MODEST 15-S

Kobe, Japan, Dec 7-11, 2015

シミュレーションが未来をひらく

理化学研究所 計算科学研究機構

RIKEN Advanced Institute for Computational Science

INTERNAL DYNAMICS OF GLOBULAR CLUSTERS: an observational perspective

BARBARA LANZONI

Physics & Astronomy Department – University of Bologna (Italy)

Kobe, December 8, 2015

Cosmic-Lab

- 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

Observational perspective to globular cluster dynamics

(1) COMBINED STUDY OF:

- **CLUSTER STRUCTURE** (density profile, core and half-mass radii, limiting radius, asymmetries, etc)
- **CLUSTER KINEMATICS** (velocity dispersion profile, rotation curve)
- **EXOTIC populations** (to be used as gravitational probes)

Blue Stragglers: Francesco talk

(2)

- **density profiles** from **RESOLVED STAR COUNTS**
  (instead of surface brightness)

to avoid shot-noise bias from a few bright stars
(see also Bianchini et al. 2015)

- **VD & rotation profiles** from
  the **RADIAL VELOCITIES OF INDIVIDUAL STARS**
  (instead of integrated-light spectroscopy)

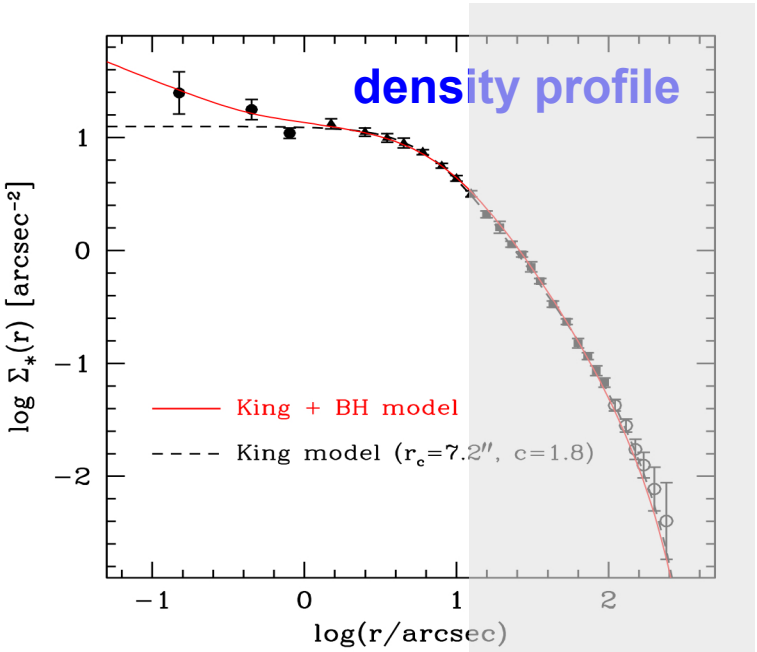
(2)

- **density profiles** from **RESOLVED STAR COUNTS**
  (instead of surface brightness)
  over the **ENTIRE CLUSTER EXTENSION**

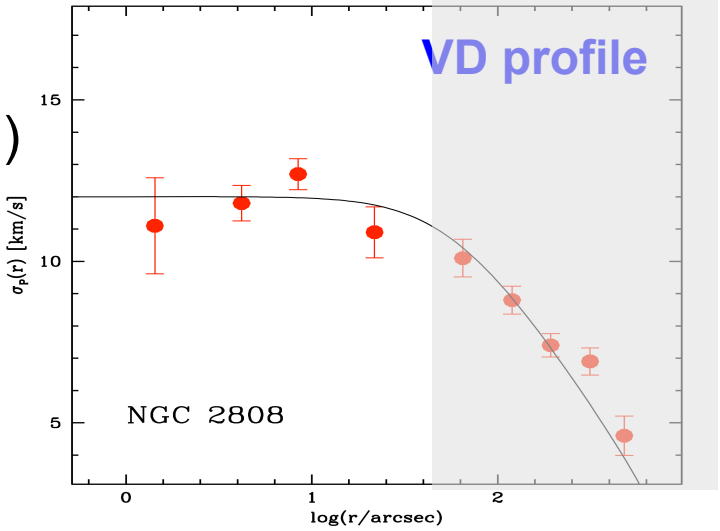
- **VD & rotation profiles** from
  the **RADIAL VELOCITIES OF INDIVIDUAL STARS**
  (instead of integrated-light spectroscopy)
  over the **ENTIRE CLUSTER EXTENSION**

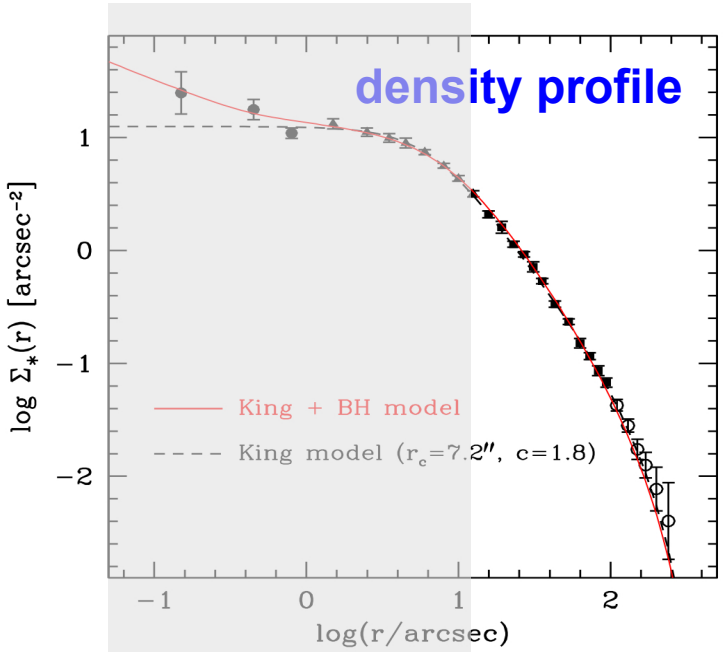
CENTRAL REGIONS

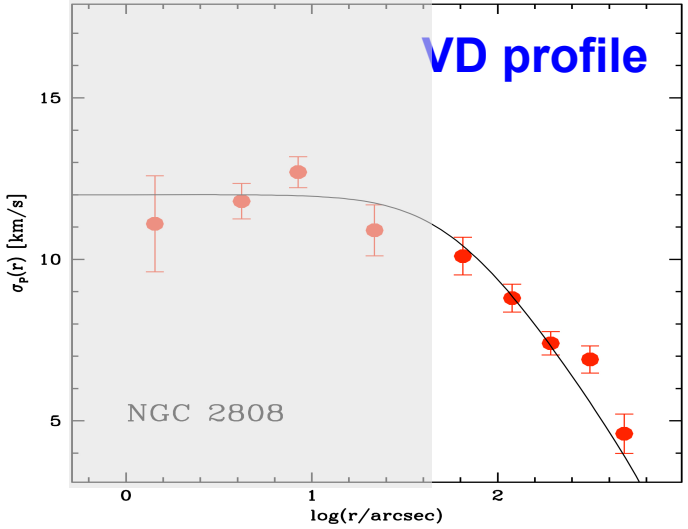
- Core size
- Central cusp (CC or IMBH?)



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







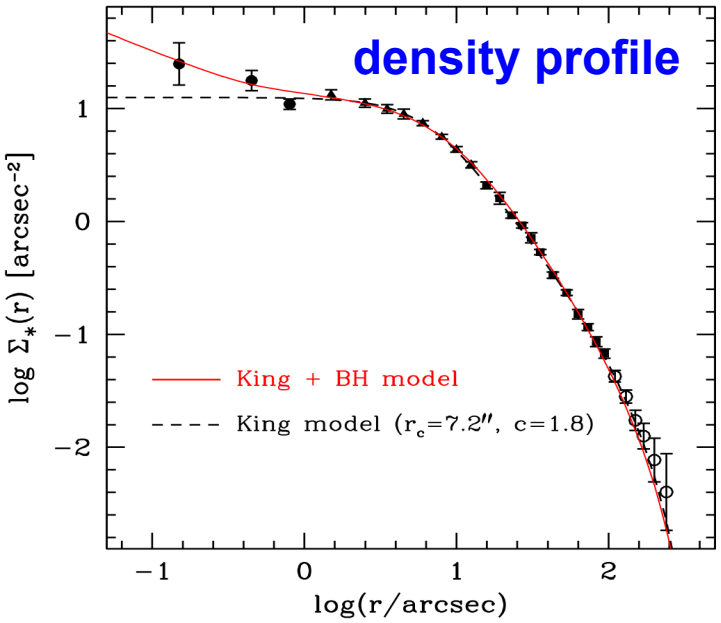
EXTERNAL REGIONS

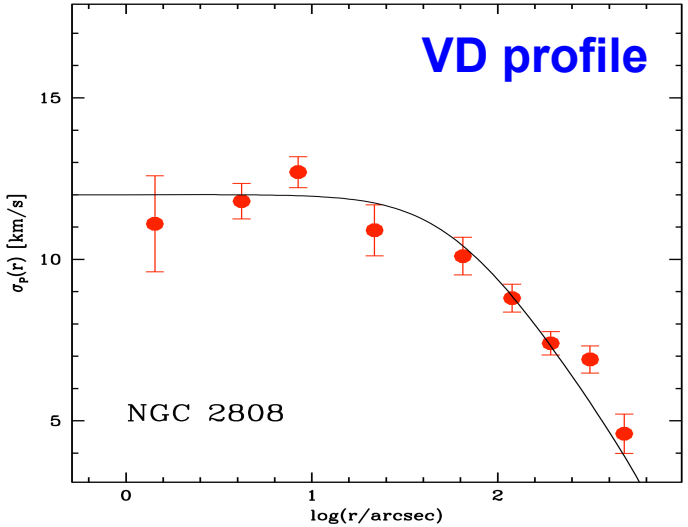
- Cluster size
- Tidal tails
- Extra-tidal halos

- Rotation
- Dark Matter??

CENTRAL REGIONS

high spatial resolution facilities





EXTERNAL REGIONS

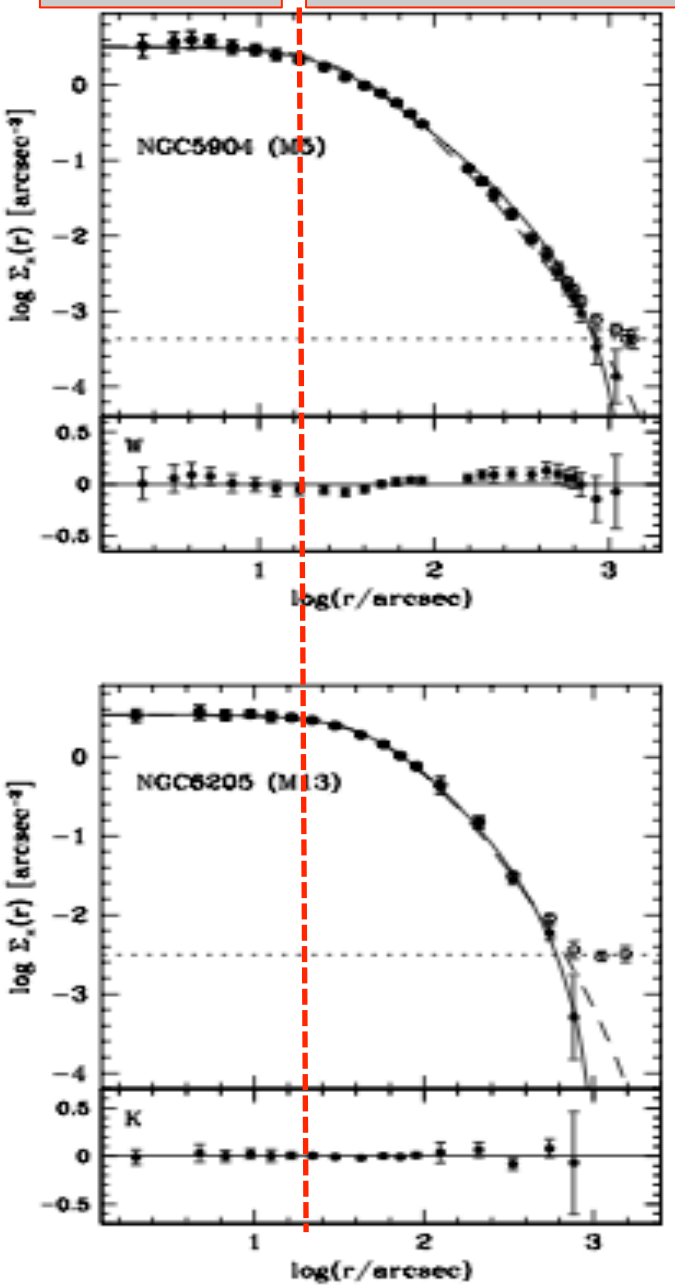
wide-field facilities

Resolved star density profiles: a multi-instrument approach

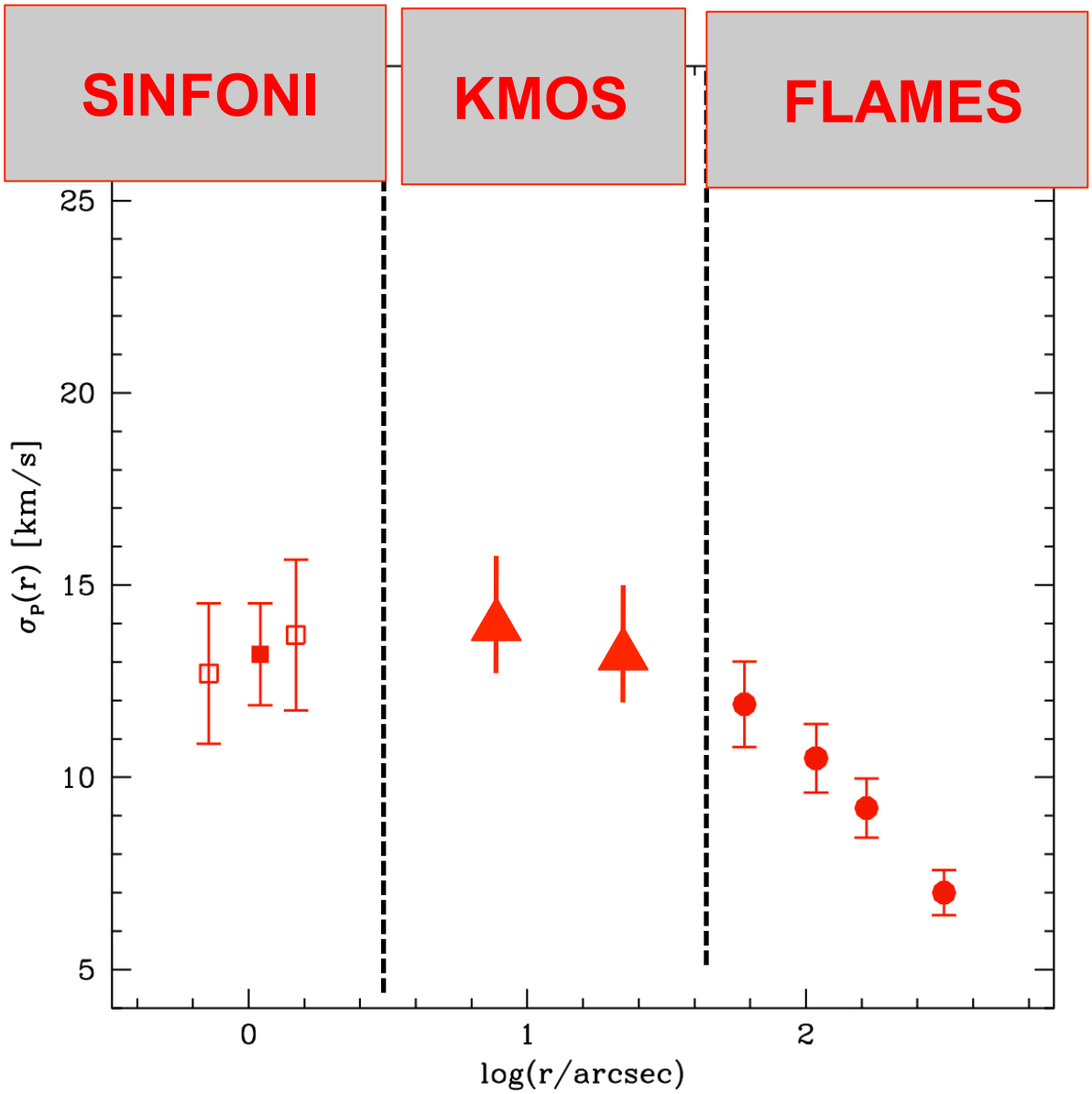
HST | WIDE-FIELD

Miocchi et al. (2013, ApJ, 774, 151)

Cosmic-Lab web site



VD & ROTATION PROFILES from the RADIAL VELOCITY of INDIVIDUAL STARS: a MULTI-INSTRUMENT approach



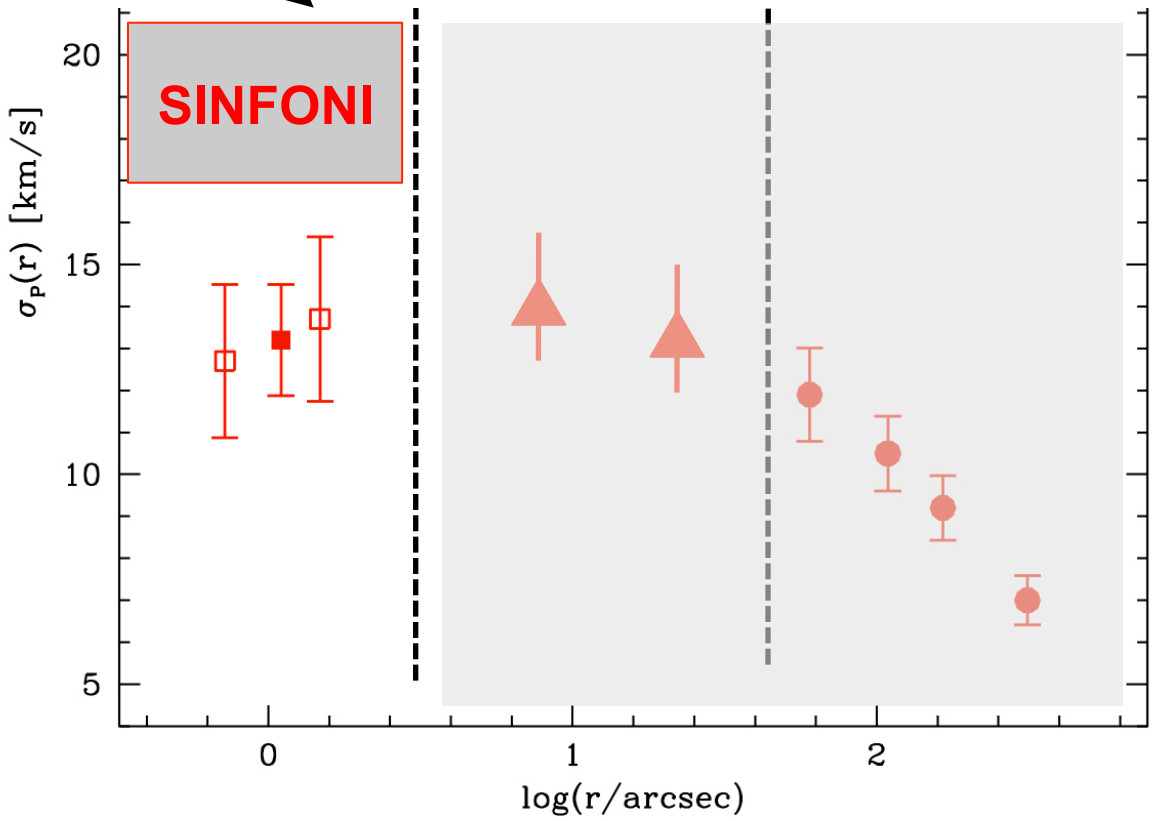
Kinematics: A MULTI-INSTRUMENT APPROACH

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

---

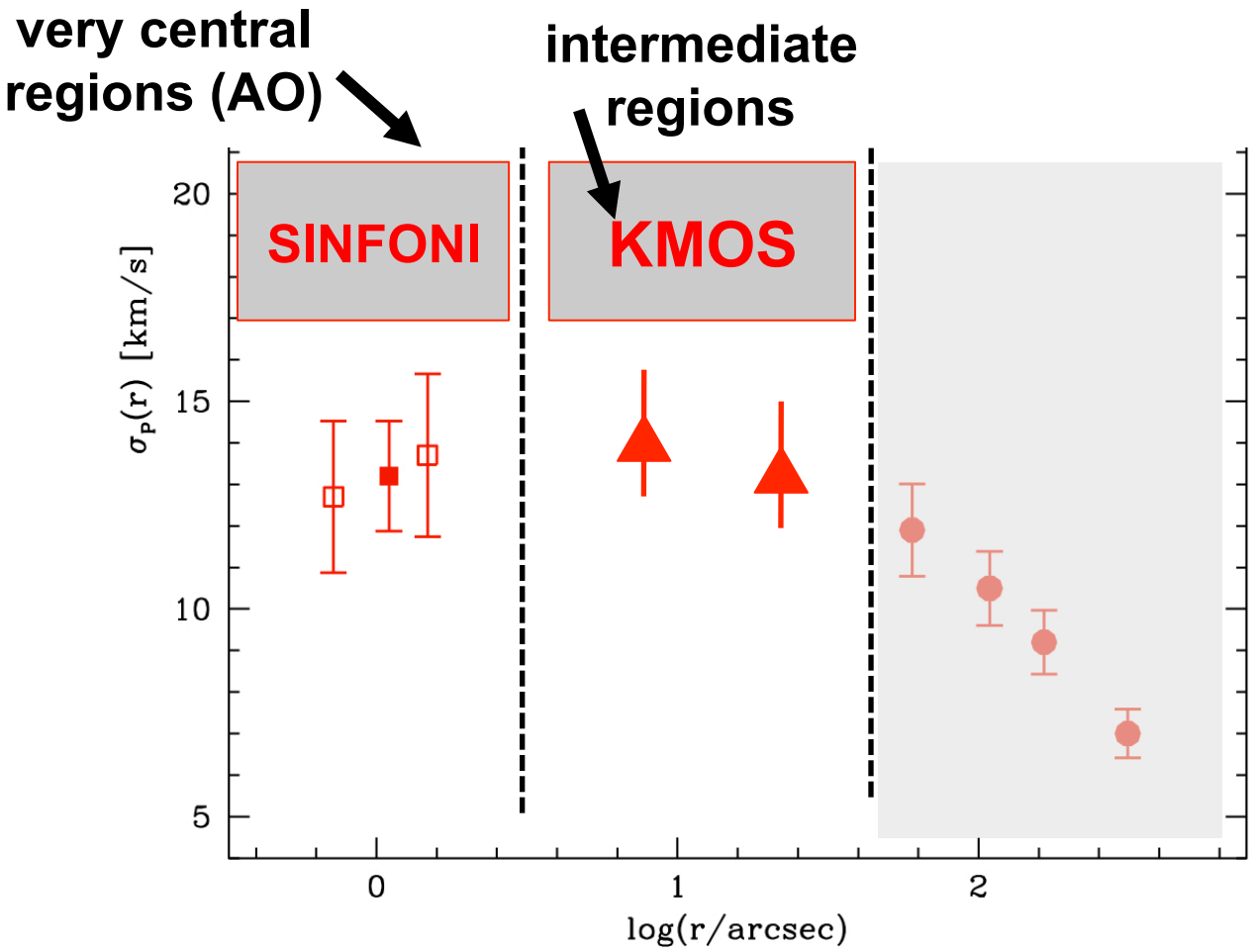
very central regions (AO)



Kinematics: A MULTI-INSTRUMENT APPROACH

KMOS

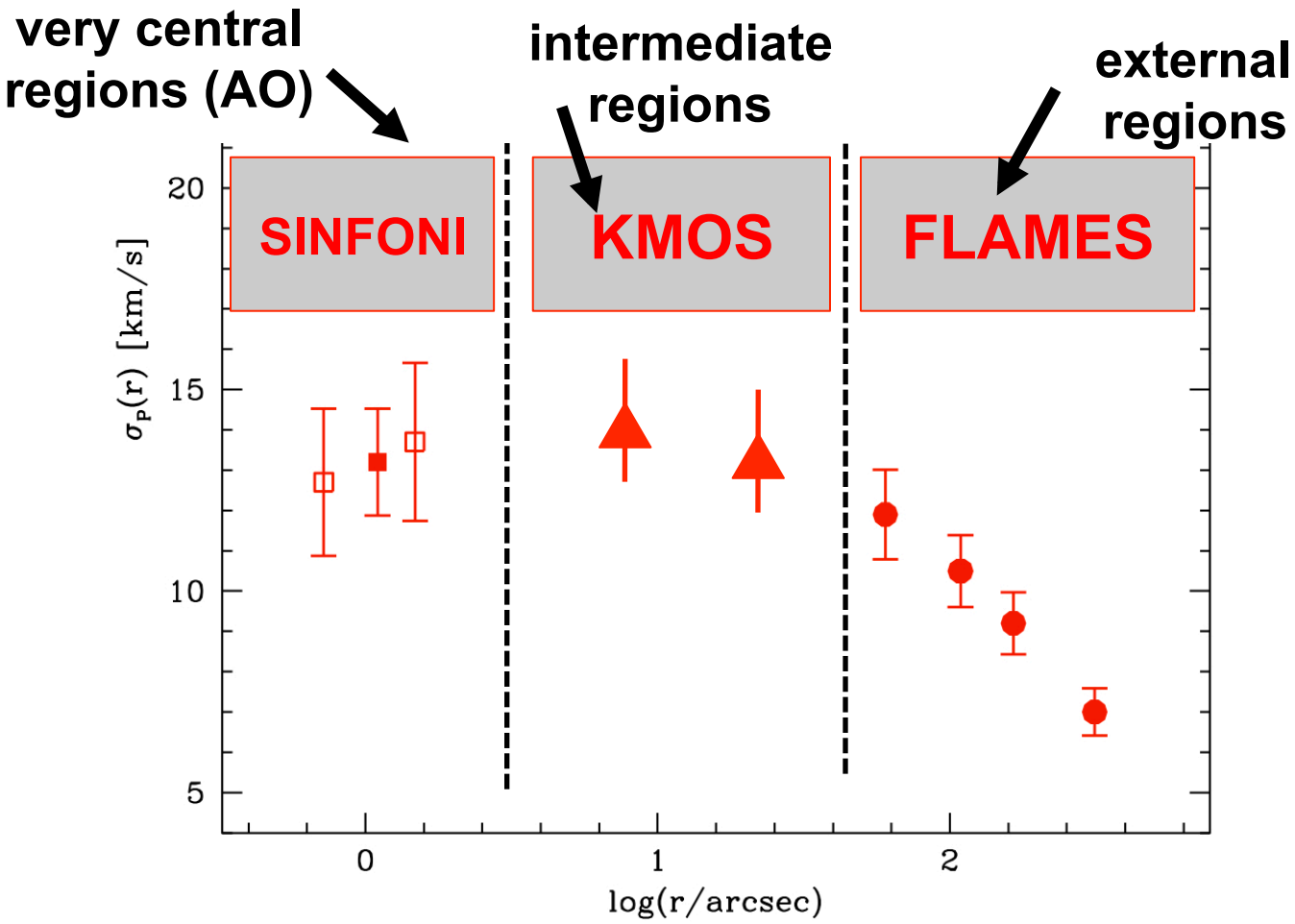
24 deployable IFUs, FoV=3”x3” each,
mid-spectral resolution (R=3400), YJ-band grating (1.00-1.35 μm)
atomic lines (TiI, MgI, FeI,..)



Kinematics: 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,...),

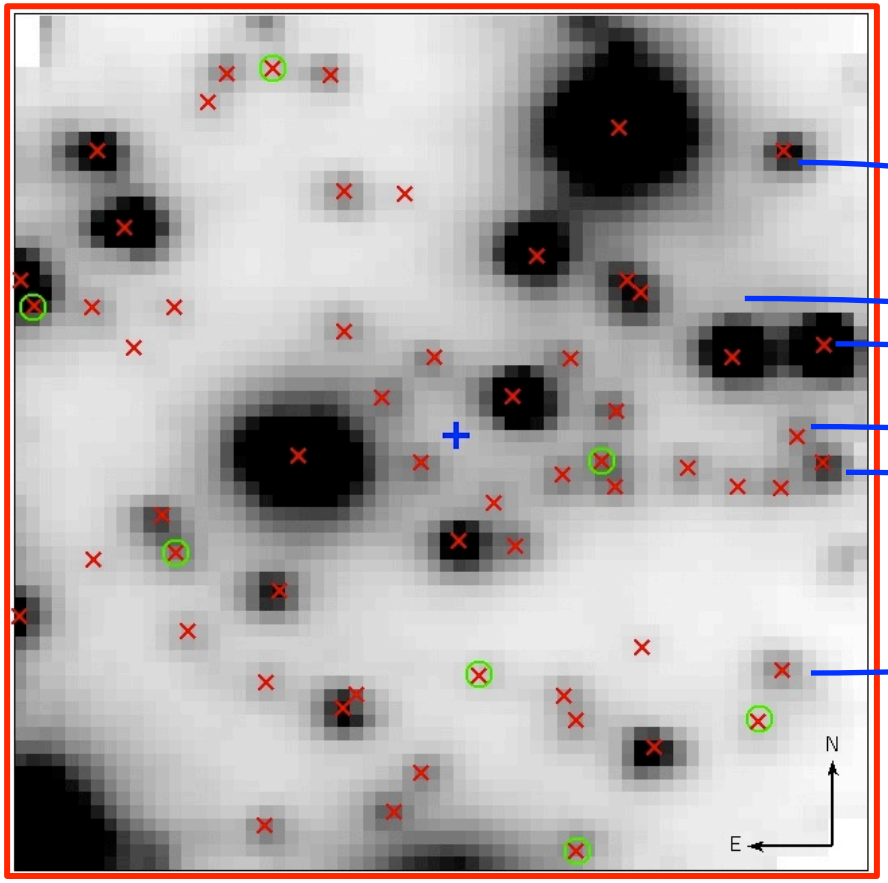


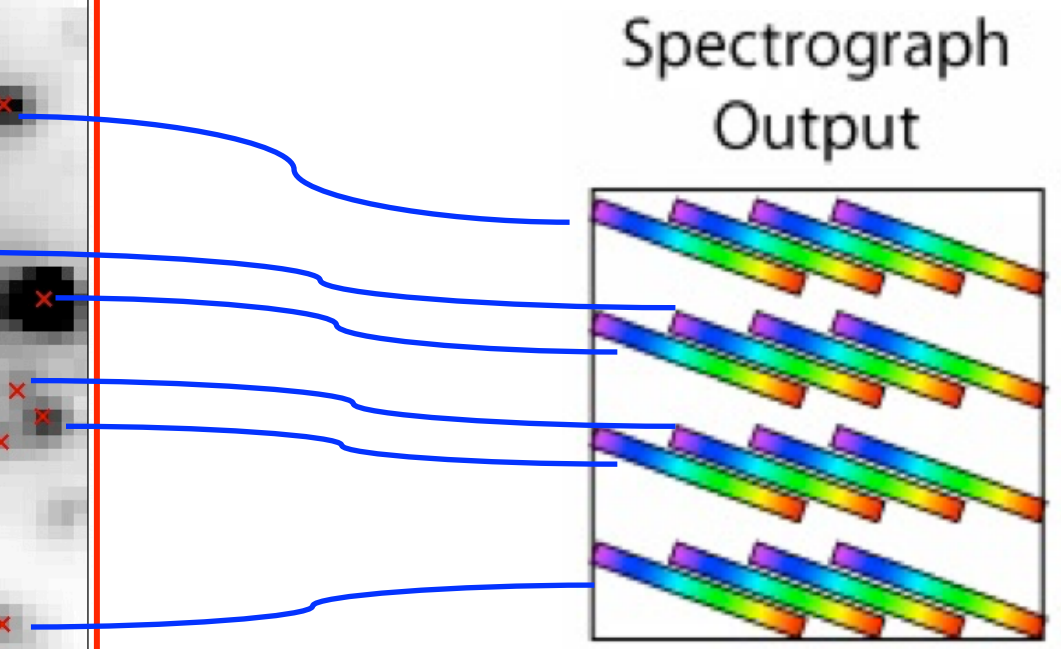
Kinematics: A MULTI-INSTRUMENT APPROACH

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

Unconventional use → extract a spectrum for each resolved star (=> AO)
(instead of integrated-light spectroscopy)

SINFONI RECONSTRUCTED IMAGE





One spectrum for every (exposed) spaxel

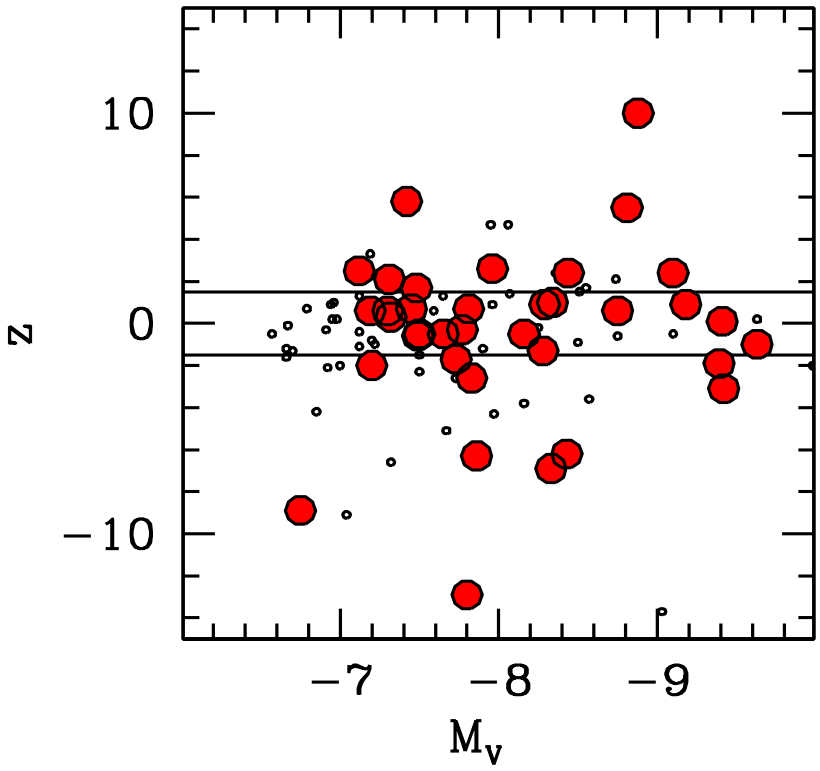
THE DATA-SET

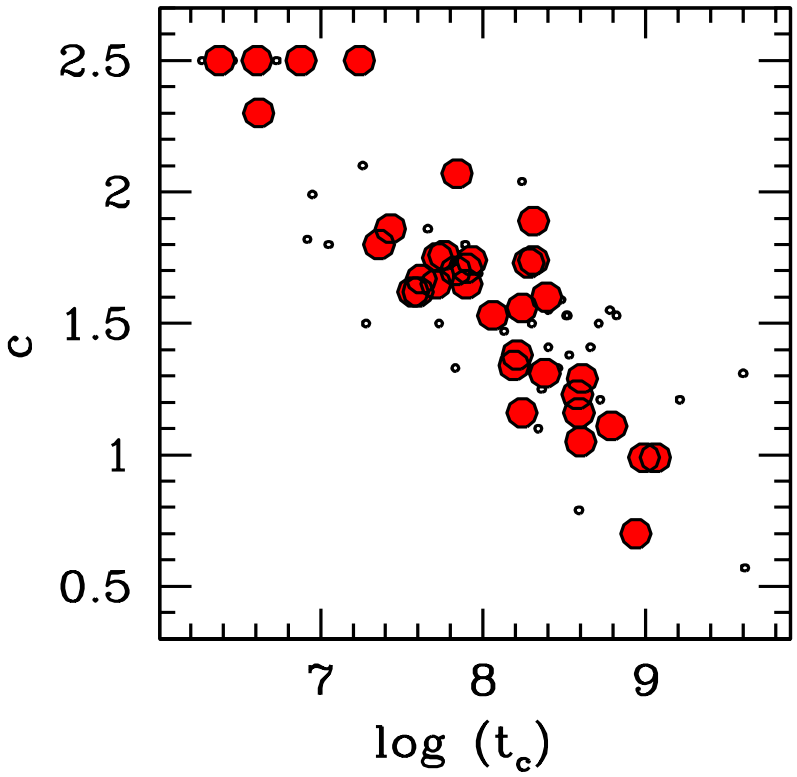
- **ESO Large Programme 193.D-0232 (PI: Ferraro):**
  - 194 hours
  - KMOS + FLAMES
  - 30 Milky Way GCs
  - 2/3 acquired and 1/3 partially analyzed

- **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

THE TARGETS (~30)

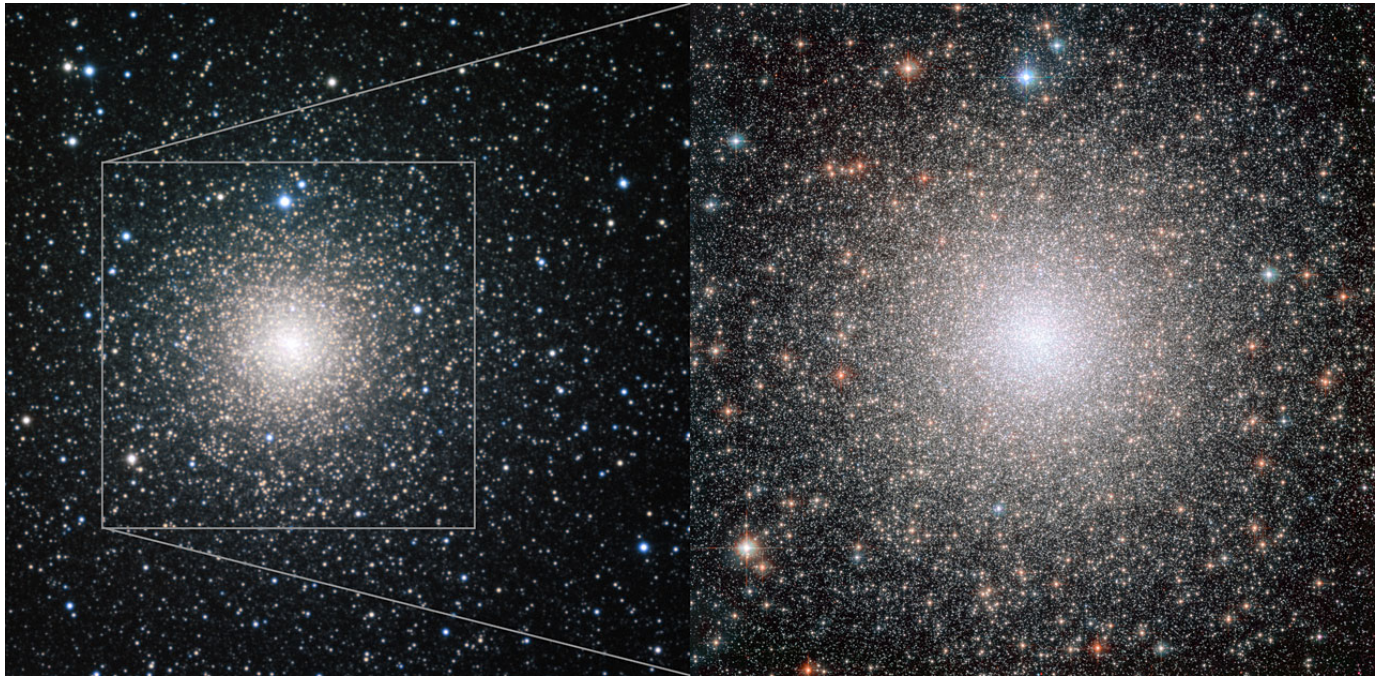




- massive (M > 5x10^5 $M_\odot$)
- spanning large ranges of log **ρ**, c and relaxation times
- covering different stages of dynamical evolution, including PCC
- spanning different environmental conditions (bulge/disk & halo populations)

NGC 6388

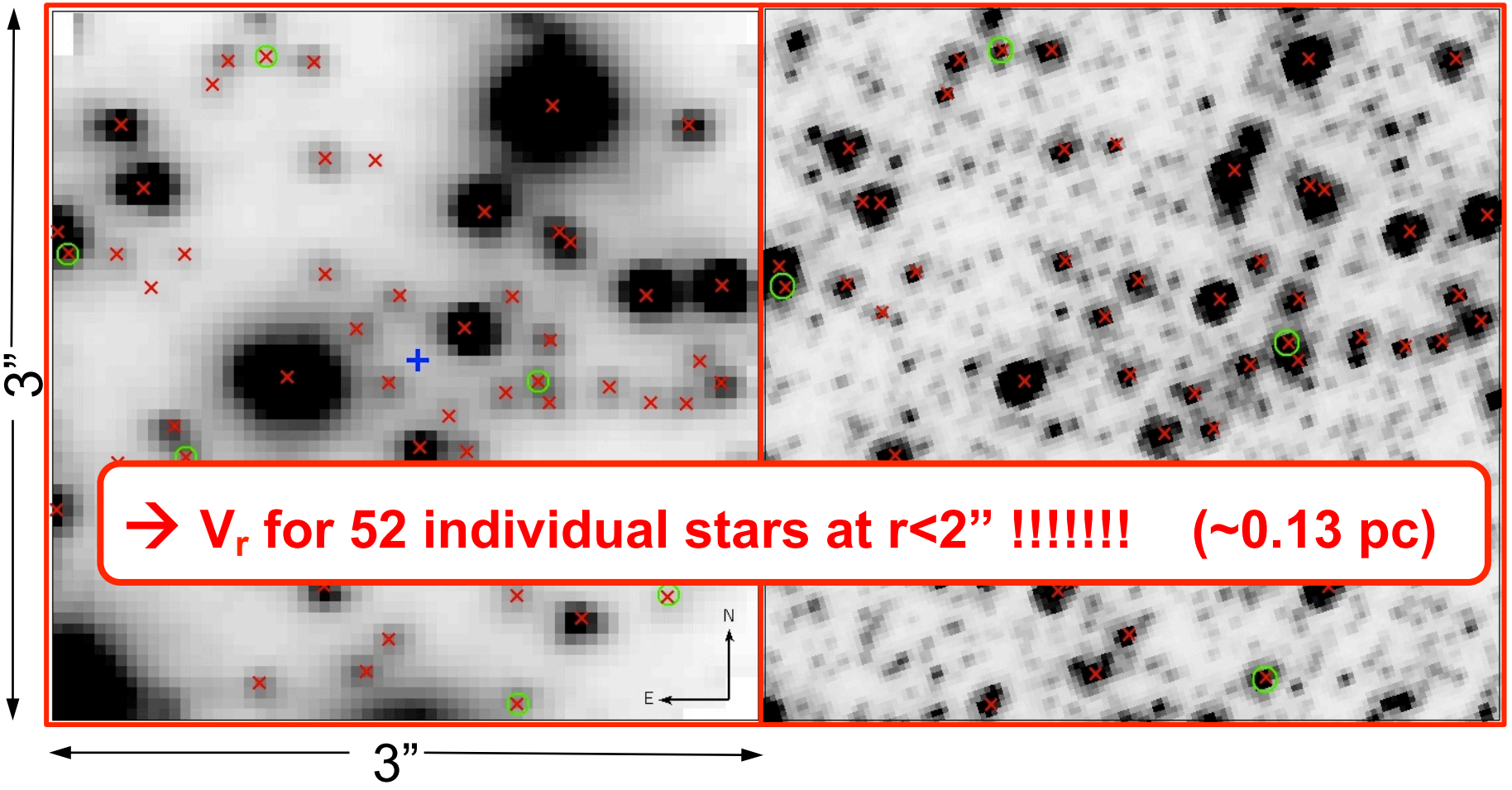
- **one of the most massive GGCs:** $M \sim 2.6\ 10^6\ M_\odot$
- **highly concentrated** (r_c=7”, $\rho_0 = 2.3 \times 10^5\ L_\odot/pc^3$)



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

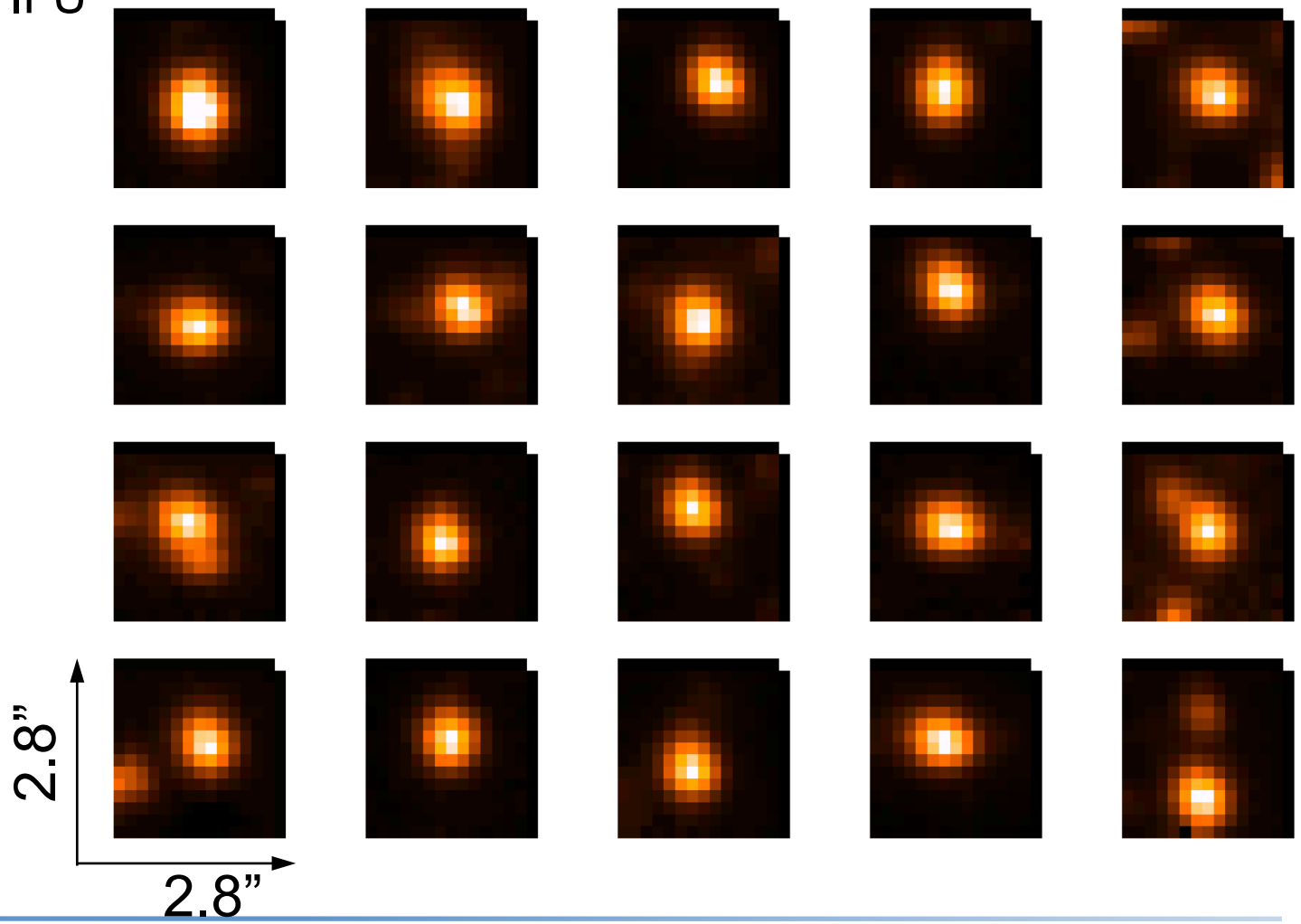
SINFONI RECONSTRUCTED **HST/ACS-HRC (0.027 arcsec/pix)**



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

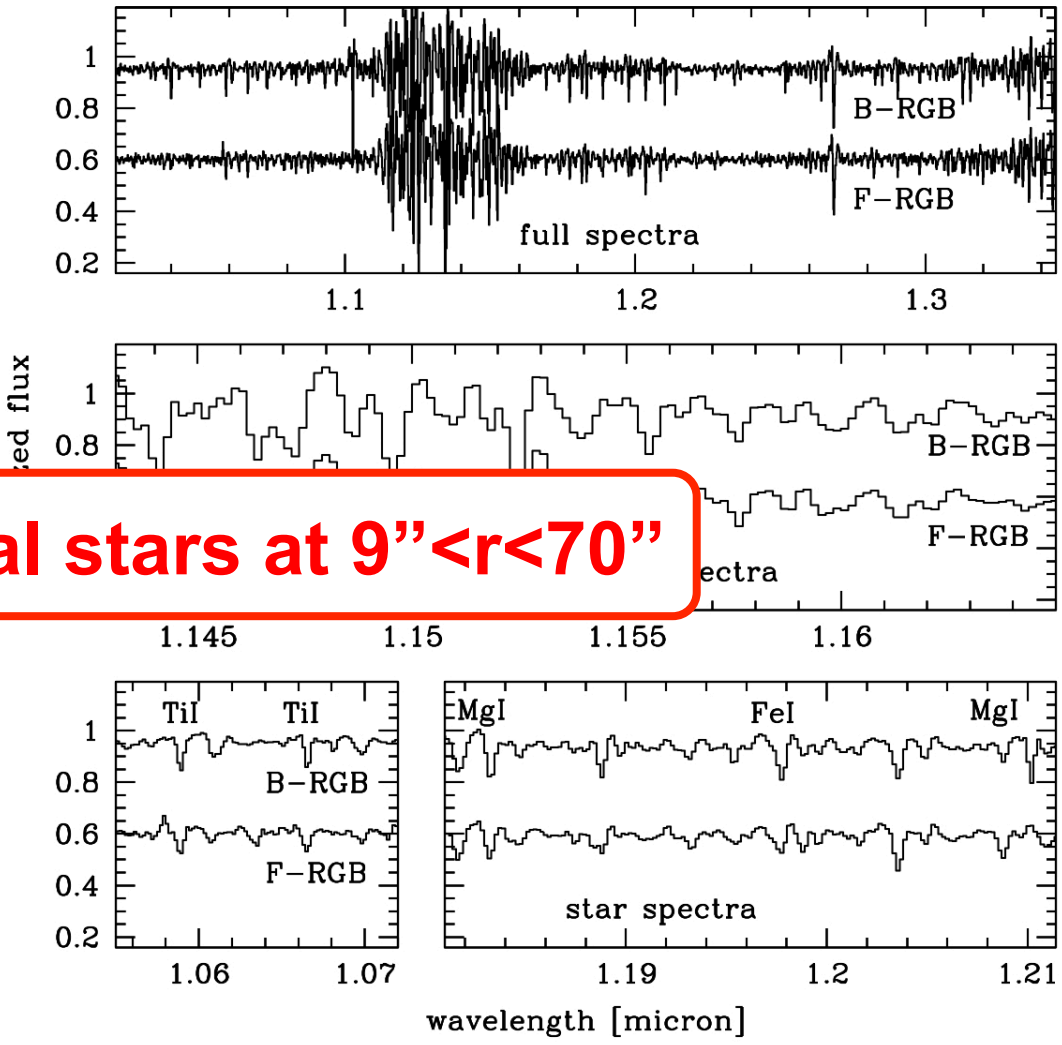
KMOS (multi-objects: 24 IFUs)→ intermediate regions

1-3 stars per IFU



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

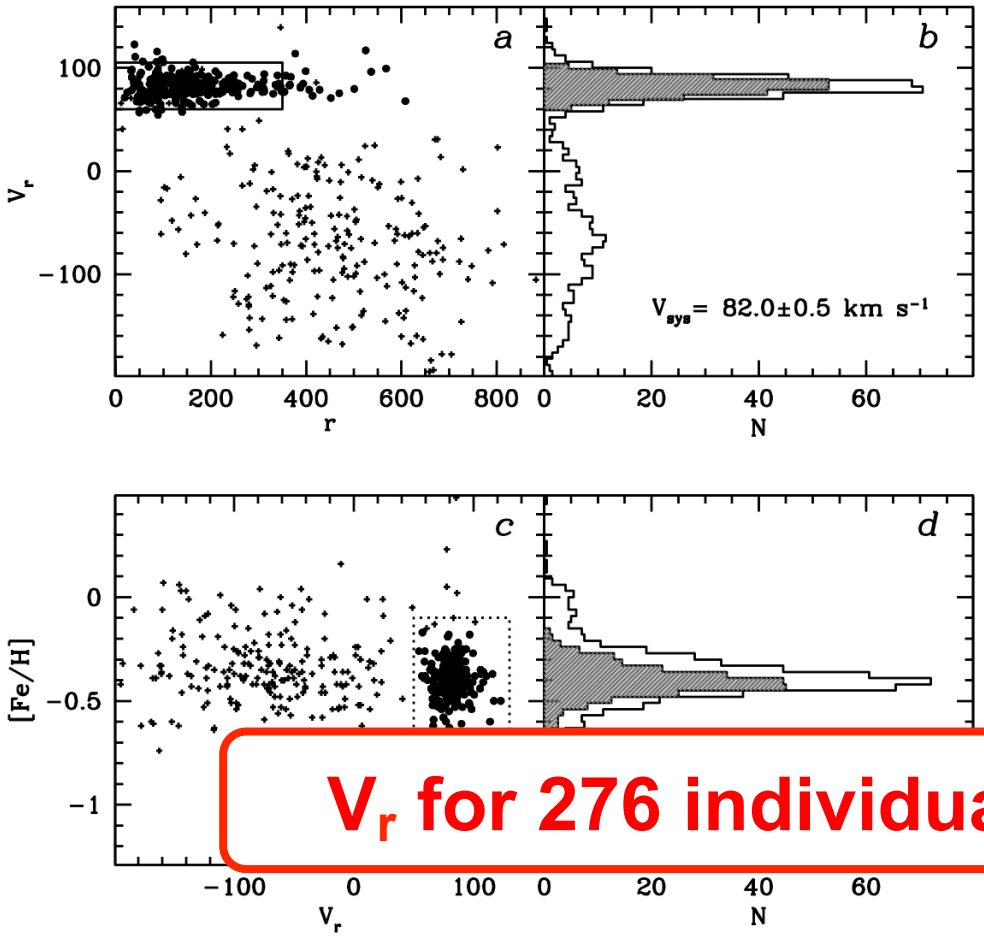
- Vr from several atomic lines
- wavelength calibration refined with telluric lines



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

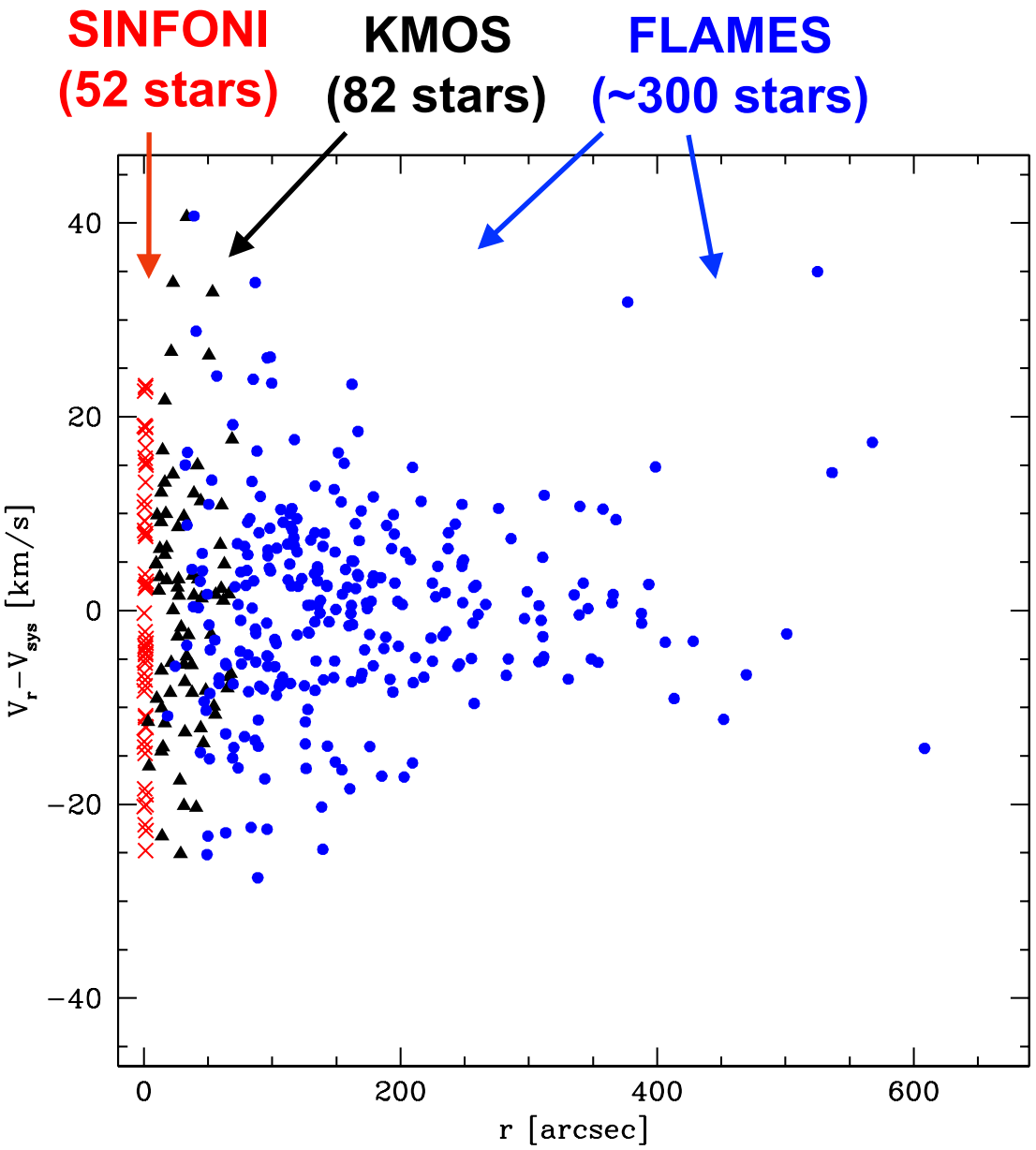
FLAMES (multi-objects: 132 fibers)→ external regions

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



276 cluster members

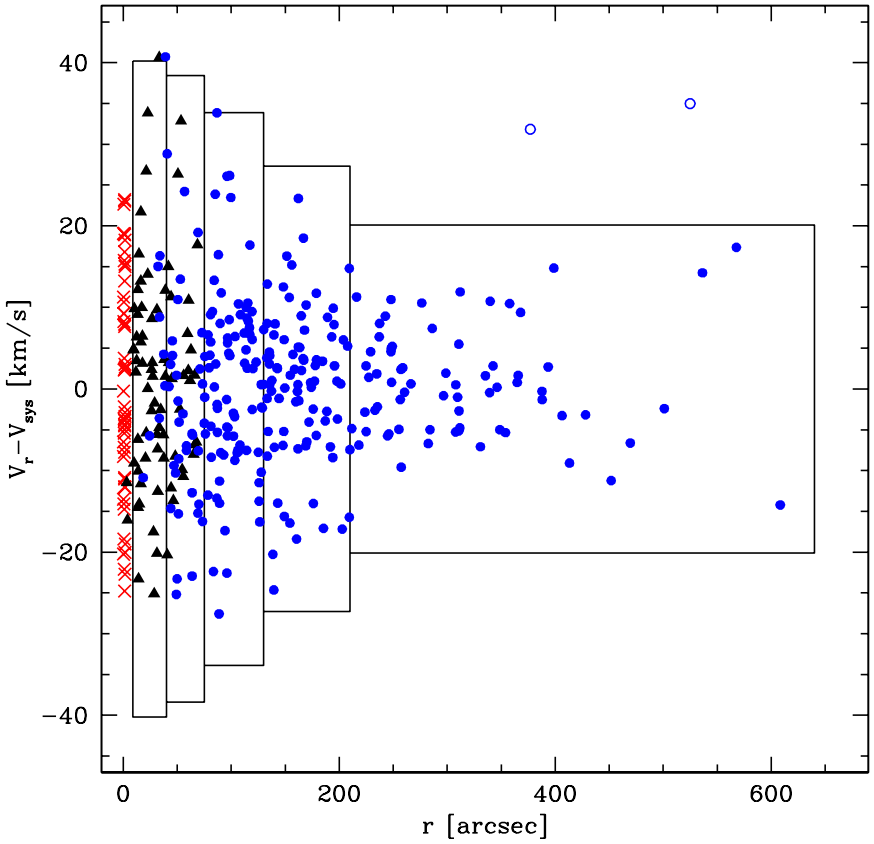
V_r for 276 individual stars at 18”<r<600”

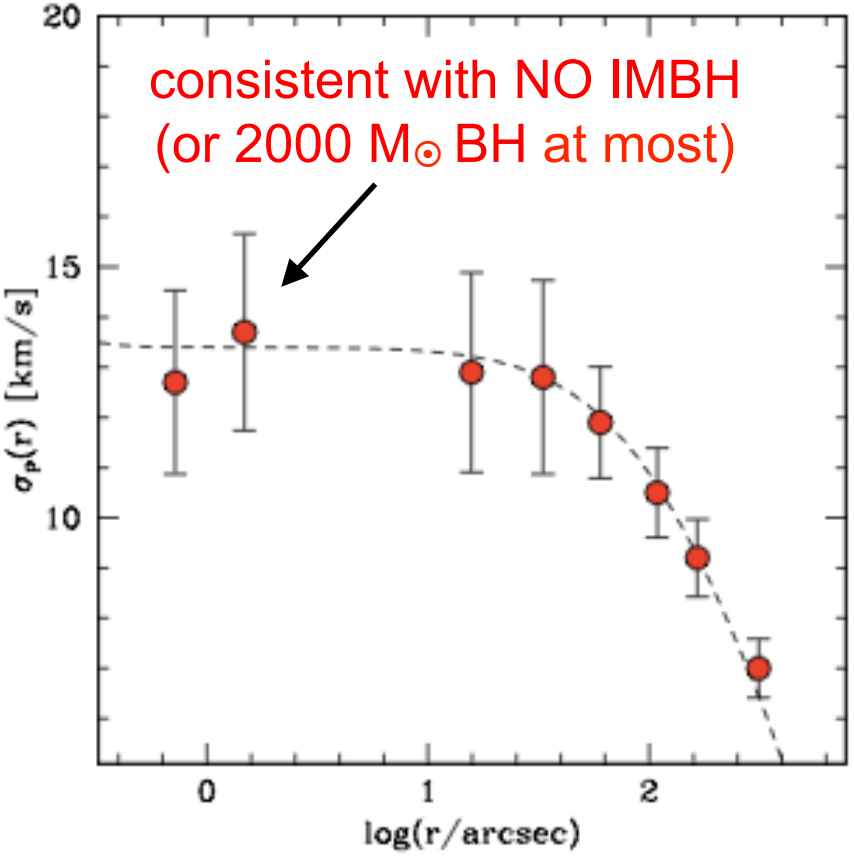

SINFONI
(52 stars)
KMOS
(82 stars)
FLAMES
(~300 stars)
40
20
0
−20
−40
$V_r - V_{sys}$ [km/s]
0
200
400
600
r [arcsec]

Velocity dispersion profile

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

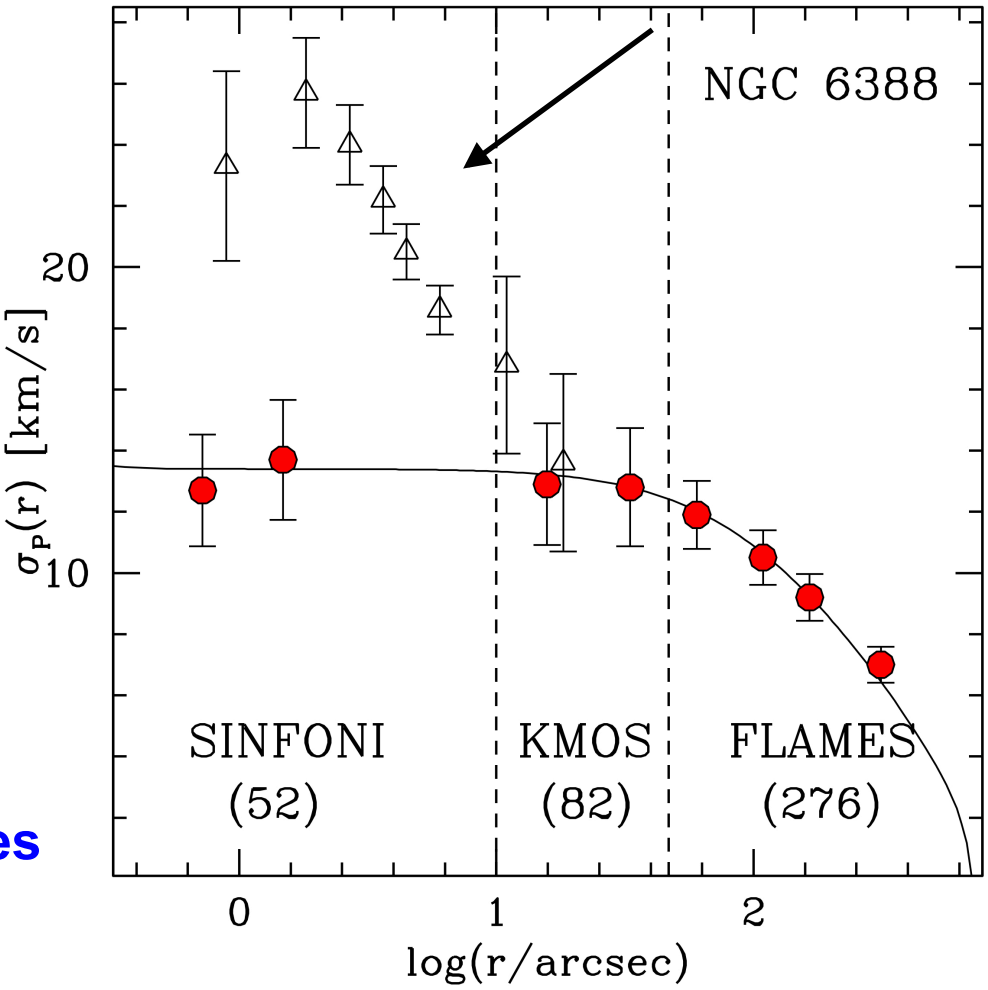
Lützgendorf et al. (2011)
(M_{BH} ~ 1.7 10^4 $M_\odot$)

σ(r) from individual V_r
(σ_0 ~ 13-14 km/s)

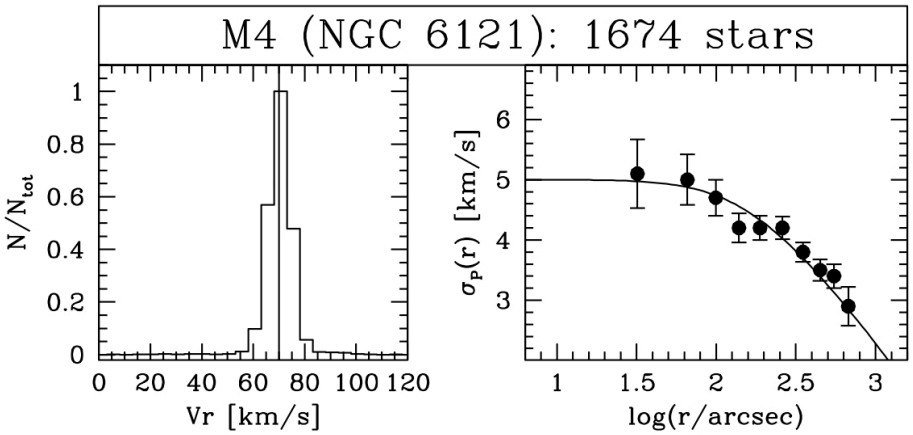
inconsistent with

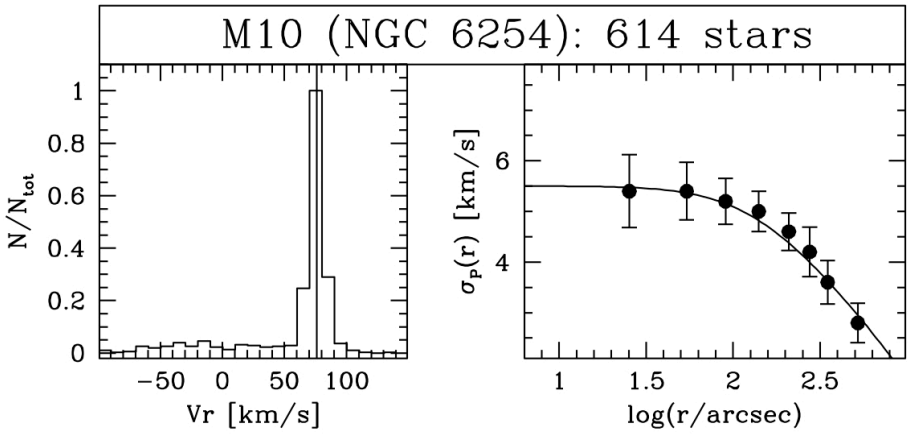
σ(r) from the line broadening of integrated-light spectra
(σ_0 ~ 23-25 km/s)

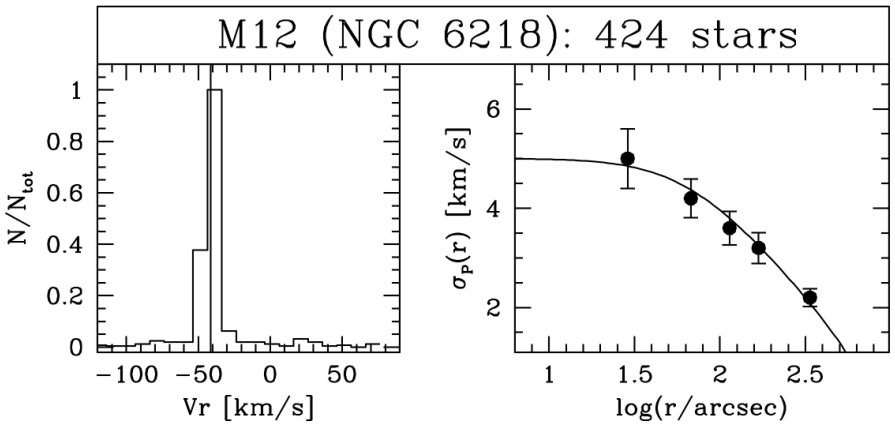
Integrated-light spectra:
shot-noise bias
due to three bright stars
with very different radial velocities

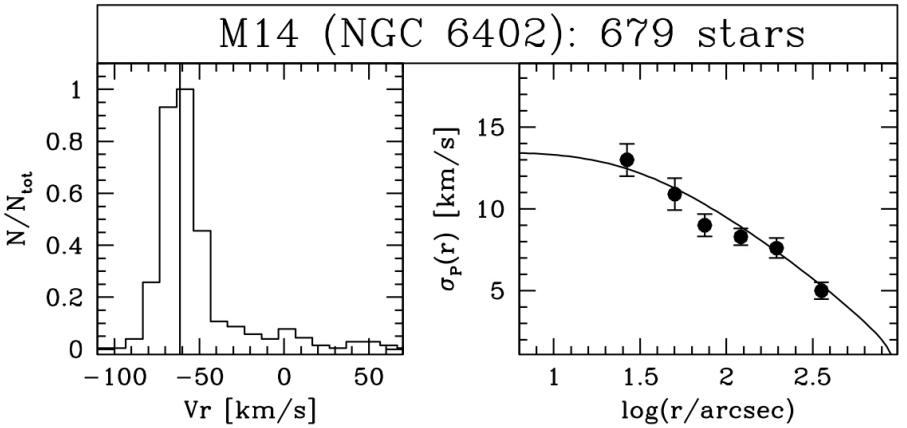


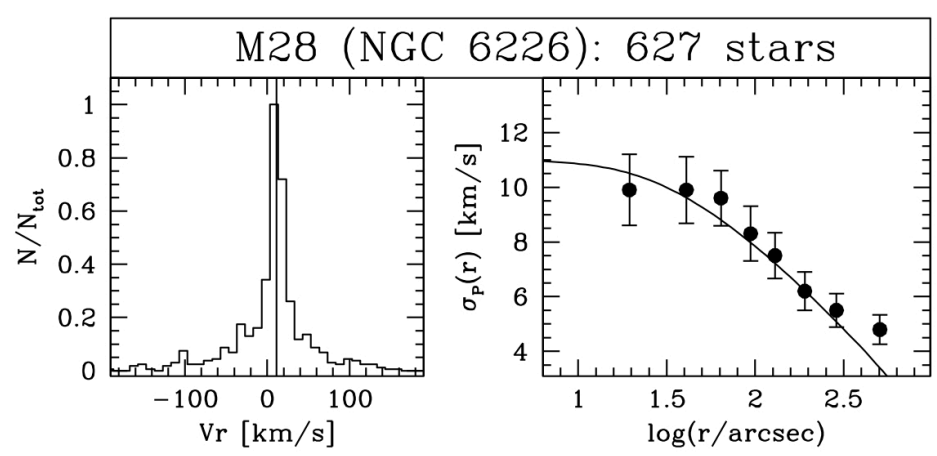
Preliminary results from KMOS+FLAMES LP (30 targets)

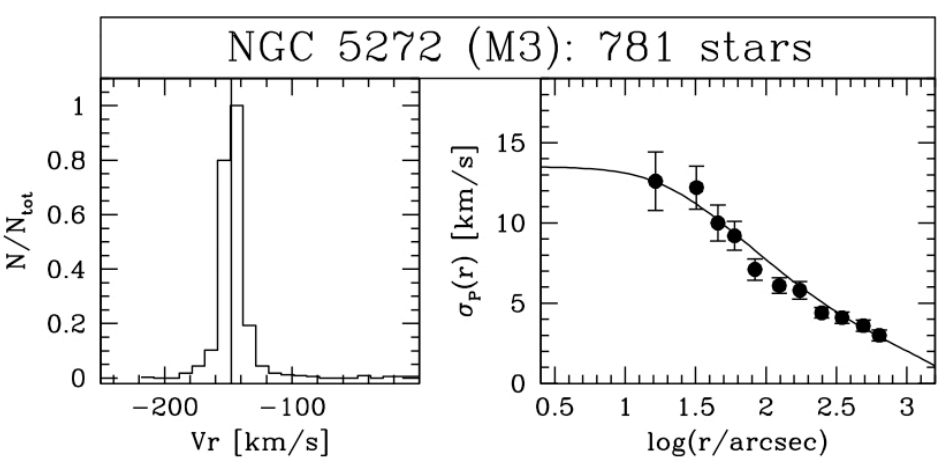


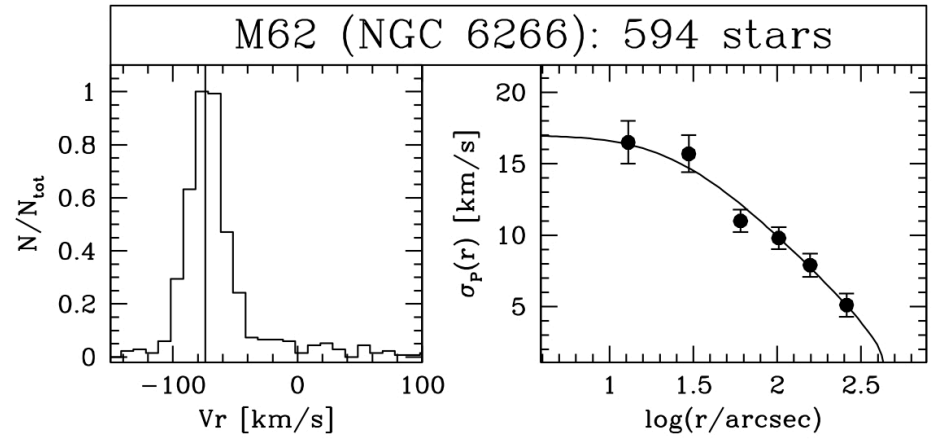


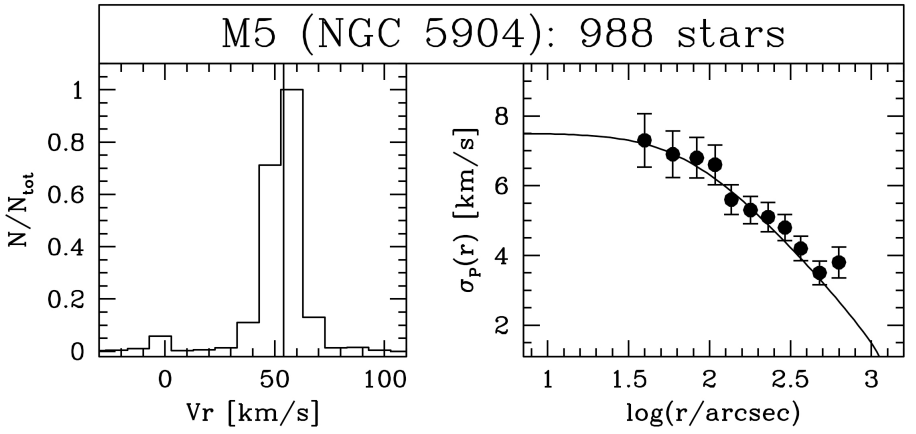


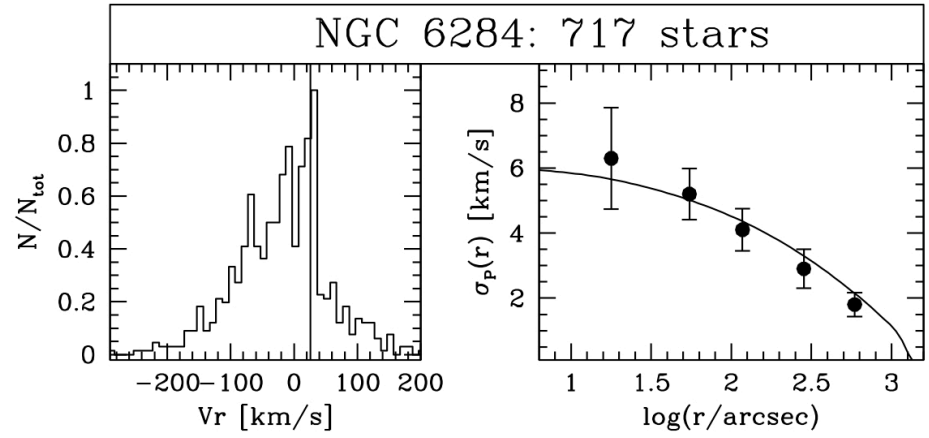


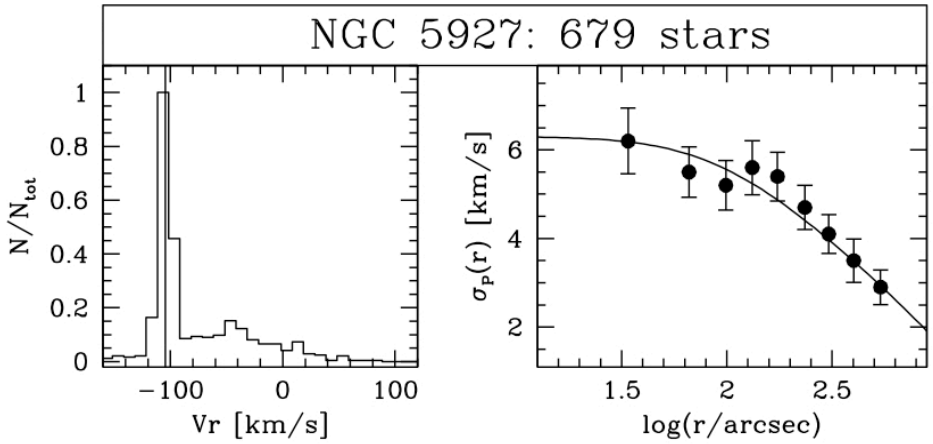

M28 (NGC 6226): 627 stars
N/N_tot
Vr [km/s]
σ_P(r) [km/s]
log(r/arcsec)


NGC 5272 (M3): 781 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)

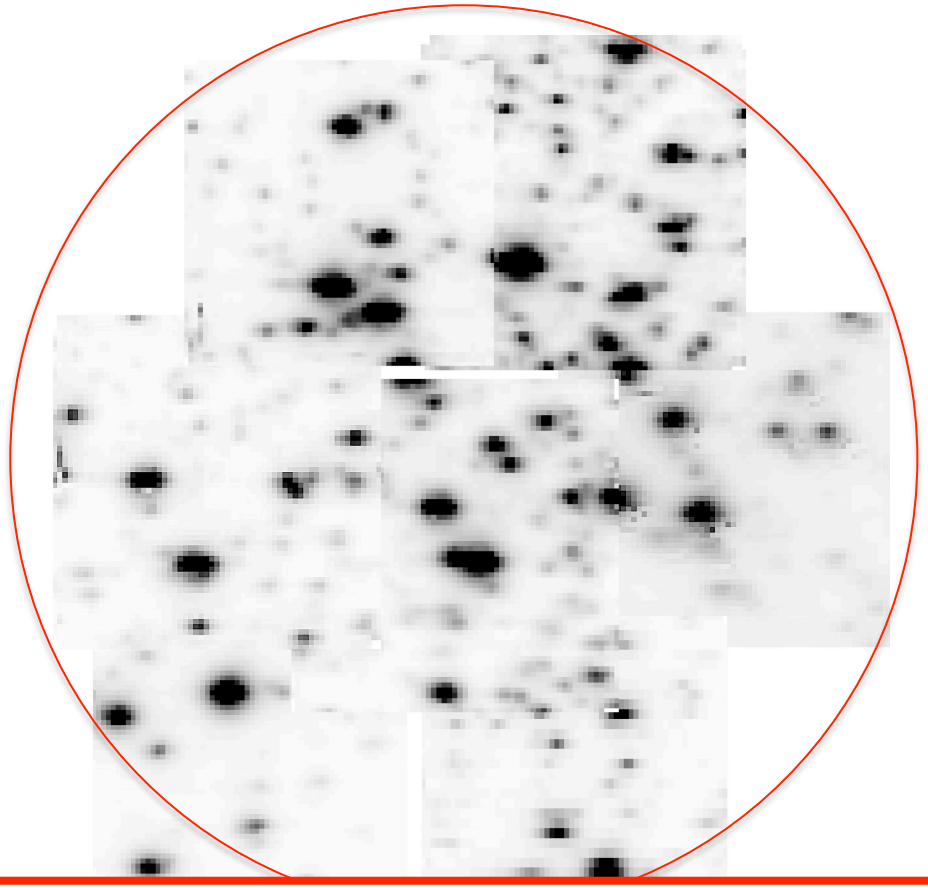

M5 (NGC 5904): 988 stars
N/N_tot
Vr [km/s]
σ_P(r) [km/s]
log(r/arcsec)


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

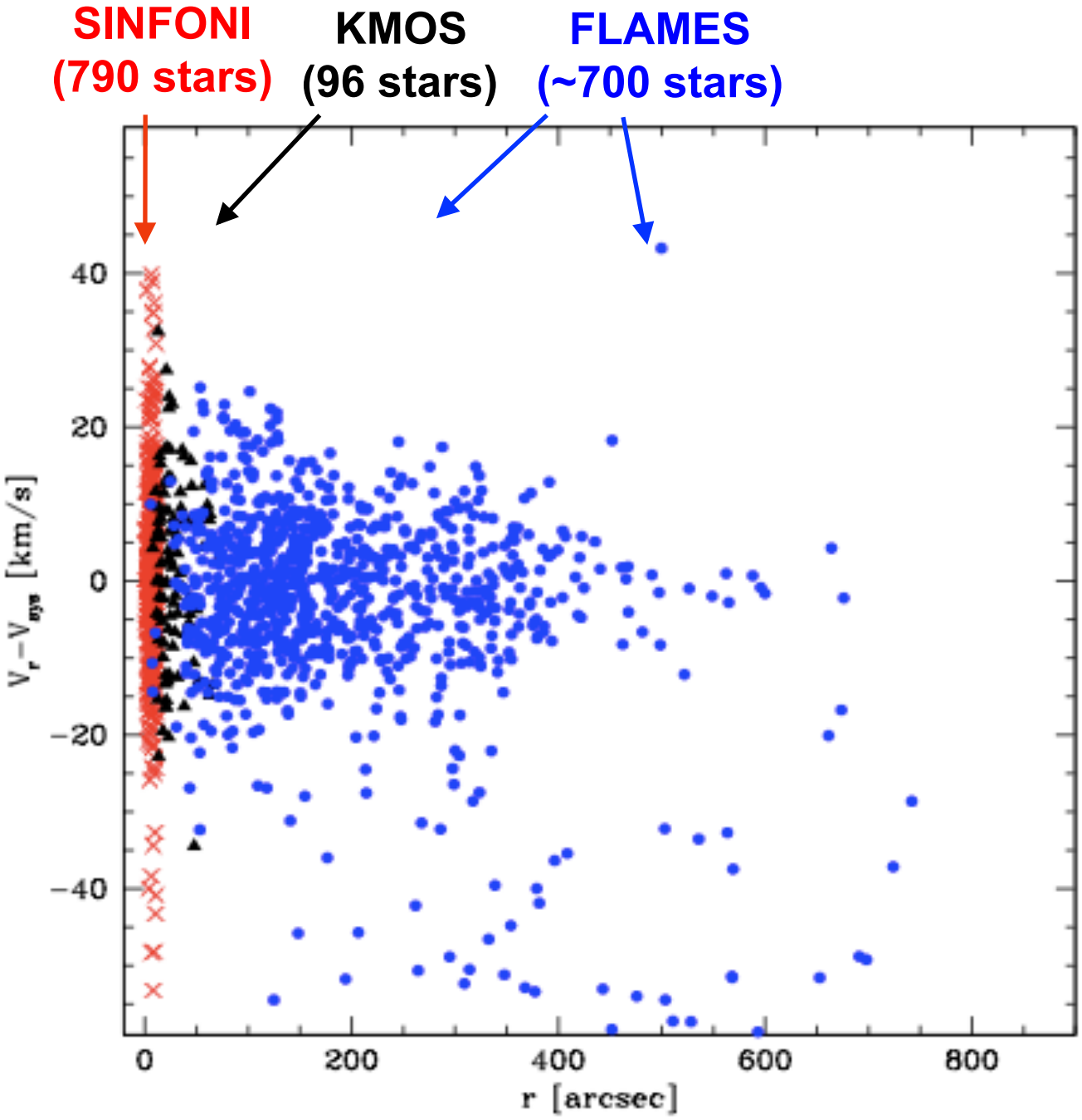

NGC 5927: 679 stars
N/N_tot
Vr [km/s]
σ_P(r) [km/s]
log(r/arcsec)

Preliminary results for NGC 2808

a mosaic of 7 SINFONI fields



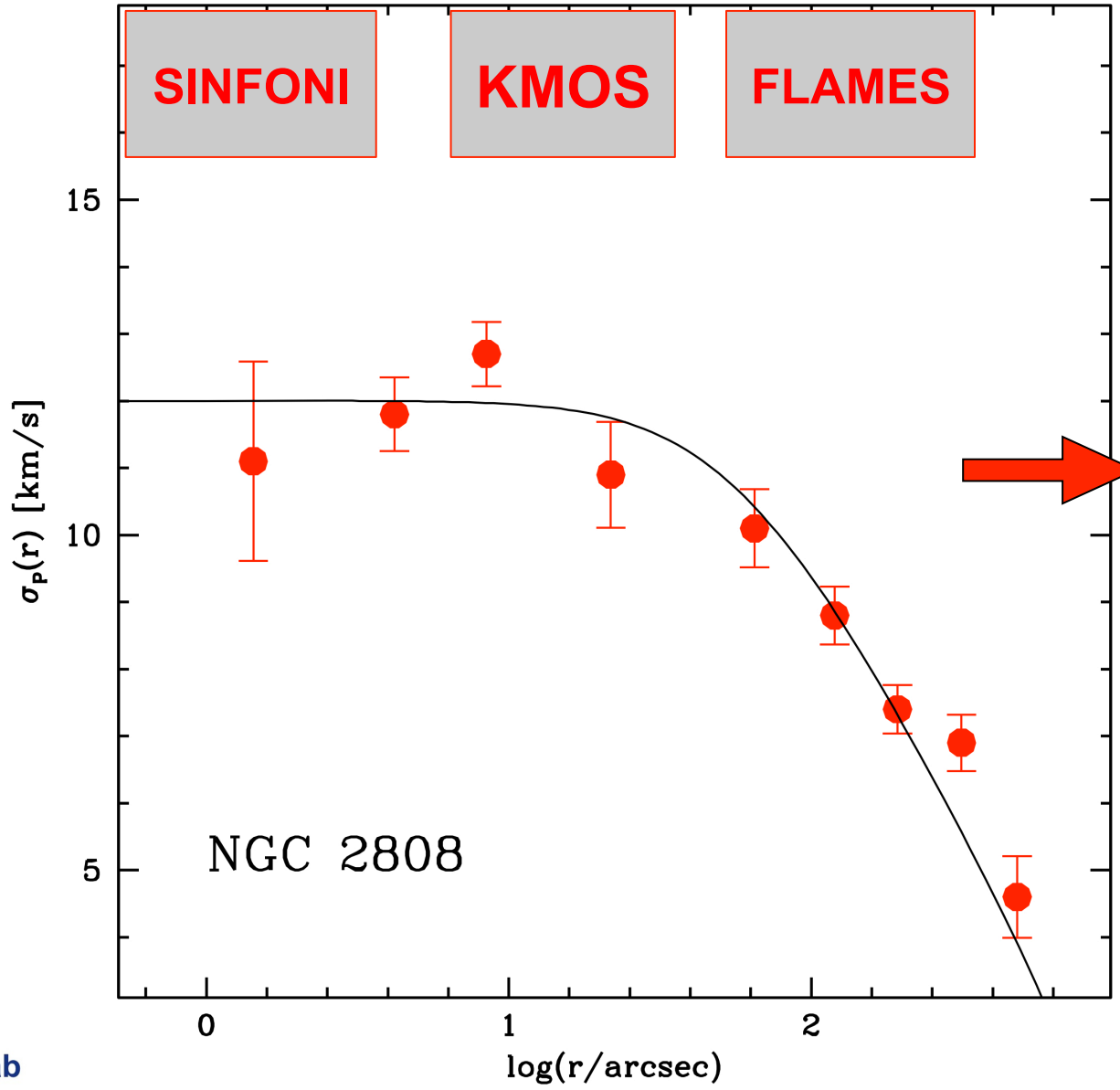
V_r for 790 individual stars at r<12" !!!



Cosmic-Lab

erc

Preliminary results for NGC 2808

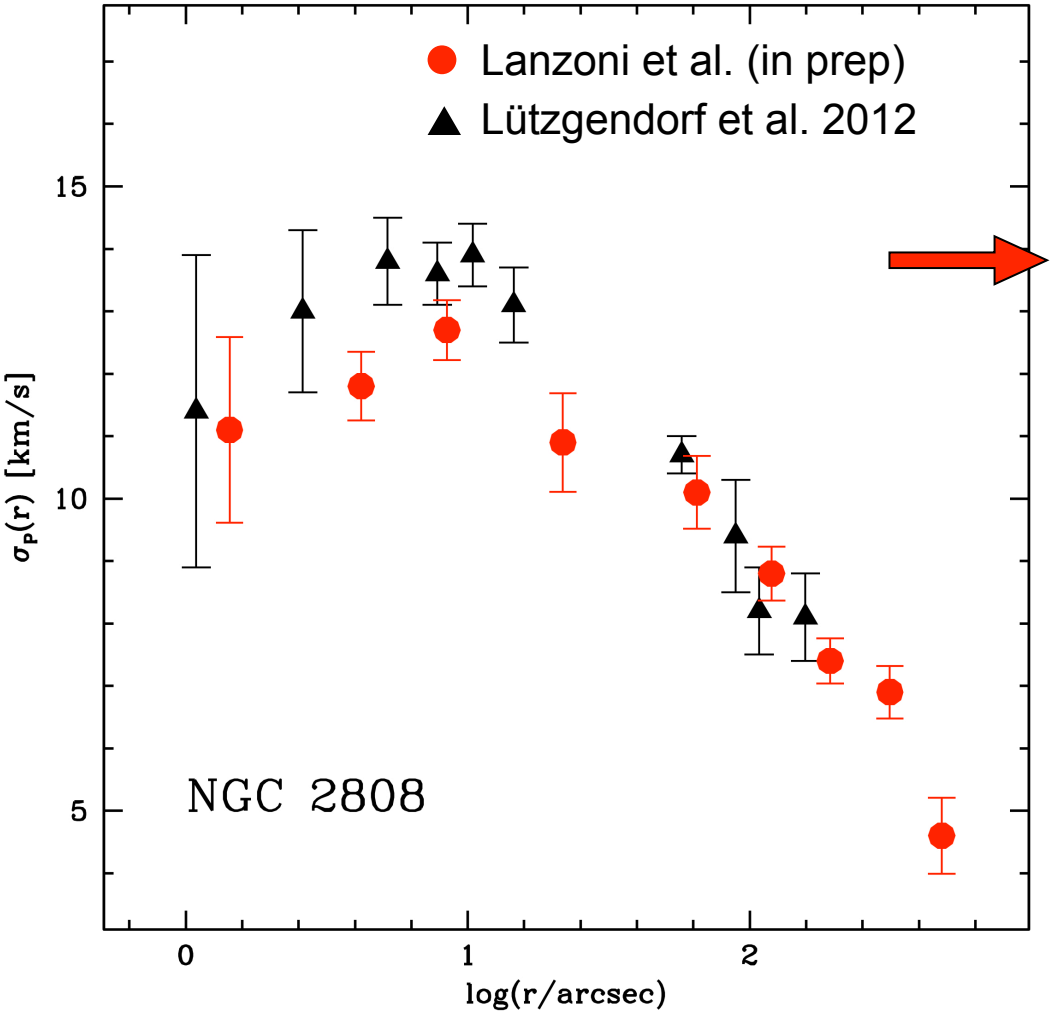


NO IMBH

Cosmic-Lab

erc

Preliminary results for NGC 2808



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

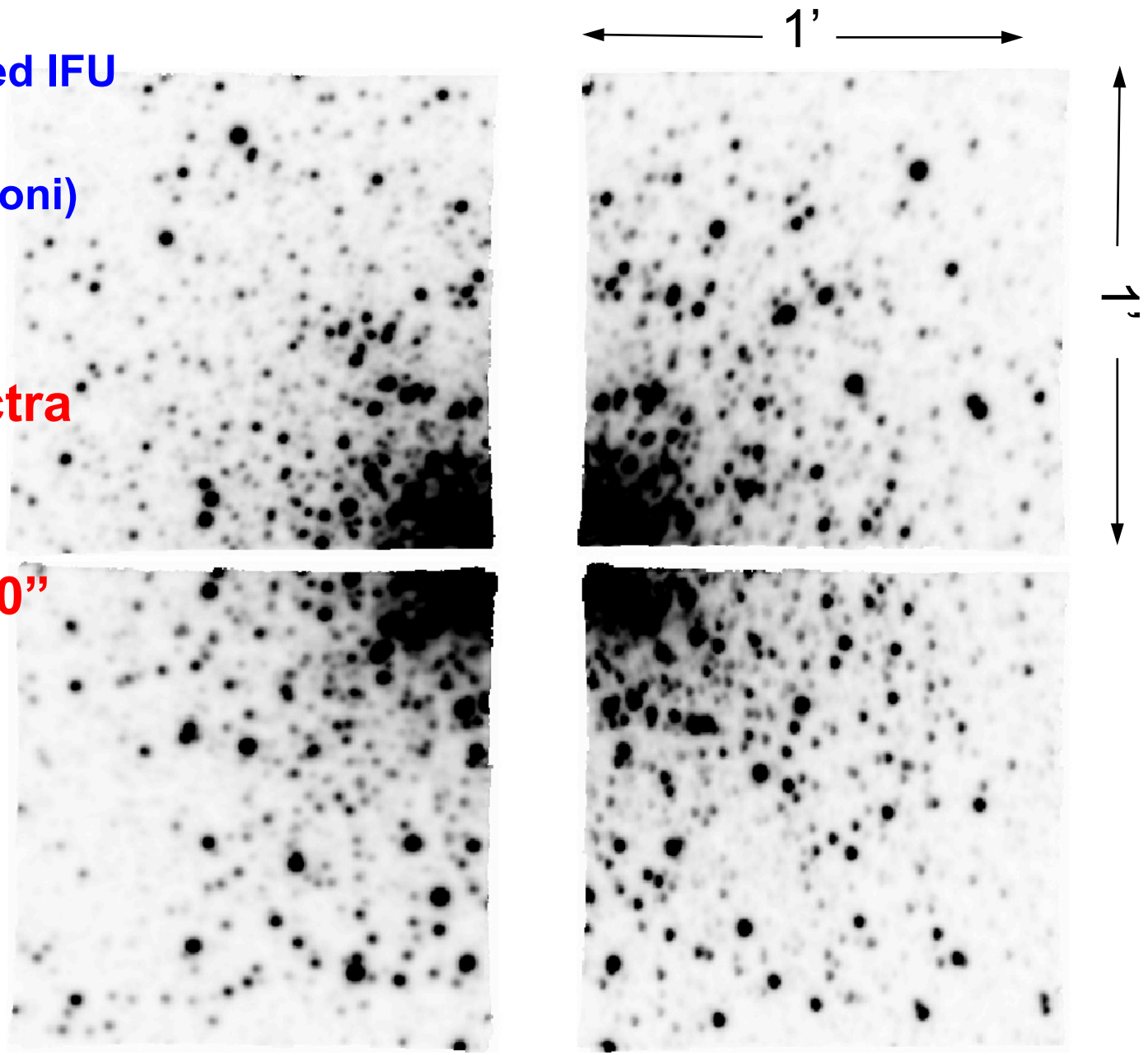
- lack of bright stars with different RVs

M15 with MUSE

- non-AO corrected IFU
- FoV=1'x1'
- SV run (PI: Lanzoni)

Individual spectra of ~700 stars

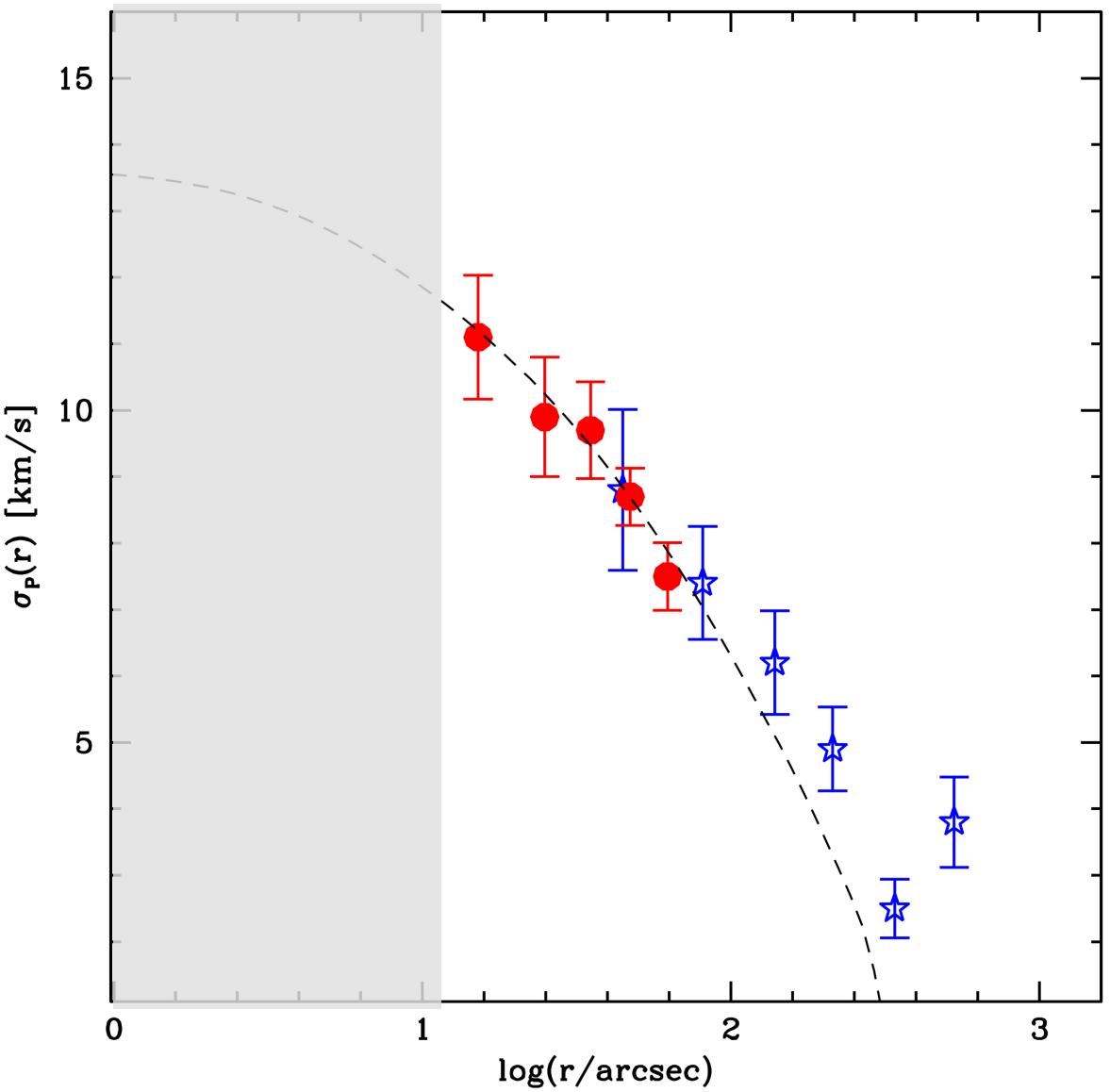
Non-AO => r>10"



M15 with MUSE

non-AO => r>10”

- individual MUSE RVs (Lanzoni et al. 2015)
- ☆ individual RVs (Lardo et al. 2015)



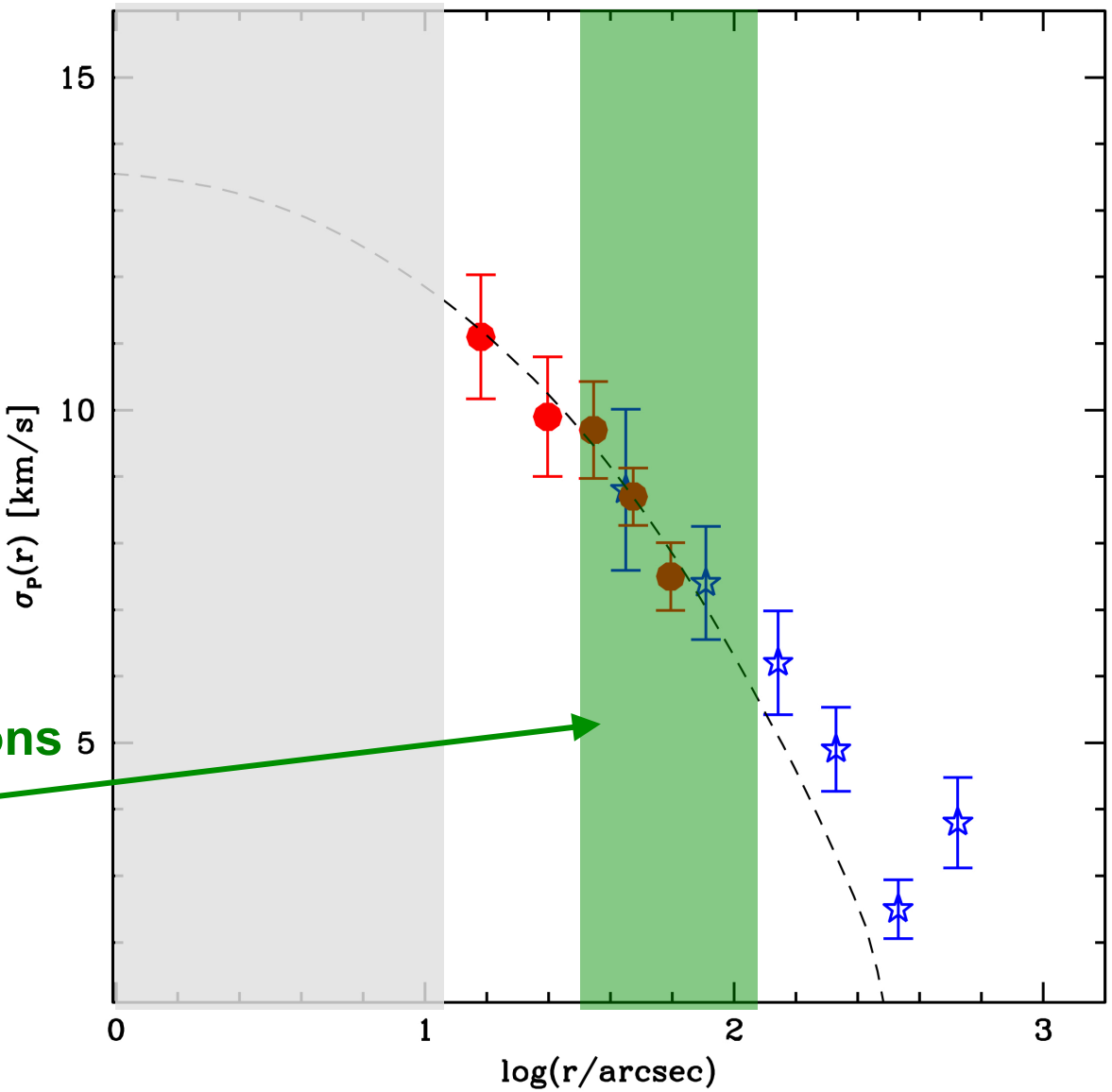
M15 with MUSE

non-AO => r>10”

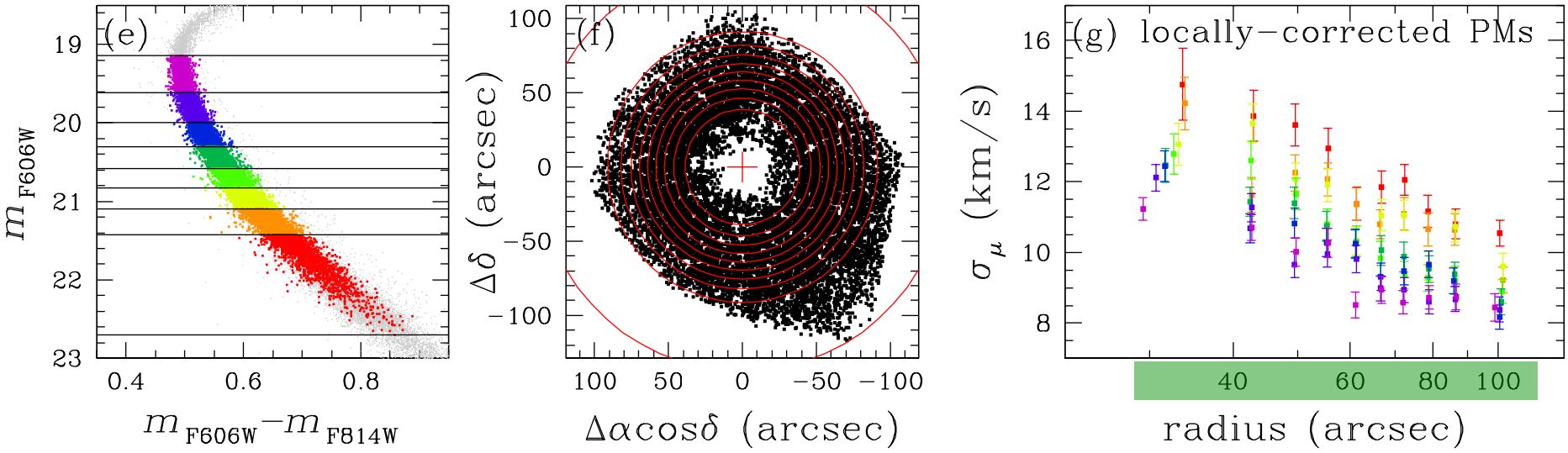
● individual MUSE RVs (Lanzoni et al. 2015)

☆ individual RVs (Lardo et al. 2015)

HSTPROMO proper motions (Bellini et al. 2014)

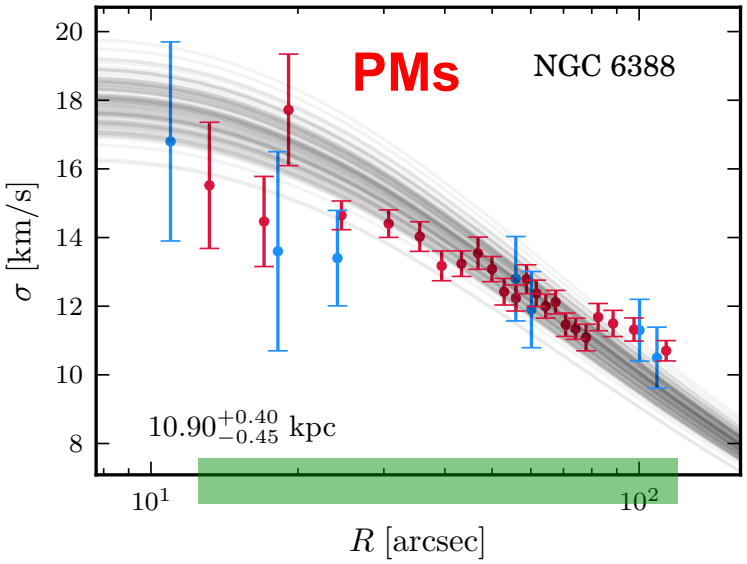


HSTPROMO proper motions of M15 (Bellini et al. 2014)

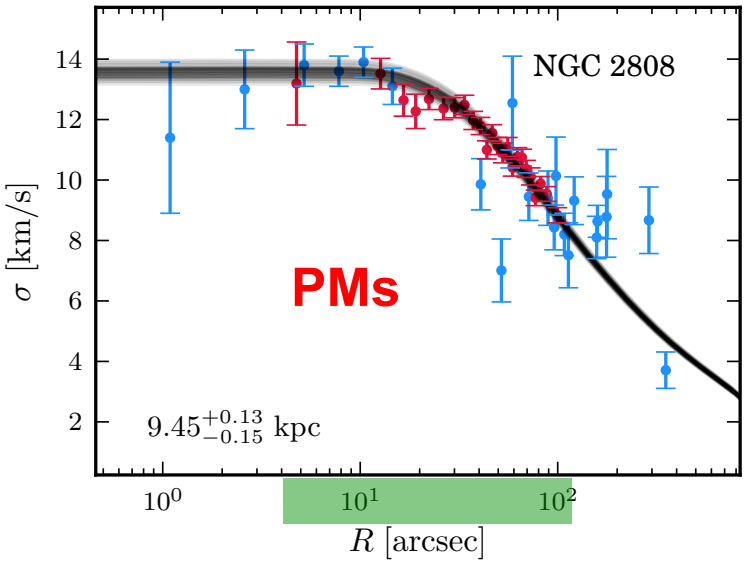


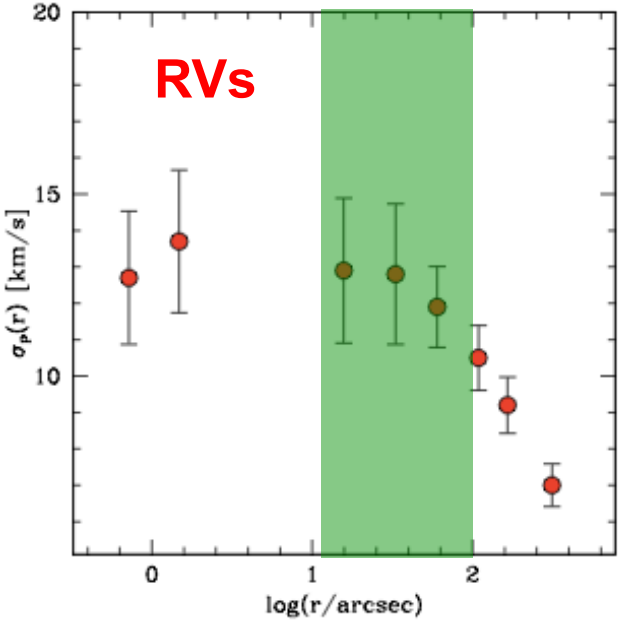
HSTPROMO PM (Watkins et al. 2015)

NGC 6388

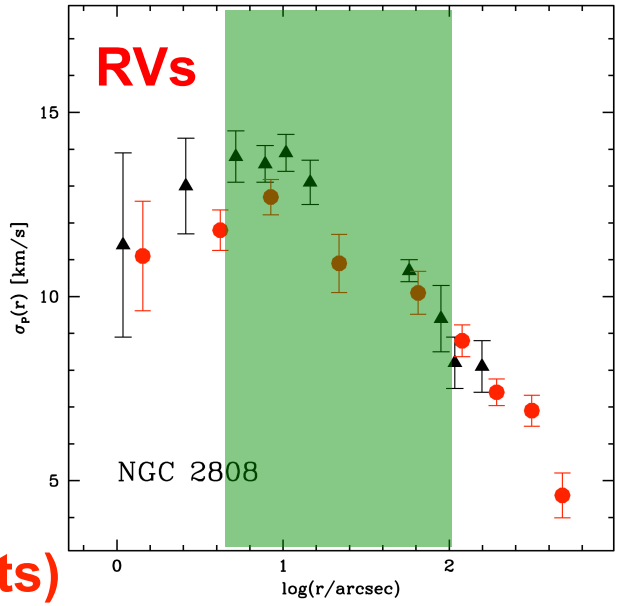


NGC 2808





centres & outskirts non-sampled by HST PMs



(Gaia→ outskirts)

CONCLUSIONS

A new generation of:

- star count density profiles
- velocity dispersion profiles
- rotation curves
- proper motions

our contribution

for a significant sample of globular clusters

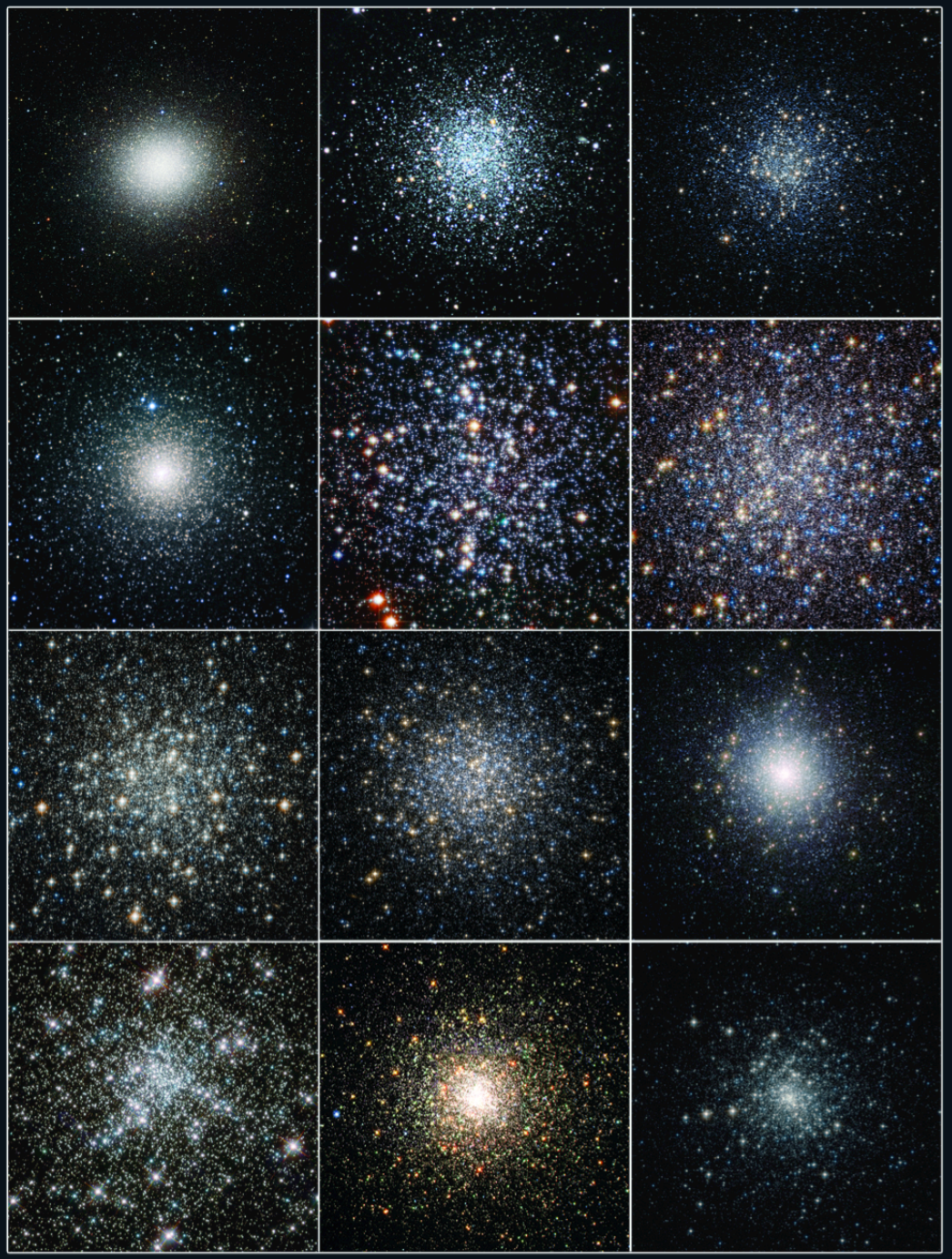
Thus,

+ the first 3D velocity map (of the cores) => info on pressure anisotropy
+ info on systemic internal rotation
+ possible evidence of IMBH

.... many new crucial constraints to theoretical modelling

In a few words: a LOT of (exciting) work for all of us!

Thank you
for your attention!



Cosmic-Lab