Milky Way 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

Constraints from simulations
Orbits of Galactic center clusters

Summary & Outlook
Milky Way starbursts today.......

Milky Way Starburst Clusters

What's interesting about starbursts?

- most massive clusters forming in MW today

- cover entire mass range known

  => 0.08 – 150 (300?) Msun

- influence of high-mass stars on the SF process

  => changes in the IMF?

- differences in SF environments:

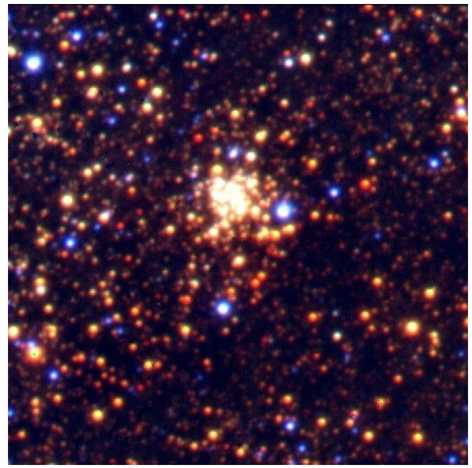
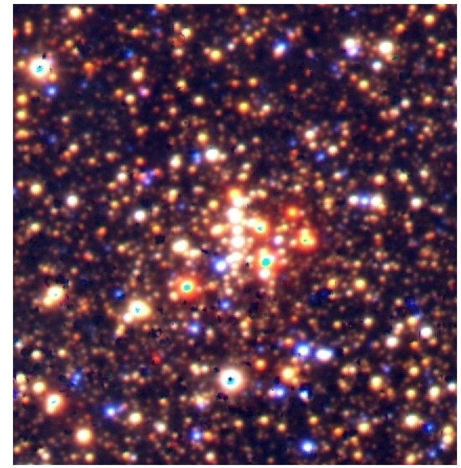
  spiral arms vs. Galactic center

- most common mode of SF in the universe?

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

NGC 3603 YC	Arches	Quintuplet	Westerlund 1

3.4 pc

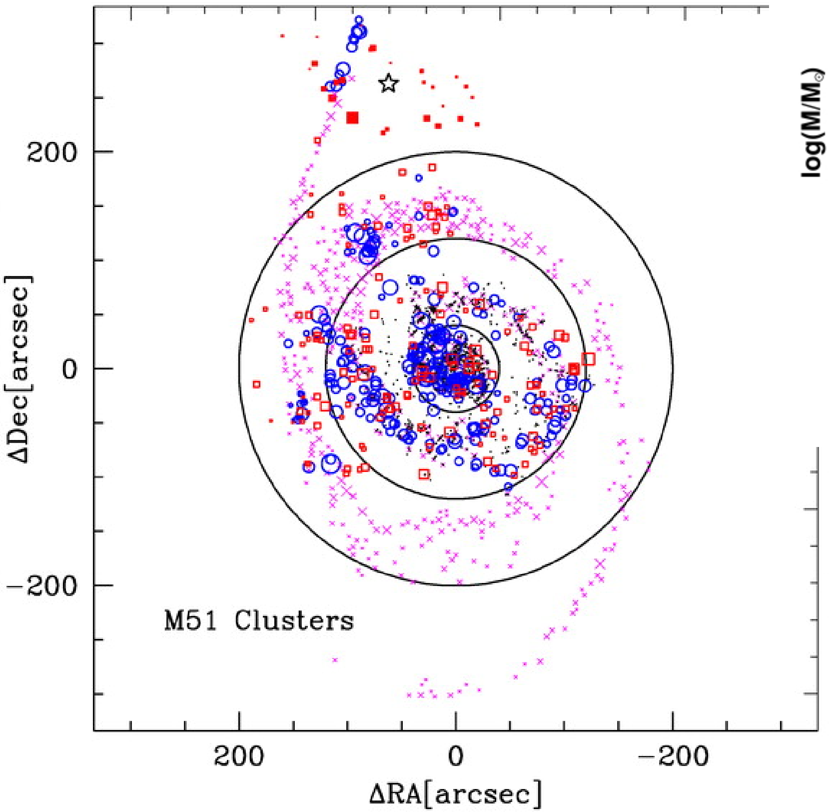




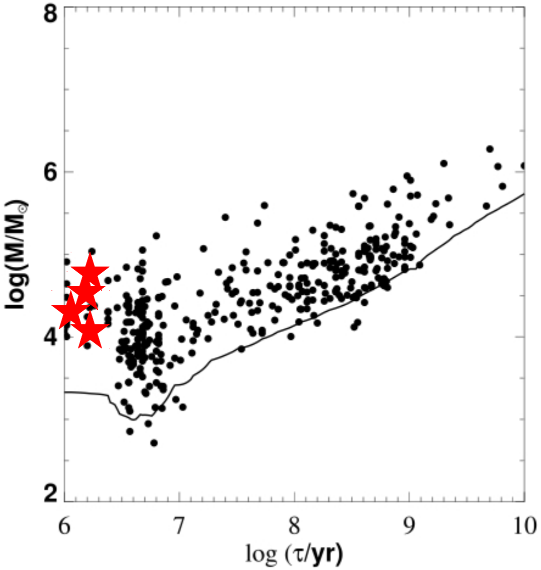

Brandl et al. 1999 *UKIDSS Galactic Plane Survey Lucas et al. 2008* *Brandner et al. 2008*

Age	**1 – 2 Myr**	**2 – 3 Myr**	**3 – 5 Myr**	**4 – 5 Myr**
Mass	**17600 +- 3800**	**15000 +- 7000**	**> 6000 ?**	**50000 Msun**
	Rochau et al. 2010	*Clarkson et al. 2012*		*Gennaro et al. 2011*

Milky Way Starburst Clusters are comparable in mass and size to young, massive extragalactic clusters

M51 starburst clusters





Young clusters

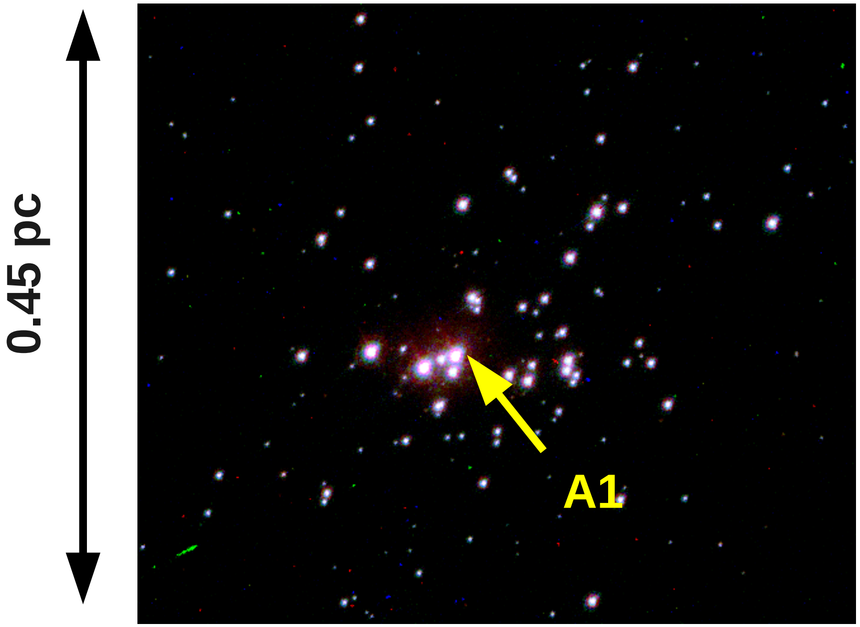
age < 100 Myr

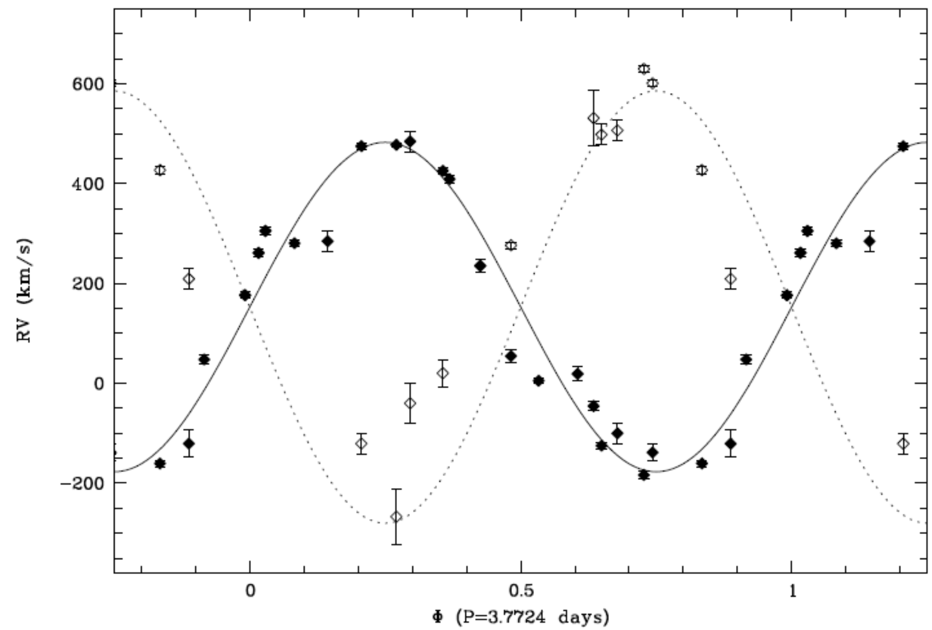
Milky starburst clusters are resolved templates for extragalactic populations.

Lee et al. 2005

Starburst Clusters contain the most massive stars observed in the Milky Way today

NGC 3603 A1 – spectroscopic, eclipsing binary





Milky starburst clusters are the places where massive binaries can be “weighted”.

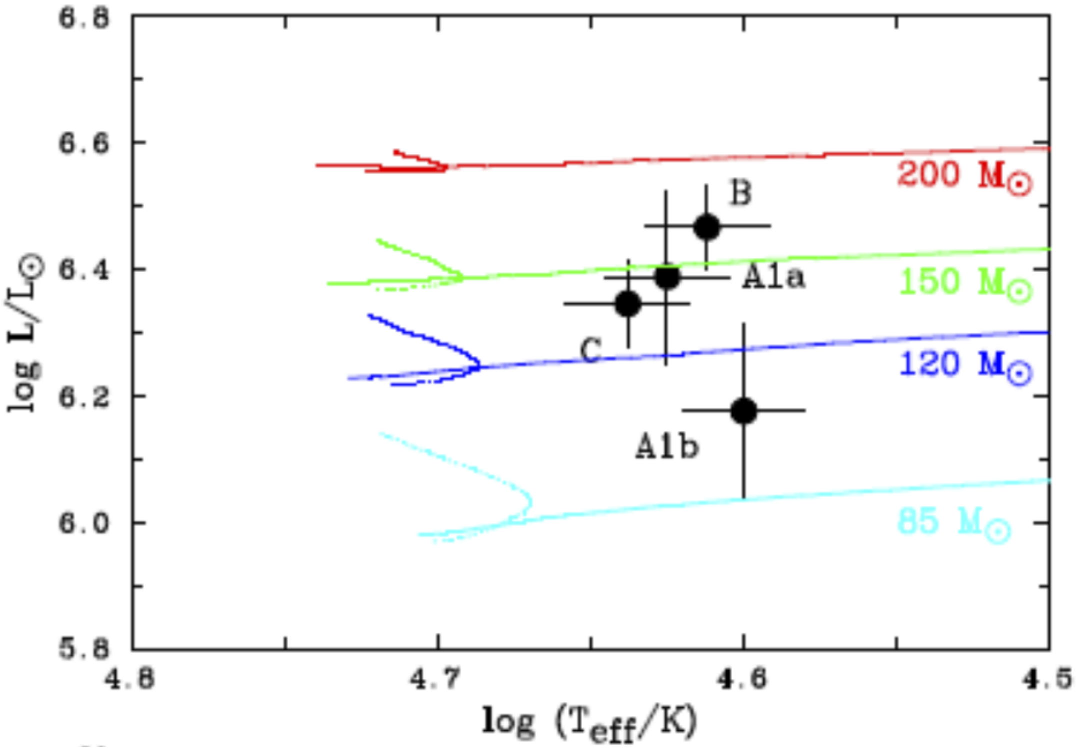
primary: $M_1 = (116 \pm 31)\ M_\odot$

secondary: $M_2 = (\ \ 89 \pm 16)\ M_\odot$

Schnurr et al. 2009

Currently most massive system with full orbital solution!

High-mass stars allow calibration of stellar evolution scenarios



Crowther et al. 2010

High-mass stellar evolution models are calibrated with these beasts.

- absolute luminosities & metallicity effects

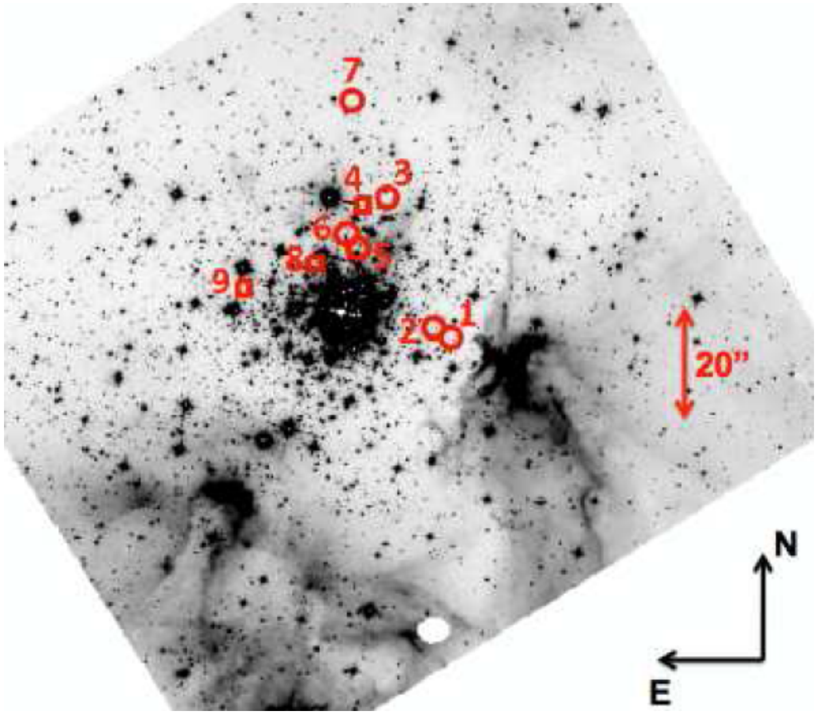
- wind properties in dependence of mass

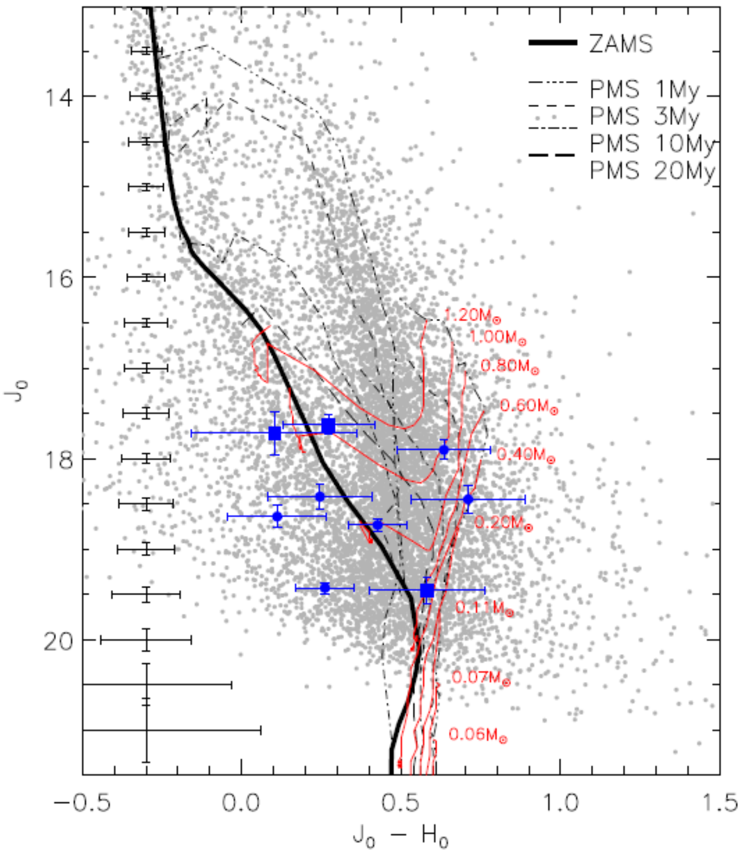
- rotation or no rotation?

but there are not only high-mass stars...

Starburst Clusters contain the full stellar mass spectrum

Low-mass objects – Brown Dwarfs – formed in starburst clusters?





Brown Dwarf candidates from water vapor absorption in their atmospheric spectral energy distributions.

Spezzi et al. 2011

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Milky Way starburst clusters & location

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

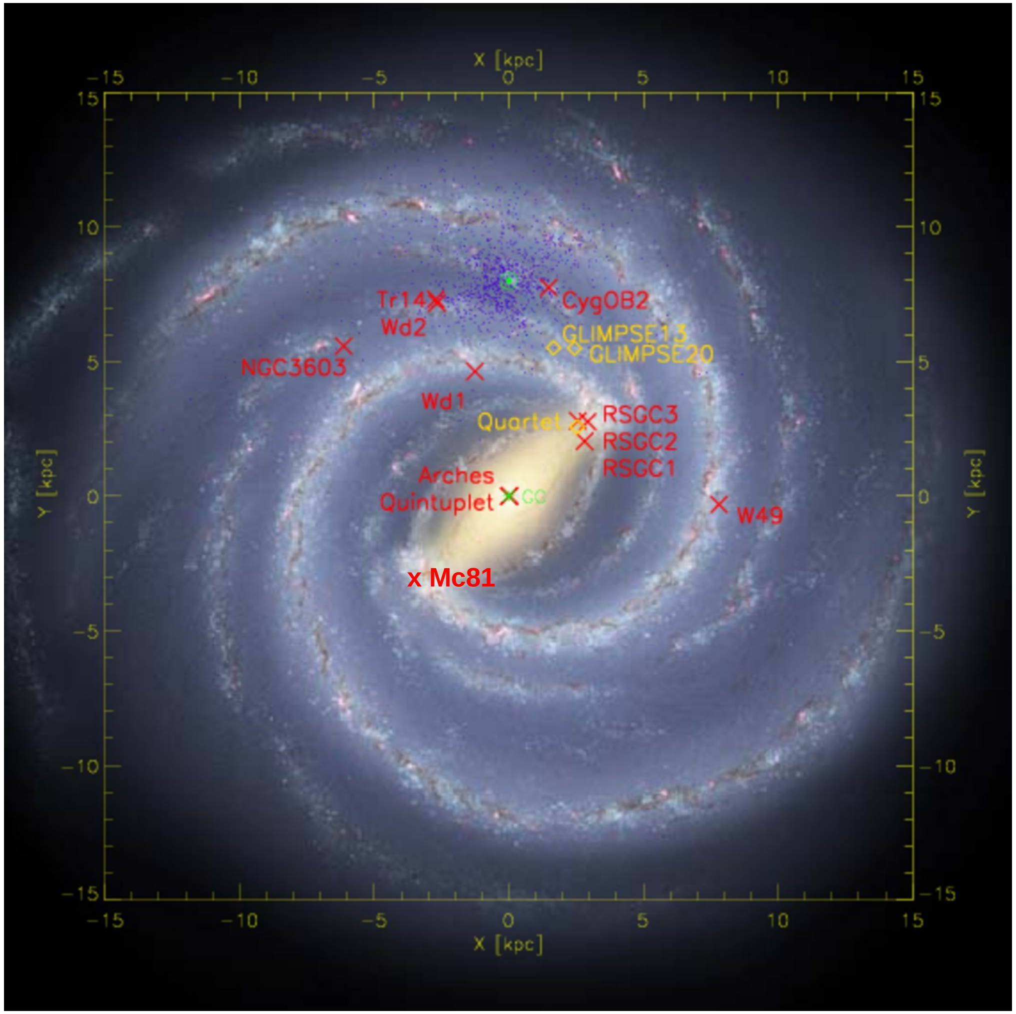
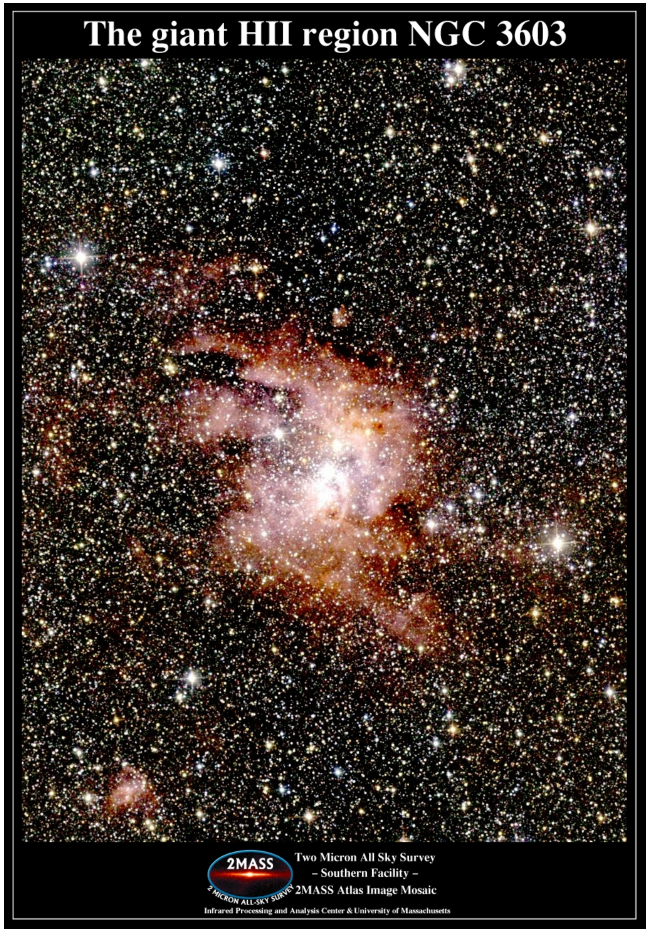


Image courtesy: Boyke Rochau & Wikipedia

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

Star cluster formation in spiral arms is an "isolated process"



Spiral arm cluster & star formation:

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

No nearby clouds, high-mass stars, radiation sources, …

=> the star formation process is determined by internal properties of the cloud

1. cloud structure, density, temperature
2. cluster members, forming high-mass stars
3. internal dynamical processes

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

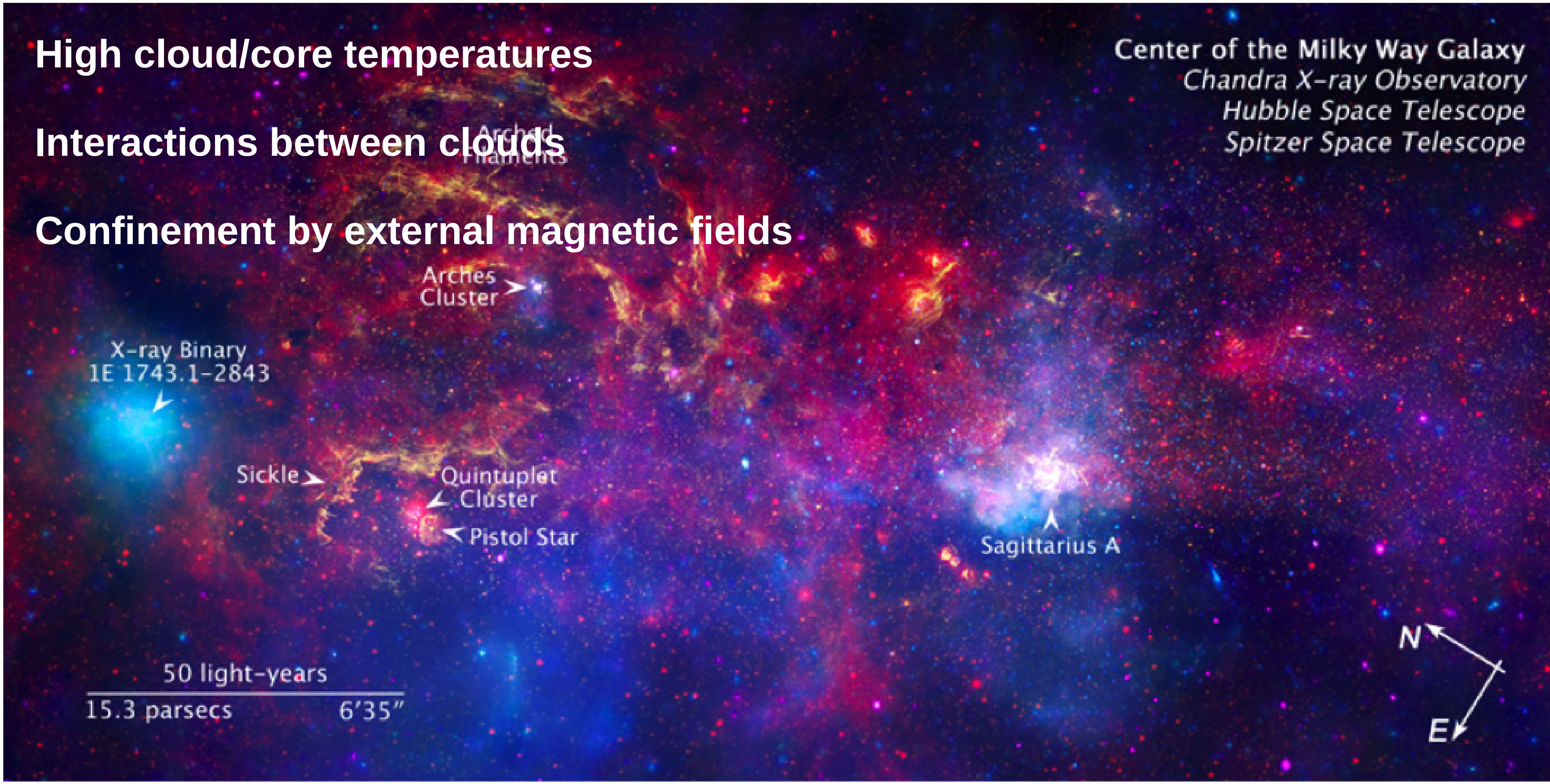
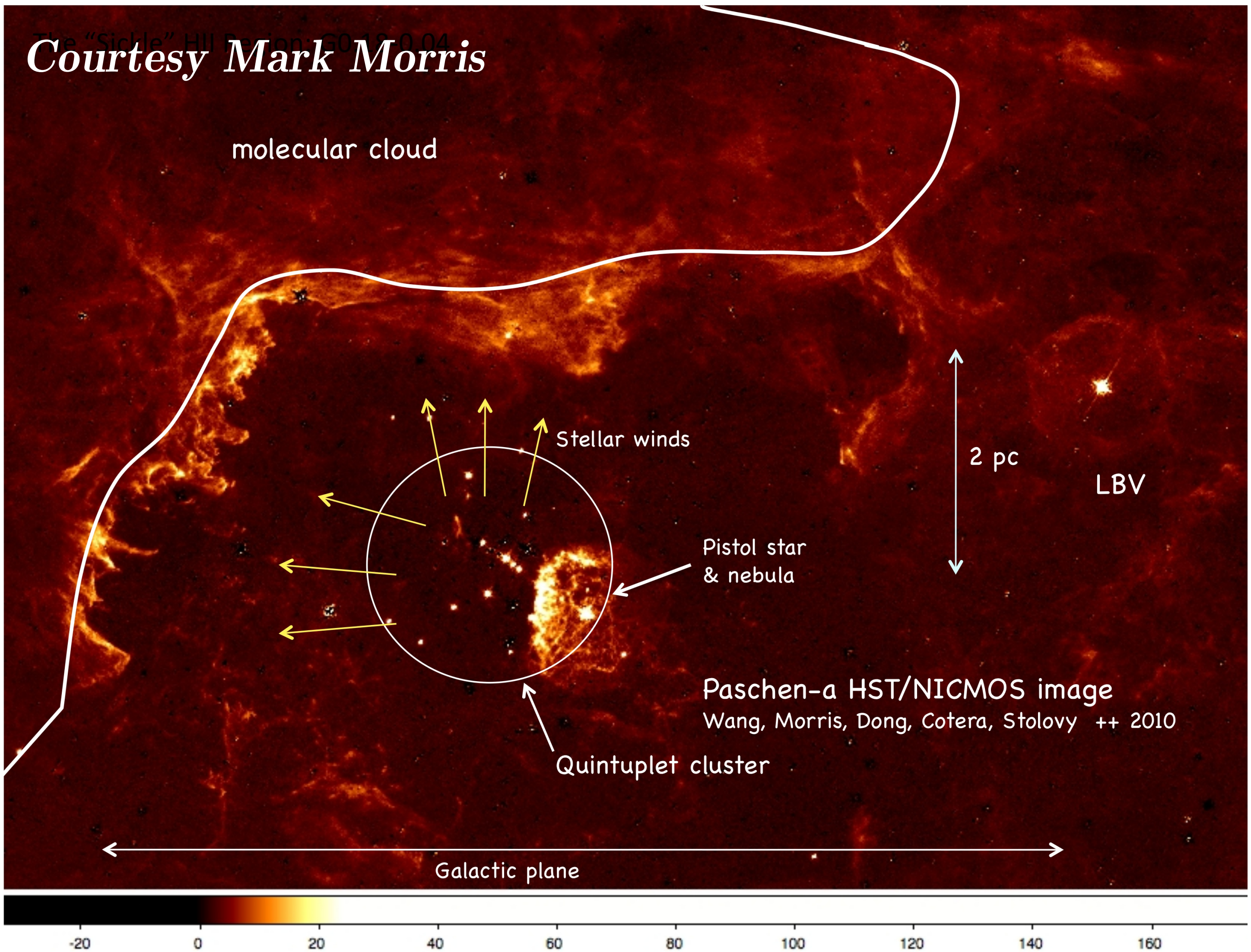


Image courtesy: Spitzer GLIMPSE & GC Paschen alpha surveys, D. Wang, A. Cotera, M. Morris et al.

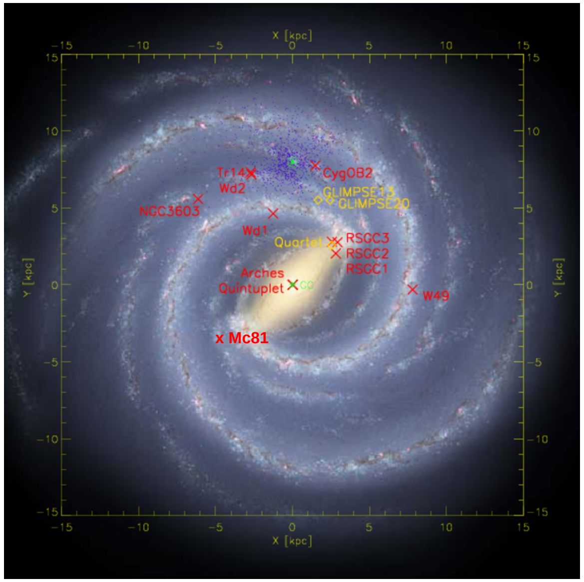
Star cluster formation in the Galactic center is a very "messy process"



The Paschen-alpha survey of the inner Milky Way --
Wang et al. 2010, Dong et al. 2011

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

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

… and there seems to be a severe overproduction of massive stars!

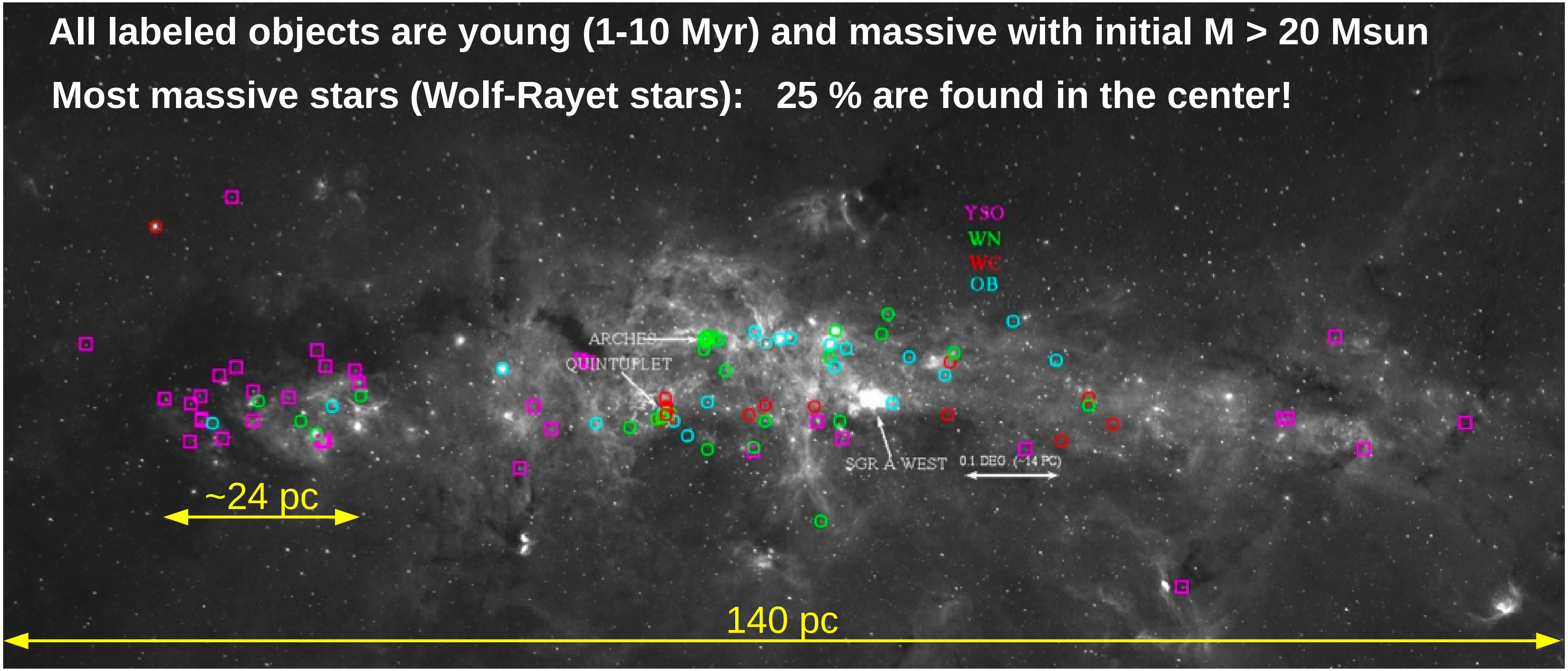


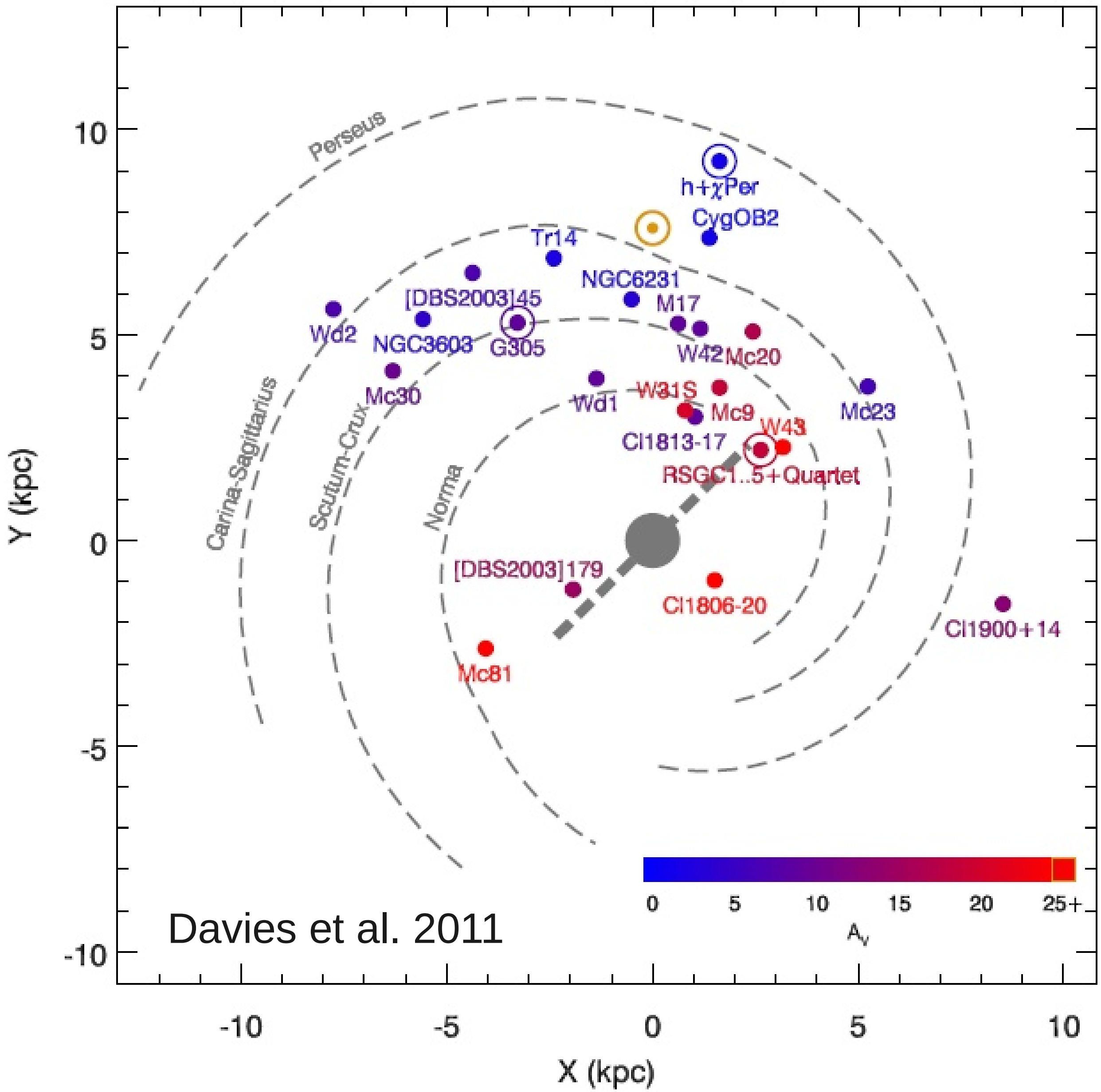
Image courtesy: A. Cotera with data from Mauerhan et al. 2010, 2011, Yusef-Zadeh et al. 2009

Star formation rate in the center of the Galaxy:

r < 200 pc	full MW disk	*Yusef-Zadeh et al. 2009*
0.14 Msun / yr	0.68 – 1.45 Msun / yr	*Robitaille & Whitney 2010*

=> 10-20 % of all stars for in the Galactic center environment

Milky Way starburst clusters & location



Milky Way Starburst Clusters

Starburst clusters cover the entire stellar mass range from 0.08 – 150 (?) Msun

High-mass stars are extremely short-lived: t_evol < 10-20 Myr

- their life stages can only be studied in massive, young clusters
- massive, young clusters are the only locus where their influence on low-mass star formation can be observed

Milky Way starburst clusters probe star formation under extreme conditions:

- starbursts are formed in spiral arms in “normal giant molecular clouds”
- starbursts are formed in the Galactic center

=> direct comparison of the star formation by environment

Starburst clusters are observed in star-forming galaxies near & far:

=> a very common mode of star formation in the universe

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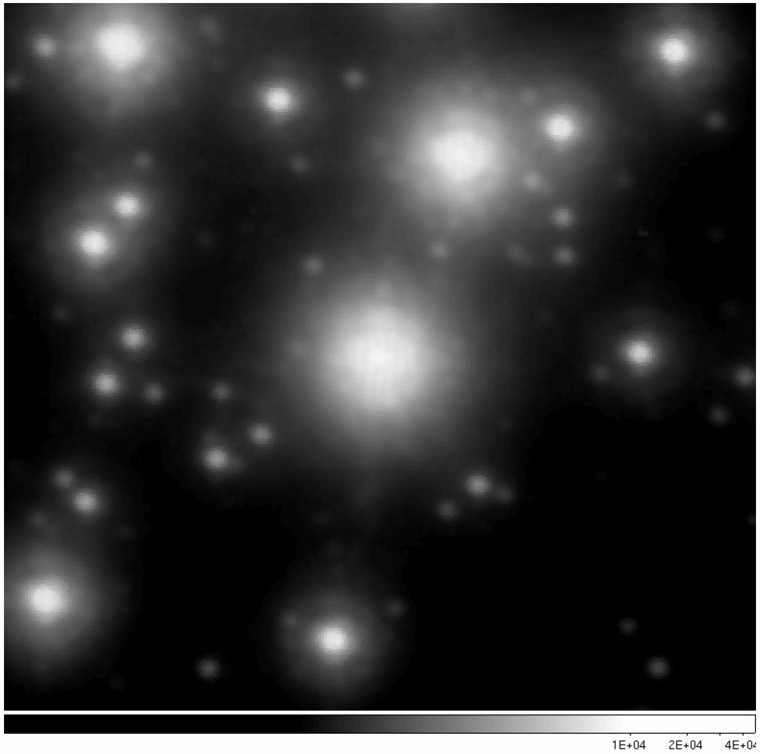
Milky Way Starburst Clusters

Changes during the past few years:

High-resolution adaptive optics imaging enables

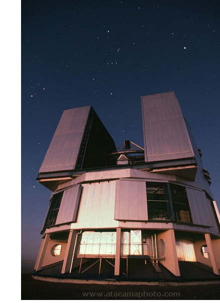
- precision astrometry for proper motion membership at d > 4 kpc
- unbiased present-day mass functions
- internal velocity dispersion
- absolute motions of Galactic center clusters

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



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

Proper motion survey of 4 Milky Way Starburst Clusters

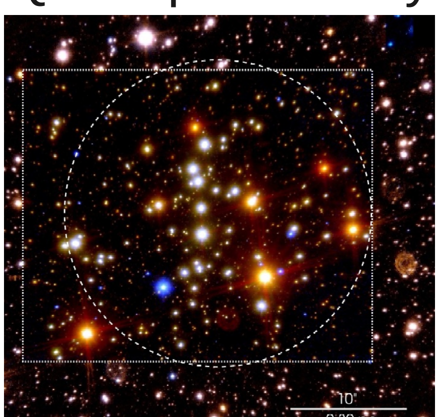


Motivation & Aims

Galactic centre

Arches 2.5 Myr

Quintuplet 3-5 Myr



Comparison of

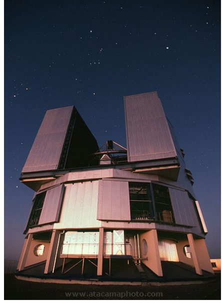
- cluster formation
- cluster dissolution
- stellar mass function

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

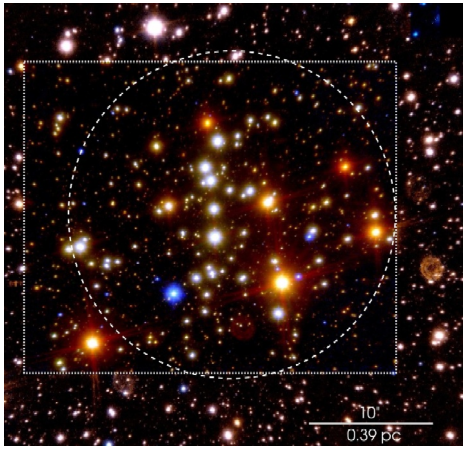
Carina arm

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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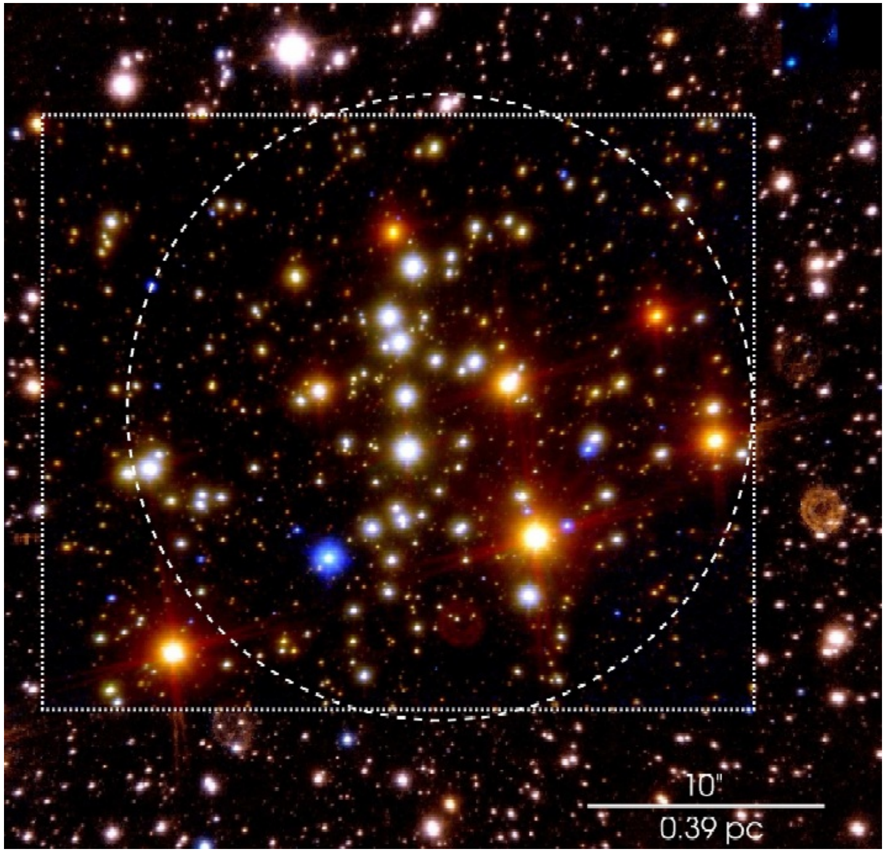
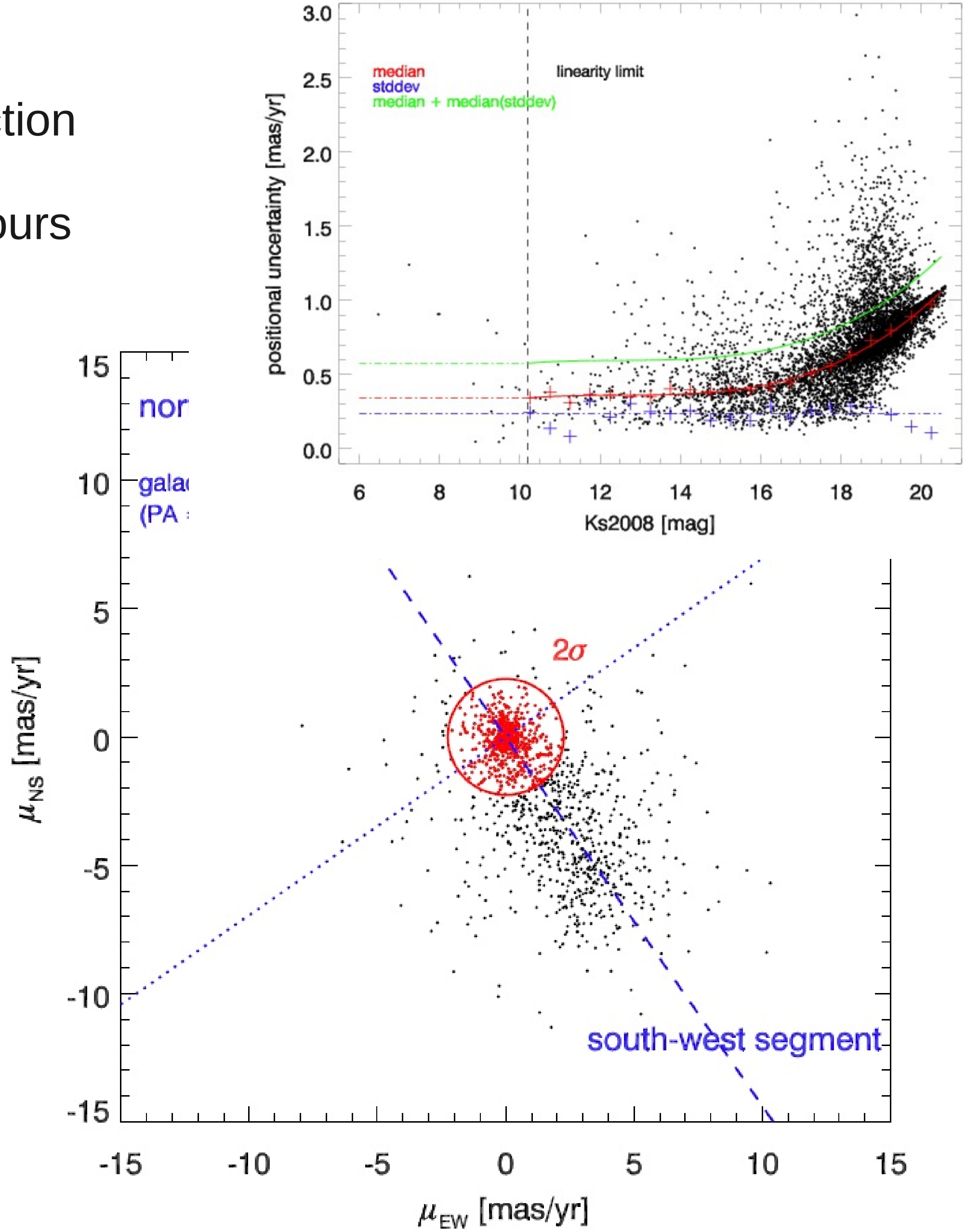
Proper motion membership as a tool to characterise starburst cluster populations

Towards an unbiased present-day mass function

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



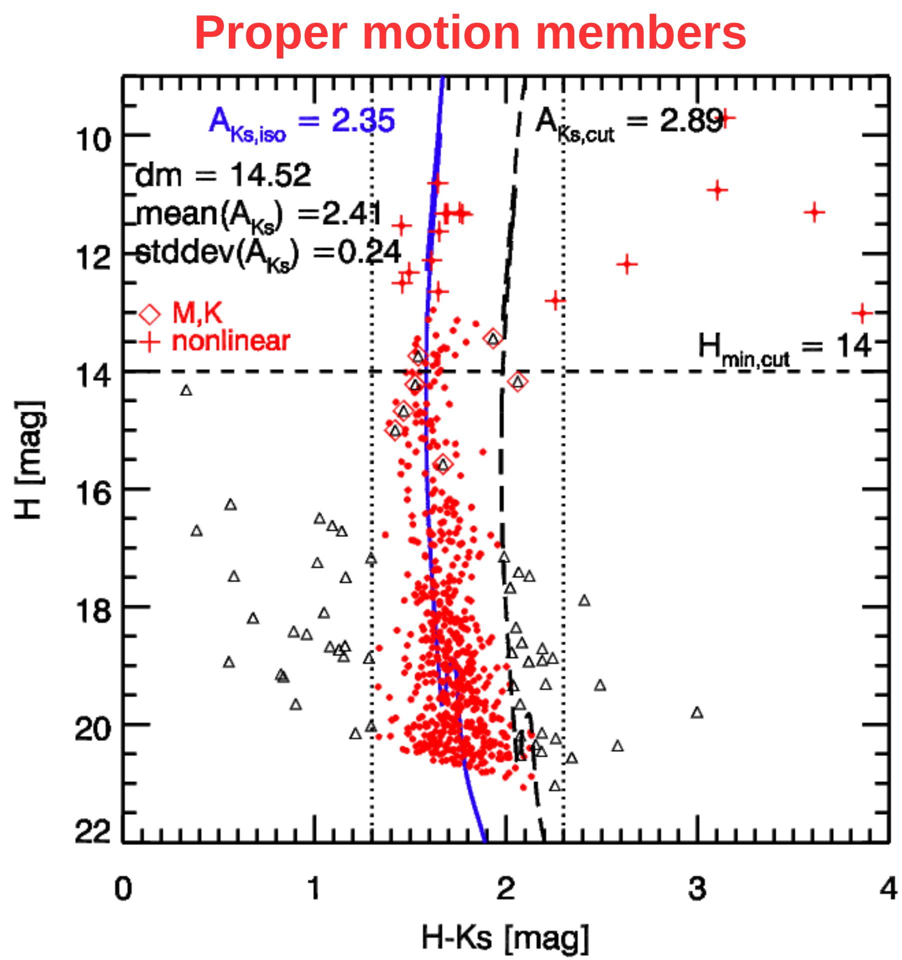


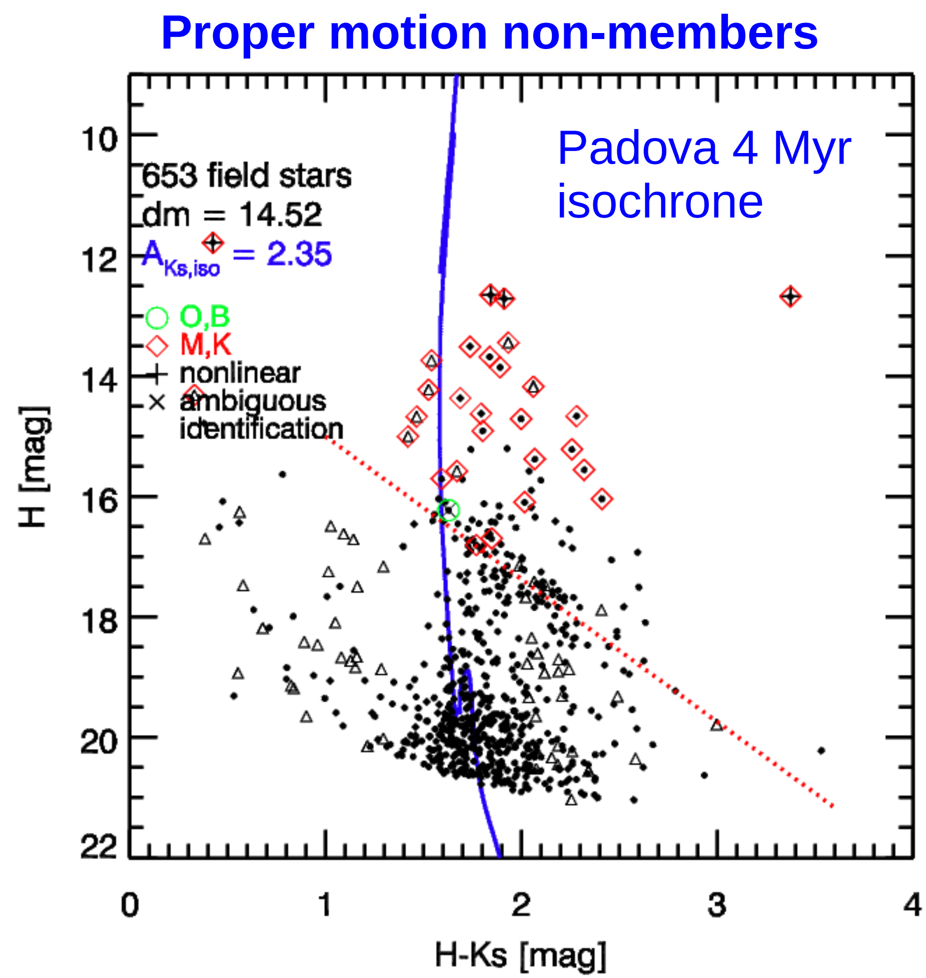
Hußmann et al. 2012

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

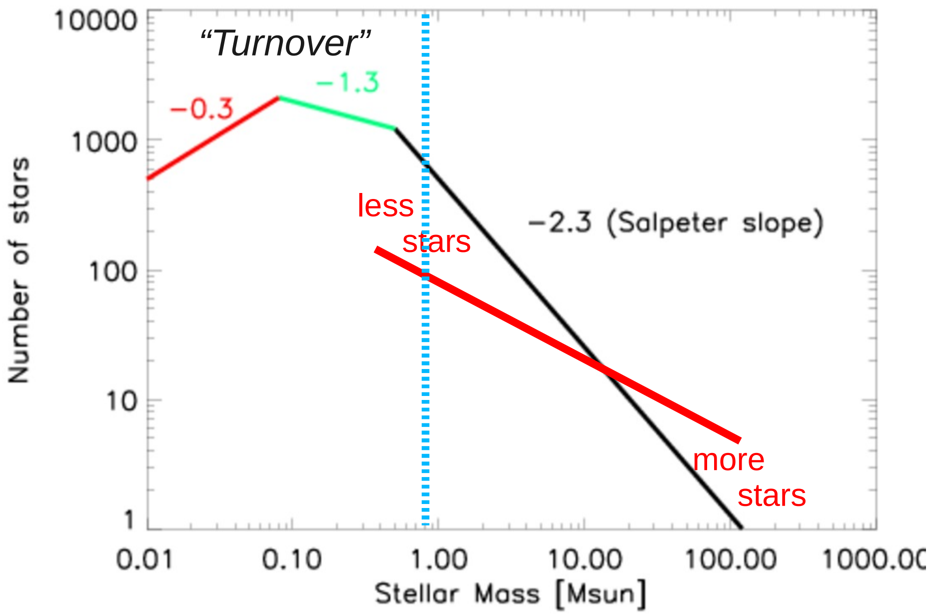




Hußmann et al. 2012

What does "top-heavy MF" mean?

Power-law description of the IMF:



The turnover mass is the most frequent mass, hence called "the characteristic mass"

$$\xi(M)\Delta M = \xi_0 \left(\frac{M}{M_{sun}}\right)^{-2.35} \left(\frac{\Delta M}{M_{sun}}\right)$$

$\xi(M)$ Number of stars per ΔM

Starburst clusters:

- only the high-mass part is observed with the completeness limitations today

A top-heavy MF (present-day or initial) means the MF biased to high-mass stars:

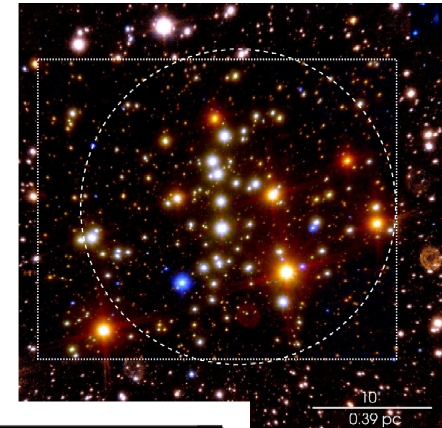
- implies a *flatter slope* than Salpeter
- or a *truncation* at the low-mass end

The measured slope determines the total, *photometric cluster mass*

=> extrapolation of the observed PDMF

Salpeter 1955, Kroupa 2001

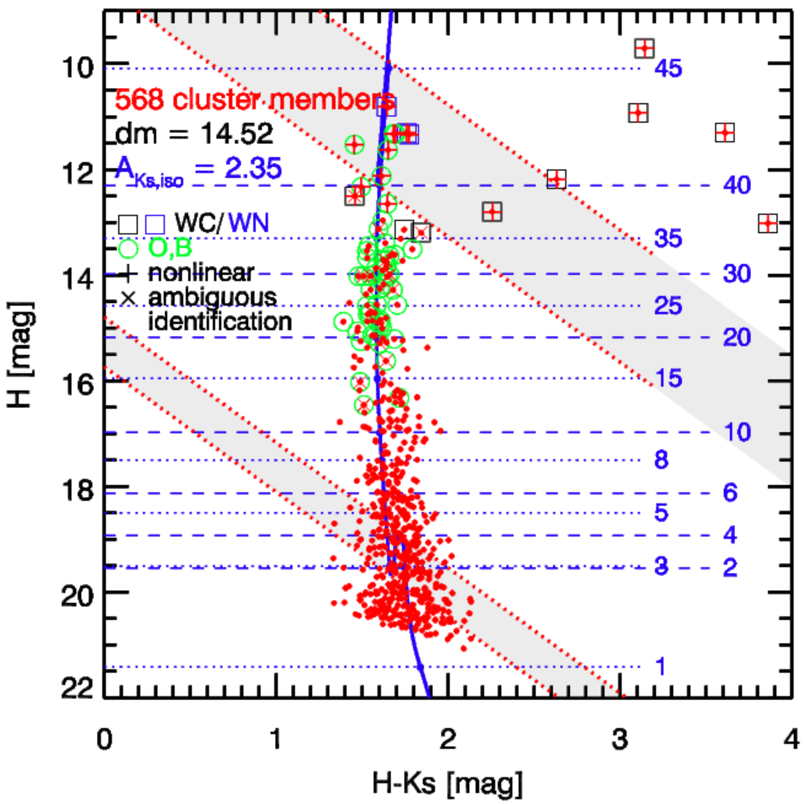
A flat (top-heavy) present-day MF in Quintuplet

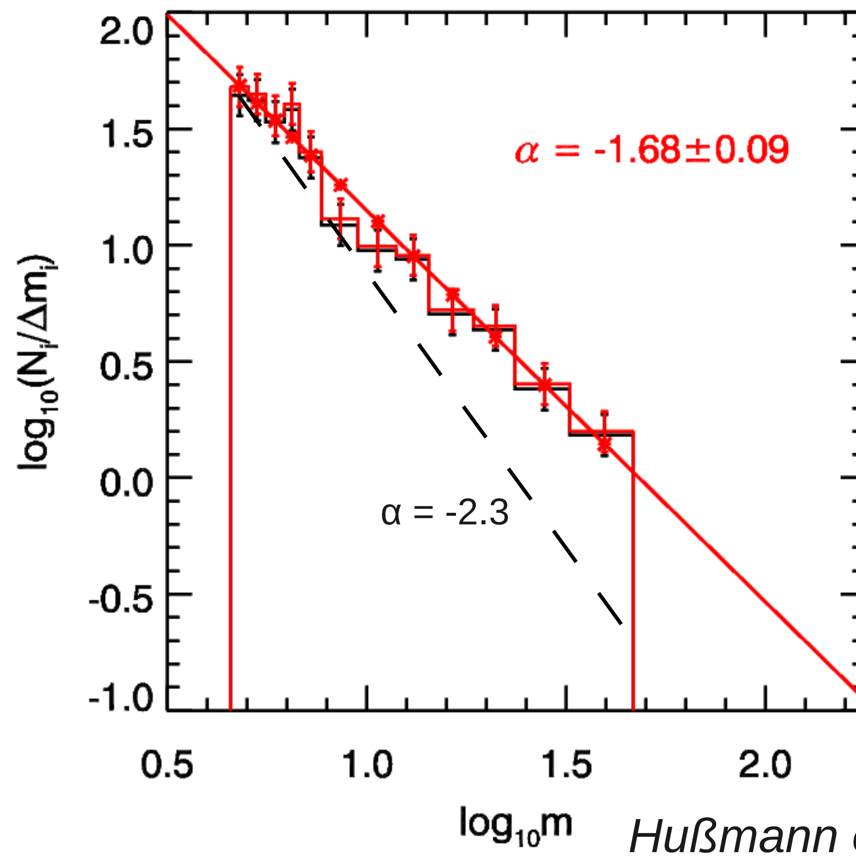


Quintuplet's mass function
from proper motion member selection

alpha = -1.68

for r < 0.5 pc



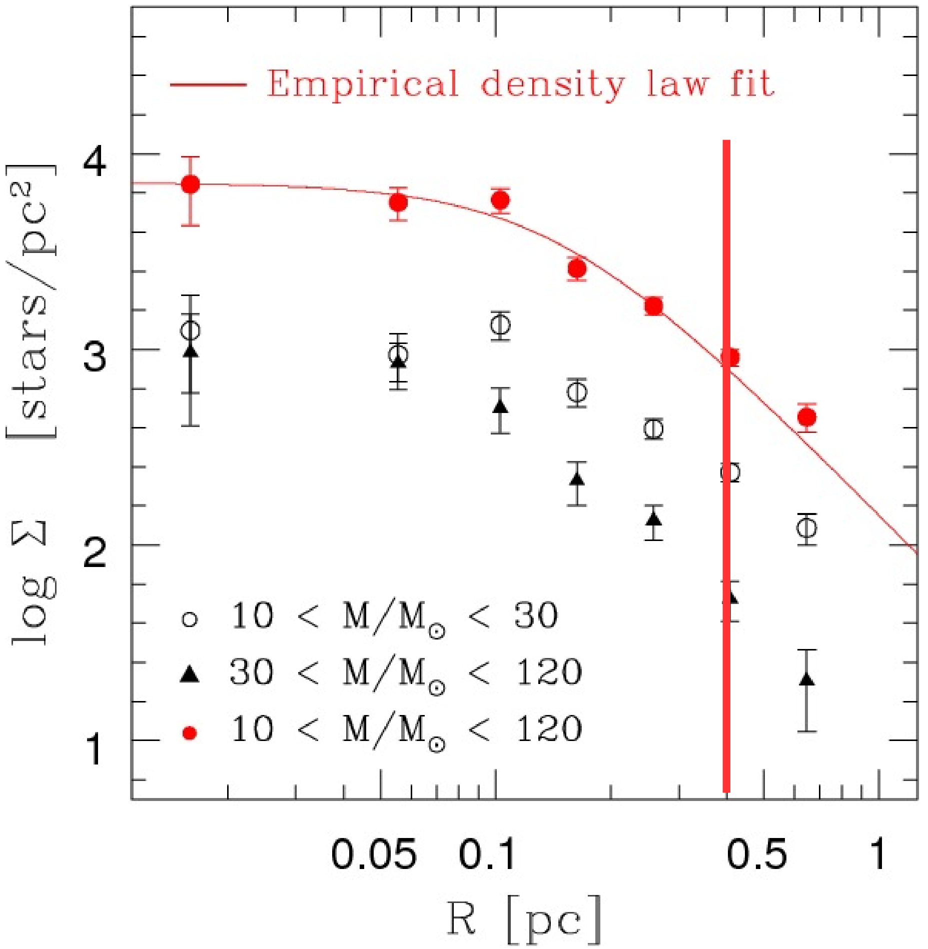


Hußmann et al. 2012

<u>Problem:</u>

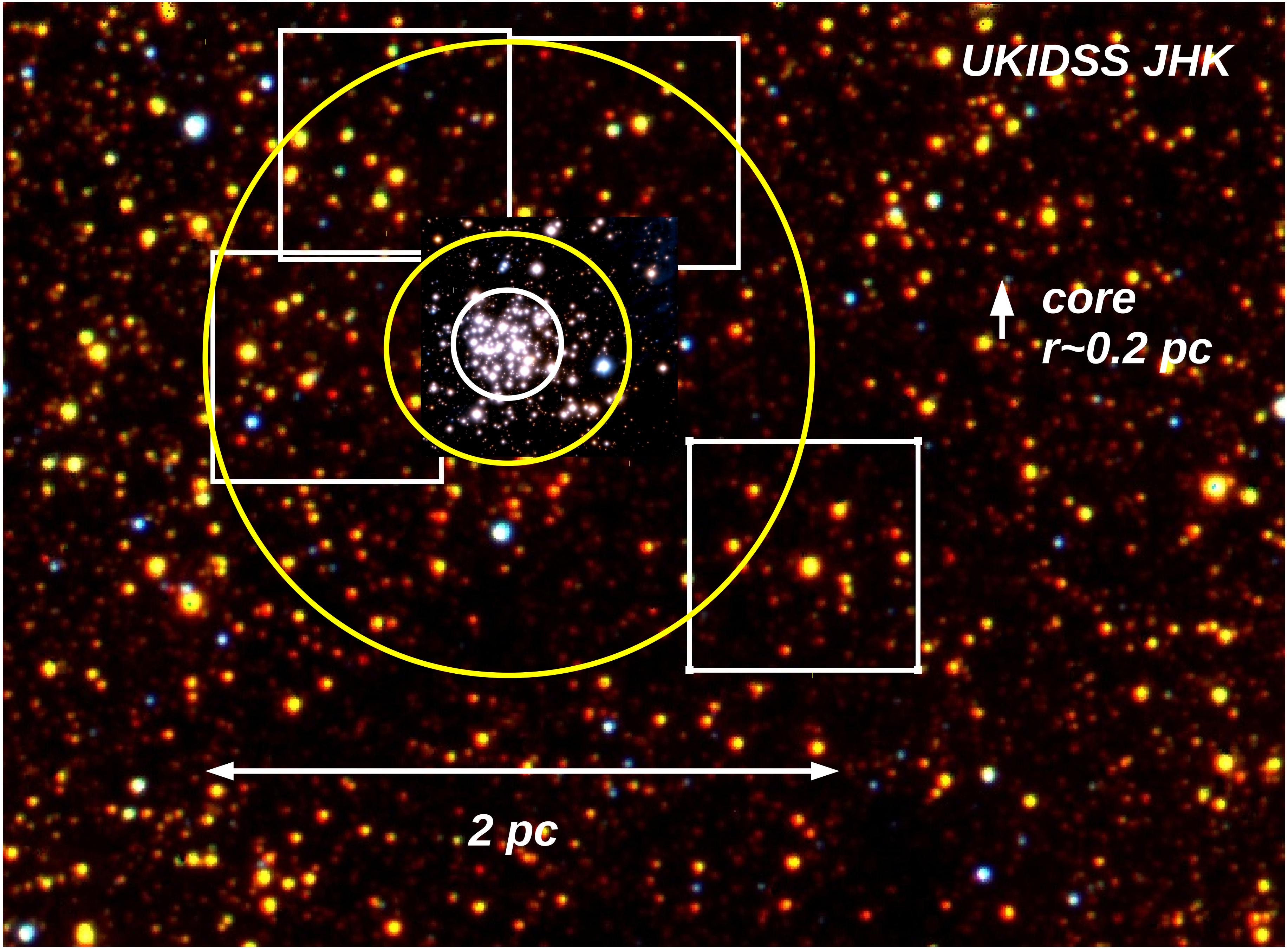
Dynamical evolution influences the *present-day* MF in the cluster center

Without membership information, only a small fraction of a cluster's area can be discerned from the field



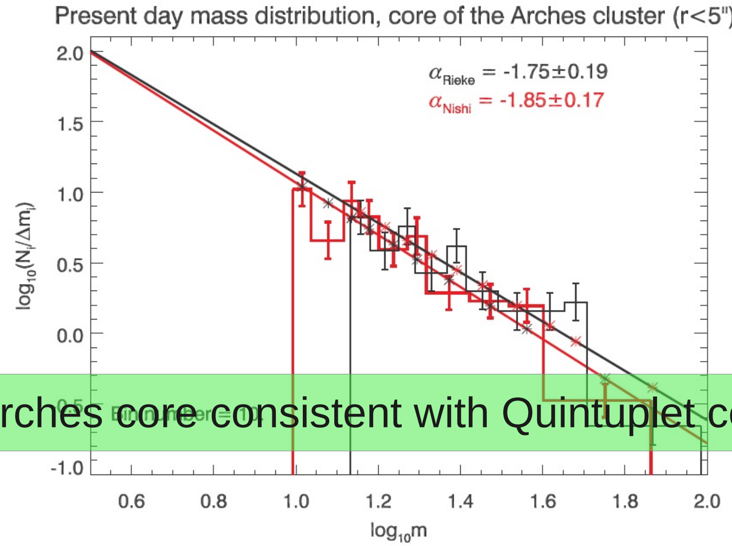
Espinoza et al. 2009

Towards a full representation of the mass distribution...

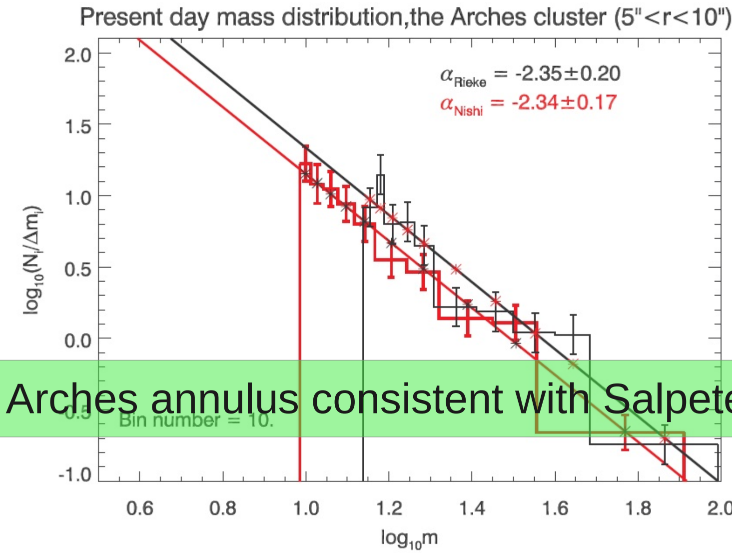


Radial variation of the present-day mass function

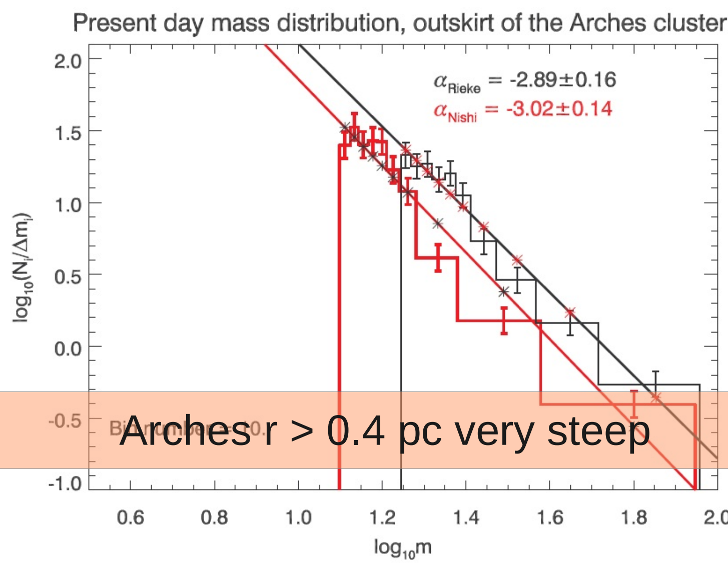
The slope of the present-day mass function steepens as a function of radius.



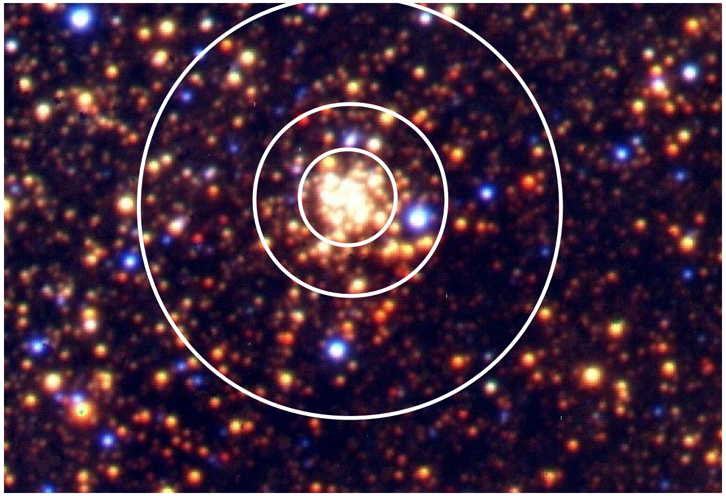
Arches core consistent with Quintuplet center



Arches annulus consistent with Salpeter MF

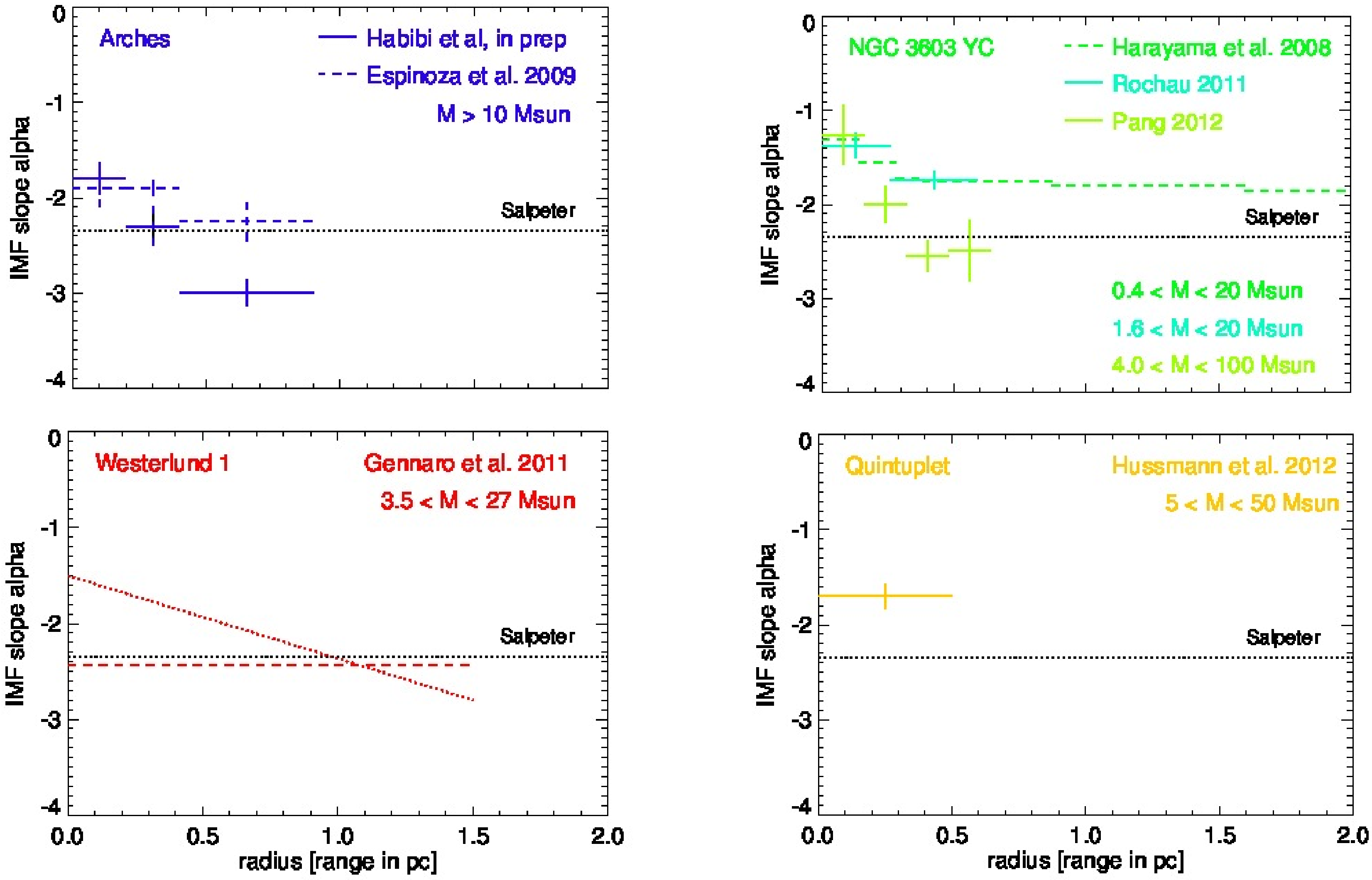


Arches r > 0.4 pc very steep

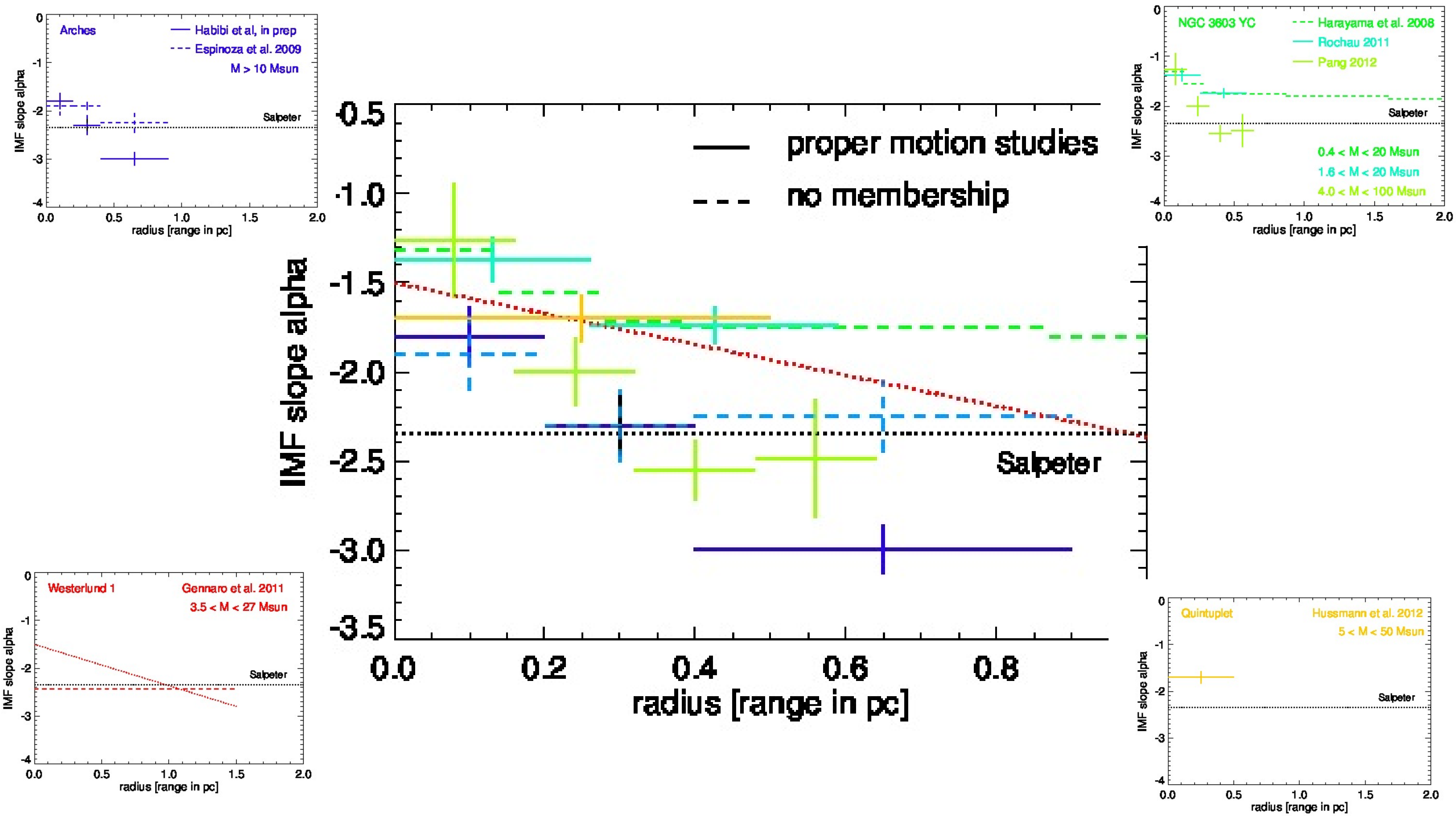


Habibi et al., in prep

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



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



Present-day MF slopes of all starburst clusters increase with radius.

The observed steepening is consistent with dynamical evolution.

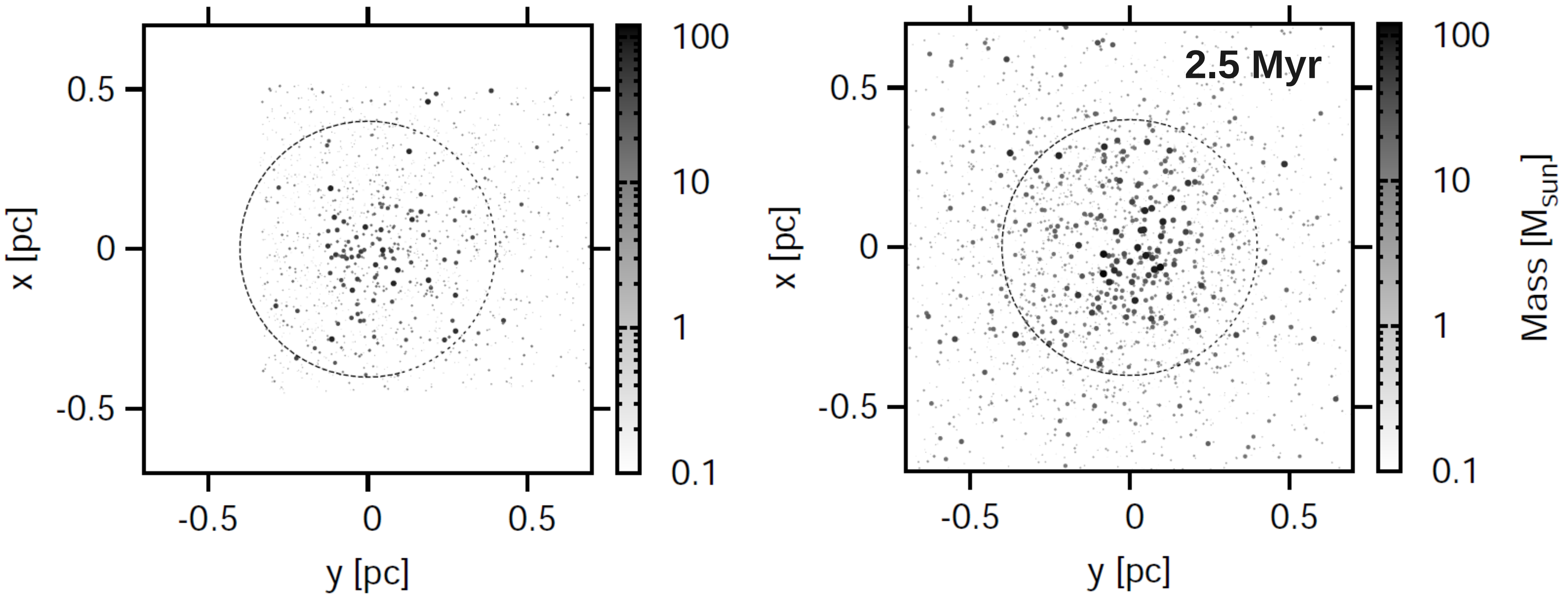
Dynamical evolution as a source for the slope variation

Arches full N-body simulations:

Constraining the initial conditions of cluster evolution

Harfst, Portegies Zwart & Stolte 2010 & in prep

220 massive stars: **observed** **simulated**



Conclusion:

*Dynamical evolution can produce a flattened present-day MF from a standard Salpeter/Kroupa **initial** mass function.*

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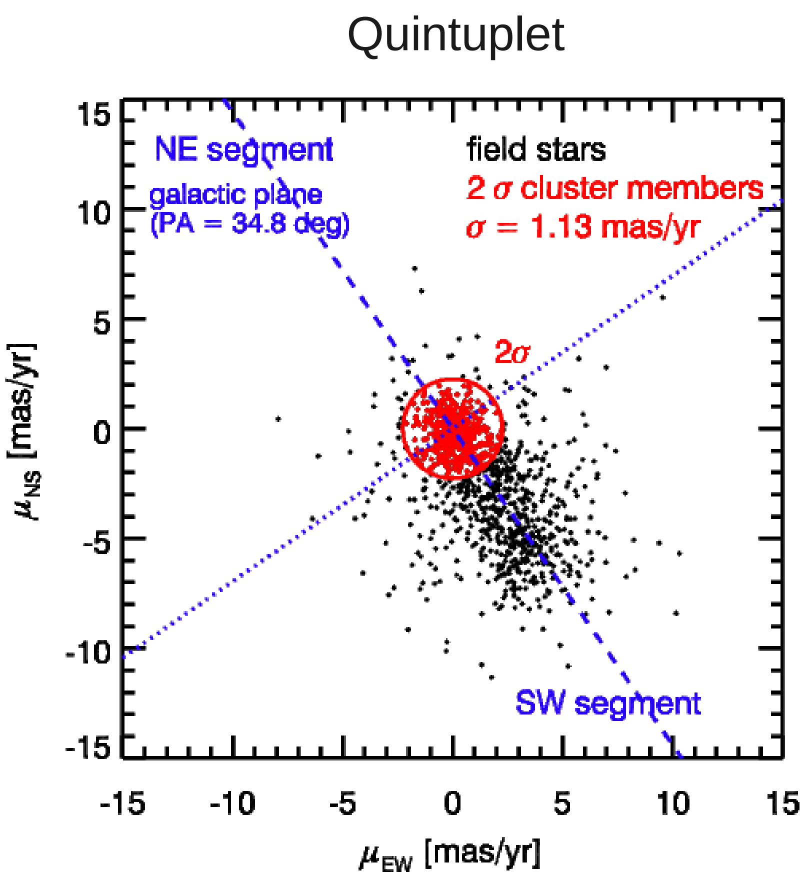
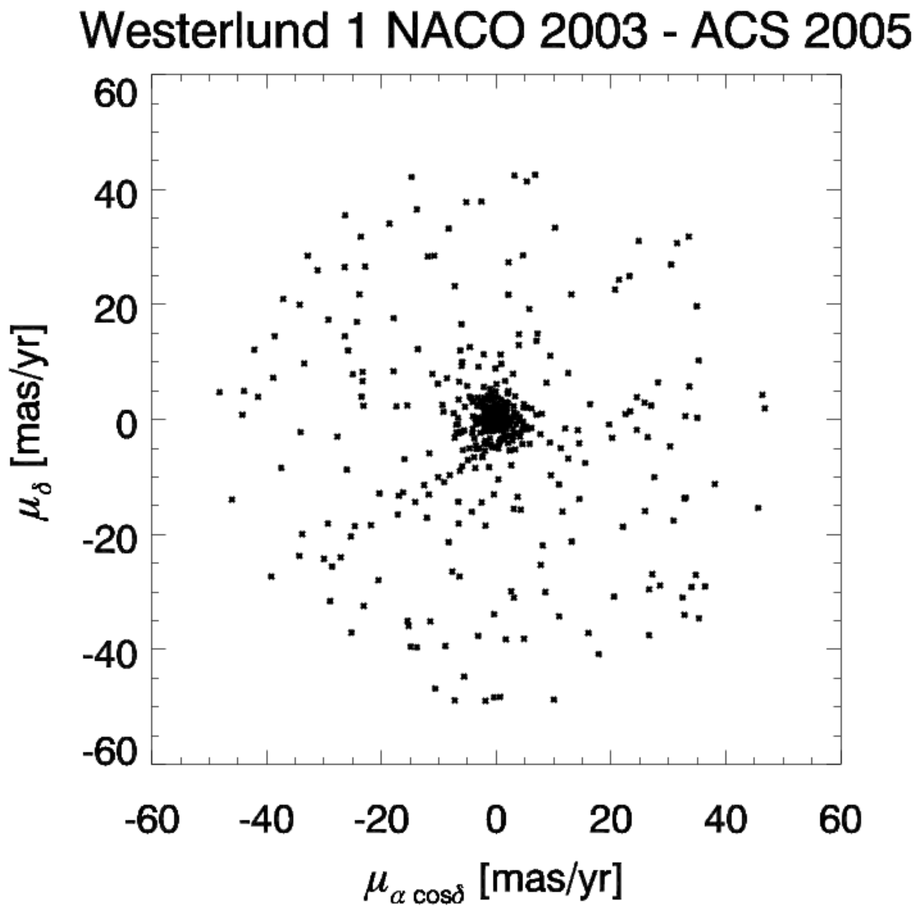
Proper motion studies: internal velocity dispersion & dynamical mass

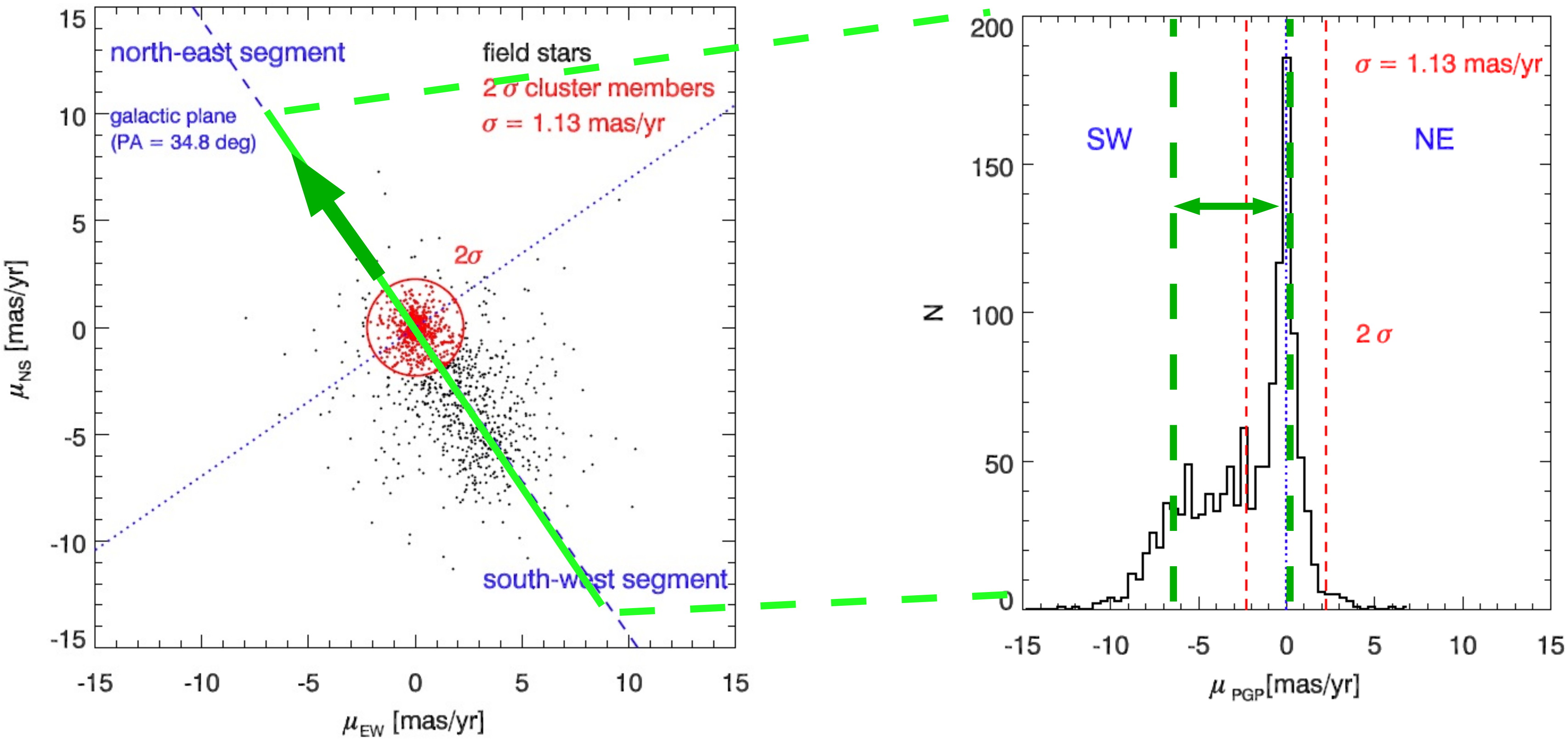




Proper motion along the Galactic plane:
Galactic center clusters display motion relative to their field

Proper motion with the spiral arm pattern:
Spiral arm clusters do not display relative motion wrt the field

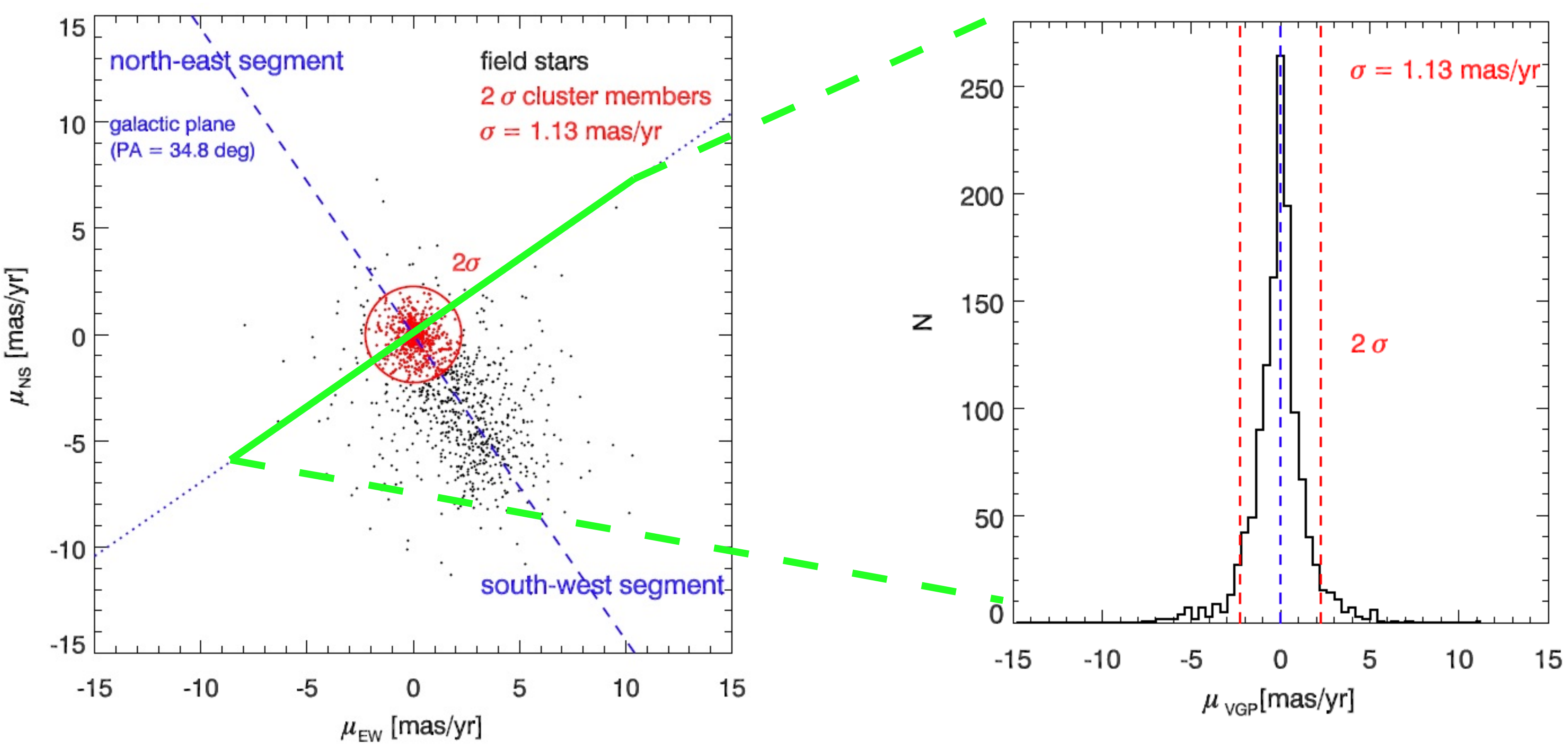
Proper motion studies: internal velocity dispersion & dynamical mass



Proper motion along the Galactic plane:

Absolute 2D orbital motion

Proper motion studies: internal velocity dispersion & dynamical mass

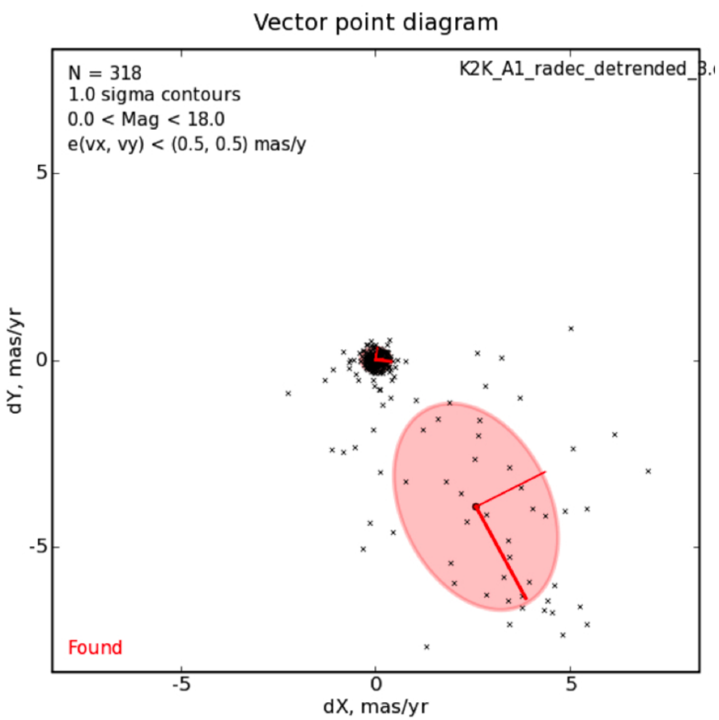


Proper motion *dispersion* perpendicular to the Galactic plane:

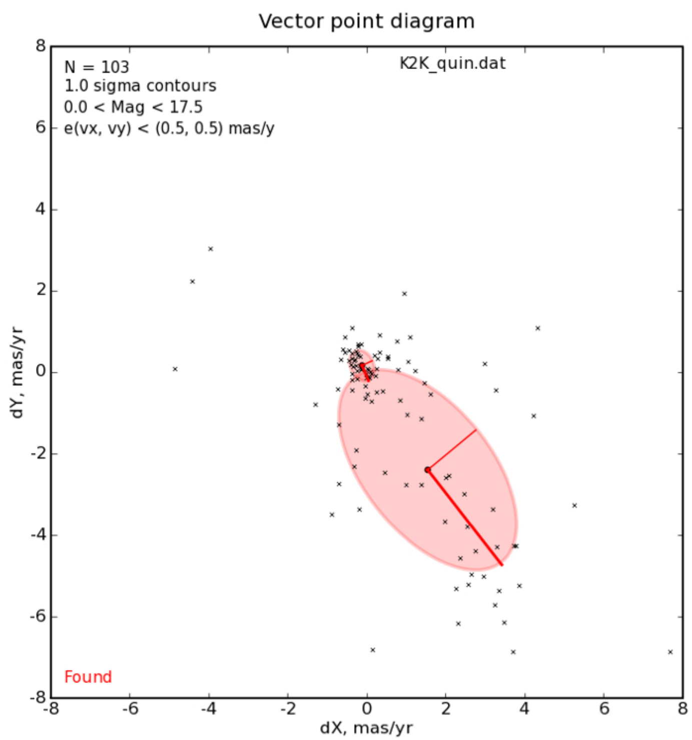
Internal velocity dispersion

Proper motion studies: internal velocity dispersion & dynamical mass

Arches



Quintuplet



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

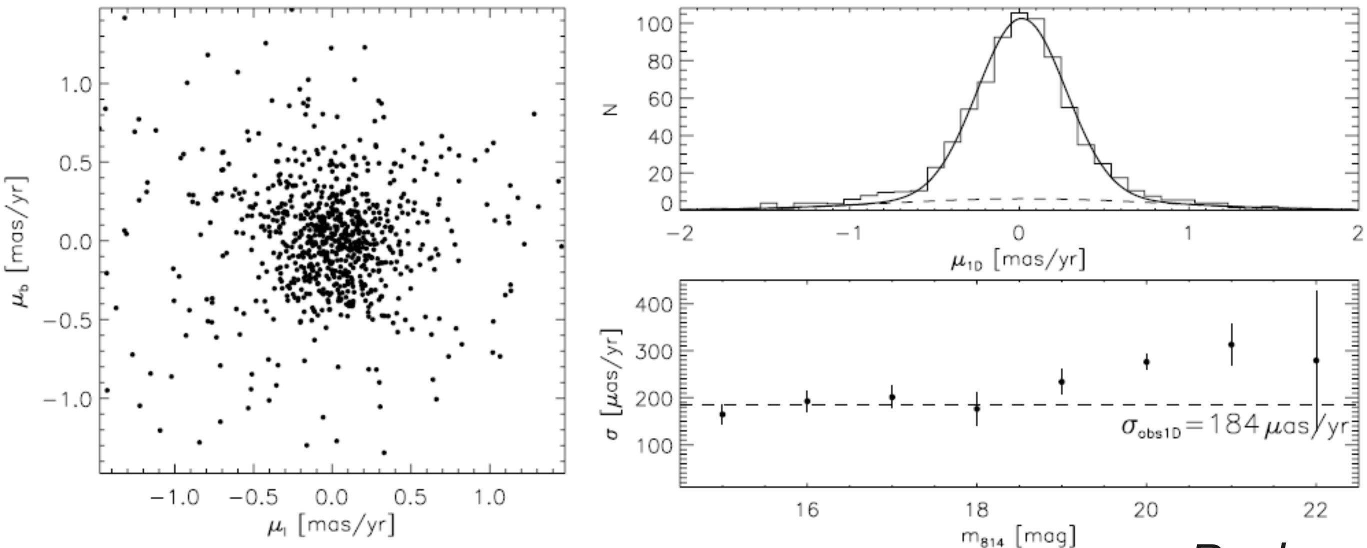
	Arches	**Quintuplet**
Internal velocity dispersion	5.4 +- 0.4 km/s	~5.6 km/s

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

Proper motion studies: internal velocity dispersion & dynamical mass

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

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

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

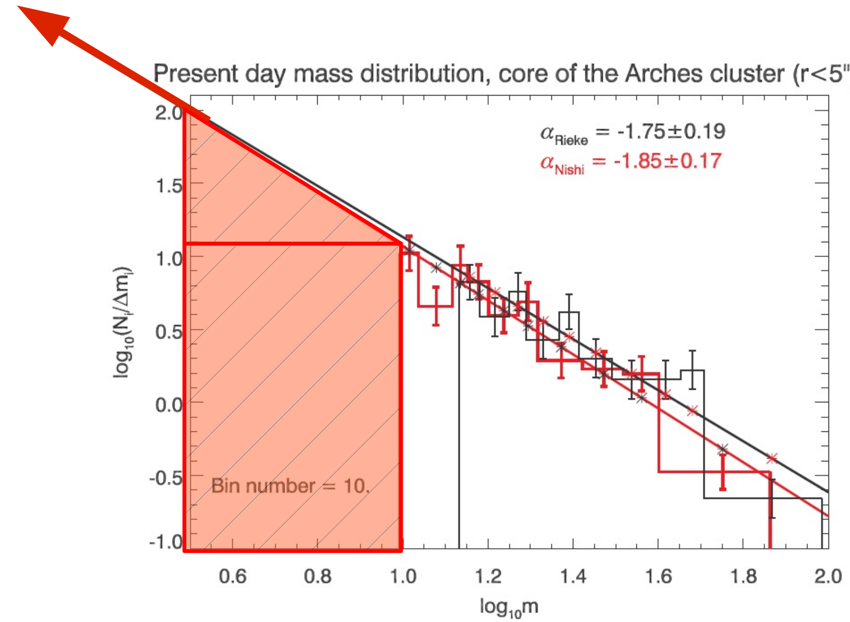
Westerlund 1

r_{hm} ~ 0.7 – 1.5 pc

Arches

r_{hm} = 0.4 pc

The photometric mass is derived from the extrapolation of the present-day mass function.



Assumptions:

- the slope of the mass function continues into the low-mass regime
- lower mass limit:

  typically 0.5 Msun

  in log space -0.30
- measured mass range:

  ranges from M > 1 Msun (spiral arm clusters)

  to M > 10 Msun (GC clusters)

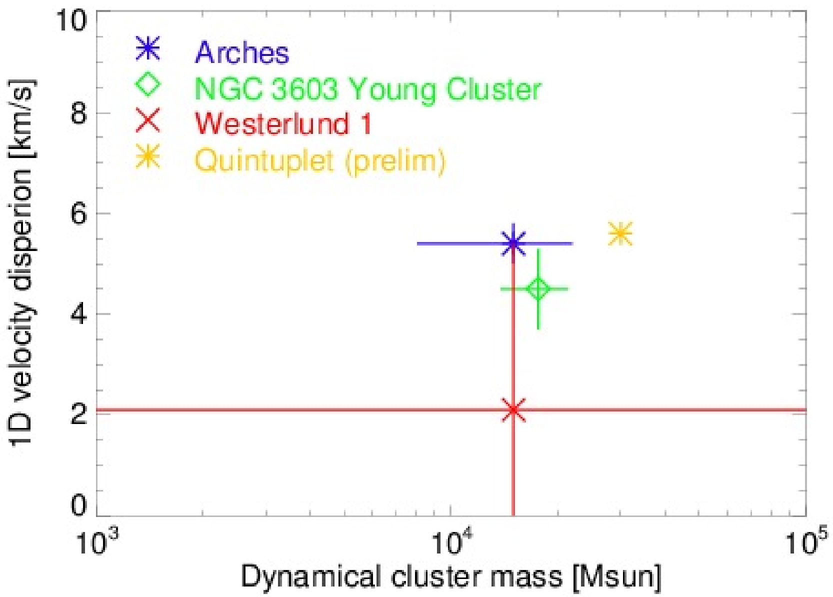
=> extrapolation to 0.5 Msun is a dramatic assumption!

Implicitely, it is also assumed that

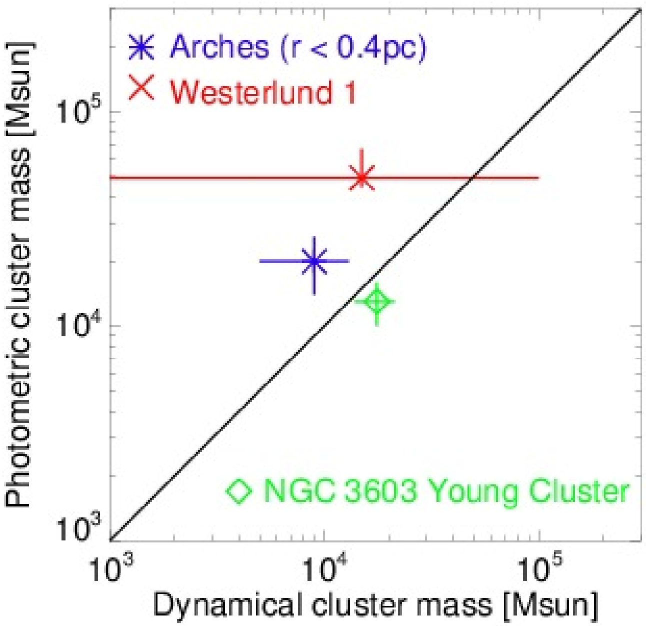
- the isochrone is correctly representing stellar evolution for all masses
- the cluster age is correct
- the metallicity is known (for starbursts: solar)

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

Internal velocity dispersion:

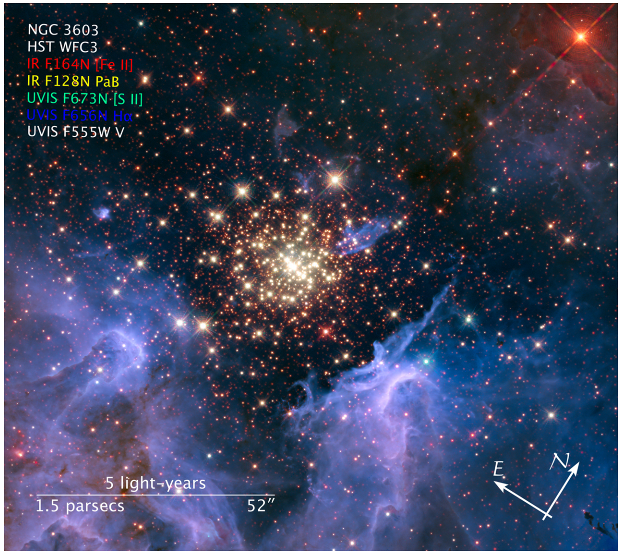


Dynamical vs photometric mass:

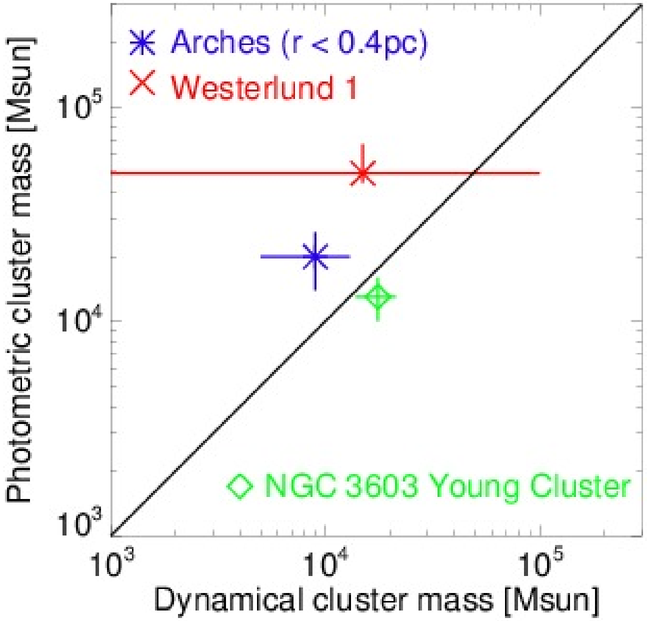


Velocity dispersions of a few km/s are consistent with virial expectations.

NGC 3603



Dynamical vs photometric mass:



NGC 3603 (spiral arm):

- dynamical and photometric mass are consistent

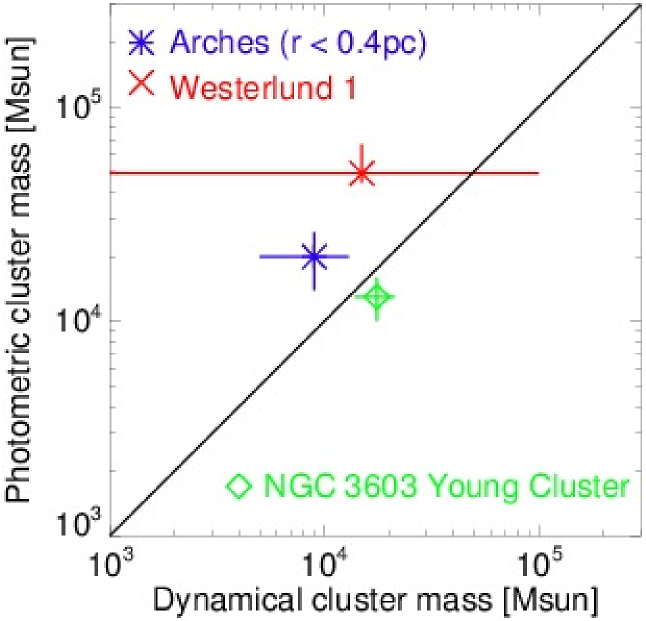
=> NGC 3603 YC is likely in virial equilibrium

=> NGC 3603 YC is dynamically stable, slowly evaporating, and likely long-lived

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

Arches

Dynamical vs photometric mass:



Arches (Galactic center):

- M_{dyn} is significantly lower than M_{phot}

  0.9 +/- 0.4 x 10^4 Msun vs 2-3 x 10^4 Msun (r < 0.4 pc)

  for an extrapolated Salpeter MF!

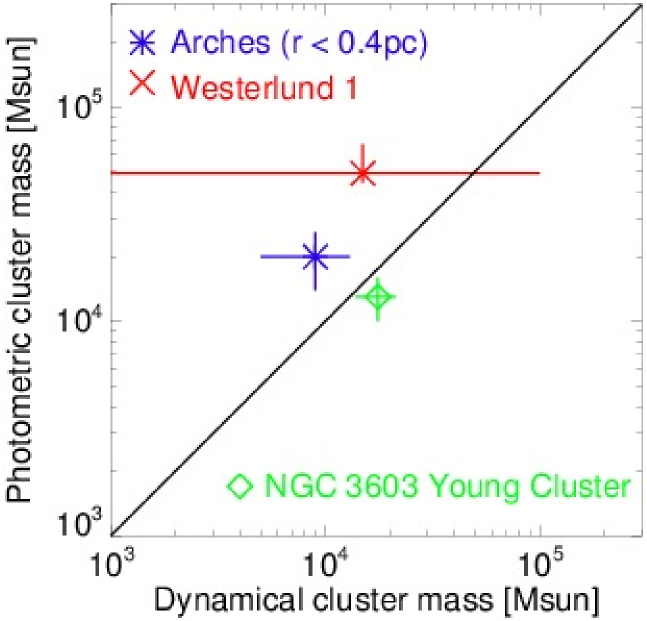
- a flat MF with α = -1.6 instead of -2.3 yields

  M_{phot} = 1-1.2 x 10^4 Msun

Velocity dispersions of a few km/s are consistent with virial expectations – at least for spiral arm clusters.......

Arches

Dynamical vs photometric mass



Arches (Galactic center):

- M_{dyn} is consistent with a flat present-day mass function

  over the entire cluster area (which is NOT observed!)

- M_{dyn} would also be consistent with a truncated PDMF, e.g.

  where M_{low} > 1-2 Msun (which cannot be observed yet)

Summary Velocity Dispersions & Dynamical cluster masses

- Internal velocity dispersions in starburst clusters cover a range from

$$\sigma_{1D} \sim 2 – 6 \text{ km/s}$$

- NGC 3603 & Westerlund 1 (spiral arm clusters):
  – consistent with virialised systems
  – survival times up to Gyr

- Arches (Galactic center cluster):
  – dynamical mass lower than photometric estimate
  – the system appears “subvirial”
  – if in virial/dynamical equilibrium, this would indicate
    * either a top-heavy present-day MF
    * or a low-mass truncated PDMF
    * or the cluster is rotating

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 & Outlook
    Milky Way starbursts today.......

Age spreads in starburst clusters –

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

- Star formation processes can yield different age distributions:
  1. high-mass stars might form last and shut off further low-mass star formation
  2. high-mass stars might accrete more rapidly (accretion rate <=> mass)

     => early UV radiation might quench SF in the dense proto-cluster cores

     => many high-, few low-mass stars in cluster centers

     => primordial mass segregation, top-heavy IMF

- Large age spreads of up to 10 Myr are observed in nearby regions

ONC:	argued age spread up to 10 Myr		*Hillenbrand et al. 1997*
	2.2 Myr coeval or 1.5-3.5 Myr		*Reggiani et al. 2011*
LH95/LMC:		2-4 Myr	*Da Rio et al. 2010*
W3 Main:		2-3 Myr	*Bik et al. 2012*

Question: In the most massive clusters, where feedback by high-mass stars dominates, do we observe evidence for age spreads?

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

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

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*

Simulations suggest that gas expulsion acts fast in dense, massive clusters, driven by the high-mass component *Baumgardt et al. 2008*

=> Star formation is instantly interrupted at ignition of most massive stars

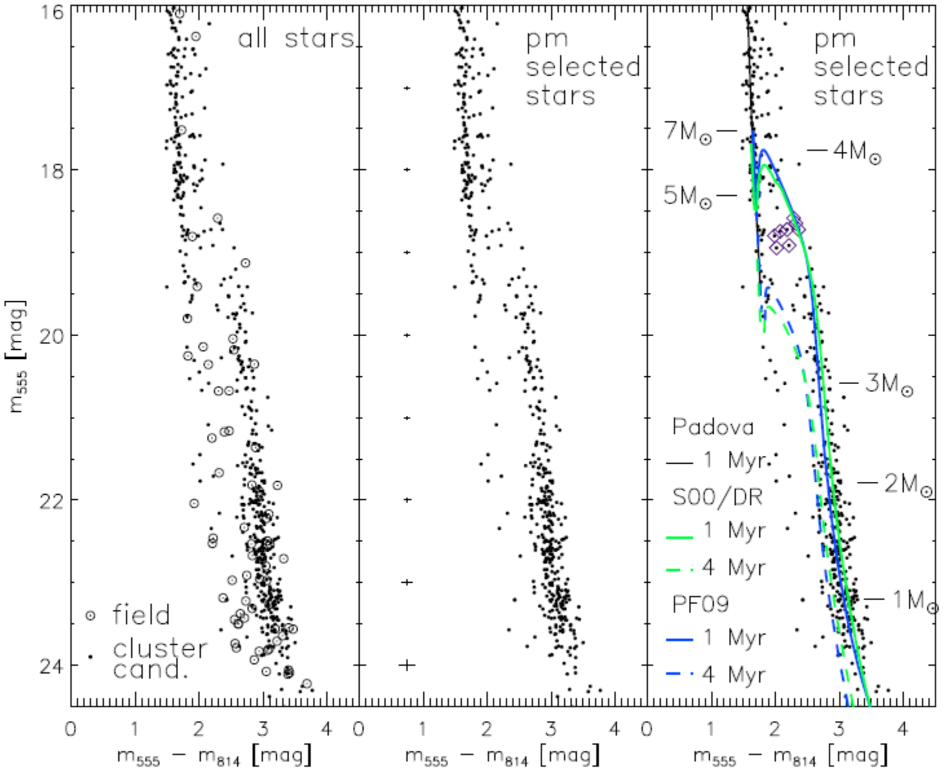
=> Star formation timescales might be different in starburst environments

Evidence for age spreads in & around 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

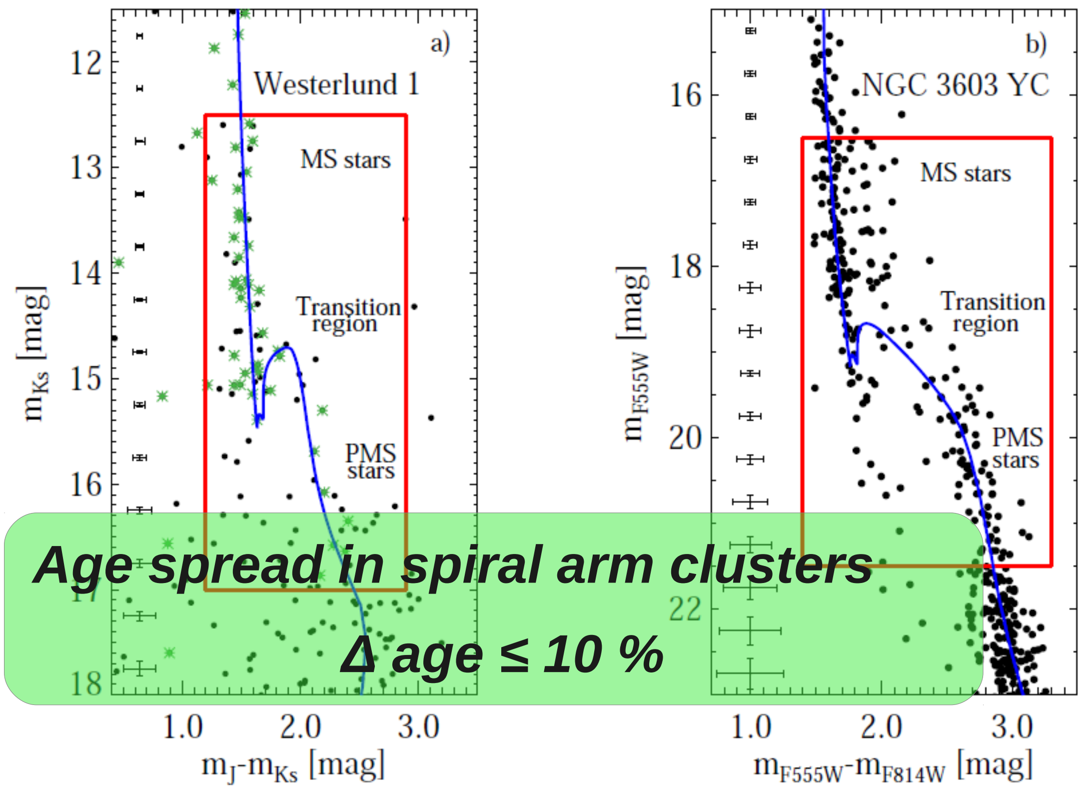
$$p\left(t \mid J_i, K_{si}\right)$$

- Global probability function

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

defines the age distribution

in each cluster



Age spread in spiral arm clusters

Δ age ≤ 10 %

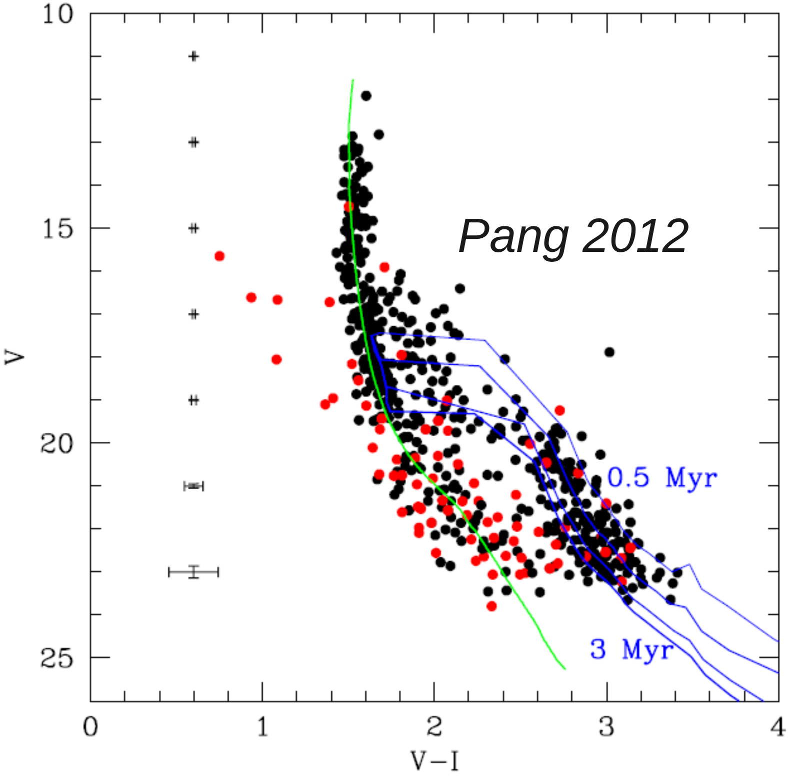
Kudryavtseva et al. 2012

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

Evidence for age spreads in the larger GMC environment

There is evidence for age spreads in the wider area around NGC 3603

NGC 3603



No Evidence for age spreads in the starburst cluster population

In the central starburst NGC 3603 YC Δ age $\leq$ 0.1 Myr

Constraining the age spread:

- grid of isochrones with

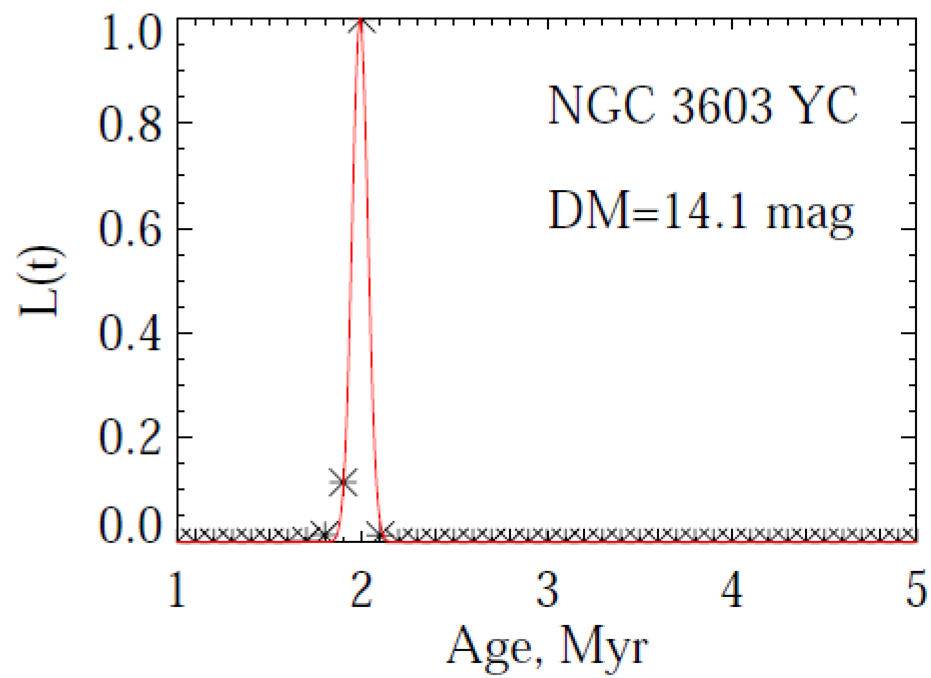
  Δ age = 0.1 Myr
- Likelyhood for each star to
  - have a certain age
  - be a cluster member

$$p(t|J_i, K_{si})$$

- Global probability function

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

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:

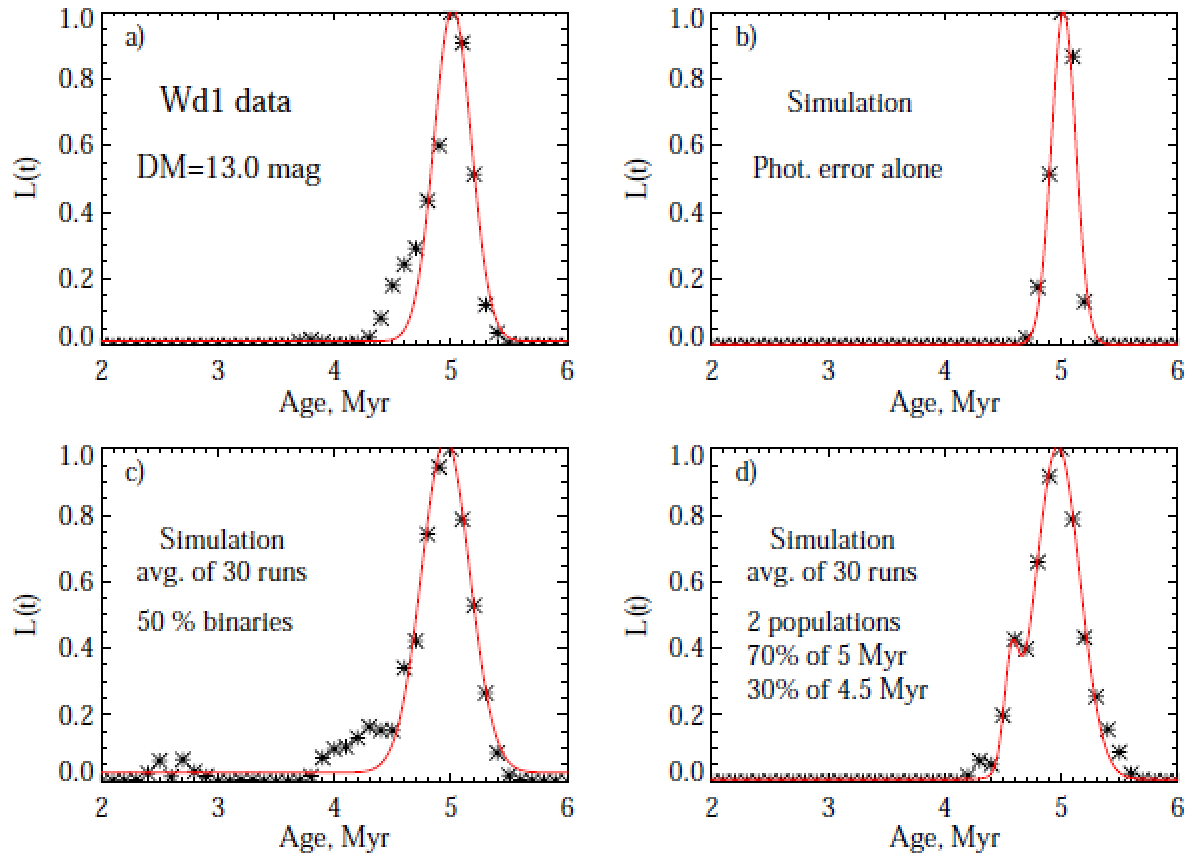
- grid of isochrones with

  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

Age spreads in starburst clusters –

*are young, massive clusters really “star**bursts**” ?*

Spiral arm clusters NGC 3603 YC & Westerlund 1
reveal ages and age spreads of

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

=> ***Age spread in spiral arm clusters*** ***Δ age ≤ 10 %***

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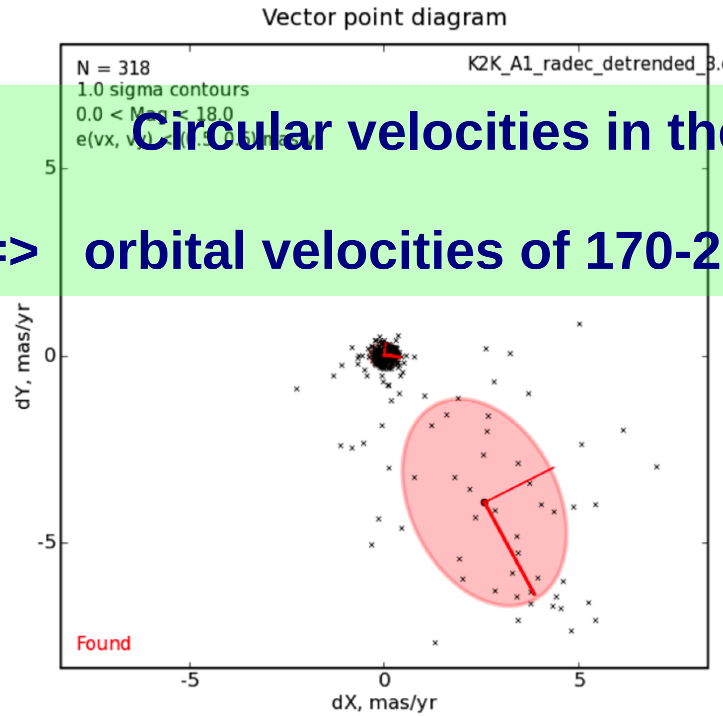
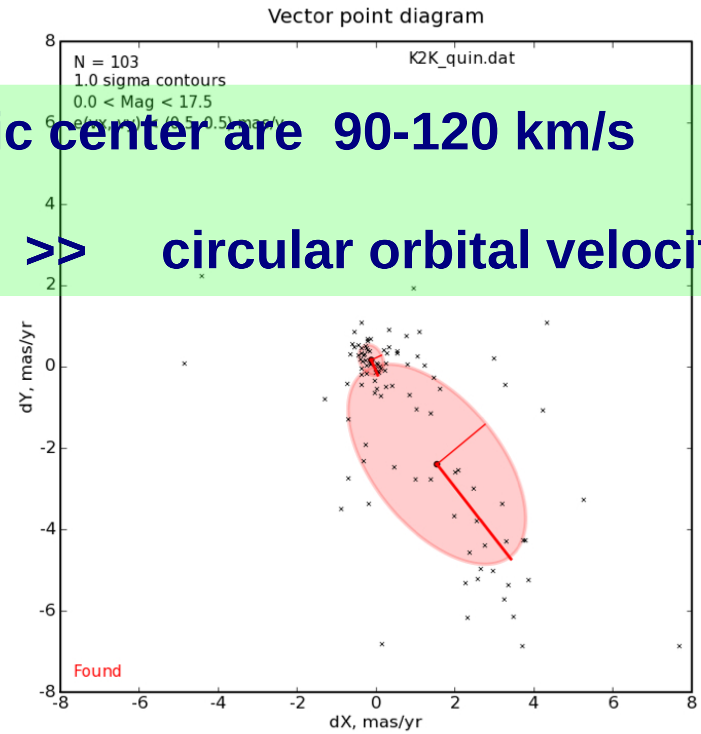
Proper motion studies: internal velocity dispersion & dynamical mass

Arches / *Quintuplet*





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

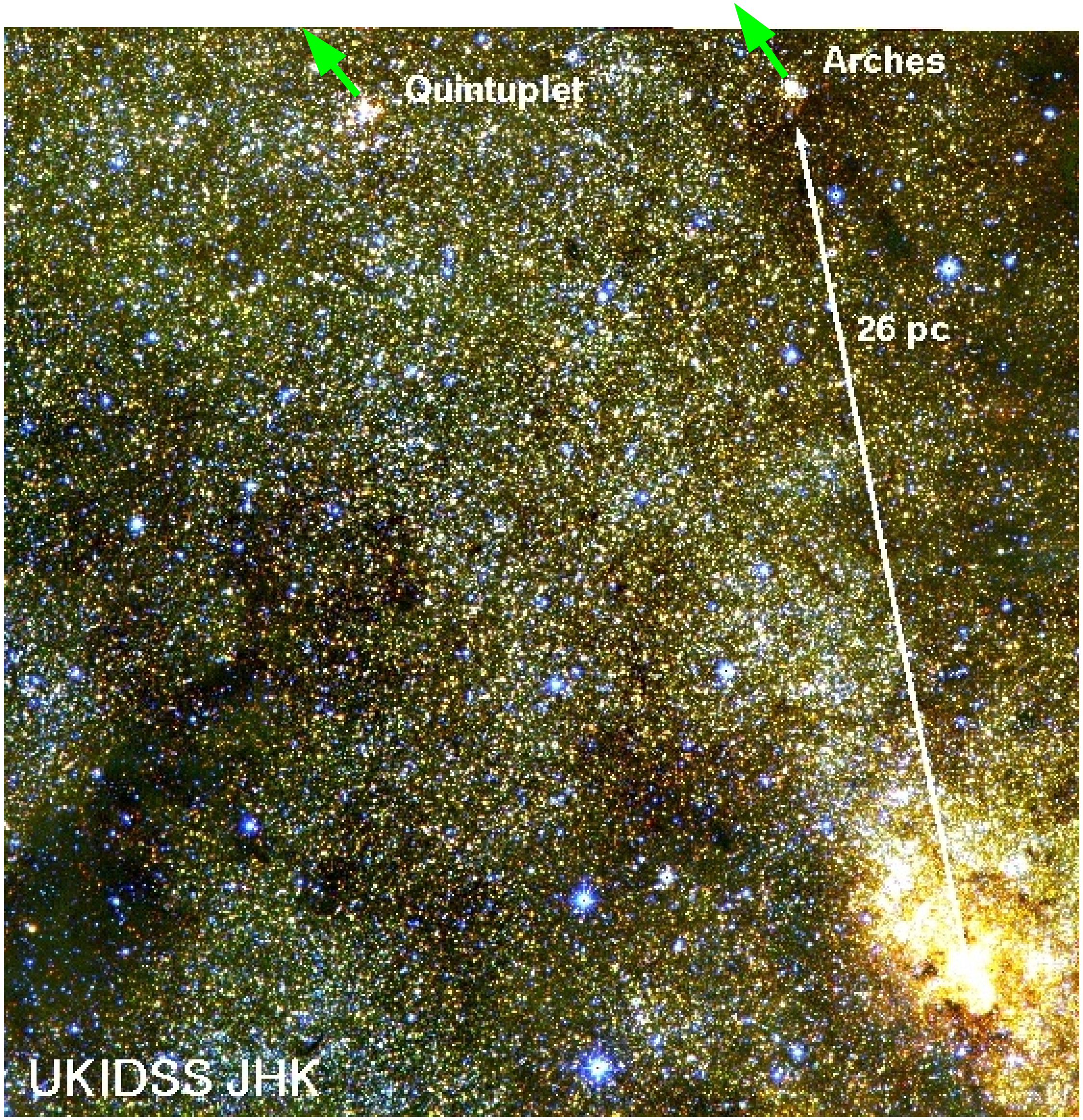
=> orbital velocities of 170-200 km/s >> circular orbital velocities

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

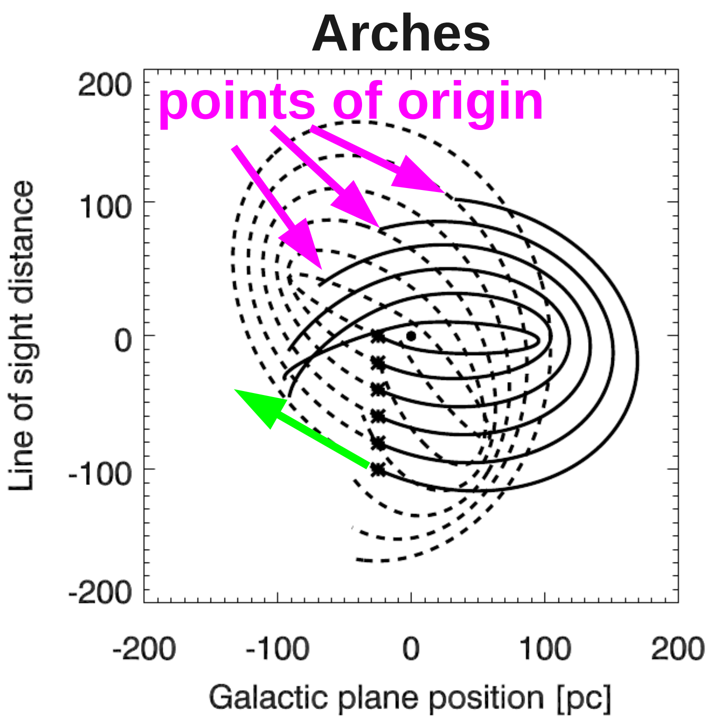
	Arches	**Quintuplet**	
2D orbital motion	172 +- 15 km/s	106 +- 50 km/s	
Radial velocity	95 km/s	130 km/s	*Figer et al. 2002, 1995*
3D orbital motion	196 km/s	167 km/s	

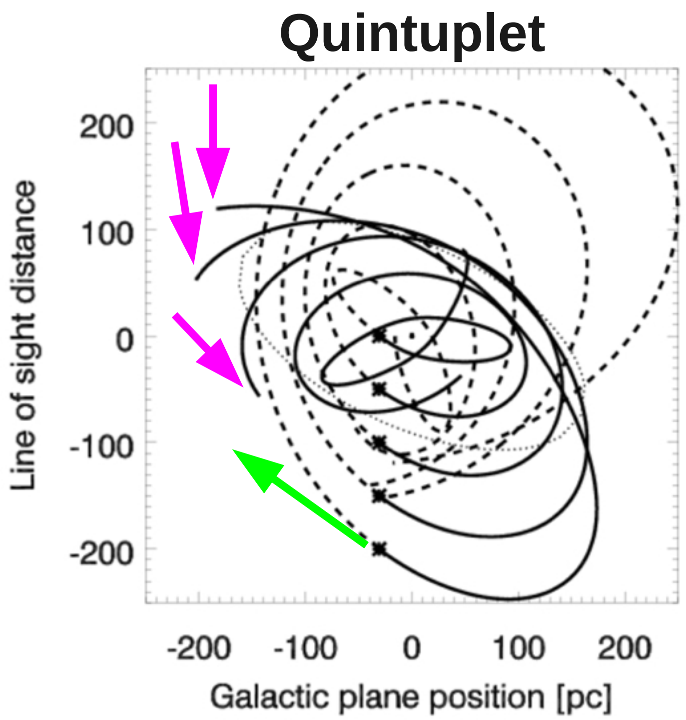
Clarkson et al. 2012, Stolte et al. In prep

Non-circular orbits in the Galactic center potential



Non-circular orbits in the Galactic center potential





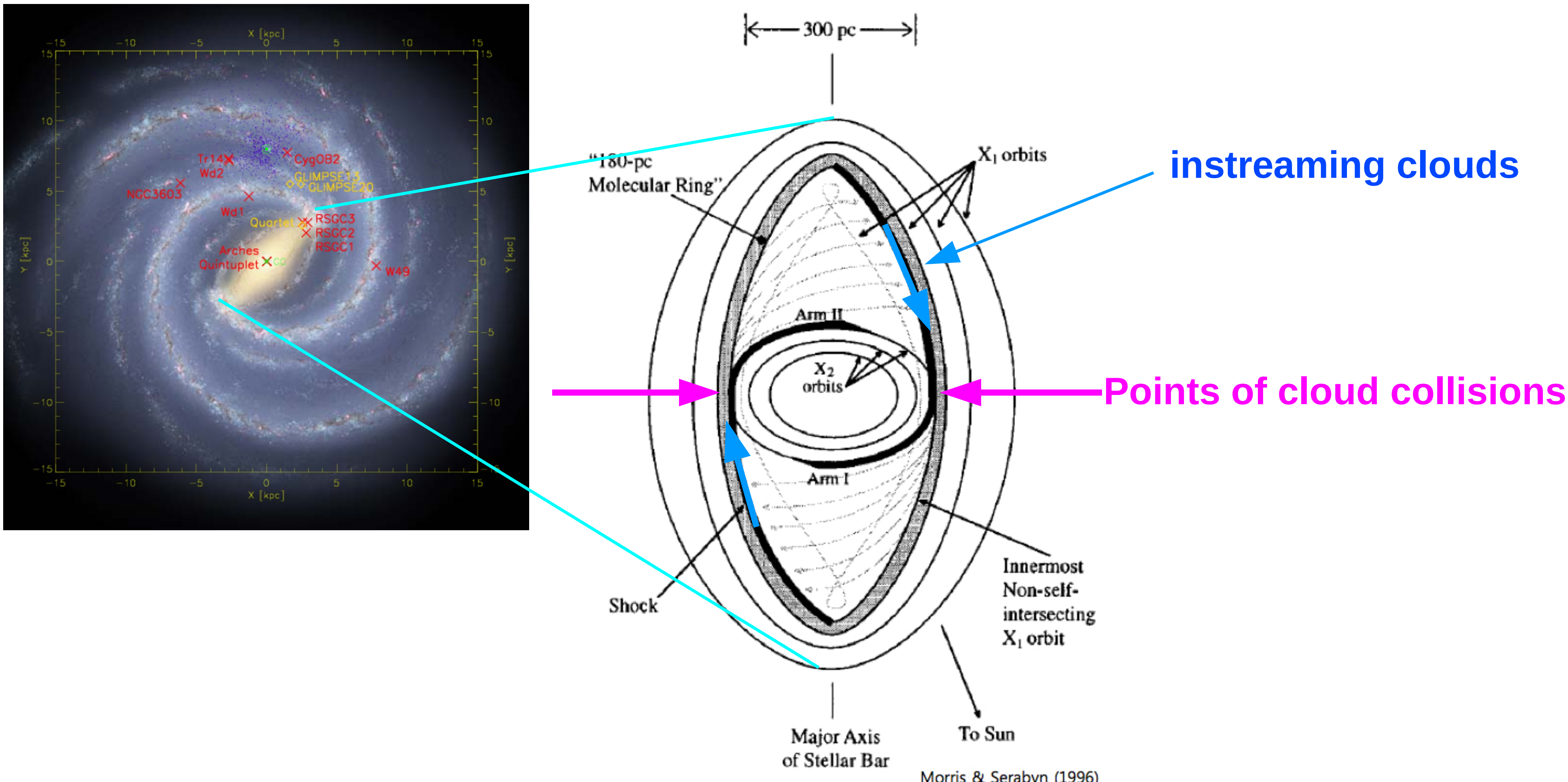
3D orbital velocity 196 +/- 20 km/s **167 +- 50 km/s**

Stolte et al. 2008, Clarkson et al. 2012 *Stolte et al., in prep*

Have both clusters emerged at a similar point of origin?

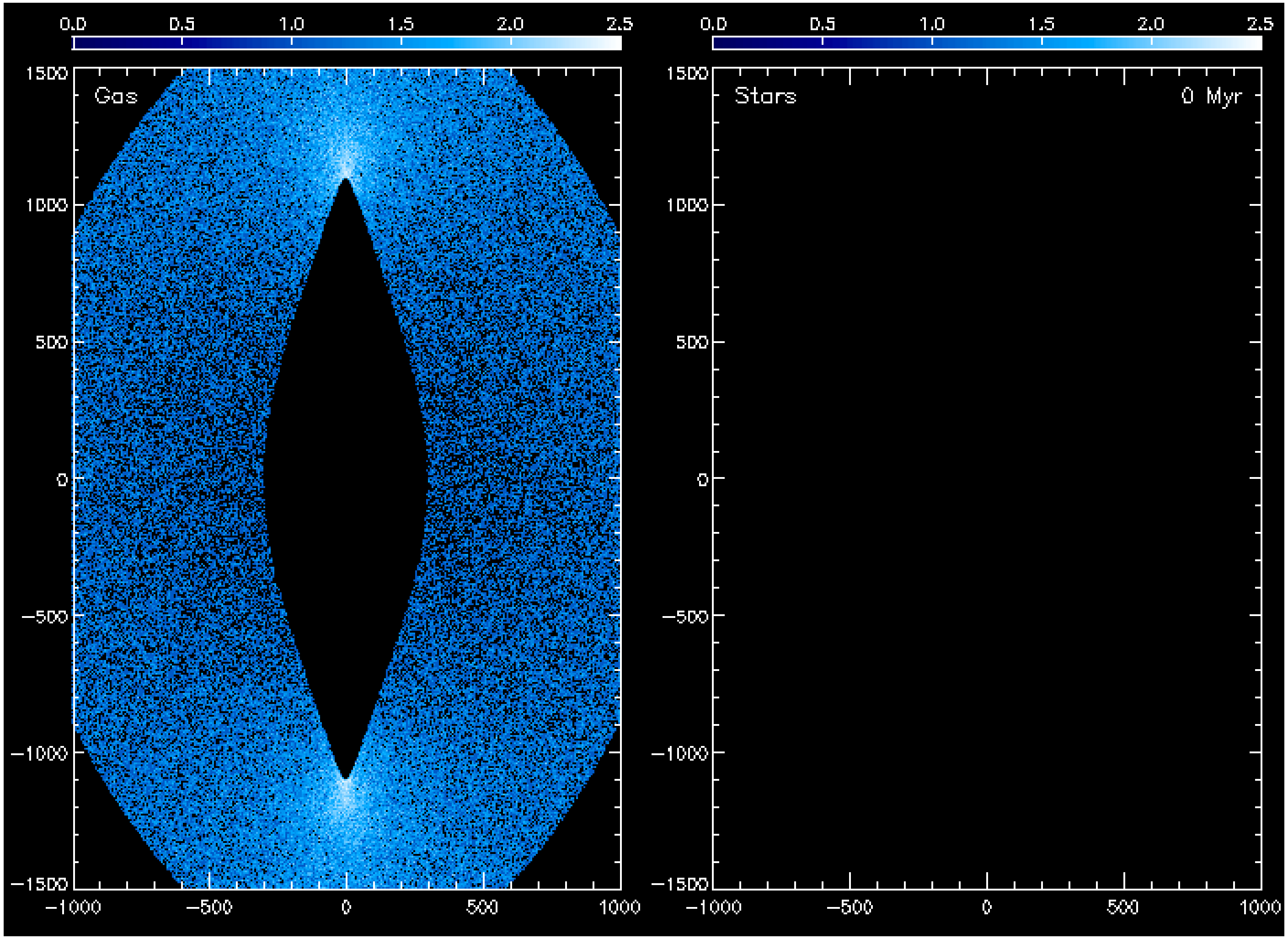
Could there be a common origin of the Arches & Quintuplet?

Stable classes of orbits in the bar potential:



Morris & Serabyn 1996

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

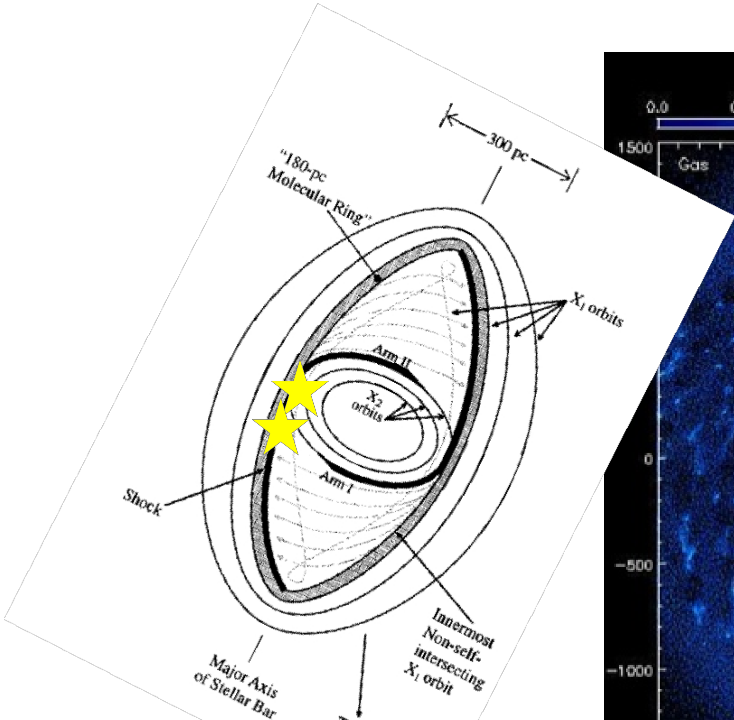


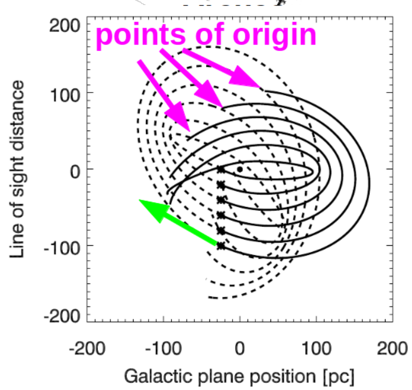
Kim et al. 2011

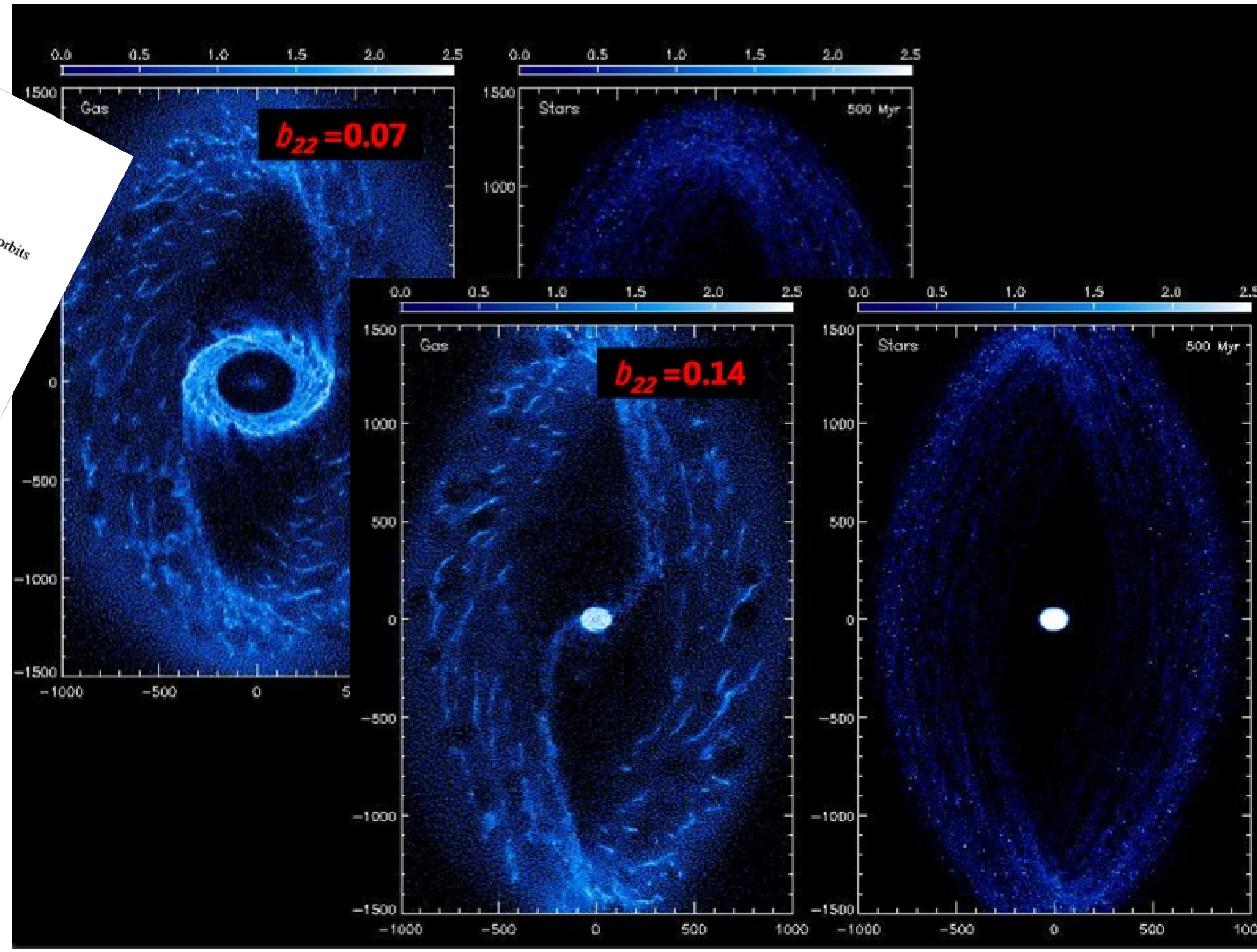
3D simulations by Kim et al suggest infalling gas forms clusters

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

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

Velocity dispersion & mass

Starburst clusters are (close to) virial

Spiral arm clusters are consistent with being in virial equilibrium

Arches in the Galactic center is subvirial, which implies

- either a MF defficient in low-mass stars
- or an extra energy sink (rotation?)

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)

Thank you very much for your attention!