IMBHs in globular clusters through individual star radial velocities

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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 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 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?

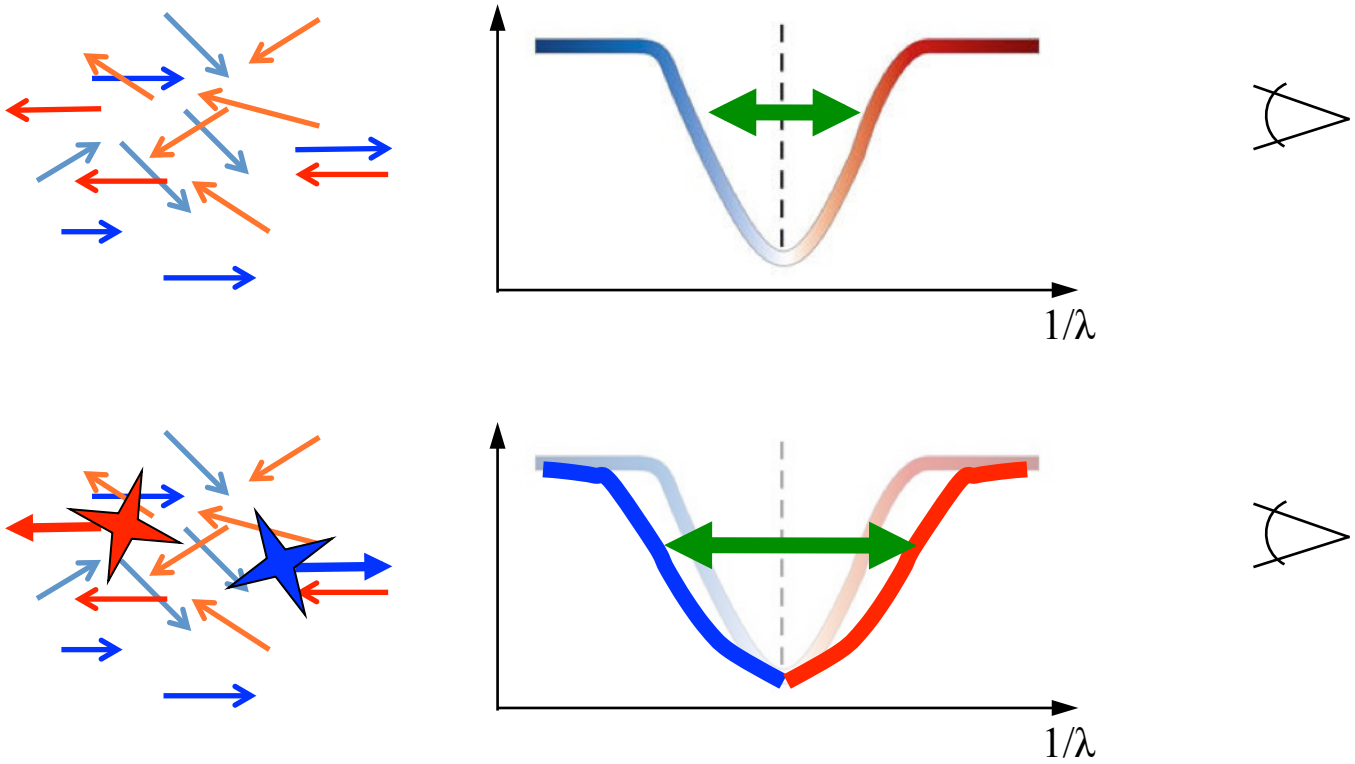
Two main differences *wrt* distant (unresolved) galaxies/stellar systems

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

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

… but only **a few** bright giants in the spectrograph slit/FOV

line broadening in integrated-light spectra



SHOT NOISE BIAS:
if 2-3 bright stars dominate the sampled light,
the spectrum does not sample the underlying stellar distribution,
but just the radial velocities of those 2-3 giants
=> this is NOT a measure of the stellar velocity dispersion

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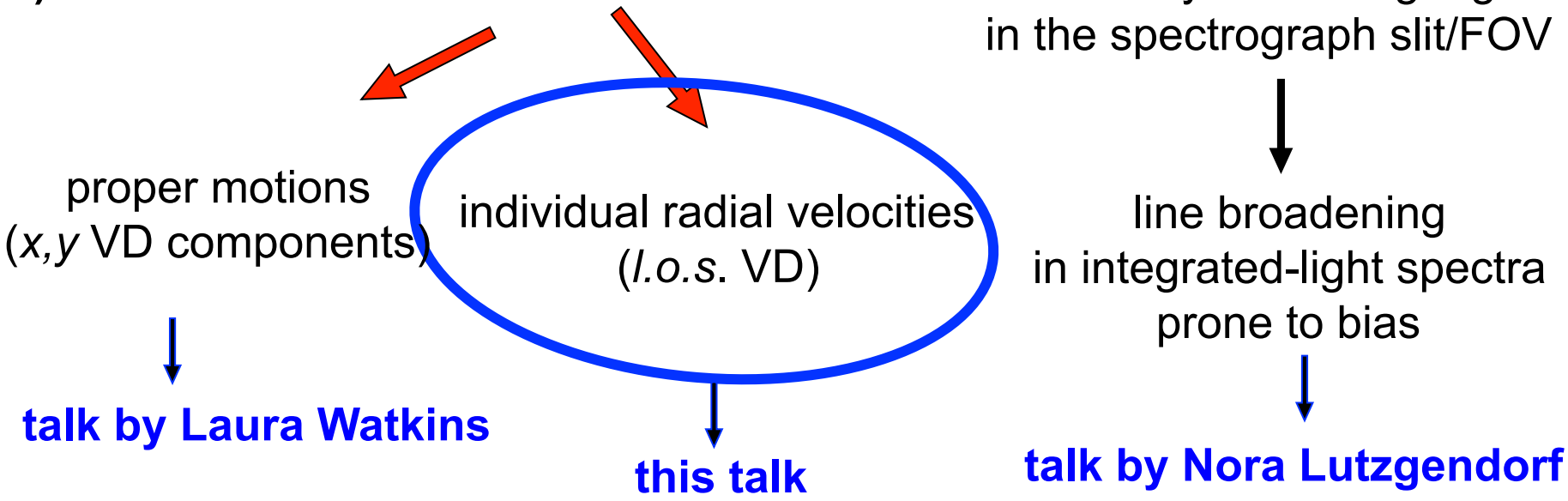


IMBH => steep VD cusp within 1”-2” from centre!

A NEW GENERATION OF GC VELOCITY DISPERSION PROFILES FROM THE RADIAL VELOCITY OF INDIVIDUAL STARS, WITH A MULTI-INSTRUMENT APPROACH @ ESO-VLT:

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

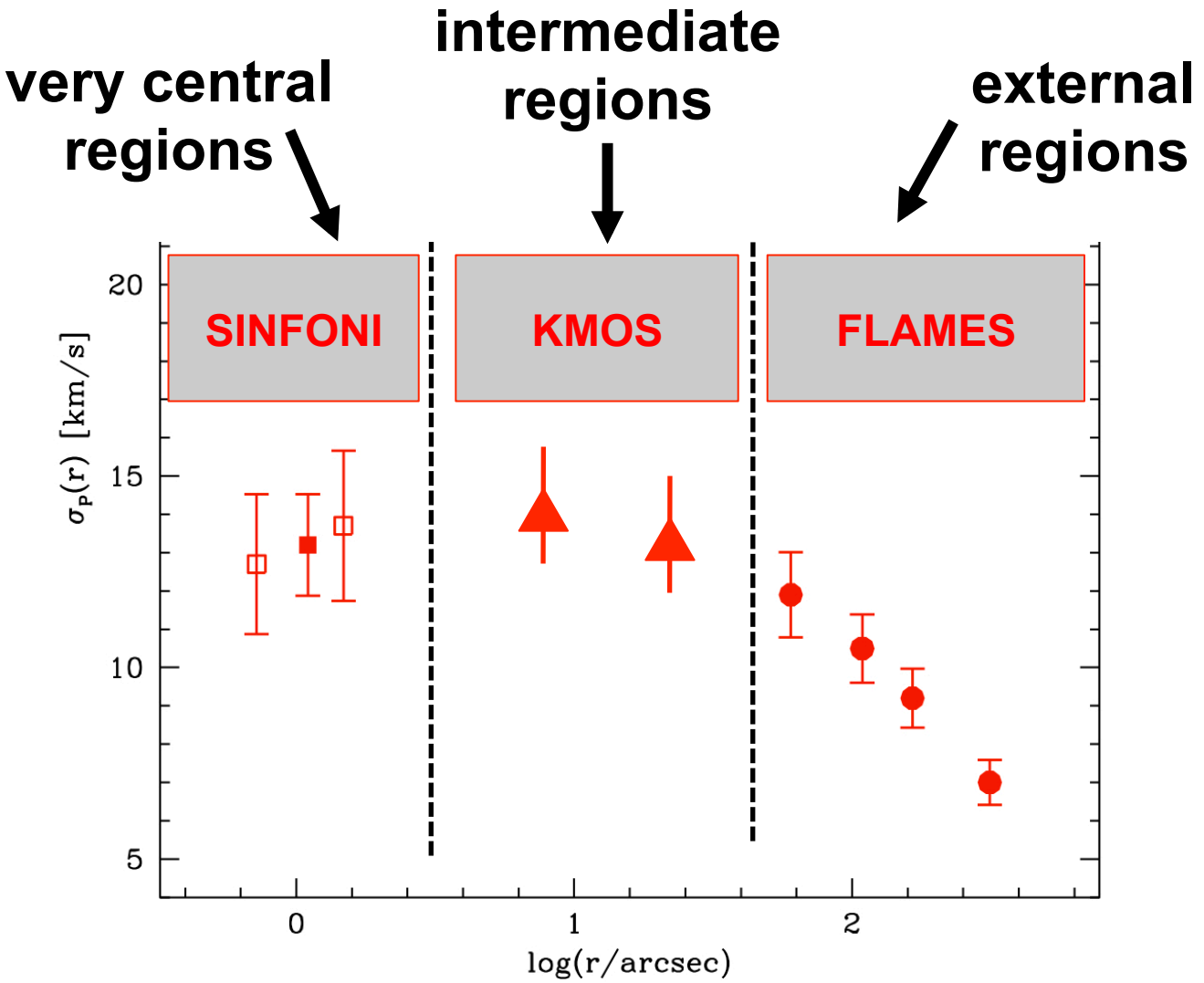
KMOS

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,..)

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 GC VELOCITY DISPERSION PROFILES FROM THE RADIAL VELOCITY OF INDIVIDUAL STARS



A NEW GENERATION OF GC VELOCITY DISPERSION 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

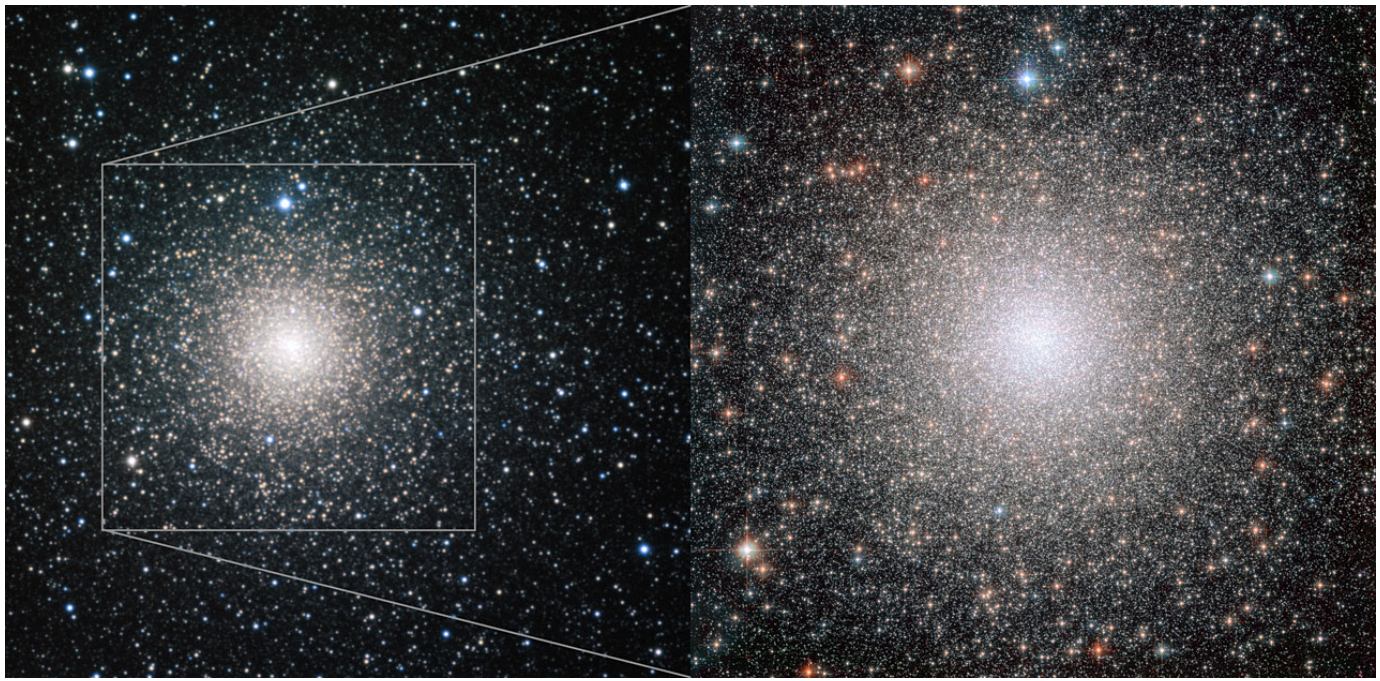
- **ESO Large Programme 195.D-0750 (PI: Ferraro):**
  - 145 hours
  - SINFONI
  - 19 high-density Milky Way GCs
  - starting next April

- **a few additional/pilot programmes (also @Keck)**

NGC 6388

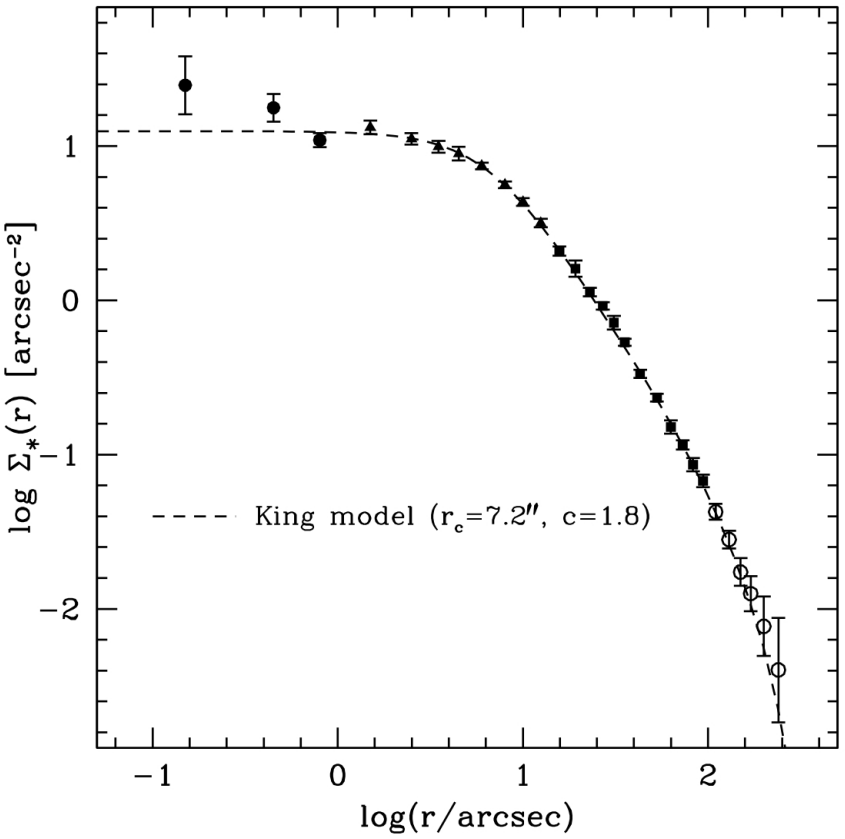
- **one of the most massive GGCs:** M ~ 2.6 10^6 $M_\odot$
- **metal-rich:** [Fe/H]=-0.44 (Carretta et al. 2007)

ESO/WFI **HST/ACS (HRC+WF)**

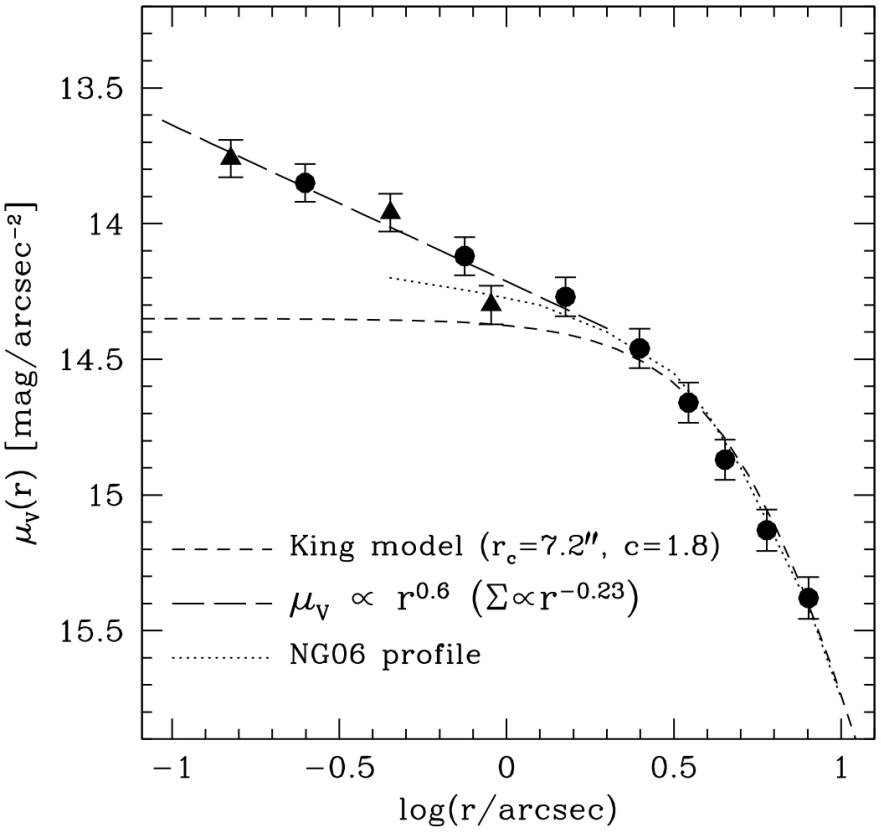


Projected density profile

(star counts in annuli)

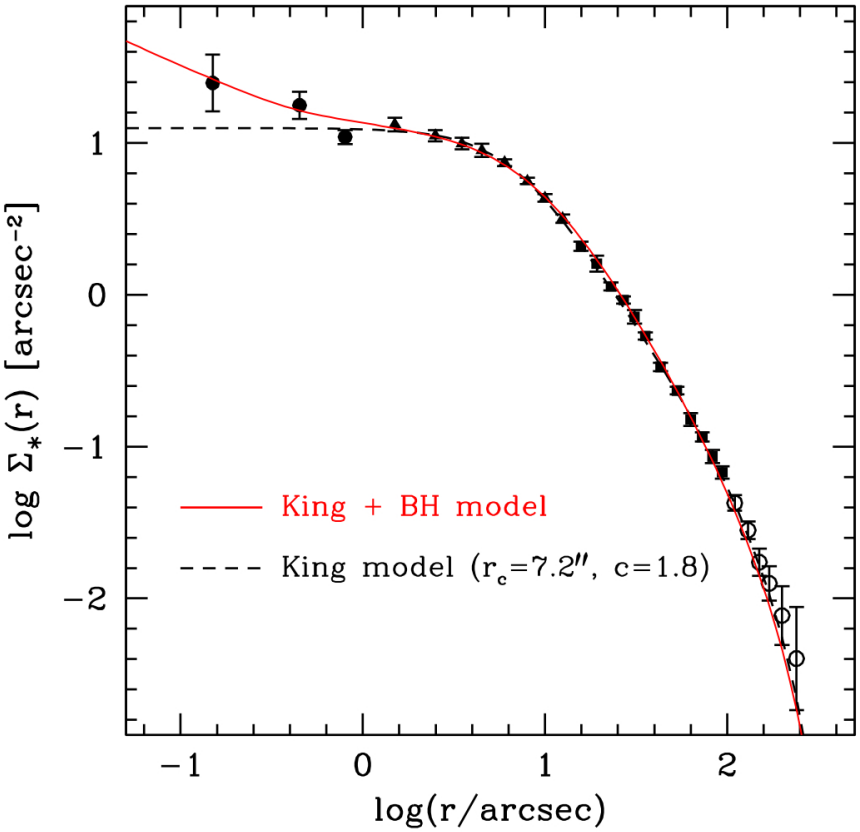


Surface brightness profile

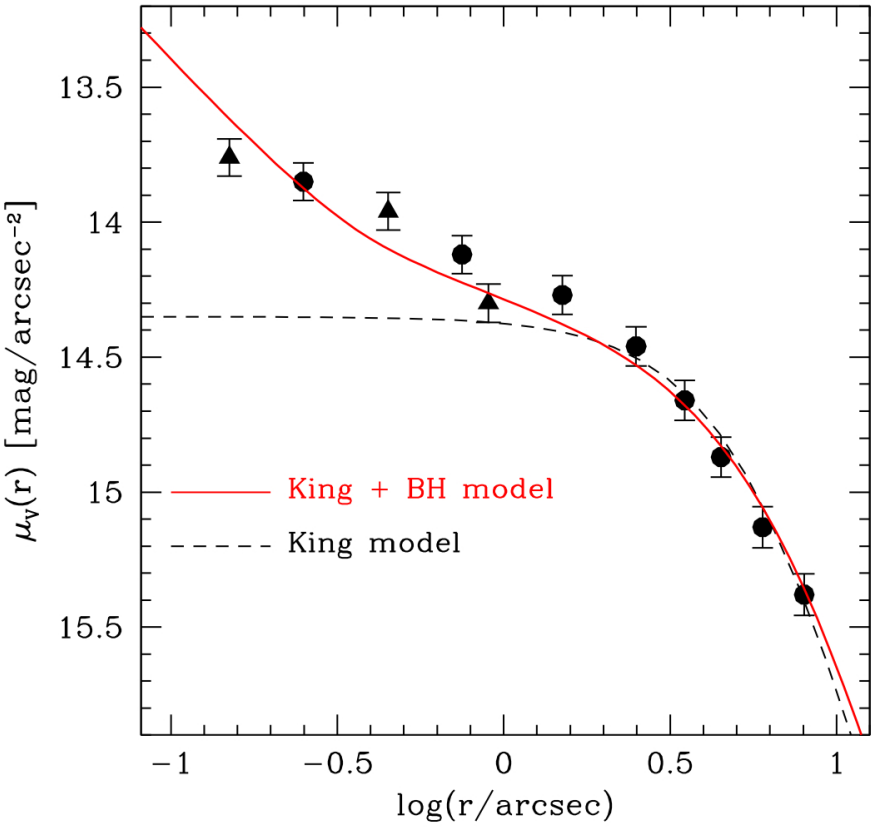


fingerprint 1: density cusp at r < 1”

projected density profile



surface brightness profile



self-consistent, multi-mass, spherical, isotropic, King models with central BH

(from Miocchi 2007) ➔ **$M_{BH} \sim 6\ 10^3\ M_\odot$**

(Lanzoni et al. 2007)

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”**

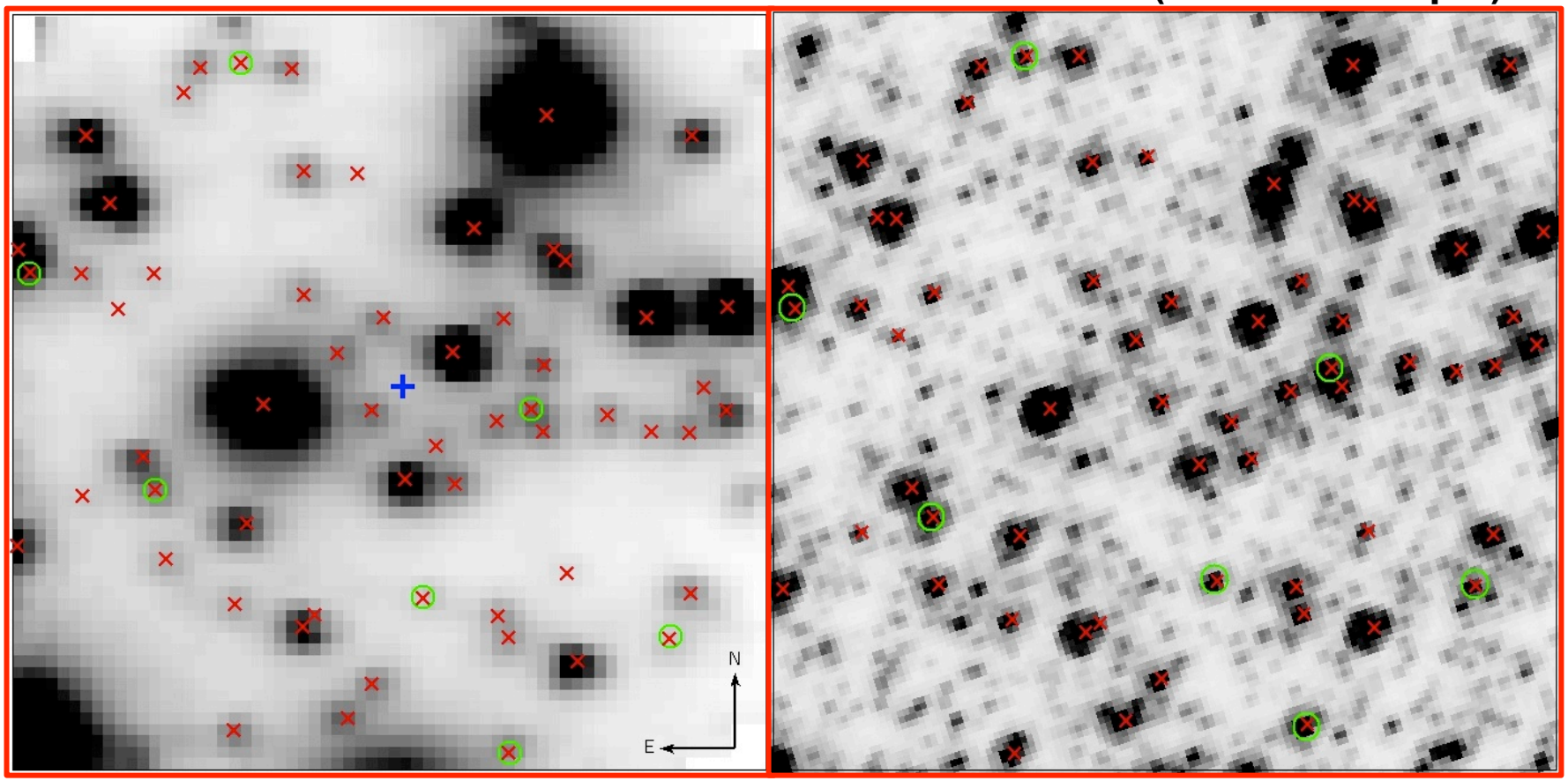
proprietary + archive data

~500 stars in total

SINFONI (AO assisted IFU)→ center

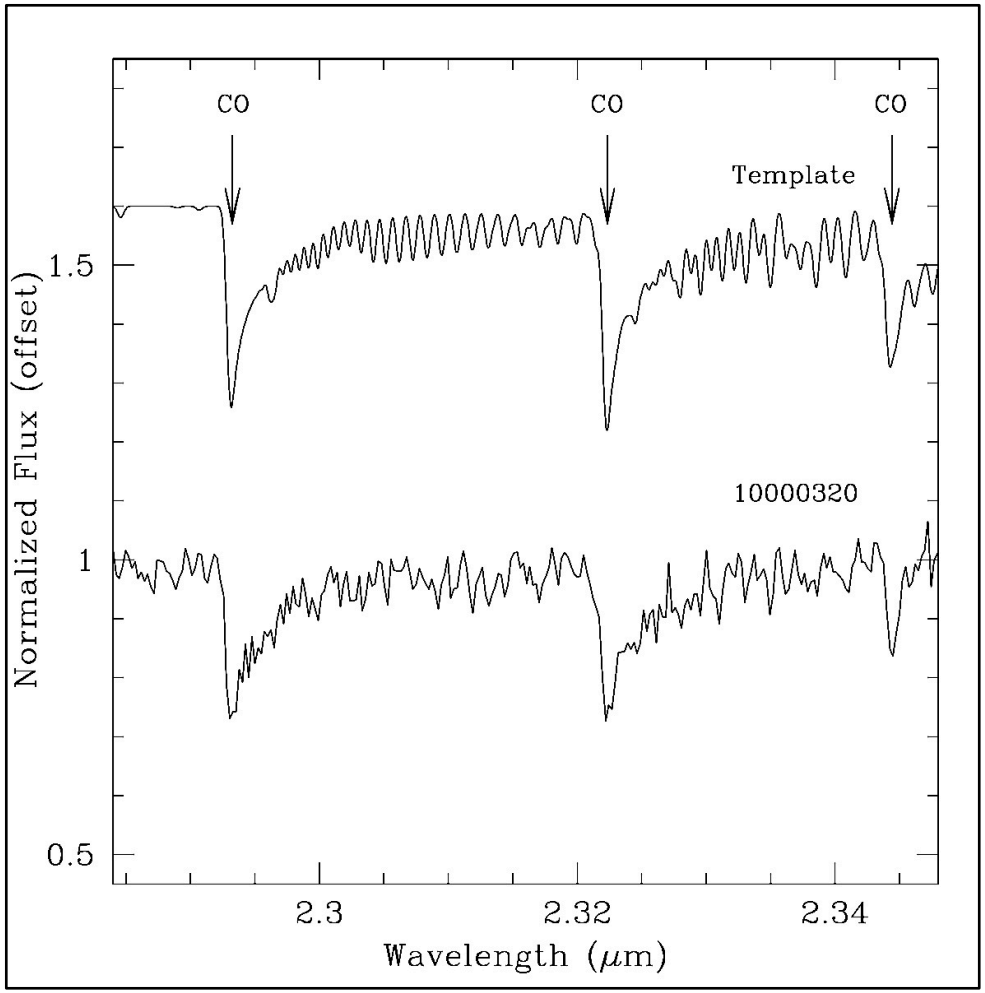
- stellar centroids from cross-correlation between SINFONI and HST/HRC
- spectra extracted from central spaxel only
- excluded low-quality spectra & blended sources

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



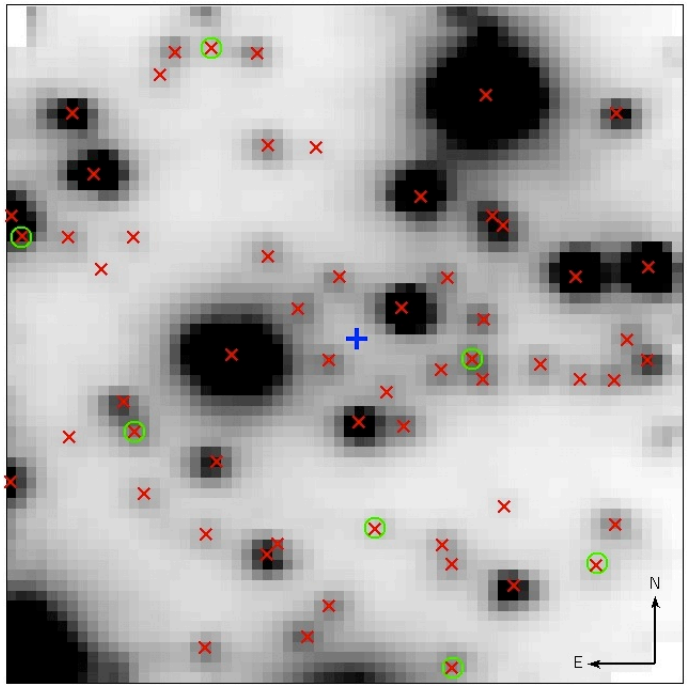
SINFONI (AO assisted IFU)→ center

- V_r from CO band-heads

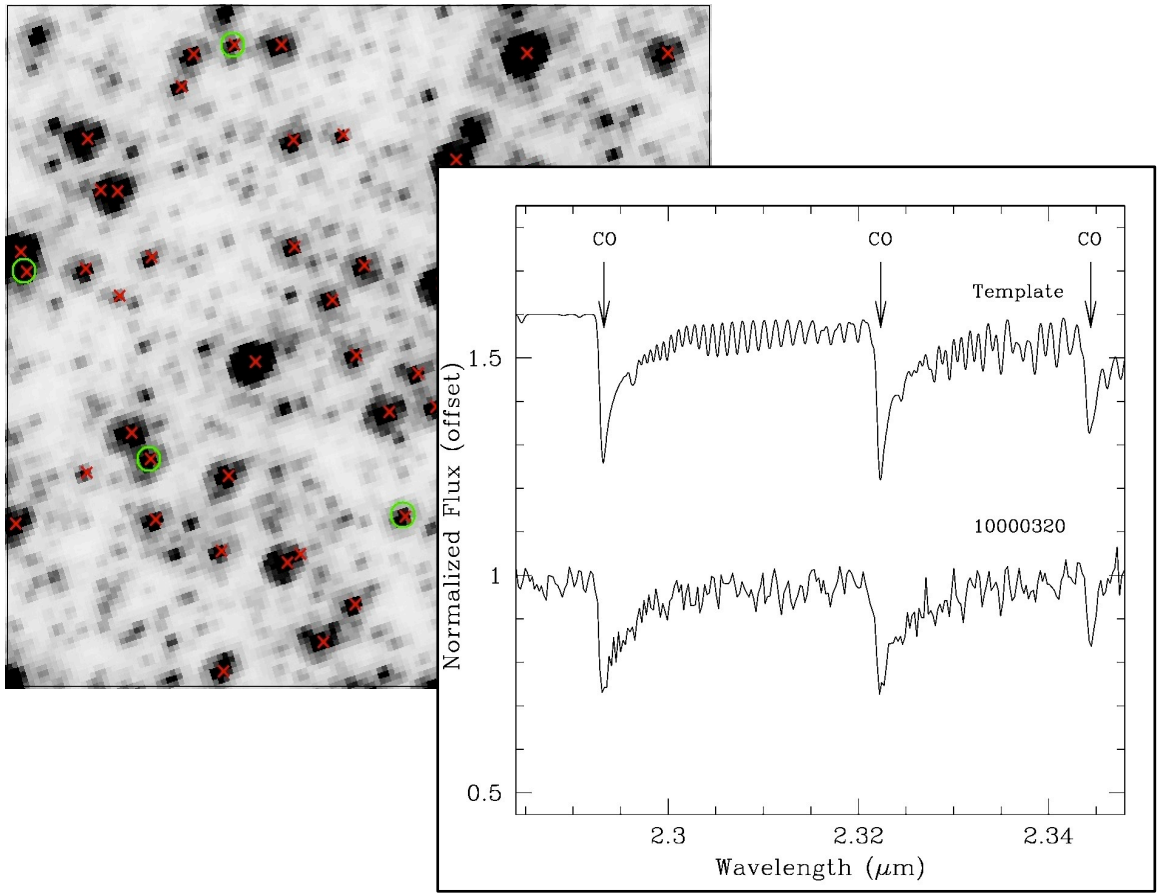


SINFONI (AO assisted IFU)→ center

SINFONI



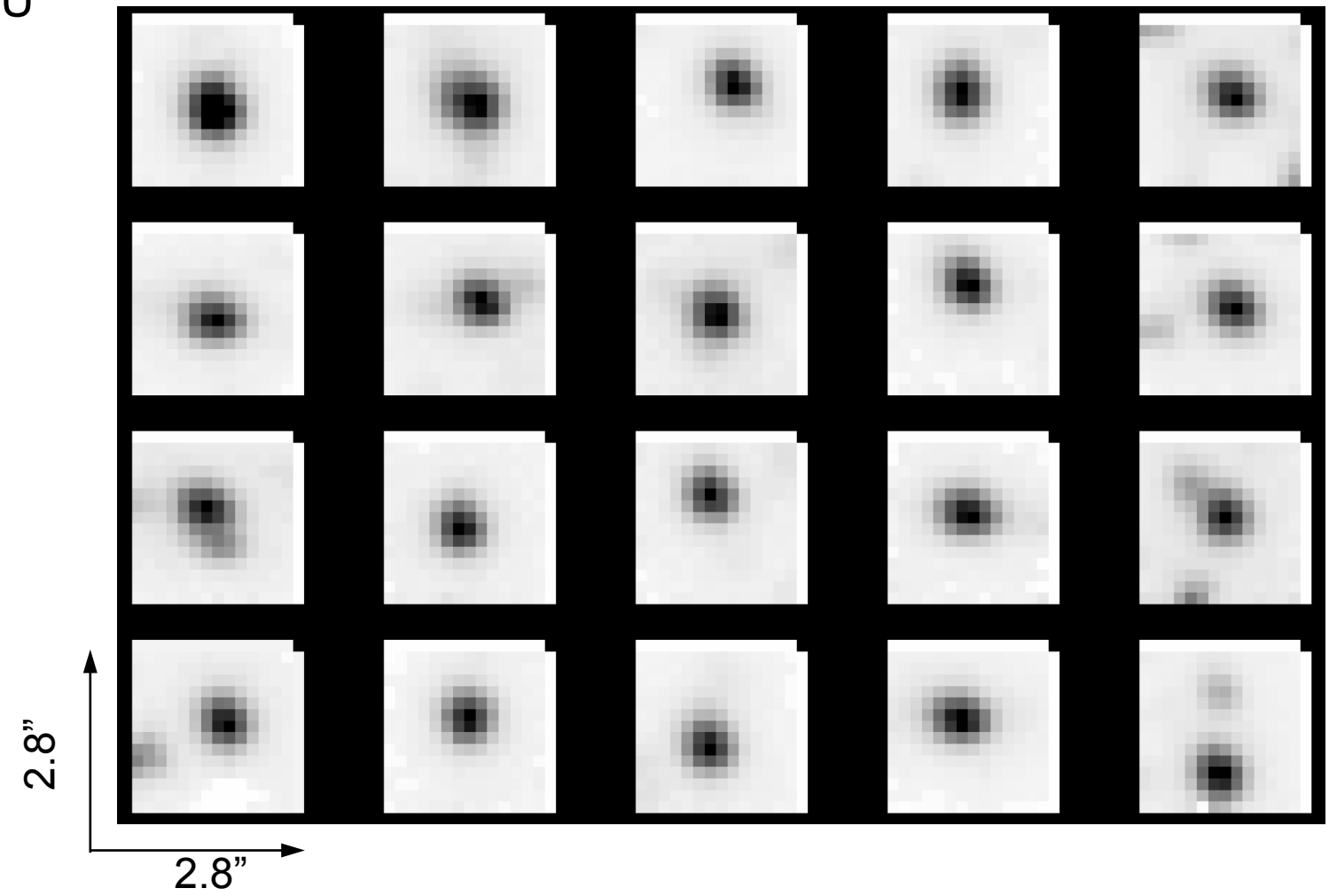
HST/HRC



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

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

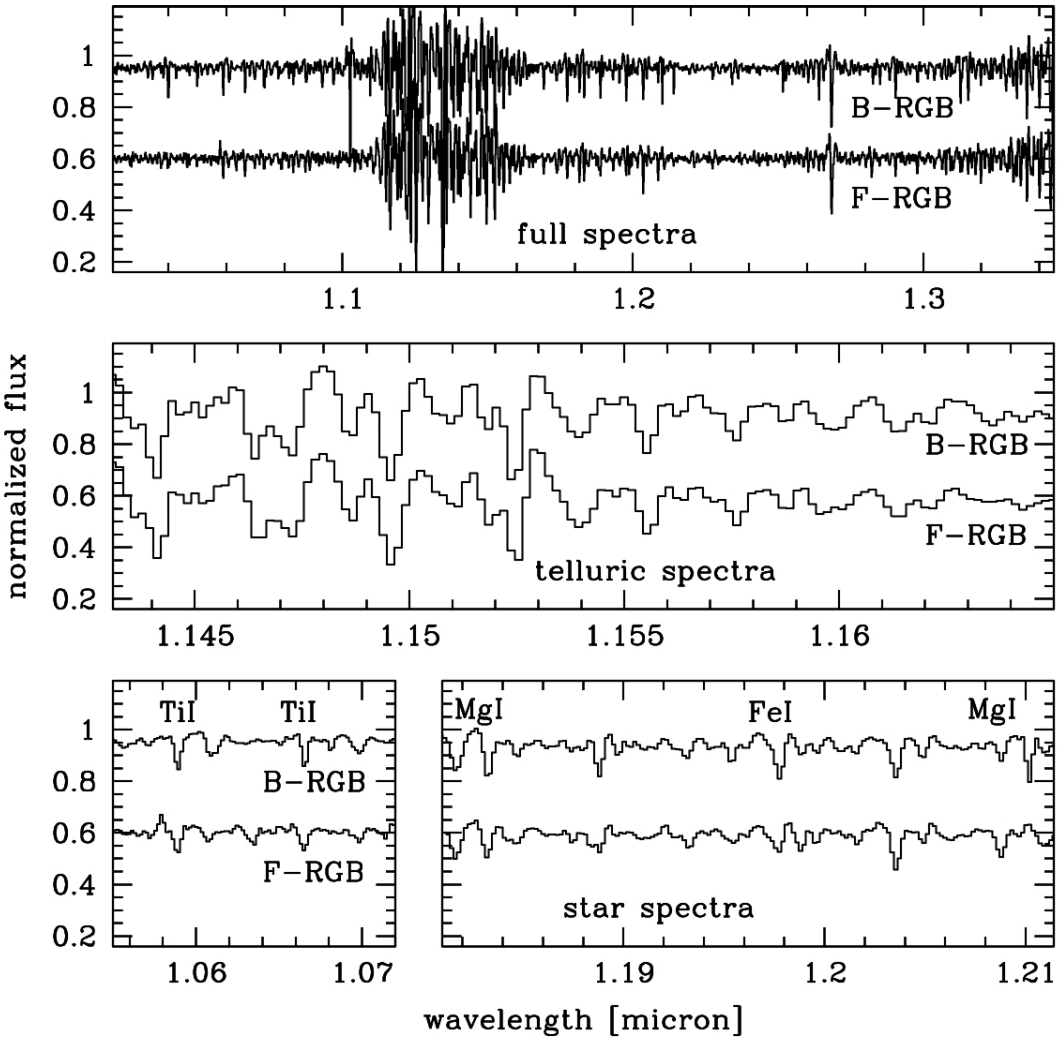
1 star per IFU



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

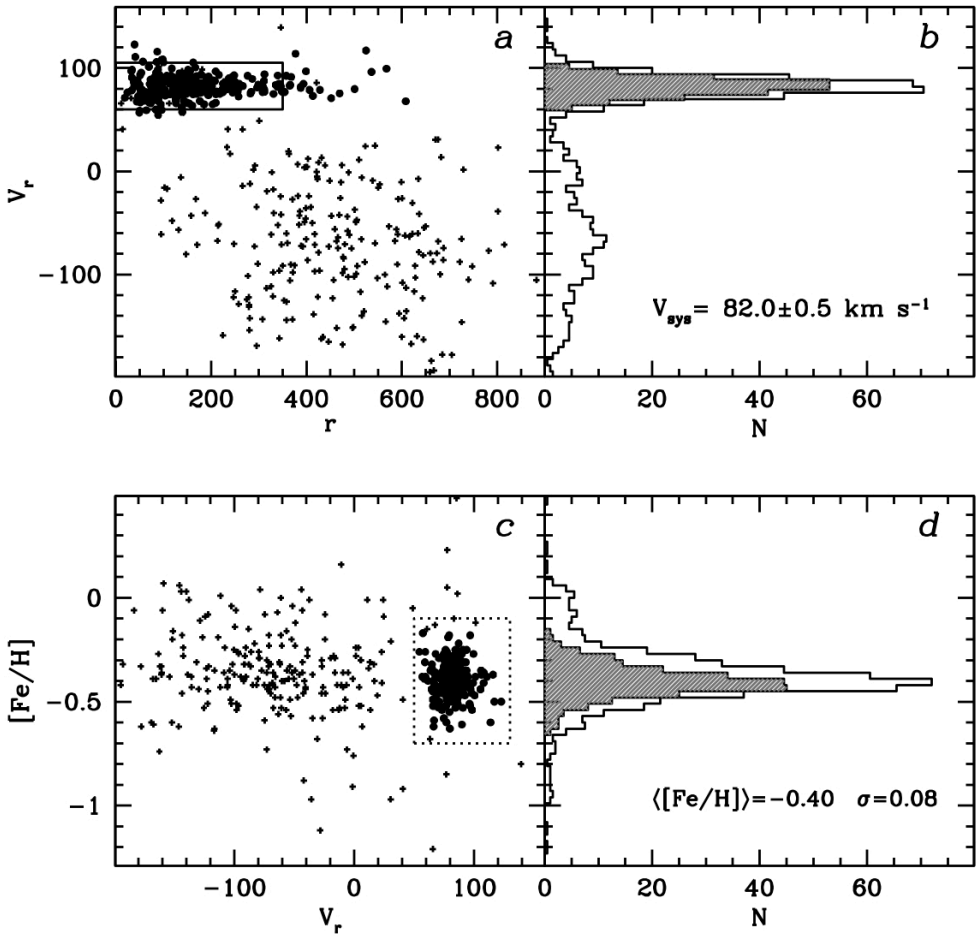
- Vr from several atomic lines
- wavelength calibration refined with telluric lines

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



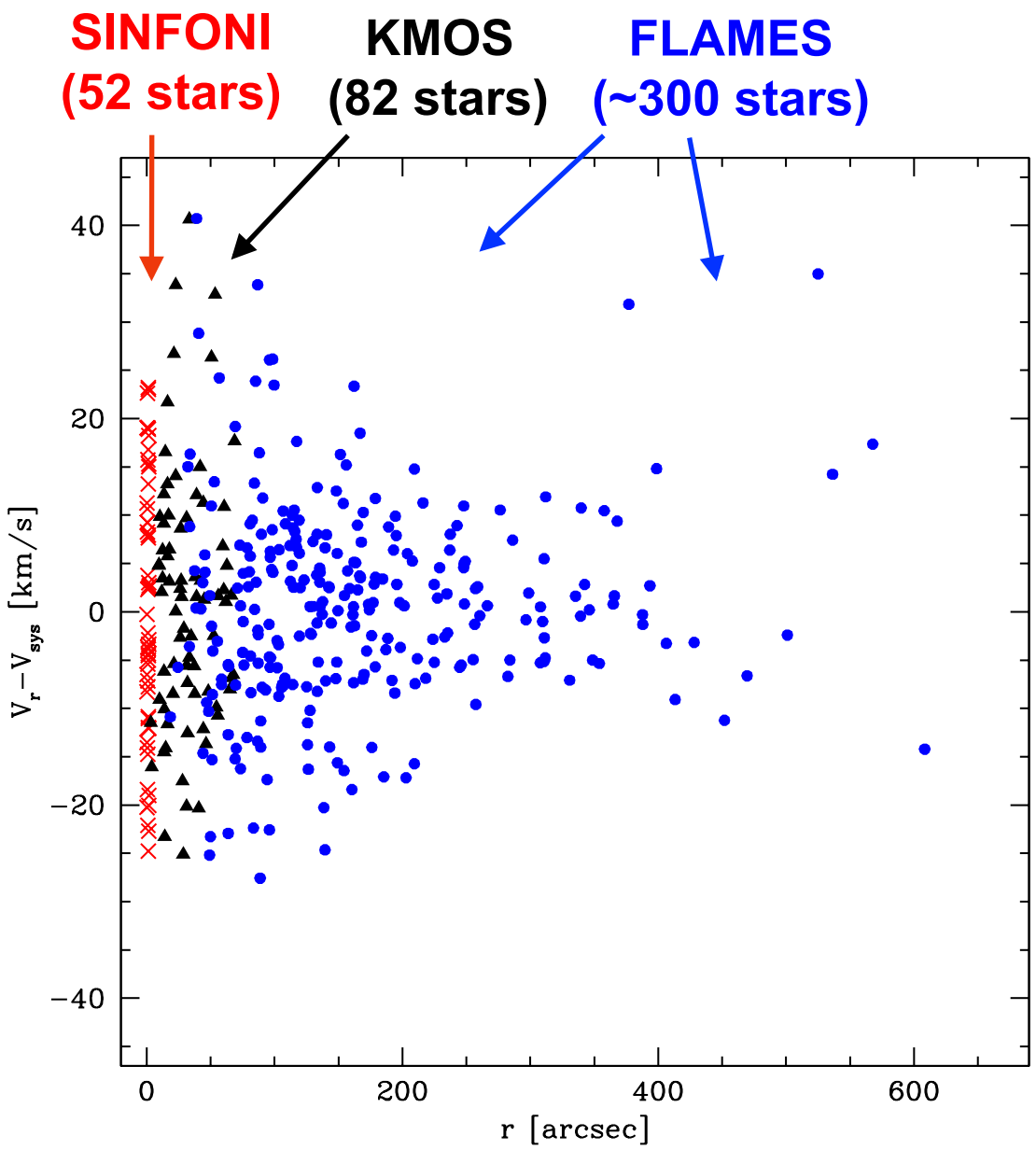
FLAMES (multi-objects: 132 fibers)→ external regions

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



276 cluster members

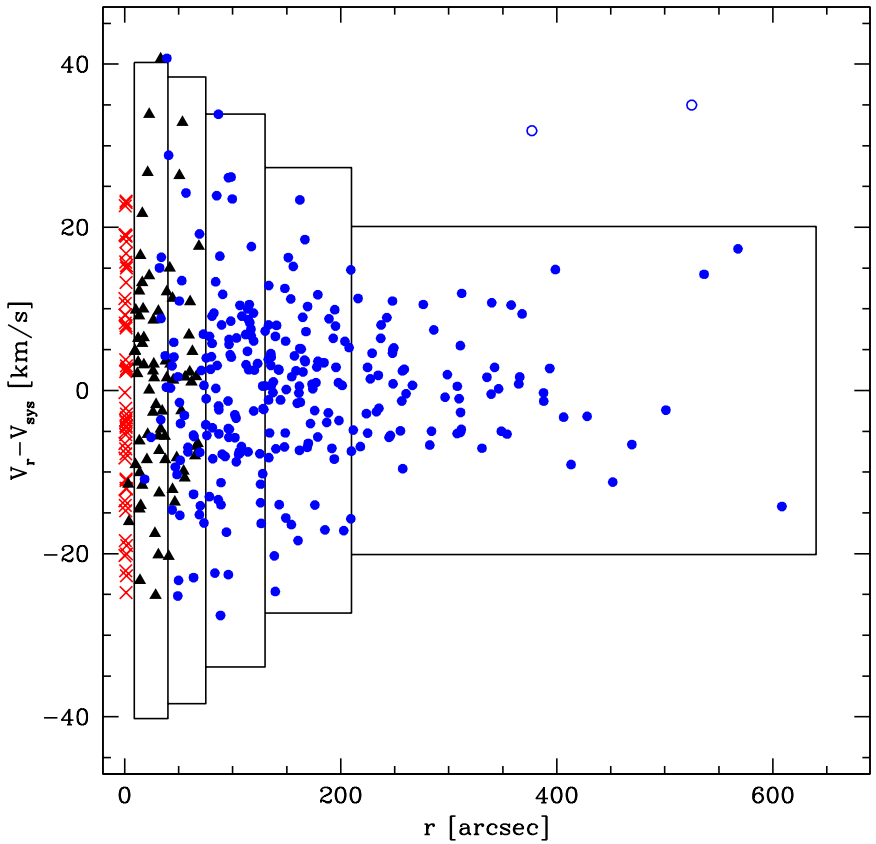
V_r for 276 individual stars at 18”<r<600”

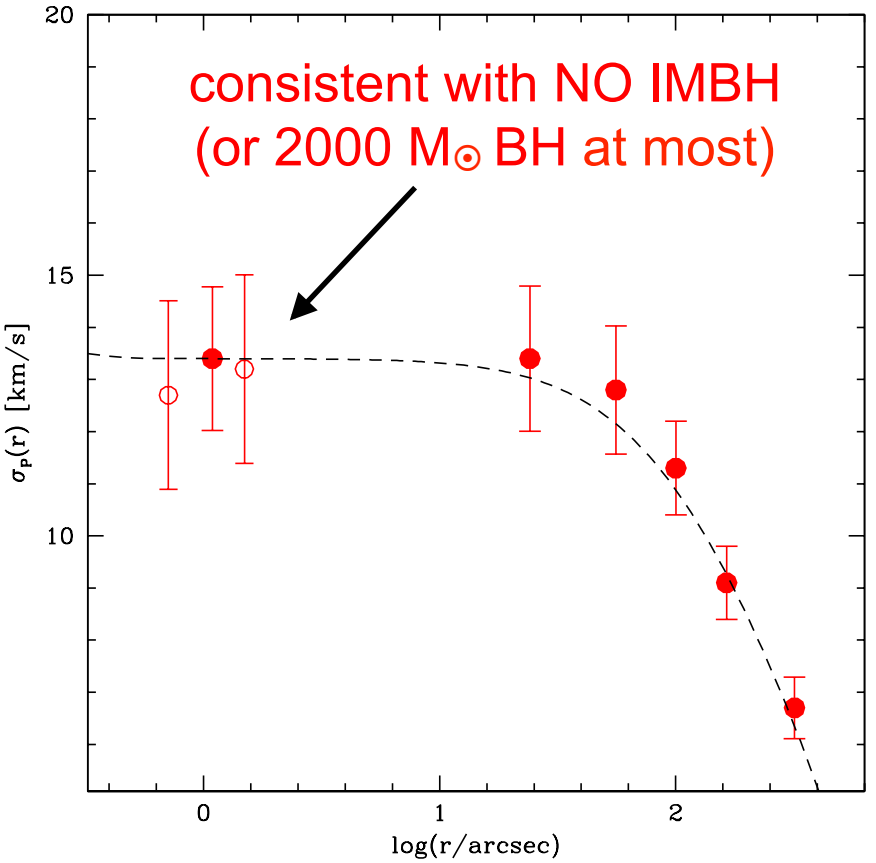

SINFONI
(52 stars)
KMOS
(82 stars)
FLAMES
(~300 stars)
40
20
0
−20
−40
$V_r - V_{sys}$ [km/s]
0
200
400
600
r [arcsec]

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

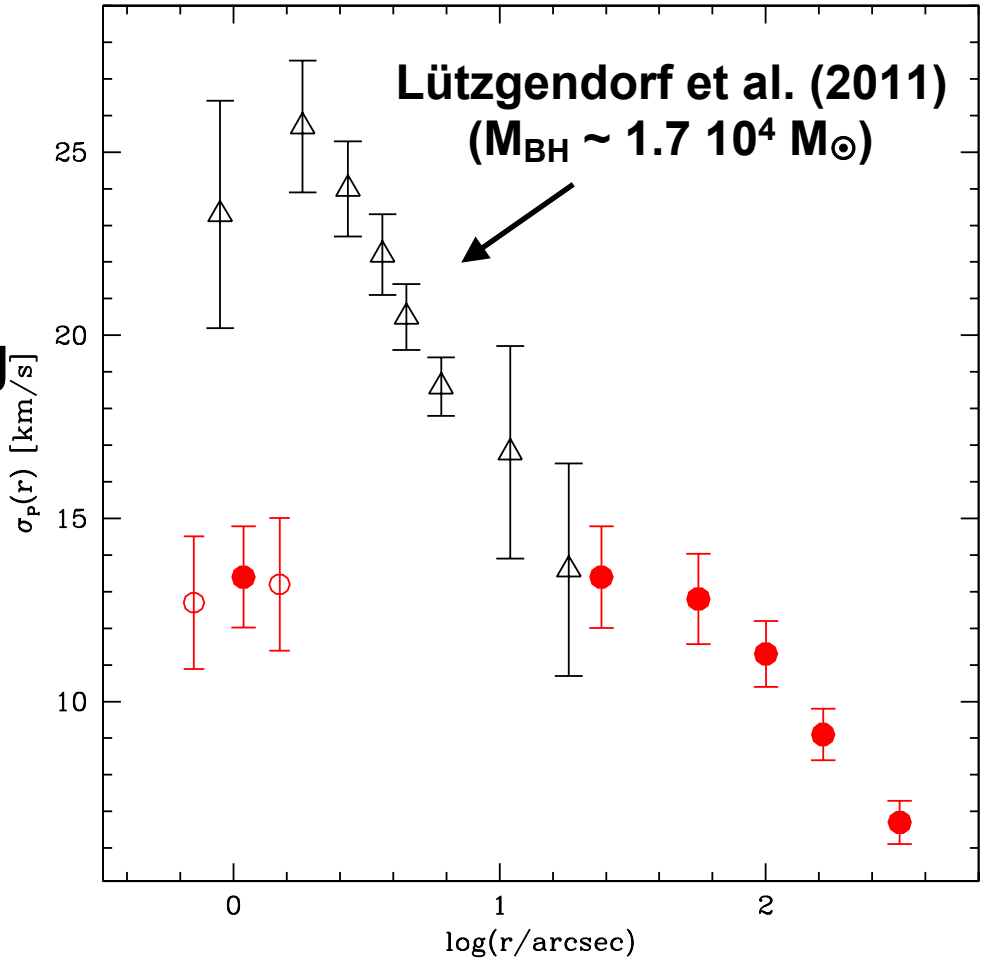
σ(r) from individual V_r
(σ_0 ~ 13-14 km/s)

inconsistent with

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

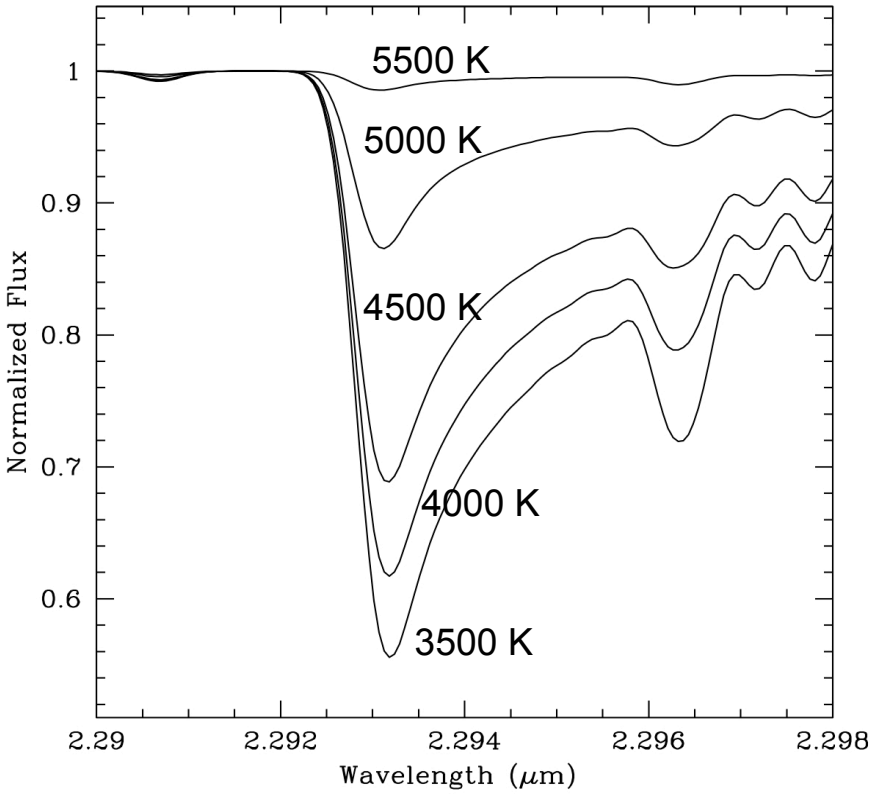
WHY ? → we underestimate

→ they overestimate

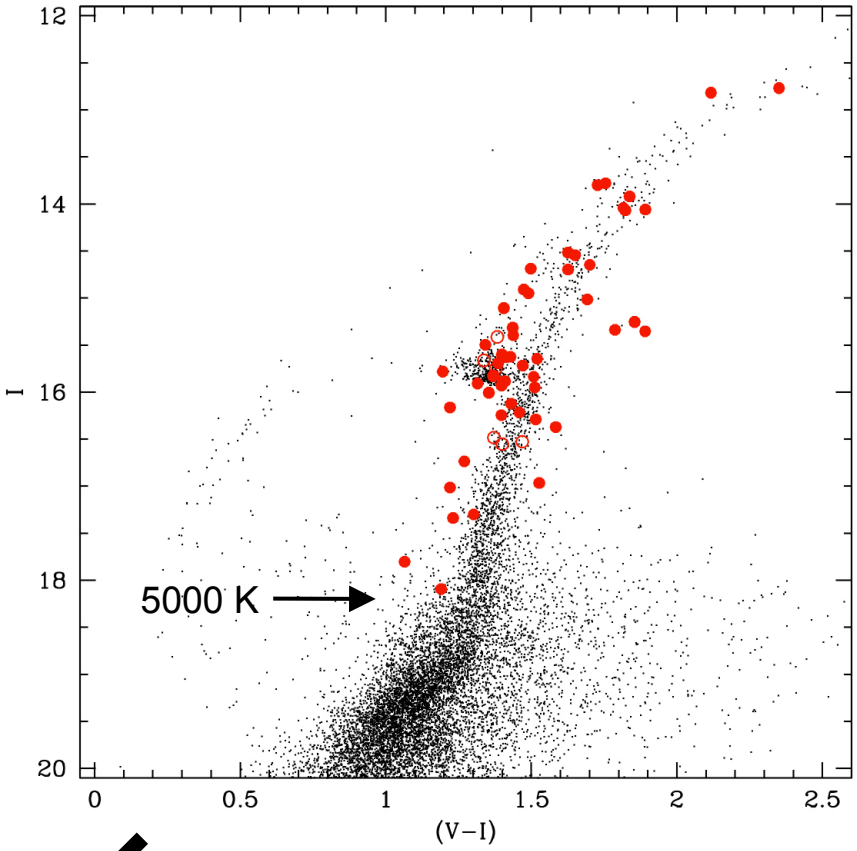


SINFONI spectra contaminated by background (=> we underestimate) ?

CO band-head disappears at T>5500 K



SINFONI CMD



no contribution from unresolved background (hotter than 5000 K)

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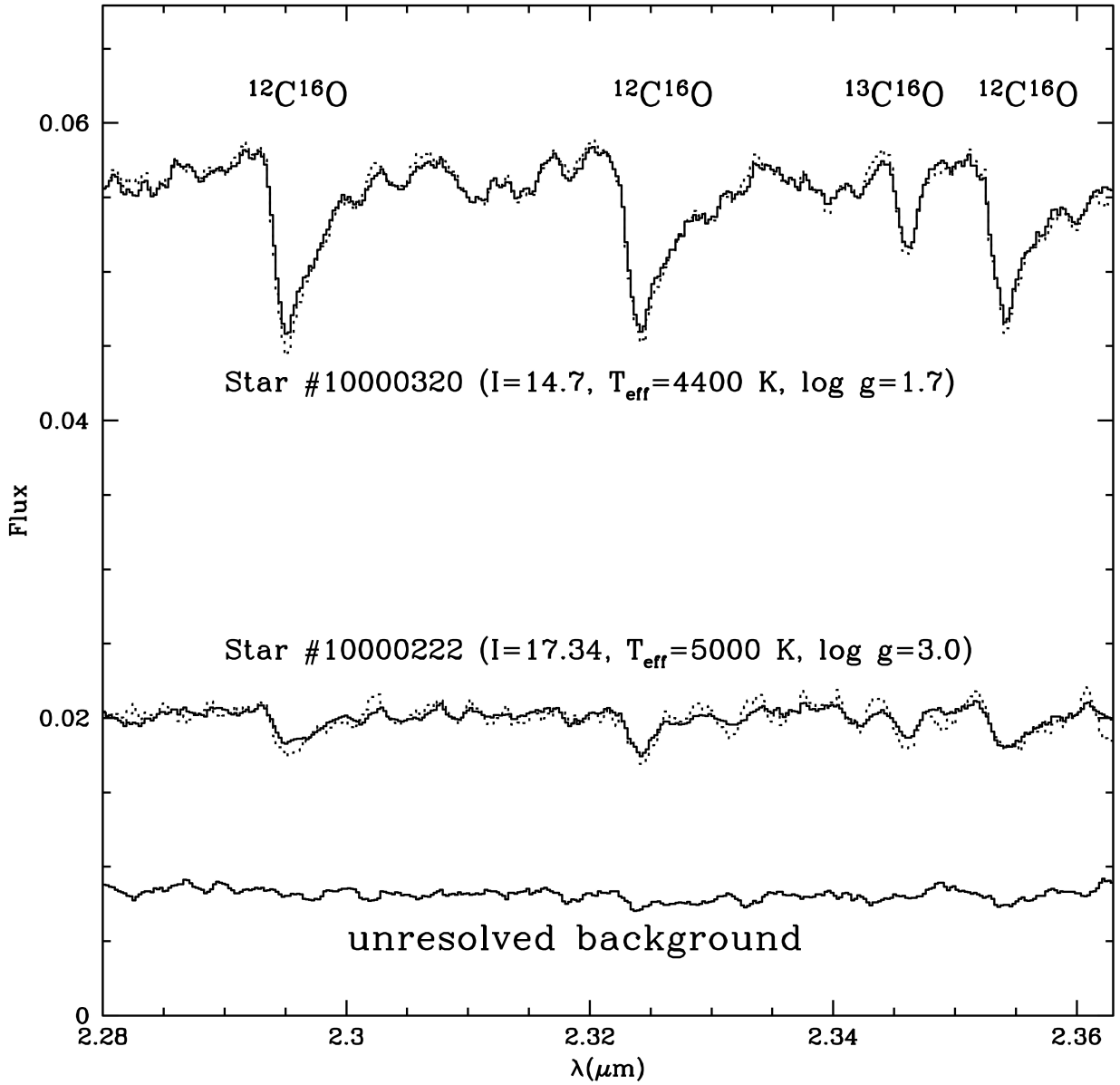
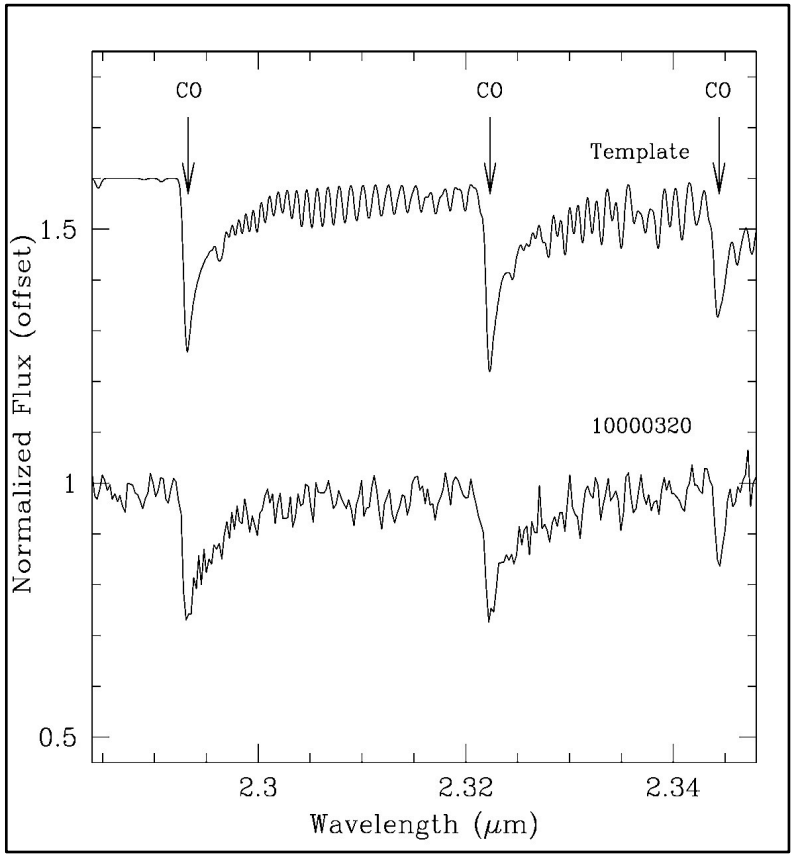


SINFONI spectra contaminated by close stars ?

- spectra extracted from CENTRAL spaxel only
- contamination in one direction only: from
  lower-Vr & brighter stars to larger-Vr & fainter stars
  (asymmetry of CO feature)
  => not necessarily systematic toward low VD



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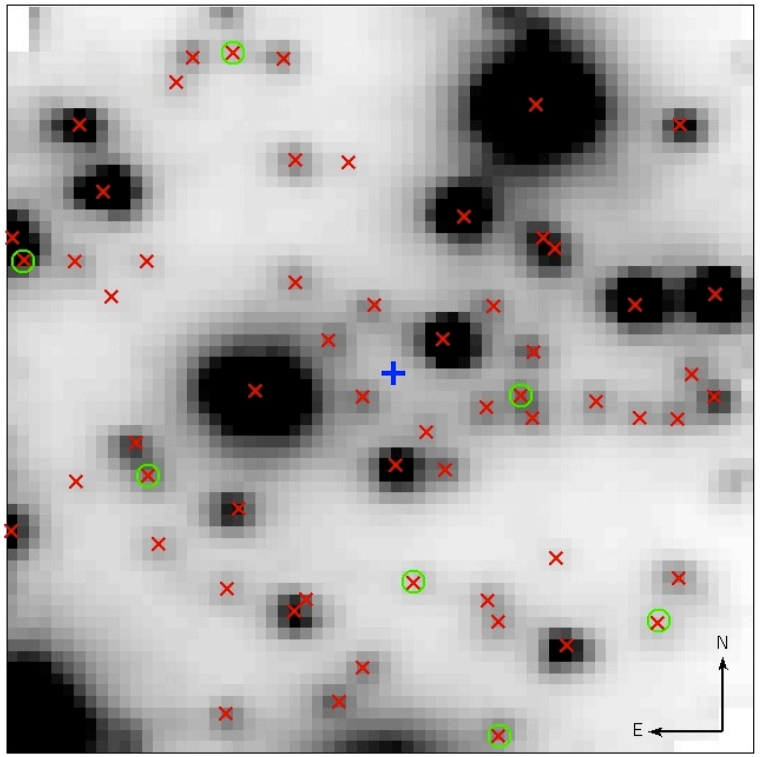
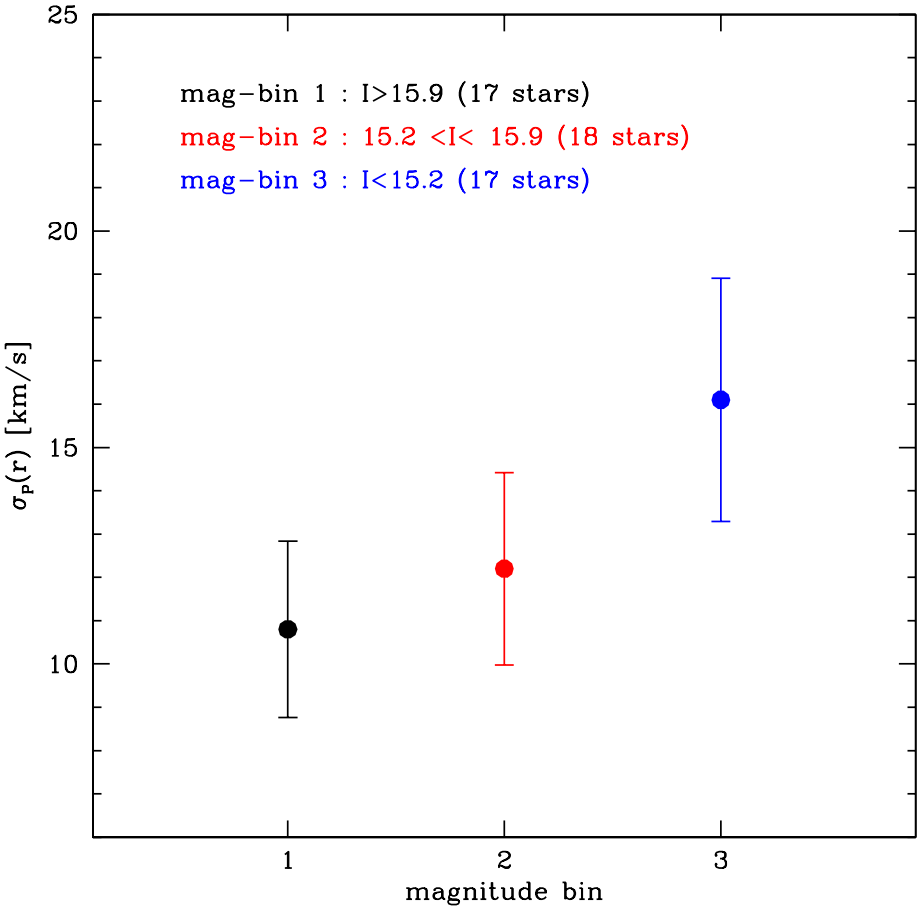
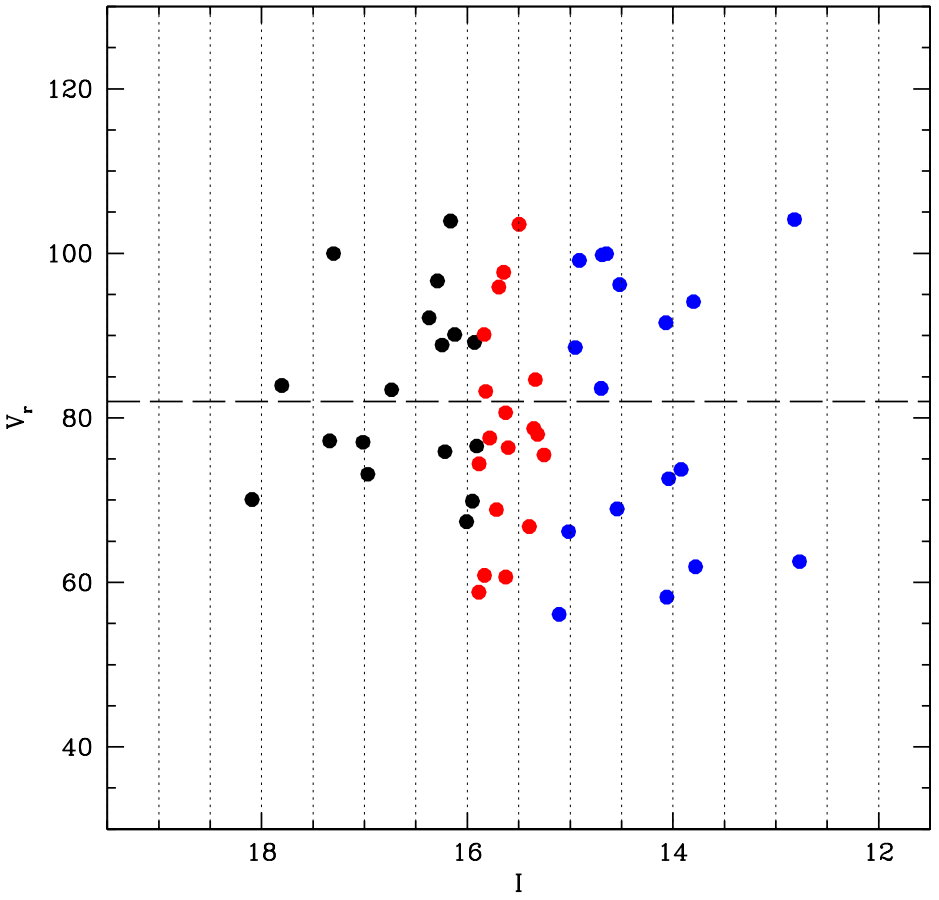
- spectra extracted from CENTRAL spaxel only
- contamination in one direction only: from
  lower-Vr & brighter stars to larger-Vr & fainter stars
  (asymmetry of CO feature)
  => not necessarily systematic toward low VD
- checked the effect of close stars by using the observed PSF
  (contaminated stars excluded from the sample)





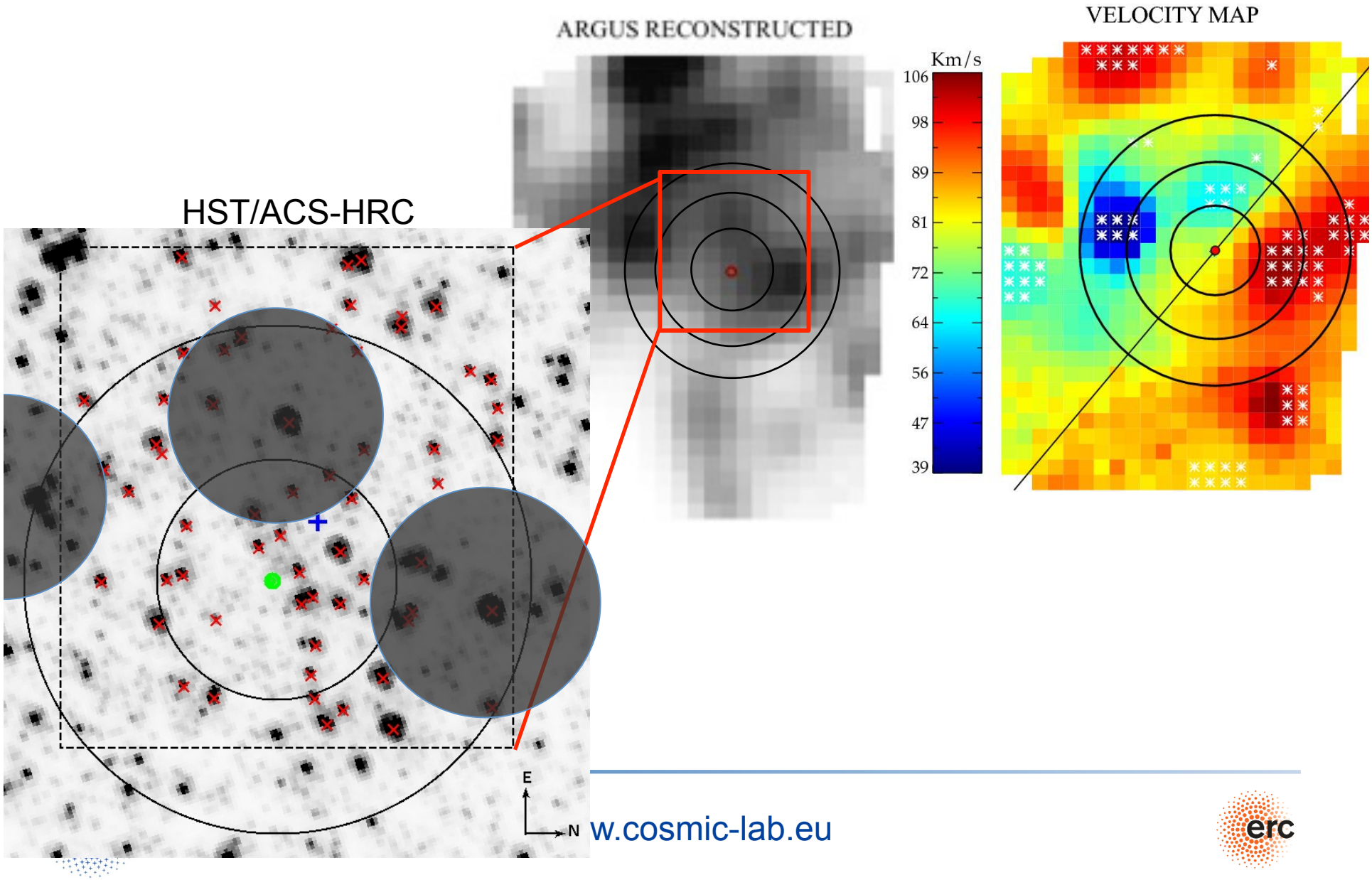


Trend driven by brightest stars

Weird Vr distribution of brightest stars (rotation?)

Trend due to weird Vr distribution of brightest stars

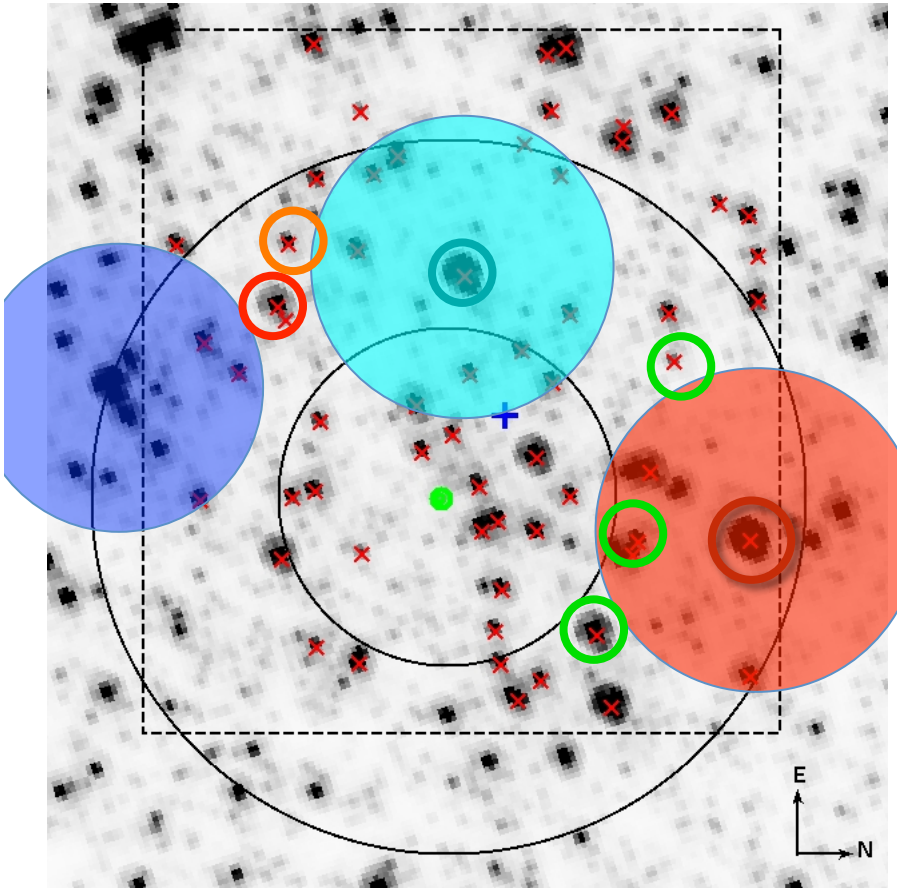
Integrated-light spectra from ARGUS (seeing-limited IFU)

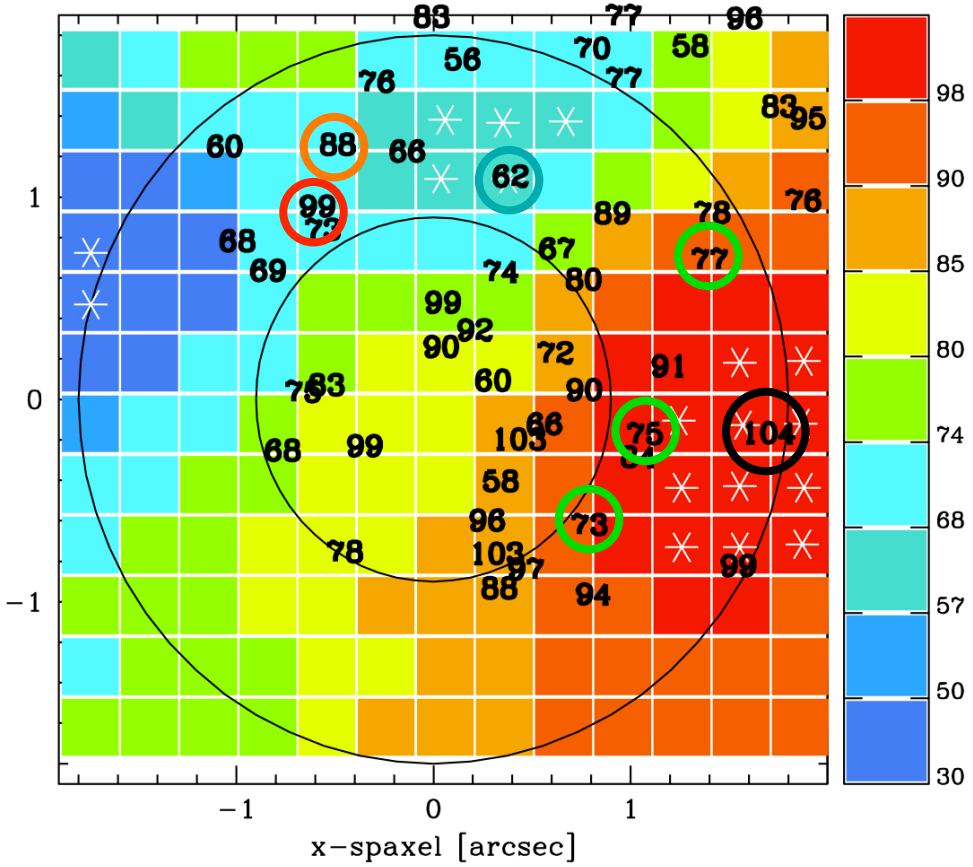


Insufficient shot-noise correction

→ **colours**: radial velocity map of L11
→ **white asterisks:** spaxels excluded by L11 for shot noise correction
→ **black values:** our V_r measurements

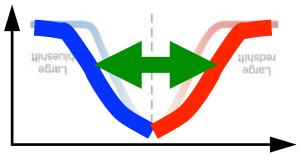
HST/ACS-HRC



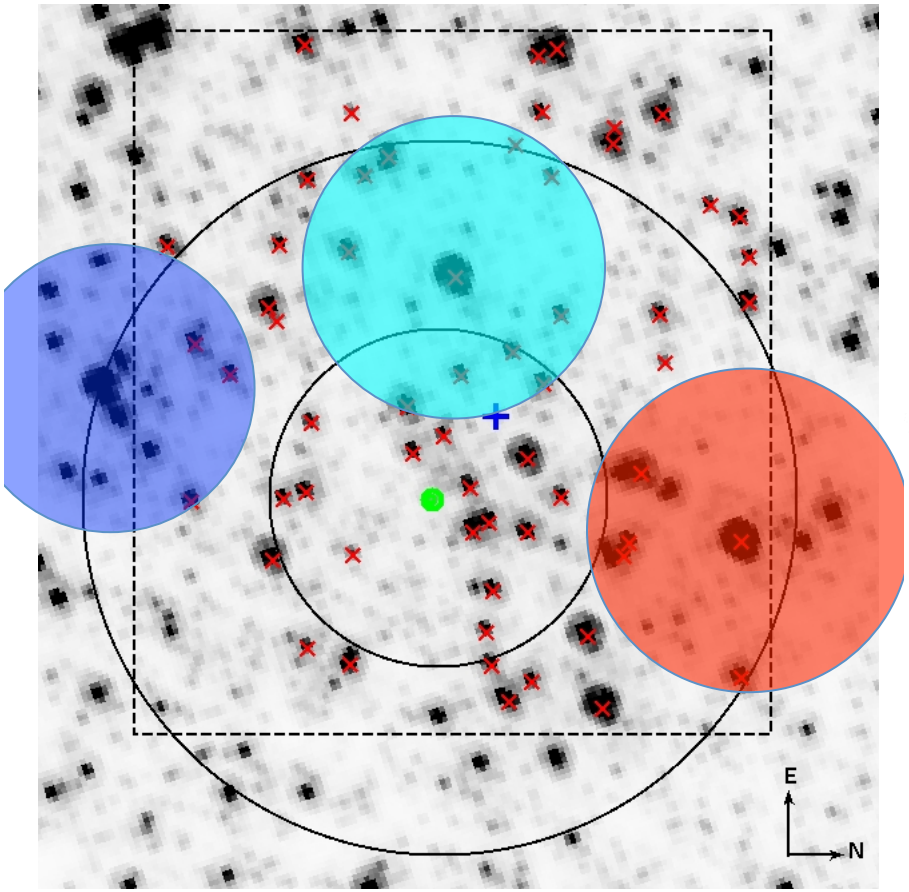


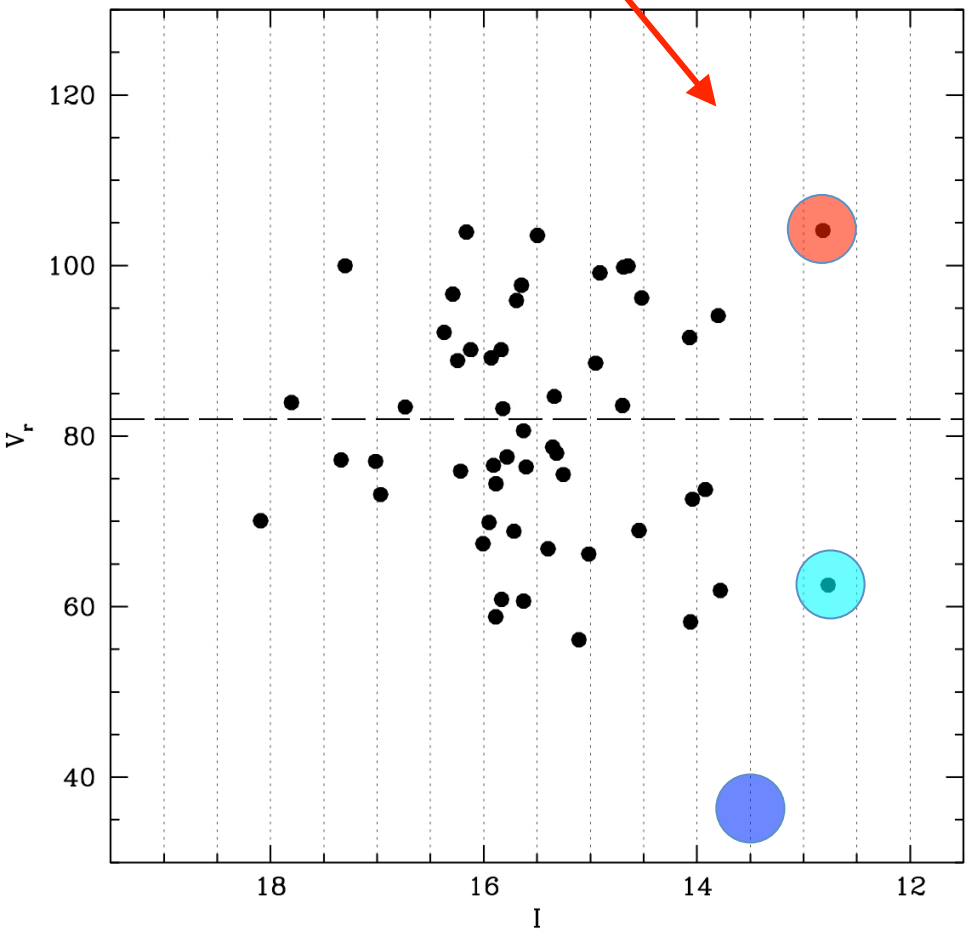
Spectra dominated by the light of a few bright stars with quite different V_r

=> artificial line broadening



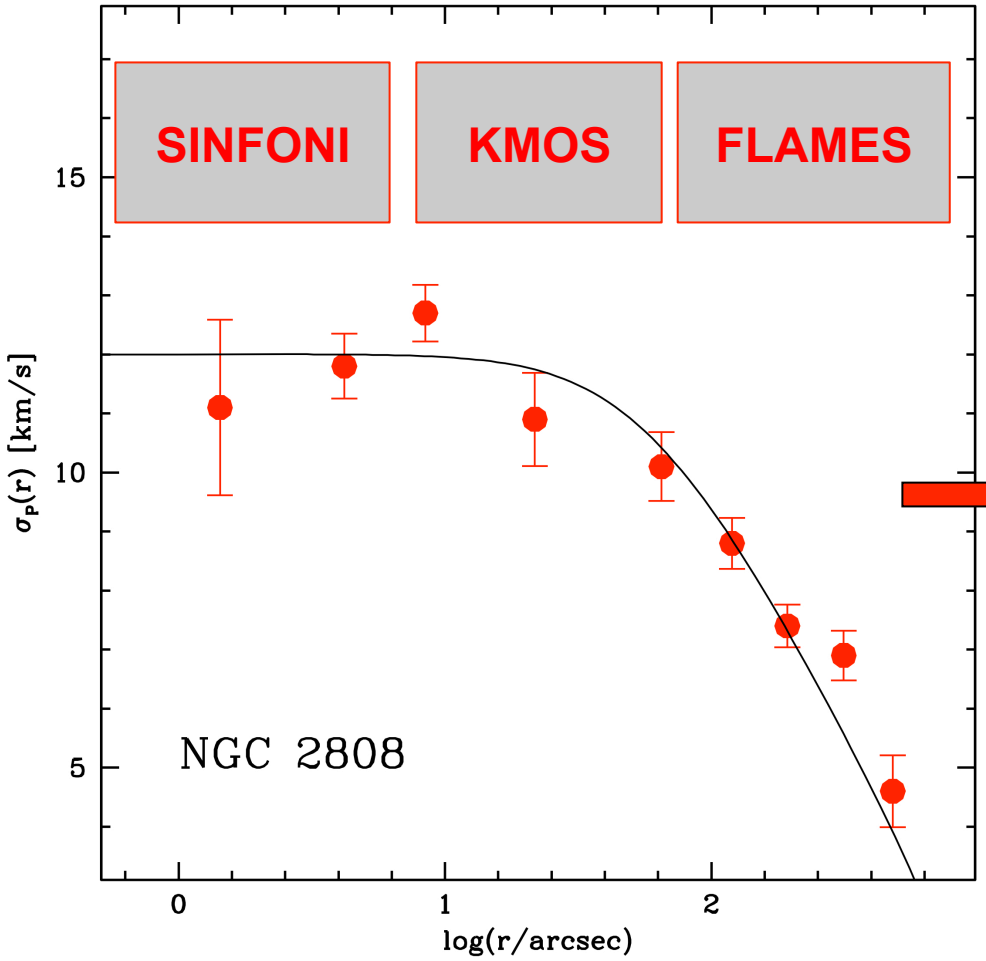
=> overestimate of σ(r) & IMBH mass





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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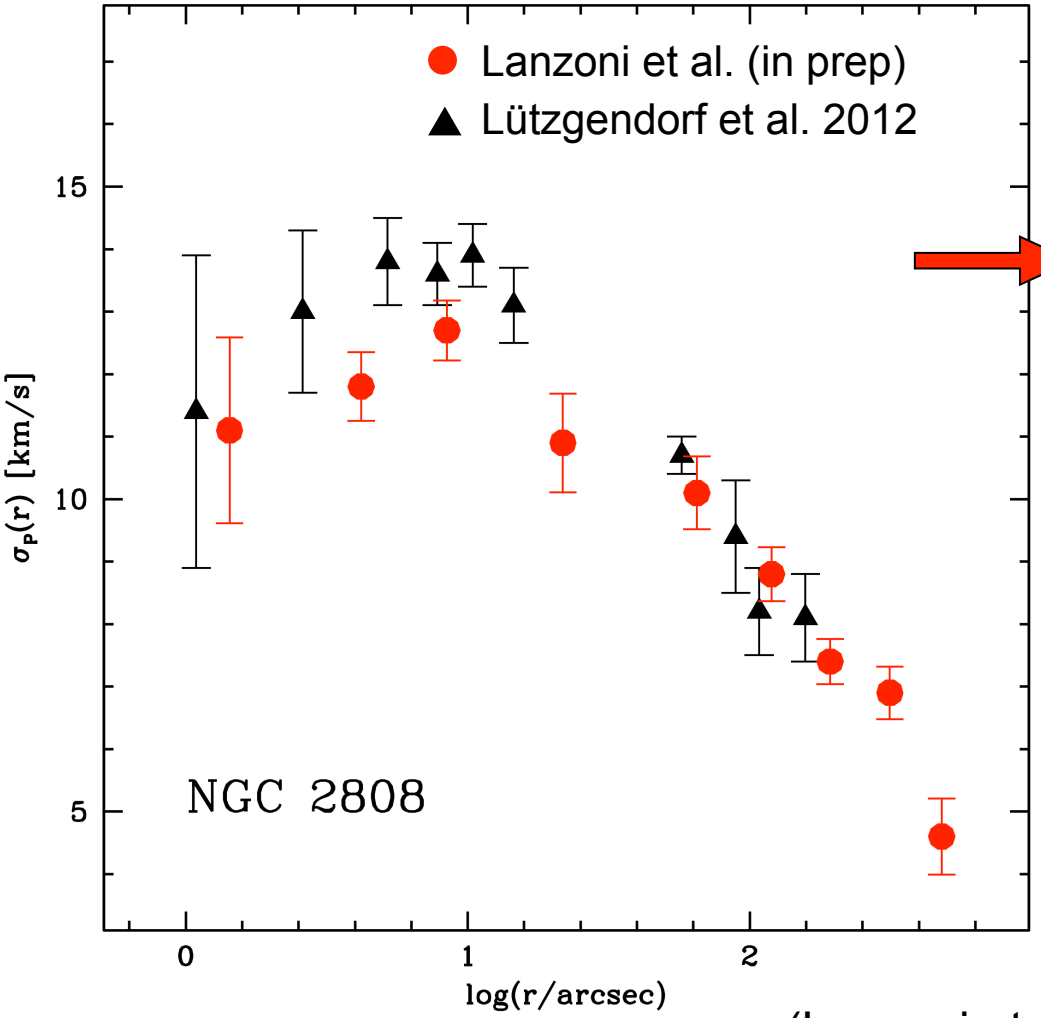
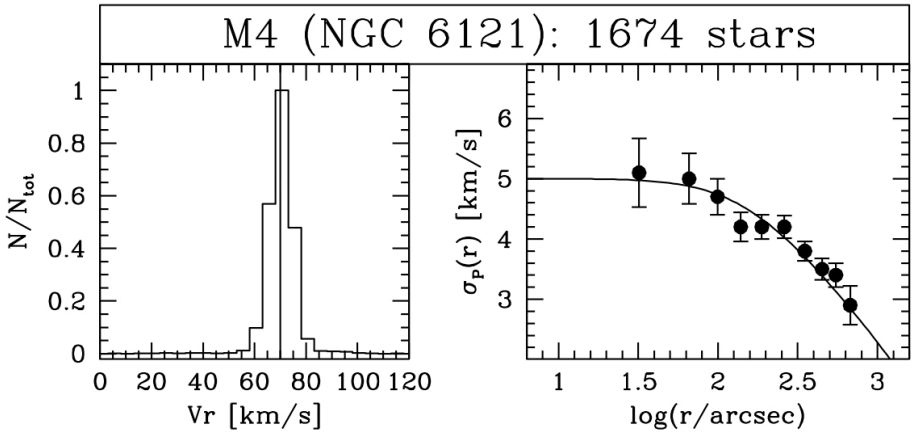
Preliminary results for NGC 2808

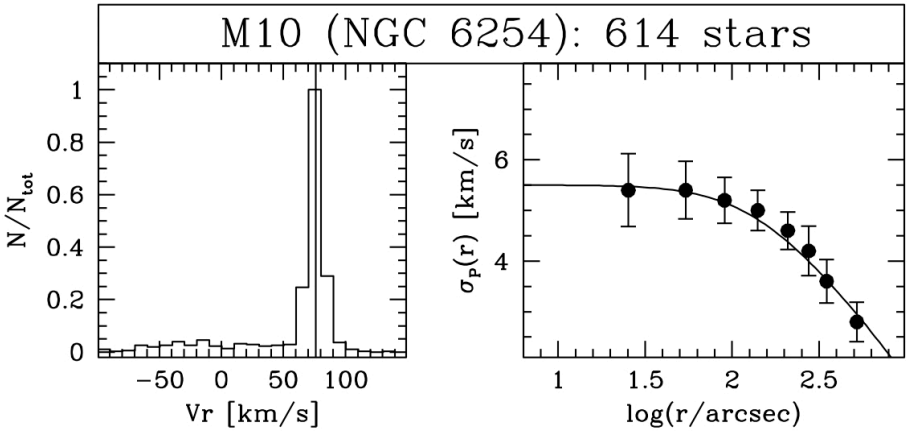


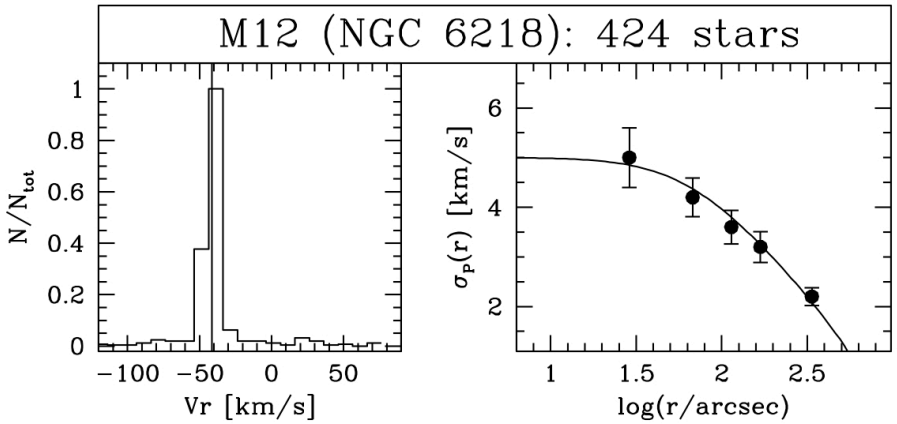
Good agreement
with integrated-light results
(Lützgendorf et al. 2012)

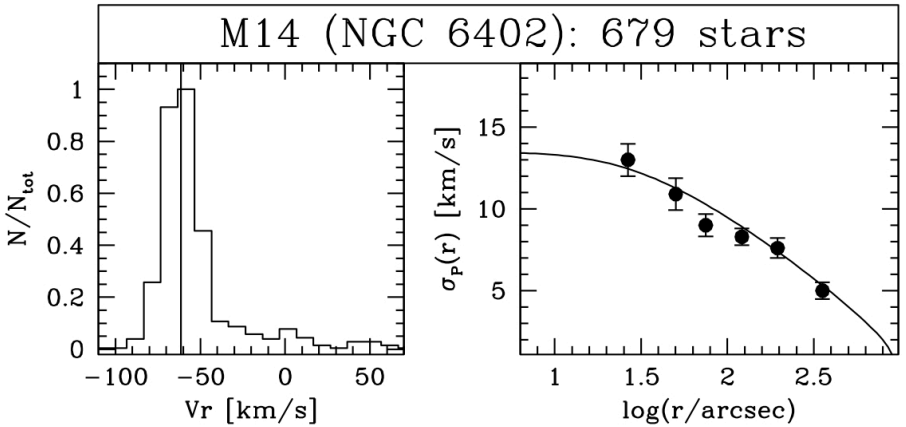
(Lanzoni et al. 2015, in preparation)

Preliminary results from KMOS+FLAMES LP









(Ferraro et al. 2015, in preparation)

Stay tuned….

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Thank you for your attention

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