Extreme Multiplex Spectroscopy on the E-ELT

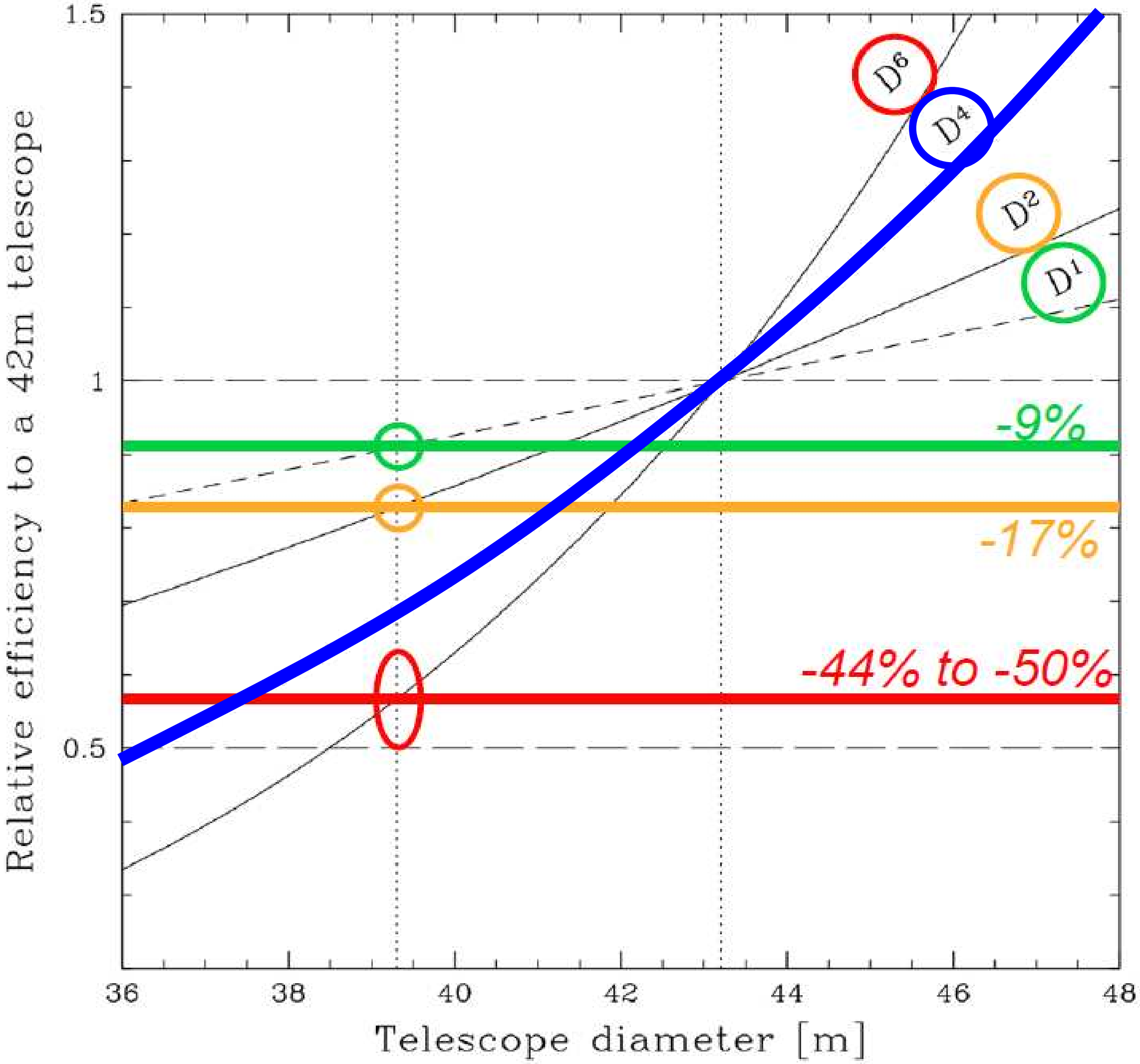
„Crowded Field 3D Spectroscopy"

Martin M. Roth
Sebastian Kamann
Lutz Wisotzki

Leibniz-Institut für Astrophysik Potsdam (AIP)
innoFSPEC Potsdam
Universität Potsdam

Shaping E-ELT Science and Instrumentation, ESO, Feb 28, 2013

E-ELT
Delta-Phase-B Trade-Off



~ **D**^{6}: *direct imaging of explanets*

~ **D**^{4}: *AO-limited observation, e.g. stellar spectroscopy in Virgo Cluster galaxies*

~ **D**^{2}: *photon-limited observations, e.g. cosmic expansion* $\rightarrow$ *CODEX*

~ **D**^{1}: *resolution limited obs., e.g. resolved stellar populations*

~ **D**^{0}: *RV research of exoplanets*

MICADO

- 3 mag sensitivity gain with AO
- reach e.g. tip of RGB in Virgo galaxies
- star clusters in z=2 galaxies
- intermediate mass black holes in GC

…

HARMONI

ELT-MOS (!)

PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC
99:191-222, March 1987

DAOPHOT: A COMPUTER PROGRAM FOR CROWDED-FIELD STELLAR PHOTOMETRY

PETER B. STETSON

Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics
5071 West Saanich Road, Victoria, British Columbia V8X 4M6, Canada

Received 1986 October 13, revised 1986 December 5

ABSTRACT

The difficult art of stellar photometry in crowded fields is currently undergoing a surge of popularity, and a number of different computer programs for deriving photometric information from two-dimensional digital images are currently in use. This paper describes one such program, DAOPHOT, which was written and continues to be developed at the Dominion Astrophysical Observatory. Emphasis is placed on the various types of philosophical and technical complications which arise when accurate photometry is sought for blended stellar images, and on the mathematical algorithms with which DAOPHOT attempts to deal with these complications, rather than on details of the coding. Some ways in which DAOPHOT resembles or differs from other similar programs are mentioned, and a discussion is presented of known shortcomings of the current program as well as possibilities for future improvement.

Key words: data-handling techniques–photometry (general)

A&A 549, A71 (2013)
DOI: 10.1051/0004-6361/201220476

Astronomy & Astrophysics

Resolving stellar populations with crowded field 3D spectroscopy⋆,⋆⋆

S. Kamann, L. Wisotzki, and M. M. Roth

Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany
e-mail: skamann@aip.de

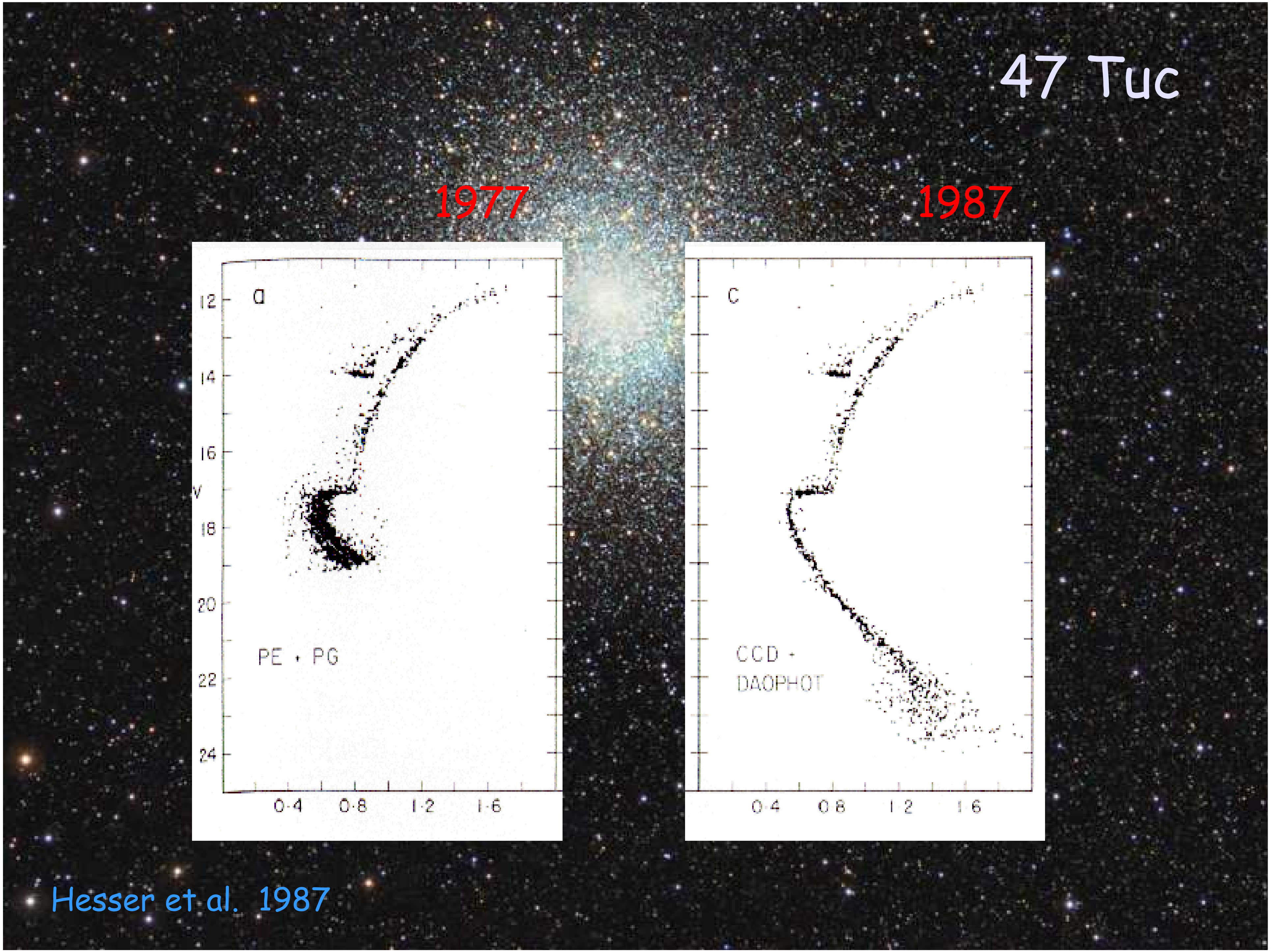
Received 1 October 2012 / Accepted 1 November 2012

ABSTRACT

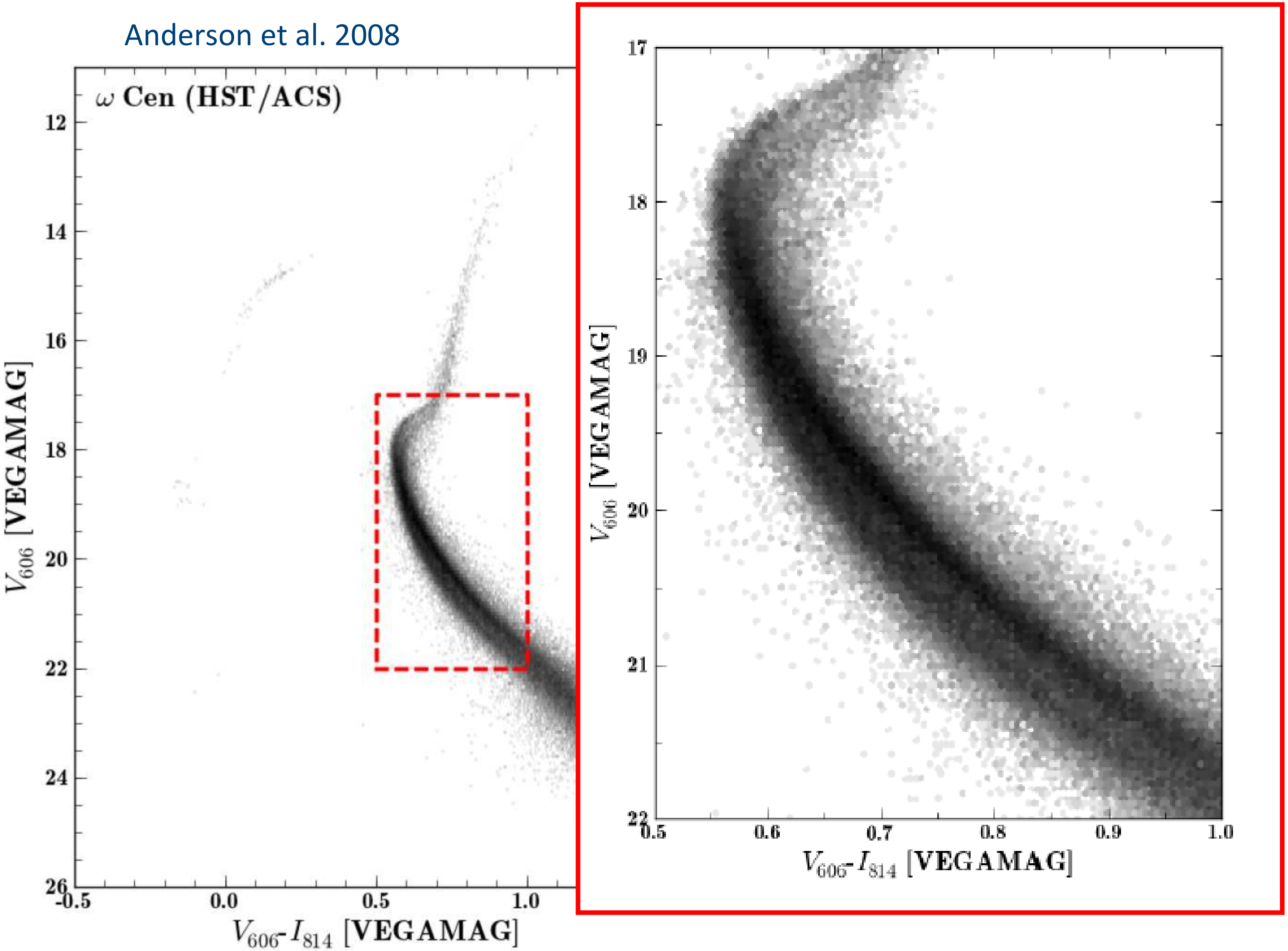
We describe a new method of extracting the spectra of stars from observations of crowded stellar fields with integral field spectroscopy (IFS). Our approach extends the well-established concept of crowded field photometry in images into the domain of 3-dimensional spectroscopic datacubes. The main features of our algorithm follow. (1) We assume that a high-fidelity input source catalogue already exists, e.g. from HST data, and that it is not needed to perform sophisticated source detection in the IFS data. (2) Source positions and properties of the point spread function (PSF) vary smoothly between spectral layers of the datacube, and these variations can be described by simple fitting functions. (3) The shape of the PSF can be adequately described by an analytical function. Even without isolated PSF calibrator stars we can therefore estimate the PSF by a model fit to the full ensemble of stars visible within the field of view. (4) By using sparse matrices to describe the sources, the problem of extracting the spectra of many stars simultaneously becomes computationally tractable. We present extensive performance and validation tests of our algorithm using realistic simulated datacubes that closely reproduce actual IFS observations of the central regions of Galactic globular clusters. We investigate the quality of the extracted spectra under the effects of crowding with respect to the resulting signal-to-noise ratios (S/N) and any possible changes in the continuum level, as well as with respect to absorption line spectral parameters, radial velocities, and equivalent widths. The main effect of blending between two nearby stars is a decrease in the S/N in their spectra. The effect increases with the crowding in the field in a way that the maximum number of stars with useful spectra is always ~0.2 per spatial resolution element. This balance breaks down when exceeding a total source density of one significantly detected star per resolution element. We also explore the effects of PSF mismatch and other systematics. We close with an outlook by applying our method to a simulated globular cluster observation with the upcoming MUSE instrument at the ESO-VLT.

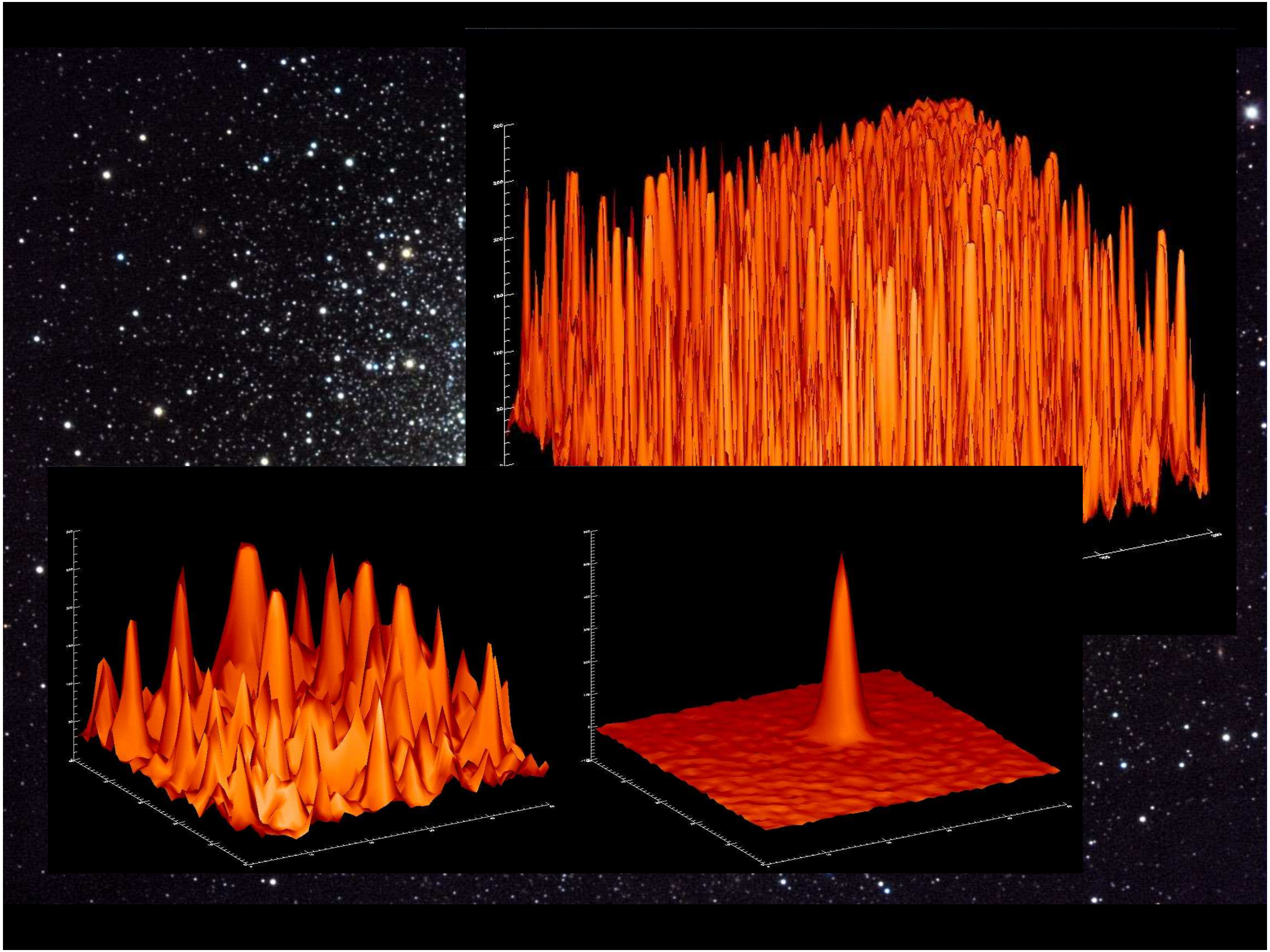
Key words. methods: data analysis – techniques: imaging spectroscopy – globular clusters: general

1. Crowded Field Photometry


47 Tuc
1977
1987
a
12
14
16
V
18
20
22
24
PE + PG
0·4
0·8
1·2
1·6
c
CCD +
DAOPHOT
0·4
0·8
1·2
1·6
Hesser et al. 1987

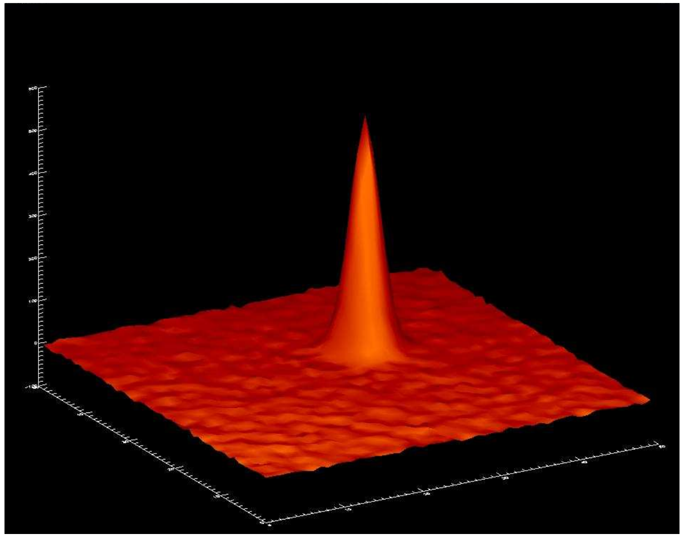
Anderson et al. 2008





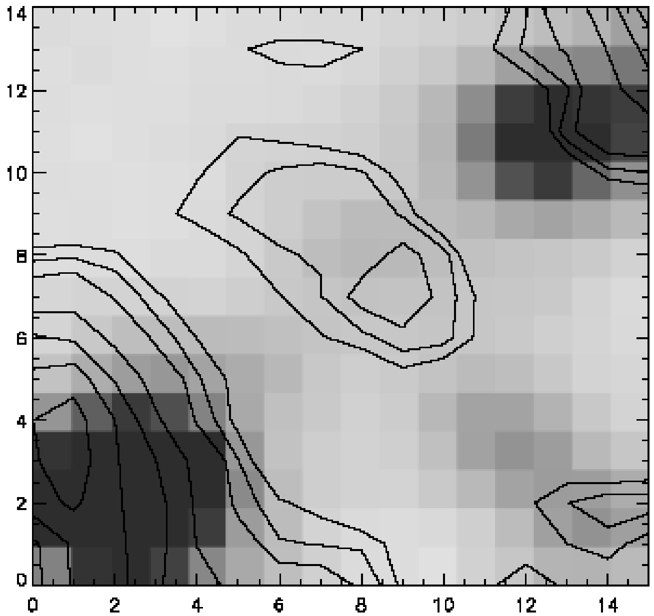
2. Crowded Field 3D Spectroscopy

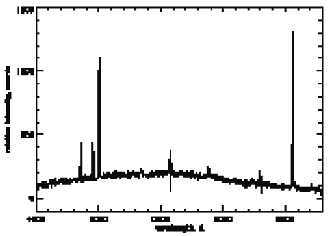
- early experiments

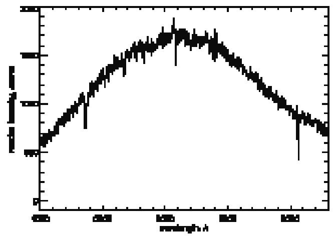


Crowded-field 3D spectroscopy

2 *Roth, Becker & Schmoll* ***(2000)***







„Crowded-field 2D spectroscopy:
promise and limitations“

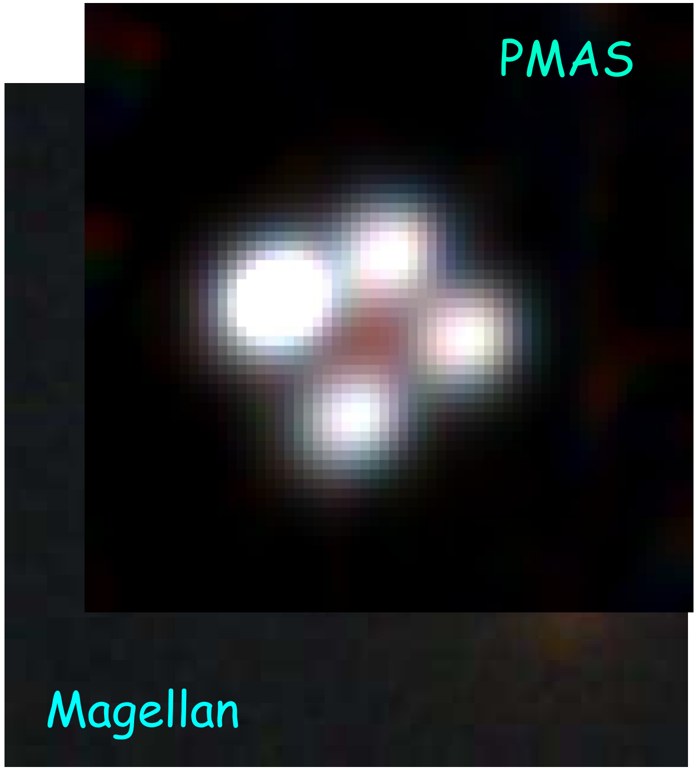
presented at

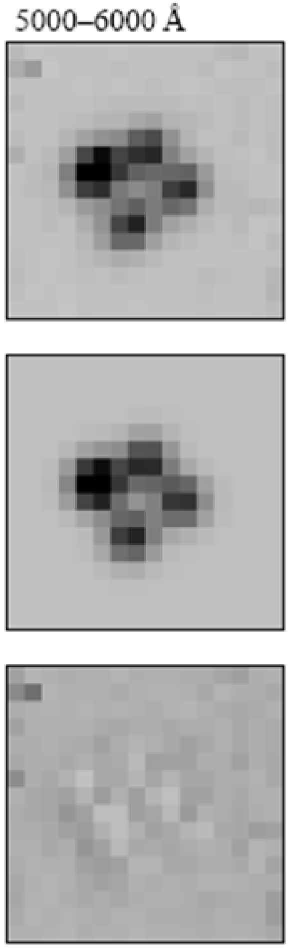
„Imaging the Universe in Three Dimensions“
Walnut Creek, March 1999

Figure 1. Crowded field 2D spectroscopy of
The greyscale image represents the continuum,
sion line surface brightness in H_α. Integrated sp
right ($m_v \approx 18$) and a nearby H II region are plotted on the right. The example demonstrates how the subtraction of the nebular emission would have been underestimated from slit spectroscopy, taking e.g. background values from above and below the star with a vertically oriented slit. MPFS data kindly provided by S. Fabrika, V. Afanasiev, S. Dodonov (SAO).

Crowded-field 3D spectroscopy

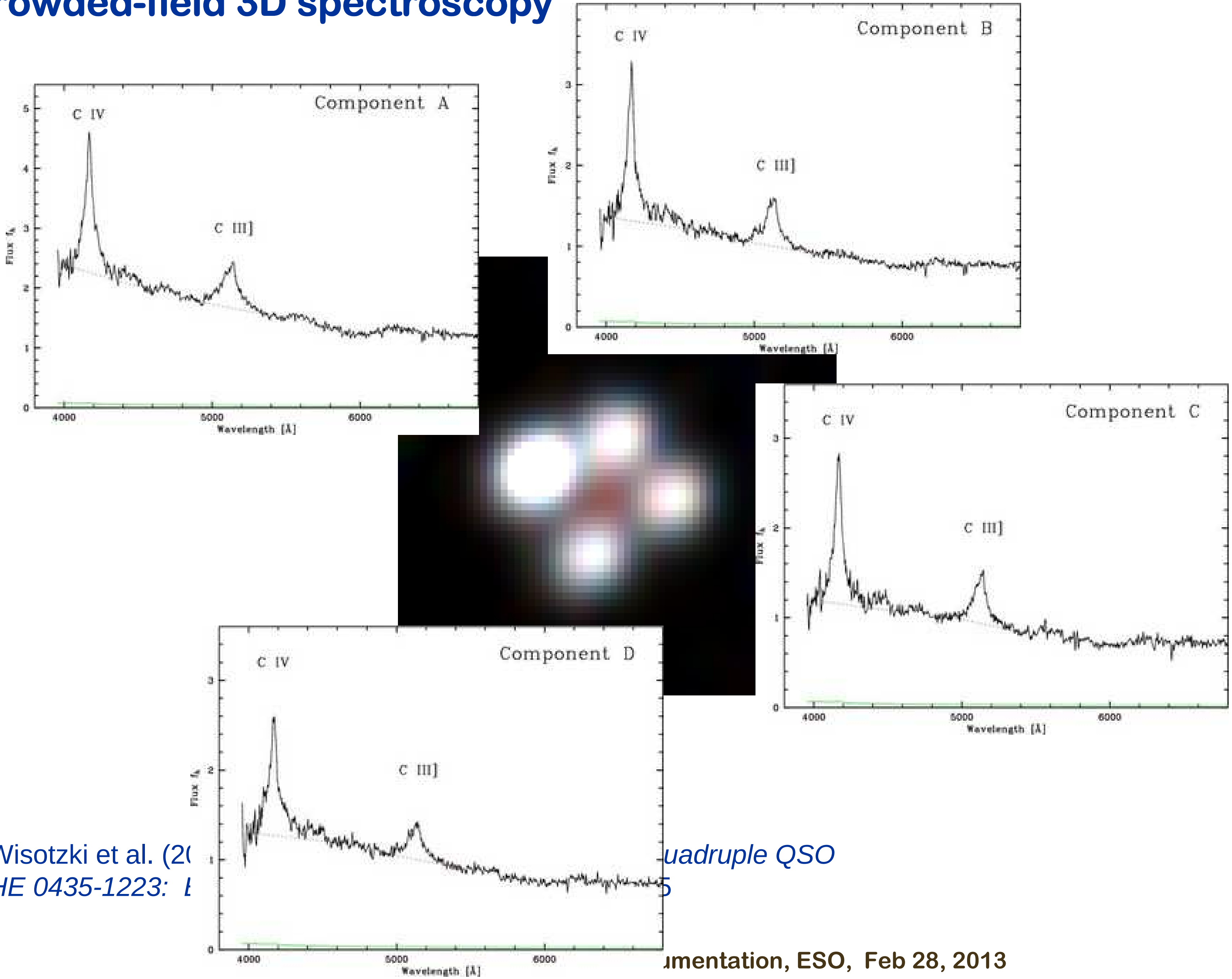
gravitational lens HE 0435-1223





Wisotzki et al. (2003), *Integral-field spectroscopy of the quadruple QSO HE 0435-1223: Evidence for microlensing,* A&A 408, 455

Crowded-field 3D spectroscopy



Wisotzki et al. (2(... uadruple QSO
HE 0435-1223: l ... 5

A&A 437, 217–226 (2005)
DOI: 10.1051/0004-6361:20035824

Astronomy & Astrophysics

Crowded field 3D spectroscopy of LBV candidates in M 33

S. Fabrika[1], O. Sholukhova[1], T. Becker[2], V. Afanasiev[1], M. Roth[2], and S. F. Sanchez[2]

[1] Special Astrophysical Observatory, Nizhnij Arkhyz, Karachaevo-Cherkesia, 369167, Russia
e-mail: fabrika@sao.ru
[2] Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482, Potsdam,
e-mail: mmroth@aip.de

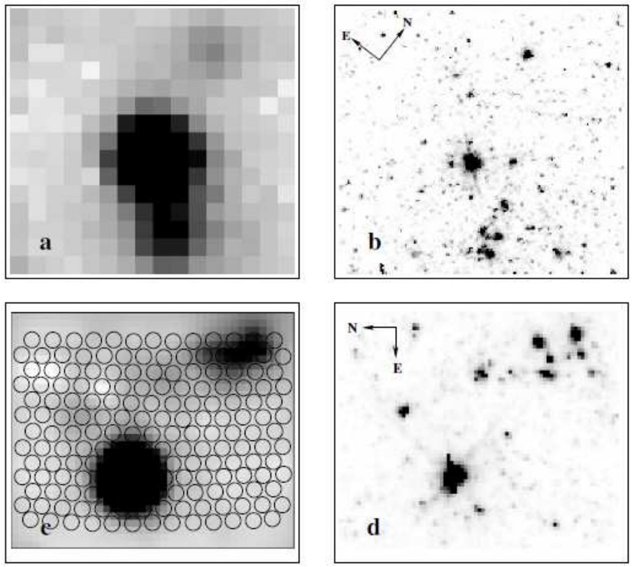
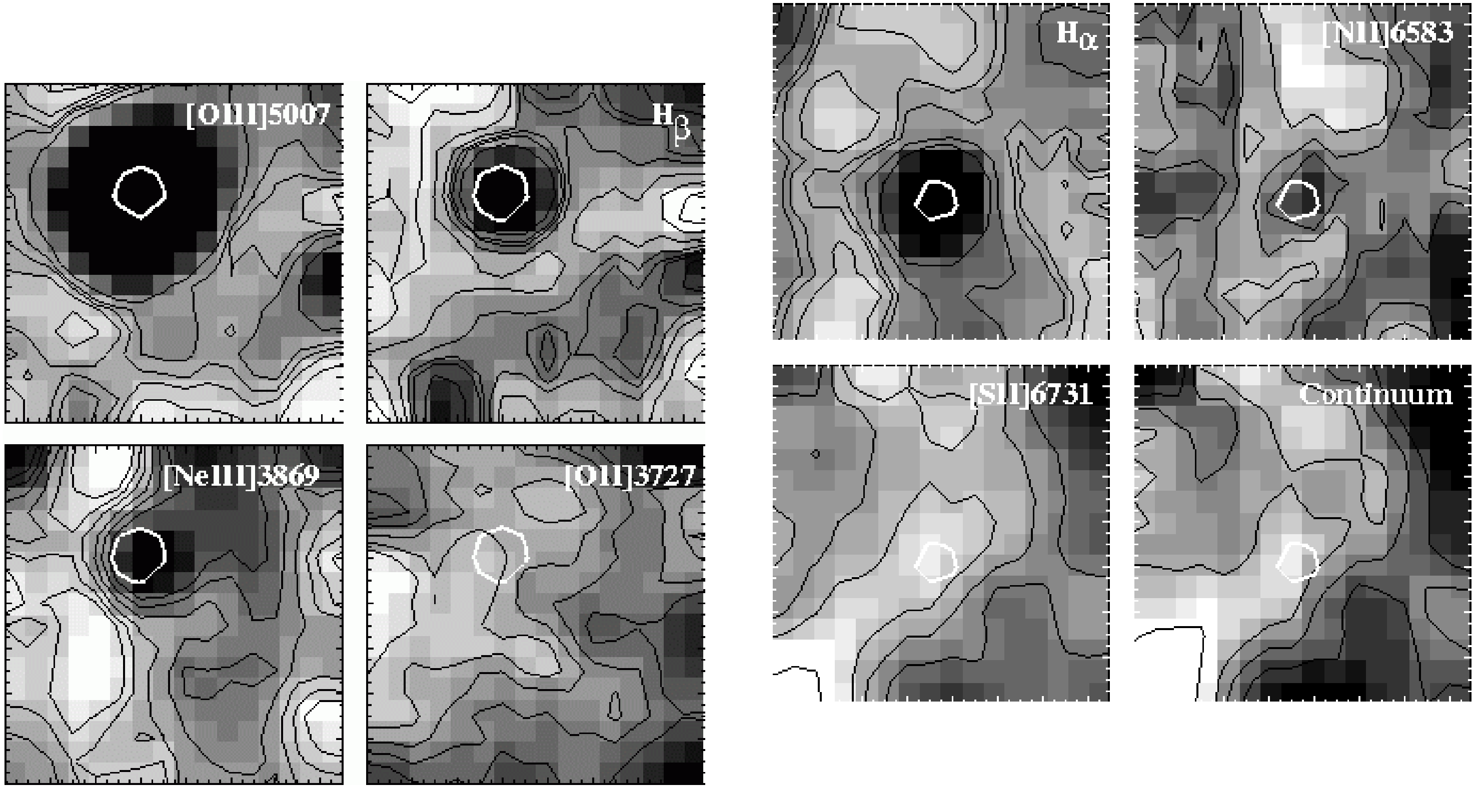


Fig. 1. a) MPFS map of B416 at 6000 Å (spatial sampling 1 arcsec, the FOV is 16 × 15 arcsec^2) and the same field **b)** from the HST WFC2 image. An enlarged fraction of this field from the INTEGRAL in the same wavelength **c)** and the corresponding enlarged HST field **d)**. Note the different orientation of the MPFS and INTEGRAL fields.

Crowded-field 3D spectroscopy

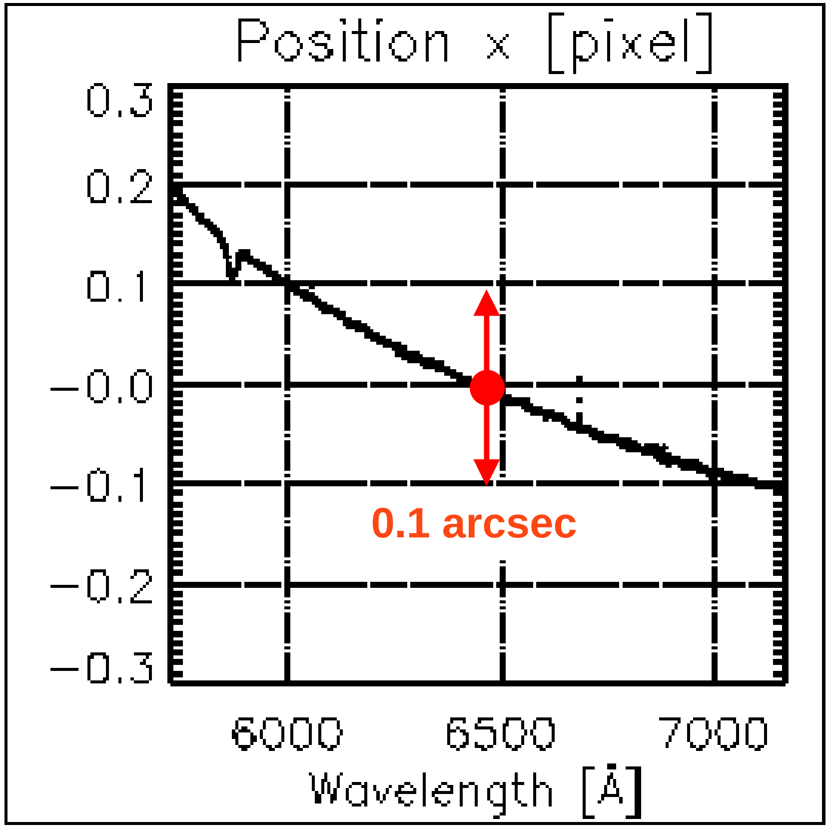
Planetary Nebulae in M31

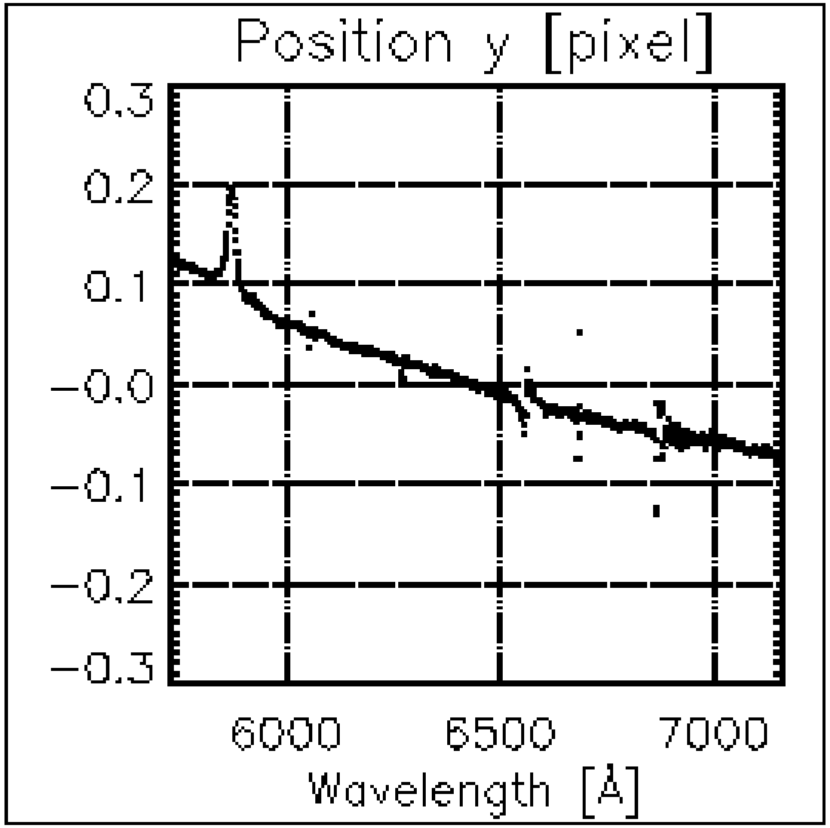


Roth et al. (2005), ApJ 603, 531

Crowded-field 3D spectroscopy

Standard Star HR 1544





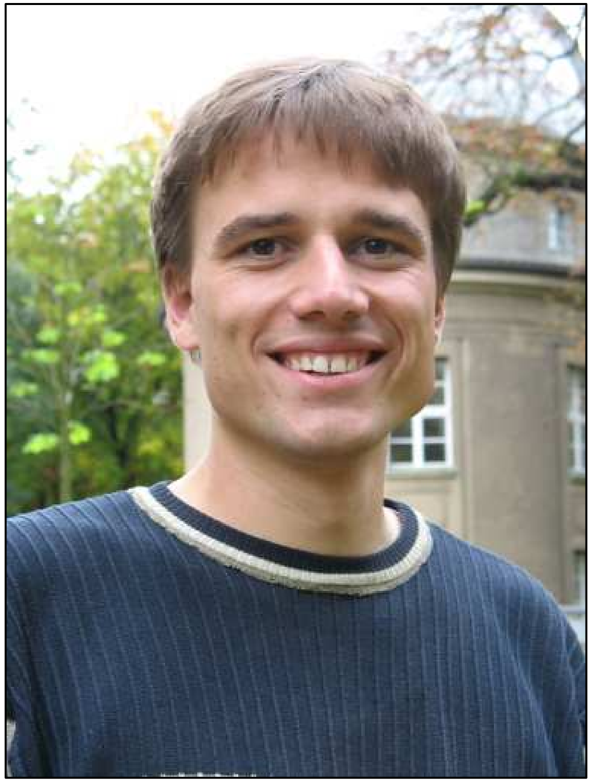
Roth et al. (2005), ApJ 603, 531

3. Crowded Field 3D Spectroscopy

- recent progress
  (thesis Sebastian Kamann)

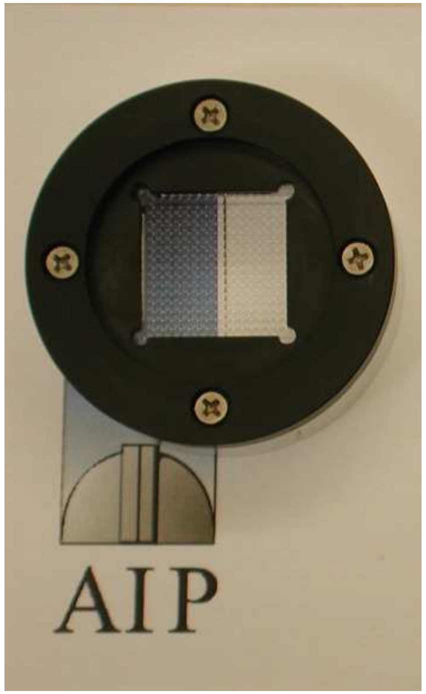
AIP

muse



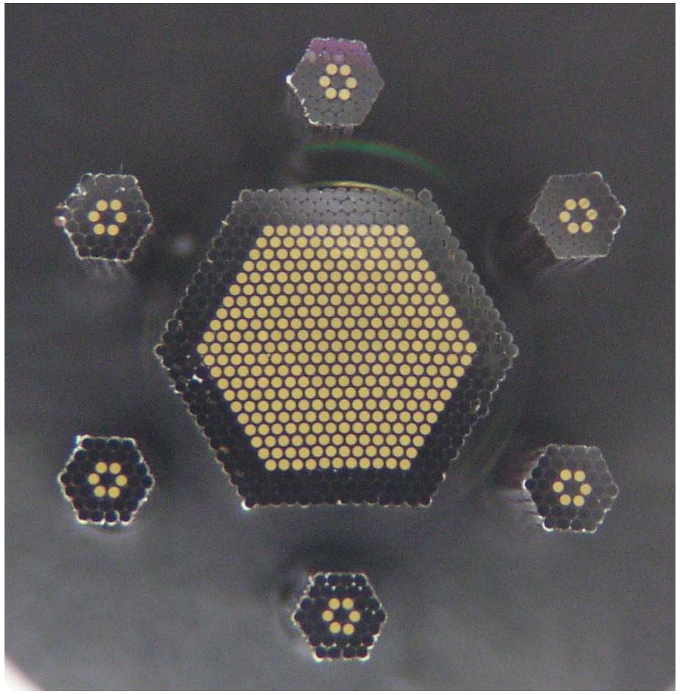
PMAS at the Calar Alto 3.5m Telescope

LARR IFU



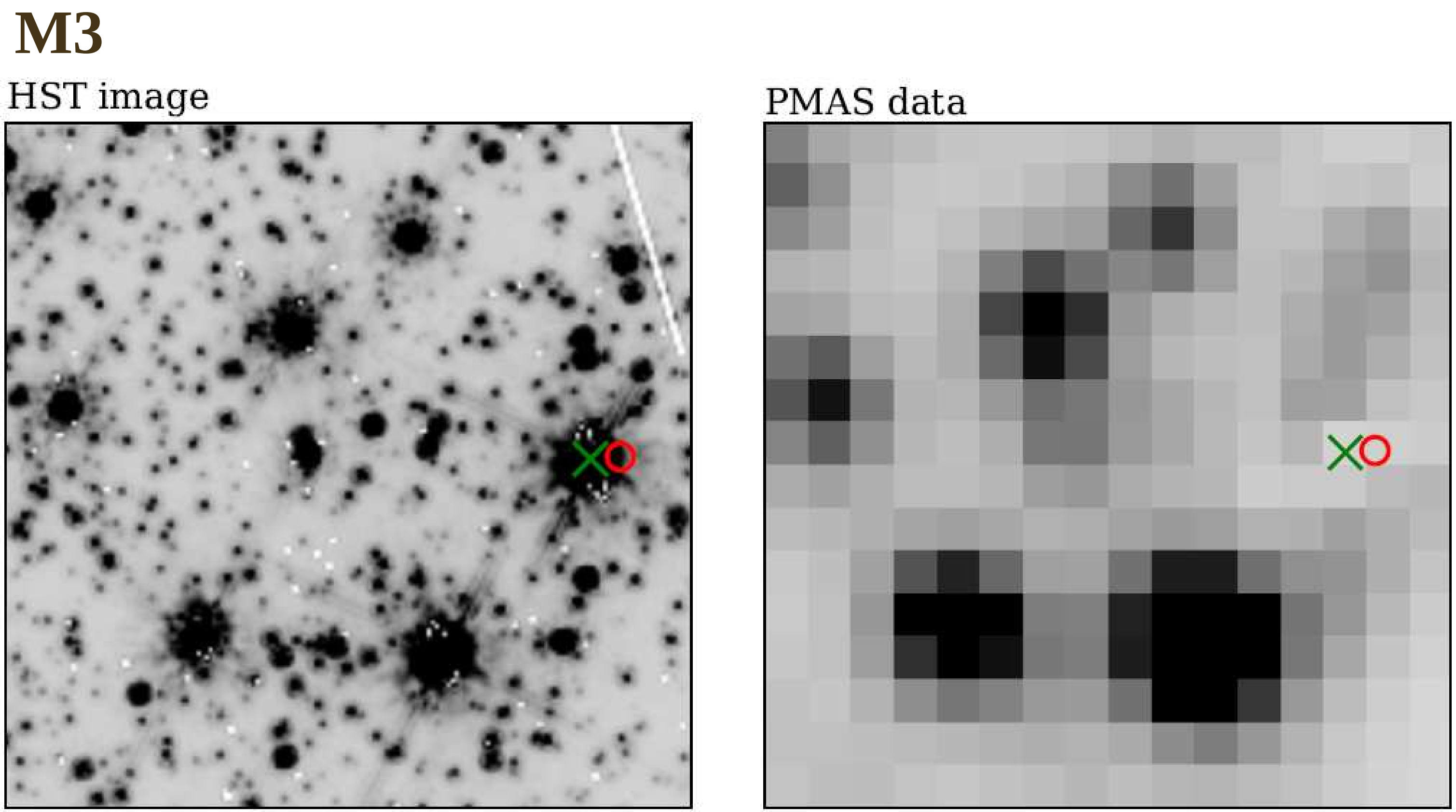
8 arcsec

PPak IFU

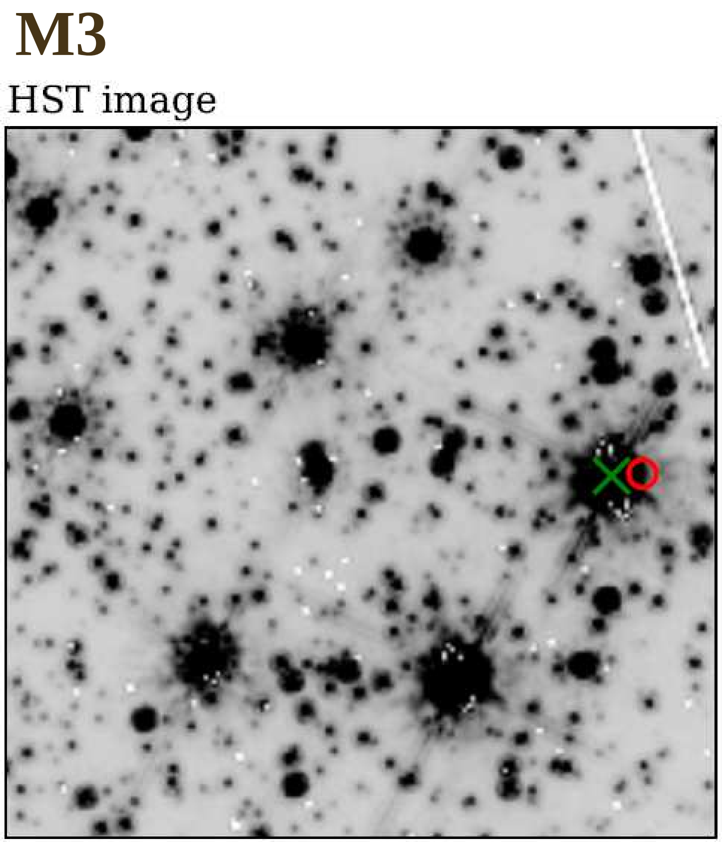


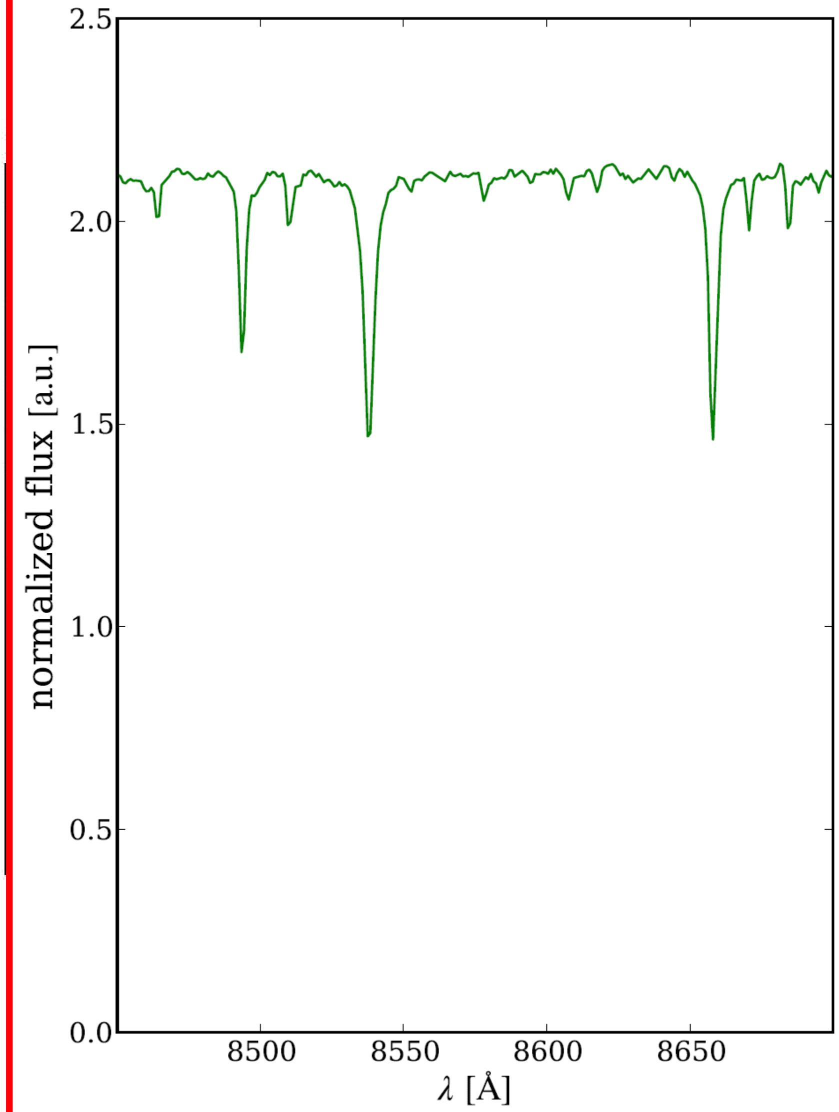
74 arcsec

PMAS at the Calar Alto 3.5m Telescope



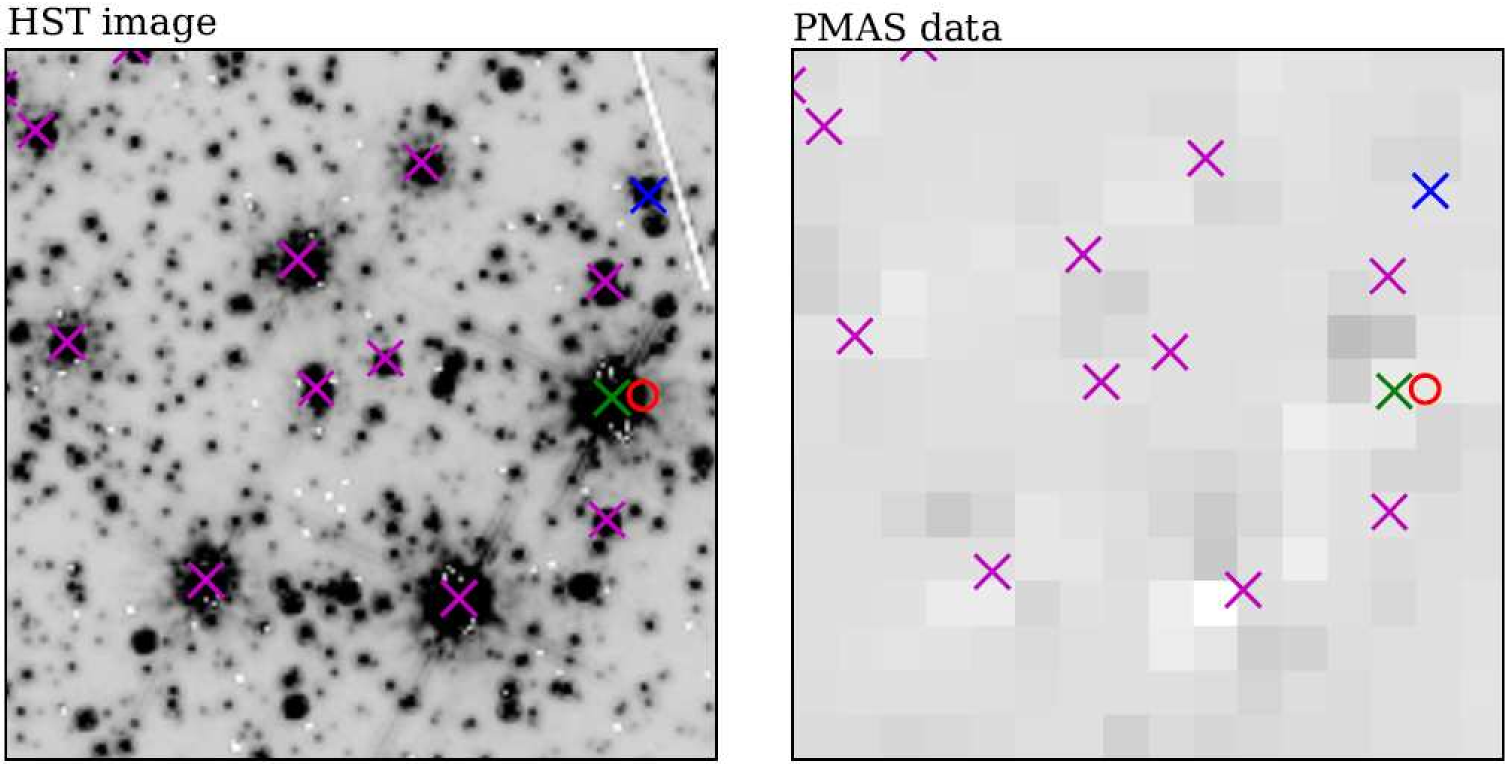
PMAS at the Calar Alto 3.5m Telescope



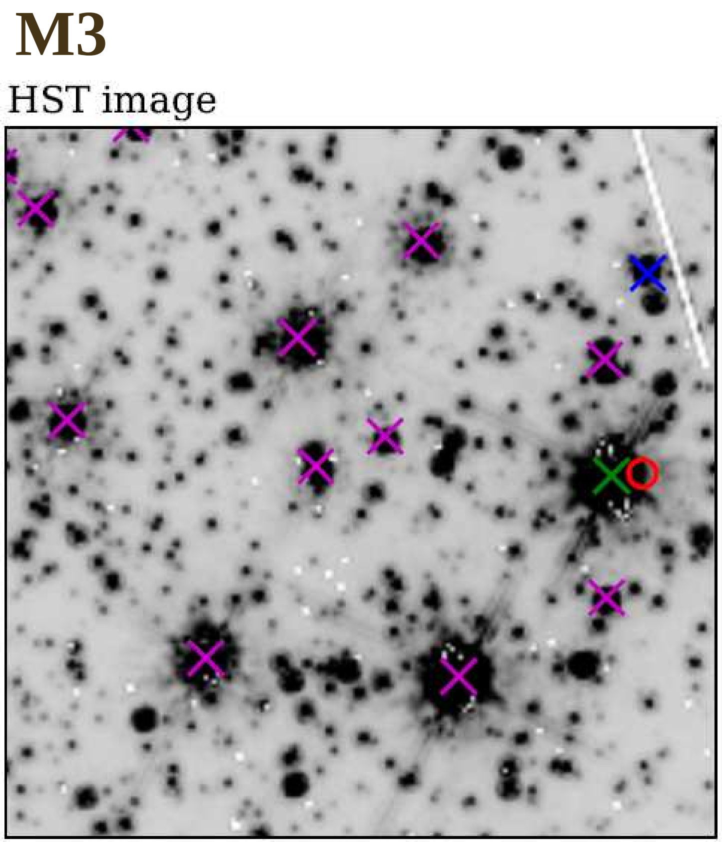


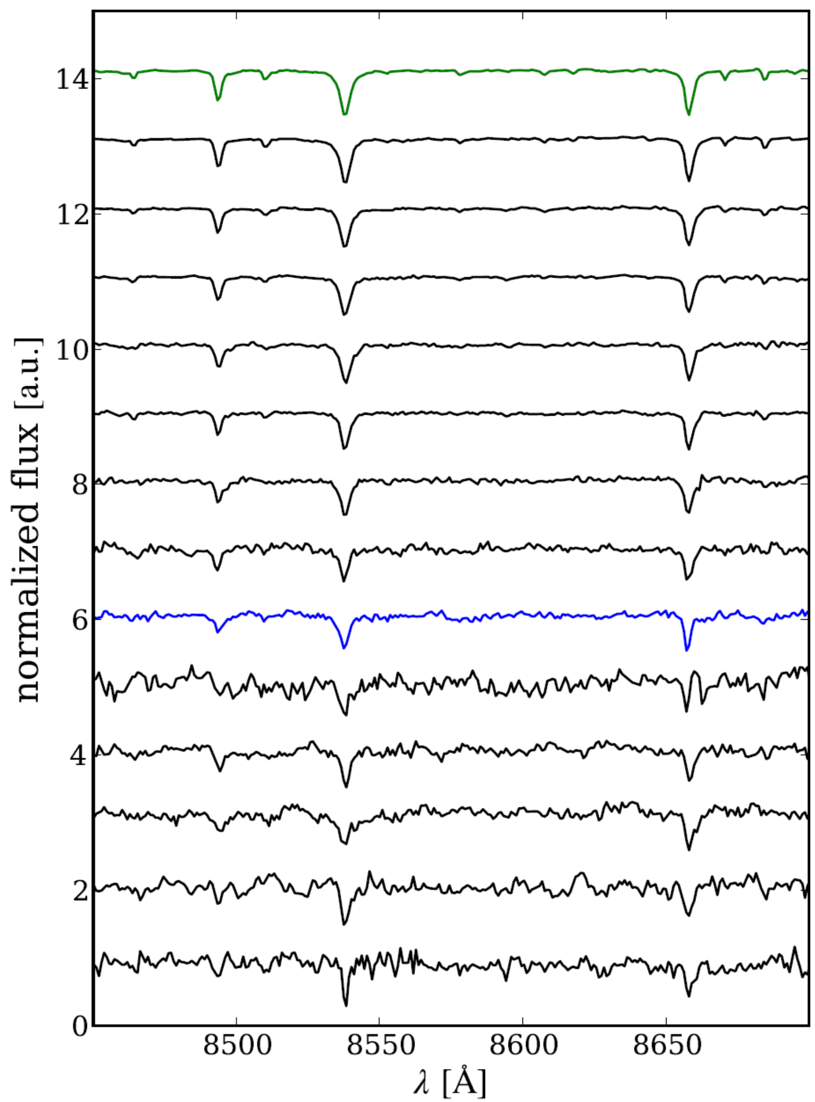
PMAS at the Calar Alto 3.5m Telescope

M3



PMAS at the Calar Alto 3.5m Telescope





PSF-fitting crowded field 3D spectroscopy, assumptions:

(1) a priori knowledge of stellar centroids

(2) smooth variation of centroids and FWHM between datacube layers (fitted by polynomials)

(3) PSF adequately described by analytical function

(4) Use of sparse matrices for source description (to make source extraction numerically tractable)

Crowded field 3D spectroscopy: Kamann et al. 2013

Modelling the Point Spread Function (PSF):

$$\hat{x} = (x - x^n)\cos\theta - (y - y^n)\sin\theta,$$

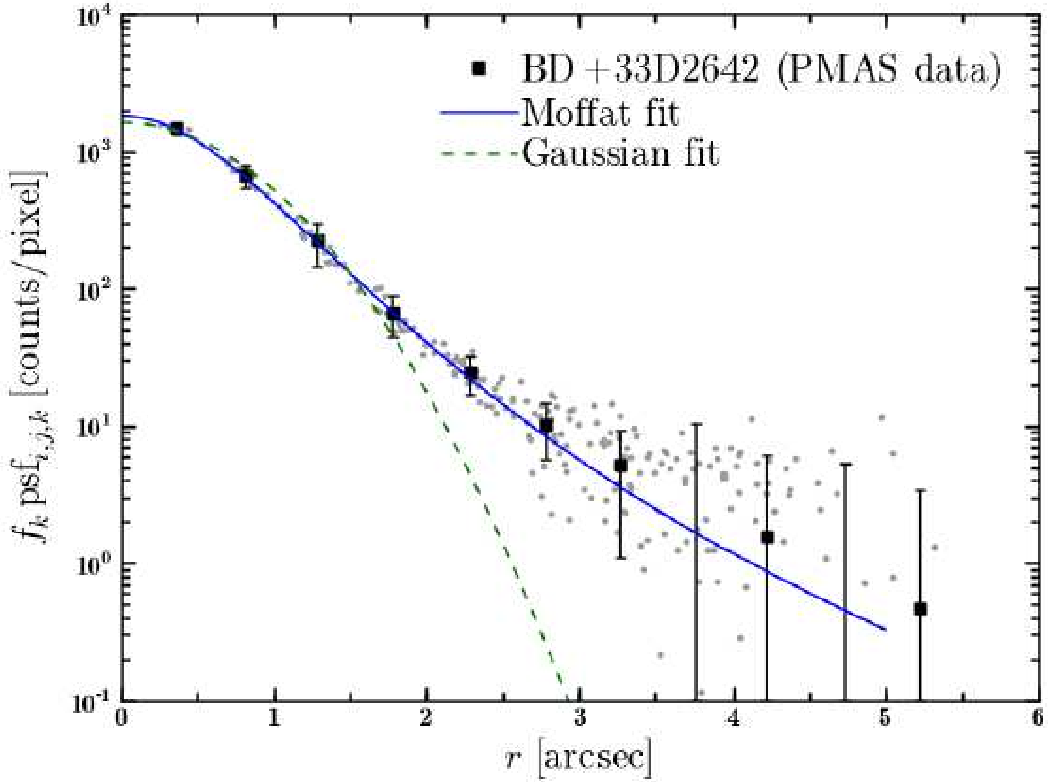
$$\hat{y} = (x - x^n)\sin\theta + (y - y^n)\cos\theta,$$

$$r(x, y) = \sqrt{\hat{x}^2 + \left(\frac{\hat{y}}{1-e}\right)^2}$$

$$M(x, y) = \Sigma_0 \left(1 + \left(\frac{r(x, y)}{r_\mathrm{d}}\right)^2\right)^{-\beta}$$

$$FWHM = 2\sqrt{2^{1/\beta} - 1}\, r_\mathrm{d}$$

Moffat Function



Crowded field 3D spectroscopy: Kamann et al. 2013

Global Model:

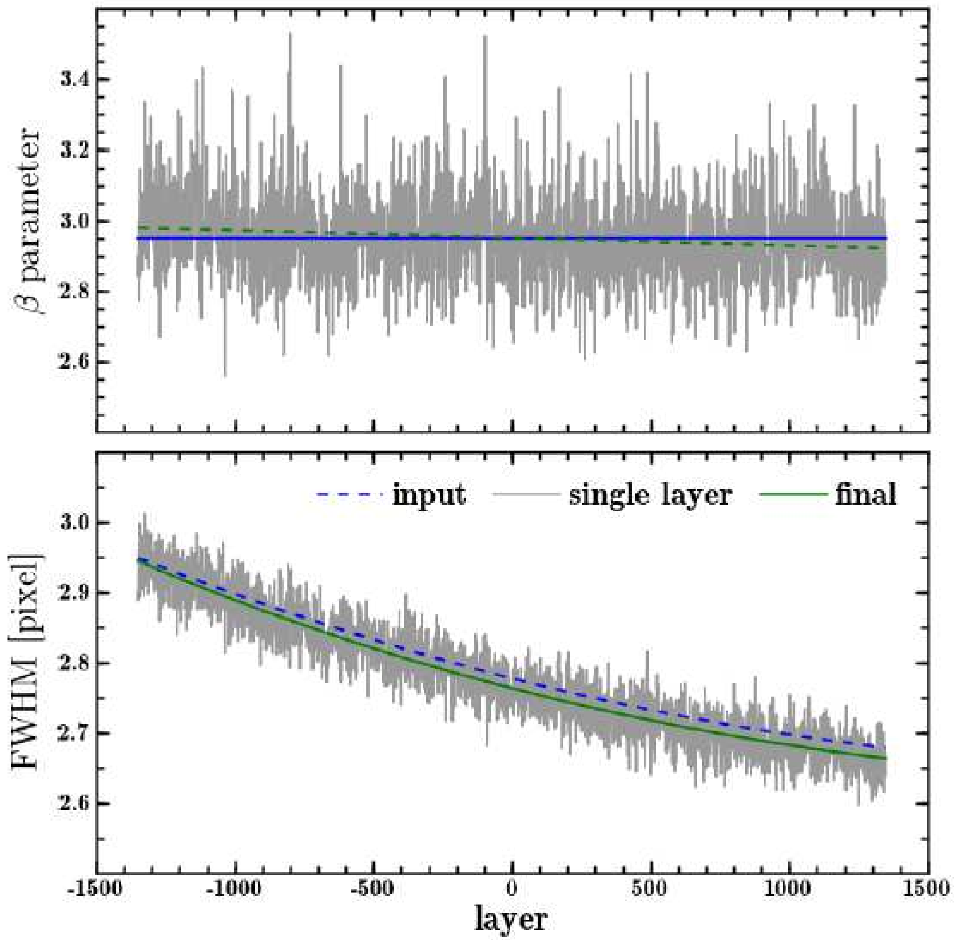
observed datacube: $\mathfrak{d}_{i,j,k}$

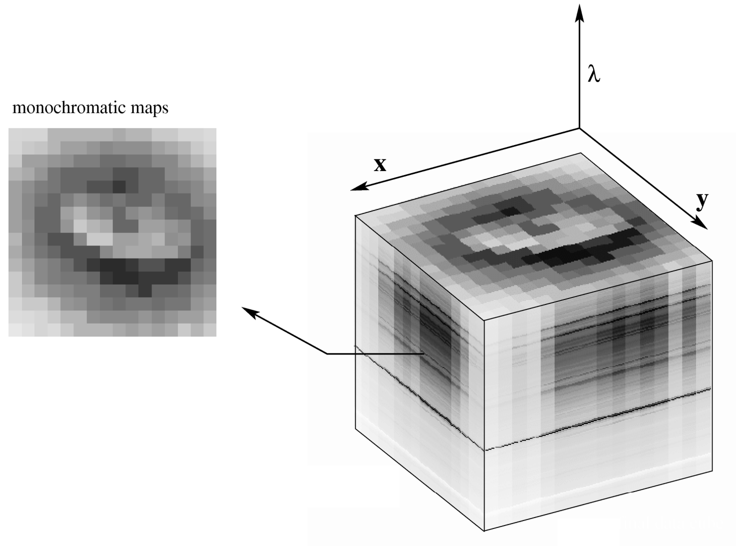
model datacube: $$\mathfrak{m}_{i,j,k} = \sum_n f_k^n \, \mathrm{psf}^n_{i,j,k} + \sum_m b^m_{i,j,k}$$

minimization: $$\chi^2 = \sum_{i,j,k} \frac{\left(\mathfrak{d}_{i,j,k} - \sum_n f_k^n \, \mathrm{psf}^n_{i,j,k} - \sum_m b^m_{i,j,k}\right)^2}{\sigma^2_{i,j,k}}$$

Crowded field 3D spectroscopy: Kamann et al. 2013

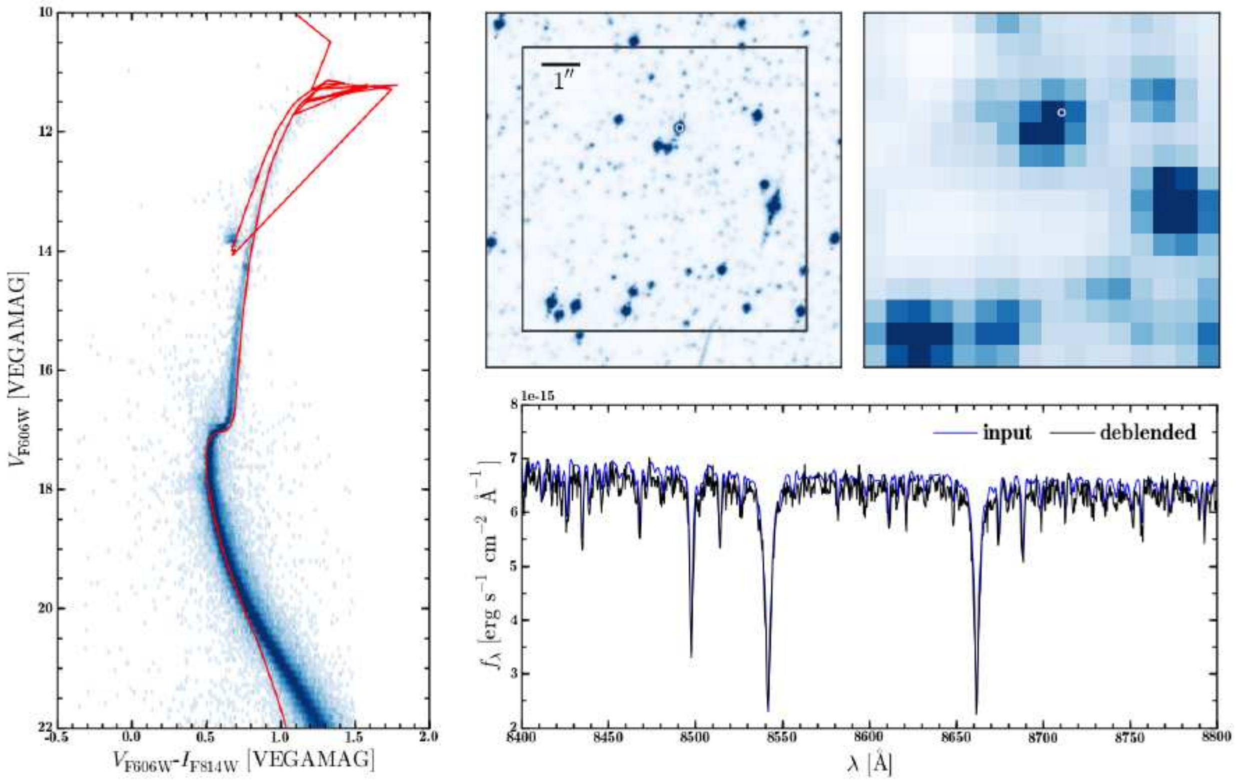
Recovering the PSF throughout the entire datacube:





Crowded field 3D spectroscopy: Kamann et al. 2013

Simulation of PMAS datacubes with 47 Tuc data



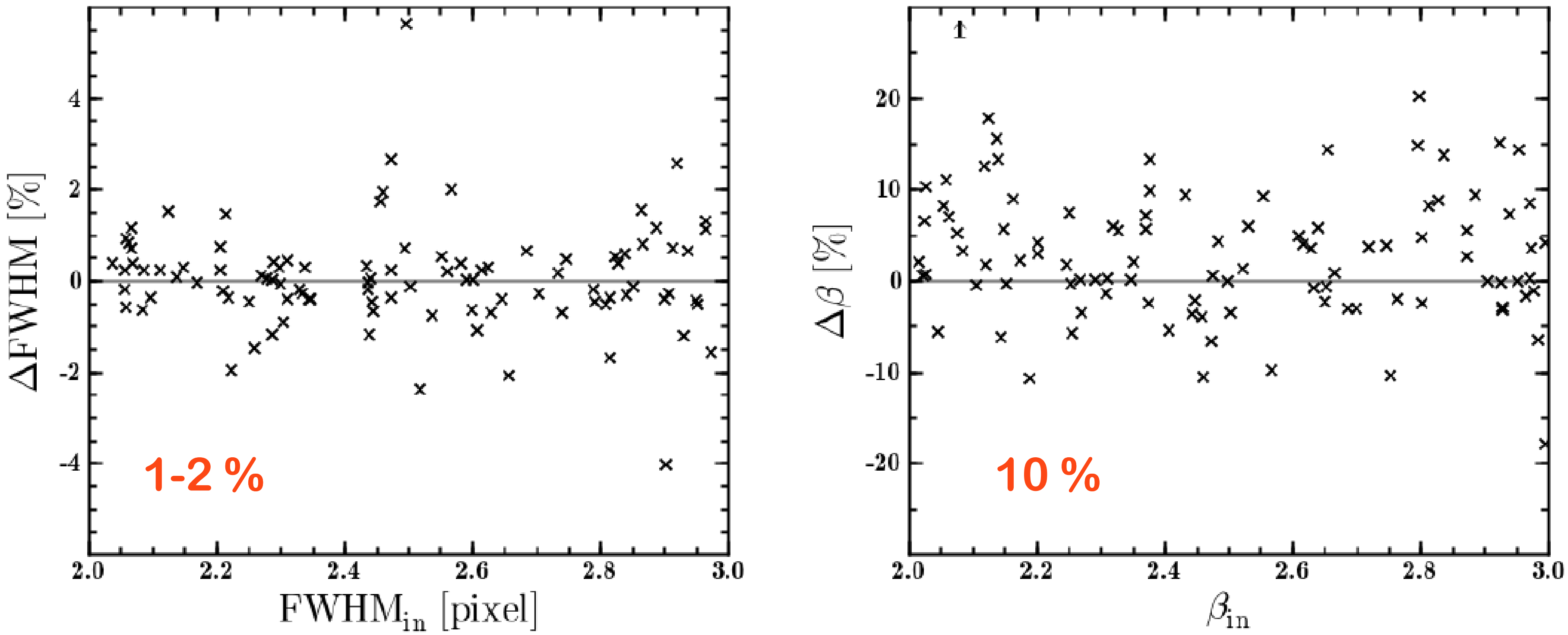
→ evidence for IMBH ?

Input:

- HST photometry Sarajedini et al. 2007, Anderson et al. (2008)
- log g, Teff from isochrone 13 Gyr, z=0.0045, Marigo et al. (2008)
- library spectra from Munari et al. (2005)
- random velocities, normal distribution (σ = 10 km/s)

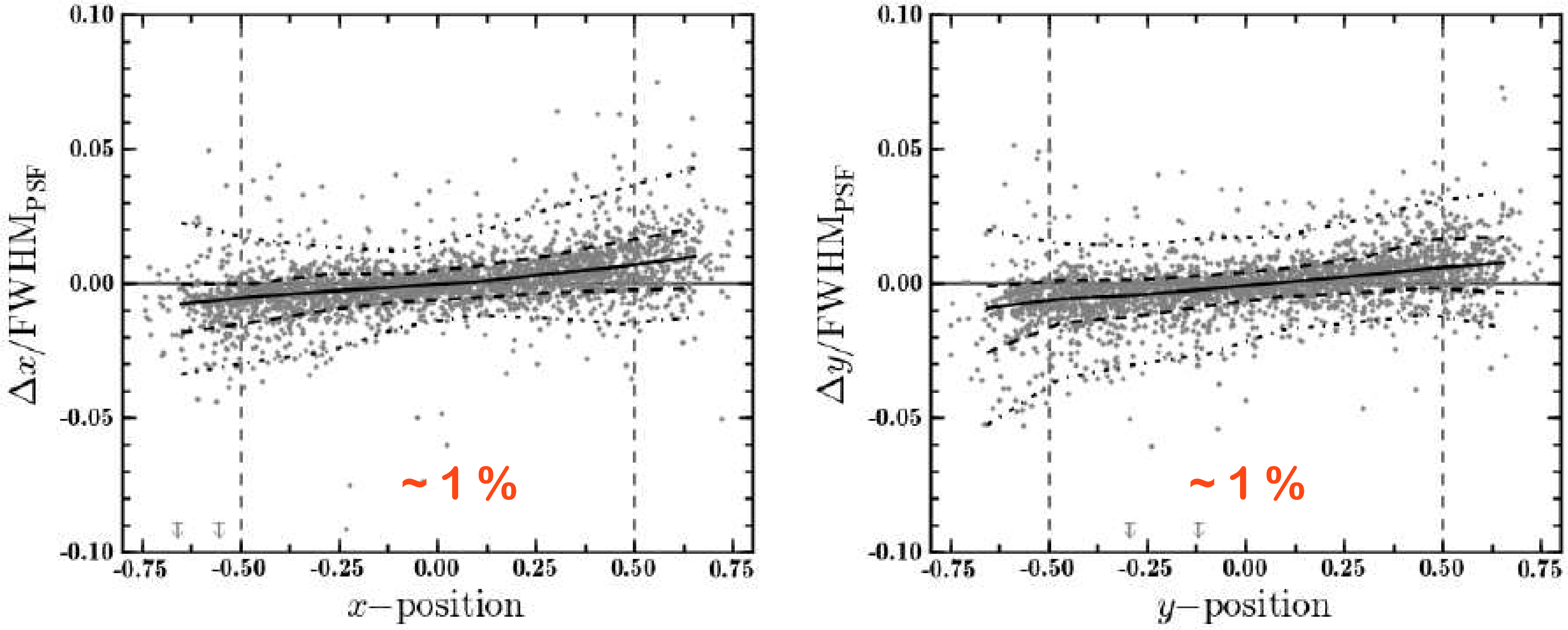
Crowded field 3D spectroscopy: Kamann et al. 2013

Simulations, recovering the PSF:



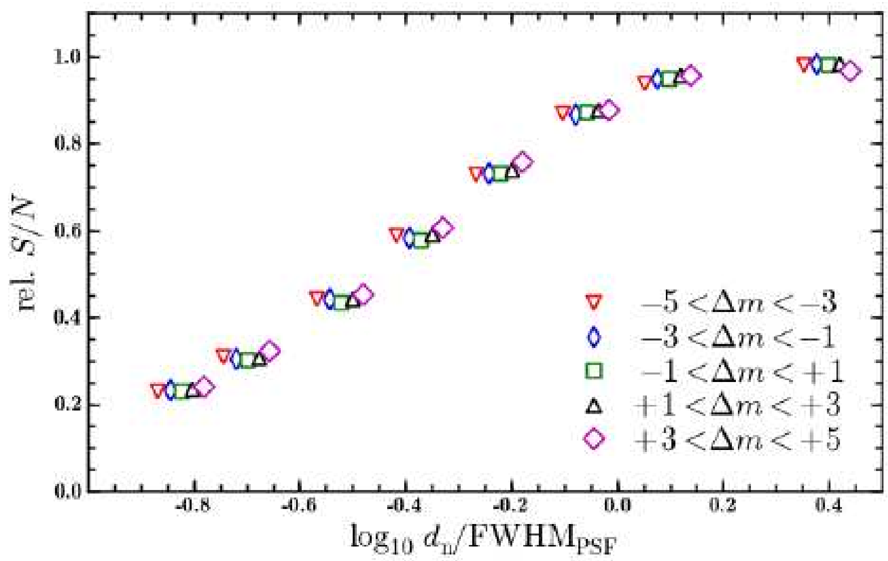
Crowded field 3D spectroscopy: Kamann et al. 2013

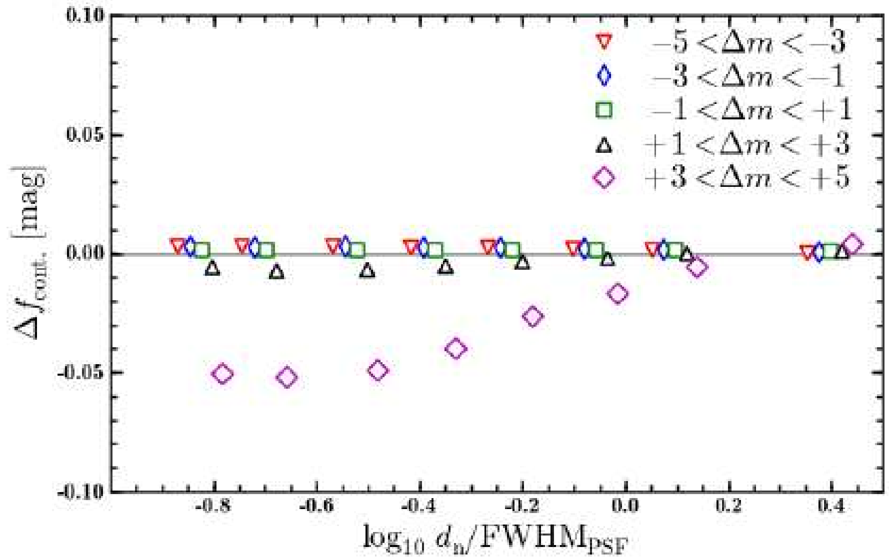
Simulations, recovering the centroid:



Crowded field 3D spectroscopy: Kamann et al. 2013

Simulations, blending effects for various levels of contrast:





S/N affected by blending

continuum affected by blending

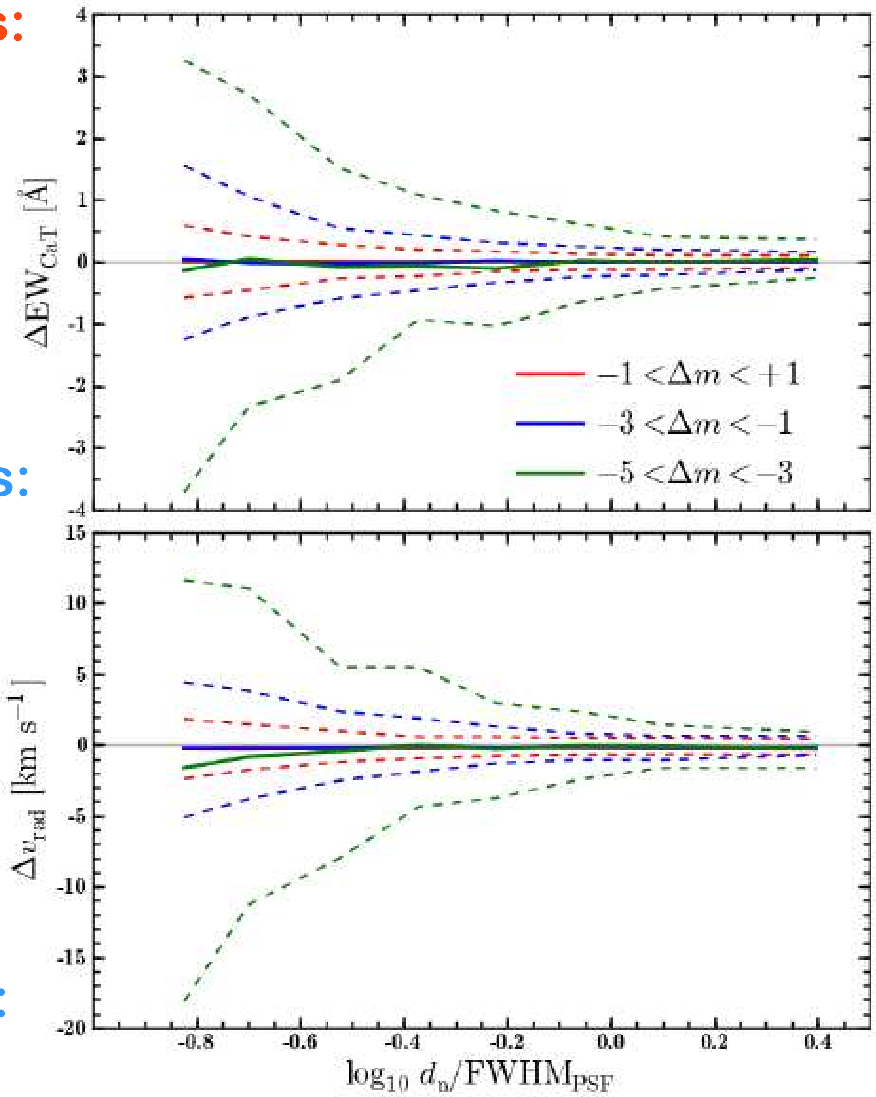
Crowded field 3D spectroscopy: Kamann et al. 2013

median and 75% percentiles

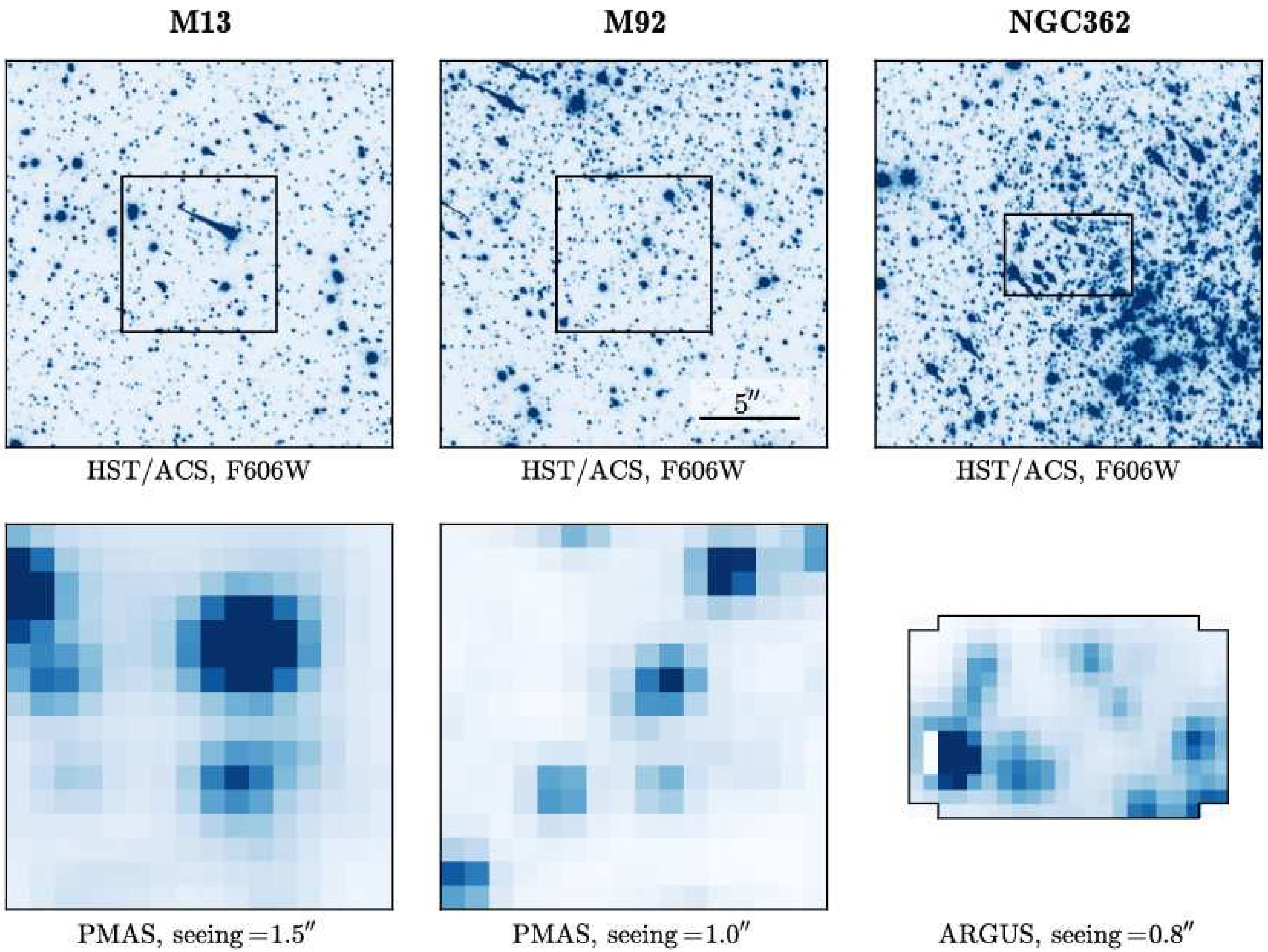
Simulations, blending effects:

equivalent widths:

radial velocities:

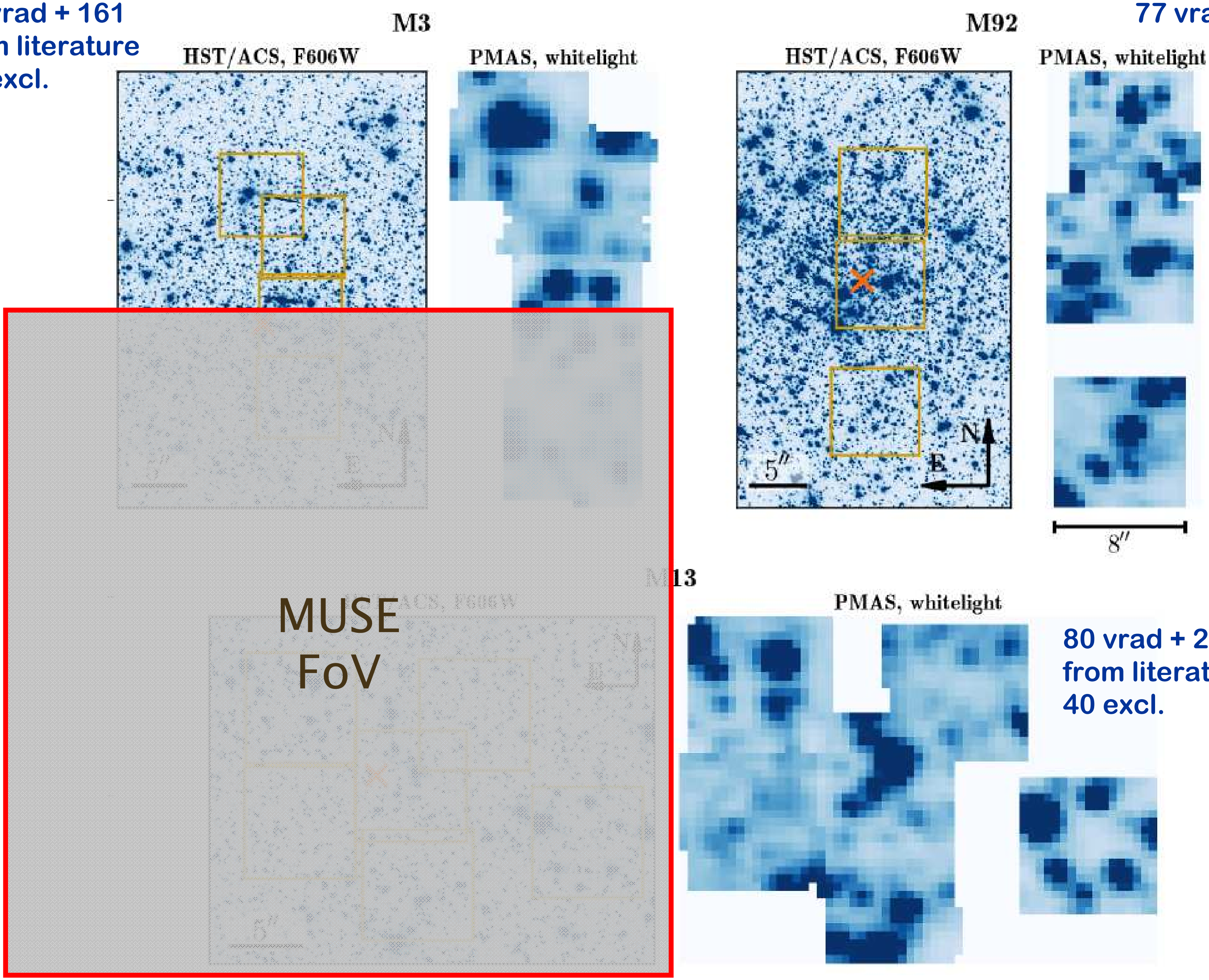


Crowded field 3D spectroscopy: Kamann et al. 2013



50 vrad + 161
from literature
17 excl.

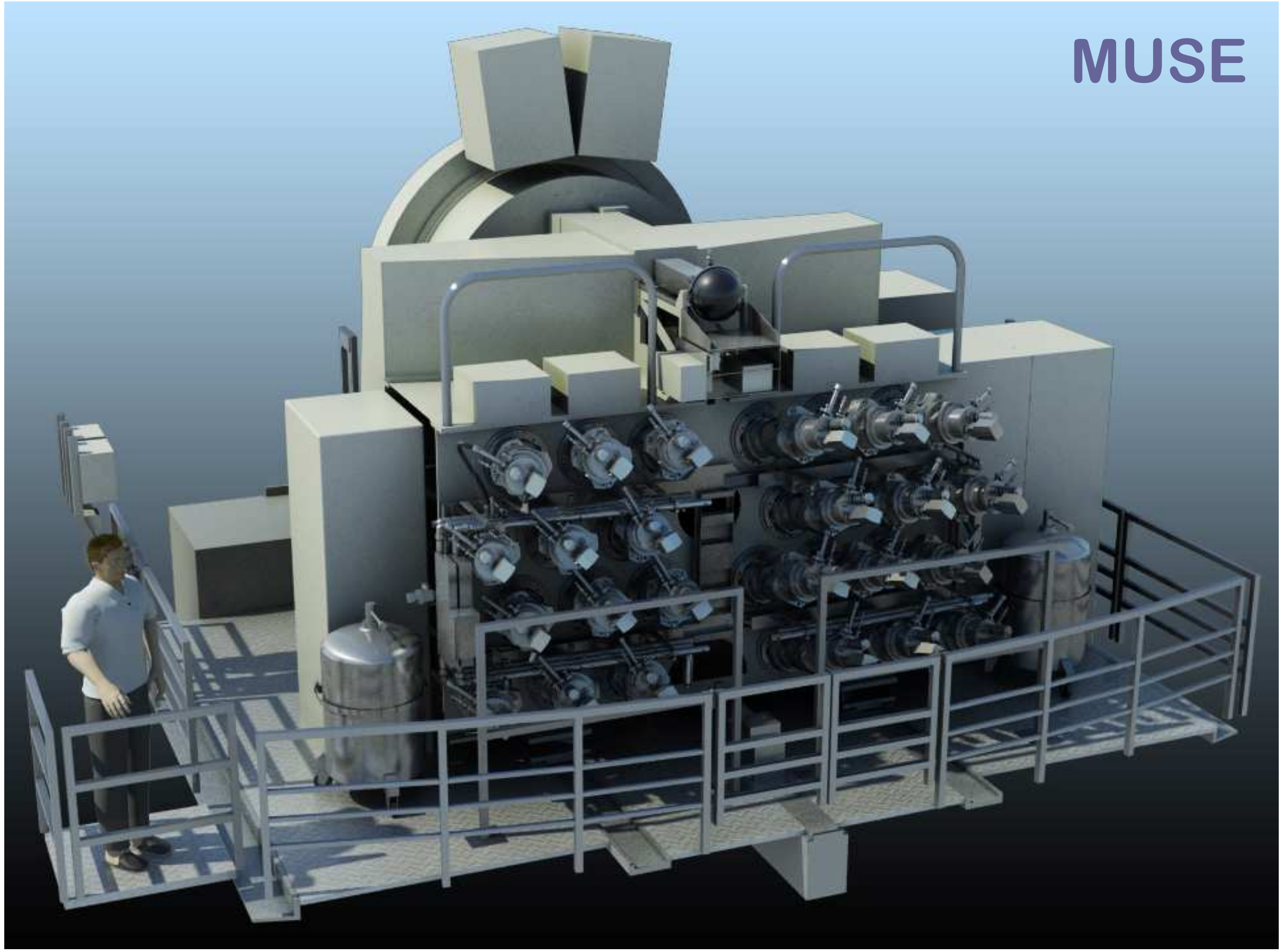
77 vrad + 308,
23 excl.



80 vrad + 256
from literature
40 excl.

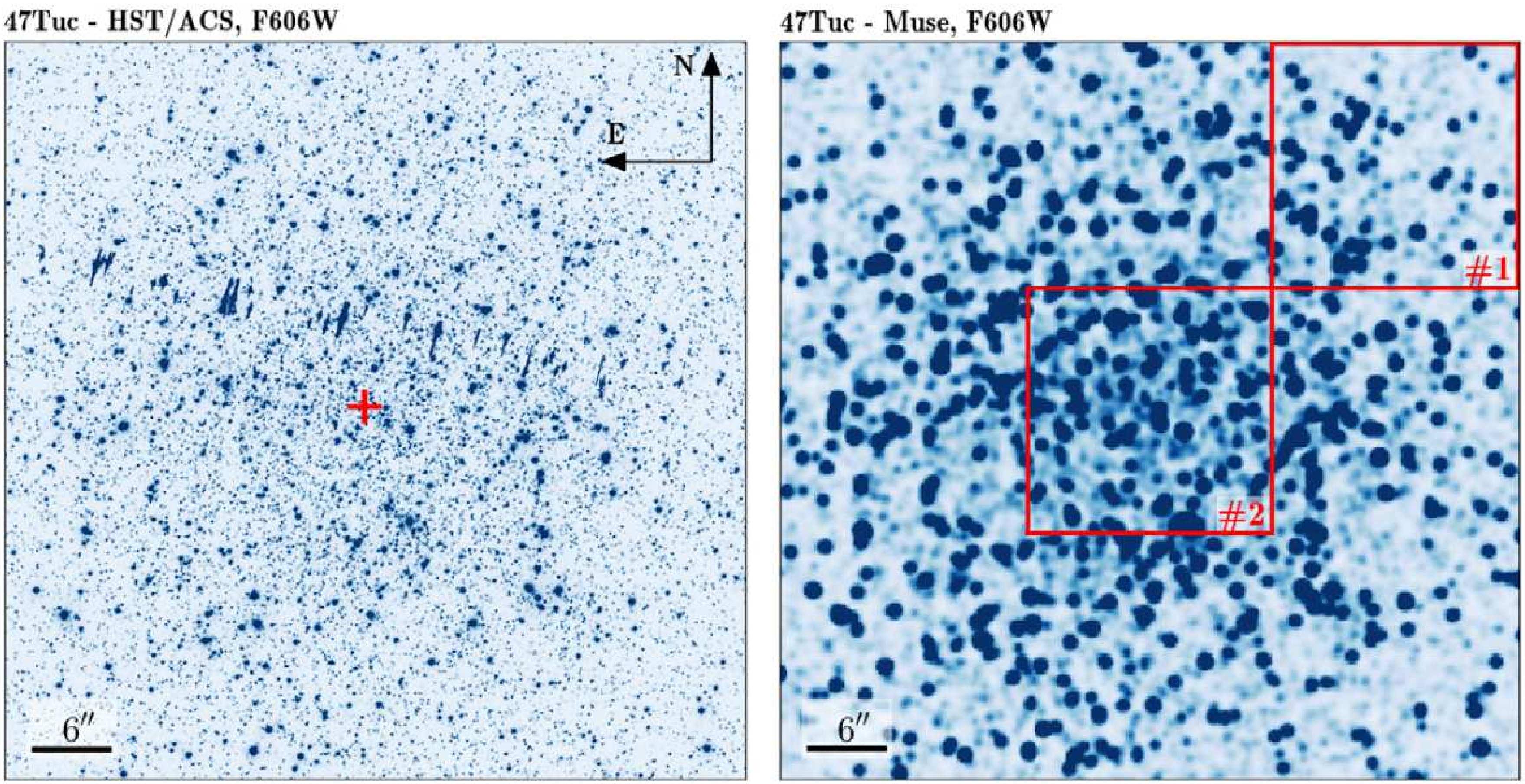
4. Crowded Field 3D Spectroscopy

- and the (very near) future



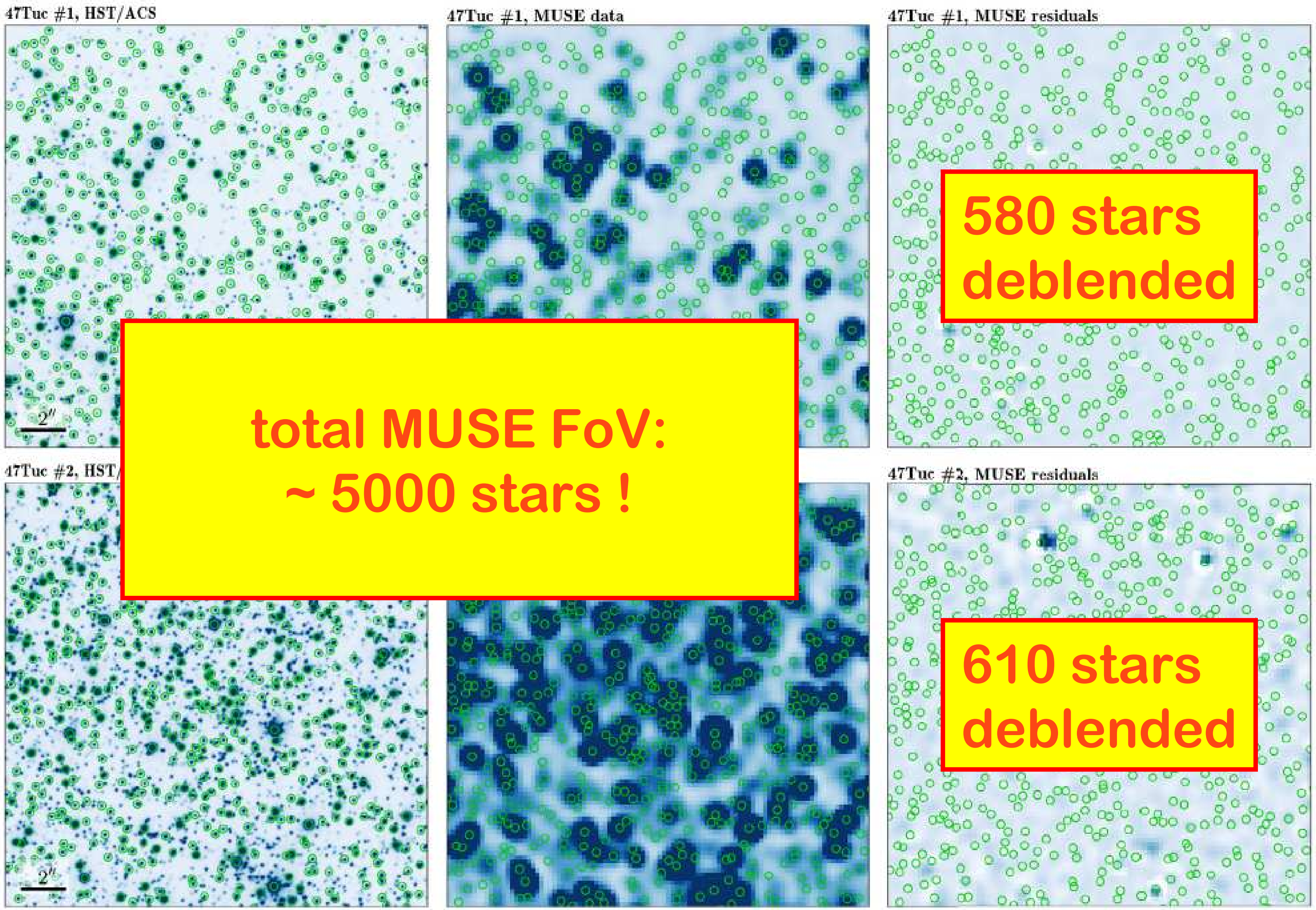
Crowded field 3D spectroscopy: Kamann et al. 2013

MUSE simulations (0.8 arcsec seeing)



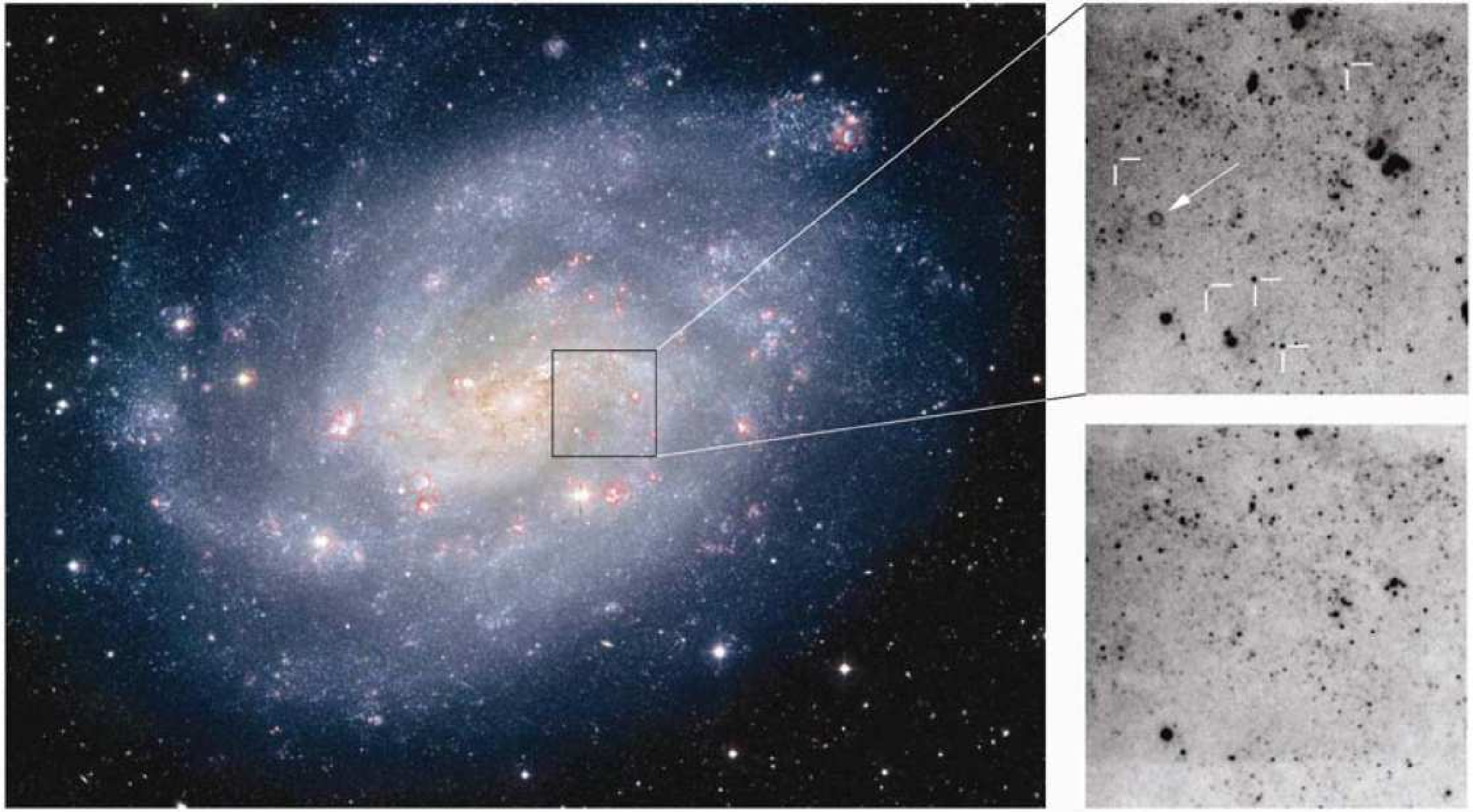
Crowded field 3D spectroscopy: Kamann et al. 2013

MUSE simulations (0.8 arcsec seeing)

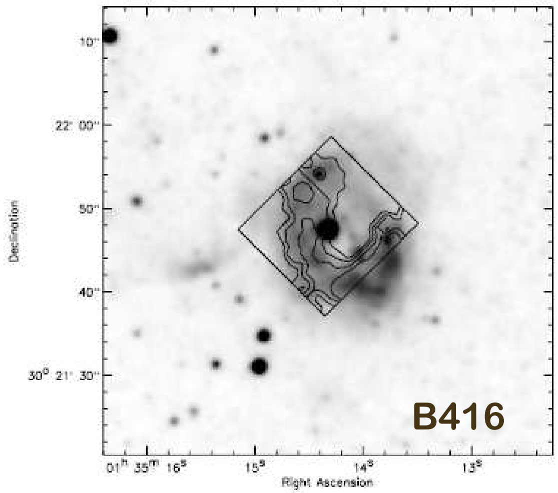


5. Crowded Field 3D Spectroscopy

- in nearby galaxies

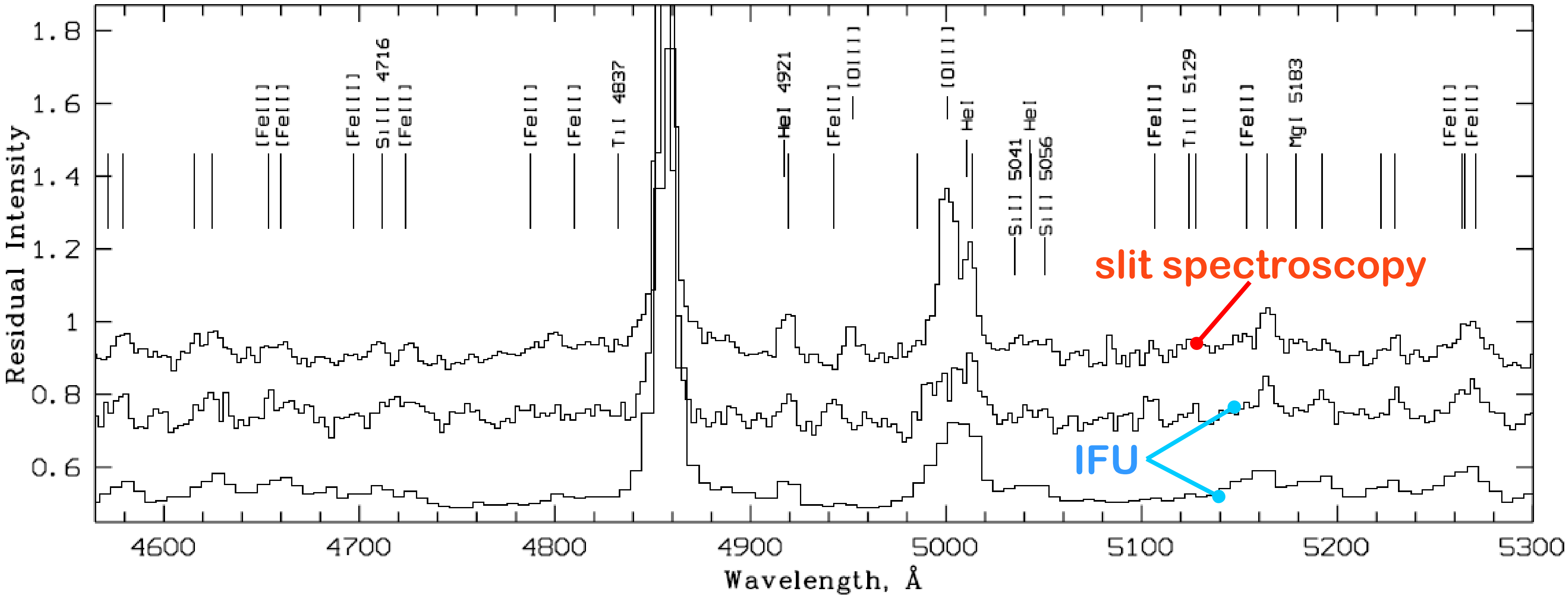


Crowded field 3D spectroscopy in nearby galaxies



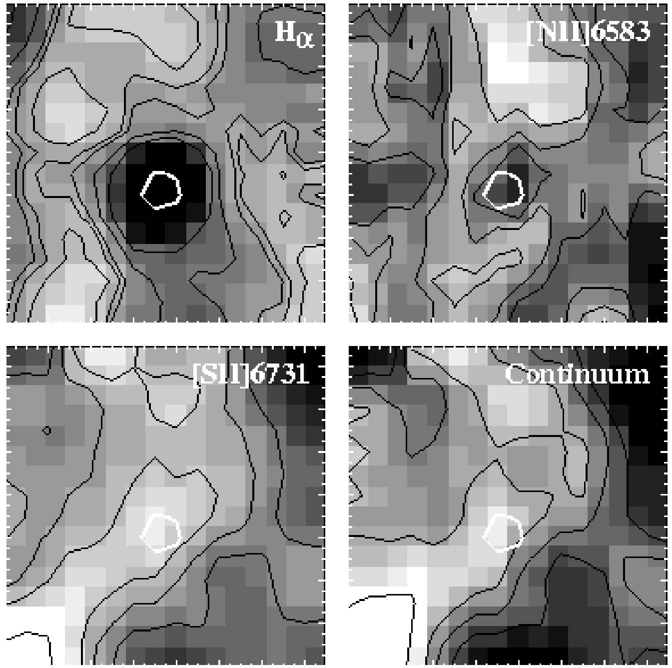
- **LBV candidate in M33**

Fabrika et al. 2005

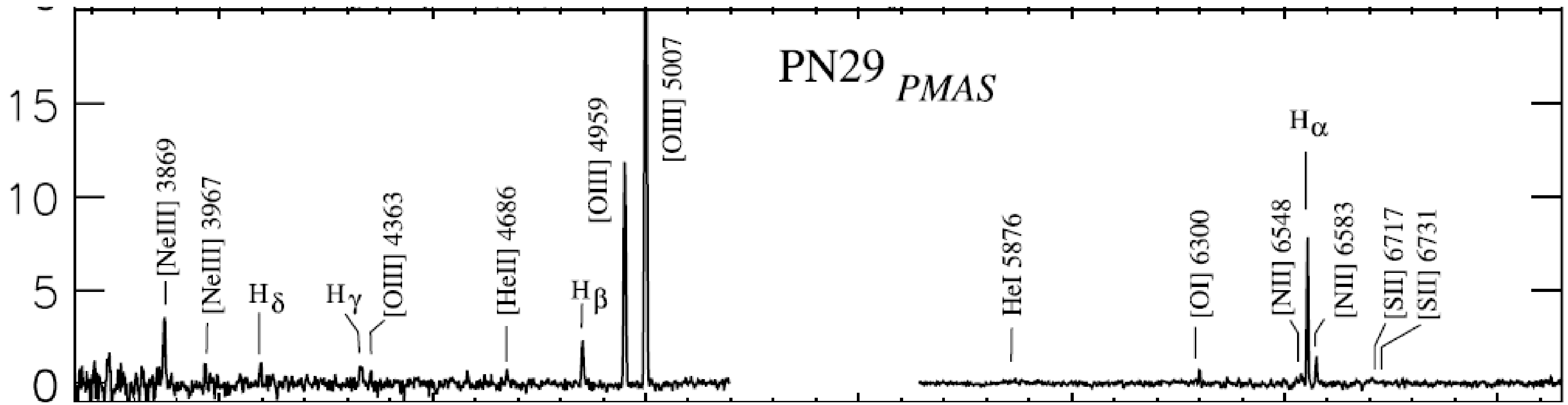


Crowded field 3D spectroscopy in nearby galaxies

- planetary nebulae in M31

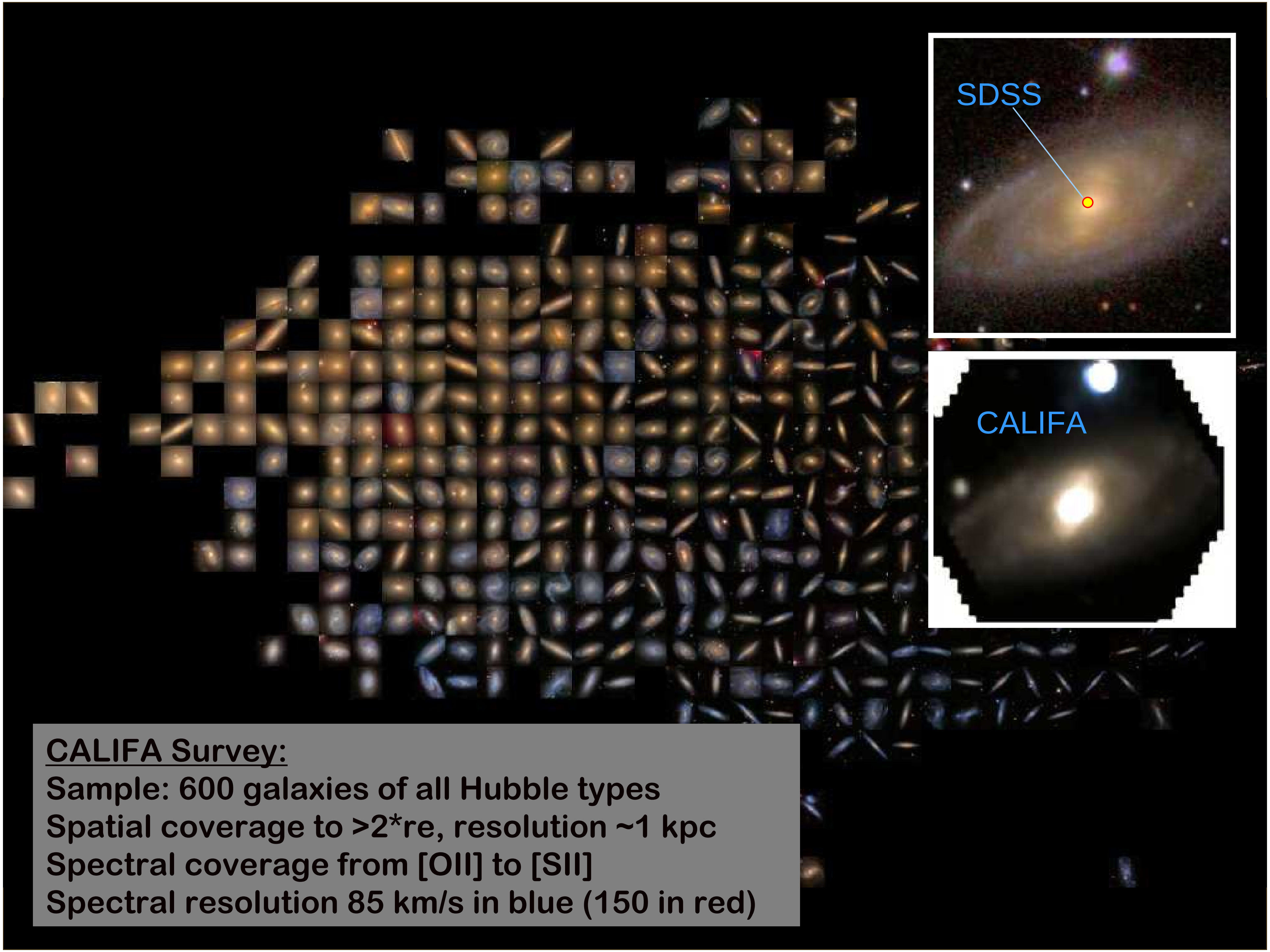


Roth et al. 2005



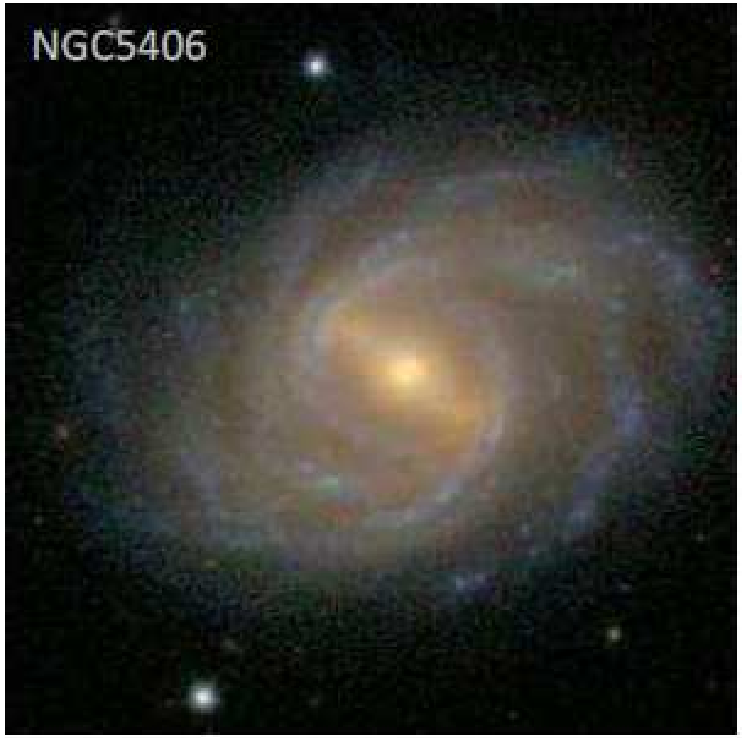
6. Crowded Field 3D Spectroscopy

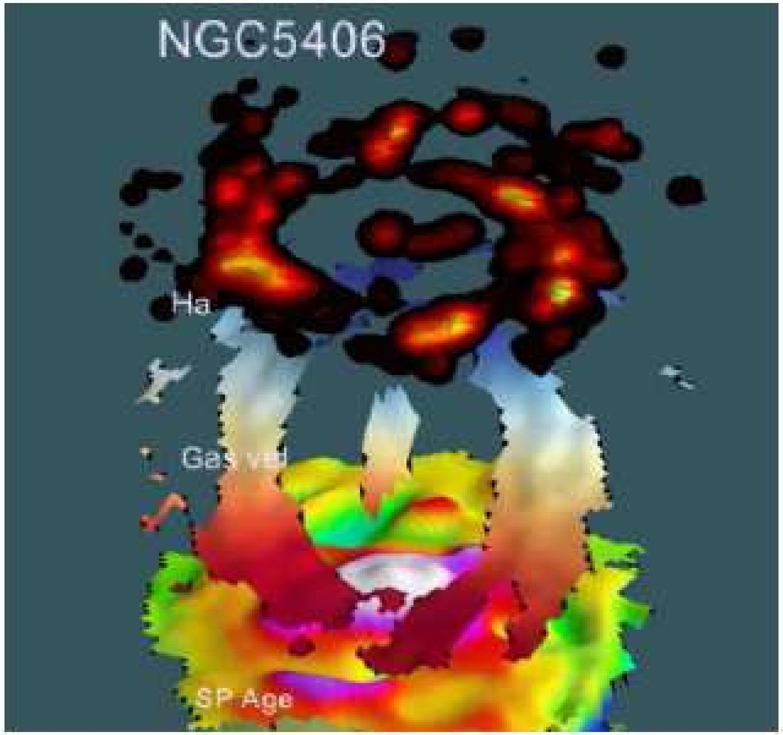
- and MOS



<u>CALIFA Survey:</u>
Sample: 600 galaxies of all Hubble types
Spatial coverage to >2*re, resolution ~1 kpc
Spectral coverage from [OII] to [SII]
Spectral resolution 85 km/s in blue (150 in red)

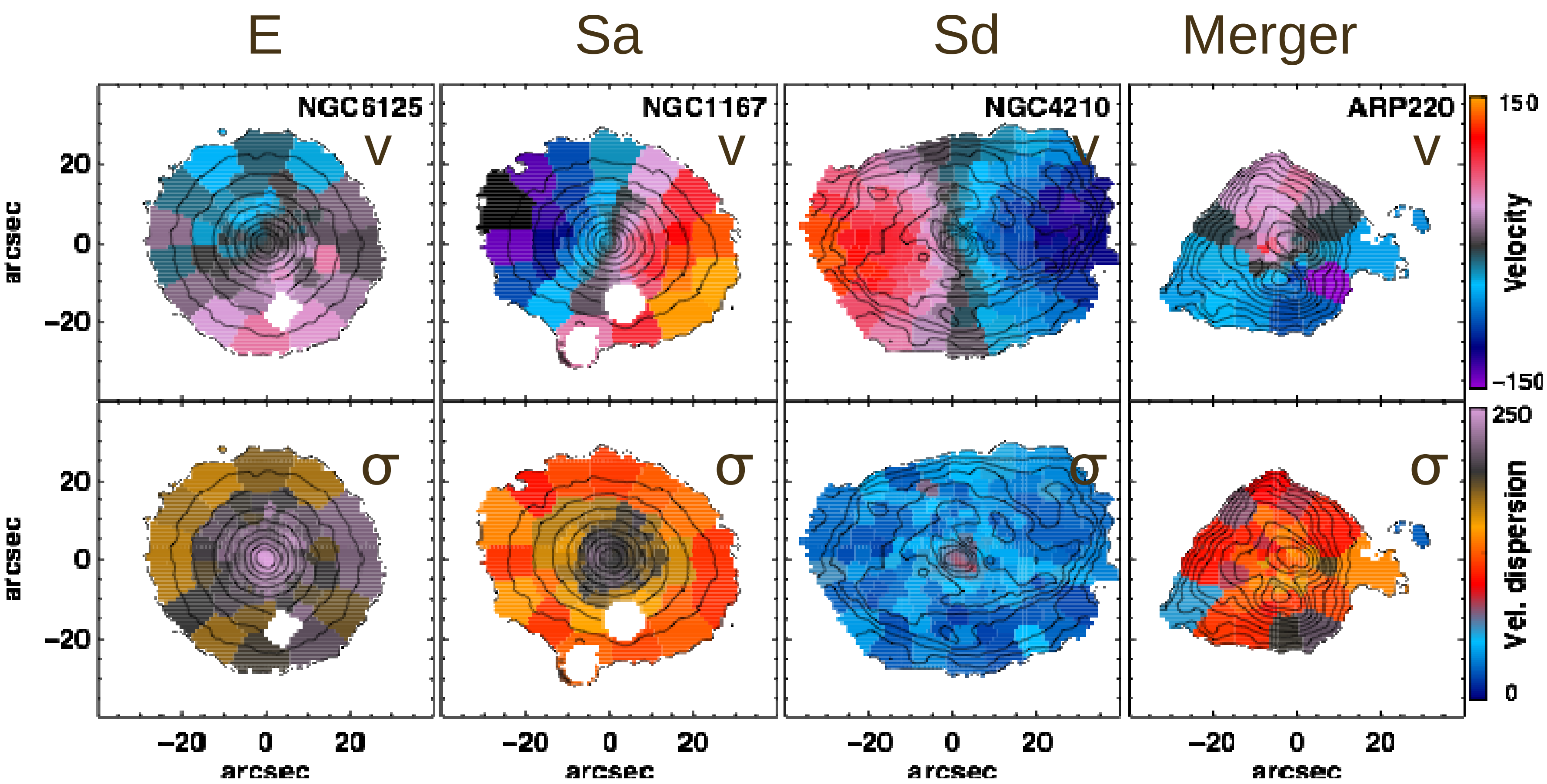
Stellar populations, gas kinematics, star formation rates





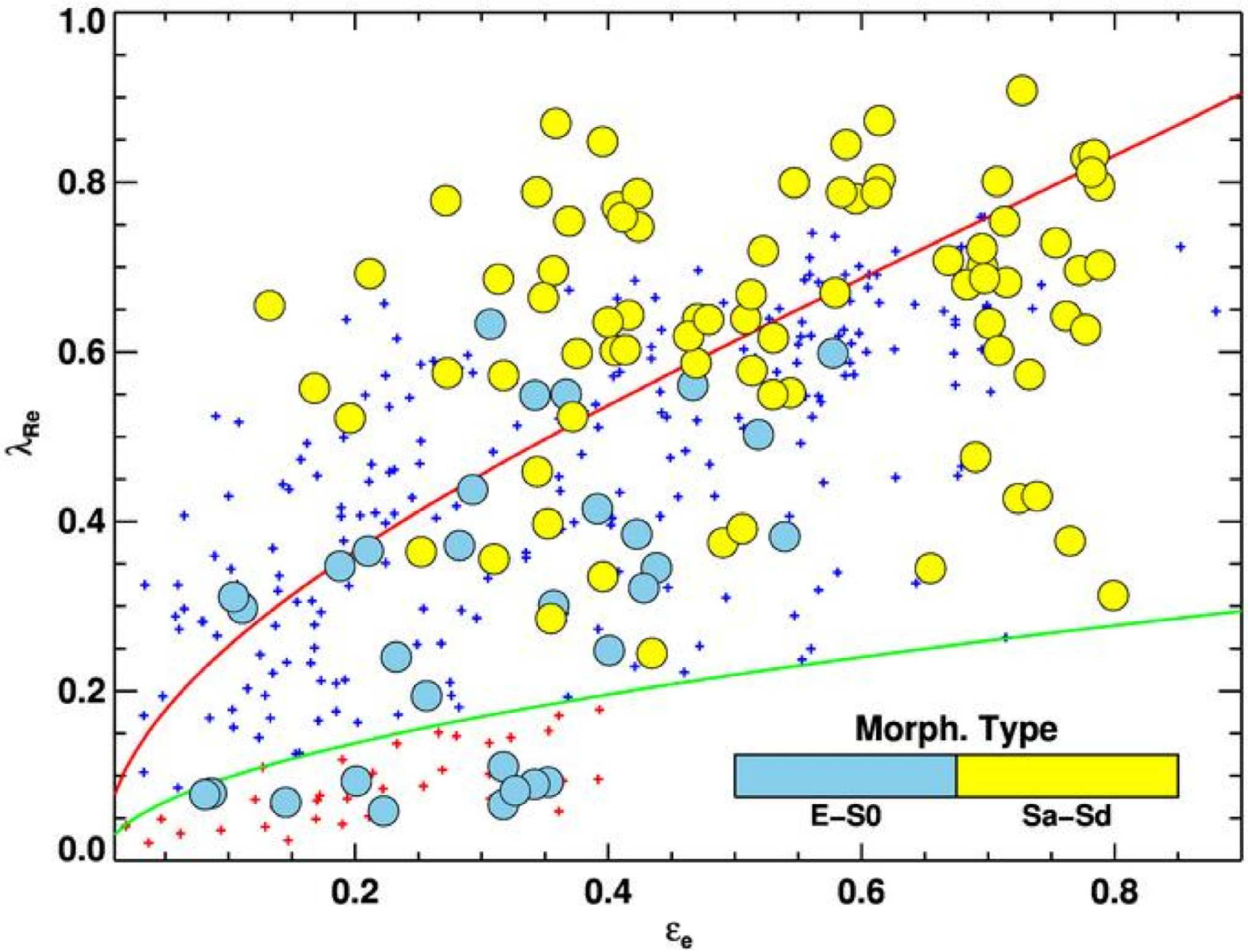
Husemann, B. et al. 2013, A&A 549, 87

Kinematic Classification



Falcon-Barroso et al., in prep.

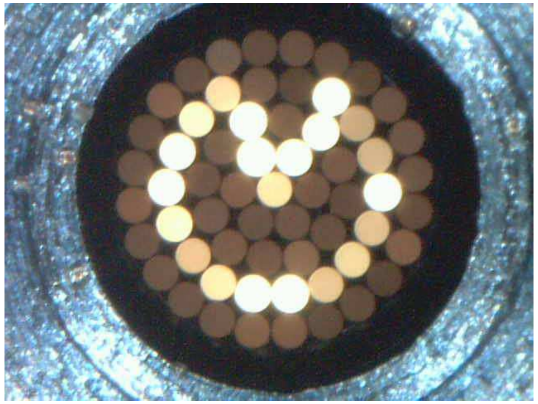
Kinematic Classification



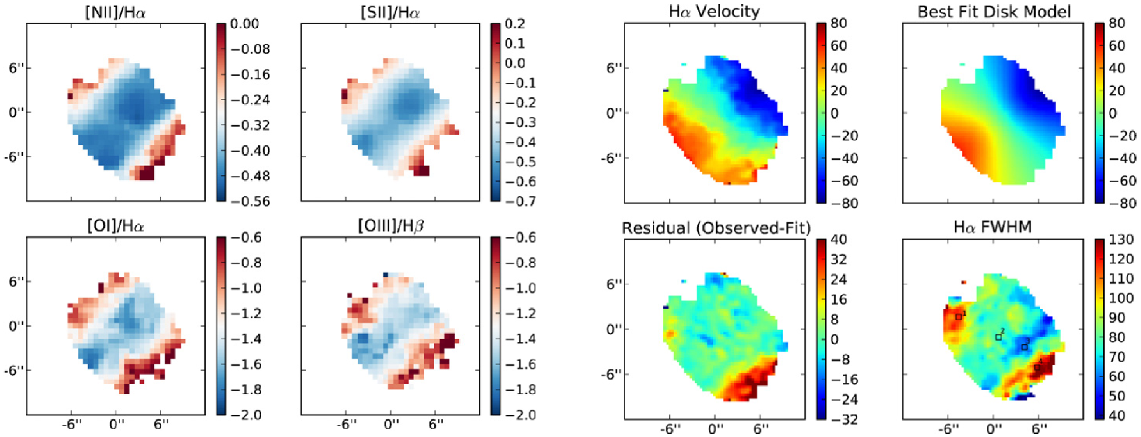
Falcon-Barroso et al., in prep.

Future IFU-MOS surveys (~5.000 galaxies)

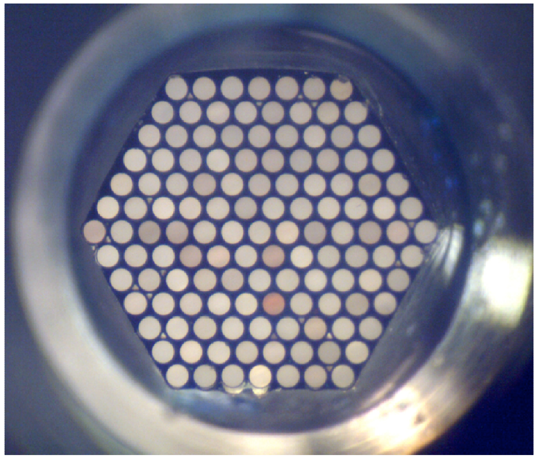
SAMI (AAO)

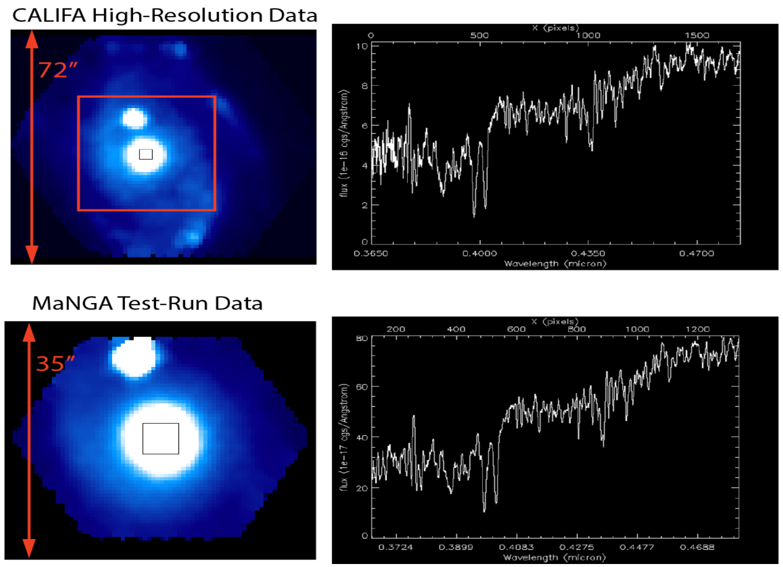


Fogarty et al. 2012



MaNGA (AS3)

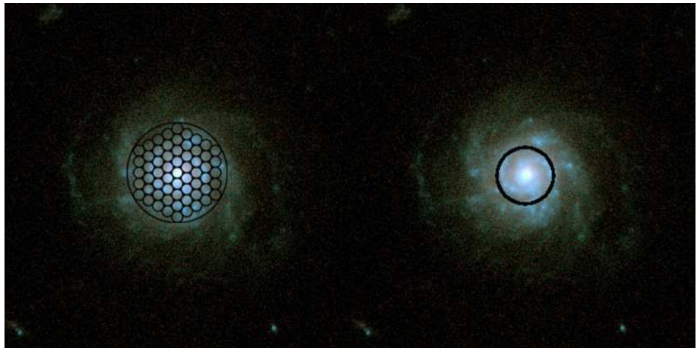


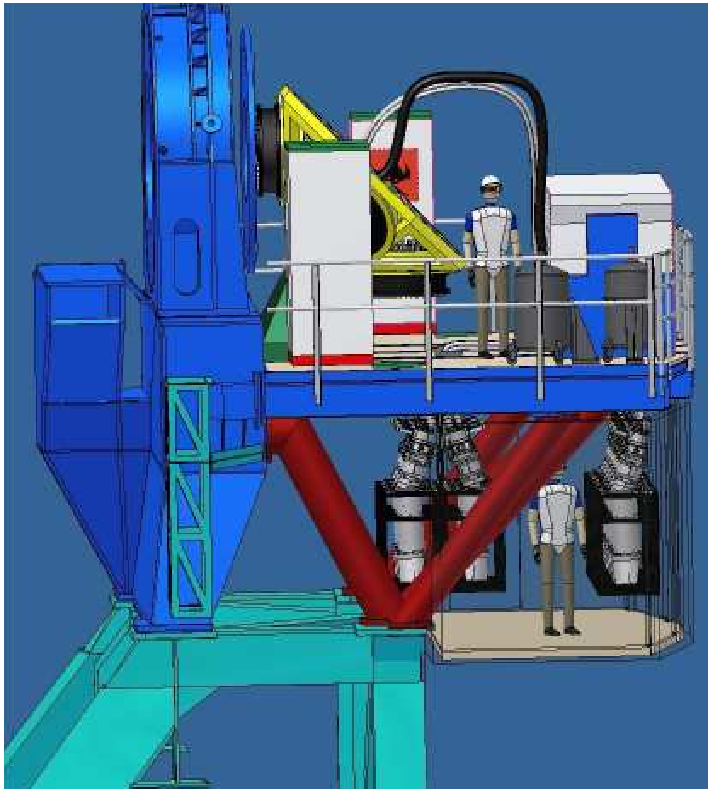


NGC 2916
(data from recent test run)

Shaping E-ELT Science and Instrumentation, ESO, Feb 28, 2013

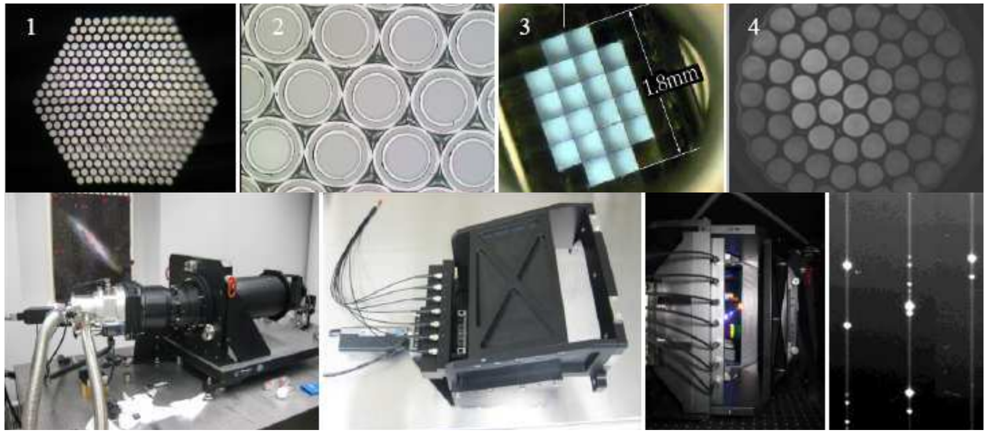
ELT-MOS pathfinder at VLT: FIREBALL concept





FIREBALL Baseline Parameters

- FLAMES OzPoz patrol field with 26’ diameter FoV
- 90 hexabundle IFUs, each with ~5” diameter FoV
- Hexabundles: 61 fibres, 0.6” projected fibre core diameter
- 6 spectrographs, adapted for fibre-feed, R~1200-2100
- free spectral range: 430-850nm (goal: blue extension)
- total throughput goal: 30%
- sensitivity: R ~19.8 survey limit, resulting in 100-160 galaxies per FLAMES field at median z ~ 0.2; typical half-light sizes for disk galaxies 2”-6” diameter
- detector head, NGC CCD controller, vacuum/cooling system adapted from MUSE
- individual spectrograph shutters
- no moving parts other than shutters + fibre positioner
- retain full existing facility and utilise as much FLAMES infrastructure as practical



ELT-MOS…

…and crowded field spectroscopy !


ELT-MOS…
…and crowded field spectroscopy !