Overview of *Integral Field Unit* techniques

Eric Emsellem

ESO

Thanks…

- **Roland Bacon (MUSE)**
- ***Matt Bershady (IFUs)***
- ***Scott Croom (SAMI)***
- ***Niranjan Thatte, Ryan Houghton (HARMONI)***
- ***Kevin Bundy, Niv Drory, Nick MacDonald (MaNGA)***
- ***Pierre Ferruit (JWST, NIRSpec)***
- ***Sebastian Sanchez (Califa)***
- ***Davor Krajnović (SAURON, MUSE)***
- ***Suzanne Ramsay (KMOS)***

Also to Richard McDermid, James Turner, Jeremy Allington-Smith

A mature field ?

- **Use 3D for science, not as a goal** [2009]
  - **Labelled papers** ("3D spectro of NGCXXX")
  - **Used in conjunction with other facilities / tools**

- **Multi λ, Multi facilities science**
  - ***Imaging + 2Ds + 3Ds + …***
  - ***λ-coverage is ESSENTIAL***
  - ***Space + Ground-based***
  - ***Modelling, simulations***

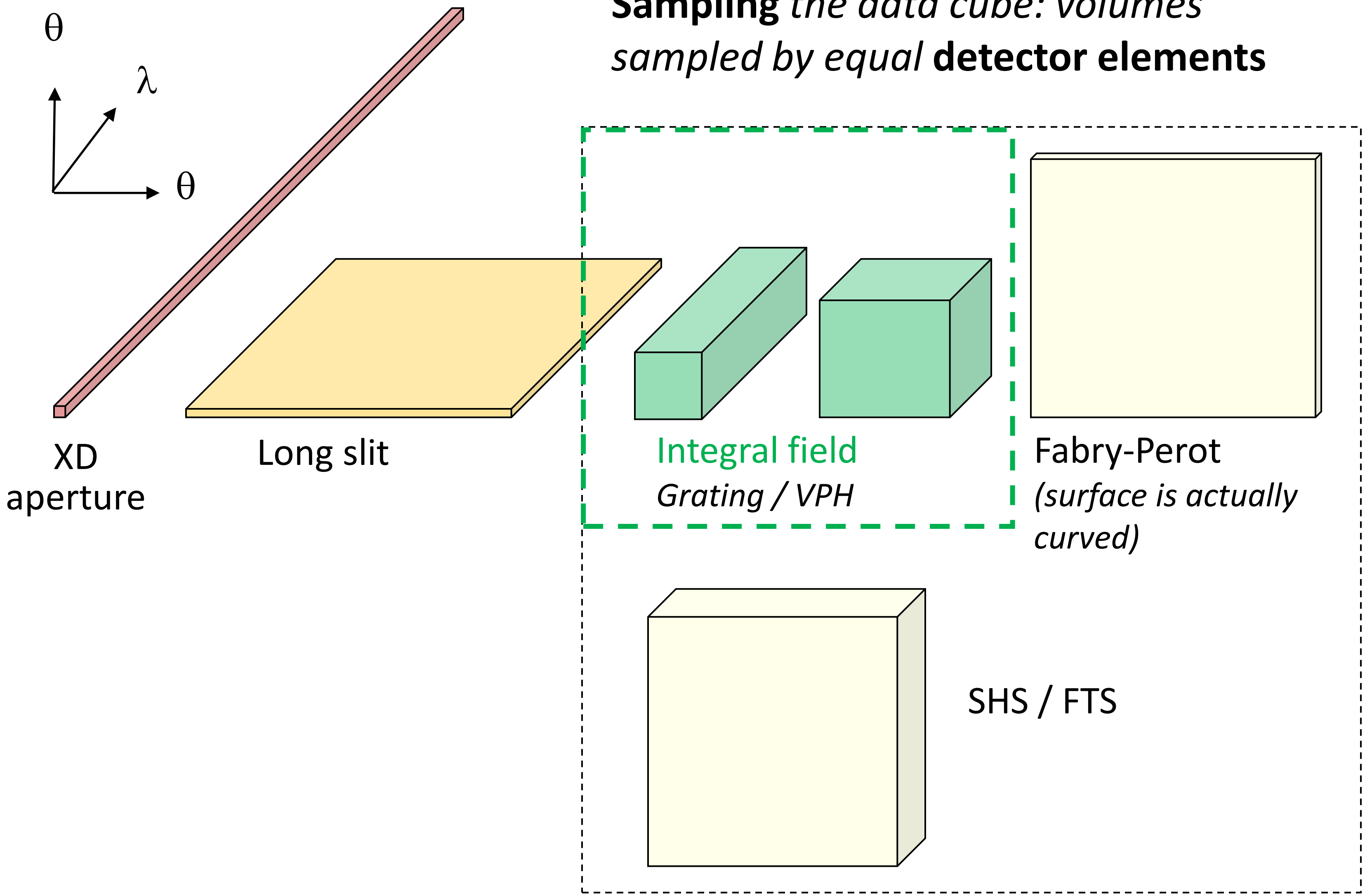
A mature technology?

- Yes
  - More systematic use of IFUs
  - Expertise is better distributed
  - Fast diversification of instruments

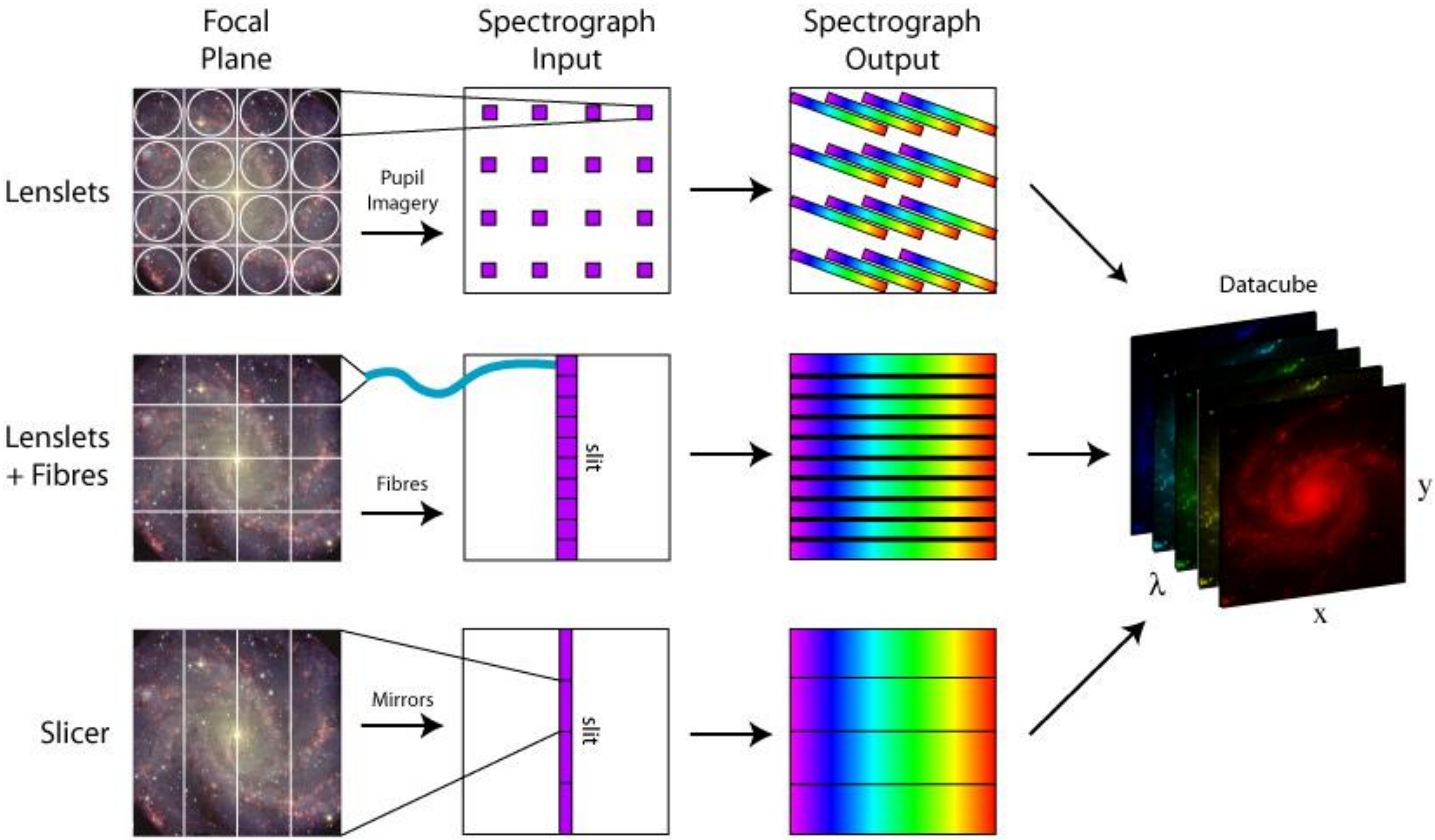
- No
  - Still seen as a specific label (“3D”)
  - Still getting specific requests as “IFU expert”
  - Fast Diversification of instruments
    - → Many different technologies
    - → new challenges
    - → Innovations

Fitting 3D onto a 2D detector

Sampling *the data cube: volumes sampled by equal* **detector elements**

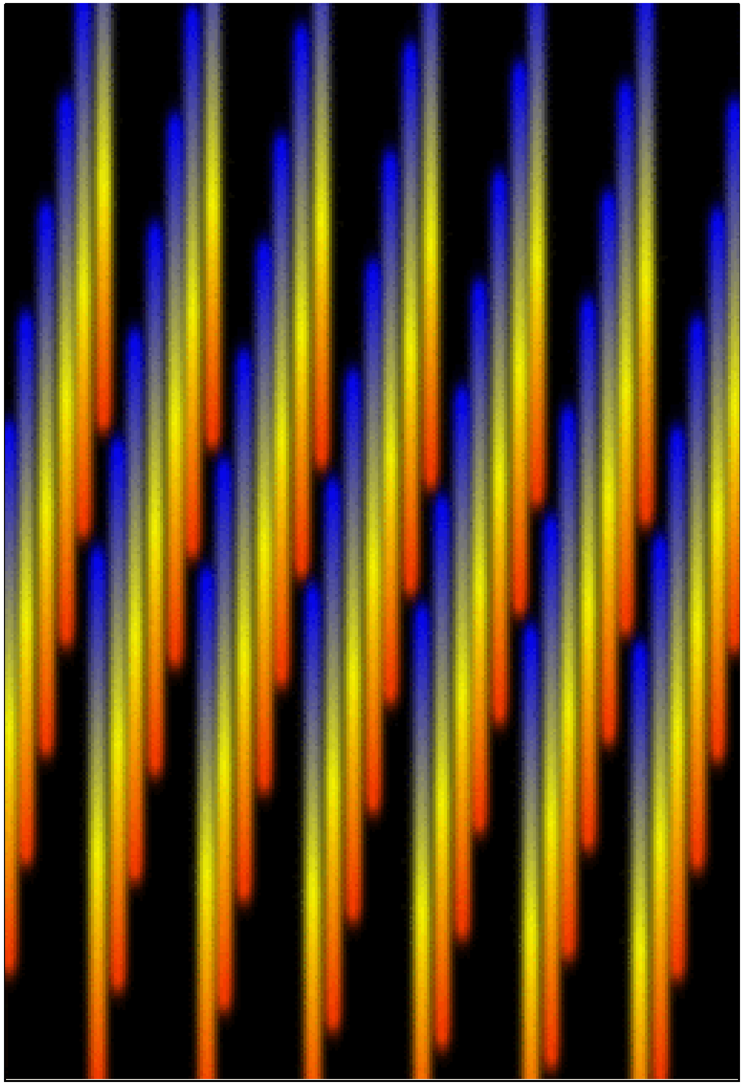


How to map 3D on 2D



© Allington-Smith, adapted by Westmoquette et al.

The TIGER concept: The trick



Uniform illumination at the entrance of the array

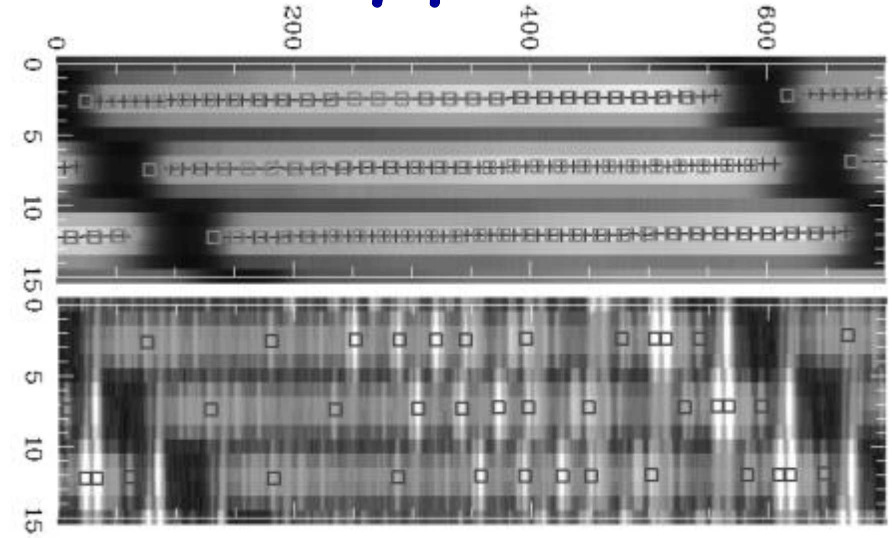
The array samples the field and focus the light into micro-pupils

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

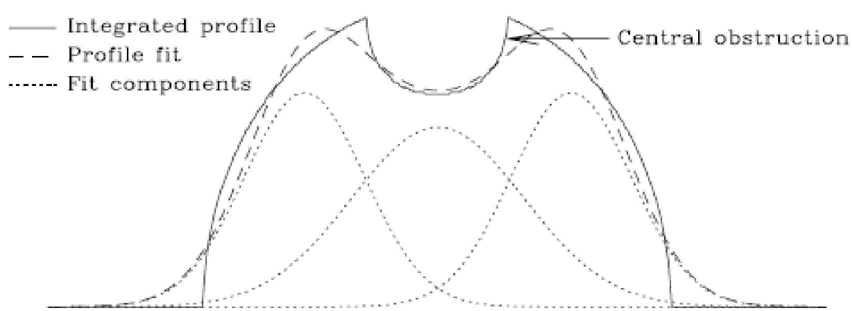
How is the 3D data mapped ?



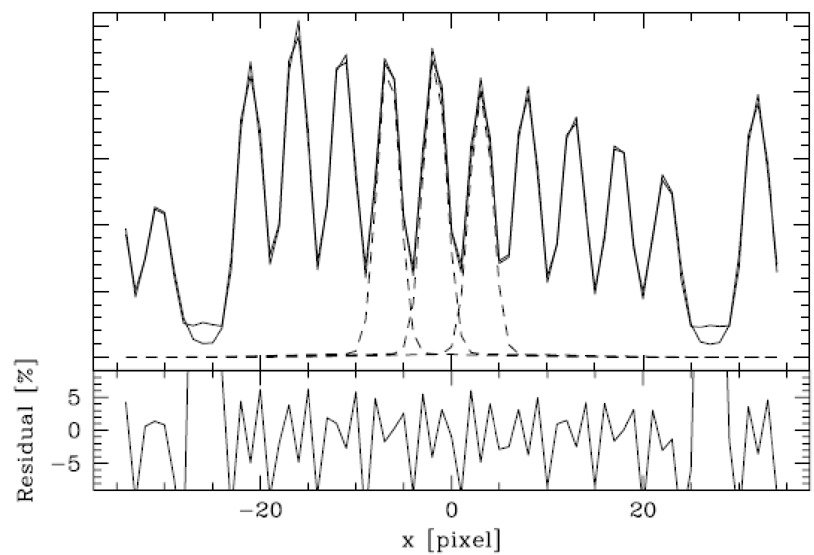
- **Example: SAURON mask**
  - Flexures: needs reference expo
  - Critical blends
  - Sampling of the spectral PSF

➔ Detailed optical model:

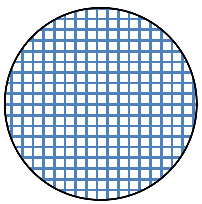
To know where each x,y,λ lie on the CCD !!

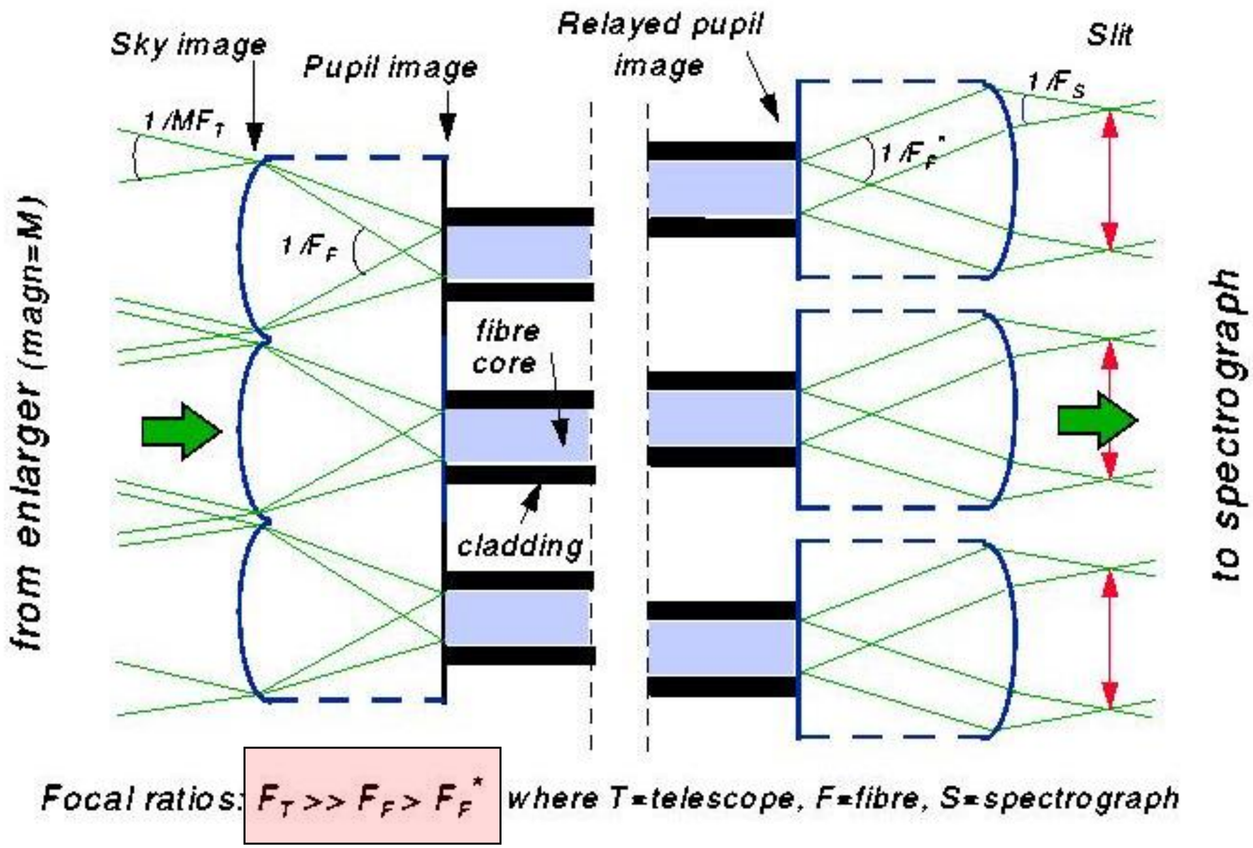


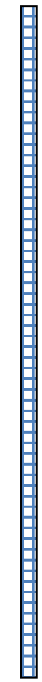
Integrated cross-dispersion profile $\mathcal{G}$ of the geometrical micropupil (solid line) and its fit (dashed line) with three Gaussian functions (dotted lines).



Microlens + Fibre

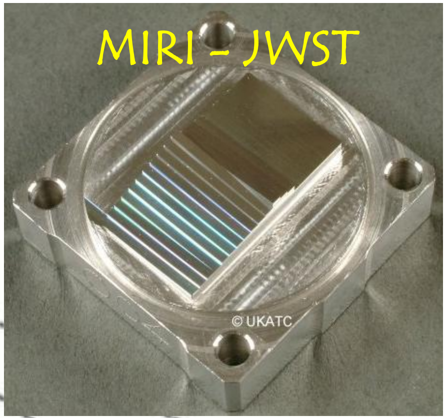


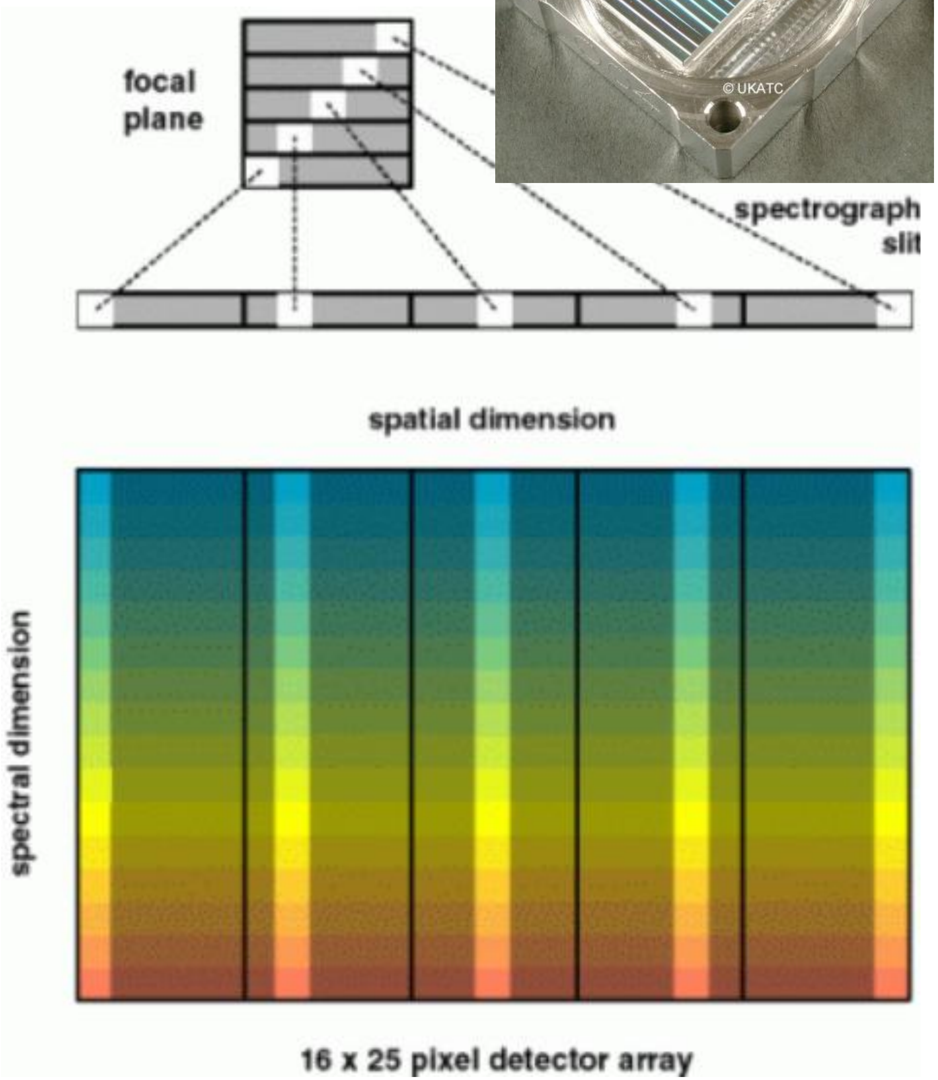




Allington-Smith & Content '98

Image Slicer





NIR Slicer (5-30 μm) : MIRI

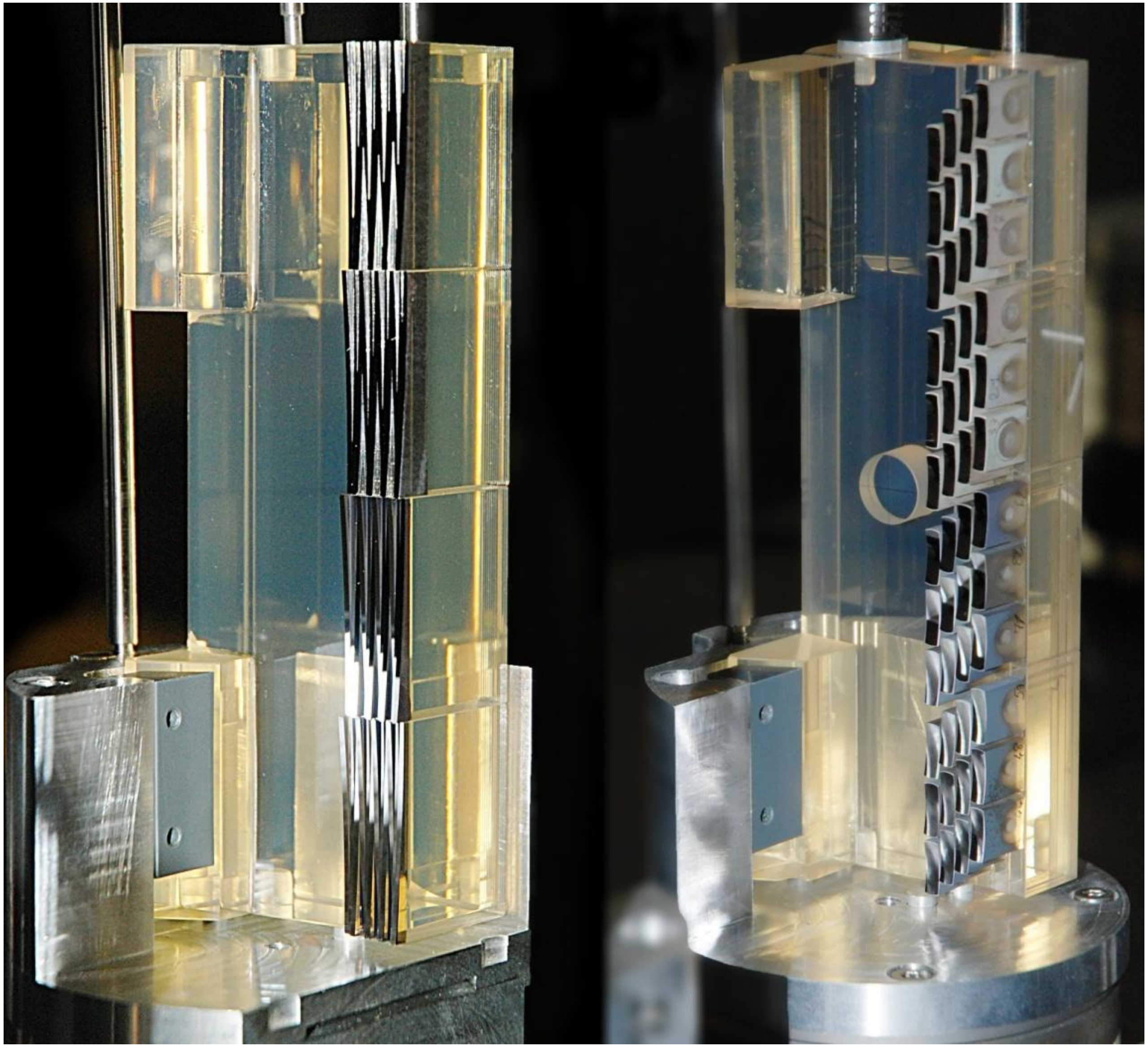
Pros:

- Compact design
- High throughput
- “Easy” cryogenics

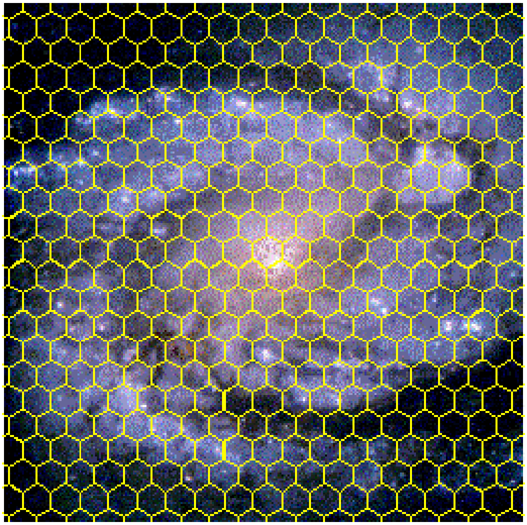
Cons:

- ***Difficult to manufacture***

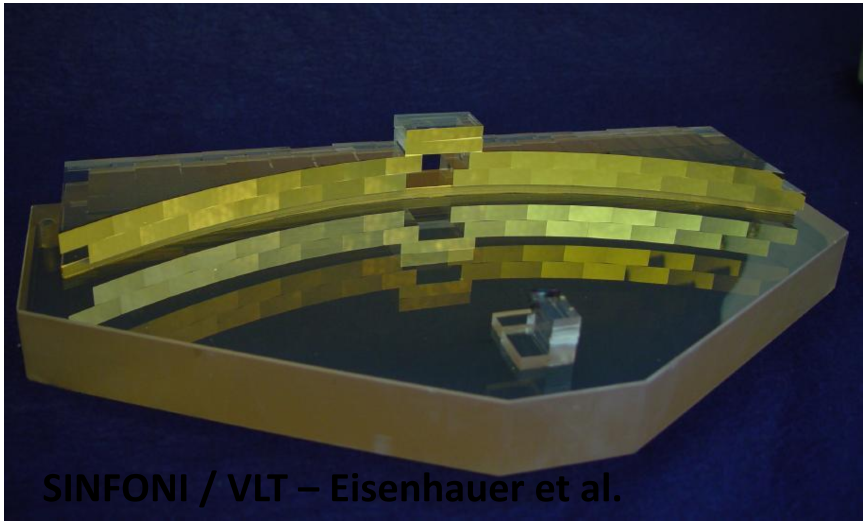
The MUSE / VLT Slicer



CCD Mapping



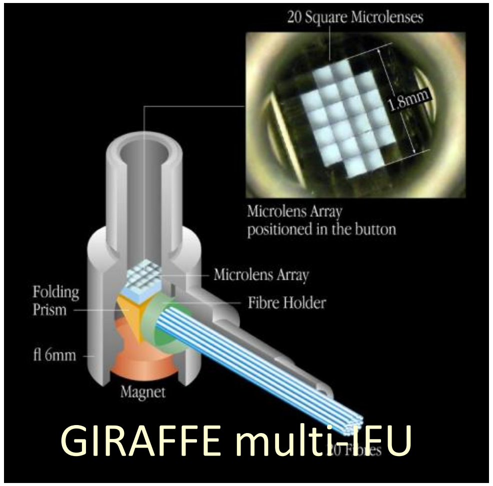
or



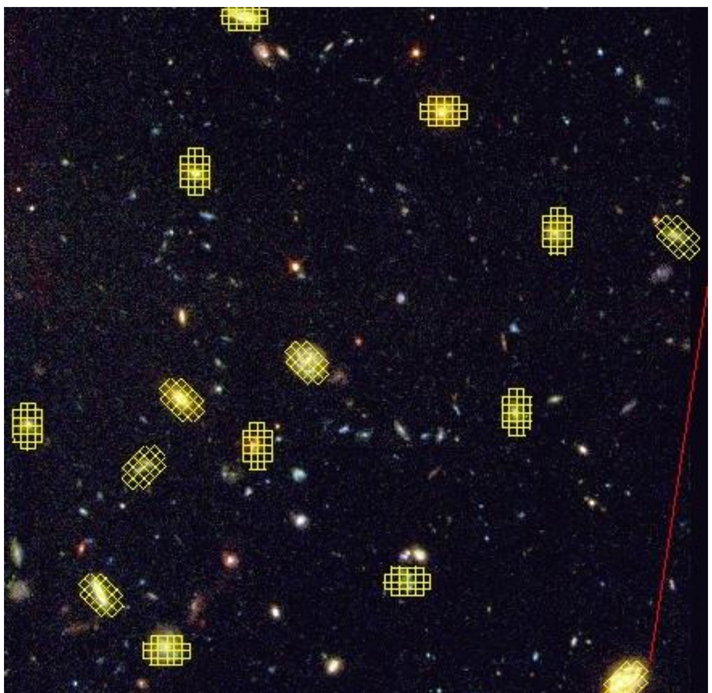
- Lenses and Fibers:
  - The spatial and spectral information are decoupled on the CCD
  - ➔ Each spectrum (x,y, for all λ) is a separate entity
- Slicers:
  - Spatial & spectral information entangled as in long-slit spectroscopy
  - ➔ Spatial dimensions x' and y' are not equivalent

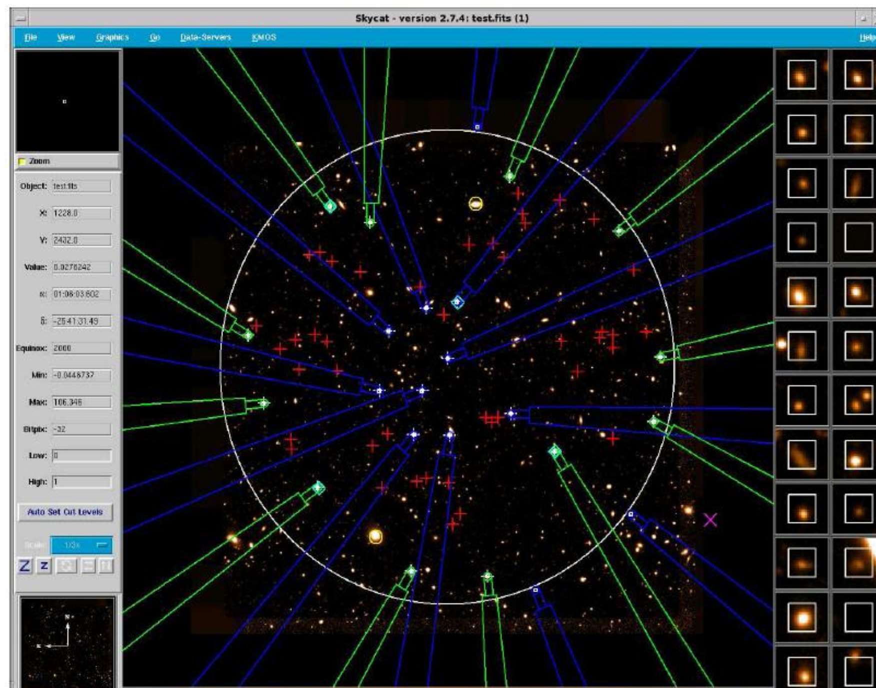
Deployable IFUs

See also e.g., Sharples, Cirasuolo's talks + KMOS session



KMOS (NIR)





Specific Information Density

Objective comparison independent of scale

resolution elements

$$Q = \eta \frac{N_p N_q N_\lambda}{N_x N_y}$$

throughput

detector pixels

$$Q_L \simeq \frac{\eta}{4d^2}\left(\frac{1}{f_G M^2}\right)$$

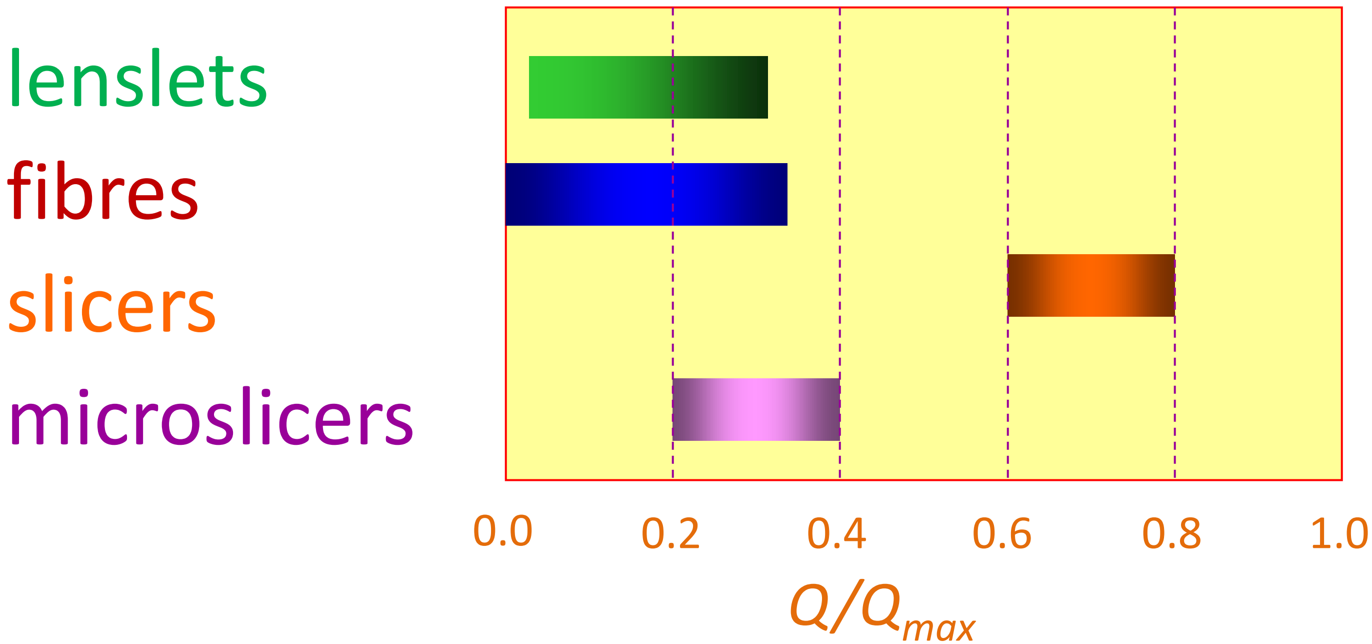
$$Q_F \simeq \frac{\eta}{4d^2}\left(1-\frac{f_G}{\sqrt{N_e}}\right)\left[\left(\frac{s}{d}\right)\sqrt{1+\left(\frac{2s}{d}\right)^2}\right]^{-1}$$

$$Q_S \simeq \frac{\eta}{4}\left[\frac{1}{2}\left(1-\frac{f_G}{\sqrt{N_e}}\right)\right]$$

$$Q_M \simeq \frac{\eta}{4}\left[M d_x\left(1+\frac{f_G}{M d_y}\right)\right]^{-1}$$

	example	d	N_R	M	η	f_G	$Q/Q\max$
Lenslet array	SAURON(5)	52	1600	0.16	0.7	1	0.02
Fibre system	GMOS-IFU(2)[1]	5.5	1500	-	0.6	4	0.11
Image slicer	GNIRS-IFU(4; 13)	1	700	-	0.8	4	0.68
Micro-slicer	MEIFU(8)[2]	15×51	$\sim 10^6$	0.29	0.7	3	0.26

Best technique?



➔ Slicers .... but difficult to make

Fibers

Table 1. Fiber Integral Field Instruments

Instrument	Coupling Method	Telescope	D_T (m)	Ω (arcsec^2)	$d\Omega$ (arcsec^2)	N_θ	$\Delta\lambda/\lambda$	R	N_R	ϵ
Existing Optical Instruments										
DensePak	fiber	WIYN	3.5	564.0	6.2	91	1.02	1000.	1024	0.04
		WIYN	3.5	564.	6.2	91	0.07	13750.	1024	0.04
		WIYN	3.5	564.	6.2	91	0.04	24000.	1024	0.04
		WIYN	3.5	119.	1.3	91	1.02	1000.	1024	0.04
		WIYN	3.5	119.	1.3	91	0.07	13500.	1024	0.04
		WIYN	3.5	119.	1.3	91	0.04	24000.	1024	0.04
SparsePak	fiber	WIYN	3.5	1417.0	17.3	82	1.02	800.	819	0.07
		WIYN	3.5	1417.	17.3	82	0.07	11000.	819	0.07
		WIYN	3.5	1417.	17.3	82	0.03	24000.	819	0.07
PPak	fiber	Calar Alto	3.5	2070.0	5.64	367	0.15	7800.0	1183	0.15
INTEGRAL	fiber	WHT	4.2	32.6	0.159	205	0.22	2350.	515	···
		WHT	4.2	32.6	0.159	205	0.94	550.	515	···
		WHT	4.2	139.3	0.64	219	0.22	2350.	515	···
		WHT	4.2	139.3	0.64	219	0.94	550.	515	···
		WHT	4.2	773.	5.73	135	0.07	2350.	300	···
		WHT	4.2	773.	5.73	135	0.90	550.	300	···
Future Optical Instruments										
VIRUS	fiber	HET	9.2	32604	1.0	32604	0.505	811.	410	0.16
Existing Near Infrared Instruments										
GOHSS	fiber	TNG	3.6	44.2	1.77	25	0.12	4380.	512	0.13
Future Near-Infrared Instruments										

Fibers + Lenslets

Table 2. Fiber+Lenslet Integral Field Instruments

Instrument	Coupling Method	Telescope	D_T (m)	Ω (arcsec^2)	$d\Omega$ (arcsec^2)	N_θ	$\Delta\lambda/\lambda$	R	N_R	ϵ
Existing Optical Instruments										
PMAS	lenslet+fiber	Calar Alto	3.5	64.	0.5	256	0.11	9400.	1000	0.15
		Calar Alto	3.5	64.	0.5	256	0.52	1930.	1000	0.15
		Calar Alto	3.5	144.	0.75	256	0.11	9400.	1000	0.15
		Calar Alto	3.5	144.	0.75	256	0.52	1930.	1000	0.15
		Calar Alto	3.5	256.	1.0	256	0.11	9400.	1000	0.15
		Calar Alto	3.5	256.	1.0	256	0.52	1930.	1000	0.15
SPIRAL-B	lenslet+fiber	AAT	3.9	251.	0.49	512	0.29	1700.	495	...
		AAT	3.9	251.	0.49	512	0.07	7500.	495	...
MPFS	lenslet+fiber	SAO	6.0	256.	1.0	256	0.12	8800.	1024	0.045
		SAO	6.0	64.	0.25	256	0.47	2200.	1024	0.045
IMACS-IFU	lenslet+fiber	Magellan	6.5	...	...	...	...	...	...	...
GMOS	lenslet+fiber	Gemini	8.0	49.6	0.04	1500	0.21	3450.	730.	...
		Gemini	8.0	49.6	0.04	1500	0.32	2300.	730.	...
		Gemini	8.0	49.6	0.04	1500	0.82	890.	730.	...
		Gemini	8.0	24.8	0.04	750	0.42	3450.	1460.	...
		Gemini	8.0	49.6	0.04	1500	0.64	2300.	1460.	...
		Gemini	8.0	49.6	0.04	1500	1.00	890.	1460.	...
VIMOS	lenslet+fiber	VLT	8.0	2916.	0.45	6400	0.6	250.	150	...
		VLT	8.0	698.	0.11	6400	0.6	250.	150	...
		VLT	8.0	729.	0.45	1600	0.2	2500.	500	...
		VLT	8.0	174.5	0.11	1600	0.2	2500.	500	...
ARGUS/IFU	lenslet+fiber	VLT	8.0	83.9	0.27	315	0.105	11000.	1155	...
		VLT	8.0	83.9	0.27	315	0.042	39000.	1625	...
ARGUS	lenslet+fiber	VLT	8.0	27.7	0.09	315	0.105	11000.	1155	...
		VLT	8.0	27.7	0.09	315	0.042	39000.	1625	...
Future Optical Instruments										
Existing Near-Infrared Instruments										
COHSI	lenslet+fiber	UKIRT	3.8	...	...	100	0.26	500.	128	...
SMIRFS	lenslet+fiber	UKIRT	3.8	24.2	0.34	72	0.023	5500.	128	...
CIRPASS	lenslet+fiber	Gemini	8.0	54.5	0.13	490	0.41	2500.	1024	...
		Gemini	8.0	54.5	0.13	490	0.085	12000.	1024	...
		Gemini	8.0	27.0	0.06	490	0.41	2500.	1024	...
		Gemini	8.0	27.0	0.06	490	0.085	12000.	1024	...
Future Near-Infrared Instruments										

Image Slicers

Table.3 Slicer Integral Field Instruments

Instrument	Coupling Method	Telescope	D_T (m)	Ω ($arcsec^2$)	$d\Omega$ ($arcsec^2$)	N_θ	$\Delta\lambda/\lambda$	R	N_R	ϵ
Existing Optical Instruments										
ESI	slicer	Keck	10.0	⋯	⋯	⋯	⋯	⋯	⋯	⋯
Future Optical Instruments										
WiFeS	slicer	ANU	2.3	775.	1.	775	1.03	3000.	3090	⋯
		ANU	2.3	775.	1.	775	0.44	7000.	3090	⋯
IMACS/GISMO	slicer	Magellan	6.5	⋯	⋯	⋯	⋯	⋯	⋯	⋯
MUSE	advanced-slicer	VLT	8.0	3600	0.04	9e4	0.67	3000.	2000	0.24
Existing Near-Infrared Instruments										
PIFS	slicer	Palomar	5.0	51.8	0.45	115	0.23	550.	128	0.22
		Palomar	5.0	51.8	0.45	115	0.10	1300.	128	0.22
GNIRS	advanced-slicer	Gemini	8.0	15.4	0.023	684	0.301	1700.	512	⋯
		Gemini	8.0	15.4	0.023	684	0.087	5900.	512	⋯
SPIFI	slicer	VLT	8.0	0.54	0.006	1024	0.34	3000.	1024	0.3
		VLT	8.0	10.2	0.001	1024	0.34	3000.	1024	0.3
		VLT	8.0	64.0	0.06	1024	0.34	3000.	1024	0.3
NIFS	advanced-slicer	Gemini	8.0	9.0	0.01	900	0.19	5300.	1007	⋯
Future Near-Infrared Instruments										
KMOS	advanced-slicer	VLT	8.0	188.0	0.04	4204	0.28	3600.	1000	⋯
FISICA/FLMINGOS	advanced-slicer	GTC	10.4	72.0	0.53	136	0.79	1300.	1024	⋯
Future Optical–Near-Infrared Space-Based Instruments										
NIRSpec	advanced-slicer	JWST	6.5	⋯	⋯	⋯	⋯	⋯	⋯	⋯
MIRI	advanced-slicer	JWST	6.5	⋯	⋯	⋯	⋯	⋯	⋯	⋯
SNAP	advanced-slicer	SNAP	2	⋯	⋯	⋯	⋯	⋯	⋯	⋯

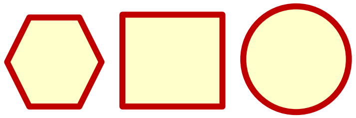
Lenslets

Table 4. Lenslet Integral Field Instruments

Instrument	Coupling Method	Telescope	D_T (m)	Ω (arcsec^2)	$d\Omega$ (arcsec^2)	N_θ	$\Delta\lambda/\lambda$	R	N_R	ϵ
Existing Optical Instruments										
SAURON	lenslet	WHT	4.2	1353	0.88	1577	0.11	1213.	128	···
OASIS	lenslet	WHT	4.2	99	0.07	1577	0.10	1475.	150	···
		WHT	4.2	1.92	0.002	1100	0.50	1000.	400	···
		WHT	4.2	31.0	0.026	1100	0.50	1000.	400	···
		WHT	4.2	180.	0.17	1100	0.50	1000.	400	···
Future Optical Instruments										
Existing Near-Infrared Instruments										
OSIRIS	lenslet	Keck	10.4	1.2	0.02	3000	0.12	3400.	400	···
		Keck	10.4	30.	0.10	3000	0.12	3400.	400	···
		Keck	10.4	0.3	0.02	1019	0.47	3400.	1600	···
		Keck	10.4	7.5	0.10	1019	0.47	3400.	1600	···
Future Near-Infrared Instruments										

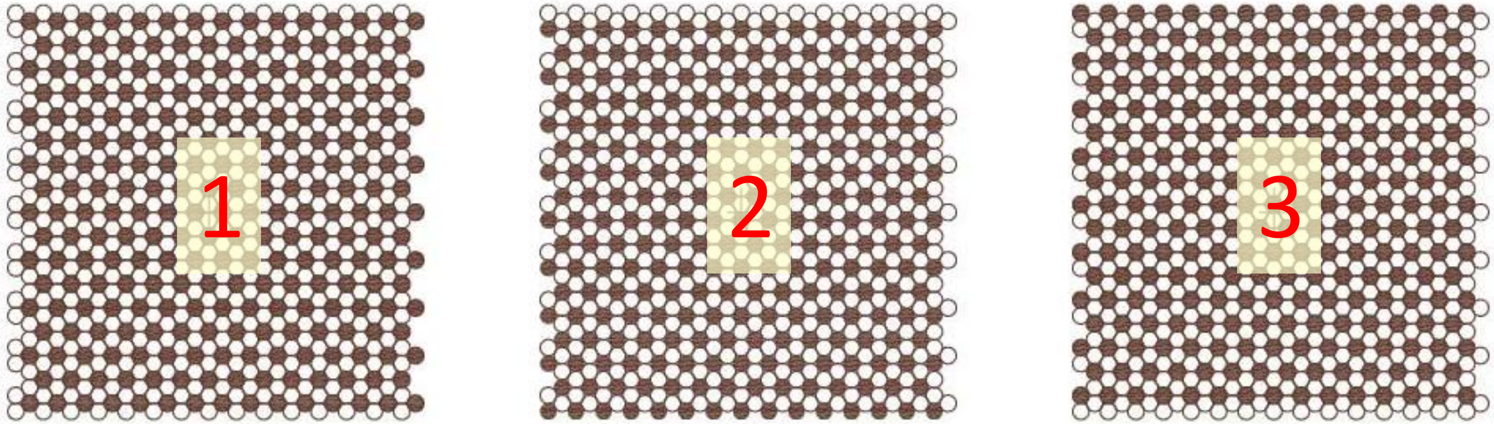
Optical/Near Infrared spectroscopy

- Resolution
  - Spectral = Shannon (Nyquist)
    - Usually FWHM or σ
  - Spatial but which SPAXEL geometry?
    - Usually FWHM or σ

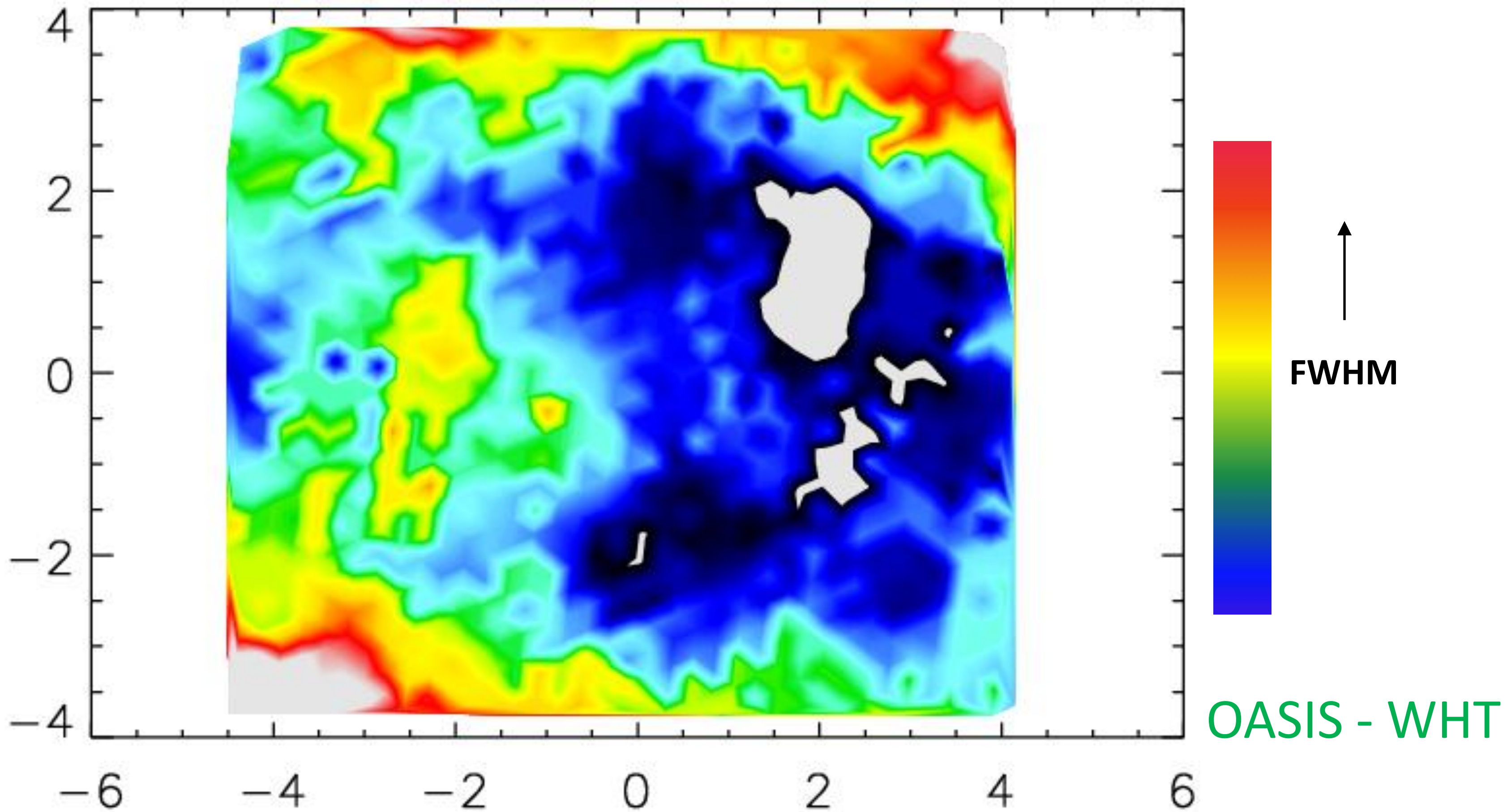


- Sampling ≠ Resolution
  - Sparse or Continuous

➔ Example : VIRUS

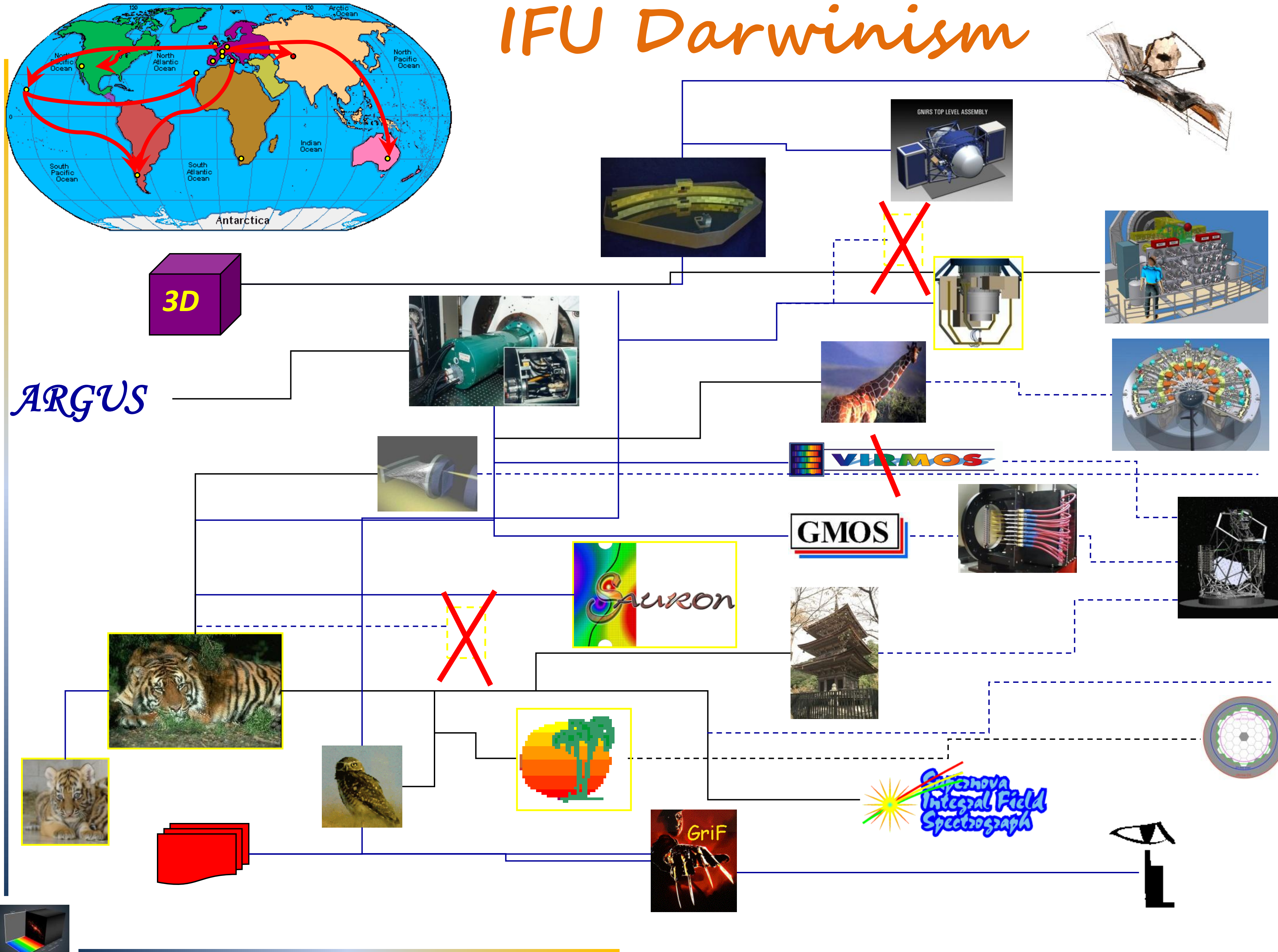


Warning: Spectral Resolution



- Variations in spectral PSF across field
- Need to homogenize before merging
- Can be measured using e.g., twilight sky

IFU Darwinism

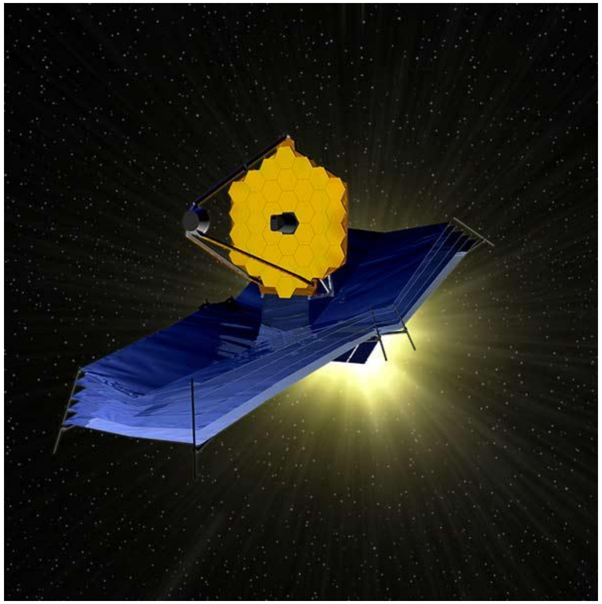


IFU evolution

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
GMOS	2001	1,500	2,048	3,072,000
VIMOS	2002	6,400	550	3,520,000
SINFONI (NIR + AO)	2005	2,048	2,048	4,194,304
OSIRIS (NIR+AO)	2005	1,019	2,048	2,086,912
MUSE	2008	90,000	4,096	368,640,000
VIRUS—HET	-	34,500	2,048	70,656,000

Survival of the fittest: An interesting example

- JWST
  - 6.5m telescope (25 m^2)
  - 0.6-29 μm coverage
  - 0.1 arcsec resolution or better
  - operating temperature < 50º K
  - 5-10 years lifetime
  - Launch 2018 → 1.5 Mkm orbit at L2



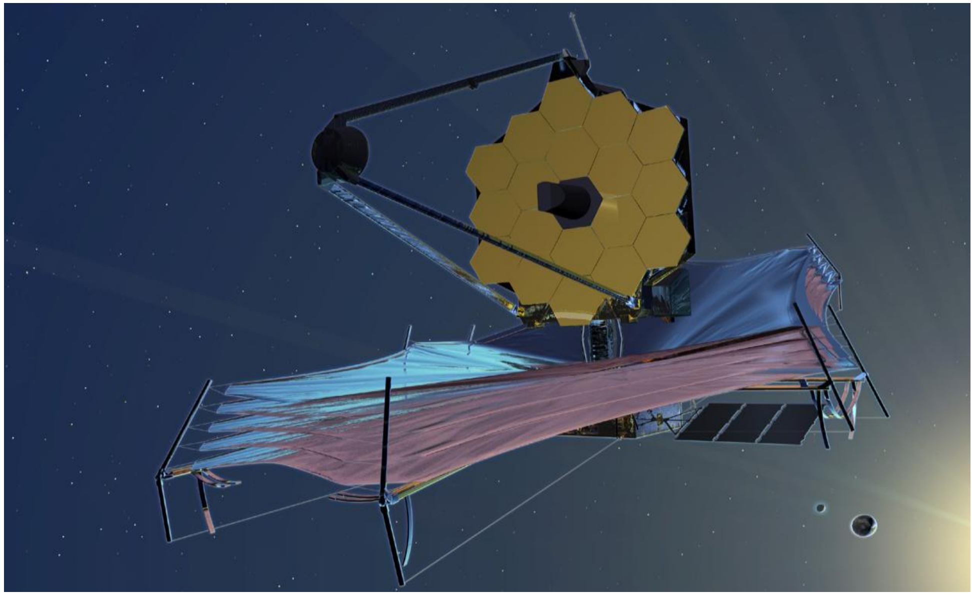
- Science mission
  - first light
  - galaxy assembly
  - birth of stars and proto-planets
  - planetary systems / origins of life

- Instruments
  - NIRCam
  - NIRSpec
  - NIRISS
  - MIRI

JWST survivors...

- An IFU in space
  - Already in use for military purposes (FTS, and also in climatology)
  - Optical device initially thought as a good technology for space
- Deep-field spectroscopy
  - Large field of view and large multiplexing capability

➔ “A la MUSE” (advanced slicer)



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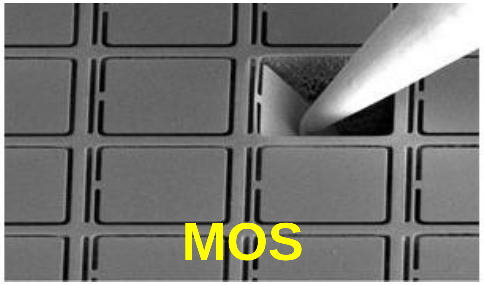
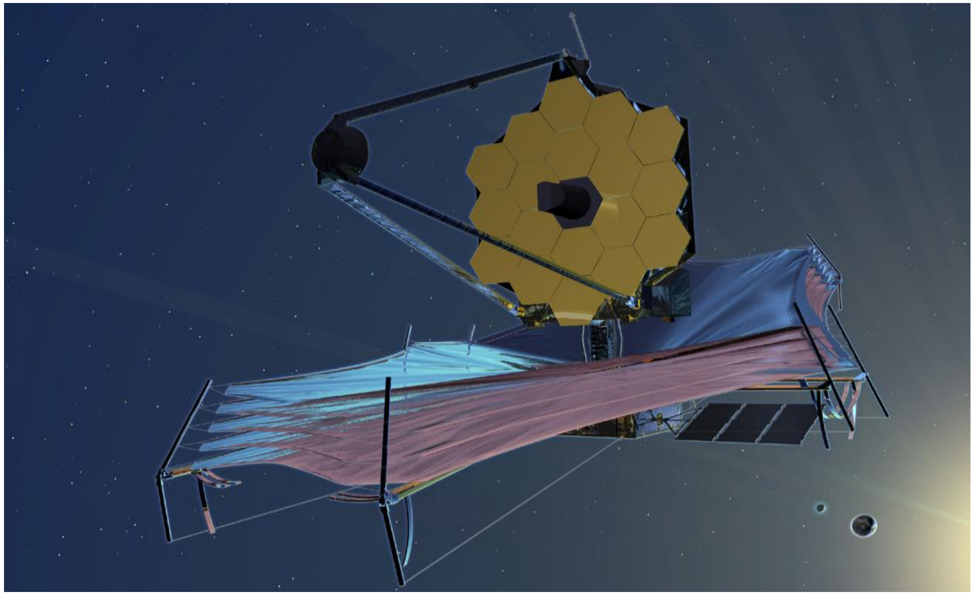
→ ~~“A la MUSE” (advanced slicer)~~



(+ NIRISS: slitless spectroscopy)



JWST survivors...

- Spatially resolved spectroscopy of individual objects
  - NIRSpec and MIRI

➔ NOT Science driven technology?

➔ Slicer approach

the 1 kg = $ 1M principle

→ cost + technical readiness

Dedicated Instruments ?

SAURON

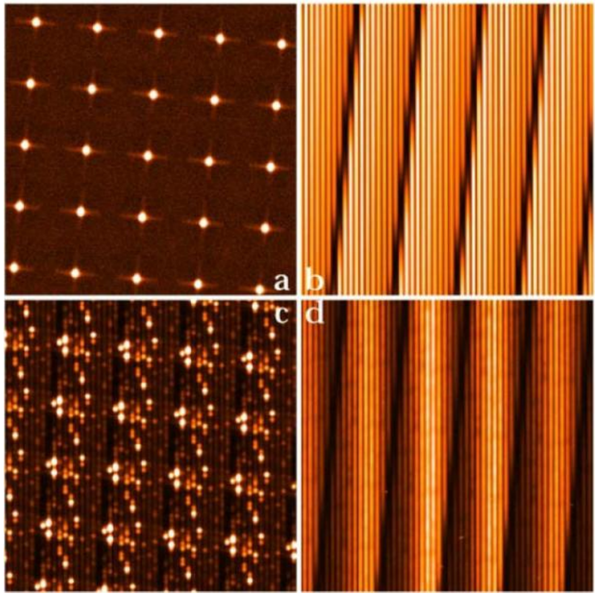
- Fast, cheap and good (really??):
  - Good marketing principle
  - But hard to implement

➔ Need for a good software

[and a few patient astronomers]

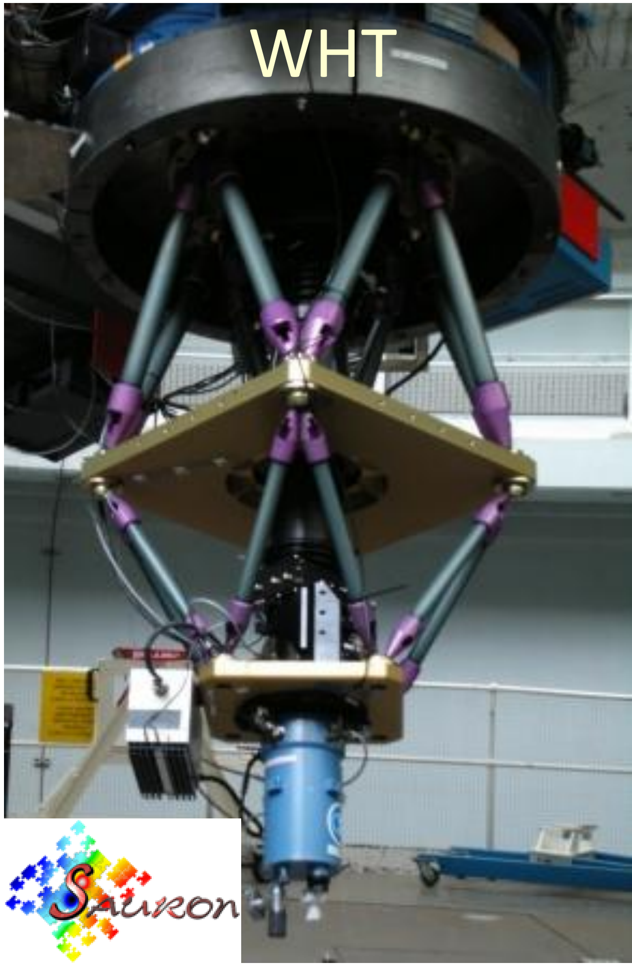
Micropupil

Continuum

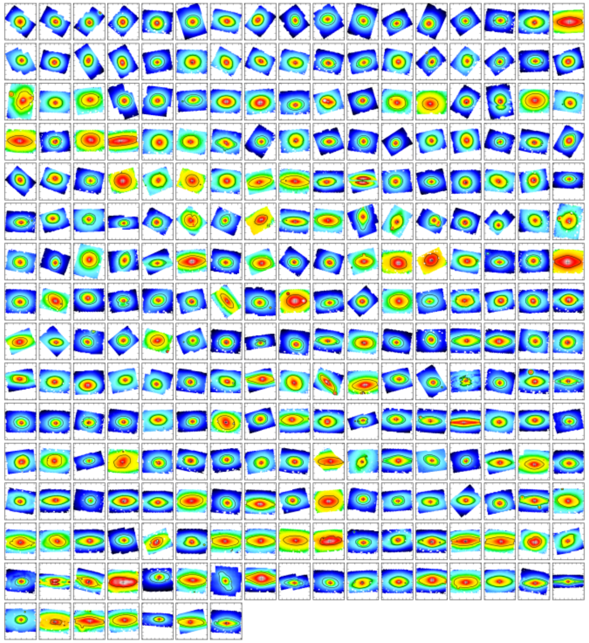


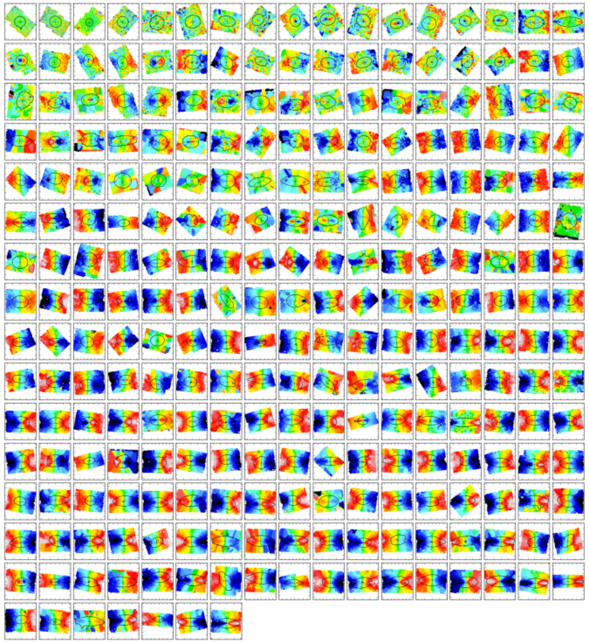
Arc

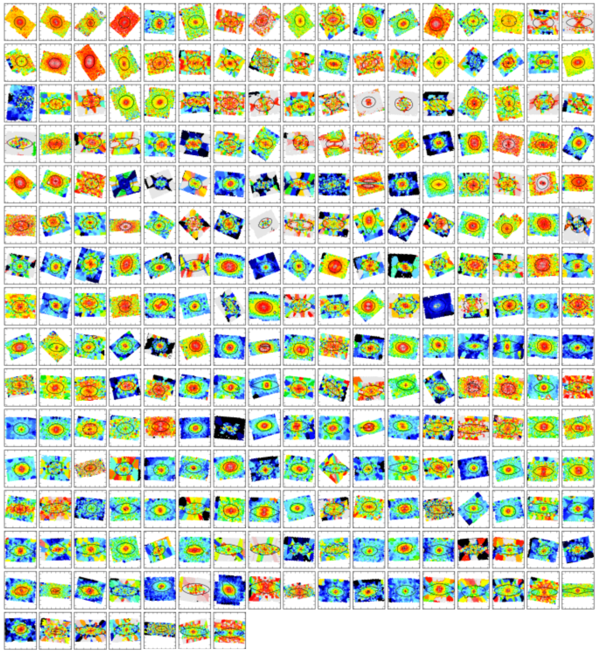
Galaxy

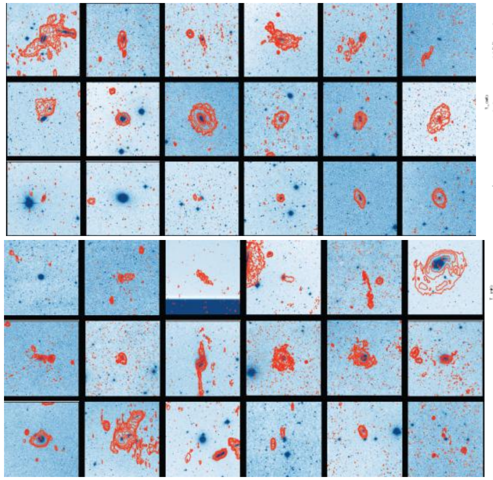


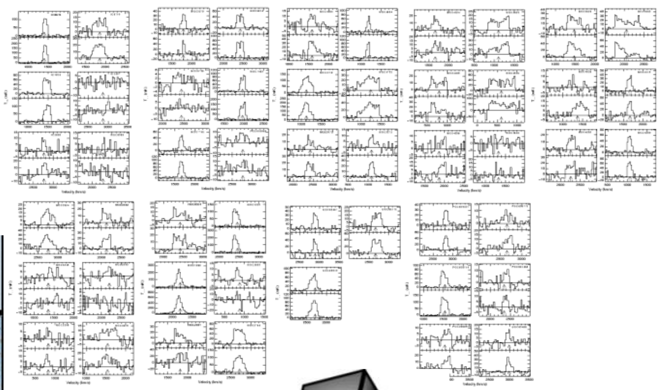
A few spectra and maps…

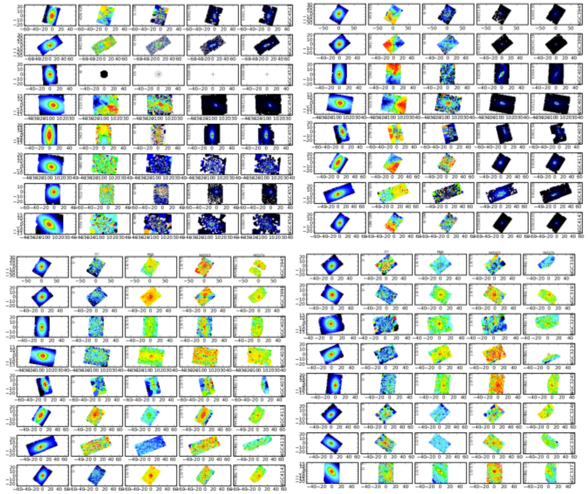






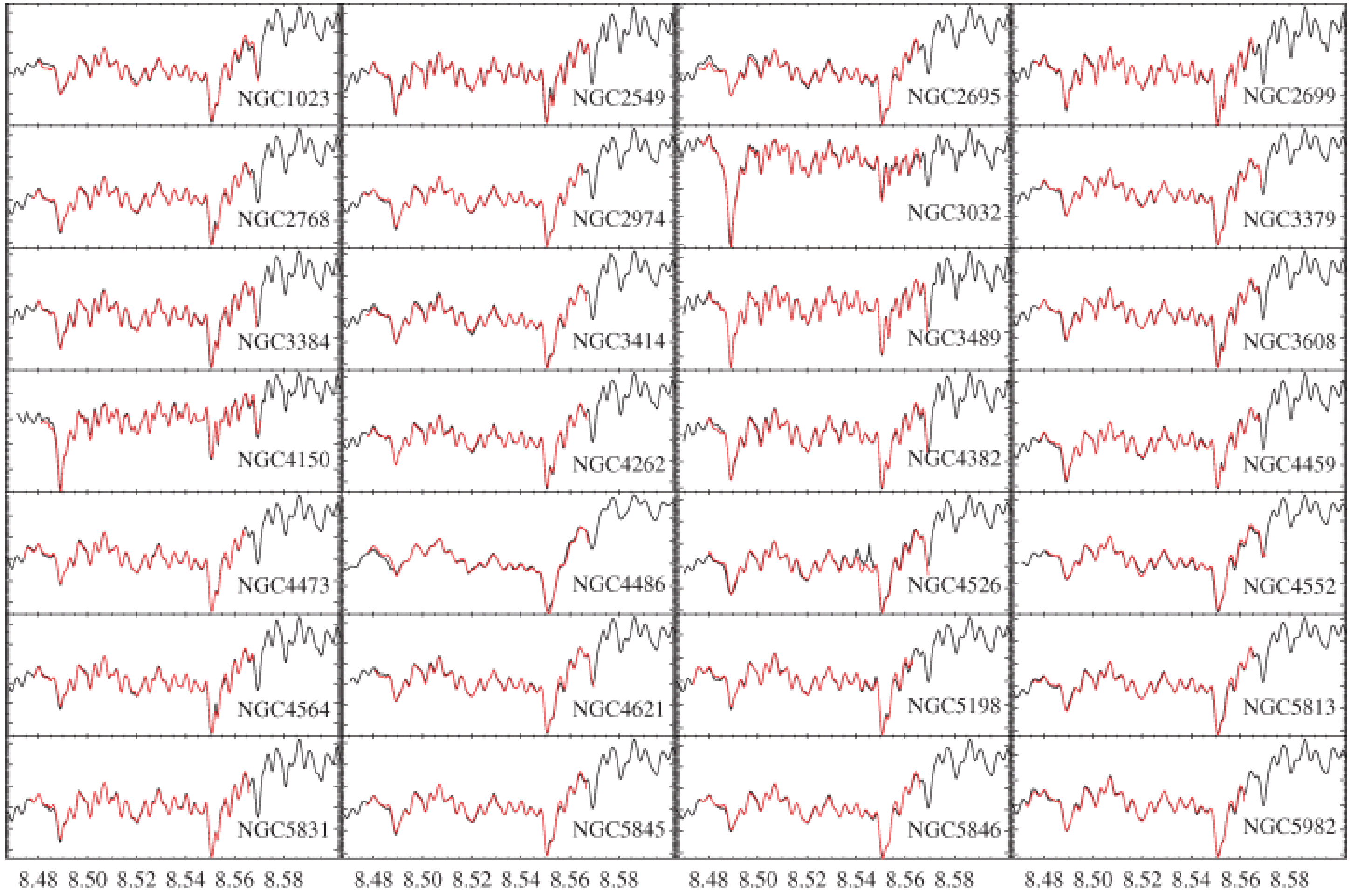






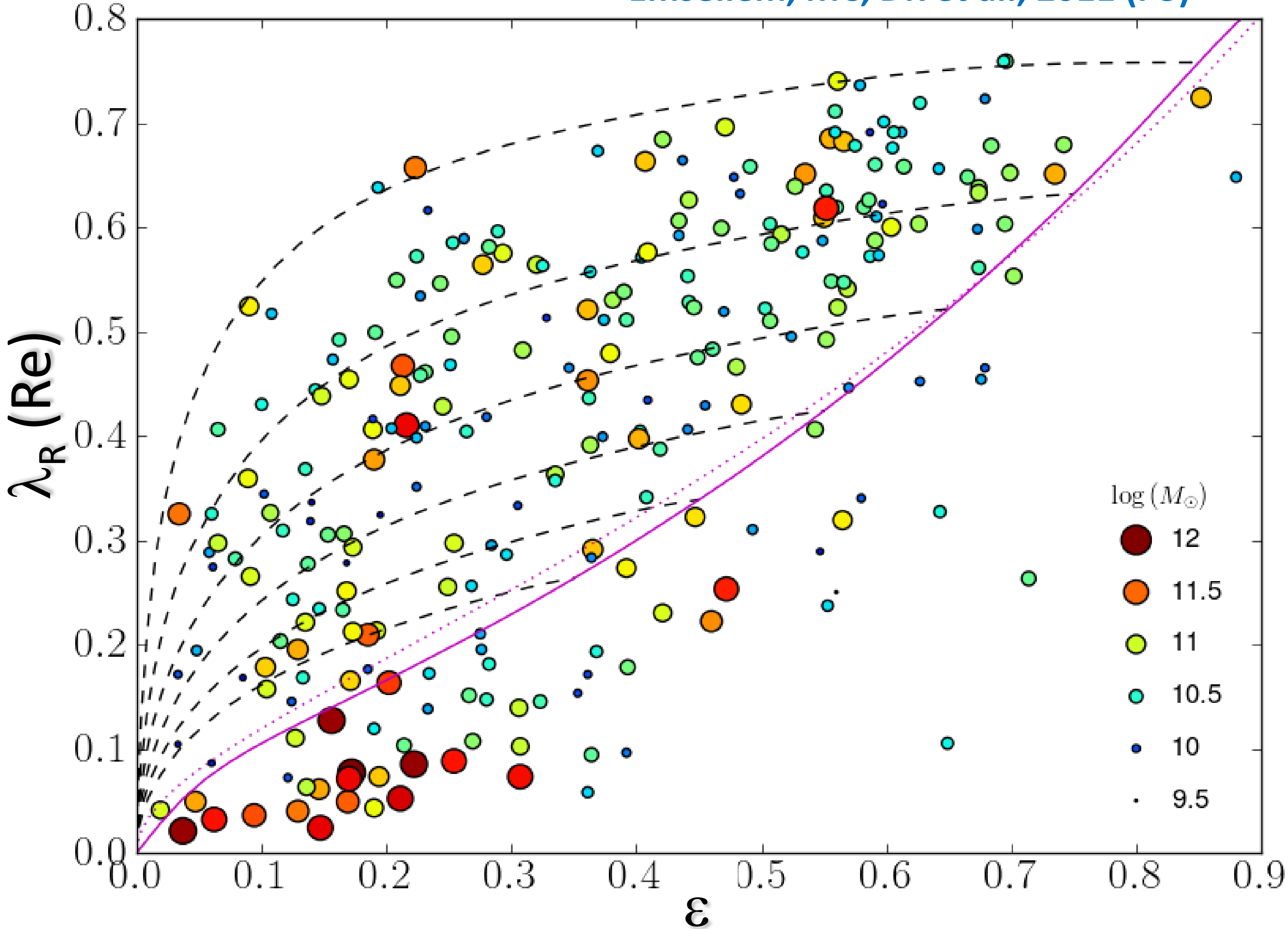
Validation
Comparing datasets

- **SAURON vs OASIS**



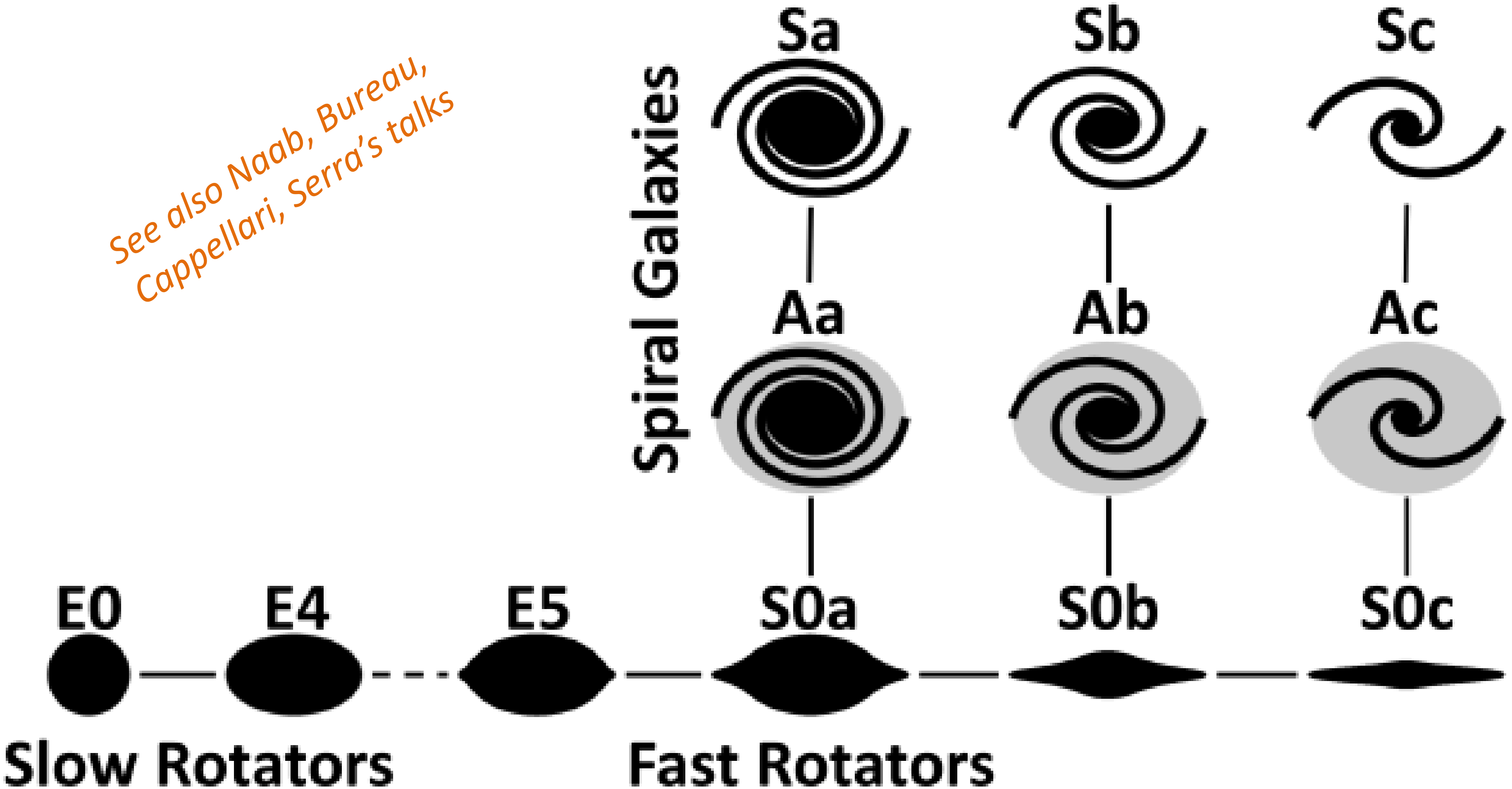
Building of angular momentum

Emsellem, MC, DK et al., 2011 (P3)



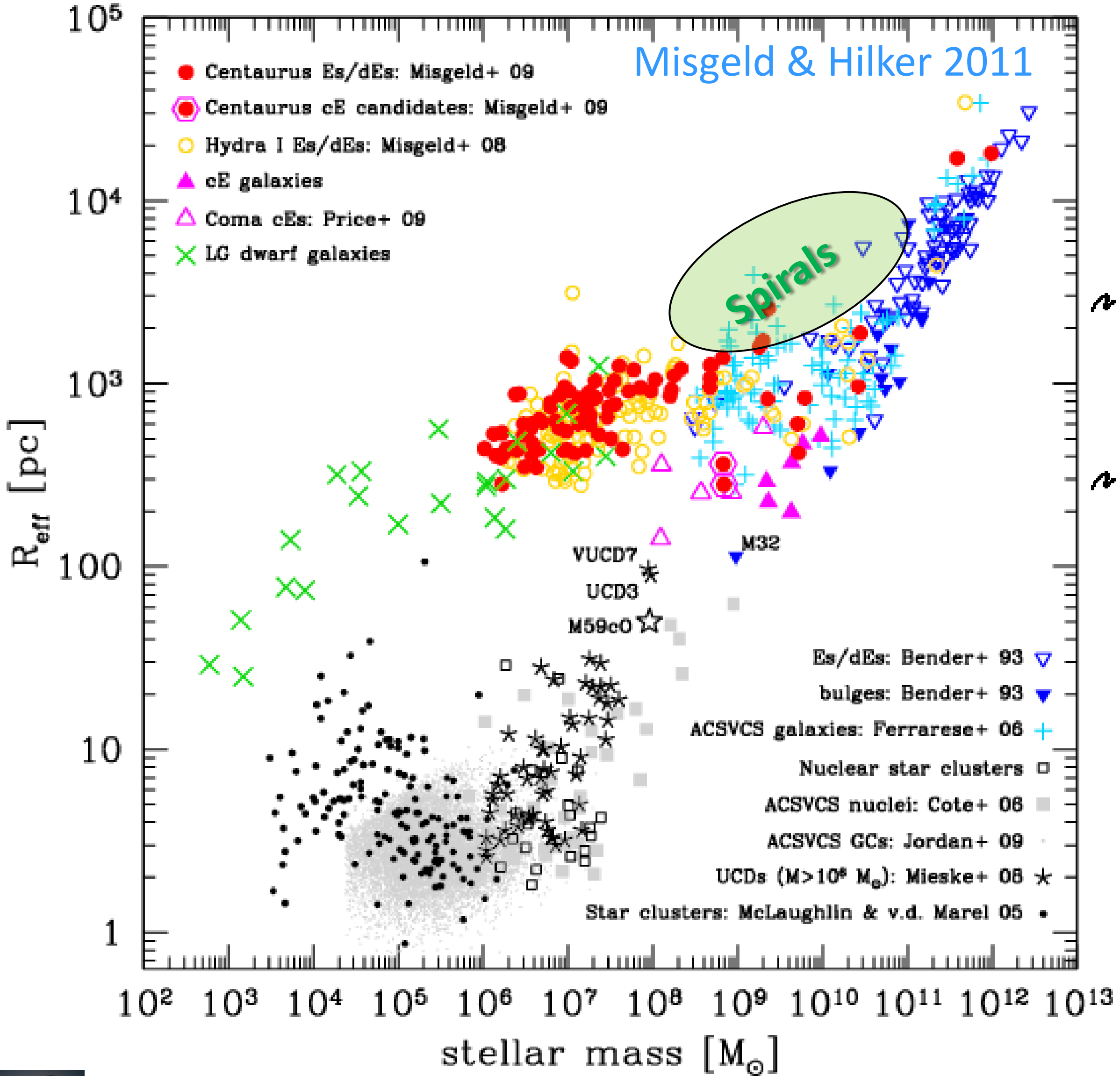
The Comb

See also Naab, Bureau, Cappellari, Serra's talks



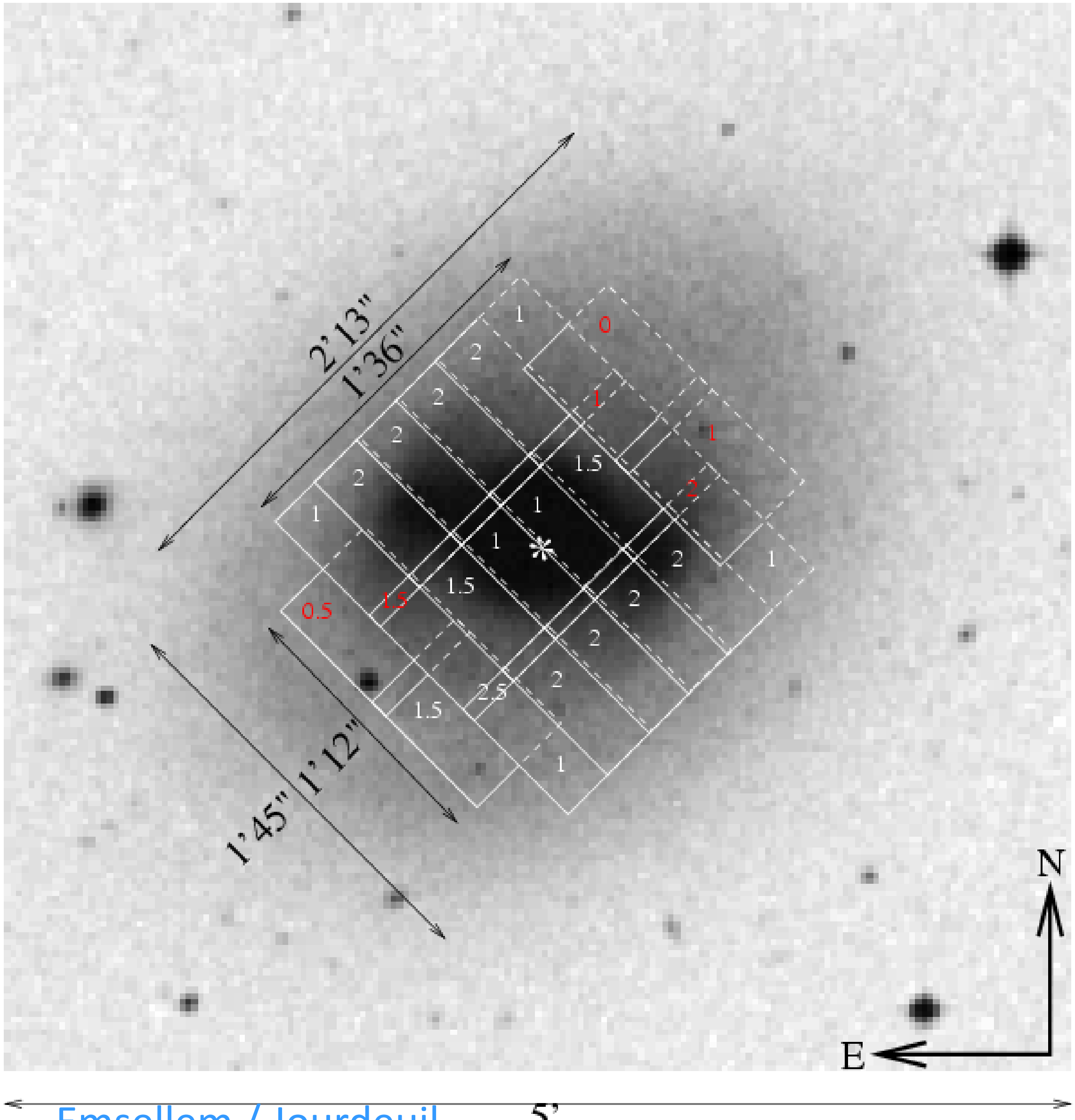
Cappellari , Emsellem, Krajnović, McDermid et al., 2011

From ETGs to Spirals



- Can we also cover Spirals?
- Can we go beyond 1 effective radius ?

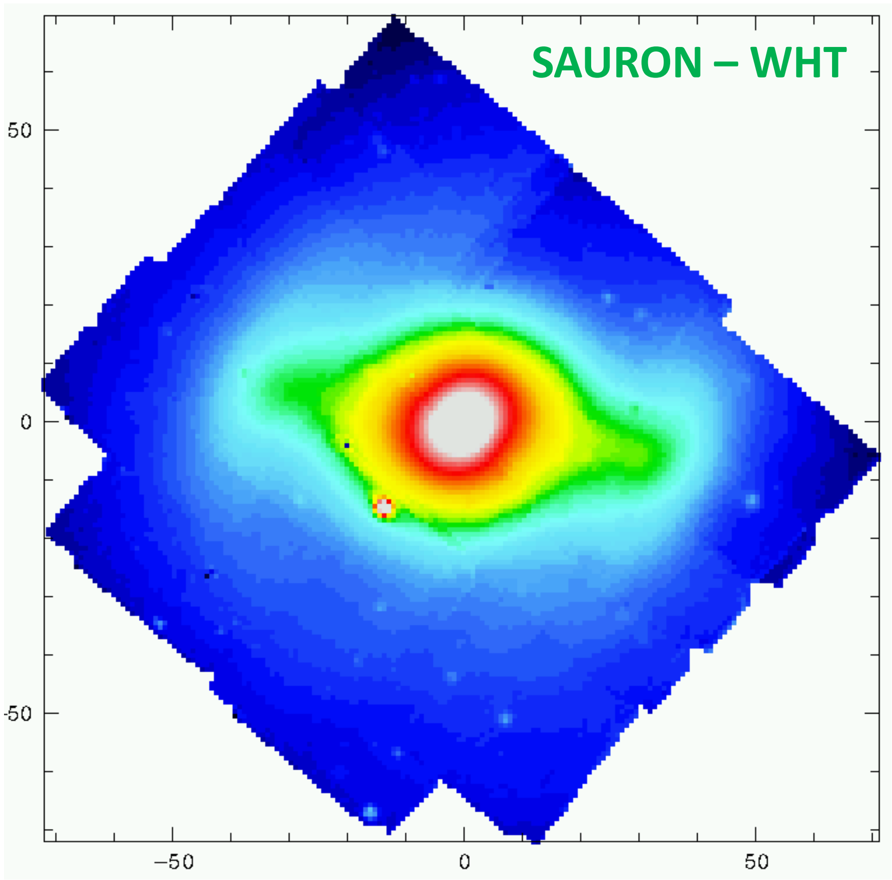
Go Broad
Mosaicing Example: NGC936



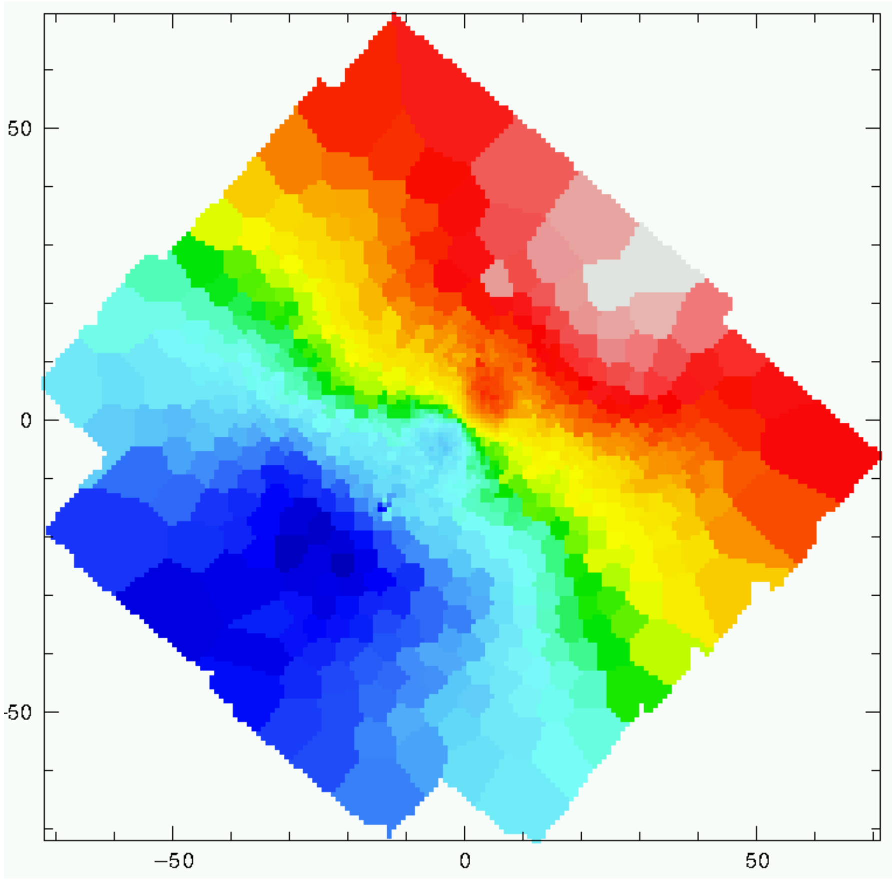
- ❖ 22 fields (37 expo) covering the full bar
- ❖ « Aligned » using HST images and ***faint field stars and star clusters***

Mosaicing Example: NGC936

Reconstructed Image

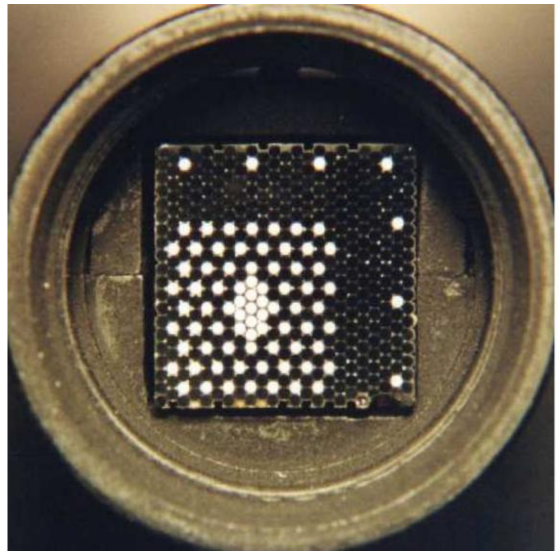


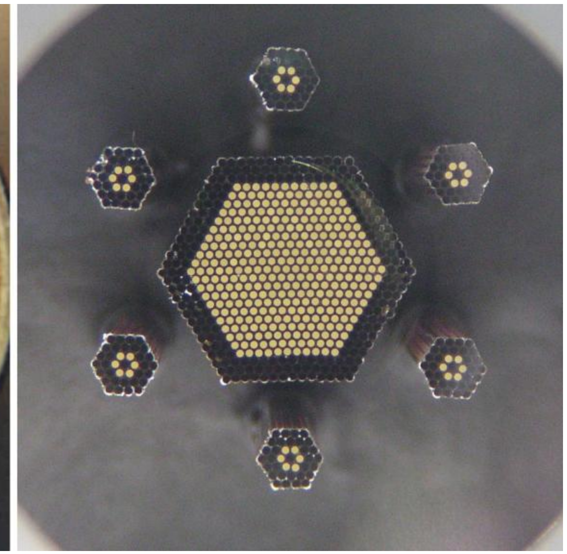
Mean Stellar Velocity



Fibers IFUs – going out

- Existing optical instruments on 3.5m telescopes: WIYN and Calar Alto -- a lineage:

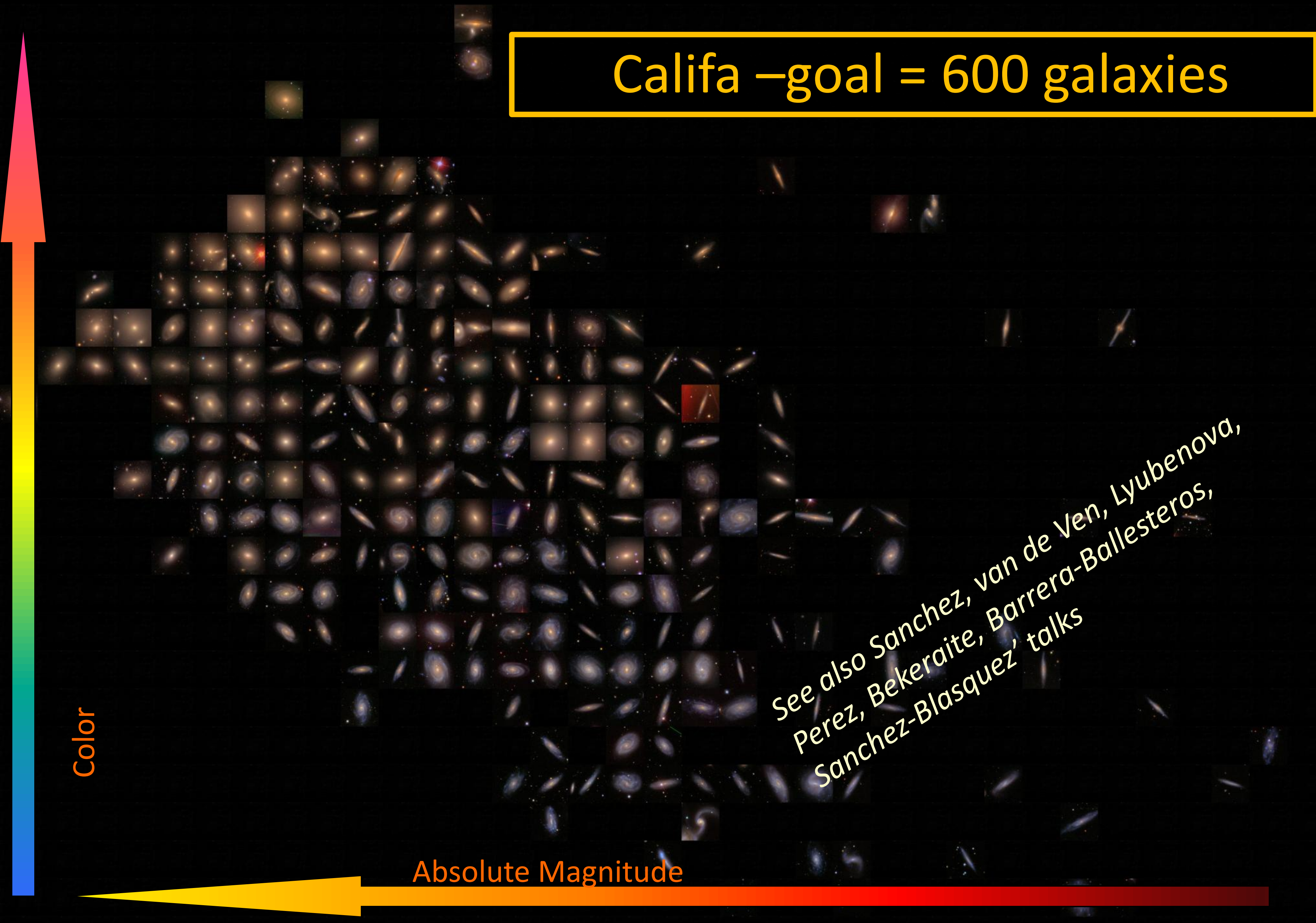




DensePak @ WIYN
90 x3”-fibers
27”x43”
Δλ/λ ~ 14,500
Barden et al. ‘98

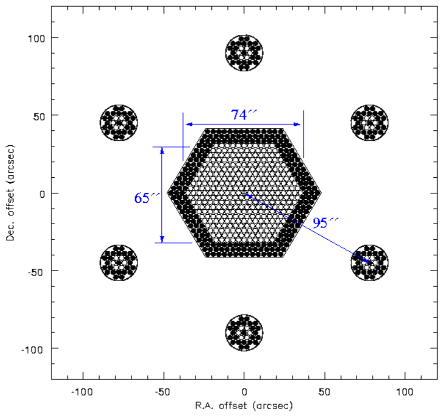
SparsePak @ WIYN
82 x 5”-fibers
70 x 70 arcsec
Δλ/λ ~ 11,500
Bershady, Andersen et al.’ 04

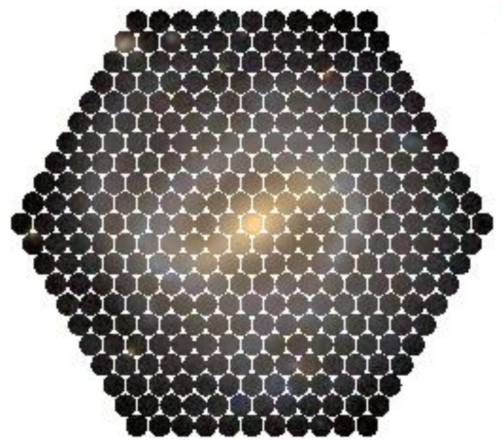
PPak @ CAHA
367 x 2.7”-fibers (65% filling)
74”x64” arcsec
Δλ/λ ~ 8000
Kelz, Verheijen et al.’ 05

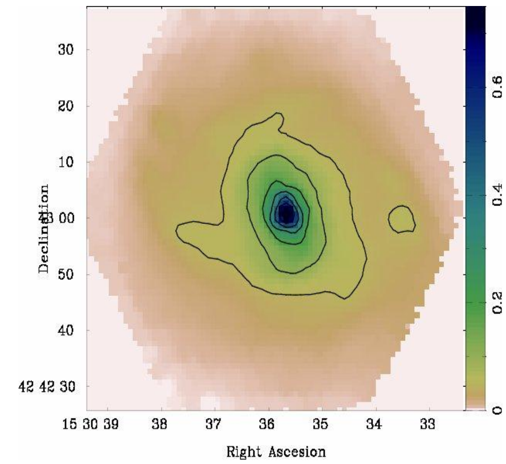


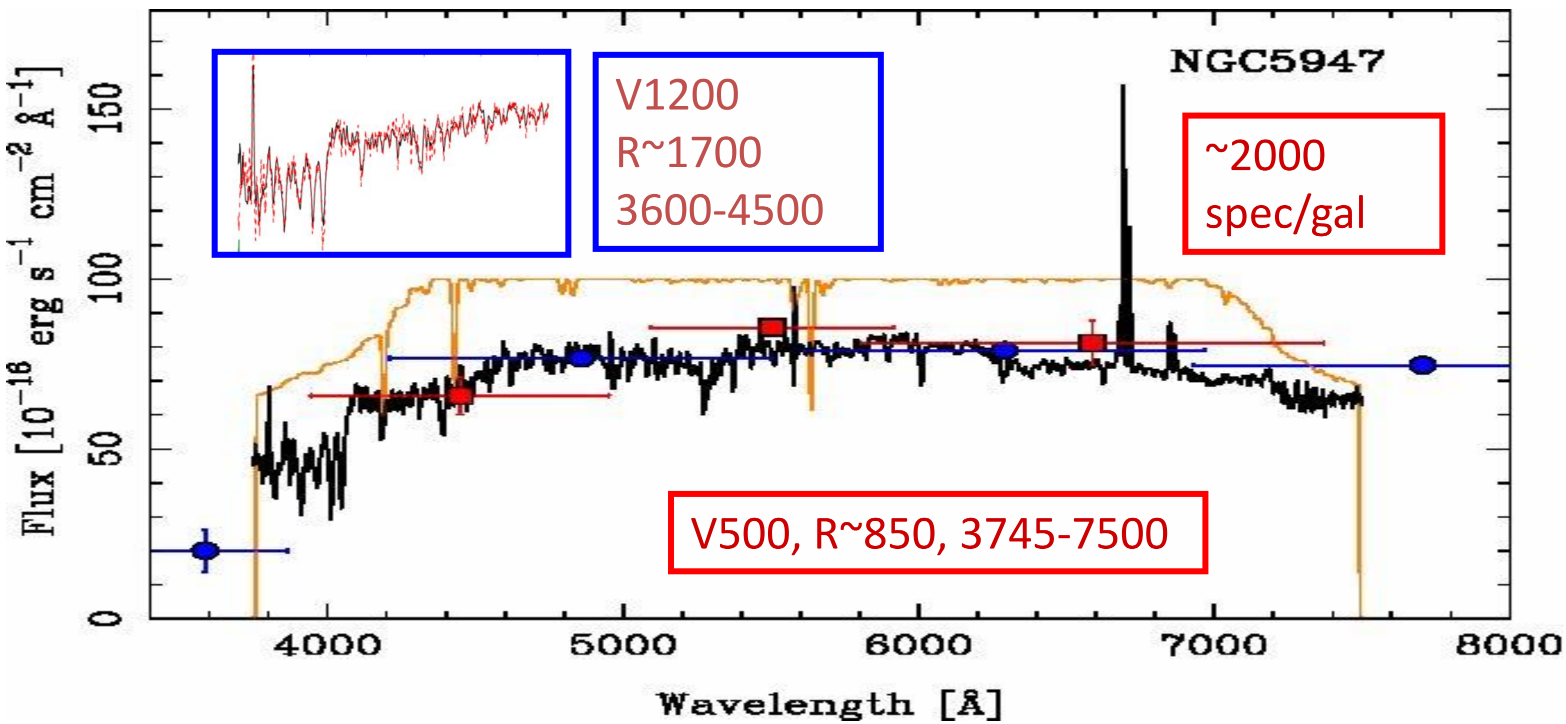
Califa –goal = 600 galaxies
See also Sanchez, van de Ven, Lyubenova,
Perez, Bekeraite, Barrera-Ballesteros,
Sanchez-Blasquez' talks
Color
Absolute Magnitude

CALIFA – Set up

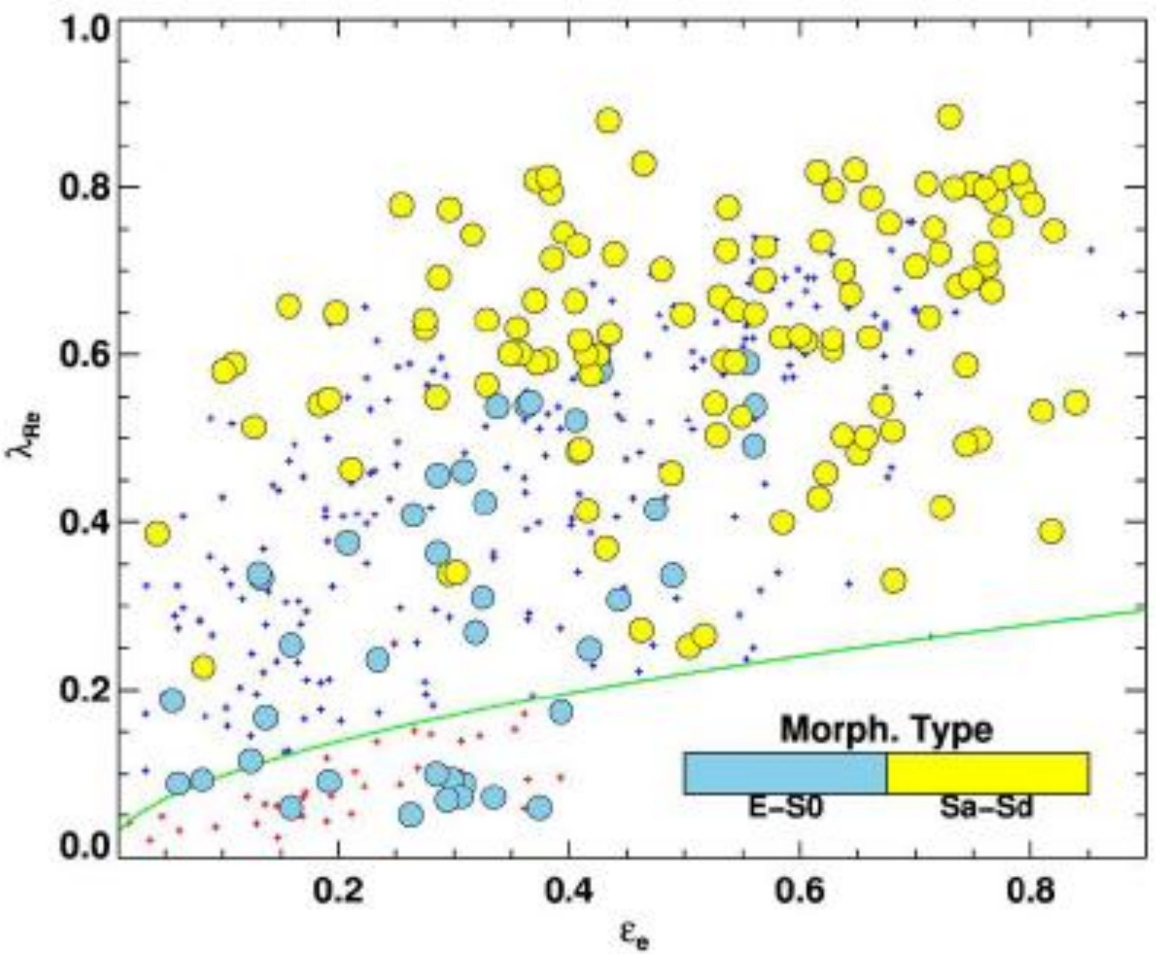


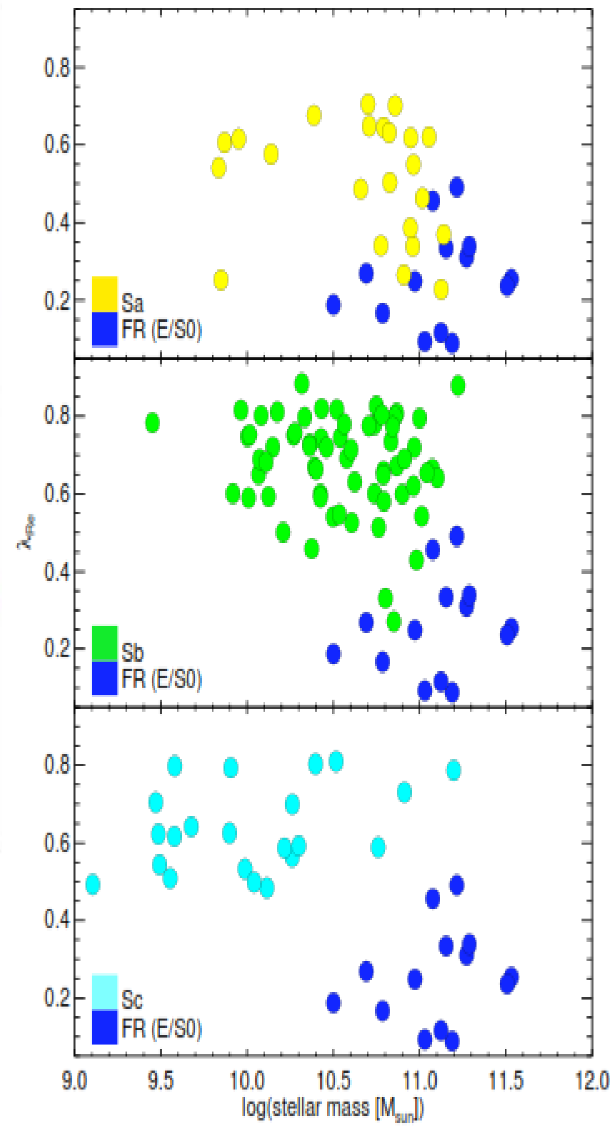






Building of angular momentum





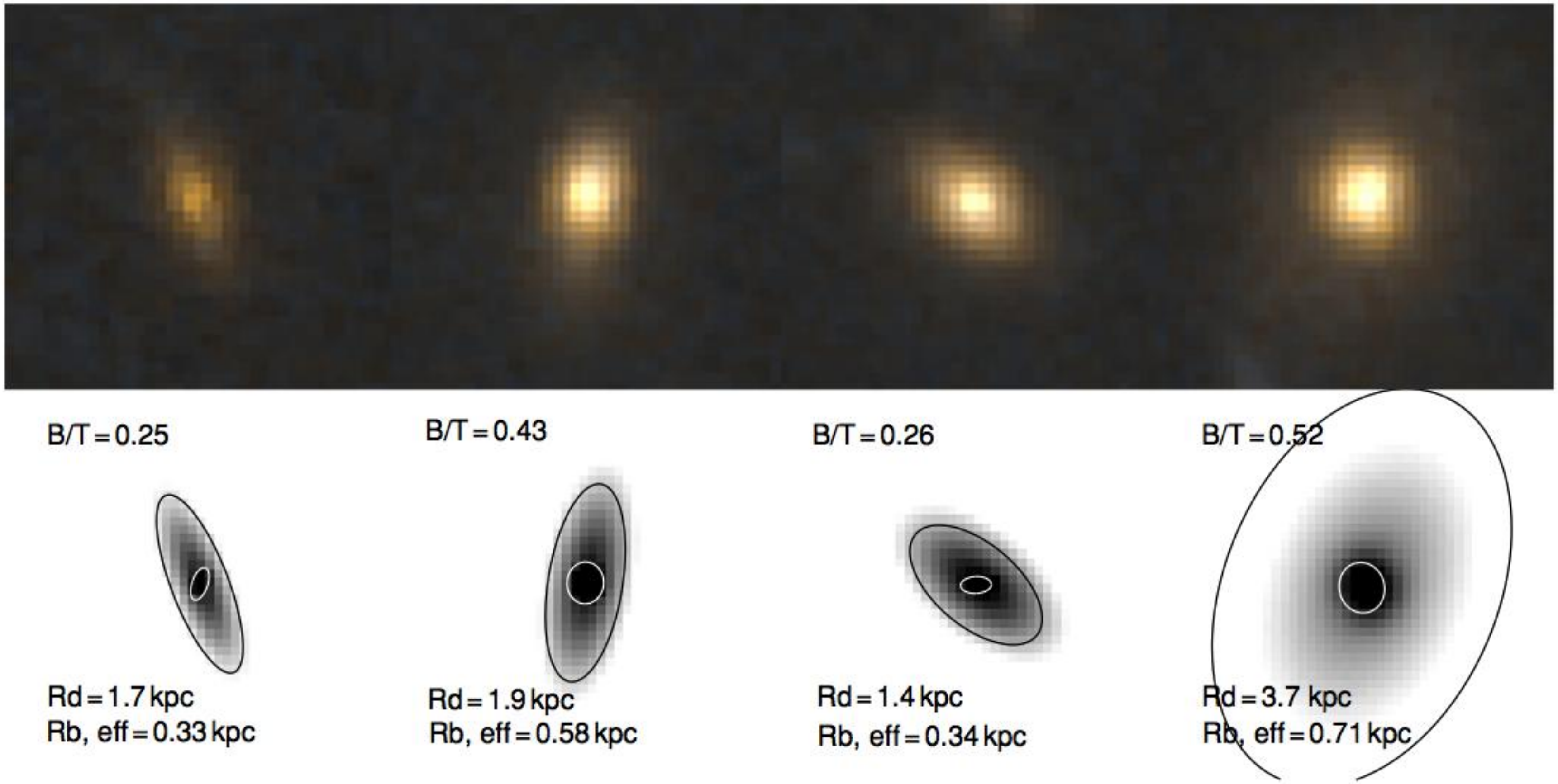
Falcón et al., in prep.

➔ Higher-z science

(individual targets)

'Red & Dead' Galaxies at z~2-3

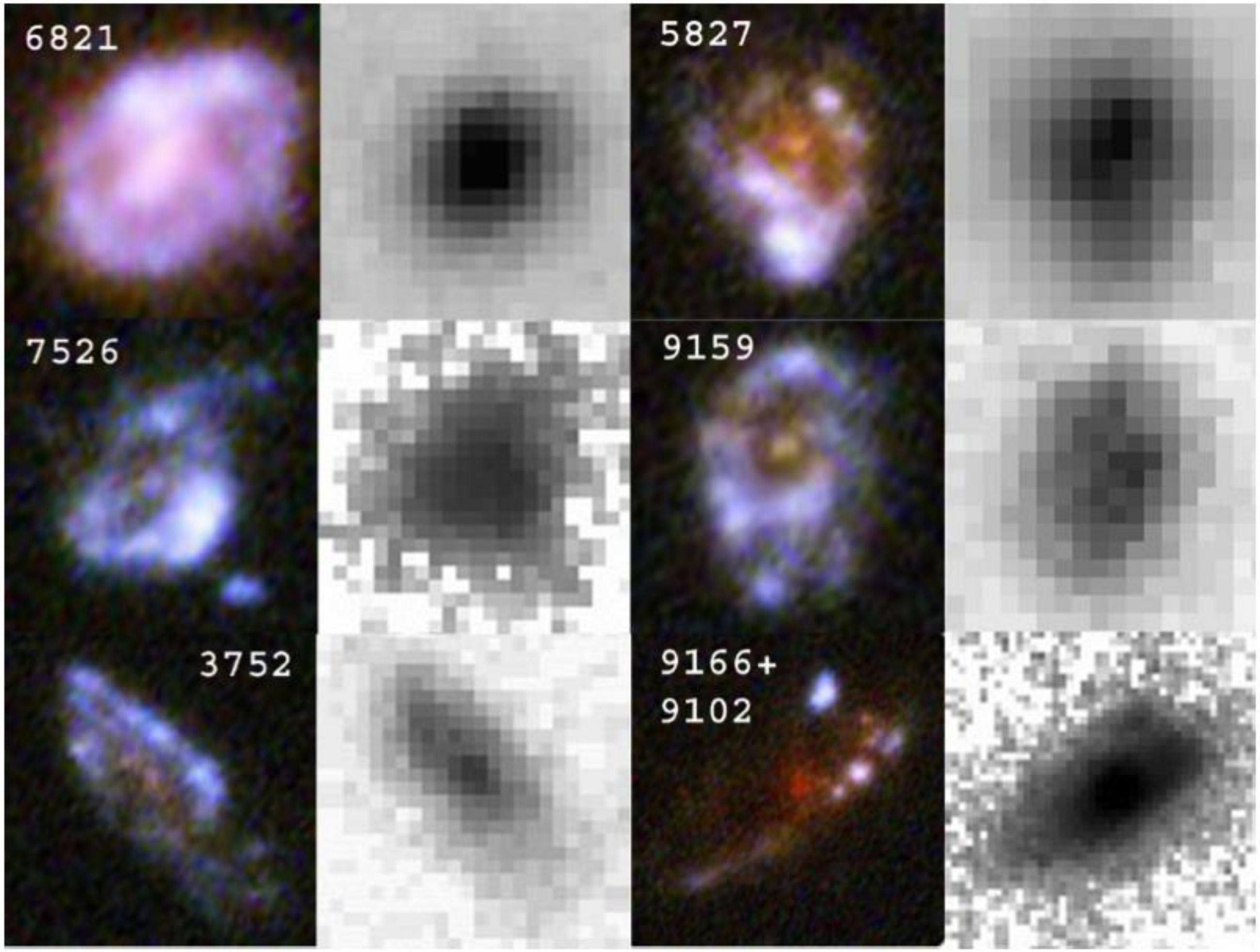
Van der Wel et al. 2011



- Hi-z ETGs are generally flattened – not spheroids

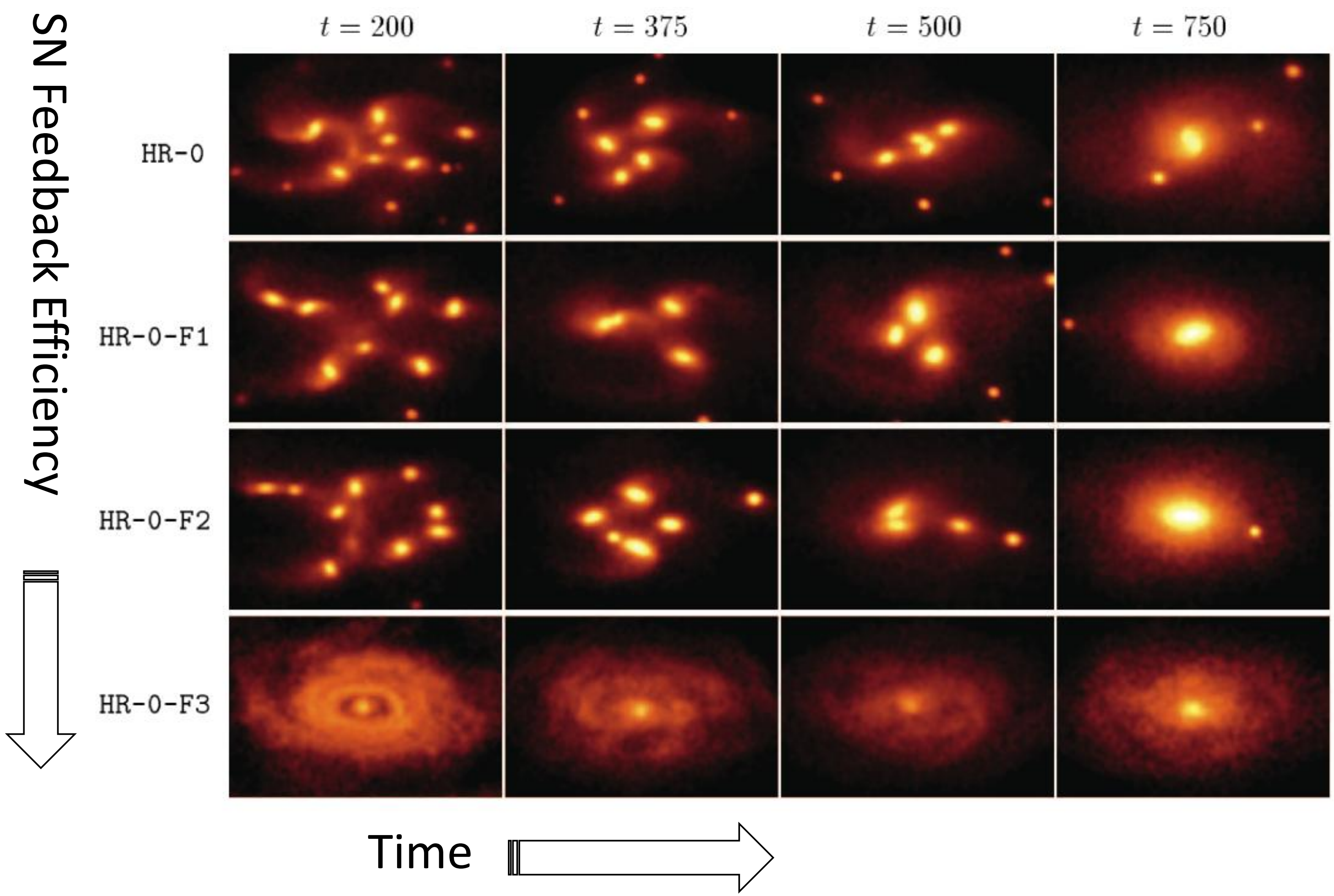
Star-Forming Massive Galaxies at z~2-3

Elmegreen et al. 2008a



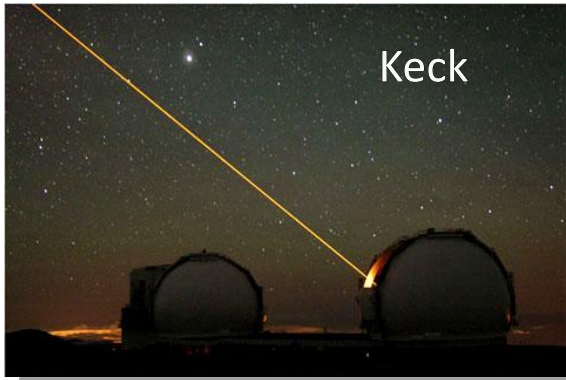
➔ Galaxies characterised by massive clumps of SF

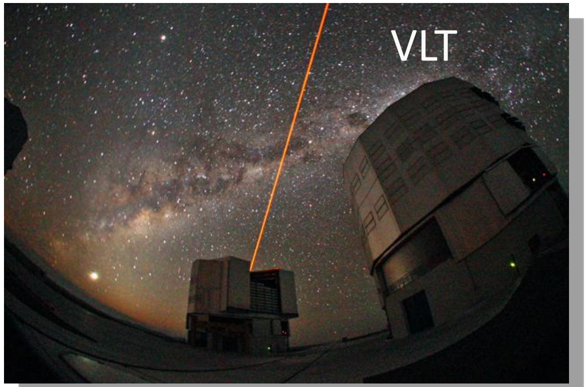
Star-Forming Massive Galaxies at z~2-3



See Elmegreen / Bournaud's papers (e.g., 2008)

➔ Need for AO+IR IFUs on 8-10m





Name	F.o.V. Δx: 0.1”	Tip/Tilt R_{mag}	Off-axis Distance
OSIRIS (Keck)	4.8x6.4”	18.0	<60”
NIFS (Gemini)	3x3”	18.5	<25”
SINFONI (VLT)	3.2x3.2”	18	<40”

Major Obstacles

Tip/tilt guide sources

- **Extended sources**
- *Generally no AGN*
- *Need steep central profile to use nucleus*

Target selection

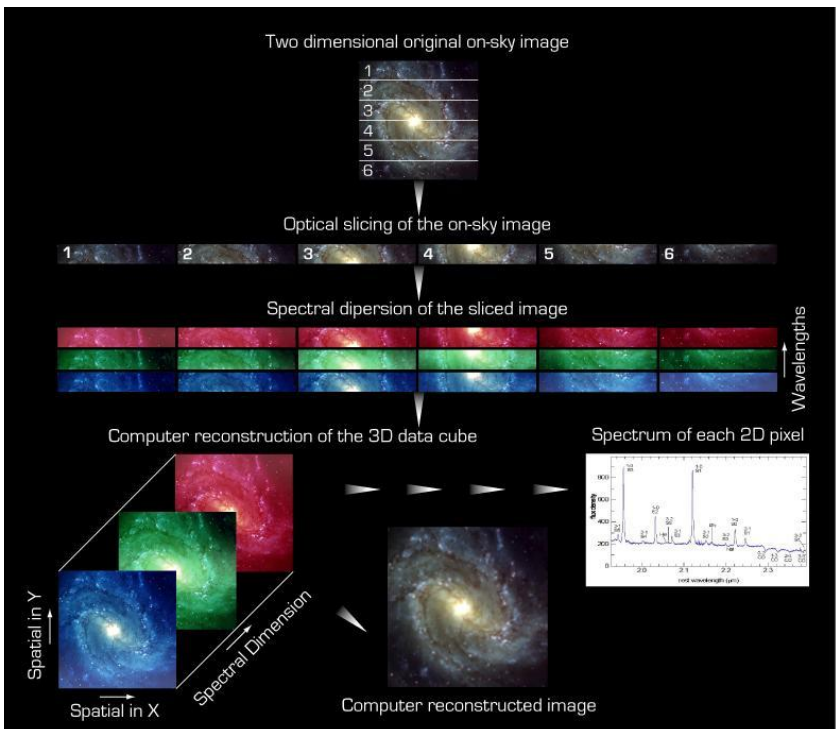
- Need source catalogues that are both deep (R<18.5) and good image quality

PSF Determination

- Rely on 1^{st} order estimates or model predictions
- Possibility to reconstruct PSF from AO system (?)

A NIR slicer IFU with AO

- SINFONI: SPIFFI + MACAO, VLT 8m
  - The power of near-infrared AO coupled to an image-slicing spectrograph
    - 32x32 element imaging field sliced into a 1024 element long-slit
    - Field coverage of 8x8 and down to 0.8x0.8 arcsec
    - JHK coverage at R = 2000-4000



Bonnet et al. '04, Iserlohe et al. '04

ESO Newsletter

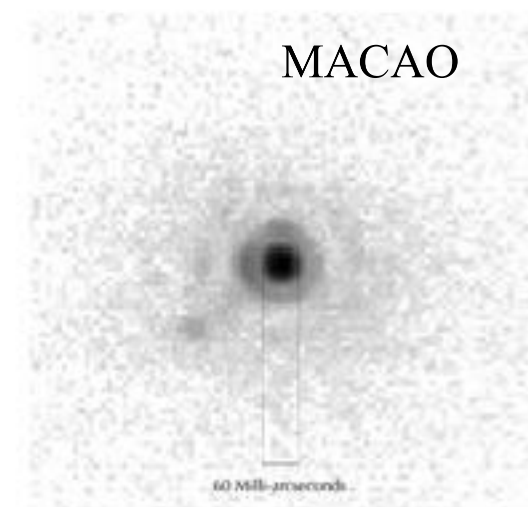


Figure 3: AO-Module first light. The magnitude of the star is ~11 in V, the seeing 0.65 arcsec. The measured Strehl is 56% (λ = 2.16 μm). The displayed FOV is 0.5 arcsec, with a sampling of 15 mas/pixel.

SPIFFI

SINFONI : the slicer

- SPIFFI slicer: pupil mirrors are flat

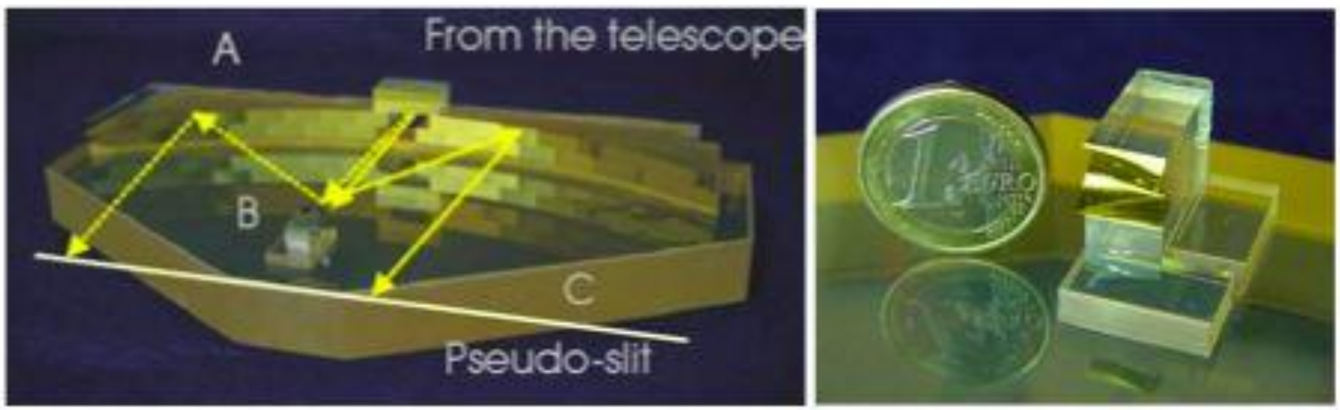
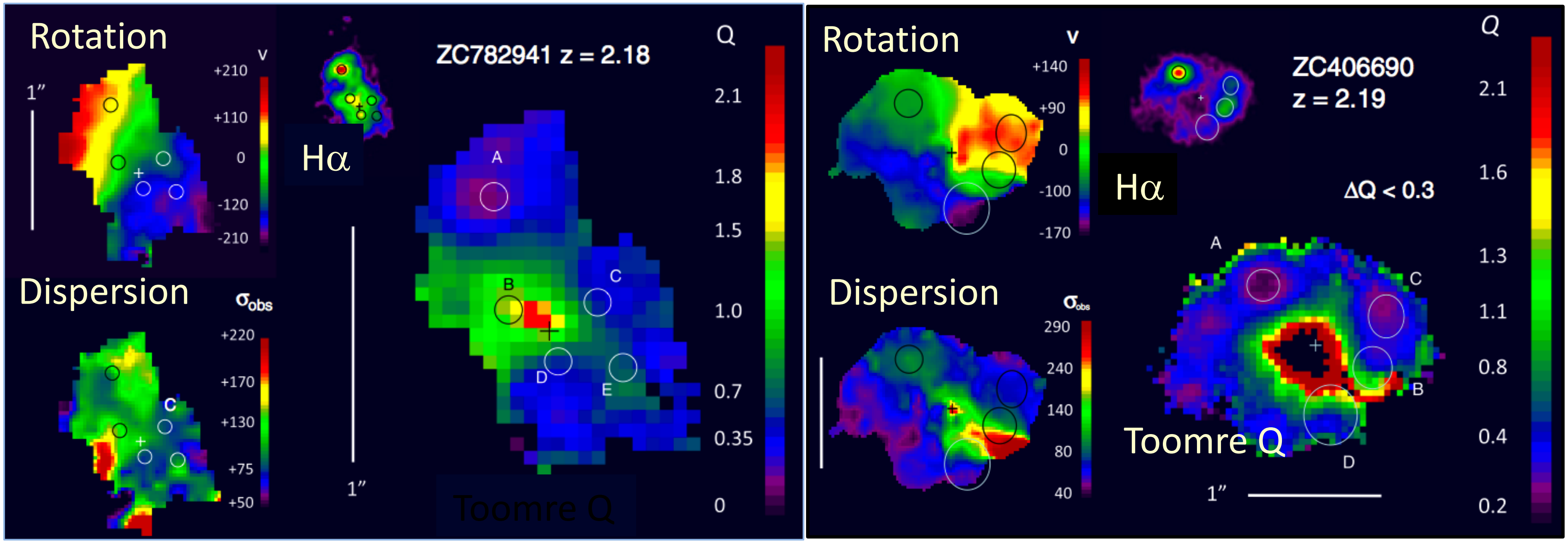


Figure 2. The image slicer: The image slicing device used in SPIFFI consists of plane mirrors. The two dimensional image (still containing light of all wavelengths of the used observing band) is sliced into thin stripes, called slitlets, which are then lined up end to end to create a pseudo long slit which is fed into the spectrometer. The small image slicer (B in left Figure) is a stack of 32 plane mirrors with a thickness of 0.3mm each. The small image slicer (right Figure) cuts the image into stripes and reflects them onto the big image slicer (A) which consists of 32 plane mirrors in two layers. The mirrors are tipped and tilted in a way that the telecentric entrance pupil is preserved. Both image slicer components are mounted to a baseplate(C). All parts are of Zerodur and are optically contacted (without using any glue).

Iserlohe et al. ‘04

Star-Forming Massive Galaxies at z~2-3

Genzel et al. '11



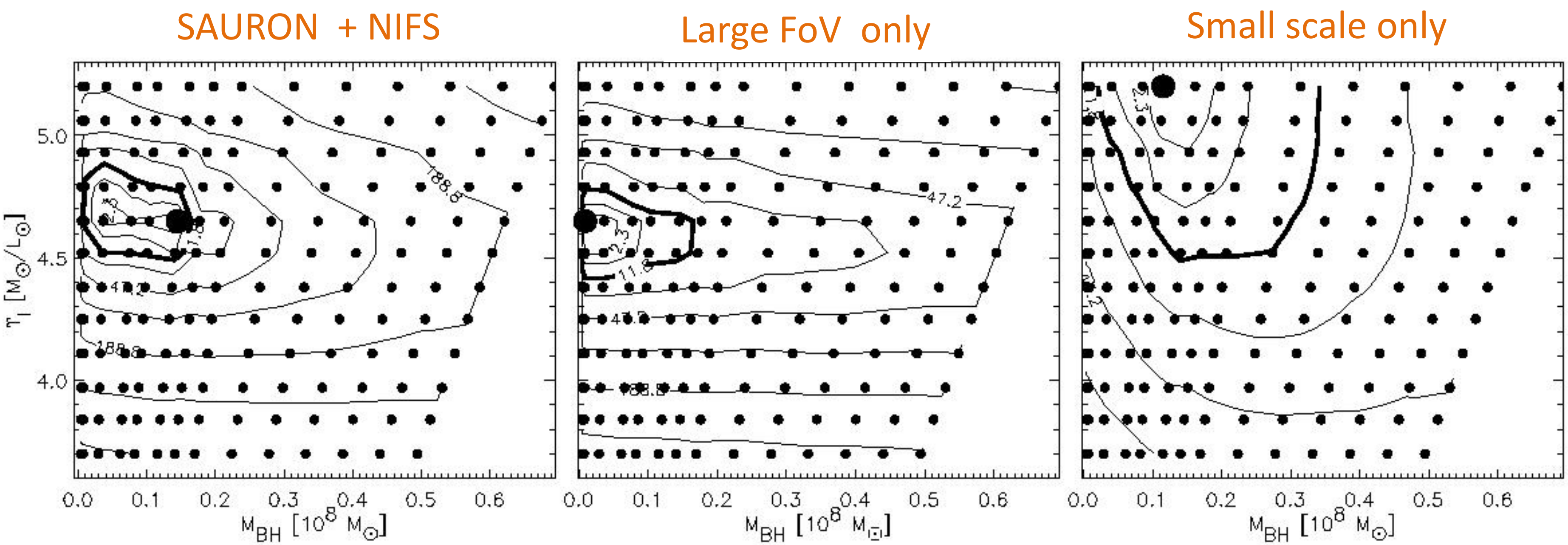
See the SINS/zC-SINF papers

See also *Gillessen, Förster Schreiber, Pérou's talks*

- Clumps are star-forming, showing outflows and rotational self-support
- Disks are much more turbulent than z=0 disk galaxies

But... The need for 2 IFU scales

- IFU crucial for robust derivation of Mbh → 2 scales important
- 1) **small scale** = high spatial resolution IFU
  - probing the BH sphere of influence
- 2) **large scale** = moderate spatial resolution (Krajnović et al. 2005)
  - probing orbital structure of the host galaxy



Krajnović et al. (2009)

Laser Guide Star
IFU observations of galaxies

- Low probability for a suitable NGS (near the nucleus)
- Two options:
  1) guide on the nucleus itself
     – possible only for steep cuspy galaxies or AGN

  2) use "seeing-enhancer" or "open-loop" modes

     (e.g. with SINFONI@VLT and NIFS@GEMINI)

     – suitable for core galaxies
- What is the achieved resolution?
  1) comparison with the higher resolution imaging (HST)

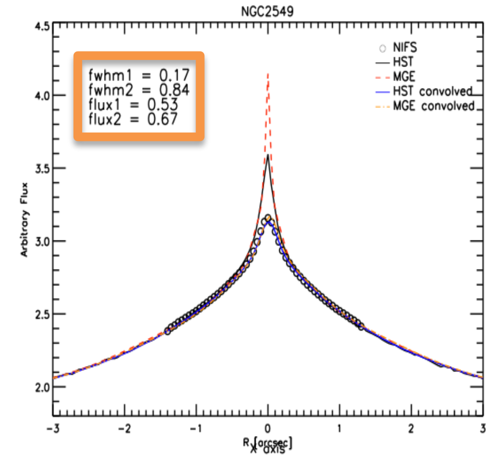
  2) monitoring of stars between on-source observations

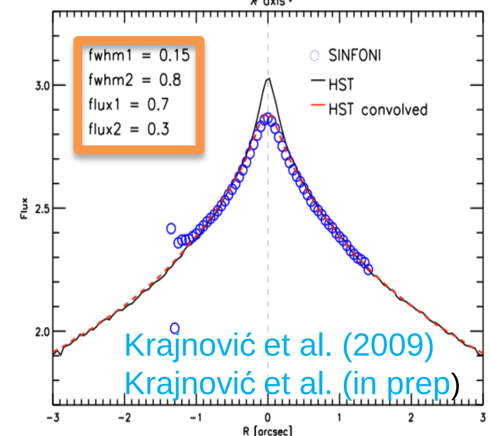
What can be achieved?

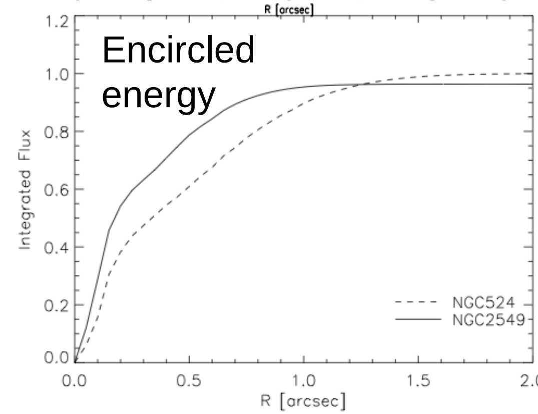
- Typically
  - FWHM of narrow Gaussian

    ~ 0.15-0.2”
  - FWHM of broad Gaussian

    ~ natural seeing (0.8” - 1”)
- Strehl ratio : ~15% only
- Encircled energy relatively high:
  - 40 - 50% within 0.2”,
  - 90% within 1”
- Wings of PSF might not be well constrained (Seth et al. 2010)

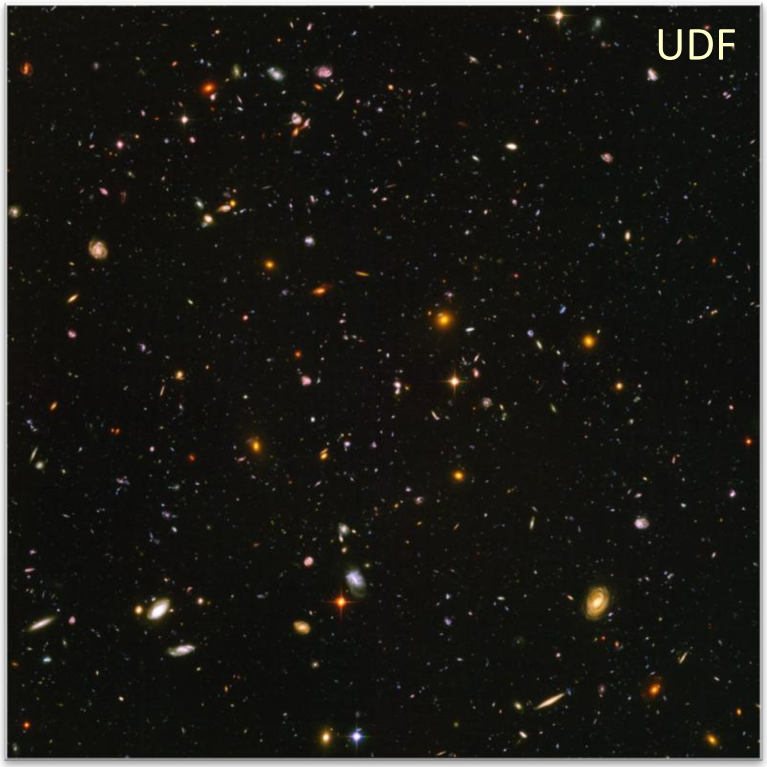






The next step: going deep

- **How to go ... DEEEEEEP** in 3D
  - **Blind** survey
  - **Large** field
  - **Large** spectral domain
  - High **Stability**
  - High **Efficiency**
  - Excellent **Image quality** (AO?)



➔ NEW generation IFU with discovery capabilities

How to combine

the discovery capabilities of an imager

with the qualities of state-of-the-art spectrographs

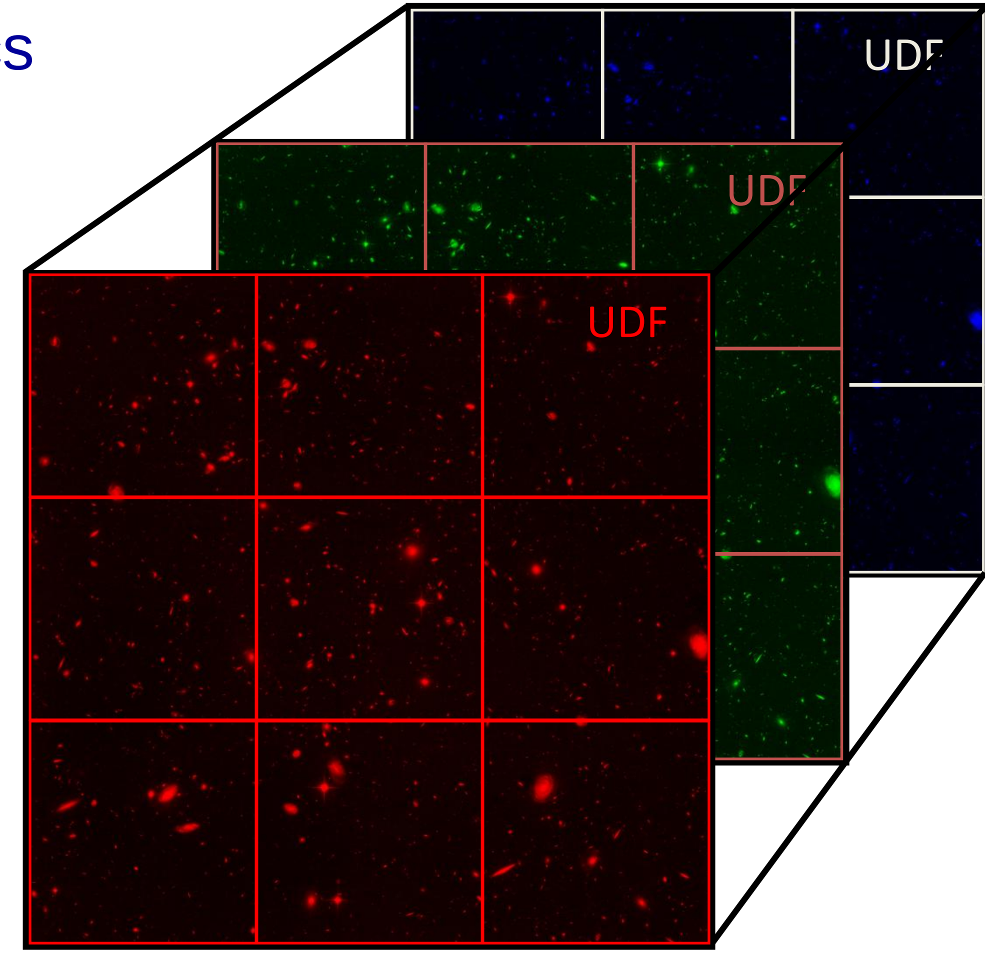
3D Deep Fields

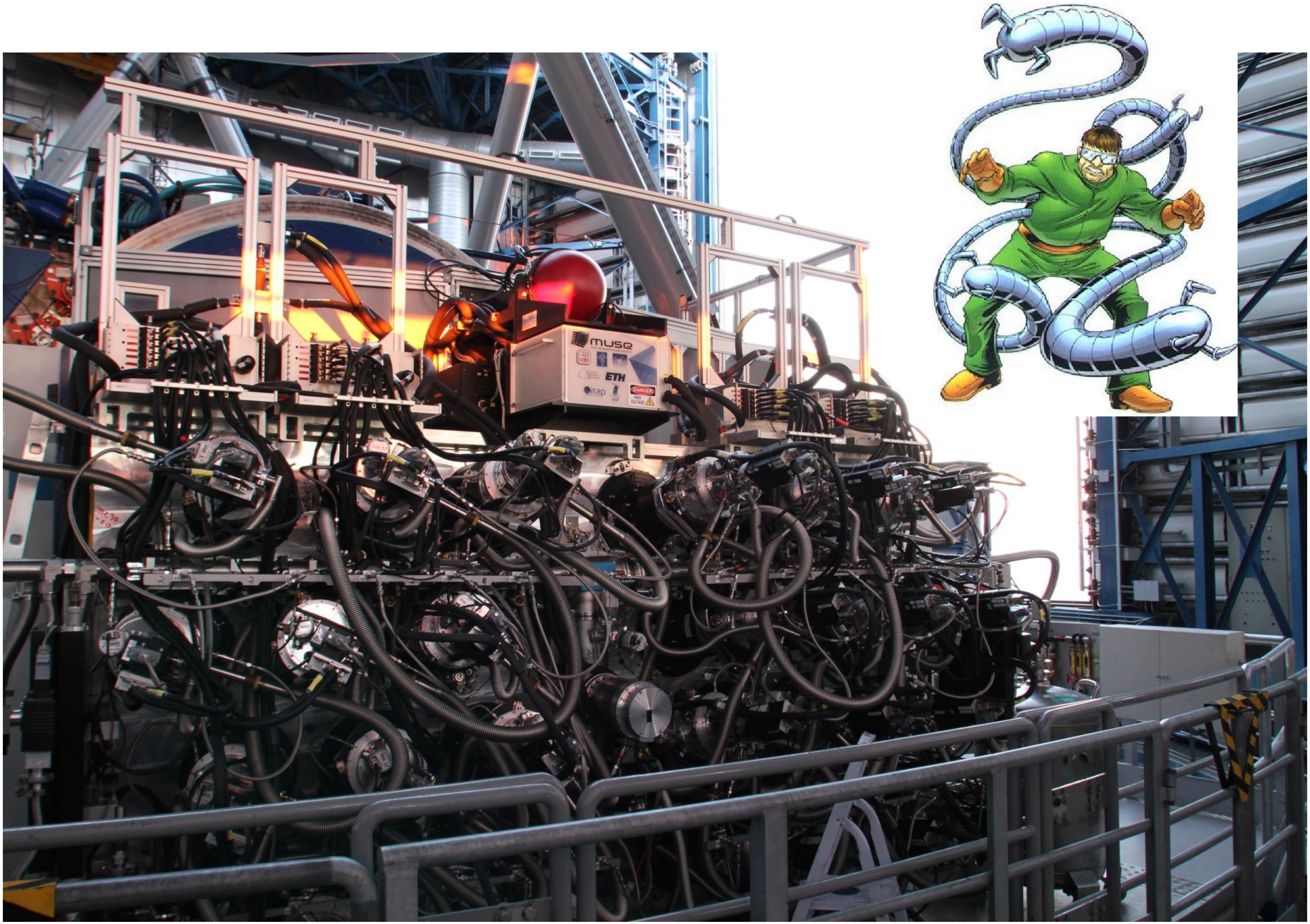
Can we get everything at the same time ?

- No pre-imaging
- No pre-selection
- Attack multiple science topics

  simultaneously
- Large discovery space

  for serendipitous sources




muse
ETH
irap
DANGER
HIGH VOLTAGE

MUSE/VLT
Scientific design drivers

- Enable very **long integrations**, up to ~100 hrs
  - gravity-invariant system
  - very few moving parts
- Search for faint Lyman-α emitters up to z ≈ 6.7
  - Good spectral resolution λ/Δλ ≈ 3000
  - Red-sensitive up to **930 nm** (→ blue limit at **465 nm**)
  - High throughput → state-of-the-art **coatings**!
- Benefit from Adaptive Optics:
  - Wide Field Mode: GLAO (seeing improvement)
  - ***Narrow Field Mode***: High order AO in red optical

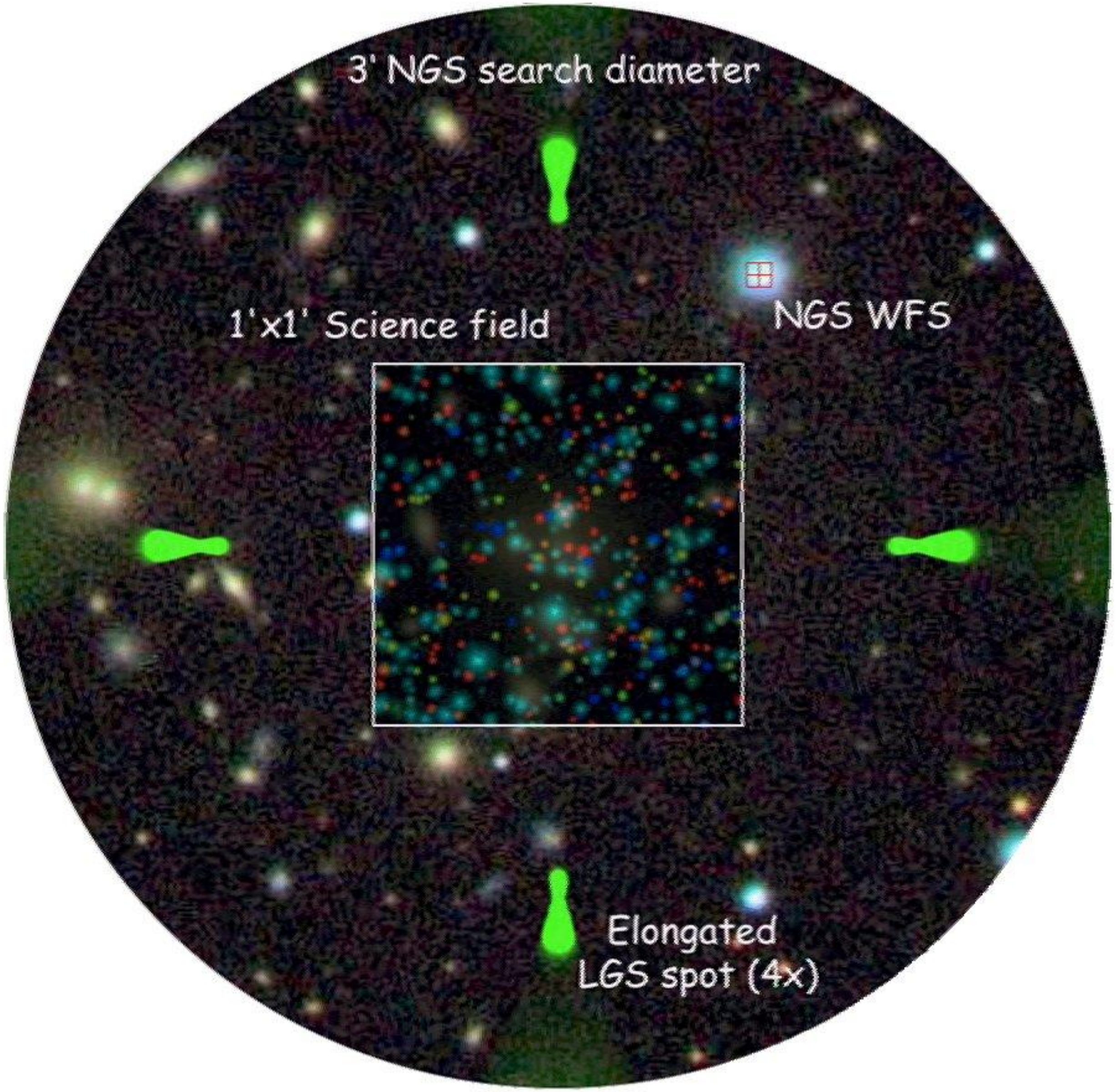
MUSE – Instrument Overview

- Integral Field Spectrograph
- Optimized for ESO AO Facility
  - but can run without AO
- ***Two modes only***
  - **WFM**: Wide Field Mode
    - 0.2 arcsec, 1x1 arcmin^2
    - Spatial resolution
      - Non AO: seeing
      - AO: 0.3-0.4 arcsec
  - **NFM**: Narrow Field Mode
    - only with AO
    - 0.025 arcsec, 7x7 arcsec2
    - Spatial resolution
      - 10-20% Strehl ratio in I band

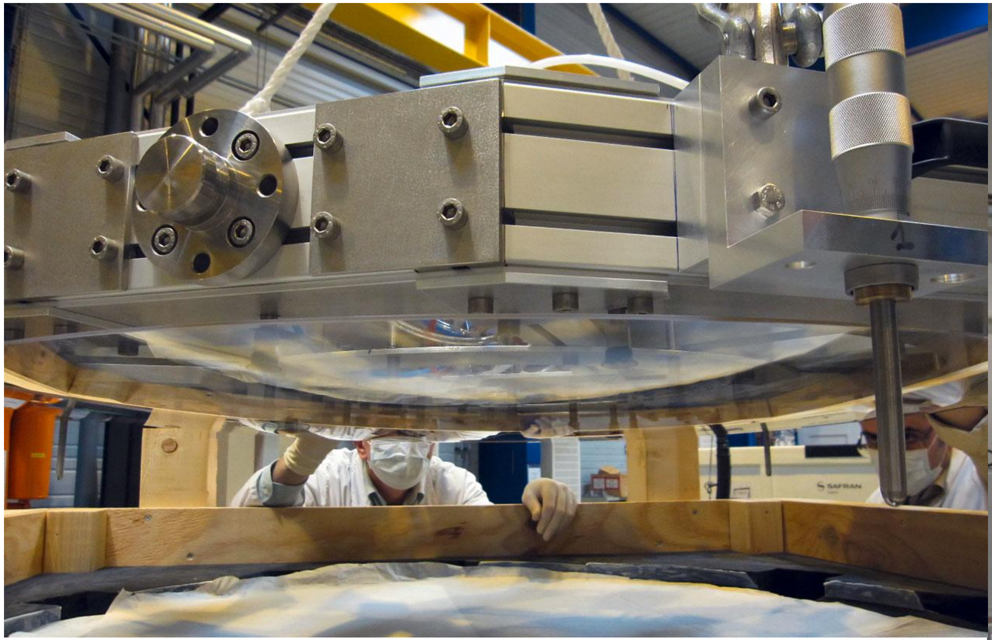
- Spectral characteristics
  - 465-930 nm simultaneous
  - R~3000
- Data volume
  - 400 10^6 pixels
  - 90,000 spectra in one exposure

See Bacon's intro + MUSE session

Laser guide stars (WFM)

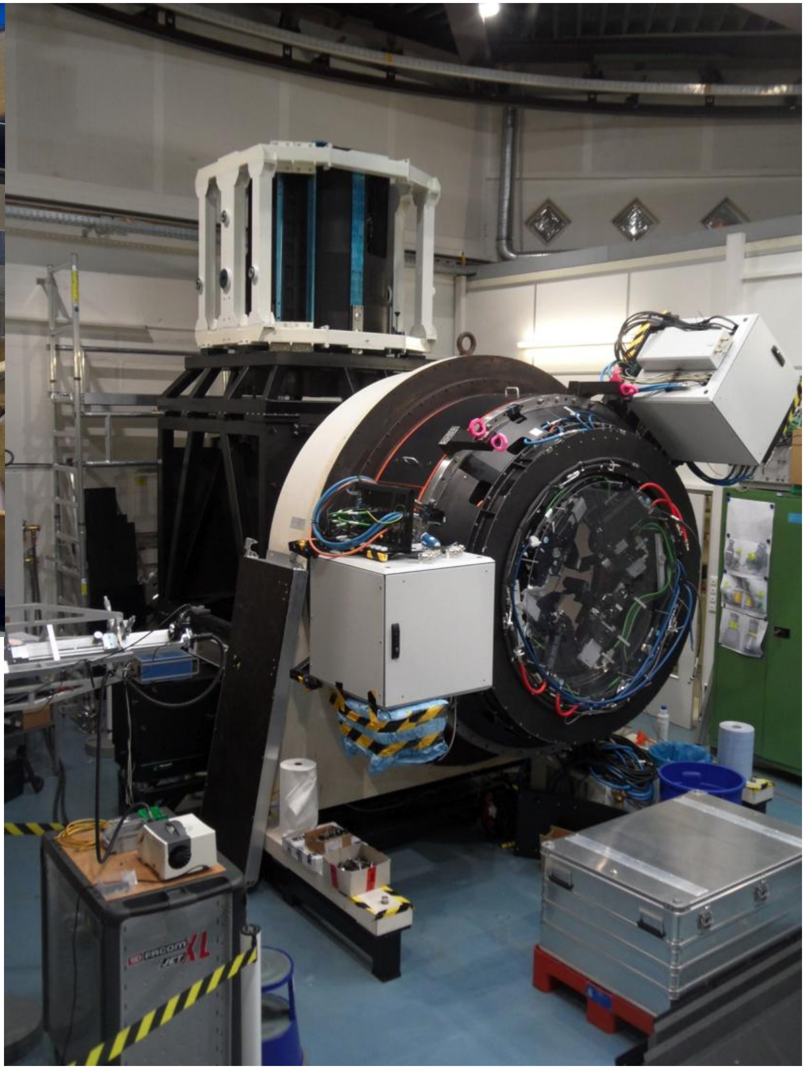


Deformable Secondary Mirror



DSM thin shell:

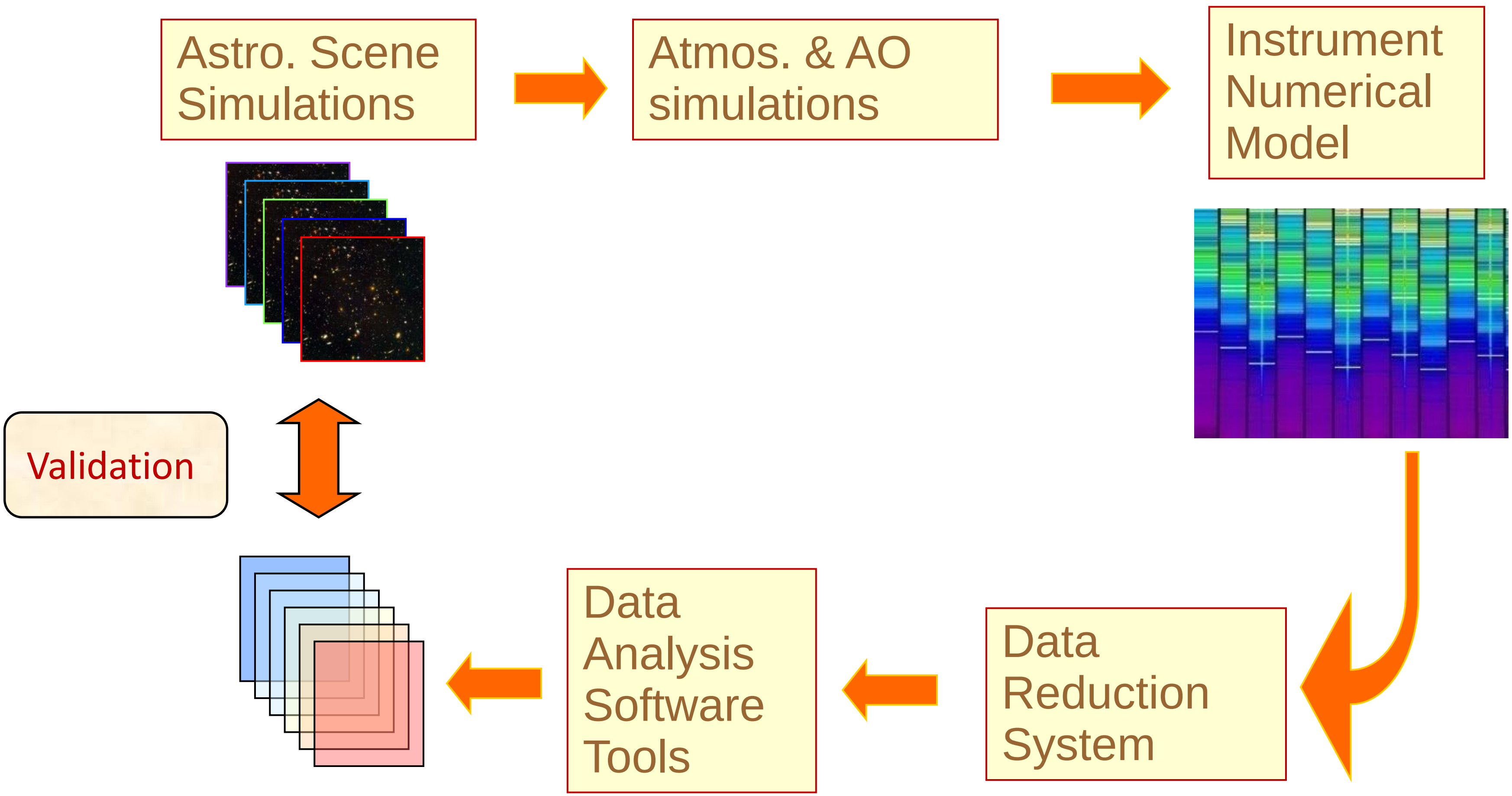
- 1120 mm diameter
- 2 mm thickness
- 1170 actuators



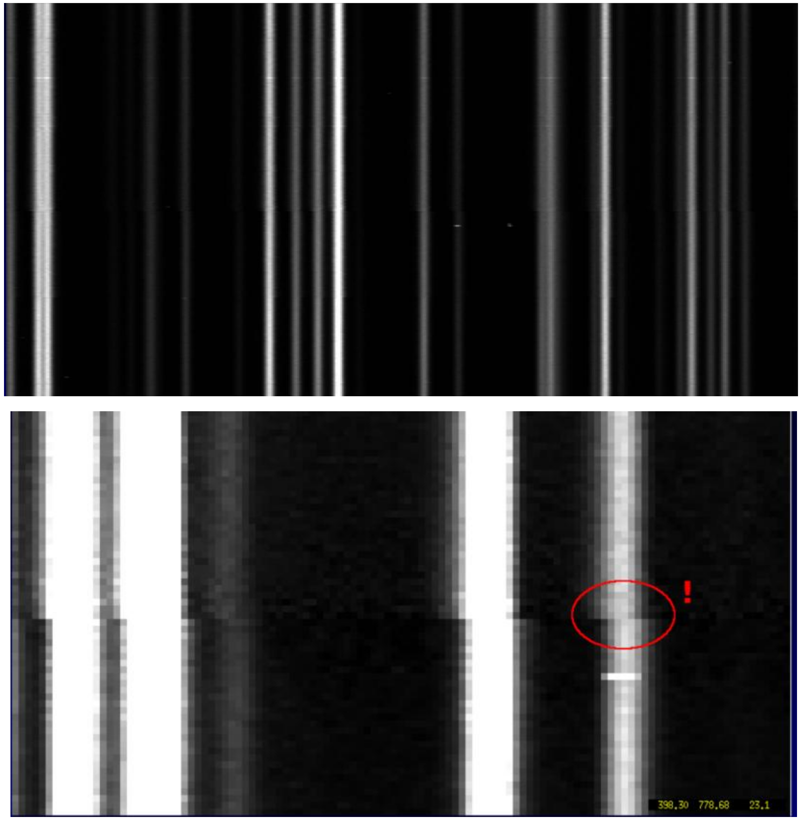
See e.g., https://www.eso.org/sci/facilities/develop/ao/sys/dsm.html

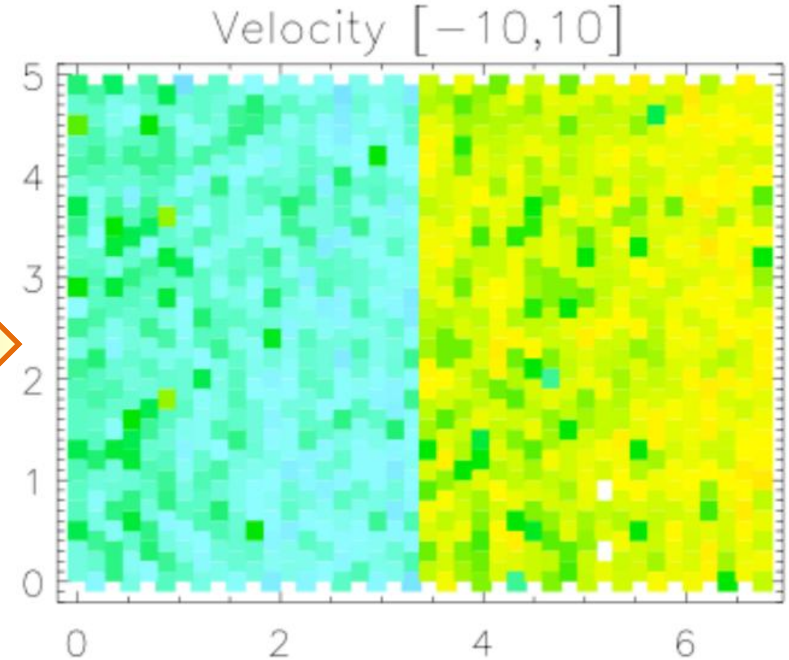
See also Bacon's talk
+ MUSE session

And…
End to End Modelling



Interesting effects 1/2





GMOS - Gemini

Not a calibration problem!

➔ Charge Transfer Efficiency: difference between 2 CCDs

➔ **Adding CCDs** may lead to complex spatial + spectral variations

What about...

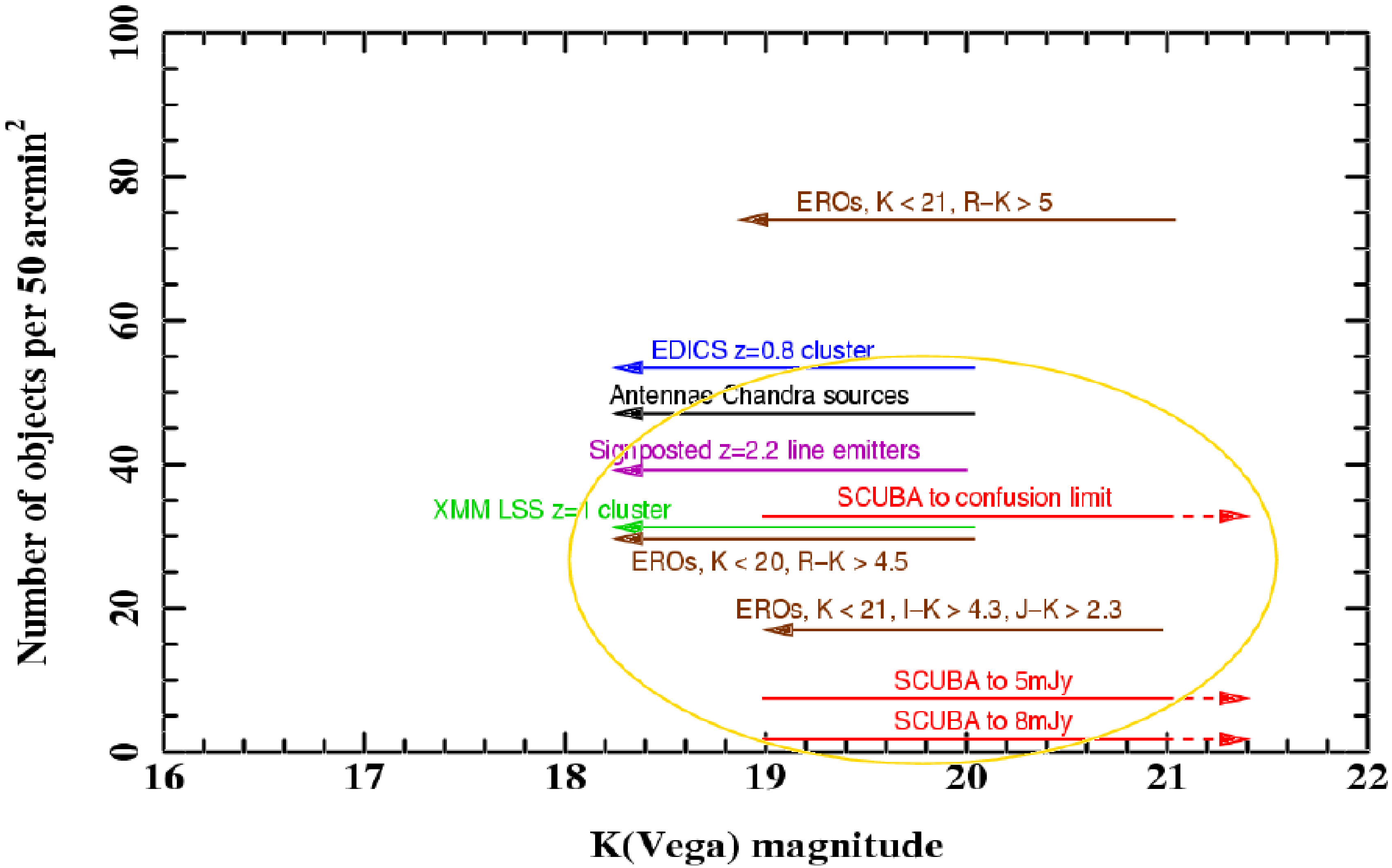
Sparsely distributed high redshift targets ?

➔ Multiplexing

and add efficiency

and go NIR

Multiplex : how many targets?



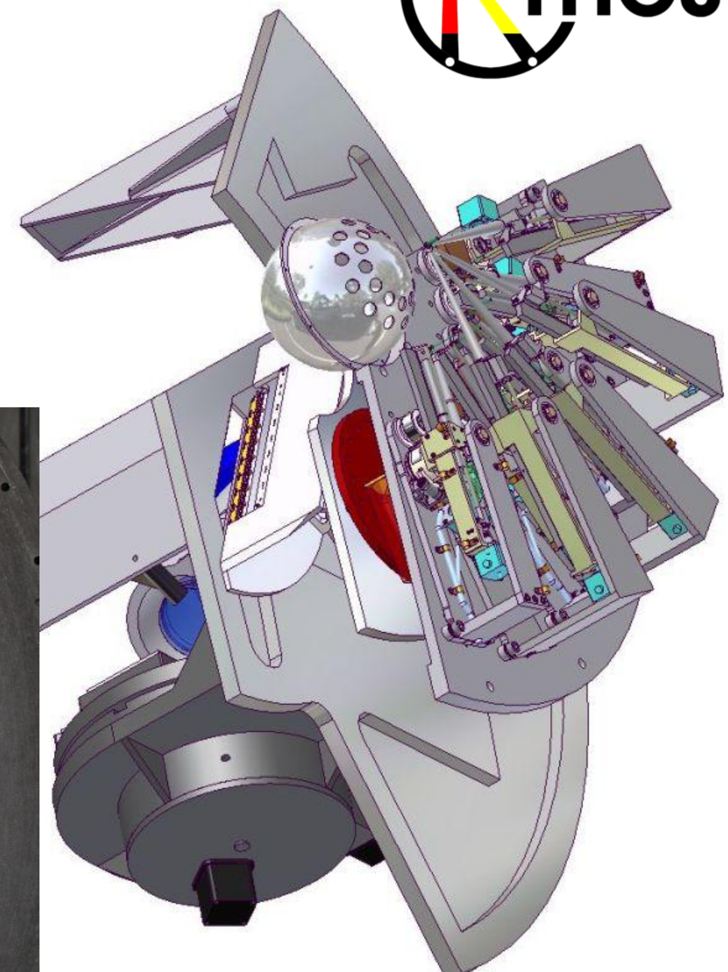
KMOS

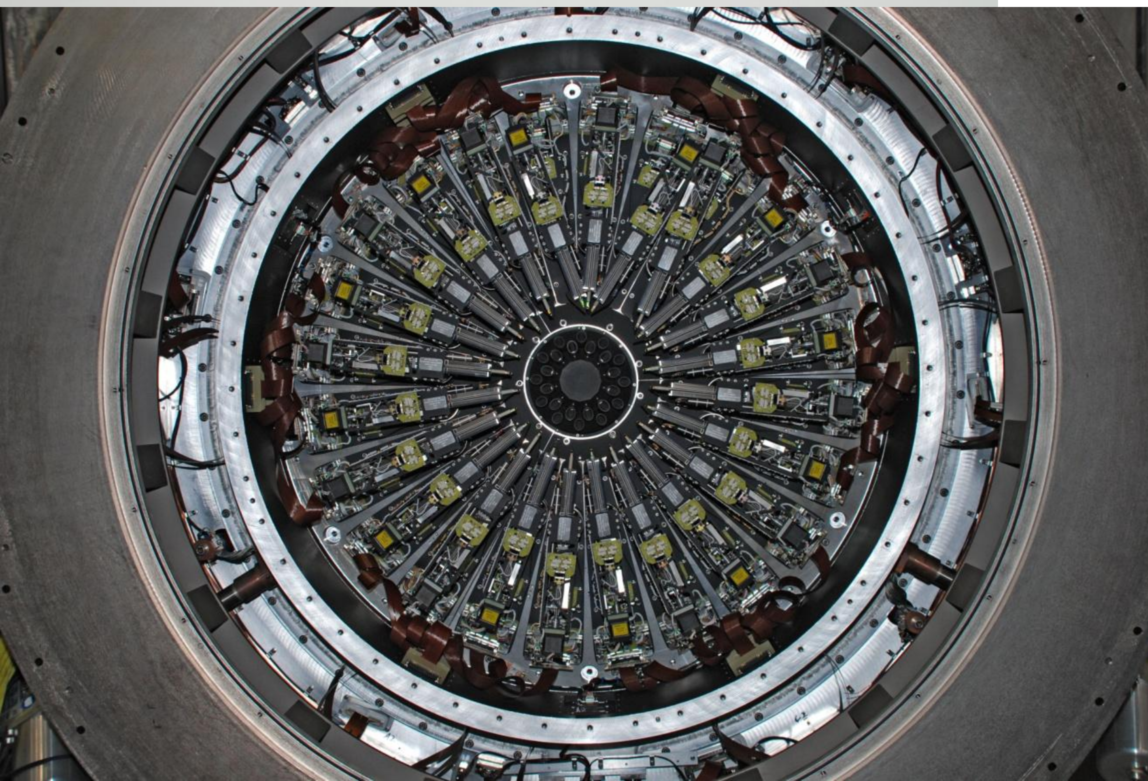
- NIR multi-IFU spectrograph
- **24 integral field units**
- IFU size: **2.8 x 2.8arcsec**
- **0.2arcsec spatial sampling** on-sky
- 7arcmin patrol field
- Ability to place IFUS close together (6arcsec)

See also e.g., Sharples, Cirasuolo's talks + KMOS session

Grating name	Wavelength range (μm)	Spectral resolving power
IZ	0.779-1.079	3400
YJ	1.025-1.344	3600
H	1.456-1.846	4000
K	1.934-2.460	4200
HK	1.484-2.442	2000

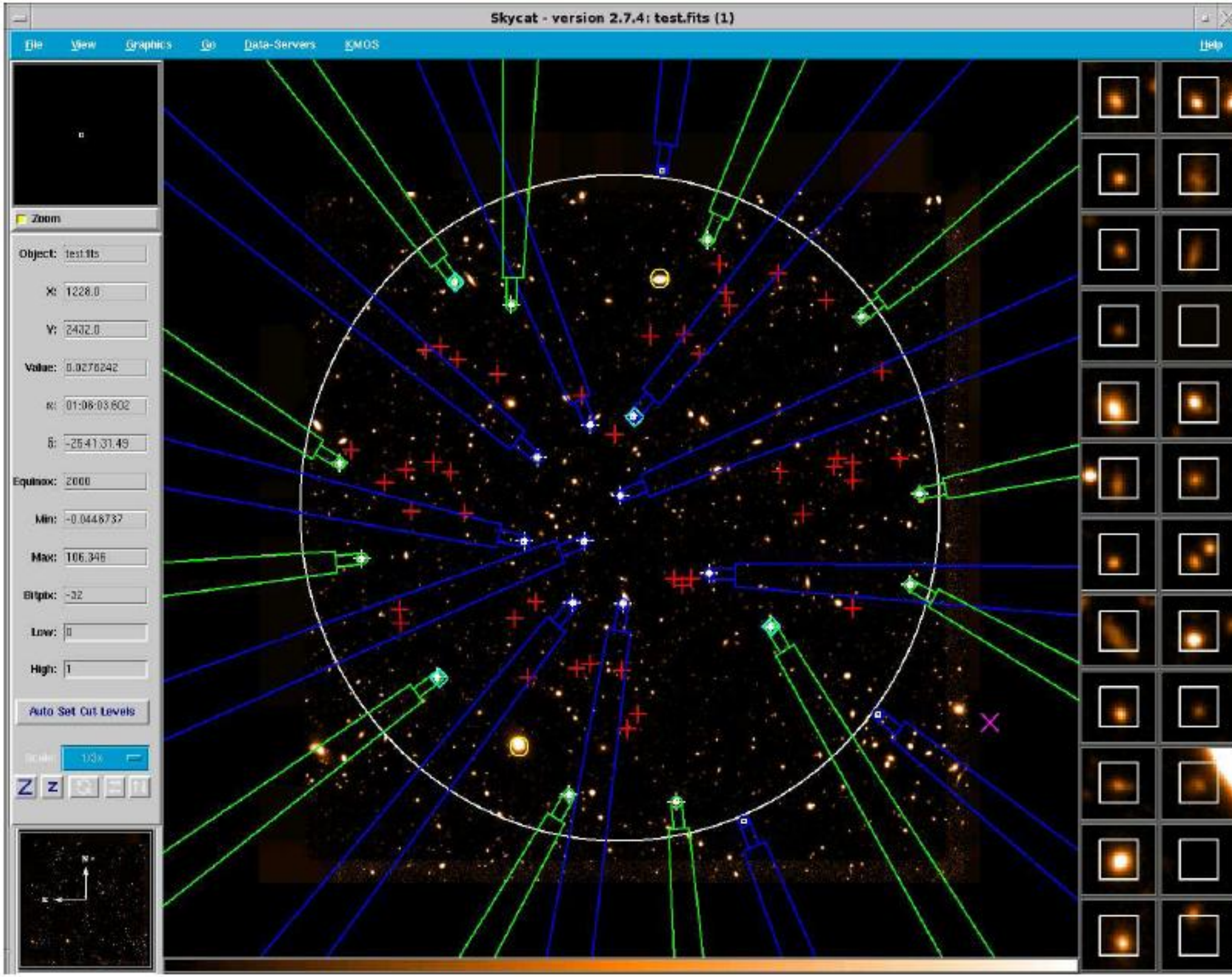
Pick-off arms





Science & Technology Facilities Council
UK Astronomy Technology Centre

KARMA: configuring the KMOS arms for science observations



IFU module

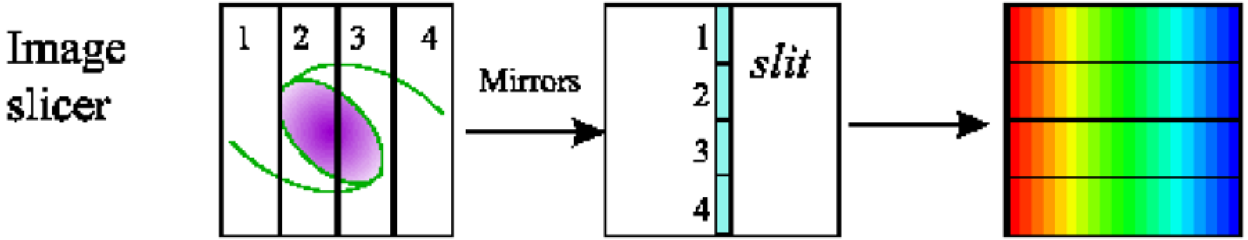
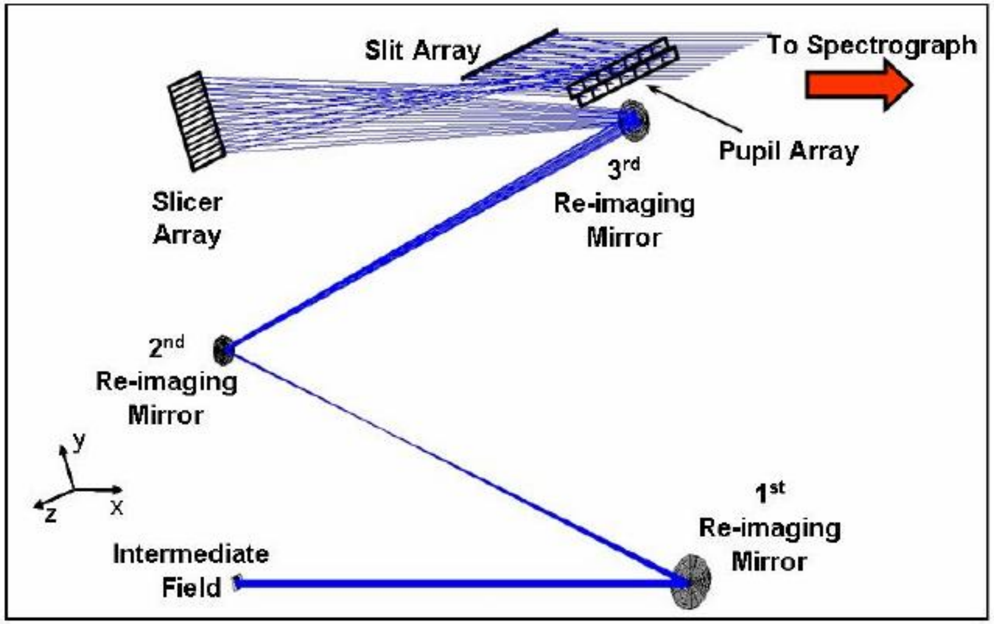
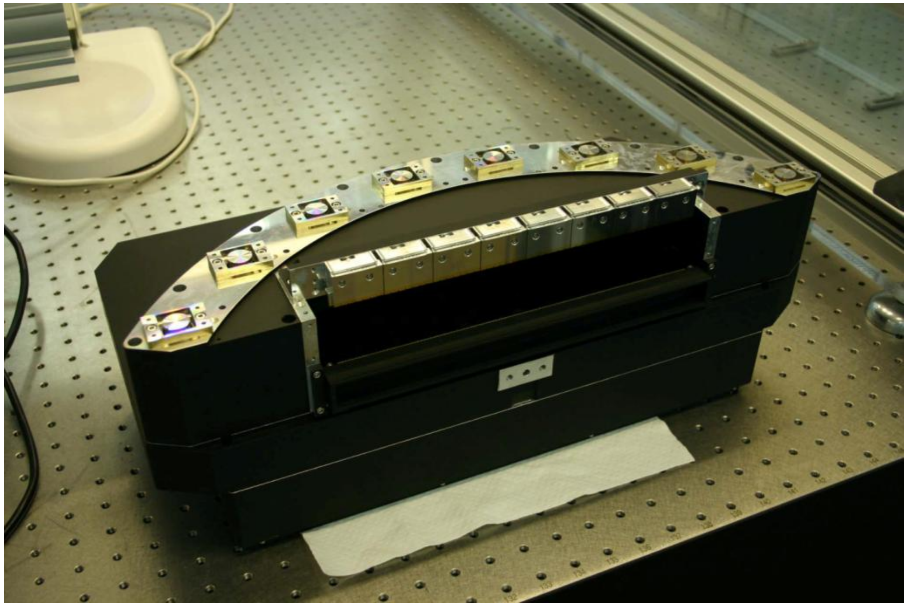
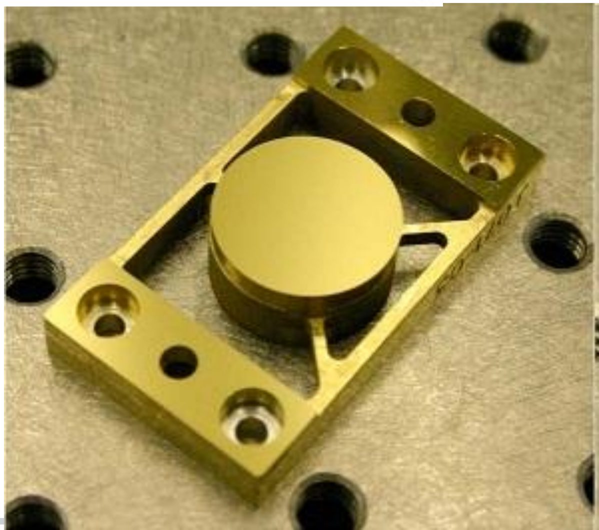


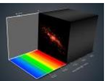
Image slicer
1
2
3
4
Mirrors
1
2
3
4
slit


Slit Array
To Spectrograph
Pupil Array
Slicer Array
3rd Re-imaging Mirror
2nd Re-imaging Mirror
y
z
x
1st Re-imaging Mirror
Intermediate Field






J062-17

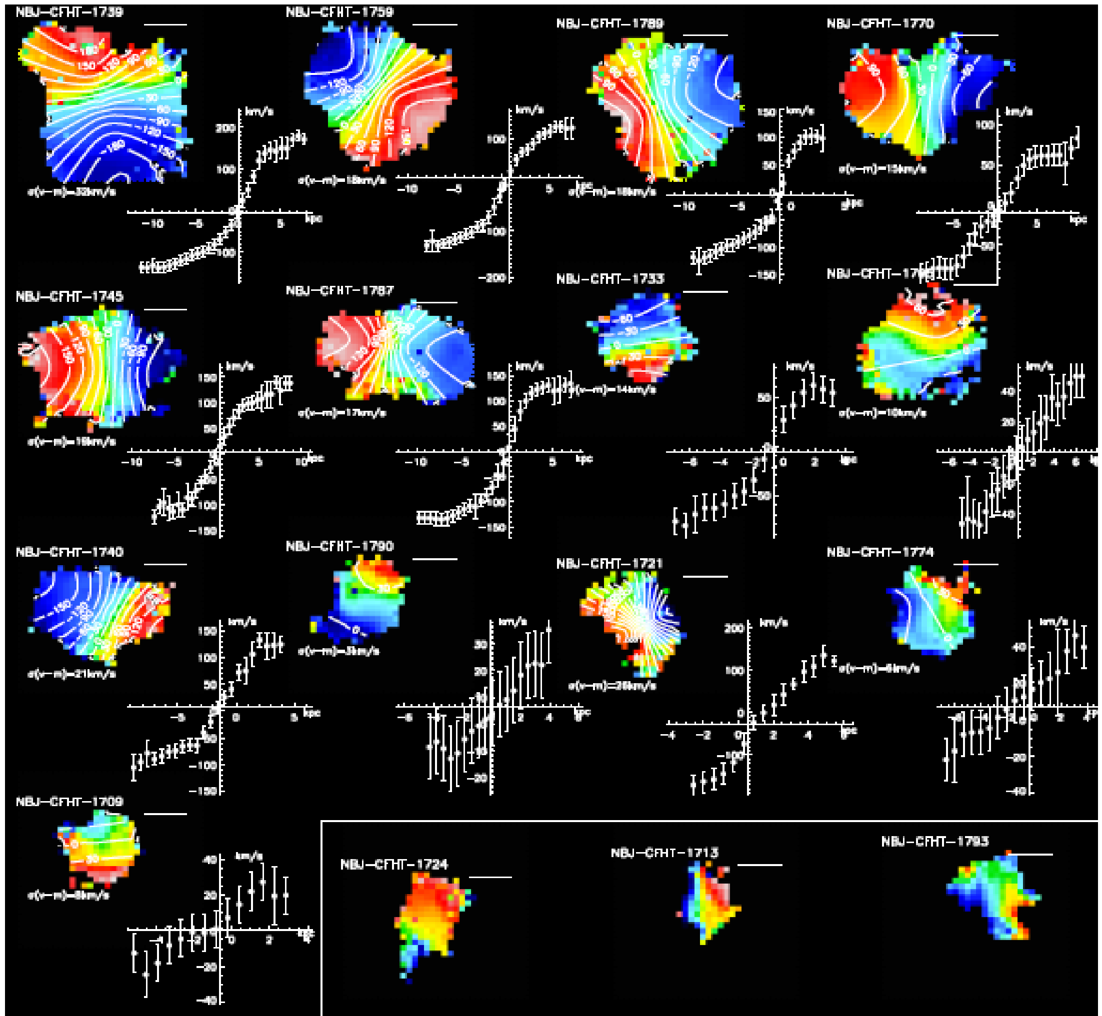


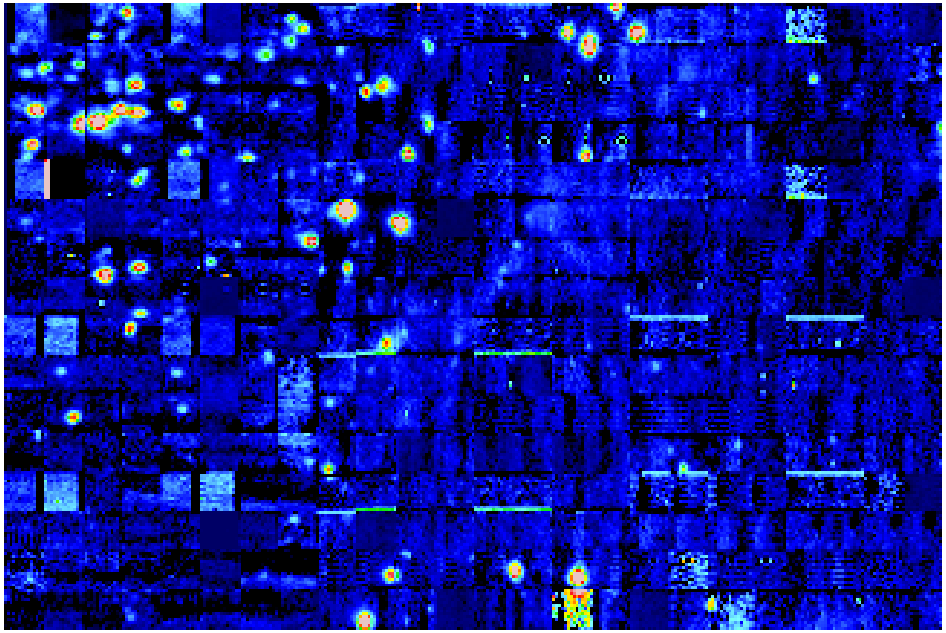
Science Verification

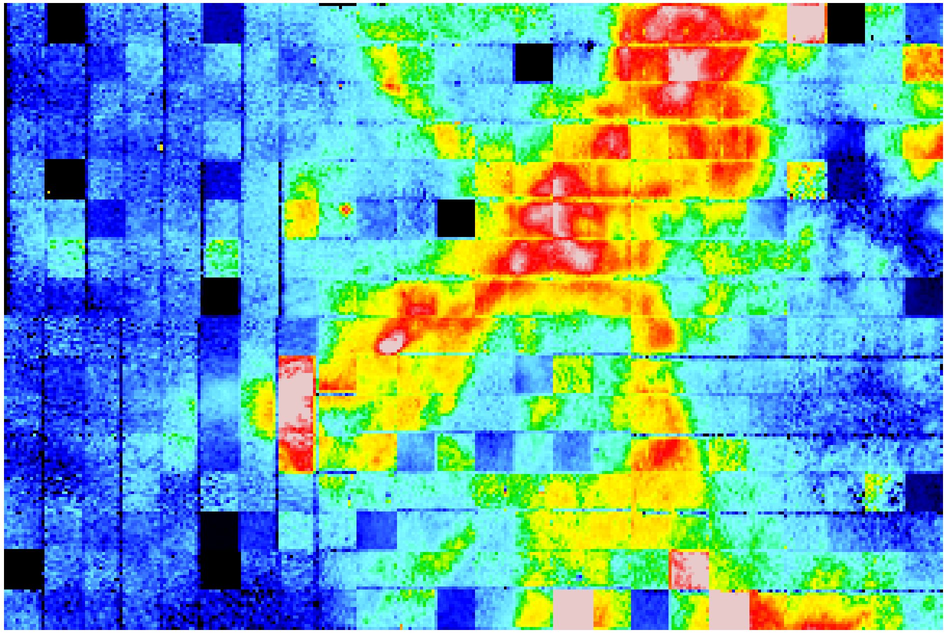
First paper accepted :

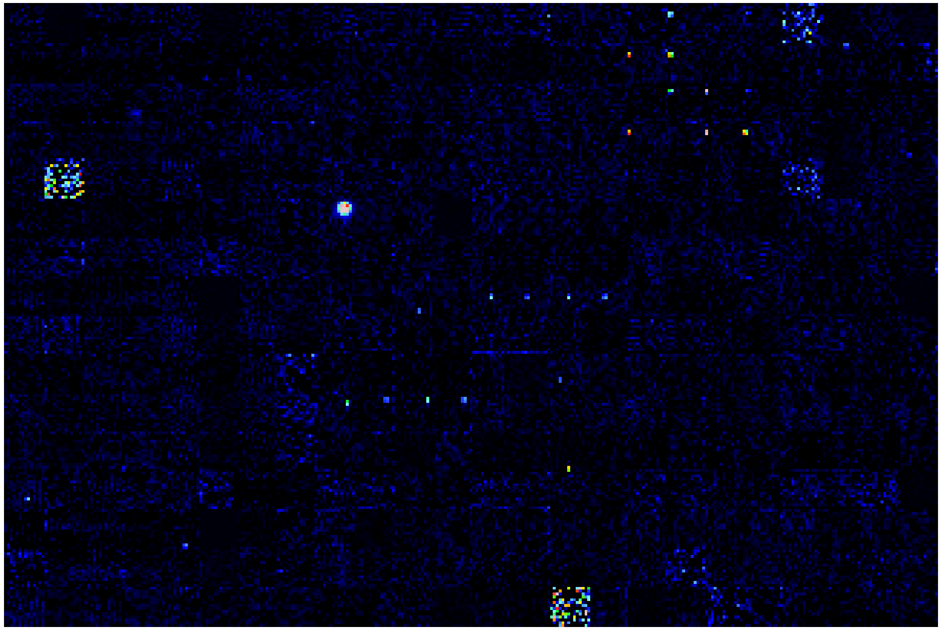
Sobral et al., astro-ph/1310.3822

The dynamics of z=0.8 H-alpha-selected star-forming galaxies from KMOS/CF-HiZELS)









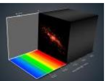
Mapping 24 observations of R136. [~ 40x60 arcsec^2]

Views are

Top left: 2.1μm continuum

Top right: Br-γ

Bottom left: broad HeII in WR star



And now ?

➔ Medium-size

(z~0) spectroscopic surveys

Going from a few hundreds…

to a few **thousands**!

SAMI Science drivers

- **What are the physical processes responsible for galaxy transformations?**
  - Morphological and kinematic transformations; suppression of star formation; internal vs. external; secular vs. fast; ram pressure stripping; harassment, strangulation; galaxy–group/cluster tides; galaxy-galaxy mergers; galaxy-galaxy interactions…
- **How does mass and angular momentum build up?**
  - The galaxy velocity function; stellar mass in dynamically hot and cold systems; galaxy merger rates; halo mass from velocity-field shear; Tully-Fisher relation…
- **Feeding and feedback: how does gas get into galaxies, and how does it leave?**
  - Winds and outflows; feedback vs. mass; triggering and suppression of SF; gas inflow; metallicity gradients; the role of AGN…
  - Important synergies with ASKAP HI surveys.

Sydney-AAO Multi-object IFS (SAMI)

- 1 degree diameter FOV
- 13 x 61 fibres IFUs using hexabundles

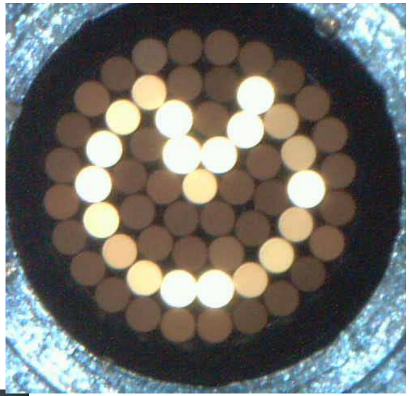
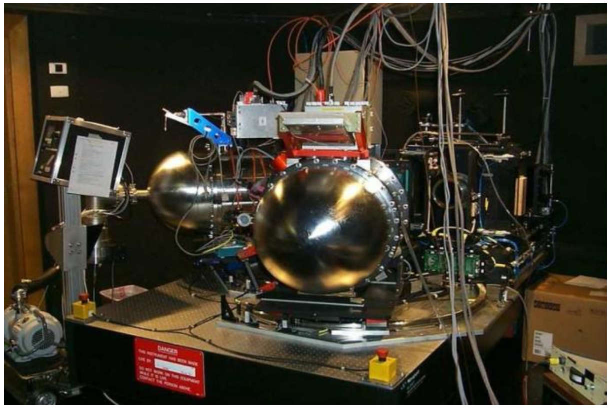
  (Bryant, Bland-Hawthorn et al.)
- 15” diameter IFUs, 1.6” diameter fibre cores
- Spectral resolution R~1700 (blue), R~4500 (red)

The Sydney-AAO Multi-object Integral-field spectrograph (SAMI)

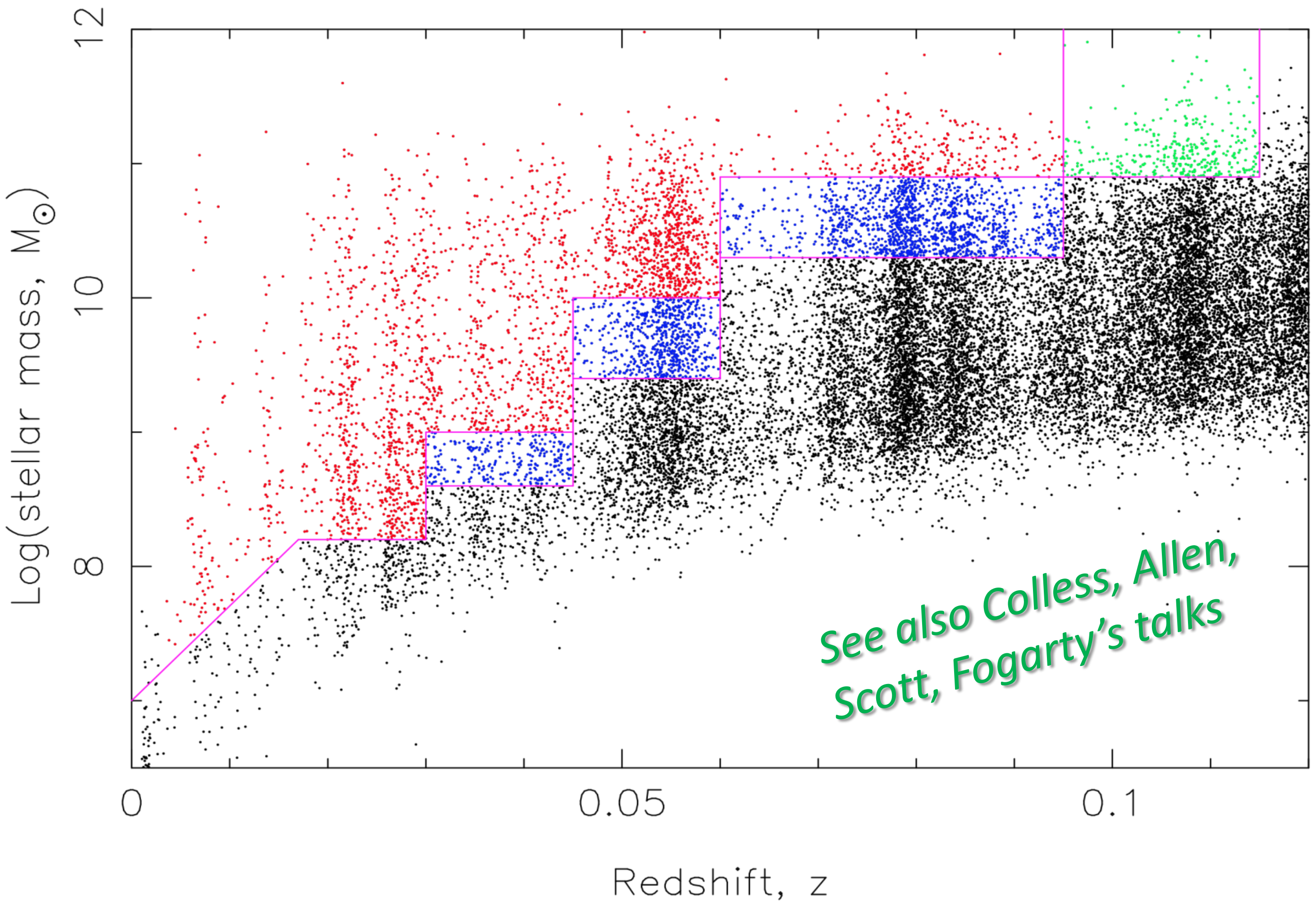
Scott M. Croom[1,2⋆], Jon S. Lawrence[3,4], Joss Bland-Hawthorn[1], Julia J. Bryant[1], Lisa Fogarty[1], Samuel Richards[1], Michael Goodwin[3], Tony Farrell[3], Stan Miziarski[3], Ron Heald[3], D. Heath Jones[5], Steve Lee[3], Matthew Colless[3,2], Sarah Brough[3], Andrew M. Hopkins[3,2], Amanda E. Bauer[3], Michael N. Birchall[3], Simon Ellis[3], Anthony Horton[3], Sergio Leon-Saval[1], Geraint Lewis[1], Á. R. López-Sánchez[3,4], Seong-Sik Min[1], Christopher Trinh[1], Holly Trowland[1]

[1] *Sydney Institute for Astronomy (SIfA), School of Physics, University of Sydney, NSW 2006, Australia*
[2] *ARC Centre of Excellence for All-sky Astrophysics (CAASTRO)*
[3] *Australian Astronomical Observatory, PO Box 296, Epping, NSW 1710, Australia*
[4] *Department of Physics and Astronomy, Macquarie University, NSW 2109, Australia*
[5] *School of Physics, Monash University, Clayton, VIC 3800, Australia*

Croom et al. 2012


Target selection



Primary sample, high mass secondary sample, low mass secondary sample

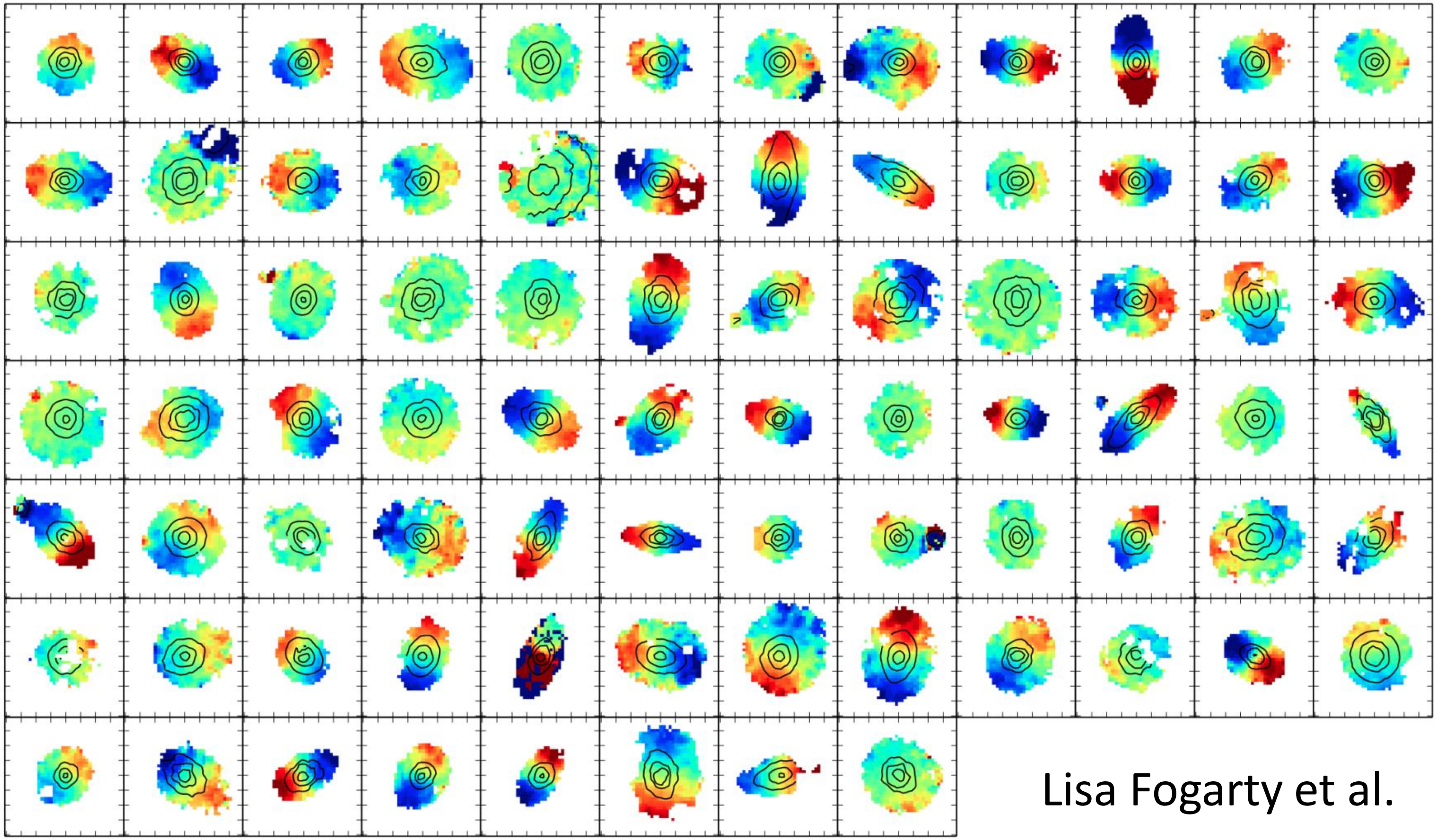
The SAMI Galaxy Survey

- Using the upgraded SAMI instrument
- Started in March 2013
- 3400 galaxies in ~200 nights, 4 hours exposure per field
- Primary fields are the Galaxy And Mass Assembly (GAMA; Driver et al. 2010) regions
  - Three 4x12 deg equatorial regions at 9hr, 12hr and 15hr RA
  - Deep, complete, spectroscopy to r=19.8 to define environment
  - Robust group catalogue (Robotham et al. 2011)
  - GALEX, SDSS, VST, UKIDSS, VISTA, WISE, Herschel imaging, 21cm ALFALFA
- Specific galaxy cluster fields to be targeted in the SGP to probe the highest density environments

➔ ***Reaching the 1000 galaxies in main survey…***

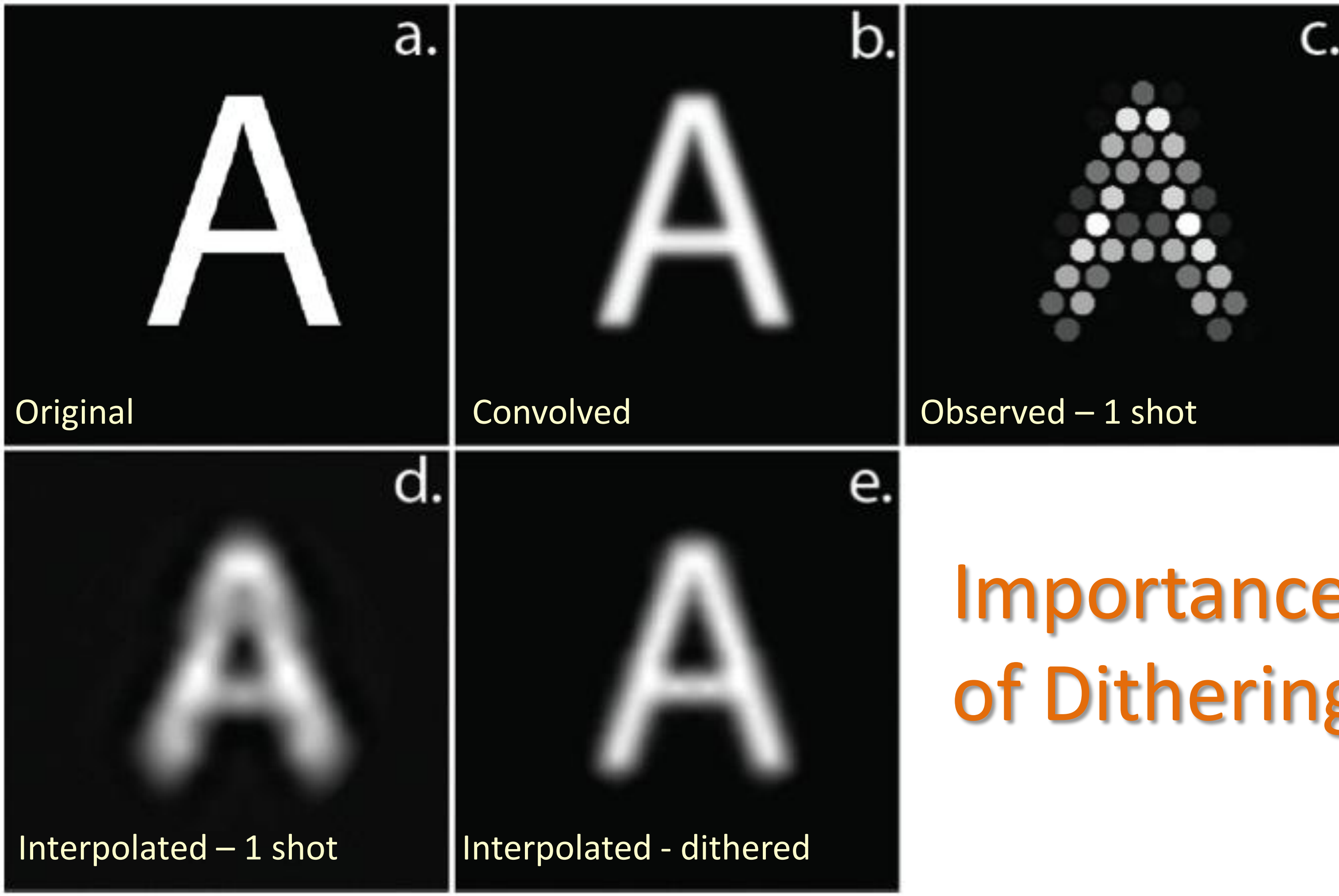
Example Science:
Stellar Angular Momentum

› Q: What drives the distribution of stellar angular momentum in galaxies? What makes a "slow rotator"?



Lisa Fogarty et al.

Image reconstruction: accuracy



Importance of Dithering

Image reconstruction: accuracy

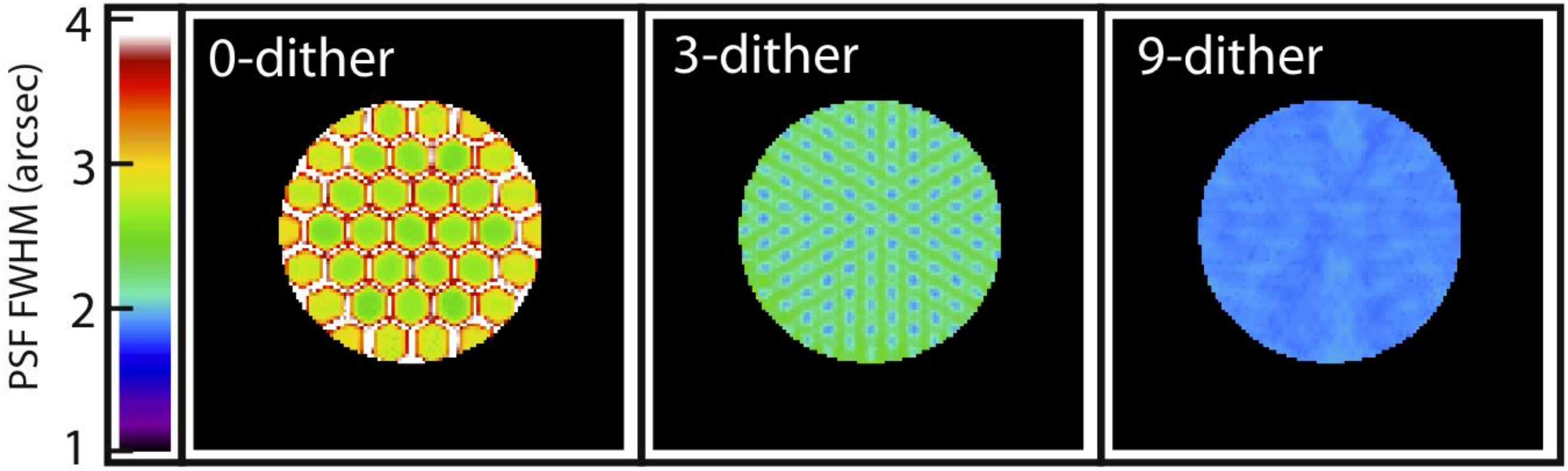
MaNGA observing Strategy

One Observing Unit = 3 dithers x 15 min

Repeat 3 times (possibly over 3 nights)

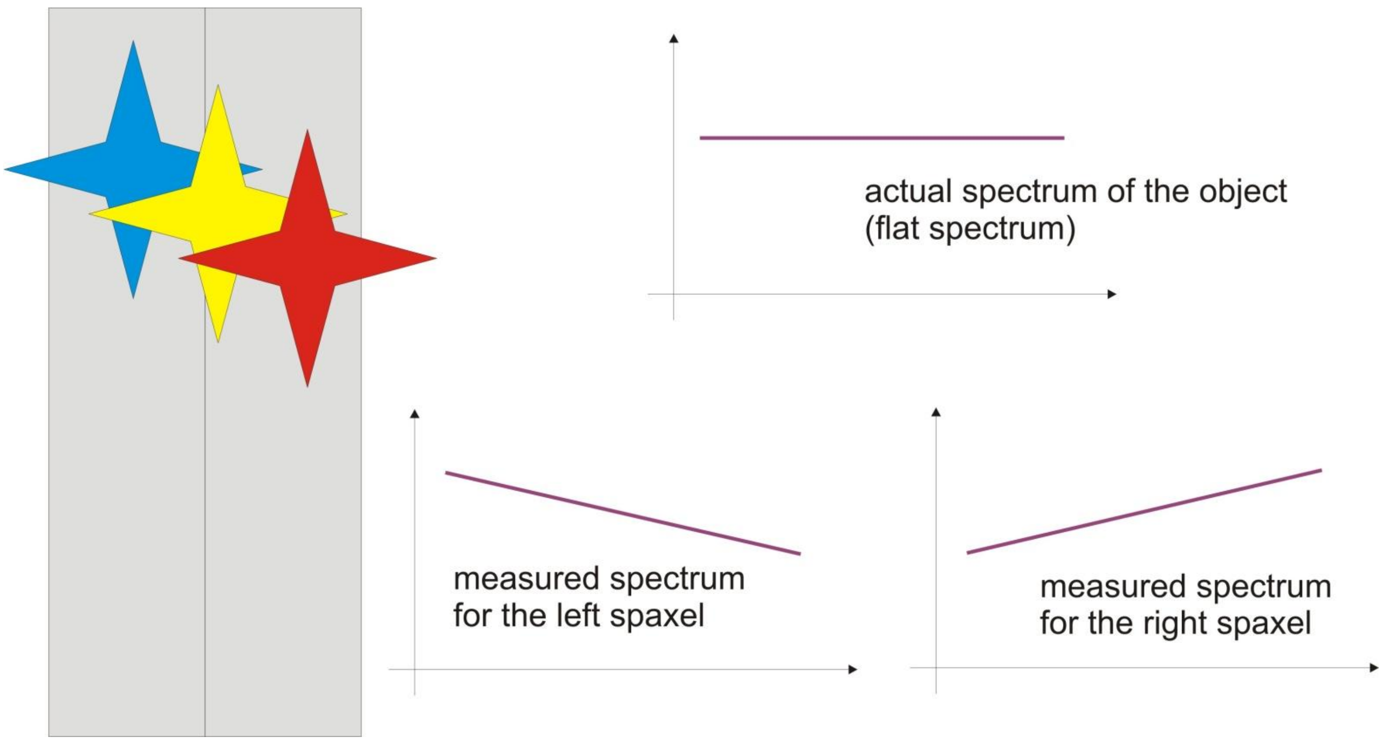
Total ~ 3 hours

Importance of Dithering



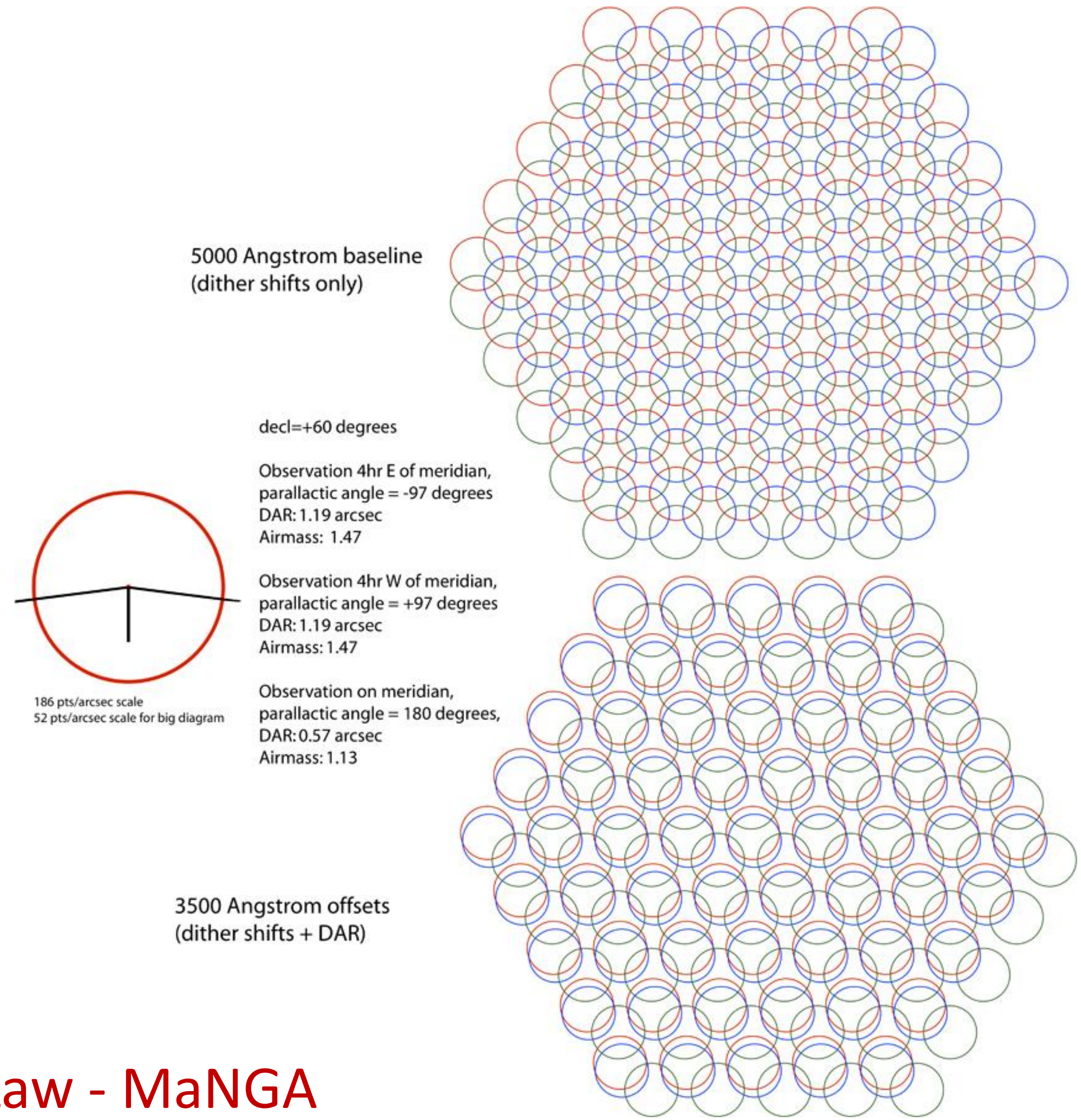
Interesting effects 2/2

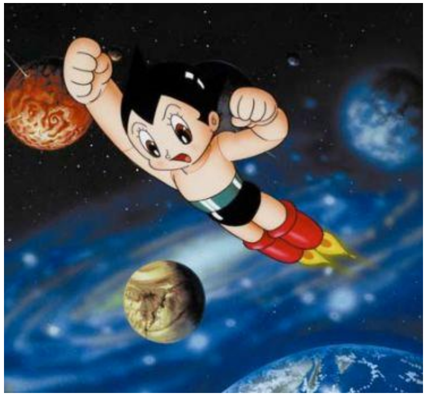
- Atmospheric refraction: images shifted with wavelength
  ➔ ***Object moving out of the slit ?***
- IFU *minimises the impact* of this effect
  ➔ possible *software* correction (or ADC)



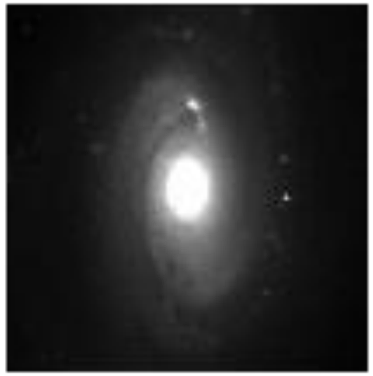
Emsellem et al. 1996; Arribas et al. 1999

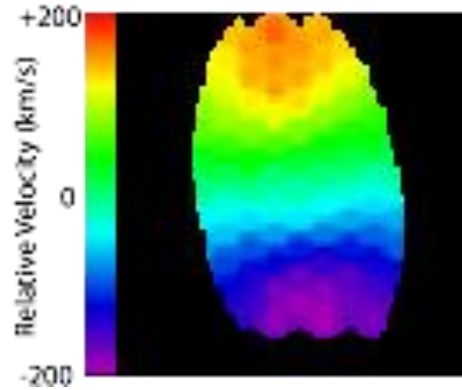
But what about Differential Atmostpheric Refraction ?





MaNGA Key Science Questions:





See Yan's talk

Life

1. How does gas accretion drive the growth of galaxy disks?
2. What are the relative roles of stellar accretion, major mergers, and instabilities in forming galactic bulges?

Death

3. What quenches star formation?
4. How do external forces affect star formation in groups and clusters?

Birth

5. How was angular momentum distributed among baryonic and non-baryonic components as the galaxy formed?
6. How do baryons and stars trace and influence the shape of dark matter halos?
7. Does galaxy growth at low and high redshifts proceed in the same way?

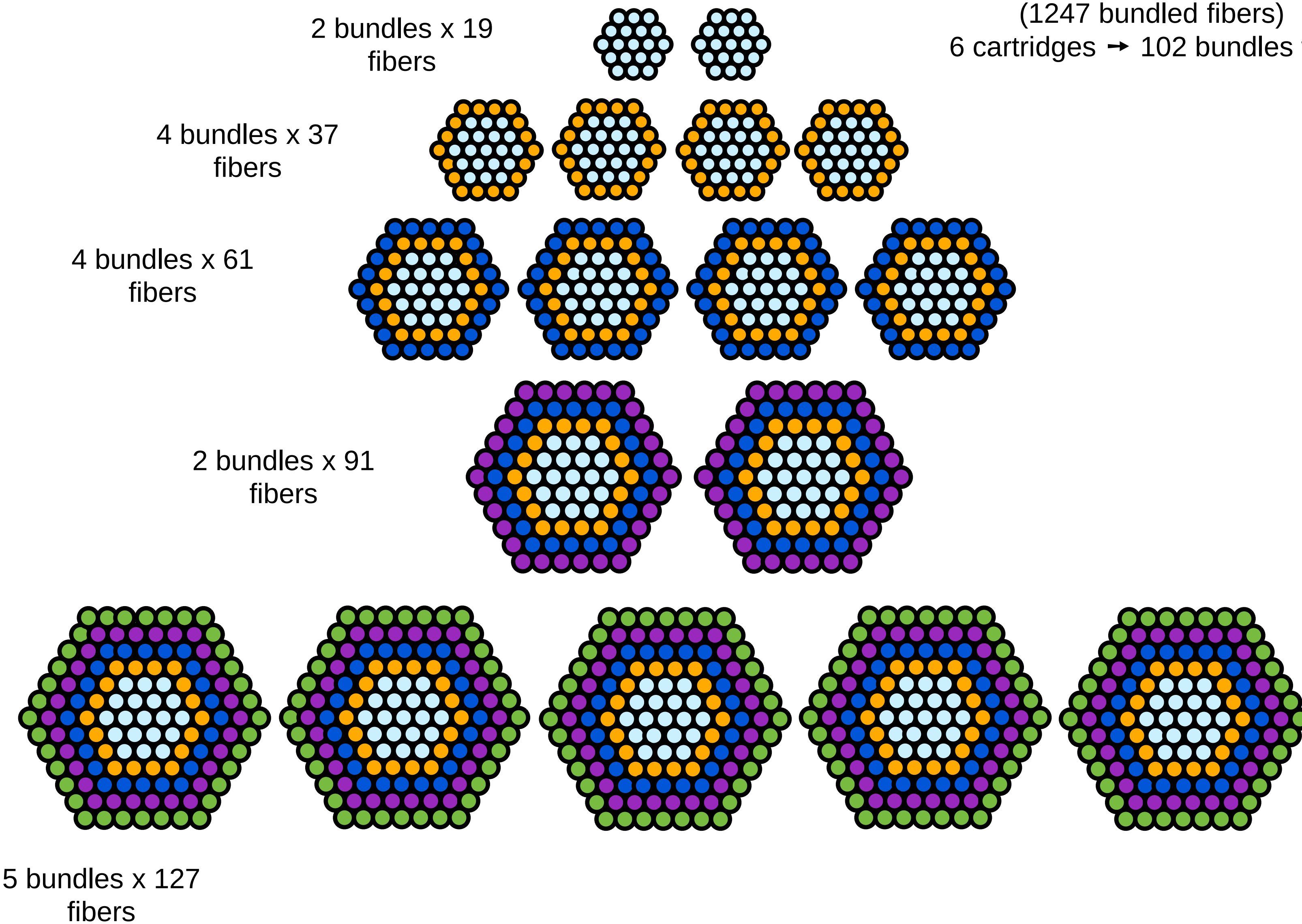
MaNGA Hardware Constraints

- **Regularity of the fiber packing** (hexabundle)
  - Use of Electric Discharge Machining
- Ridged quality control procedures
  - Measuring all the hardware components
  - Lower the need for low assembly tolerance

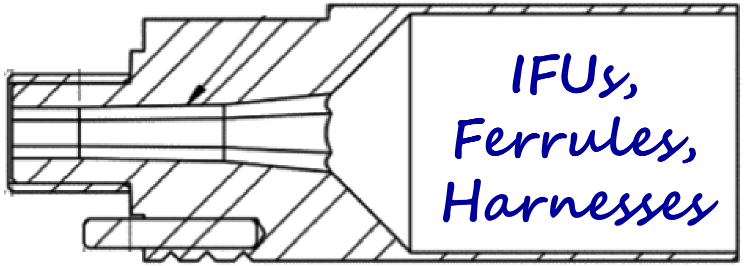
    ➔ 1-3 μm positional accuracy!
- Production: approach and environment
  - Achievable cost
  - Molding (“Califa”) too expensive and time-consuming
  - Ferrules: general tool for hexabundles of various sizes
- And others
  - AR coating on the bare fiber, sky fibers near the targets

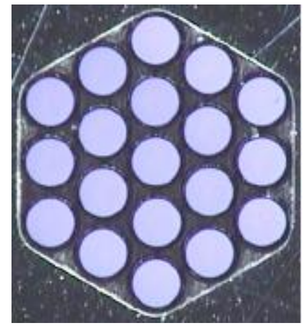
Bundle size distribution

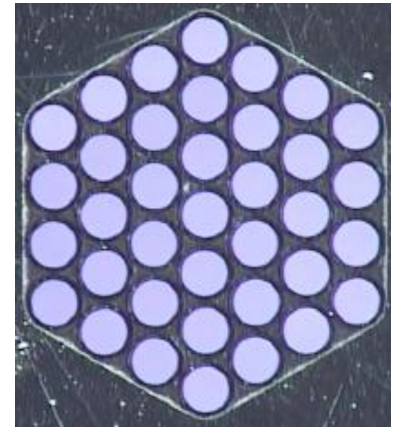
17 bundles per cartridge
(1247 bundled fibers)
6 cartridges → 102 bundles total

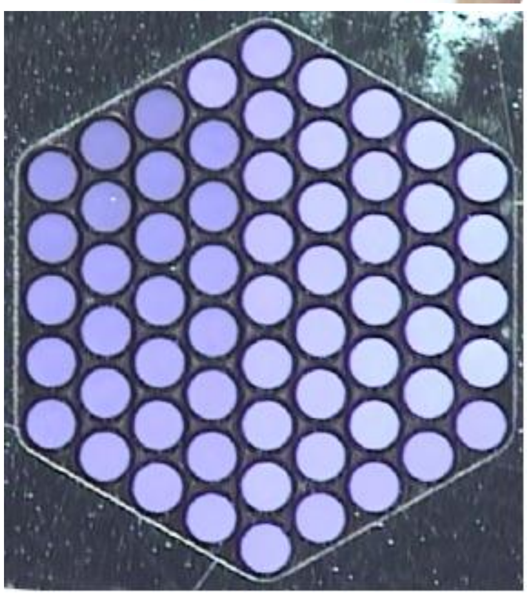


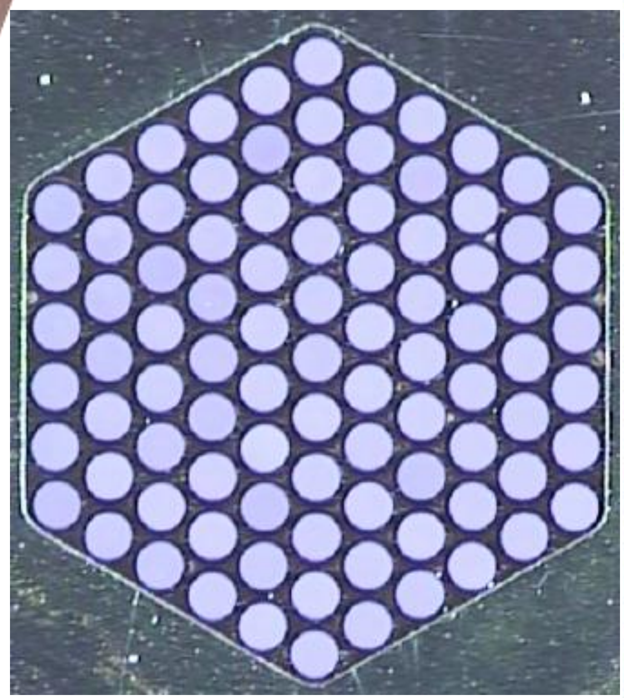
The real thing

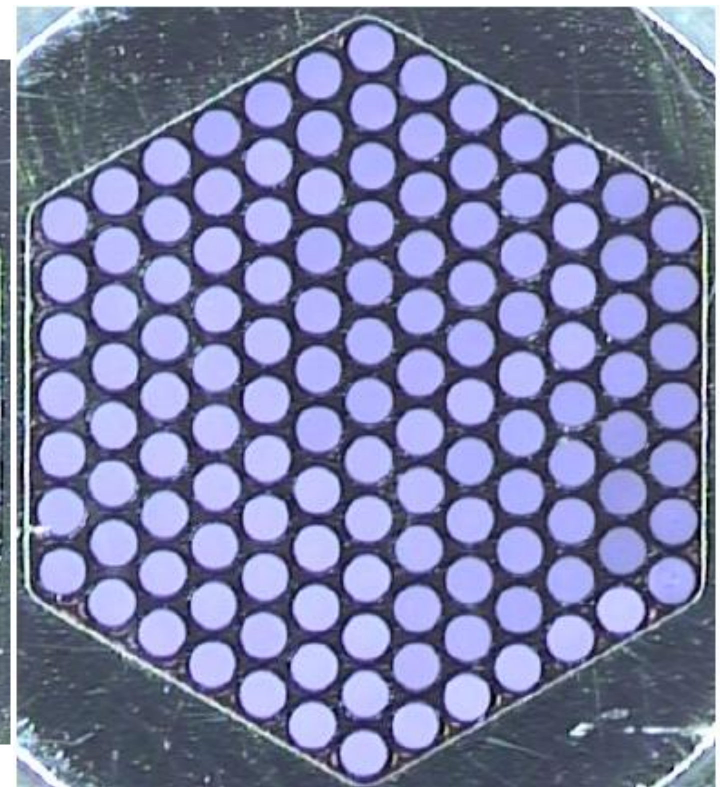


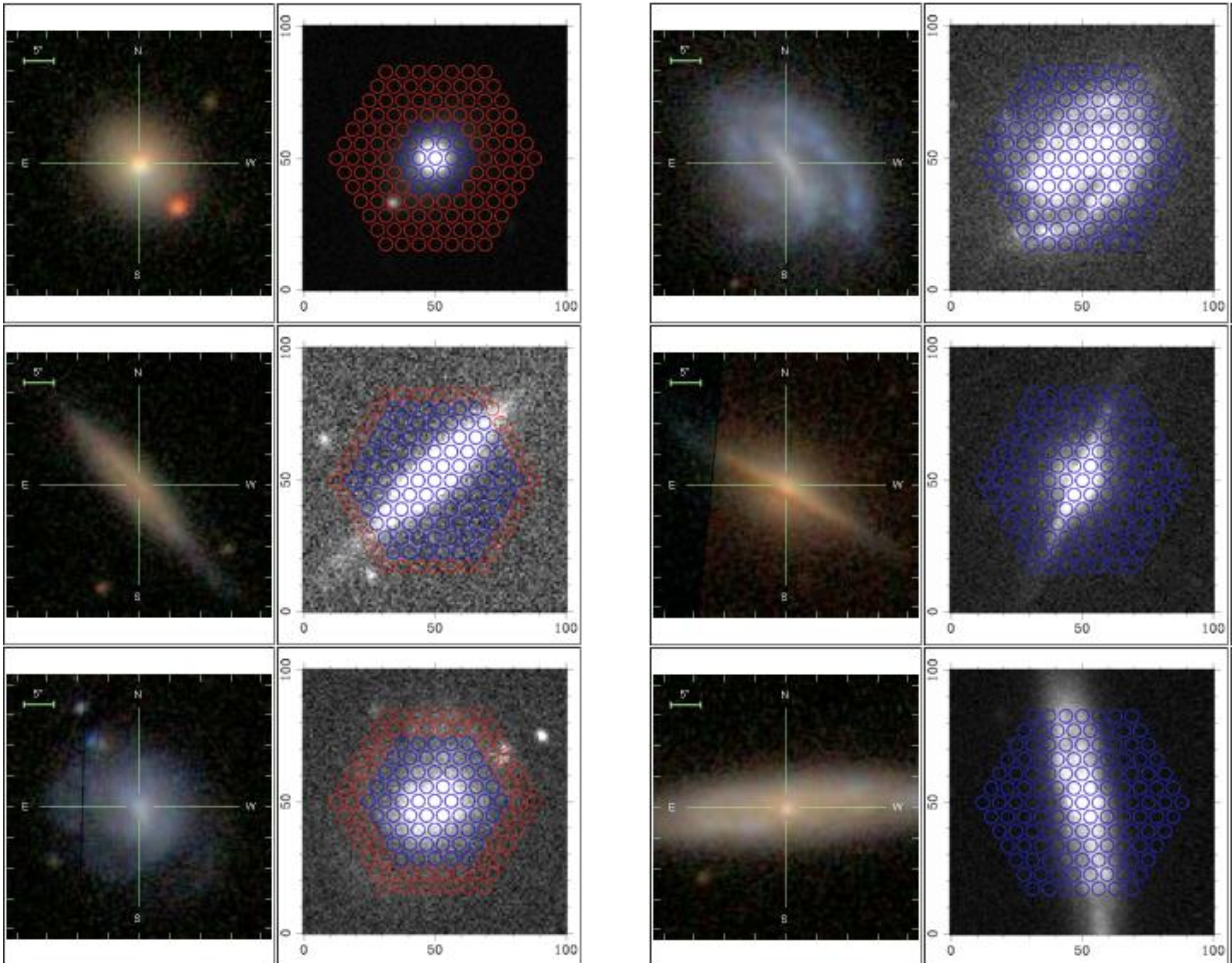












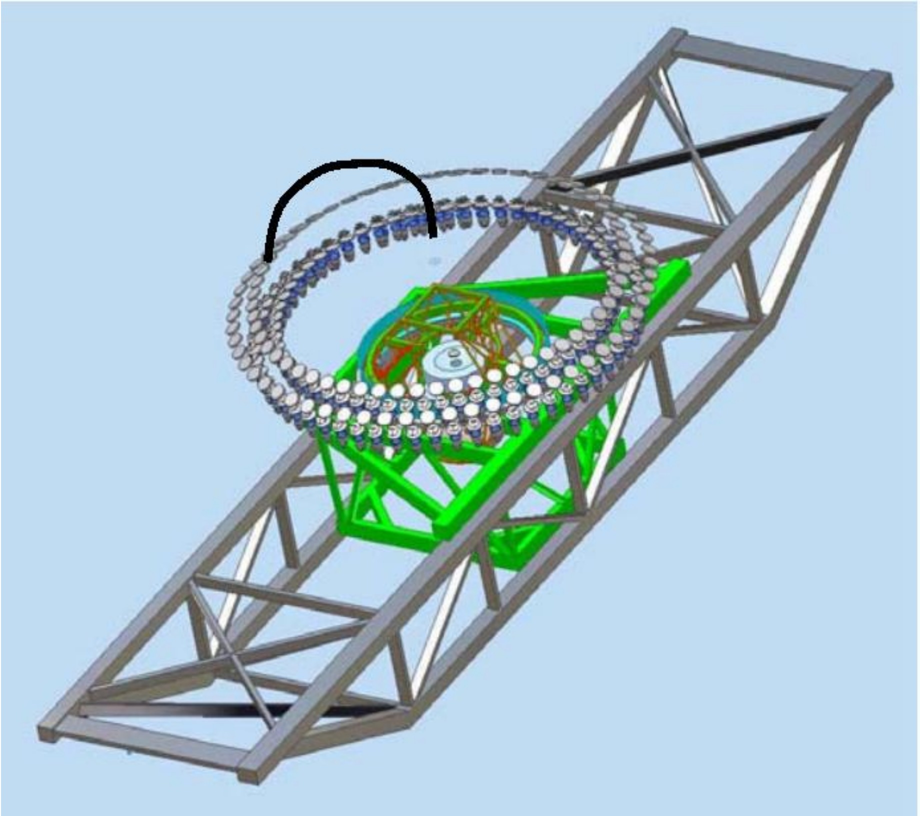
sample selection led by David Wake


Niv Drory
Nick MacDonald

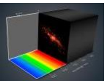
And many more

- X-Shooter: spectral resolution versus field
- SITELLE-CFHT (FTS)
- WiFES: multi-slit approach
- VIRUS-P and VIRUS/HET (132 IFUs)

See also Blanc's talk (VENGA)

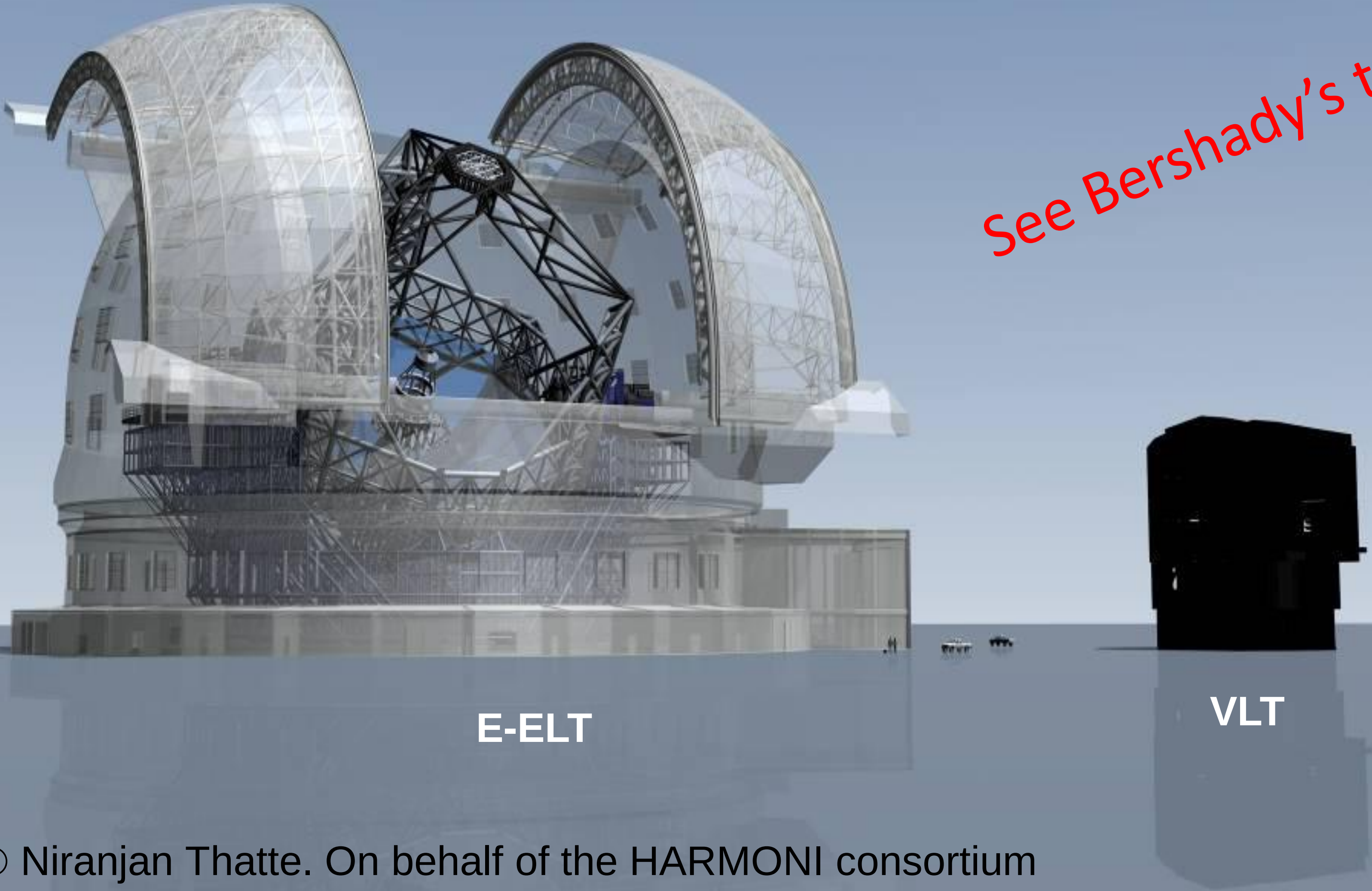


- ...



HARMONI – the first light integral field spectrograph for the E-ELT

See Bershady's talk



© Niranjan Thatte. On behalf of the HARMONI consortium

Personal recommendations

- Keep track of the noise pattern
- Characterise the instrument (and data reduction)
- Develop Software on realistic data:
  - Instrument Numerical Model
- 1 SINGLE (evolving) version for the data reduction software
- Develop (and diffuse!) tools to handle the data
- Allow CALIBRATION PROPOSALS

2007

Most statements NOT specific to IFUs

Personal recommendations

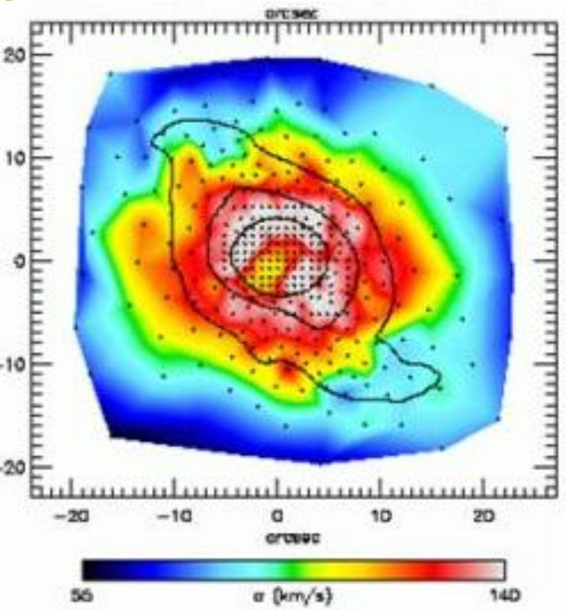
- Keep track of the noise pattern
- Characterise the instrument (and data reduction)
- Develop Software on realistic data:
  - Instrument Numerical Model
  - Compare data sets
- **Coordinate efforts on analysis tools**
- **Think about your data products**
- **Think about how to present + distribute your data**
- **Make sure you know how to compare with theory**
- **Make sure you adapt some theory to your data**

2012

Most statements NOT specific to IFUs

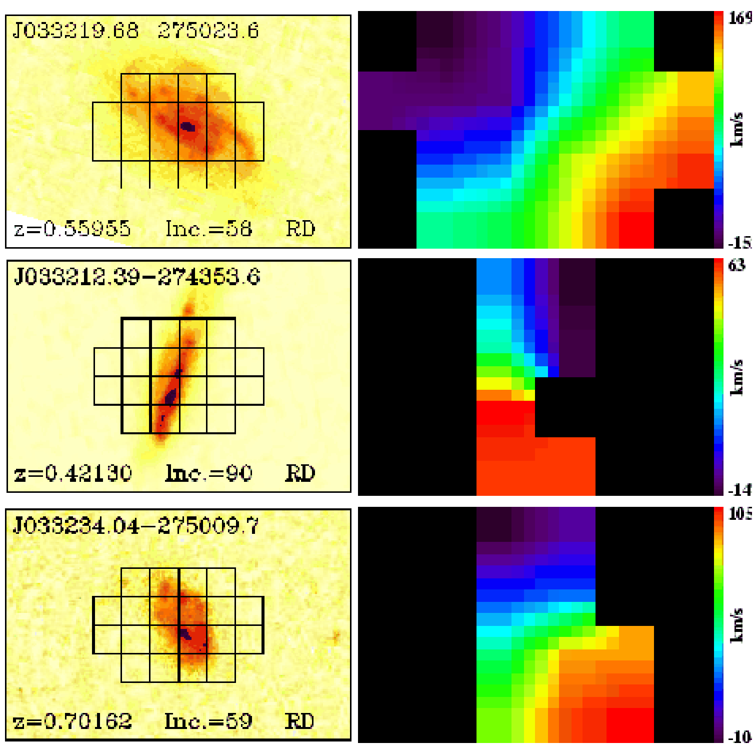
Maps look good, so...

- **Beware of interpolation**
- **Colours** ***or the importance of being earnest***

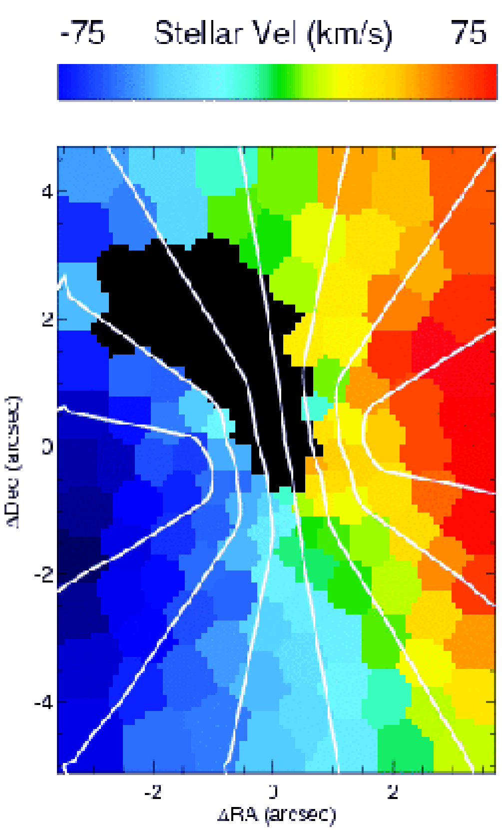


Cappellari et al.

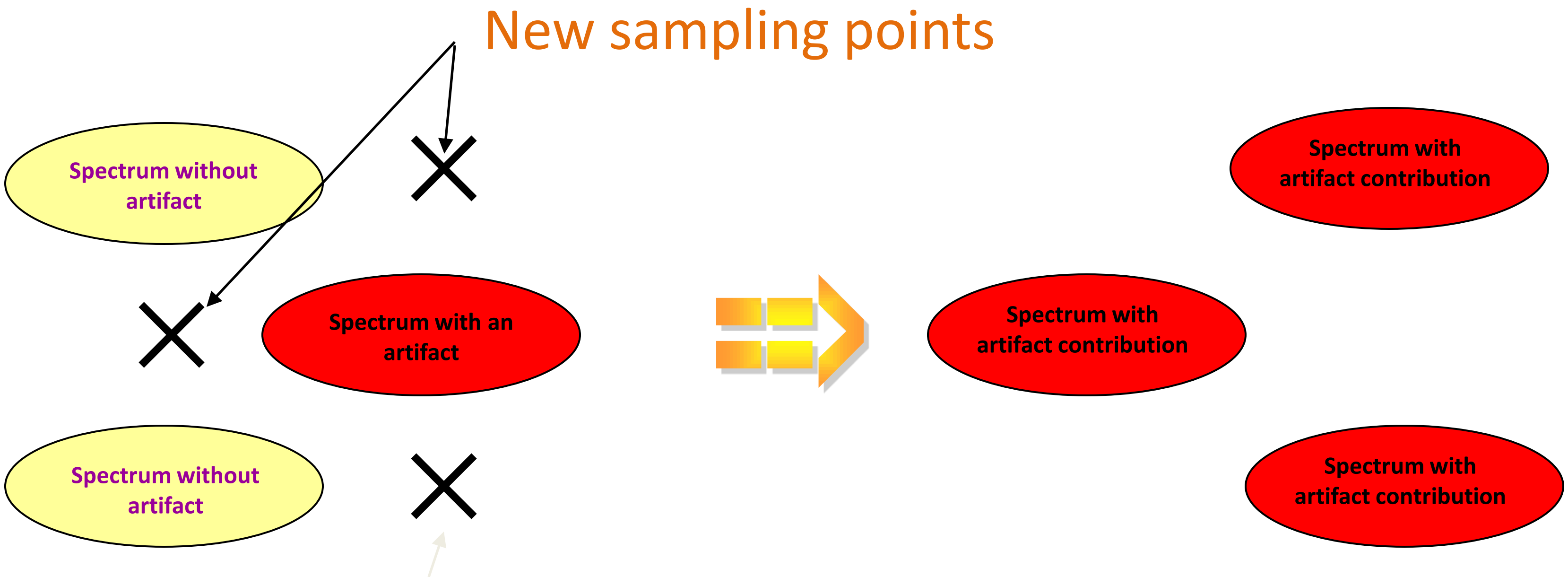
Puech et al.



Gerssen et al.



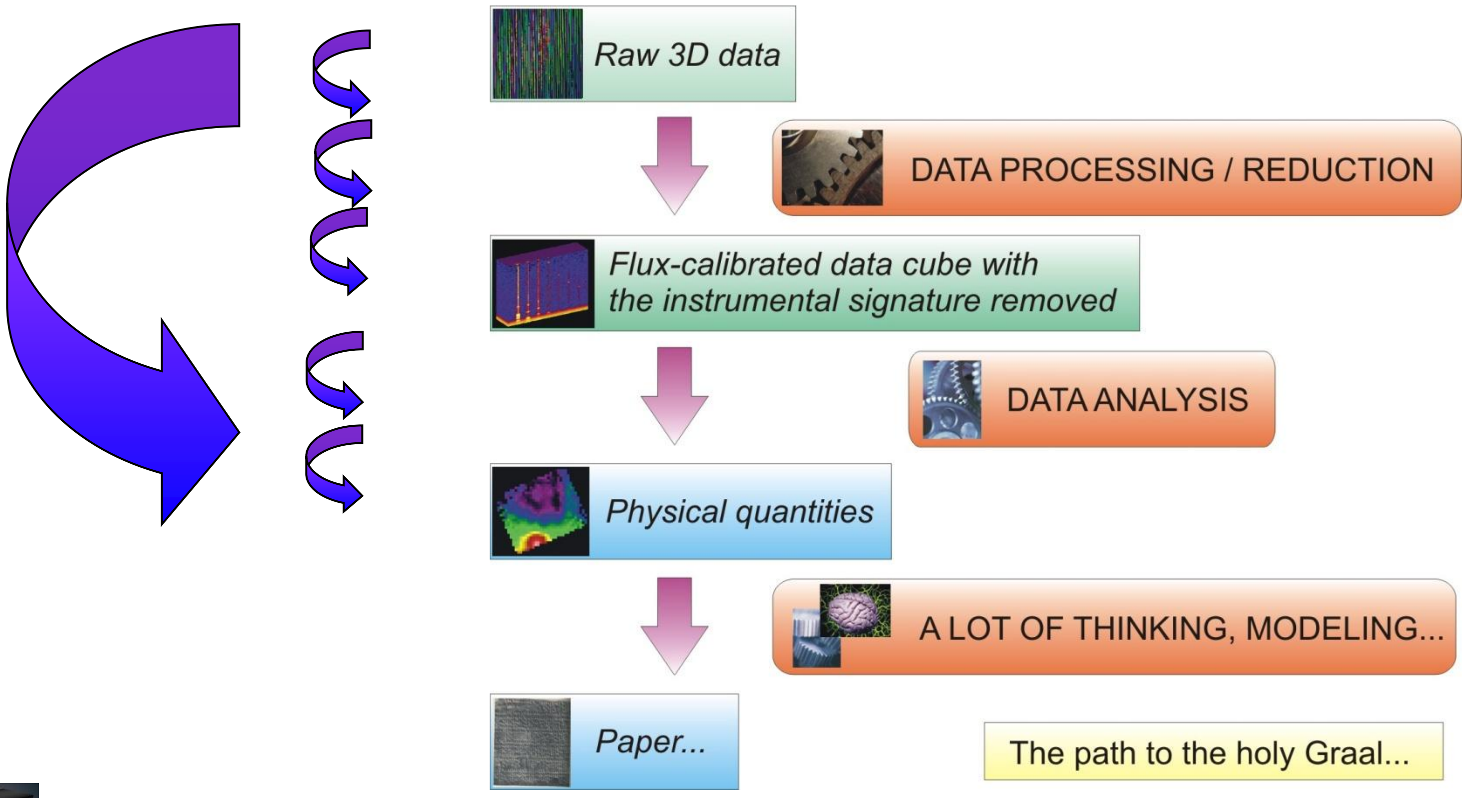
Propagation of artefacts



- **Artifact** has been
  - spread
  - attenuated: less likely to be identified

The all-in one solution ?

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



Concluding remarks

- **IFUs are everywhere**
  - *Mature "principle"*
  - *But many innovations: new ways to go "3D"*
- **Going 3D comes at a price**
  - *Controlling systematics*
  - *Monitoring errors, data quality*
  - *DRS, DAS, Visualisation, data mining*
- **The importance of software**
  - *As part of the instrument*
  - *Models, Analysis: before, during, after*
- **Specific science goals**
  - *One IFU should not be designed to do everything*

➔ *let's be ambitious & pragmatic*