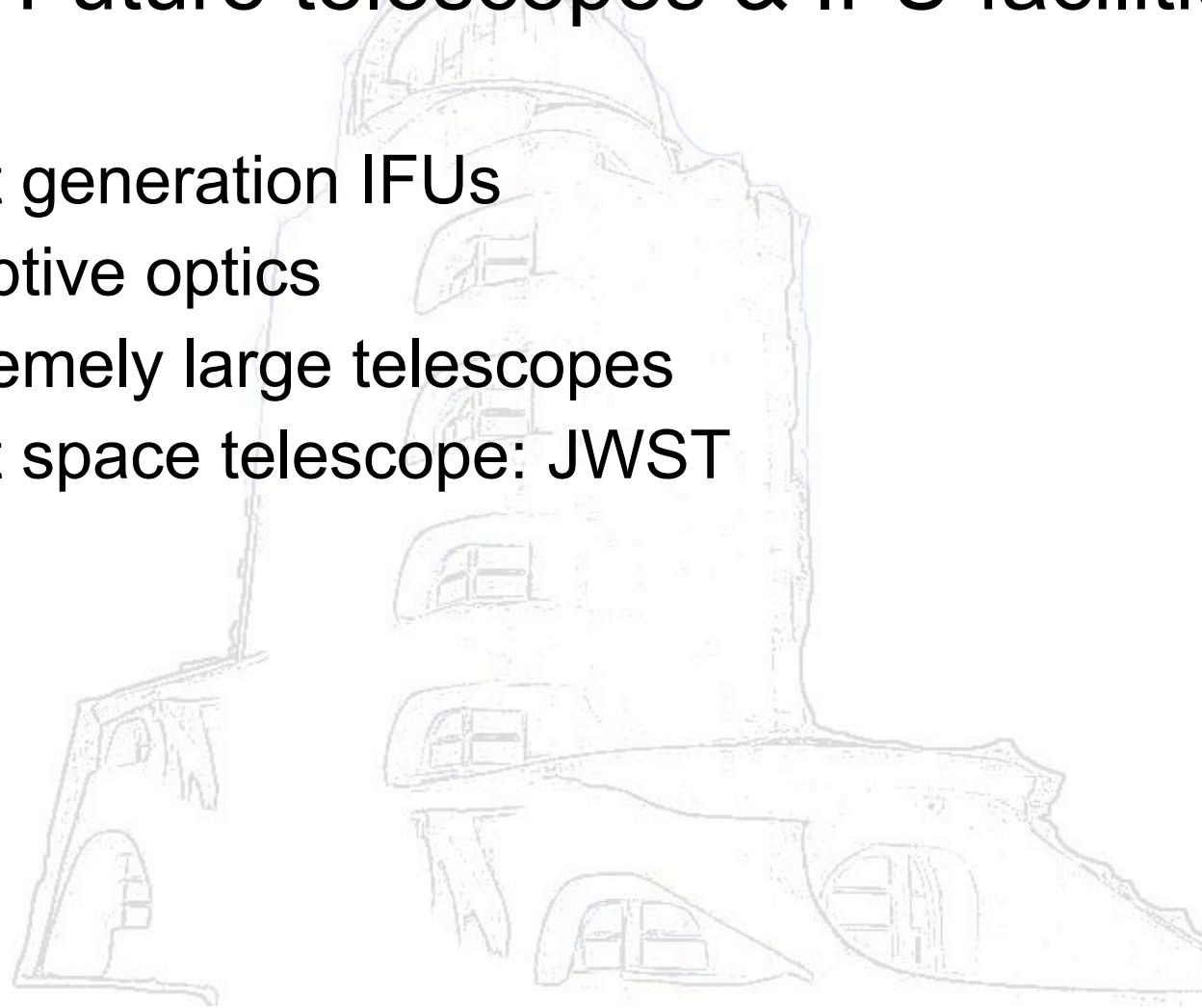
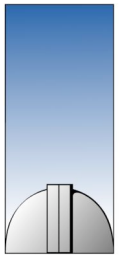


4. Future telescopes & IFU facilities

- Next generation IFUs
- Adaptive optics
- Extremely large telescopes
- Next space telescope: JWST

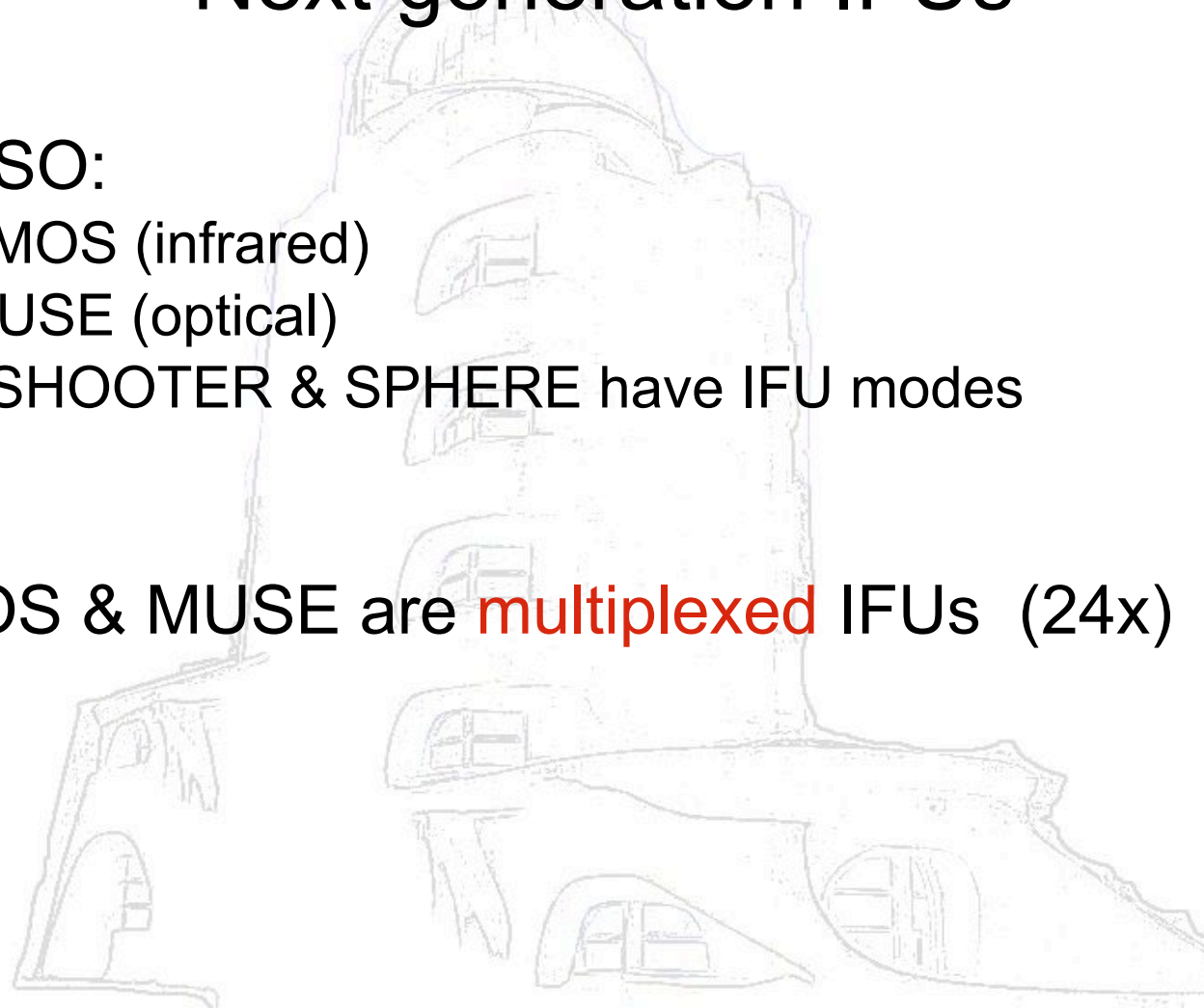


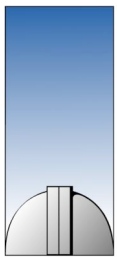


AIP

Next generation IFUs

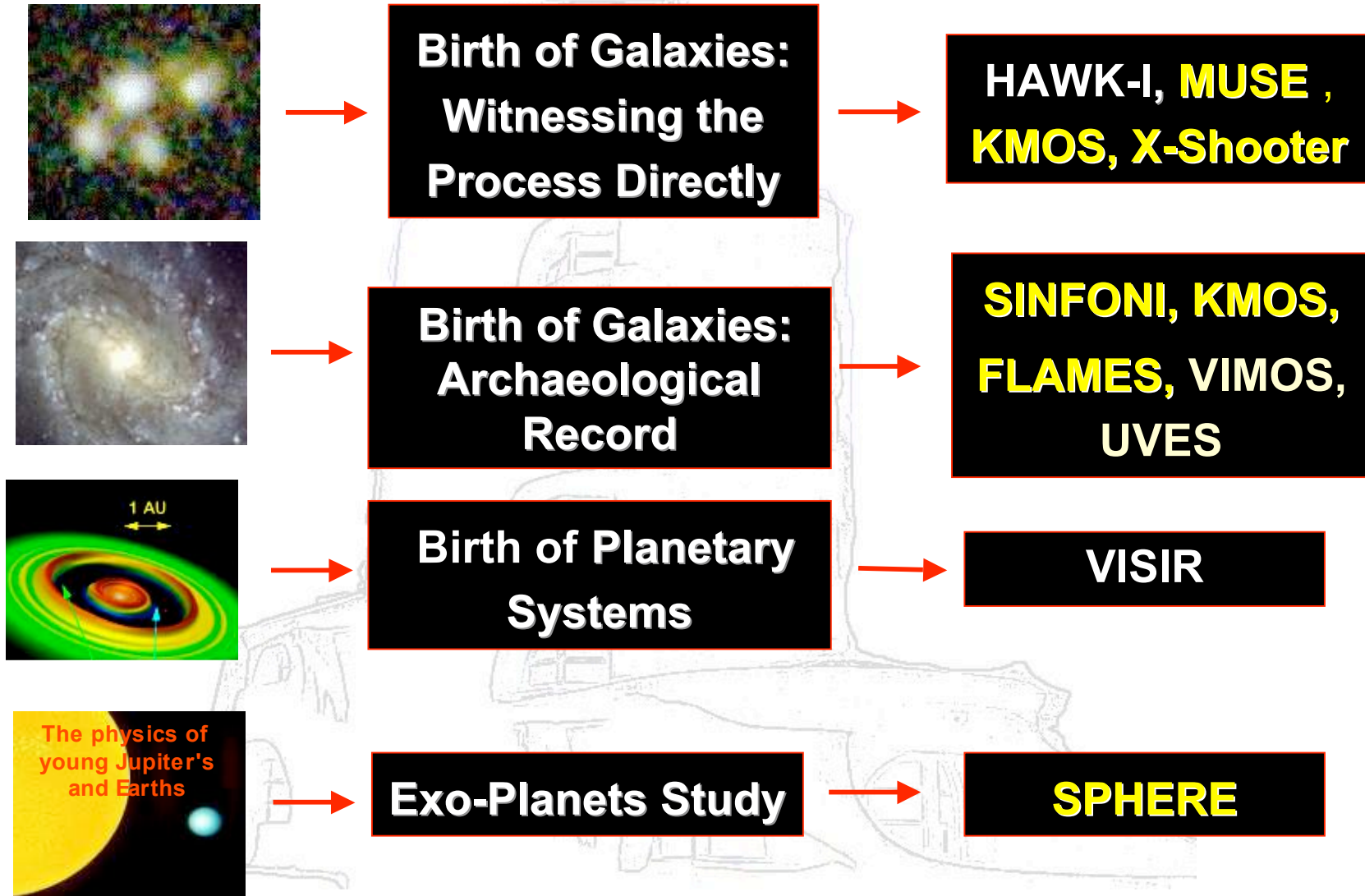
- At ESO:
 - KMOS (infrared)
 - MUSE (optical)
 - XSHOOTER & SPHERE have IFU modes
- KMOS & MUSE are **multiplexed** IFUs (24x)





AIP

(IFU-based) VLT Instruments circa 2012





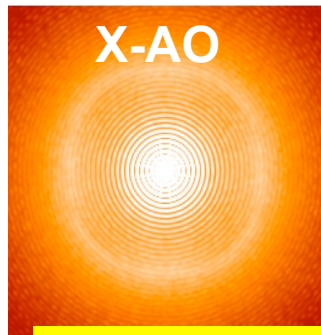
AIP

SPHERE

- Objective: direct detection of exo-solar planets:
 - Contrast 10^{6+} ; 0".1 - 1" separation
- IFU mode
 - IFU D-L spectrometer as a coronagraph
 - IFU D-L spectrometer as a speckle suppressor

SPHERE IFU

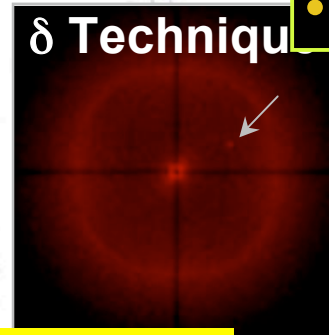
- micro lens
- 1.35" x 1.35" (goal: 3x3)
- sampling: 13 mas
- 0.95 - 1.7 μm
- $R \sim 30$



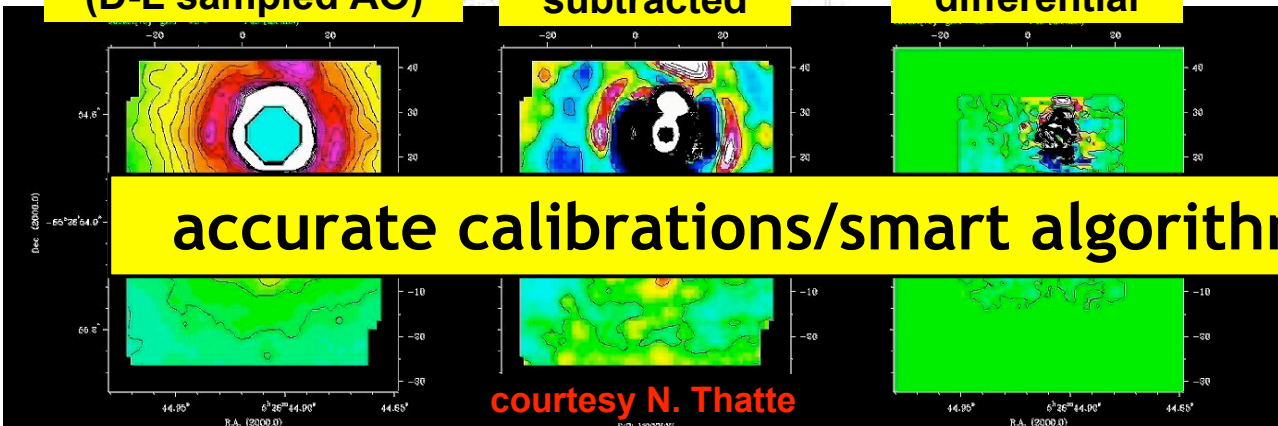
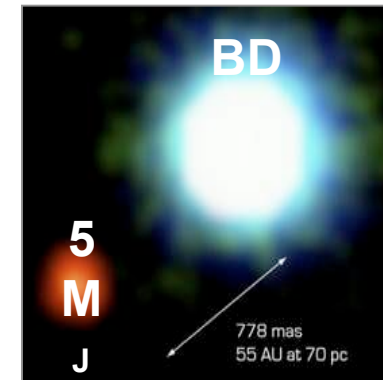
SINFONI 2.2 μm slice (D-L sampled AO)



Star profile subtracted



λ -scaling differential



accurate calibrations/smart algorithms essential

courtesy N. Thatte



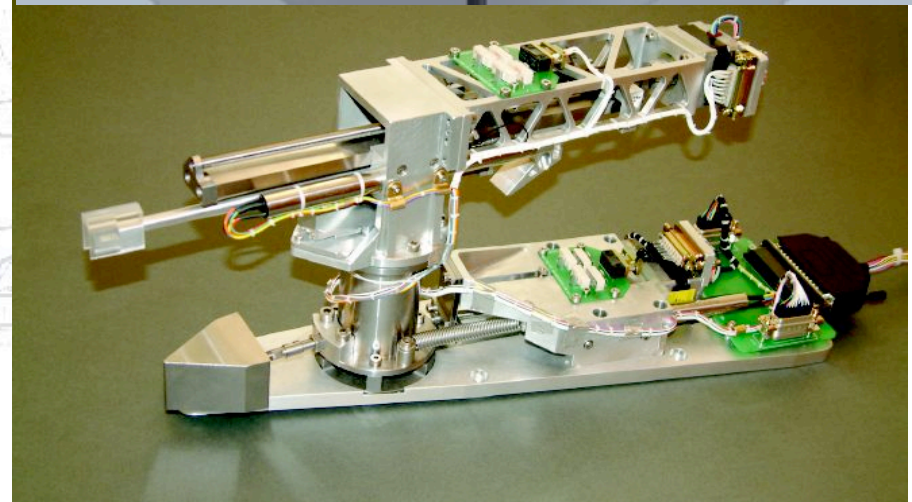
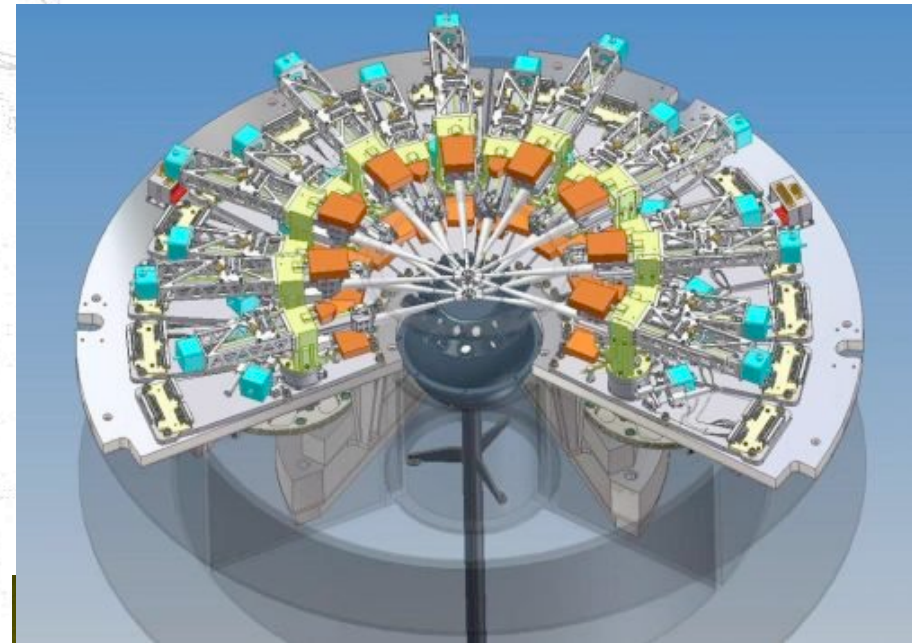
AIP

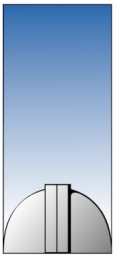
KMOS

- Cryogenic multiplexed IFU on an 8-m class telescope (VLT)
- Available by 2011

KMOS

- 24 deployable IFUs
- Patrol field: 7.2 arcmin \varnothing
- 2.8" x 2.8" field sliced at 0.2"
- 0.8 - 2.4 μm (I, Z, J, H & K)
- R ~ 3500



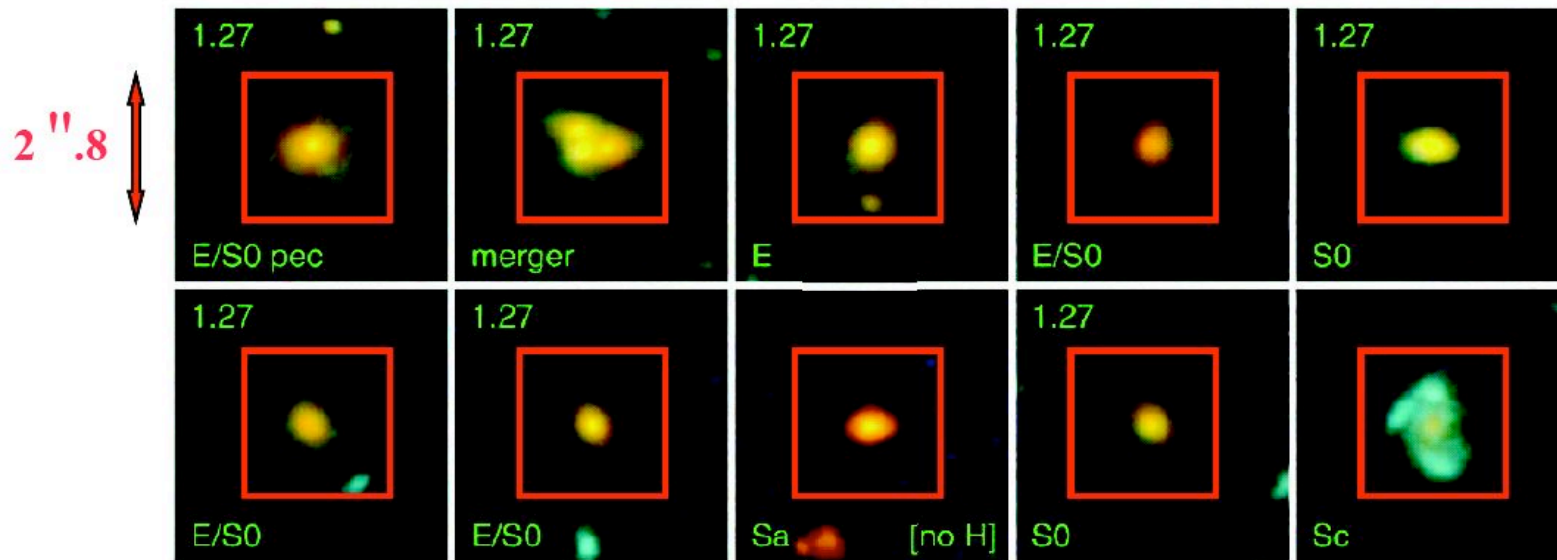


AIP

KMOS science

- Galaxy formation processes in the range $1 < z < 10$
- Star-formation properties and histories
- Dynamically masses
- Complementary to JWST

10 brightest galaxies in RX J0848+4453 $z=1.27$



HST images: H-band & F702W (rest-frame V), van Dokkum et al. 2001



AIP

Multi Unit Spectroscopic Explorer

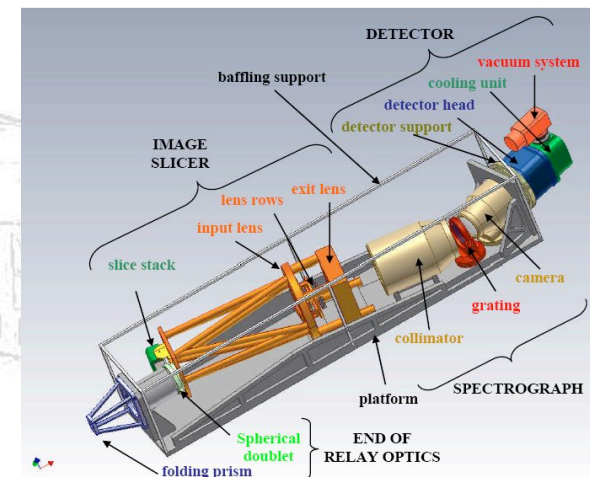
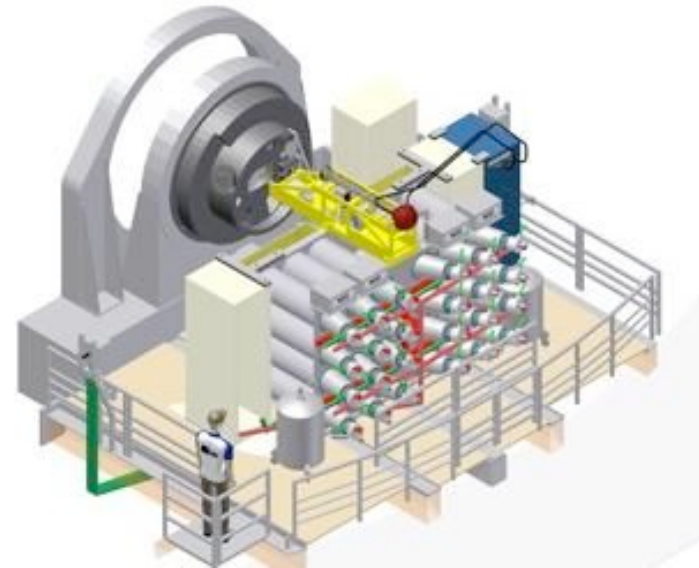
- Wide field optical IFU with Adaptive Optics correction
- Available by 2013

MUSE

- 24 'fixed' IFUs (slicers)
- WFM: 60" x 60" field sliced at 0.2"
- NFM: 7.5" x 7.5", 0.025" sampling
- 0.465 - 0.93 μm
- $R \sim 3000$

Sampling and FoV \rightarrow 90,000 spectra each
~4000 pixels long

Cheaper to split the instrument in sub units rather than create one very large (and very expensive) unit: industrial replication





AIP

MUSE field of view

MUSE WFM

– 60x60 arcsec²

– 0.2 arcsec

SAURON

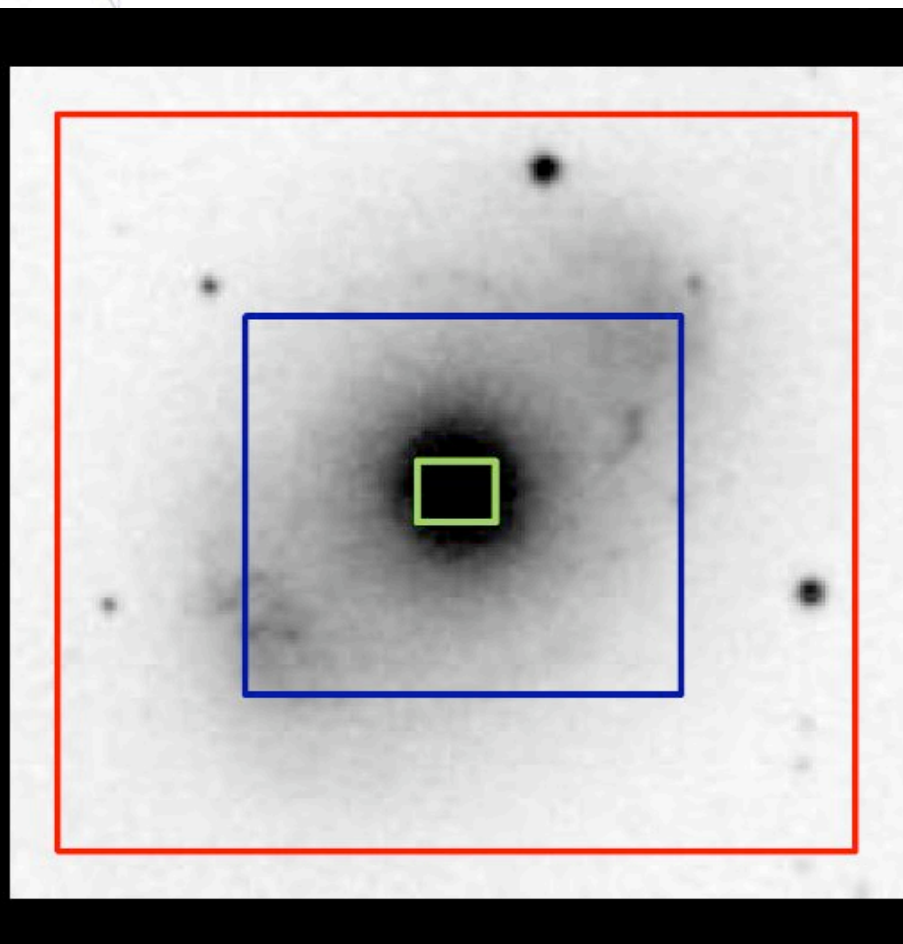
– 40x30 arcsec²

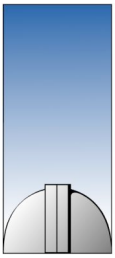
– 0.94 arcsec

OASIS

– 10x7 arcsec²

– 0.27 arcsec

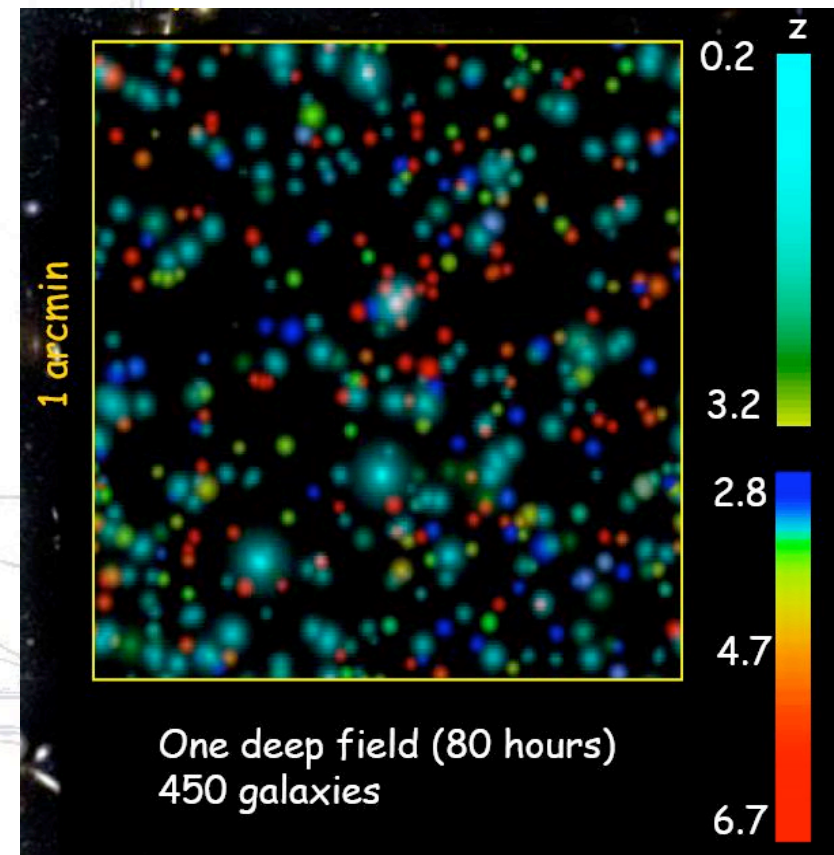
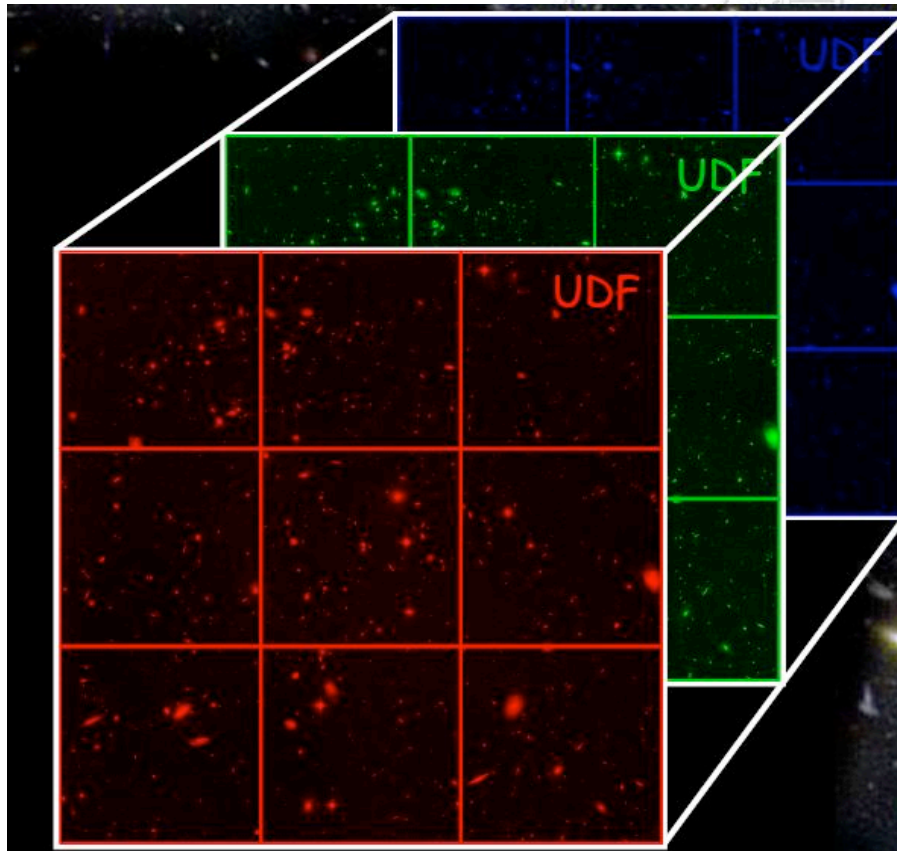


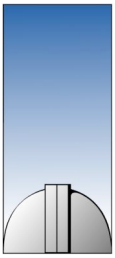


AIP

MUSE science

- It is a survey instrument, large **discovery potential**
- Major science goal: deep field
 - As the HST deep fields but now including the 3rd dimension





AIP.

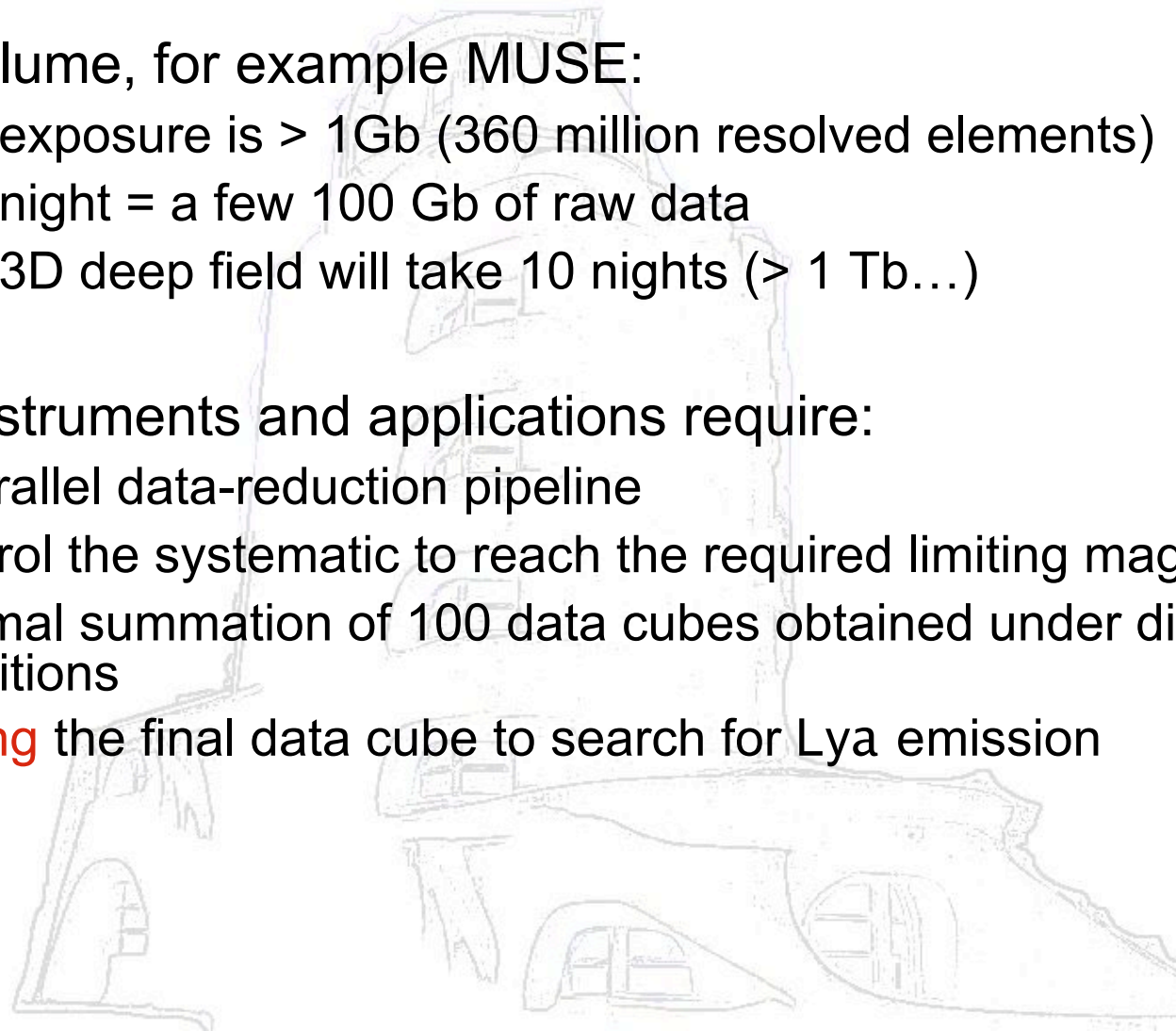
Data reduction and analysis challenges

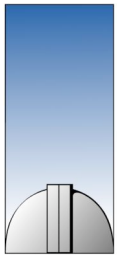
Data volume, for example MUSE:

- One exposure is $> 1\text{Gb}$ (360 million resolved elements)
- One night = a few 100 Gb of raw data
- One 3D deep field will take 10 nights ($> 1\text{Tb}\dots$)

• 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 Ly α emission

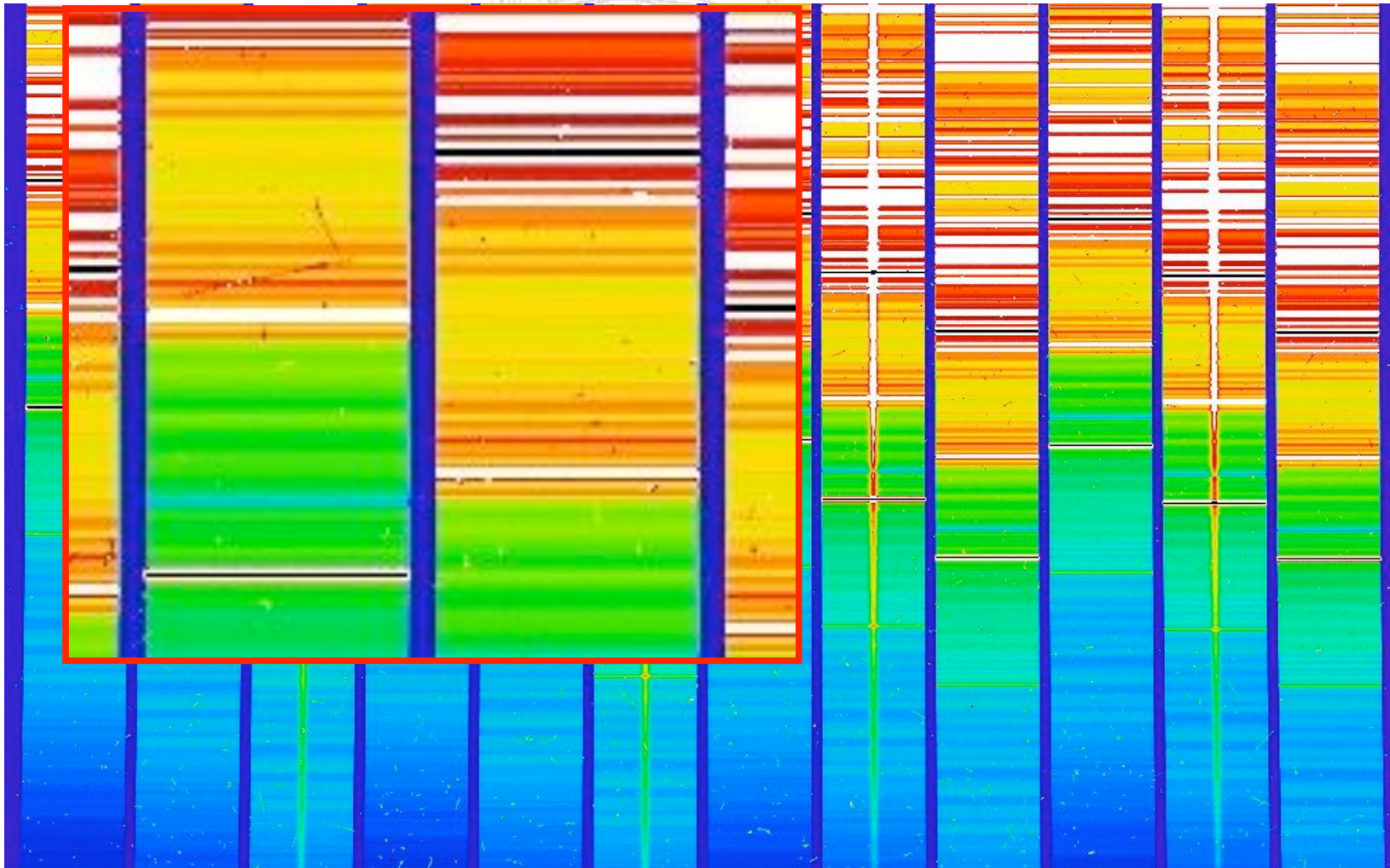


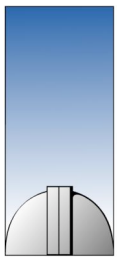


AIP

MUSE mock data

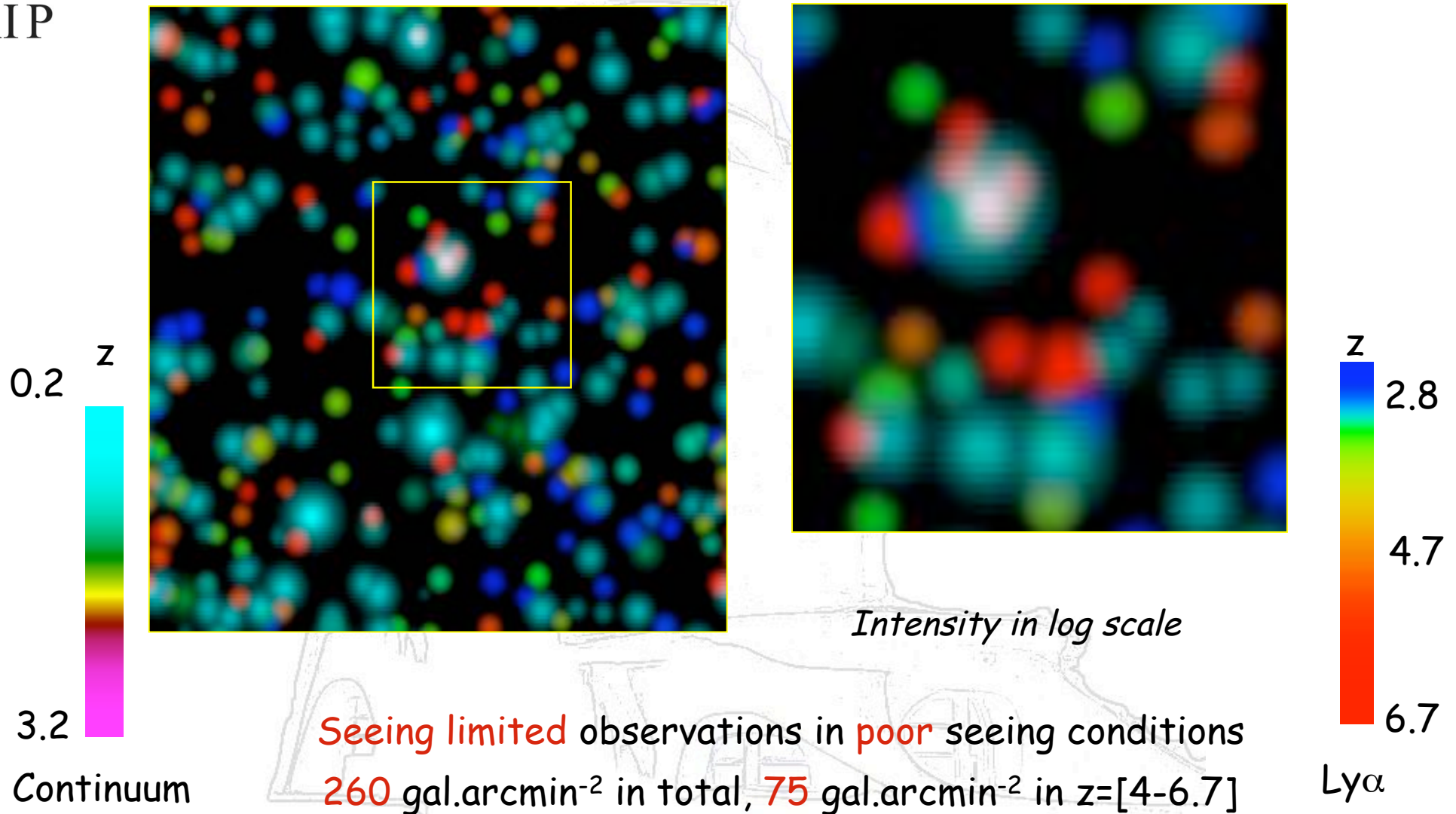
- Part of a single MUSE frame (4k x 4k)
- 1/24 of full MUSE FoV is sliced in 48 slitlets (each 15 x 0.2 arcsec)

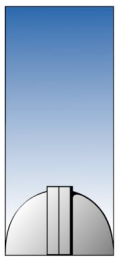




AIP

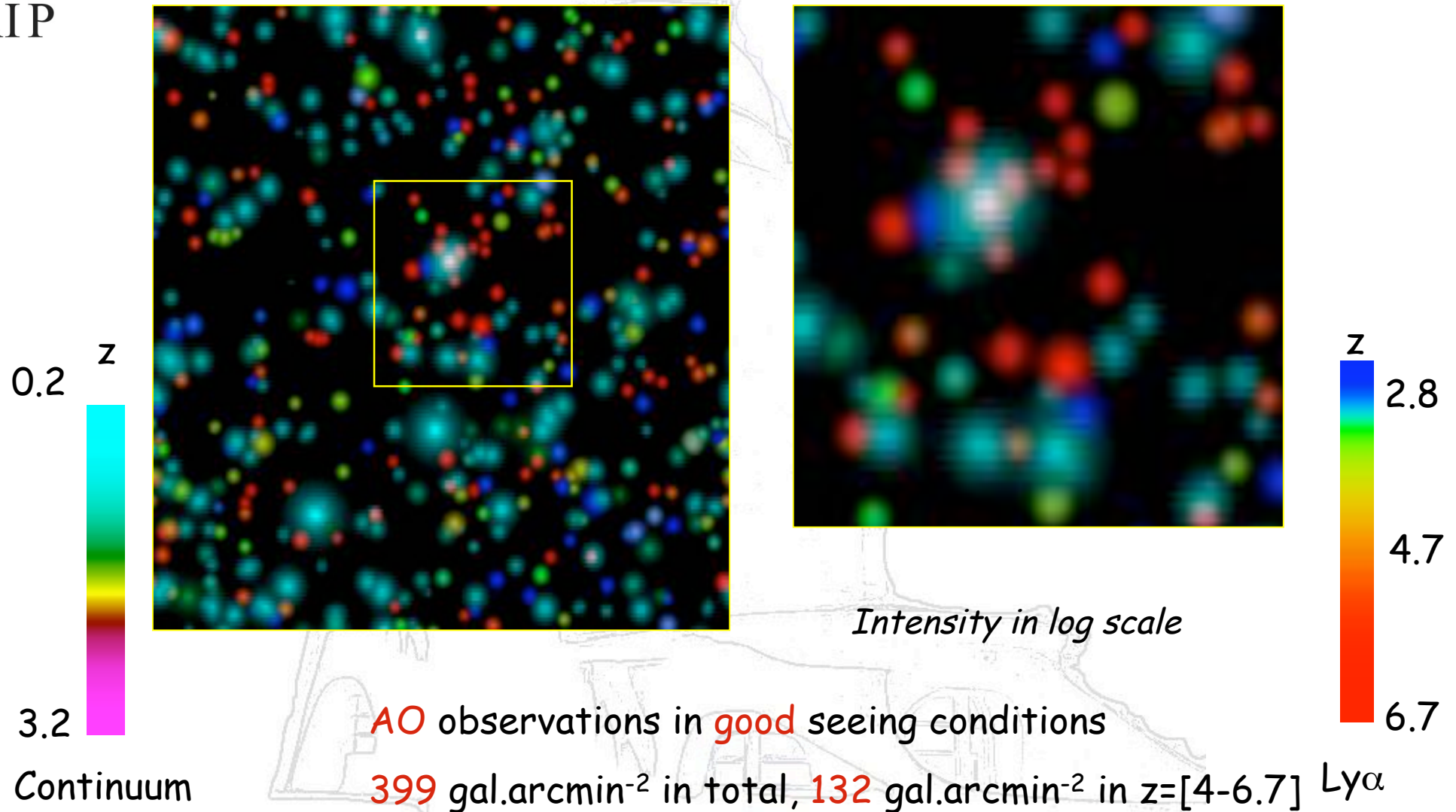
Effect of spatial resolution





AIP

Effect of spatial resolution



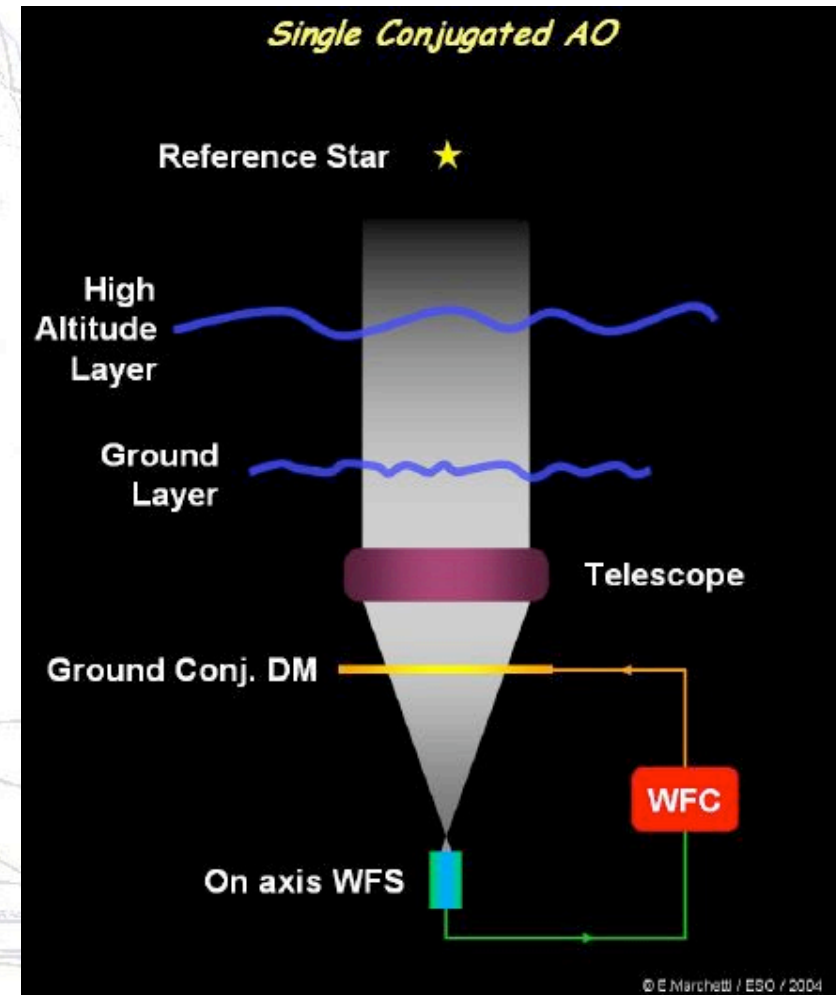
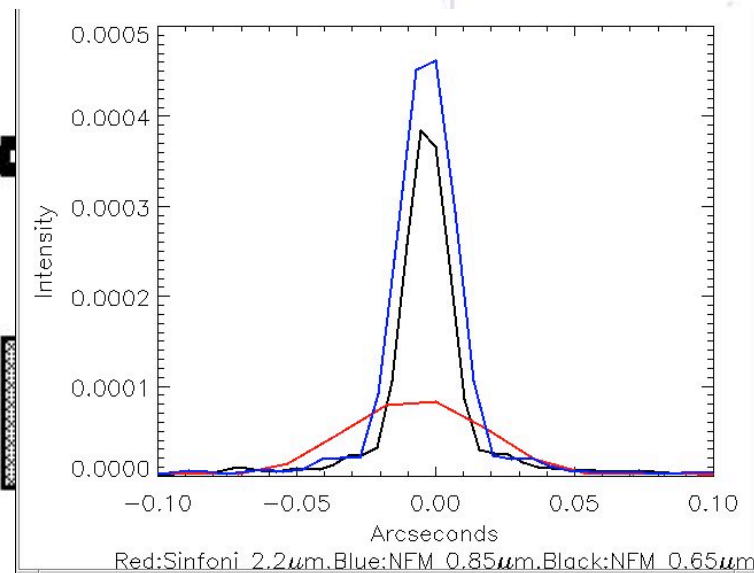
Adaptive Optics

Correct for atmospheric distortion due to turbulence

Need a (bright) reference point source to measure the distortion

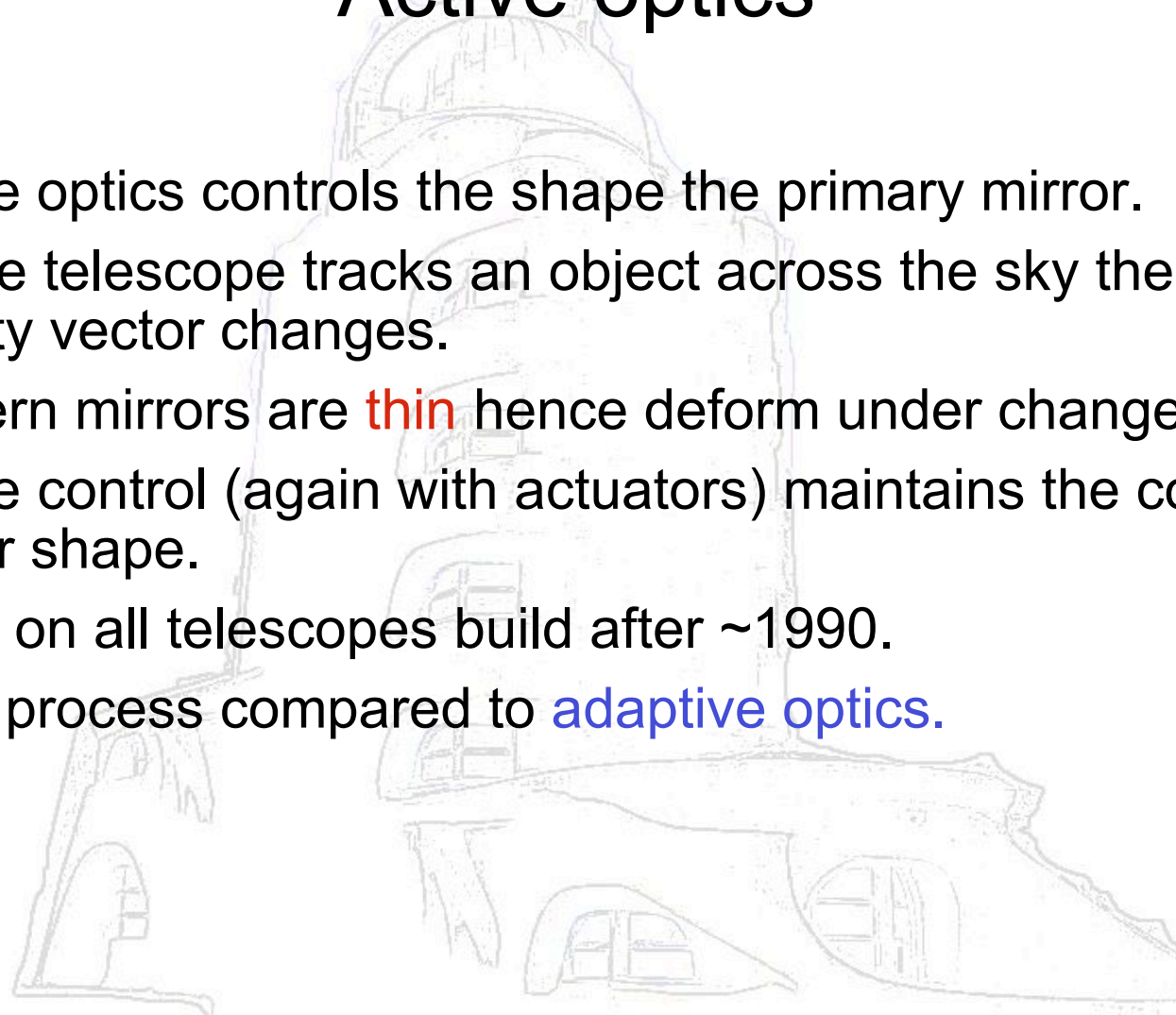
Correct distortions using deformable mirror(s)

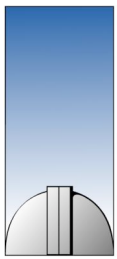
Area over which correction is effective varies from **30" (infrared)** to **2" (optical)**



Active optics

- Active optics controls the shape the primary mirror.
- As the telescope tracks an object across the sky the gravity vector changes.
- Modern mirrors are **thin** hence deform under changes in g .
- Active control (again with actuators) maintains the correct mirror shape.
- Used on all telescopes build after ~1990.
- Slow process compared to **adaptive optics**.

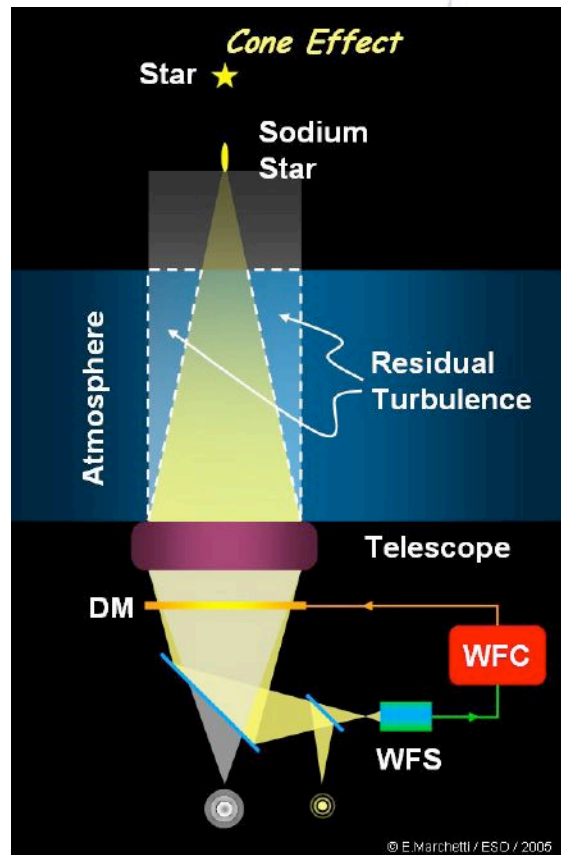




AIP

Laser Guide Star

- Improves sky coverage
 - But still need a Natural Guide Star to correct for tip-tilt
- Suffers from cone effect as wave front is not flat

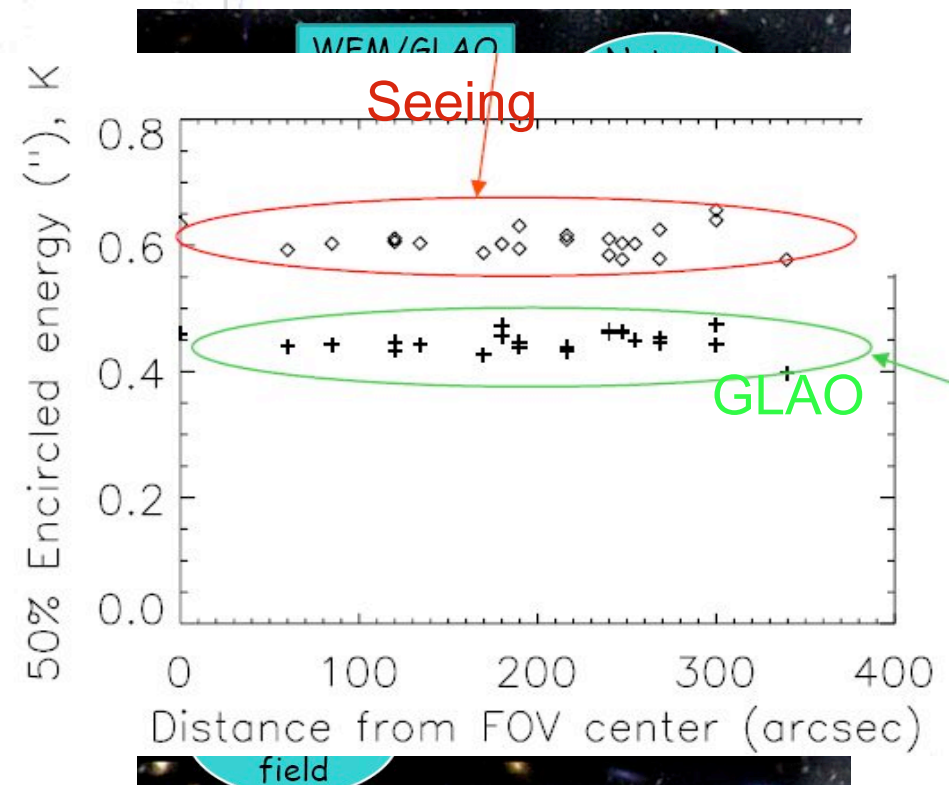
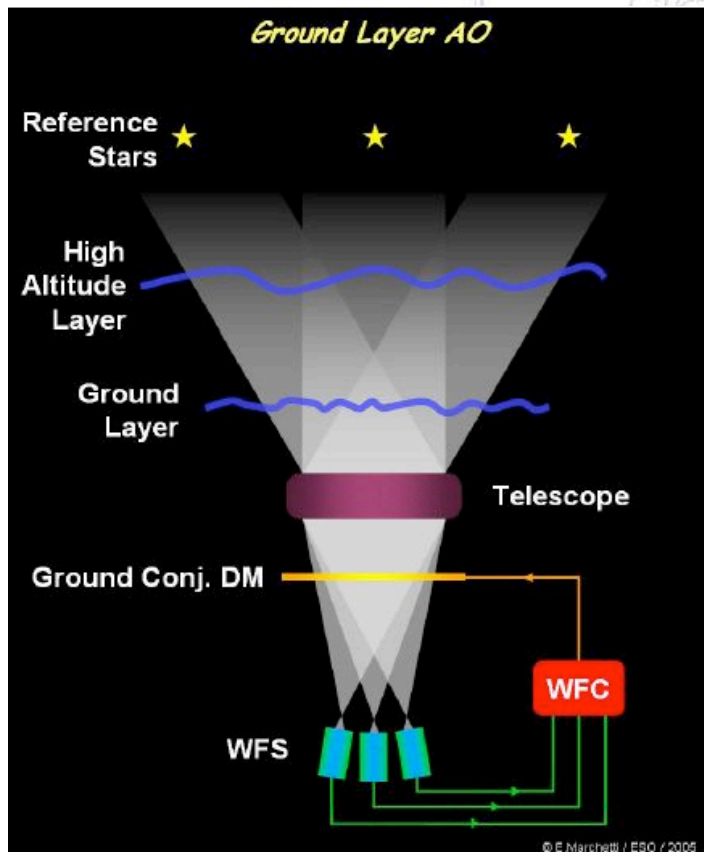




AIP

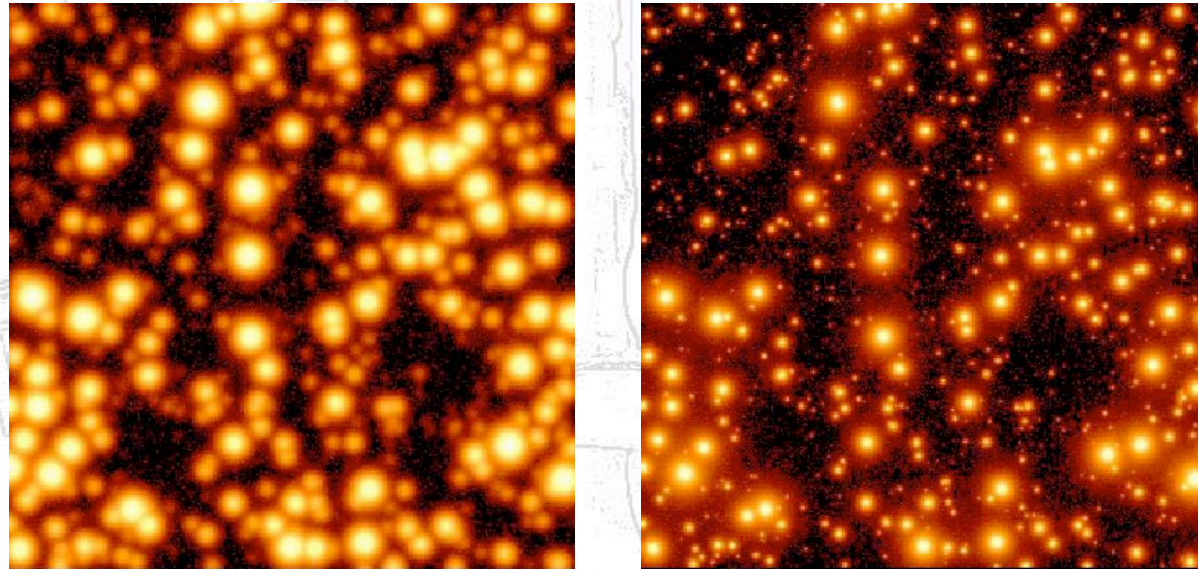
MUSE AO unit (GALACSI)

- One VLT secondary mirror will be a DM (diameter 1m)
- Correct ground layer disturbance to homogenize the PSF
- This GLAO system is a 'seeing reducer'
- Metric: Encircled Energy, improvement a factor ~ 2

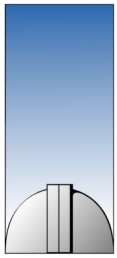


AO challenges

- AO with LGS is technically very challenging
- Duty cycle currently ~30% with a single laser
- Atmospheric conditions will always be limiting factor
 - Surprisingly, behaviour of sodium layer is not well known
- AO is **essential** for the next generation of telescopes



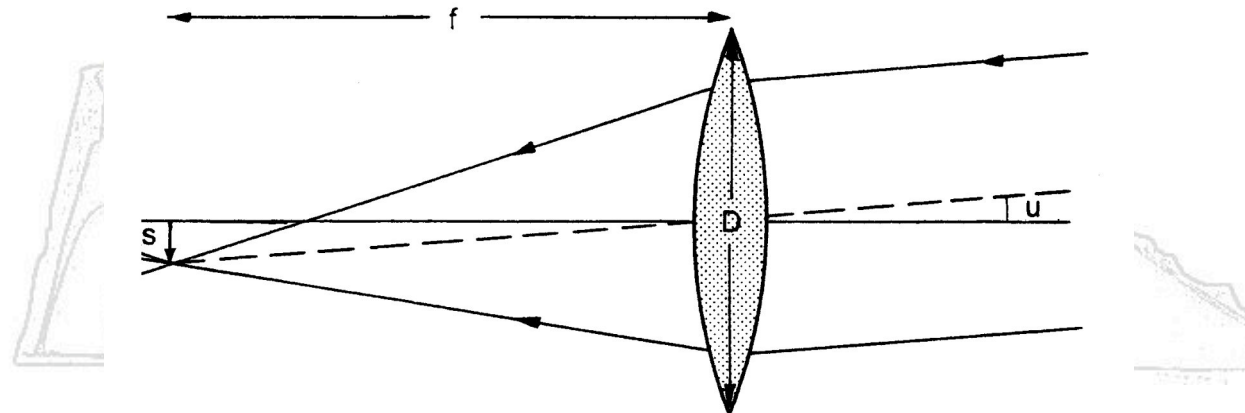
MUSE simulation of a dense stellar cluster

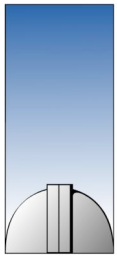


AIP

Telescope properties

- Plate scale: relation between an angular distance on the sky and a physical distance in the telescope's focal plane: $s \propto 1/D$
- Example: we have two telescopes T1 & T2. Mirror diameter of T2 is five times T1.
 - If $s_1 = 1''/\text{cm}$ then $s_2 = 0.2''/\text{cm}$
 - Detector pixel size is fixed, say 0.5 cm
 - Seeing limited observations: resolution $\sim 1.0''$
 - Therefore, T1 image ($1''$ is 1.0 cm) is correctly sampled at 2 pixels
 - But for T2 ($1''$ is 5.0 cm) 10 pixels are used to image $1'' \Rightarrow$ **waste of pixels**





AIP

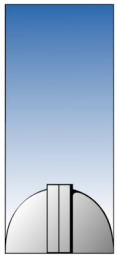
VLT Instrumentation

Photon-starved Mode

- **D = 8 m Telescope diameter**
- **0.5 μm seeing = 0".65-median; 0".3-10%**
- **p = 12 μm (4k)² V/NIR pixels (market)**
- **F/ ω Camera: $\omega \geq 1.4$; d \geq 80 mm (optics)**
 $\Rightarrow \alpha_{\text{sky}} = 0".44$ (2-pixel sampling)

sampling ~ OK; A.O. correction optional

image slicers not always required



AIP

ELT IFU-based Instrumentation

Photon-starved Mode

- $D = 42$ m Telescope diameter
 - H 'improved' Seeing $\approx 0''.35$ -median
 - $p = 12 \mu\text{m}$ pixel; F/1.4 Camera
- $\Rightarrow \alpha_{\text{sky}} = 0''.084$ (2-pixel sampling)

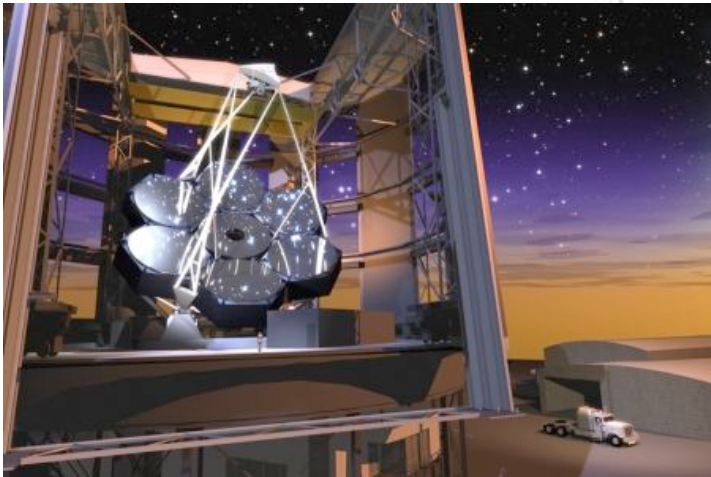
'full' AO correction or pixel 'waste'

Image Slicers and/or pupil dividers mandatory

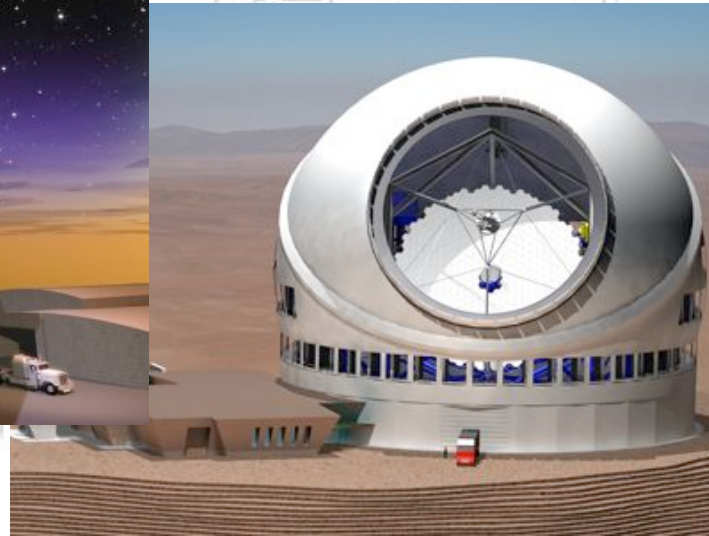
Extremely Large Telescopes

- Three 'competing' projects to be completed within ~10 yr
- Not possible to create a monolithic mirror of this size.
- Build from actively controlled segments (like 10m KECK)
 - All segments need to be 'phased'

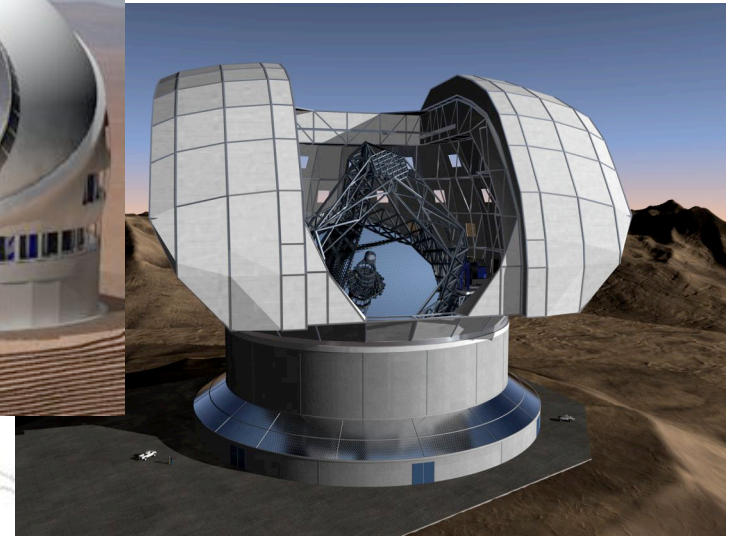
GMT: 24 m



TMT: 30(?) m

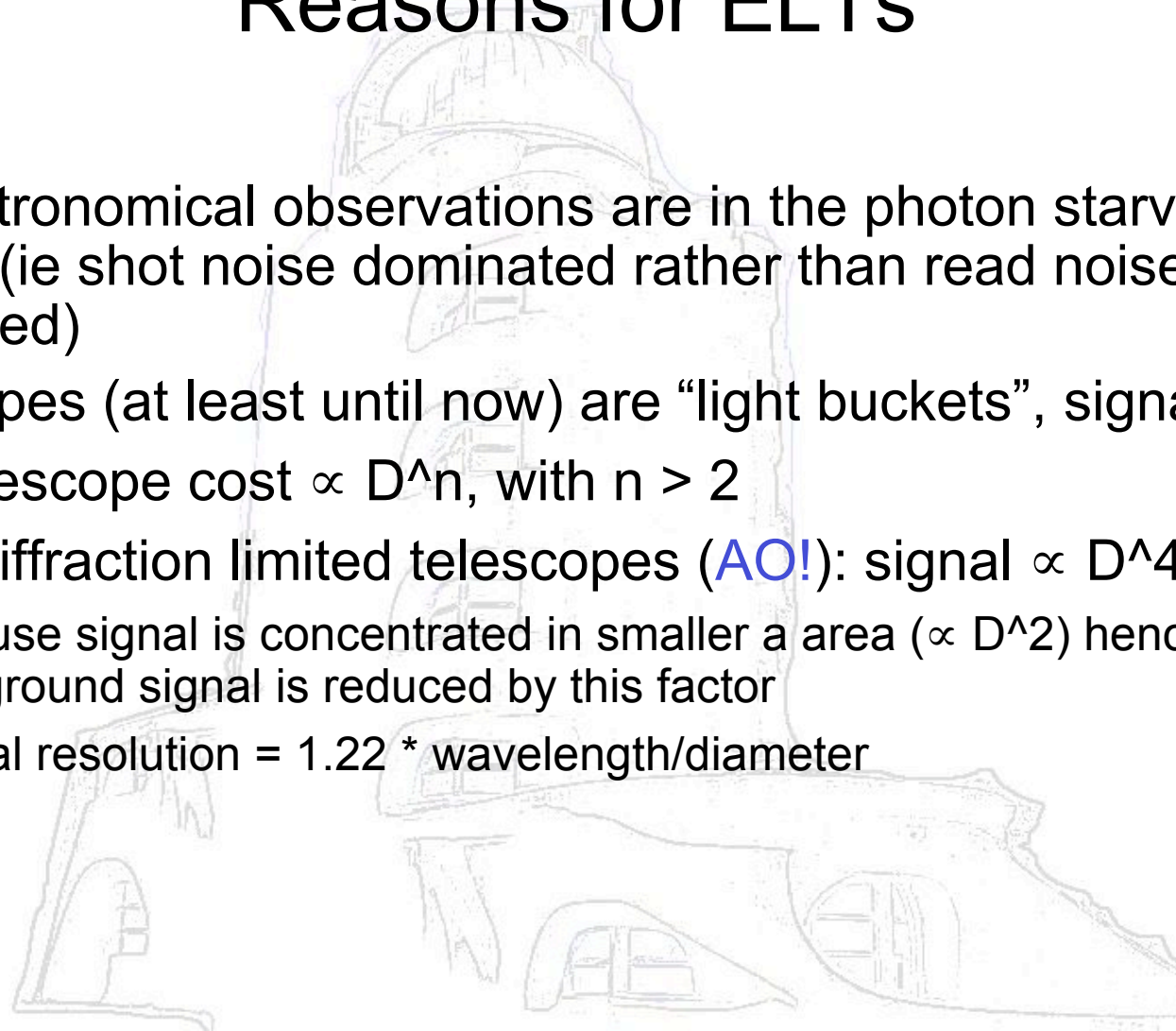


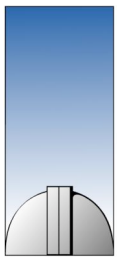
E-ELT: 42 m



Reasons for ELTs

- Most astronomical observations are in the photon starved domain (ie shot noise dominated rather than read noise dominated)
- Telescopes (at least until now) are “light buckets”, signal $\propto D^2$
- **Bad:** telescope cost $\propto D^n$, with $n > 2$
- **Good:** diffraction limited telescopes (**AO!**): signal $\propto D^4$
 - Because signal is concentrated in smaller area ($\propto D^2$) hence background signal is reduced by this factor
 - Spatial resolution = $1.22 * \text{wavelength}/\text{diameter}$

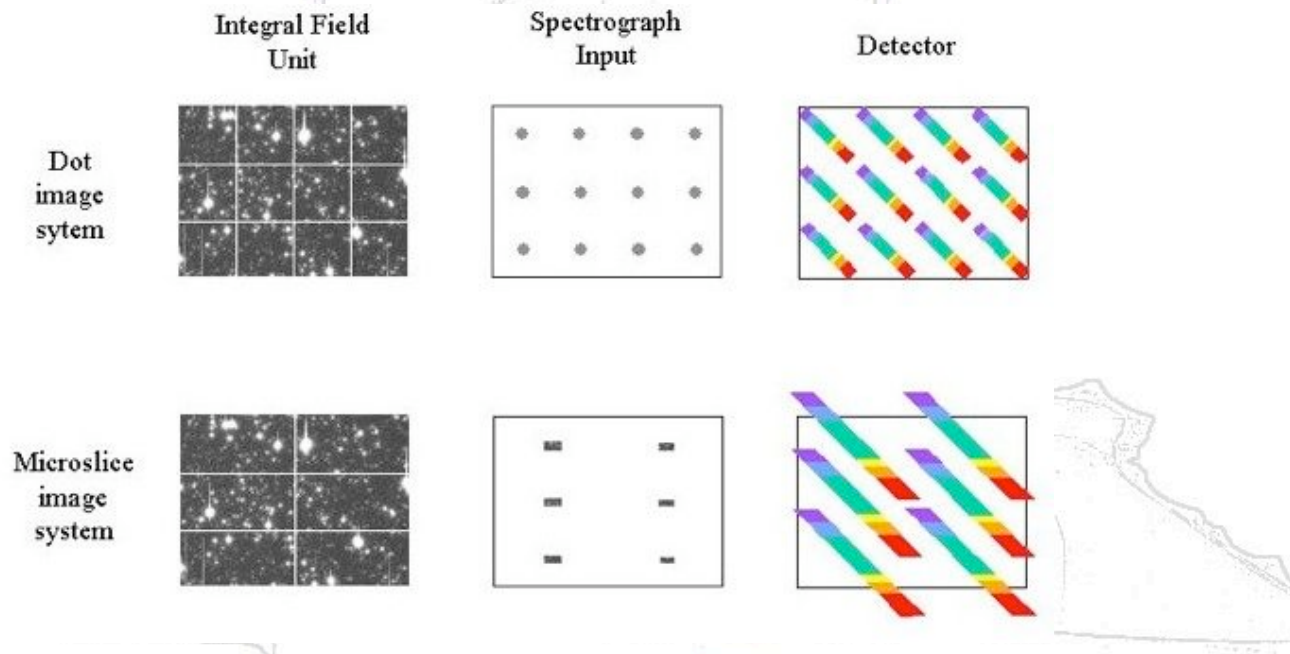




AIP

Smoothing AO evolution

- AO is very much R&D at the moment
- May not be fully available when ELTs come online
- Need instruments that can “adapt” to AO improvements
- One concept is microslicing:

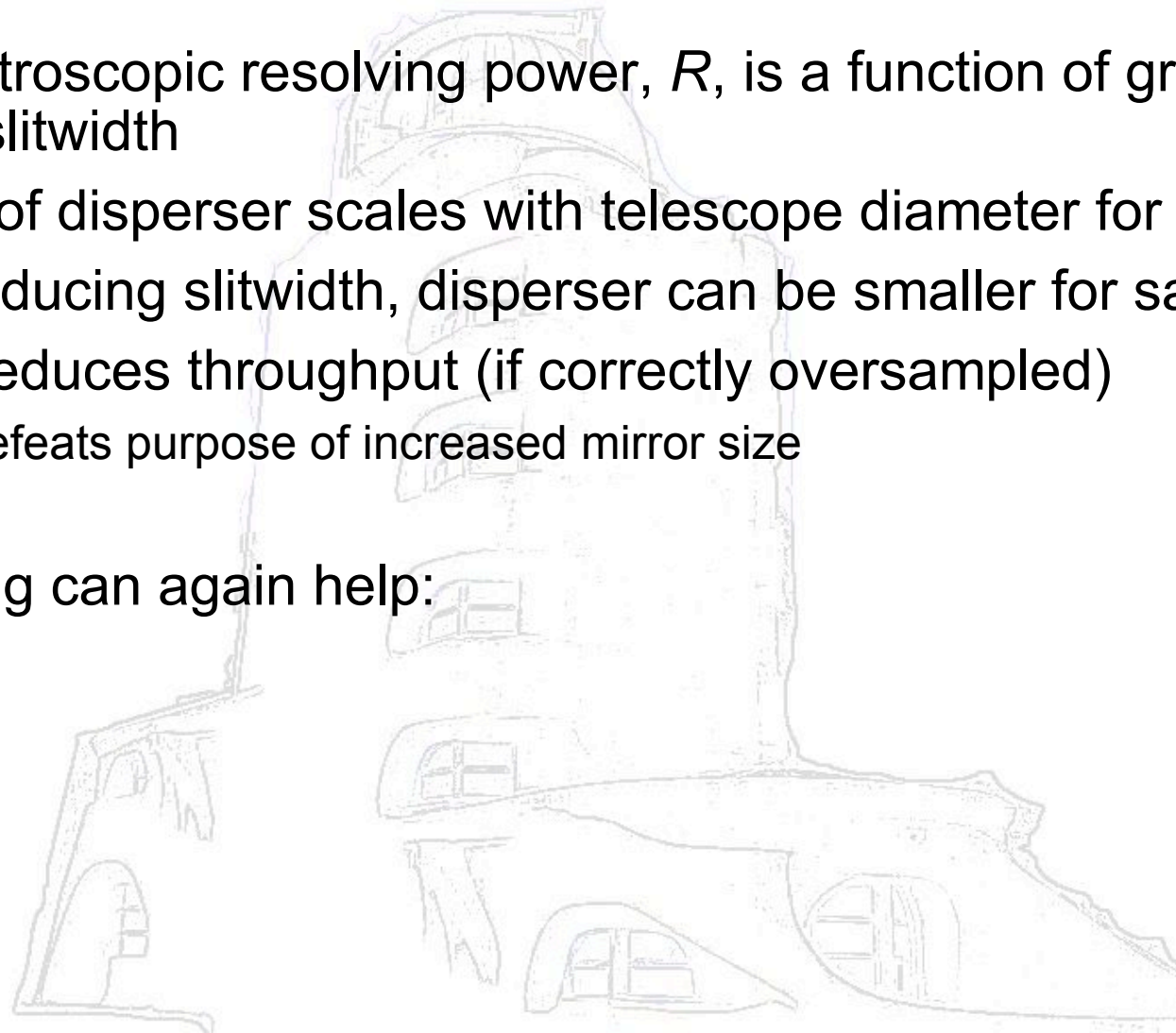




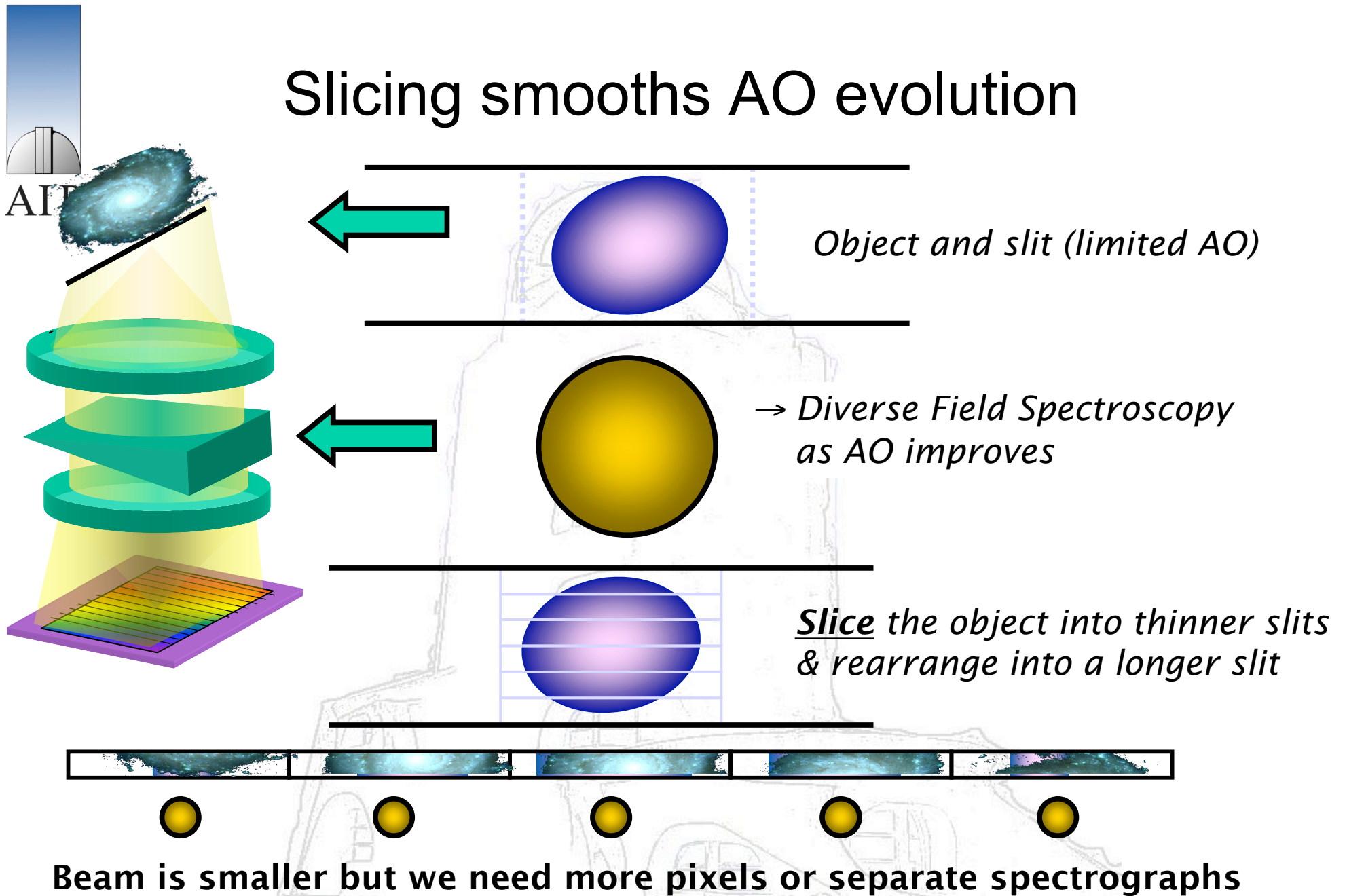
AIP

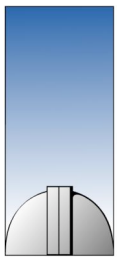
Smoothing AO evolution

- Spectroscopic resolving power, R , is a function of grating and slitwidth
- Size of disperser scales with telescope diameter for fixed R
- By reducing slitwidth, disperser can be smaller for same R
- But reduces throughput (if correctly oversampled)
 - Defeats purpose of increased mirror size
- Slicing can again help:



Slicing smooths AO evolution





AIP

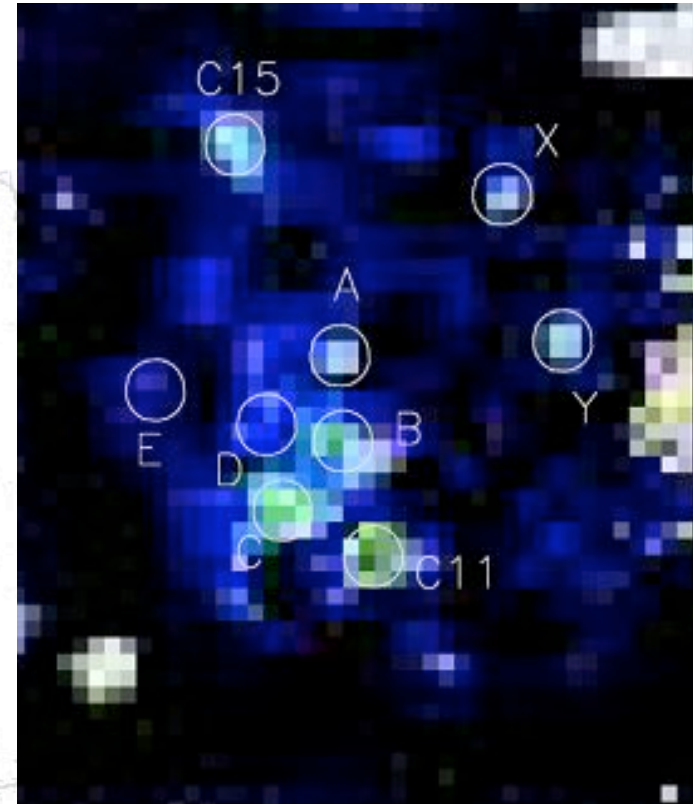
What ELTs will see?

Ly α -emitting region LAB1 in the SSA 22 protocluster region at $z = 3.09$

Physical extent ~ 100 kpc, Ly α luminosity $\sim 10^{37}$ W

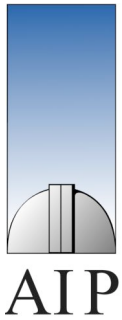
Representative of high-z universe?

- How many spaxels do we really need if observed with an ELT?
- We can't sample 10 arcmin field at the diffraction limit!
- \rightarrow dilute sample by factor 100-10000



Arbitrary mixture of contiguous and non-contiguous regions

\rightarrow **Diverse Field Spectroscopy**

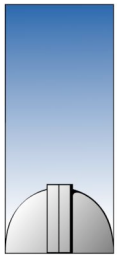


VLT/E-ELT & IFUs: Conclusions

IFS a major mode for VLT-class Spectrometry

IFS almost mandatory for ELT Spectrometry

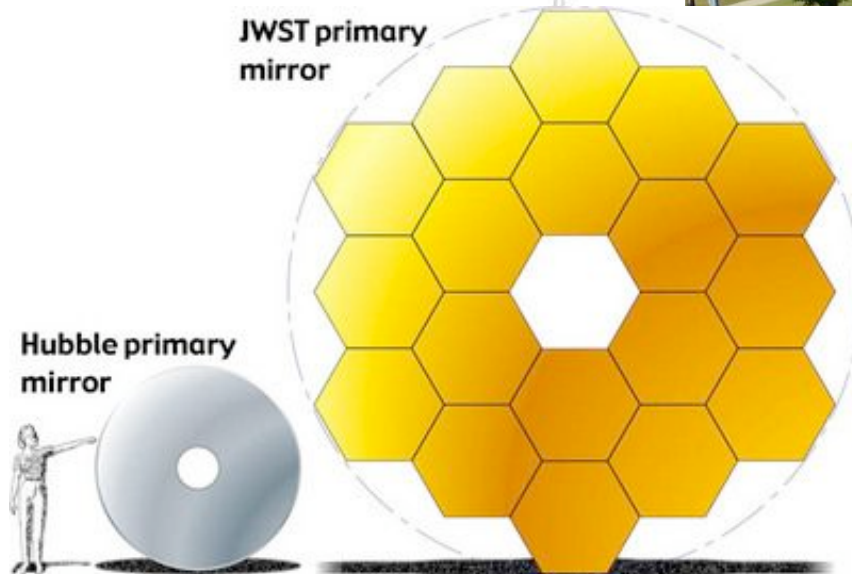
data analysis/calibration drive IFS performance

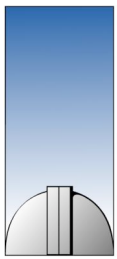


AIP

The James Webb Space Telescope

- Successor to Hubble Space Telescope
- 6.5 m primary mirror, four infrared instruments (1 - 27 μm)
- Passively cooled to operate in a stable cryogenic environment
- Launched to an orbit around L2 in 2013



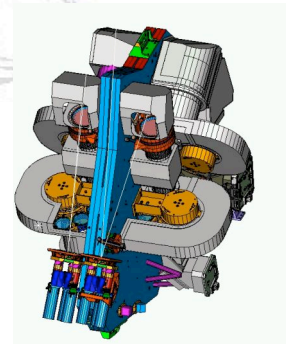
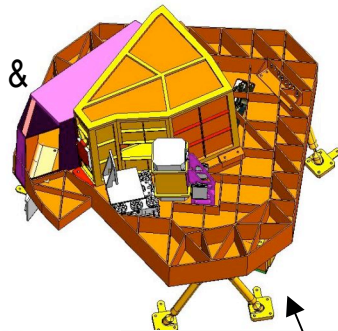


AIP

The JWST instruments

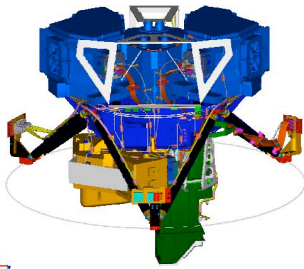
Fine Guidance Sensor (FGS) and the Tunable Filter Imager (TFI)

- Includes a scanning 3D device (TFI)
- Developed by Canadian Space Agency & COM DEV



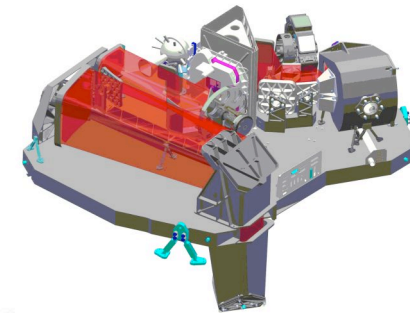
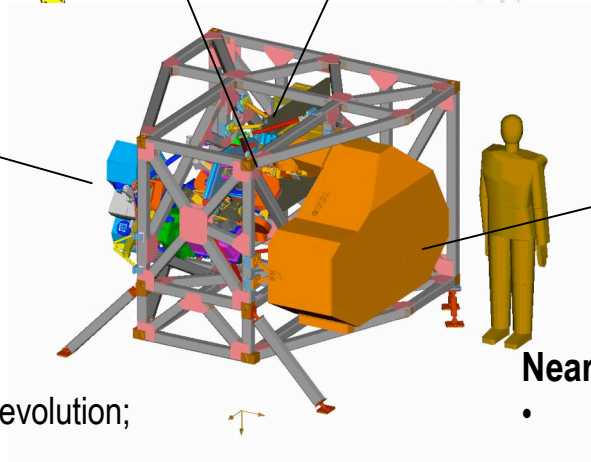
Near Infra-Red Camera (NIRCam)

- Detects first light galaxies and observes galaxy assembly sequence
- 0.6 to 5 microns
- Supports Wavefront Sensing & Control
- Developed by Univ. of AZ & LMATC



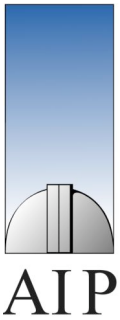
Mid-Infra-Red Instrument (MIRI)

- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development



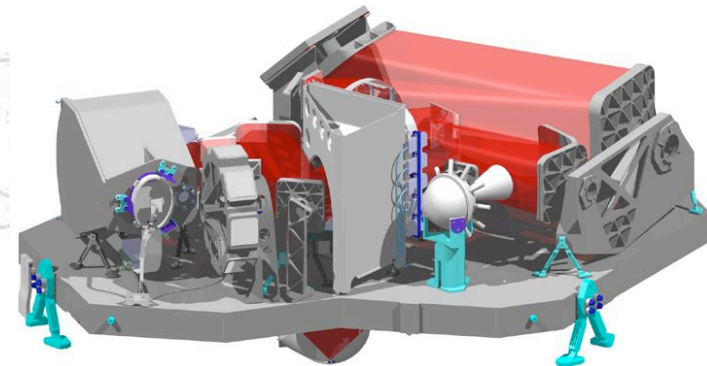
Near Infra-Red Spectrograph (NIRSpec)

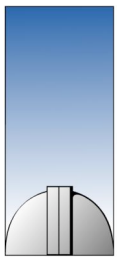
- Measures redshift, metallicity, star formation rate in first light galaxies
- 0.6 to 5 microns
- Simultaneous spectra of >100 objects
- Developed by ESA & EADS with NASA/ GSFC Detector & Microshutter Subsystems



NIRSpec in a nut shell

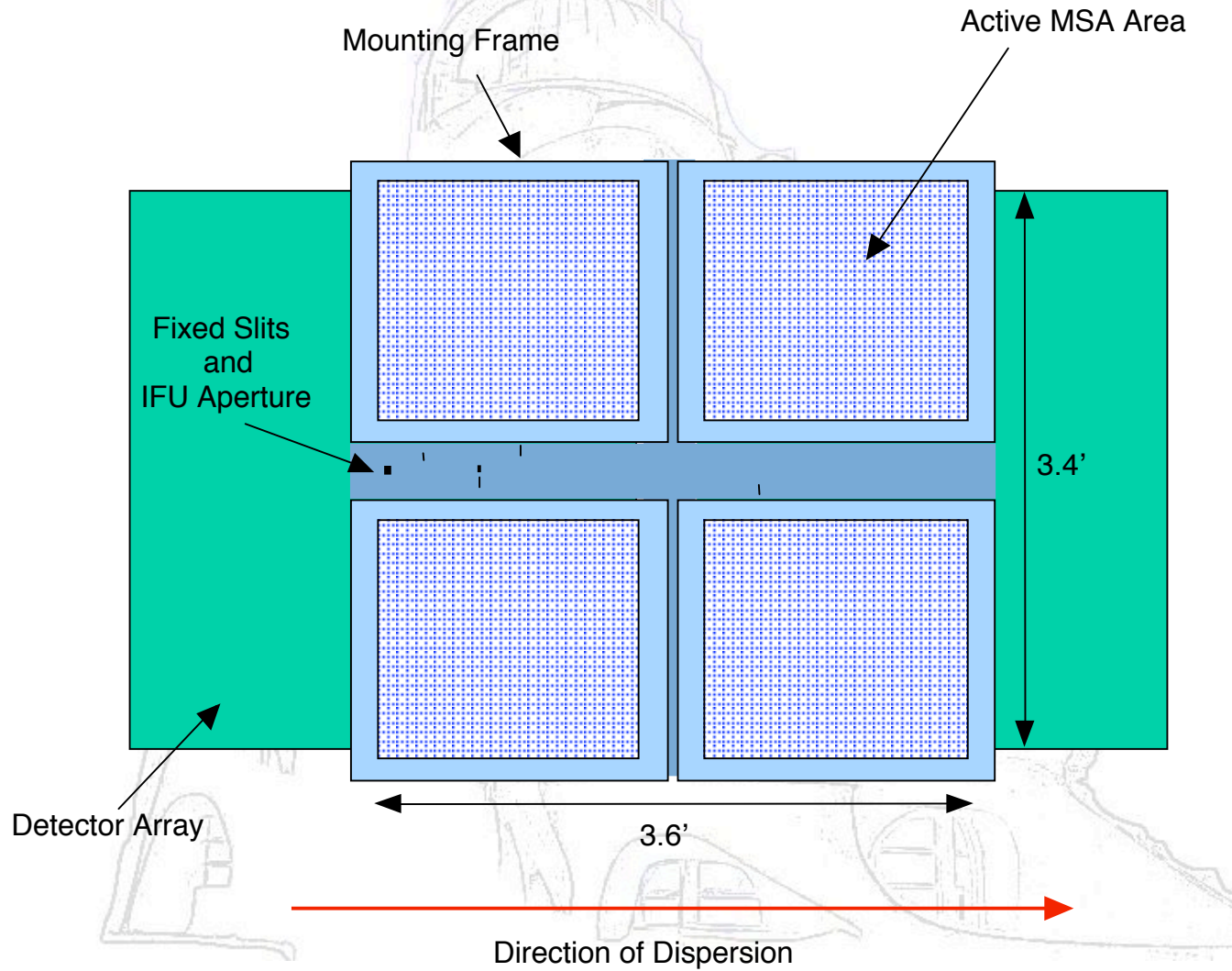
- Near-infrared spectrograph covering the 0.6-5.0 μm wavelength range
- 3 spectrographic modes: MOS, **IFU** and SLIT
- Total field of view of 3.6 arcmin \times 3.4 arcmin
- Low (≈ 100), medium (≈ 1000) and high (≈ 2700) spectral resolutions
- Operating temperature of 35-40 K
- Detector system made of two 2K \times 2K HgCdTe arrays
- To be delivered to NASA at the end 2009

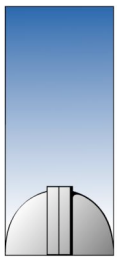




AIP

Layout of NIRSpec modes



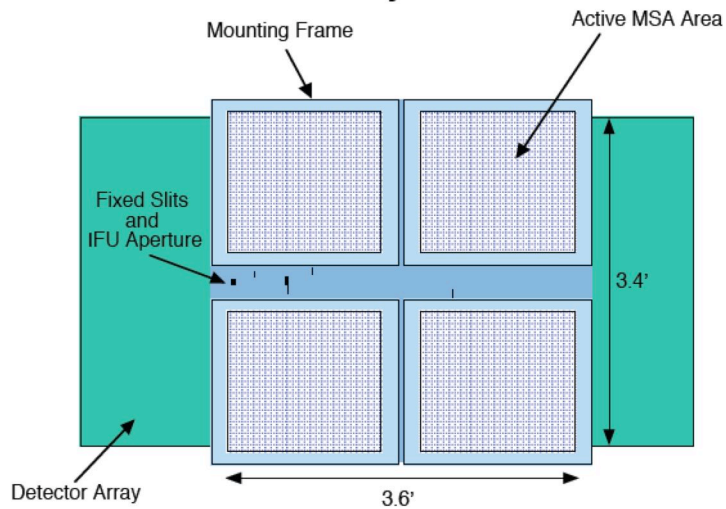


AIP

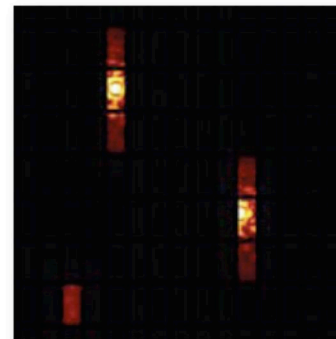
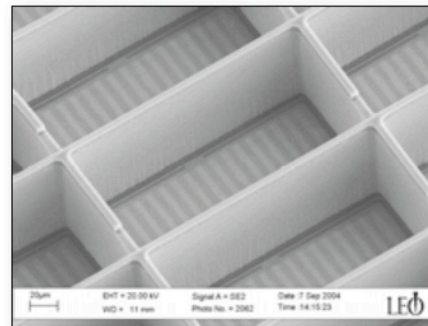
The MOS mode of NIRSpec



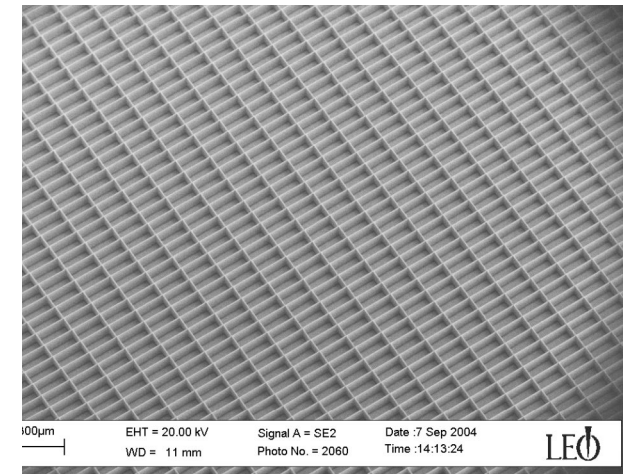
- Shutters Individually addressable
- Magnetically activated
- Electrostatically latched



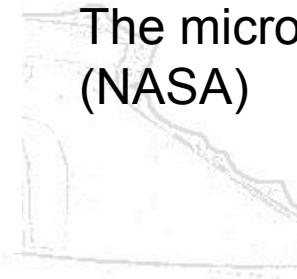
4 x 365 x 171 Shutters
9 arcmin² of MSA Area



3 x 200 mas x 470 mas 'slitlet'



The micro-shutter array (NASA)





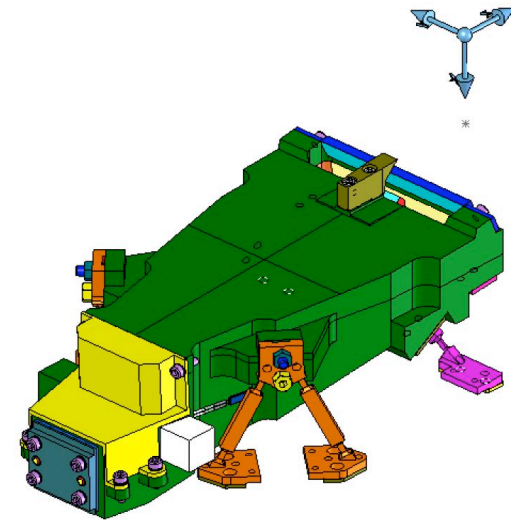
AIP

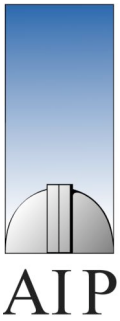
NIRSpec IFU

- The NIRSpec IFU must “plug in” the overall NIRSpec MOS design
- Minimum disturbances to the NIRSpec design
- Must “steal” some small part of the field of view in the plane of the micro-shutter array, re-arrange it and re-inject it in the NIRSpec spectrograph
 - Stringent envelope and mass constraints
 - Size of a shoe-box and less than 1 kg
- IFU based on the advanced slicer concept

NIRSpec IFU

- Slicer
- 3" x 3" field sliced at 0.1"
- 0.7 - 5.0 μm (four exposures)
- $R \sim 100, 1000 \text{ \& } 2700$





Summary

- IFS (2d spectroscopy) is a major aspect of all new observing facilities.
- This is driven by science goals as well as technical issues.
- IFS data reduction is complex
 - Dedicated software is essential
- Data analysis and physical interpretation is equally challenging

