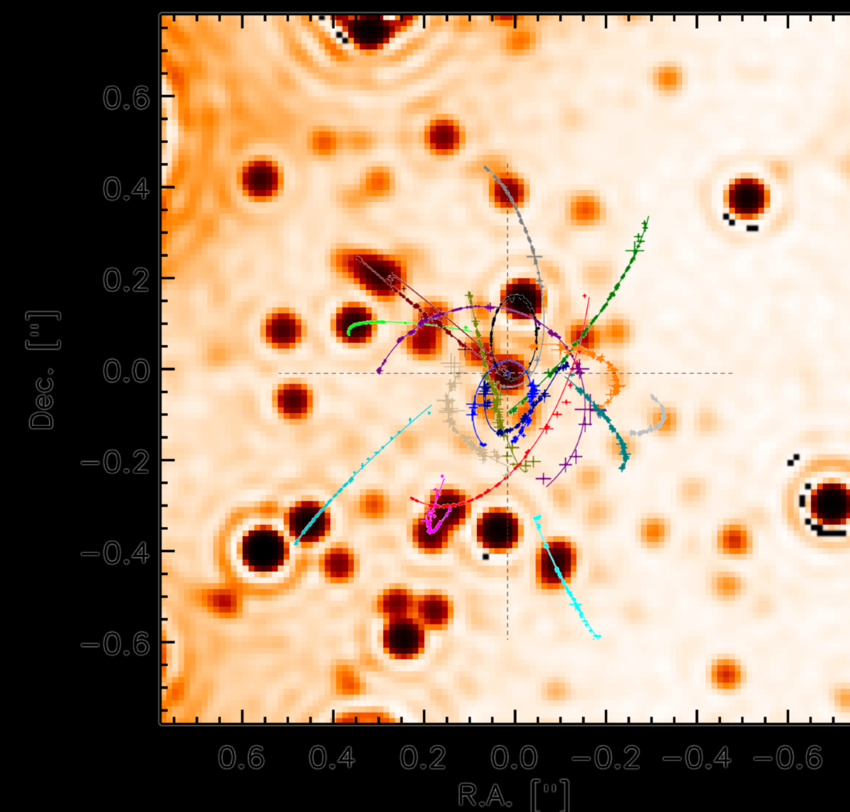
The Galactic Center and Gravitational Waves

in memoriam Tal Alexander







Rainer Schödel - IAA (CSIC)
2nd Institute of Space Sciences
Summer School
IEEC, Barcelona, 7 July 2018

European Research Council
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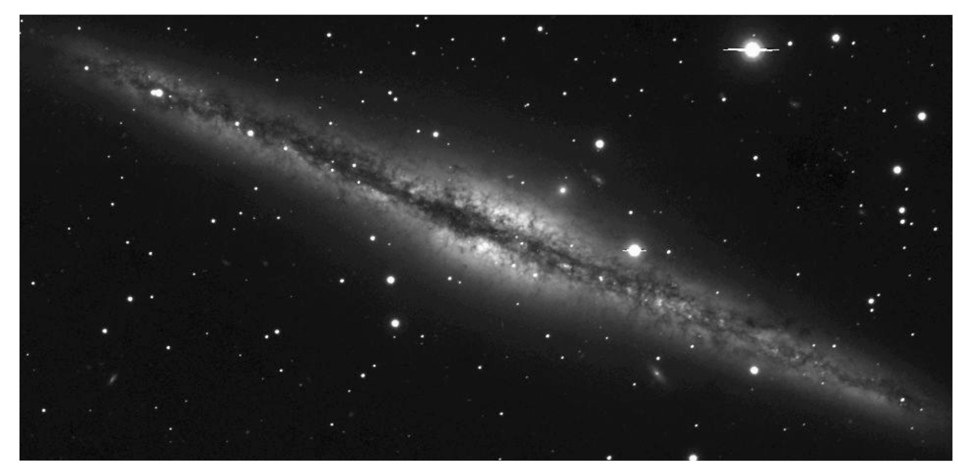
1. Galactic nuclei
2. Dynamics near a massive black hole
3. GW sources in Galactic nuclei
4. The center of the Milky Way
5. The stellar cusp around Sgr A*
6. GW events from GC-like nuclei

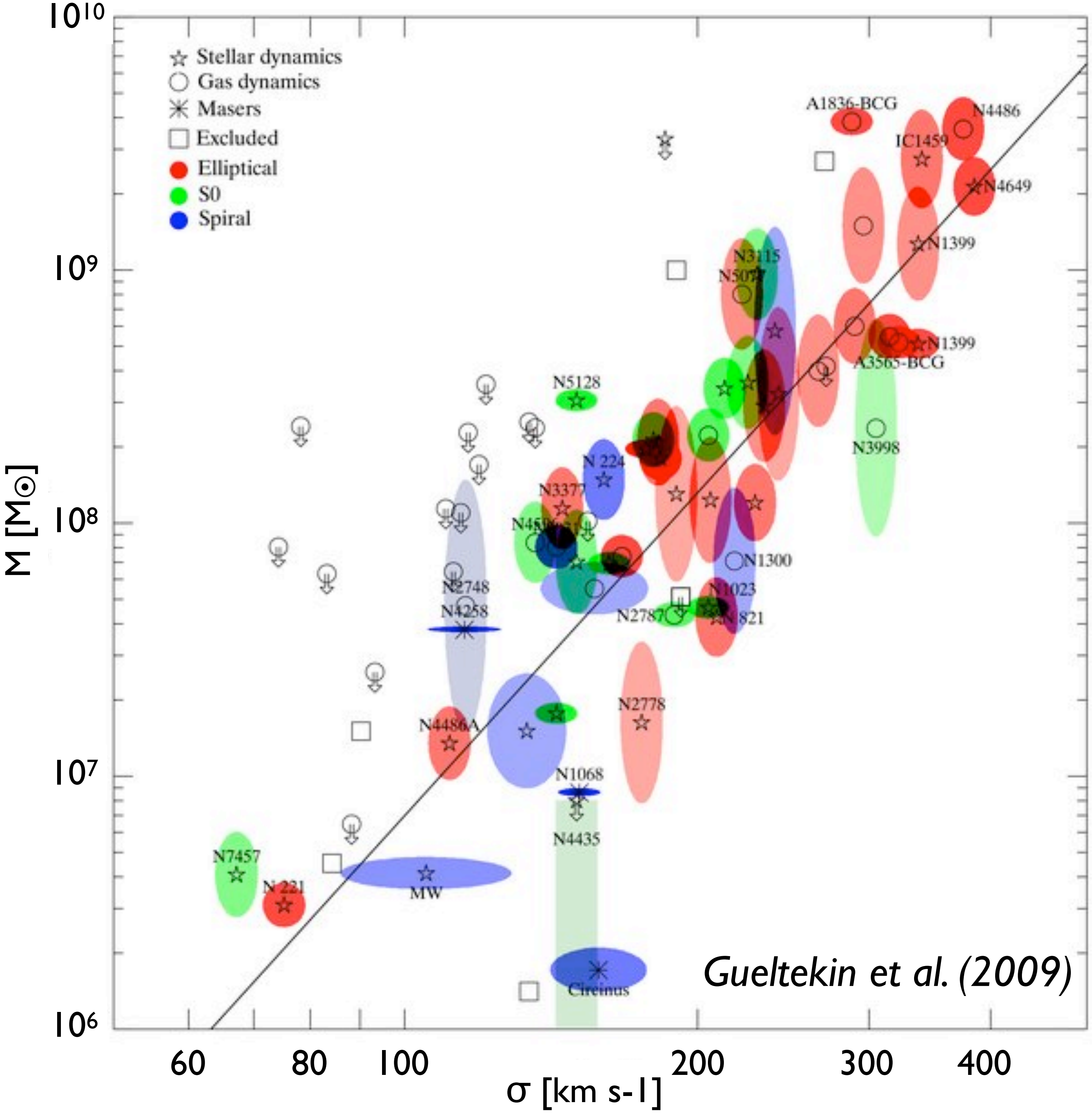
1. Galactic nuclei

Nuclei of galaxies
=
super massive black holes + nuclear star clusters

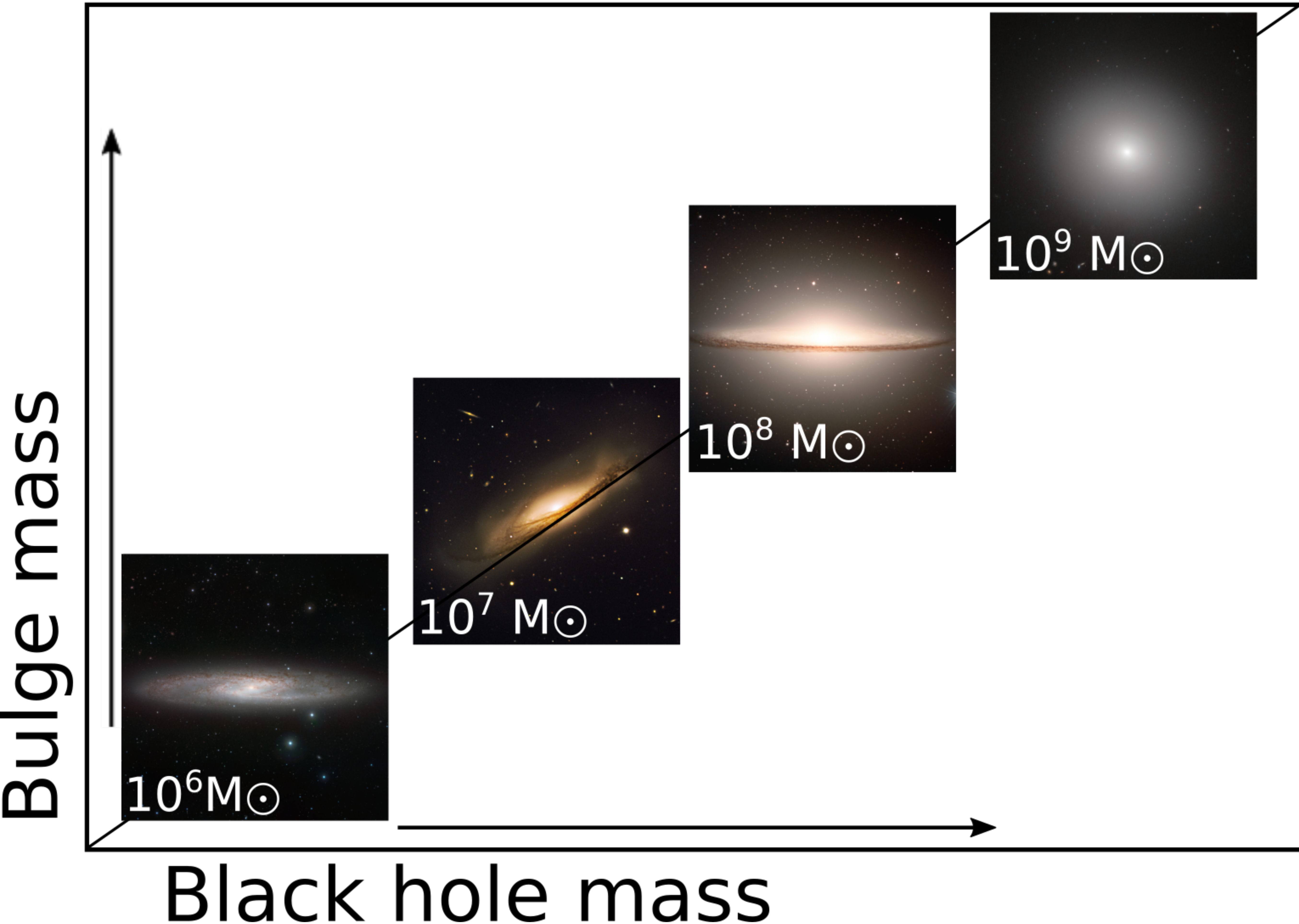




(Super)Massive Black Holes



see also Haering & Rix (2004), Tremaine et al. (2002), Ferrarese & Merritt (2000), Magorrian et al. (1998) ...



Bulge mass
Black hole mass
10^6M⊙
10^7 M⊙
10^8 M⊙
10^9 M⊙

Nuclear star clusters

Animation Credit: NASA, Z. Levay and G. Bacon (STScI)

Nuclear star clusters

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Nuclear Star Clusters (NSCs)

NSCs detected *unambiguously* in 50%-75% of spiral, spheroids ("dwarf ellipticals"), and S0 galaxies. Actual rate of occurrence may be close to 100%.

NSCs absent in elliptical galaxies that are products of major mergers.

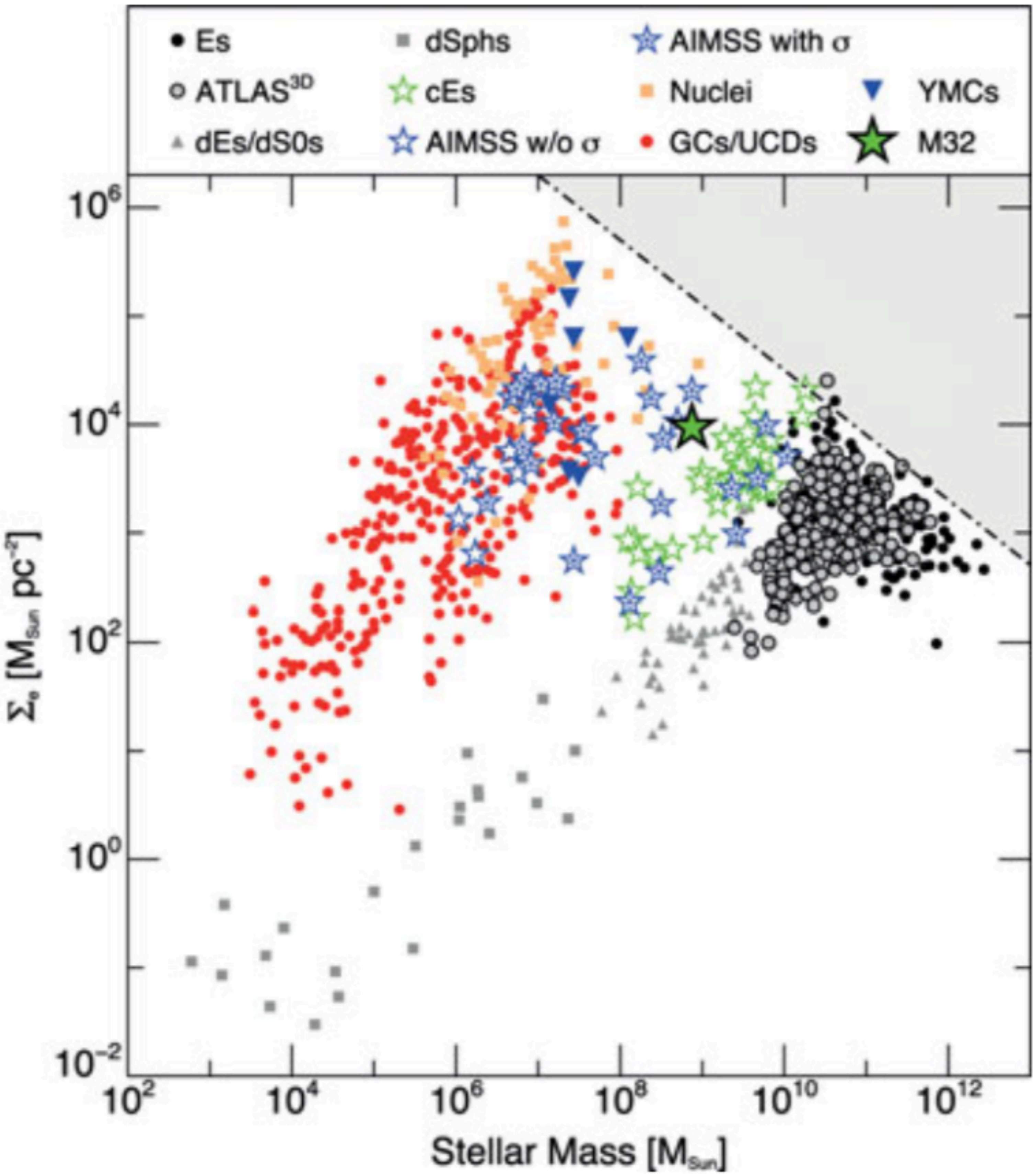
see also, e.g., Phillips+ 1996; Carollo+ 1998; Matthews+ 1999; Böker+ 2002, 2004; Balcells+ 2003; Ferrarese+ 2006; Kormendy+ 2009

Nuclear star clusters

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

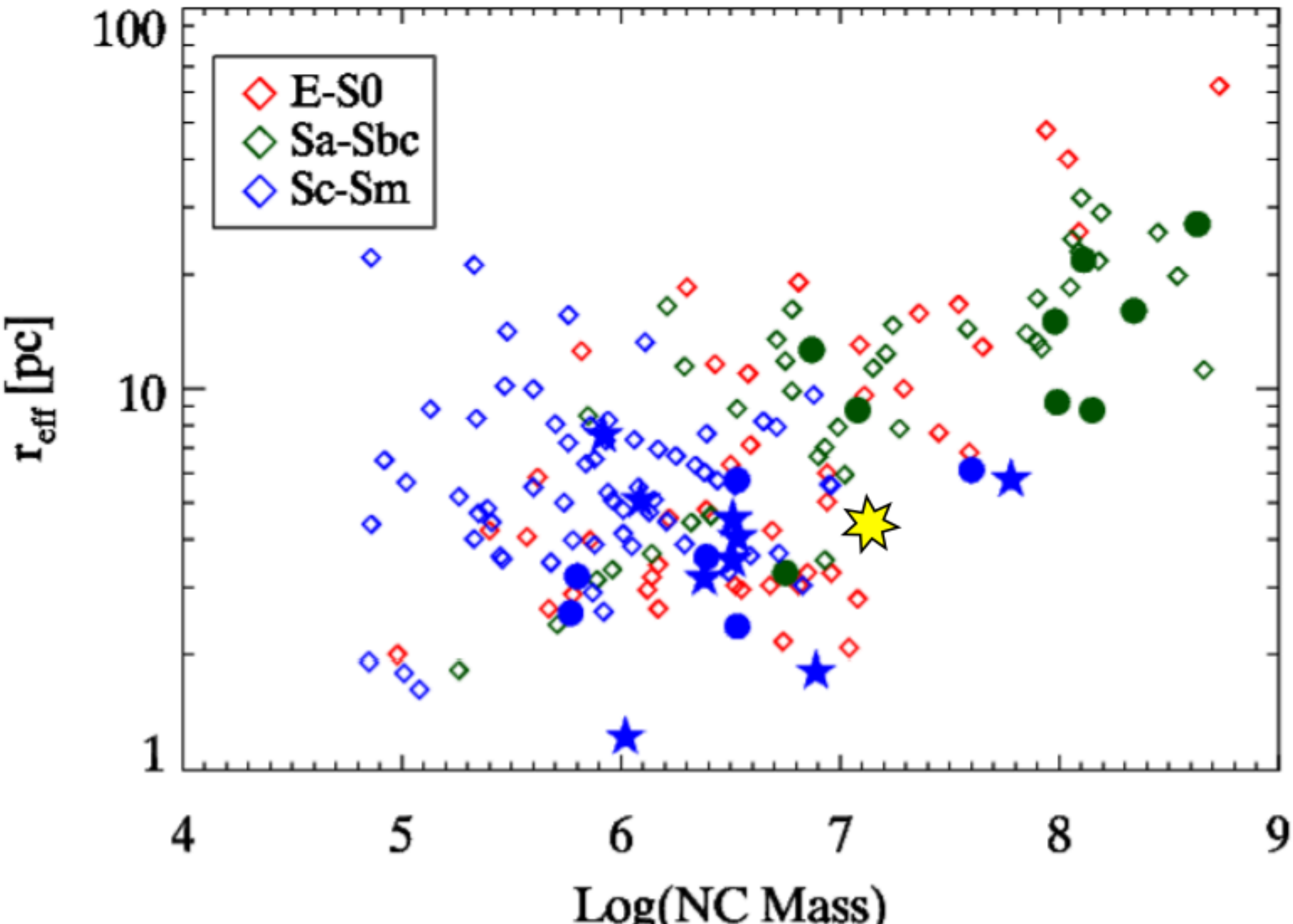
see, e.g., review by T. Böker (2008)

Nuclear star clusters



Norris et al. (2014)

The MW NSC in context



Seth et al. (2008), Feldmeier et al. (2014), Schödel et al. (2014)

2. Dynamics near a MBH

Dynamical relaxation near a MBH

BH radius of influence: r_h

$-GM_\bullet/r_h = \phi(r_h)$, with $\phi(r_h)$ potential without BH

Singular isothermal distribution: $\rho_\star = \sigma^2/2\pi G r^2 \Rightarrow r_h = GM_\bullet/\sigma^2$

Stellar mass inside rh is $\mathcal{O}(M_\bullet)$.

At $r \ll rh$, $N_\star M_\star/M_\bullet \ll 1$

For $r \gg r_g$, dynamics are Newtonian over timescales $\gg P = 2\pi \sqrt{(a^3/GM_\bullet)}$

Parameters:

- $Q = M_\bullet/\langle\langle M_\star\rangle\rangle, \langle\langle M^2{}_\star\rangle\rangle^{1/2}$
- $N_\star(r) = N_h\ (r/r_h)^{3-\alpha}$ with $n(r)\sim r^{-\alpha}$

Dynamical relaxation near a MBH

Non-resonant (NR) relaxation, two-body relaxation

$$T_{\rm NR}(r) = \frac{\sigma^2}{\langle \Delta v^2 \rangle} \sim \frac{\sigma^3}{G^2 M_\star^2 n_\star \log \Lambda} \sim \frac{Q^2 P(r)}{N_\star(r) \log Q}$$

For mass spectrum $M^2_\star n_\star \rightarrow \langle M^2_\star \rangle n_\star$

$\langle M^2_\star \rangle \geq \langle M_\star \rangle^2 \Rightarrow$ faster relaxation for system with realistic mass spectrum. Presence of massive perturbers (GMC, IMBHs) will greatly accelerate relaxation

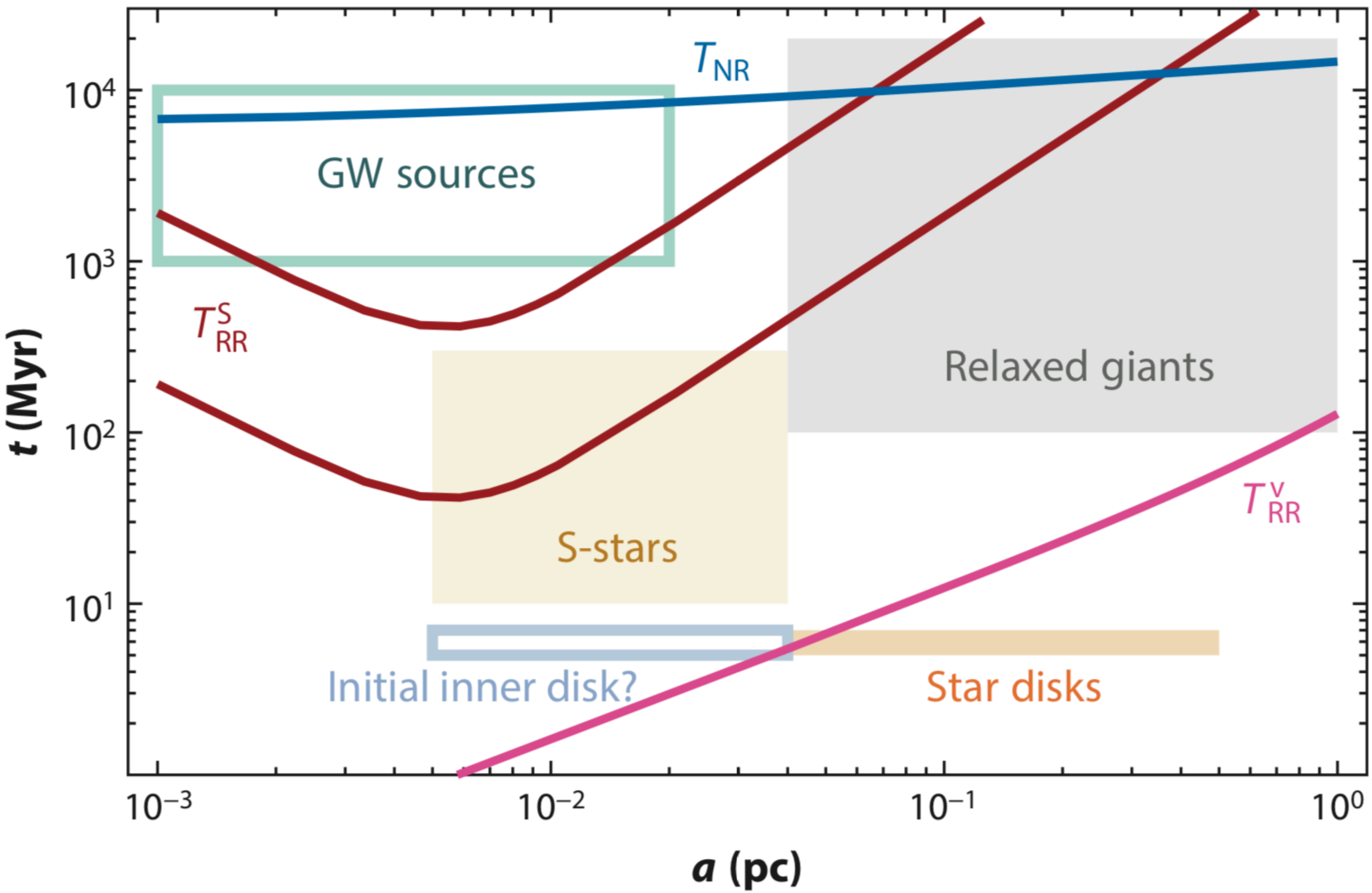
Nuclei with MBH $\lesssim$ a few 10^7 $M_\odot$ that evolve in isolation, will be dynamically relaxed (Bar-Or et al. 2013; Alexander 2017).

Dynamical relaxation near a MBH

$r \ll r_h \rightarrow$ stars move on fixed ellipses around MBH
Approximation by "mass wires"

Residual torques $\Rightarrow$ rapid angular momentum relaxation:

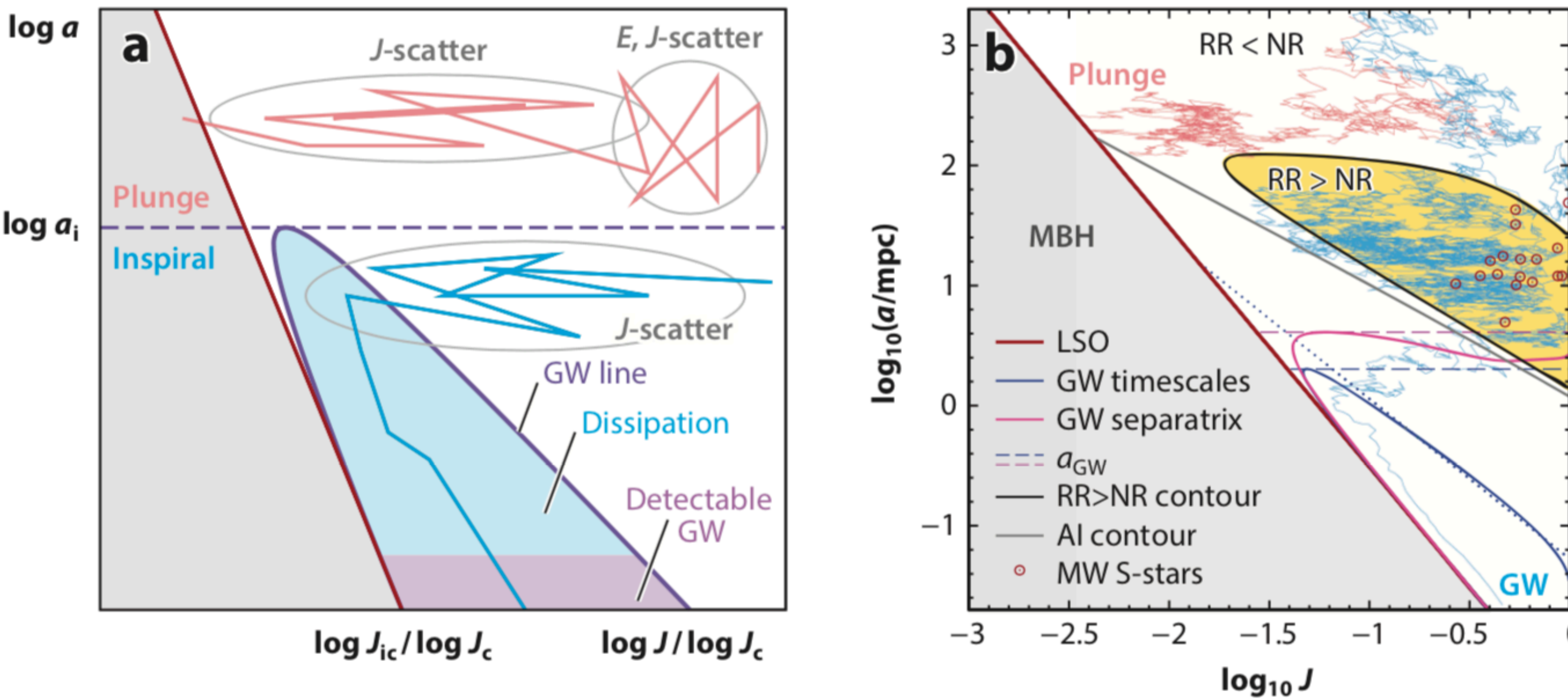
Scalar Resonant Relaxation (SRR)
$T_{SRR} \ll T_{NR}$



Presence of massive stars will significantly shorten TNR *(Preto & Amaro-Seoane 2010)*.

Figure 3, Alexander (2017)

Dynamical relaxation near a MBH



Evolution in J much faster than in E for $J < J_c = \sqrt{(GM_\bullet/a)}$

Figure 3, Alexander (2017)

Formation of a stellar cusp

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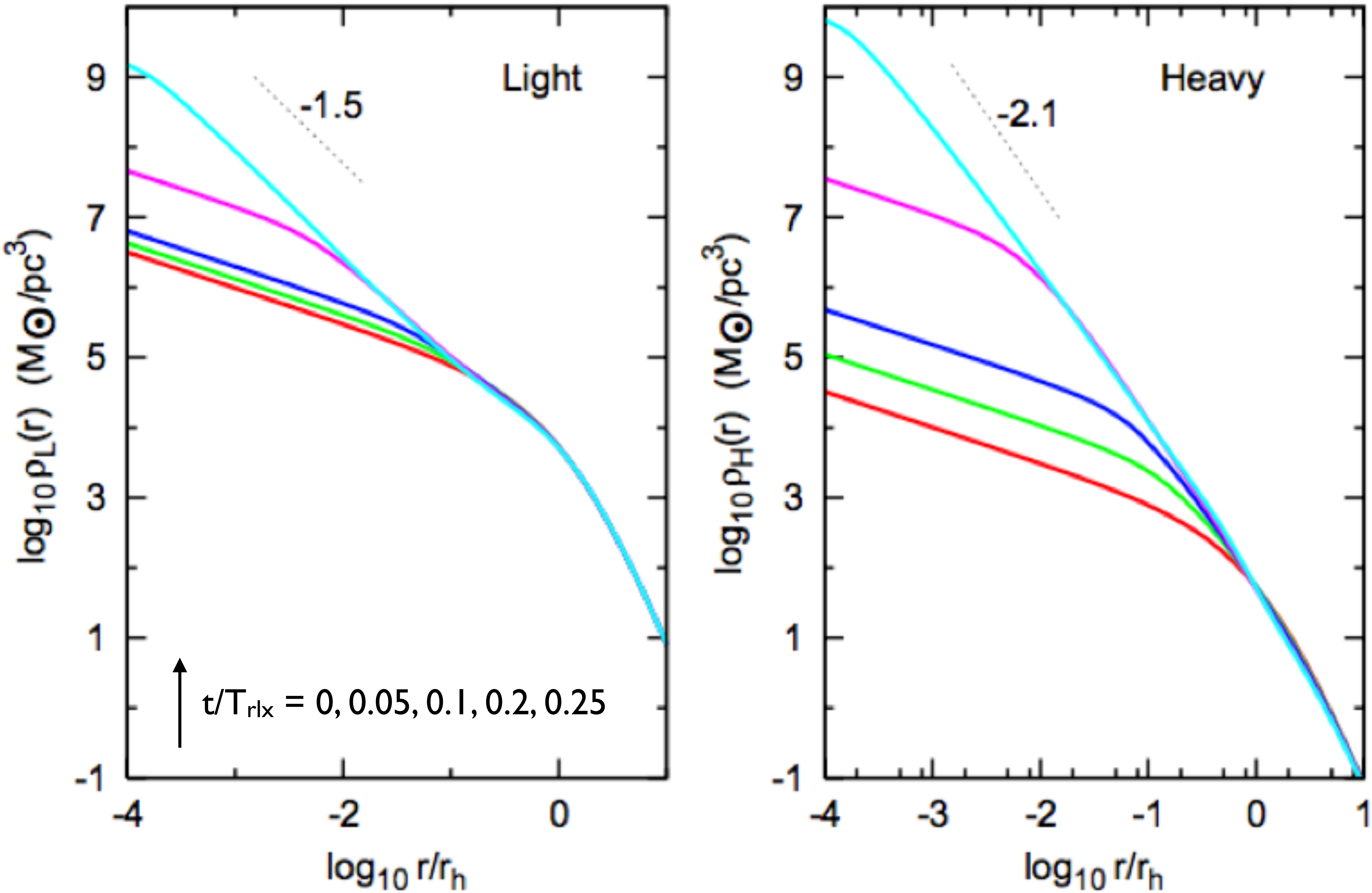

Preto & Amaro-Seoane (2010)

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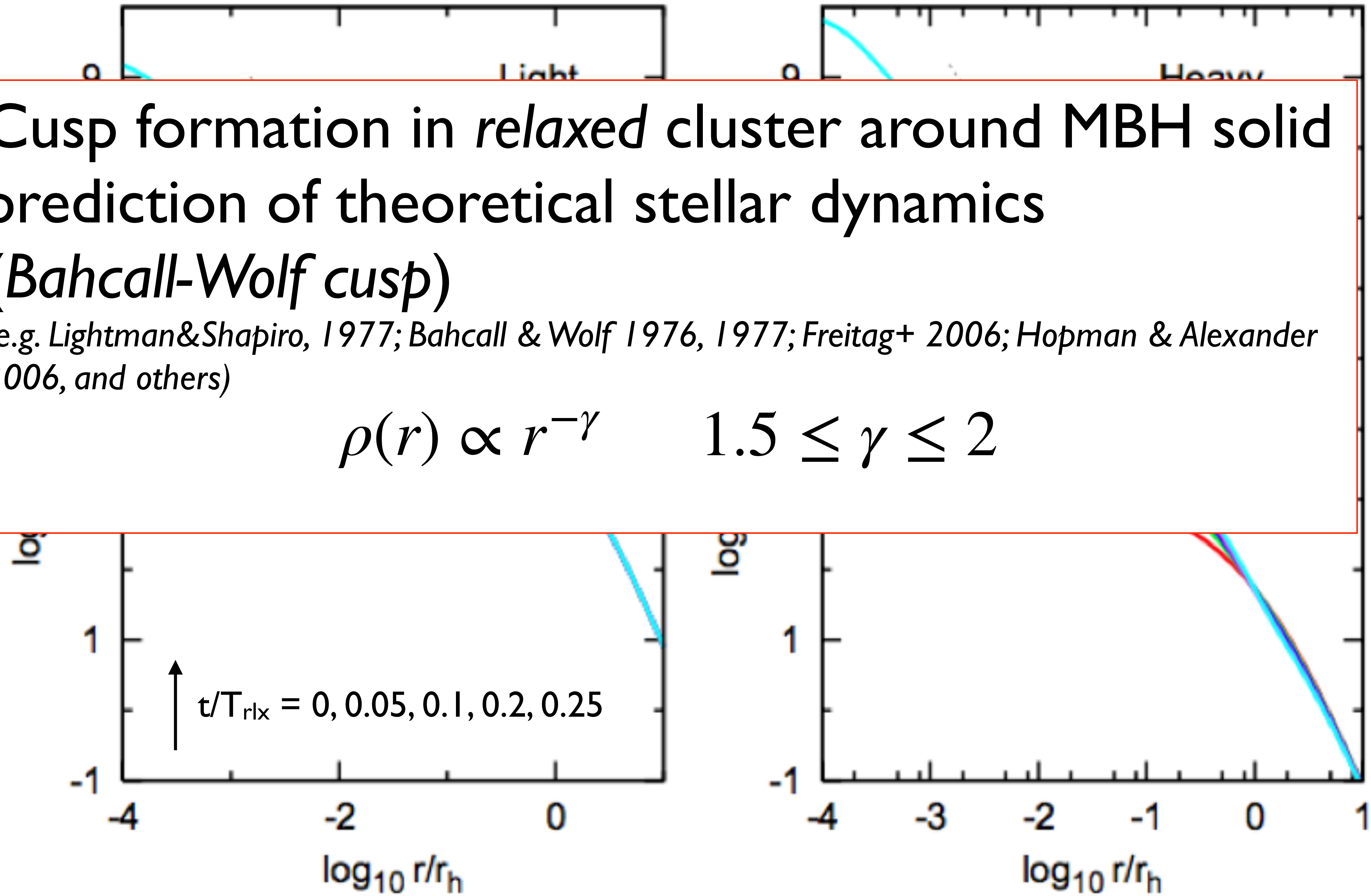

Cusp formation in *relaxed* cluster around MBH solid prediction of theoretical stellar dynamics (*Bahcall-Wolf cusp*)

(e.g. Lightman&Shapiro, 1977; Bahcall & Wolf 1976, 1977; Freitag+ 2006; Hopman & Alexander 2006, and others)

$$\rho(r) \propto r^{-\gamma} \qquad 1.5 \leq \gamma \leq 2$$

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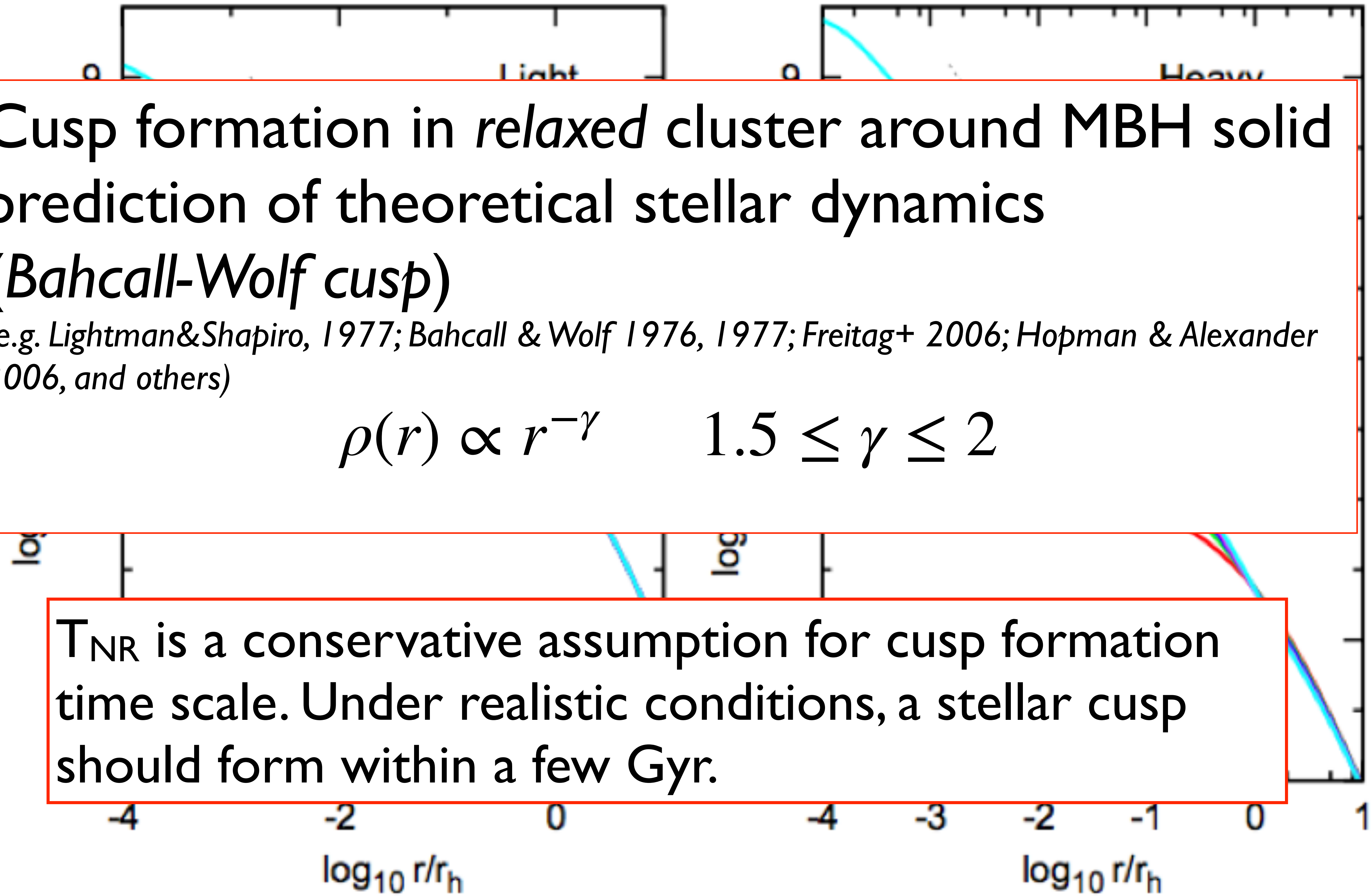

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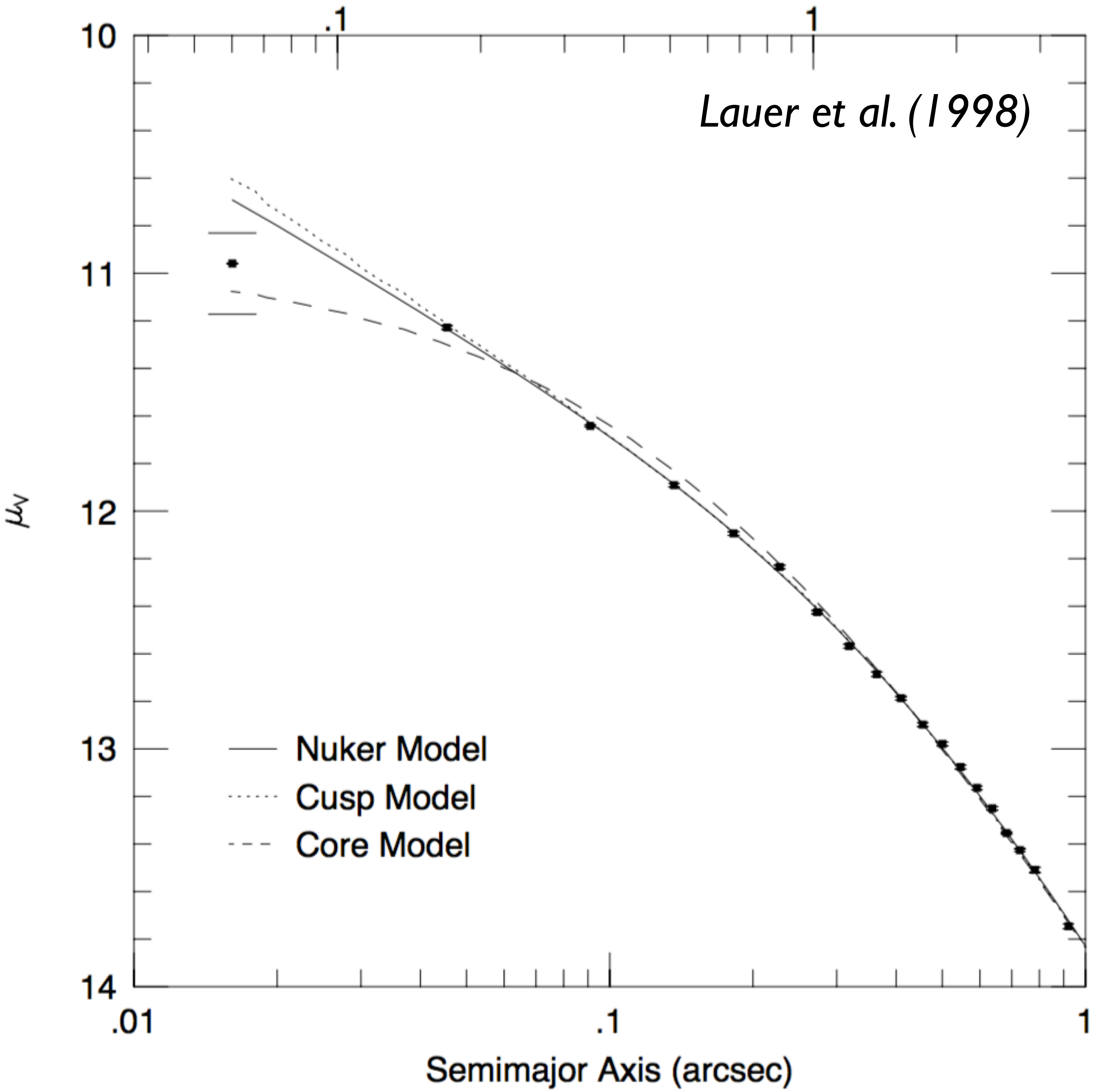
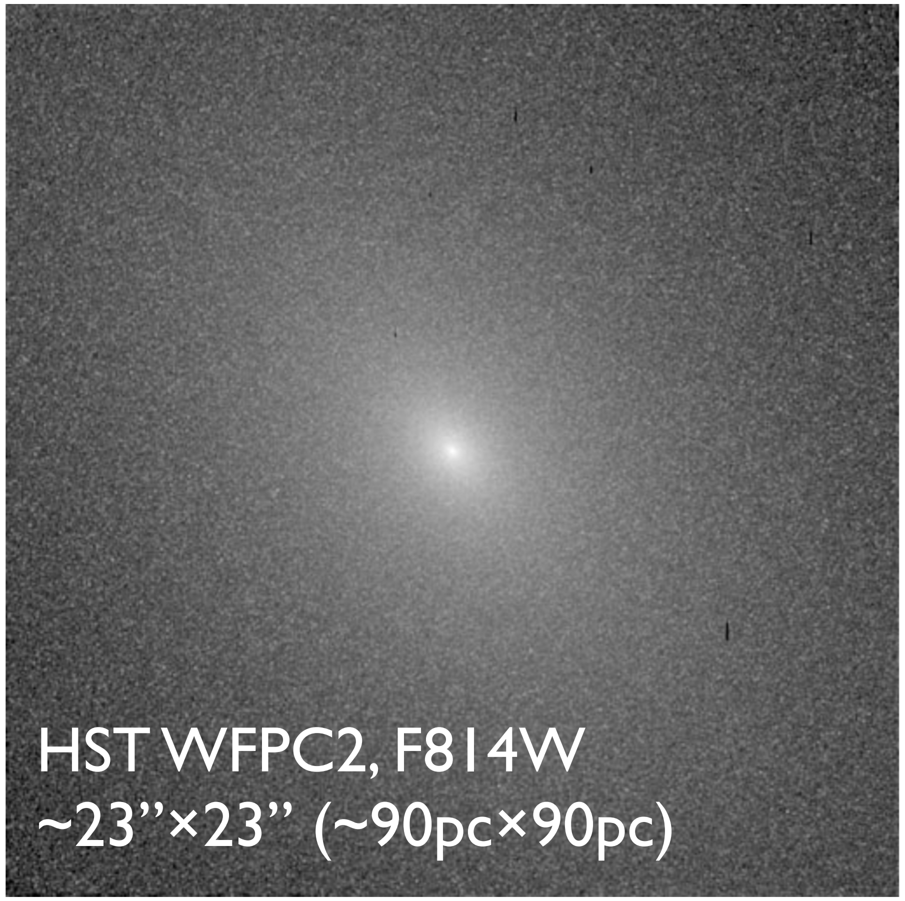
T_{NR} is a conservative assumption for cusp formation time scale. Under realistic conditions, a stellar cusp should form within a few Gyr.

Preto & Amaro-Seoane (2010)

For example: M32

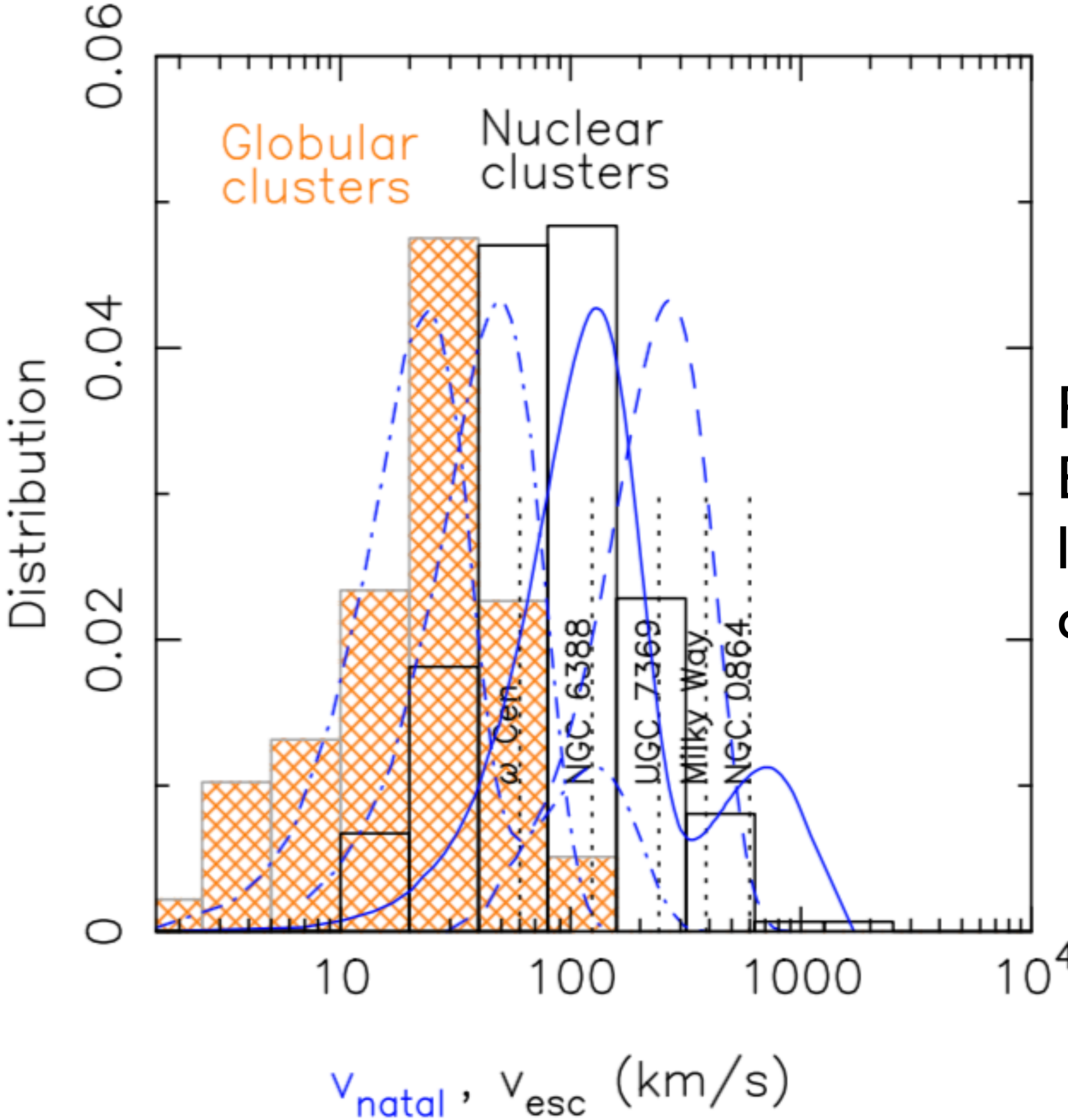


- Nearby dwarf elliptical
- No dust, no recent star formation
- No NSC
- BH of a few 10^6 $M_\odot$
- Consistent with $r^{-1.5}$ cusp



3. GW sources in galactic nuclei

Natal kick vs escape velocities



Retention fraction of BHs in NSC much larger than in globular clusters

Figure 1, Antonini & Rasio (2016)

Dynamical friction

$$t_{\rm rh} \approx 4.2 \times 10^9 \left(\frac{15}{\ln \Lambda}\right) \left(\frac{r_{\rm h}}{4\,{\rm pc}}\right)^{3/2} \left(\frac{M_{\rm cl}}{10^7\,M_\odot}\right)^{1/2} \,{\rm years} \qquad (2)$$

$$t_{\rm df} \approx 0.42 \times 10^9 \left(10 \frac{m_\star}{m_\bullet}\right) \left(\frac{t_{\rm rh}}{4.2 \times 10^9\,{\rm years}}\right) {\rm years}, \qquad (3)$$

BHs will segregate to centres of NSCs
(see also Morris 1993)

Equ. (3), Antonini & Rasio (2016); see Binney & Tremaine (1987)

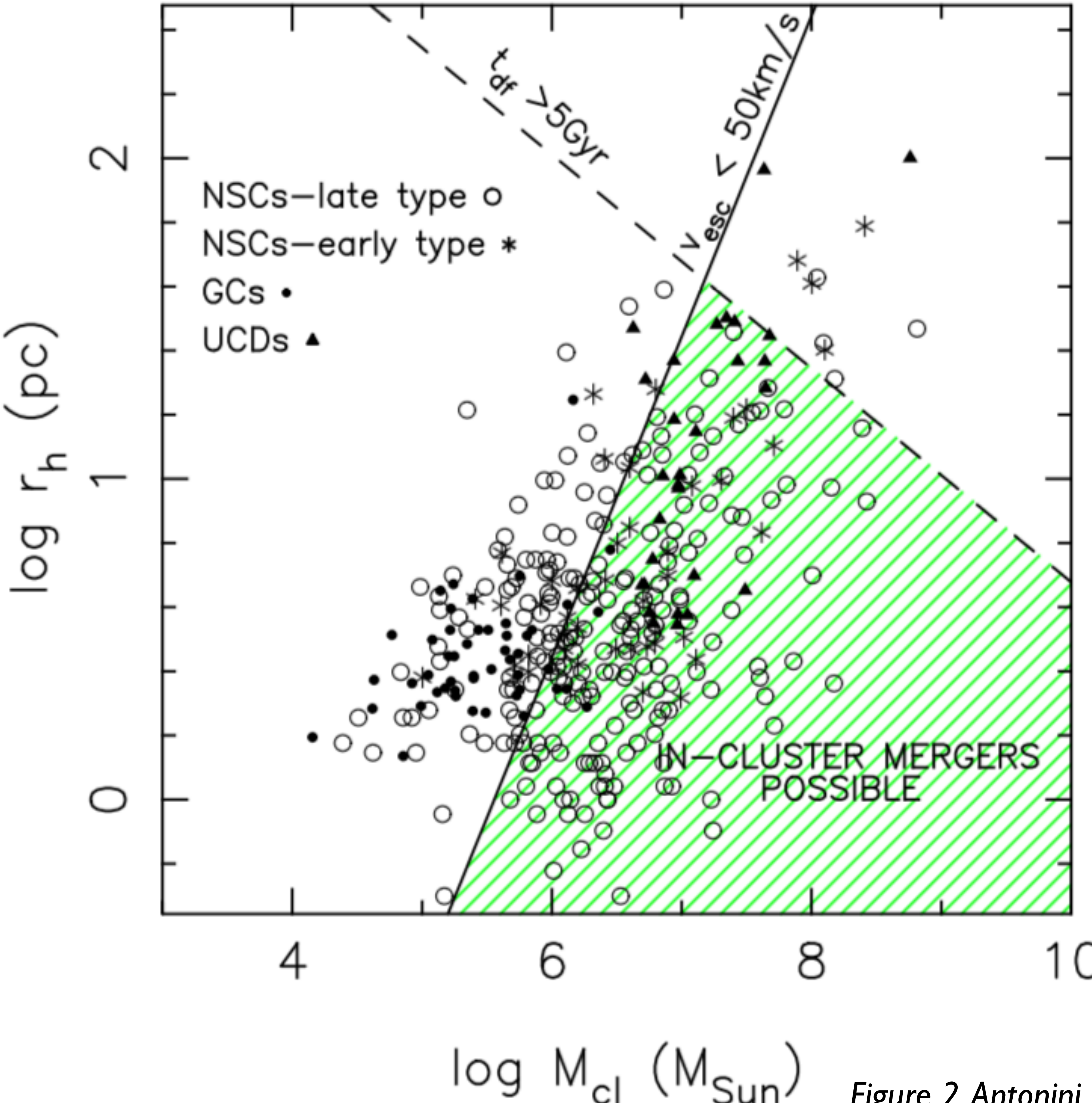


Figure 2, Antonini & Rasio (2016)

Channels to grow binary BHs dynamically

1. Three-body encounters during core-collapse
2. Exchange interactions with stellar binaries
3. GW bremsstrahlung

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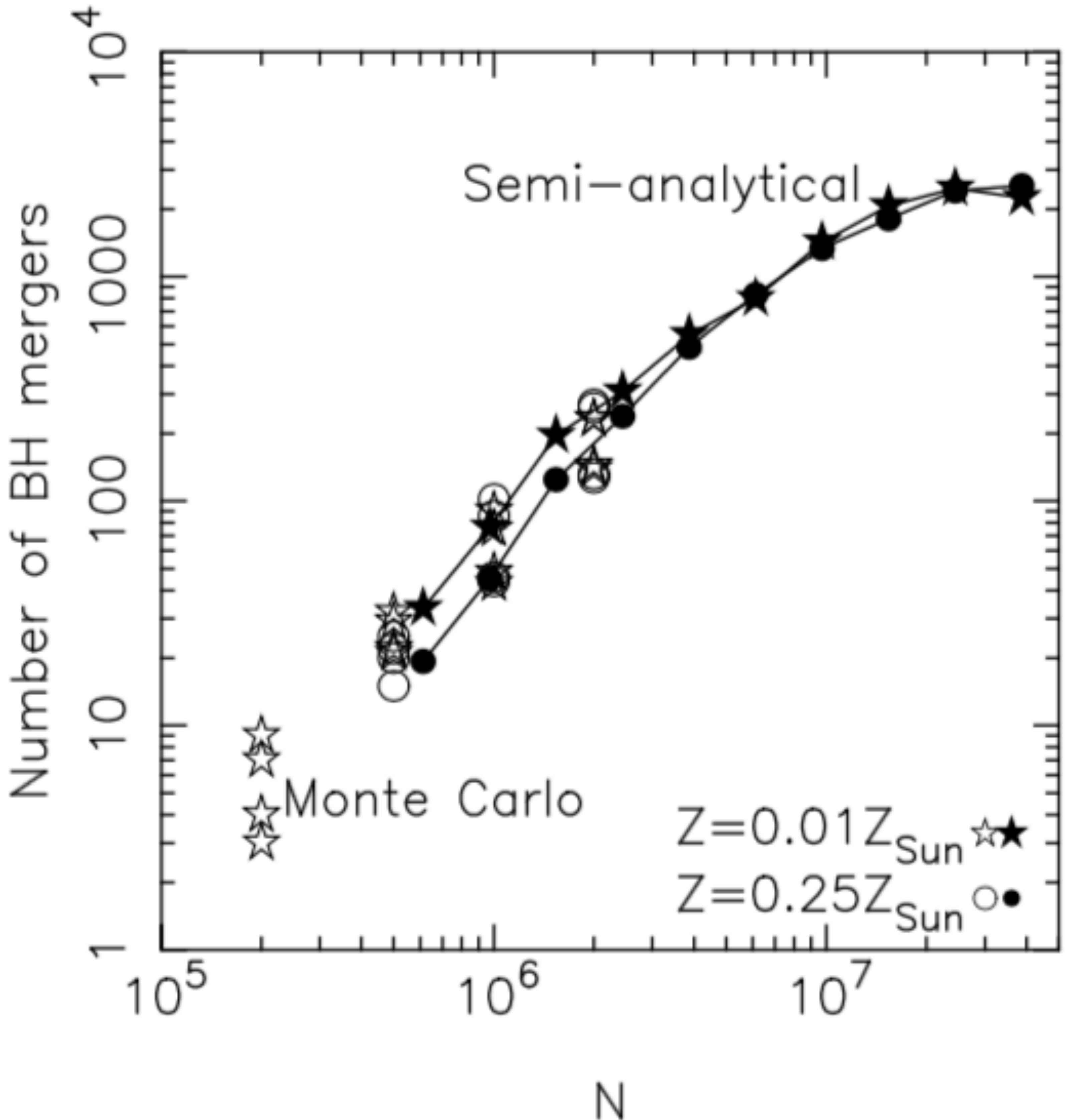
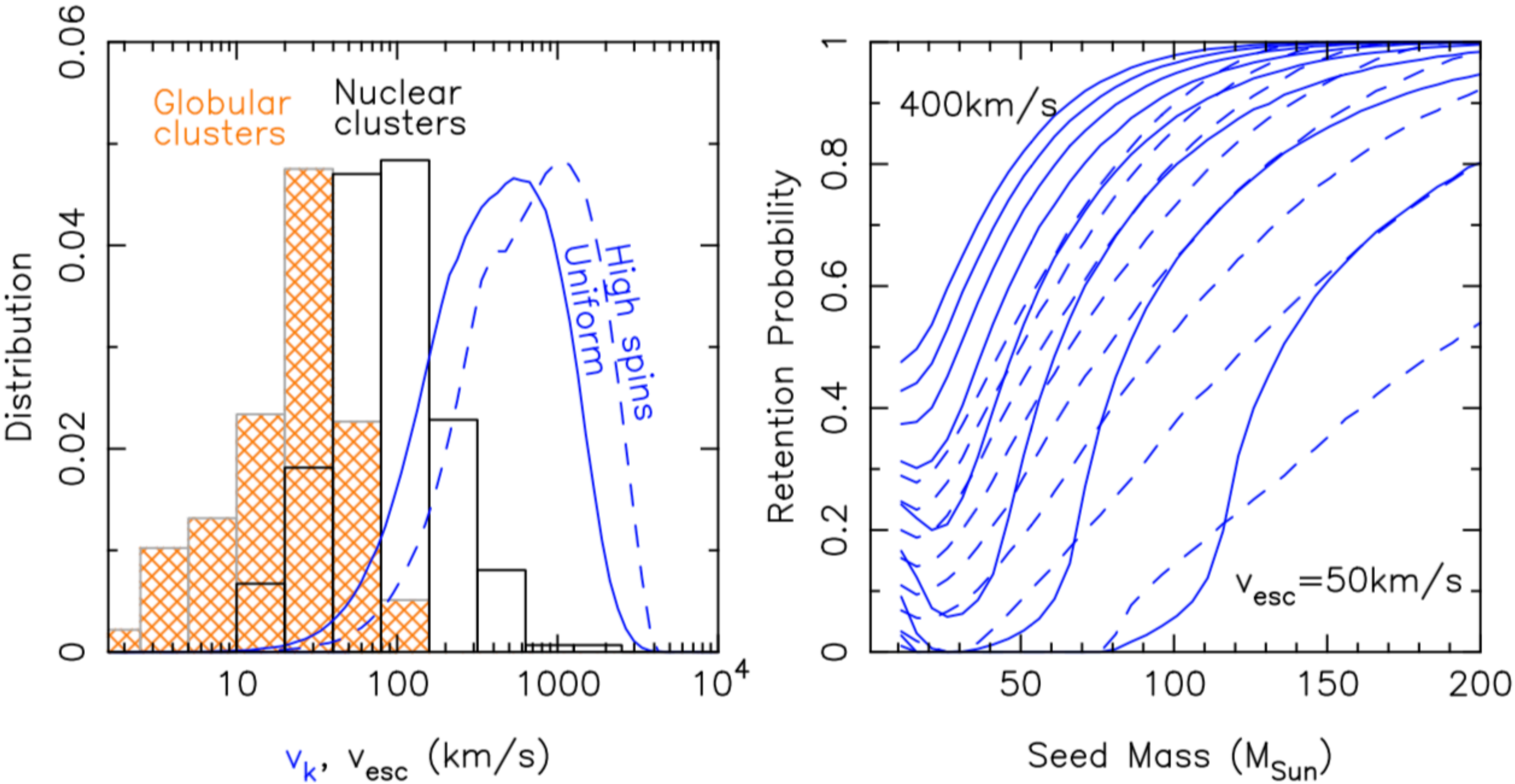
Merger products likely to be retained in massive NSCs. Repeated mergers possible.



"…NSCs are a natural environment for BH mergers that are observable by aLIGO detectors."

Figure 5, Antonini & Rasio (2016)

Retention of BHs after GW kick



Massive NSCs are natural breeding grounds for high-mass BH mergers

Figure 3, Antonini & Rasio (2016)

Fraction of galaxies containing an NSC but no MBH as a function of galaxy mass.

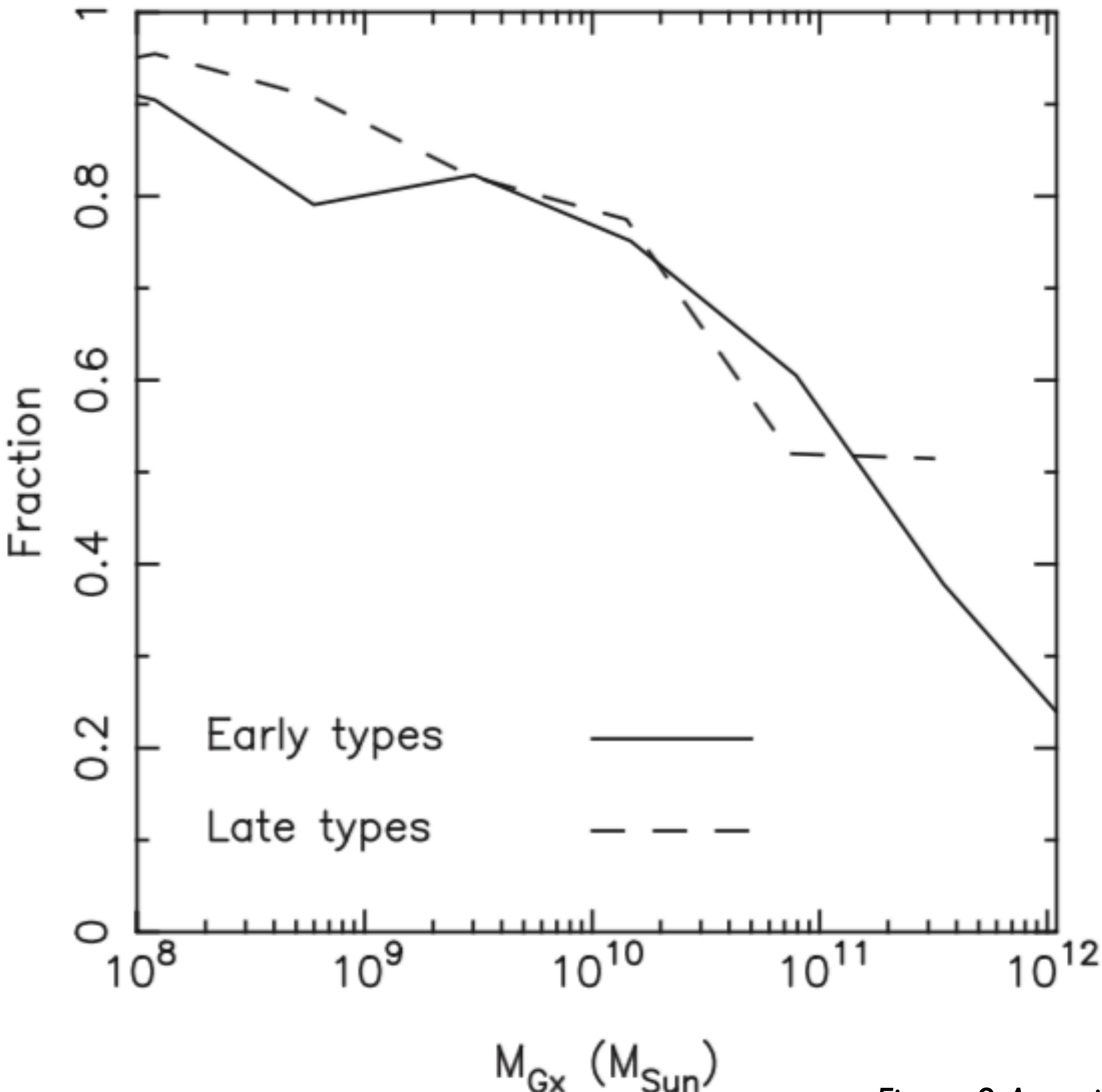
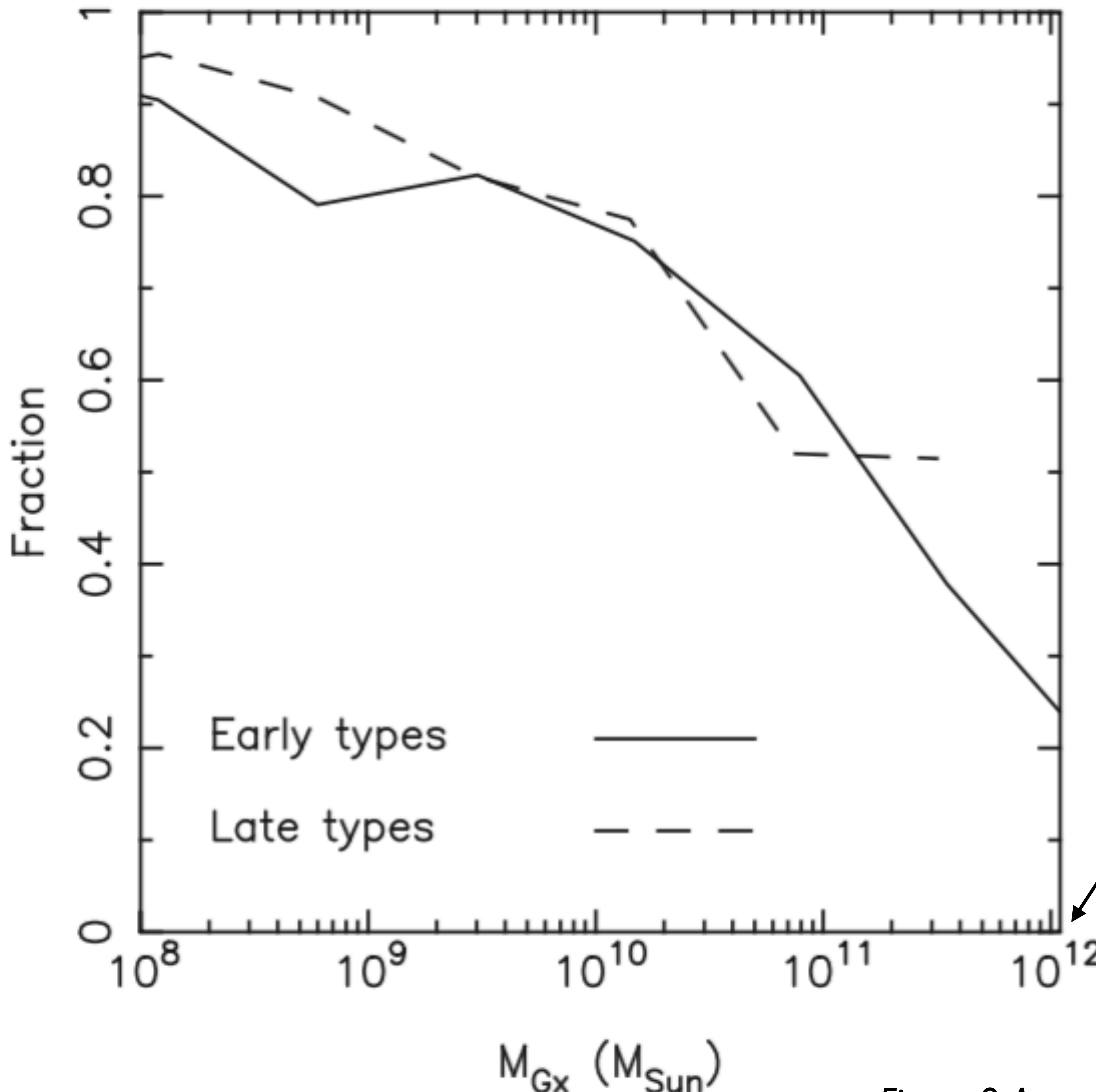


Figure 8, Antonini & Rasio (2016)

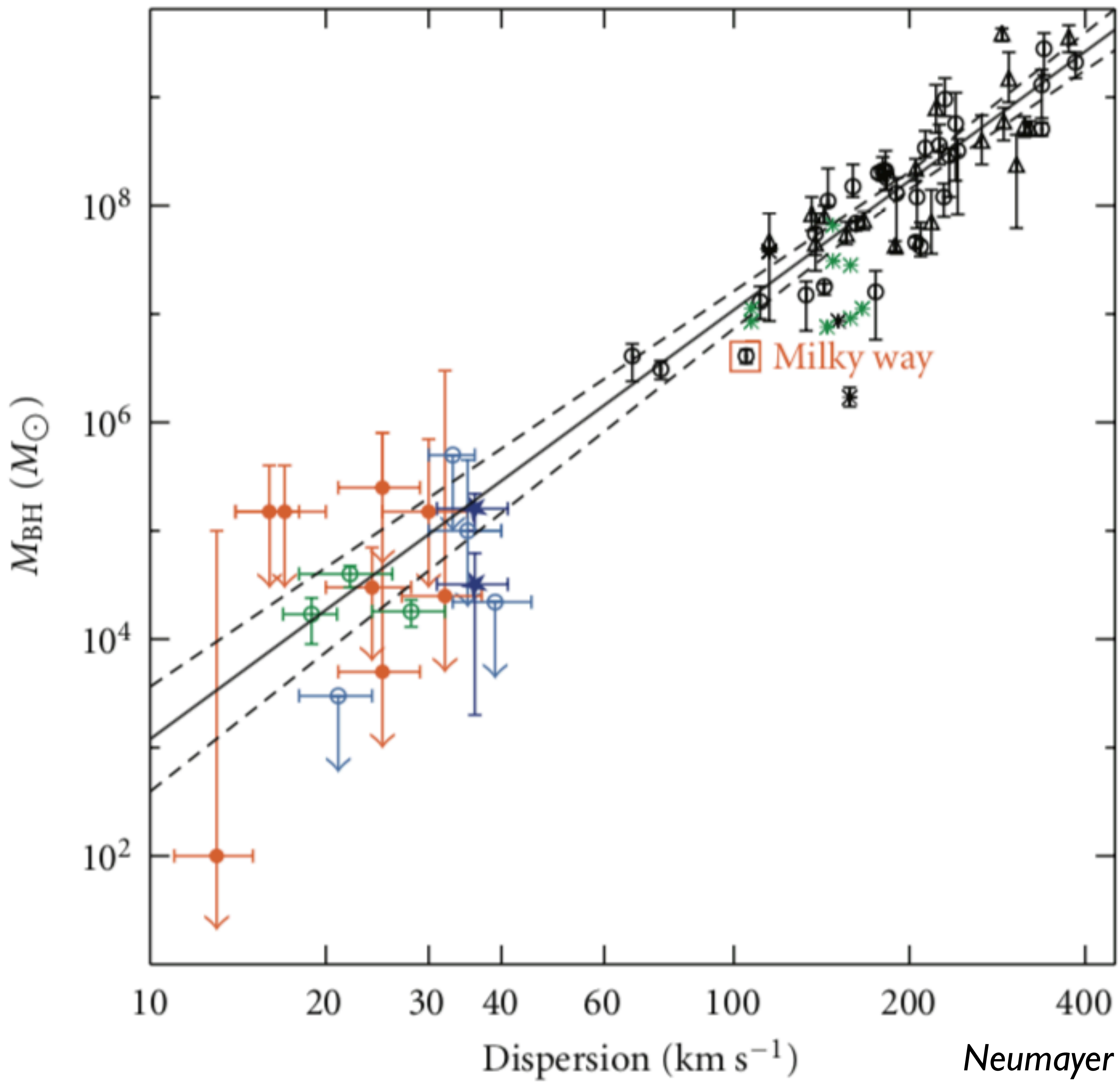
Fraction of galaxies containing an NSC but no MBH as a function of galaxy mass.



Milky Way

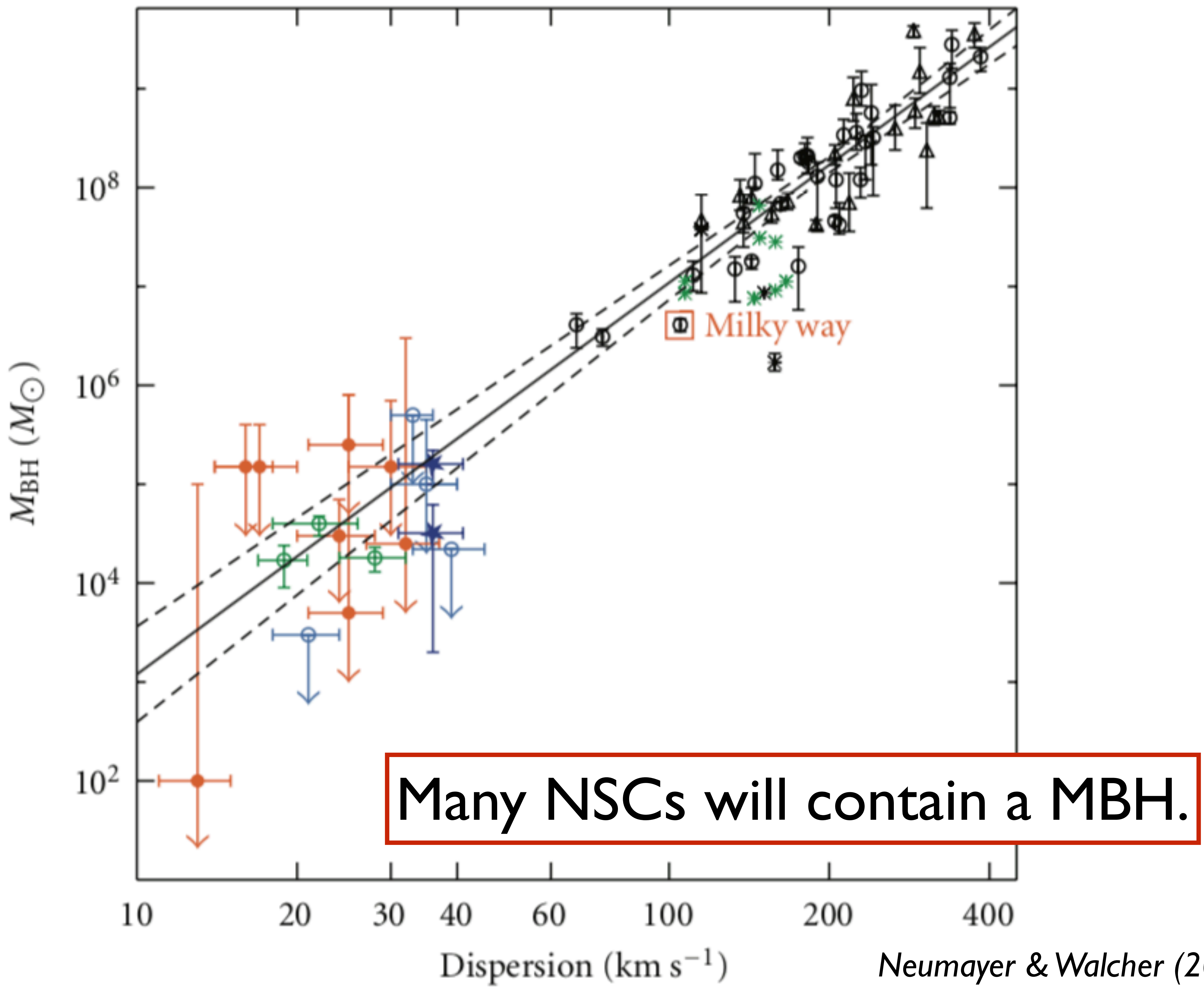
Figure 8, Antonini & Rasio (2016)

Effect of a central MBH



Neumayer & Walcher (2012)

Effect of a central MBH



Neumayer & Walcher (2012)

Effect of a central MBH

Suppression of core-colapse
Formation of Bahcall-Wolf cusp
No hard binaries; 3-body interactions will lead to evaporation of binaries

Binaries well inside the influence radius of an MBH will be essentially all soft and will be disrupted over the typical timescale (Binney & Tremaine 1987):

$$t_{\rm ev} = \frac{m_{12}\sigma}{16\sqrt{\pi}\,Gm_{\star}\rho a \ln\Lambda} \approx 10^{7}\frac{\sigma}{100\ \mathrm{km\ s^{-1}}} \left(0.5\frac{m_{12}}{m_{\bullet}}\right)\left(\frac{\ln\Lambda}{10}\frac{\rho}{10^{6}\ M_{\odot}\ \mathrm{pc}^{-3}}\frac{a}{1\ \mathrm{au}}\right)^{-1}. \quad (26)$$

BH density ≳ stellar density at $r \lesssim 0.1 r_h$

(Hopman & Alexander 2006; Gualandris & Merritt 2012)

see Antonini & Rasio (2016)

Effect of a central MBH

Mergers may be induced by KL or GW bremsstrahlung

KL requires steady supply of binaries (star formation, cluster inspiral)

GW capture highly improbable (~0.01 Gpc^{-3} yr^{-1}, Tsang 2013)

Merger rate of BHs in NSC with MBH highly uncertain. Detailed modelling necessary.

see Antonini & Rasio (2016)

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$\boxed{\text{But: Now we can observe EMRIs!}}$

see Antonini & Rasio (2016)

Summary: BH mergers in NSCs

(1) NSCs produce BH-binary mergers at a realistic rate of »1.5 Gpc-3 yr-1.

(2) BHs in NSCs can experience a number of mergers and grow to masses up to a few hundred solar masses. Although rare, such high mass BH mergers at low redshifts are unique to NSCs, because these are the only clusters with sufficiently high escape velocities such that they can retain a large fraction of their merging BHs

(3) Depending on natal kicks, BH merger rate from NSCs is similar to or could even dominate over (massive) BH mergers from globular clusters or isolated binary evolution.

see Antonini & Rasio (2016)

EMRIs

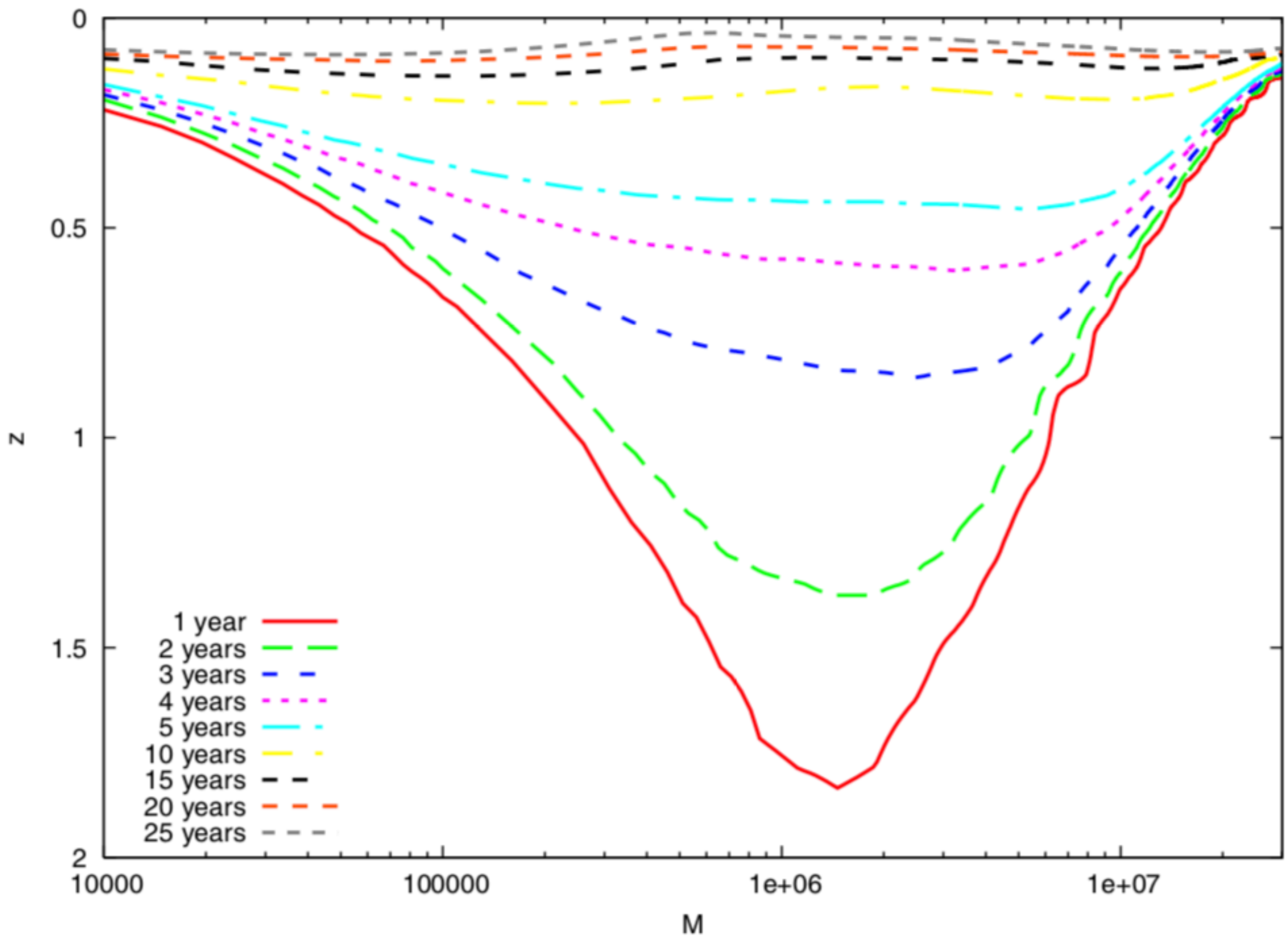


Figure 7. Contours of constant 'detectable lifetime' (as defined in the text) for the circular-equatorial inspiral of a $10M_\odot$ black hole into an MBH with spin $a = 0.99$, as a function of MBH mass M and redshift z.

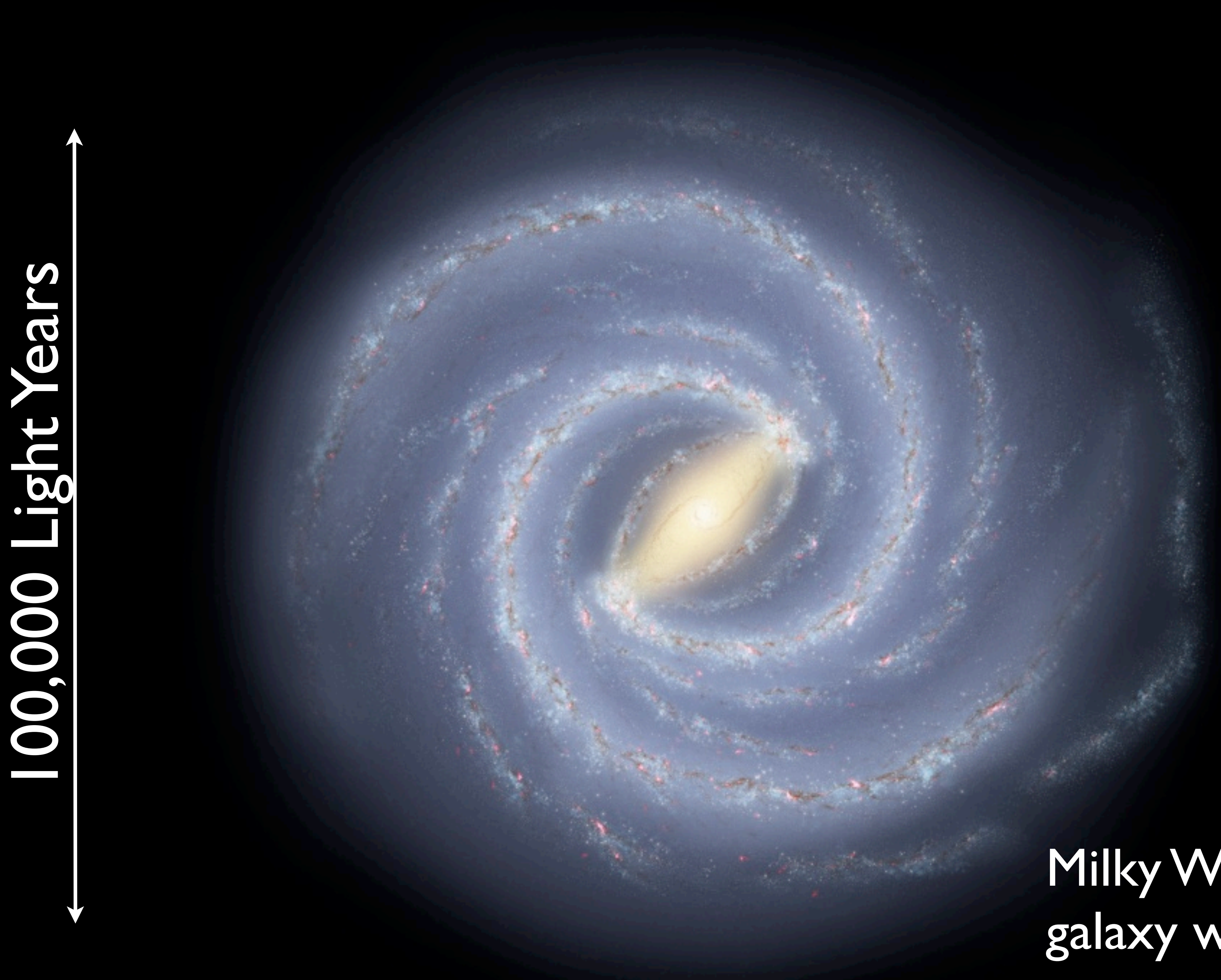
Amaro-Seoane (2007)

4. The centre of the Milky Way

Motivation

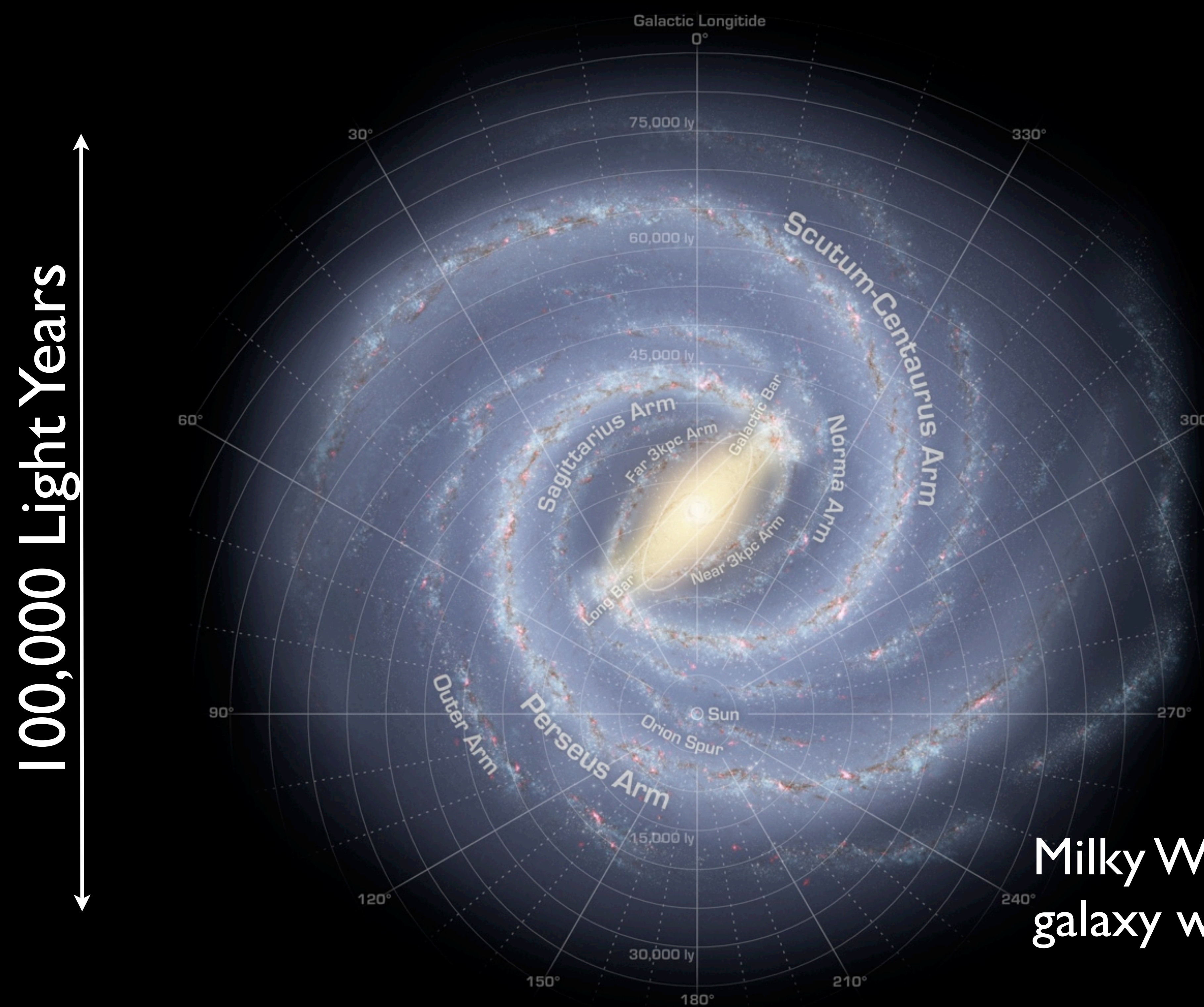
The question of the stellar density and the dynamical state around Sgr A* is important because the rate of strong interactions with the MBH scales with the stellar density close to it. In particular, the Milky Way serves, by a coincidence of technology,[3] as the archetypal nucleus for cosmic sources of low-frequency GWs from stellar BHs inspiraling into an MBH (extreme mass-ratio inspiral events, EMRIs), which are targets for planned spaceborne GW detectors. [The central role of the Milky Way in the planning of such experiments is reflected by the fact that the target galactic nuclei are sometimes denoted Milky Way equivalent galaxies (MWEGs).] The numbers and dynamics of stars and compact objects in the inner few$\times$0.01 pc of Sgr A* therefore have, by extrapolation, direct bearings on the predicted cosmic low-frequency GW event rates (Section 5.1).

[3] The longest laser interferometric baseline that can be reliably maintained in space at present is $\mathcal{O}(10^6$ km), which has maximal sensitivity to GWs in the 1–10 mHz range. This corresponds to GWs emitted from near the horizon of an $\mathcal{O}(10^6\,M_\odot)$ MBH (Amaro-Seoane et al. 2007).



Milky Way is barred spiral galaxy with mass ~10^{12} $M_\odot$

Churchwell et al. (2009, PASP): The Spitzer/GLIMPSE Surveys: A New View of the Milky Way



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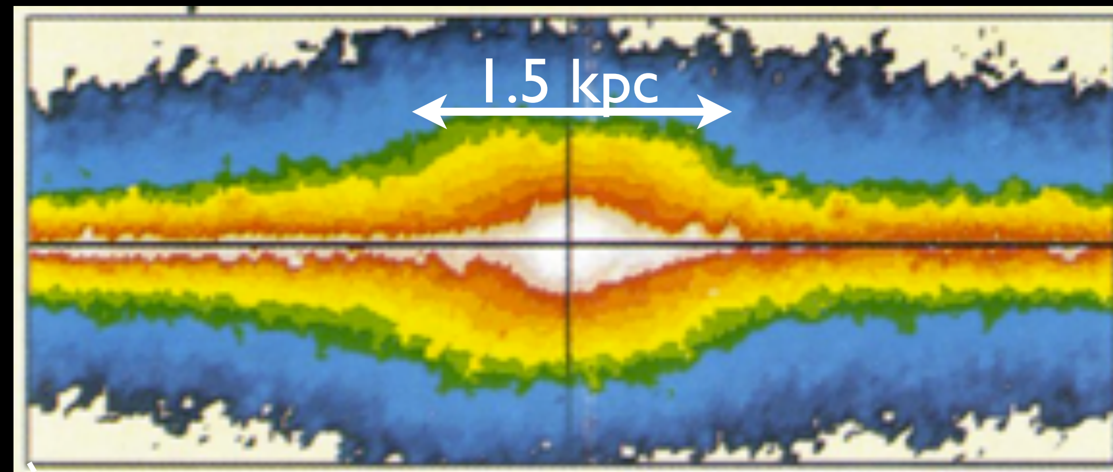
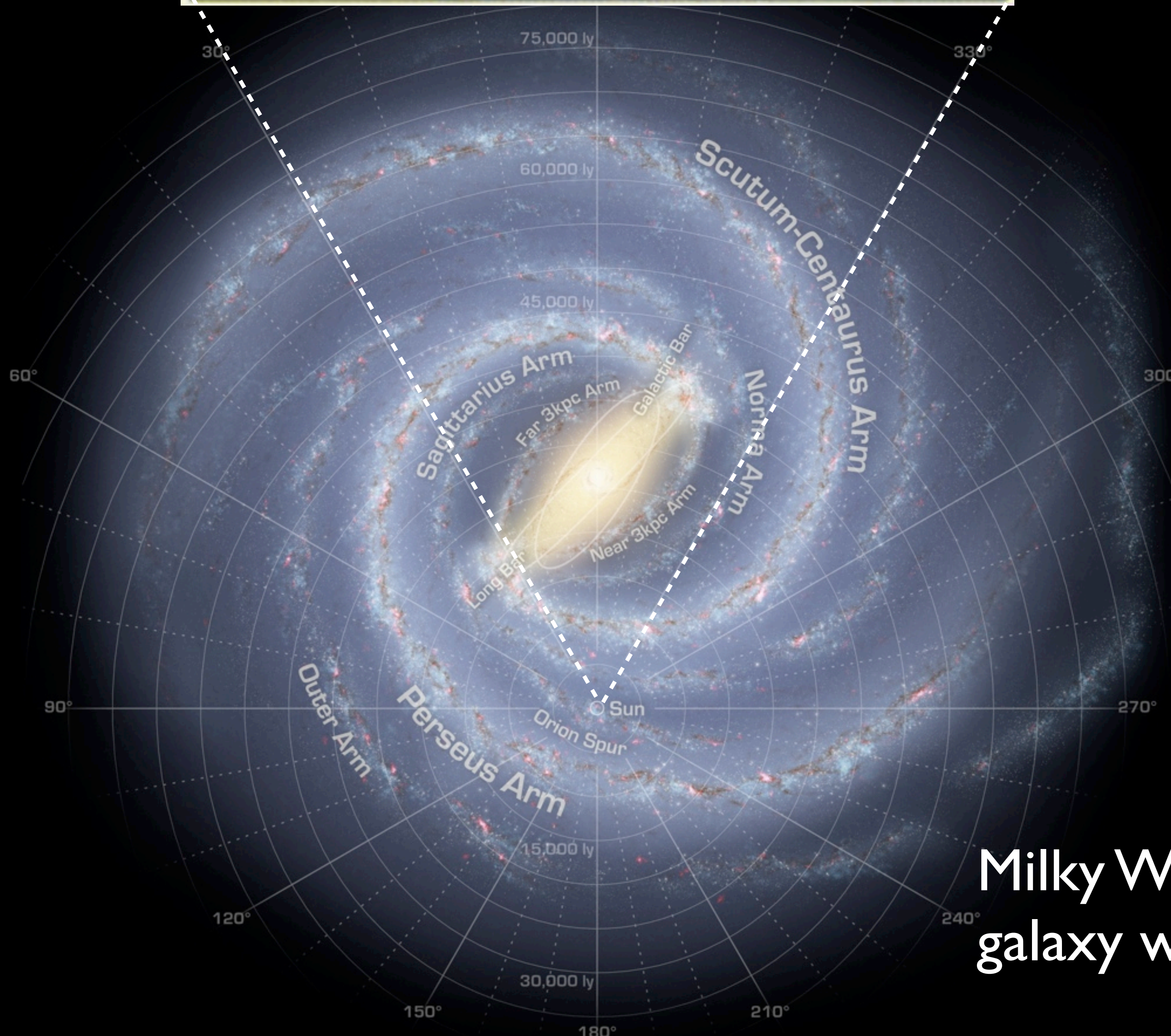


4.9 μm COBE/DIRBE
(Weiland et al., 1994)

100,000 Light Years



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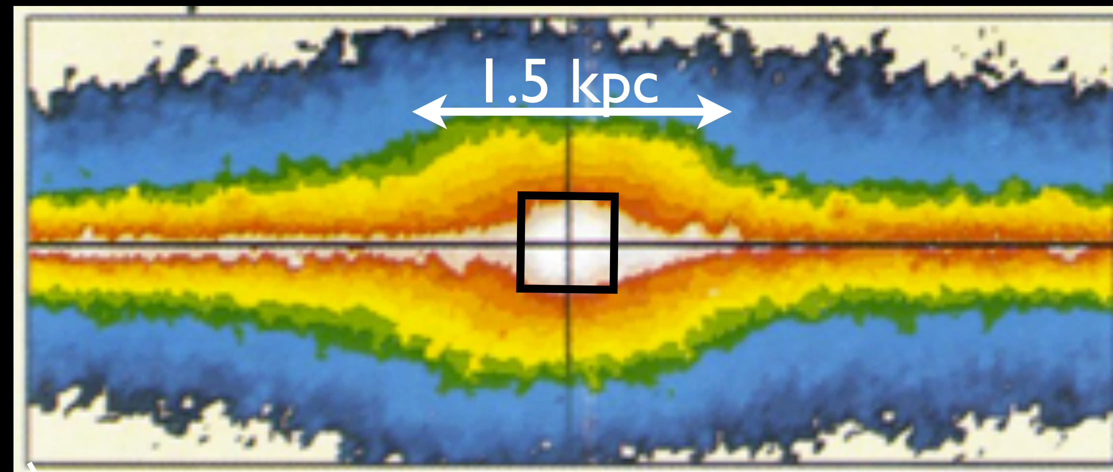

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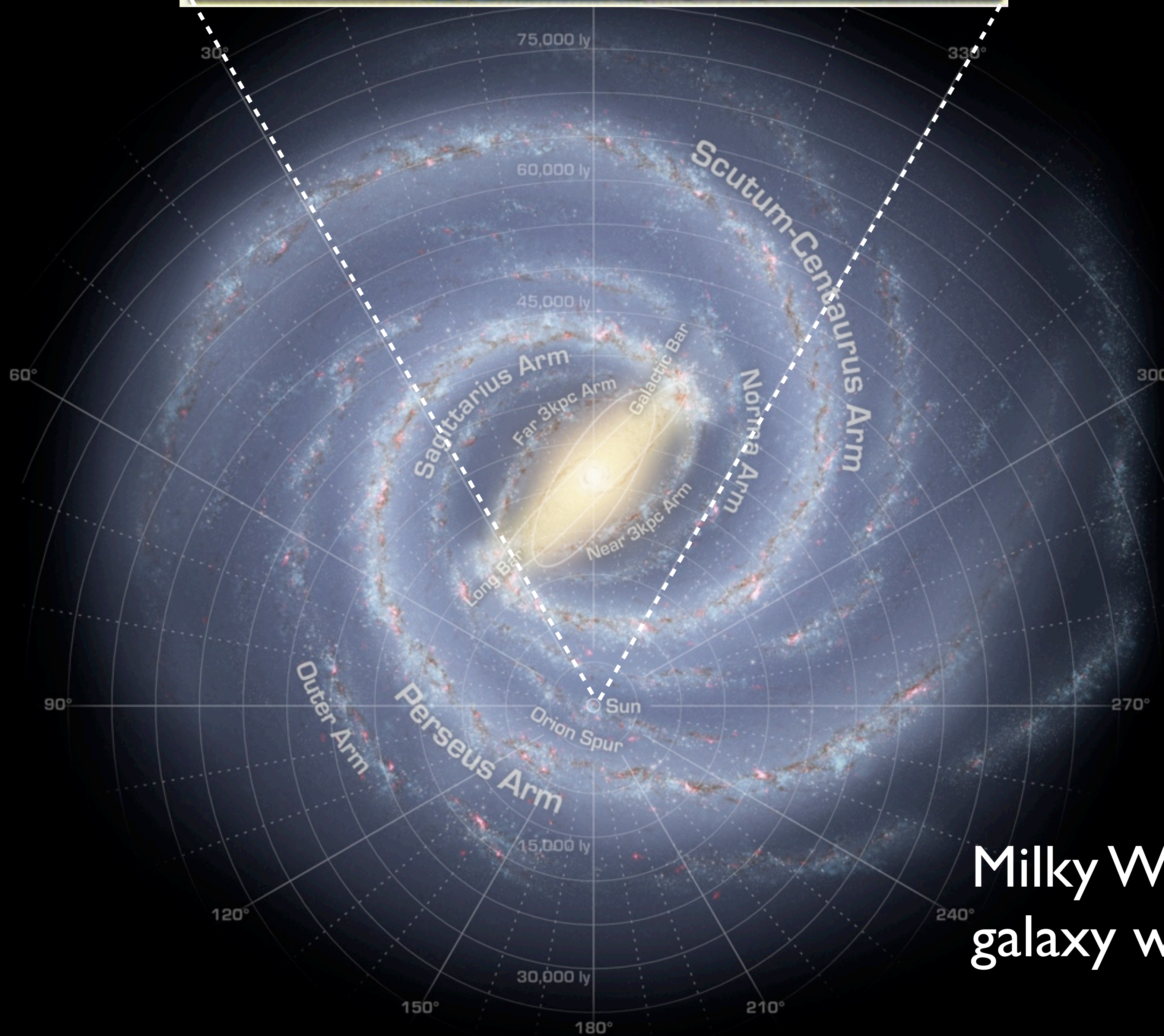

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High-resolution view of a nearby nucleus

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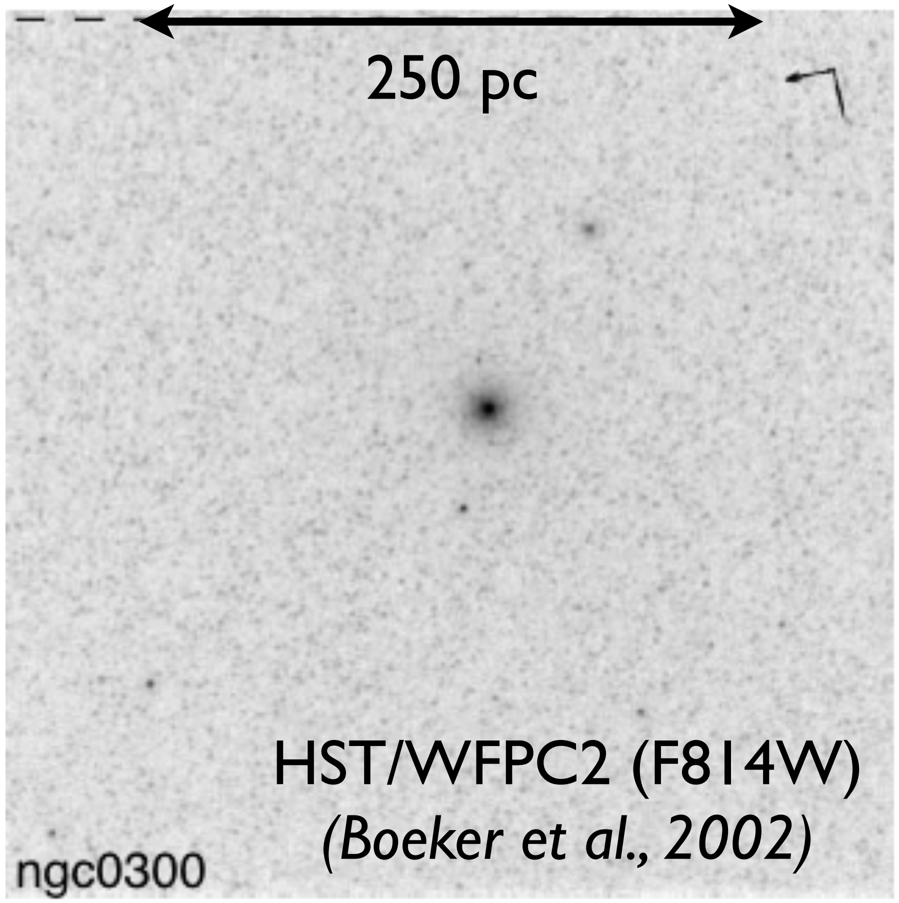
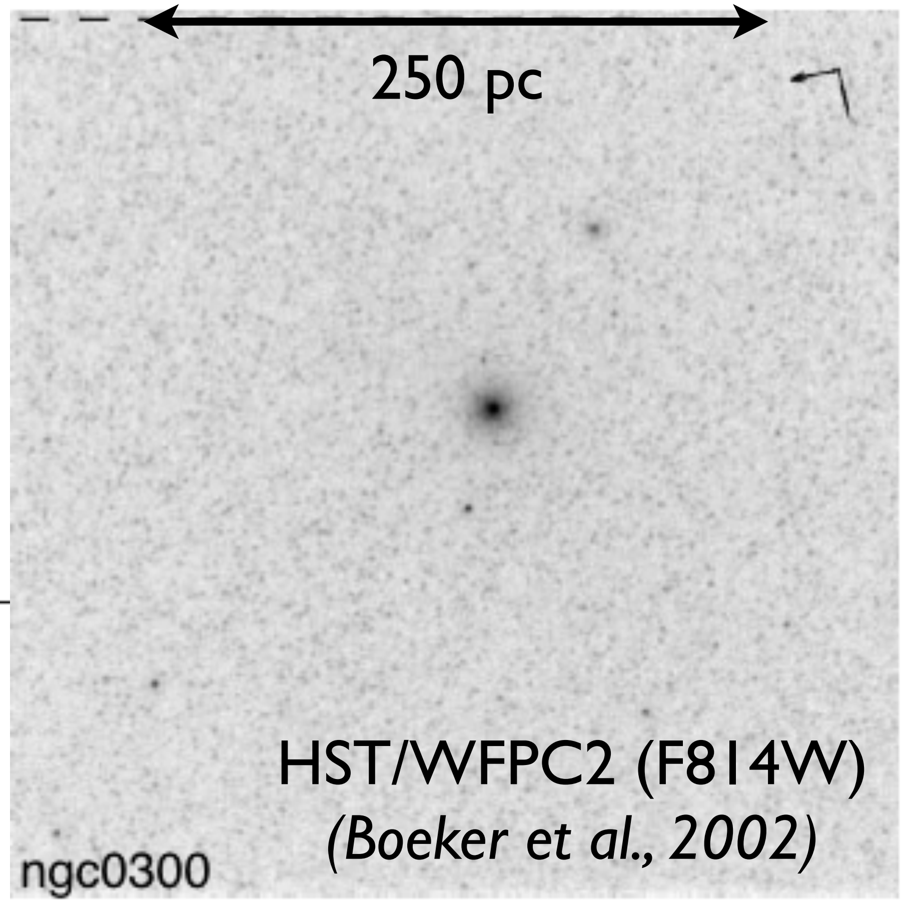
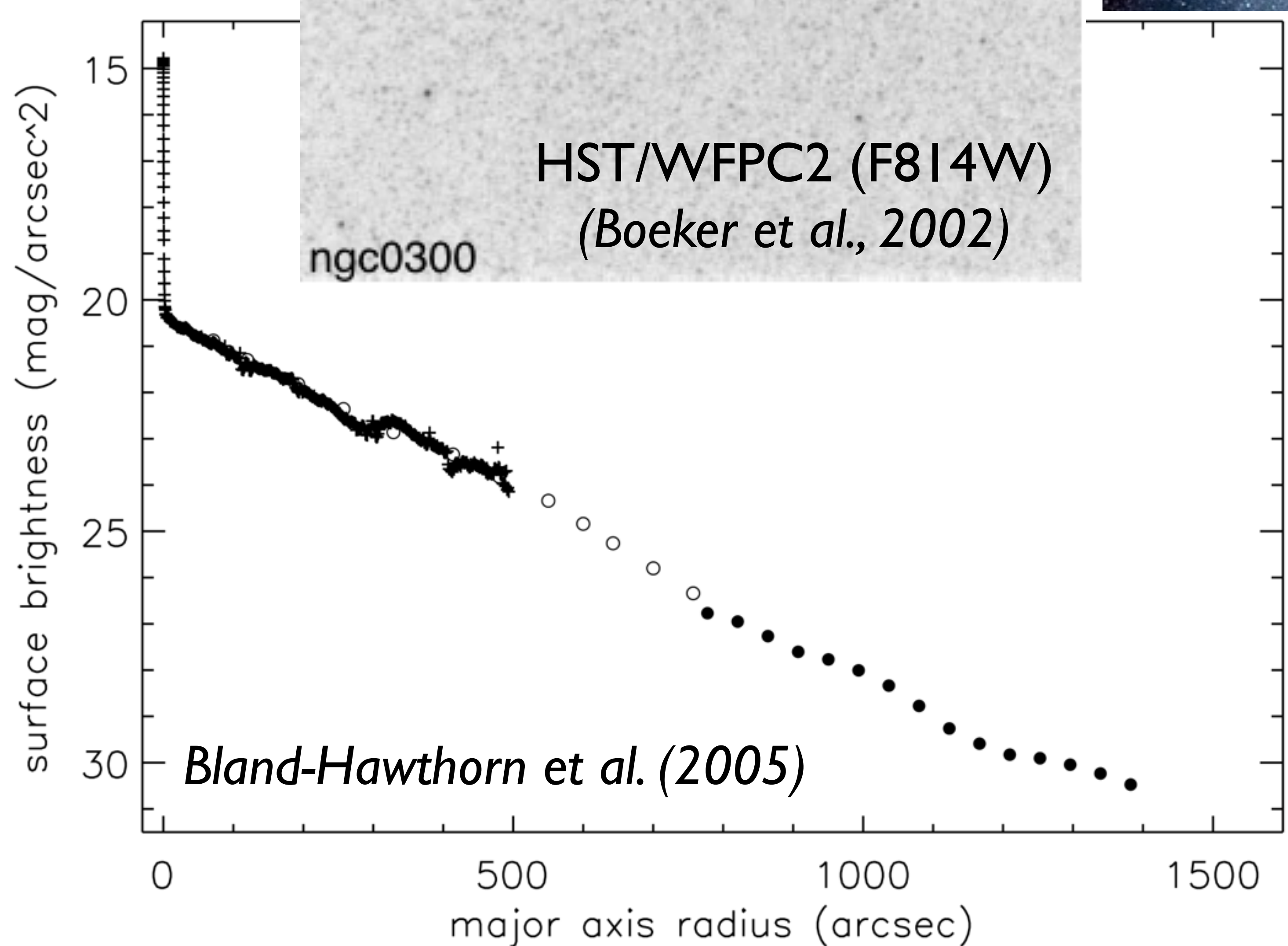
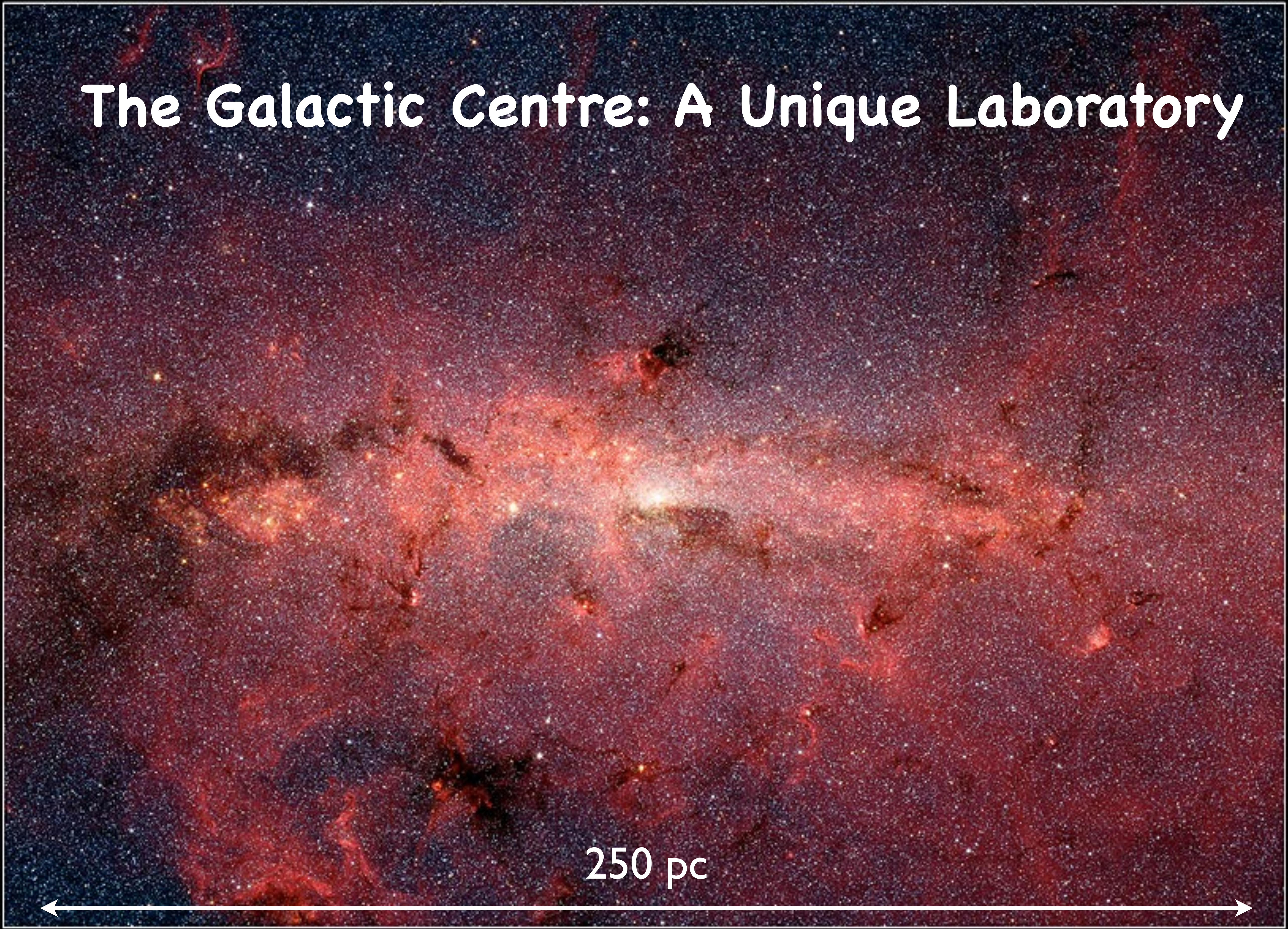


High-resolution view of a nearby nucleus





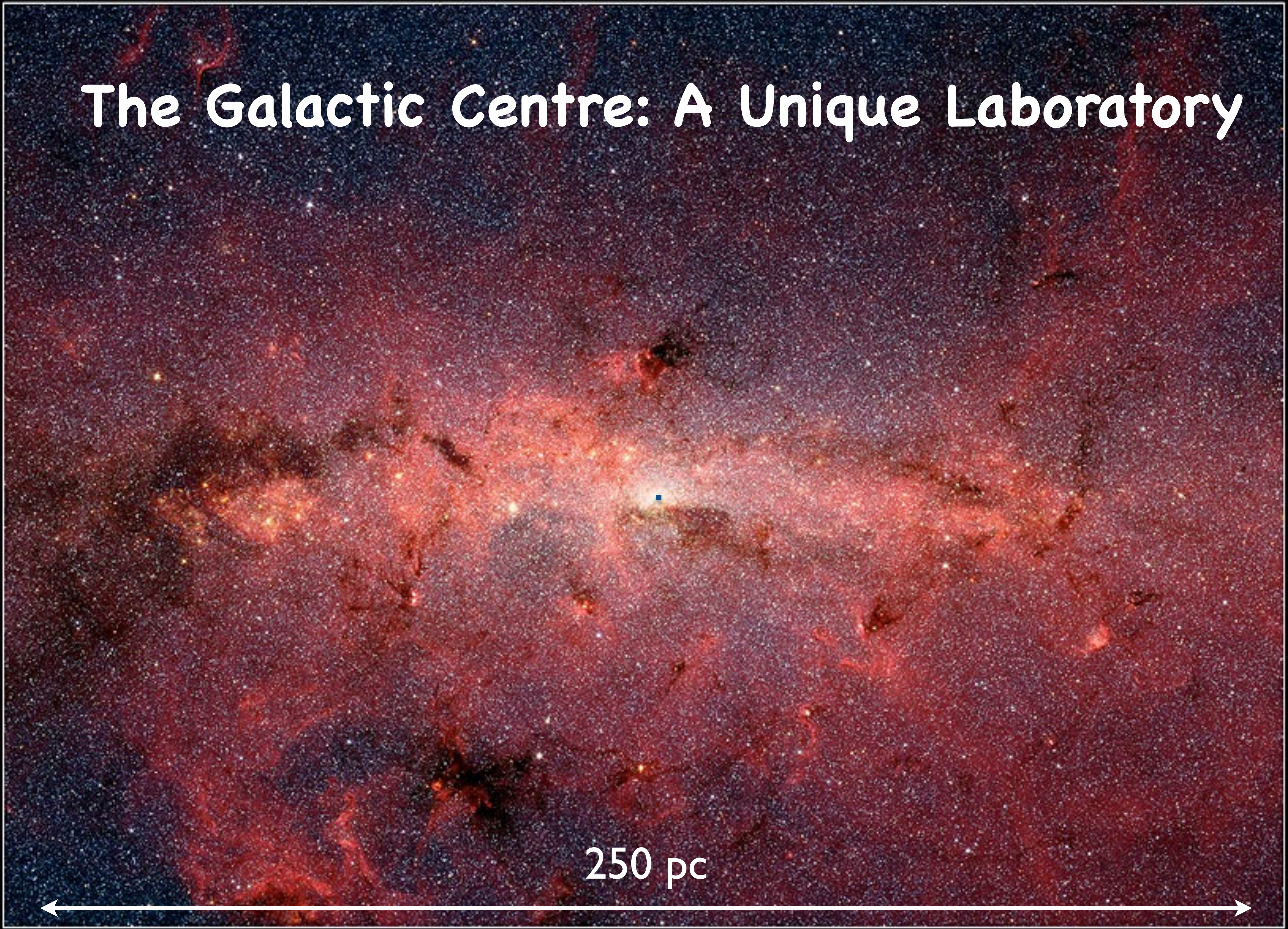
The Galactic Centre: A Unique Laboratory



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

Spitzer Space Telescope • IRAC
ssc2006-02a

The Galactic Centre: A Unique Laboratory



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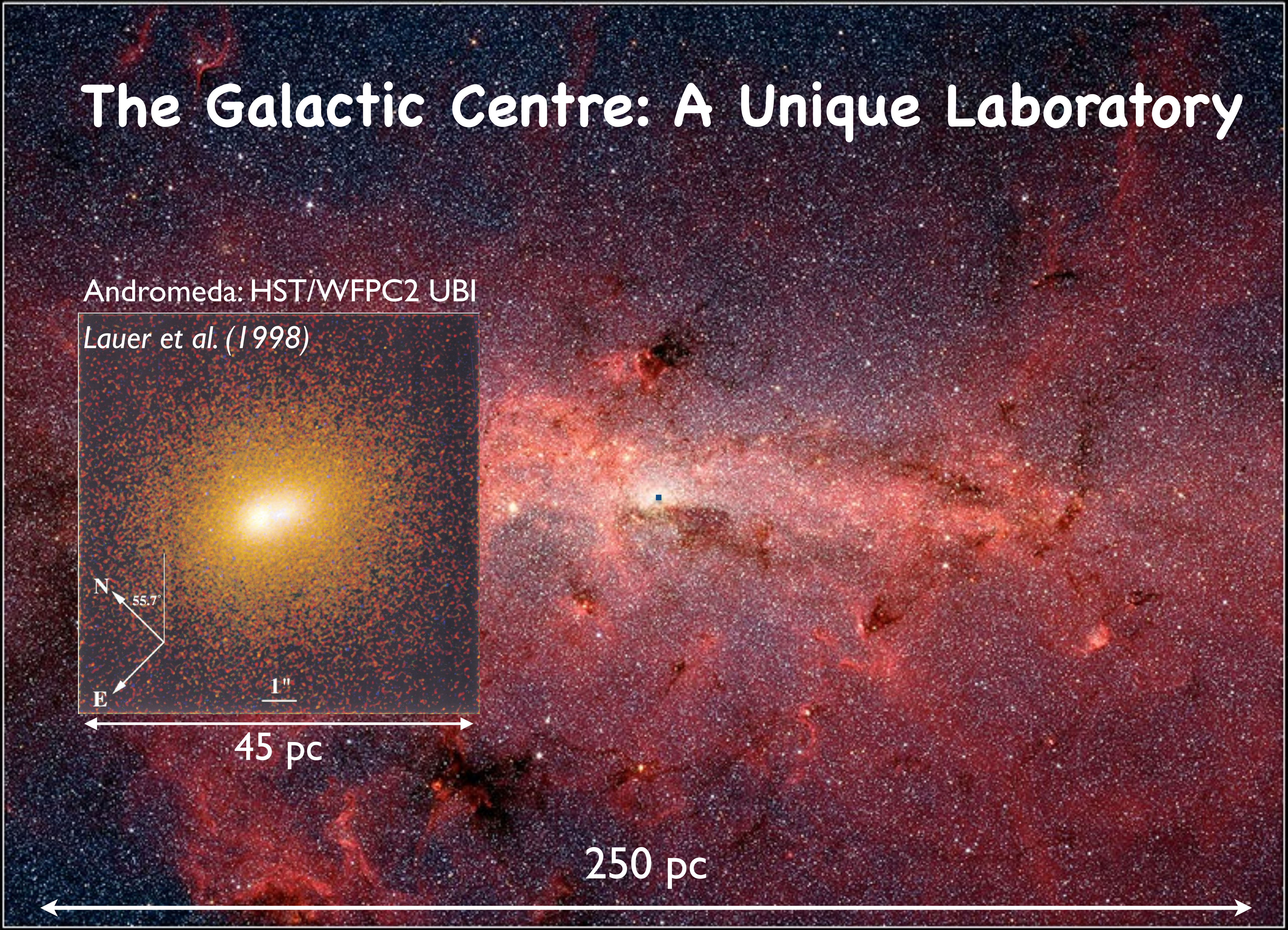

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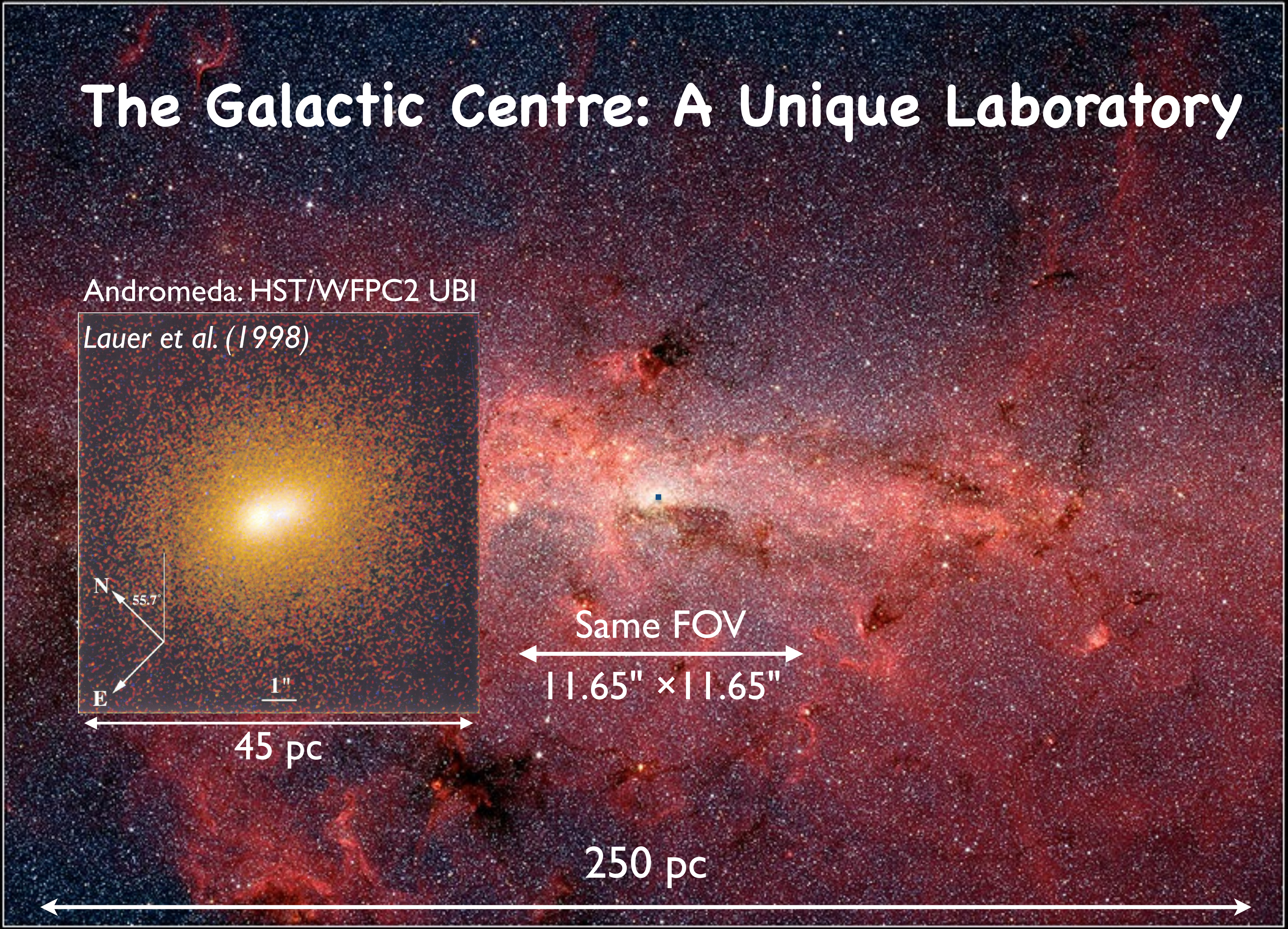

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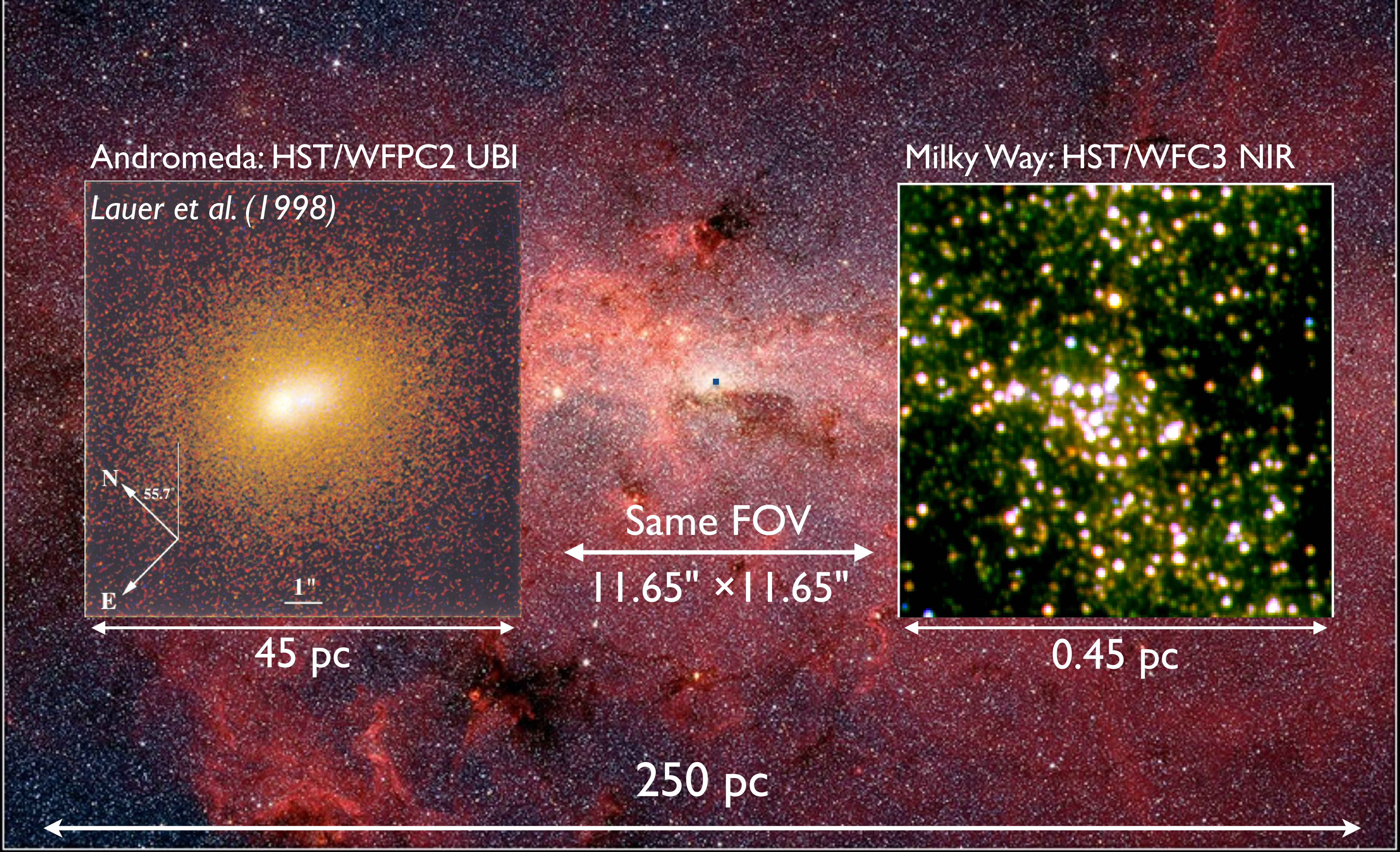

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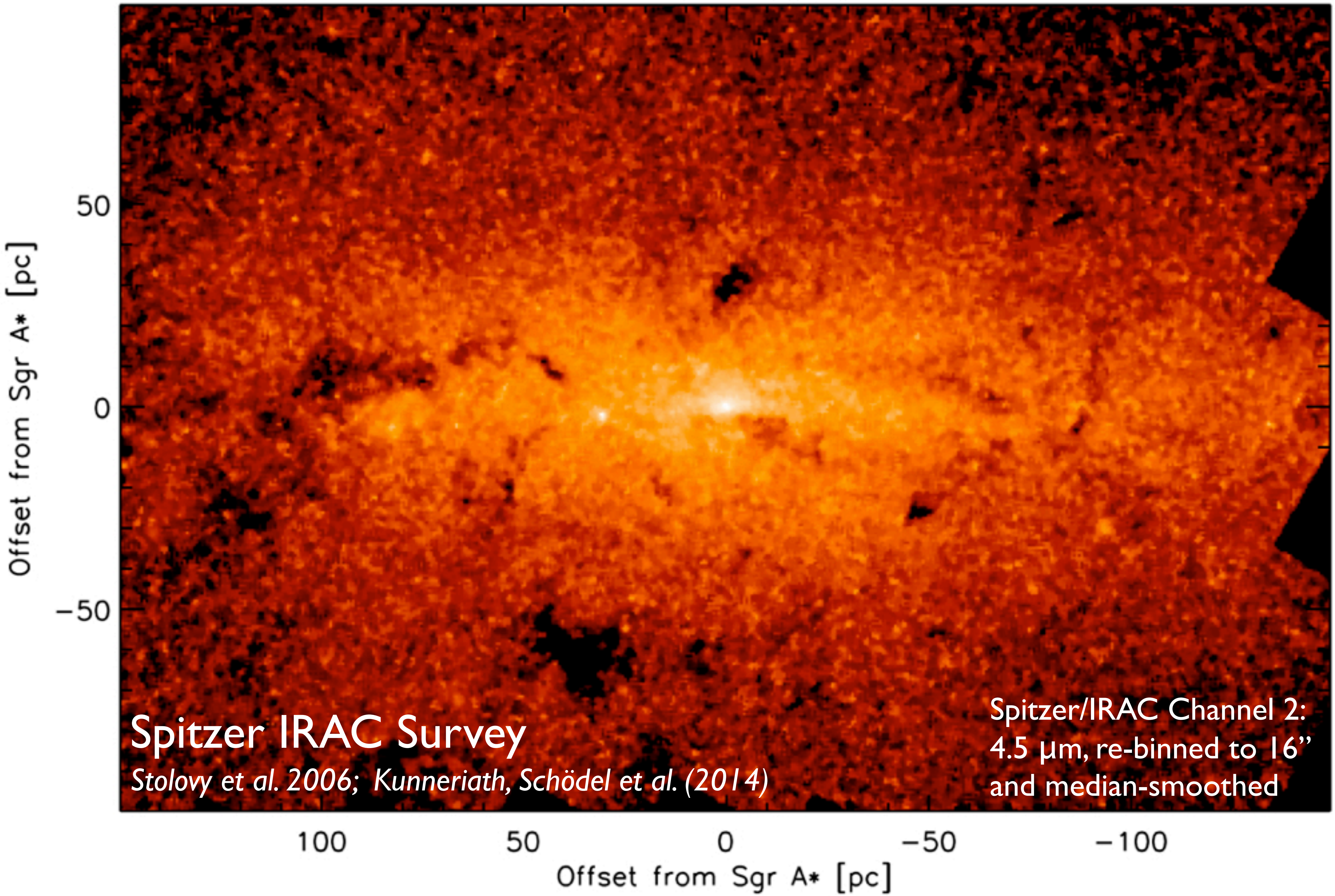
Overview of the GC



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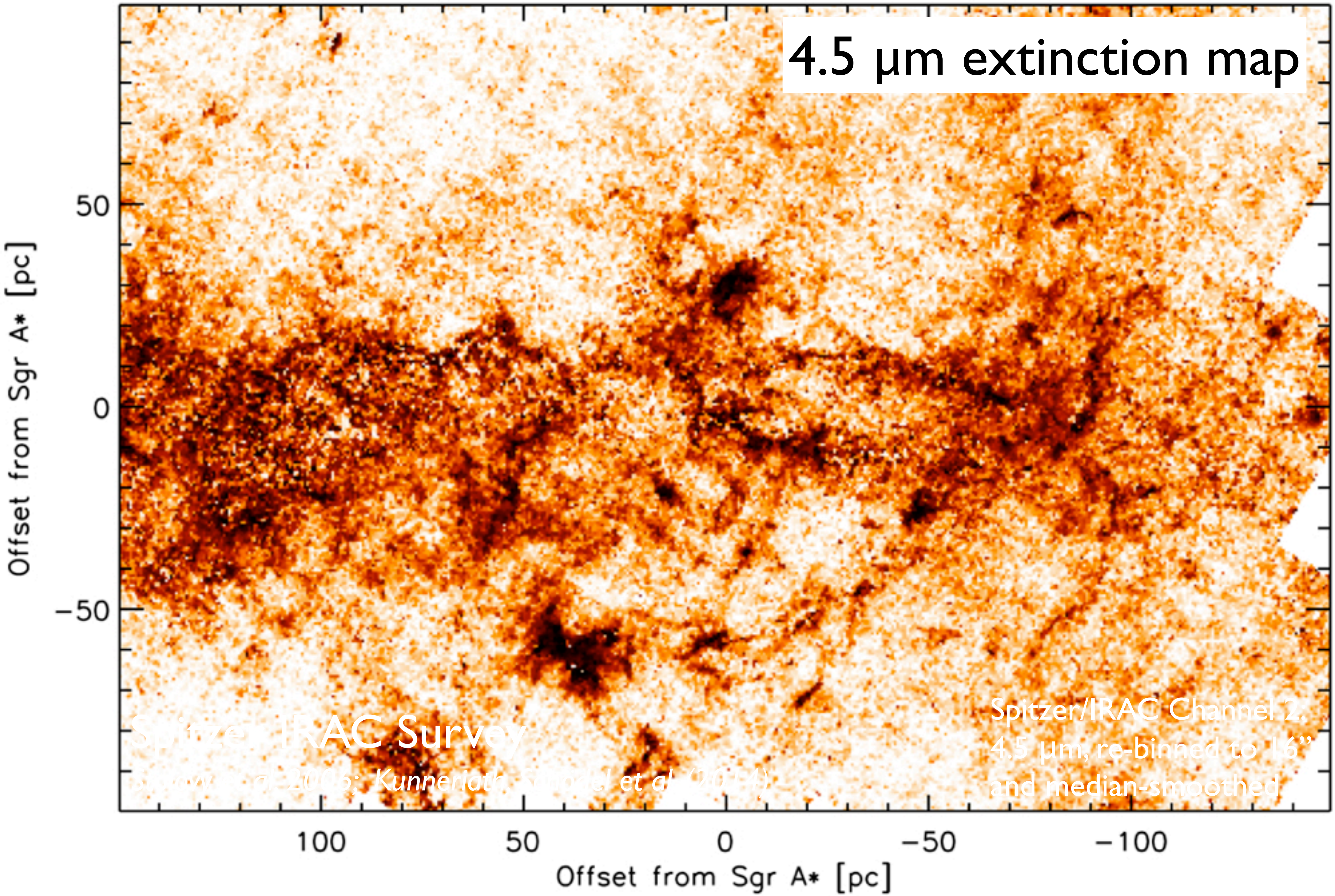
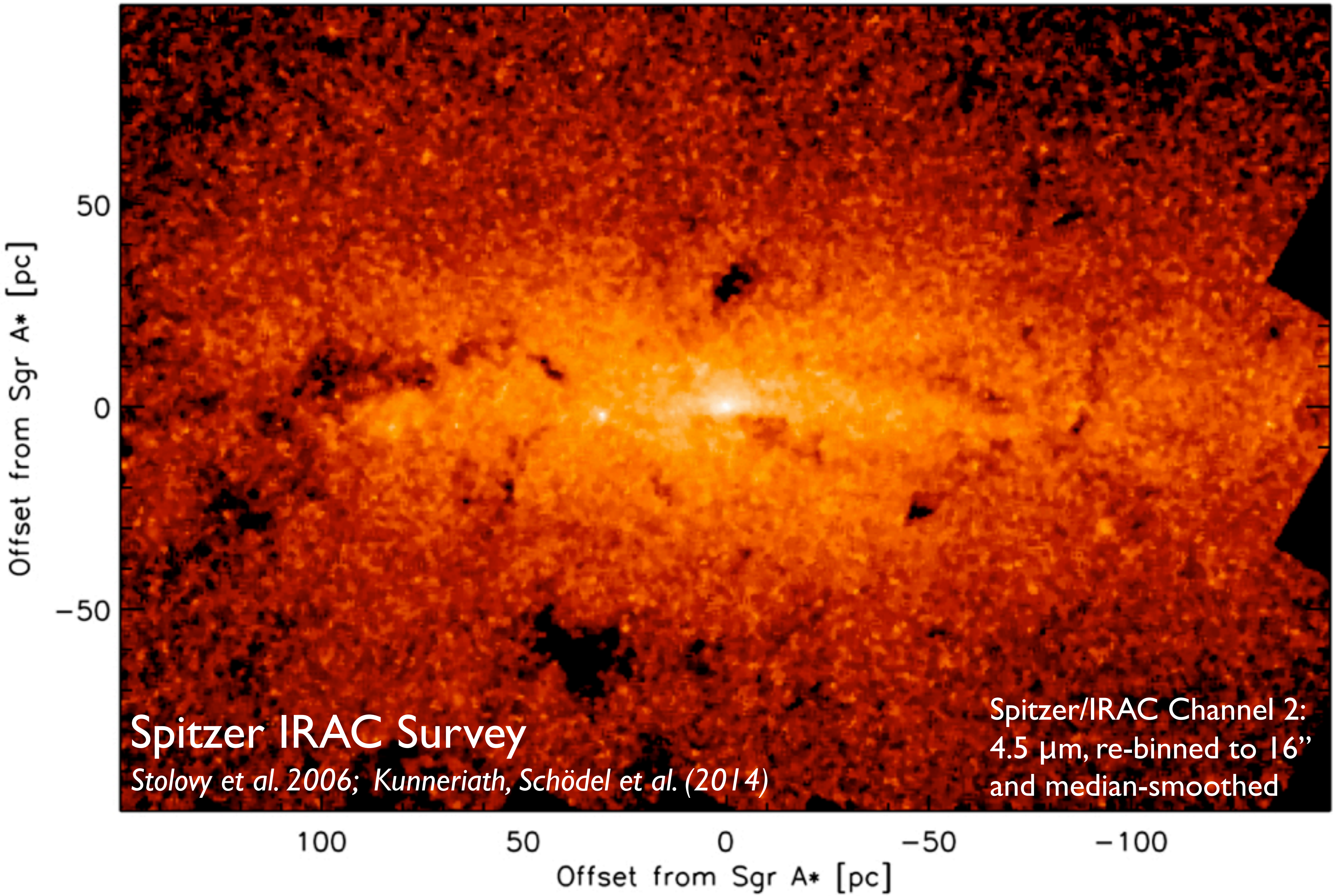
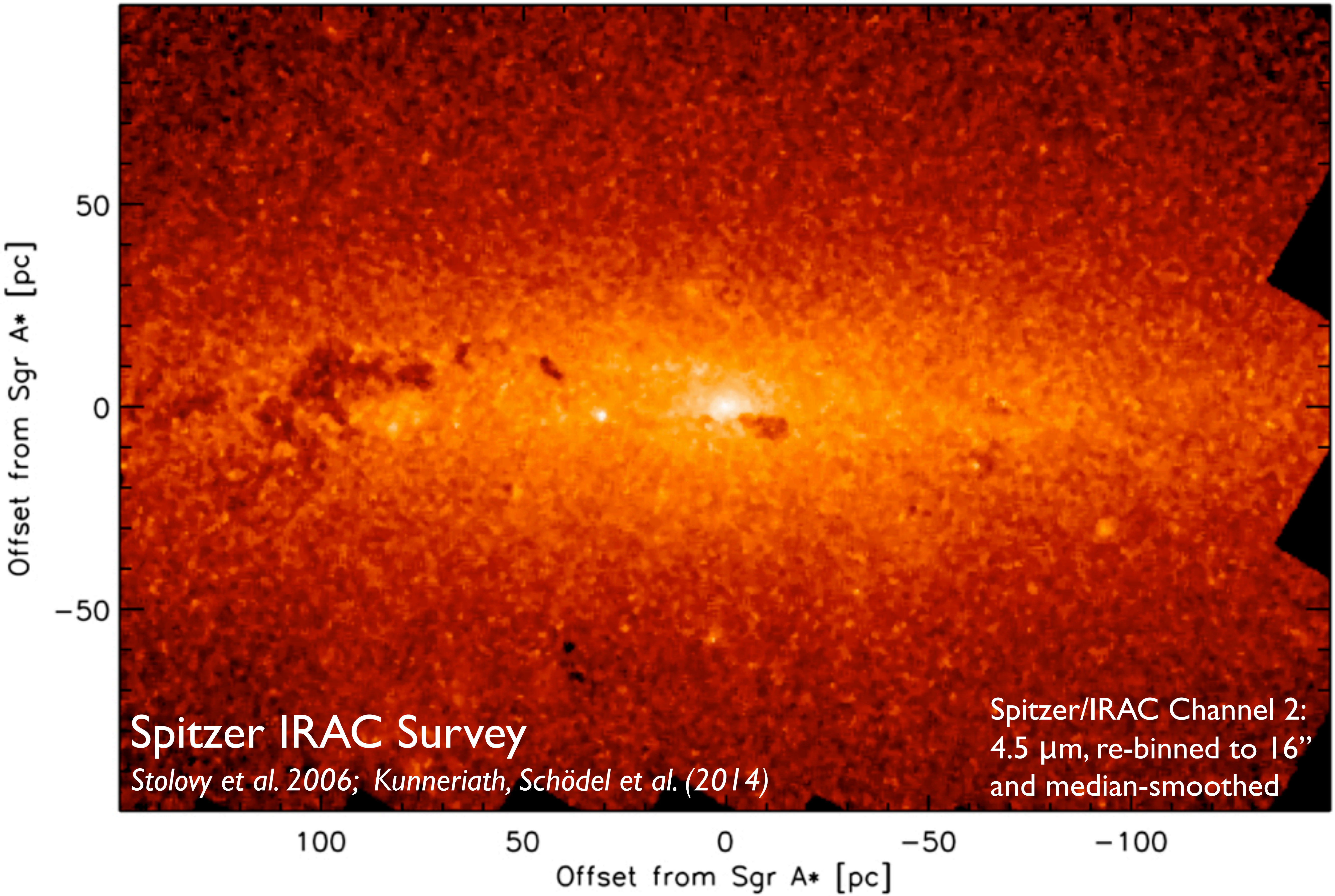


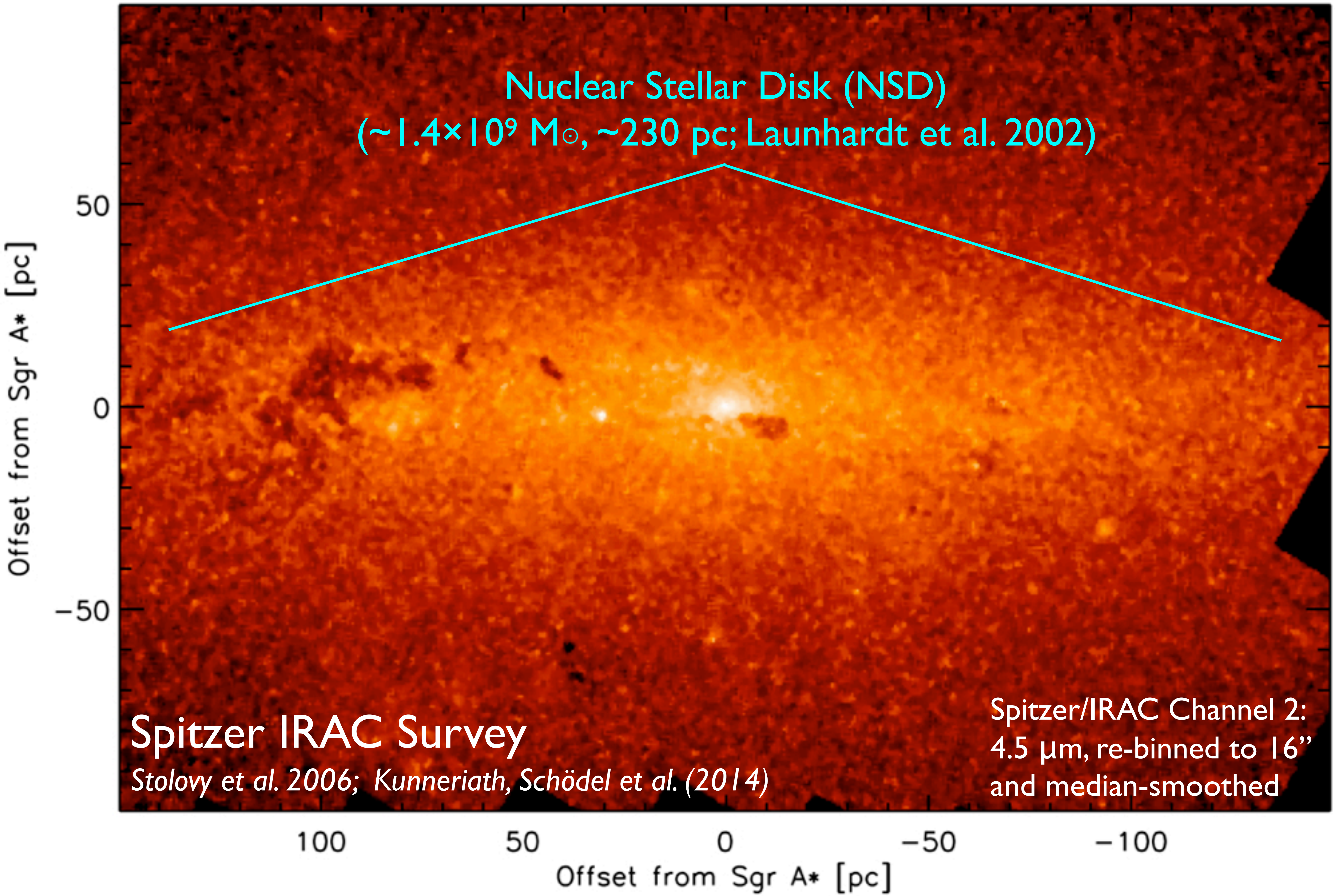
Overview of the GC



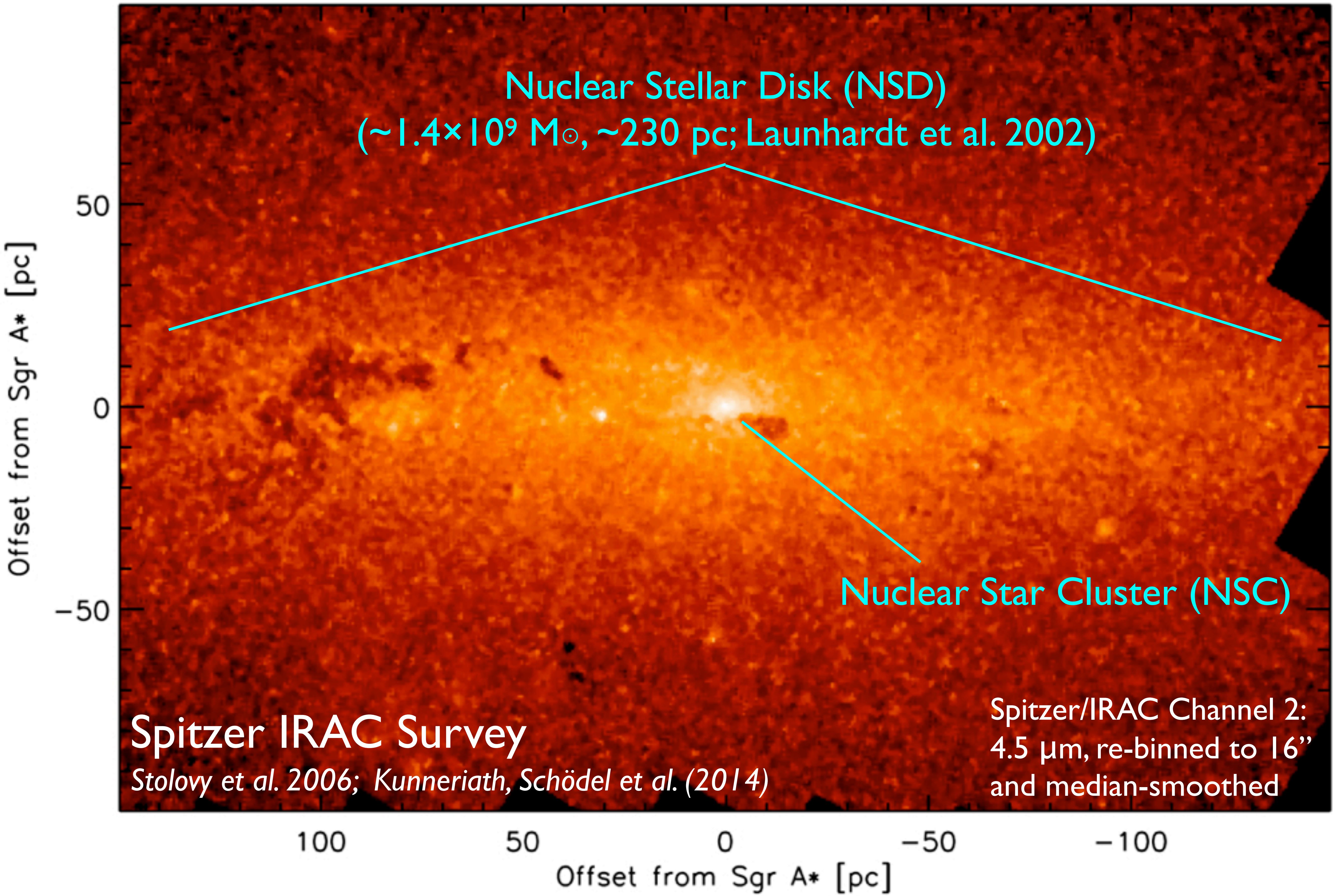
Overview of the GC



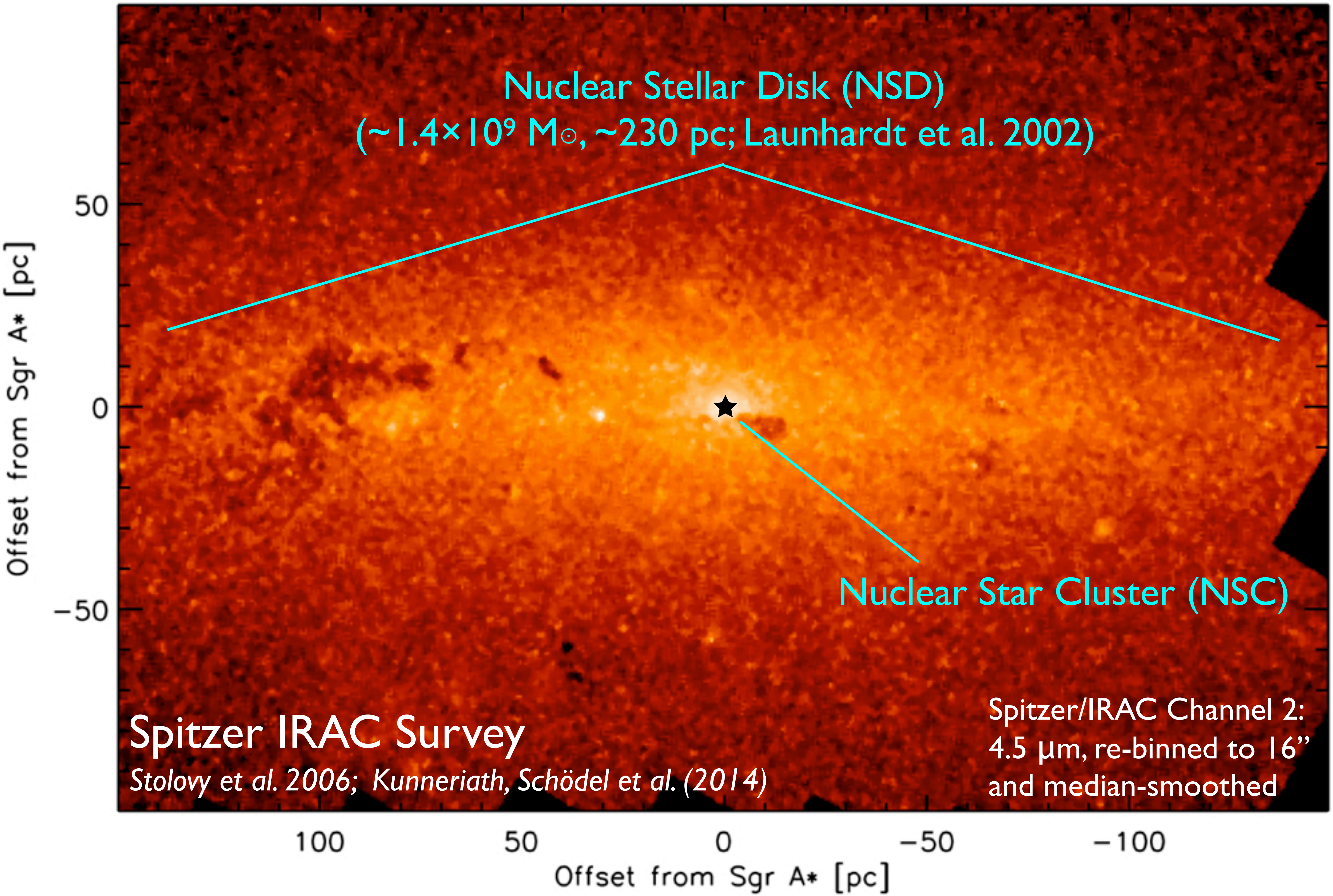
Overview of the GC



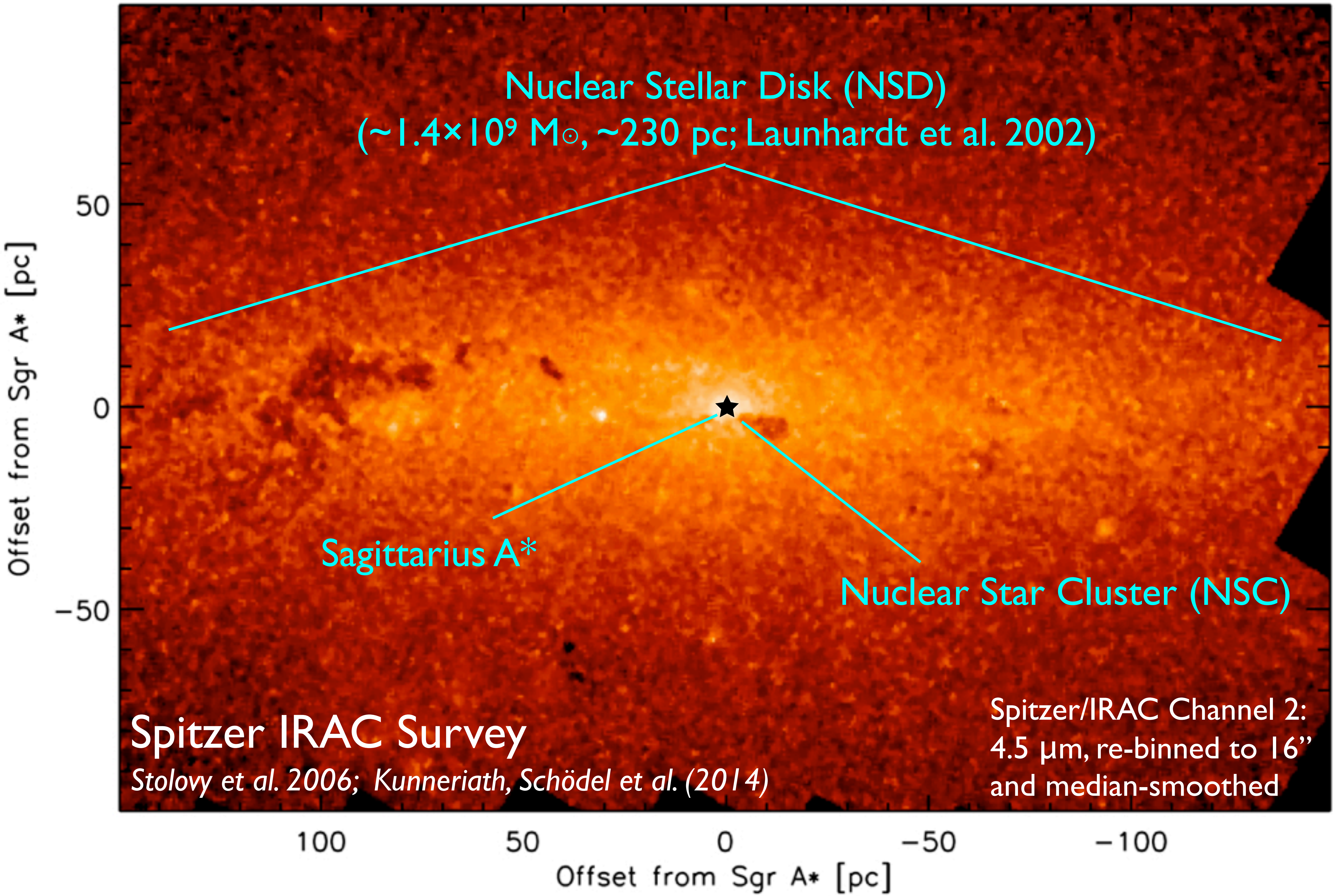
Overview of the GC



Overview of the GC



Overview of the GC



Observational Challenges

Observational Challenges

Strong and highly variable interstellar extinction combined with extreme source crowding make observations of the GC very challenging.

We can currently detect only ~5-10% of the stars.

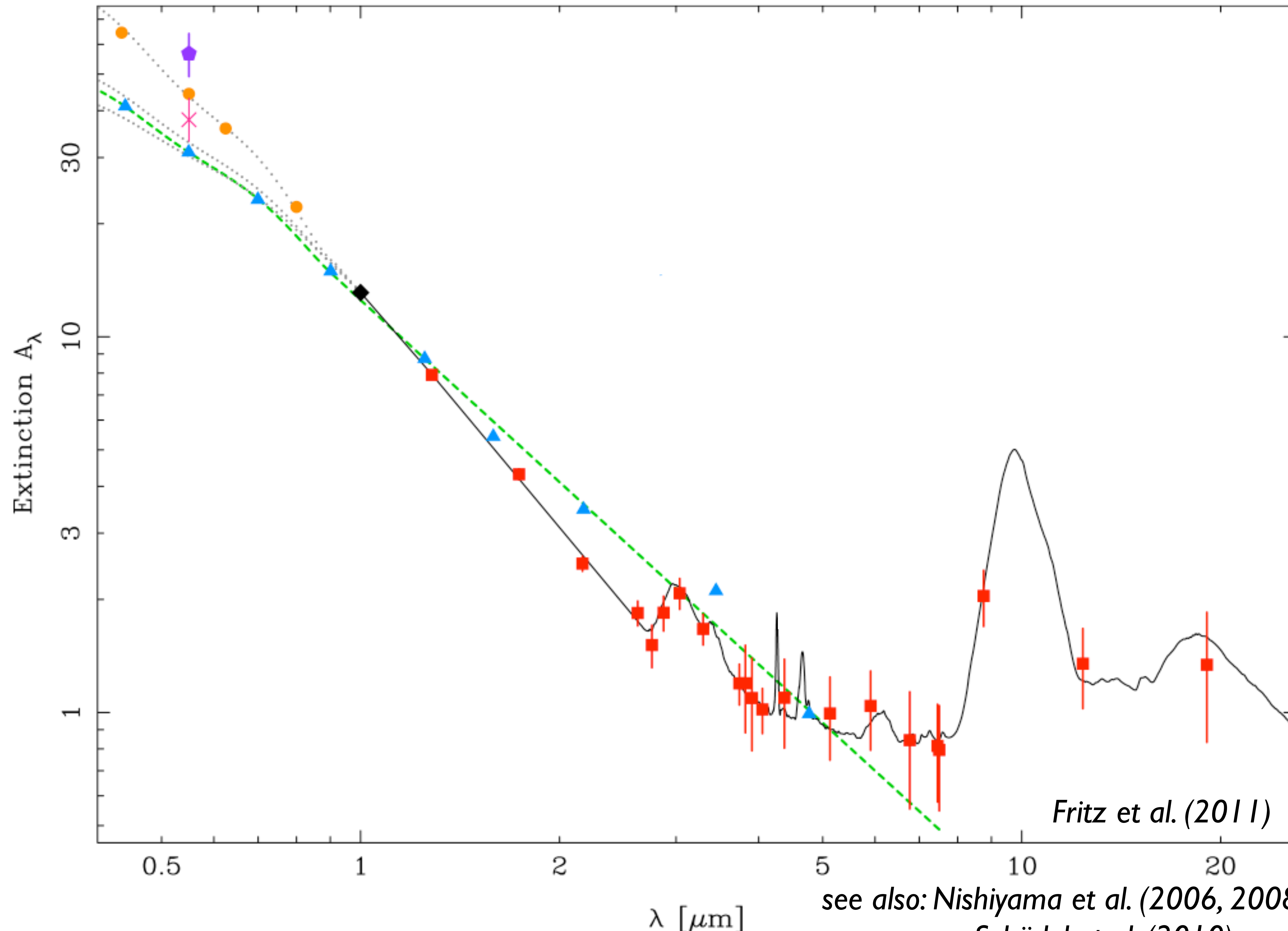
Current detection limit for MS stars at GC is ~ 2 $M_\odot$

Main tracers for <u>structure</u>: *red clump* stars
Main tracers for <u>star formation</u>: O/B stars, WR stars, AGB stars

The problem of surveying our own galaxy may be likened to the problem of drawing a map of New York City on the basis of observations made from the intersection of 125th Street and Park Avenue. Although it would be clear to an observer at this spot that the city is a big one, any statement as to its extent and layout would clearly be impossible. London would offer an even better analogy, for the neighborhood is not only congested but foggy.

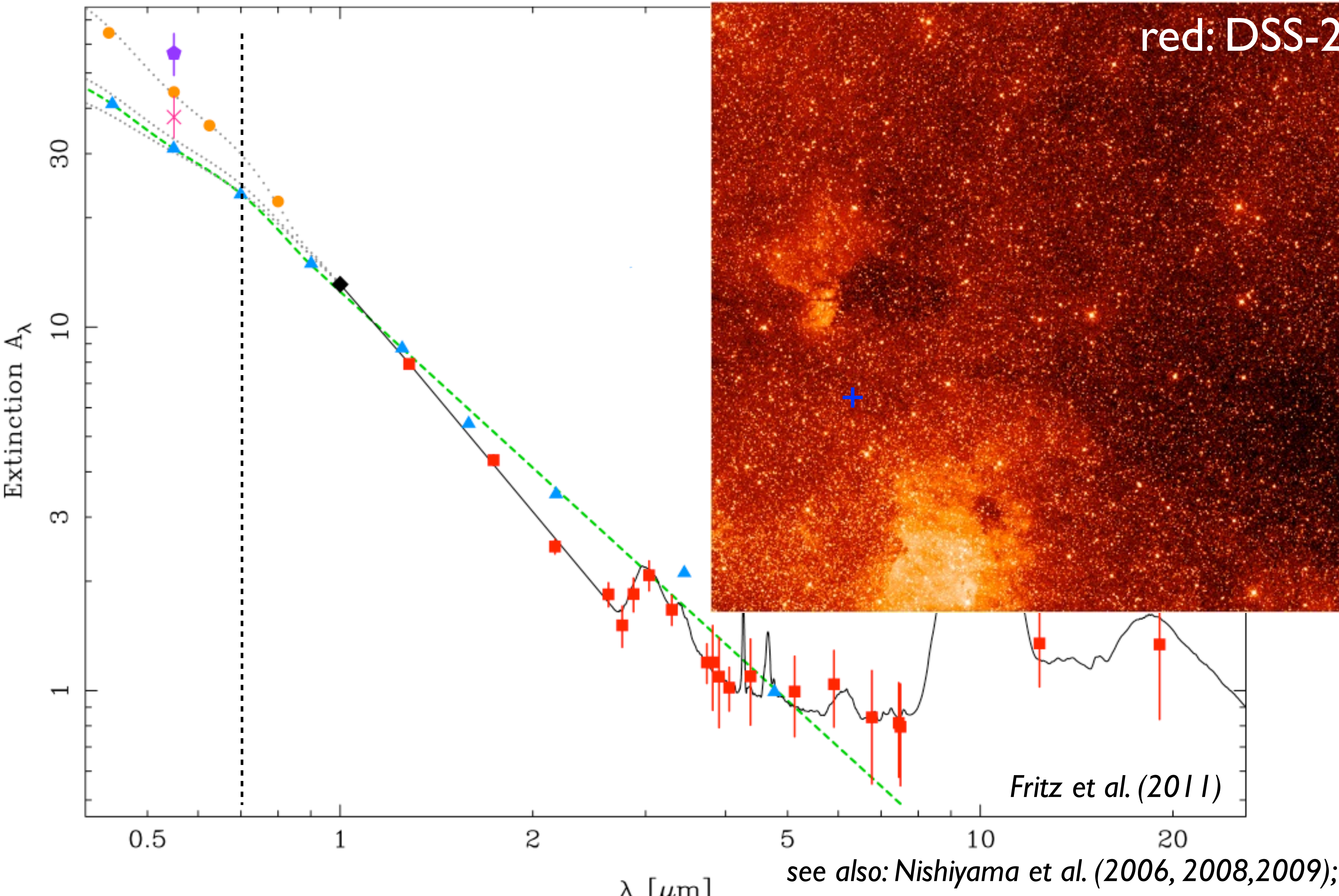
C. H. Payne-Gaposchkin

Interstellar Extinction



see also: Nishiyama et al. (2006, 2008,2009); Schödel et al. (2010)

Interstellar Extinction



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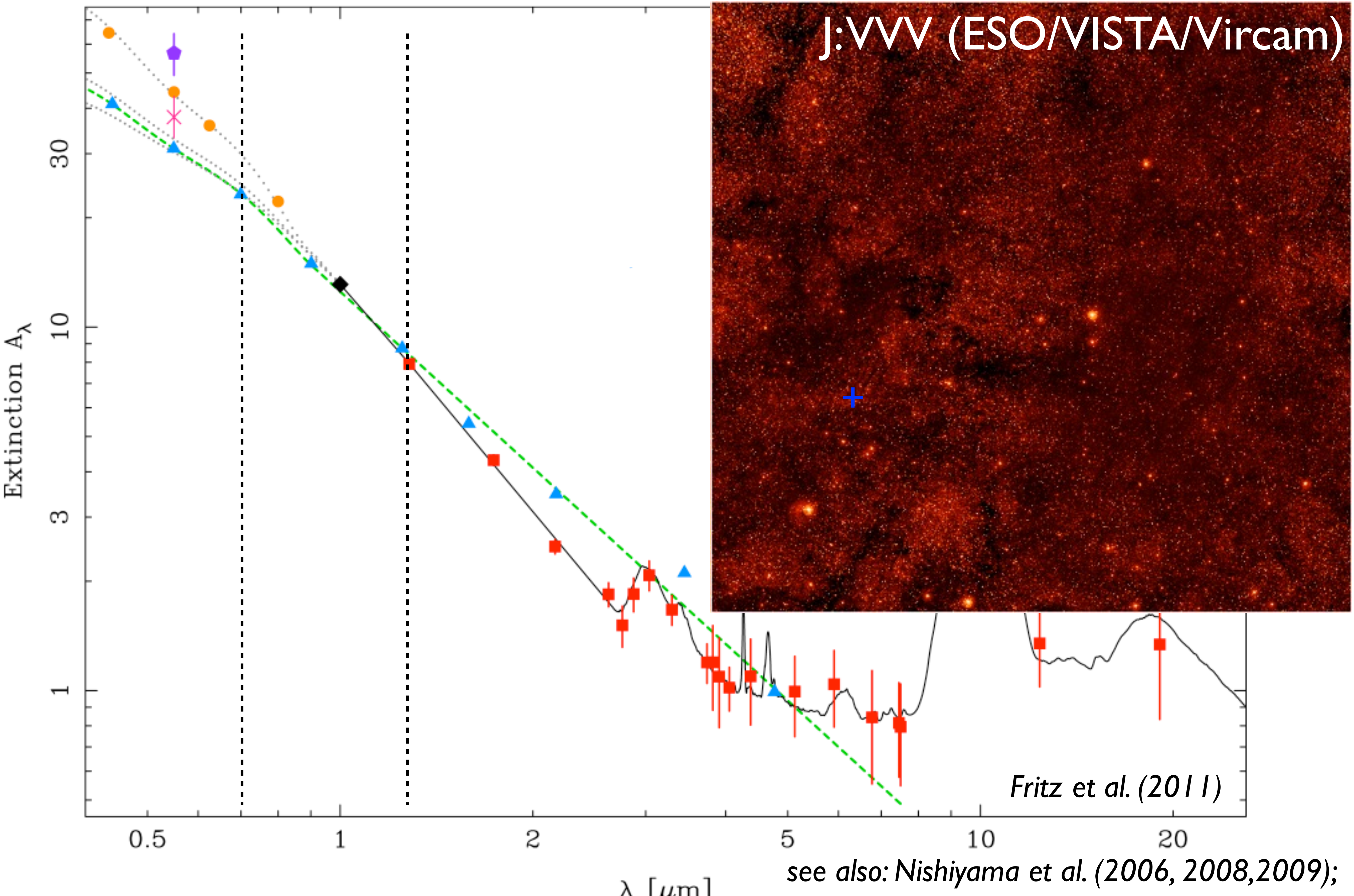
Interstellar Extinction



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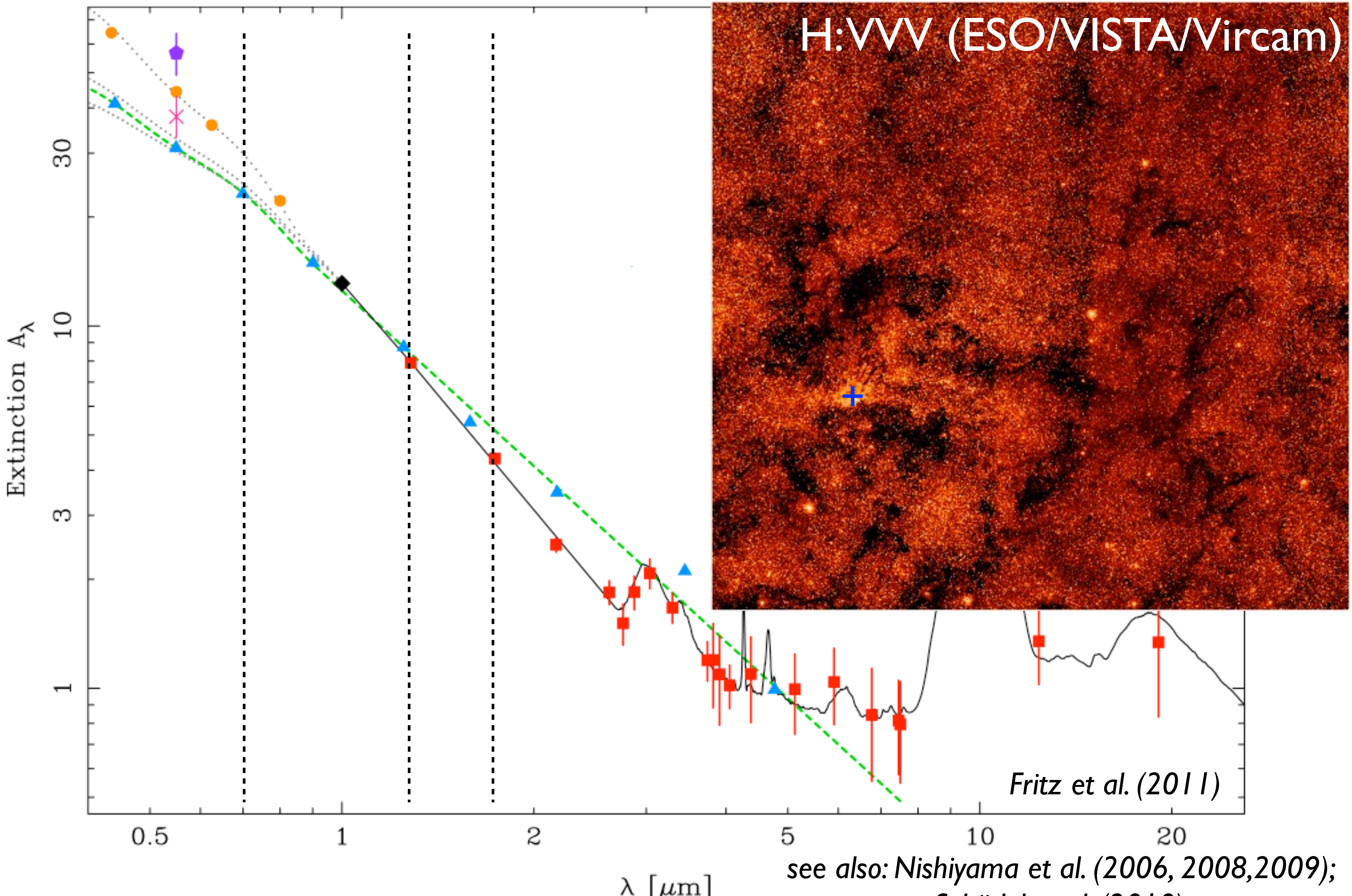
Interstellar Extinction



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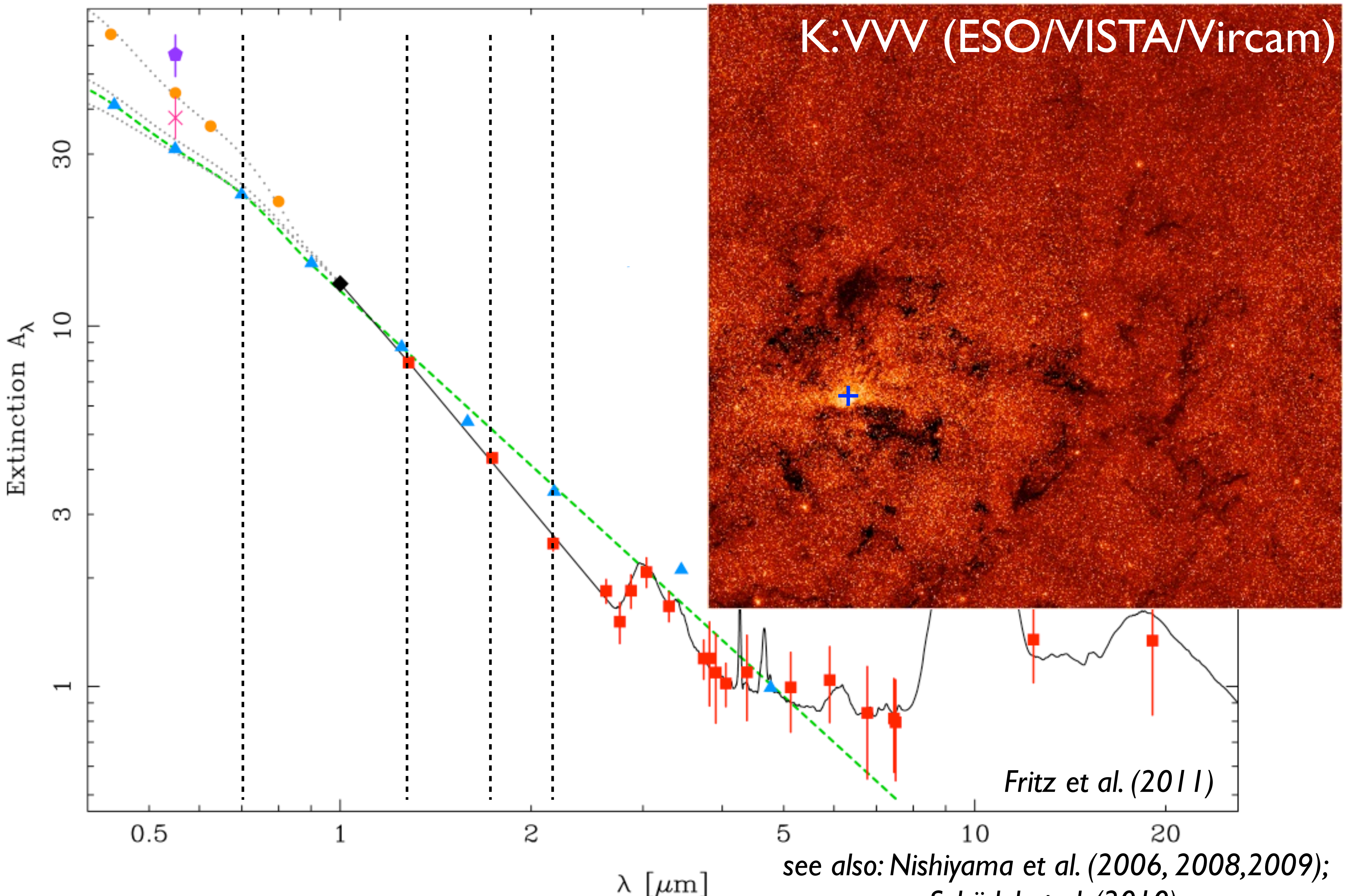
Interstellar Extinction



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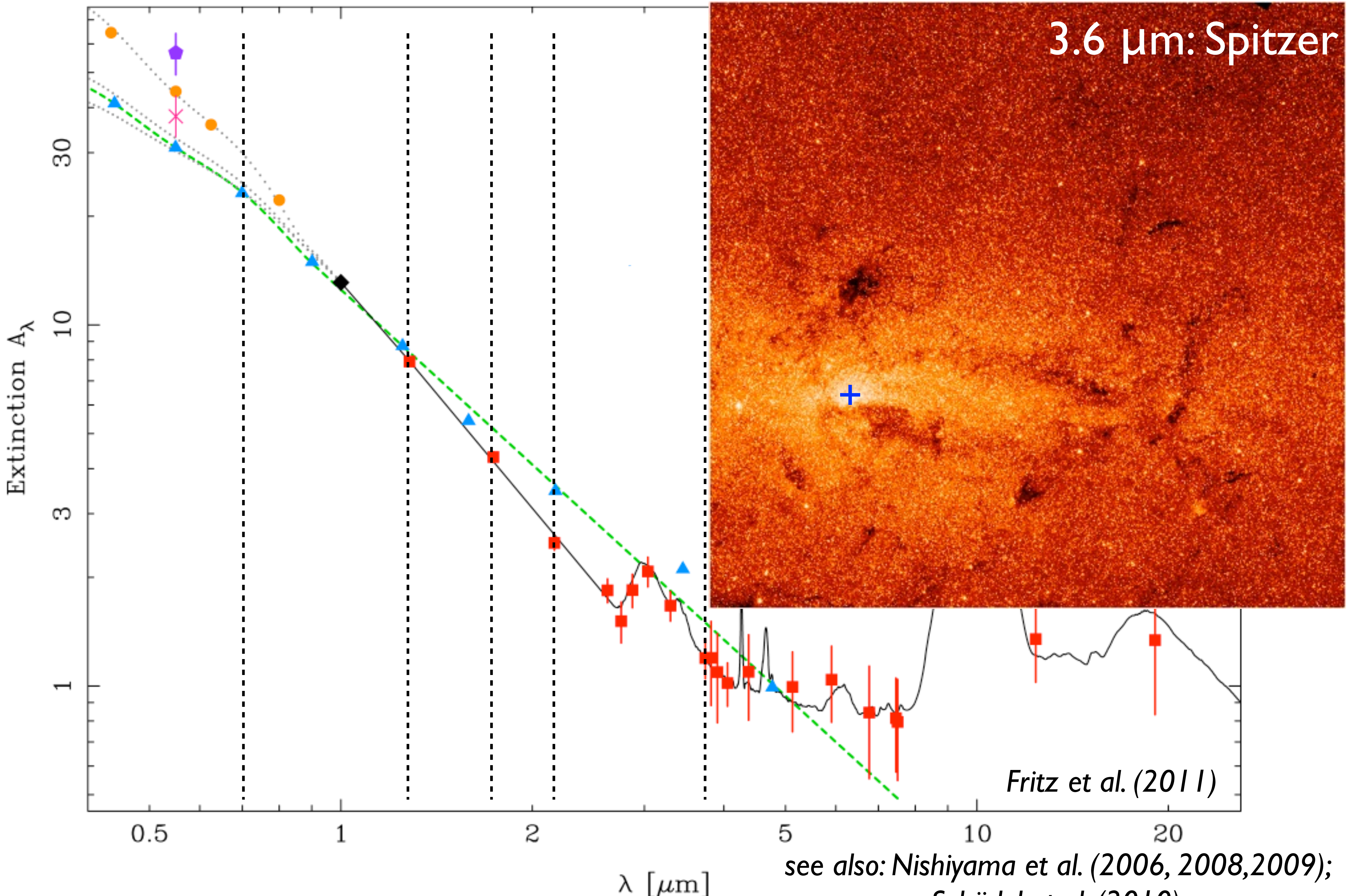
Interstellar Extinction



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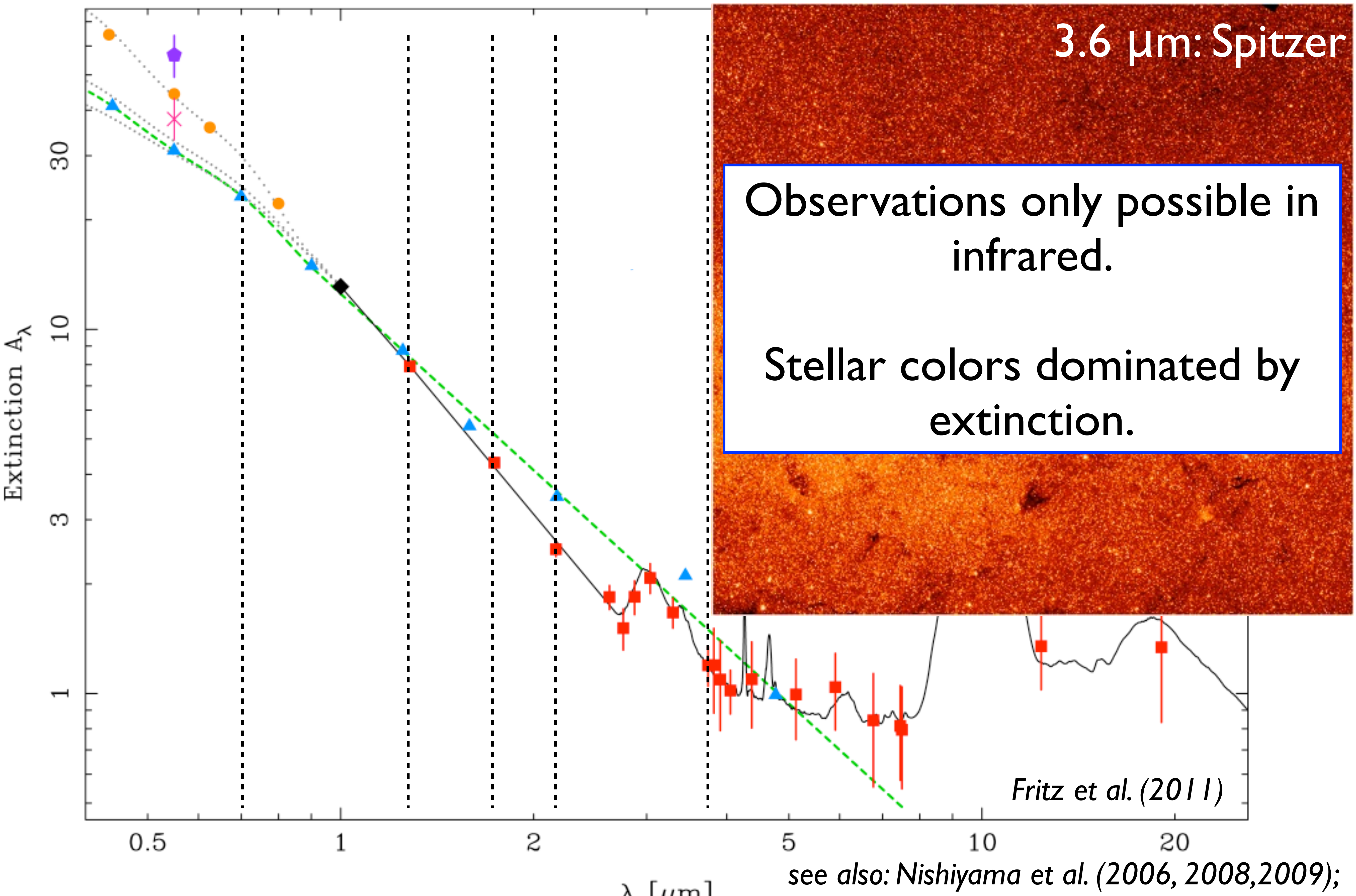
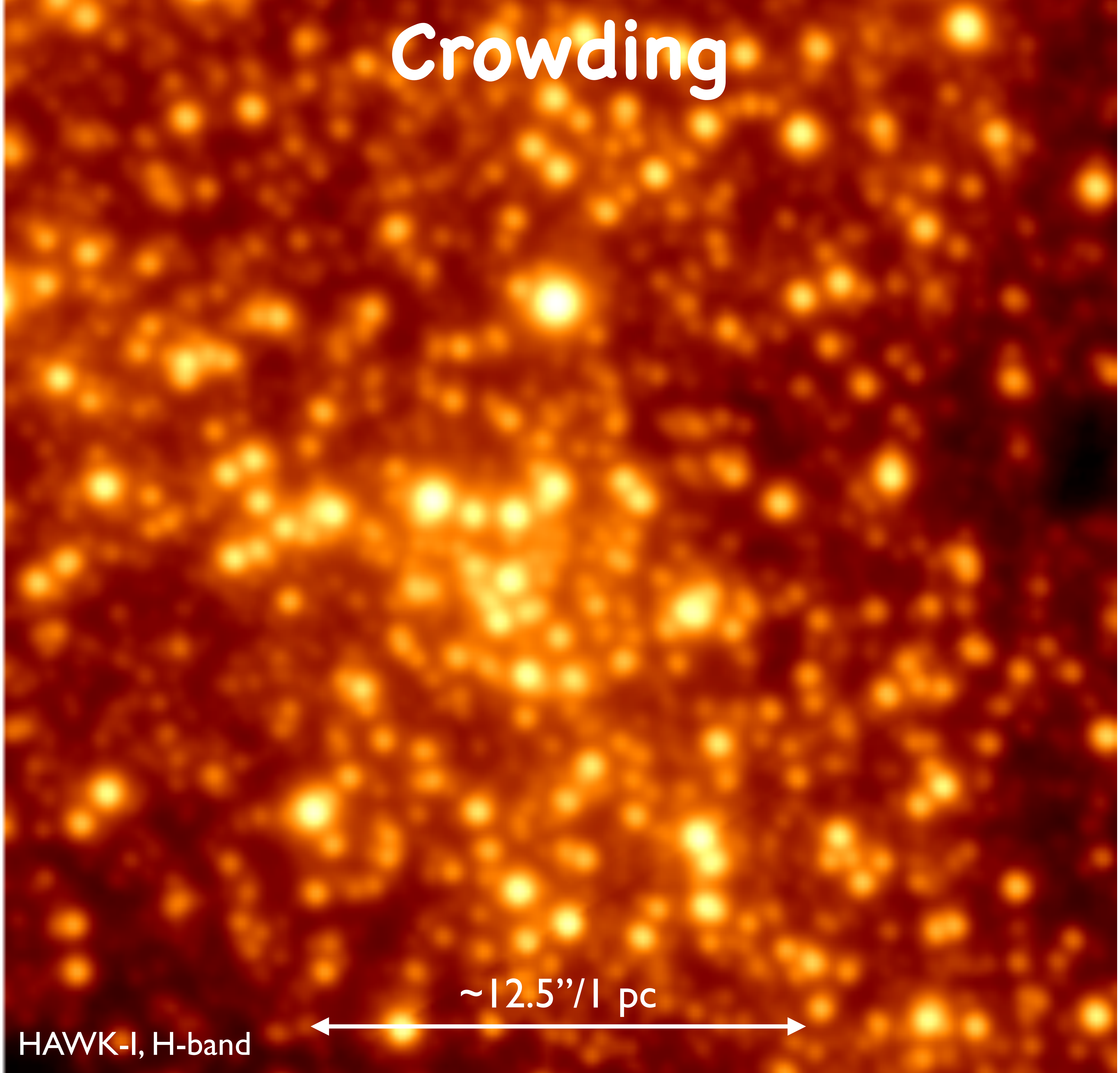
Interstellar Extinction

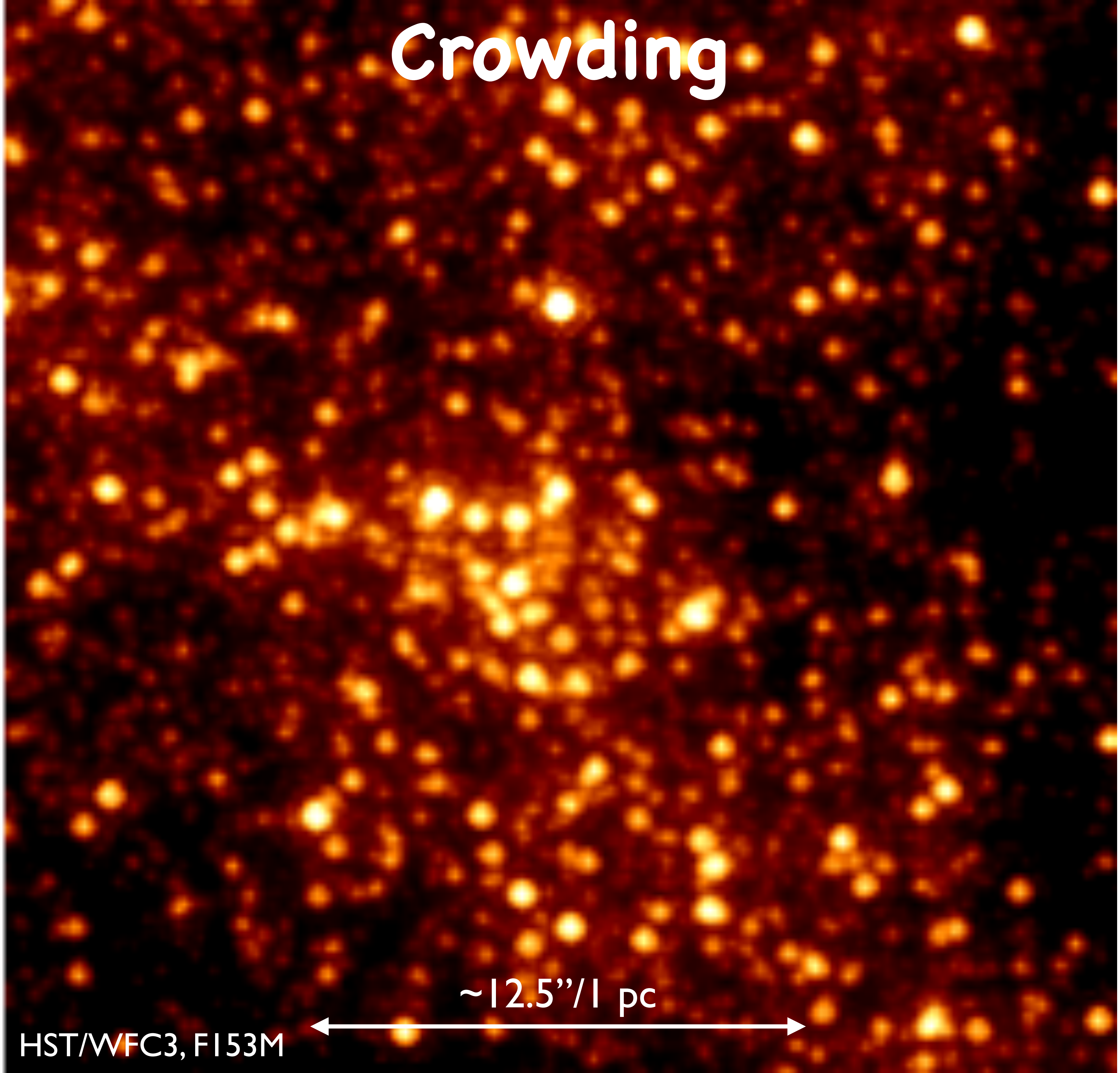


Observations only possible in infrared.

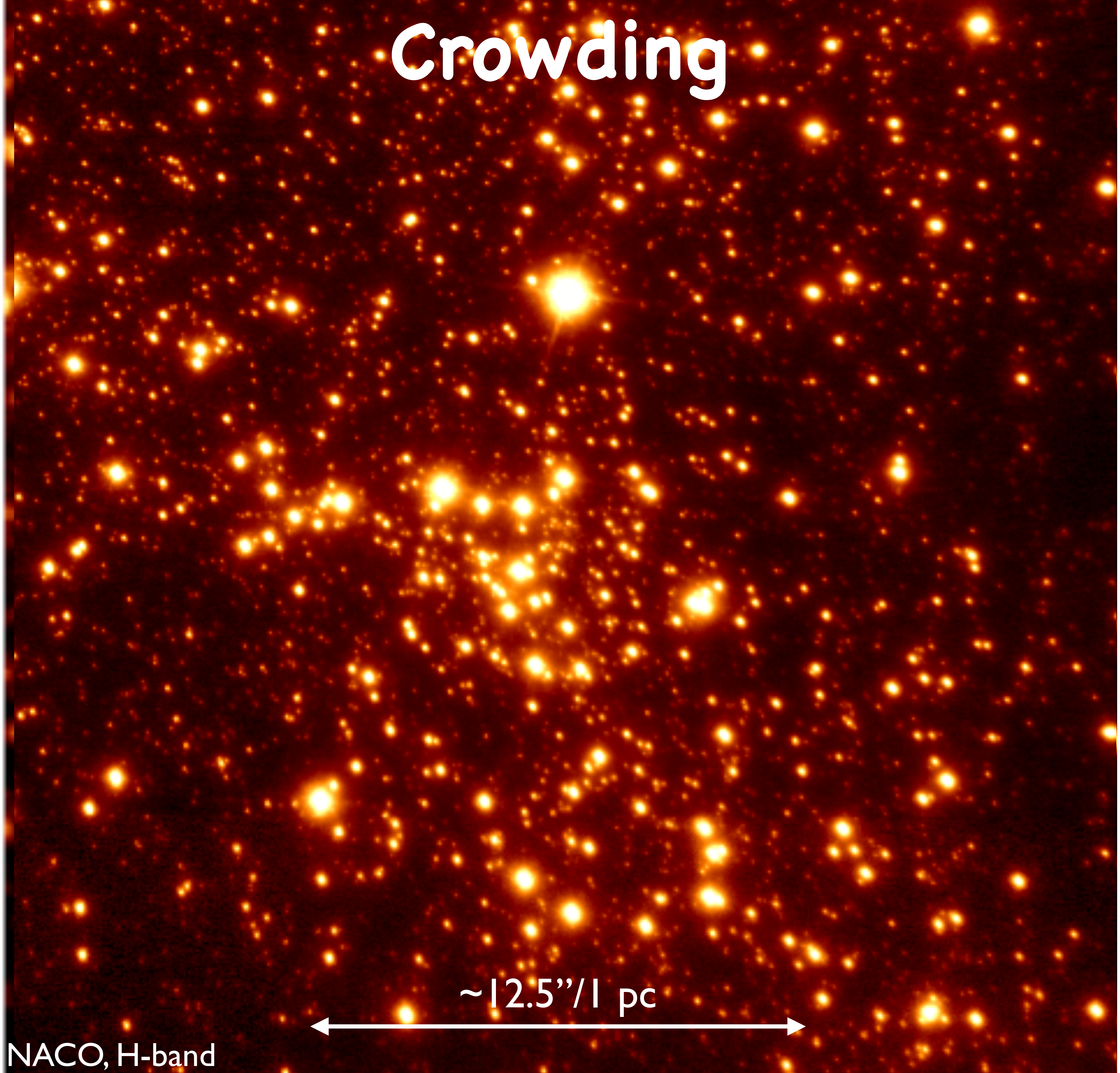
Stellar colors dominated by extinction.

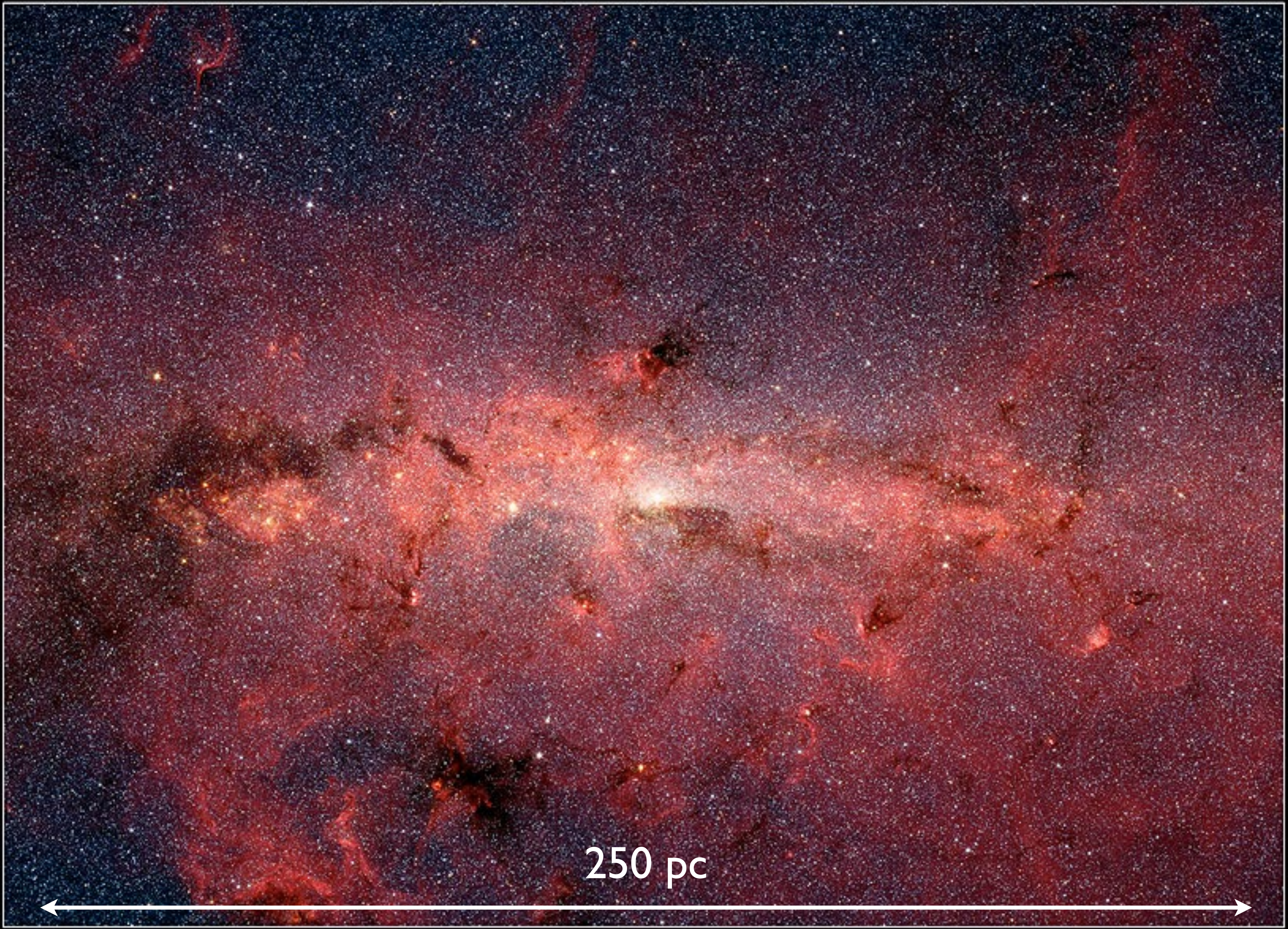
see also: Nishiyama et al. (2006, 2008,2009); Schödel et al. (2010)


Crowding
~12.5"/1 pc
HAWK-I, H-band


Crowding
~12.5''/1 pc
HST/WFC3, F153M

Crowding



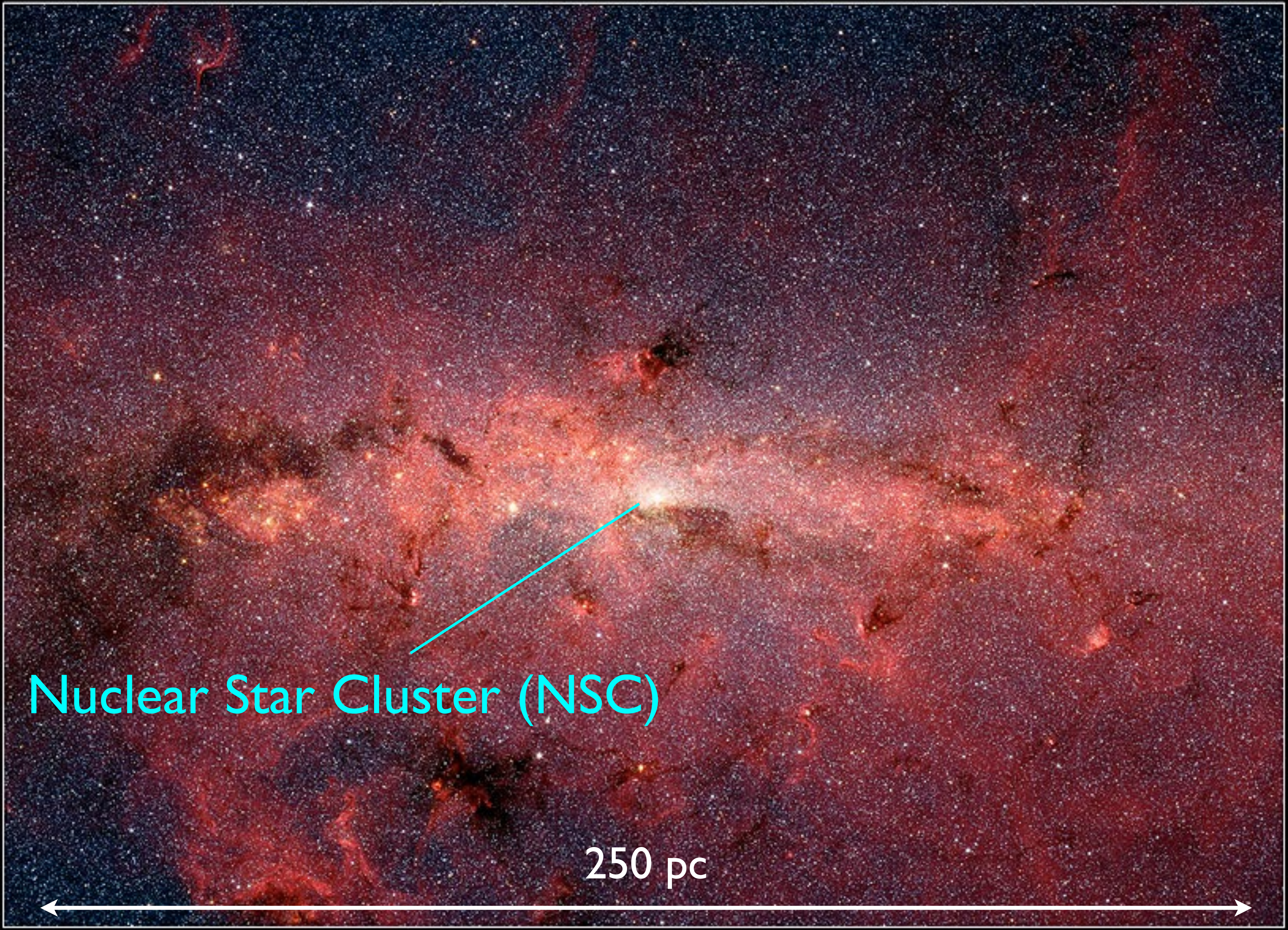


The Center of the Milky Way Galaxy

NASA / JPL-Caltech / S. Stolovy (Spitzer Science Center/Caltech)

Spitzer Space Telescope • IRAC

ssc2006-02a



The Center of the Milky Way Galaxy

Spitzer Space Telescope • IRAC

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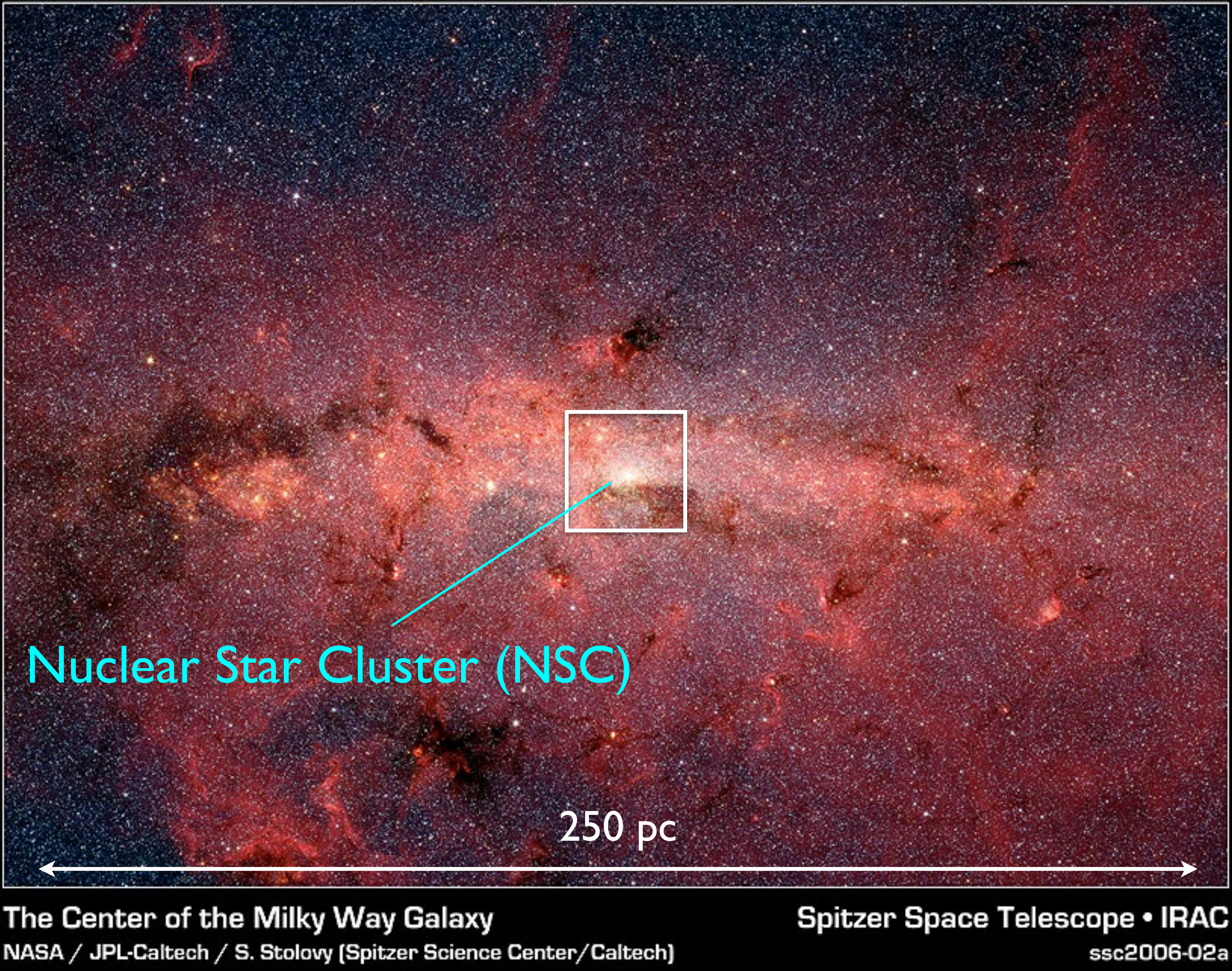
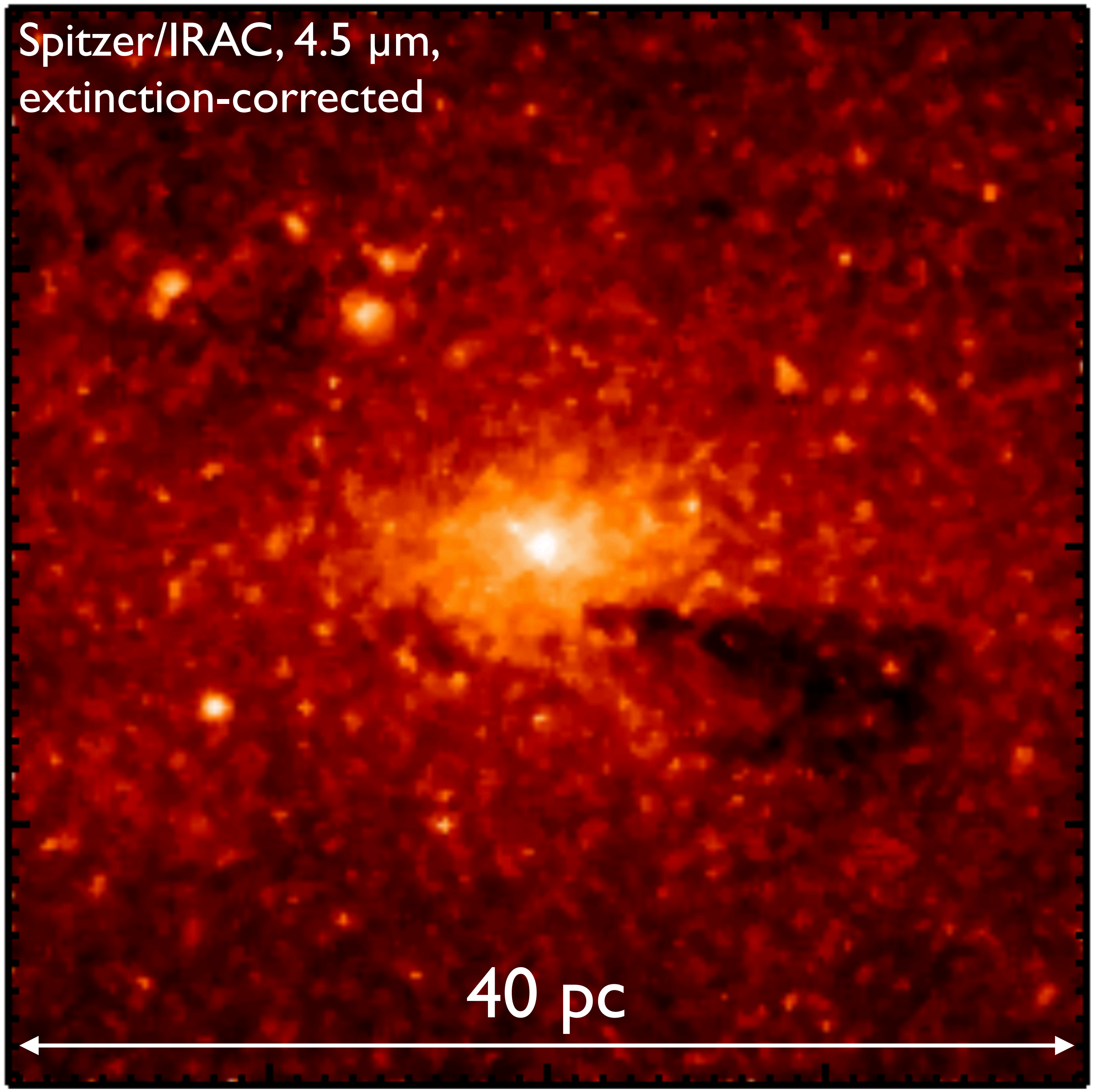
ssc2006-02a


Nuclear Star Cluster (NSC)
250 pc
The Center of the Milky Way Galaxy
Spitzer Space Telescope • IRAC
NASA / JPL-Caltech / S. Stolovy (Spitzer Science Center/Caltech)
ssc2006-02a

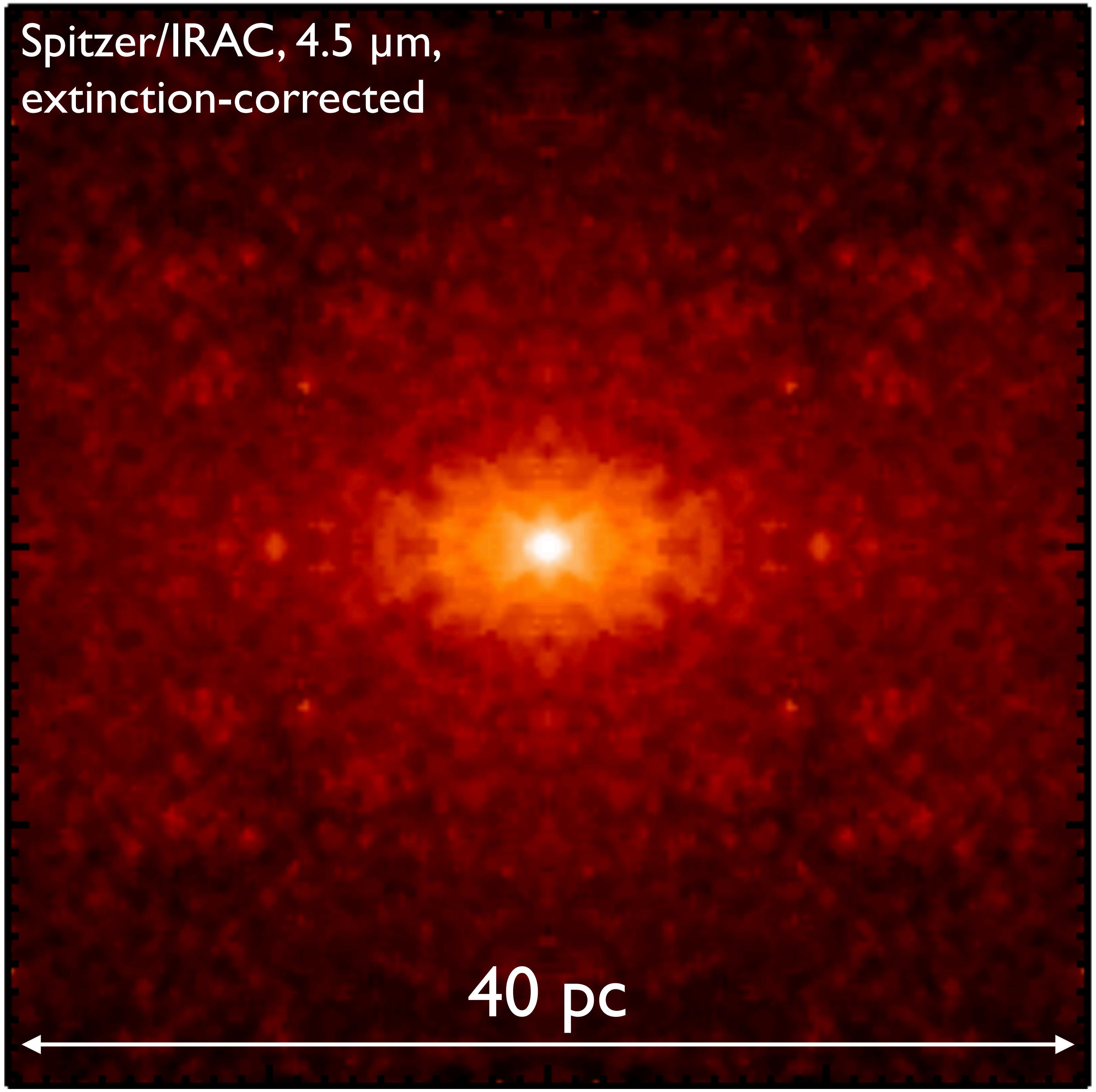
Nuclear Star Cluster and MBH



- Centred on Sgr A*
- Flattened along Galactic Plane
- Half light radius = 4.2 ± 0.4 pc
- Mass 2.5 ± 0.4 × 10^7 $M_\odot$
- M_{MBH} = 4 × 10^6 $M_\odot$

Schödel, et al. 2014; Feldmeier et al. 2014; Fritz et al. 2016; Gallego-Cano et al. (in prep.)

Nuclear Star Cluster and MBH



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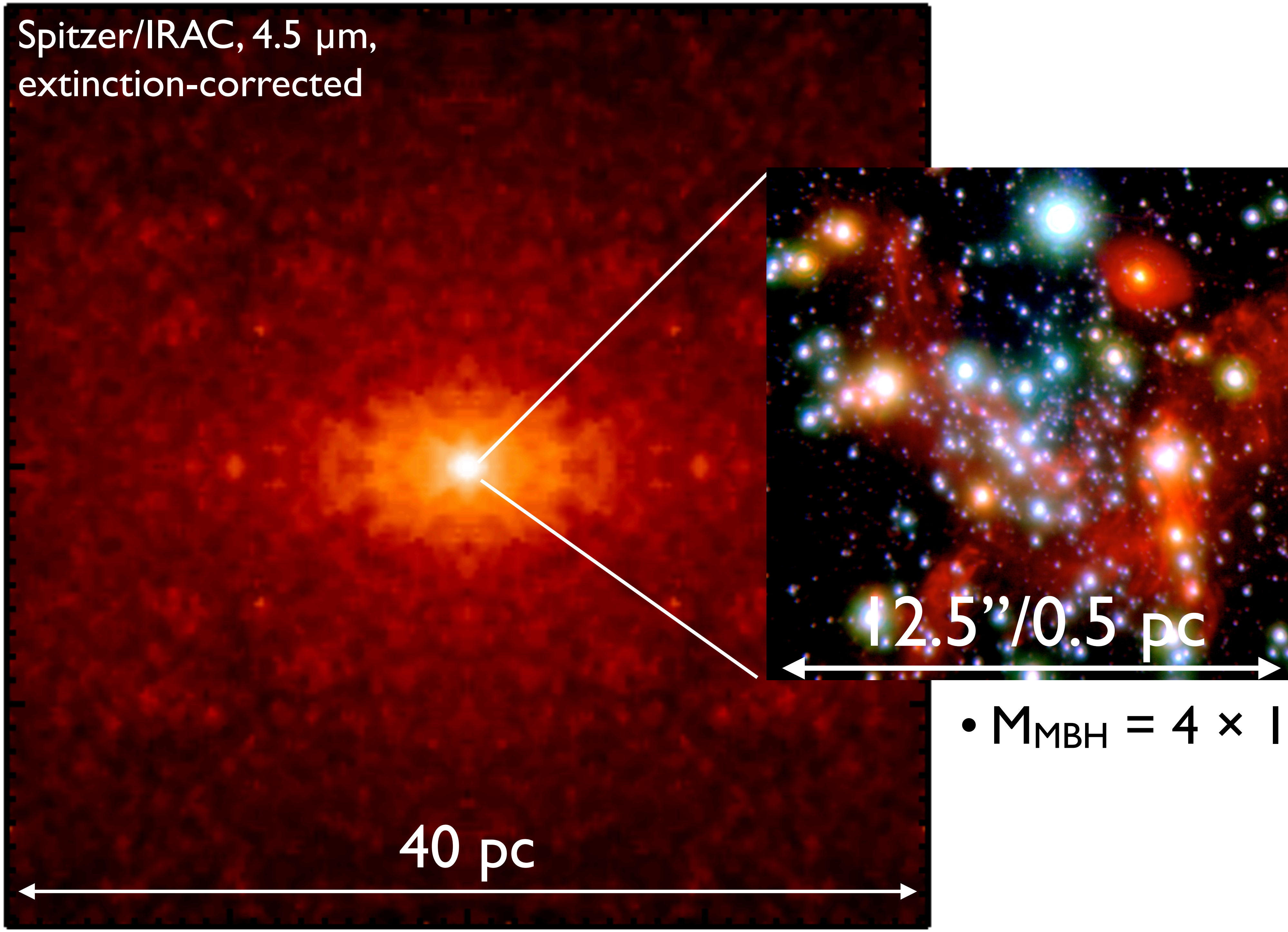
Nuclear Star Cluster and MBH



gr A*

g Galactic Plane

us = 4.2 ± 0.4 pc

4 × 10^7 $M_\odot$

- M_{MBH} = 4 × 10^6 $M_\odot$

Schödel, et al. 2014; Feldmeier et al. 2014;
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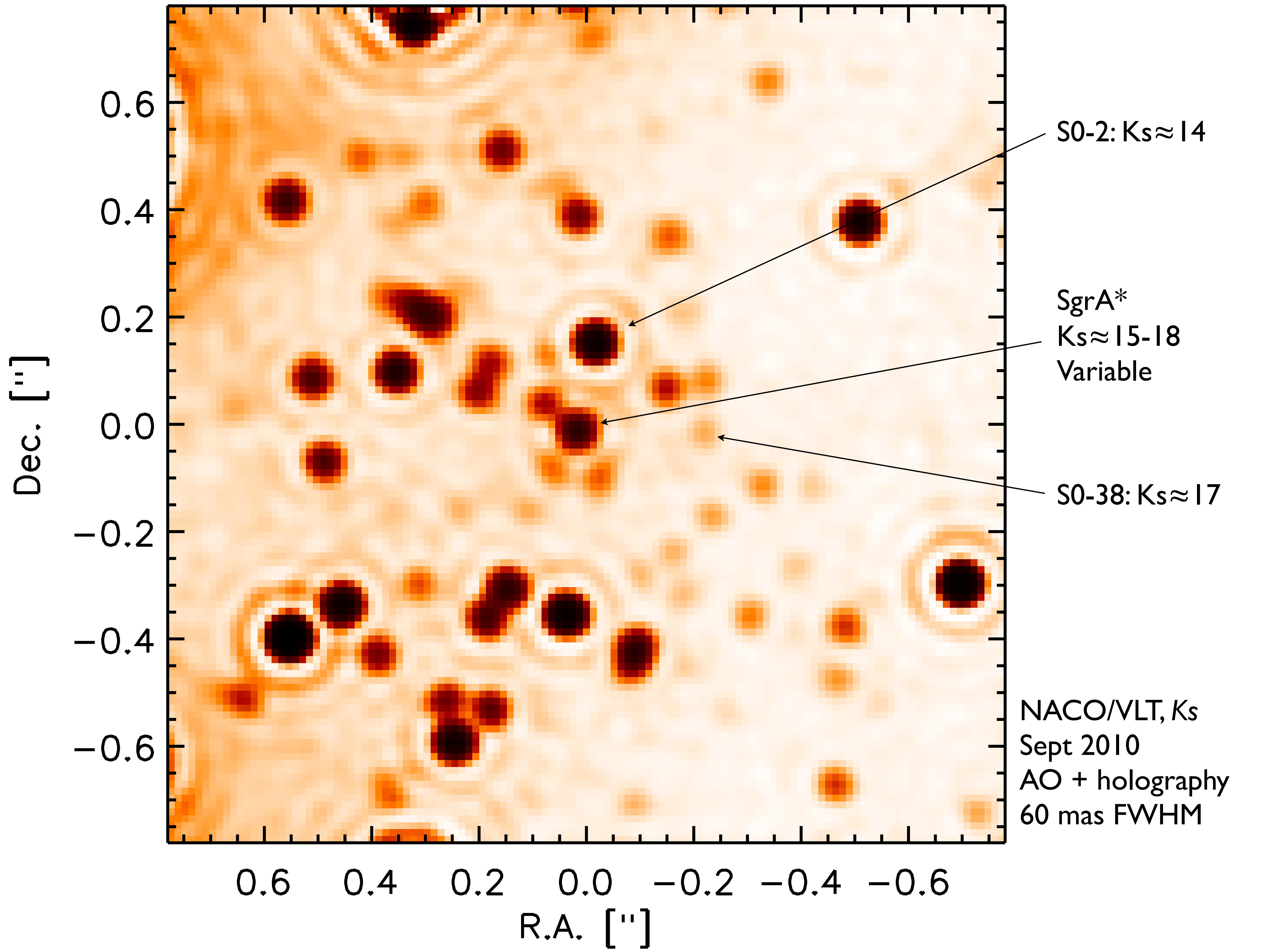
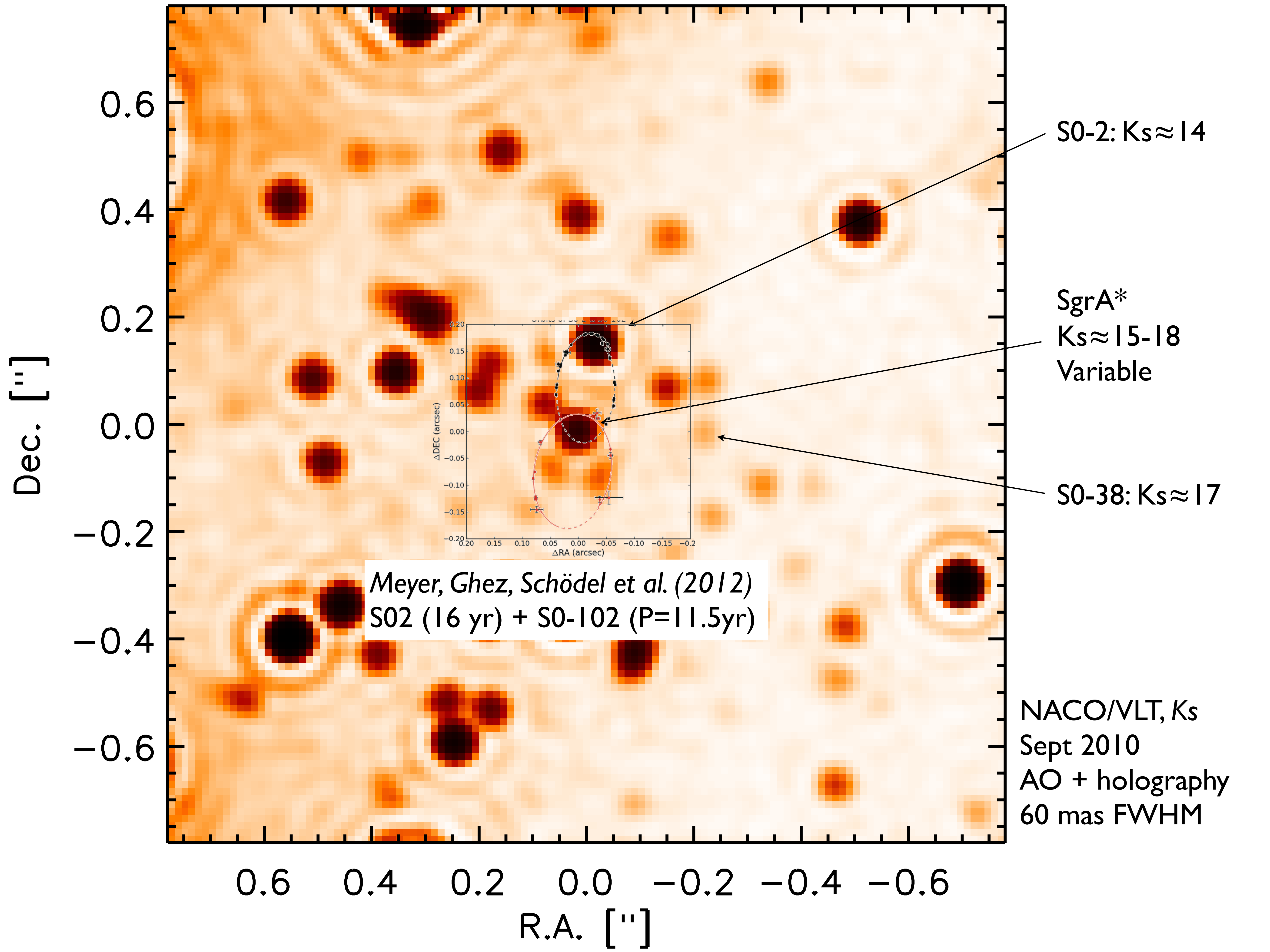
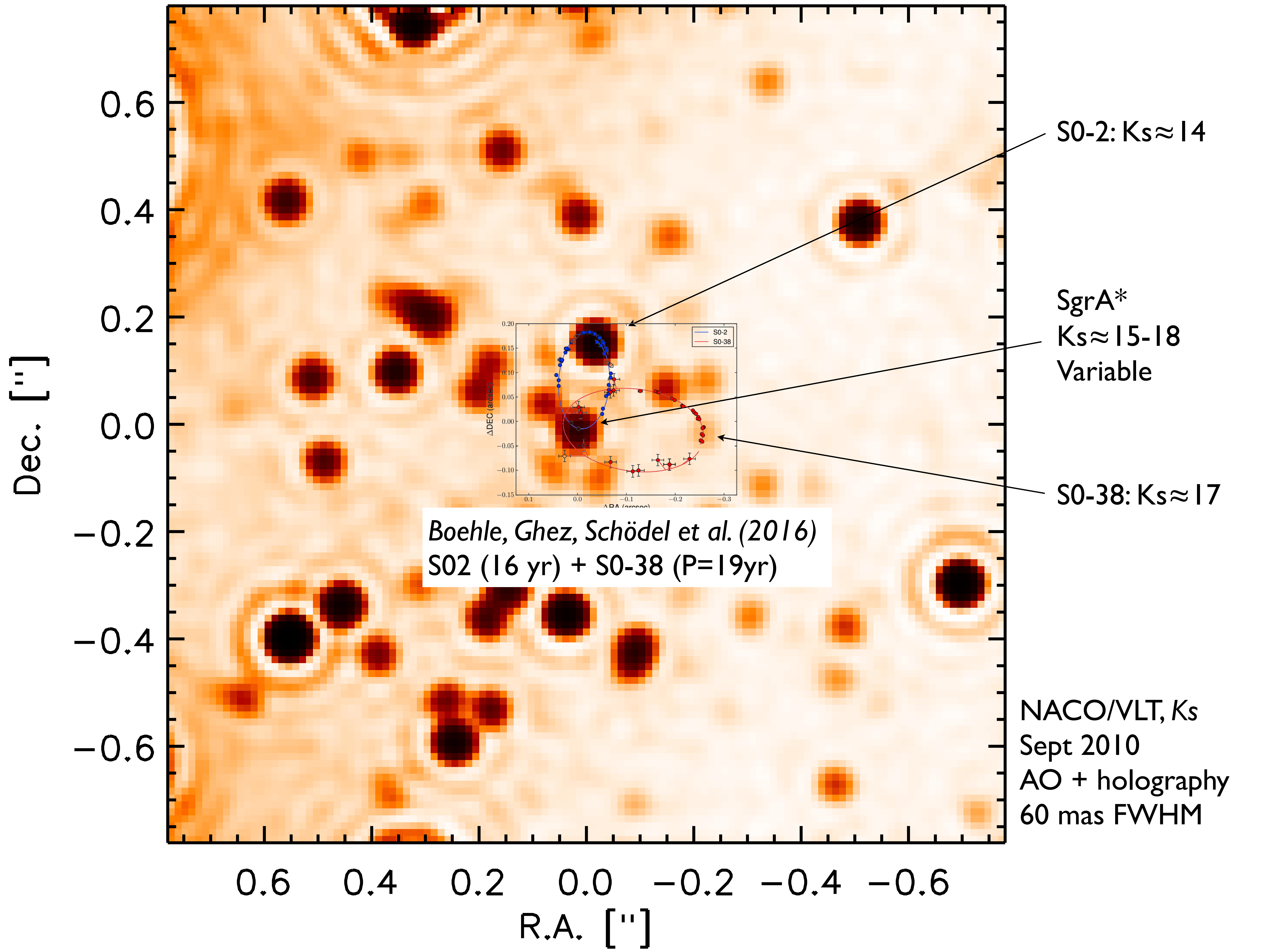
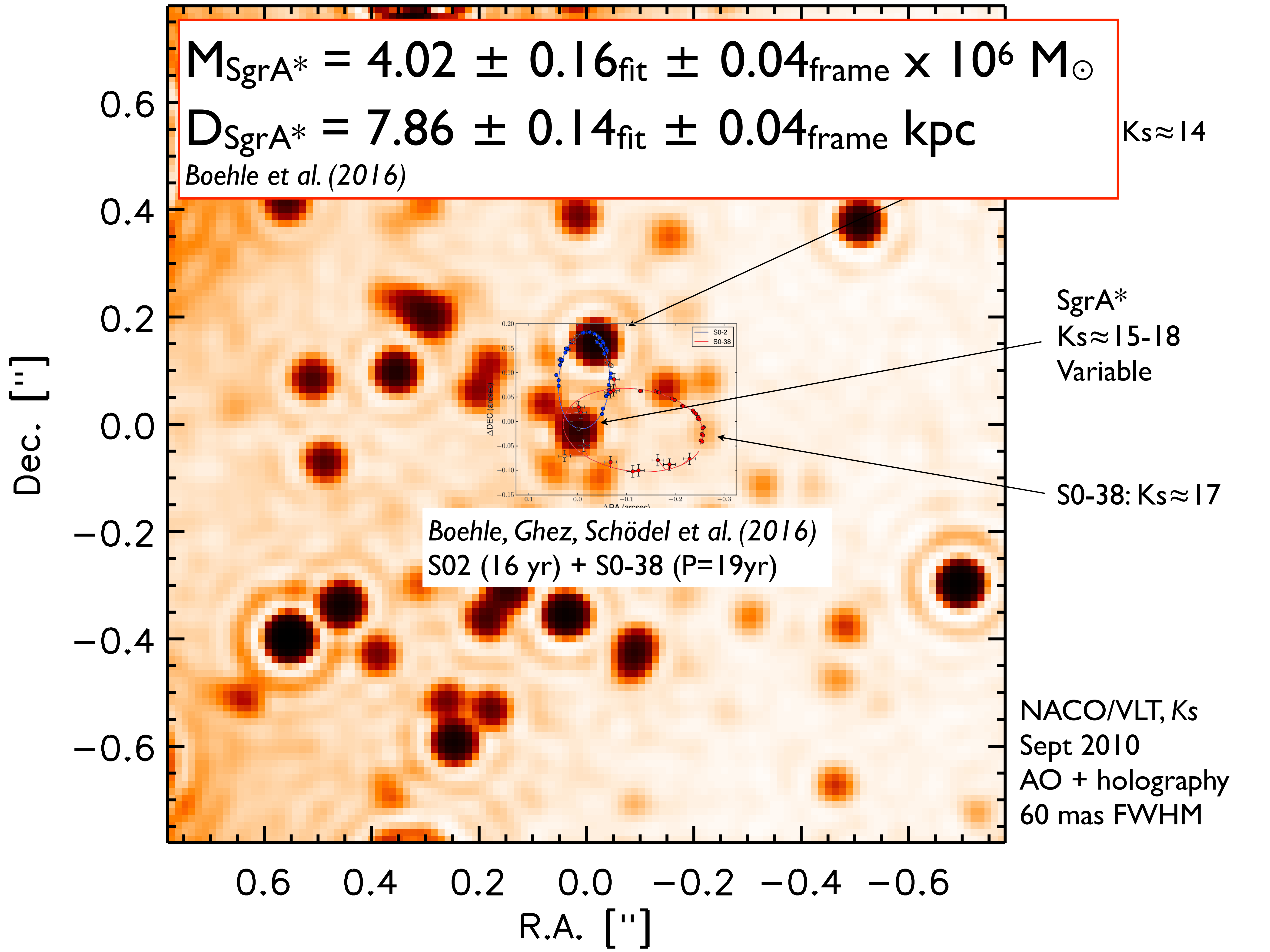


S0-2: Ks≈14
SgrA*
Ks≈15-18
Variable
S0-38: Ks≈17
NACO/VLT, *Ks*
Sept 2010
AO + holography
60 mas FWHM
Dec. ['']
R.A. ['']
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6


S0-2: Ks≈14
SgrA*
Ks≈15-18
Variable
S0-38: Ks≈17
Meyer, Ghez, Schödel et al. (2012)
S02 (16 yr) + S0-102 (P=11.5yr)
NACO/VLT, Ks
Sept 2010
AO + holography
60 mas FWHM
Dec. ['']
R.A. ['']
ΔDEC (arcsec)
ΔRA (arcsec)



S0-2: Ks≈14
SgrA*
Ks≈15-18
Variable
S0-38: Ks≈17
Boehle, Ghez, Schödel et al. (2016)
S02 (16 yr) + S0-38 (P=19yr)
NACO/VLT, Ks
Sept 2010
AO + holography
60 mas FWHM
Dec. ['']
R.A. ['']
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6



$M_{SgrA*} = 4.02 \pm 0.16_{fit} \pm 0.04_{frame} \times 10^6\ M_{\odot}$
$D_{SgrA*} = 7.86 \pm 0.14_{fit} \pm 0.04_{frame}$ kpc
Boehle et al. (2016)
Ks≈14
SgrA*
Ks≈15-18
Variable
S0-38: Ks≈17
S0-2
S0-38
Boehle, Ghez, Schödel et al. (2016)
S02 (16 yr) + S0-38 (P=19yr)
NACO/VLT, *Ks*
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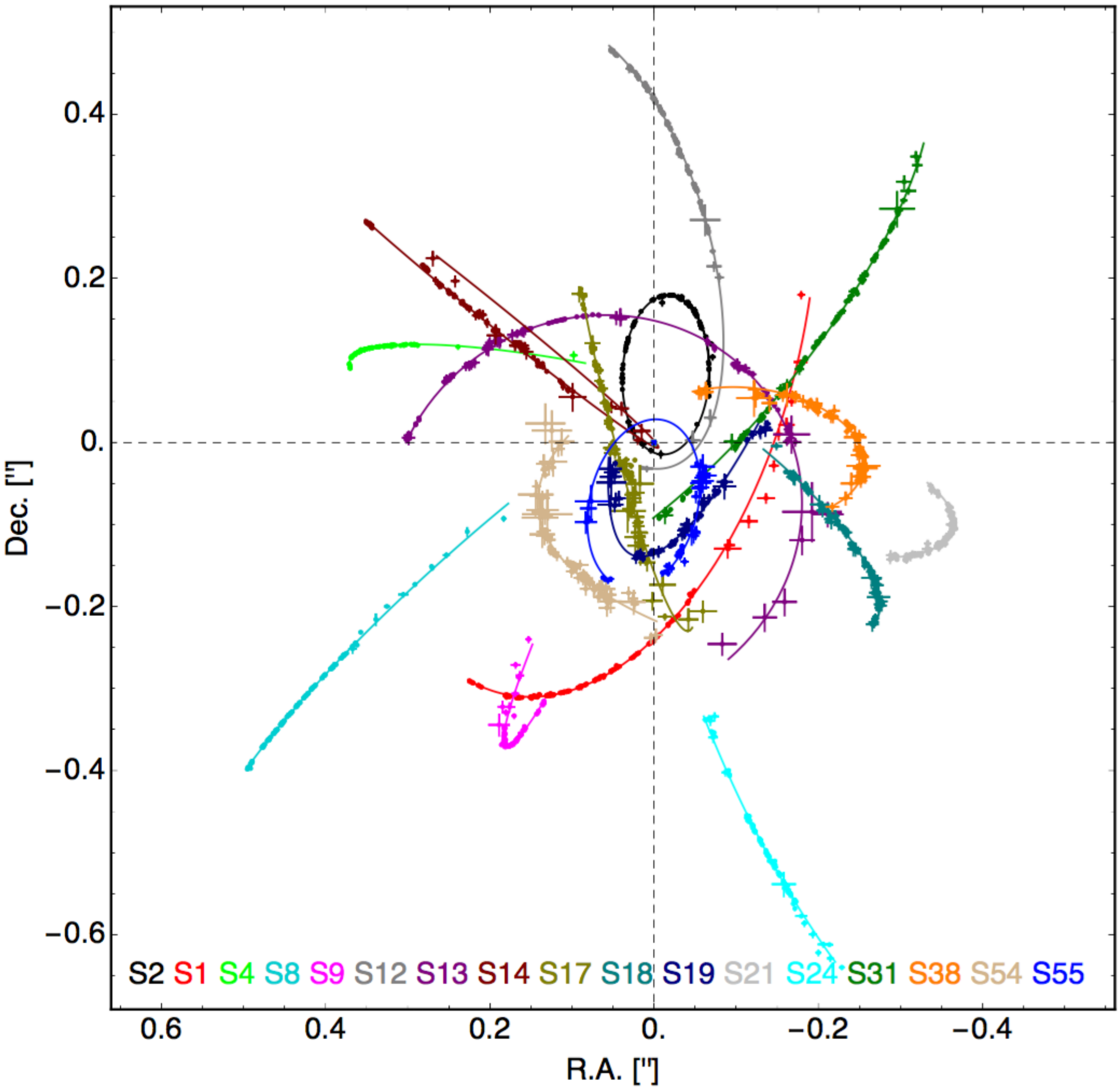
60 mas FWHM
Dec. ['']
R.A. ['']
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6

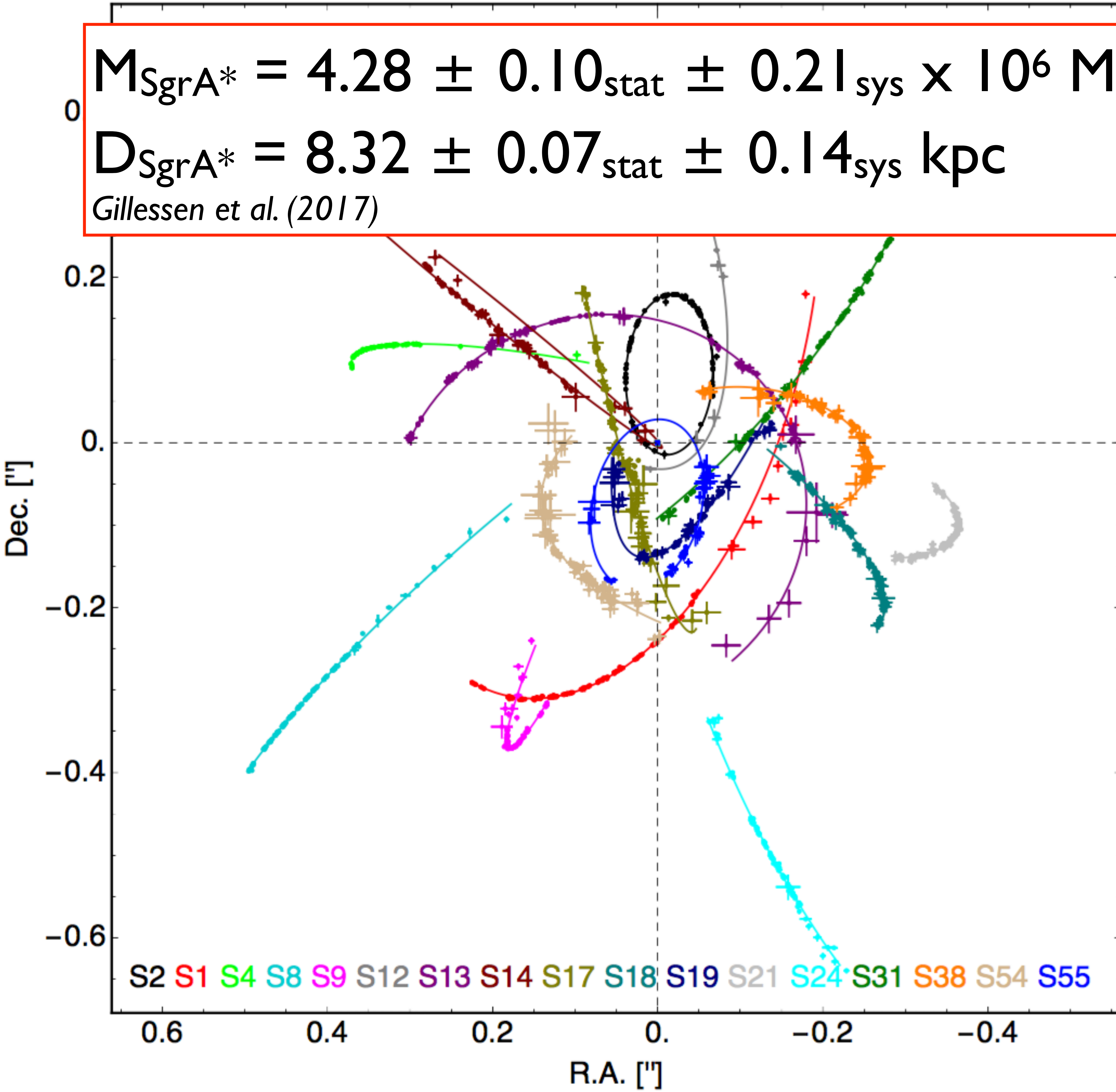


0.4
0.2
0.
−0.2
−0.4
−0.6
Dec. ['']
0.6
0.4
0.2
0.
−0.2
−0.4
R.A. ['']
S2 S1 S4 S8 S9 S12 S13 S14 S17 S18 S19 S21 S24 S31 S38 S54 S55

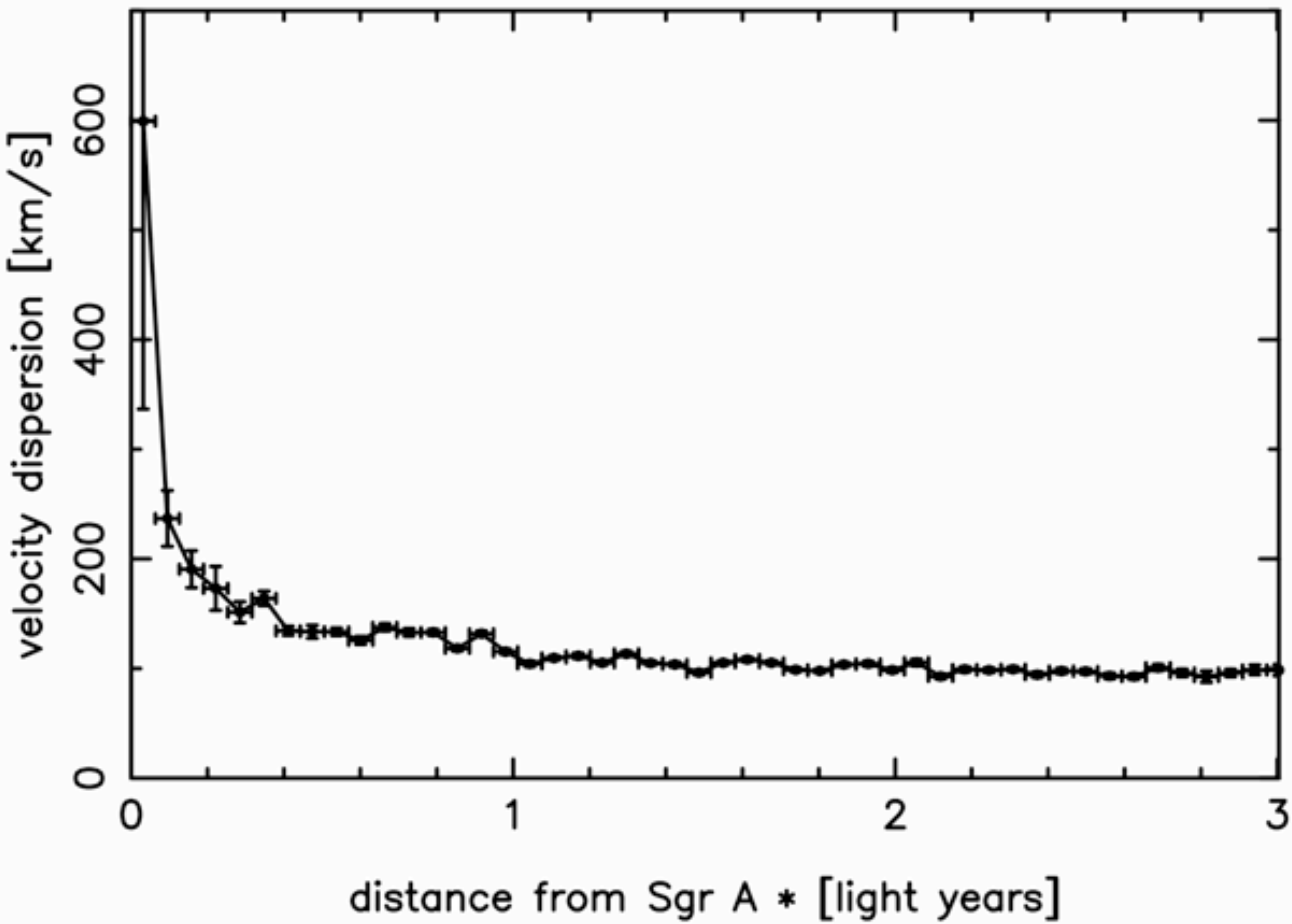
$M_{SgrA*} = 4.28 \pm 0.10_{stat} \pm 0.21_{sys} \times 10^6\ M_\odot$

$D_{SgrA*} = 8.32 \pm 0.07_{stat} \pm 0.14_{sys}$ kpc

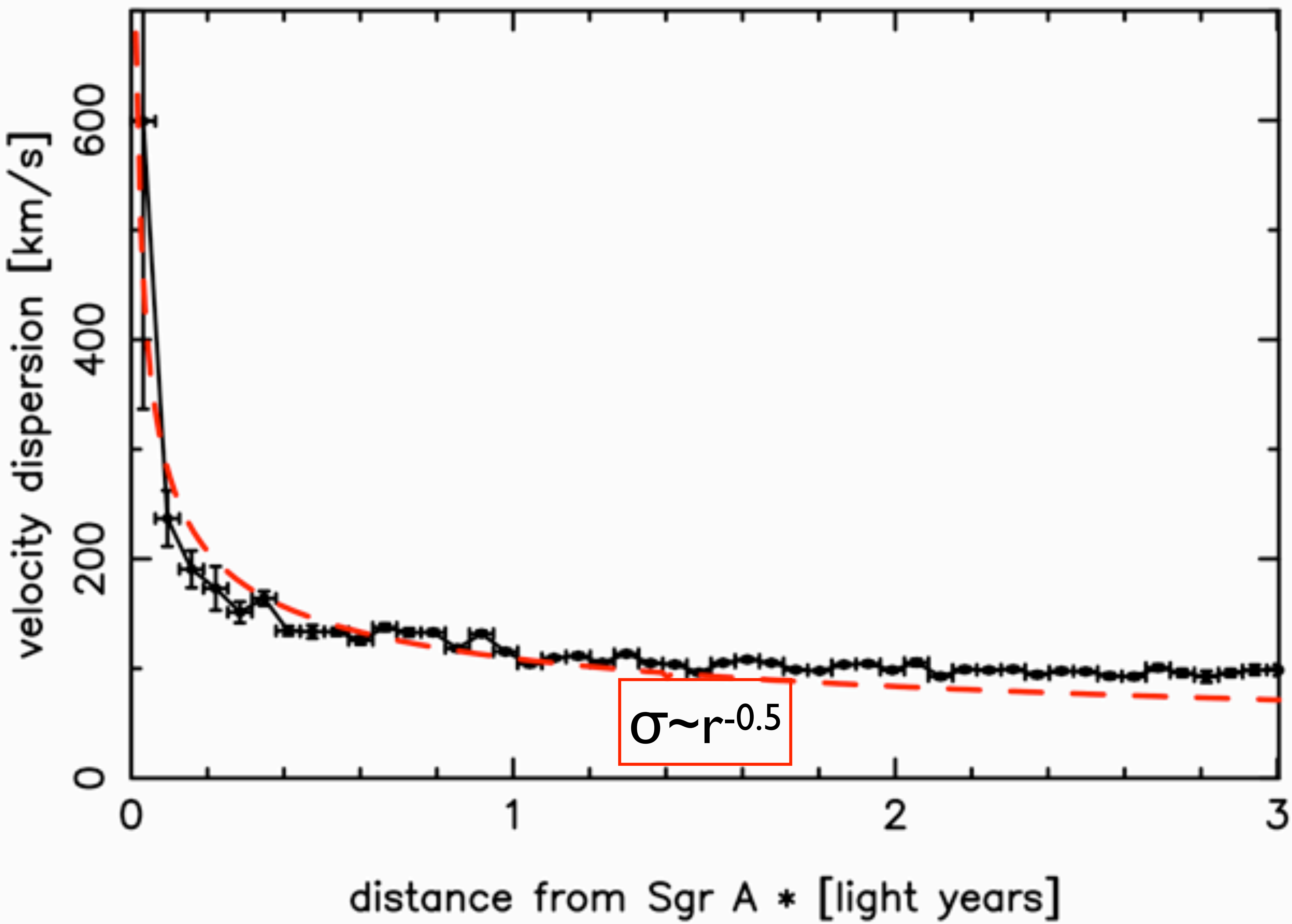
Gillessen et al. (2017)



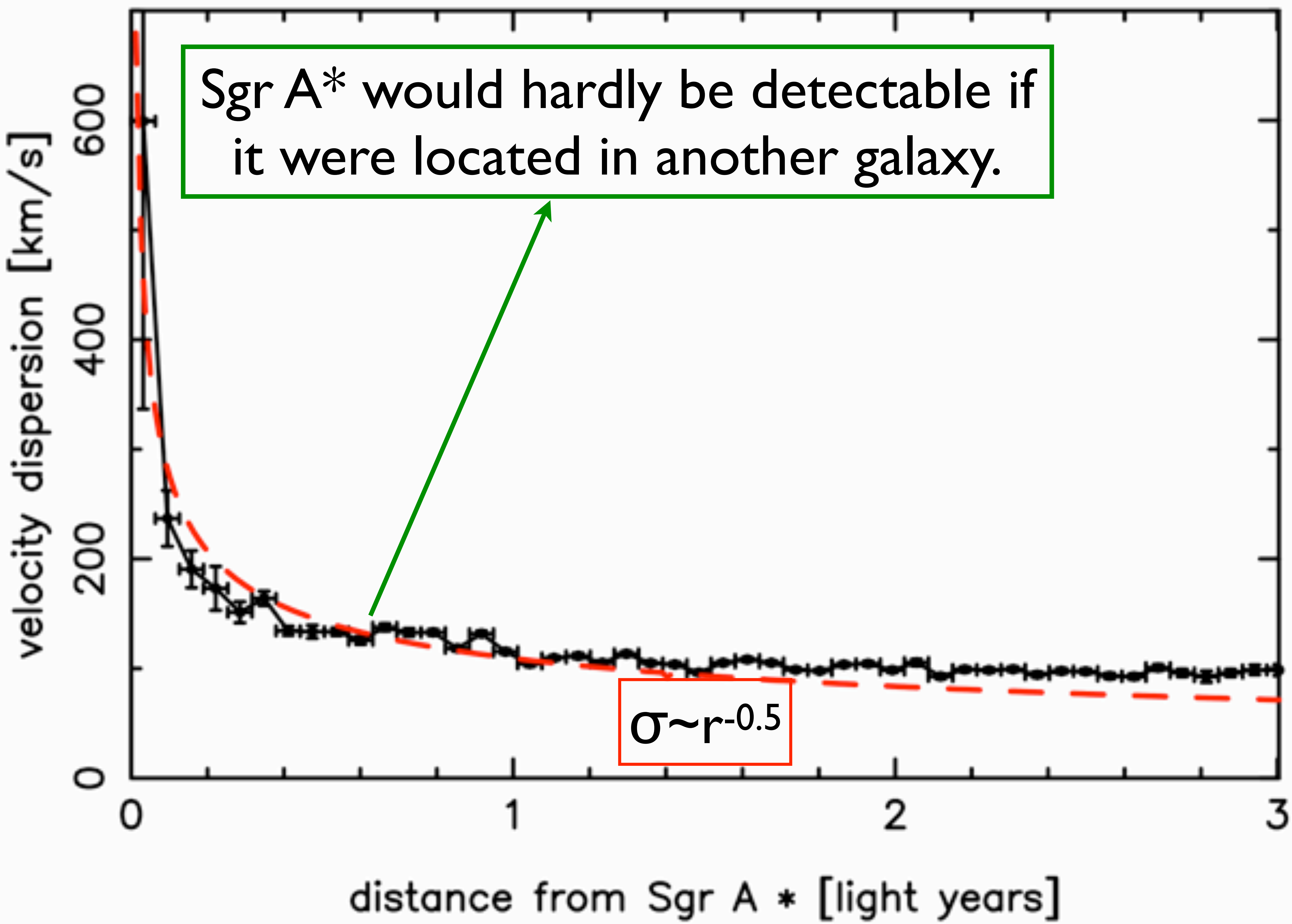
Velocity dispersion at the Galactic Center



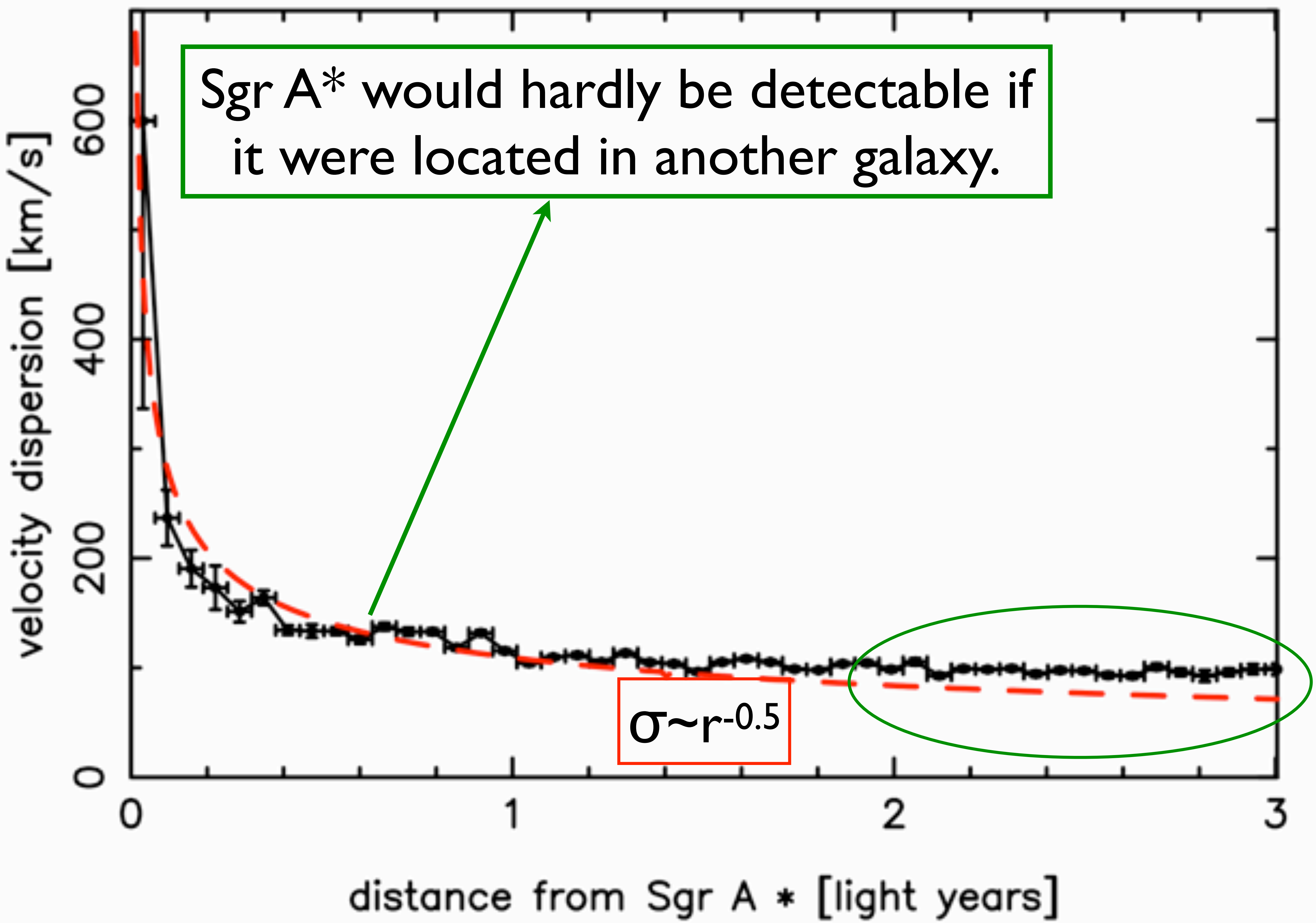
Velocity dispersion at the Galactic Center



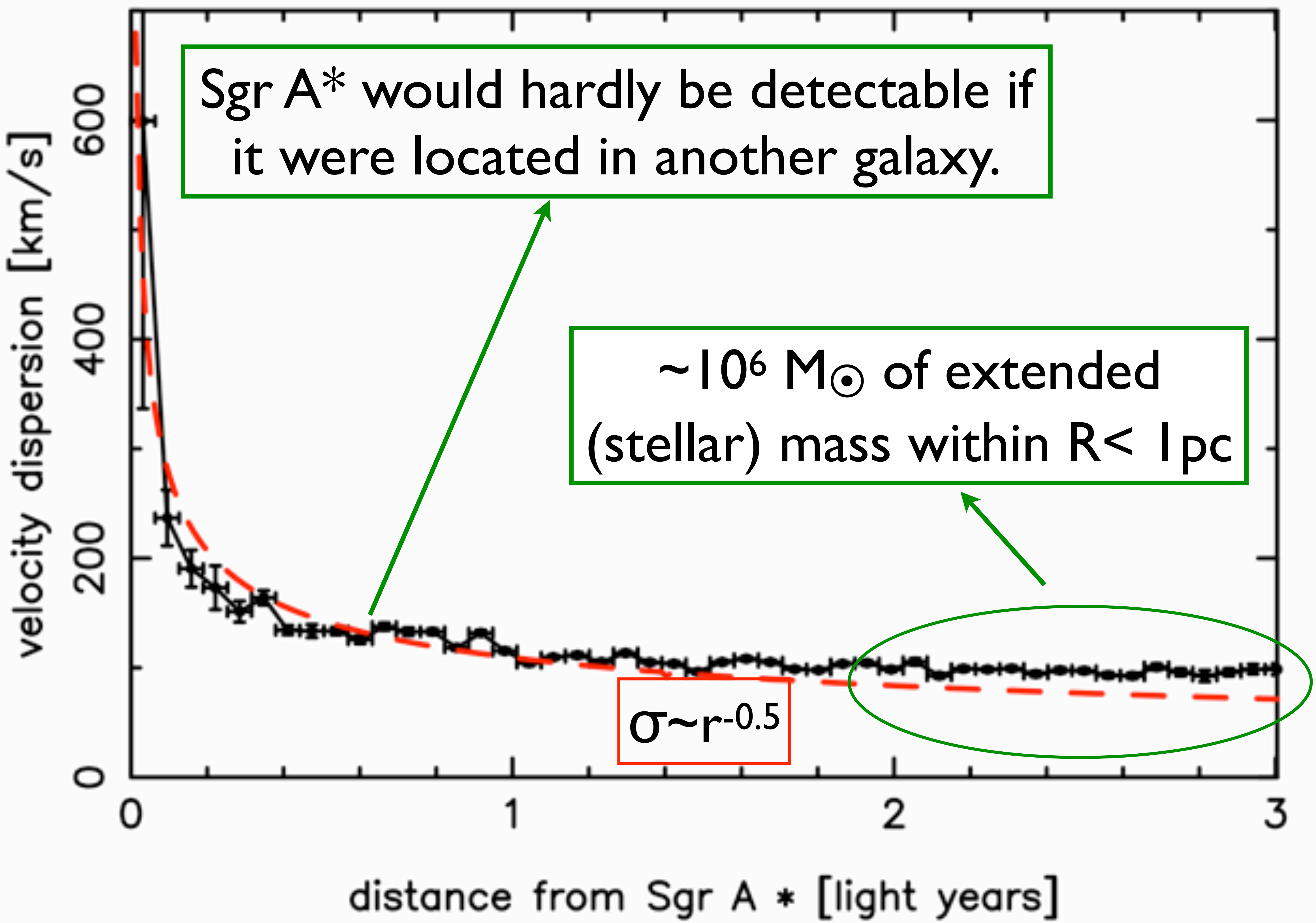
Velocity dispersion at the Galactic Center



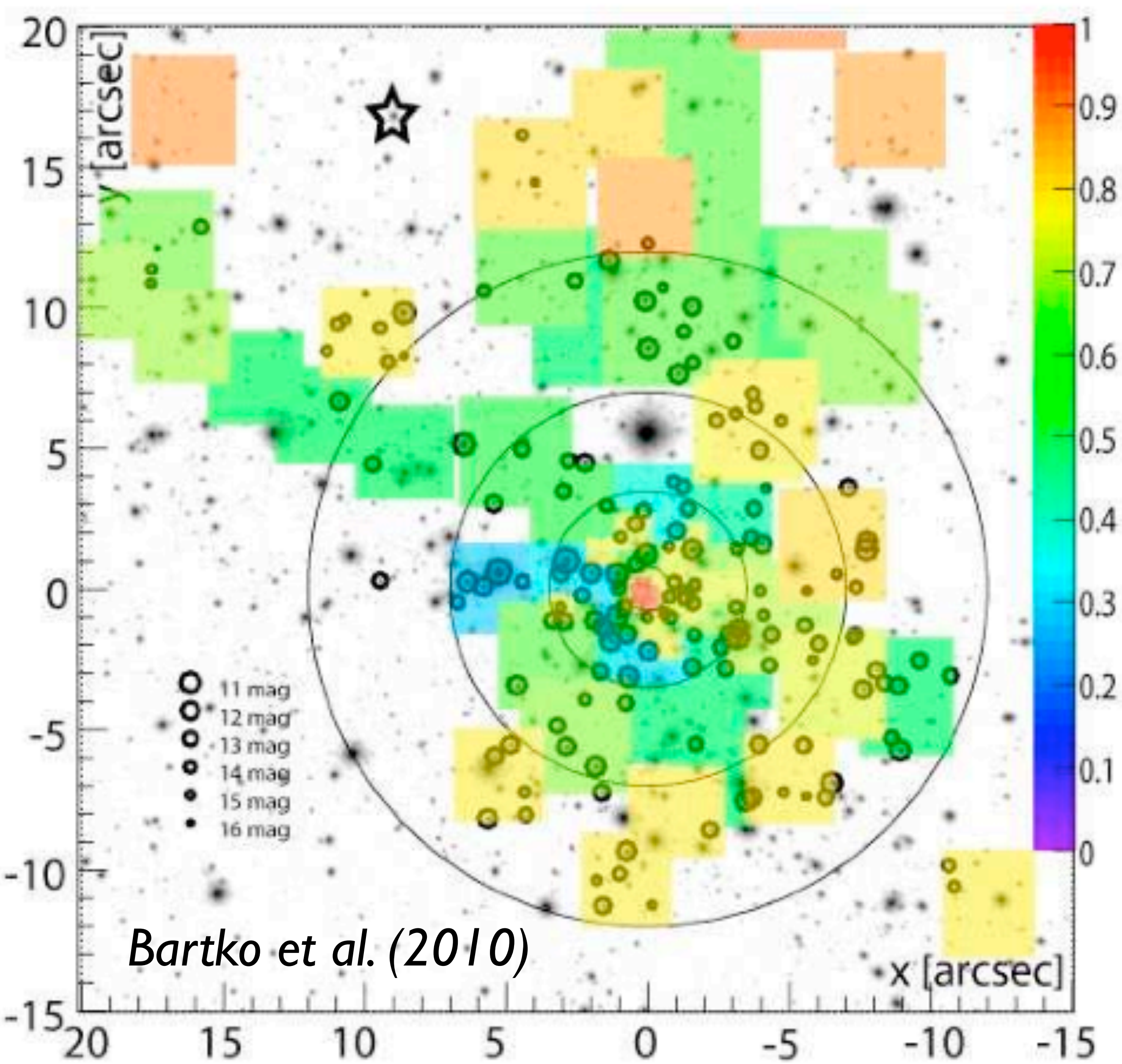
Velocity dispersion at the Galactic Center



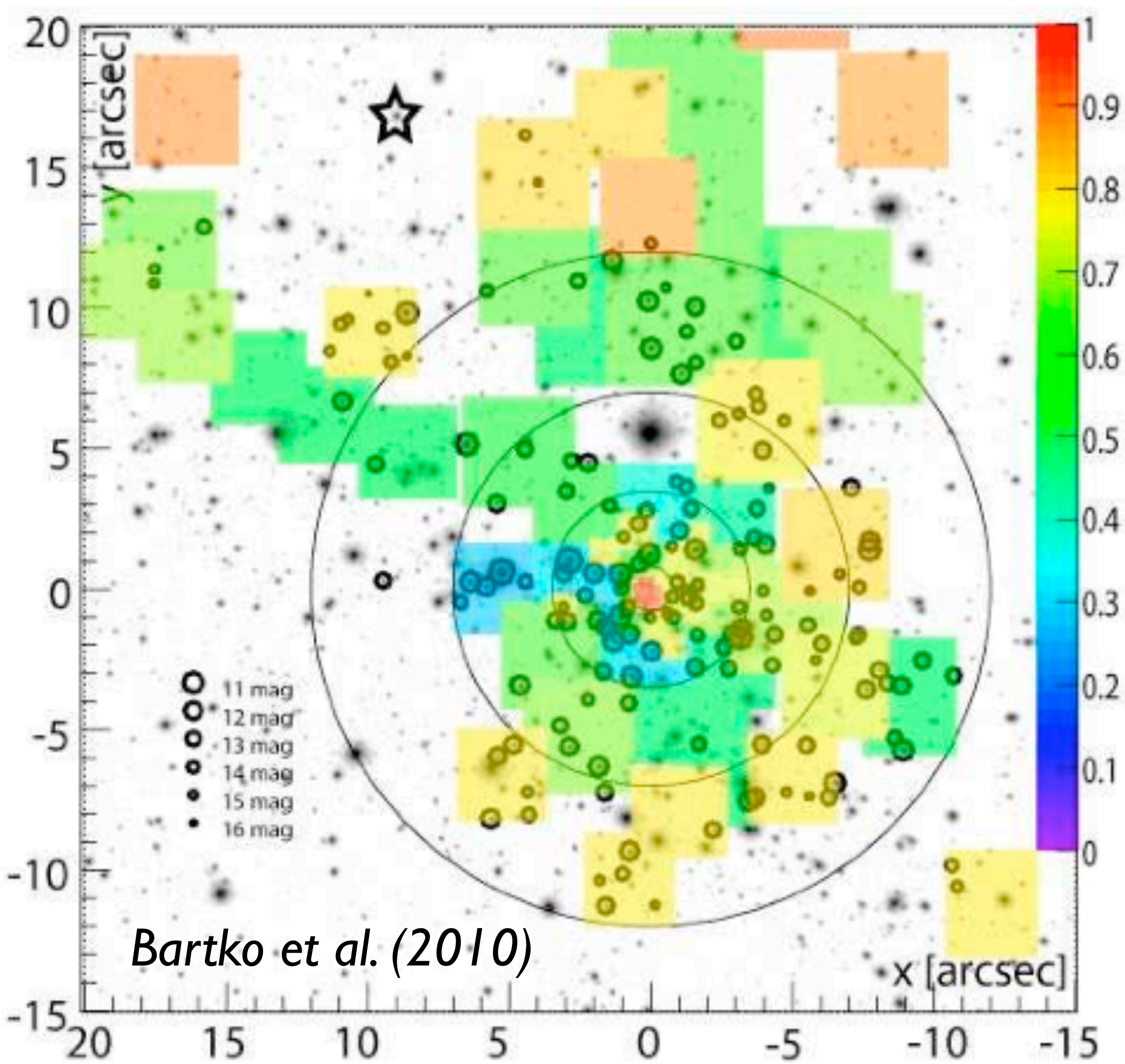
Velocity dispersion at the Galactic Center



Star formation at the GC



Star formation at the GC

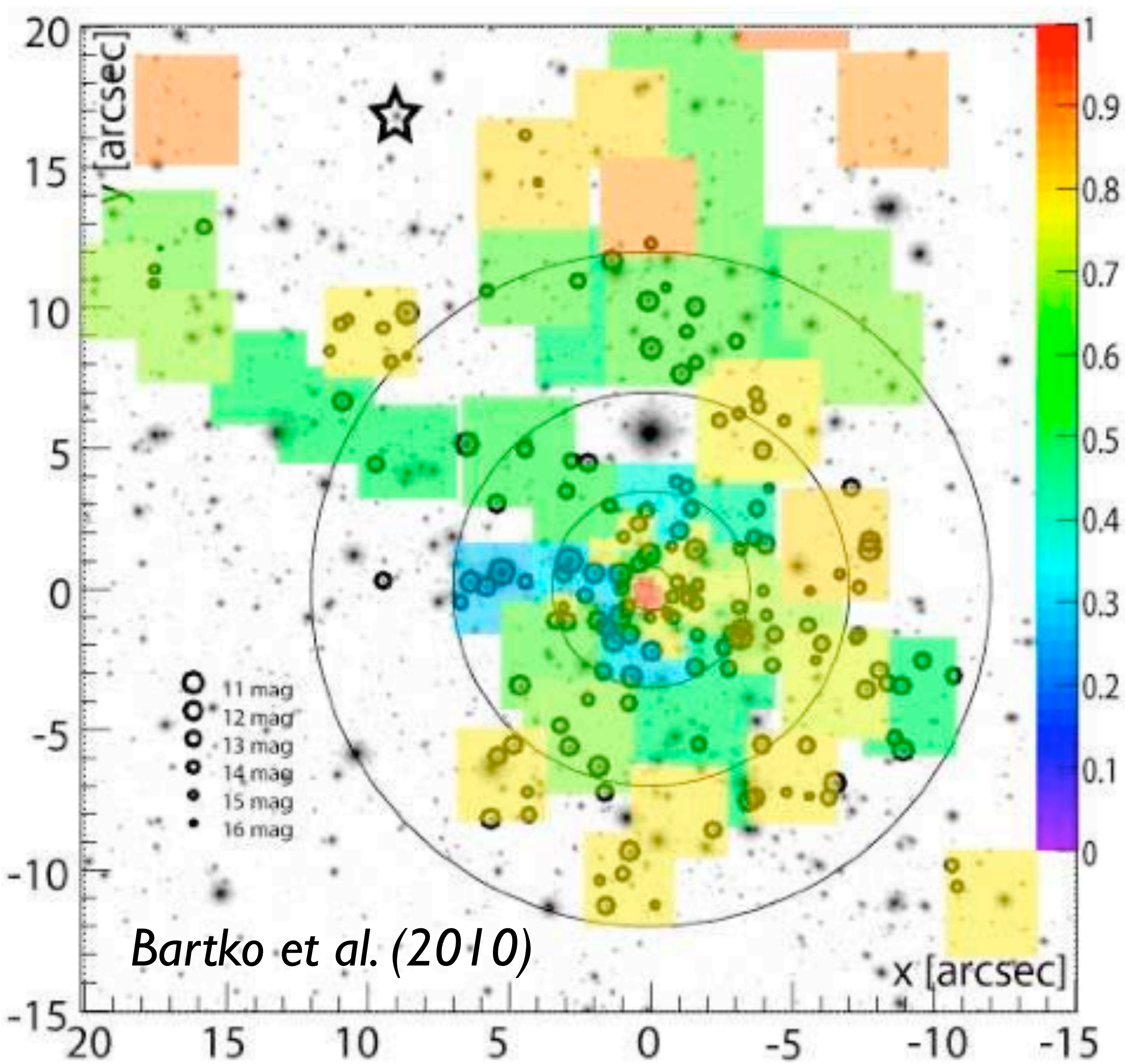


~200 massive, young stars within 0.5 pc of Sgr A*

⇒ star burst of ~1.5×10^4 $M_\odot$

occurred ~6 Myr ago.

Star formation at the GC



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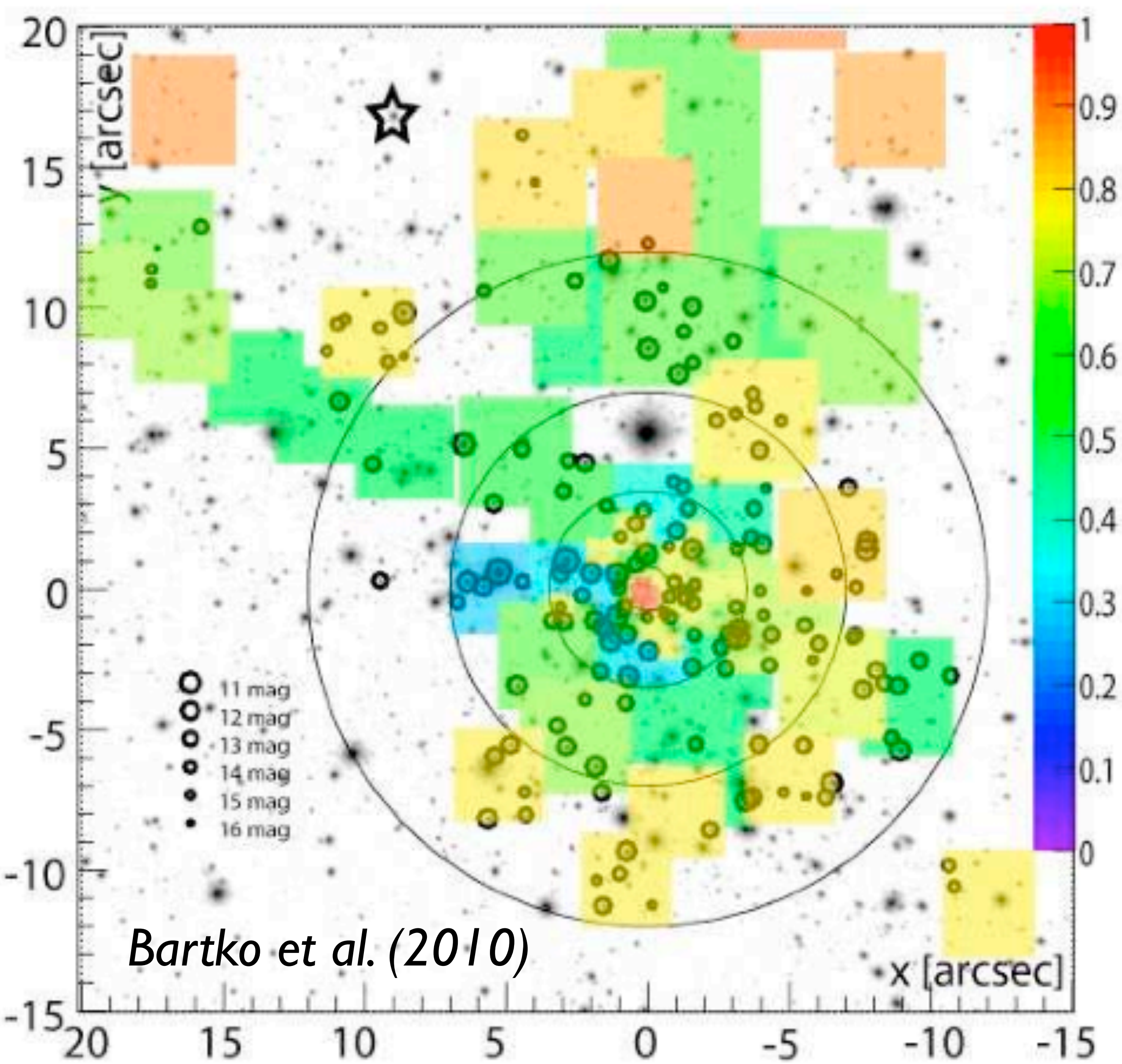
Repeated star formation can replenish binary BH population

Star formation at the GC



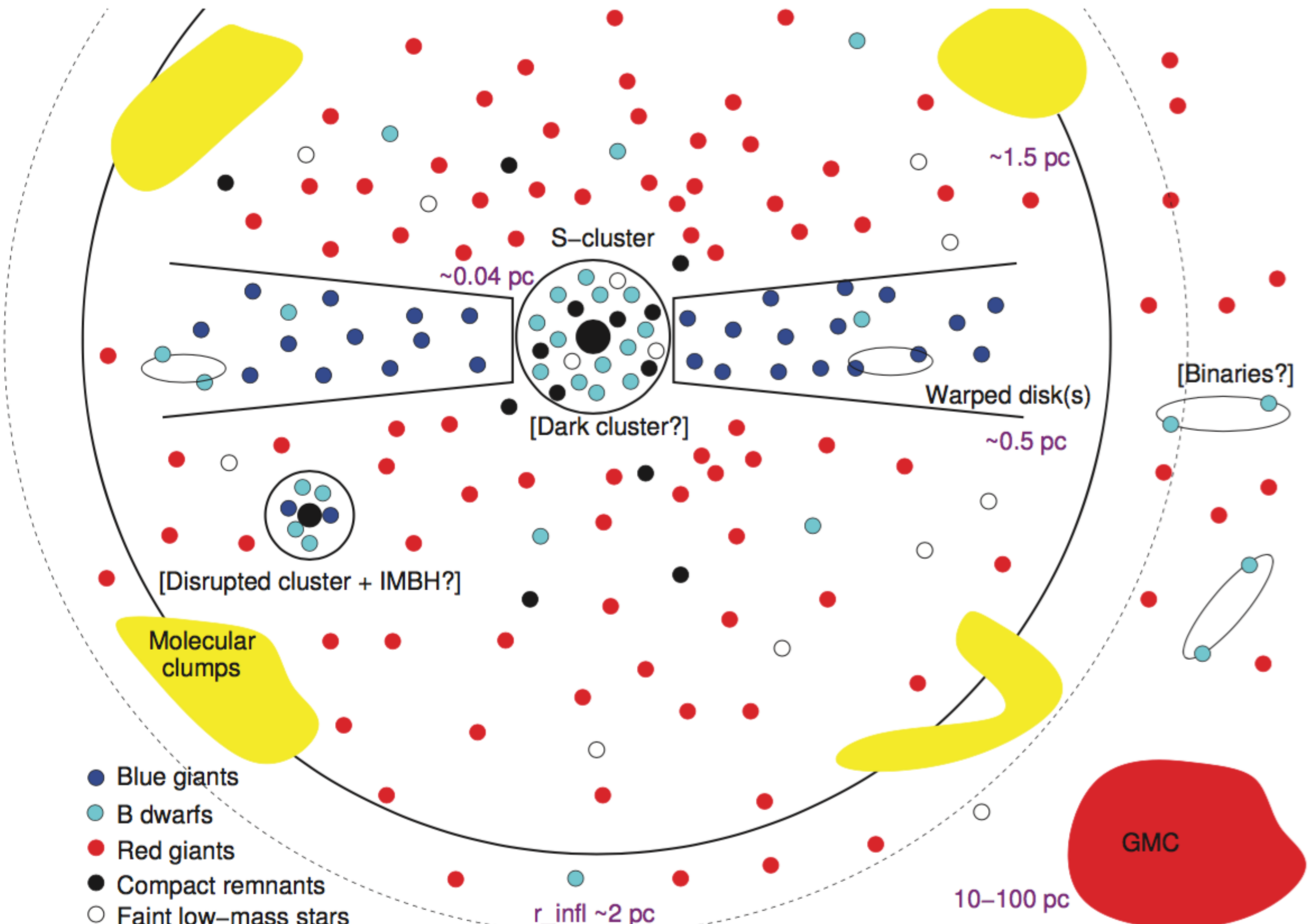
~200 massive, young stars within 0.5 pc of Sgr A*

⇒ star burst of ~$1.5\times10^4\ M_\odot$ occurred ~6 Myr ago.

Repeated star formation can replenish binary BH population

Probably top-heavy initial mass function (IMF) → stellar BH factory

Schemtic of the GC



Alexander (2011, 2017)

5. The stellar cusp around Sagittarius A*

A MBH surrounded by a cluster

A MBH surrounded by a cluster

- **Cusp formation** in relaxed cluster solid prediction of stellar dynamics *(e.g., Lightman&Shapiro, 1977; Bahcall & Wolf 1976, 1977; Freitag+ 2006; Hopman & Alexander 2006)*: $\rho(r) \propto r^{-\gamma}$ with $1.5 \leq \gamma \lesssim 2$ (increasing γ for larger stellar masses)

- **Difficult to study** in extragalactic systems.

- **Galactic centre** (GC) is unique test case

Implications: Collisions, tidal disruptions, EMRIs….

Why is this relevant?

1. Do we have the theory on stellar dynamics right?

2. Physics of stars and stellar remnants near Sgr A* and similar MBHs: Frequency of collisions, tidal flares, or Extreme Mass Ratio Inspirals (EMRIs; *e.g. Amaro-Seoane et al. 2007)*, *cusp of stellar mass black holes*

3. What is the formation history of the NSC?

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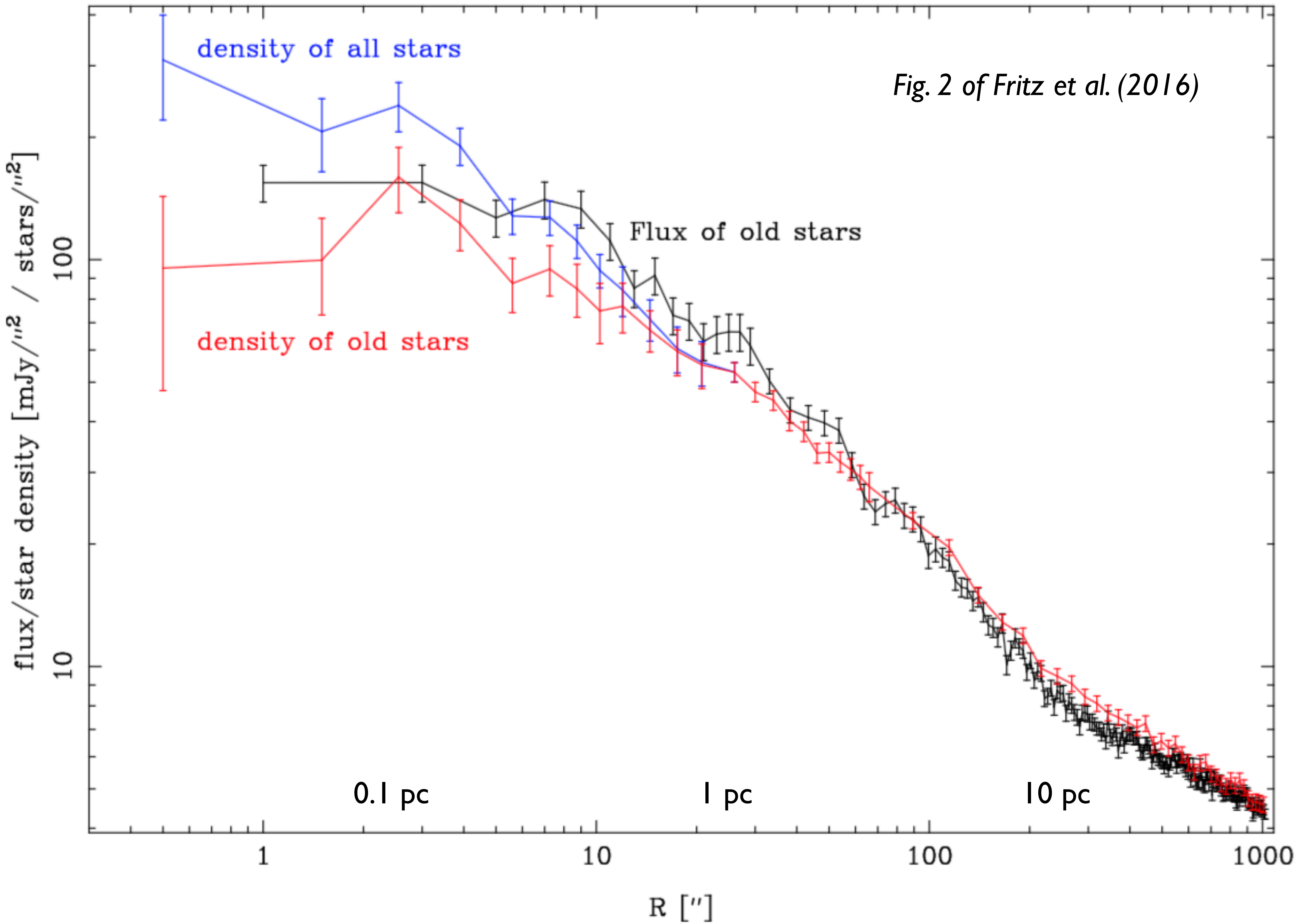
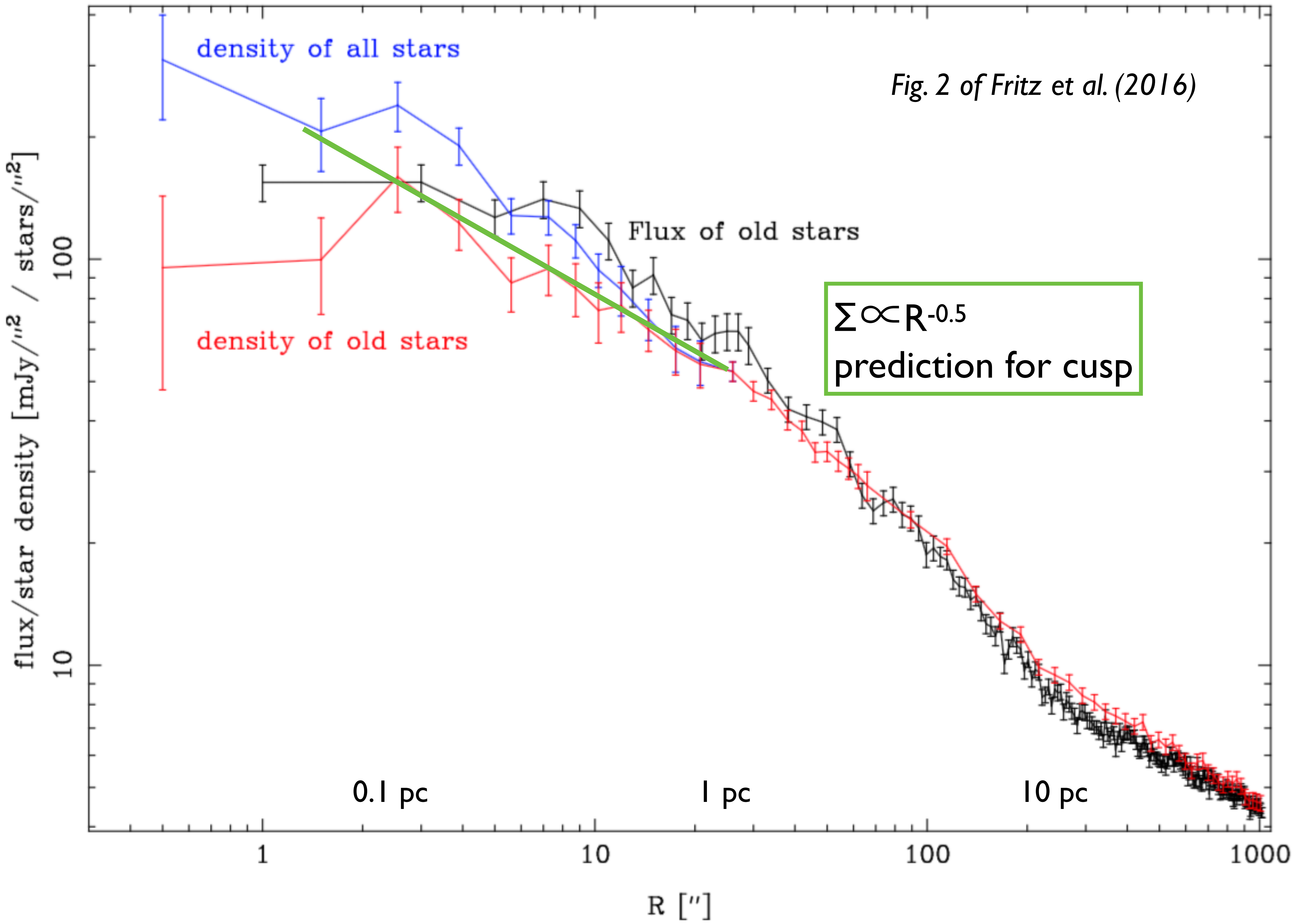
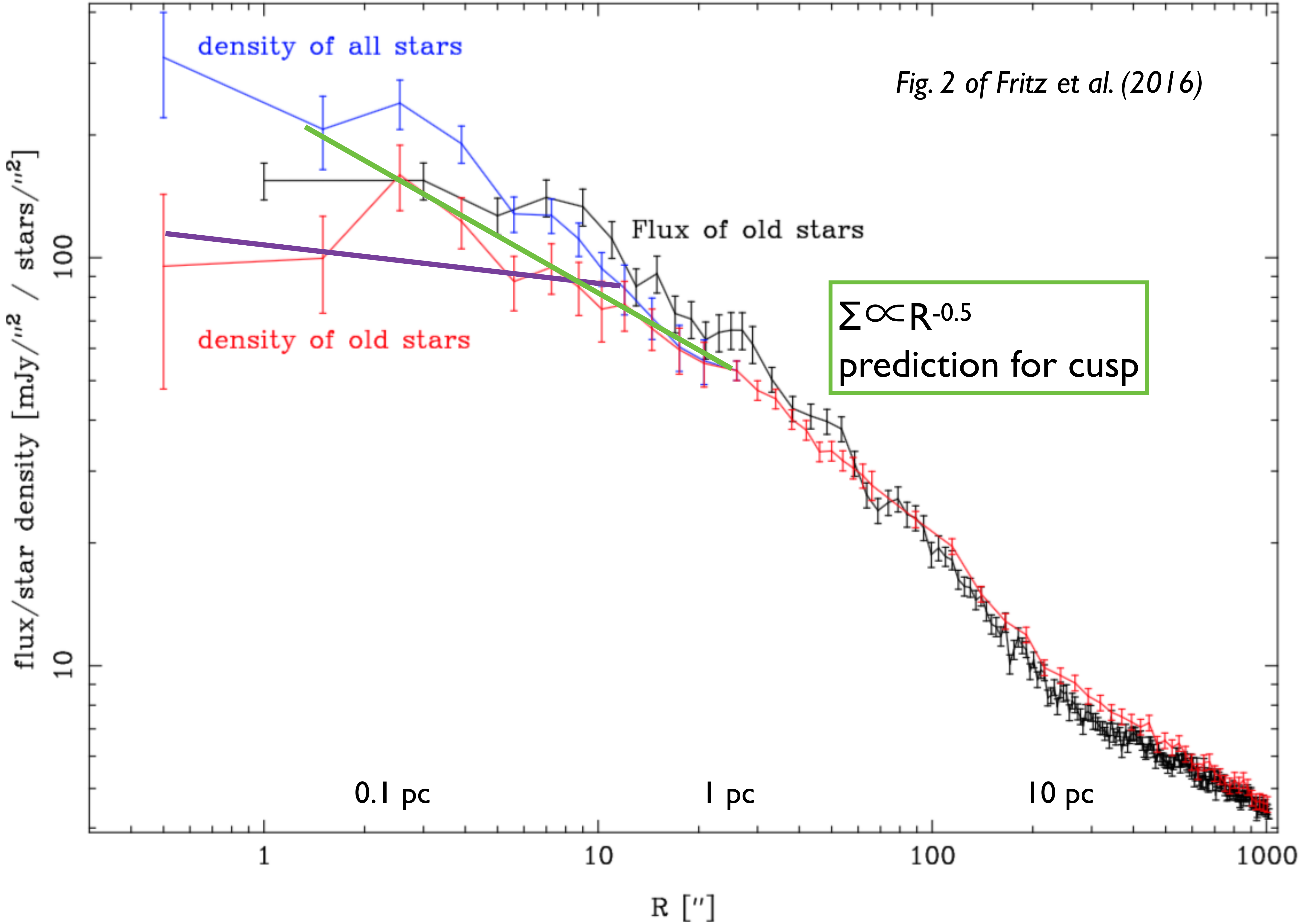
3. What is the formation history of the NSC?

So, is there a stellar cusp around the MBH at the GC?


density of all stars
Fig. 2 of Fritz et al. (2016)
Flux of old stars
density of old stars
flux/star density [mJy/″2 / stars/″2]
100
10
0.1 pc
1 pc
10 pc
1
10
100
1000
R [″]



density of all stars
Fig. 2 of Fritz et al. (2016)
Flux of old stars
density of old stars
$\Sigma \propto R^{-0.5}$
prediction for cusp
flux/star density [mJy/″² / stars/″²]
100
10
0.1 pc
1 pc
10 pc
1
10
100
1000
R [″]



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100
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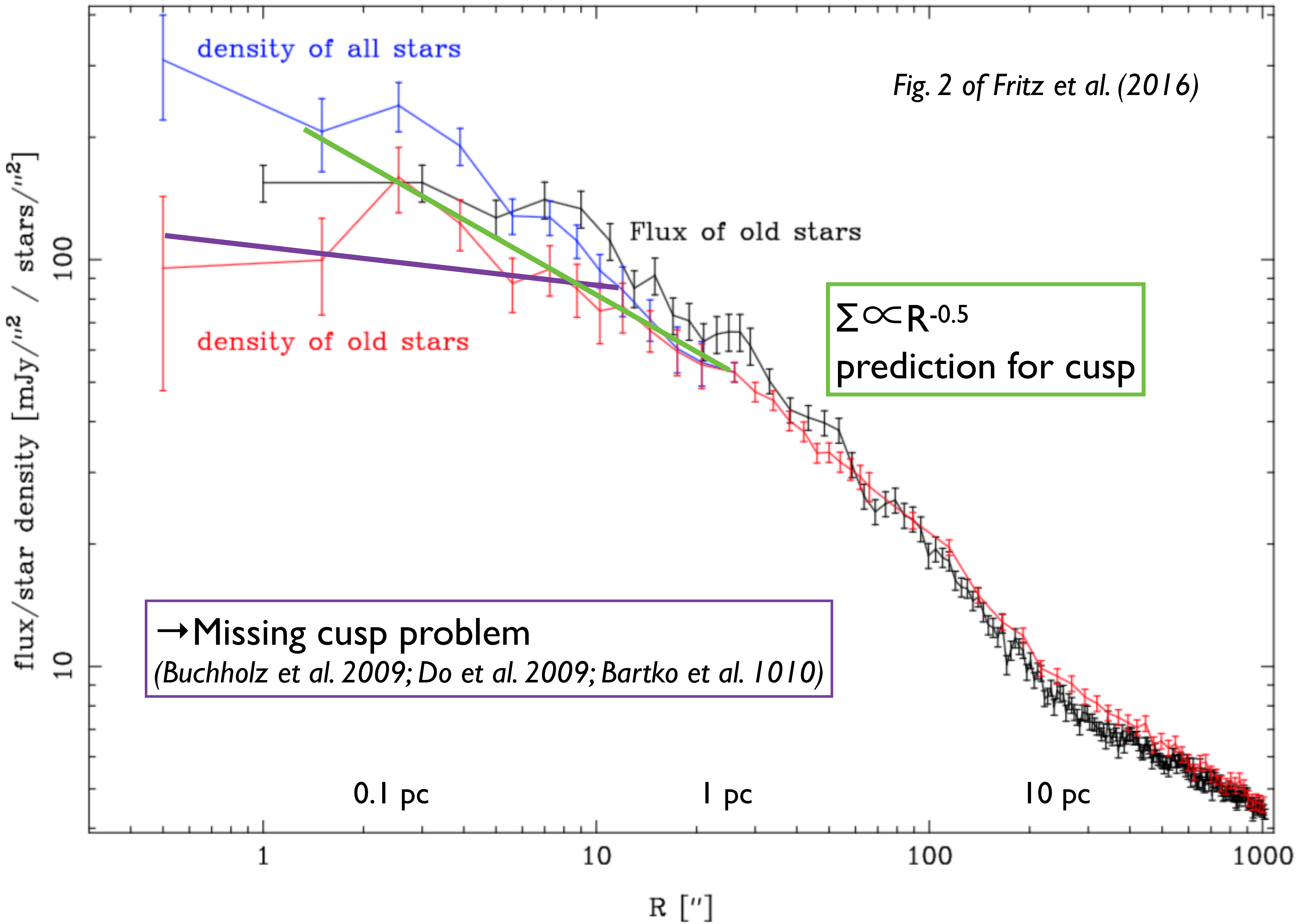
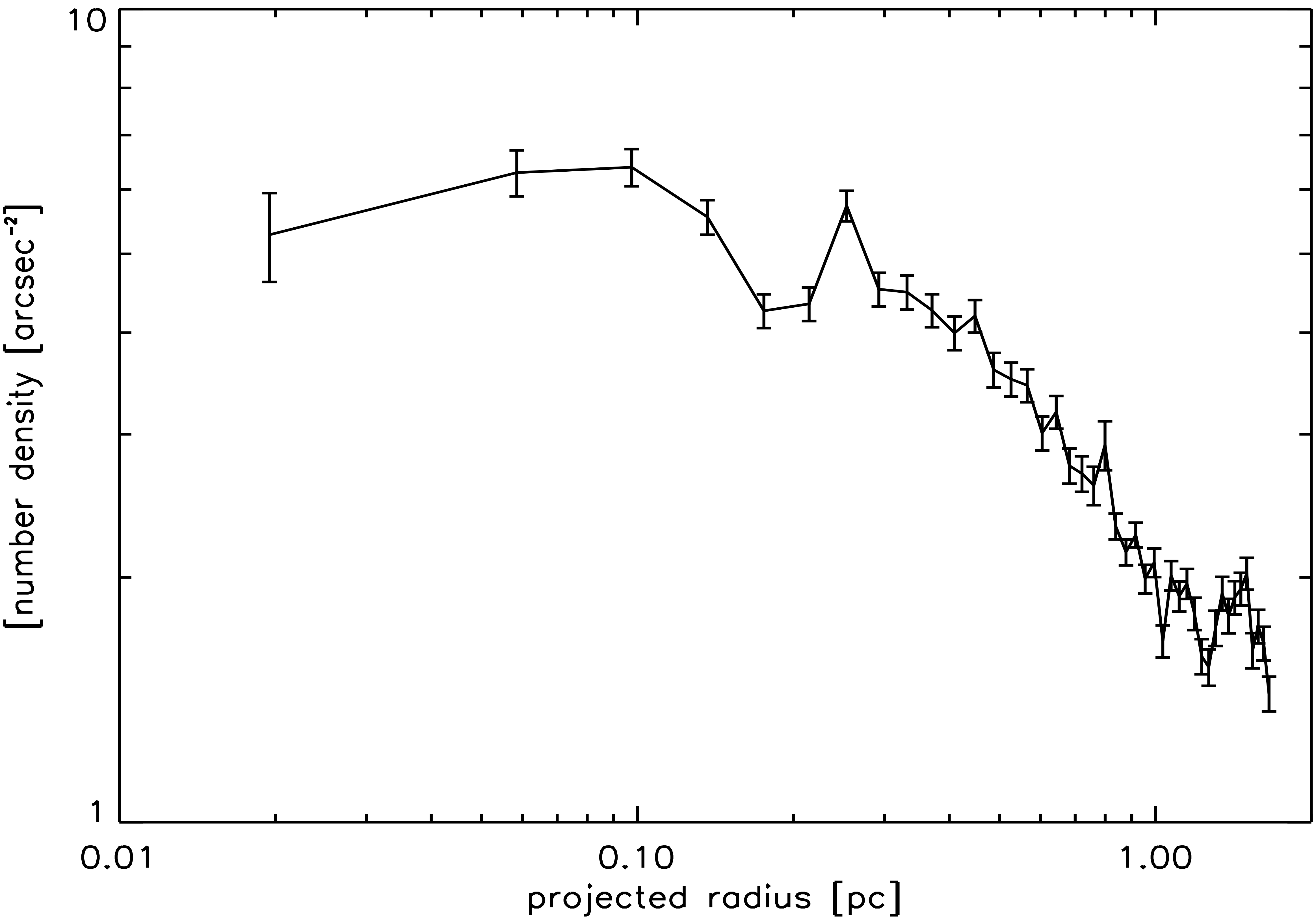
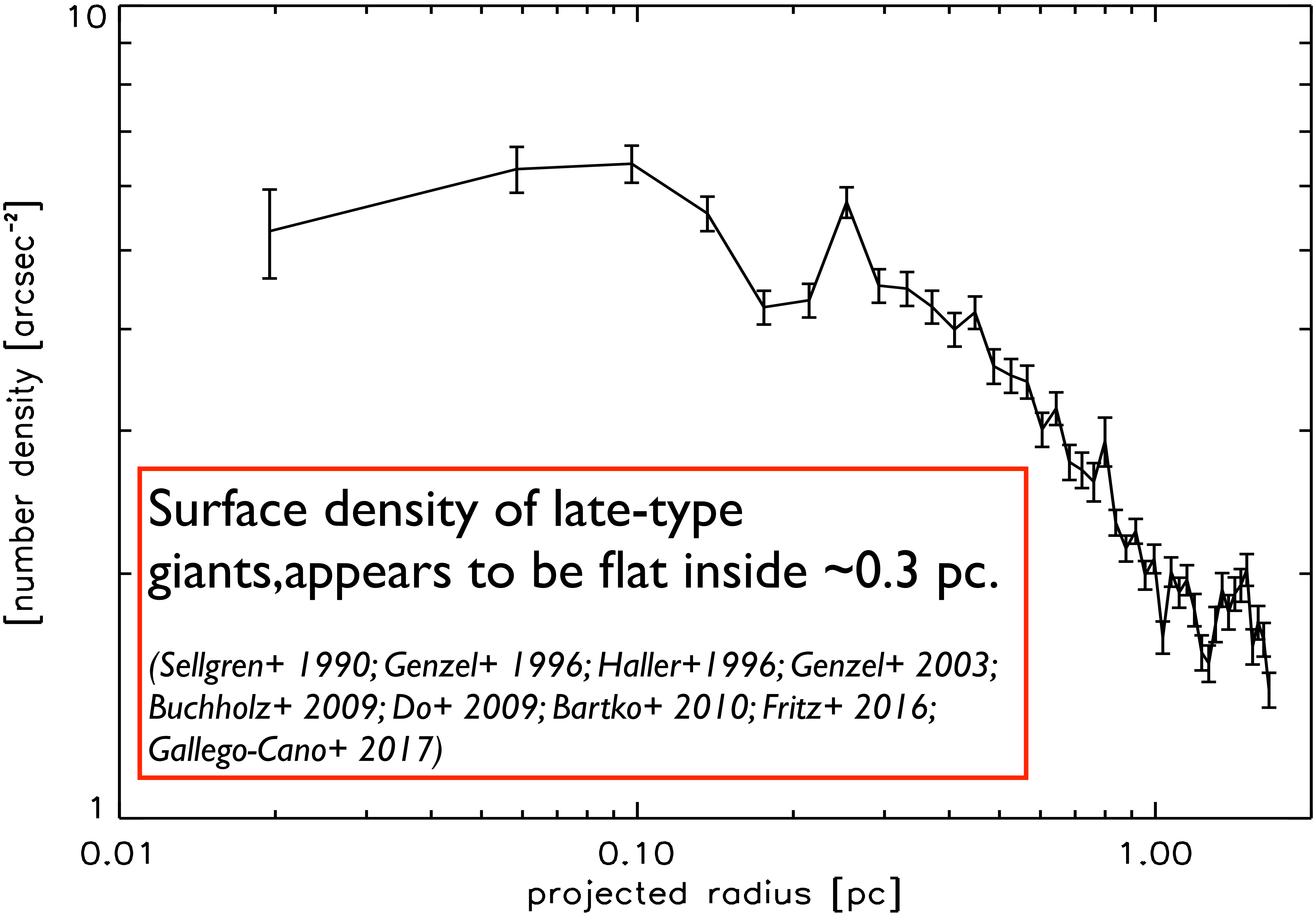


density of all stars
Fig. 2 of Fritz et al. (2016)
Flux of old stars
density of old stars
$\Sigma \propto R^{-0.5}$
prediction for cusp
→Missing cusp problem
(Buchholz et al. 2009; Do et al. 2009; Bartko et al. 1010)
0.1 pc
1 pc
10 pc
flux/star density [mJy/″2 / stars/″2]
100
10
1
10
100
1000
R [″]

Density of giants



Density of giants



The missing cusp problem

The missing cusp problem

$\boxed{\text{Deficit of giants around Sgr A*}}$

The missing cusp problem

$\boxed{\text{Deficit of giants around Sgr A*}}$

Representative for entire old population: **absence of cusp**

The missing cusp problem

Deficit of giants around Sgr A*

Representative for entire old population: **absence of cusp**

Representative only for giants: **“hidden” cusp**

The missing cusp problem

Deficit of giants around Sgr A*

Representative for entire old population: **absence of cusp**

Not yet formed
(e.g., Merritt et al. 2010)

Representative only for giants: **“hidden” cusp**

The missing cusp problem

Deficit of giants around Sgr A*

Representative for entire old population: **absence of cusp**

Not yet formed
(e.g., Merritt et al. 2010)

Destroyed
(e.g., Merritt & Szell 2006)

Representative only for giants: **“hidden” cusp**

The missing cusp problem

Deficit of giants around Sgr A*

Representative for entire old population: **absence of cusp**

Not yet formed
(e.g., Merritt et al. 2010)

Destroyed
(e.g., Merritt & Szell 2006)

Representative only for giants: **"hidden" cusp**

Giants' envelopes destroyed
(e.g., Dale et al. 2009; Amaro-Seoane & Chen 2014).

The missing cusp problem

Deficit of giants around Sgr A*

Representative for entire old population: **absence of cusp**

Not yet formed *(e.g., Merritt et al. 2010)*

Destroyed *(e.g., Merritt & Szell 2006)*

Representative only for giants: **“hidden” cusp**

Giants’ envelopes destroyed *(e.g., Dale et al. 2009; Amaro-Seoane & Chen 2014)*.

How solid are the data and our interpretation?

Digging deeper…

1. **Deep star counts**
- Stack data
- Improved reduction (rebinning)
- Improved PSF fitting

(Gallego-Cano et al. 2017)

2. **Unresolved stellar light**
- Improved PSF fitting
- Analysis of diffuse emission

(Schödel et al. 2017)

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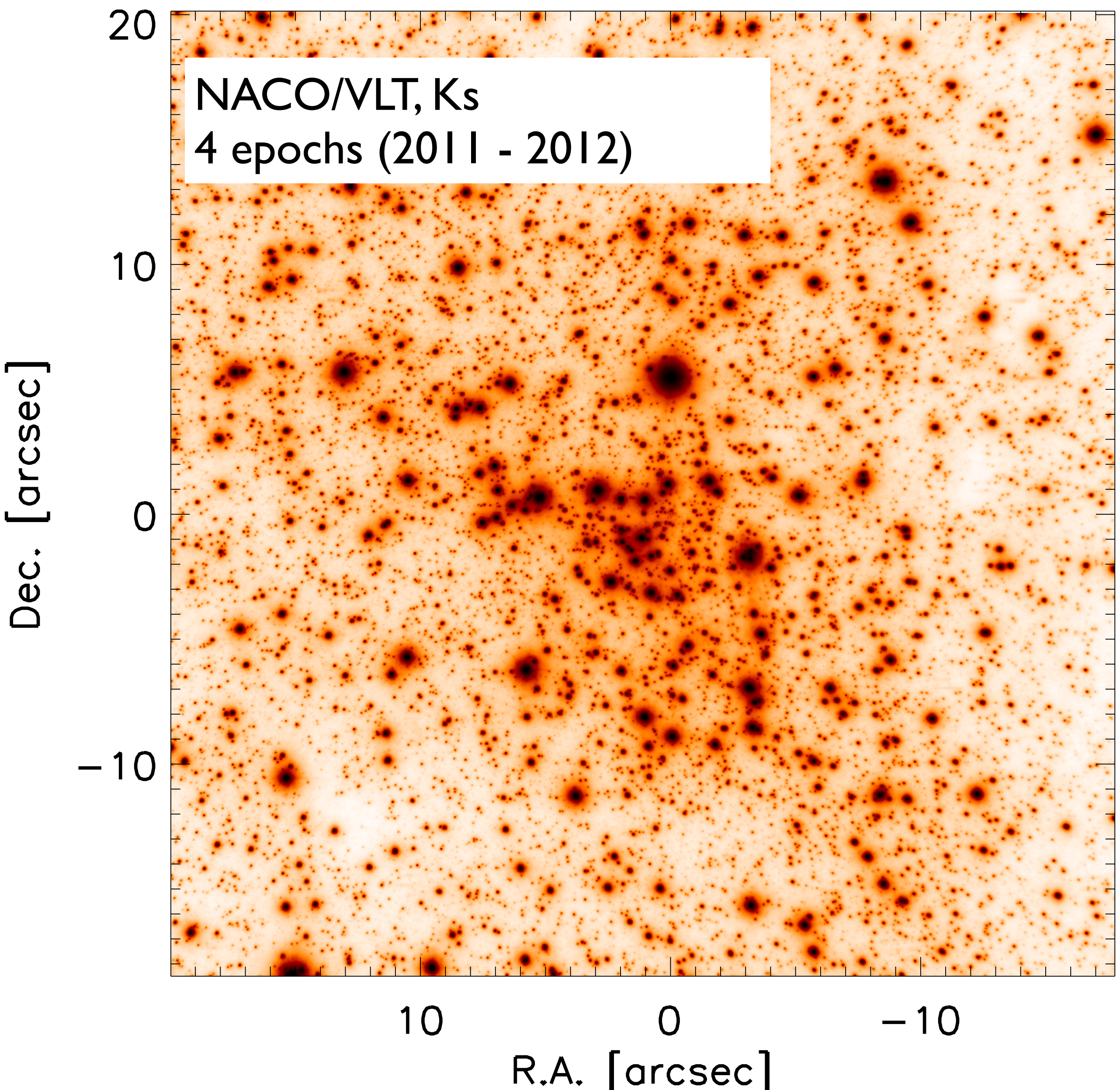

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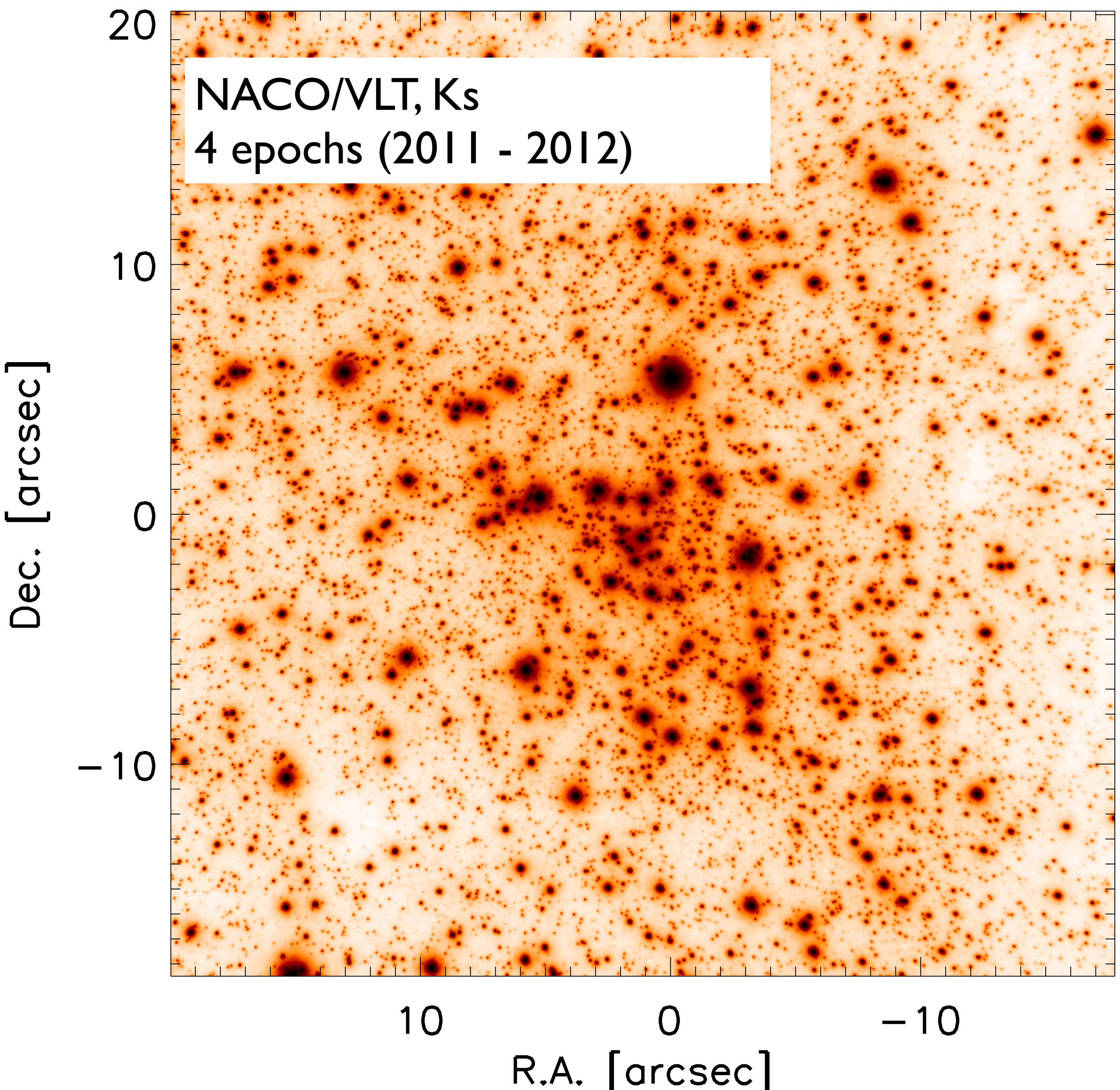
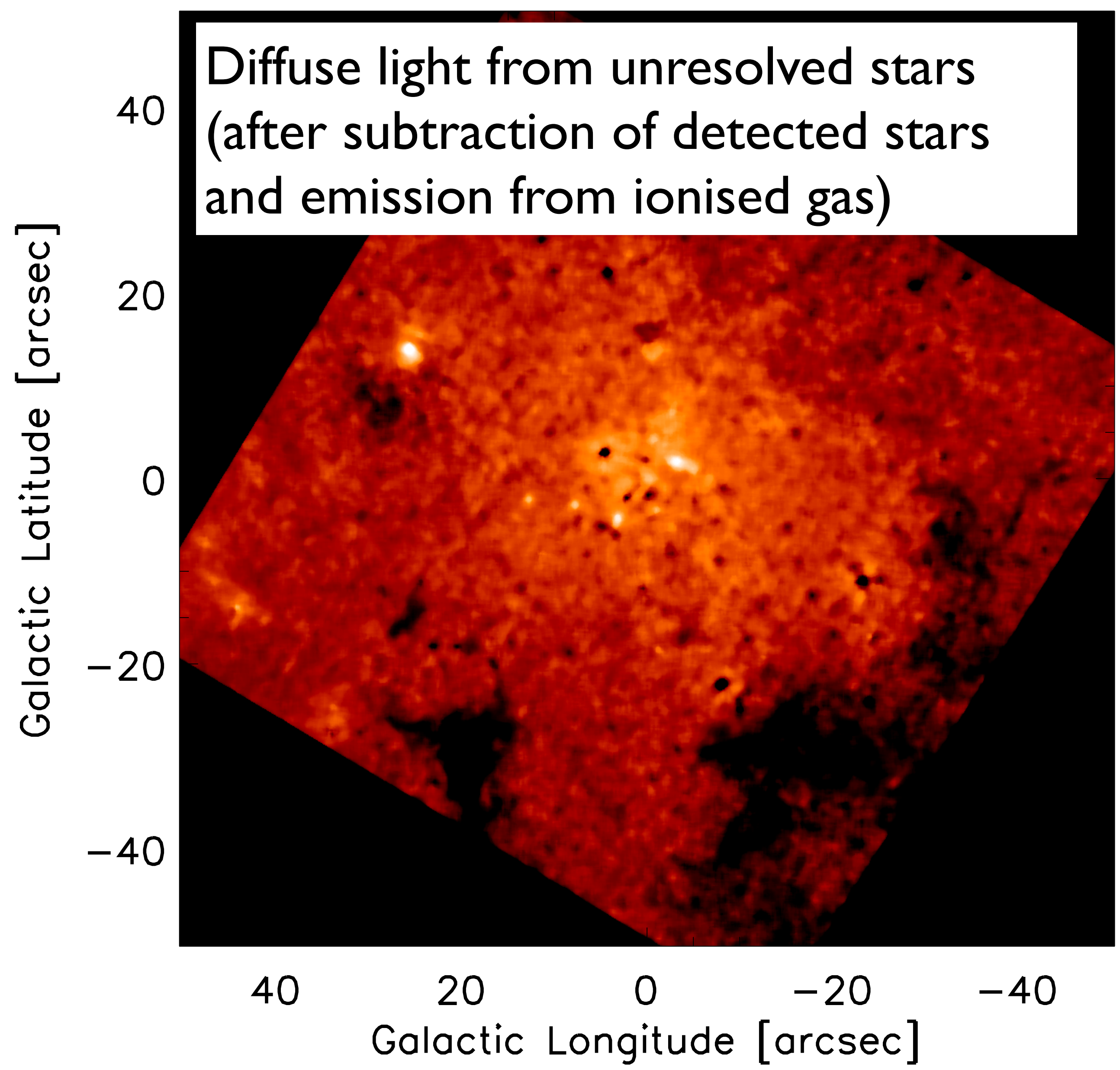
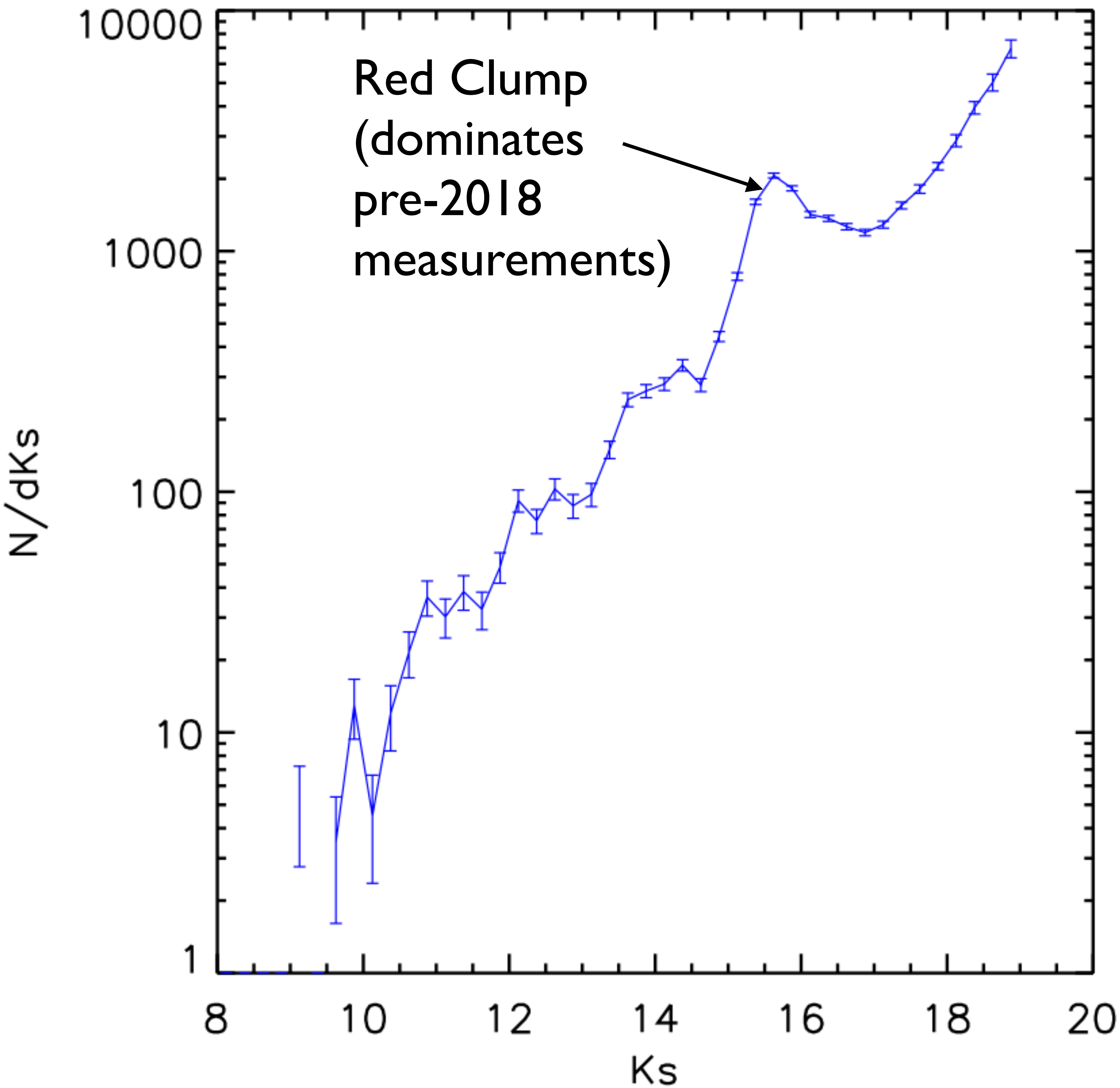




Luminosity function



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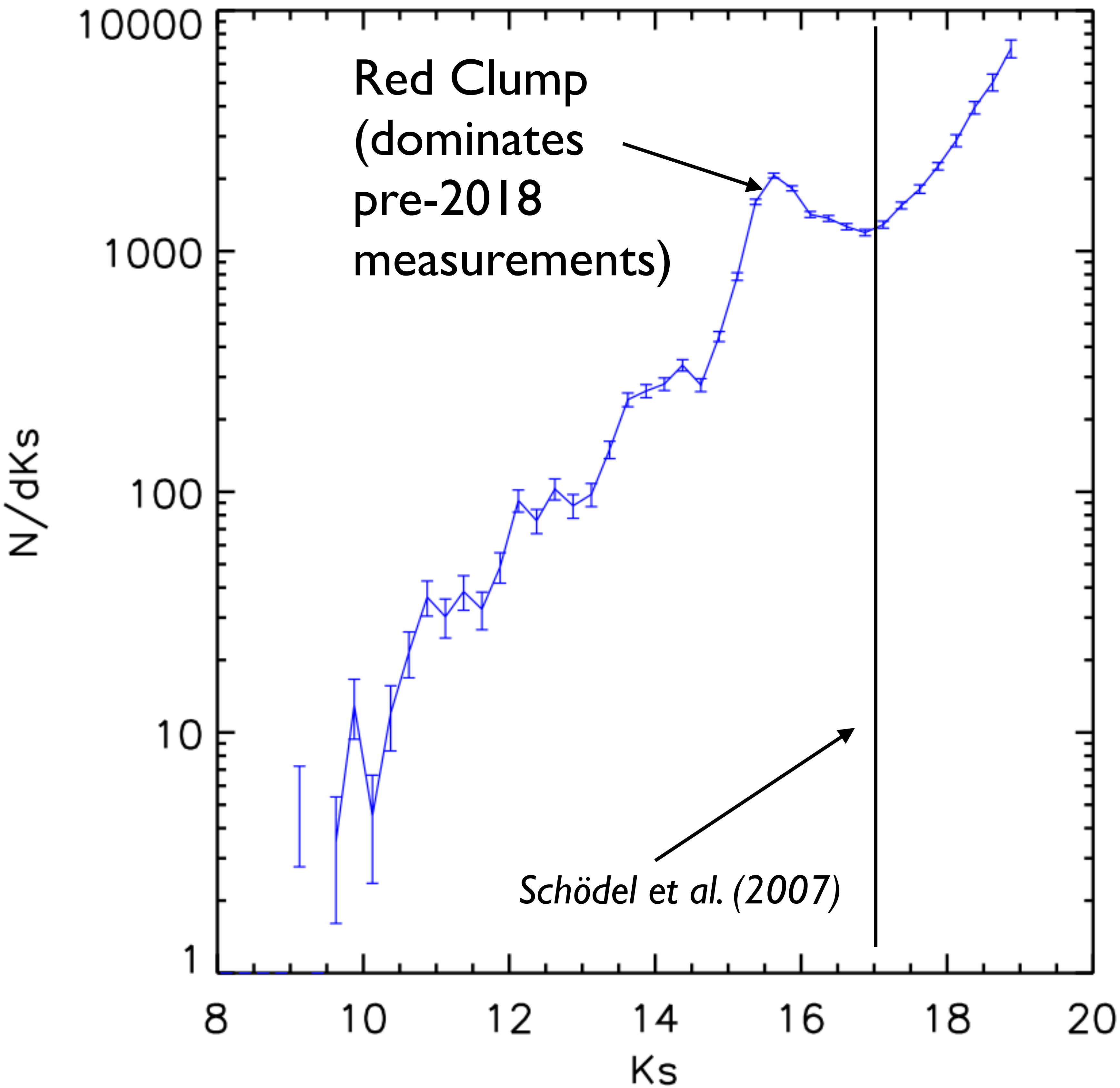

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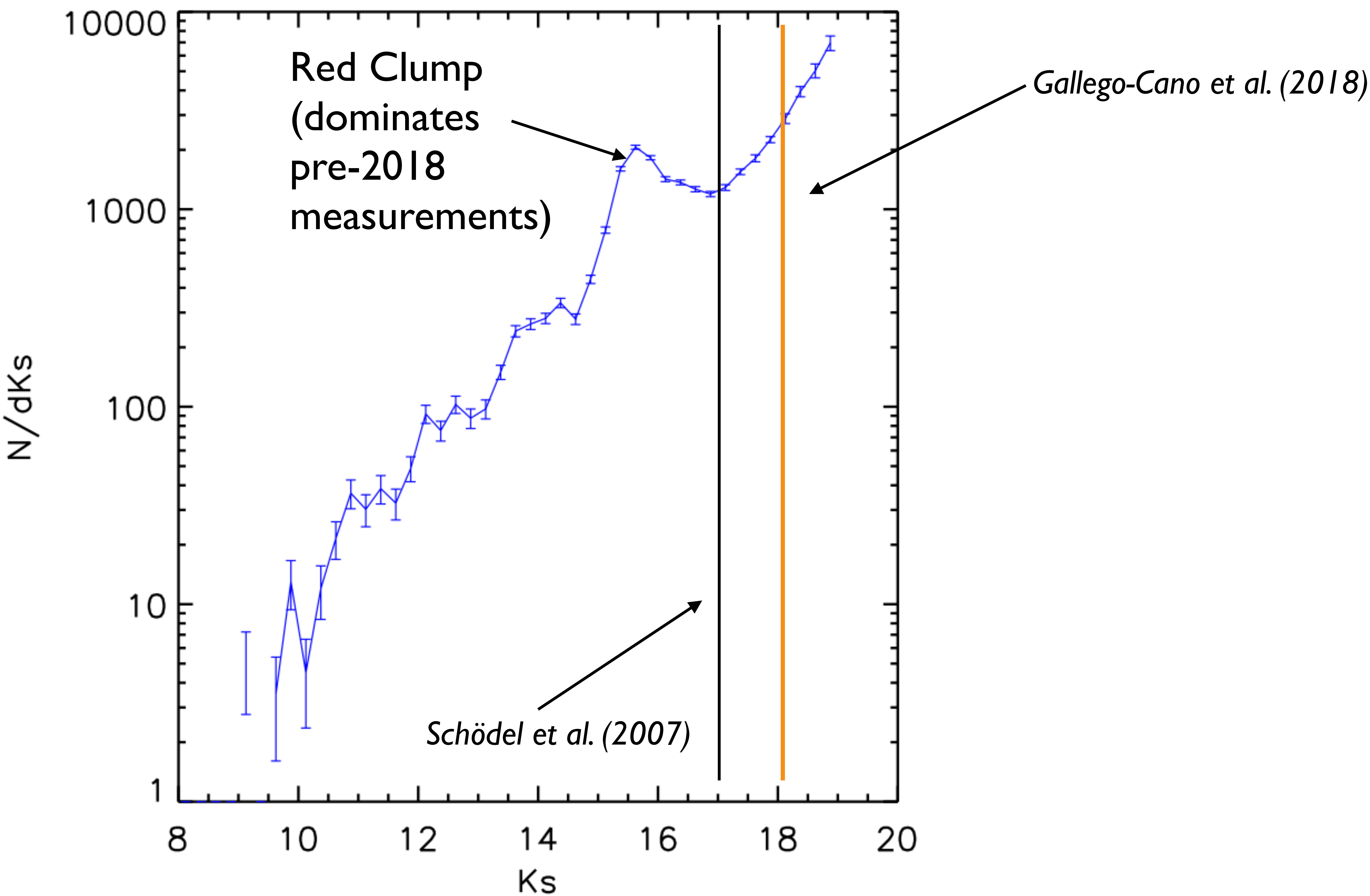

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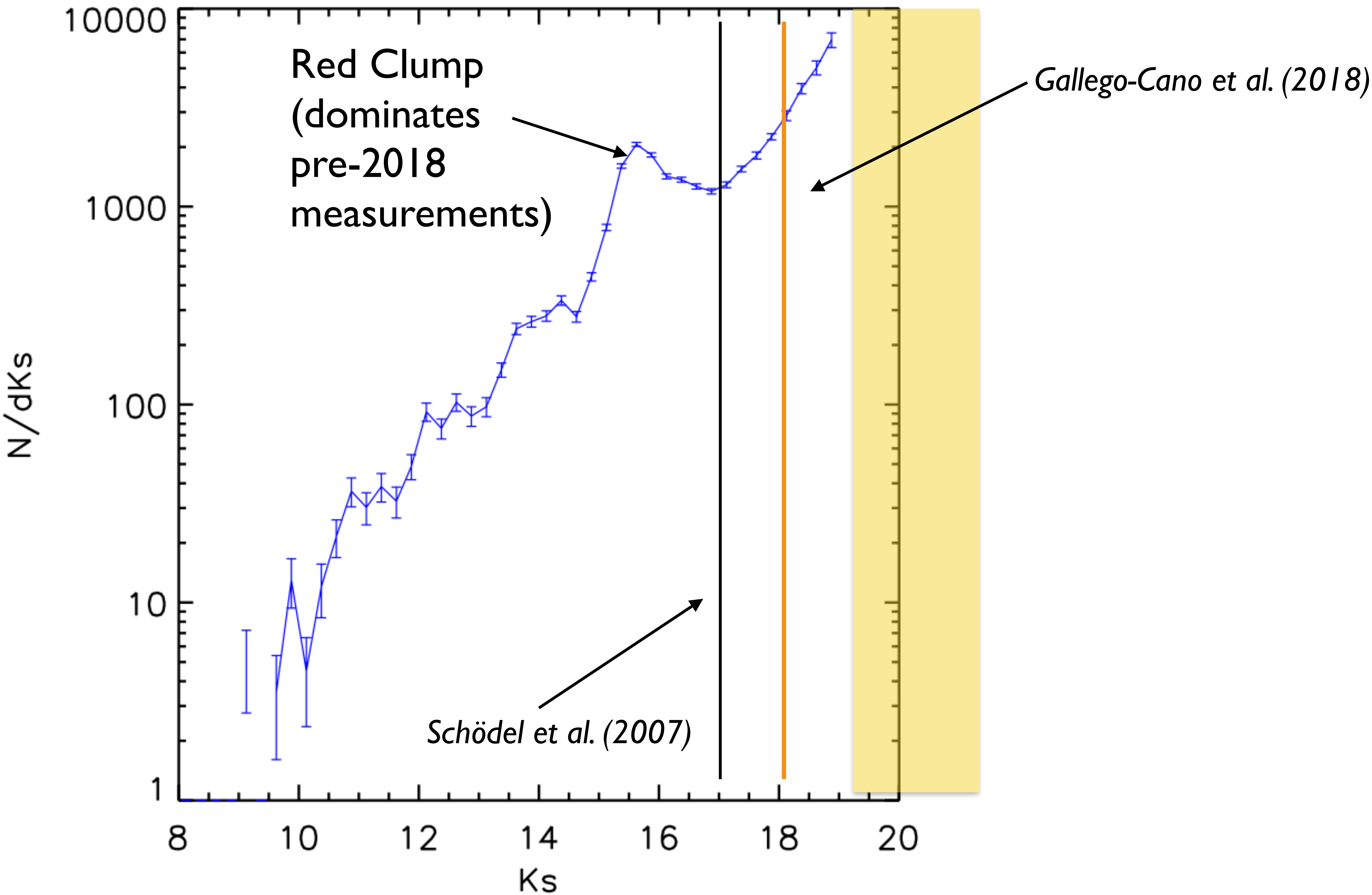

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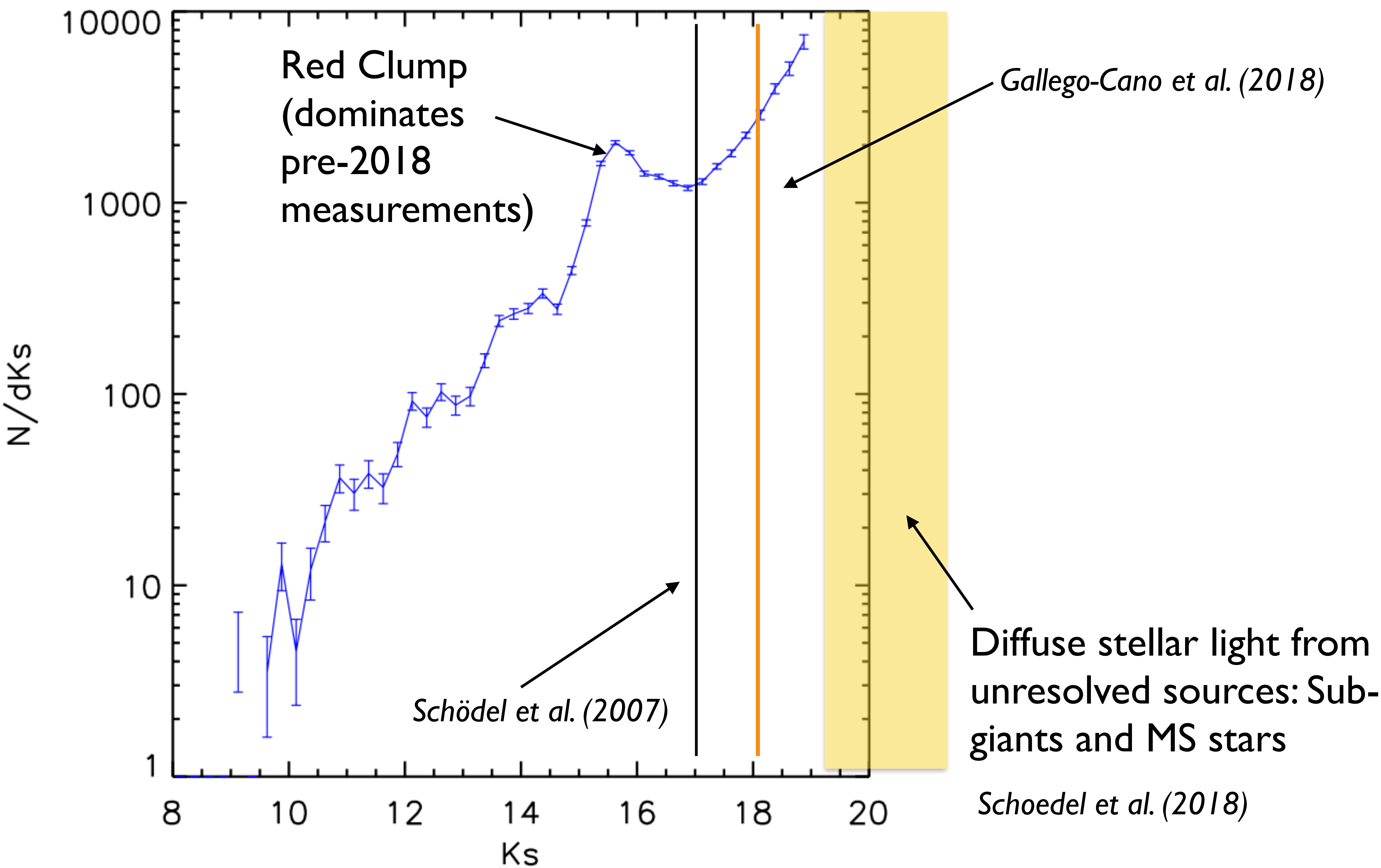

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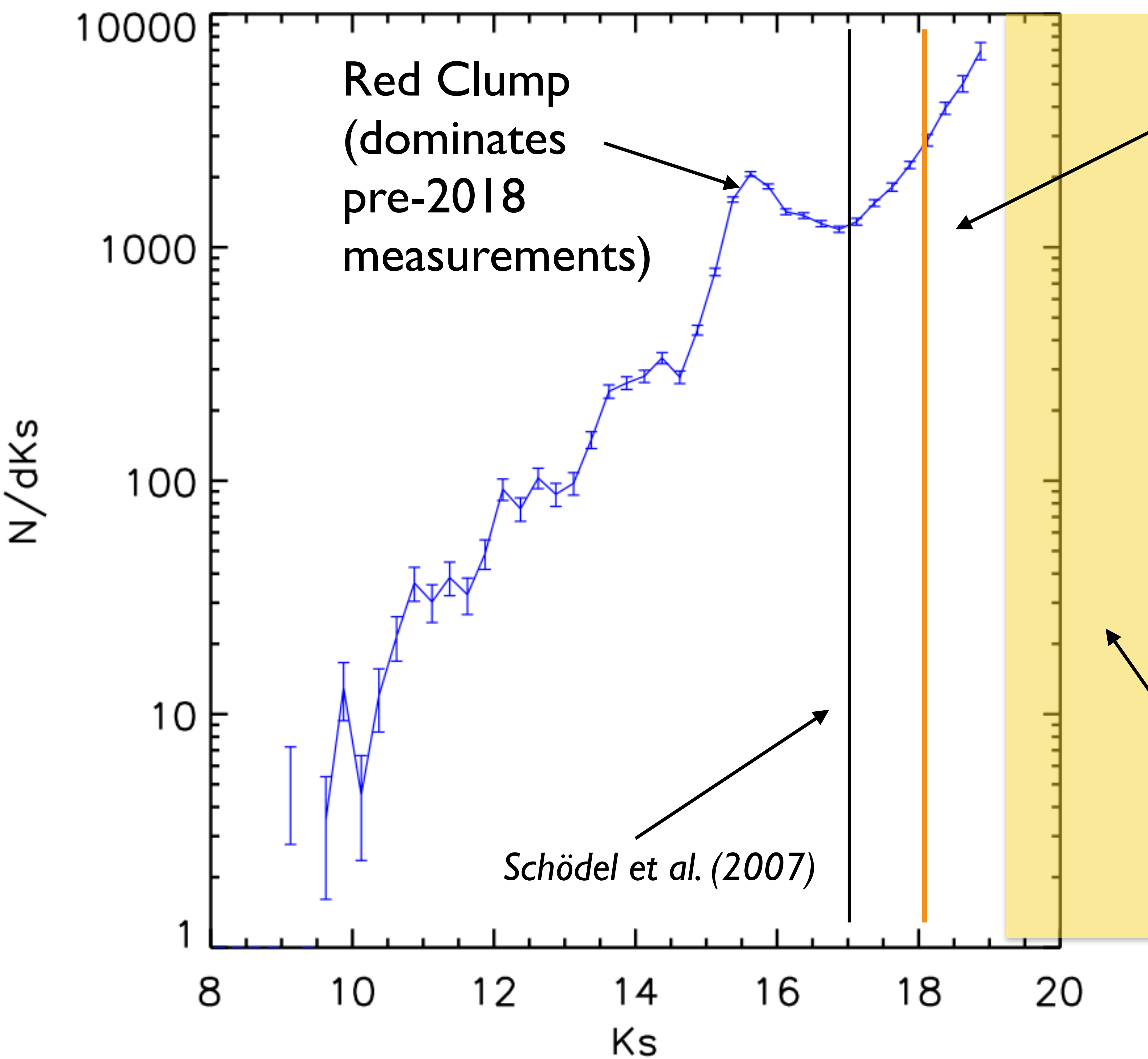
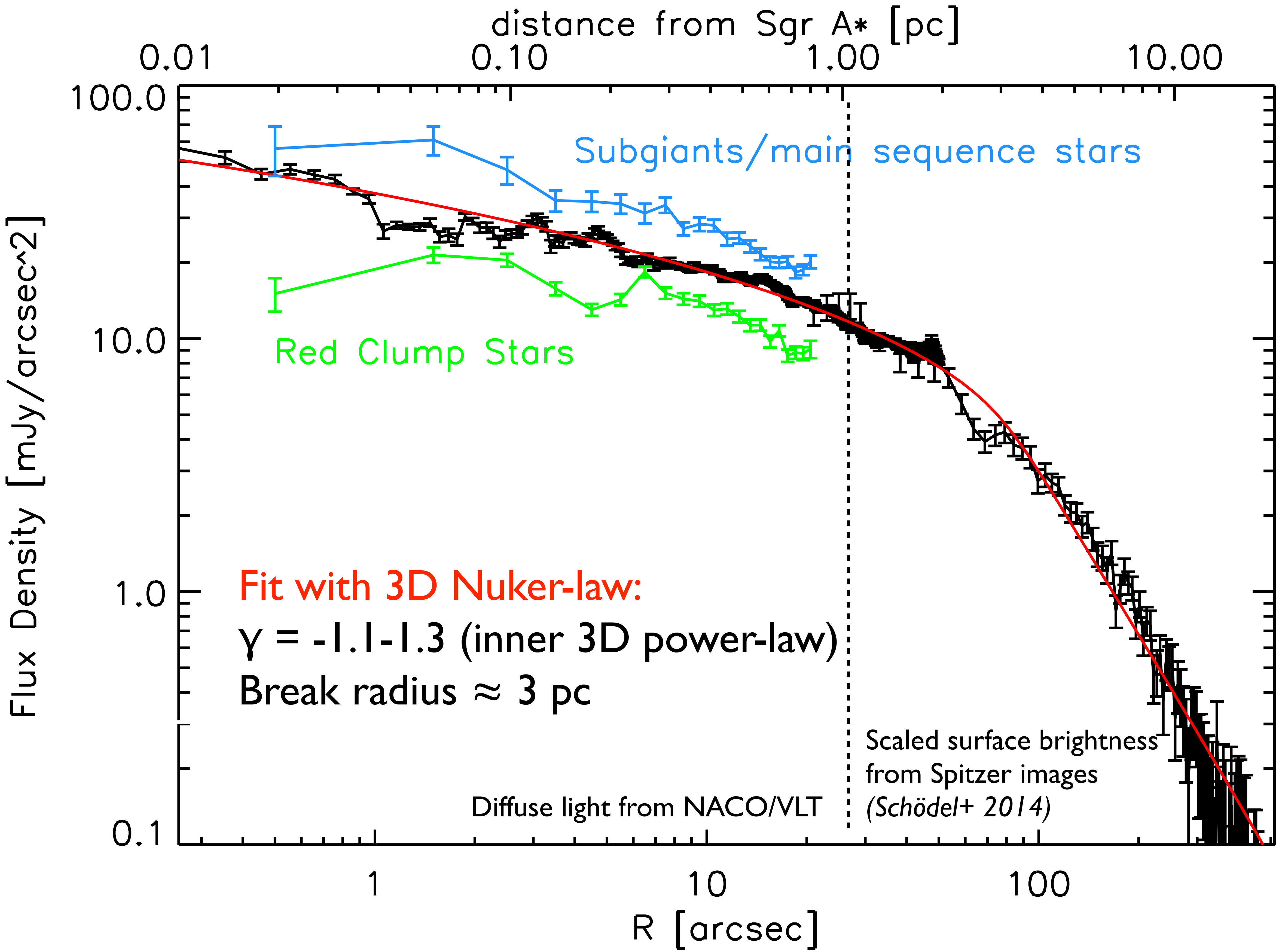


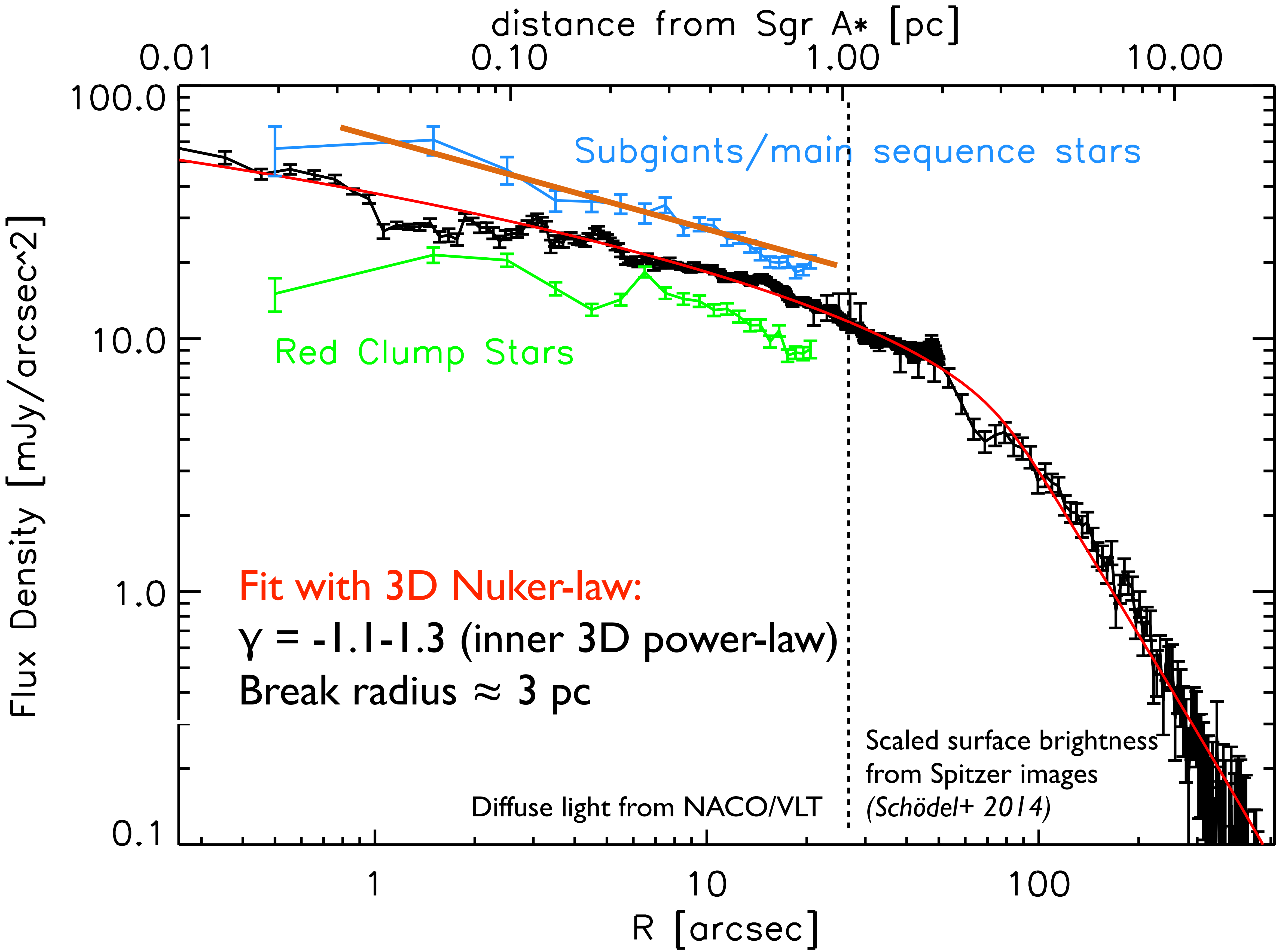
Tracer stars have 1-2 $M_\odot$

Diffuse stellar light from unresolved sources: Sub-giants and MS stars

Schoedel et al. (2018)



Gallego-Cano et al. (2018), Schödel et al. (2018)



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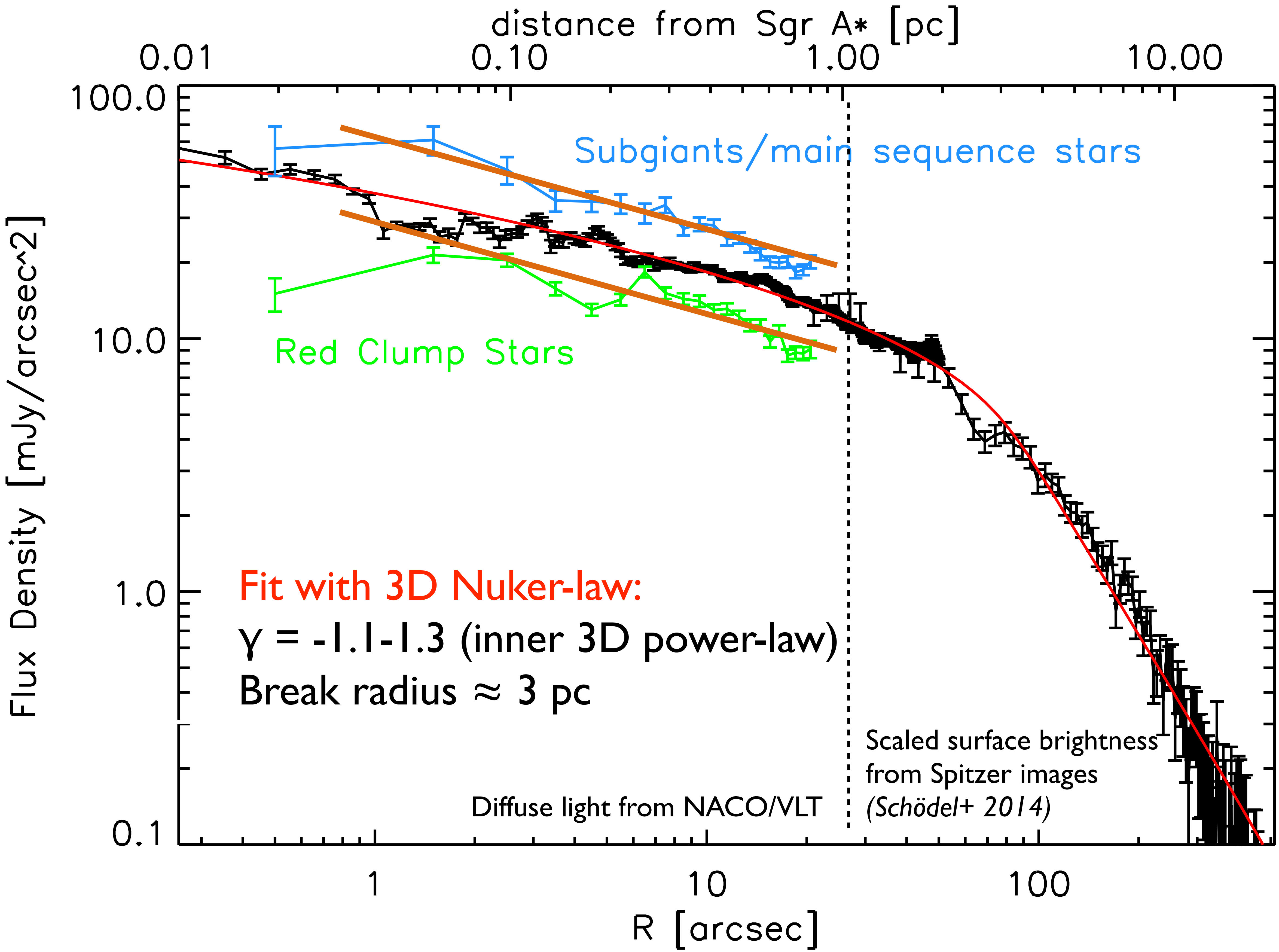

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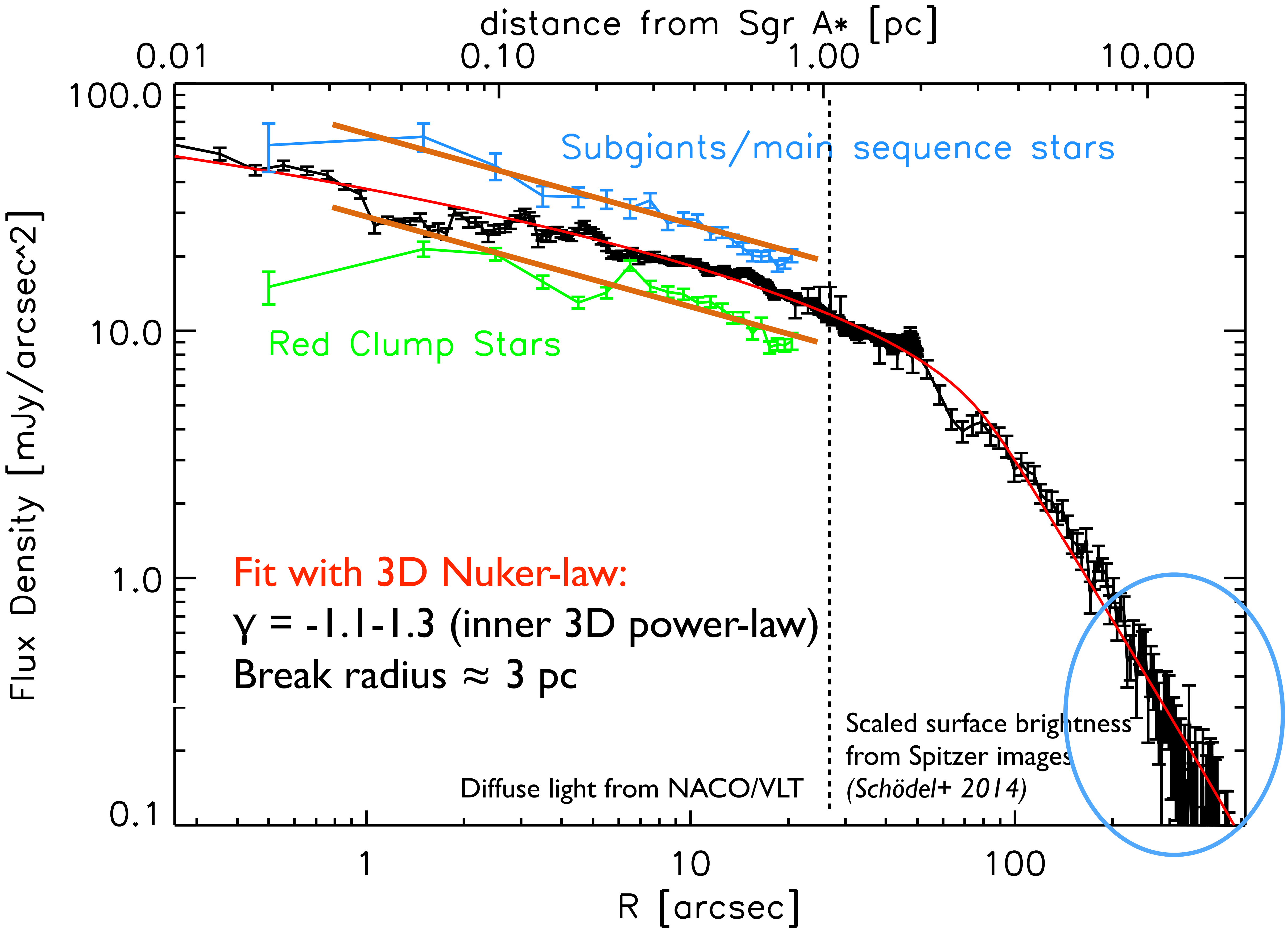

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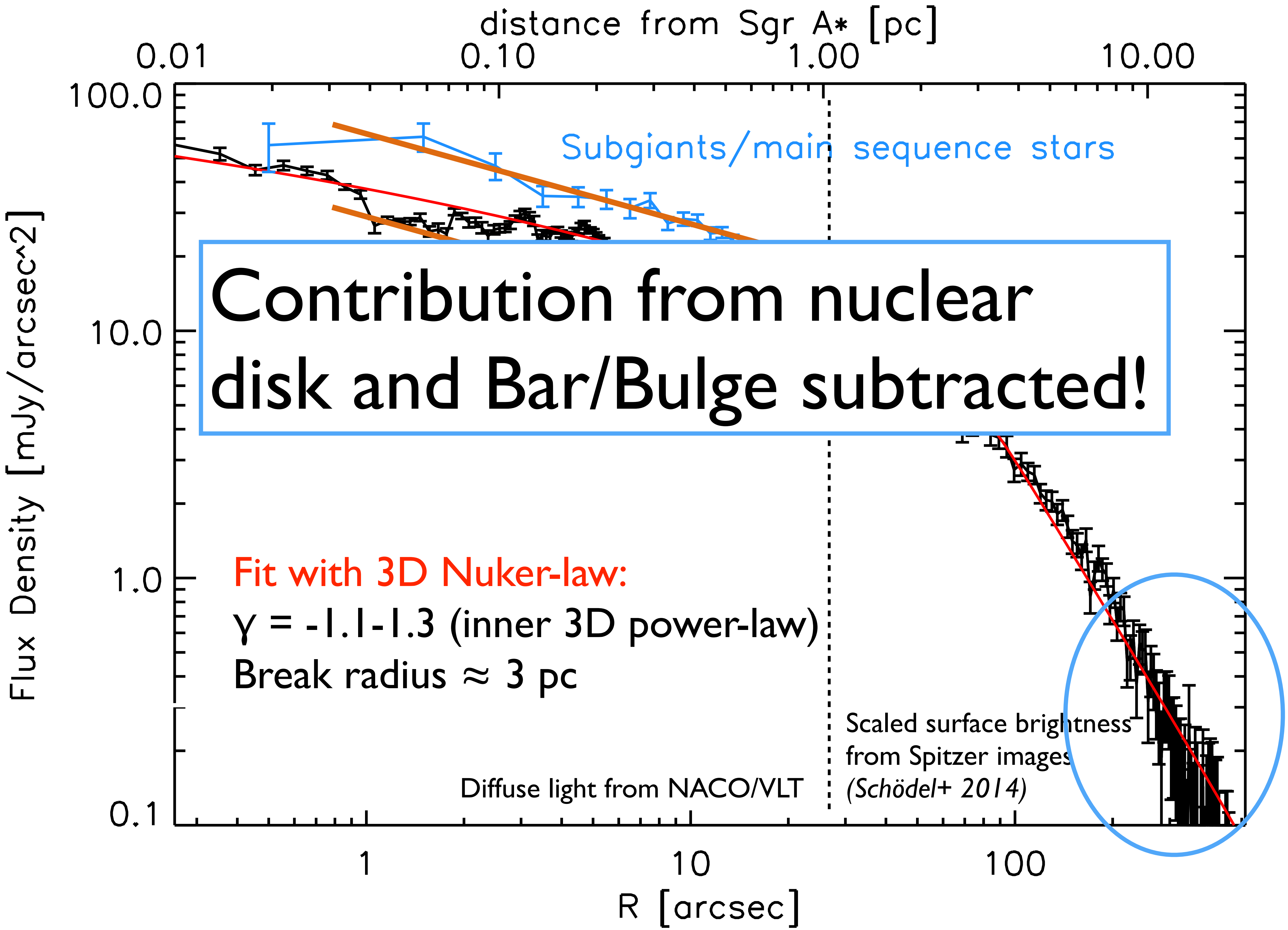

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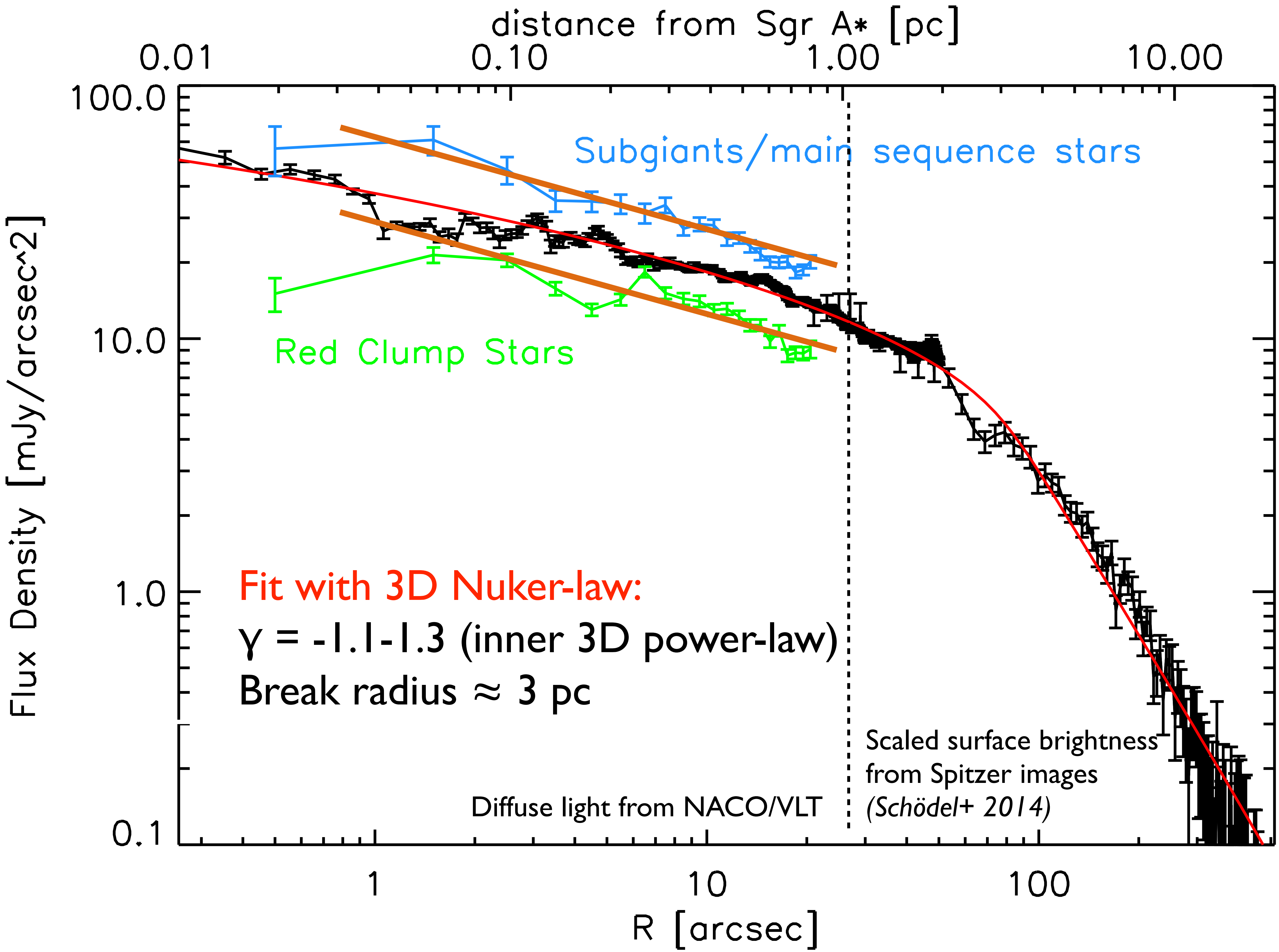

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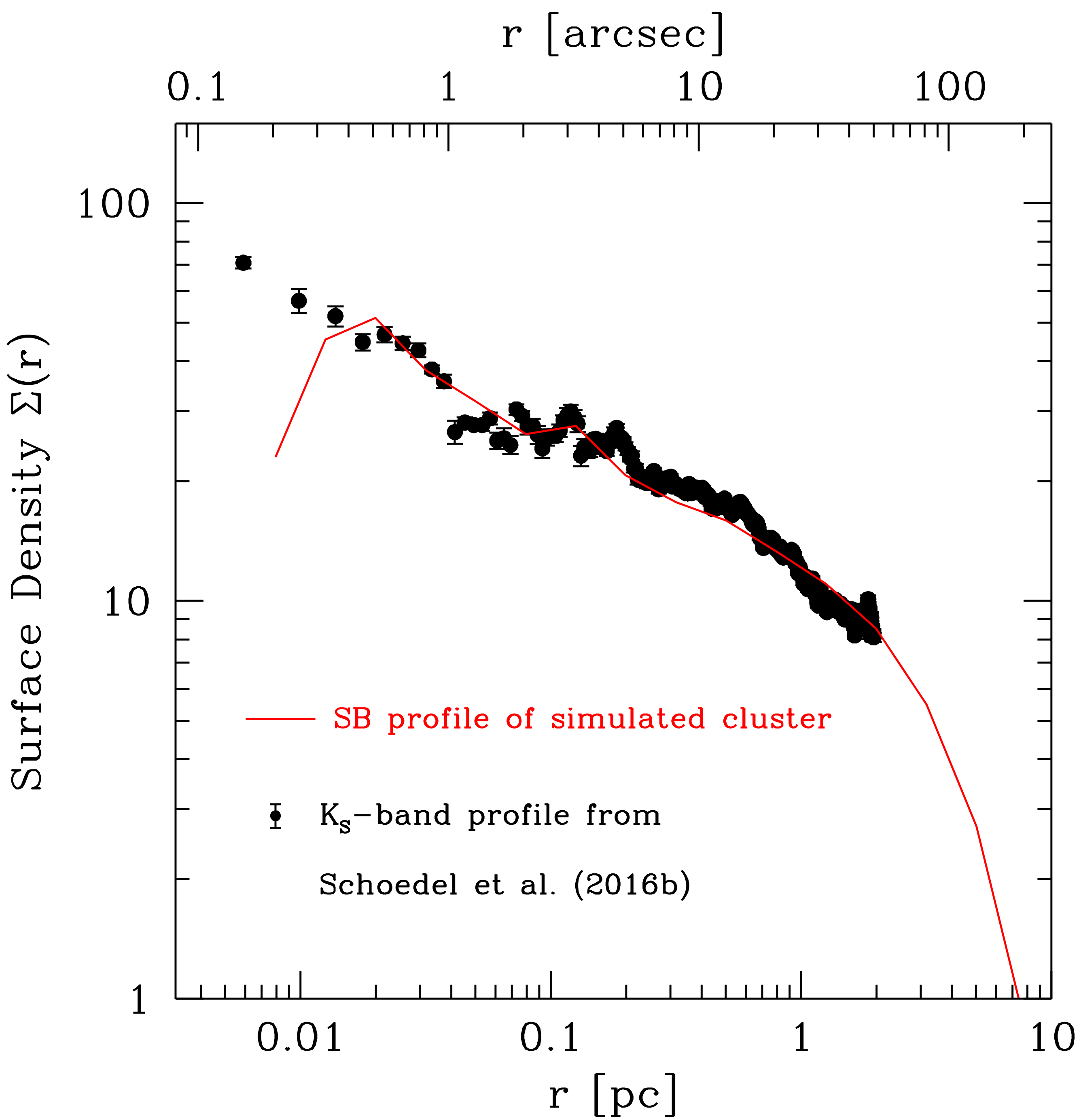
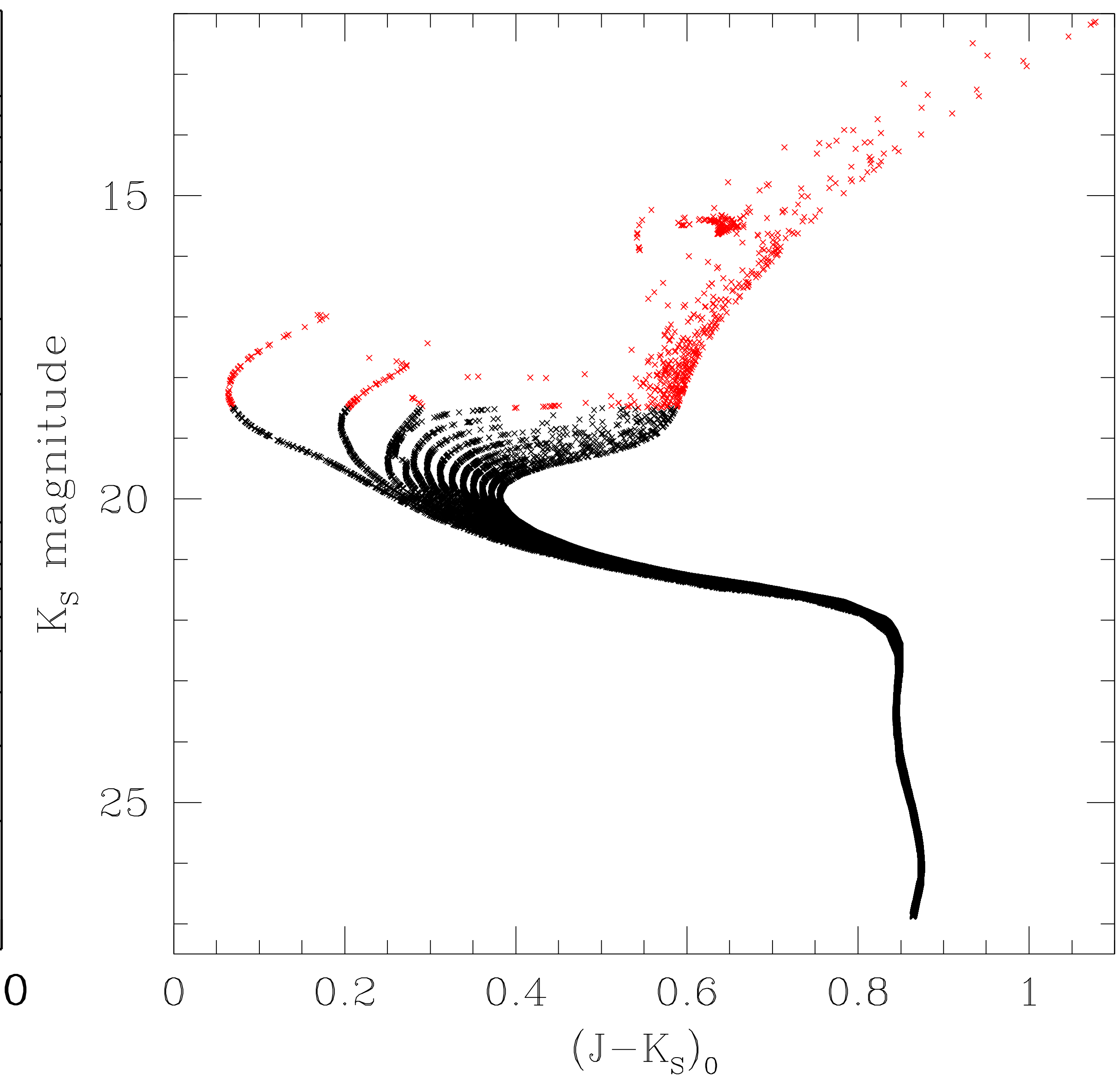
Comparison with simulations





1. NBODY6
2. Repeated star formation
3. One Hubble time (not multiple t_{relax})

Baumgardt, Amaro-Seonae & Schödel (2018)

Agreement between observations and theory, finally!

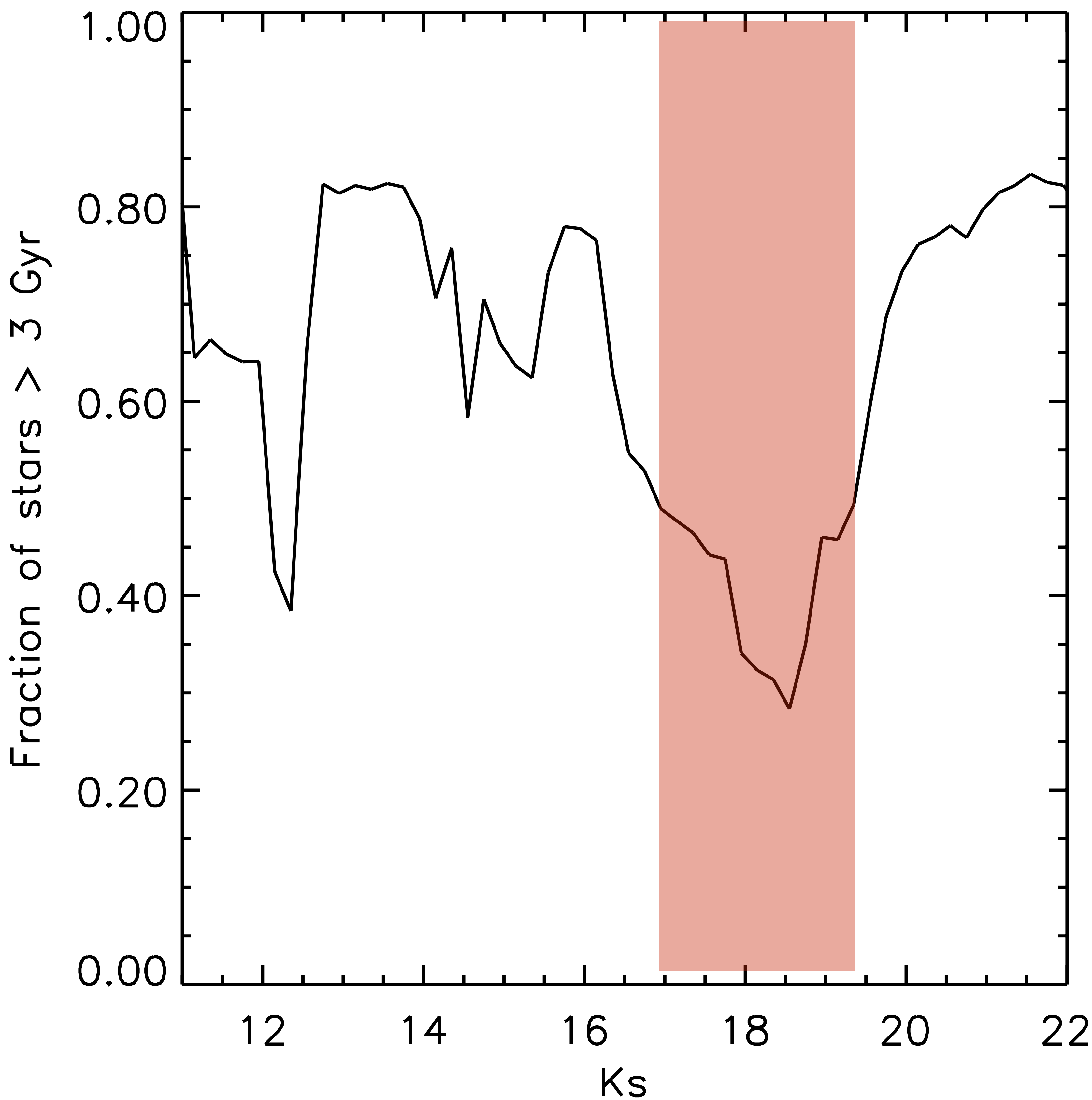
Caveat

Giants mostly old.

Diffuse light ok.

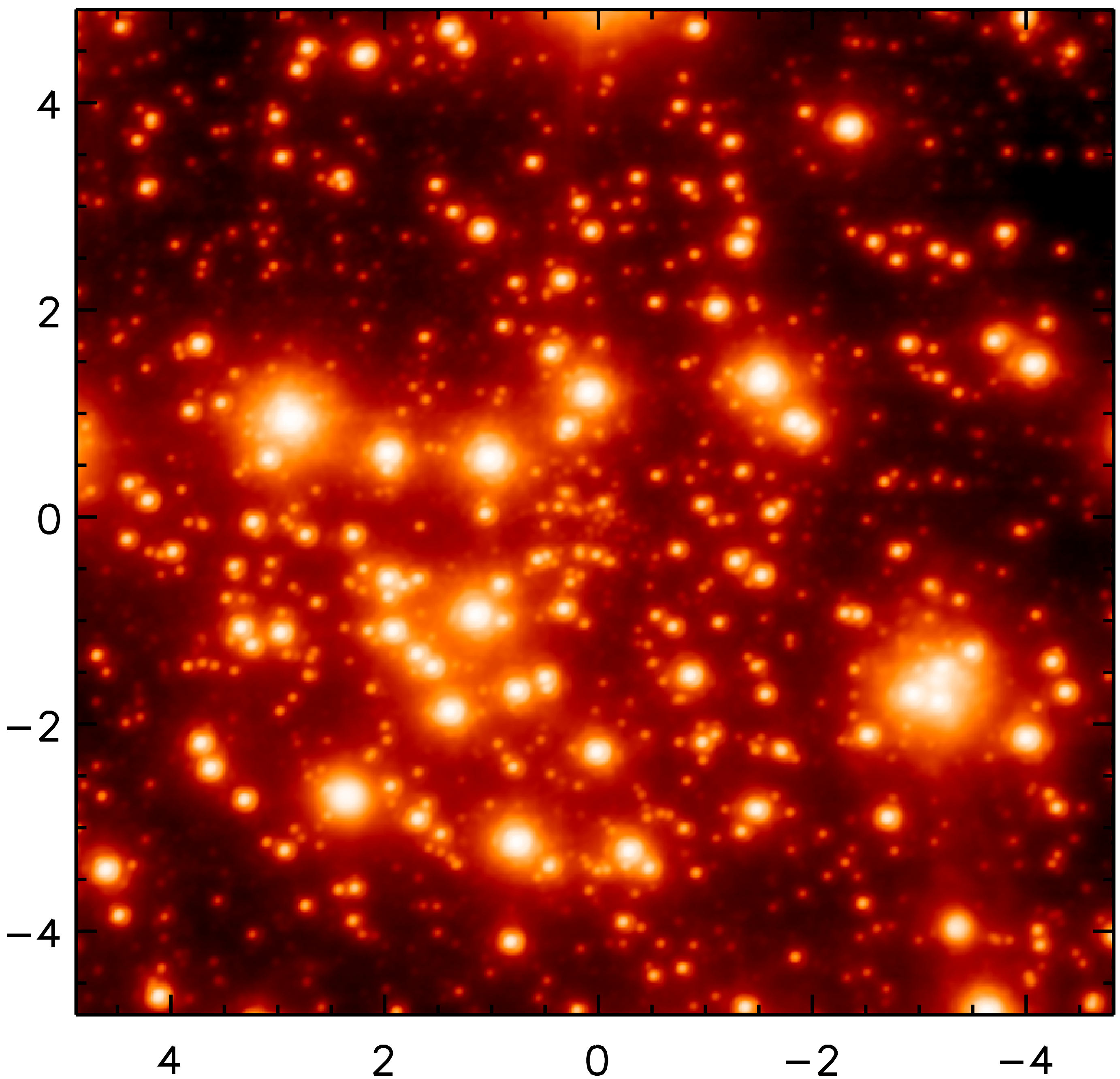
Faintest detectable stars subject to great uncertainty because of largely unknown properties of star formation ~100 Myr ago.

Star formation history for central parsec: Pfuhl et al. (2011)



... and deeper

Stacked 1.6h of 1s exposures from epoch 2012 with *speckle holography* technique
Exquisite calibration of PSF and fully-diffraction limited images.



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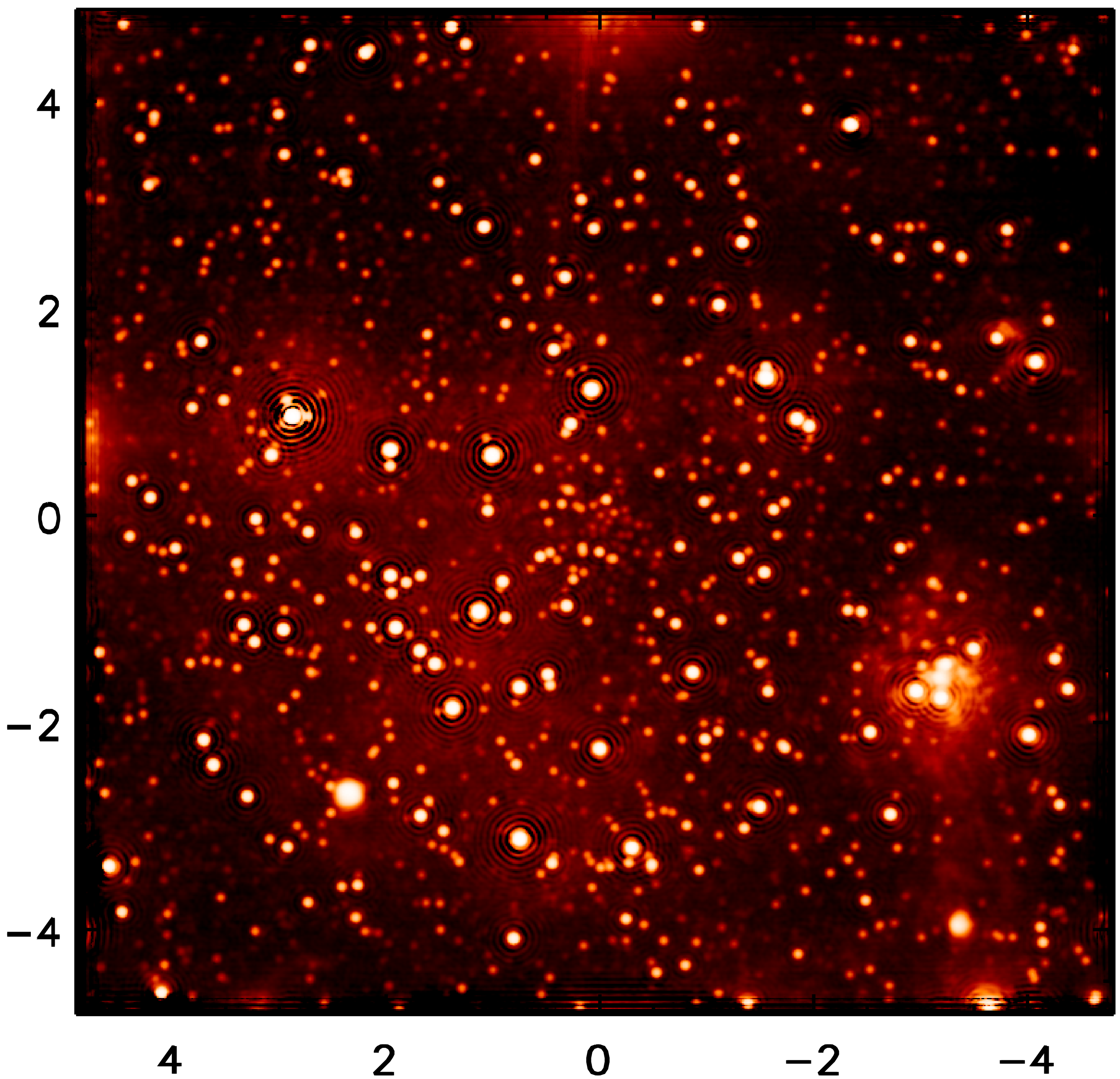

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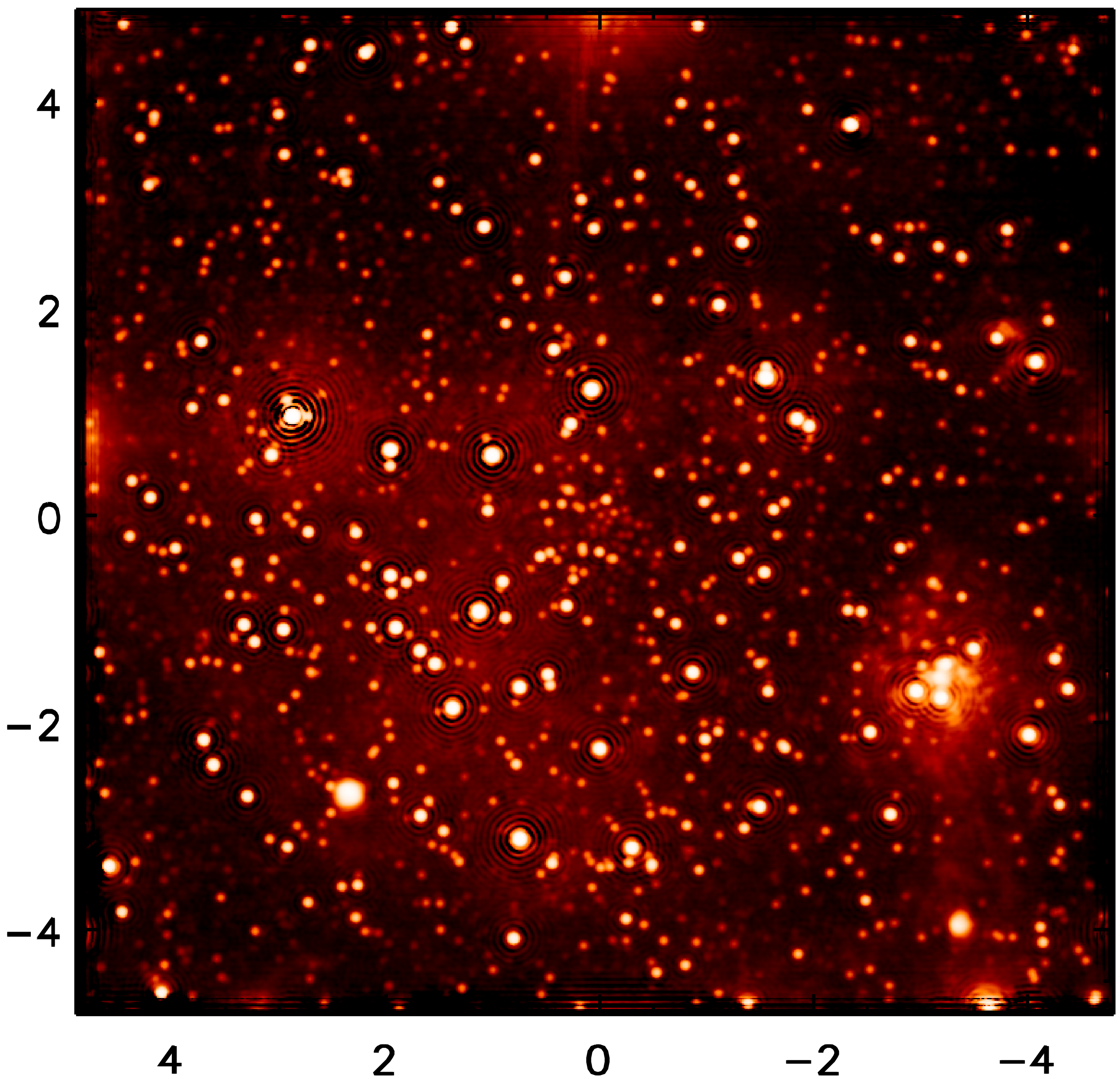

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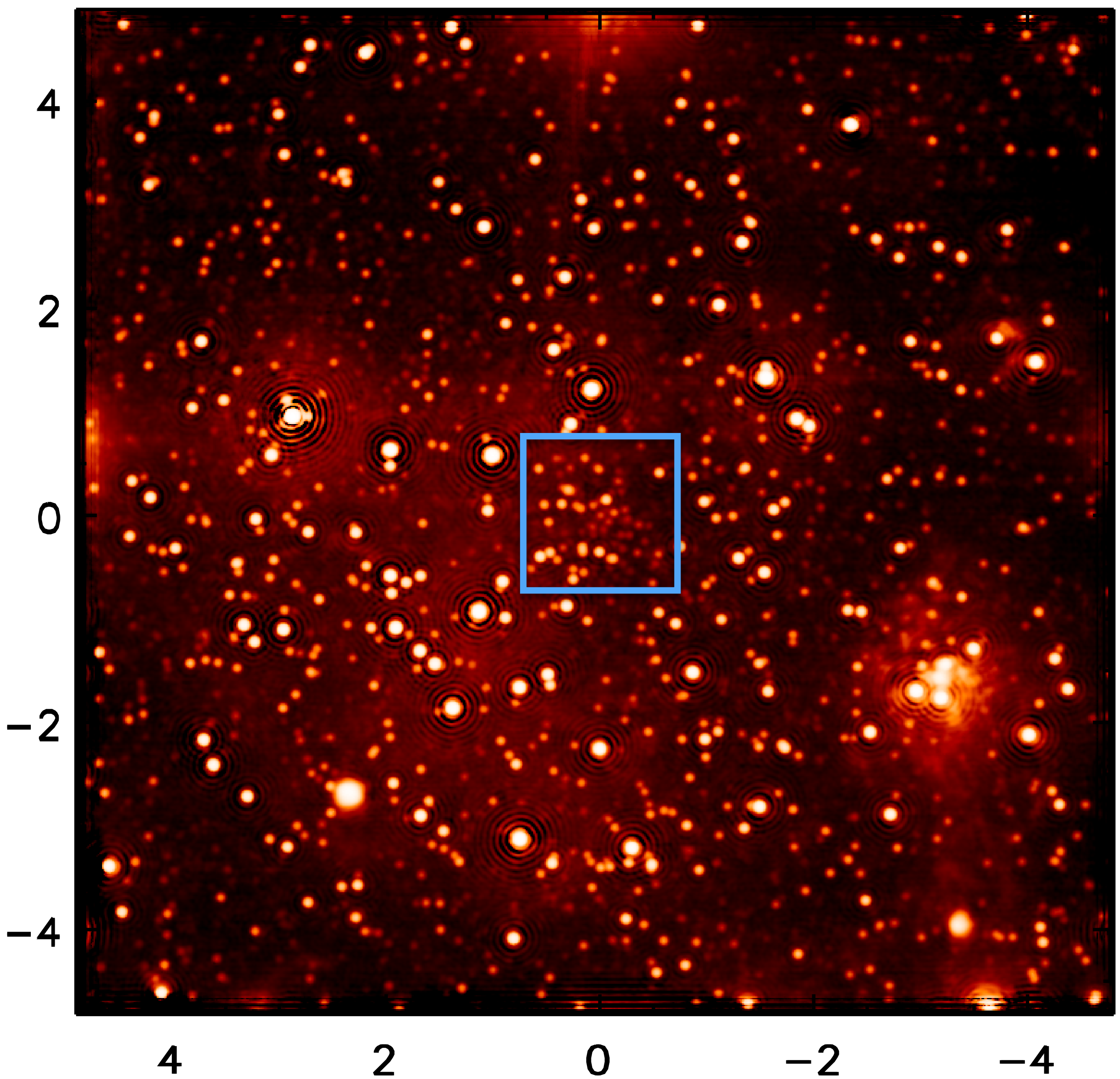

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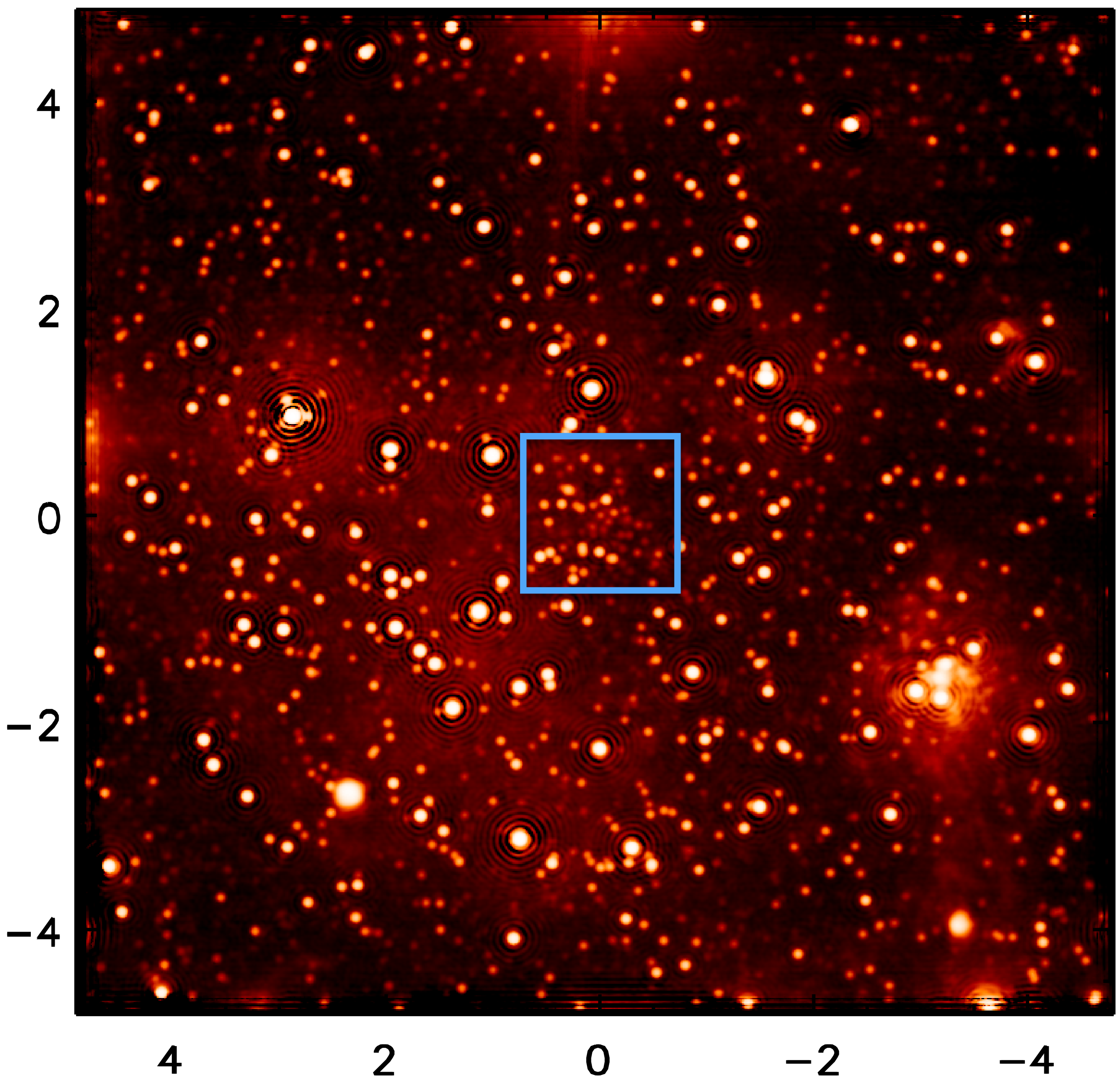

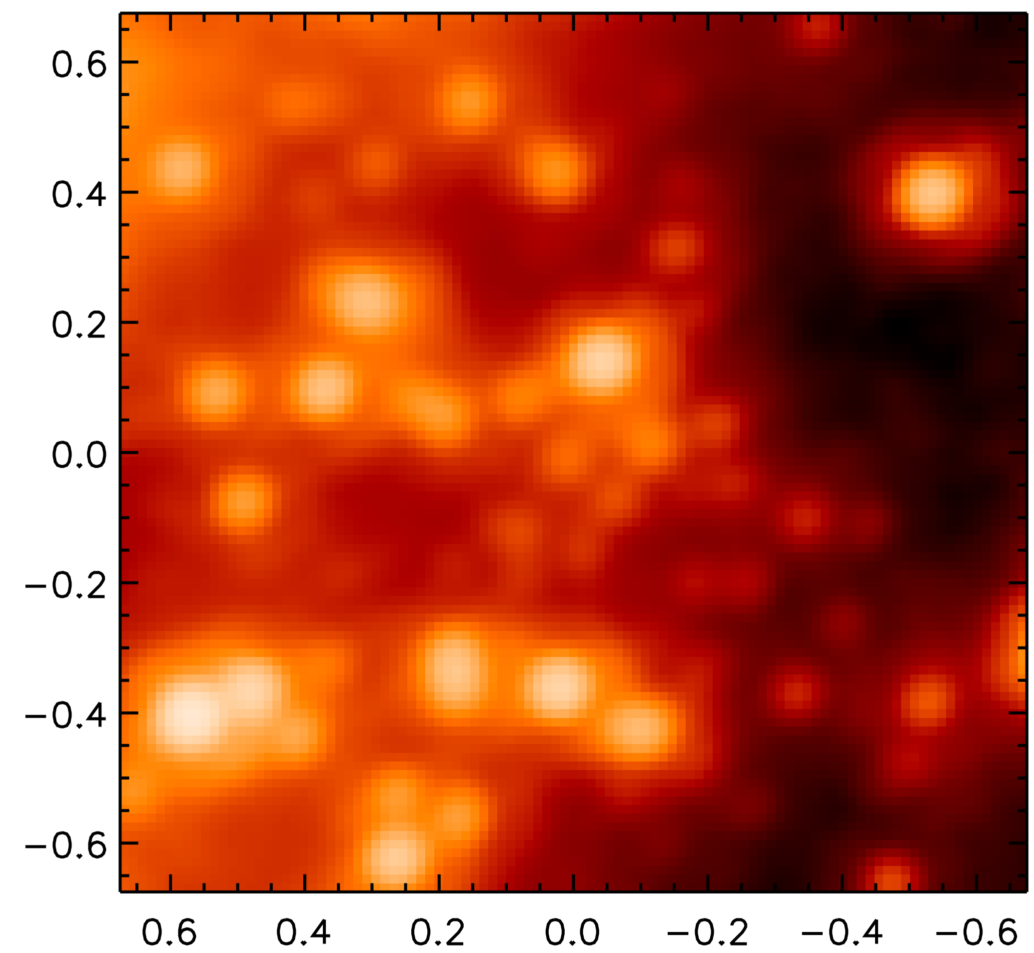

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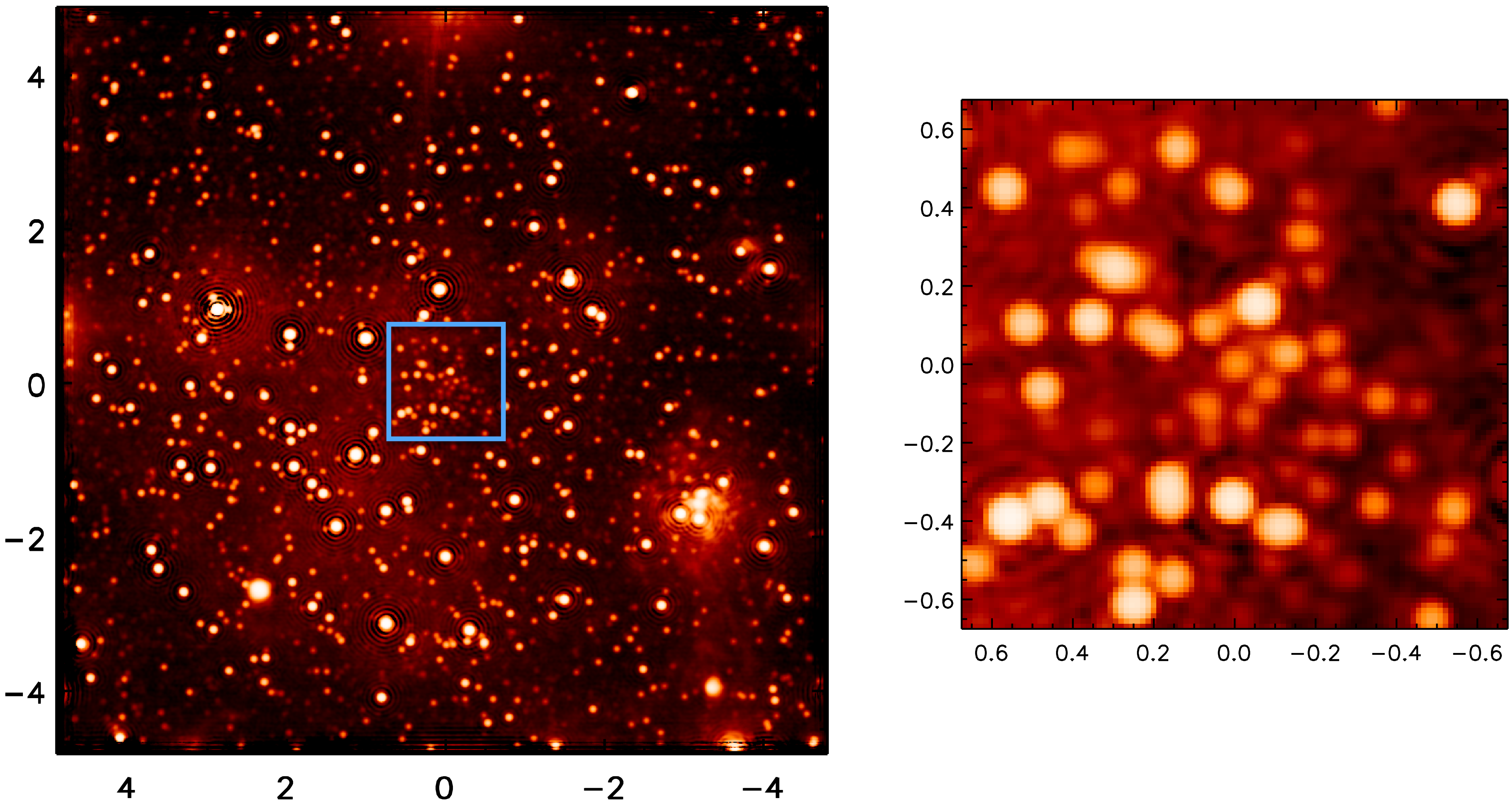

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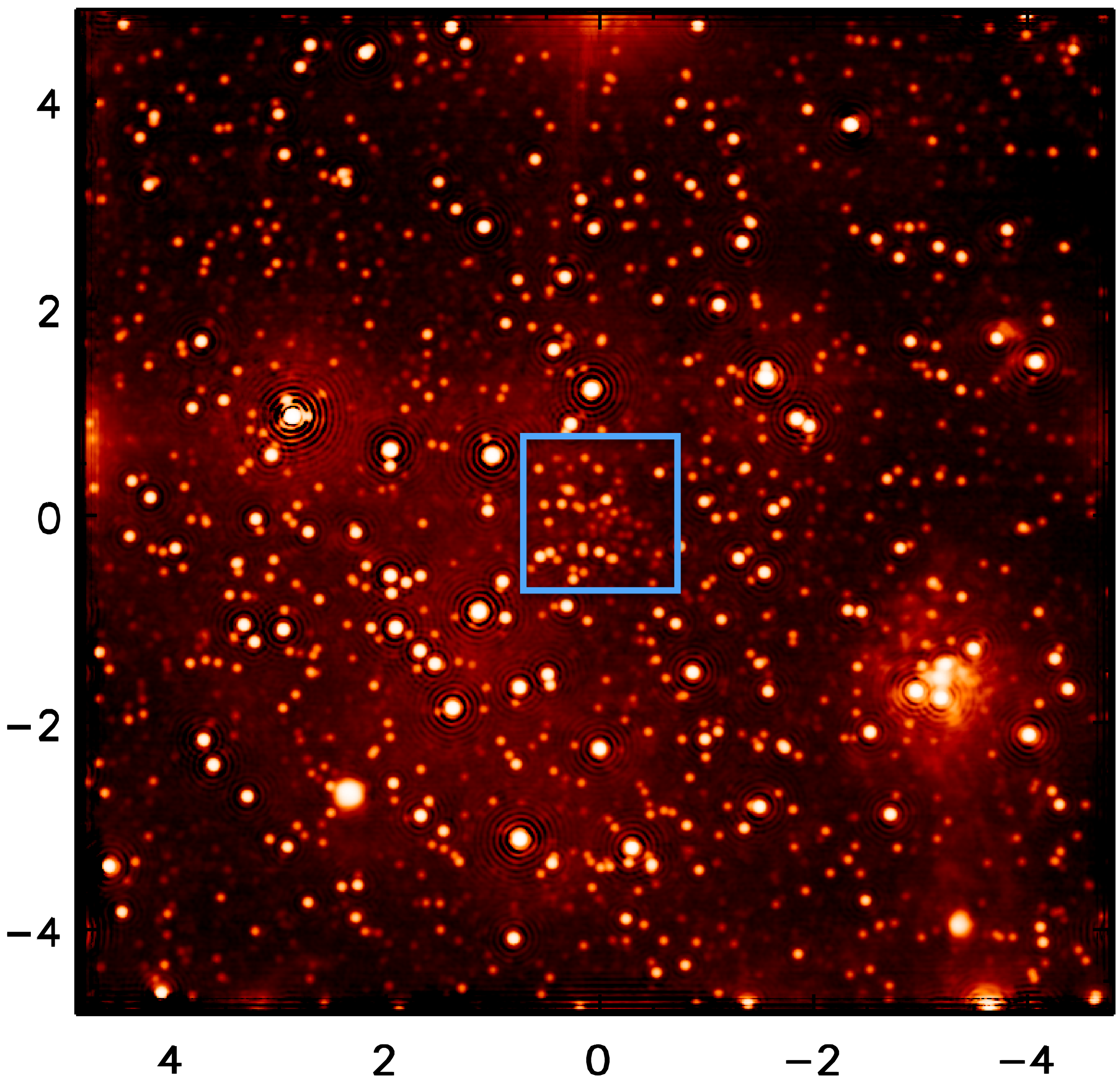

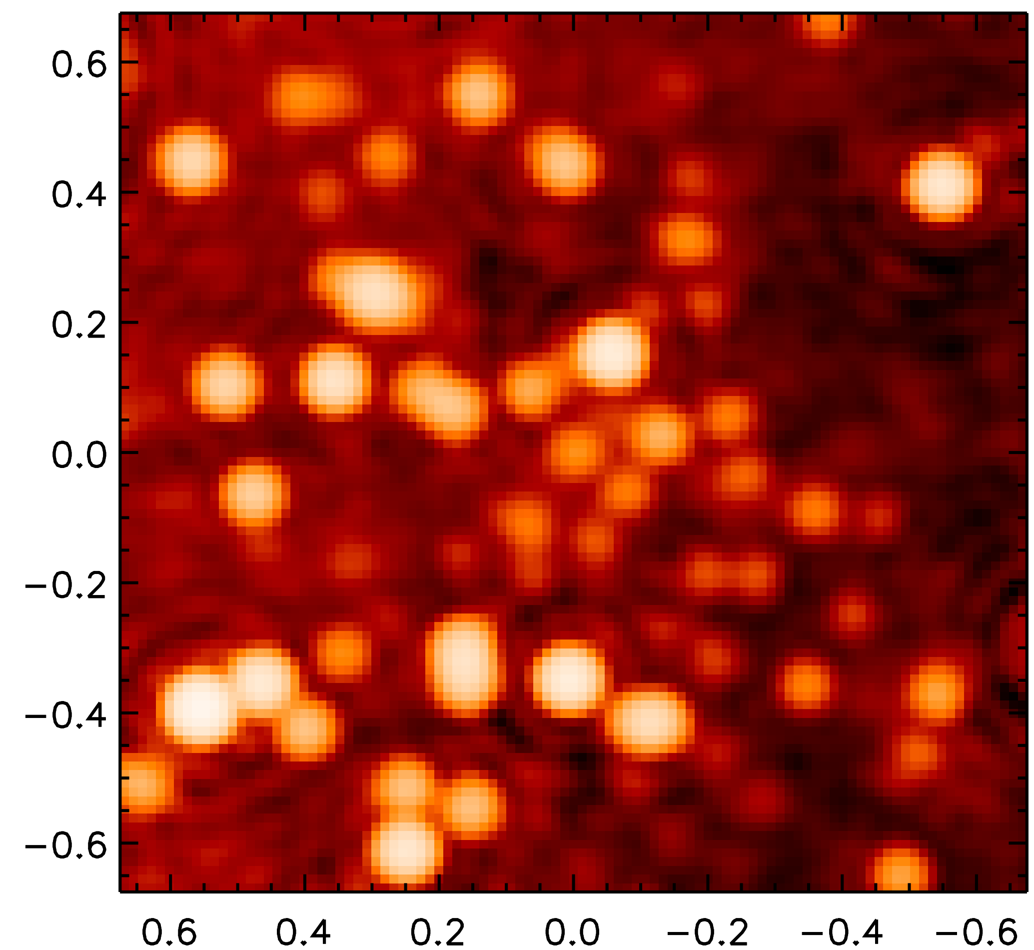

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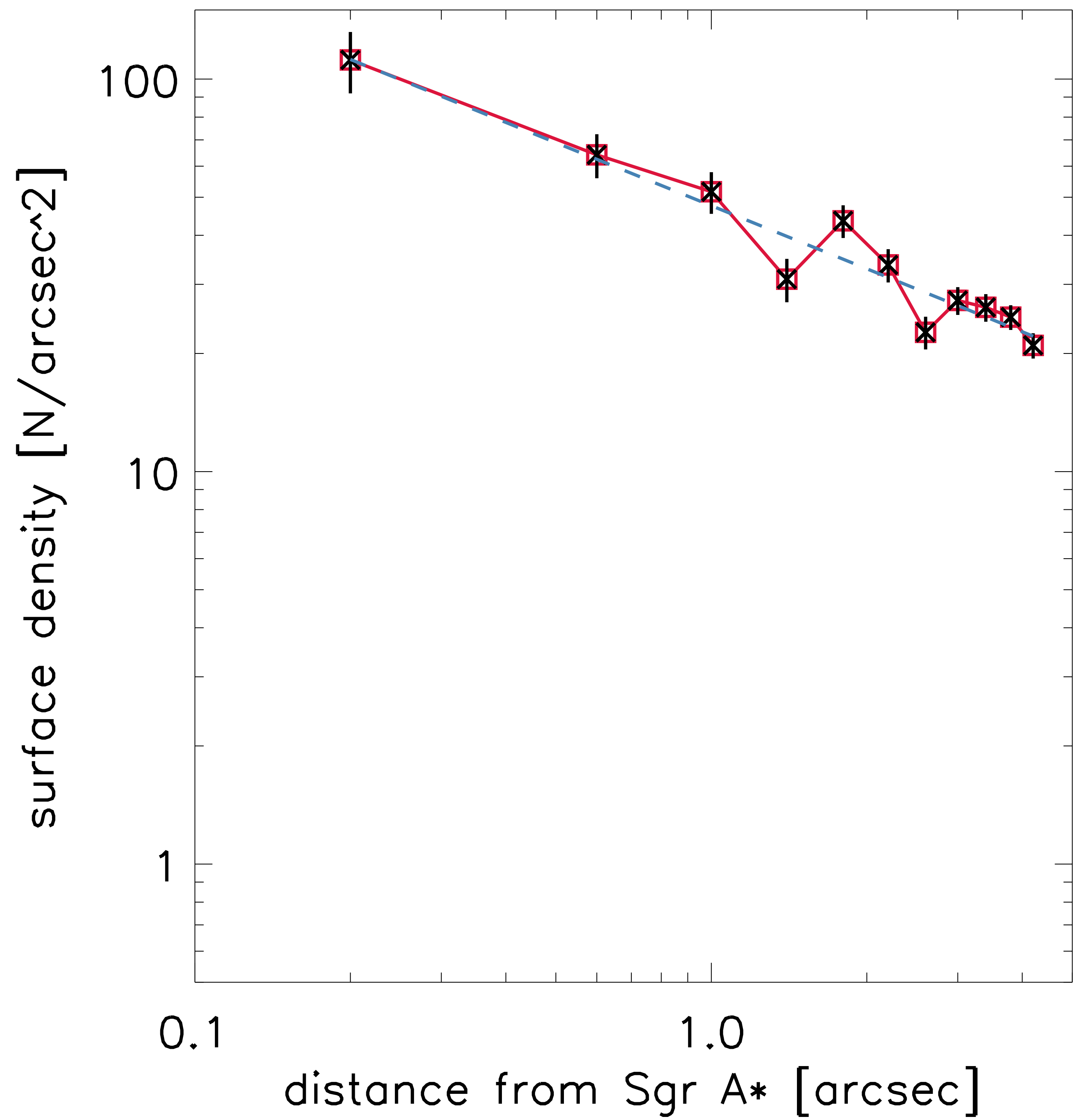

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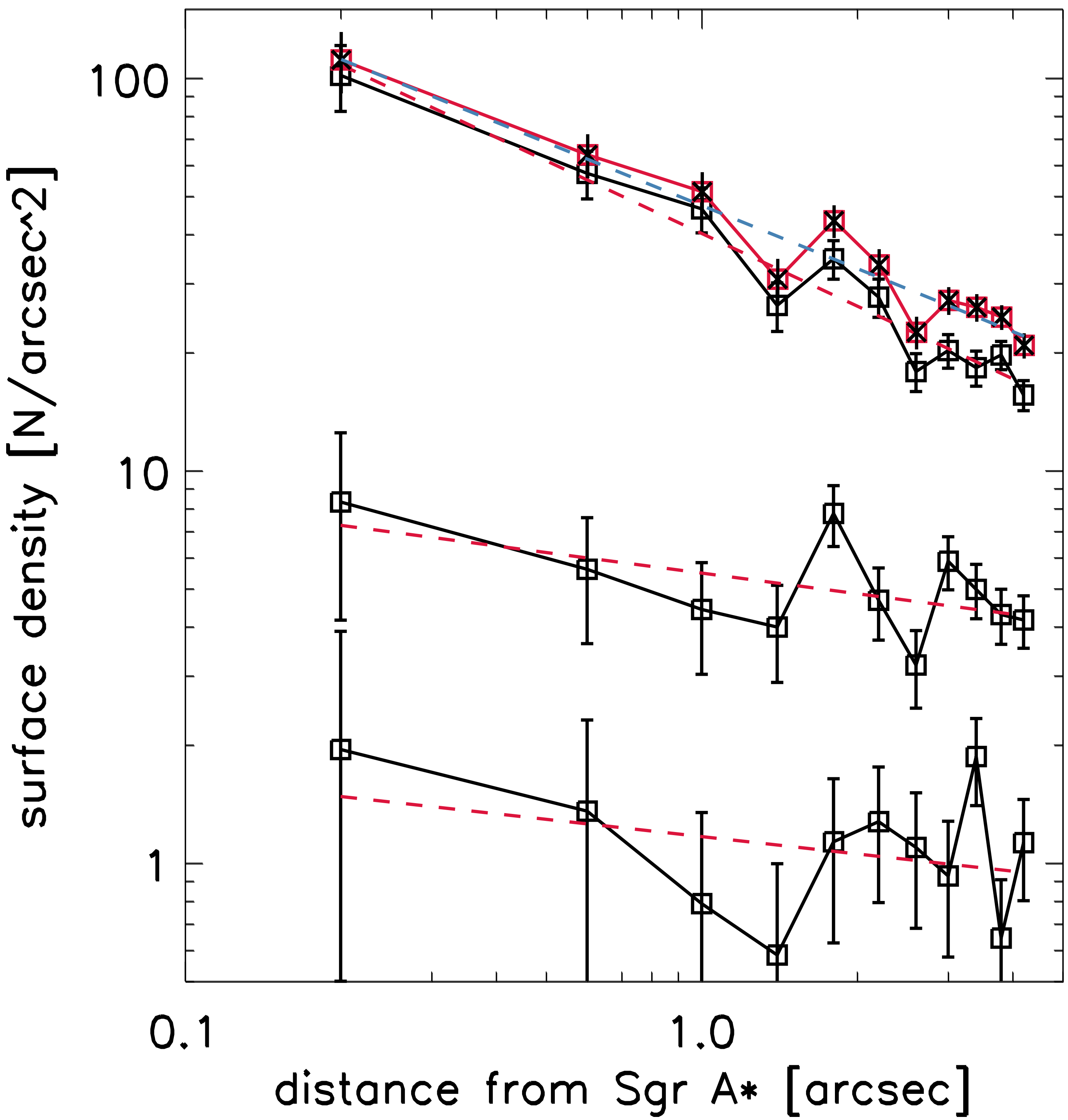

K_s = 16.5-19

K_s = 15-16.5

K_s = 10-14.5

… and deeper

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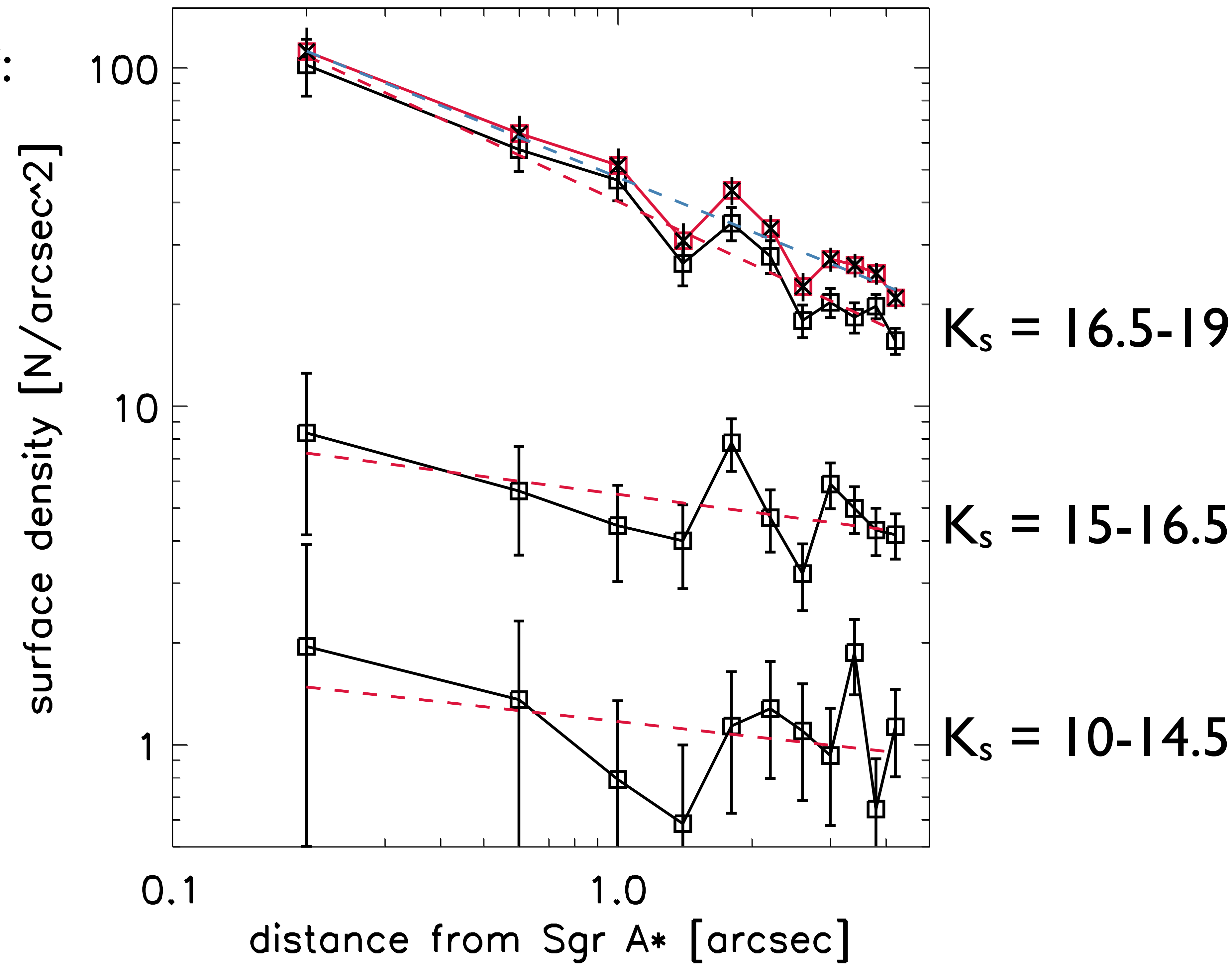
Faint stars near Sgr A*:
$\Gamma \approx -0.5 \pm 0.1$
As expected for
Bahcall-Wolf cusp!



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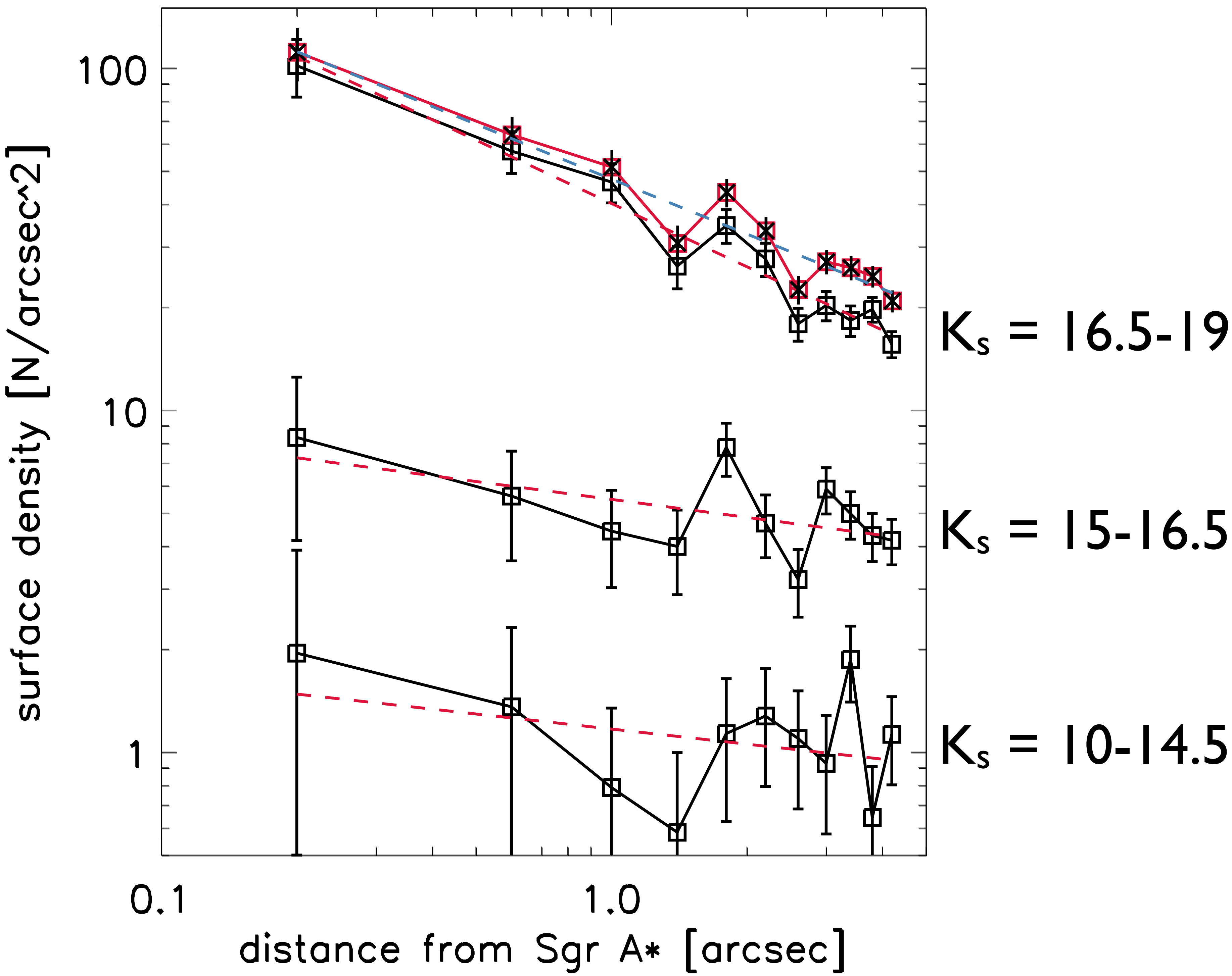
Caveat: Star
Formation History



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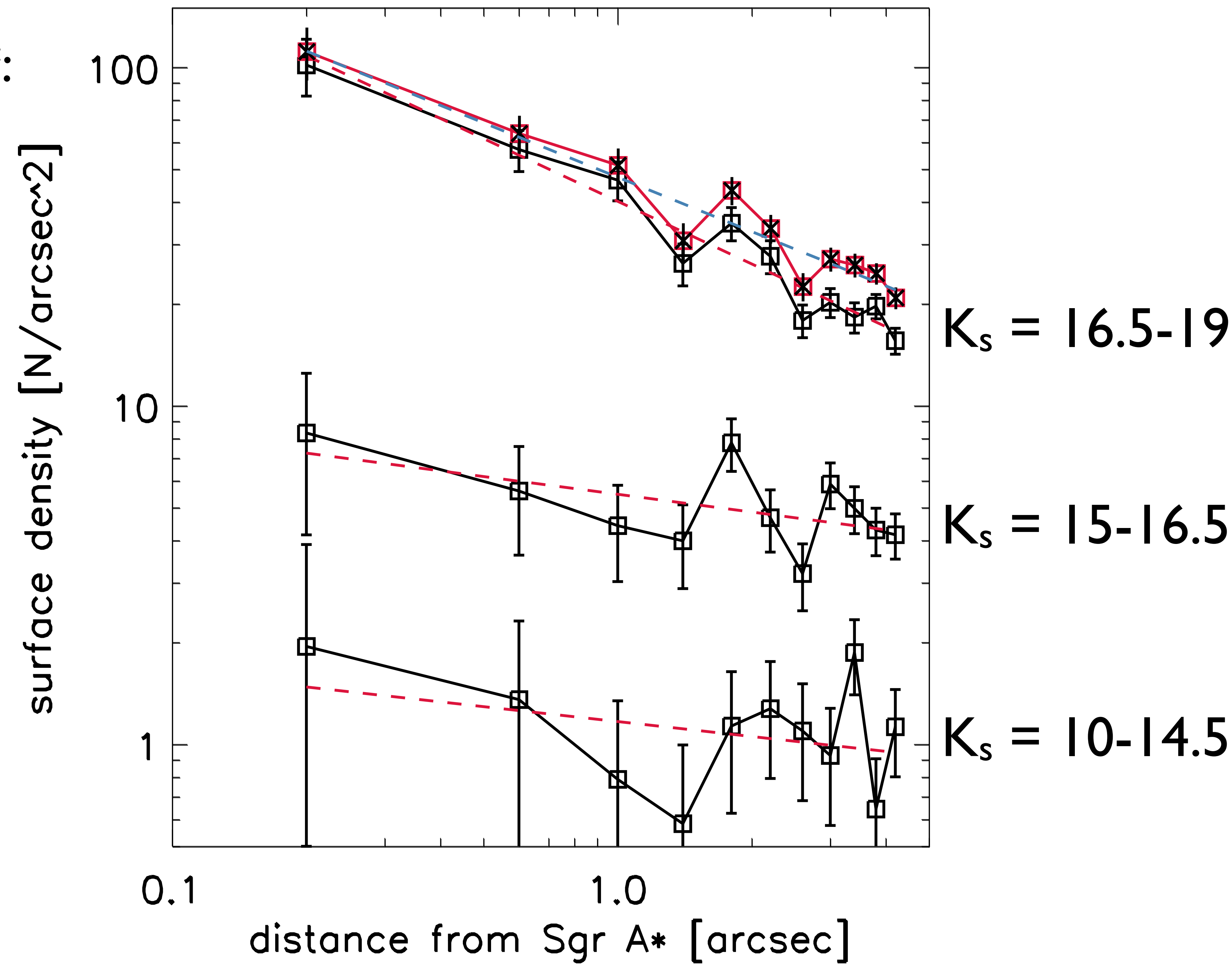
Caveat: Star Formation History

There is a problem with the giants!



Conclusions

1. Cusp detected at faint stellar magnitudes (~1 $M_\odot$ stars)

2. Agreement between theory and observations (finally!)

3. Caveat: Consider star formation history when interpreting density data

4. ***Missing cusp*** is a ***hidden cusp***

5. *Missing giants problem* at <0.2 pc (5")

6. Stellar density at 0.1 pc: ~10^7 $M_\odot$ pc^{-3} possibly sufficiently high to explain missing giants problem via star-cloud collisions *(Amaro-Seoane & Chen 2014)*

7. Mass segregation makes existence of **stellar BH cusp** very likely.

Gallego-Cano et al. (2018) Schödel et al. (2018), Baumgardt et al. (2018)

A cusp of stellar mass BHs

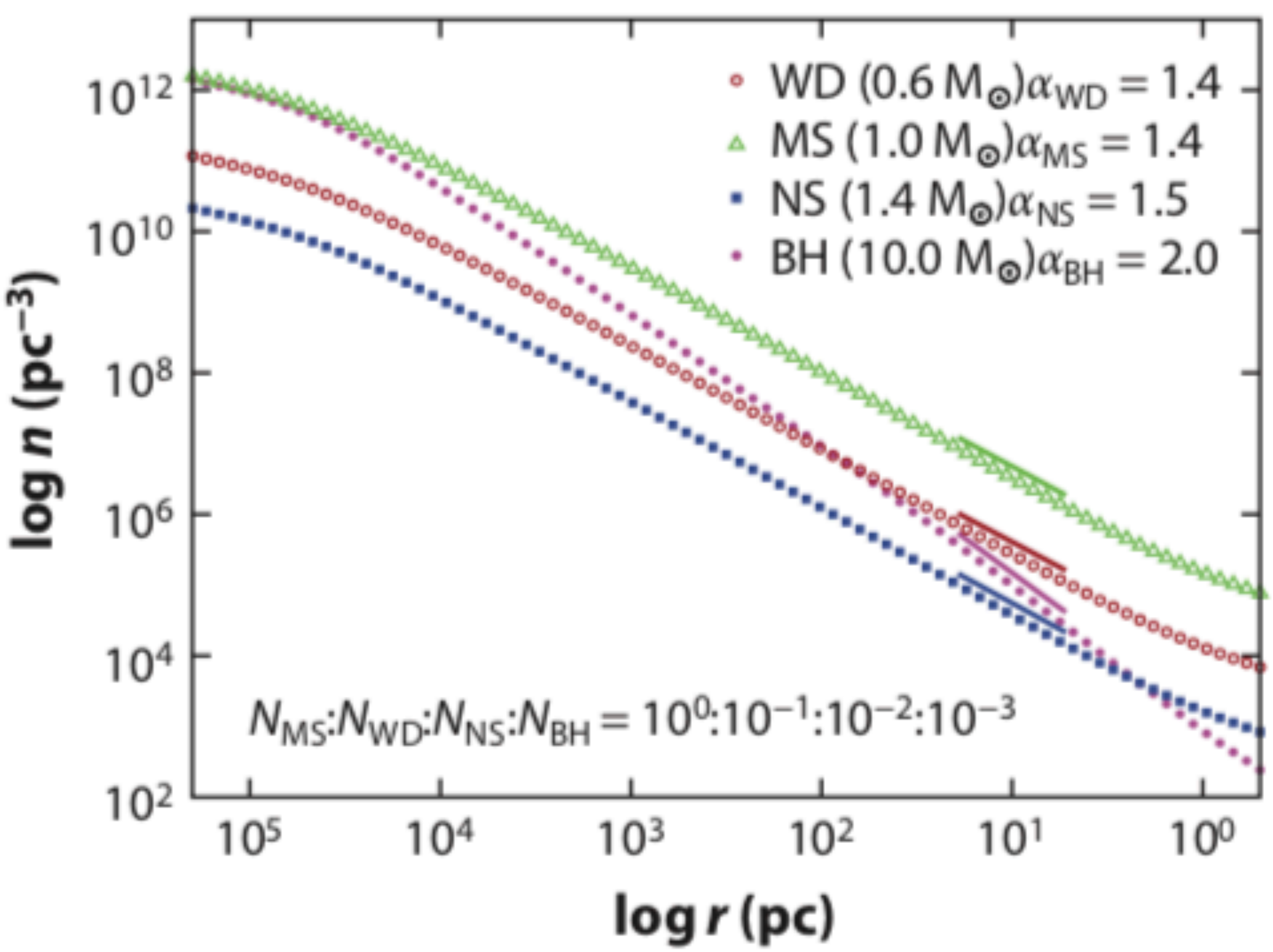
1. Stellar BHs will sink to GC because of dynamical friction

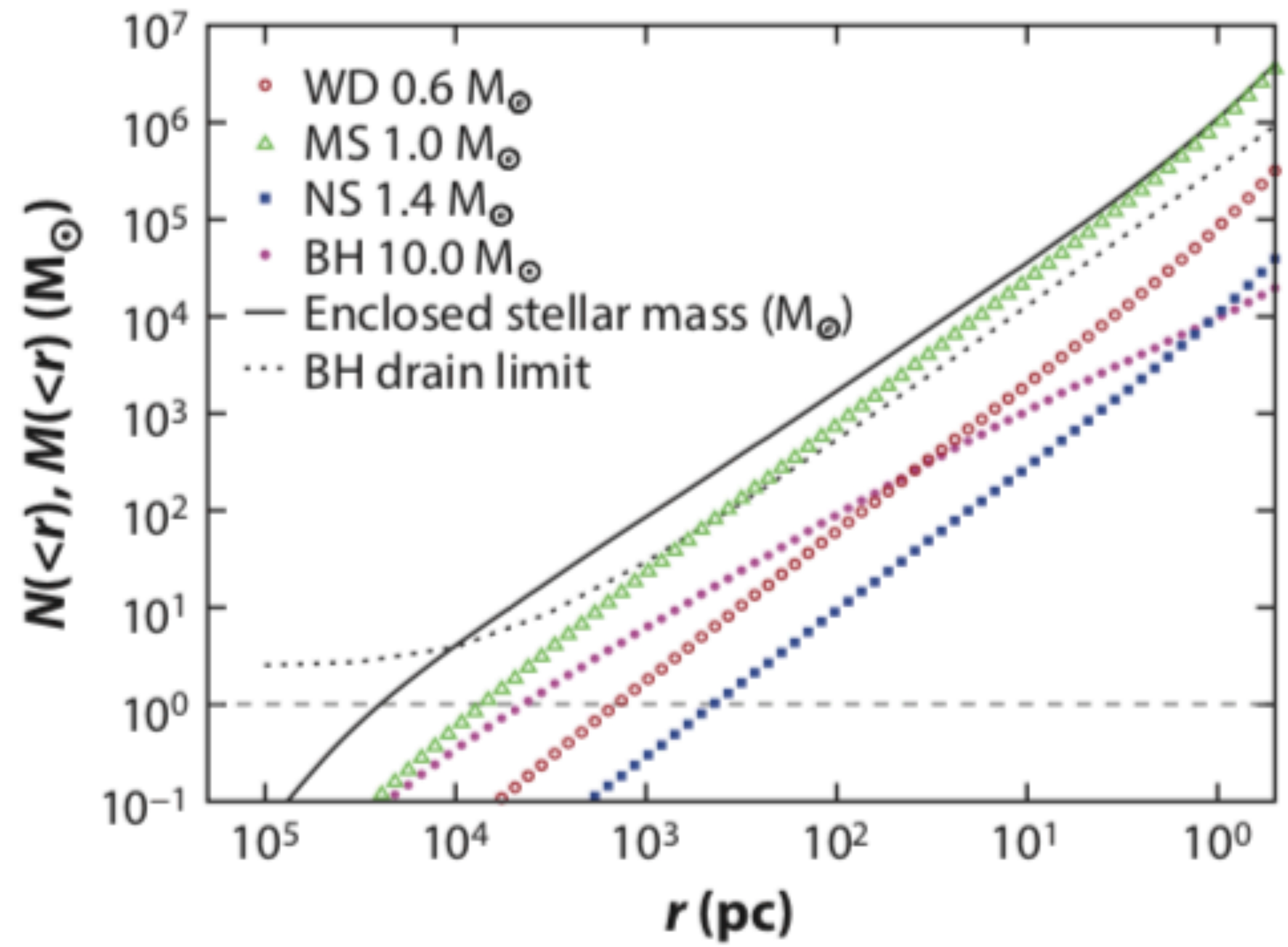
2. Massive star formation may take place frequently at the GC

3. The initial mass function (IMF) at the GC favours high-mass stars (at least in most recent event)

4. Several 1000s of stellar BHs expected to be present near Sgr A*

A cusp of stellar mass BHs





T. Alexander (2017)

A cusp of stellar mass BHs

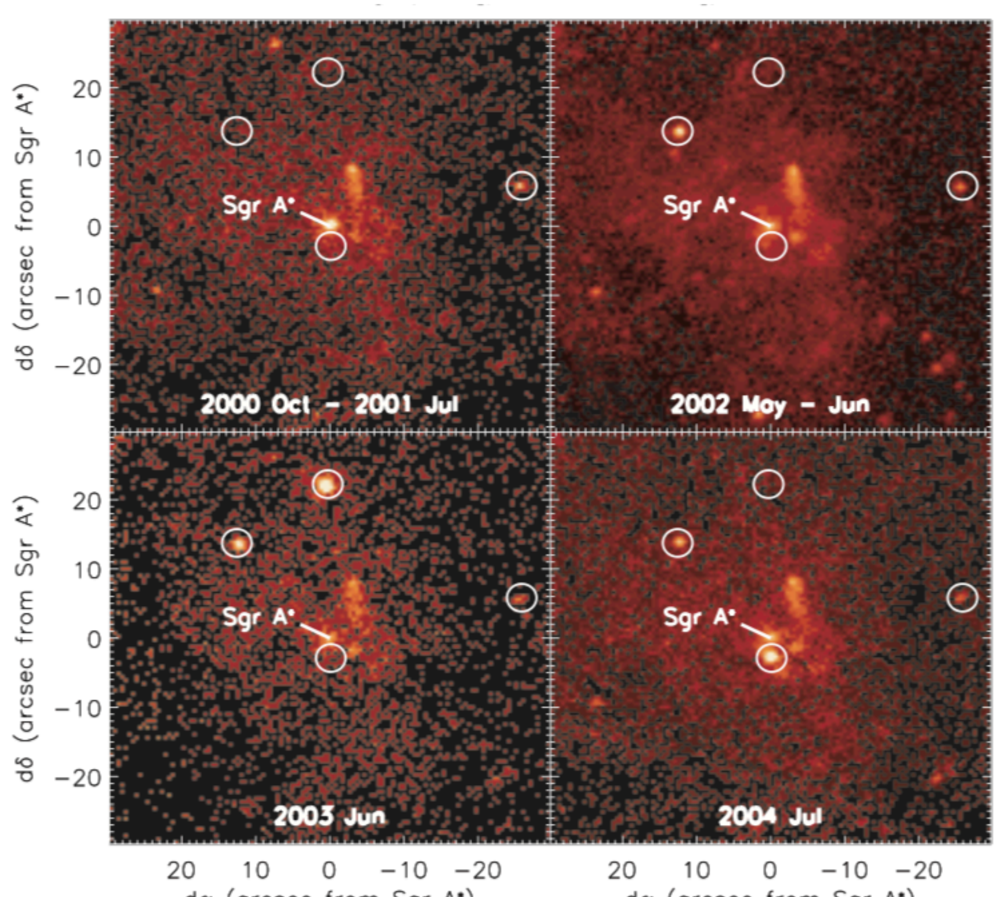
The Astrophysical Journal, 622:L113–L116, 2005 April 1

AN OVERABUNDANCE OF TRANSIENT X-RAY BINARIES WITHIN 1 PARSEC OF THE GALACTIC CENTER

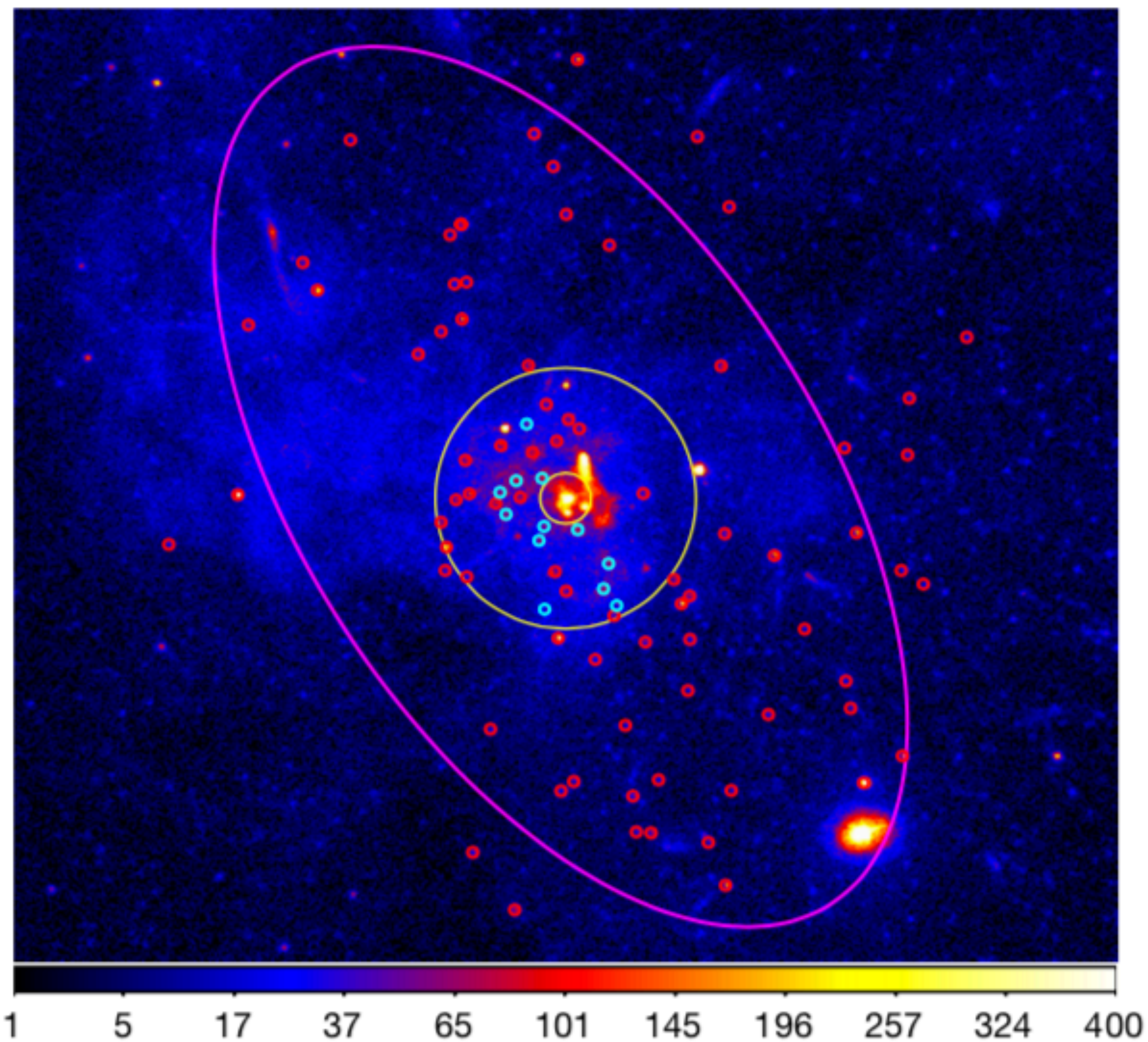
M. P. Muno,[1,2] E. Pfahl,[3] F. K. Baganoff,[4] W. N. Brandt,[5] A. Ghez,[1] J. Lu,[1] and M. R. Morris[1]
Received 2004 December 17; accepted 2005 February 17; published 2005 March 11

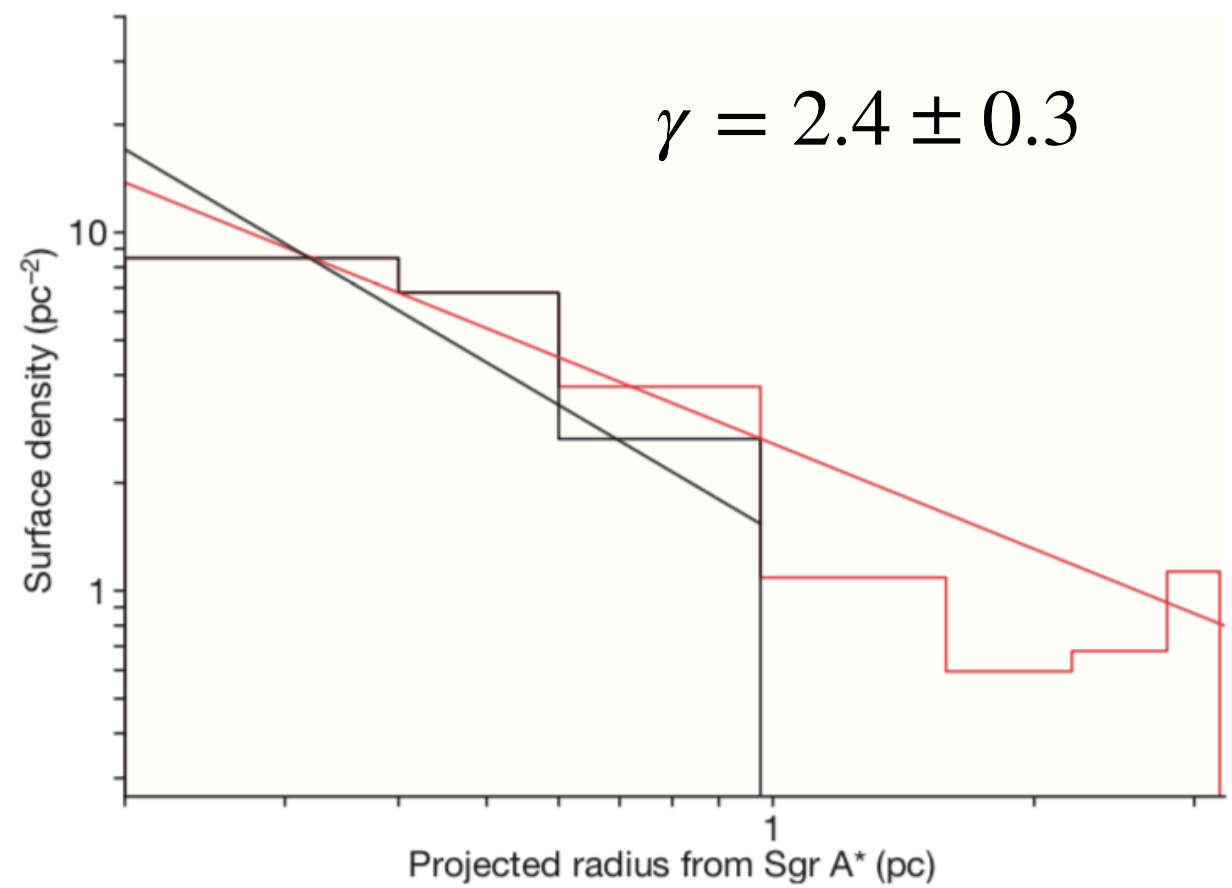
ABSTRACT

During 5 years of *Chandra* observations, we have identified seven X-ray transients located within 23 pc of Sgr A*. These sources each vary in luminosity by more than a factor of 10 and have peak X-ray luminosities greater than 5×10^{33} ergs s^{-1}, which strongly suggests that they are accreting black holes or neutron stars. The



A cusp of stellar mass BHs





Hailey et al. (2018)

A cusp of stellar mass BHs

1.Several 100 BH XRBs in central pc

2. Implies existence of ~10,000 isolated BHs

3. < 200 rotationally powered millisecond pulsars at GC

4. XRBs can be formed by tidal capture of stars

Hailey et al. (2018), Generozov et al. (2018)

IMBHs in the GC?

1. Intermediate-mass BHs may form in stellar clusters
2. IMBHs may be seeds of MBHs
3. Will sink to the GC due to dynamical friction

Two claims for IMBHs in GC environment:

1. Maillard et al. (2004): IMBH in IRS 13E, 0.13pc from Sgr A*
2. Oka et al. (2016, 2017): IMBH in molecular cloud at ~60 pc from Sgr A*

However, see counterarguments in Schödel et al. (2005), Fritz et al. (2010), Tanaka (2018): **No smoking gun!**

Extraordinary claim requires extraordinary evidence.

6. GW events from GC-like nuclei

EMRIs

Existence of relaxed stellar cusp is pre-requisite to have a sufficiently high density of BHs (neutron stars) near the MBH.

Recent work (Gallego-Cano et al., Schödel et al., Baumgardt et al. 2018; Schödel et al. in prep) gives high confidence in existence of such a Bahcal-Wolf cusp at the GC and (by Kopernican principle) at the nuclei of other galaxies.

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EMRI rate

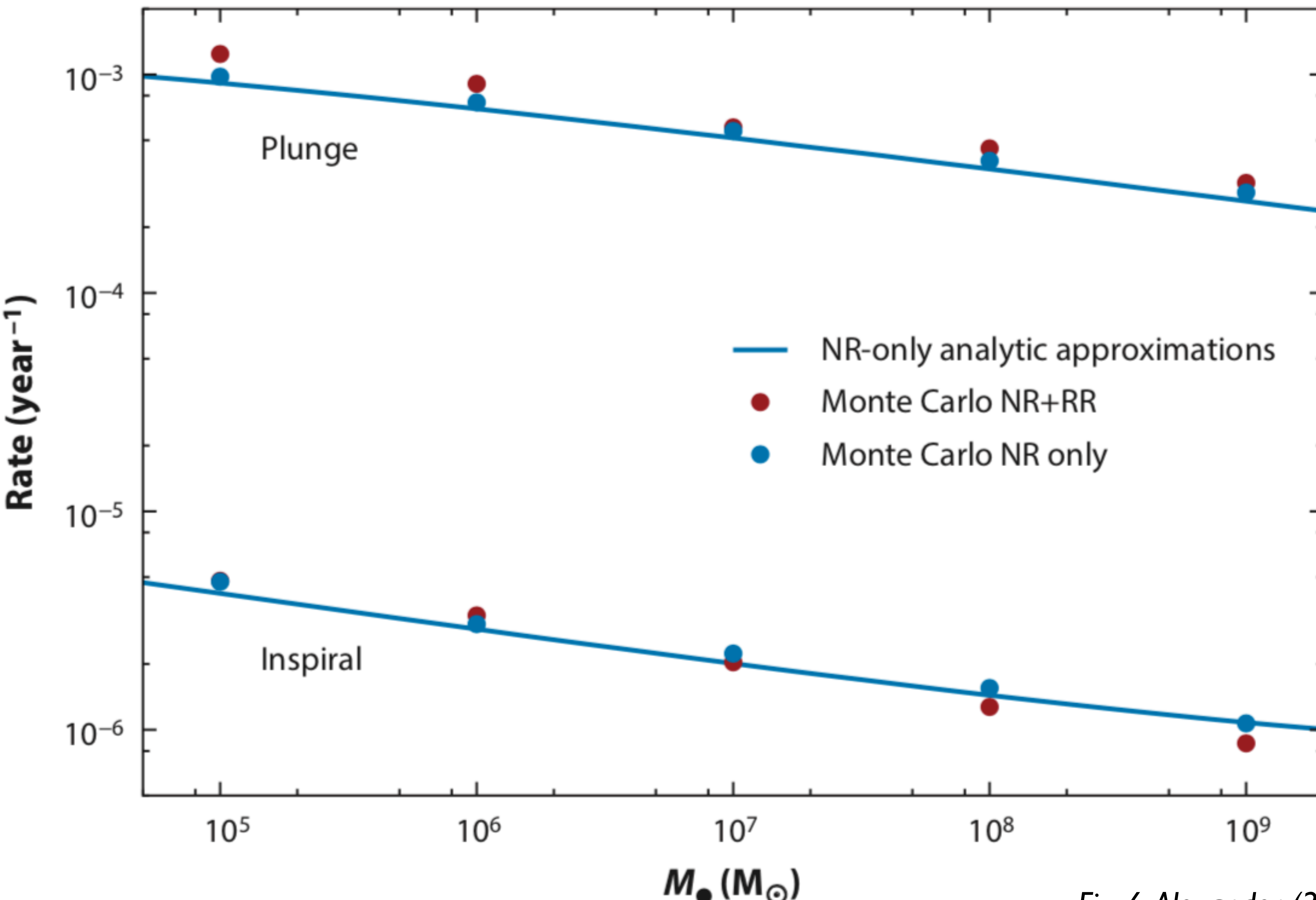

Fig. 6, Alexander (2017)

Mergers of binary BHs

Probably high density of stellar BHs near Sgr A*.

Not clear how many binary BHs.

Repeated massive star formation near Sgr A* may replenish binary BH population.

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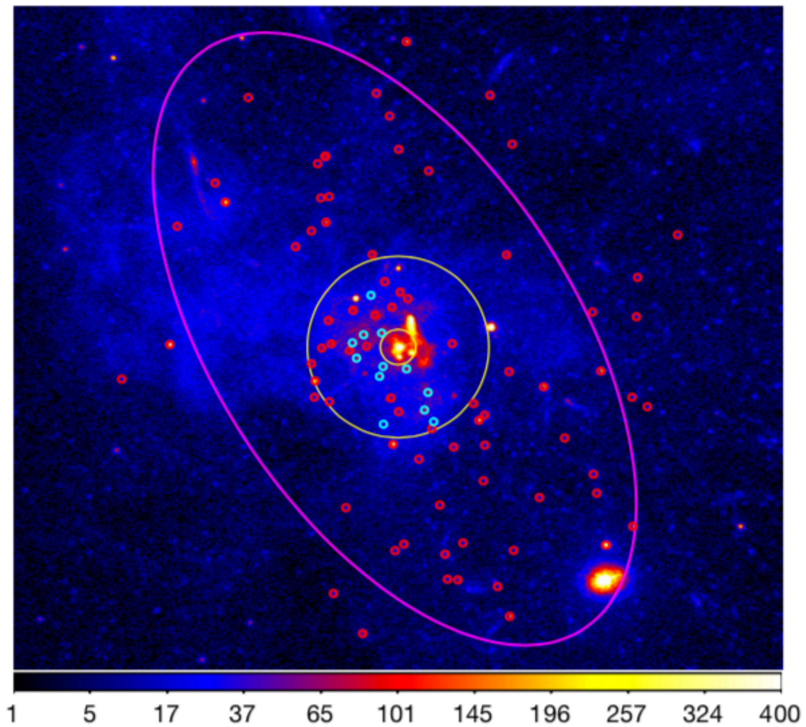
Repeated massive star formation near Sgr A* may replenish binary BH population.

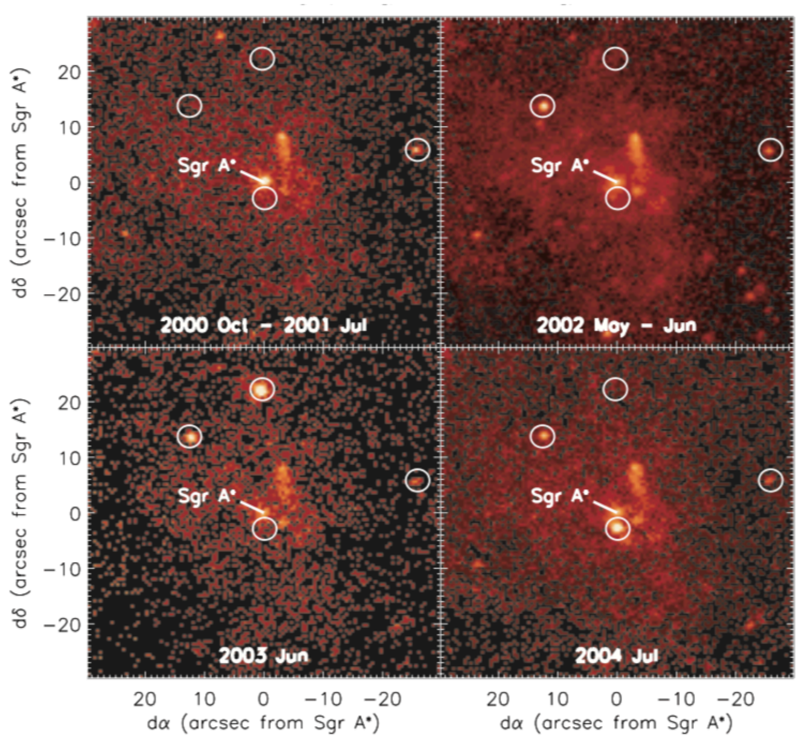
Great uncertainty. GW observations needed!

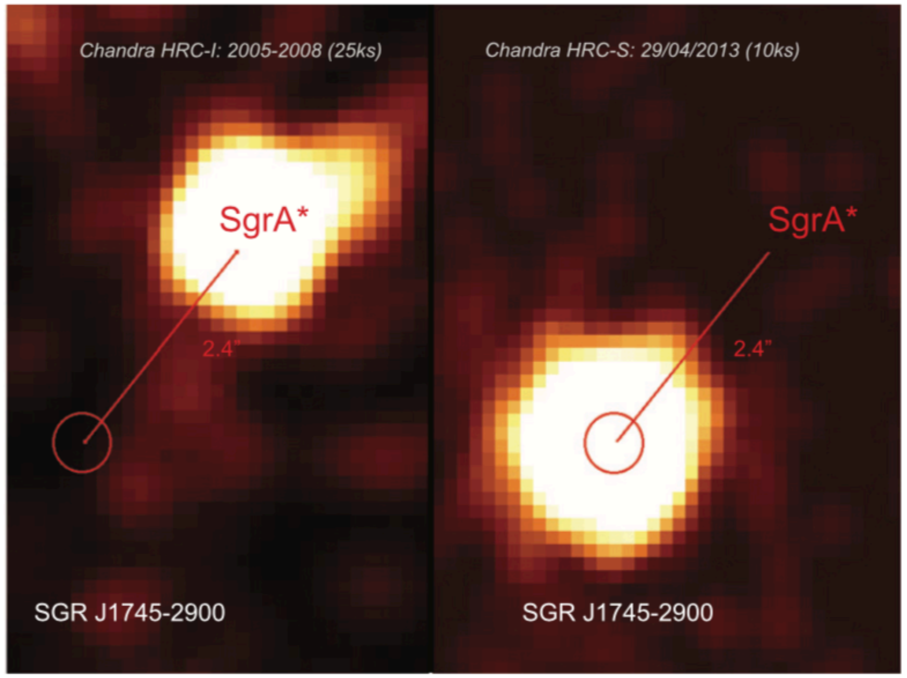
Mergers of binary NSs

Not clear how many binary NSs. Higher birth kick velocity and lower mass may lead to less NS-NS binaries.

LMXRBs near SgrA* indicate existence of NSs, so does the magnetar near the GC (Rea et al. 2013).







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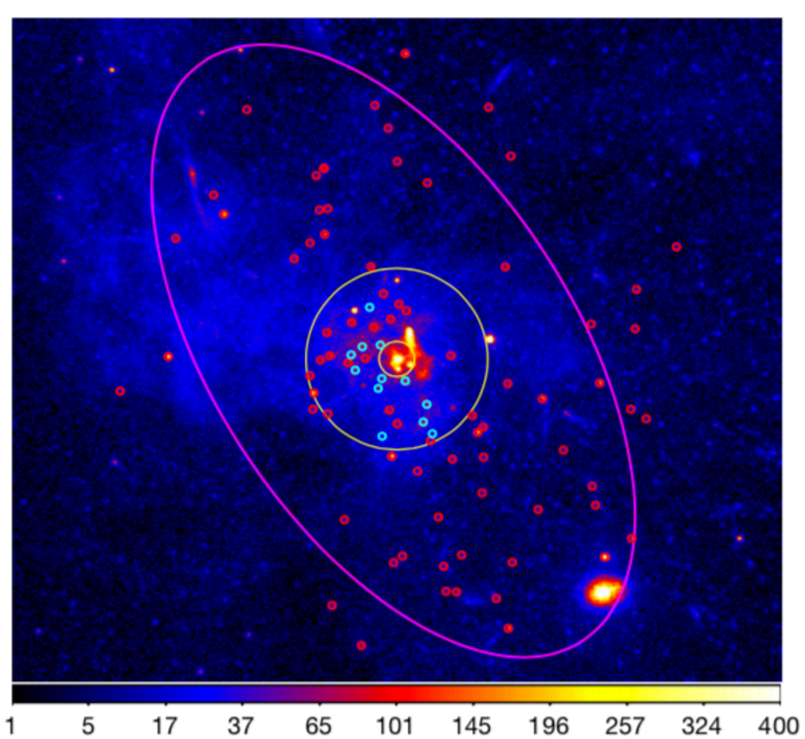

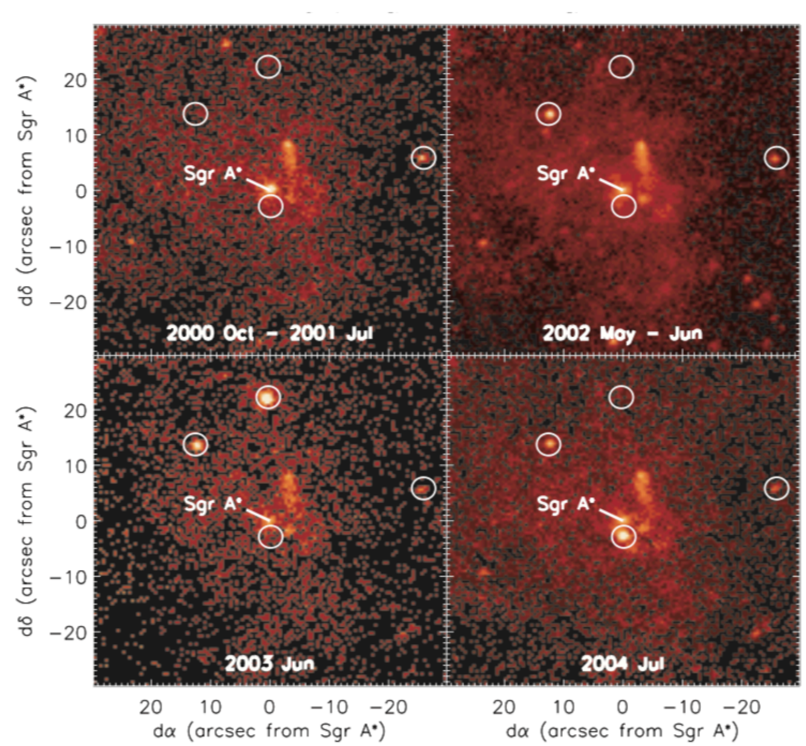

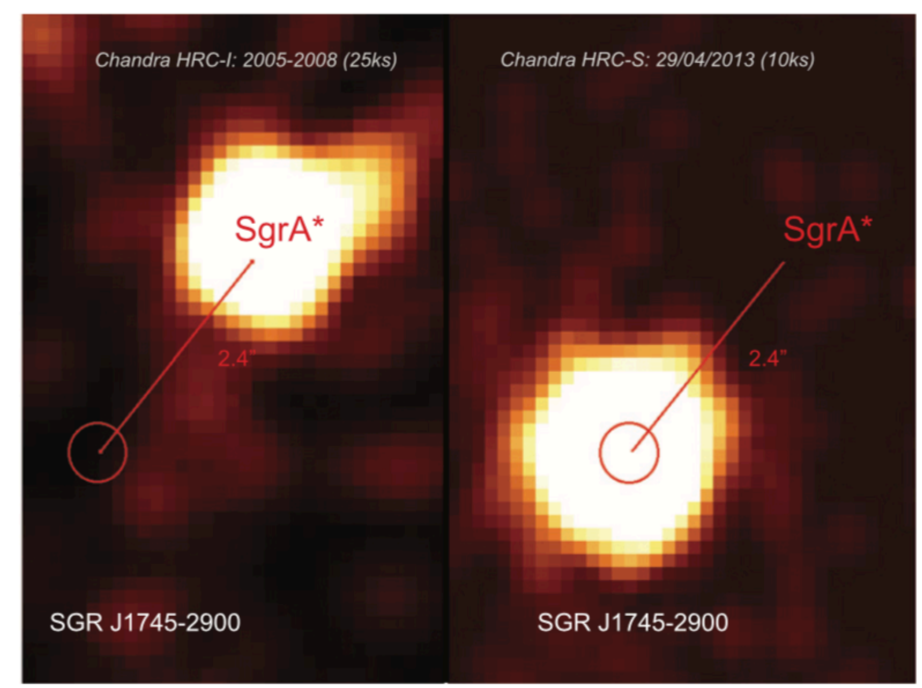

e.g. Muno et al. (2005), Rea et al. (2013), Hailey et al. (2018)


Thank you!