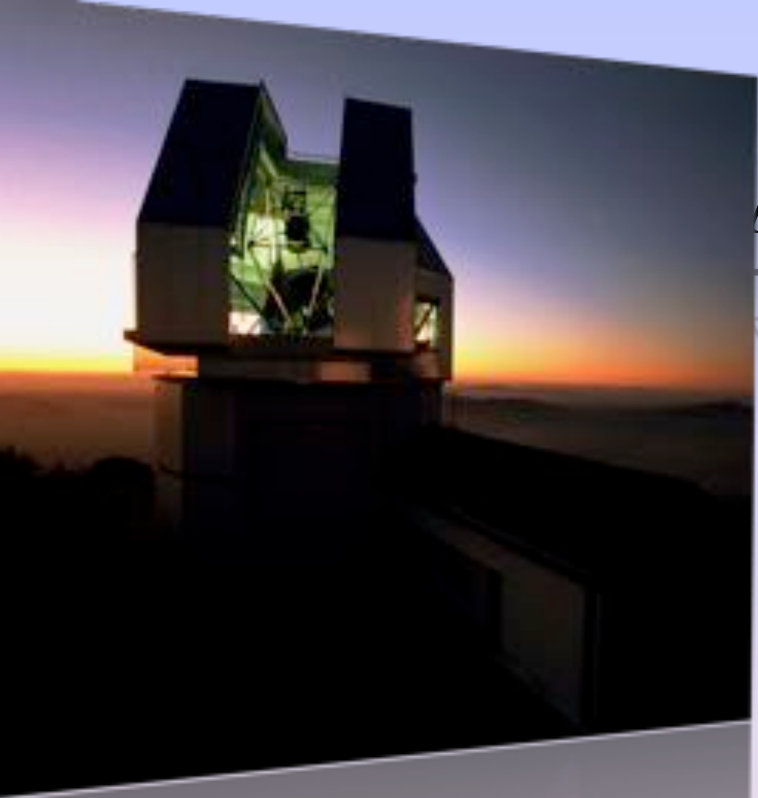


Astro 500

Techniques of Modern
Observational Astrophysics

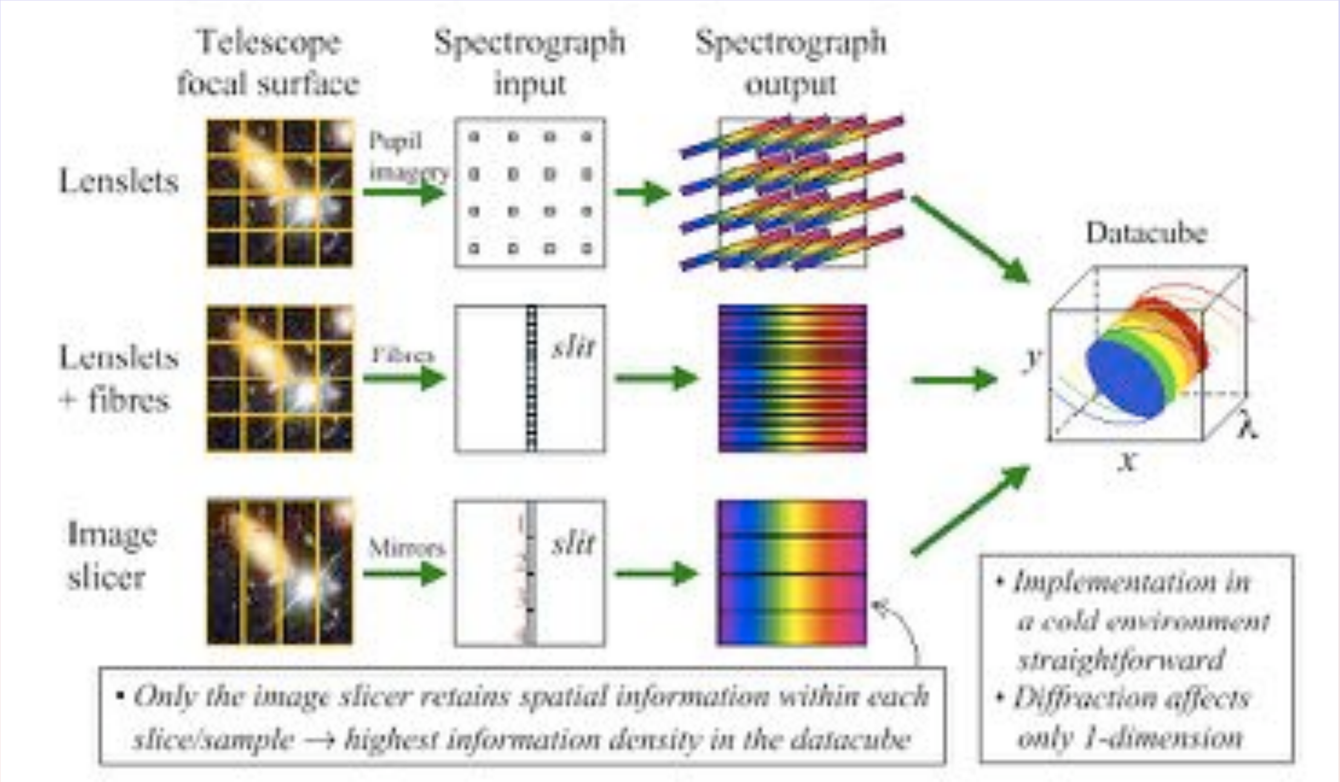
Matthew Bershady
University of Wisconsin

Approaches

Examples of available instruments

- ✓ Grating-dispersed spectrographs
  - ✓ basic spectrograph design
  - ✓ dispersive elements
  - ✓ Long-slit spectrographs
    - ✓ General Observing Considerations
  - ✓ Double spectrographs
  - ✓ Multi-objects spectrographs: slitlets vs fibers
  - ✓ Echelle spectrographs
  - ➢ 3D spectroscopy: coupling formats and methods
    - ✓ Fiber
    - o Fiber+lenslet
    - o Slicer
    - o Lenslet
    - o Filtered multi-slit
    - o 3D MOS
  - ➢ Current instruments
    - o summary of considerations
    - o sky subtraction

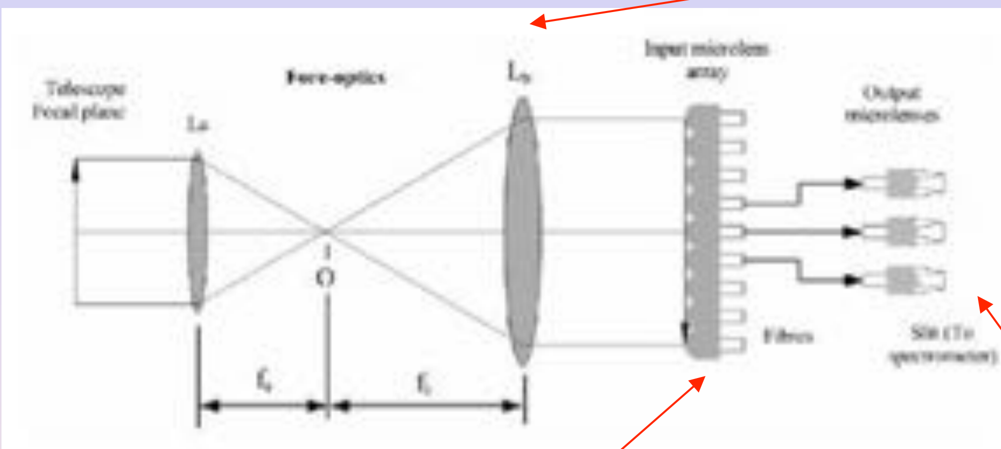
IFUs



Telescope focal surface
Spectrograph input
Spectrograph output
Lenslets
Pupil imagery
Datacube
Lenslets + fibres
slit
y
λ
x
Image slicer
Mirrors
slit
• Implementation in a cold environment straightforward
• Diffraction affects only 1-dimension
• Only the image slicer retains spatial information within each slice/sample → highest information density in the datacube

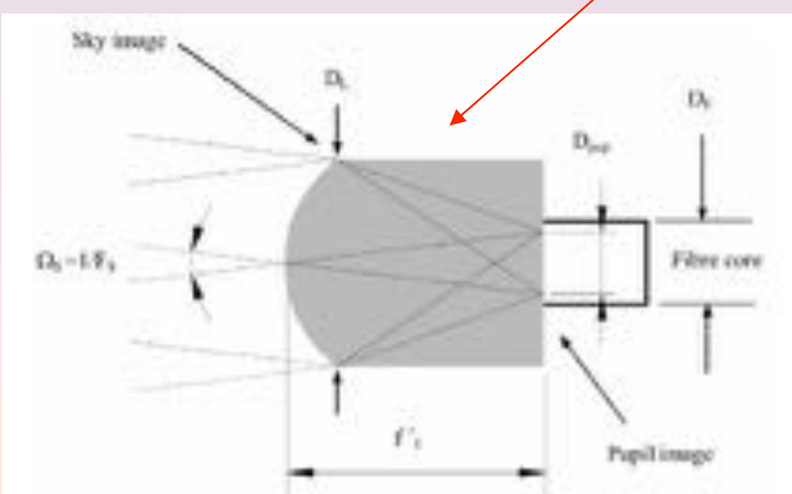
Grating-dispersed spectrographs
fibers + lenslet feeds

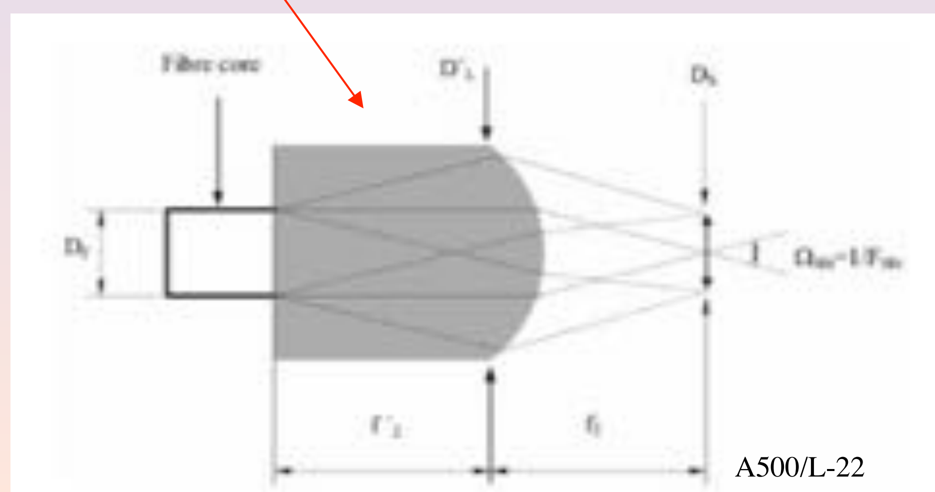
- concept:



- Focal exander matches to scale of lenslet array
- Micro-lens forms pupil image on fiber
- Pupil image is smaller; angles are larger (AΩ again)
- Option to reform slit-image with output micro-lens

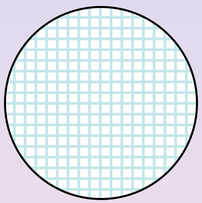
Ren & Allington-Smith ‘02

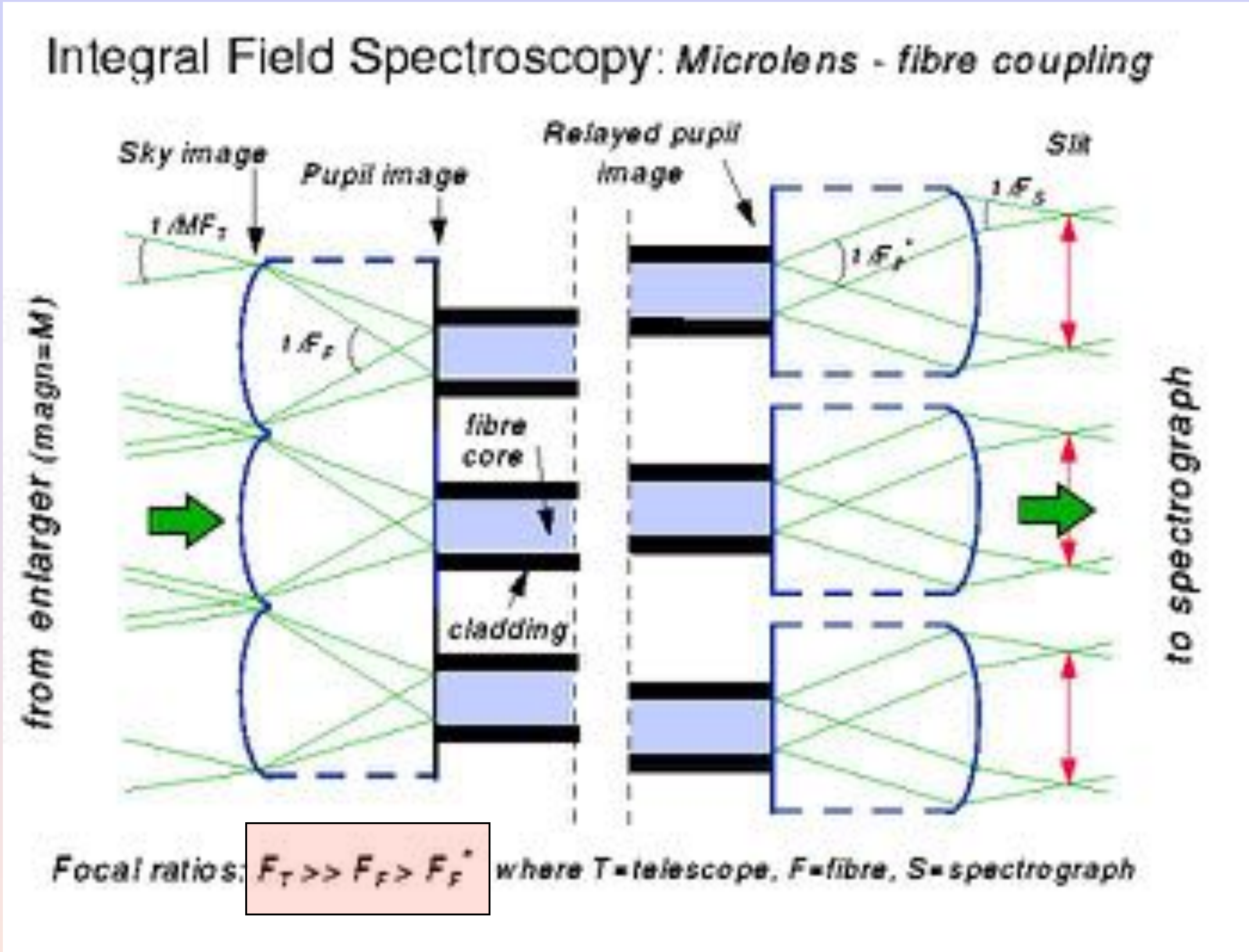




Grating-dispersed spectrographs

fibers + lenslet feeds





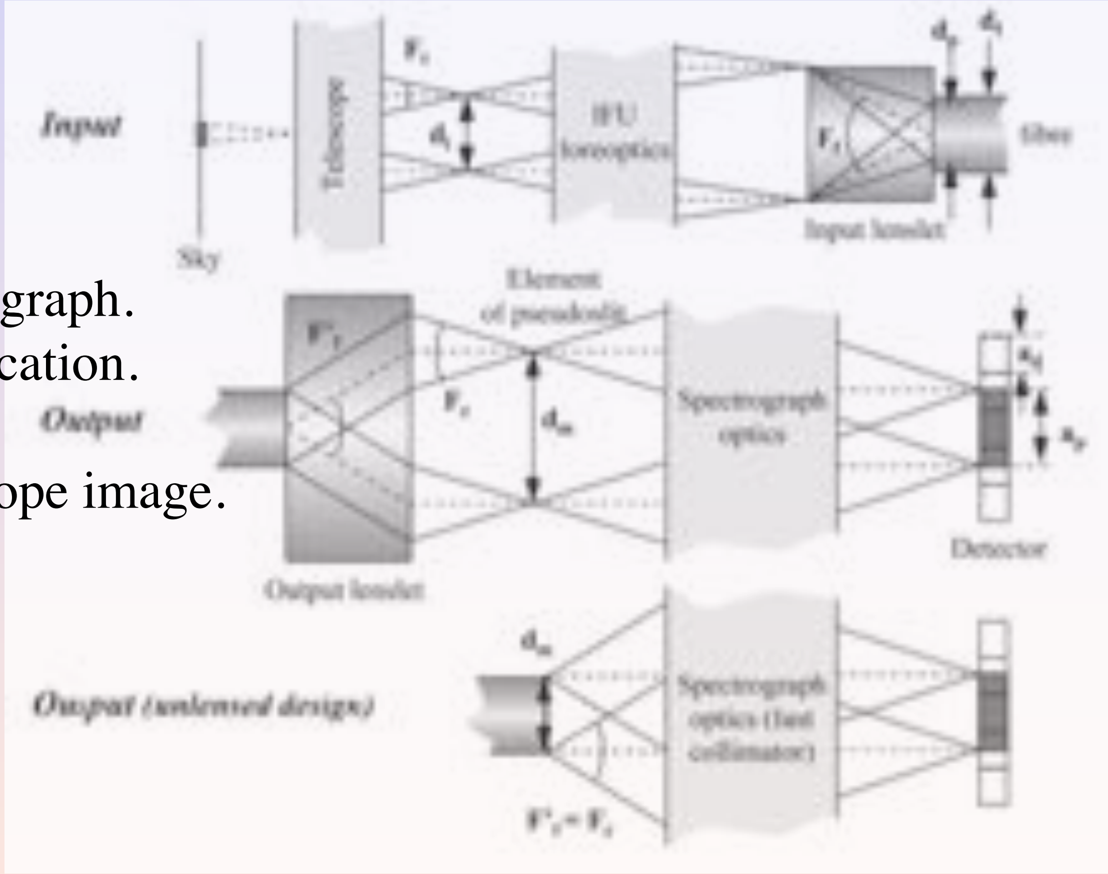
Allington-Smith & Content '98

Grating-dispersed spectrographs
fibers + lenslet feeds

Allington-Smith & Content ‘98

Note: don’t have to use lenslets at output end:

- ➢ Higher input f-ratio to spectrograph.
- ➢ Less possibility for demagnification.
- ➢ Spectrograph images pupil.
- ➢ Ray-bundle varies with telescope image.



Grating-dispersed spectrographs
fibers + lenslet feeds

- pros and cons
  - Improves filling factor to near unity
  - Allows for control of input and output *f*-ratio
    - Effective coupling of slow telescope *f*-ratio to fiber input
    - Effective coupling of fiber output to spectrograph
  - May introduce scattered light (depends on lenslet)
  - Lower throughput (reflection, scattering, misalignment)
  - For science premium on truly integral field, above two factors don't out-weight filling factor improvements.
  - More subtle effect: *output lenslets?*
    - far-field vs near-field: where to control systematics:
    - Is your spectrograph seeing-limited or aberration limited?

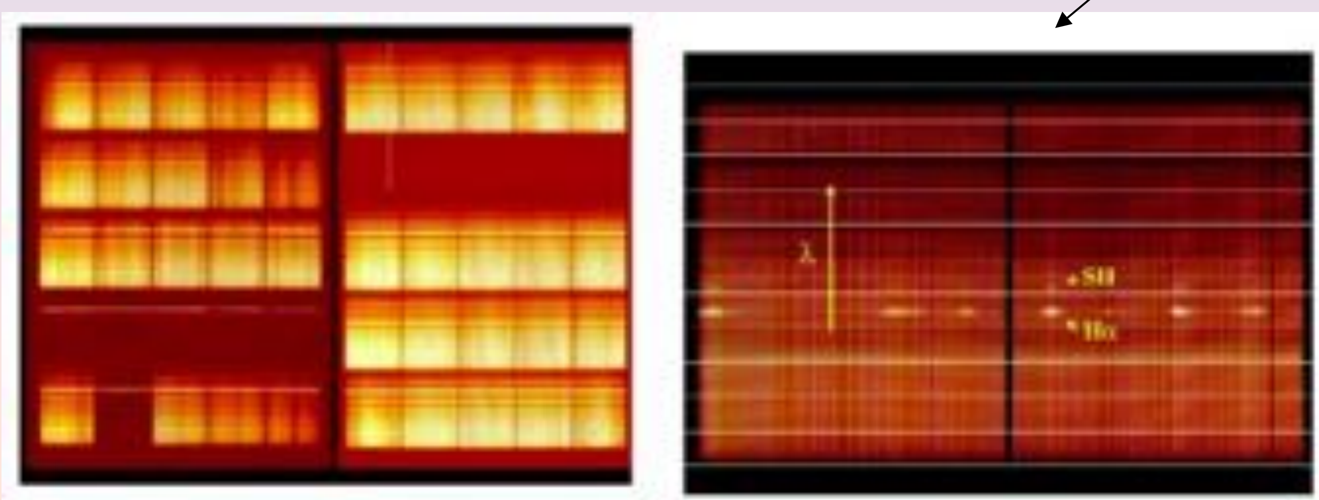
Grating-dispersed spectrographs

fibers + lenslet instruments

- VIMOS, VLT 8m
  - 6400 or 1600 elements
  - 0.33 or 0.67 arcsec sampling
    - 13x13 arcsec up to 54x54 arcsec FoV
  - 360-1000 nm range
  - R = 200-2500

These are just two of 4 channels of 1600 fibers

These are just two of 20 groups of 80 fibers.



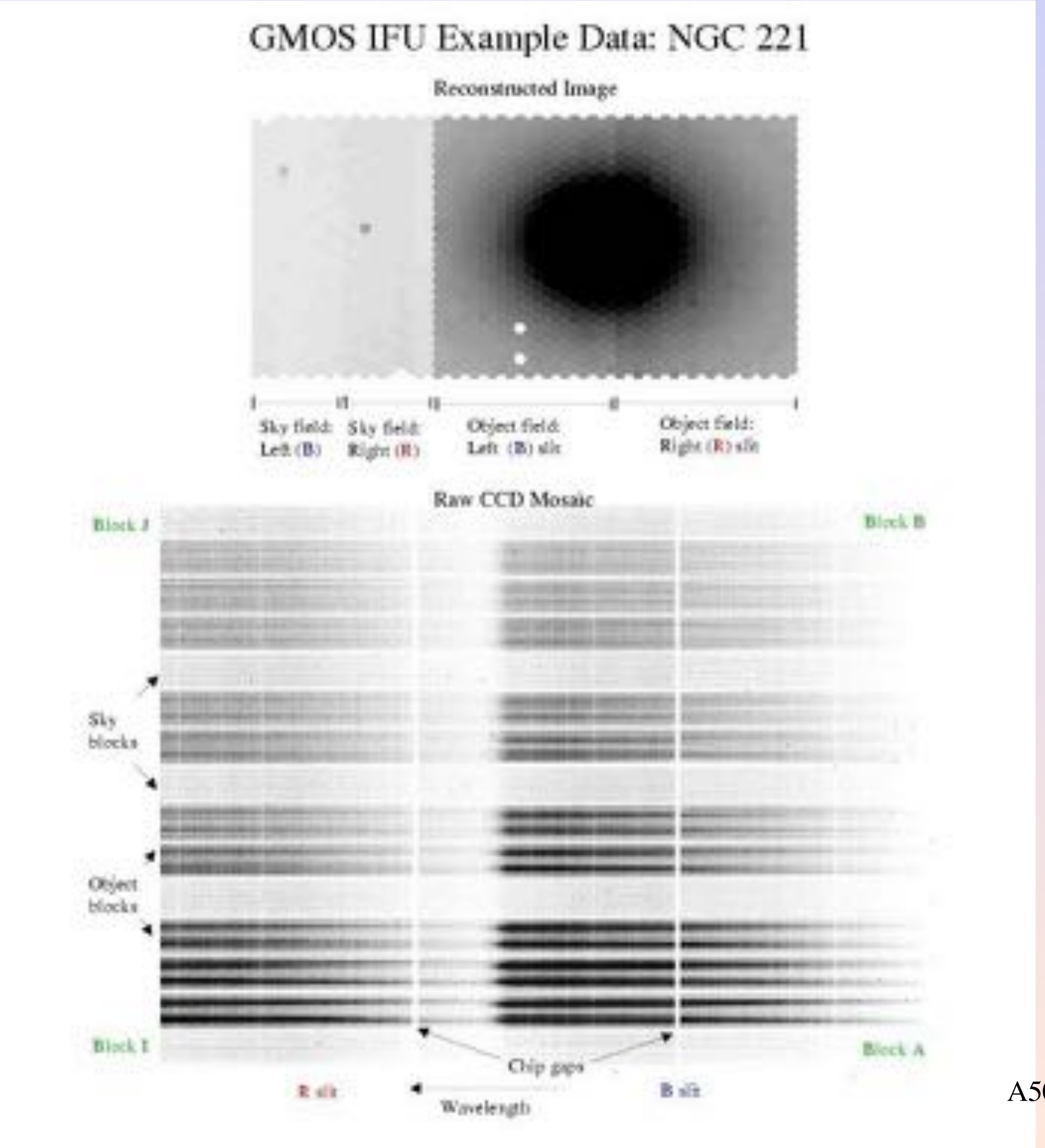
Le Fevre et al. 2003

commissioning data

Grating-dispersed spectrographs
fibers + lenslet instruments

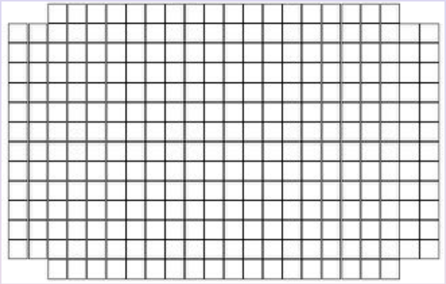
- GMOS, Gemini 8m
  - 1500 lenslets: 1000 object + 500 sky bundles
  - 0.2 arcsec per lenslet (7x5 arcsec + 5x3.5 arcsec FoV)
  - Two-slit and one-slit modes
  - R = 800-3500 (claim 10,000 achievable)
  - 400-1100 nm range

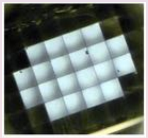
Allington-Smith et al.



Grating-dispersed spectrographs
fibers + lenslet instruments

- FLAMES/GIRAFFE: ARGUS, VLT 8m
  - 22x14 rectangular array
    - 0.52 arcsec per lens: 11.5x7.3 arcsec FoV
    - 0.3 arcsec per lens: 6.6x4.2 arcsec FoV
  - 15 20-element IFUs
    - 0.52 arcsec sampling (2x3 arcsec FoV)
  - R = 11,000-39,000 !
  - 370-950 nm range





(more about this instrument later)

Grating-dispersed spectrographs
fibers+lenslet instruments - summary list

- Existing optical instruments
  - PMAS, Calar Alto 3.5m
  - Spiral B, AAT 3.9m
  - MPFS, SAO 6m
  - IMACS-IFU, Magellan 6.5m
  - GMOS, Gemini 8m
  - VIMOS, VLT 8m
  - FLAMES/GIRAFFE ARGUS/IFU, VLT 8m
- Future optical instruments
- Existing infrared instruments
  - COHSI, UKIRT 3.8m (defunct?)
  - SMIRFS, UKIRT 3.8m (defunct?)
  - CIRPASS, Gemini 8m
- Future NIR instruments

No future?
Hard to believe.

Grating-dispersed spectrographs
fibers+lenslet instruments - summary list

Table 2. Fiber+Lenslet Integral Field Instruments

Instrument	Coupling Method	Telescope	D_T (m)	Ω (arcsec^2)	$d\Omega$ (arcsec^2)	N_σ	$\Delta\lambda/\lambda$	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	0.32	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	0.32	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	0.32	1930.	1000	0.15
SPIRAL-B	lenslet+fiber	AAT	3.9	251.	0.49	512	0.29	1700.	493	···
		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	0.043
		SAO	6.0	64.	0.25	256	0.47	2200.	1024	0.043
IMACS-IFU	lenslet+fiber	Magellan	6.5	···	···	···	···	···	···	···
GMOS	lenslet+fiber	Gemini	8.0	49.6	0.04	1500	0.22	3410.	730.	···
		Gemini	8.0	49.6	0.04	1500	0.32	2300.	730.	···
		Gemini	8.0	49.6	0.04	1500	0.82	800.	730.	···
		Gemini	8.0	24.8	0.04	750	0.42	3410.	1460.	···
		Gemini	8.0	49.6	0.04	1500	0.64	2300.	1460.	···
		Gemini	8.0	49.6	0.04	1500	1.00	800.	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	26000.	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	26000.	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	34.5	0.13	490	0.41	2500.	1024	···
		Gemini	8.0	34.5	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										

Grating-dispersed spectrographs
image slicer feeds

- Concept
  - S1: Slicer mirrors at telescope focal plane divide it into strips; mirrors have power to place telescope pupil on next element.
  - S2: Pupil mirrors (one per slice) reformat the slices into a pseudo-slit, where they form an image of the sky.
  - S3: Field lens control location of pupil stop in spectrograph.
- All-mirror and catadioptric designs exist.

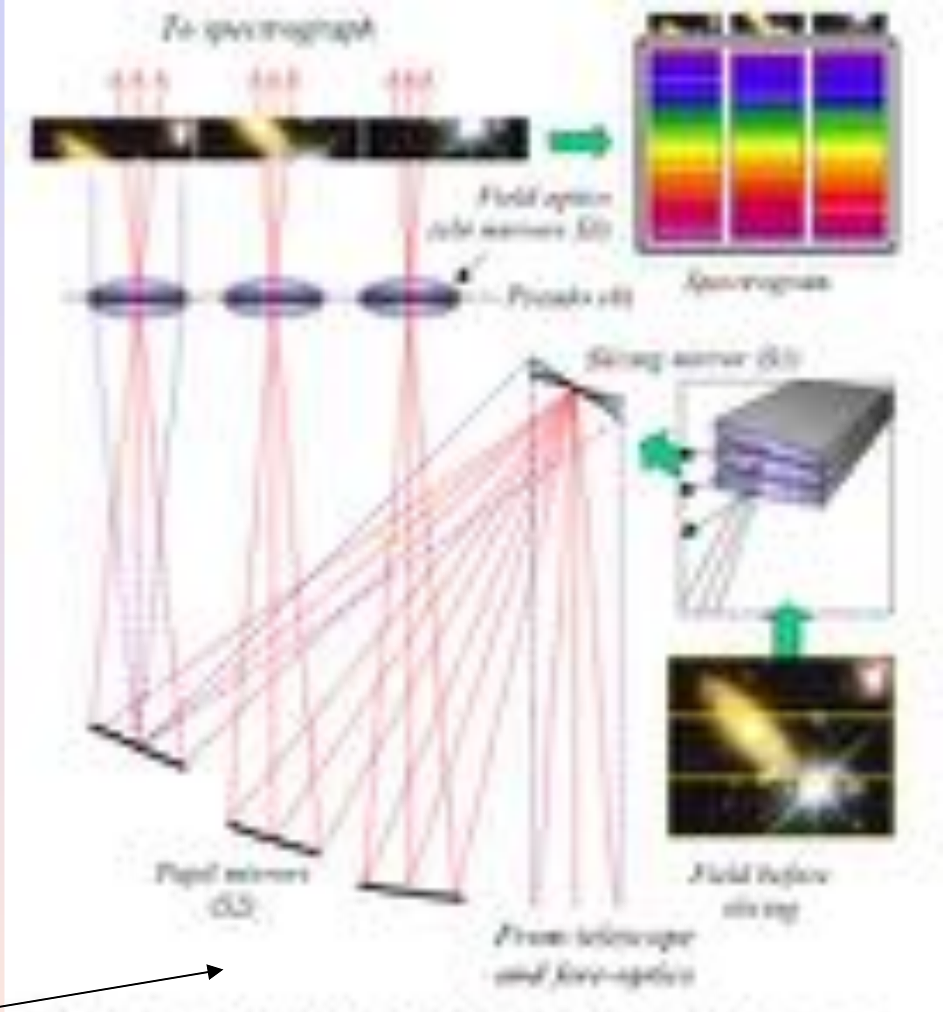


Figure 4. Image slicer principle (courtesy J. Allington-Smith, Durham U.)

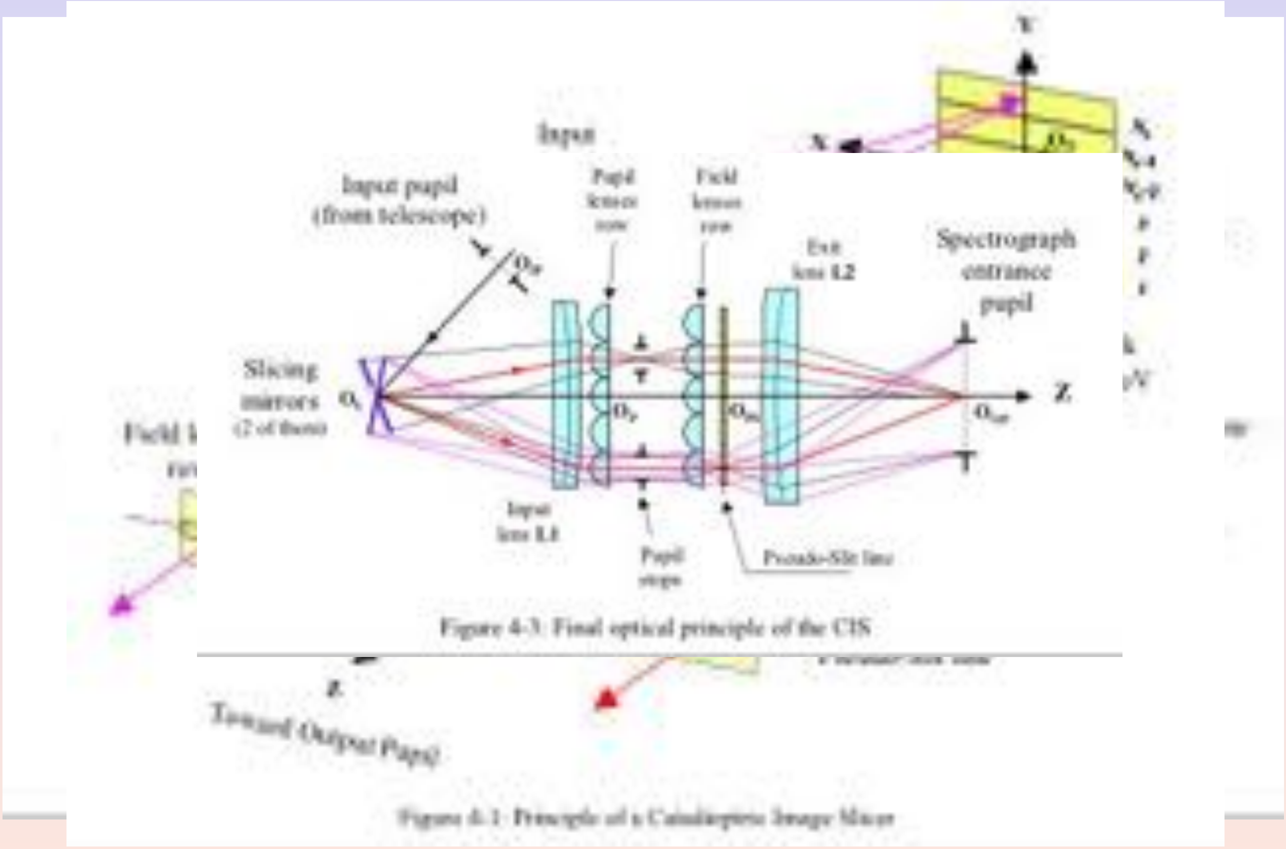
The so called "advanced image slicer"

Grating-dispersed spectrographs
image slicer feeds

- All mirror design for FISICA
  - ➢ Eikenberry et al. '04
    - o For FLAMINGOS
    - o 16x33 arcsec FoV on KPNO 4m
    - o 6x12 arcsec FoV on GTC
    - o JHK bands
    - o R = 1300

Grating-dispersed spectrographs
image slicer feeds

- Catadioptric Image Slicer (CIS) for MUSE



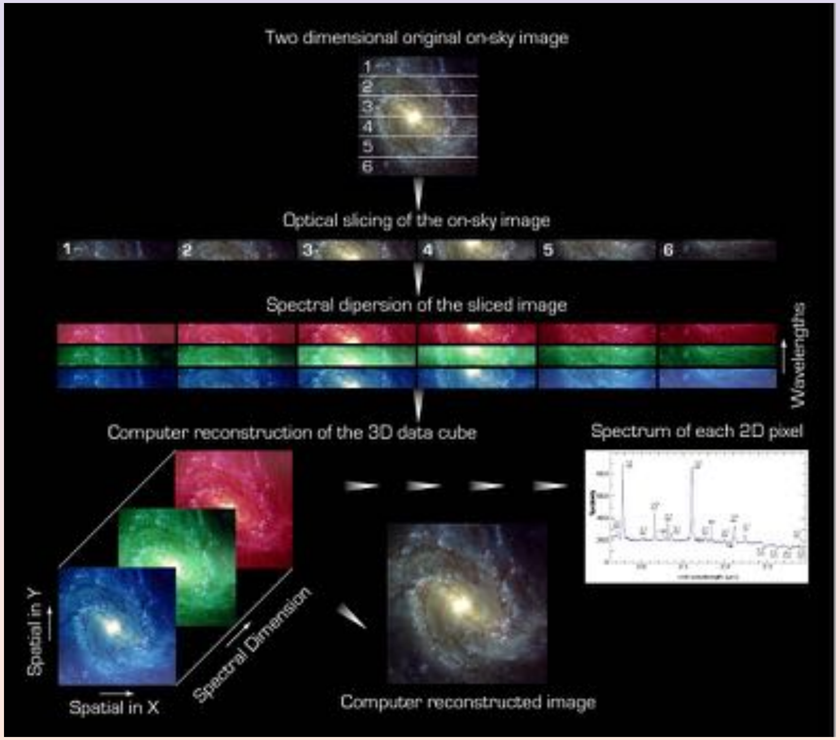
Henault et al. '03

Grating-dispersed spectrographs
image slicer feeds

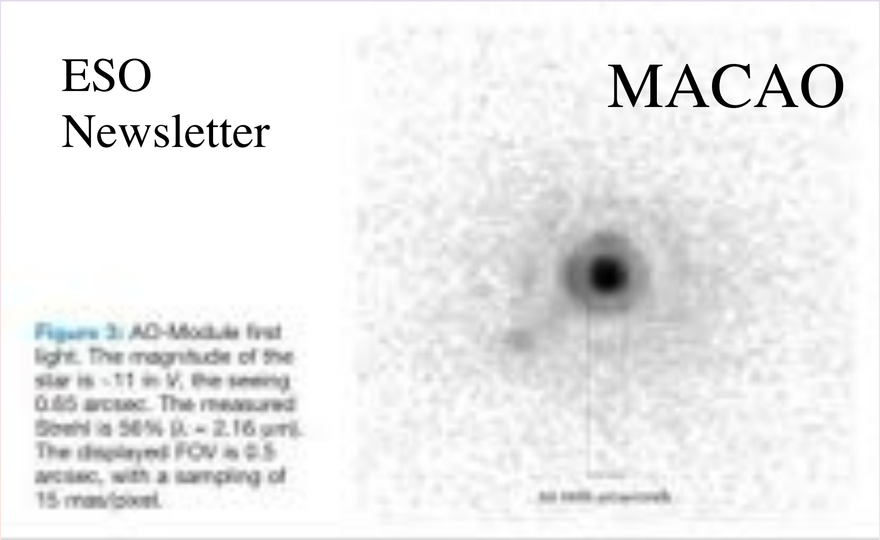
- Pros and cons
  - Image slicers are the only IFU mode to preserve all spatial information.
    - All other modes destroy spatial information within sampling element.
  - Most compact at reformating the focal plane onto detector.
  - Can be used in cryogenic systems and at long wavelengths where fibers don’t transmit.
    - Lenslet arrays also accomplish this, e.g., OSIRIS (Keck)
  - Issues of scattered-light with diamond-turned optics mean optical slicers must be made differently.

Grating-dispersed spectrographs
image slicer instruments

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



Bonnet et al. ‘04, Iserlohe et al. ‘04



SPIFFI

Grating-dispersed spectrographs
image slicer instruments

- SPIFFI slicer: pupil mirrors are flat

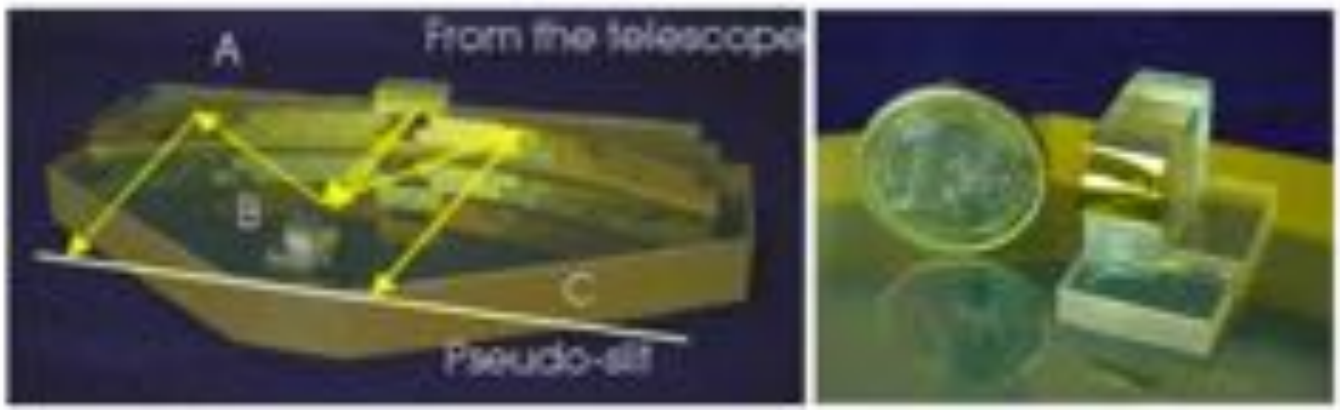
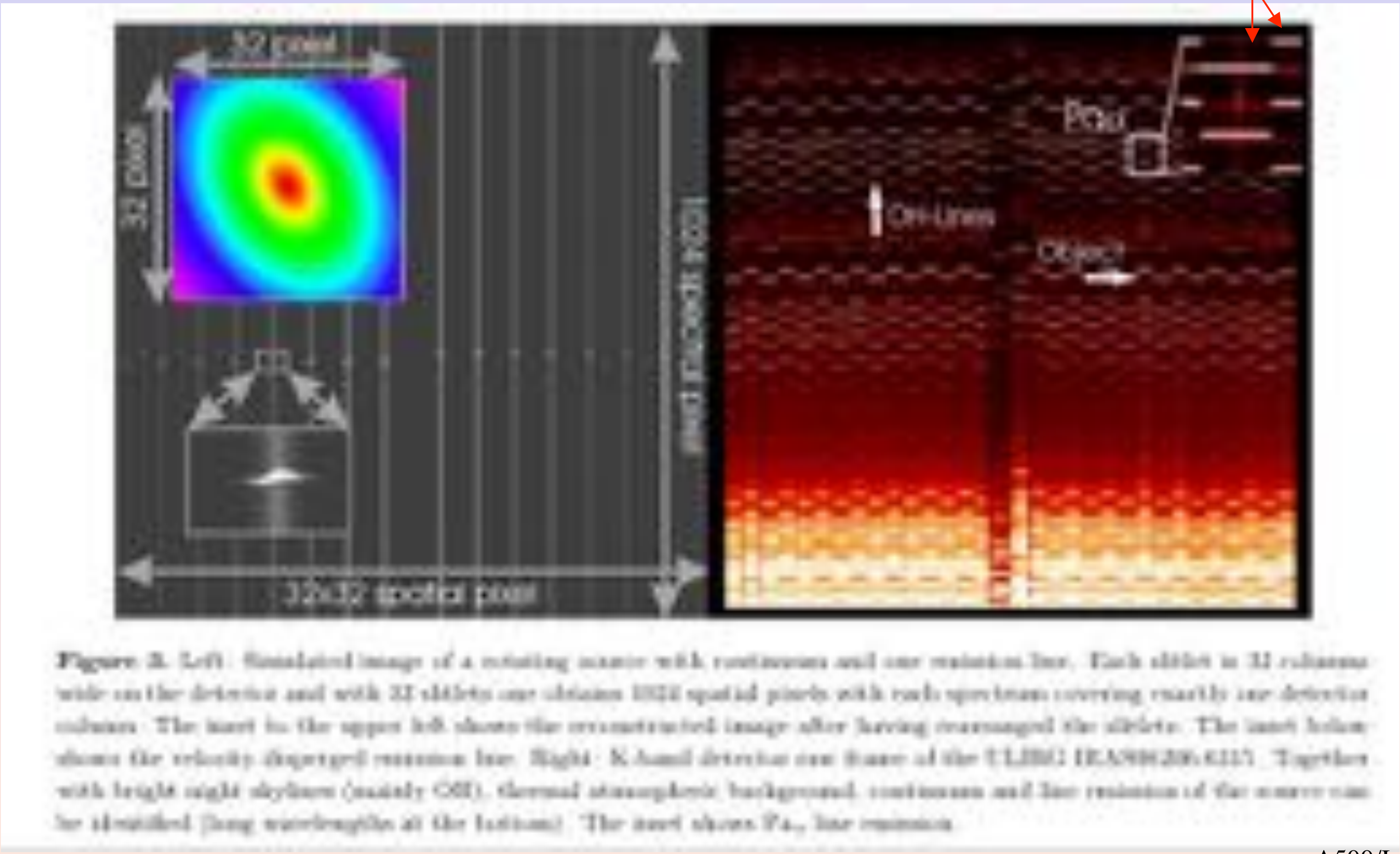


Figure 2. The image slicer: The image slicing device used in SPIFFI consists of plane mirrors. The two-dimensional image (still containing light of all wavelengths of the used observing band) is sliced into thin stripes, called slitlets, which are then lined up end to end to create a pseudo long slit 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

- SPIFFI data and format

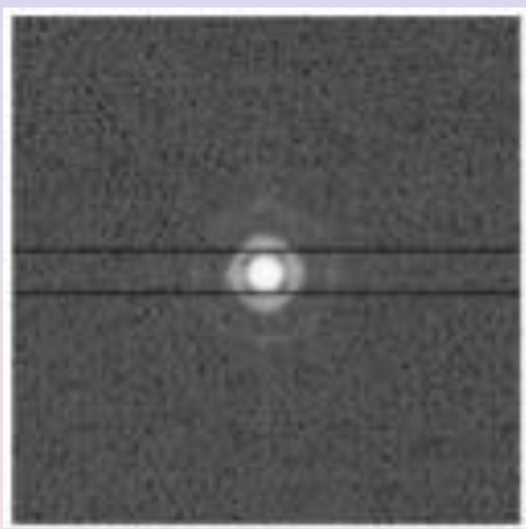
Note shifts in adjacent slices: different field-angles from two slicer layers



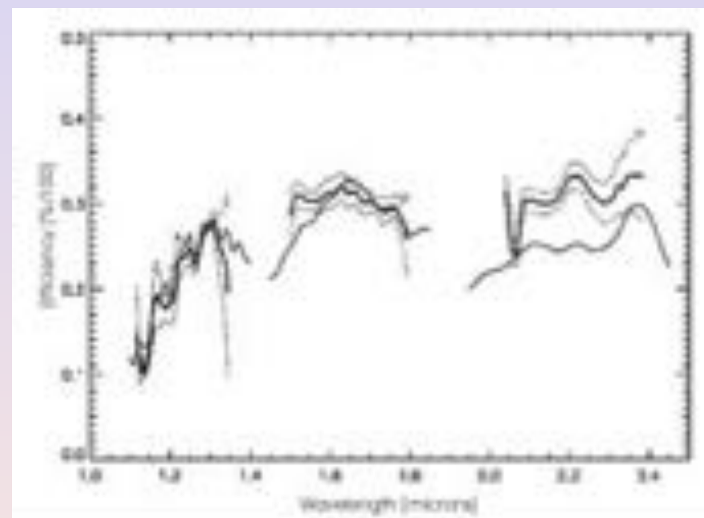
Iserlohe et al. '04

Grating-dispersed spectrographs
image slicer instruments

- SINFONI efficiencies:



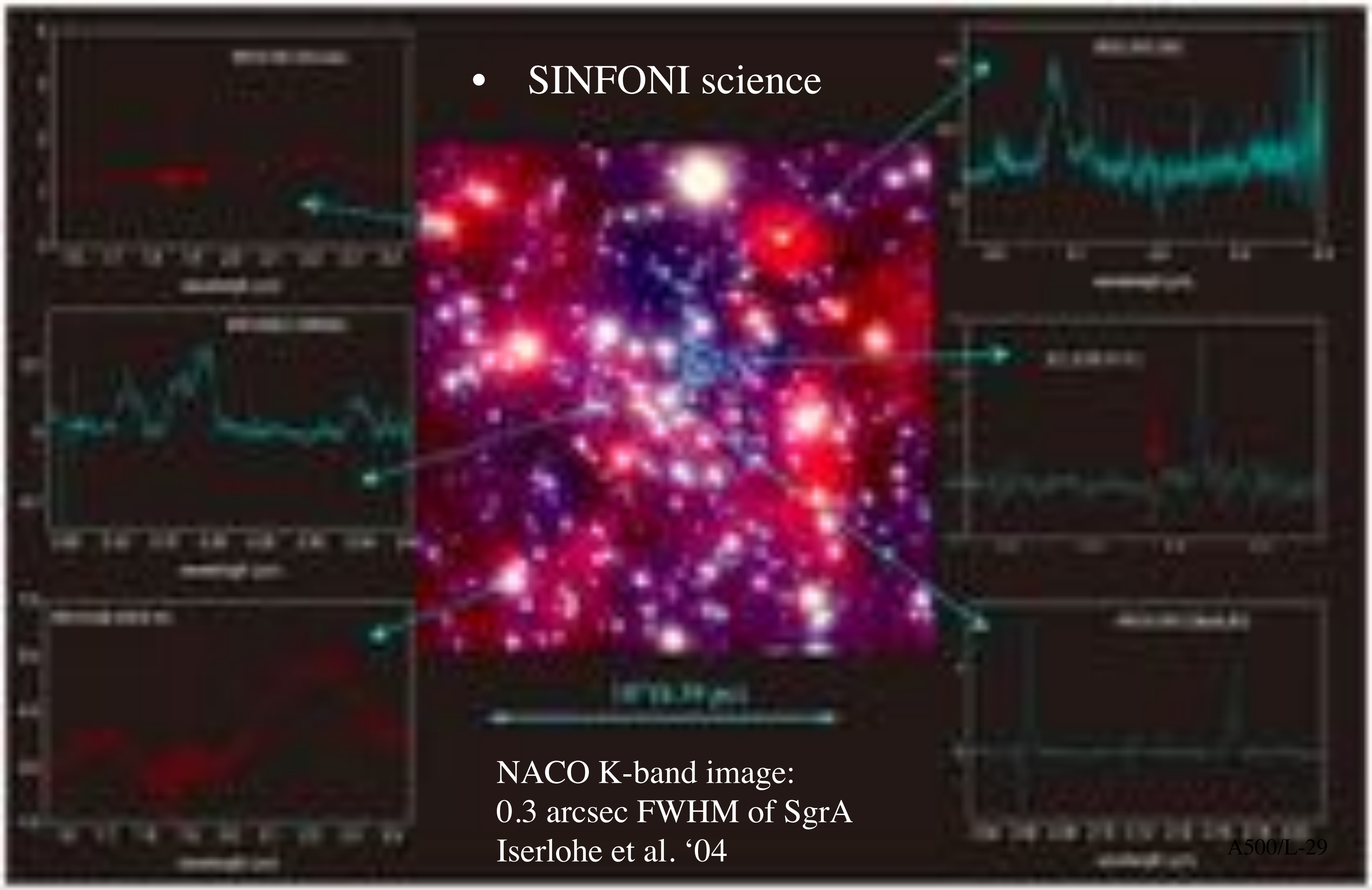
Slicer mirror width



Total system throughput 20-30%

Iserlohe et al. '04

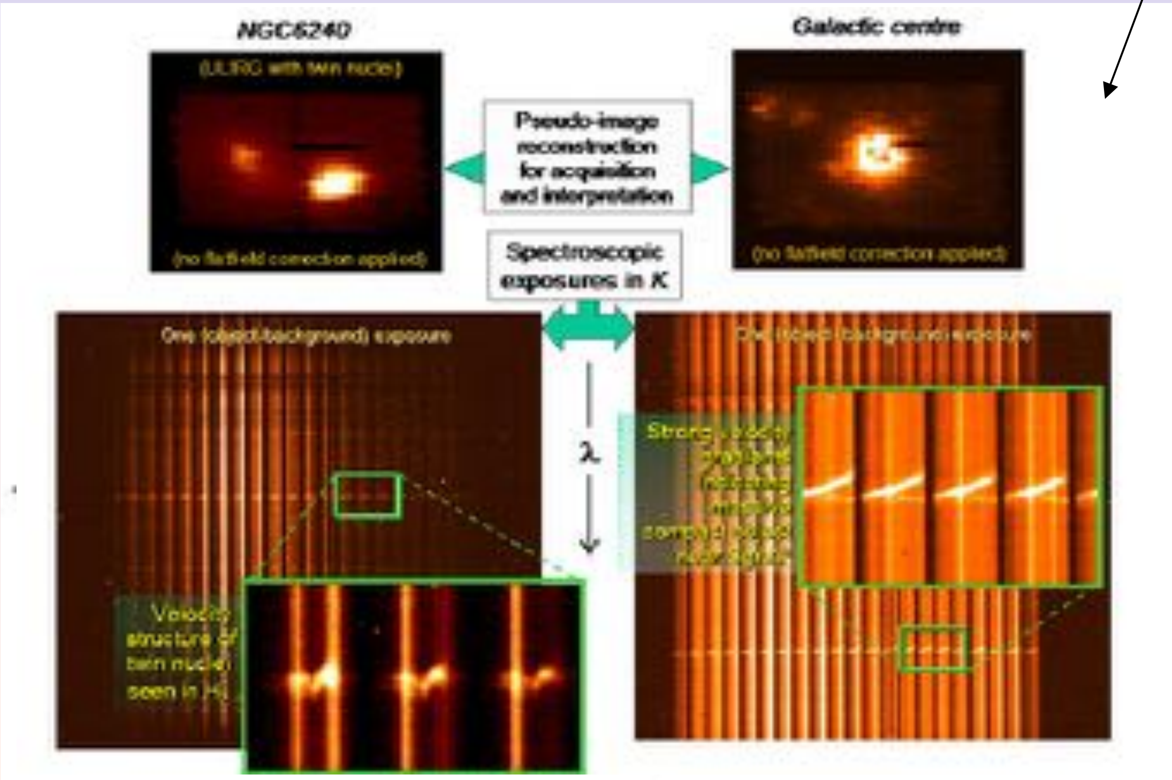
Grating-dispersed spectrographs
image slicer instruments



Grating-dispersed spectrographs
image slicer instruments

- GNIRS, Gemini-S, 8m
  - 4.8x3.2 arcsec FoV (0.15 arcsec slices)
  - R = 1700 and 5900
  - 0.9-5.5 μm range (2.5-5.5 μm not commissioned)

Allington-Smith et al. '04
Commissioning data



Grating-dispersed spectrographs
image slicer instruments - summary list

- Existing optical instruments
  - ESI, Keck 10m
- Future optical instruments
  - WiFeS, ANU 2.3m
  - SWIFT, Palomar 5m (see: Goodsall poster)
  - GISMO, Magellan 6.5m
  - MUSE, VLT 8m
- Existing NIR instruments
  - UIST, UKIRT 3.8m
  - MPE-3D, AAT 3.9m (defunct)
  - PIFS, Palomar 5m
  - GNIRS, Gemini 8m
  - SPIFFI, VLT 8m
  - NIFS, Gemini 8m
- Future NIR instruments
  - KMOS, VLT 8m
  - FISICA, GTC 10.4m
  - NIRMOS, GMT 25.4m (see: Brown poster)
- Future NIR instruments in space
  - NIRSpec, JWST 6.5m
  - MIRI, JWST 6.5m
  - SNAP/IFU, SNAP 2m

Note extensive NIR instrumentation;
Just now pushing to optical.

Grating-dispersed spectrographs

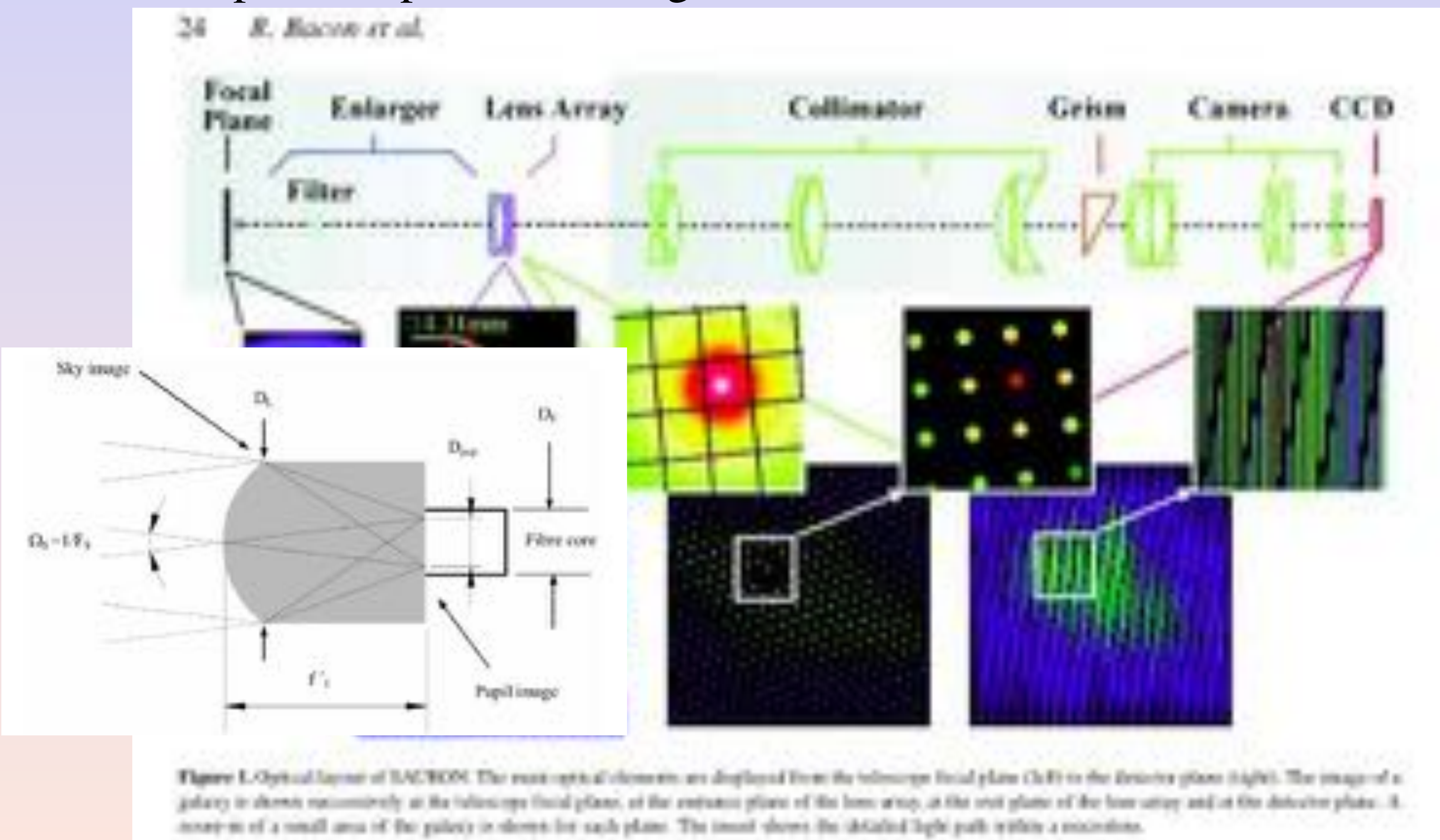
image slicer instruments - summary list

Table 3 Slicer Integral Field Instruments

Instrument	Coupling Method	Telescope	D_T (m)	Ω (arcsec^2)	$\delta\Omega$ (arcsec^2)	N_s	$\Delta\lambda/\lambda$	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	···	···	···	···	···	···	···

Grating-dispersed spectrographs
lenslet feed

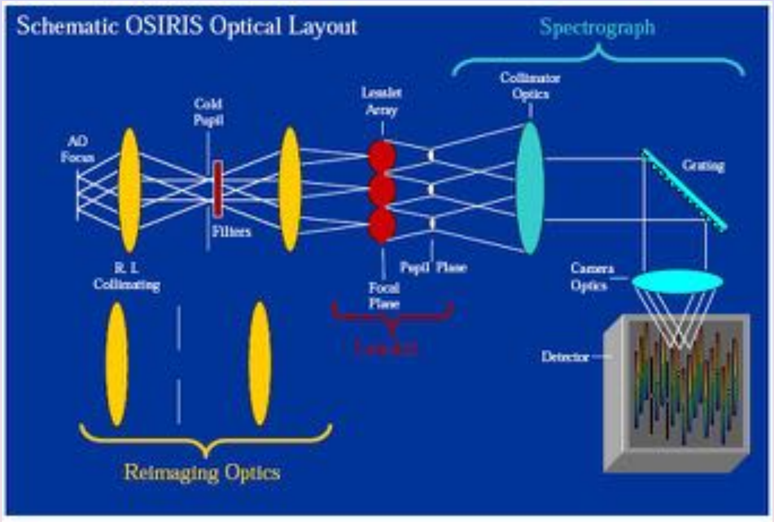
- Concept: pupil imaging spectroscopy using lenslets. No fibers to reformat telescope focal plane into long-slit.



SAURON: Bacon et al. ‘01 “1577 eyes see all”

Grating-dispersed spectrographs
lenslet feed: pros and cons

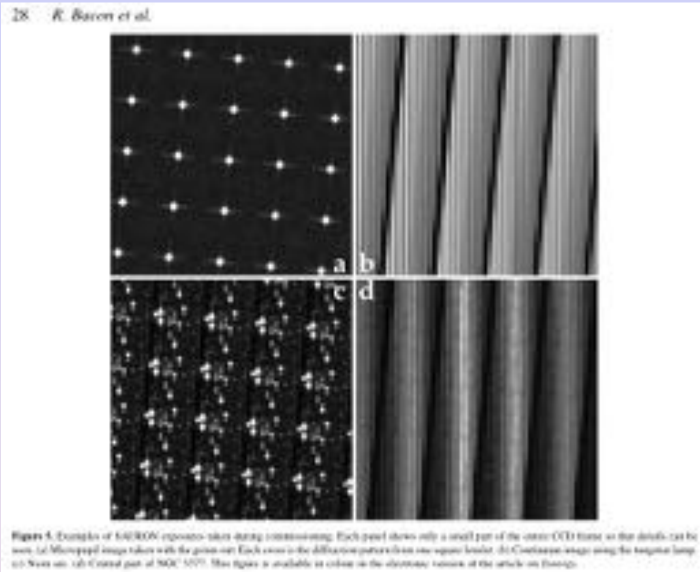
- Excellent fill factor
- Low dispersion due to grism limitations
- Grating implementation now exists in the near-infrared:
- VPH grisms and gratings with articulated camera would yield higher resolution
- implications of formatting for efficiency and scattered light
  - good data packing on detector, but limited spectral coverage/resolution
  - scattered light from lenslets may be significant

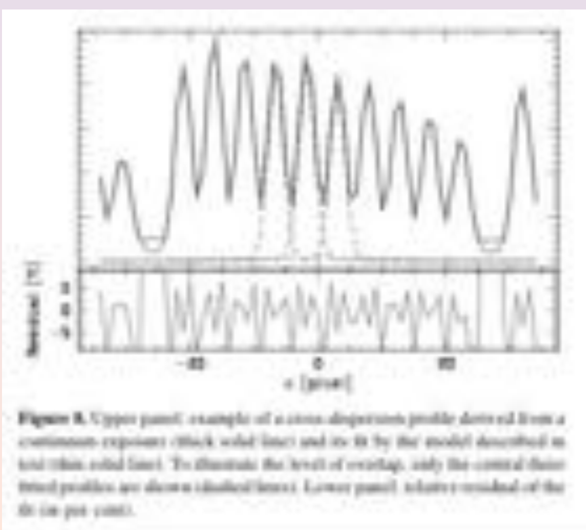


OSIRIS (Keck 10m)

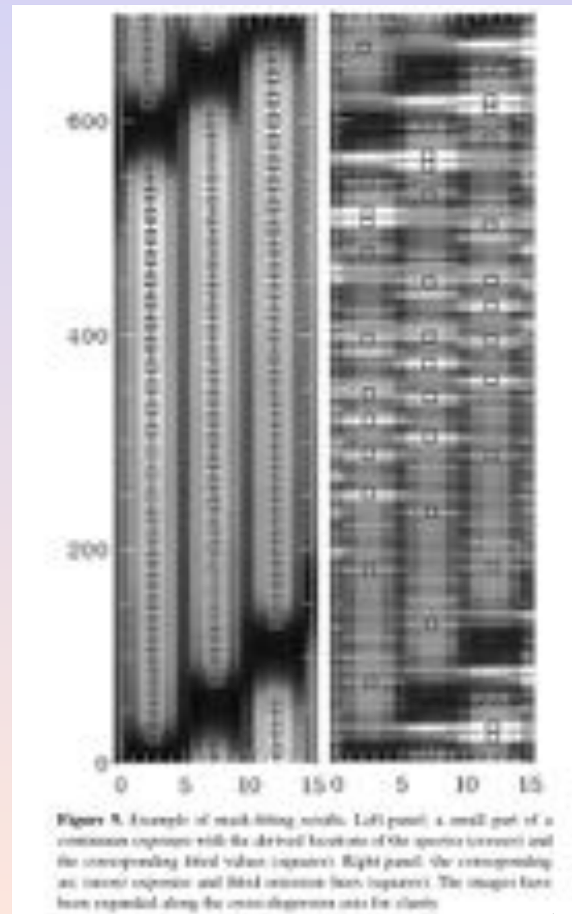
Larkin et al.'03

Grating-dispersed spectrographs
lenslets: formatting





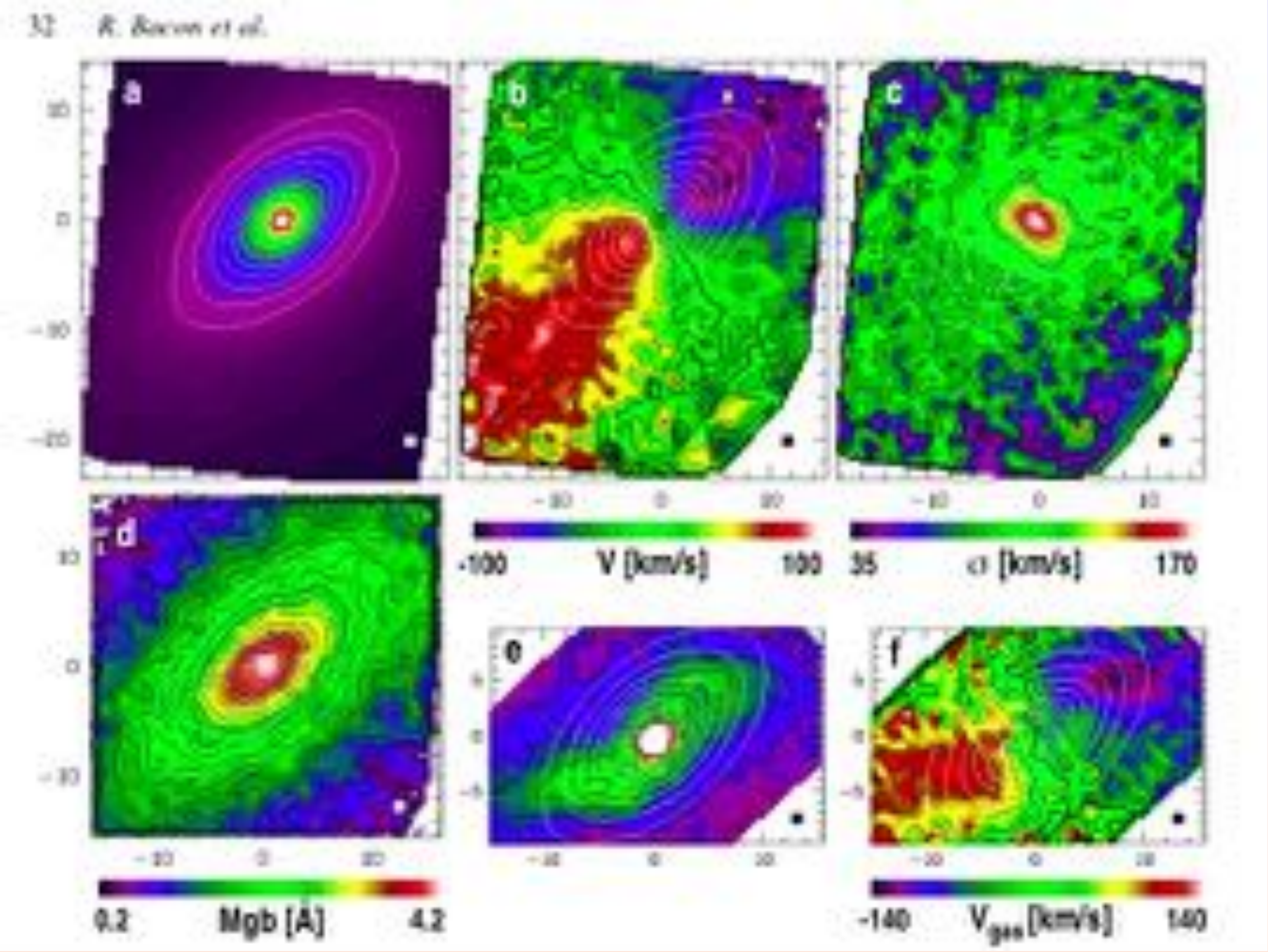
- Spectral extraction critical to minimize crosstalk



SAURON

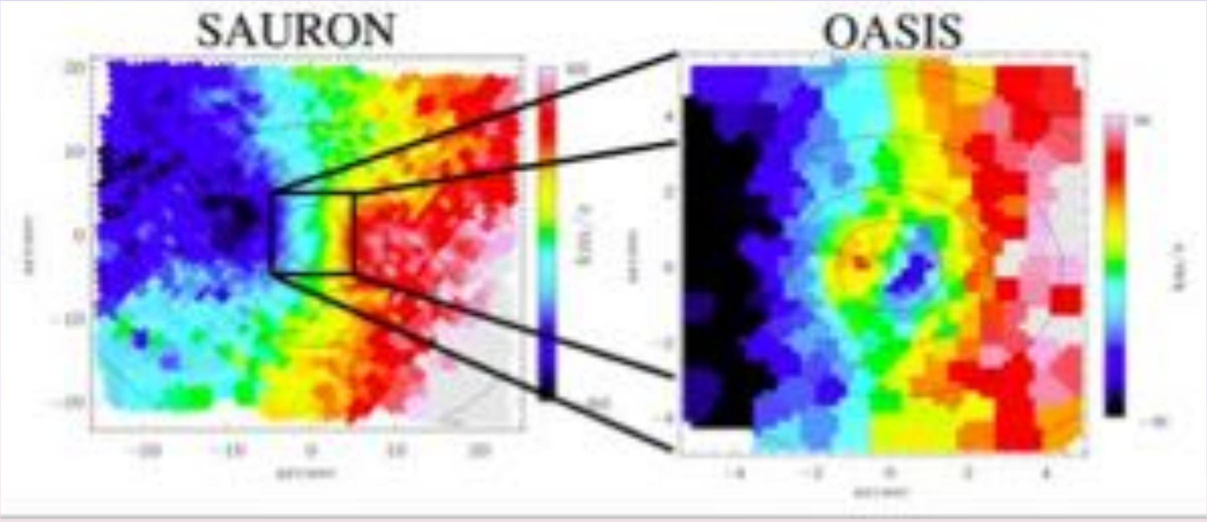
Grating-dispersed spectrographs
lenslets science

- impressive science results from SAURON



Grating-dispersed spectrographs
lenslets science

- The power of AO coupling to truly integral field: OASIS on WHT



McDermid et al. ‘04

Grating-dispersed spectrographs
lenslet instruments - summary list

- Existing optical instruments
  - OASIS, WHT 4.2m (formerly on CFHT 3.5m)
  - SAURON, WHT 4.2m
- Future optical instruments
- Existing NIR instruments
  - OSIRIS, Keck 10m
- Future NIR instruments
  - Planet Finder, VLT 8m (see Jacopo poster)

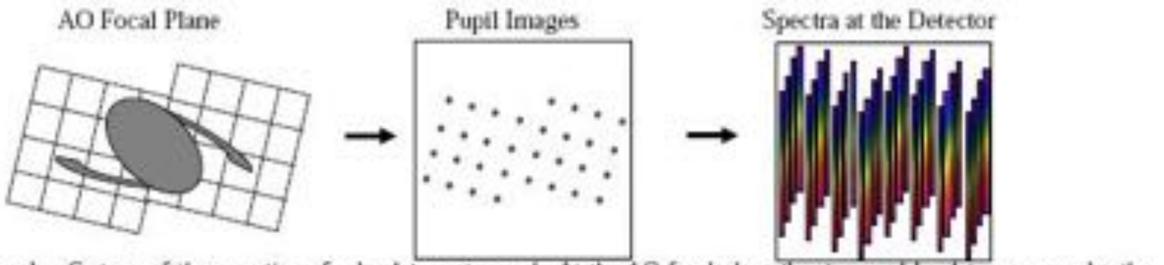


Figure 1 – Cartoon of the operation of a lenslet spectrograph. At the AO focal plane the staggered lenslet array samples the image and each lens produces a pupil image roughly one focal length behind the array. This plane is used to feed the collimator of a standard spectrograph. Since the pupils are well separated, the spectra can be interleaved between each other and can cover most of the detector.

Grating-dispersed spectrographs

lenslet instruments - summary list

Table 4. Lenslet Integral Field Instruments

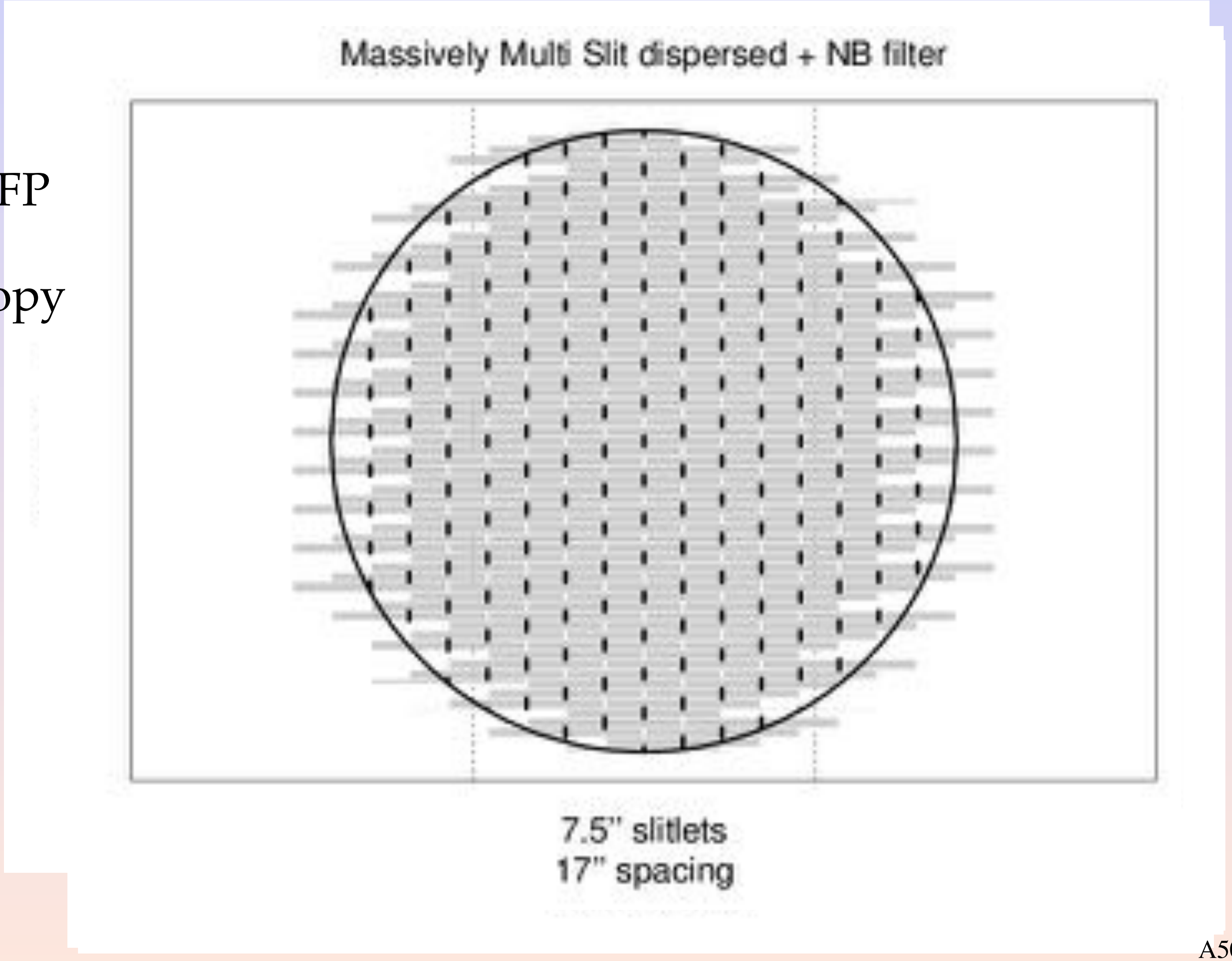
Instrument	Coupling Method	Telescope	D_T (m)	Ω (arcsec^2)	$d\Omega$ (arcsec^2)	N_s	$\Delta\lambda/\lambda$	R	N_λ	ϵ
Existing Optical Instruments										
SAURON	lenslet	WHT	4.2	1353	0.88	1577	0.11	1213.	128	···
		WHT	4.2	99	0.07	1577	0.10	1475.	150	···
OASIS	lenslet	WHT	4.2	1.92	0.002	1100	0.50	1000.	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										

New Modes for using RSS

Tuning the trade-off between spatial and spectral multiplex

Imaging/FP

Spectroscopy



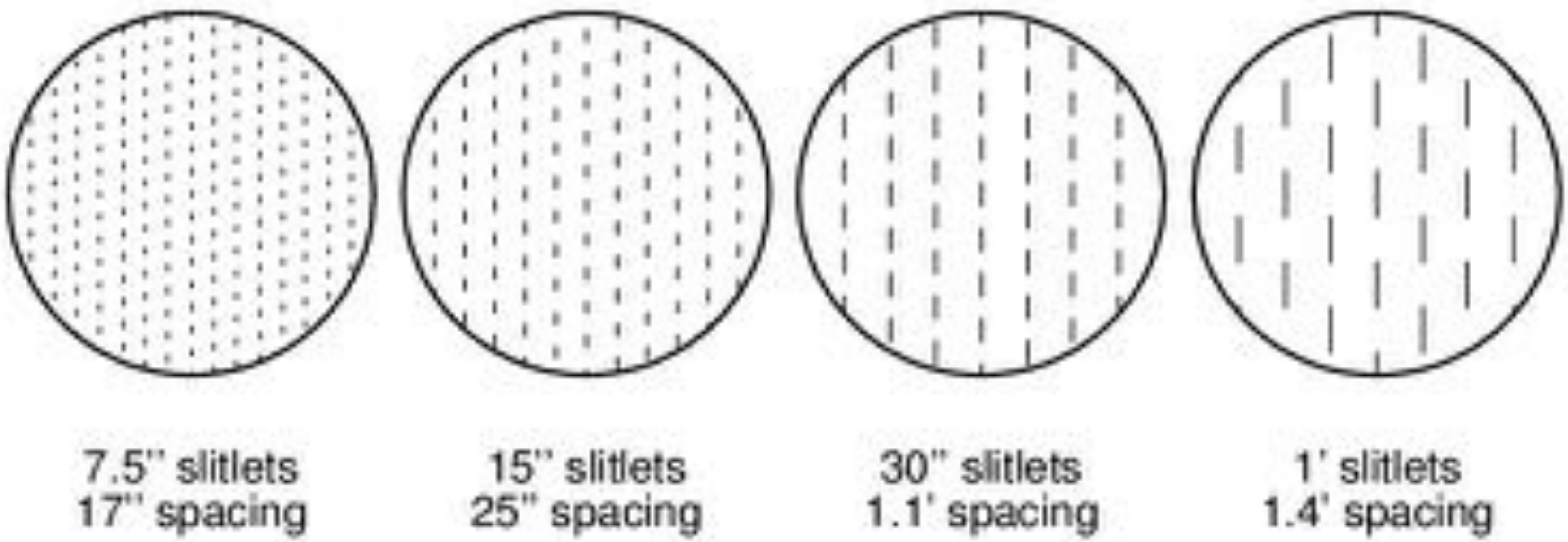
*M*assively *M*ultiplexed *S*litlets

PFIS:

3000 l/mm VPH grating + 0.6" slit: R = 10,000

+ NB filter: R = 50

→ 10 nm at 510 nm A: $N_{\Delta\lambda} = 1000$



NGC 6744 and RSS: MMS-1’

NGC 6744 and RSS MMS-7.5''