3D spectroscopy of massive stars, SNe, and other point sources in crowded fields

Martin M. Roth
Sebastian Kamann, Christer Sandin, Ana Monreal, Peter Weilbacher, Lutz Wisotzki

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Universität Potsdam

Overview:

1. Motivation
2. Crowded Field Photometry
3. Crowded Field 3D Spectroscopy – early results
4. Crowded Field 3D Spectroscopy and IMBH in GC
5. SN Ia and their environments
6. The (near) future
7. Outlook

PMAS

Design Study
for a Multi-Aperture Spectrophotometer
with 2-dimensional spatial Resolution

Martin M. Roth
– Astrophysikalisches Institut Potsdam –

2. August 1996

PMAS Science Case (1996)

„In summary, the main advantages of the method are:

• simultaneous spectra with full 2-dimensional spatial resolution
• break-up of the classical coupling of spectral and spatial resolution (slit-width) with micropupil principle
• sub-arcsec spatial resolution
• absence of slit eects (light-loss, wavelength is dependent on PSF center-of-gravity
• on slit, dierential atmospheric dispersion)
• aperture-free ux measurement
• a-posteriori advantage for objects with unknown properties (spectral structure vs.
• surface brightness distribution)
• uncritical telescope pointing for objects at detection limit
• allows for spectrophotometry of faint point sources on a bright, variable background (similar to CCD photometry)
• upgrade for high spectral resolution (FP) possible
• upgrade for 2D-spectropolarimetry possible“

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- **sub-arcsec spatial resolution**
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Other topics of potential interest:

- T Tauri stars
- faint central stars in high surface-brightness planetary nebulae
- stars in globular clusters
- stellar populations in nearby galaxies (OB associations, A supergiants, WR stars,etc.)
- 2D-spectroscopic extension of surface brightness fluctuation measurements
- spectrophotometry and spectropolarimetry of supernovae
- spectropolarimetry of AGN (scattered light, dust tori)
- quasars and quasar host galaxies
- gravitational lenses

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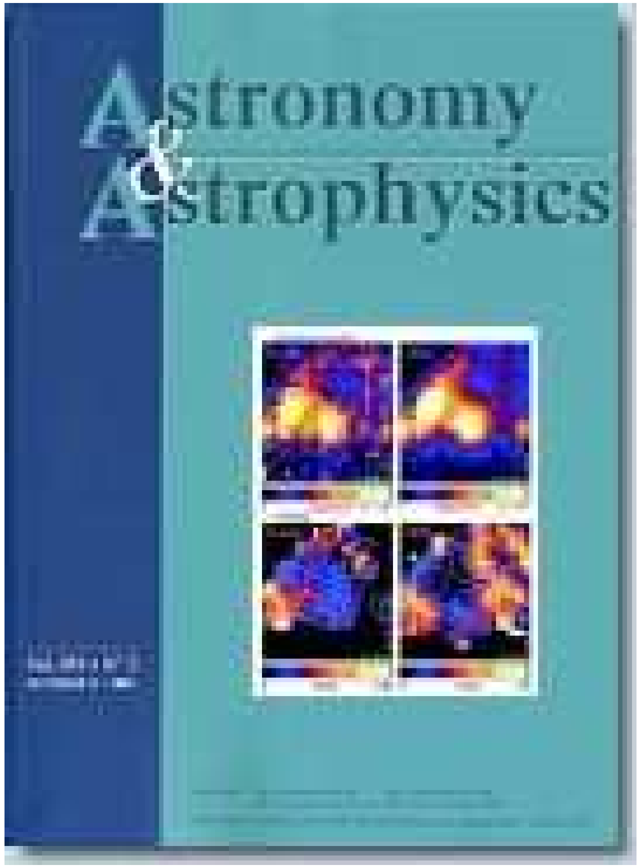
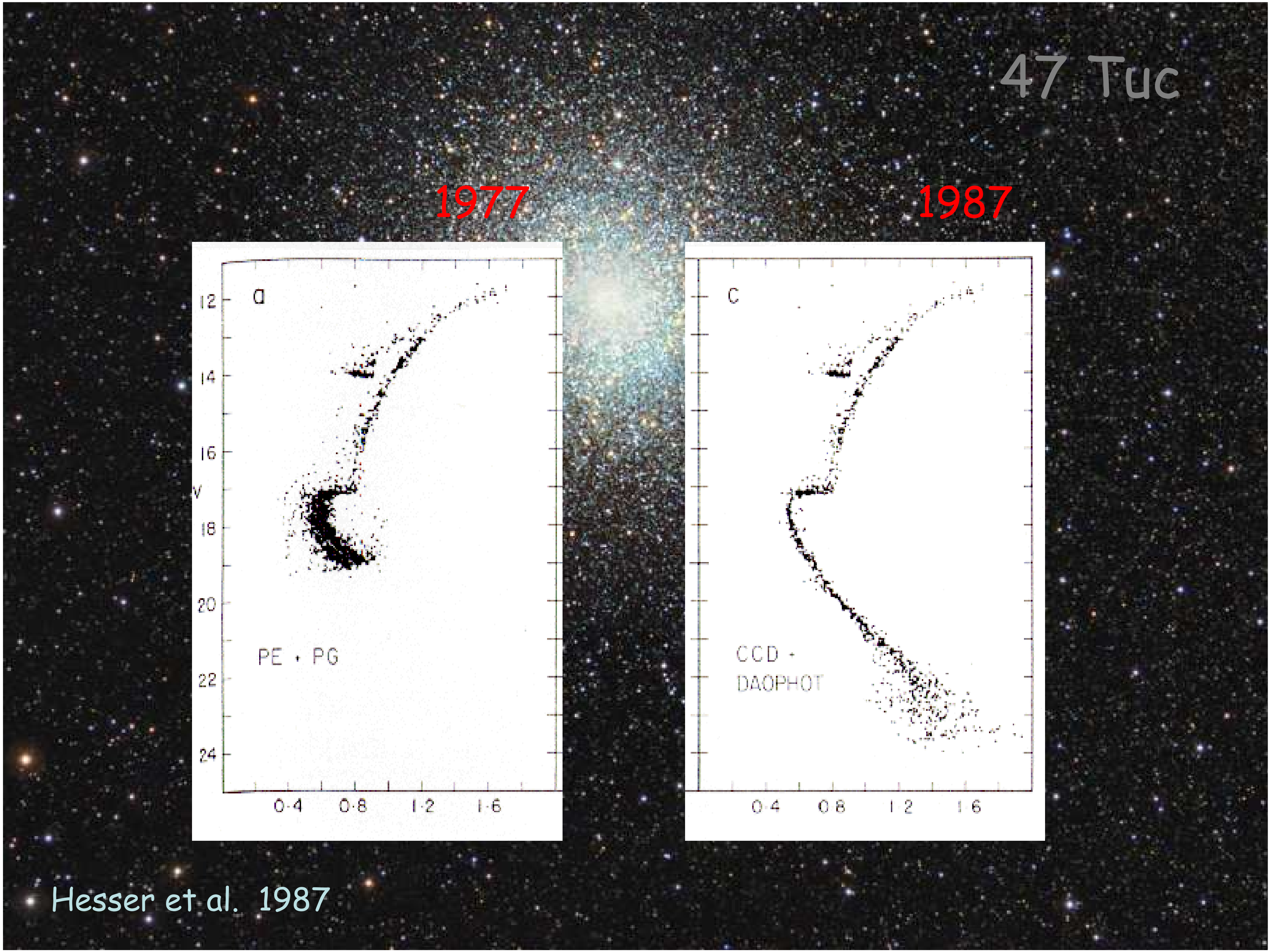
1.Motivation:

part 2



Lehmann, I. Becker, T., Fabrika, S., Roth,M.M., Miyaji, T., Afanasief, V., Sholukhova, O., Sánchez, S.F., Greiner, J., Hasinger, G., Constantini, E., Surkov, A., Burenkov, A. (2005), ***"Integral field spectroscopy of the ultraluminous X-ray source Holberg II X-1",*** **A&A, 431 (2005) 847**


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

2. Crowded Field Photometry

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

DAOPHOT: A COMPUTER PROGRAM FOR CROWDED-FIELD STELLAR PHOTOMETRY

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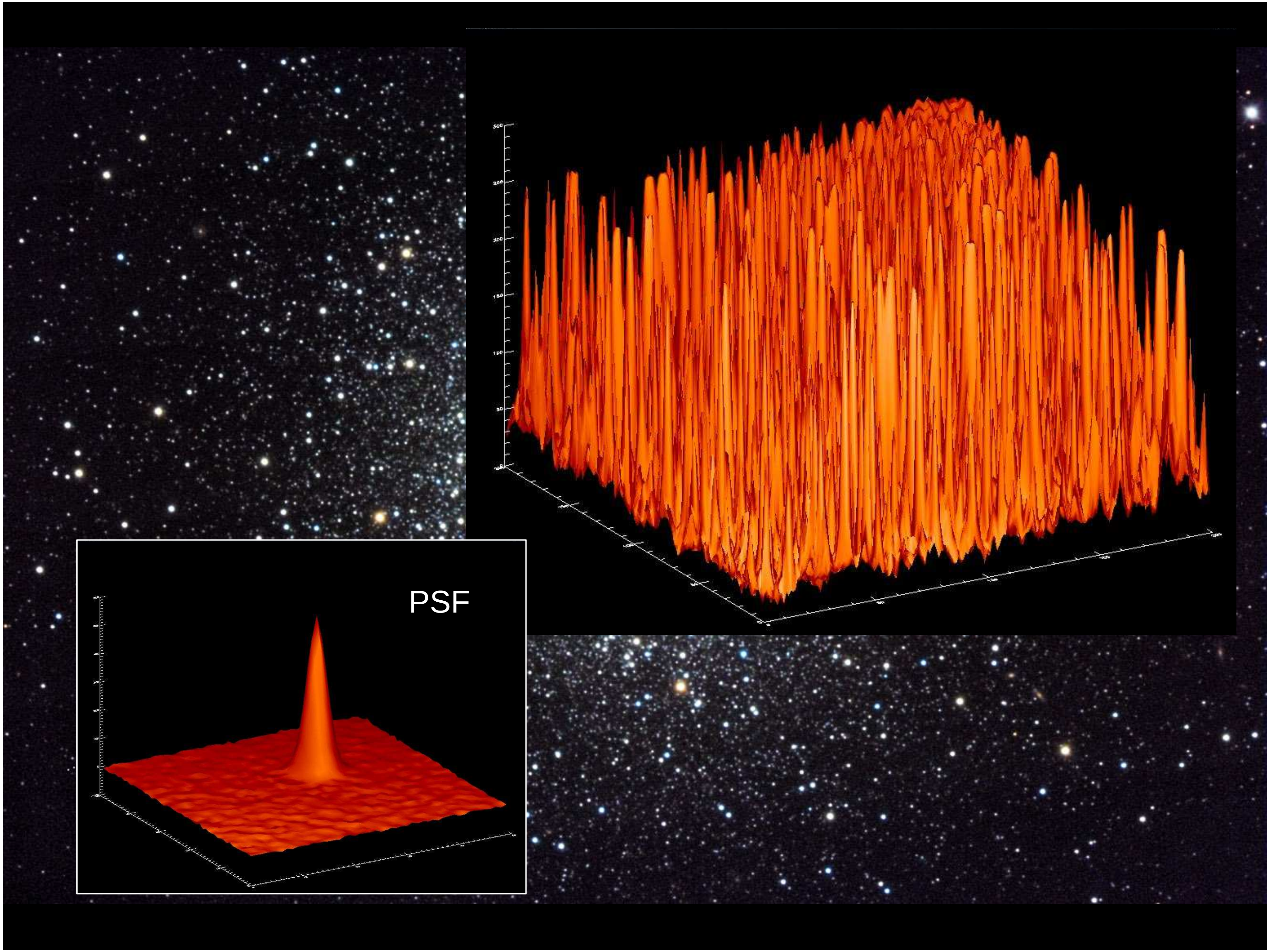
Received 1986 October 13, revised 1986 December 5

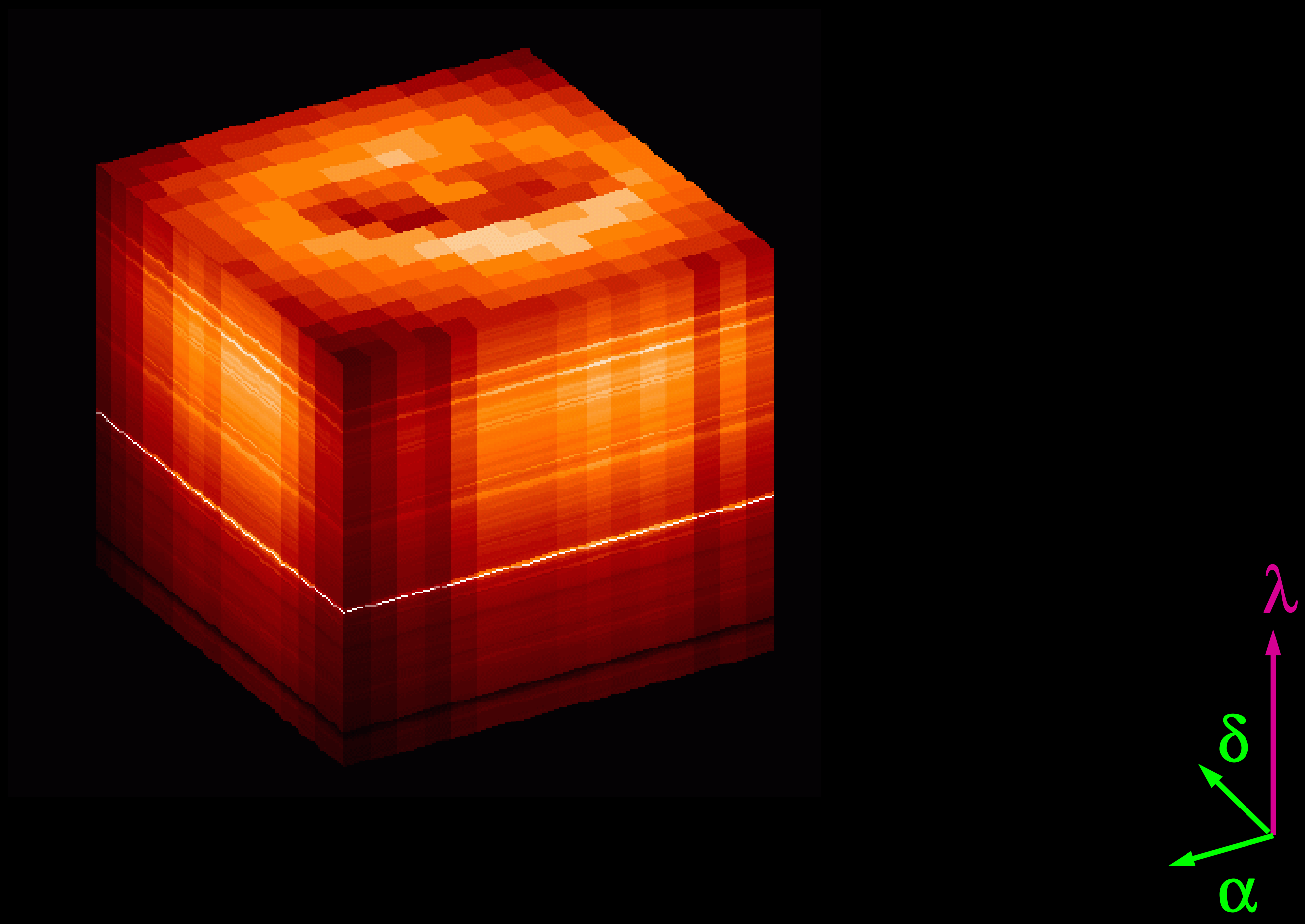
ABSTRACT

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)

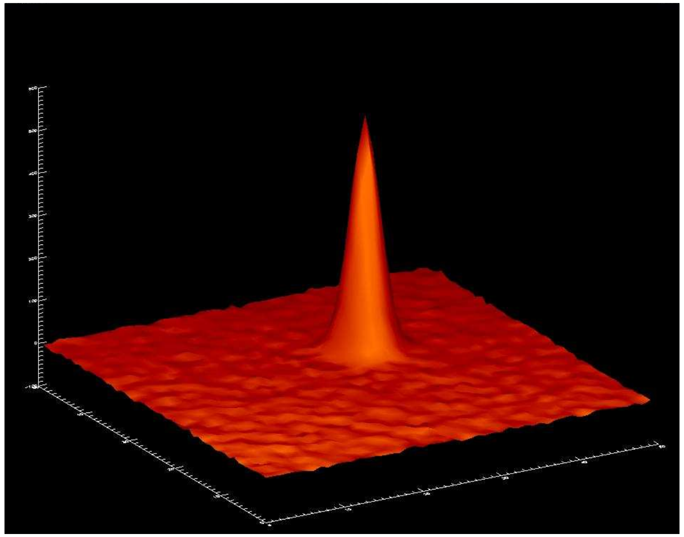

PSF

Integral field "3D" Spectroscopy

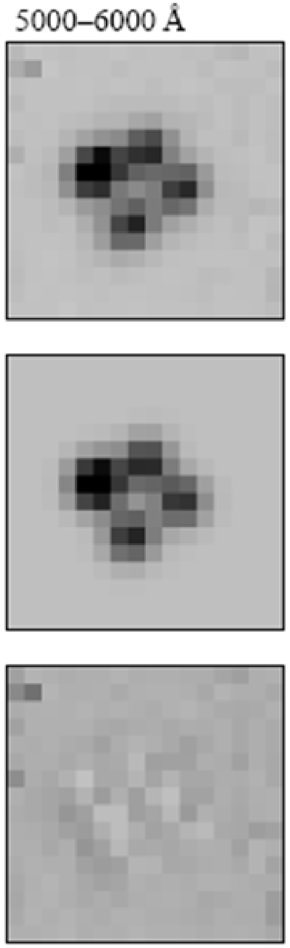


3. Crowded Field 3D Spectroscopy

- early experiments

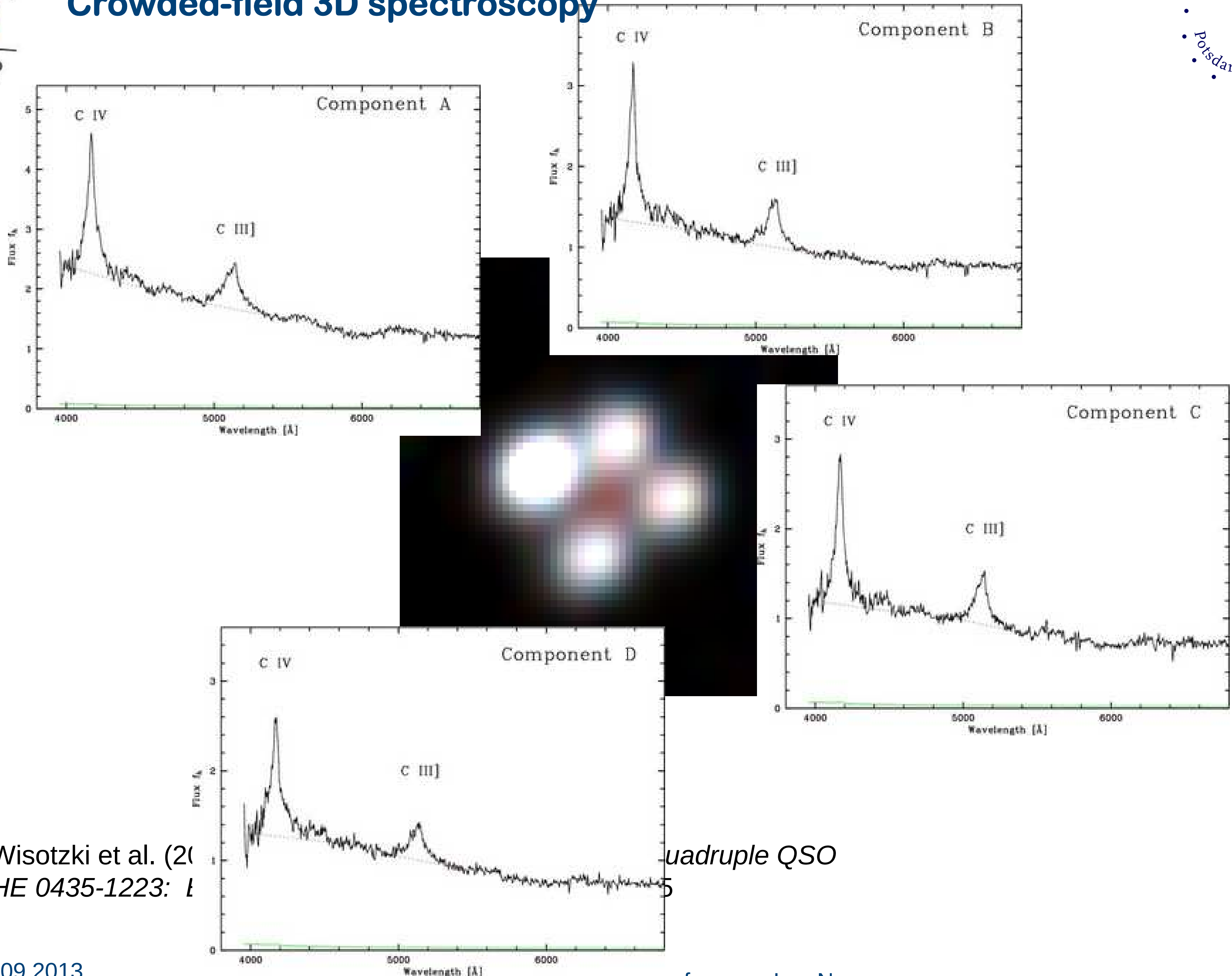


gravitational lens HE 0435-1223



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: E ... 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

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[2] Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482, Potsdam,
e-mail: mmroth@aip.de

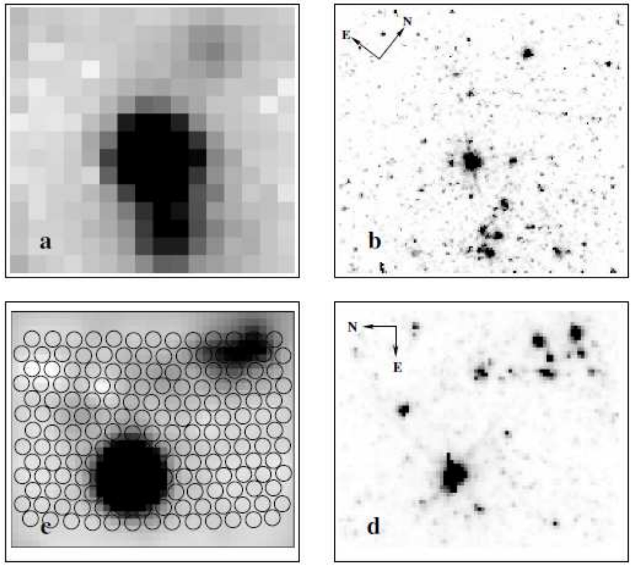
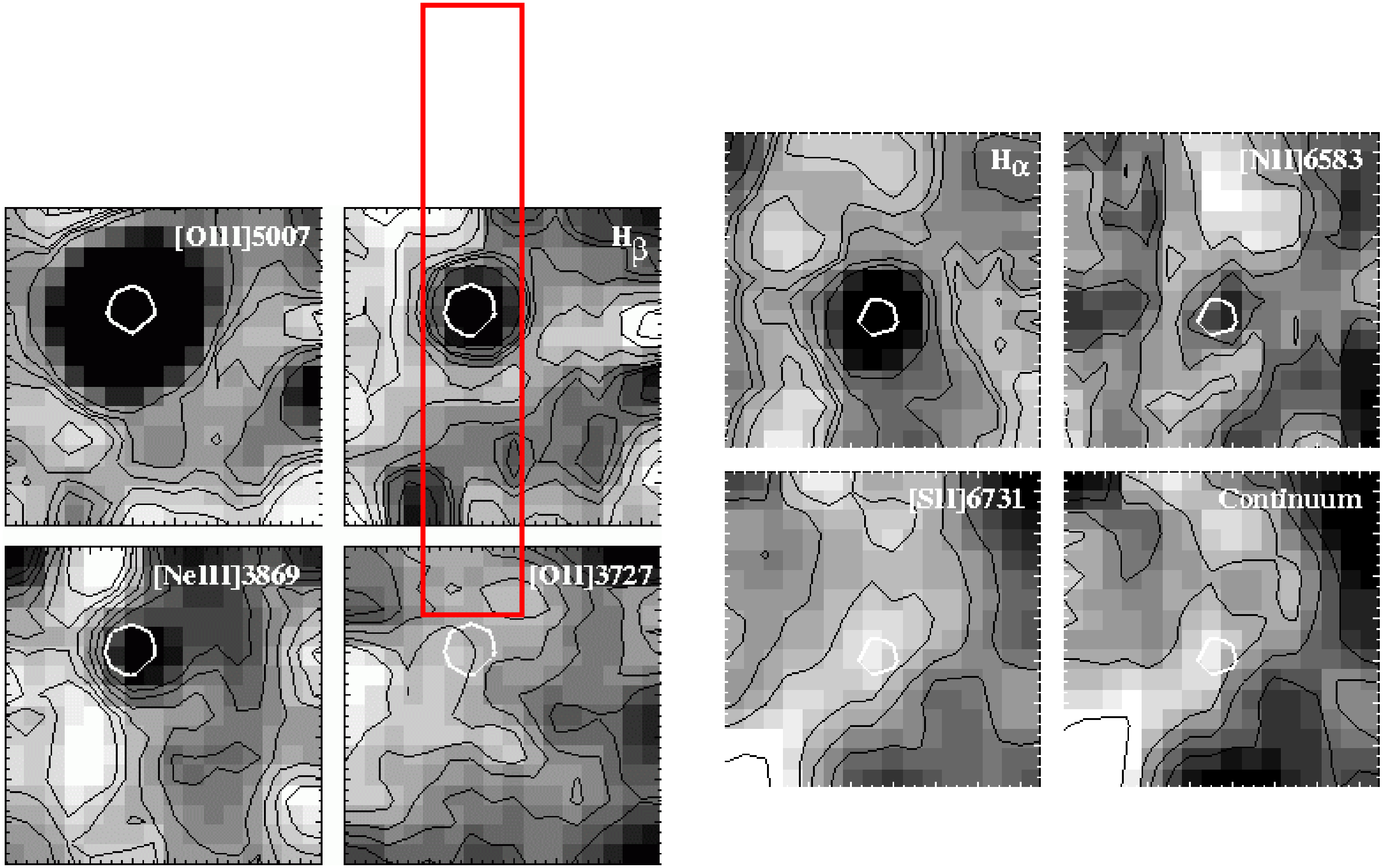


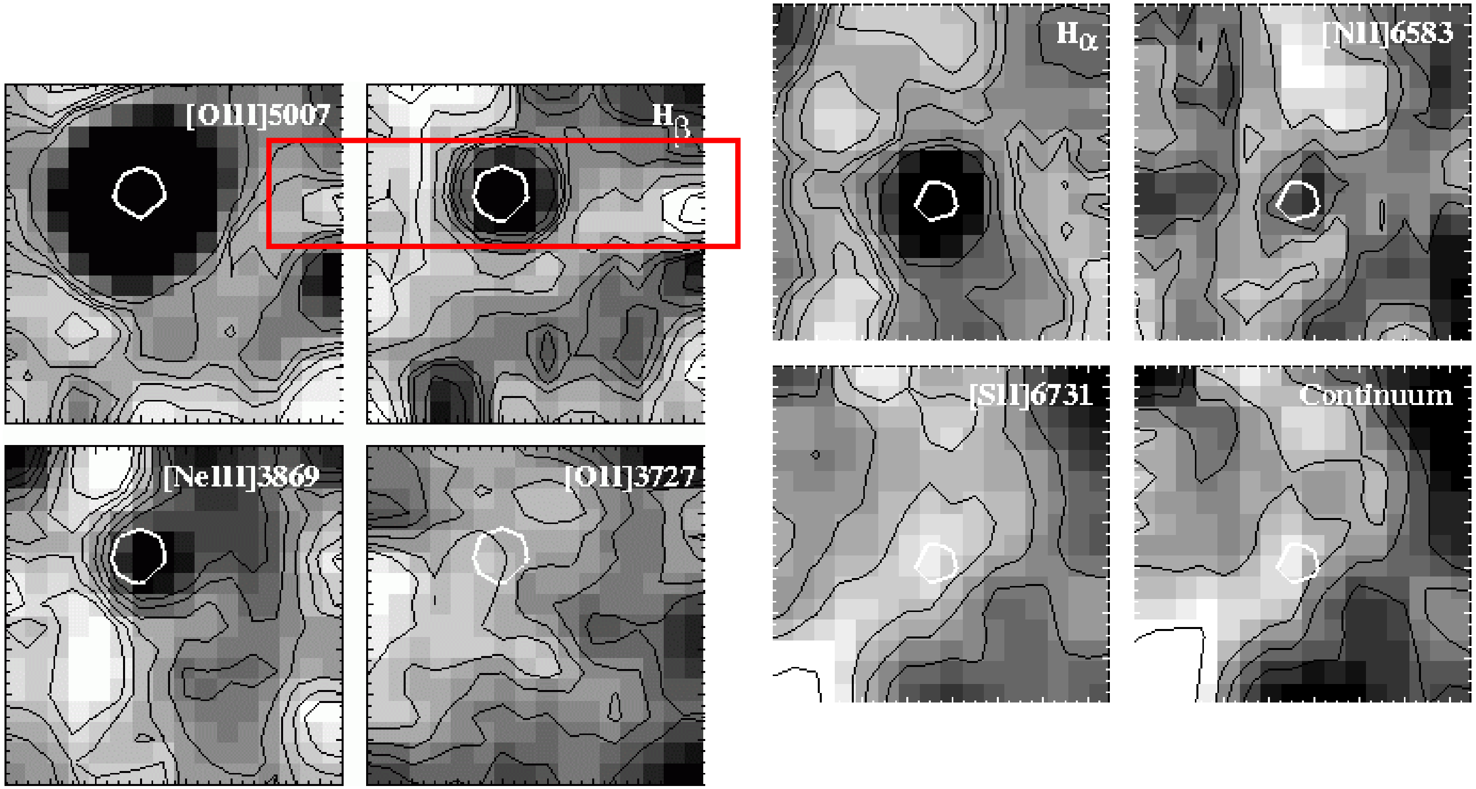
Fig. 1. a) MPFS map of B416 at 6000 Å (spatial sampling 1 arcsec, the FOV is 16 × 15 arcsec^2) and the same field **b)** from the HST WFC2 image. An enlarged fraction of this field from the INTEGRAL in the same wavelength **c)** and the corresponding enlarged HST field **d)**. Note the different orientation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

Planetary Nebulae in the Bulge of M31

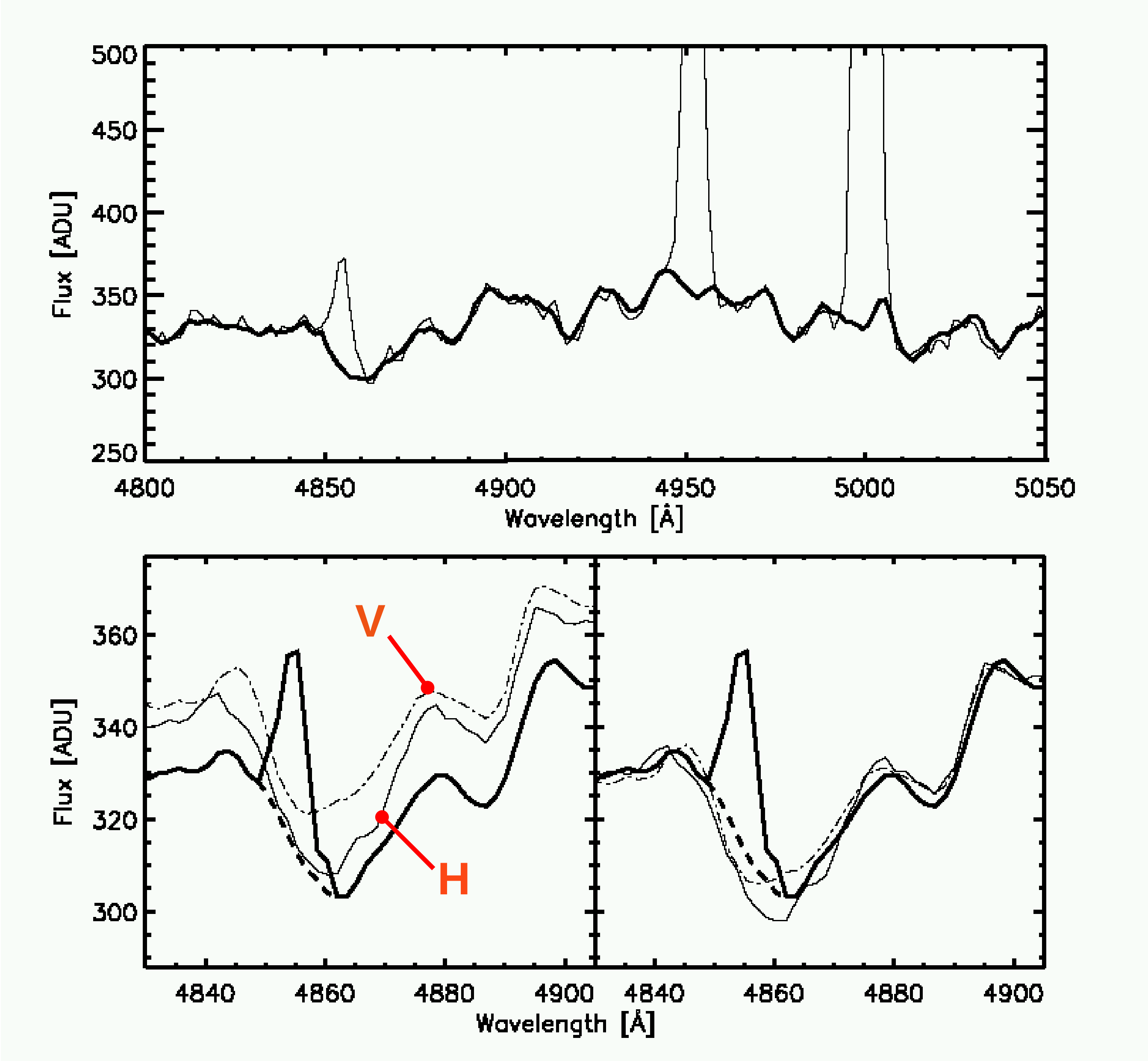


Roth et al. (2004), ApJ 603, 531

Planetary Nebulae in the Bulge of M31



Roth et al. (2004), ApJ 603, 531



500
450
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Flux [ADU]
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V
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4840
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4880
4900
4840
4860
4880
4900
Wavelength [Å]

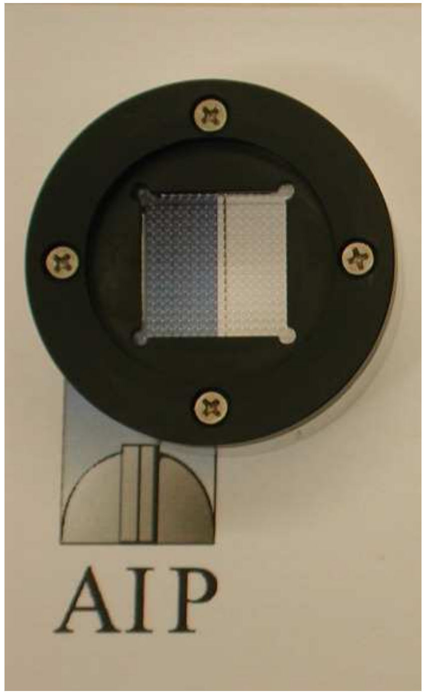
4. Crowded Field 3D Spectroscopy in Globular Clusters

recent progress
→ thesis Sebastian Kamann

S. Kamann, L. Wisotzki, M.M. Roth 2013,
Resolving stellar populations with crowded field 3D spectroscopy
A&A 549, 71

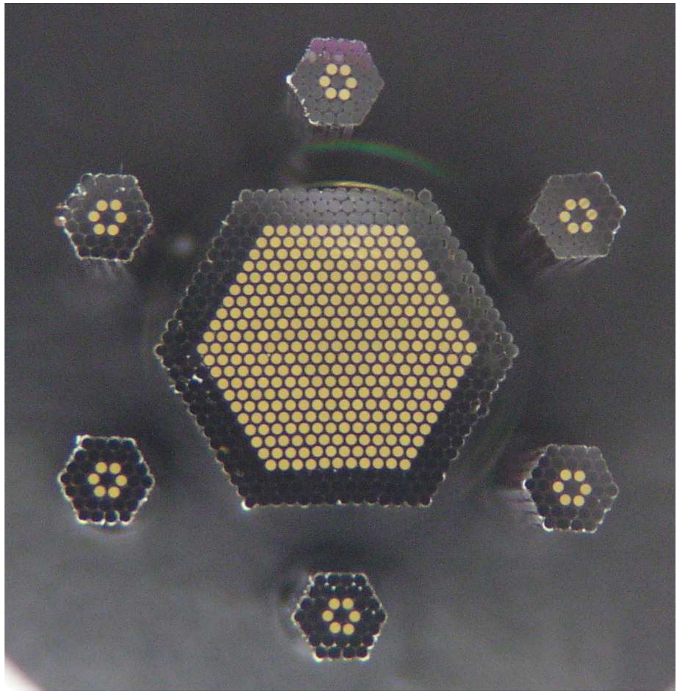
PMAS at the Calar Alto 3.5m Telescope

LARR IFU



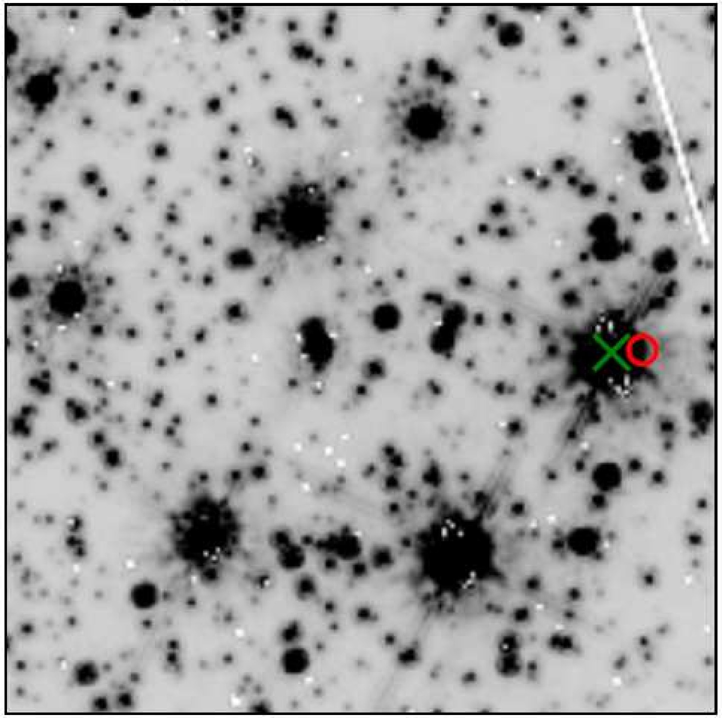
8 arcsec

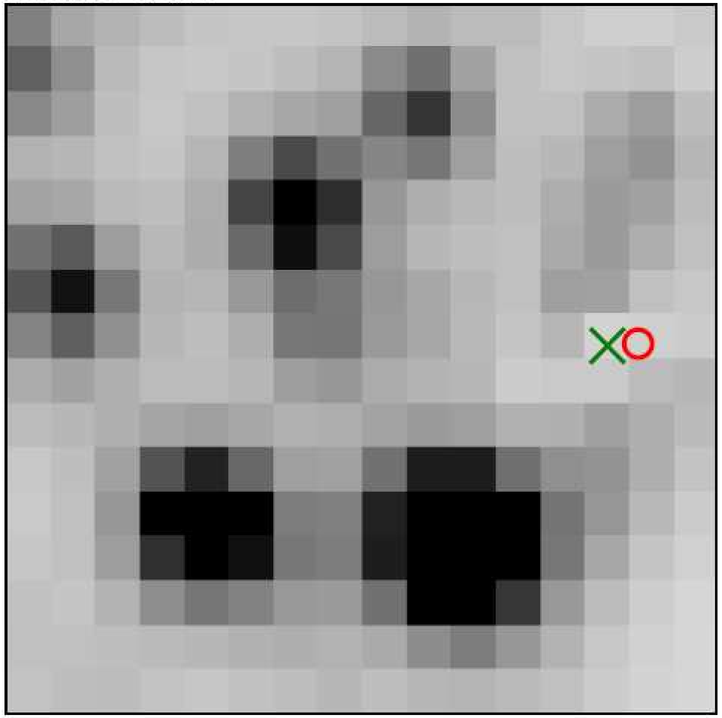
PPak IFU



74 arcsec

M3

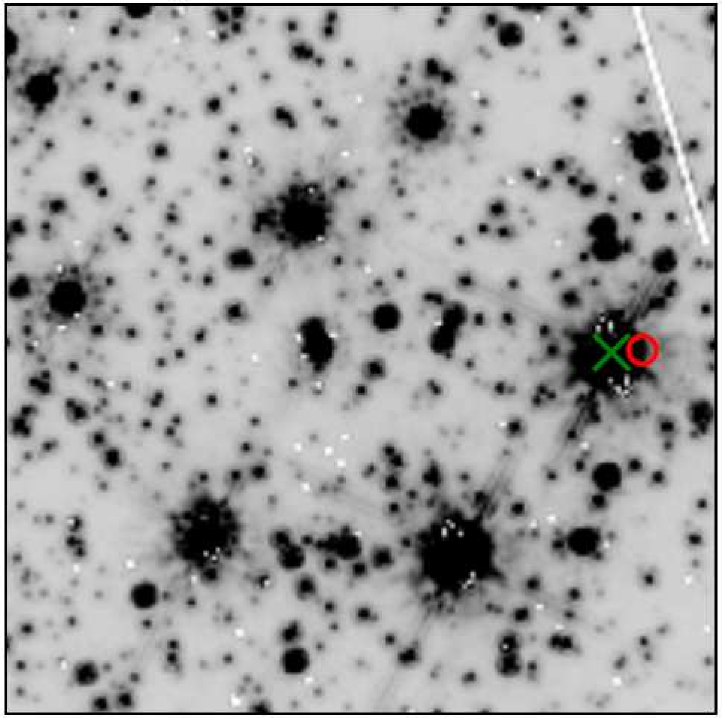


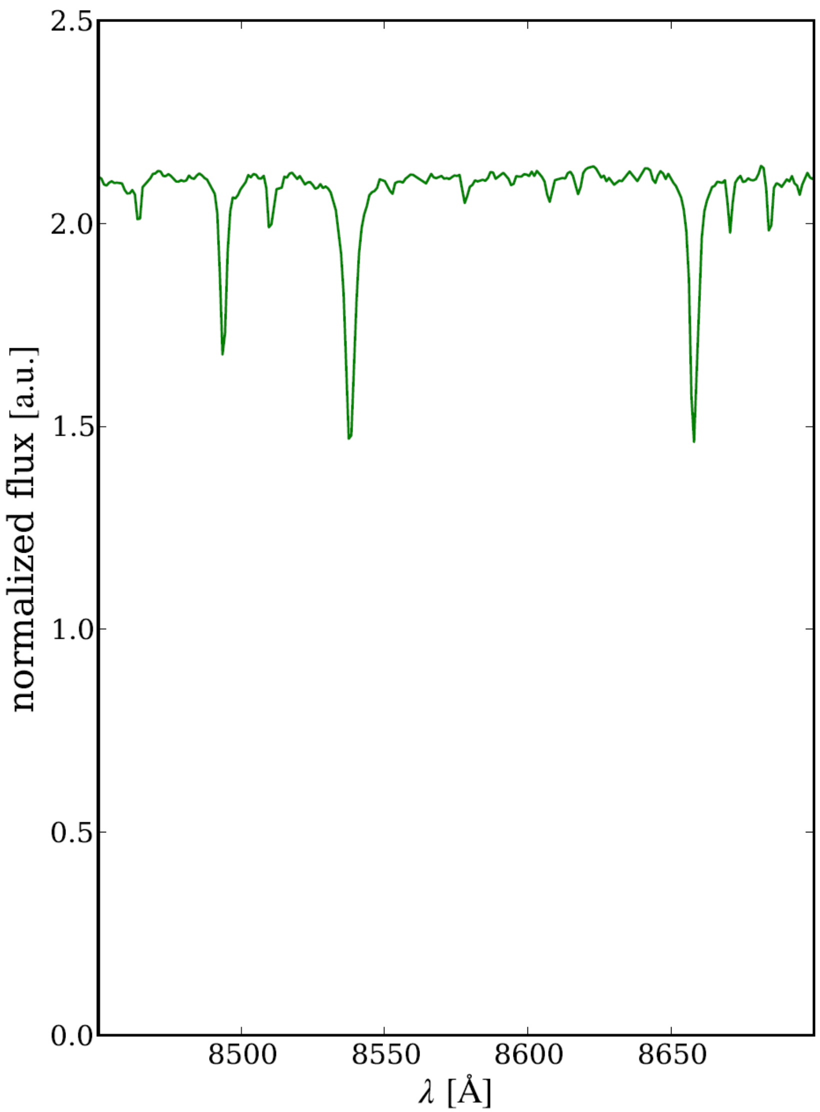


PMAS at the Calar Alto 3.5m Telescope

M3

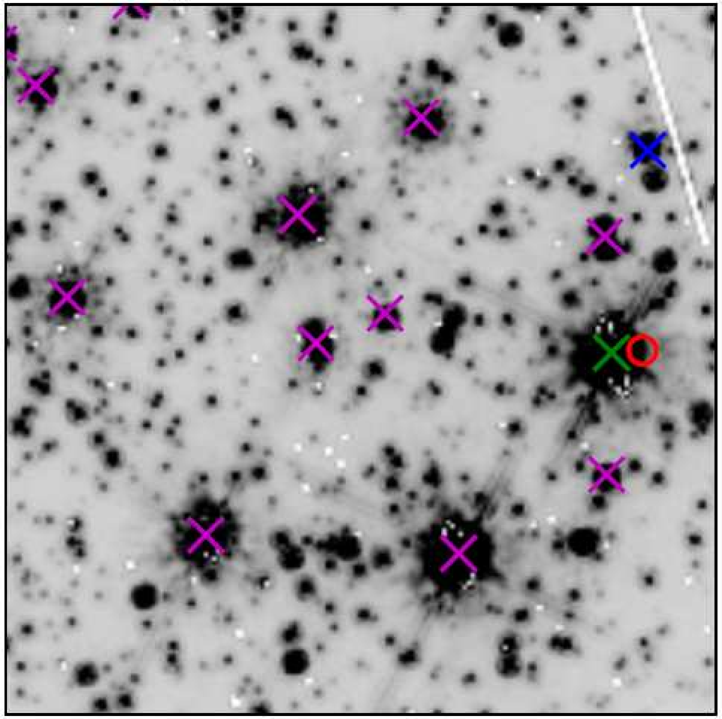
HST image



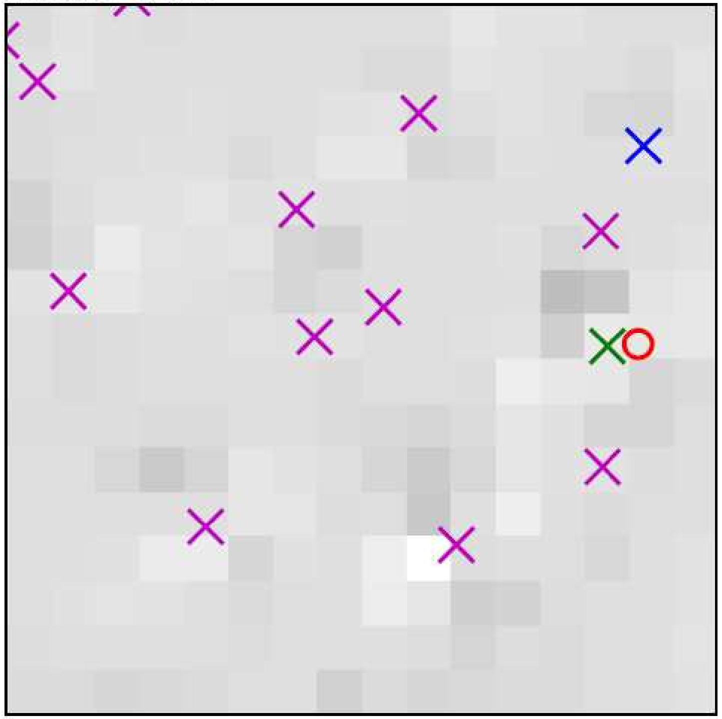


M3

HST image

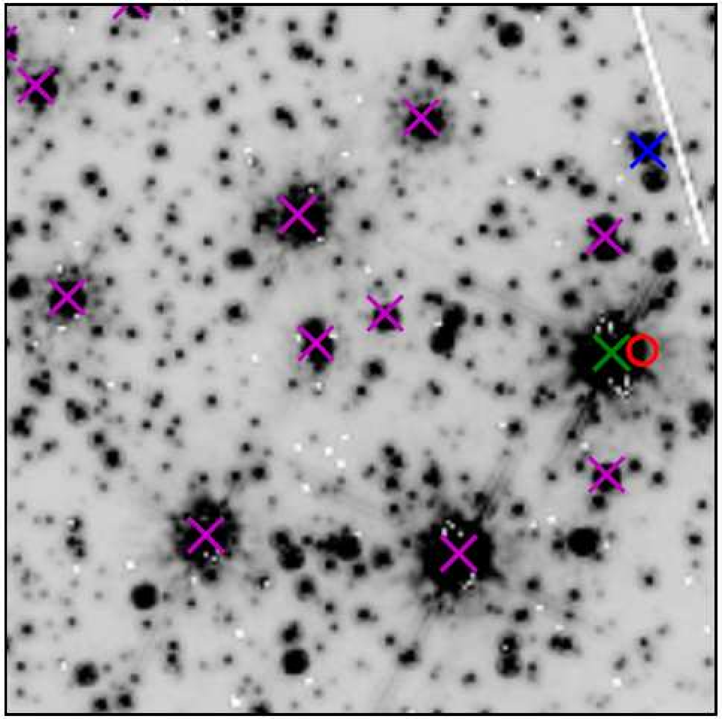


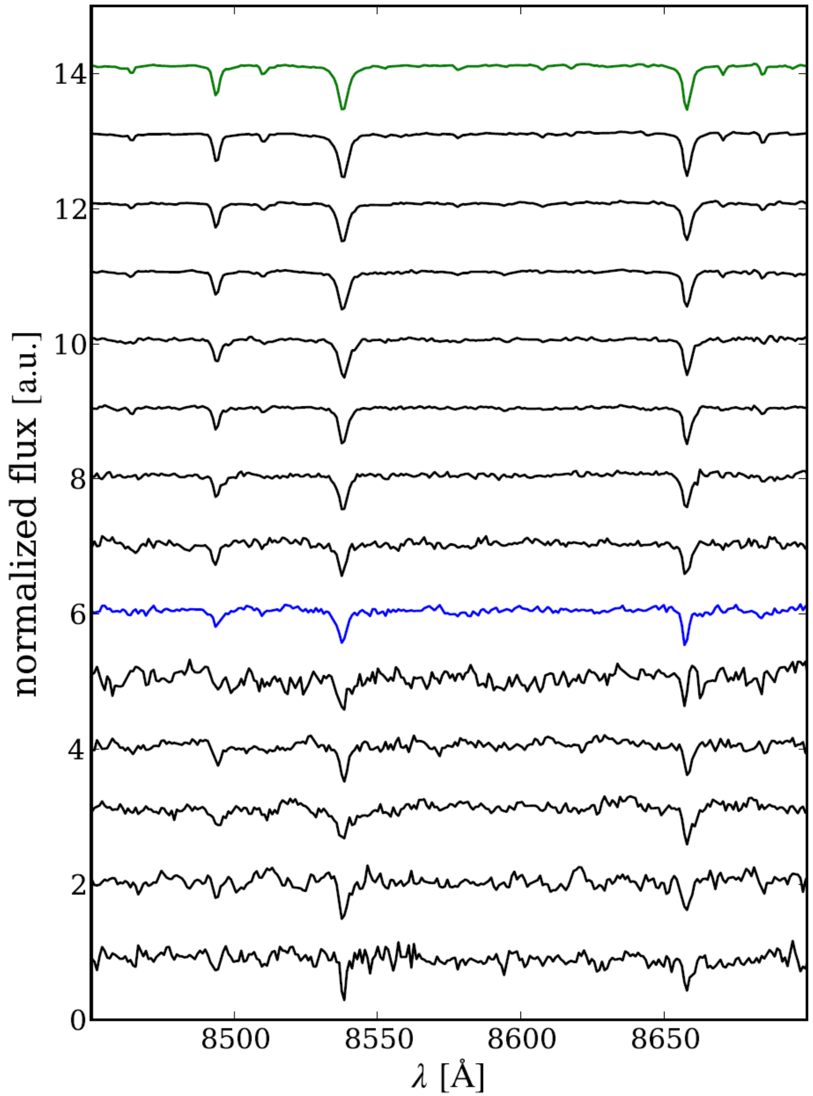
PMAS data



M3

HST image





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)

Modelling the Point Spread Function (PSF):

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

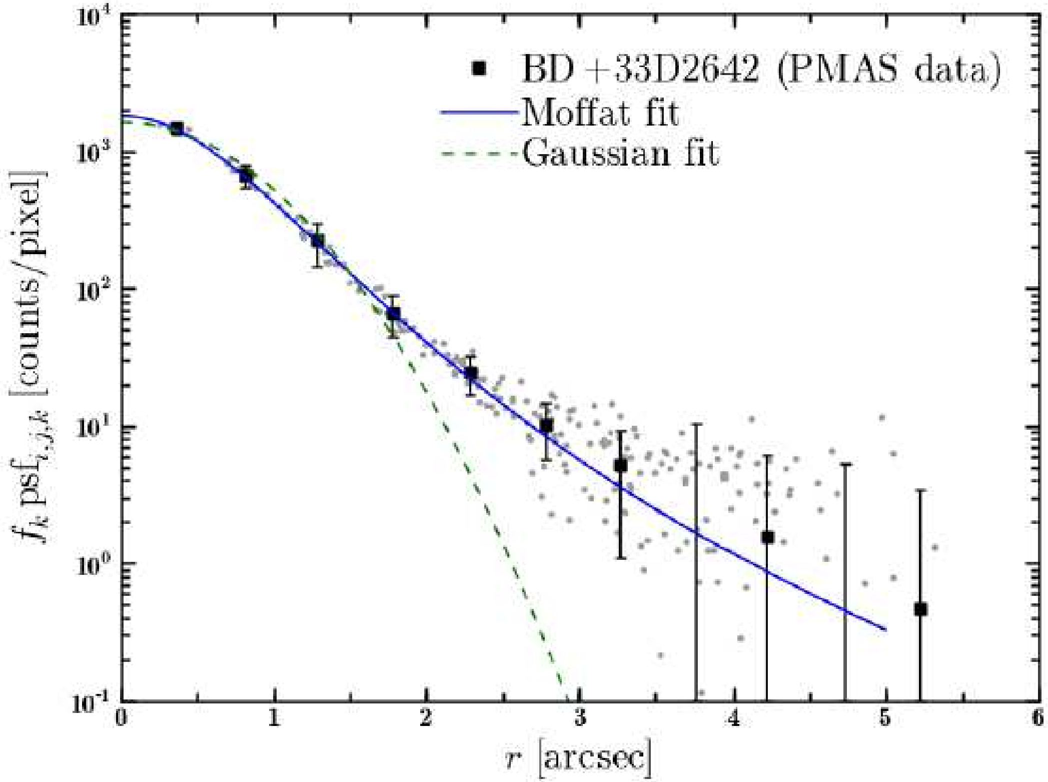
$$\hat{y} = (x - x^n)\sin\theta + (y - y^n)\cos\theta,$$

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

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

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

Moffat Function



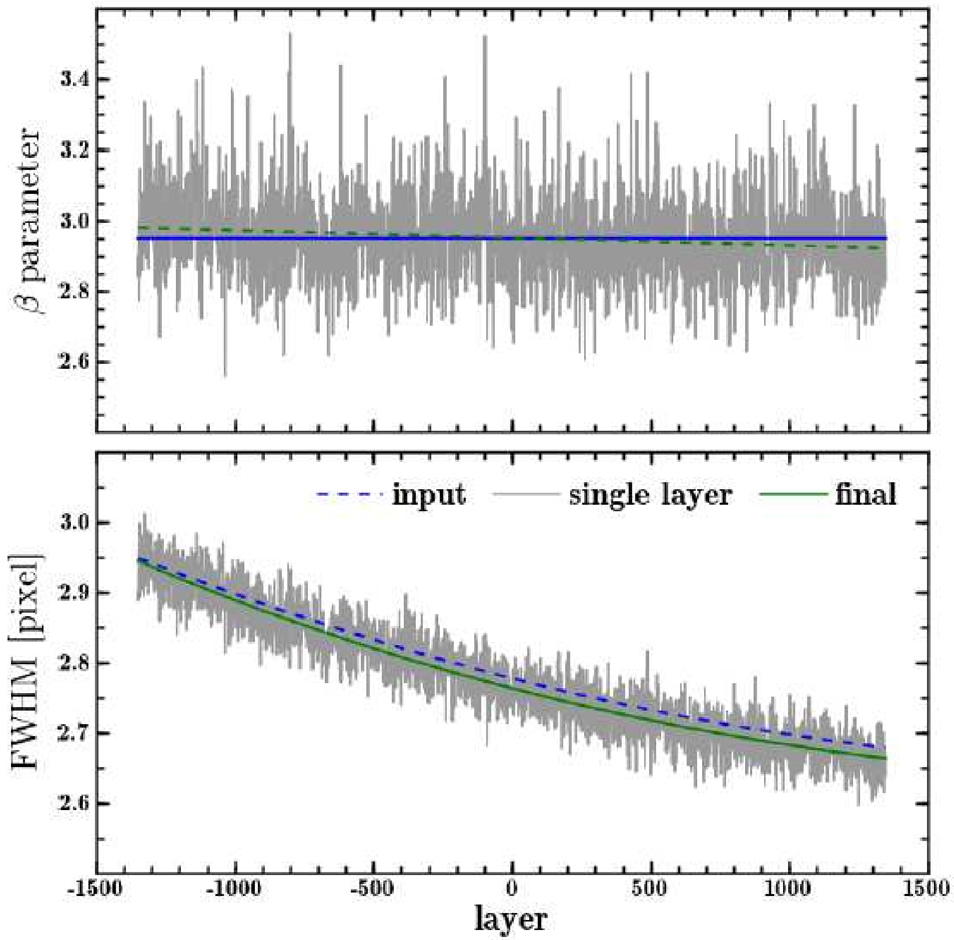
Global Model:

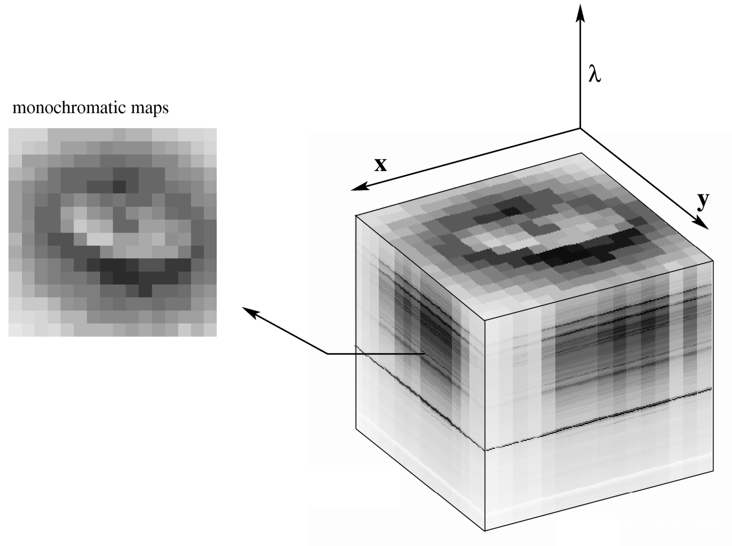
observed datacube: $\mathfrak{d}_{i,j,k}$

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

Recovering the PSF throughout the entire datacube:

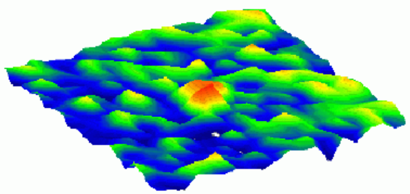


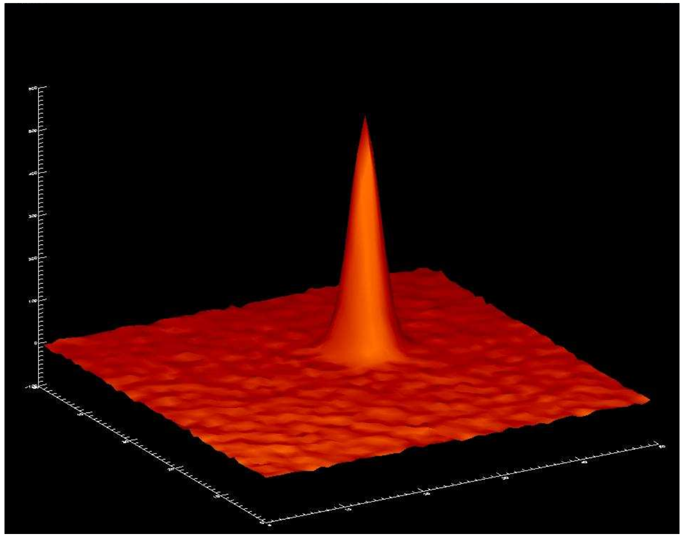


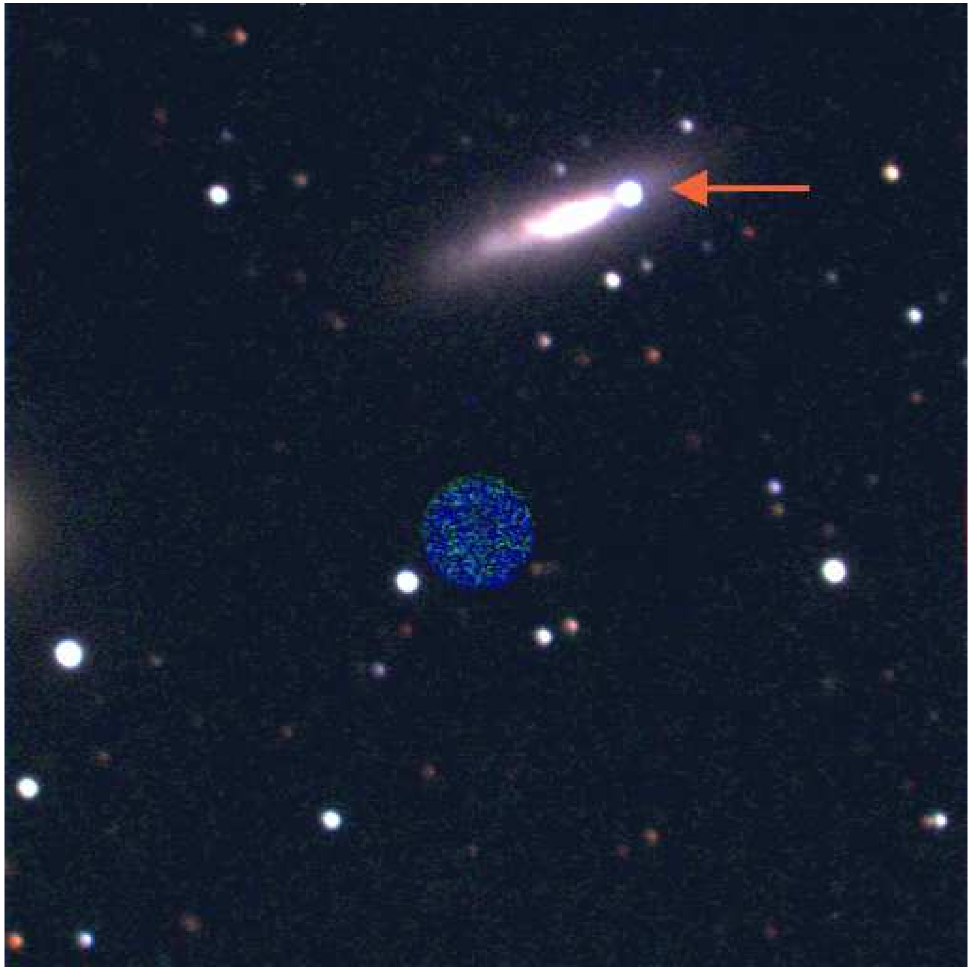
Extensive tests using numerical simulations:

- recovering the PSF
- recovering the centroid
- measuring effect of blending on flux
- measuring effect of blending on S/N
- measuring effect of blending on equivalent width
- measuring effect of blending on radial velocities

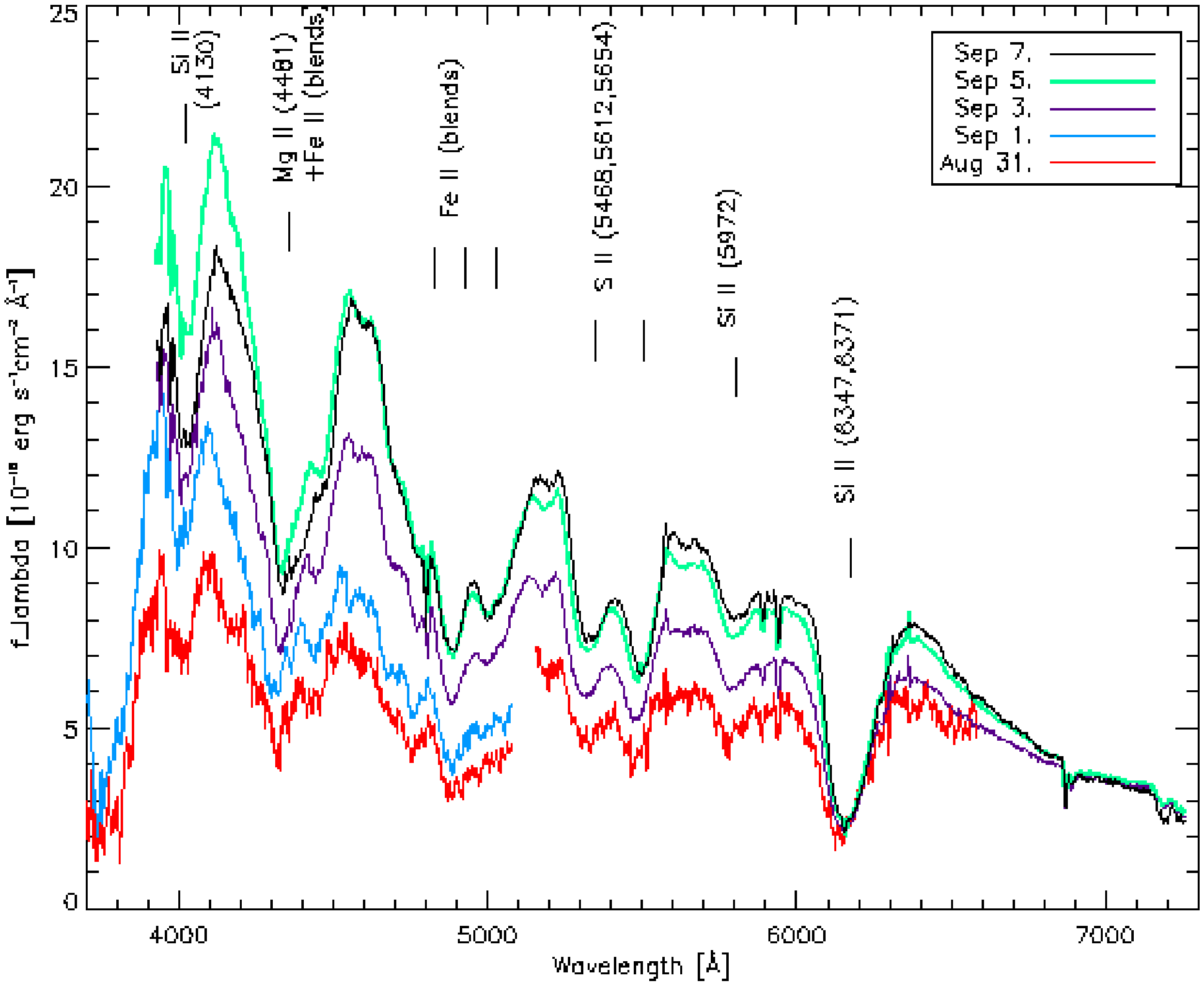
5. SN Ia and their environment







Christensen L., Becker T., Jahnke K., Kelz A., Roth M. M., Sánchez S. F., Wisotzki L.
Integral field spectroscopy of SN2002er with PMAS
A&A, 401 (2003) 479



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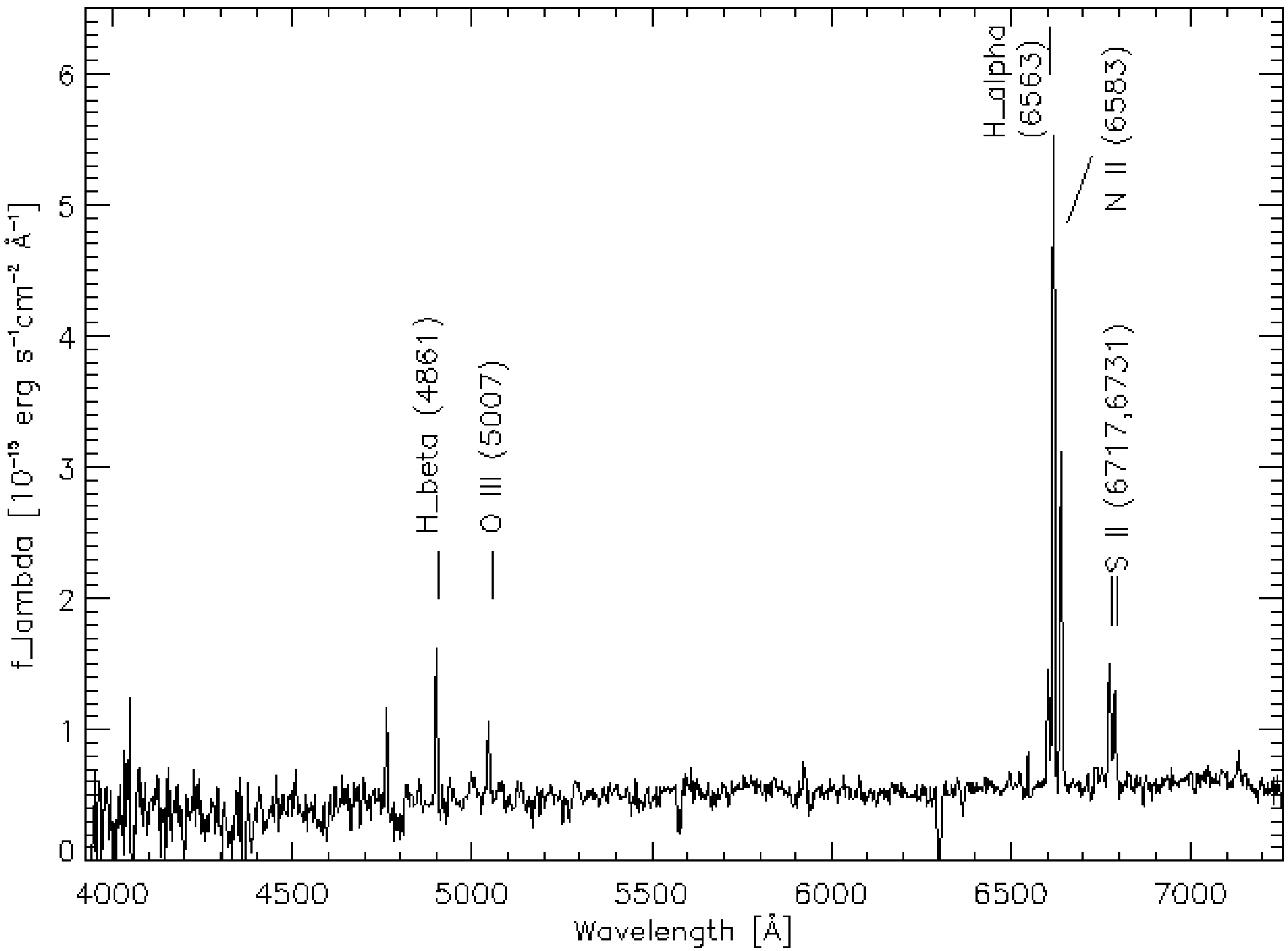

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Astronomy & Astrophysics manuscript no. Halpha_environment
September 11, 2013

arXiv:1309.1182v2

Evidence of Environmental Dependencies of Type Ia Supernovae from the Nearby Supernova Factory indicated by Local Hα

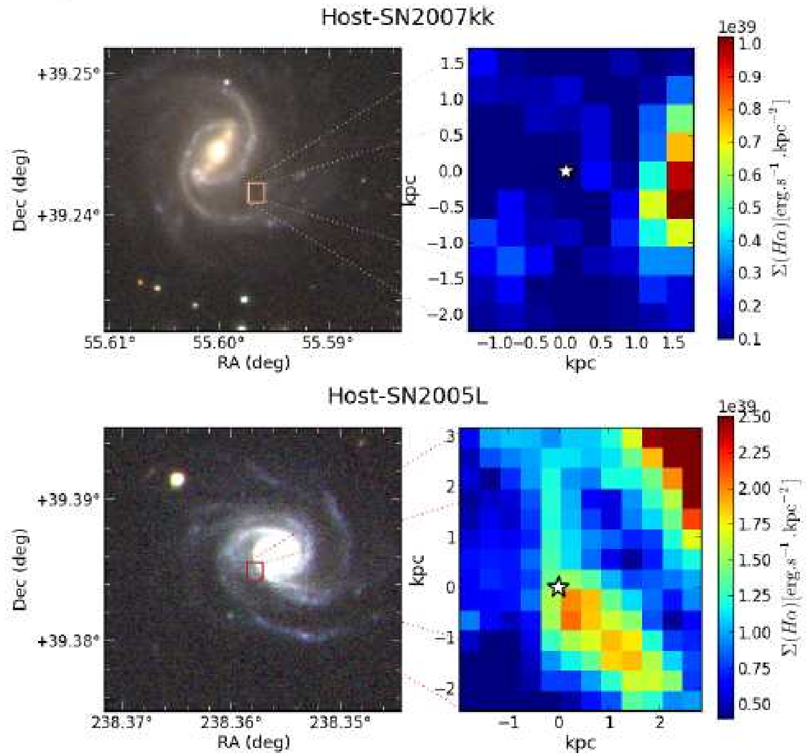
M. Rigault[1], Y. Copin[1], G. Aldering[2], P. Antilogus[3], C. Aragon[2], S. Bailey[2], C. Baltay[4], S. Bongard[3], C. Buton[5], A. Canto[3], F. Cellier-Holzem[3], M. Childress[6], N. Chotard[1], H. K. Fakhouri[2,7], U. Feindt[5], M. Fleury[3], E. Gangler[1], P. Greskovic[5], J. Guy[3], A. G. Kim[2], M. Kowalski[5], S. Lombardo[5], J. Nordin[2,8], P. Nugent[9,10], R. Pain[3], E. Pécontal[11], R. Pereira[1], S. Perlmutter[2,7], D. Rabinowitz[4], K. Runge[2], C. Saunders[2], R. Scalzo[6], G. Smadja[1], C. Tao[12,13], R. C. Thomas[9], and B. A. Weaver[14]
(The Nearby Supernova Factory)

- SNIFS at UH 2.2m
- 89 SN Ia host galaxies, $0.03 < z < 0.08$
- SN environment < 1 kpc
- use Hα as SF indicator with 2 groups:

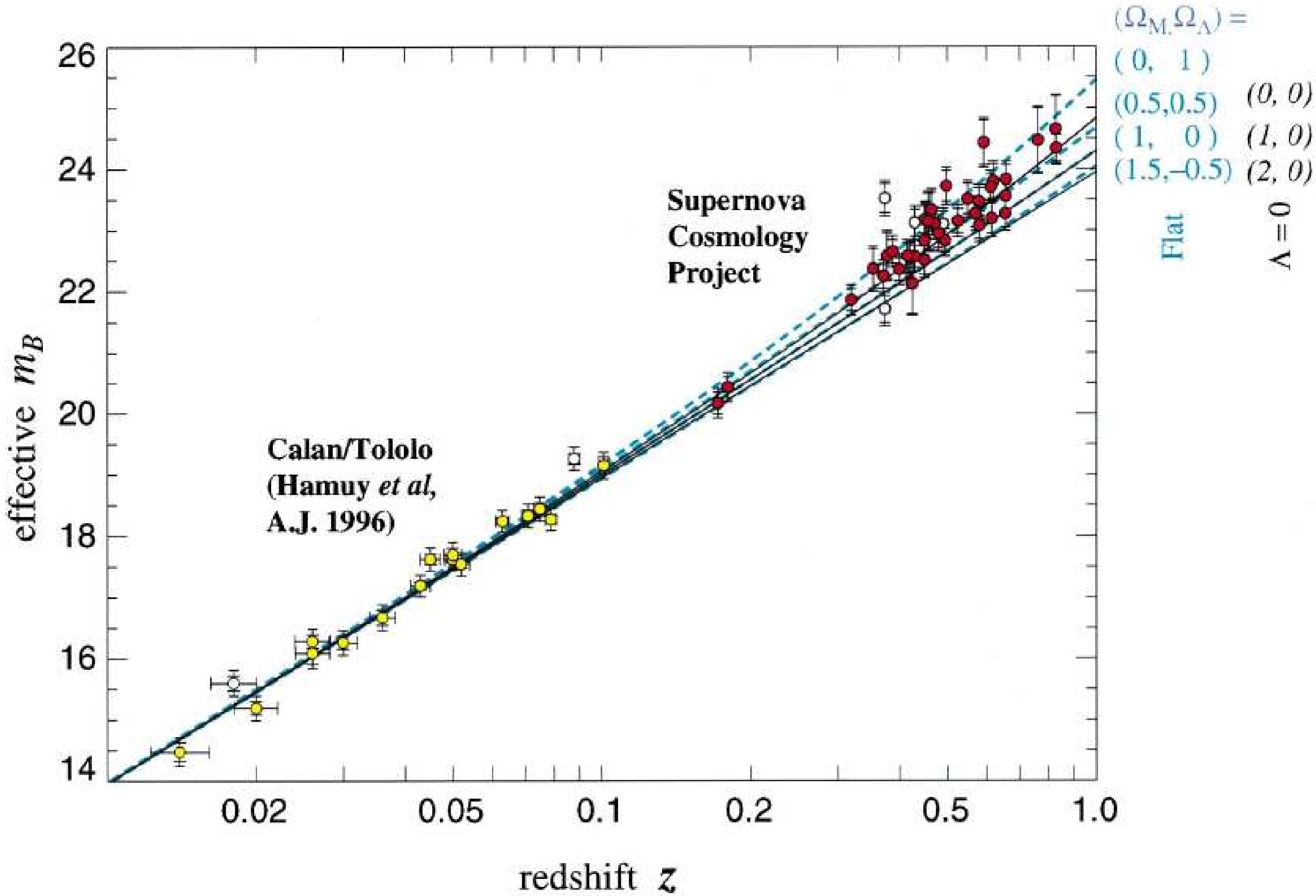
(1) $\log \Sigma \mathrm{H}\alpha > 38.3$ erg s^{-1} kpc^{-2}
„locally starforming“

(2) $\log \Sigma \mathrm{H}\alpha < 38.3$ erg s^{-1} kpc^{-2}
„locally passive“

► SN$^{(1)}$ 0.09 mag *fainter* than SN$^{(2)}$

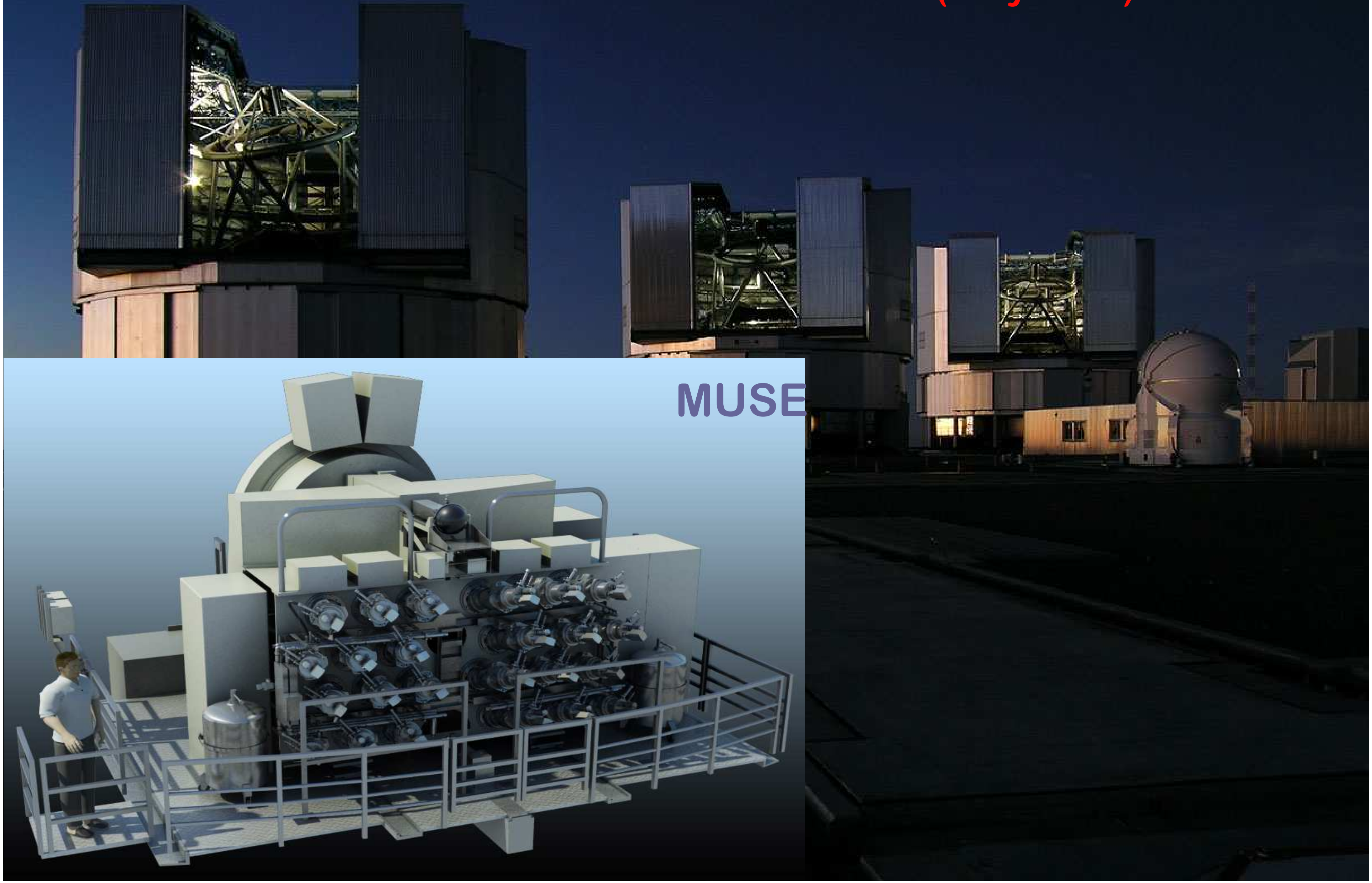


Bias on equation of state:
$\Delta w \sim -0.06$



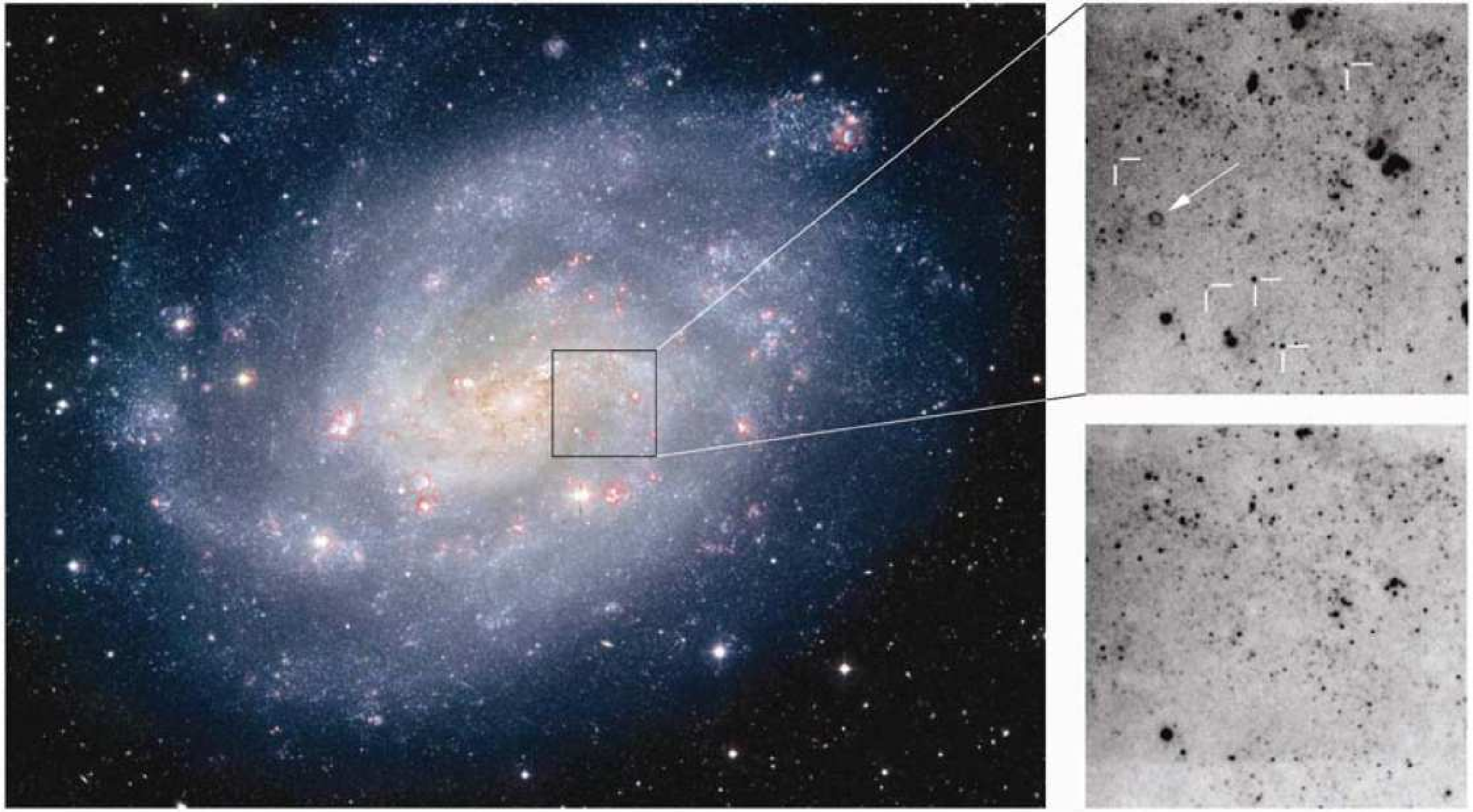
6. Crowded Field 3D Spectroscopy

- in the (very near) future

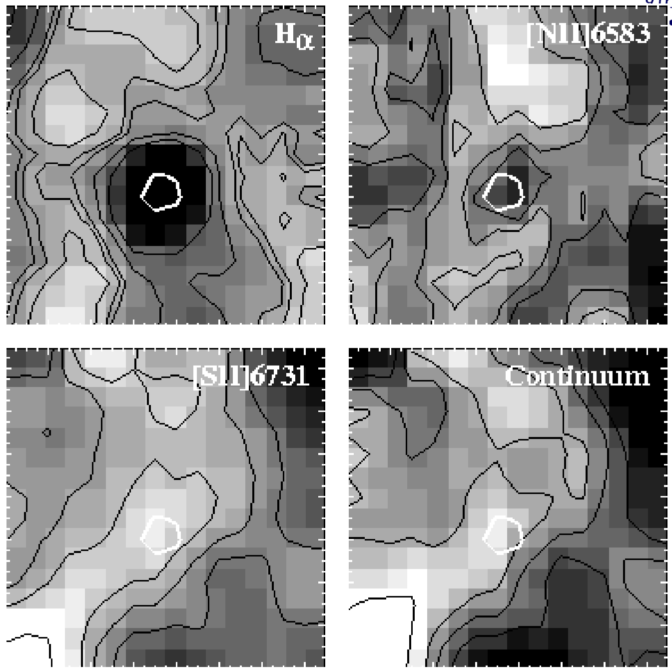


6. Crowded Field 3D Spectroscopy

- in nearby galaxies

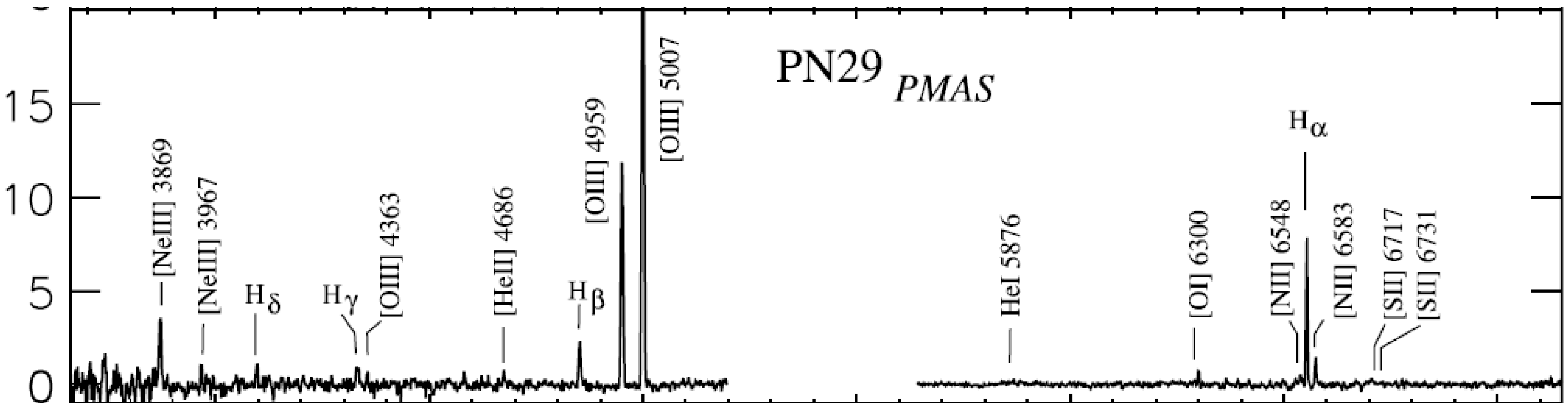


Crowded field 3D spectroscopy in nearby galaxies

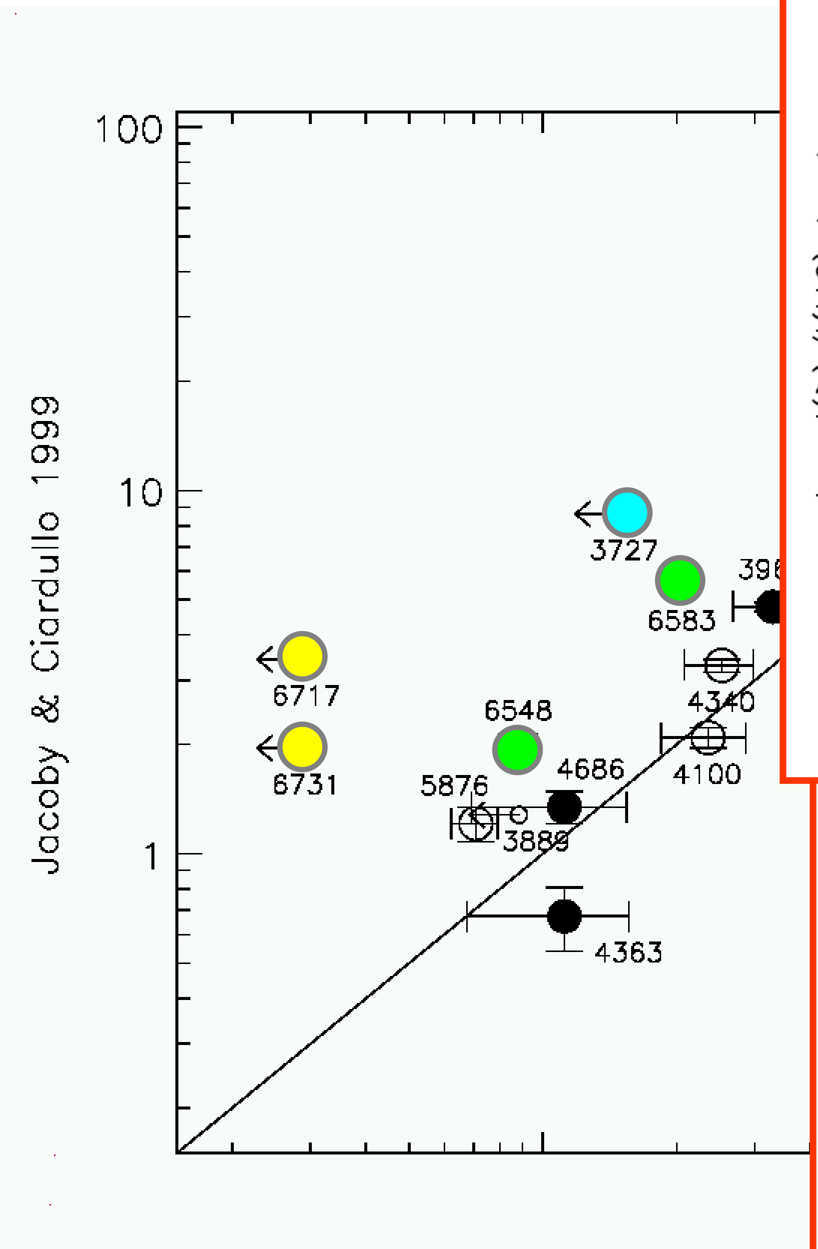


beat the background limit !

Roth et al. 2005



AIP



100
10
1
Jacoby & Ciardullo 1999
3727
6583
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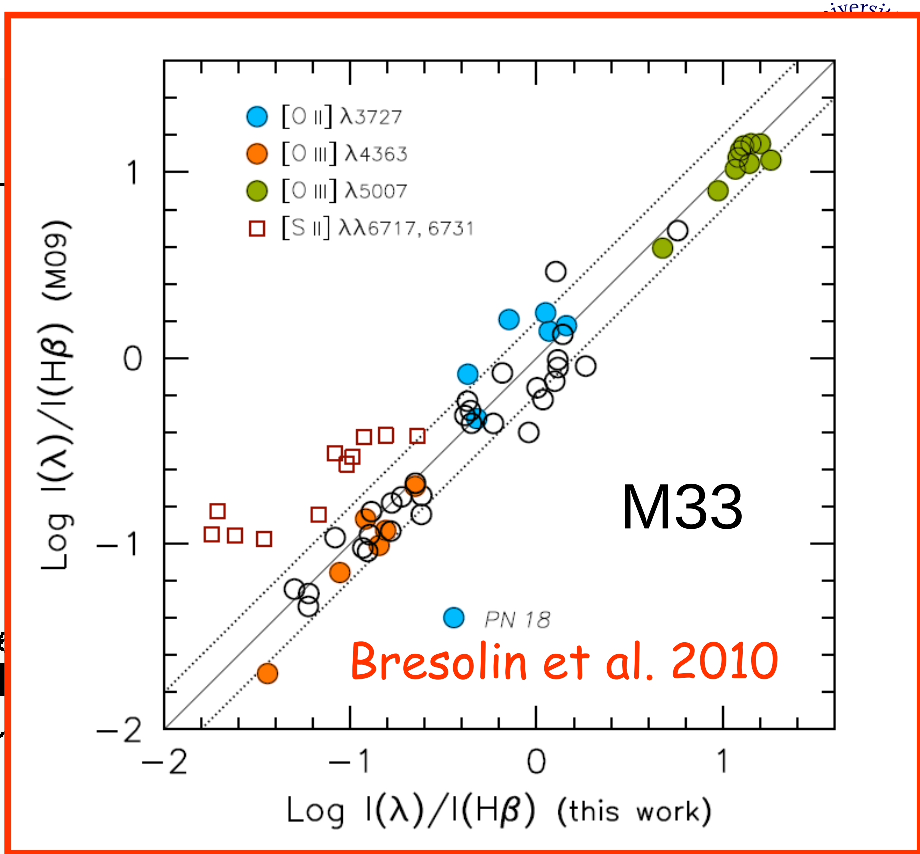
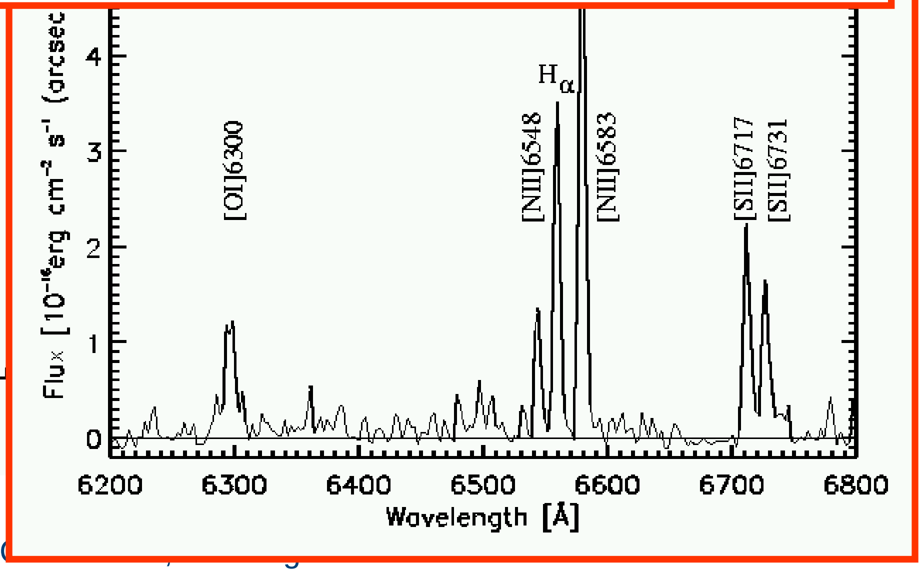
5876
4686
3889
4363
4340
4100



[O II] λ3727
[O III] λ4363
[O III] λ5007
[S II] λλ6717, 6731
M33
PN 18
Bresolin et al. 2010
Log I(λ)/I(Hβ) (M09)
Log I(λ)/I(Hβ) (this work)
1
0
−1
−2

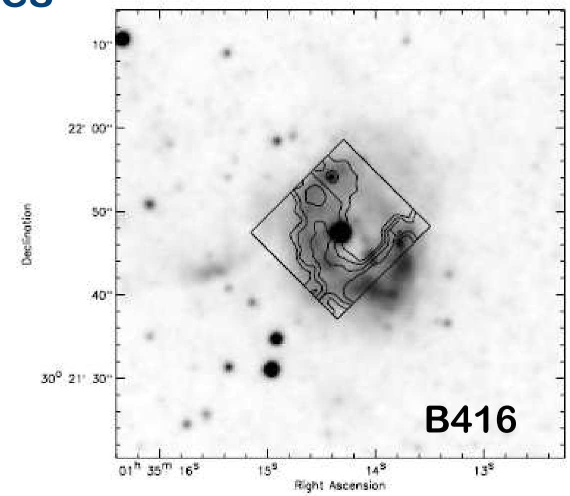


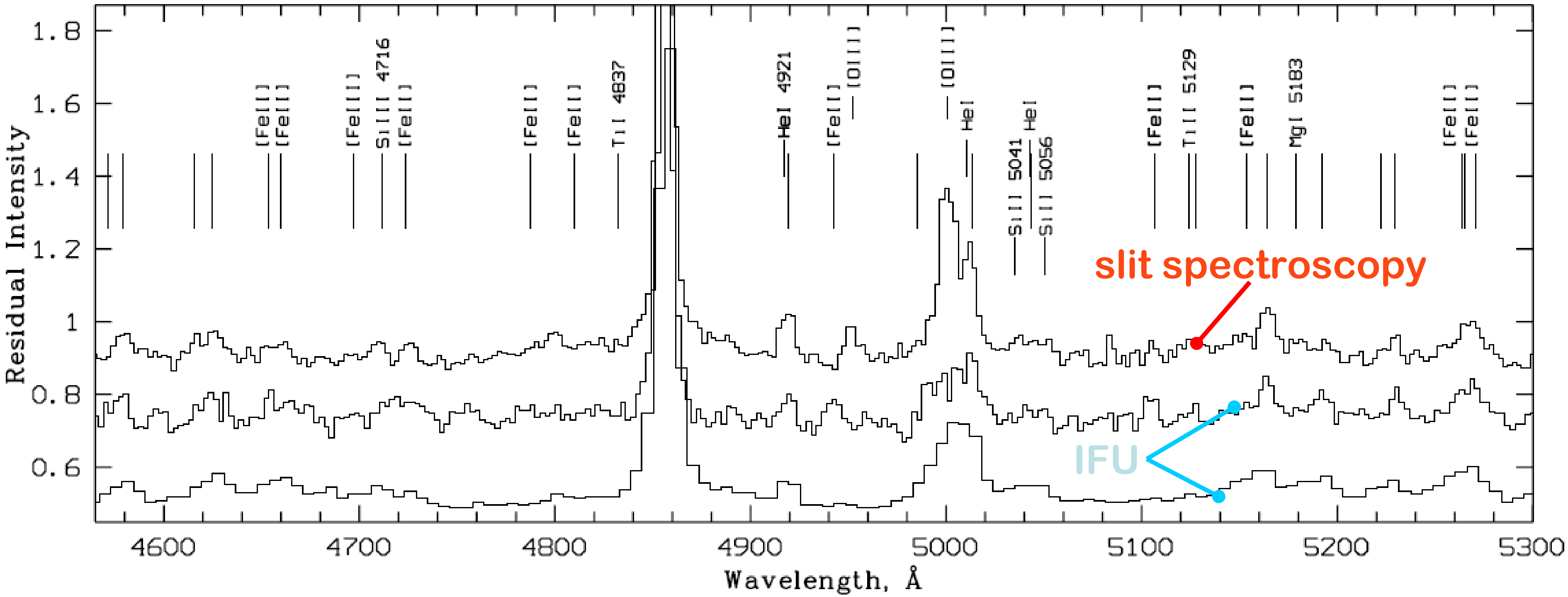
[OI]6300
[NII]6548
Hα
[NII]6583
[SII]6717
[SII]6731
Flux [10⁻¹⁶erg cm⁻² s⁻¹ (arcsec
Wavelength [Å]
6200
6300
6400
6500
6600
6700
6800

AIP

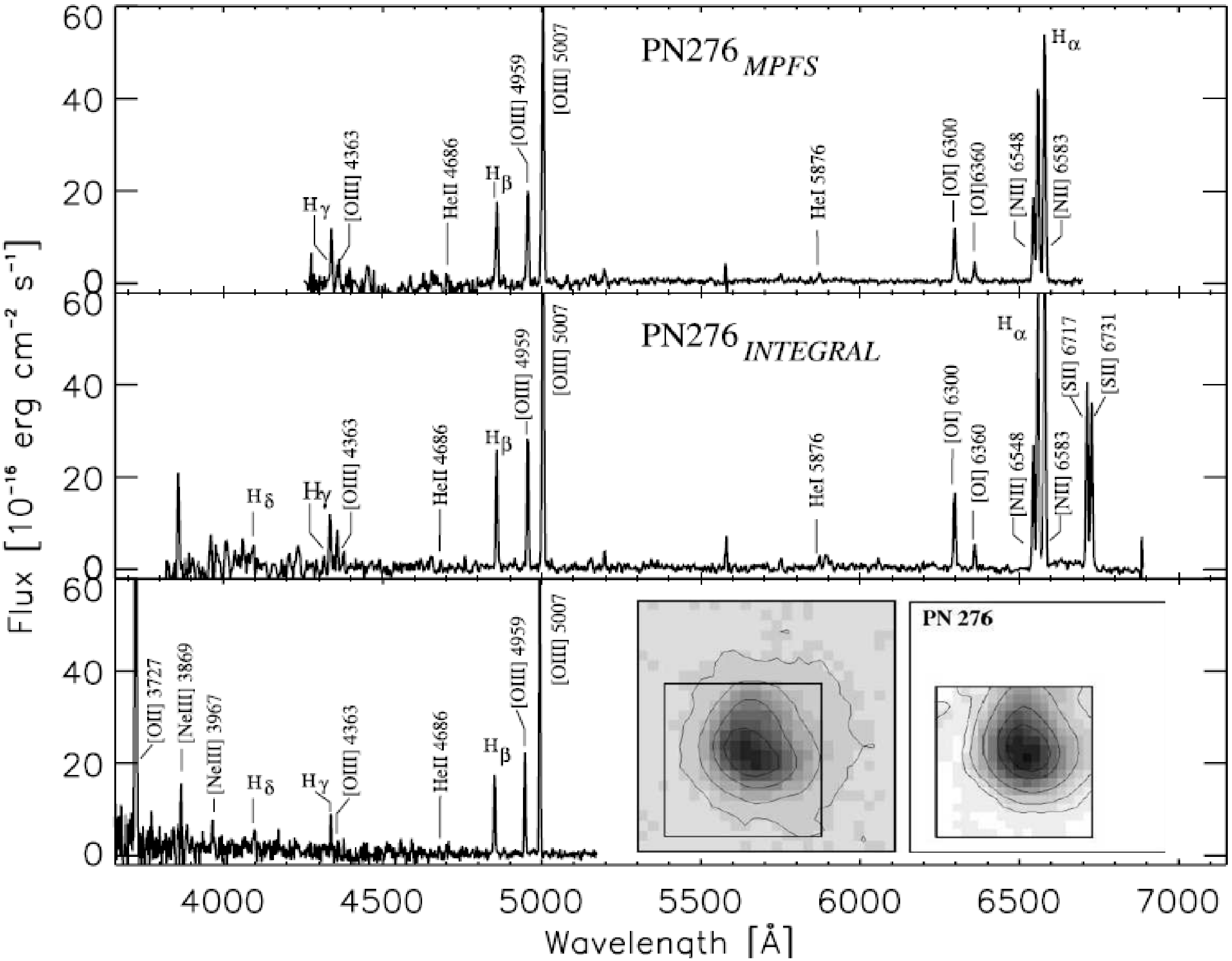
▶ LBV candidate in M33

Fabrika et al. 2005





Serendipity discoveries

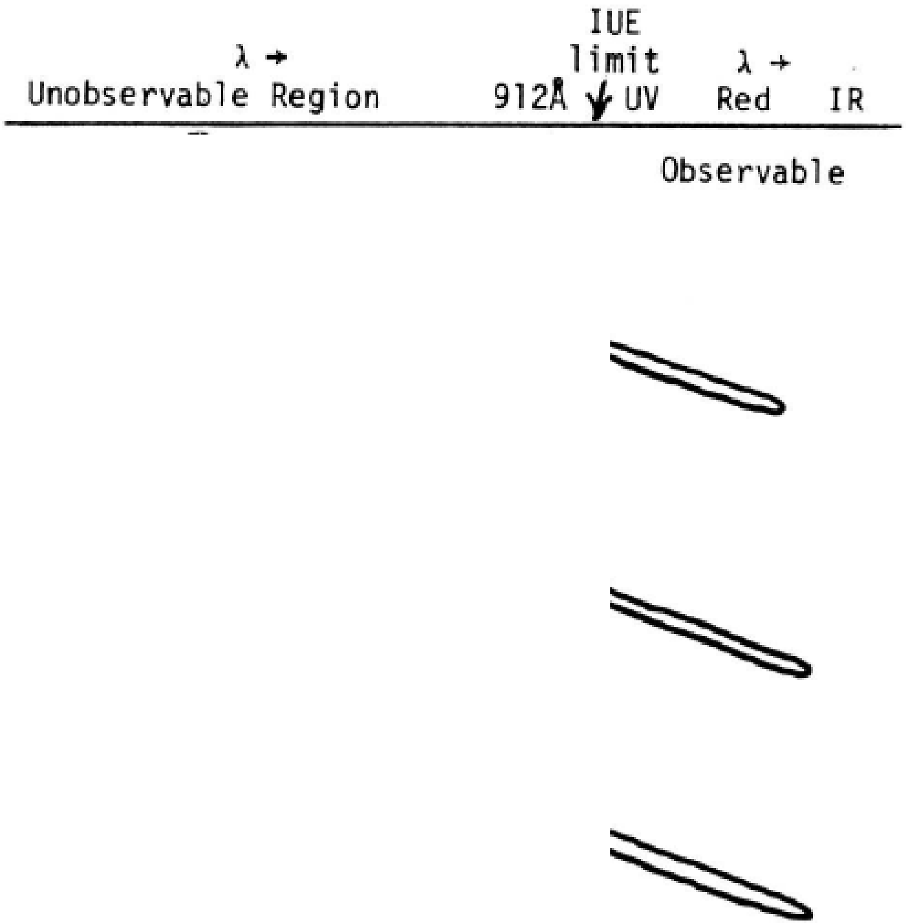


PN survey in LMC (Reid & Parker 2006)

Object	Previously known	Newly confirmed
PNe ‘true’	162(−2)	291
PNe ‘likely’	1	54
PNe ‘possible’	4	115
Emission-line stars	55	622
WR stars	14	8
Late-type stars	10	247
Variable stars	61	28
Other stars	1	72
H II regions	85	69
Emission objects of unknown nature	12	25
SNR	9	18
S/N too low for ID		32

PROBLEMS WITH CONTINUUM MEASURES OF HOT STARS ...

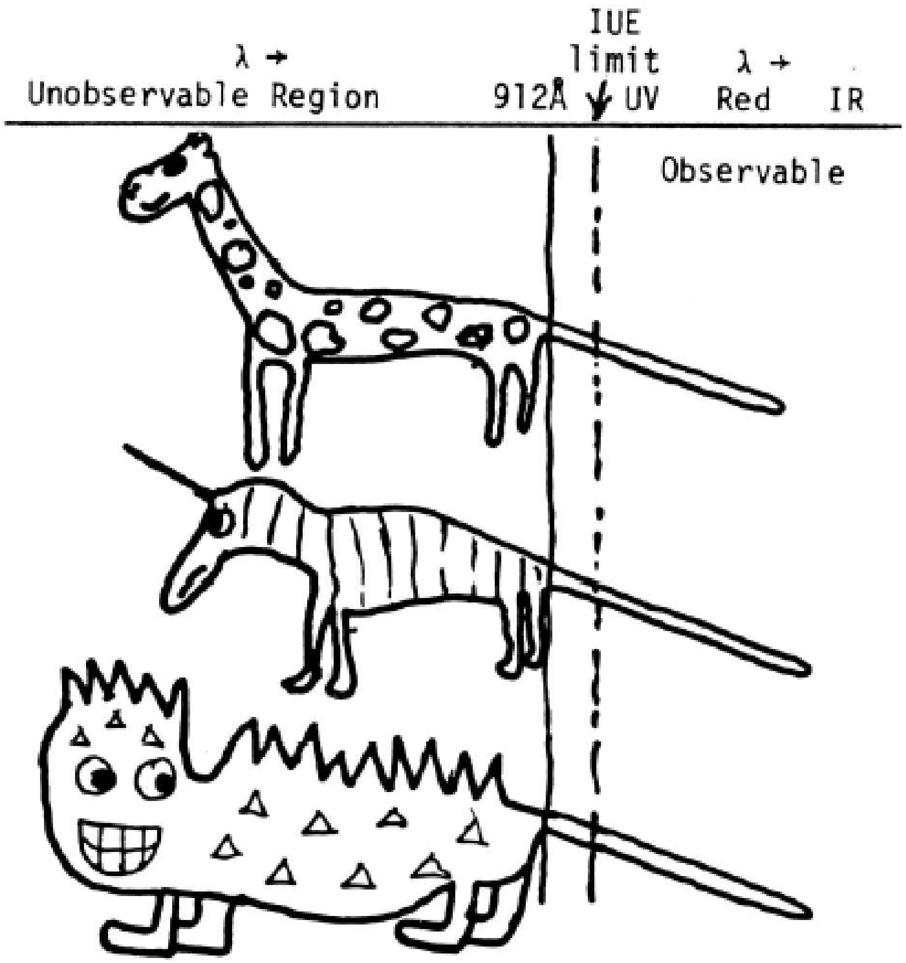
(with apologies to H.J.G.L.M.L.)



P. Conti

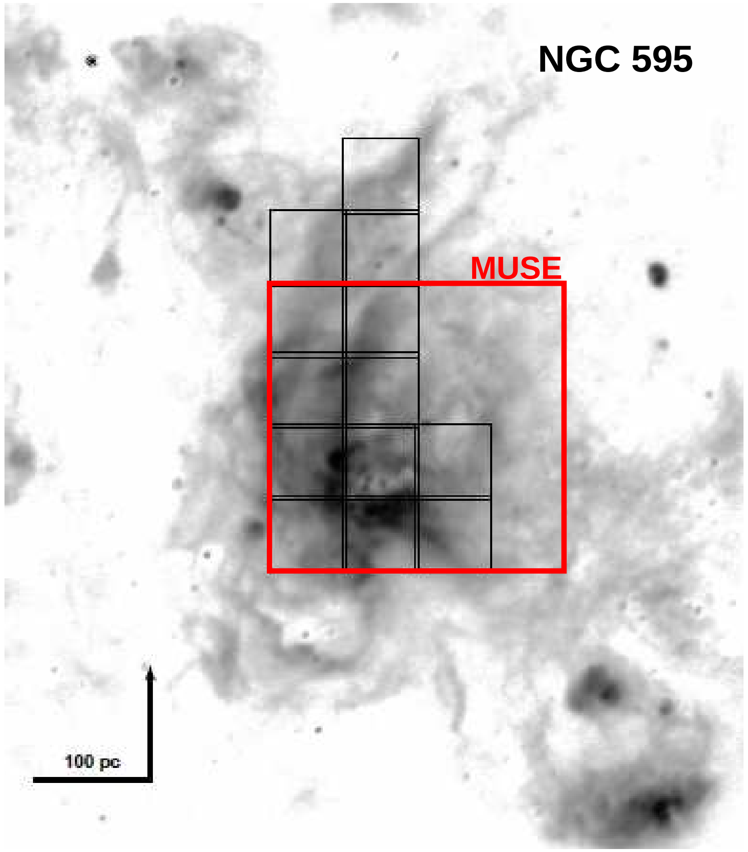
PROBLEMS WITH CONTINUUM MEASURES
OF HOT STARS ...

(with apologies to H.J.G.L.M.L.)

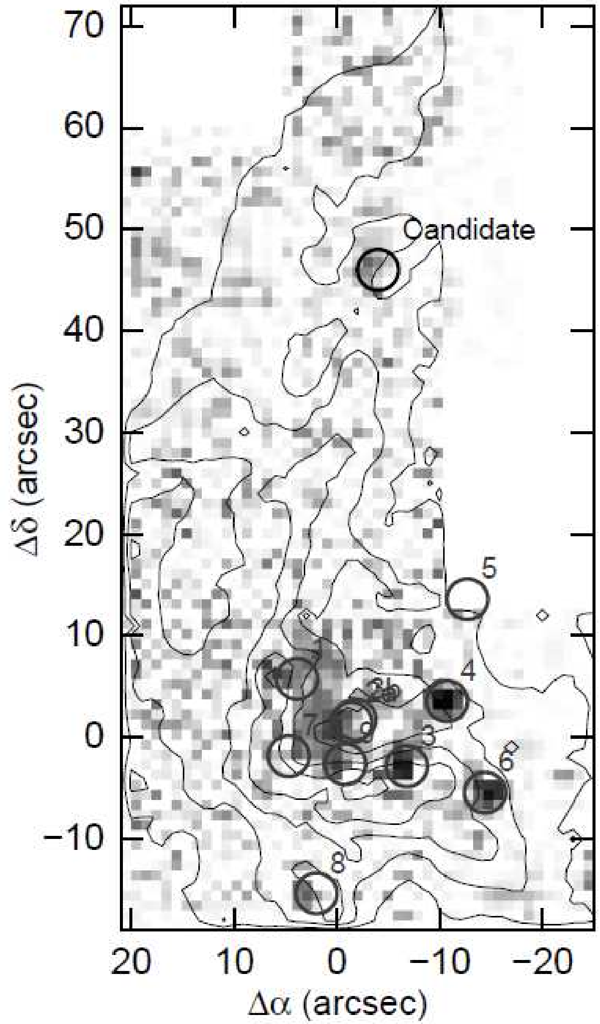


P. Conti

M33



Relano et al. 2010, MNRAS 402, 1635



Science drivers for future legacy IFU surveys in local volume galaxies:

1) Comprehensive inventory of massive stars, planetary nebulae, H II regions, SNRs, SSX sources, and other emission line objects, down to faint limits

2) Quantitative spectroscopy of massive stars and the physical properties of the surrounding gas (ne, Te, extinction, metallicity, kinematics)

3) Evolution of massive stars: the evolutionary connections between the different types of massive stars (i.e. WR, LBV, Ofpe/WNL, etc.)

4) Search for the nebular HeII4686 emission line objects and ionization source

5) Feedback from massive stars and chemical enrichment in the ISM

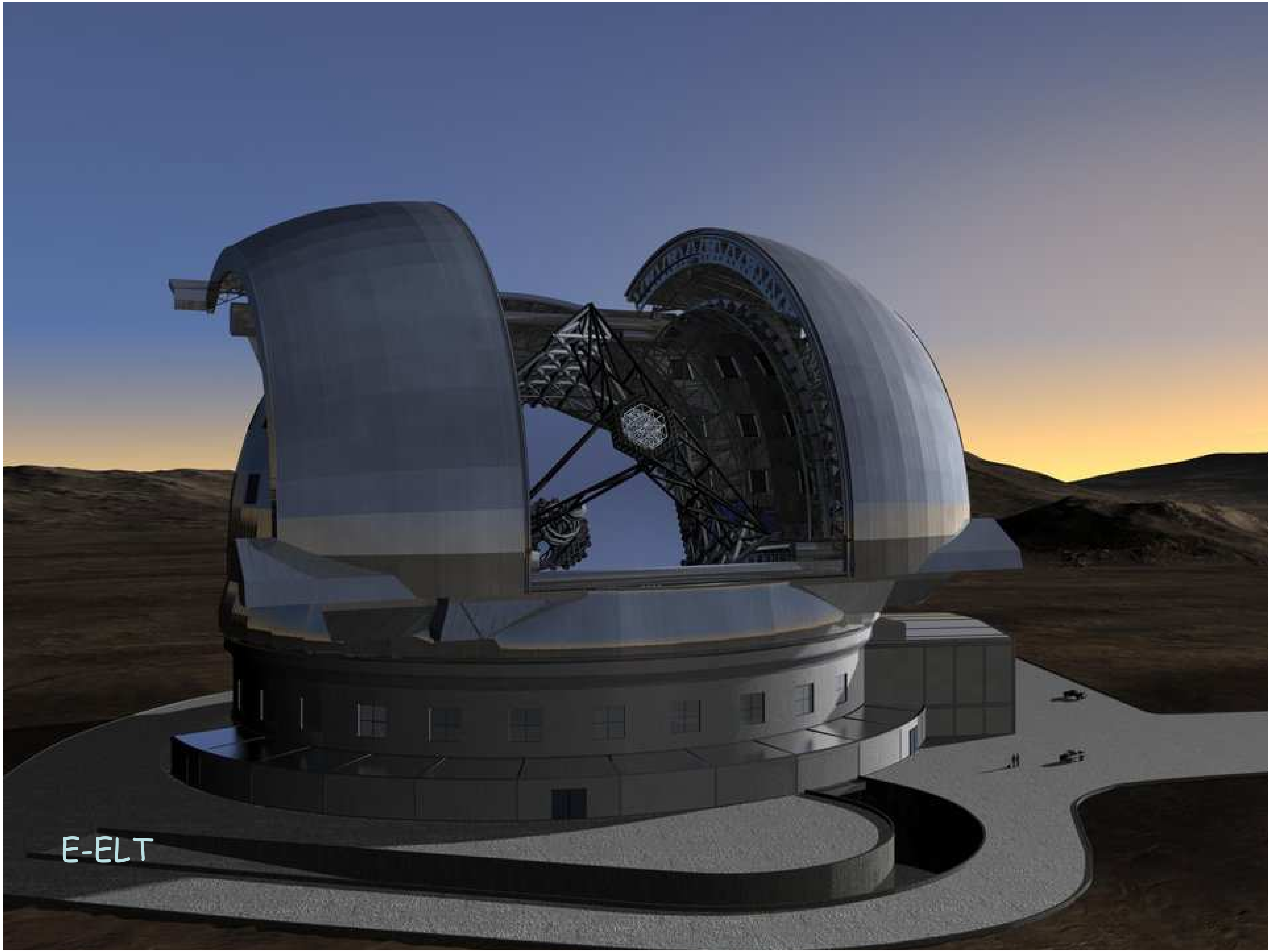
6) Lyman-alpha escape fraction, studied in detail in nearby galaxies

7) PN luminosity function to faint magnitudes, abundance gradients

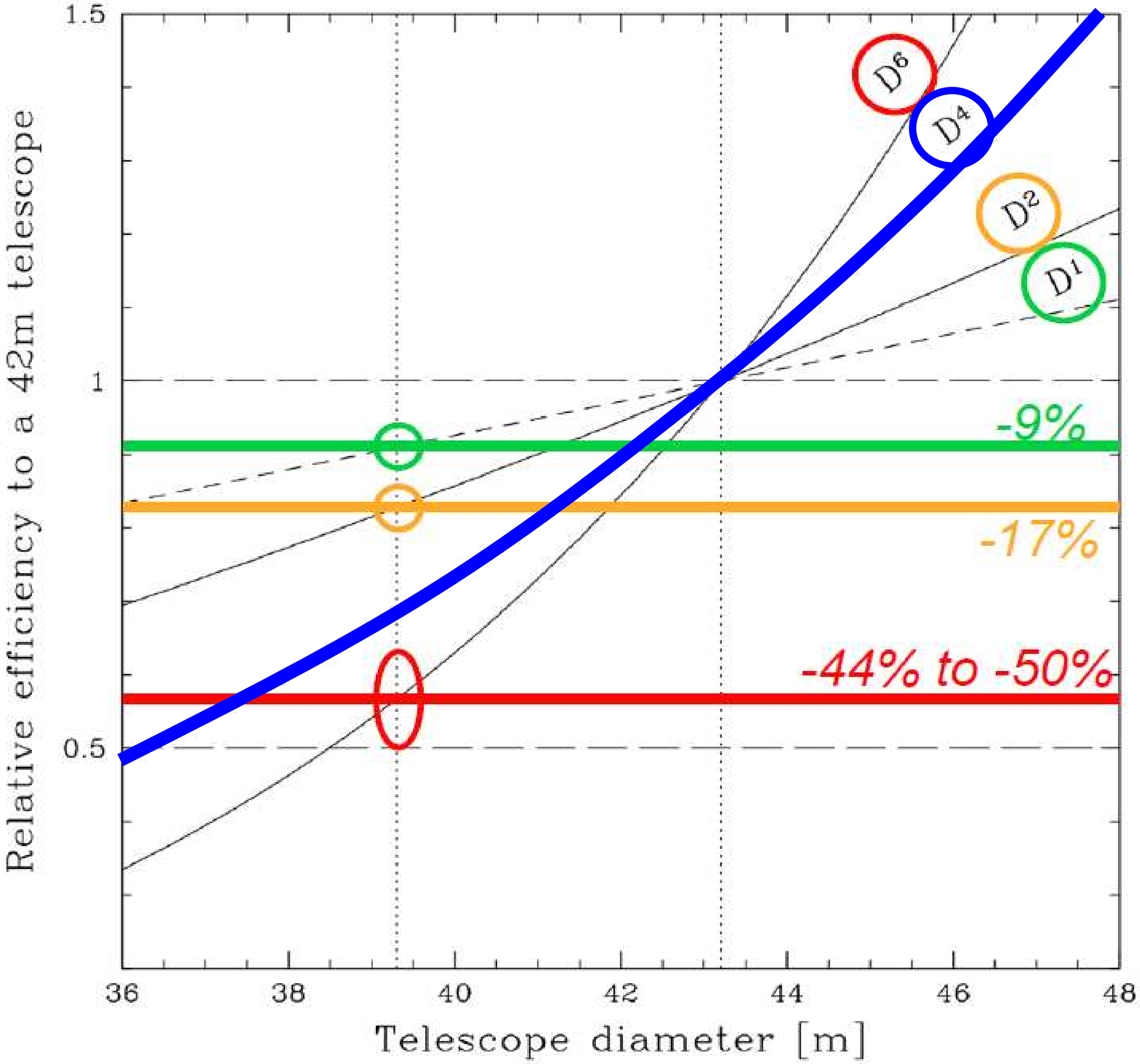
8) time domain (variable stars)

. . .

7. Outlook


E-ELT

E-ELT
Delta-Phase-B Trade-Off



~ D^6: *direct imaging of explanets*

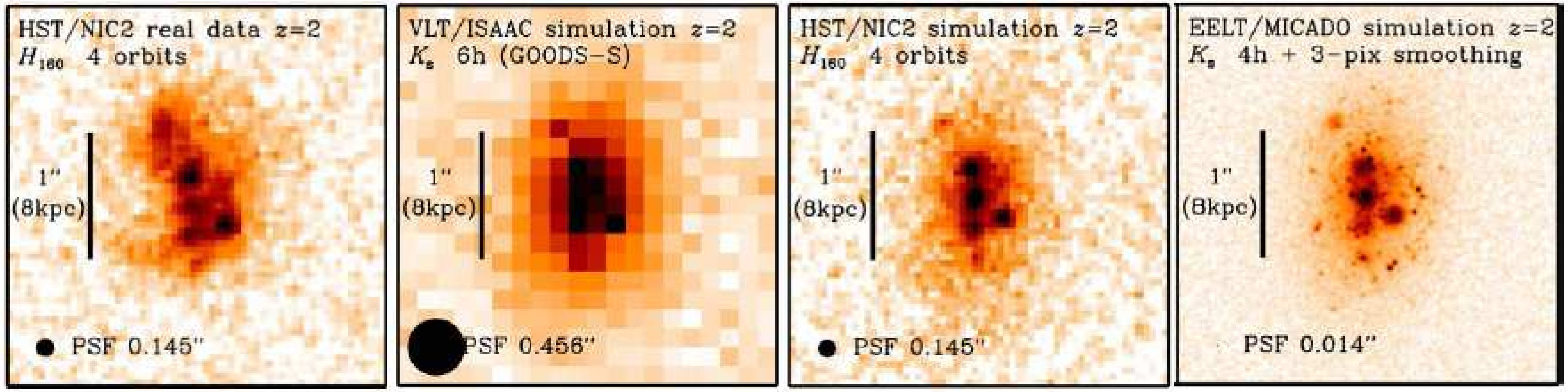
~ D^4: *AO-limited observation, e.g. stellar spectroscopy in Virgo Cluster galaxies*

~ D^2: *photon-limited observations, e.g. cosmic expansion → CODEX*

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

~ D^0: *RV research of exoplanets*

Expected E-ELT Performance (Davies 2013)



simulation of a large bright disk galaxy at z = 2.3 ($R_{1/2}$ = 5 kpc, K_{AB} = 21.3), showing that MICADO will be able to measure sizes, distribution and luminosity functions of compact clusters to K_{AB} ~ 28.5

MICADO

HARMONI

ELT-MOS