The Milky Way's Central Molecular Zone and Its Stellar Population

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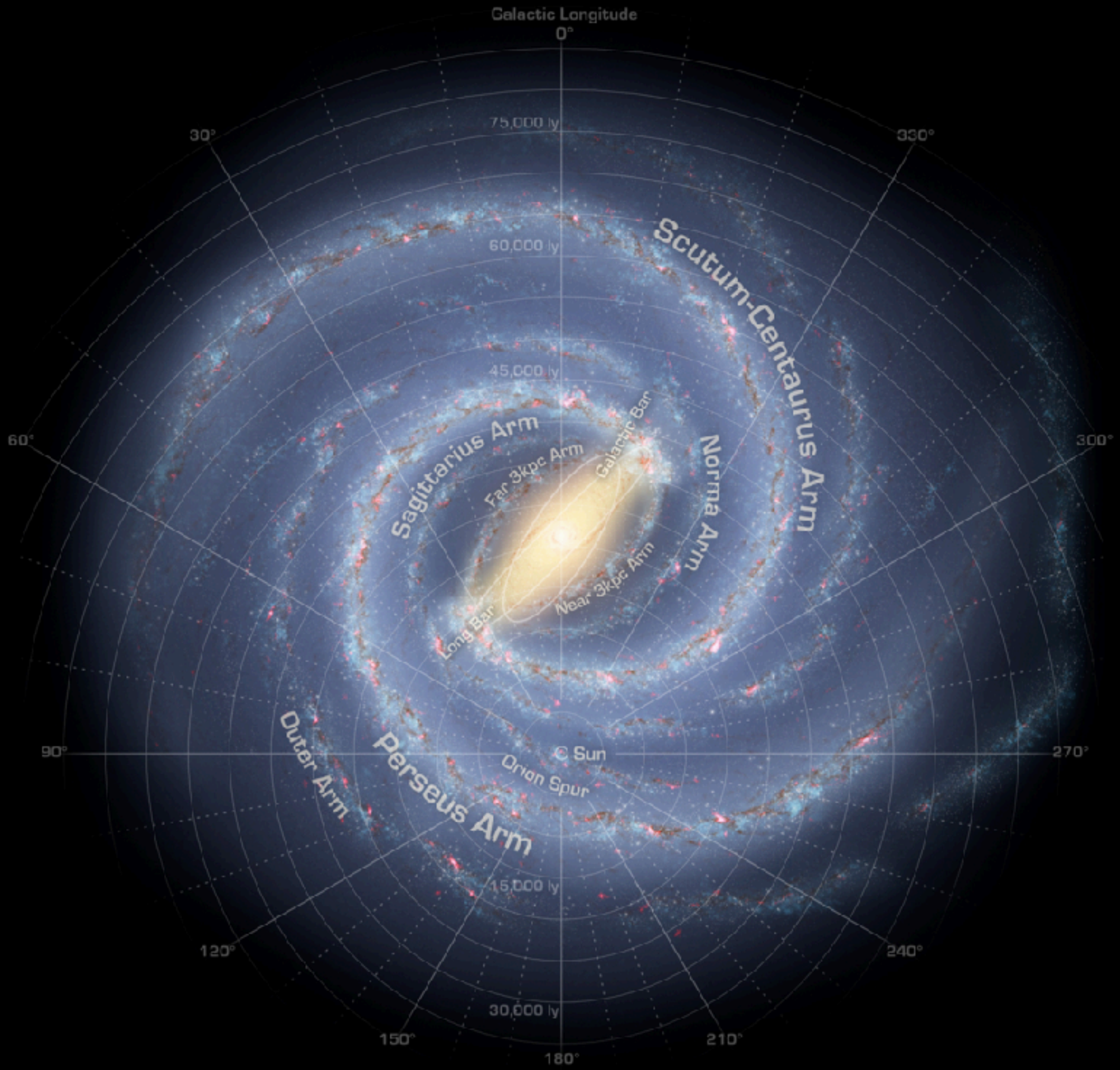
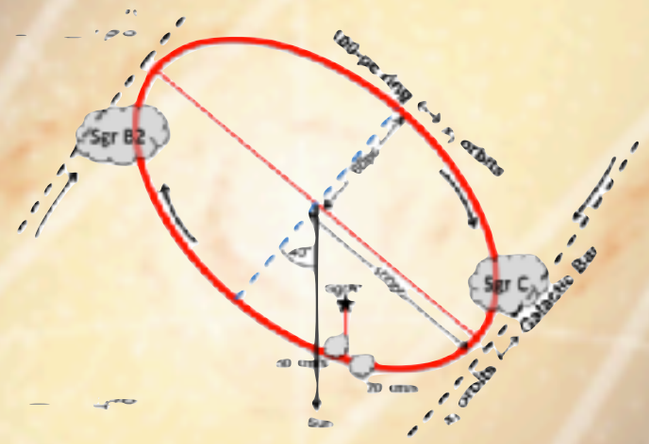

Galactic Longitude
0°
30°
330°
60°
300°
90°
270°
120°
240°
150°
210°
180°
75,000 ly
60,000 ly
45,000 ly
30,000 ly
15,000 ly
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Sun
Orion Spur

Sagittarius

Far 3kpc Arm

Galac



Bar

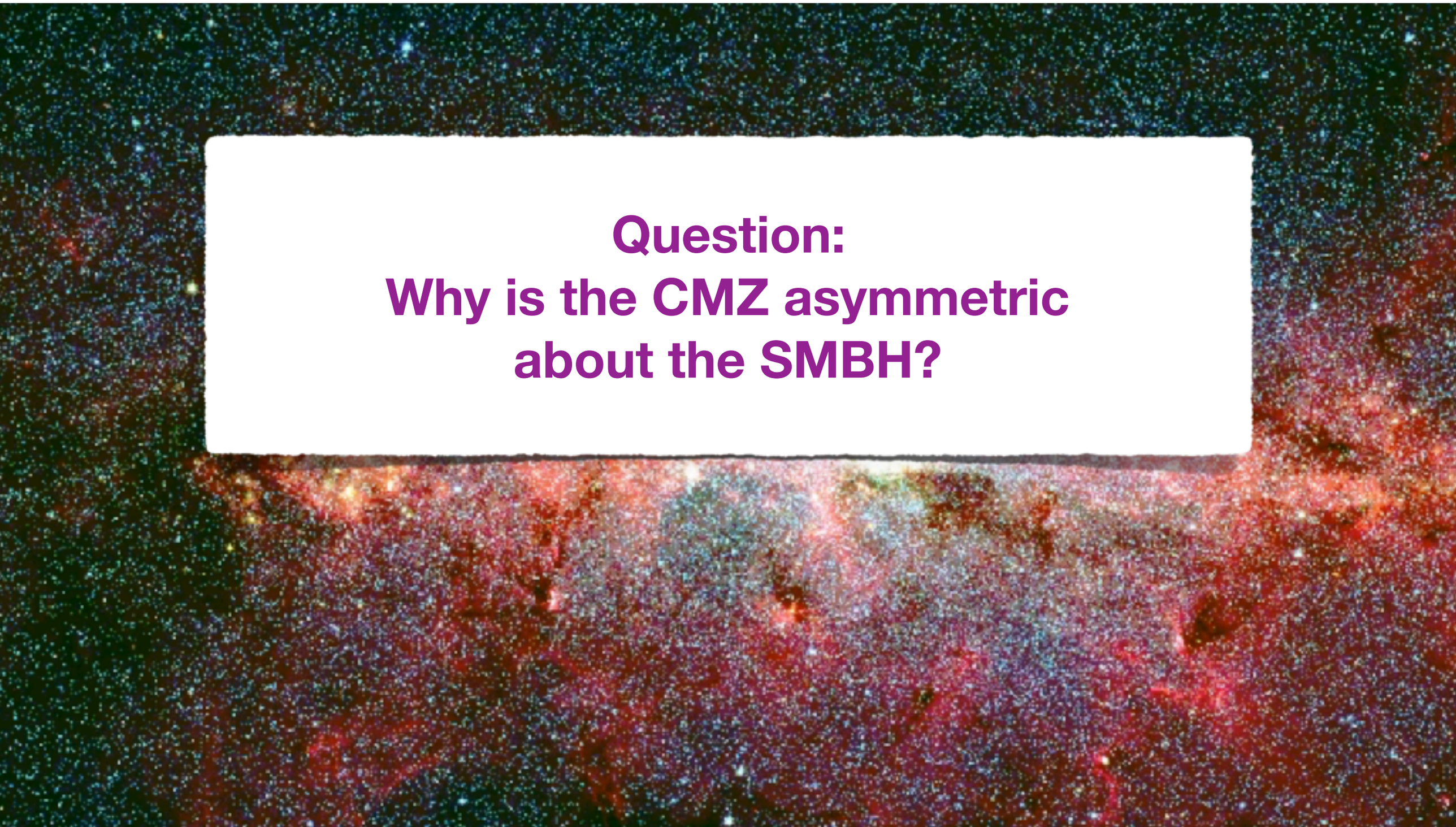
Near 3kpc Arm

Molinari+ 2011

Central Molecular Zone

r~100 - 200 pc
~10^8 M_{sun} in H_2
High T, B, ρ, σ_{turb}

Morris & Serabyn 1996
Molinari+ 2011
Kruijssen & Longmore 2013
Henshaw+ 2016



Question:
Why is the CMZ asymmetric about the SMBH?

HST NICMOS
Spitzer IRAC

Arched
Filaments

Arches
Cluster

2-3 Myr

Quintuplet
Cluster

Pistol Star

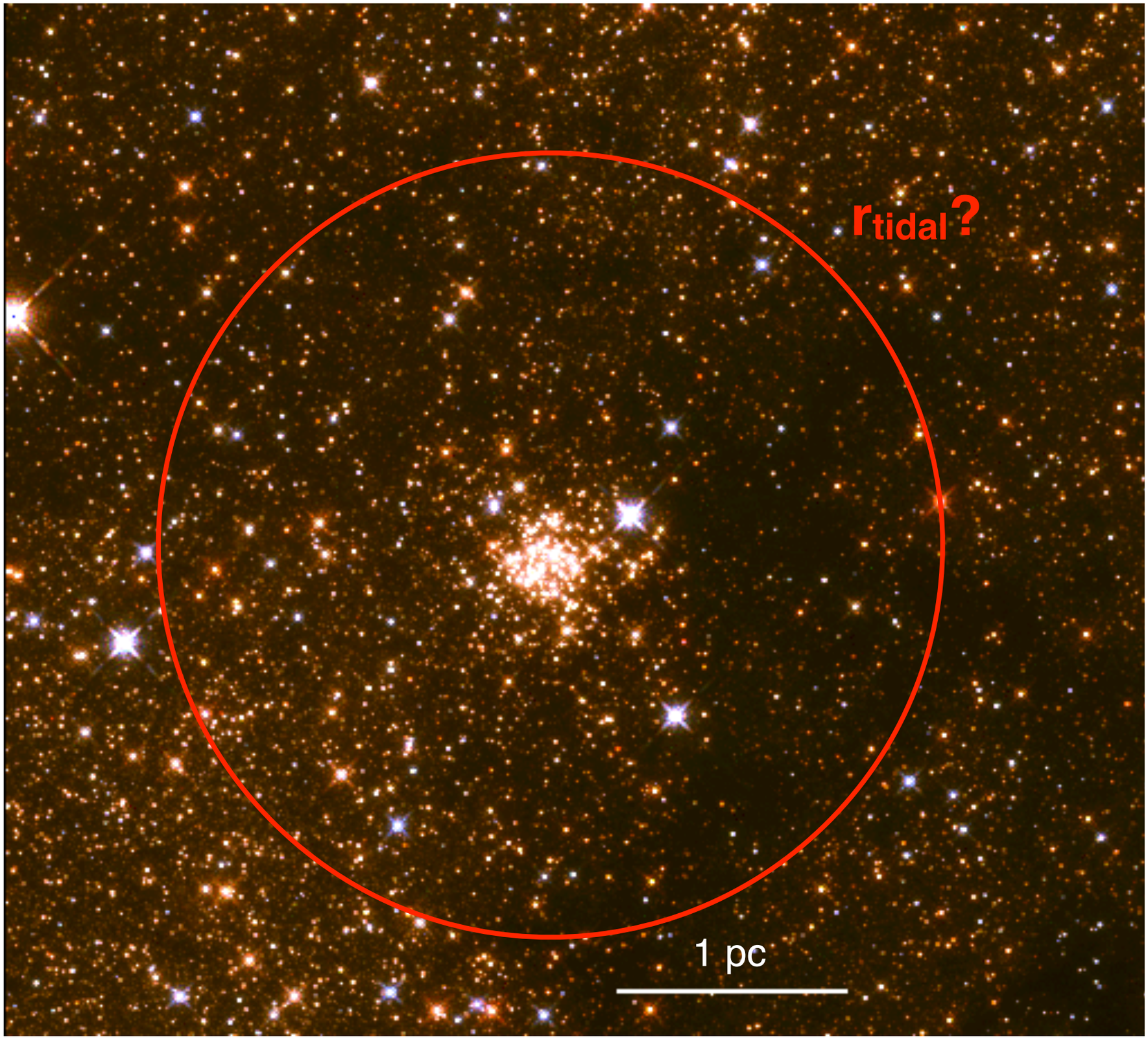
3-5 Myr

4-6 Myr

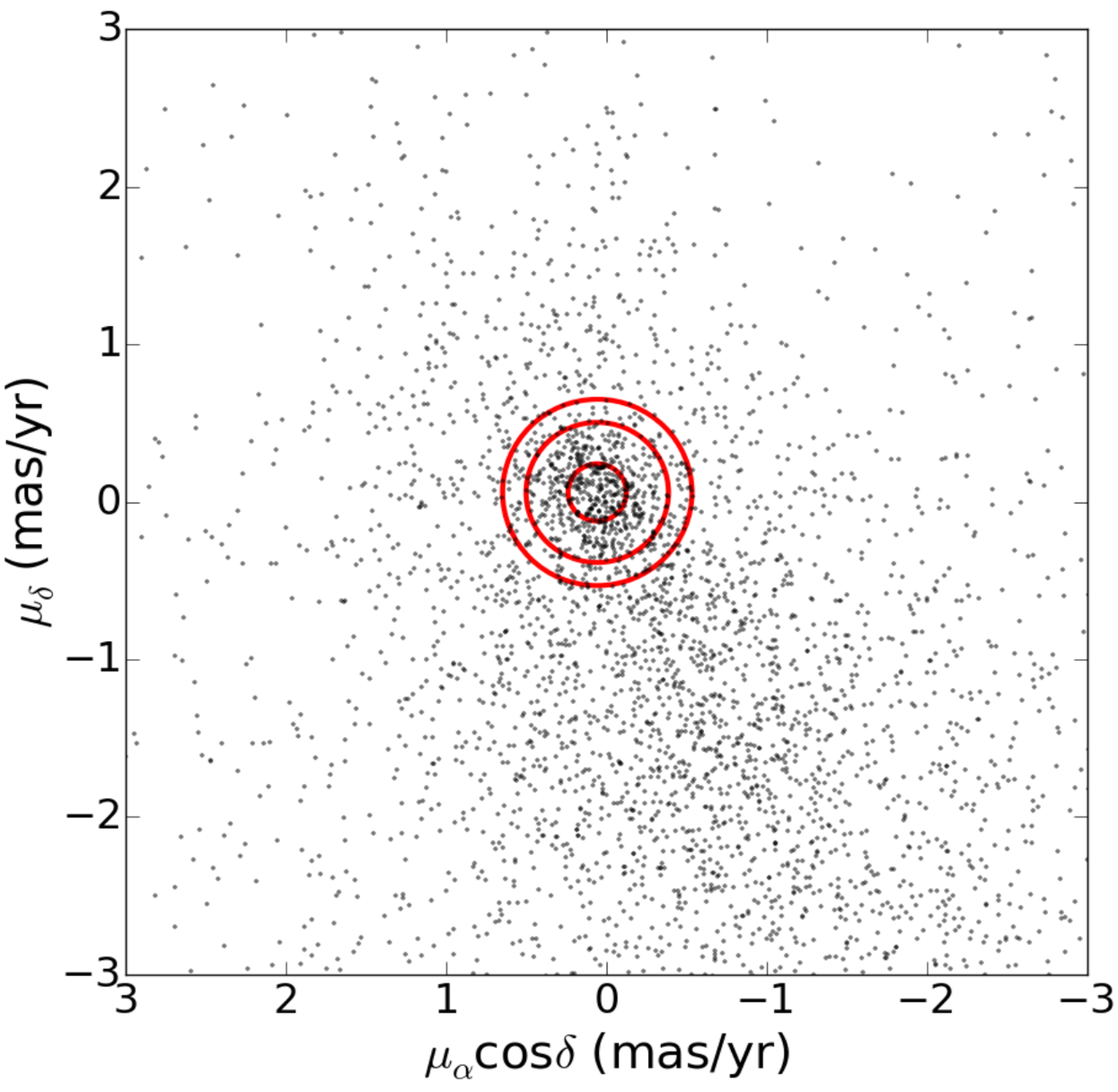
Sgr A

Arches Cluster: Structure and Dynamics

How does the strong tidal field effect the Arches cluster structure, dynamics, evolution, and mass function?



Keck AO and HST astrometry on the Arches cluster selects cluster members and gives precise proper motions.



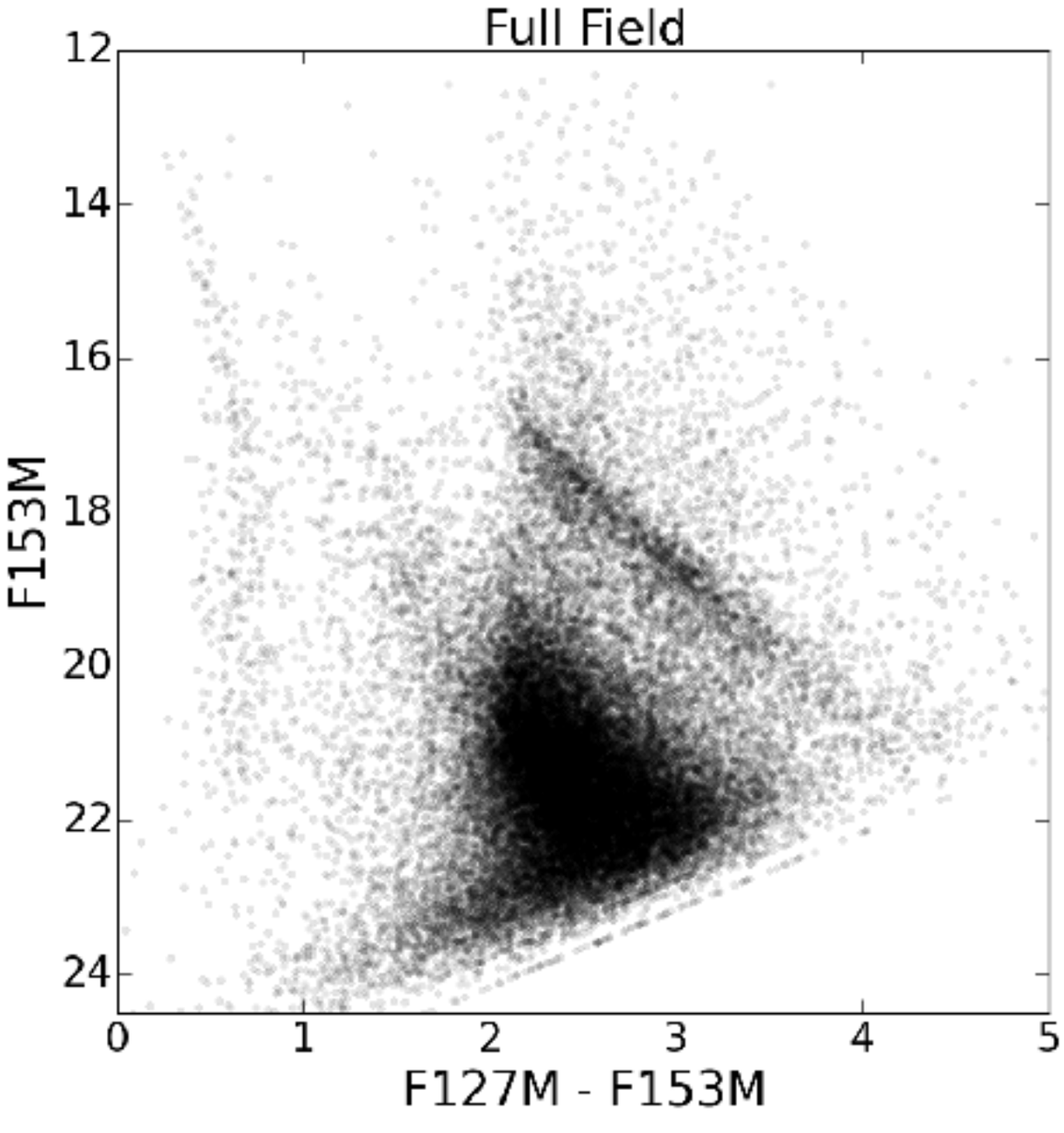
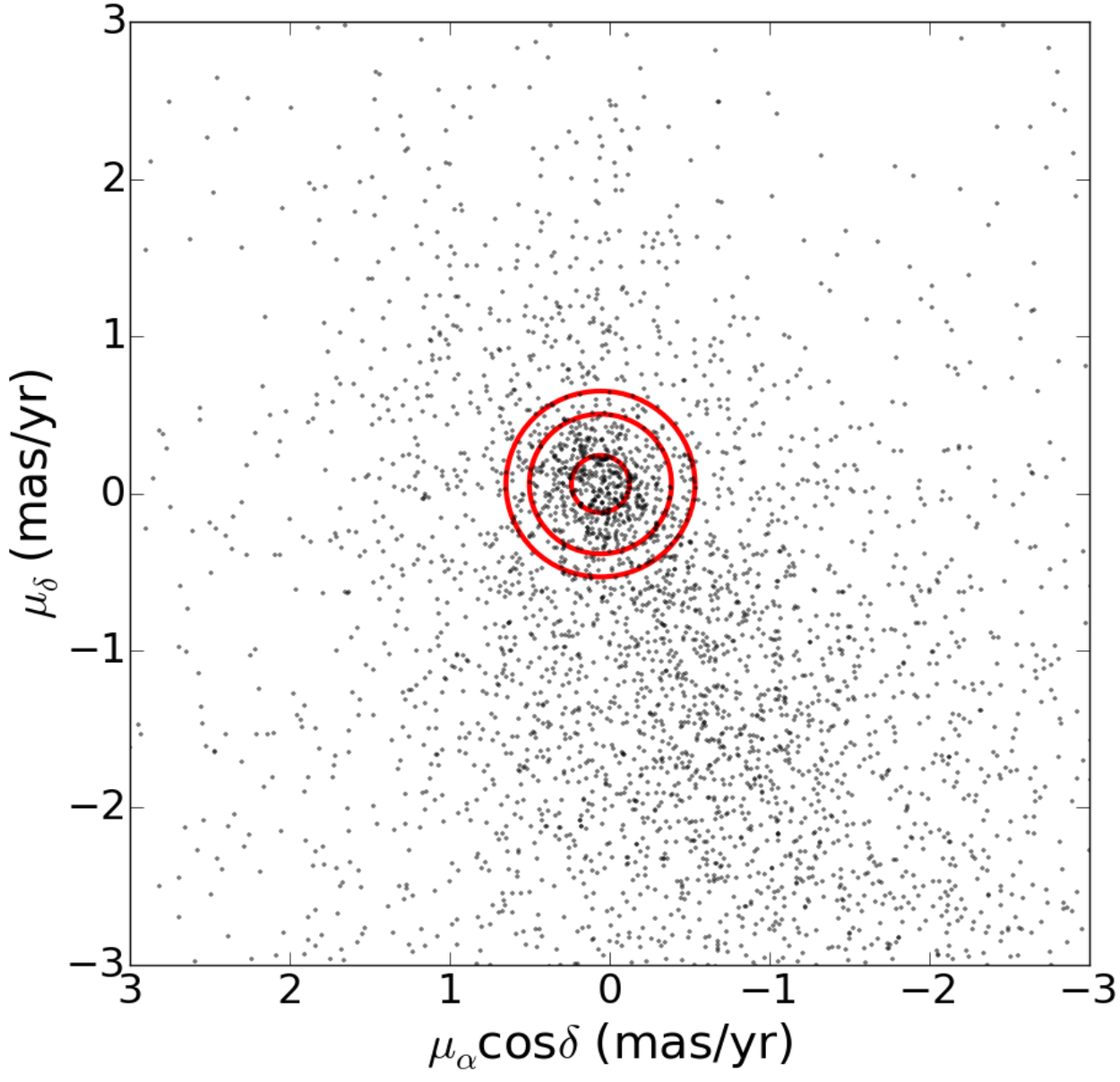
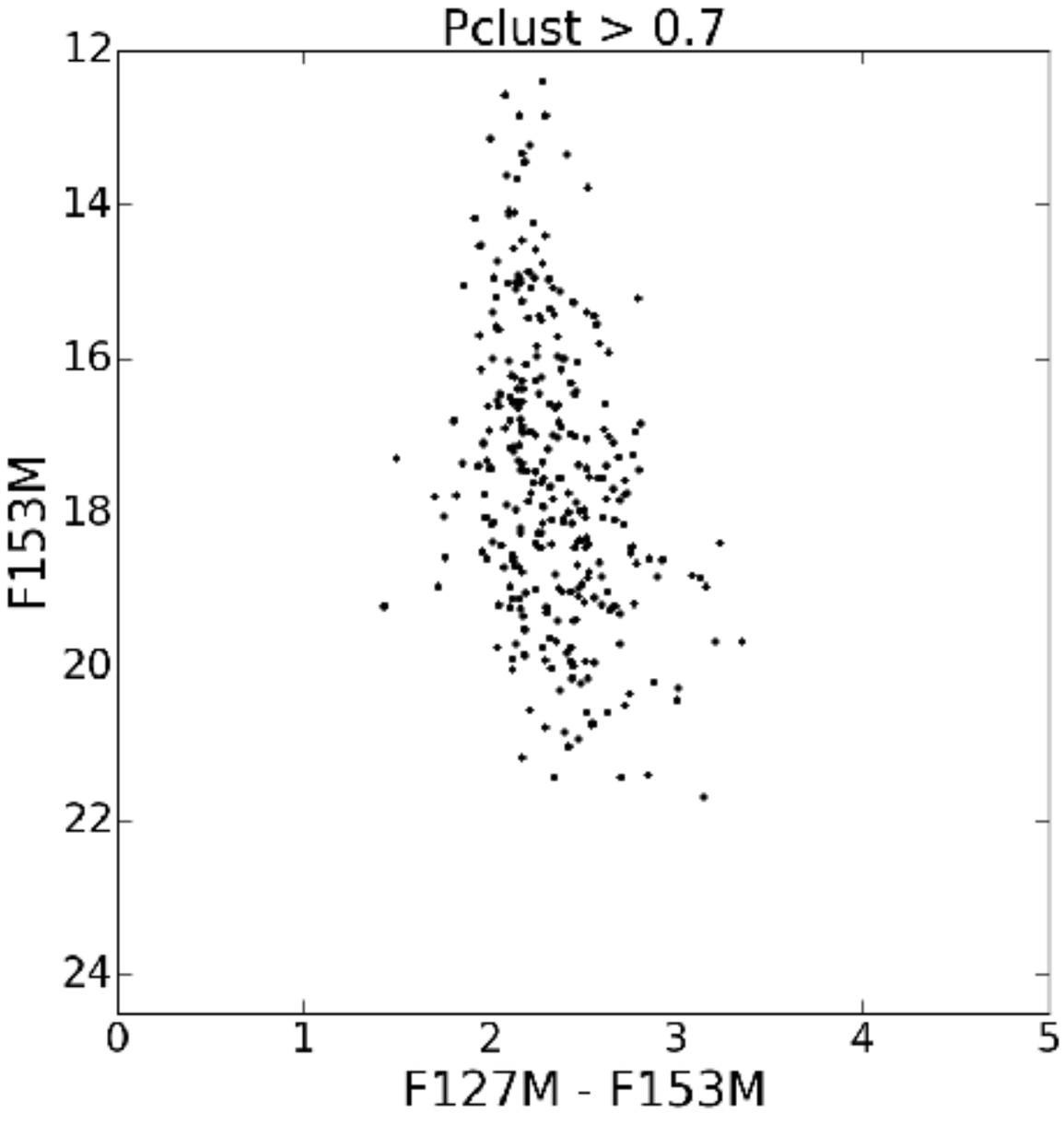


Figure from Hosek+ 2015

Keck AO and HST astrometry on the Arches cluster selects cluster members and gives precise proper motions.





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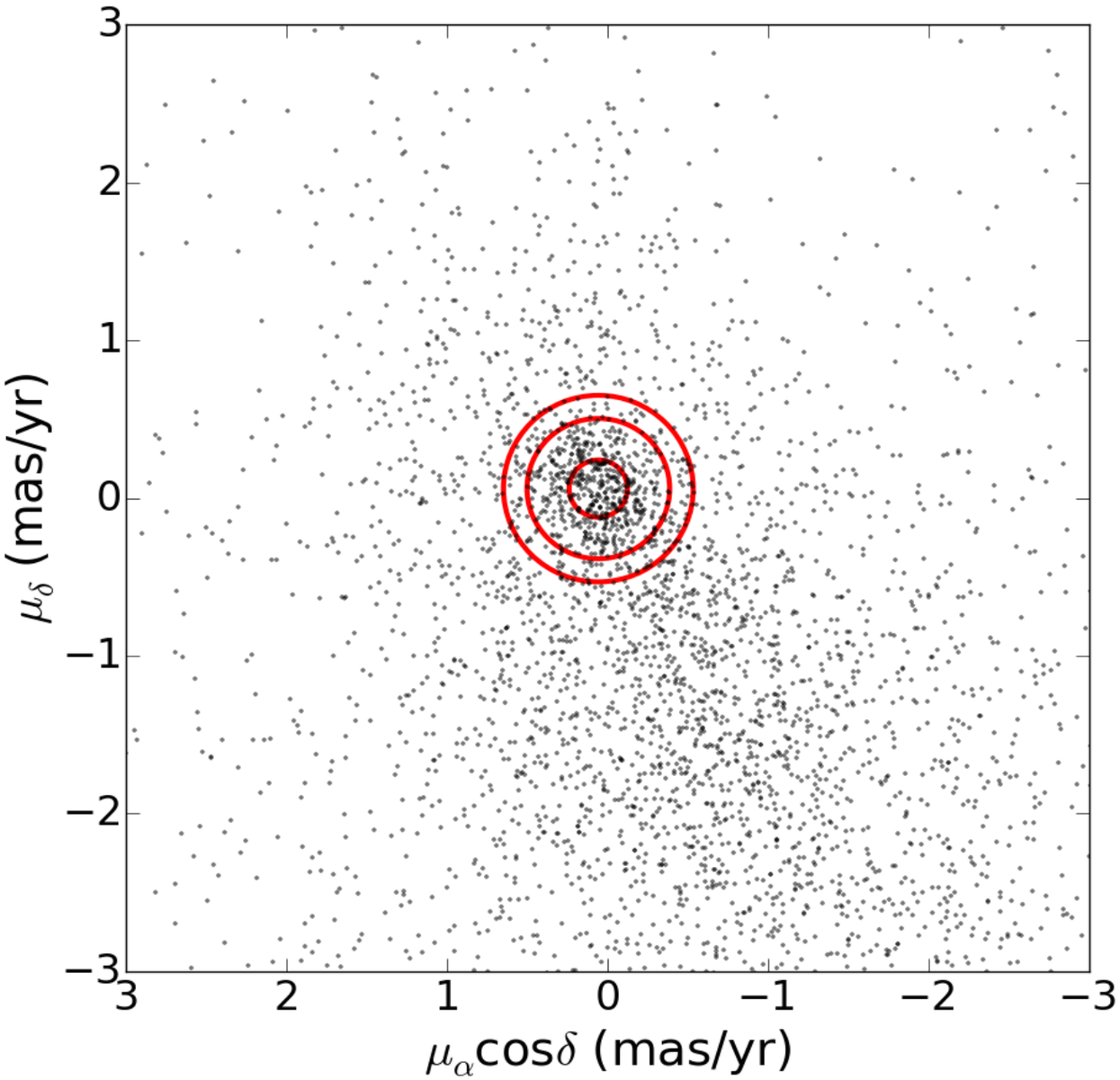
Keck AO and HST astrometry on the Arches cluster selects cluster members and gives precise proper motions.



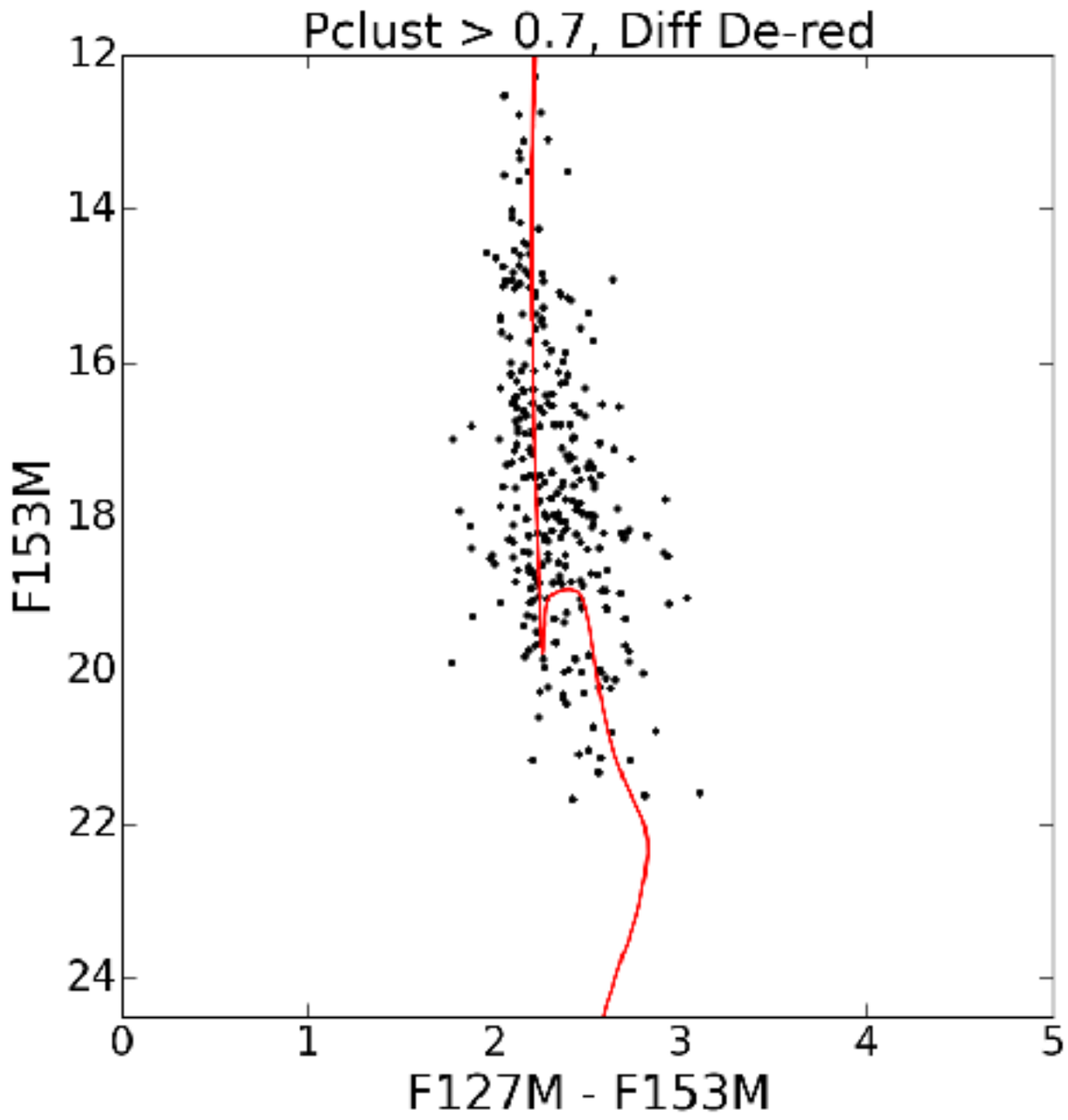


Figure from Hosek+ 2015

The Extended Radial Profile of the Arches Cluster

Model:

Power-Law + Constant

$$L_i(r, \Gamma, b) = A_0 r_i^{-\Gamma} + b$$

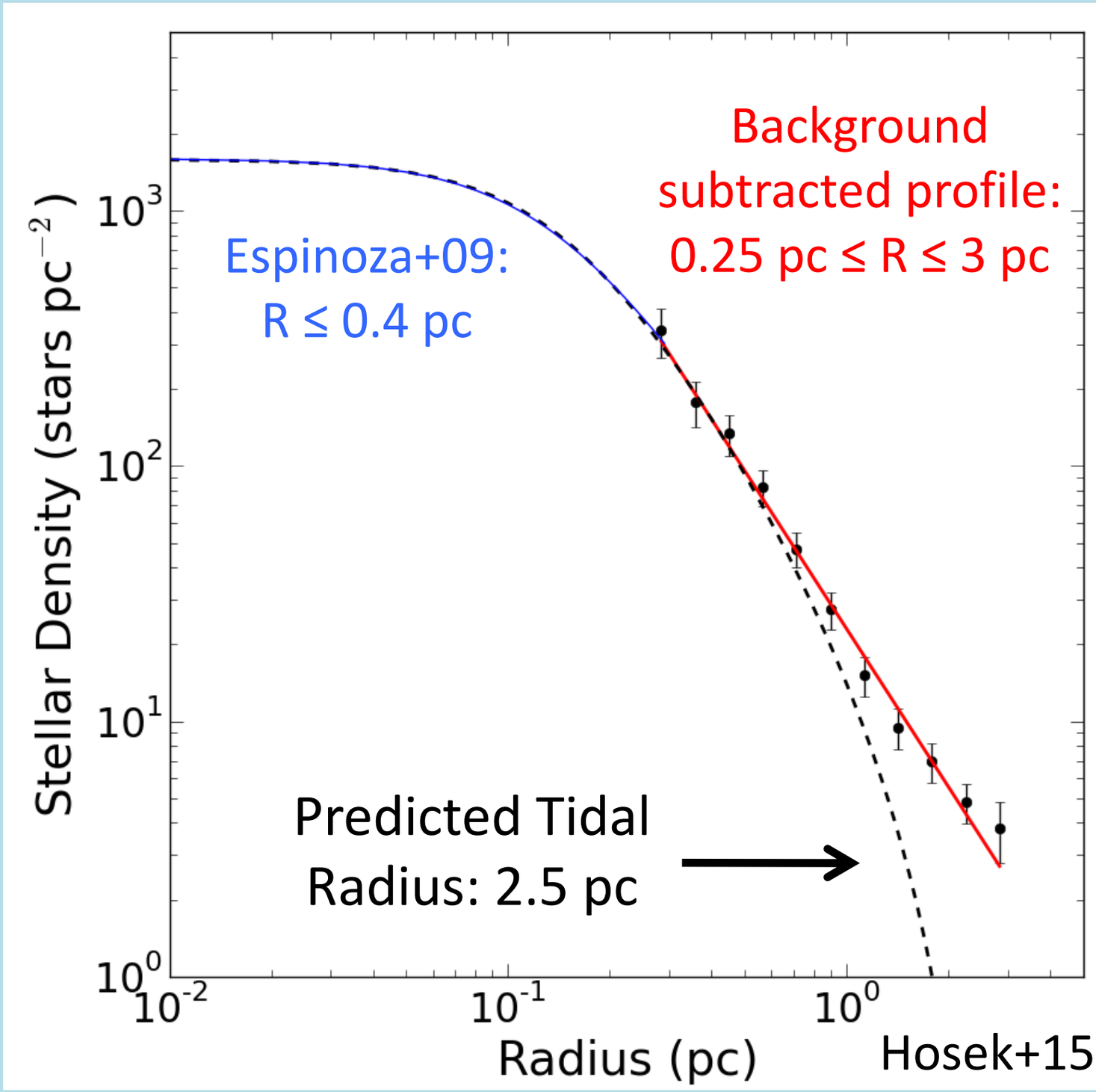
Best-Fit Params:

$\Gamma = 2.06 \pm 0.17$

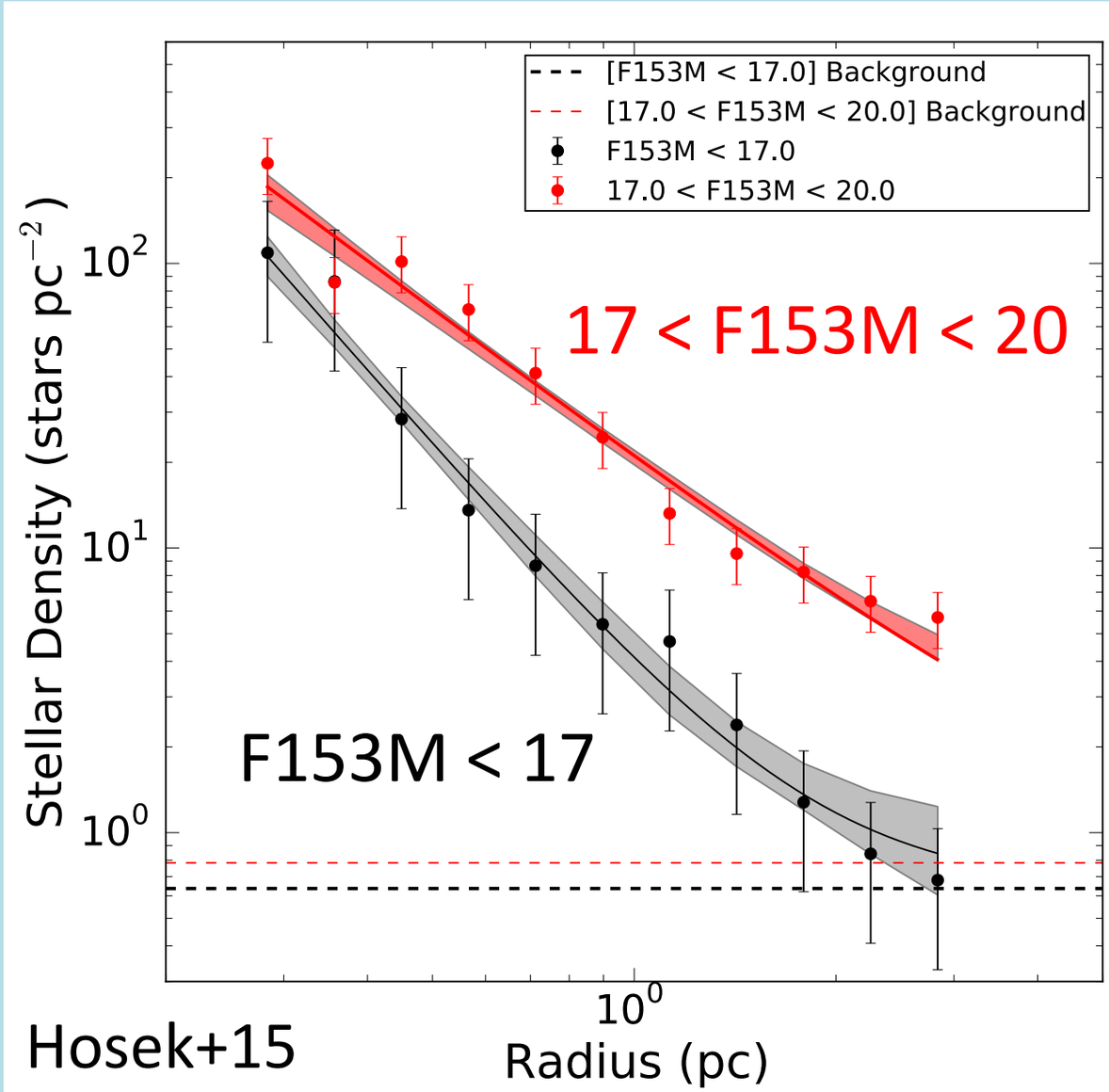
$b = 2.52 \pm 1.32$ stars/pc^2

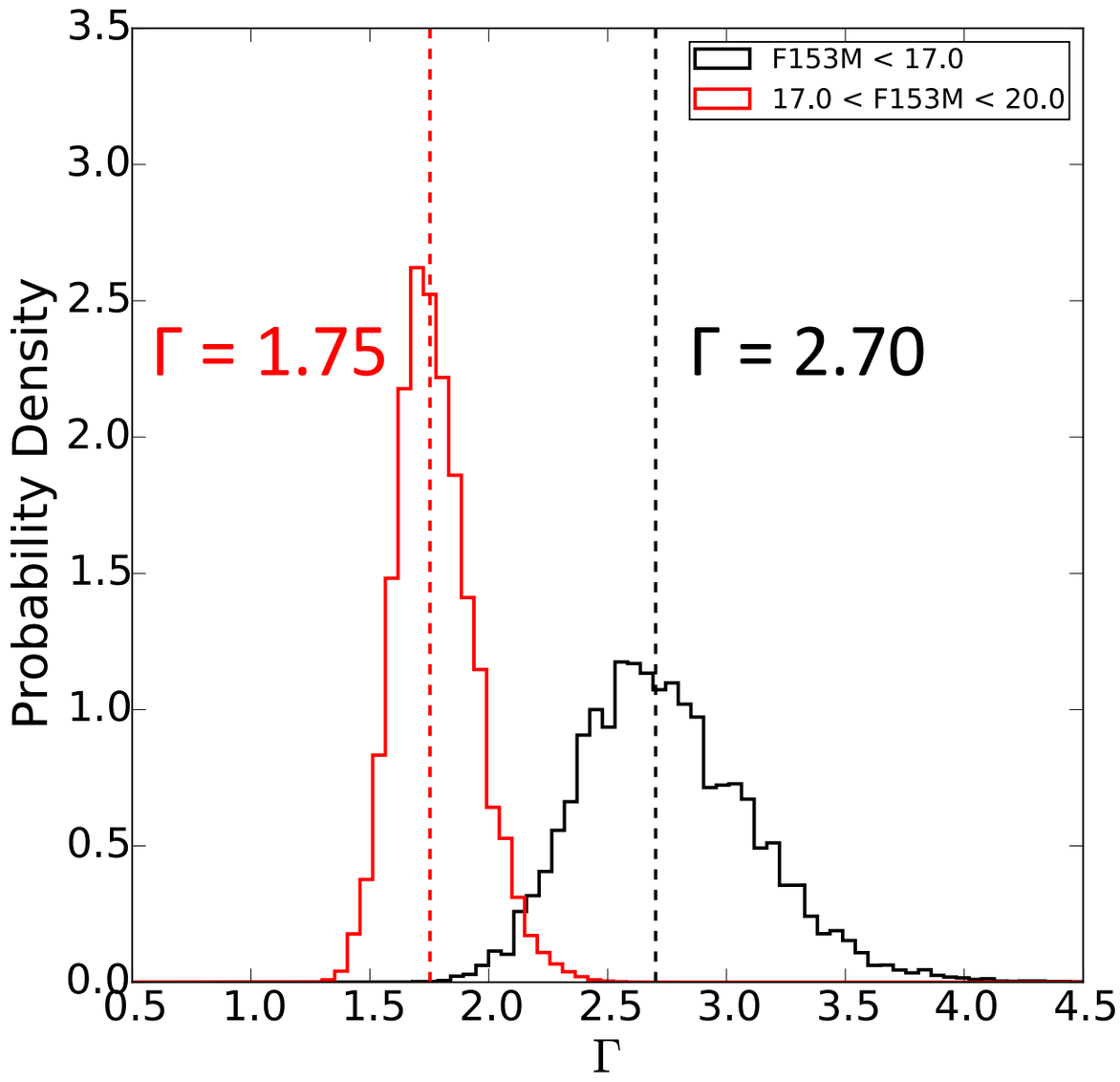
$A_0 = 23.09 \pm 3.5$ stars

3σ lower limit on tidal radius: 2.8 pc



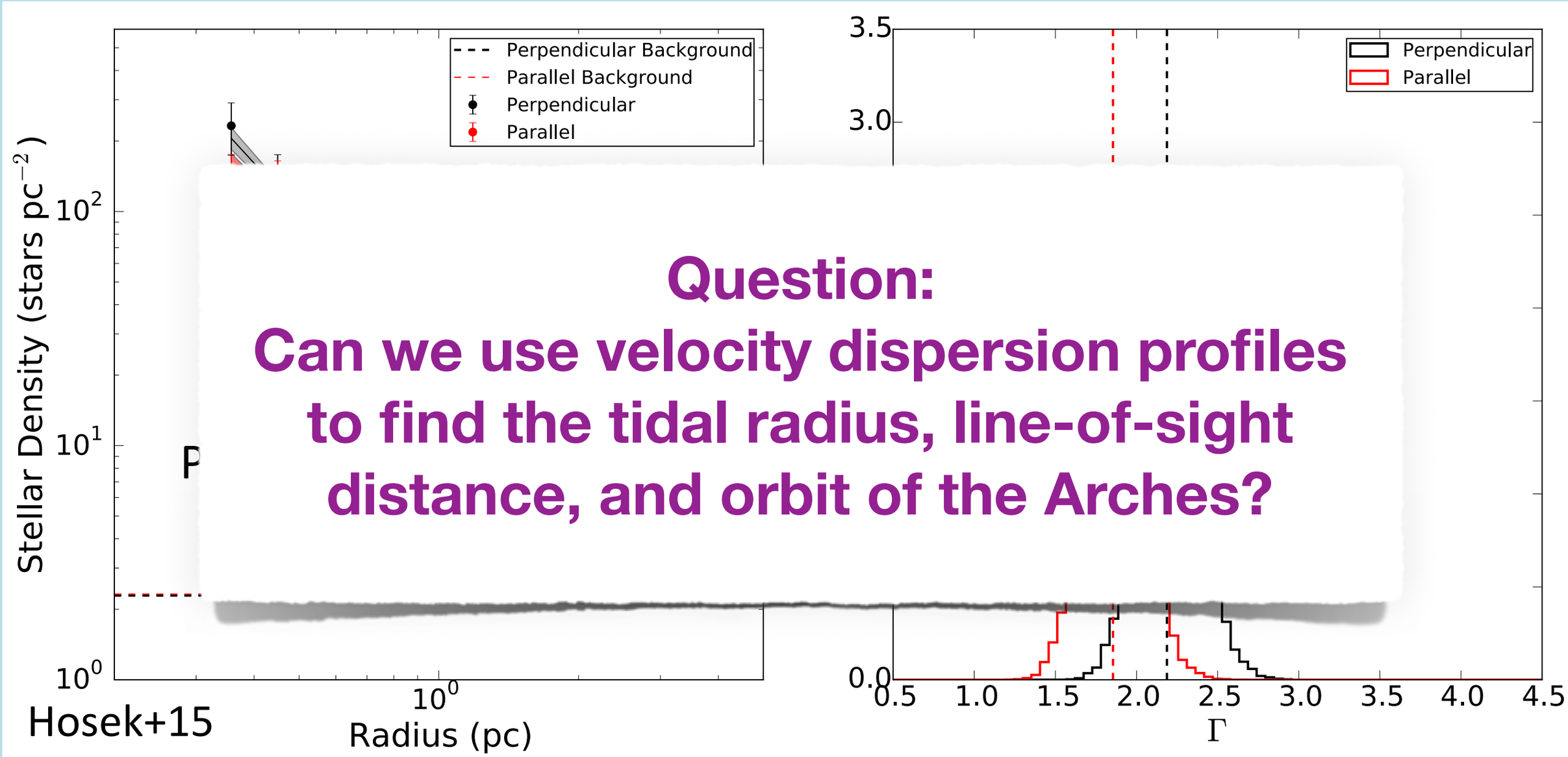
Mass Segregation Throughout Cluster





- KS test: not drawn from same parent population
  - Stolte+05, Espinoza+09, Habibi+13

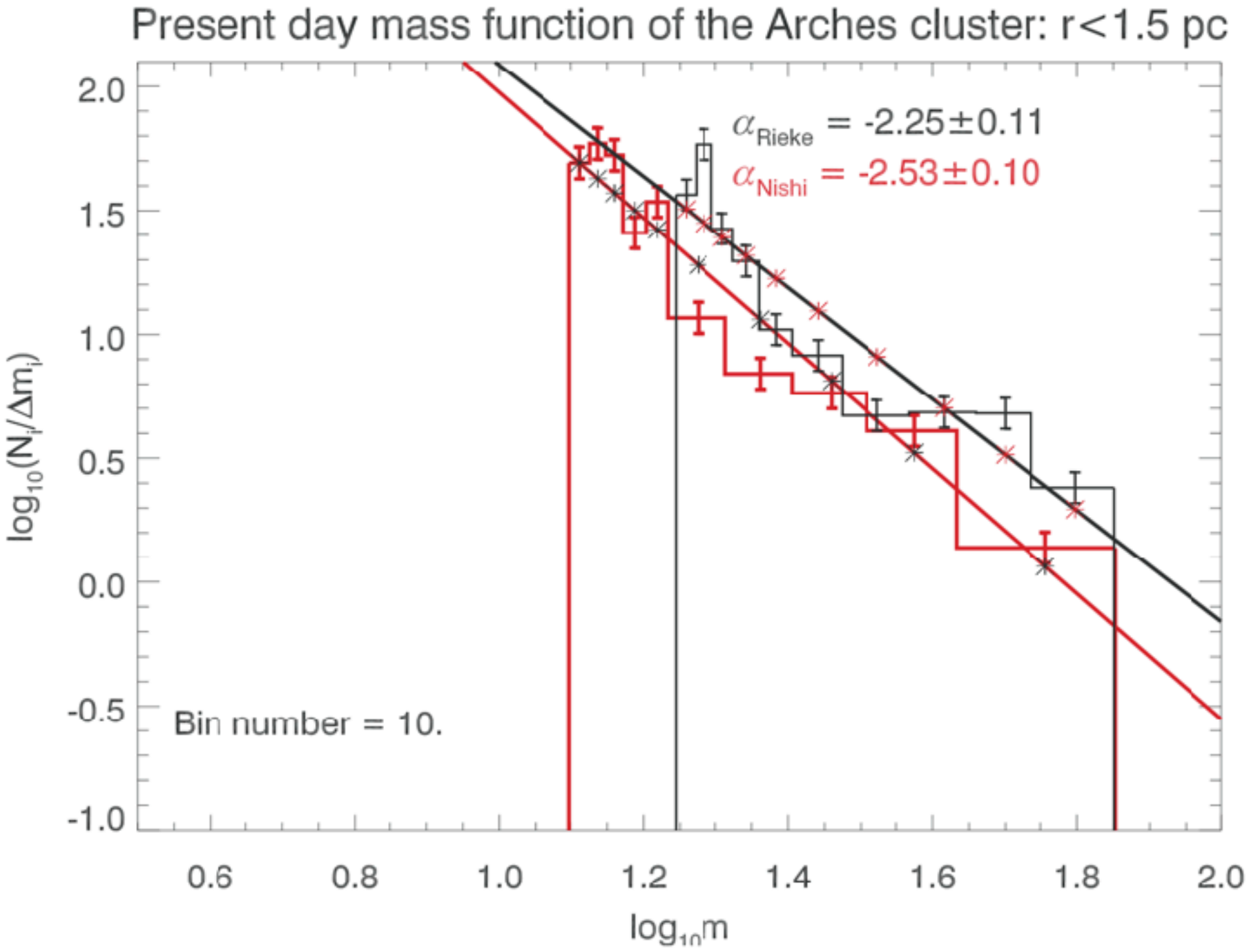
No Evidence of Tidal Tails

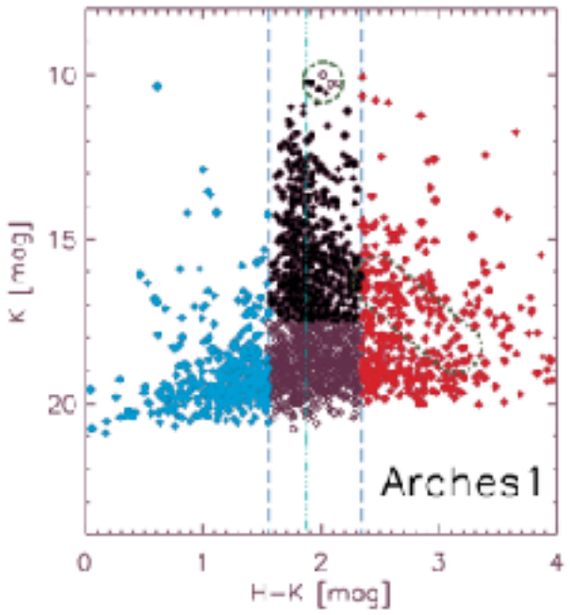


- KS test: cannot discount same parent population

Arches Cluster: Mass Function

Mass function from star counts: mass segregated, consistent with Salpeter…





Figures from Habibi+ 2013

Espinoza+ 2009
Stolte+ 2002, 2005
Kim+ 2006

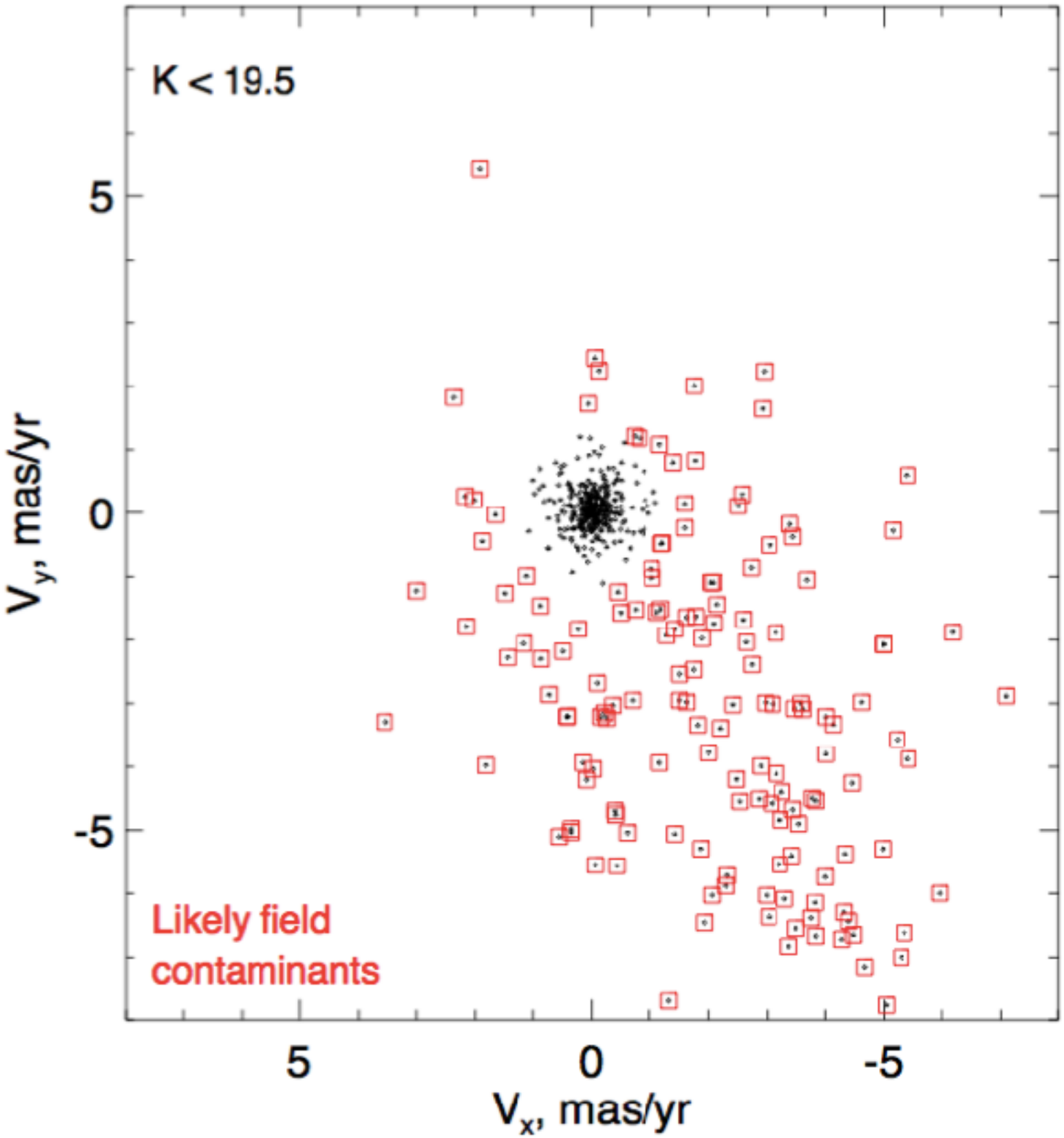
BUT

No proper motion membership.

M>10 M_{sun}

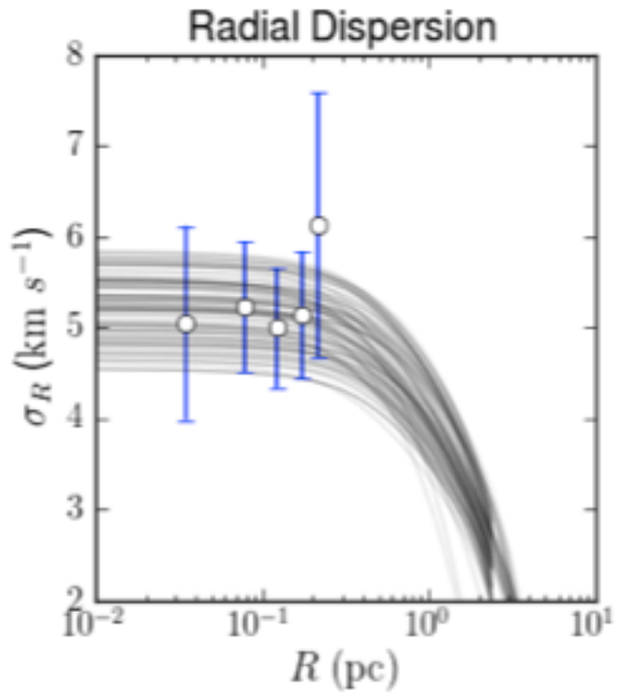
Keck AO (and soon HST) astrometry on the Arches cluster *center* used to measure internal velocity dispersion.

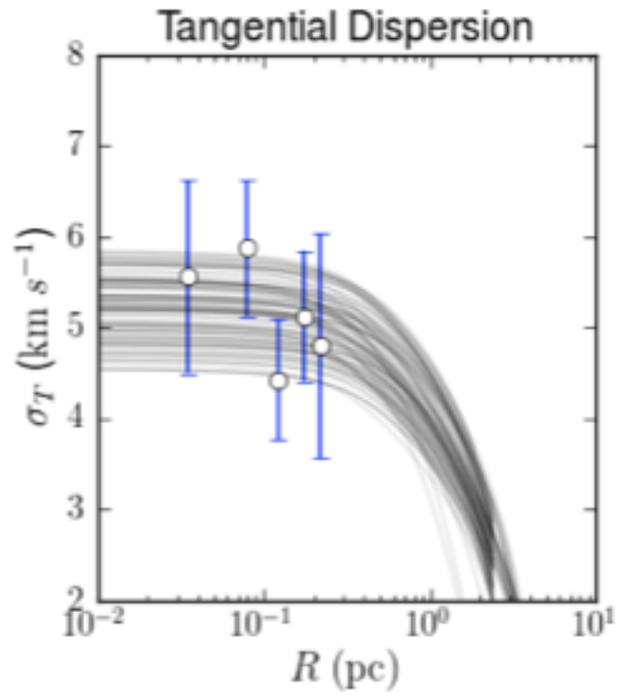
Velocity Vector Point Diagram

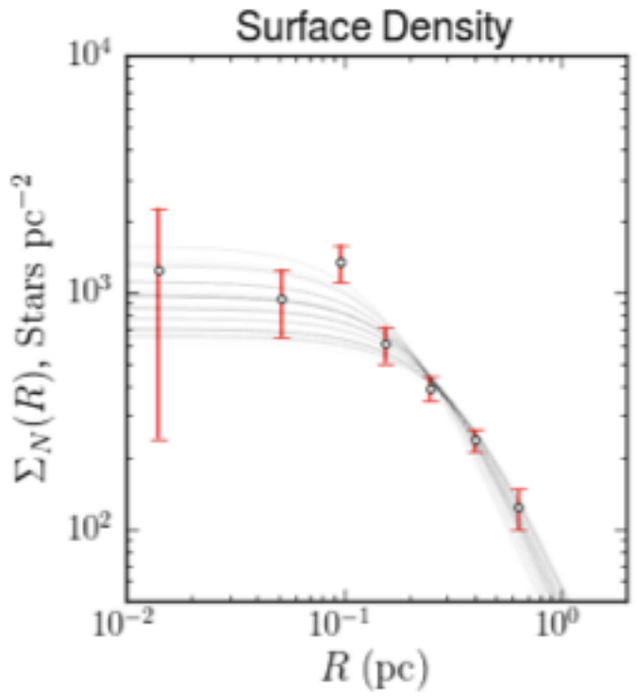


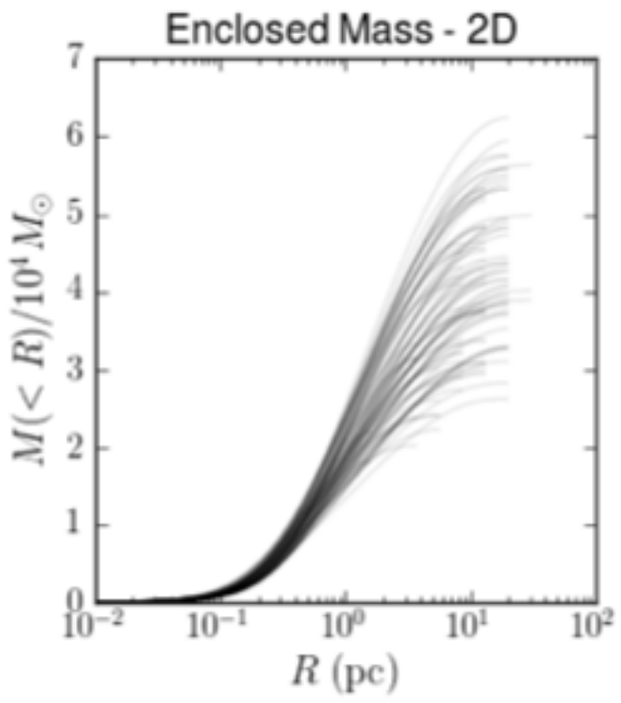
Clarkson+ 2012
Stolte+ 2008

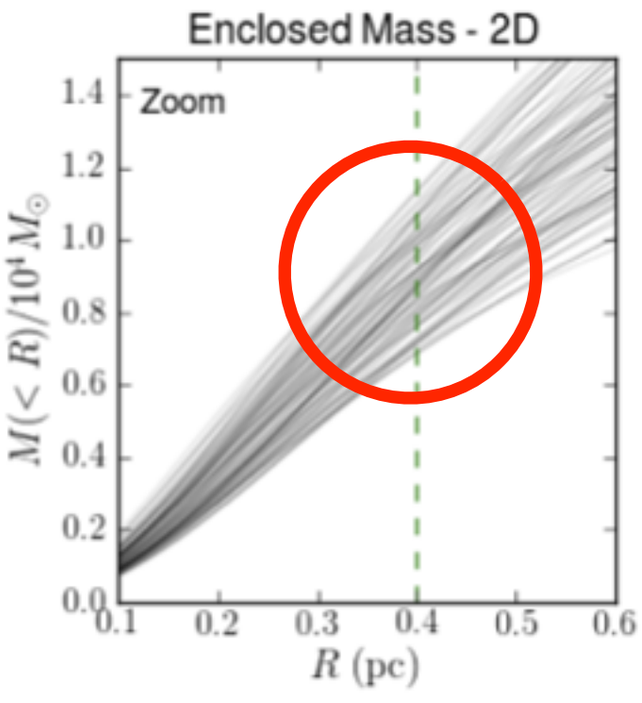
The Arches has ~10^4 M_{sun} within 0.4 pc.

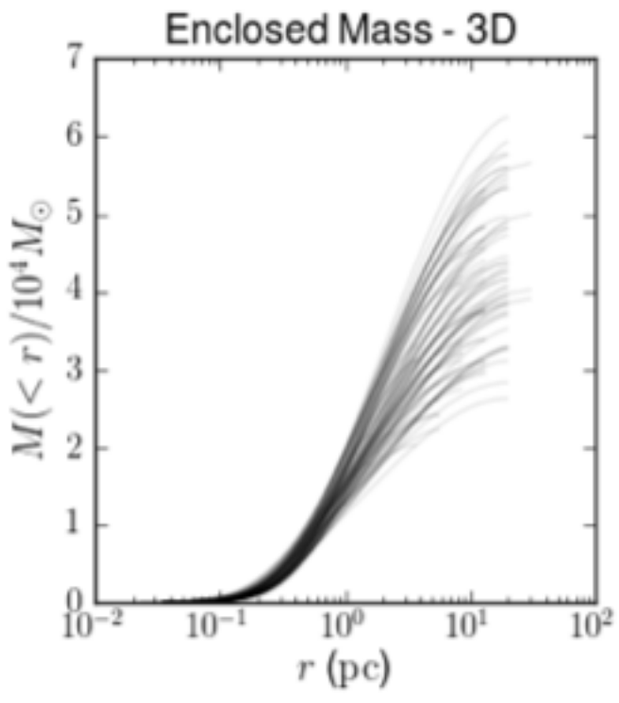








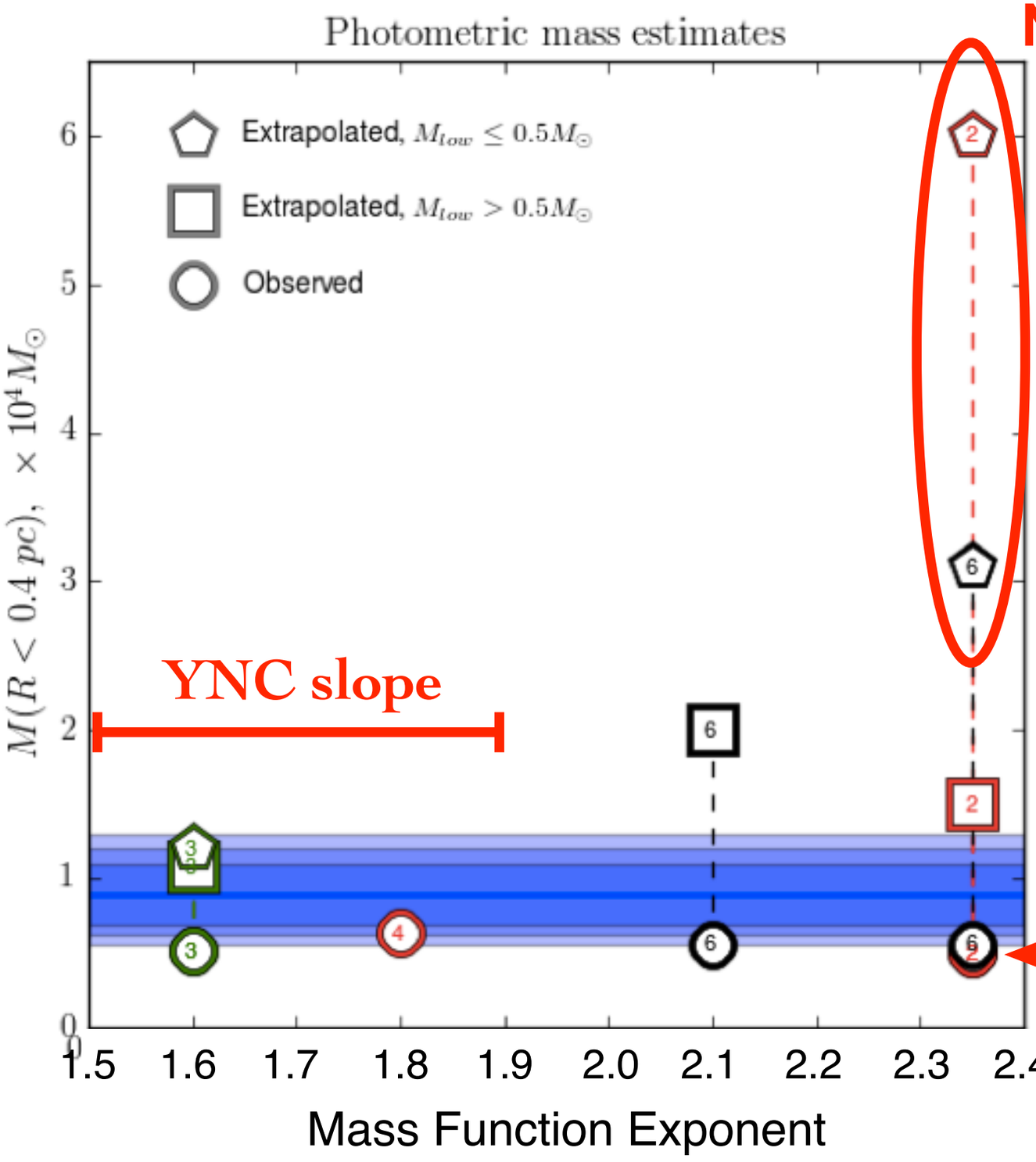




~10^4 M_{sun} in r<0.4 pc

Clarkson+ 2012

The dynamical mass is *inconsistent* with a normal IMF.



Normal

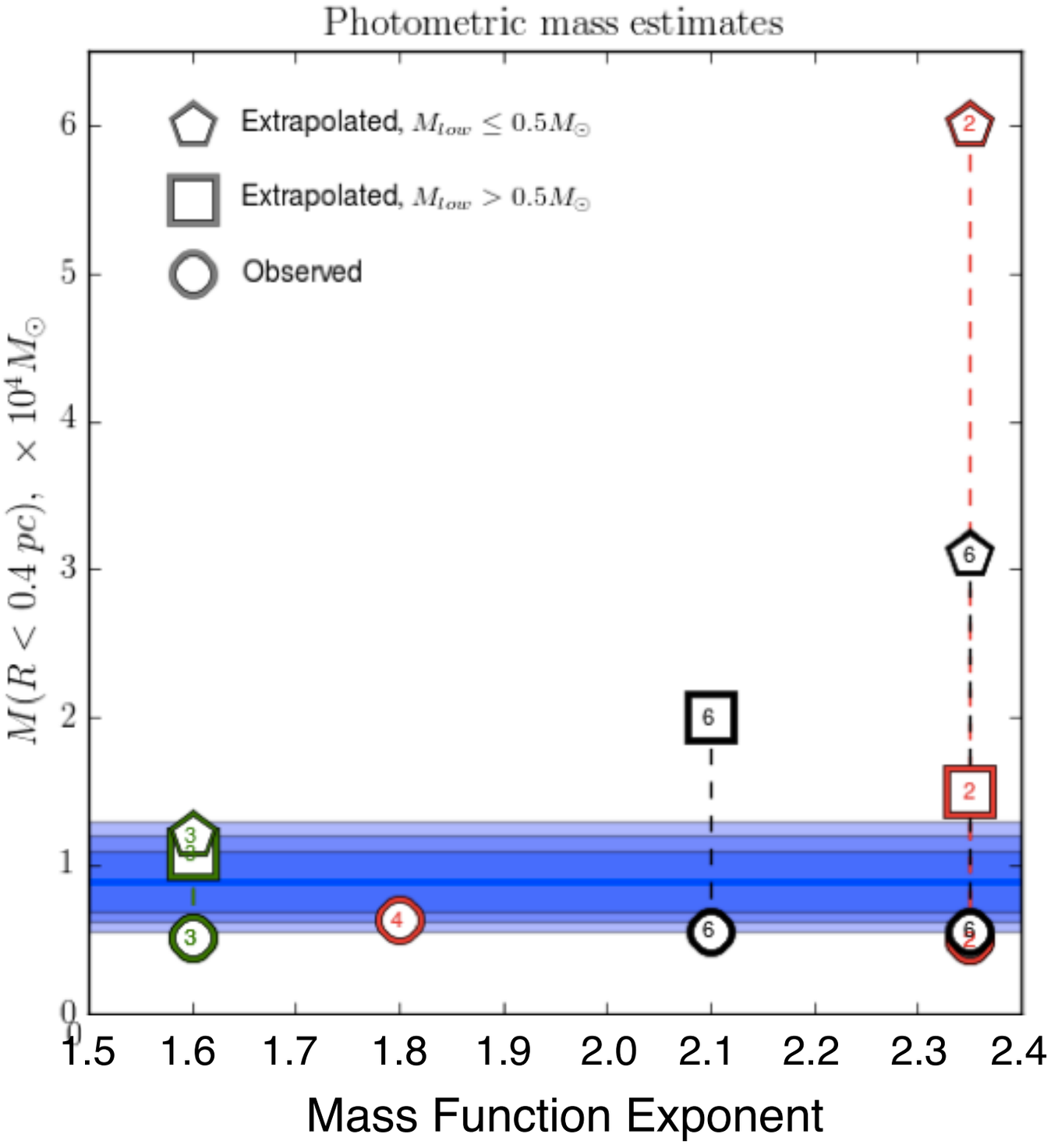
Viable Options:

- Bottom-light IMF
- Top-heavy IMF

Mass Function slope from photometrically observed stars (>5 M_{sun}).

Clarkson+ 2012

LOTS of assumptions about the structural and dynamical state of the cluster.



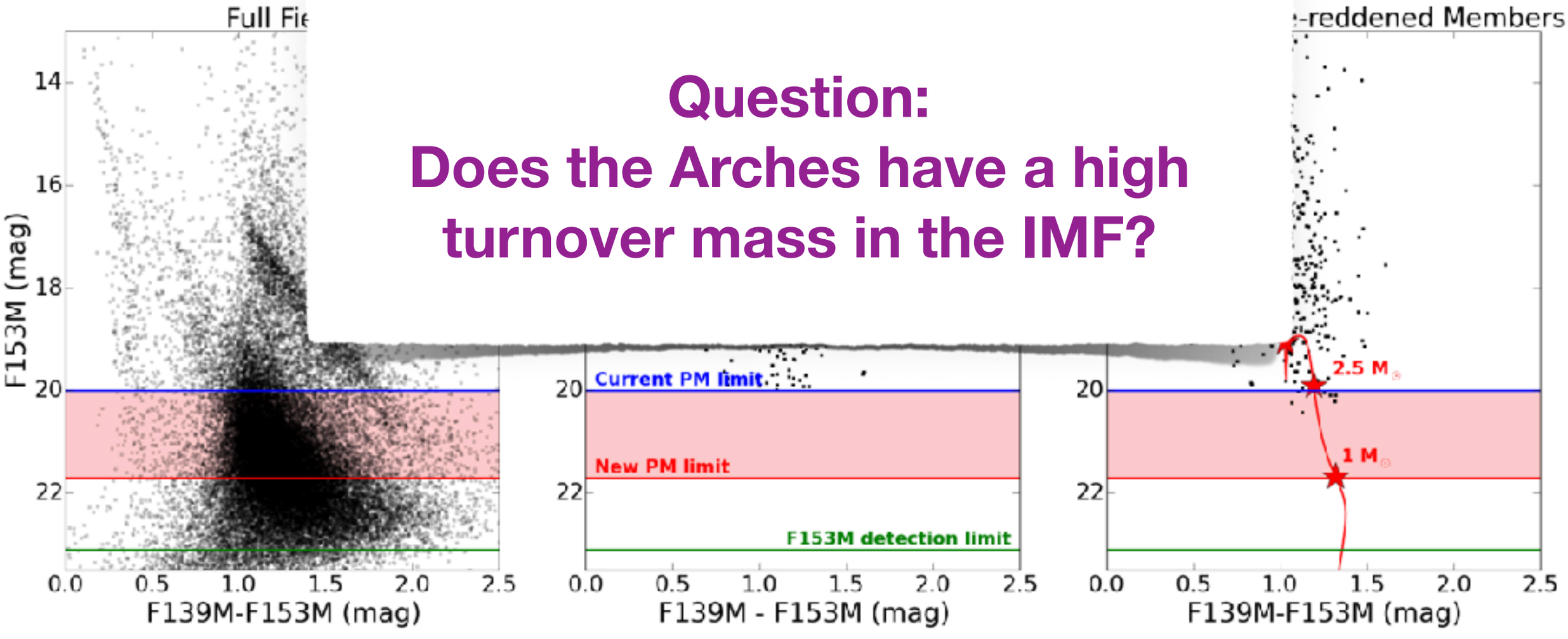
Assumptions

- Measured radial profile
- Virialized
- Mass-segregation doesn't impact.

Arches Cluster: Combined Structure, Dynamics, and Mass Function

coming soon… Hosek+ in prep

Question:
Does the Arches have a high turnover mass in the IMF?



HST NICMOS
Spitzer IRAC

Arched
Filaments

2-3 Myr

Arches
Cluster

Quintuplet
Cluster

Pistol Star

3-5 Myr

4-6 Myr

Sgr A

Towards a complete view of the nuclear star cluster.

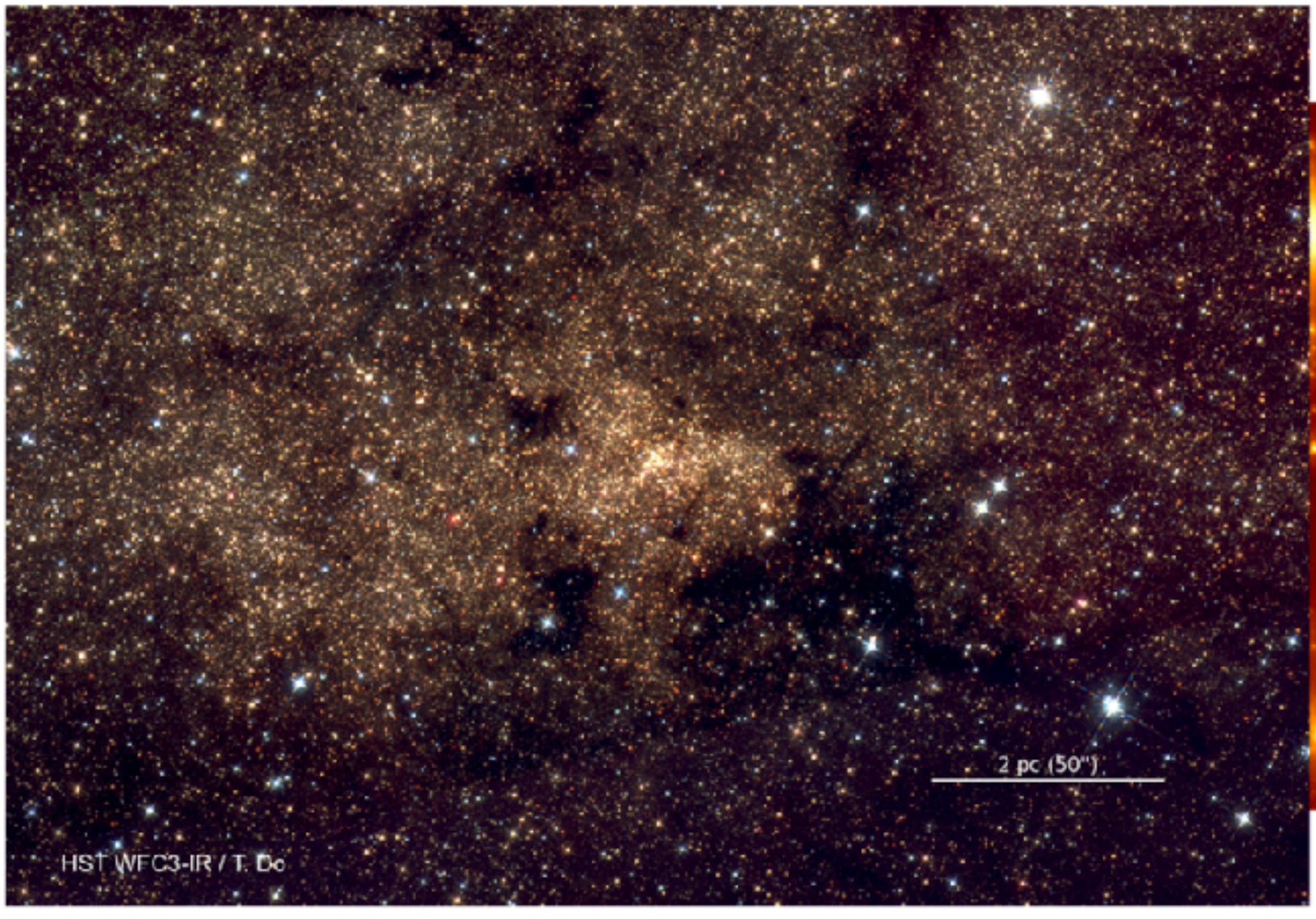
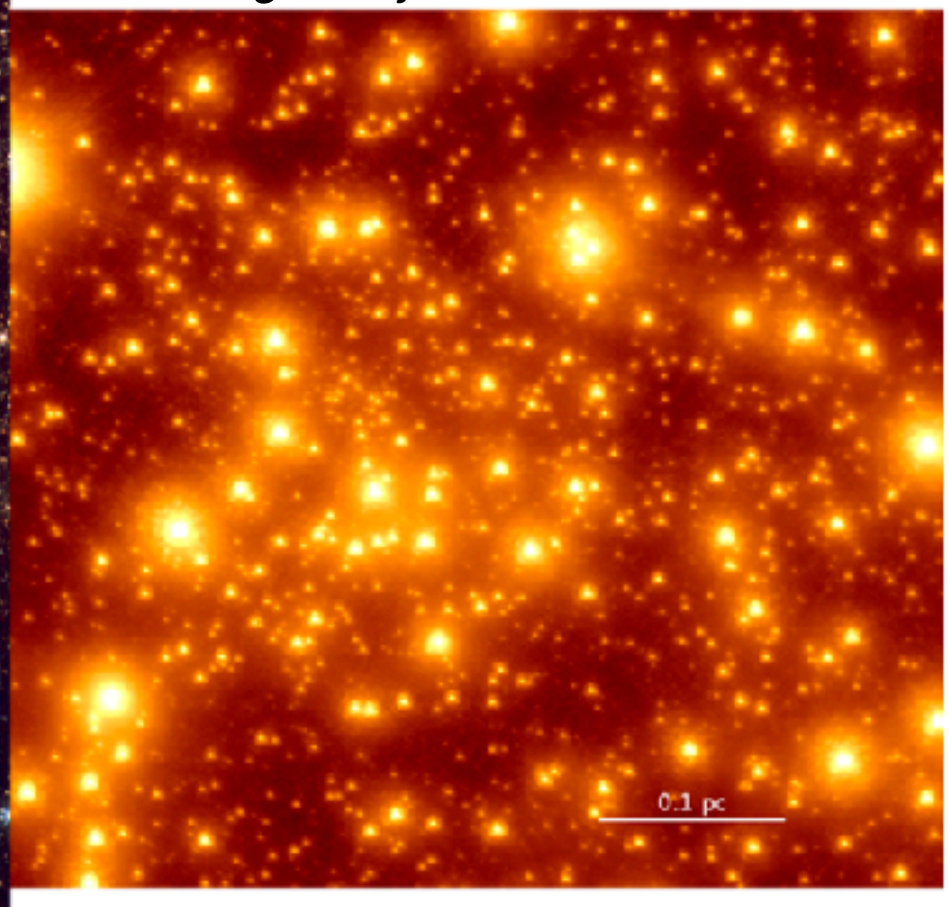


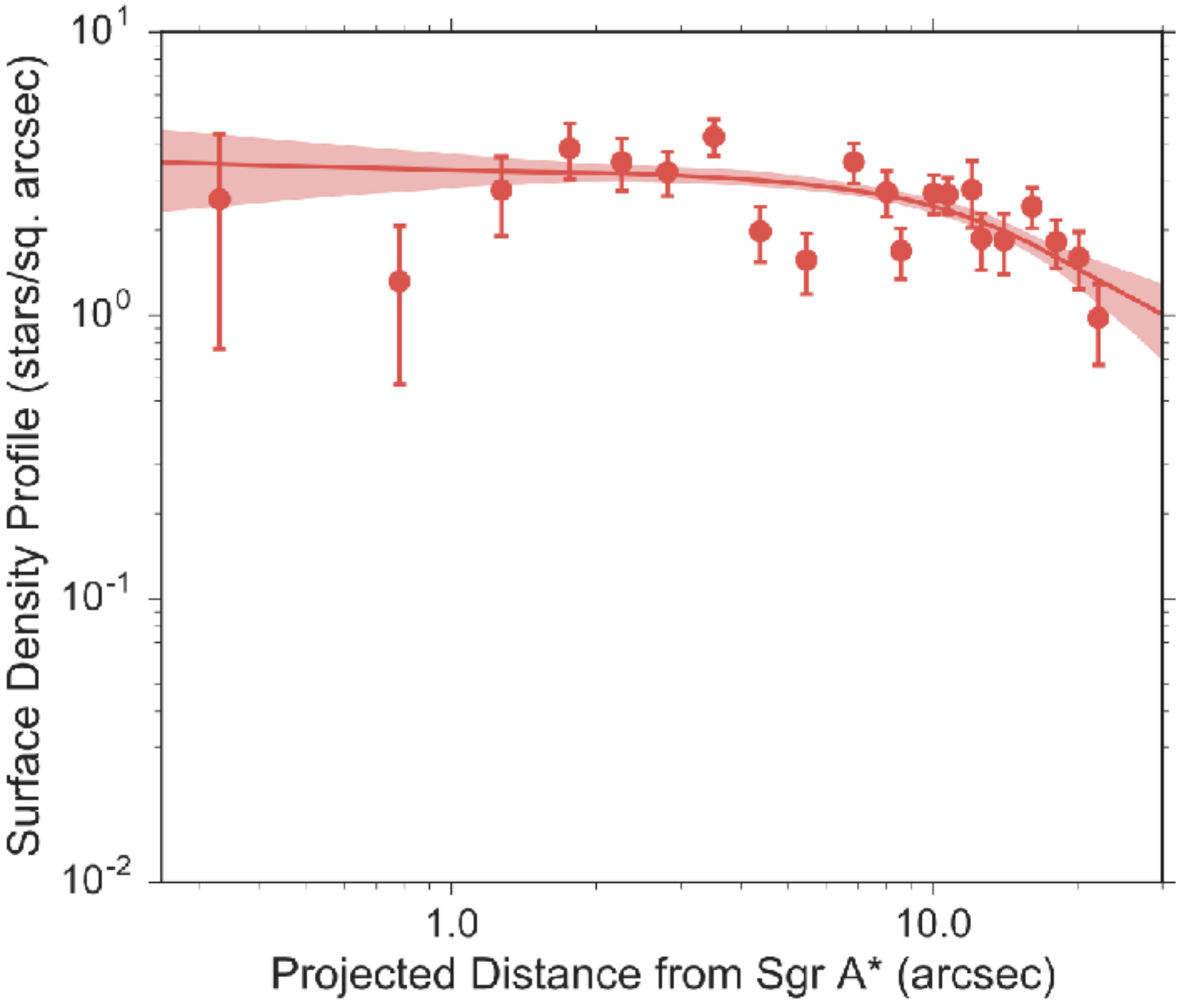
Figure by Do et al. 2016



Photometry - star counts, masses
Astrometry - proper motions, accelerations
Spectroscopy - RVs, T_{eff}, [Fe/H]

Feldmeier-Krause+ 2015, 2016
Nishiyama+ 2016
Stostad+ 2015
Schodel+ 2014
Do+ 2013, Lu+ 2013
Pfuhl+ 2011, Bartko+ 2010

The *old nuclear star cluster* has an unexpected radial profile.



No Bahcall-Wolf cusp.

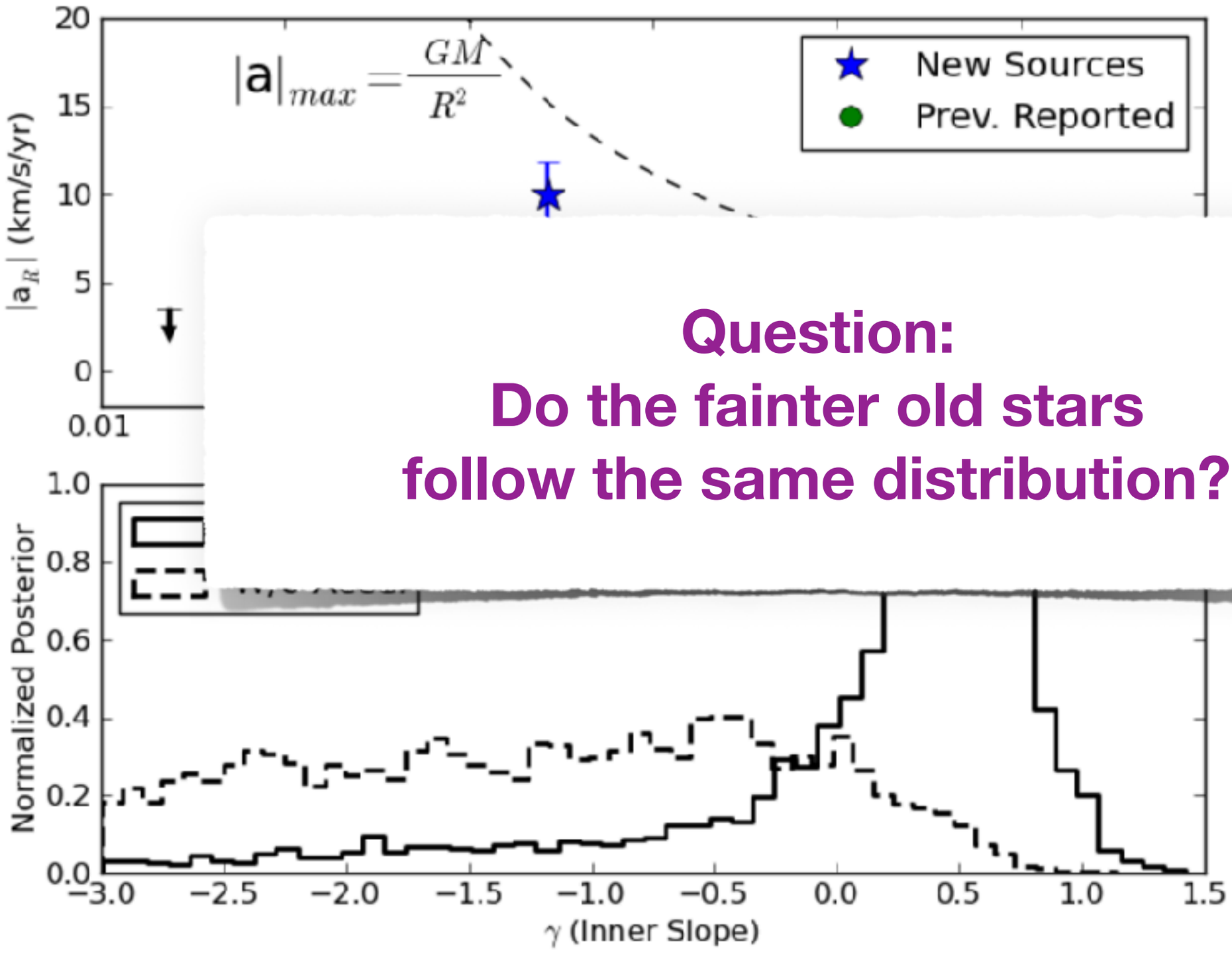
Flat within ~10” (0.4 pc) in projection.

Figure from Do+ 2016

also talk by Feldmeier-Krause

Feldmeier-Krause+ 2015
Schodel+ 2014
Do+ 2009, 2013
Bartko+ 2010
Buchholz+ 2009

The old nuclear cluster is likely cored - there isn't a hole.



Accelerations of old stars constrain line-of-sight distance.

m
- 2016

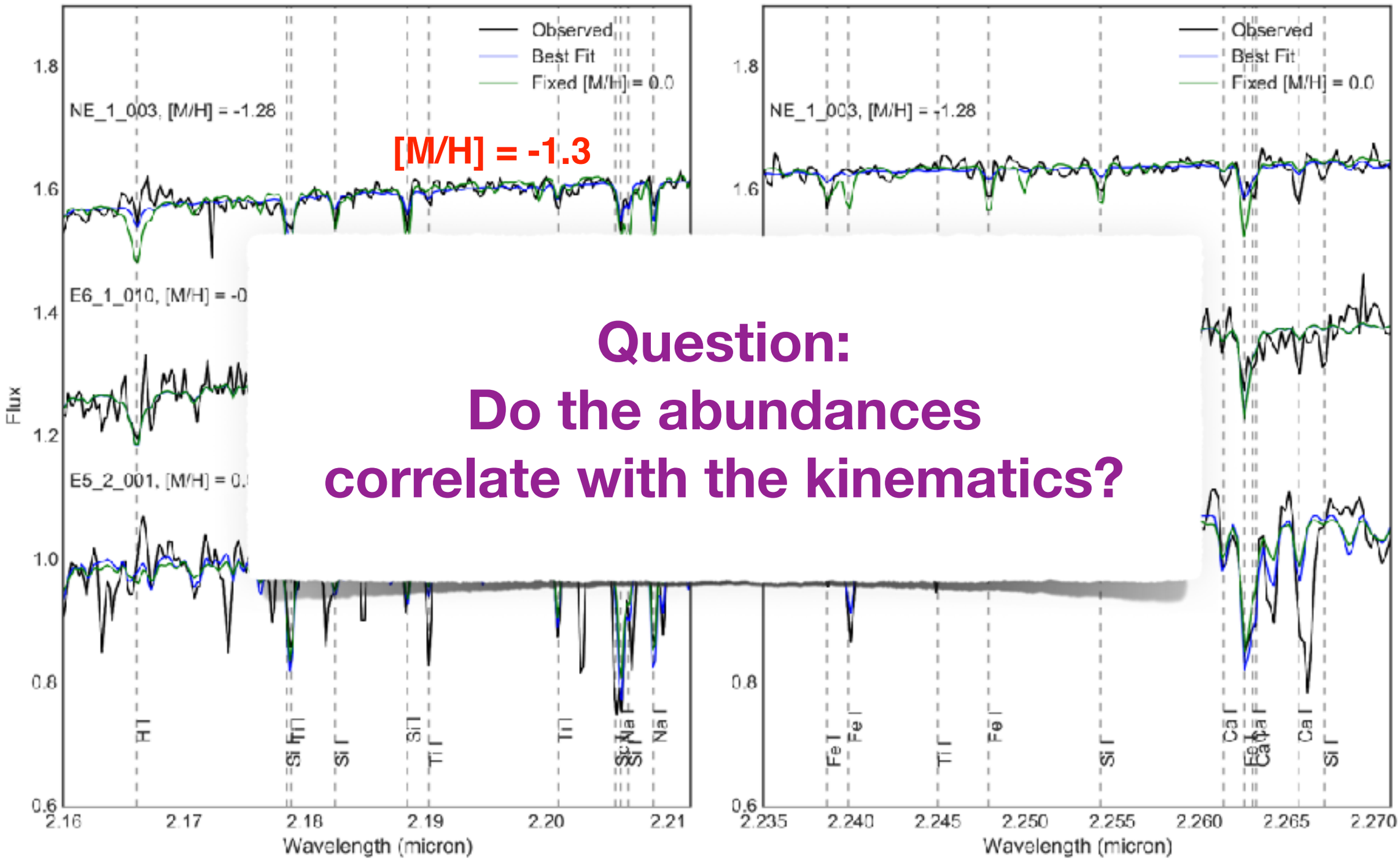
- in prep

Question:
Do the fainter old stars follow the same distribution?

BEWARE:

Magnitude limited sample (K<16)

Metallicity distribution in the central parsec is broad with extremes in high and low metallicity.



Question:
Do the abundances correlate with the kinematics?

Figure from Do+ 2015

Feldmeier-Krause+ 2015
but see Ryde+ 2016

Young Nuclear Cluster

Spectroscopic ID

10"

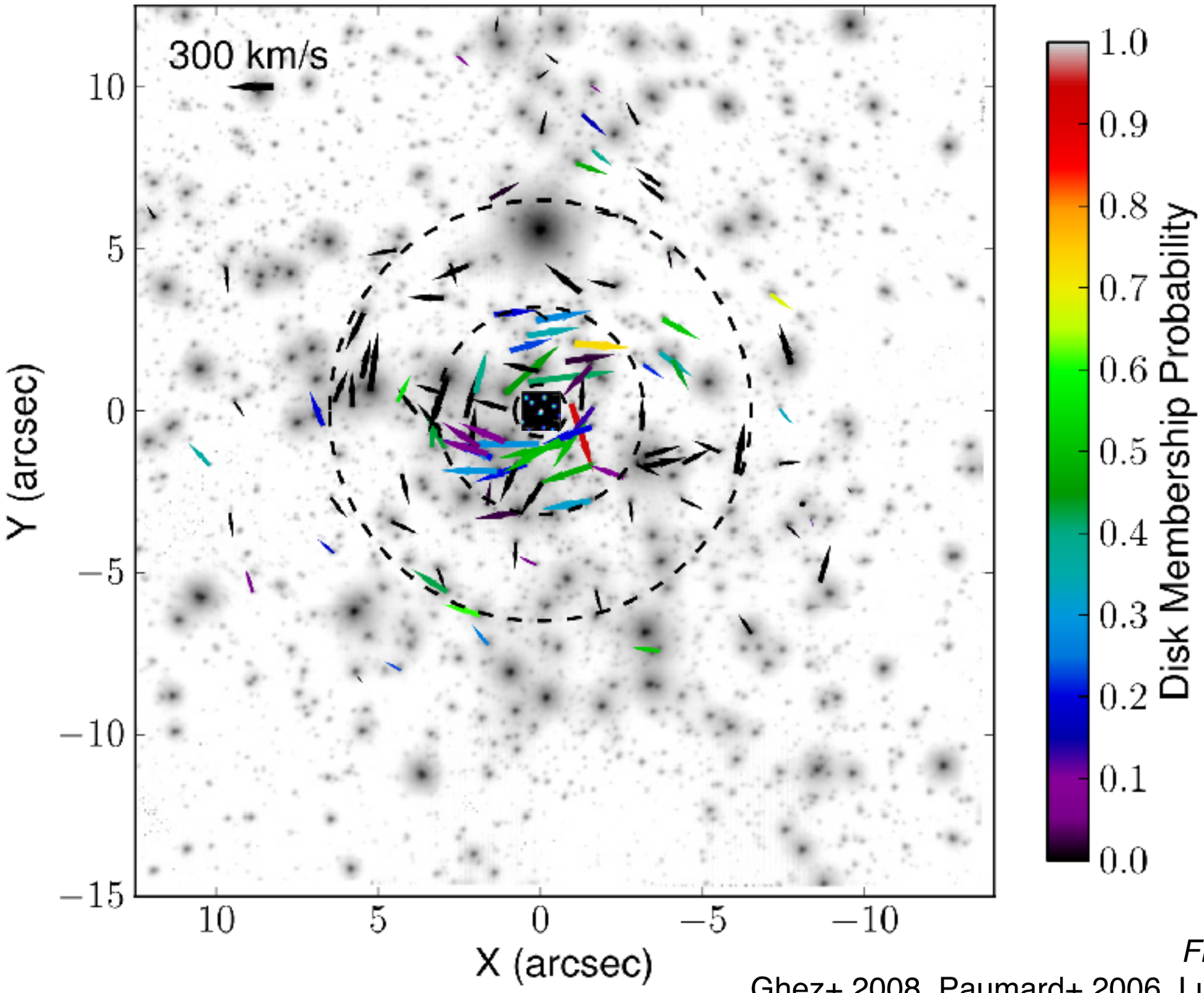
0.4 pc

N

E

Overlays from Do 2009, 2013; Bartko 2013

YNC stars distributed in disk (20%) + off-disk (80%).



~120 OB stars
(not complete)

r < 0.5 pc

25” = 1 pc

Figure from Yelda+ 2014

Ghez+ 2008, Paumard+ 2006, Lu+ 2009, Bartko+ 2009,
Feldmeier-Krause+ 2015, Stostad+ 2015, Boehle+ 2016

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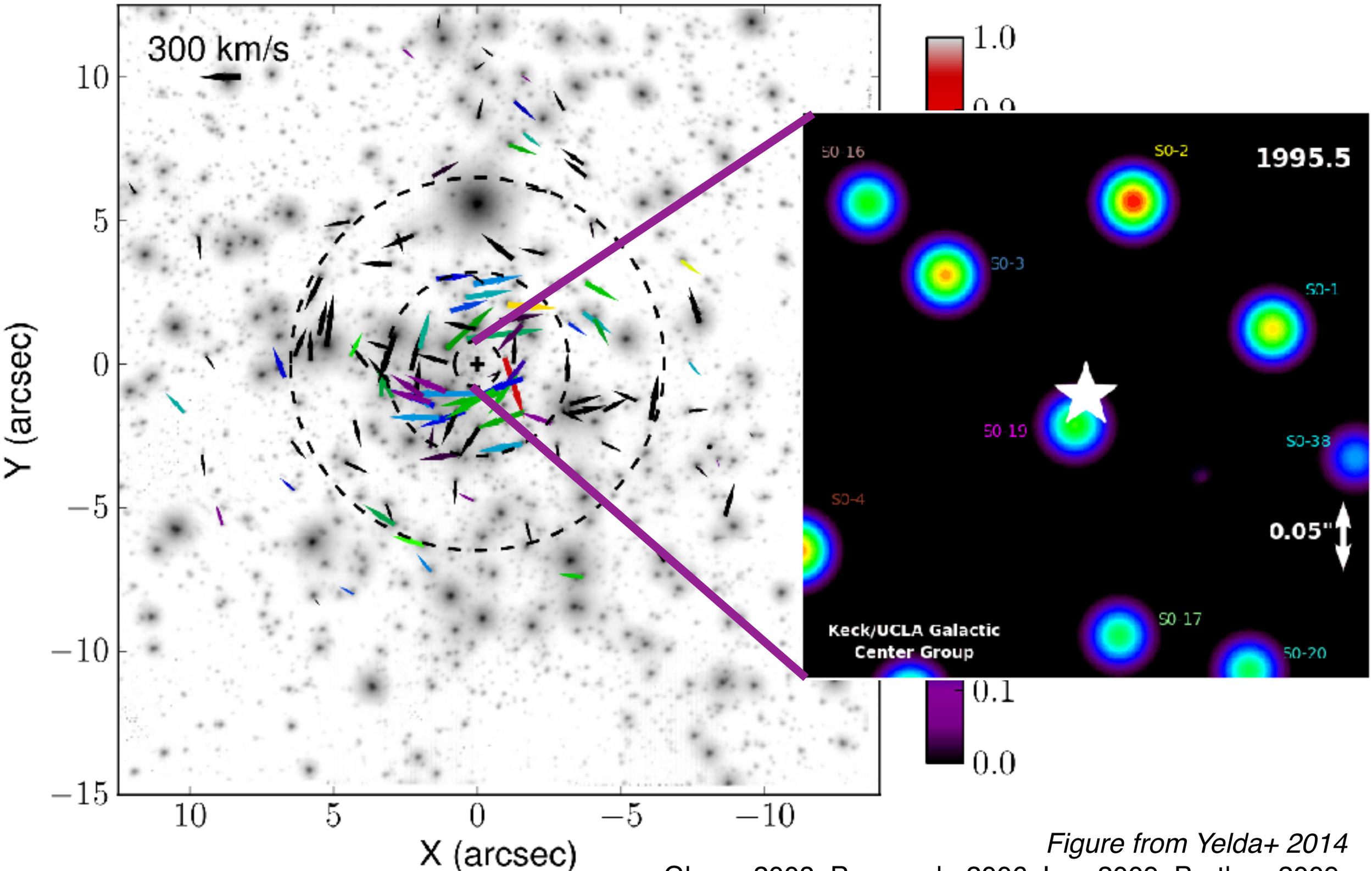
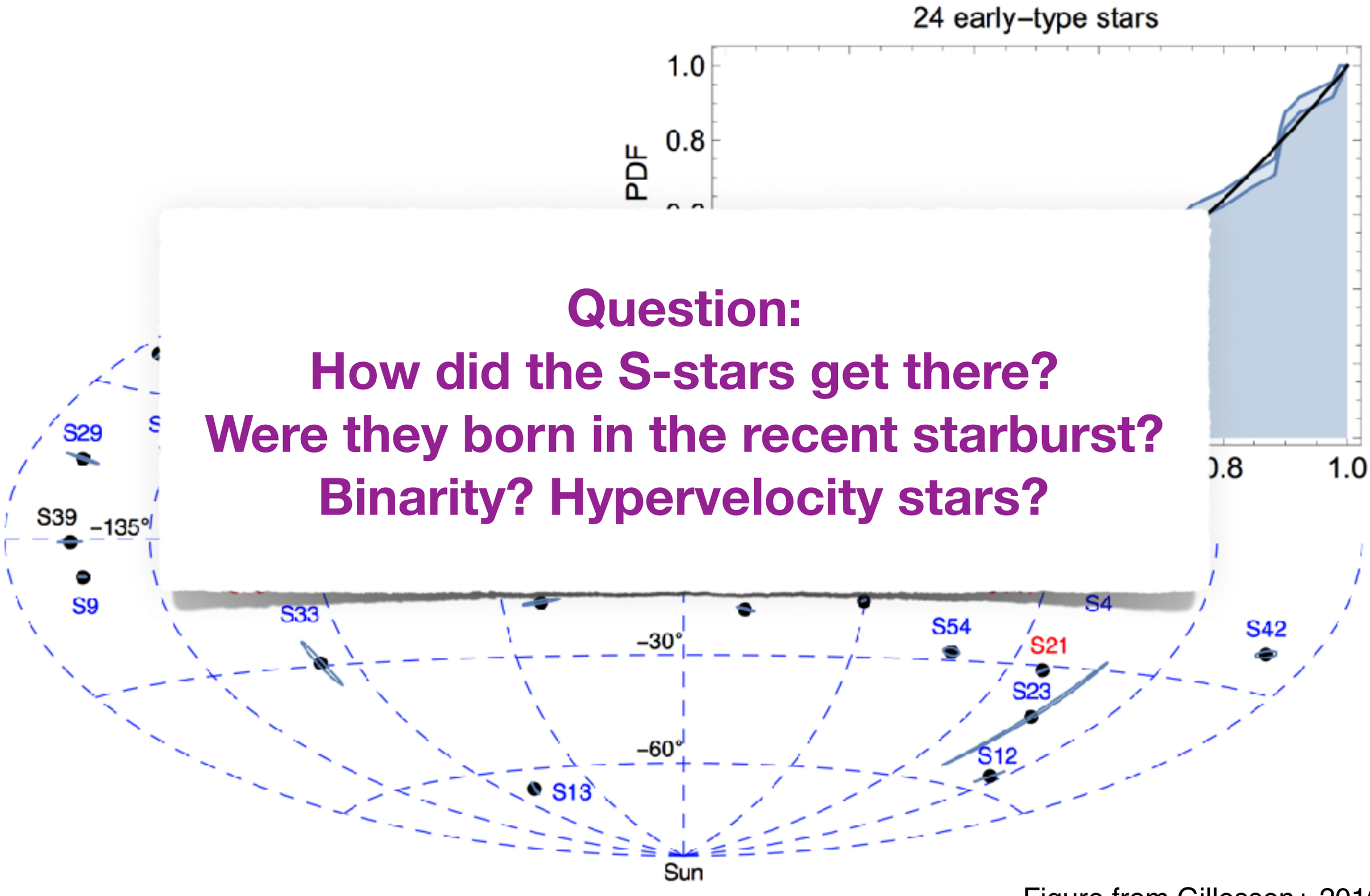


Figure from Yelda+ 2014

Ghez+ 2008, Paumard+ 2006, Lu+ 2009, Bartko+ 2009, Feldmeier-Krause+ 2015, Stostad+ 2015, Boehle+ 2016

Inner S-star cluster: randomly oriented, thermal eccentricities.

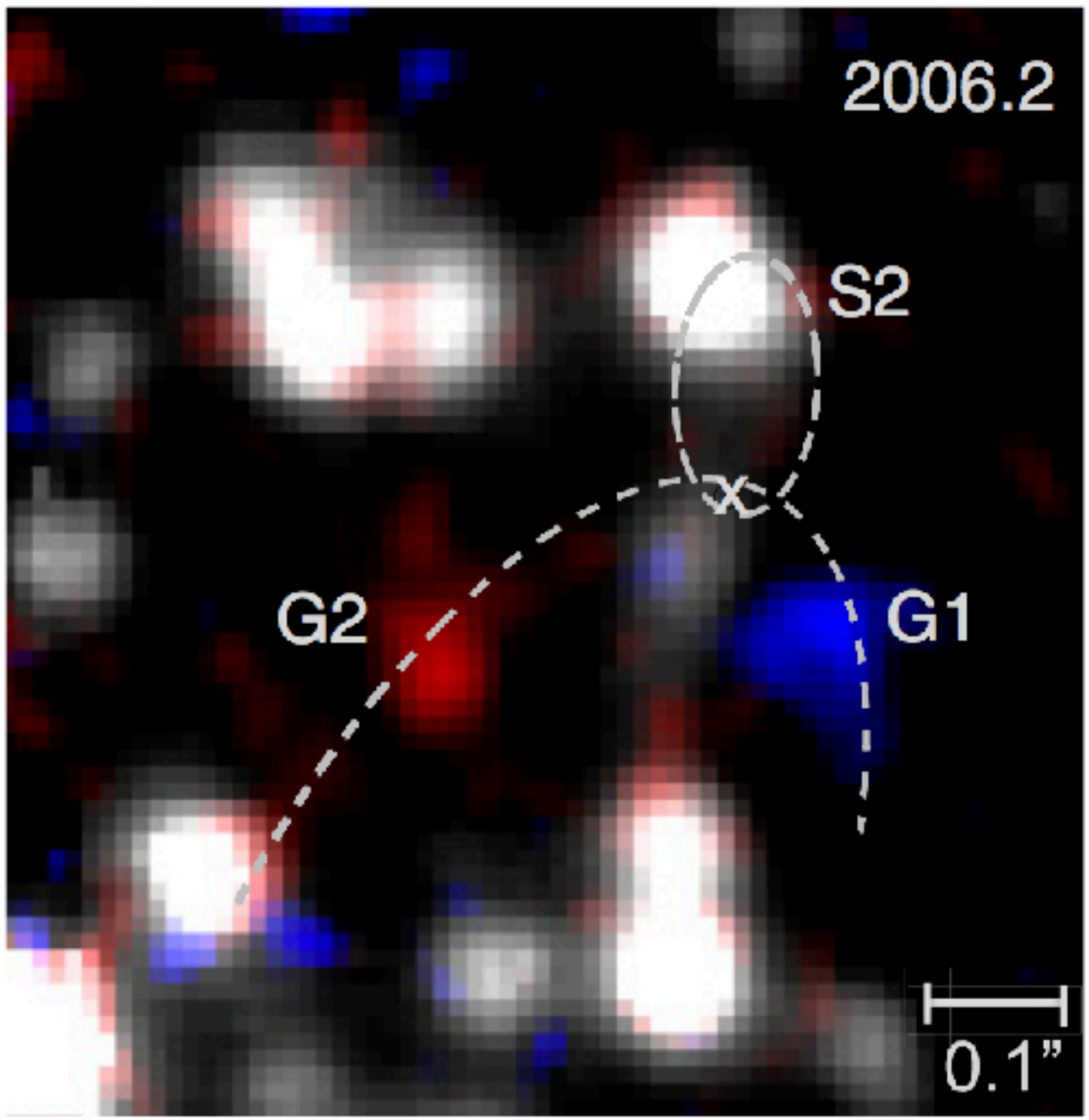


Question:
How did the S-stars get there?
Were they born in the recent starburst?
Binarity? Hypervelocity stars?

Figure from Gillessen+ 2016;

What are the G2-like sources?

Detected in Br-gamma emission line, L-band continuum.



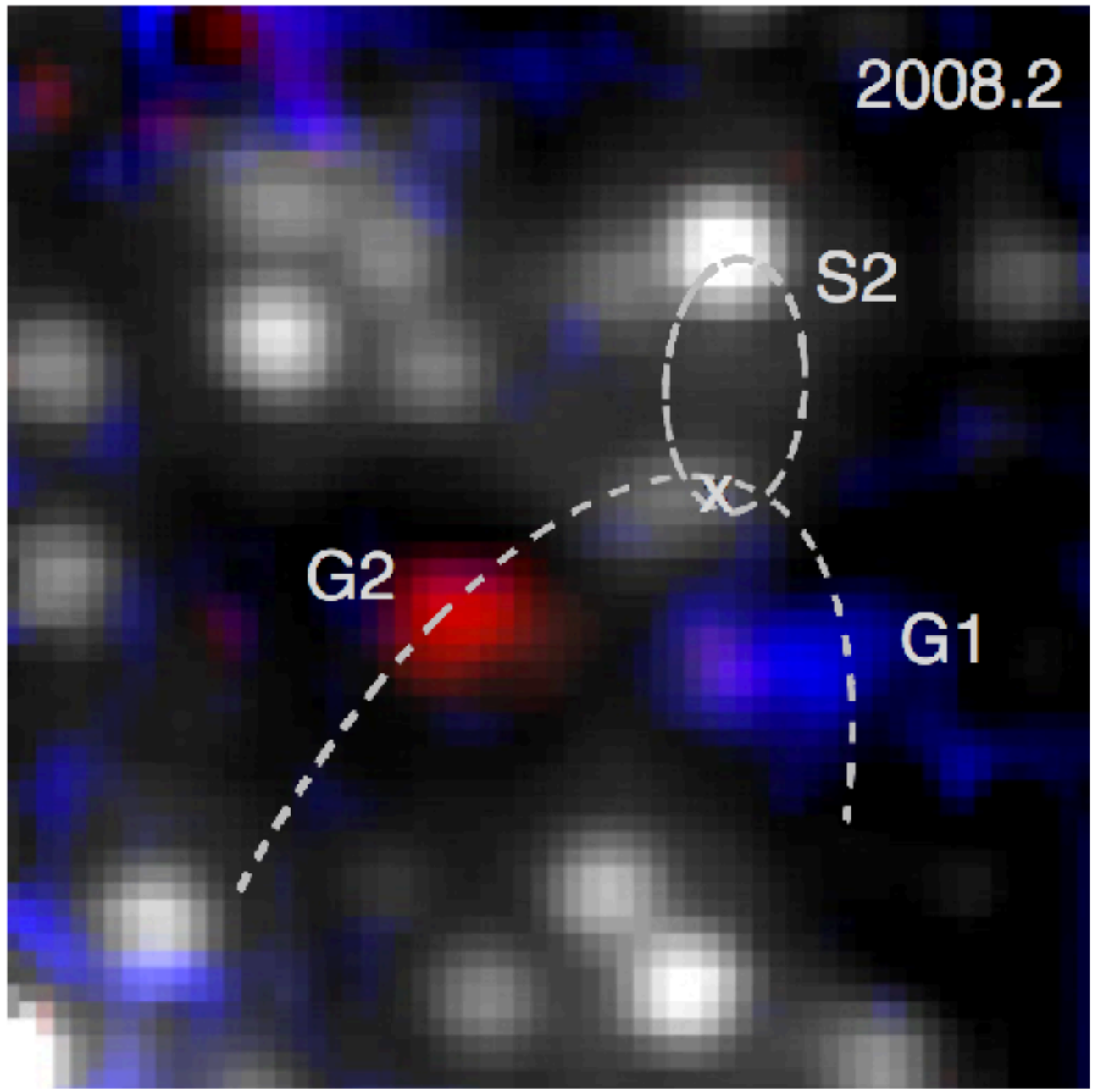
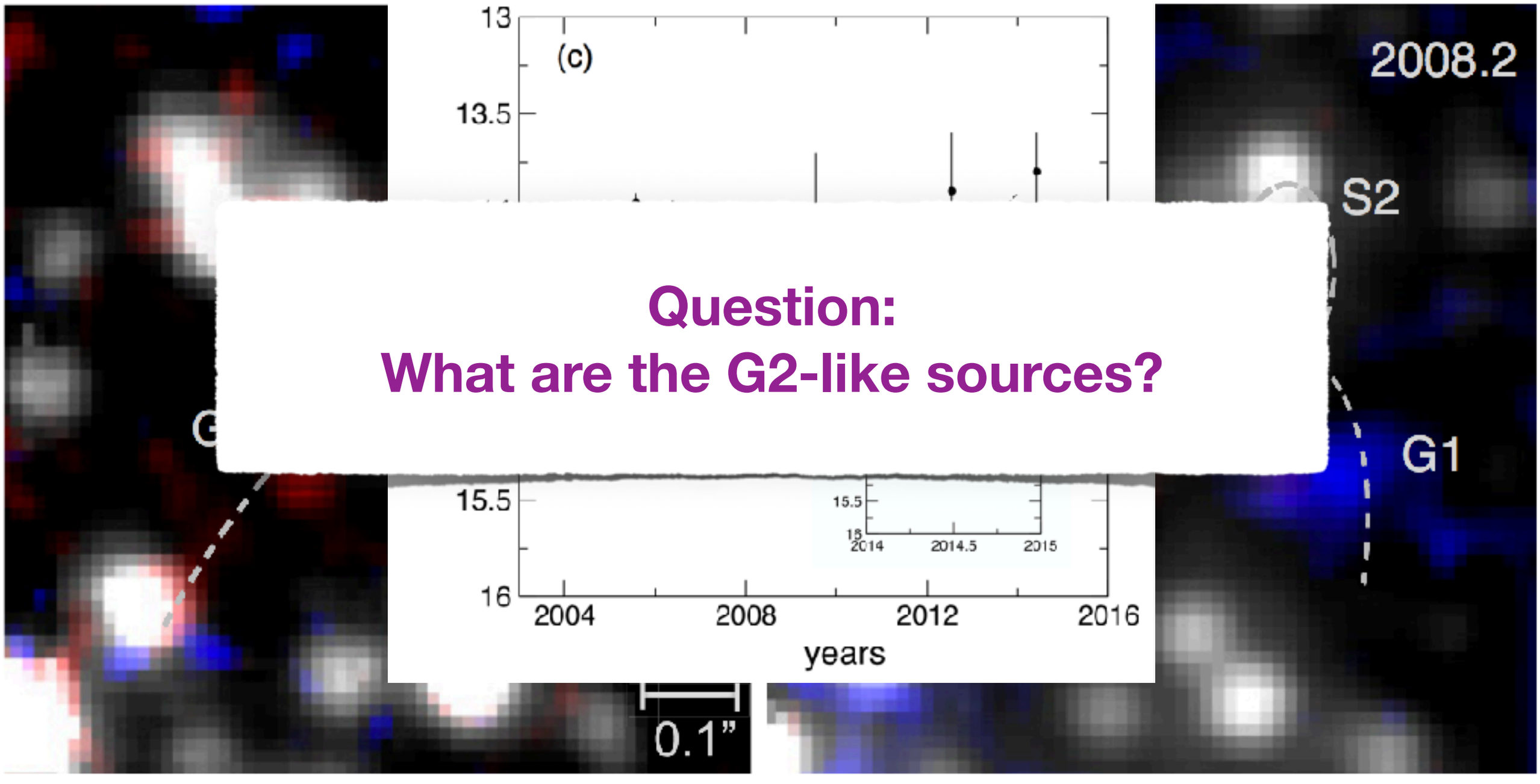


Figure from Pfuhl+ 2015

Gillessen+ 2013, Ghez+ 2014, Witzel+ 2014, …

What are the G2-like sources?

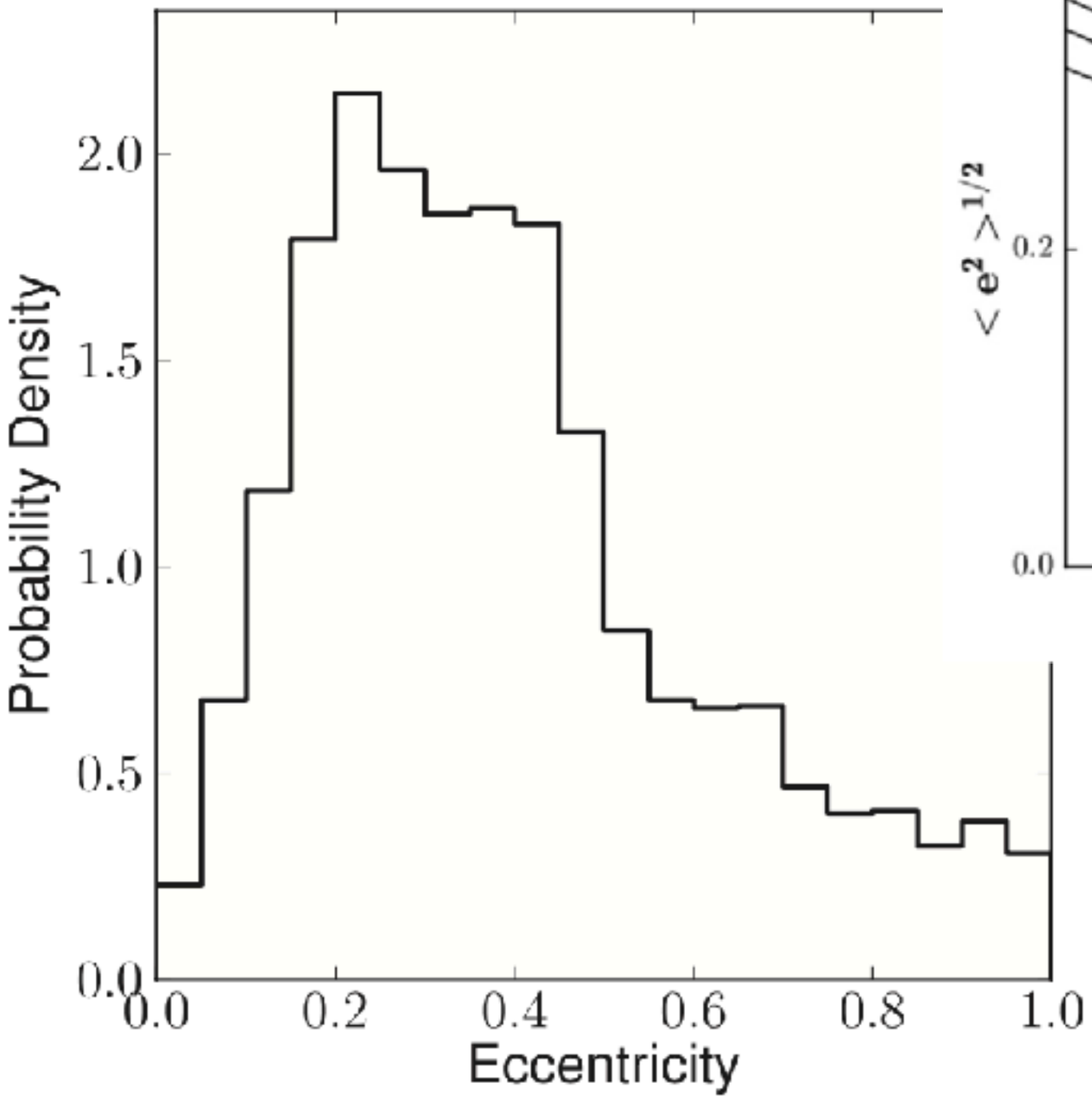
Detected in Br-gamma emission line, L-band continuum.
G2 survived periapse passage (in L-band).



Question:
What are the G2-like sources?

Figure from Pfuhl+ 2015, Witzel+ 2014
Gillessen+ 2013, Ghez+ 2014, Witzel+ 2014, …

YNC disk has non-zero eccentricity… today.



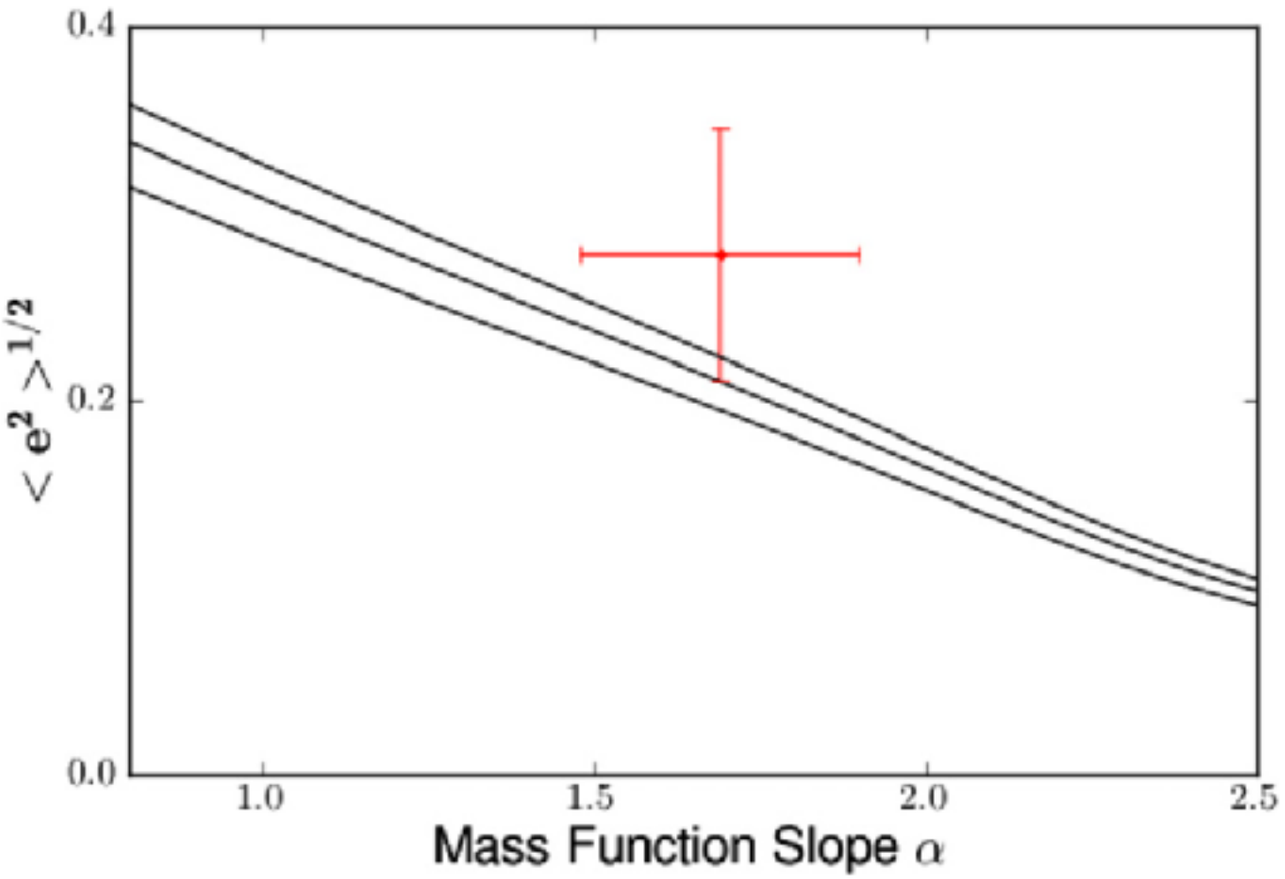


Figure from Yelda+ 2014; Lu+ 2013, Alexander+ 2007

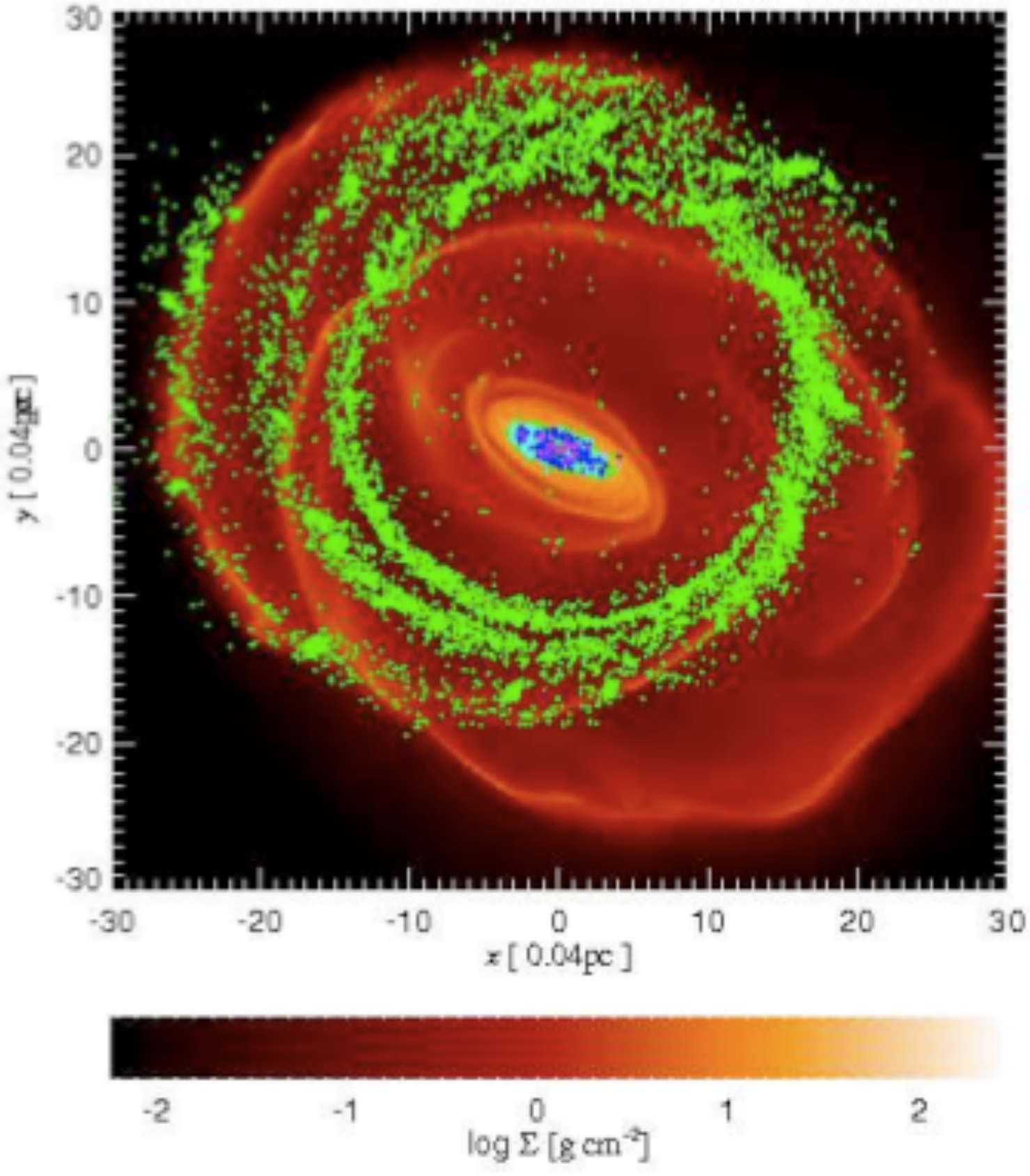
In situ formation is well-supported.

Cloud dump

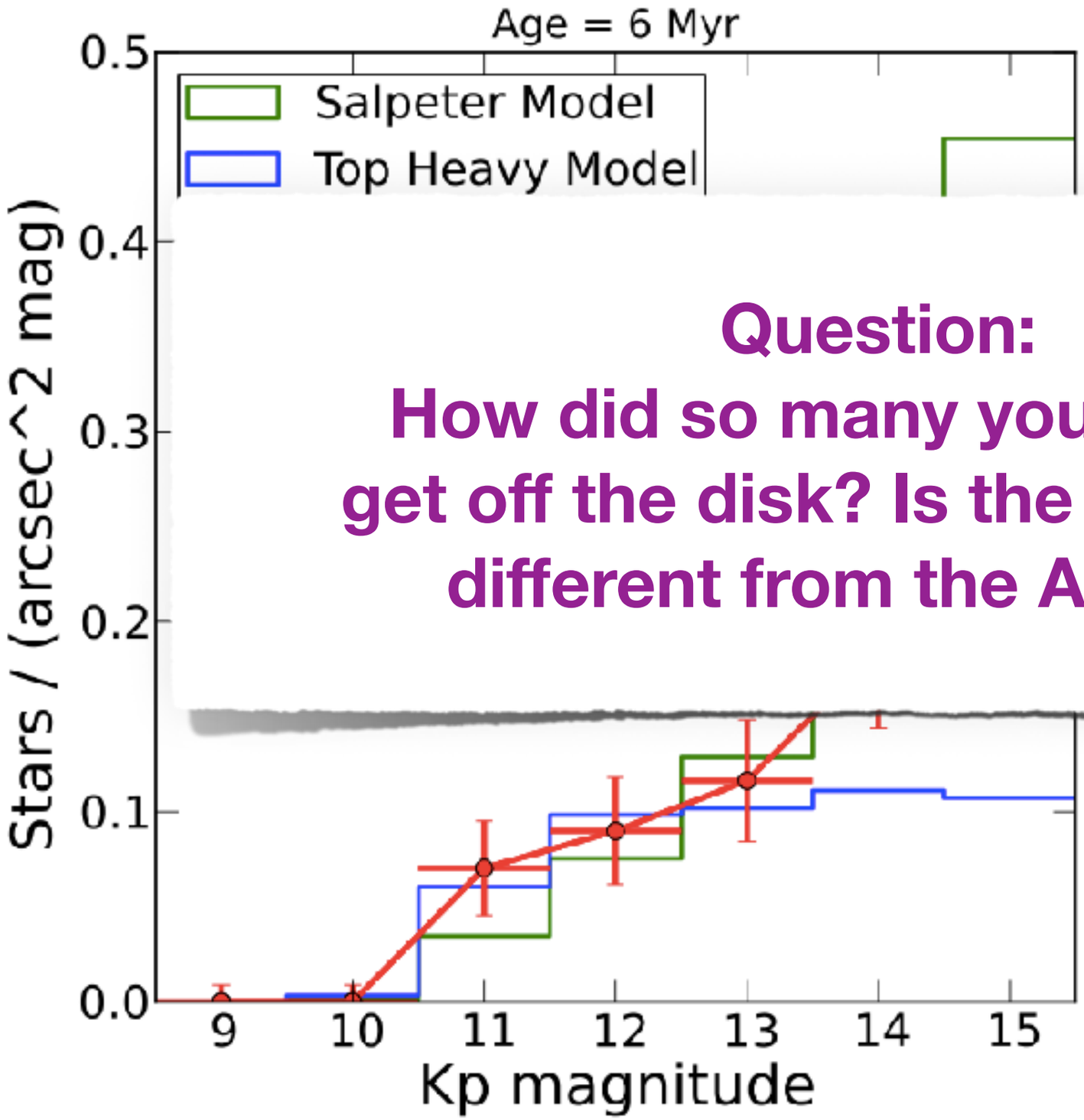
Cloud-cloud collision

Figure from Hobbs & Nayakshin 2009

BUT requires radial cloud infall



We observe a moderately top-heavy IMF, above 8 M_{sun}.

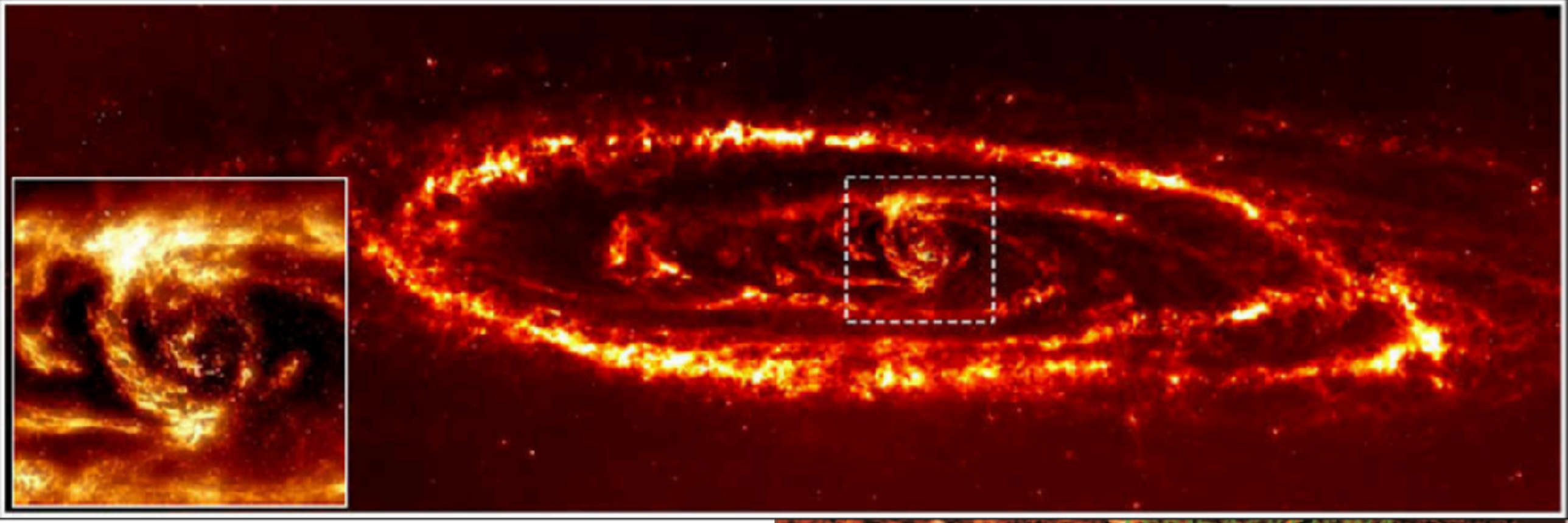


IMF slope = 1.7 +/- 0.2

.35 with nce

Question:
How did so many young stars get off the disk? Is the IMF really different from the Arches?

Lu+. 2013
Do+ 2013

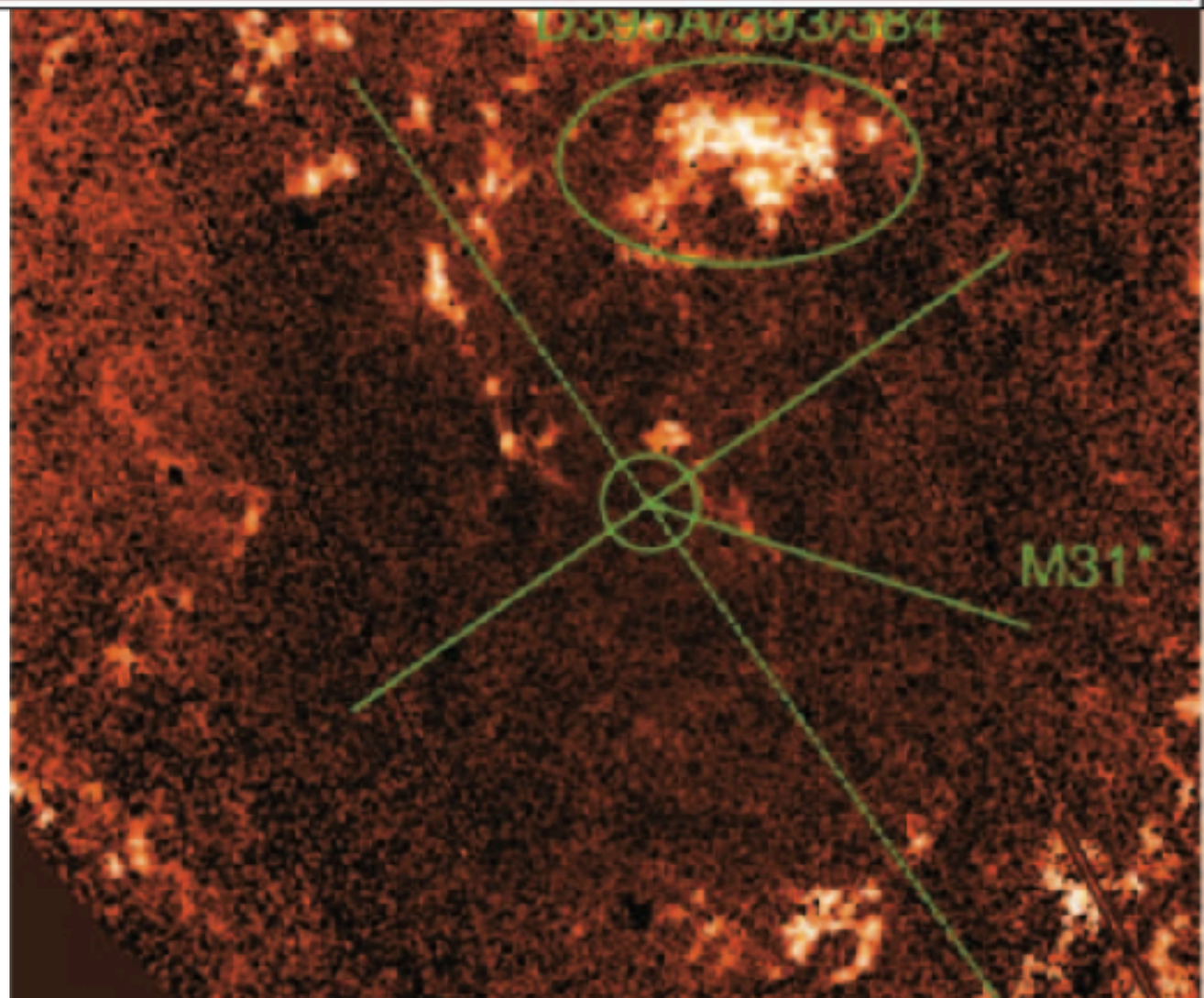


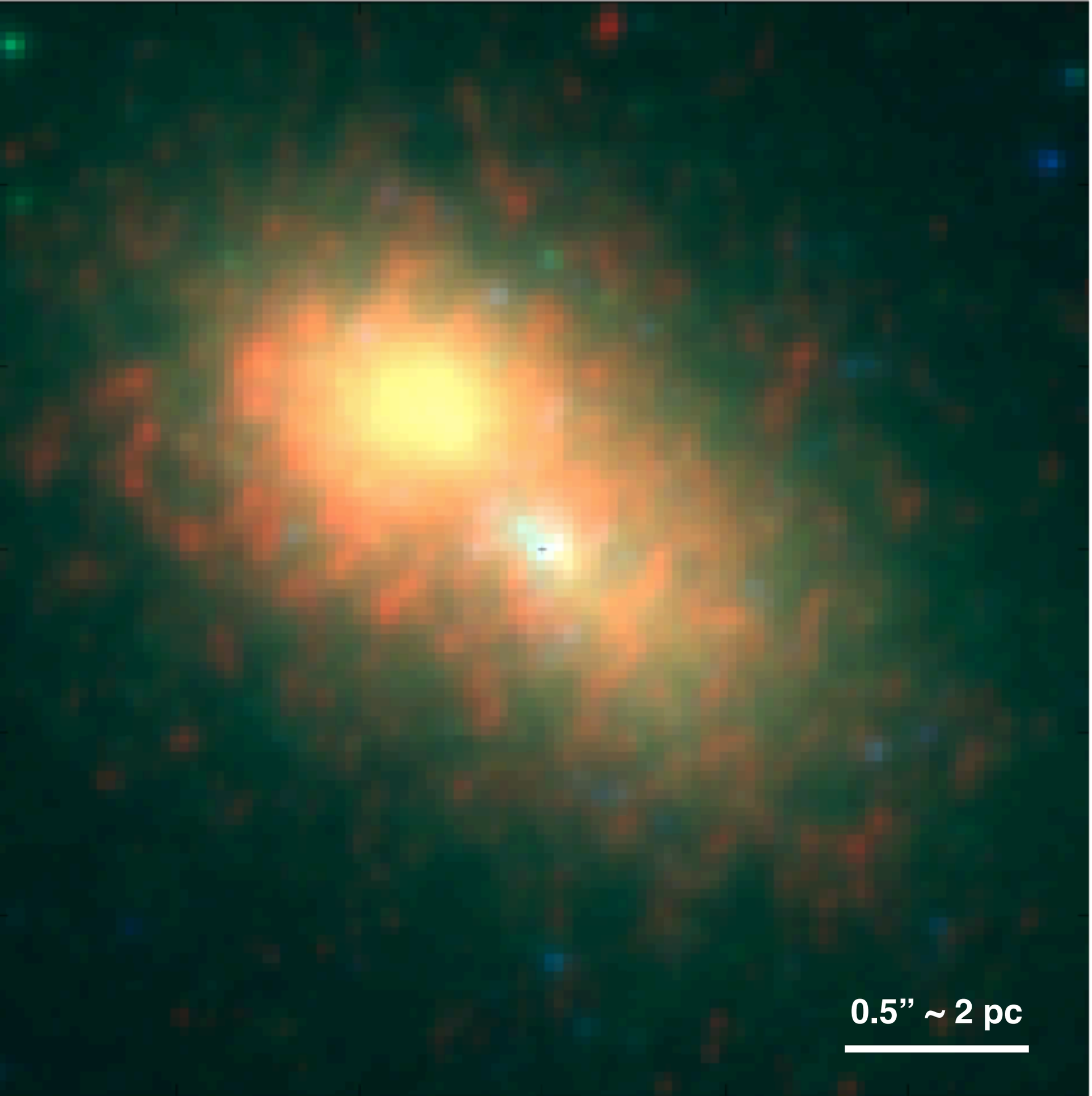
M31 Context

Nearly gas free within 100 pc.

No Arches-like clusters.

Lower figure from Dong+ 2016





M31 Nuclear “Cluster”

Coherent Eccentric Disk of Old Stars

Compact Disk of Young Stars (50-100 Myr)

Black Hole ~10^8 M_{sun}

Figure from Lockhart, Lu, et al., in prep.

M31 Dynamics Fun!
— stay tuned…

Question:
Could we see an M31-like eccentric disk in the MW? In other nearby NSCs?

Figure from Lockhart, Lu, et al., in prep.

Future: Gaia, JWST, WFIRST, ELTs

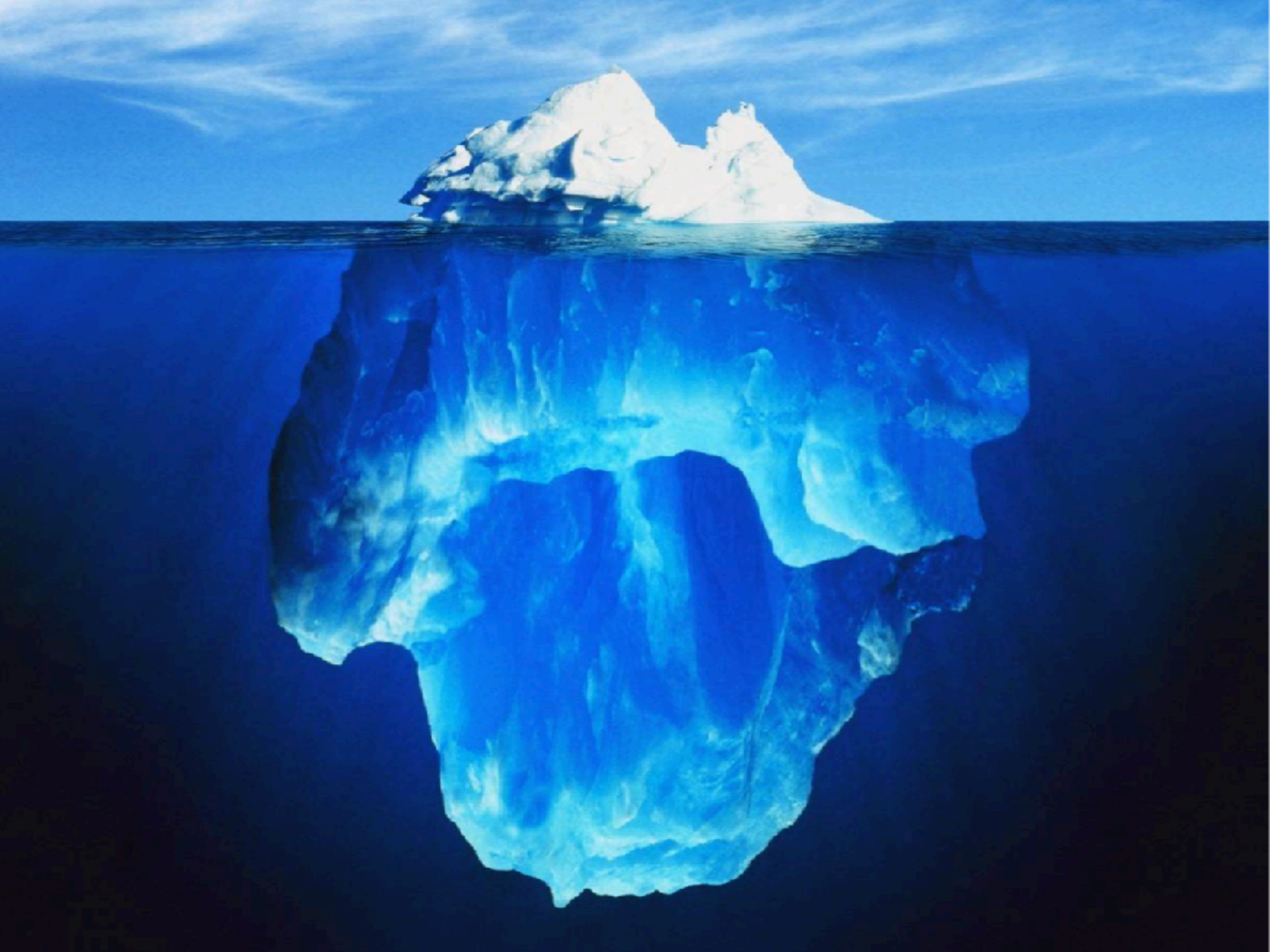
Current Observational Limits on the Galactic Center

K-band (2 microns)

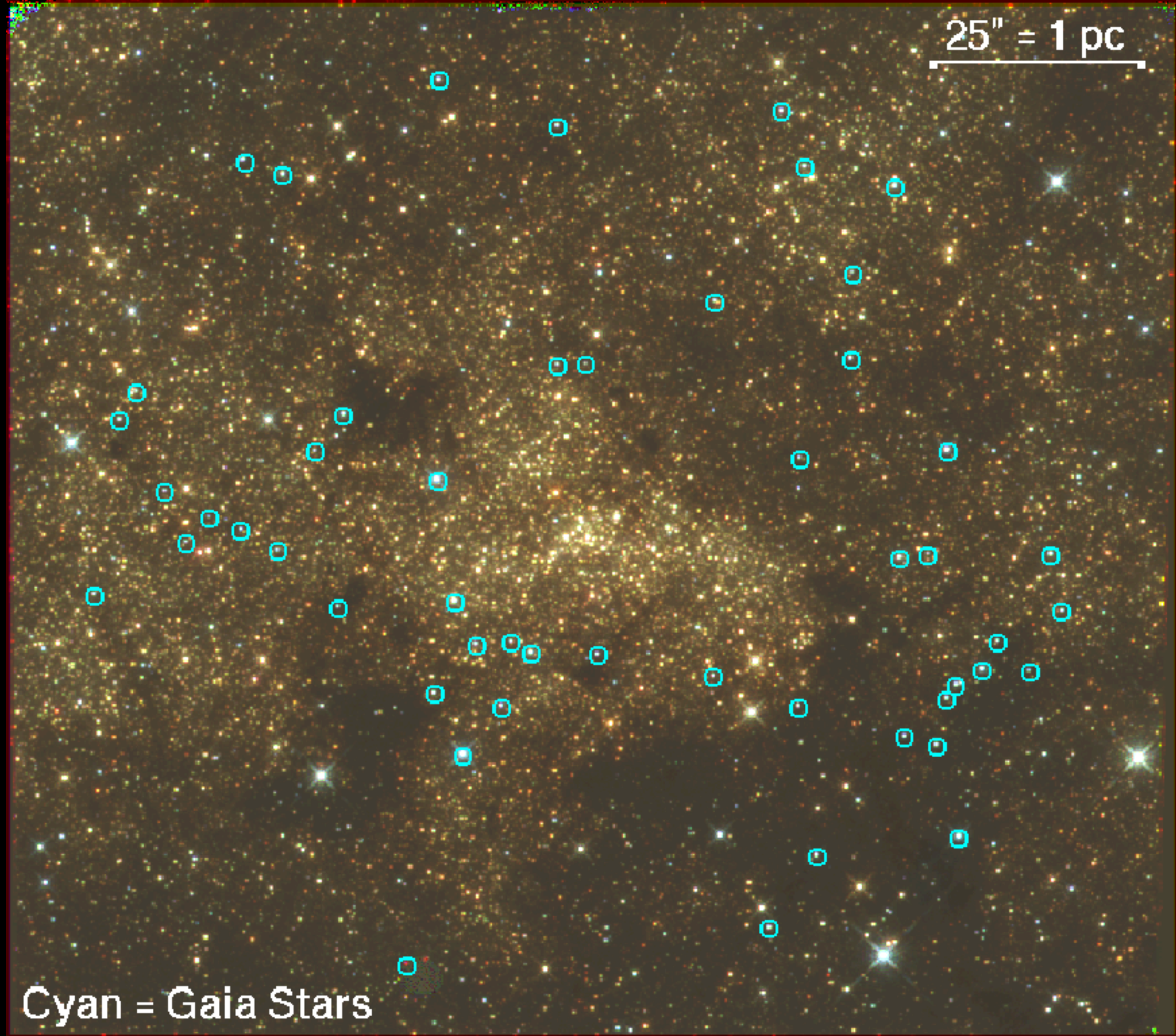
Imaging ~ 20 mag
Spectroscopy ~ 16 mag
Absolute Astrometry over ~30”
Relative Astrometry over 10” - 2’

YNC: ~8 M_{sun} (B V stars)
Arches: ~2.5 Msun (PMS transition)

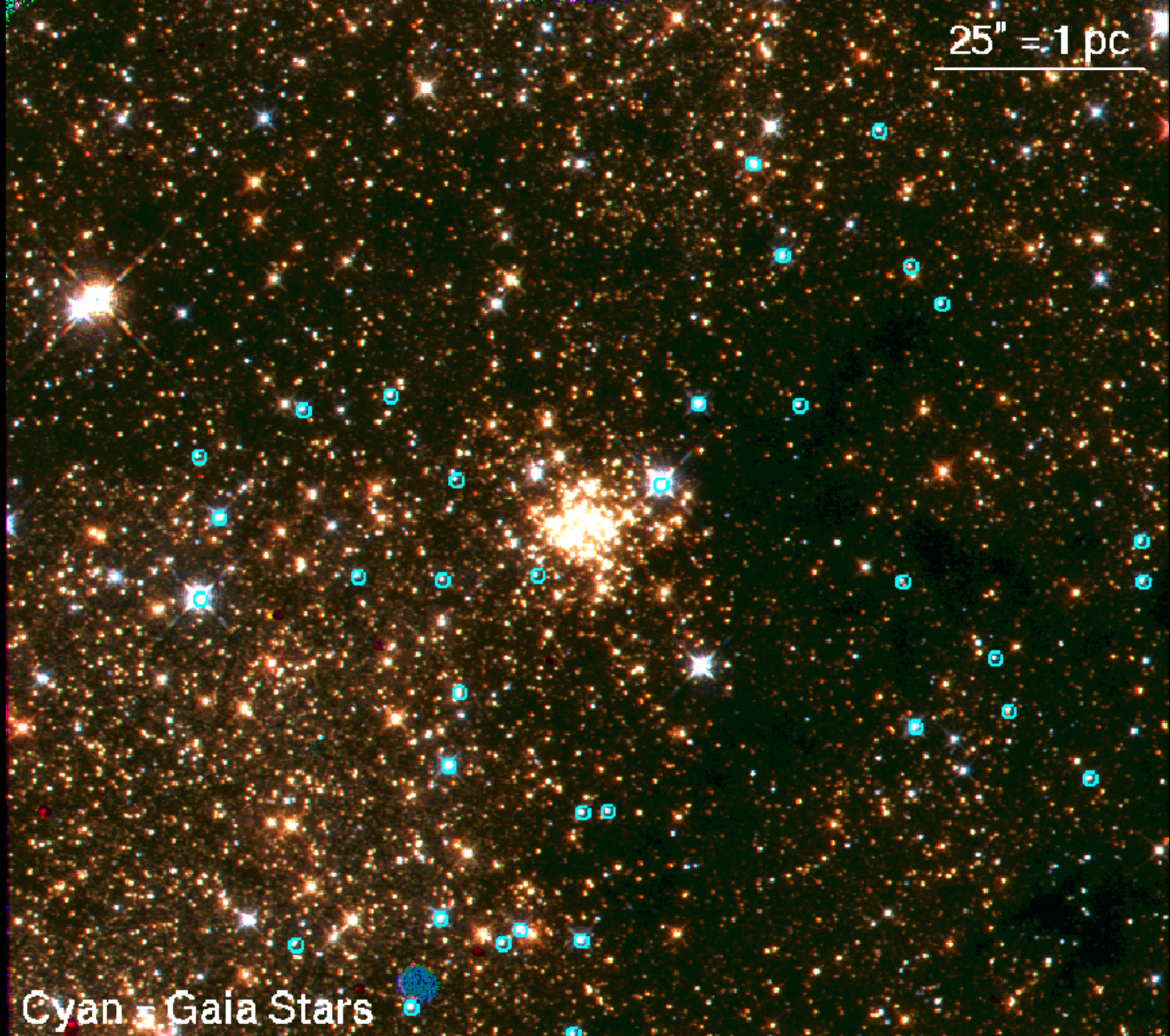
Old Nuclear Cluster: Giant Branch



Nuclear
Star
Cluster

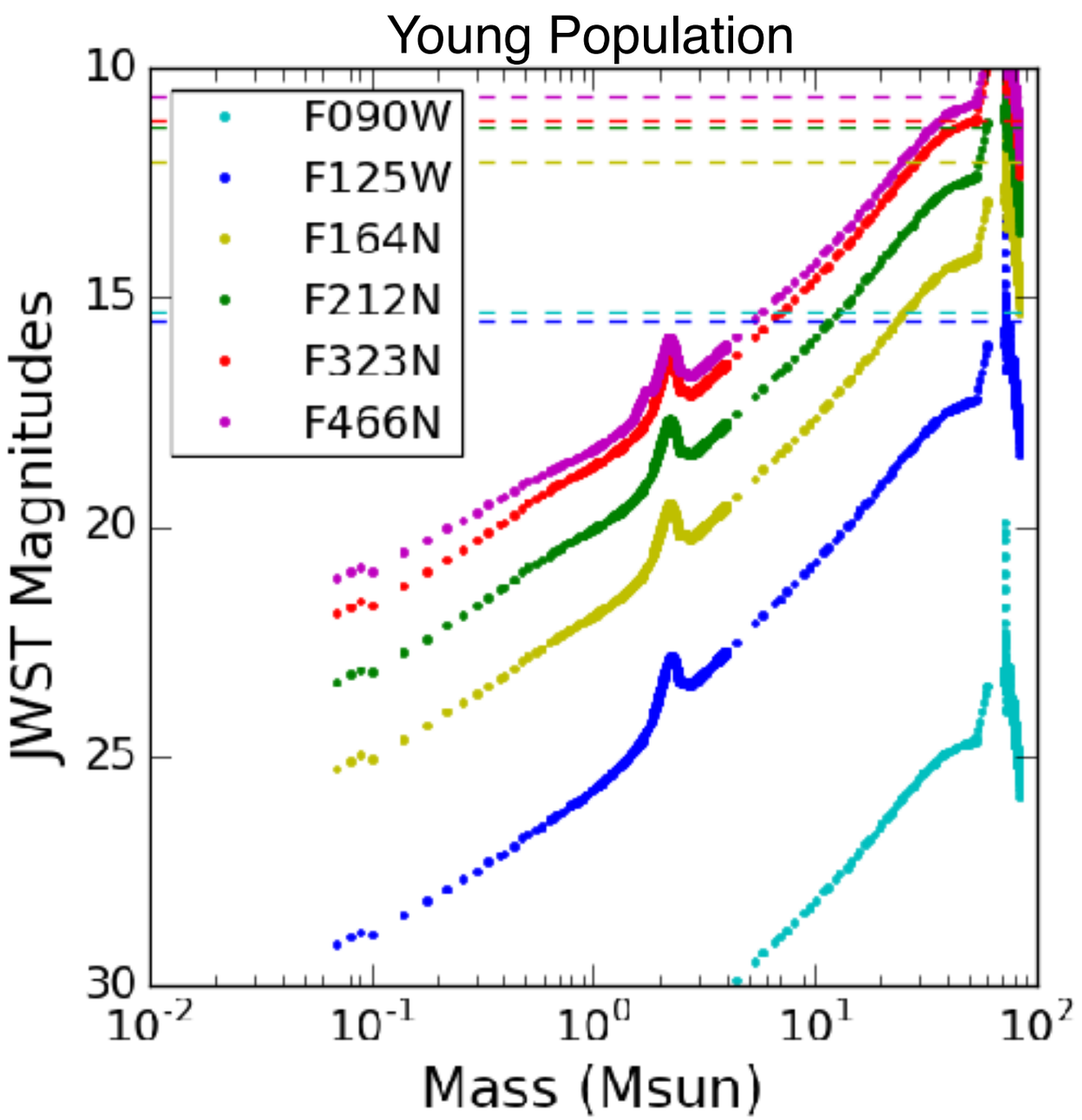


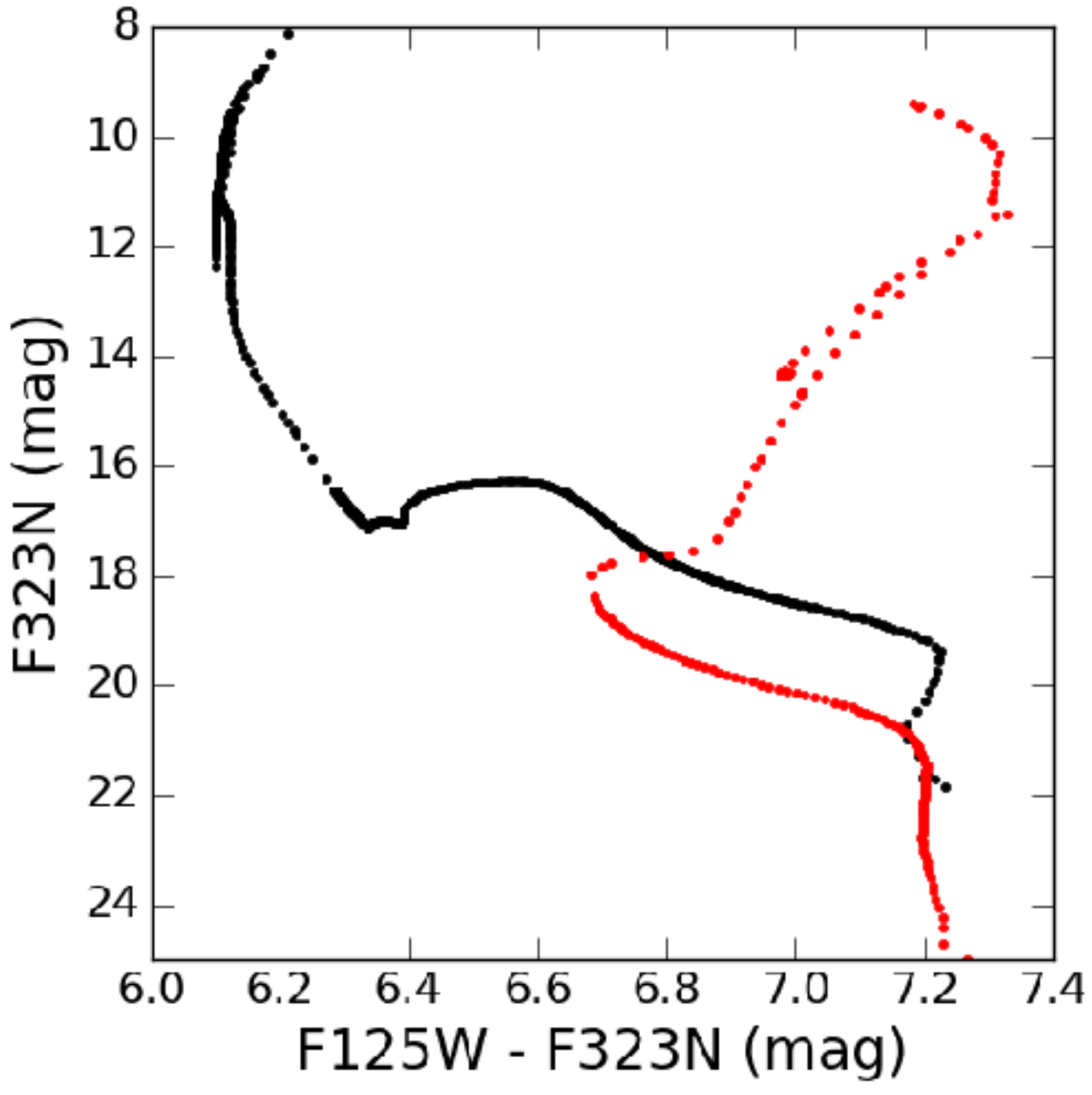
Arches Cluster



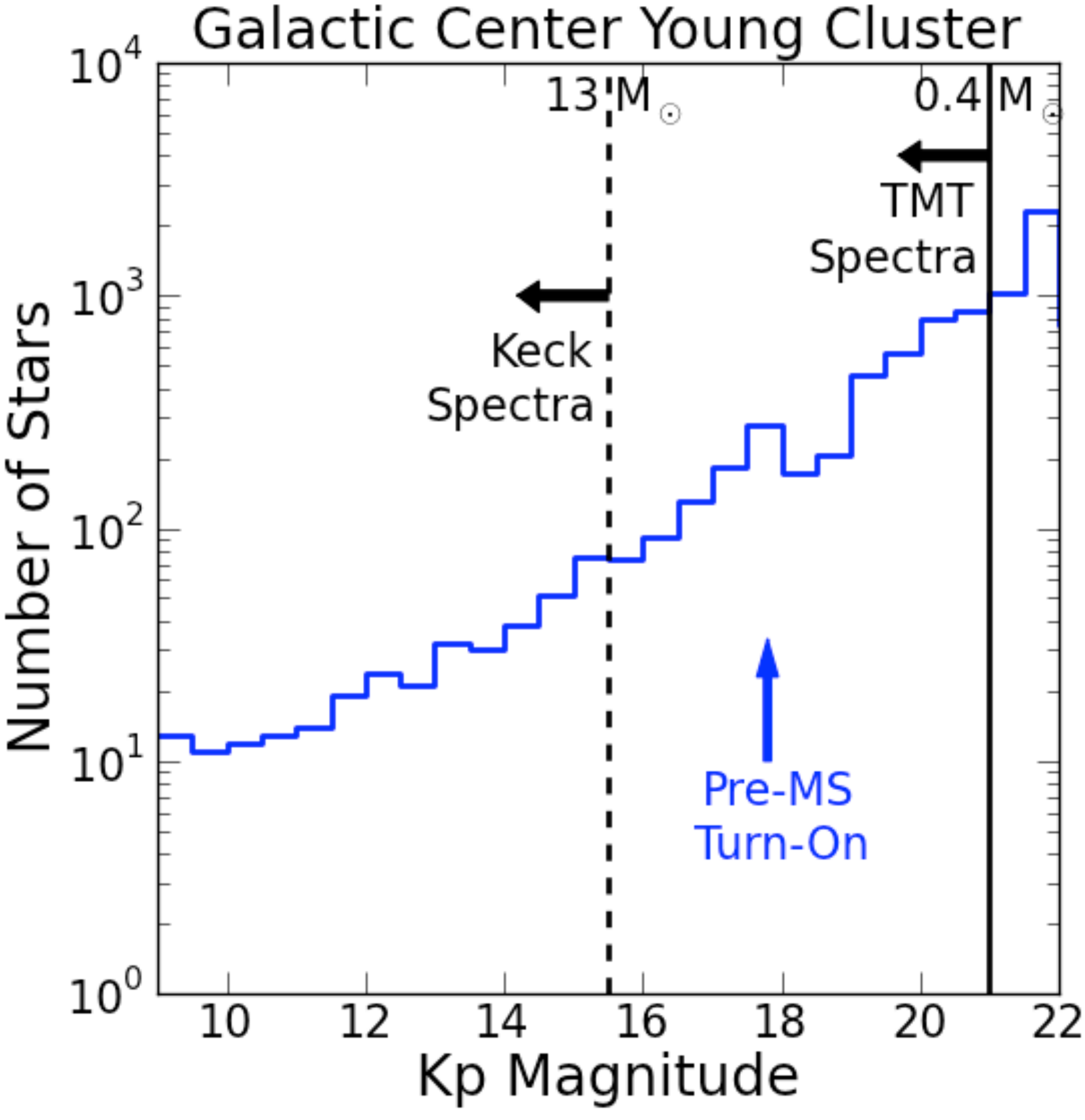
Added wavelength coverage and sensitivity of JWST is powerful:

Simulated CMDs (t=4 Myr and t=5 Gyr, AKs=2.7, d=8 kpc)





+IFU and MOS Spectroscopy (R~2700)



YNC
Future Studies

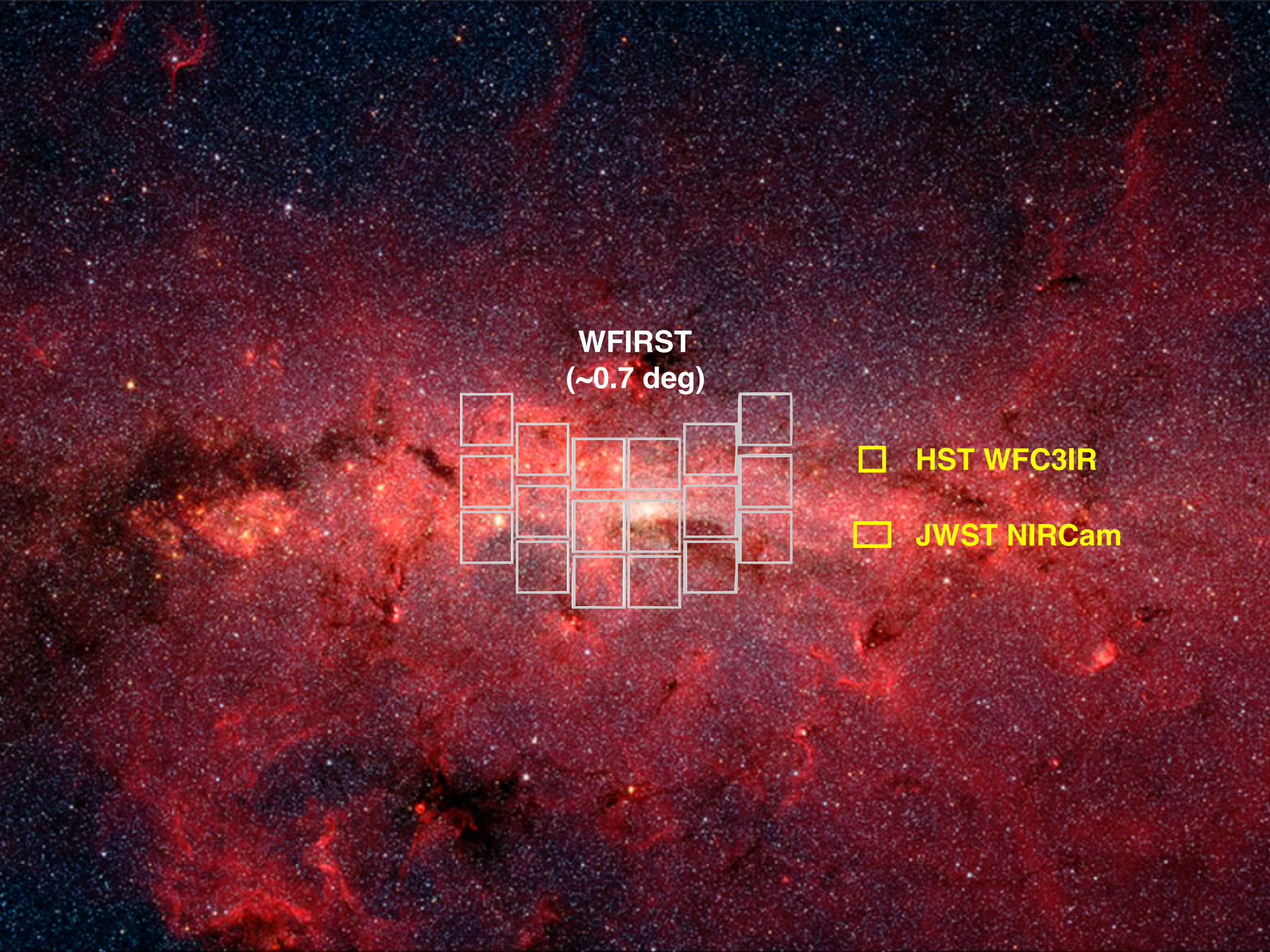
astrometry
ages well

more spectra

multiplicity

pre-main-
sequence

Lu+. 2013


WFIRST
(~0.7 deg)
HST WFC3IR
JWST NIRCam

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Ethan Tweedie Photography