INTERNAL KINEMATICS OF GLOBULAR CLUSTERS

FRANCESCO R. FERRARO

Physics & Astronomy Department – University of Bologna (Italy)

CEFALU`, September 7, 2015

✦5-year project (web site at **www.cosmic-lab.eu**)

✦ *Advanced Research Grant* funded by the European Research Council (ERC)

✦ PI: Francesco R. Ferraro (Dip. of Physics & Astronomy – Bologna University)

✦ AIM: **to understand the complex interplay between dynamics & stellar evolution**

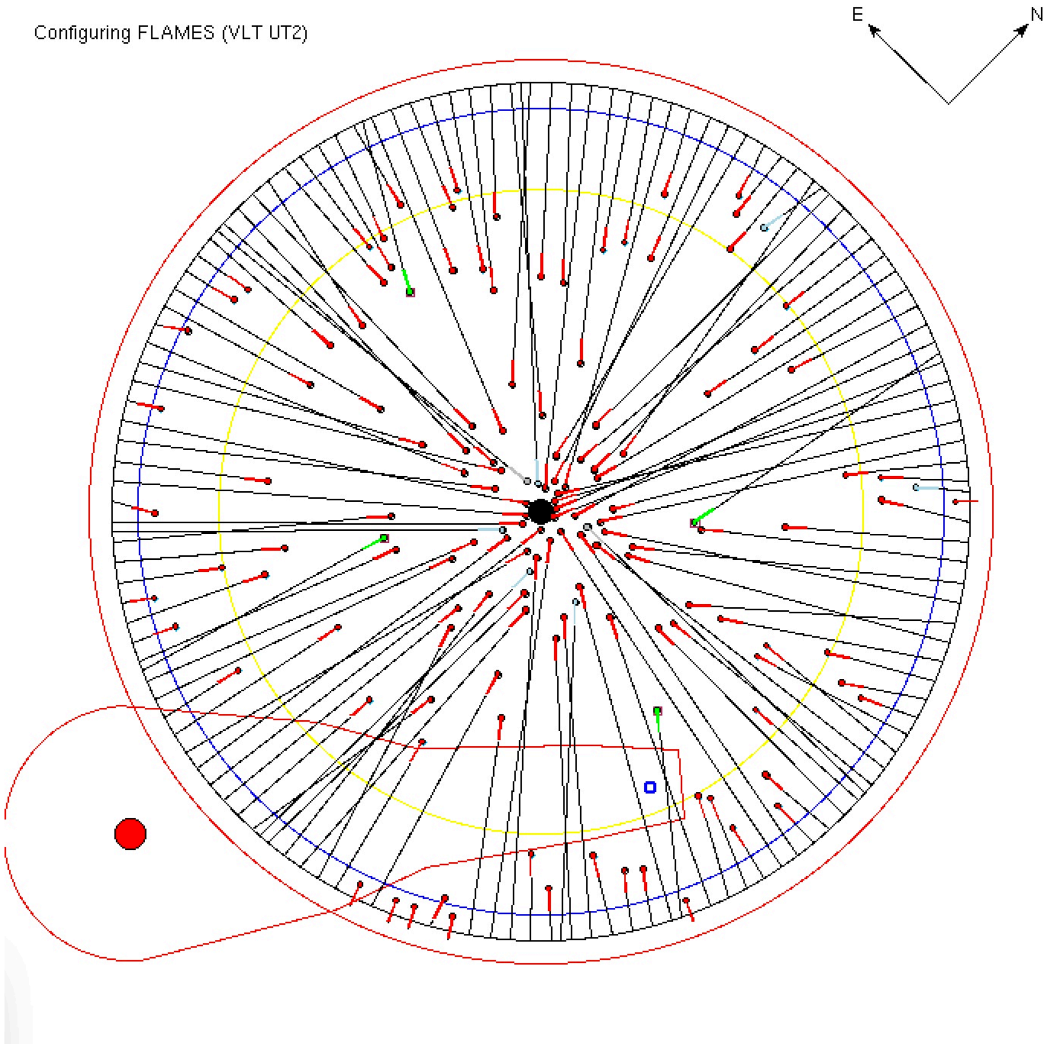
✦ HOW: using **globular clusters** as cosmic laboratories and

Blue Straggler Stars
Millisecond Pulsars
Intermediate-mass Black Holes

as probe-particles

MOS SPECTROSCOPY & GLOBULAR CLUSTERS

MOS Spectroscopy has had a huge impact on the GC Science



FLAMES @ ESO-VLT
in the COMBINED mode
GIRAFFE/MEDUSA+UVES
FoV of 25' diameter

GIRAFFE/MEDUSA:
multi-object spectrograph (132 fibres), intermediate-high spectral resolution (R>10,000)

UVES/FIBER: multi-object spectrograph (8 fibres), high spectral resolution (R=40,000)

MOS SPECTROSCOPY & GLOBULAR CLUSTERS

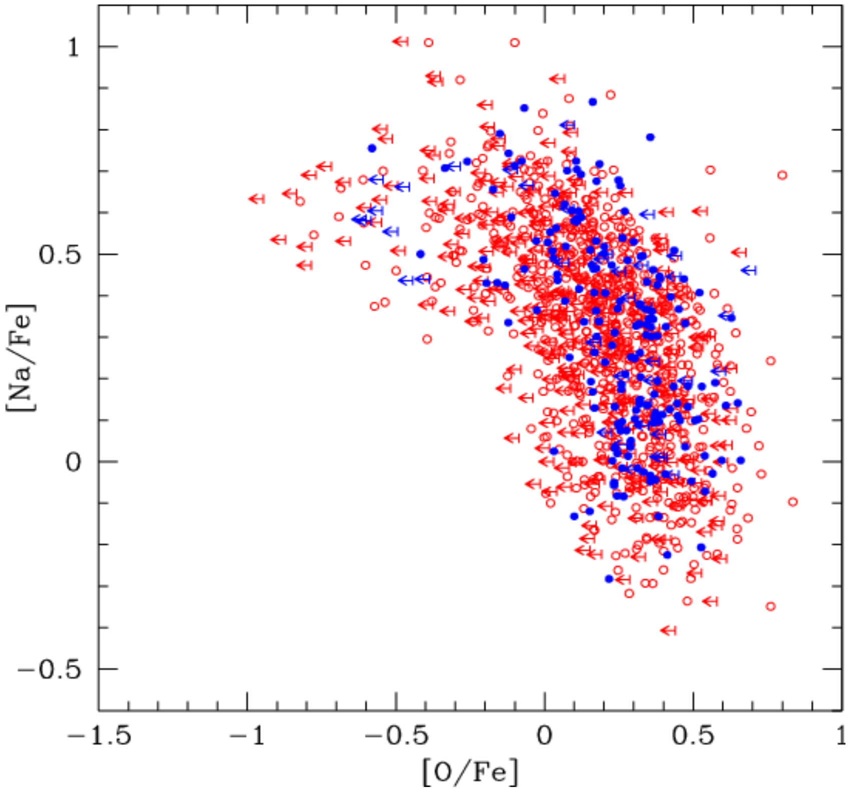
Although chemical inhomogeneities in light-element abundances were known since many year ONLY Systematic observations (mainly with **ESO-VLT/FLAMES**) have shown that they define clear **“anti-correlations”** .

These are the signature of **p-capture processes** (high-temperature extension of the CNO cycle) occurring at 40-70 x 10^6 K.

These temperatures are NOT reached in present day GC main sequence and red giant stars.

more the 1 generation of stars in GCs

(GC formation history is much more complex than previous thought).

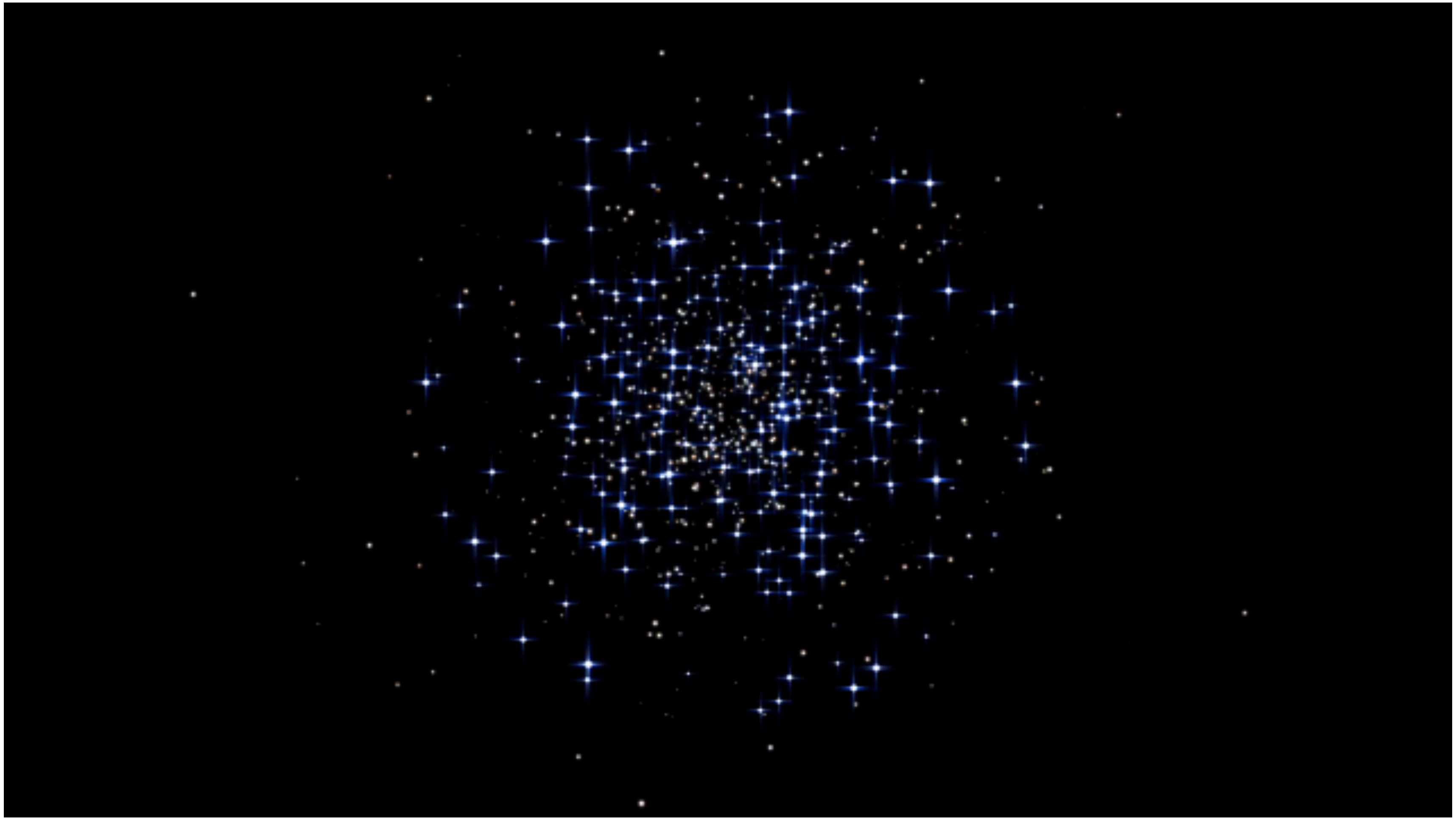


Cumulative behaviour of [Na/Fe] as a function of [O/Fe] for 19 Galactic GCs (Carretta et al. 2009)

MOS SPECTROSCOPY & GLOBULAR CLUSTERS

Today I'm going to show
how an appropriate combination
of the current generation of MOS facilities
promises to open a golden age in the field of the
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.

This dynamical activity can generate **exotica**

A NEW UNDERSTANDING OF THE PHYSICS OF DENSE STELLAR SYSTEMS

From the observational point of view, we need:

1. **CLUSTER STRUCTURE** (core radius, concentration, center, etc)

2. **KINEMATICS** (velocity dispersion profile, rotation curve)

3. **EXOTIC population** which can be used as gravitational probe-particle

THE PROJECT

1. A proper determination of the cluster structure, from **A NEW GENERATION STAR DENSITY PROFILES FROM RESOLVED STAR COUNTS** covering **the entire cluster extention**

2. A detailed knowledge of the internal kinematics, from **A NEW GENERATION OF VELOCITY DISPERSION & ROTATION PROFILES FROM THE RADIAL VELOCITY OF INDIVIDUAL STARS over the entire cluster extension**

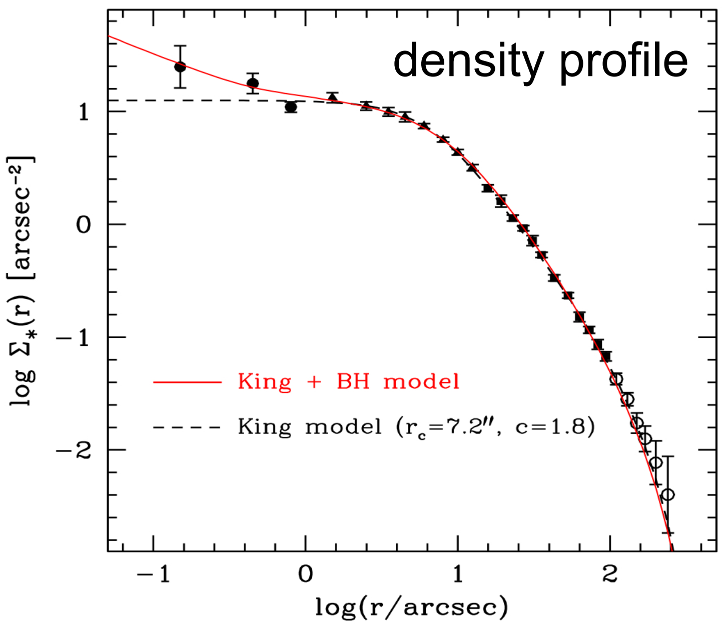
3. The accurate study of **BSS** which are the ideal gravitational probe-particle in GGCs

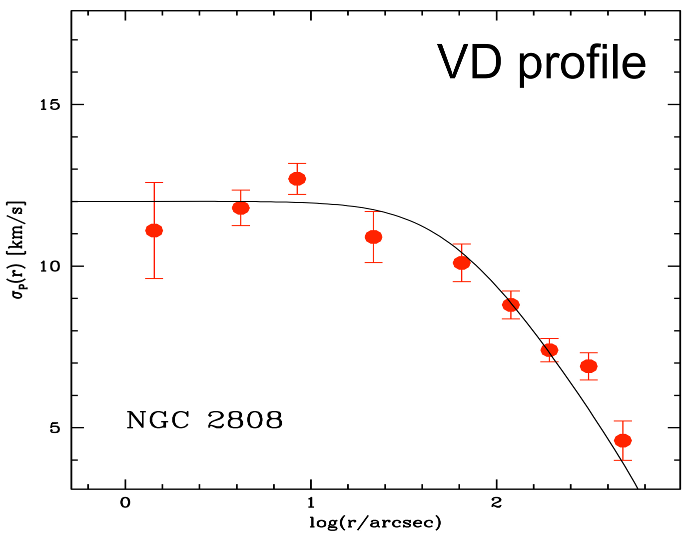
THE PROJECT

1. A proper determination of the cluster structure, from **A NEW GENERATION STAR DENSITY PROFILES FROM RESOLVED STAR COUNTS** covering **the entire cluster extention**

2. A detailed knowledge of the internal kinematics, from **A NEW GENERATION OF VELOCITY DISPERSION & ROTATION PROFILES FROM THE RADIAL VELOCITY OF INDIVIDUAL STARS** **over the entire cluster extension**

3. The accurate study of **BSS** which are the ideal gravitational probe-particle in GGCs

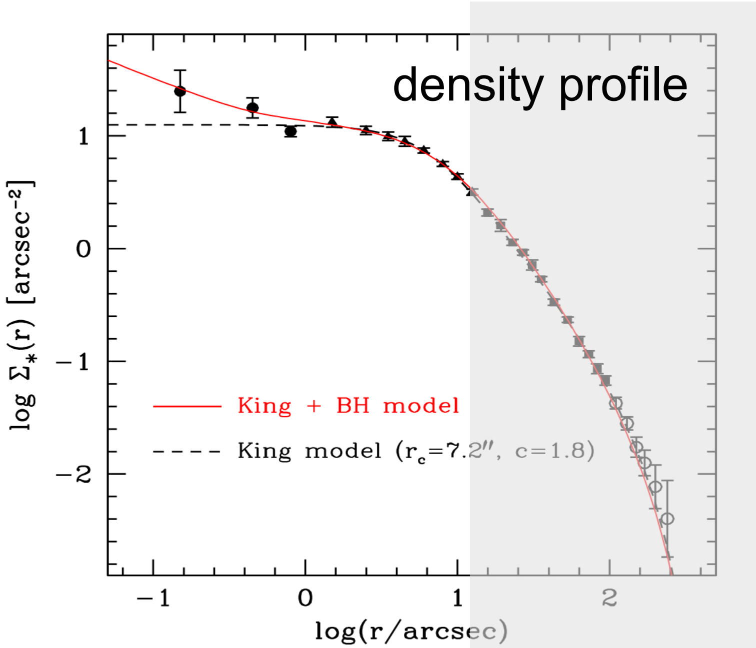

density profile
King + BH model
King model (r_c=7.2″, c=1.8)
log $\Sigma_*(r)$ [arcsec^{-2}]
log(r/arcsec)


VD profile
NGC 2808
$\sigma_p(r)$ [km/s]
log(r/arcsec)

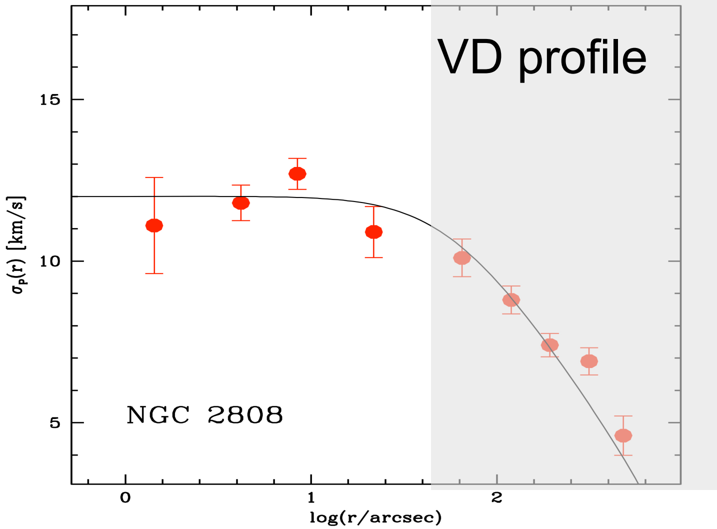
CENTRAL REGIONS

- Core size
- Central cusp

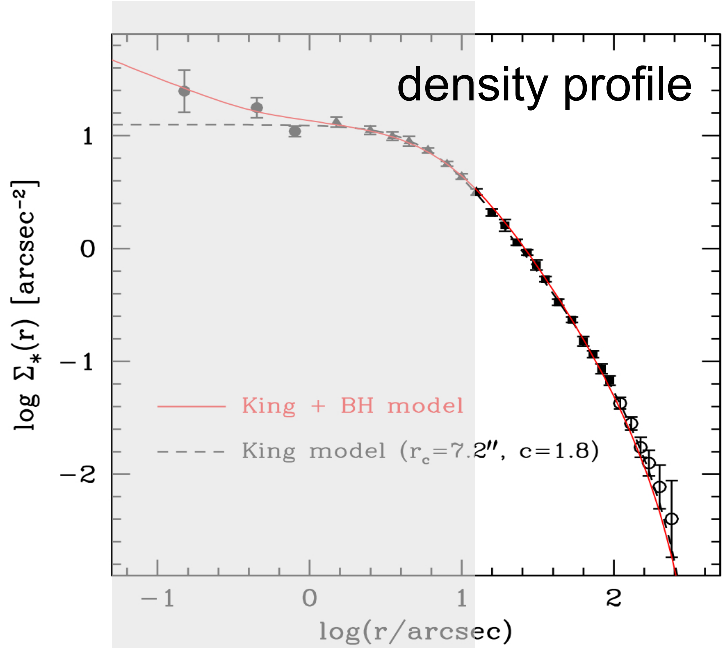
(CC or IMBH?)



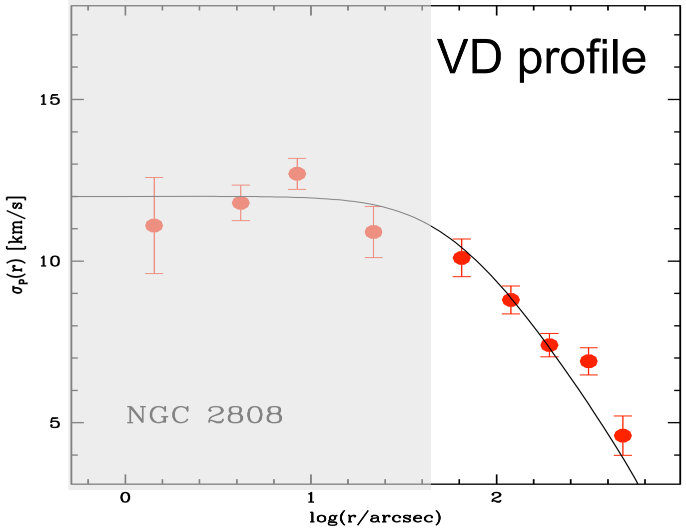
- Central VD
- Cusp (IMBH !)
- High-velocity stars
- Rotation?
- Anisotropy?



EXTERNAL REGIONS

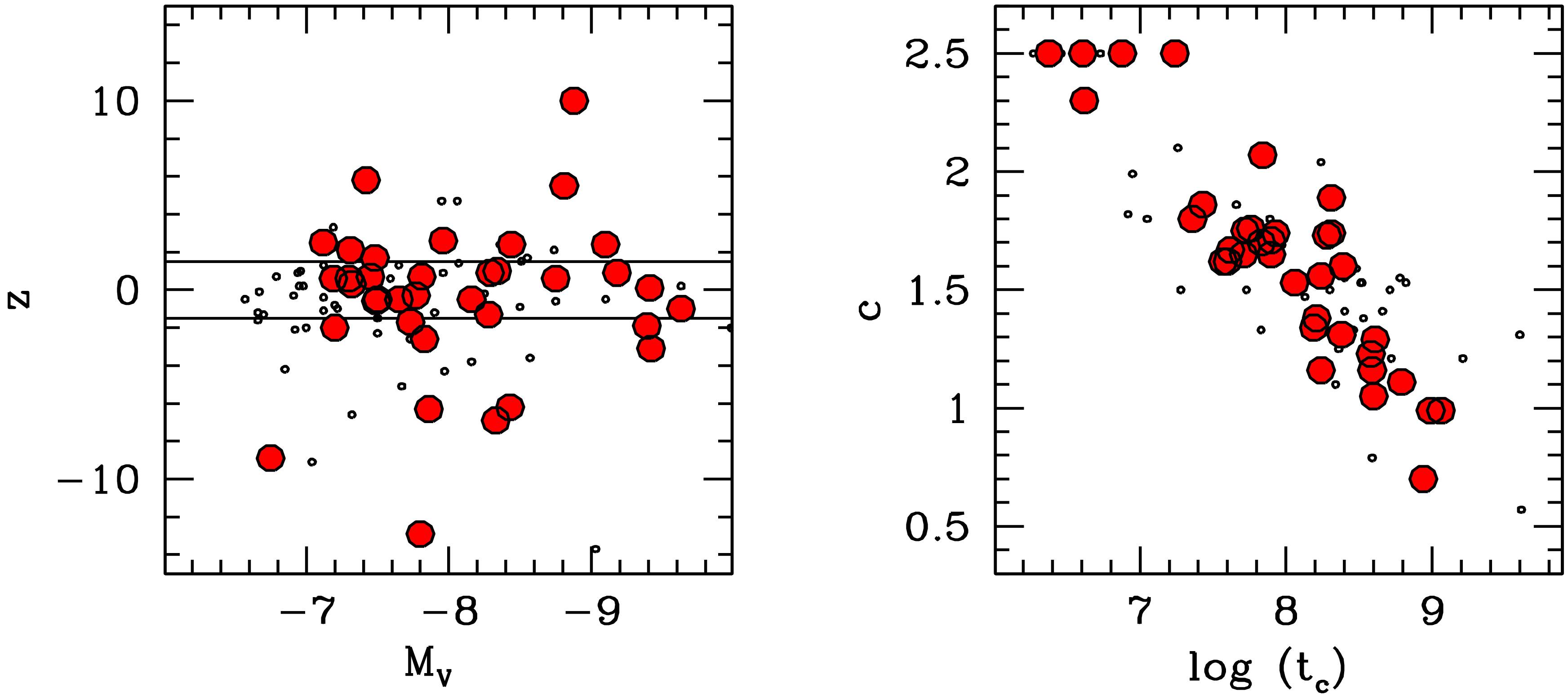


- Cluster size
- Tidal tails
- Extra-tidal halos



- Rotation
- Dark Matter??

THE TARGETS



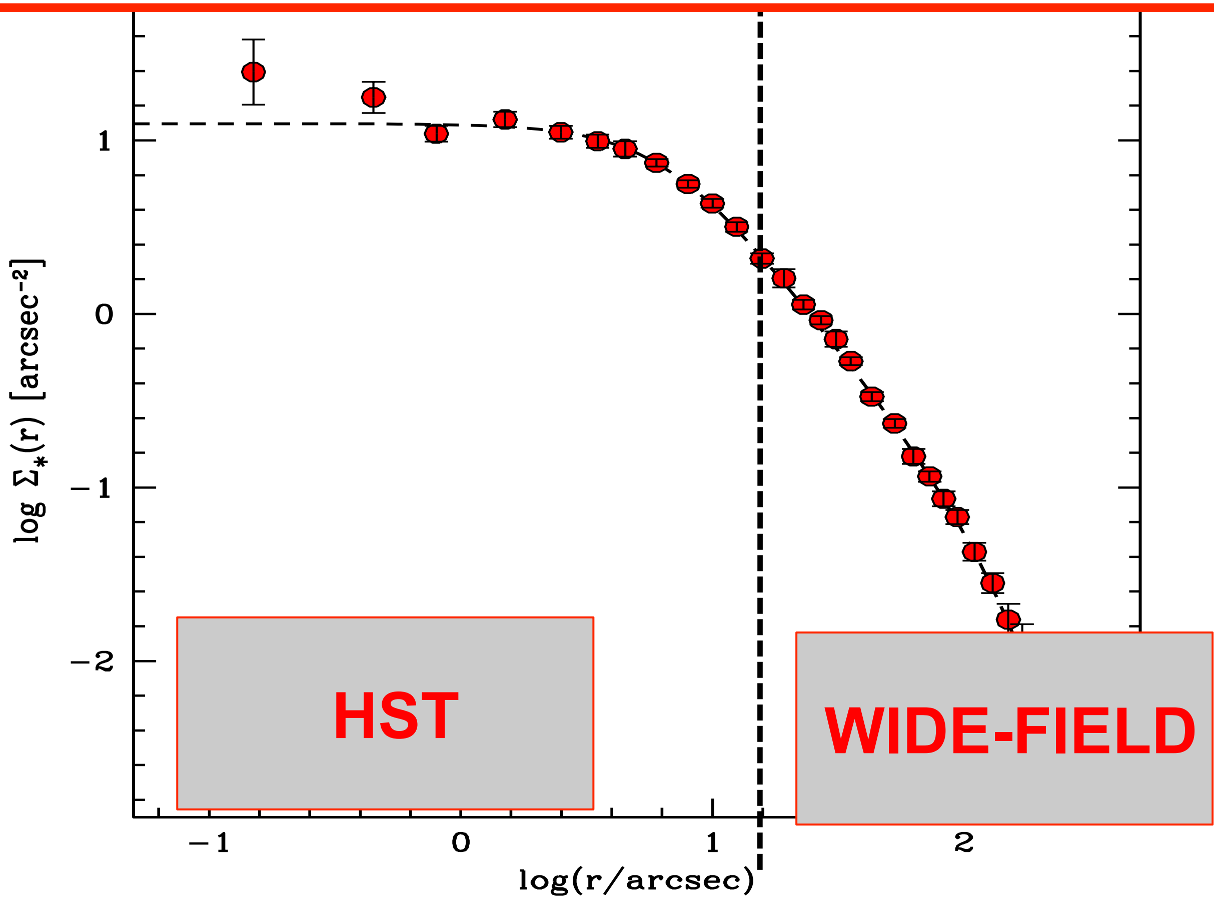
(i) they are massive ($M > 5x10^5\ M_\odot$)

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

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

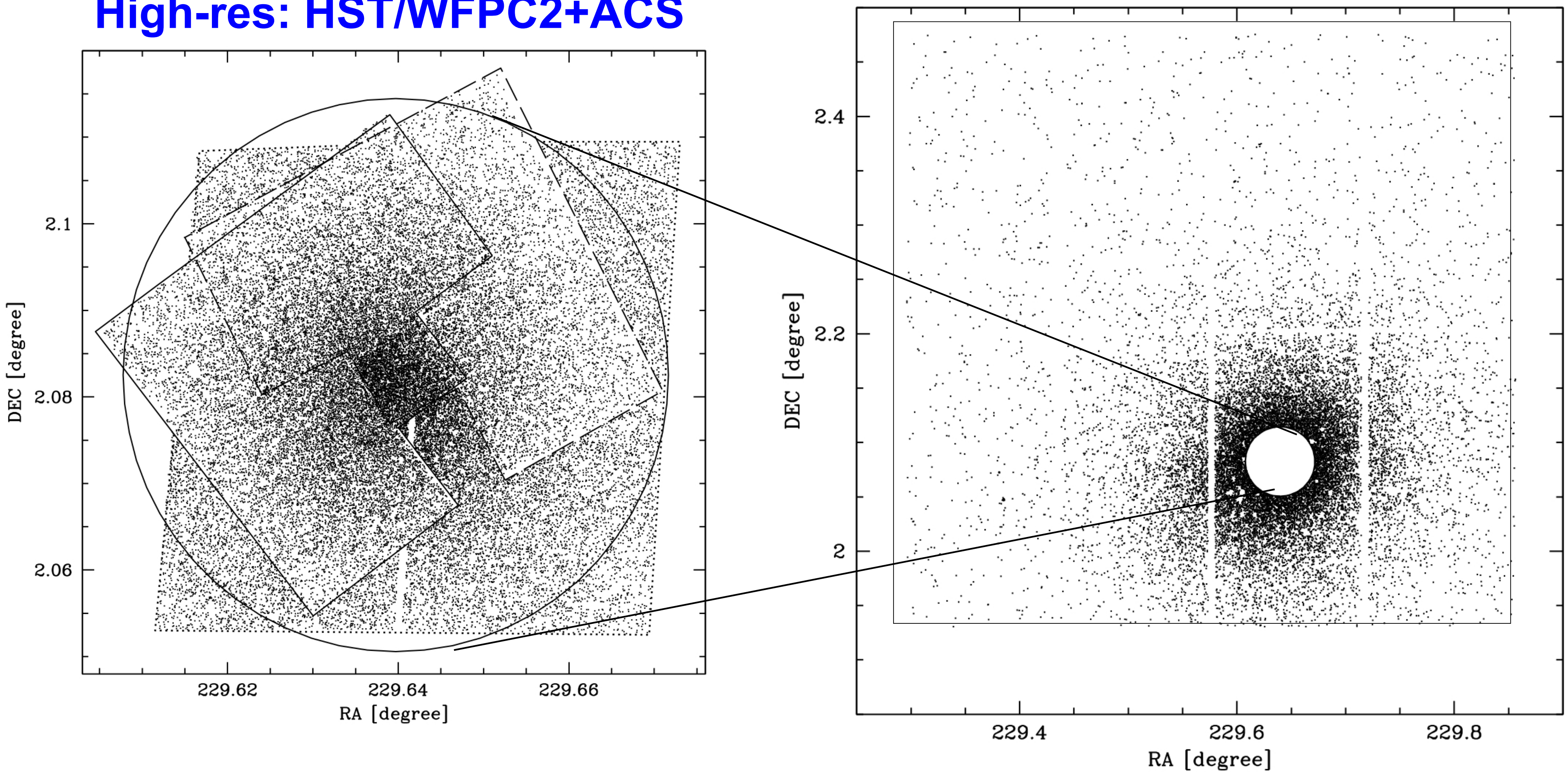
(iv) They span different environmental conditions (sampling both the bulge/disk and the halo populations)

THE PROJECT
I. A NEW GENERATION OF STAR DENSITY PROFILES FROM RESOLVED STAR COUNTS USING A MULTI-INTRUMENT APPROACH



A NEW GENERATION OF STAR DENSITY PROFILES

High-res: HST/WFPC2+ACS



Wide-field ground-based imaging

GO 5903 - PI:Ferraro	6 orbits	GO 6607 - PI:Ferraro	11 orbits
GO 8709 - PI:Ferraro	13 orbits	GO10524 - PI:Ferraro	11 orbits
GO11975 - PI:Ferraro	177 orbits	GO12516 - PI:Ferraro	21 orbits

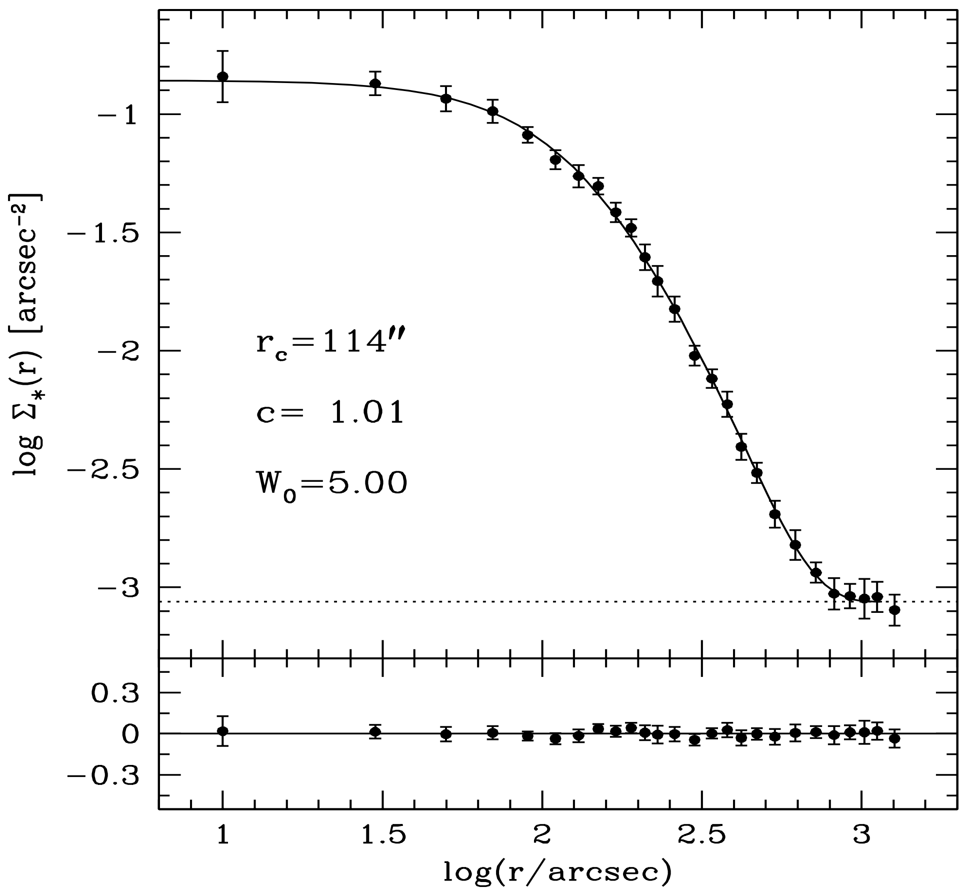
Grandtotal 239 orbits

RESOLVED STAR DENSITY profiles

instead of

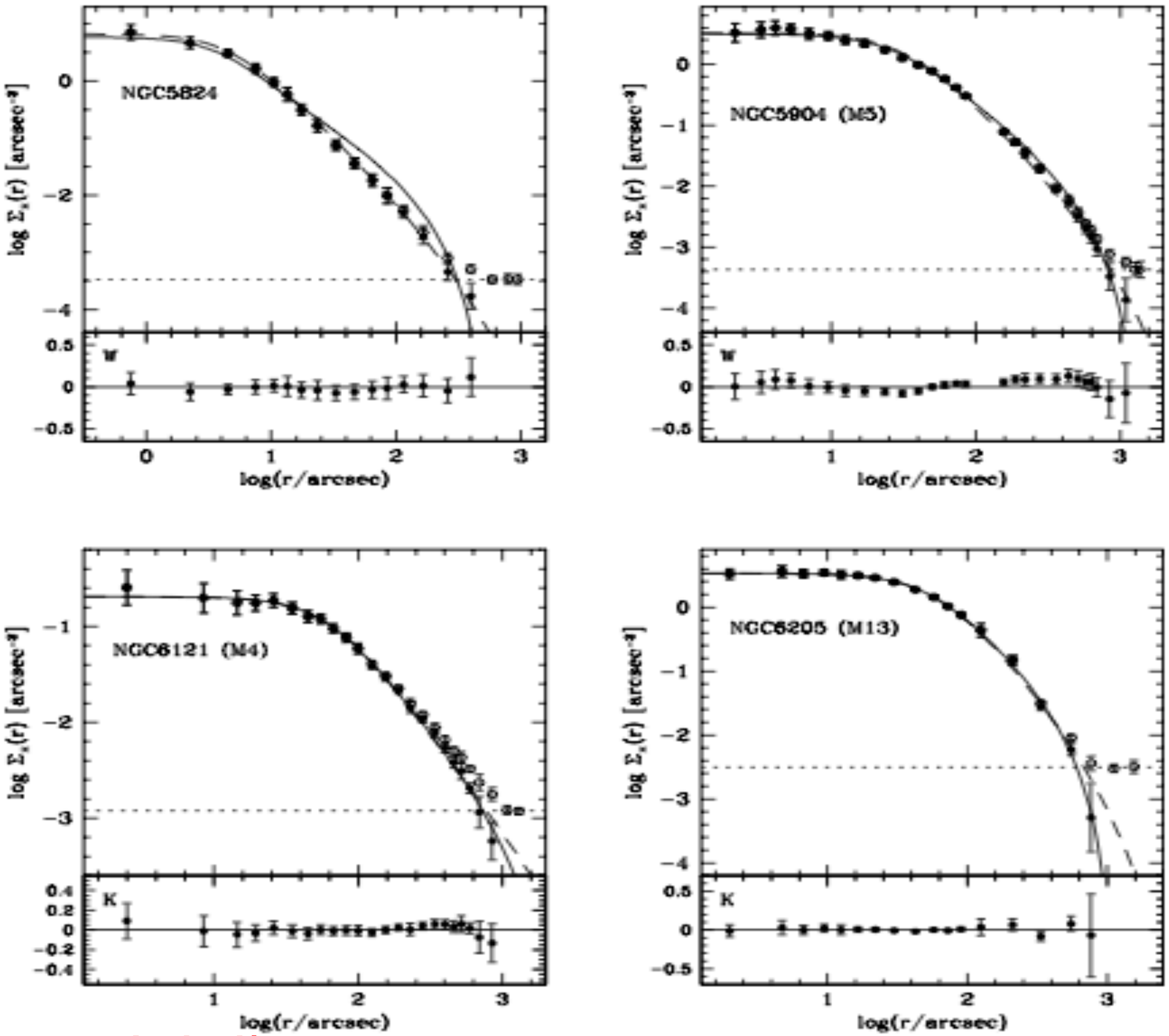
SURFACE BRIGHTESS profile (SBP)

SBP is easily biased by the presence of a few bright stars
(which dominate the contribution to the surface brightness)



First results in Miocchi et al. (2013, ApJ, 774, 151) + Cosmic-Lab web site

Resolved star density profiles covering the entire cluster extension:



Miocchi et al. (2013, ApJ, 774, 151)
Cosmic-Lab web site

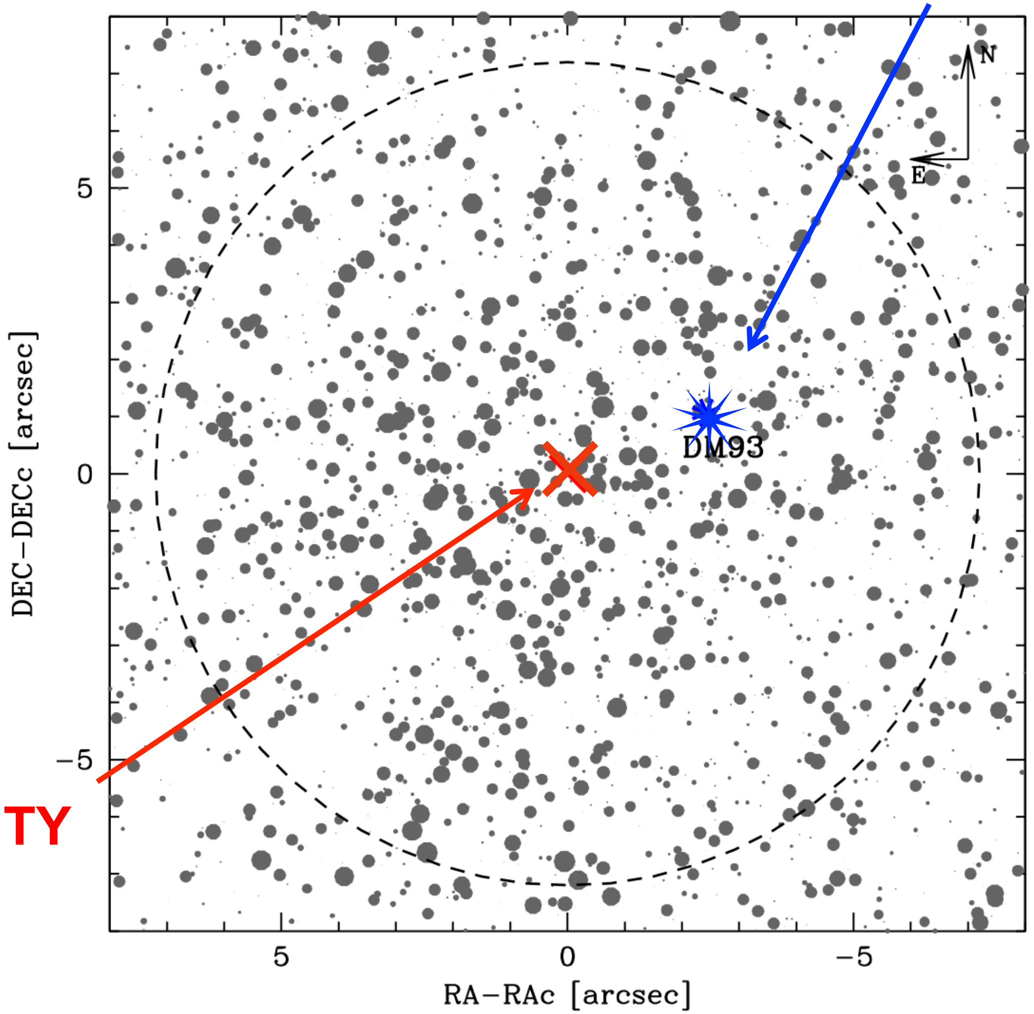
Determination of the centre

CENTER of GRAVITY by averaging the positions of a few 1000 stars :

typically a few arcsec different from old **(LUMINOSITY CENTER)** determinations

(see for example Djorgovski & Meylan 1993)

LUMINOSITY CENTER

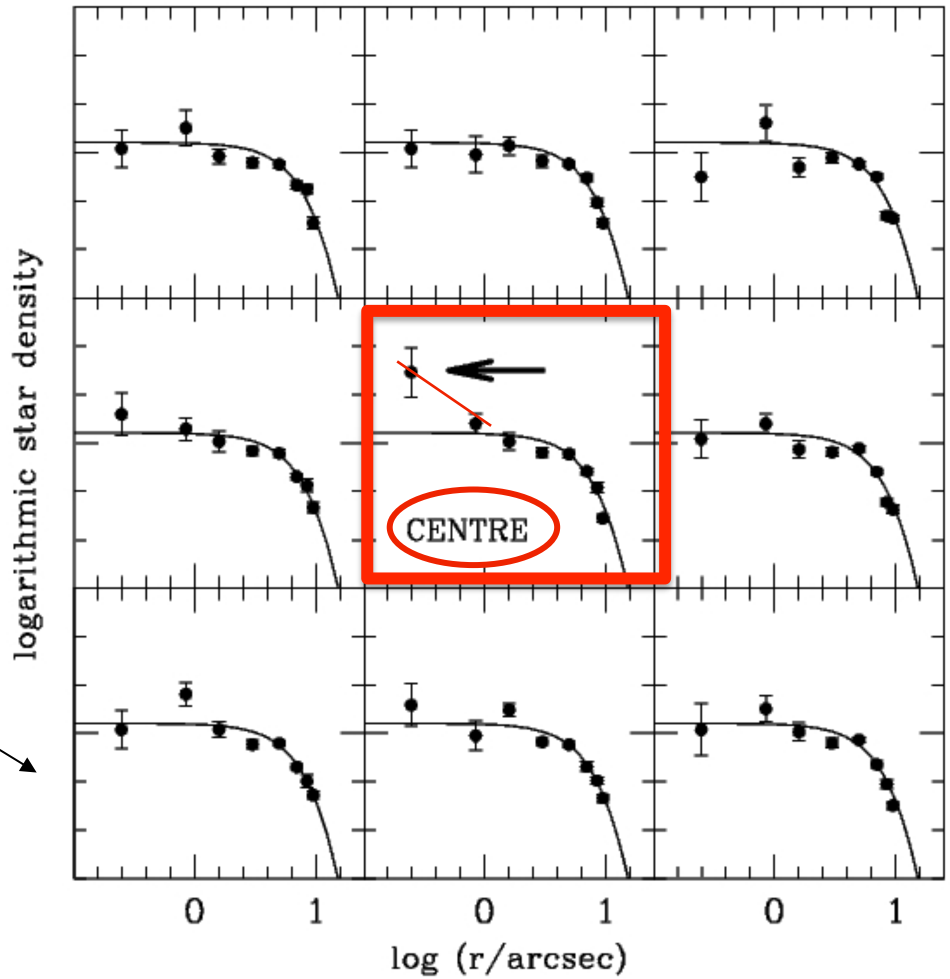


CENTER of GRAVITY

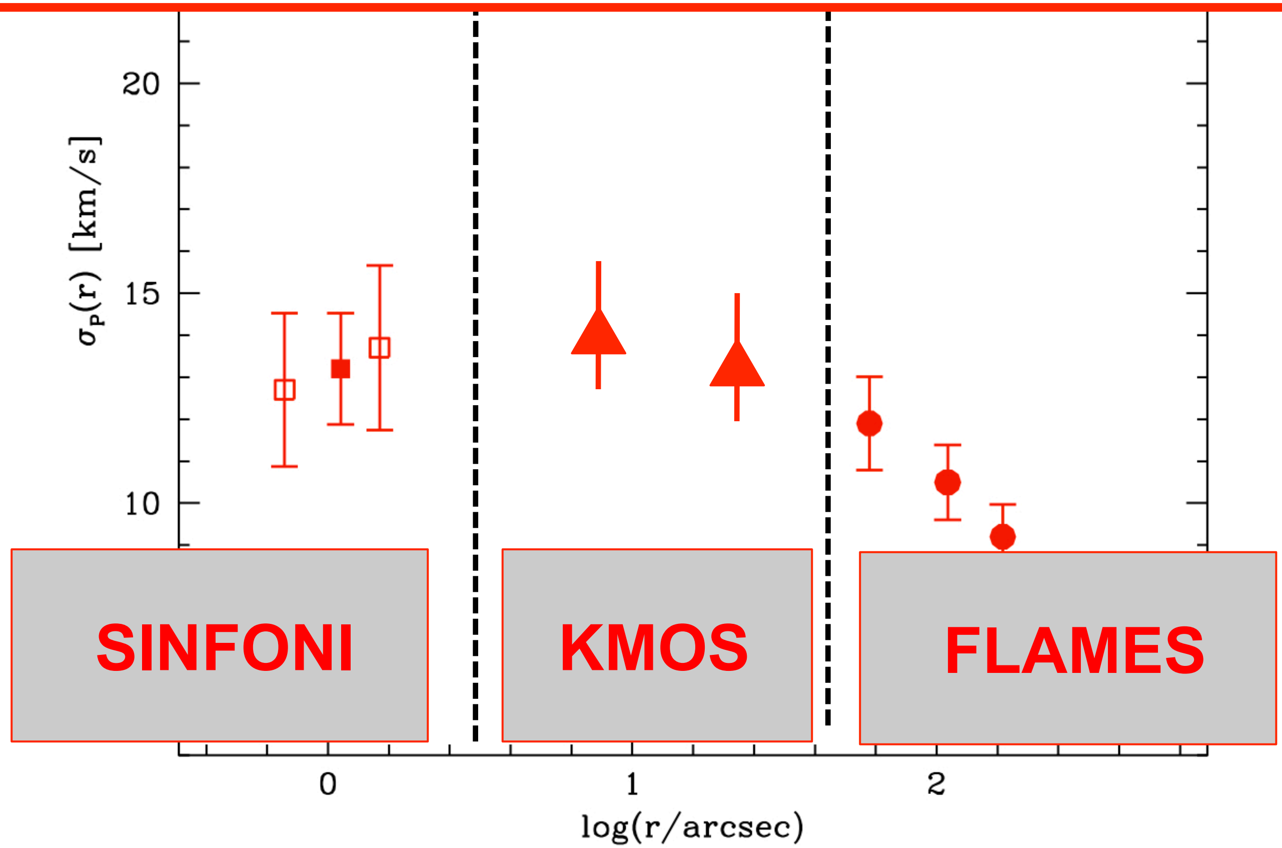
Determination of the centre

even an error of a few 0.1" is sufficient to artificially flatten the derived profile and hide the central cusp!

shifts of ± 0.5" with respect to the right centre !



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

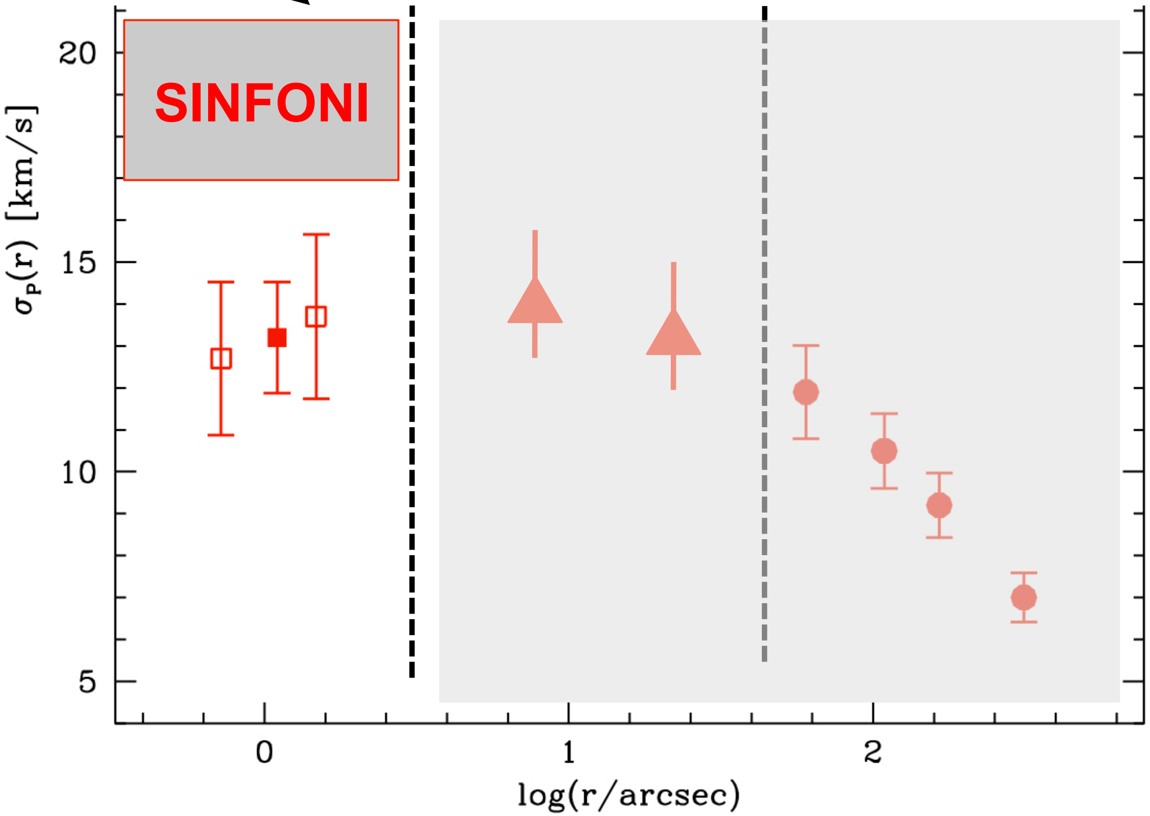


A MULTI-INSTRUMENT APPROACH

SINFONI

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

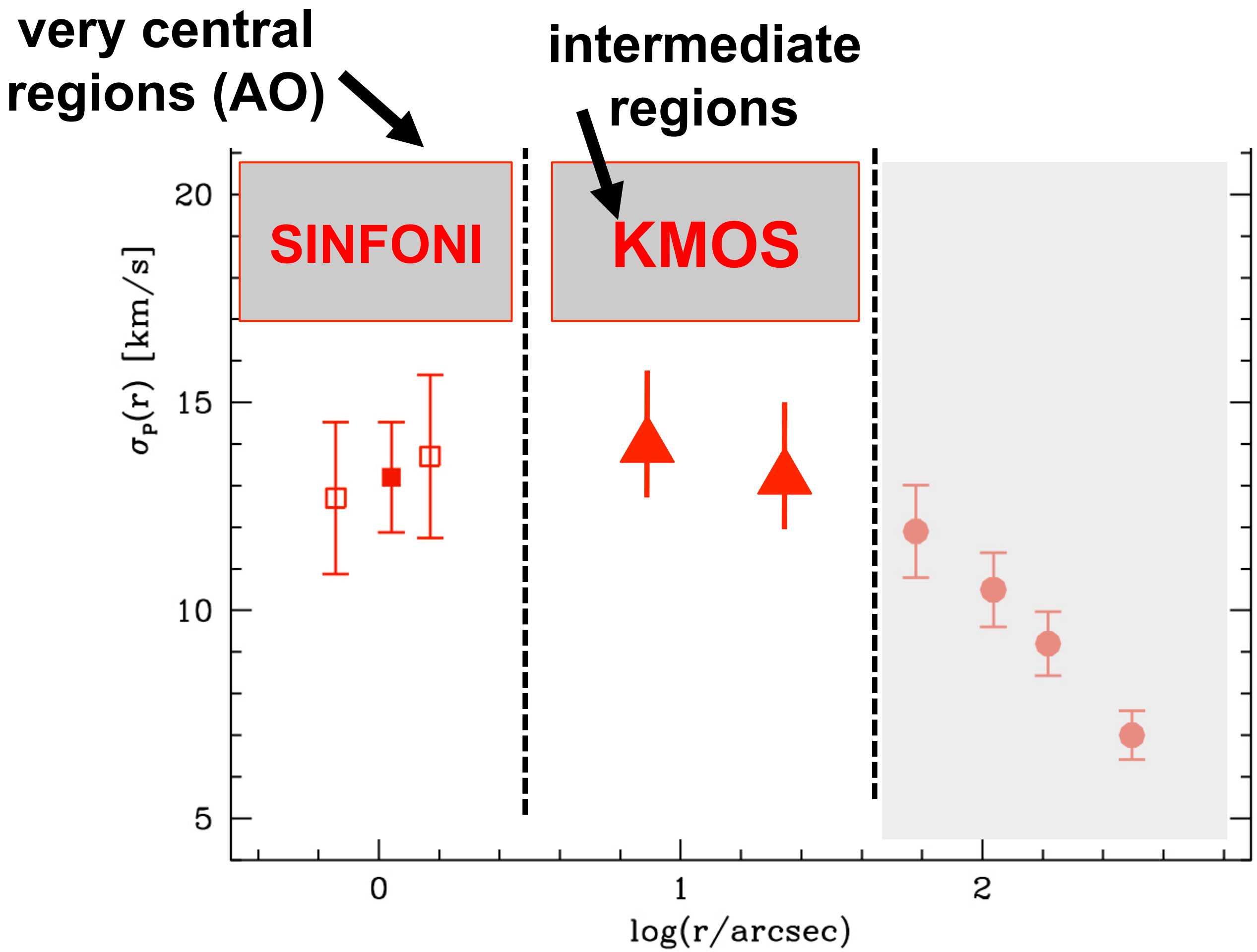
very central regions (AO)



A MULTI-INSTRUMENT APPROACH

KMOS

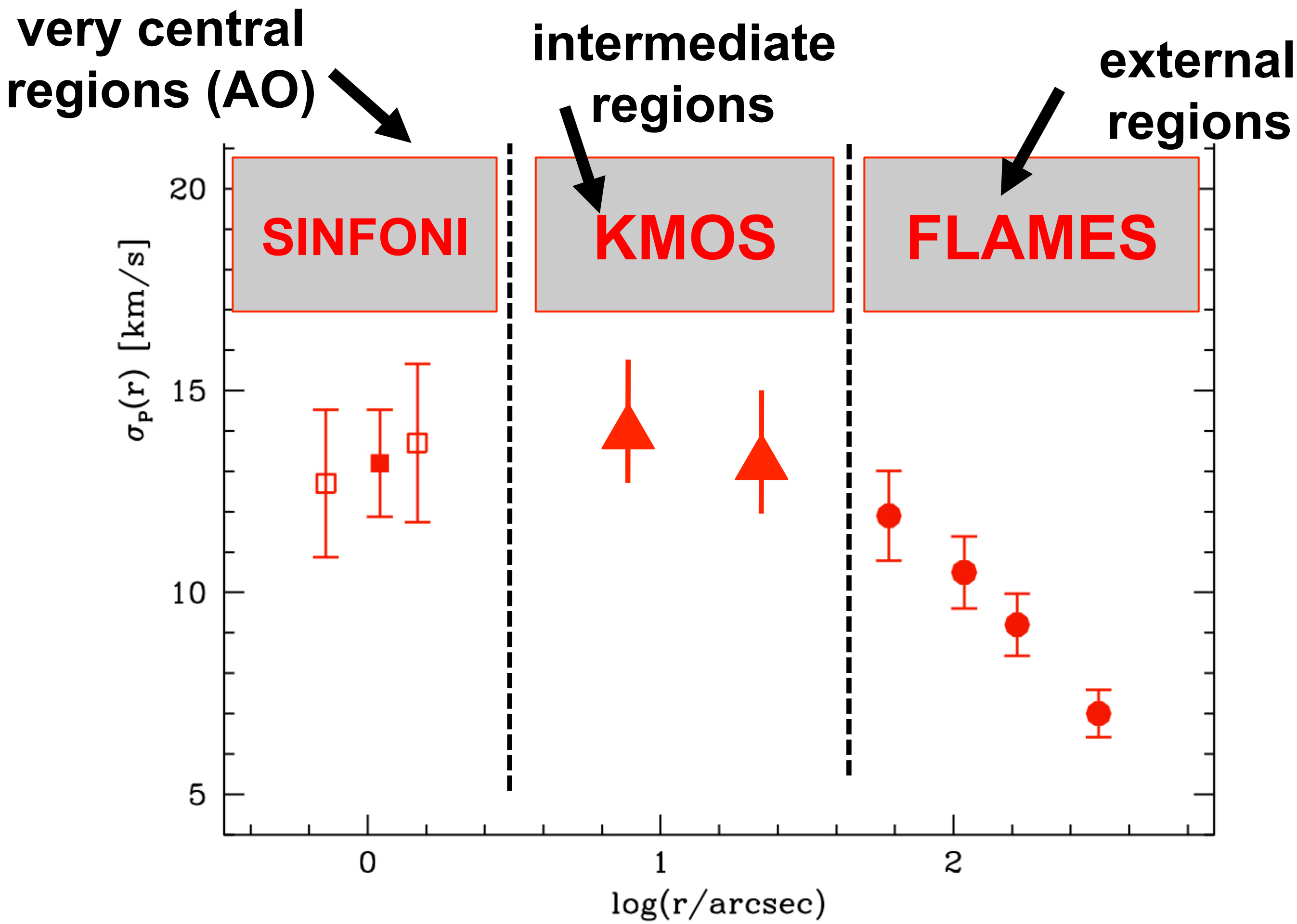
24 deployable IFUs, FoV=3”x3” each,
mid-spectral resolution (R=3400), YJ-band grating (1.00-1.35 μm),
atomic lines (TiI, MgI, FeI,..)



A MULTI-INSTRUMENT APPROACH

FLAMES

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

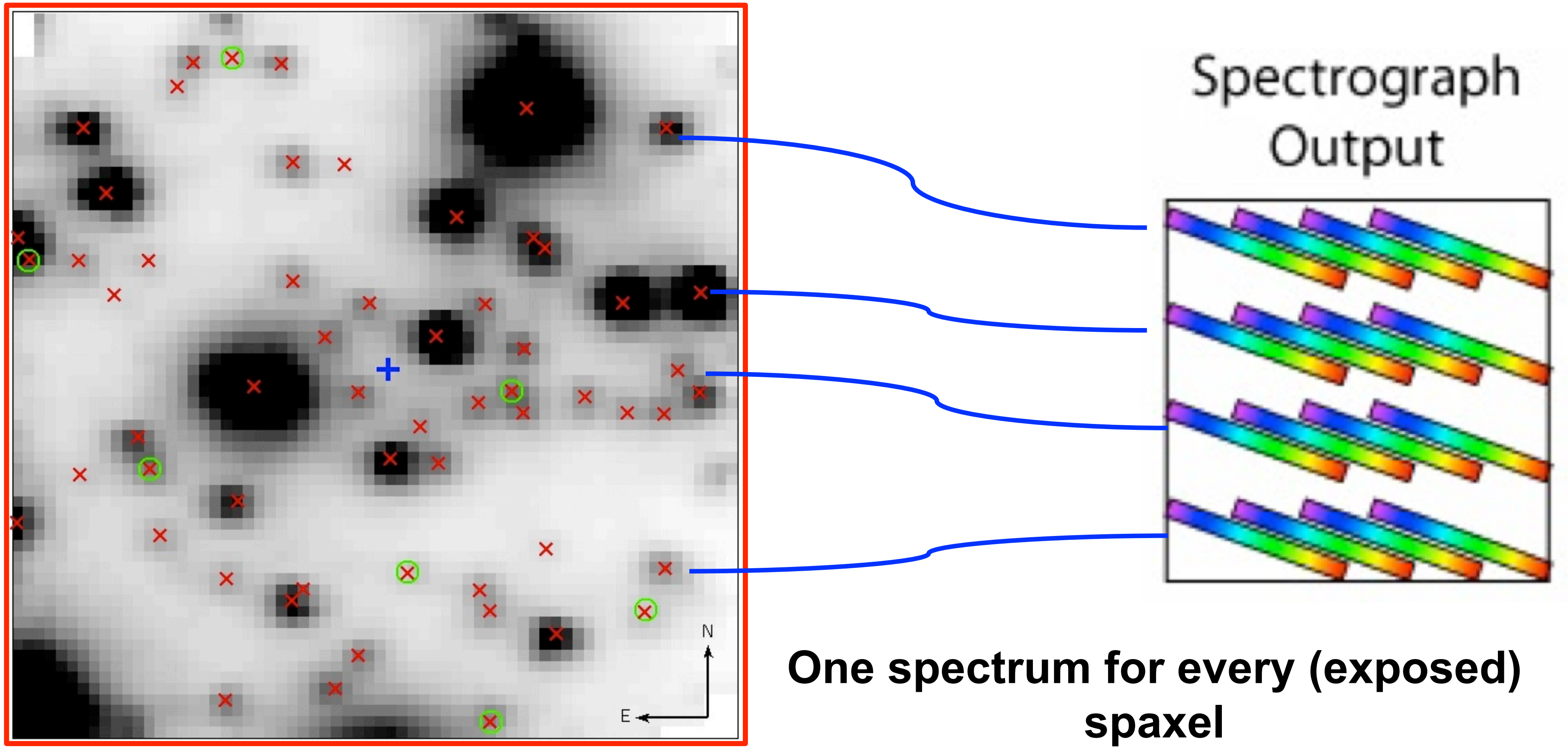


A MULTI-INSTRUMENT APPROACH

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 DATA-SETS

✦ **ESO Large Programme 193.D-0232 (PI: Ferraro):**

194 hours
KMOS + FLAMES
30 Milky Way GCs
2/3 acquired and 1/3 partially analyzed

✦ **ESO Large Programme 195.D-0750 (PI: Ferraro):**

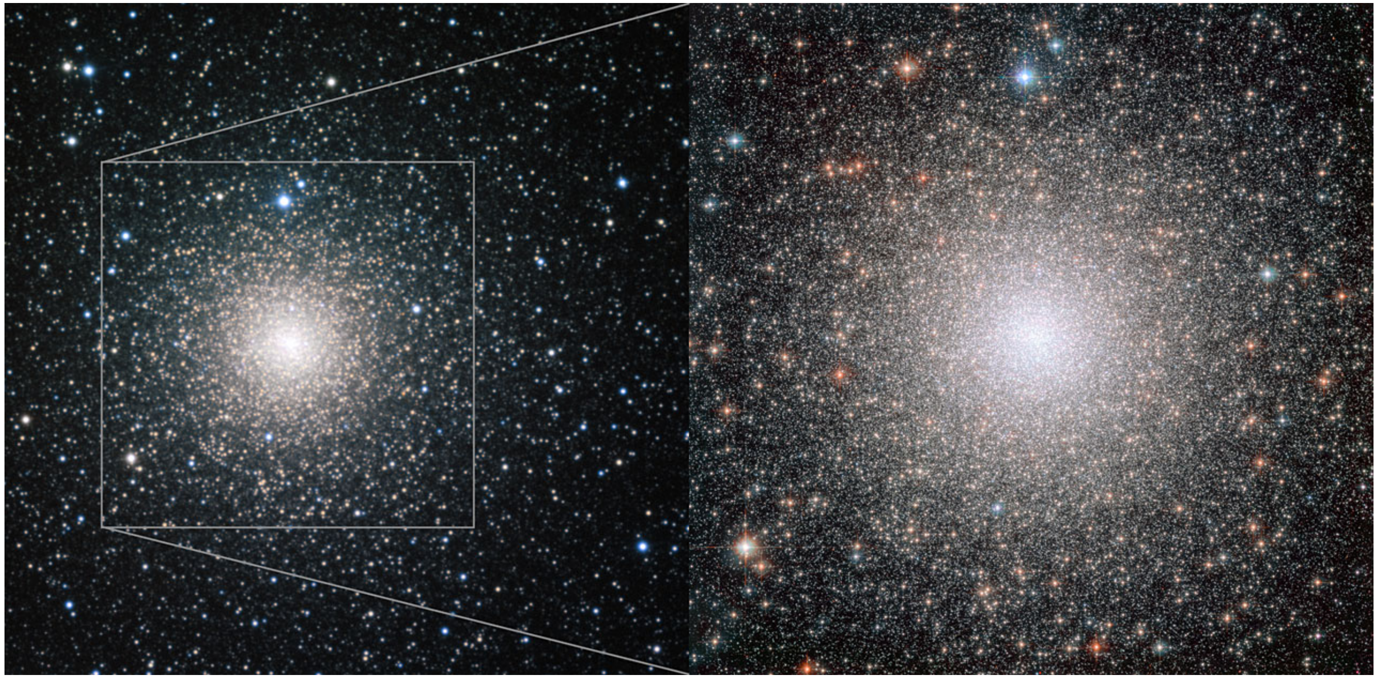
101 hours
SINFONI
15 high-density Milky Way GCs
½ acquired

✦ **a few additional programmes @Keck:**

OSIRIS + MOS-FIRE + DEIMOS

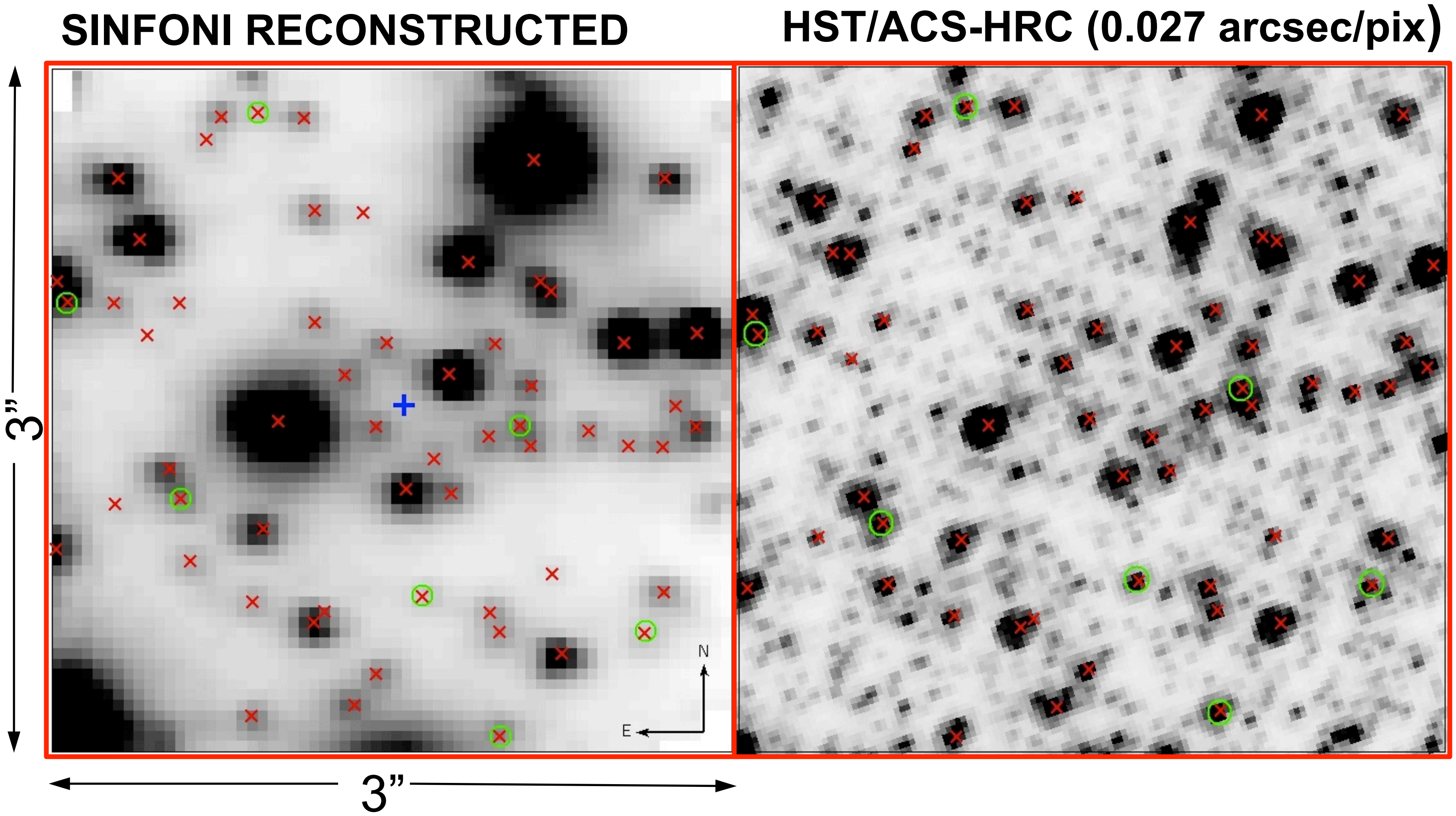
NGC 6388

- **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 $L_\odot/pc^3$)



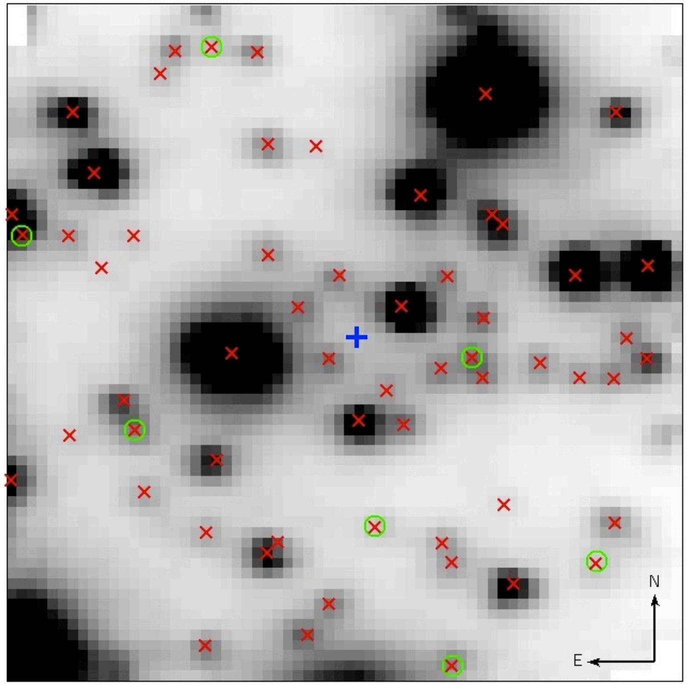
SINFONI (AO assisted IFU)→ center

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

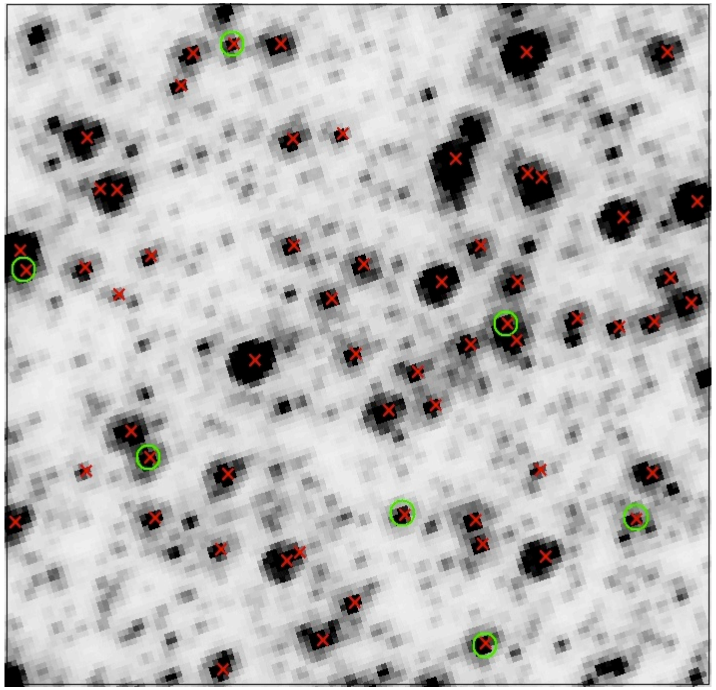


SINFONI (AO assisted IFU)→ center

SINFONI



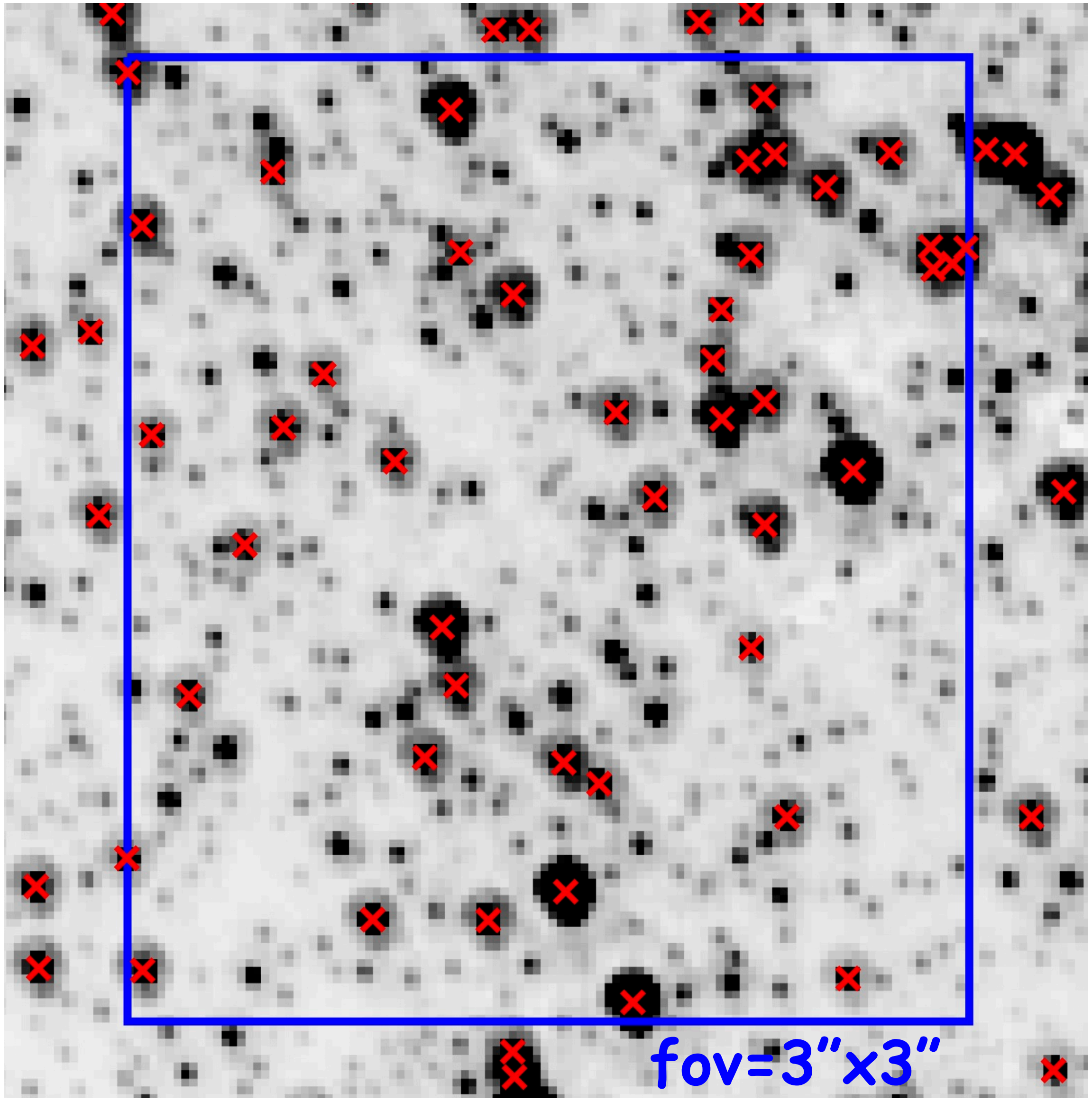
HST/HRC



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

The E-ELT Era: NGC6388 core with HARMONI

ACS-HRC 25 mas/pix



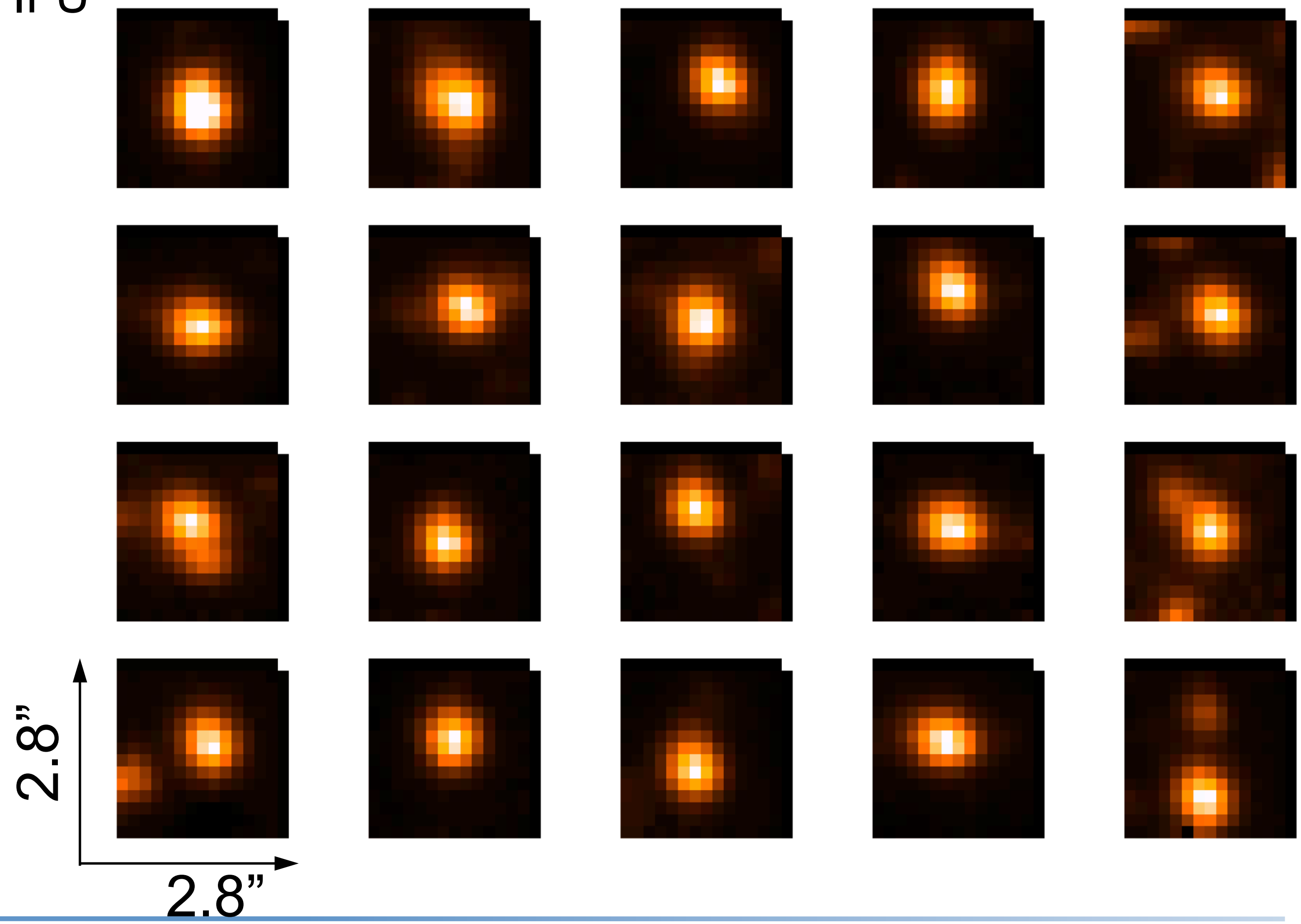
in the central 3"x3"

with SINFONI (50x100 mas)
~60 giants stars down to H~15
R~4,000
RVs with a few km/s accuracy
VD profile in bins of ~0.8"

with HARMONI (20x20 mas)
~600 stars down to H~19
R~20,000
chemical abundances
RVs with <1 km/s accuracy
VD profile in bins of ~0.3"

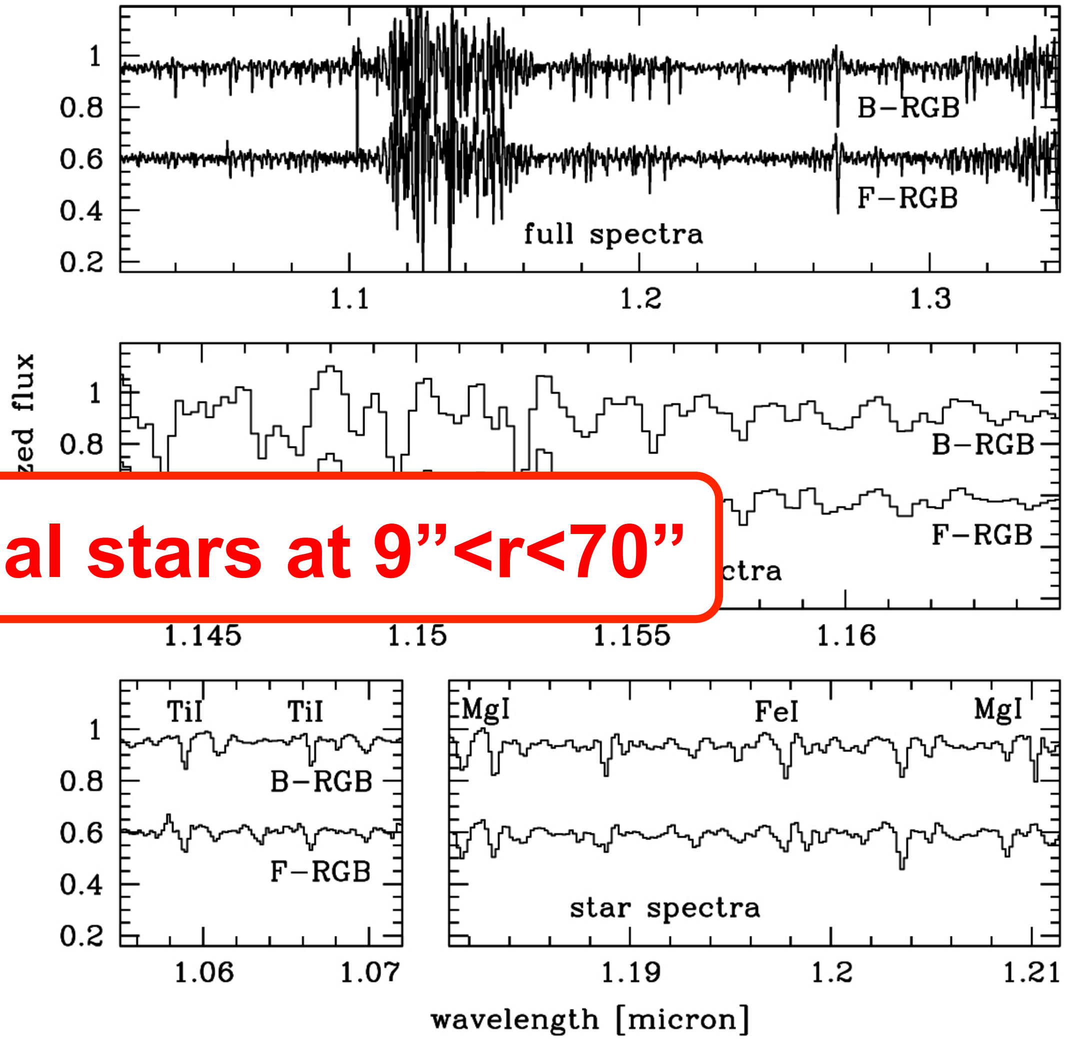
KMOS (multi-objects: 24 IFUs)→ intermediate regions

1-3 stars per IFU



KMOS (multi-objects: 24 IFUs)→ intermediate regions

- Vr from several atomic lines
- wavelength calibration refined with telluric lines

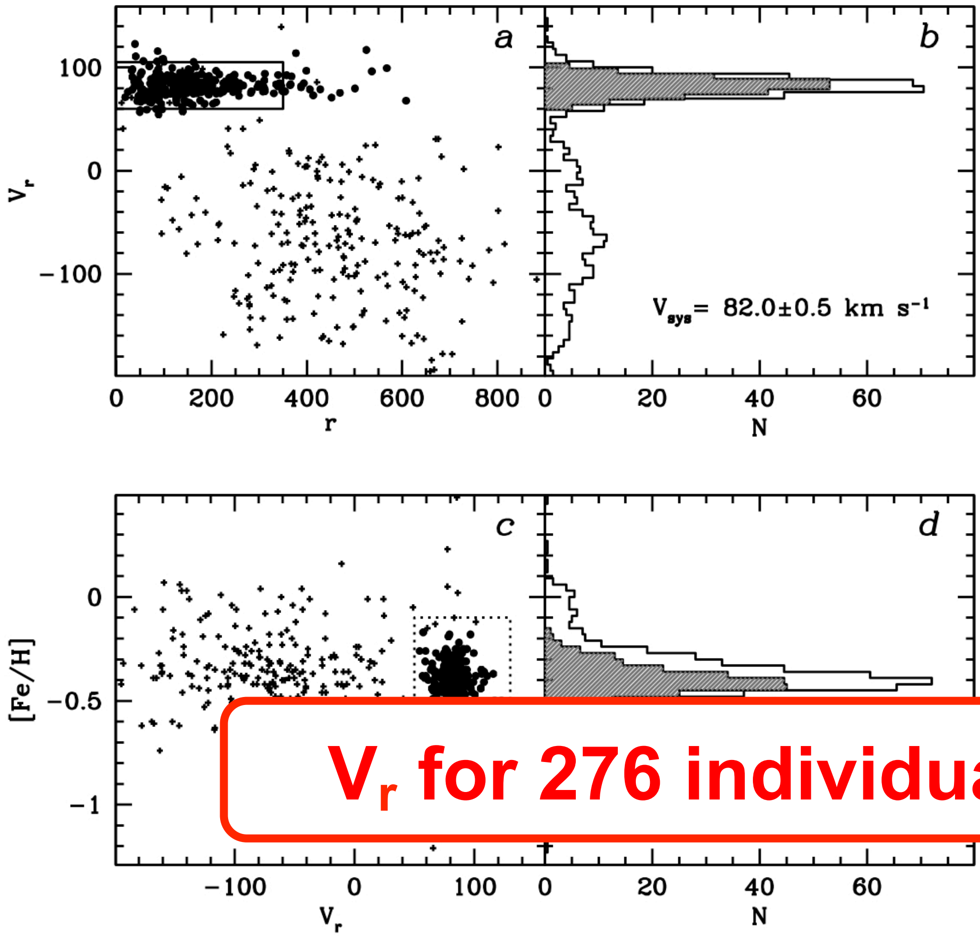


→ V_r for 82 individual stars at 9”<r<70”

See details in the poster by Lapenna et al.

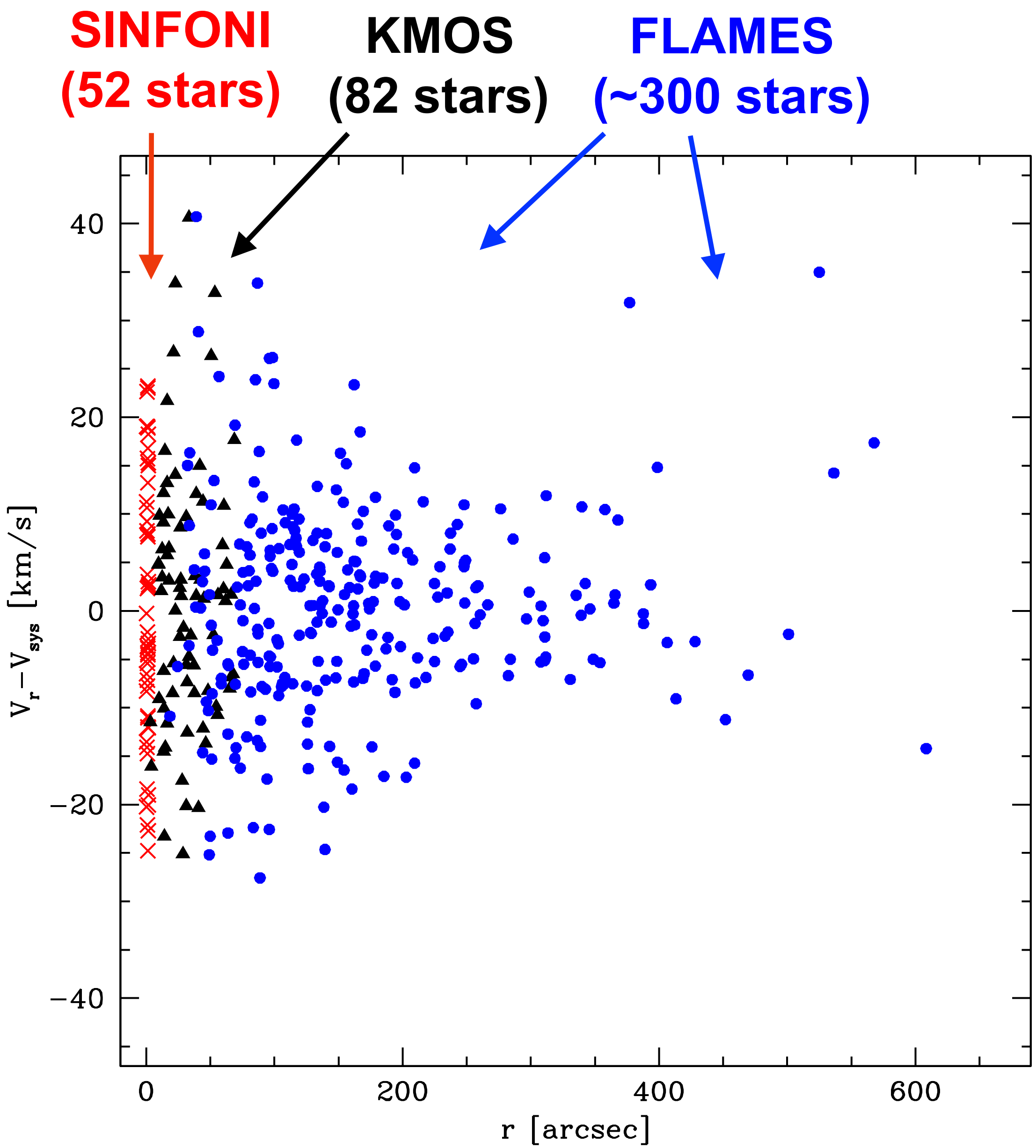
FLAMES (multi-objects: 132 fibers)→ external regions

- 5 shots => V_r & [Fe/H] for 508 stars



276 cluster members

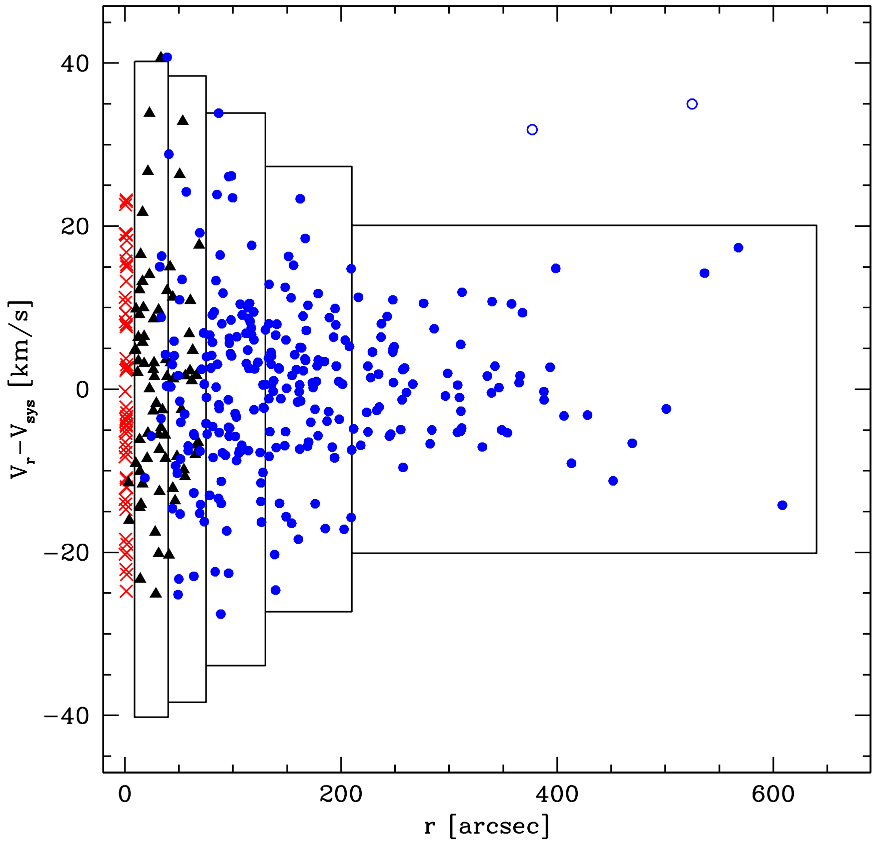
V_r for 276 individual stars at 18”<r<600”

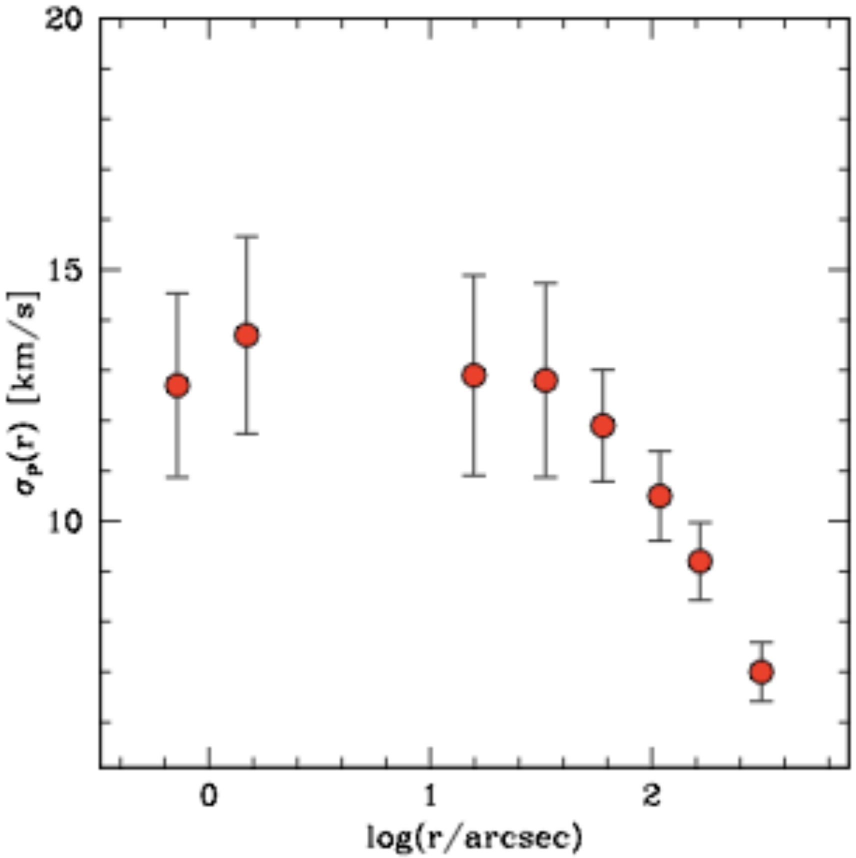

SINFONI
(52 stars)
KMOS
(82 stars)
FLAMES
(~300 stars)
40
20
0
−20
−40
$V_r - V_{sys}$ [km/s]
0
200
400
600
r [arcsec]

Velocity dispersion profile

$\sigma(r)$ from the dispersion of V_r in radial bins of ≥ 50 stars

(following the Maximum Likelihood method of Walker et al. 2006)

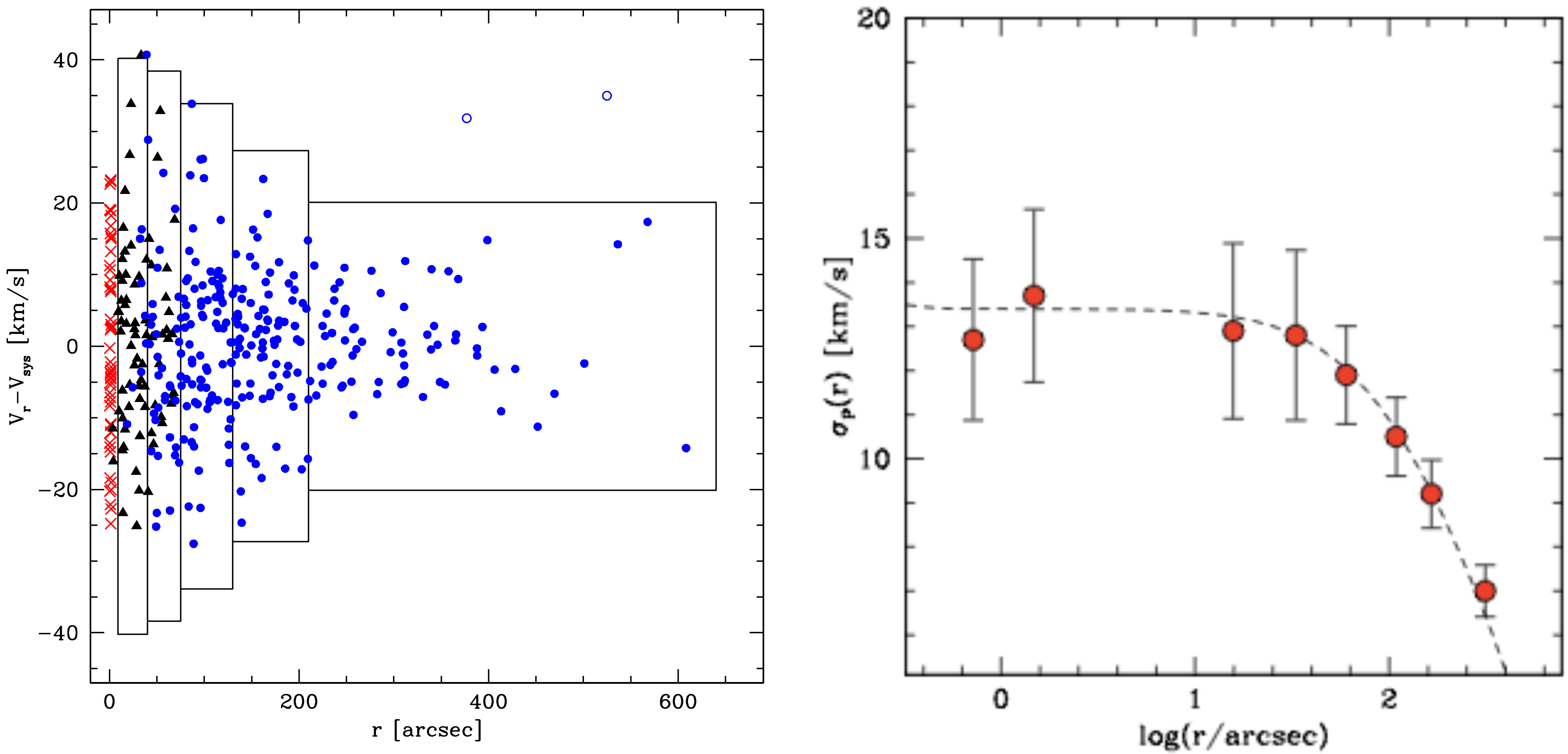




Velocity dispersion profile

σ(r) from the dispersion of V_r in radial bins of ≥ 50 stars

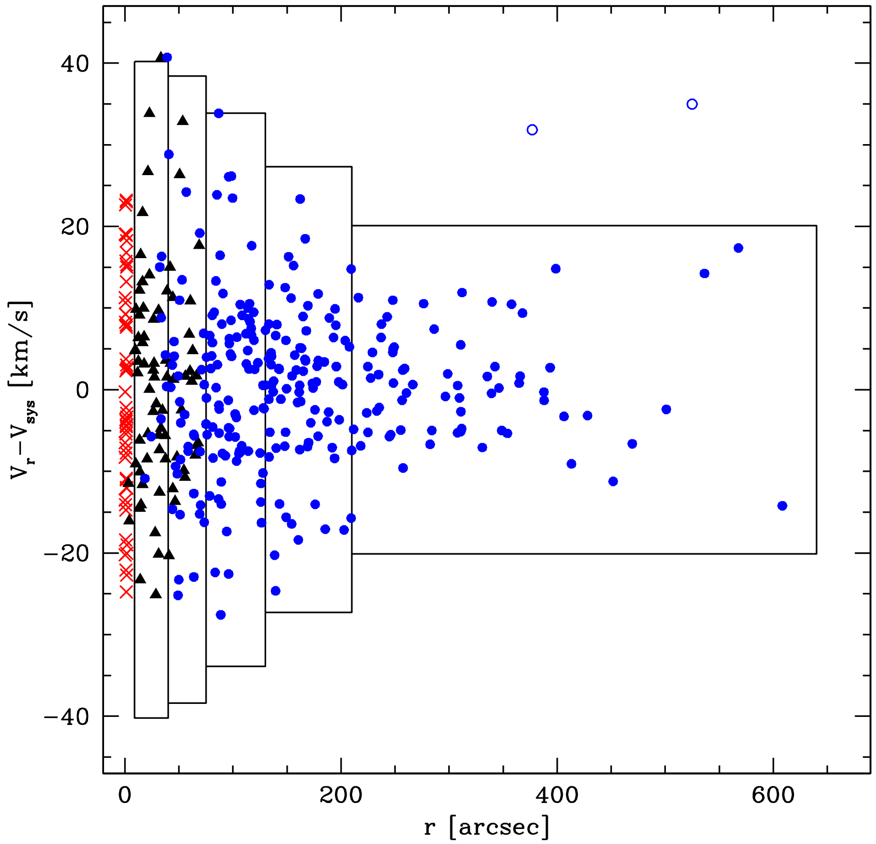
(following the Maximum Likelihood method of Walker et al. 2006)

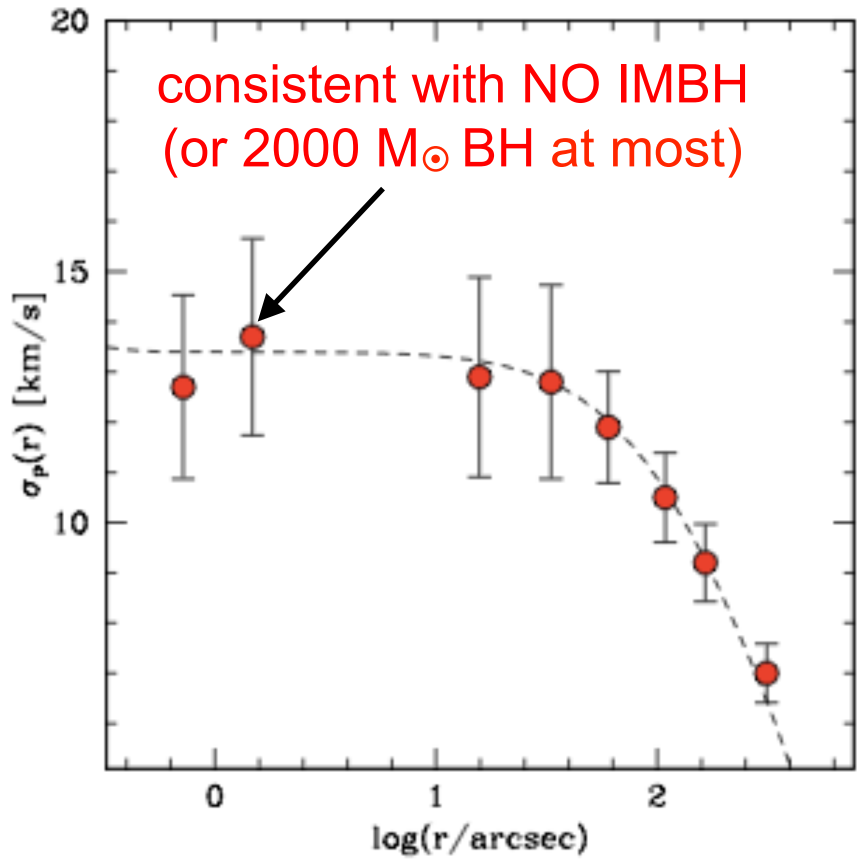


Velocity dispersion profile

$\sigma(r)$ from the dispersion of V_r in radial bins of ≥ 50 stars

(following the Maximum Likelihood method of Walker et al. 2006)





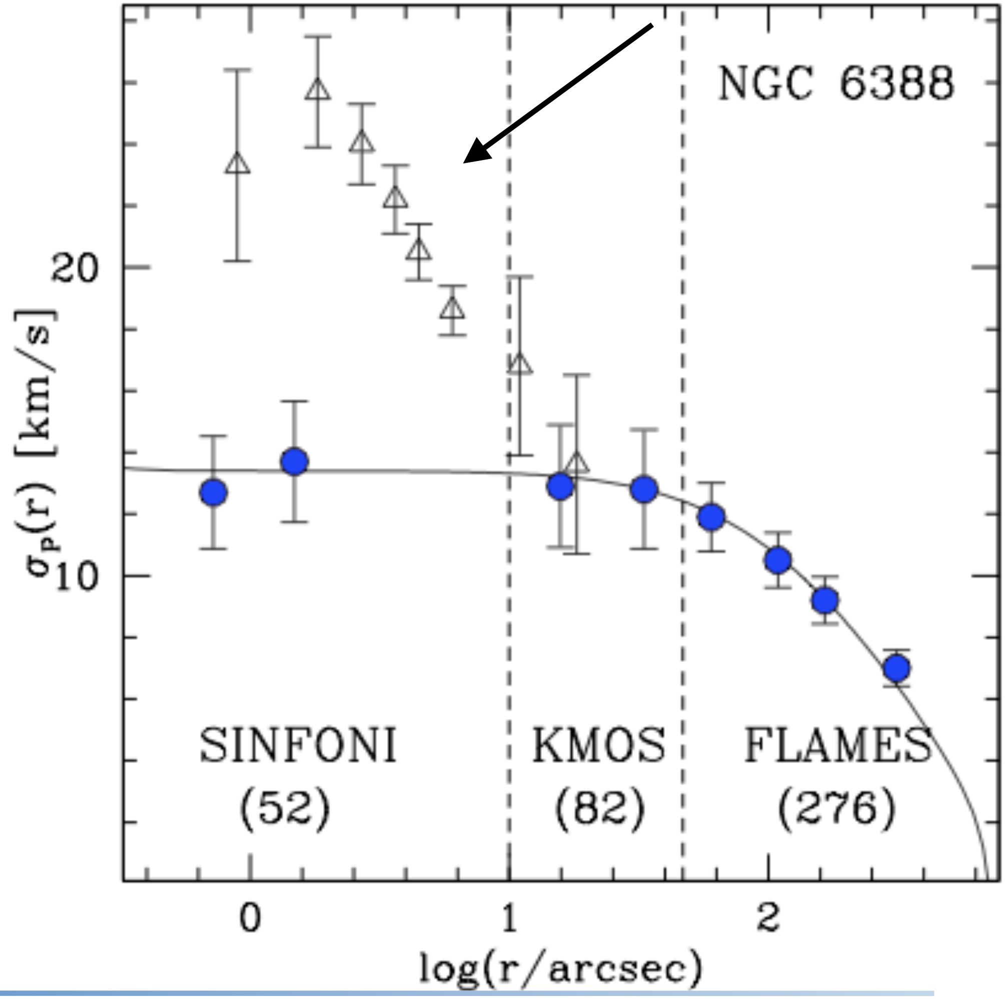
Velocity dispersion profile

Lützgendorf et al. (2011)
(M_{BH} ~ 1.7 10^4 $M_\odot$)

$\sigma(r)$ from individual V_r
(σ_0 ~ 13-14 km/s)

inconsistent with

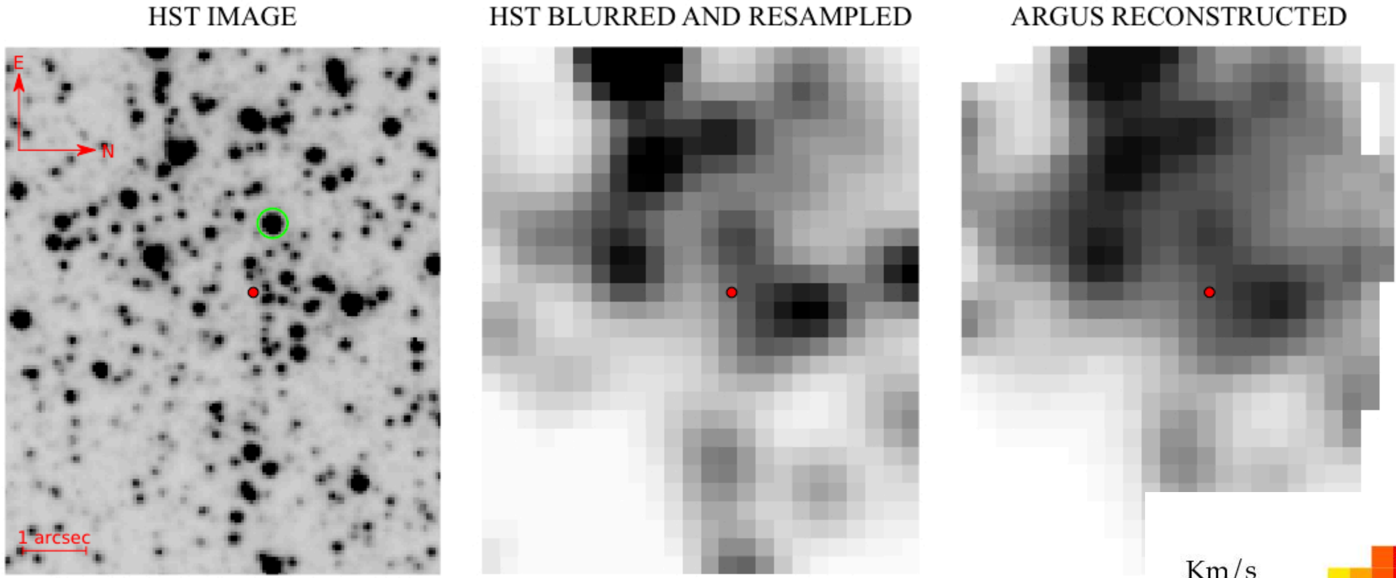
$\sigma(r)$ from the line broadening of integrated-light spectra
(σ_0 ~ 23-25 km/s)

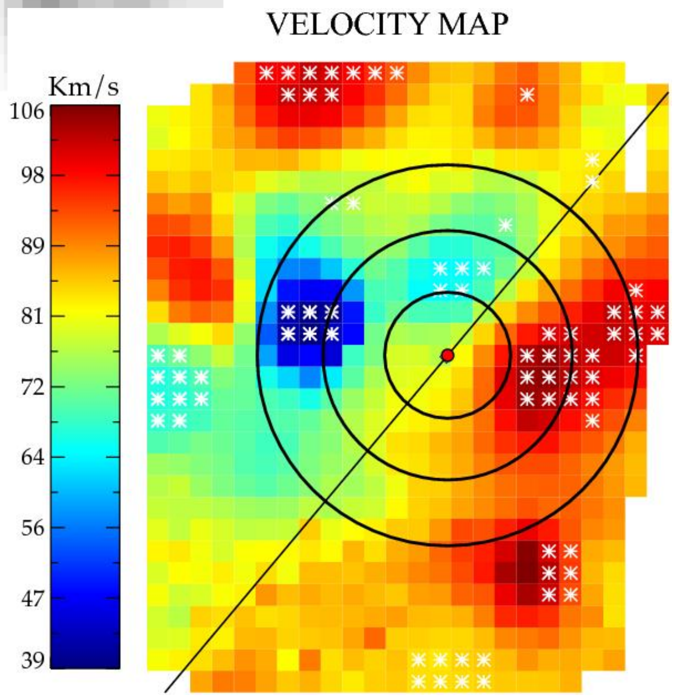


WHY ?

• Velocity dispersion from integrated light spectroscopy

ARGUS (non-AO assisted IFU@VLT)





Velocity dispersion profile from the broadening of the specral lines

(Lützgendorf et al. 2011 – L11)

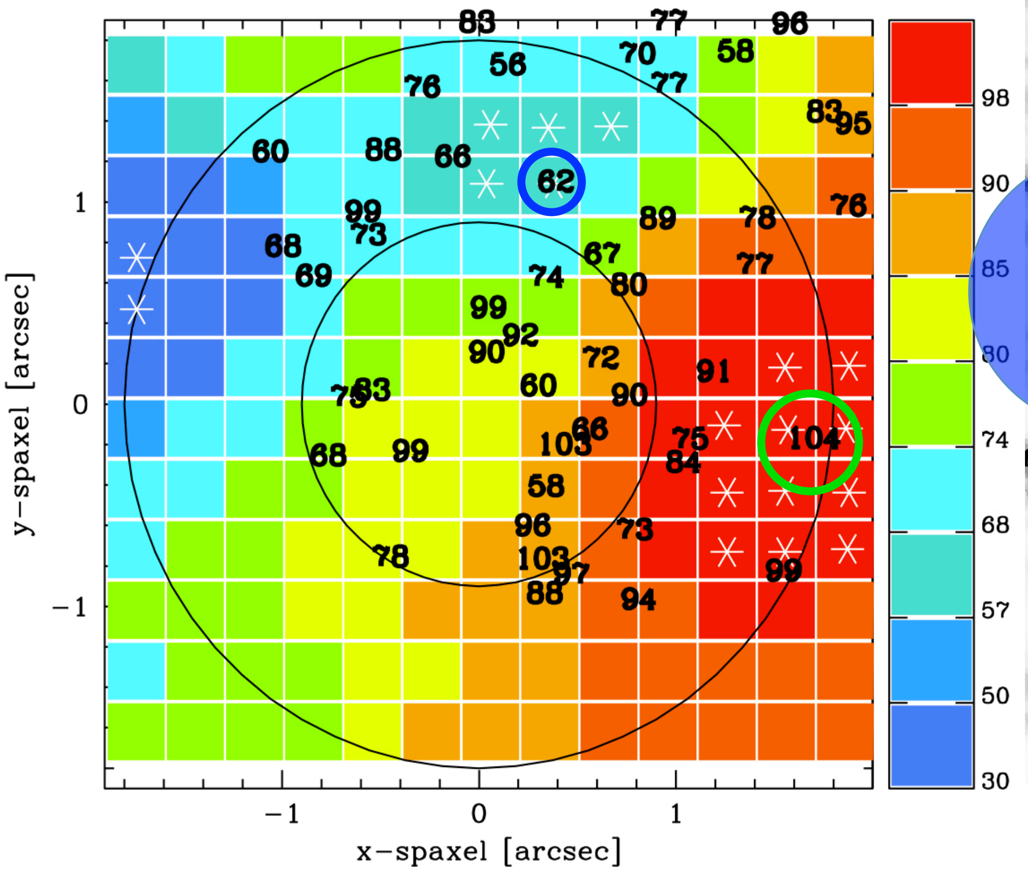
Cosmic-Lab

Insufficient shot-noise correction

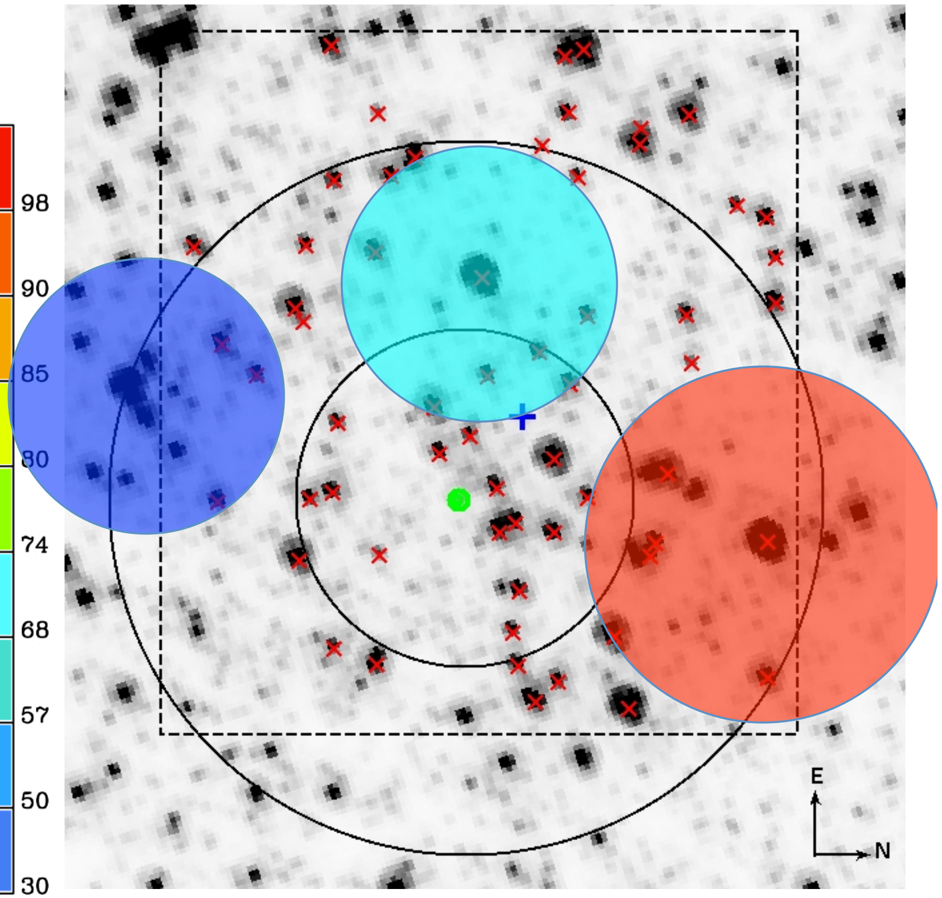
→ **colours**: radial velocity map of L11

→ **white asterisks:** spaxels excluded by L11 for shot noise correction

→ **black values:** our V_r measurements

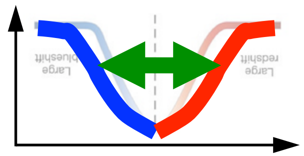


HST/ACS-HRC

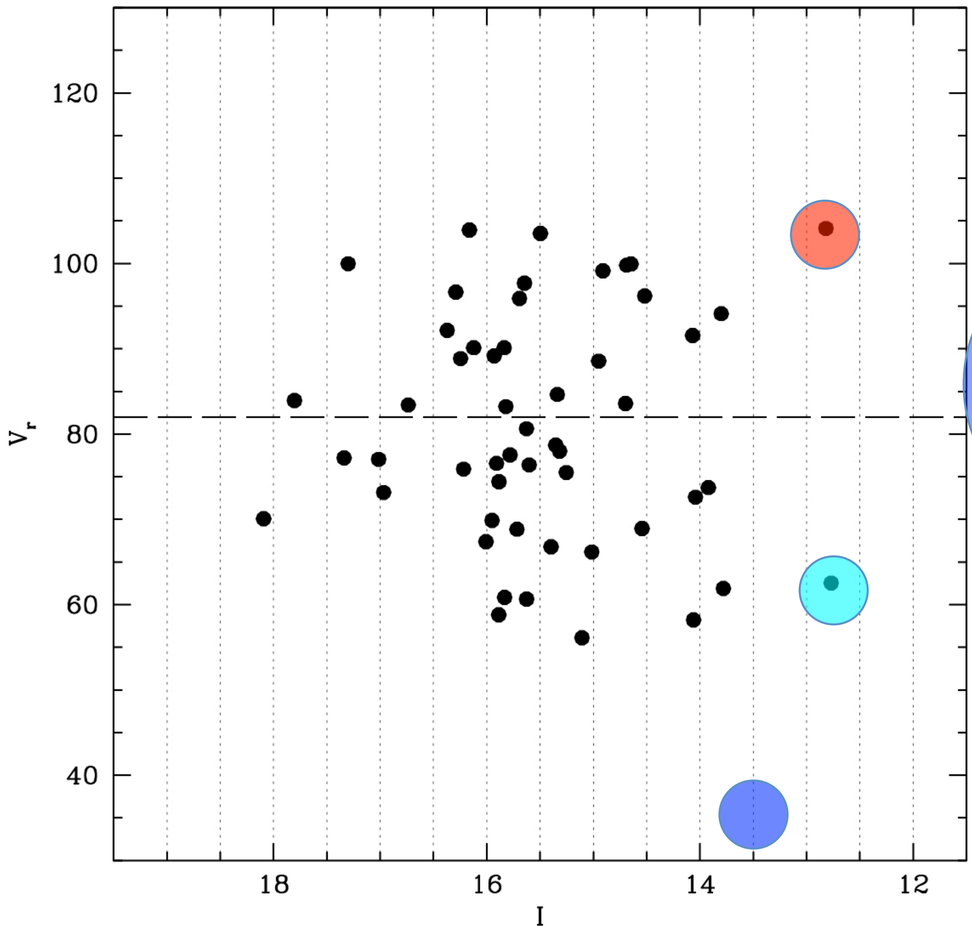


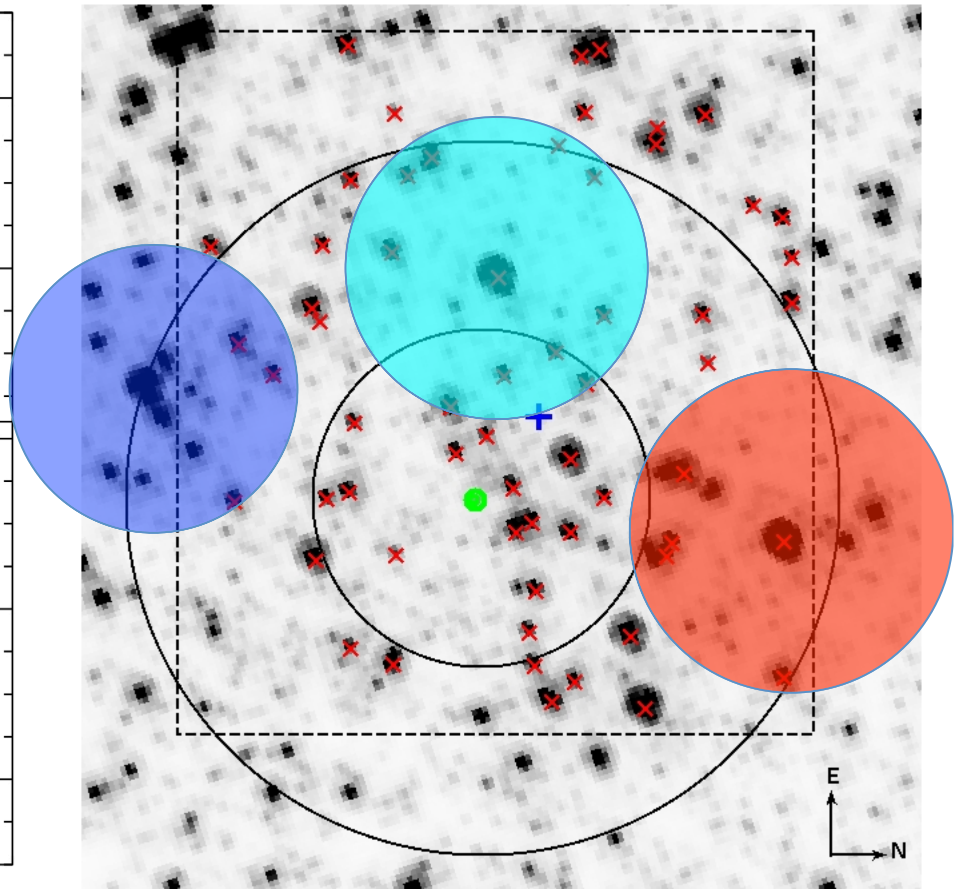
Spectra dominated by the light of a few bright stars with quite different V_r

⇒ **artificial line broadening**



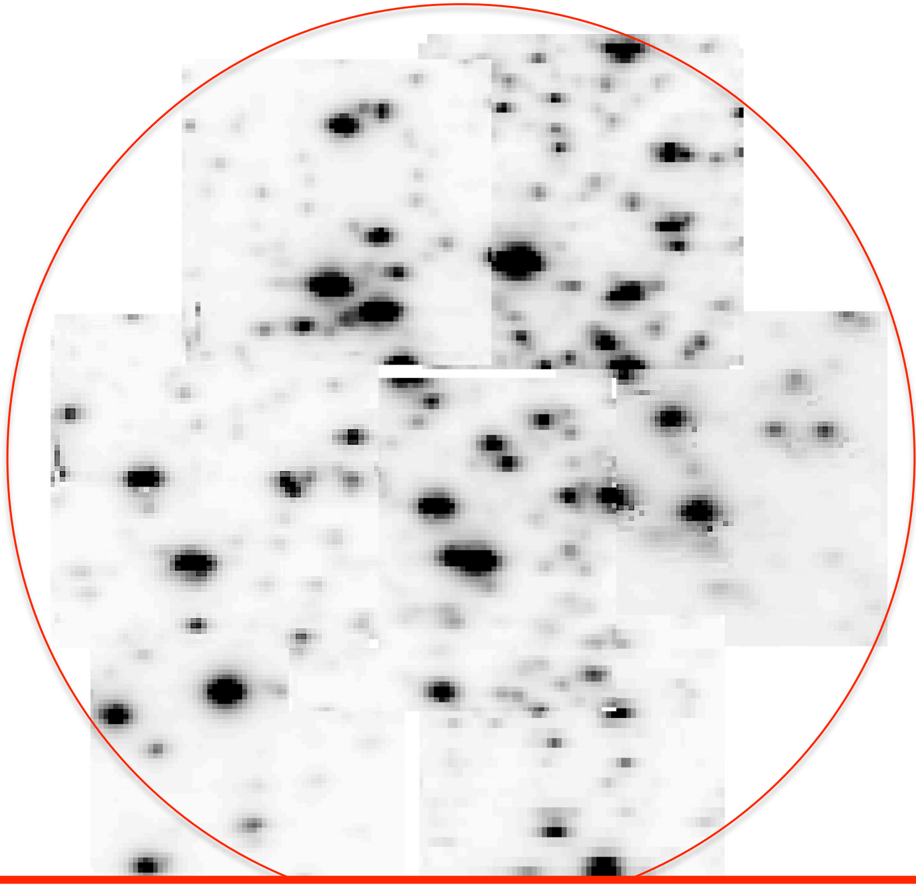
⇒ **overestimate of σ(r) & IMBH mass**



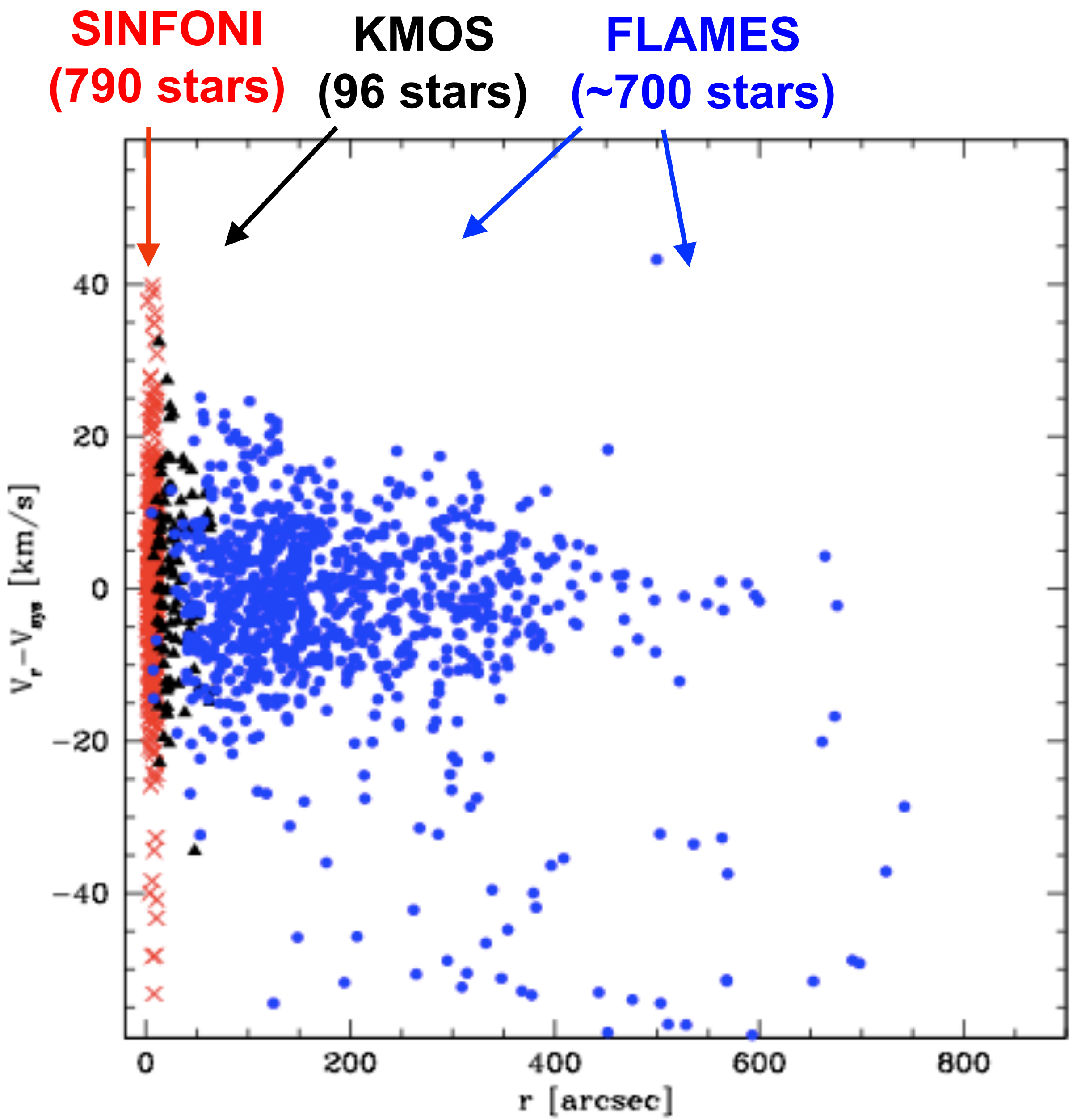


Very preliminary results for NGC 2808

A mosaic of 7 SINFONI field

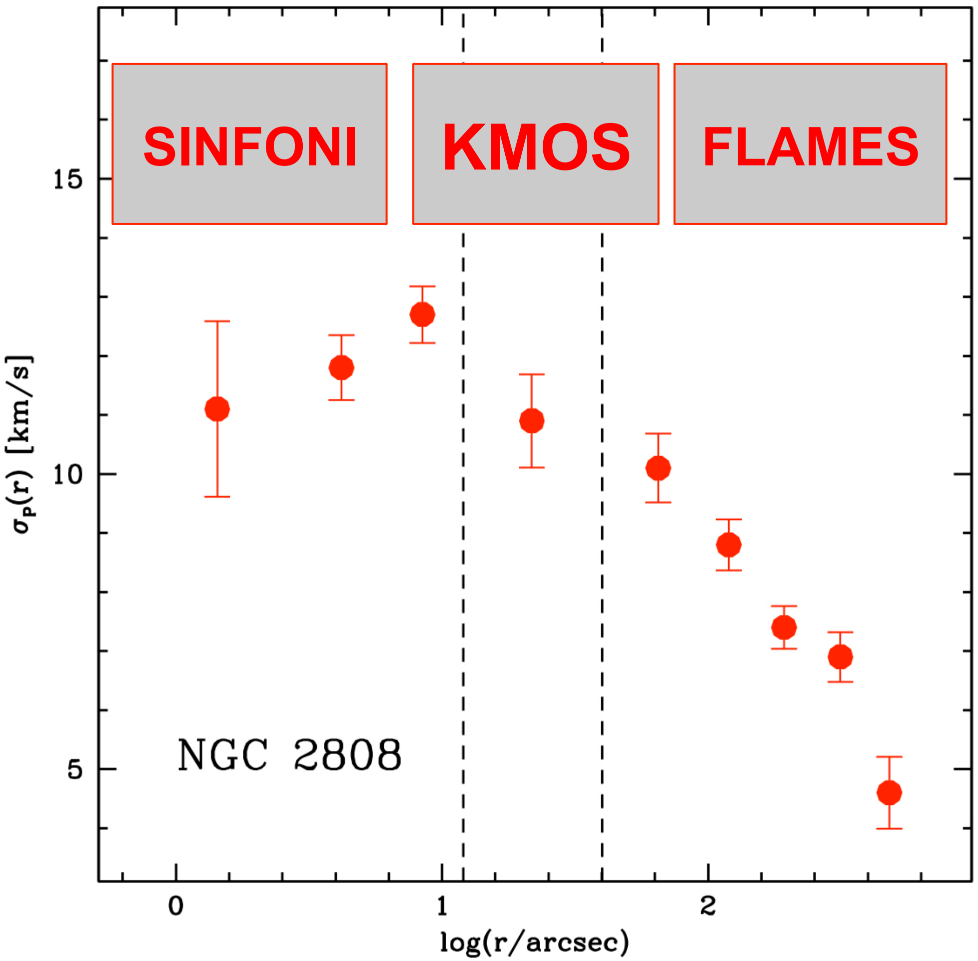


V_r for 800 individual stars at r<12” !!!!!!


SINFONI
(790 stars)
KMOS
(96 stars)
FLAMES
(~700 stars)
40
20
0
−20
−40
0
200
400
600
800
$V_r - V_{sys}$ [km/s]
r [arcsec]

Very preliminary results for 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)

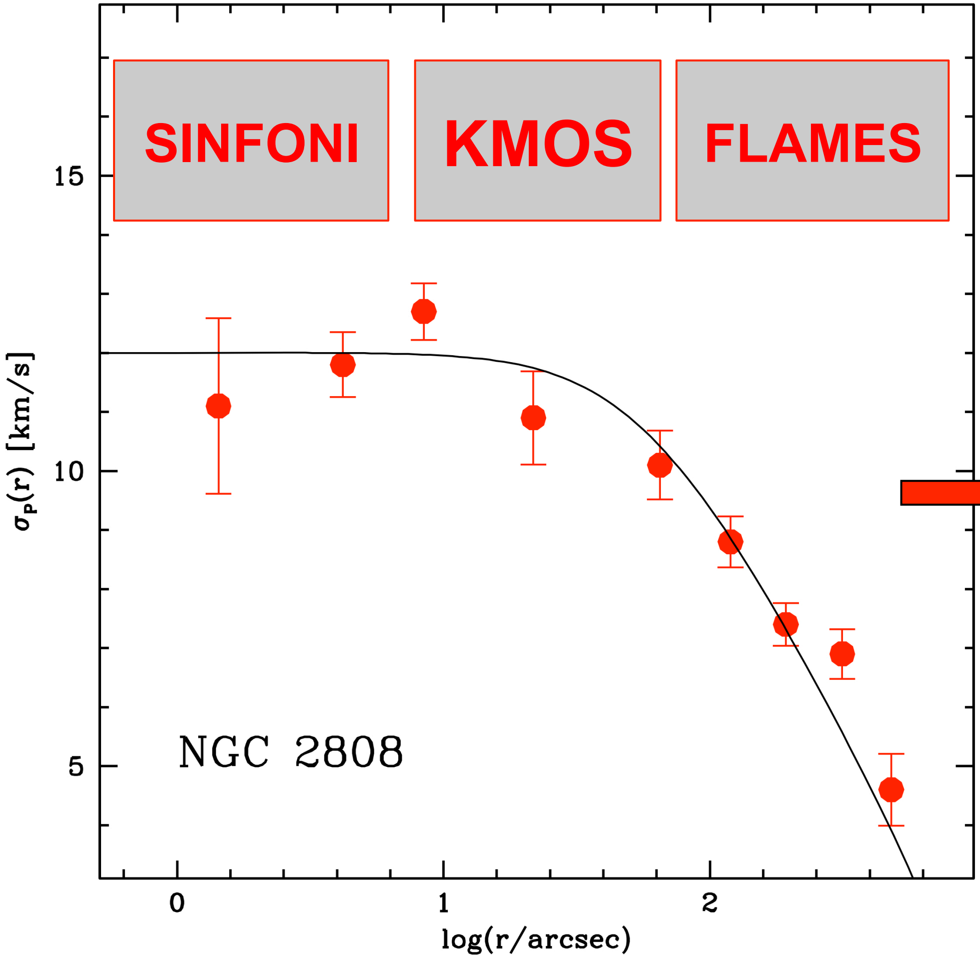


Counting ~1600 measured stars, this is one of the most accurate RV dispersion profile obtained so far for a GC

b.eu

Very preliminary results for 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)

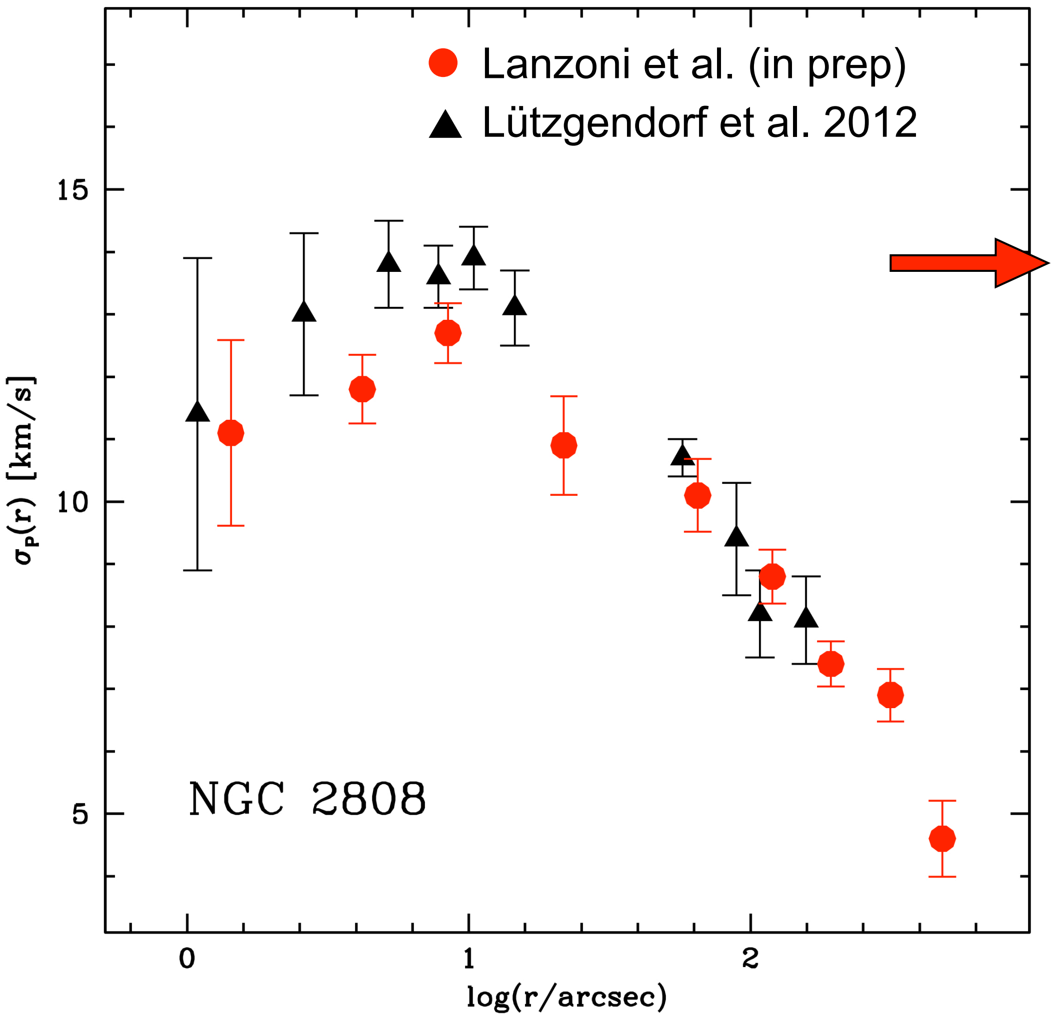


NO IMBH

Cosmic-Lab

erc

Preliminary results for NGC 2808



Good agreement with integrated-light results (Lützgendorf et al. 2012)

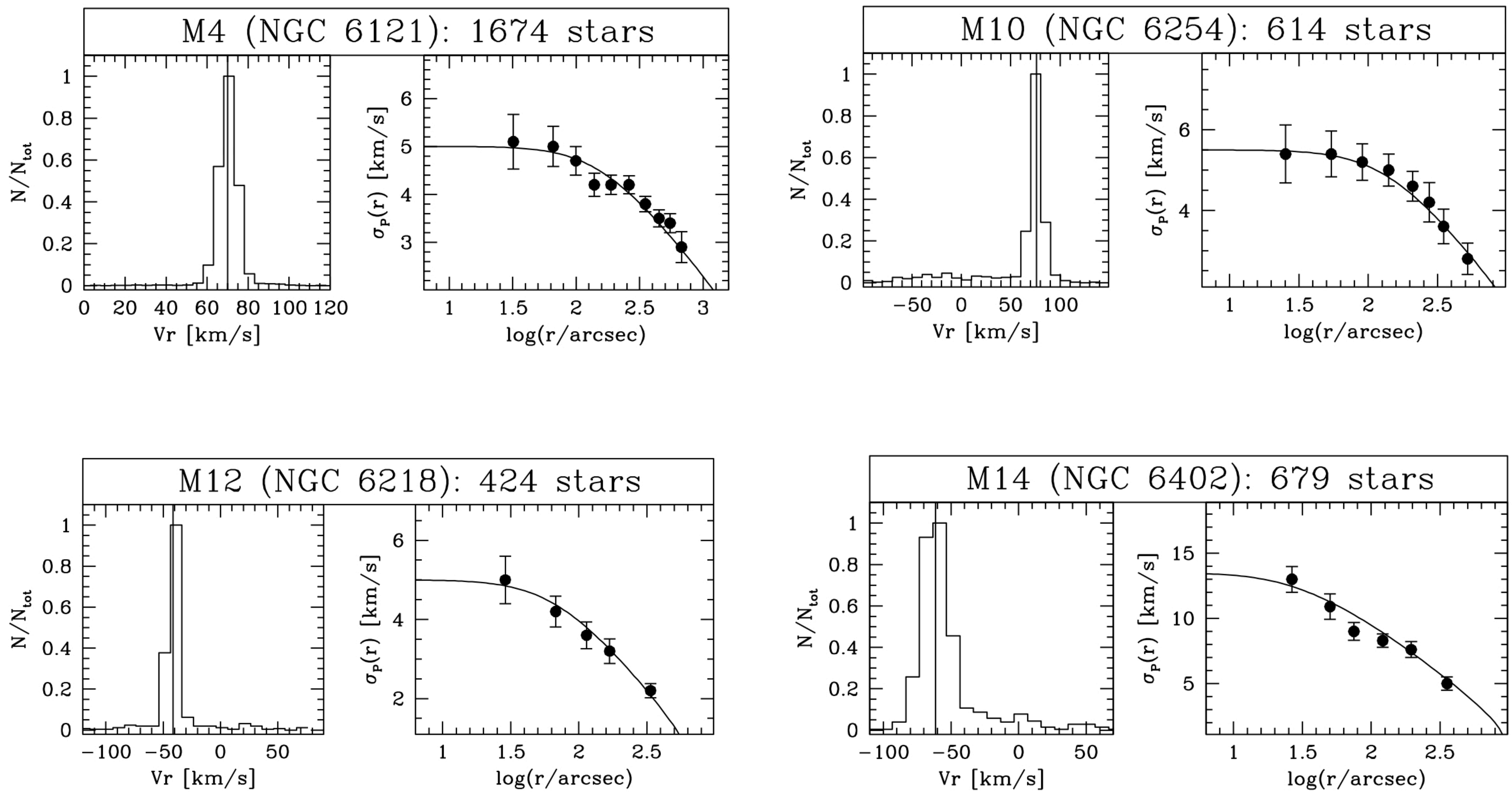
✦ Absence of bright stars with quite different RV.

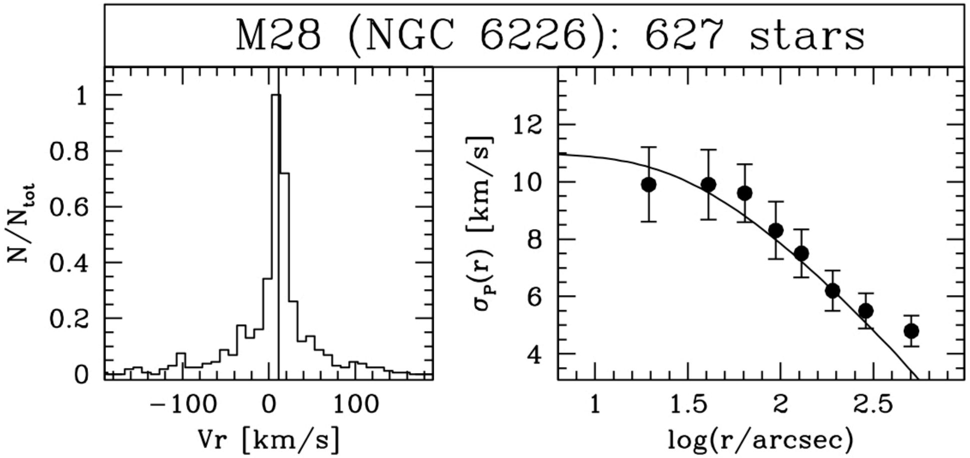
Integrated-light vs individual stars spectroscopy in Galactic GCs (resolved SP)

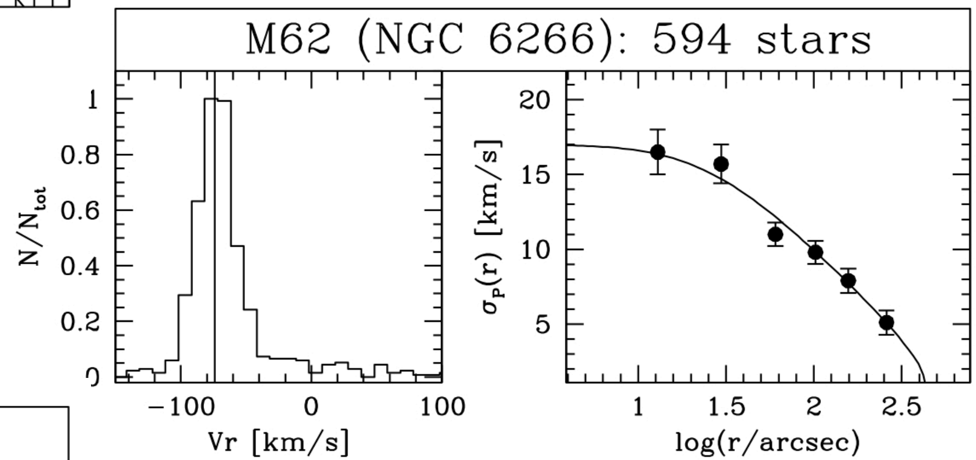
An HEAVY masking procedure (properly taking into account the EXTENDED PSF wings) is mandatory in the INTEGRATED LIGHT approach

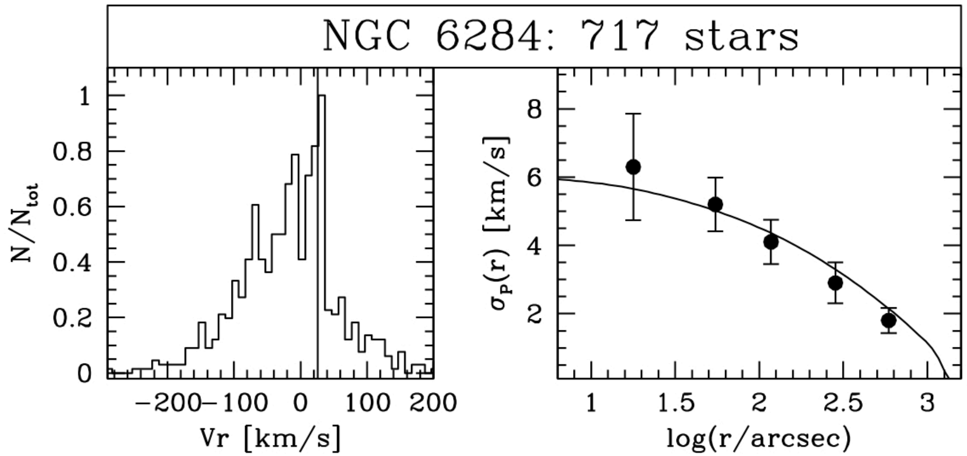
The case of NGC6388 has demonstrated that the VD from individual stars is the safest way to proceed in GCs

Preliminary results from KMOS+FLAMES LP




M28 (NGC 6226): 627 stars
N/N_tot
Vr [km/s]
σ_P(r) [km/s]
log(r/arcsec)

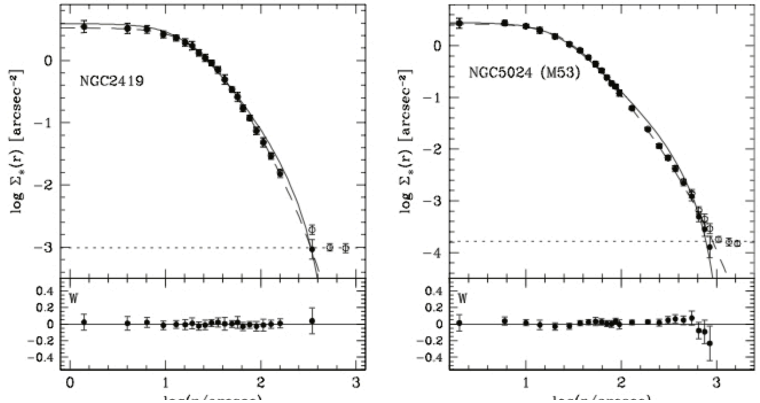

M62 (NGC 6266): 594 stars
N/N_tot
Vr [km/s]
σ_P(r) [km/s]
log(r/arcsec)


NGC 6284: 717 stars
N/N_tot
Vr [km/s]
σ_P(r) [km/s]
log(r/arcsec)

Stay tuned….

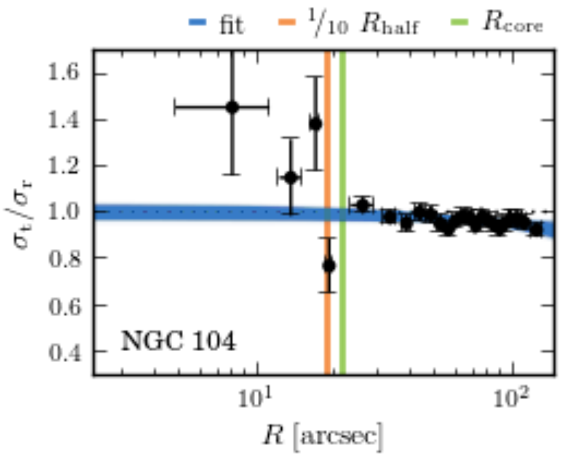
This is the most extensive and complete approach ever attempted to study the internal dynamics of GCs

ESO-VLT LP = The new generation of velocity dispersion profiles (Lanzoni et al. 2013, Lapenna et al 2014)



+ The new generation of Star density profiles of 40 GGCs (Miocchi et al. 2013 + Ferraro et al 2014)

+ internal proper motions from multi-epoch HST observations (see Watkins et al 2015)



---

provide the FIRST 3D velocity map of the cores
\+ evidence of any systemic internal rotation
\+ evidence of any IMBH
for a significant sample of clusters.

Thank you
for your attention!

Cosmic-Lab