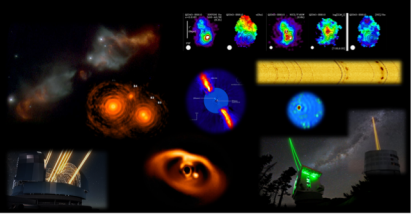


Astrofisica di frontiera con l'ottica adattiva italiana
Roma, Accademia Nazionale dei Lincei 17-18-19 Febbraio 2020

AO-assisted spectroscopy in crowded stellar fields: present and future science opportunities

Livia Origlia, INAF - OAS Bologna, livia.origlia@inaf.it

1-100 stars/*arcsec*^{2} spectroscopically measurable

- central regions of Galactic globular clusters
- the Galactic center and the nuclear star cluster
- star clusters in the LG and beyond

spectroscopy in dense stellar fields

Top Level Requirements

- **spatial resolution**:
  20-200mas ➔ to resolve stars down to the limiting magnitude

- **multiplex**:
  >10 to >100 ➔ population studies

- **minimum FoV**:
  from a few arcsec^2 (densest [sub-]structures)
  to several tens arcmin^2 (entire extension)

- **spectral resolution**:
  R<5,000 ➔ RVs with a few km/s accuracy and global metallicity
  5,000<R<20,000 ➔ progressively optimal for RVs and reasonable for some chemical abundances
  R>20,000 ➔ progressively optimal for detailed chemical abundances

- **simultaneous spectral coverage**:
  >50nm, *goal* >100nm ➔ minimum of spectral features for science analysis and at least one telluric line for RV zeropoint

spectroscopy in dense stellar fields

matching science TLRs with instrument capabilities ➔ *trade-offs*

finite number of detector pixels

- finite number of spectral elements
  trade-off between **spectral resolution** and **coverage**
- finite number of spatial elements
  trade-off between **spatial resolution** and **FoV**
- finite number of spatial & spectral elements
  trade-off between **resolution, coverage & multiplex**

limited sensitivity

trade-off between **resolution** and **depth**

however, note that …

in dense stellar fields **more sensitivity ➔ fainter BUT more crowding**

hence **more sensitivity AND spatial resolution**

spectroscopy in dense stellar fields

matching science TLRs with instrument capabilities

multi-instrument approach

high multiplex, limited spectral resolution and coverage

- wide-field, multi-object spectroscopy at lower densities
- high spatial res, integral field spectroscopy at the highest densities

low multiplex, enhanced spectral resolution & coverage

- echelle spectroscopy

spectroscopy in dense stellar fields

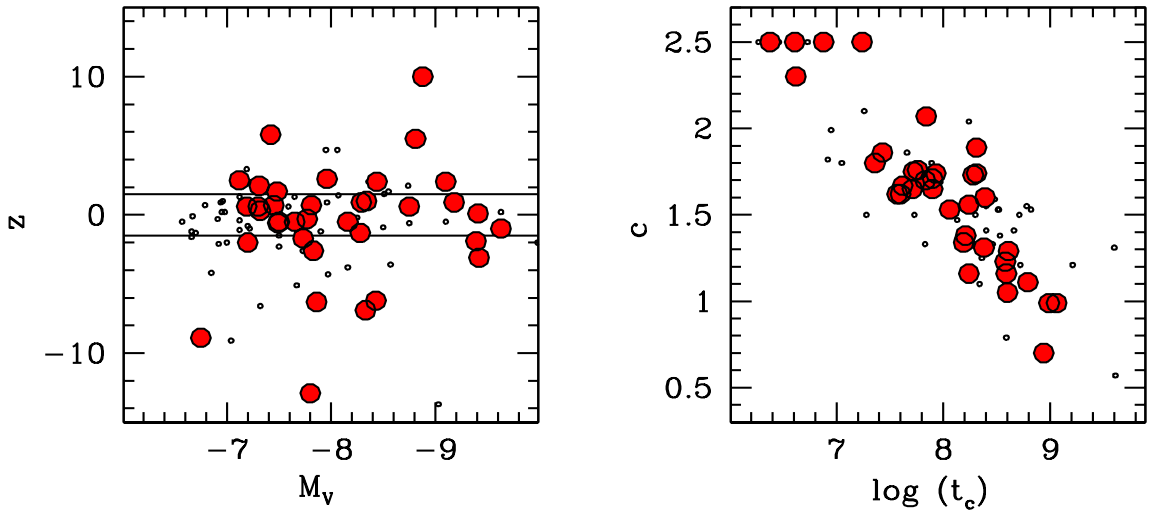
science case #1: internal kinematics of globular clusters

Multi Instrument Kinematic Survey (MIKiS) of GGCs

UniBO (Ferraro, Lanzoni, Mucciarelli, Pallanca *etal*), INAF-OAS (Dalessandro, Origlia, Bellazini *etal*)

- ESO LP 193.D-0232 194 hr with KMOS+FLAMES
- ESO LP 195.D-0750 101 hr with SINFONI
- other normal programmes with
  MUSE-AO, FLAMES & XShooter at VLT (about 100 hrs)
  OSIRIS-AO, NIRSPEC & DEIMOS at Keck (about 70 hrs)

the sample of GGCs



Ferraro+ 2018 ApJ, 860, 50

(i) massive ($M > 5\times10^5\ M_\odot$)

(ii) a wide range of Log ρ, c & relaxation times

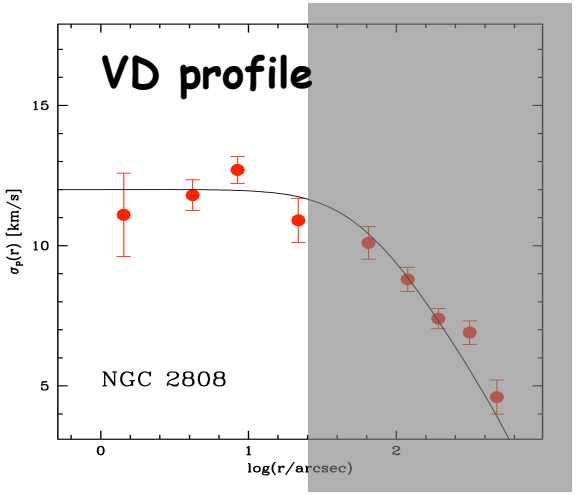
(iii) different stages of dynamical evolution, including PCC

(iv) different environmental conditions (sampling halo & bulge/disk populations)

spectroscopy in dense stellar fields

science case #1: internal kinematics of globular clusters

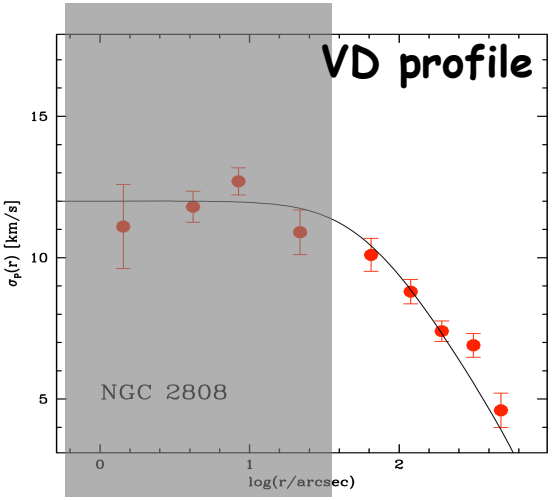
VELOCITY DISPERSION & ROTATION PROFILES
from RVs of individual stars over the entire cluster extension



central VD

flat ?
- isothermal core

central cusp or dip ?
- IMBH ?
- rotation?
- anisotropy?



outer VD

- rotation?
- tidal tails?
- dark matter halo?

combined with

- HST & Gaia PMs for a 3D view of the velocity space
- HST and other wide-field photometry to obtain LFs & density profiles for determining structural parameters, dynamical evolution *etc.*

impact at large

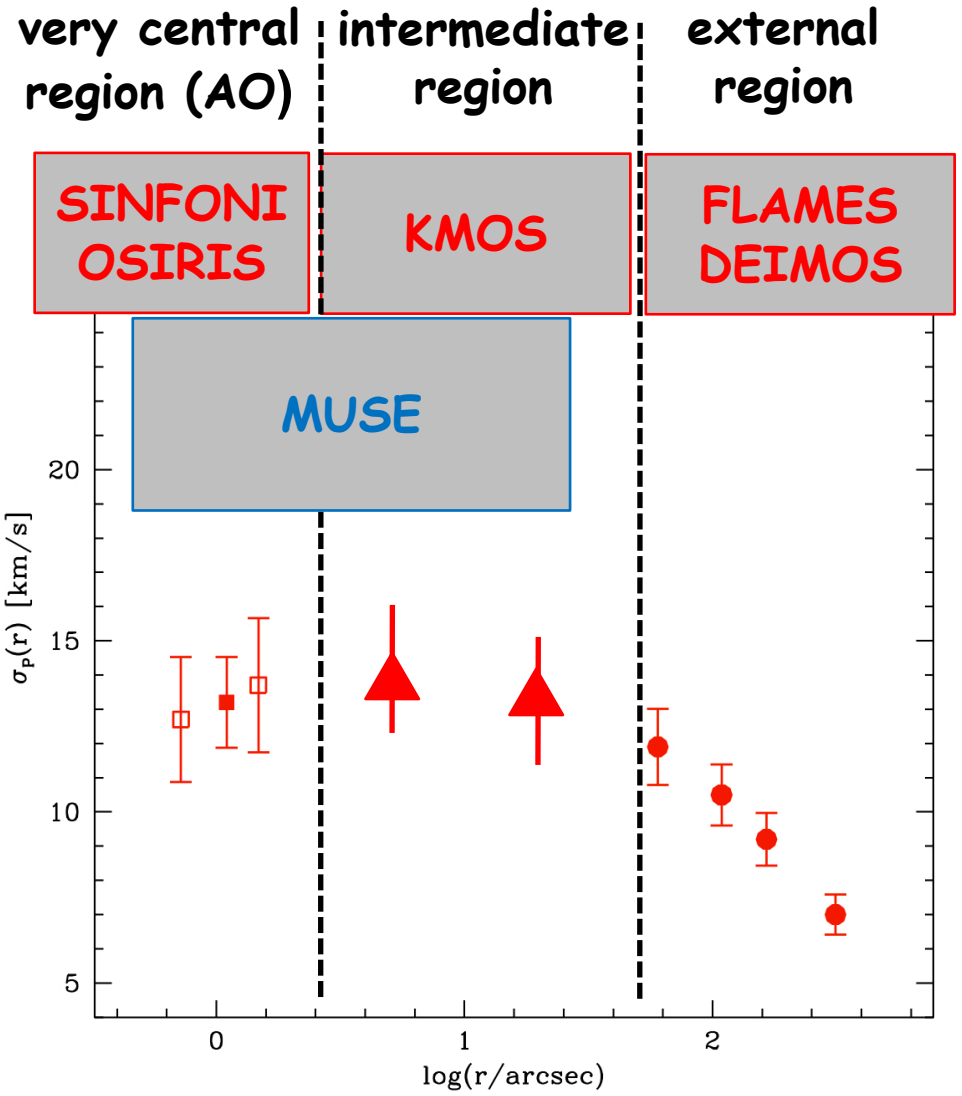
- formation and evolution of collisional systems
- interplay between dynamics and stellar + chemical evolution

spectroscopy in dense stellar fields

science case #1: internal kinematics of globular clusters

RVs of individual stars over the entire cluster extension

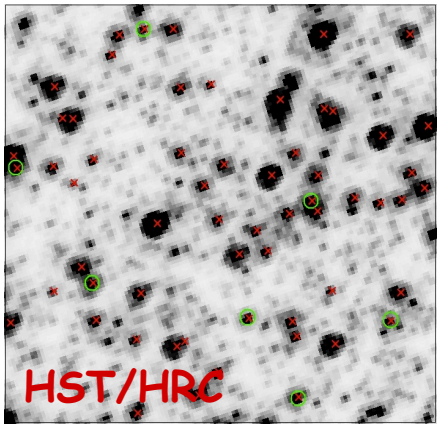
a multi-instrument approach

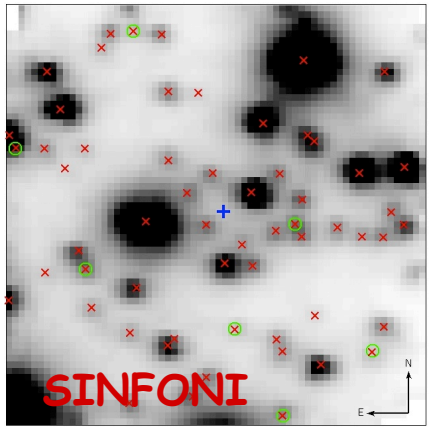


spectroscopy in dense stellar fields

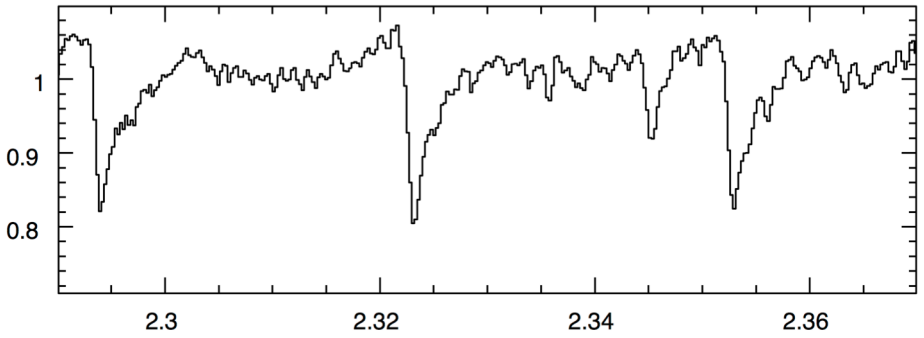
science case #1: internal kinematics of globular clusters

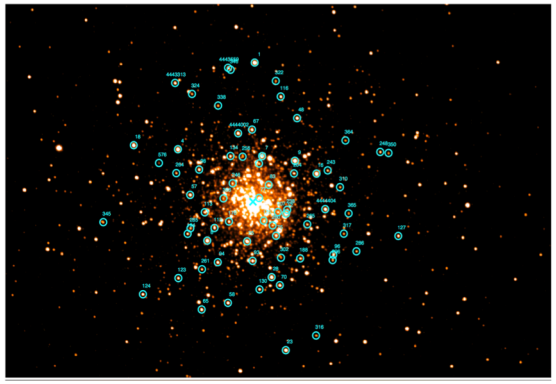
the pilot project: NGC6388

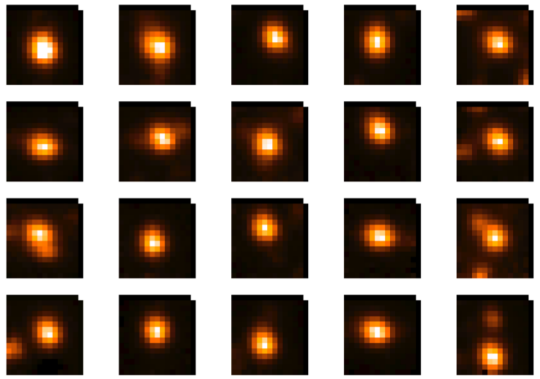


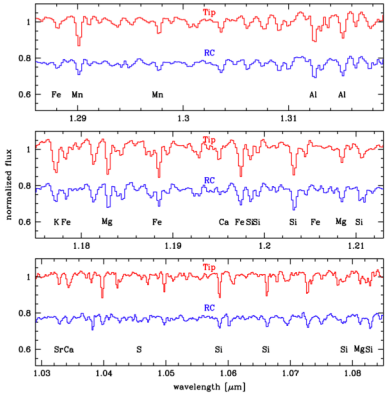


SINFONI+AO K-band spectra
R~4000, ~60 stars at r<1.6"

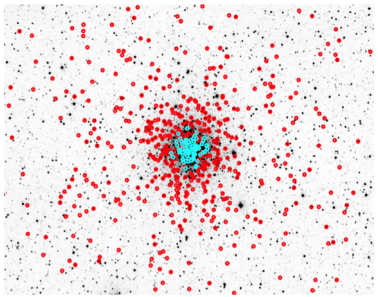








KMOS YJ spectra
R~3,400
4 pointings
~90 stars at r<70"

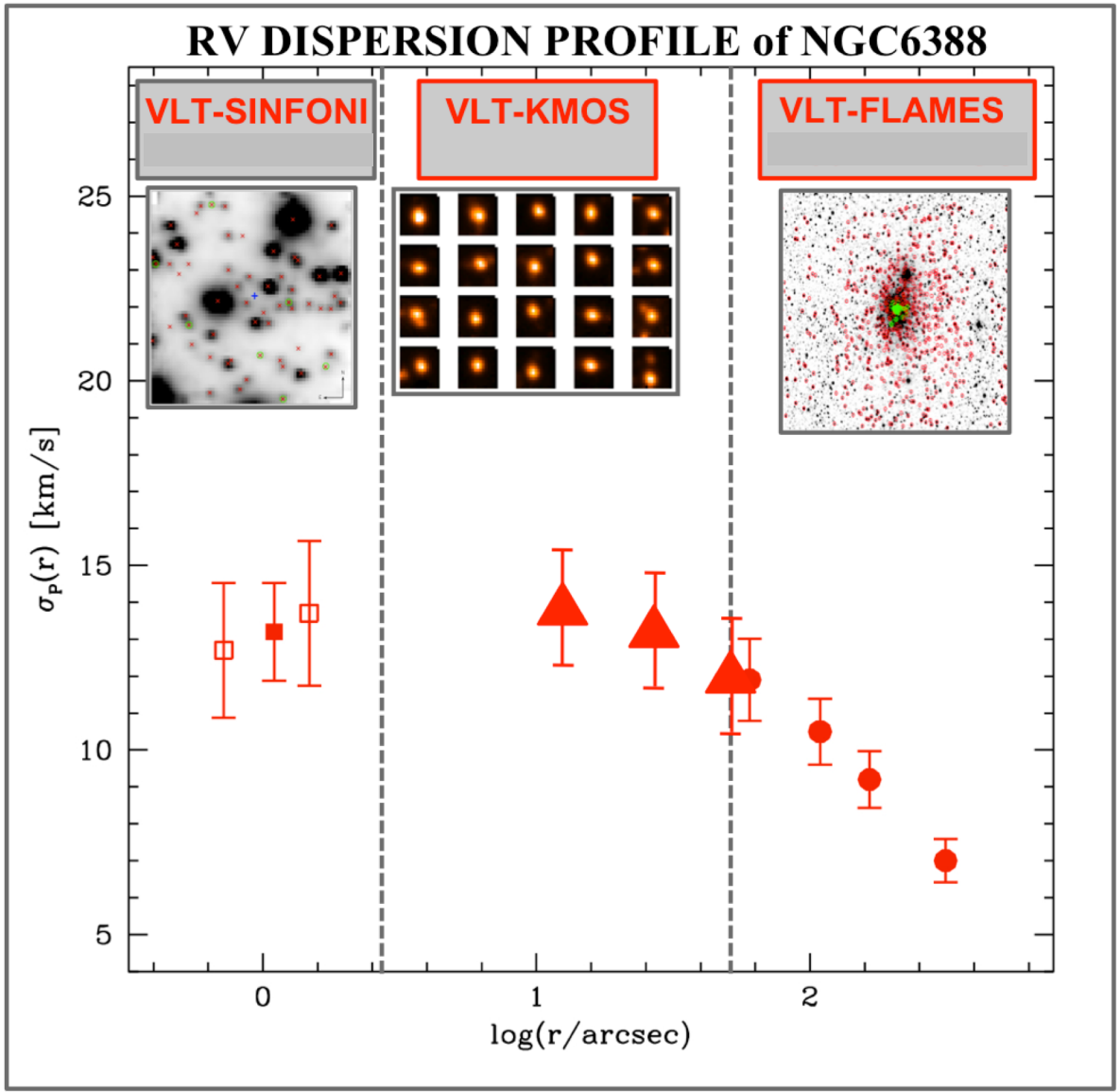


FLAMES CaT spectra
a few pointings
~220 stars at 70"<r<600"

spectroscopy in dense stellar fields

science case #1: internal kinematics of globular clusters

the pilot project: NGC6388



at odds with the claim by Lützgendorf+ (2011) of a $M_{BH} \sim 1.7\ 10^4\ M_o$ from integrated spectroscopy

<u>we find</u>

no evidence

or at most an

IMBH<$2 \times 10^3\ M_o$

evidence of some rotation in the core

Lanzoni+ 2013

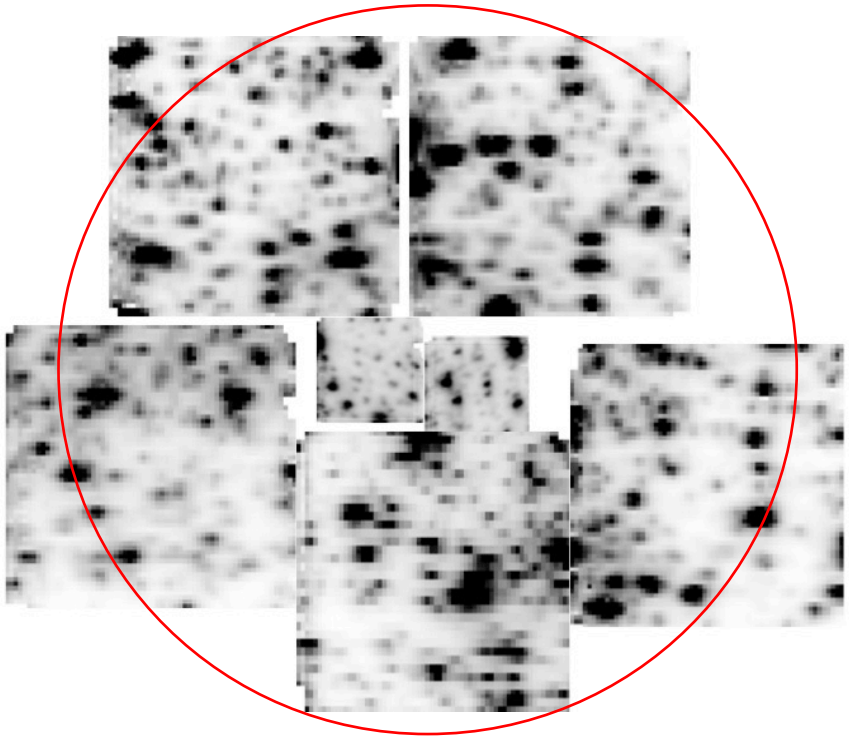
spectroscopy in dense stellar fields

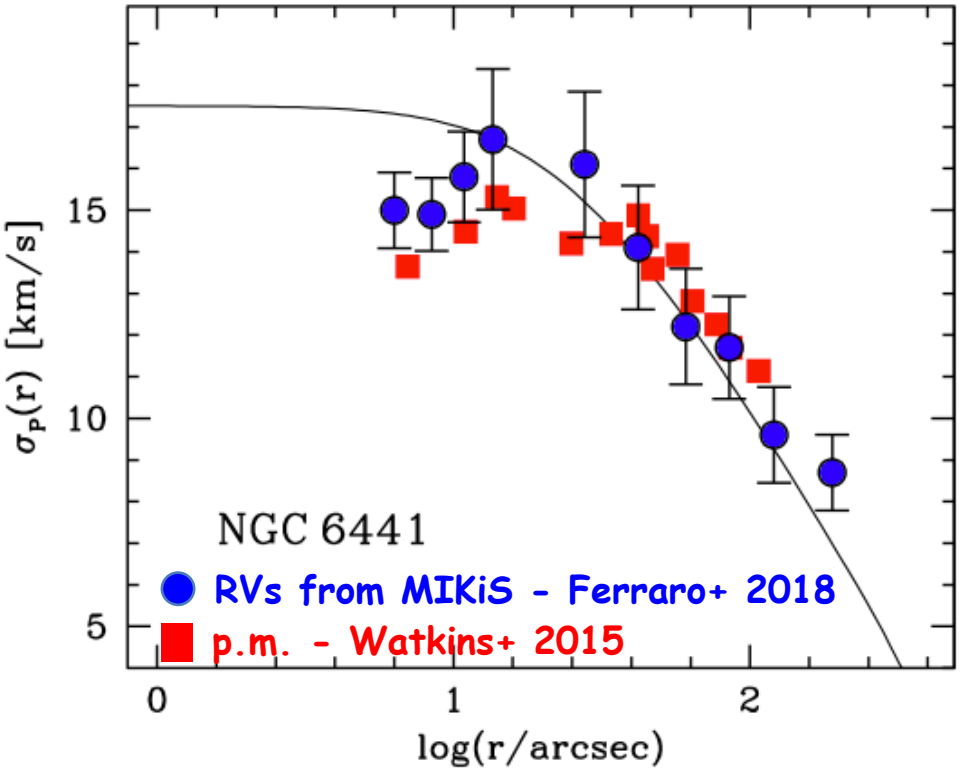
science case #1: internal kinematics of globular clusters

NGC 6441 (r_c=7 arcsec)

SINFONI mosaic: 2 HR + 5 LR

700 stars in the central R<10"



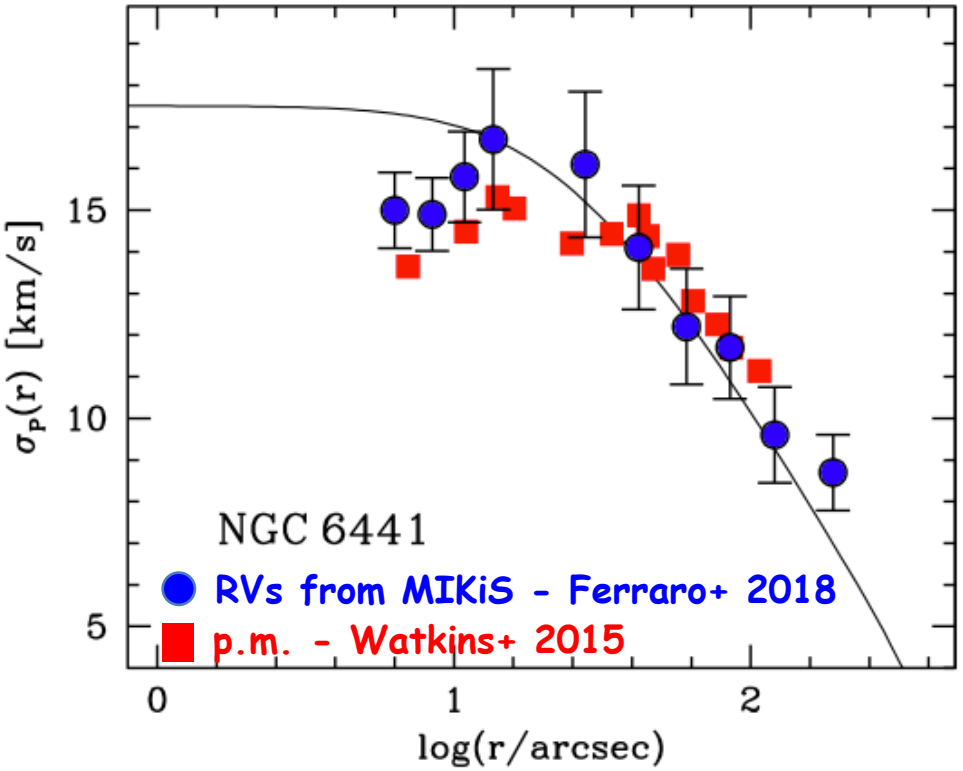


VD dip in the core

tangential anisotropy?
rotation ?

spectroscopy in dense stellar fields

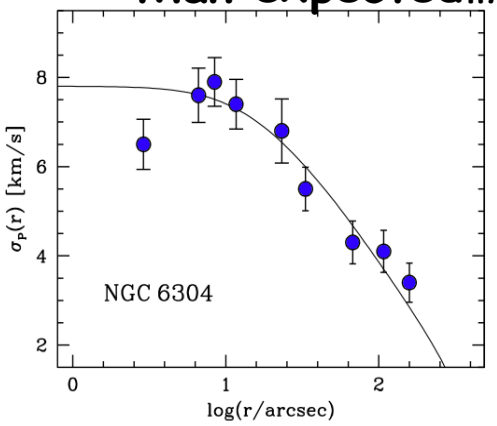
science case #1: internal kinematics of globular clusters

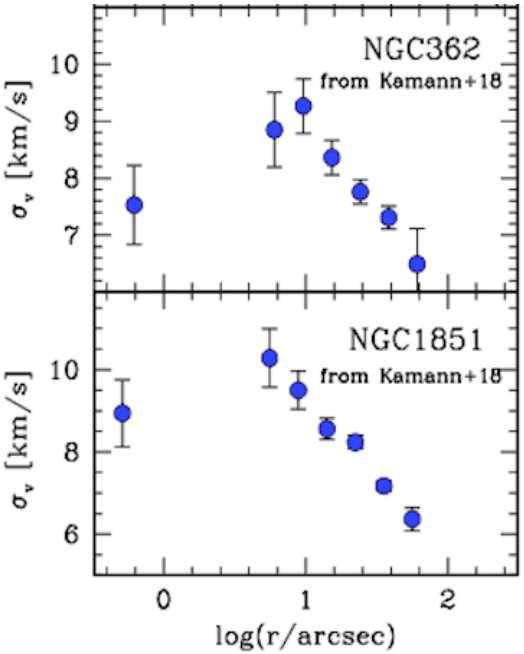


VD dip in the core

tangential anisotropy ?
rotation ?

...more common than expected...





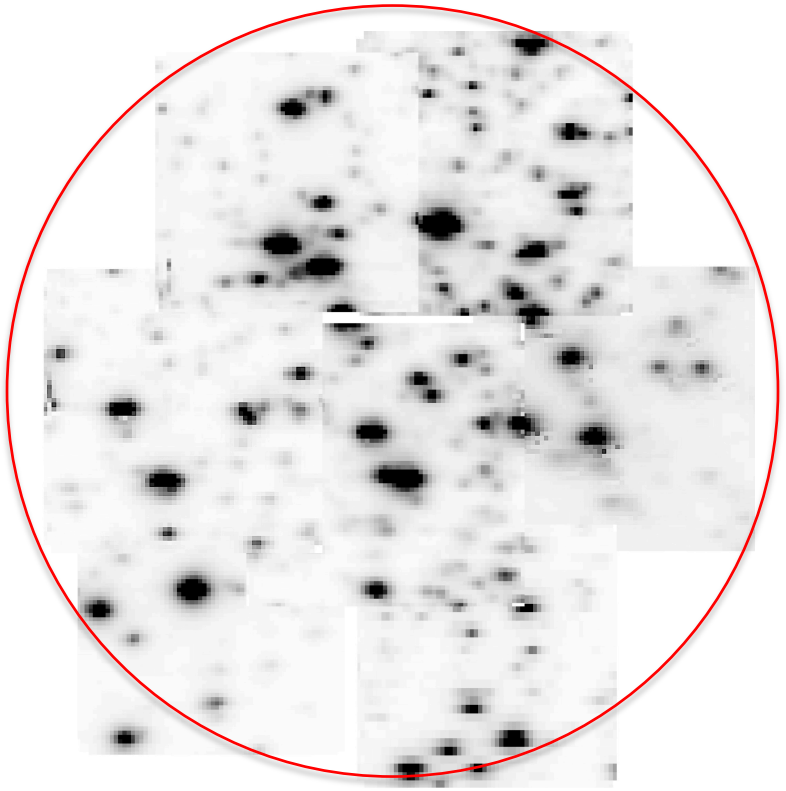
spectroscopy in dense stellar fields

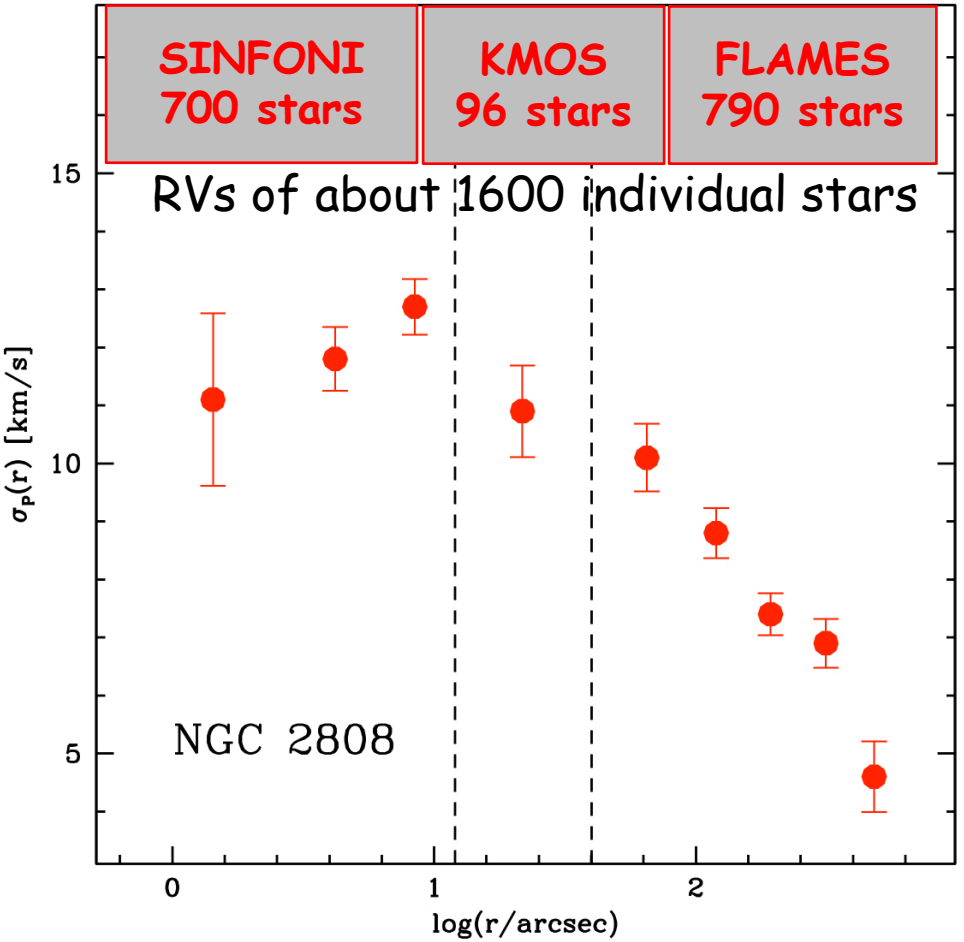
science case #1: internal kinematics of globular clusters

NGC 2808 (r_c=7 arcsec)

SINFONI mosaic: 7 LR

700 stars in the central R<12"



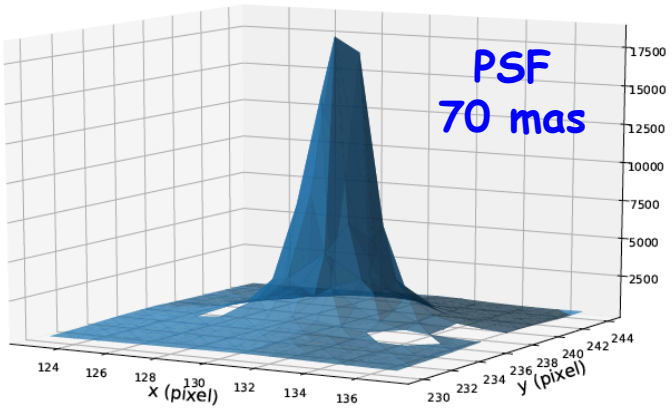


no VD cusp in the core

no evidence of an IMBH

spectroscopy in dense stellar fields

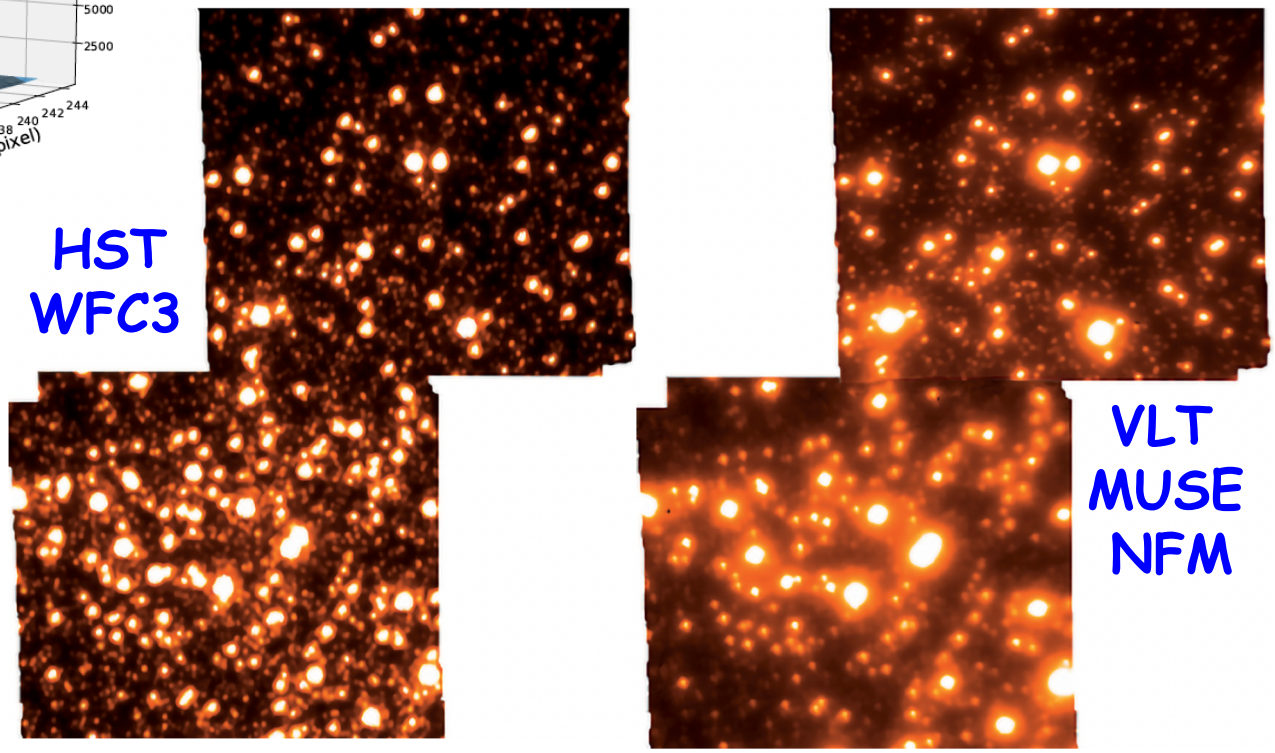
science case #1: internal kinematics of globular clusters



NGC 6440 (r_c=8 arcsec)

Science Verification of MUSE/NFM

(program 60.A-9489 - PI:Ferraro)

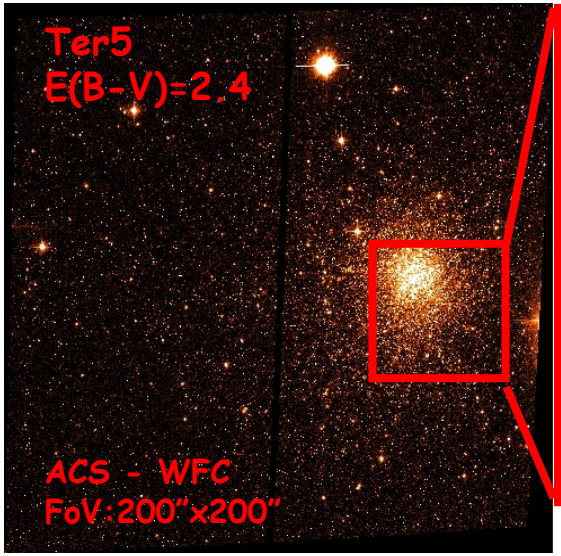


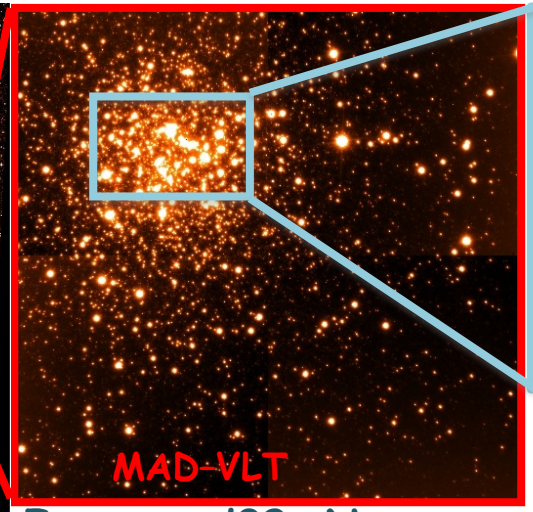
600+ stars in the central R<4 arcsec

one of the major highlight in the Leibundgut+ 2019 MUSE-NFM SV summary

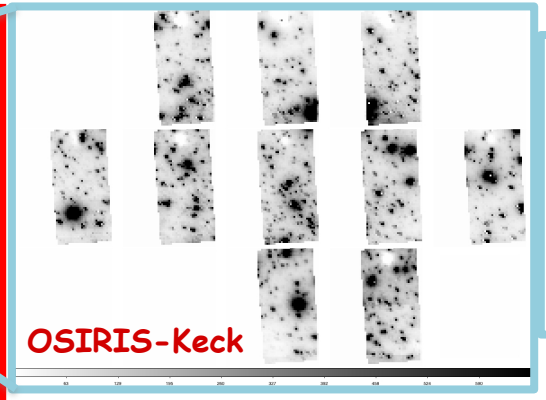
spectroscopy in dense stellar fields

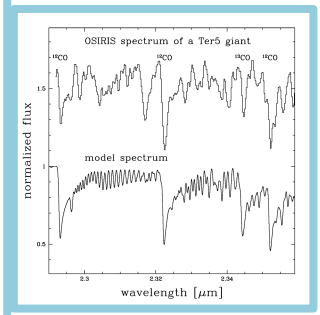
science case #2: internal kinematics & chemistry of Ter5





Ferraro+ '09, Nature



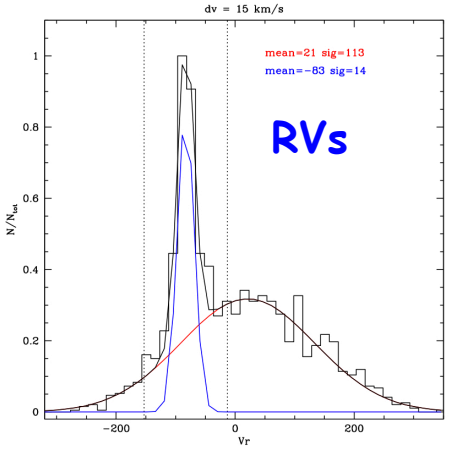


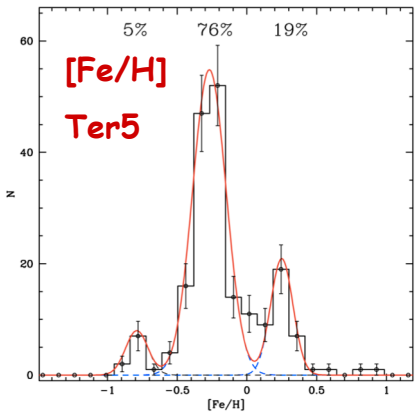
OSIRIS+AO, 10 pointings, 5hr
~500 stars at r<7" & K<15

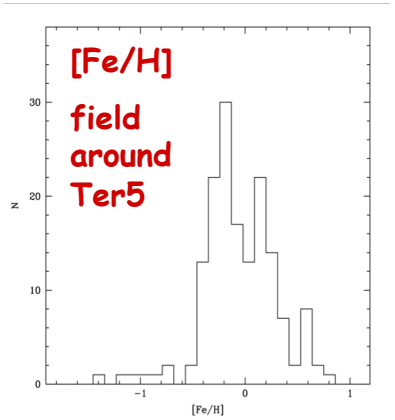
X-Shooter+NIRSPEC , ~120 stars at r<60"

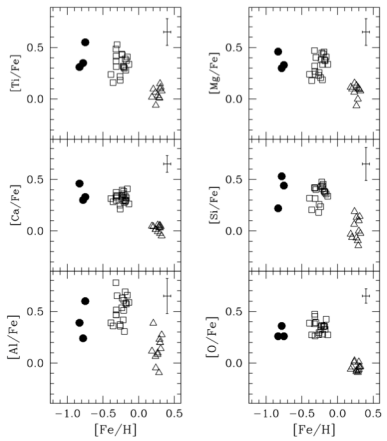
FLAMES+DEIMOS, ~1500 stars out to 800"

RVs & chemical abundances
Origlia+ '11,'13; Massari+ '14



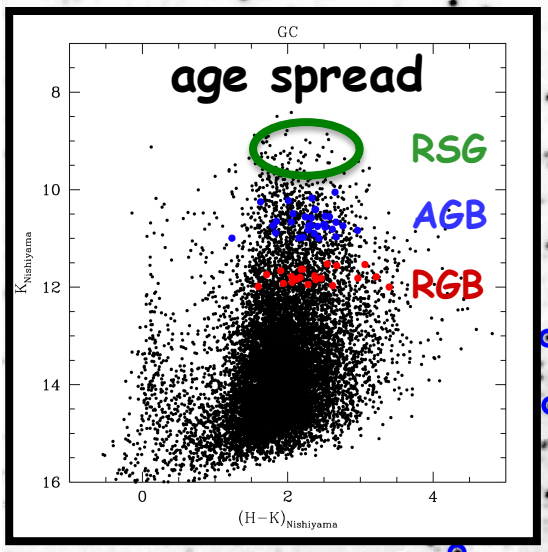






spectroscopy in dense stellar fields

science case #3: kin+chem of the nuclear star cluster

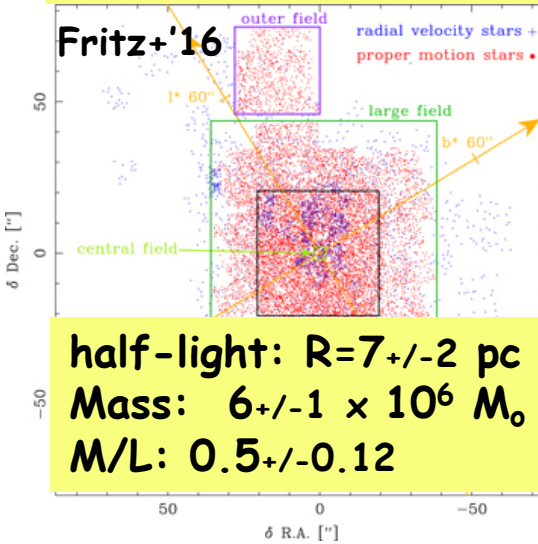


Av>30 mag!

mostly K-band only

structure, PMs & RVs

VISTA, WFC3/IR,
VLT/NACO+SINFONI



half-light: R=7+/-2 pc

Mass: 6+/-1 x 10^6 M_o

M/L: 0.5+/-0.12

chemistry – high res spec

RSGs: [Fe/H]~solar

Ramirez+'00 CSHELL@IRTF
Cunha+'07 PHOENIX@Gemini
Davies+'09 NIRSPEC@Keck

RGB: [Fe/H]~+0.1, [a/Fe]~solar

Ryde & Schultheis '15 CRIRES@VLT
Rich+'17, Nandakumar+'18, Thorsbro+'20

but also metal-poor!

Do+'15, Schultheis+'15, Ryde+'16

K-band UKIDSS fov ~3'x3' → ~50 pc^2

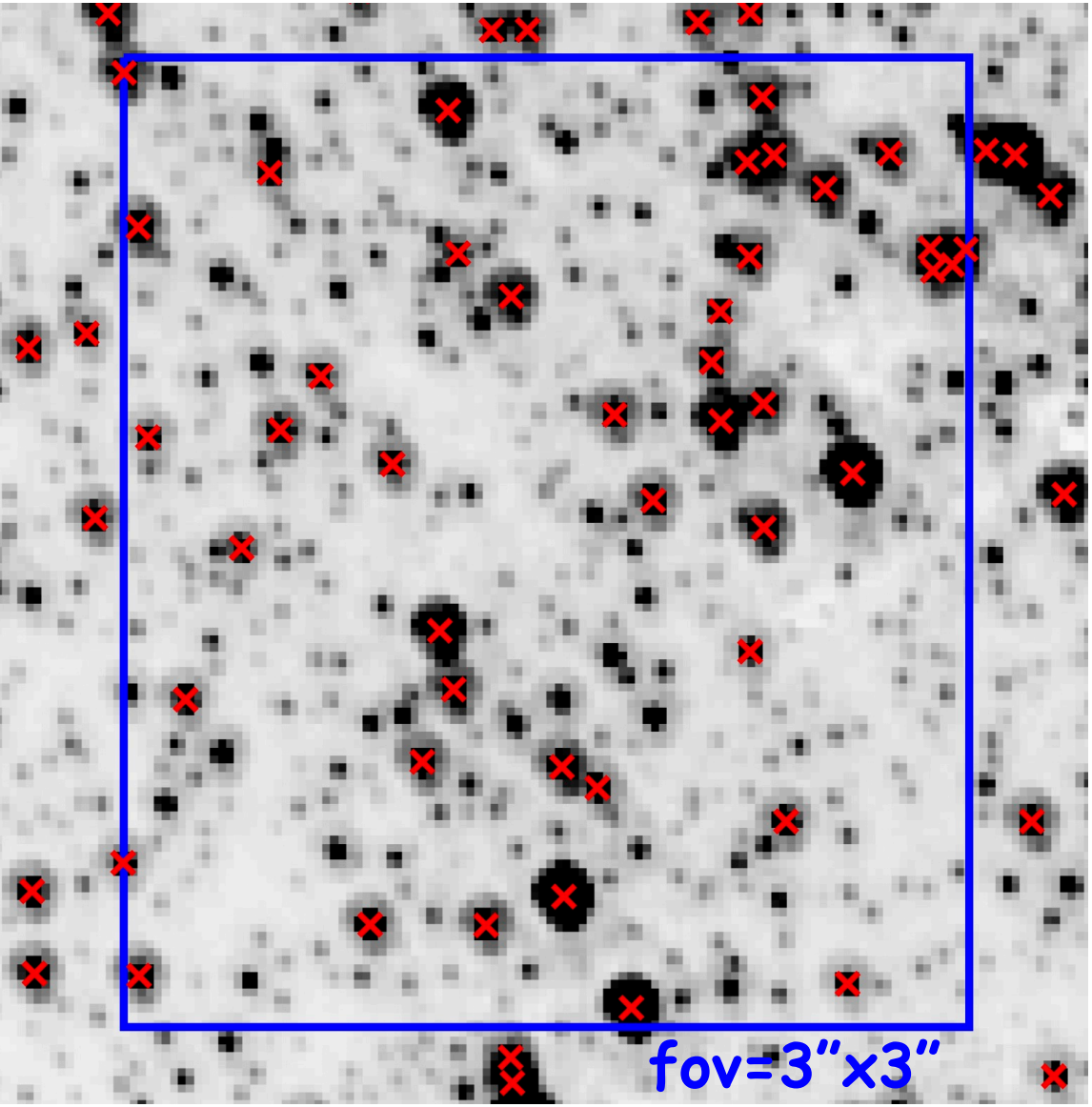
IFU spectroscopy in dense stellar fields

spectrograph	telescope	spectral range	max spec resolution	max f.o.v.	max spaxel
IFU – diffraction limited					
~~SINFONI~~	~~VLT~~	~~YJ,H,K~~	~~4,000~~	~~8" x 8"~~	~~250mas~~
OSIRIS	Keck	YJ,H,K	4,000	4.8" x 6.4"	100mas
MUSE	VLT	visible	4,000	7.5" x 7.5" NFM	25mas
NIRSPEC	JWST	YJ,H,K,L,M	2,700	3" x 3"	100mas
ERIS	VLT	J,H,K	4&8,000	8" x 8"	250mas
MAVIS	VLT	visible	5&12,000	8" x 8"	50mas
IFU – GLAO/seeing limited					
KMOS	VLT	YJ,H,K	4,000	24 IFUs 2.8"x2.8"	200mas
MUSE	VLT	0.465-0.930	4,000	1' x 1' WFM	200mas

current generation of IFUs have only low spectral resolution
mostly RVs with a few km/s errors and a global metallicity

ELT-HARMONI spectroscopy in dense stellar fields

ACS-HRC 25 mas/pix



Galactic star cluster

Mass = 2.6 x 10^6 M_o

R_{core} = 7.2" c=1.8

in the central ~3"x3"

spaxel of 20mas, R~20,000

~600 stars down to H~19

chemical abundances

RVs with <1 km/s accuracy &

VD profile in bins of ~0.3"

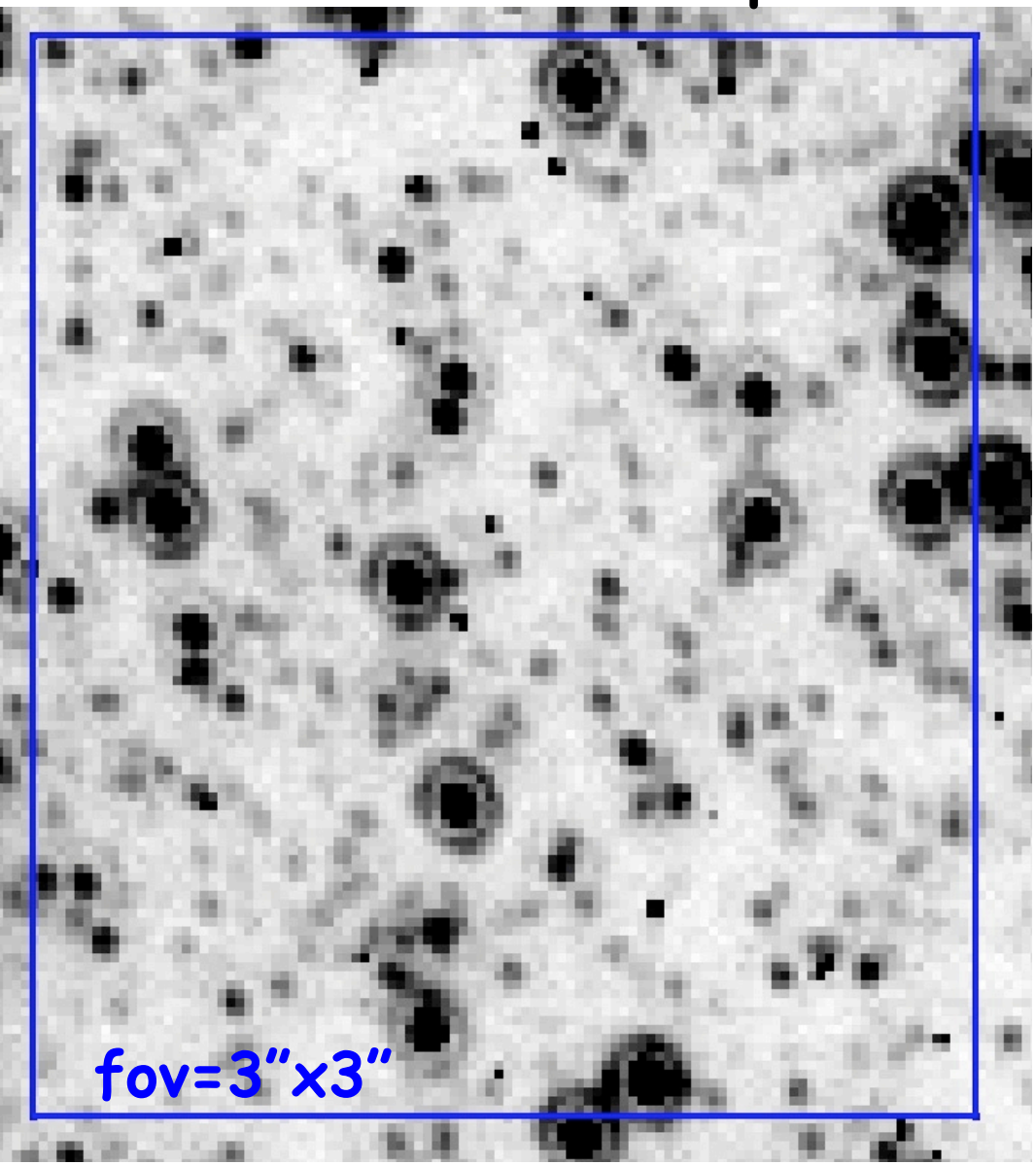
central 1 arcsec →
sampling the sphere of influence of an IMBH

$r_{BH} \sim G \times M_{BH}/\sigma^2 \sim 0.9$"

$M_{BH}=2\times10^3$ M_o σ=14 km/s D=10 kpc

ELT-HARMONI spectroscopy in dense stellar fields

ACS-HRC 25 mas/pix



NGC 121

SMC star cluster

Mass = 3 x 10^5 M_o

R_{core} = 10" c=0.9

in the central 3"x3"

spaxel of 20mas, R~20,000

~200 stars down to H~20

chemical abundances

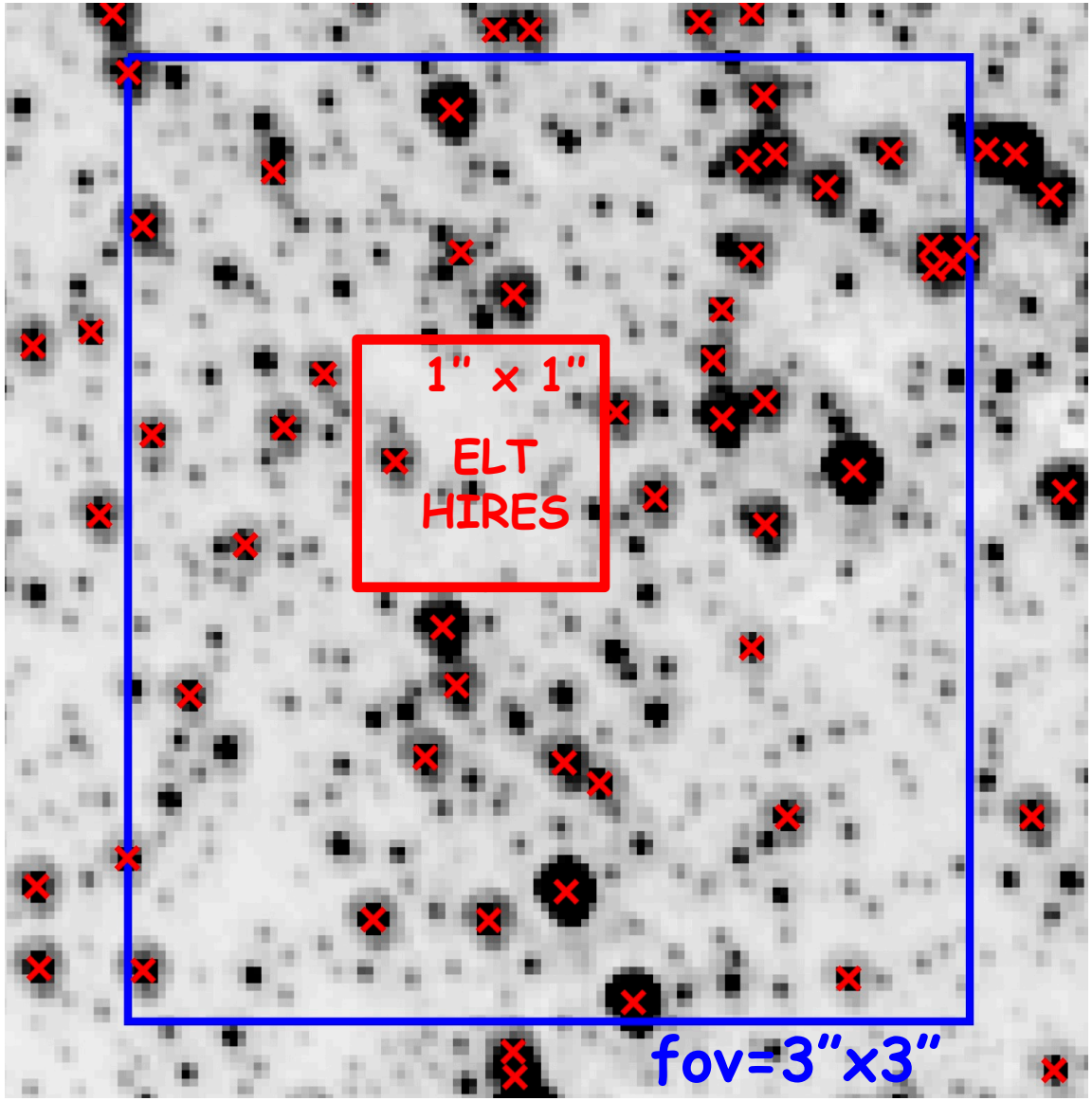
RVs with <1 km/s accuracy &

VD profile in bins of ~0.5"

ELT-HIRES spectroscopy in dense stellar fields

current design

small IFU+SCAO with 69 spaxels of possible scales from 7 to 120 mas



R=100,000

full spectral coverage in one exposure from 0.9 to 1.8 micron

complementary to HARMONI

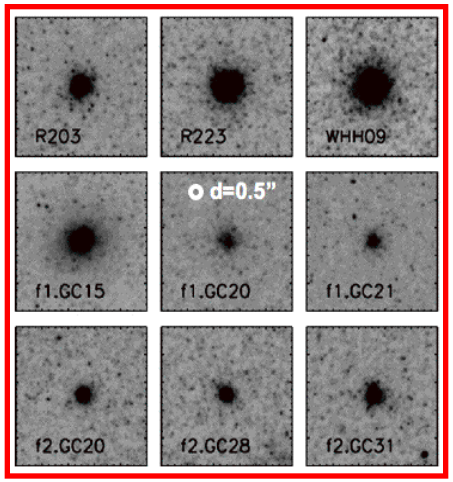
detailed chemistry

of <10 stars simultaneously

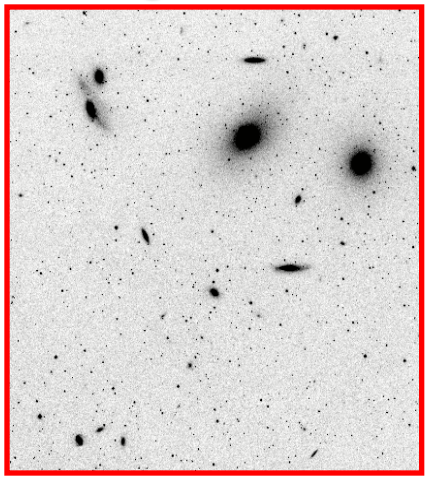
ELT spectroscopy in dense stellar fields

extra-galactic star clusters ➔ UCDs at 5-20 Mpc
tracers of the stellar pops, IMFs etc. of their host galaxy

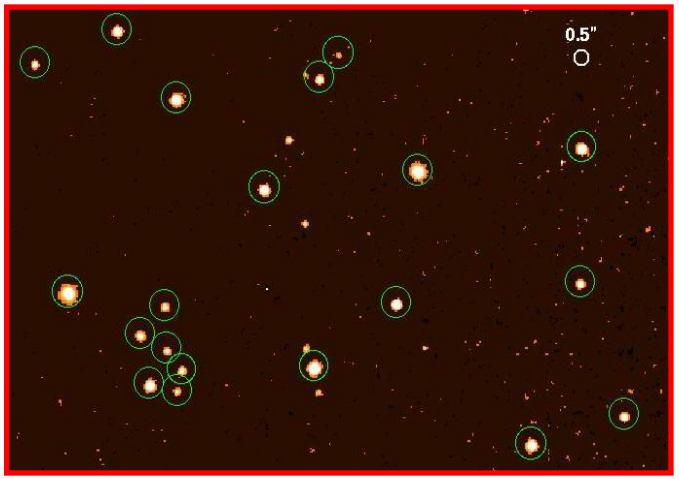
Centaurus



Virgo Cluster



M87



typical extension ➔ from a few hundreds mas to a few arcsec

integrated light ➔ detailed chemistry & dynamical mass

velocity dispersion & rotational profiles in annuli of some core radii (~100mas) out to a few tidal radii ➔ check for DM halos