Dynamical stability & (no) age spreads in starburst clusters

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Milky Way Starburst Clusters

Outline

Milky Way starburst clusters:
- **Definition & Location**
- Formation environments

The clusters 2D survey

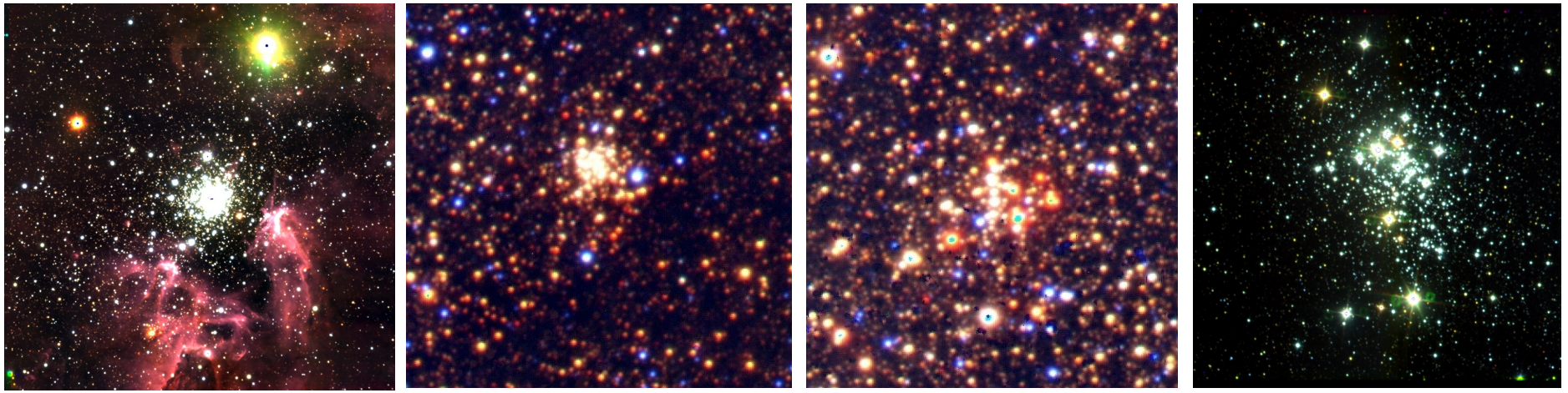
Characteristics of starburst clusters
- Present-day mass function
- Velocity dispersion & cluster mass
- Age spread

Summary
- Milky Way starbursts today.....

Starburst Clusters are the most massive clusters forming in the Milky Way today

NGC 3603 YC | **Arches** | **Quintuplet** | **Westerlund 1**

3.4 pc



Brandl et al. 1999 | *UKIDSS Galactic Plane Survey* *Lucas et al. 2008* | *Brandner et al. 2008*

Age **1 – 2 Myr** | **2 – 3 Myr** | **3 – 5 Myr** | **4 – 5 Myr**

Mass **17600 +- 3800** | **36000 +- 6000** | **> 6000 ?** | **50000 Msun**

Rochau et al. 2010 | *Habibi et al. 2013* | *Gennaro et al. 2011*

Milky Way starburst clusters & location

Ongoing infrared surveys have revealed, and still reveal, numerous massive clusters some of which classify as starbursts

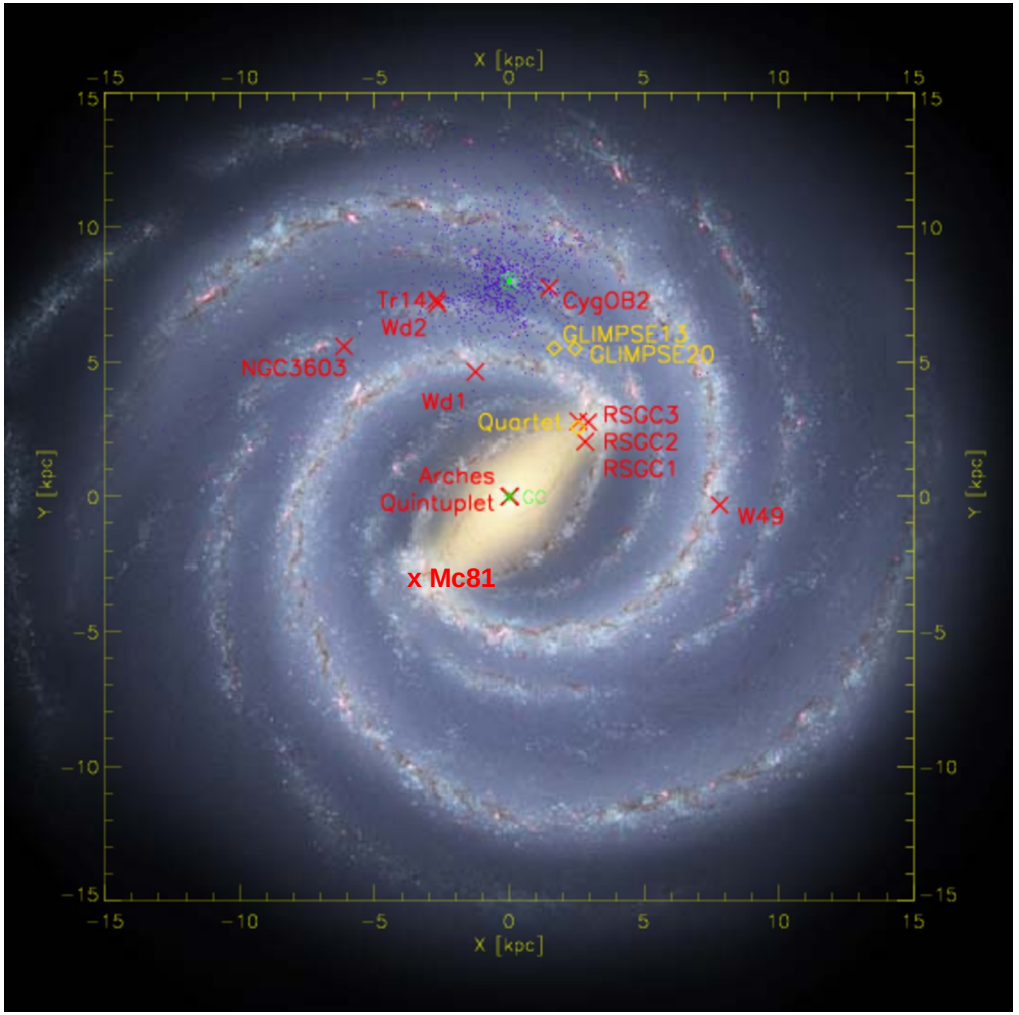


Image courtesy: Boyke Rochau & Wikipedia

In the Milky Way, starburst clusters form in two very distinct environments...

Star cluster formation in the Galactic center is a very "messy process"

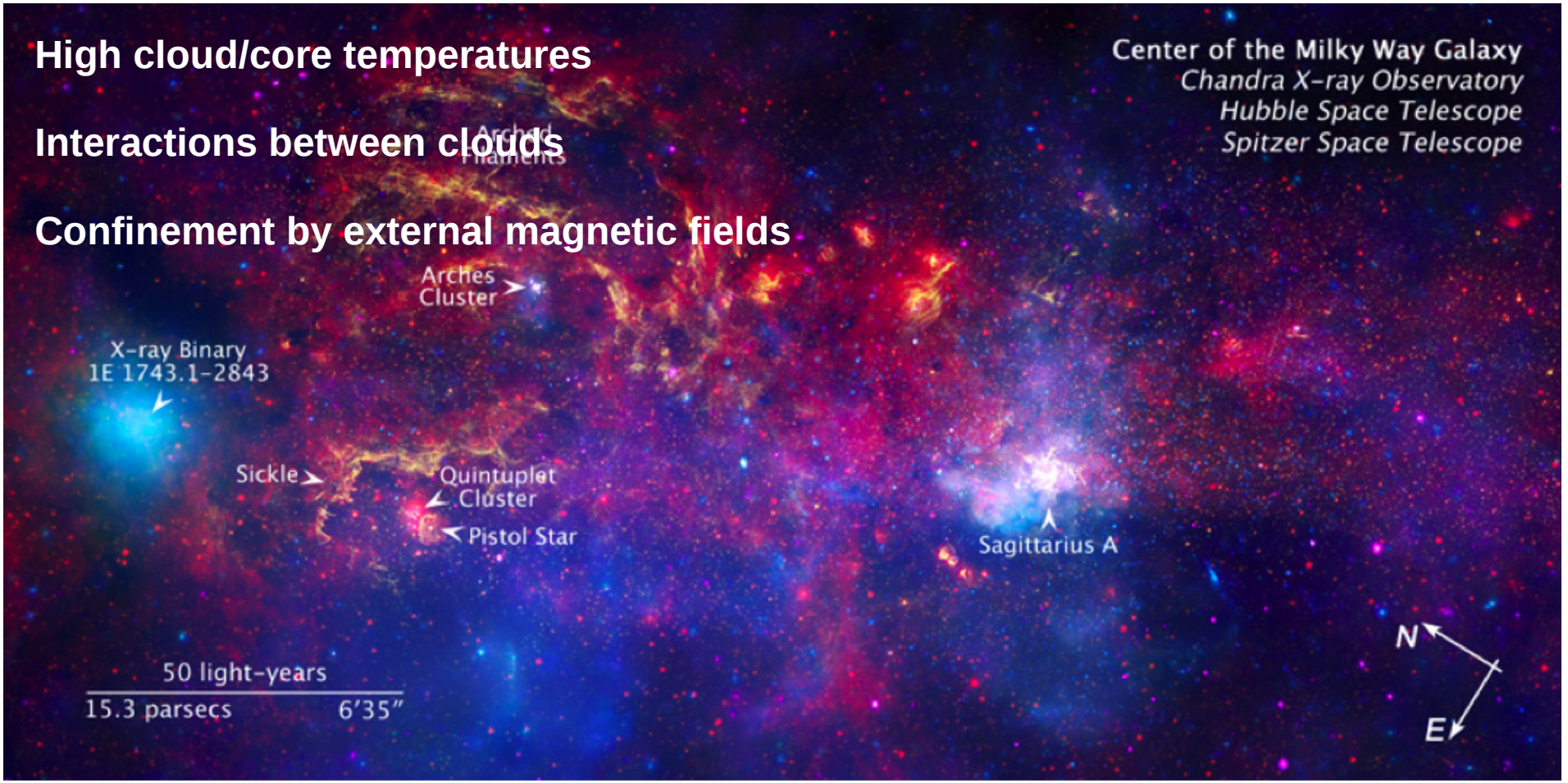
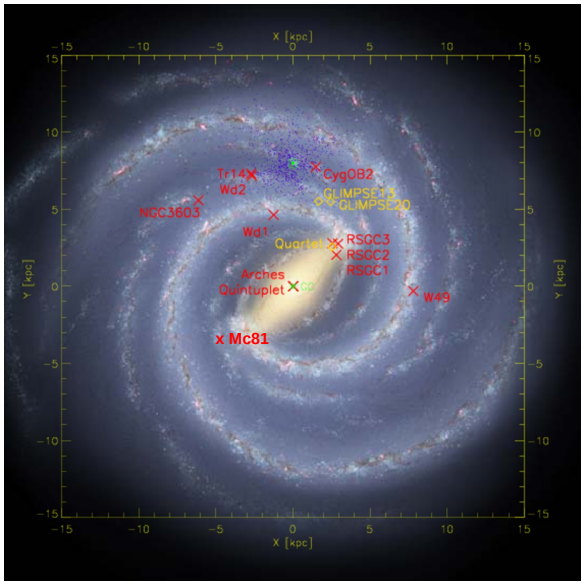


Image courtesy: Spitzer GLIMPSE & GC Paschen alpha surveys, D. Wang, A. Cotera, M. Morris et al.

Milky Way starburst clusters & location

Two very different formation environments:



Spiral arm cluster & star formation:

- core temperatures 10-20 K
- low magnetic field
- no background UV field

Galactic center cluster & star formation:

- core temperatures 70 K
- strong magnetic field
- UV field from multi-generations of high-mass stars

Expectation (in the simplest of worlds):

High temperatures & densities influence the Jeans mass,
and hence the smallest possible fragmenting element:

$$M_{Jeans} \sim T^{3/2} \rho^{-1/2}$$

=> the environment should influence the initial stellar mass distribution (IMF)

=> ***M*** $_{Jeans}$ might increase from ***0.5 Msun to 5 Msun***

Morris 1993, Morris & Serabyn 1996

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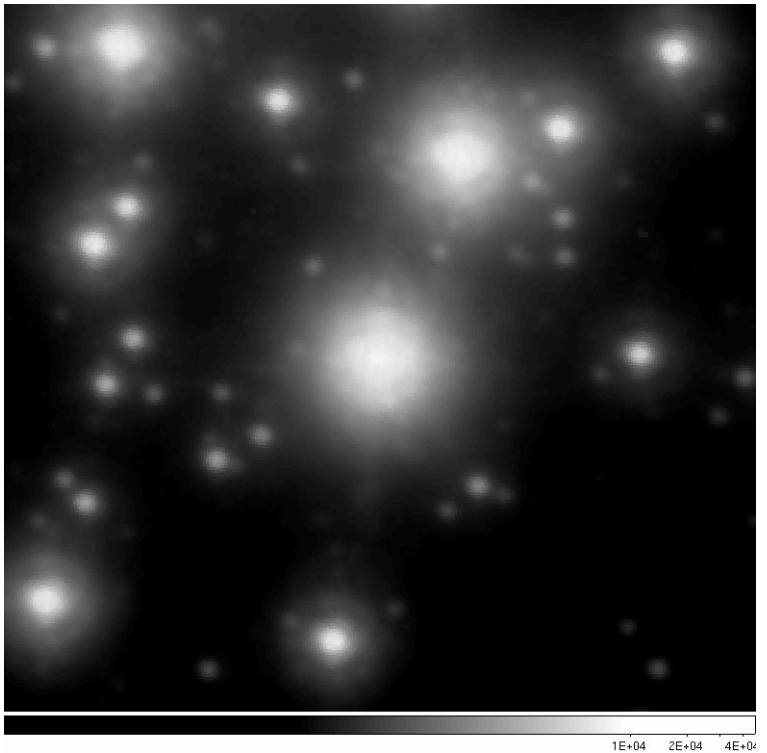


VLT/NACO 2002
Keck/NIRC2 2006
Keck/NIRC2 2008

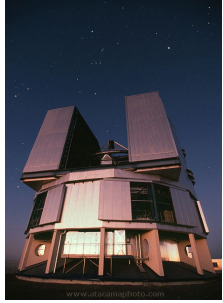
Changes during the past few years:

High-resolution adaptive optics imaging enables

- precision astrometry for proper motion membership at d > 4 kpc
- unbiased present-day mass functions
- internal velocity dispersion
- absolute motions of Galactic center clusters

=> constraints on star formation in the GC & spiral arms

Proper motion survey of 4 Milky Way Starburst Clusters

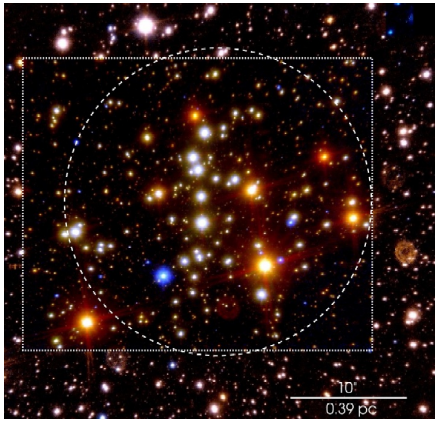


Motivation & Aims

Galactic centre

Arches 2.5 Myr

Quintuplet 3-5 Myr



Comparison of

- cluster formation
- cluster dissolution
- stellar mass function

in the *Galactic centre*
and *spiral arm* environments

Carina arm

NGC 3603 1-2 Myr

Westerlund 1 4-5 Myr

Method

- precision astrometry
  from diffraction-limited imaging

- 4 clusters with 2 epochs

  VLT/NAOS-CONICA 27” field
  HST/WFPC2 160” extent

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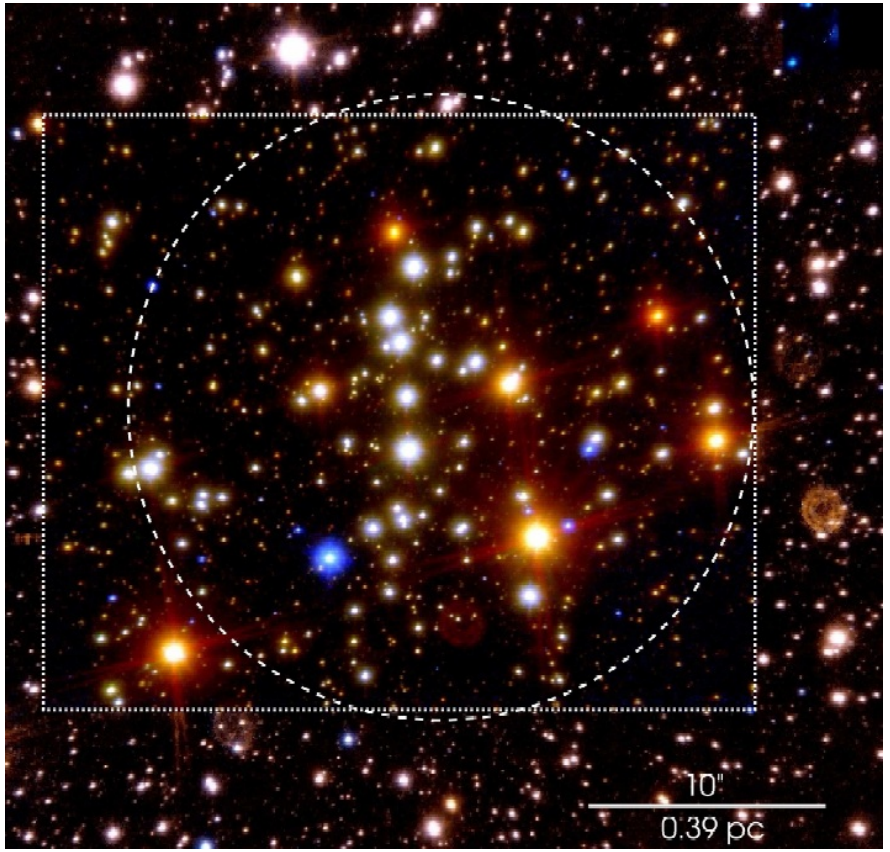
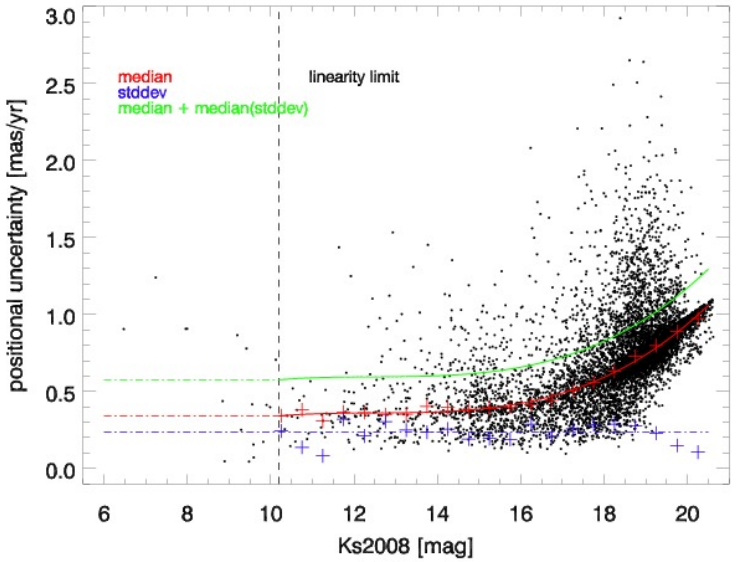
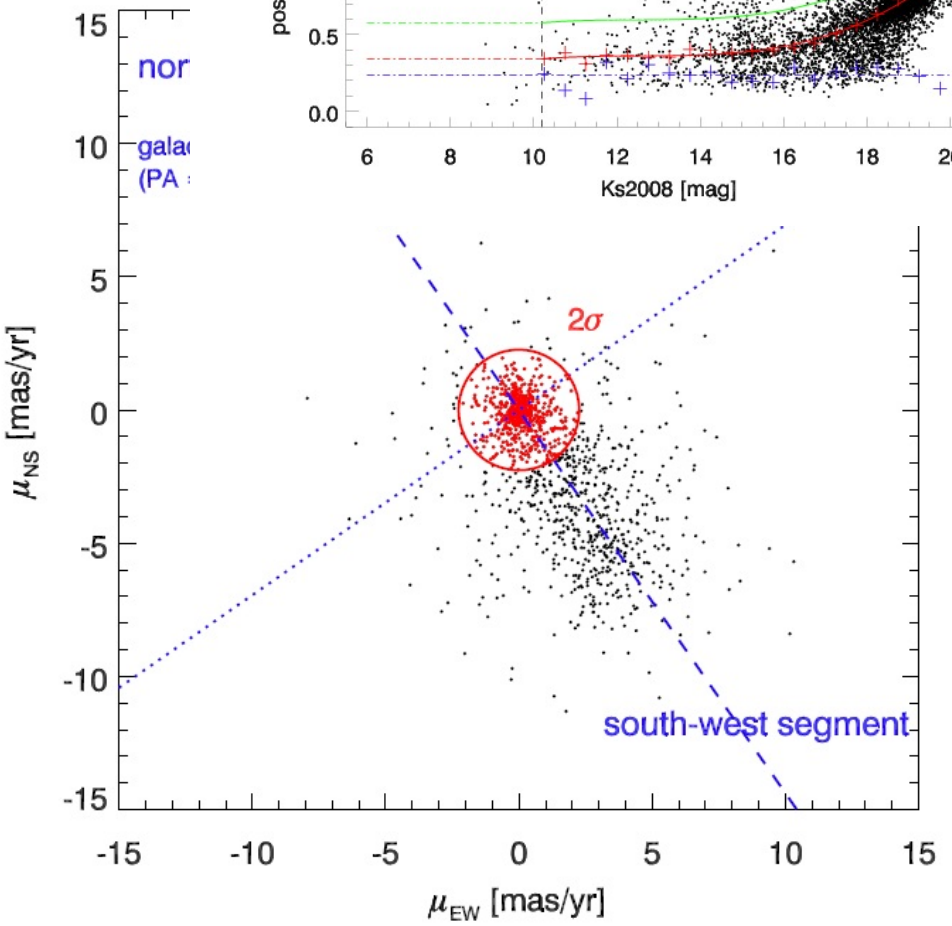
Proper motion membership as a tool to characterise starburst cluster populations

Towards an unbiased present-day mass function

- field stars in the Galactic center have colours comparable to cluster stars







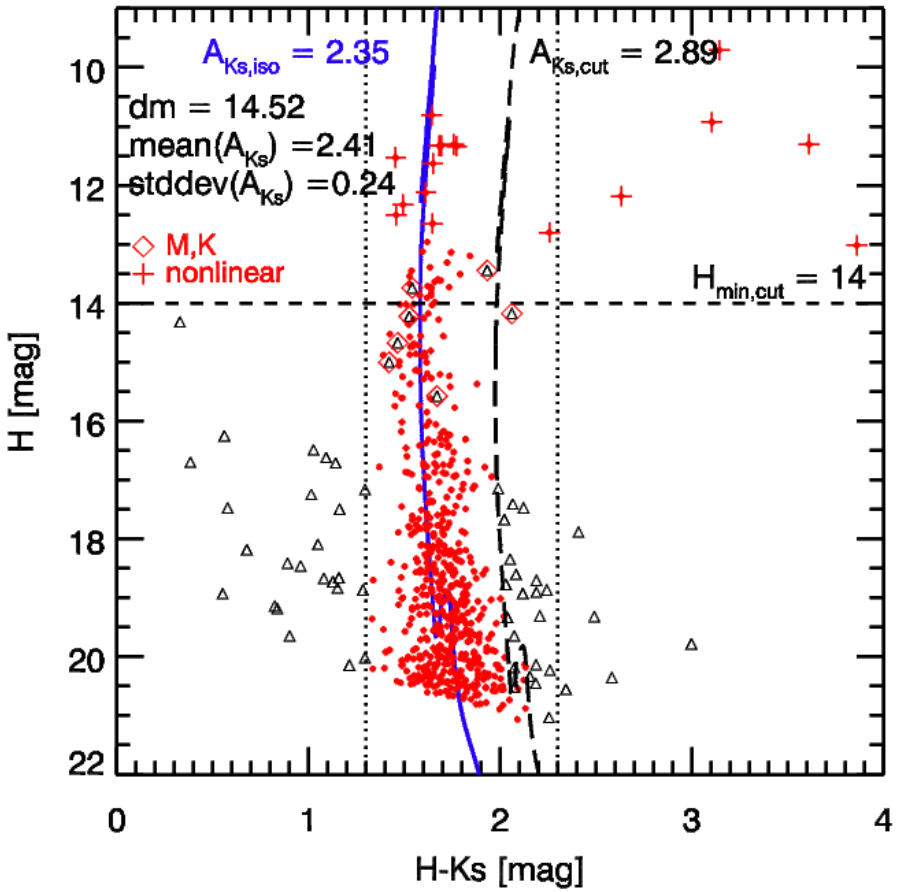
Hußmann et al. 2012

Efficiently selecting cluster members using proper motion

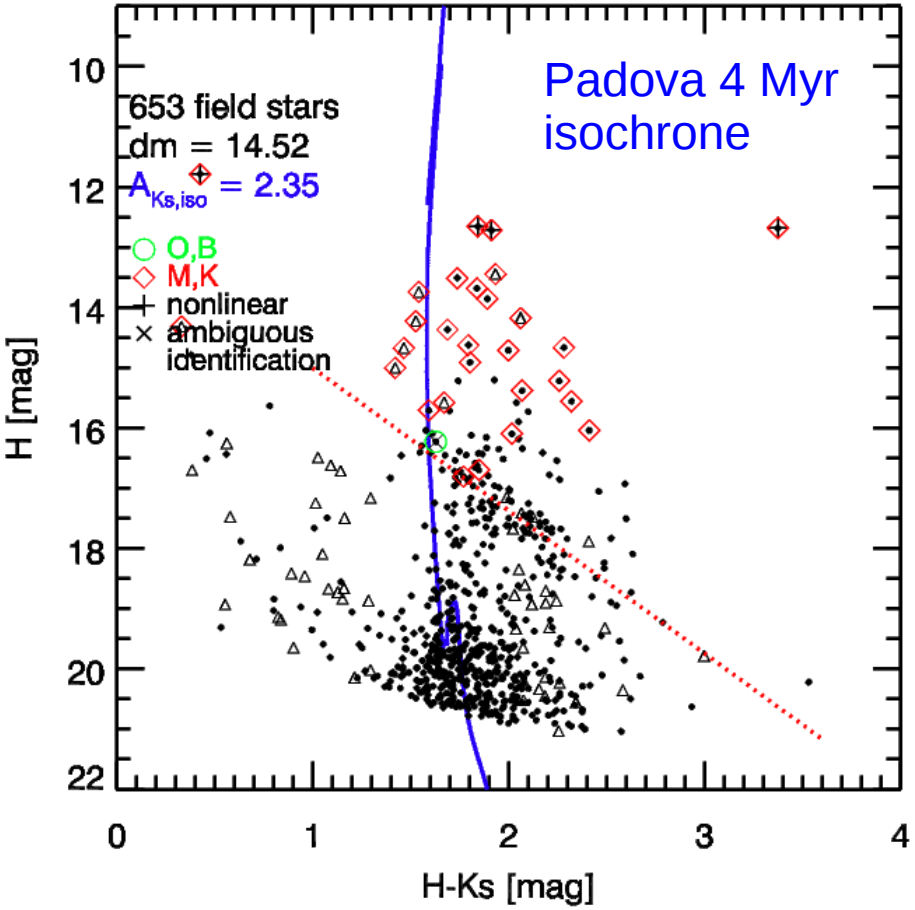
Towards an unbiased present-day mass function

- field stars in the Galactic center have colours comparable to cluster stars

Proper motion members

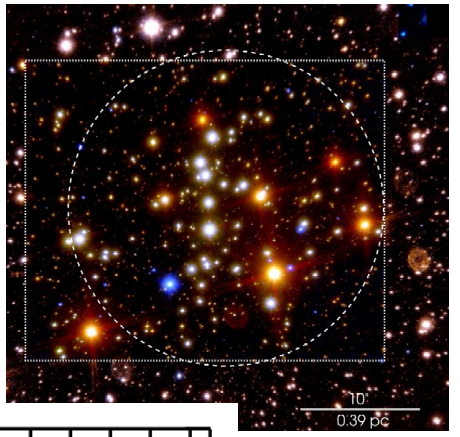


Proper motion non-members



Hußmann et al. 2012

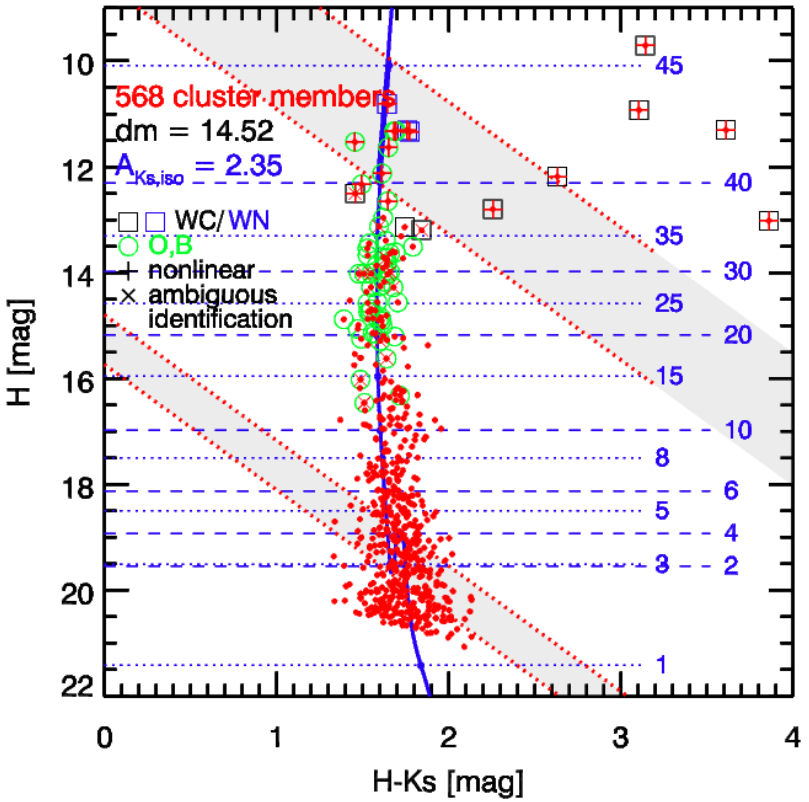
A flat (top-heavy) present-day MF in Quintuplet

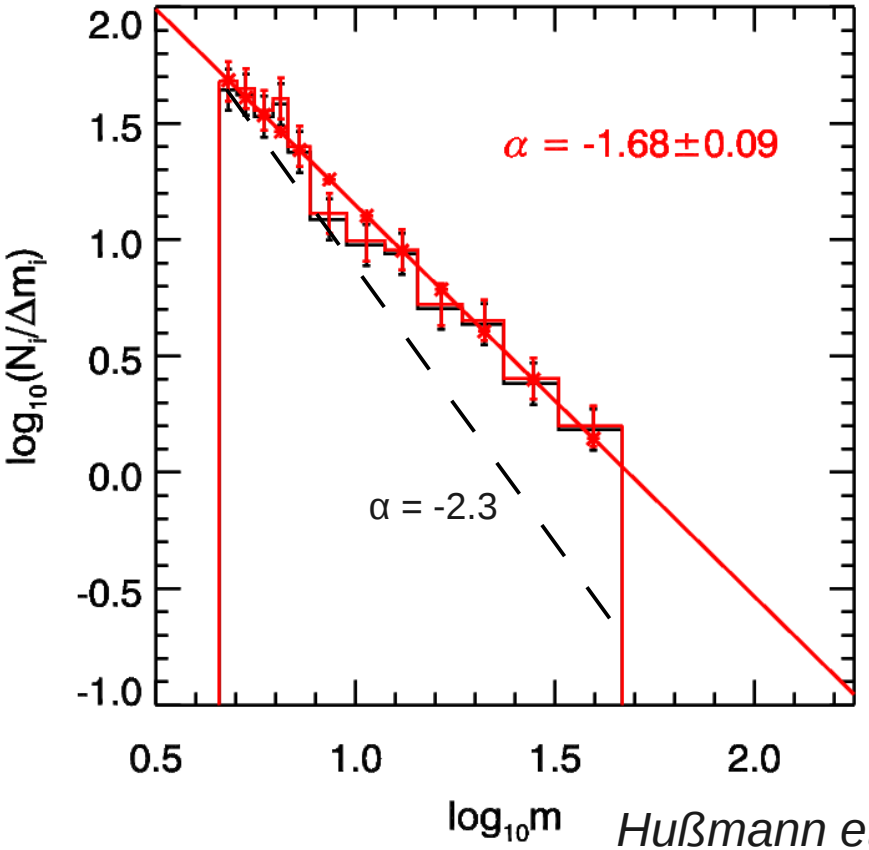


Quintuplet's mass function
from proper motion member selection

alpha = -1.68

for r < 0.5 pc





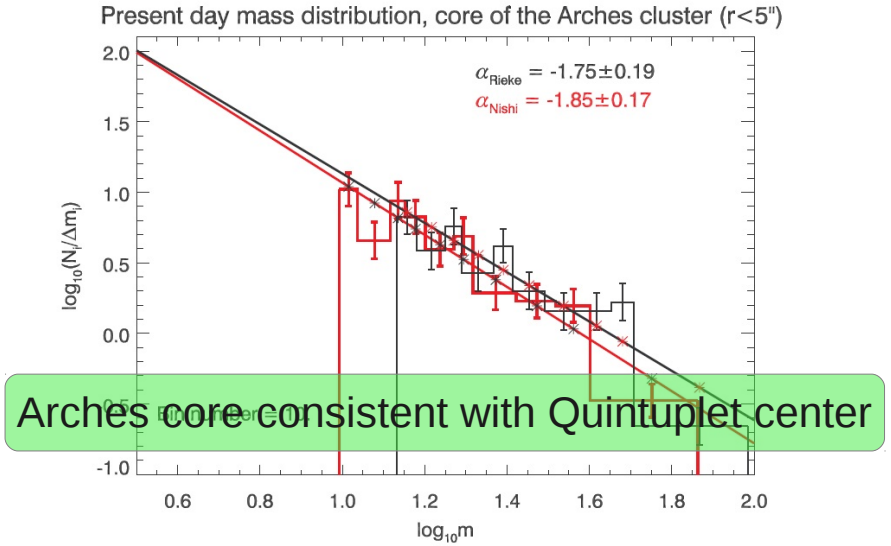
Hußmann et al. 2012

Problem:

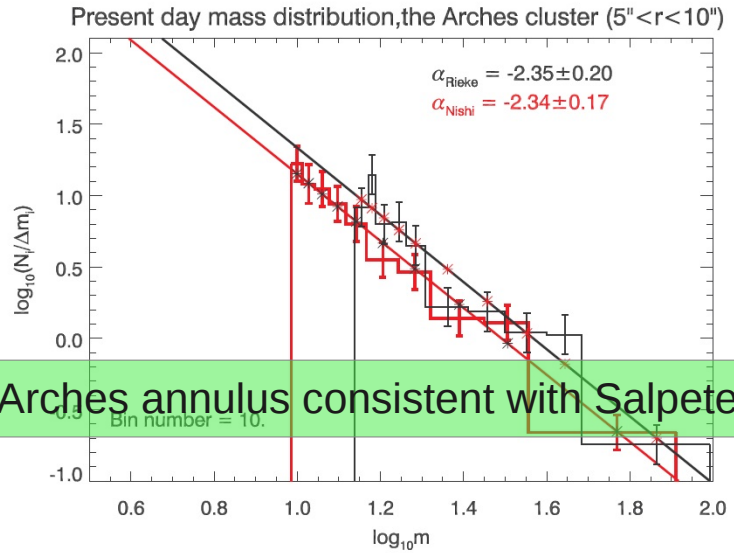
Dynamical evolution influences the *present-day* MF in the cluster center

Radial variation of the present-day mass function

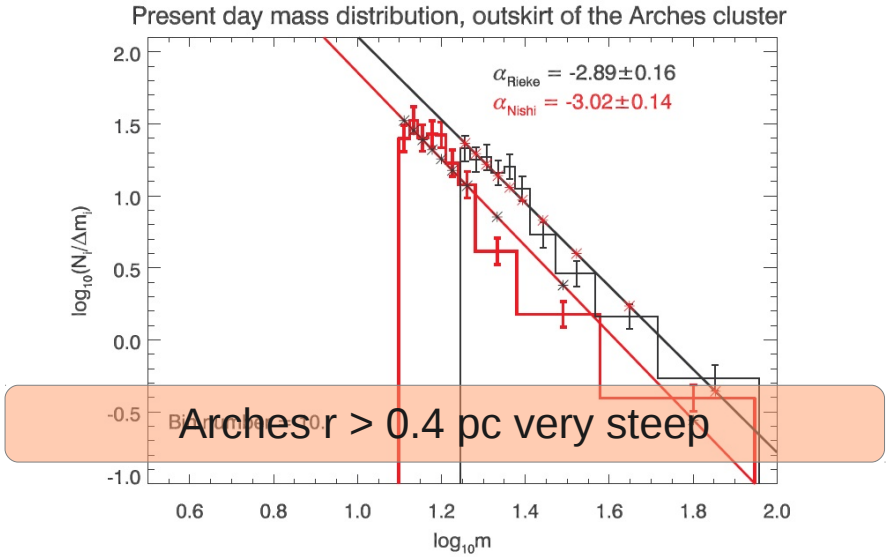
The slope of the present-day mass function steepens as a function of radius.



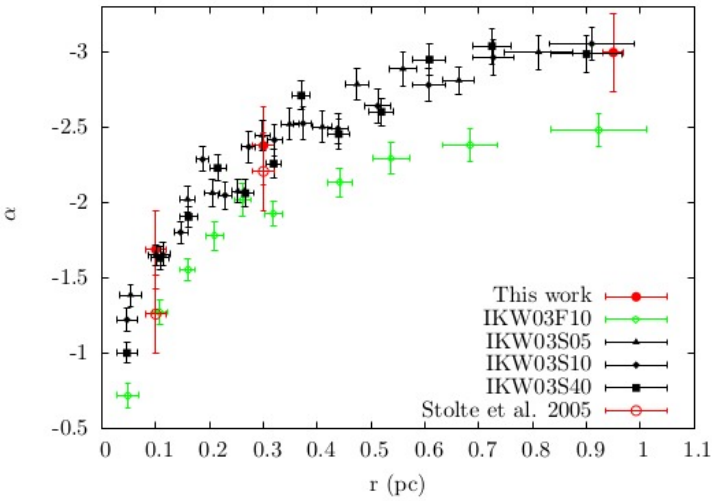
Arches core consistent with Quintuplet center



Arches annulus consistent with Salpeter MF

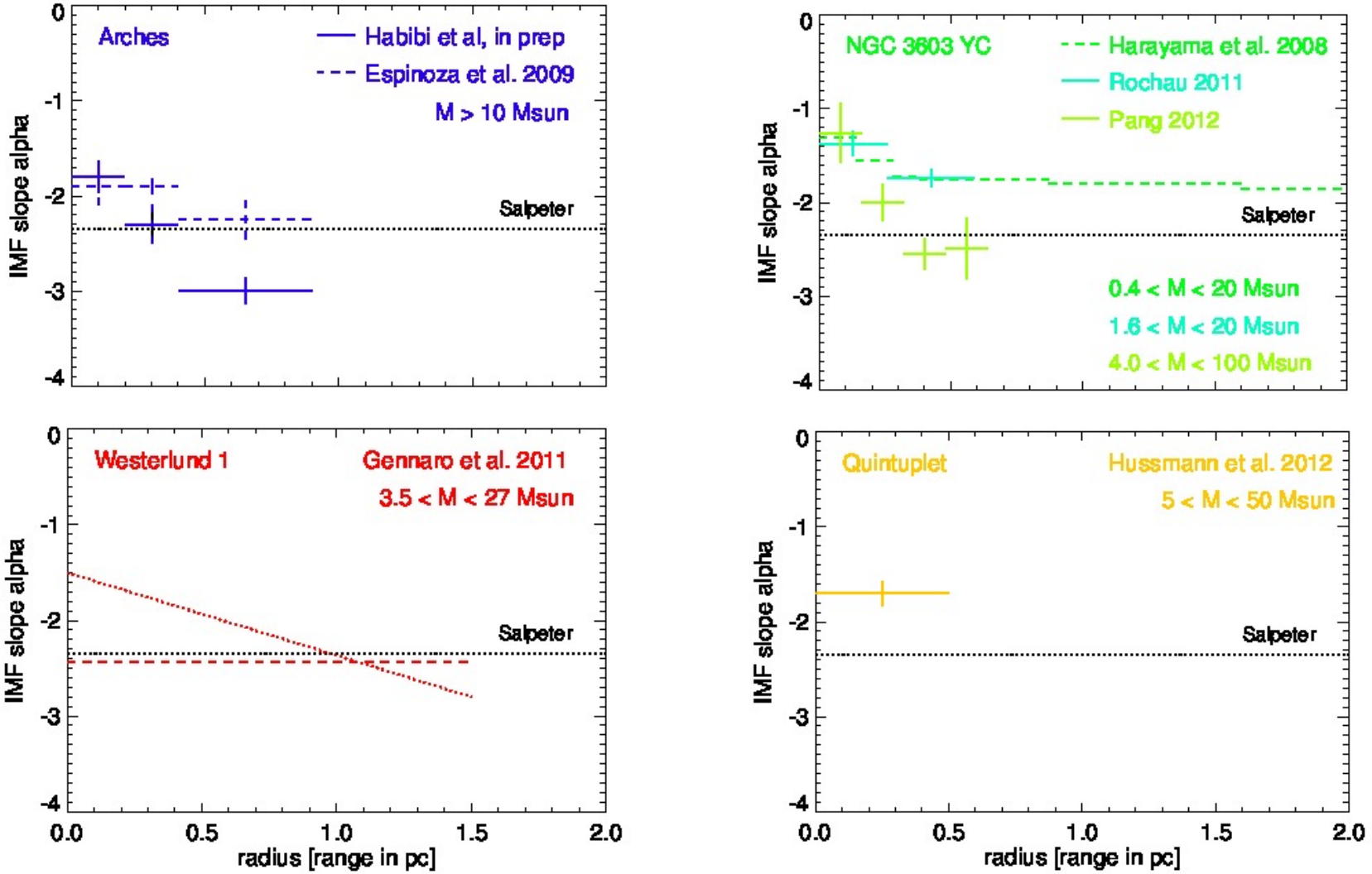


Arches r > 0.4 pc very steep



Habibi et al., in prep

Present-day mass functions indicate starburst clusters are mass segregated in their cores & high-mass component.



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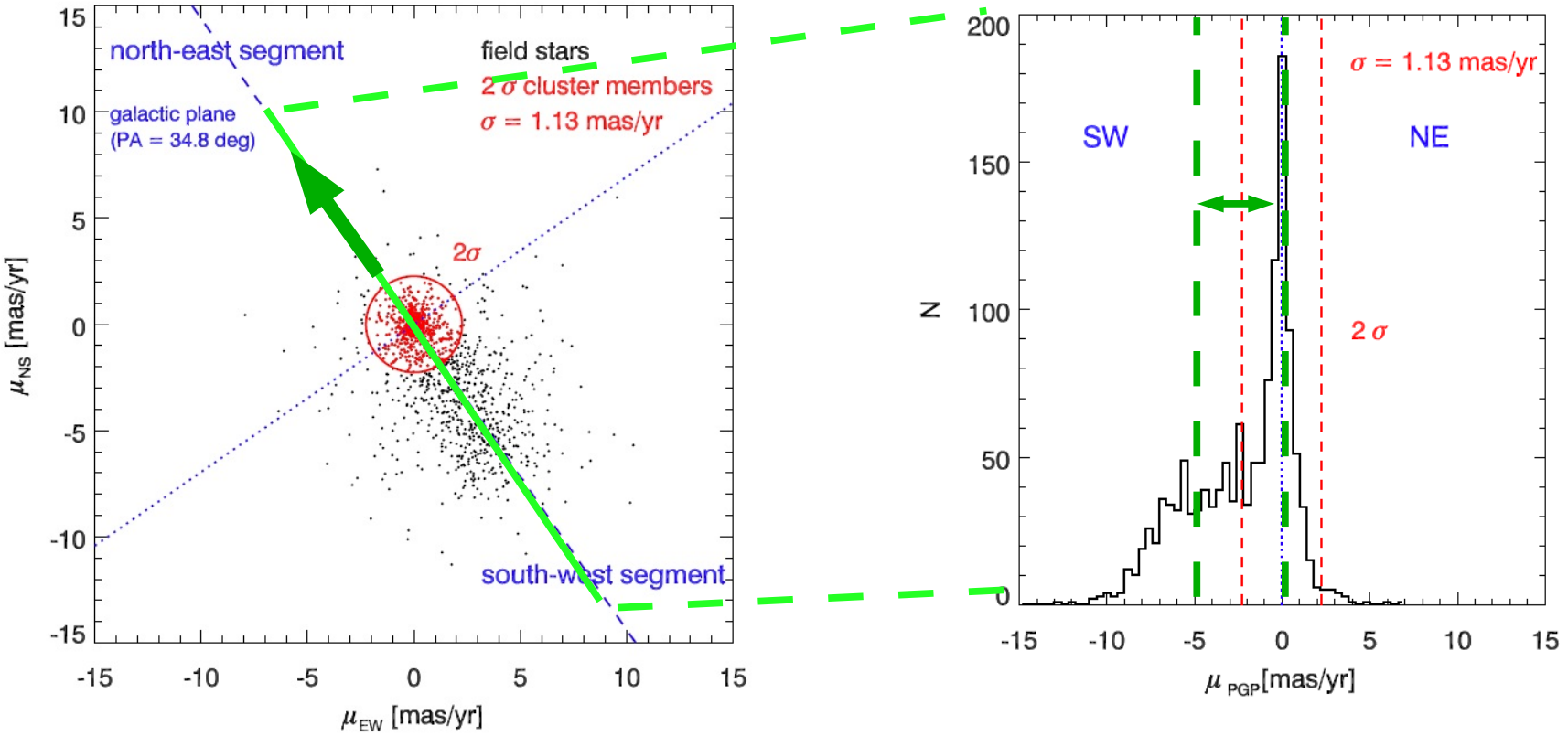
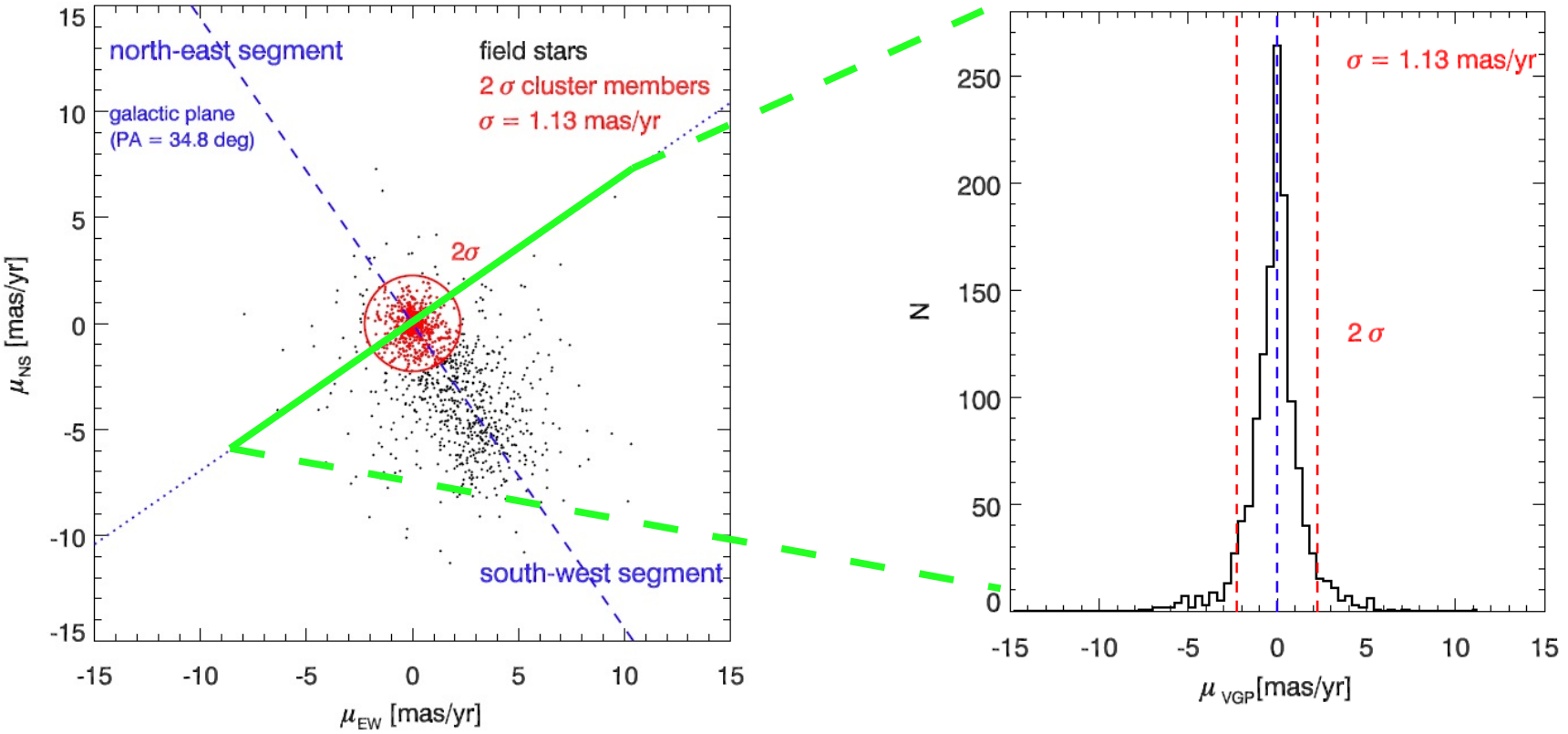
Proper motion studies: internal velocity dispersion & dynamical mass



Proper motion along the Galactic plane:

Absolute 2D orbital motion

Proper motion studies: internal velocity dispersion & dynamical mass

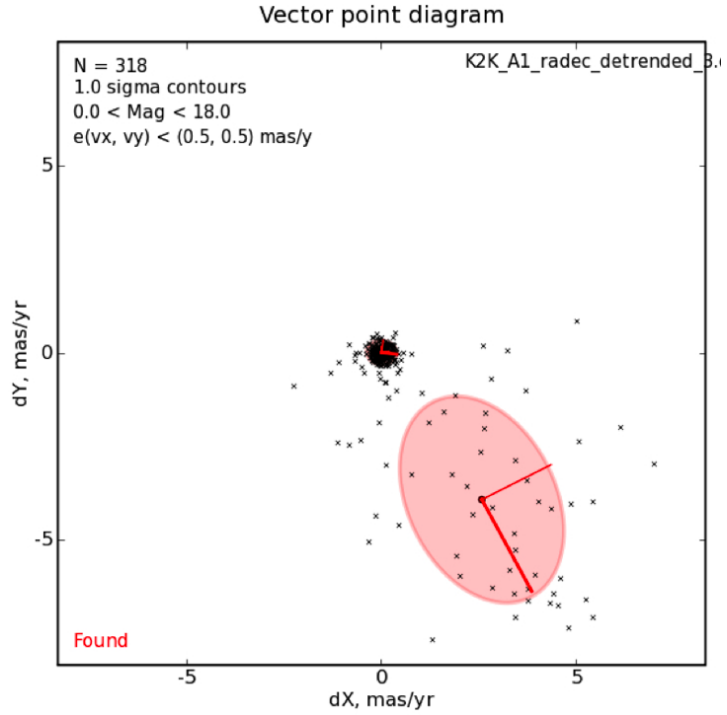


Proper motion *dispersion* perpendicular to the Galactic plane:

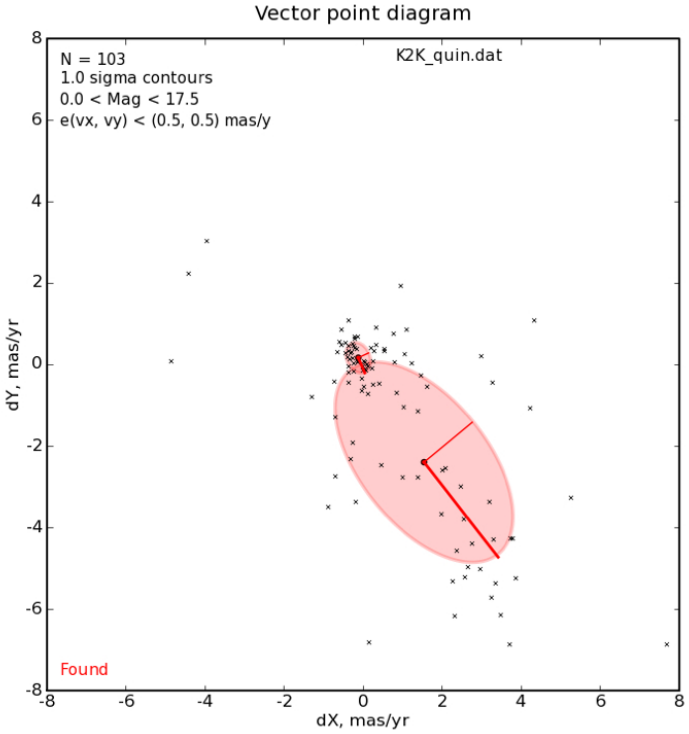
Internal velocity dispersion

Proper motion studies: internal velocity dispersion & dynamical mass

Arches



Quintuplet



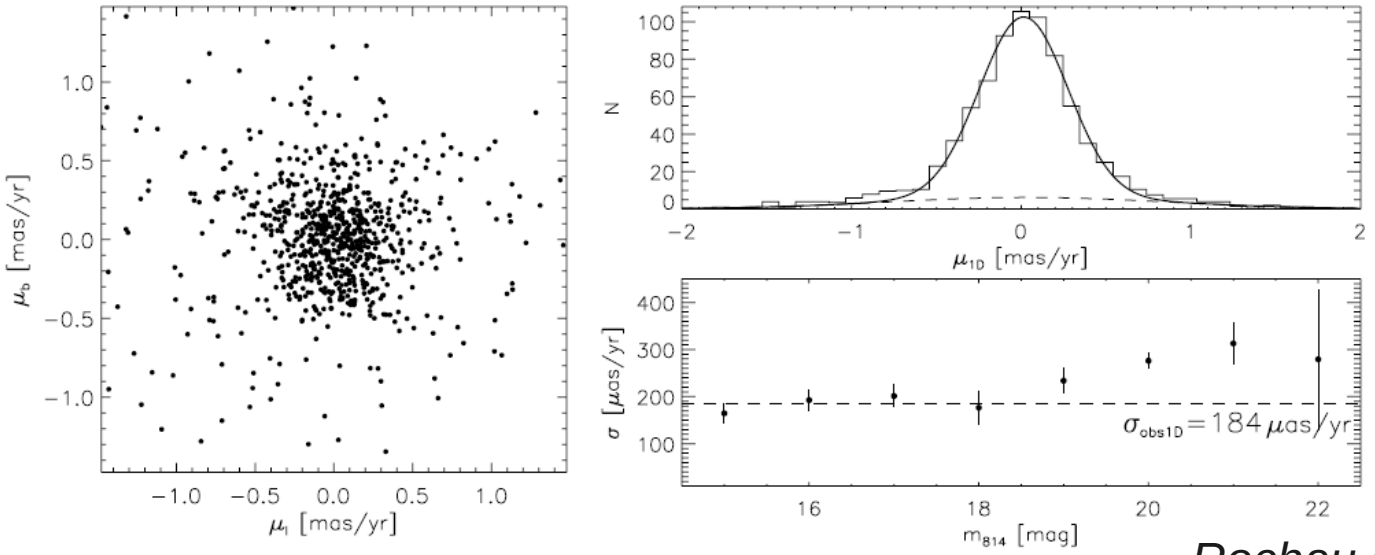
Fitting the field and cluster populations in the proper motion plane simultaneously:

	Arches	**Quintuplet**
Internal velocity dispersion	5.9 +- 0.4 km/s	~5.6 km/s

Clarkson et al. 2012, Stolte et al. In prep

NGC 3603 Young Cluster

Spiral arm clusters move with the spiral arm pattern,
but have substantially lower velocity dispersions than field stars



Rochau et al. 2010

Subtraction of a statistical field component yields the unbiased internal dispersion:

	NGC 3603	**Westerlund 1**
Internal velocity dispersion	4.5 +- 0.8 km/s	2.1 +3.3/-2.1 km/s

Westerlund 1's velocity dispersion was derived from spectroscopic radial velocities

Cottaar et al. 2012

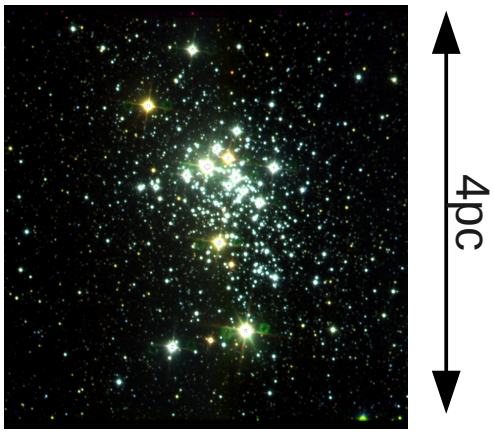
The dynamical mass is a measure for the present-day total mass In the cluster system.

Assumptions:

- the cluster is close to virial equilibrium
- the cluster is dynamically far from core collapse

$$M_{dyn} = \frac{\eta \sigma_{1D}^2 r_{hm}}{G}$$

Westerlund 1



r_{hm} ~ 0.7 – 1.5 pc

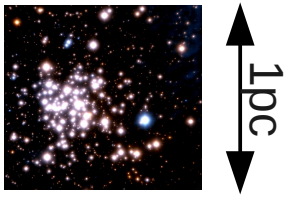
η = structure parameter: depends on density, shape...
typical values: 2.5 ... 10

σ = 1-dimensional internal velocity dispersion

r_{hm} = projected half-mass radius

G = gravitational constant

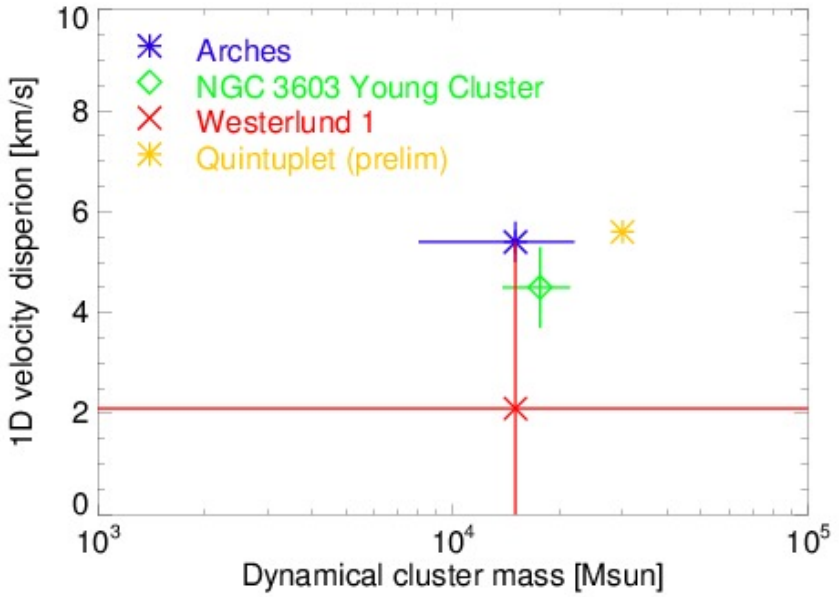
Arches



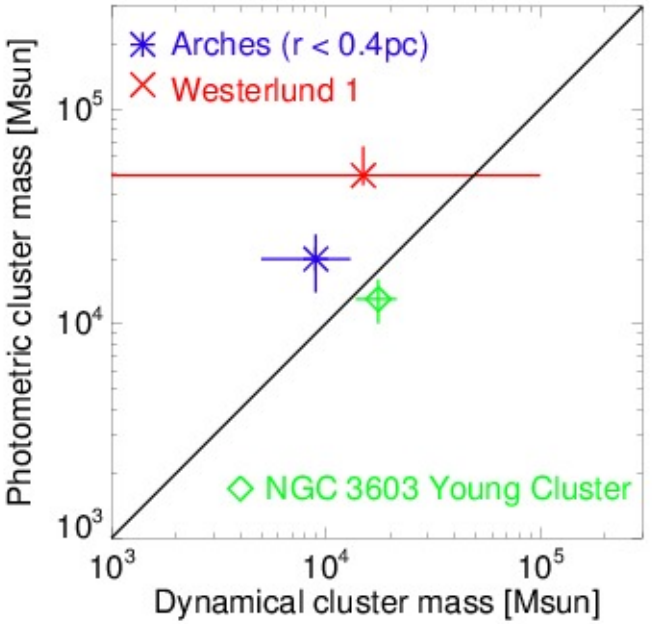
r_{hm} = 0.4 pc

Velocity dispersions of a few km/s are consistent with virial expectations.

Internal velocity dispersion:



Dynamical vs photometric mass:



NGC 3603 & Westerlund 1 (spiral arm clusters):

– consistent with virialised systems

– survival times up to Gyr

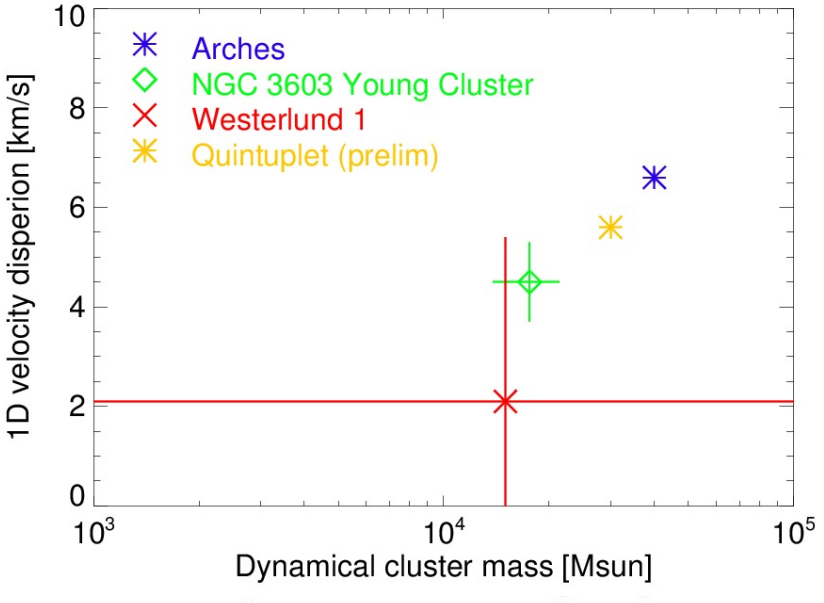
Arches:

– apparently subvirial, but...

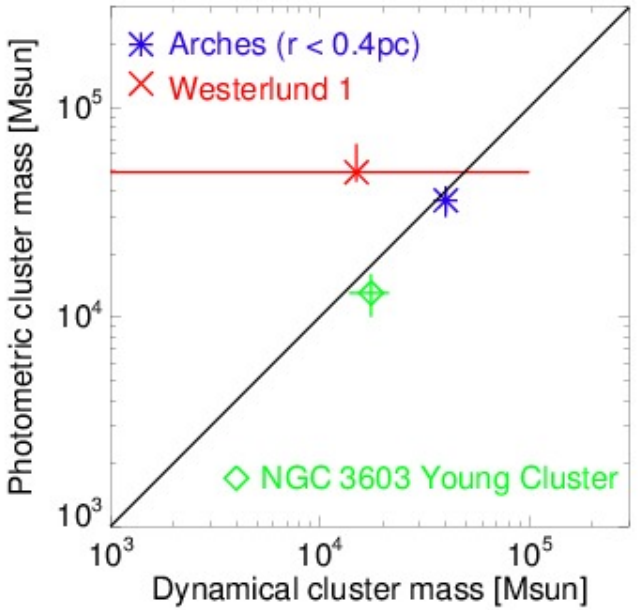
if we include mass segregation....

Velocity dispersions of a few km/s are consistent with virial expectations.

Internal velocity dispersion:



Dynamical vs photometric mass:



NGC 3603 & Westerlund 1 (spiral arm clusters):

– consistent with virialised systems

– survival times up to Gyr

Arches (GC cluster):

– likely virialised

– best fitting model => rotating

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Age spreads in starburst clusters –

*are young, massive clusters really "star**bursts**" ?*

- Crossing times in starburst clusters are exceptionally short:

$$t_{dyn} = \left(\frac{GM_{cl}}{r_{vir}^3} \right)^{-1/2} = 2\,x\,10^4\ \boldsymbol{yr} \left(\frac{M}{10^6\ Msun} \right)^{-1/2} \left(\frac{r_{vir}}{pc} \right)^{3/2}$$

Spitzer 1987, Portegies Zwart, McMillan & Gieles 2010

- With masses of 10^4 – 10^5 Msun & half-mass radii of 0.4 – 1 pc

$$t_{dyn} \sim 2 \text{ x } 10^4 - 2 \text{ x } 10^5 \text{ years}$$

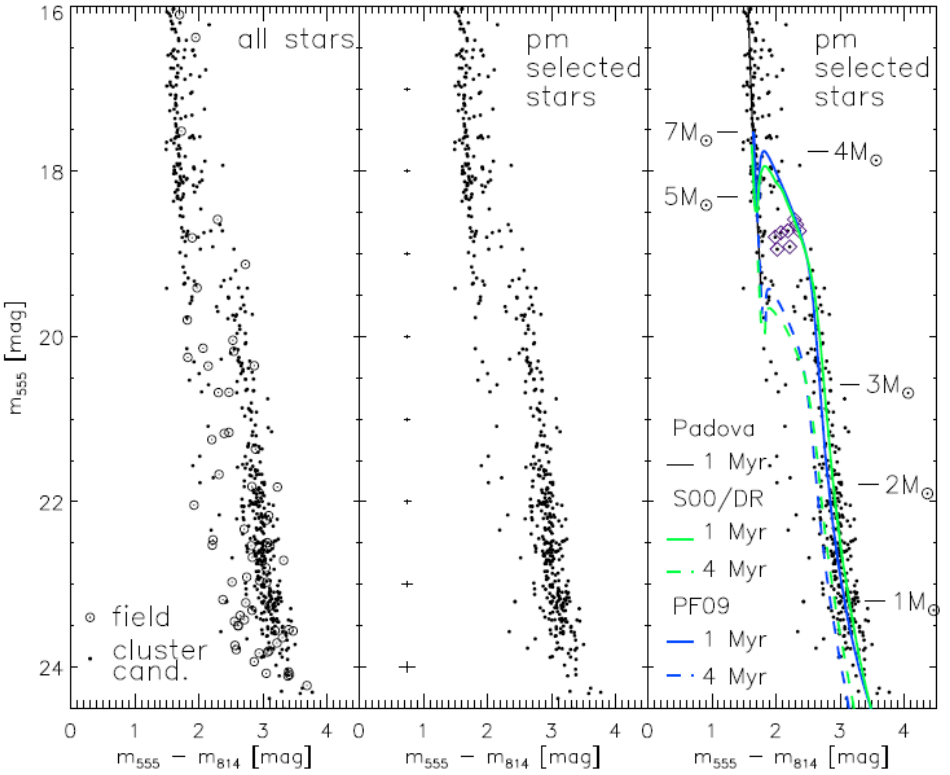
NGC 3603 YC:	0.03 Myr	*Pang et al. 2010*
NGC 3603 YC:	0.05 Myr	*Rochau et al. 2010*
Westerlund 1:	0.3 Myr	*Brandner et al. 2008*

Evidence for age spreads in starburst clusters

Ages & age spreads are derived from the pre-main sequence/main sequence transition

With the current astrometric accuracy, age spreads were studied in the spiral arm clusters NGC 3603 & Westerlund 1

NGC 3603



Rochau et al. 2010

Evidence for age spreads in & around starburst clusters

Effective selection of proper motion members in Westerlund 1 & NGC 3603

Constraining the age spread:

- grid of isochrones with

  Δ age = 0.1 Myr

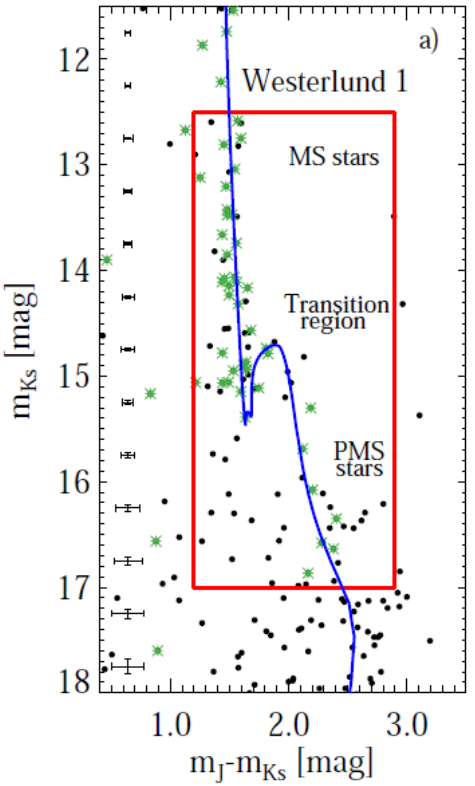
- Likelyhood for each star to
  - have a certain age
  - be a cluster member

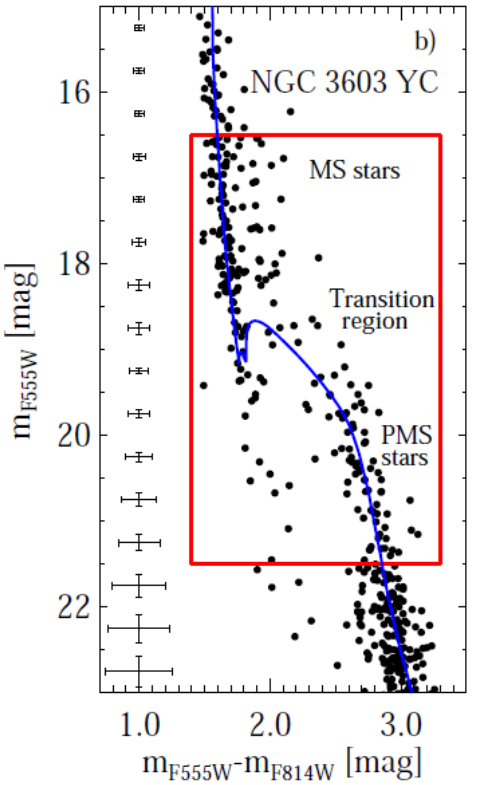
$$p\left(t \mid J_i, K_{si}\right)$$

- Global probability function

$$L(t) = \prod p\left(t \mid J_i, K_{si}\right)$$

defines the age distribution in each cluster





Kudryavtseva et al. 2012

No Evidence for age spreads in the starburst cluster population

In the central starburst NGC 3603 YC Δ age ≤ 0.1 Myr

Constraining the age spread:

- grid of isochrones with

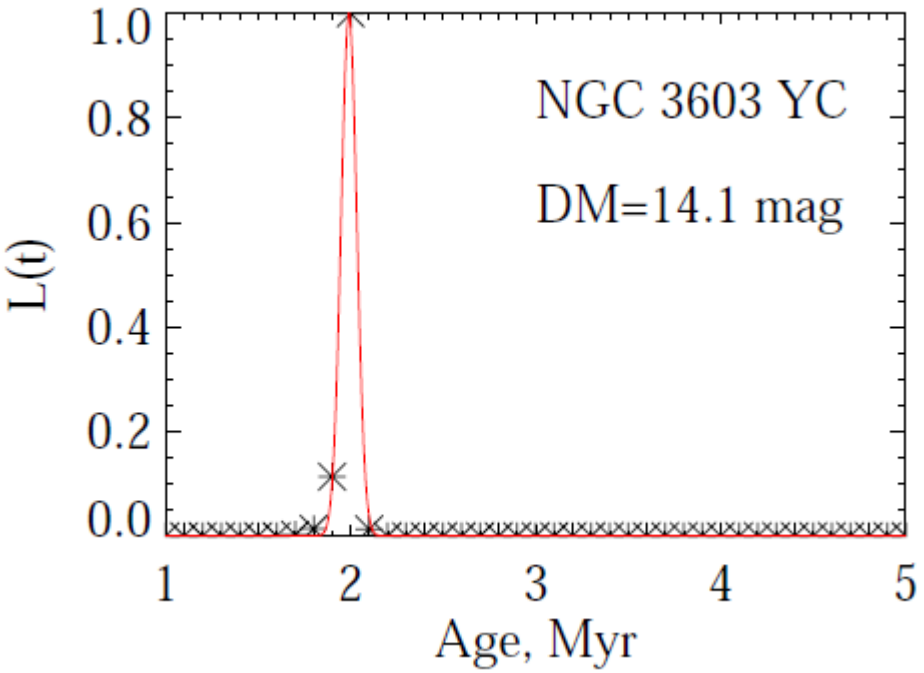
  Δ age = 0.1 Myr
- Likelyhood for each star to
  - have a certain age
  - be a cluster member

$$p\left(t \middle| J_i, K_{si}\right)$$

- Global probability function

$$L(t) = \prod p\left(t \middle| J_i, K_{si}\right)$$

defines the age distribution in each cluster



Kudryavtseva et al. 2012

No Evidence for age spreads in the starburst cluster population

In the central region of Westerlund 1 — Δ age ≤ 0.4 Myr

Constraining the age spread:

- grid of isochrones with

  Δ age = 0.1 Myr

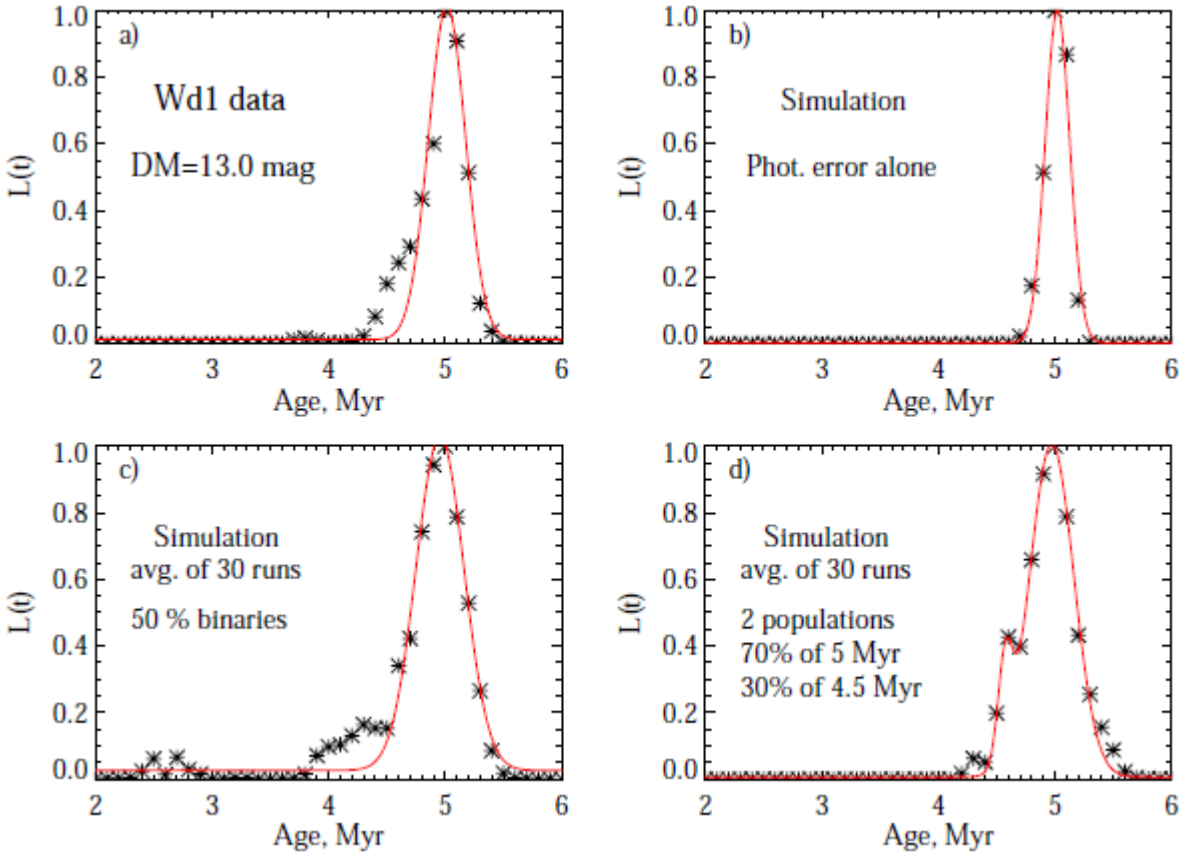
- Likelyhood for each star to
  - have a certain age
  - be a cluster member

$$p\left(t \middle| J_i, K_{si}\right)$$

- Global probability function

$$L(t) = \prod p\left(t \middle| J_i, K_{si}\right)$$

defines the age distribution in each cluster



Kudryavtseva et al. 2012

Evidence for age spreads in & around starburst clusters

Effective selection of proper motion members in Westerlund 1 & NGC 3603

Constraining the age spread:

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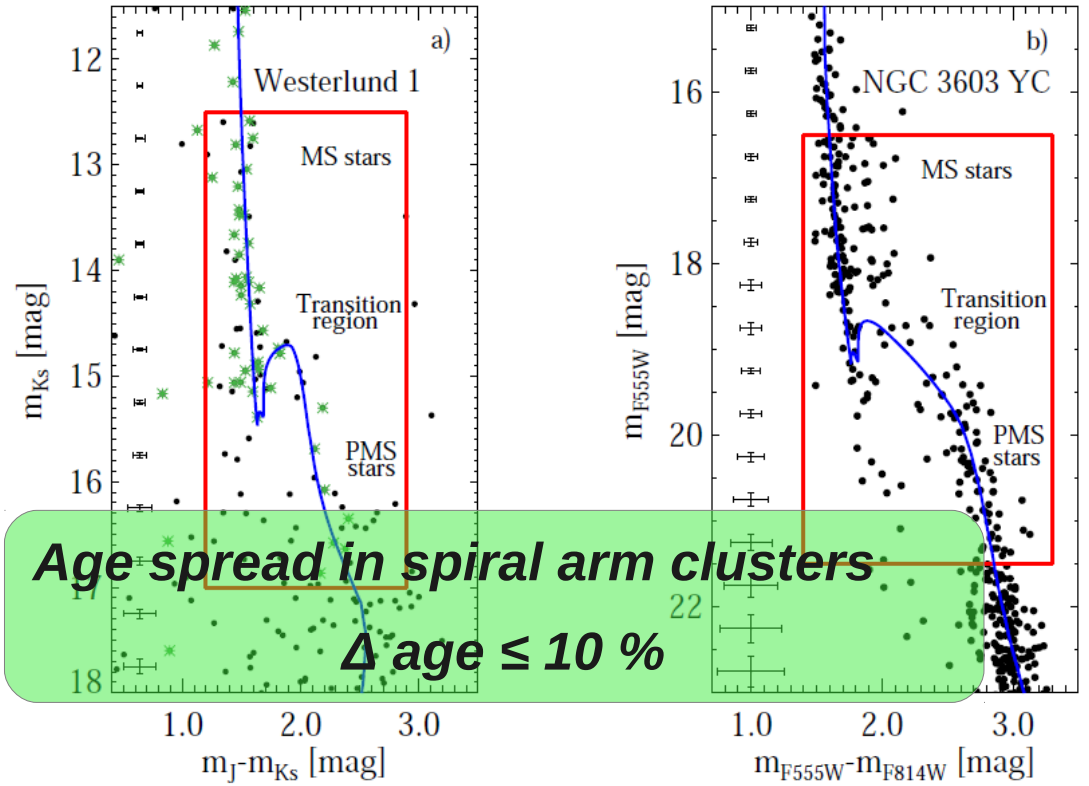
$$L(t) = \prod p\left(t \middle| J_i, K_{si}\right)$$

defines the age distribution in each cluster



Age spread in spiral arm clusters

Δ age ≤ 10 %

Kudryavtseva et al. 2012

Westerlund 1	4 – 5 Myr	Δ age ≤ 0.4 Myr
NGC 3603 YC	1 – 2 Myr	Δ age ≤ 0.1 Myr

Summary

Present-day mass functions

Starburst clusters are mass segregated

Dynamical segregation is sufficient to explain their MF slopes

Age spreads

Starburst clusters have small age spreads

Delta age <~ 10 % of the cluster age

- this distinguishes starbursts from local star-forming regions, where significant age spreads are observed

Thank you very much for your attention!

Velocity dispersion & mass

Starburst clusters are (close to) virial

Velocity dispersions are 2-6 km/s

and yield dynamical masses:

15000 – 40000 Msun

Good prospects for astrometry

E-ELT science & GAIA

- micro-arcsecond astrometry
- E-ELT embedded & Galactic plane clusters (mid-infrared)
- GAIA outside Galactic plane out to 10 kpc (optical)

Milky Way Starburst Clusters

Outline

Milky Way starburst clusters:
- Definition & Location
- Formation environments

The clusters 2D survey

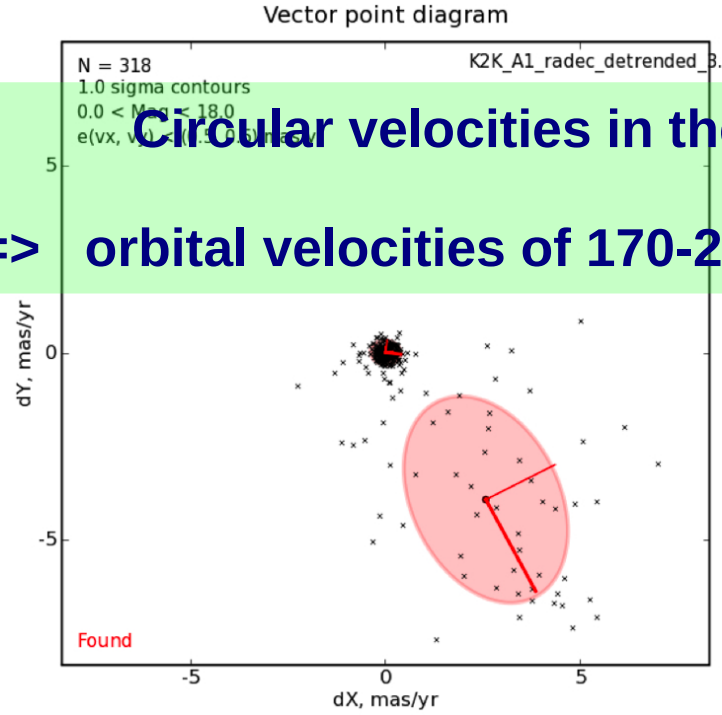
Characteristics of starburst clusters
- Present-day mass function
- Velocity dispersion & cluster mass
- Age spread

Constraints from simulations
- **Orbits of Galactic center clusters**

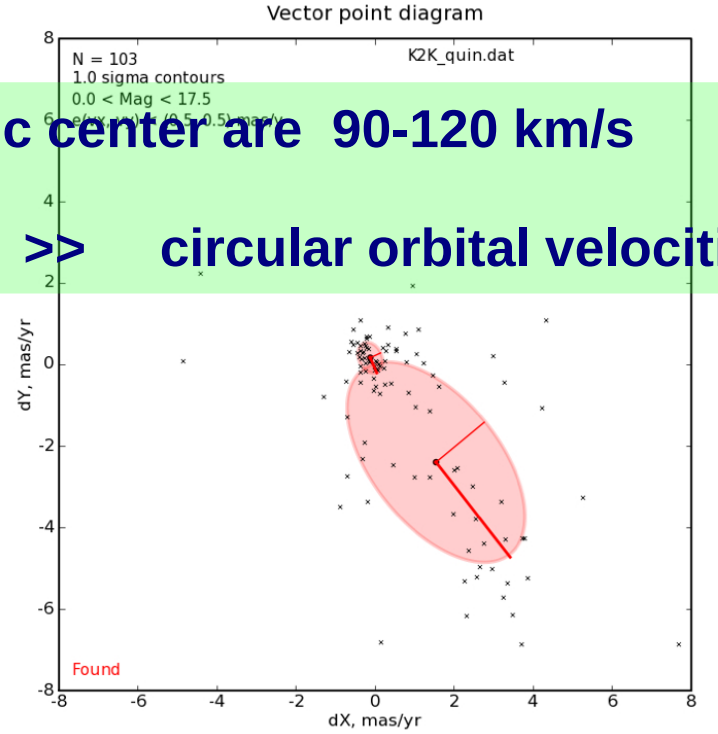
Summary
- Milky Way starbursts today.....

Proper motion studies: internal velocity dispersion & dynamical mass

Arches



Quintuplet



Circular velocities in the Galactic center are 90-120 km/s

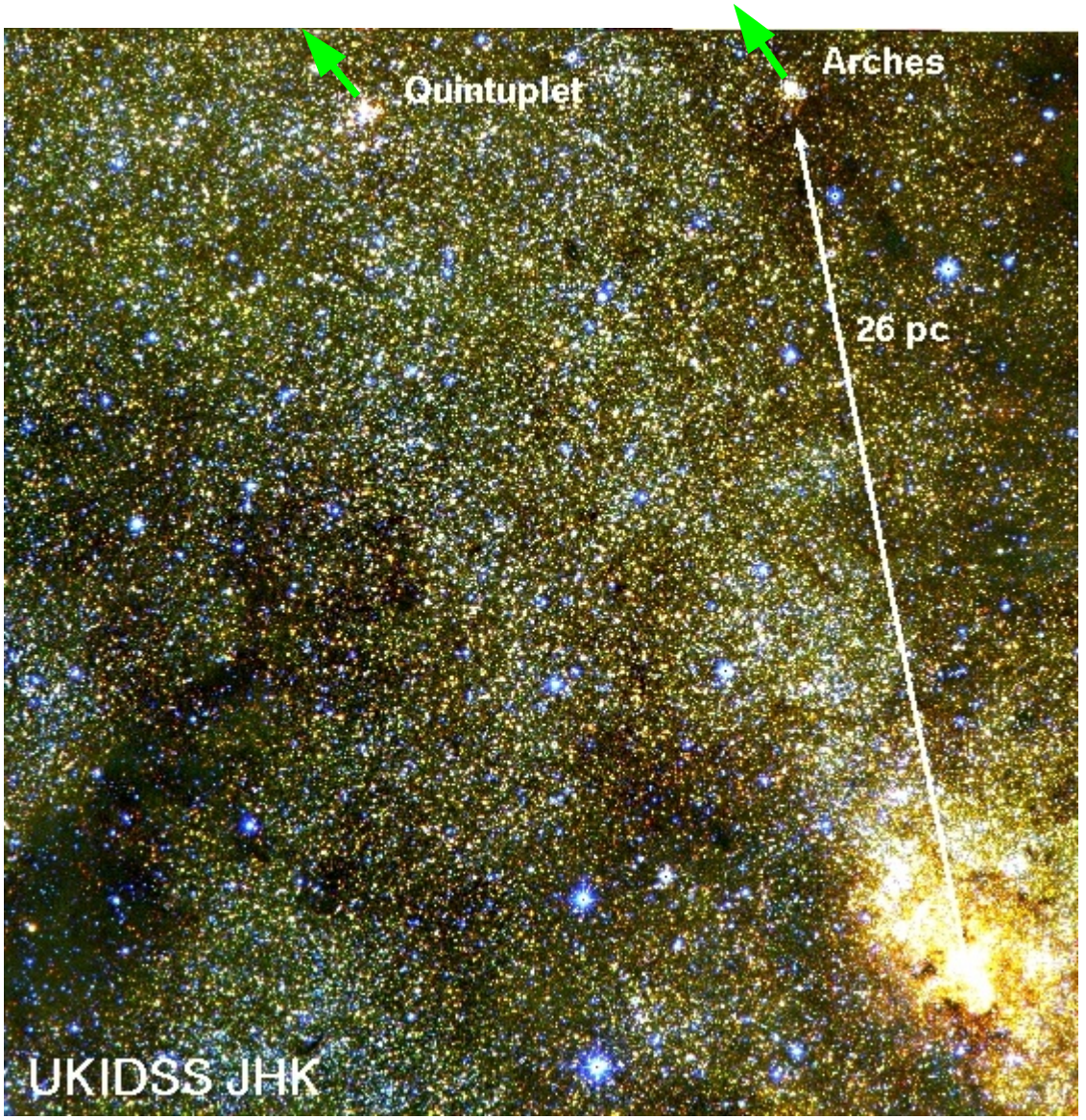
=> orbital velocities of 170-200 km/s >> circular orbital velocities

Fitting the field and cluster populations in the proper motion plane simultaneously:

	Arches	**Quintuplet**	
2D orbital motion	172 +- 15 km/s	106 +- 50 km/s	
Radial velocity	95 km/s	130 km/s	*Figer et al. 2002, 1995*
3D orbital motion	196 km/s	167 km/s	

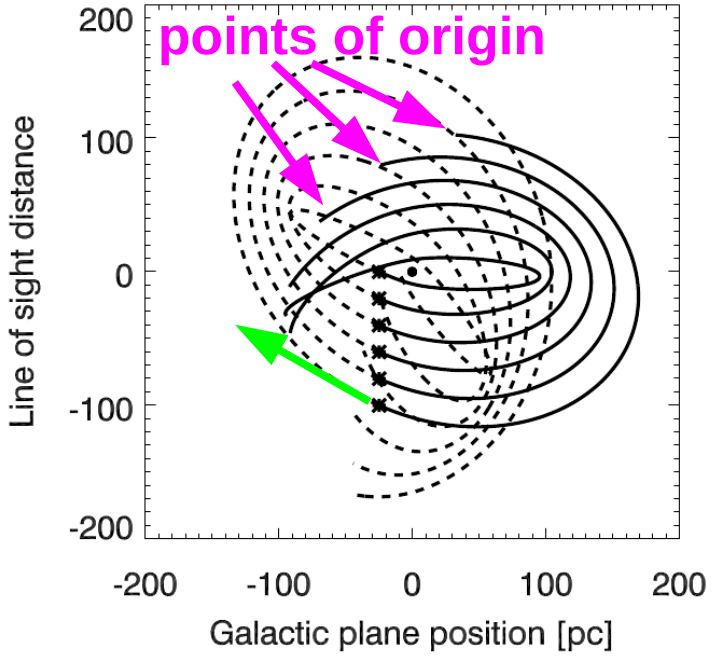
Clarkson et al. 2012, Stolte et al. In prep

Non-circular orbits in the Galactic center potential

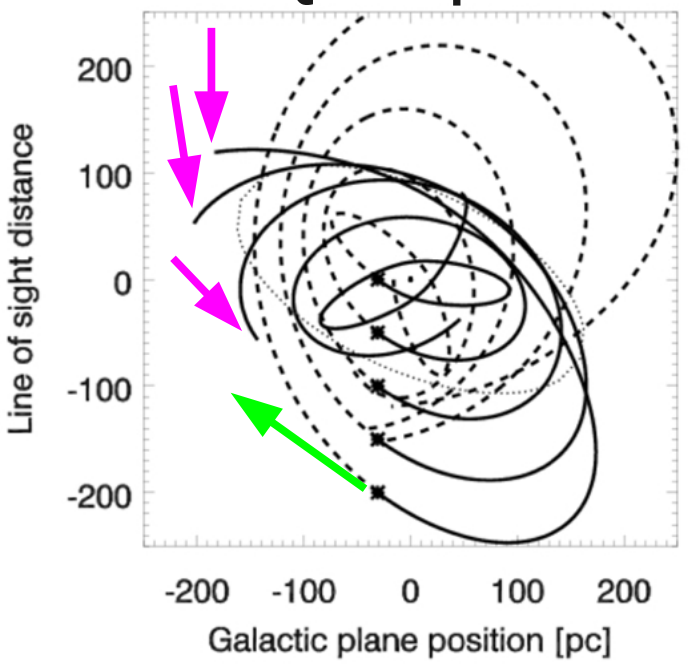


Non-circular orbits in the Galactic center potential

Arches



Quintuplet



3D orbital velocity 196 +/- 20 km/s

Stolte et al. 2008, Clarkson et al. 2012

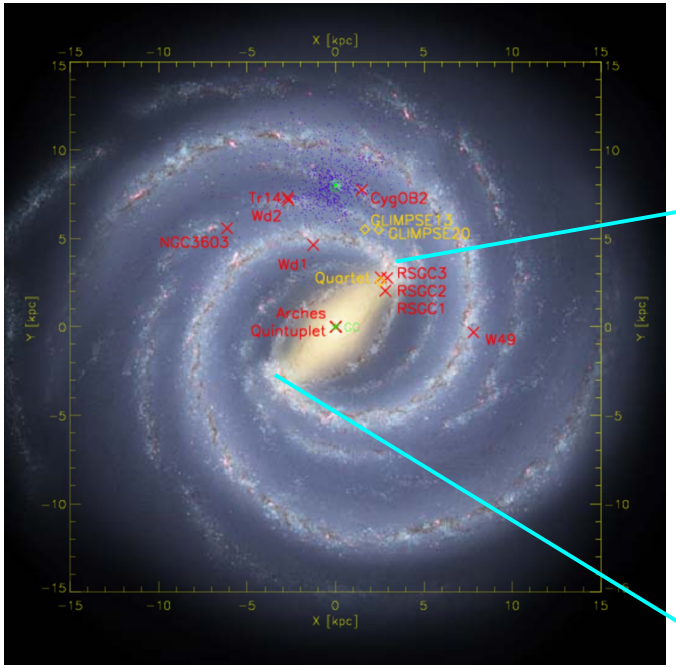
167 +- 50 km/s

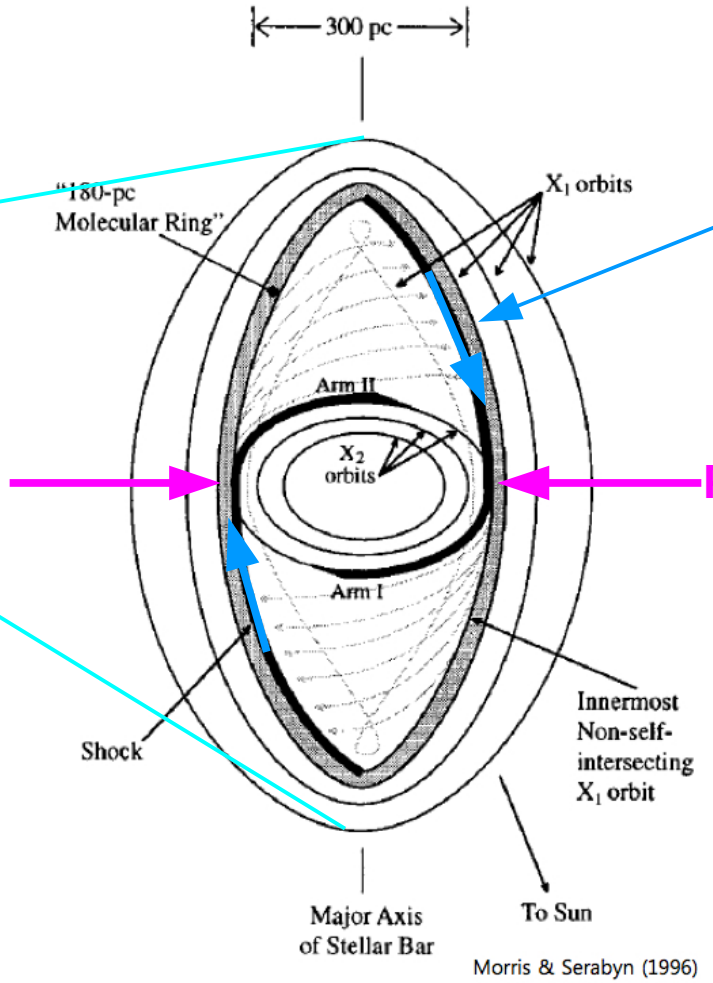
Stolte et al., in prep

Have both clusters emerged at a similar point of origin?

Could there be a common origin of the Arches & Quintuplet?

Stable classes of orbits in the bar potential:



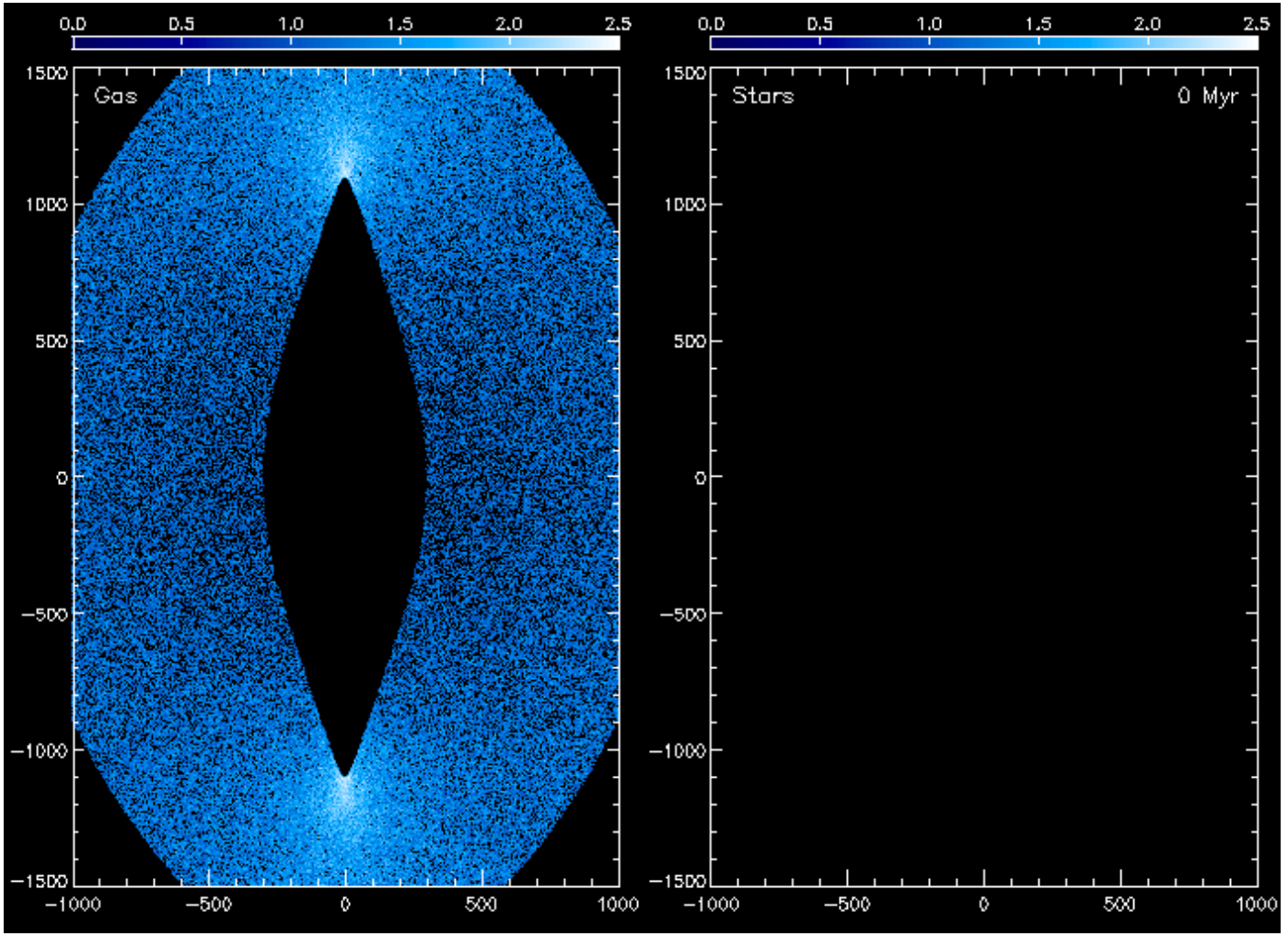


instreaming clouds

Points of cloud collisions

Morris & Serabyn 1996

3D simulations by Kim et al suggest infalling gas forms clusters

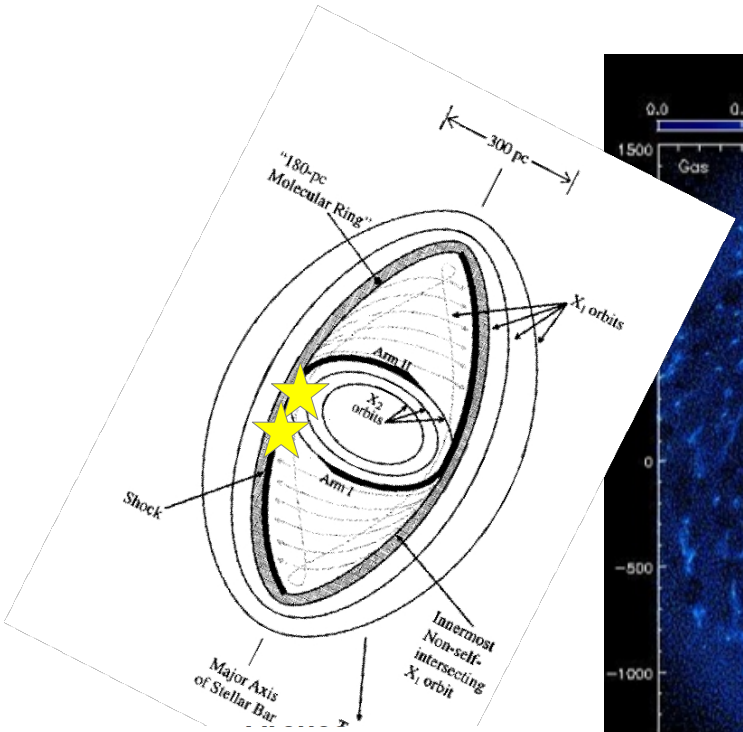


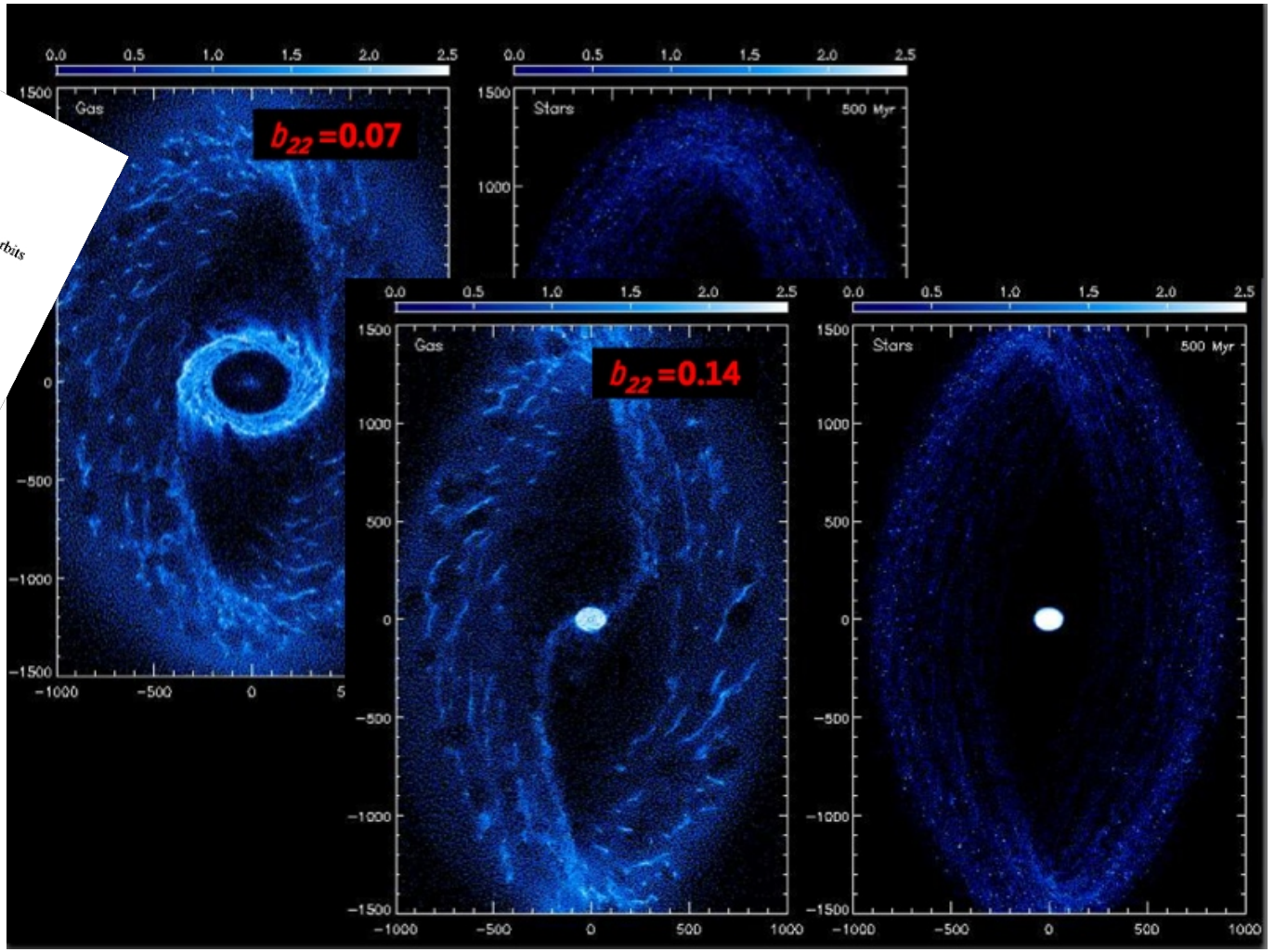
Kim et al. 2011

3D simulations by Kim et al suggest infalling gas forms clusters

Kim et al. 2011

Could there be a common origin of the Arches & Quintuplet?





Kim et al. 2011

Conclusion:

Galactic center cluster might form from instreaming clouds