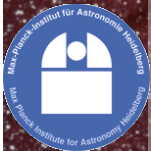


Nuclear Star Clusters

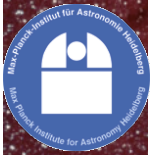
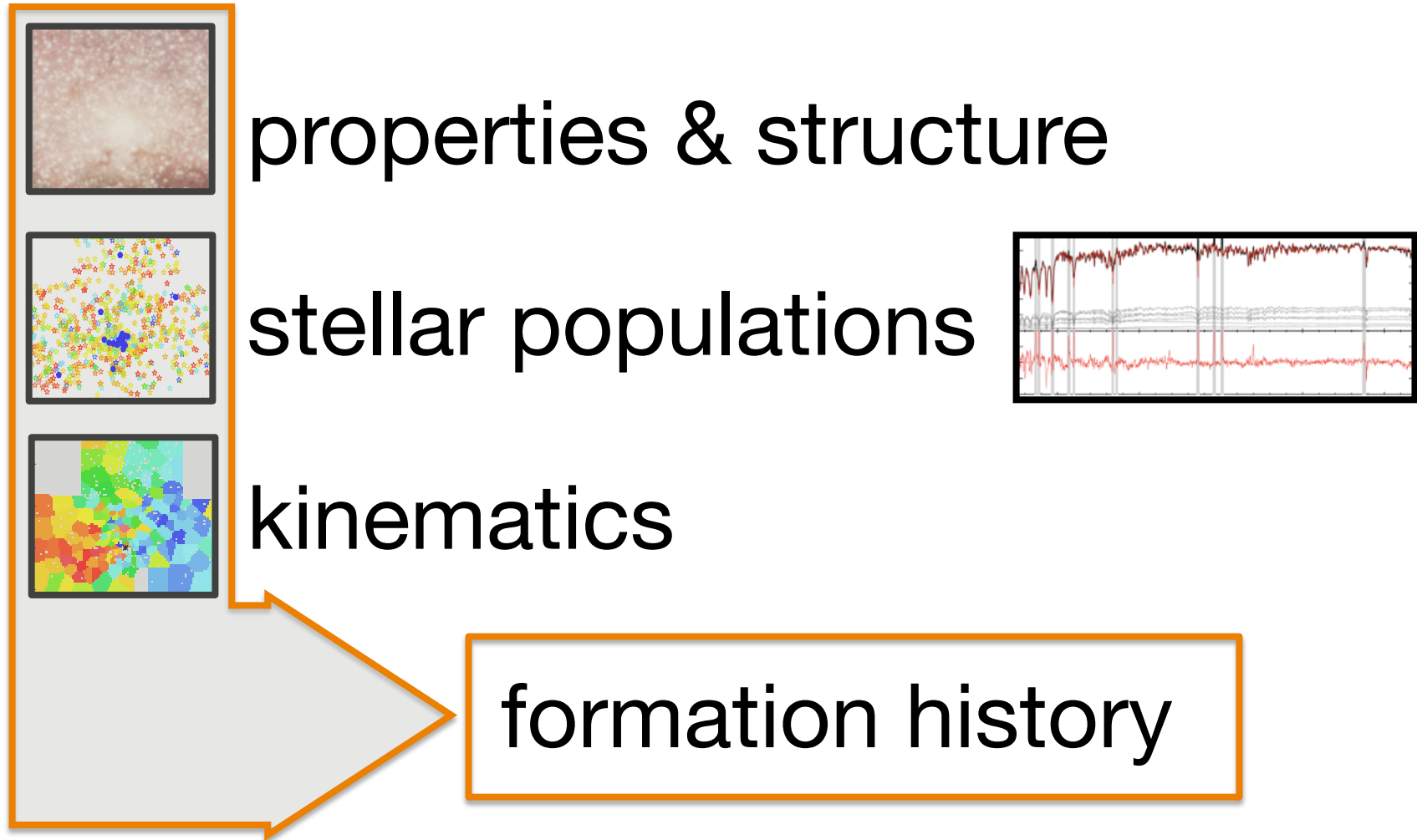
formation mechanisms and observations

Nadine Neumayer

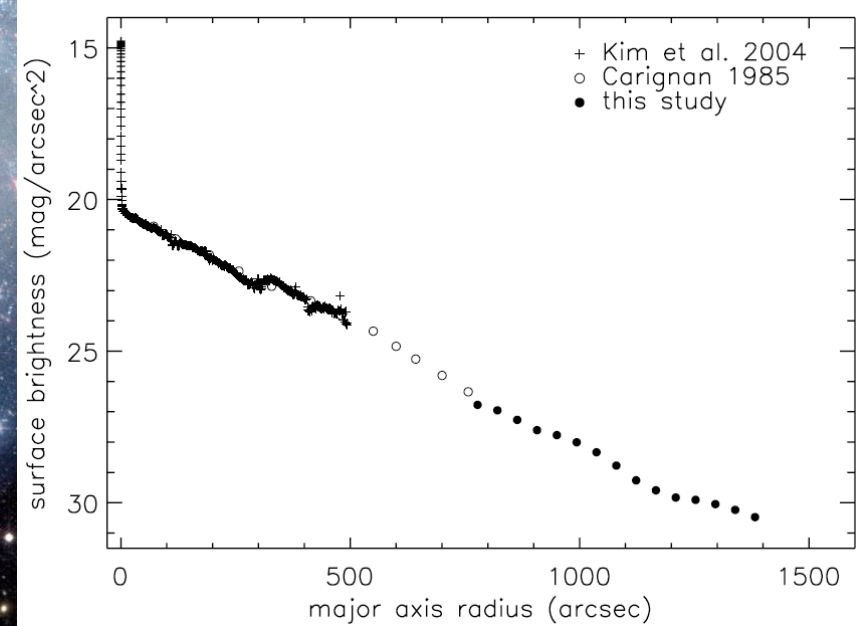
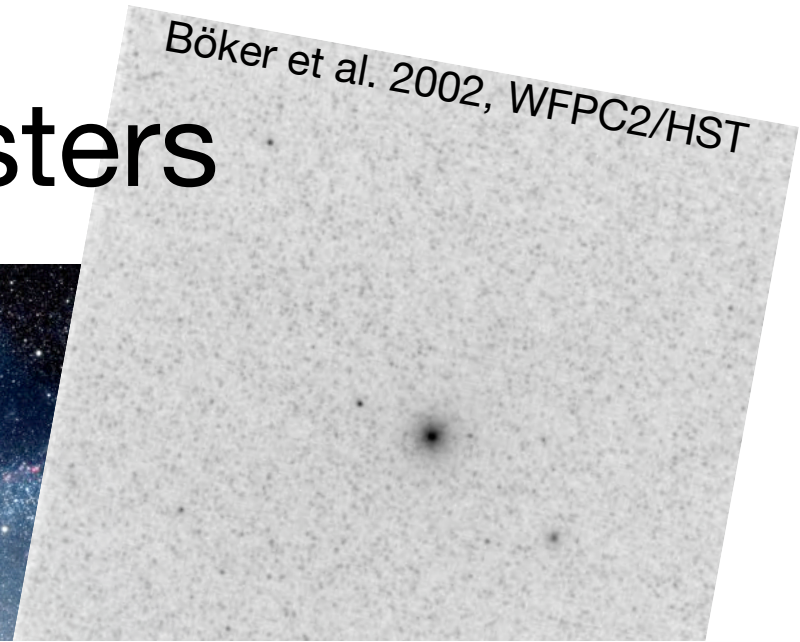
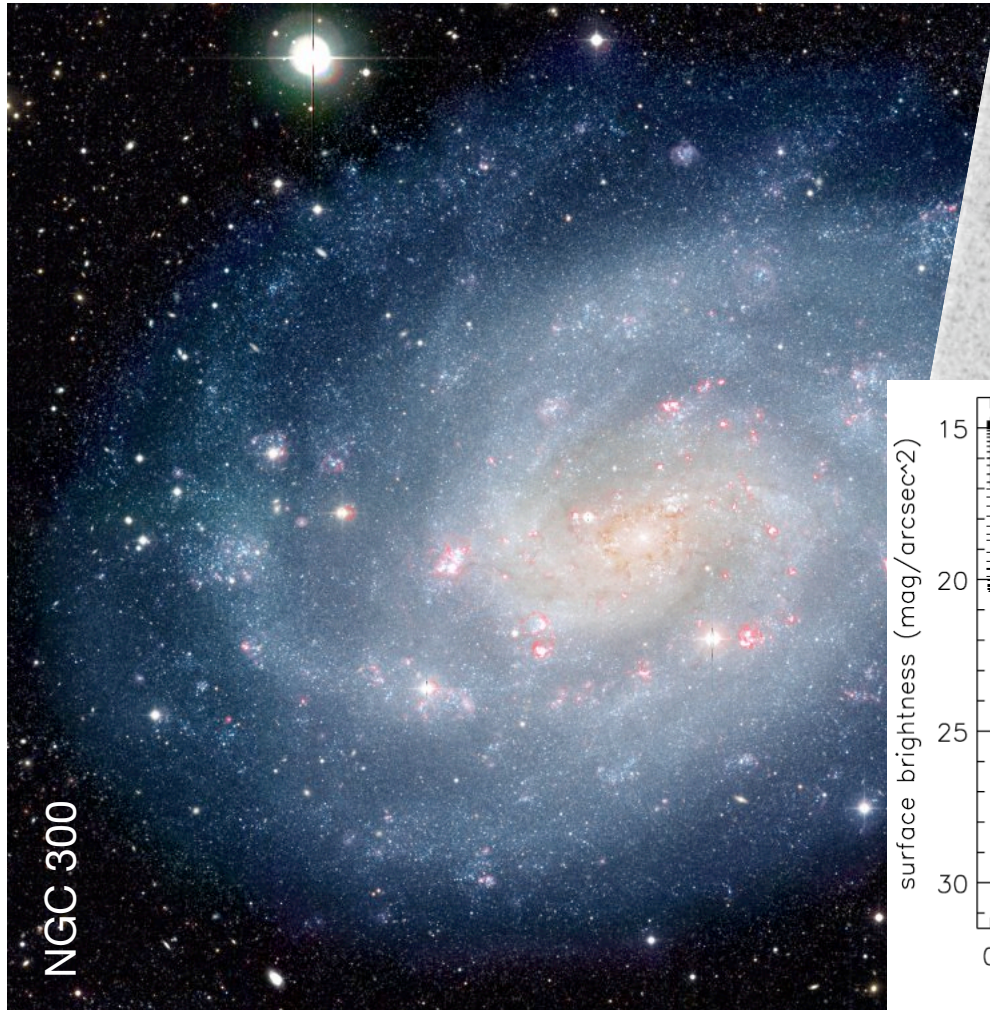
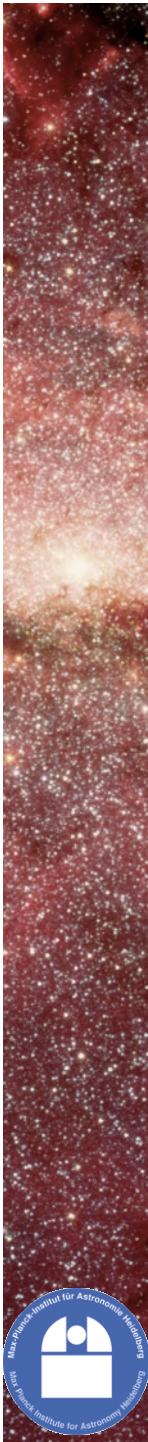
Max-Planck Institute for Astronomy Heidelberg



Nuclear Star Clusters



Nuclear Star Clusters



Bland-Hawthorn et al. 2005

Formation of nuclear star clusters

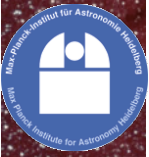
Two competing formation scenarios:

Star cluster infall and merger

In-situ formation at the centre

e.g. Tremaine et al. 1975, Capuzzo-Dolcetta 1993, Lotz et al. 2004, Agarwal & Milosavljevic 2011, Gnedin et al. 2013, Antonini 2013, 2014, Arca-Sedda & Capuzzo-Dolcetta 2014...

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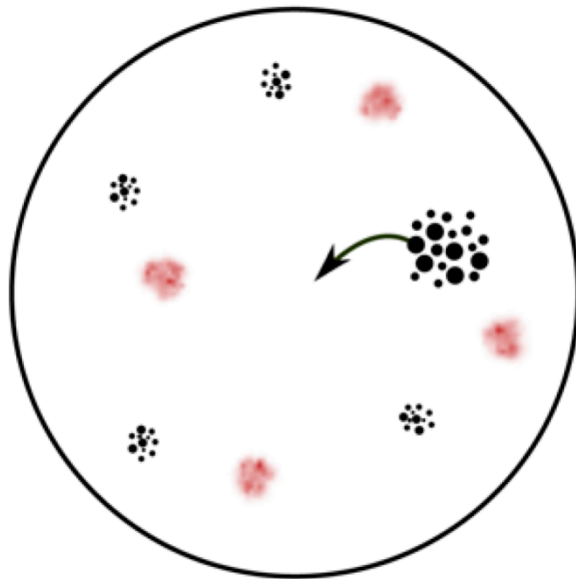


Formation of nuclear star clusters

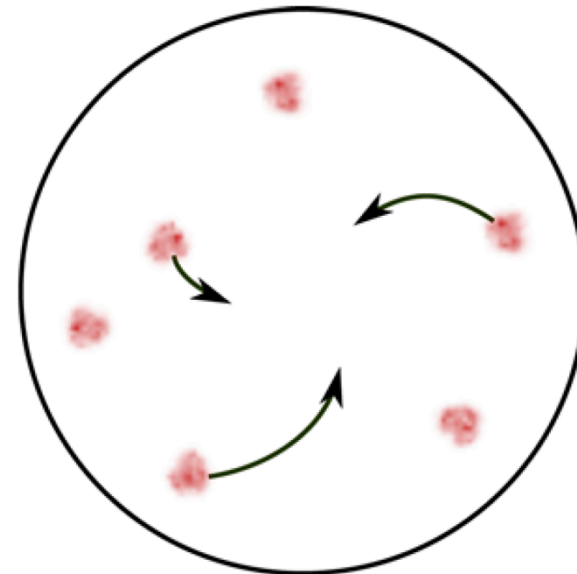
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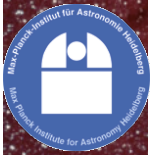


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Guillard, Emsellem & Renaud 2016

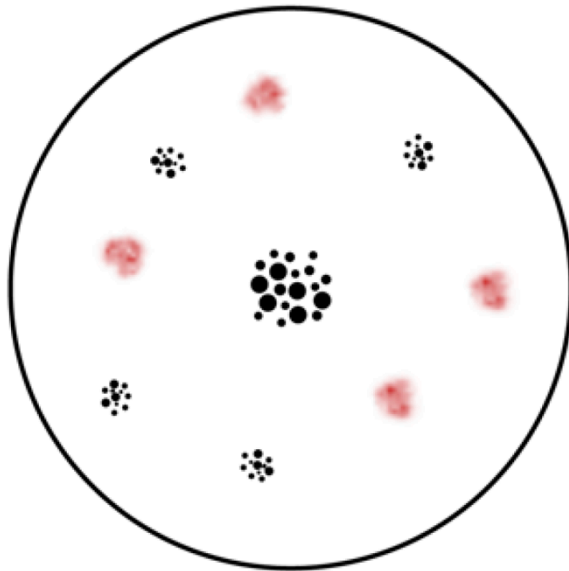


Formation of nuclear star clusters

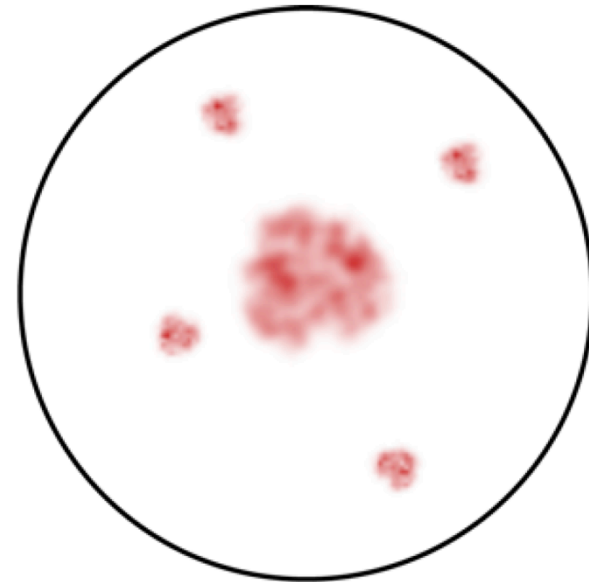
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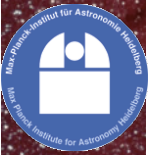


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Guillard, Emsellem & Renaud 2016

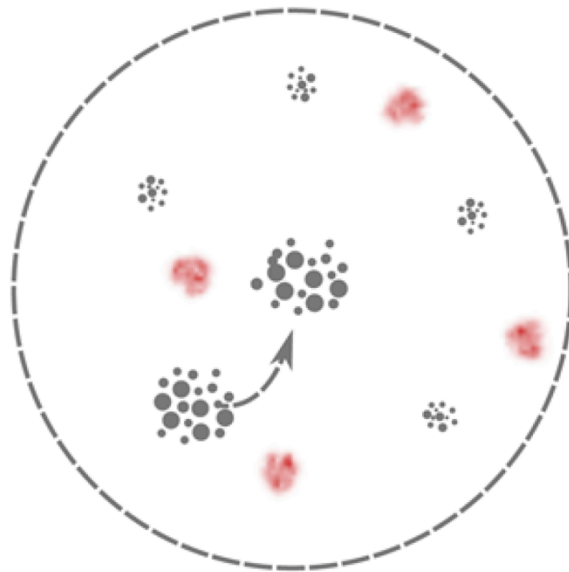


Formation of nuclear star clusters

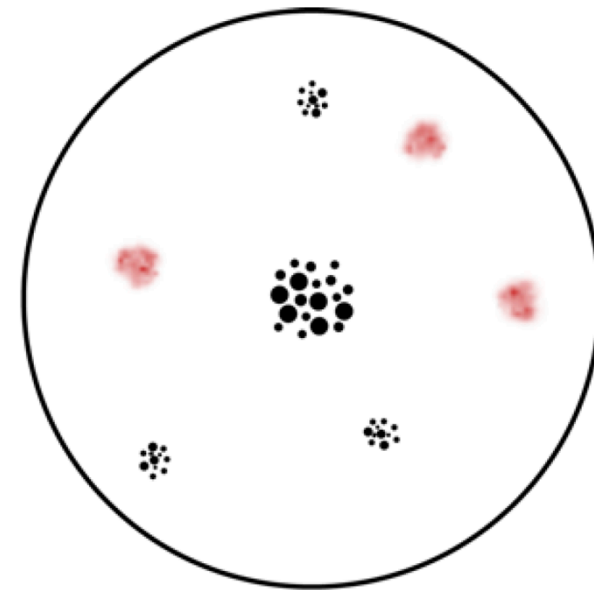
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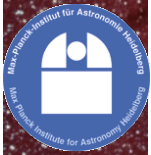


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Guillard, Emsellem & Renaud 2016

Likely it is a combination of both...

e.g. Hartmann et al. 2011, Neumayer et al. 2011, Turner et al. 2012, de Lorenzi 2013, Feldmeier et al. 2014, den Brok et al. 2014, Feldmeier-Krause et al. 2015 & 2017, Guillard et al. 2016

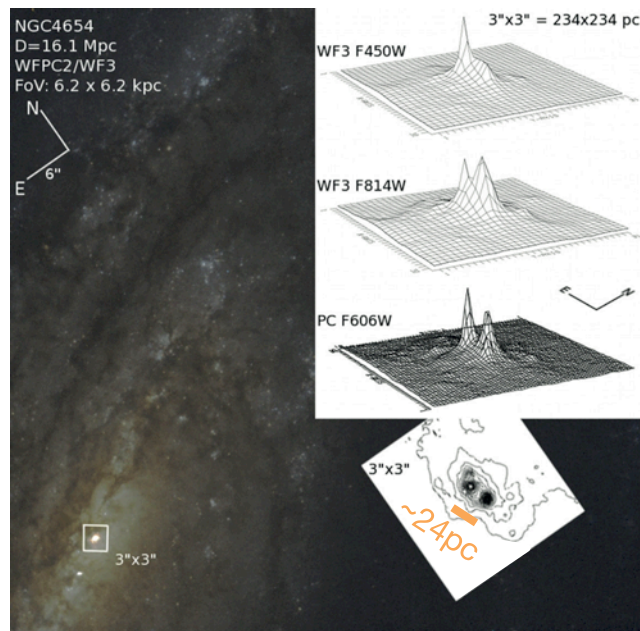


Formation of nuclear star clusters

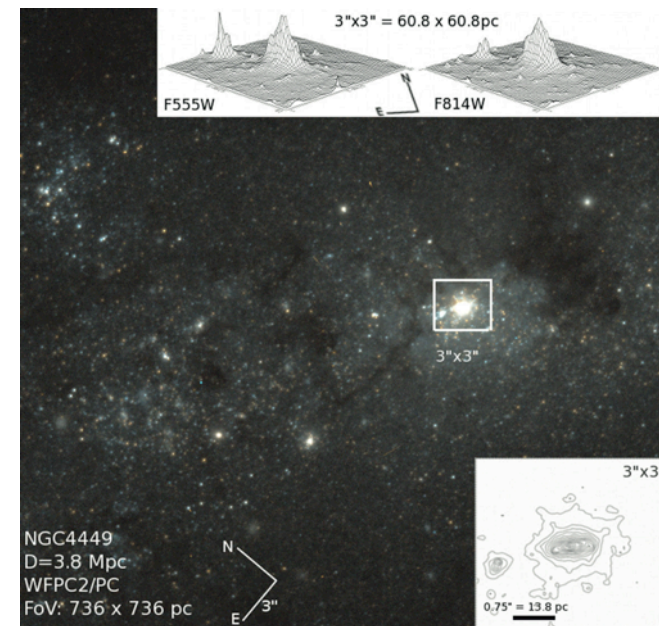
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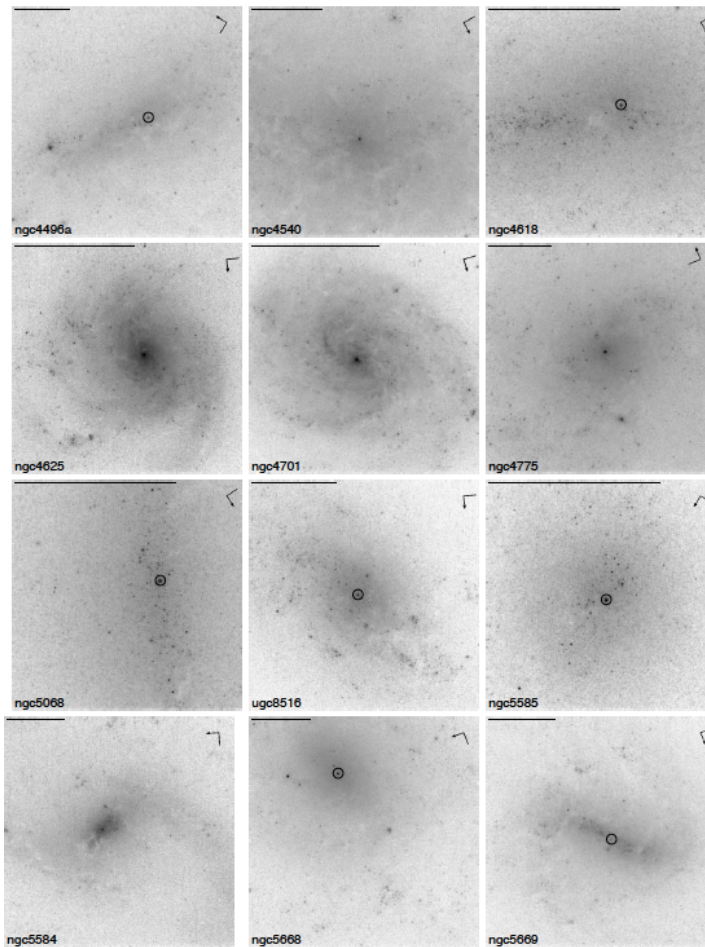
Georgiev & Böker 2014

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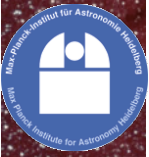


NSC properties & structure



- Detected in ~50-75% of all galaxies

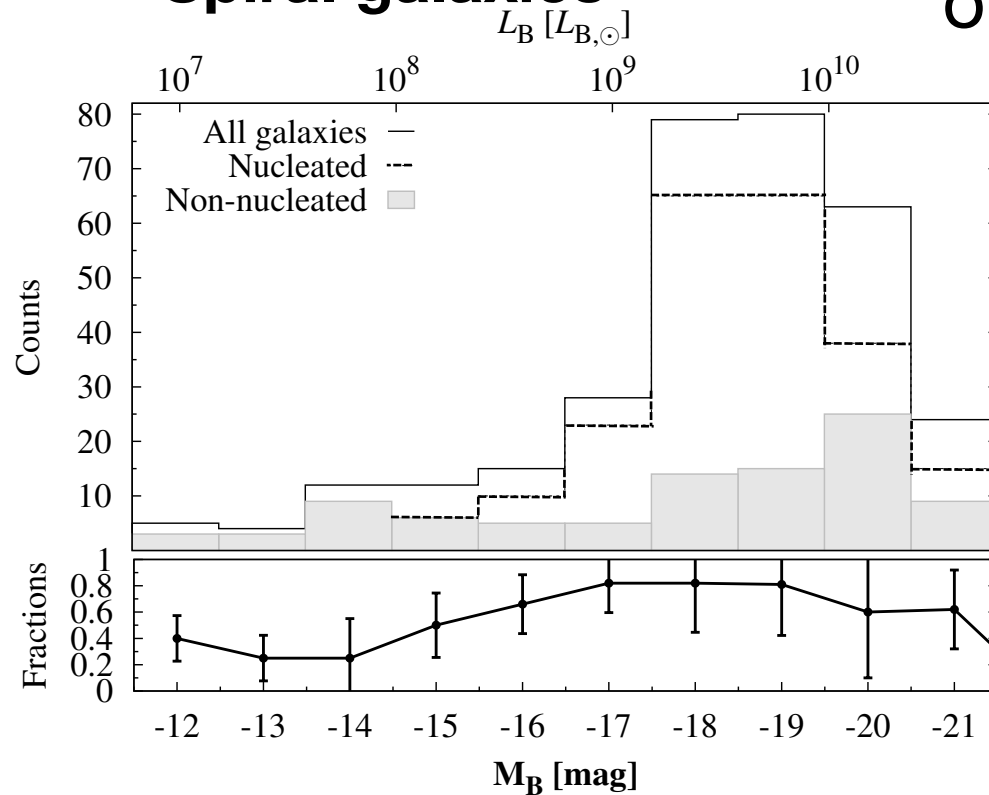
Böker+ 2002, 2004; Carollo+ 2002; Coté+ 2006; Balcells+ 2007; Georgiev & Böker 2014; den Brok+ 2014



NSC properties & structure

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Spiral galaxies



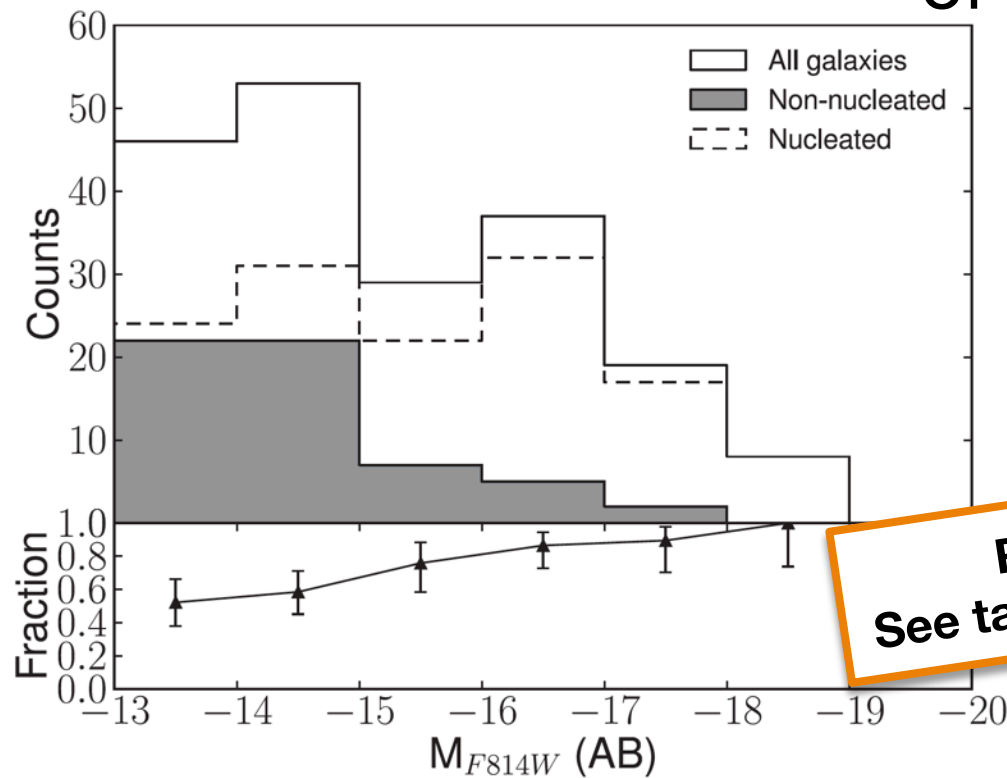
After Georgiev & Böker 2014



NSC properties & structure

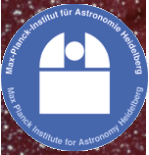
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Elliptical galaxies



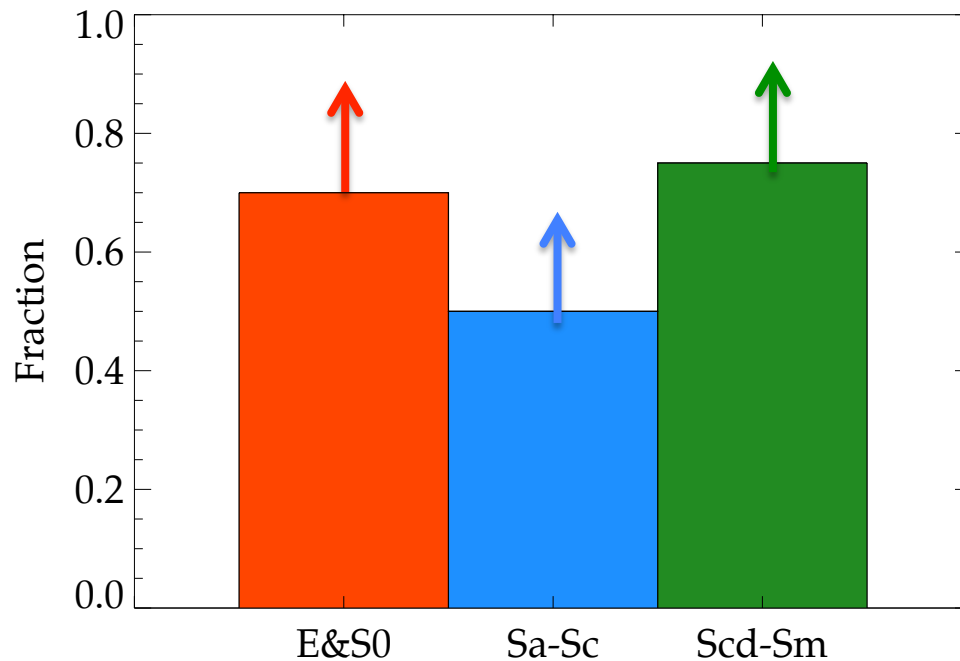
Results for Virgo Cluster:
See talk by R ben Sanchez-Janssen

den Brok et al. 2014

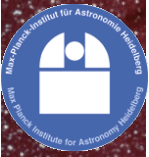


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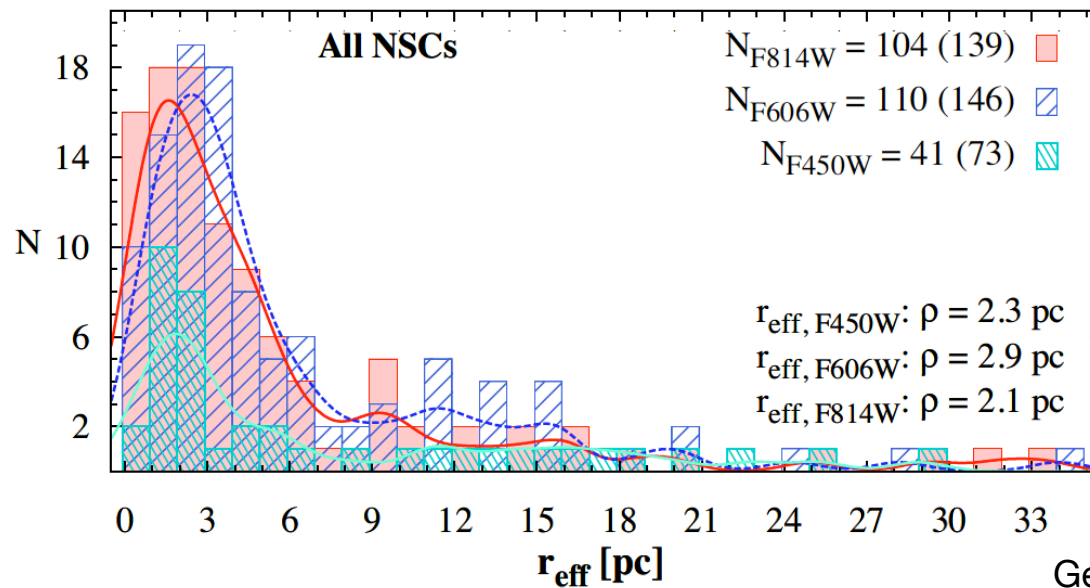


NSC properties & structure

Milky Way:
 $4.2 \text{ pc} \pm 0.4 \text{ pc}$

Schödel et al. 2014

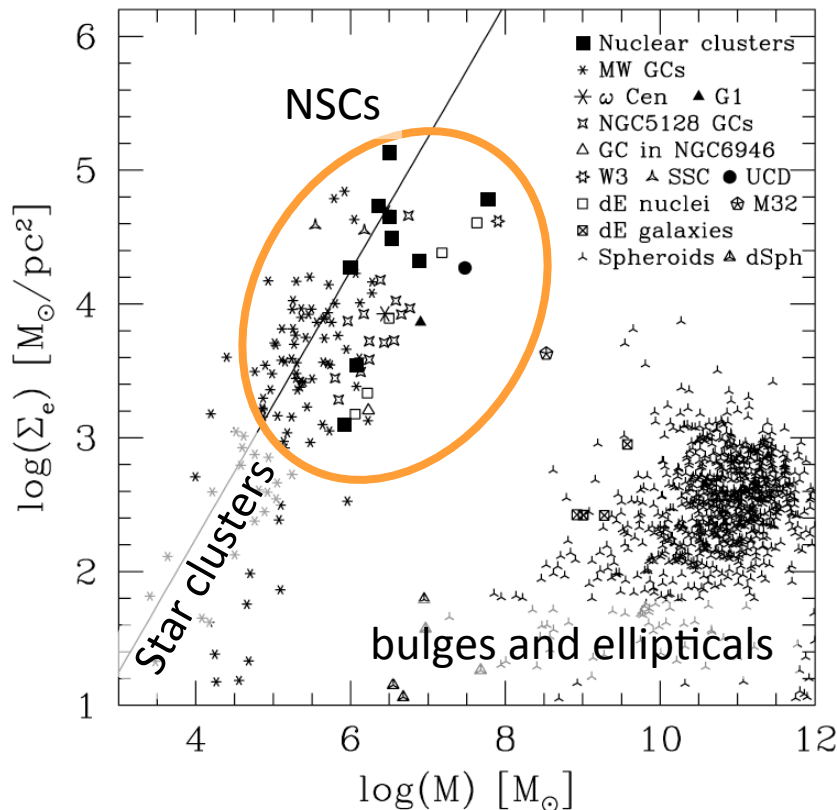
- Detected in $\sim 50\text{-}75\%$ of all galaxies
- Half-light radii 2-5 pc



Georgiev & Böker 2014



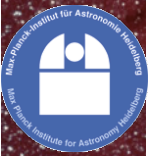
NSC properties & structure



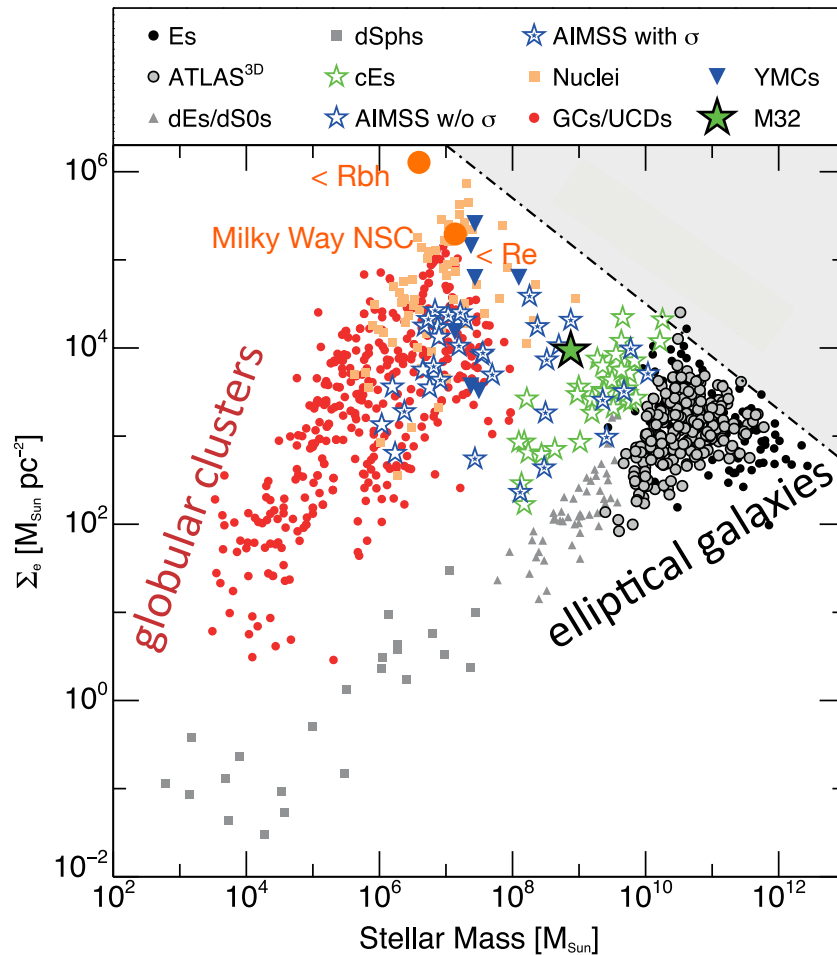
Walcher et al. 2005

- Detected in ~50-75% of all galaxies
- Half-light radii 2-5 pc
- Masses $10^6 - 10^7 M_\odot$
MW: $3 \times 10^7 M_\odot$

Feldmeier et al. 2014



NSC properties & structure



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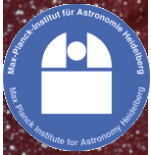
Feldmeier et al. 2014

NSCs have the highest stellar densities in the universe.

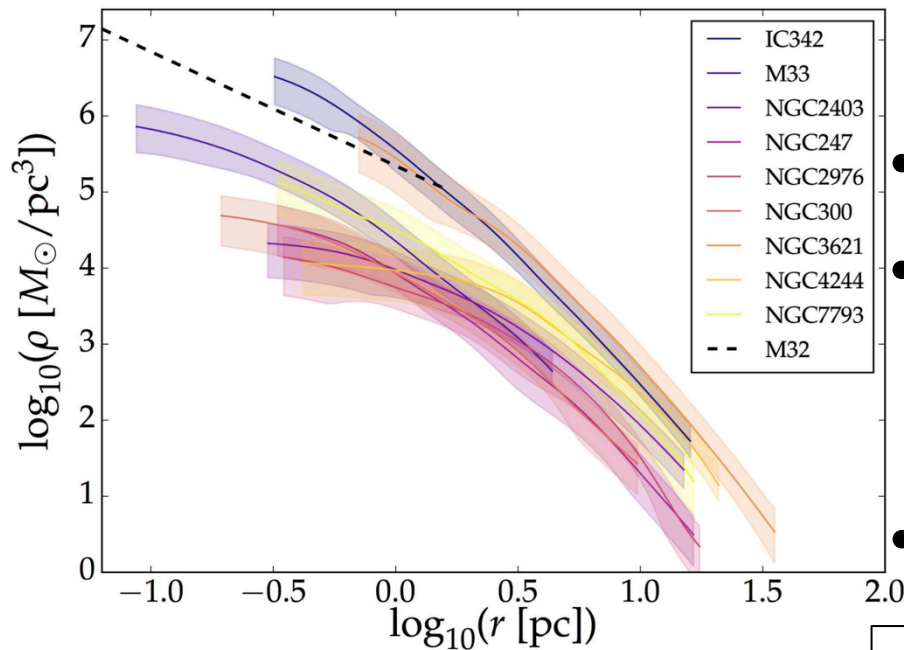
Walcher et al. 2005, Mergeld & Hilker 2011, Norris et al. 2014

Heraeus Seminar *Stellar aggregates*, December 4 - 9, 2016

Nadine Neumayer



NSC properties & structure



Carson et al. submitted

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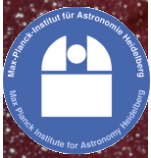
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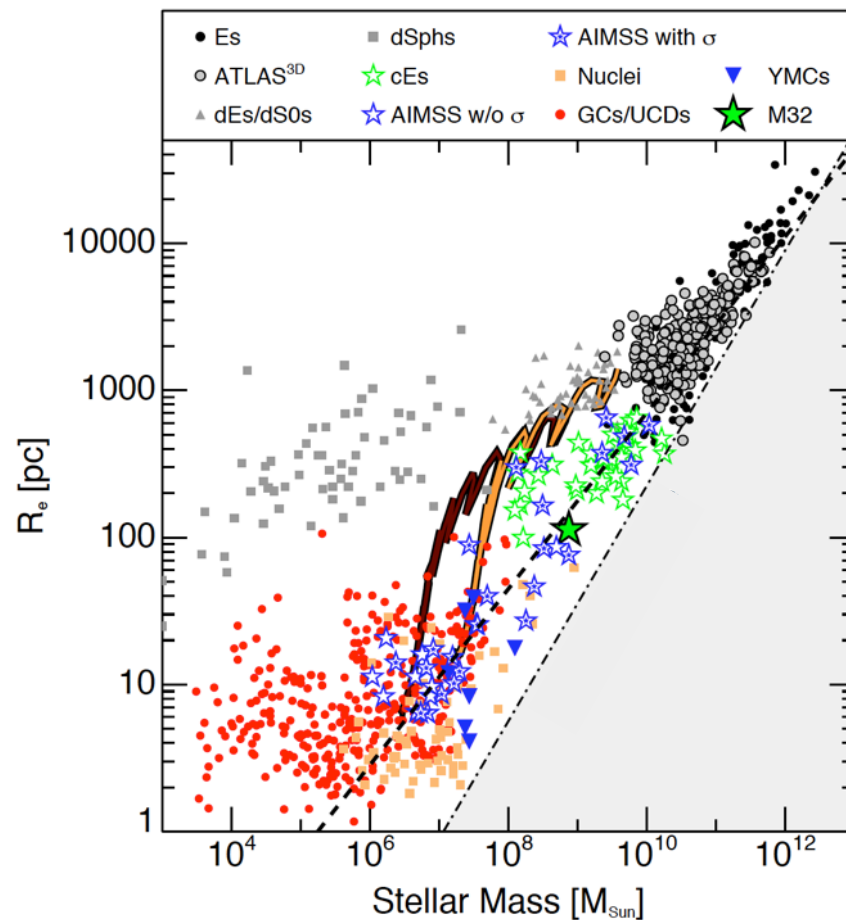
Feldmeier et al. 2014

- densities $< 10^7 M_{\odot}/\text{pc}^3$

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NSC properties & structure



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- Half-light radii 2-5 pc

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Feldmeier et al. 2014

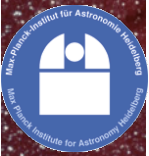
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- Mass-size relationship

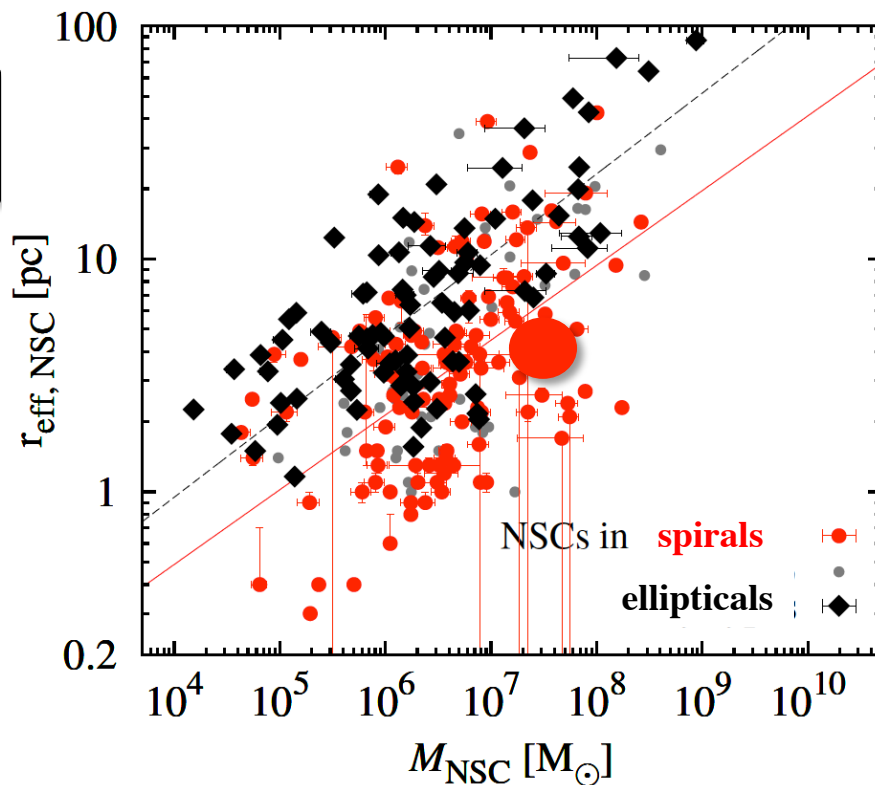
Norris et al. 2014

Heraeus Seminar *Stellar aggregates*, December 4 - 9, 2016

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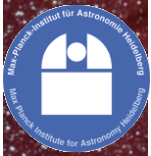
NSC properties & structure



Georgiev et al. 2016

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Feldmeier et al. 2014



NSC properties & structure



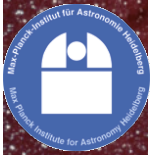
Galactic Centre / Spitzer / S. Stolovy

- Detected in ~50-75% of all galaxies
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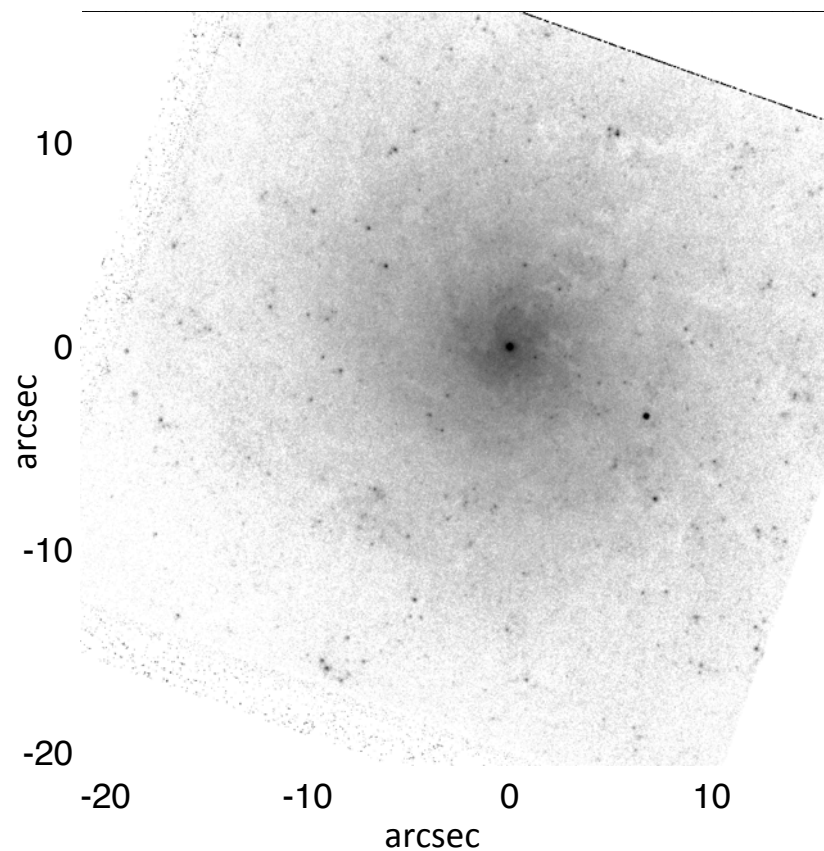
Feldmeier et al. 2014

- densities $< 10^7 M_{\odot}/\text{pc}^3$
- Mass-size relationship
- co-exist with black holes

**Scaling relationships:
See talk by Alister Graham**



A special place in the galaxy

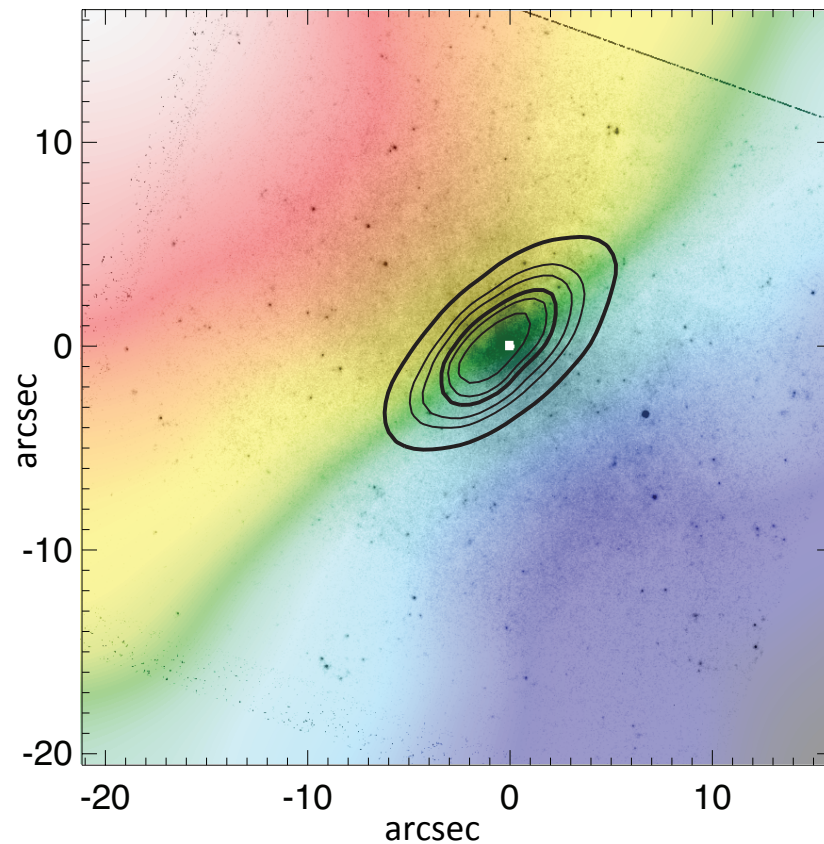


- NSCs truly sit at the center of the potential

Neumayer et al. 2011



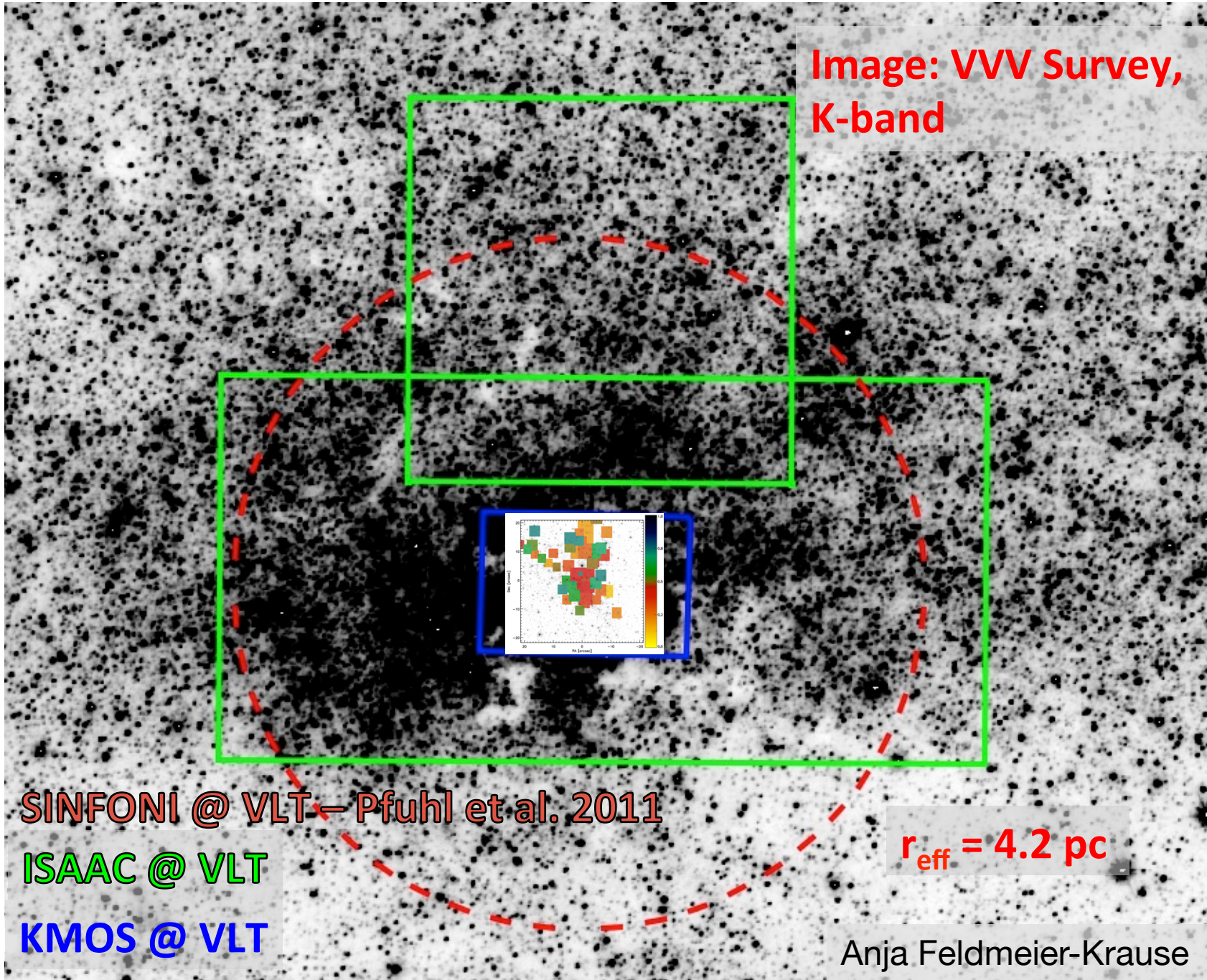
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- NSCs truly sit at the center of the potential

Neumayer et al. 2011





SINFONI @ VLT – Pfuhl et al. 2011

ISAAC @ VLT

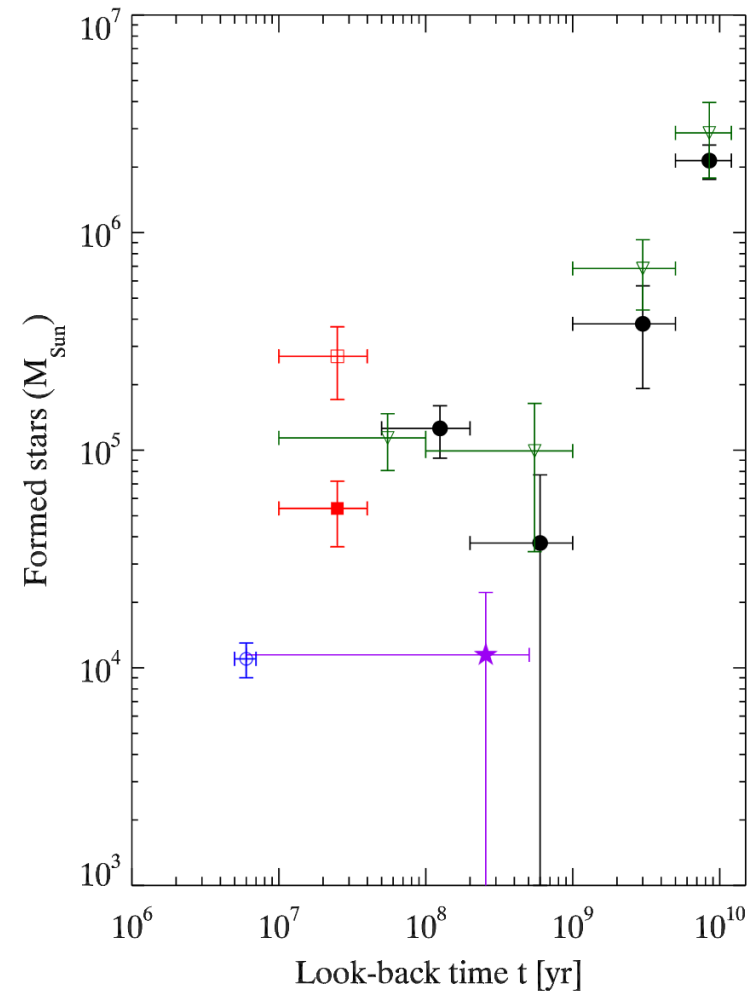
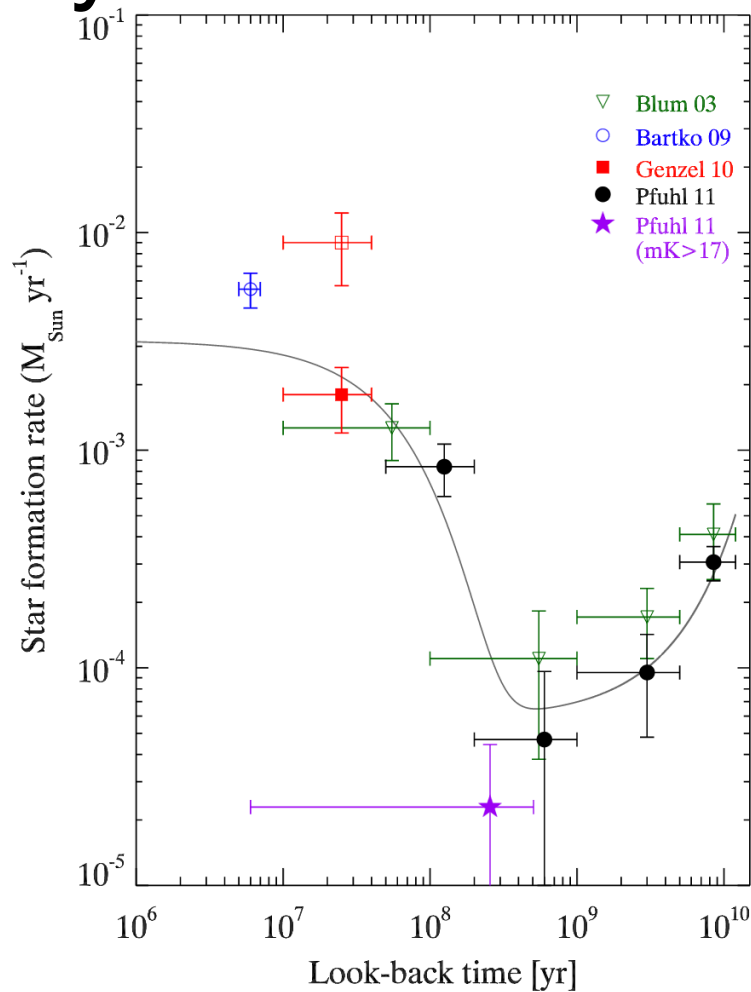
KMOS @ VLT

$r_{\text{eff}} = 4.2 \text{ pc}$

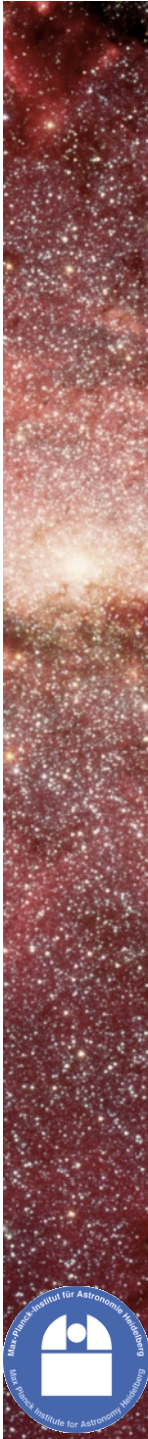
Anja Feldmeier-Krause

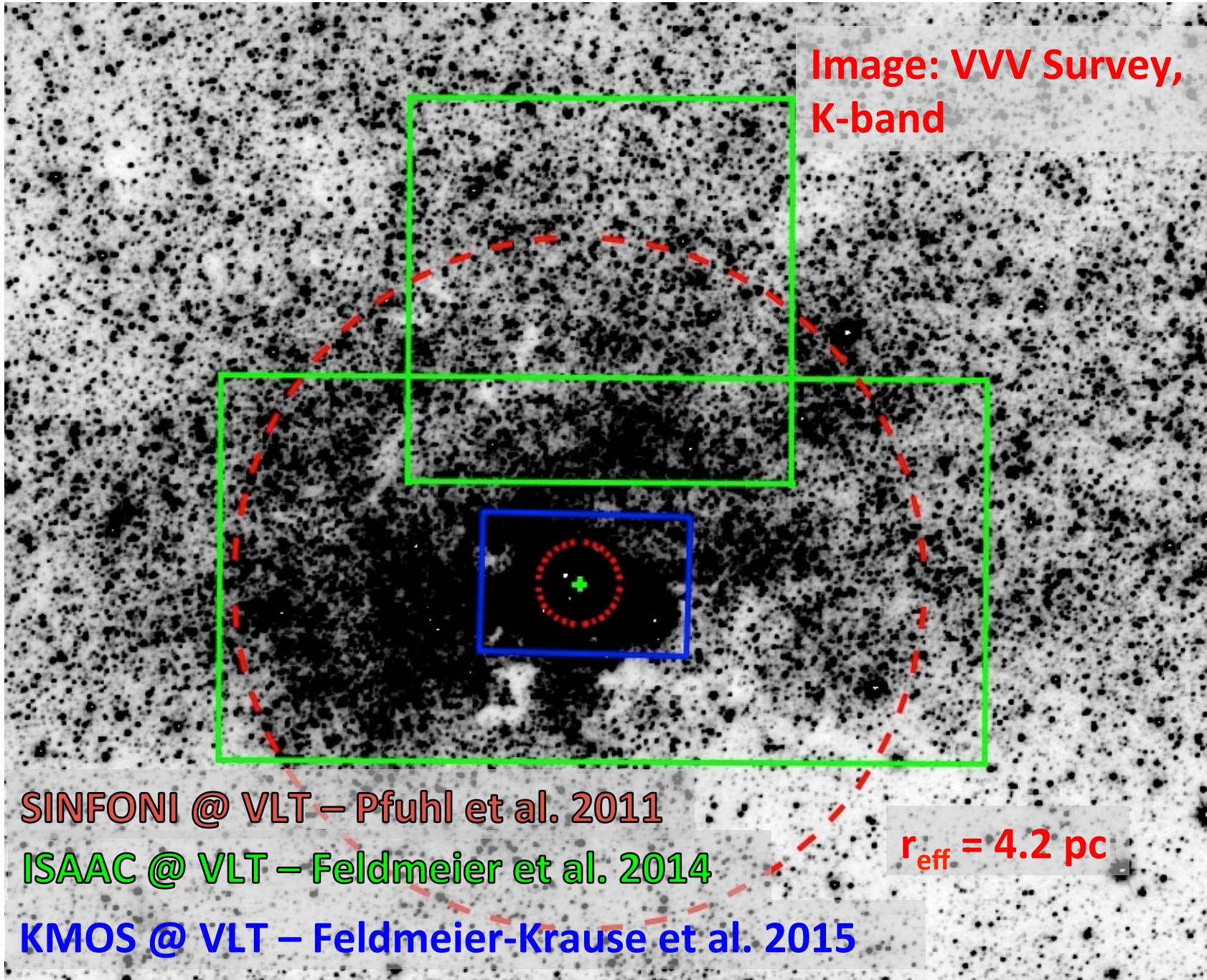


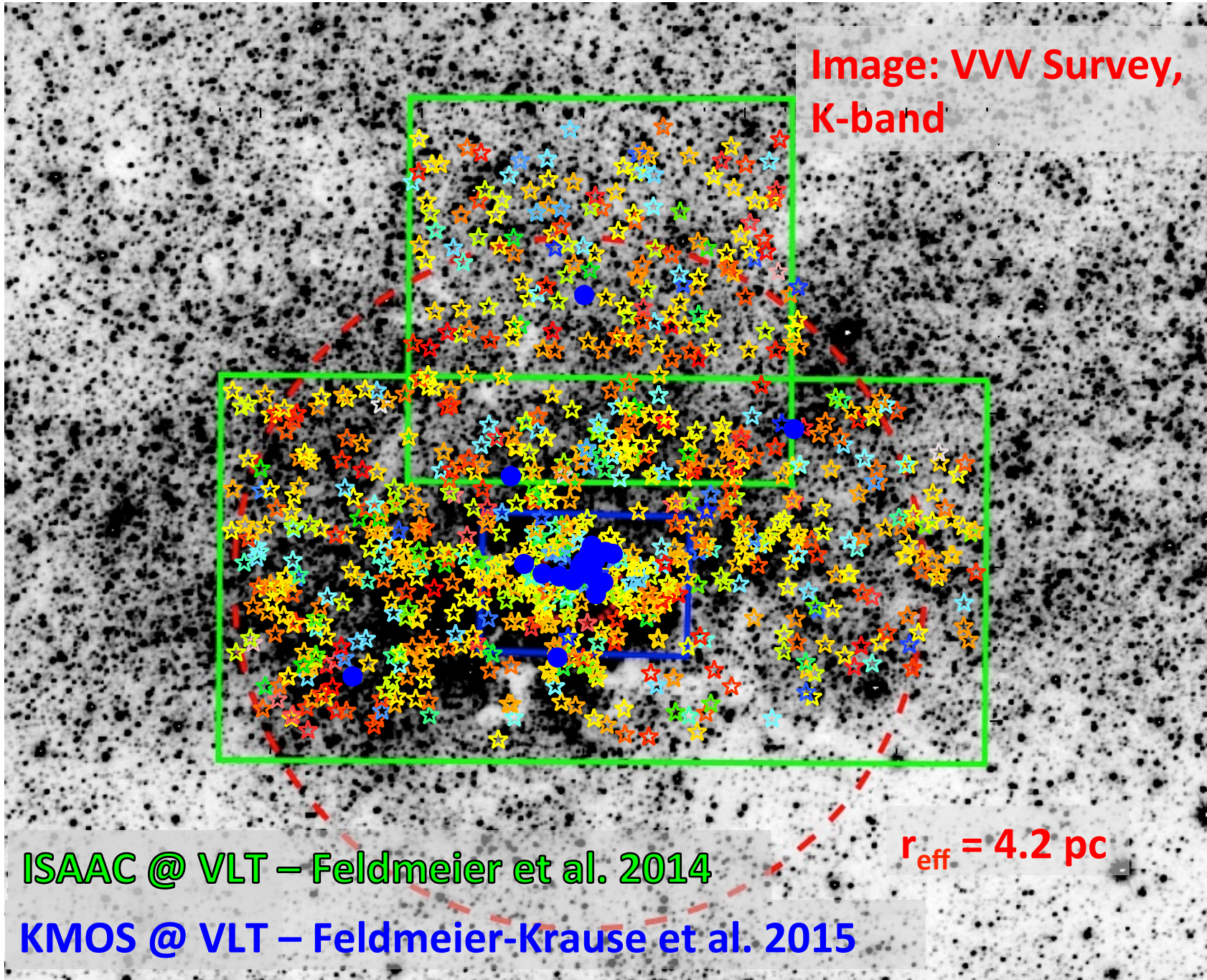
Star formation history of the Milky Way NSC



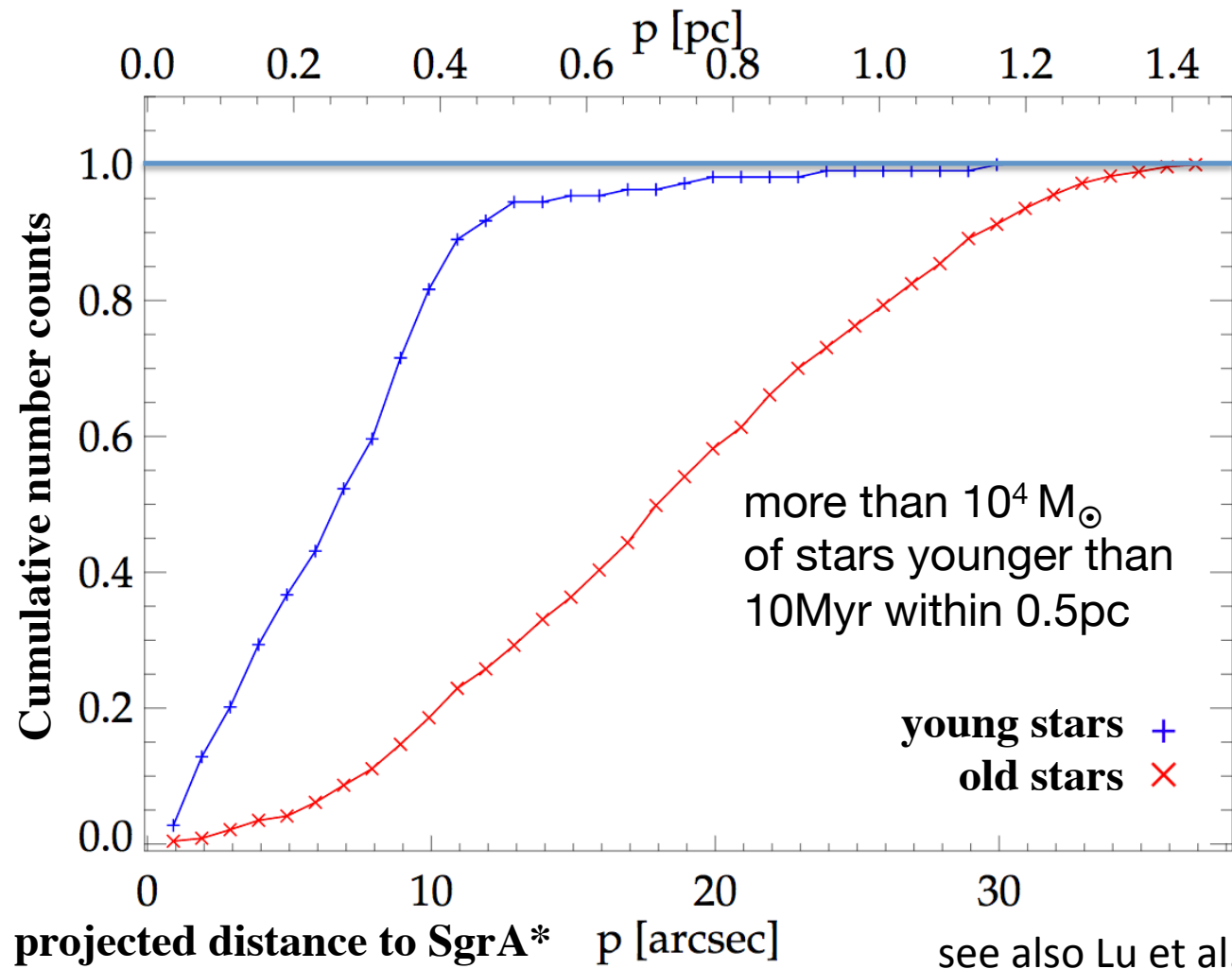
Pfuhl et al. 2011







Distribution of stars in the central pc

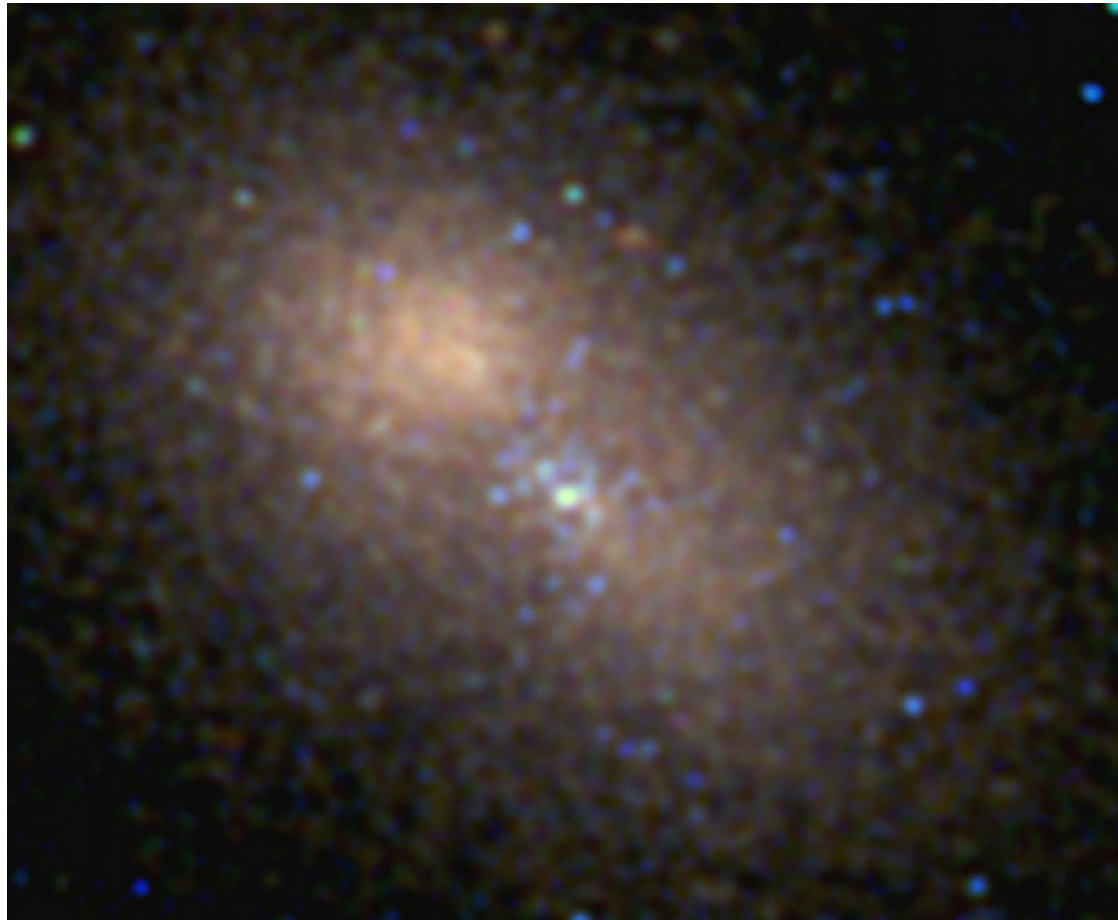


Feldmeier-Krause et al. 2015



Nucleus of M31

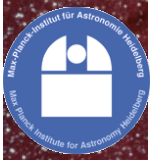
Cluster of blue stars of
age 100-200 Myr
around the black hole

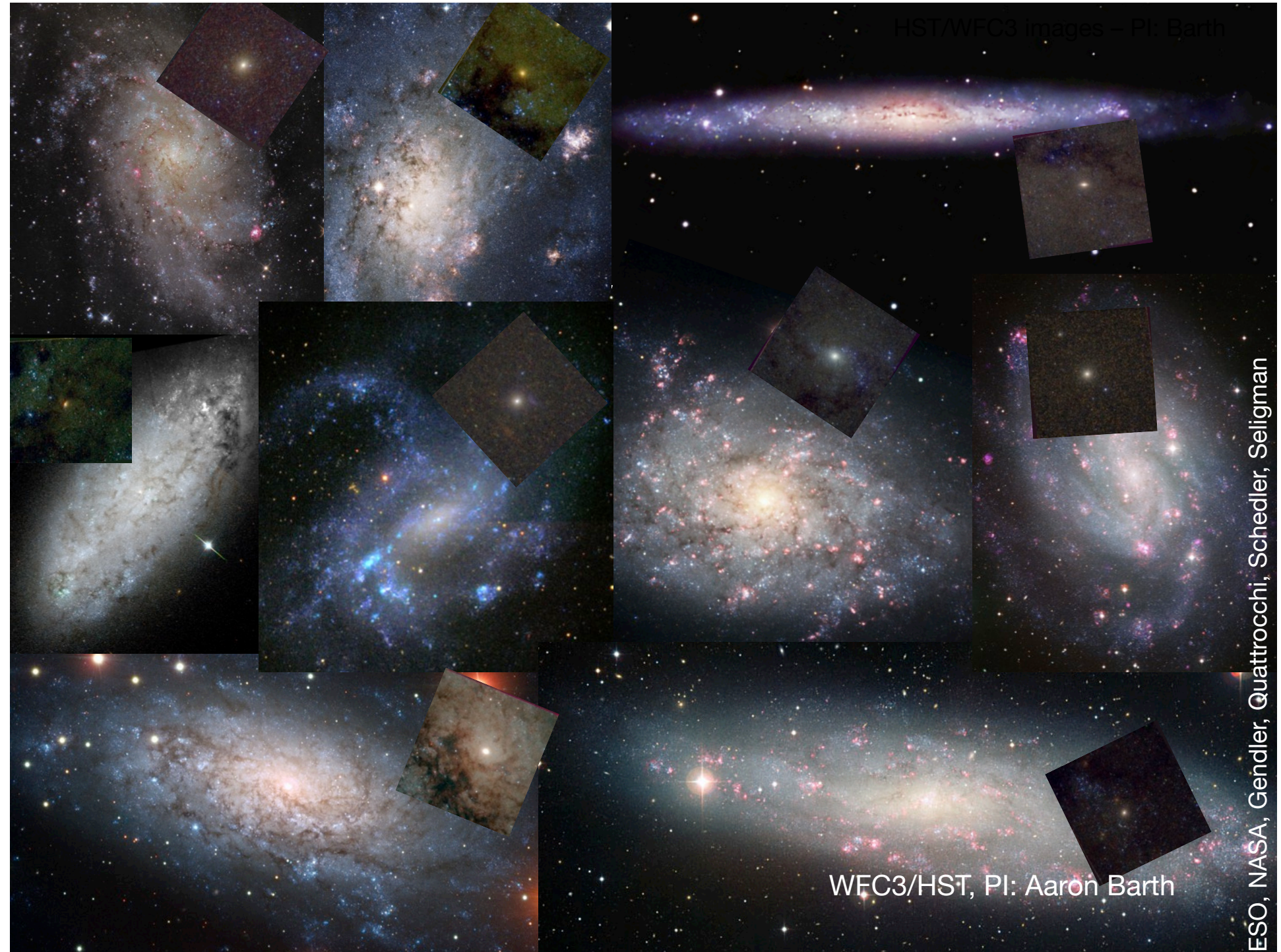


3" or
10 pc

Lauer et al. 2012

HST/ACS - UVB



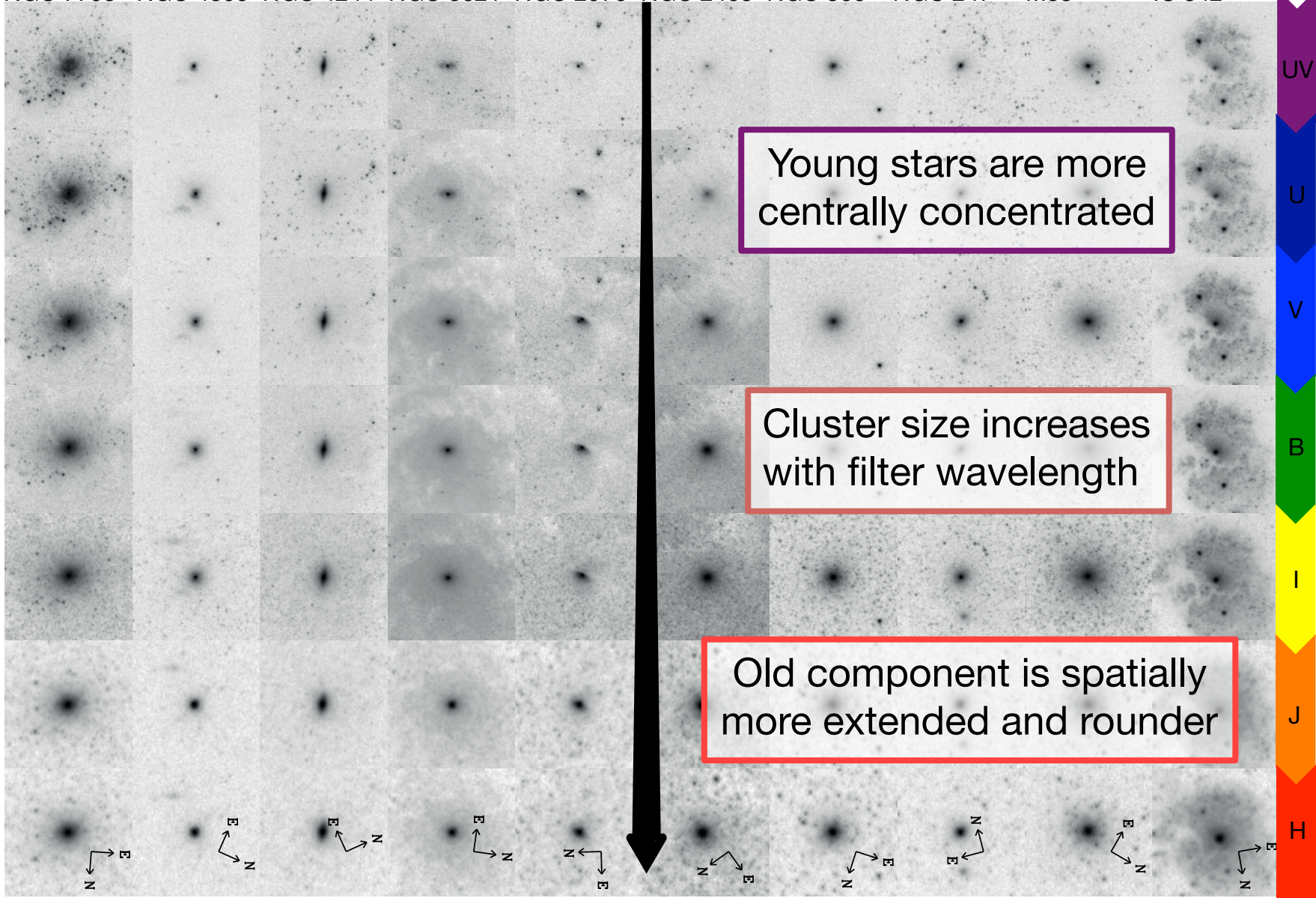


HST/WFC3 images – PI: Barth

WFC3/HST, PI: Aaron Barth

ESO, NASA, Gendler, Quattrocchi, Schedler, Seligman

NGC 7793 NGC 4395 NGC 4244 NGC 3621 NGC 2976 NGC 2403 NGC 300 NGC 247 M33 IC 342



Young stars are more centrally concentrated

Cluster size increases with filter wavelength

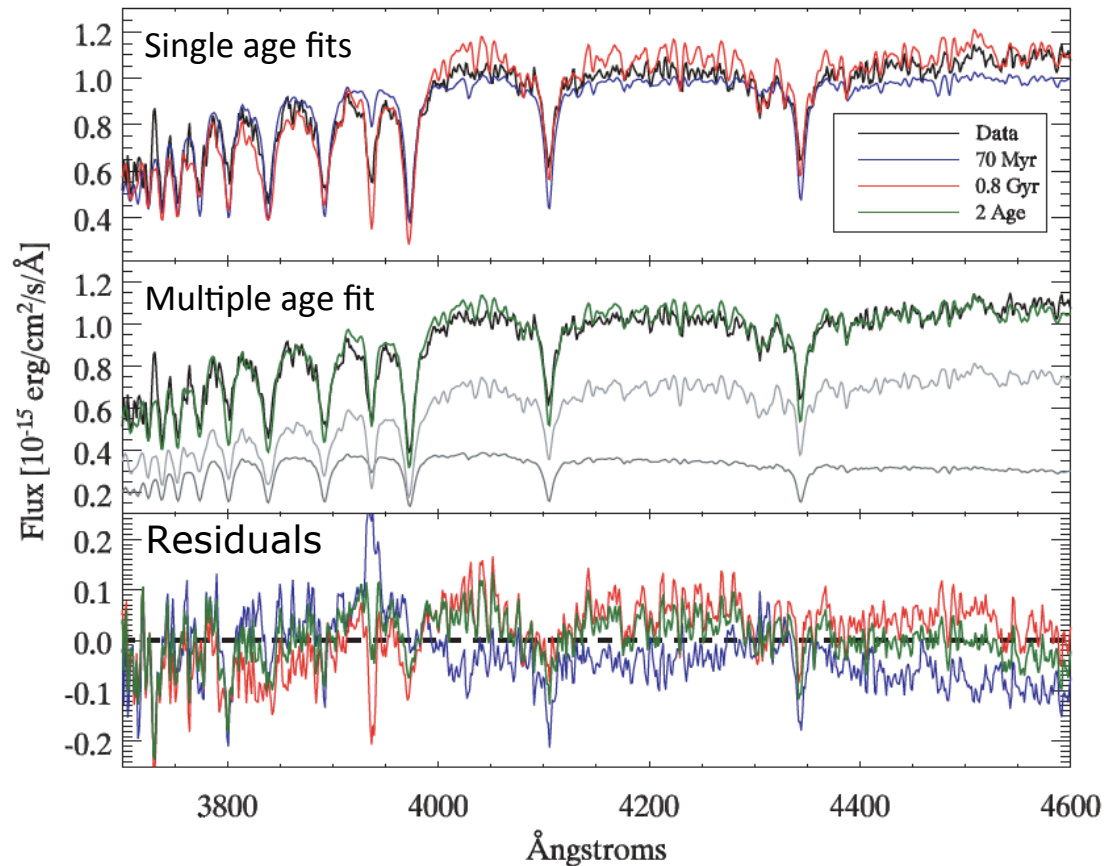
Old component is spatially more extended and rounder

Carson et al. 2015

Young stars form at the center of the clusters.



Stellar populations



Late type spirals:

SSP models do not fit

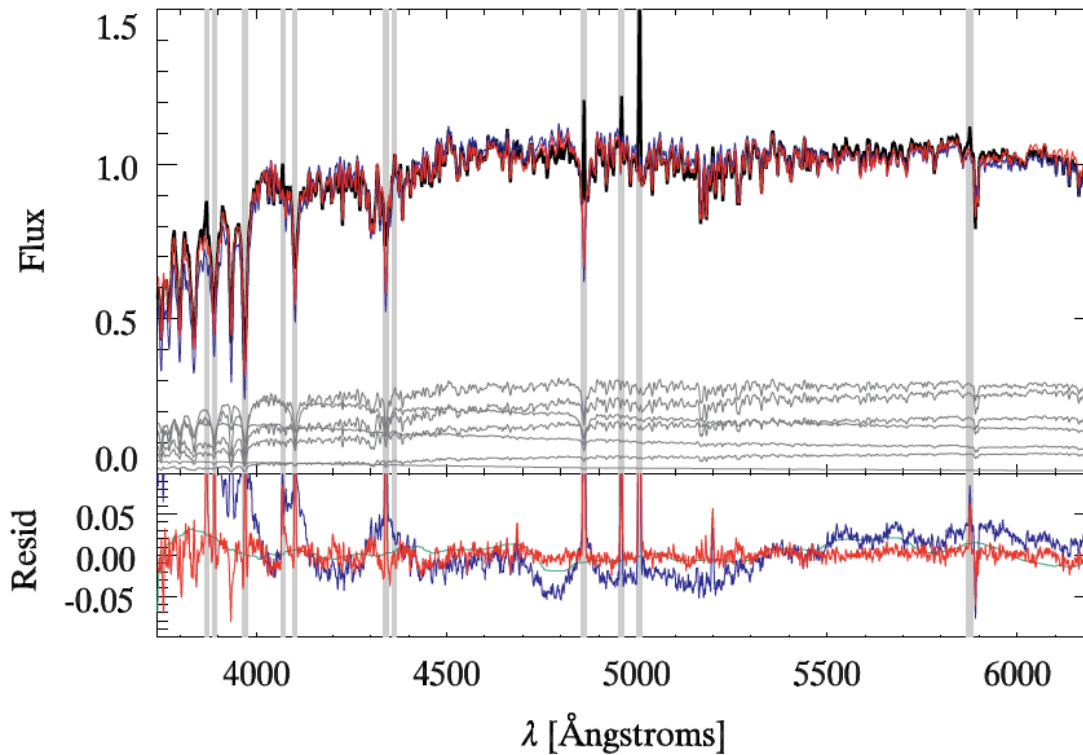
light dominating the NCs
has $\langle T \rangle \sim 10^8$ yrs

-> Recurrent SF with
 $\Delta T = 10^8$ yrs
 $\Delta M = 2.5 \times 10^5 M_{\odot}$

Walcher et al. 2006, Seth et al.
2006, Rossa et al. 2006



Stellar populations



Early type galaxies

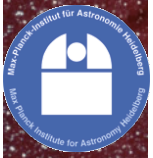
NGC404

Nearest S0 galaxy

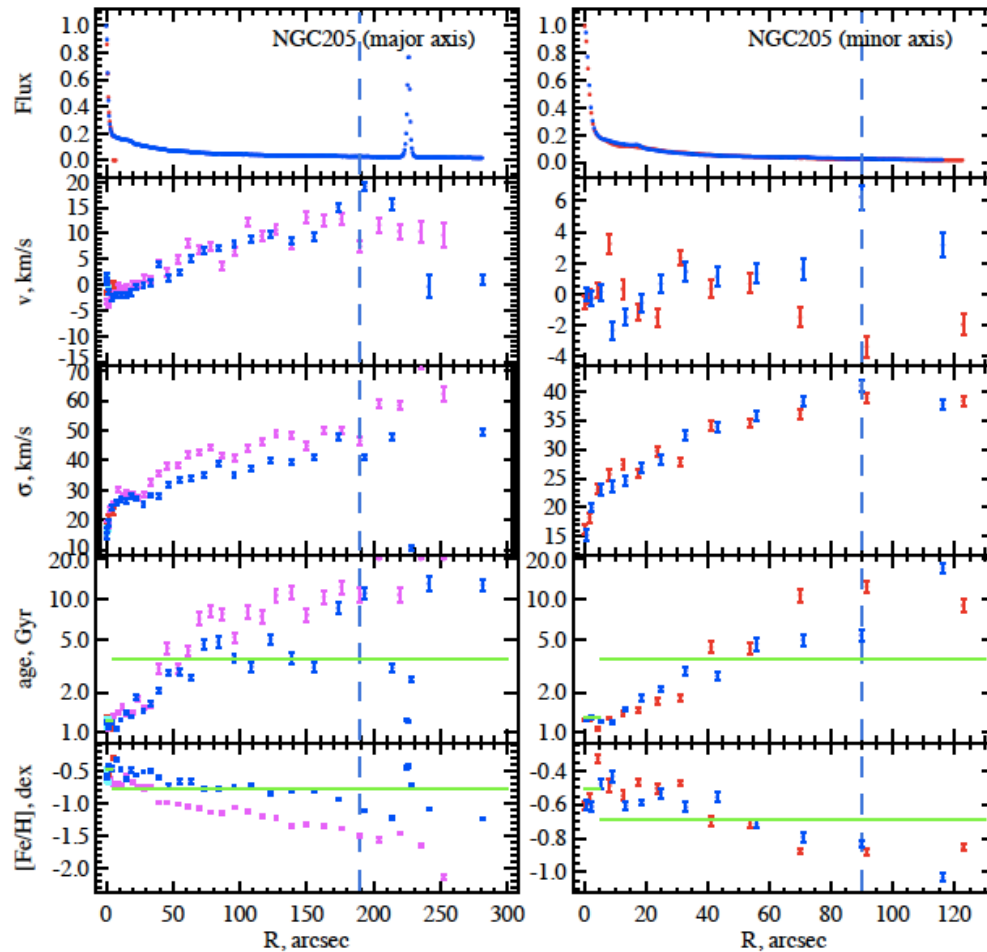
single age fit

multiple age fit

Seth et al. 2010,
Lyubenova et al. 2013



Stellar populations



Early type galaxies

NGC 205:
metallicity and age gradient
towards the nucleus

the nucleus is

- younger and
- more metal rich

Koleva et al. 2011

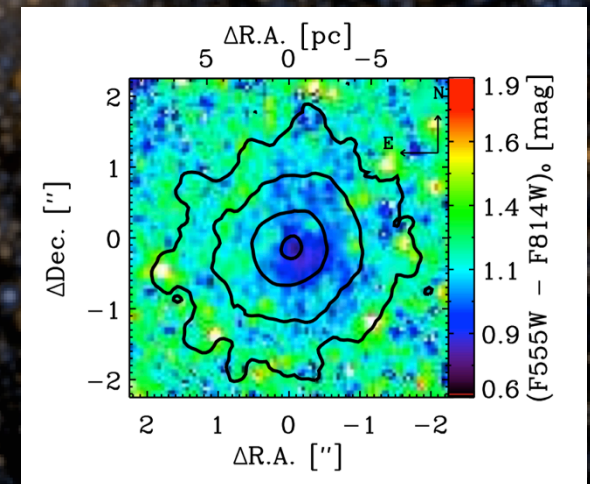
also Koleva et al. 2009 and

Paudel et al. 2011, Lyubenova et al. 2013b

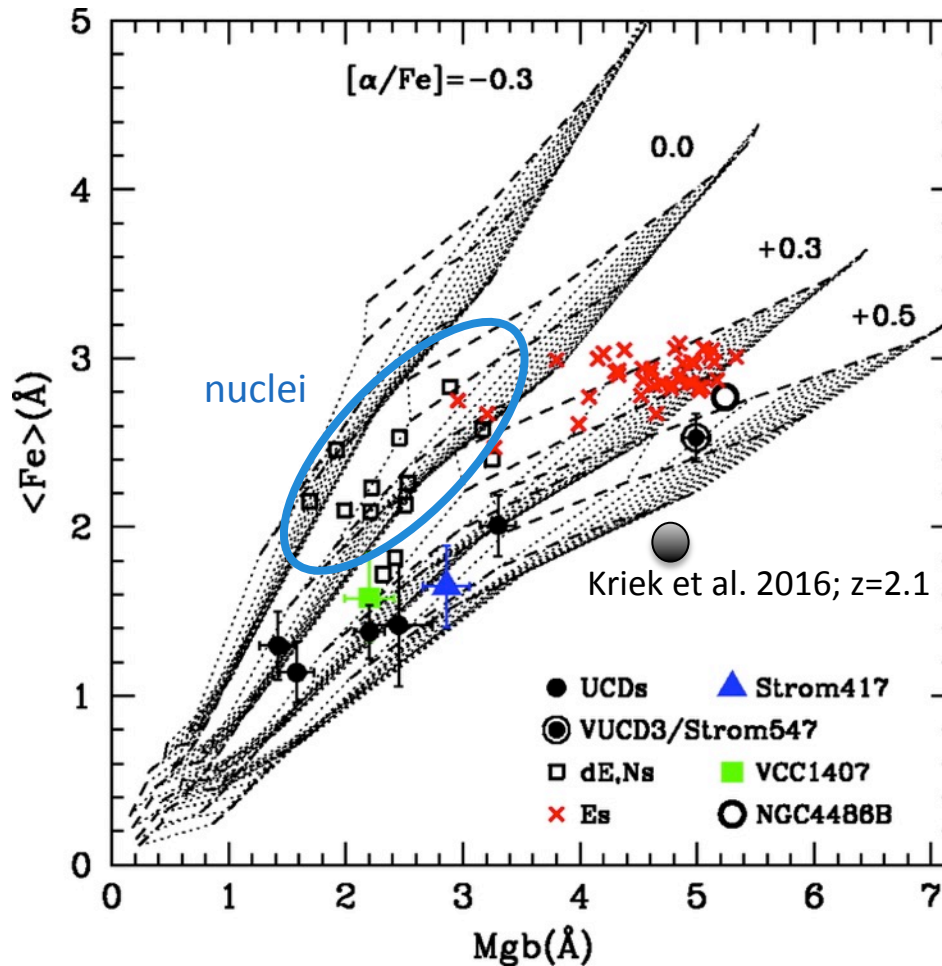


NGC 205: <100 Myr populations
Monaco et al. 2009

Young populations are not universal (Paudel et al. 2011)



Stellar populations



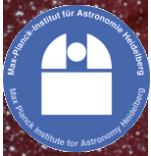
Abundance ratios:

NSCs: $[\alpha/Fe] \sim 0.0\text{dex}$

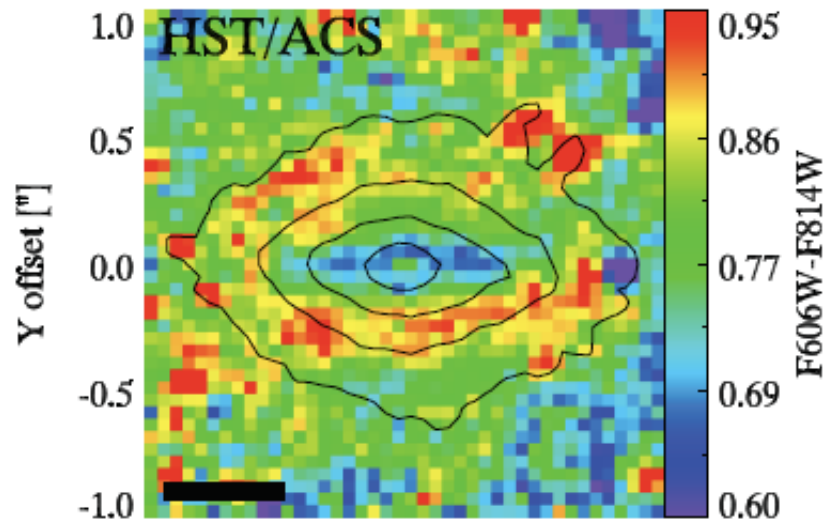
GCs: $[\alpha/Fe] \geq 0.3\text{dex}$

Evstigneeva et al. 2007

Worthy 2004 & Rose et al. 2005 (M32)



Stellar populations



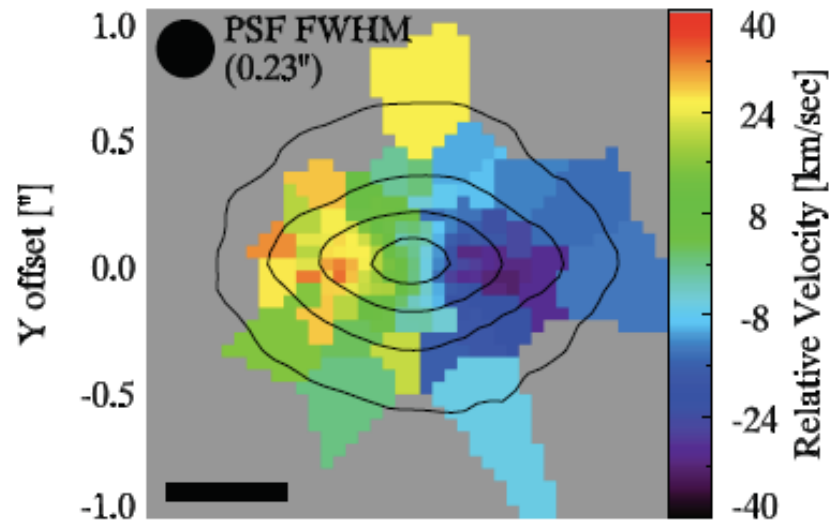
NGC4244

Seth et al. 08b

- NCs have multiple stellar populations
- Show distinct components: old/red spheroid and young/blue disk



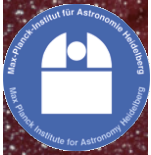
Kinematics



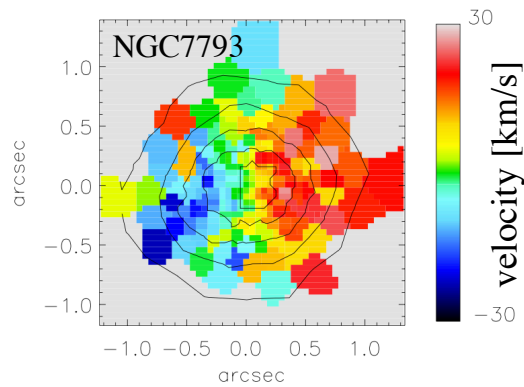
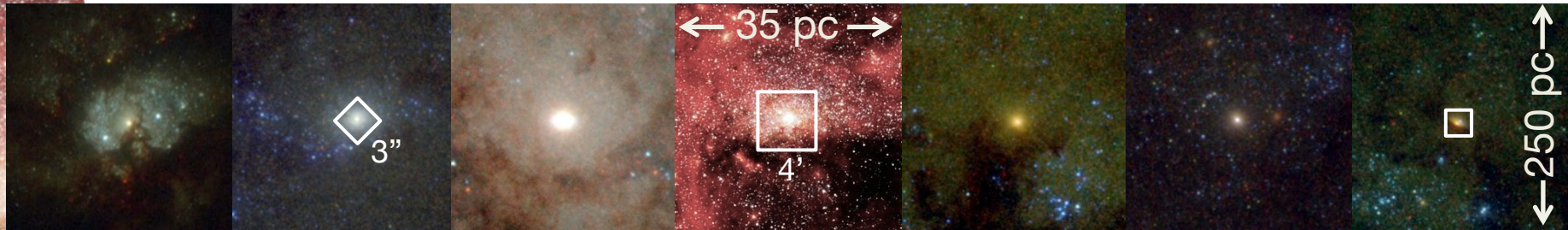
NGC4244

Seth et al. 08b

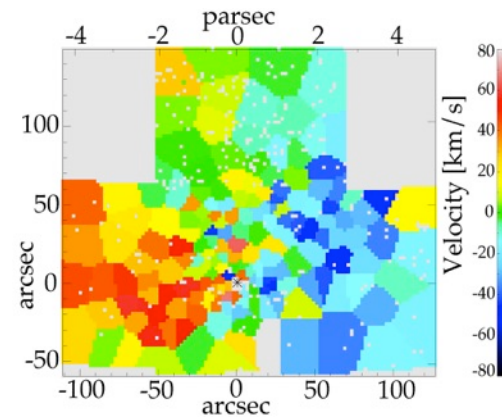
- NCs have multiple stellar populations
- Show distinct components: old/red spheroid and young/blue disk
- Both rotate



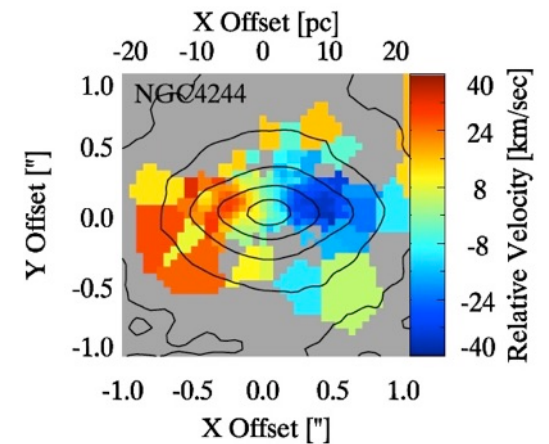
Nearby nuclear star clusters



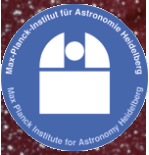
Picotti, Neumayer, et al. in prep.



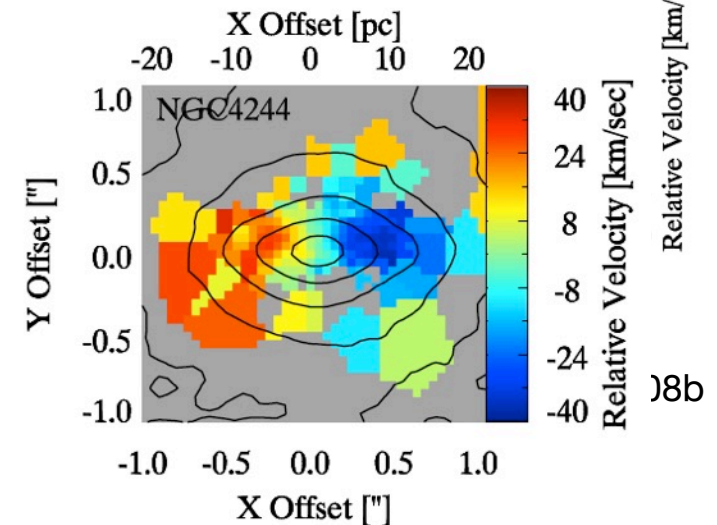
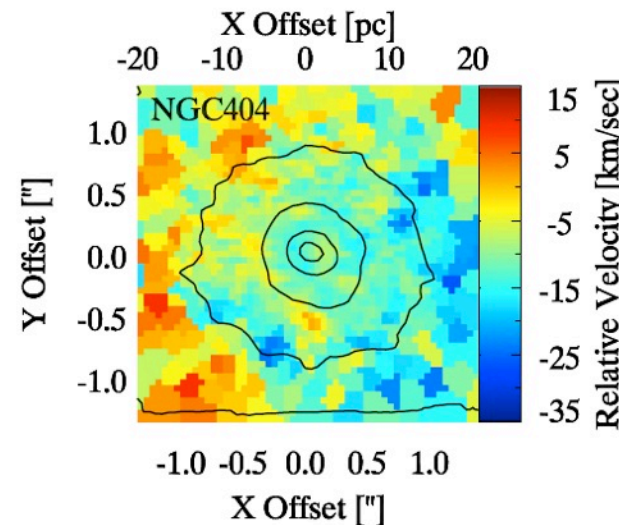
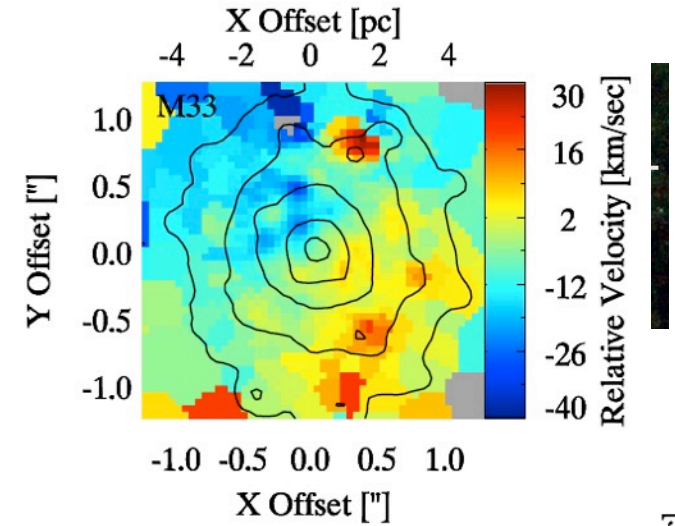
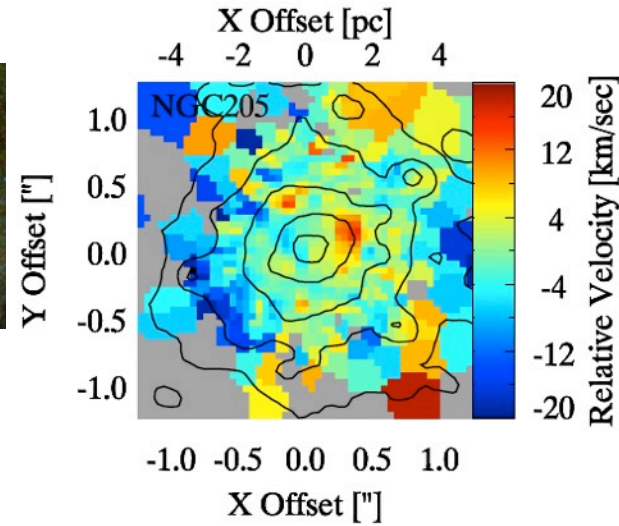
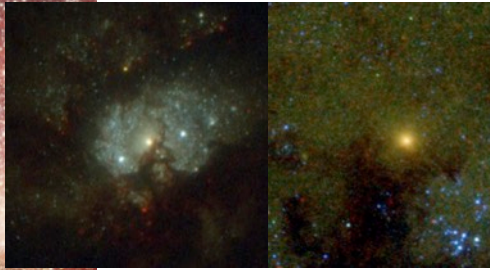
Feldmeier, Neumayer et al. 2014



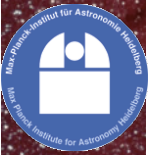
Seth et al. 2008b



NSCs typically rotate with $v/\sigma \sim 1$



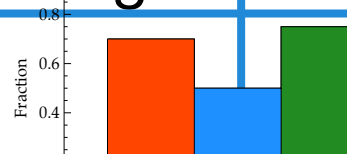
Neumayer/Seth Lyubenova



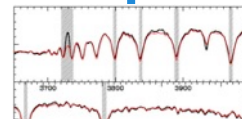
Formation of Nuclear Clusters

Two competing formation scenarios:

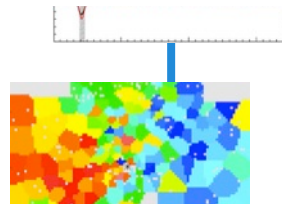
Star cluster infall and merger | In-situ formation at the centre



NSCs are common: >65% nucleation fraction

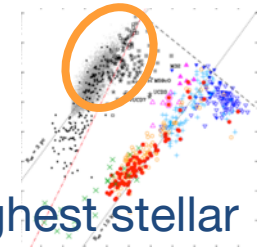


Complex star formation histories

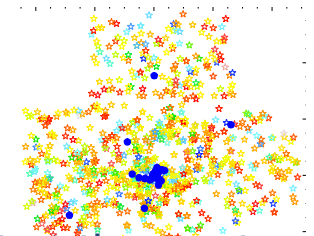


Clusters rotate

... and have complex kinematics



have the highest stellar densities in the universe



Young stars sit at the center

It is a combination of both...

Heraeus Seminar *Stellar aggregates*, December 4 - 9, 2016

Nadine Neumayer

