Star clusters at the centre of the Galaxy -- their orbital motion and mysterious formation

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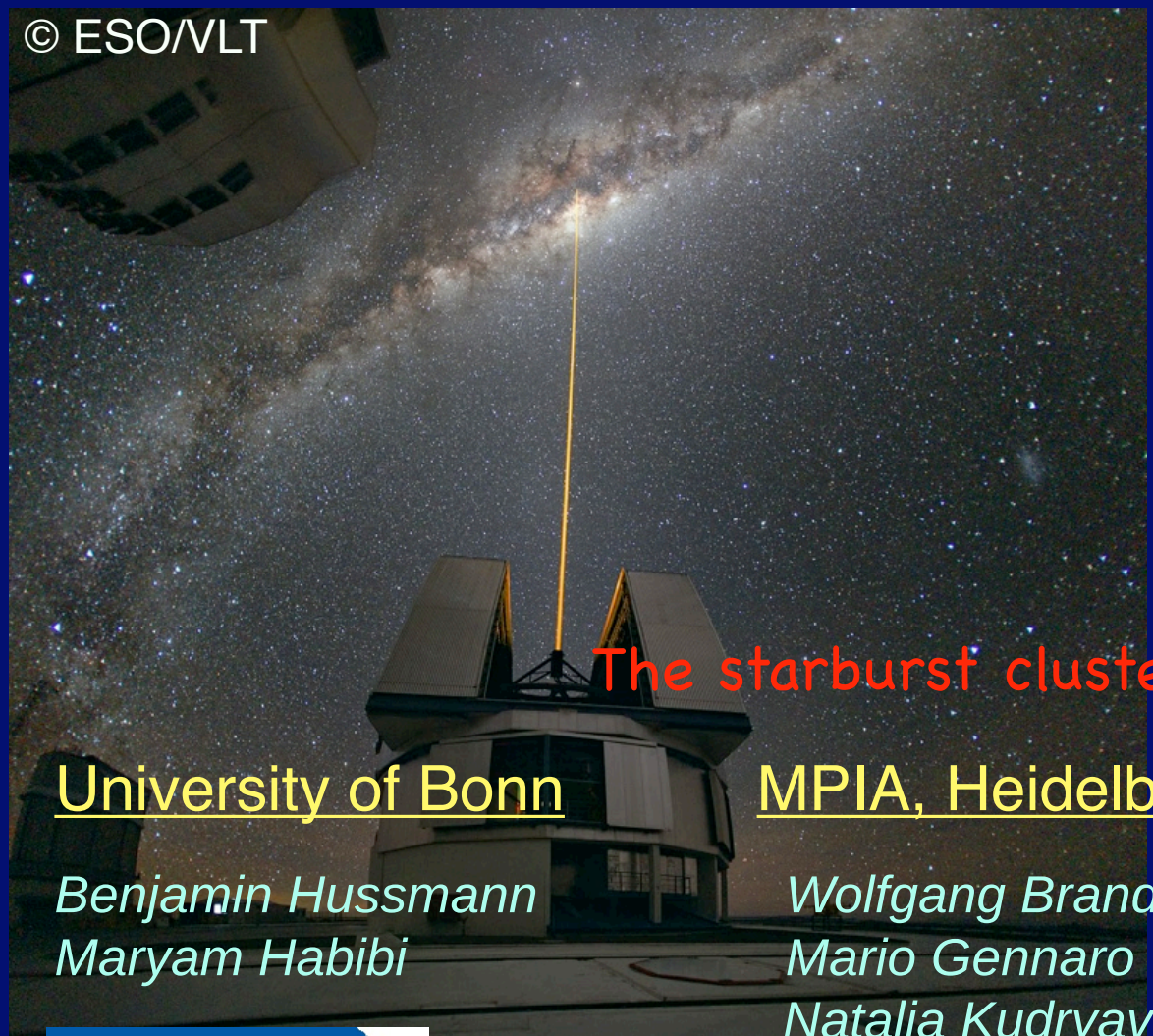
18. Novembre 2010

A dedicated high-precision proper motion survey of Milky Way starburst clusters



The starburst cluster connection

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Emmy Noether-Programm
Deutsche Forschungsgemeinschaft DFG

Star clusters at the centre of the Galaxy -- their orbital motion and mysterious formation

1. Starburst clusters in the Milky Way
2. The Galactic centre star formation environment
3. News from the Arches
   - the cluster orbital motion
   - cluster formation scenarios
4. The mystery deepens... the Quintuplet
5. Conclusion: A possible formation mechanism?

1. Starburst clusters in the Milky Way

Why do we care ?

Young, massive star clusters are special in the Milky Way

Only 6 clusters classified as "starburst" in the MW today

- most basic common property: *M(cl)* > 10^4 *Msun*
- cluster formation in *spiral arms vs. the "extreme" GC*
- only resolved sites with star formation over the *entire mass regime* up to 120-200 *Msun* (?)
- cluster *survival/disruption*

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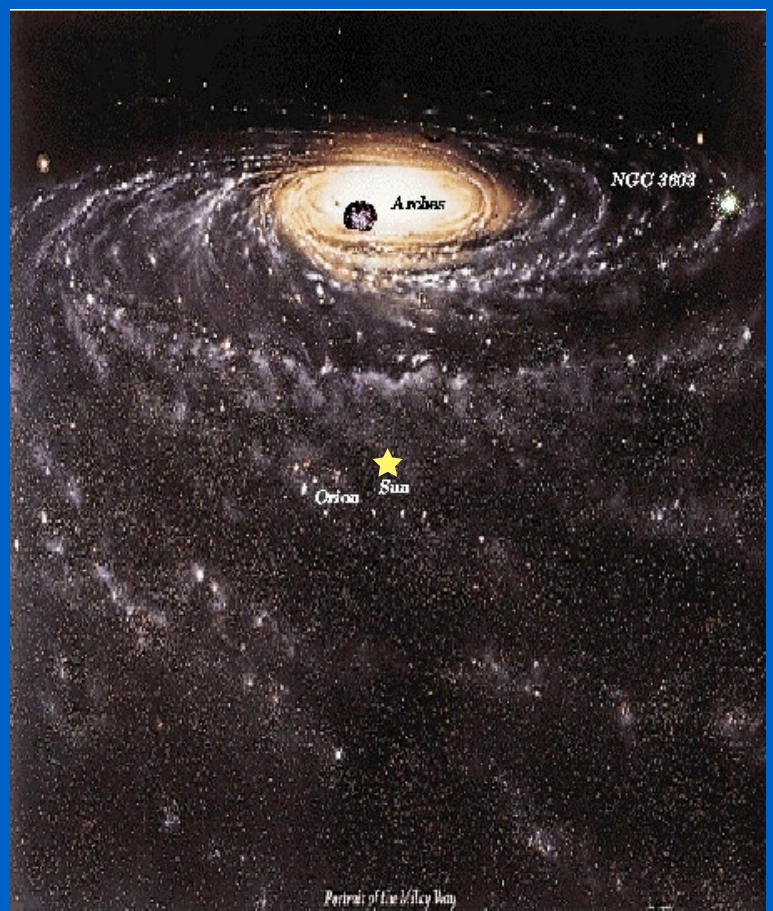
- cluster *survival/disruption*

The Galactic centre hosts 3 of the most massive young clusters in the Milky Way: Arches, Quintuplet, Young nuclear cluster

⇒ probe star formation in the *densest MW environment*

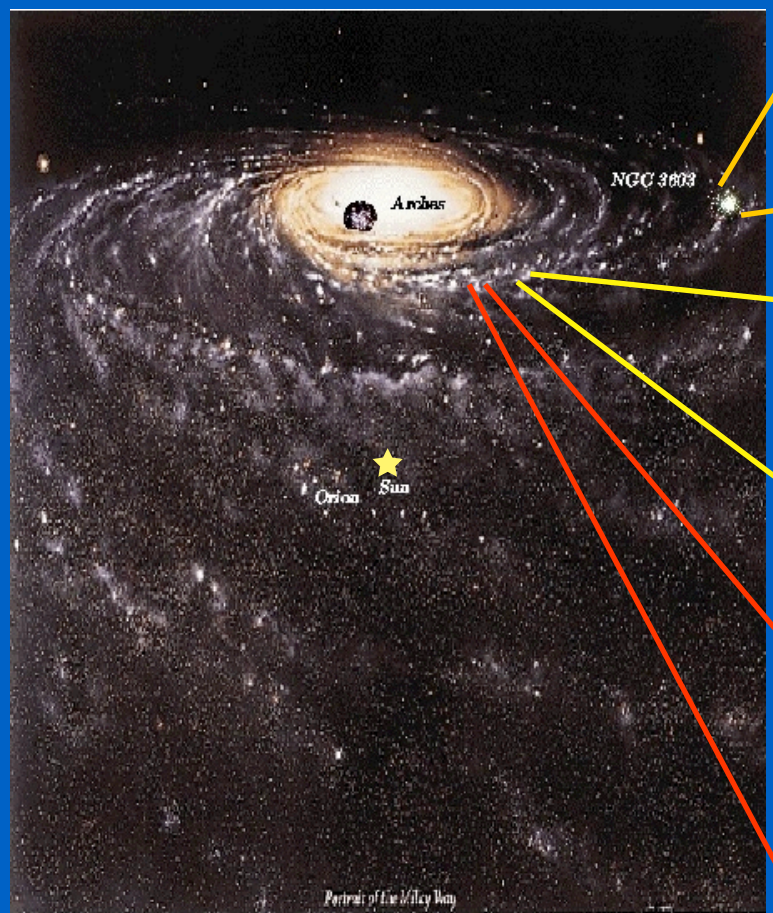
⇒ star formation in the *nuclei of distant spiral galaxies*

The Milky Way Starburst Cluster Zoo



Portrait of the Milky Way *Jon Lomberg*

The Milky Way Starburst Cluster Zoo



Portrait of the Milky Way *Jon Lomberg*

3'

NGC 3603 YC
Stolte et al. 2004

4'

Westerlund 1
Brandner et al. 2008

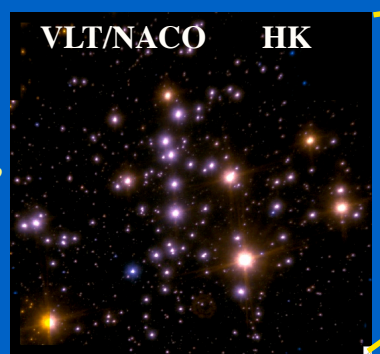
3.6'

Westerlund 2
Ascenso et al. 2007

The Milky Way Starburst Cluster Zoo

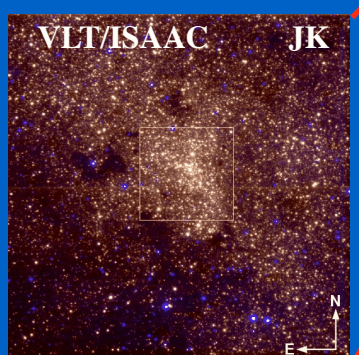
27”

GC Arches
Stolte et al. 2005



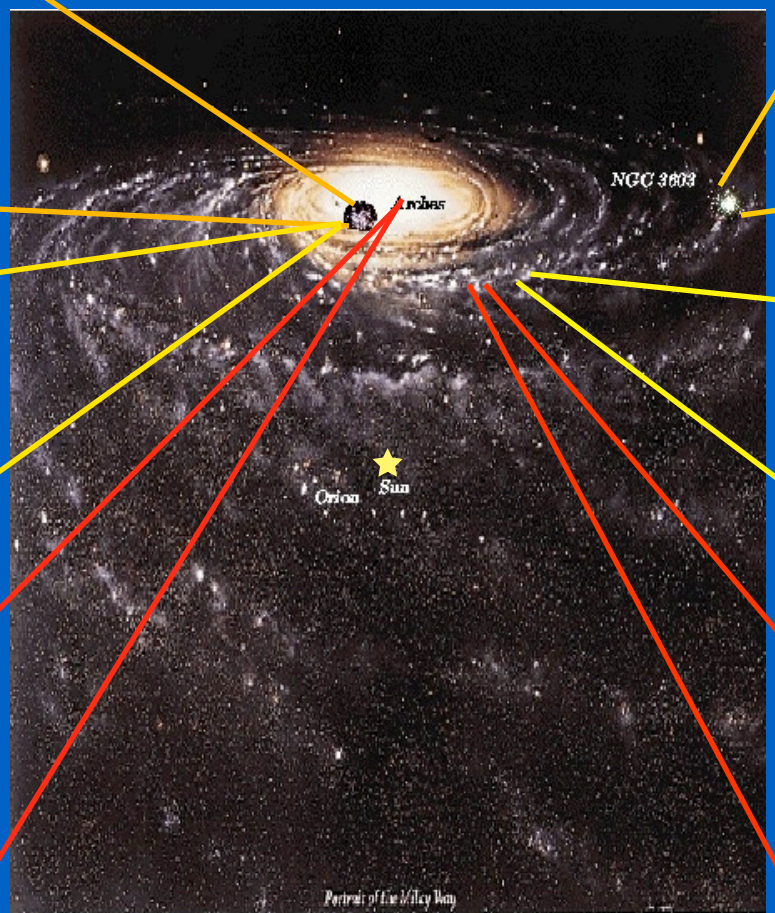
27”

GC Quintuplet
Stolte et al., in prep



2.5’

Nuclear cluster
Schoedel et al. 2007



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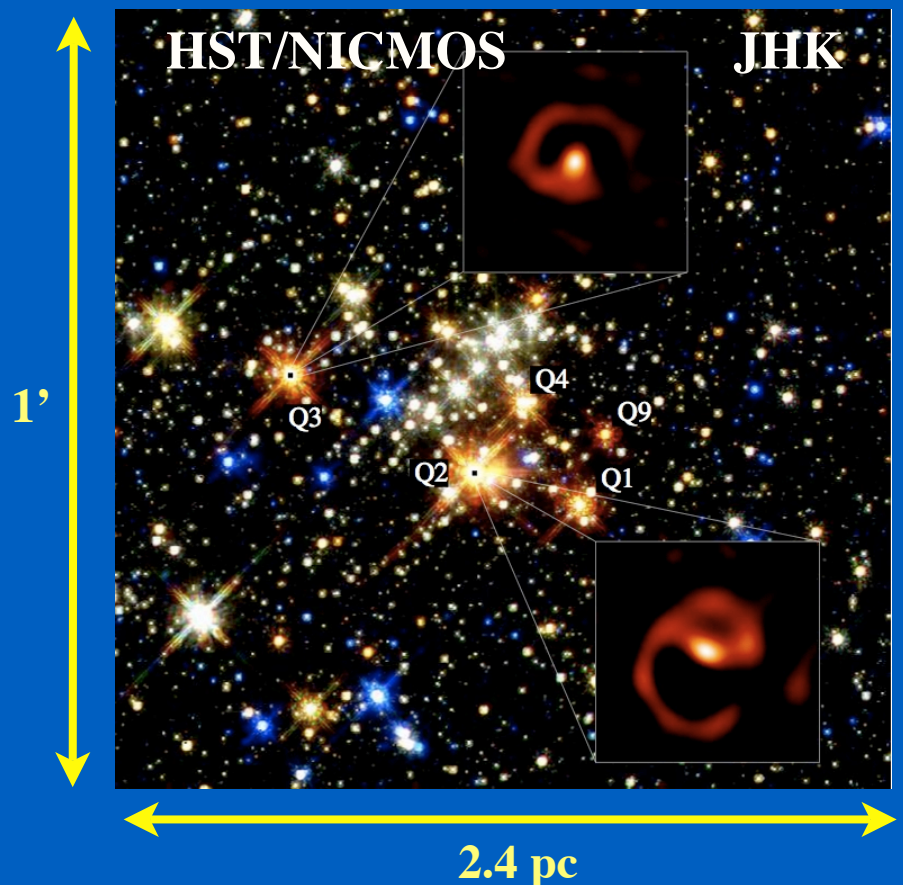
Quintuplet - a unique laboratory for high-mass stellar evolution



Tuthill et al. 2006

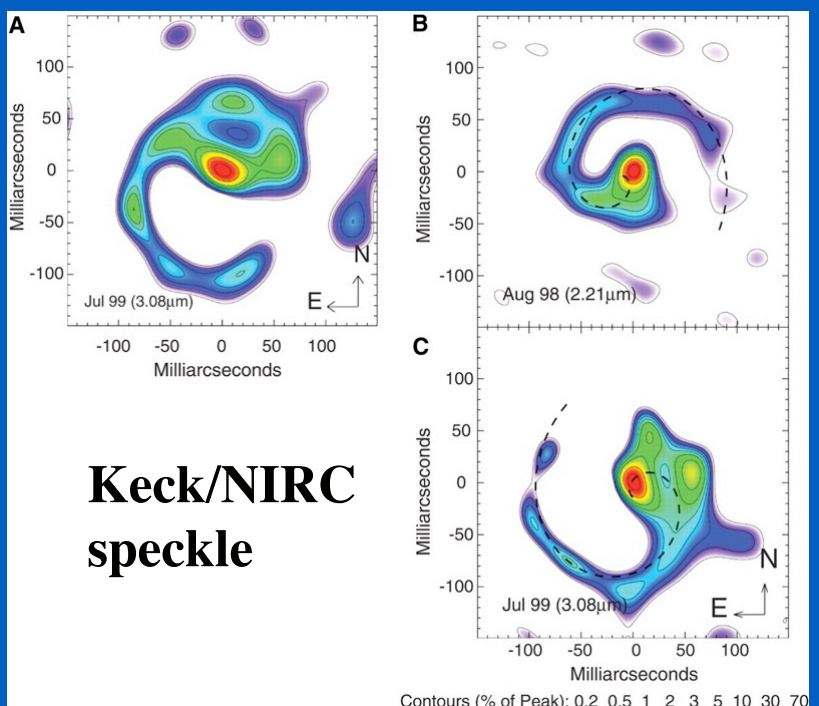
The cocoon stars:

- featureless MIR spectra

  not YSO, not late-type AGB/WC

  Moneti et al. 2001

- interacting wind binaries

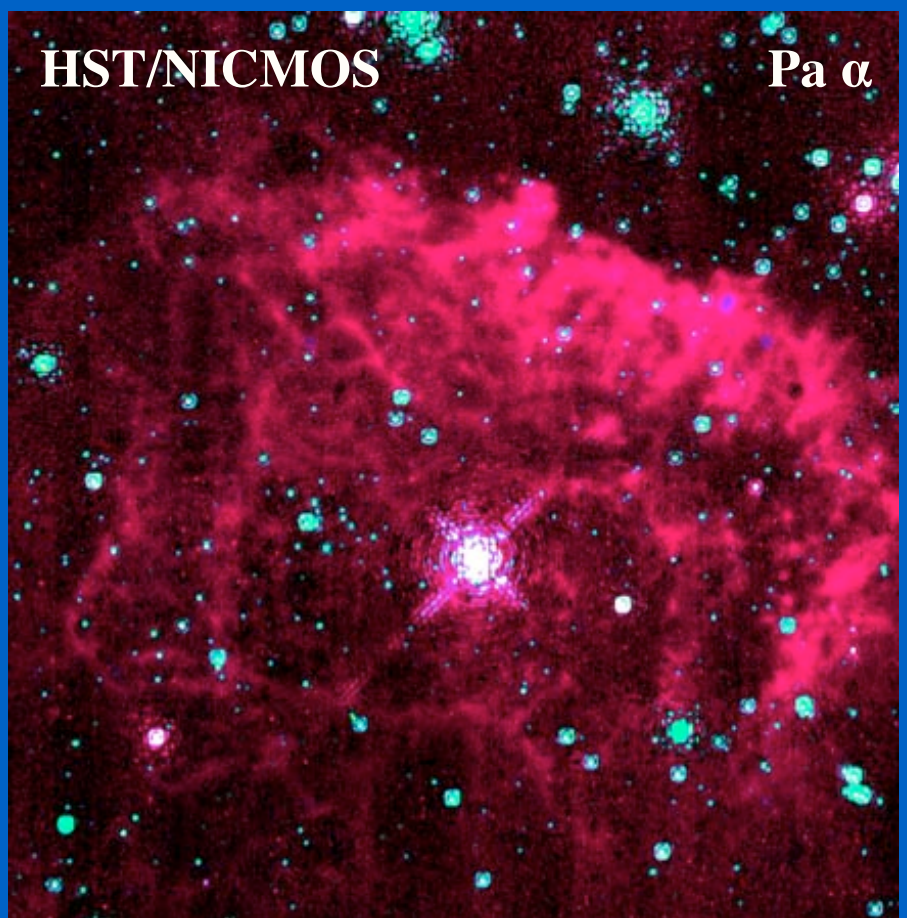


Keck/NIRC speckle

1 yr

Quintuplet - host of the most massive star in the Galaxy?

Pistol star



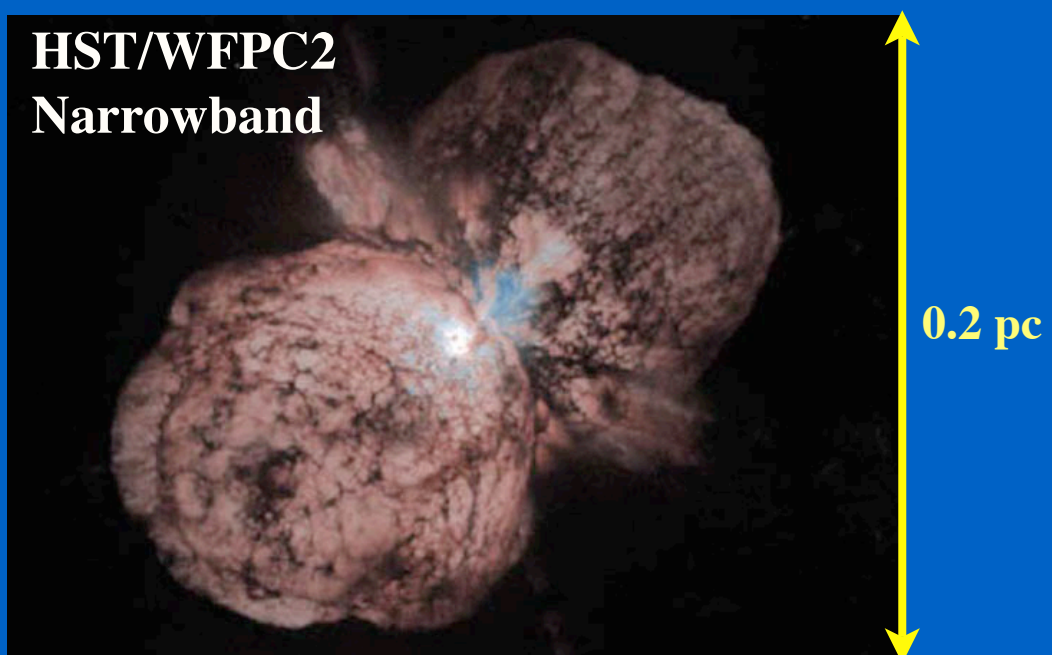
Figer et al. 1999, STScI, NASA

- LBV
- initial mass ~ 200 Msun

Yungelson et al. 2008

- age ~ 2 - 4 Myr *Figer et al. 1999*

eta Carinae



Morse, Davidson, STScI, NASA

Outstanding questions on GC starburst clusters

The most important GC starburst cluster characteristics are not well constrained

- **cluster mass extrapolated from high-mass *present-day* MF**
- **cluster extent virtually unconstrained**
- **internal velocity dispersion marginally constrained (but...)**
- **dynamical evolutionary state unknown (relaxation???)**

⇒ primordial vs. dynamical mass segregation cannot be distinguished

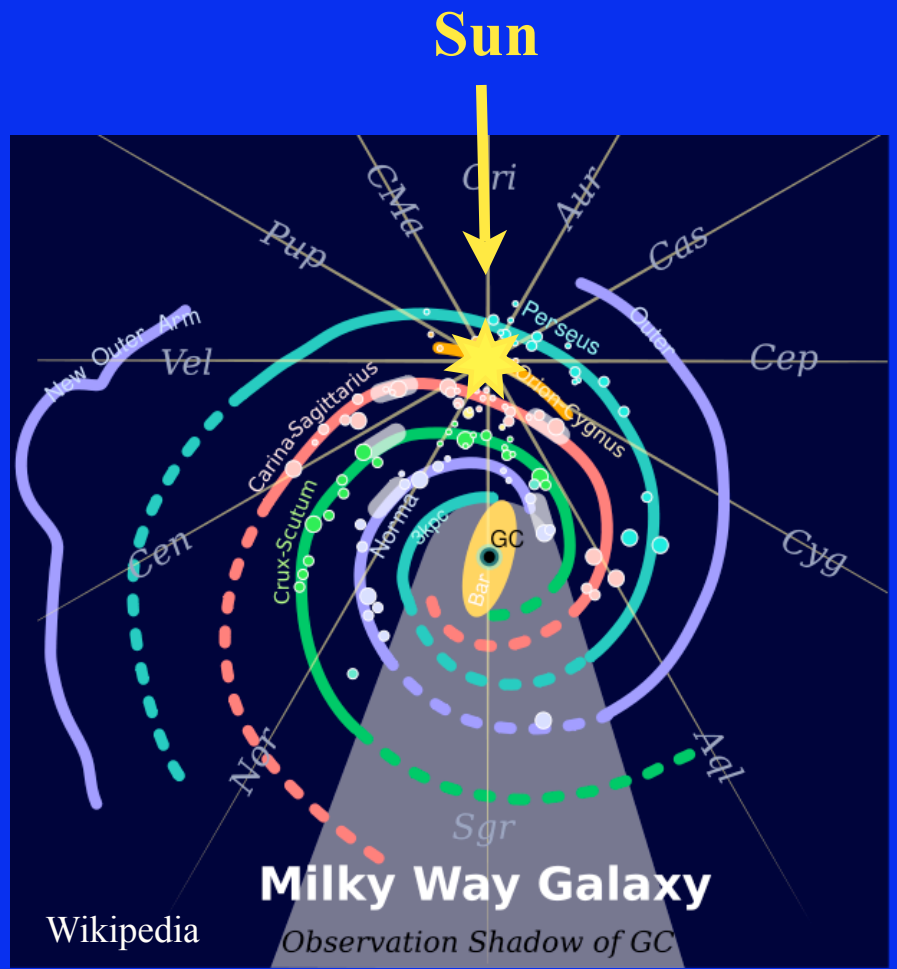
While the present-day mass function can be measured,

the stellar initial MF is unknown !!!

2. The GC star formation environment - near and far from the black hole

Why so special ?

From spiral arms to the center of the Milky Way



Milky Way Bar

Binney et al. 1991

Englmaier & Gerhard 1999

Bissantz et al. 2003

Rattenbury et al. 2007

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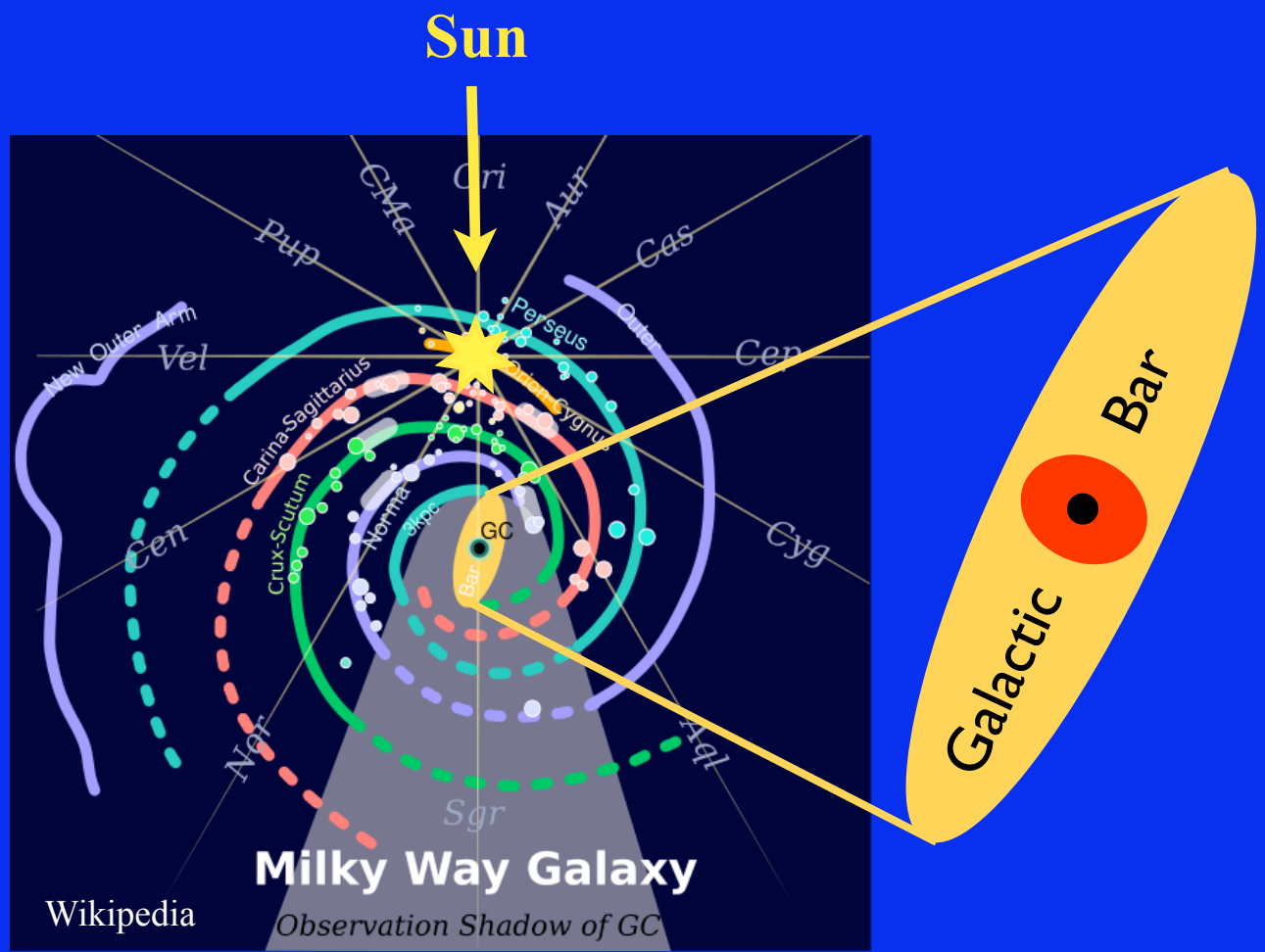

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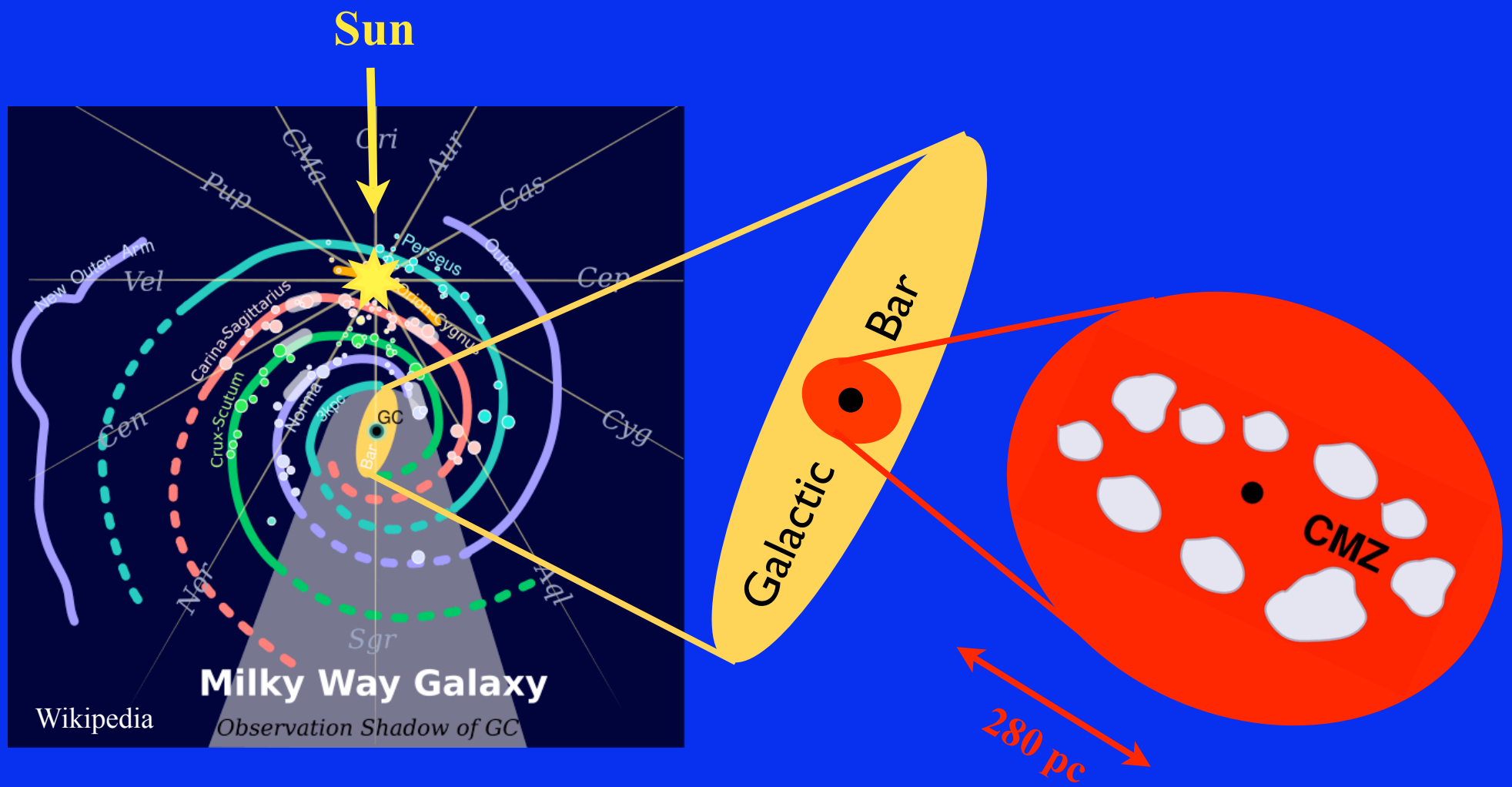

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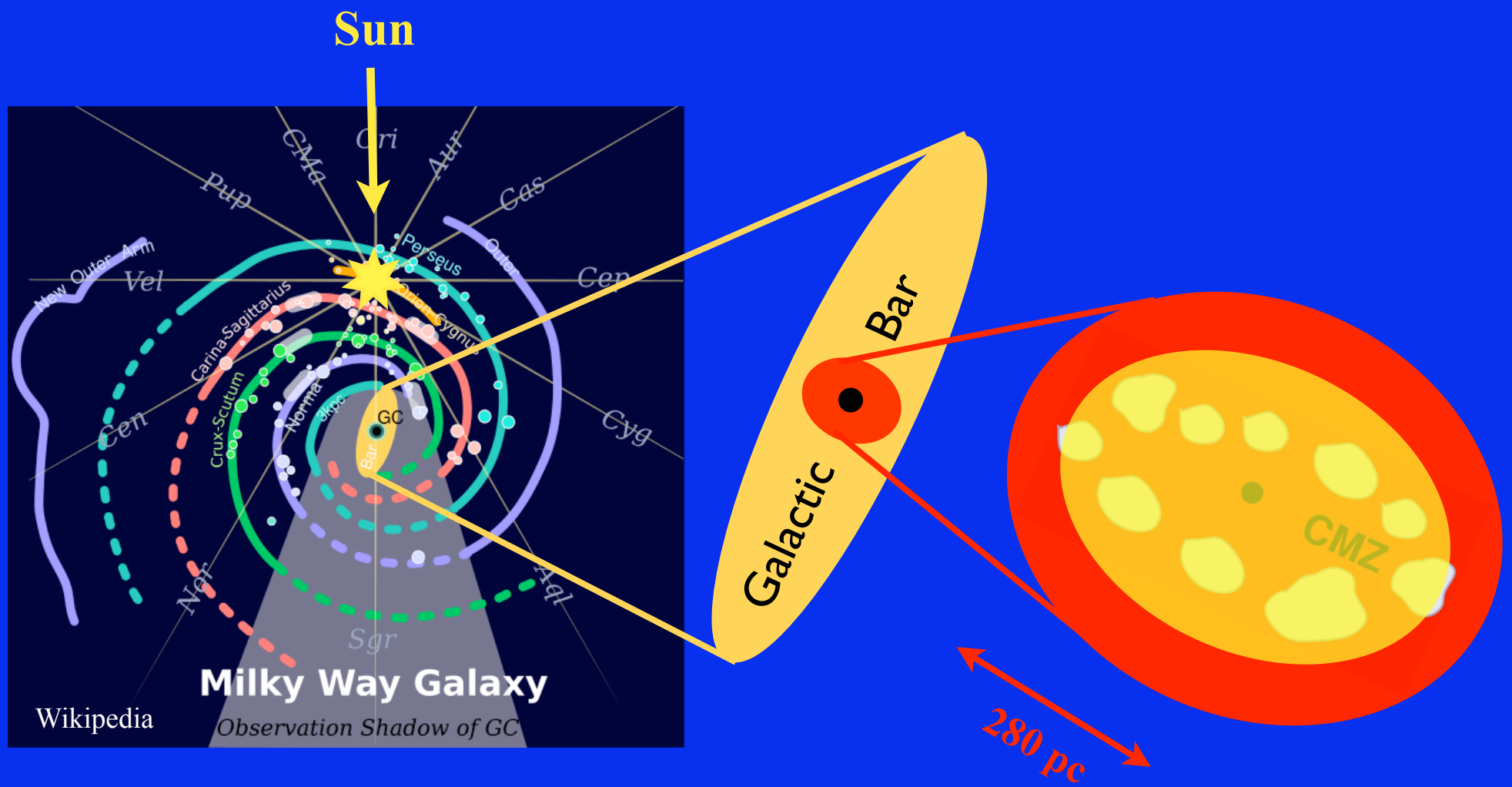

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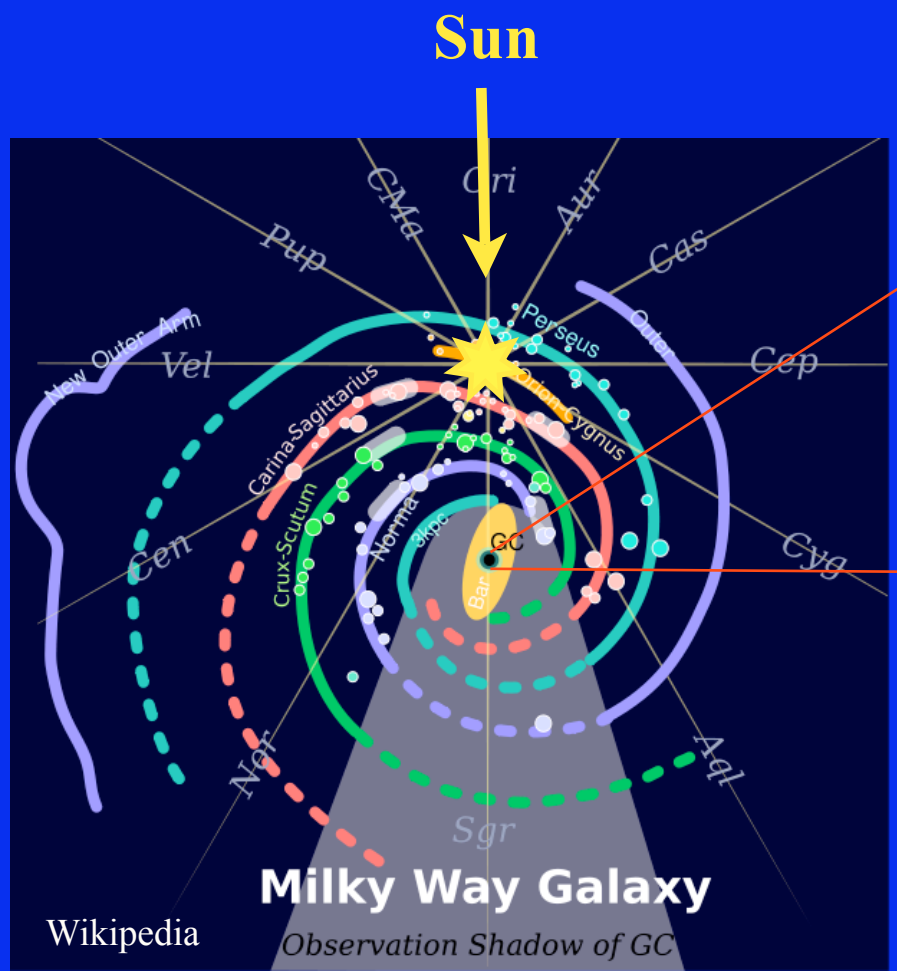
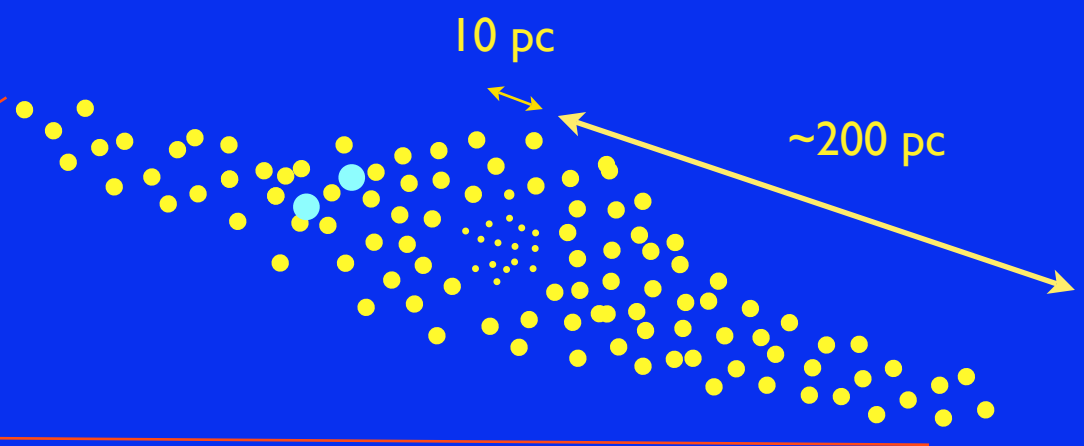
The stellar population inside the central molecular zone





Nuclear Cluster	3 x 10^7 Msun
Nuclear Stellar Disk	1 x 10^9 Msun
Black Hole	4 x 10^6 Msun

Stellar population in the nuclear bulge

Launhardt et al. 2002

Star formation in the Galactic center
Numerical predictions - a top-heavy IMF ?

Obstacles to star formation in the CMZ:

- high cloud temperatures: T ~ 70 K >> Jeans mass

  Larson 2005

- enhanced magnetic and UV radiation fields >> characteristic mass

  Shu et al. 2004, Stolte et al. 2005, but see Zhi-Yun et al. 2010

- tidal shear forces disrupt molecular clouds >> fragmentation mass

  Morris 1993, Morris & Serabyn 1996

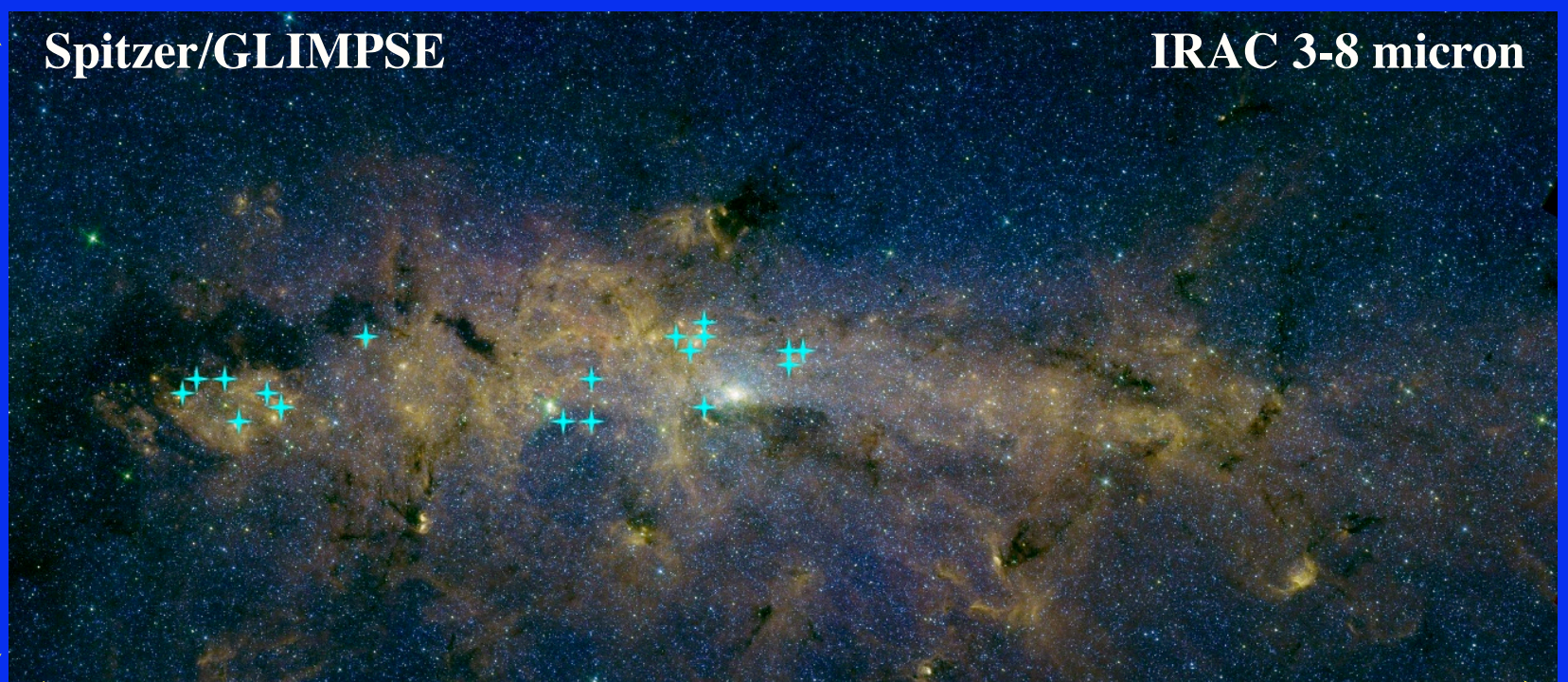
⇒ **all star-forming scenarios predict a top-heavy IMF**

⇒ **star formation in the GC is difficult!**

Star formation in the Galactic center
Observations reveal numerous star-forming regions

Star formation sites throughout the CMZ:

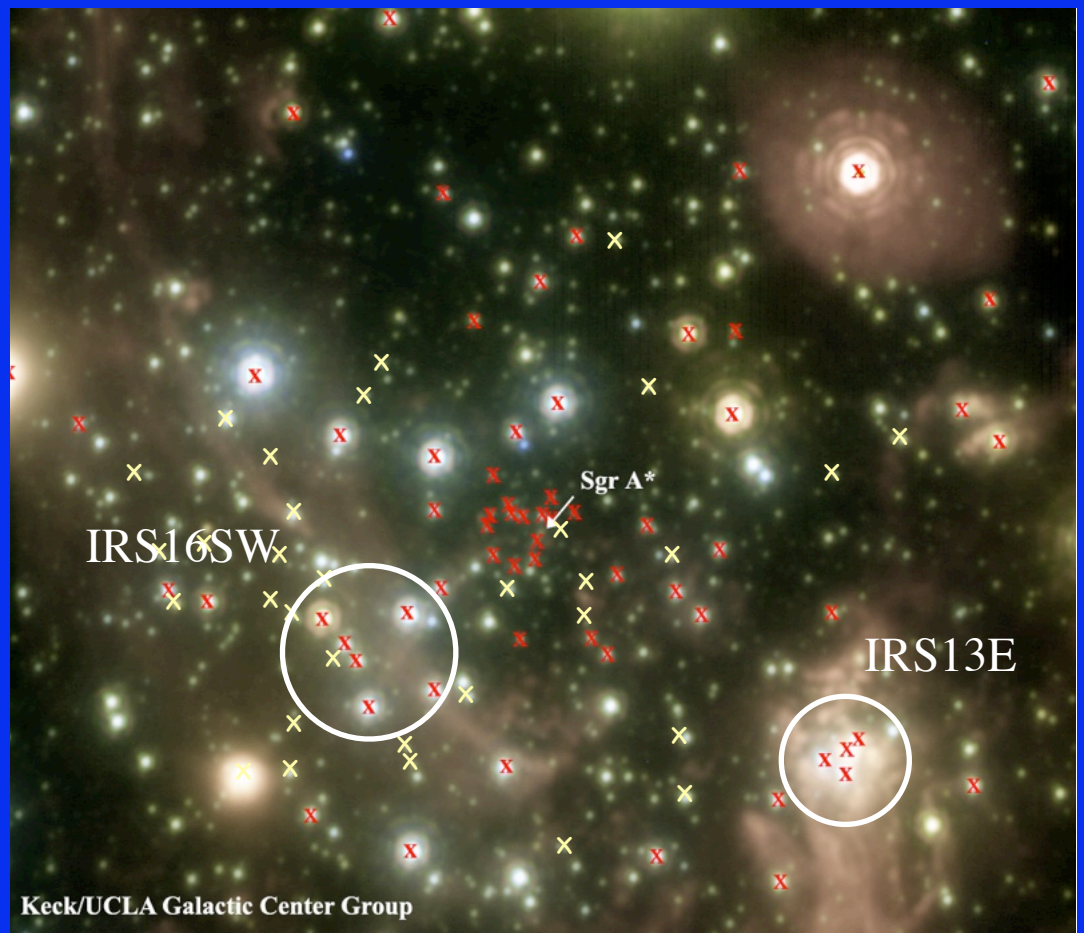
- young, massive clusters: Arches, Quintuplet
- extended HII regions: Sgr B2
- massive, evolving Wolf-Rayet stars with ages ~few Myr



Location of Wolf-Rayet stars/supergiants: Mauerhan et al. 2007, 2009, 2010

Image credit: S. Stolovy & SSC, GLIMPSE survey

Young stars near the supermassive black hole



10”

0.4 pc

XX Confirmed young stars

◯ Comoving groups

- dense groups of young stars
- disk-like orbital motion

Levin & Belobodorov 2003
Lu et al. 2005
Paumard et al. 2006
Do et al. 2009

How did these young stars get there ???

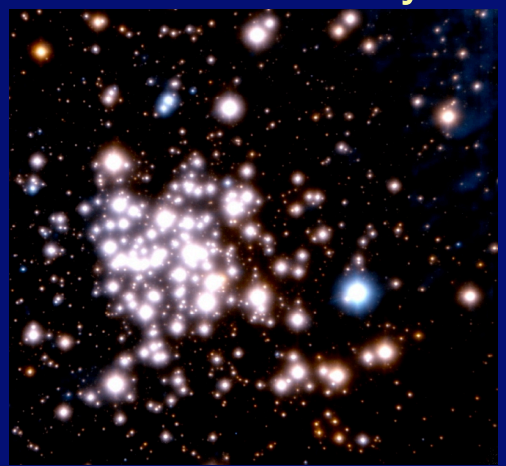
1. in-situ: massive disk
e.g., Nayakshin et al. 2006

2. in-spiraling clusters
e.g., Gerhard 2001

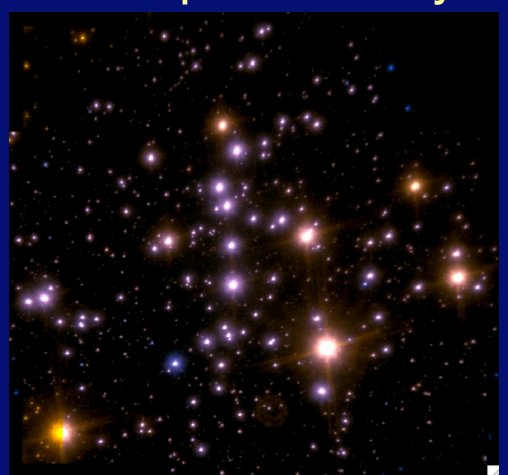
Proper motion survey of 4 Milky Way starbursts

Galactic centre

Arches 2.5 Myr



Quintuplet 4-5 Myr



Comparison of

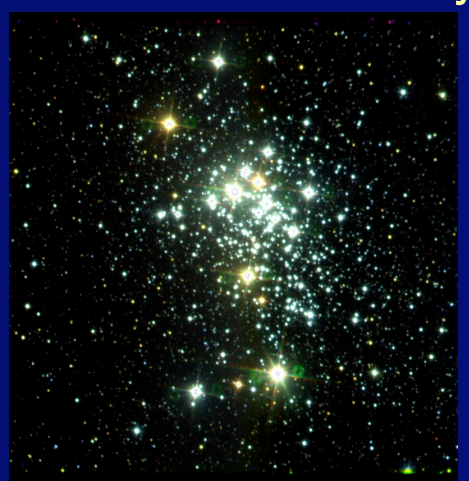
- cluster formation
- cluster dissolution
- stellar mass function

in the Galactic centre
and spiral arm environments

Carina arm

NGC3603 2 Myr

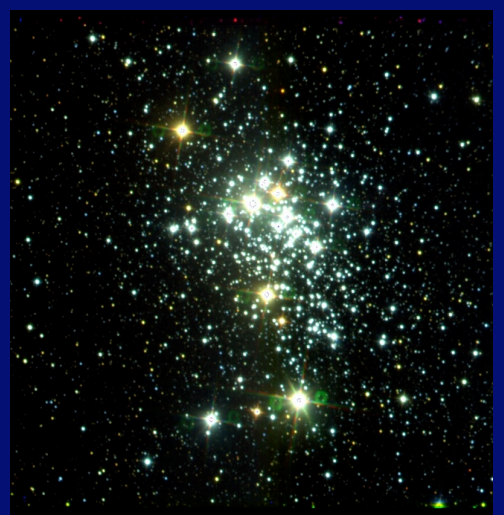
Westerlund 1 3-5 Myr



Proper motion survey of 4 Milky Way starbursts

The Milky way starburst cluster survey

Motivation & Aims:

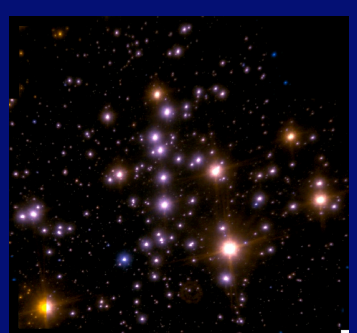


- Global motion relative to field
- Proper motion membership

  ⇒ reconstruction of IMF
- Internal cluster dynamics

  ⇒ tidal debris, expansion & disruption

  ⇒ velocity dispersion & radial variation

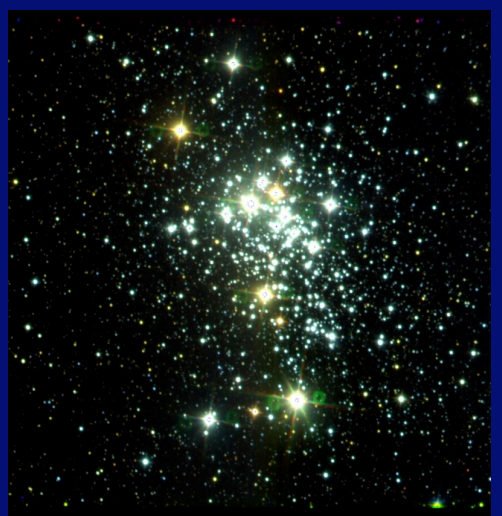


Proper motion survey of 4 Milky Way starbursts

The Milky way starburst cluster survey

Method:

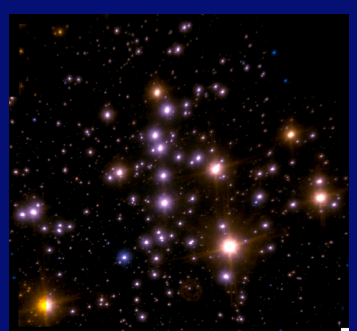
- precision astrometry
  from diffraction-limited imaging



- 4 clusters with 2 epochs

  VLT/NAOS-CONICA 27” field

  HST/WFPC2 160” extent



3. News from the Arches

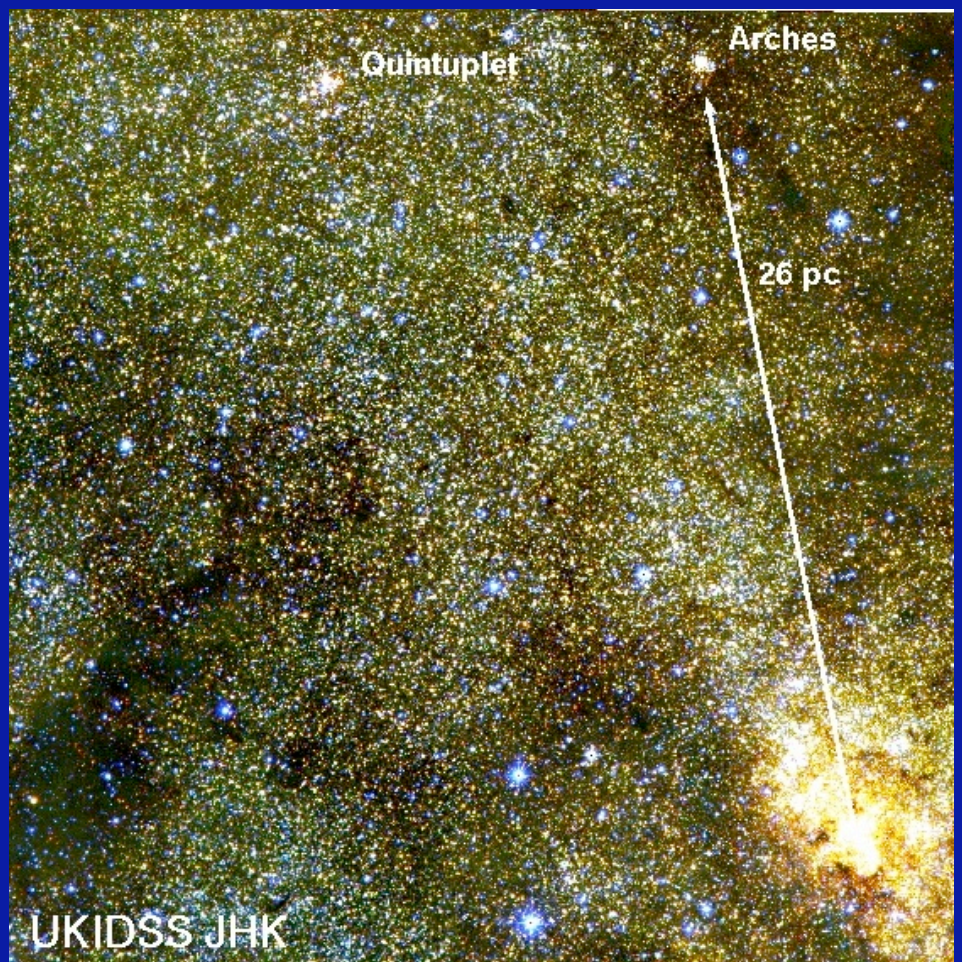
The Mystery of the Arches orbital motion

Young, massive star clusters in the CMZ

as inspiraling progenitors to the nuclear cluster ???

Starburst clusters near the Galactic centre

UKIDSS JHK image of the Arches/Quintuplet region



The Arches cluster:

- **> 10,000 solar masses**
- **~120 O-type stars**

Figer et al. 1999, Stolte et al. 2005

- **core density 2 x 10^5 Msun/pc^3**

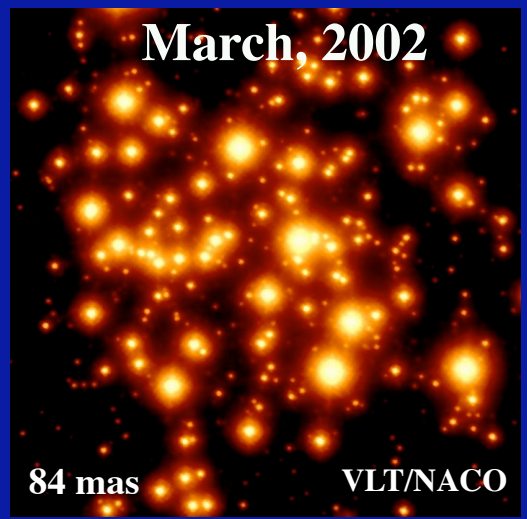
Espinoza et al. 2009

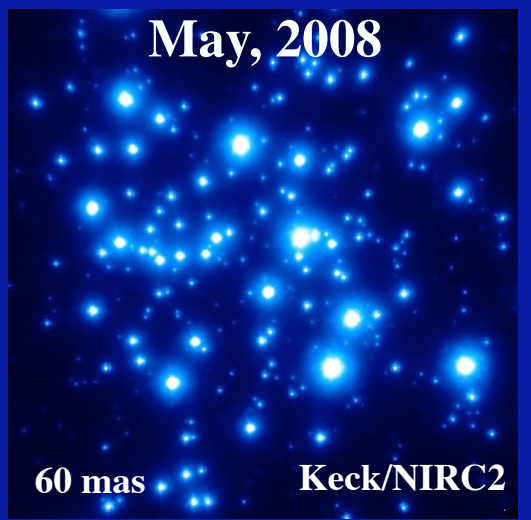
- **age 2.5 Myr**

Martins et al. 2008

Measuring cluster proper motions with Keck and VLT

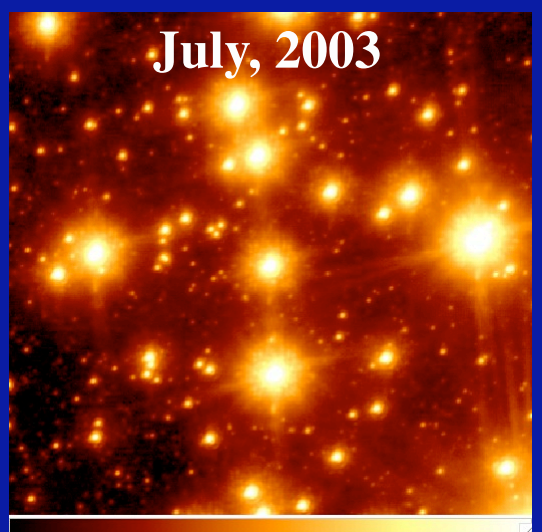
VLT/NAOS-CONICA *Keck/NIRC2 LGS*





10”

Arches



10”

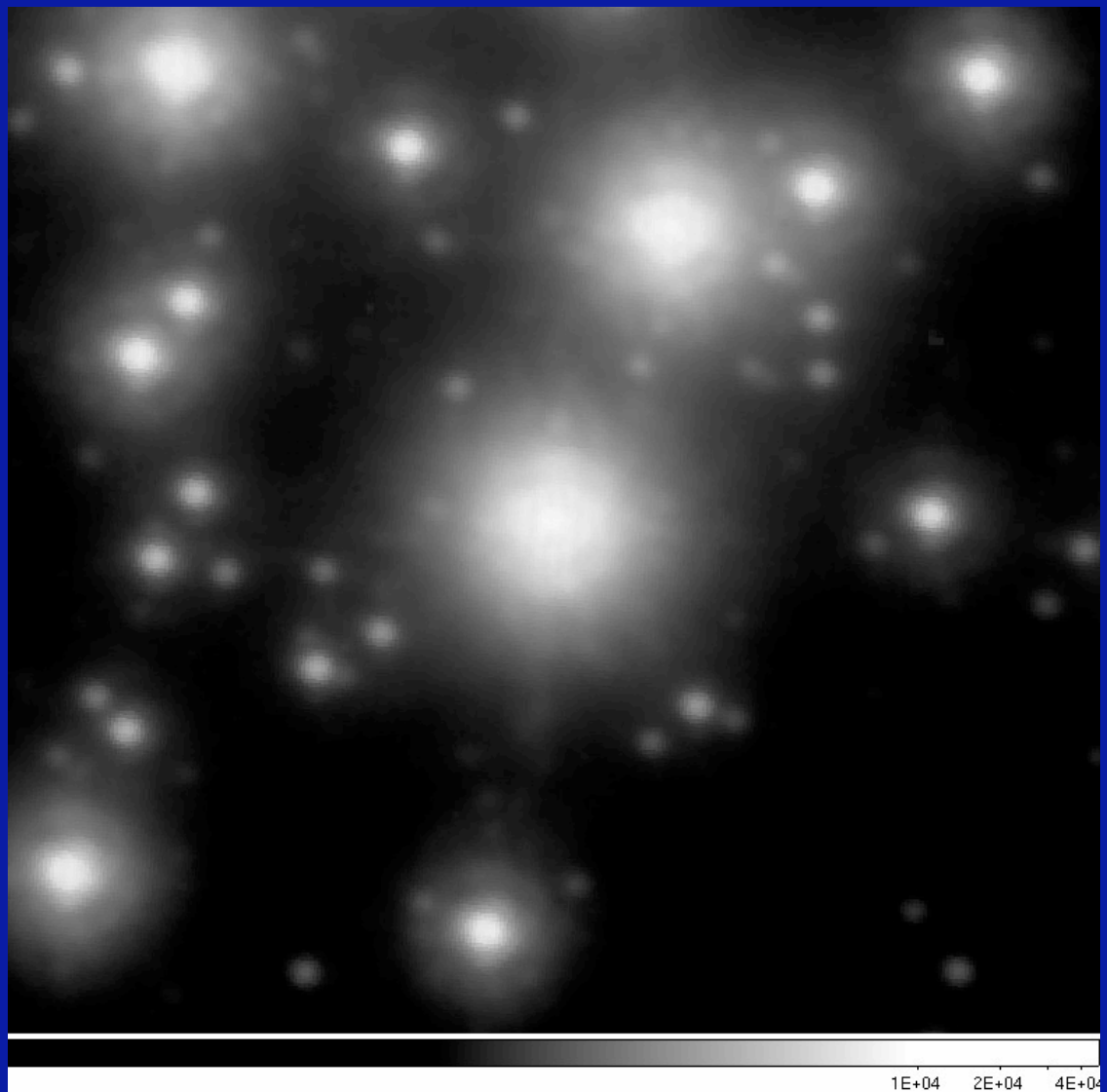
Quintuplet

0.4 pc 0.4 pc 0.4 pc

Brighter and fainter stars move different ways...

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

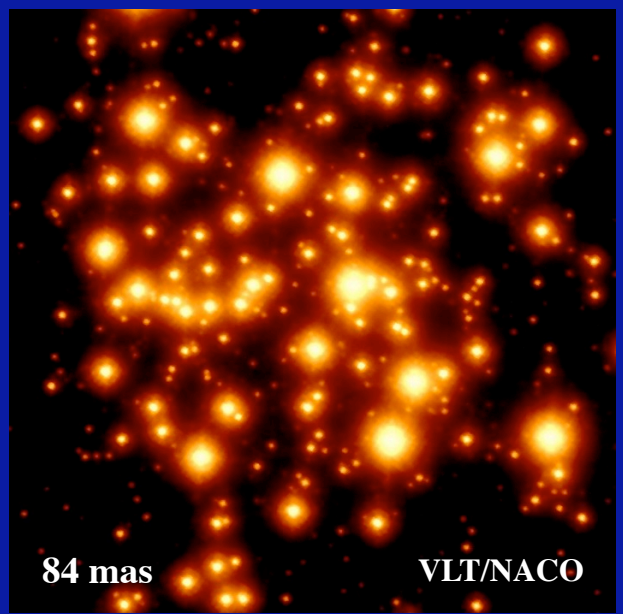
3.6 ”



The Arches cluster proper motion with Keck and VLT

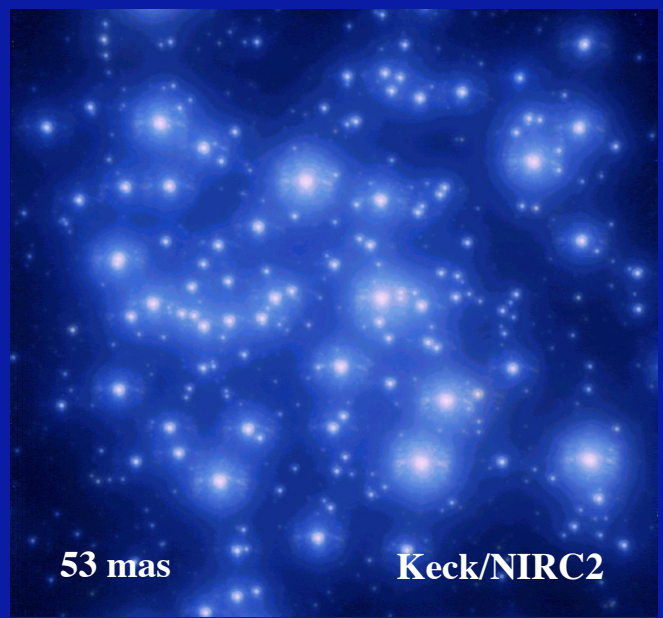
VLT/NAOS-CONICA *84 mas* *Keck/NIRC2 LGS* *53 mas*

10”



March, 2002

10”



July, 2006

Astrometric precision as low as 1/20 pixel ~ 1-2 mas

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VLT/NAOS-CONICA *84 mas* *Keck/NIRC2 LGS* *53 mas*

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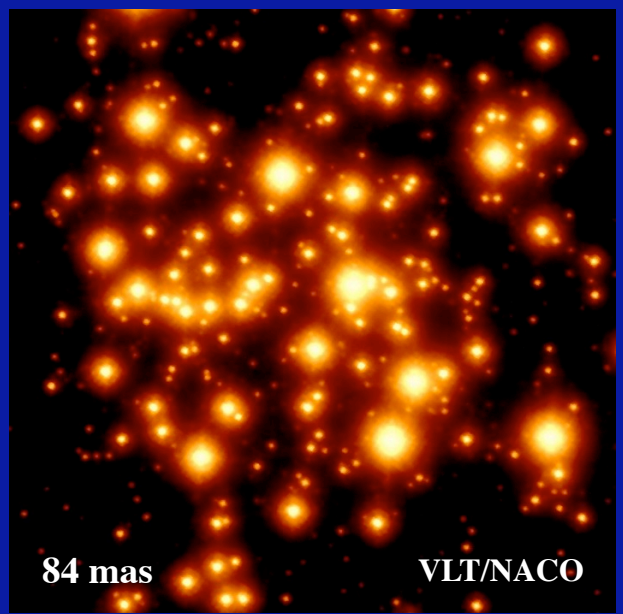

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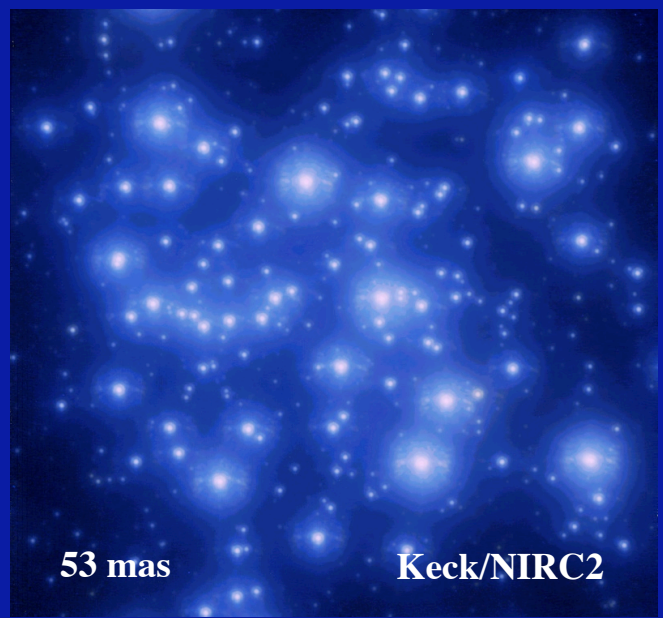

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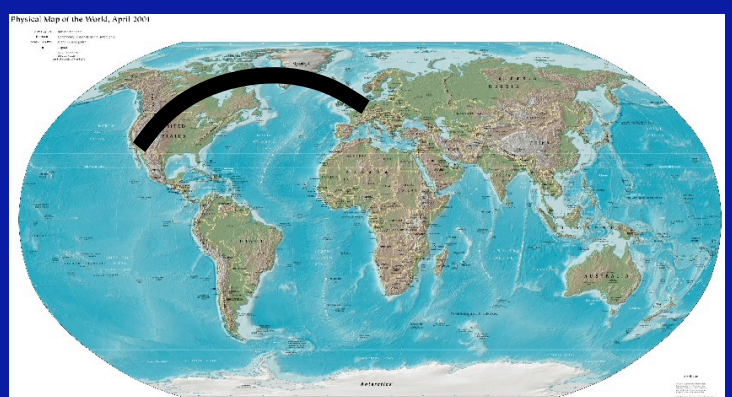

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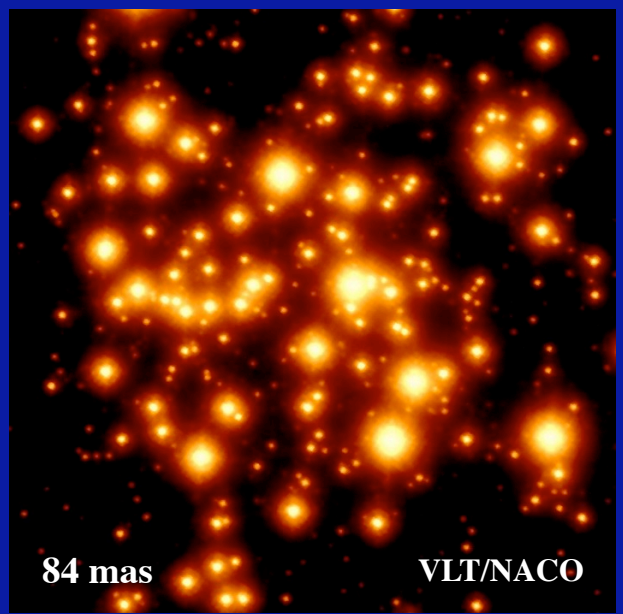

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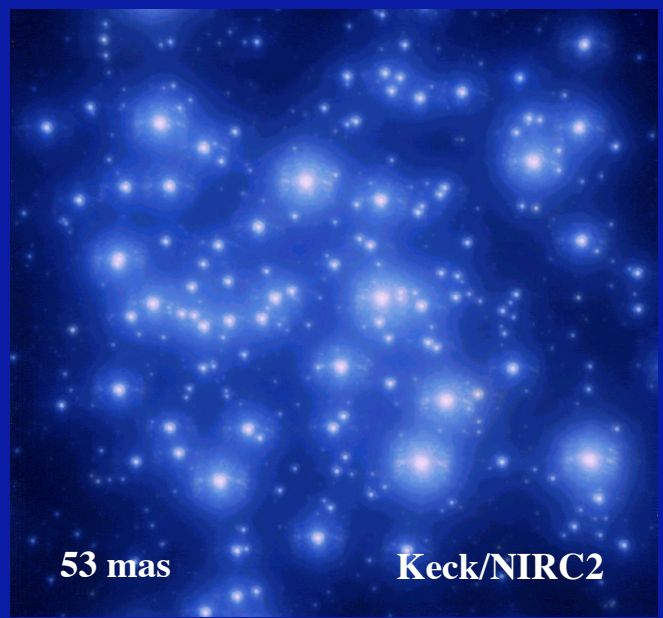

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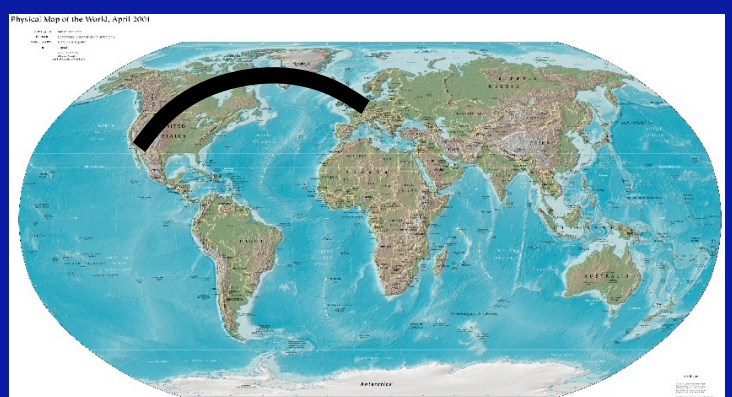
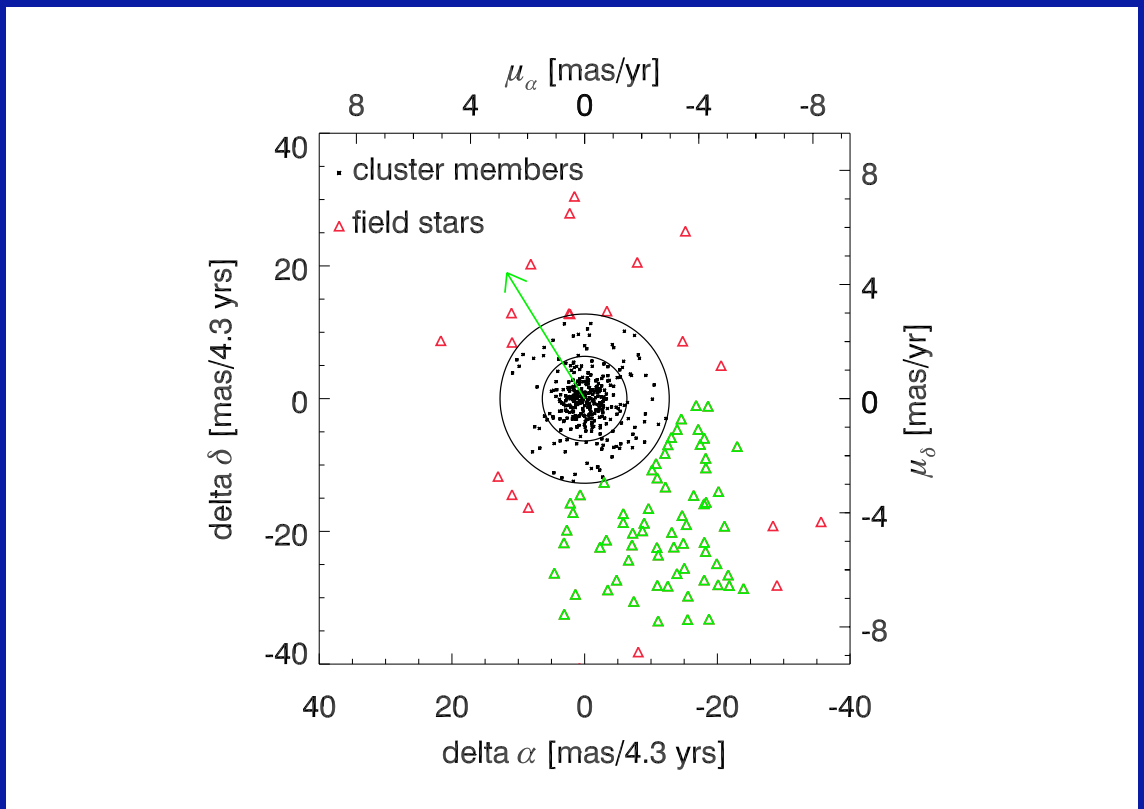


The Arches cluster proper motion - it's fast !!!

Keck/NIRC2 + VLT/NACO = 4.3 year baseline



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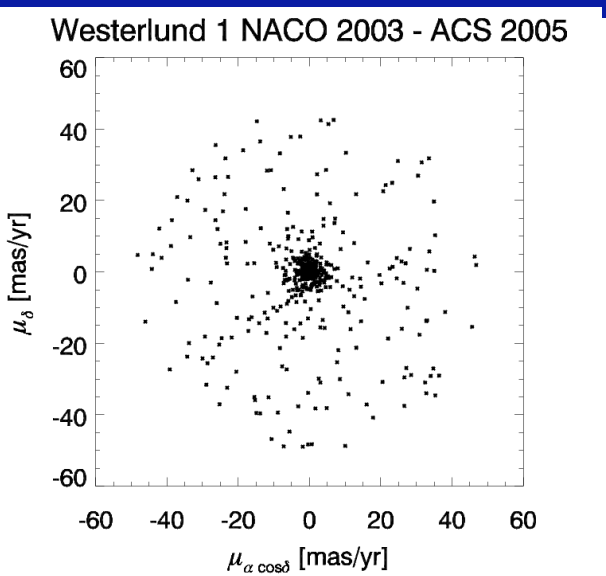

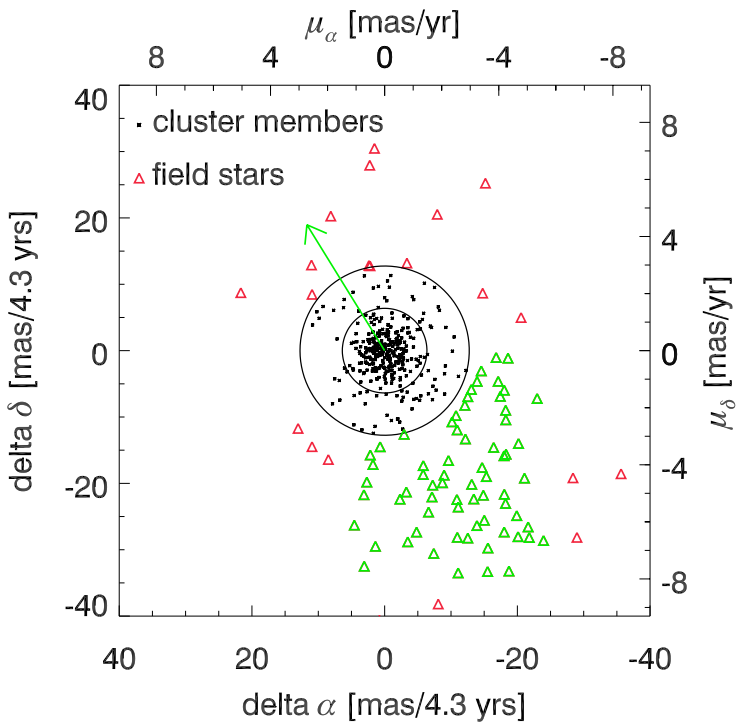

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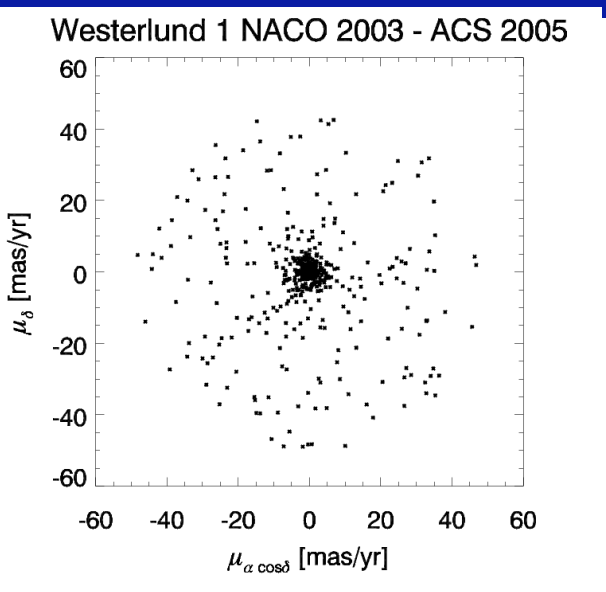

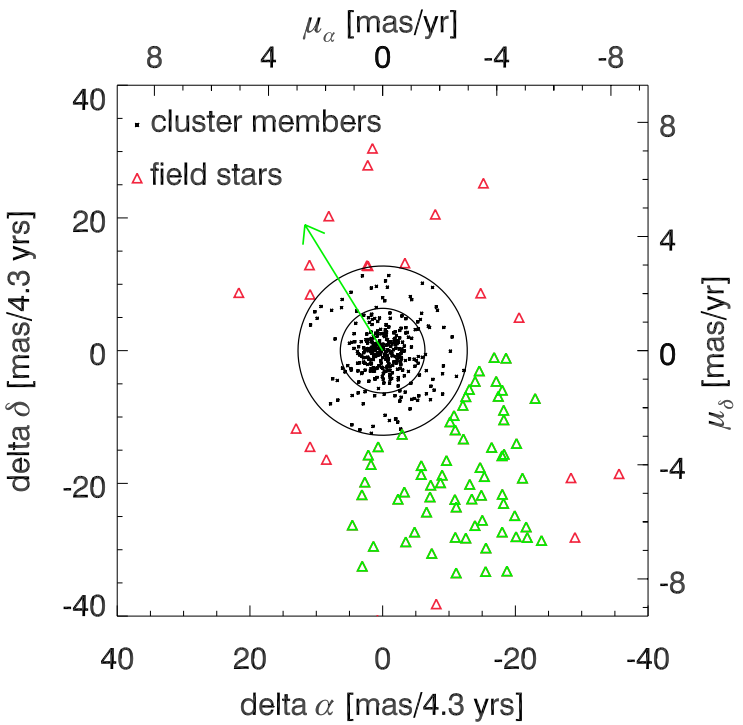

Arches moves relative to field population

proper motion: ***5.6 +/- 0.5 mas/yr = 212 +/- 29 km/s***

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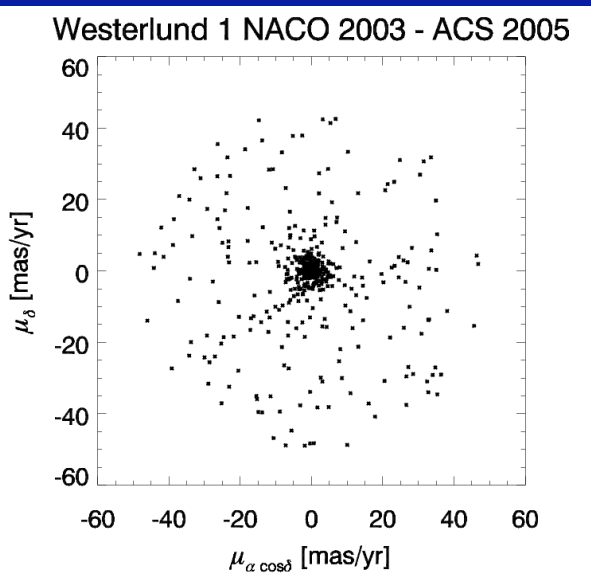
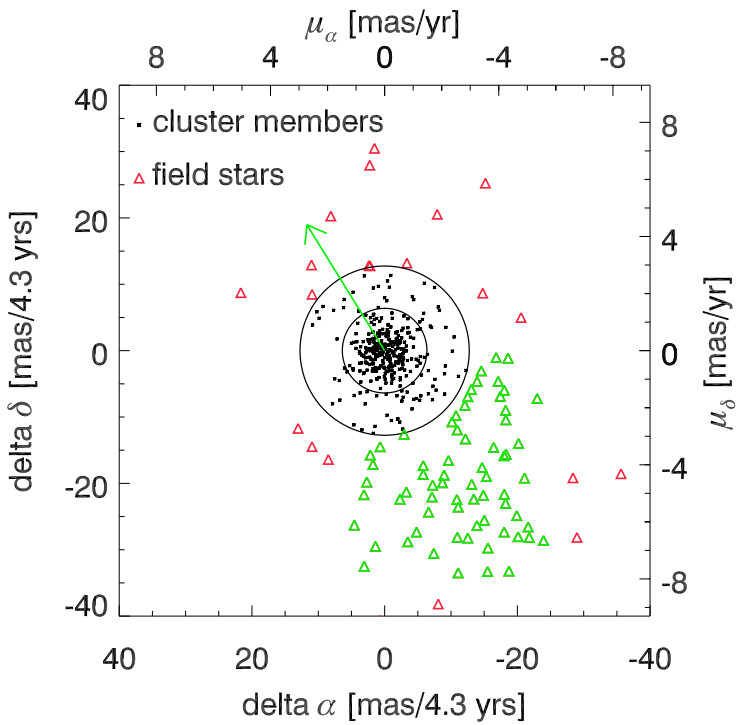




Arches moves relative to field population

proper motion: ***5.6 +/- 0.5 mas/yr = 212 +/- 29 km/s***

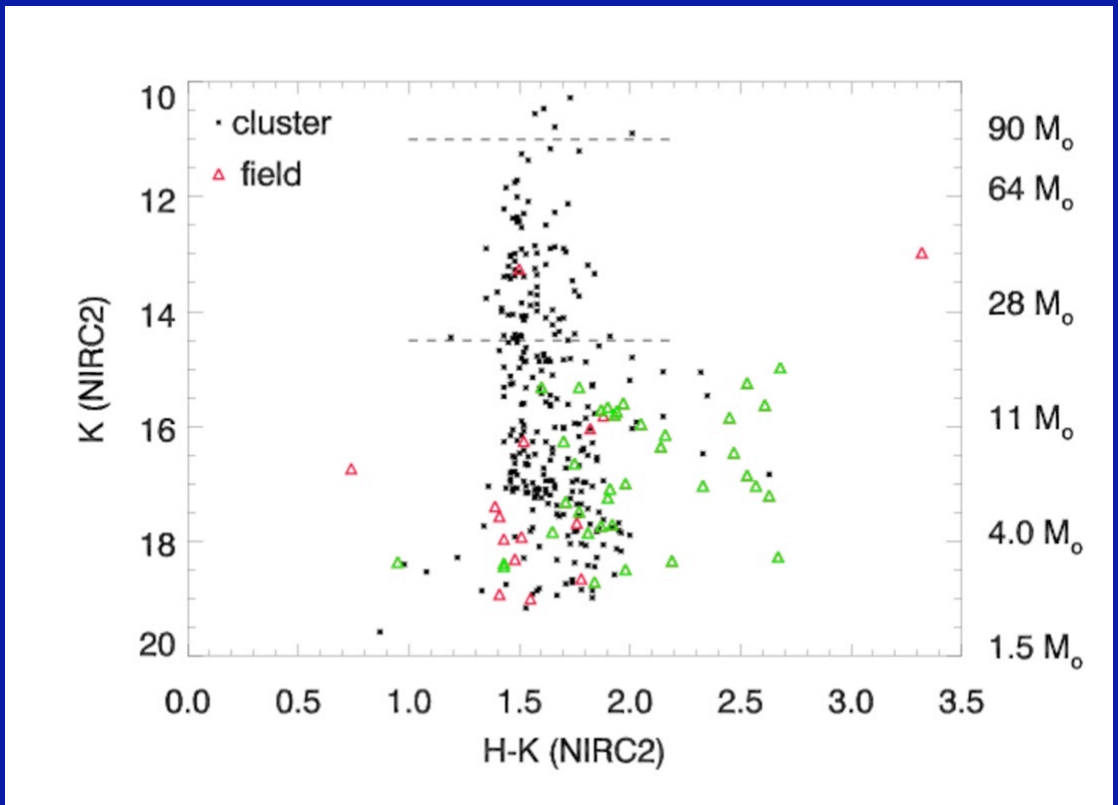
radial velocity: ***vr*** = +95 km/s *Figer et al. 2002*

3D space velocity *v3d* = 232 +/- 30 km/s

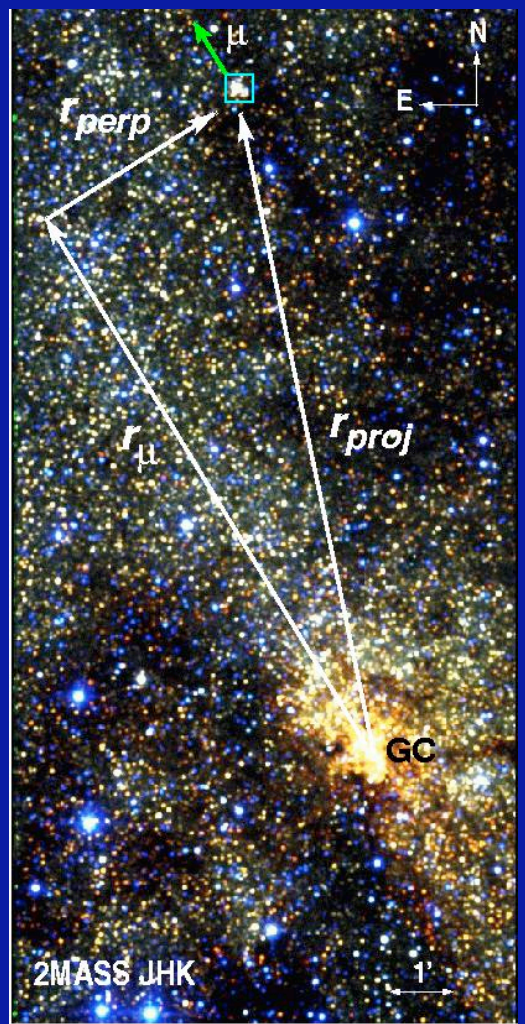
The use of proper motion - an unbiased member sample

Cluster Membership:

- towards an unbiased mass function
- population study at the low(er) mass end



Formation scenarios for the Arches from CMZ clouds



Space motion:

v = 230 +/- 30 km/s

How can such a cluster be formed ?

- velocity inherited from its natal cloud

  CMZ dense clouds $vr < 120$ km/s

  Tsuboi et al. 1999

- cloud-cloud collision

  Sgr B2 suggested to be triggered

  Hasegawa et al. 1994

  Arches cluster-cloud X-ray interaction

  Wang et al. 2006

A cloud-cloud collision as the origin of the Arches ?

Cloud-cloud collision scenarios

Transition x1-x2 orbits

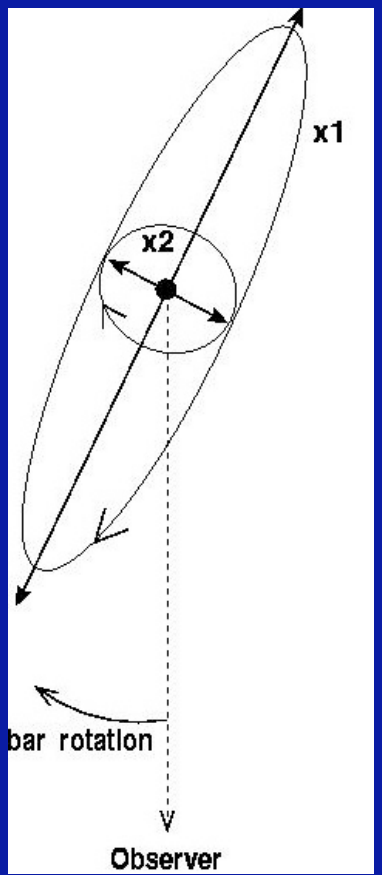
- x1-x2 bar orbits in the inner Galaxy

  Binney et al. 1991, Englmaier & Gerhard 1999

- observed low-density x1 clouds ***vr <*** 270 km/s

  Dame et al. 2000

Needs high-density cloud in x1 orbit !!!



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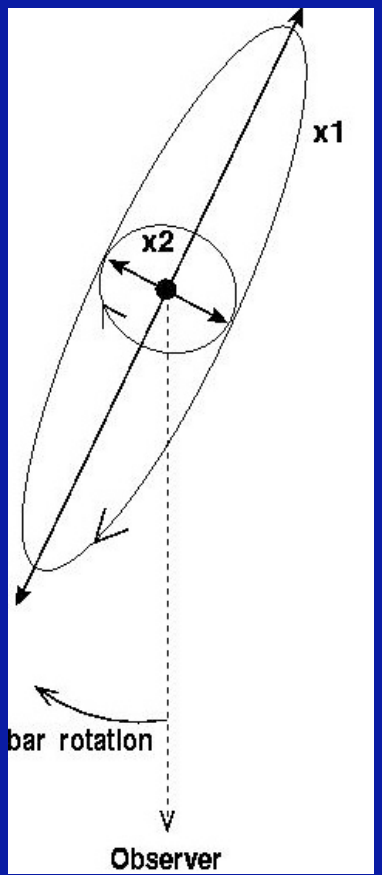

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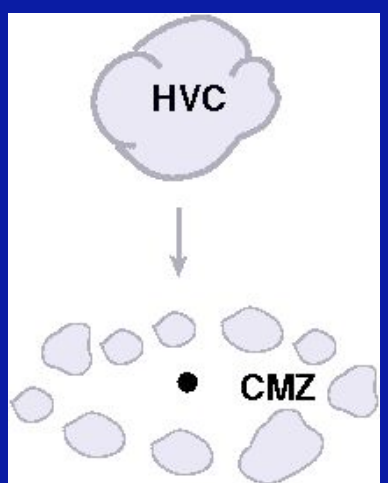
Infalling cloud



- high-V cloud from the outer Galaxy

  Crawford et al. 2002
- inclined stream falling onto the plane

  Bally et al. 1989

but negligible vertical motion...

Simulating the Arches cluster orbit

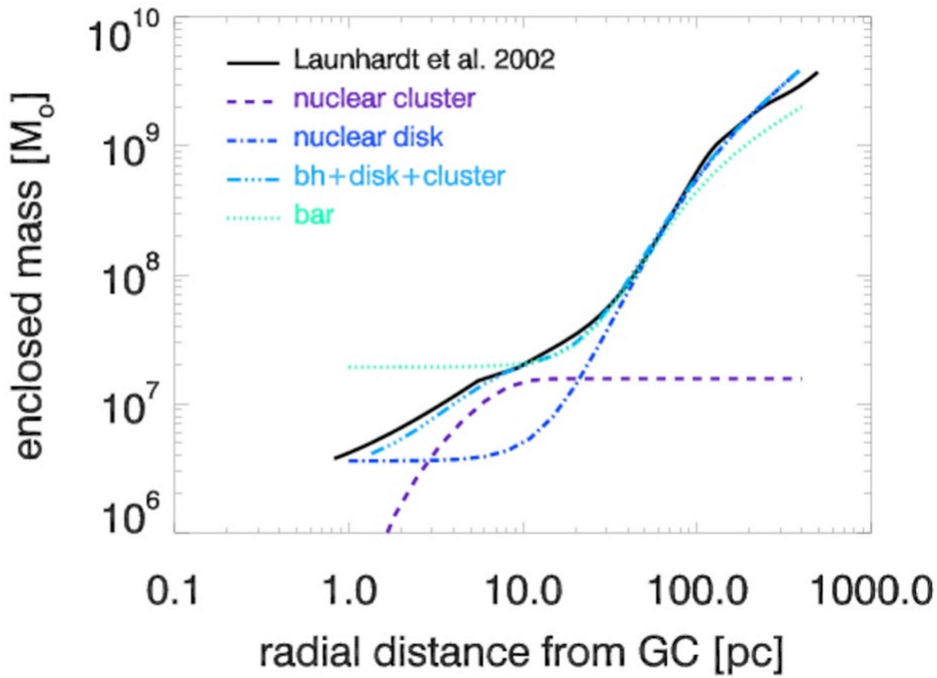
Gravitational potential in the inner Galaxy

- Black Hole 3.6 x 10^6 Msun
- Nuclear Cluster 3 x 10^7 Msun
- Nuclear (Stellar) Disk

- Bar potential r > 200 pc

Logarithmic approximation

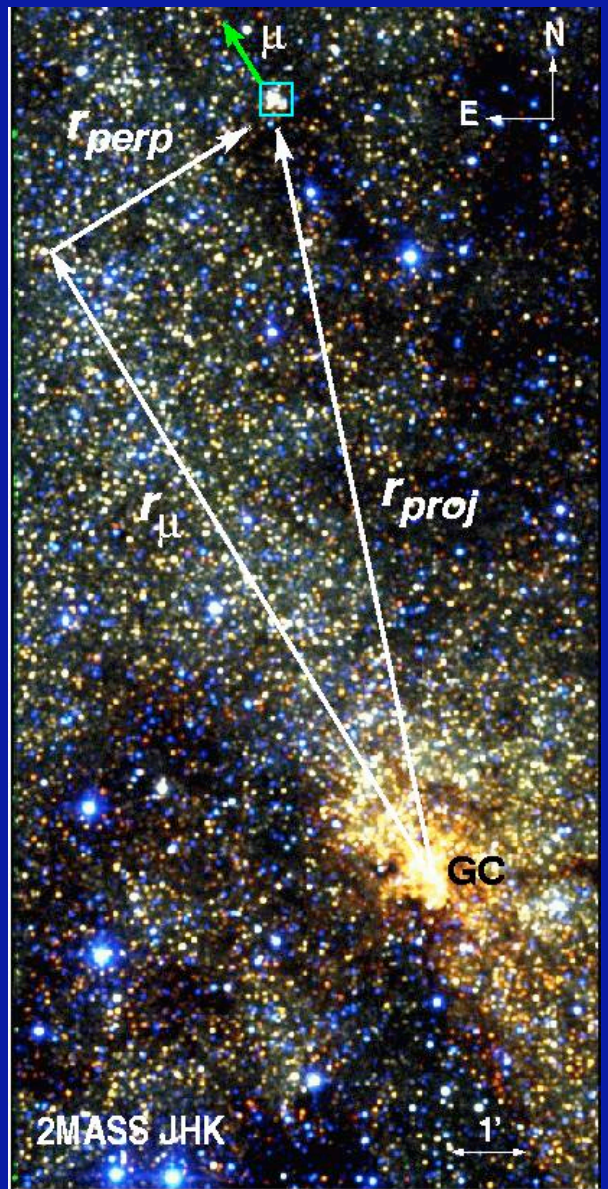
$$\Phi = 0.5 v_0^2 \log(R_c^2 + \frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2})$$



flattened rotation curve with asymptotic velocity v_0 , core radius Rc
stretching parameters a, b, c adjustable to potential shape

⇒ smooth transition between nucleus and bar

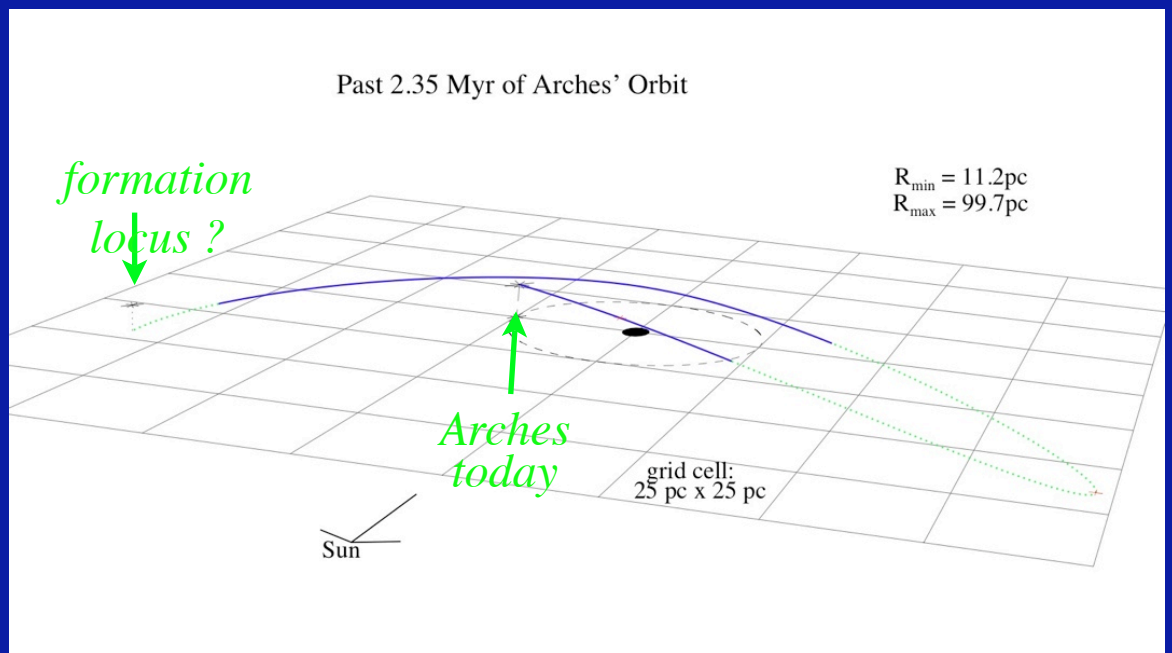
Orbital motion close to the Galactic plane



GC cluster formation scenarios:

Families of orbits point to the clusters' origin

Is there a special cluster formation locus ?



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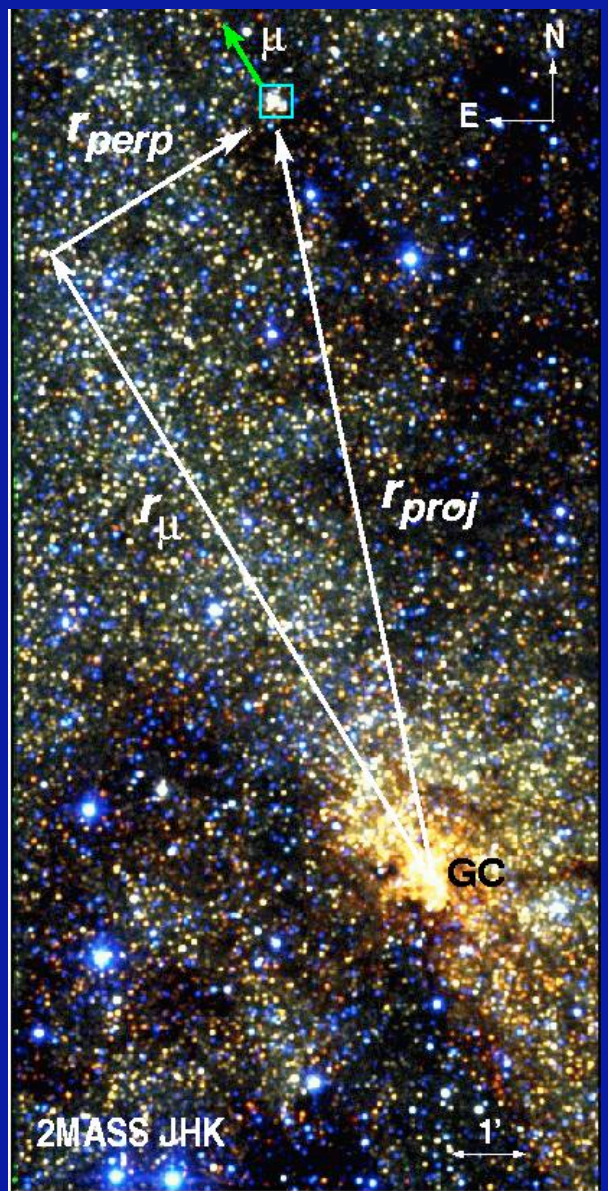

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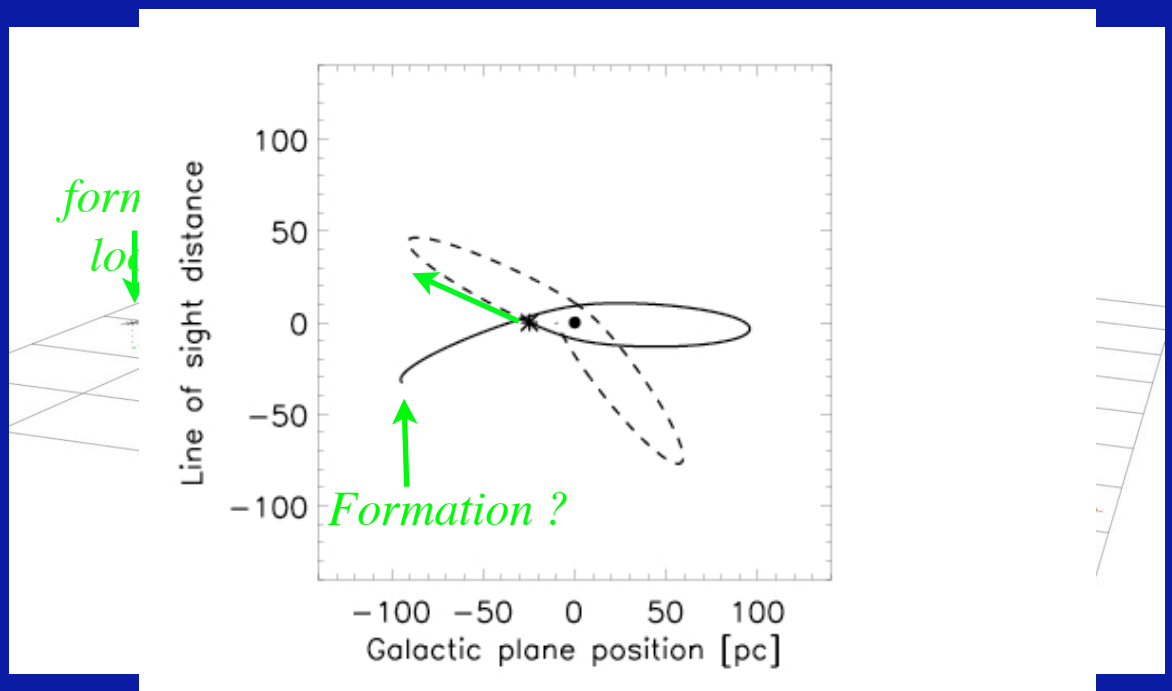
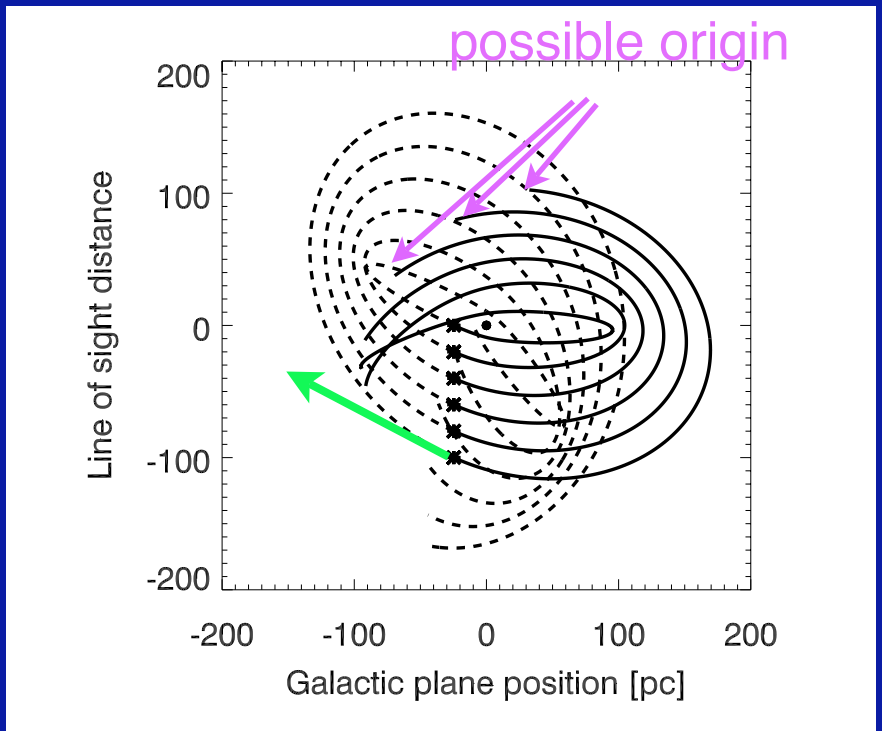


The Arches cluster orbital motion in the Galactic Plane

solid lines:
2.5 Myr past

dashed lines:
360 deg future
(3-15 Myr)



Arches reaches the central few pc only on almost radial orbits !!!

Orbital simulations:

Tidal stripping and cluster dissolution

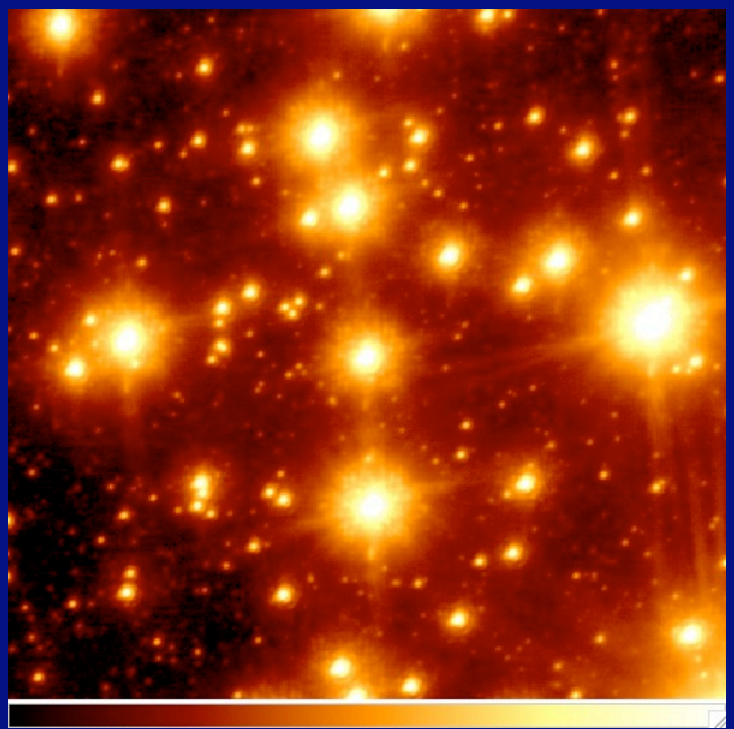
Harfst, Portegies Zwart & Stolte 2010

4. The mystery deepens...

The motion of the Quintuplet cluster

The Mystery deepens: The Quintuplet cluster's motion

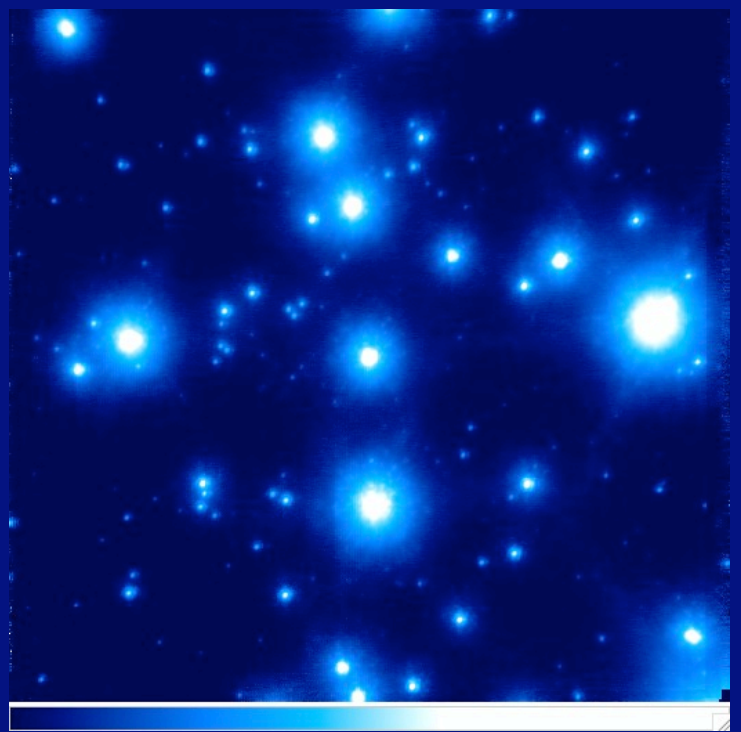
VLT/NACO NGS-AO



10”

July, 2003

Keck/NIRC2 LGS-AO

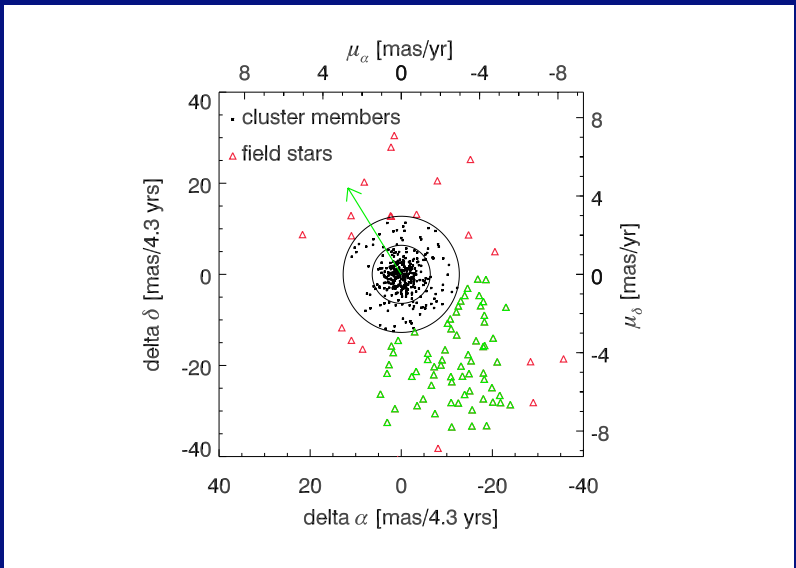


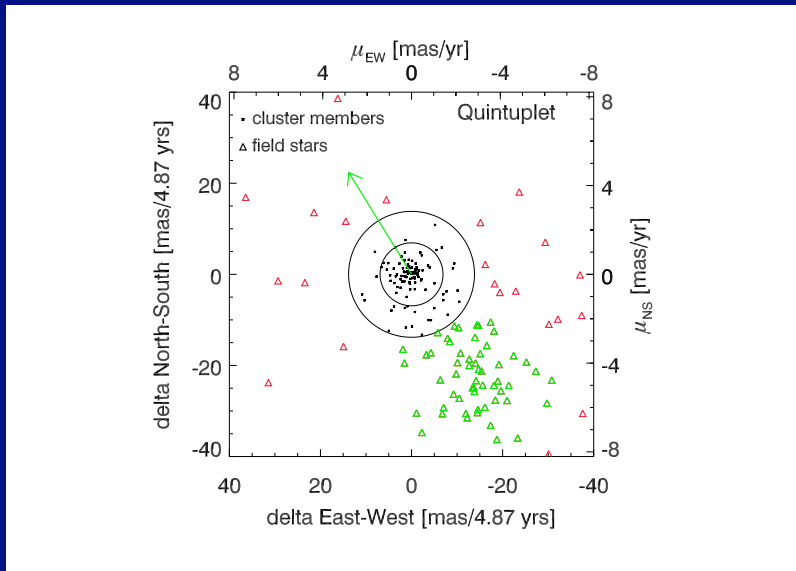
10”

May, 2008

Twin clusters = 2 problems instead of 1 !!!

Quintuplet: Keck/NIRC2 + VLT/NACO = 4.87 year baseline





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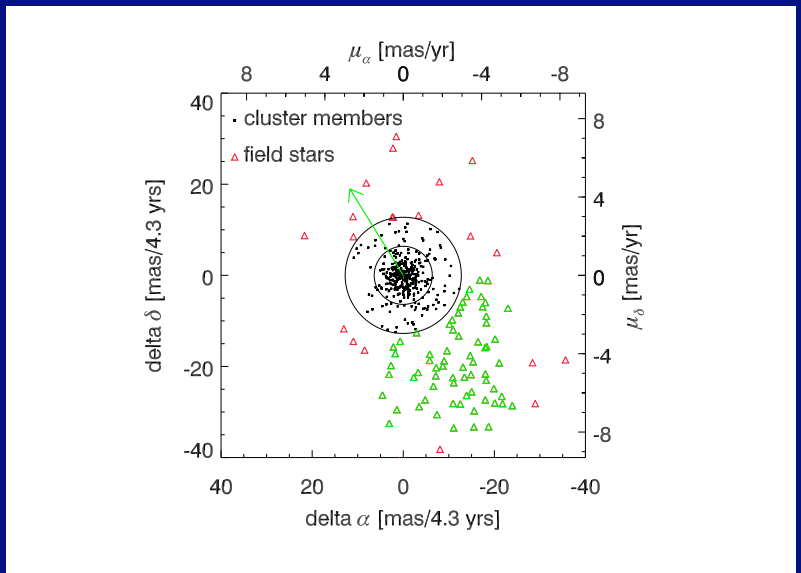
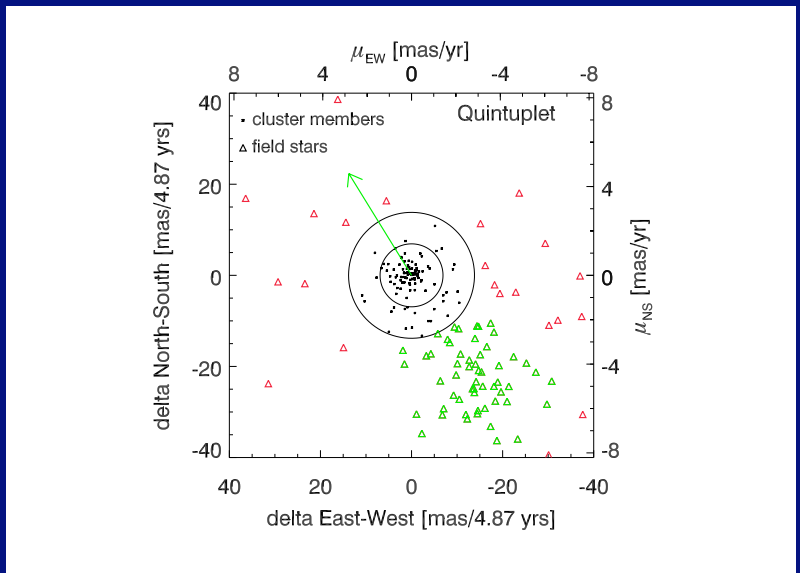




Arches

5.6 +/- 0.5 mas/yr = 212 +/- 29 km/s

3D orbital velocity 232 +/- 30 km/s

vr = +95 km/s *Figer et al. 2002*

Quintuplet

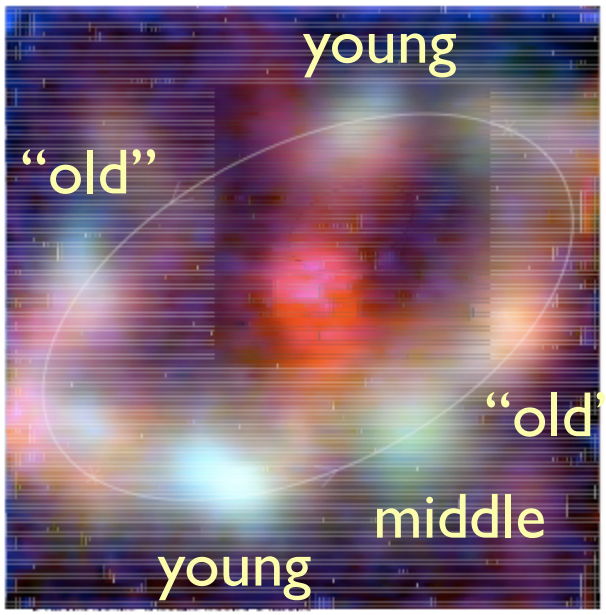
5.6 +/- 0.4 mas/yr = 211 +/- 20 km/s

3D orbital velocity 248 +/- 22 km/s

vr = +130 km/s *Figer 1995*

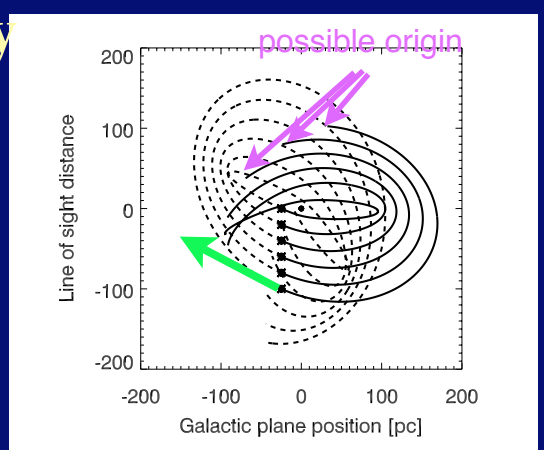
Arches & Quintuplet are very unusual twins...

Evidence for circumnuclear star-formation in spiral galaxies



600 pc

Starburst rings are frequent in *barred* spiral galaxies (frequently accompanied by AGN activity)



Athanassoula 1992
Elmegreen 1994
Regan & Teuben 2003

Summary I - the Mystery deepens.....

- **Precision astrometry yields proper motion in Arches & Quintuplet clusters for the first time**

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Arches & Quintuplet -- Orbital Conclusions

- **Cluster formation scenarios in the central molecular zone**

1. need to explain **high velocity > 200 km/s**

   best candidate: **cloud collision**

2. Arches (2.5 Myr), Quintuplet (4 Myr), Sgr B2 (< 1 Myr)

   formation rate ≥ 1 cluster in 2 Myr

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  => star-formation at the end points of the inner Lindblad resonance

Proper motion promotes sequential cluster formation in the Galaxy's central molecular zone

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Watch out for zooming clusters - more to come !

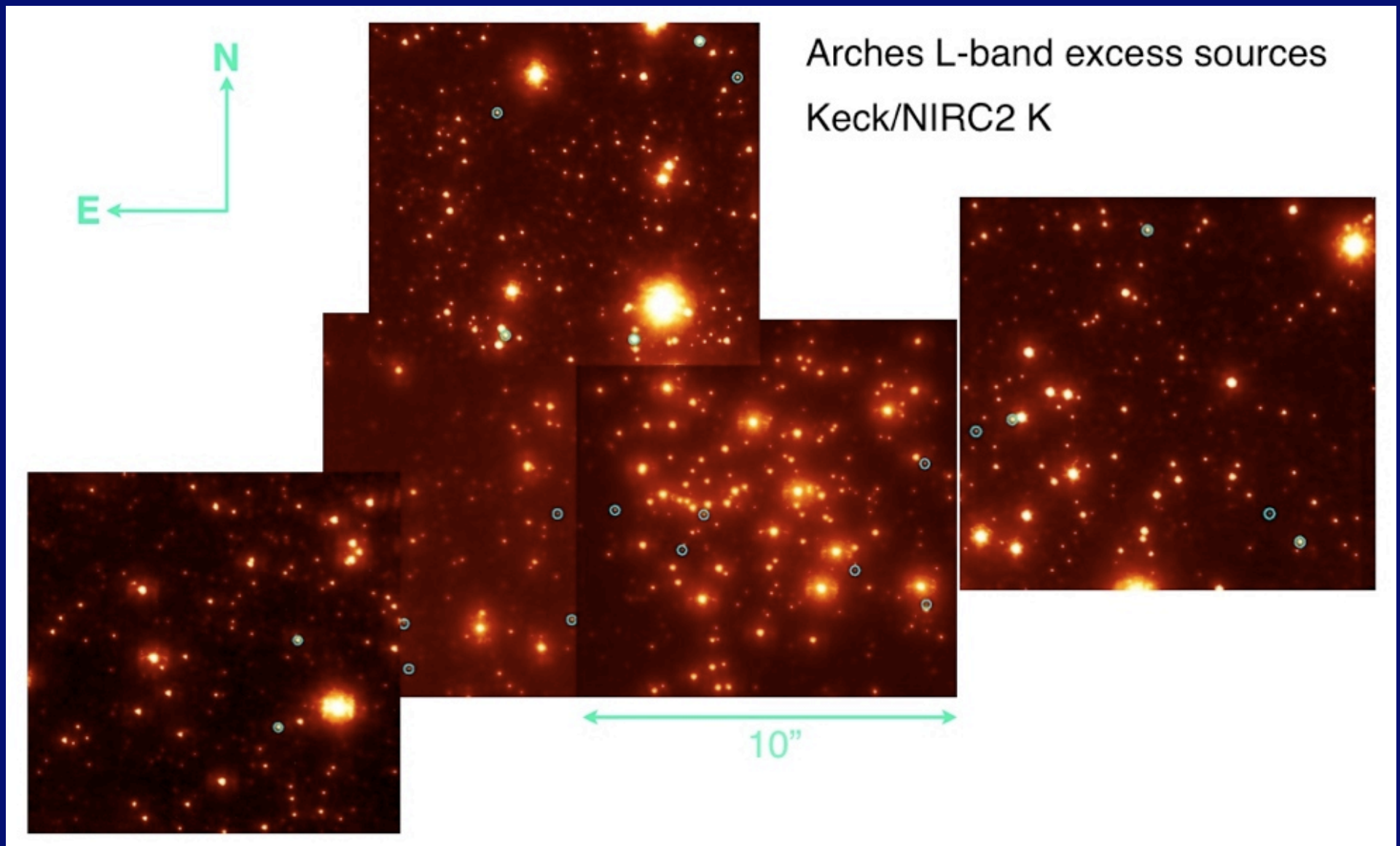
Thanks!!!

Mystery 2: An unexpected population of L-band excess sources

Can disks survive in starburst clusters ???

Keck/NIRC2 HKL mosaic for extinction measurements

Ingredients for a Mystery: 1. nice data +



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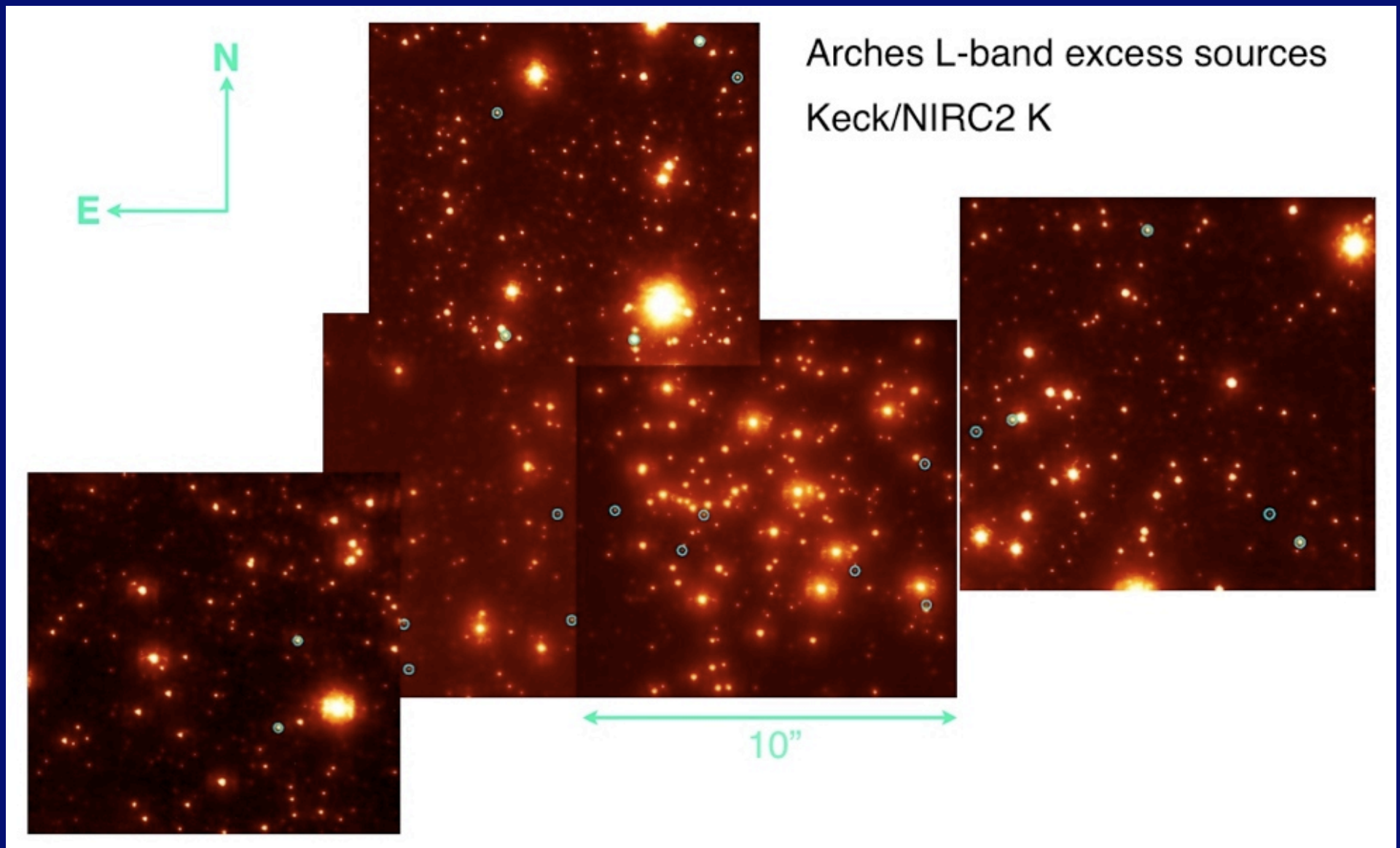
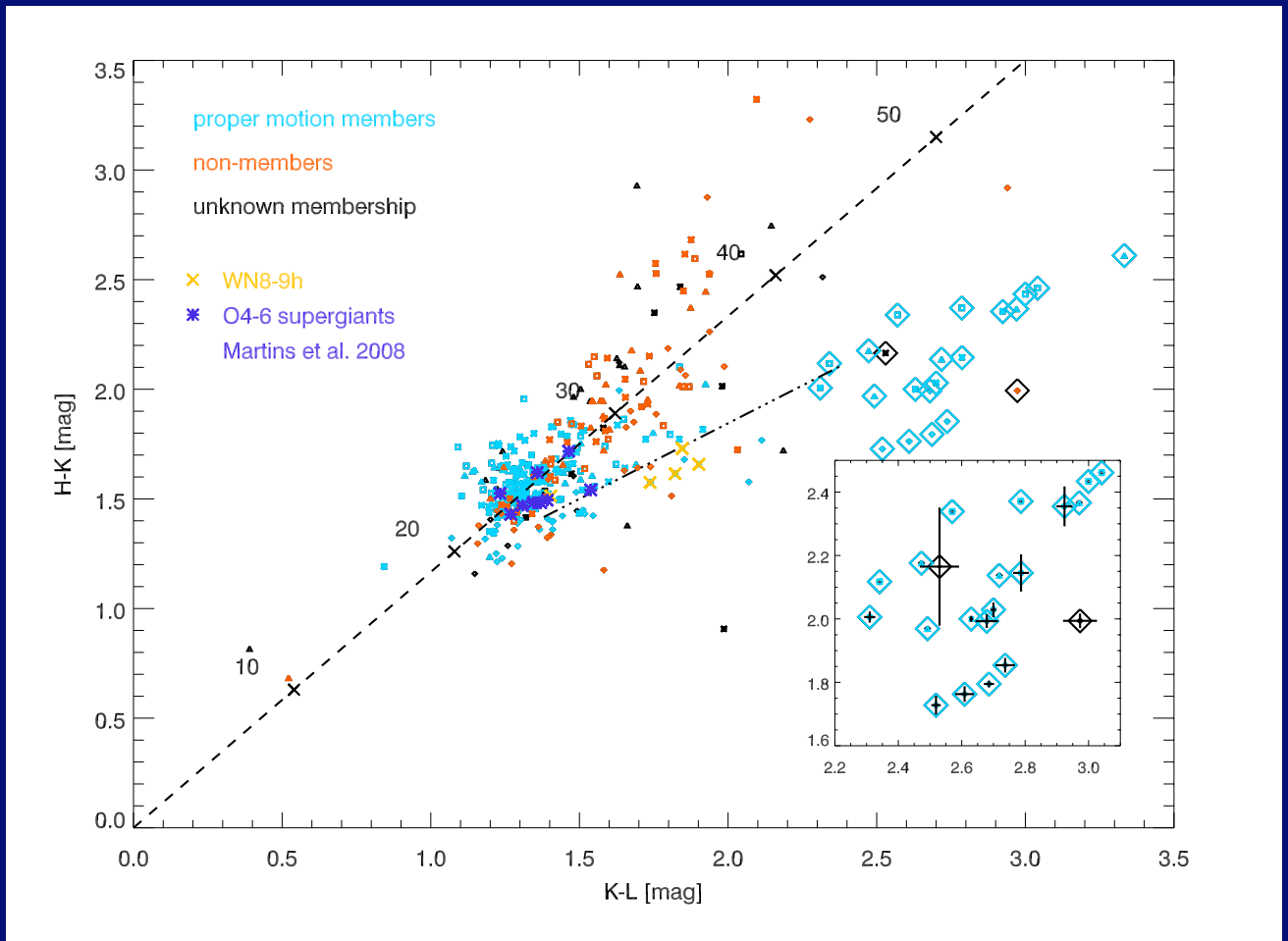
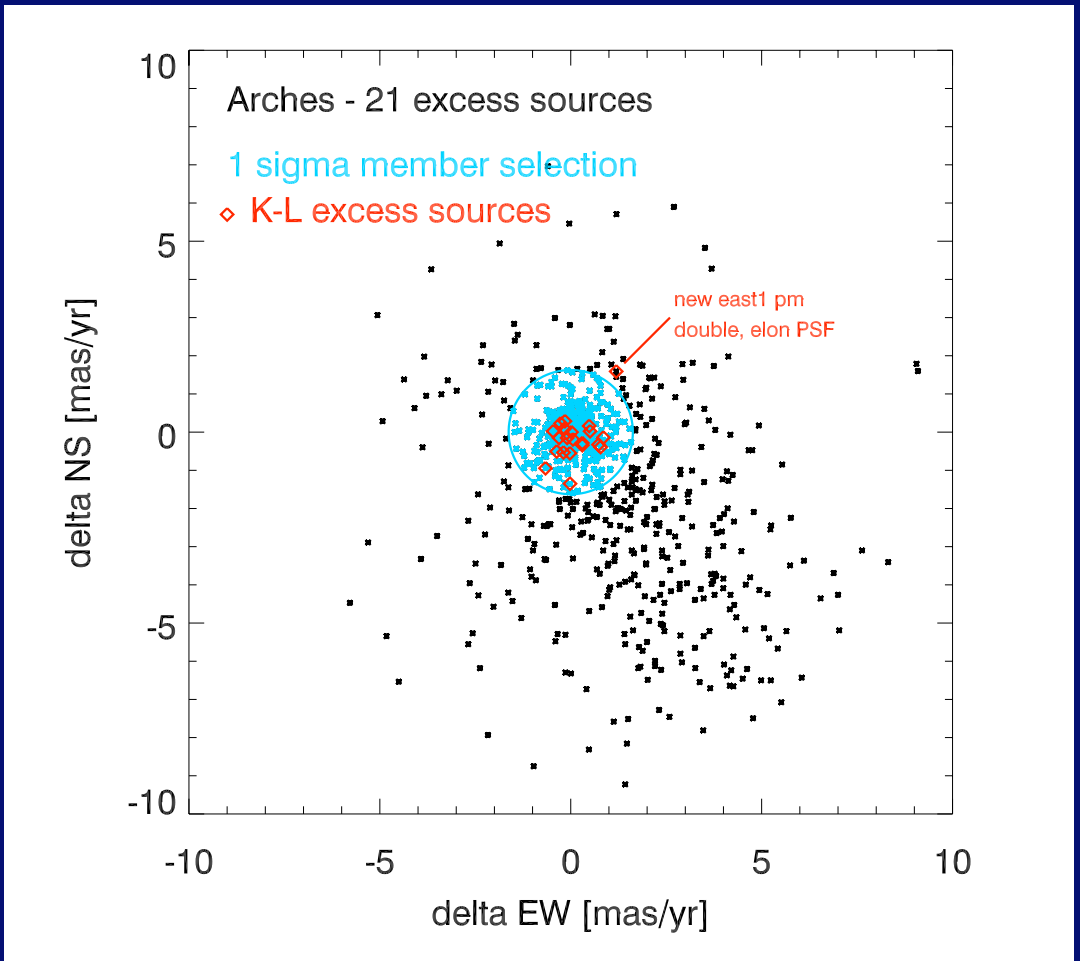


Detection of HKL excess sources... a surprise!



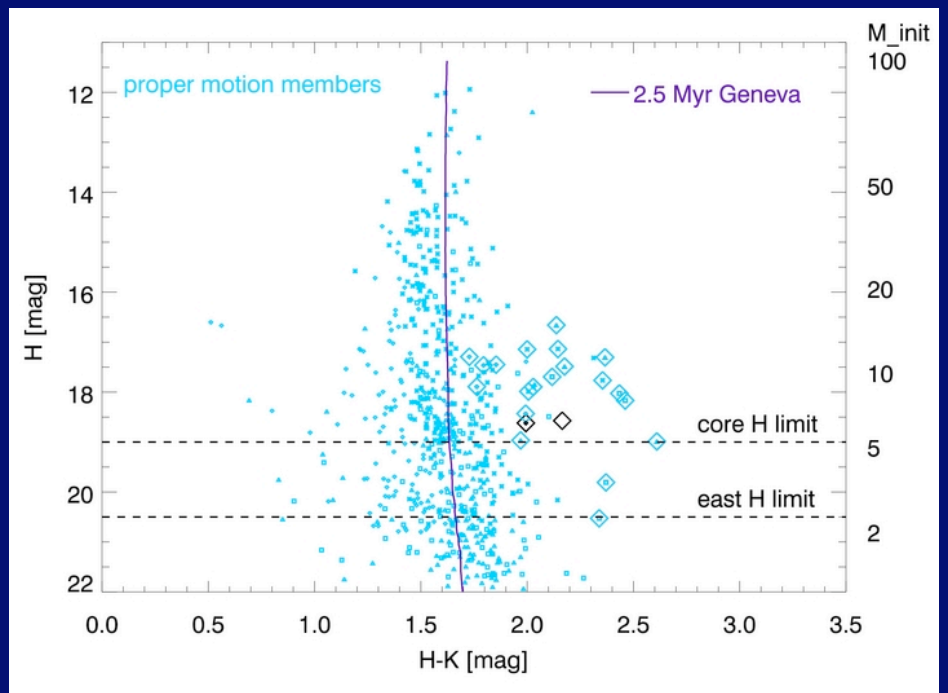
and their relation to the Arches...

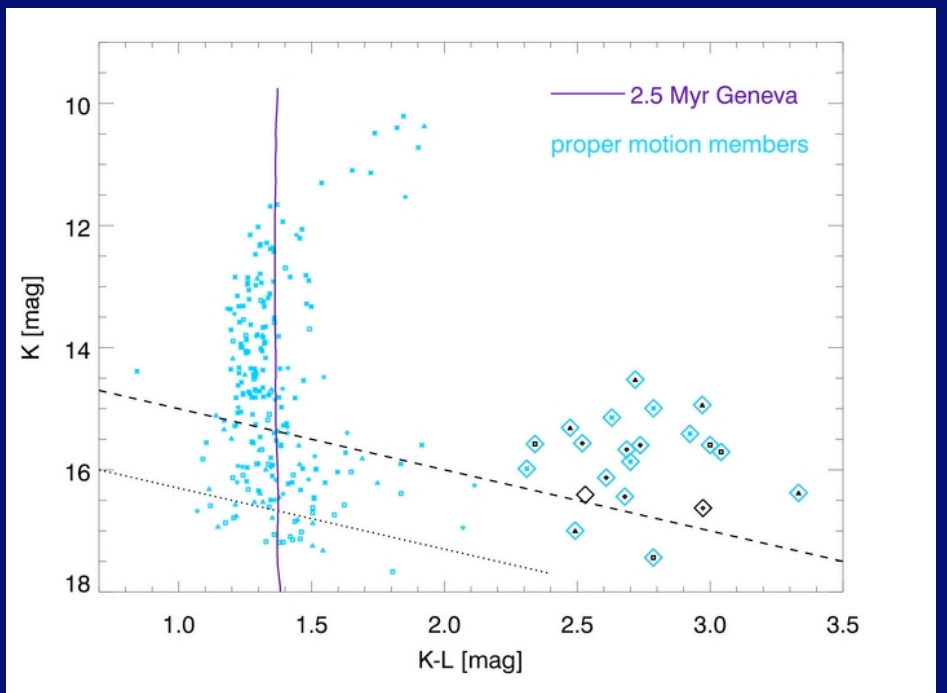
L-band excess sources and proper motion membership



All excess sources with proper motion ARE MEMBERS !!!

Excess sources are distinct only in L-band



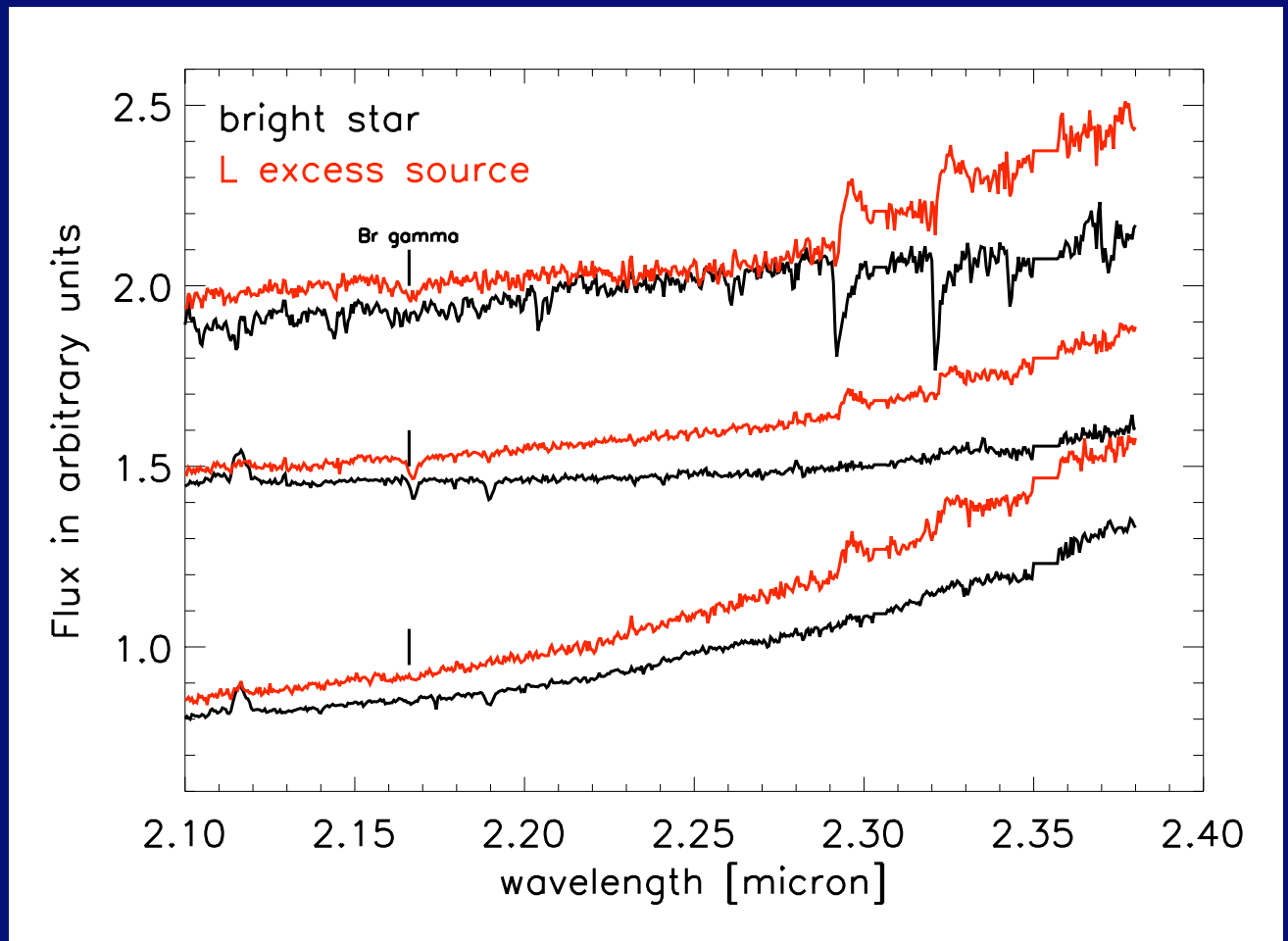


Properties of excess sources:

- K-L ~ **2.5 - 3.0** mag
- H-K ~ 1.7 - 2.4 mag
- H mag suggests **5-15 Msun**

⇒ **Herbig Be stars with massive disks ?**

Herbig Be disks at 2.5 Myr ?



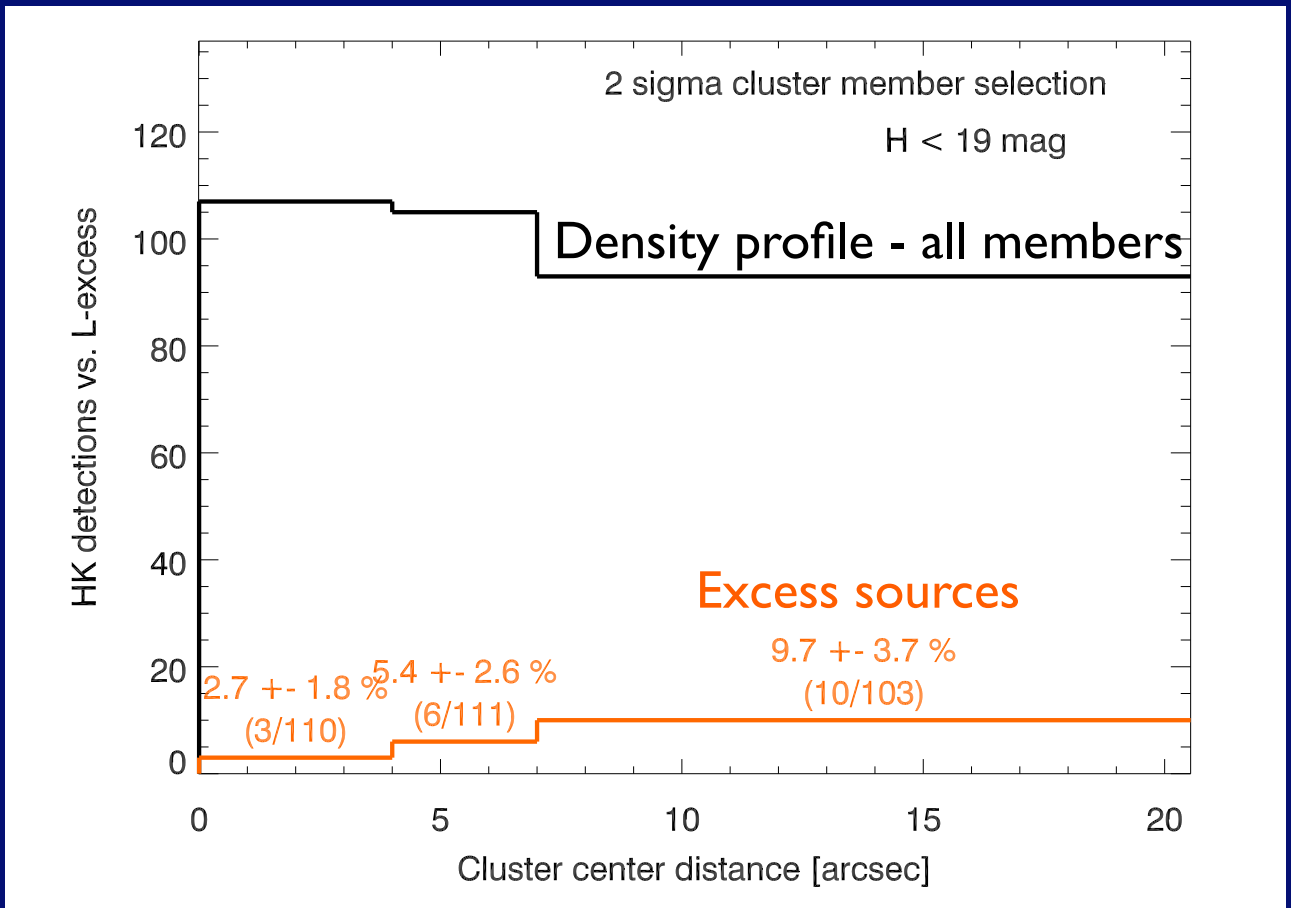
All excess sources with spectra display CO emission !!!

+ evidence of rotation in the blue wings...

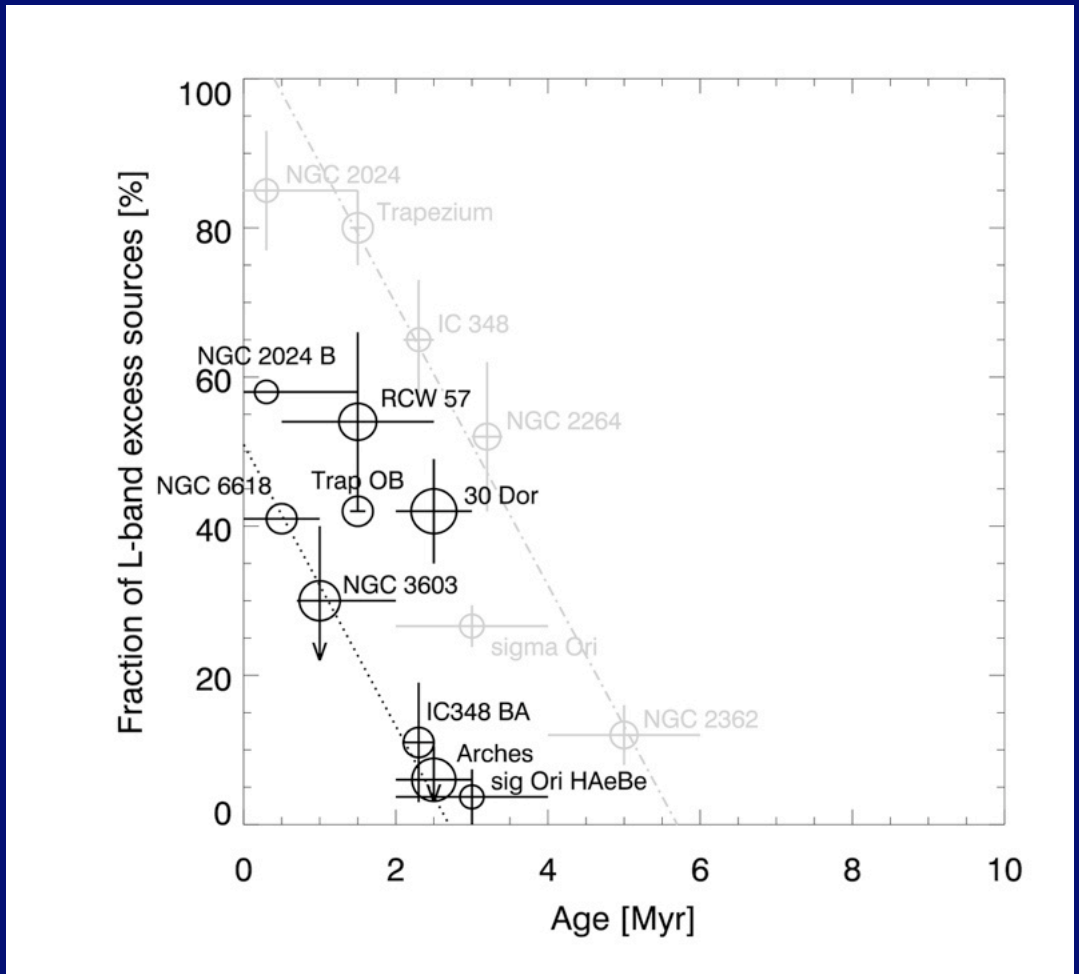
Photoevaporation and dynamical interactions

Starburst clusters host > 120 O-type stars

=> Disk destruction?!



Do starburst clusters have their own disc depletion timescale ?



Haisch et al. 2001

Hernandez et al. 2007

Hoffmeister et al. 2006

Maercker & Burton 2005

Maercker et al. 2006

Implications:

- low disc fraction at very early ages < 1 Myr => environement?

- the loss rate might be similar to low-density sf regions

=> dictated by the central star ?

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Mystery 1 - the orbital coincidence

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  Radial trend suggests depletion in the cluster center

  How do these disks survive ???

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Leiden: ***Simon Portegies Zwart, Stefan Harfst***
UCLA: ***Andrea Ghez, Mark Morris, Jessica Lu, Sylvana Yelda, Tuan Do, Chris Ballard, Elizabeth Mills***
MPIA: ***Wolfgang Brandner, Arjan Bik, Boyke Rochau, Natalia Kudryavtseva***

Summary - the Mystery deepens.....

Mystery 1 - the orbital coincidence

- **Precision astrometry yields proper motion in Arches & Quintuplet for the first time**

  Membership & orbital motion

- **Arches & Quintuplet are very unusual twins**

- **Arches unlikely to reach central parsec**

  1. not feeding young stars to the GC
  2. progenitors of central cluster NOT observed

  Indirect support for in-situ star formation

- **Cluster formation in the GC still a mystery**

Mystery 2 - dusty business !

- **Arches L-band excess sources display CO emission**

  Herbig Be disks

  Radial trend suggests depletion in the cluster center

How do these disks survive ???

Ideas solving these mysteries are welcome!

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Thanks!!!

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GC travelers - watch out for zooming starbursts !

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