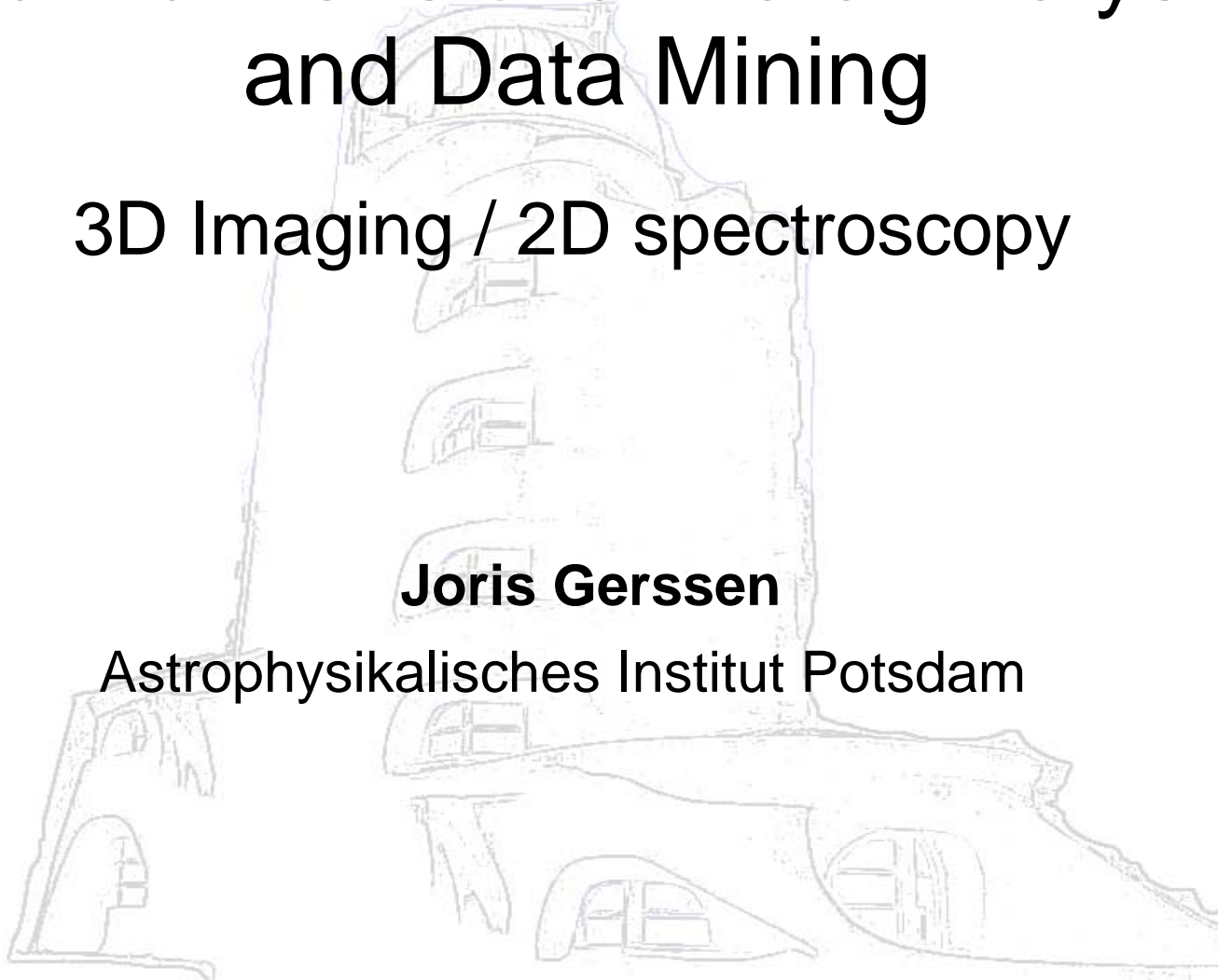


Multi-dimensional Data Analysis and Data Mining

3D Imaging / 2D spectroscopy

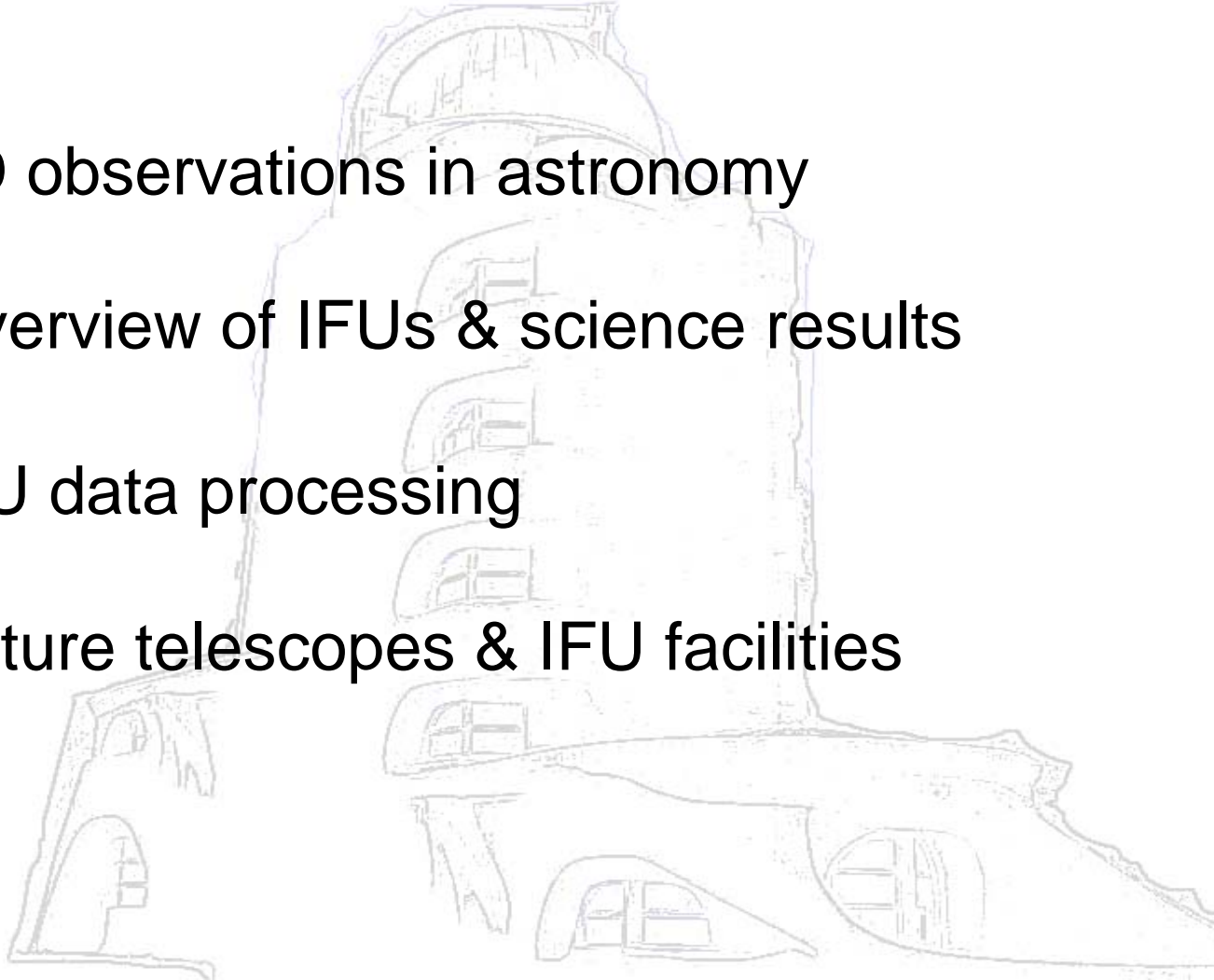
Joris Gerssen

Astrophysikalisches Institut Potsdam



Outline of the talks

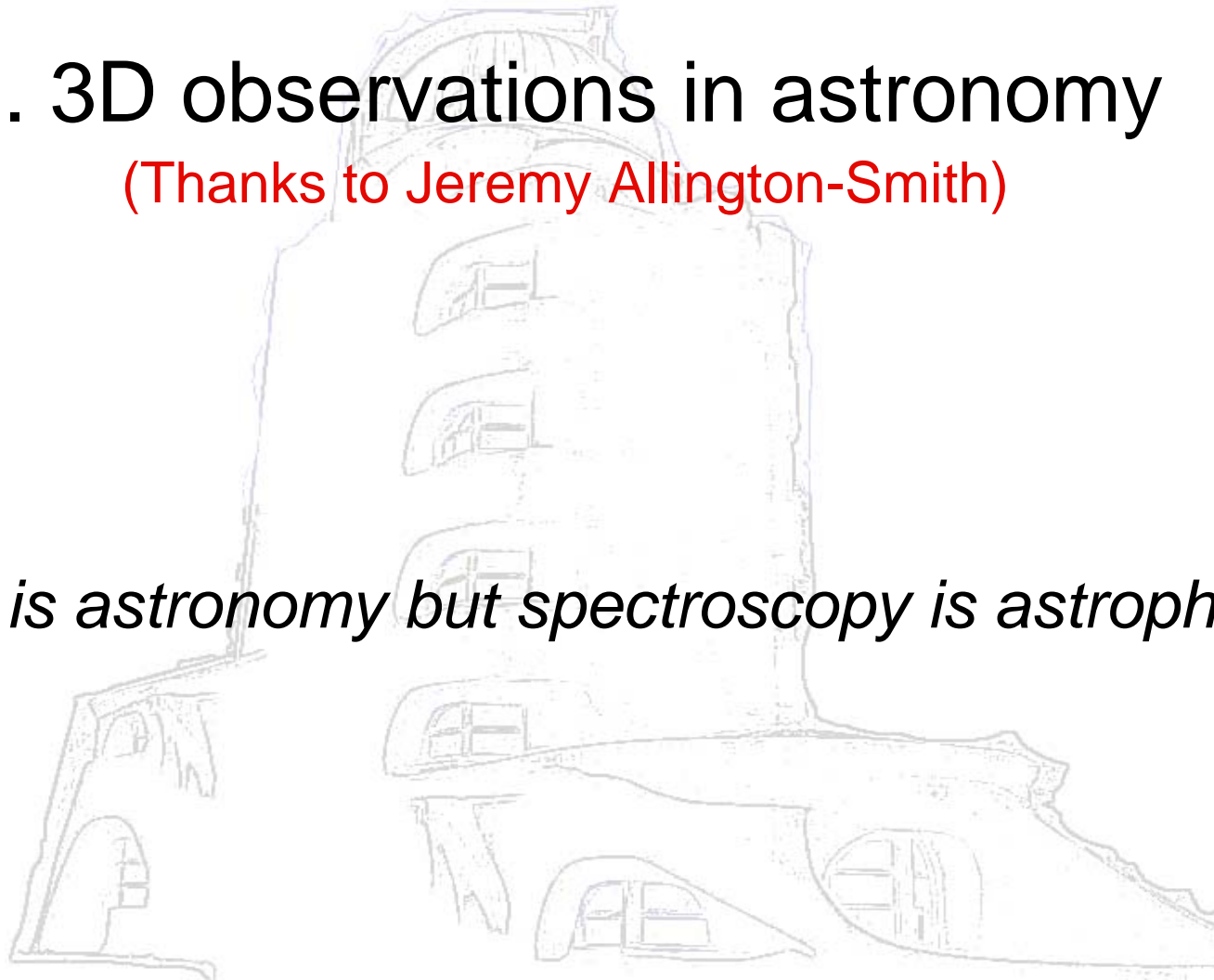
1. 3D observations in astronomy
2. Overview of IFUs & science results
3. IFU data processing
4. Future telescopes & IFU facilities



1. 3D observations in astronomy

(Thanks to Jeremy Allington-Smith)

“Imaging is astronomy but spectroscopy is astrophysics”



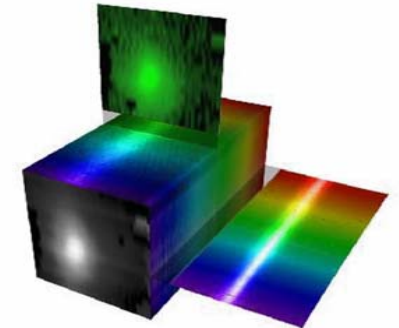
Definitions

3D = 3D imaging =
2D spectroscopy (**≠ 3D spectroscopy!**)
a.k.a. Hyperspectral imaging
Bidimensional spectroscopy

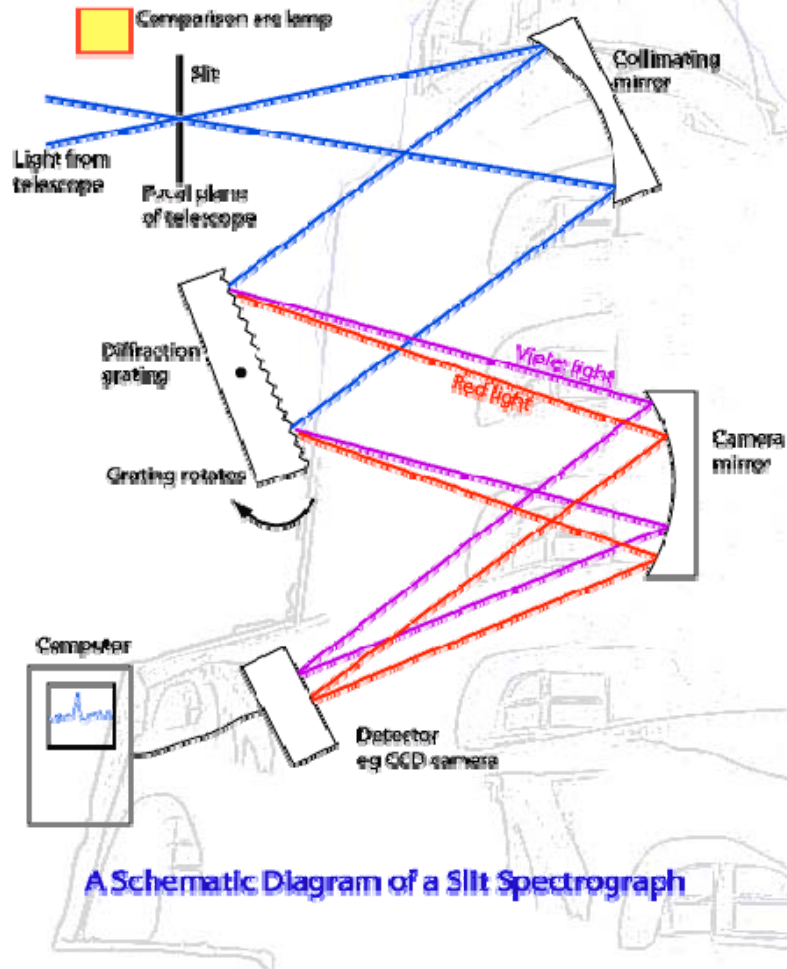
= any technique that produces a **datacube**:
intensity as a function of x , y , λ

Spaxel = spatial sampling element (Δx , Δy)

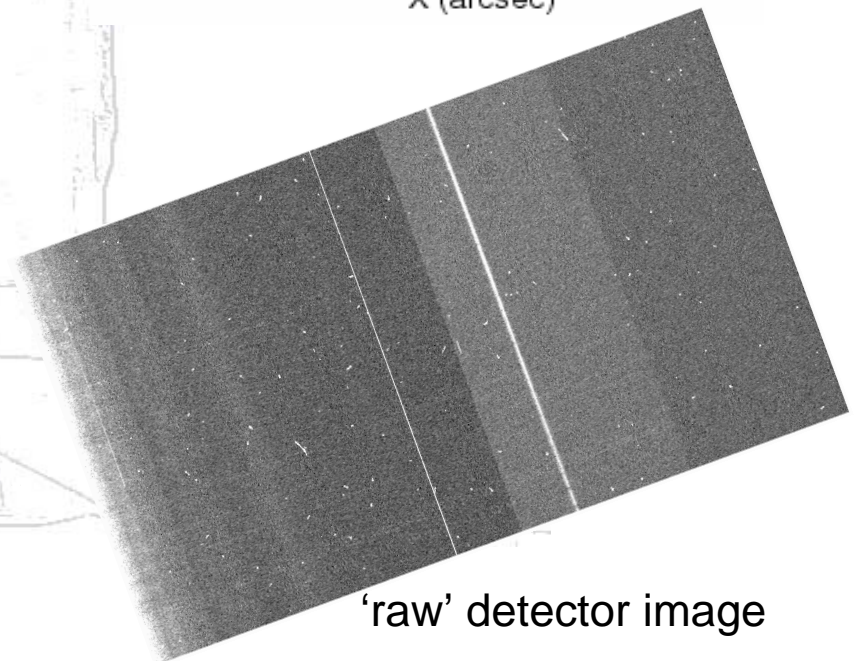
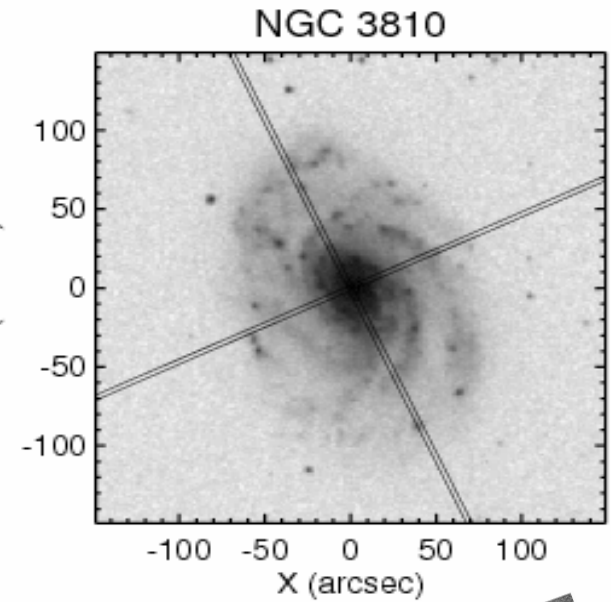
Voxel = 3D sampling element (Δx , Δy , $\Delta \lambda$)



Spectroscopy

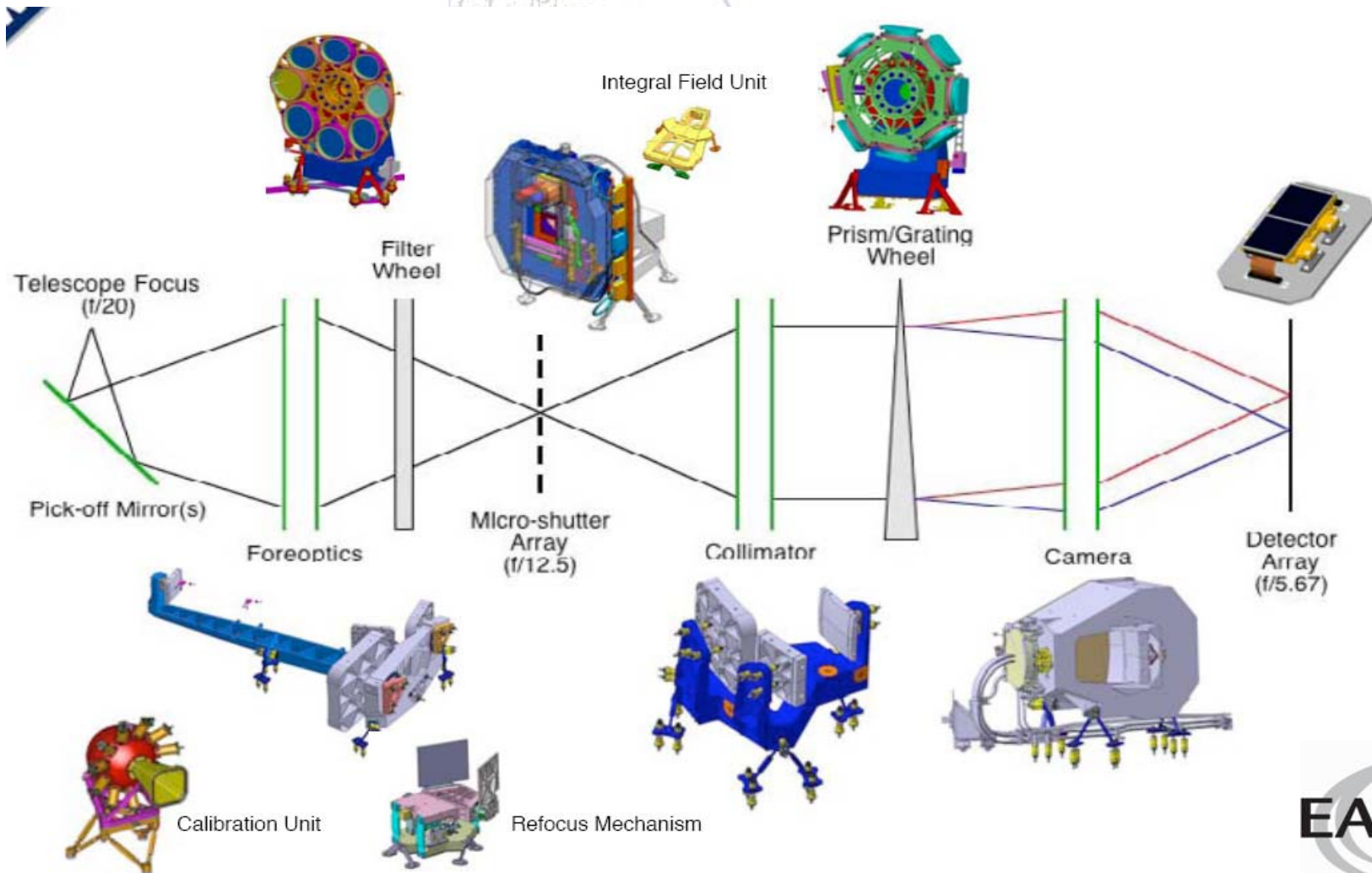


A Schematic Diagram of a Slit Spectrograph



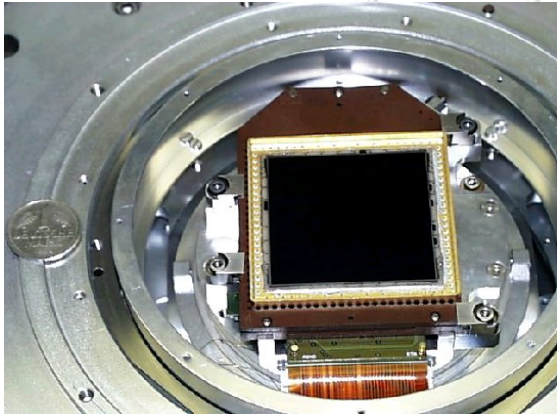
Spectroscopy (2)

Example: NIRSpec



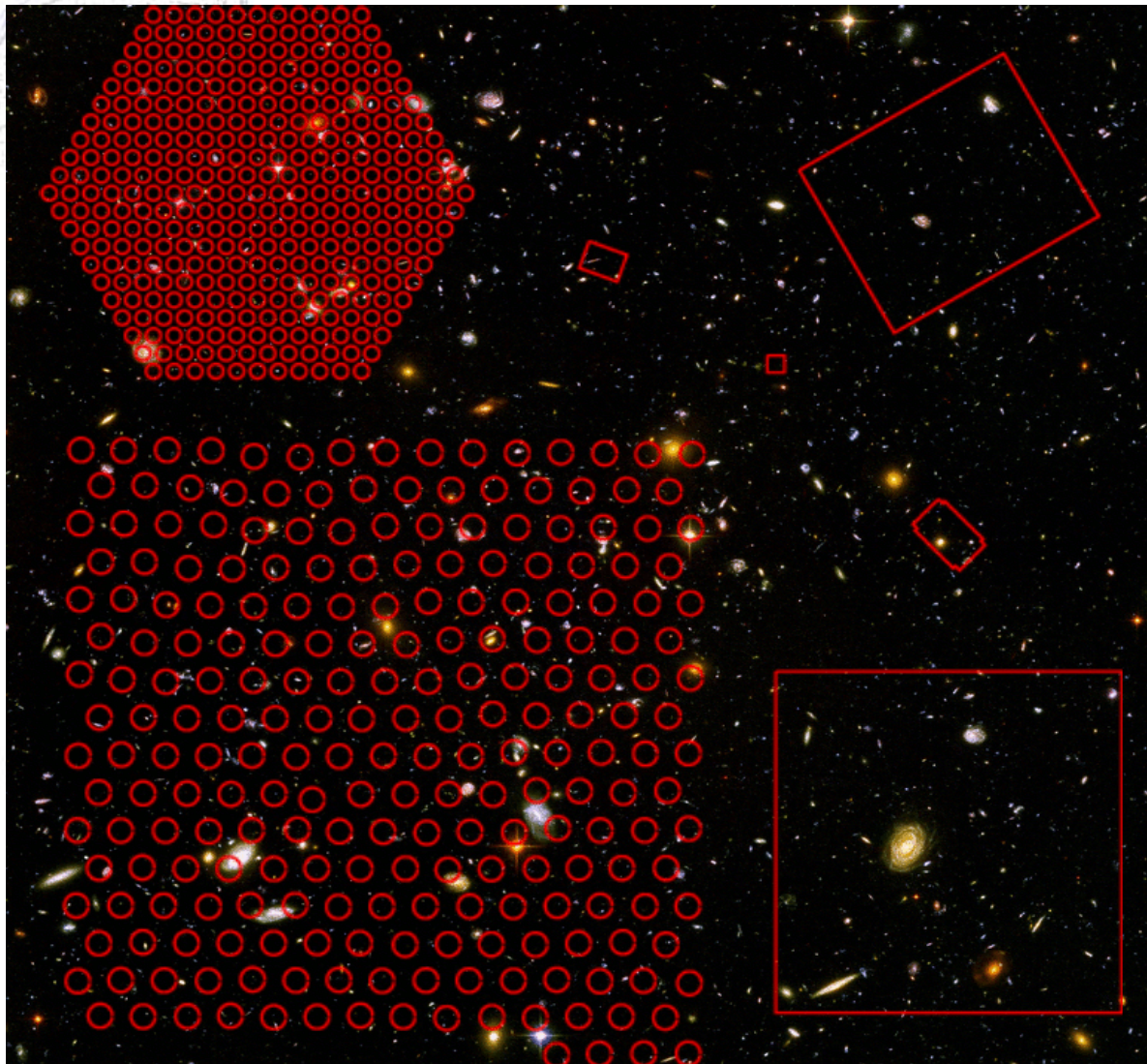
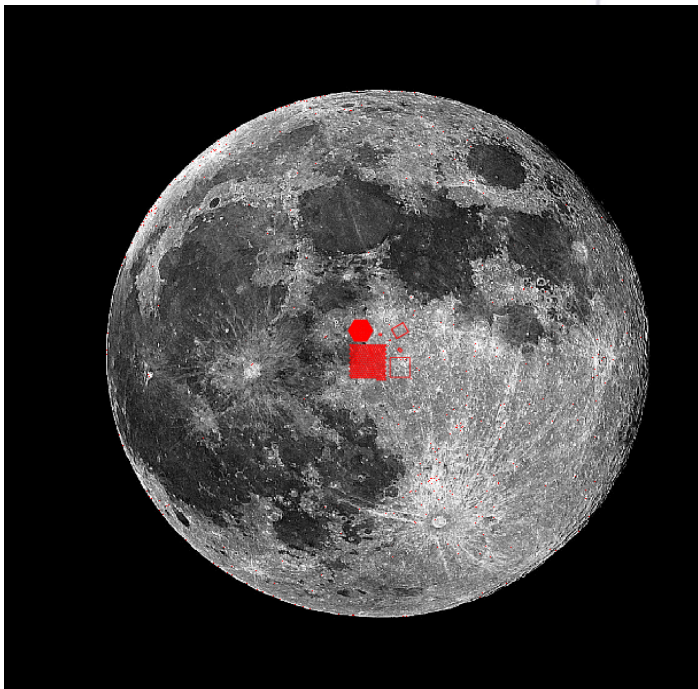
How to squeeze 3D in 2D ?

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



- Either fix one spatial or one spectral dimension and scan with time
- Or, use *TRUE Integral-Field Spectrographs* (no scanning!)

Field of View of 2D spectrographs



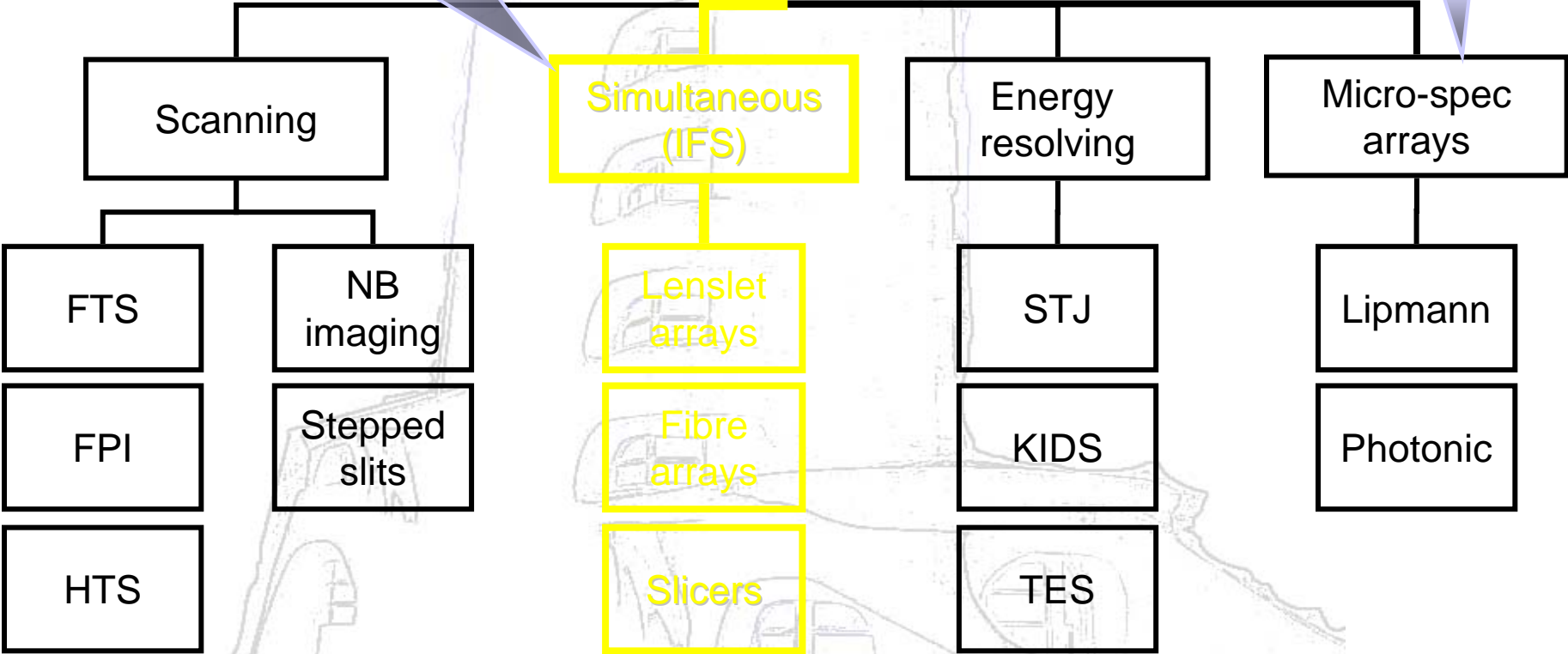
3D observations

- **Goal:** obtain spectra over contiguous (or well sampled non-contiguous) regions of:
 - Galaxies: AGN and normal galaxy kinematics
 - star clusters: IMBH etc.
 - YSOs, stellar disks... with coronagraphy, polarimetry
- **Warning:** photon-starved – light subdivided spatially and spectrally
- **State of the art:** throughput of 50-90% with thousands of spaxels (millions of voxels) in visible and near-IR (→mid-IR) and radio

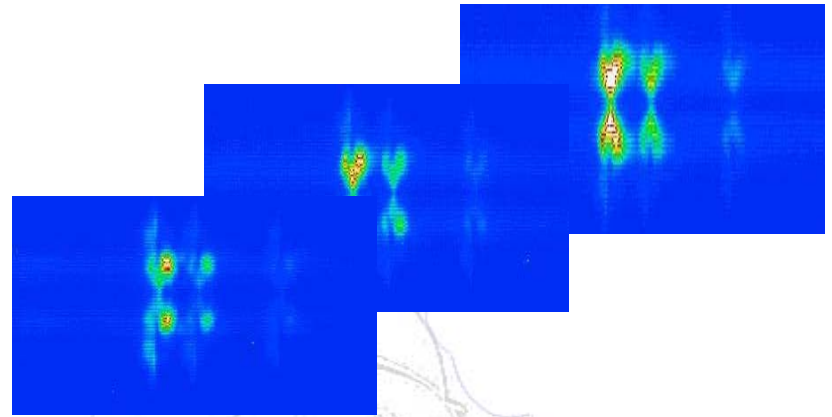
Immune to variation in background, PSF, noise sources transience

3D

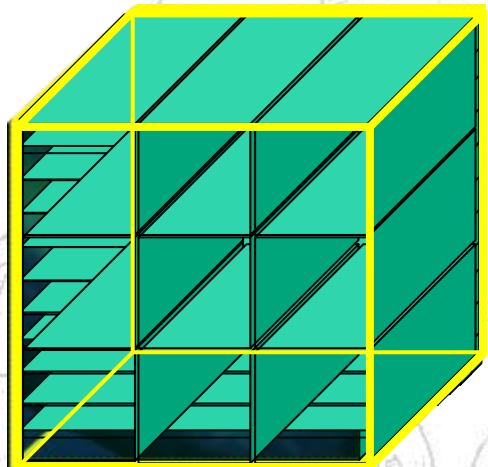
Future dreamtime



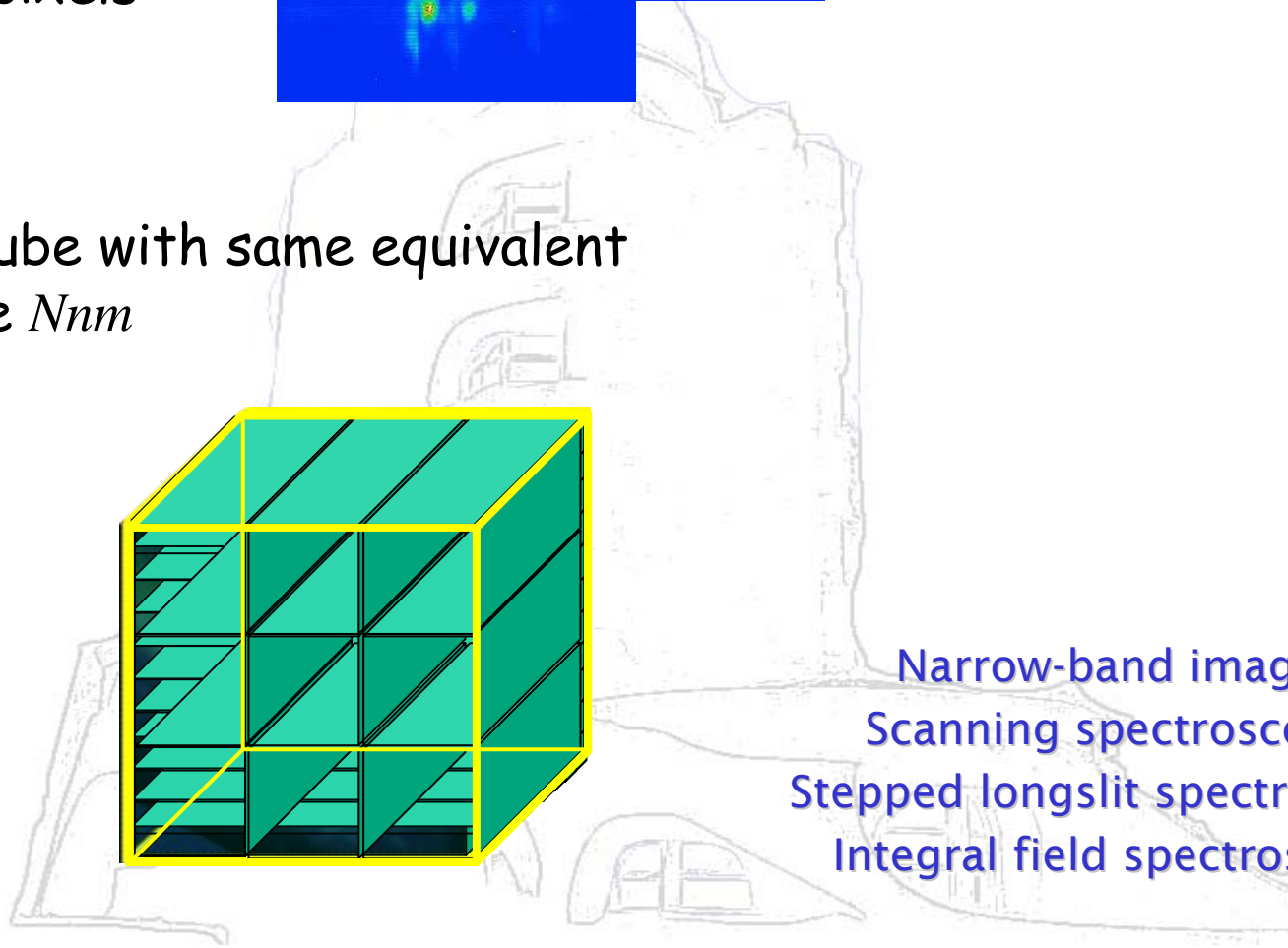
N observations
each with
 $n \times m$ pixels



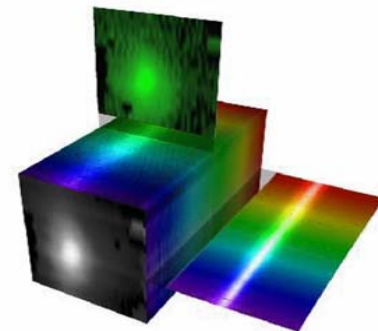
Datacube with same equivalent
volume Nnm



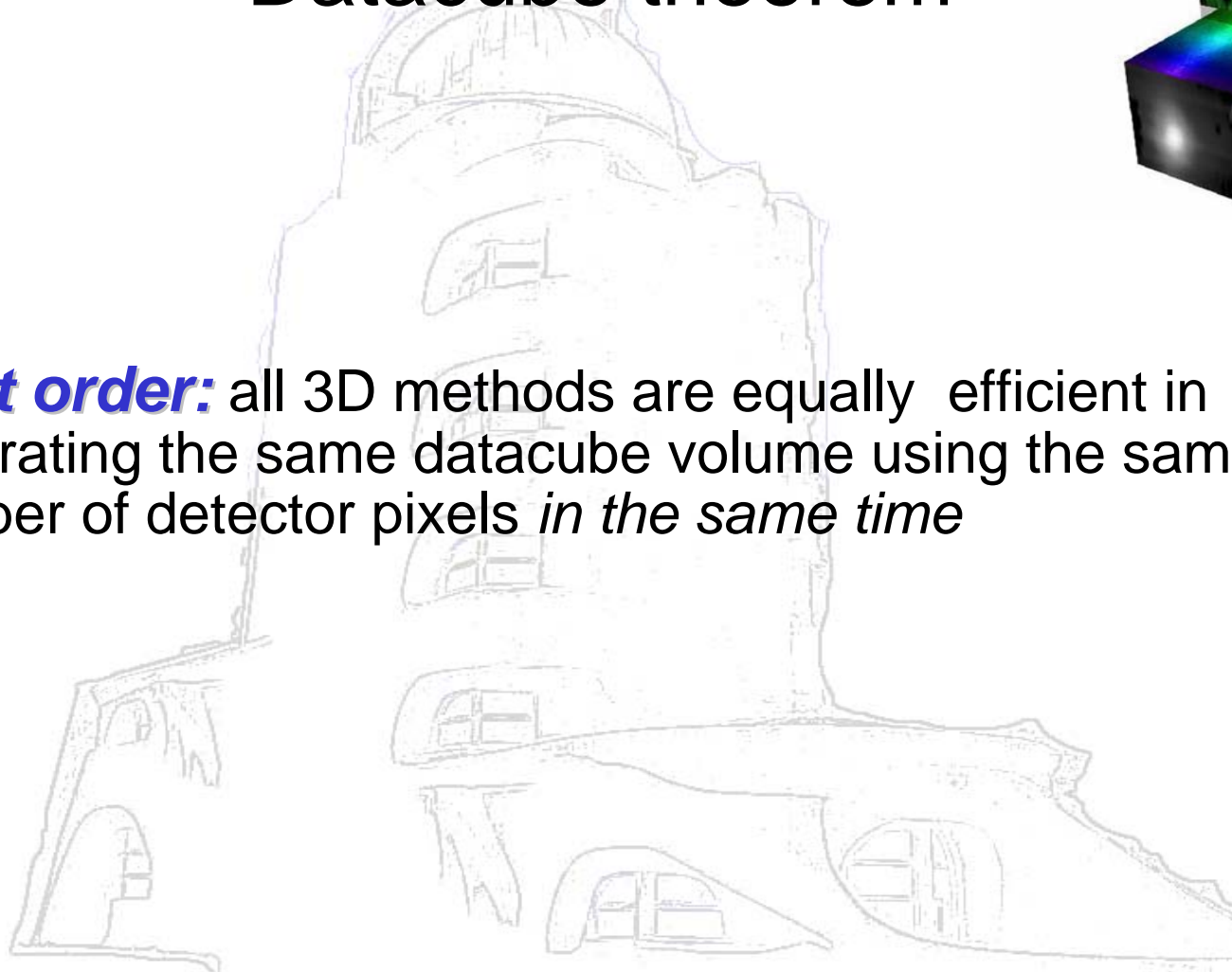
- Narrow-band imaging
- Scanning spectroscopy
- Stepped longslit spectroscopy
- Integral field spectroscopy



Datacube theorem



To first order: all 3D methods are equally efficient in generating the same datacube volume using the same number of detector pixels *in the same time*



... to second order

depends on....

- the dominant noise source
 - detector read noise; dark current
 - photon noise from sky; object
 - *temporal variability in sky background*
- details of the scientific application, especially:
 - the required field, sample size and contiguity
 - the required length and sampling of the spectrum

IFS often wins if you observe from the ground....

3D techniques

Narrow-band imaging

- Complete image in narrow passband
- No spectral information within slice

Scanning spectroscopy

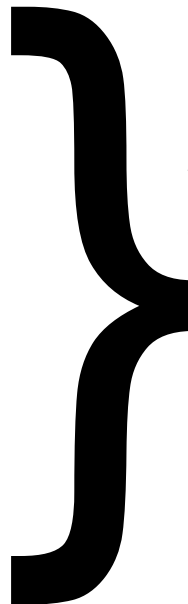
- Series of images in limited wavelength range
- Large field in each

Stepped longslit spectroscopy

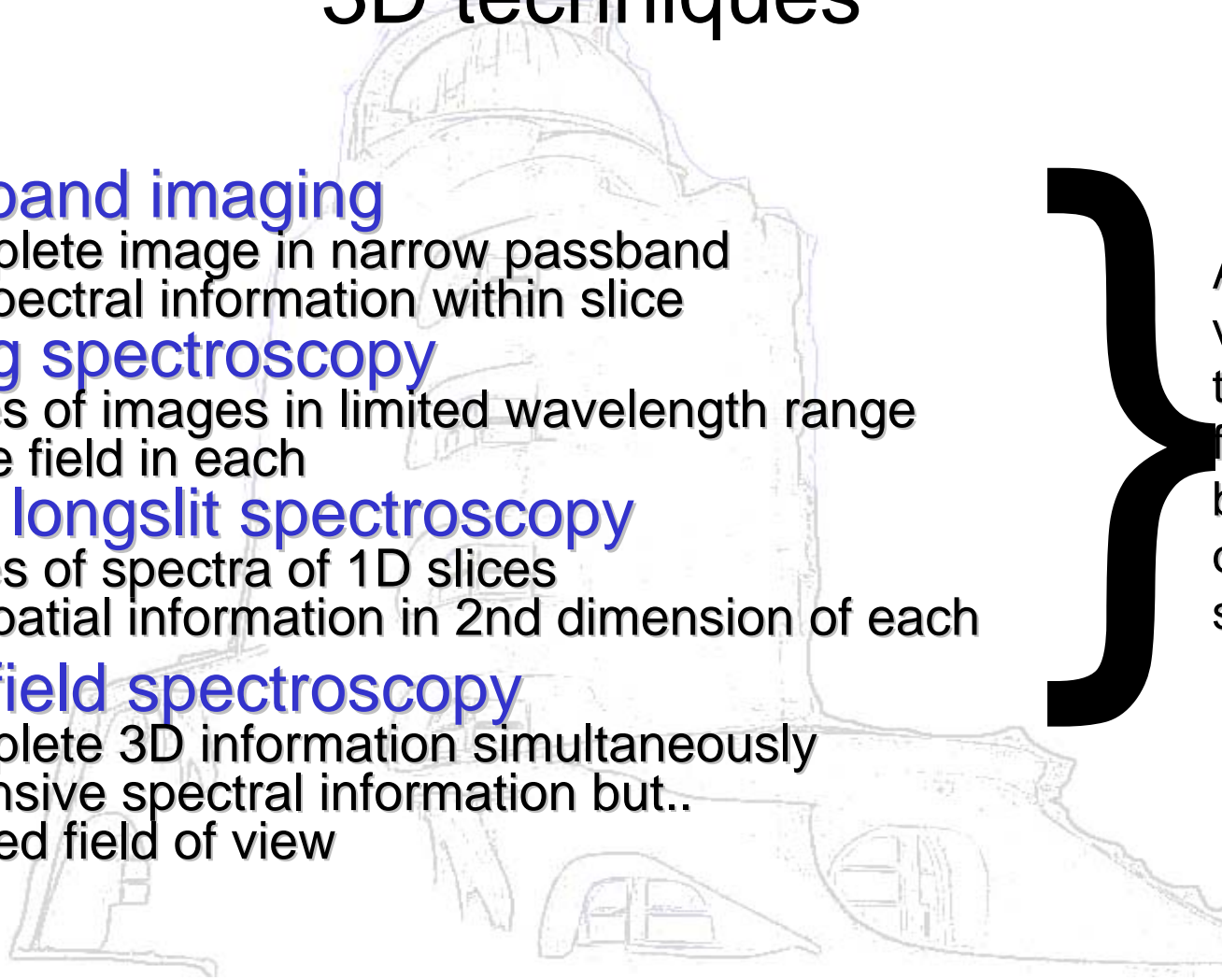
- Series of spectra of 1D slices
- No spatial information in 2nd dimension of each

Integral field spectroscopy

- Complete 3D information simultaneously
- Extensive spectral information but..
- Limited field of view



All these
vulnerable to
temporal
fluctuations in
background or
other noise
sources



Scanning 3D techniques

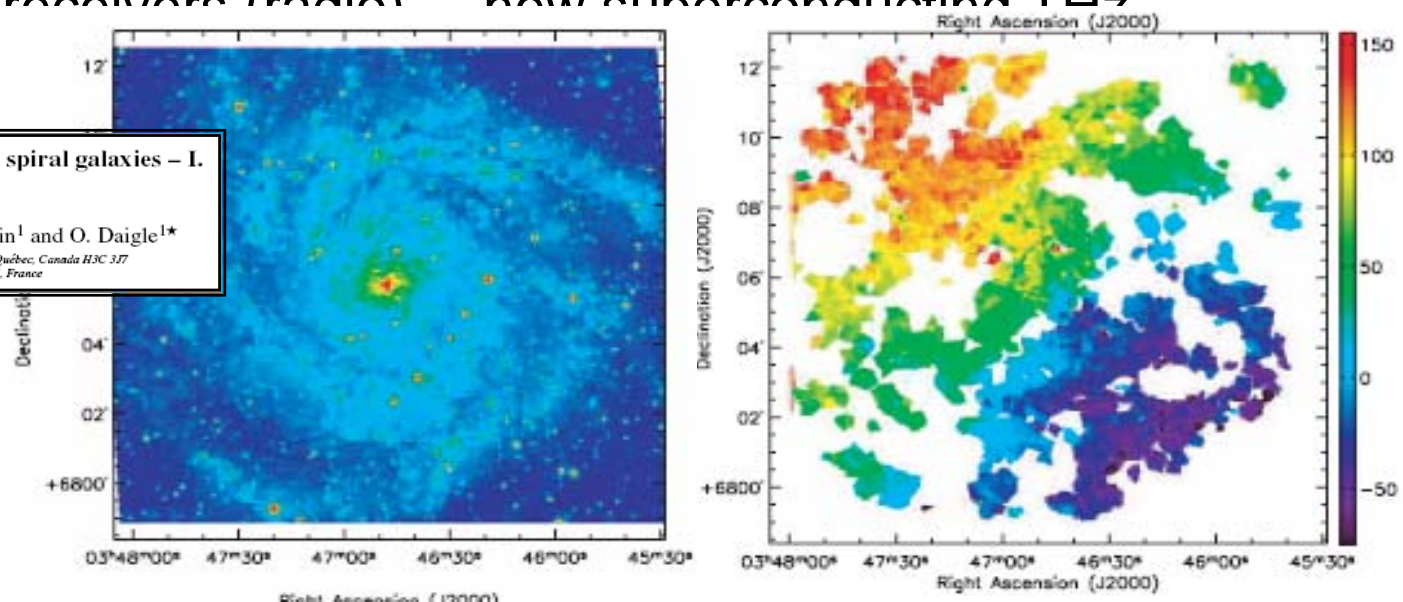
Wide field scanning interferometers

- Fabry-Perot interferometers (scan OPD in etalon cavity)
- Fabry-Perot tunable filters (scan OPD in etalon cavity + filters)
- Imaging Fourier Transform spectroscopy (scan OPD in Michelson)
- Hadamard Transform spectroscopy (scan coded mask in image)
- Spectral line receivers (radio) new superconducting THz

BH α BAR: big H α kinematical sample of barred spiral galaxies – I.
Fabry-Perot observations of 21 galaxies

O. Hernandez,^{1,2*} C. Carignan,^{1*} P. Amram,^{2*} L. Chemin¹ and O. Daigle^{1*}

¹Observatoire du mont Mégantic, LAE, Université de Montréal, CP 6128 succ. centre-ville, Montréal, Québec, Canada H3C 3J7
²Observatoire Astronomique de Marseille Provence et LAM, 2 pl. Le Verrier, 13248 Marseille Cedex 04, France



Non-dispersive 3D techniques

Photon-counting energy-resolving position sensors:

Estimate photon energy by number of secondary (quasi-) particles

- Superconducting Tunnel Junctions (STJ; $M \sim 10^2$; $R \sim 15+$, htr)
- Kinetic Inductance Detectors (KID; $M \sim 10^4+$; $R \sim 30+$; htr)
- Transition Edge Sensors (TES; $M \sim 10^2+$; $R \sim 20+$; htr)

Superconducting Kinetic Inductance Photon Detectors

Benjamin A. Mazin^a, Peter K. Day^b, Henry G. LeDuc^b,
Anastasios Vayonakis^a, and Jonas Zmuidzinas^a

^aCalifornia Institute of Technology, 1200 E. California Blvd., Pasadena, CA, 91125

^bJet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA, 91109

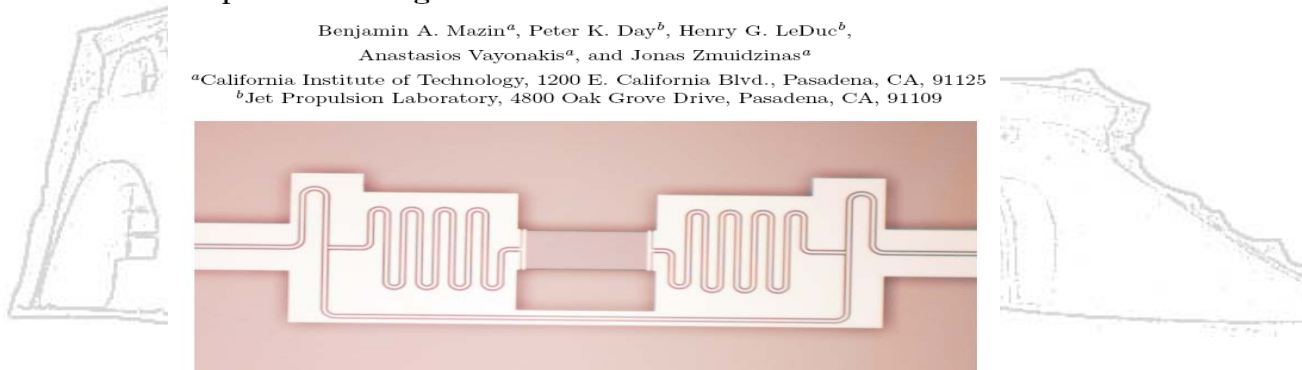
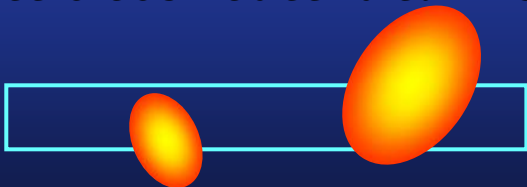


Figure 8. A position sensitive x-ray detector based on two aluminum CPW resonators at the either end of a tantalum absorber.

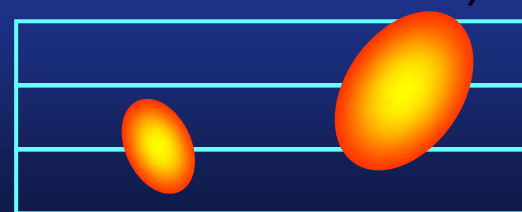
Advantage of IFS

- **High system efficiency:** no slit loss compared to slit spectroscopy
- **Background estimation** can be obtained *simultaneously*
- **Spectral resolution** NOT determined by *field size*
- **Point and shoot** target acquisition
- **Image reconstruction** tells where you were *actually* pointing
- **Atmospheric dispersion** correction (and achromatic refraction)
- **Radial velocity determination** more accurate & unbiased :
 - *Global* velocity field - not just a 1-D section
 - Can remove *slit-barycentre errors*

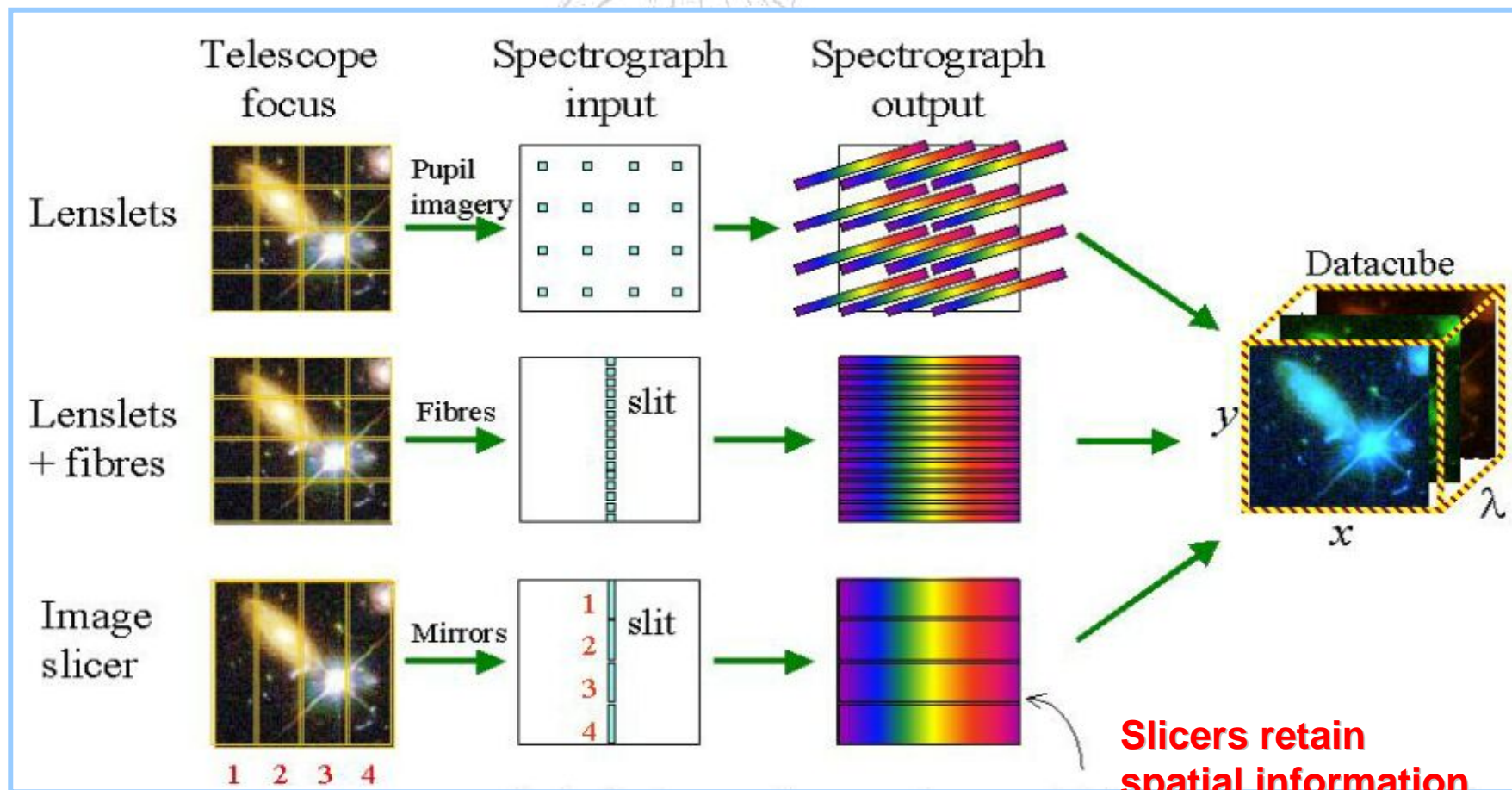
Slit spectroscopy - velocities in error
since blobs not centred in slit



IFS - use information from adjacent
slices to correct velocity data



Main IFS Techniques

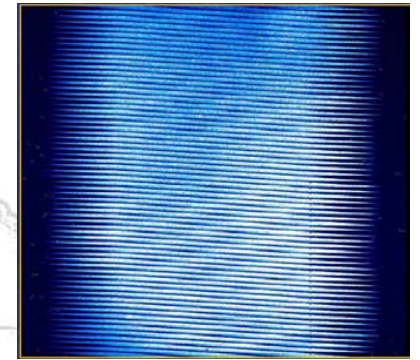
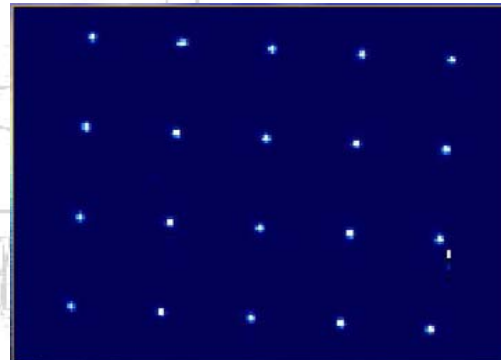


Lenslet systems

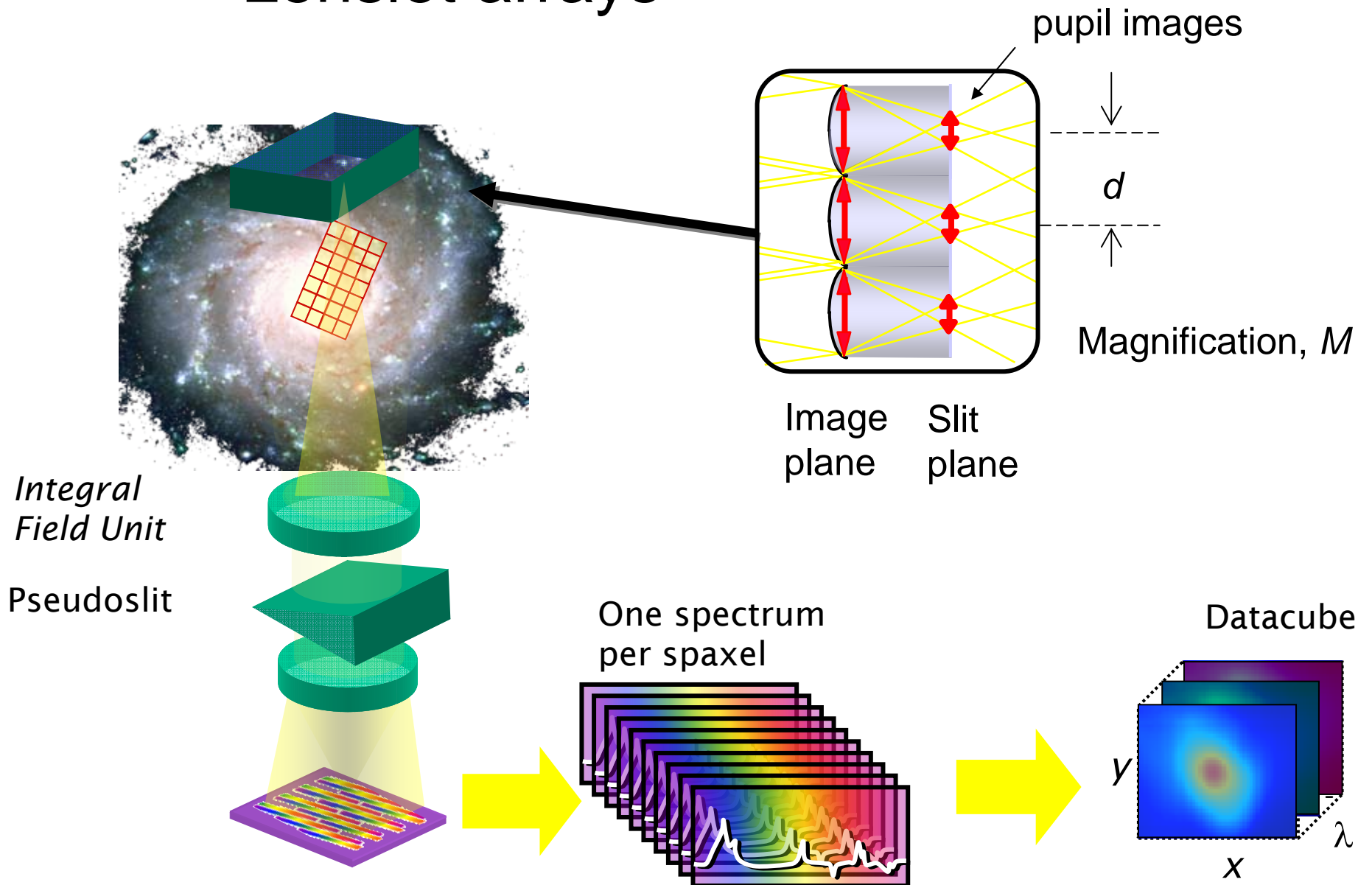
- Courtès, G. 1982 (in *Instrumentation for Astronomy with Large Optical Telescopes*, ed. C.M. Humphries, Dordrecht: Reidel, Astrophysics and Space Science Library, v. 92, p123)
- Afanasiev, V.L. et al. 1990 (SAO Preprint No. 54; 1995 Tridimensional Optical Spectroscopic Methods in Astrophysics, ASP Conf. Ser 71, p276.)
- Tigre/Tiger (**Bacon** et al.1995. A&AS 113, 347)

→ OASIS, SAURON

→ OSIRIS (Larkin)

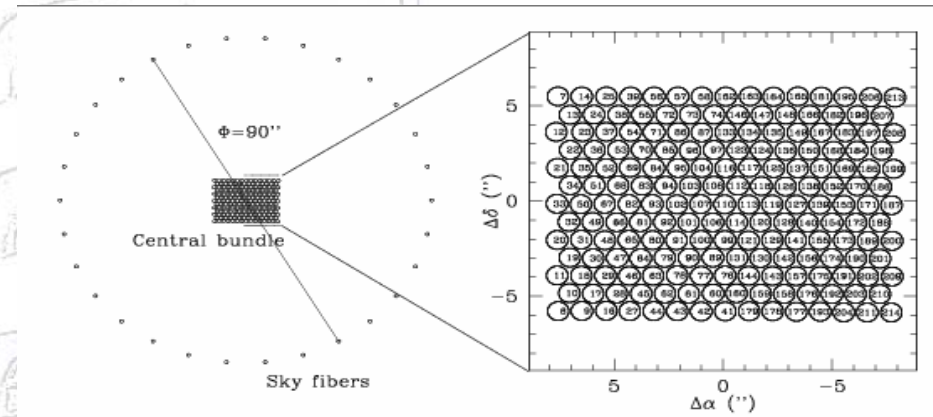
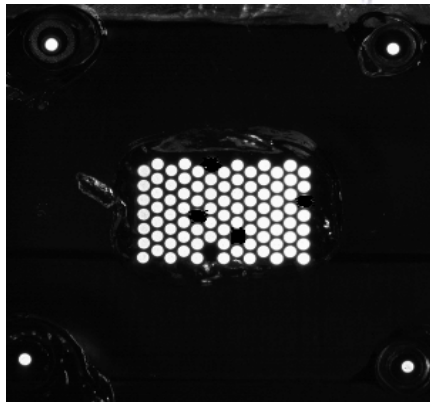


Lenslet arrays



Fibre systems

- **Densepak** (Barden S. & Wade R. 1988. In: Fiber optics in astronomy, Astronomical Society of the Pacific, p. 113-124.)
- **Integral** (Arribas, S. et al. 1998. in Fiber Optics in Astronomy III. ASP Conference Series, Vol. 152, p.149)



Use with lenslet arrays for better efficiency:

→ GMOS-IFU etc, → PMAS/PPAK etc.

Lenslet-coupled fibre arrays

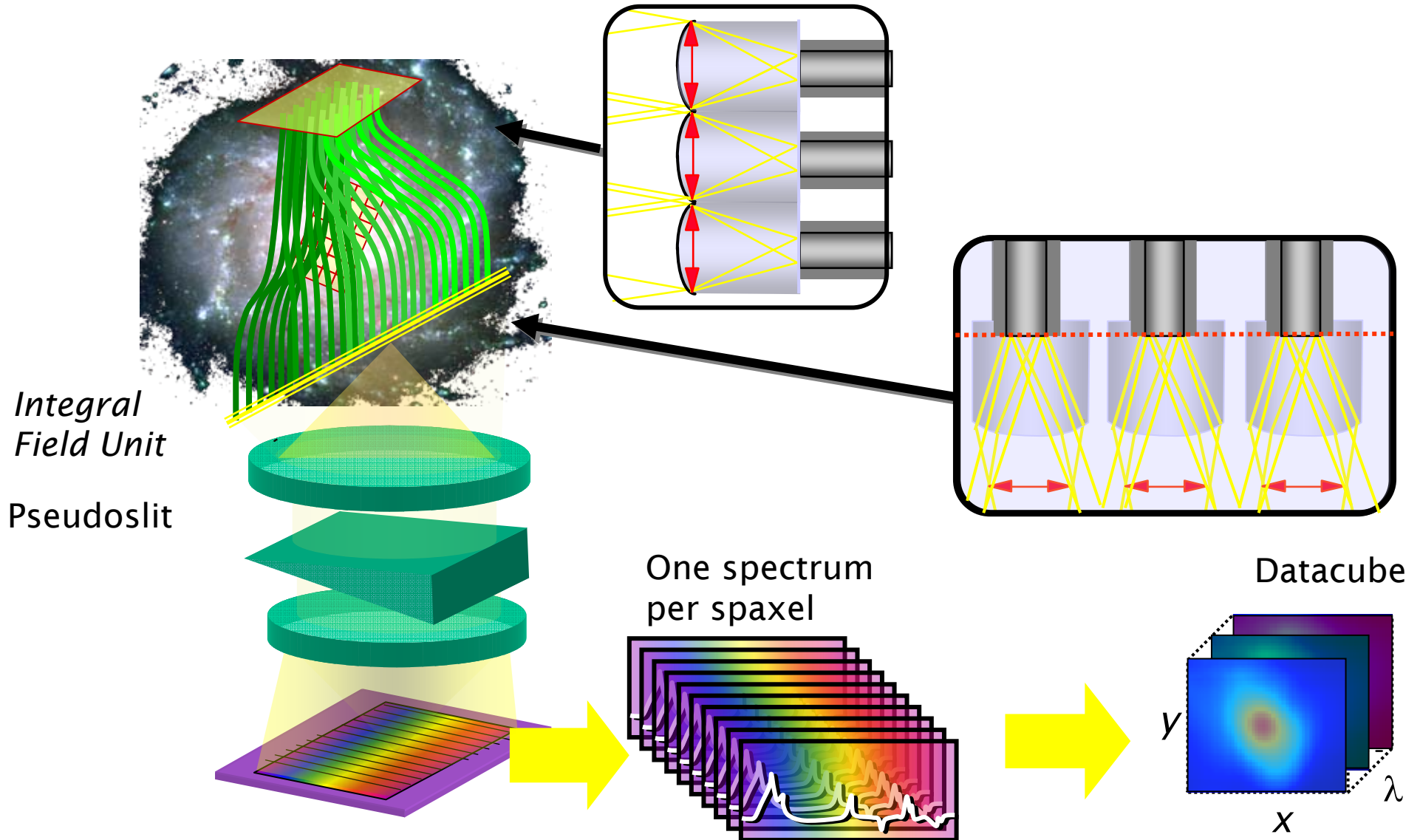


Image slicers

Boost spectral resolution without light loss

- **Bowen & Walraven slicer** (Bowen I.S. 1938 ApJ 88, 113)
- **Confocal Image Slicer** (Diego F. 1993. Appl. Opt. 32, 6284)
- **Monolithic glass slicer** (Richardson, H. et al. 1999)

To spatially resolve in dispersion direction

- **3D** (Weitzel, L. et al 1996, A&AS 119, 531) → SINFONI
- **AIS** (Content, R. 1997. SPIE 2871,1295) → GNIRS, JWST-NIRSpec etc

Since changes in area of the image are ineffective in increasing the efficiency, one is led to the remaining method of changing the shape of the image without altering its area. The optimum shape is obviously a long, narrow band whose width is equal to that of the slit.

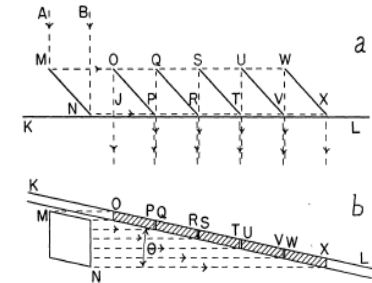


FIG. 1

If this can be accomplished by reflections at plane surfaces, the angle of the cone of incident light is not altered in any way, and therefore the equality of F_i and F_e is not disturbed.

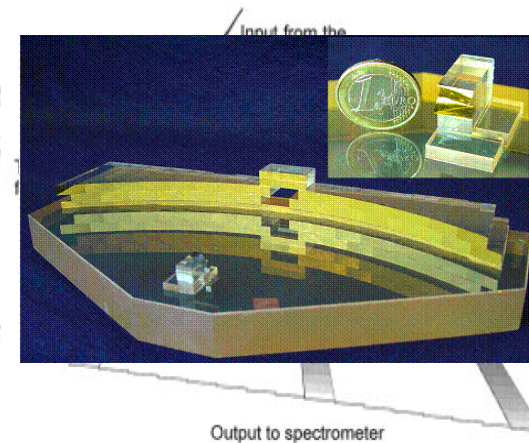
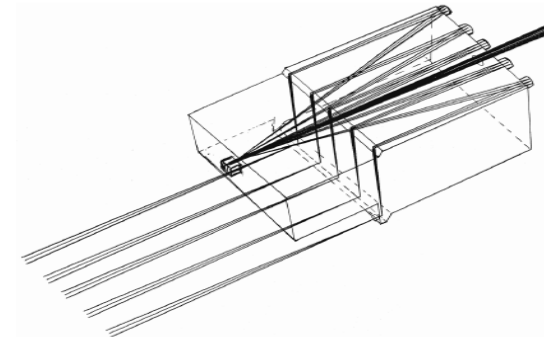
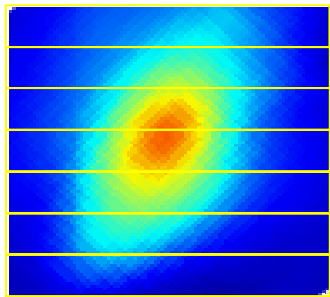
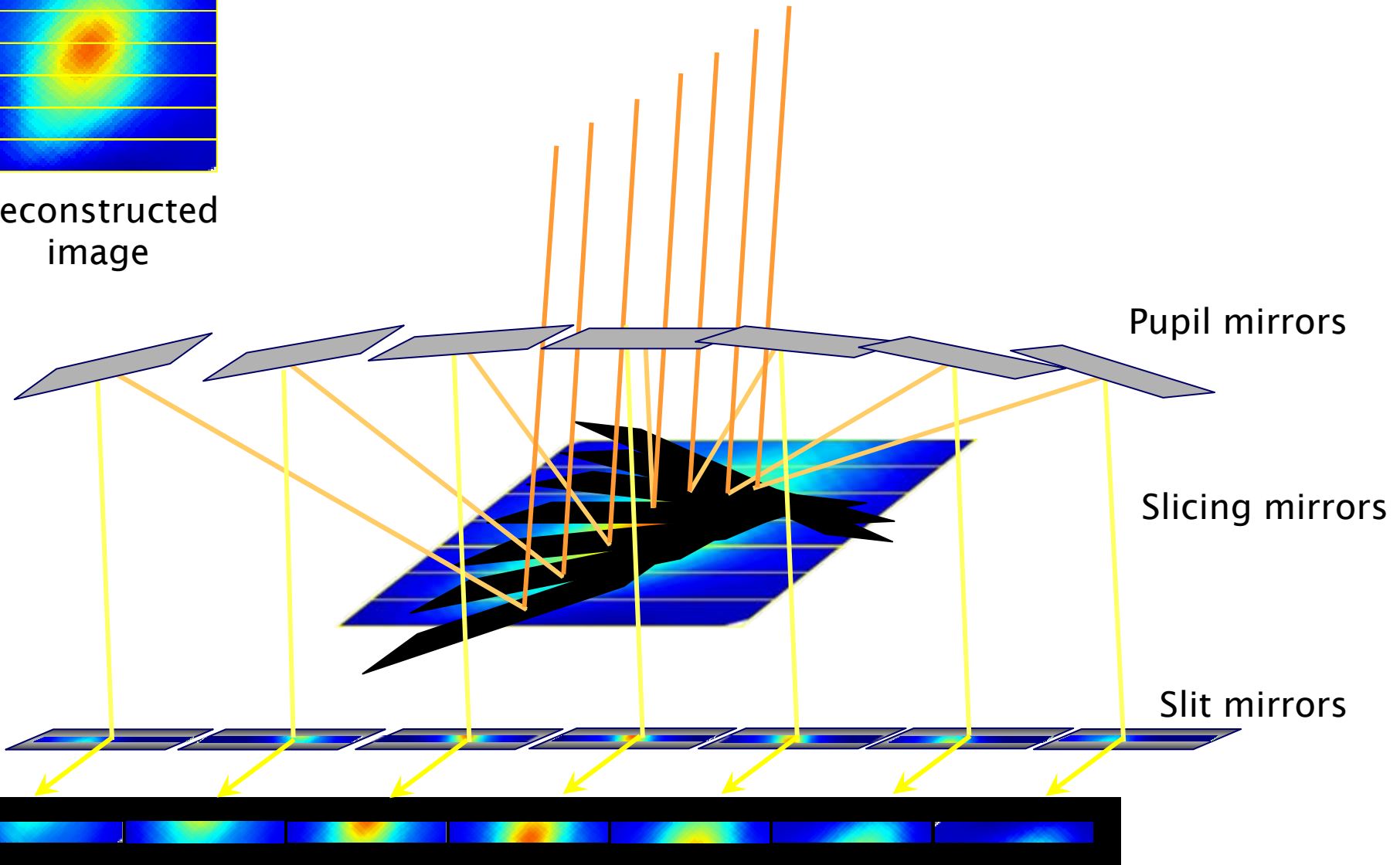


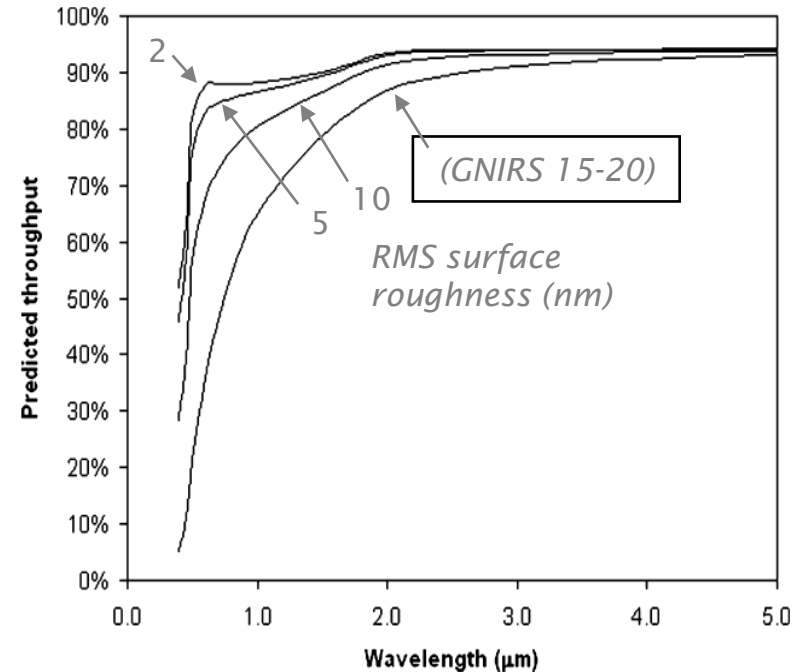
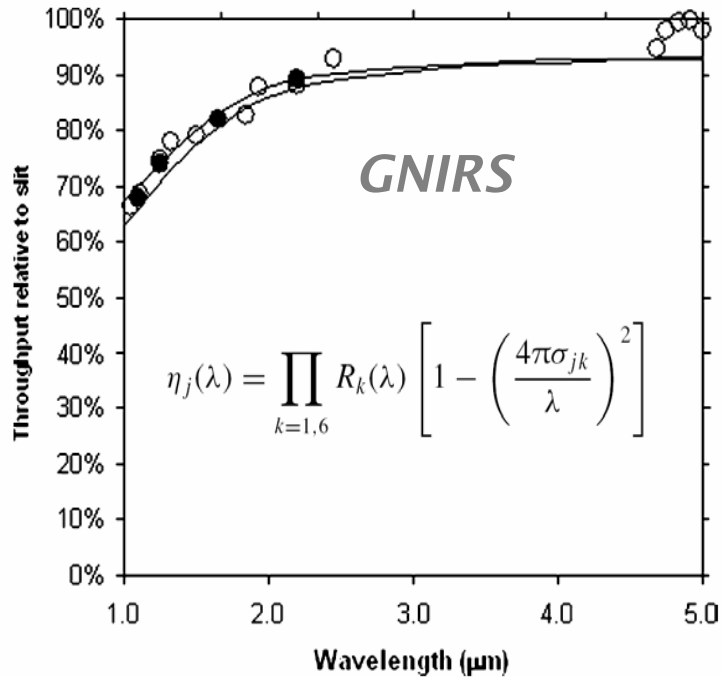
Image slicing



Reconstructed image



Efficiency: slicer throughput



- Simple scatter model verified by *GNIRS*
- Predictions for 3 fore optics + 3 multifaceted IFU optics
- Coating gold ($>1\mu\text{m}$), aluminium ($\leq 0.4\mu\text{m}$) or silver
- **Need 5nm RMS for 400nm capability**

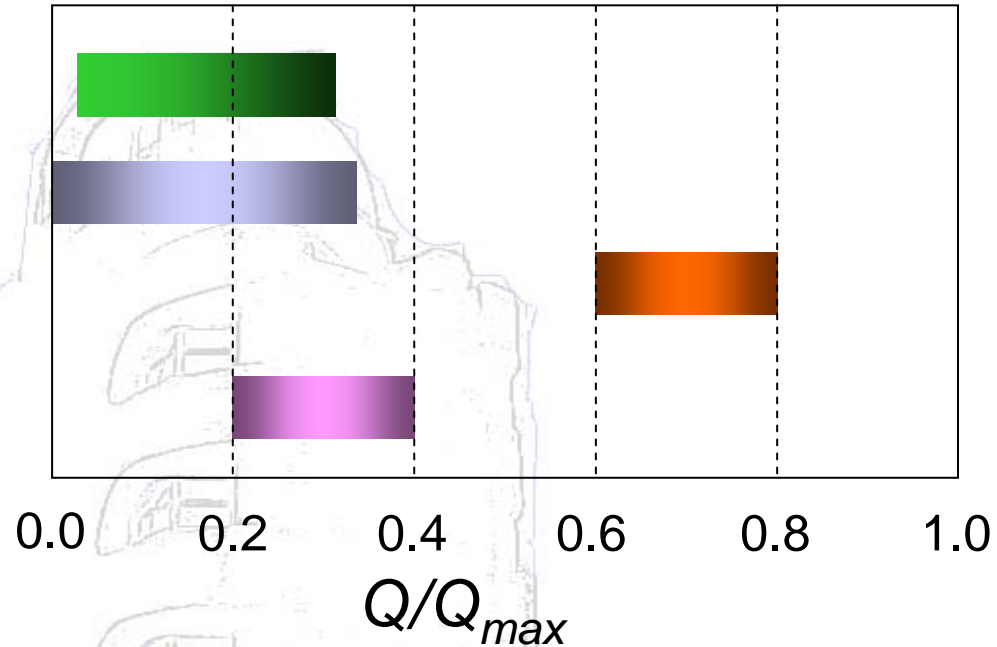
Best technique?

lenslets

fibres

slicers

microslicers



....*slicers*.... but difficult to make

Specific Information Density

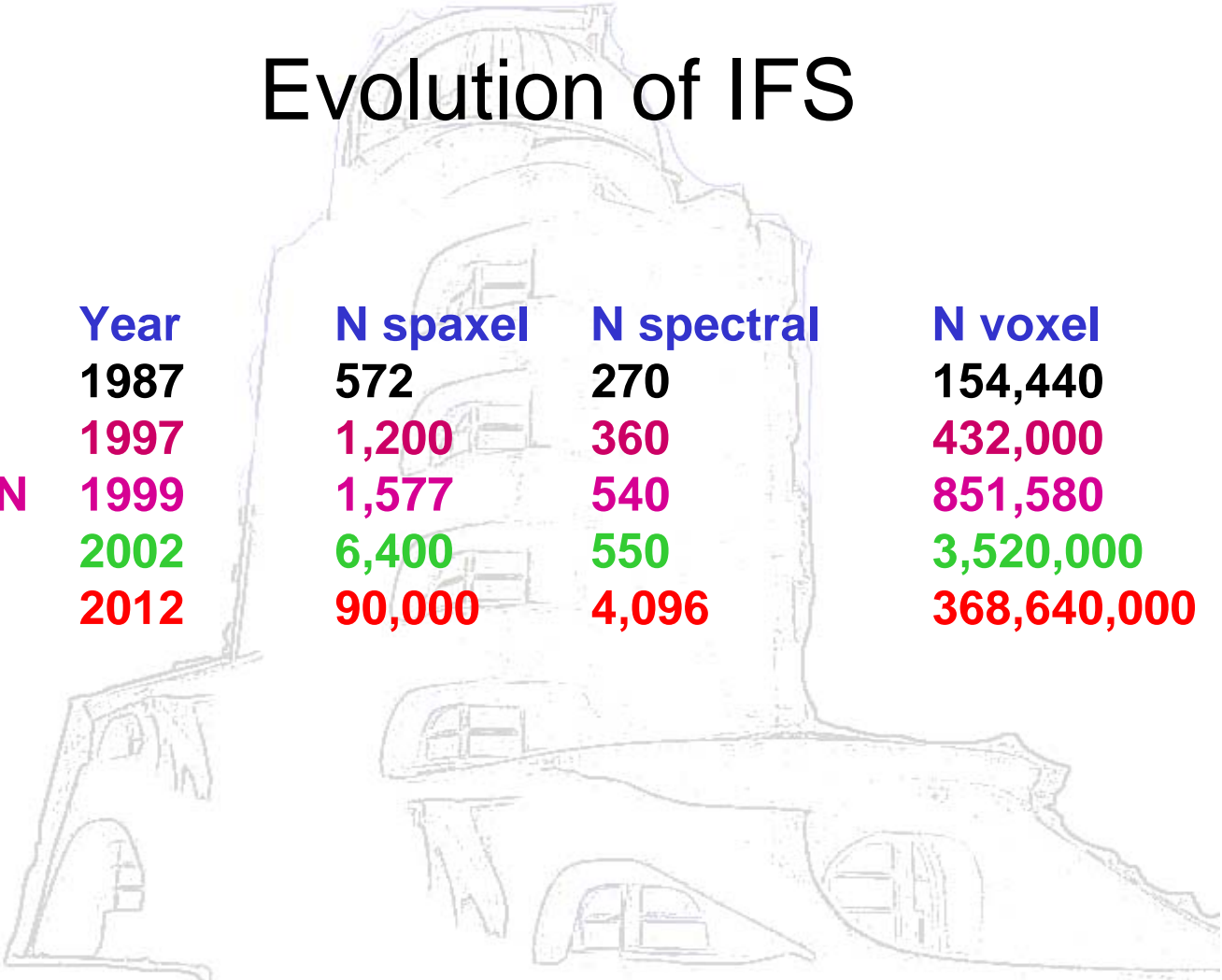
resolution elements

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

throughput

detector pixels

Evolution of IFS



Name	Year	N spaxel	N spectral	N voxel
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	2012	90,000	4,096	368,640,000

Summary

- Integral field spectroscopy now standard technique
- Many examples, technology becoming mature
- Image slicing optimal but difficult
- Alternatives to trade cost with performance
- ELTs need multiplexed IFS to sample the field **lecture 4**
- Slicing can reduce size of instruments without AO **lecture 4**

