IMBHs (& velocity dispersion profiles) in Galactic globular clusters through radial velocities of individual stars

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Cosmic-Lab

www.cosmic-lab.eu

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Cosmic-Lab

- 5-year project
- *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

IMBHs (10^3-10^4 $M_\odot$): why interesting?

- could be the **seeds of SMBHs**
  → **galaxy formation & co-evolution with AGN**

- could be at the origin **of ultra-luminous X-ray sources (ULX)**

- would be important **gravitational waves emitters** detectable by the next generation detectors

- **expected in dense stellar systems**, affecting their **dynamical evolution**

IMBHs in GCs: several fingerprints predicted

(Baumgardt et al. 2005; Miocchi 2007; Heggie et al. 2007; Trenti et al. 2007, 2010; Dukier & Bailyn 2003; Maccarone 2004, 2007; Gill et al. 2008; Vesperini & Trenti 2010; Noyola & Baumgardt 2011; Umbreit & Rasio 2013; ...)

1) shallow density cusp at the very centre

2) steep inner cusp (r < 1”-2”) in the velocity dispersion profile

3) a few stars accelerated to very high-velocities (even ~100 km/s)

4) universal, large core to half-mass radii ratios (r_c/r_h >0.1)

5) quenching of mass segregation

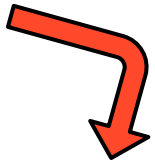
6) X-ray and radio emission

How to measure velocity dispersion (VD) in Galactic GCs?

Two main differences *wrt* distant (unresolved) galaxies/stellar systems

1) no gas => only **stellar** velocity dispersion

2) close to Earth => stars are **resolved**



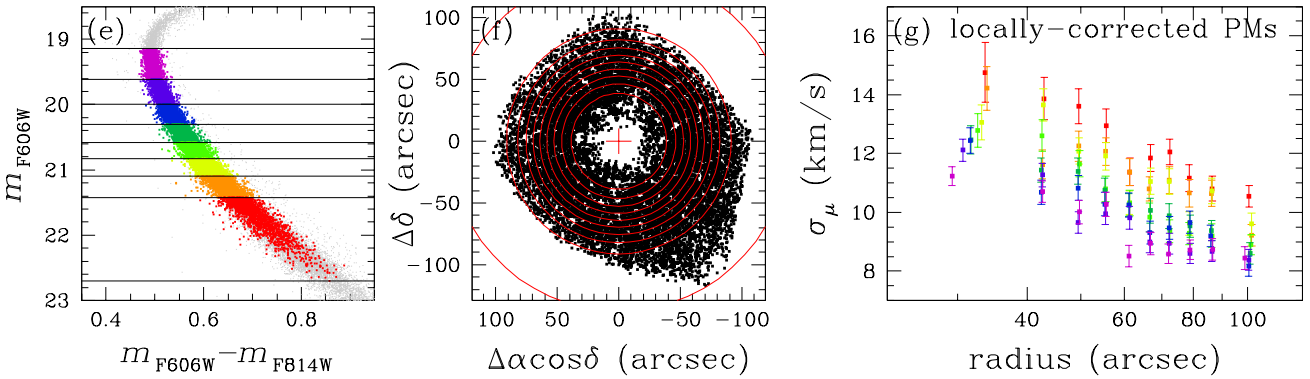
- **proper motions** (2 VD components: *x, y*)
- **individual radial velocities** (*l.o.s*. VD)

→ dispersion about the mean of stellar velocities

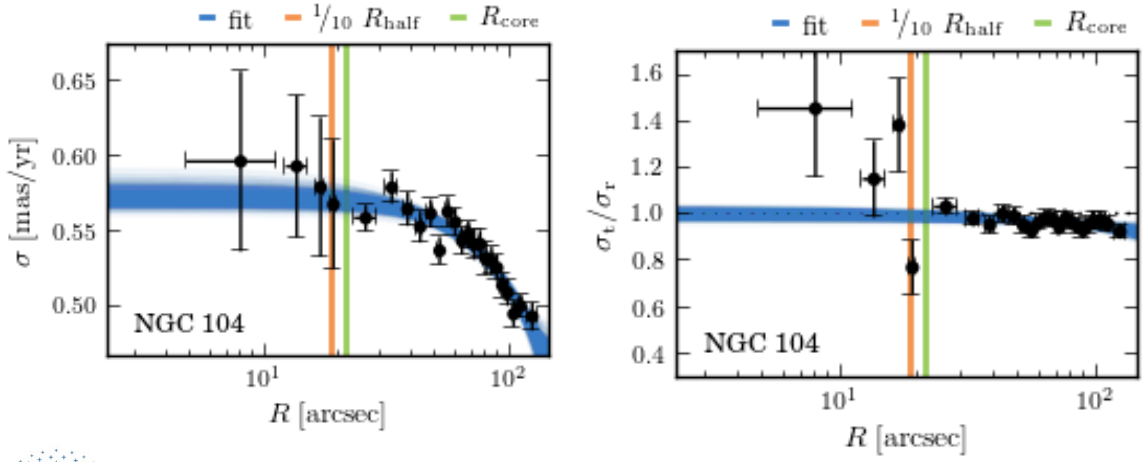
- **integrated-light spectra** (*l.o.s*. VD) → Doppler broadening of spectral lines

Proper motions

- ✓ **2 VD components => also orbital anisotropy information**
- ✓ **VD for different stellar mass**
- x **still miss the very central regions (stellar crowding)**



Bellini et al. 2014
(M15)



Watkins et al. 2015
(22 GGCs)

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How to measure velocity dispersion (VD) in Galactic GCs?

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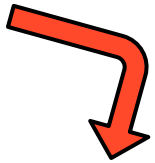


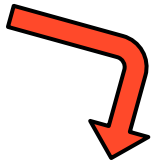
- proper motions (2 VD components: *x, y*) → still miss central regions
- individual radial velocities (*l.o.s*. VD)
- integrated-light spectra (*l.o.s*. VD) → prone to bias from few bright giants (Bianchini talk)

How to measure velocity dispersion (VD) in Galactic GCs?

Two main differences *wrt* distant (unresolved) galaxies/stellar systems

1) no gas => only **stellar** velocity dispersion

2) close to Earth => stars are **resolved**



- proper motions (2 VD components: *x, y*)
- individual radial velocities (*l.o.s.* VD) → our approach
- integrated-light spectra (*l.o.s.* VD)

A NEW GENERATION OF VELOCITY DISPERSION & ROTATION PROFILES FROM THE RADIAL VELOCITY OF INDIVIDUAL STARS WITH A MULTI-INSTRUMENT APPROACH

A NEW GENERATION OF VELOCITY DISPERSION & ROTATION PROFILES FROM THE RADIAL VELOCITY OF INDIVIDUAL STARS

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

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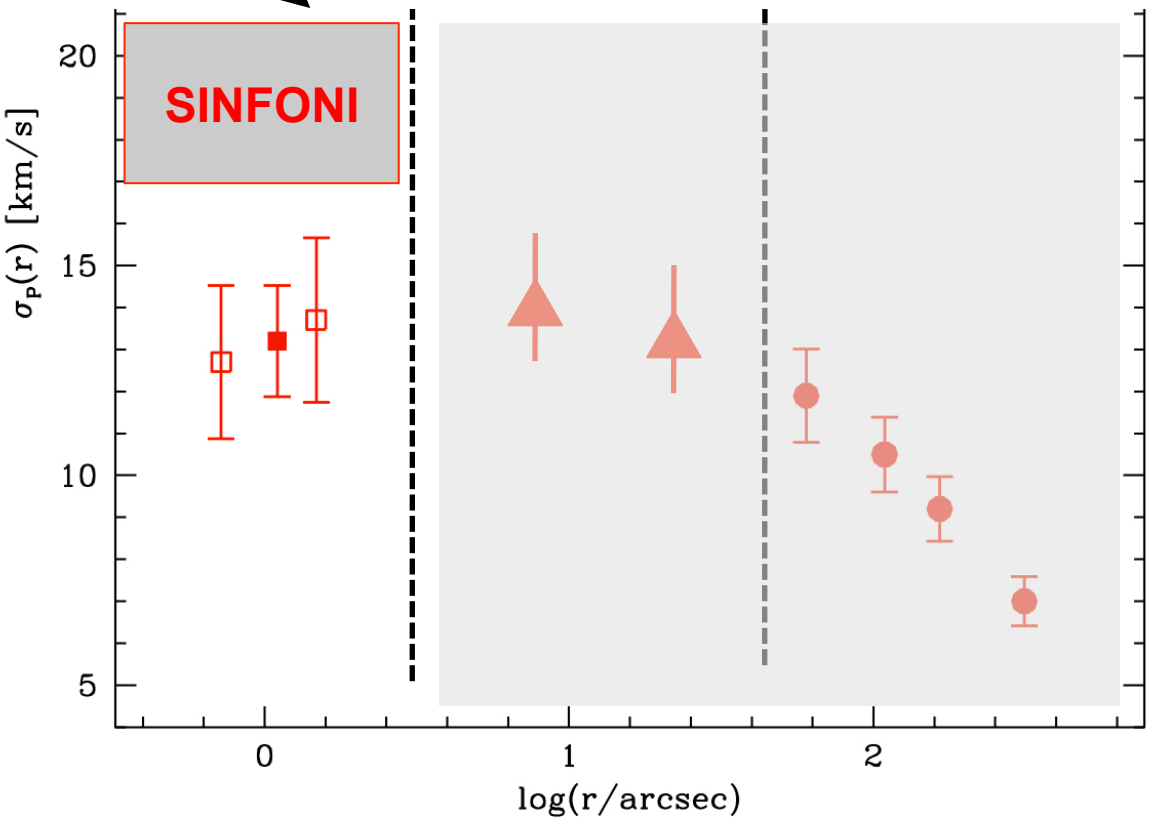
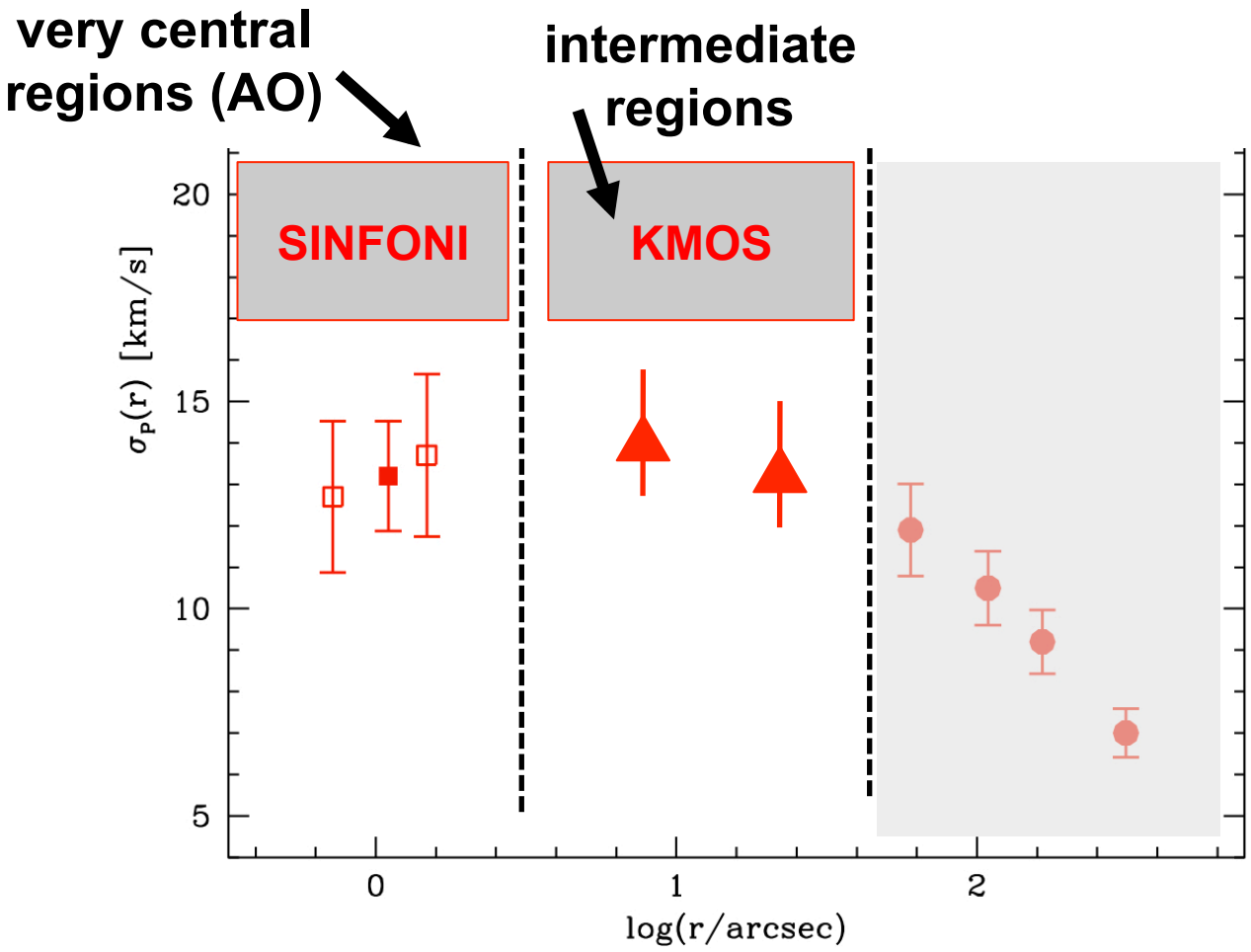
very central regions (AO)



A NEW GENERATION OF VELOCITY DISPERSION & ROTATION PROFILES FROM THE RADIAL VELOCITY OF INDIVIDUAL STARS

KMOS

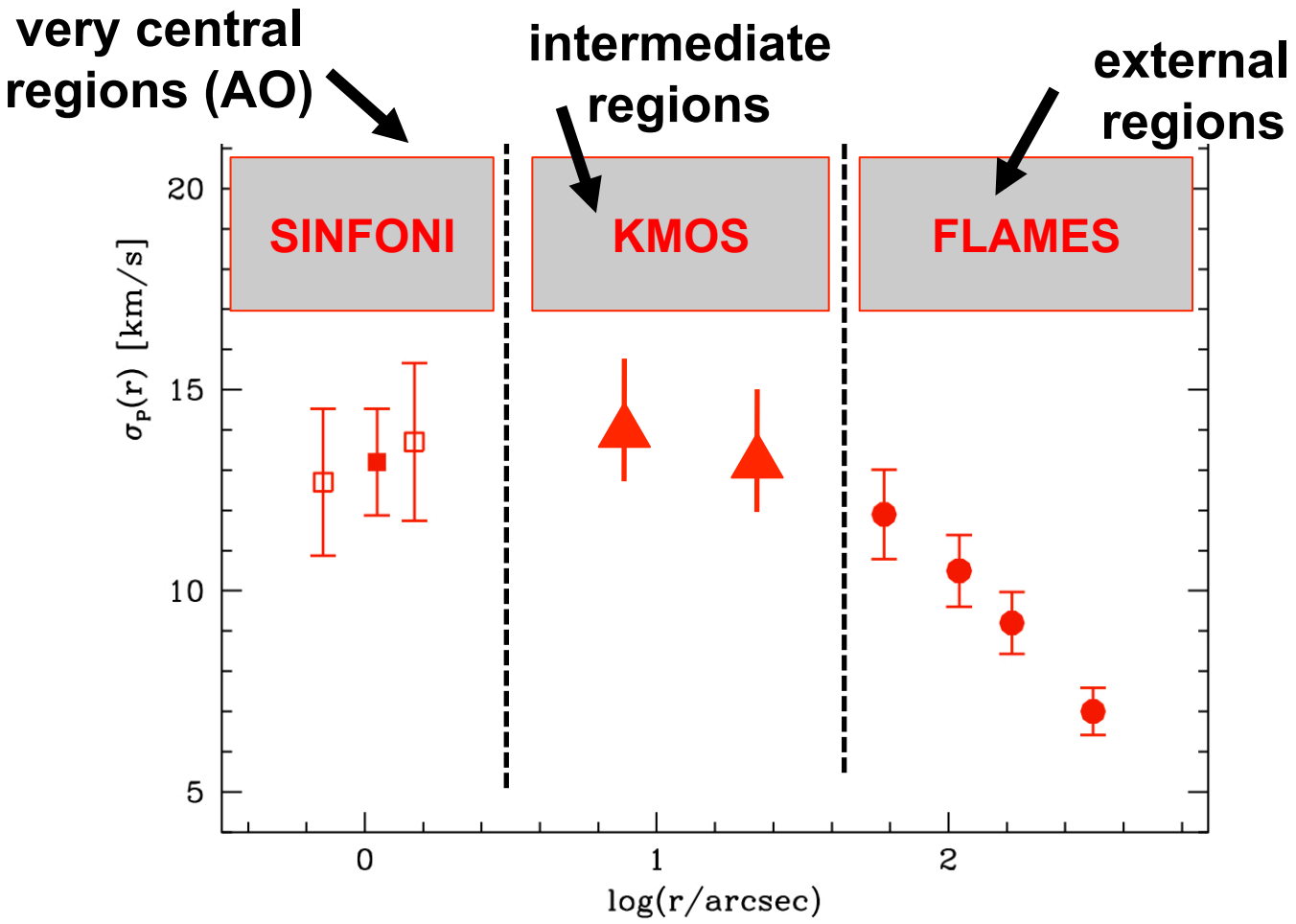
24 deployable IFUs, FoV=3”x3” each,
mid-spectral resolution (R=3400), YJ-band grating (1.00-1.35 μm),
atomic lines (TiI, MgI, FeI,..)



A NEW GENERATION OF VELOCITY DISPERSION & ROTATION PROFILES FROM THE RADIAL VELOCITY OF INDIVIDUAL STARS

FLAMES

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



A NEW GENERATION OF VELOCITY DISPERSION & ROTATION PROFILES FROM THE RADIAL VELOCITY OF INDIVIDUAL STARS

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

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

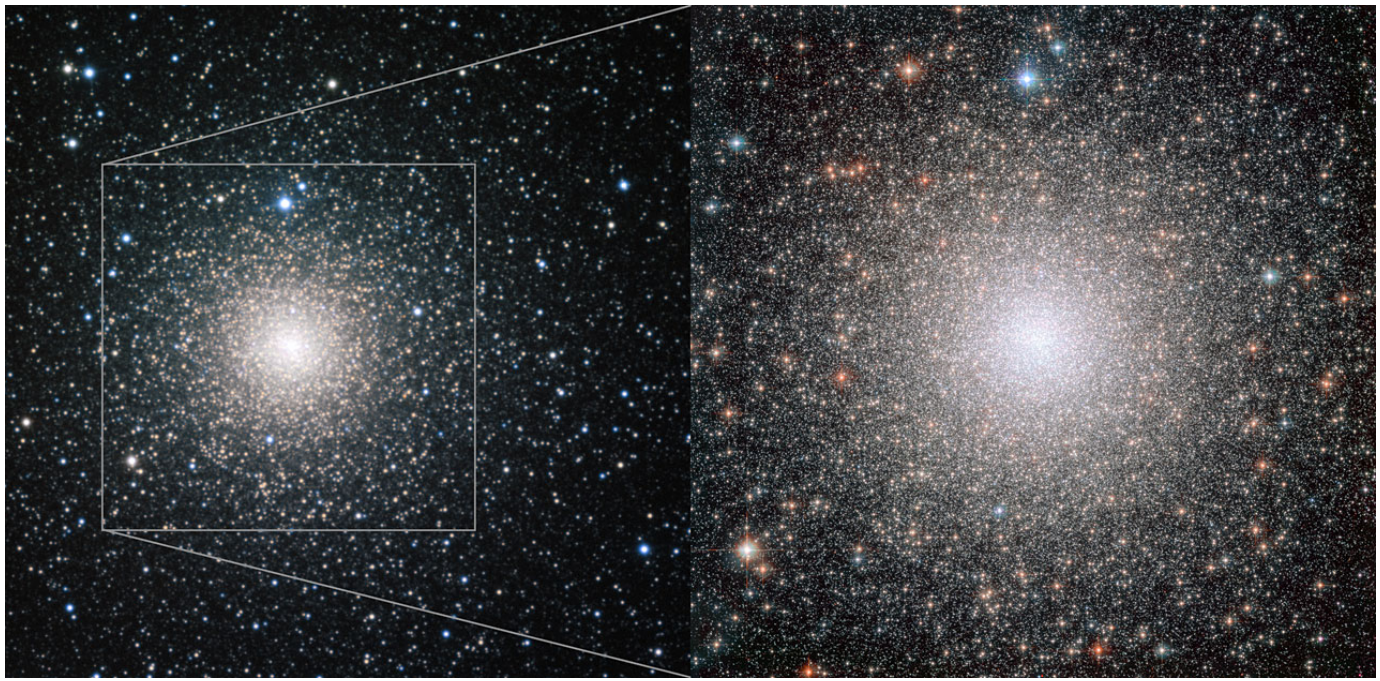
✦ ESO Large Programme 195.D-0750 (PI: Ferraro):

145 hours
SINFONI
19 high-density Milky Way GCs
starting next April

✦ a few additional/pilot programmes (also @Keck)

NGC 6388

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



Velocity dispersion from radial velocity of individual stars

(Lanzoni et al. 2013 + Lapenna et al. 2014)

SINFONI (AO assisted IFU): **r< 2”**

~ 2h exposure on target

~ 30% Strehl ratio

KMOS (multi-object: 24 IFUs): **9”<r<70”**

4 pointings

1.5 h (SV run)

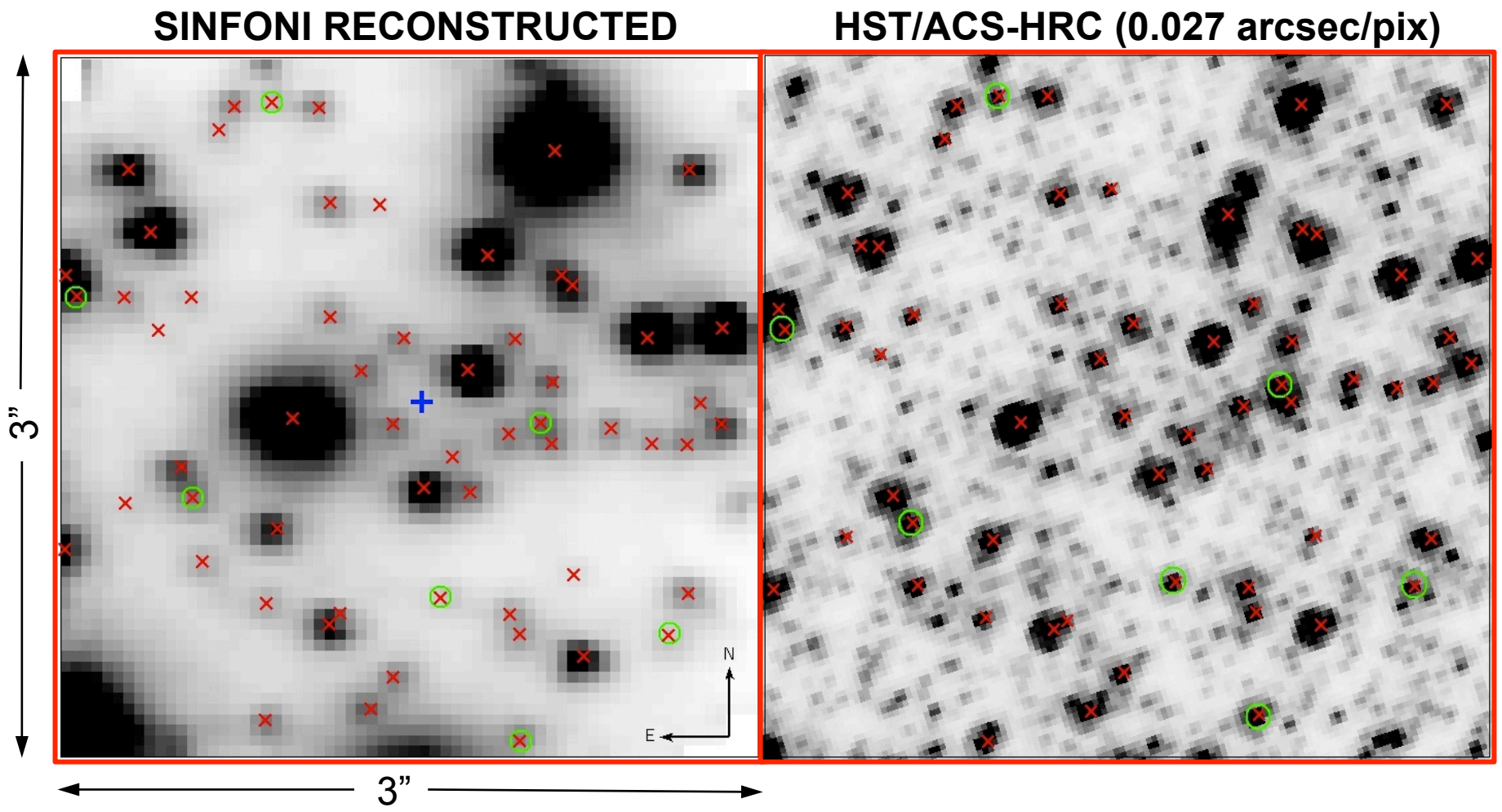
FLAMES (multi-object: 132 fibers): **60”<r<600”**

proprietary + archive data

~500 stars in total

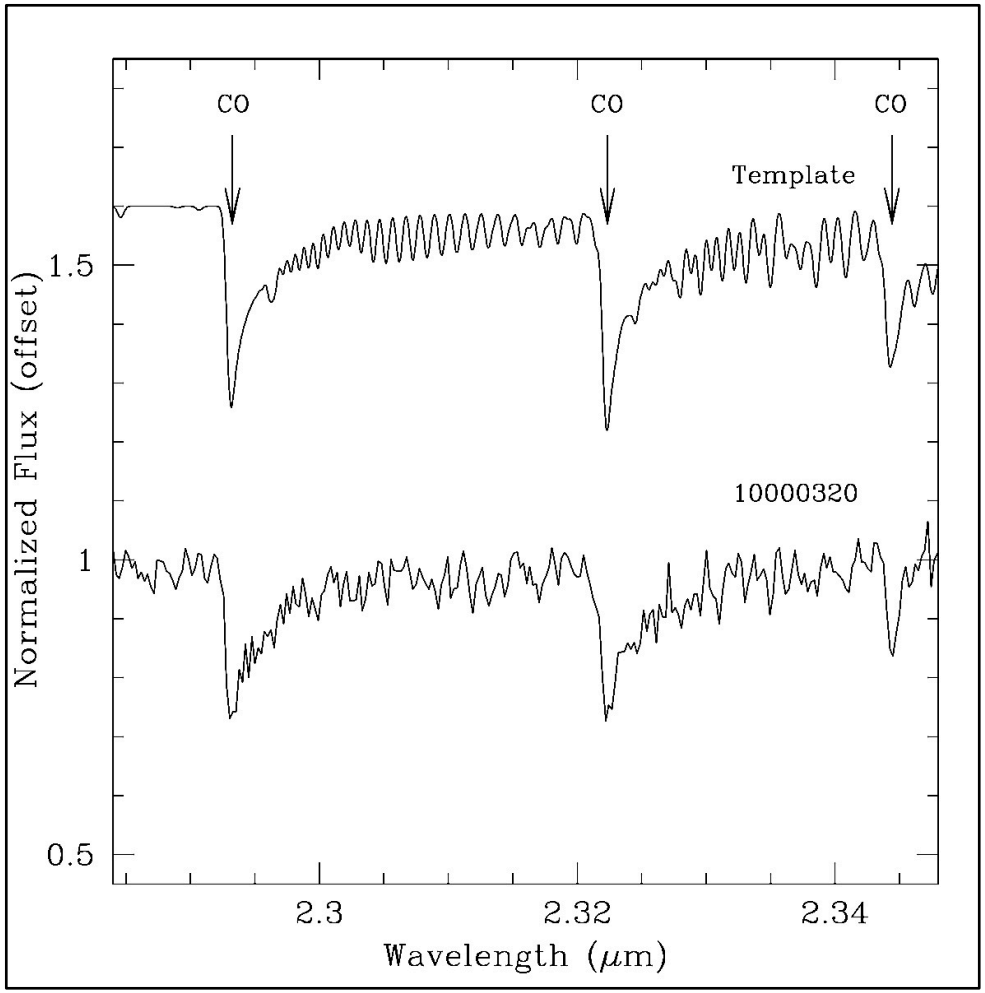
SINFONI (AO assisted IFU)→ center

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



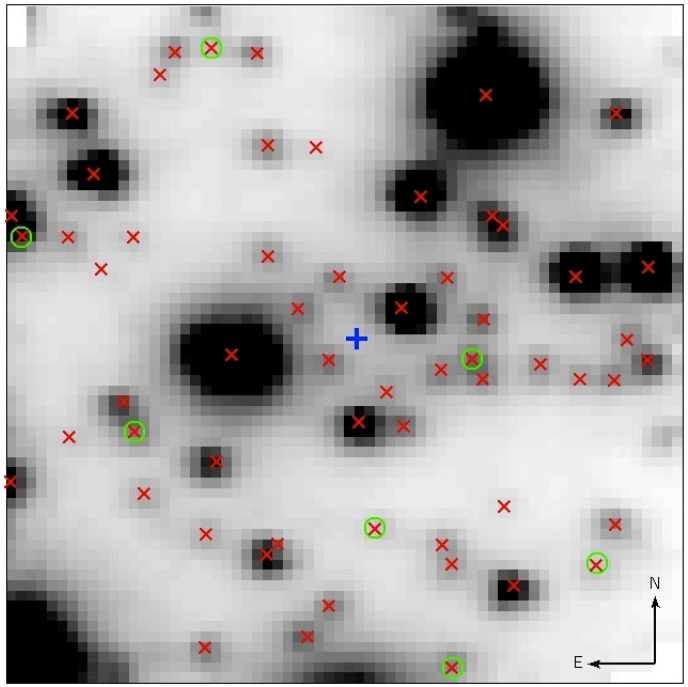
SINFONI (AO assisted IFU)→ center

- V_r from CO band-heads

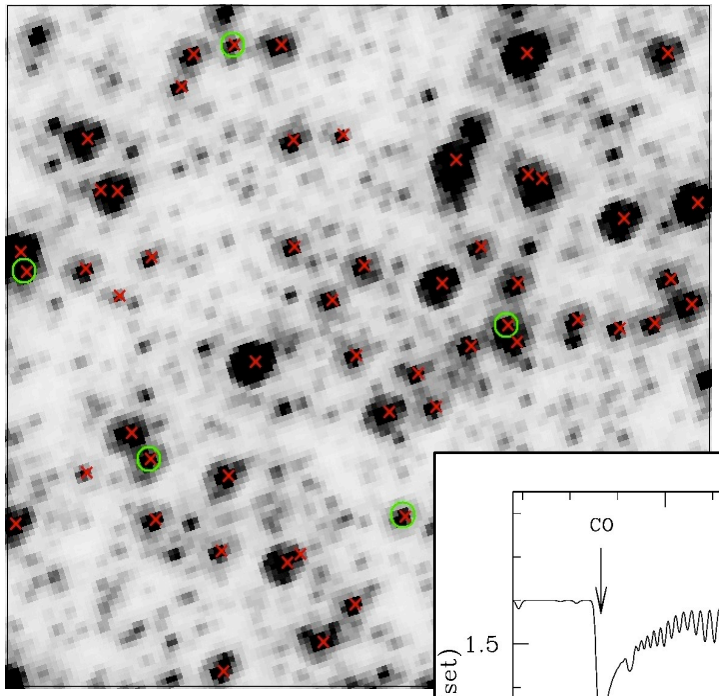


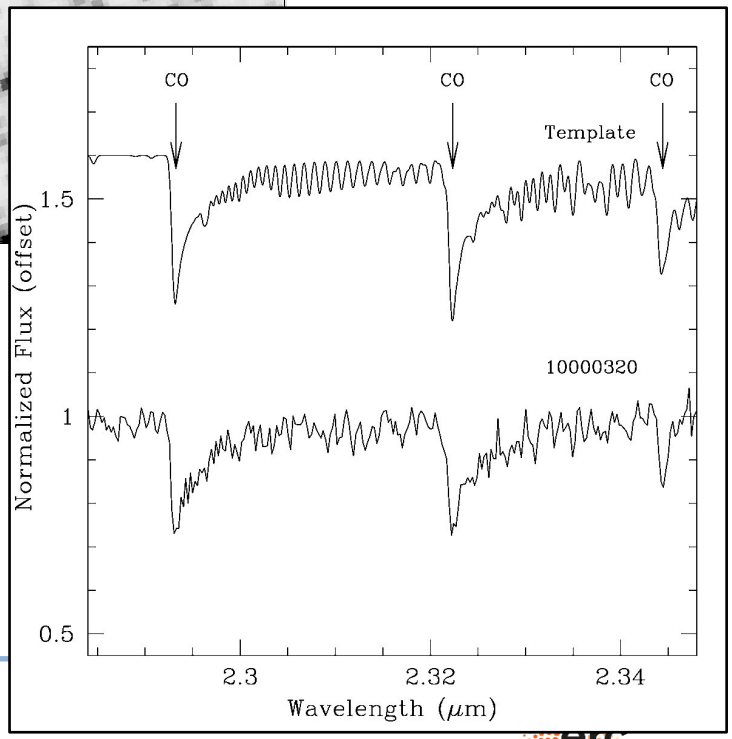
SINFONI (AO assisted IFU)→ center

SINFONI



HST/HRC

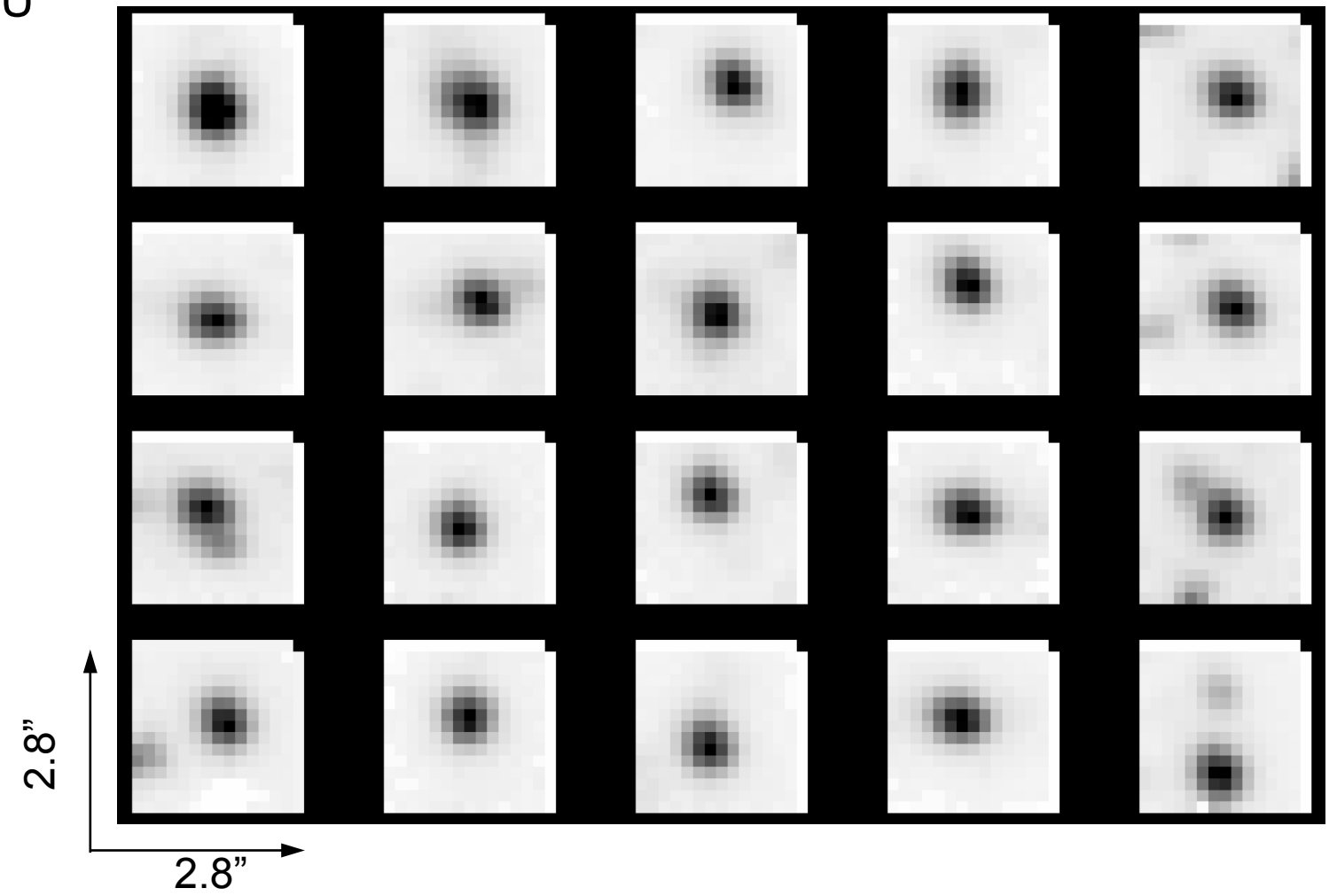




→ V_r for 52 individual stars at r<2” (~0.13 pc)

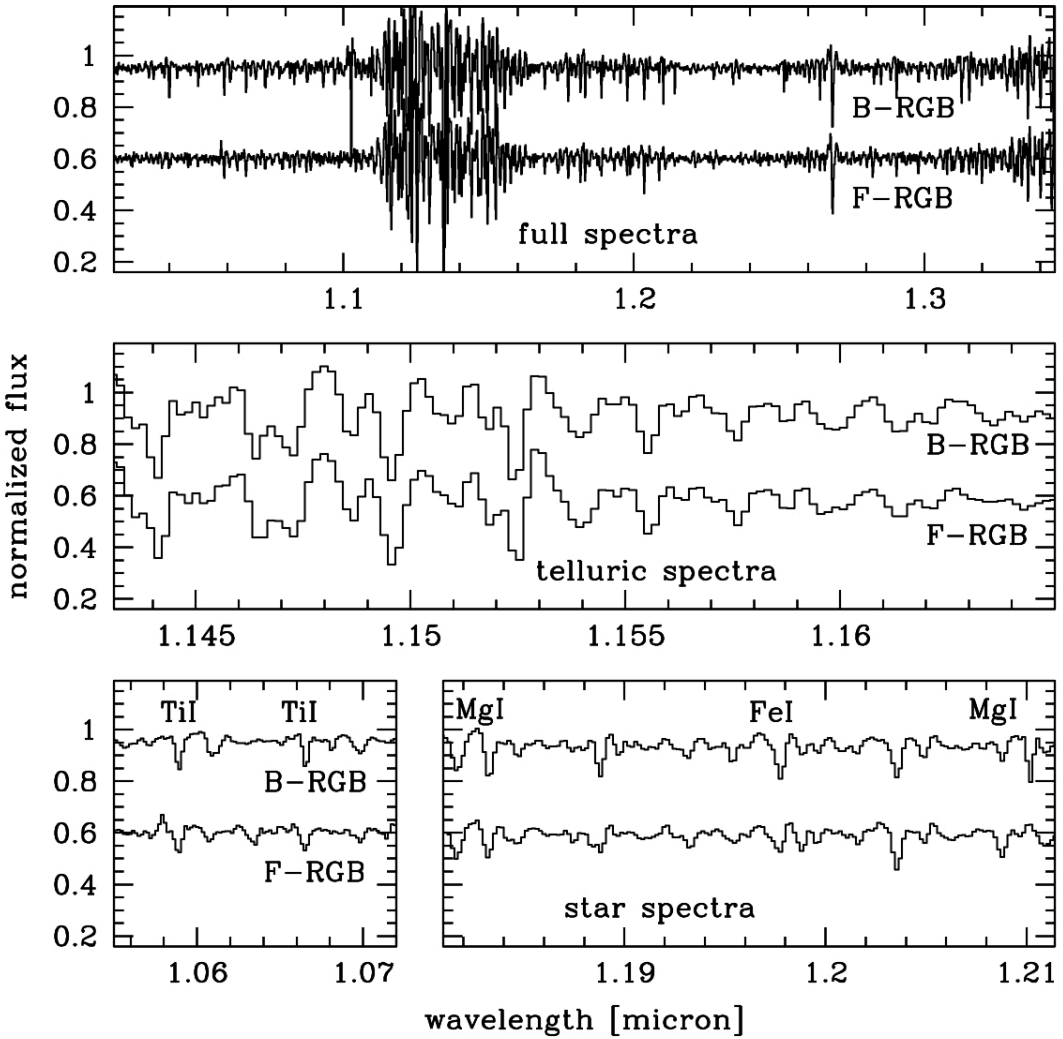
KMOS (multi-objects: 24 IFUs)→ intermediate regions

1 star per IFU



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

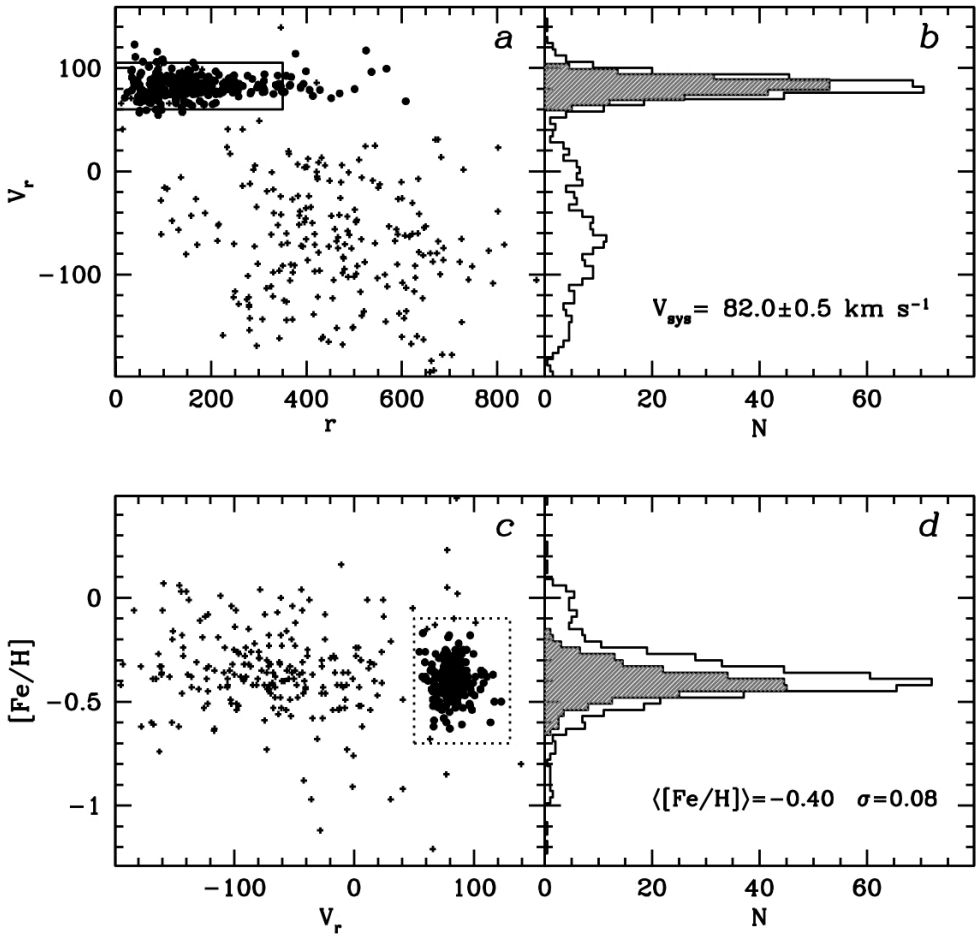
- Vr from several atomic lines
- wavelength calibration refined with telluric lines



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

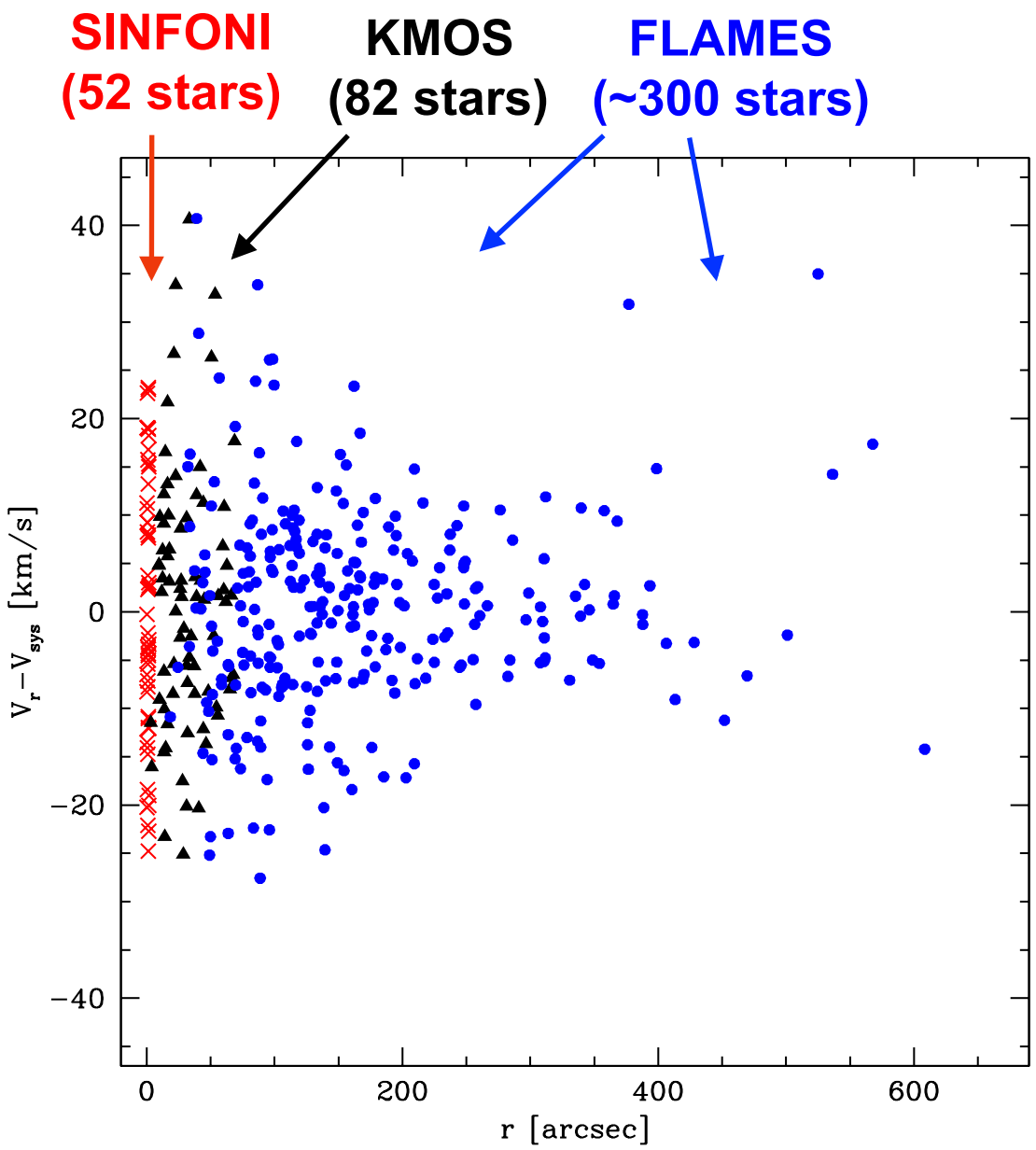
FLAMES (multi-objects: 132 fibers)→ external regions

- 3 programs => V_r & [Fe/H] for 508 stars



276 cluster members

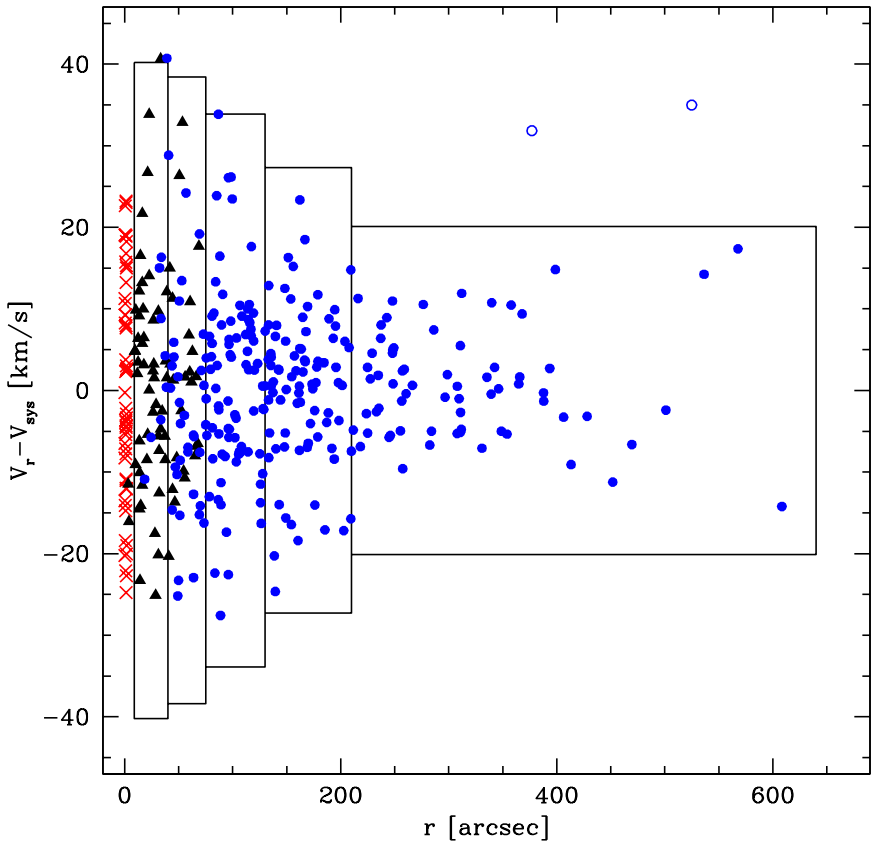
V_r for 276 individual stars at 18”<r<600”

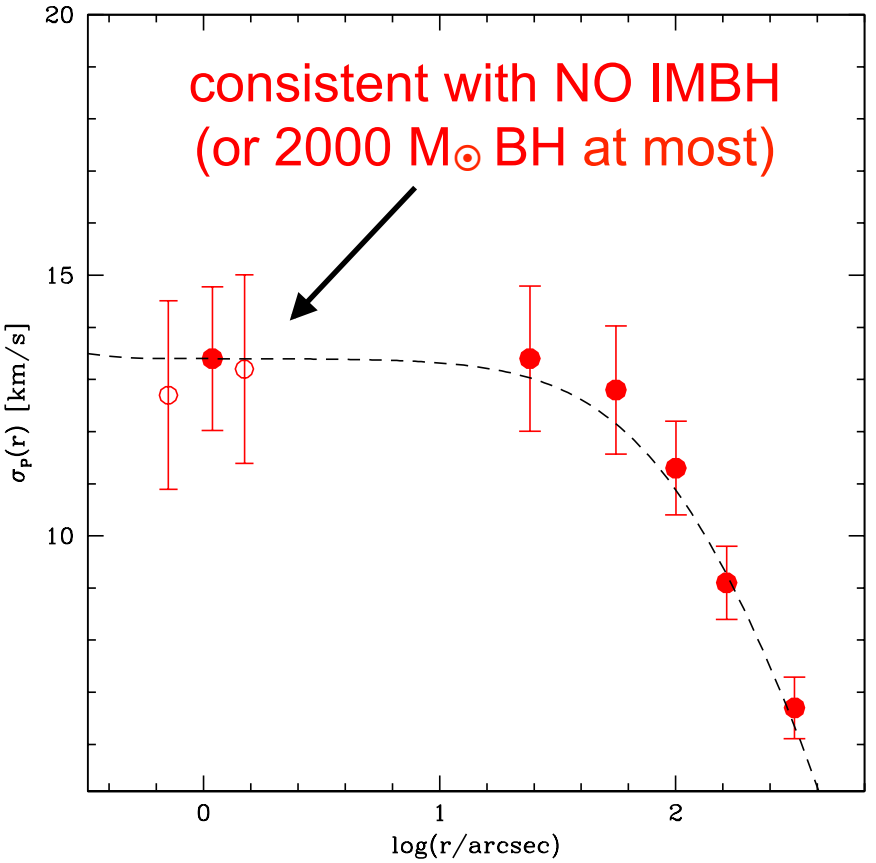

SINFONI
(52 stars)
KMOS
(82 stars)
FLAMES
(~300 stars)
40
20
0
−20
−40
$V_r - V_{sys}$ [km/s]
0
200
400
600
r [arcsec]

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)





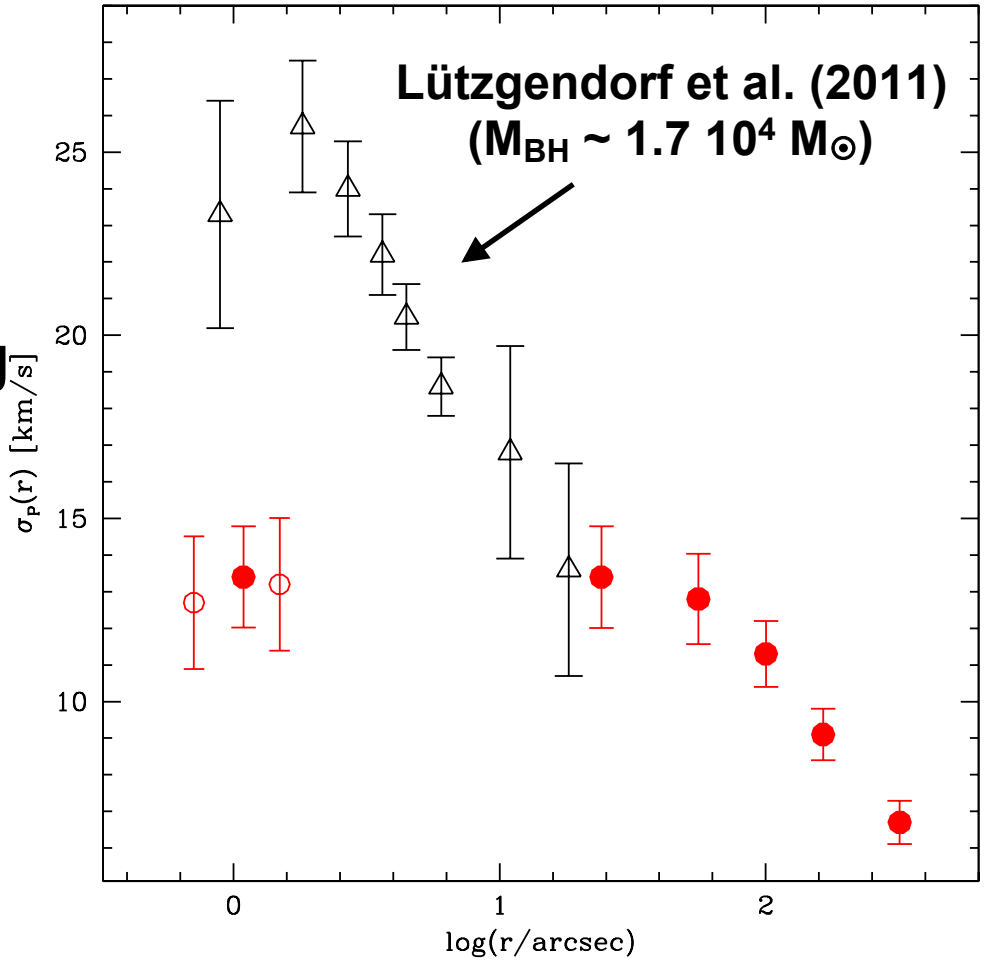
Velocity dispersion profile

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

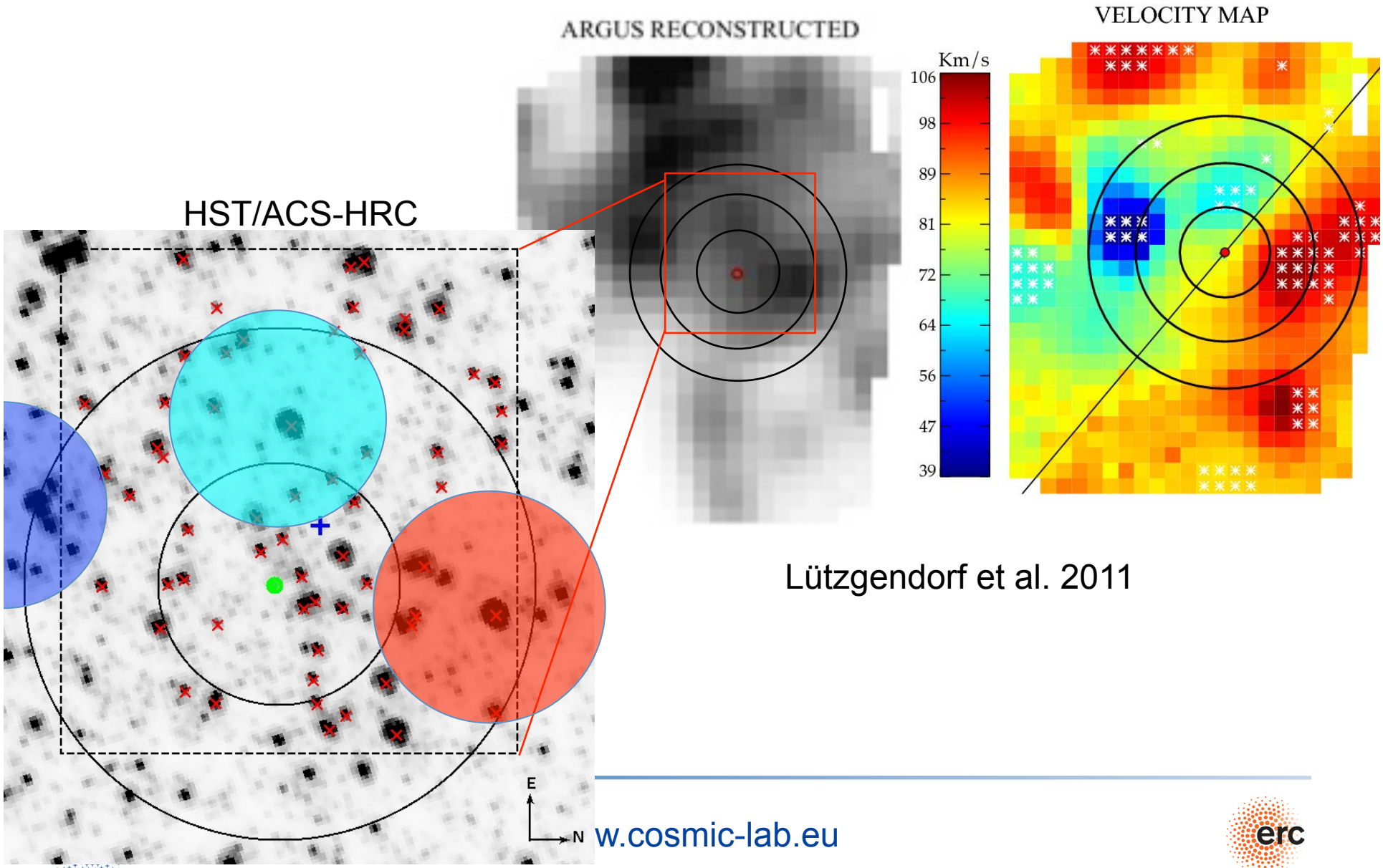
inconsistent with

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

WHY ?

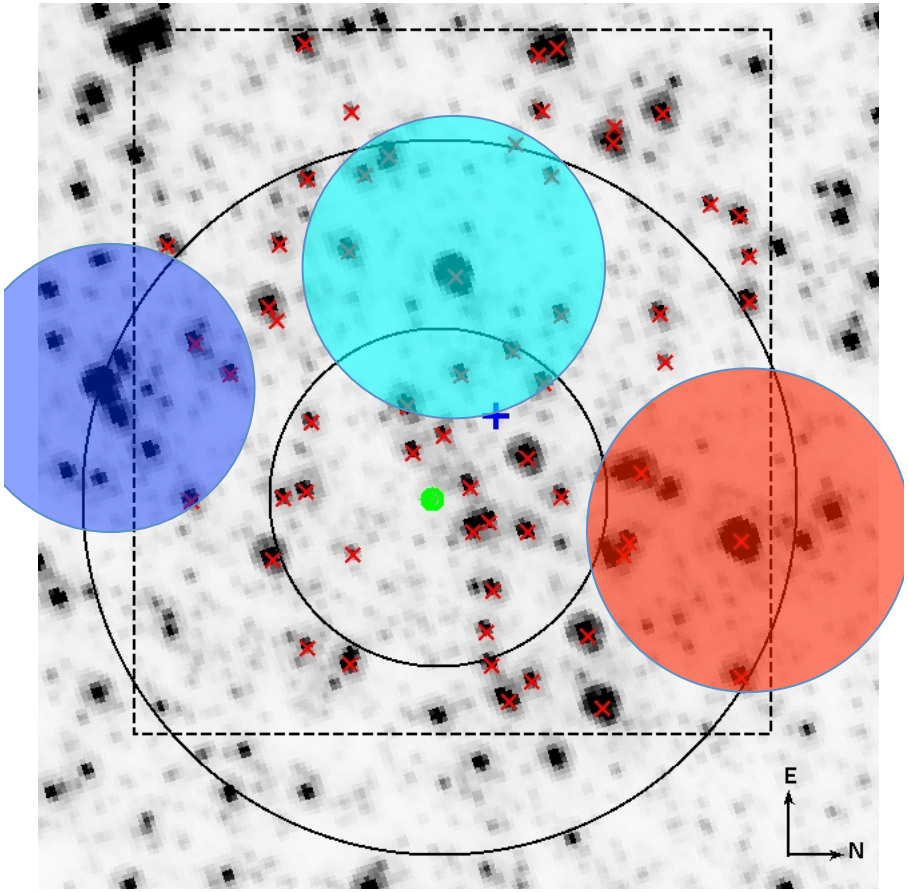


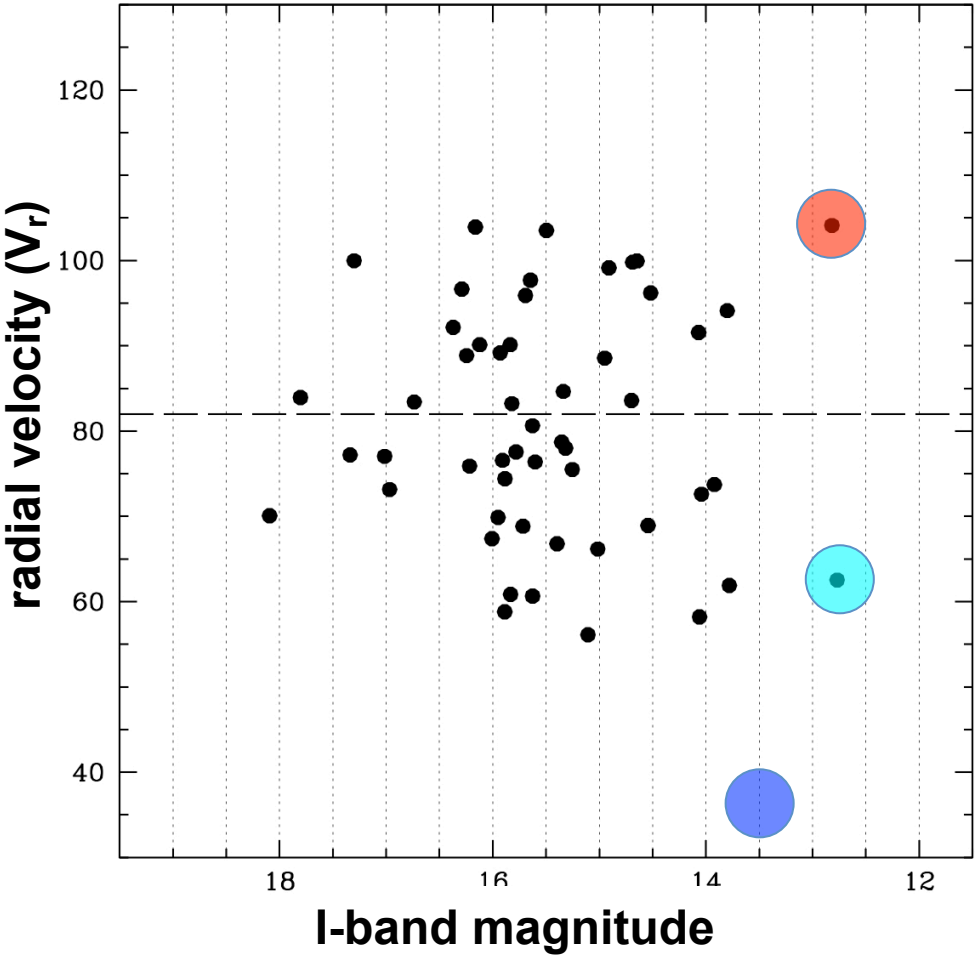
Insufficient masking in integrated-light spectra (ARGUS: seeing-limited IFU)



Lützgendorf et al. 2011

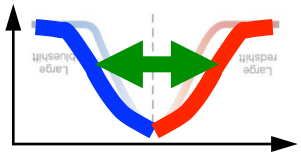
Insufficient masking in integrated-light spectra (ARGUS: seeing-limited IFU)



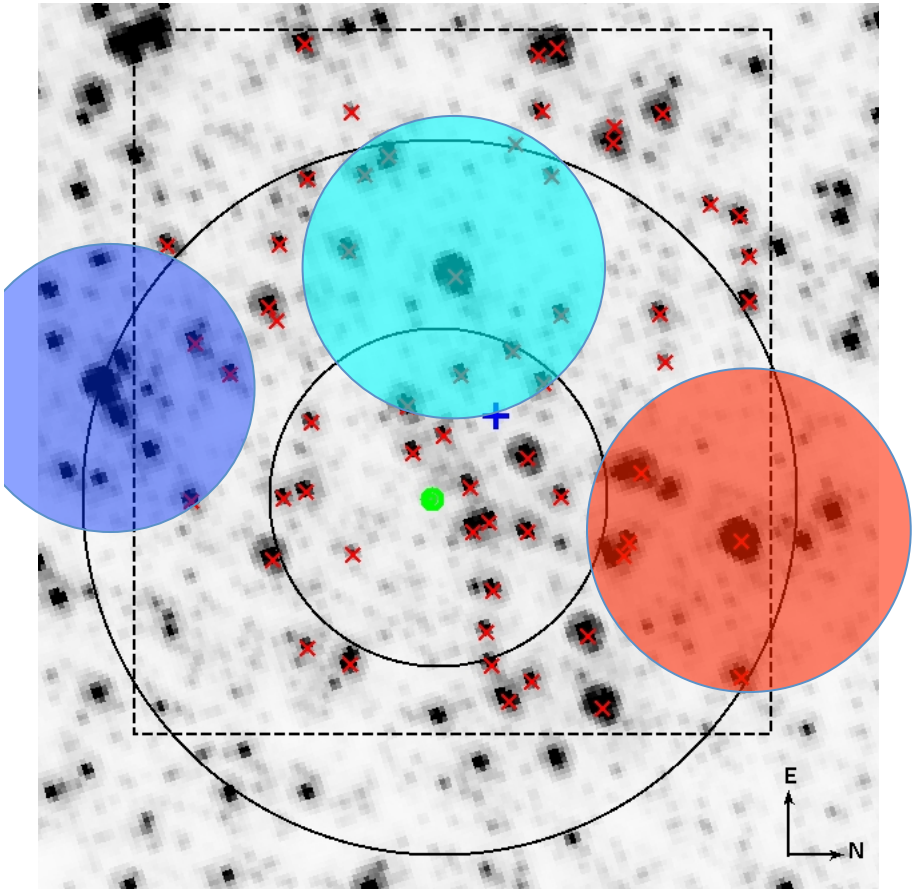


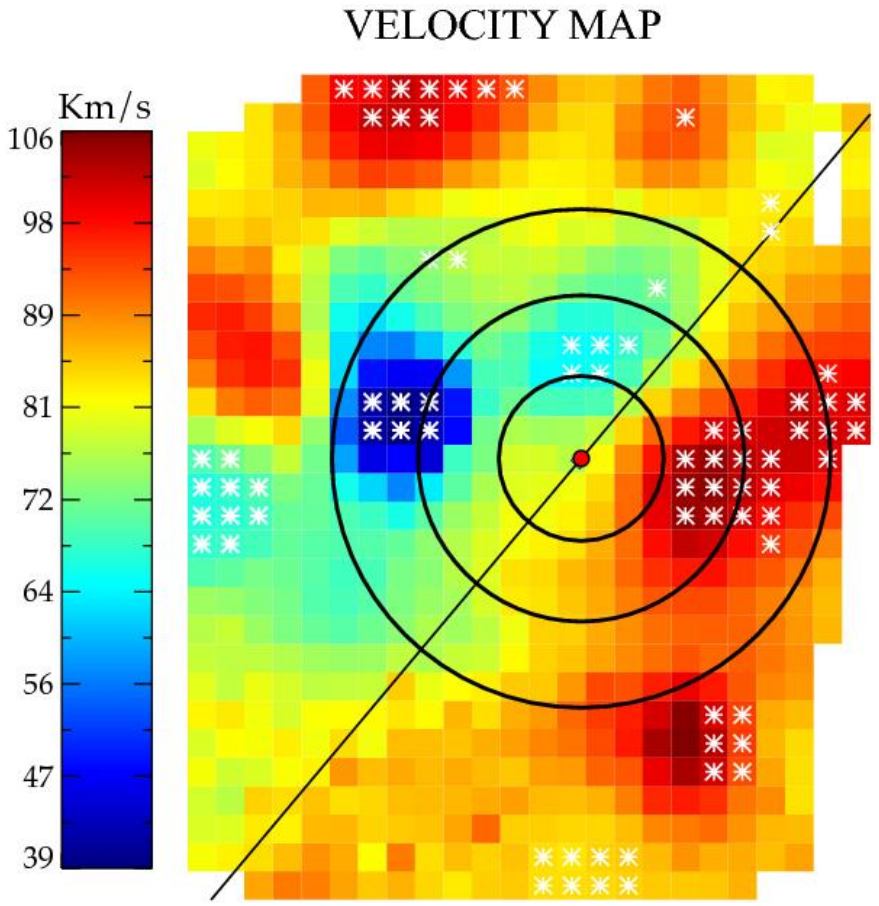
Spectra dominated by the light of a few bright stars with quite different V_r

⇒ **artificial line broadening**



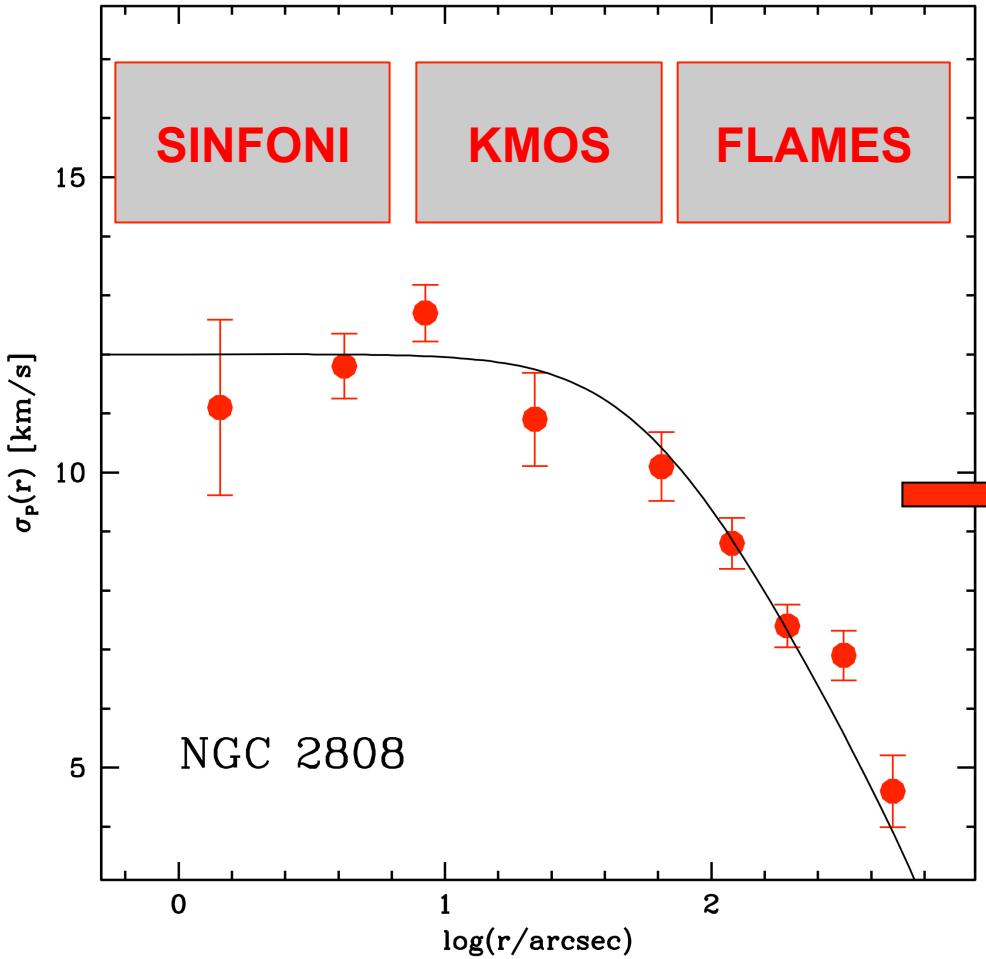
⇒ **overestimate of σ(r) & IMBH mass**





Preliminary results for NGC 2808

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



NO IMBH

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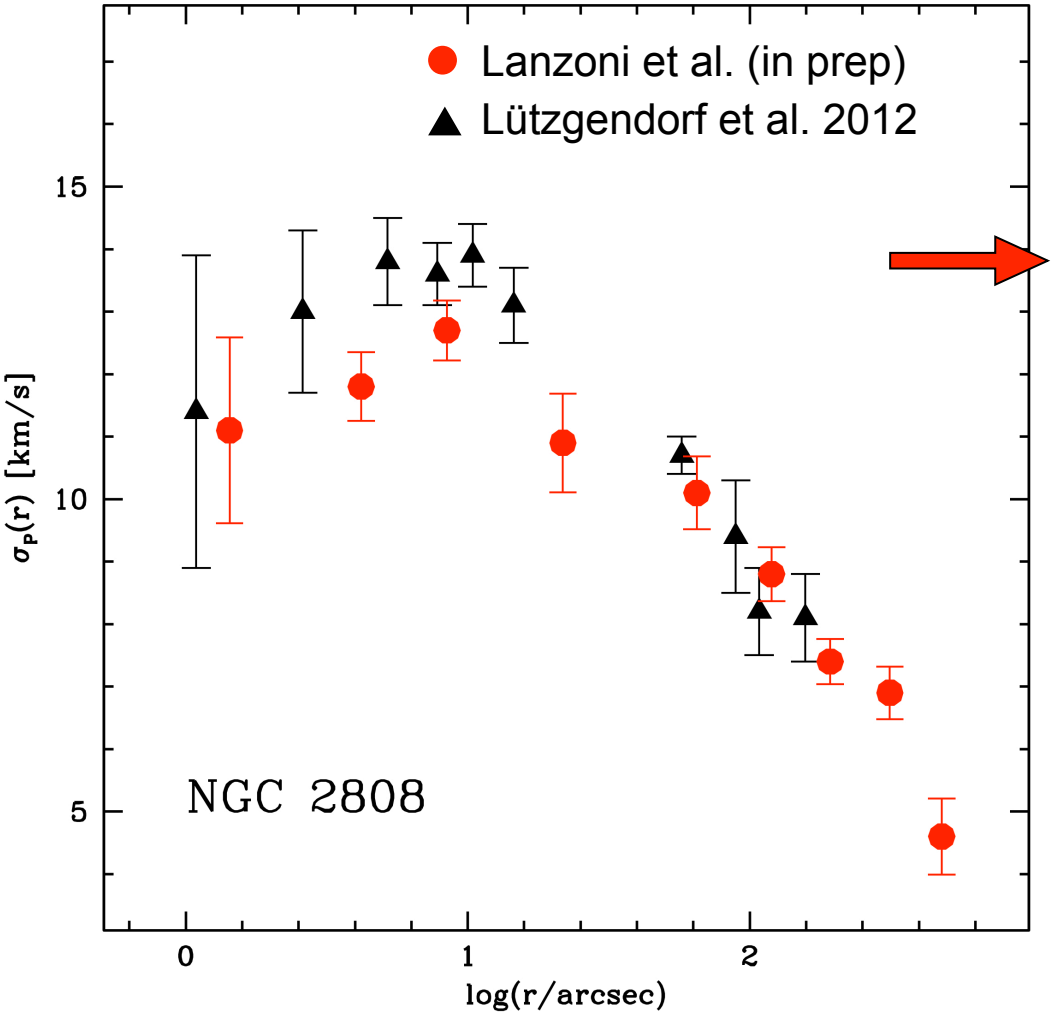
Preliminary results for NGC 2808



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

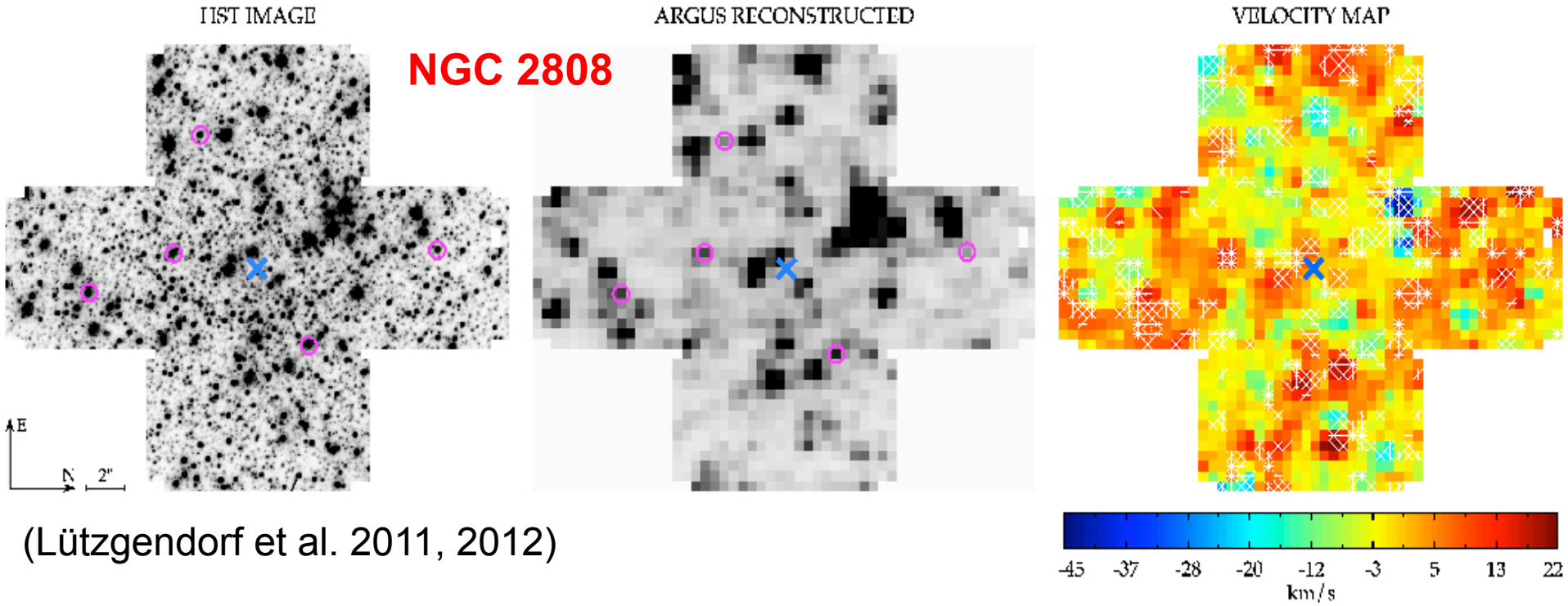
WHY ?

- NGC 2808 much looser than NGC 6388

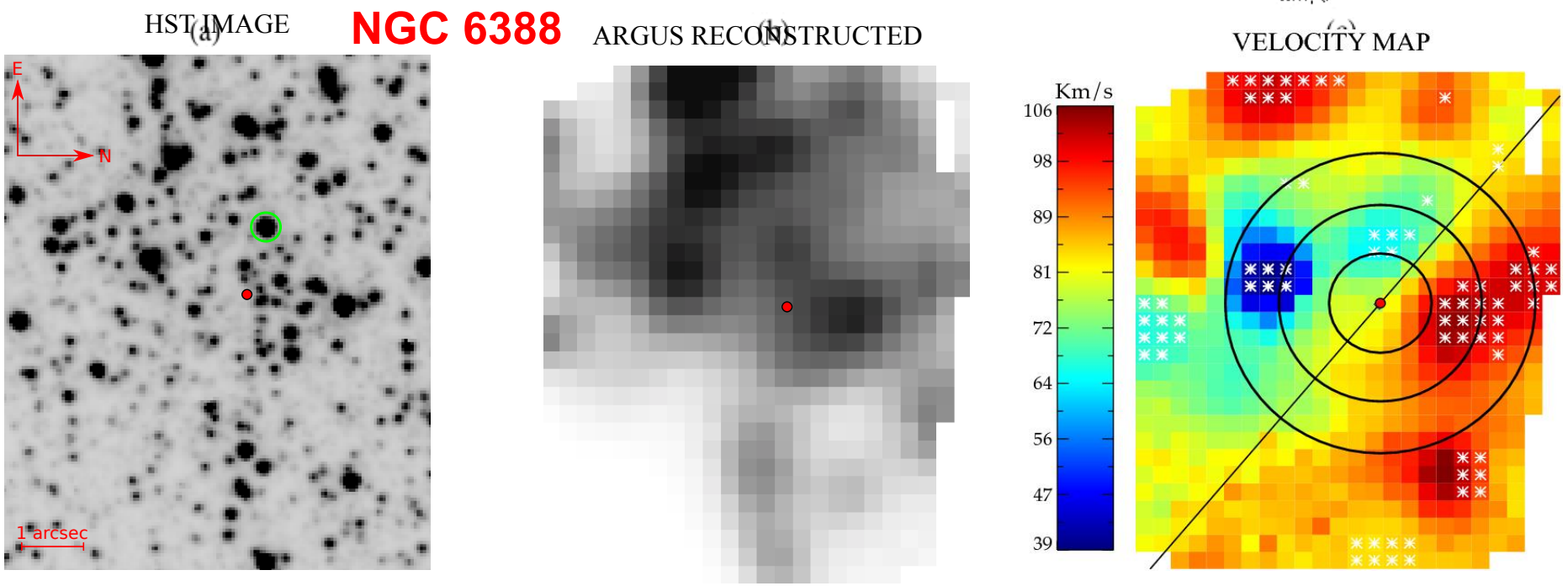
	core radius	ρ_0 [$L_\odot/pc^3$]
NGC 2808	15”	0.5×10^5
NGC 6388	7”	2.3×10^5

- more appropriate masking of bright stars?

- better seeing conditions for NGC 2808
  (FWHM=0.8”, FWHM=0.9” for NGC 6388, … & very different PSF wings?)



(Lützgendorf et al. 2011, 2012)



Integrated-light spectroscopy in Galactic GCs (resolved SP)

Masking procedures (properly taking into account the PSF wings) are mandatory

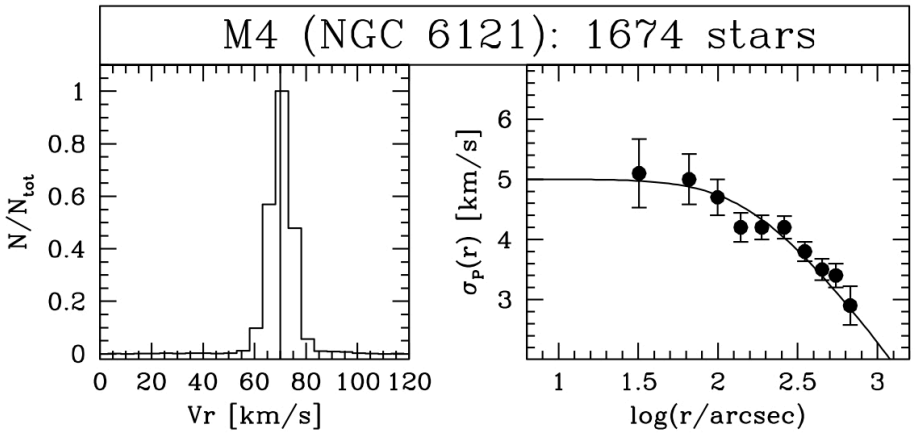
Additional effects:

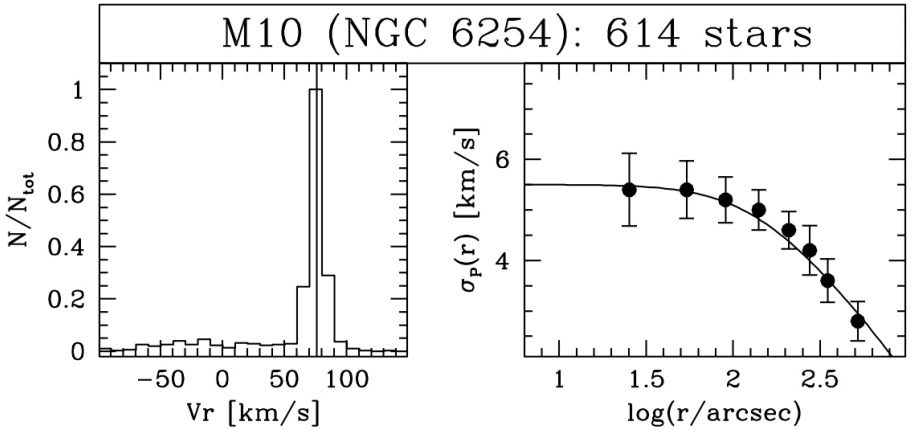
- cluster density (core radius)
- cluster central luminosity density
- (stochastic) presence of bright stars (and their velocity)

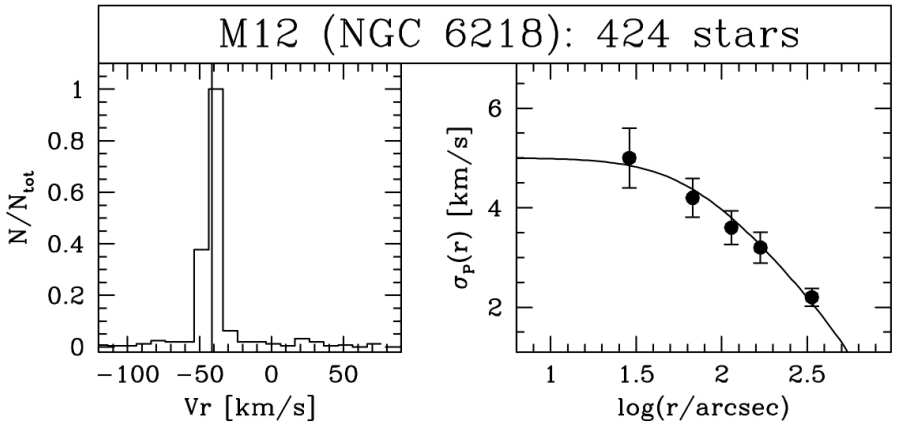
	core radius	ρ_0 [$L_\odot/pc^3$]
NGC 2808	15”	0.5×10^5
NGC 6388	7”	2.3×10^5
Bianchini simulated GC	27”	

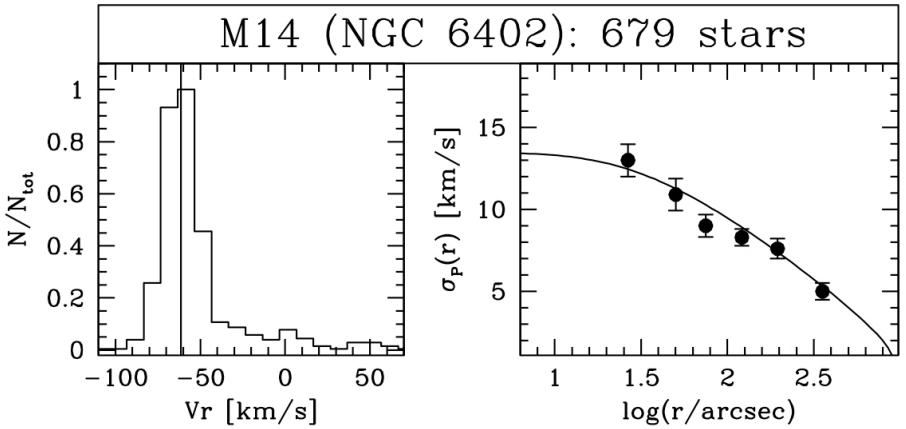
not comparable to NGC 6388 or NGC 2808
(how much masking needed for denser GCs?)

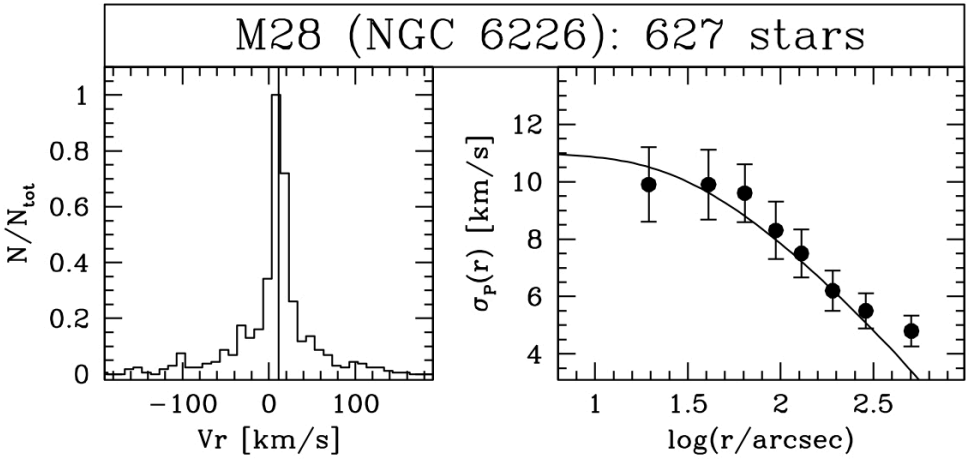
Preliminary results from KMOS+FLAMES LP

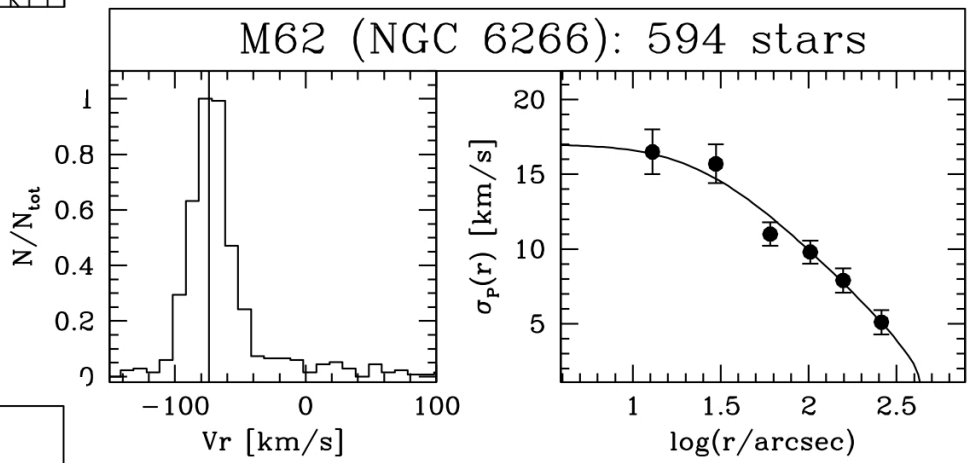


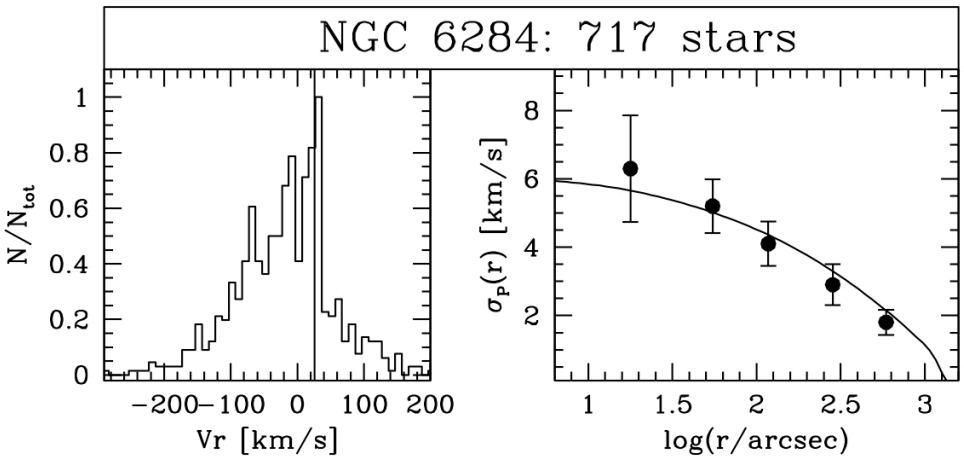




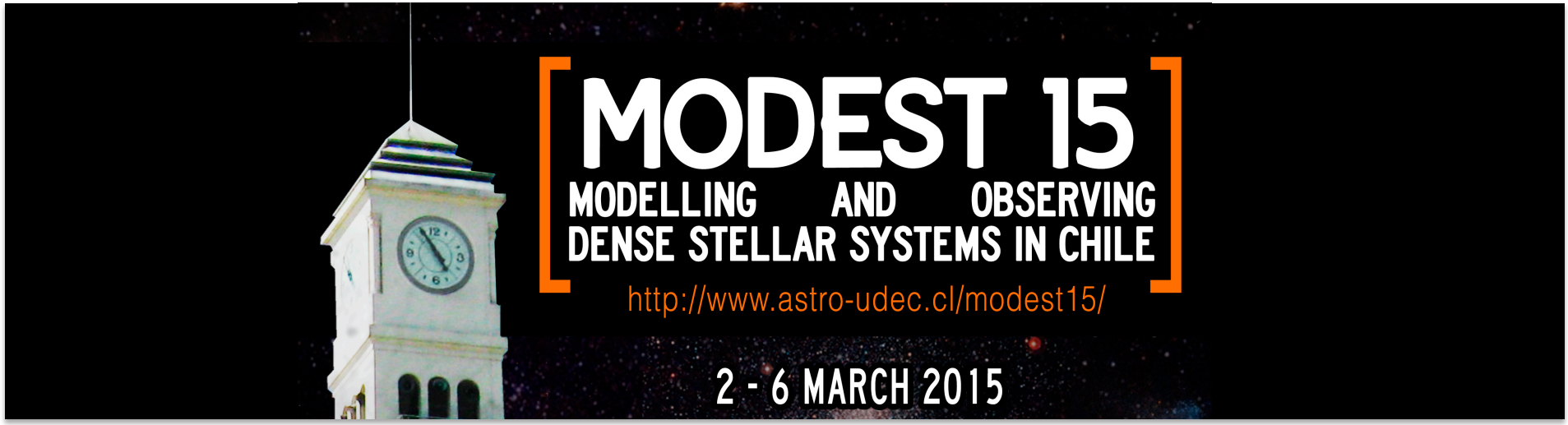



M28 (NGC 6226): 627 stars
N/N_tot
Vr [km/s]
σ_P(r) [km/s]
log(r/arcsec)


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….



Thank you for your attention

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