Astro 500

Techniques of Modern Observational Astrophysics

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Approaches

Examples of available instruments

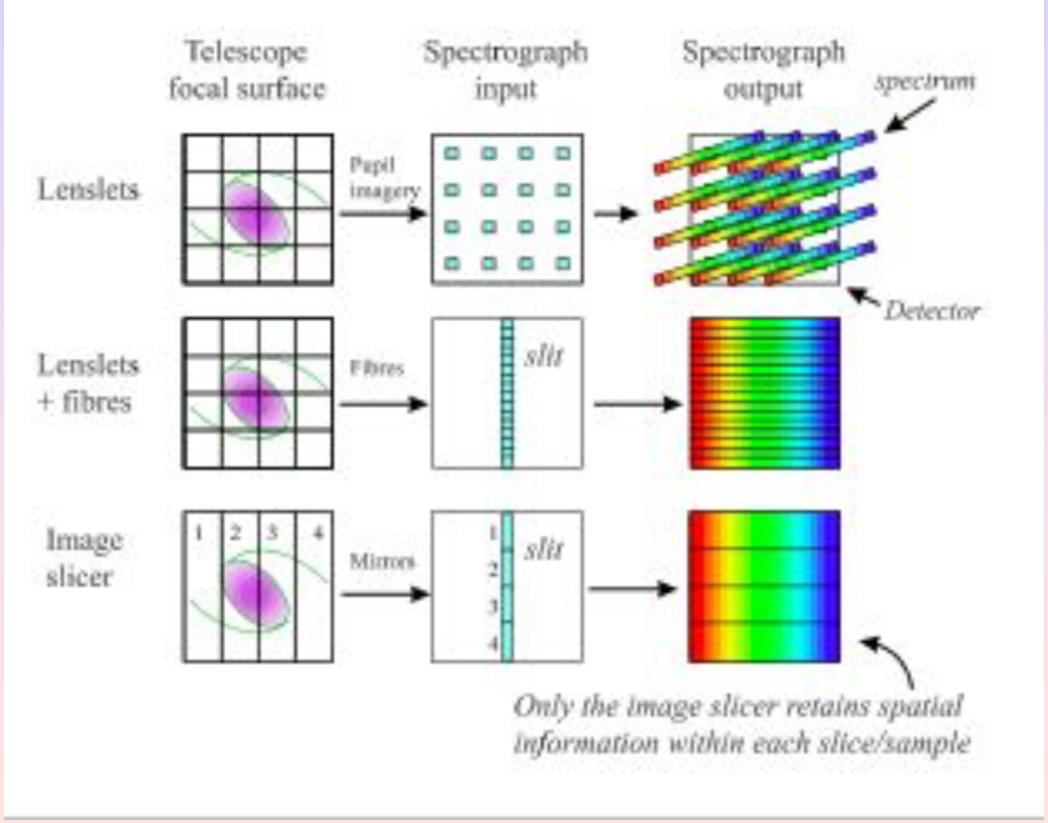
Spectroscopy from a 3D Perspective

- ✓ 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
    - o Fiber
    - o Fiber+lenslet
    - o Slicer
    - o Lenslet
    - o Filtered multi-slit
    - o 3D MOS
  - ➢ Current instruments
    - o summary of considerations
    - o sky subtraction

Grating-dispersed spectrographs
coupling formats and methods

- Reformatted longslit or multi-longslit
  - fiber
  - fiber+lenslet
  - image slicer
- Lenslet arrays: pupil-imaging spectroscopy
- Filter-multiplexed slit-lets
- Multi-object configurations

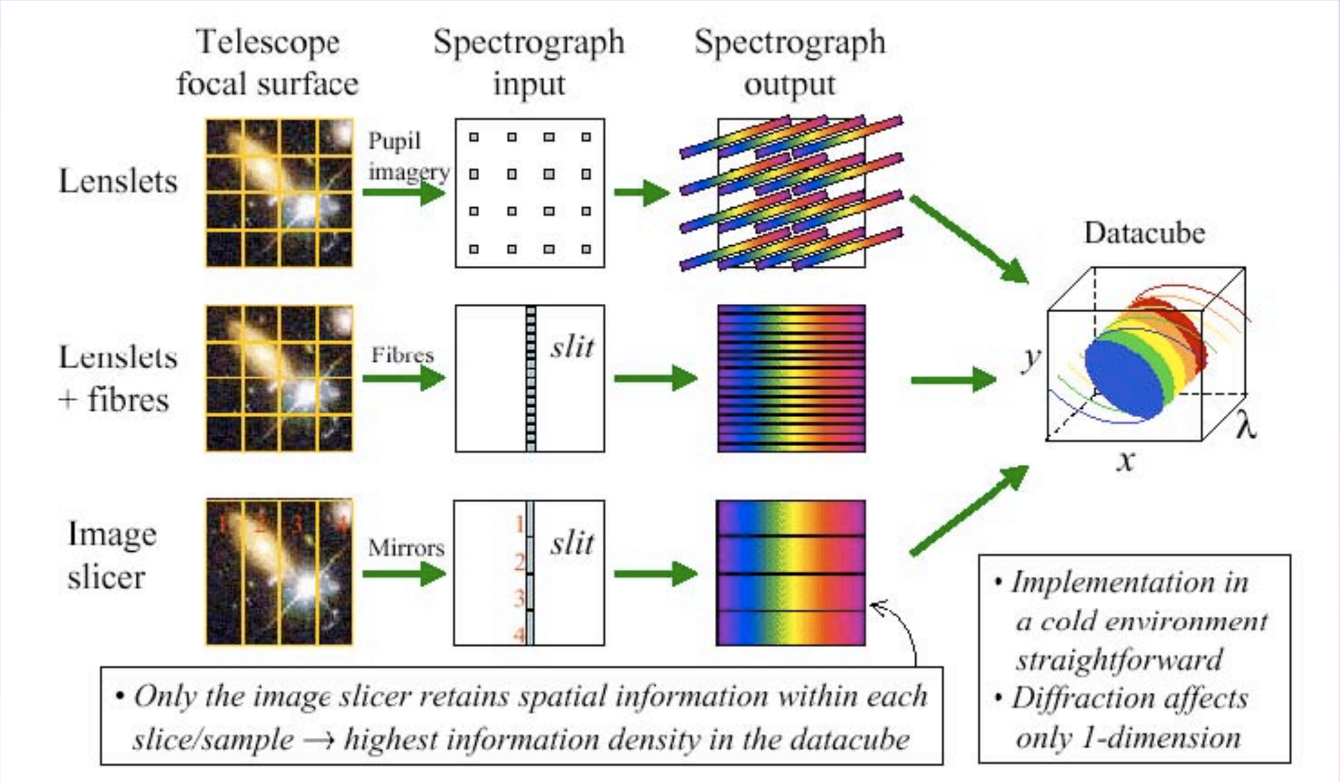
- Implications of coupling methods



recent summary: see Alighieri et al. '05

Allington-Smith & Content '98

IFUs


Telescope focal surface
Spectrograph input
Spectrograph output
Lenslets
Pupil imagery
Datacube
Lenslets + fibres
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
fiber feeds: pros and cons

- The simplest and oldest of all methods:
  - Bare fibers map telescope to spectrograph-input focal plane
- Low cost yet flexible
  - Easy to mix sky and object fibers along slit
- The best? Maybe in some cases where near-integral field is ok.
- Focal ratio degradation (FRD) and scrambling represent information loss / entropy increase.
  - FRD results in a faster output focal ratio
  - This has spectrograph design or performance impact:
    - Either spectrograph is lossy or
    - Spectrograph has to be designed for proper feed f-ratio
    - PMAS is an excellent example of how to do it right
- Telecentricity also critical
- Scrambling helps and hurts

Grating-dispersed spectrographs
FRD basics

- FRD represents the increase in the output f-ratio due to fiber properties.
- This represents a real loss of information:
  - ➢ spectrograph collimator must get faster, which degrades spectral resolution; or
  - ➢ light is lost in optical system (vignetting).

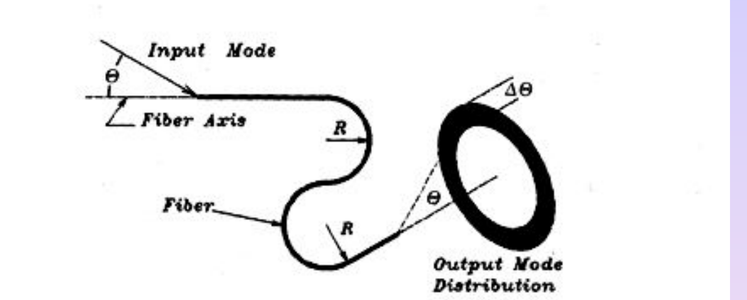
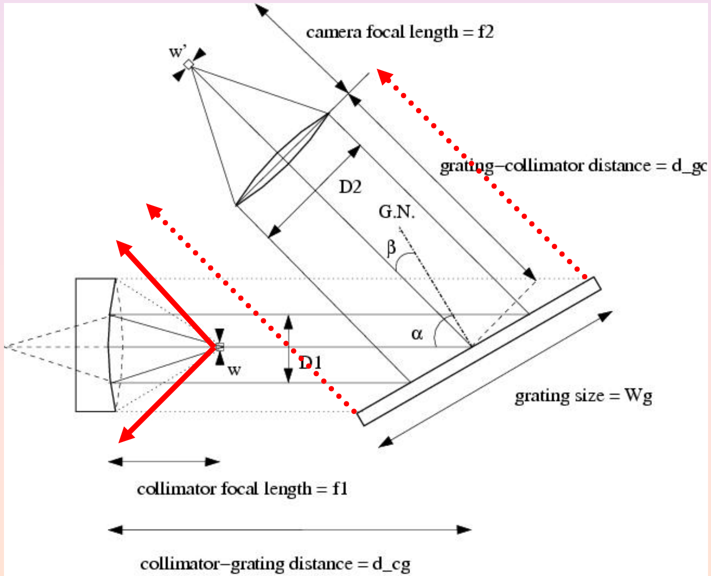


Fig. 2 We illustrate here the basic definition of FRD. As single "mode" is inserted into the fiber. It is azimuthally dispersed or "scrambled" and also dispersed to a lesser extent radially. This radial dispersion is the FRD.

Ramsey '88



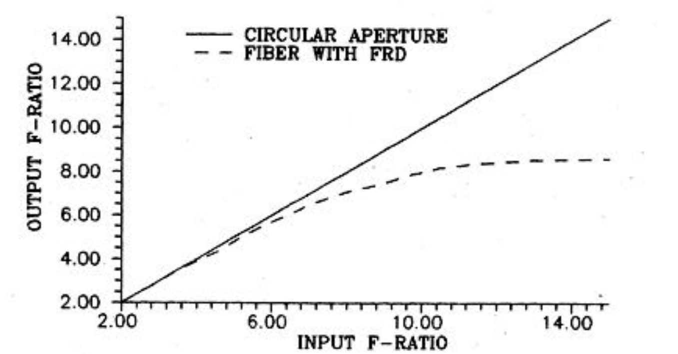
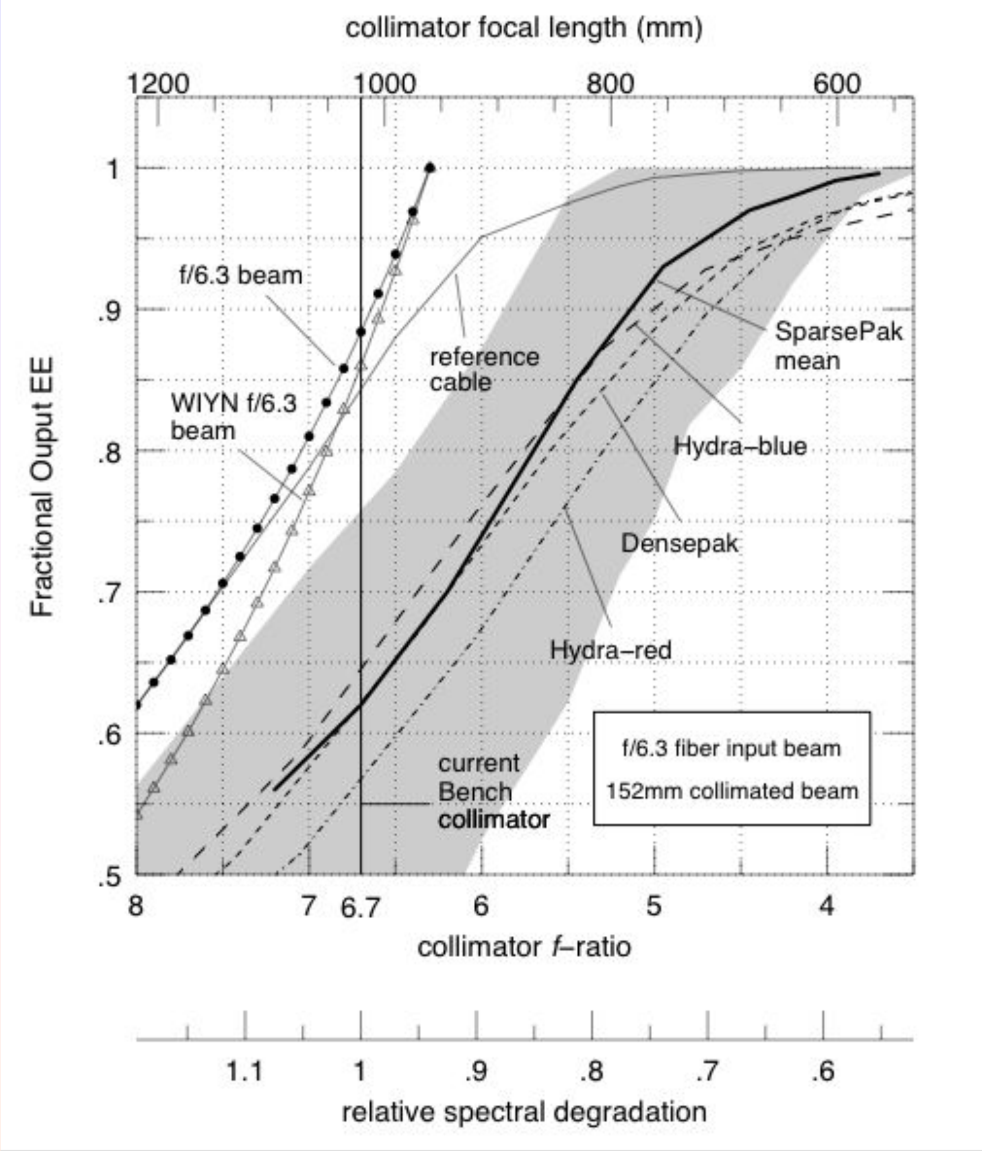


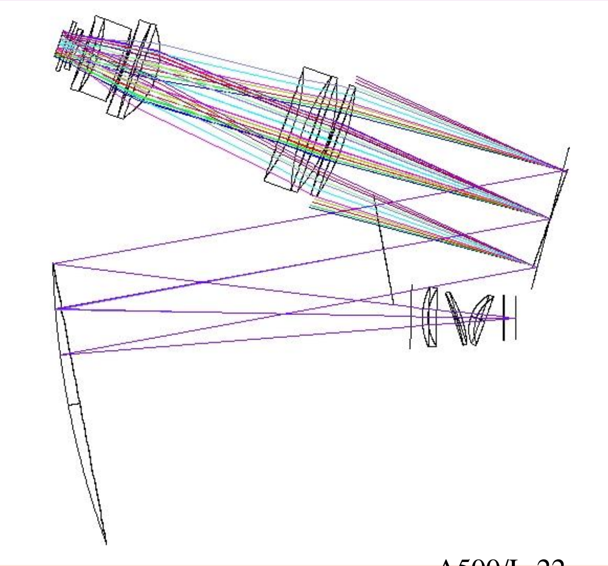
Fig. 3 The Focal Ratio Degradation (FRD) of a typical fiber is compared to the throughput of a circular aperture of the same diameter as the core of the fiber.

Grating-dispersed spectrographs

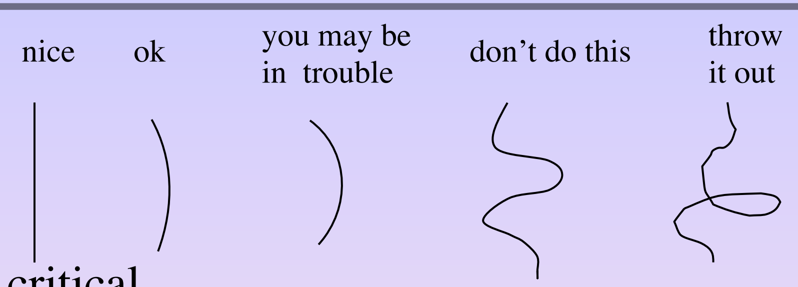
FRD information loss



- Example: WIYN Bench Spectrograph.
- Result: we're building a new, faster collimator to regain 50% of the light (double throughput) at 25% loss in resolution.
  - Additional gain from off-axis collimator: no feed vignetting and access to pupil.



Grating-dispersed spectrographs
FRD causes



- Stress is bad:
  - Don’t pull, twist, or bend
  - Cable preparation and installation critical
    - Hectospec / Hectechelle (Fabricant, MMT) are best examples of how to do it right.
  - Fiber termination and polishing must not stress ends.
    - See Bershady et al. ‘04 for discussion of some IFU related issues.
- But even for perfectly handled fibers there is additional scattering. Possibilities:
  - Rayliegh scattering: variations in fiber refractive index
  - Mie scattering: fiber inhomogeneiti
  - ~~Stimulated Raman and Brillouin sc~~
  - Micro-bending

large power levels only; not astronomy!

unsubstantiated favorite

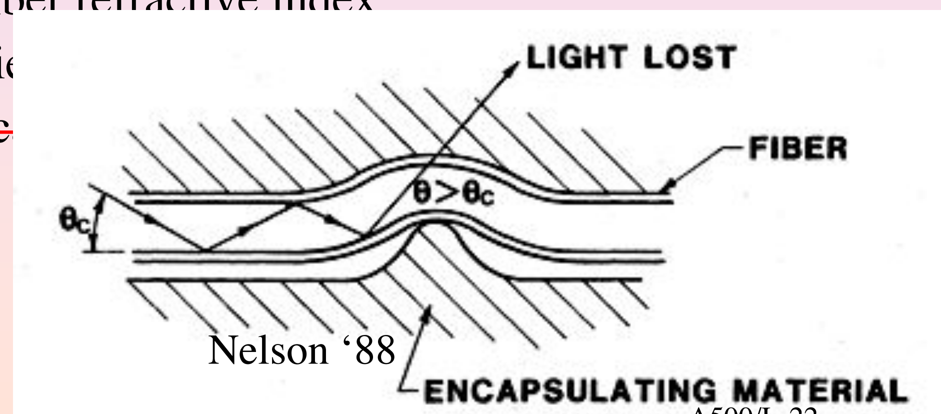
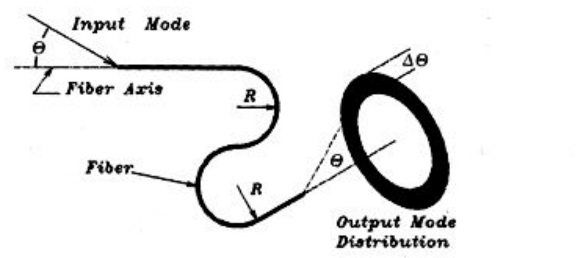


Fig. 3 Microbend.

Grating-dispersed spectrographs
FRD causes

- Micro bend model predicts wavelength-dependent FRD (nightmare if true)
  - Carrasco & Parry ‘04 see tentative effect.
    - Determine FRD via laser injection (collimated beam) and measuring $\delta\theta$ at discrete angles, 2 wavelengths.
  - Schmoll et al. ‘03 and Bershady et al. ‘04 don’t see effect.
    - Determine FRD via injection of light cone at known *f*-ratio, and measuring output encircled energy (EE) as a function of *f*-ratio.
  - Difference measuring methods?
  - Wrong FRD model?
  - More work to be done!!



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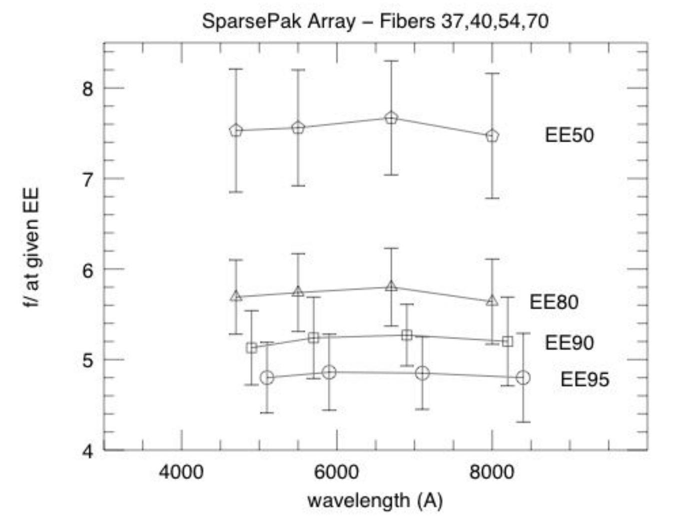
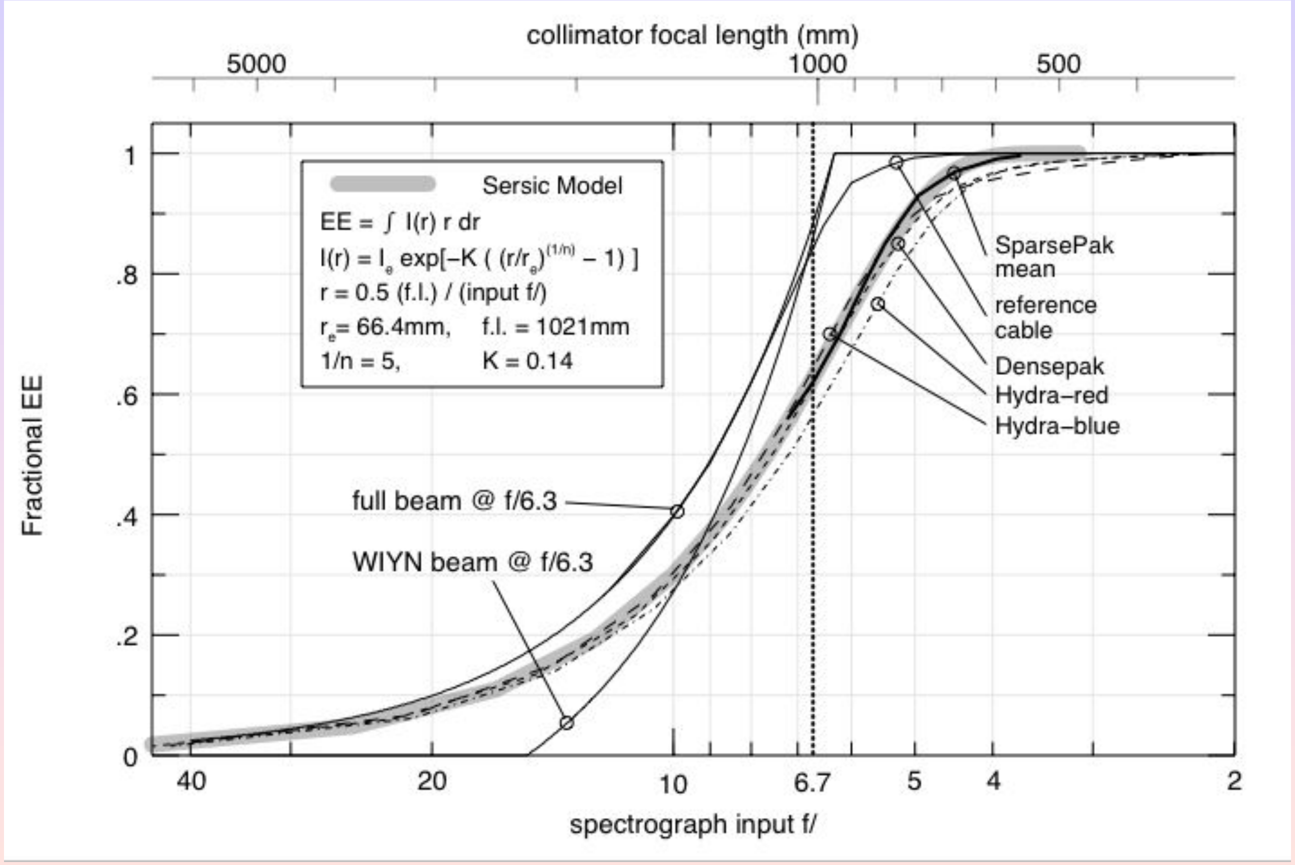


Bershady et al. ‘04

Grating-dispersed spectrographs

FRD parametrization

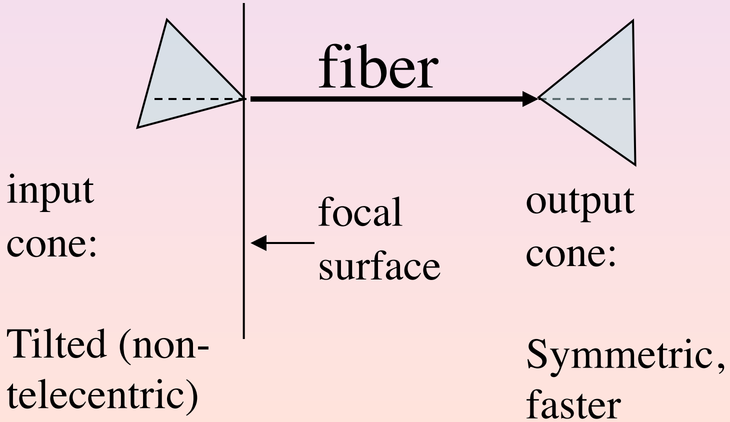
- FRD EE vs *f*-ratio can be modeled with a Sersic profile
- This either says something about the right scattering model, or, how seriously to take the interpretation of Sersic-law profiles when fit to galaxies!

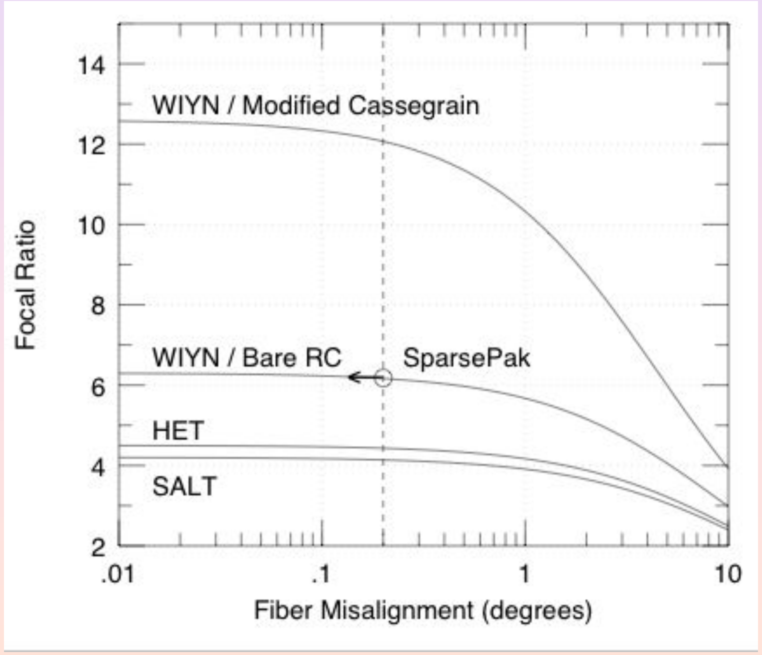


Credit: Steve Crawford

Grating-dispersed spectrographs
FRD - other known causes

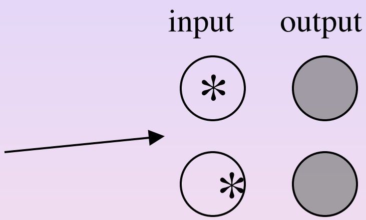
- Input light-cone mis-alignment with fiber axis
- Azimuthal scrambling symmetrizes output beam
  - Example (left) of non-telecentric focal surface
  - Other causes from fiber mechanical alignment





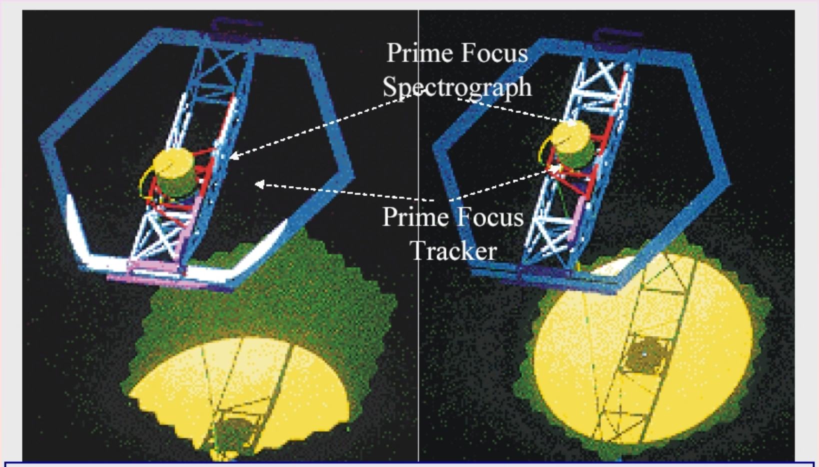
Grating-dispersed spectrographs
FRD and azimuthal scrambling - advantages

- Azimuthal scrambling symmetrizes output beam
  - Ameliorates effect of changing telescope pupil, e.g., HET, SALT, by homogenizing ray bundle.
  - Contribution of spectrograph optical aberrations to final spectral image is more stable.
    - This is a far-field effect.
- Radial scrambling homogenizes near-field illumination
  - Seeing-dependance (i.e., the "slit function") is decreased.
    - This is a near-field effect



Near-field: the light distribution at the focal surface, e.g, fiber ends, or what is reimaged onto CCD

Far-field: the ray-bundle distribution, i.e., the cross-section intensity profile of the spectrograph beam.



Motion of tracker and illumination of primary mirror as an object sets

Grating-dispersed spectrographs

FRD: telescope and spectrograph design implications

- Radial scrambling and FRD are one and the same -- *maybe*
  - ➢ Compromise information loss with stability
    - o PMAS uses reimaged input *f*-ratio = 3 for fibers.
    - o HET and SALT chose prime focus *f*-ratio = 4-4.5 for direct fiber injection.
- With fast input/output *f*-ratio's this limits possible spectrograph demagnification since it is hard to build faster than f/2 for wide-field cameras

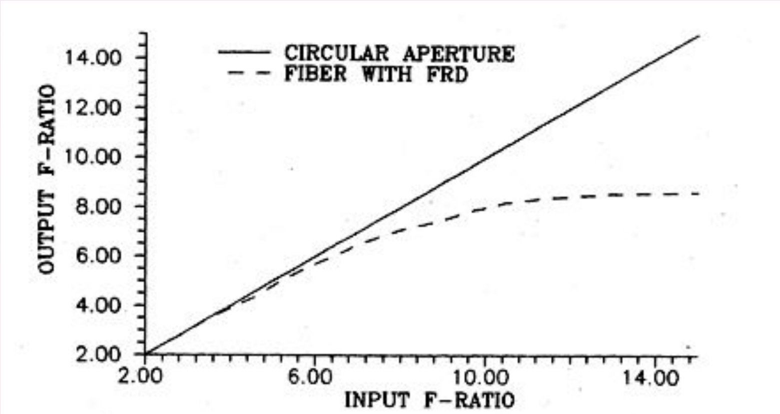
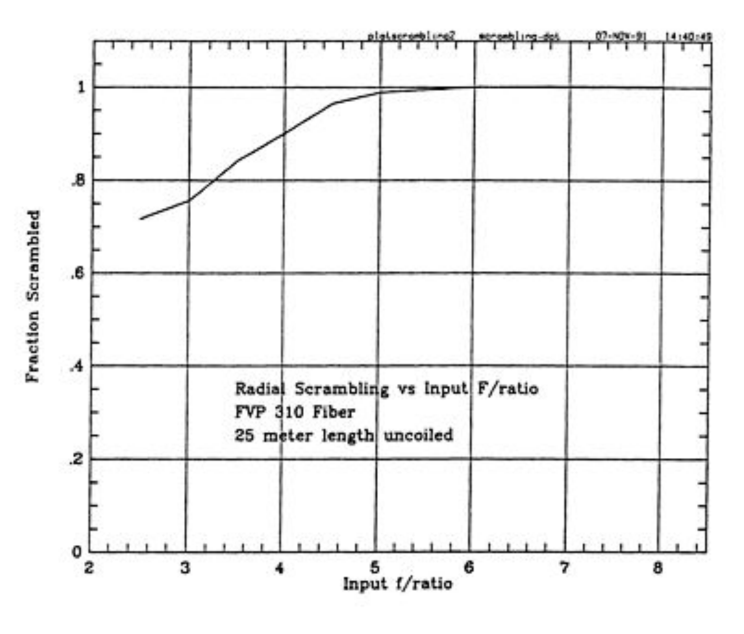


Fig. 3 The Focal Ratio Degradation (FRD) of a typical fiber is compared to the throughput of a circular aperture of the same diameter as the core of the fiber.

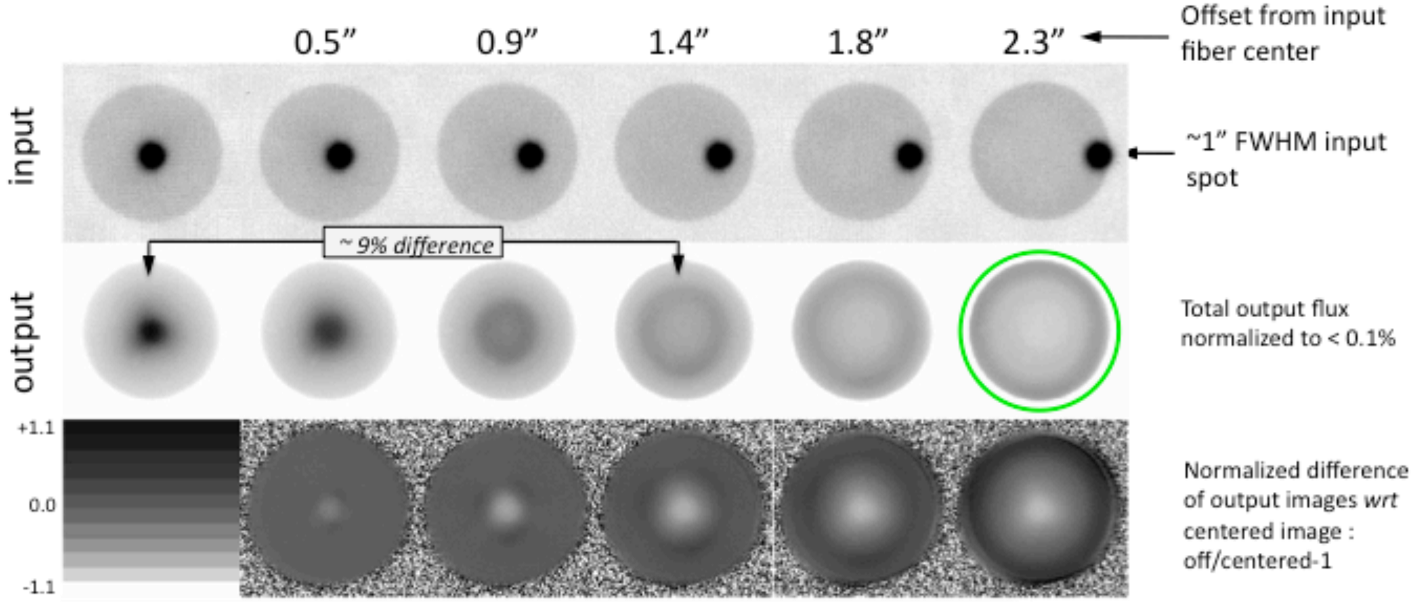
Ramsey '88

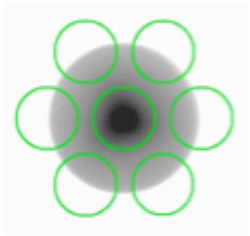


Barden et al. '93

Radial scrambling

2m length of 300 µm core FBP





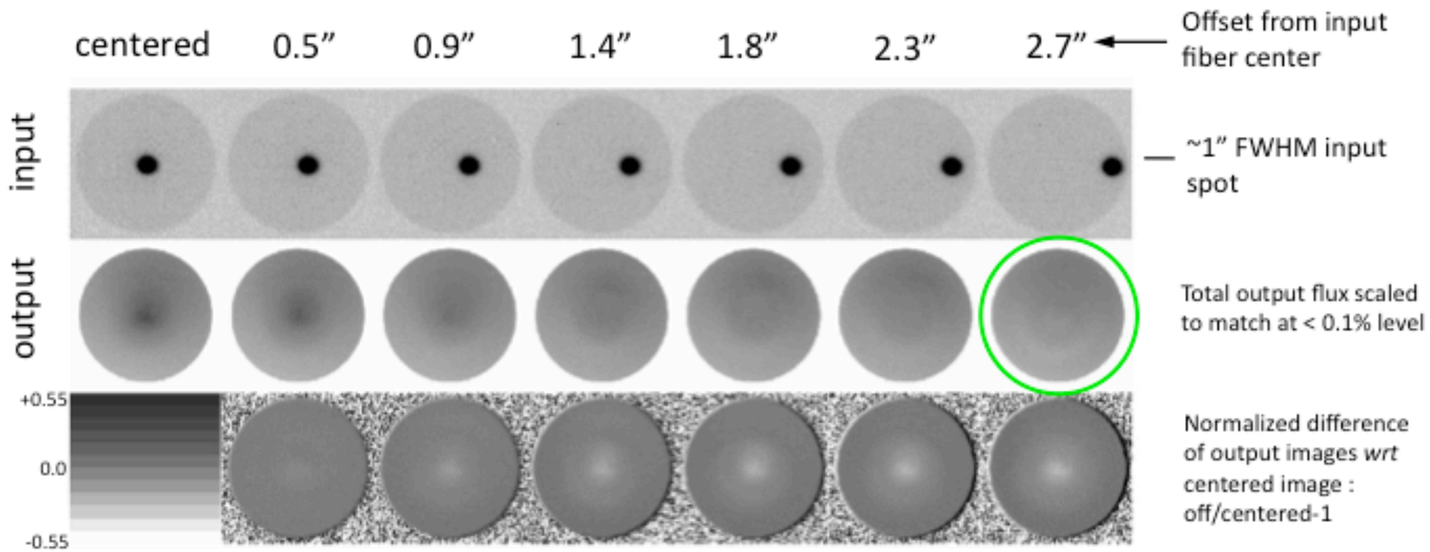
Aperture photometry simulating densely packed 7-fiber array of 120 µm core, 150 µm spacing

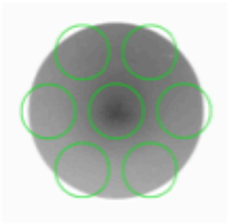
Variation in mean flux of 7 fibers over all 6 input-spot locations:

3.5% rms
8.9% full range

Radial scrambling

25m length of 400 μm core FBP





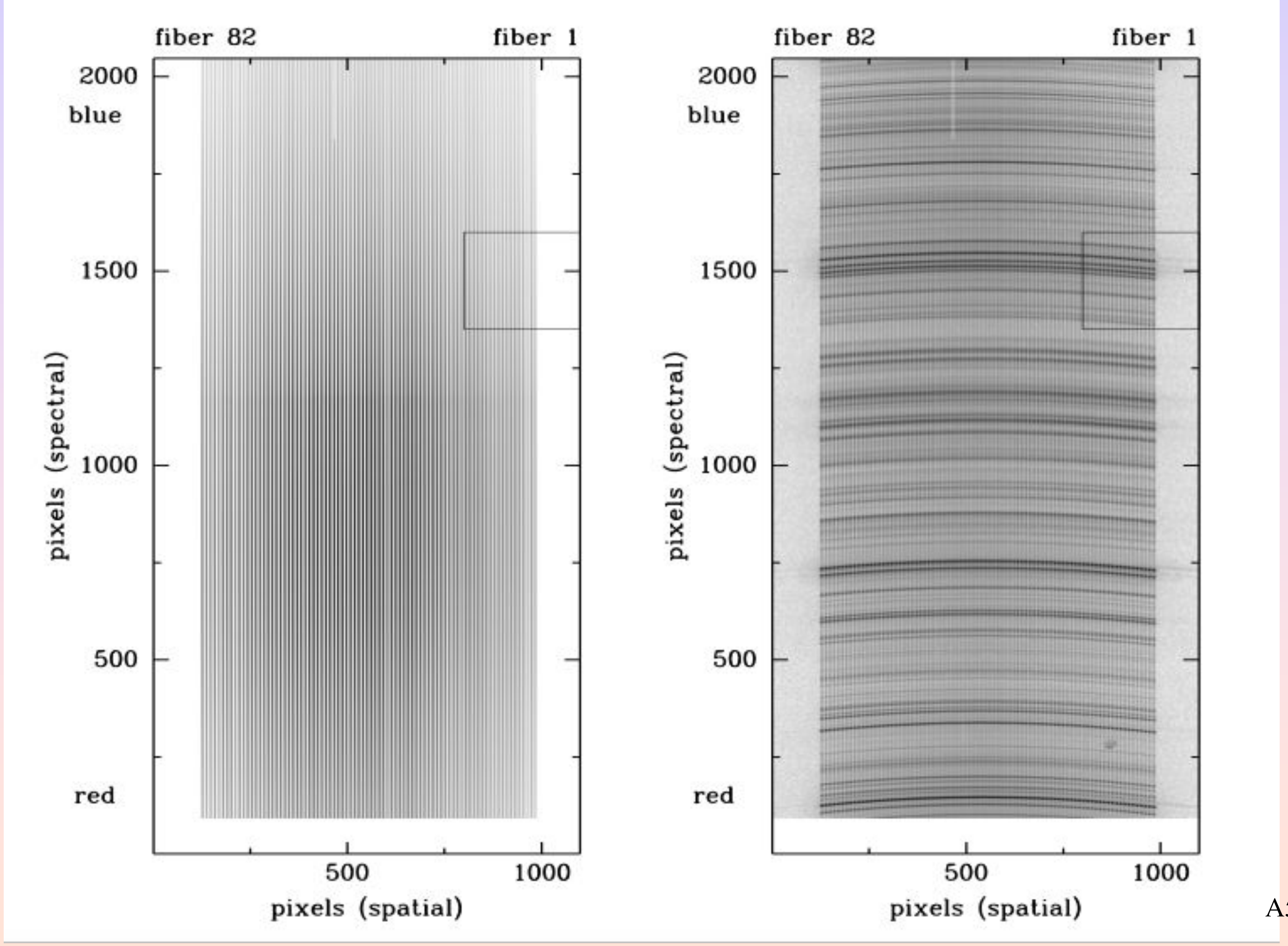
Aperture photometry simulating densely packed 7-fiber array of 120 μm core, 150 μm spacing

Variation in mean flux of 7 fibers over all 7 input-spot locations:

0.3% variation, full range

Grating-dispersed spectrographs
fiber feeds: packing on the focal plane

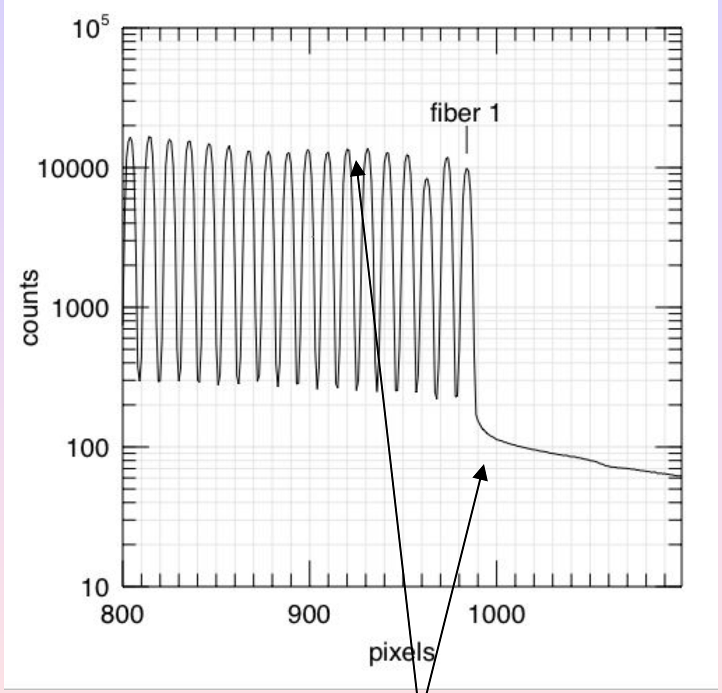
- SparsePak raw dome and lamp spectra

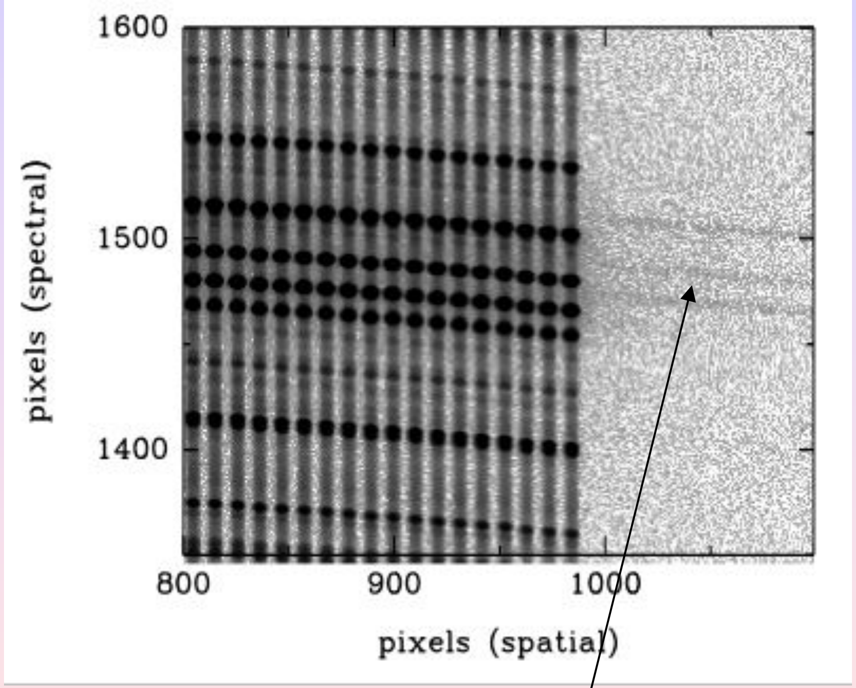


Grating-dispersed spectrographs
fiber feeds: packing on the focal plane

- SparsePak raw dome and lamp spectra: blow-up

Fiber seperation: 10 pix
Reimaged fiber diameter: 4.5pix





- Amplitude of scattered light is low, fiber separation is large and ghosting is negligible:

➢ This spectrograph + feed is optimized for clean extraction with little cross-talk.

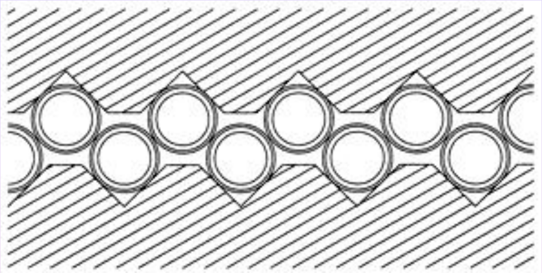
➢ Information packing in spatial dimension is modest due to fiber separation;

➢ Information packing in spectral dimension is high due to large anamorphic factors.

Grating-dispersed spectrographs

fiber feeds: packing on the focal plane

- Greed:



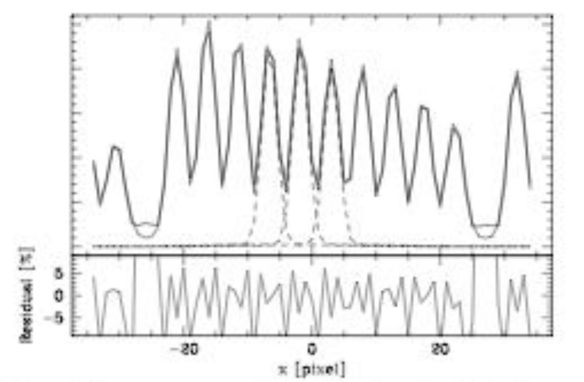


Figure 8. Upper panel: example of a cross-dispersion profile derived from a continuum exposure (thick solid line) and its fit by the model described in text (thin solid line). To illustrate the level of overlap, only the central three fitted profiles are shown (dashed lines). Lower panel: relative residual of the fit (in per cent).

- + scatted light

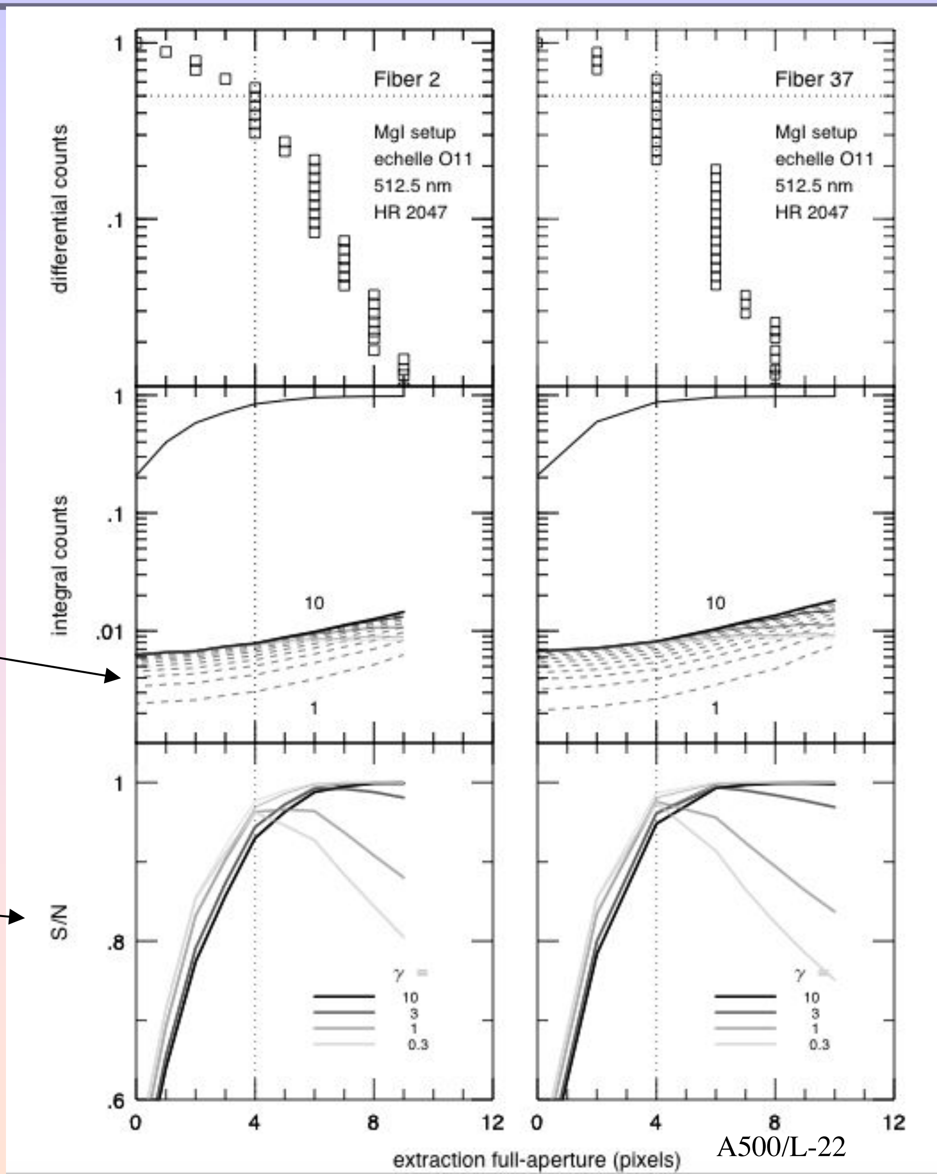
  - Difficult to extract a clean spectrum and optimize S/N.
  - Azimuthal scrambling means that spatial information in telescope focal plane is coupled to all adjacent fibers in slit.

Grating-dispersed spectrographs
fiber feeds: extraction at the focal plane

- Here's the situation on a clean system (SparsePak / Bench spectrograph)
  - ➢ Optimum extraction aperture is modest in low-light regime:
  - ➢ About 4-5 pixels, or the reimaged fiber diameter

Scattered light from 1 to 10 nearest neighbor fibers

S/N in photon and RN limits



Grating-dispersed spectrographs
fiber instruments

- The first fiber IFU:
  - DensePak-1: KPNO 4m, feeding the RC spectrograph
    - Barden and Scott, 1986
  - DensePak-2: Barden and Wade, 1988

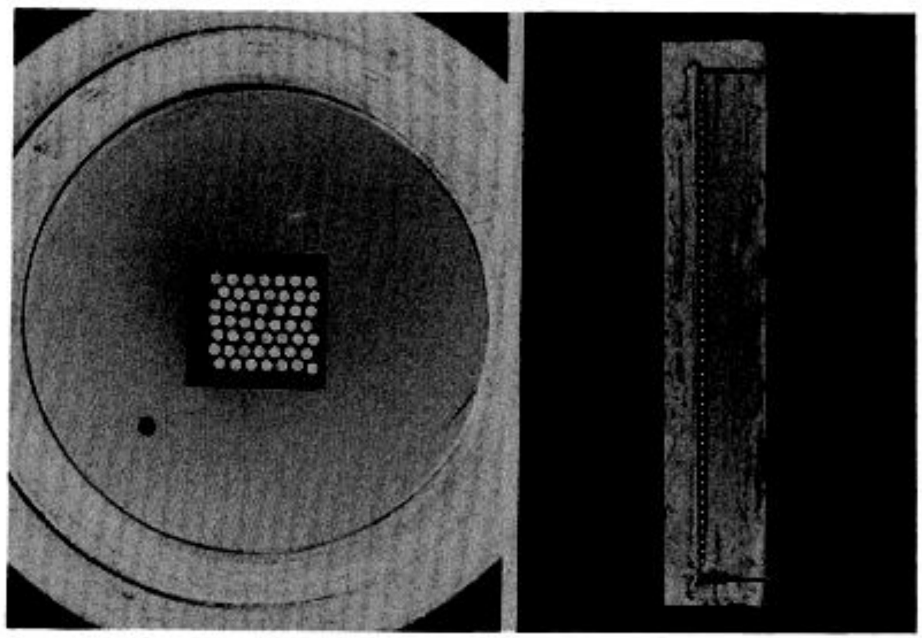
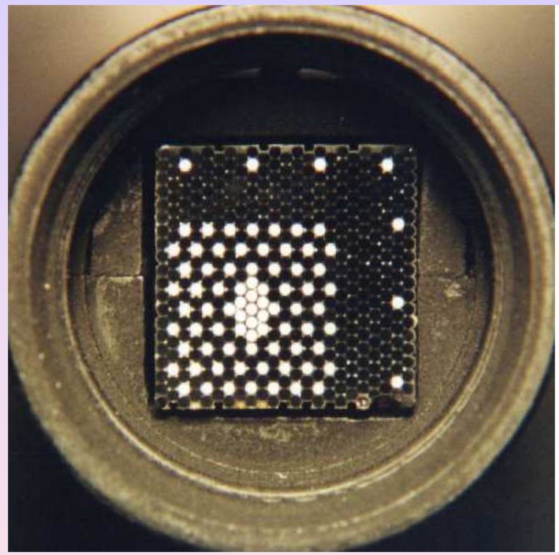
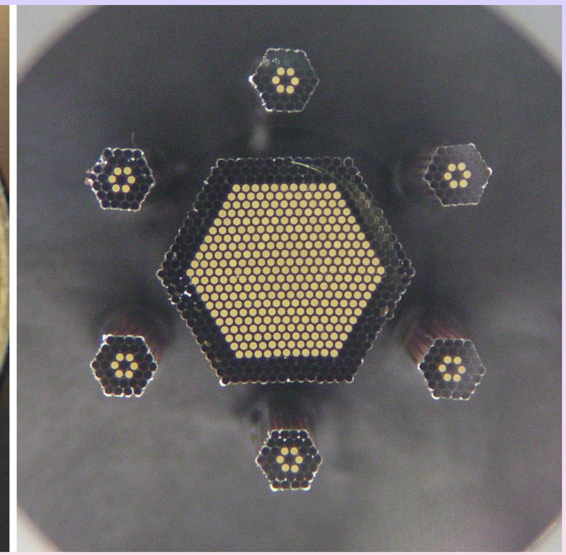


Fig. 1 DensePak II. The left shows the 7 by 7 array installed in the

Grating-dispersed spectrographs
fiber instruments

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





DensePak @ WIYN
90 x3"-fibers
27"x43"
$\Delta\lambda/\lambda \sim$ 14,500
Barden et al. '98

SparsePak @ WIYN
82 x 5"-fibers
70 x 70 arcsec
$\Delta\lambda/\lambda \sim$ 11,500
Bershady, Andersen et al.'04

PPak @ CAHA
367 x 2.7"-fibers
74"x64" arcsec
$\Delta\lambda/\lambda \sim$ 8000
Kelz, Verheijen et al.'05

Grating-dispersed spectrographs

fiber instruments

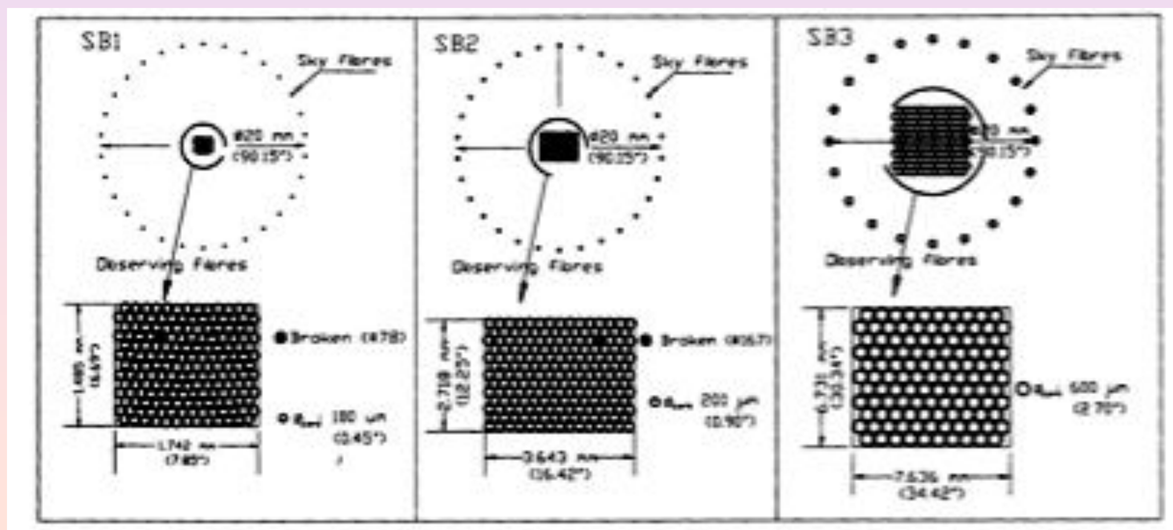
- Existing optical instruments on WHT 4.2m telescope: INTEGRAL
  $\Delta\lambda/\lambda \sim 2300$ (4200)

Arribas et al. ; 98

Table 1. Characteristics of INTEGRAL fiber bundles

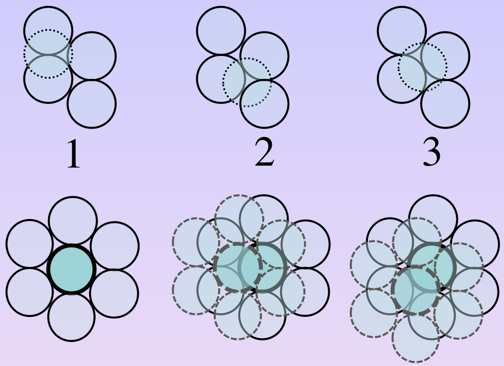
Bundle	1	2	3	4	5	6
sb1	0.45	0.7	205 (175+30)	7.80×6.40	variable	90
sb2	0.90	1.4	219 (189+30)	16.0×12.3	4.6	90
sb3	2.70	4.0	135 (115+20)	33.6×29.4	7.4	90

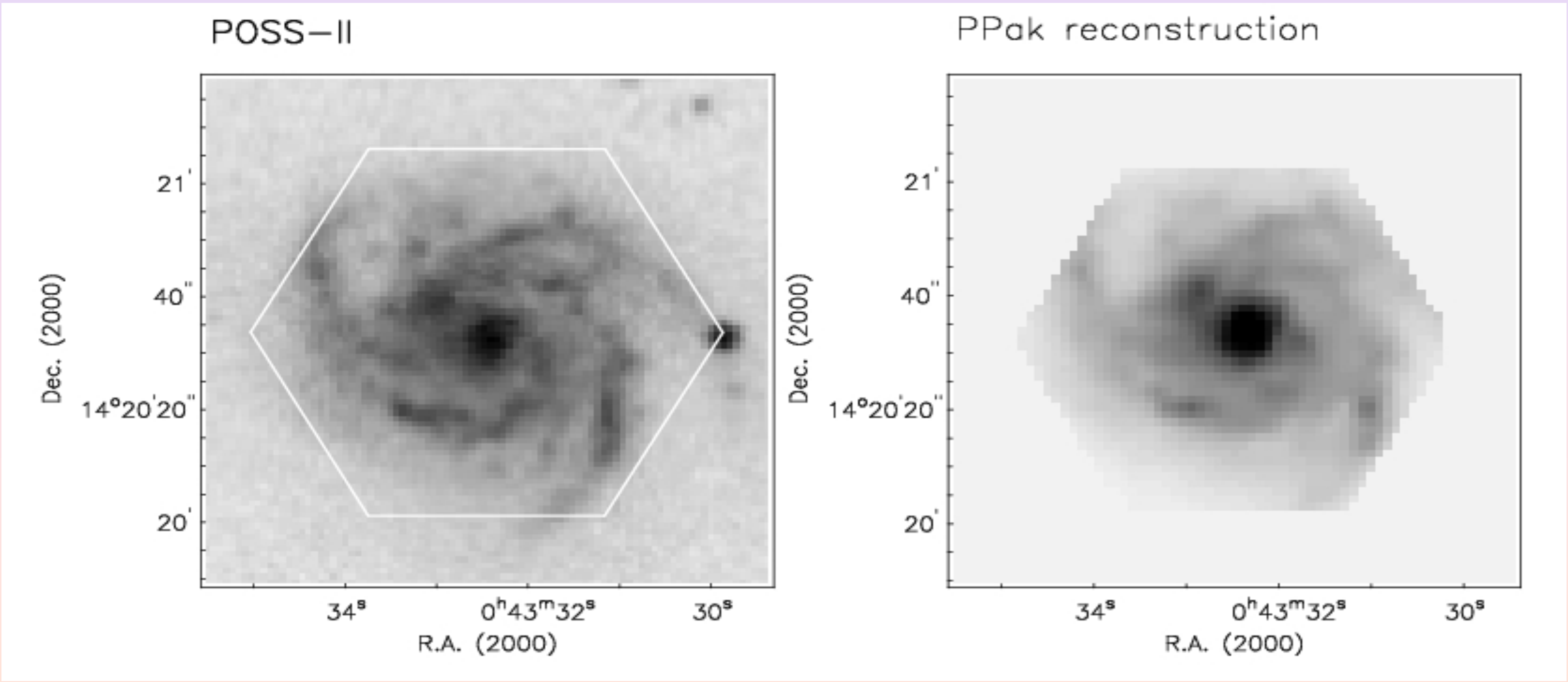
1 – fiber core diameter (arcsec)
2 – fiber image size on the detector (to be convolved with a 1.4–2.6 pixel PSF)
3 – total number of fibers (rectangle + ring)
4 – spatial coverage of the central rectangle (arcsec × arcsec)
5 – distance between adjacent fiber/spectra at the CCD (in pixels)
6 – diameter of the outer ring (arcsec)



Spectral Imaging with fiber arrays:
UGC 463 with PPak

• Even without lenslets, densely sampled fibers provide excellent image reconstruction on spatial scales of the fiber diameter.
• Achieve best theoretical sampling with 3-position half- fiber-diameter dithers (e.g, see Fosbury in context of under-sampled HST WFPC-2 data).





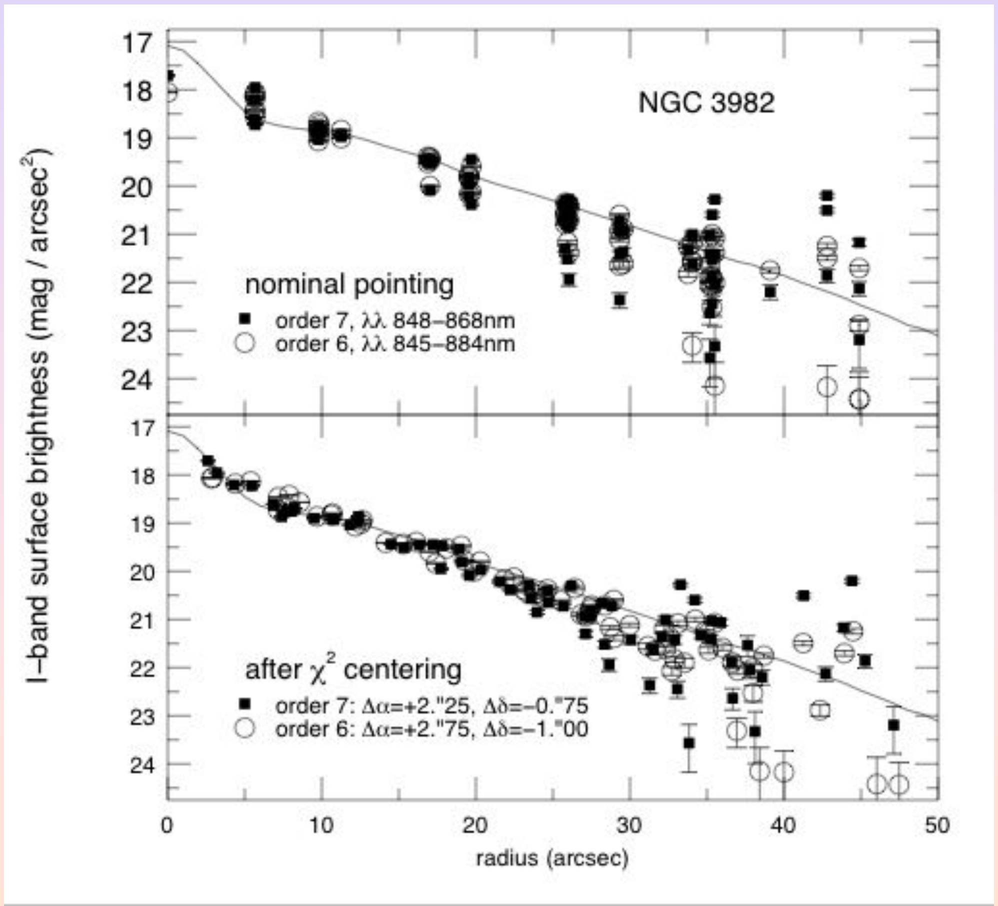
Verjheijen et al. 04

Registration with sparse fiber arrays:
NGC 3982 with SparsePak

- Even with sparse sampling, registration of data-cube with broad-band images can be achieved to 10% of the fiber diameter.
- Cross-correlate spectral continuum w.r.t. broad-band image or even integrated light profile.

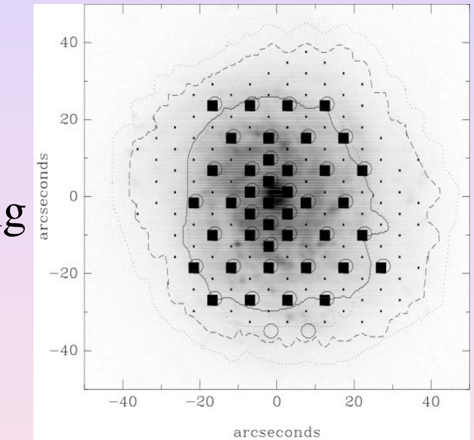
before

after

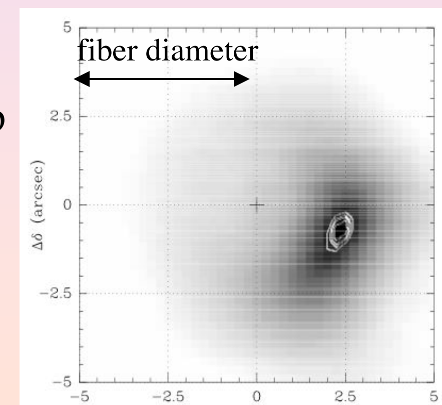


Bershady et al. 04

sampling



χ^2 map



Grating-dispersed spectrographs
fiber instruments - summary list

- Existing optical instruments
  - DensePak (Bench Spectrograph), WIYN 3.5m
  - SparsePak (Bench Spectrograph), WIYN 3.5m
  - PPak (PMAS), Calar Alto 3.5m
  - Integral (WYFFOS), WHT 4.2m
- Future optical instruments
  - VIRUS, HET 9.2m
- Existing NIR instruments
  - GOHSS, TNG 3.6m
- Future NIR instruments

Grating-dispersed spectrographs
fiber instruments - summary list

Table 1. Fiber Integral Field Instruments

Instrument	Coupling Method	Telescope	D_T (m)	Ω (arcsec^2)	$d\Omega$ (arcsec^2)	N_g	$\Delta\lambda/\lambda$	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										