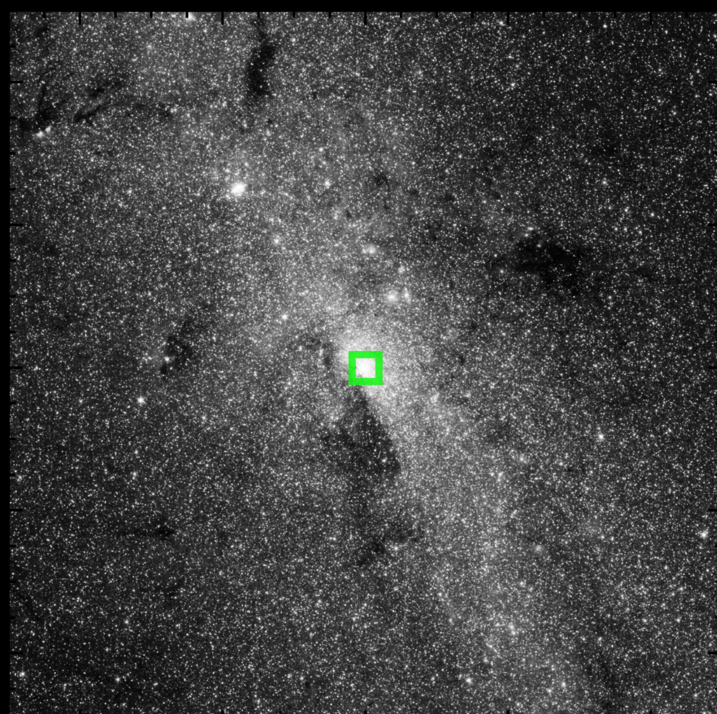
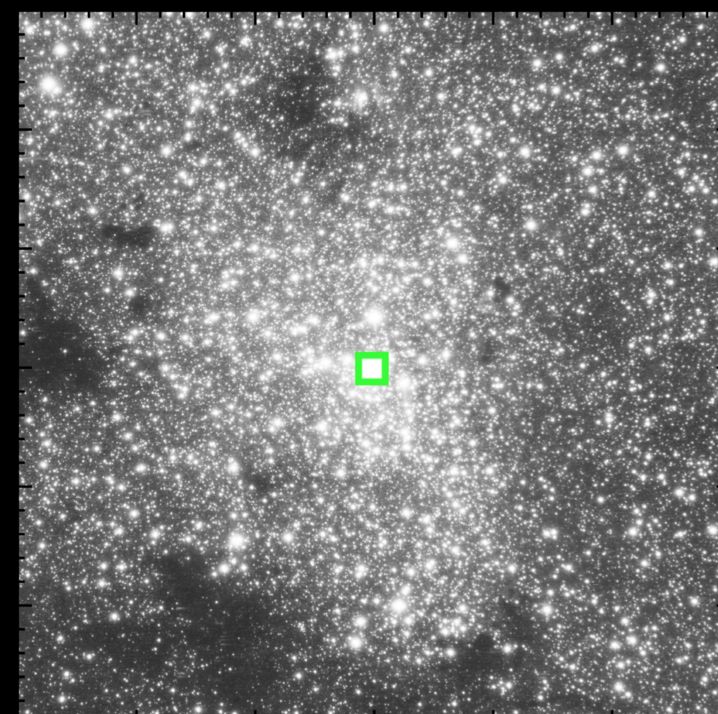
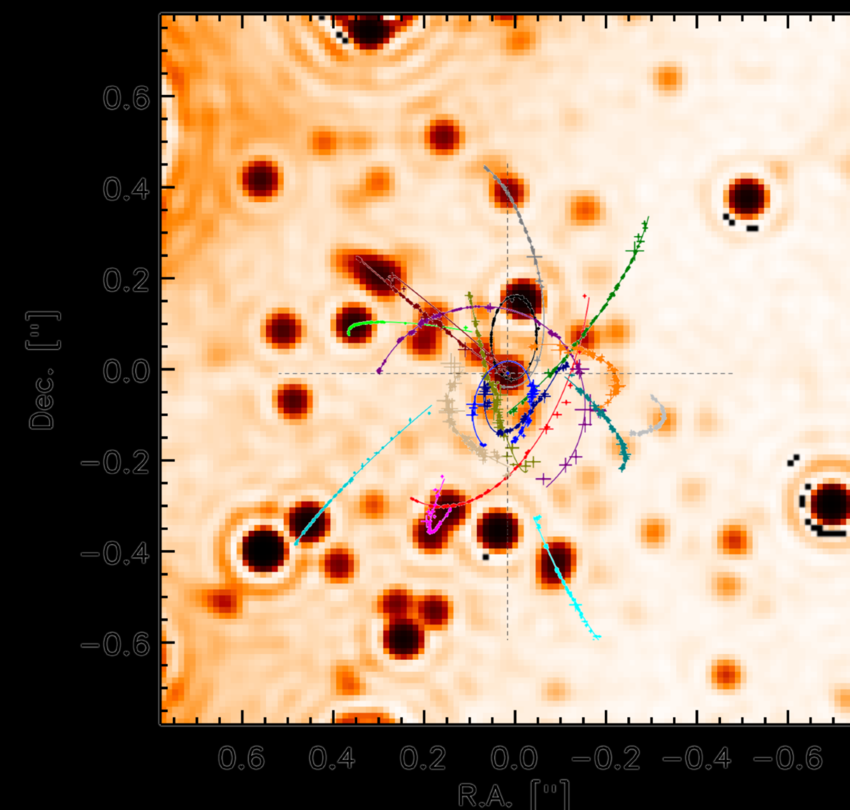
The Stellar Cusp around the Milky Way’s MBH

in memoriam Tal Alexander







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Rainer Schödel - IAA(CSIC)

MODEST - 18
Firá, Santorini, 29 June 2018

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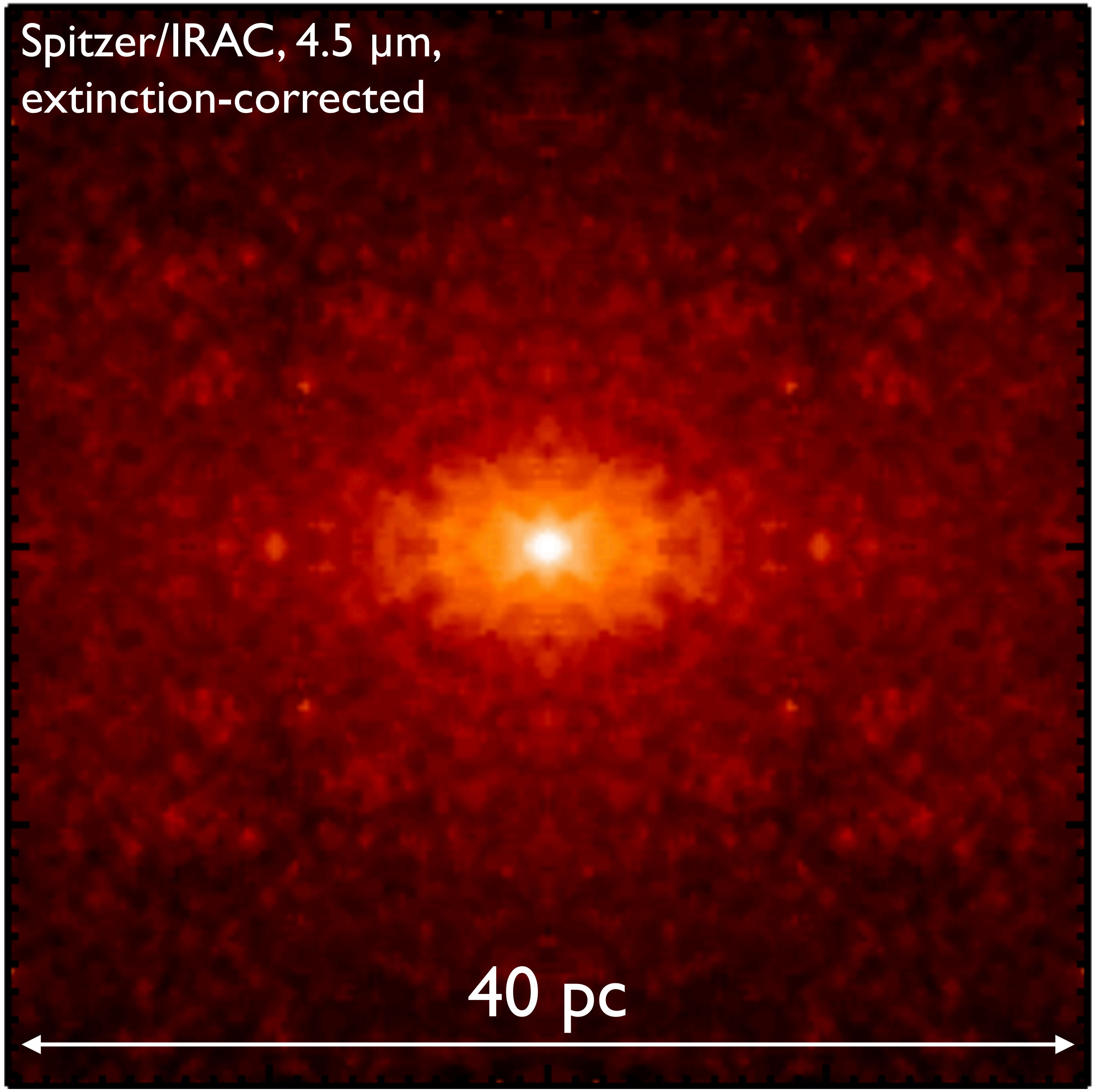
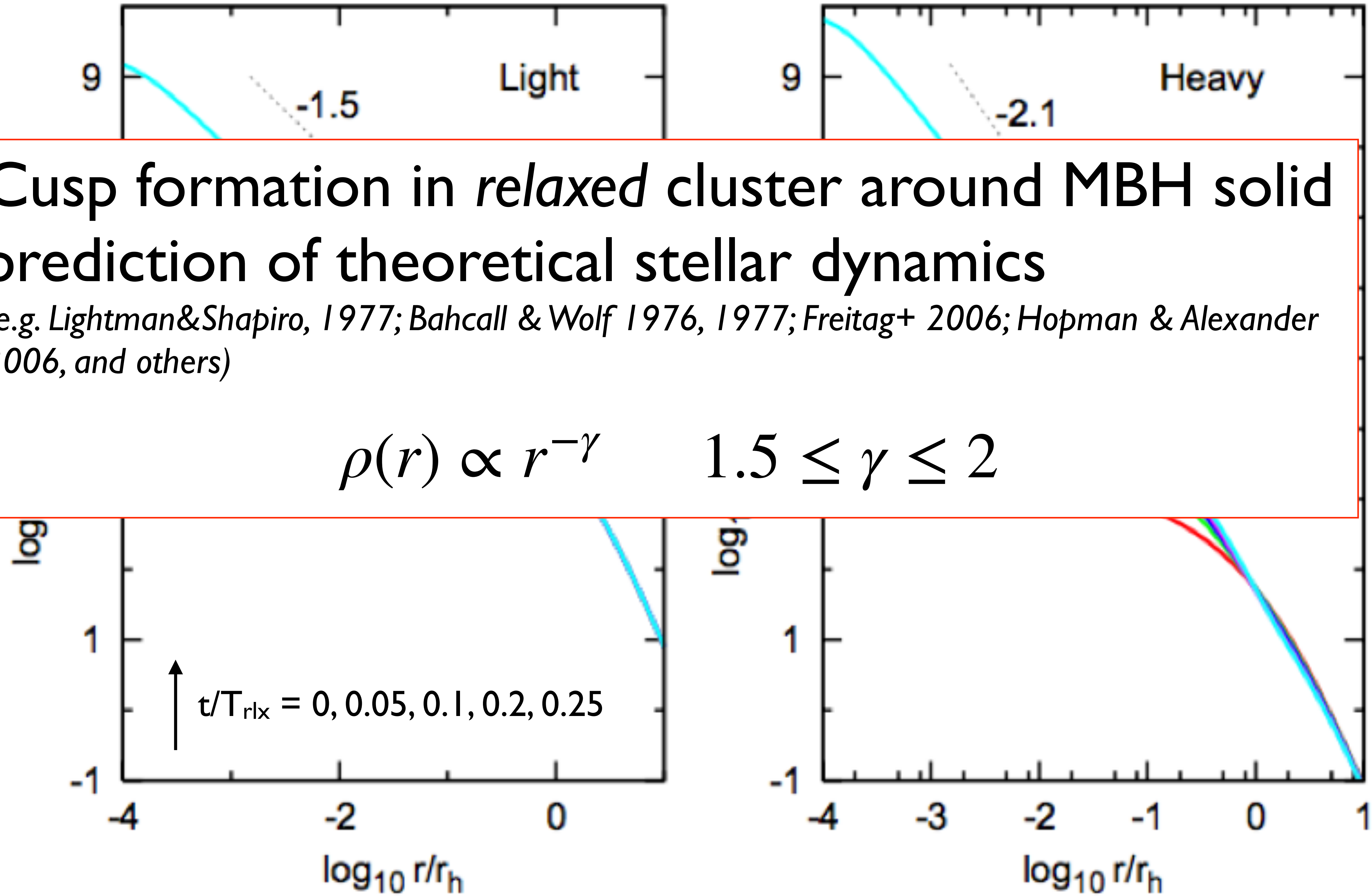
The Milky Way's Nuclear Star Cluster



- 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.)

Formation of a stellar cusp

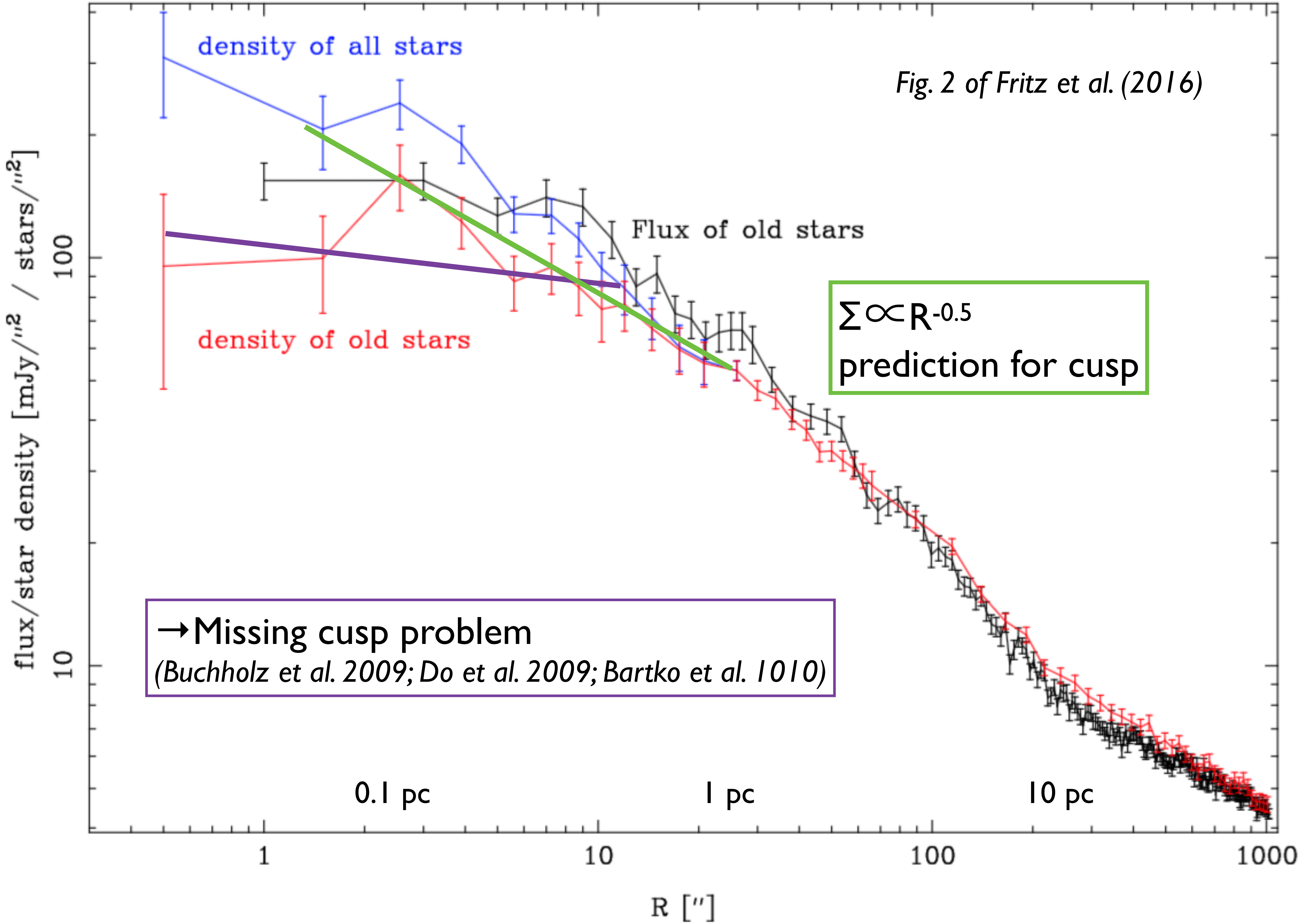


Cusp formation in *relaxed* cluster around MBH solid prediction of theoretical stellar dynamics

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

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

Preto & Amaro-Seoane (2010)


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 [″]

The missing cusp problem

Deficit of giants around Sgr A* (K<15.5).

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

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

Representative only for (bright) giants: **"hidden" cusp**

Not yet formed

(e.g., Merritt et al. 2010)

Destroyed

(e.g., Merritt & Szell 2006)

How can data analysis be improved?

nts' envelopes destroyed

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

Observational difficulties

<u>Observational difficulties</u>

1. Extreme and highly variable extinction and crowding

2. NSC is not isolated

3. Complex stellar population/star formation history


We only see the tip of the iceberg.

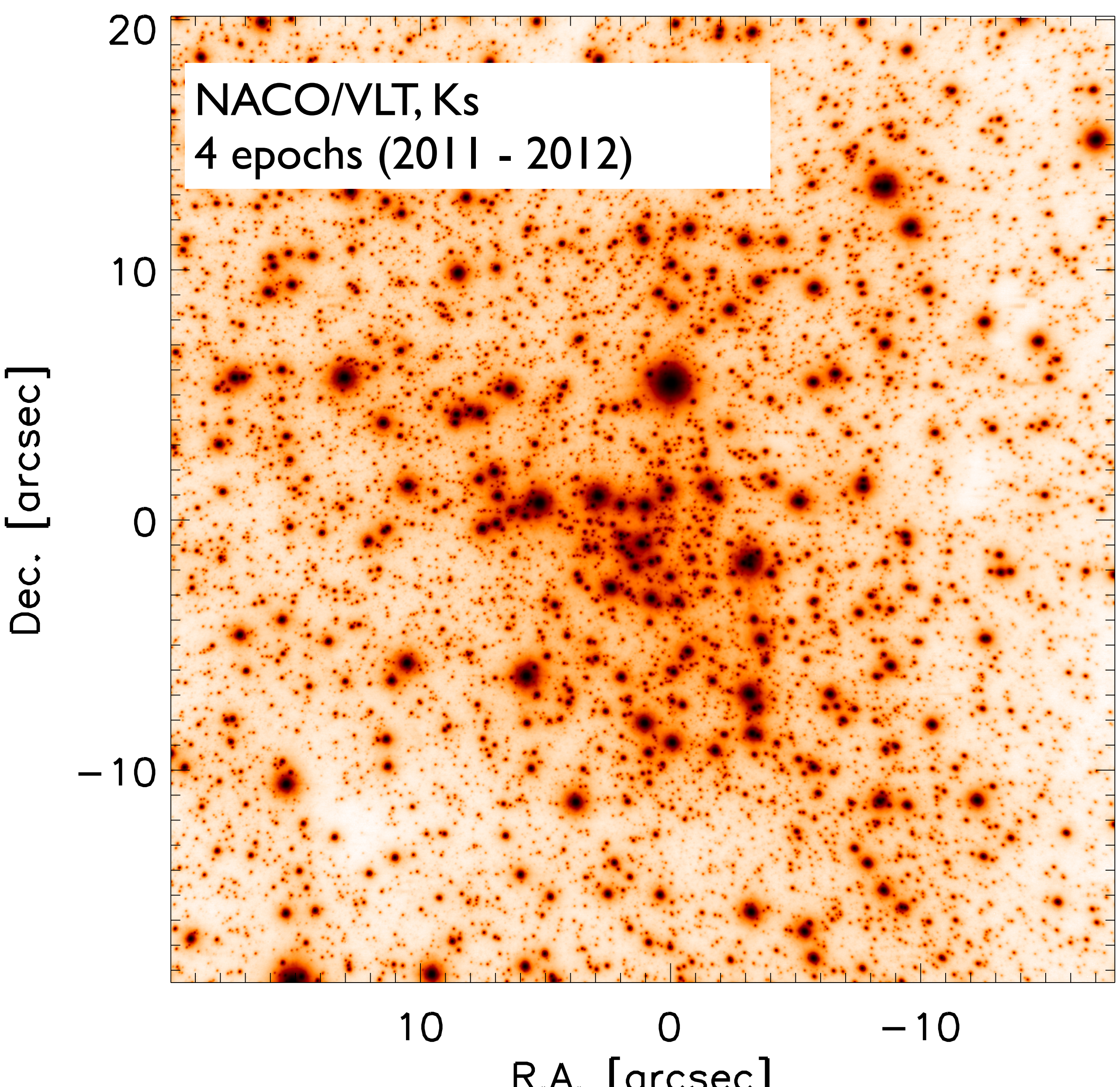
The problem of surveying our own galaxy may be likened to the problem of drawing a map of New York City on the basis of observations made from the intersection of 125th Street and Park Avenue. Although it would be clear to an observer at this spot that the city is a big one, any statement as to its extent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

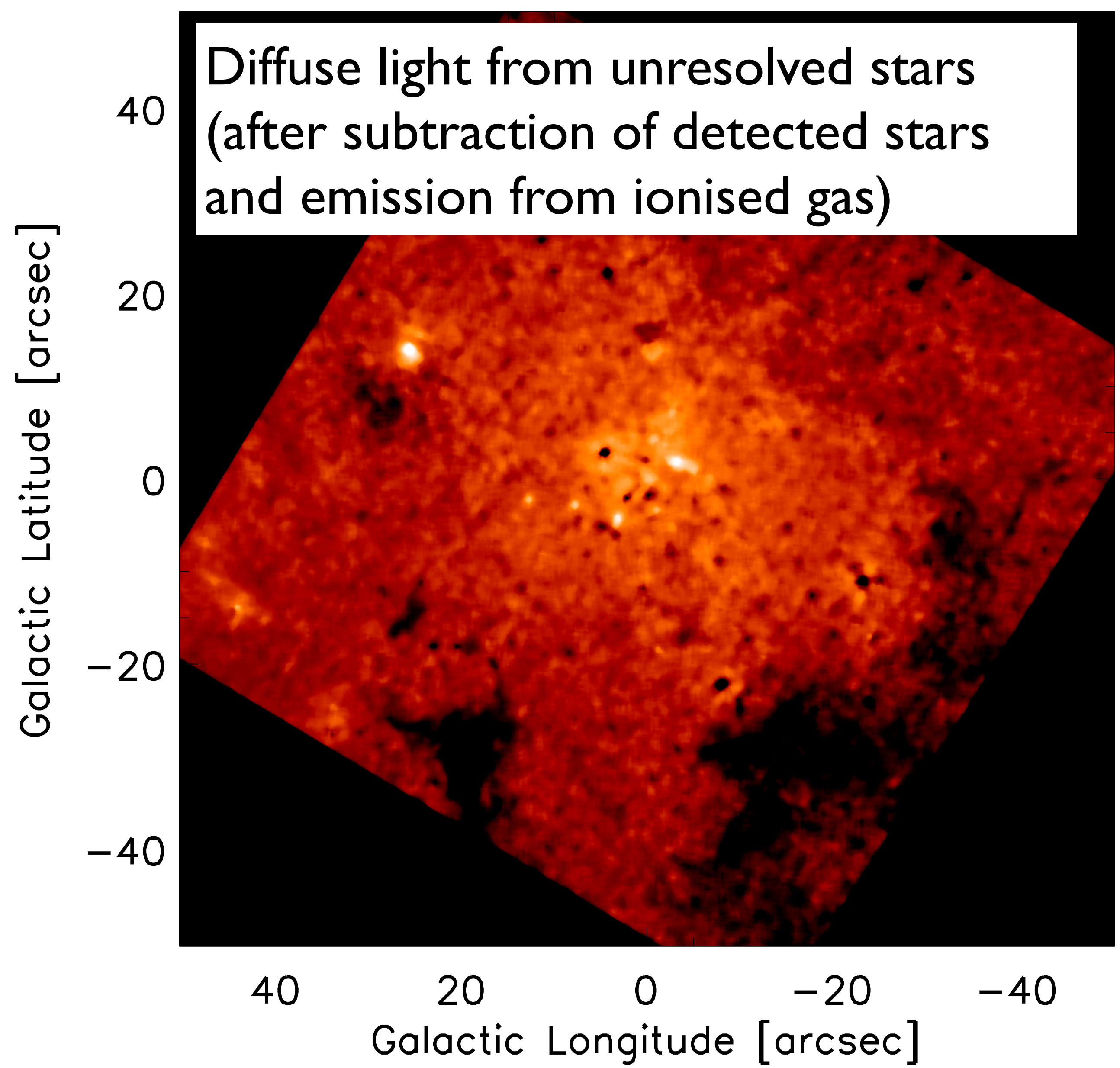
C. H. Payne-Gaposchkin

Digging deeper…

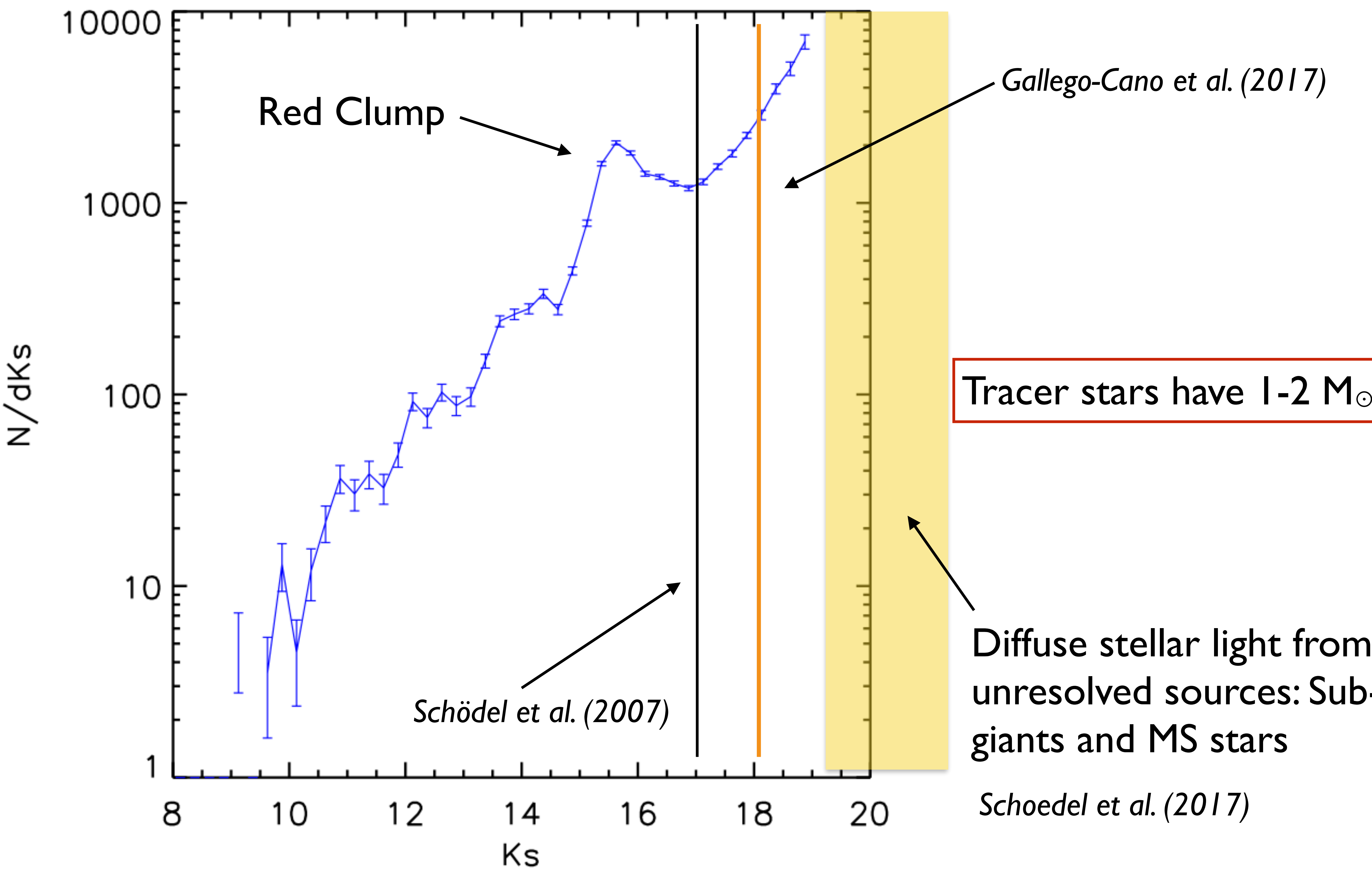
1. Deep star counts
- Stack data
- Improved reduction (rebinning)
- Improved PSF fitting

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



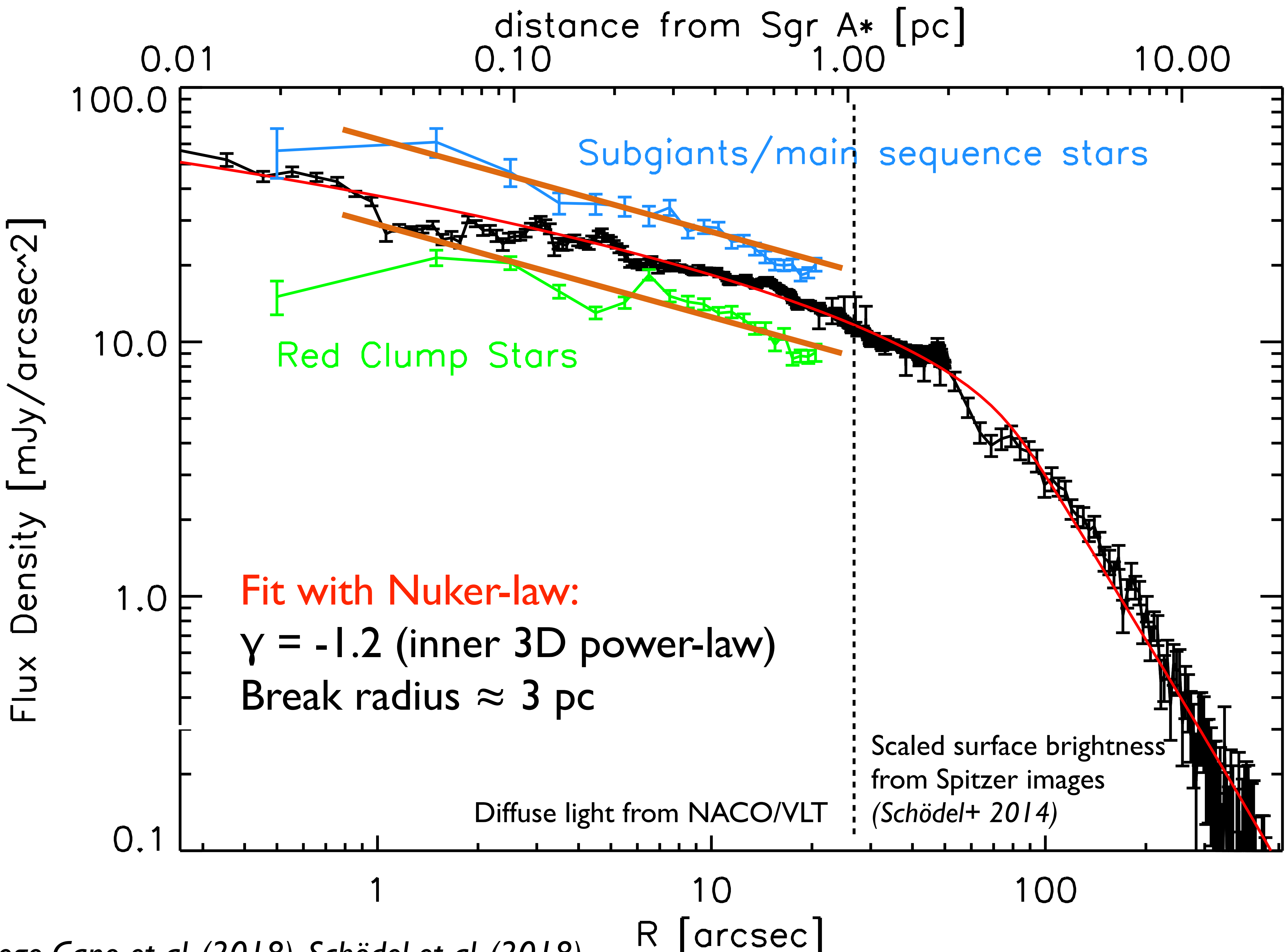


Luminosity function



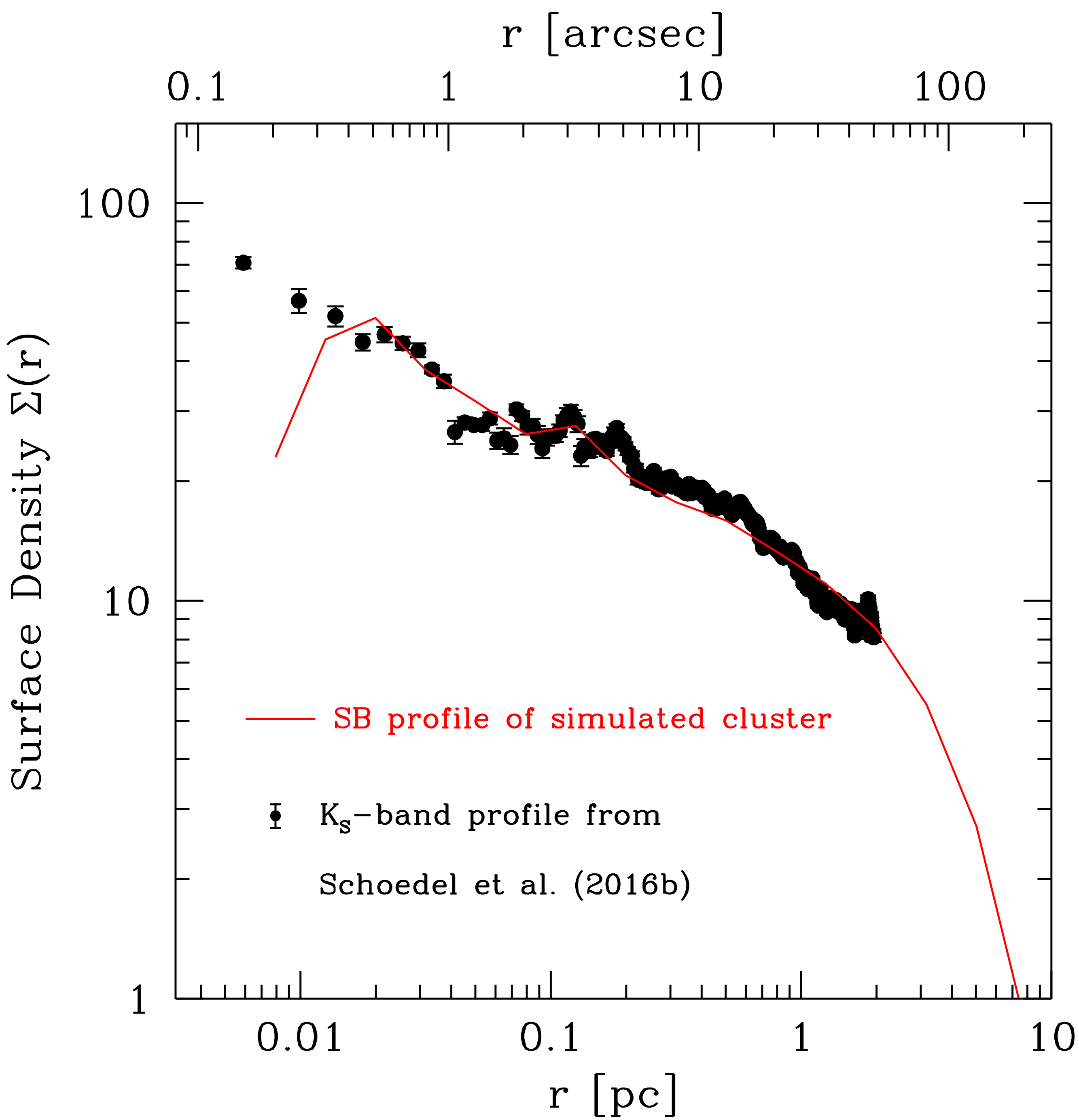
Schoedel et al. (2017)

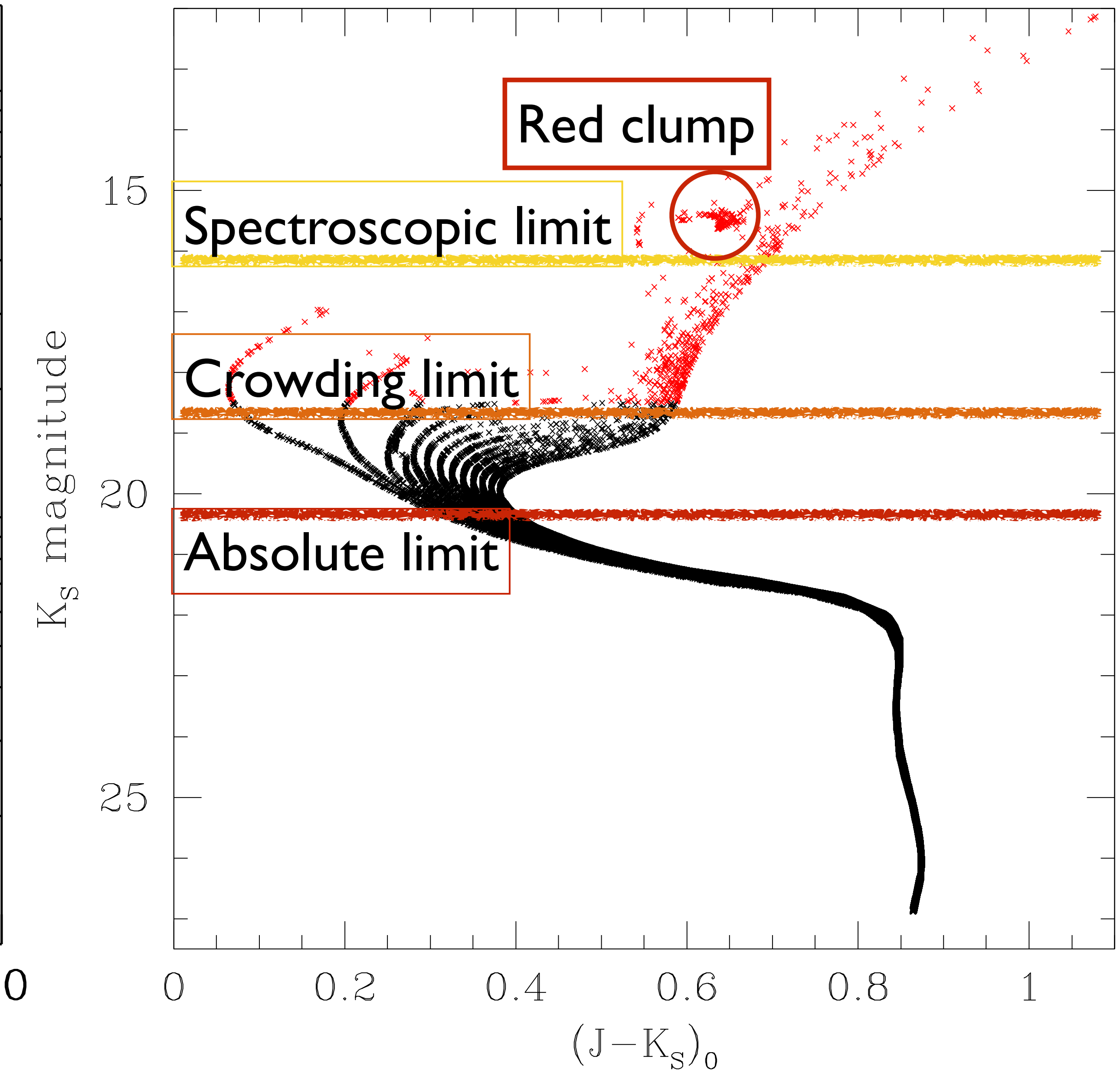
Surface density of stars at GC



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

Comparison with simulations





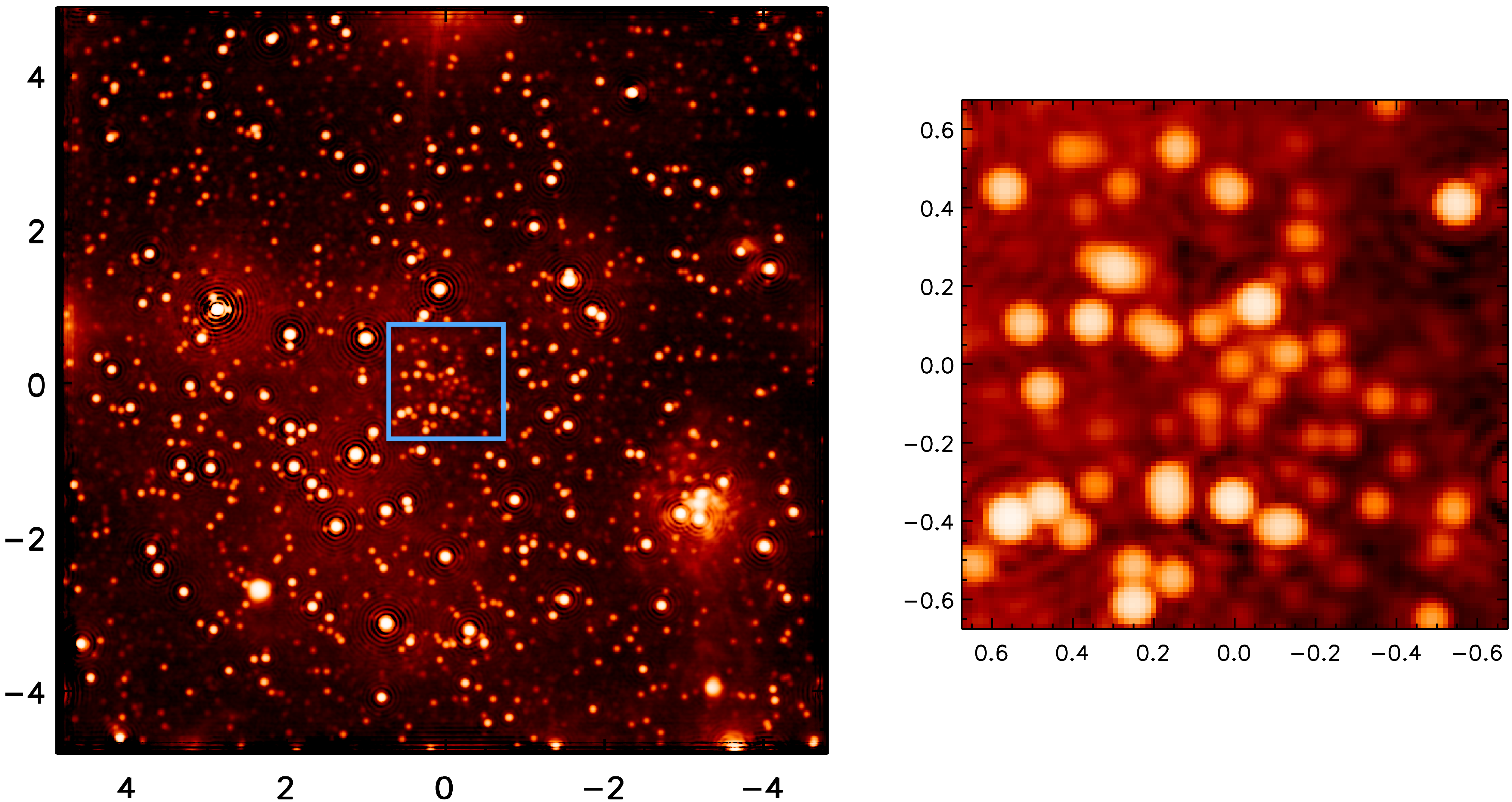
1. NBODY6
2. Repeated star formation
3. One Hubble time (not multiple t_{relax})

Baumgardt, Amaro-Seonae & Schödel (2018)

Agreement between observations and theory, finally!

… and deeper

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



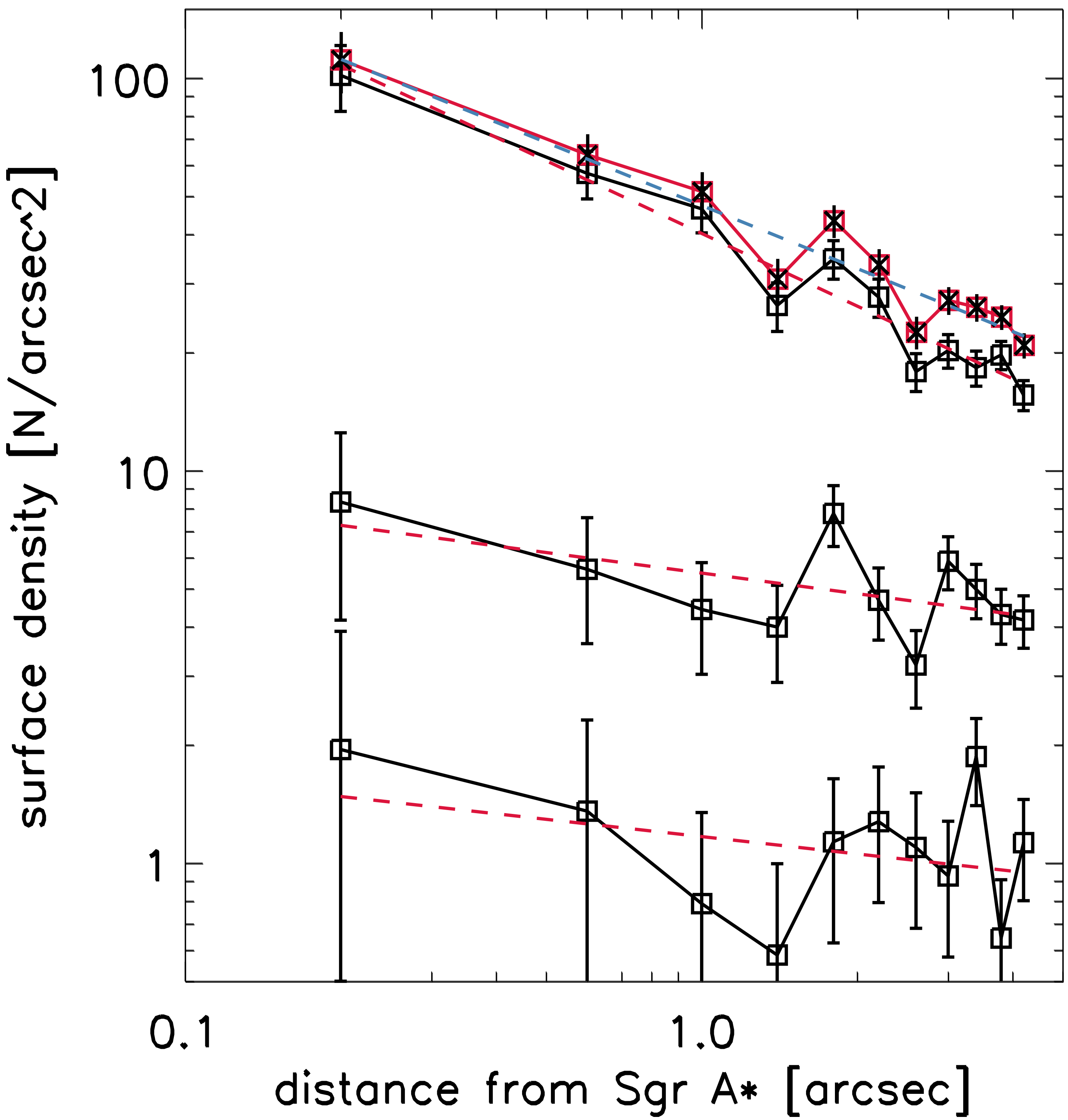
... and deeper

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

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

Caveat: Star
Formation History

There is a problem
with the giants!

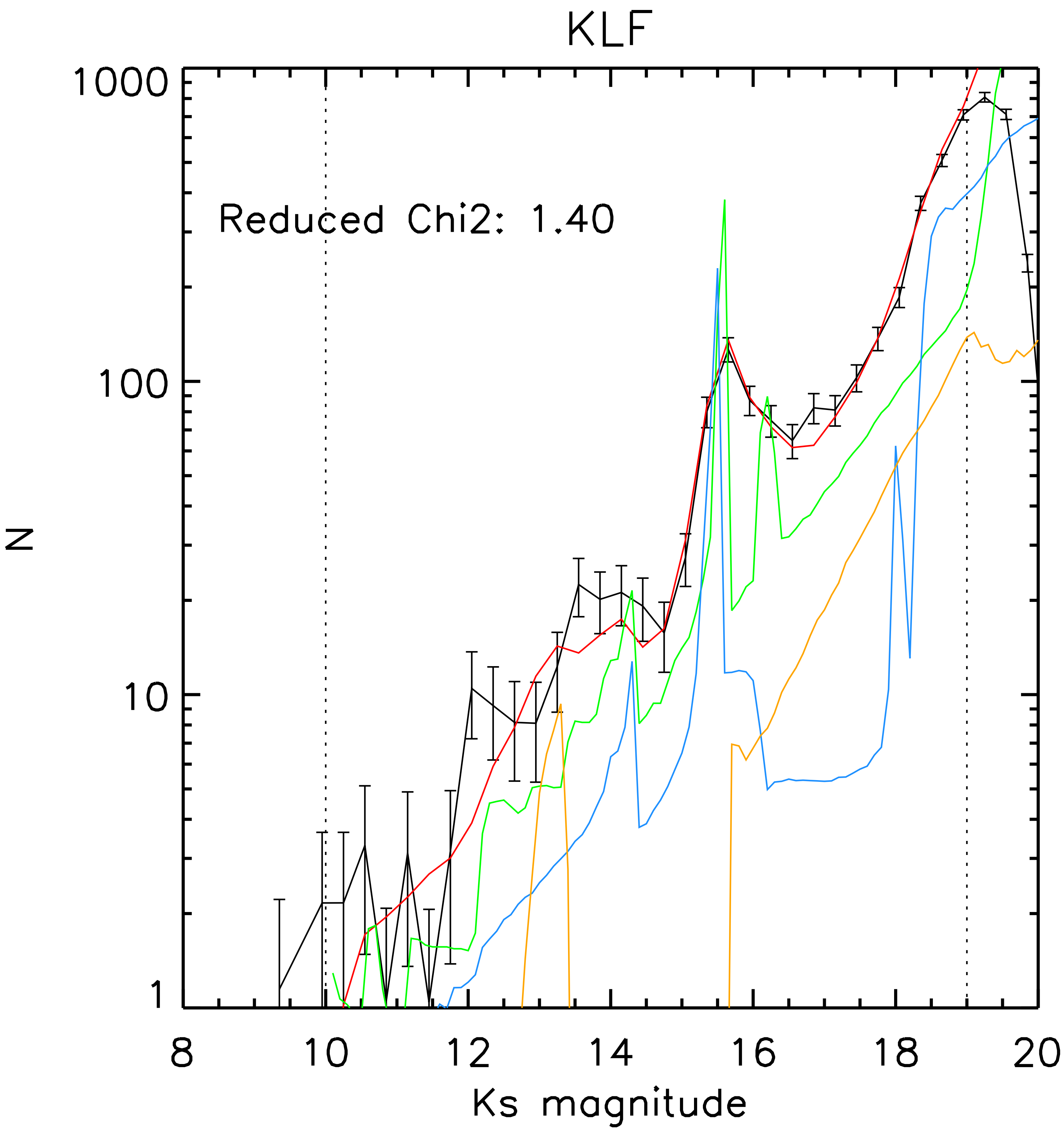


K_s = 16.5-19

K_s = 15-16.5

K_s = 10-14.5

Are the stars old enough?



11 Gyr

3 Gyr

0.2 Gyr

Amaro-Seoane & Preto (2011): Cusp (re-)growth time ~3 Gyr

Pfuhl et al. (2011): 80% of population older than 5 Gyr

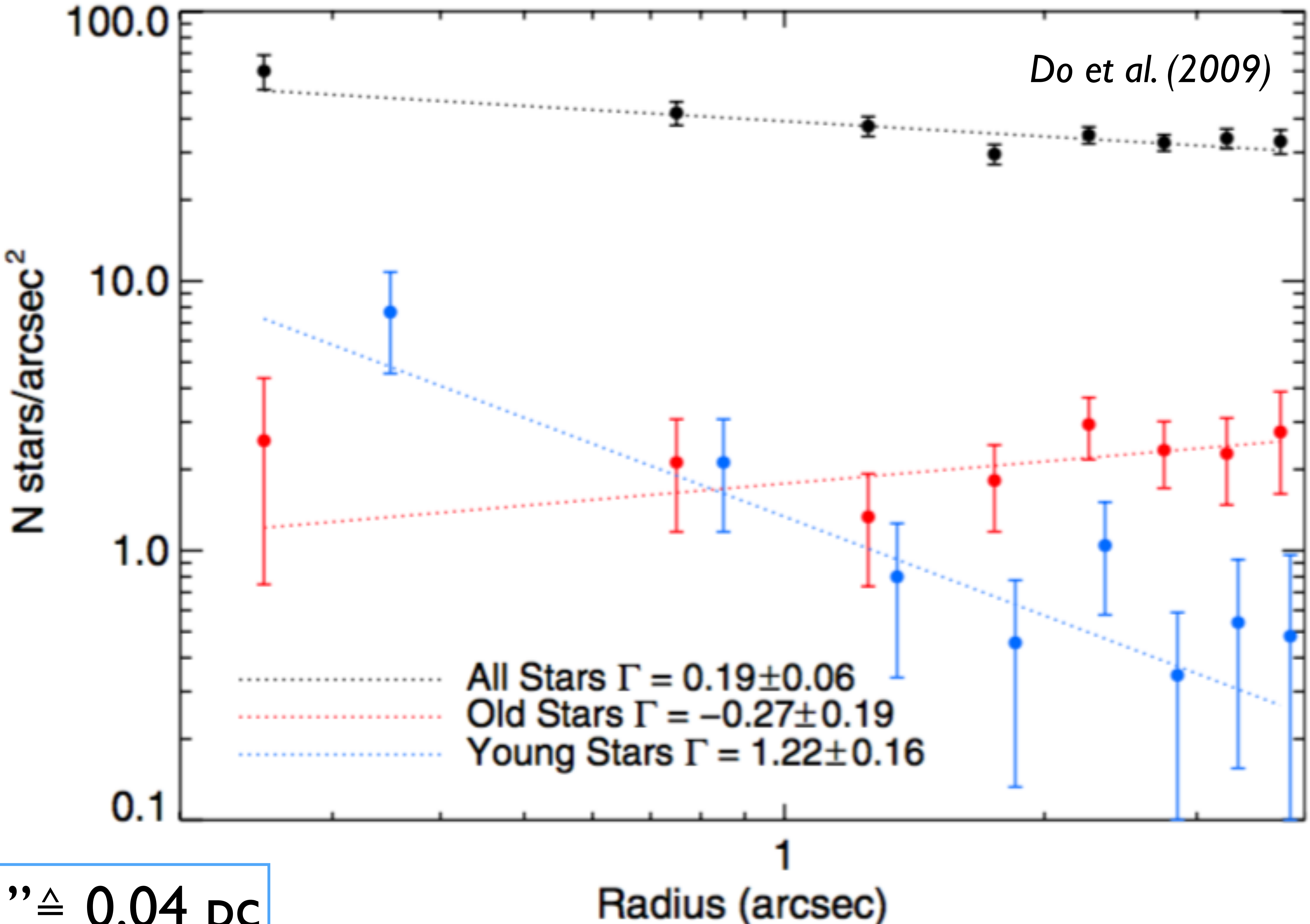
Conclusions

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 <0.08 pc (2")
6. Stellar density at 0.1 pc: ~$10^7\ M_\odot\ pc^{-3}$ possible sufficiently high to explain missing giants problem via star-cloud collisions *(Amaro-Seoane & Chen 2014)*

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

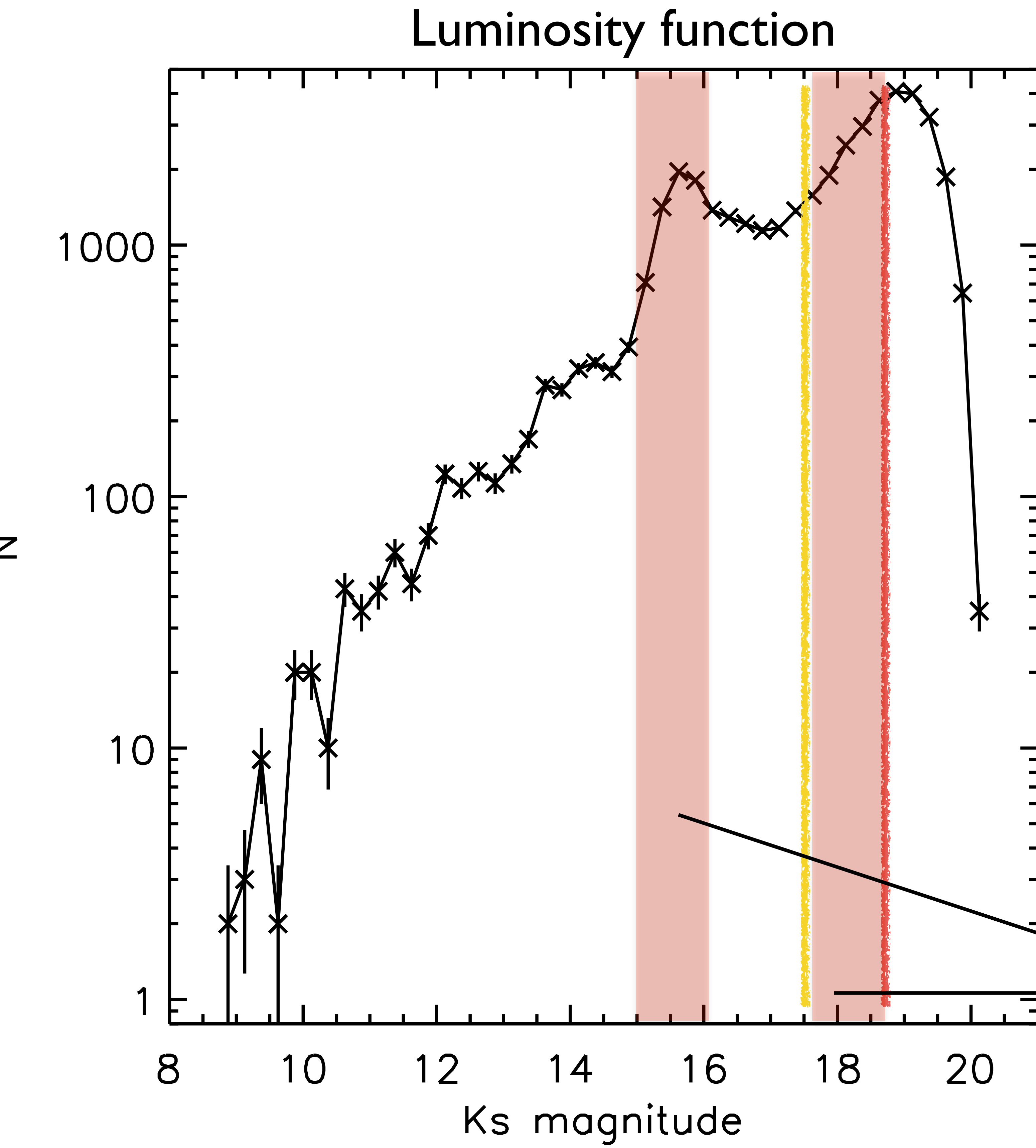
Thank you!

Stellar density in the GC



1'' ≙ 0.04 pc

1. Star counts

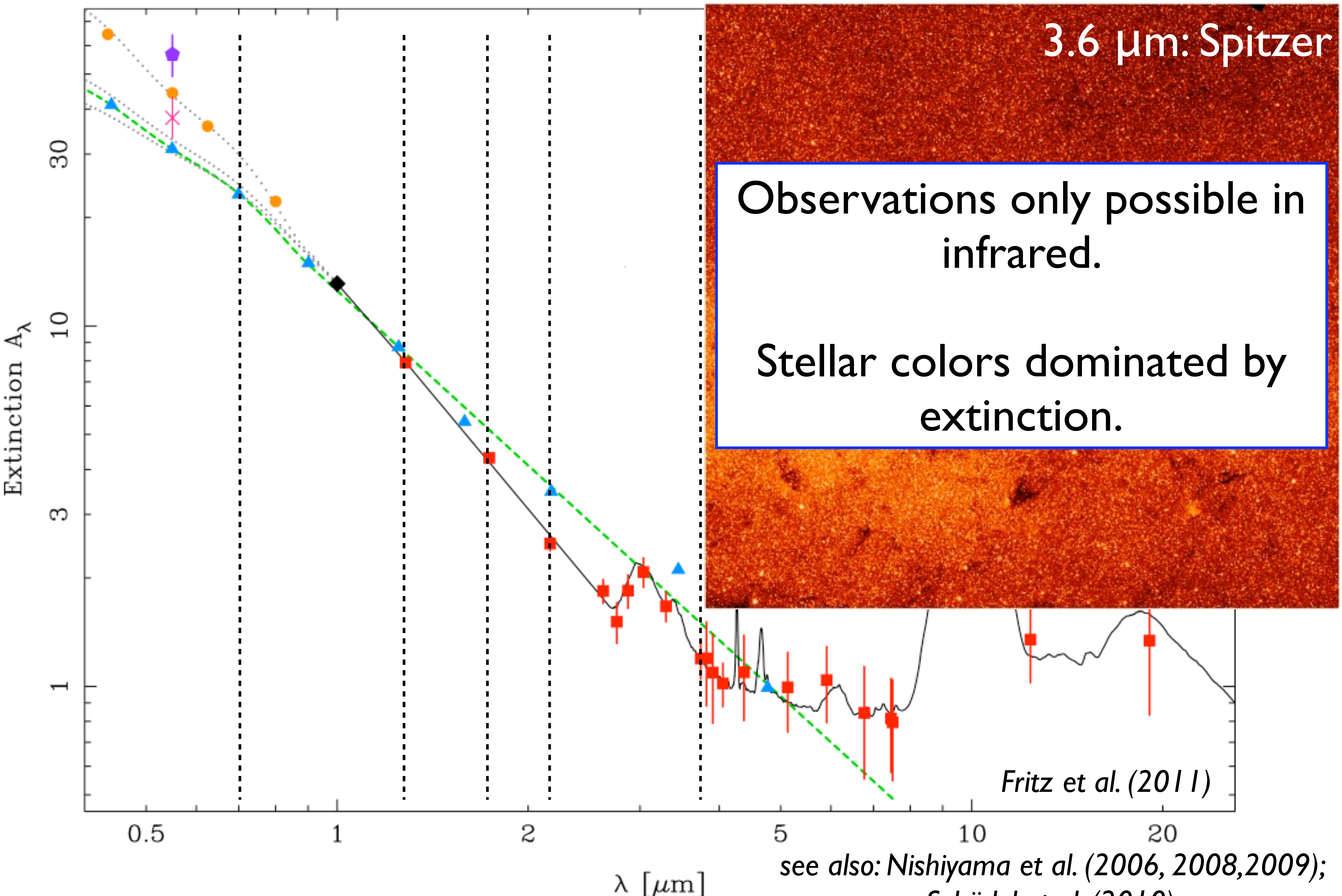


Old completeness limit for density studies
(Schödel et al. 2007)

New completeness limit from improved analysis of NACO/VLT data
(Gallego et al., in prep)

Similar masses, ages of a few Gyr

Interstellar Extinction



Observations only possible in infrared.

Stellar colors dominated by extinction.

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

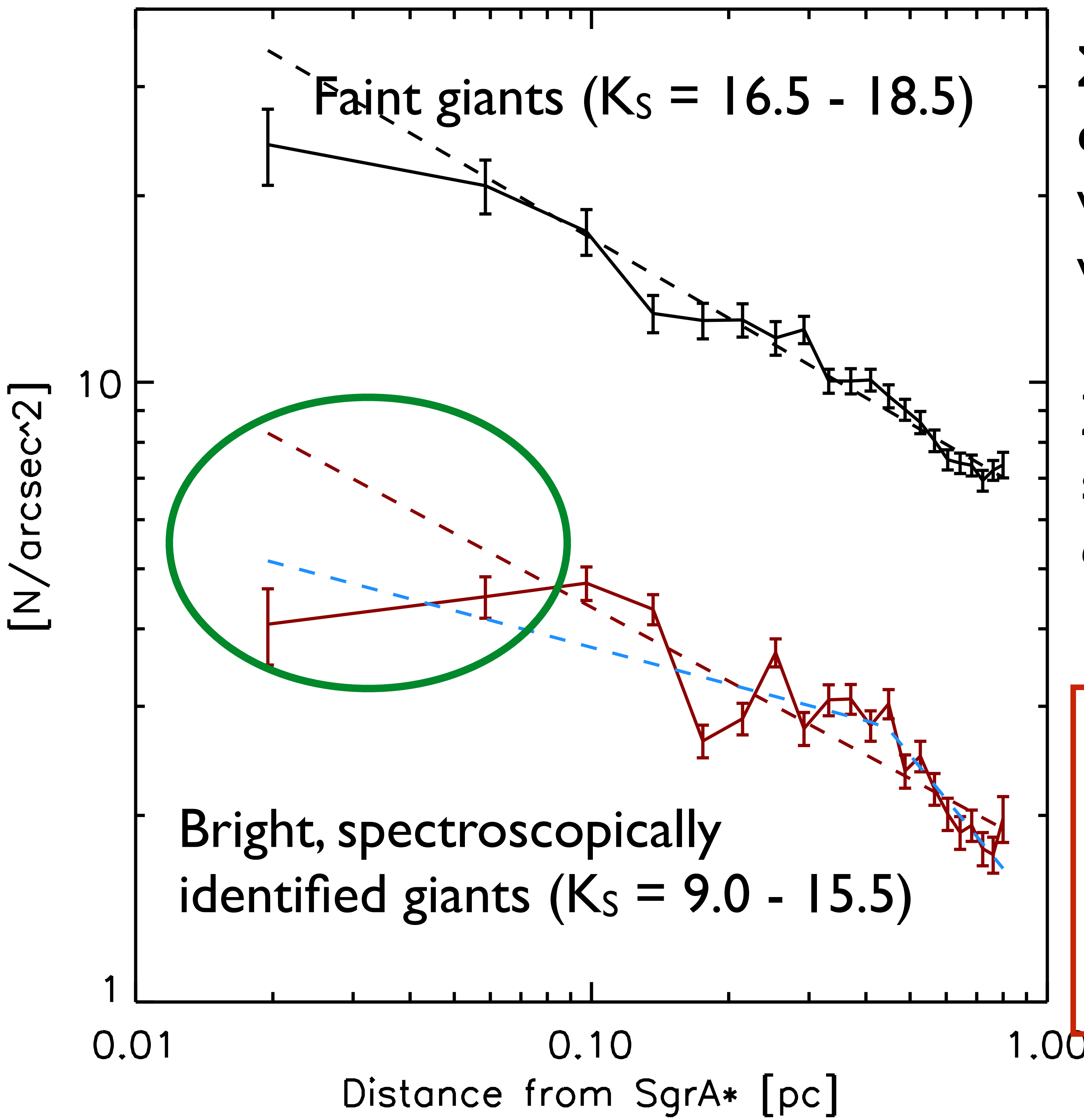
Why is this relevant?

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)*

3. What is the formation history of the NSC?

Missing cusp problem

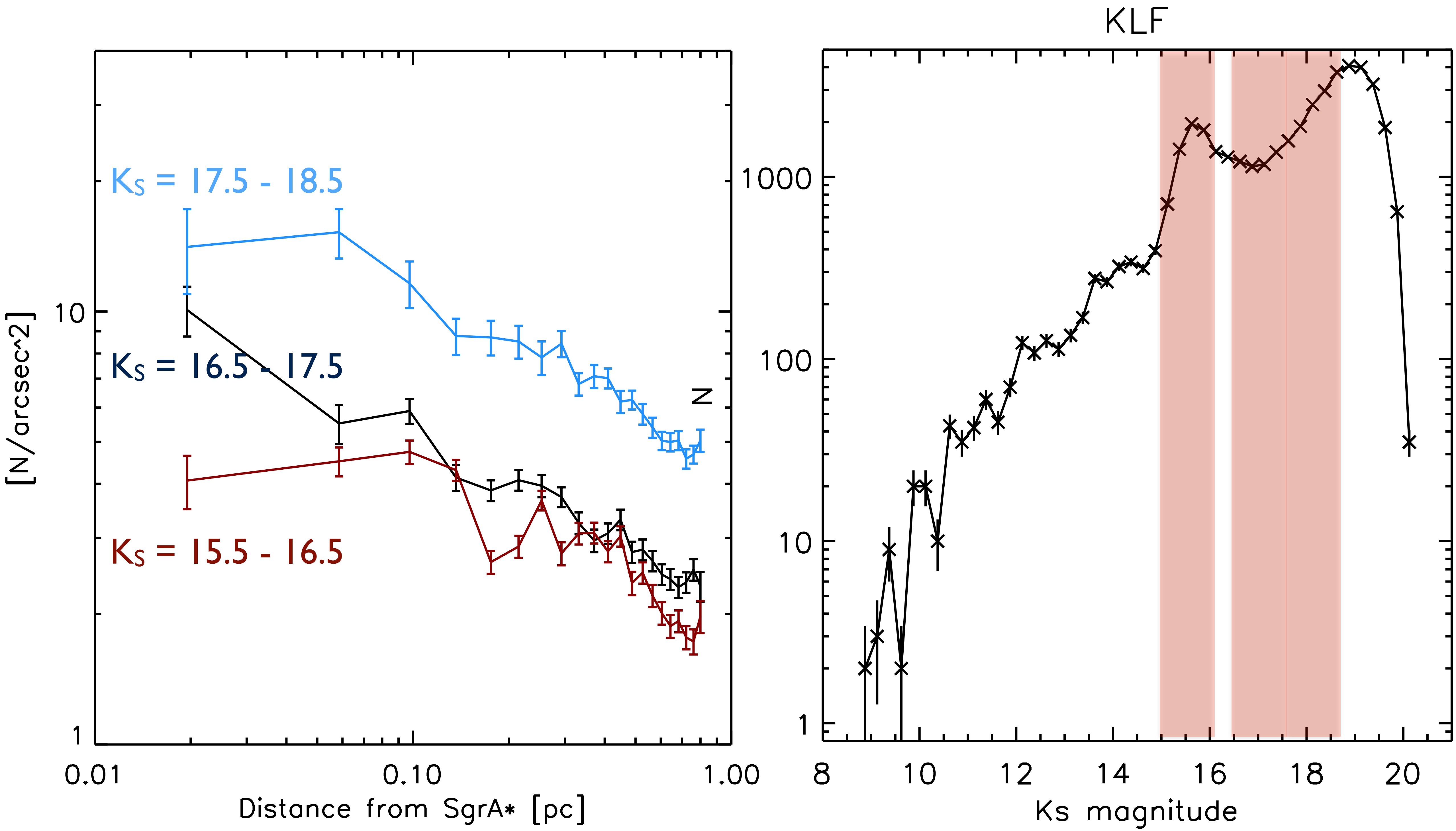


Σ of *faint* giants (some contamination possible) fit well by simple power law with Γ≈-0.4.

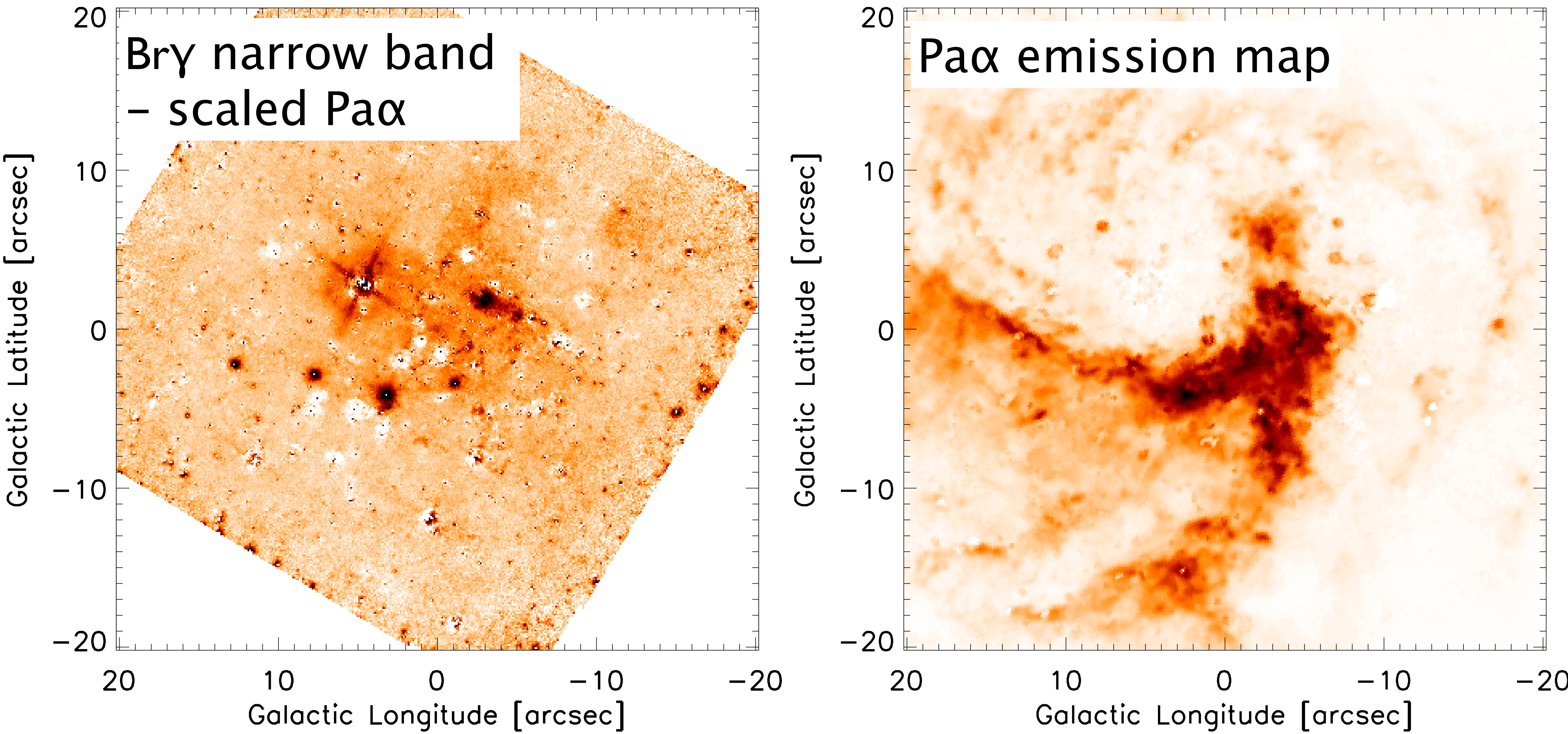
Σ of *bright* giants fit well by simple power law with Γ≈-0.4 *at* R > 0.05 pc (*broken* power-law Γ≈-0.2).

Missing cusp problem is only *missing bright giants* problem! Can be explained with star-cloud collisions (Amaro & Chen 2014)

1. Star counts

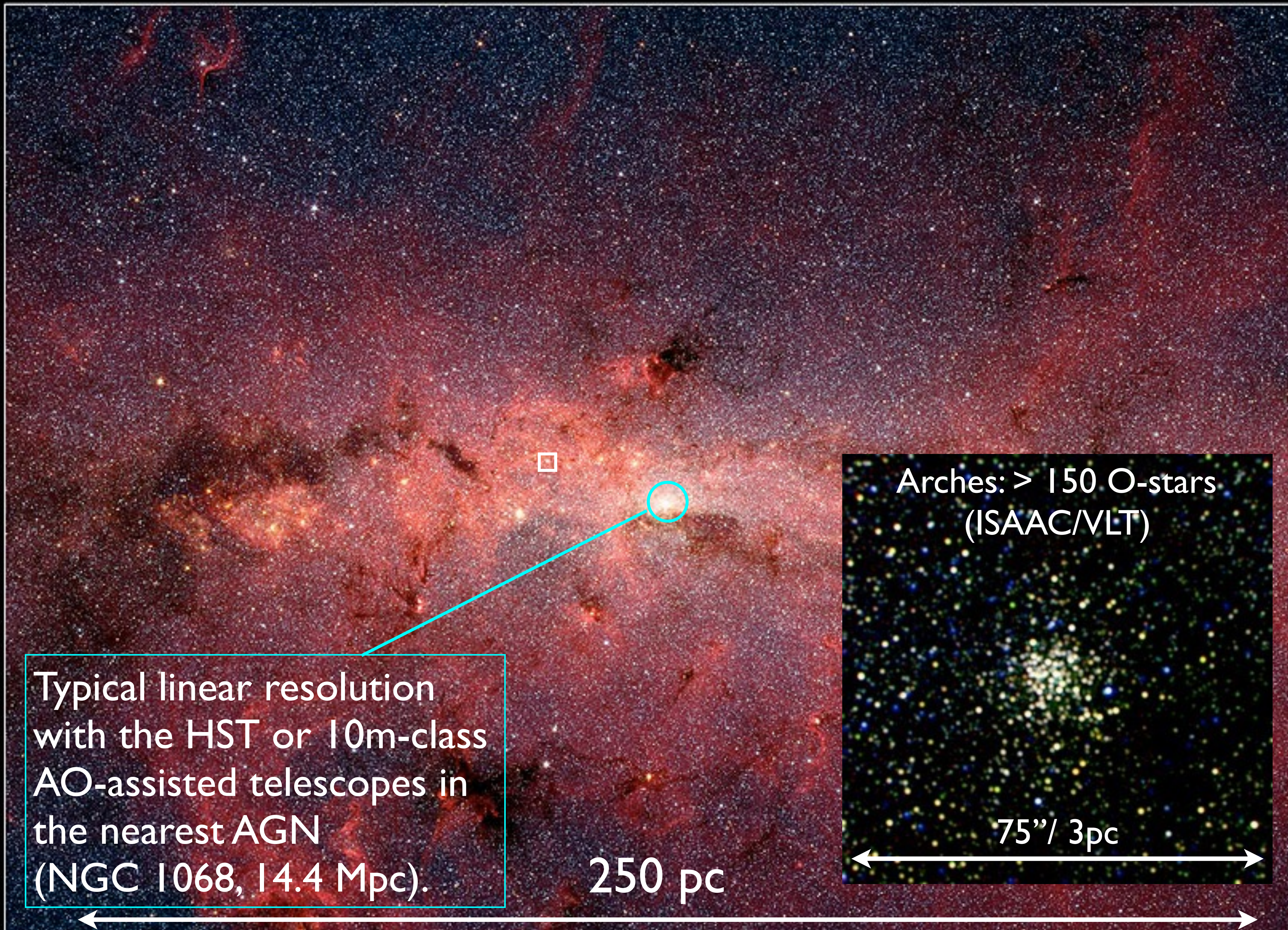


2. Diffuse light



Diffuse light contaminated by emission from ionised gas.
Paα map from HST (Wang et al. 2012, Dong et al. 2011).

Low-resolution view of the Galactic Center



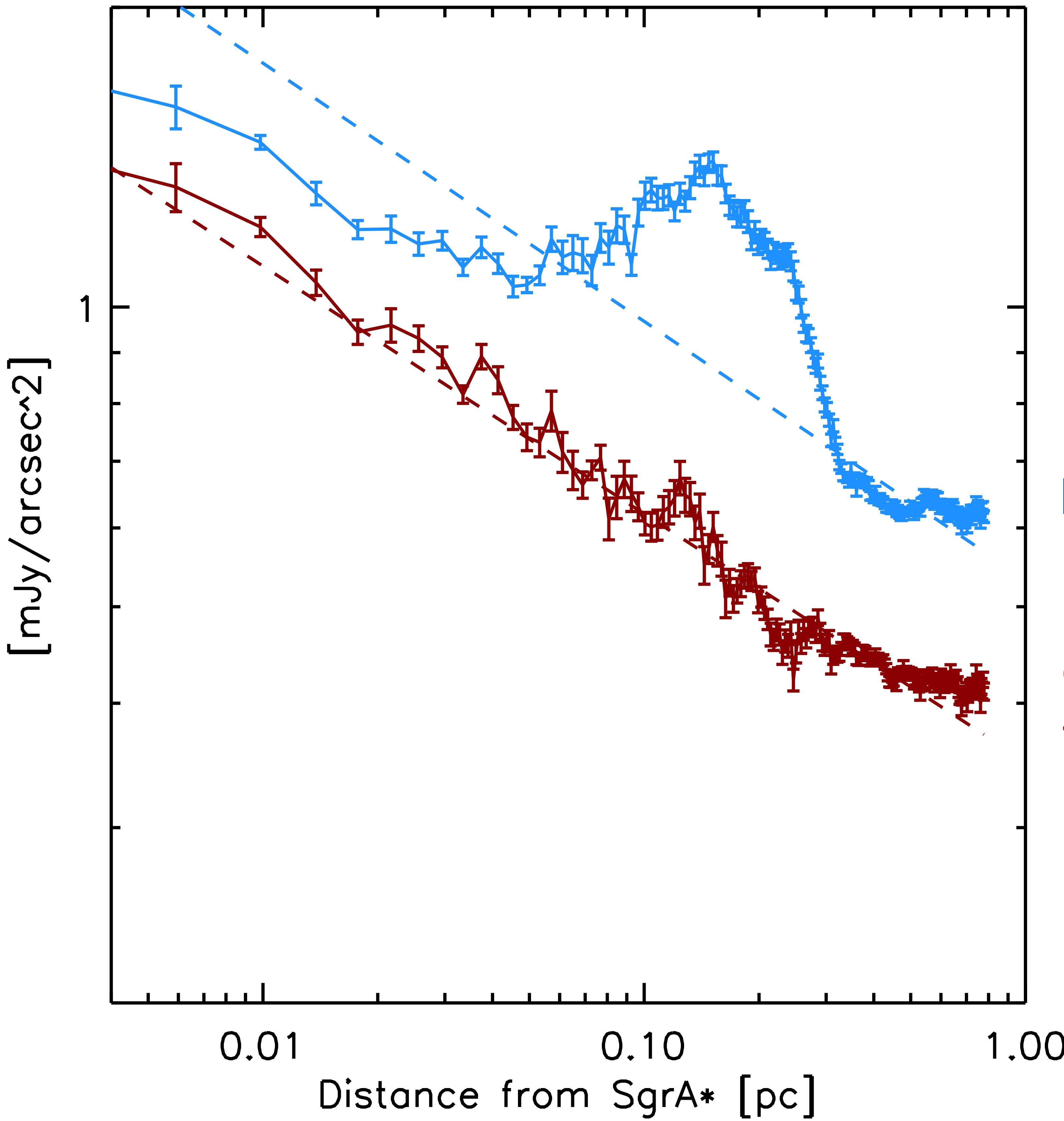
The Center of the Milky Way Galaxy

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

Spitzer Space Telescope • IRAC

ssc2006-02a

2. Diffuse light

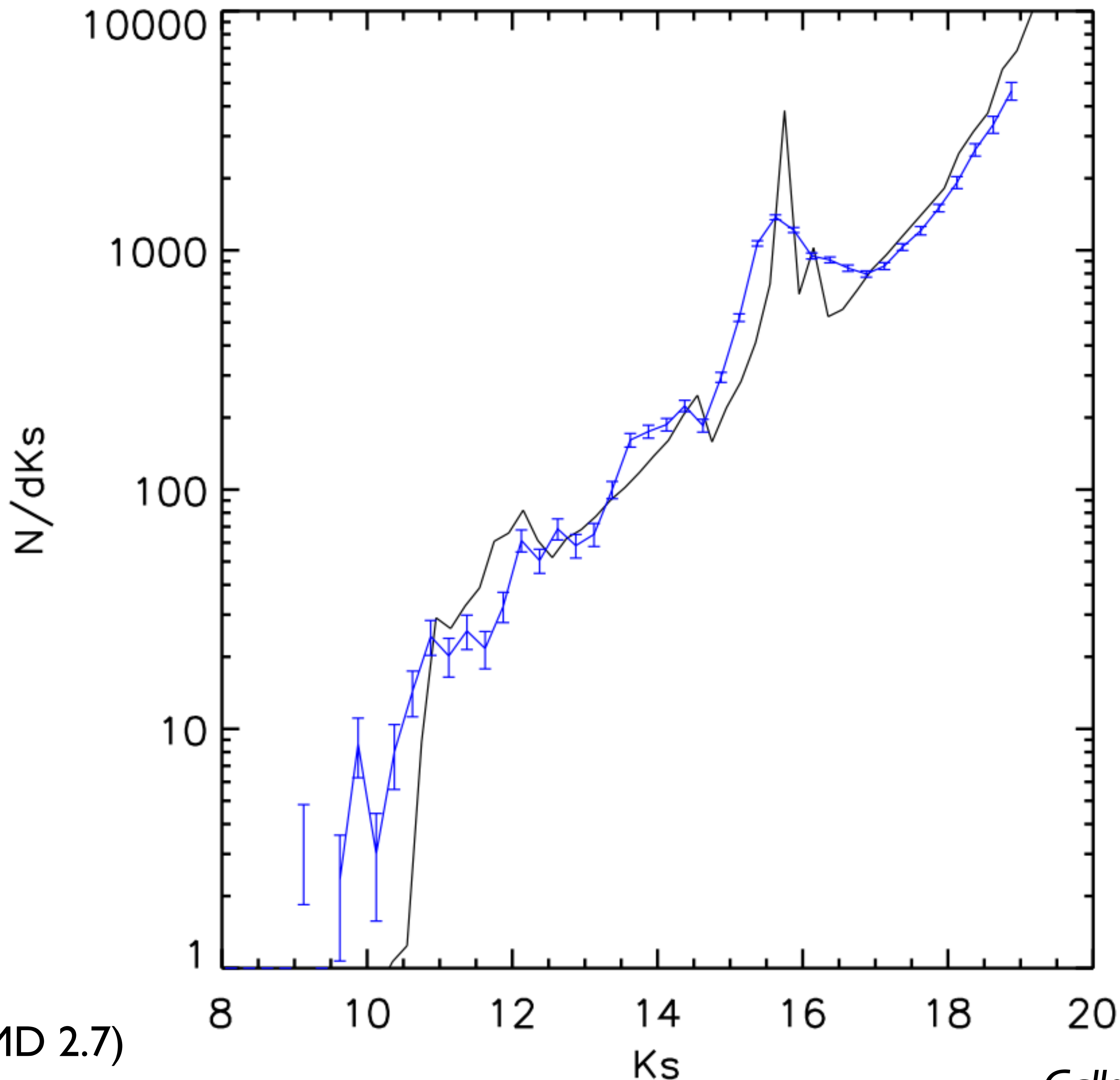


Brγ surface flux density

Corrected Brγ surface flux density

Discussion

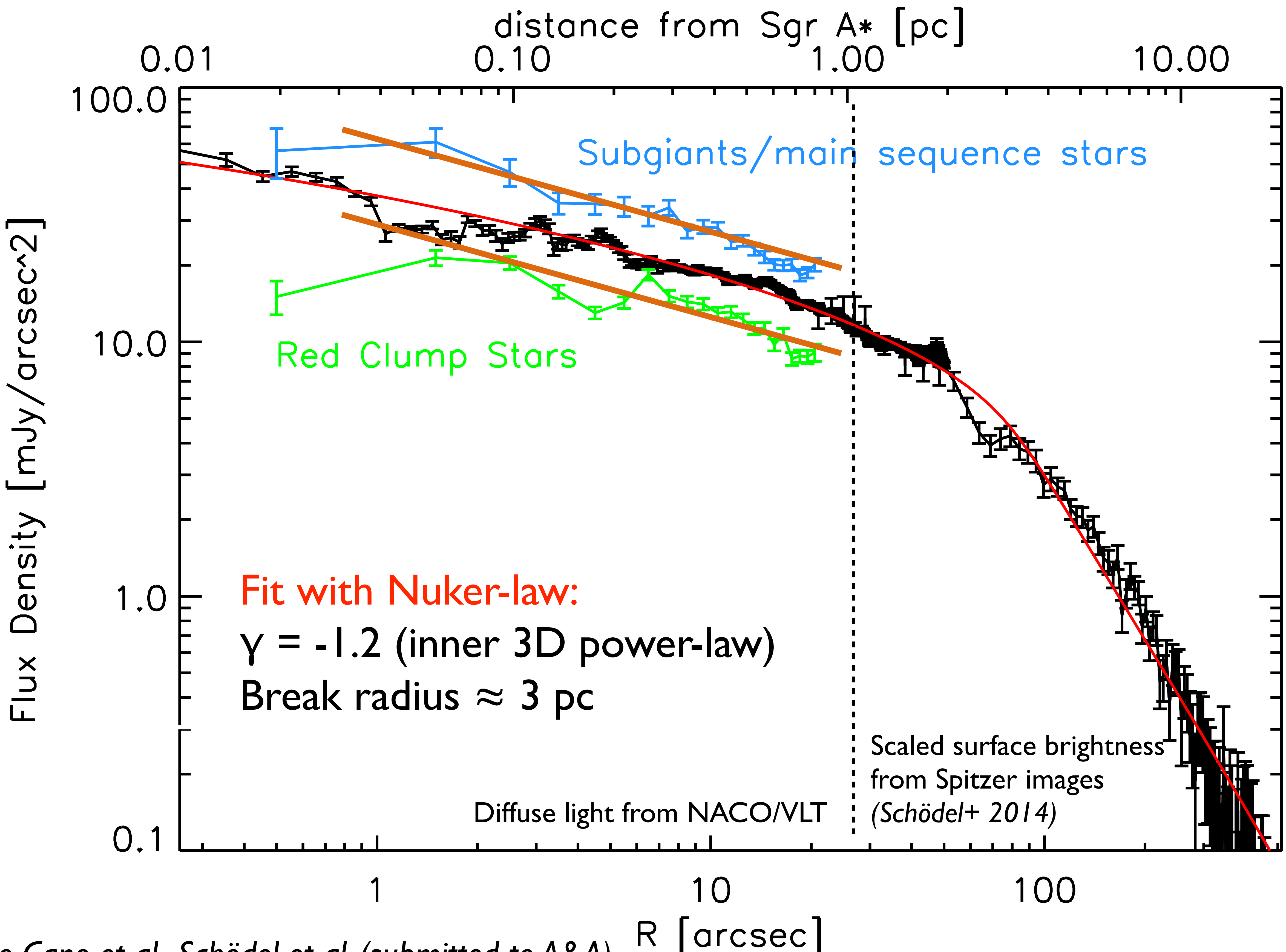
Star formation history of the NSC



Model LF (CMD 2.7)

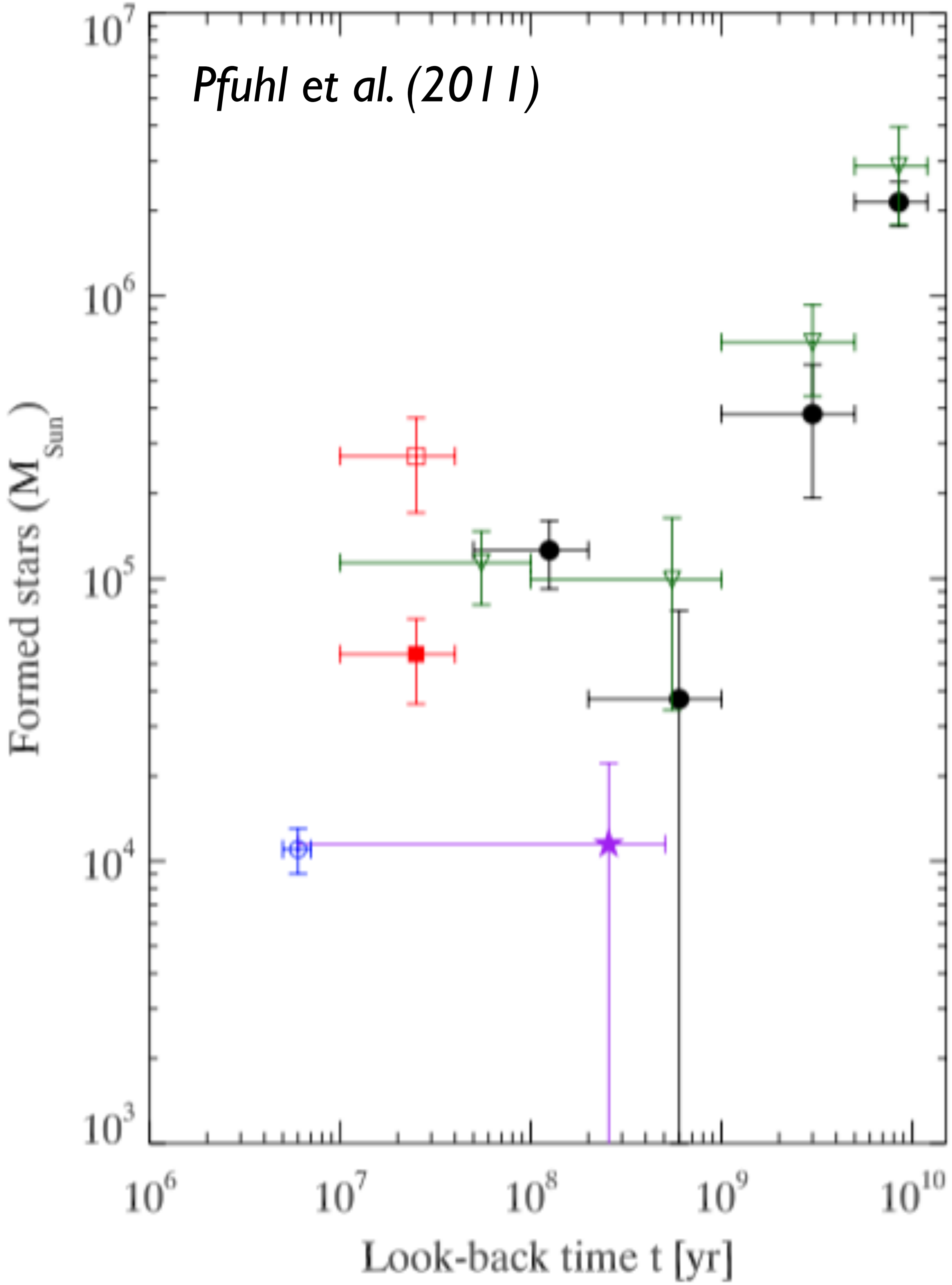
Gallego-Cano et al. (2017)

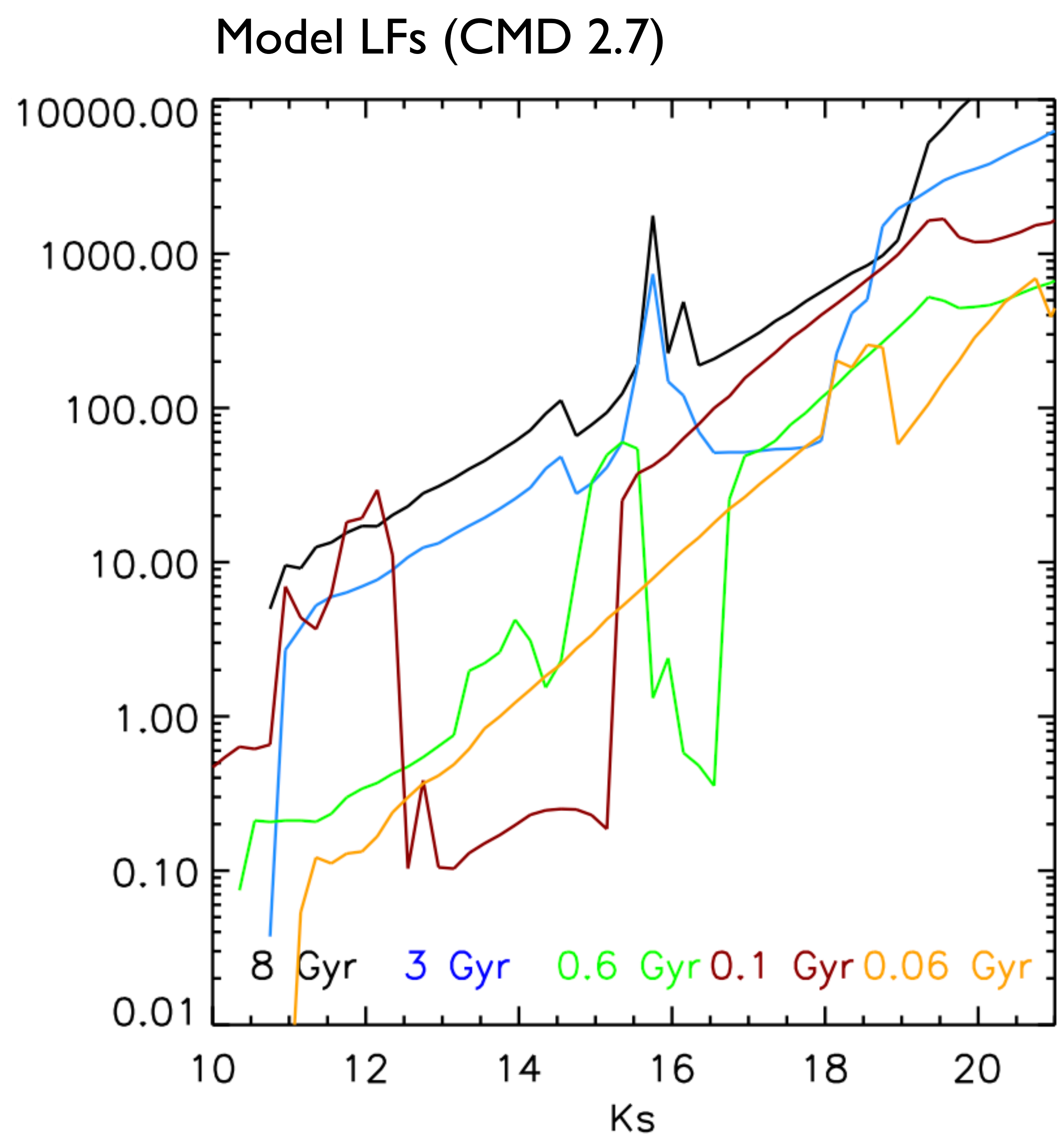
Surface density of stars at GC

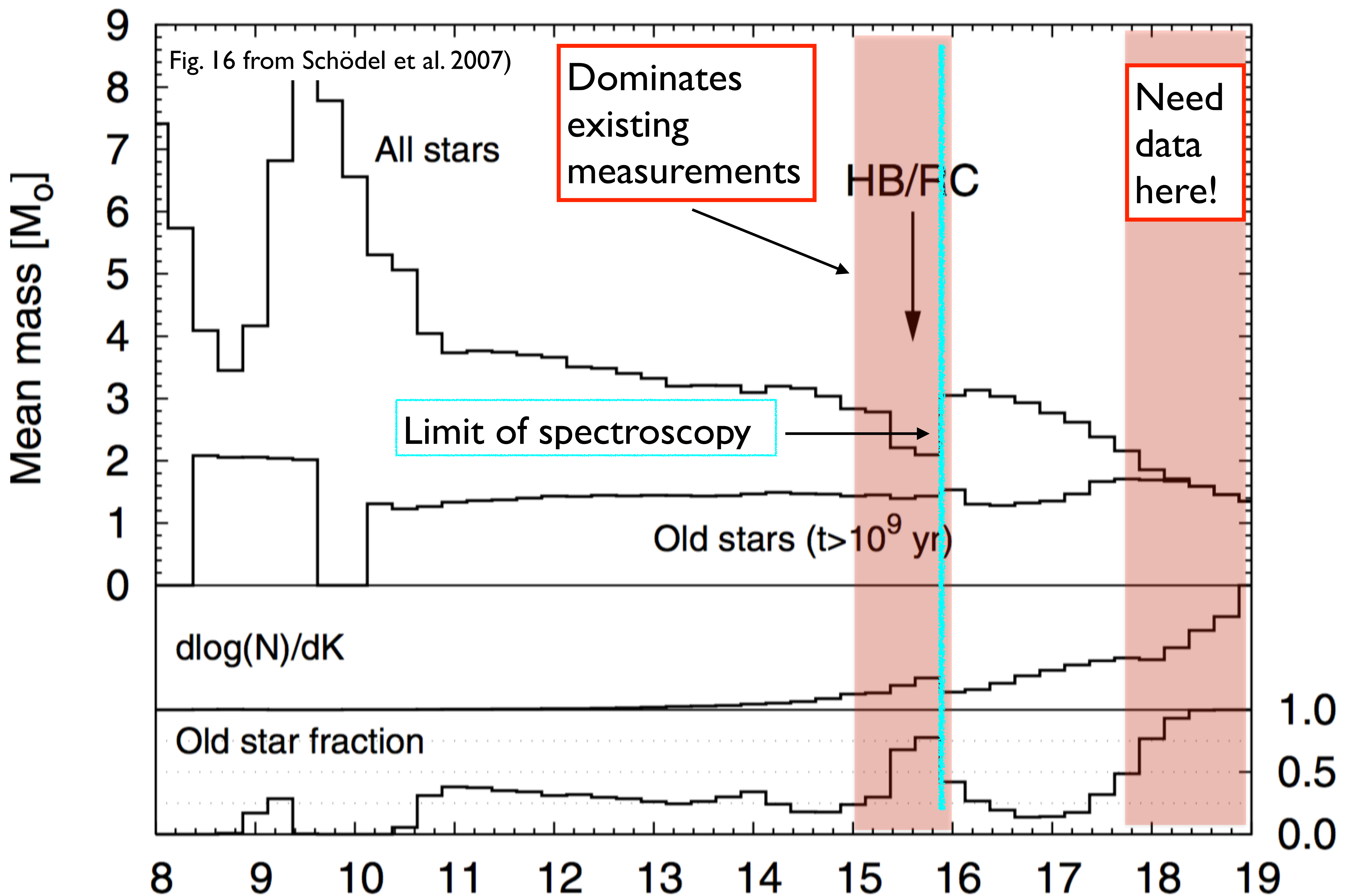


Gallego-Cano et al., Schödel et al. (submitted to A&A)

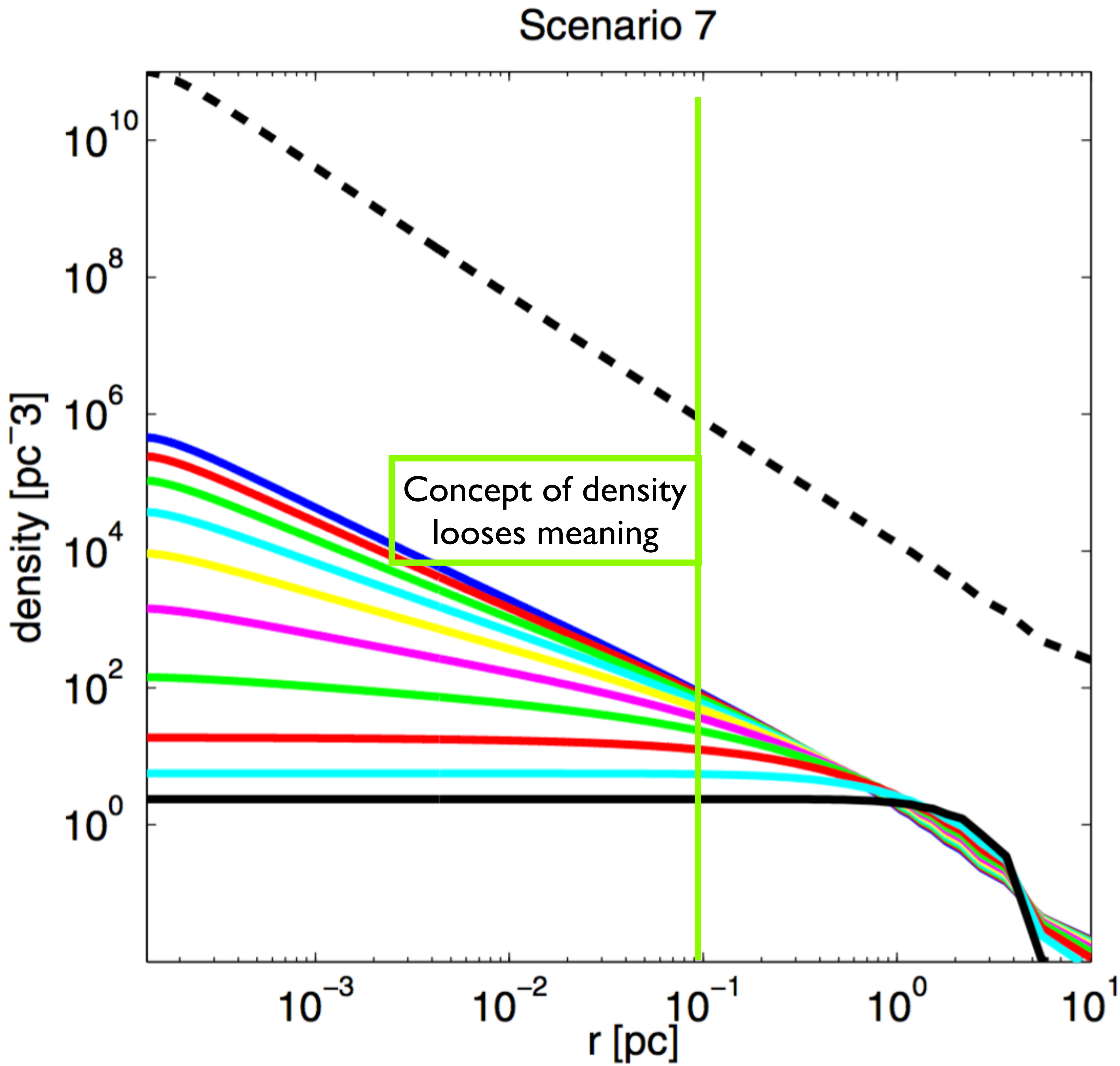
Star formation history of the NSC





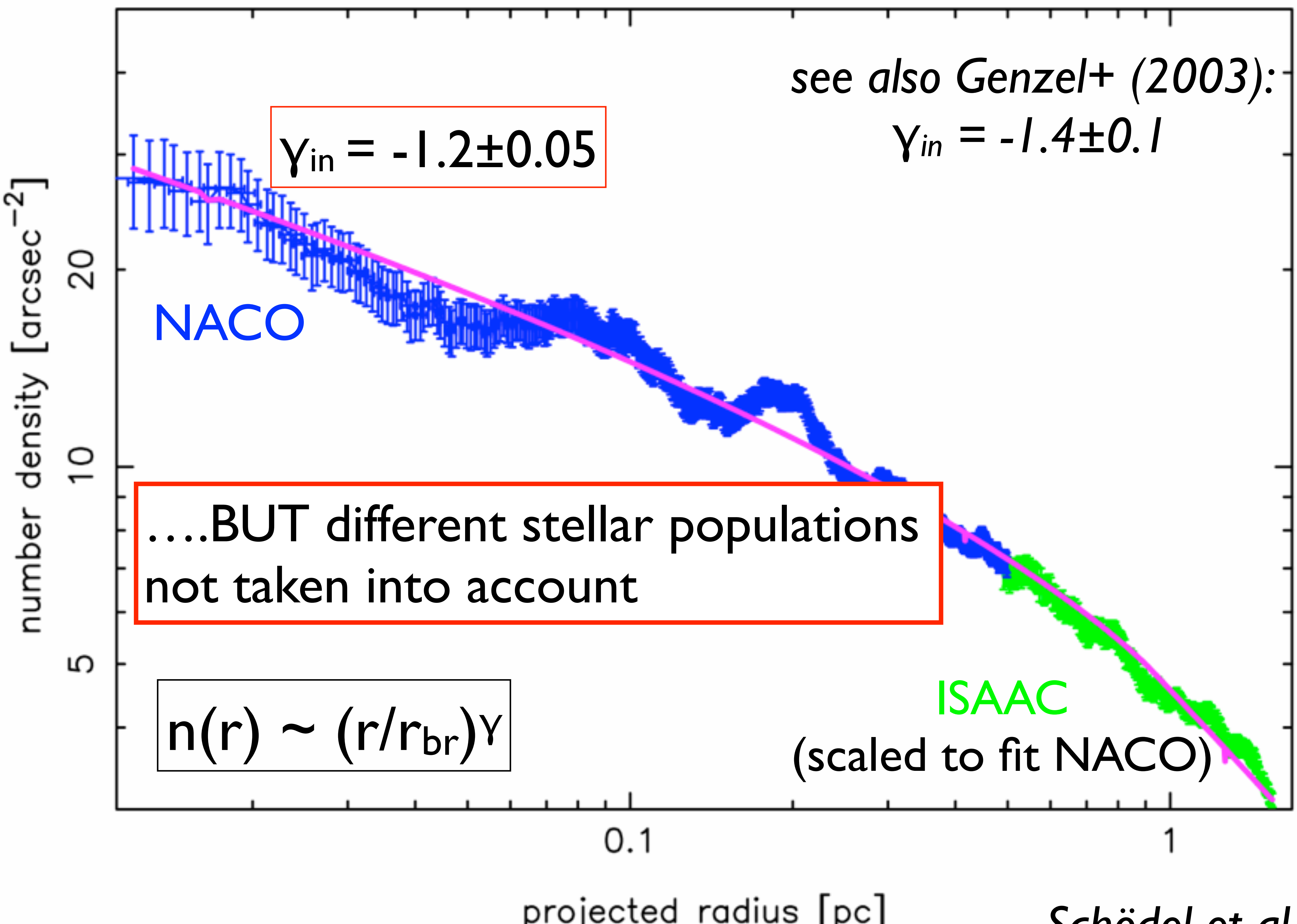


Cusp only appears in relaxed population; slope depends on stellar mass.



Scenario 7
Concept of density looses meaning
density [pc^-3]
10^10
10^8
10^6
10^4
10^2
10^0
10^-3
10^-2
10^-1
10^0
10^1
r [pc]

Stellar number density at GC



Schödel et al. (2007)