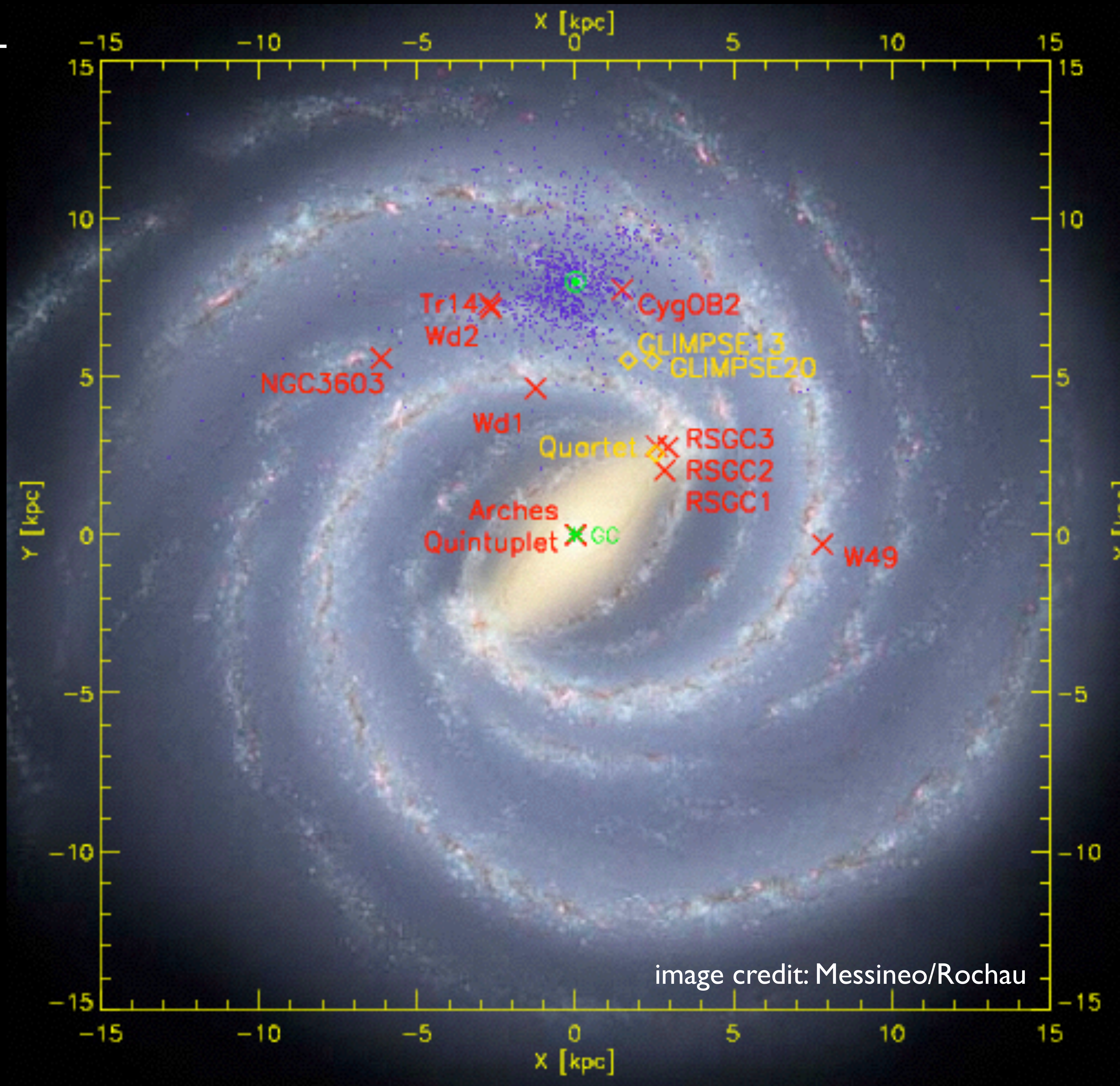
Young massive Star Clusters in the Milky Way



Team

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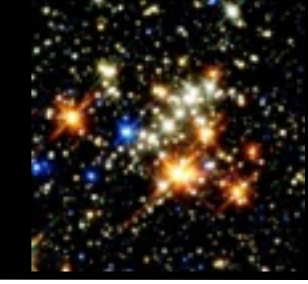
Motivation

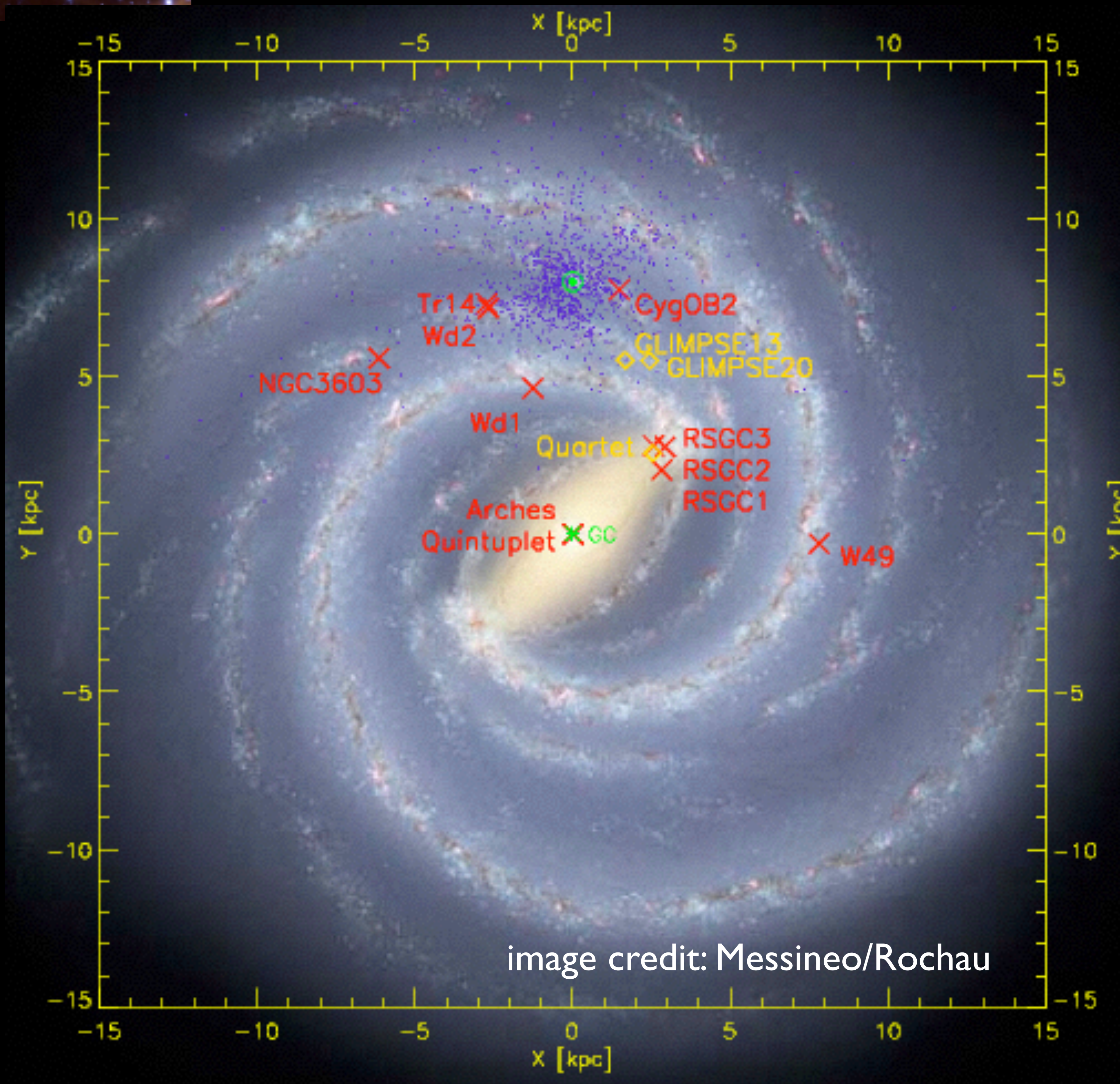
starburst cluster serve as “templates” for extragalactic starburst: Milky Way starburst clusters can be **resolved into individual members down to sub-solar masses**

=> radial mass profile of cluster
=> mass function slope, evidence for mass cut-offs?
=> mass segregation
=> internal dynamics: how far are clusters from virial equilibrium
=> orbital motion to get clues on formation and “fate”: dissolution into the field, do clusters in the Galactic Center region contribute to the Nuclear cluster?

Caveat: focus of talk is on observational findings!

Definition: what is a MW starburst cluster?





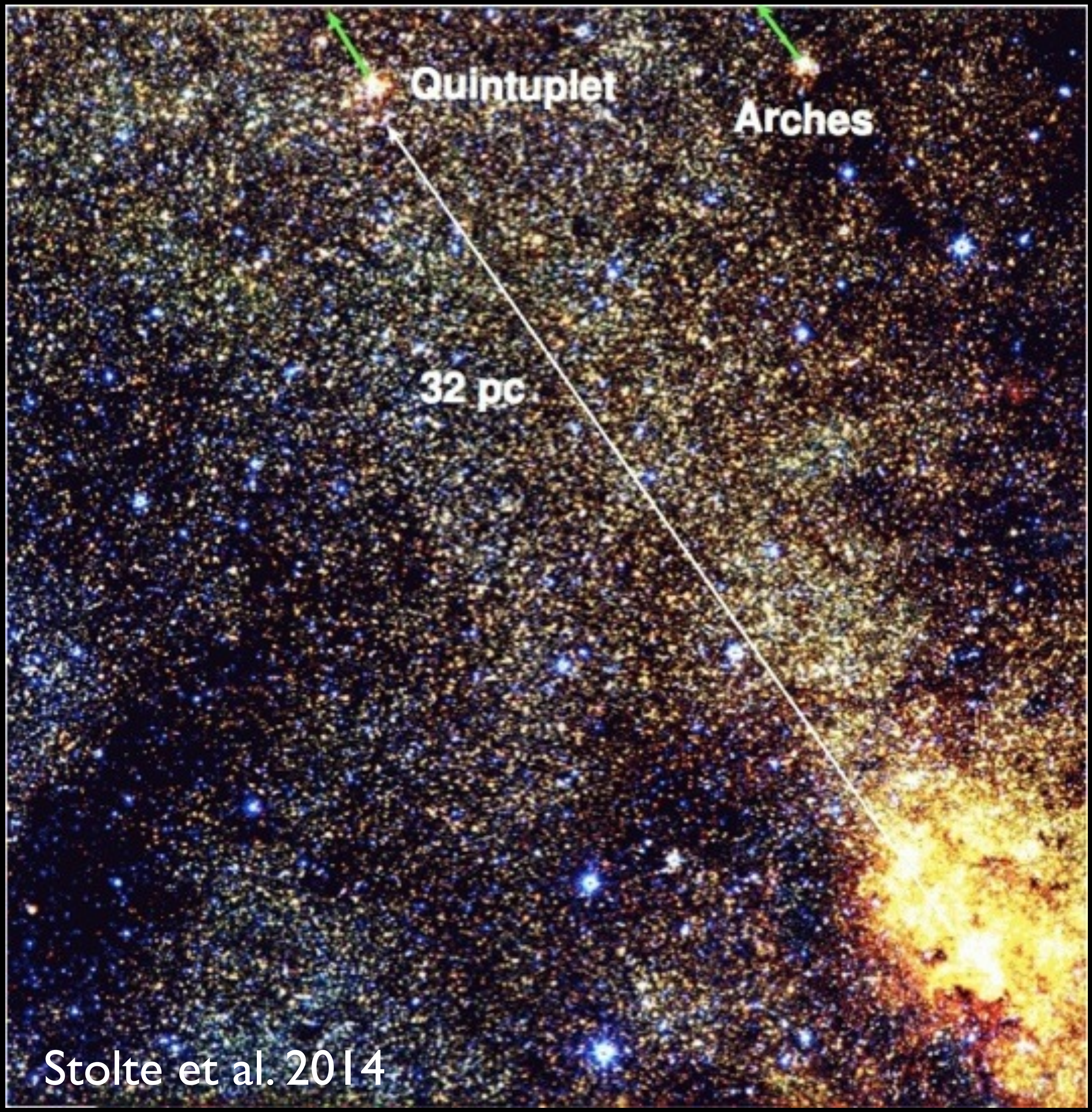
MW Starburst clusters:

- most massive young clusters
- entire IMF populated (up to ~120 M_{Sun})
- mass: ≥10 000 to 10^5 M_{Sun}
- age: 1 to ~6 Myr
- size: $r_{halfmass} \lesssim 1$ pc

Preferred location:

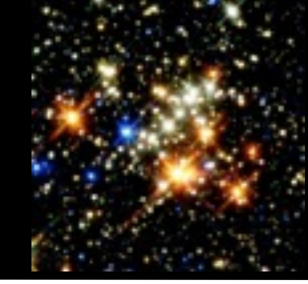
- spiral arms
- tip of the bar
- Galactic Center region

The sample



focus on
2 spiral arm clusters (NGC 3603 YC, Westerlund 1) and
2 Galactic Center region clusters (Arches, Quintuplet)

Observational challenges

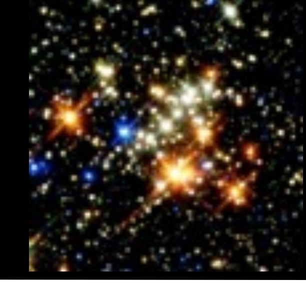


clusters located in the galactic plane at several kpc distance:

cluster	distance	l, b [deg]	Av [mag]	mass [Msun]	r
Arches	8 kpc	0.12, 0.02	>25	≈20000	0.2
Quintuplet	8 kpc	0.16, -0.06	>23	<40000	0.4
NGC 3603	6 kpc	292, -0.5	4.5	≤15000	0.25
Westerlund 1	4 kpc	340, -0.4	10	≈50000	1

- crowding ⇒ need high angular resolution: HST, VLT, Keck, Gemini, …
- extinction ⇒ need observations in the near infrared
- field star contamination ⇒ multi-epoch observation for astrometric membership selection

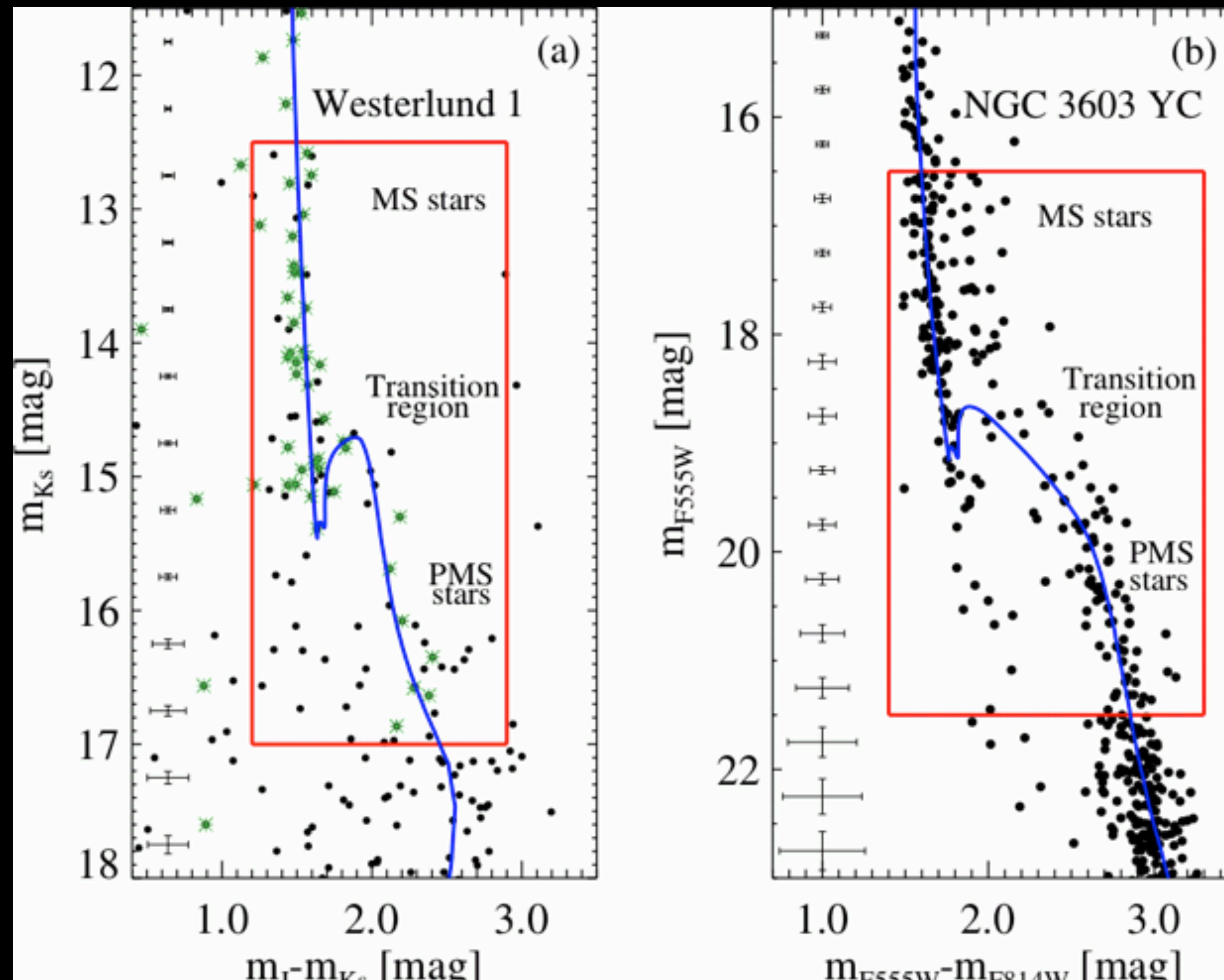
Colour-magnitude diagrams of young massive cluster



3 domains:
* pre-main sequence
* transition region
* main sequence

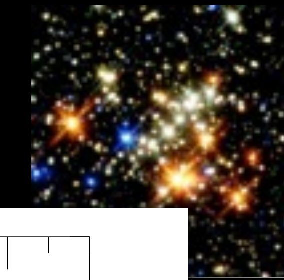
<=> use **evolutionary models** to determine masses of individual stars

artificial star tests:
=> correction for (in-) completeness
=> photometric uncertainty

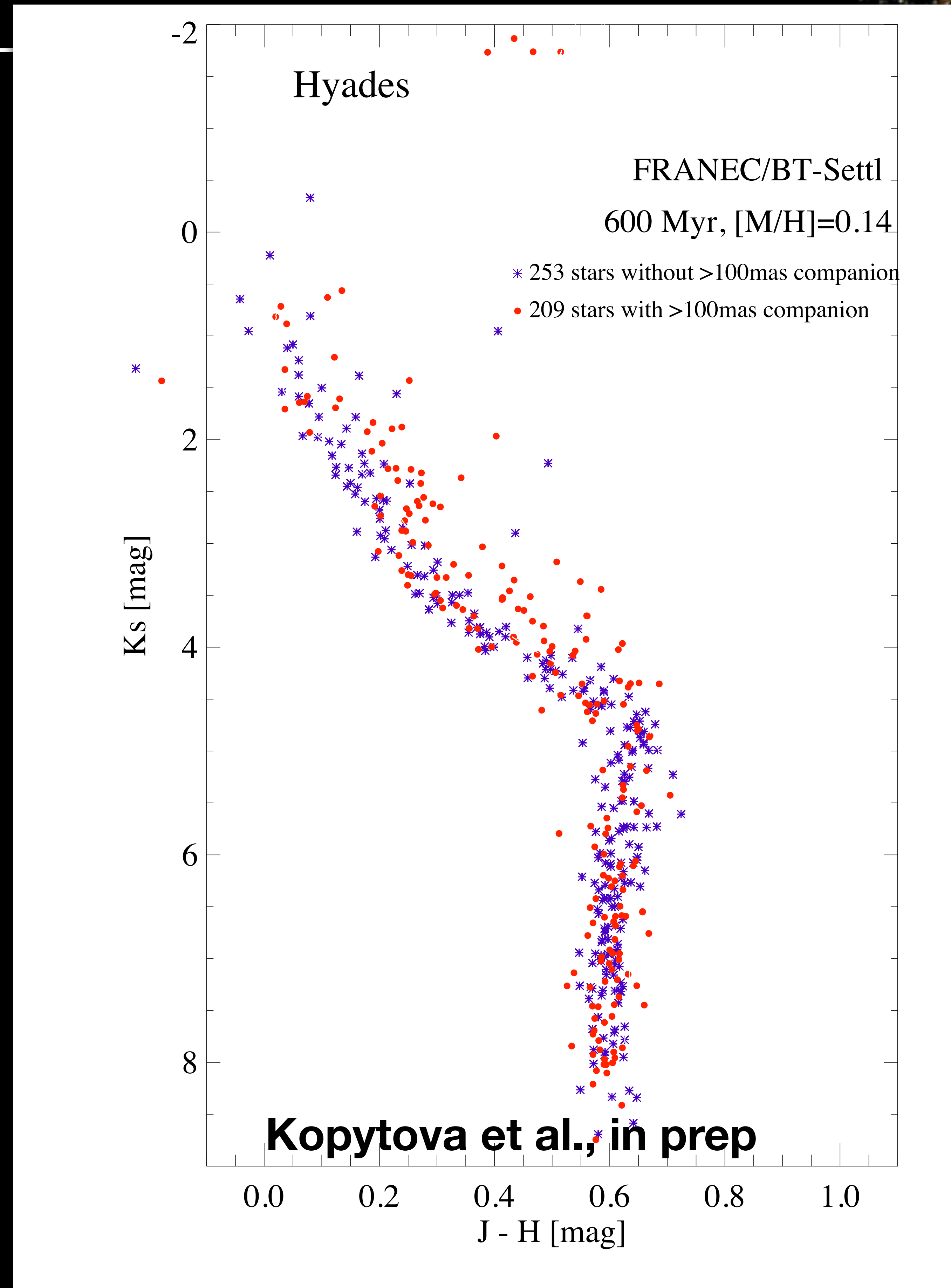


Kudryavtseva et al. 2012

Observational bias



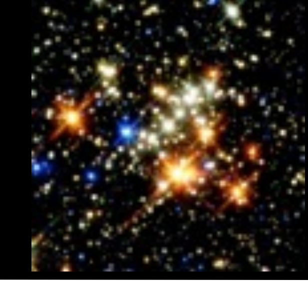
Hyades: single and multiple stars



unresolved binary stars results to an **apparent broadening** of the cluster sequence

For the starburst clusters we are still ignorant about multiplicity (blending, interacting binaries, …), metallicity, stellar rotation, …

Cluster properties to investigate



Radial profile

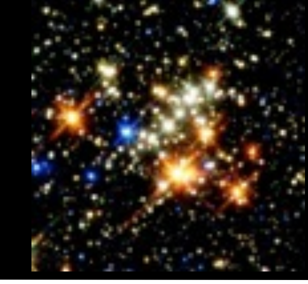
Mass segregation

Velocity dispersion & dynamical state

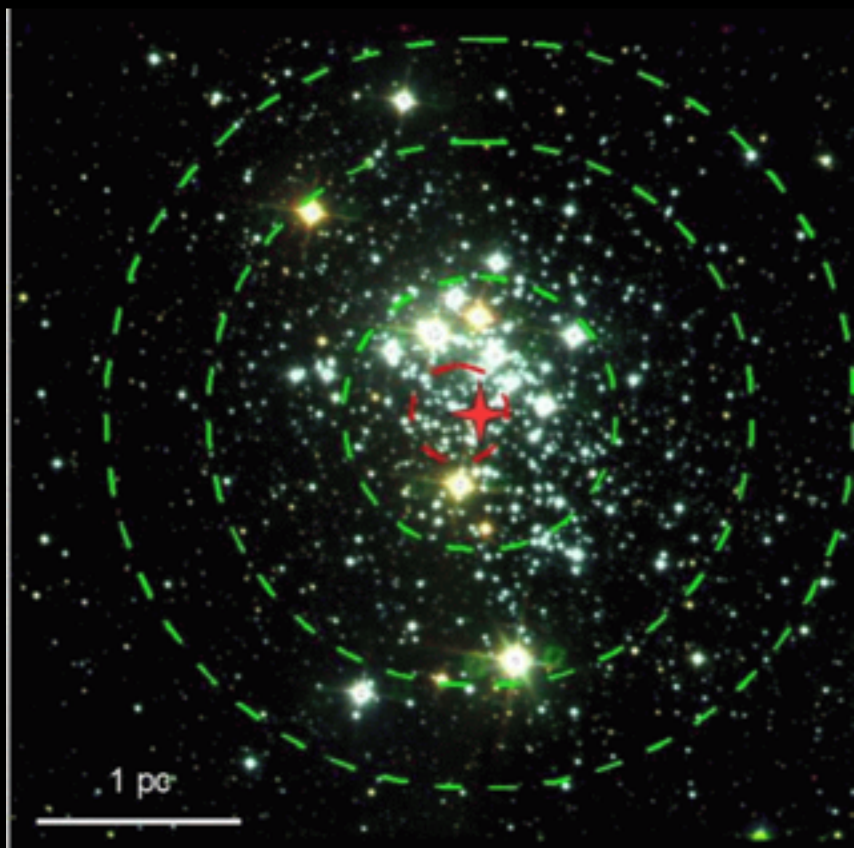
Age spread

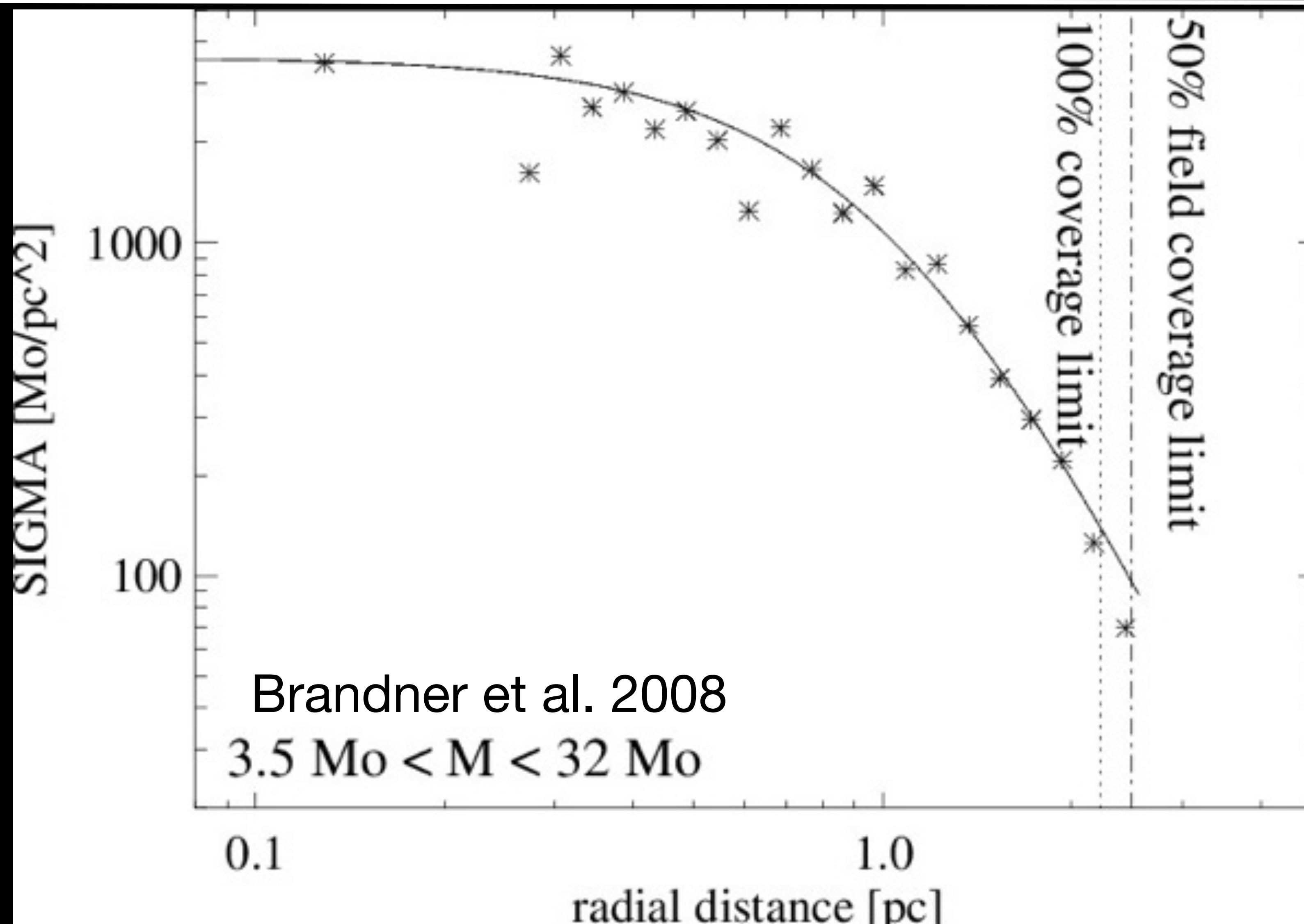
Orbits and formation loci

Radial Mass profile of Westerlund 1



half mass radius ~ 1 pc



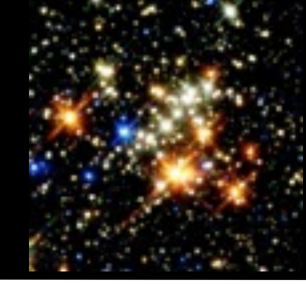


mass surface density (for stars in the range 3.5 to 32 Msun, and r≤ 2 pc):

SIGMA(r) ~ $(1+(r/a)^2)^{-2}$ with a=1.1 pc
(following Elson et al. 1987)

<=> Westerlund 1 is elongated along galactic plane with eccentricity 0.15 to 0.19!!!
=> rotation or formation out of subclusters? (-> talk by Alison Sills)

Cluster properties to investigate



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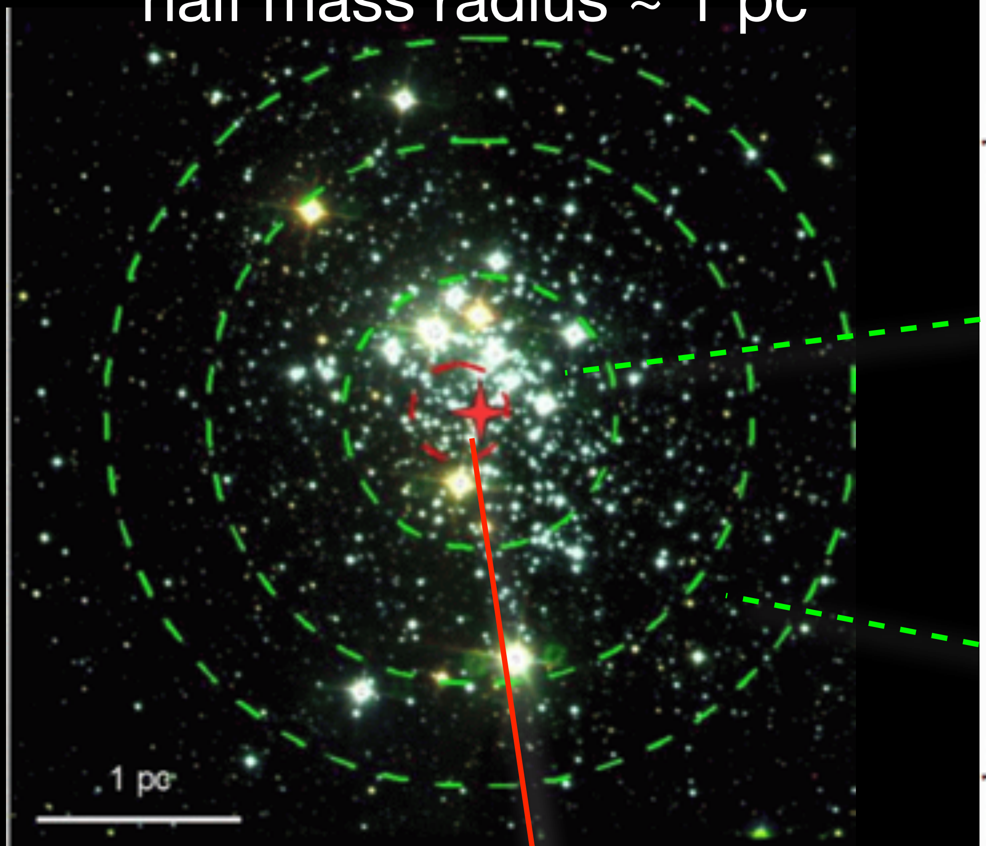
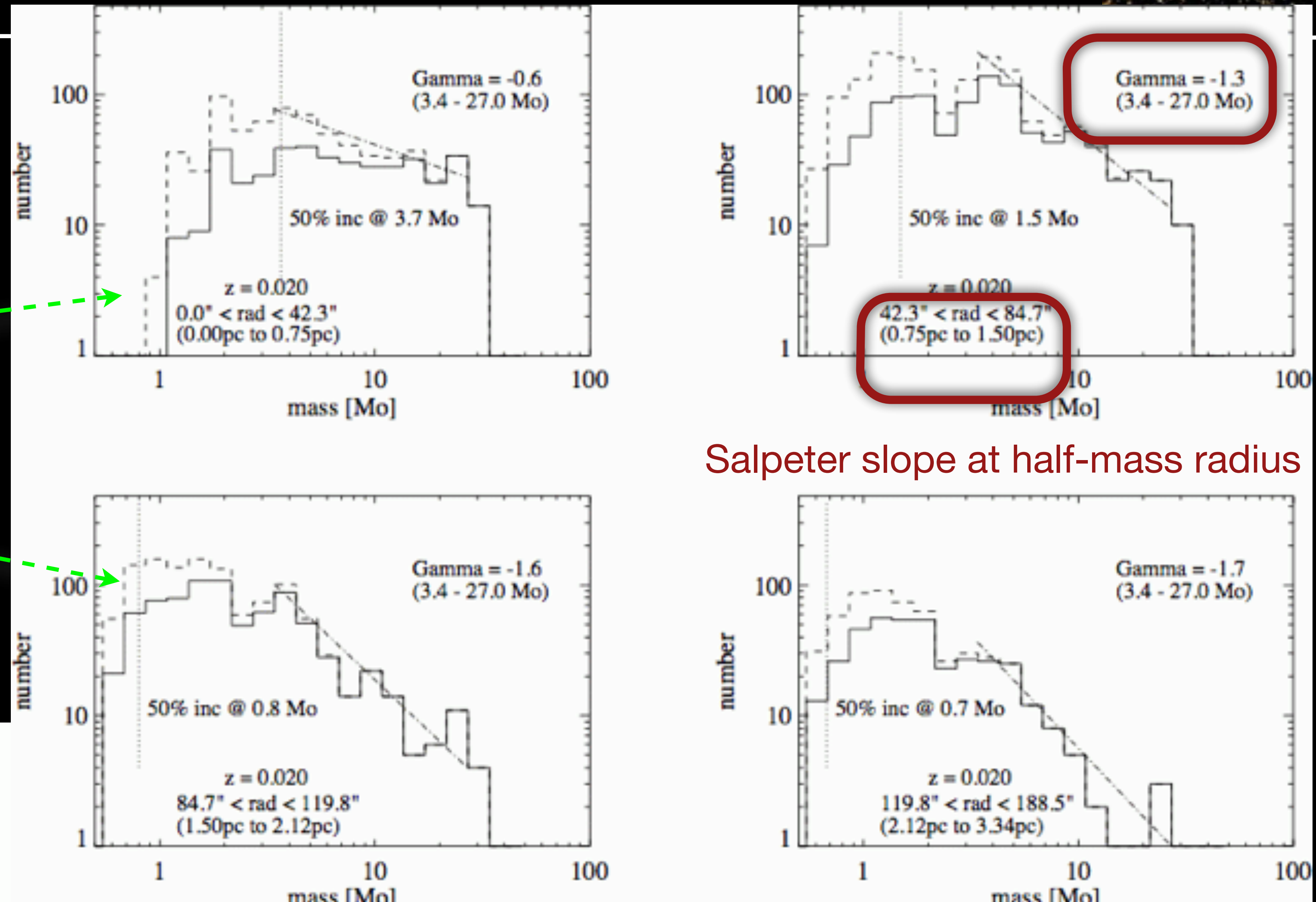
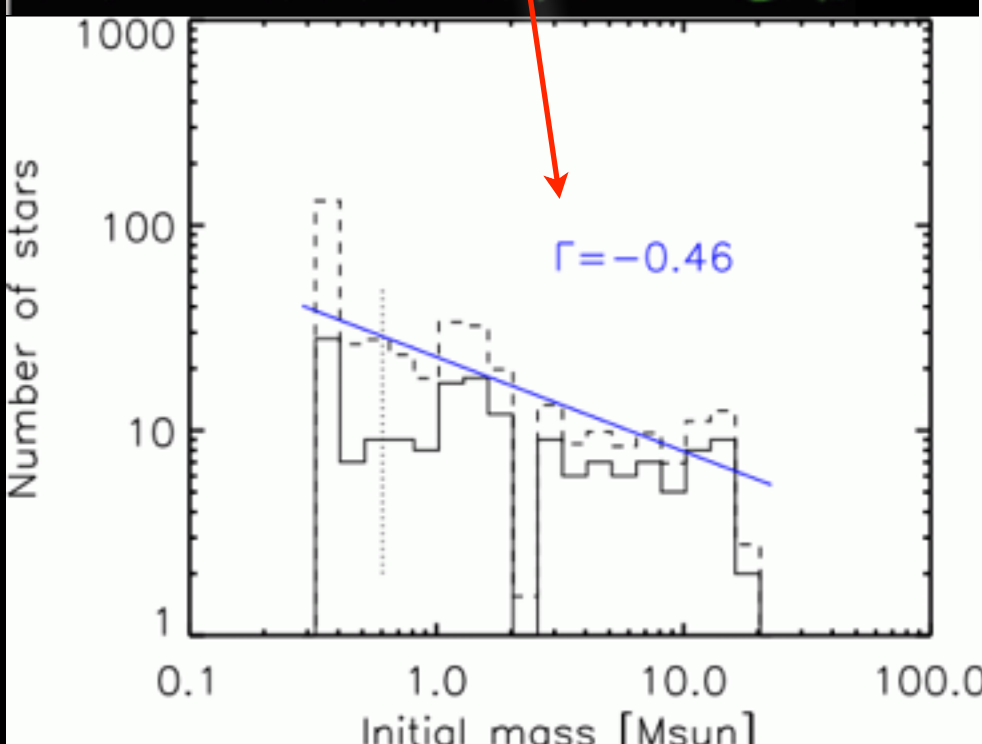
Mass segregation in Westerlund 1

half mass radius ~ 1 pc



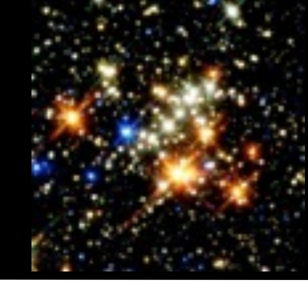




All MW starburst clusters show clear evidence for mass segregation (Brandner et al. 2008; Gennaro et al. 2011; Kudryavtseva 2012; Habibi et al. 2013, Hußmann 2013).

Radially averaged mass functions are in good agreement with a Kroupa-type IMF.

Cluster properties to investigate



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Dynamical state of MW starburst clusters

cluster	mass	r	σ [km/s]	t	t	age [Myr]
Arches	≈20000	0.2	≈7	0.03	18	2
Quintuplet	<40000	0.4	<7	>0.05	>56	5
NGC 3603	≤15000	0.25	≤5.5	>0.04	>19	1
Westerlund 1	≈50000	1	5	0.2	260	4

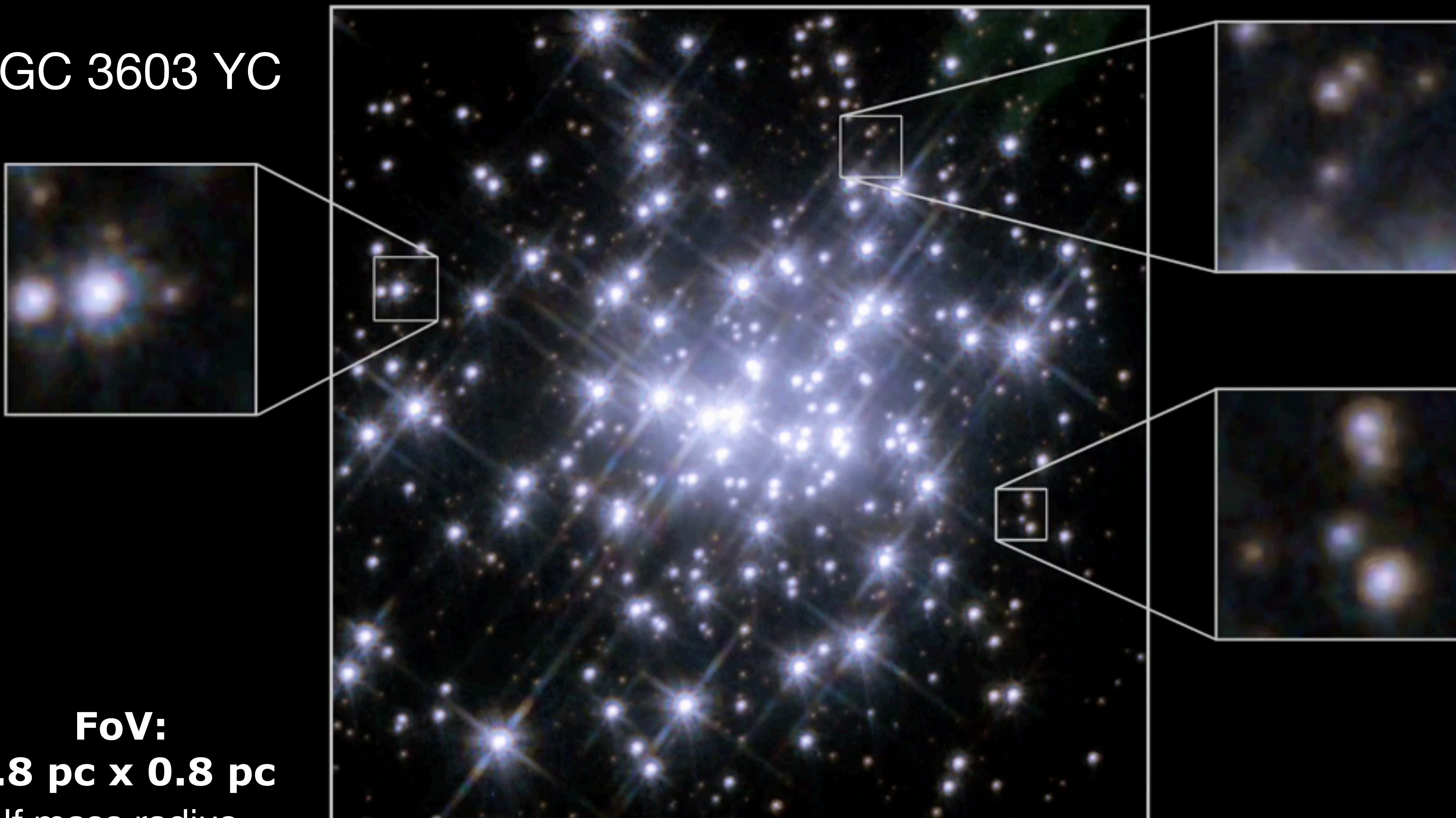
note: theoretical velocity dispersion σ assumes relaxed system

Westerlund 1: cluster age of ~4 Myr, i.e. 1/65 of the relaxation time, the cluster is not dynamically relaxed.
=> Mass segregation could be evidence of age ~20 crossing times

clusters are dynamically young and still evolving
=> try to measure actual velocity dispersion

Astrometric analysis of NGC 3603 data
10 year epoch difference

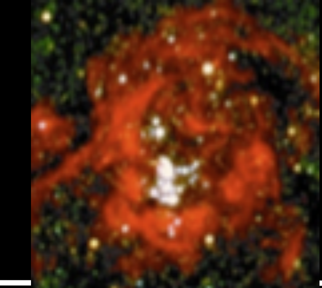
NGC 3603 YC

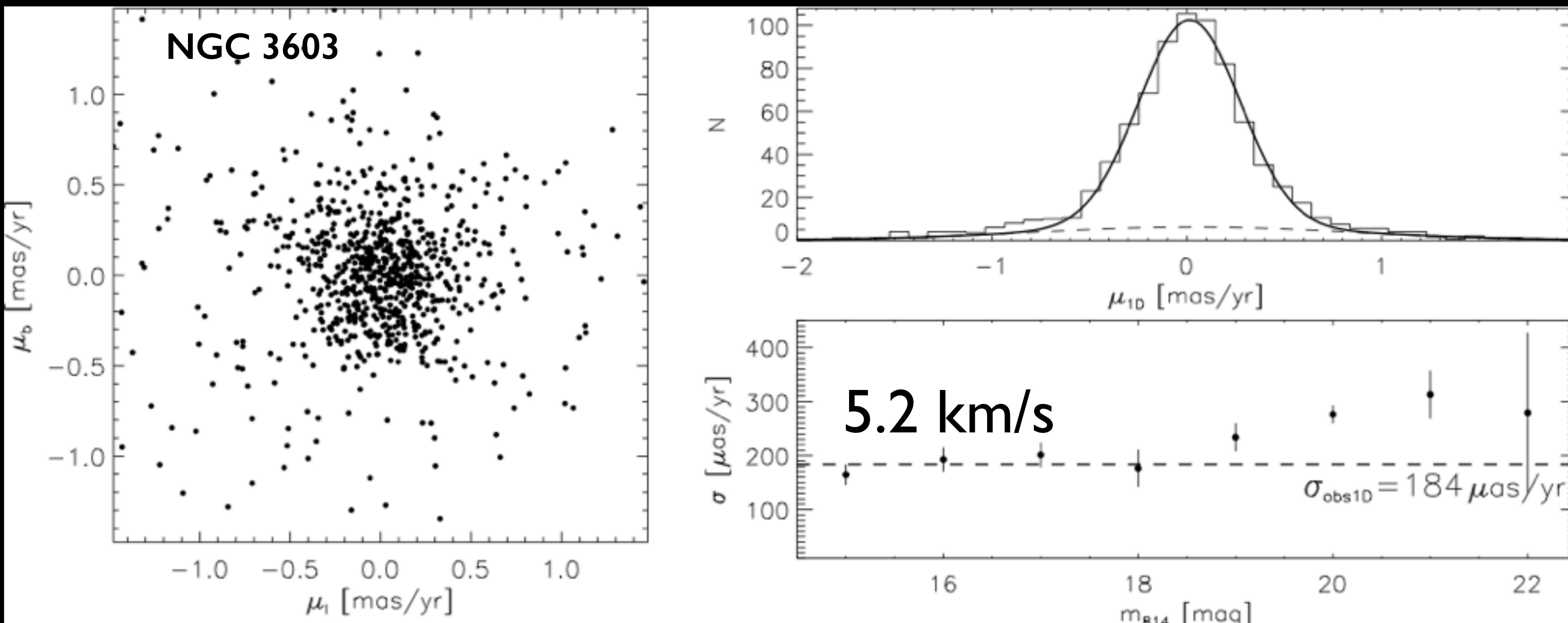


FoV:
0.8 pc x 0.8 pc
half mass radius
~ 0.25 pc

"Hubble catches stars on the move" (Rochau et al. 2010)

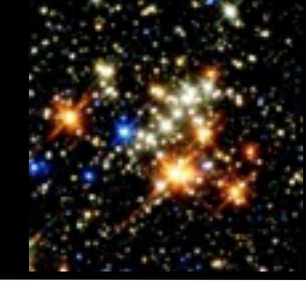
Astrometry gives 2D velocity dispersion (Rochau et al. 2010)





Small velocity dispersion of ≲5 km/s indicates virial mass of ~18 000 solar masses in good agreement with masses derived from stellar population photometry (12 000 to 16 000 solar masses). => MW starburst clusters are dynamically stable and could survive for extended periods of time (Rochau et al. 2010)

Cluster properties to investigate



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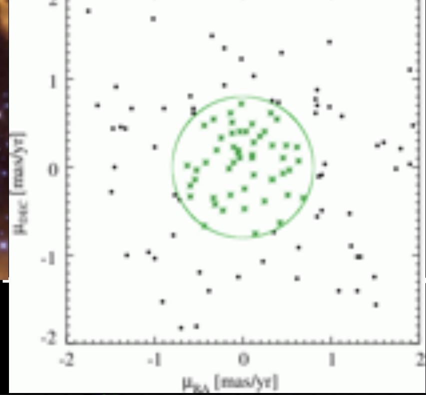
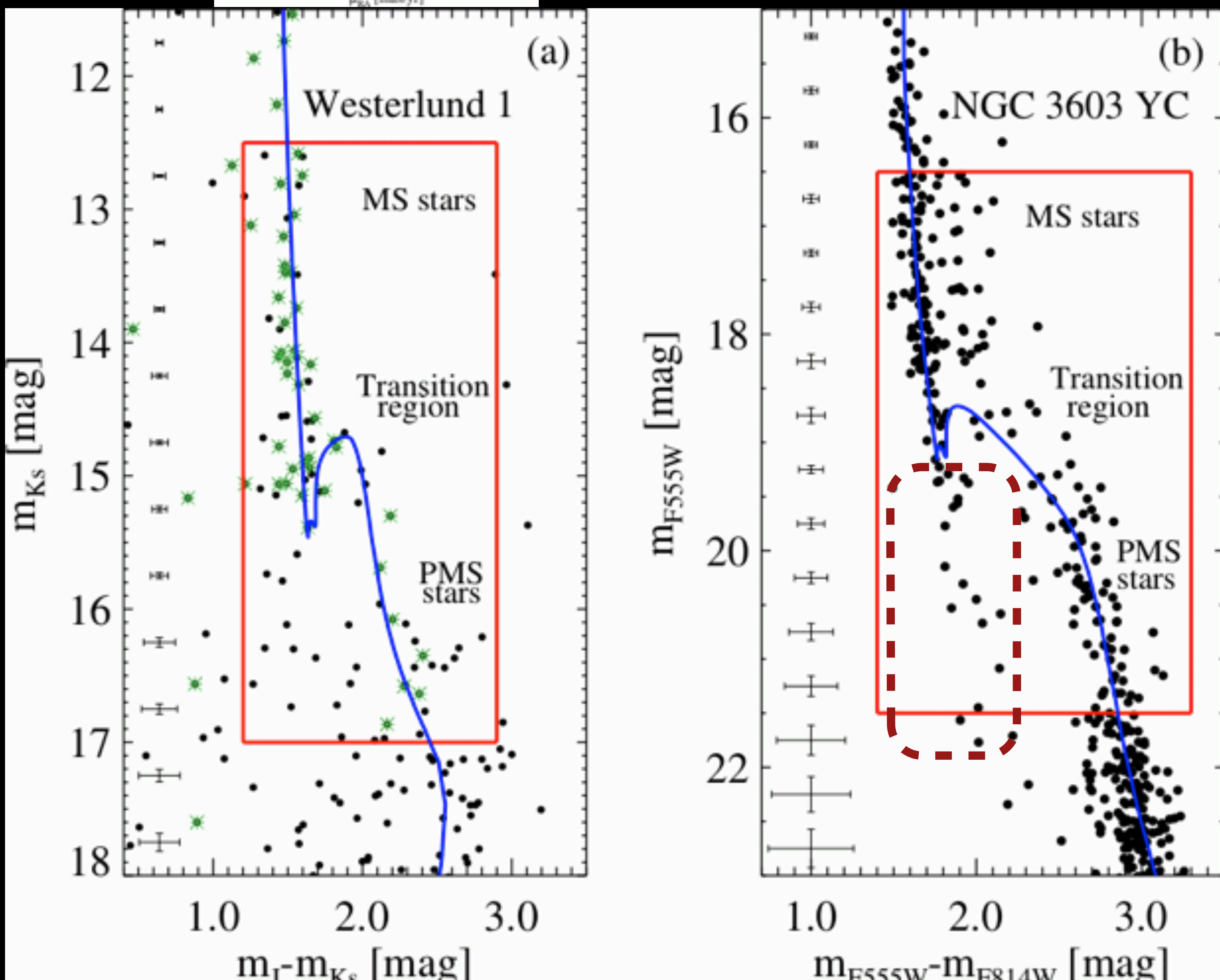
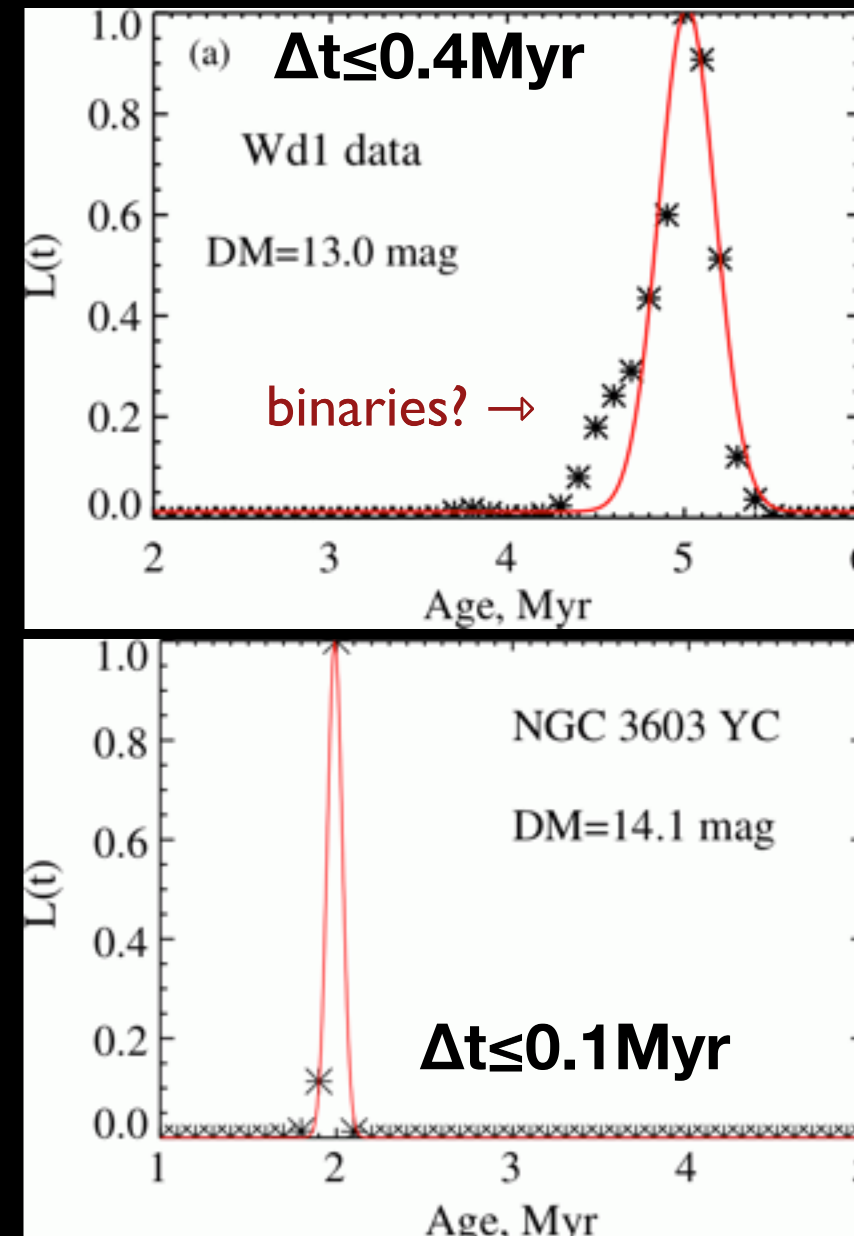


Age spread of cluster members

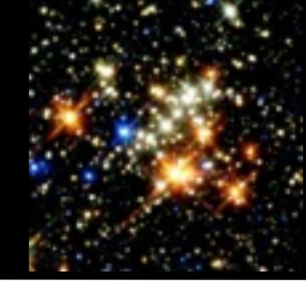
Assign most likely (Bayesian) age to each cluster member

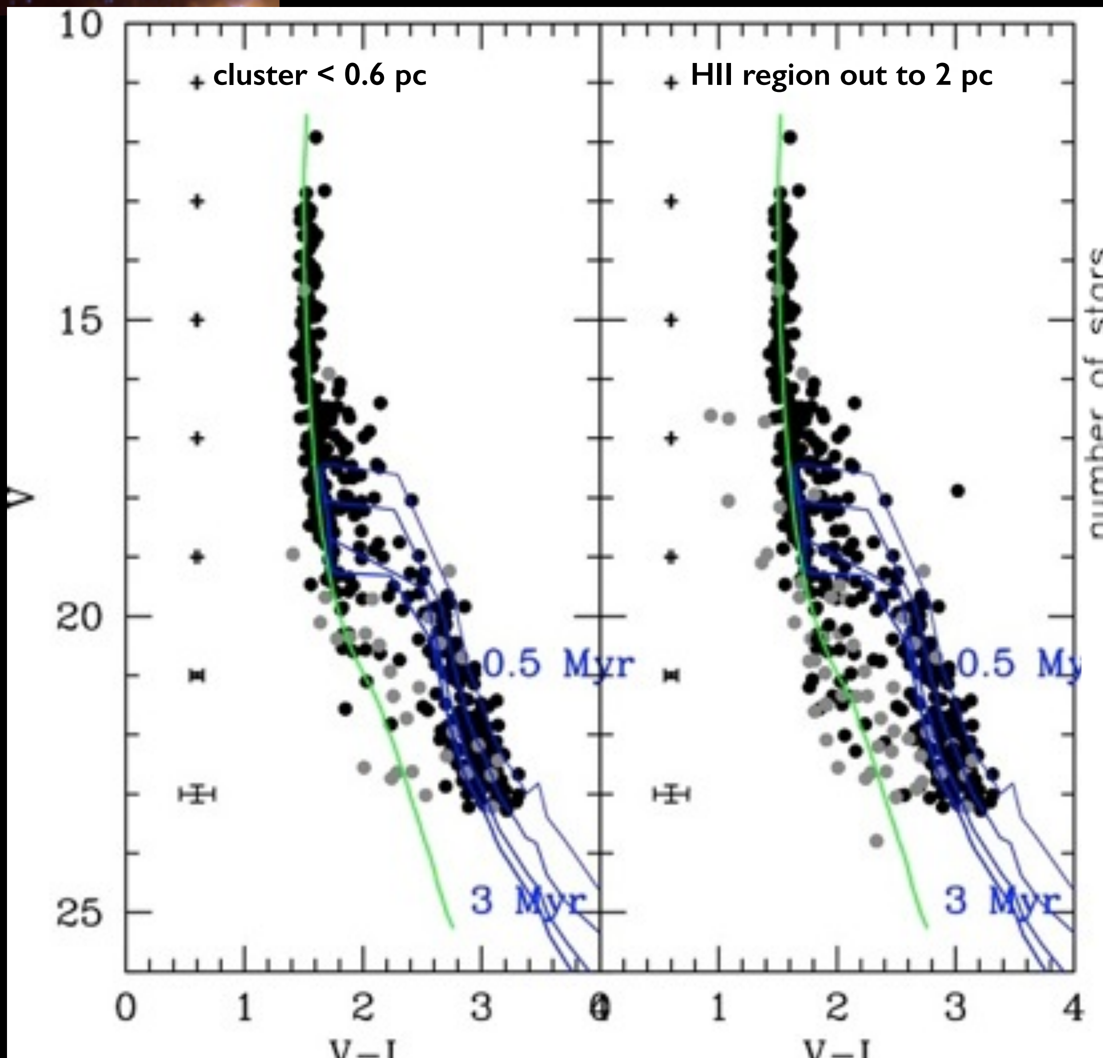




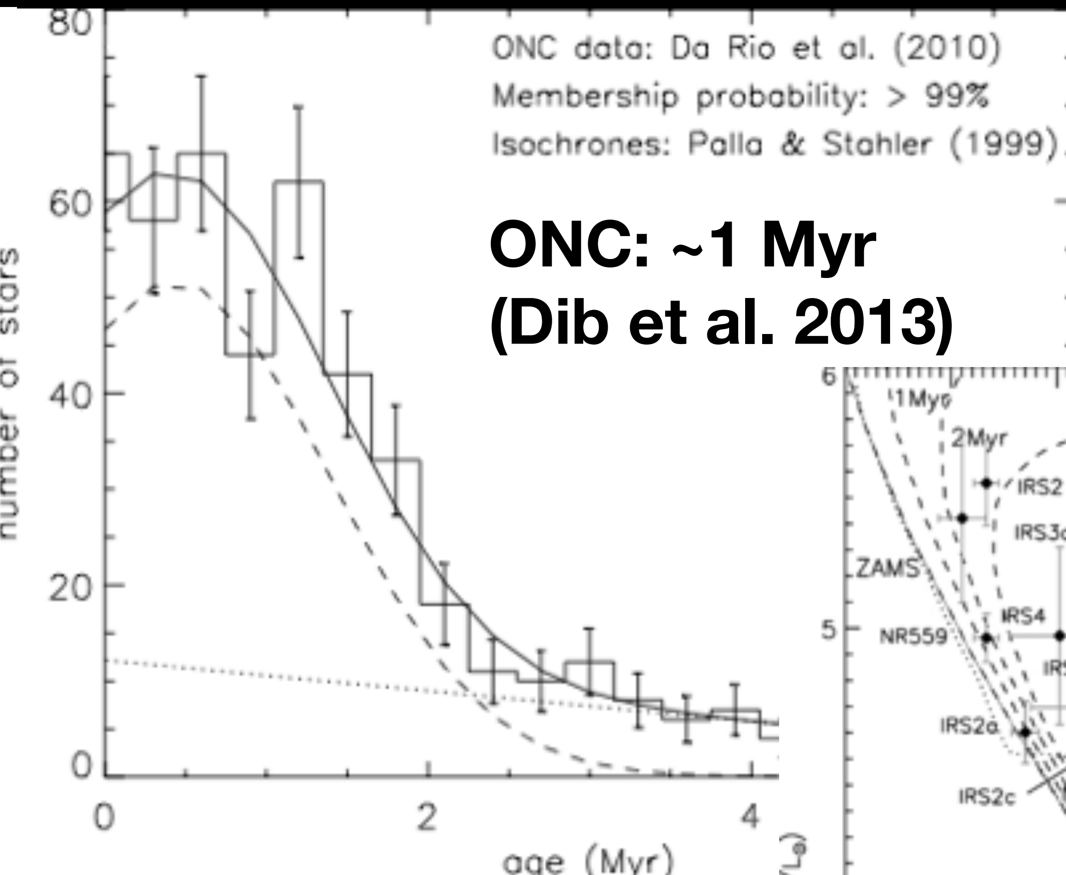
Well defined cluster sequences and small spreads in the global age probability function L(t) indicate that the clusters must have formed almost instantaneously (age spreads ≲0.1 Myr and ≲0.4 Myr for NGC 3603 YC and Westerlund 1, respectively; Kudryavsteva et al. 2012,) <=> but...

Age spread in cluster

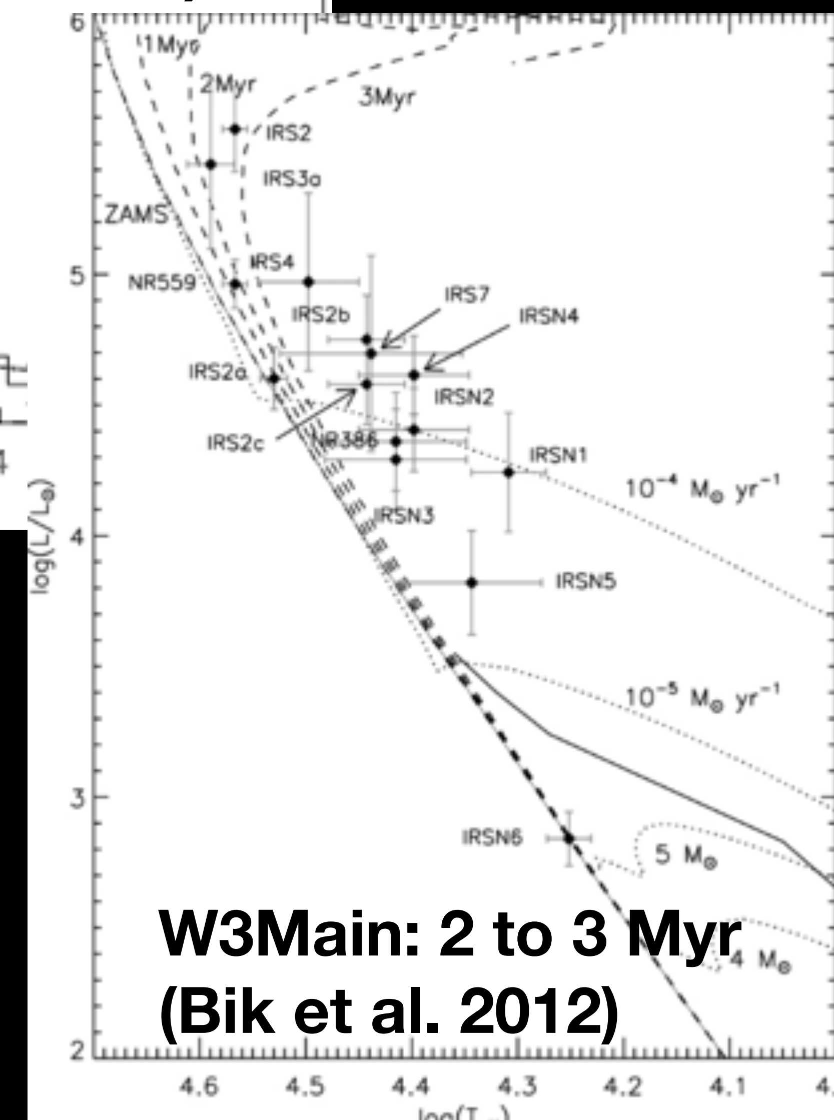




NGC 3603 HII region:
up to 3 Myr
(Pang et al. 2013)



ONC: ~1 Myr
(Dib et al. 2013)



W3Main: 2 to 3 Myr
(Bik et al. 2012)

=> clusters can be embedded in larger star forming regions with a larger spread in age <=> next talks by Banerjee & Beccari
+ variations in age spread with star formation environment

Cluster properties to investigate

Radial profile

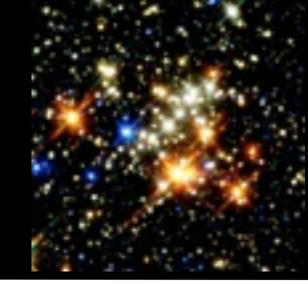
Mass segregation

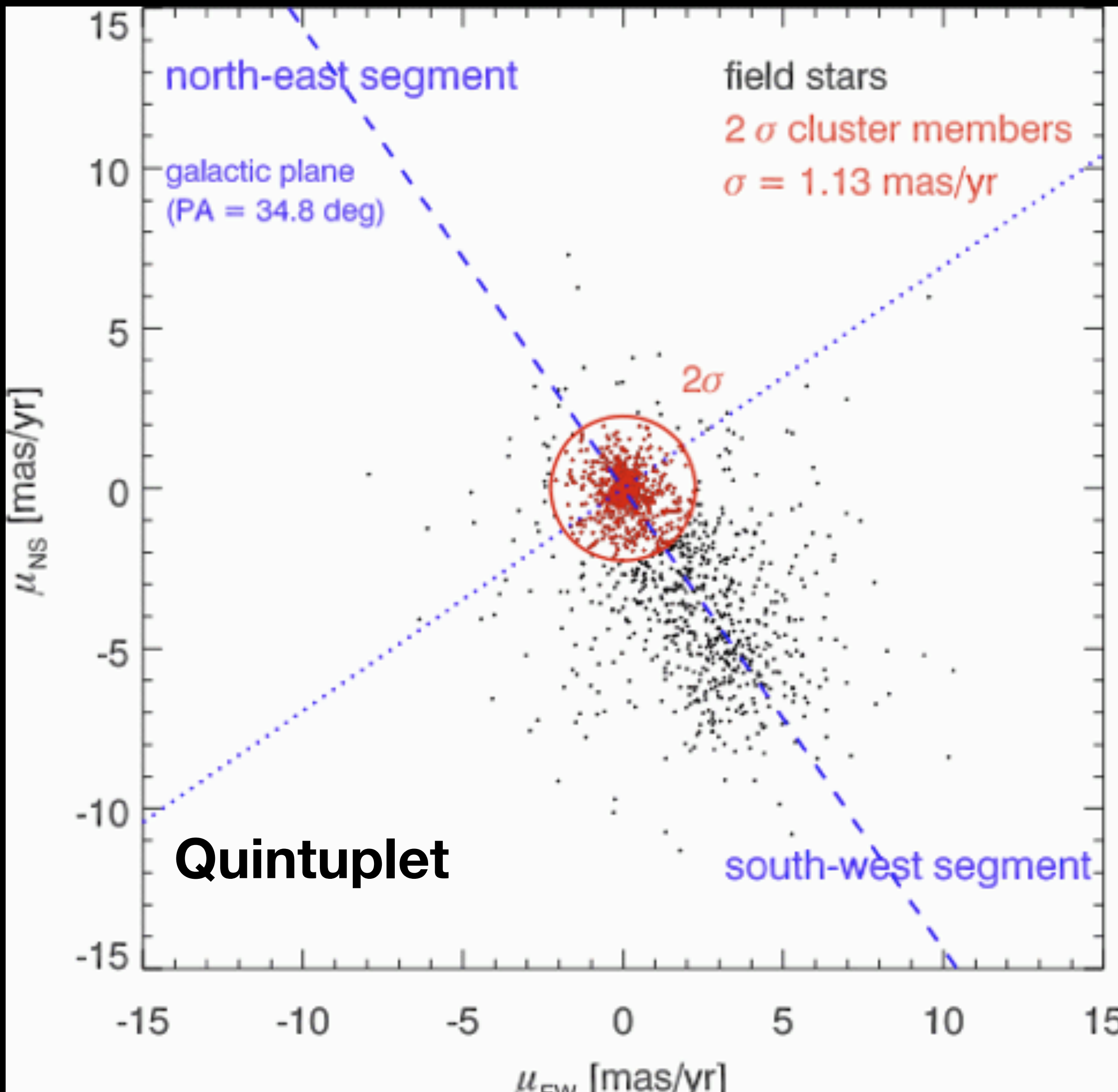
Velocity dispersion & dynamical state

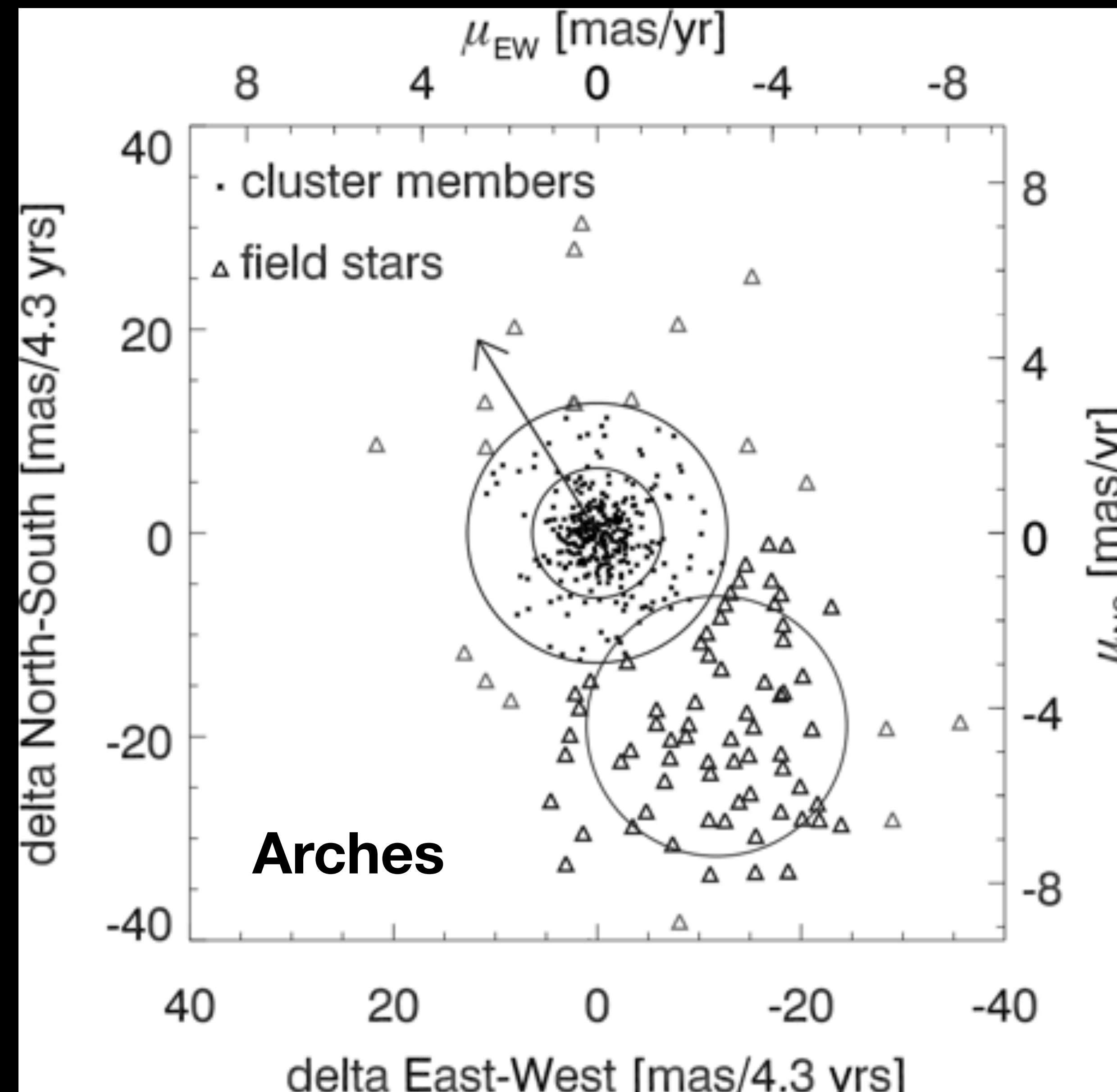
Age spread

Orbits and formation loci

Galactic orbits and formation places



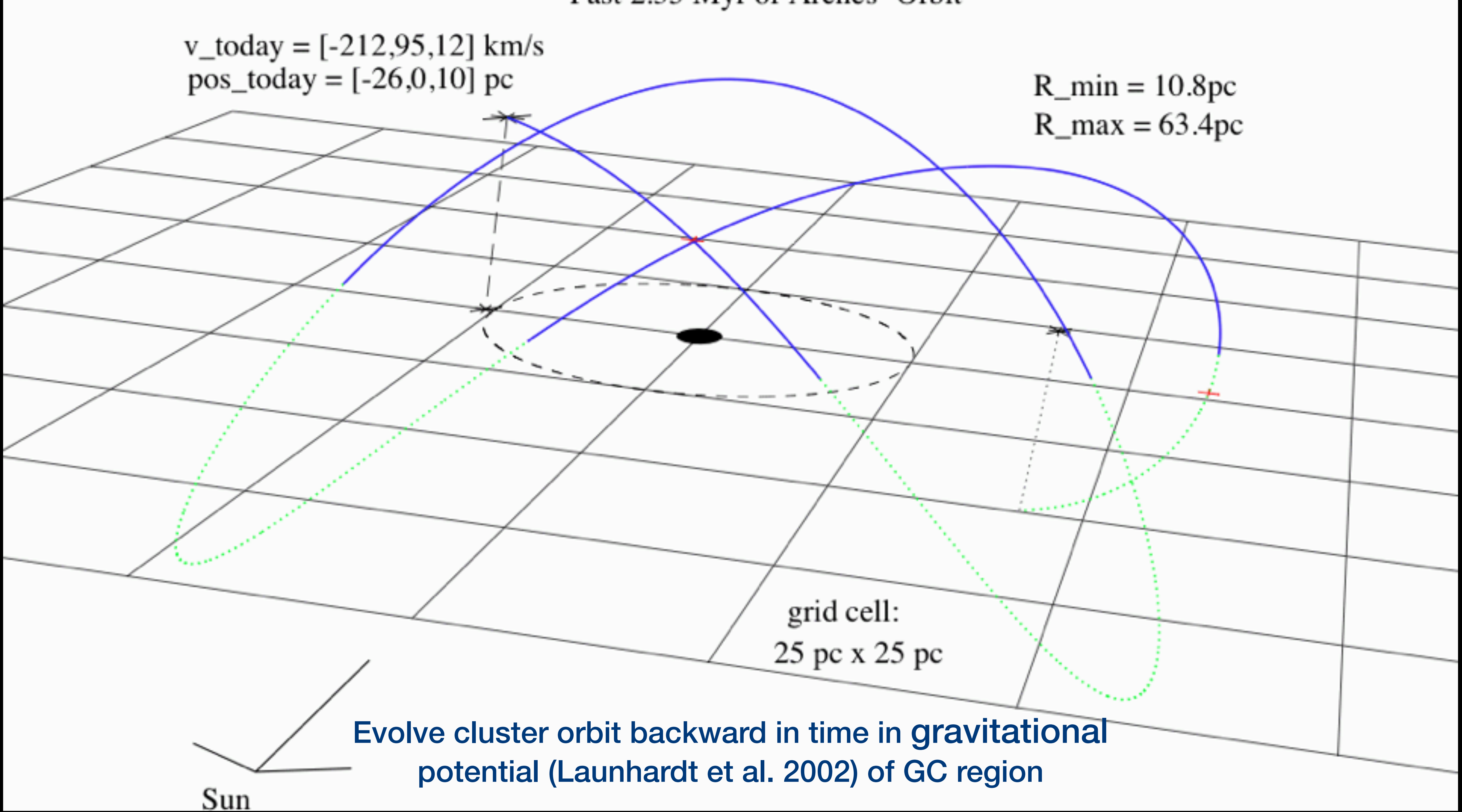




Proper motion studies reveal that Quintuplet and Arches have transversal motions of 130 km/s and ~170 km/s, respectively, relative to the field, indicating that they are not on simple "circular" orbits around the GC (Stolte et al. 2008, 2014; Hußmann et al. 2012; Clarkson et al. 2012)

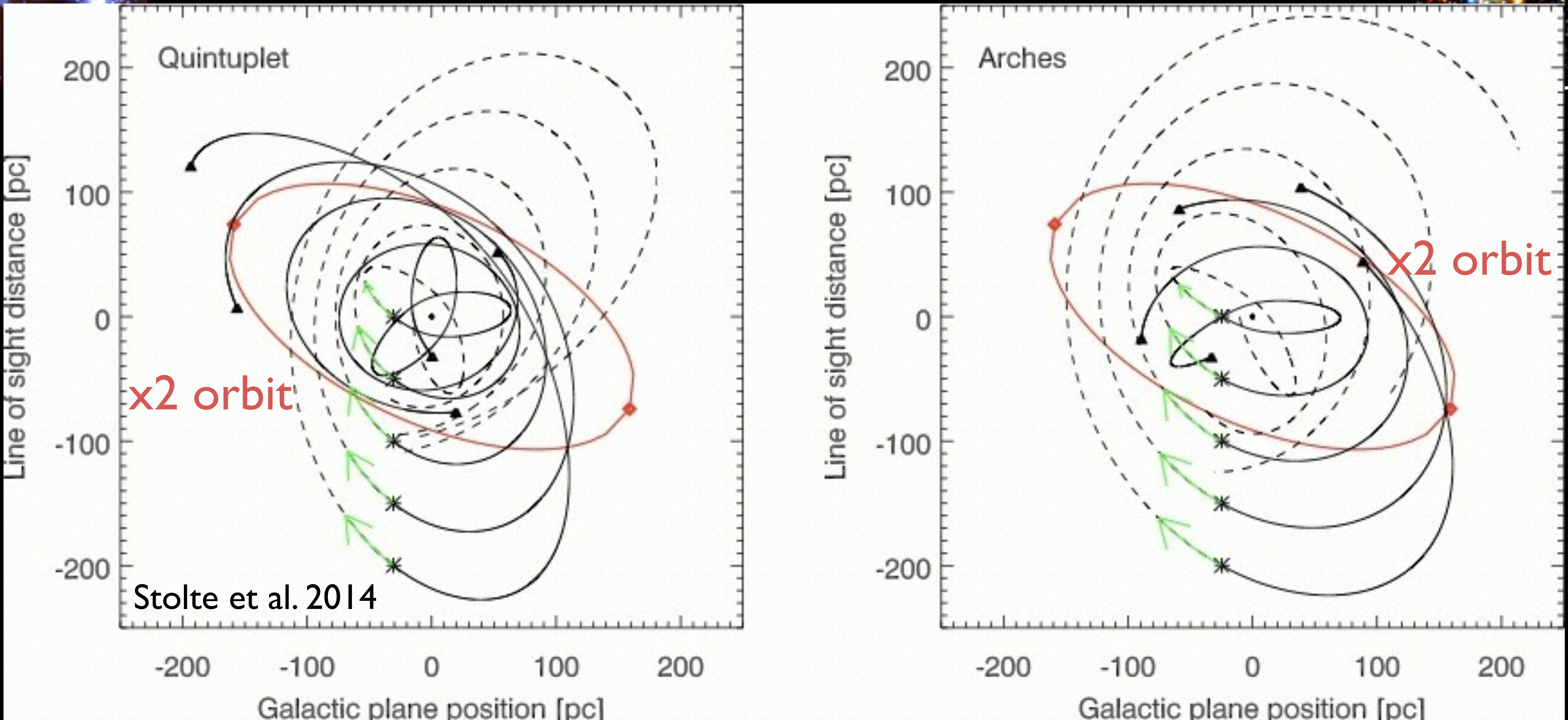
Galactic orbits and formation places

known quantities: 3D velocity vector, l, b
but exact line-of-sight distance from the Galactic Center is uncertain



Evolve cluster orbit backward in time in gravitational potential (Launhardt et al. 2002) of GC region

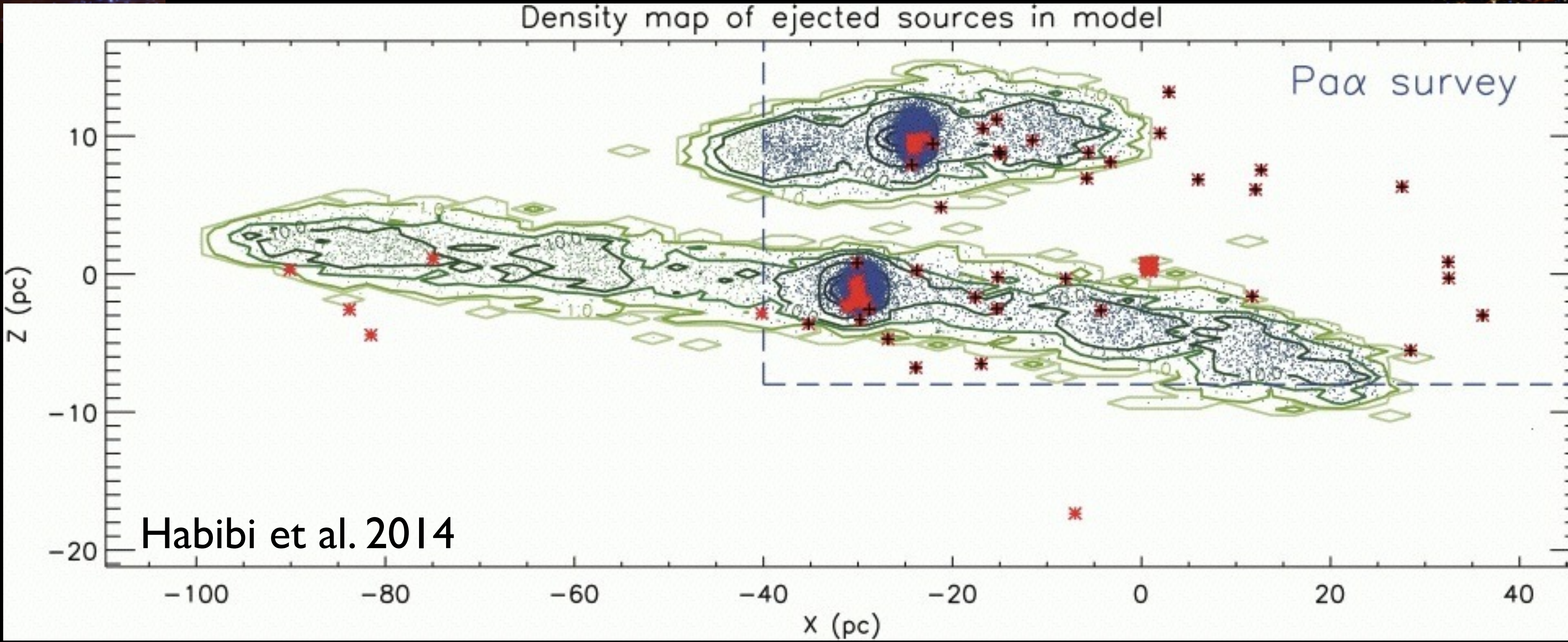
Galactic orbits and formation places



* current position, ▲ origin

For some orbits, the origin of Arches and Quintuplet is close to the outer x2 orbit (Stolte et al. 2014)
=> possible formation by cloud-cloud collision (see also Fukui et al. 2013 for NGC 3603)

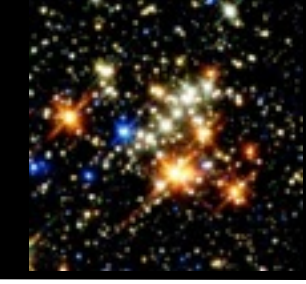
Galactic orbits and tidal stripping



Arches and Quintuplet could be responsible for the majority of "isolated" massive stars (*) in the GC region (Habibi et al. 2014)

Arches and Quintuplet will not significantly contribute young stars to the Nuclear cluster (Stolte et al. 2014)

Summary



- **Mass segregation** is present already at very young ages (1 Myr)
- **Standard mass function**, no evidence for low- or high-mass cut-off
- Clusters do **not** appear to be **super-virial**, i.e. no evidence for rapid dispersal (what about binaries?)
- **Small age spread** among cluster members (spiral arms) and high-energy (non-circular) orbits of GC clusters => formation by cloud-cloud collisions?
- **GC clusters** do **not contribute** young stars **to the nuclear cluster**, but might be the **origin** of a large fraction of the **“isolated” massive stars** in the GC region