Integral Field Spectrography

Techniques & Specifics

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Menu

- **Historical perspective**
  - 1D – 2D – 2.5D and 3D
- **Basics of 3D spectroscopy**
  - Techniques and examples
- **Specifics**
- **From sky to cubes**
  - Basic principles
- **A (short) word on *Softwares***

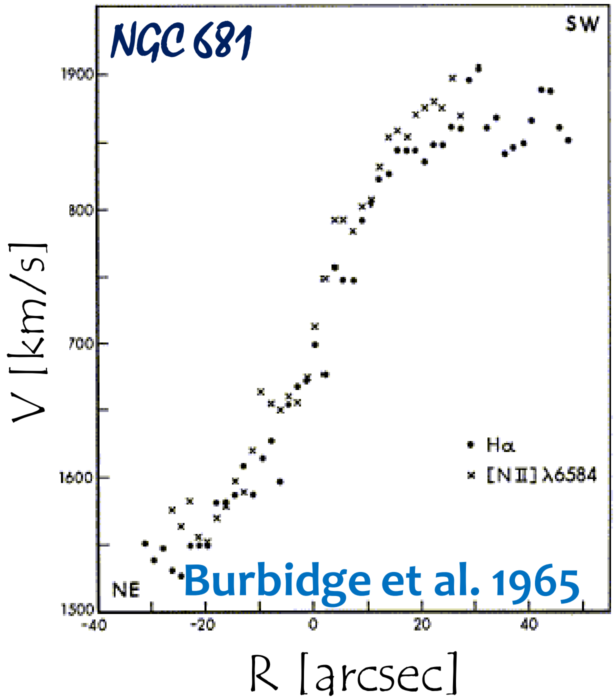
- **Concluding remarks**

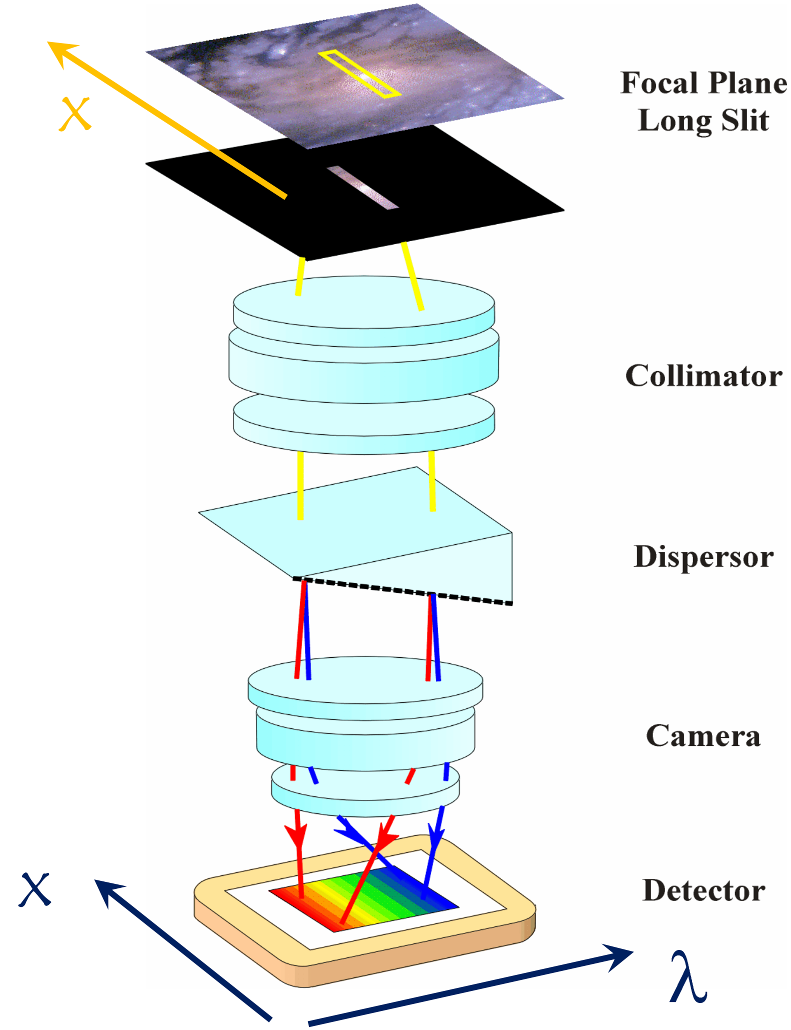
3D Spectrography

Historical perspective

From 1D to 2D

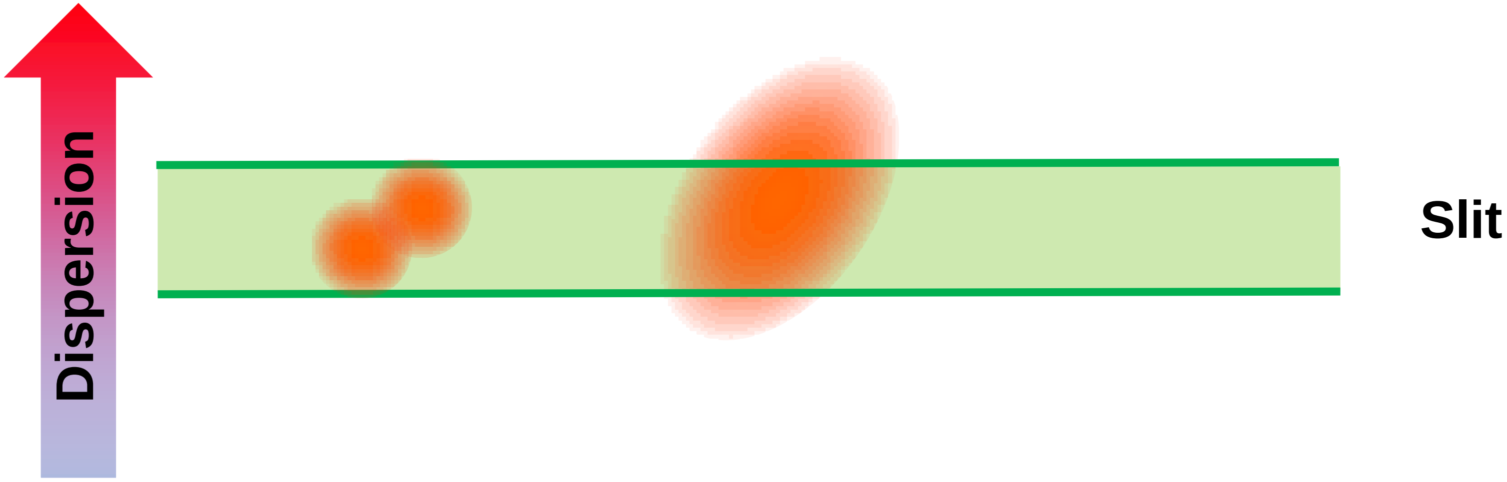
- Aperture spectrometry → Long-slit spectroscopy
- Efficient use of
  - 2D photographic plates
  - CCDs
- « Easy » data reduction





Why is 2D not enough ?

- Morphology of real object rarely follows slit geometry
- Centring on the target
- Light losses
- The slit effect
- Spectral resolution depends on the slit itself



How to squeeze 3D in 2D ?

- **Modern detectors are 2D (optical, near-infrared)**

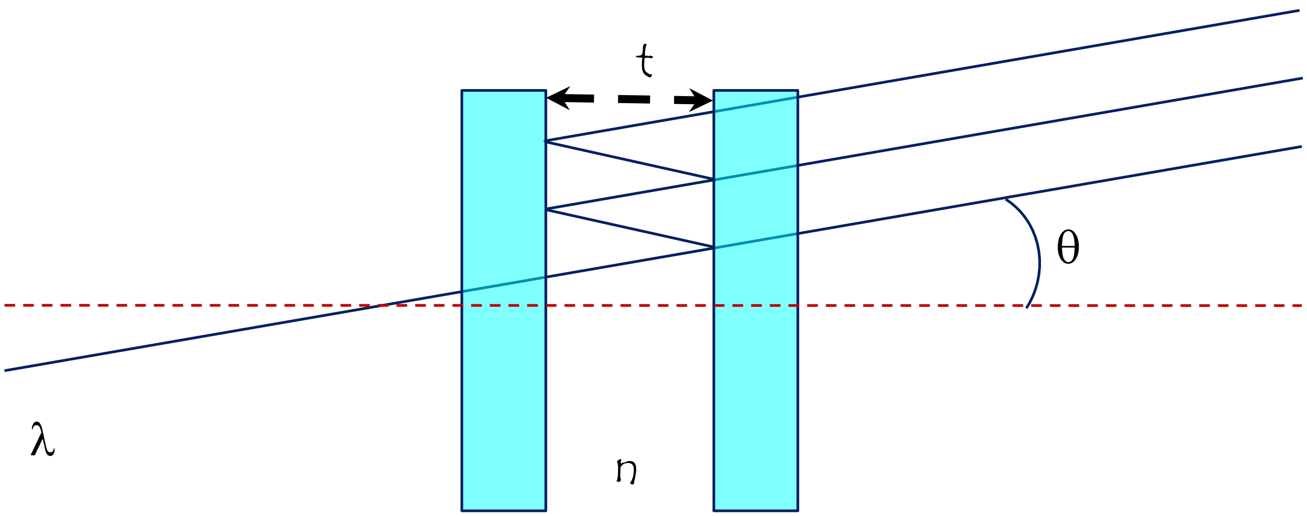
- **We can thus either fix one spatial or one spectral dimension and scan with time:**
  - Fabry-Perot interferometers
  - Scanning long-slit spectrographs

- **But also:**
  - Fourier Transform spectrometers
  - Hadamar Transform spectrometers (masks)

Fabry-Perot interferometers

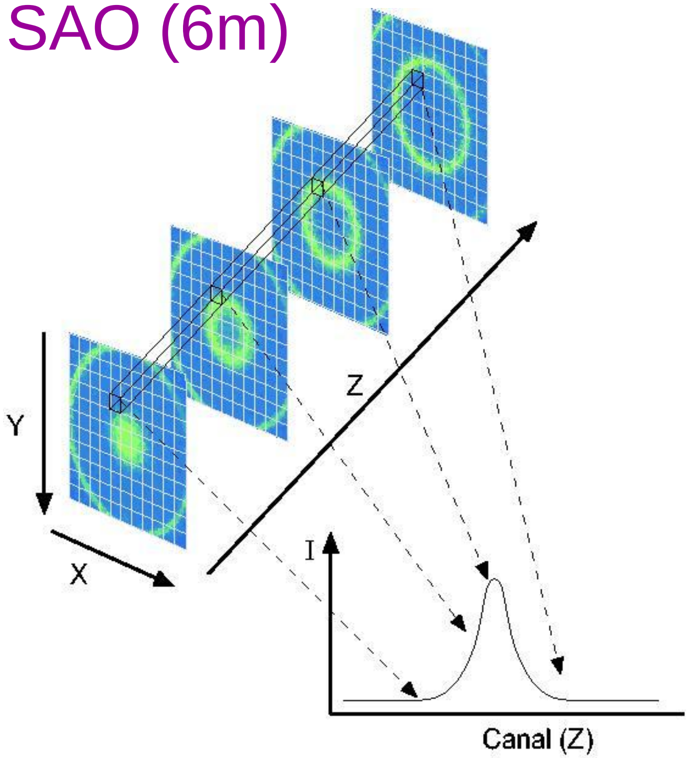
- **A Fabry-Perot etalon acts as a interference filter:**
  - **Incidence θ**
  - **Wavelength λ**
  - **Index n**
  - **Inter plate t**

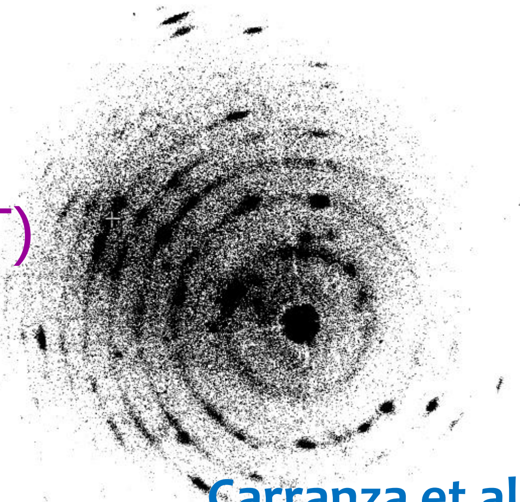
Fabry & Perot 1901, ApJ 13, 265



Fabry Perot interferometers

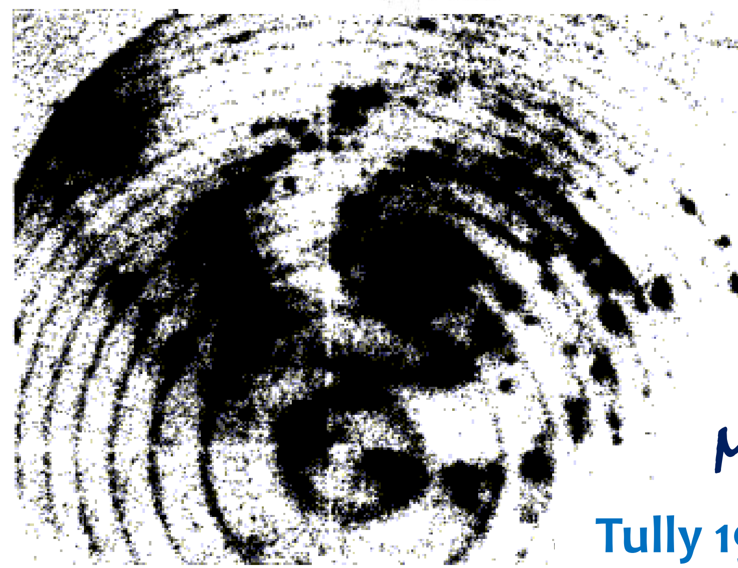
- Tough data reduction (but doable)
- Very efficient for emission lines!
  - TAURUS (AAT, WHT), HIFI (CFHT)
  - CIGALE (➔ 3D NTT)
  - SAO (6m)





M33

Carranza et al. 1968



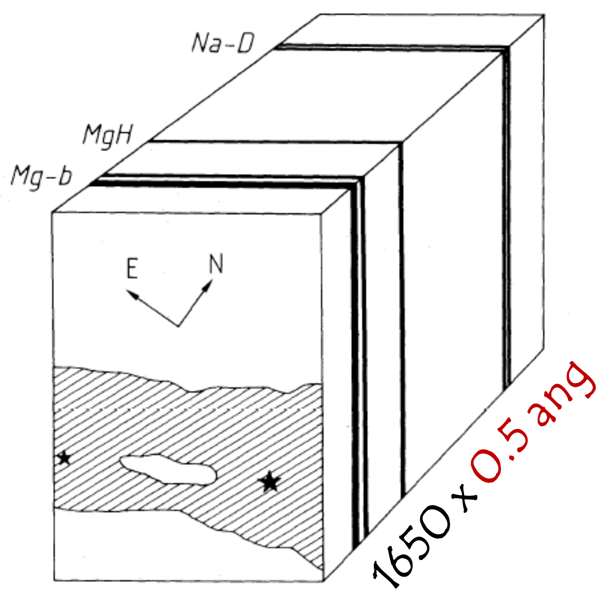
M51

Tully 1973

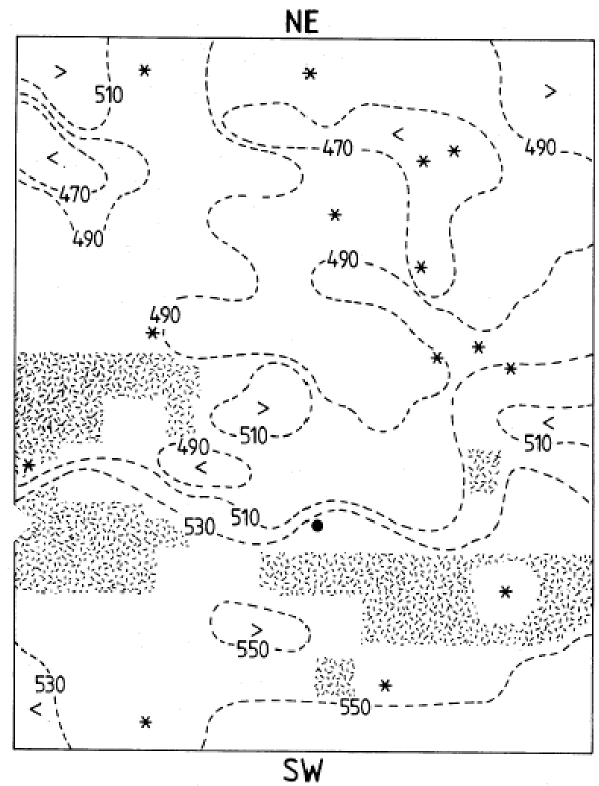
Scanning: more space

- FPs limited to single emission lines
- Not ideal to tackle continuum + absorption lines
- Problem of TIME scanning:
  - what about long-slits?

71 x 2.4 arcsec



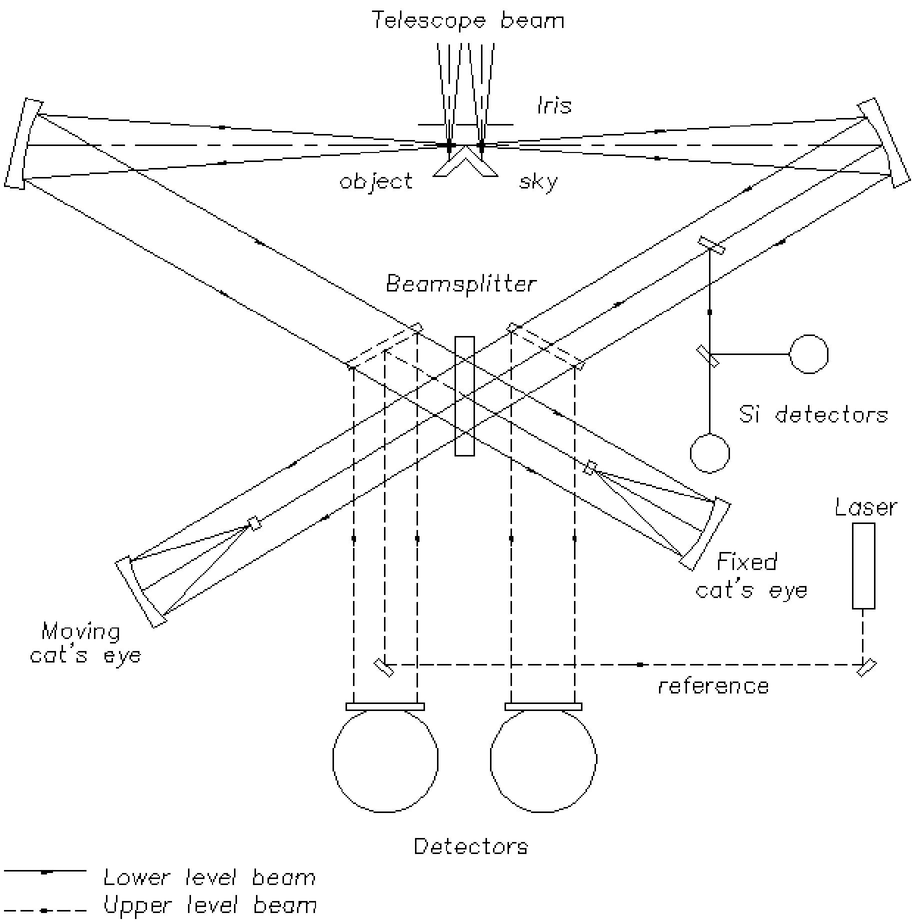
61 x 2.2 arcsec

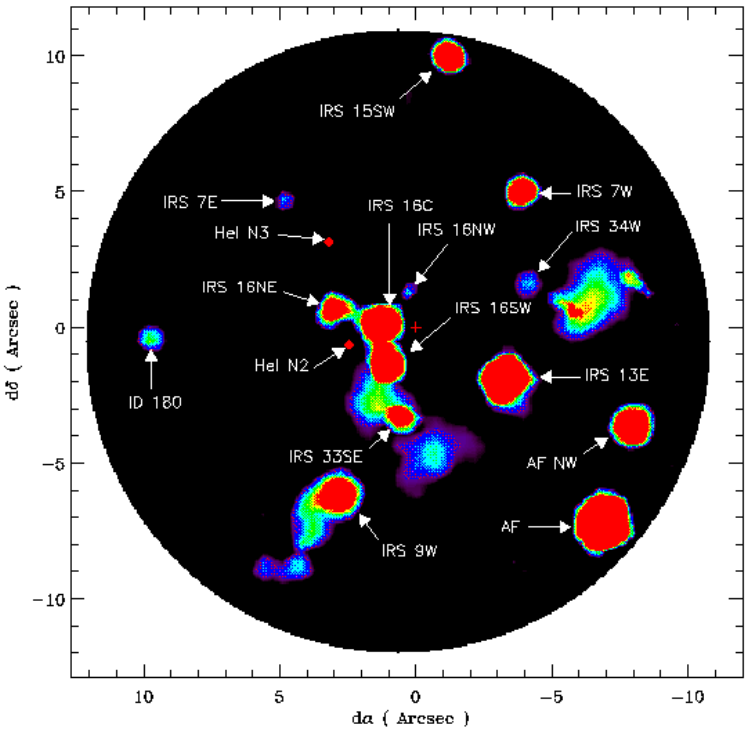


Wilkinson, A. Sharpless, R.M., Fosbury, A.E.M., Wallace, P.T. (1986)
“ Stellar Dynamics of Cen A ” MNRAS 218, 297

Fourier transform spectrometer

- **Frequency scanning:**
  - Bear at CFHT: 2 arms interferometer





The Galactic center
(Maillard, Paumard)

Scanning with time

- **Problems linked with the scanning:**
  - **Variation of the observing conditions**
    - **Data characteristics & controls ?**
  - **Accuracy of positioning to rebuild the 3D data**
  - **Need of relatively bright objects**

➔ **Inhomogeneities in the reconstructed datacubes**

3D Spectroscopy

The Dawn of Speciation

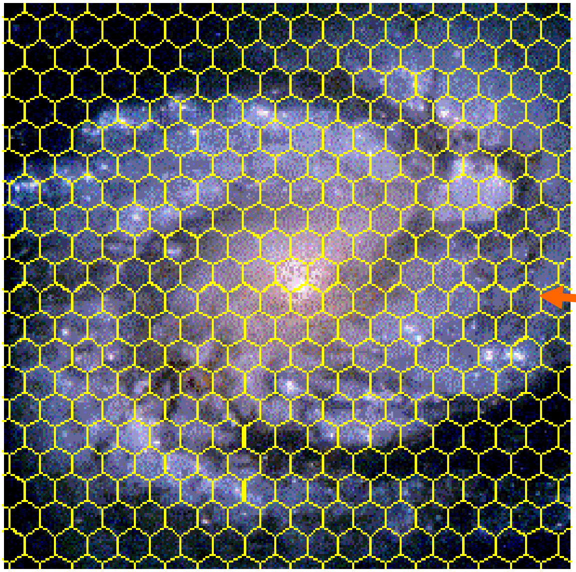
On the way to real 3D

- **1960's : aperture photometry to long-slit**
  - Wide spectral range
- **1970's: Fabry Perot interferometers**
  - Large field of view, but narrow spectral range

- **1980's:**
  - advent of modern CCDs
  - New ways to split the field
    - Using Fibers
    - Using micro-lenses
    - …

Advantage of true IFUs

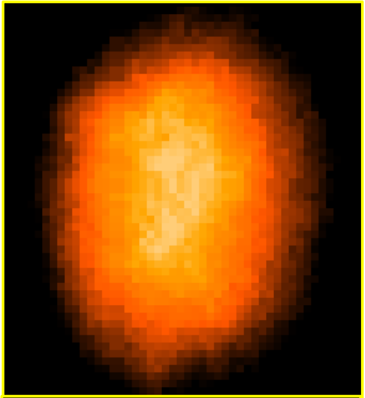
- **Large spectral range (but smaller FOV than FPs)**
- **Multiplex advantage**
  - Save telescope time (not necessarily)
  - Homogeneous data (?)
  - Spatial location and PSF can be measured a posteriori
- **Spectrophotometry !**

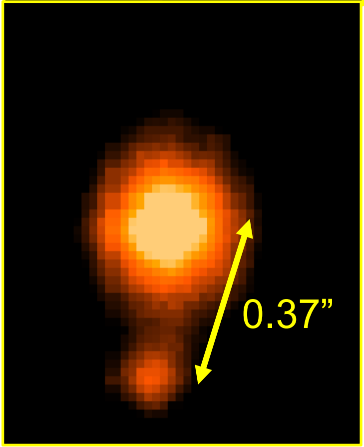


Spaxel

Optical/Near Infrared spectroscopy

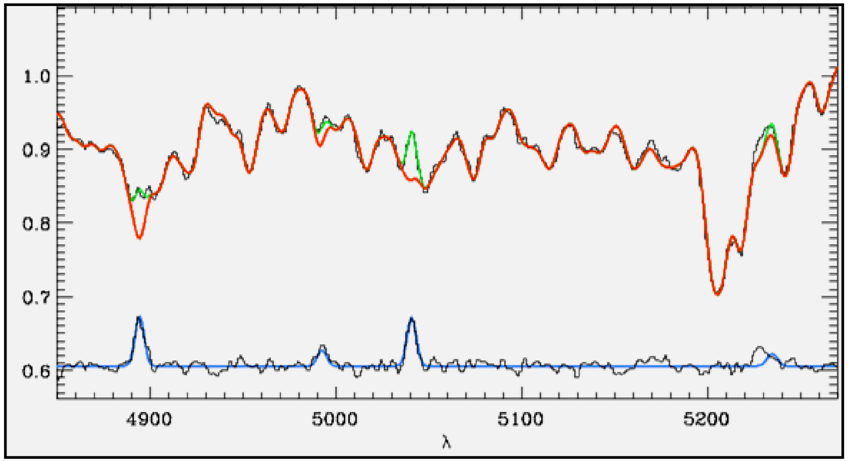
- **The Atmosphere (ground-based instruments)**
  - Transparency variations
  - Sky Background: emission and absorption
  - Spatial resolution : Point Spread Function
    - Typical **PSF** widths :
      - 0.5 – 2 arcsec in the optical
      - 0.3 – 1 arcsec in the NIR
    - But usually **not a Gaussian-like PSF**
    - Possibility to fully exploit Adaptive Optics
  - Differential refraction



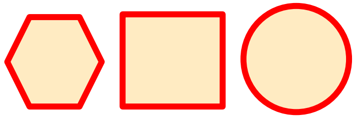


Optical/Near Infrared spectroscopy

- **Specifics:**
  - Spectra with Continuum and absorption lines



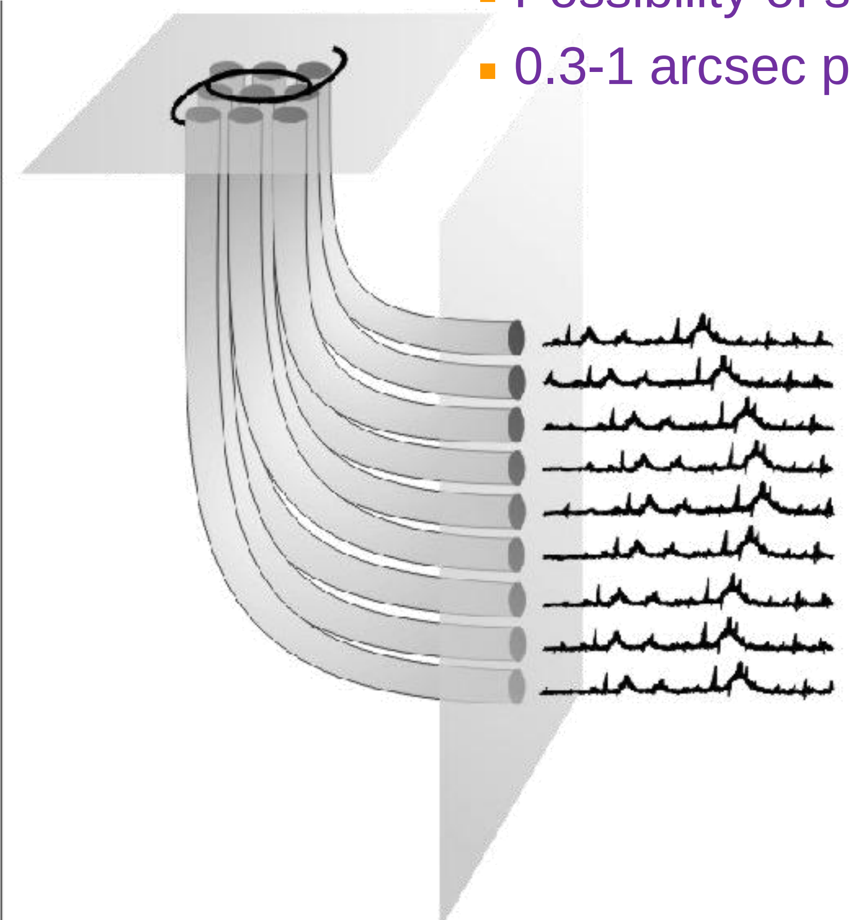
- **Resolutions**
  - Spectral = Shannon (Nyquist)
    - Usually FWHM or σ
  - Spatial = SPAXEL shape?
    - Difference between resolution and sampling!
    - Usually FWHM or σ

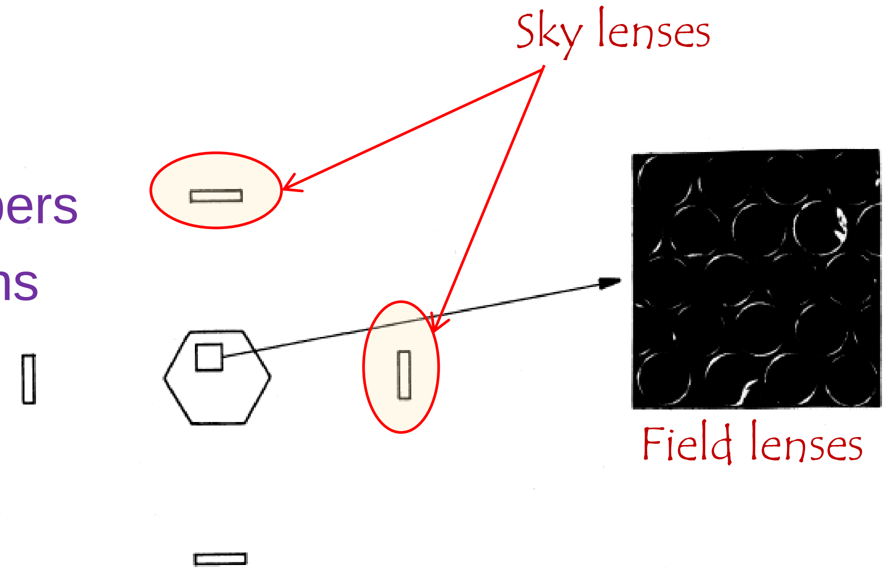


Splitting the field

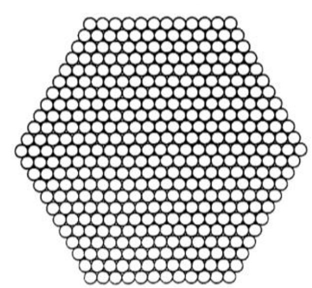
❖ **Fibers !**

- Few 100s fibers
- Possibility of sky fibers
- 0.3-1 arcsec per lens





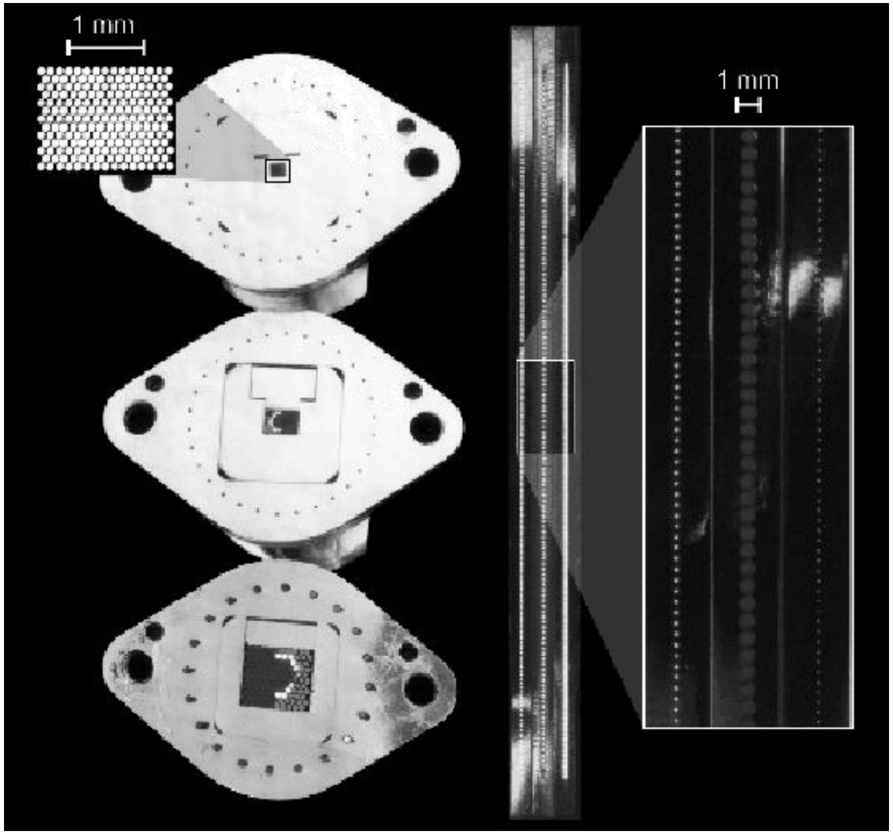
Vanderriest, C. (1980), PASP 92, 858
" Fiber-Optics Dissector for Spectroscopy of Nebulosities around Quasars and similar Objects"



Vanderriest, C. (1993), ASP Conf. Ser. 37, 338
"Integral Field Spectrography with optical Fibers at the C.F.H. Telescope"

Fiber fed spectrographs

- **INTEGRAL @ the WHT (4.2m)**
  - Several configurations
  - Dedicated Sky fibers

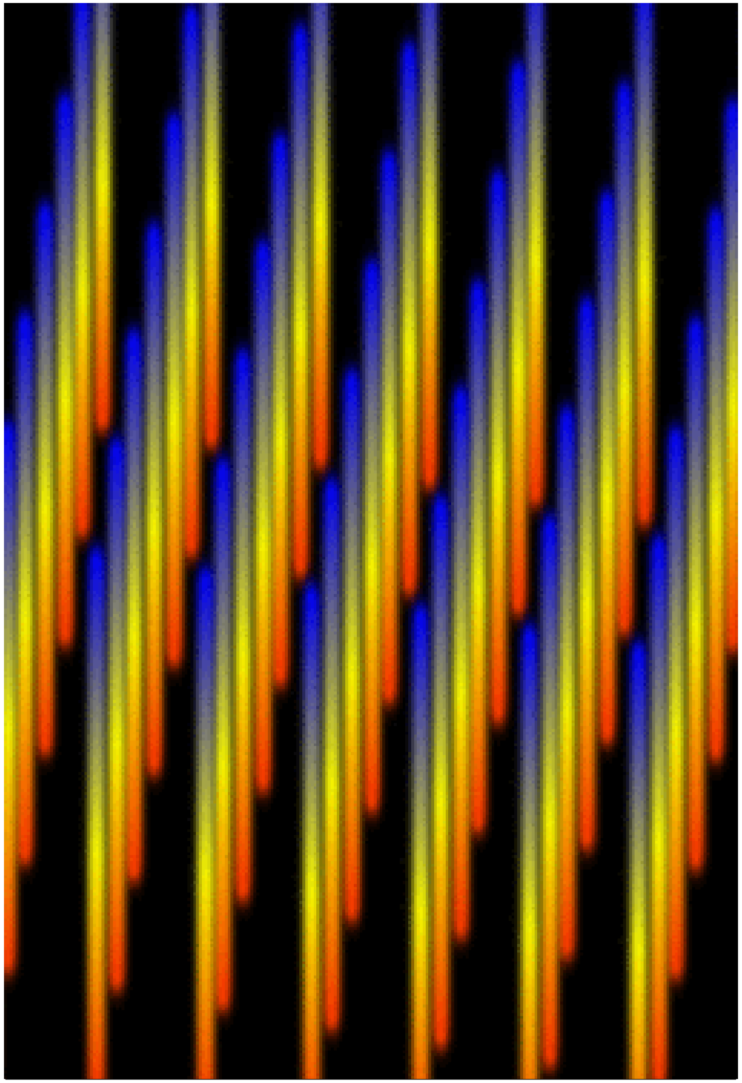


Fiber-fed spectrographs

- **Advantages :**
  - Simplified output onto a slit
  - Full use of the CCD for the spectral coverage

- **Disadvantages:**
  - Light losses, performances
  - Stability of the instrument
  - Spectrophotometry?

The TIGER concept: The trick



Uniform illumination at the entrance of the array

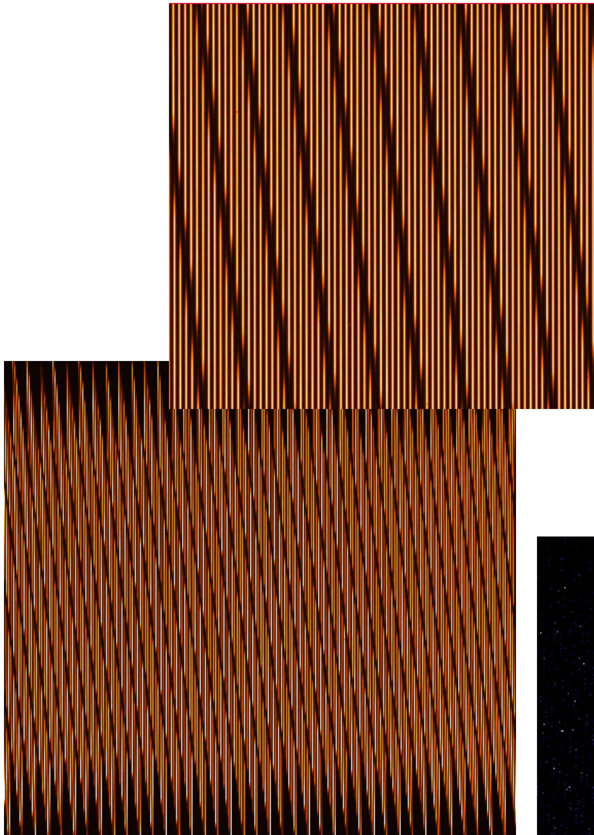
The array samples the field and focus the light into micro-pupils

The array is rotated to avoid overlapping between the spectra

The micro-pupils are dispersed via a classical spectrograph

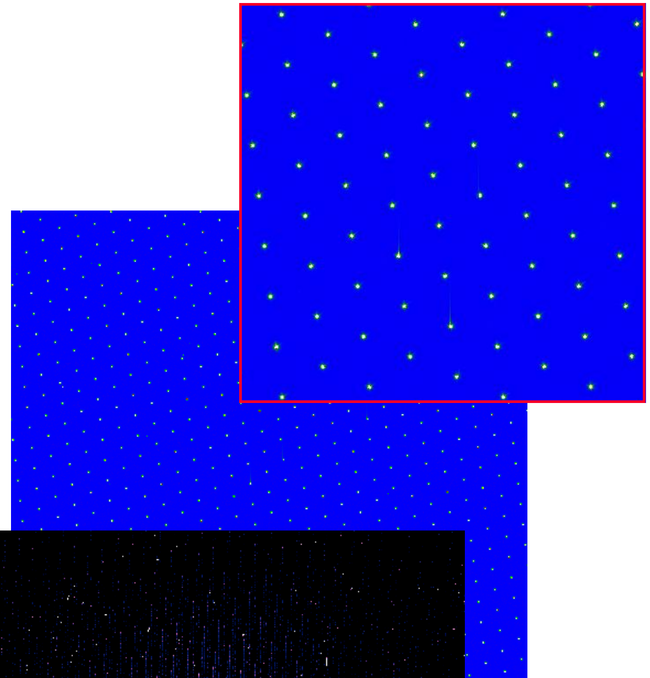
A filter limits the Y range

OASIS Raw Exposures

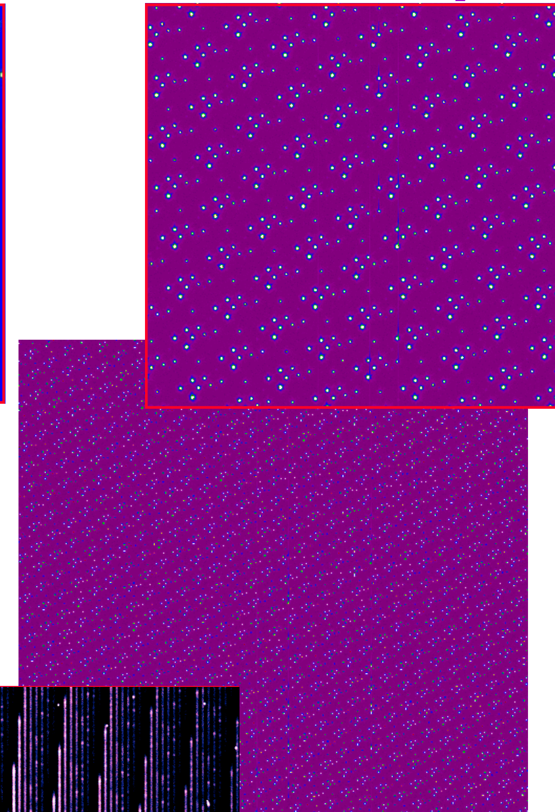


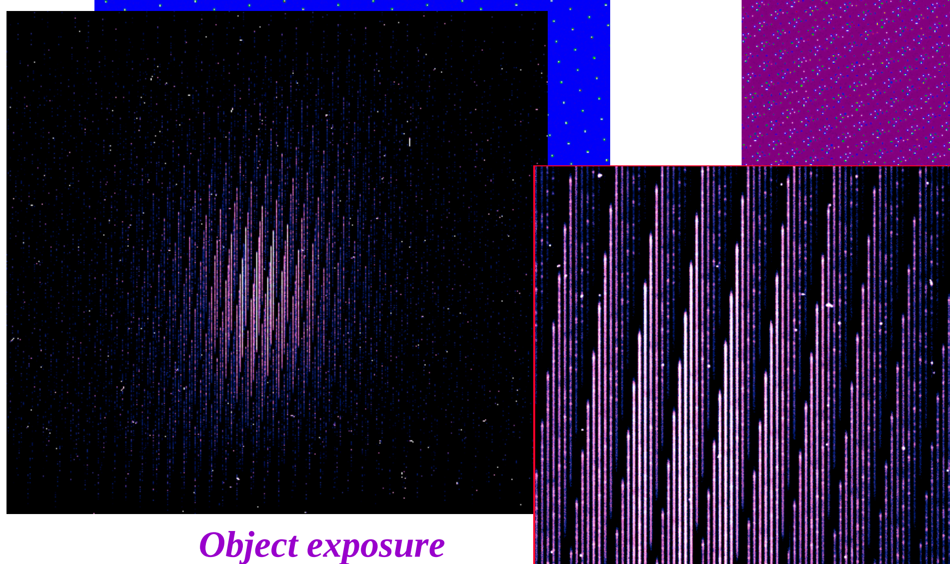
Flatfield exposure

Micropupil exposure



Neon Calibration exposure



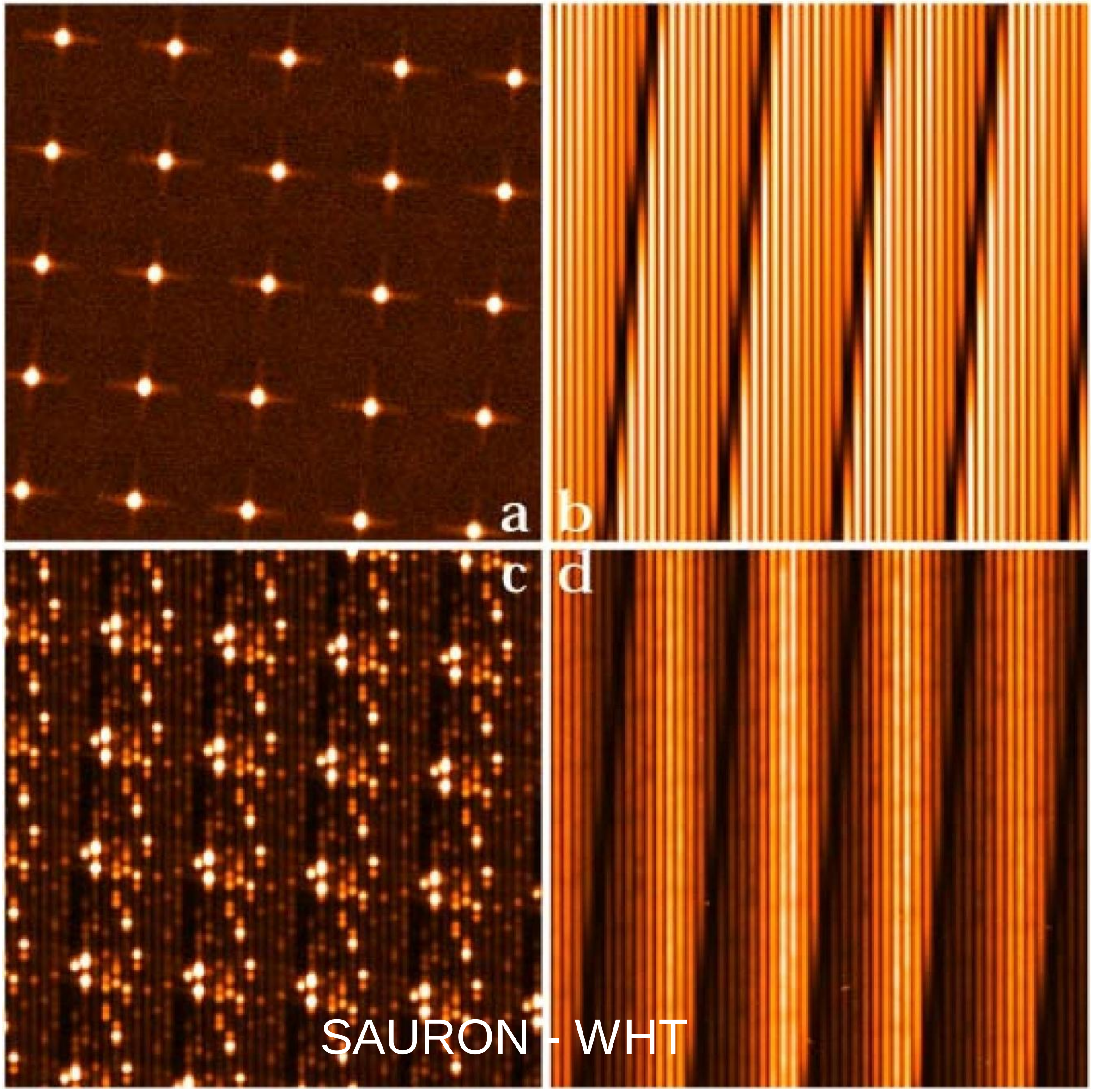


Object exposure

Lens Array – Raw Data

Micropupil

Continuum



Arc

Galaxy

TIGER-like spectrographs

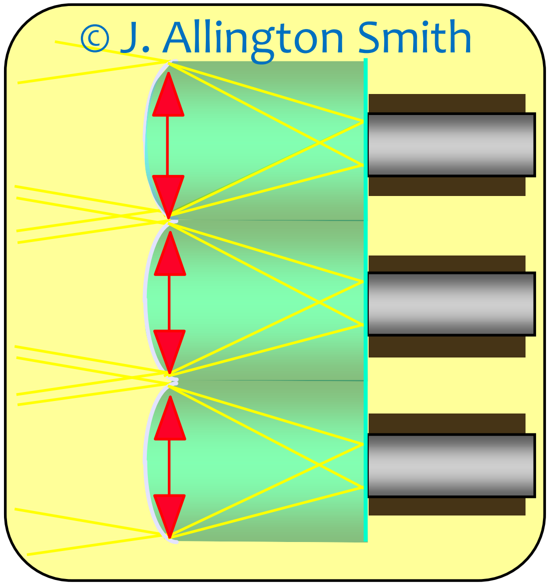
- TIGER (CFHT), OASIS (CFHT/WHT)

… SAURON (WHT), SNIFs (UH 2.2m)

- OSIRIS (Keck) in the NIR

- **Advantages :**
  - Spatial & spectral information
  - No light loss (in principle)
  - Spatial scale can be easily changed
- **Disadvantages:**
  - Complex data format
  - Requires clean separation of spectra on the CCD
    - Not optimal use of the CCD pixels

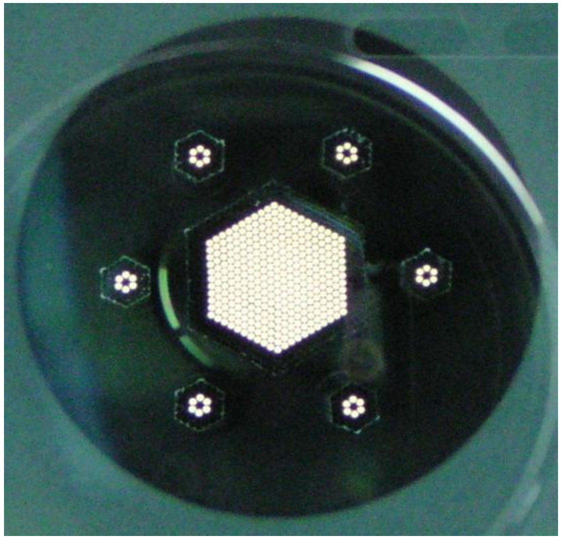
Fiber + Lenses



- PMAS, CIRPASS
- VIMOS, FLAMES, GMOS

- **Advantages :**
  - Separation of spatial and spectral information
  - No light loss
  - Reconfiguration of SPAXELS on the detectors
  - Better controled stability (?)
- **Disadvantages:**
  - Fibers…
  - Spectrophotometric properties?

IFU Techniques: Optical Fibres



Pros:

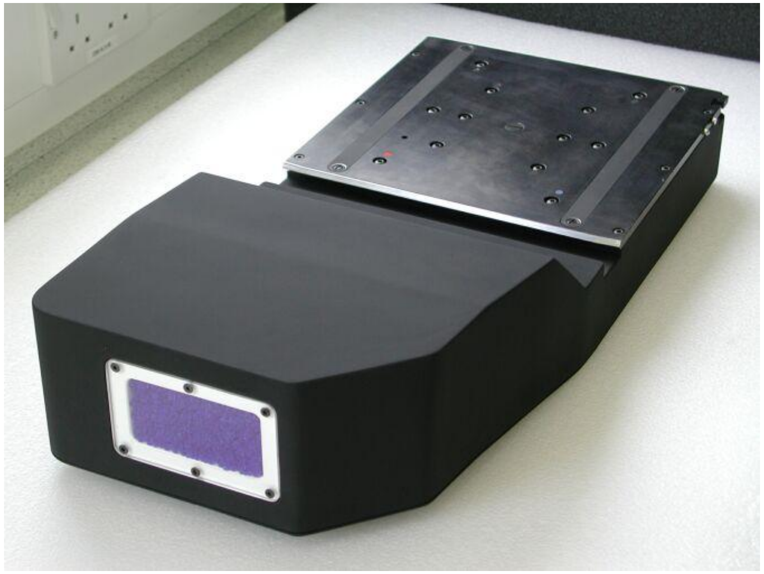
- Flexible design
- Optimise CCD area

Cons:

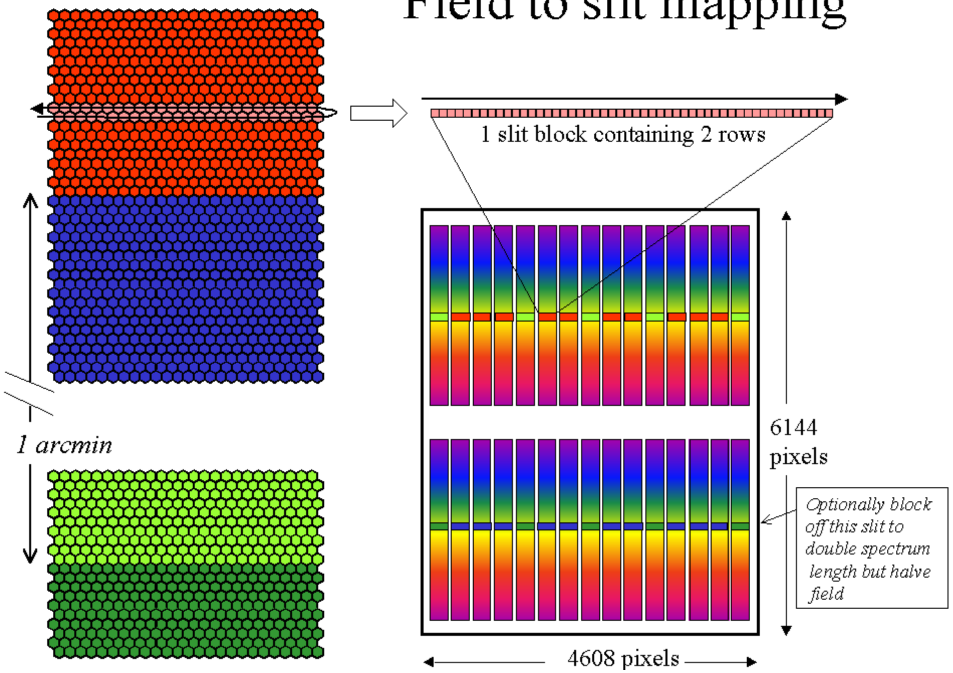
- Poorer throughput
- Calibration-heavy

GMOS-IFU

- 0.4 - 1.0μm
- Hexagonal - contiguous
- 5 x 7 arcsec @ 0.2 arcsec

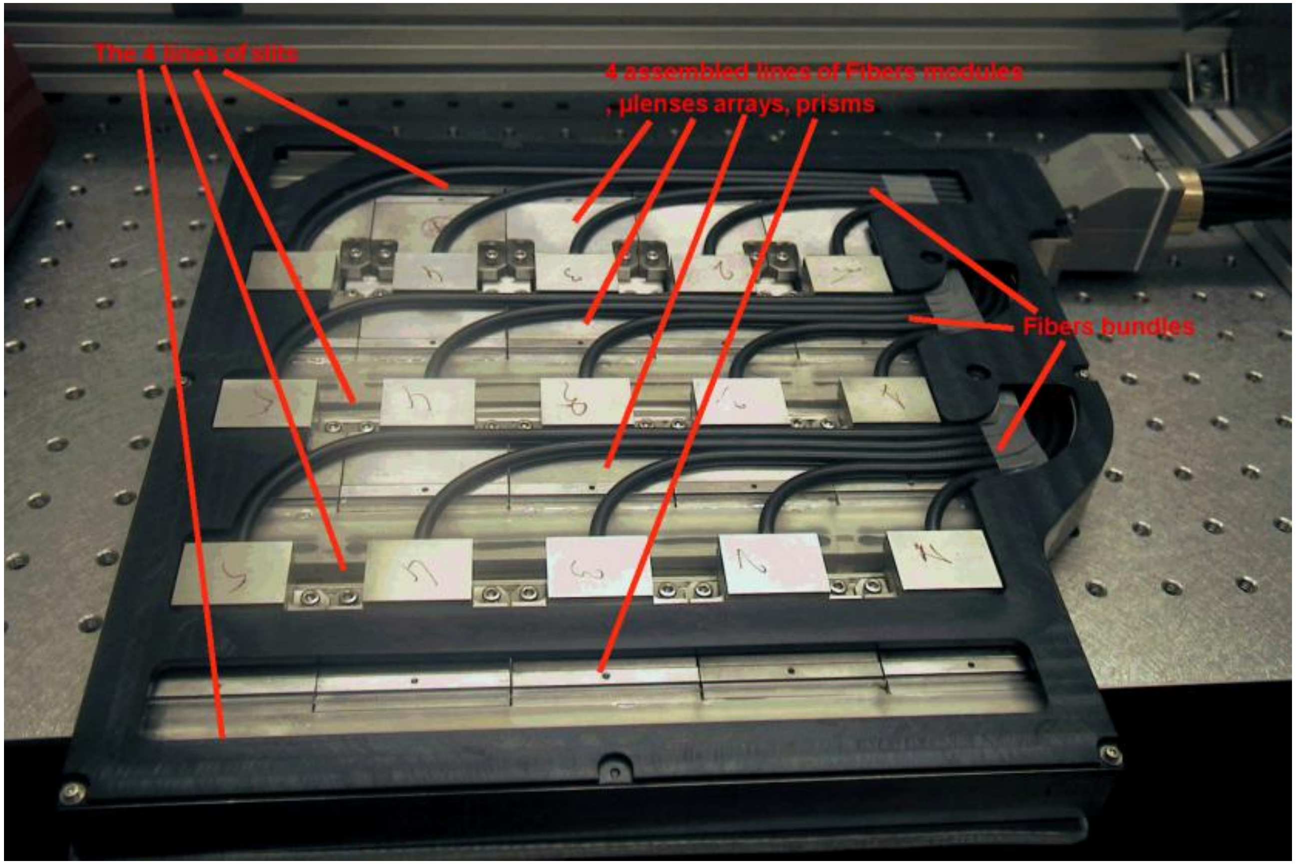


Field to slit mapping



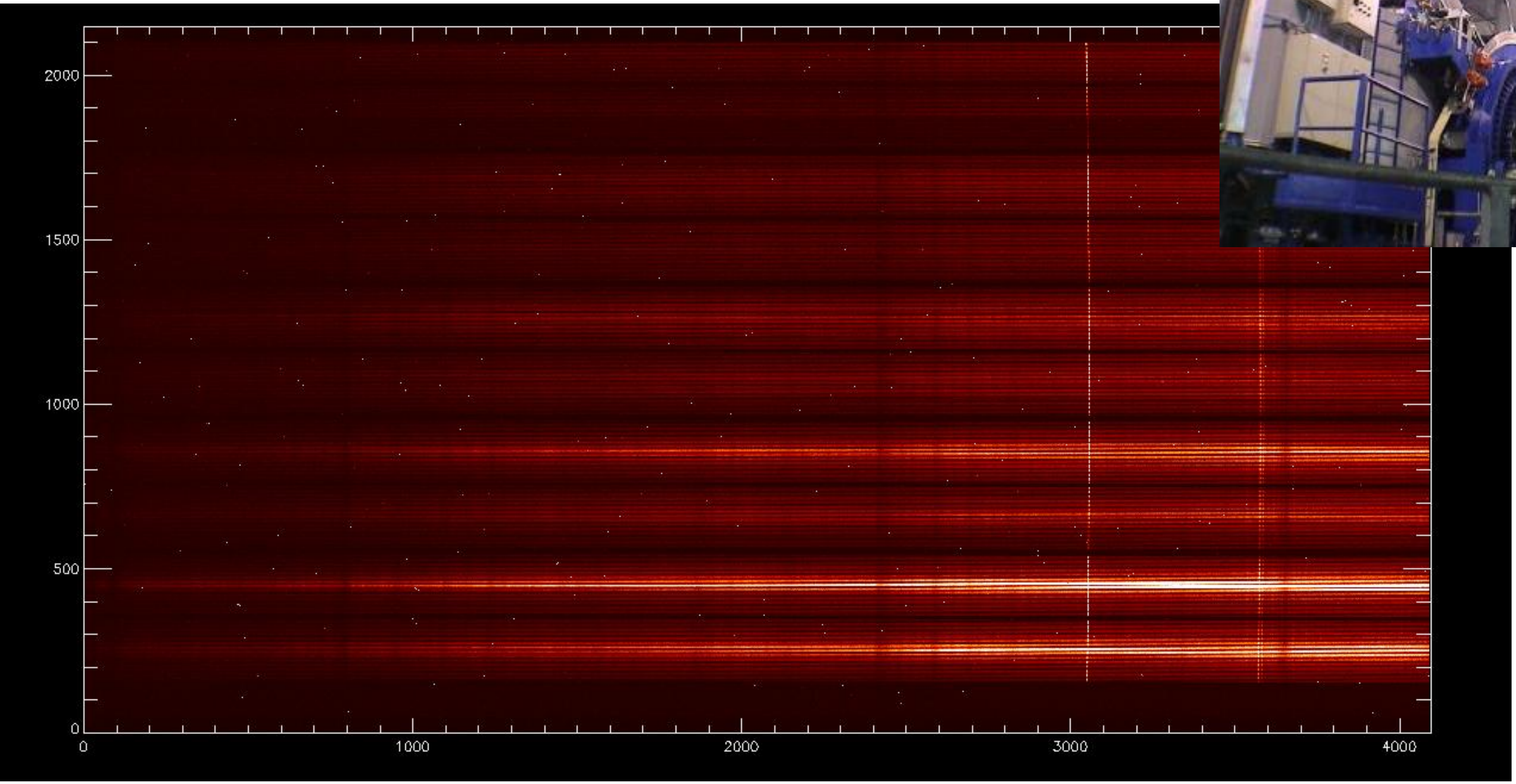
VIMOS-IFU

- 0.4 - 1µm
- 54x54/27x27 arcsec @ 0.7/0.3''
- 4 x EEV CCDs



VIMOS Raw Data

VIMOS - VLT

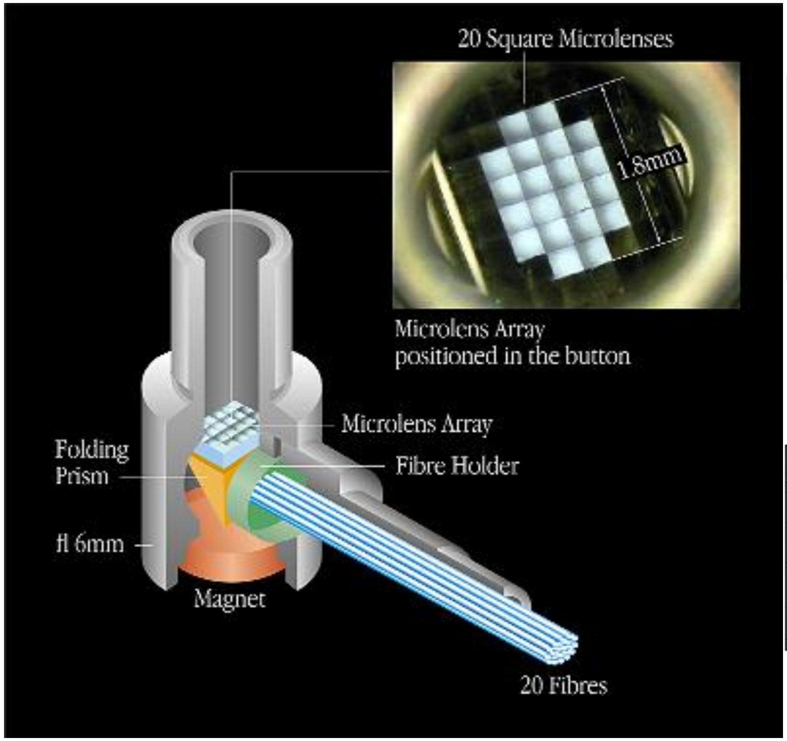


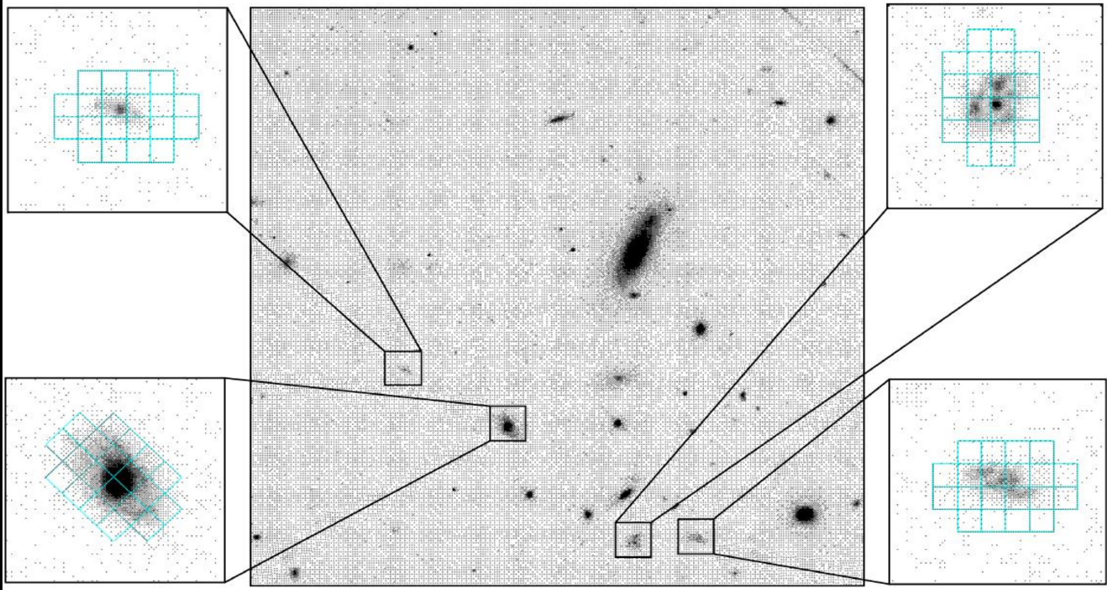
Fiber

Wavelength

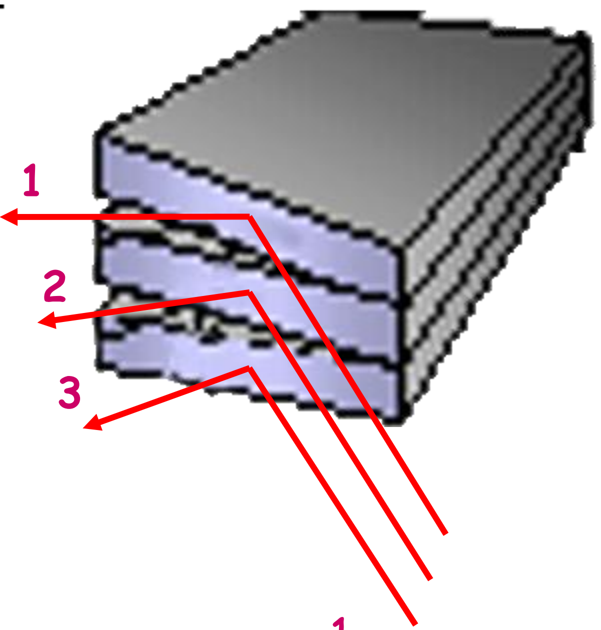
IFU Techniques: Optical Fibres

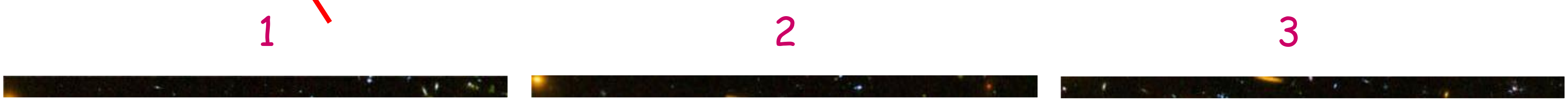
FLAMES - VLT





IFU Techniques: Principles of a Slicer





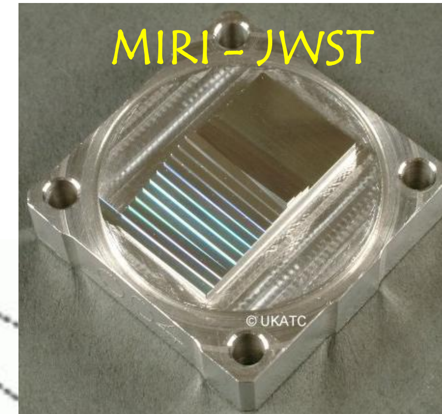
IFU Techniques: Image Slicer

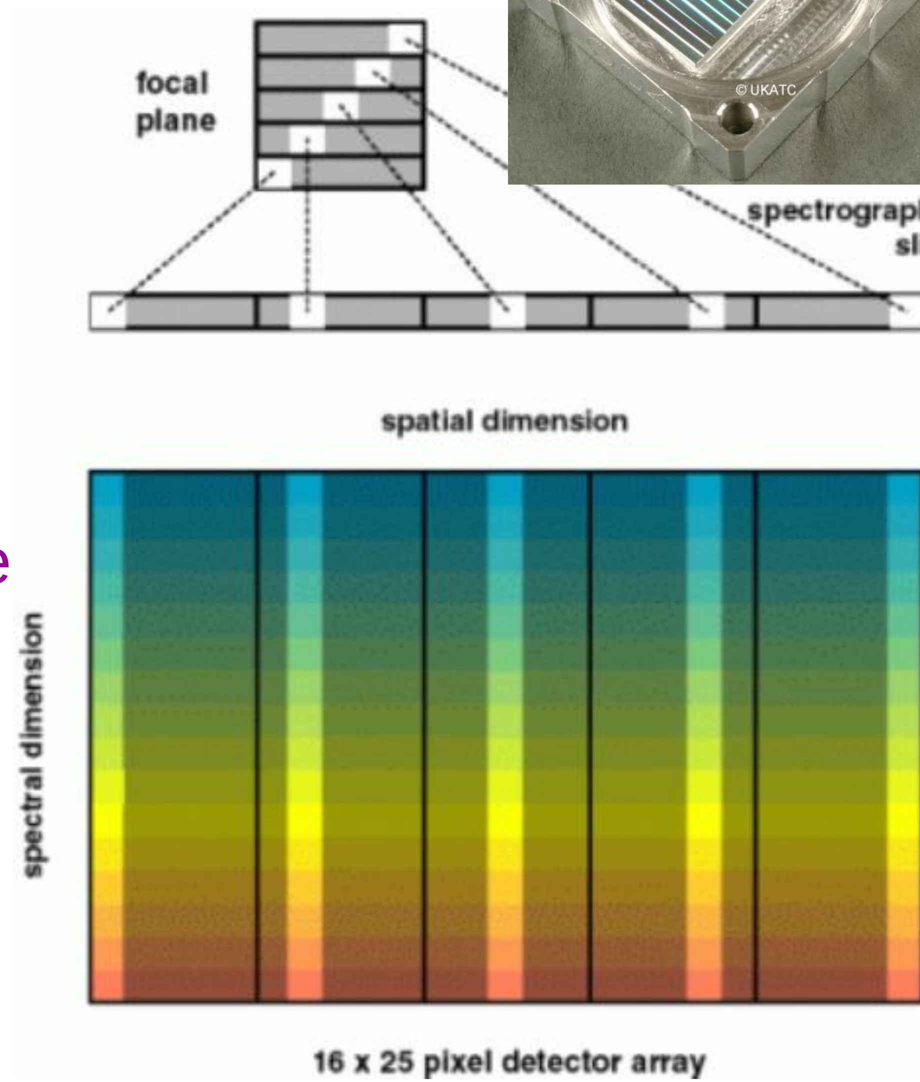
Pros:

- Compact design
- High throughput
- “Easy” cryogenics

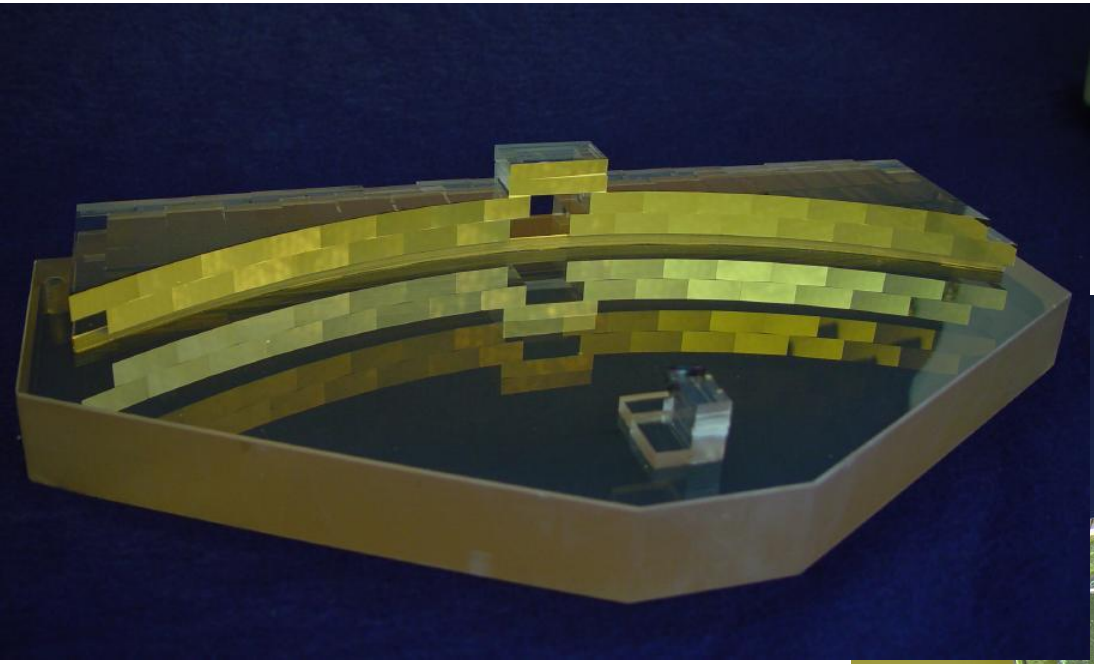
Cons:

- Difficult to manufacture





From MPE-3D to SINFONI / VLT



SINFONI / VLT – Eisenhauer et al.

The MUSE / VLT Slicer

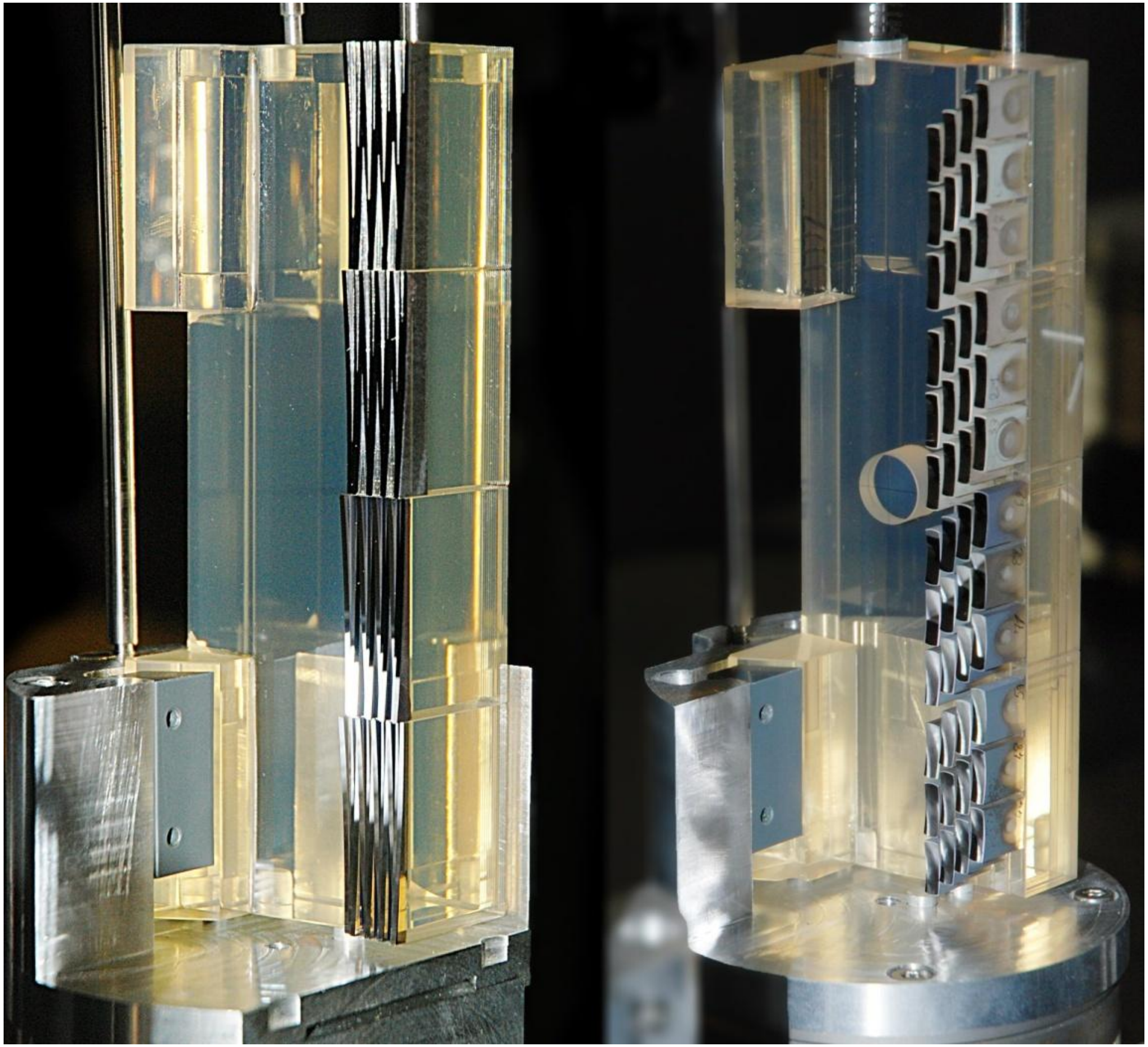
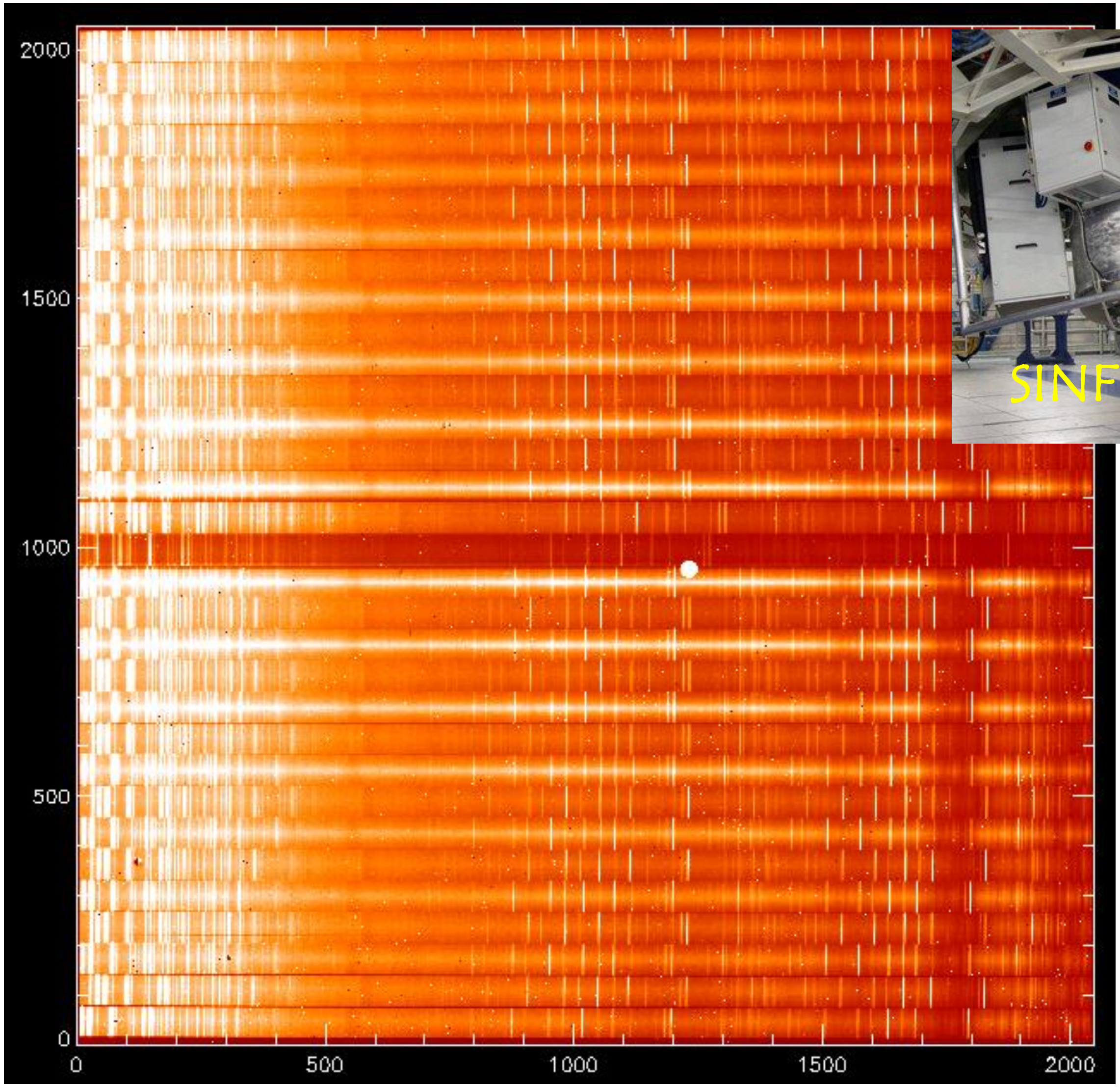


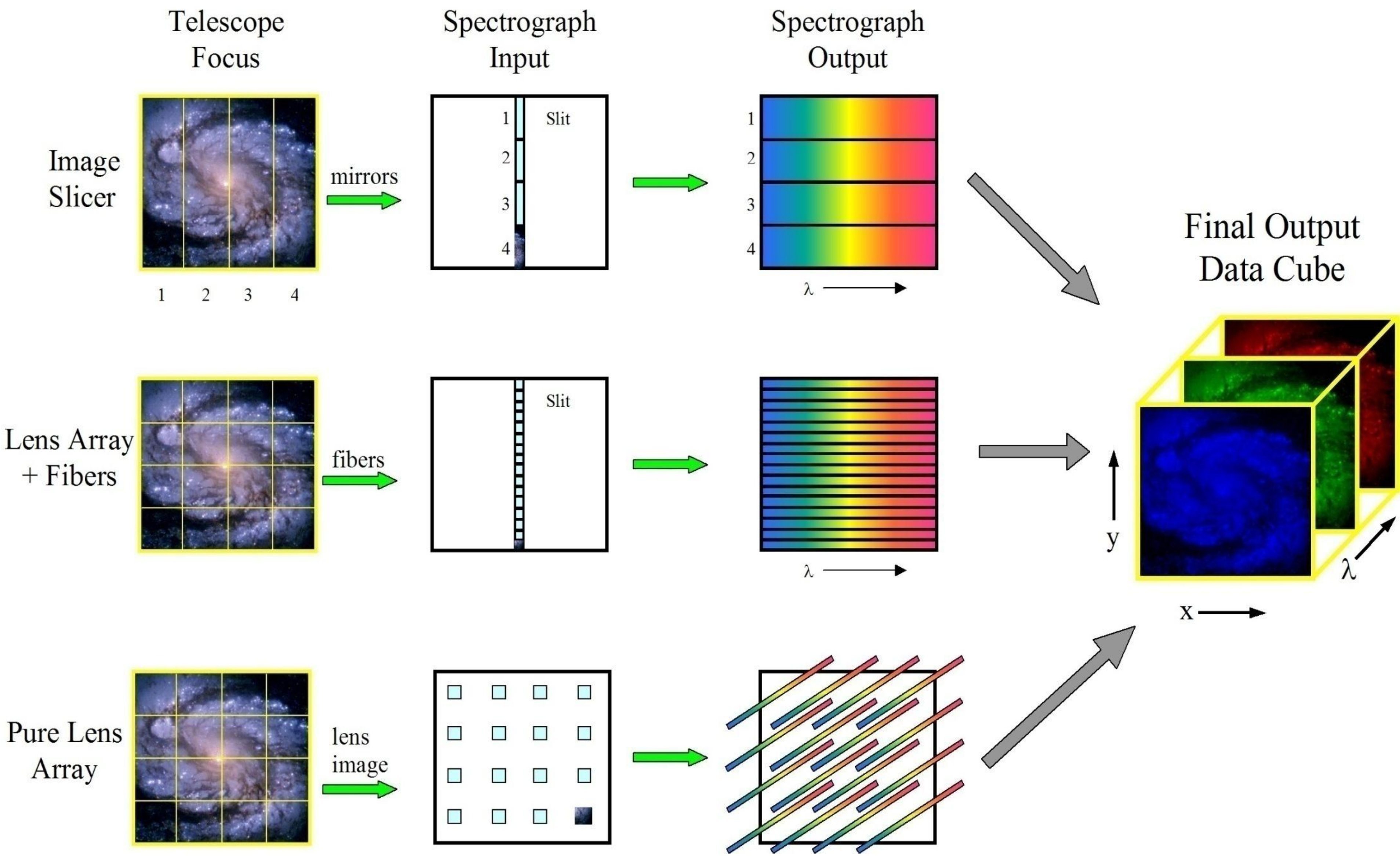
Image Slicer – Raw Data



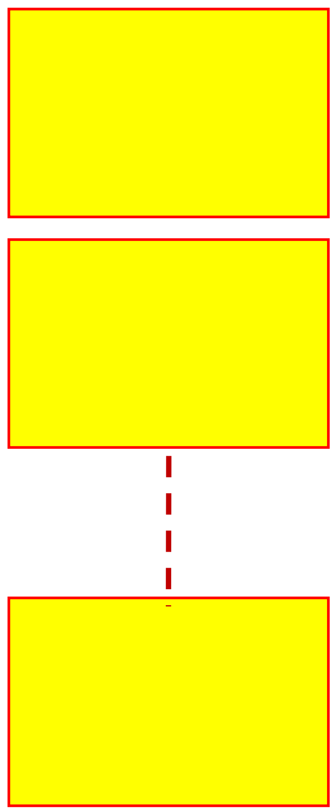
Slice

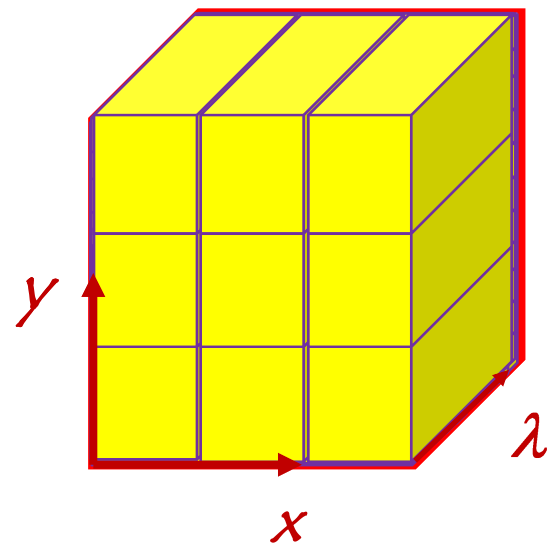
Wavelength

IFU Zoo: How to map 3D on 2D



Filling Data-cubes





Narrow-band imaging
Fabry-Perot/Fourier Transform
Stepped long-slit spectroscopy
Integral field spectroscopy

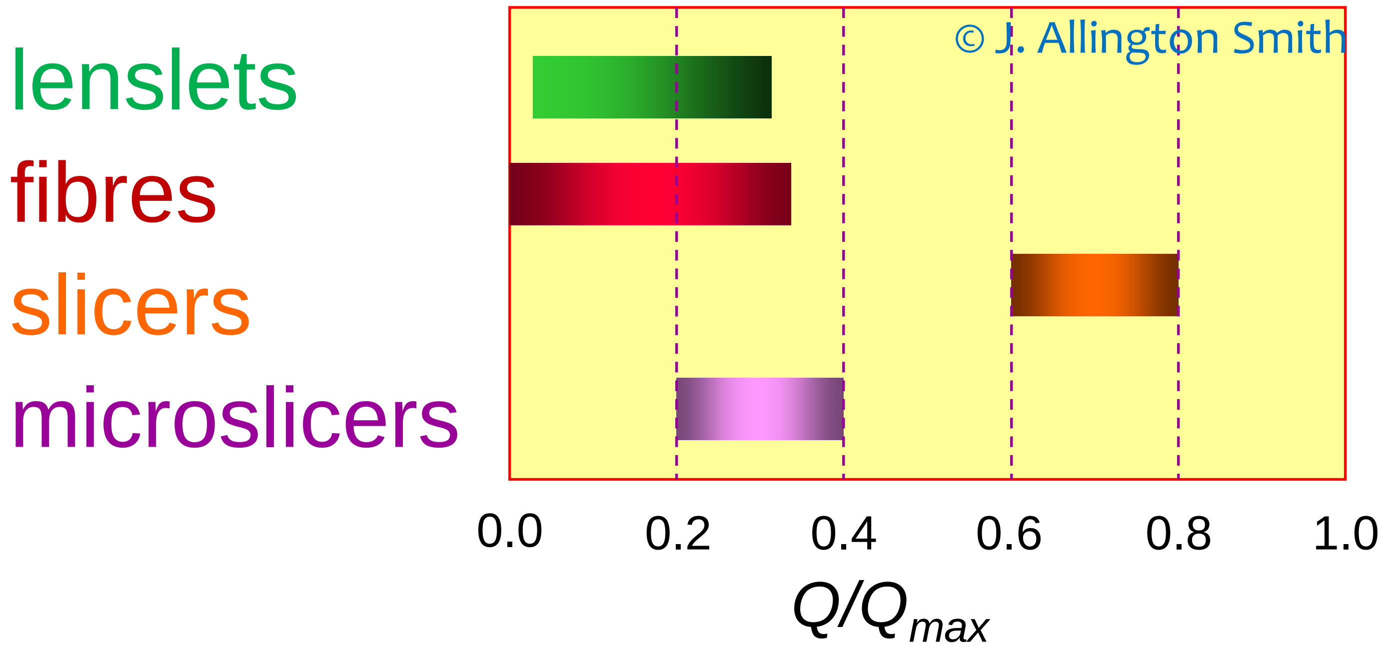
To first order: all 3D methods are equivalent

➔ same number of Detector pixels = same Data volume

But it is NOT equivalent

- **Efficiency of packing on the CCD → Q_{max}**
- **Noise issues**
- **Separation of spectral versus spatial information:**
  - better handle on spectrophotometry
  - But low packing efficiency
- **Slice = spatial continuity**
  - Continuous variation
  - High packing efficiency
  - But the 2 spatial dimensions are not on a similar ground

Best technique?



➔ **Slicers .... but difficult to make**

From Sky to Datacubes

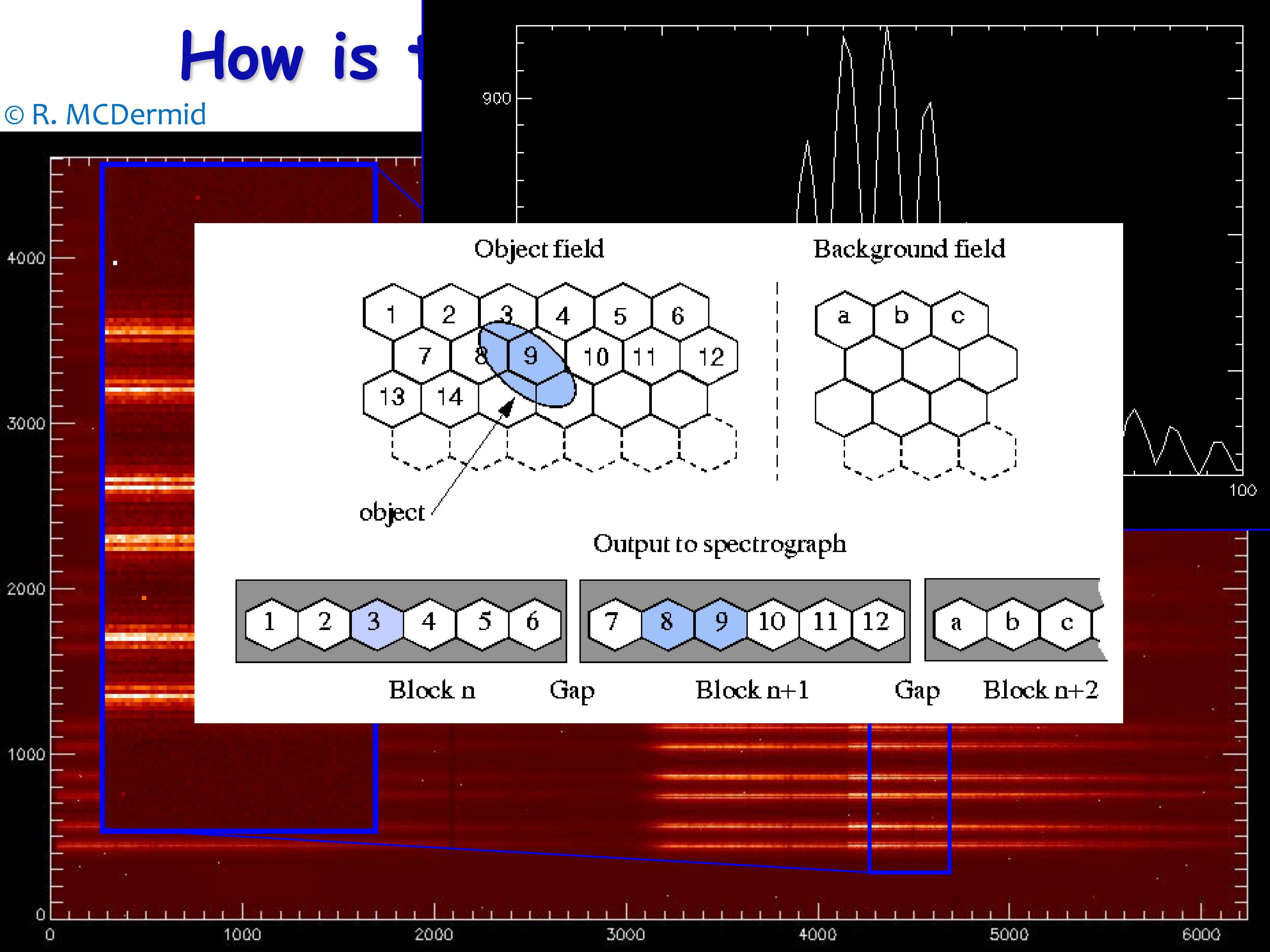
We wish to retrieve the full 3D information from an observed astrophysical object

- **Issues**
  - *Atmosphere*
    - *Transparency, PSF, refraction, time variations*
  - *Optical path (telescope/instrument)*
    - *distortions, achromatism, diffraction, …*
  - *Splitting the field, sampling issues*
  - *CCD signatures*
    - *dark current, bias, artefacts, non linearity, irregularities, CTE*
- **An Inverse problem with knowns and unknowns:**
  - HOW to *recover* the best signal out of a given exposure
  - HOW to *robustly estimate* the quality of the data

How to un-map 2D to 3D ?

- Standard = to ‘extract’ 2D data into 3D (x,y,λ) ‘data-cube’
- Cubes are then resampled to linearize the 3D
- Initial extraction ➔ extra resampling step
- Very difficult to retain the original sampling during extraction
- Assumption of *smoothly-varying properties* accross a CCD ?

How is t



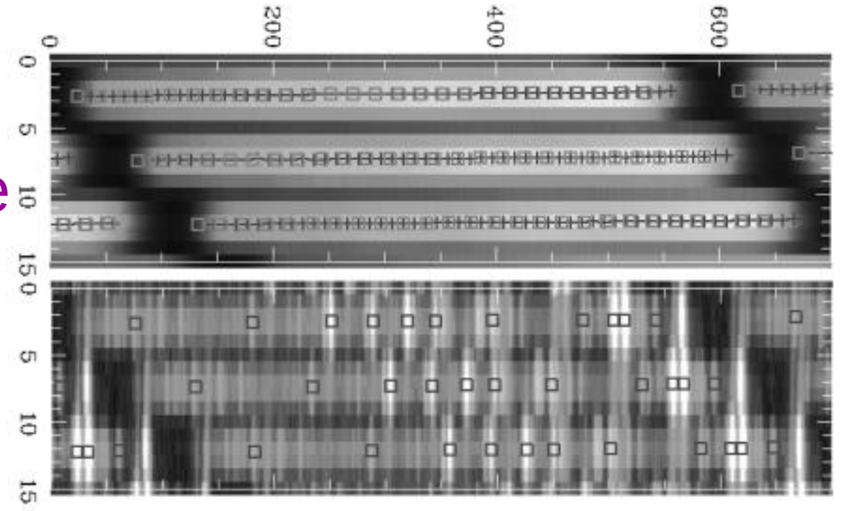
900
100
4000
3000
2000
1000
0
0
1000
2000
3000
4000
5000
6000
Object field
Background field
1 2 3 4 5 6
7 8 9 10 11 12
13 14
a b c
object
Output to spectrograph
1 2 3 4 5 6
7 8 9 10 11 12
a b c
Block n
Gap
Block n+1
Gap
Block n+2

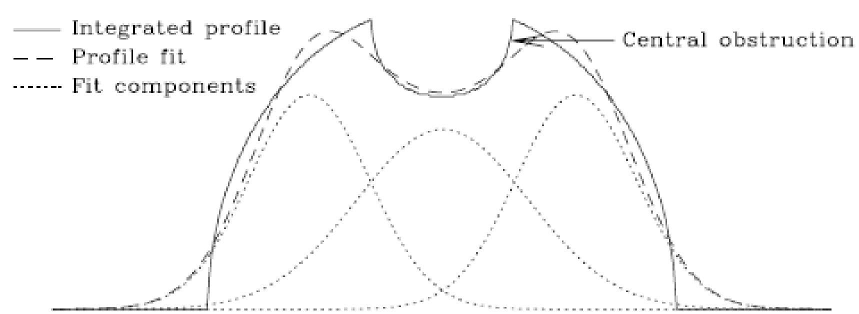
How is the 3D data mapped?

- Example: SAURON mask
  - Flexures ➔ reference exposure
  - Critical blends
  - Sampling of the spectral PSF

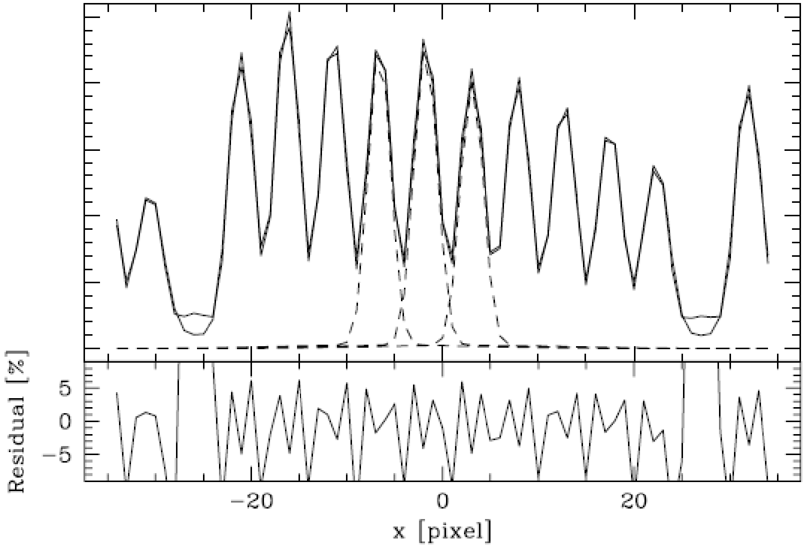
➔ Detailed optical model:

To know where each x,y,λ lie on the CCD !!



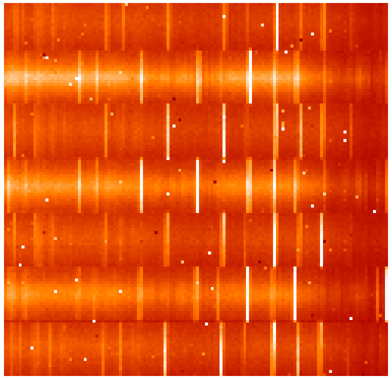


Integrated cross-dispersion profile $\mathcal{G}$ of the geometrical micropupil (solid line) and its fit (dashed line) with three Gaussian functions (dotted lines).



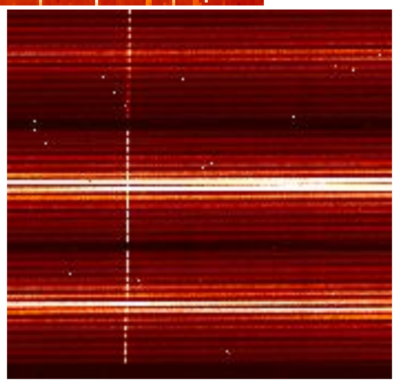
Extracting Different Instruments

Slicer



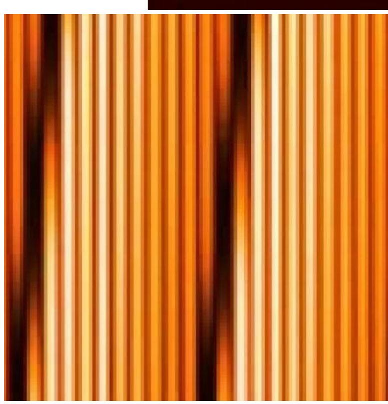
- Within a slice, CCD pixels are neighbouring in (x,y,λ) - no de-blending
- Slices are independent
- No common wavelength axis

Fiber



- Spatial axes can be arranged arbitrarily
- Fibres may need de-blending
- Wavelength axis is common to all fibres
- Fibres usually treated as independent

Lenslet



- Both spatial and spectral axes re-arranged
- CCD pixels fully decoupled from (x,y,λ)
- Deblending is critical
- Each lens is independent

The Noise issue

- Noise from the instrument
  - Detector noise
    - Read-out noise, shot noise from the dark current
  - Noise introduced during the data processing
    - E.g., due to the finite S/N of calibration exposures

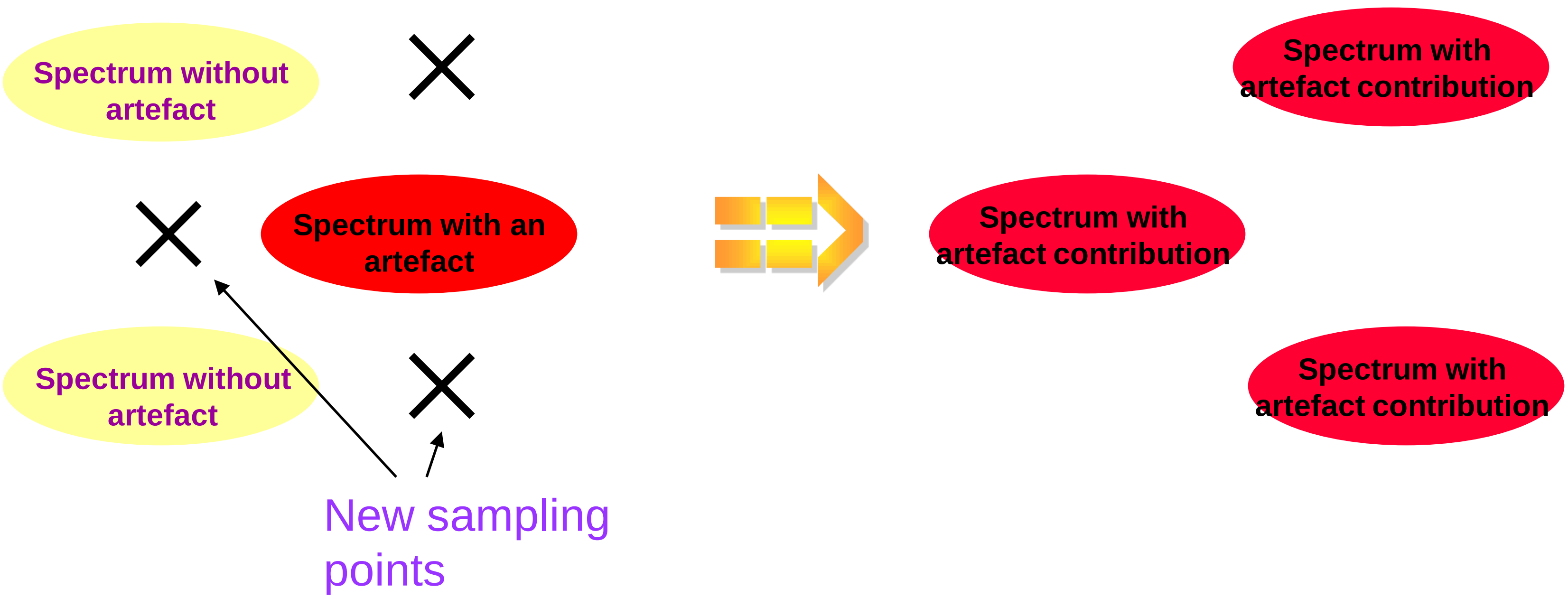
- Noise from the undesired backgrounds
  - Shot noise from the backgrounds will remain even after a perfect subtraction of the undesired background

- Shot noise from the signal itself

- S/N of a dataset = key element for the analysis

  How real/robust are features you will detect / use ?

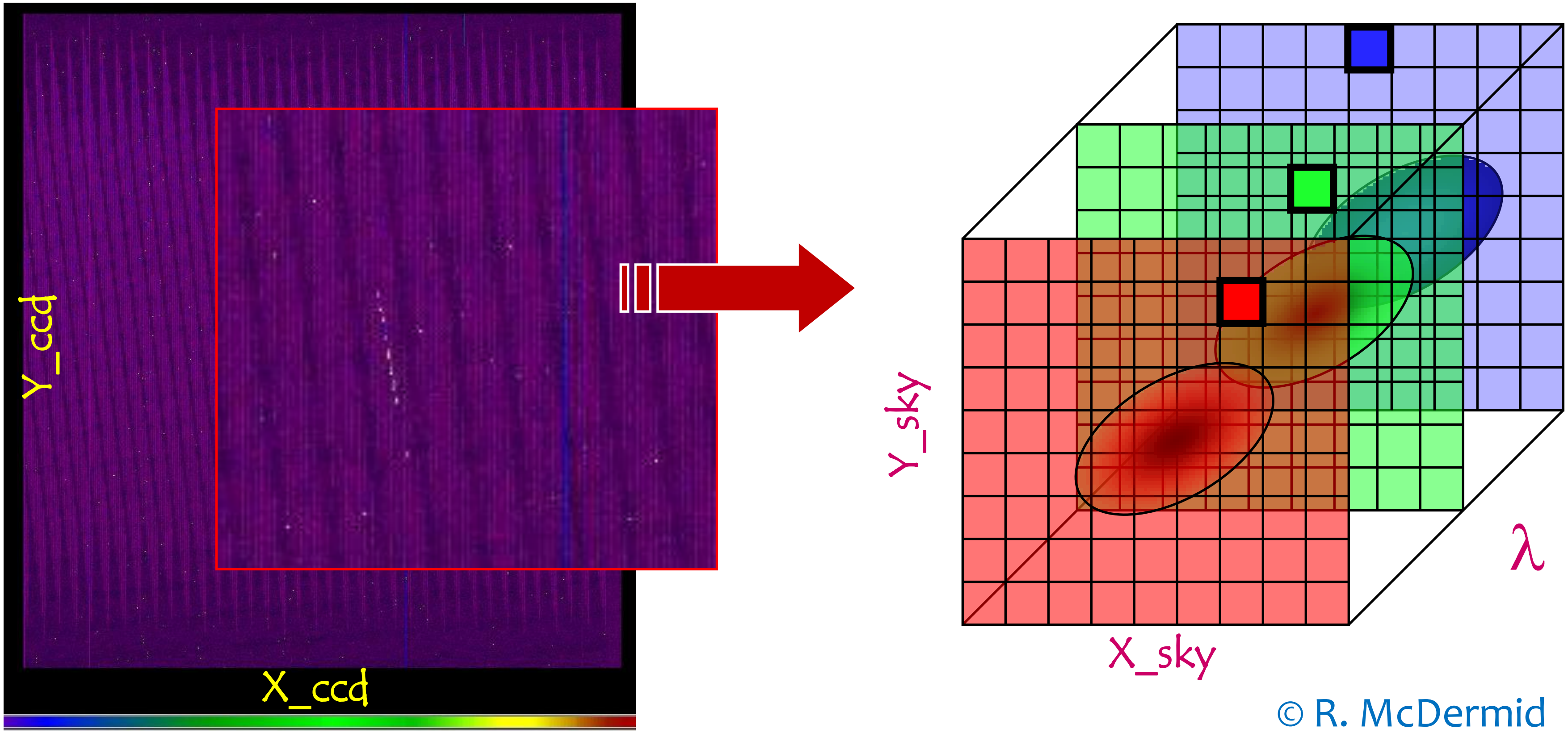
Propagation of artefacts



- Artefact has been:
  - spread out - more data loss
  - attenuated - less likely to be identified

Cosmic Rays

- CCD coordinates are decoupled from data-cube coordinates
- Cosmics have high contrast in image planes
- Real features follow smooth/PSF distribution
- But better to do before resampling

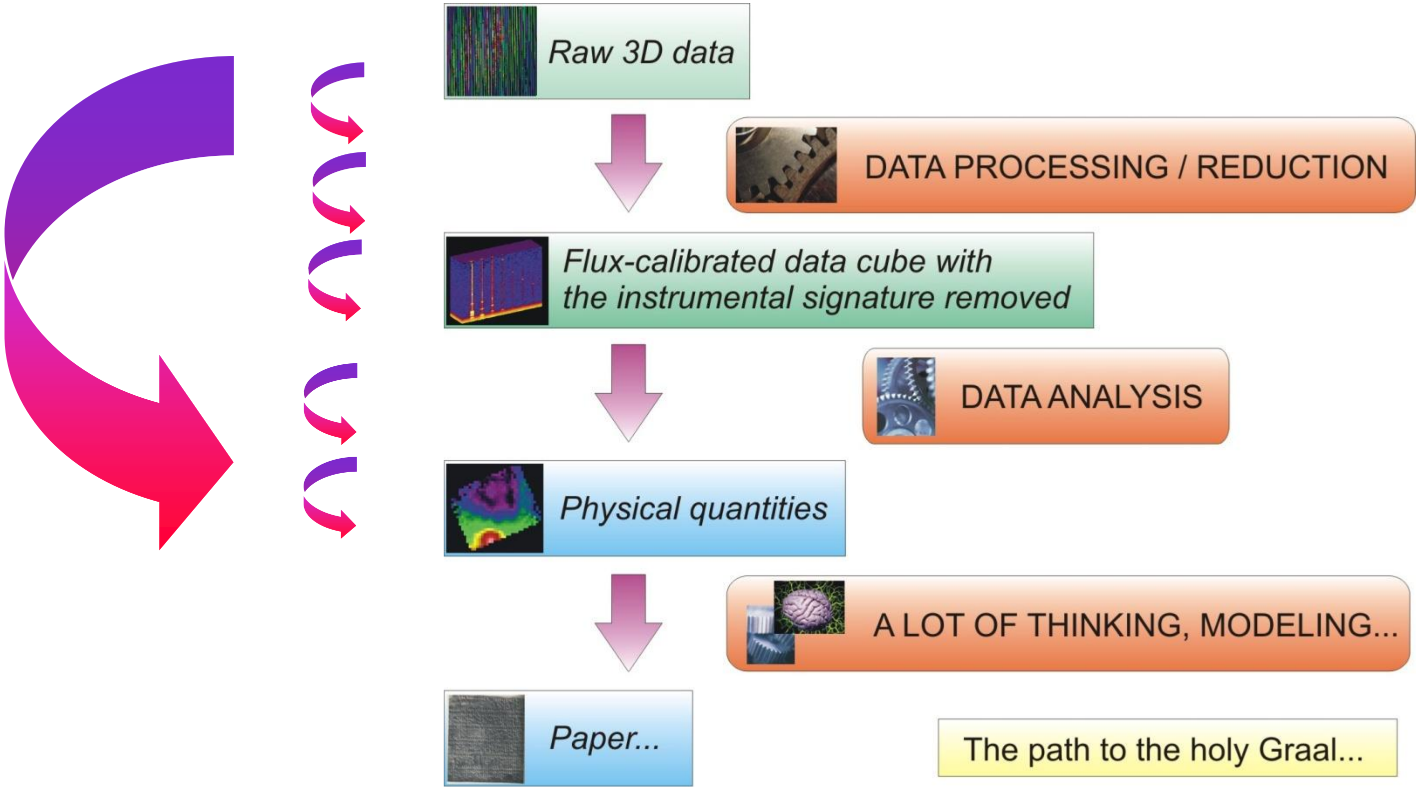


Common data reduction steps

- Linearity correction
- Dark current subtraction
- Extraction
- Spatial calibration/ tracing
- Detector flat
- Bias subtraction
- Wavelength calibration
- IFU flat
- Flux correction
- Instrumental background removal
- Atmospheric dispersion correction
- Bad pixel identification/ removal
- Sky subtraction
- Telluric correction
- Binning
- Dithering/ mosaicing

The all-in one (magic!) solution ?

- *Minimise* the number of steps including a resampling
- Associate data analysis tools with data reduction software
  - The "ultimate" solution : to keep working with the detector pixels
  - ➔ real nightmare (and a 3D one!)
    - "less" true for densely-packed fiber systems and image slicers ?



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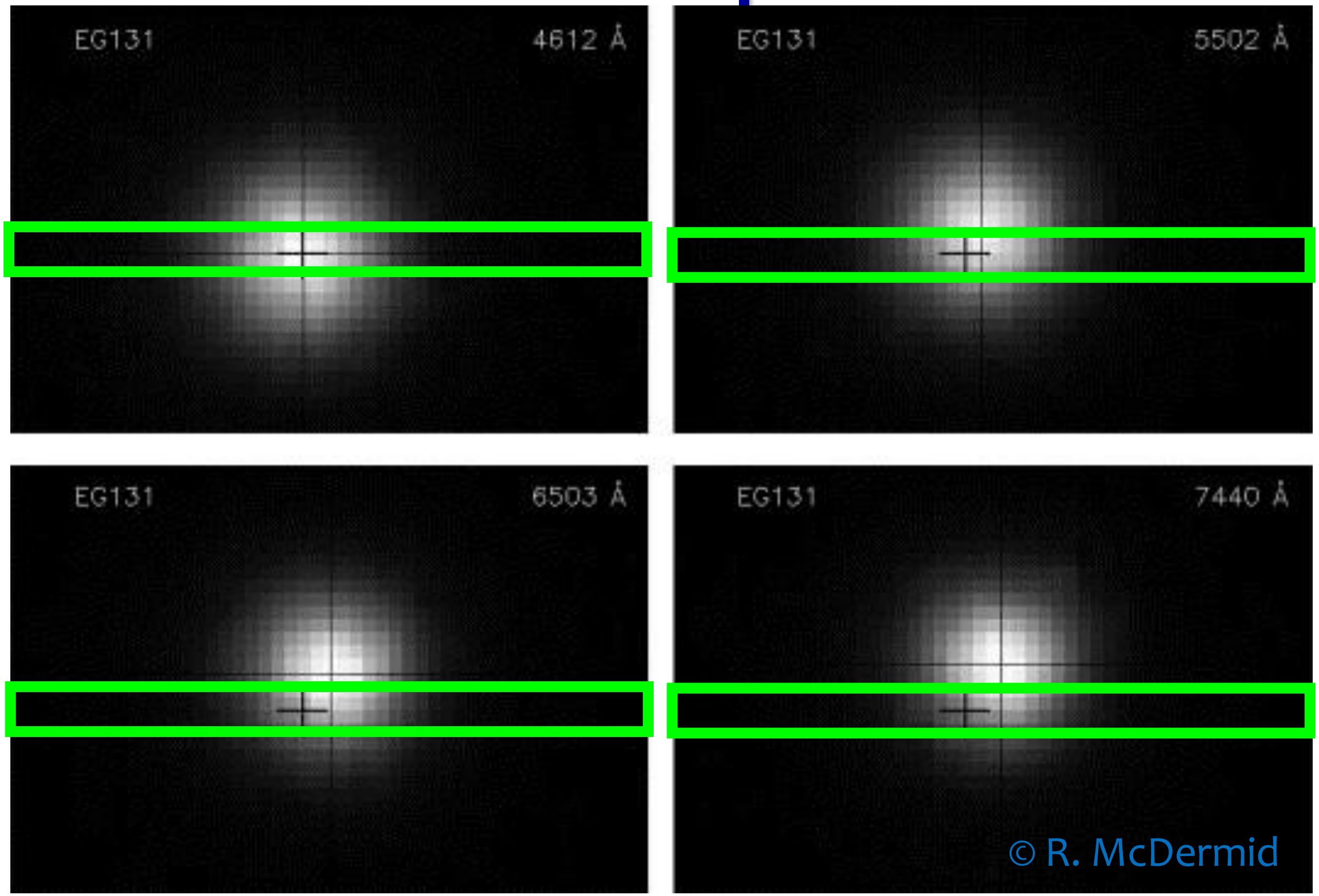
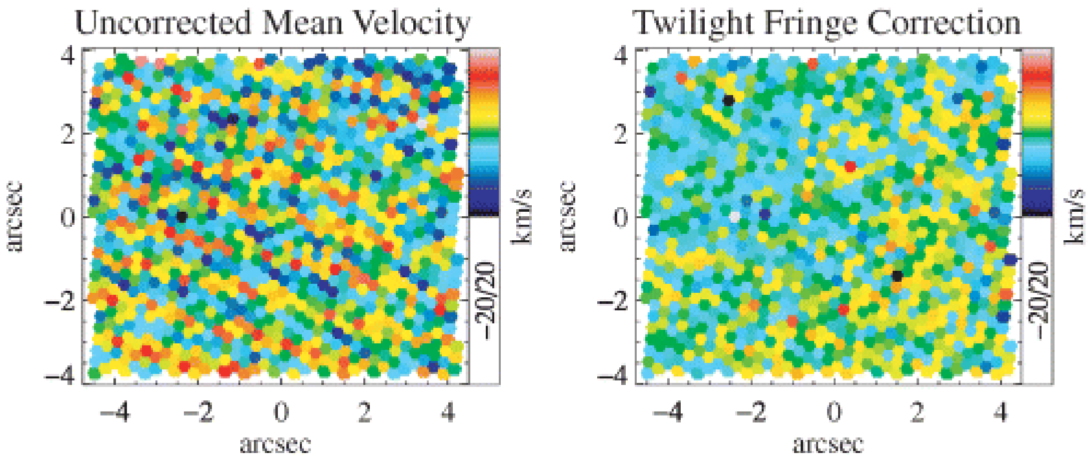
IFU Issues: Atmospheric Refraction



- Atmospheric refraction = image shifts as function of wavelength
- Shifts largest at blue wavelengths
- Can be corrected during reduction by shifting back each λ plane

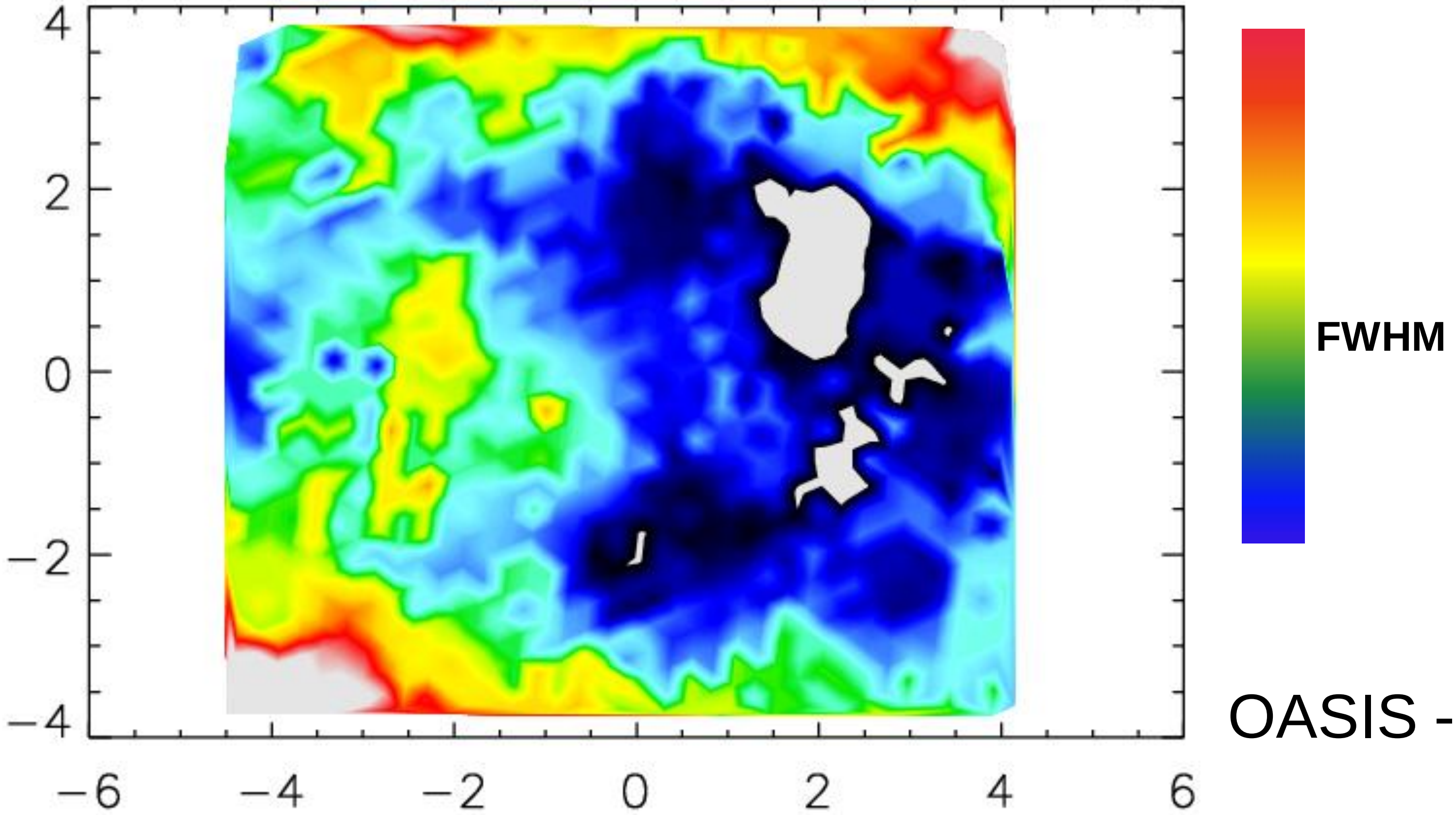
Fringing from bad flat fielding



OASIS

McDermid et al. 2006

IFU Issues: Spectral Resolution



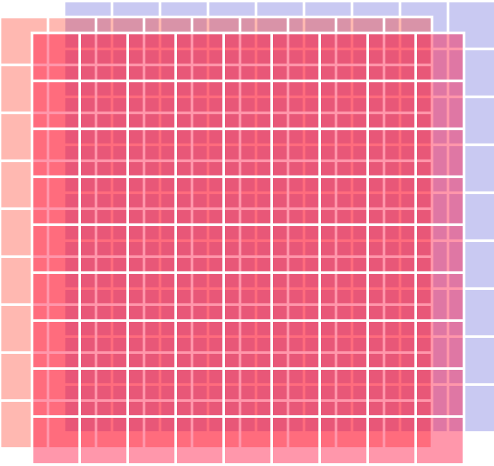
OASIS - WHT

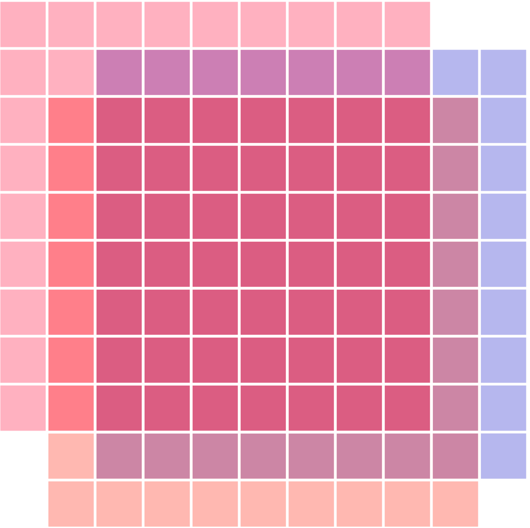
- Variations in spectral PSF across field
- Need to homogenize before merging
- Measured using twilight sky

Co-Adding Data Cubes

Two approaches:

1. Dithering by non-integer number of spaxels:
   - Allows over-sampling, via ‘drizzling’
   - Resampling introduces correlated noise
   - Good for fairly bright sources





2. Dither by integer number of spaxels
   - Allows direct ‘shift and add’ approach
   - No resampling:- better error characterisation
   - Assumes accurate (sub-pixel) offsetting
   - Suitable for ‘deep-field’ applications

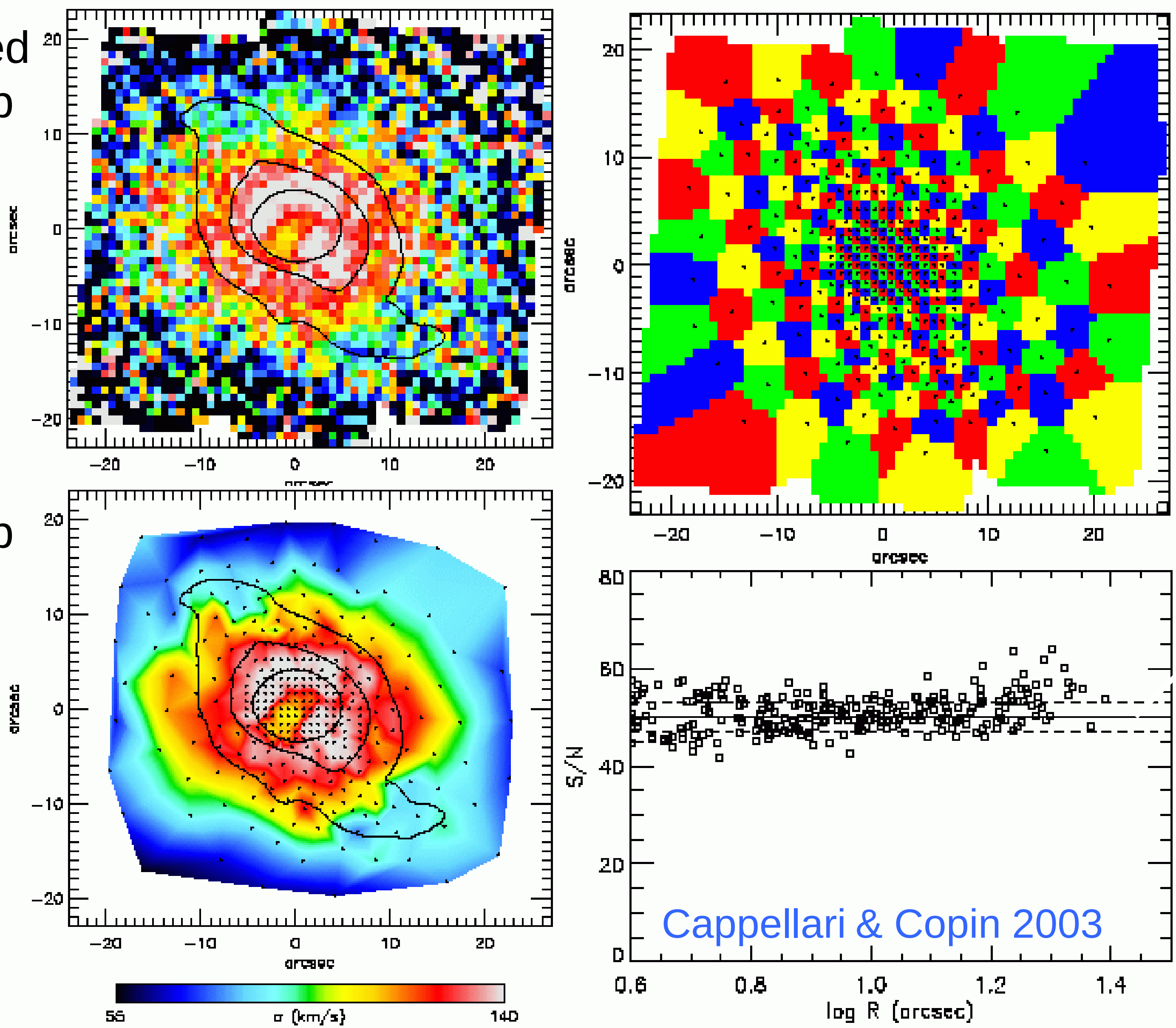
IFU Issues: Spatial Binning

Unbinned S/N map

Voronoi tessellation

S/N map After binning

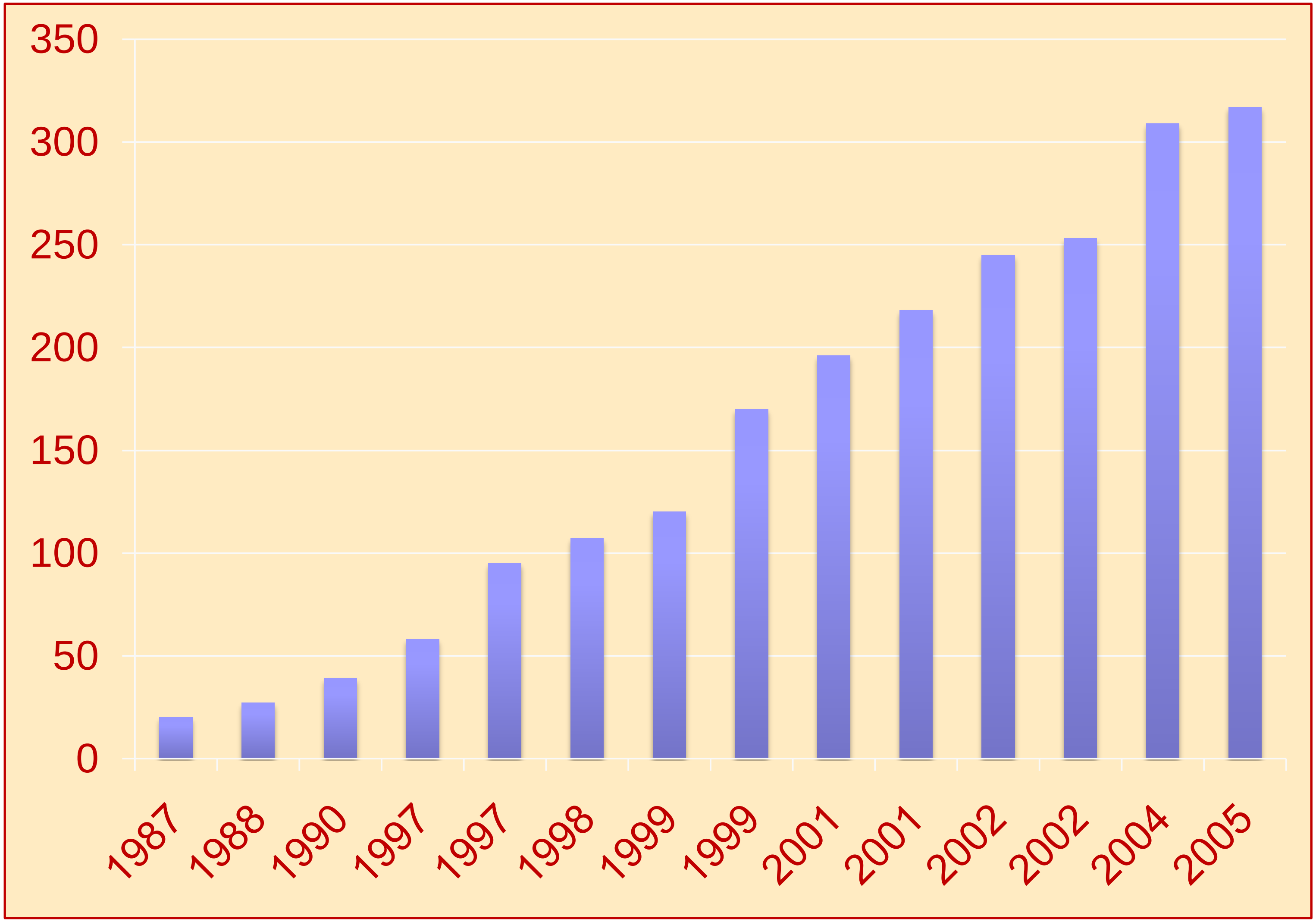
Target S/N



IFU evolution

Instrument	Type	N Spat	N Spec	Domain μm	Spaxel arcsecond	R	AO	Year	Telescope
TIGER	Lens	572	270	0.45 – 1	0.4	1200		1987	CFHT - 3.6m
ARGUS	Fibres	622	2048	0.3 – 1	0.4	450 – 2500		1997	WHT - 4.2m
MPE-3D	Slicer	256	256	1.48 – 2.41	0.3 – 0.5	1100, 2100	AO	1997	C. Alto - 3.5m / AAT - 3.9m
INTEGRAL	Fibres	205	200	0.45 – 1	0.45 – 2.7	450 – 2200		1997	WHT - 4.2m
SMIRFS	Lens	72	256	1 – 2.5	0.63	300-6000		1997	UKIRT
OASIS	Lens	1200	360	0.45 – 1	0.04 – 0.4	1000 – 2500	PUEO	1998	CFHT - 3.6m
MPFS	Lens+Fibers	256	1024	0.45 – 1	0.5 – 1	500 – 2000		1998	Zelenchuk - 6m
PIFS	Slicer	120	256	1 – 5	0.67	600, 1300		1998	Palomar - 5m
SAURON	Lens	1520	500	0.48 – 0.54	0.27 – 0.94	1600		1999	WHT - 4.2m
Spiral B	Lens	512	500	0.48 – 1	0.7	1150 – 11000		2000	AAT - 3.9m
TEIFU	Lens	1000	1024	0.40 – 1	0.13 – 0.25	2000	NAOMI	2000	WHT - 4.2m
Kyoto 3D	Lens	1000	500	0.36 – 0.9	0.42	1200		2000	Nogayama – 2m
Kyoto 3D	—	—	—	—	0.093	3500		2002	Subaru – 8m
VIMOS	Lens+Fibres	6400	2046	0.27 – 1	0.33 – 0.67	180 – 2520		2001	VLT - 8.2m
FLAMES	Lens+Fibres	308	2048	0.37 – 0.95	0.3 – 0.52	7500-25000		2001	VLT - 8.2m
CIRPASS	Fibres	490	1024	0.85 – 1.8	0.05 – 0.35	3000			Gemini N – 8m
UIST	Slicer	72	1024	1 – 5	0.24	300-6000		2001	UKIRT
GMOS	Lens+Fibres	1500	2048	0.36 – 1.1	0.2	670 – 4400		2001	Gemini N/S - 8.2m
IMACS	Lens+Fibres	1000	1024	0.4 – 0.9	0.2	1800 – 10000		2001	Magellan - 6.5m
PMASS	Lens+Fibres	256	2048	0.35 – 0.9	0.5 – 1	500 – 3000		2002	Calar Alto - 3.5m
OASIS	Lens	1200	360	0.43 – 1	0.09 – 0.42	1100 – 2400	NAOMI	2002	WHT - 4.2m
PPAK	Lens+Fibres	316	2048	0.35 – 0.9	2.7	500 – 3000		2002	Calar Alto - 3.5m
SINFONI	Slicer	1024	2048	1 – 2.5	0.025 – 0.25	2000-4500	AO	2002	VLT - 8.2m
GNIRS	Slicer	1500	1024	1 – 5.5	0.04 – 0.15	6000		2003	Gemini S - 8.2m
SNIFS	Lens	225	2048	0.32 – 1	0.6	1500		2004	UH - 2.2m
NIFS	Lens	1000	1024	0.95 – 2.42	0.1	5000	Altair	2005	Gemini N - 8m
OSIRIS	Lens	1000 – 2500	4096	1 – 2.5	0.02 – 0.1	3800	AO	2008	Keck - 10m
VIRUS	Lens+Fibres	247x132	4000	0.34 – 0.57	1	1000		2010	HET - 9.2m
KMOS	Slicer	24x196	2000	1 – 2.5	0.2	3500		2010	VLT - 8.2m
MUSE	Slicer	90000	4096	0.45 – 0.9	0.05 – 0.2	3000	MCAO	2013	VLT - 8.2m

IFU papers



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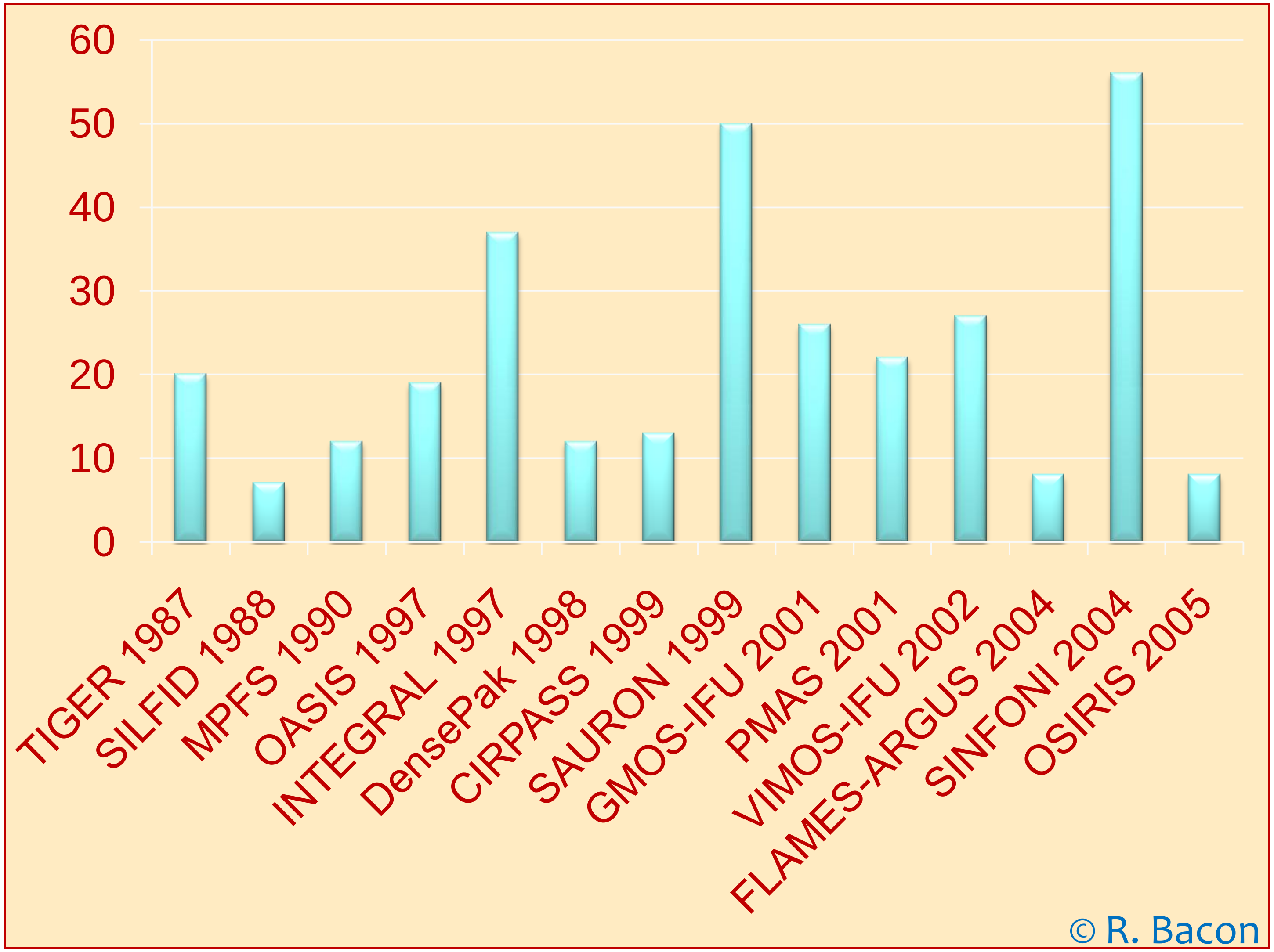
IFU Papers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50
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TIGER 1987
SILFID 1988
MPFS 1990
OASIS 1997
INTEGRAL 1997
DensePak 1998
CIRPASS 1999
SAURON 1999
GMOS-IFU 2001
PMAS 2001
VIMOS-IFU 2002
FLAMES-ARGUS 2004
SINFONI 2004
OSIRIS 2005
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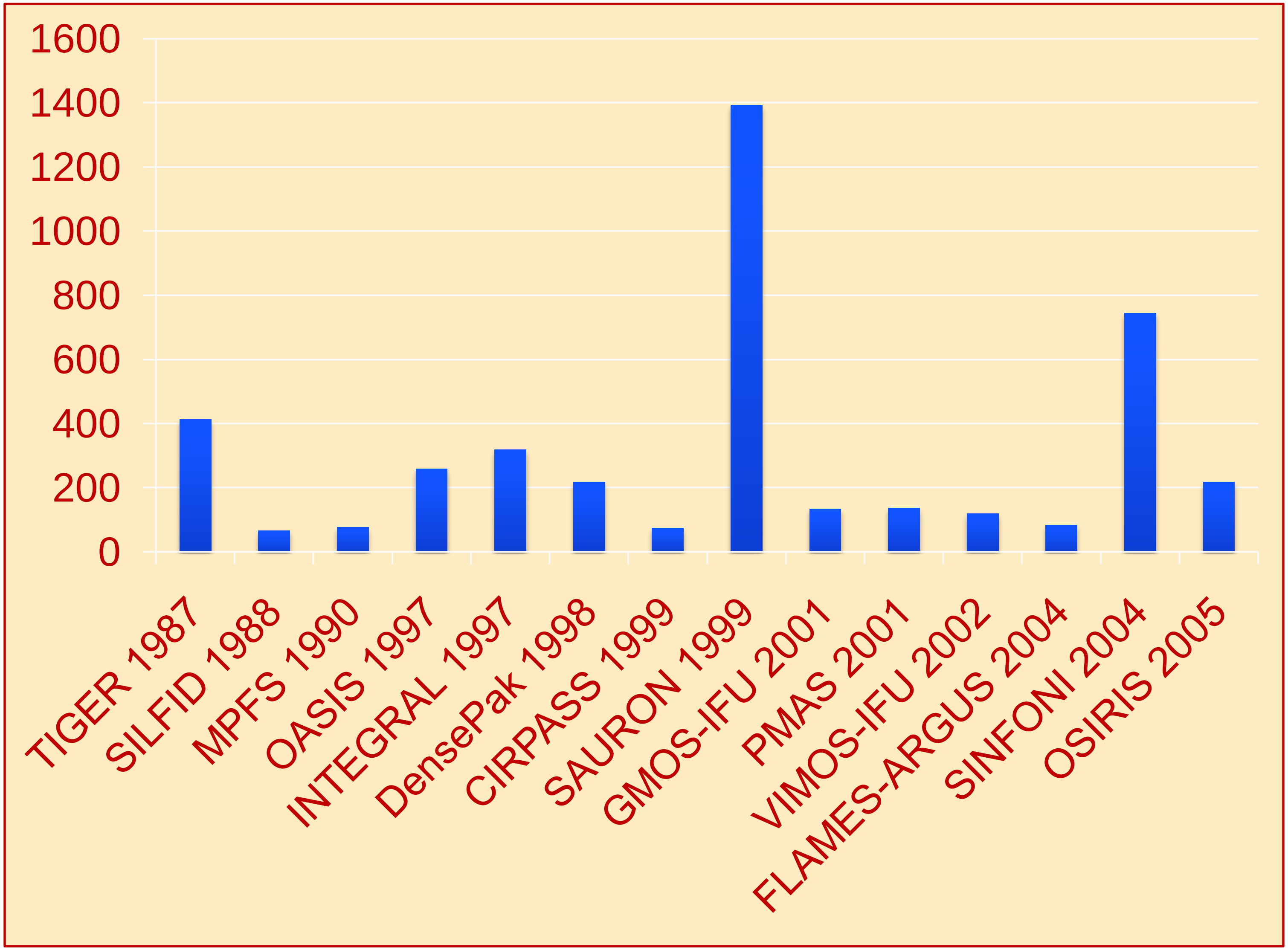
Citations


1600
1400
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TIGER 1987
SILFID 1988
MPFS 1990
OASIS 1997
INTEGRAL 1997
DensePak 1998
CIRPASS 1999
SAURON 1999
GMOS-IFU 2001
PMAS 2001
VIMOS-IFU 2002
FLAMES-ARGUS 2004
SINFONI 2004
OSIRIS 2005

IFU (biased) evolution

Name	Year	N spatial	N spectral	N total
TIGER	1987	572	270	154,440
OASIS	1997	1,200	360	432,000
SAURON	1999	1,577	540	851,580
VIMOS	2002	6,400	550	3,520,000
MUSE	2008	90,000	4,096	368,640,000

Data reduction and analysis challenges

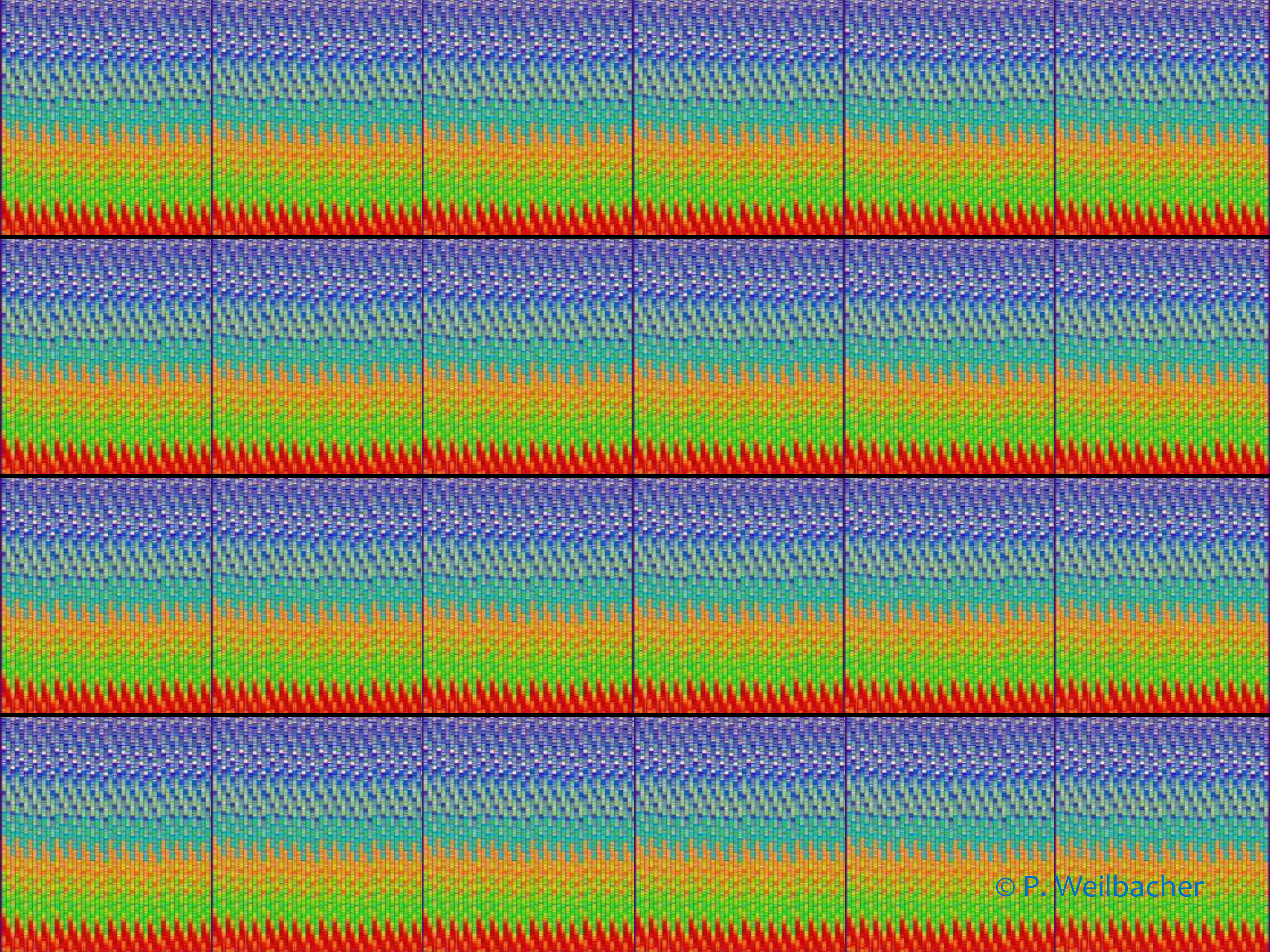
- **Data complexity:**
  - Optimal extraction ➔ Good data model
  - 2D mapping of 3D data
  - Data characteristics: noise and systematics

- **Lack of robust tools:**
  - Each instrument has different characteristics
  - Observing strategy can condition the data reduction
  - Lack of manpower
  - Community ?
    - Success ! : Euro3D
    - Failure : Euro3D

Data reduction and analysis challenges

- **Data volume, for example MUSE:**
  - **One exposure is** > 1Gb (360 million resolved elements)
  - One night = a few 100 Gb of raw data
  - One 3D deep field will take 10 nights (> 1 Tb…)

- **Such instruments and applications require:**
  - A parallel data-reduction pipeline
  - Control the systematic to reach the required limiting magnitude
  - Optimal summation of 100 data cubes obtained under different sky conditions
  - Mining the final data cube to search for Lyα emission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3D Darwinism