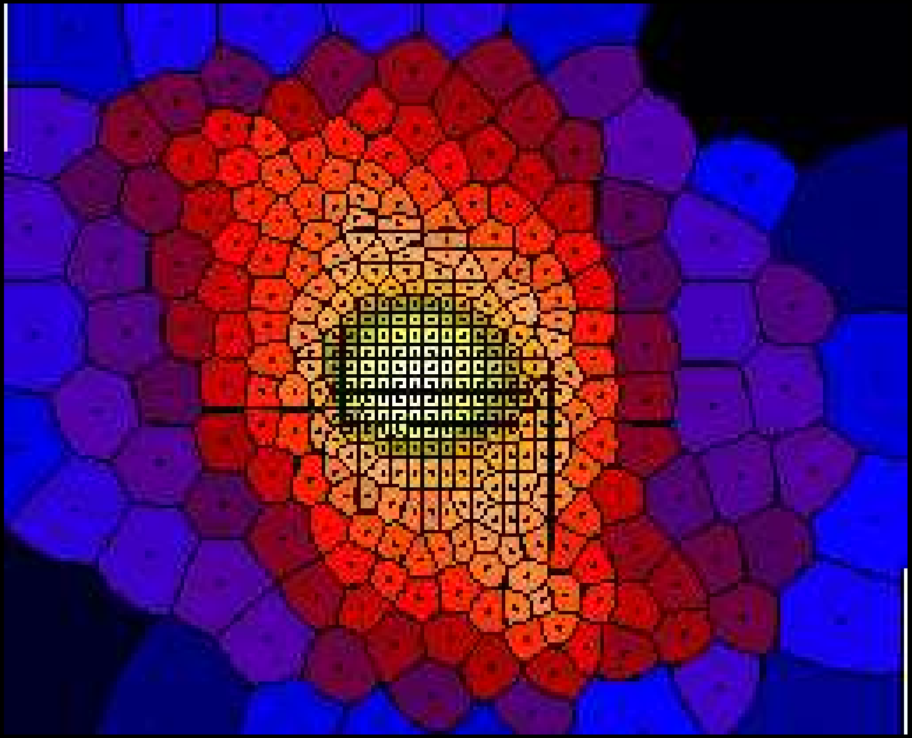
Integral Field Spectrography



Yannick Copin — Institut de physique nucléaire de Lyon — Université de Lyon

Outline of the presentation

- Introduction
  - What is "integral field spectrography"?
- Science cases
  - What is it for?
- Instruments
  - How to do such a thing?
- Tea break
- Algorithms
  - General and specific processing algorithms
- Conclusions

Introduction

The astronomical signal

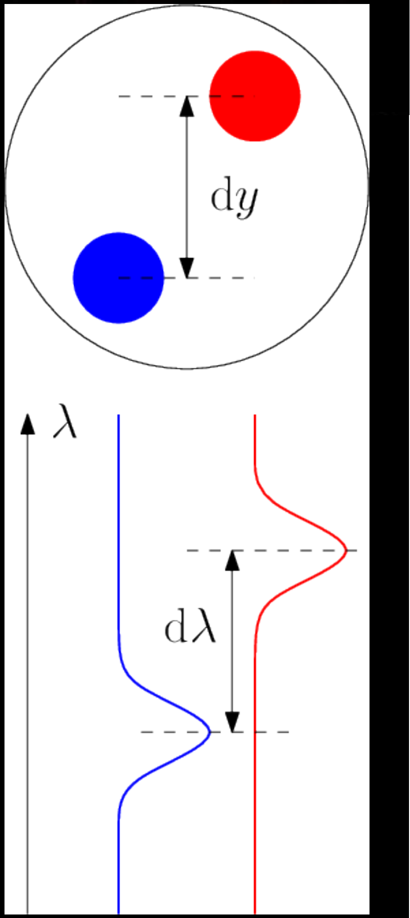
- Restricting to “optical” electromagnetic waves
  - Two spatial dimensions: (x, y) or (α, δ)
  - One spectral dimension: λ
  - Two polarizations
  - One temporal dimension: t
- Usually 2D-detectors (e.g. CCD/CMOS): $s(i[,j])$

How to acquire 3D-observations $f(x, y, \lambda)$

on 2D-detectors?

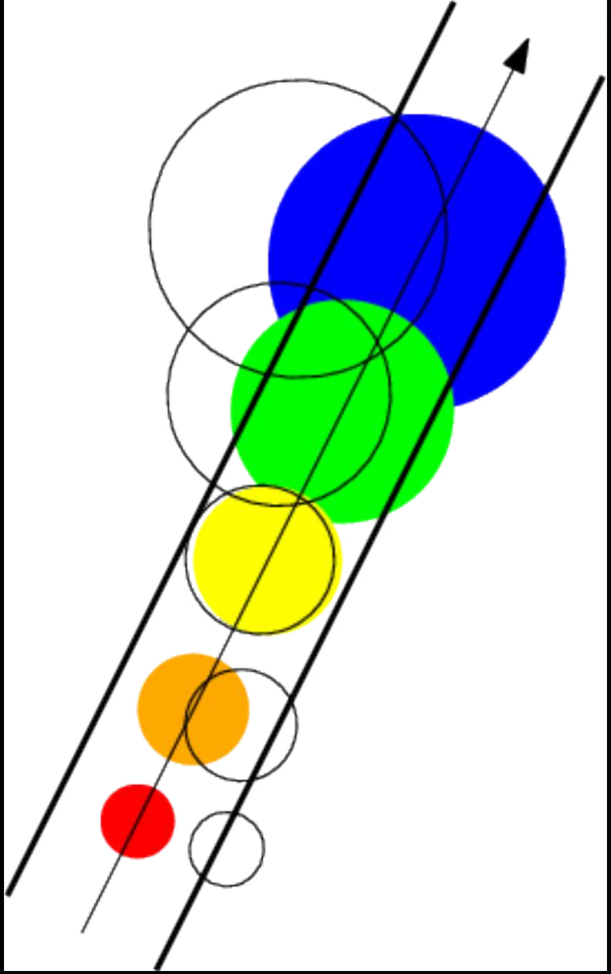
Aperture – 1D – spectroscopy

- 1D spectroscopy s(i) ↔ f(λ) discards both spatial directions (integration or sampling)
- Optimal aperture size fixed by seeing
  - Atmospheric Differential Refraction ADR(t, λ)
  - Seeing(t, λ)
- Fixed aperture on the sky ⟺ ≠ physical radius
- No feedback on effective spatial properties
- (aperture) Multi-Object Spectrograph: multiplexing on 2D detectors



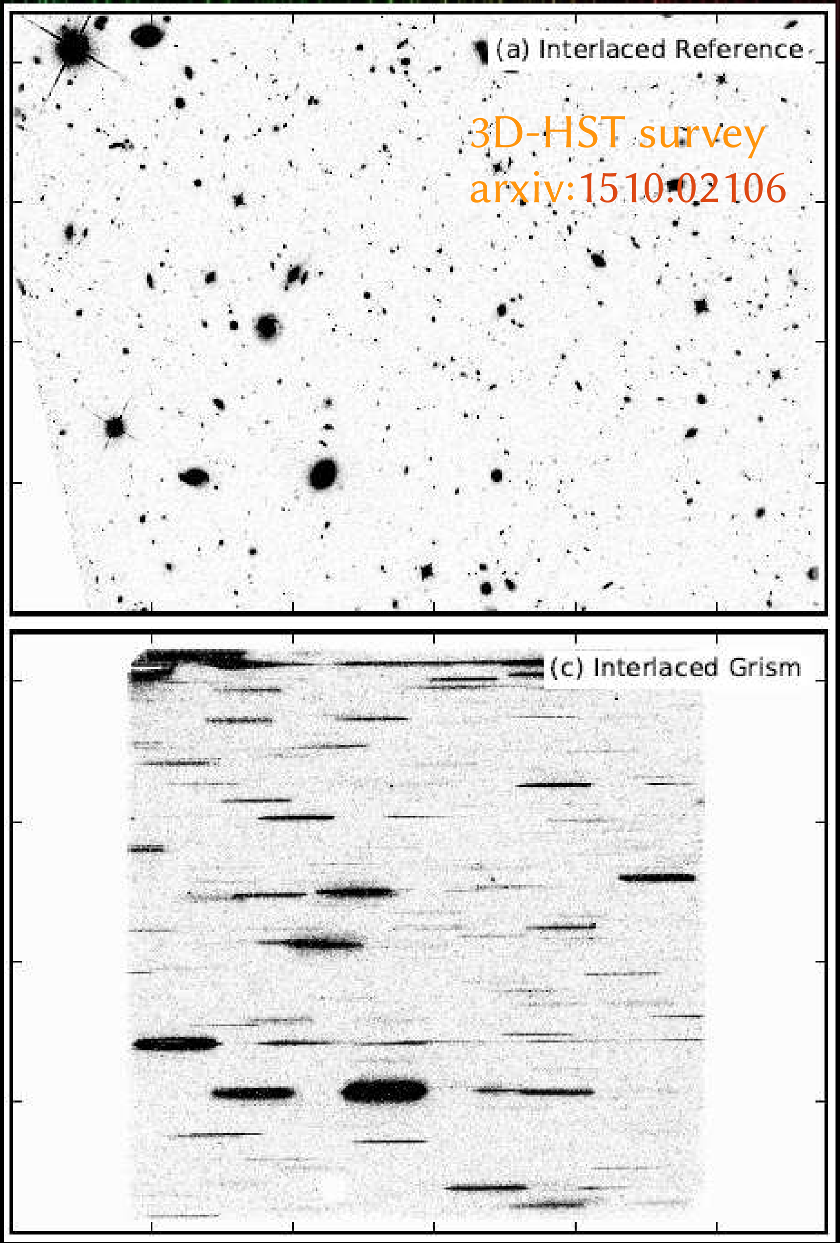
Slit – 2D – spectroscopy

- 2D spectroscopy s(i, j) ↔ f(x, λ) retains one spatial direction
- Optimal slit position and width are imposed
  - Slit position set by ADR
  - Slit width set by seeing
  - But ADR(t, λ) and seeing(t, λ)…
- Sparse use of 2D detectors ⟹ “slitlet” MOS



Slitless spectroscopy

- The image is directly dispersed in the FP
  - Intricate mixing of spatial and spectral informations: $s(i, j) \not\leftrightarrow f(x, y, \lambda)$
  - Partial (model-dependent) demixing using different dispersion orientations and/or external priors (e.g. images for position and shapes)



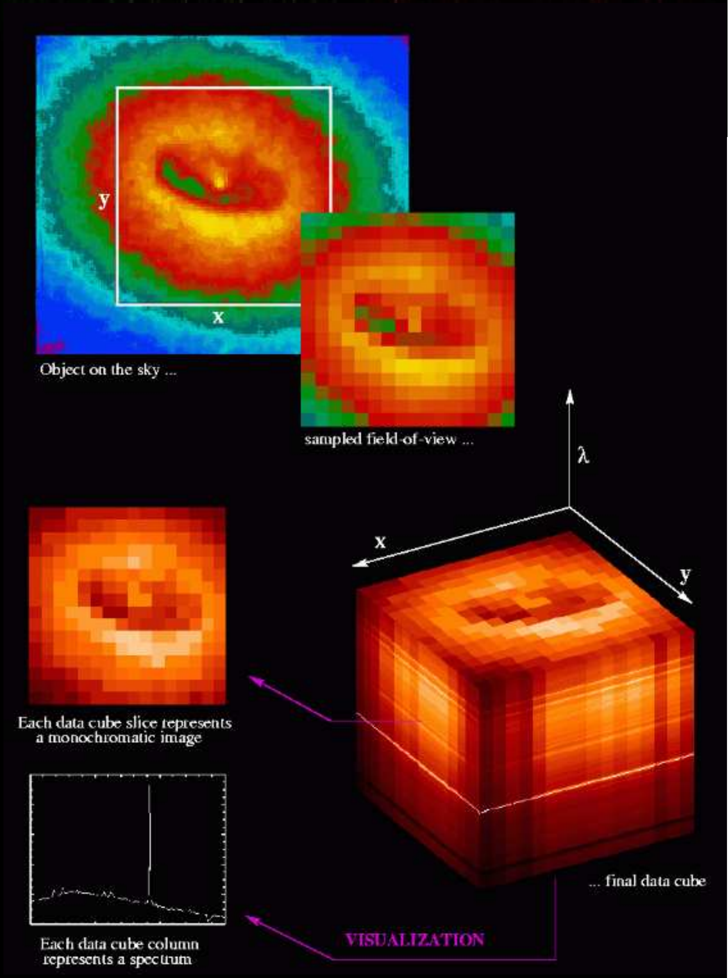
3D-HST survey
arxiv:1510.02106

What IFS is

Simultaneous spectroscopy on contiguous spatial elements

- ◆ **Pixel** = PIXture ELement
- ◆ **Spaxel** = SPAtial piXture ELement
- ◆ **Voxel** = VOlume piXture ELement

- A 3D datacube $f(x, y, \lambda)$ is:
  - ◆ A contiguous collection of mono-chromatic images $f_\lambda(x, y)$ (“slices”)
  - ◆ A dense collection of localized spectra $f_{x,y}(\lambda)$



Roth 2002

Muse on NGC 4650A

ESO

www.eso.org

What IFS is not

- Slitless spectroscopy
  - Spatial and spectra information entangled on detector
- Multi-Object Spectroscopy
  - Discrete (non-contiguous) spatial samples
- Sequential (time-dependent) observations
  - Scanning long slits, Fabry-Perot (tunable filter) or Michelson (Fourier-transform) spectroscopies
- “Radio” and X-ray observations
  - Radio/FIR can retain phase, X-ray can measure photon energy

Science cases

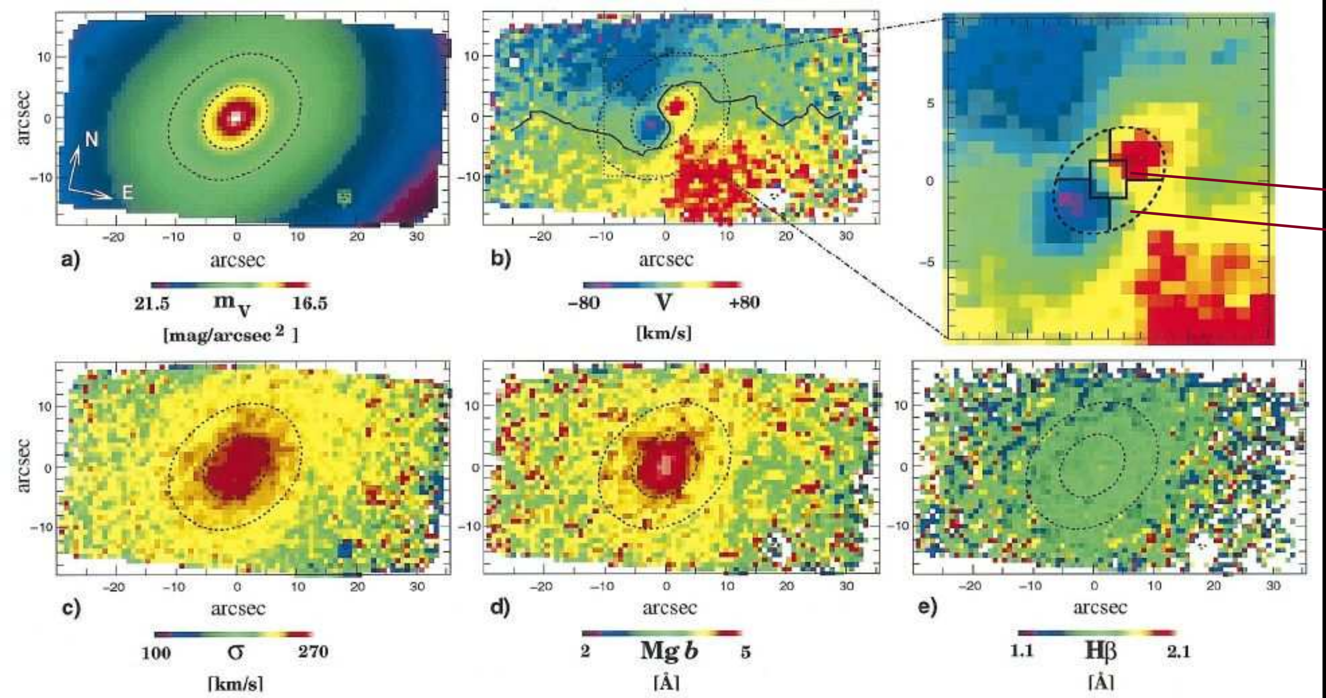
Science cases

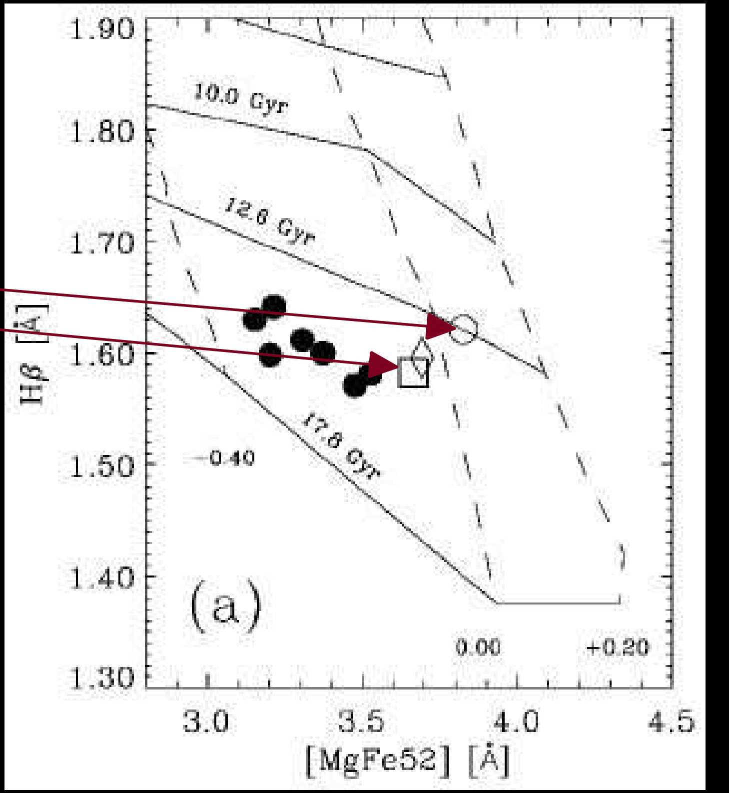
- Spatially extended objects
  - Galaxies – stellar populations (age, metallicity), gas content, kinematics –, AGN
  - *Young stellar objects*
  - *Solar system objects: Sun, planets & asteroids*
  - Strong lenses, *galaxy clusters (X-ray)*
- Point source spectro-photometry
  - High spatial resolution spectroscopy (spectro-astrometry)
  - Structured background: type Ia supernovae
  - Resolved stellar populations (crowded field spectro-photometry): stellar clusters, PNe
  - *Exo-planets (coronography)*
- *Serendipitous observations: inter-galactic medium*

Individual galaxies

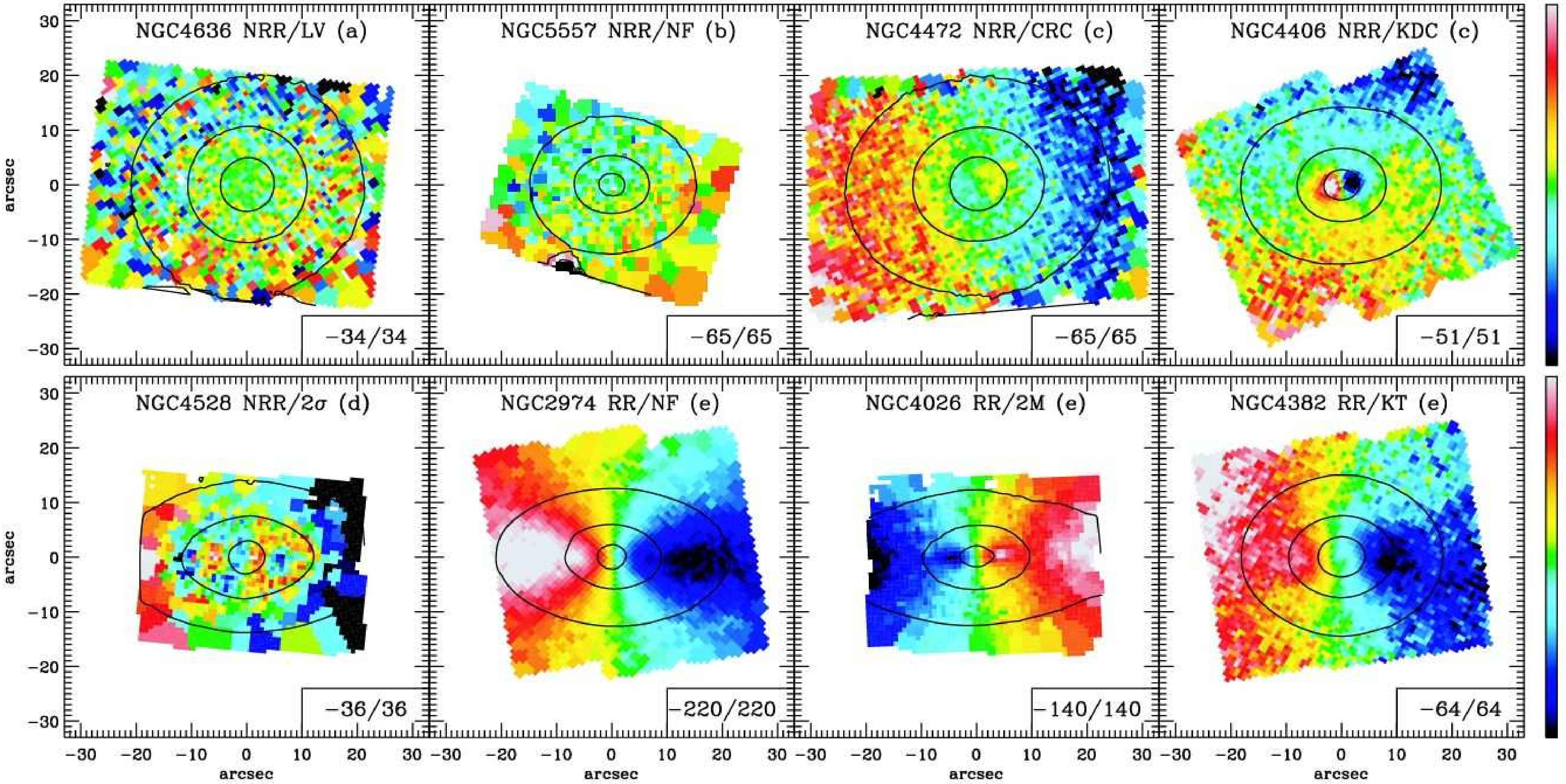
- Stellar and gas kinematics
- Stellar populations (age & metallicity)
- Gas content, etc.

NGC 4365, 1st SAURON paper
Davies+ 2001ApJ...548L..33D



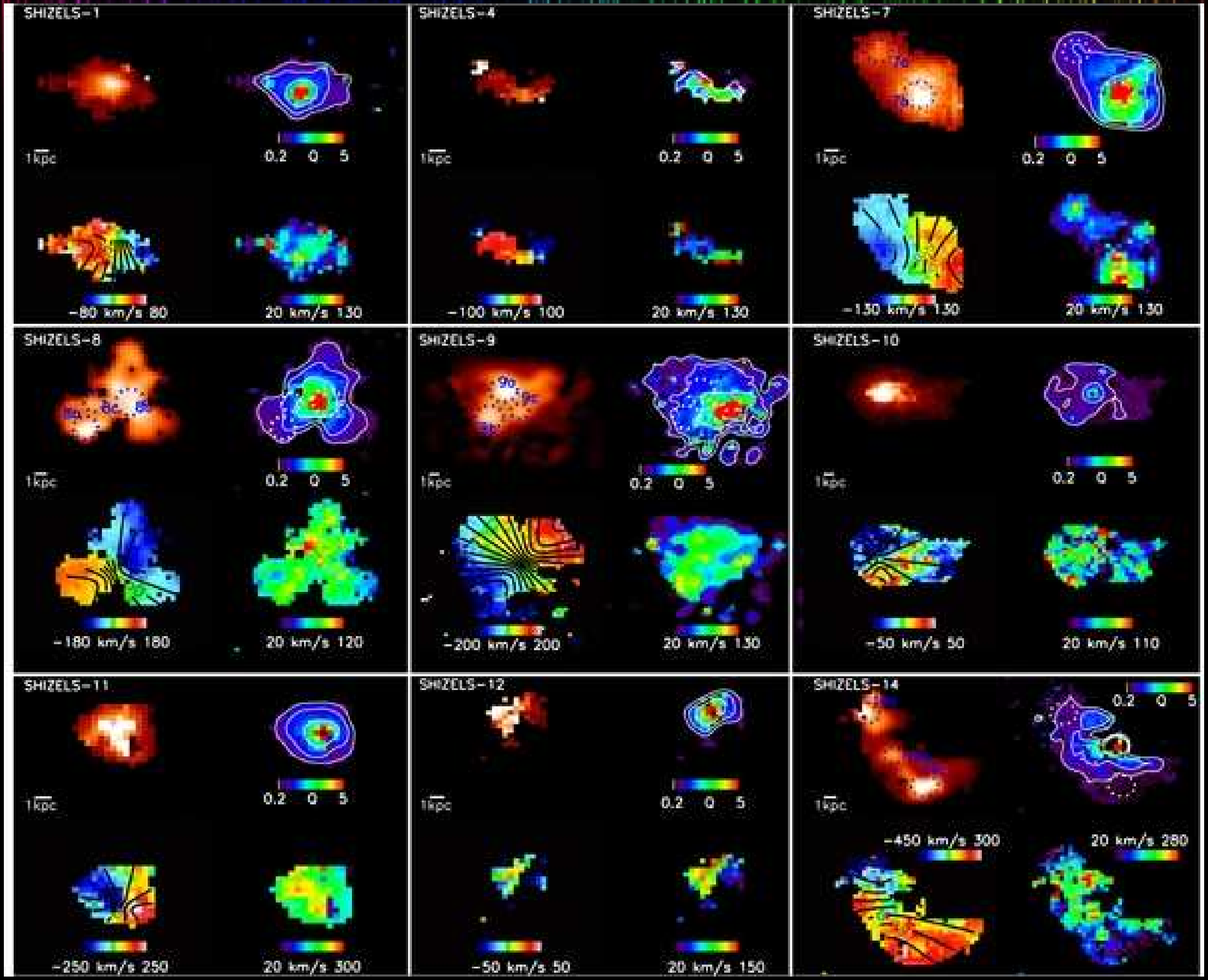


Kinematics from ATLAS^{3D}



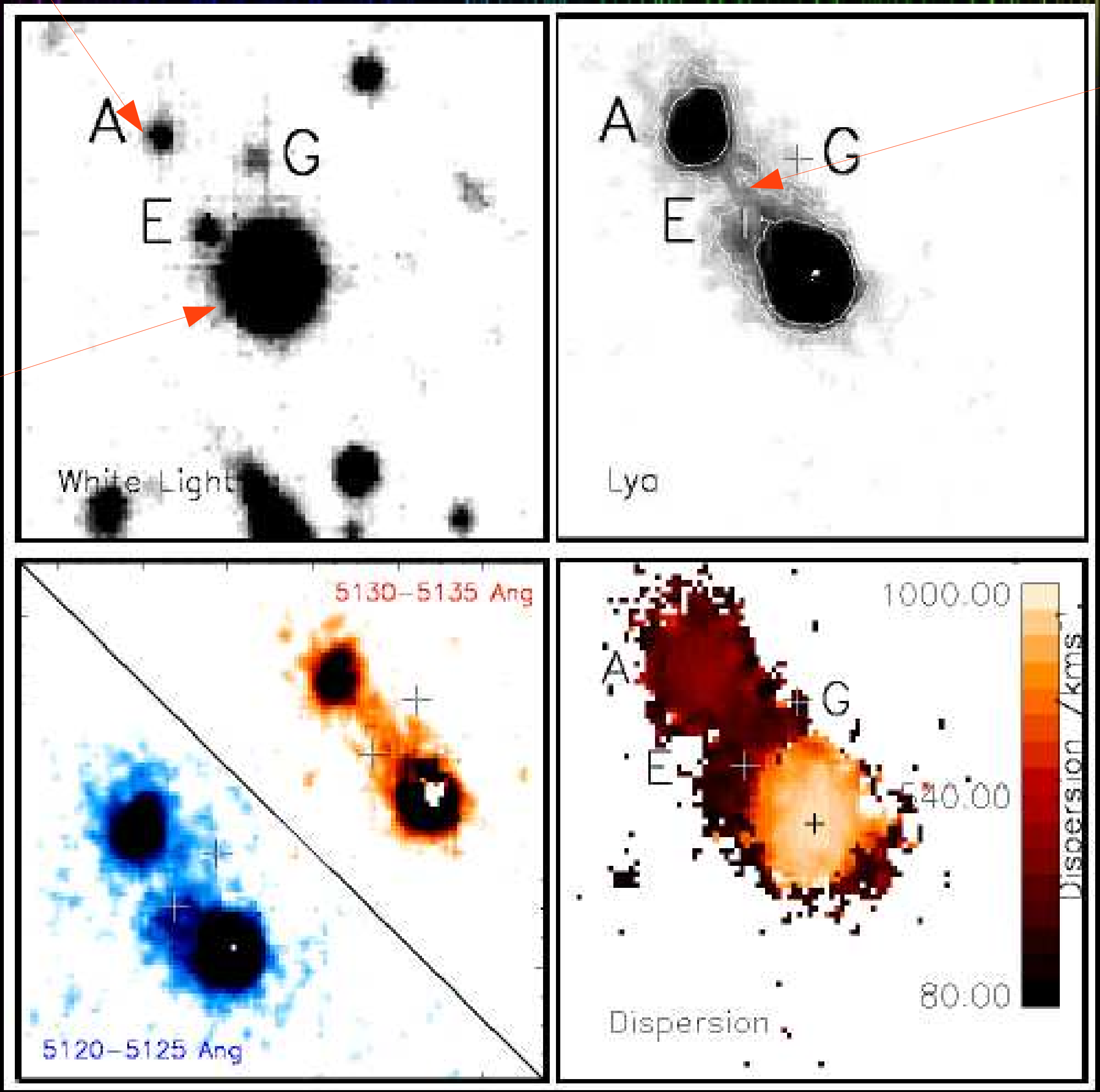
Krajnovic+ 2011MNRAS.414.2923K

Gas analyses



Star-forming ISM, z=0.8 – 2.2
AO + SINFONI 2012MNRAS.426..935S

AGN



AGN companion galaxy

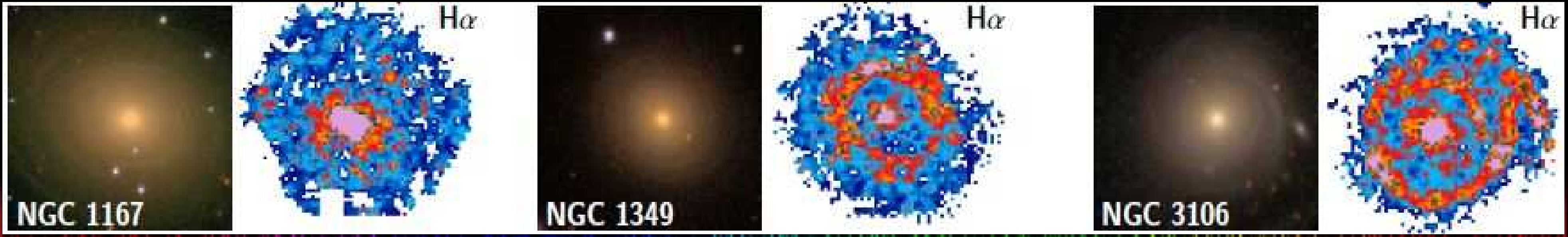
bridge of material

PKS1614+051
quasar @z=3.2

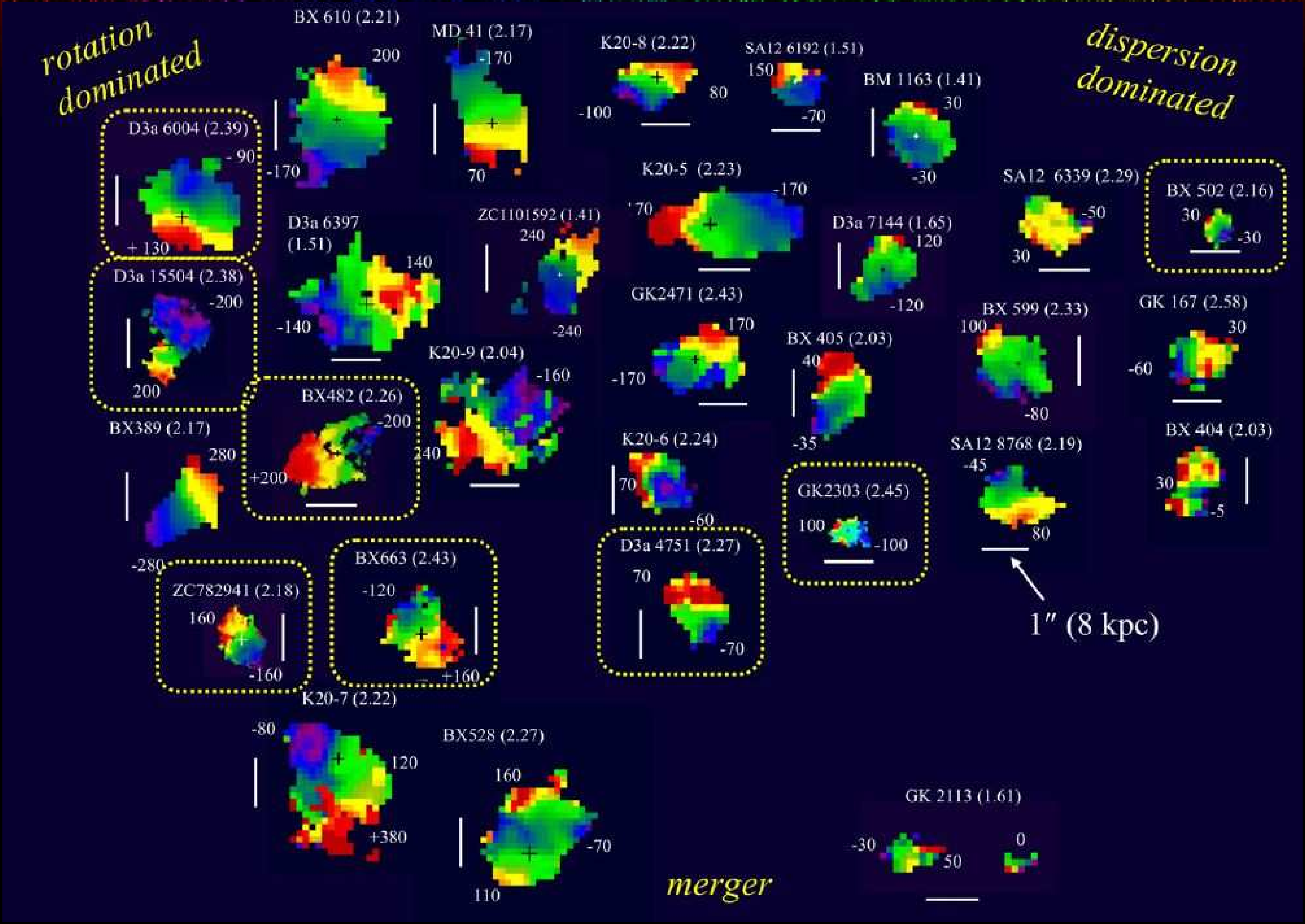
Muse science verification data (20''×18'')
Husband+ 2015MNRAS.452.2388H

Galaxy surveys

- Spatially-resolved observations
  - Kinematics, stellar populations, star formation, gas content, etc. ⟹ dynamics, contents, formation history
- Fixed aperture biases
  - Fixed aperture on the sky ⟺ ≠ physical radius, and bias is function of redshift (e.g. CALIFA 2015arXiv151101300G)
  - Integrated quantities are flux weighted, not spatial means
- IFS surveys
  - Low-redshift: Sauron/Atlas3D, DiskMass, Pings, Venga
  - z > 0.7: Massiv, Sins, Glace, Images

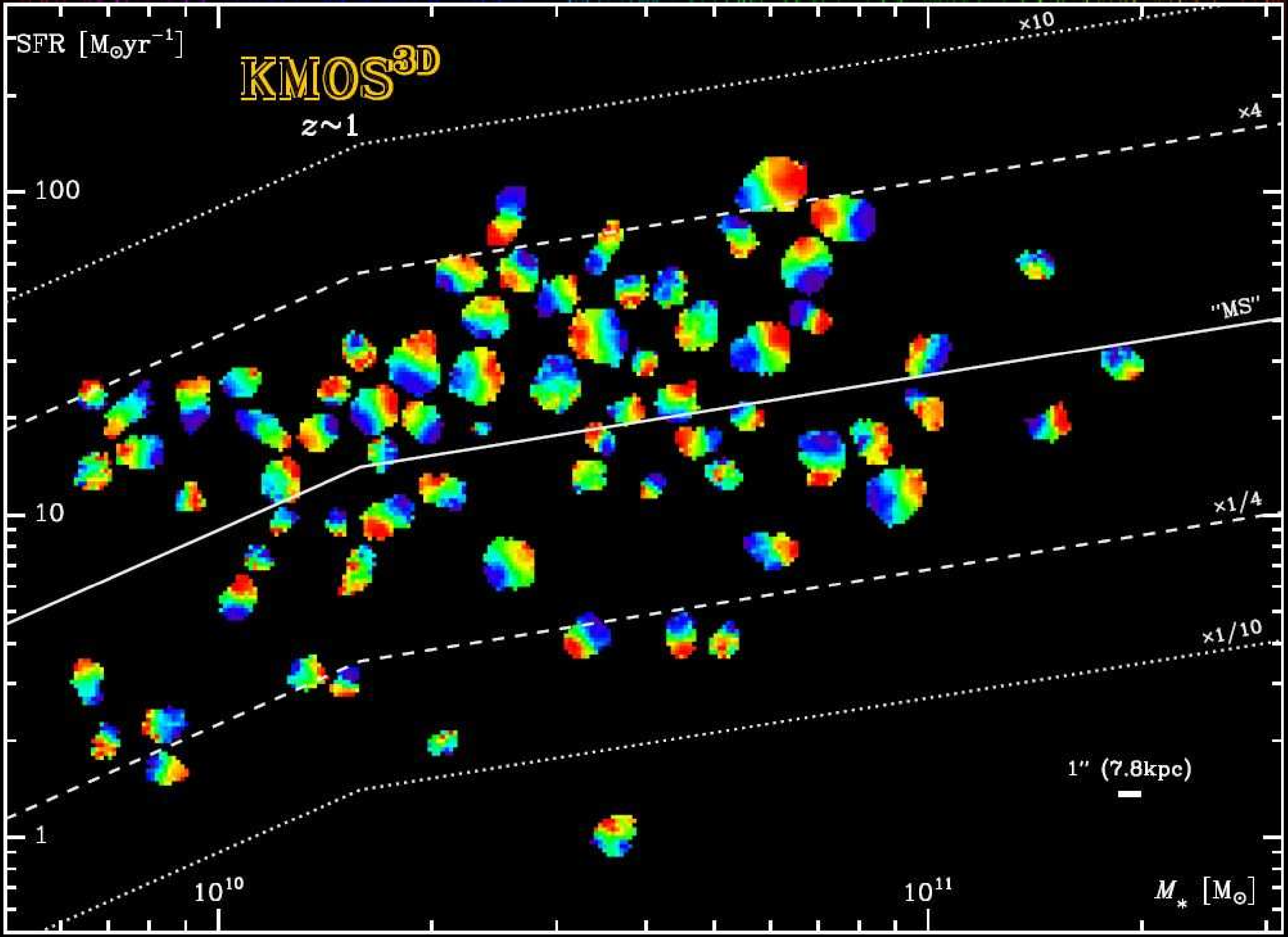


SINS survey



SINFONI IFS of z ~ 2 Star-forming Galaxies
Förster Schreiber+ 2009ApJ...706.1364F

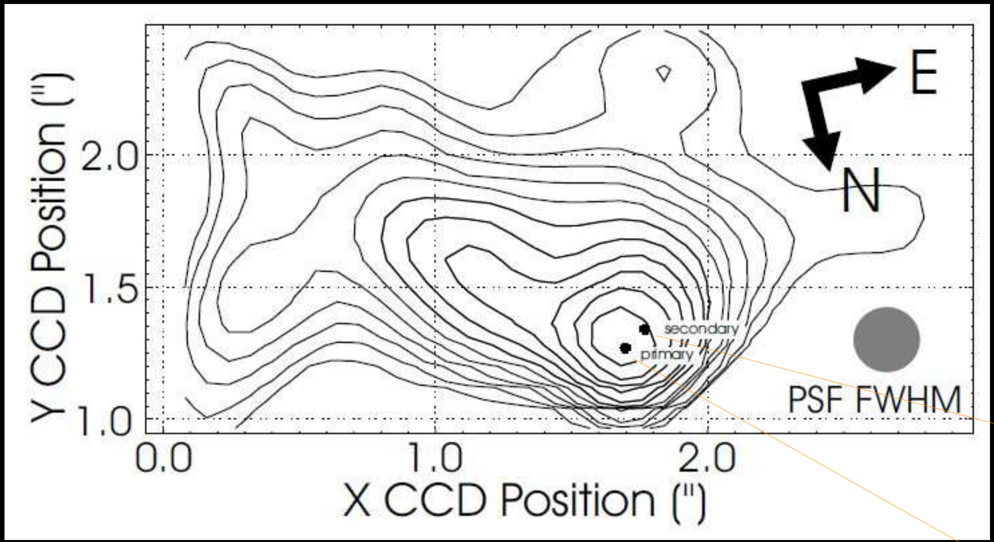
KMOS^{3D}



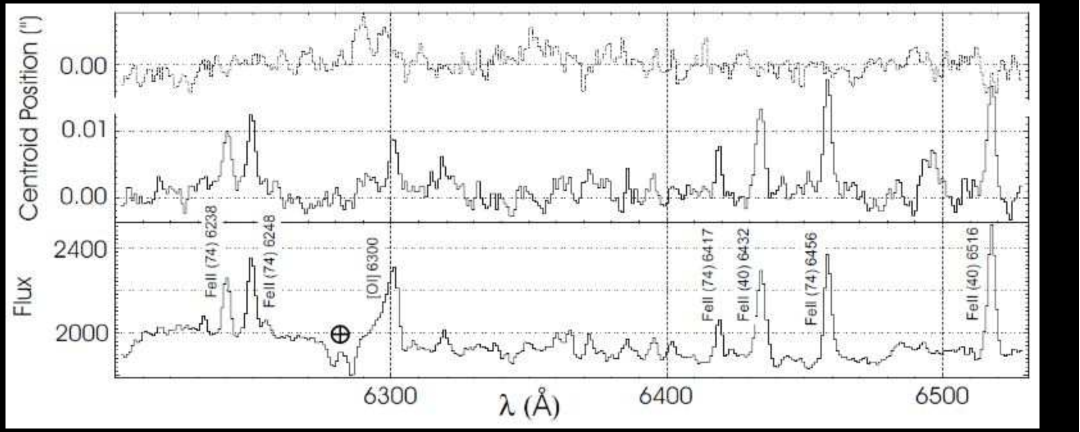
600 galaxies, z = 0.7 − 2.7
Wisnioski+ 2015ApJ...799..209W

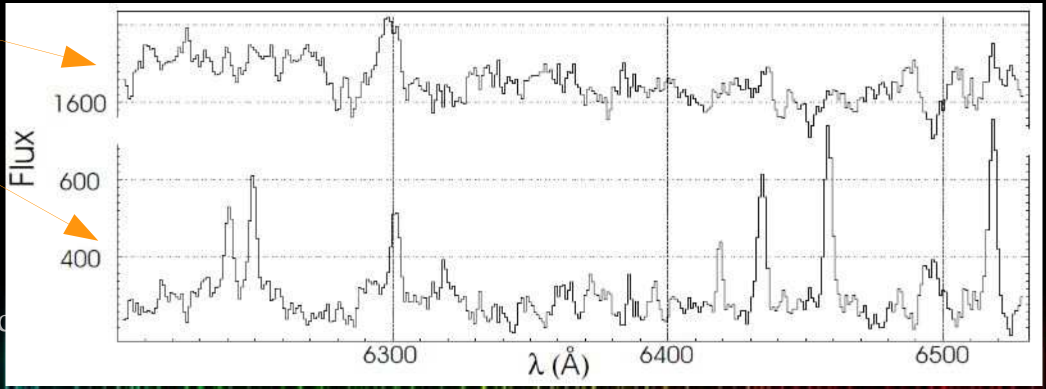
Spectro-astrometry

- Spectroscopy of 2 unresolved point sources
  - The integrated spectrum is the sum of the 2 spectra
  - Barycenter position depends on the ratio of the 2 spectra
- Review: 2008LNP...742..123W (not IFS specific)



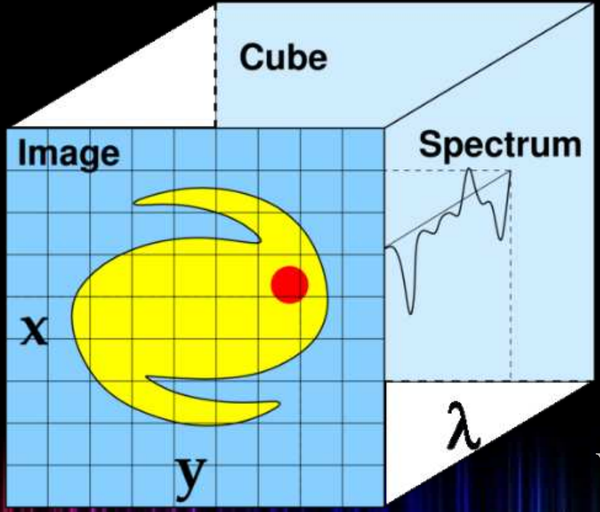
ZCMa observed with OASIS
Garcia+ 1999A&A...346..892G





Spectro-photometry

- IFS is the tool of choice for spectro-photometry
  - Aperture spectro-photometry is “difficult”
  - 3D PSF spectro-photometry requires good knowledge of spatial properties

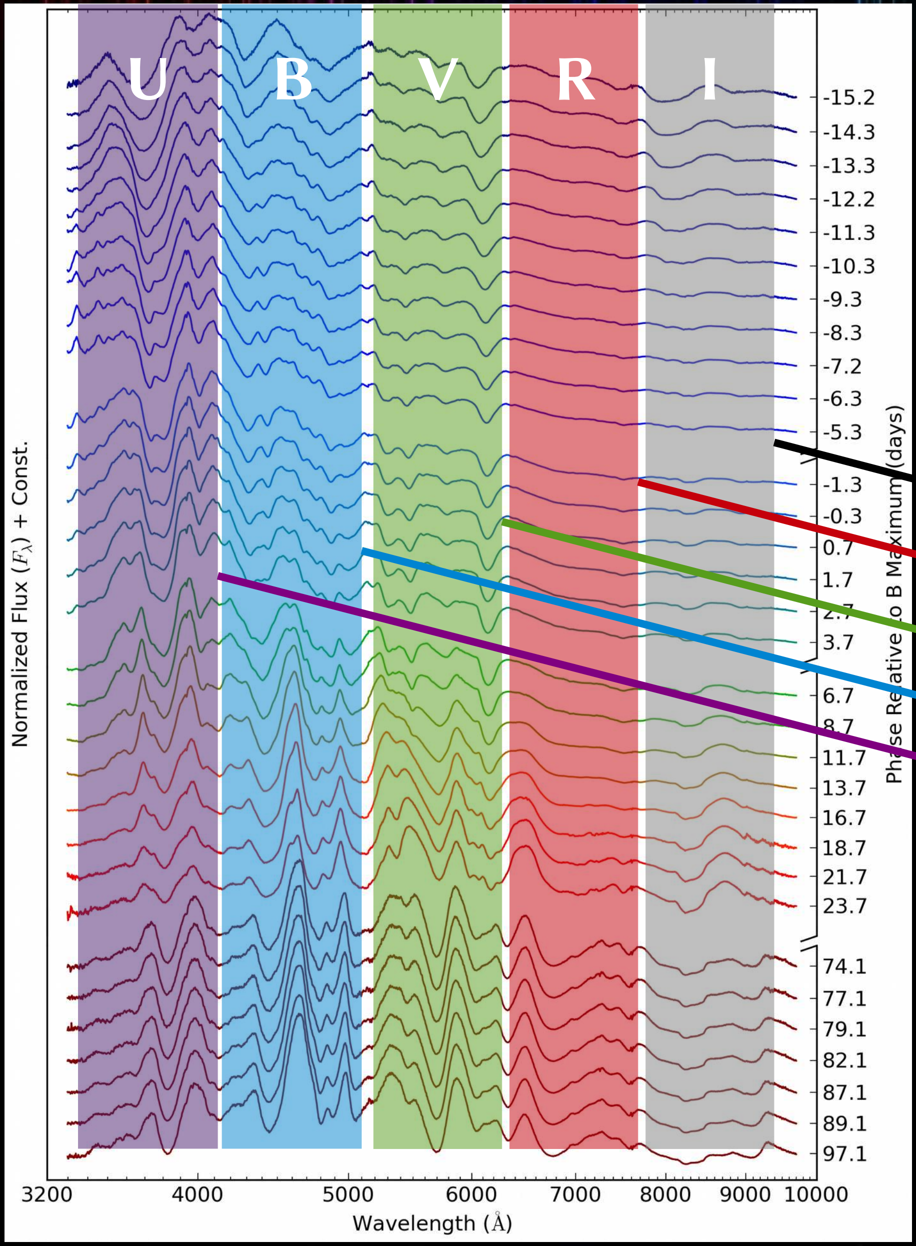


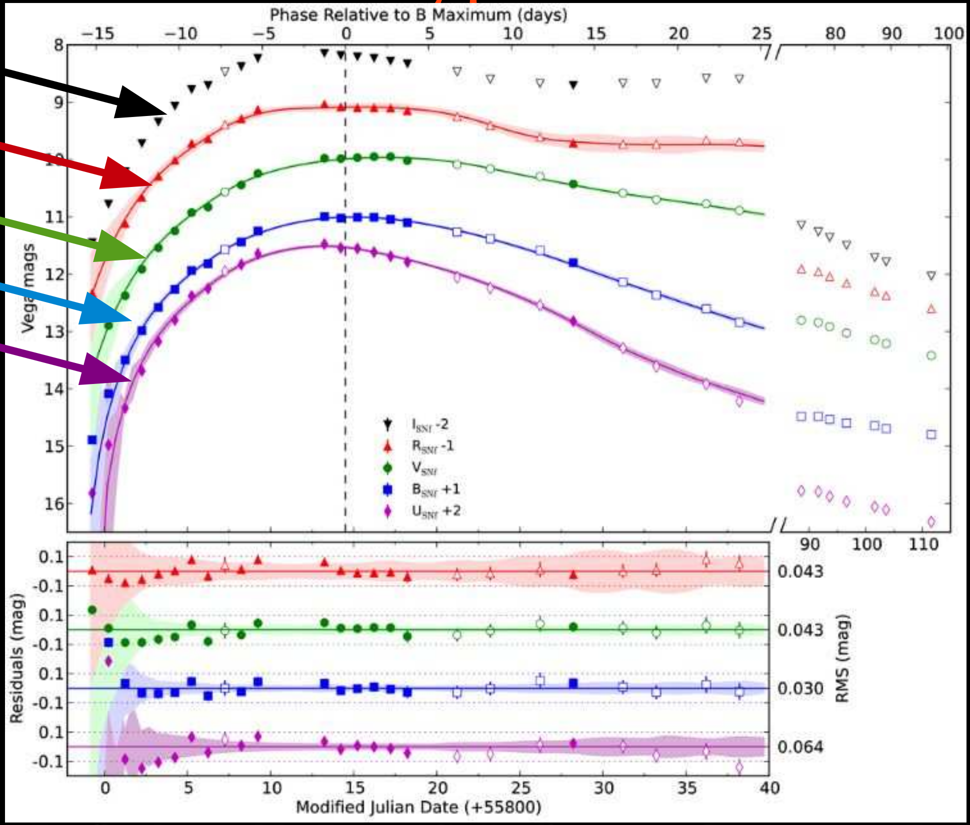
- Primary objective for SNIFS
  - High spectro-photo. accuracy on the whole SN time-series
    - …despite the moon, clouds, atmosphere, etc.
    - … despite the galaxy background
    - …notwithstanding a complex instrument and data-reduction flow
  - “Usual” in photometry, but new in transient spectroscopy
    - Photometry makes strong assumption on sources (extinction, colors, K-corrections)

Time series & synthetic photometry

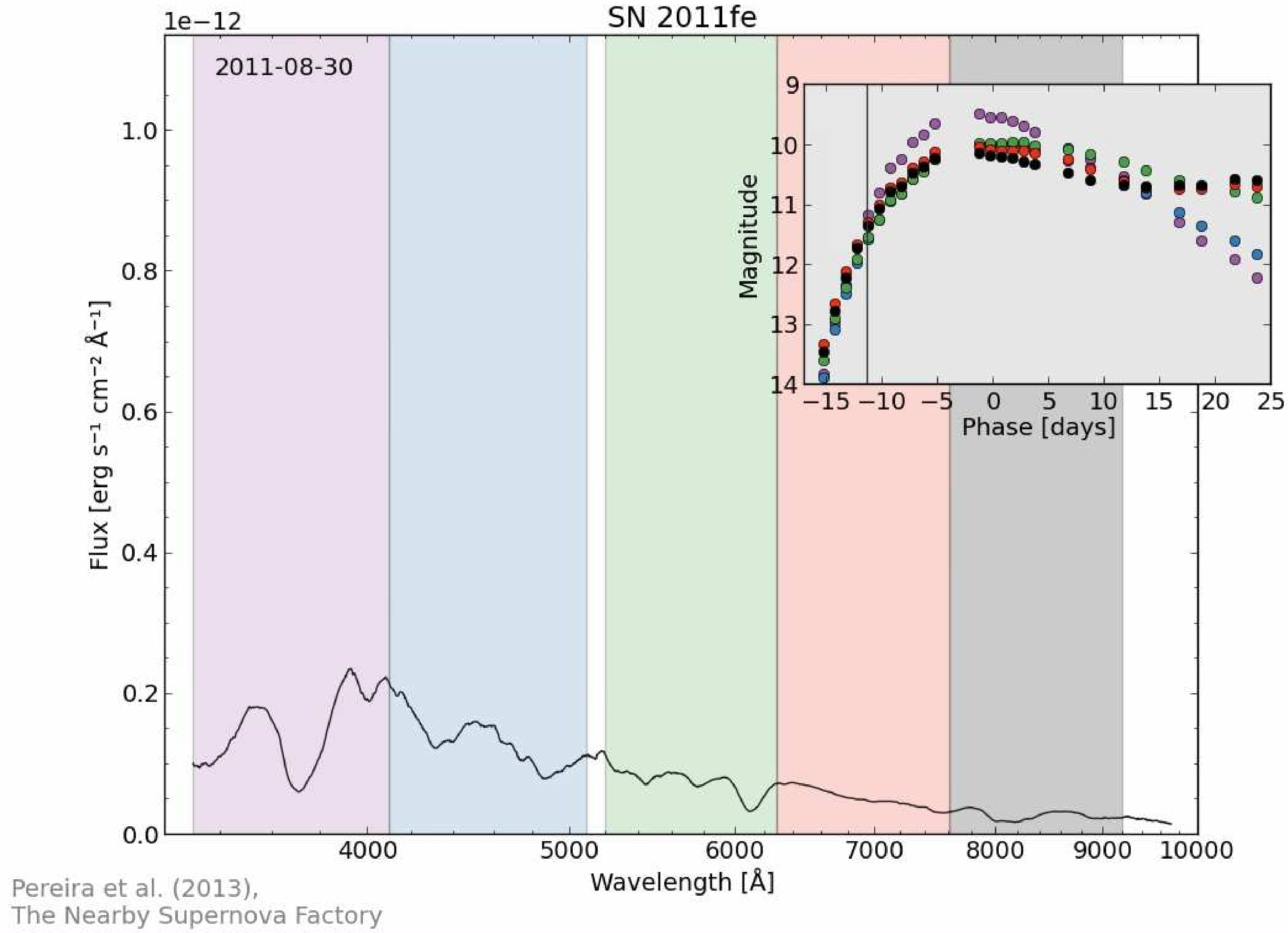
Pereira+2013

- SN2011fe
  - The closest SN in the last 25 years (M101, 6.4 Mpc)
  - An archetypal SN Ia



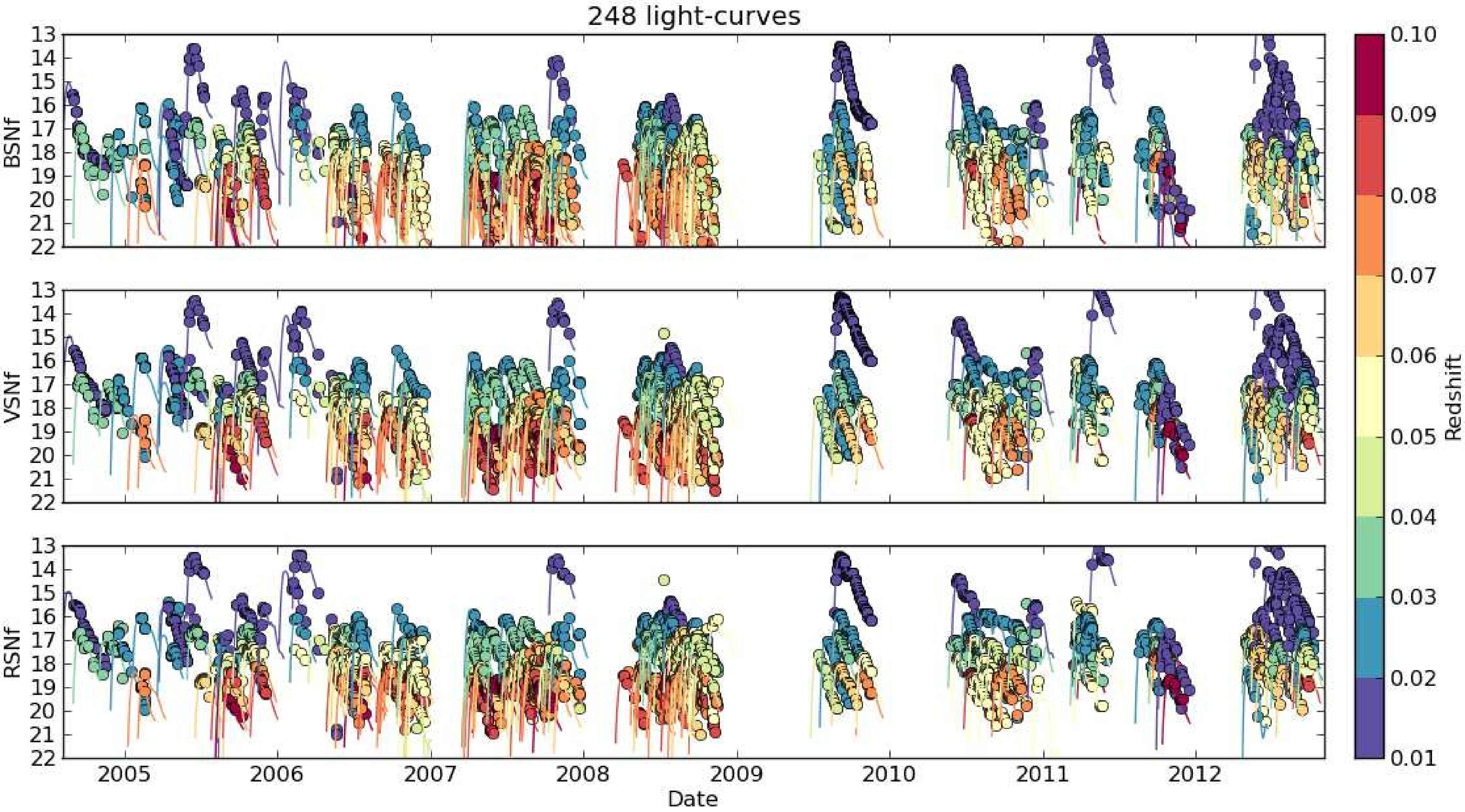


SN 2011fe time series

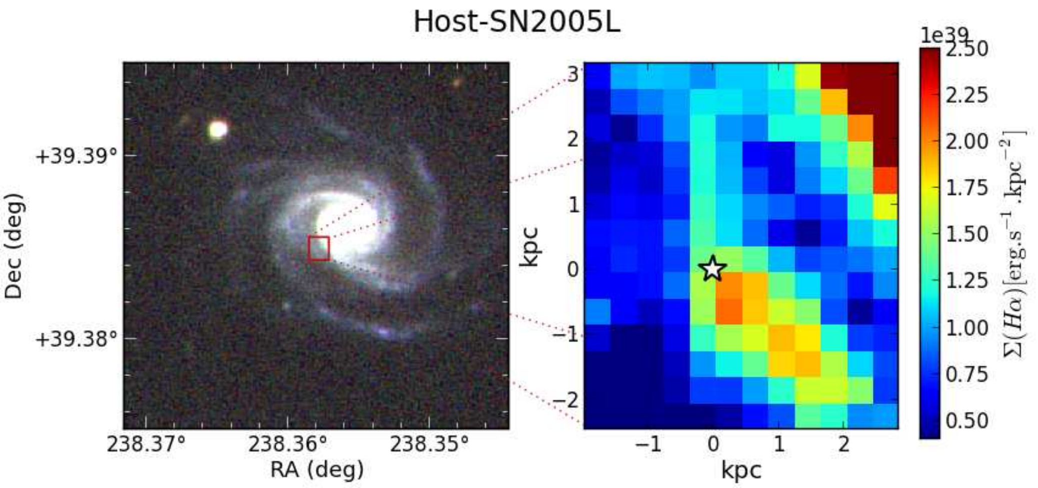


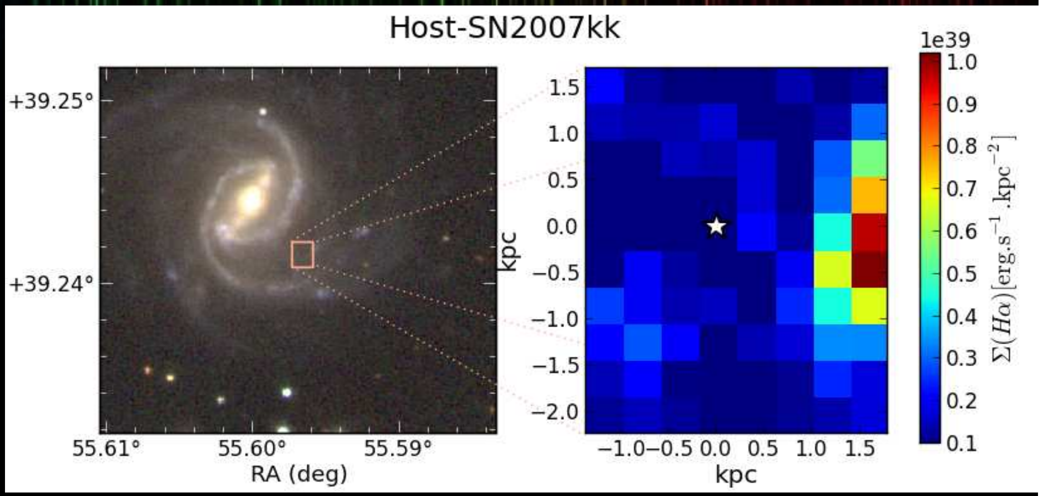
Pereira et al. (2013),
The Nearby Supernova Factory

SNfactory SN Ia light curves

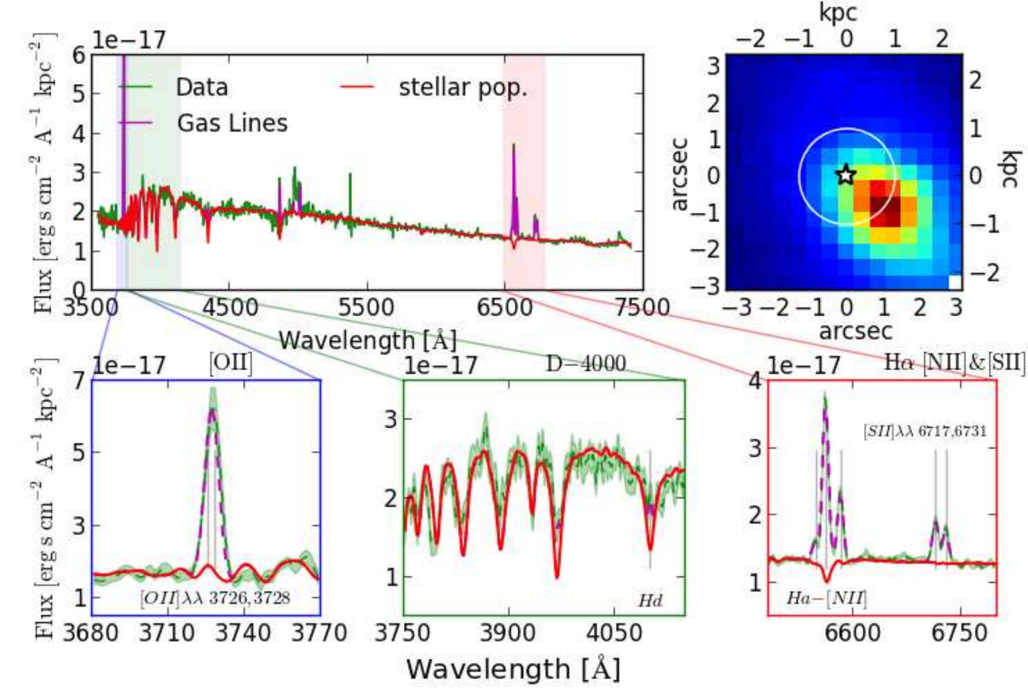


Global vs. local host studies





Rigault+ 2013A&A...560A..66R



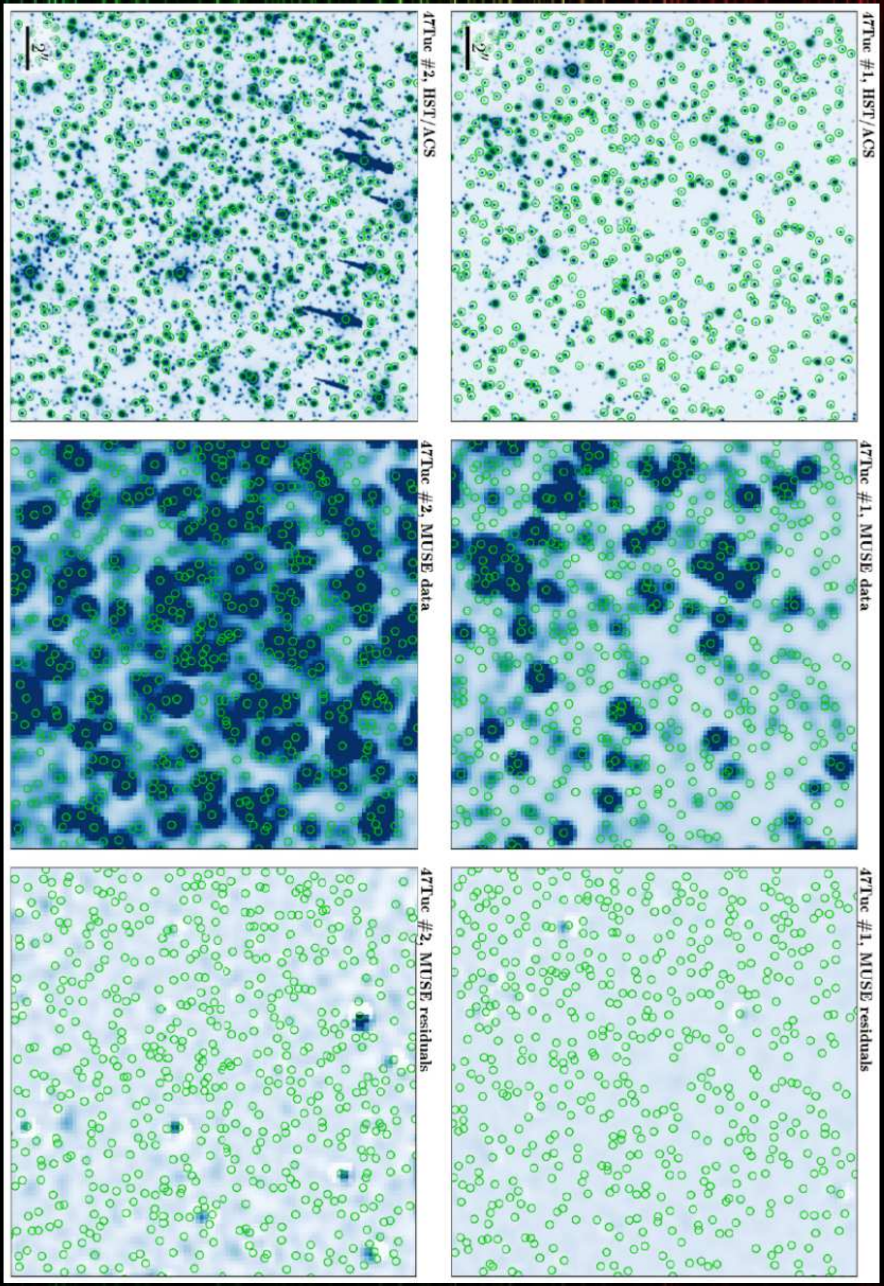
Global ≠ Local

- Use SNIFS FoV to probe local environment of SN (~1 kpc)
  - SN subtraction
  - Full time series cube merging
  - ULySS spectrum modeling
    - Stellar & gas components

K-corrections

- Difference in effective band passes between rest- and observer frames
  - Rest frame: $X_{RF} = -2.5 \log \int_X f(\lambda)\, d\lambda$ ⟶ that's what you want
  - Obs. frame: $X_{OF} = -2.5 \log \int_X f(\lambda/(1+z))\, d\lambda$ ⟶ that' what you get
  - $X_{RF} = X_{OF} + K_{OF\rightarrow RF}$
- No problem if you perfectly know f(λ)
  - But usually you don't know *that much* f(λ)
  - “Initiated guess” on f(λ) provides the correction factor
- Traditional photometry
  - Flux calibration to the mmag level
  - But K-correction systematic errors severely under-estimated

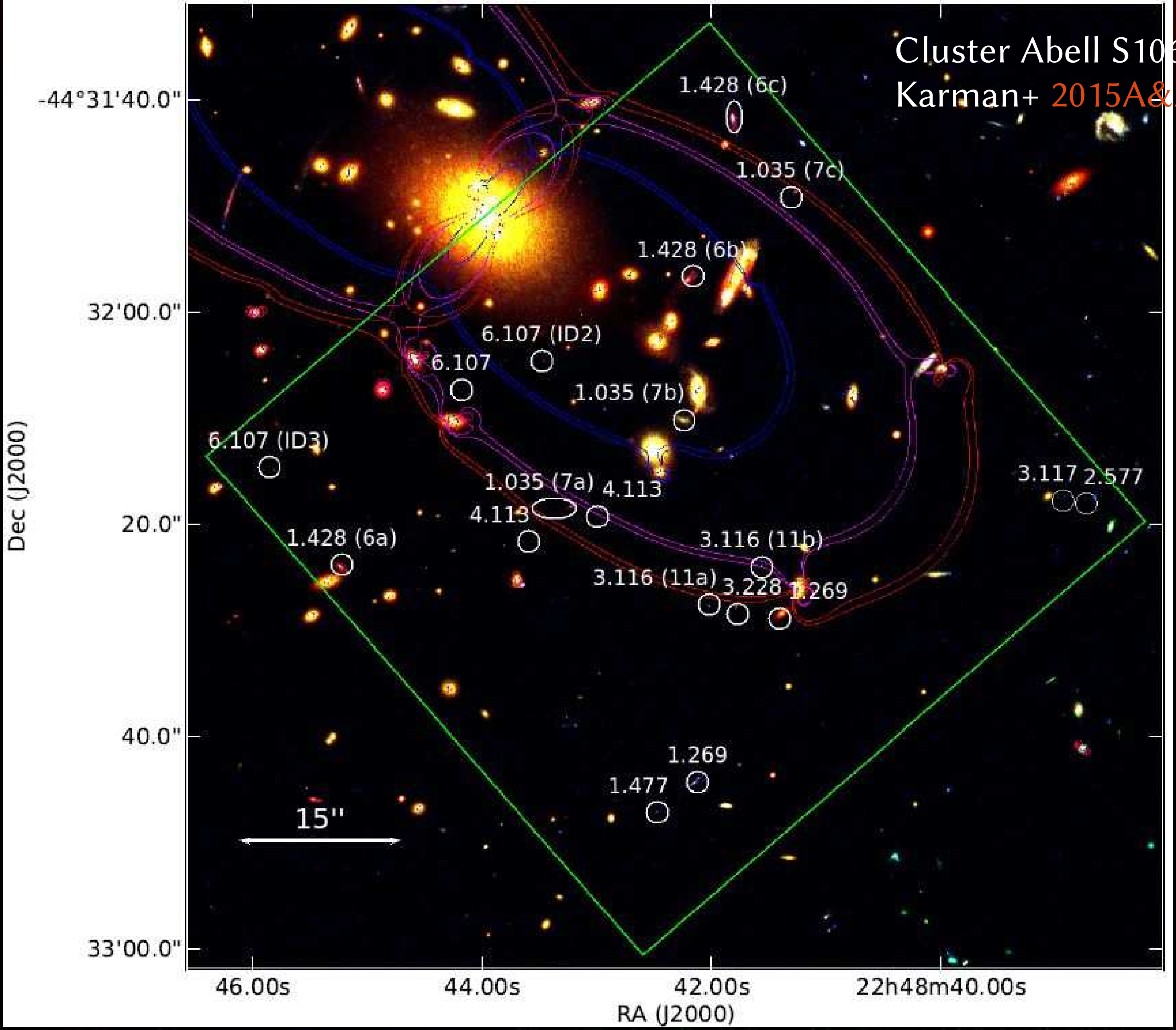
Crowded-field spectroscopy



Resolved stellar populations & kinematics

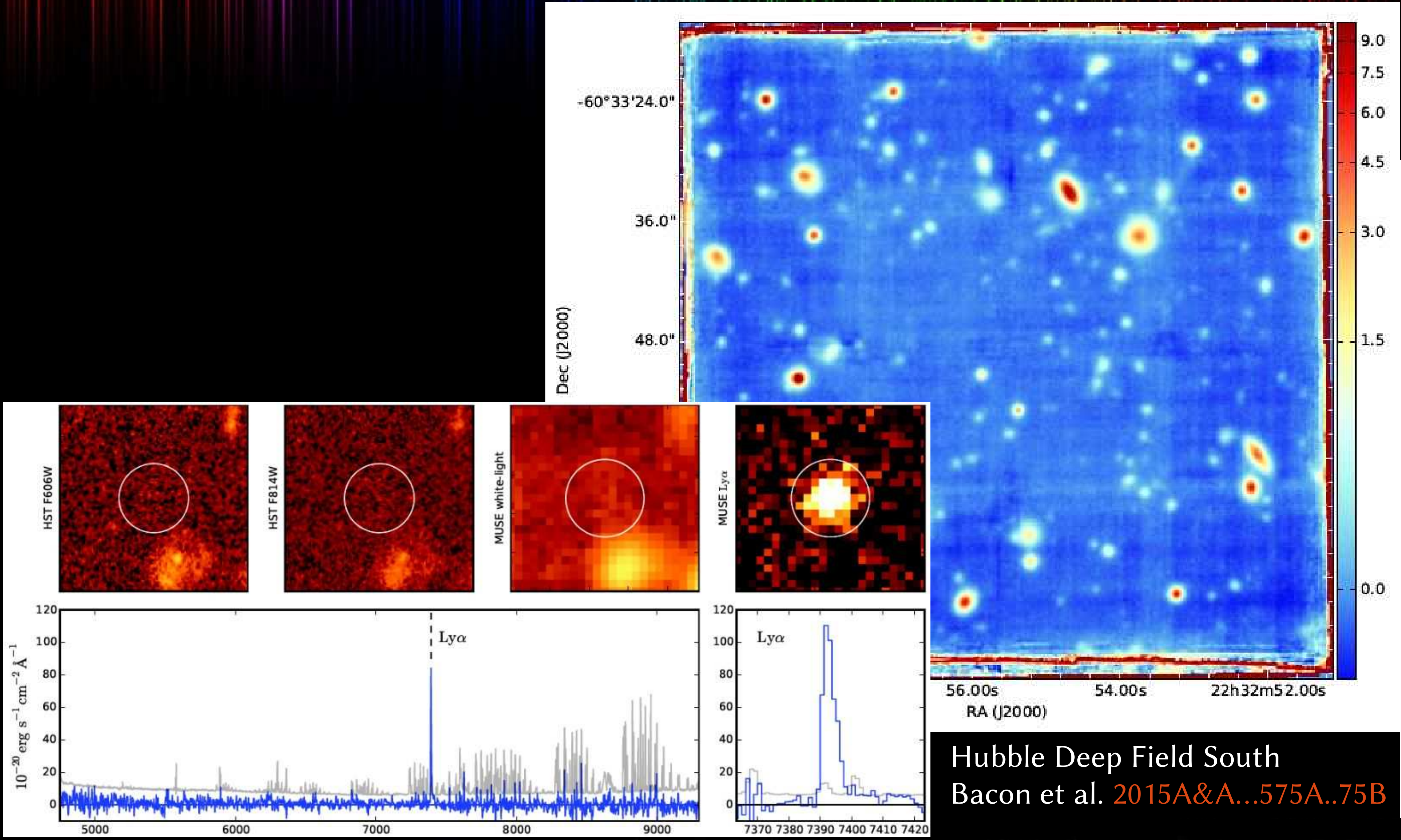
- PSF-fitting spectro-photometry
  - ◆ "DAOphot in 3D"
  - ◆ Kamann+ 2013A&A...549A..71K
- Requires a precise PSF spectro-spatial model
  - ◆ Radial profile, chromaticity, ADR

Strong lenses



Cluster Abell S1063 by MUSE
Karman+ 2015A&A...574A..11K

3D data mining

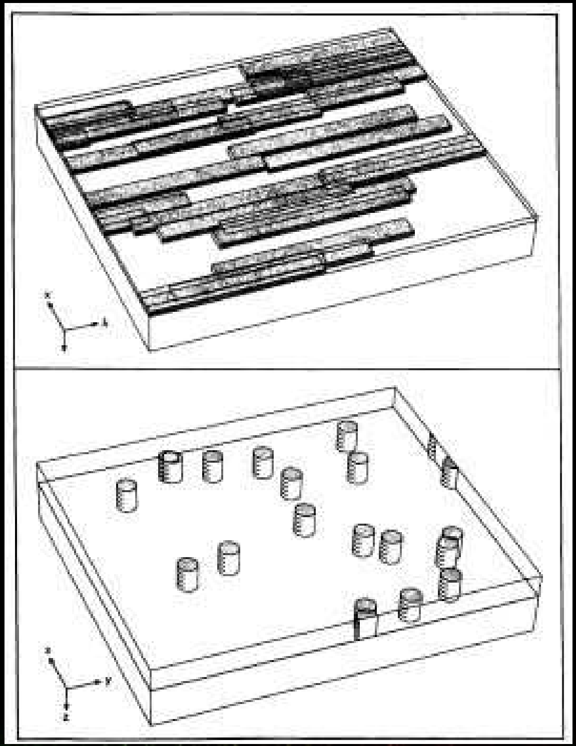


Hubble Deep Field South
Bacon et al. 2015A&A...575A..75B

Instruments

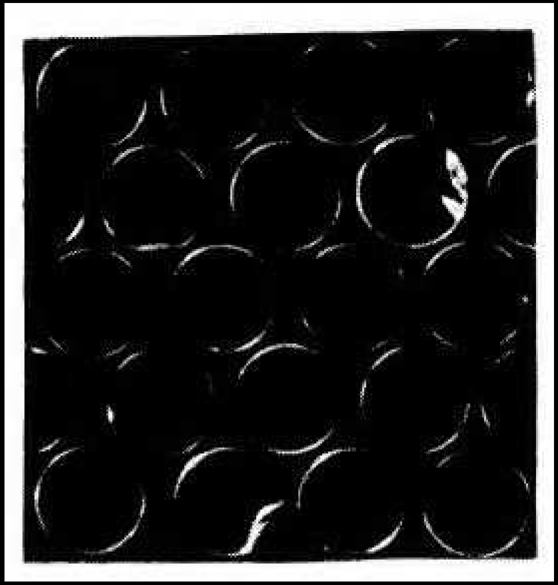
Pre-history – 3D-spectroscopy

- *The Image-Slicer a Device for Reducing Loss of Light at Slit of Stellar Spectrograph*, Bowen, 1938ApJ....88..113B
- *Holography at the telescope - an interferometric method for recording stellar spectra in thick photographic emulsions*, Lindegren & Dravins, 1978A&A....67..241L
  - Lippmann color photography principle
  - Store FT of stellar spectra in the emulsion thickness



History – Fiber-fed IFS

- *A fiber-optics dissector for spectroscopy of nebulosities around quasars and similar objects*, C. Vanderriest, 1980PASP...92..858V
  - Pseudo-slit of 200 fibers of ⌀ 100 μm



History – MLA-based IFS

- *An Integral Field Spectrograph (IFS) for Large Telescopes*, G. Courtès 1982ASSL...92..123C
  - TIGER-like IFS (Oasis, Sauron, SNIFS)
  - Applicable to fiber-fed IFS to improve throughput

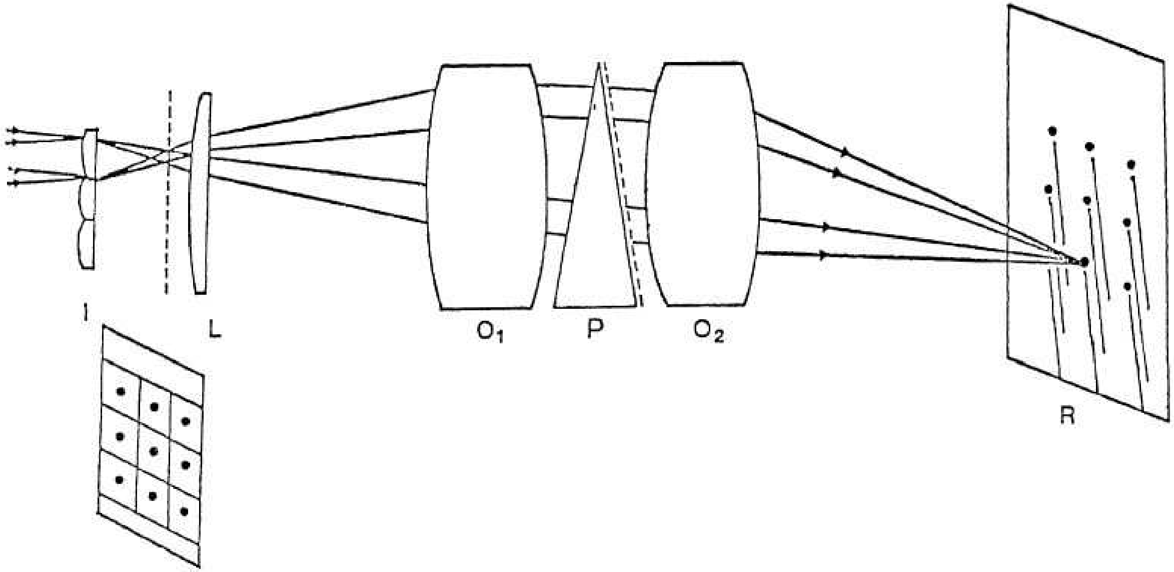
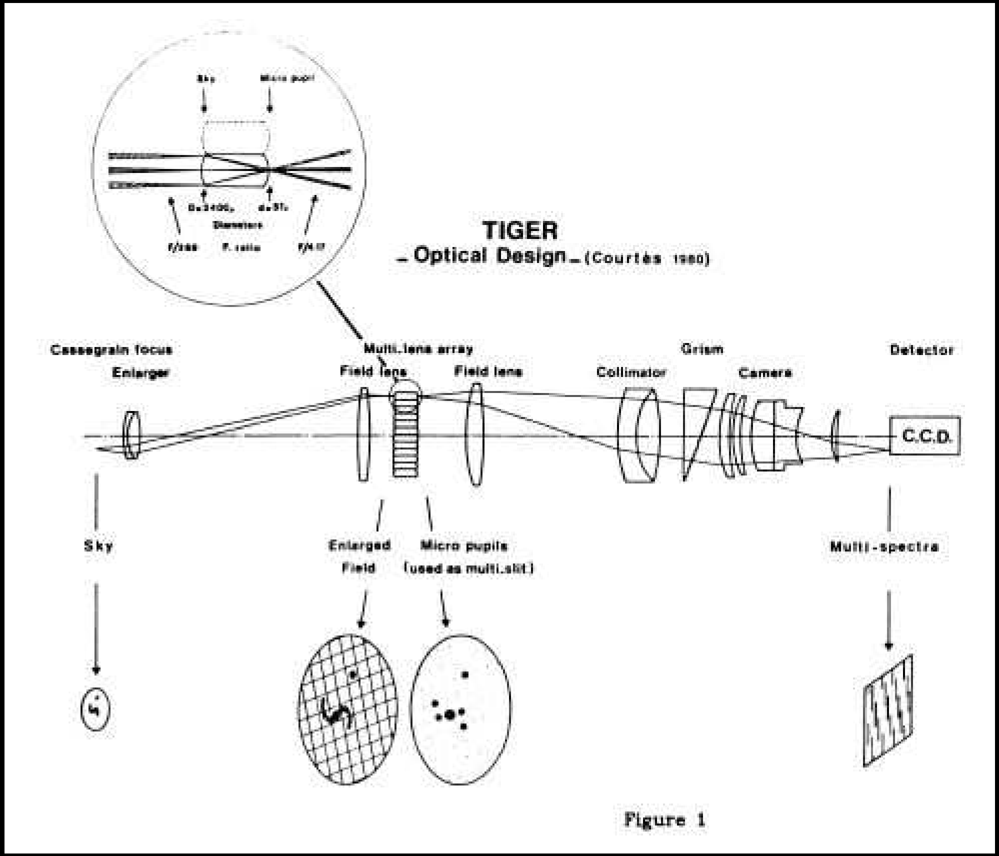
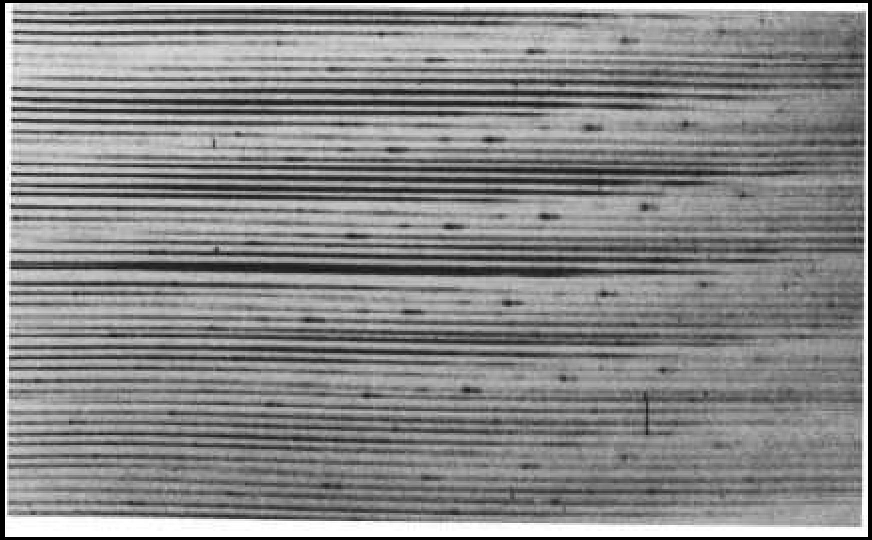


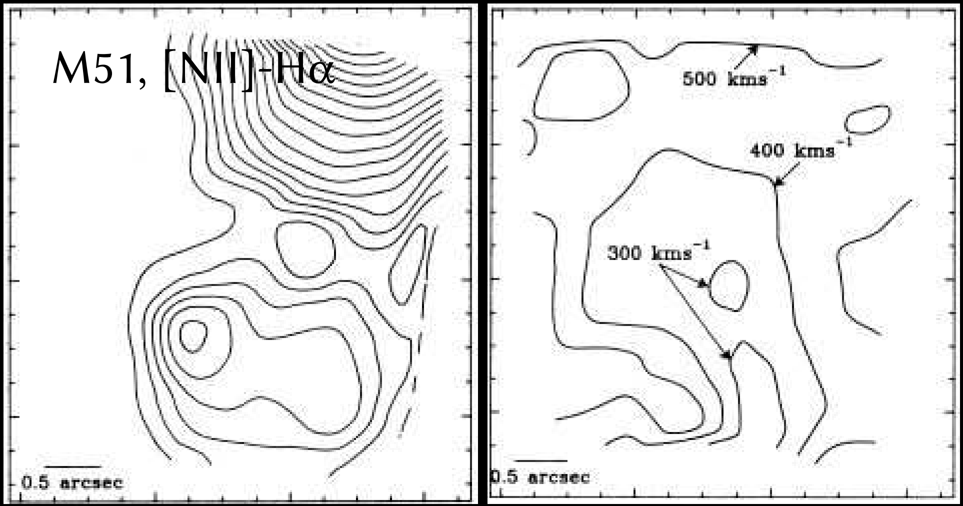
Figure 1. Integral Field Spectrograph: The array of lenses I is placed in the telescope focal plane and produces a chequer pattern of exit pupils; the focal reducer LO_1O_2, equipped with a Carpenter prism-grating P, gives a two-dimensional distribution of the spectra corresponding to each pupil.

History – TIGER paper

- *The Integral Field Spectrograph TIGER*, Bacon et al., 1988ESOC...30.1185B



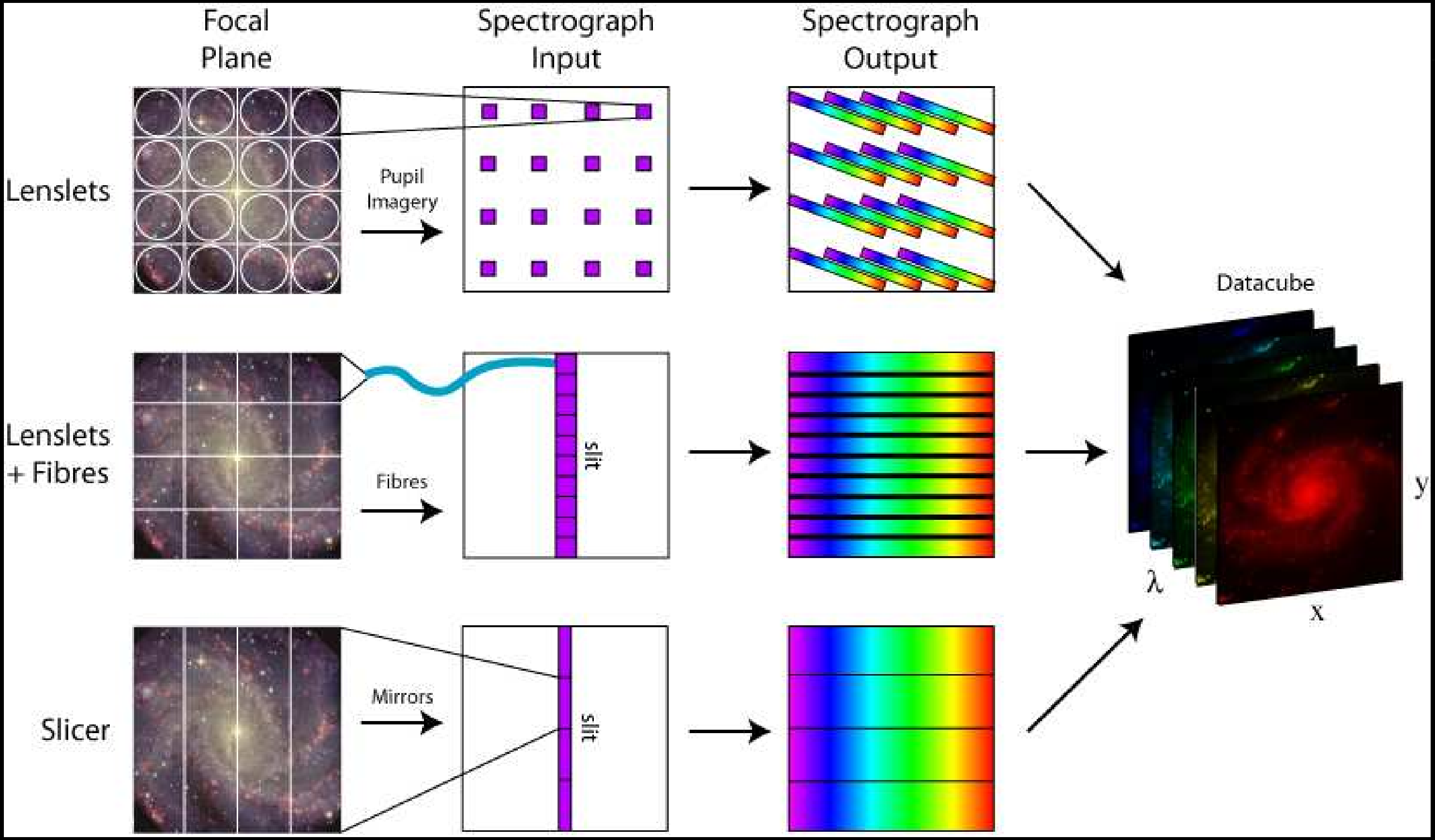



M51, [NII]-Hα

Methods of spatial sampling

Different sampling
of the FoV

Different usage
of the detector



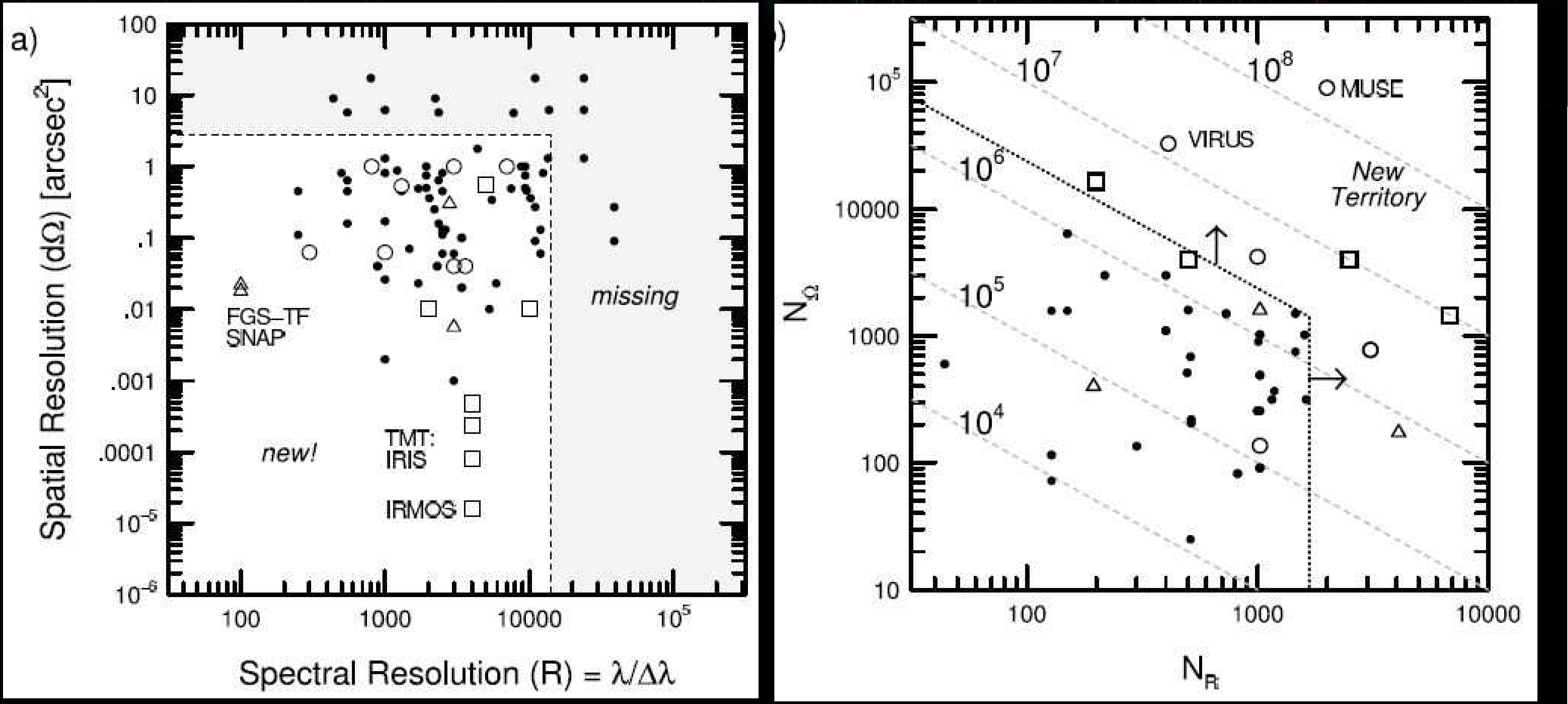
Allington-Smith et al. 1998

In any case, beware the overlapping of different dispersion orders on the detector!

Figure of merits

- Instruments are defined by
  - Spectral coverage Δλ and resolution element δλ
    - Spectral resolution R = λ/δλ
    - Spectral elements n = Δλ/δλ
  - Spatial coverage Ω and resolution element δΩ
    - Spatial elements N = Ω/δΩ
  - Collecting area A
    - Grasp ≙ A×Ω
    - Specific grasp ≙ A×δΩ
  - Total transmission ε
    - Etendue ≙ A×Ω×ε
- FoM is science driven
  - Spectral cov. vs. resolution
  - Spatial FoV vs. resolution
  - Spatial vs. spectral
  - Photon noise vs. sky noise vs. RoN/dark
  - MAKE YOUR CHOICE
- N×n = total nb of elements to be stored on the detector
  - Account for overheads
- See *3D Spectroscopic Instrumentation* (Bershady 2009arXiv0910.0167B)

FoM



Bershady 2009arXiv0910.0167B

Fiber-fed IFS

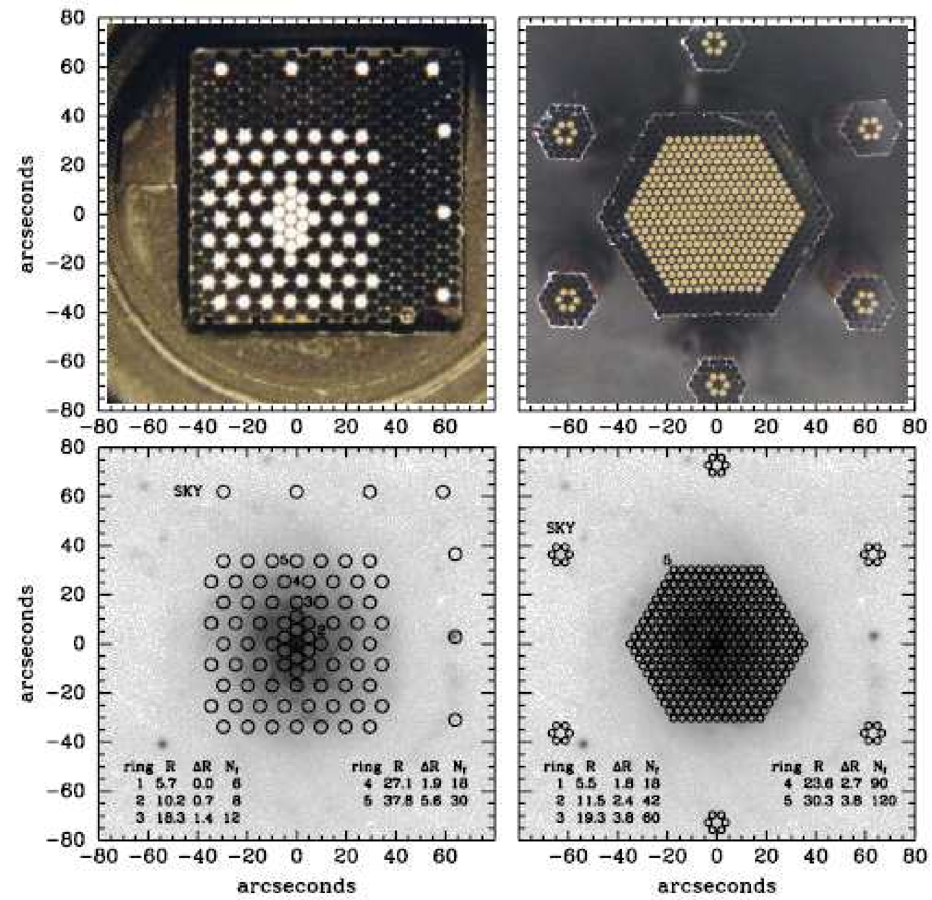
- Two possible couplings
  - Direct fiber coupling (DC)
    - Direct imaging
  - Frontend/backend MLA coupling (LC)
    - Pupil imaging
- Pros
  - Flexibility to "reformat" the field to match the spectrograph (e.g. pseudo-slit IFUs)
  - Efficient data packing (≈50%)
  - DC: Low cost, high throughput
  - FC: filling factor close to 100%
- Cons
  - DC
    - Focal Ratio Degradation (light loss/scattered light)
    - Incomplete fill factor (<65%)
    - Aperture effect
  - LC
    - Scattered light (MLA)
    - Lower throughput
  - Fiber transmission: not IR, not cryo, variable

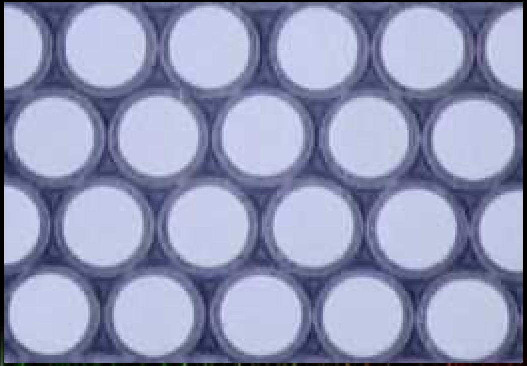
Fiber-fed IFS

- Notable examples
  - Direct coupling
    - PPAK (Calar Alto), VIRUS (HET)
    - SAMI (hexabundles)
  - Lenslet coupling:
    - PMAS (Calar Alto)
    - VIMOS & Flames-Giraffe (VLT), GMOS & CIRPASS (Gemini)

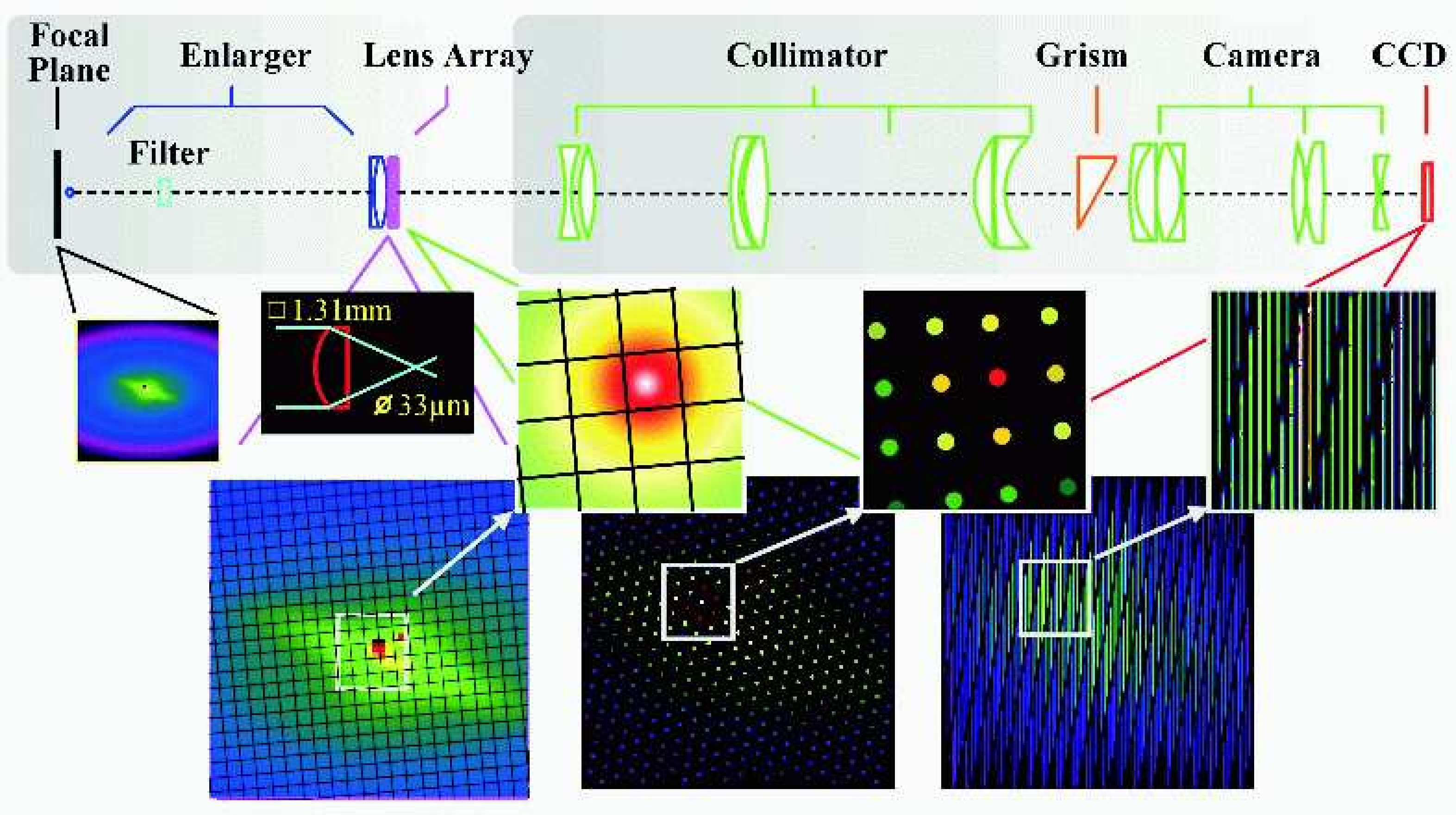
Fiber-fed IFS

- DiskMass survey
  - SparsePak (WYIN 3.5 m)
  - PPak (Calar Alto 3.5 m)
  - Bershady+ 2010ApJ...716..198B
- MaNGA (Sloan 2.5 m)
  - DC, fill factor of 56%
  - Drory+ 2015AJ....149...77D





Pupil imaging (MLA) IFS

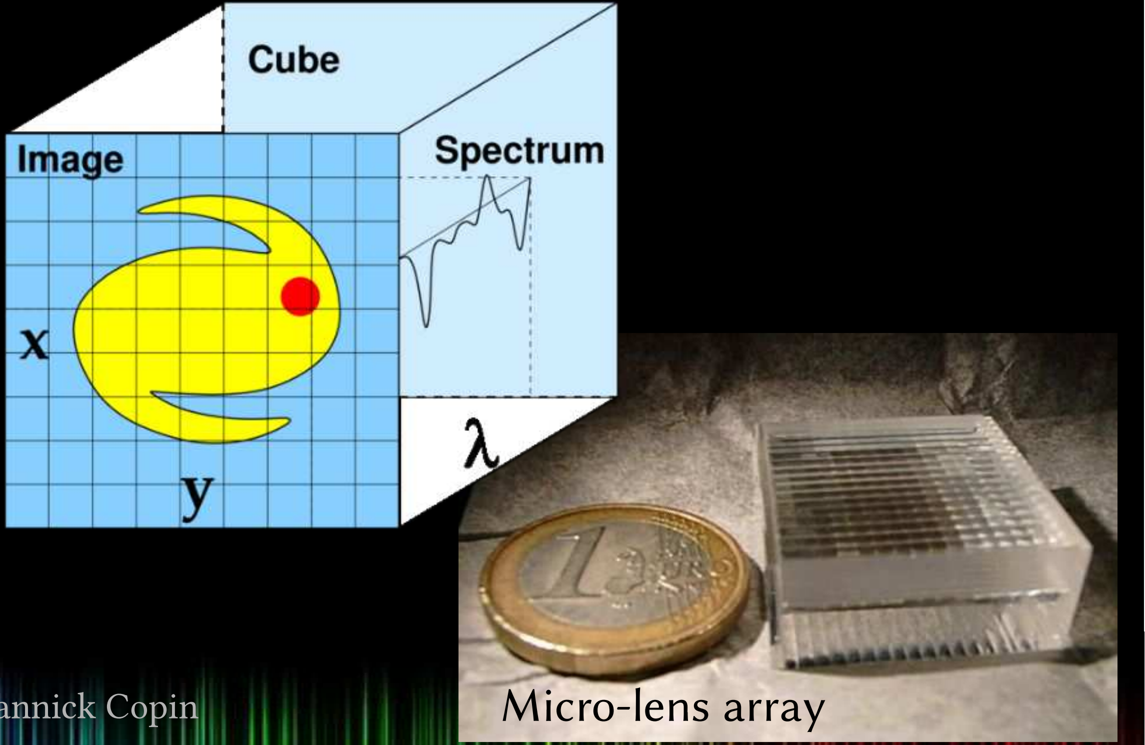


Pupil imaging (MLA) IFS

- Pupil imaging using Micro Lens Array
  - E.g. epoxy replicate or fused Si cross barrels
- Pros
  - Simple design, high throughput
  - Clean decoupling of spatial & spectral dimensions
- Cons
  - Inefficient data packing on detector ($\approx$25%) $\Longrightarrow$ small FoM
  - Complex data reduction from interlaced spectra (x-talk)
- Examples
  - Oasis/Sauron (WHT), SNIFS (UH)
  - Osiris (Keck)

SuperNova Integral Field Spectrograph

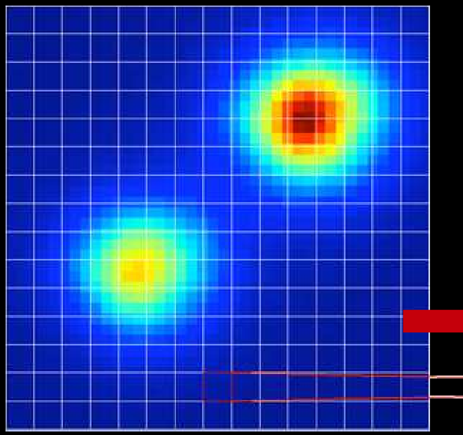
- Spectro-photometric goals
  - Spatial stage
    - 15×15 spx of 0"43
    - 6"4×6"4 field of view
  - Spectral stage
    - 2 spectroscopic channels
      - B: 320–520 nm @2.4 Å
      - R: 510–1000 nm @2.9 Å
  - Calibration unit
- Photometric channel
  - Target acquisition
  - Guiding
  - Atmospheric extinction
  - BVugriz imagery



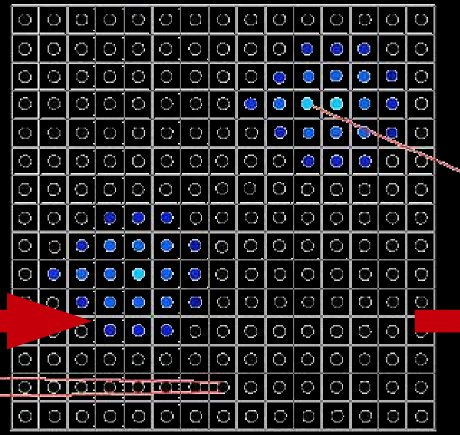
Micro-lens array

Optical design of SNIFS

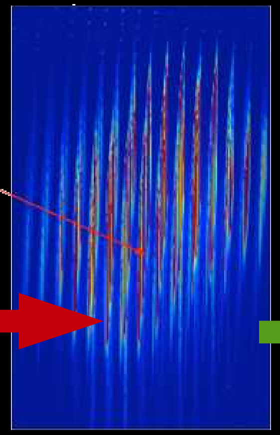
Focal plan
(0''43/spx)



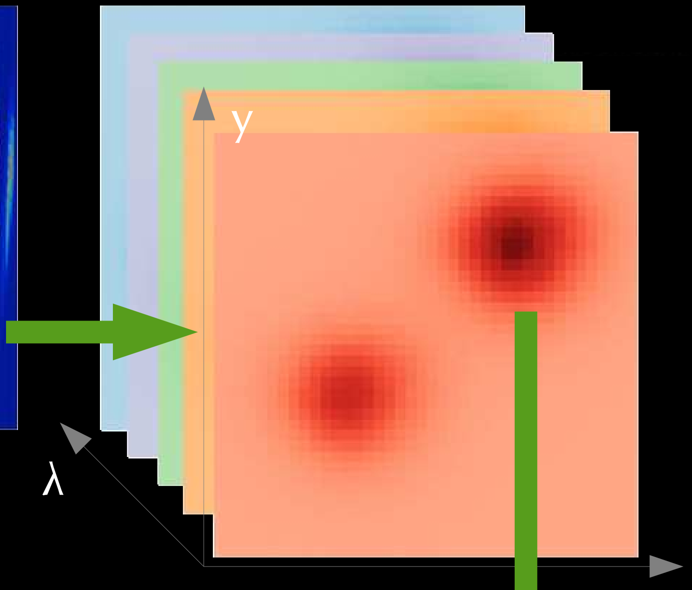
Spectrograph
entry

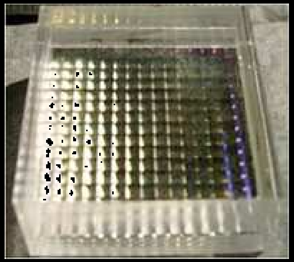


CCD
(225 spectra)

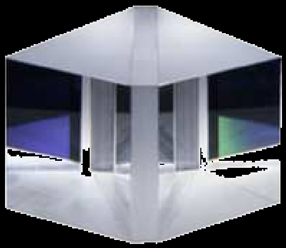


Cube
(x,y,λ)





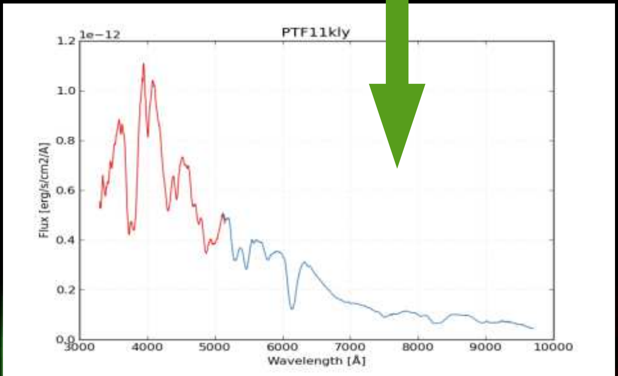
Micro-lens array
(15×15)



Spectrograph

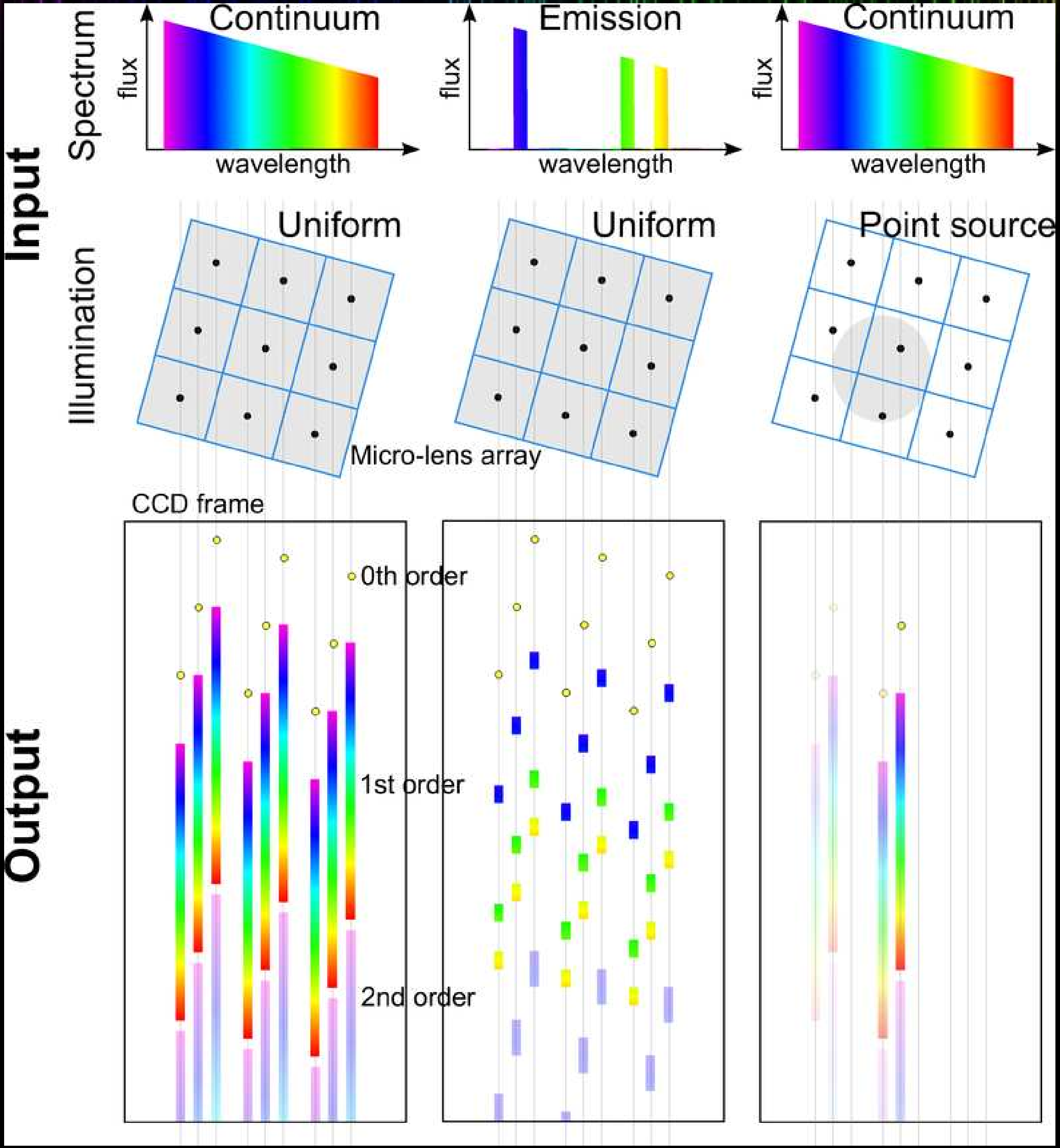
Point source
extraction

Flux calibration

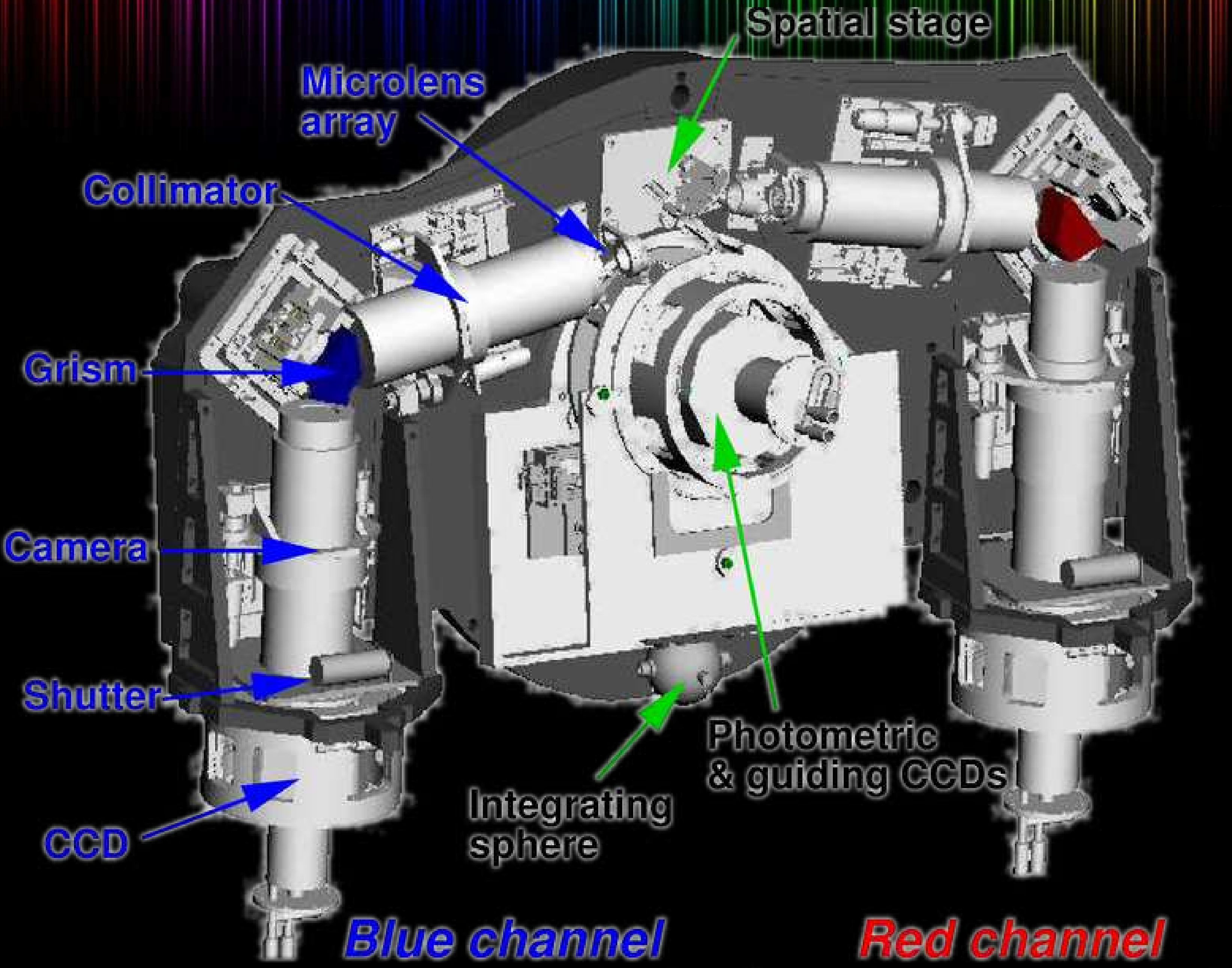


(Fig. C. Buton)

Structure of SNIFS frames



SNIFS mechanical design



SNIFS on UH 2.2 m telescope

- Permanently mounted on UH88 since '04 (900 nights!)
- Remote semi-automatic operations
  - Queue scheduling, virtual control room, AI support

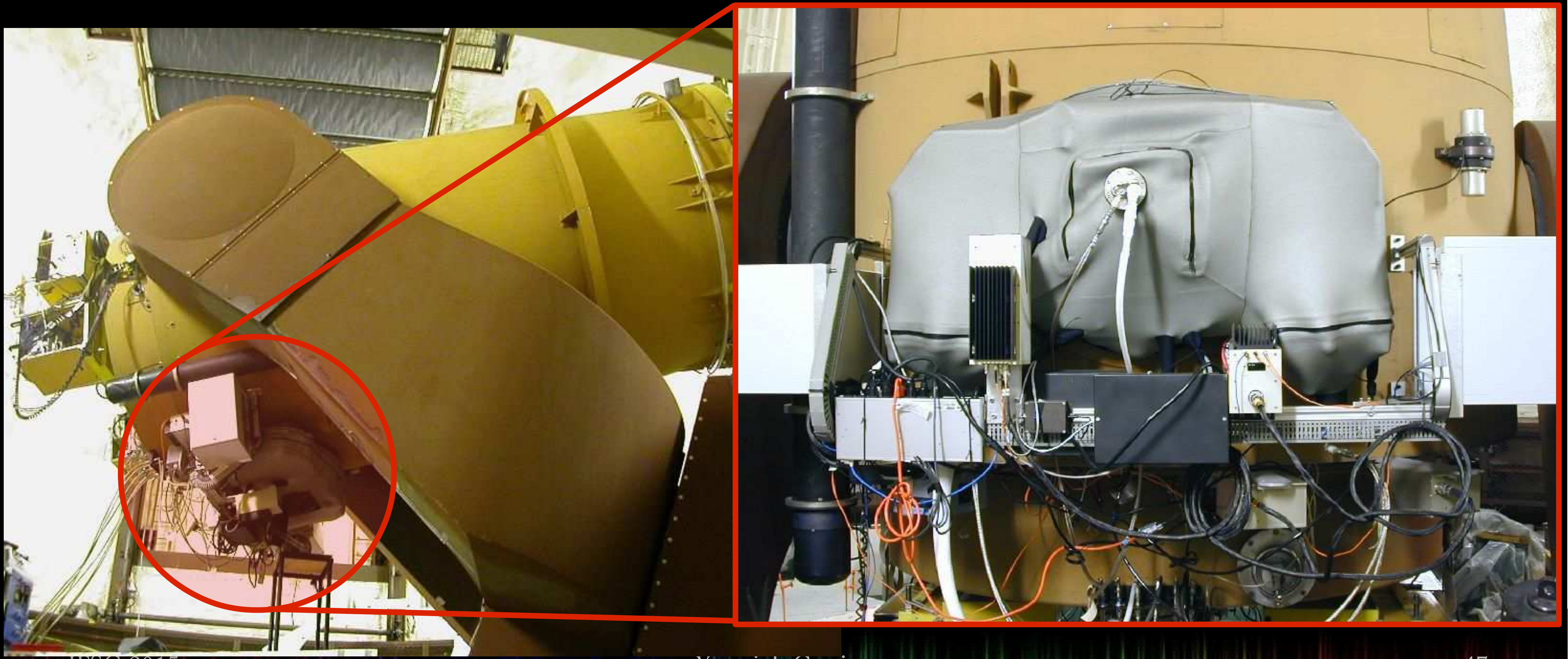
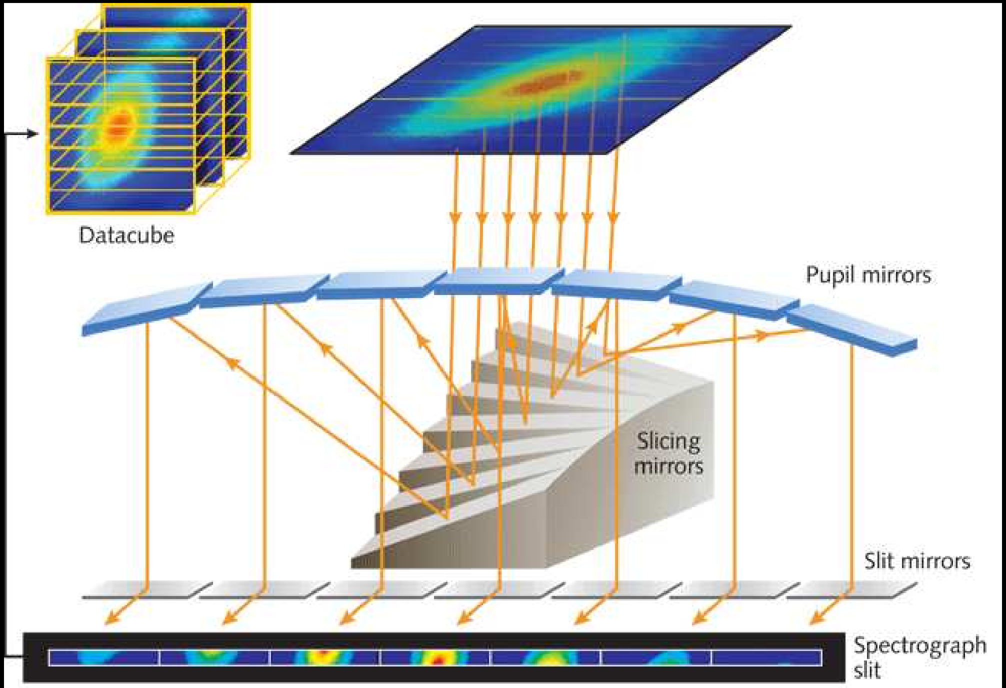


Image slicers

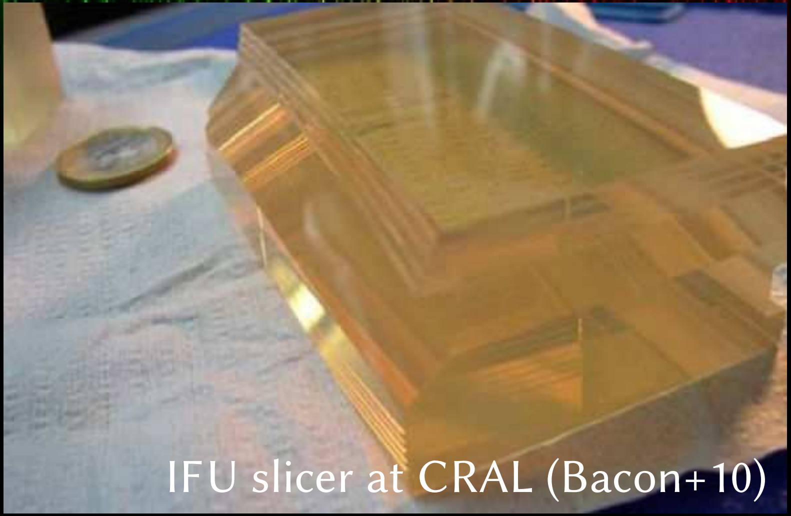
- Advanced Image Slicer
  - Slicer stack
  - Pupil imaging
- Pros
  - Compact design, potentially cryogenic (IR)
  - Very efficient use of detector
  - Can use all reflective optics (IR)
- Cons
  - Complex design of the slicer
  - x & y directions are not sampled the same way



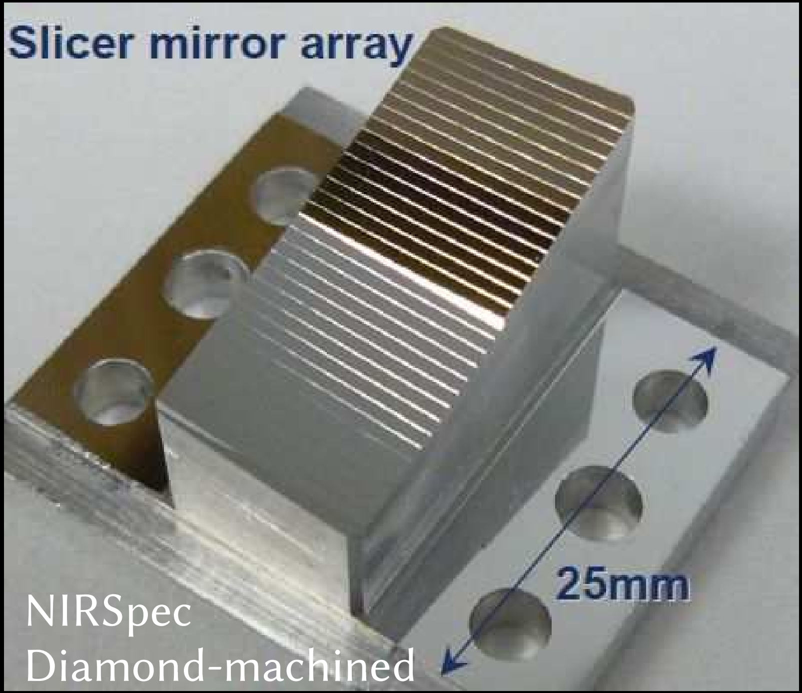
Durham Univ.

Image slicers

- Notable examples
  - FISICA (GTC)
  - SPIFFI, MUSE and KMOS (VLT)
  - *NIRSpec* (JWST, cryo)
  - *Harmoni* (E-ELT)

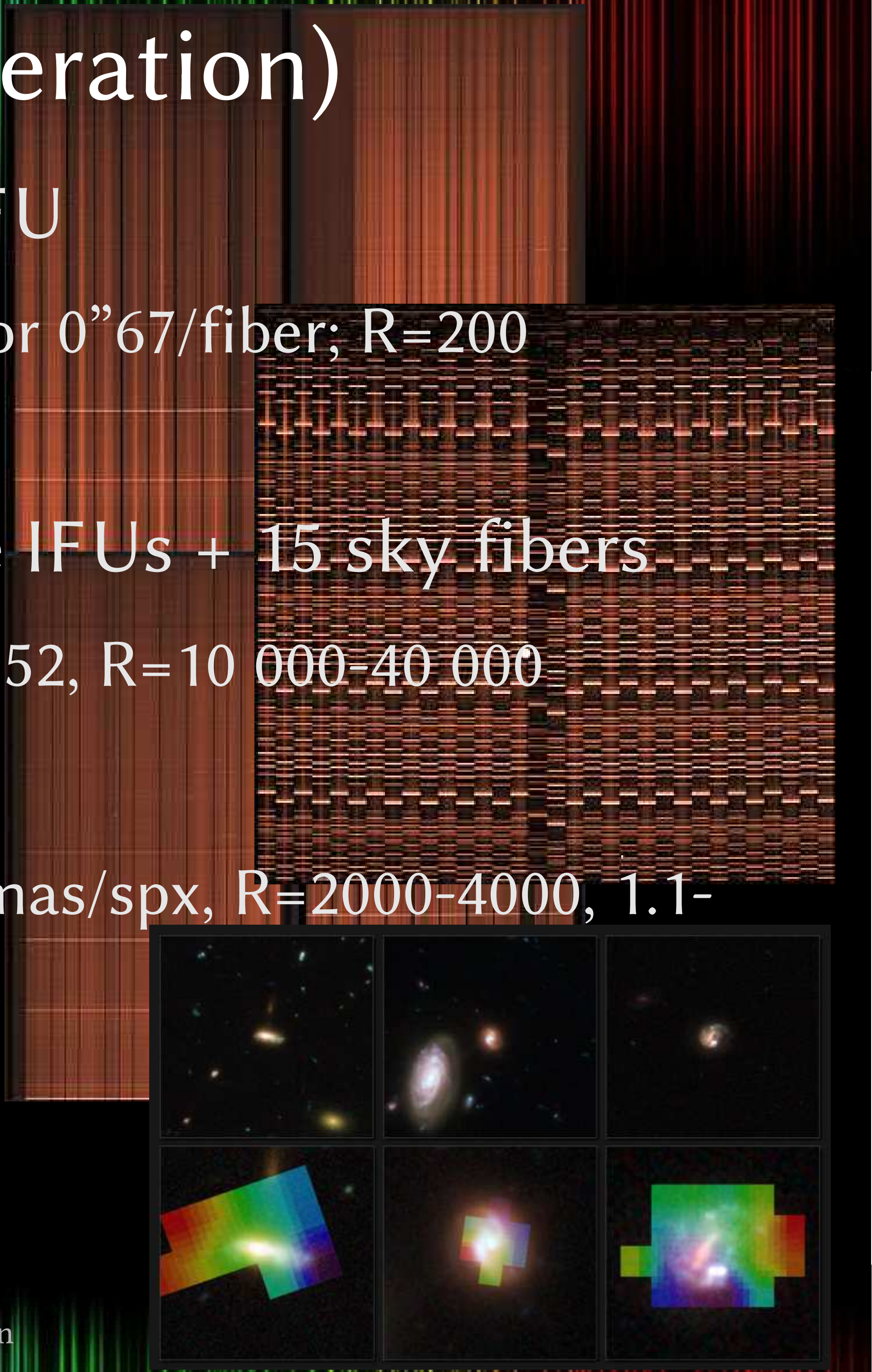


IFU slicer at CRAL (Bacon+10)



NIRSpec
Diamond-machined

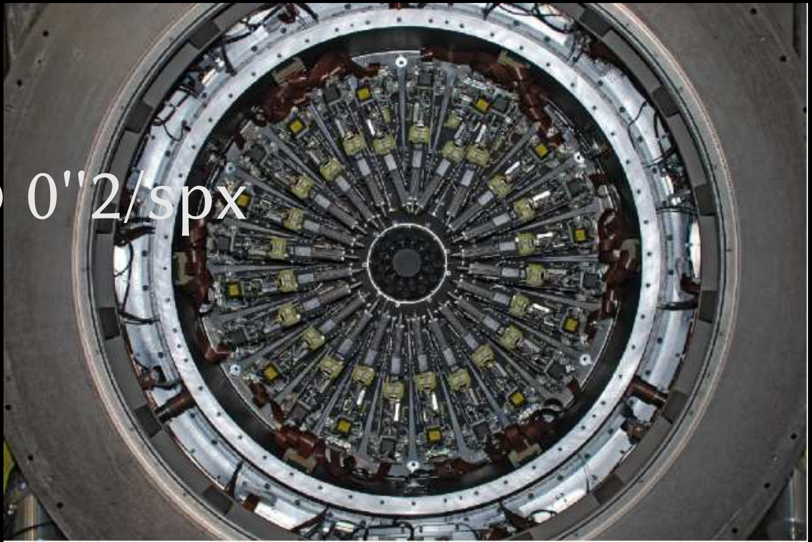
VLT (1st generation)



- **VIMOS**: massive fiber-fed IFU
  - LR: MLA + 6400 fibers @0”33 or 0”67/fiber; R=200
  - HR: 1/4th of the FoV, R=2500
- **FLAMES**-IFU: 15 deployable IFUs + 15 sky fibers
  - MLA + 20 fibers on 2"×3" @ 0”52, R=10 000-40 000
- **SINFONI**: AO + NIR IFU
  - Slicer 32×64 @ 250, 100 or 25 mas/spx, R=2000-4000, 1.1-2.45 µm

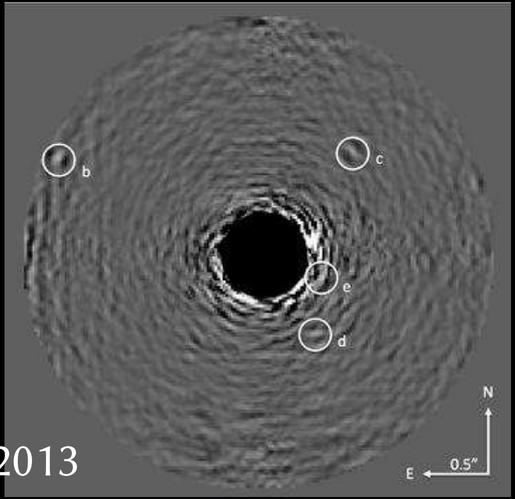
VLT (2^{nd} generation)

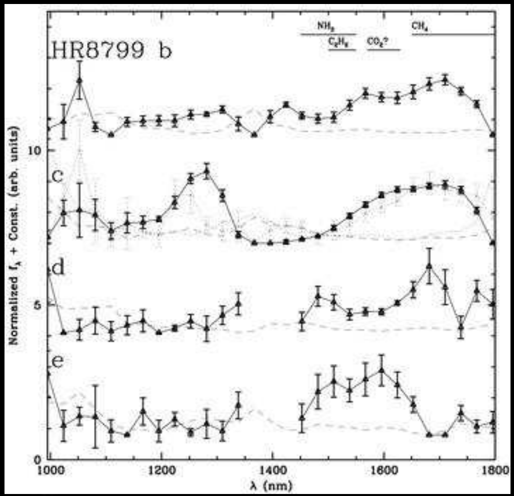
- **MUSE**: wide-field IFU
    - 24 image slicers
    - FoV 60"×60" @ 0"2/spx
    - R=3000, optical (480-930 nm)
    - HR-mode not yet functional
- **KMOS**: deployable IFUs
    - Fully cryogenic
    - 24 deployable slicers of 2"8×2"8 @ 0"2/spx
    - Patrol field: 7'2 diameter
    - R~3000, IR (0.8-2.5 μm)



5 m Hale Telescope (Palomar)

- **Cosmic Web Imager**: wide-field IFS (2009)
  - Image slicer ×24, 60"×40", R=5000, 370-950 nm
- **Oxford SWIFT**: AO-fed IFS (2009)
  - Image slicer, 10"×21" @0”23, R=4000, 0.65-1 µm
- **Project 1640**: AO + Lyot coronograph + IFS (2008)
  - MLA, 4"×4", R=45, 0.9-1.8 µm

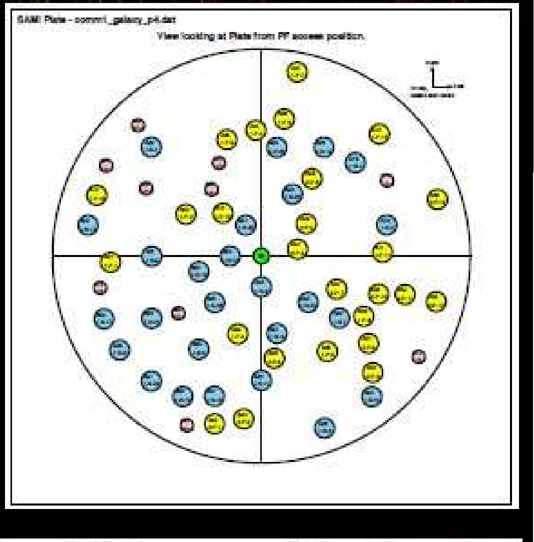




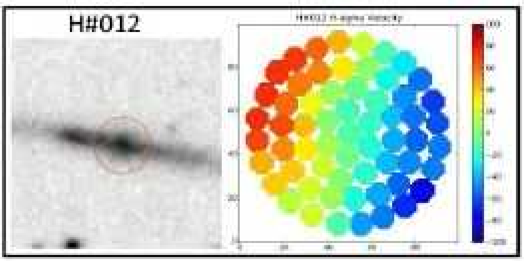
HR8799
Oppenheimer et al. 2013

SAMI

- Sydney-AAO Multi-object Integral-field spectrograph
  - ◆ “Giraffe mode”: fiber-based multi-object IFU
  - ◆ 13×61 fused hexabundles on a 1 sq.° FoV
  - ◆ Croom+ 2012MNRAS.421..872C



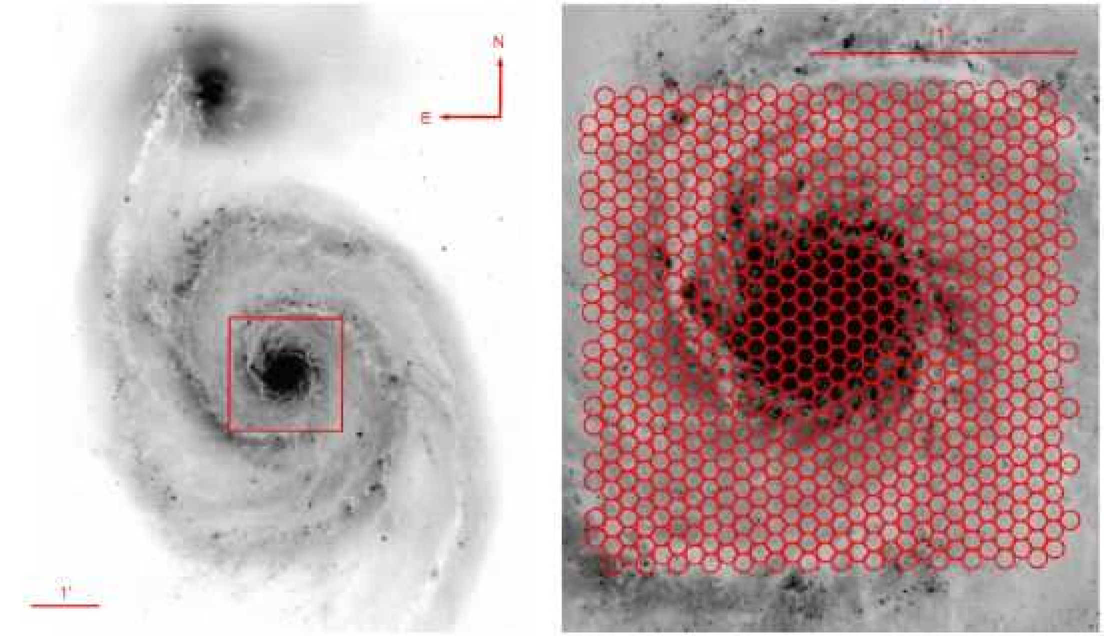
Bryant+ 2011MNRAS.415.2173B



- SAMI galaxy survey of ~3400 galaxies in 3 years
  - ◆ Bryant+ 2015MNRAS.447.2857B

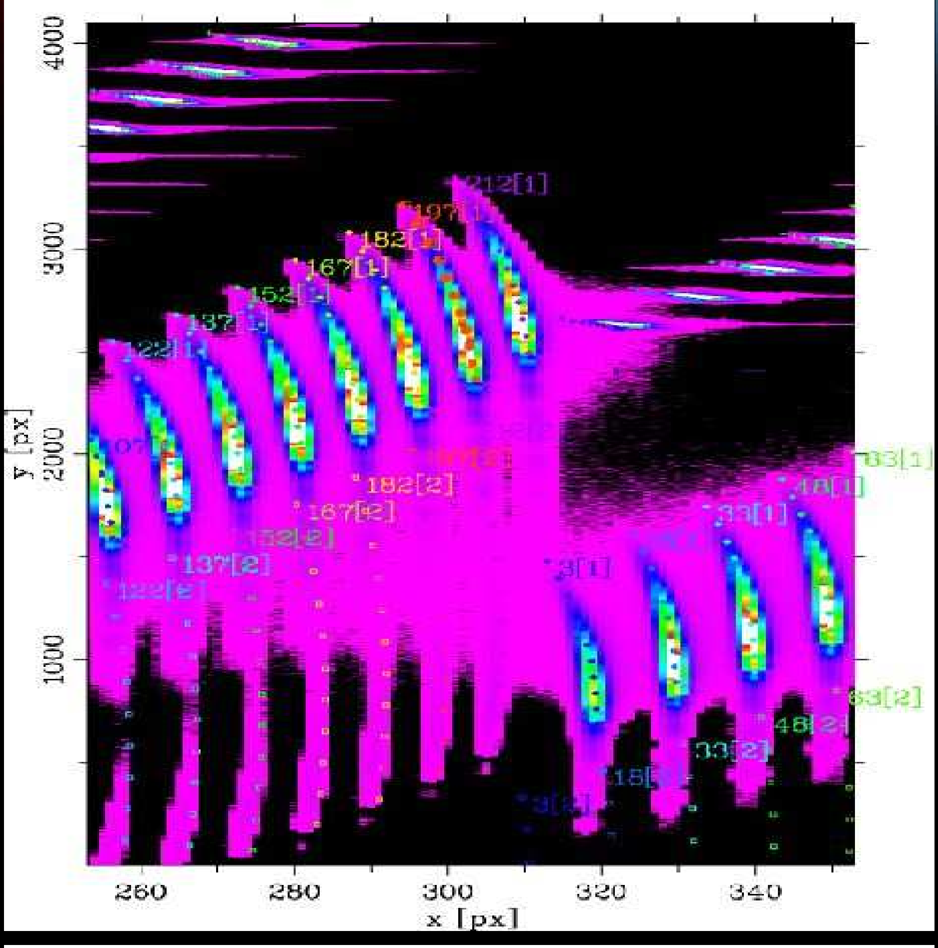
Hobby-Ederly 9.2m Telescope

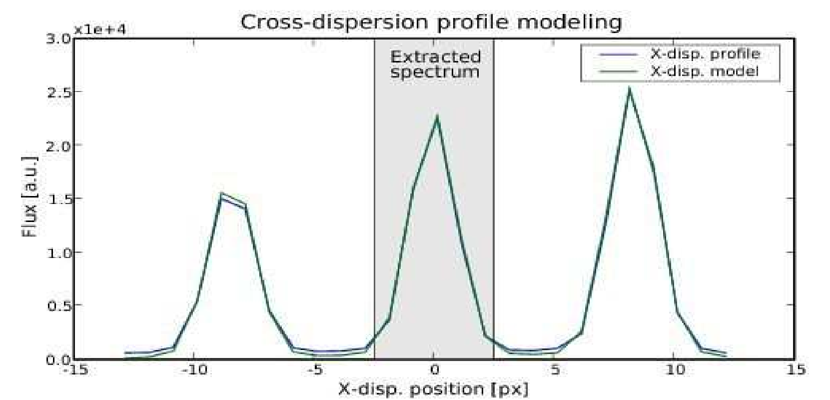
- McDonald observatory (TX)
- VIRUS-P: largest FoV (1.7' × 1.7')
  - VENGE, MASSIVE surveys
- VIRUS: massively parallel for HET Dark Energy Exp.
  - 156 channels, 34 944 fibers on 78 IFUs on 22' FoV



Algorithms

Cube reconstruction (e.g. SNIFS)





- CCD preprocessing
  - Beware of all subtle effects: bias/dark structures, non-linearity, CTE, etc..
- Diffuse-light subtraction
- Instrument optical model
  - Unbiased flux extraction
- Spectral calibration

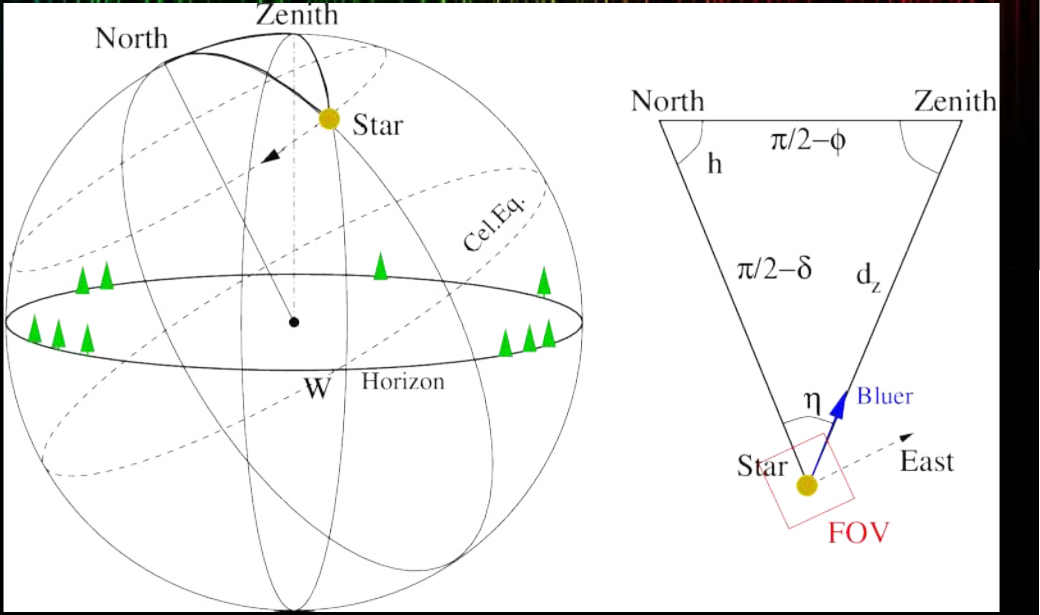
Control of biases at low flux levels

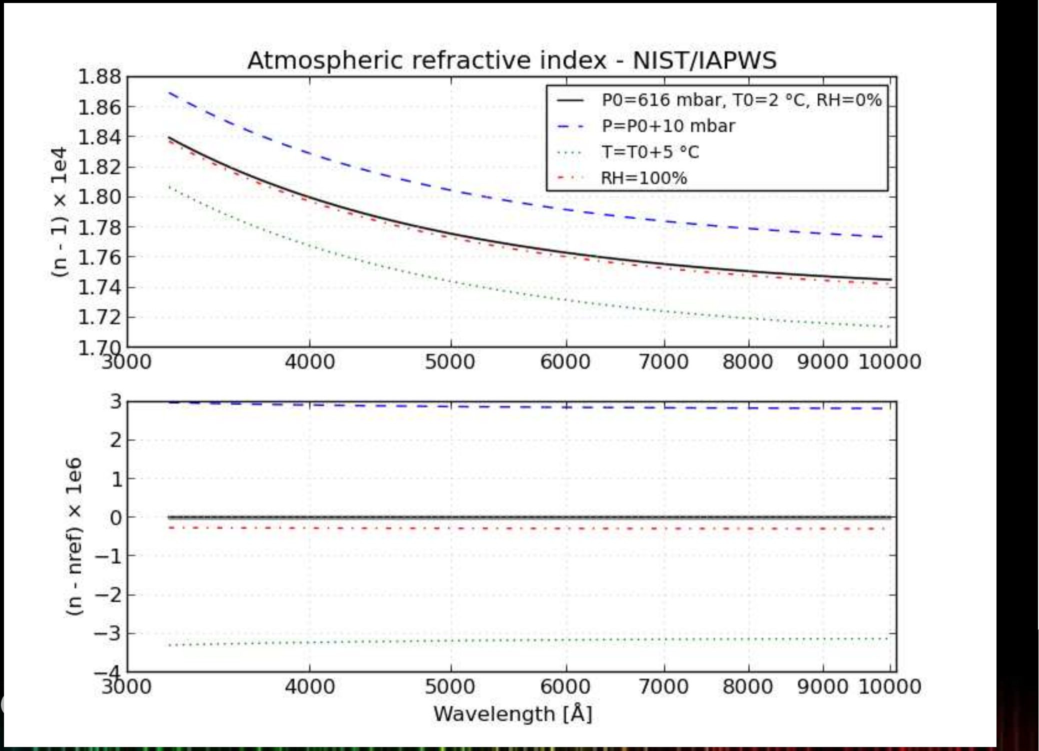
Cube calibration

- Wavelength solution (per spx)
  - Using internal arc spectrum and/or sky lines
- Flat-field
  - Detector level: px-to-px gain fluctuations, spectrograph vignetting
    - Beware: the gain is chromatic, a FF might be difficult to acquire
  - Spatial directions: spx-to-spx transmission fluctuations (fibers, MLA), telescope vignetting
    - Internal reference (integrated sphere), twilight
  - Spectral direction: chromatic instrumental transmission
    - Internal reference (continuum spectrum), per spx
- Cosmic rays
  - At detector level (2D, e.g. pyCosmic) or at cube level (3D)

Atmospheric Differential Refraction

- Dispersion by atmosphere
  - Refractive index n(λ, P, T, RH)
- 2 observational quantities
  - Airmass X ≈ $1/\cos(d_z)$
  - Parallactic angle η
- 0th-order atmospheric refraction usually handled by telescope
  - Targeting and guiding done in a spectral band, e.g. V
  - Telescope can include AR corrector
- ADR = 1st-order terms

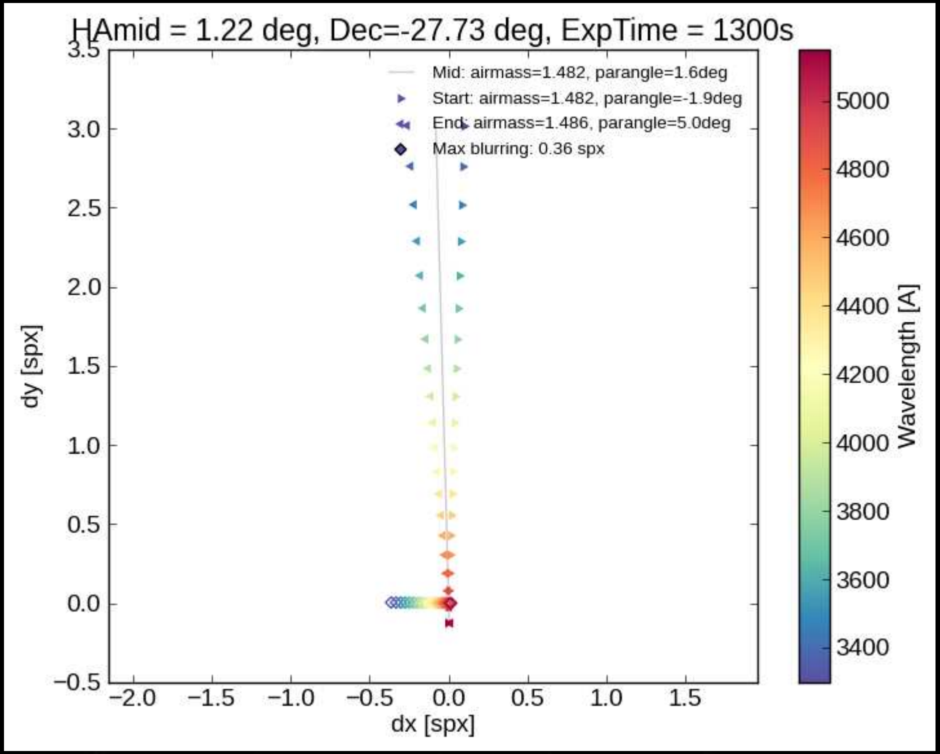




Atmospheric Differential Refraction

- 3 types of ADR
  - Chromatic: source position in FP is function of λ
    - Offset dx, dy function of λ
  - Temporal: source position in FP is function of t
    - Blurring as function of λ
  - Spatial: both effects are functions of position in FP
    - ADR(x, y) for large FoV
- Use effective quantities

- E.g.: SNIFS, 0"43 / spx
  - Chromatic: few spx
  - Temporal: sub-spx
  - Spatial: ~0 (FoV 7"×7")



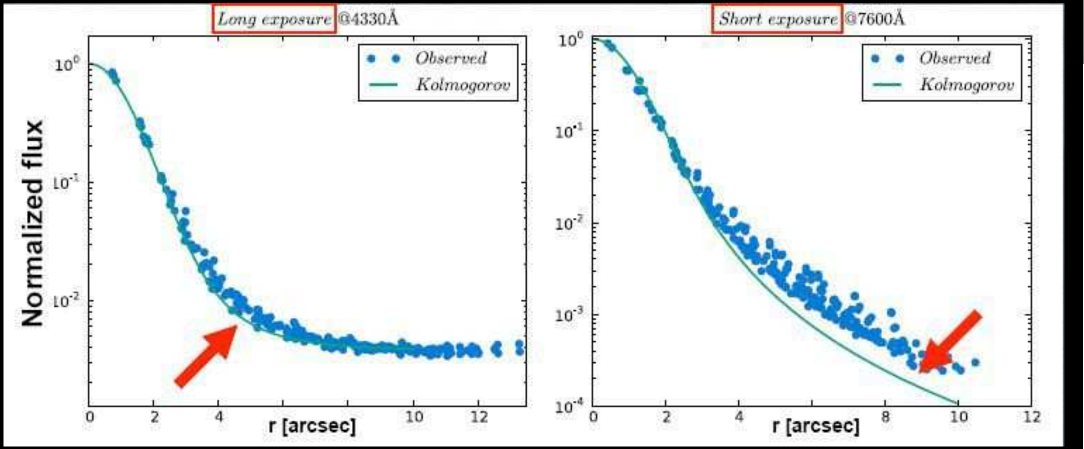
Sky background subtraction

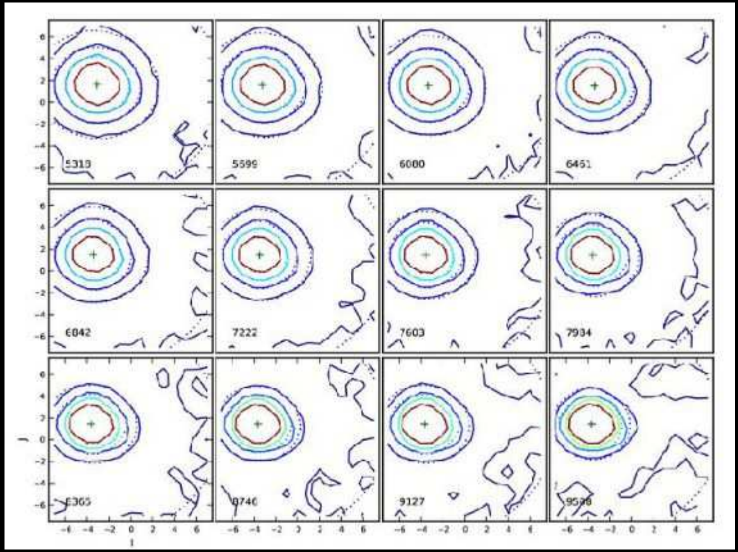
- Best option: dedicated fibers or spaxels
  - Complex optical design
- DANGEROUS: FoV areas supposedly free of signal
  - The background inaccuracy is amplified by source extent
- Modeling of the sky spectrum (e.g. PCA)
  - OK for emission lines, not really for sky continuum

3D PSF photometry

C. Buton (PhD 2009)

- FoV might be too small for accurate aperture photometry and sky subtraction
  - This is the case for 7"×7" SNIFS
- Standard Kolmogorov profile is probably not adapted
  - Existence of a large-scale diffuse component
  - Described in the Fourier space



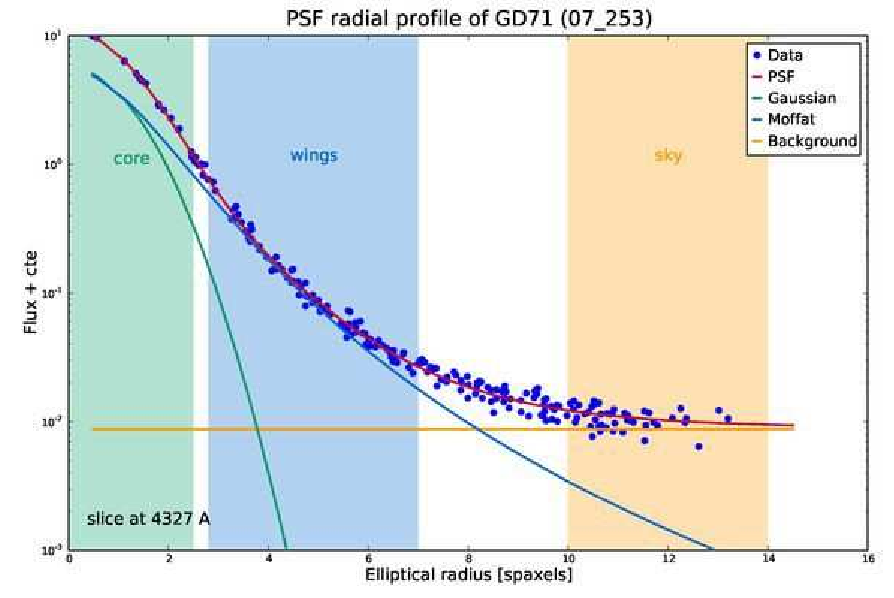


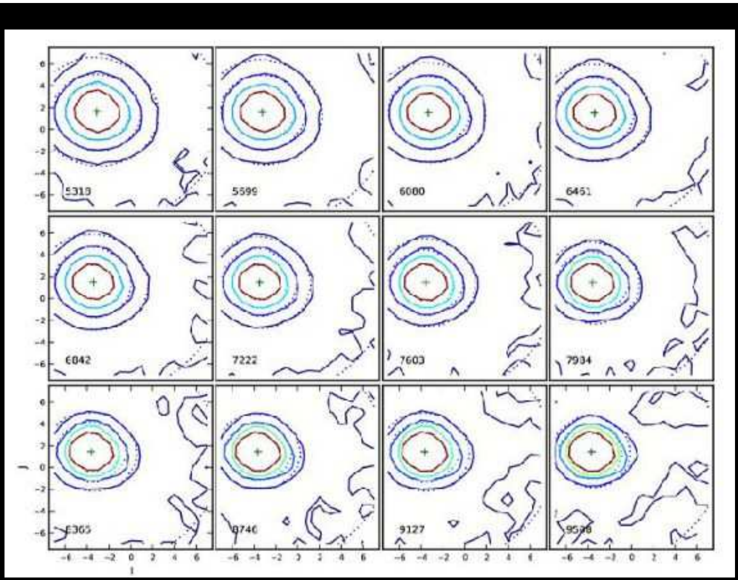
3D PSF photometry with SNIFS

C. Buton (PhD 2009)

- Empirical constrained Gaussian+Moffat model
  - Radial×azimuthal factorization
  - Trained on high-S/N standard stars
  - 2 shape parameters: “Seeing” & “focus/guiding”
  - Chromatic modeling: ADR, seeing(λ)

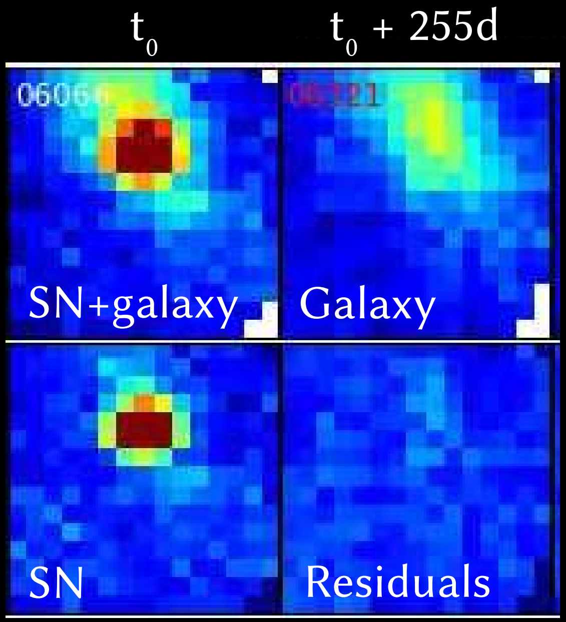
▸ Flux accuracy: 0.7–1.5%





Galaxy background subtraction (SNIFS)

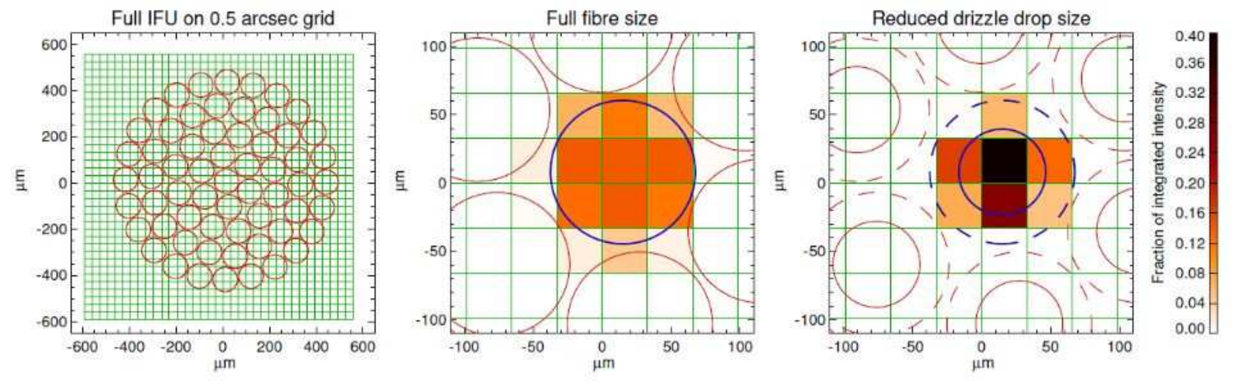
- PSF photometry applies to point sources without structured background: standard stars or SNe without significant host galaxy
- For SNe with galaxy: diffuse background subtraction
  - Construction of a galaxy model from 3D deconvolution
    - Use of reference exposures (once the SN has vanished)
    - Registration and PSF matching (seeing)



Bongard+2011

Dithering & mosaicking

- Dithering: moving FoV by fraction of px/spx
  - Can circumvent spatial under-sampling (which is never good...)
  - Initially developed for HST imaging
    - Drizzle, 2002PASP..114..144F
- Applicable to 3D spectroscopy
  - Sharp+ 2015MNRAS.446.1551S
- Beware: resampling (ADR, dithering) induce covariant errors!



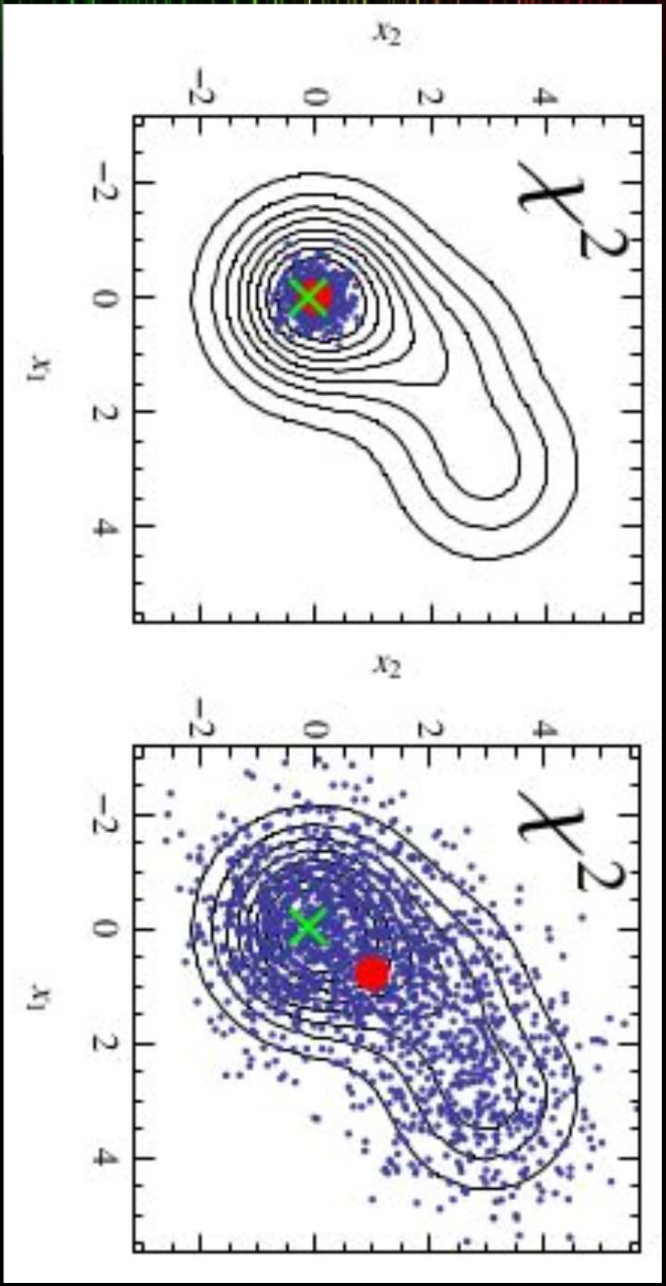
Increase S/N

Should you try to increase the Signal/Noise?

- Nothing is free: it will decrease the nb of independent measurements
- Forward modeling: directly model the observations
  - χ^2 or maximum likelihood, Bayesian estimates
  - A precise knowledge of noise properties is crucial
  - *The less you manipulate the data, the better*
  - **NO**
- Backward modeling: model quantities derived from observations
  - Sometimes a minimal S/N is required
  - **MAYBE**

Minimal S/N

- High S/N or linear model
  - χ^2 is (reasonably) quadratic in the parameters
  - MLE are unbiased
- Low S/N and non-linear
  - Quadratic approximation does not hold anymore
  - MLE are biased
- There's a minimal S/N requirement
  - It depends on your science



Cappellari 2009arXiv0912.1303C

Smoothing vs. binning

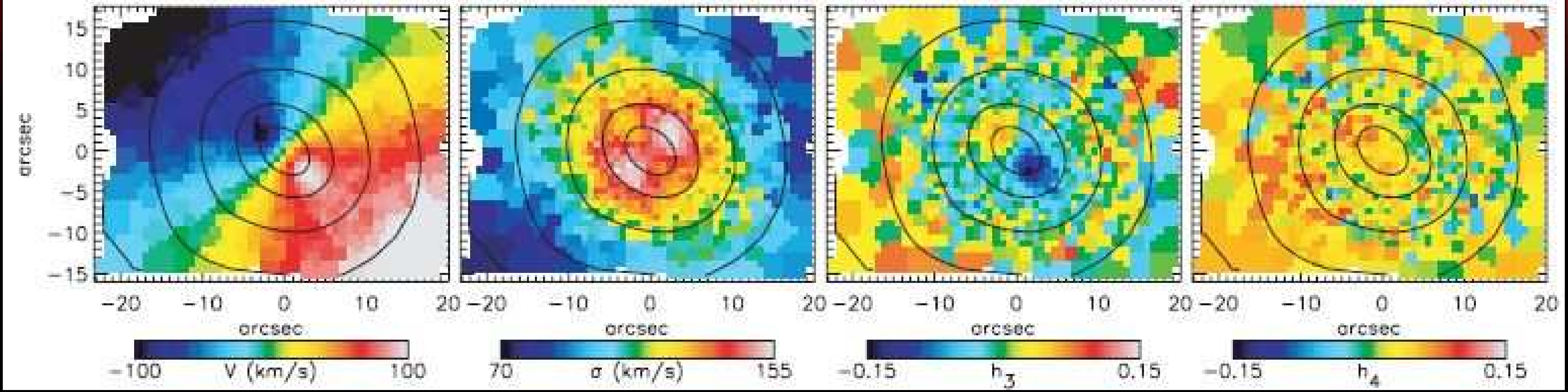
How to increase Signal/Noise ?

- Smoothing: introduce correlation and *usually ignore it afterwards...*
  - Boxcar filtering, Gaussian convolution, etc.
  - **DON'T DO THIS**: false sense of improvement!
- Binning: explicitly regroup data in adjacent bins
  - Bins are (at least as) independent (as before)
  - Easy to implement in 1D
  - Trickier for higher dimension: ensure tessellation and compactness
- Adaptive scheme
  - Preserve resolution while requesting minimal S/N

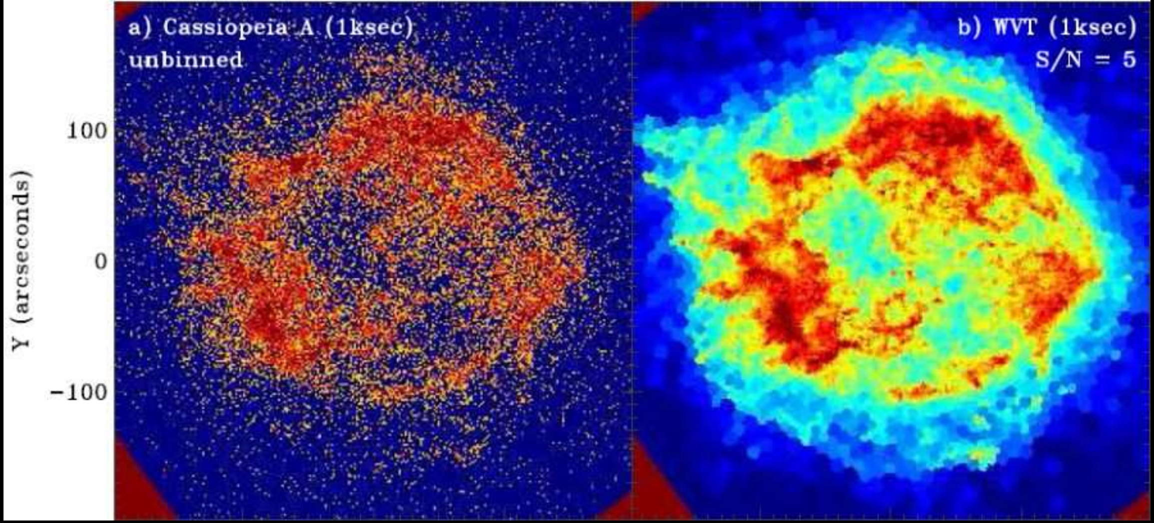
Voronoi binning

- Cappellari & Copin 2003MNRAS.342..345C
- Very general objectives
  - Topological: proper tessellation (no hole nor overlap)
  - Morphological: as compact bin as possible
  - Uniformity: obj. fun. (e.g. S/N) as constant as possible
- Two steps
  - Bin accretion: describe bins as from the seeds of a Voronoi Tessellation
  - Bin regularization: build a Centroidal or Weighted Voronoi Tessellation
- Reference implementation in IDL/python

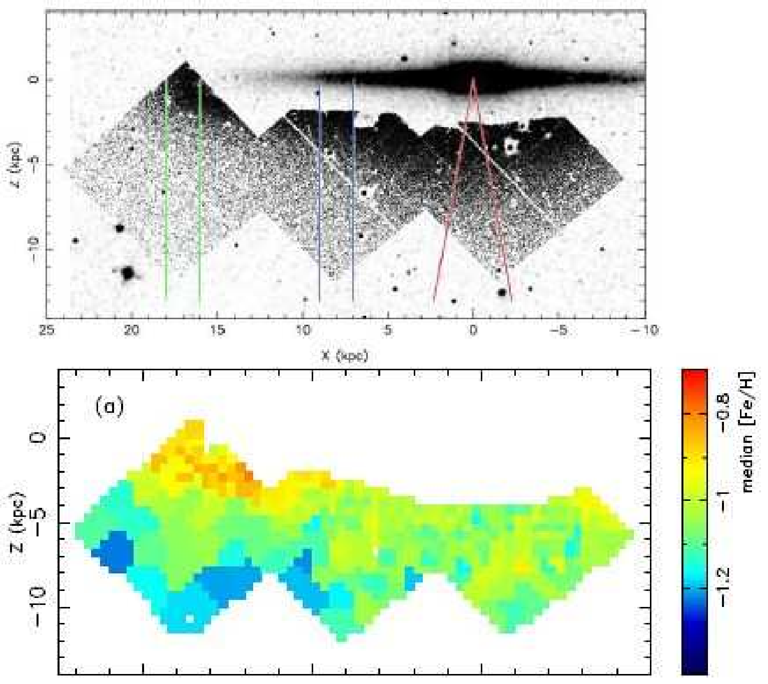
Voronoi binnings



Cappellari & Emsellem 2004PASP..116..138C



Diehl & Statler 2006MNRAS.368..497D



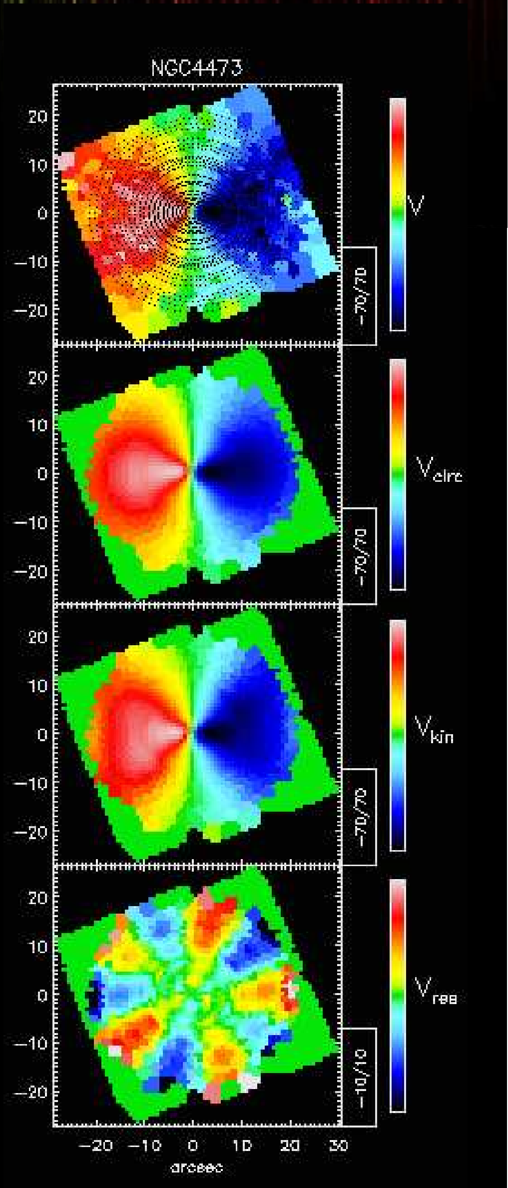
Ibata+ 2009MNRAS.395..126I

Photometry & kinematics

- Galaxy dynamics
  - Core quantity: distribution function $f(x, y, z, v_x, v_y, v_z)$
- Resolved observations = integral along the LoS
  - Photometry: $\mu(x,y) = \int f\, d^3v\, dz$ = 0th order
    - Modeling (e.g. GalFit): radial profile, flattening, PA, etc.
  - LOSVD: $L_{x,y}(v_z) = \int f\, dv_x\, dv_y\, dz$
    - Complete kinematic information
    - $\bar{v}$: 1st-order moment
    - $\sigma, h_3, h_4, \ldots$: higher orders
- Kinemetry = quantify kinematic maps
  - Copin 00, Krajnovic+ 2006MNRAS.366..787K

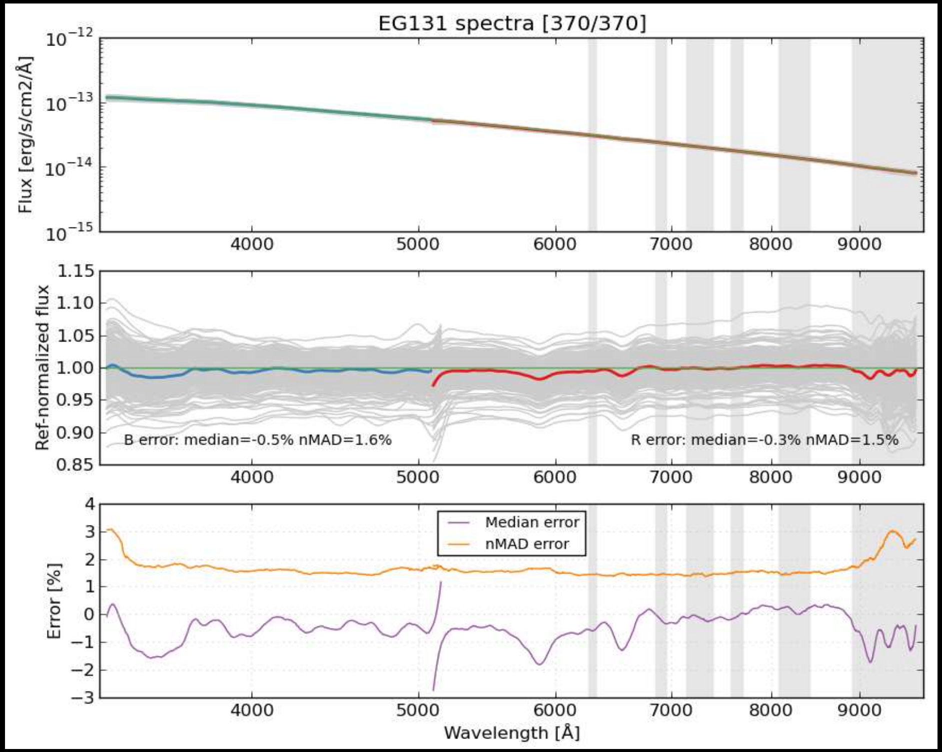
Kinemetry

- Basically a Fourier expansion of the kinematic fields in polar coordinates
  - E.g. $v(r, \varphi) = v_0 + \sum_i v_i \cos(\varphi - \varphi_i)$
- Two main usages
  - Quantify kinematic fields
    - Kinematic angle, twists
    - Kinematically Decoupled Core
  - Enforce specific symmetries
    - E.g. 2-integral Jean models are symmetric



Spectro-photometric accuracy (SNIFS)

- From comparison to reference flux tables of std stars
  - UBVRI: 25 mmag (RMS)
    - P: 21 mmag, NP: 28 mmag
    - nMAD: 18 mag
  - B-V: 10 mmag (RMS)
- A lower bound
  - High flux regime (V<14)
  - No galaxy subtraction
- Standard star network at the mmag level
- SNIFS Calibration Apparatus



Data format

- Traditional FITS
  - NAXIS=3 “true” cube (x, y, λ)
    - Ease of use: each slice is an image, each spx is a spectrum
    - Only for evenly sampled square spaxels OR require resampling
      - TRY NOT RESAMPLING your cubes prior to analysis!
      - WCS can help to manage spatial/spectral distortions
  - Euro3D format (Kissler-Patig+ 2004AN....325..159K)
    - Pure Multi-Extension FITS file
    - Spaxel-oriented: no need for resampling
- HDF5
  - Very versatile format, efficient IO

Conclusions

IFS pros and cons

- Pros
  - High multiplexing
  - Management of ADR
  - Full spectro-spatial PSF
    - Clean spectro-spatial disambiguation
  - Synthetic measurements
    - Binning, PSF photometry, …
    - Synthetic photometry is K-correction free
  - Ease-of-use (e.g. targeting)

- Cons
  - "Complex" data treatment, format and analysis
  - Scattered light from spatial dissector (MLA, slicer)

It all depends on your science case!

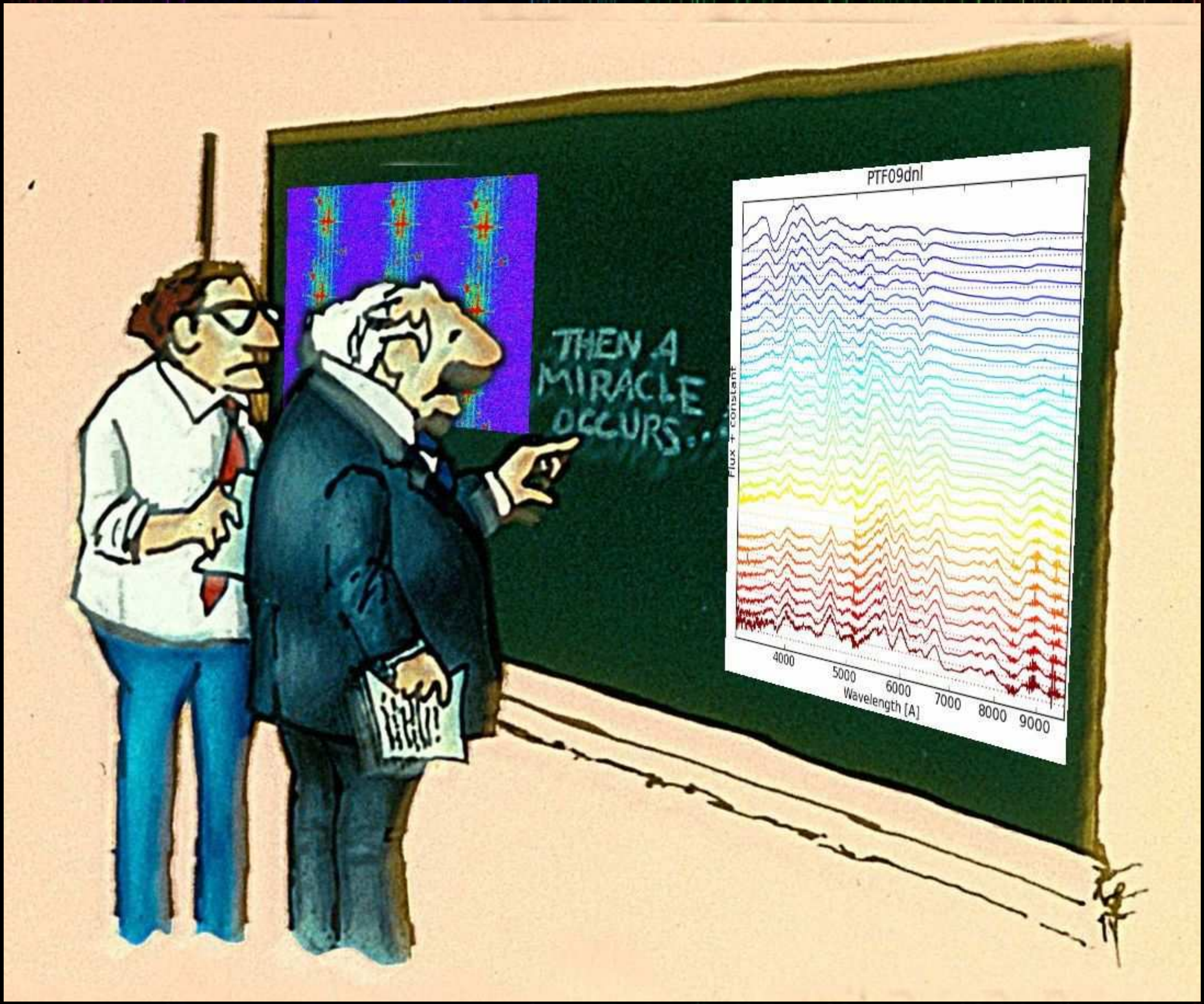
Look at your science case

- Your science case should drive your choice
  - Think the science objectives, express your technical constraints, find the best instrumental setup
  - IFS are most probably a good choice, but consider alternatives: slitless spectroscopy, MOS, imagery
- Be rigorous, trust statistics and respect Shannon
- Think out of the box
  - "Step back and think" is sometimes more efficient than "focus and work"
- Don't reinvent the wheel, improve the rocket!
  - Contribute to open source softwares

The future of IFS

- Related activities
  - X-rays: X-IFU on Athena X-ray Observatory (2028+)
- Transverse/upcoming technologies
  - Hyperspectral imagers: multi-band imaging
    - Impressive performances in geoscience, medical imagery, etc.
    - Not used in astronomy, yet? (SED machine)
  - Integrated astro-photonics
    - Stationary-Wave Integrated Fourier Transform Spectrometer (2014SPIE.9147E..29B)
    - Photonic Lantern/Arrayed Waveguide Gratings (2013MNRAS.428.3139H)
    - Binary optics: integrated diffractive optics (MLA)
  - Energy-sensitive detectors
    - Multi-layer detectors (e.g. commercial FOVEON X3)
    - Superconducting Tunneling Junction (R=10–100 in optical)

3D spectroscopy in few words



Project

https://dl.univ-lyon1.fr/995sivtoh4