Looking at the Universe in colour: commissioning and the first results with MUSE

Davor Krajnović
and the MUSE Consortium

Zagreb, PMF, 21.11.2014.

What is MUSE?

- MUSE - Multi Unit Spectroscopic Explorer, is a panoramic integral-field spectrograph, a second generation VLT instrument
- Built to achieve
  - true imaging capabilities
    - large field of view, excellent image quality, high throughput
  - excellent spectrographic capabilities
    - large wavelength range, good spectral resolution

ESO - Göttingen - Leiden - Lyon - Potsdam - Toulouse - Zurich

muse

ESO - Göttingen - Leiden - Lyon - Potsdam - Toulouse - Zurich

MUSE Multi unit spectroscopic explorer (in short)

- Panoramic integral field unit
- 1x1 arcmin^2 Field of view in Wide Field Mode (WFM)
  - 7x7 arcsec^2 in NFM
- 0.2 arcsec sampling in WFM
  - 0.025 arcsec in NFM
- High image quality
- 4650-9300 A simultaneous wavelength range
- R = 1500-3500
- ~90000 spectra
- End-to-end throughput 0.35
- Advanced data reduction pipeline

- Optical derotator
- 24 Advanced slicers
- 24 Spectrographs
- 24 VHG gratings
- 24 (4k)^2 red sensitive CCDs with graded AR coating
- Optimized AR 80 layers dielectric mirror coatings
- Slow guiding system
- Optimized to work with AOF (GALACSI module)
- 7 tons weight, 30 m^3
- 2500 optical elements
- 21 M€ total cost (200 FTE)

ESO - Göttingen - Leiden - Lyon - Potsdam - Toulouse - Zurich

Consortium & Partners

MUSE team

Technical & ESO staff

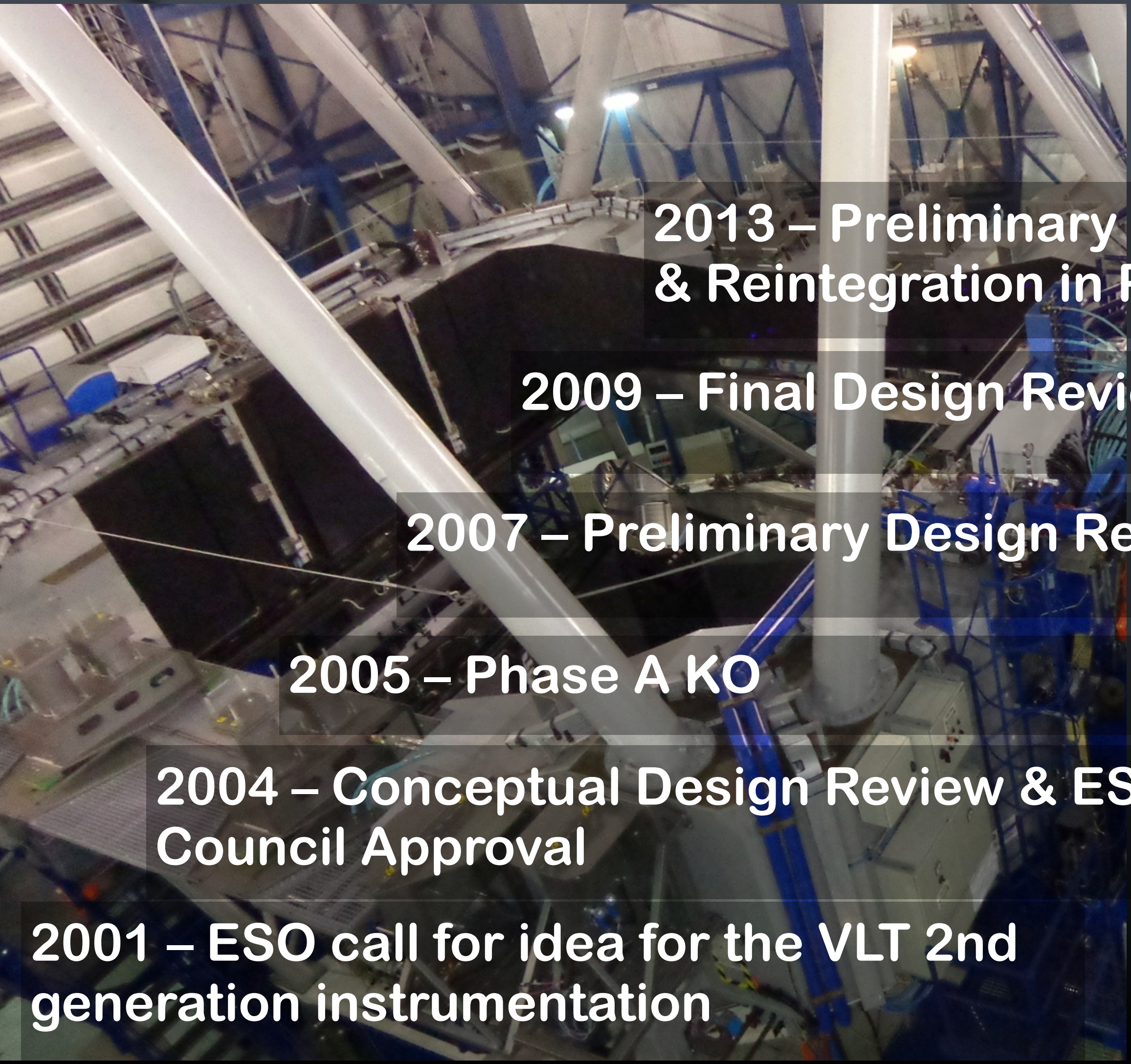
Accardo M, Adjali L, Anwand H, Bauer S-M, Boudon D, Brotons L, Cailler P, Capoani L, Comin M, Cumani C, Daguisé E, Deiries S, Delabre B, Dubois J-P, Dupieux M, Dupuy C, Fleischmann A, François M, Gallou G, Gharsa T, Girard N, Glindmann A, Gonté F, Hahan T, Hansali G, Hofmann D, Jarno A, Kelz A, Kiekebush M, Knudstrup J, Koehler C, Kosmalski J, Laurent F, LeFloch M, Lizon J-L, Loupias M, Manescau A, Monstein C, Nicklas H, Olaya J-C, Palsa R, Parès L, Pasquini L, Pécontal A, Petit C, Piqueras L, Popow E, Reiss R, Remillieux A, Renault E, Rhode P, Selman F, Streicher O, Stuik R, Valentin H, Vernet J, Vriend W-J, Zins G

Science Team

Bacon R, Blaizot J, Borosiva E, Bouche N, Bouwens R, Brinchmann J, Cantalupo S, Carollo M, Carton D, Caruana J, Contini T, Divoy C, Dreizler S, Emsellem E, Epinat B, Franx M, Garel T, Guiderdoni B, Herenz C, Husser T-O, Kamann S, Kovač K, Krajnović D, Lilly S, Martinsson T, Michel-Dansac L, Monreal-Ibero A, Pello R, Richard J, Roth M, Sandin C, Schaye J, Slezak E, Soto K, Soucail G, Steinmetz M, Turner M, Verhamme A, Weilbacher P, Wendt M, Wisotzki L

Contractors

Winlight System (France), e2v (UK), Kaiser Optical Systems (USA), Streicher (Deutchland), Balzers Coating (Luxembourg & Germany), Clappaz SARL (France), POG (Germany), MGS (France)



2013 – Preliminary Acceptance in Europe & Reintegration in Paranal

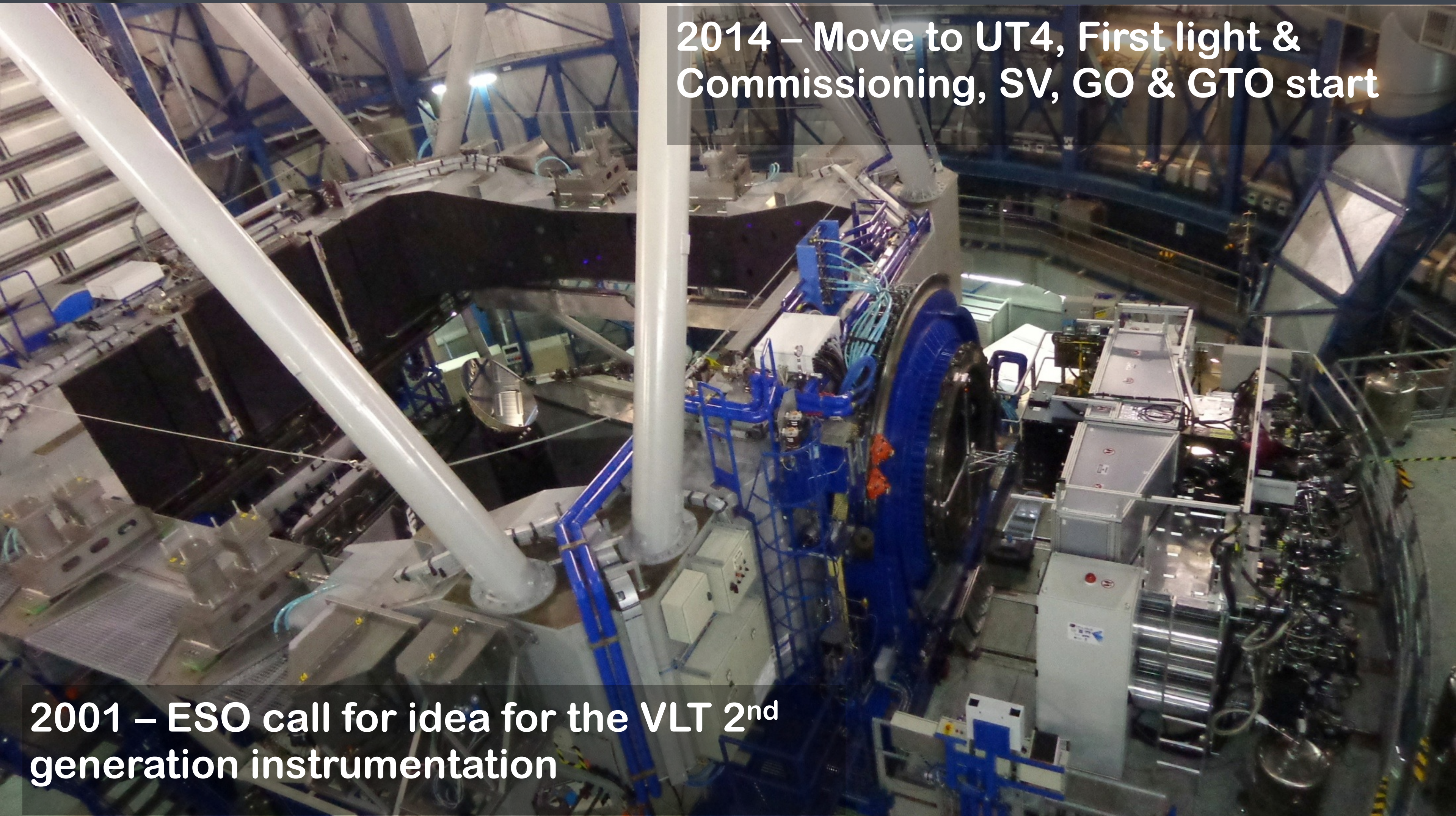
2009 – Final Design Review

2007 – Preliminary Design Review

2005 – Phase A KO

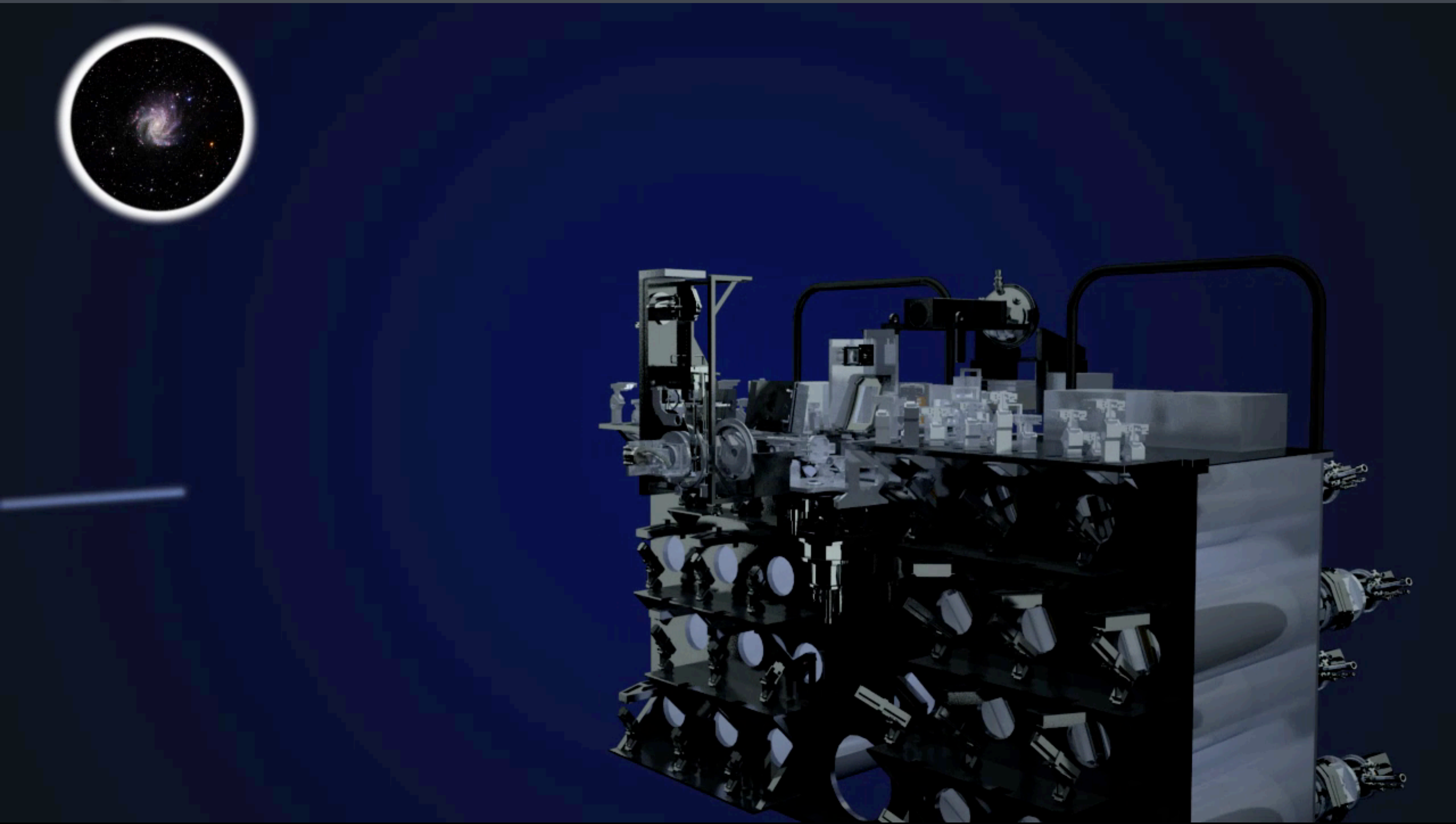
2004 – Conceptual Design Review & ESO Council Approval

2001 – ESO call for idea for the VLT 2nd generation instrumentation



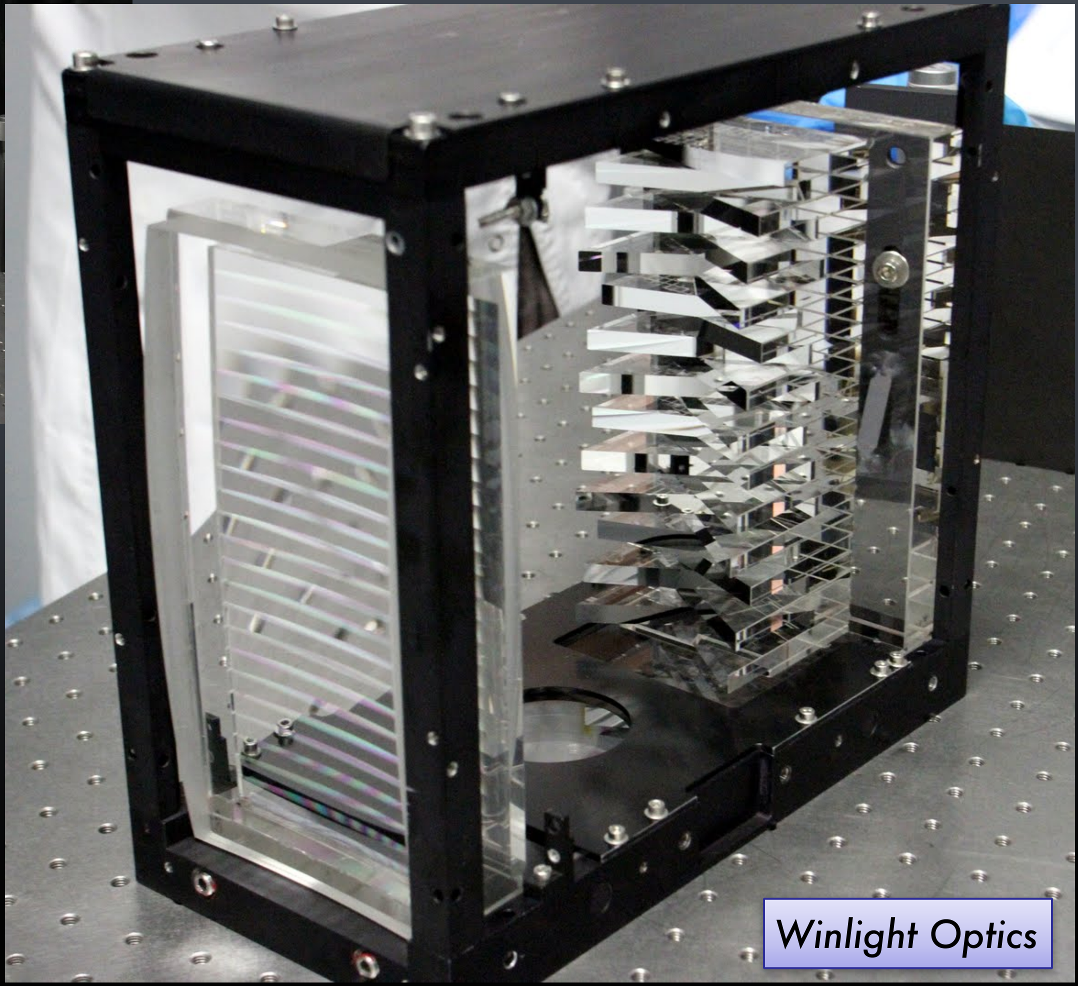
2014 – Move to UT4, First light & Commissioning, SV, GO & GTO start

2001 – ESO call for idea for the VLT 2nd generation instrumentation

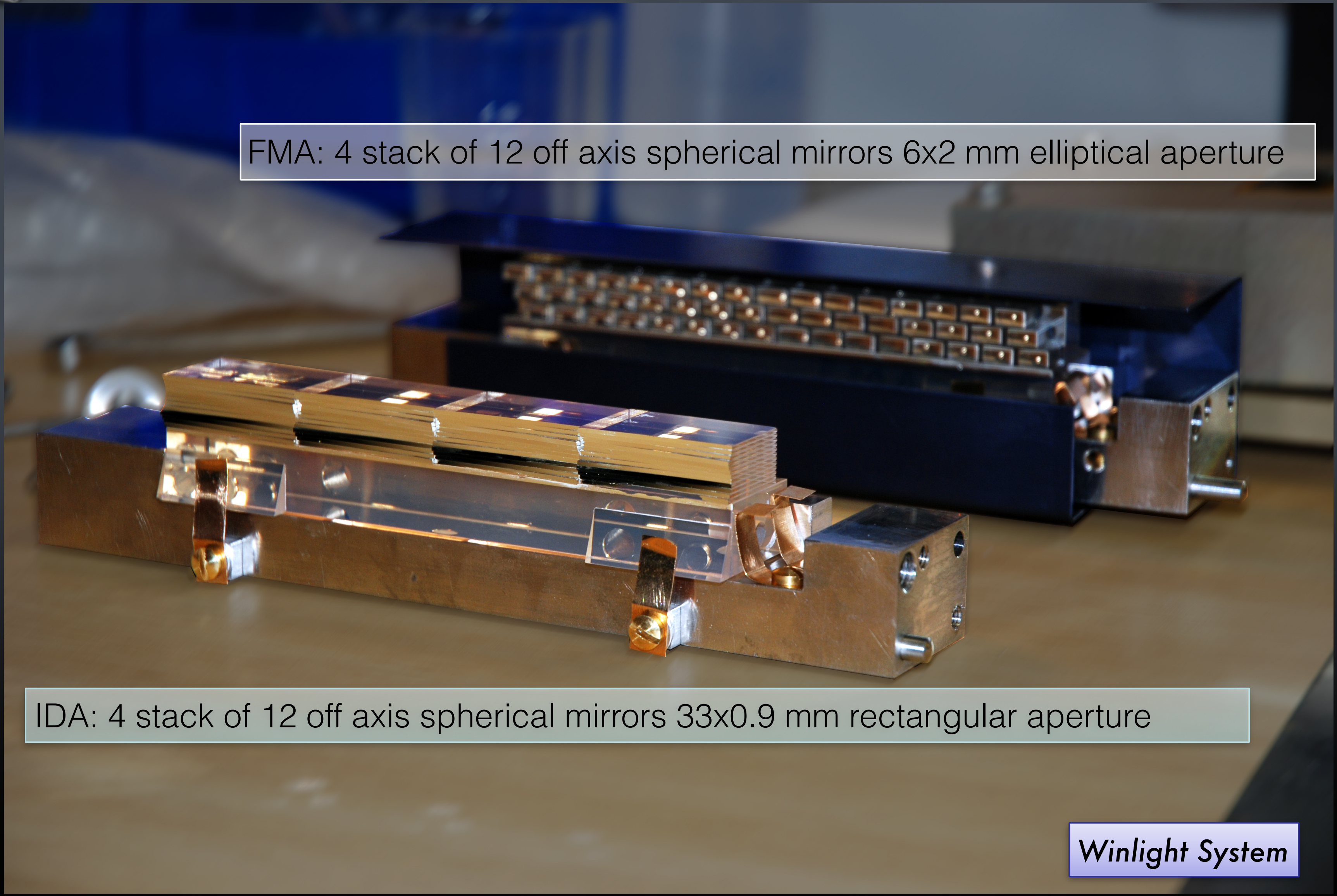


Field Splitter Unit

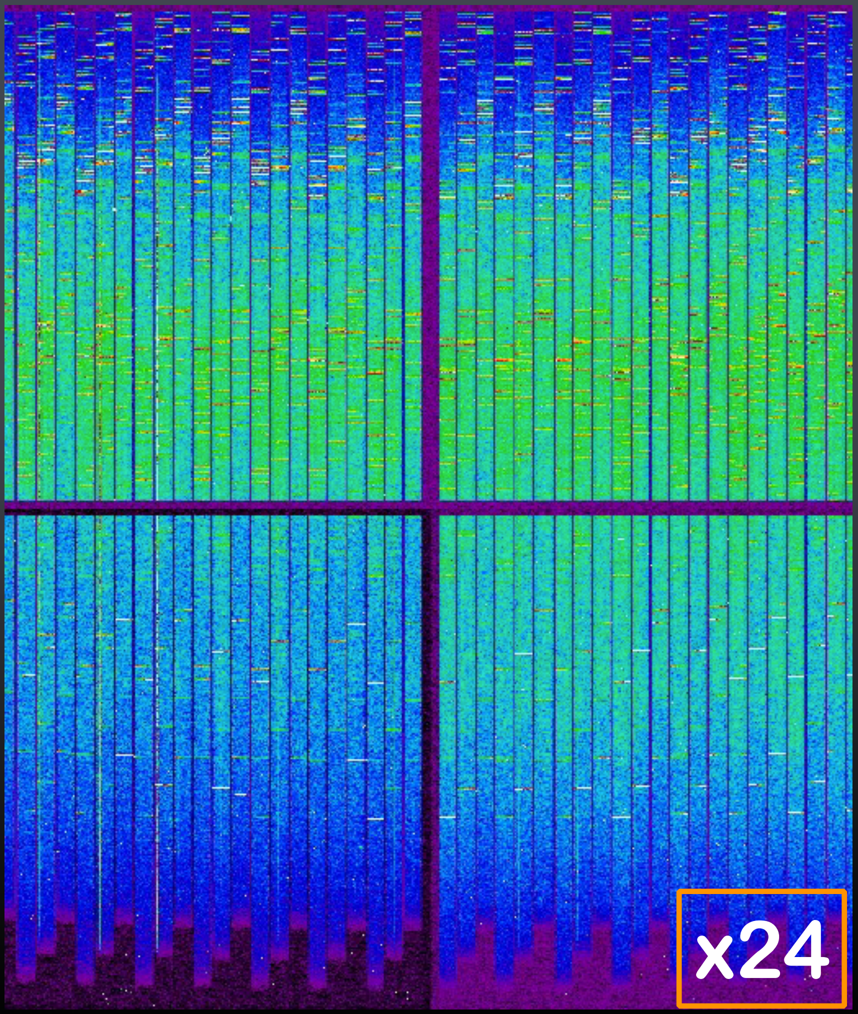
Delivery of FSU at CRAL in Feb 2013
F. Laurent (CRAL) & Y. Salaun (Winlight)



Slicer x 24


FMA: 4 stack of 12 off axis spherical mirrors 6x2 mm elliptical aperture
IDA: 4 stack of 12 off axis spherical mirrors 33x0.9 mm rectangular aperture
Winlight System

Data (Reduction)



N exposures of $4x10^8$ pixels each

Multi-core work station

- 30 Gb RAM minumim
- 150 Gb RAM recommended for full reduction
- LOTS of disk space

1 fully calibrated MUSE cube (with noise info)

~3Gb


Reintegration of MUSE in Paranal
and installation on UT4

October 2013: 24 tons & 200 m^3 of material delivered to Paranal

October – Dec 2013: Reintegration and Tests

18 Jan 2014: Move from Base Camp to UT4

muse

19 Jan 2014: MUSE land on UT4 Nasmyth Platform

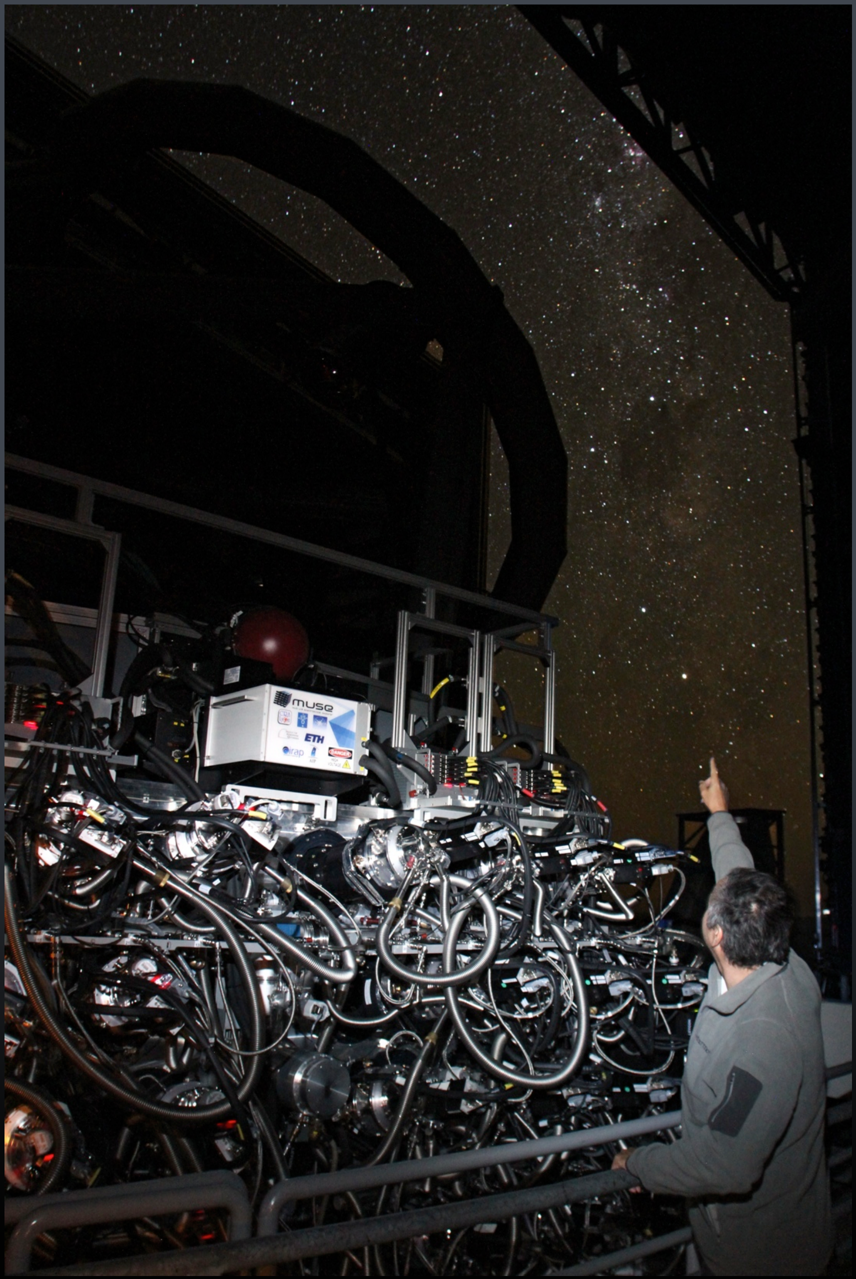
31 Jan 2014: First light

13 years later, the light is captured by Channel 6 of MUSE

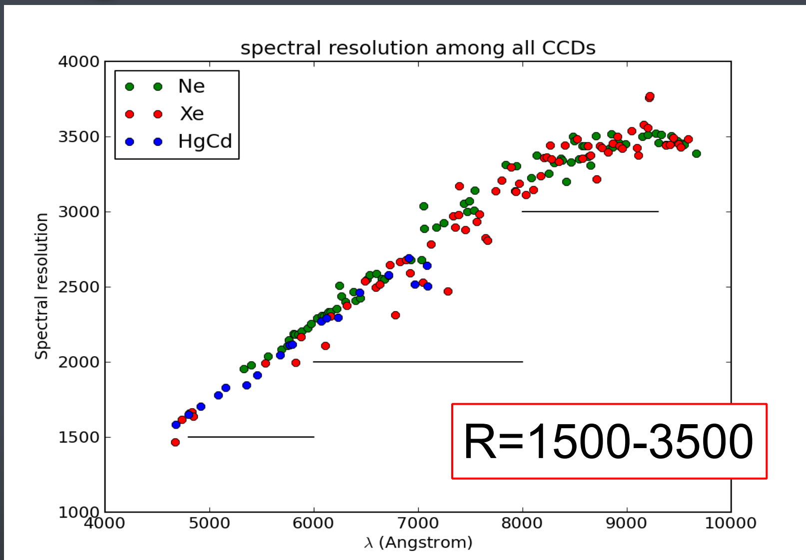
Commissioning Results

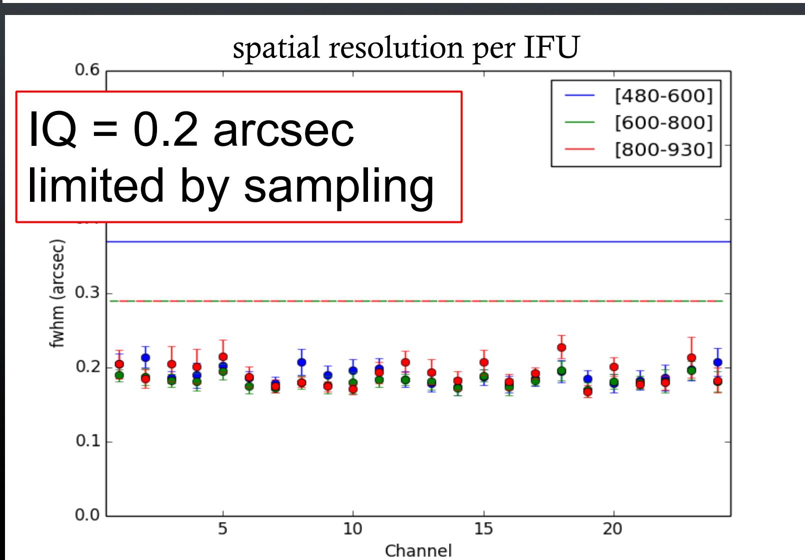
Wide Field Mode without AO

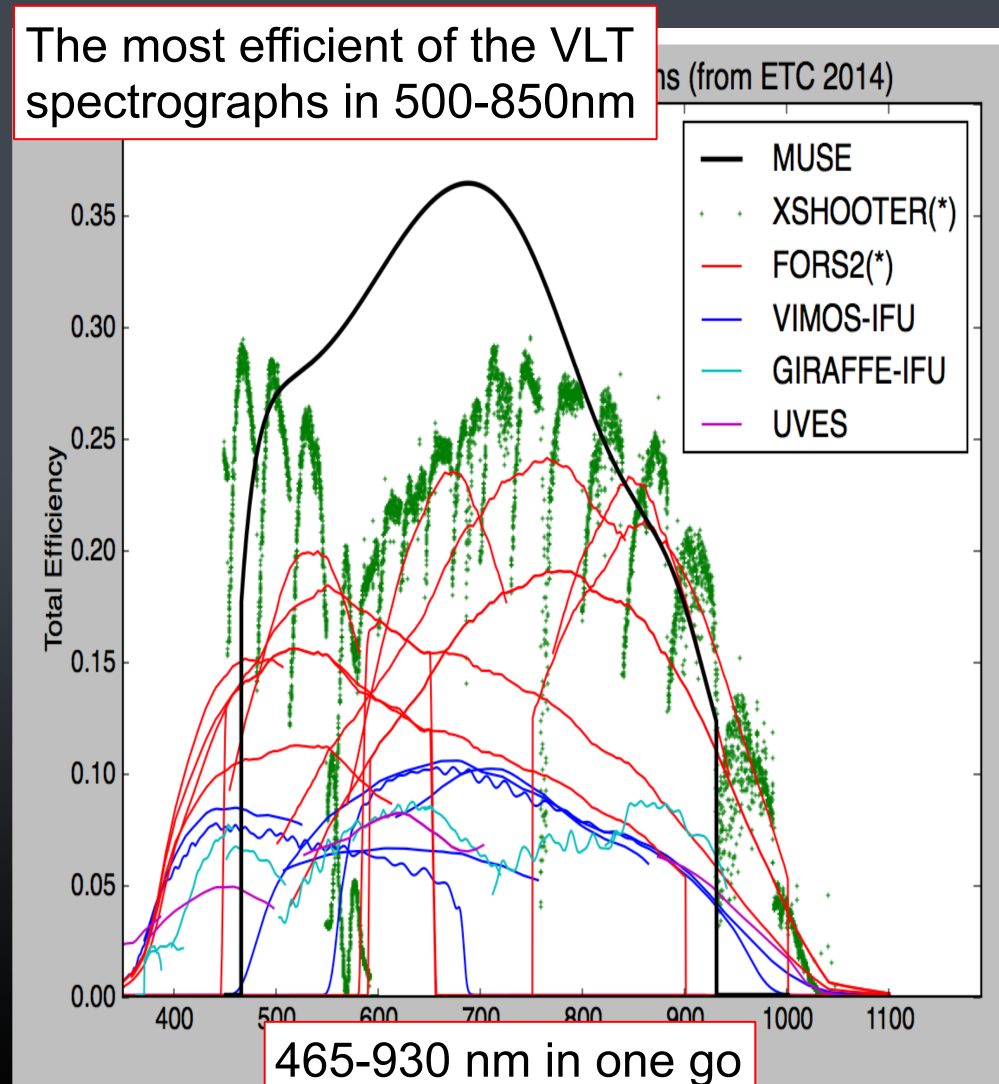
- **Comm1 07/2-21/2**
  - 15 nights in bright time
  - Functional tests, Performance and Show Cases
  - 24/24 hours, day & night shifts
  - ½ billion of spectra obtained
- **Comm2A 27/4-06/5**
  - 10 nights in dark time
  - 24/24 hours, 3 shifts
  - Study systematics, performance in deep exposures
- **Comm2B 25/7-03/8**
  - 10 nights in dark time
  - Calibration & observing strategy
  - Readiness for operation



Instrument Performances

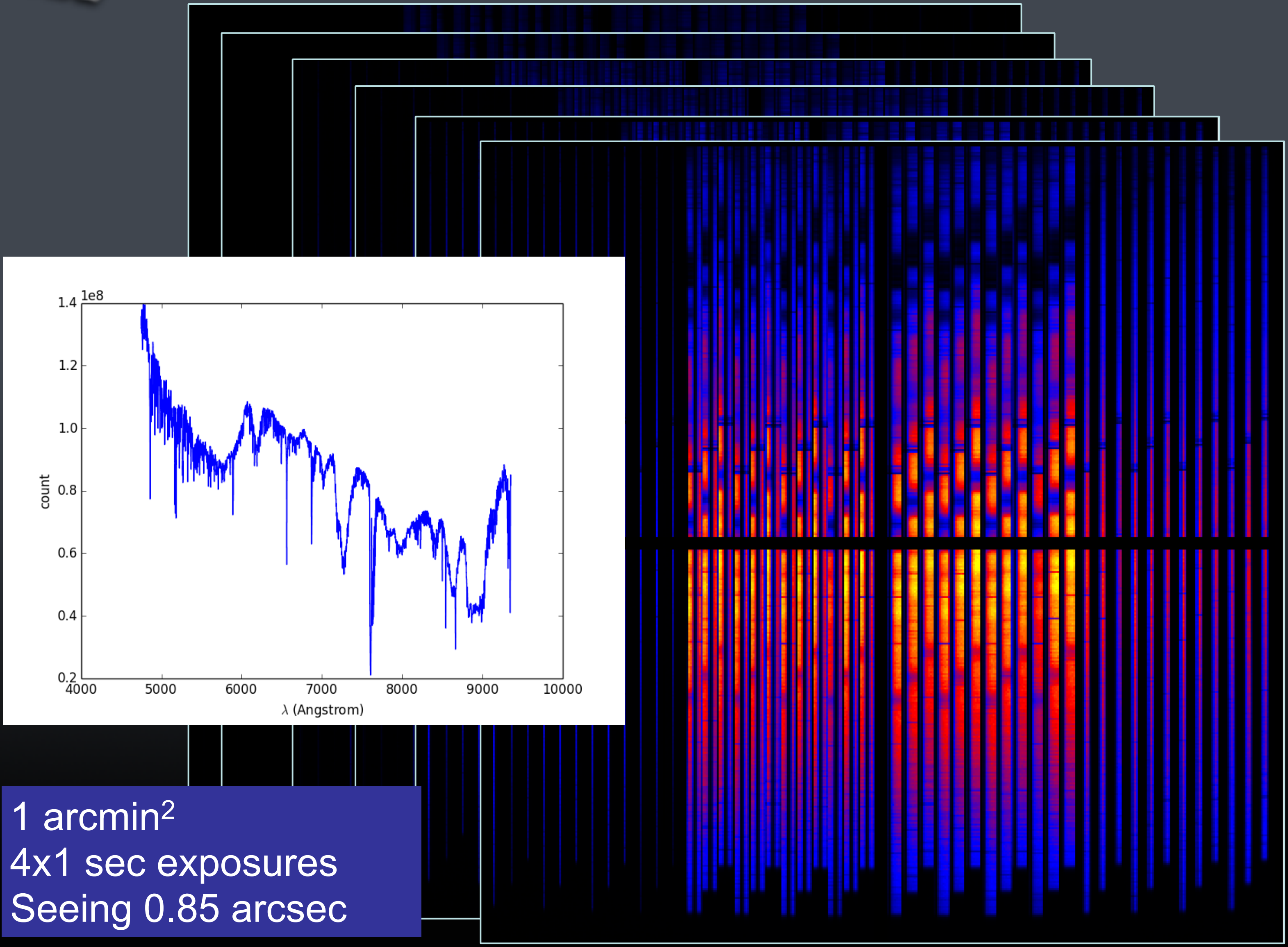






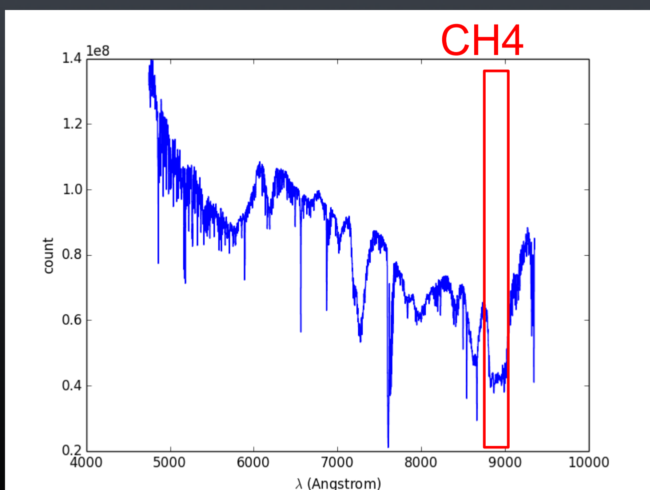
(*) 17% Slit loss included in FORS2 & XSHOOTER (e.g. 1 arcsec slit with 0.8 arcsec seeing)

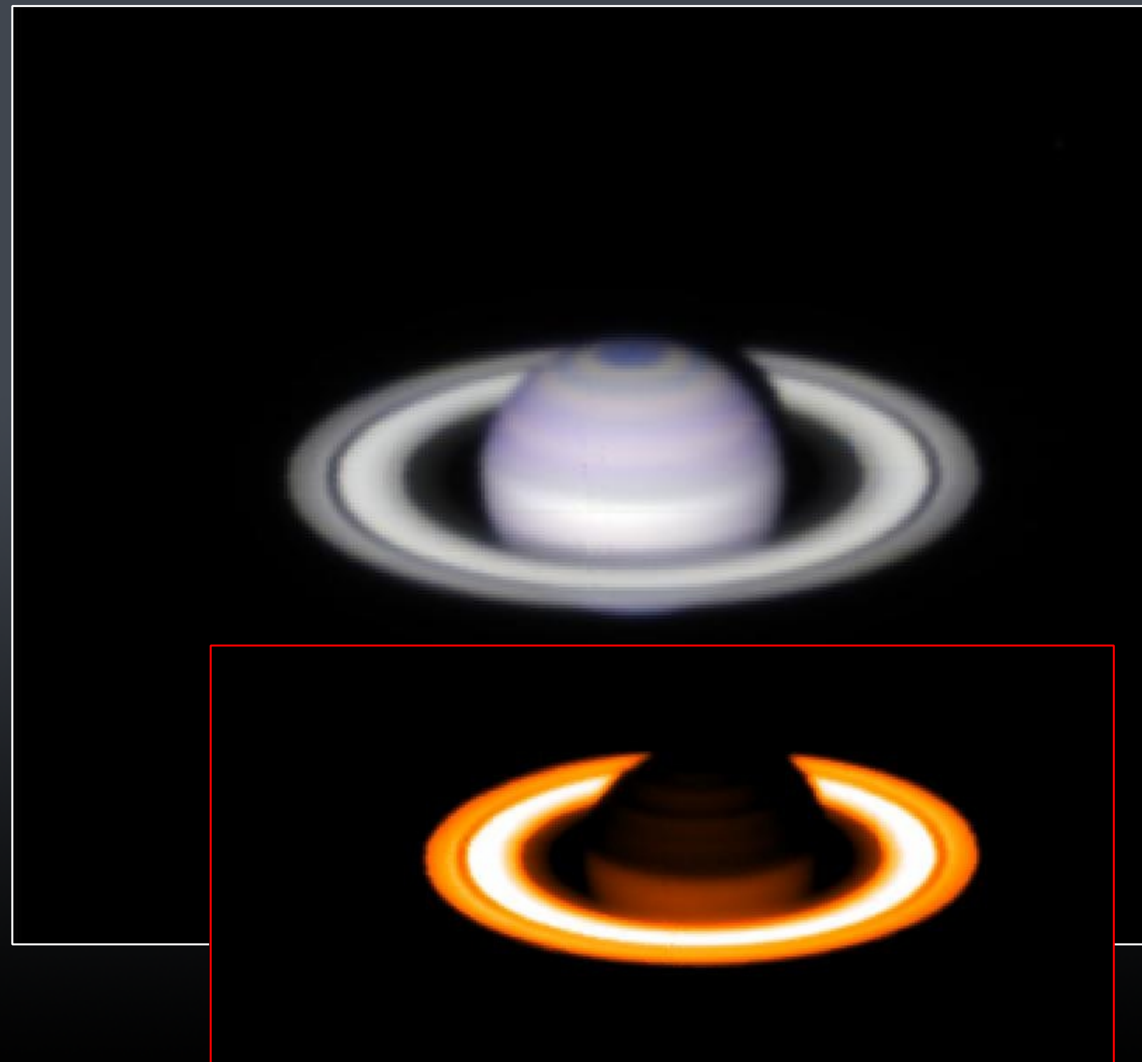
First reconstructed image: **Saturn**



1 arcmin^2
4x1 sec exposures
Seeing 0.85 arcsec

First reconstructed image: **Saturn**





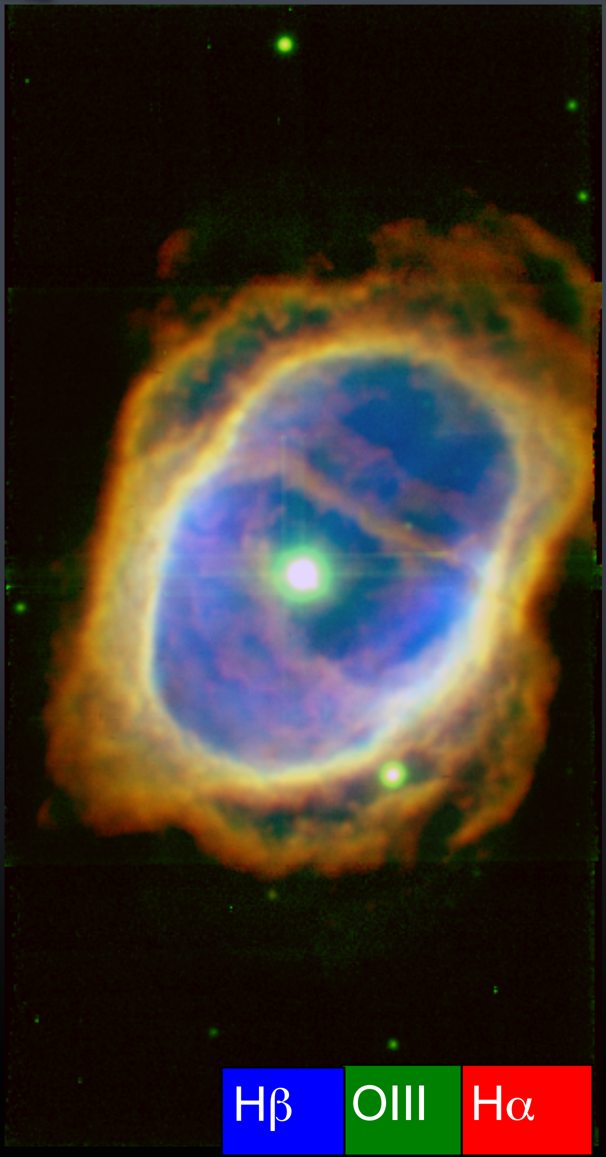
Prepared by Johan Richard, CRAL

Europa transit across Jupiter

www.eso.org

Prepared by Johan Richard, CRAL & ESO Outreach

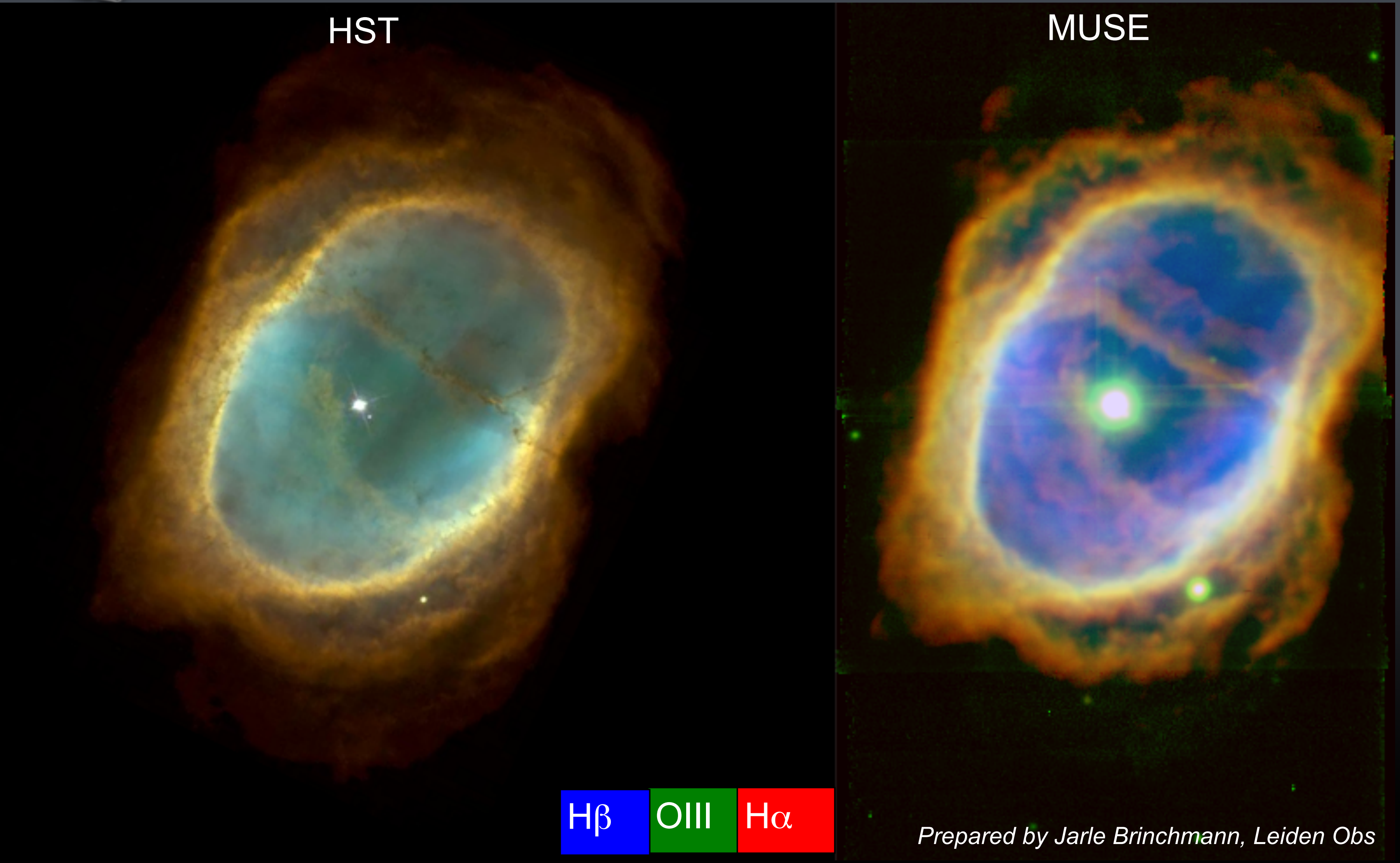
The Planetary Nebula: **NGC 3132**



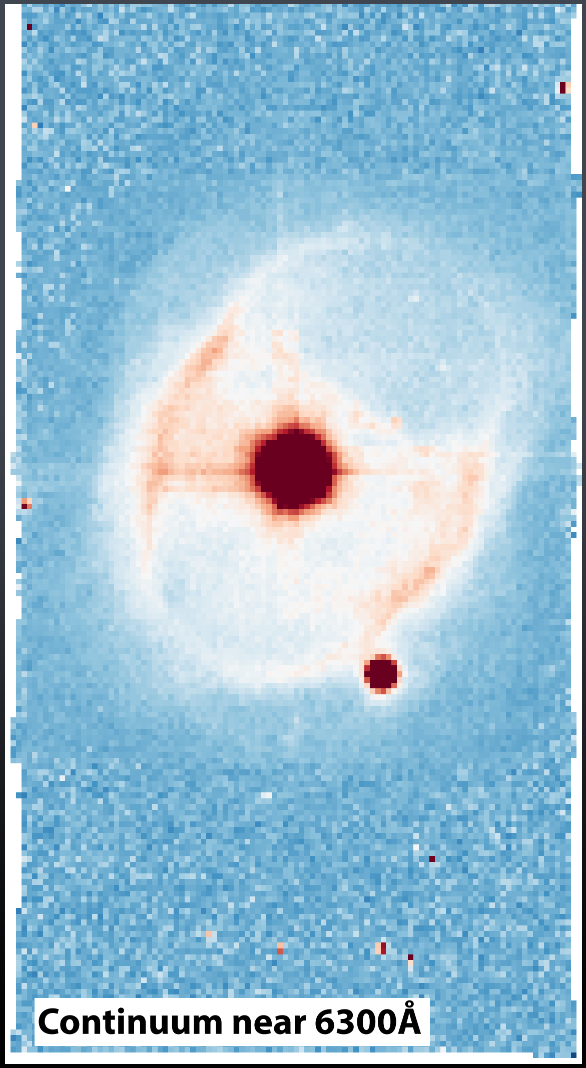
3x1 arcmin^2
Mosaic of 3 fields
13 x 1 mn exposures
Seeing 0.7-0.8 arcsec

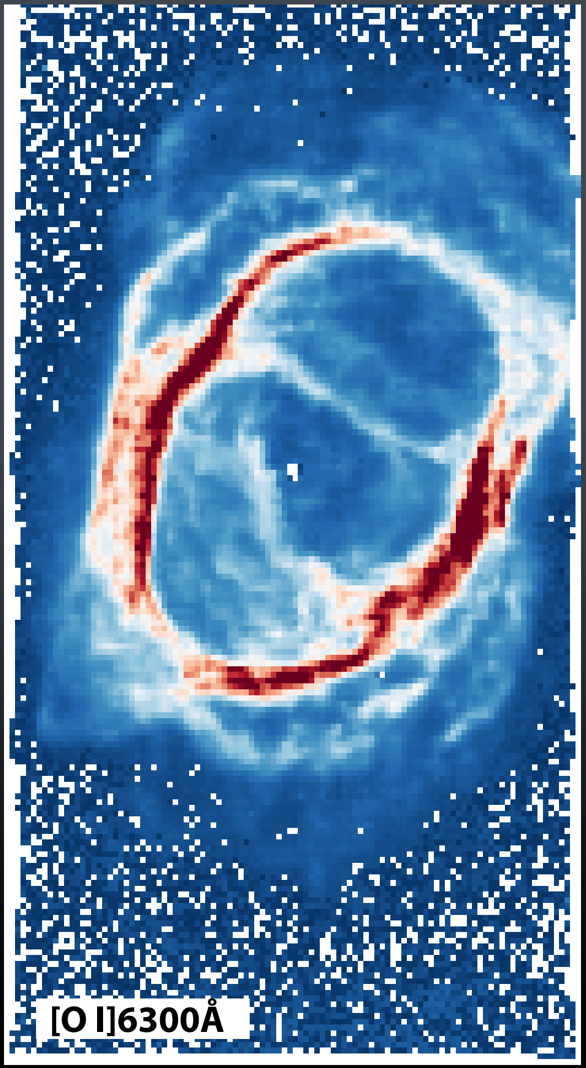
Prepared by Jarle Brinchmann, Leiden Obs

The Planetary Nebula: **NGC 3132**



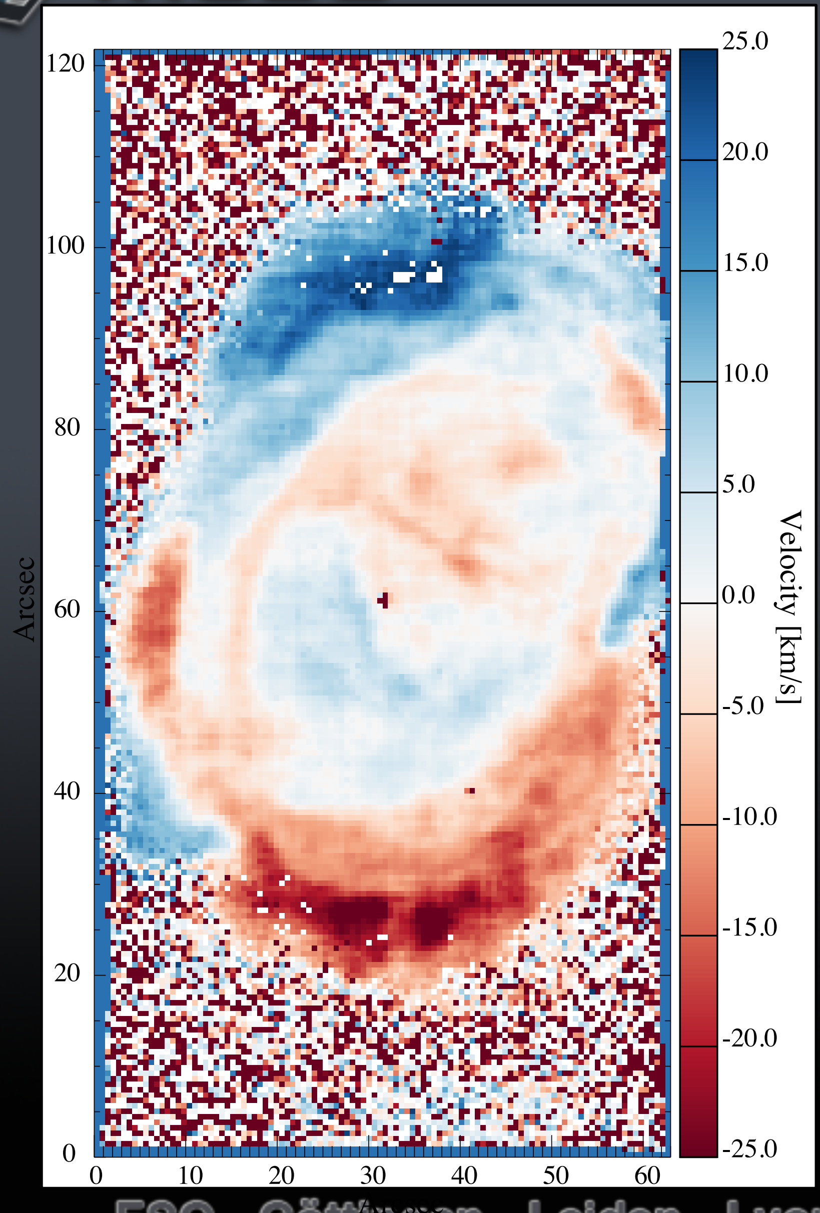
The Planetary Nebula: **NGC 3132**





Prepared by Jarle Brinchmann, Leiden Obs

The Planetary Nebula: **NGC 3132**



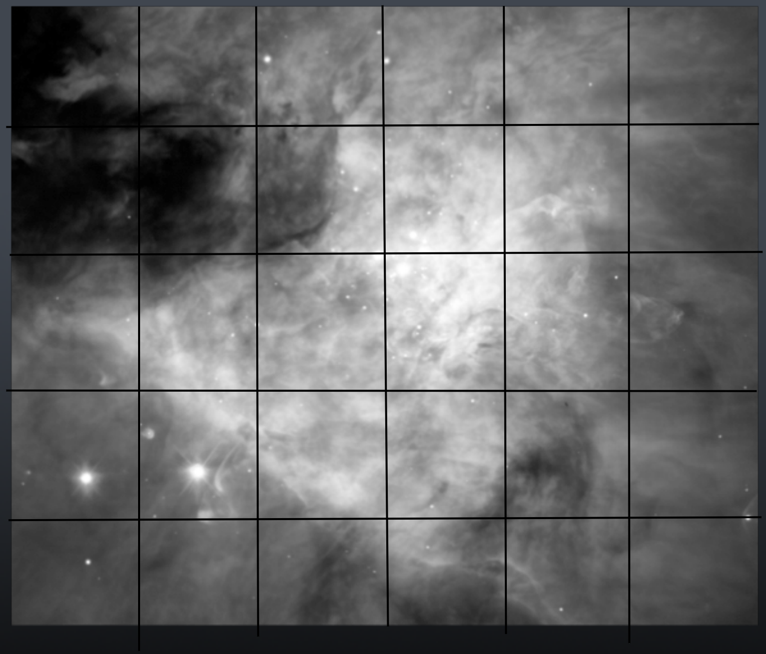
Gas Velocity field

V_{max} = 20 km/s

Accuracy ~1 km/s

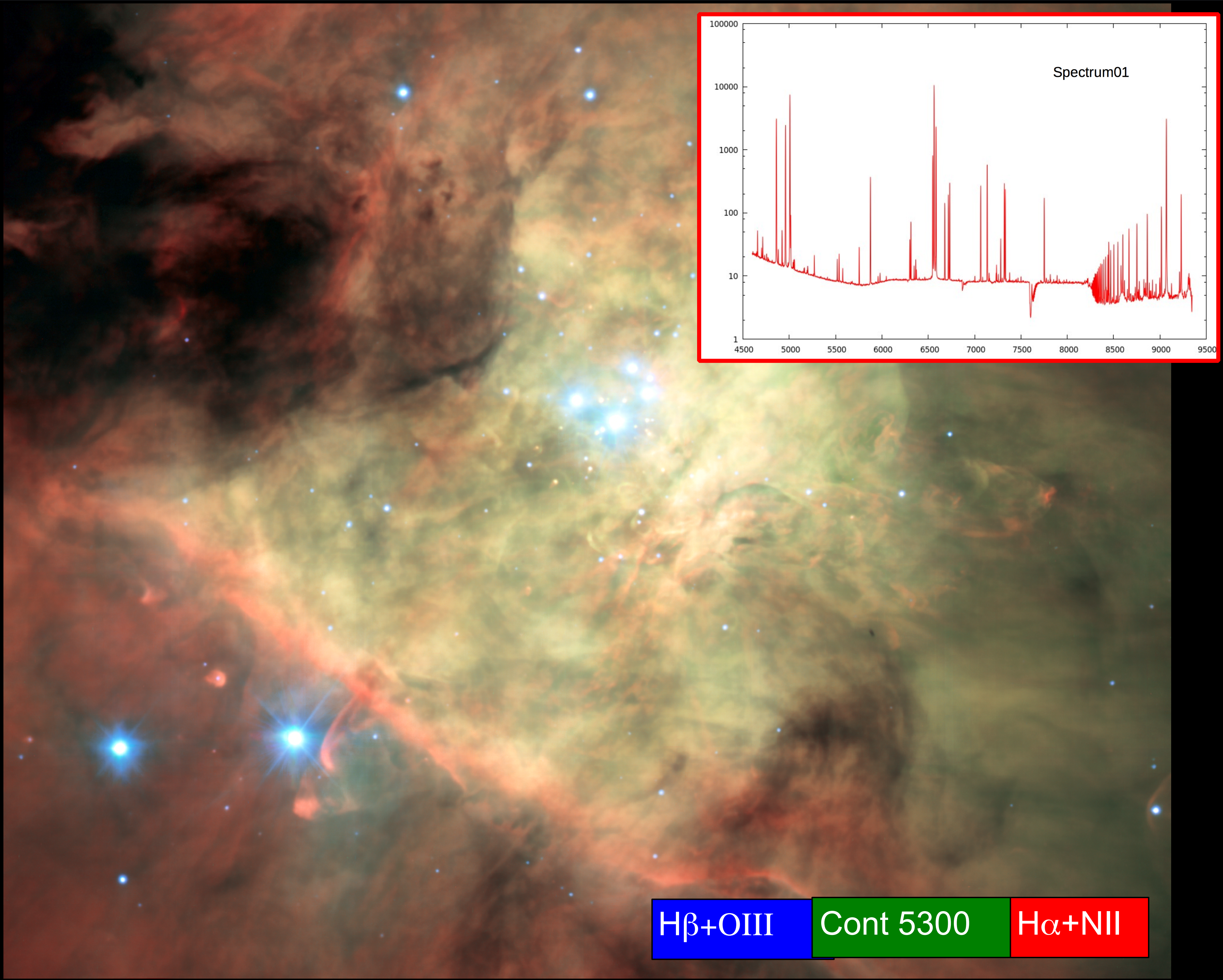
Prepared by Jarle Brinchmann, Leiden Obs

Mapping large area: **the Orion Nebula**

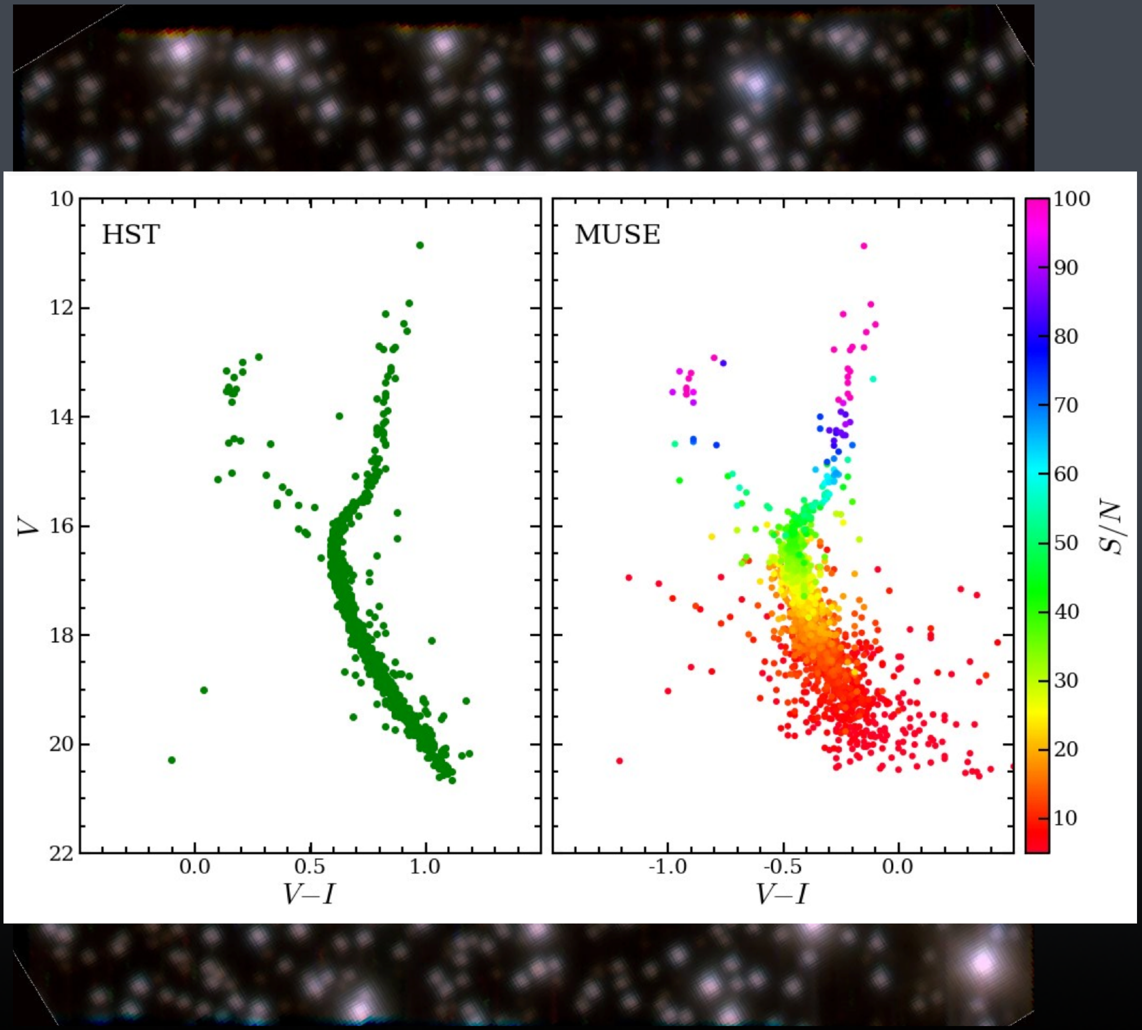


- 6x5 $arcmin^2$
- 30 fields, 60 exposures of 5 sec integration
- 2.5 hours total
- 5 millions of spectra
  - 300 spectra/sec (overhead included)
- Datacube of 1748x1460x4000 pixels

Prepared by Peter Weilbacher, AIP


Spectrum01
100000
10000
1000
100
10
1
4500
5000
5500
6000
6500
7000
7500
8000
8500
9000
9500
Hβ+OIII
Cont 5300
Hα+NII

Why multiplex matters:
The Globular Cluster NGC 6397



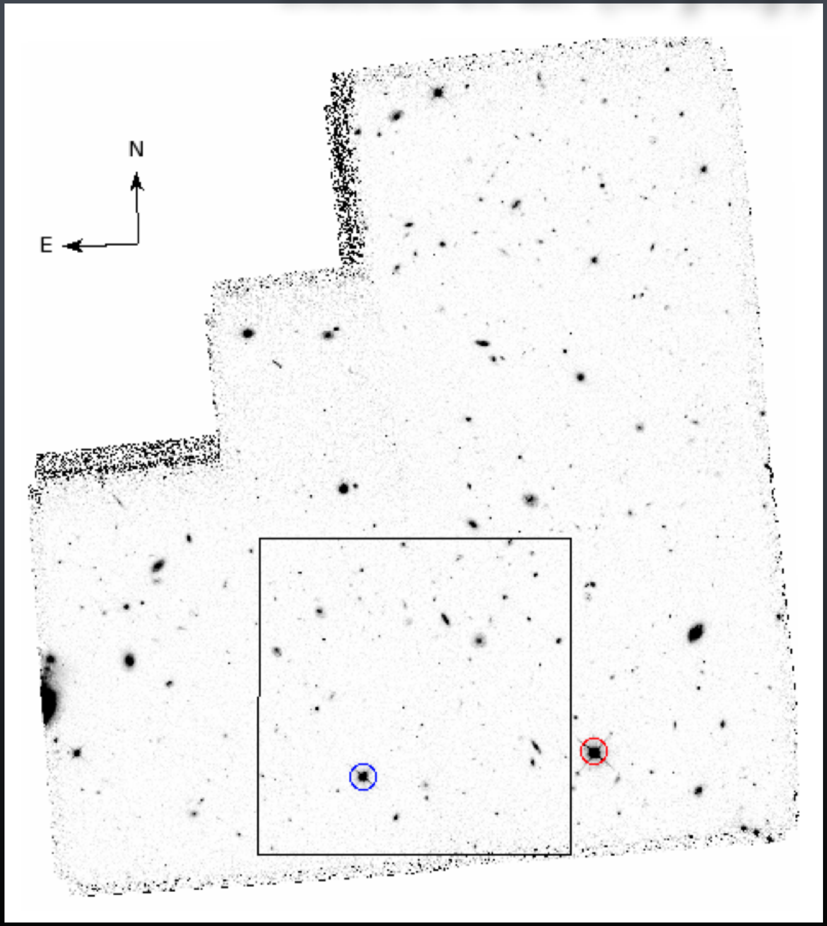
- 60 sec exposure
- FWHM 0.5 arcsec
- 4600 stars extracted
- Accurate stellar parameters for SN>30
- spectra across complete colour-magnitude diagram (in 60 sec !)

Prepared by Sebastian Kamann (AIG)

Going Deep: The Hubble Deep Field South

- **WFPC2 & NICMOS deep observations**
  - Williams R.et al (2000), Casertano, S. et al. (2000)
  - Limiting magnitude AB ~ 30
- **Follow-up spectroscopic observations**
  - 18 known spectroscopic redshifts in MUSE area
- **MUSE observations**
  - July 2014 during Comm2B run
  - 27 hours (54 exposures)

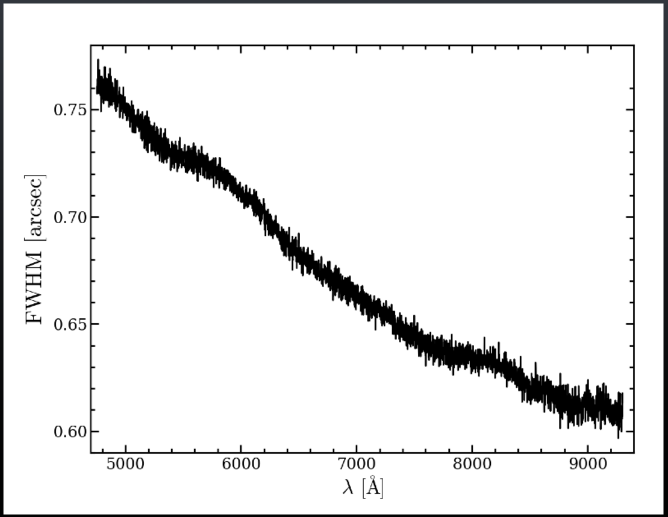
Bacon et al. (in prep)

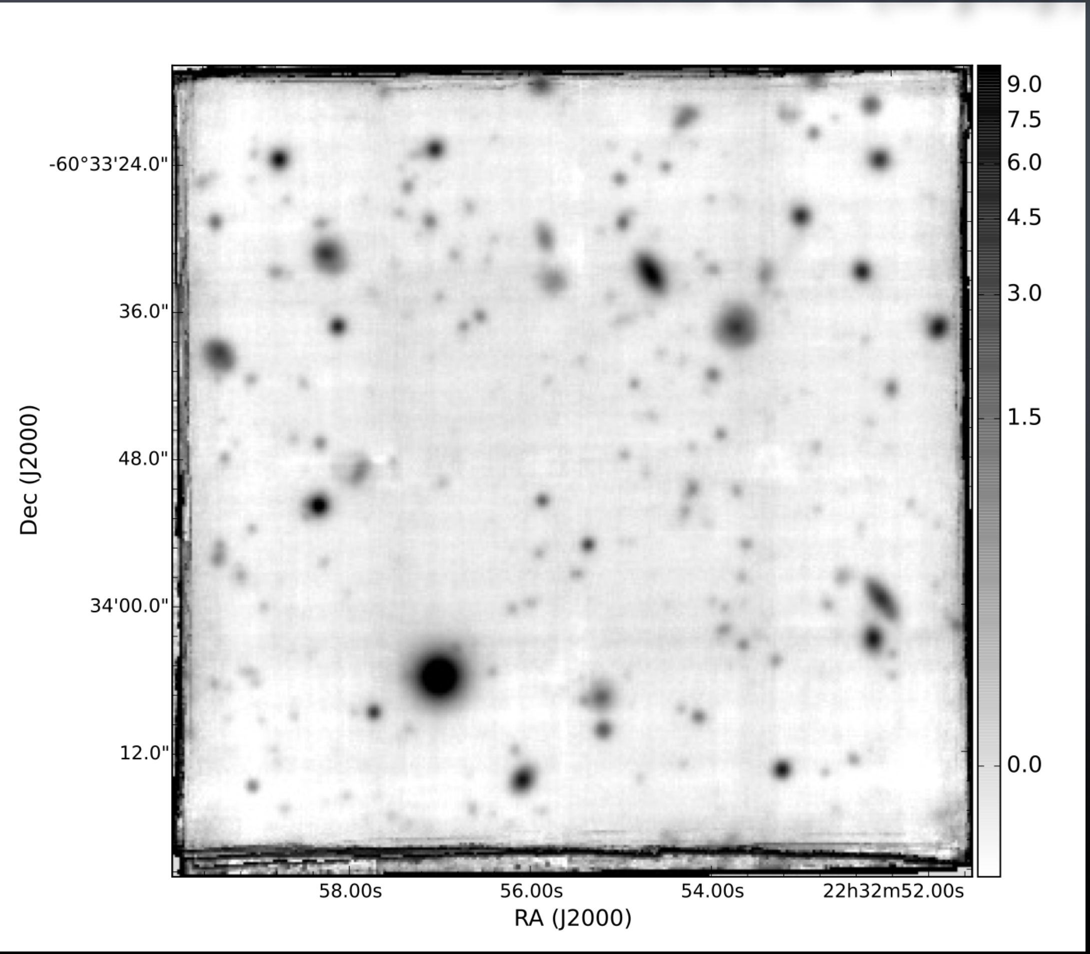


The Hubble Deep Field South

- **White light image**
  - FWHM 0.61-0.76 arcsec
  - Depth ~27 R_{AB}

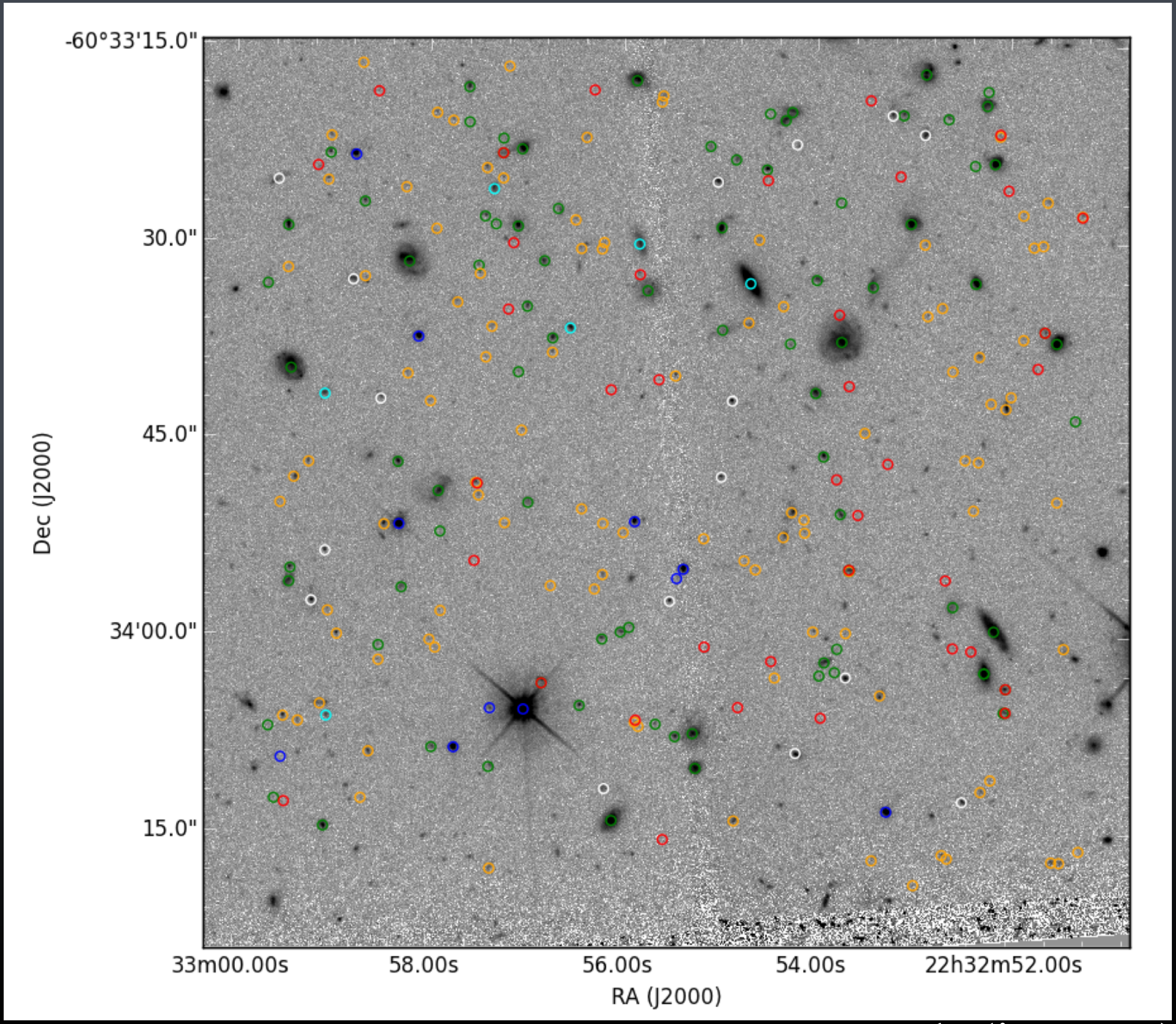
Bacon et al. (in prep)





The Hubble Deep Field South

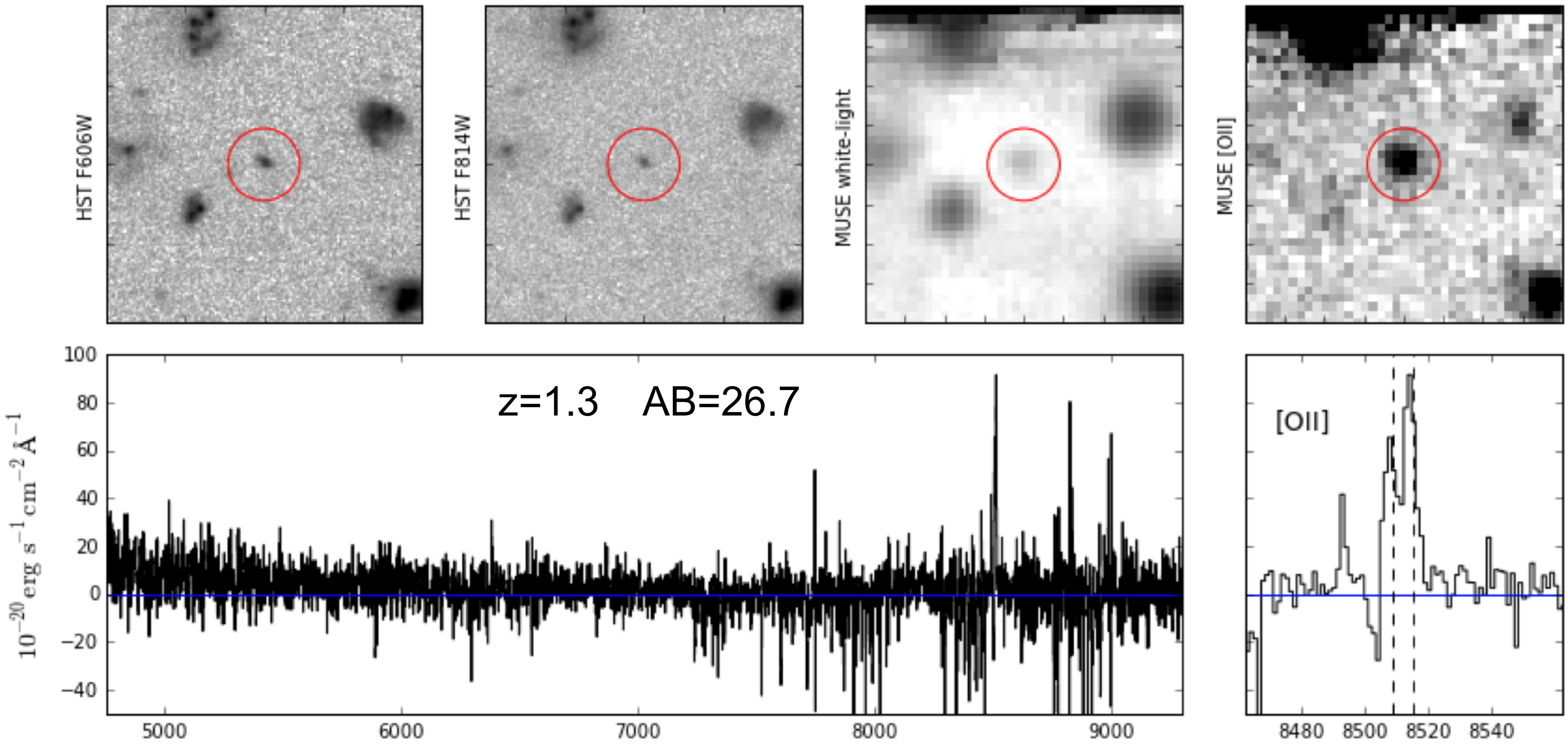
- **Source Identification**
  - 255 redshifts measured
  - Stars, [OII], Lya emitters, QSOs, CIII] emitters, …



Bacon et al. (in prep)

The Hubble Deep Field South

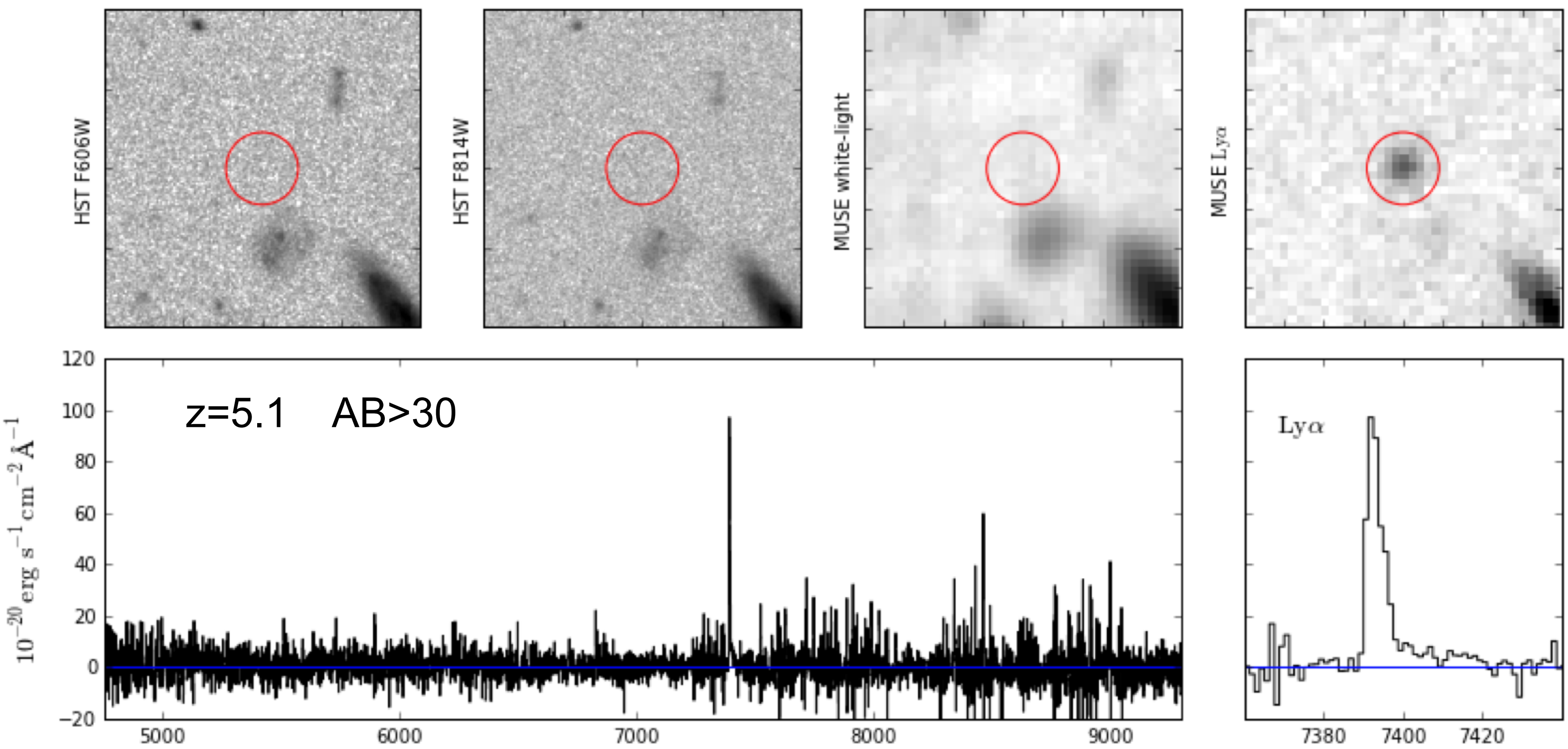
Bacon et al. (in prep)



Prepared by Jarle Brinchmann, Leiden Obs

The Hubble Deep Field South

Bacon et al. (in prep)

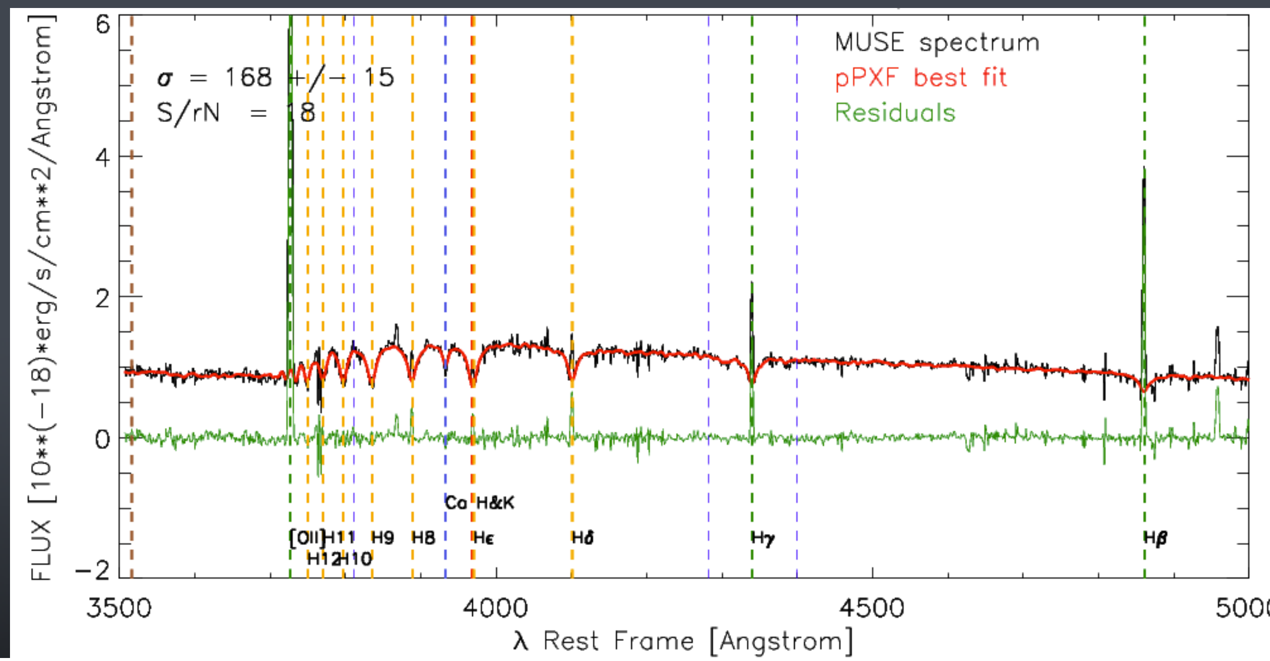


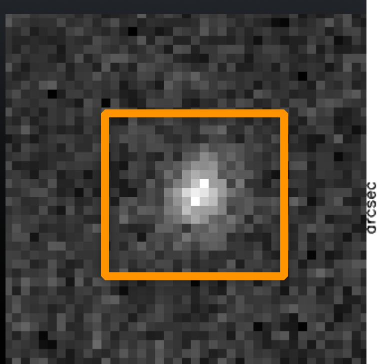
Prepared by Jarle Brinchmann, Leiden Obs

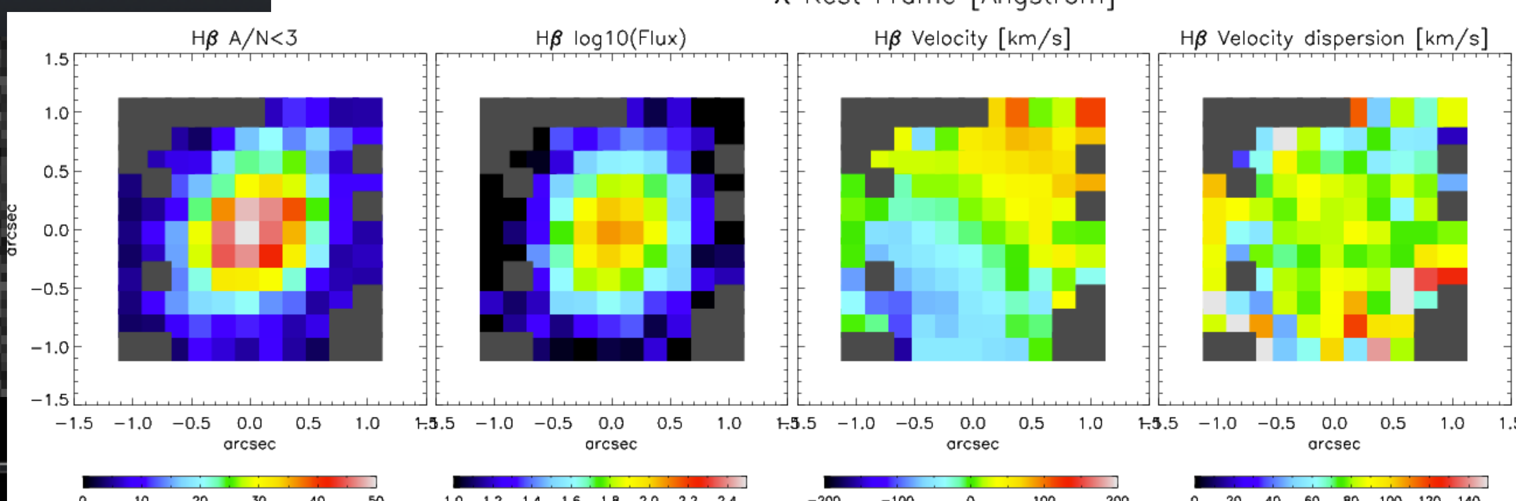
The Hubble Deep Field South

Prepared by Davor Krajnović, Potsdam

- HDFS extended object
- z = 0.563
- stellar continuum and emission-lines







ESO

Science Verification

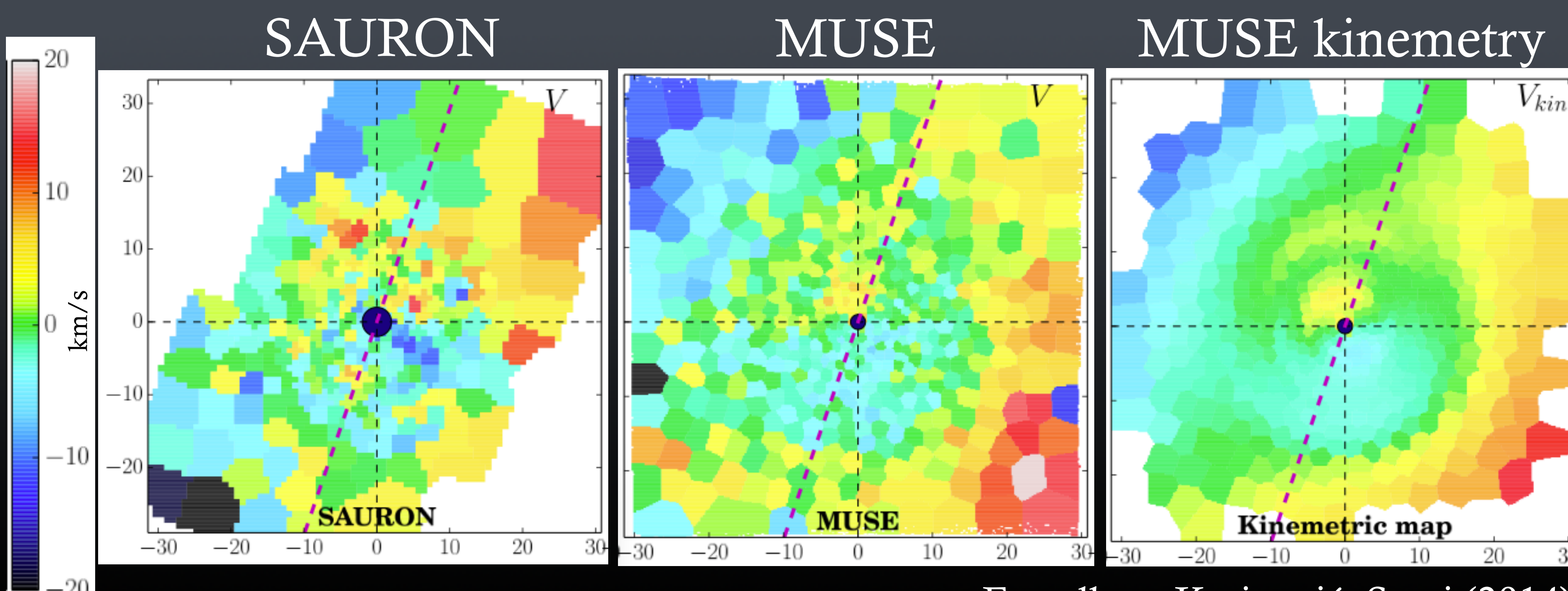
First Paper on MUSE

- Science Verification - an open call to community to test the instrument capabilities
- 2 weeks in July and August 2014
- ~80 proposals
- Observations of M87 (NGC4486) in the centre of virgo

Image credit: APOD

Prolate-like rotation and a kinematically distinct core in M87

- previously considered a ‘non-rotator’
- formal errors on stellar velocity1-2 km/s
- triaxial structure + complex history of merging



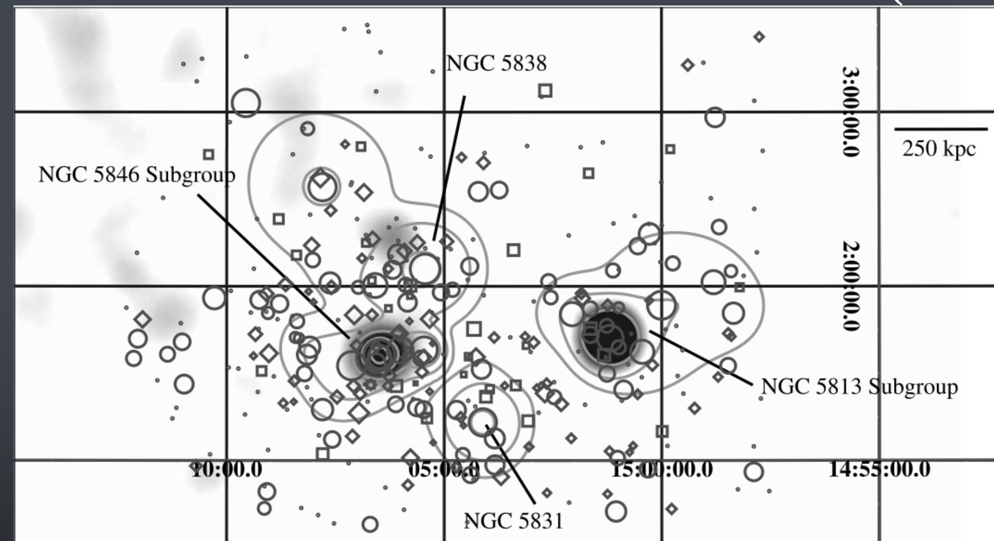
Emsellem, Krajnović, Sarzi (2014)

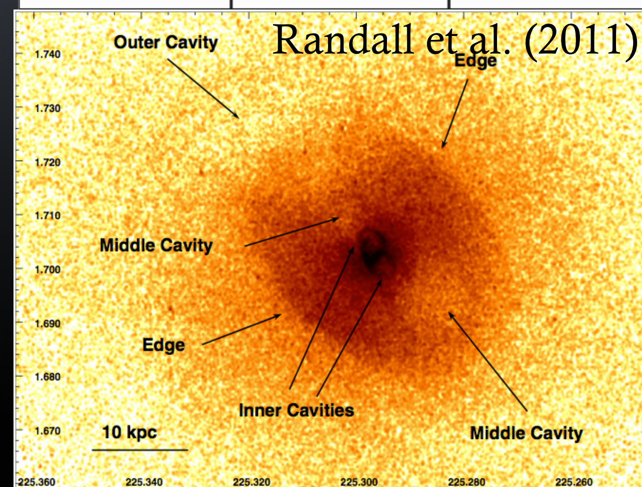

Counter-rotating origin of the
kinematically distinct core in
NGC5813

NGC 5813: a subgroup of a well isolated group

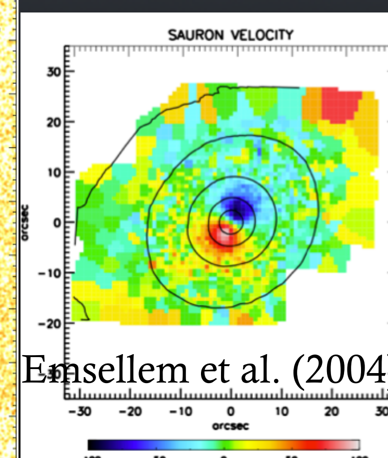
- in a well isolated group
- centre of a sub-group
- X-ray cavities: recent AGN activity
- famous kinematically distinct core - KDC

Mahdavi et al. (2005)





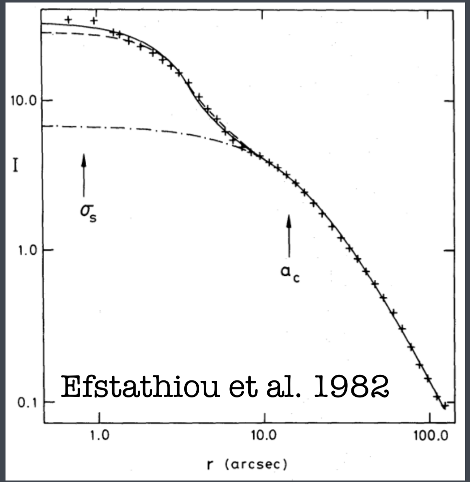
Randall et al. (2011)

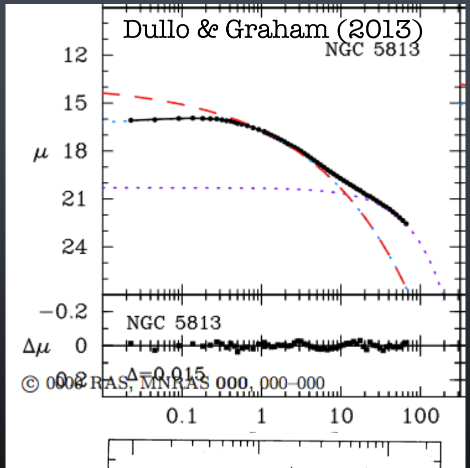


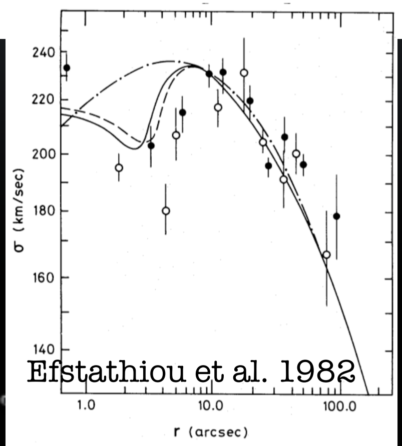
Emsellem et al. (2004)

KDC in NGC5813

- 1st KDC discovered (Efstathiou, Ellis & Carter, 1980, 1982)
- “core-within-a-core” due to its light profile (Kormendy 1984)
- core-Sersic + exponential profile (Dullo& Graham 2013, Rusli et al. 2013)
- KDC very old (12-13 Gyr)
- very unusual velocity dispersion profiles (Efstathiou, Ellis & Carter 1982)

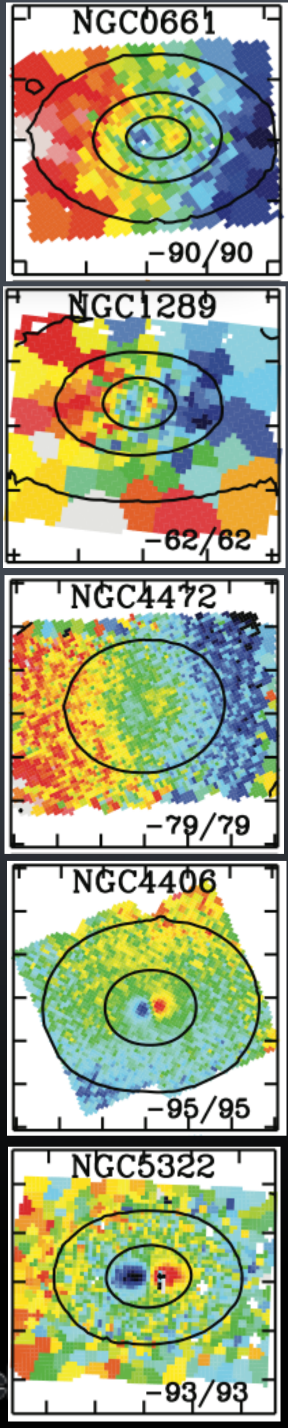






Kinematically distinct core KDC

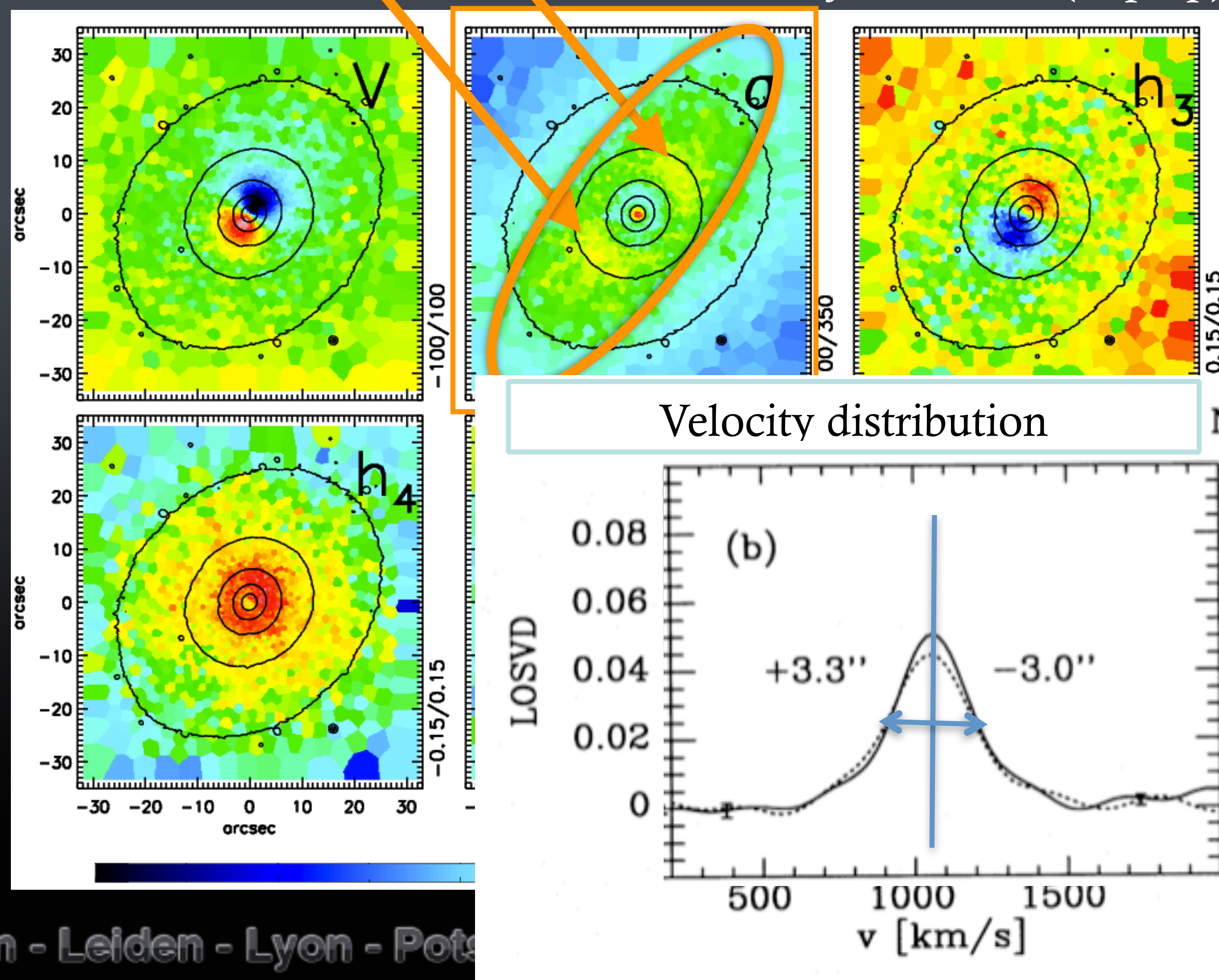
- Kinematically distinct core - KDC
- what is their origin?
  - evidence for mergers
  - are they relic cores swallowed by larger brothers (e.g. Kormendy 1984)?
  - ‘discs’ formed from accreted gas (e.g. Franx & Illingworth 1988)?
  - remnants of gas rich mergers (Bender & Surma 1992)
- hosts look normal (many have nuclear discs and dust)
  - no difference in colour (Carollo et al. 1997)
  - no difference in stellar pops (Davies et al. 2001, McDermid et al. 2006, Kuntschner et al. 2010)



MUSE kinematics

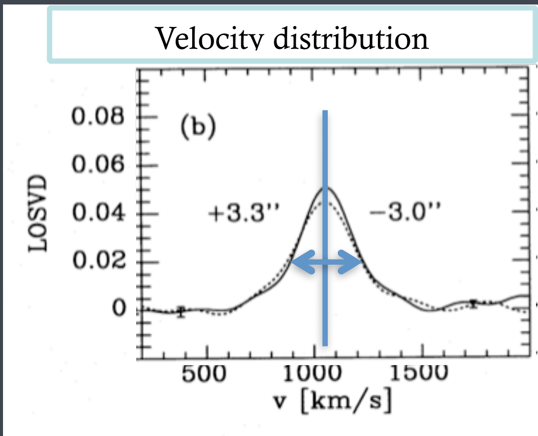
- Commissioning 1 data (on of the first objects observed)
- MUSE kinematics consistent with previous (SAURON)
- new evidence for the origin of the KDC
- σ map holds the clue

Krajnović et al. (in prep)

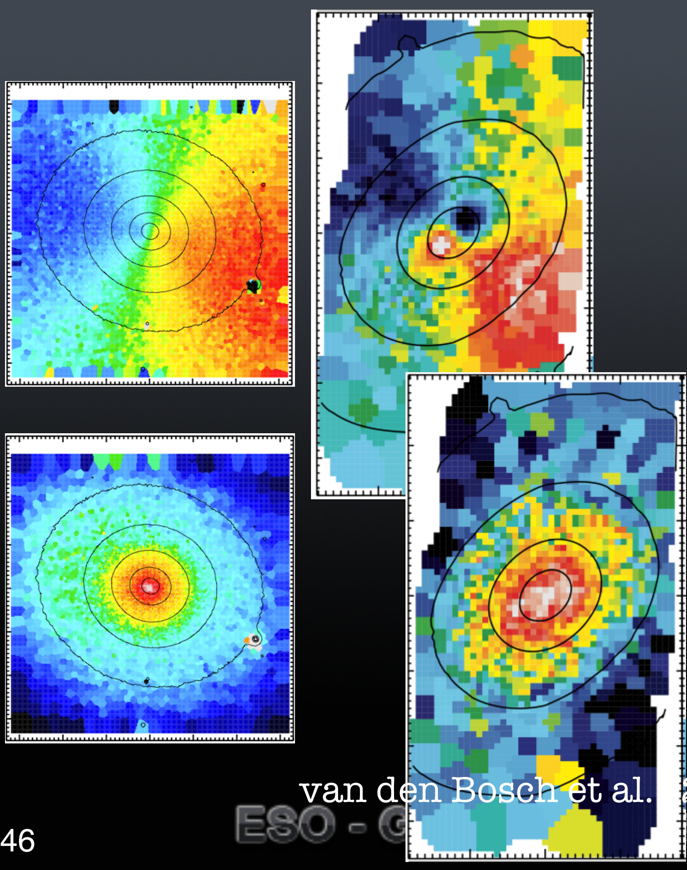


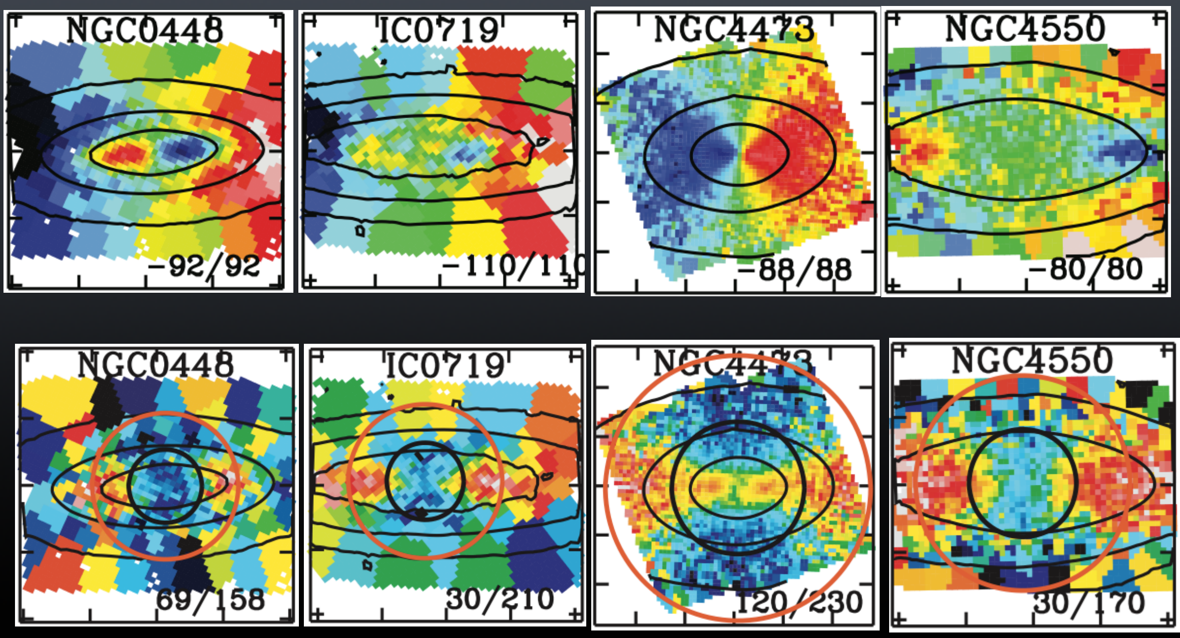
Counter-rotation

- Specific signature in the velocity dispersion
  - 2 peaks along the major axis
- 4% of ETG —> until now only in flat(-ish) (edge-on) Fast Rotators



Krajnović et al. 2011

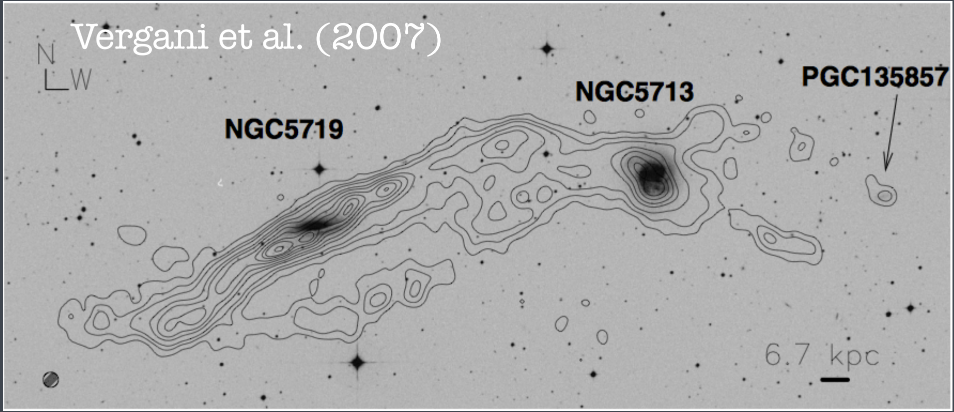


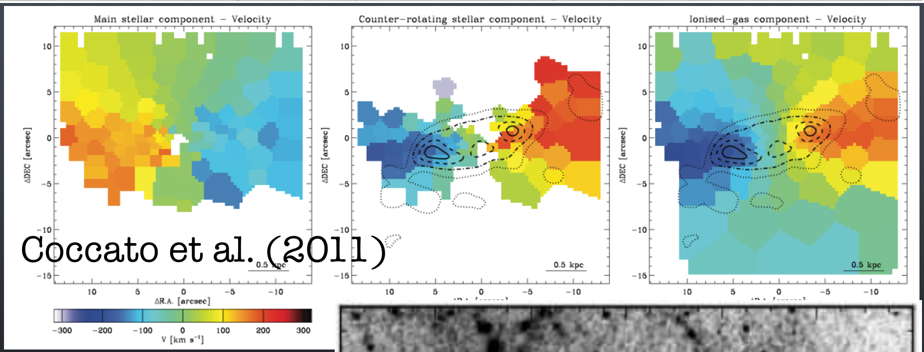


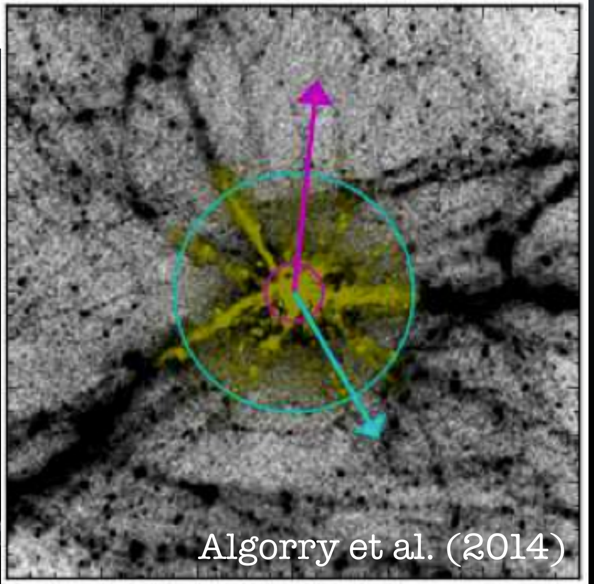
van den Bosch et al. (2008)

Counter-rotation

- 2σ peaks explained as counter-rotating disc (Rubin et al. 1992, Rix et al. 1992)
- or counter-rotating fast rotating structures (Krajnović et al. 2006, Cappellari et al. 2007)
- origin:
  - merger of two discs/capture of gas (e.g. Coccato et al. 2011)
  - intersection of cooling streams (Algorry et al. 2014)
- Could the KDC in NGC5813 be a result of two counter-rotating structures?

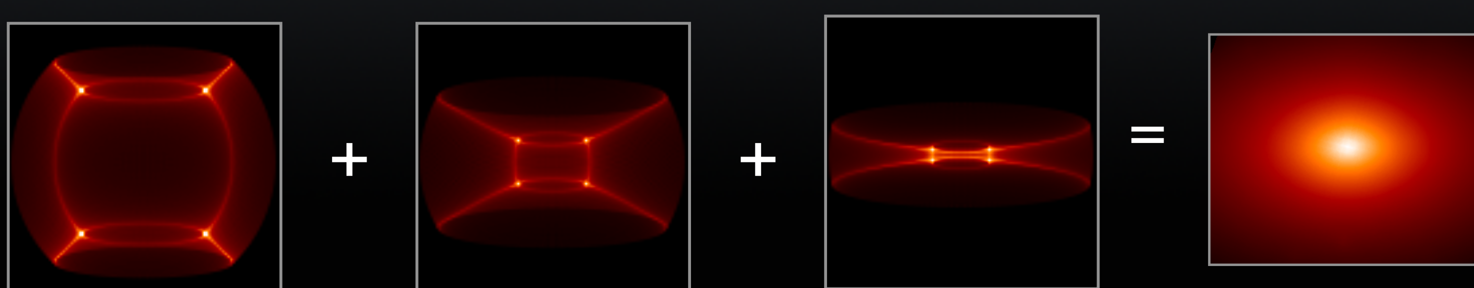






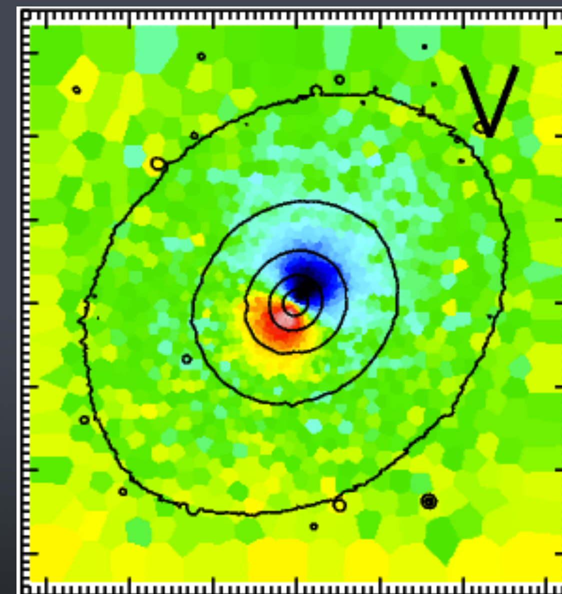
Dynamical model

- orbit superposition dynamical models a la Schwarzschild (1979, 1982)
- Leiden code (Cappellari et al. 2006, 2007; Krajnović et al. 2009)
- Steps:
  - 1) parameterise light —> gravitational potential
  - 2) build an orbit library (assuming axisymmetry)
  - choose from the orbit library those set of orbits that will reproduce the observed MUSE kinematics (and light distribution)

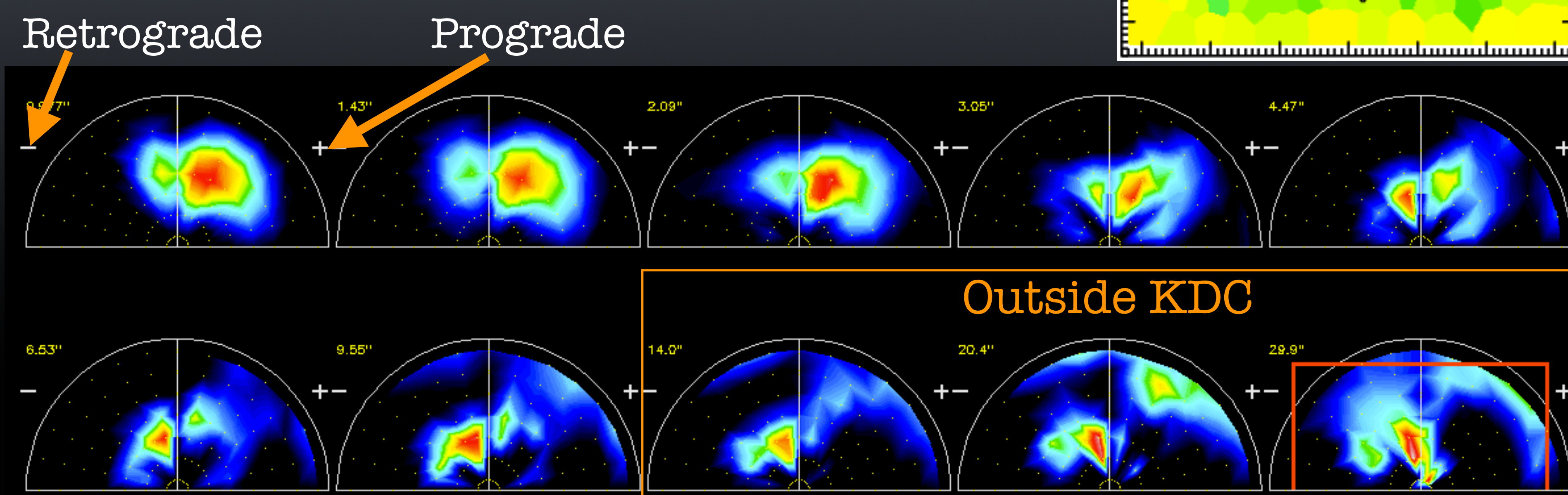


Dynamical model

Krajnović et al. (in prep)

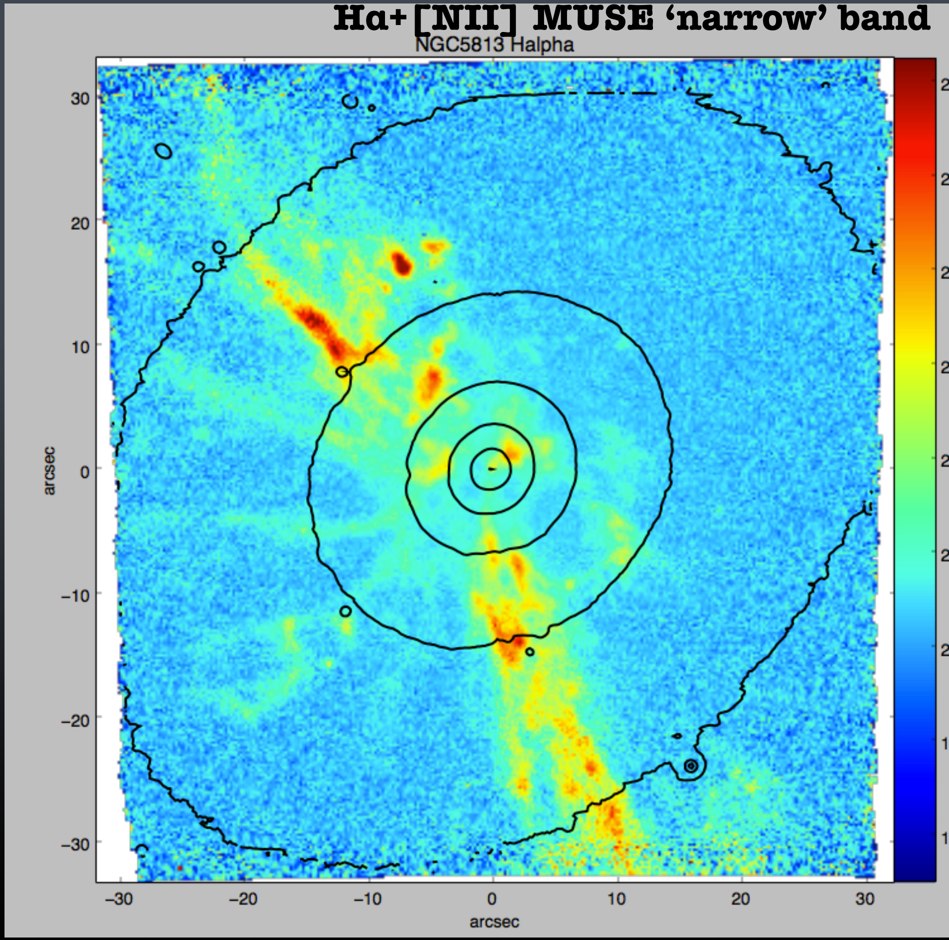


- orbital space is dominated by two families of short axis tubes with opposite angular momentum
    - within KDC: (+)70 % vs (-)30 % of mass—> KDC
    - outside KDC: (+)45 % vs (-)55 % of mass—> no rotation



Emission-line gas flows

- complex emission-line structure
- linked to the X-ray cavities and AGN activity
- possible cooling (in-)flow of gas (which is being ionised by stars)



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Emission-line gas flows

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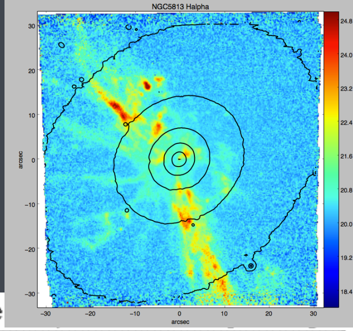
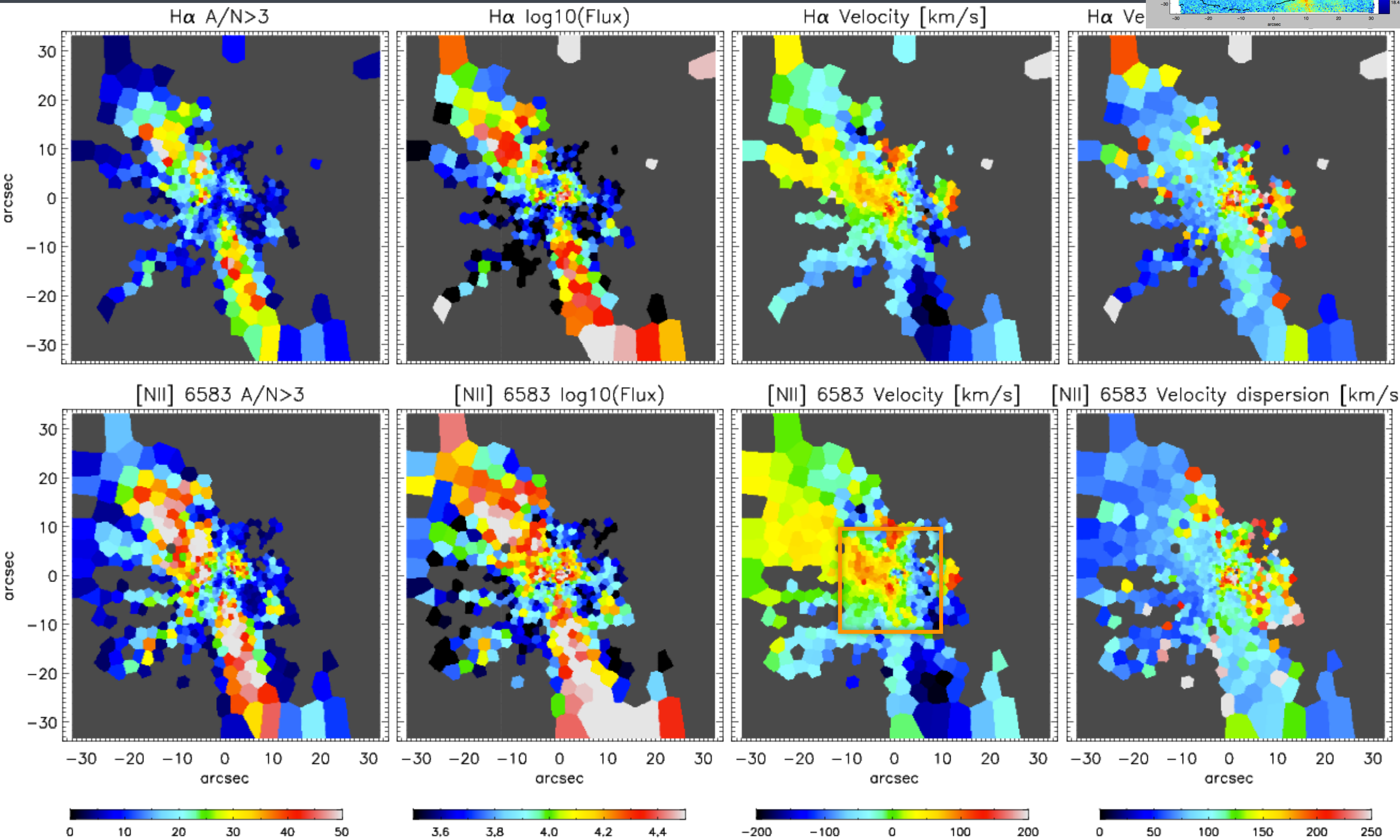
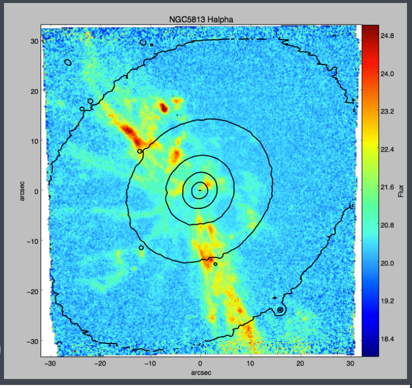




Emission-line gas decoupling

- central 3” x 3” show gas decoupling
- orientation as for the KDC and the dust disc (HST)
- is the gas feeding KDC?
  - KDC is old (12-13 Gyr; Kuntschner et al. 2010, McDermid et al. 2014)
  - probably a recent event (last 3x10^6 yr; Randall et al. 2011)



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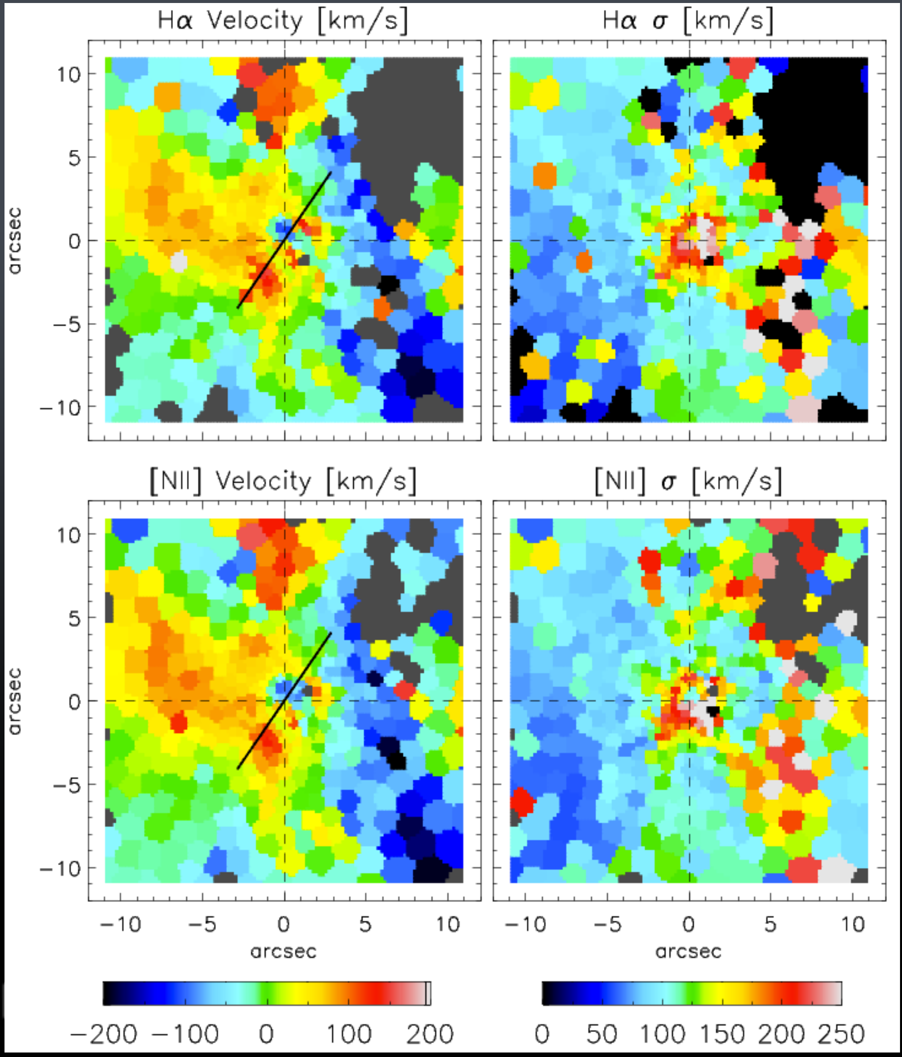

Summary of evidence for counter-rotation origin of KDC

- double light profile: (core-)Seric + exponential —> 'disc-like' structures
- velocity dispersion map - major axis maxima
- two orbital families of opposite angular momentum:
  - 70 - 30 % within KDC
  - 45 - 55 % outside (no rotation!, high σ)
- Ionised gas 'feeding' KDC —> material for (steady) orbital built-up regulated by the AGN cycles

KDC in NGC5813 (science-fiction)

- it is not an ‘eaten’, small galaxy
- could have same origin as 2σ galaxies:
  - capture of gas on retrograde orbits
  - intersection of cooling flows (centre of a group)
  - very early (at least 10 Gyr ago, z>2)
- KDC as an orbital composite
  - not an accreted body
  - similar to NGC4365 (van den Bosch et al. 2008)
  - what about other KDC? (MUSE!)

Conclusions

- MUSE is the next step forward in integral field spectroscopy
- It is unique and has a high potential of discoveries
- It will be even more powerful when coupled with GALACSI-AOF