# Astro 500

## Techniques of Modern Observational Astrophysics

Matthew Bershady
University of Wisconsin

# Approaches

## Examples of available instruments

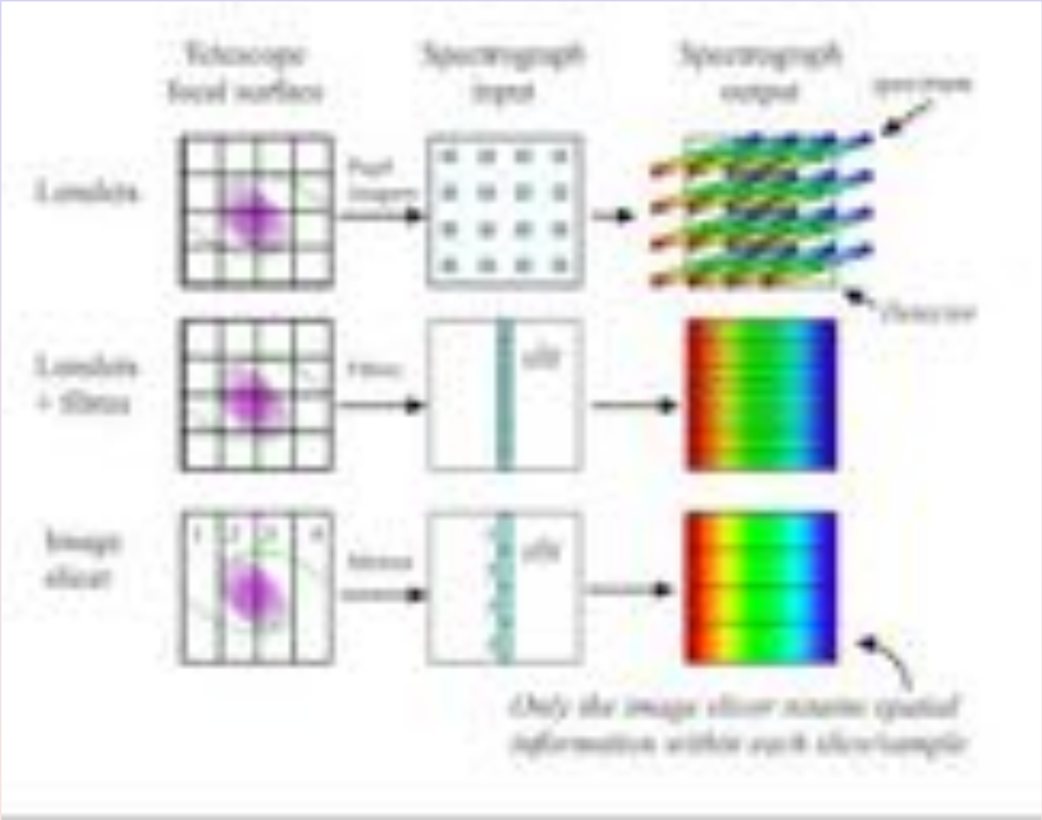
*Spectroscopy from a 3D Perspective*

- ✓ 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

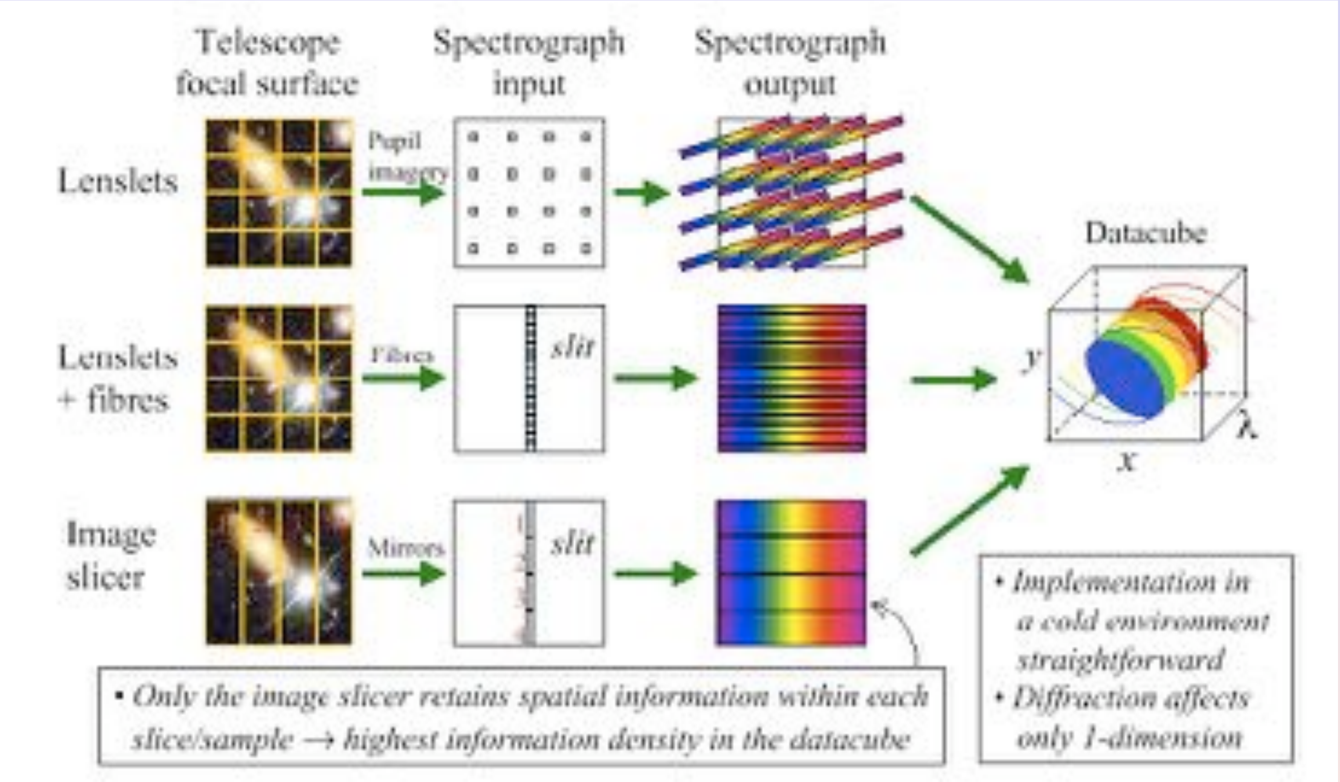
- Implications of coupling methods



Allington-Smith & Content '98

recent summary: see Alighieri et al. '05

# 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).

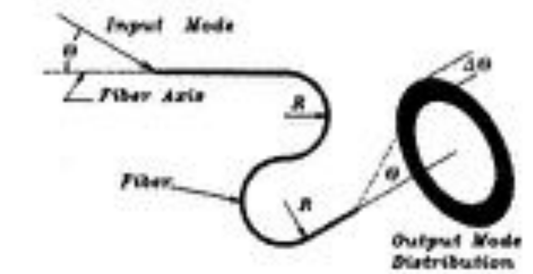



Fig. 2 We illustrate here the basic definition of FRD. An single "mode" is inserted into the fiber. It is azimuthally dispersed or "scrambled" and also dispersed to a lesser extent radially. This radial dispersion is the FRD.

Ramsey '88

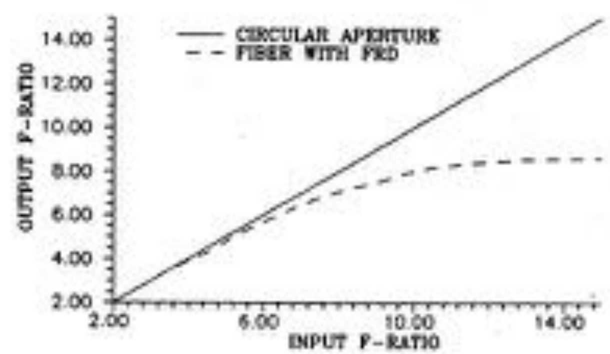
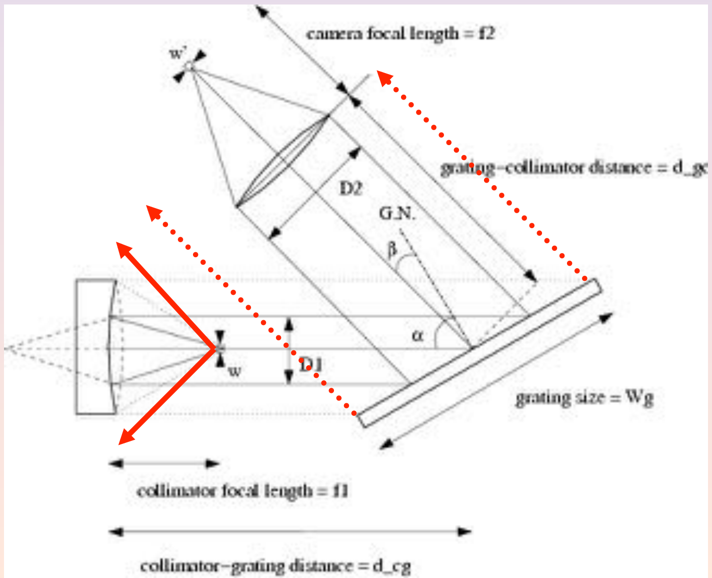
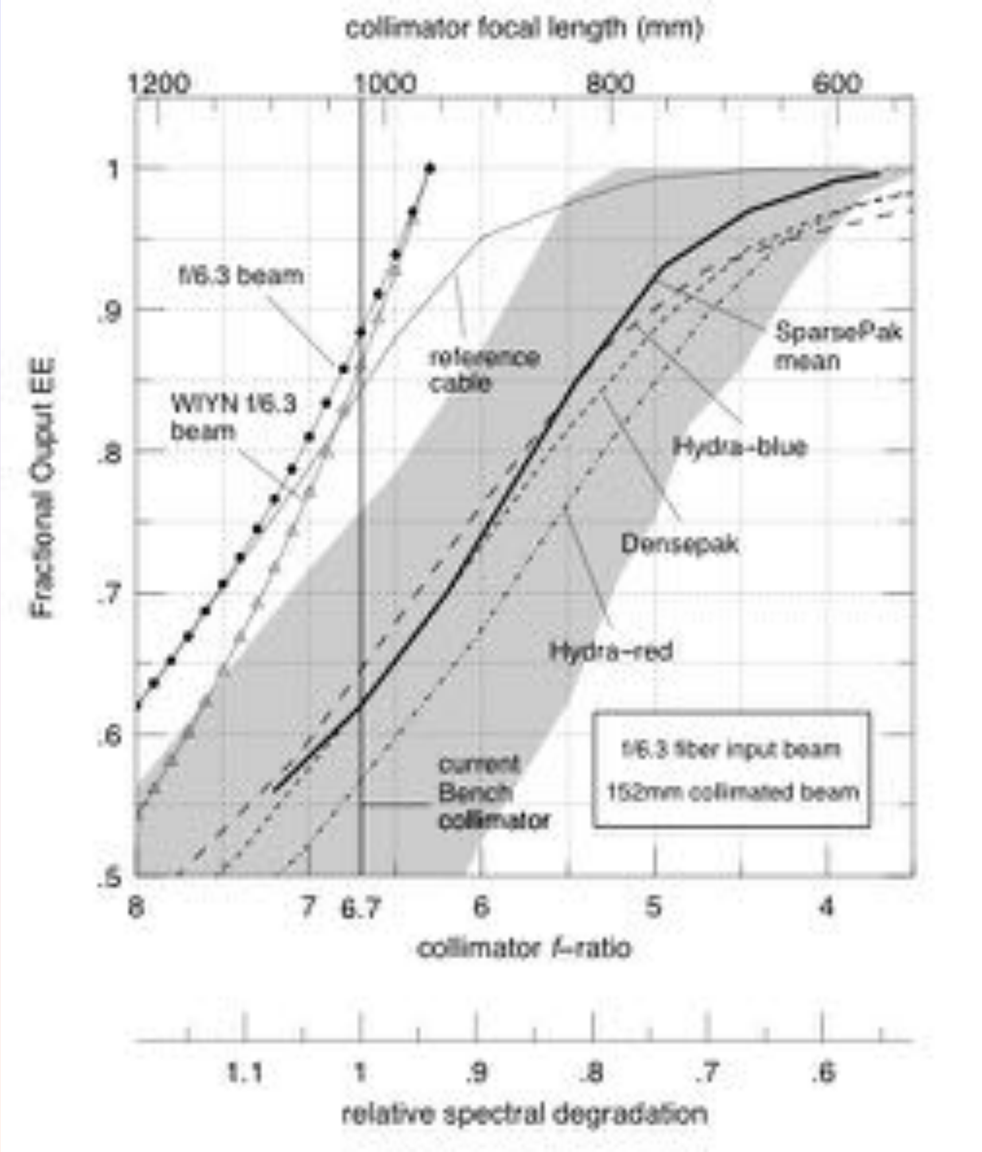


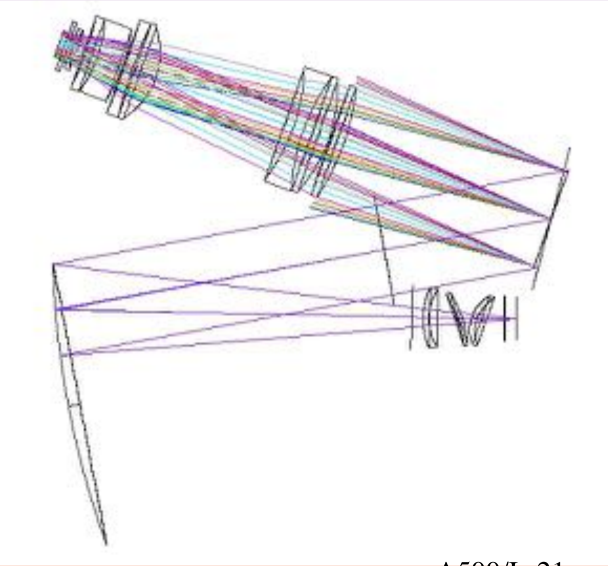

Fig. 3 The Focal Ration Degradation (FRD) of a typical fiber is compared to the throughput of a circular aperture of the same diameter as the core of the fiber.



# Grating-dispersed spectrographs
## FRD information loss

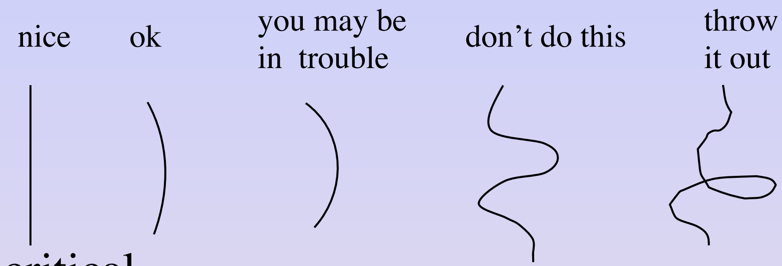



- Example: WIYN Bench Spectrograph.
- Result: we're building a new, faster collimator to regain 50% of the light (double throughput) at 25% loss in resolution.
  - Additional gain from off-axis collimator: no feed vignetting and access to pupil.



# 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 inhomogeneitie
  - ~~Stimulated Raman and Brillouin sc~~
  - Micro-bending

large power levels only; not astronomy!

*unsubstantiated favorite*

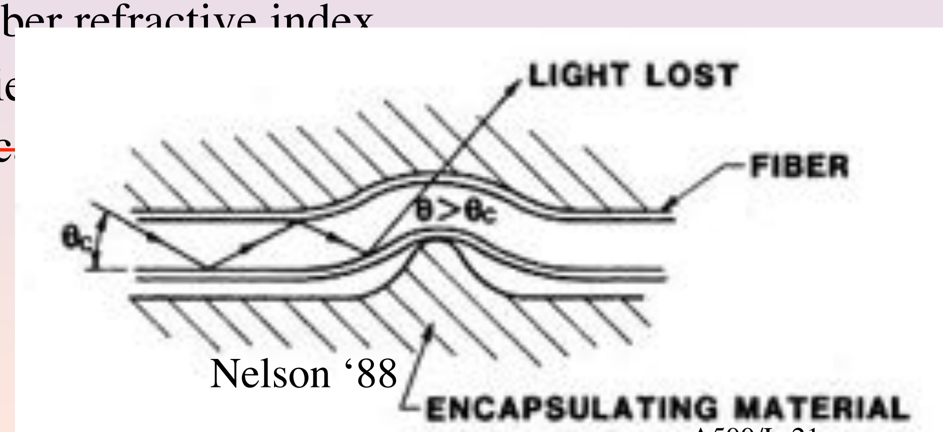
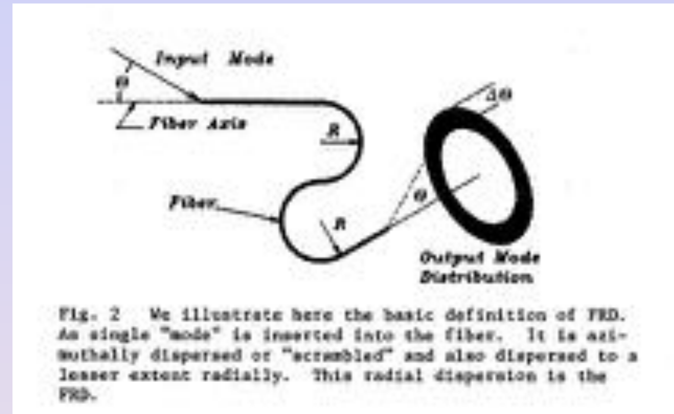



Fig. 3 Microbend.

Nelson ‘88

# 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 δθ 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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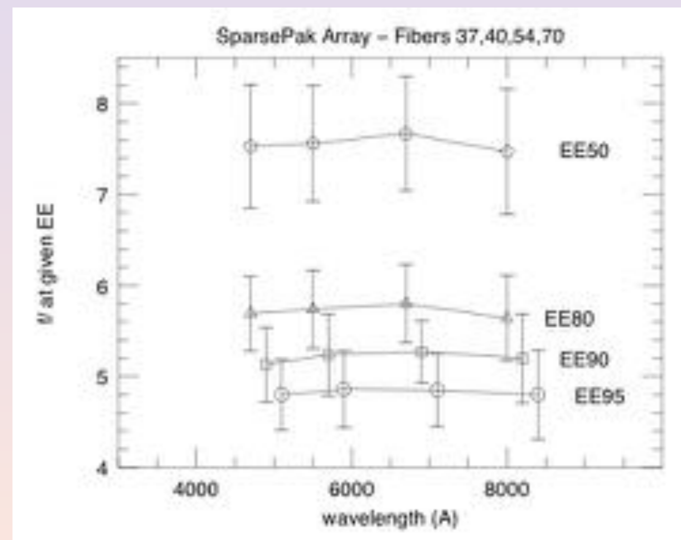
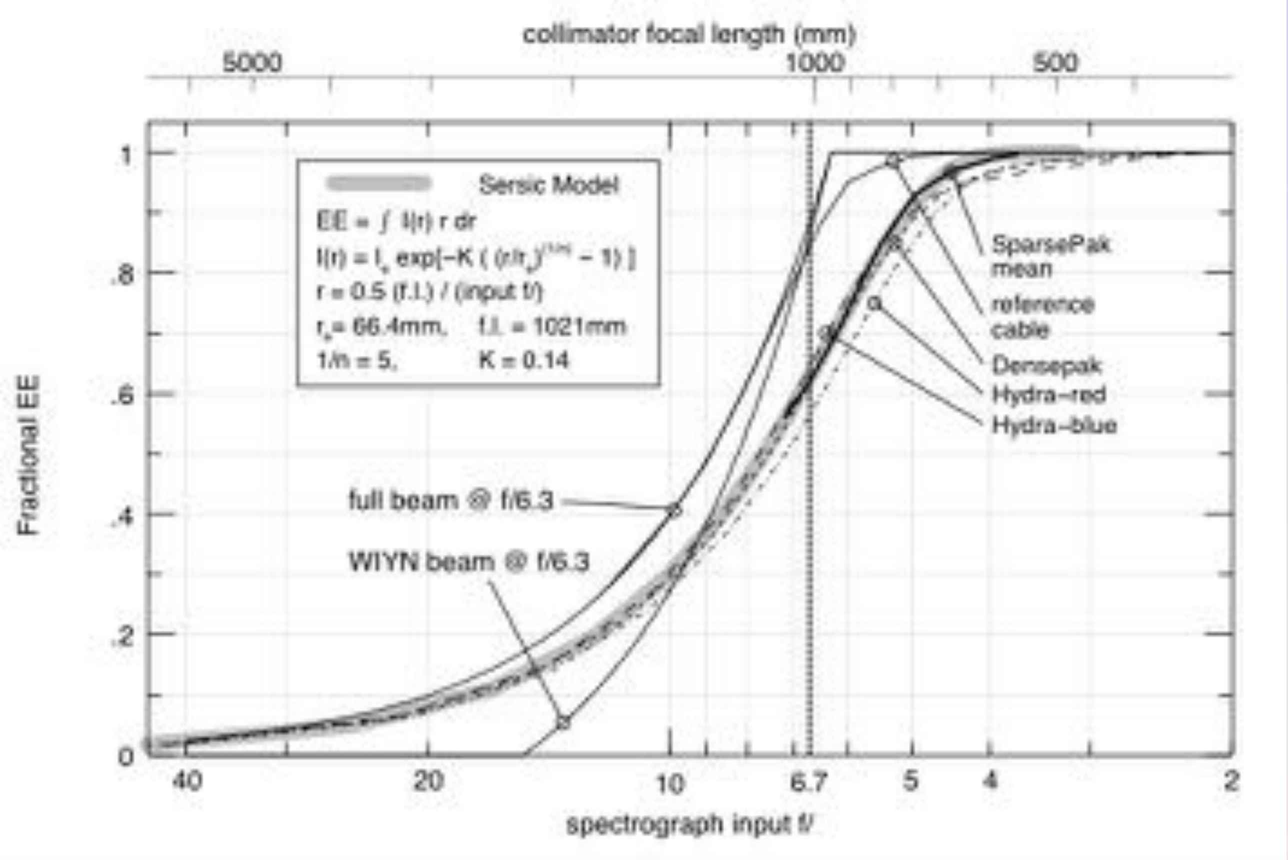



Bershady et al. '04

# 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!

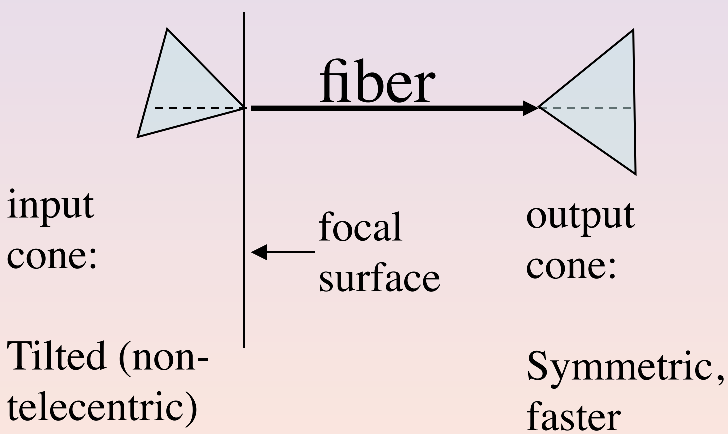


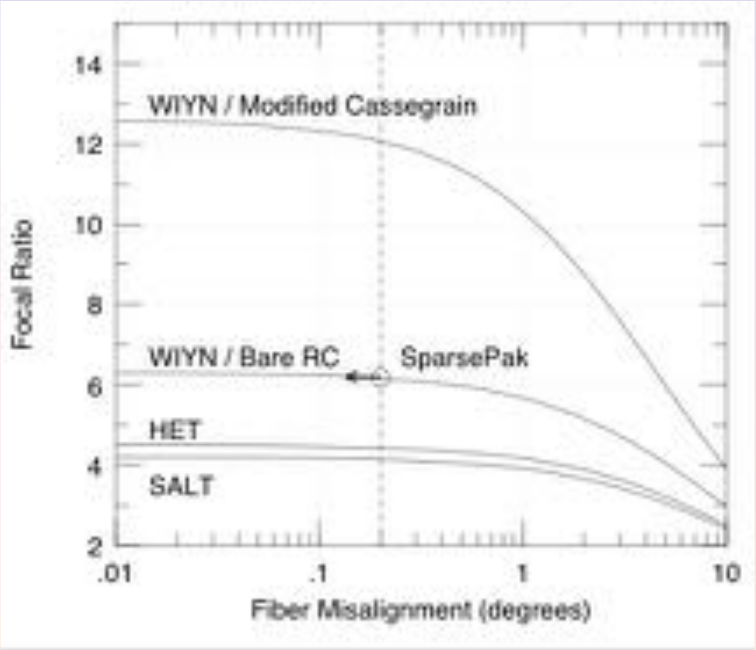

Credit: Steve Crawford

# Grating-dispersed spectrographs

## FRD - other known causes

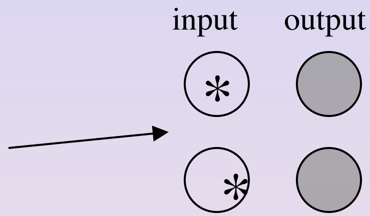
- Input light-cone mis-alignment with fiber axis
- Azimuthal scrambling symmetrizes output beam
  - Example (left) of non-telecentric focal surface
  - Other causes from fiber mechanical alignment



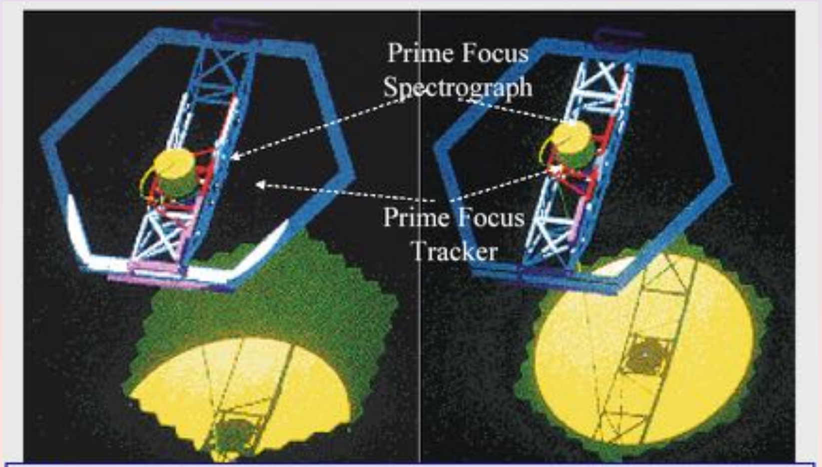
# Grating-dispersed spectrographs
## FRD and azimuthal scrambling - advantages

- 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

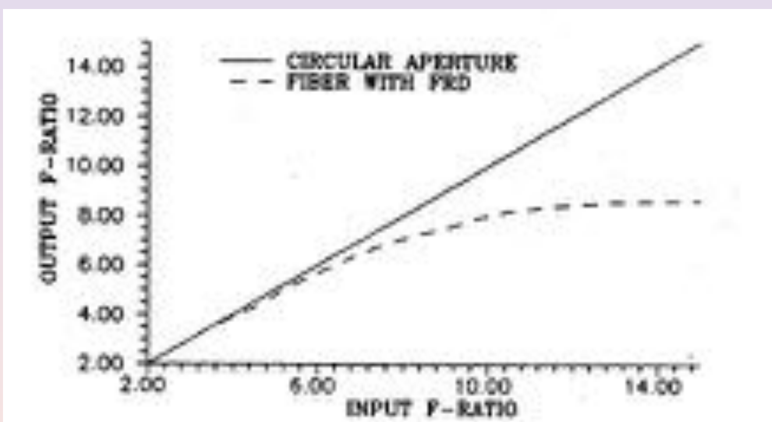
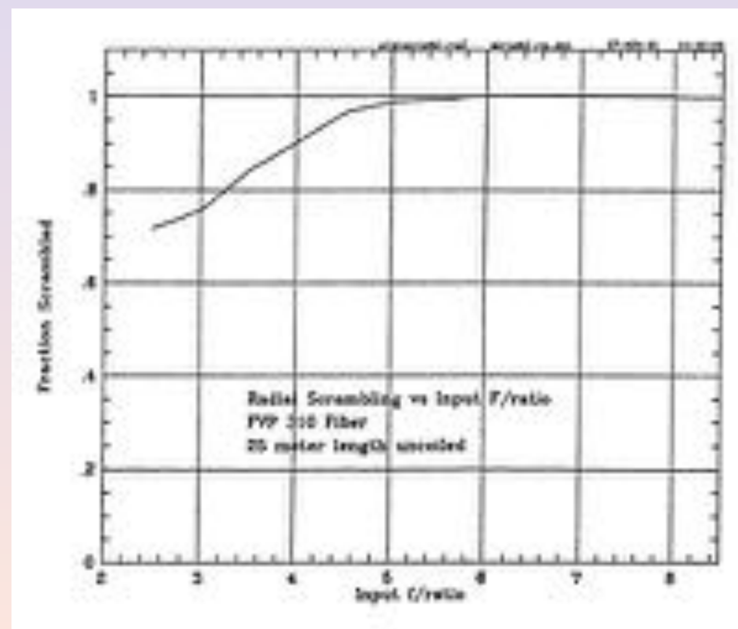


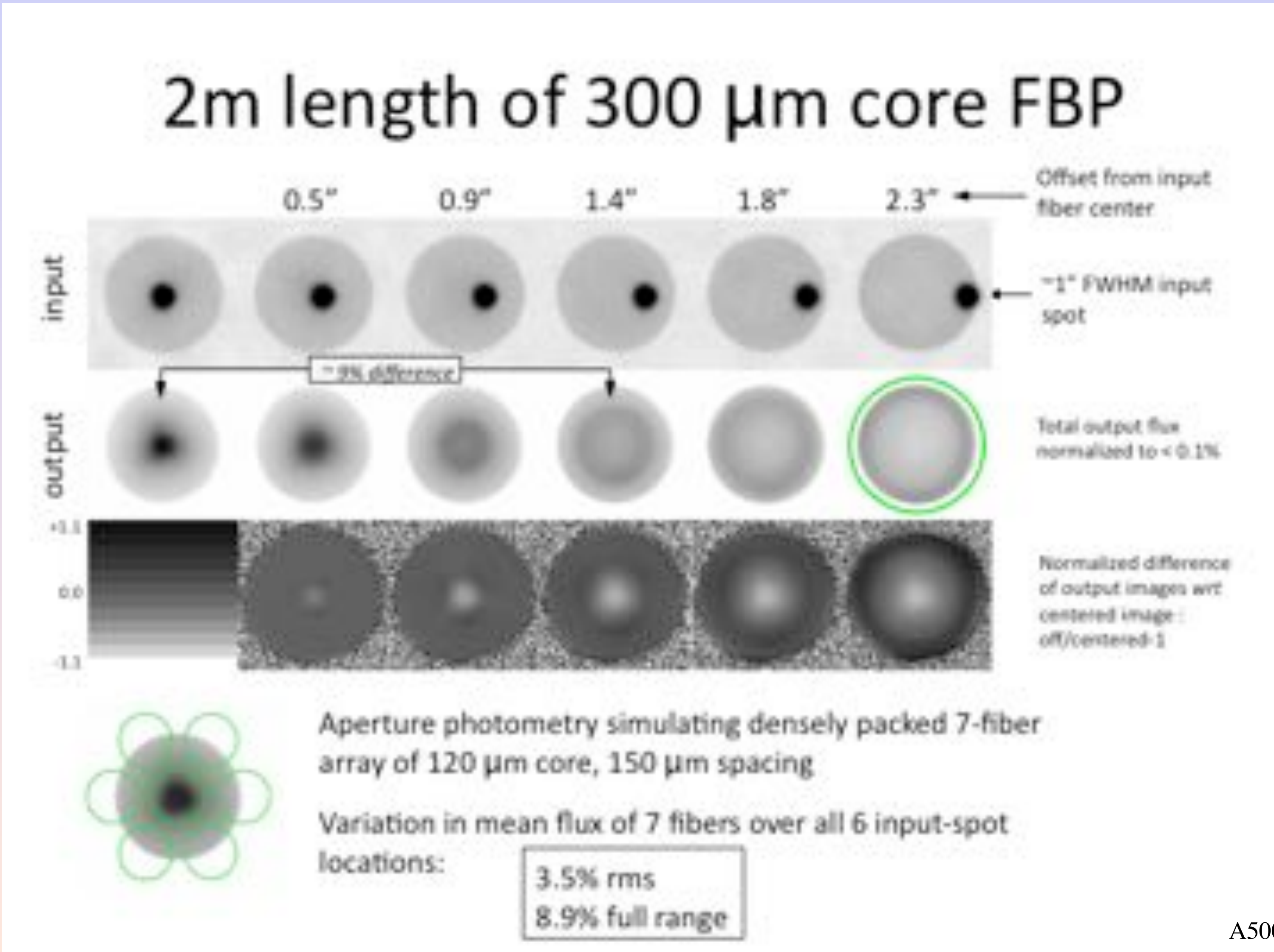

Fig. 3 The Focal Ration Degradation (FRD) of a typical fiber is compared to the throughput of a circular aperture of the same diameter as the core of the fiber.

Ramsey '88

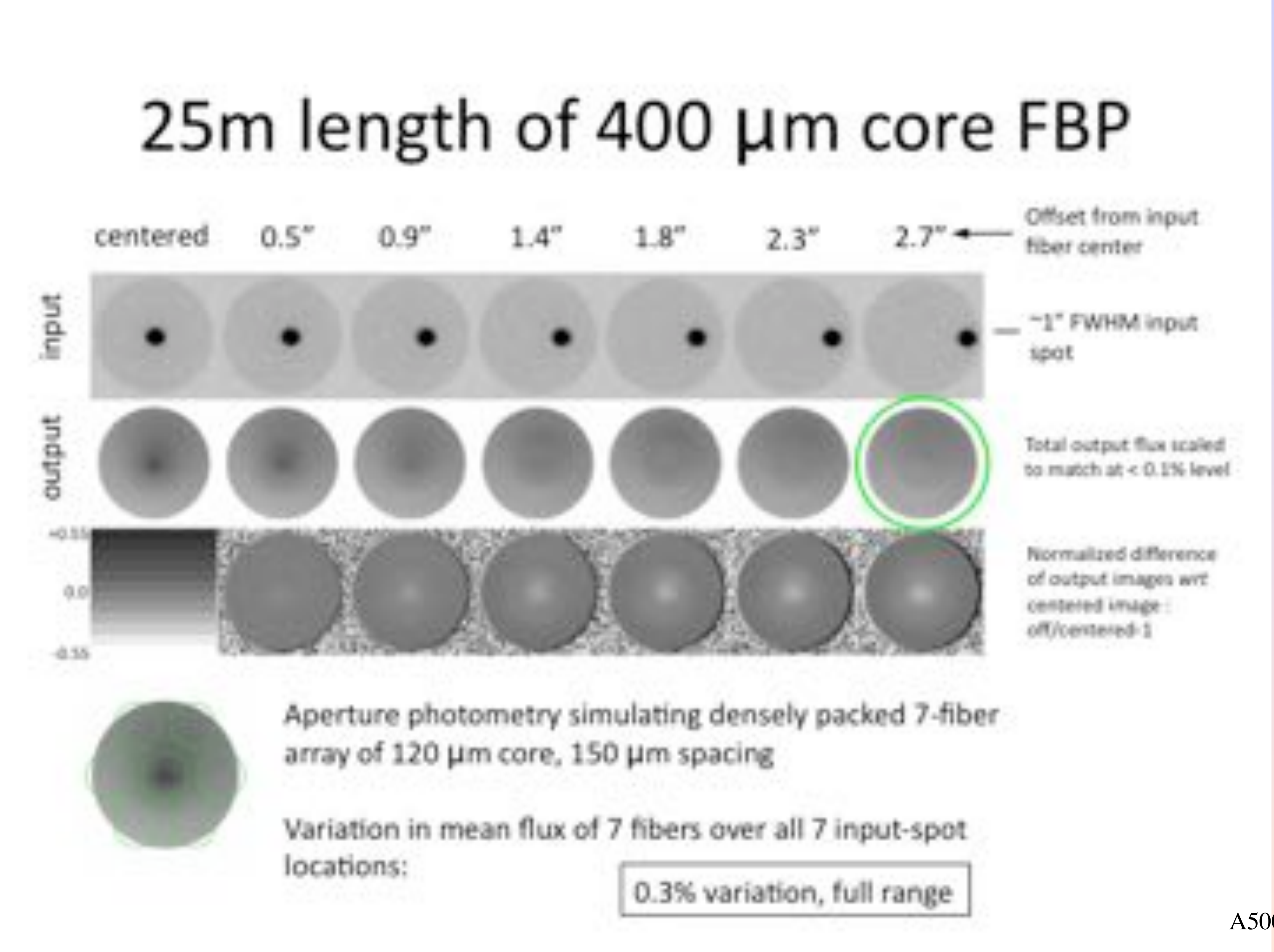



Barden et al. '93

# Radial scrambling

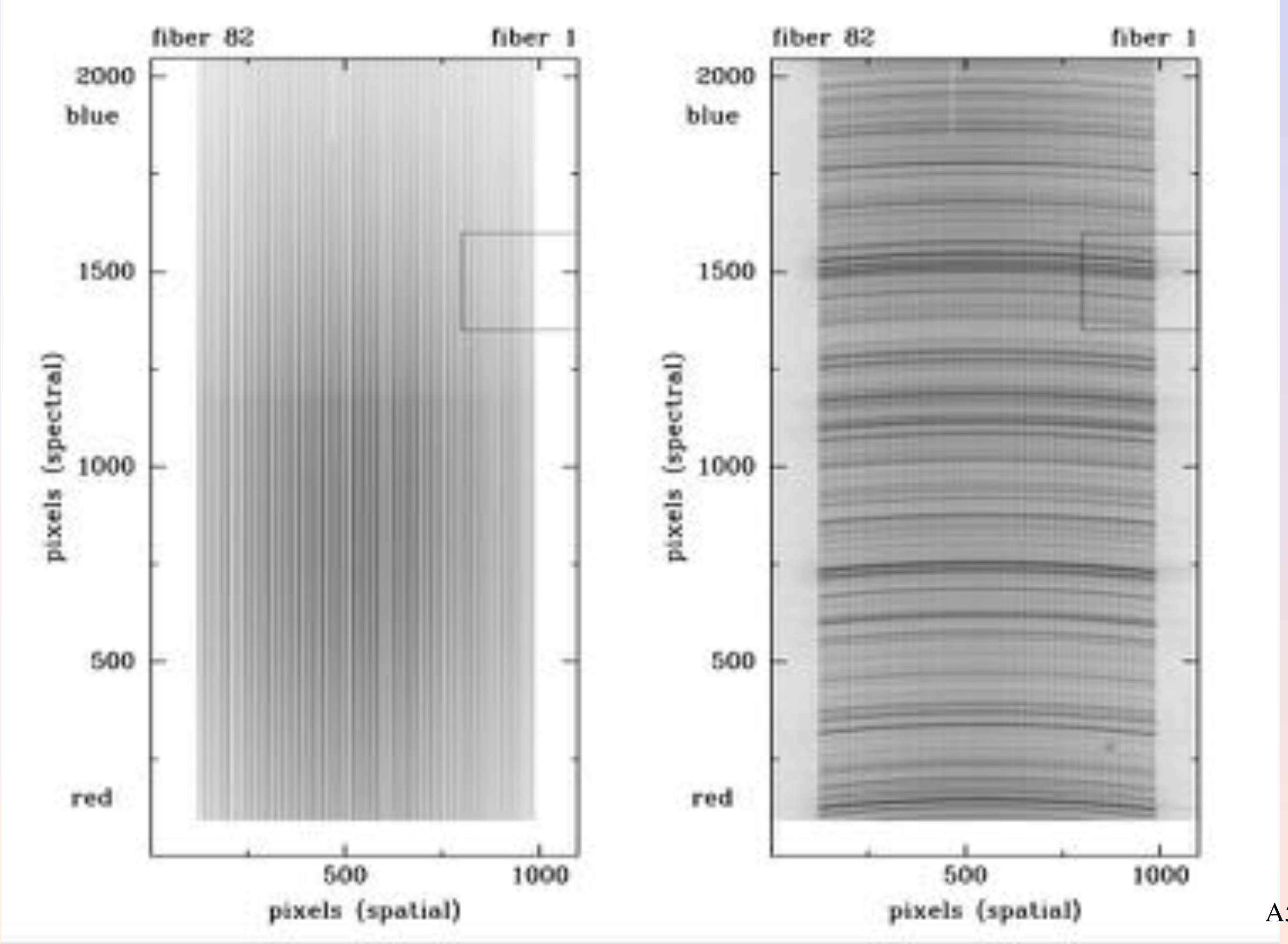


# Radial scrambling



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

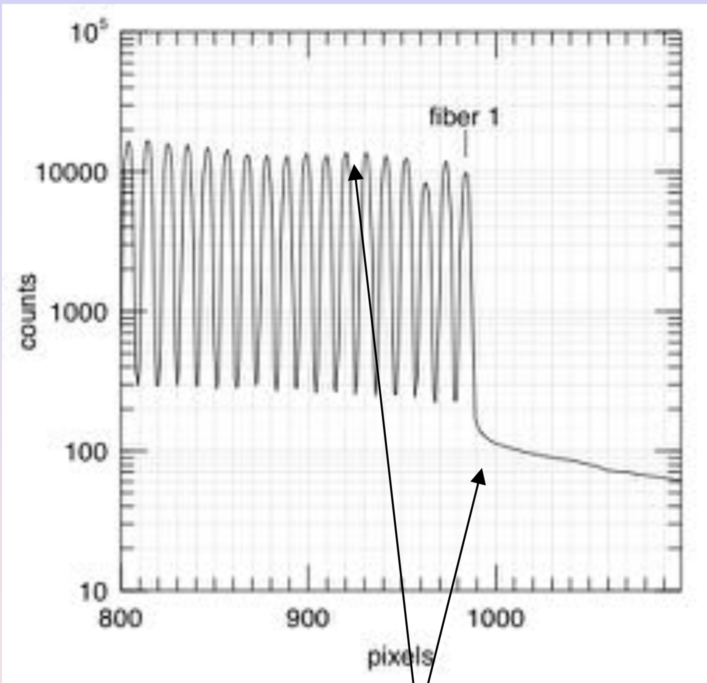
- SparsePak raw dome and lamp spectra

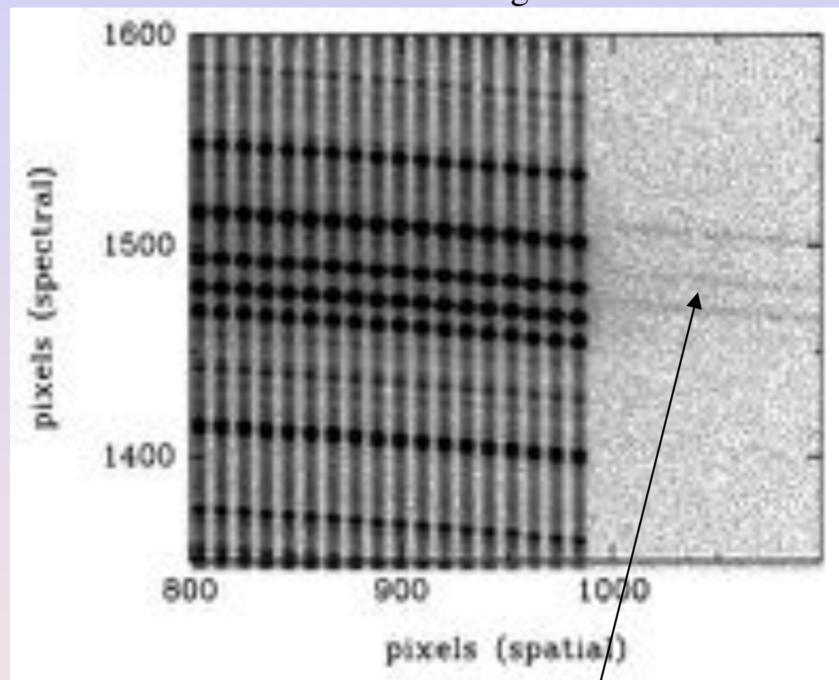


# Grating-dispersed spectrographs
## fiber feeds: packing on the focal plane

- SparsePak raw dome and lamp spectra: blow-up

Fiber seperation: 10 pix
Reimaged fiber diameter: 4.5pix

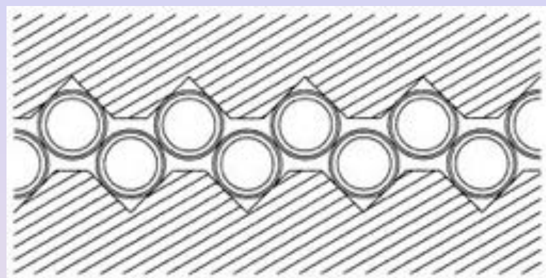


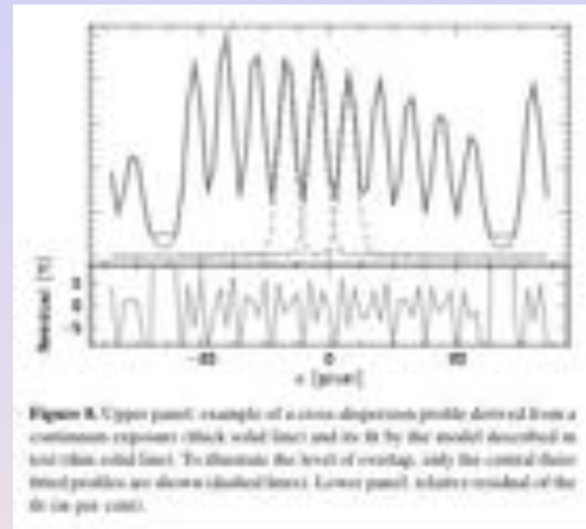




- Amplitude of scattered light is low, fiber separation is large and ghosting is negligible:
  - This spectrograph + feed is optimized for clean extraction with little cross-talk.
  - Information packing in spatial dimension is modest due to fiber separation;
  - Information packing in spectral dimension is high due to large anamorphic factors.

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

- Greed:





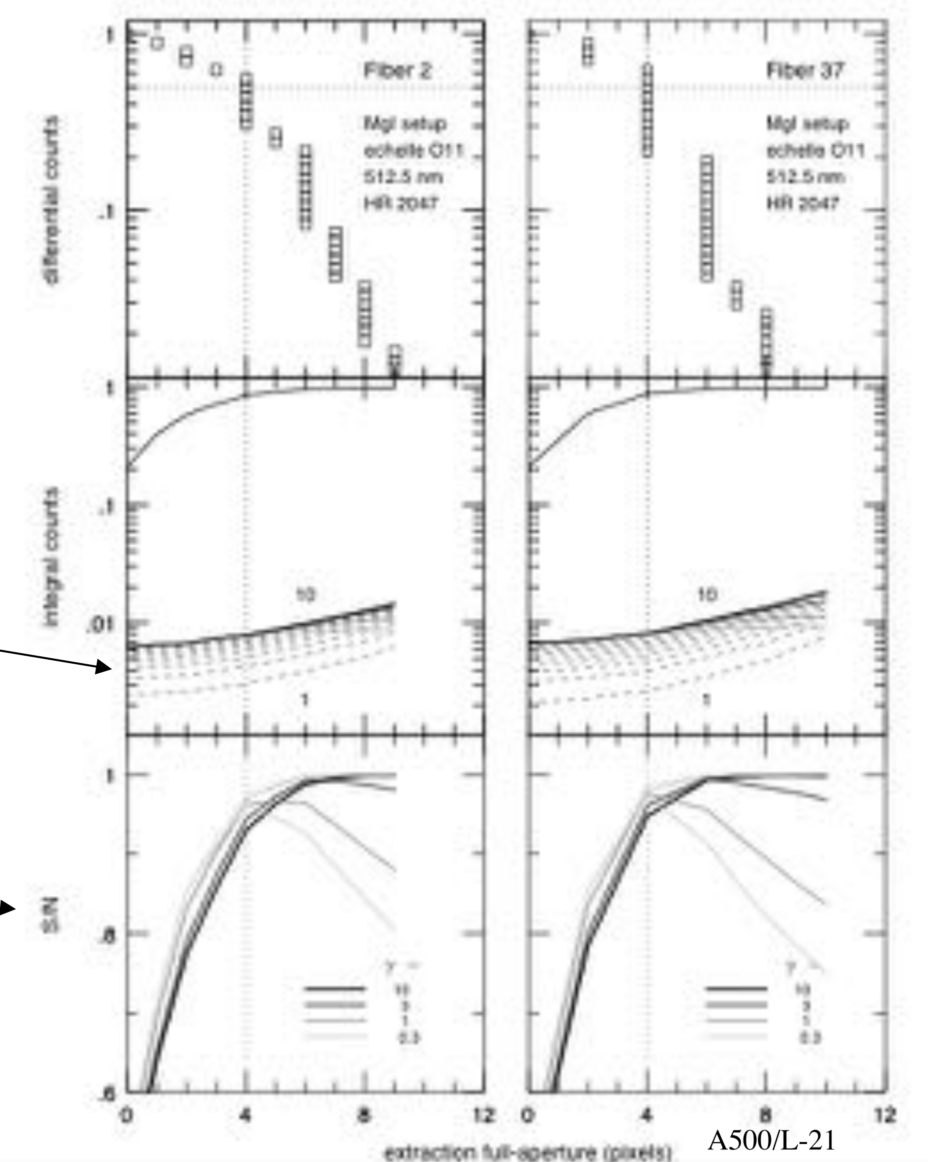
- + scatted light
  - ➢ Difficult to extract a clean spectrum and optimize S/N.
  - ➢ Azimuthal scrambling means that spatial information in telescope focal plane is coupled to all adjacent fibers in slit.

# 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

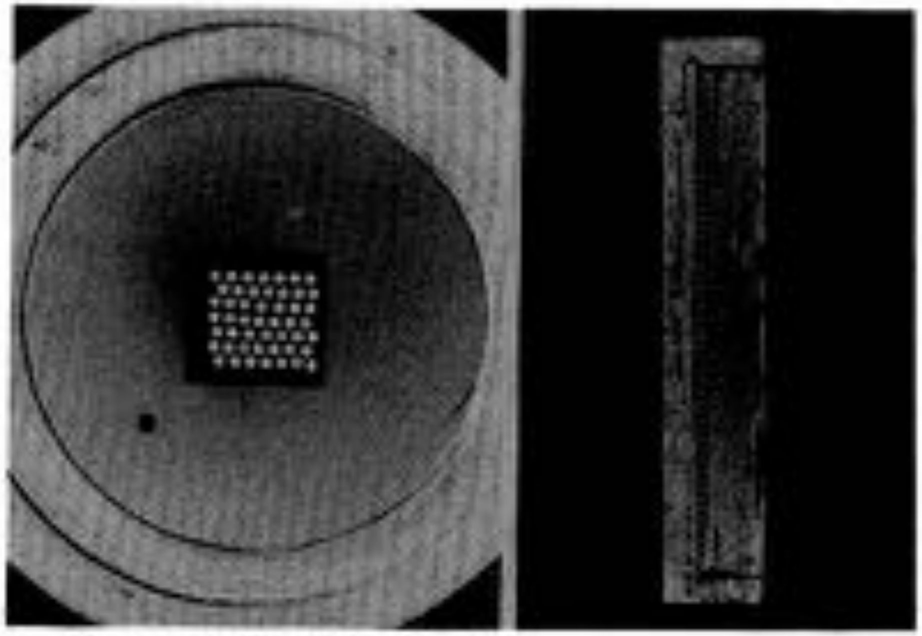
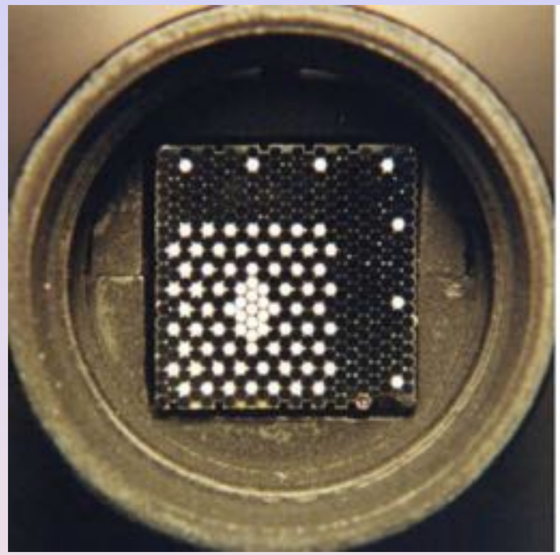


Fig. 1 DensePak II. The left shows the 7 by 7 array installed in the

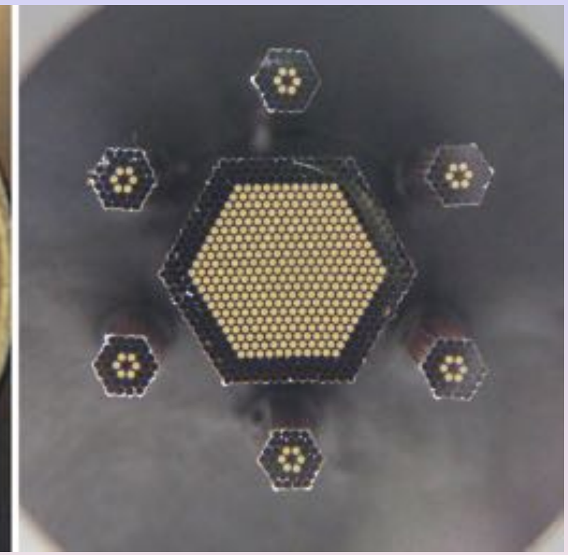
# Grating-dispersed spectrographs
## fiber instruments

- 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

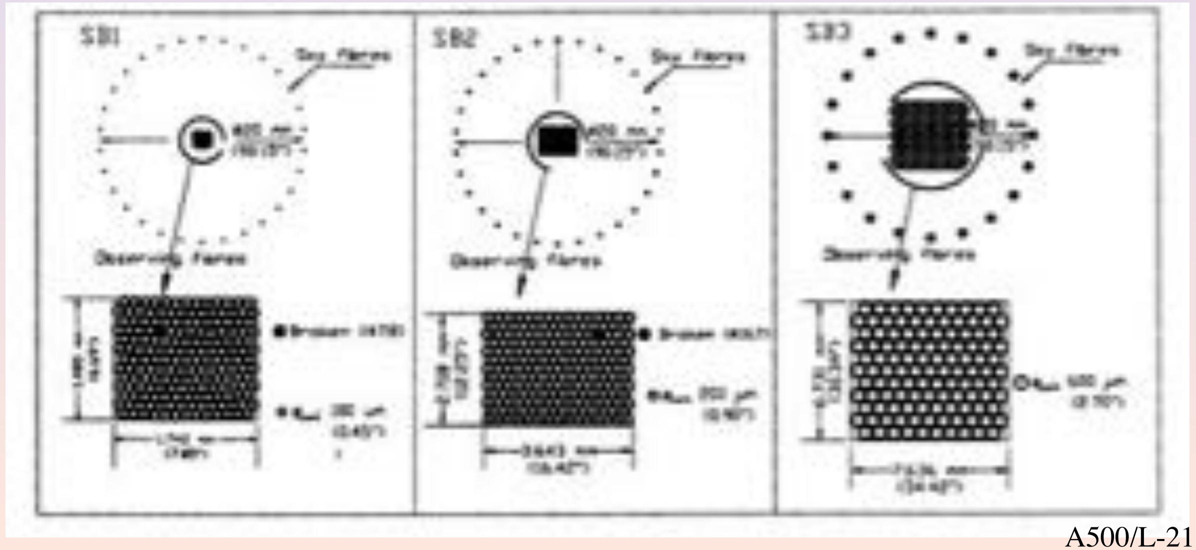
- Existing optical instruments on WHT 4.2m telescope: INTEGRAL
  $\Delta\lambda/\lambda \sim 2300$ (4200)

Arribas et al. ; 98

Table 1. Characteristics of INTEGRAL fiber bundles

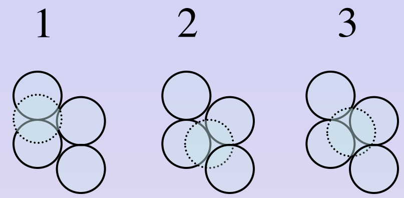
| Bundle | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| sb1 | 0.45 | 0.7 | 205 (175+30) | 7.80×6.40 | variable | 90 |
| sb2 | 0.90 | 1.4 | 219 (189+30) | 16.0×12.3 | 4.6 | 90 |
| sb3 | 2.70 | 4.0 | 135 (115+20) | 33.6×29.4 | 7.4 | 90 |

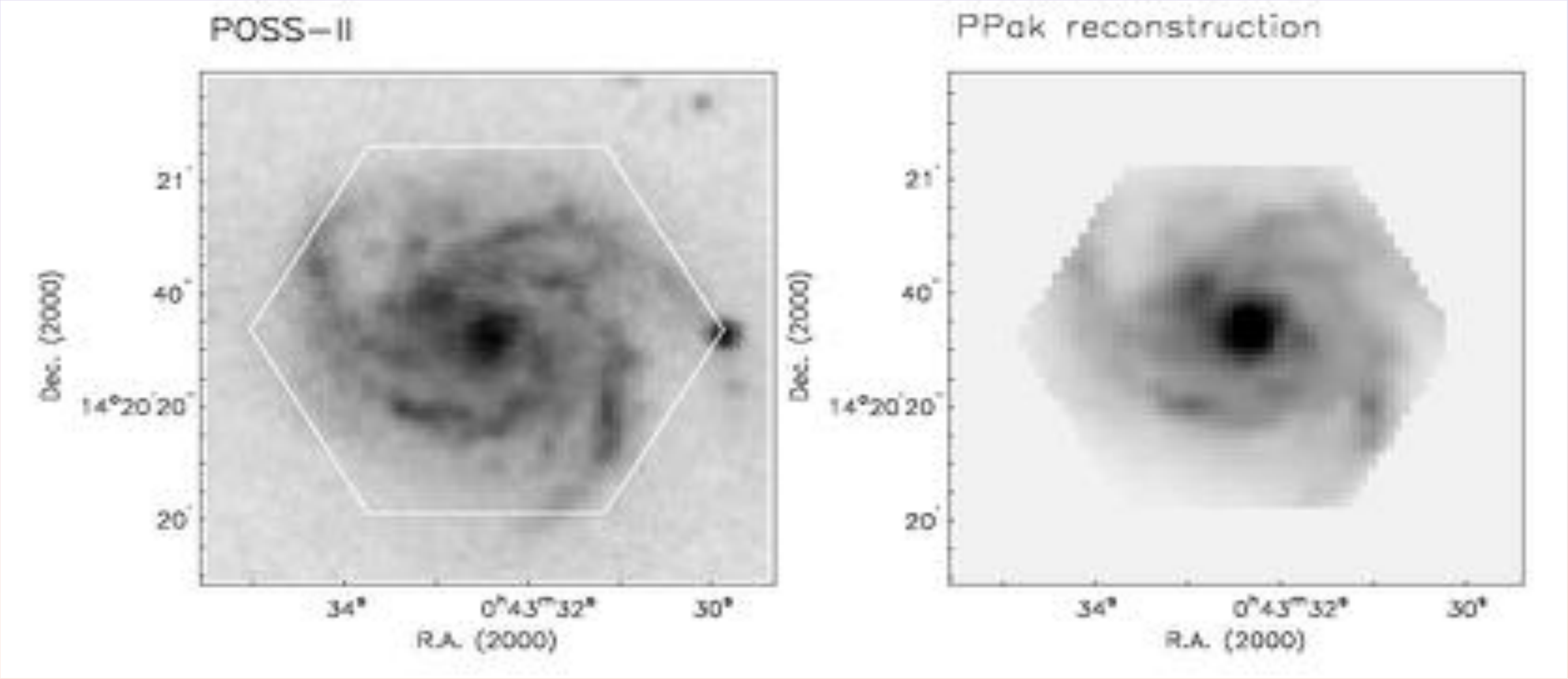
1 – fiber core diameter (arcsec)
2 – fiber image size on the detector (to be convolved with a 1.4-2.6 pixel PSF)
3 – total number of fibers (rectangle + ring)
4 – spatial coverage of the central rectangle (arcsec × arcsec)
5 – distance between adjacent fiber/spectra at the CCD (in pixels)
6 – diameter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

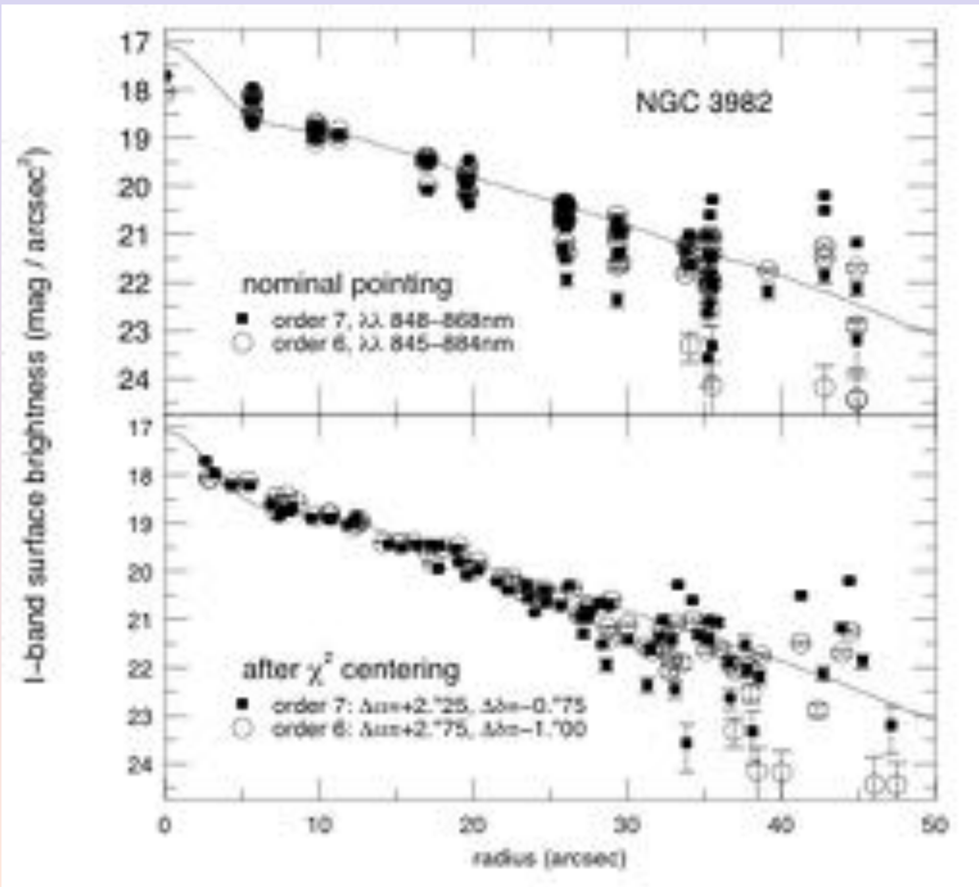
# Registration with sparse fiber arrays:
## NGC 3982 with SparsePak

- 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.

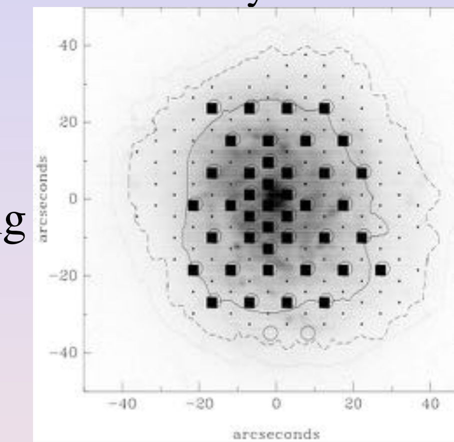
Bershady et al. 04

before

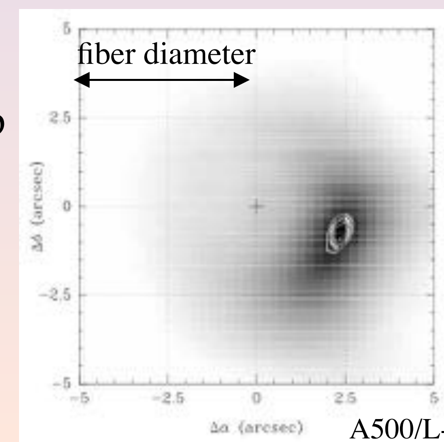
after




sampling




$\chi^2$ 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) | $\Omega$ (arcsec$^2$) | $d\Omega$ (arcsec$^2$) | $N_s$ | $\Delta\lambda/\lambda$ | R | $N_g$ | $\epsilon$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 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 | 0.150 | 205 | 0.22 | 2350. | 515 | ··· |
| | | WHT | 4.2 | 32.6 | 0.150 | 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 | 0.565 | 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 | | | | | | | | | | |