MIKiS: the ESO-VLT Multi-Instrument Kinematic Survey of Galactic Globular Clusters

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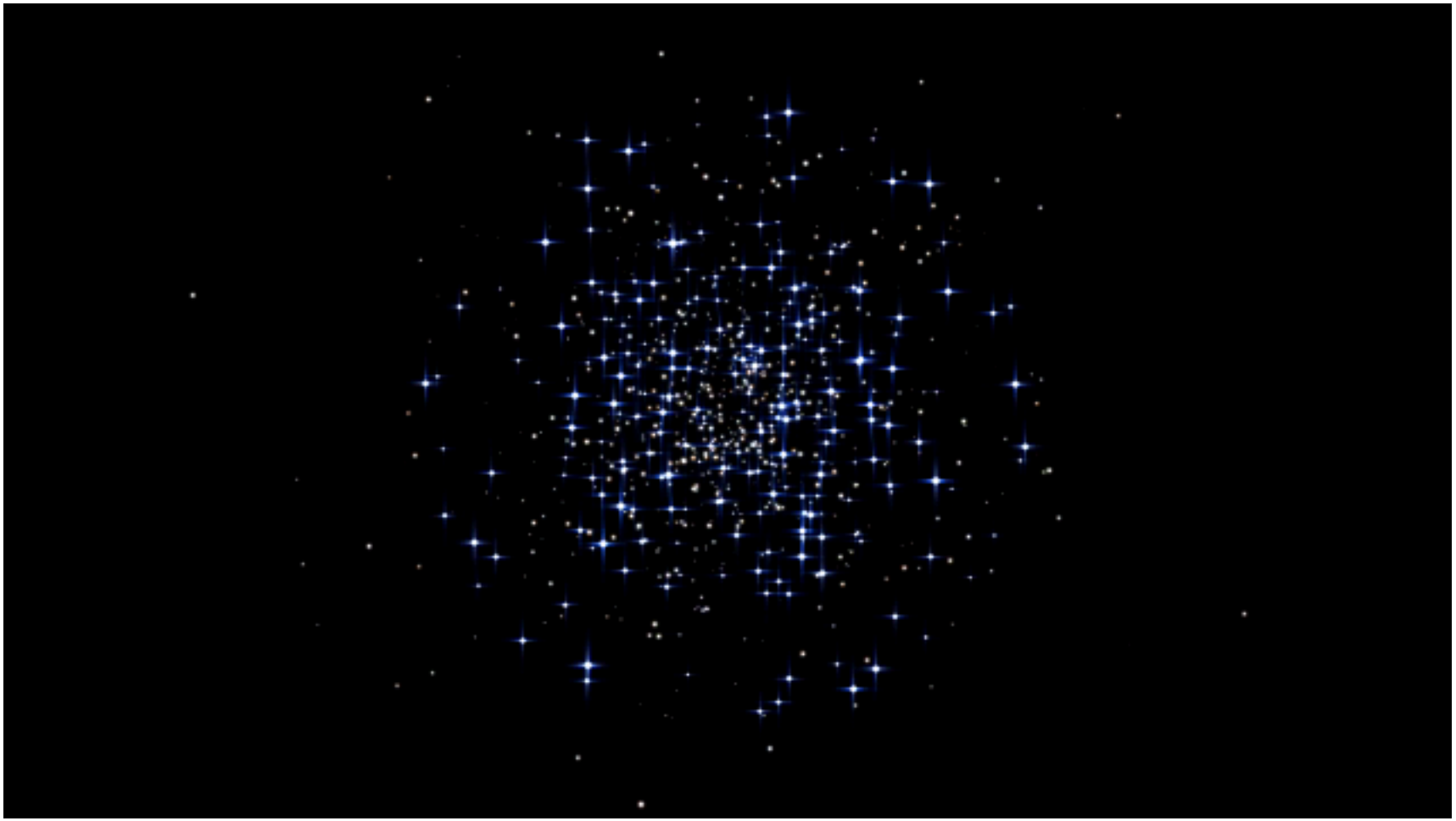
The MIKiS survey:
Multi Instrument Kinematic Survey of GGCs
MOS + NIR IFU SPECTROSCOPY

A survey specifically designed to exploit
the perfect synergy between
MOS facilities (FLAMES) and near infrared
IFU spectroscopy (KMOS+SINFONI)
with the aim of exploring
GC INTERNAL DYNAMICS

WHY GCs?



GC are the only stellar systems able to undergo nearly all the physical processes known in stellar dynamics over a time scale significantly shorter than the Hubble time.

Natural laboratories were multi-body dynamics can be studied.

THE GLOBAL PROJECT:
A NEW UNDERSTANDING OF THE PHYSICS OF COLLISIONAL SYSTEMS

1. A detailed study of **SPECIFIC EXOTIC POPULATIONS** used as gravitational probe-particles to describe the dynamical evolution of collisional systems

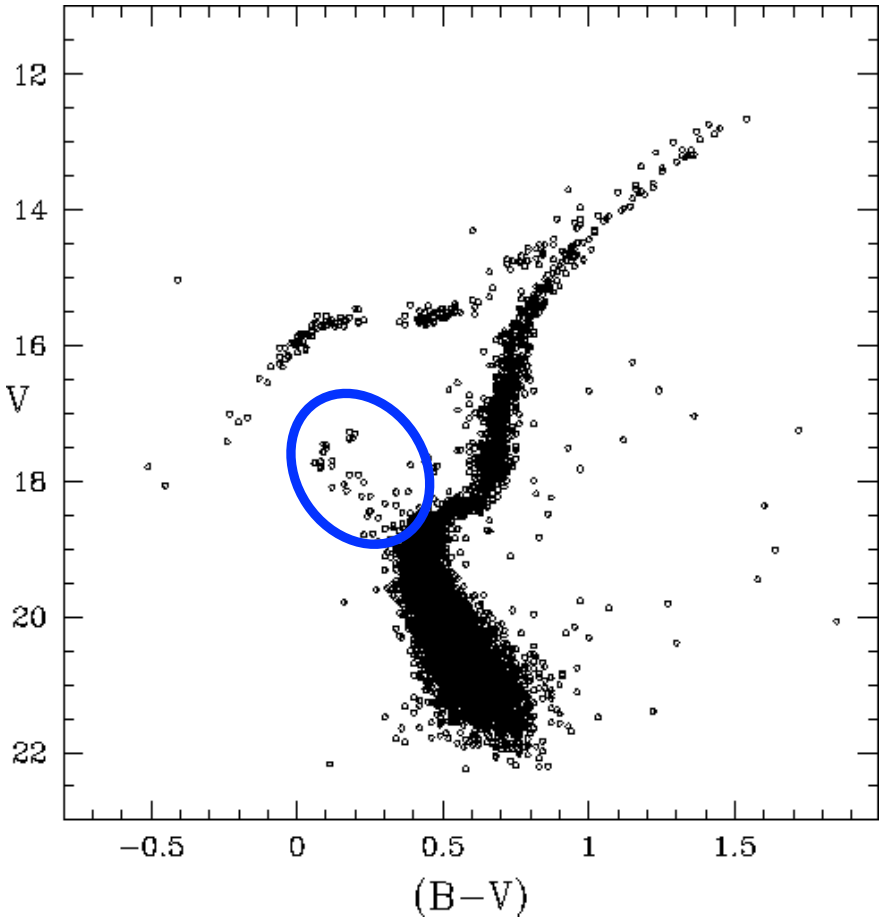
2. A full characterization of VD and rotation profiles
   3D view in velocity space, by combining PM (HST+Gaia) with **A NEW GENERATION OF VELOCITY DISPERSION & ROTATION PROFILES FROM THE RADIAL VELOCITY OF INDIVIDUAL STARS over the entire cluster extension**

Both approaches require a proper knowledge of the cluster structure (center of gravity, core radius, tidal radius,...) derived from resolved star counts

Blue Straggler Stars (BSS)

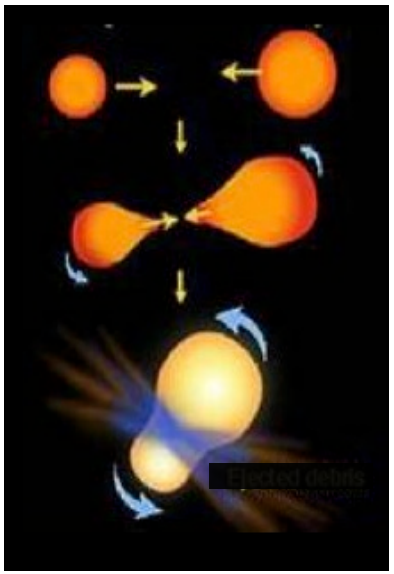
AN EXOTIC stellar population

stars brighter and bluer (hotter) than the cluster MS-TO

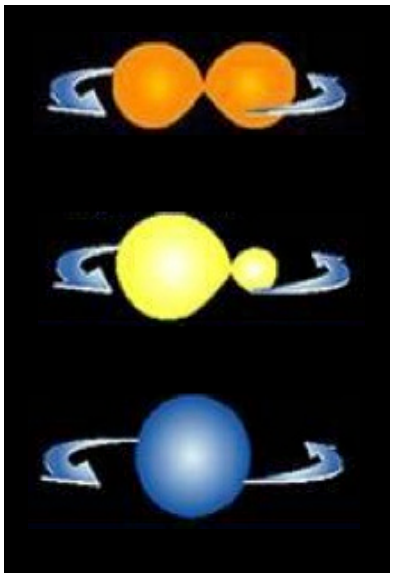


Their existence CANNOT be interpreted in terms of the evolution of a "normal" single star

COLLISIONS



MASS-TRANSFER



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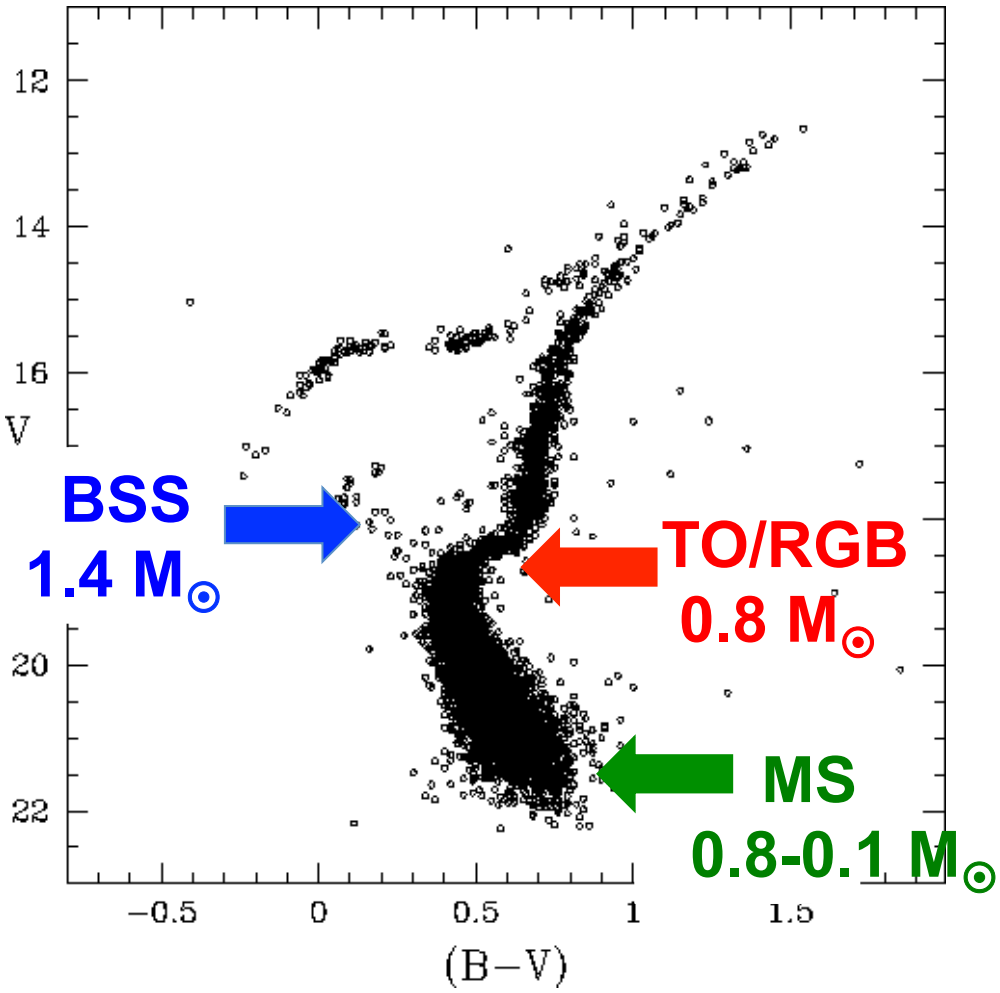


BSS
more massive
than normal stars

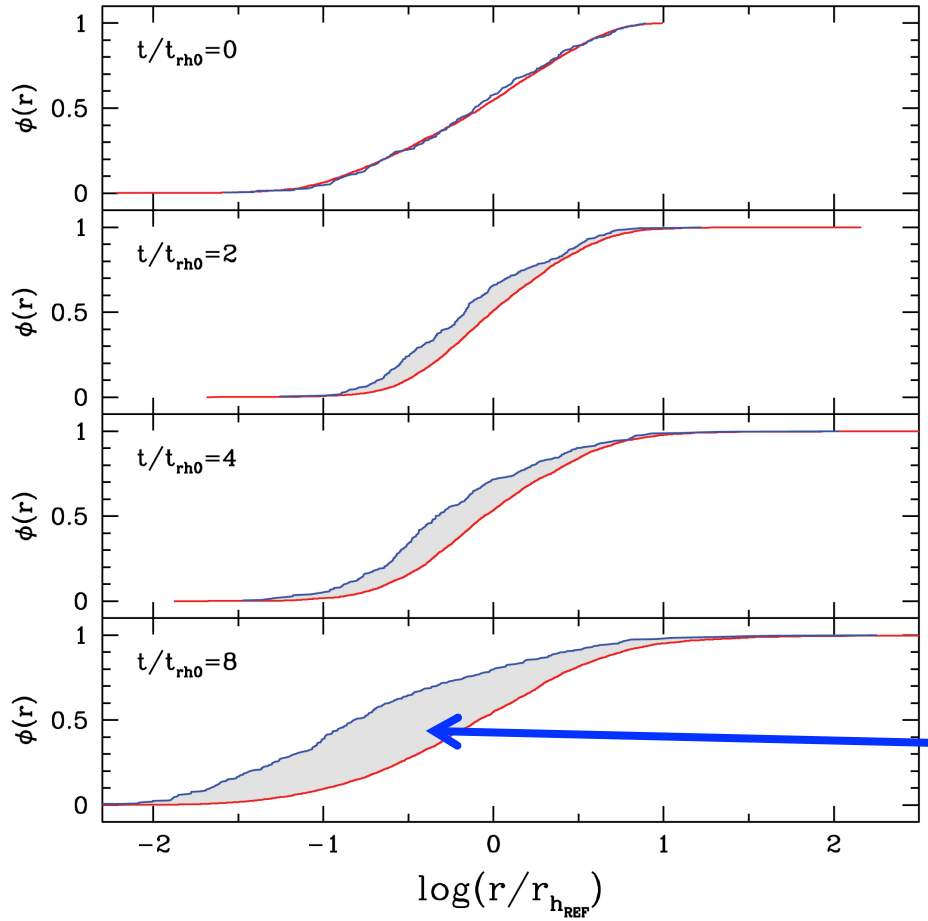
(see also Shara et al. 1997, Fiorentino et al 2014)

They are crucial gravitational probe-particles to test GC internal dynamical processes

The dynamical clock

Ferraro et al.12 (Nature,492,1028)+ Ferraro et al. 2018 (ApJ,860,36)

BSS are heavy stars (M_{BSS} = 1.2-1.4 $M_{\odot}$) orbiting a "sea" of "normal" light stars (M_{mean} = 0.4 $M_{\odot}$): they are subject to **Dynamical Friction (DF)** that progressively makes them sink toward the cluster center



Cumulative radial distributions as a function of time

BSS

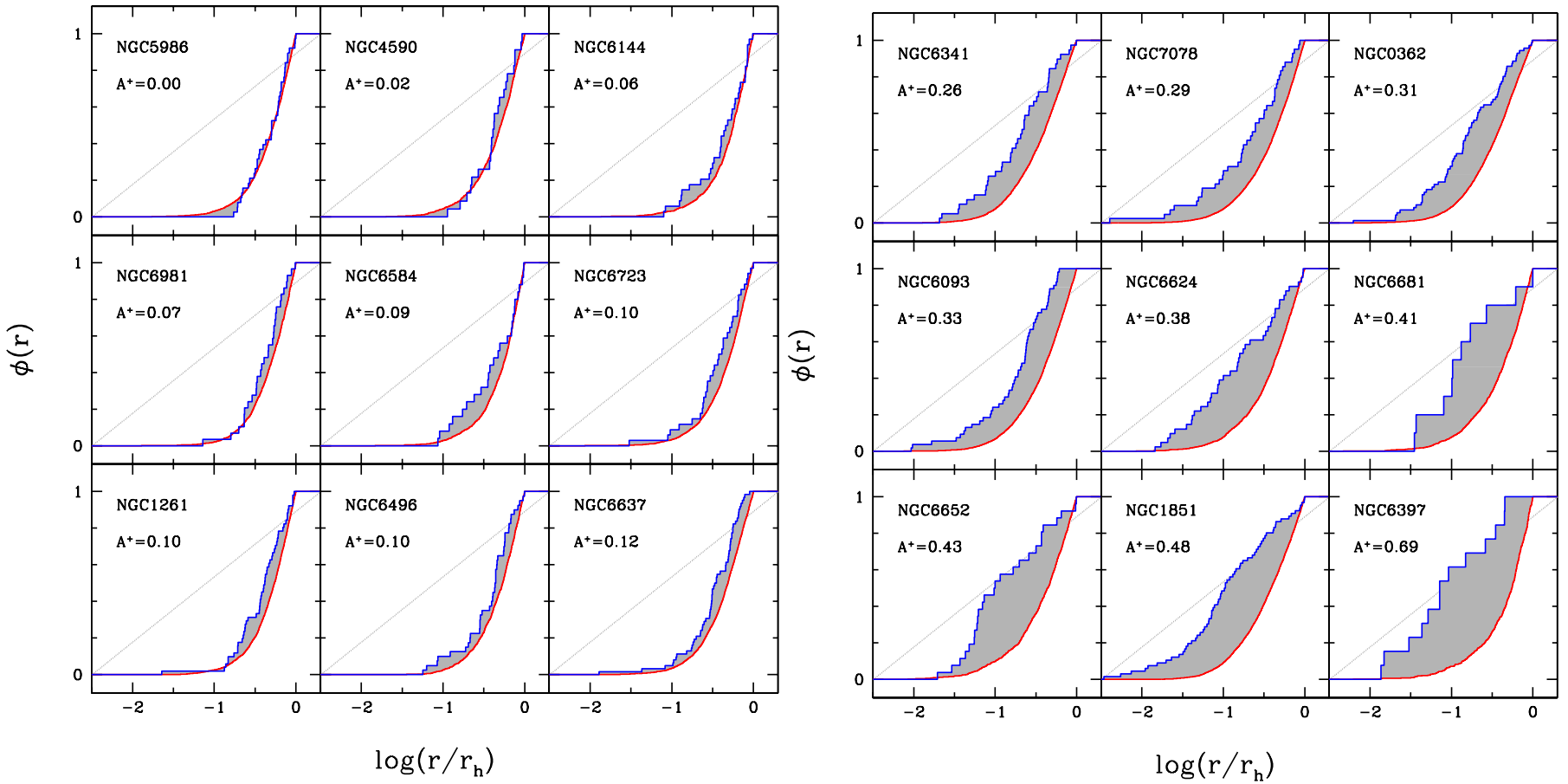
REF population

A+

Alessandrini+16, ApJ, 833,252

The dynamical clock

Ferraro et al.12 (Nature,492,1028)+ Ferraro et al. 2018 (ApJ,860,36)



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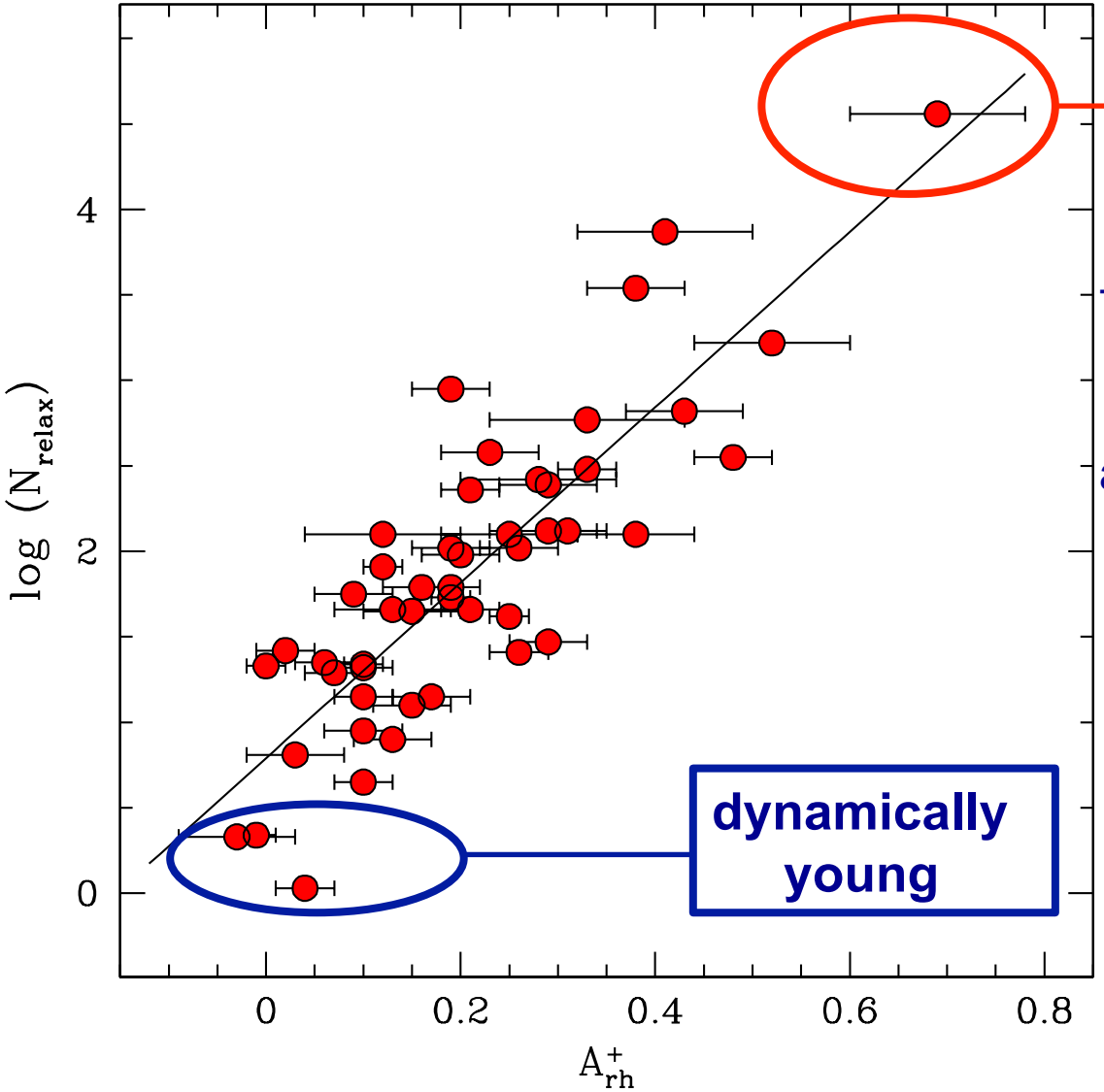

The sedimentation level of BSS (measured by the parameter **A+**) is a powerful empirical tool able to measure the **dynamical age** of a stellar system

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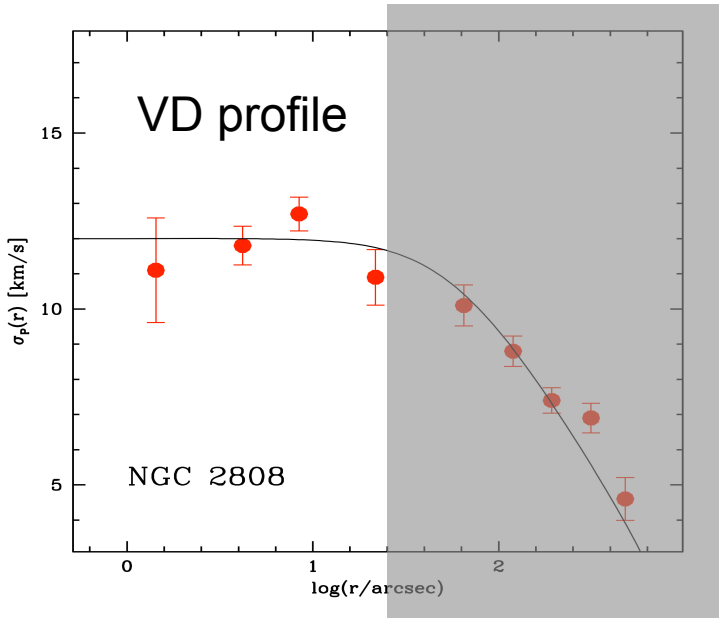
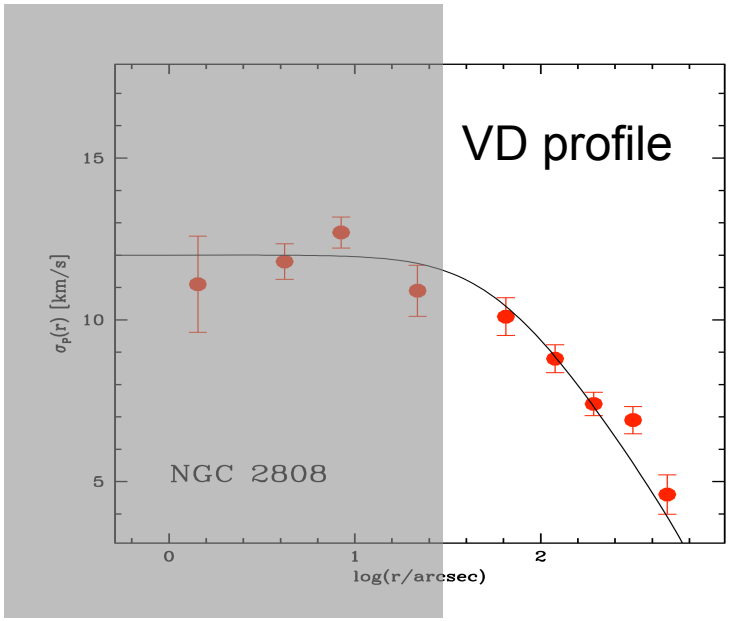
CENTRAL REGIONS

- Central VD cusp (IMBH !)
- High-velocity stars
- Rotation?
- Anisotropy?

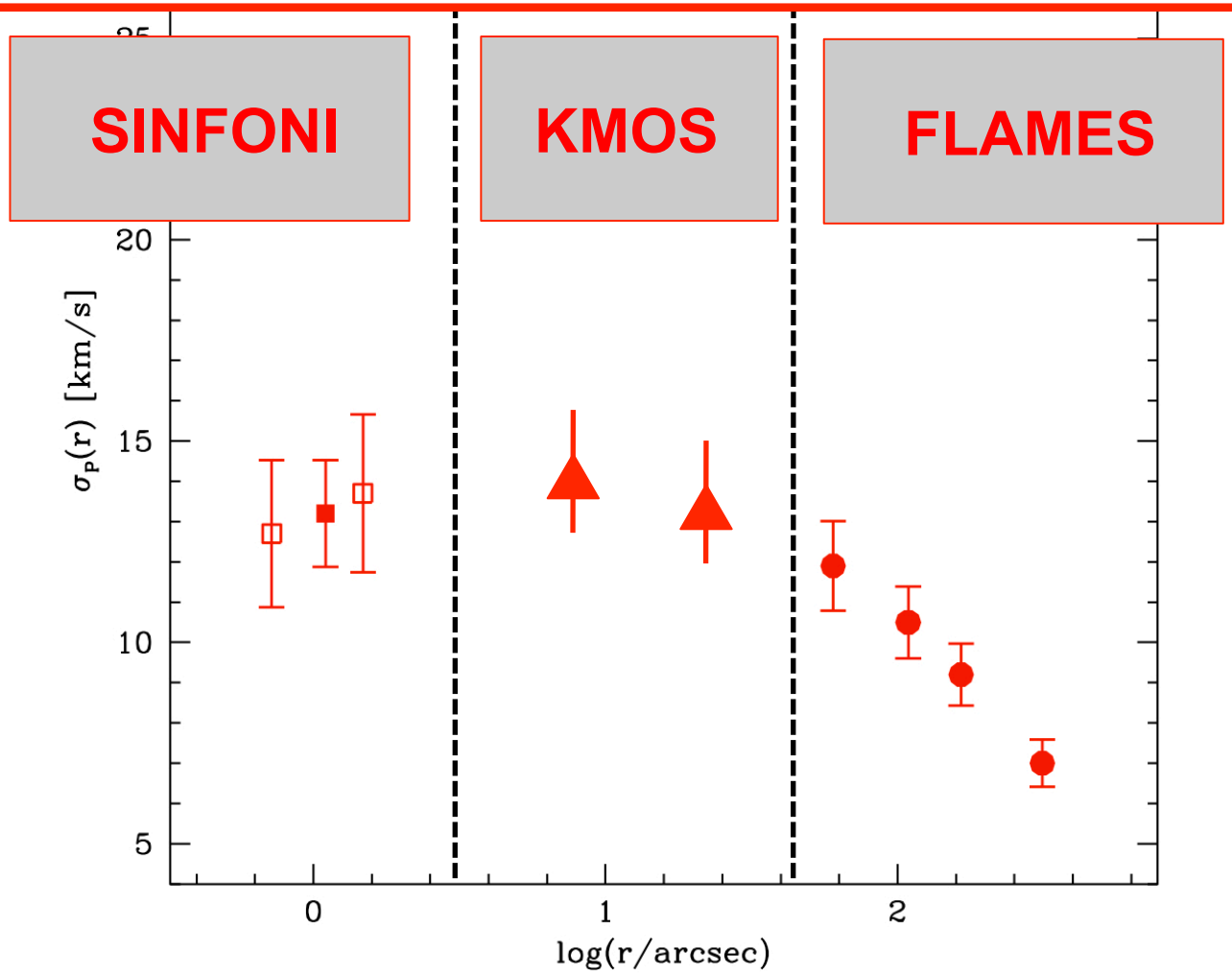




EXTERNAL REGIONS

- Rotation
- Potential escapers/ Extra-tidal tails
- Dark Matter??

THE ESO-VLT MIKiS survey:
a new generation of VD & ROTATION profiles
from the RADIAL VELOCITY of INDIVIDUAL STARS
using a MULTI-INTRUMENT approach



The MIKiS survey

Ferraro et al (2018,ApJ,860,50)

SINFONI

AO-assisted IFU, 0.1” spatial resolution, FoV=3.2”x3.2”/8”x8” mid-spectral resolution (R=4000), K-band grating (1.95-2.45 μm), CO band-heads

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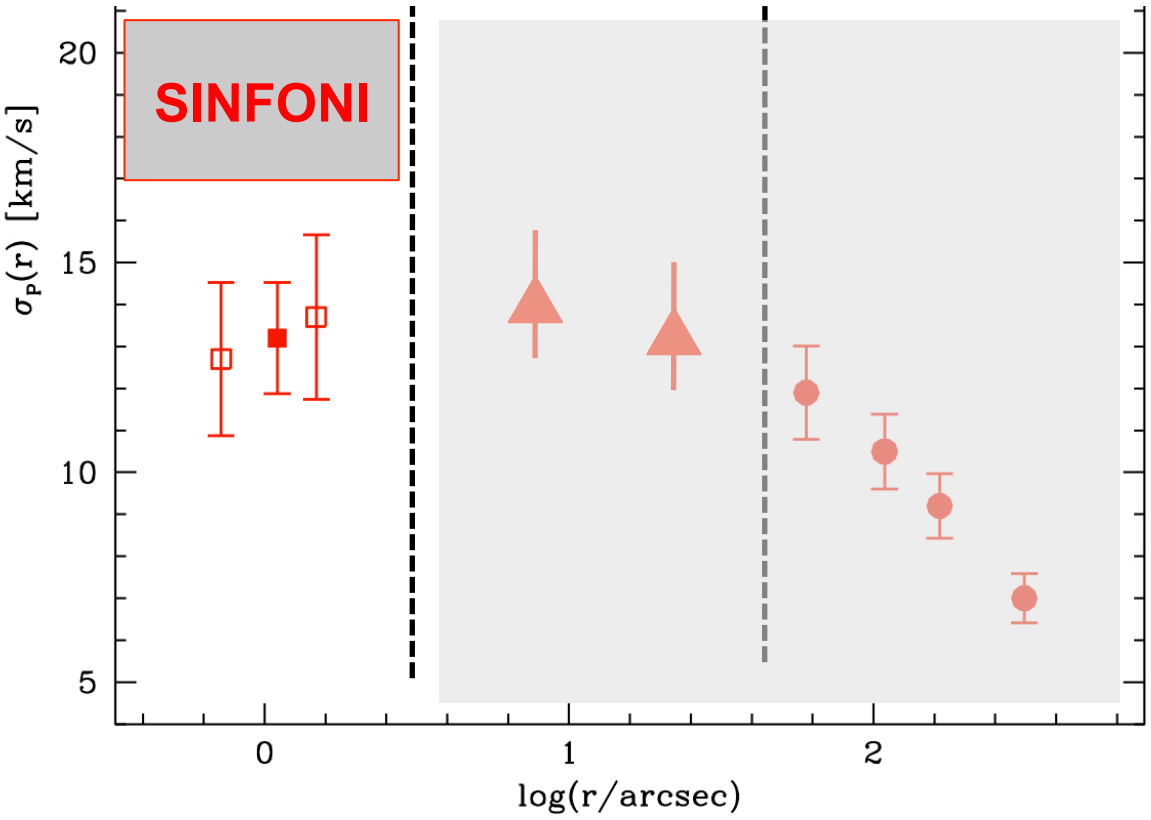
very central regions (AO)

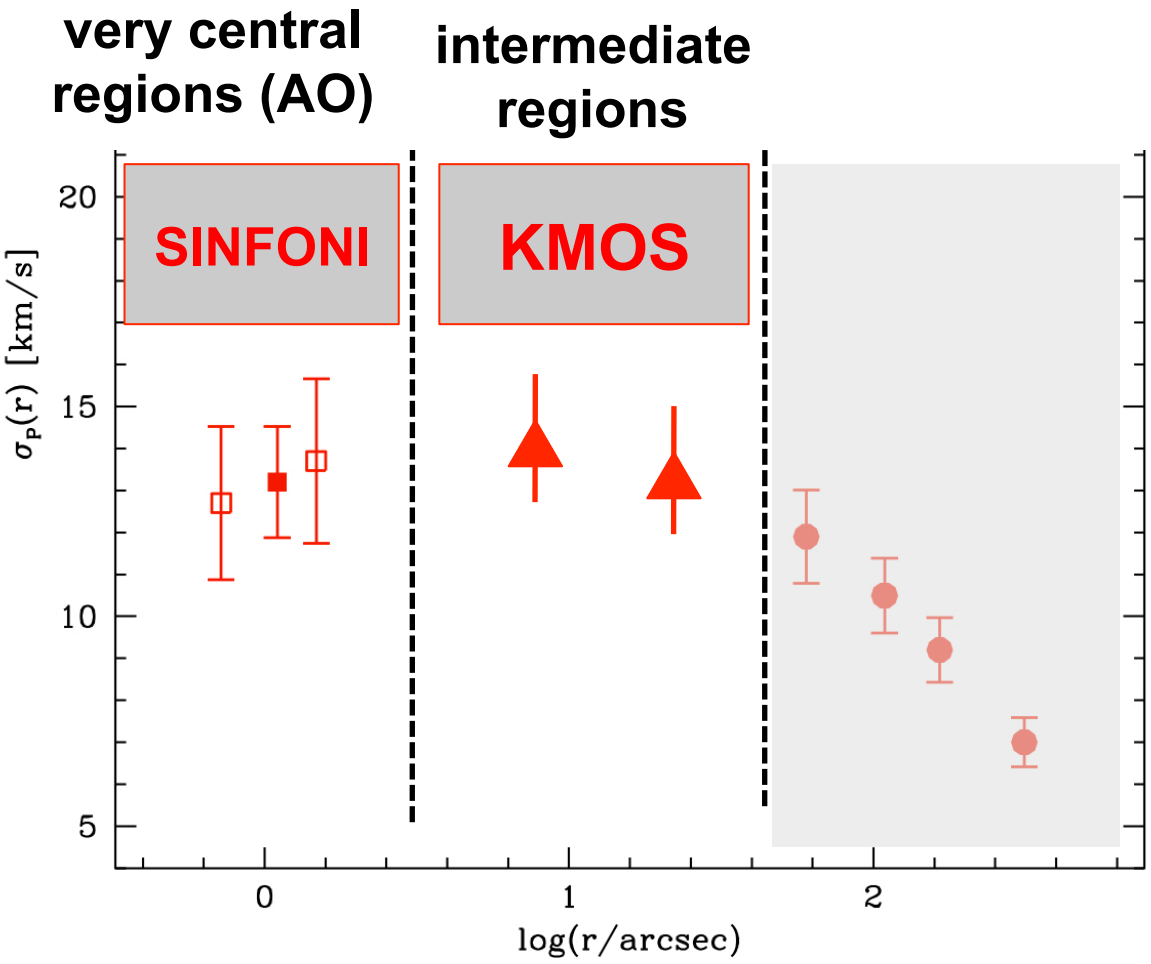


The MIKiS survey

Ferraro et al (2018,ApJ,860,50)

KMOS

24 deployable IFUs, FoV=3”x3” each,
mid-spectral resolution (R=3400), YJ-band grating (1.00-1.35 μm)
atomic lines (TiI, MgI, FeI,..)



The MIKiS survey

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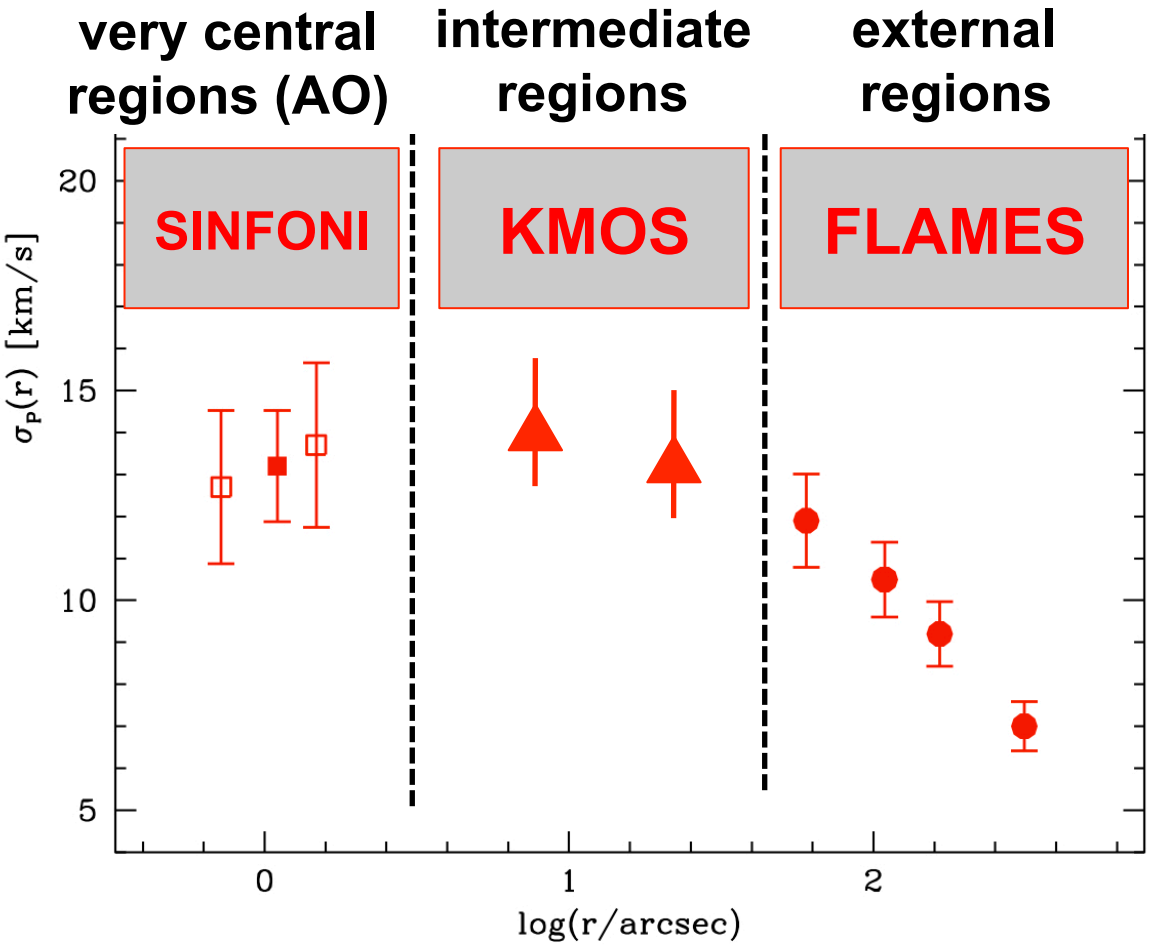
FLAMES

GIRAFFE/MEDUSA: multi-object spectrograph (132 fibres), 25' FoV
high spectral resolution (R>10,000),
HR 21 optical band (Ca triplet, Fe, MgI,...),



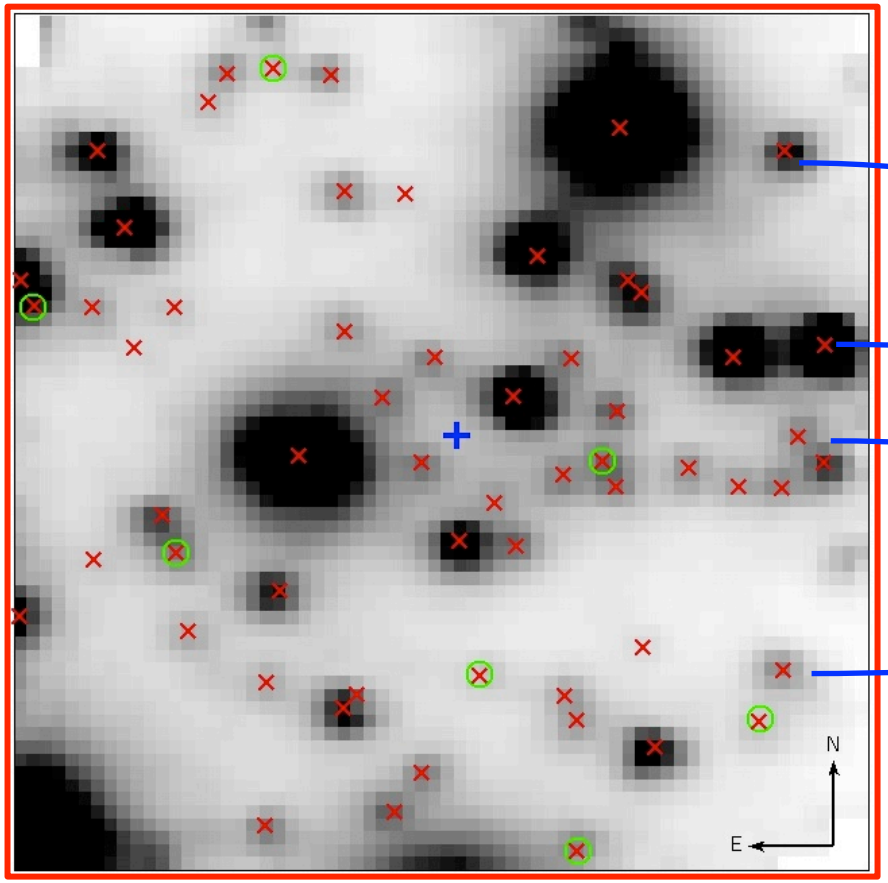
The MIKiS survey

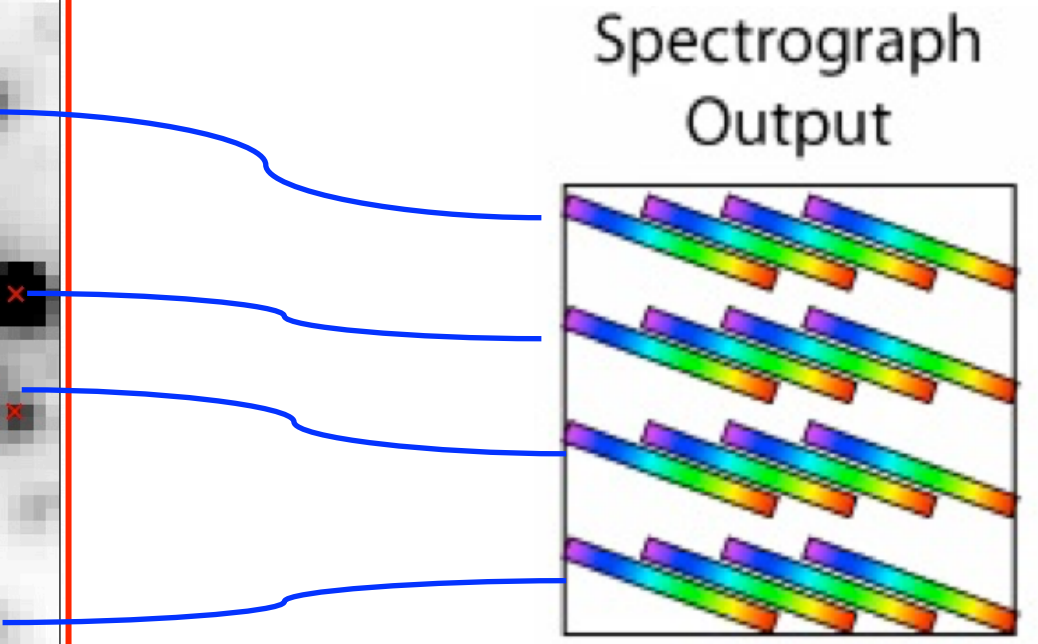
Ferraro et al (2018,ApJ,860,50)

IFU spectroscopy (SINFONI@VLT, KMOS@VLT, OSIRIS@Keck)

Unconventional use → extract a spectrum for every resolved star
(instead of integrated-light spectroscopy)

SINFONI RECONSTRUCTED

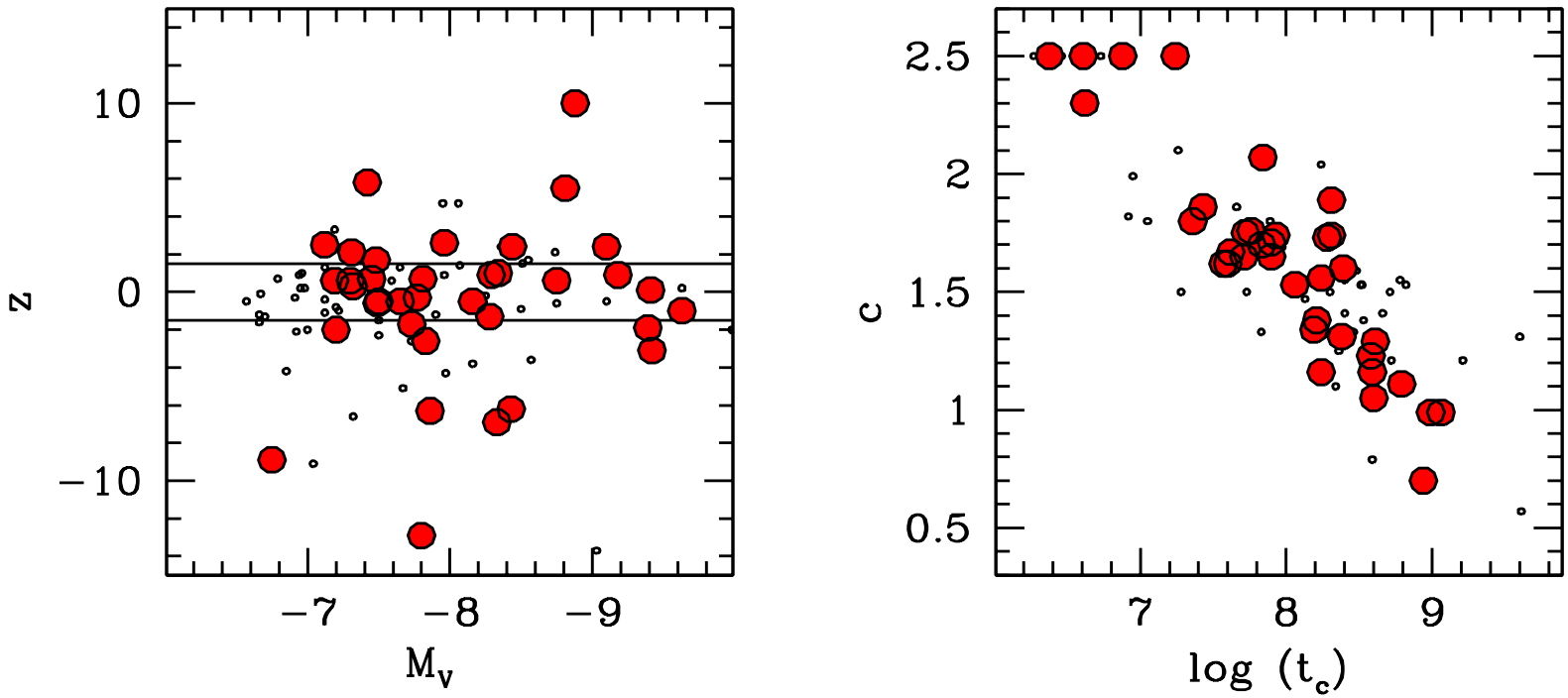




One spectrum for every (exposed) spaxel

The MIKiS survey: the sample

Ferraro et al (2018,ApJ,860,50)



(i) they are massive ($M > 5x10^5 M_\odot$)

(ii) they span a large range of Log **ρ**, c and relaxation times

(iii) they cover different stages of dynamical evolution, including PCC

(iv) They span different environmental conditions (sampling both the bulge/disk and the halo populations)

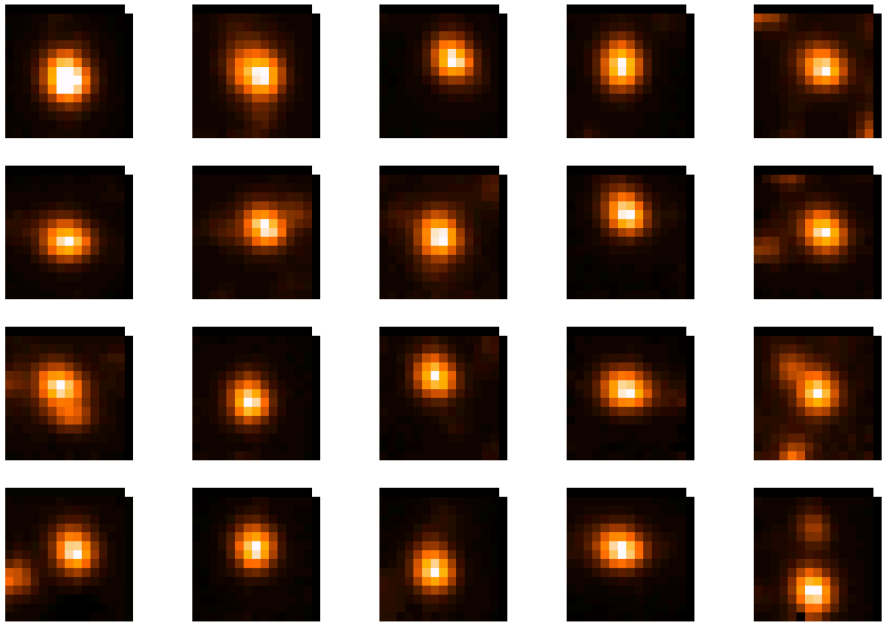
✦ **ESO LP 193.D-0232 (PI: Ferraro):** 194 hours (KMOS + FLAMES)

✦ **ESO LP 195.D-0750 (PI: Ferraro):** 101 hours (SINFONI)

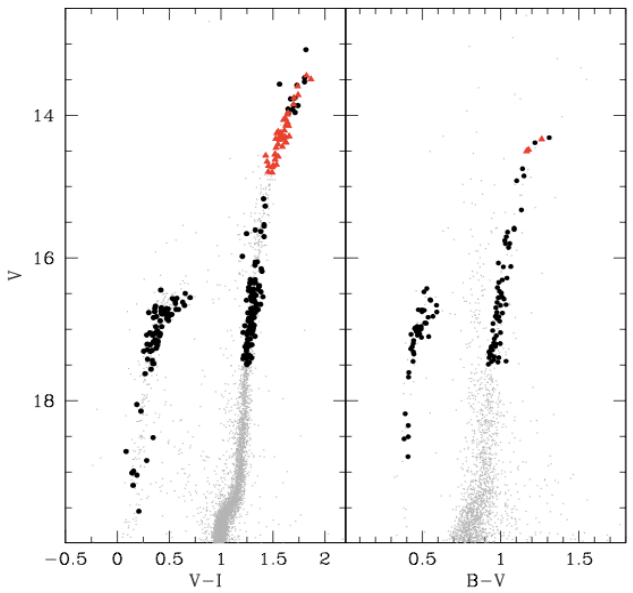
✦ **ESO pilot "normal" programes (PI: Ferraro/Lanzoni)**

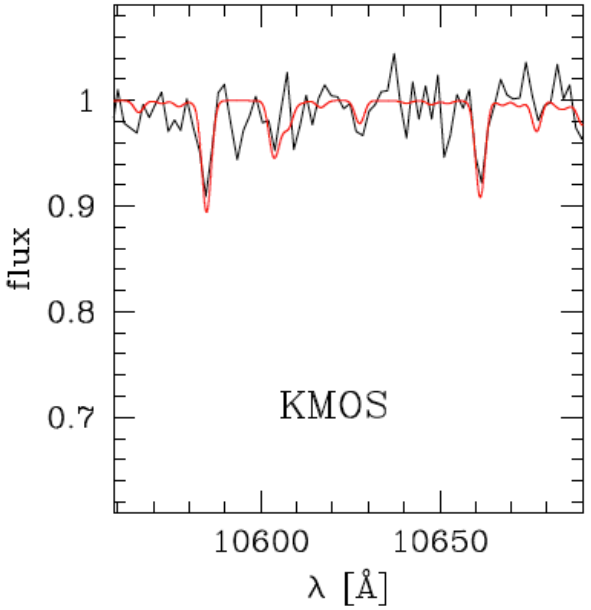
The MIKiS survey

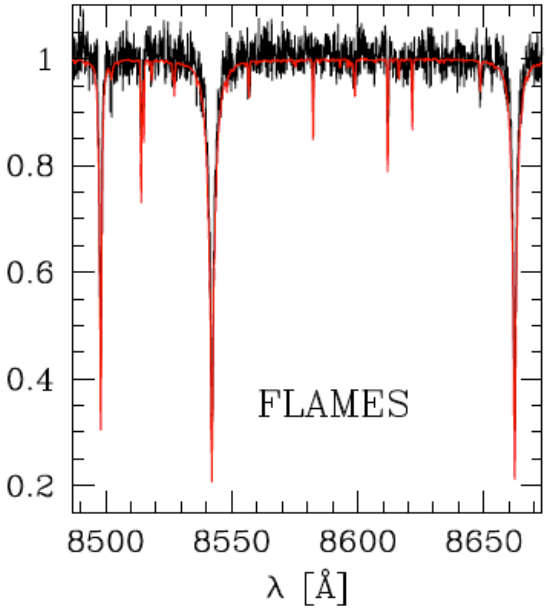
Ferraro et al (2018,ApJ,860,50)



RV measurements were obtained by cross-correlating observed spectra with a grid of synthetic templates of know velocities obtained by adopting the cluster metallicity and appropriate atmospheric parameters according to the evolutionary stage of the targets (essentially RGB, AGB and HB stars)







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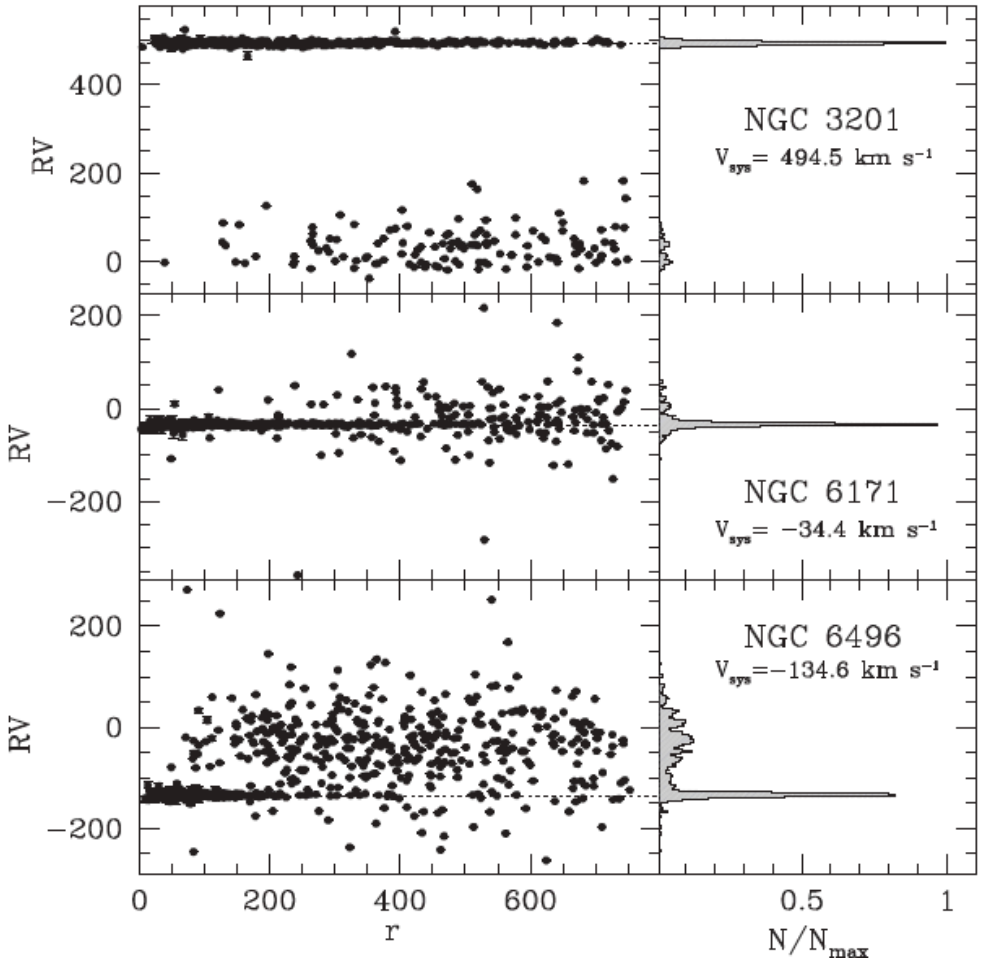
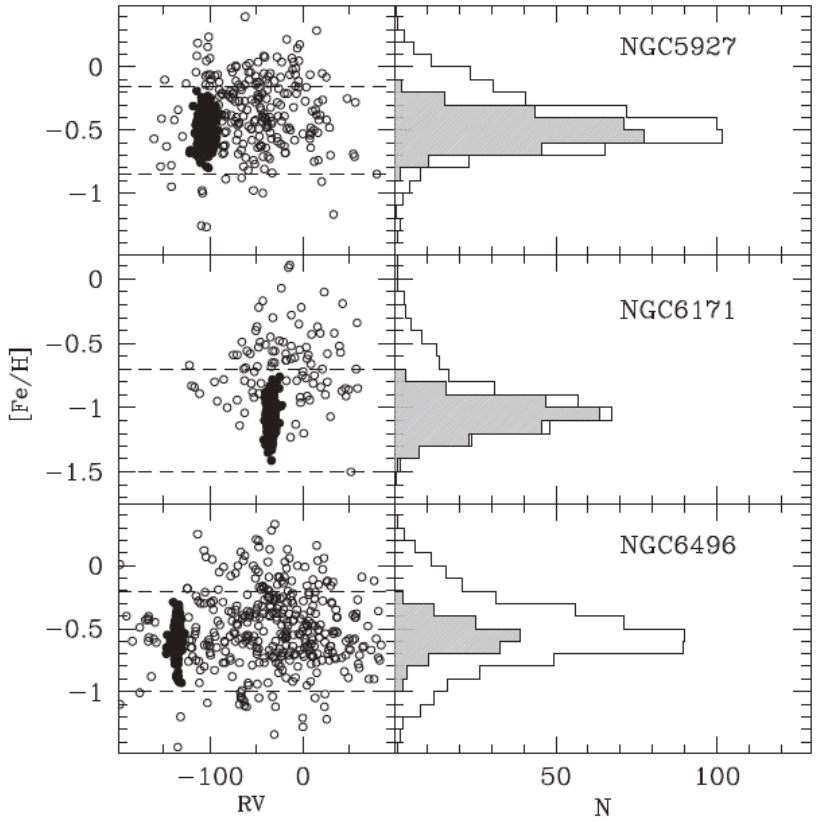


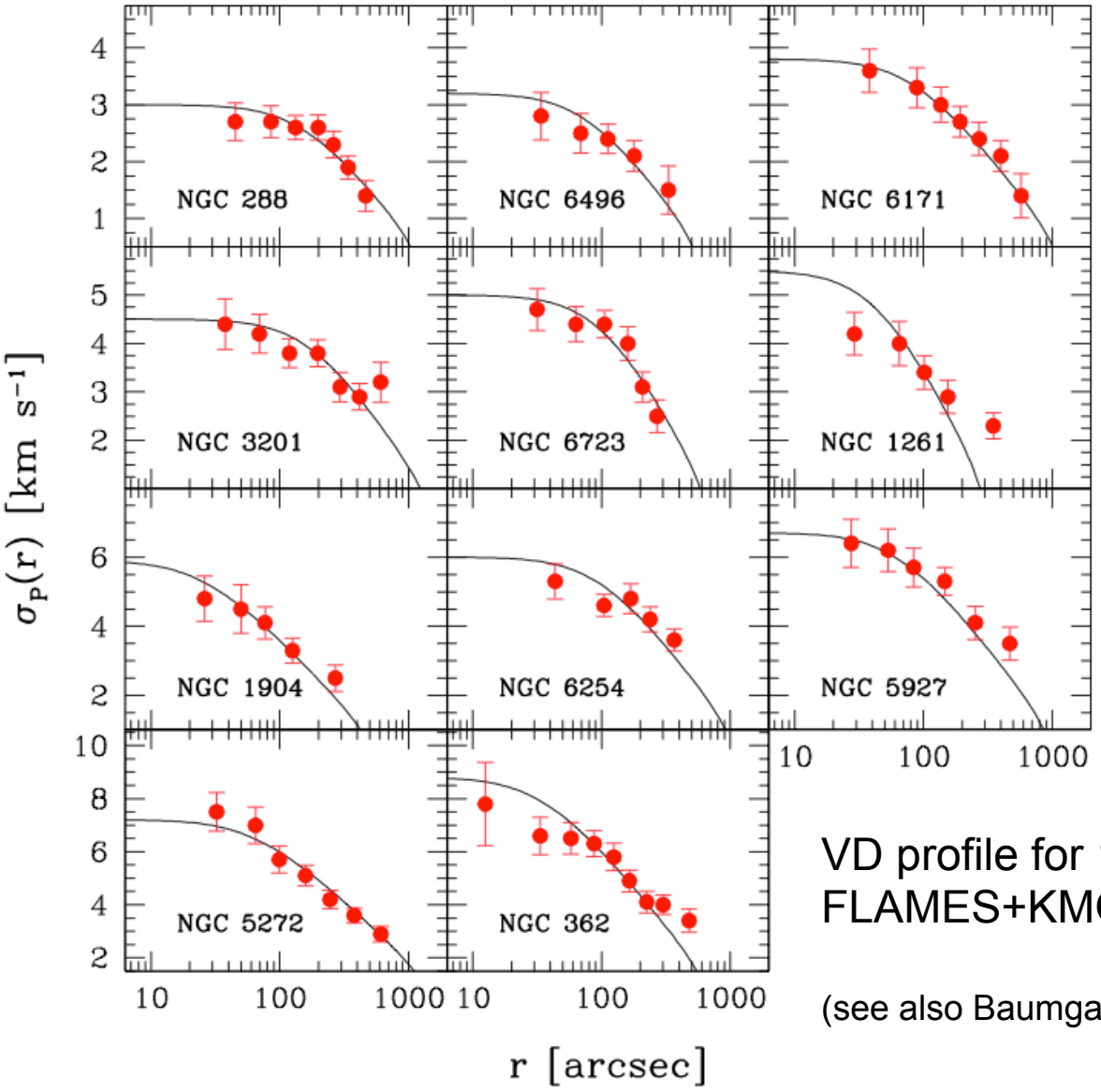
The population of cluster members is clearly distinguishable as a narrow, strongly peaked component, which dominates the sample at radii smaller than ~ 500″ .



An additional constrain to the cluster membership can be obtained from the stellar metallicity

The MIKiS survey: VD Profiles

Ferraro et al (2018,ApJ,860,50)

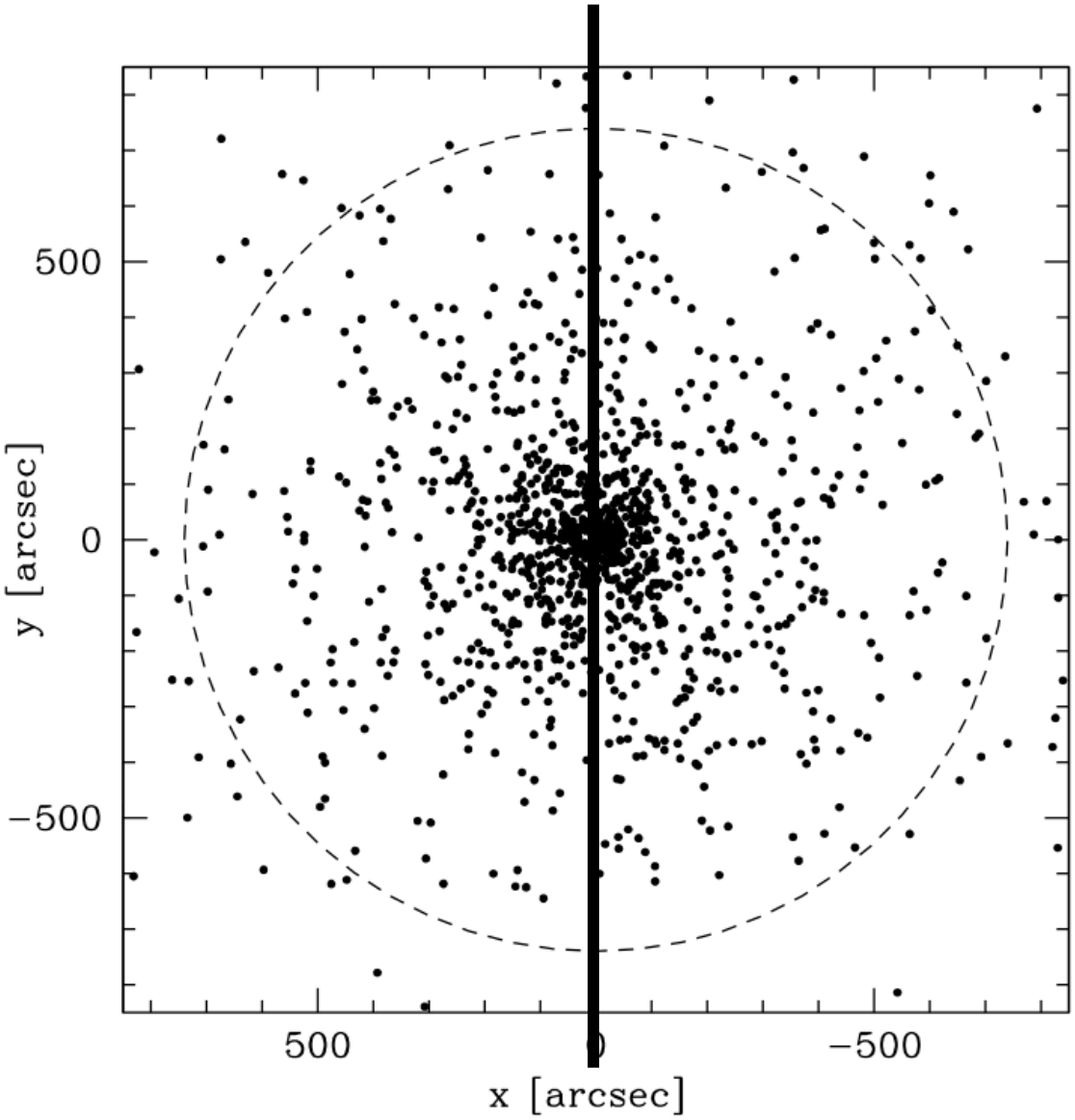


7000 stars in 11 GCs
sampling the clusters
up to several half-mass radii

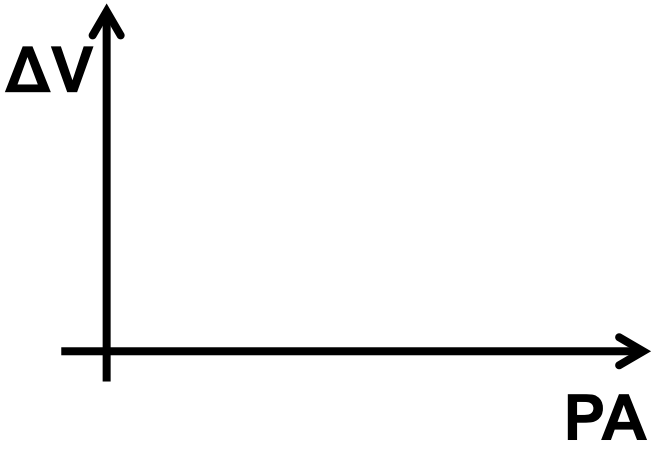
VD profile for 11 clusters for which only
FLAMES+KMOS observations were granted

(see also Baumgardt & Hilker, 2018 and Kaman et al 2018)

The MIKiS survey: Rotational velocity



$\Delta V = V2 - V1$

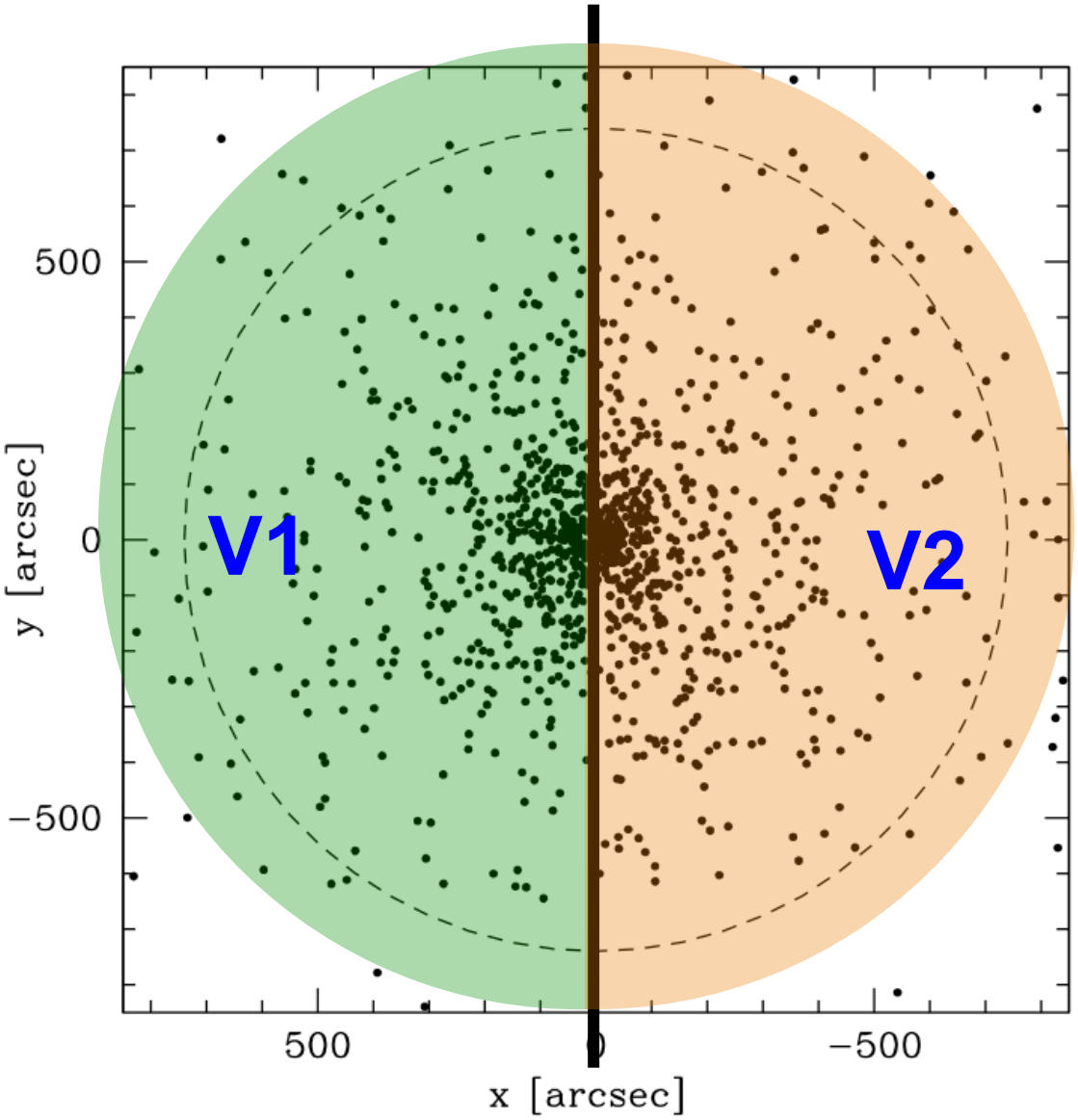


-split the RV data-set in 2 sub-samples with a line passing through the cluster center

- determine the difference between the mean velocity of the 2 groups

- repeat the procedure by varying the position angle (PA) of the splitting line

The MIKiS survey: Rotational velocity



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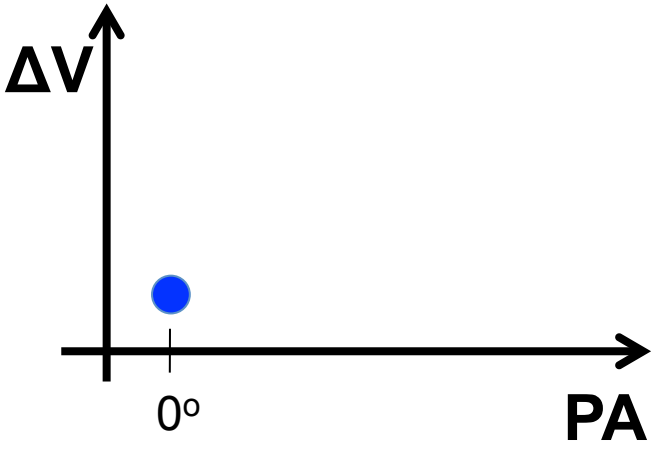

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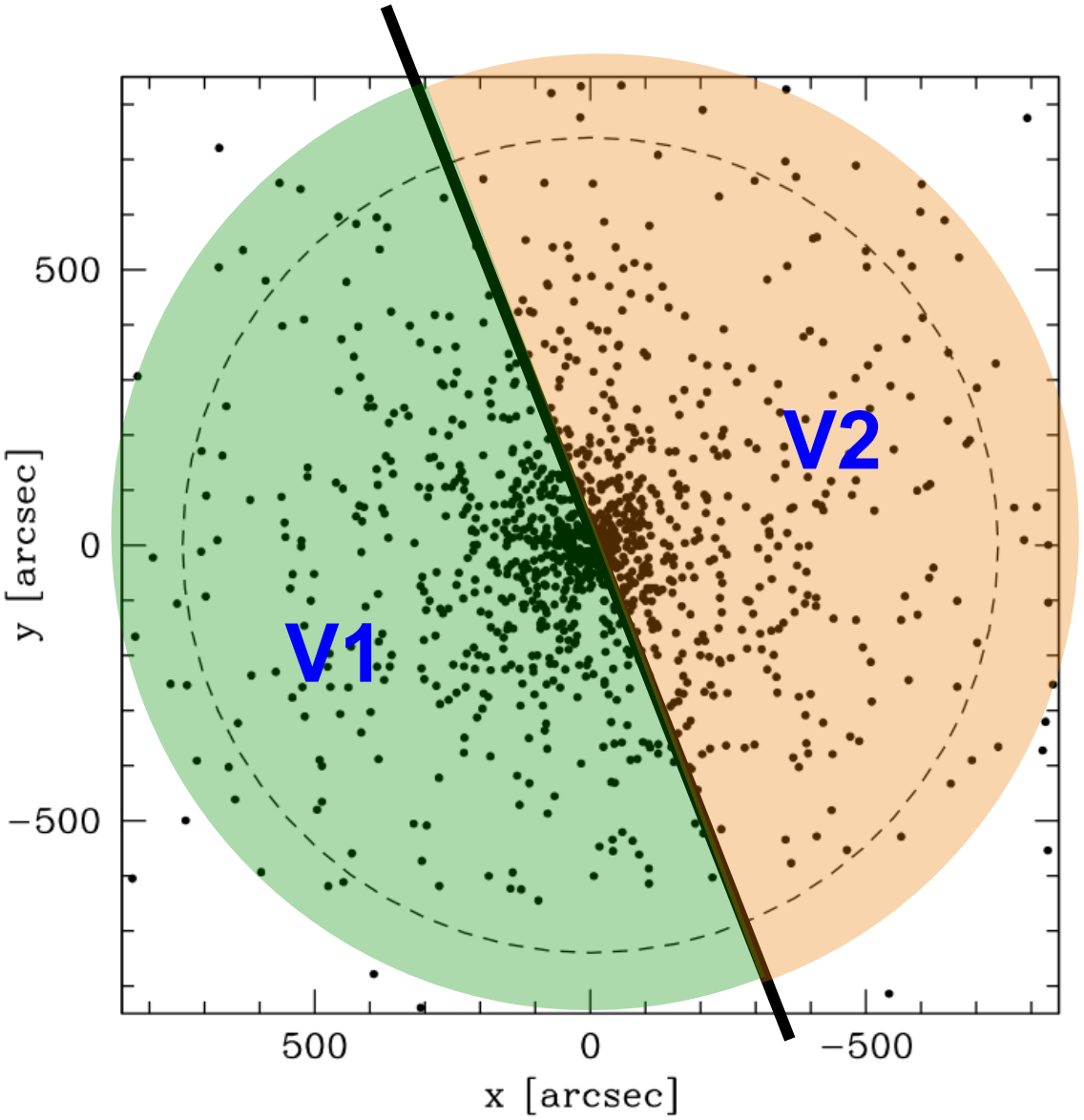

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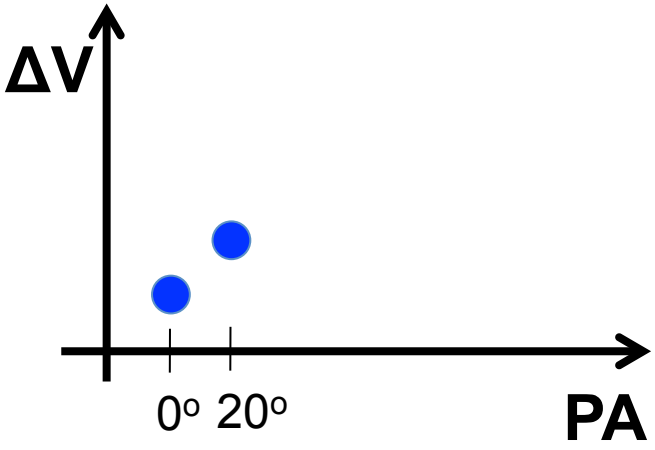

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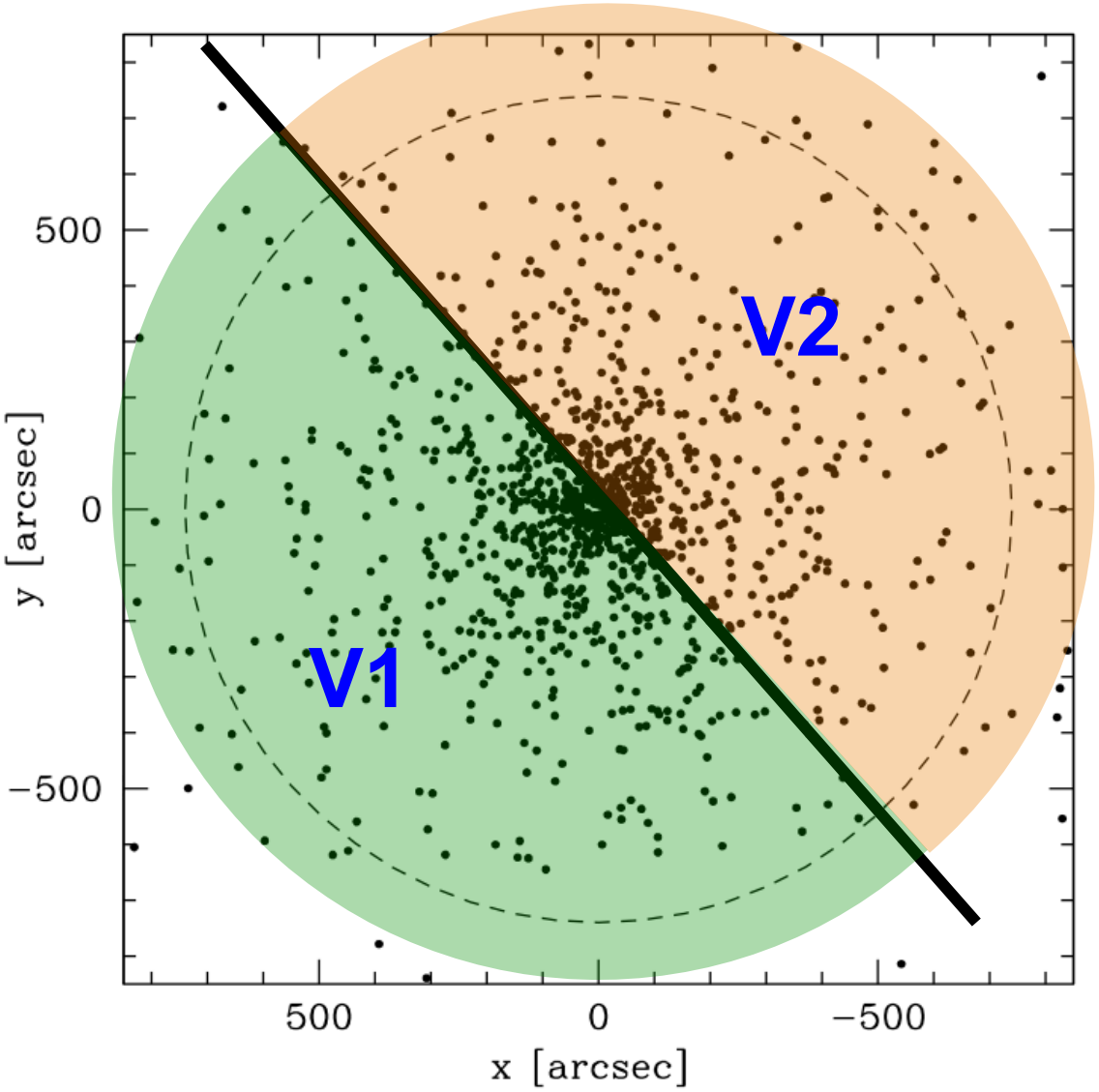

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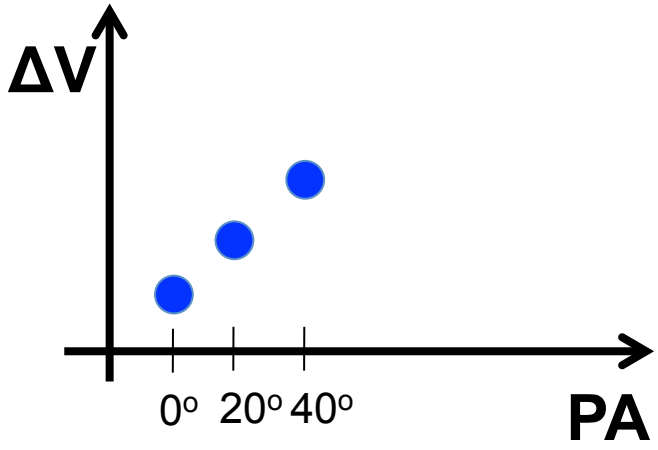

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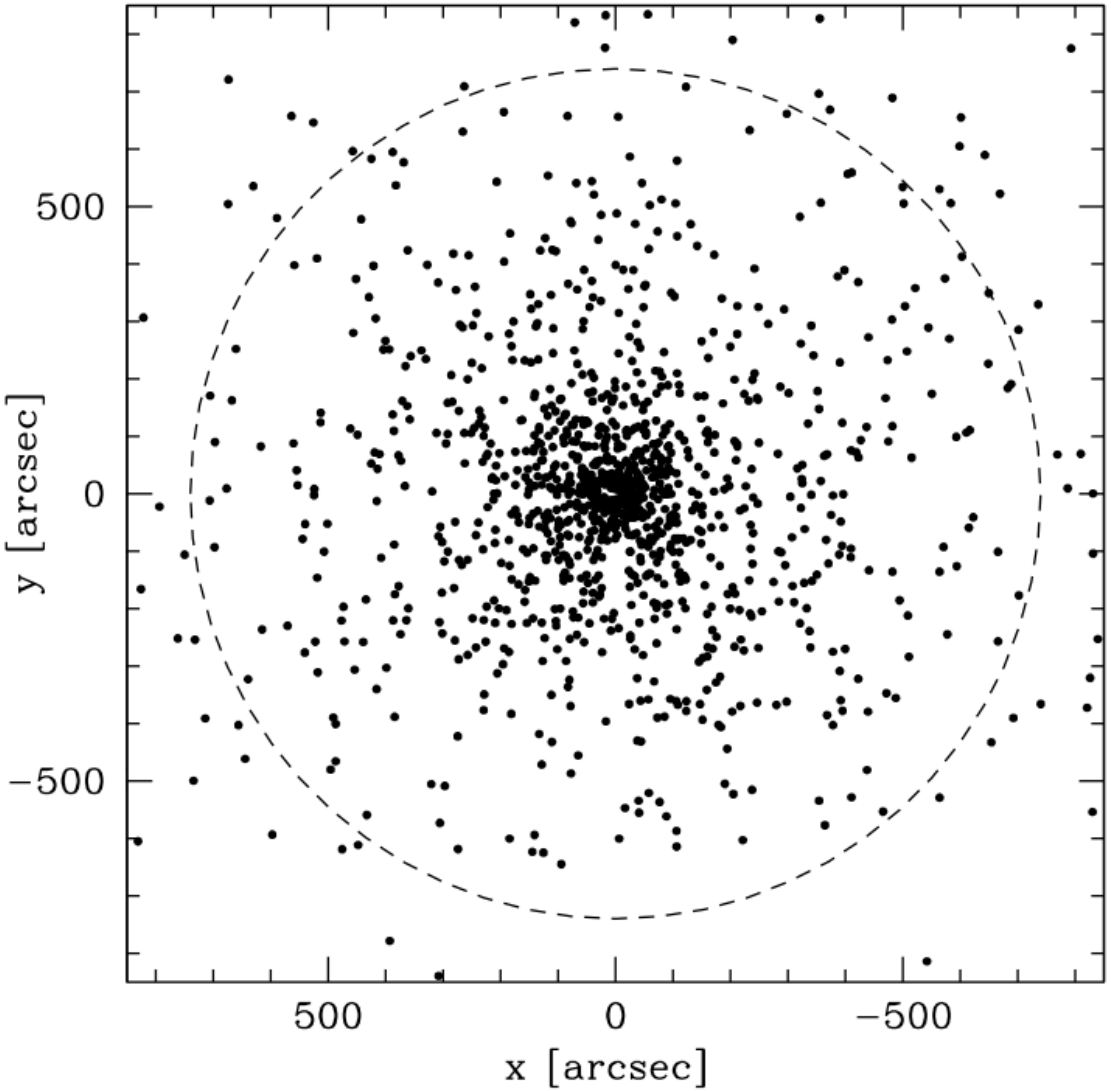

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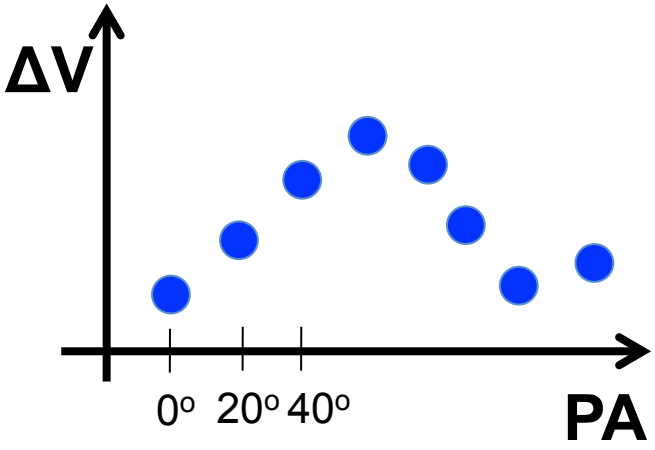

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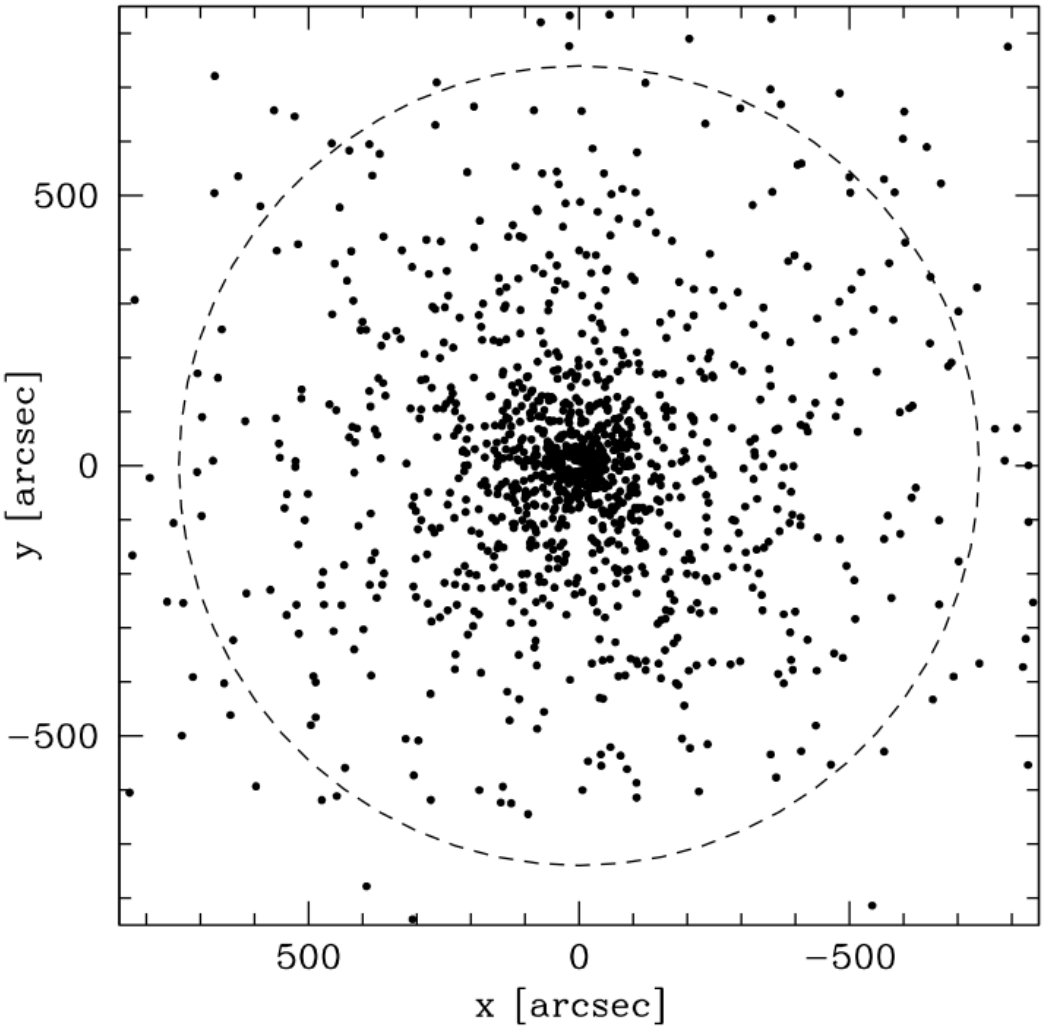

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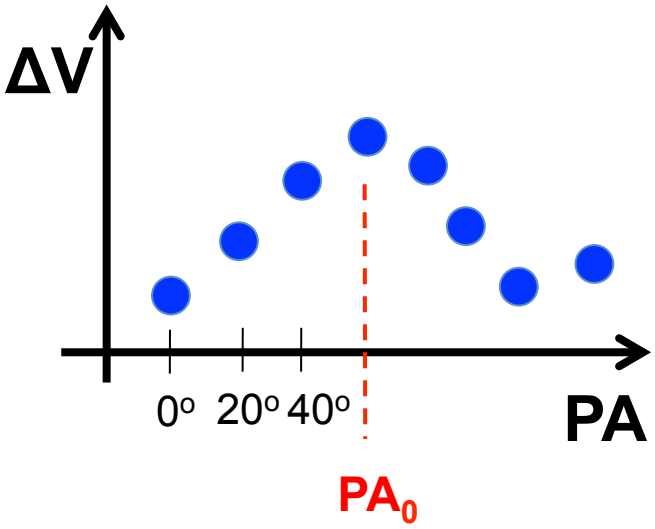
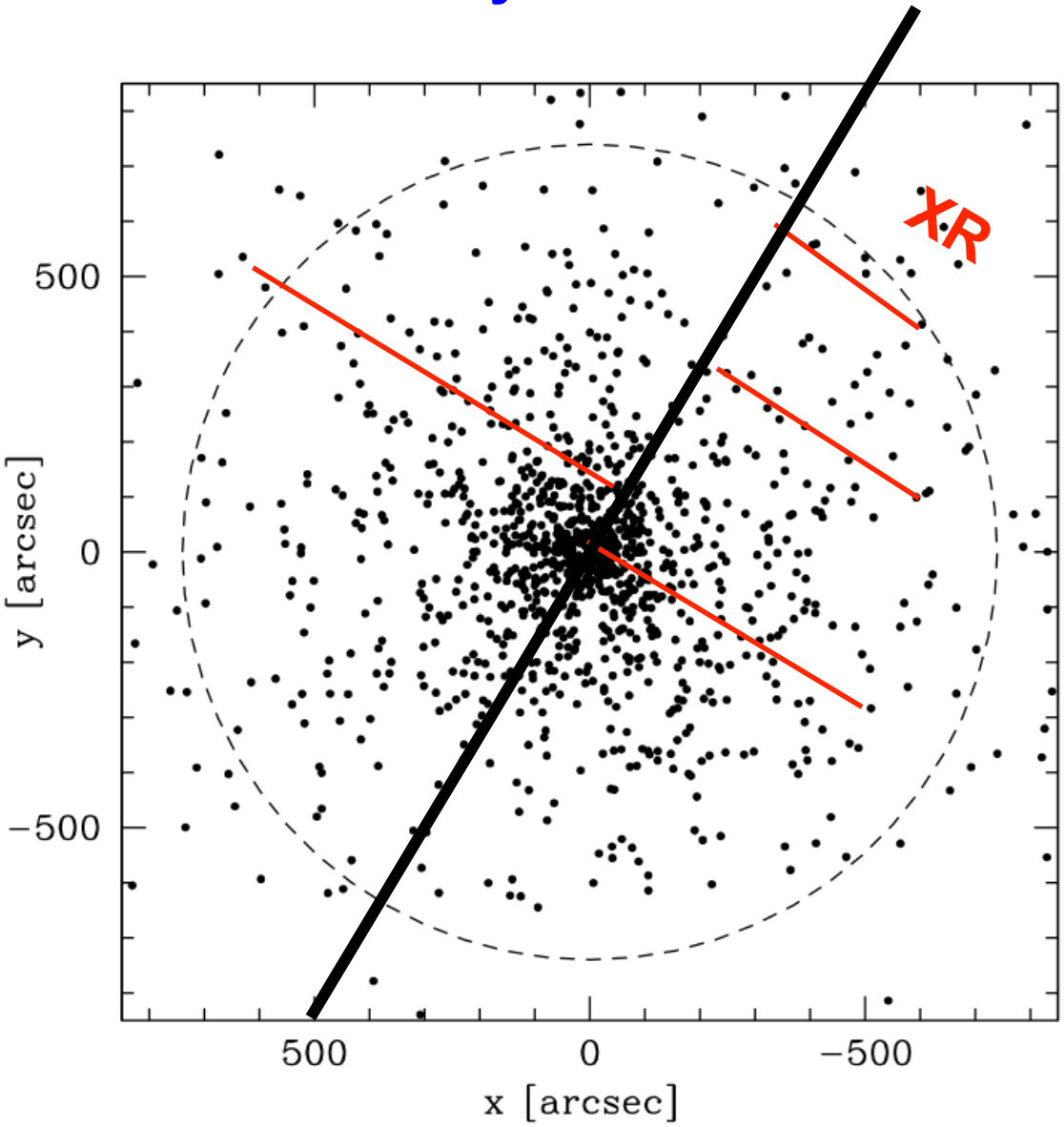


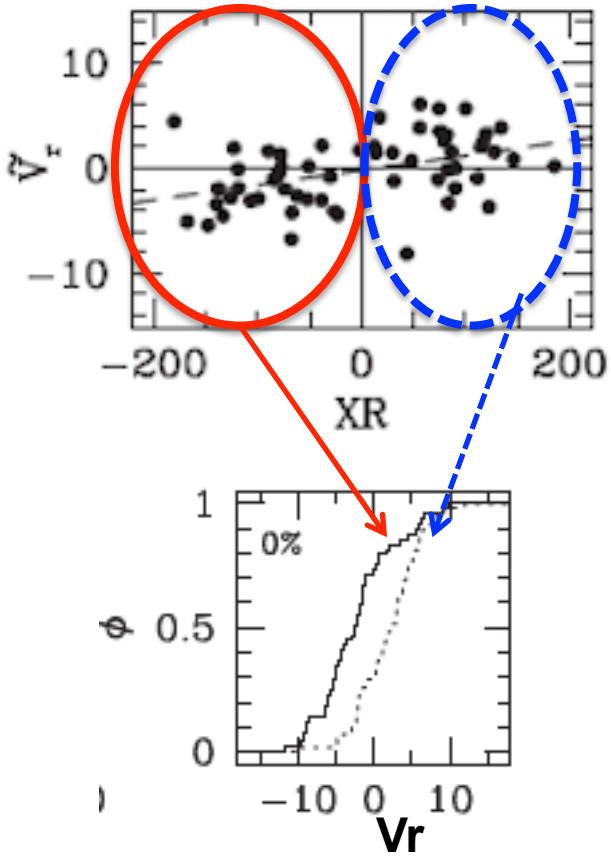
If the cluster is rotating, a **coherent sinusoidal pattern** is obtained and the **PA of the rotation axis** (PA_0) and the **amplitude** can be derived

The MIKiS survey: Rotational velocity



Once the PA_0 is set, we determine the projected distance XR of each star from the rotation axis.

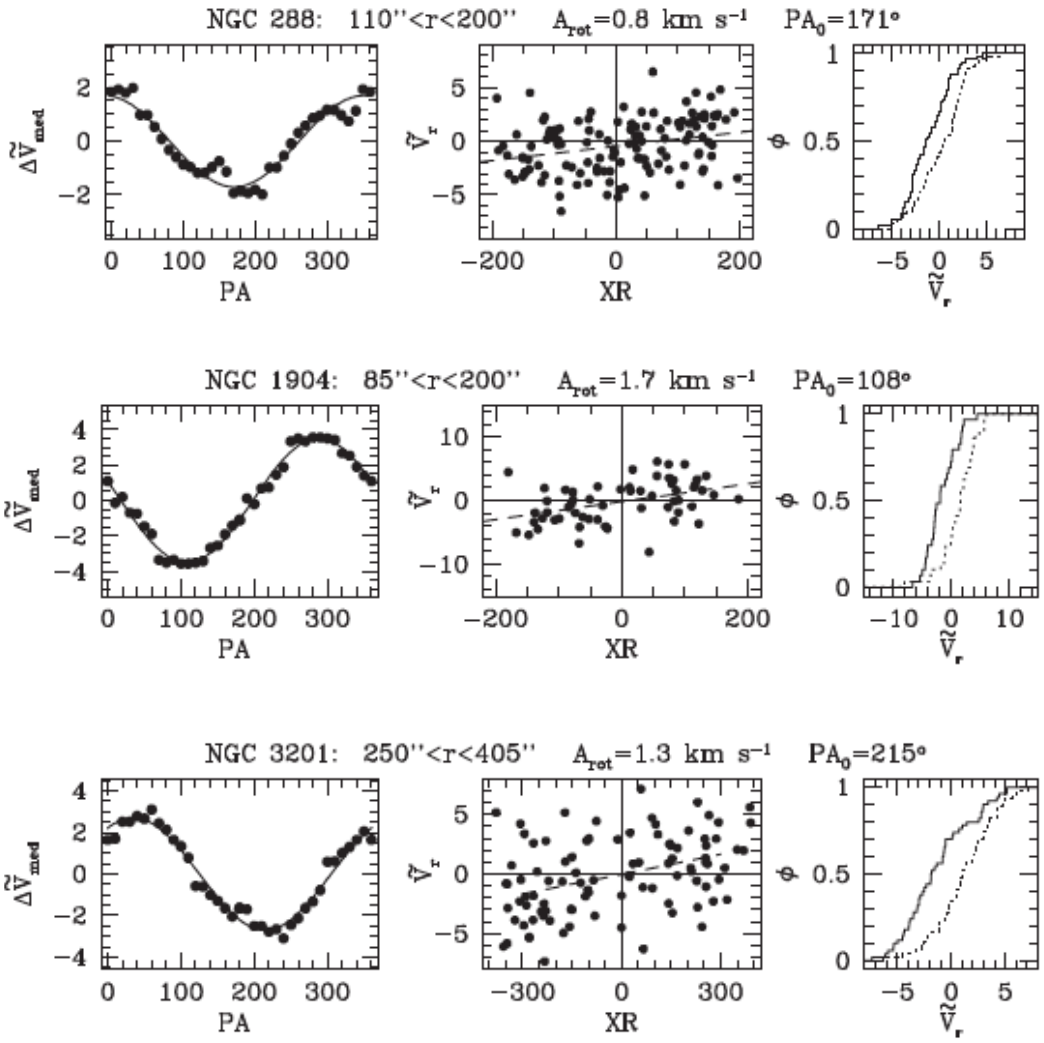
In the case of rotation, the stellar distribution in the RV-XR diagram shows a clear asymmetry

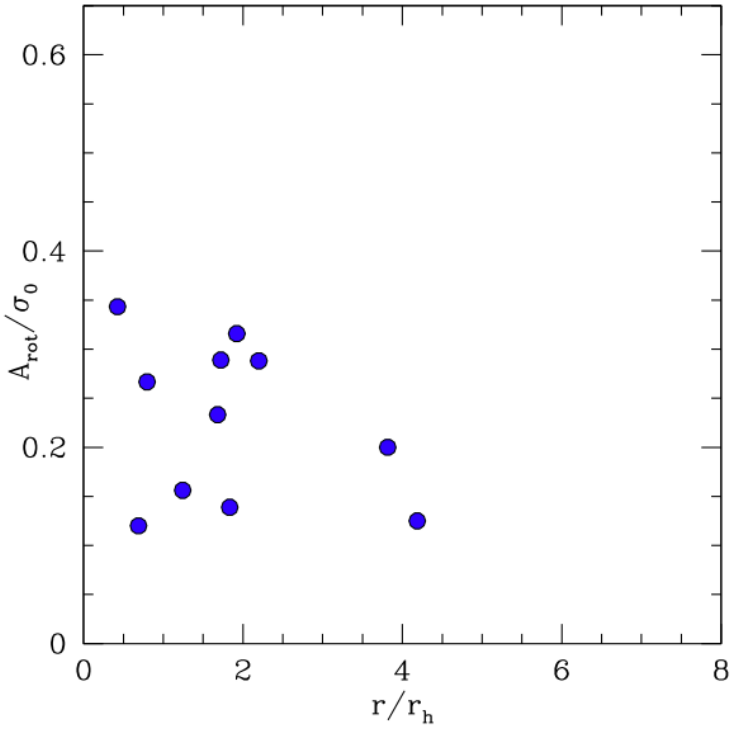


The MIKiS survey: rotation signals

Ferraro et al (2018,ApJ,860,50)

In the majority of the surveyed systems we find evidence of rotation within a few half-mass radii from the center.

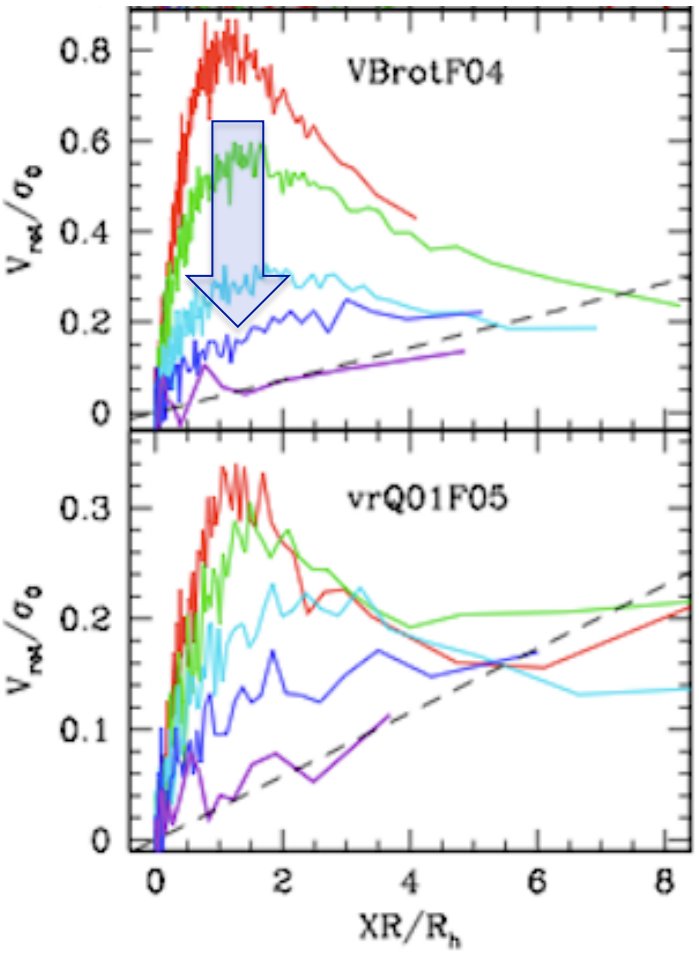




The amplitude of the rotation is a few km/s(≈ 0.1-0.4 σ_0)

But even weak signals are important: **observational evidence that most of the clusters were born with significant amounts of ordered motions**

The detected rotation signals are the relics of significant internal rotation set at the epoch of the cluster's formation?



Long-term evolution of GC rotational properties
(N -body simulations of Tiongco et al. 2017):

- end of the initial violent relaxation phase →
  → **well-defined peak at a few r_h** in the radial profile of the cluster rotation velocity
  (in all the explored models)

- then → progressive decline of the rotation peak (because of angular momentum transport and loss due to the escape of stars)

The peak remains essentially located in a region around a few r_h for most of the cluster' s evolution.
The amplitude of the rotation peak decreases by one order of magnitude (from ~ 0.8-0.3 σ_0 , down to ~ 0.05σ_0 in the most evolved systems)

Thus, the detected weak rotation signals might be the remnant of a much larger amount of ordered motion imprinted at birth, which gradually dissipated via two-body relaxation

The MIKiS survey

Ferraro et al (2018,ApJ,860,50)

The **ubiquity** of detections of **modest signatures of rotation** in globular clusters (see also Kamann+18, MNRAS,473,5591) indicates that **most of these systems were born with significant amounts of ordered motion**, thus providing significant constraints on globular cluster formation models (see Bekki 2010, ApJL, 724, L99, Mapelli 2017,467, 3255).

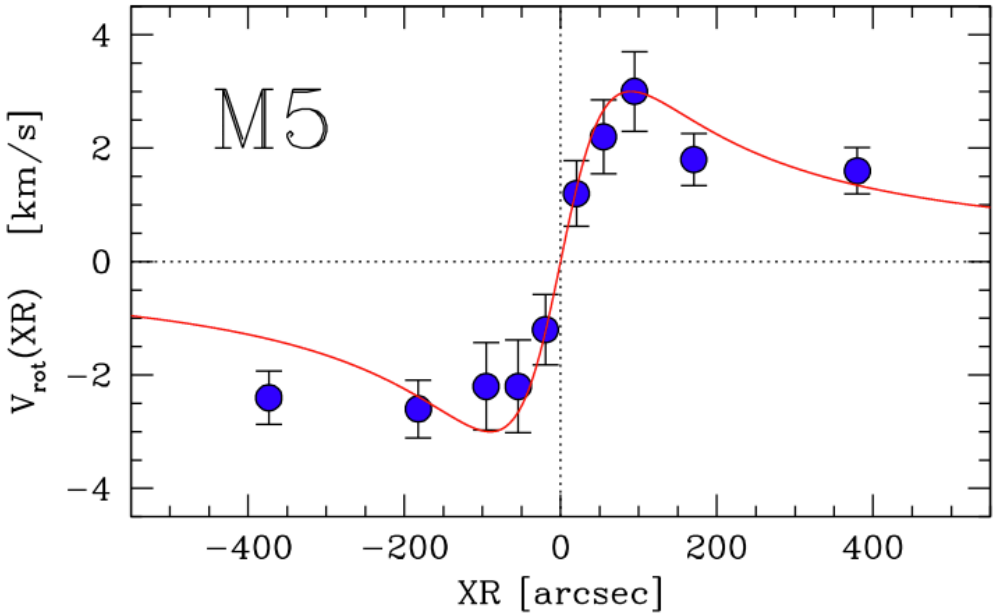
Two additional intriguing cases: M5 & NGC 5986

The MIKiS survey: M5

Lanzoni et al (2018a,ApJ,861,16)

The strong Rotation of NGC 5904 (M5)

one of the cleanest and most coherent rotation patterns ever observed in globular clusters



A_{peak} = 3 km/s

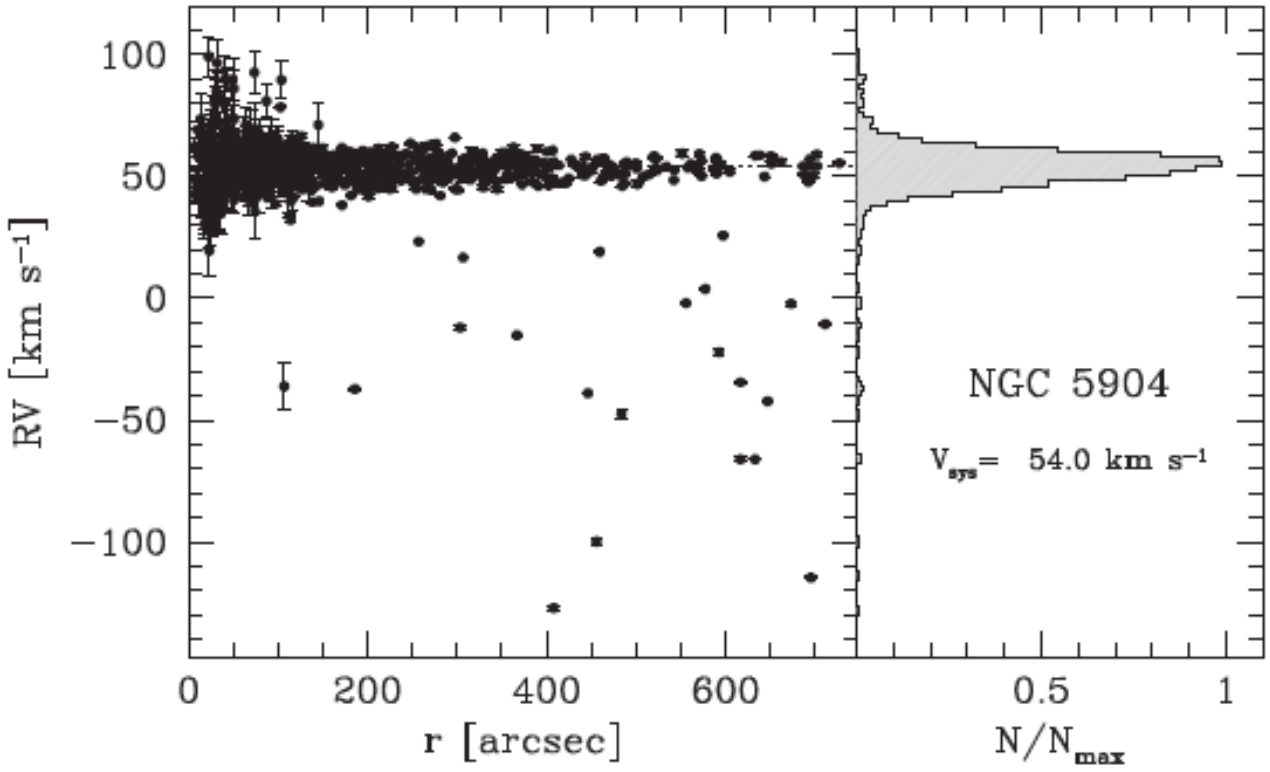
XR_{peak} = 90” (~0.6 rh)

Red line = analytical relation expected for a cylindrical rotation by Lynden-Bell 1967

The MIKiS survey: M5

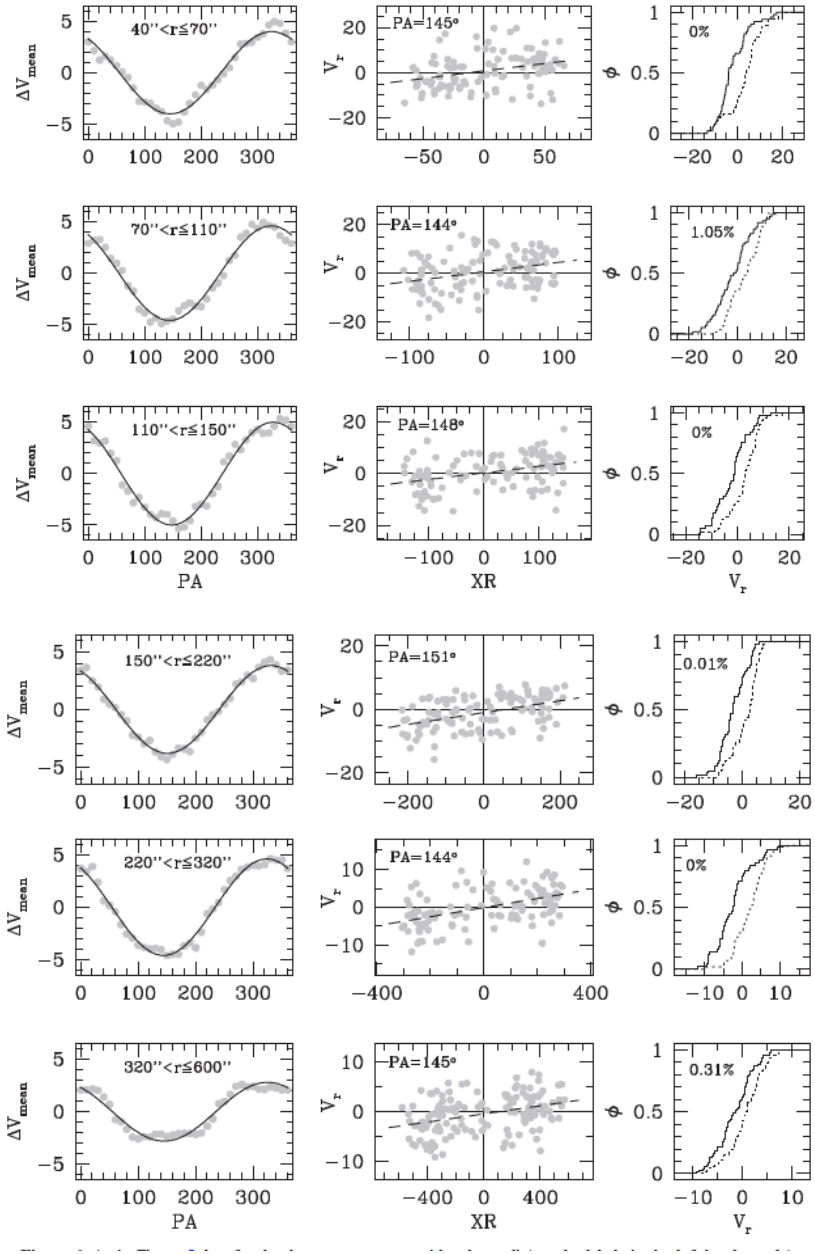
Lanzoni et al (2018a,ApJ,861,16)

Radial velocities of more than 800 individual stars observed out to 700″ (~ 5 half-mass radii) from the center

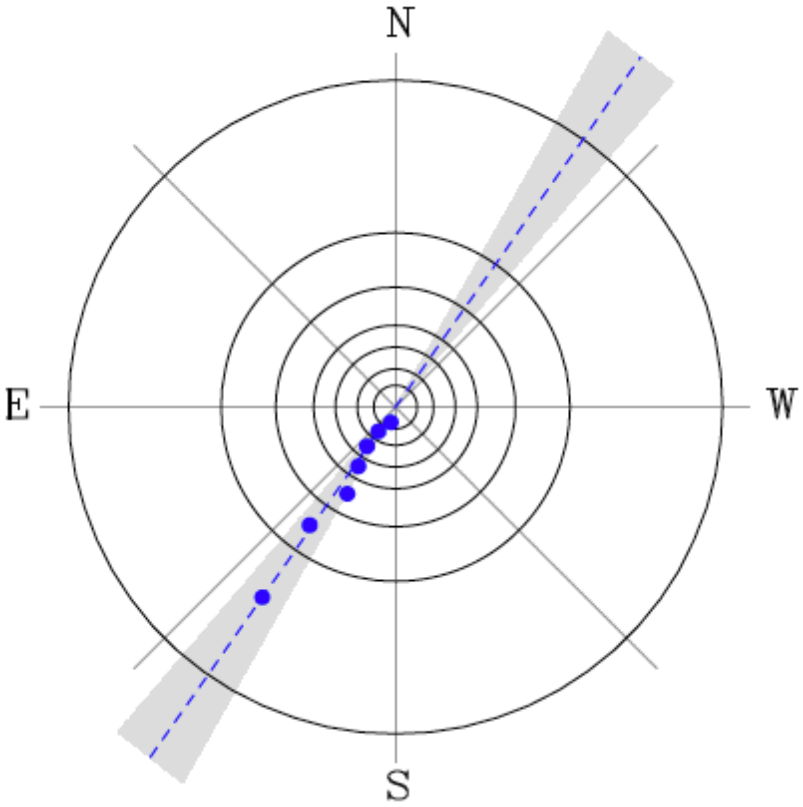


The MIKiS survey: M5

Lanzoni et al (2018a,ApJ,861,16)

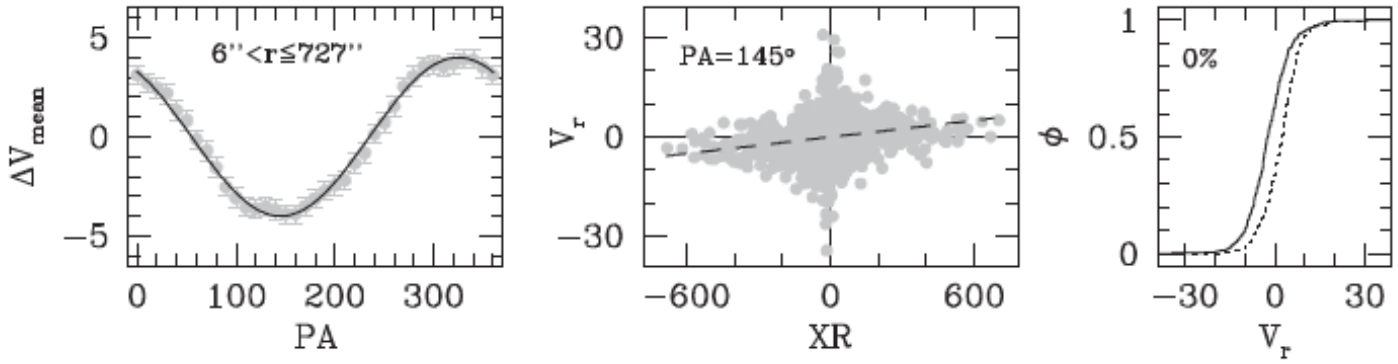


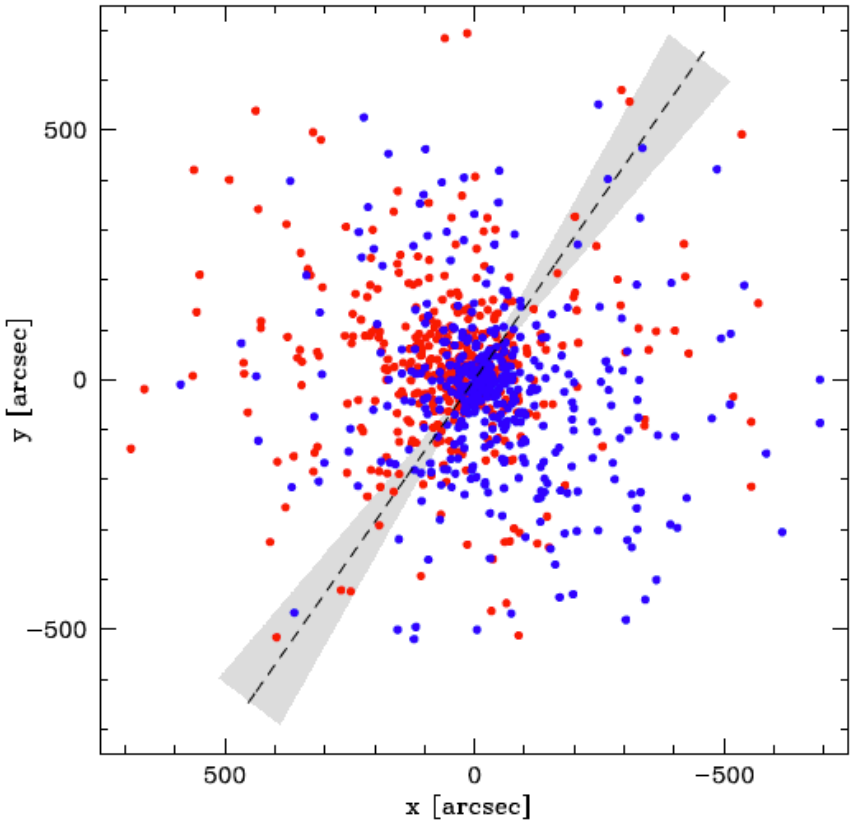
The analysis of the rotation signal in concentric radial bins spanning 700” (5 half-mass radii) from the center yielded the discovery of a coherent and stable signal over the entire cluster extension



The MIKiS survey: M5

Lanzoni et al (2018a,ApJ,861,16)





RED: $V_r > V_{sys}$

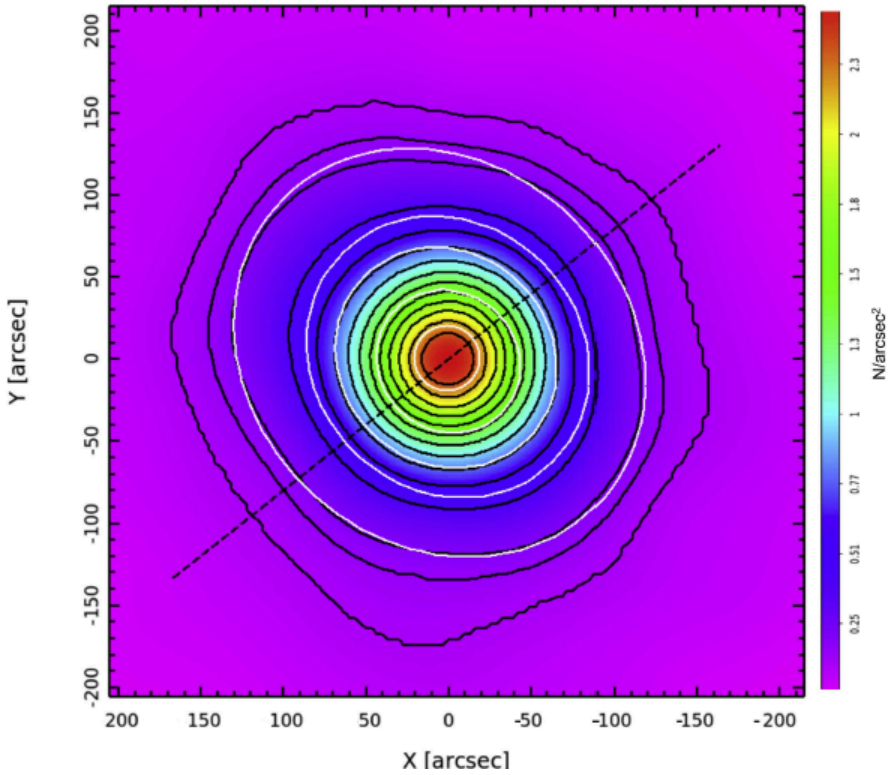
BLUE: $V_r < V_{sys}$

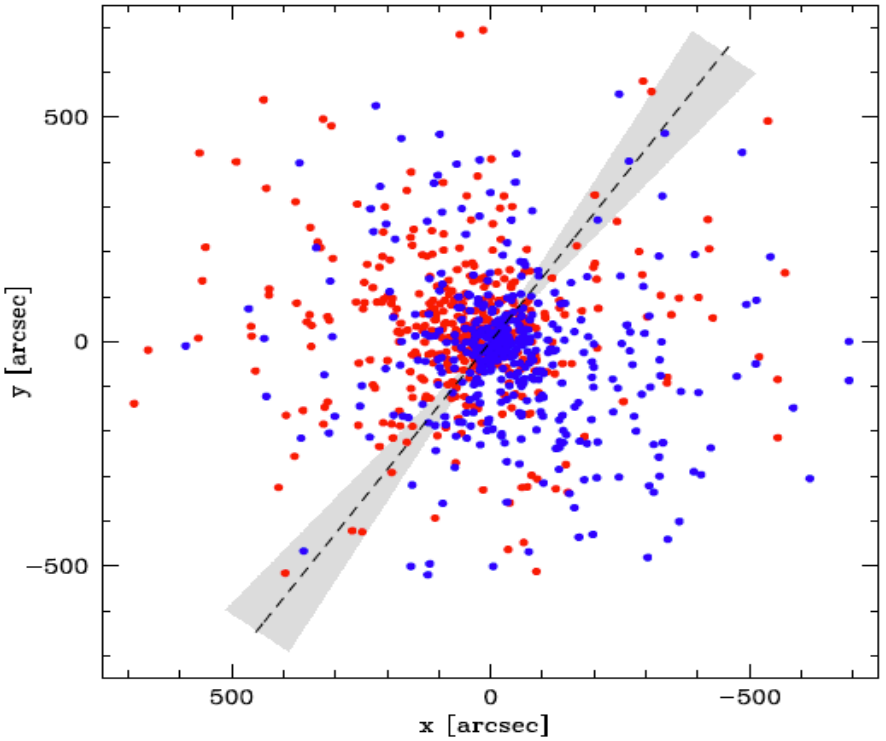
The MIKiS survey: M5

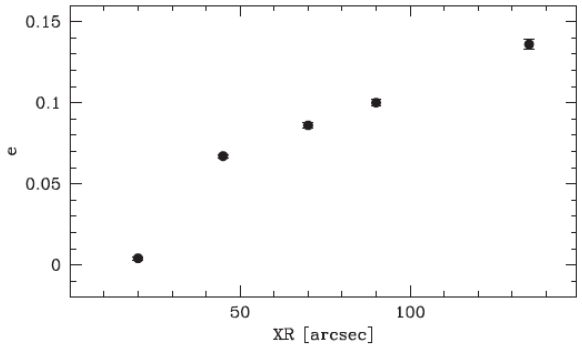
Lanzoni et al (2018a,ApJ,861,16)

A rapidly rotating system also is expected to be flattened in the direction perpendicular to the rotation axis.

Star density map (HST/ ACS and ESO-WFI data)







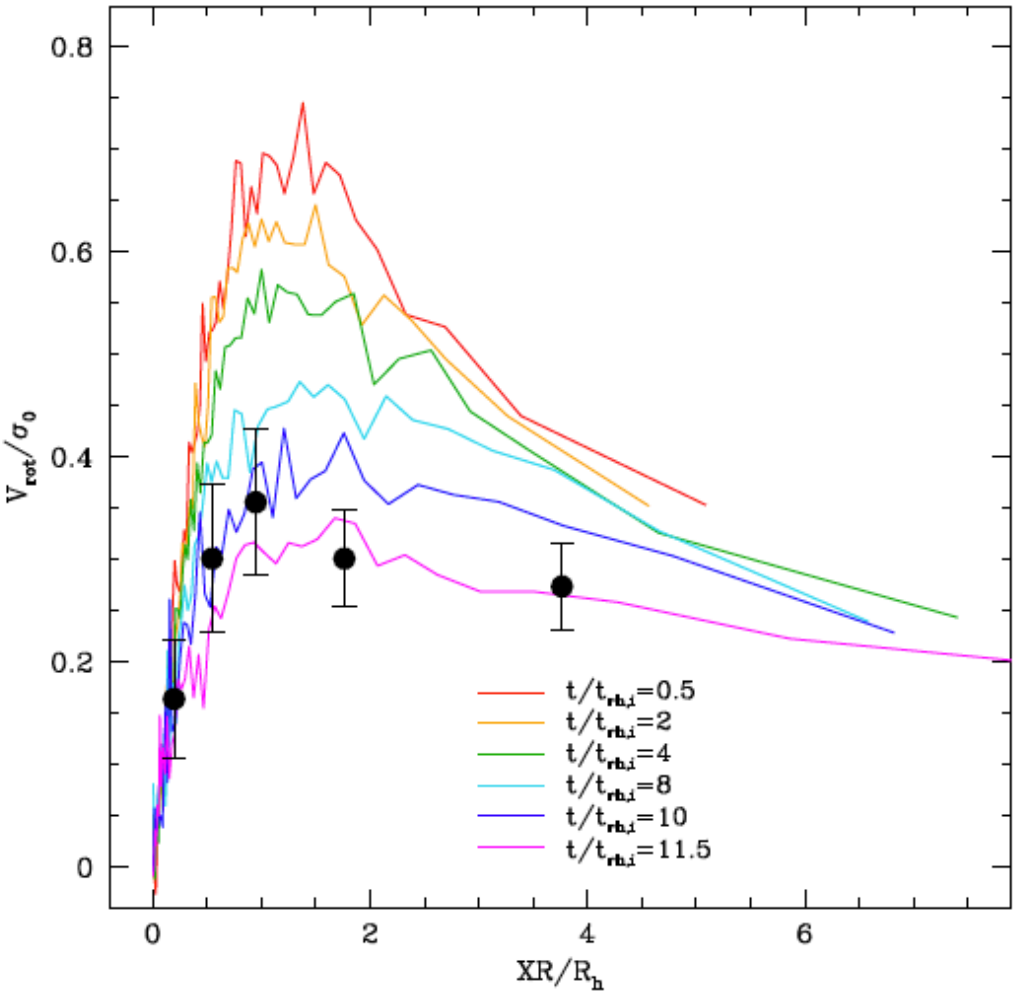
Ellipticity radial profile:

- spherical symmetry in the center
- increasing ellipticity for increasing radius.

The MIKiS survey: M5

Lanzoni et al (2018a,ApJ,861,16)

The comparison with a N-body model from Tiongco+16,18 supports the conclusion that M5 has already experienced the effects of two-body relaxation and angular momentum transport over several initial half-mass relaxation times ($t_{rh,i}$) (= intermediate/old dynamical age).



This simple analysis shows the potentiality of the approach, with the concrete possibility of constructing detailed N-body models which can put severe constraints to the amount of rotation that a GC possessed at birth

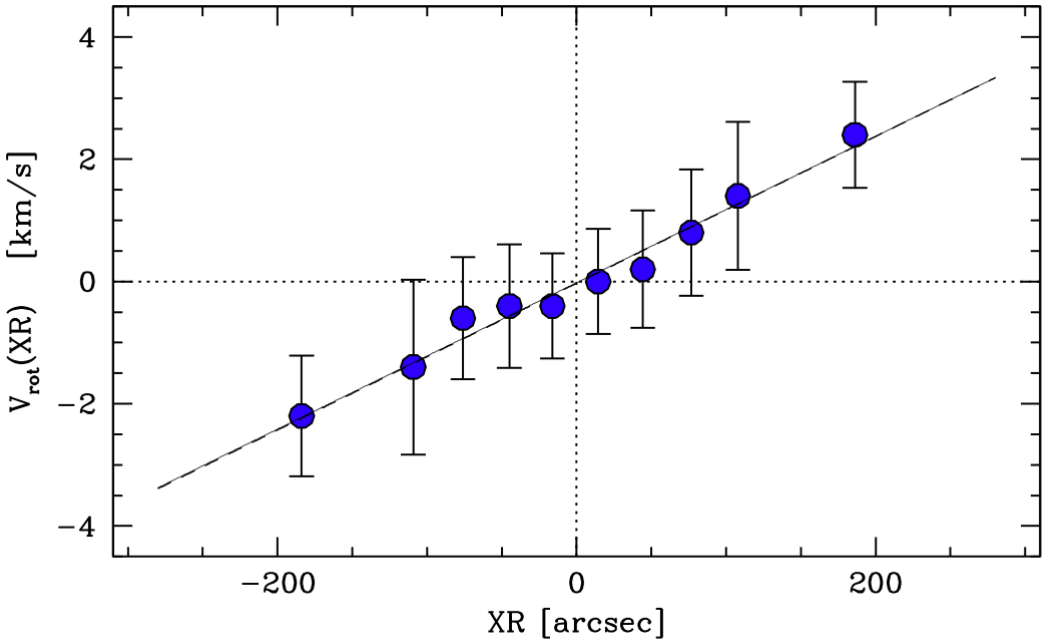
R_h = 140”

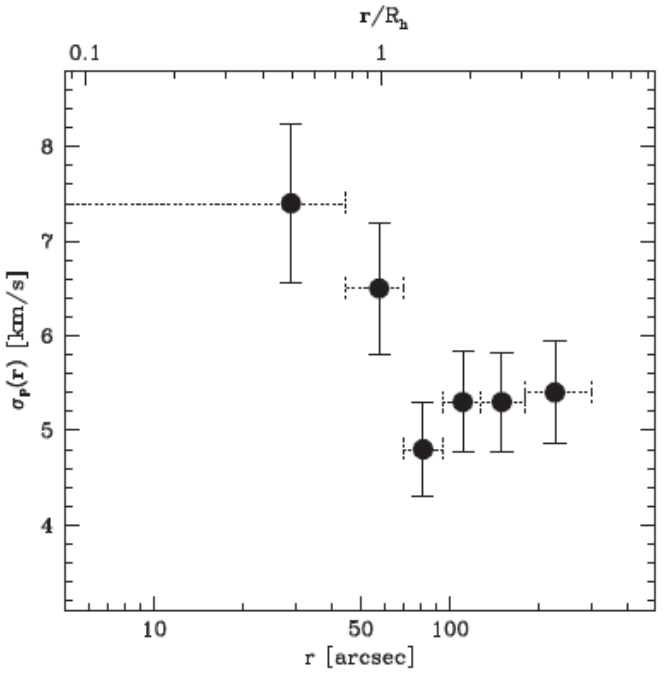
The MIKiS survey: NGC5986

Lanzoni et al (2018b,ApJ,865,11)

The anomalous case of NGC 5986

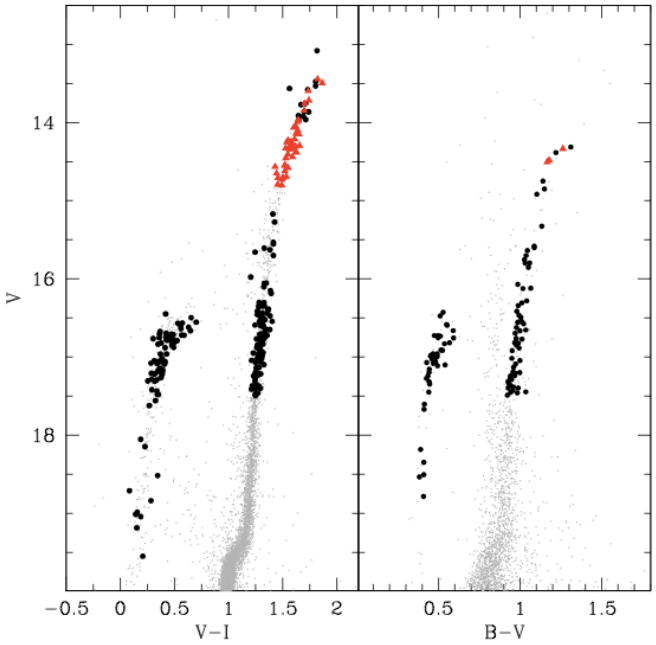
Solid-body rotation along the entire cluster extension & constant VD profile at large radii





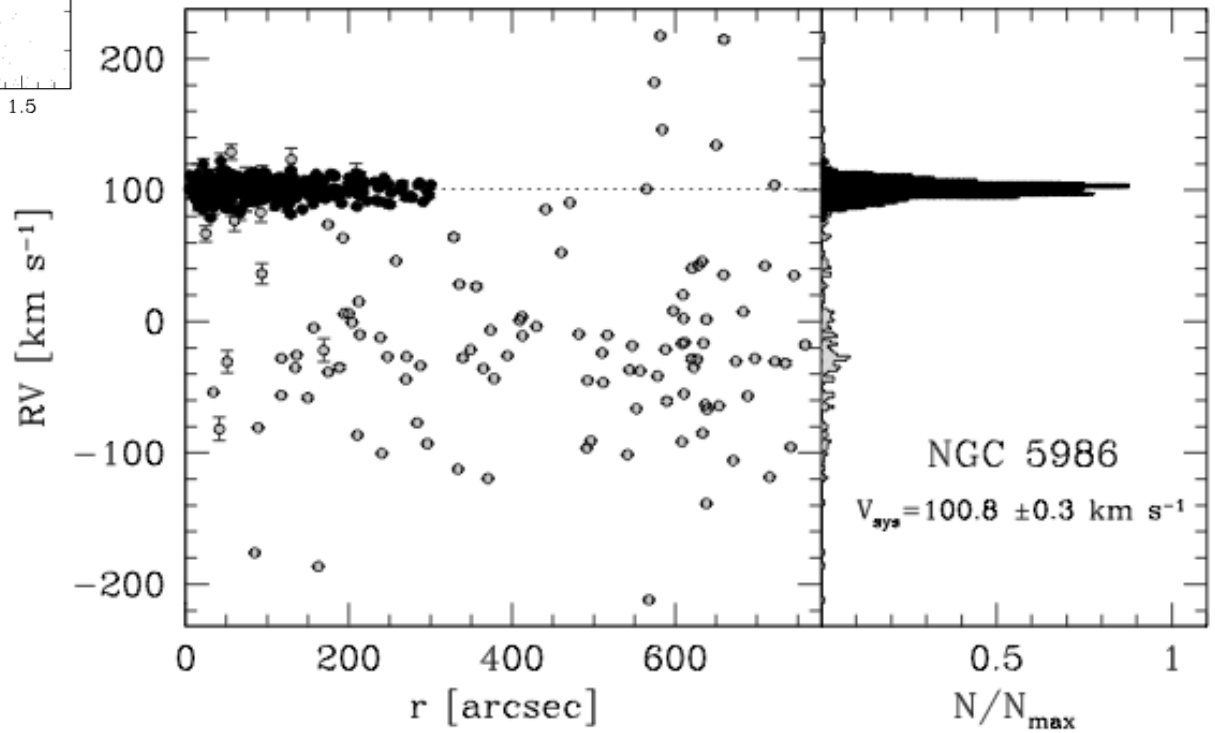
The MIKiS survey: NGC5986

Lanzoni et al (2018b,ApJ,865,11)



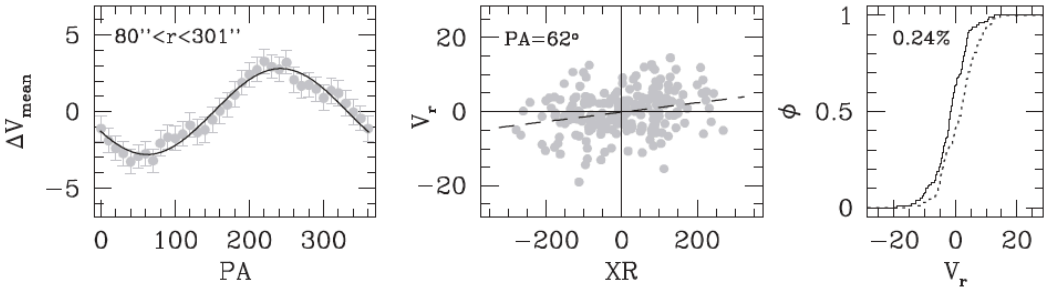
~ 470 stars measured out to 700” from the center

Cluster members found out to 300” from the center (~ 4 r_h)

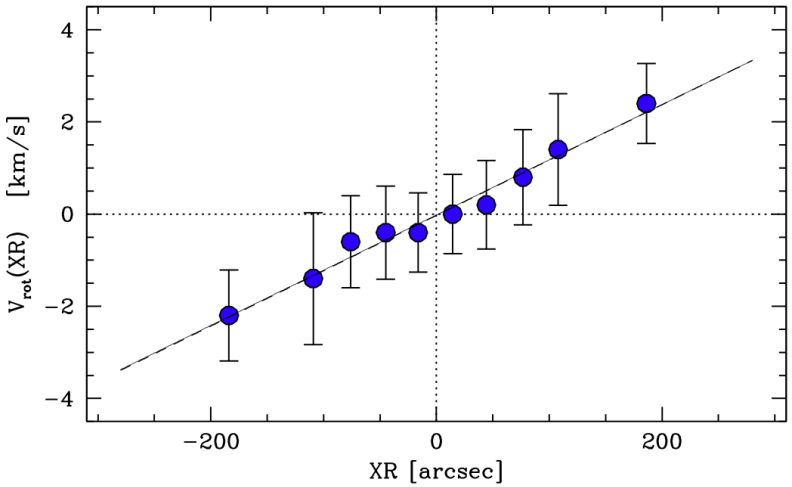


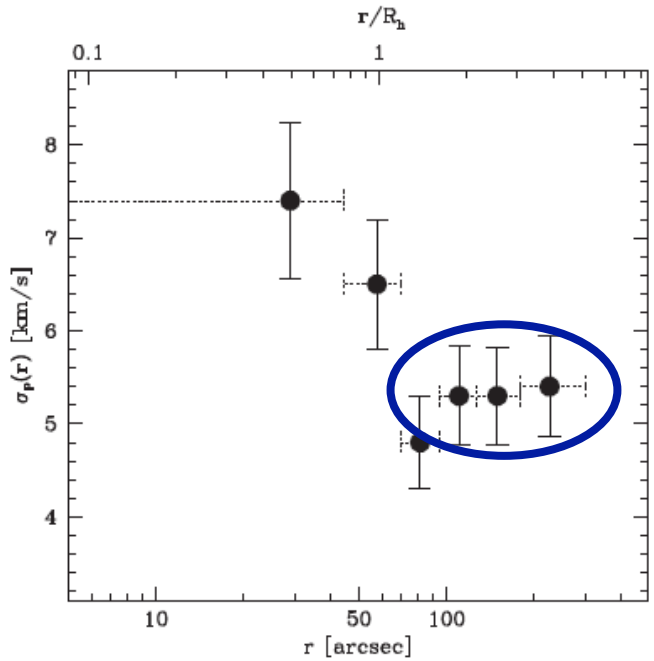
The MIKiS survey: NGC5986

Lanzoni et al (2018b,ApJ,865,11)



a clear signature of rotation with a PA=62 . The derived rotation curve shows a clear solid-body rotation pattern, monotonically increasing from 0 km/s in the center, up to ~2 km/s at the outermost sample distances (4 half-mass radii).





VD profile:

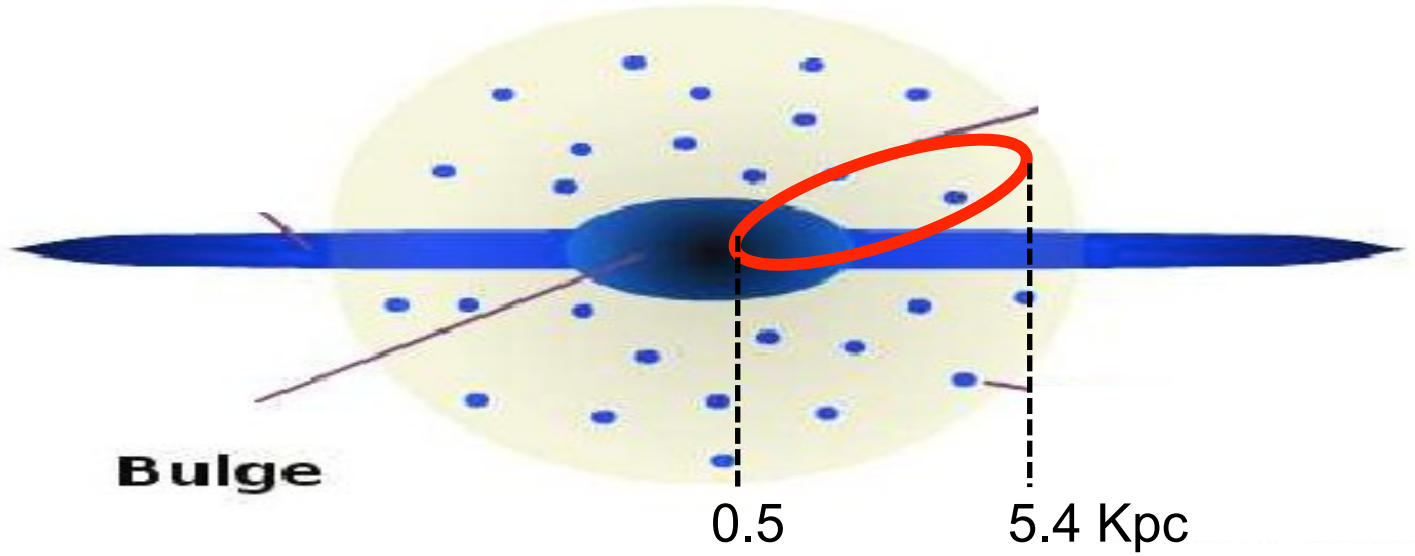
- decline between 0″ and ~ 90″
- constant at ~ 5 km/s out to the outermost distance

suggesting the existence of a population of "potential escapers" (energetically unbound stars) generated by strong interactions with the galactic potential field

$R_h \approx 60$”

The MIKiS survey: NGC5986

Lanzoni et al (2018b,ApJ,865,11)



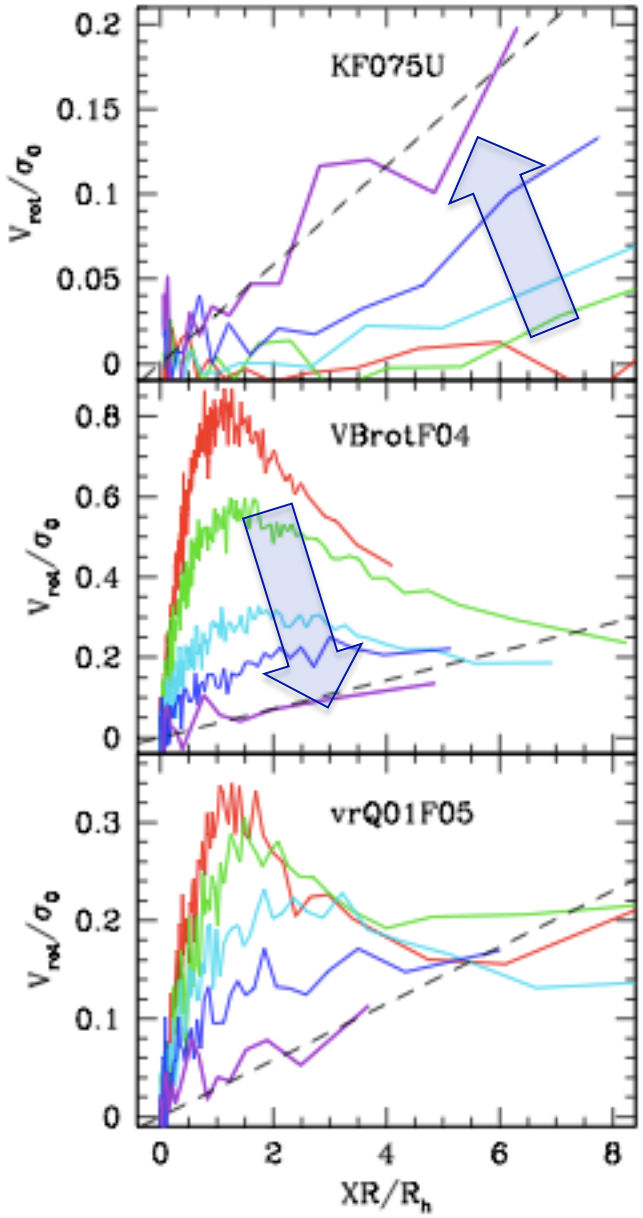
By combining the new determination of the systemic line-of-sight velocity Vsys = 100.8 km/s with the cluster PM by Casetti-Dinescu et al. (2007) or Helmi et al. (2018), the system turns out to have a **highly eccentric orbit (e = 0.80)**, practically plunging into the central part of the MW.

The orbit is confined within rp = 0.5 kpc and ra = 5.4 kpc. orbital radial period of only ~ 60 Myr, corresponding to a few hundred passages of the cluster close to the Galactic center during its lifetime (t = 12 Gyr) .

The orbital parameters suggest quite intense interactions with the central regions of the Galaxy

The MIKiS survey: NGC5986

Lanzoni et al (2018b,ApJ,865,11)



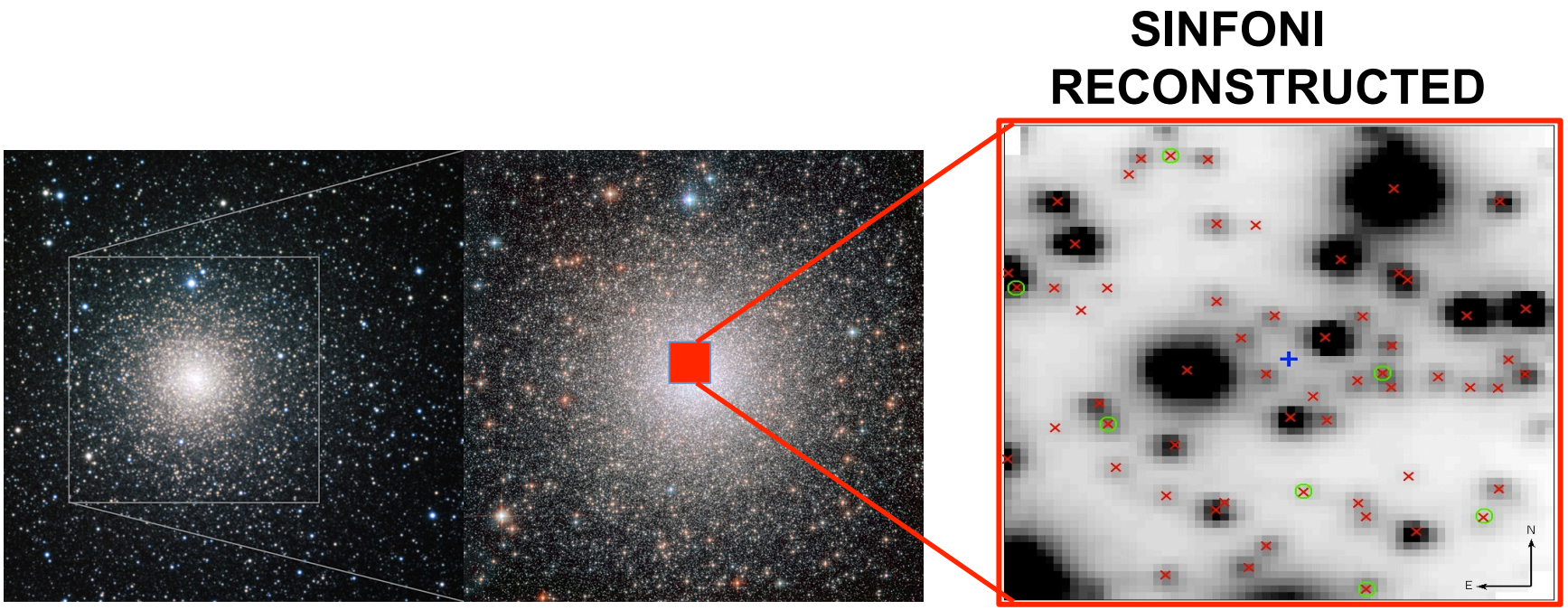
Tidally perturbed clusters, during their dynamical evolution tend to develop a signature of solid-body rotation

Case1 **– Initially non rotating cluster** -N-body simulation starts from initial conditions sampled from a King (1966) equilibrium model, which is initially non-rotating, and is evolved on a circular orbit in the tidal field of a Keplerian potential

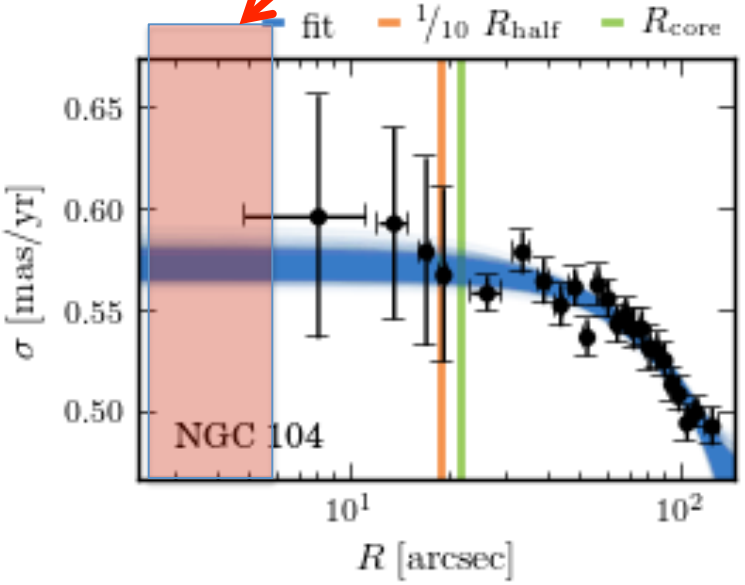
Case 2 **– Initially rotating cluster -** collisional system which is initially characterized by some intrinsic internal rotation and is progressively evolving towards a condition of solid-body rotation (starting from its central to intermediate regions), as a result of the angular momentum transport and loss, induced by two-body relaxation processes.

The MIKiS survey

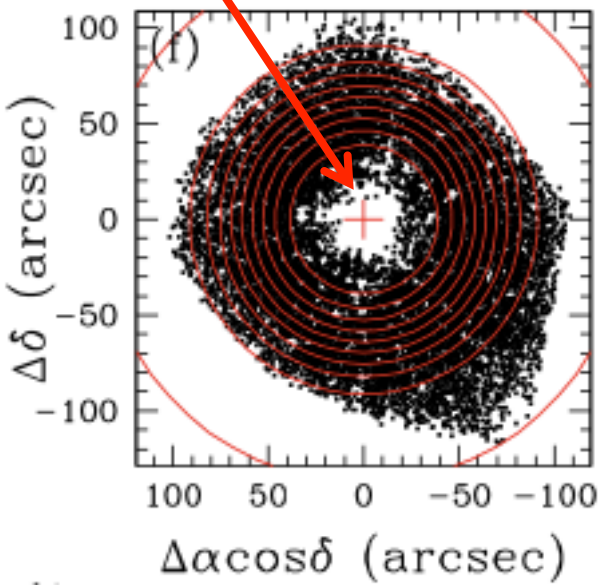
The exploration of the high-density cluster cores at **sub-arcsec scale** with SINFONI !



HST Proper Motions are still missed in the very central regions of high-density clusters (stellar crowding)



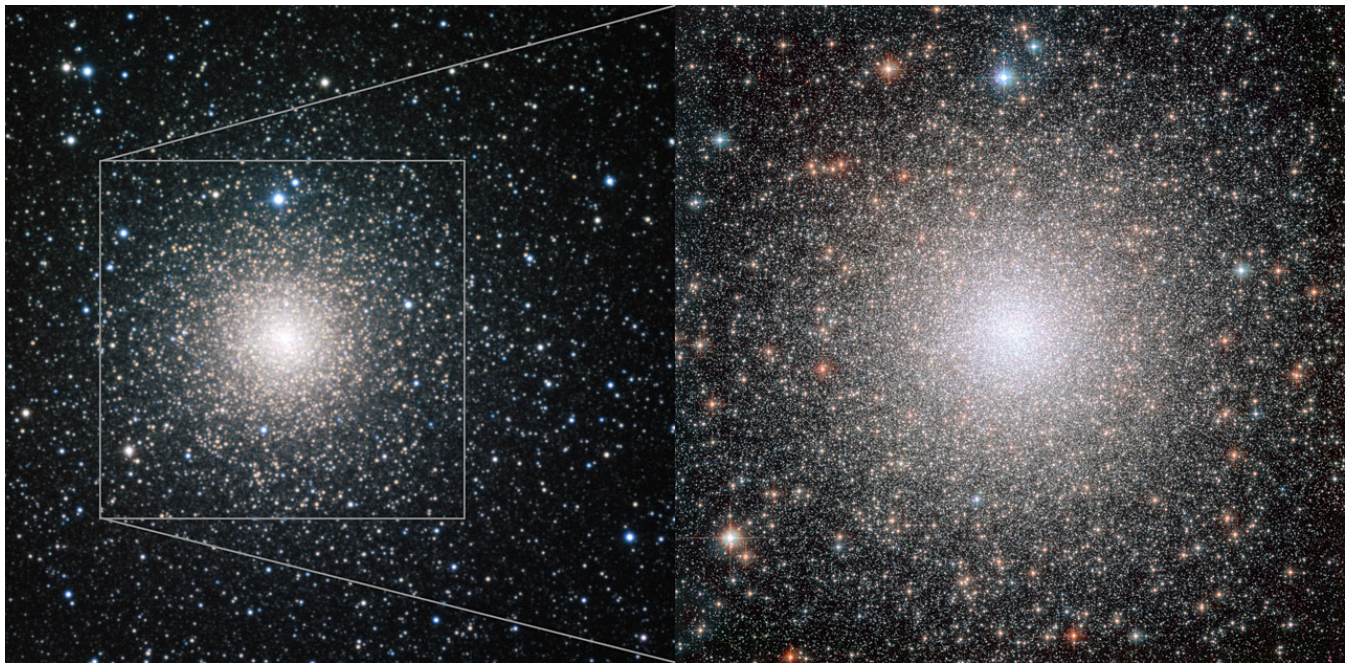
Watkins et al. 2015
(47 Tuc)



Bellini et al. 2014
(M15)

The MIKiS survey: NGC 6388

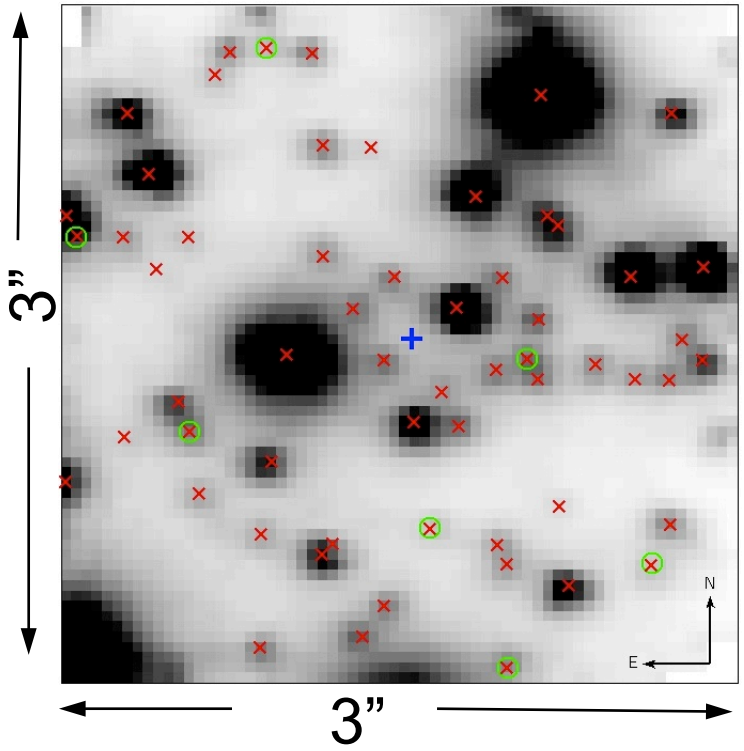
- **one of the most massive GGCs:** M ~ 2.6 10^6 $M_\odot$
- **highly concentrated** (r_c=7”, ρ_0 = 2.3 x 10^5 $L_\odot/pc^3$)



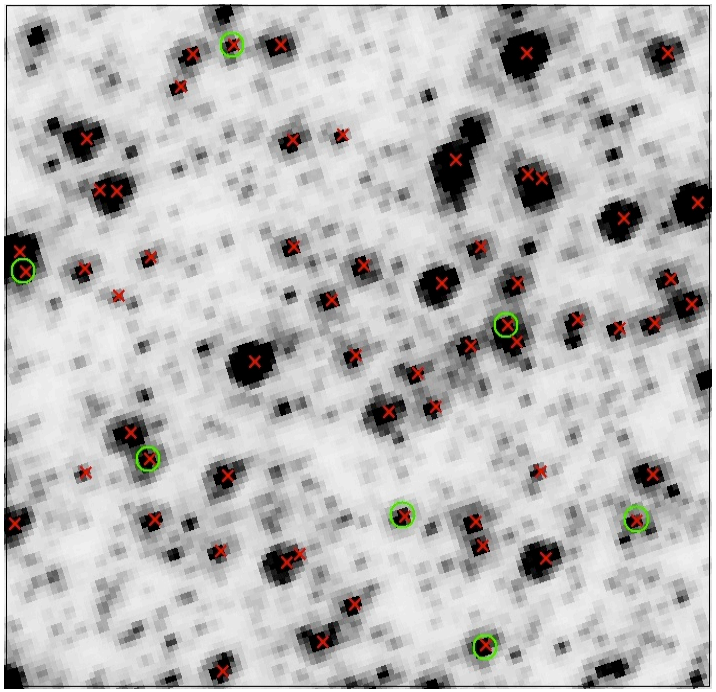
The MIKiS survey : NGC 6388

- stellar centroids from cross-correlation between SINFONI and HST/HRC
- spectra extracted from central spaxel only
- excluded low-quality spectra & blended sources

SINFONI



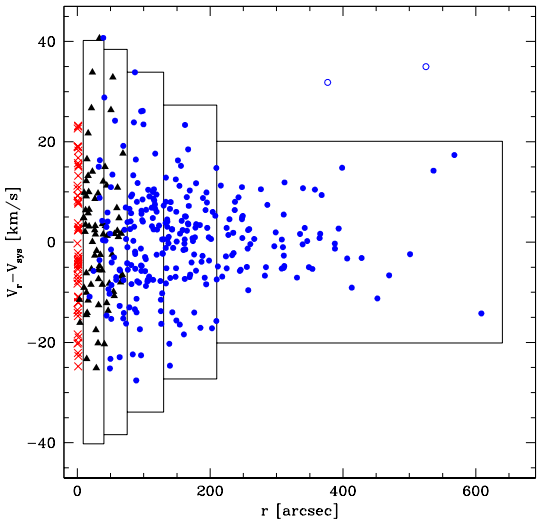
HST/HRC



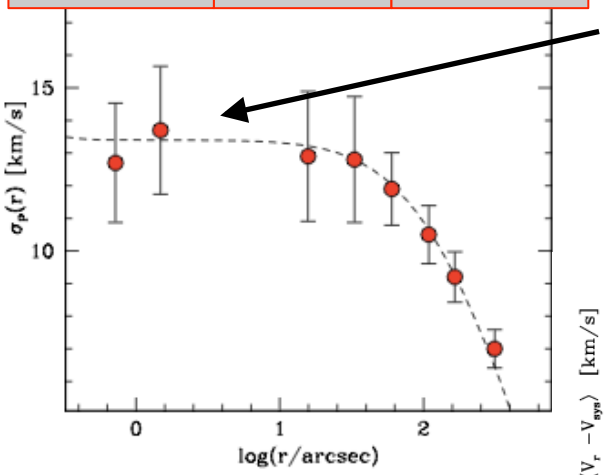
→ V_r for 52 individual stars at r<2” !!!!!!! (~0.13 pc)

The MIKiS survey: NGC 6388

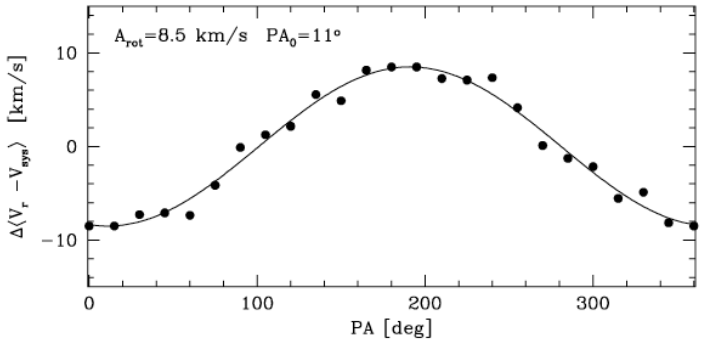
No detection of IMBH in the center of NGC 6388 at odds with the claim by Lützgendorf et al. (2011) of a $M_{BH} \sim 1.7\ 10^4\ M_\odot$



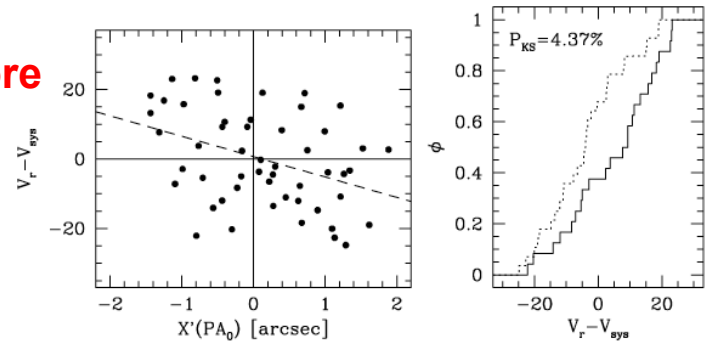
SINFONI | KMOS | FLAMES



consistent with NO IMBH (or 2000 $M_\odot$ BH at most)



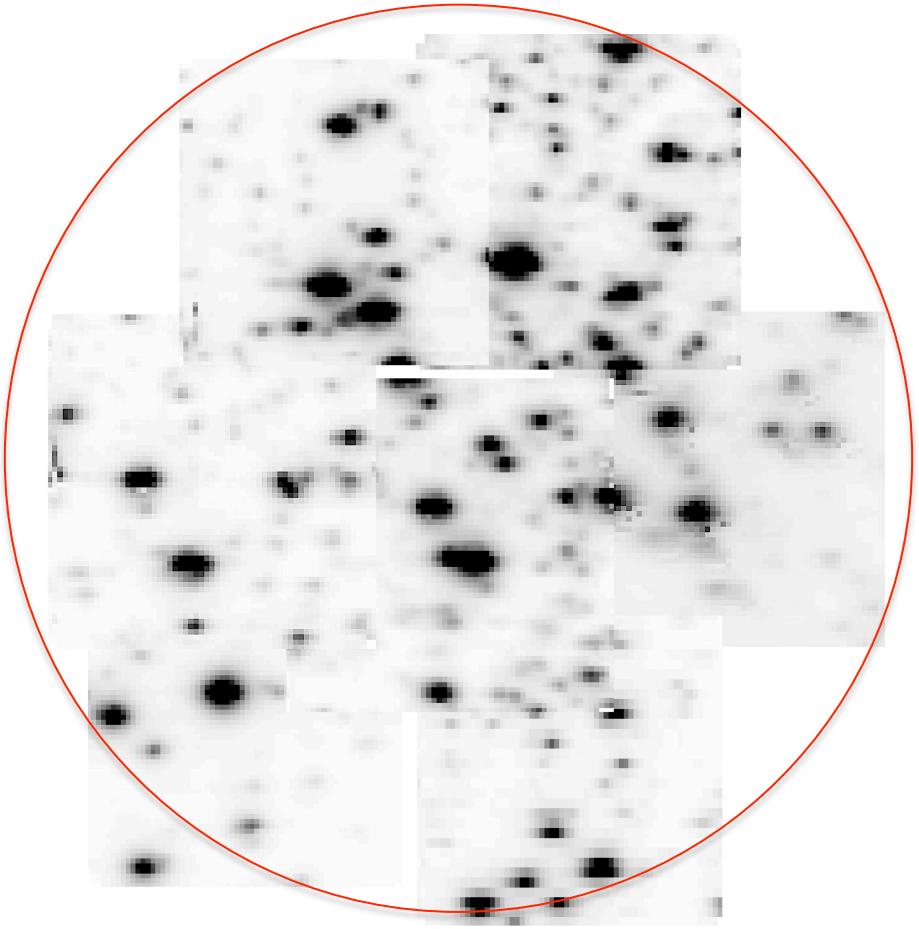
evidence of systemic rotation in the inner core with amplitude of several km/s



Lanzoni+13, ApJ, 769, 107; Lapenna+15, ApJ, 798, 23

The MIKiS survey: NGC 2808

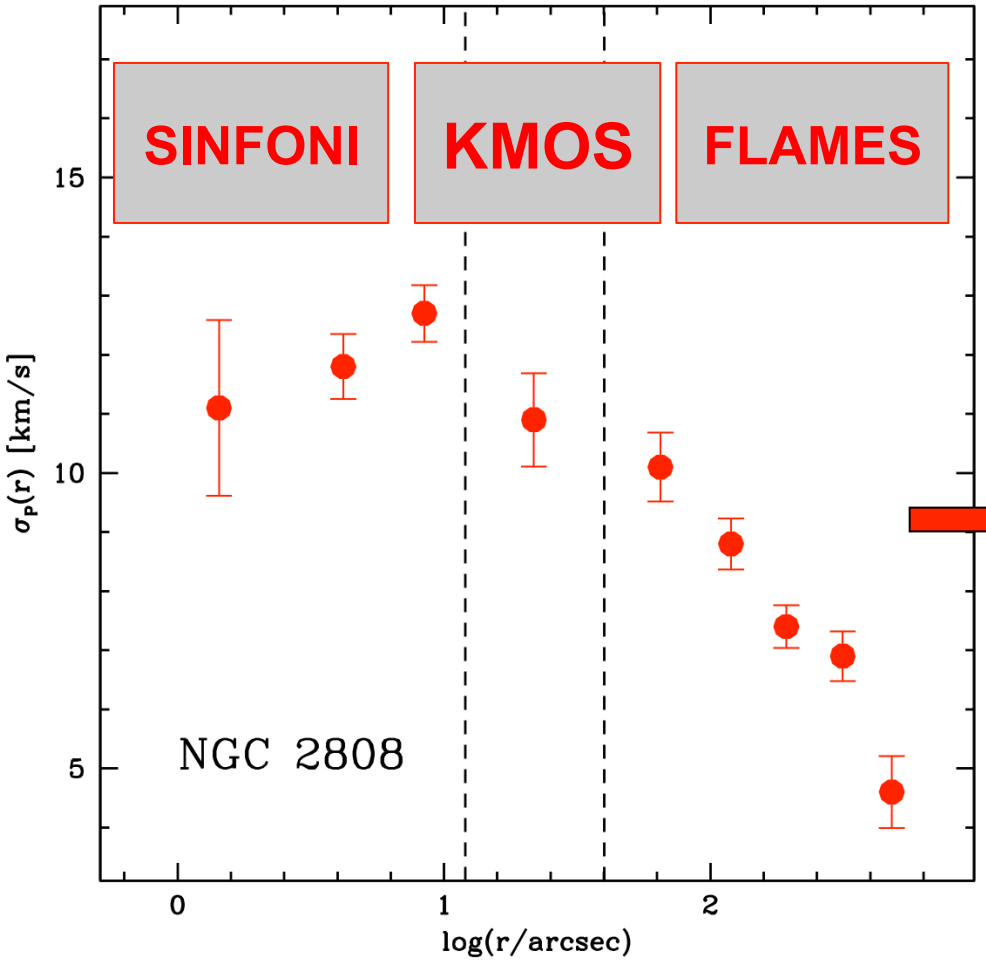
A mosaic of 7 SINFONI field



V_r for 700 individual stars at r<12” (~0.6 pc) !!

The MIKiS survey: NGC 2808

- **FLAMES** (external regions): ~ **790** stars, mainly at 40”<r<700”
- **KMOS** (intermediate region): ~ **96** stars, mainly at 12”<r<40”
- **SINFONI** (innermost region): ~ **700** stars, at 0.5”<r<12” (7 fields 8”x8” each)

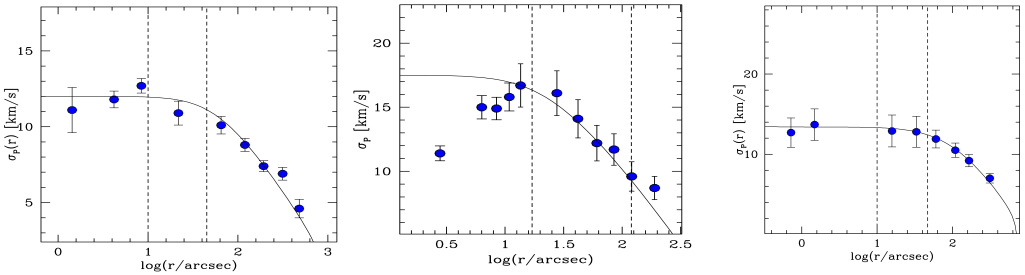


~1600 measured stars resolving the cluster core at sub-arcsec scale

NO IMBH

Toward the 3D view of the velocity space

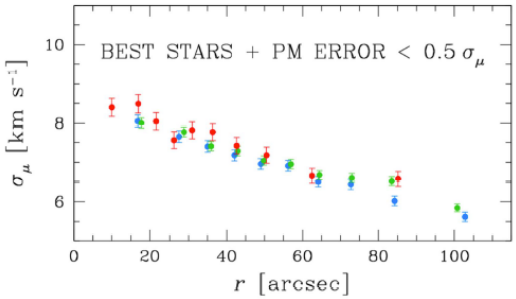
MIKiS survey: RVs



+

internal proper motions from:

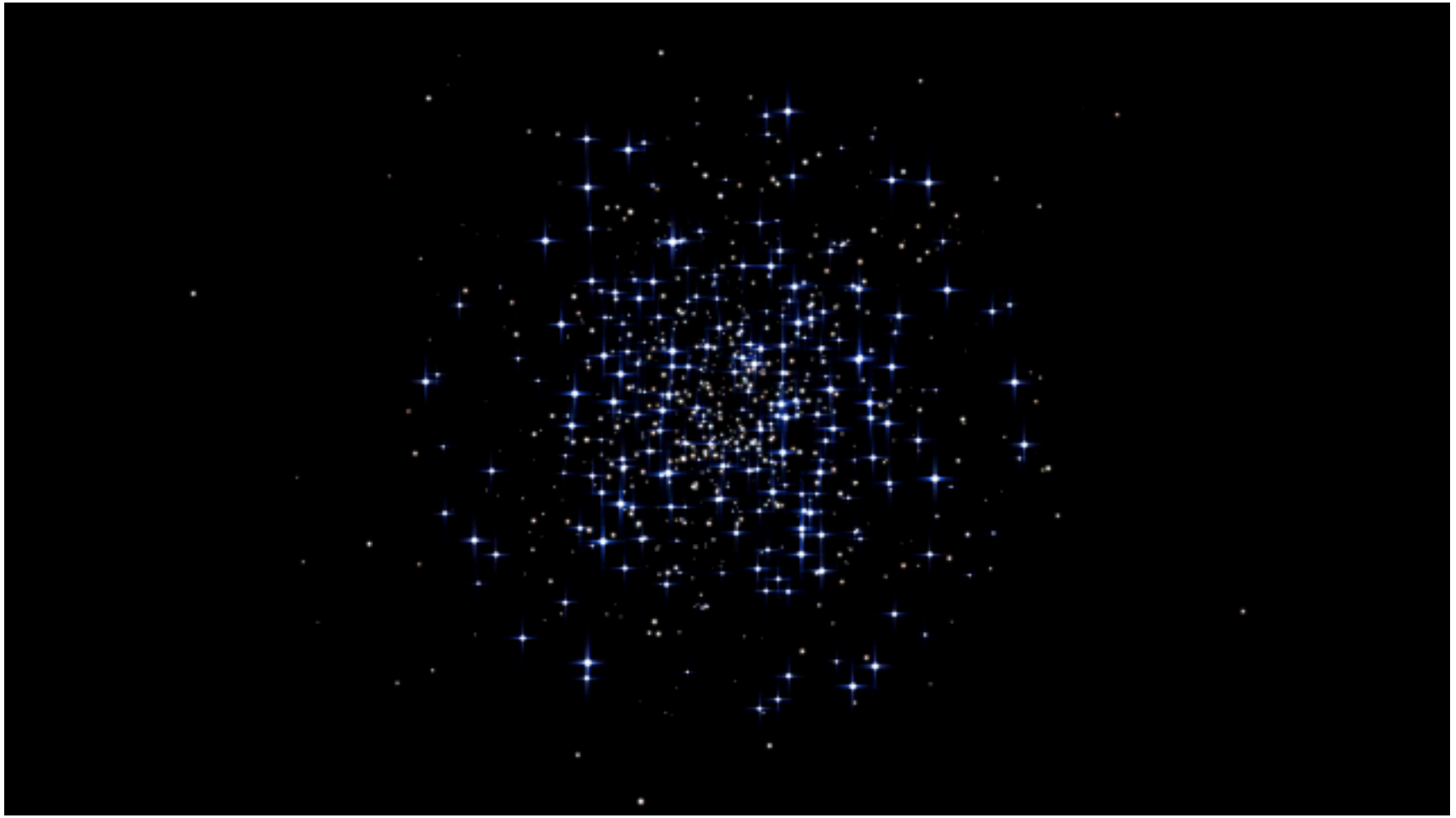
- multi-epoch HST observations (center) → GO155232- PI: Ferraro
- and Gaia → outskirts



Libralato+18, ApJ,861,99

the FIRST 3D velocity map of Galactic GCs

+ full characterization of systemic internal rotation
+ full characterization of VD anisotropies
+ possible evidence of IMBHs



Thank you for your attention !!!