Astro 500

Techniques of Modern Observational Astrophysics

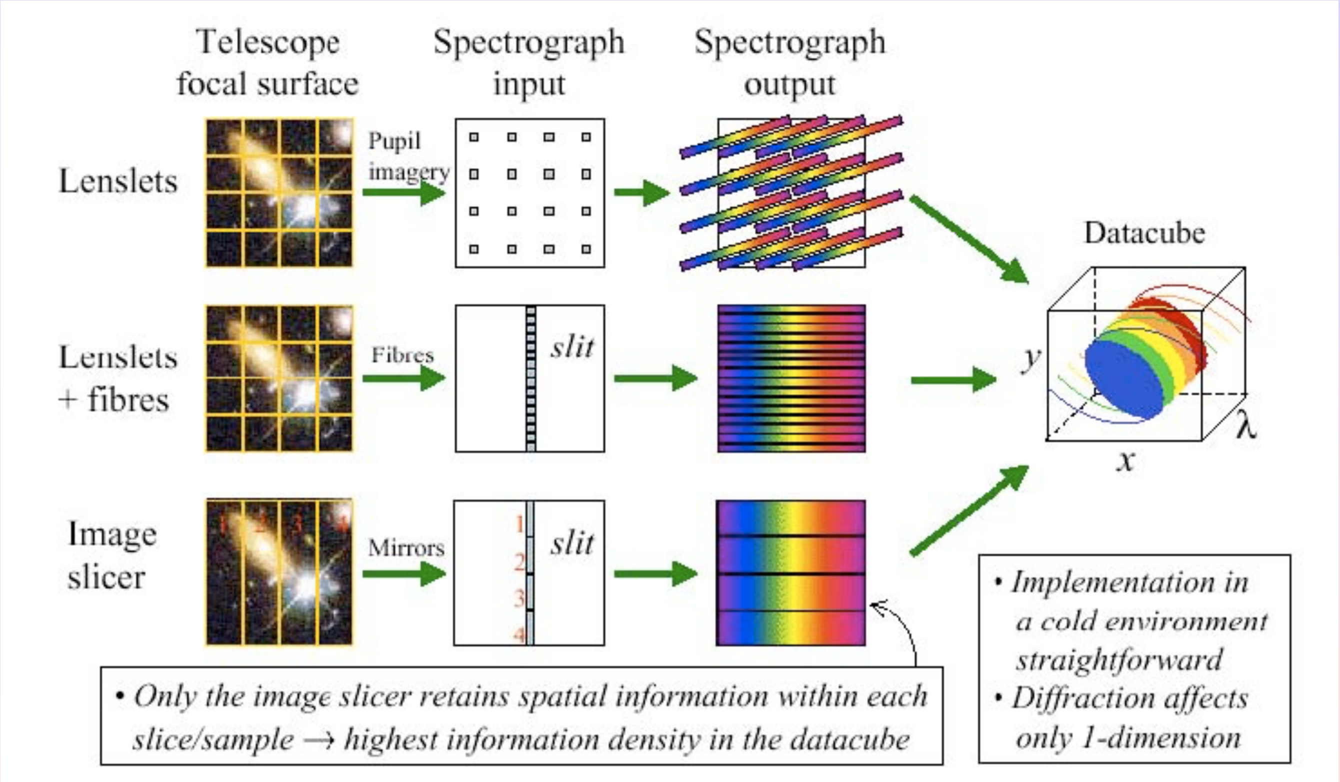
Matthew Bershady

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
    - ✓ Fiber+lenslet
    - ✓ Slicer
    - ✓ Lenslet
    - ✓ 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
Fibres
slit
y
λ
x
Image slicer
1
2
3
4
Mirrors
slit
1
2
3
4
• 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

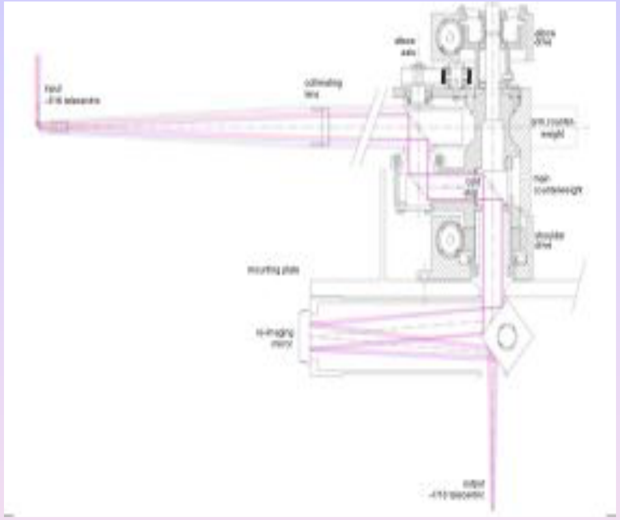
Grating-dispersed spectrographs

Multi-object configurations

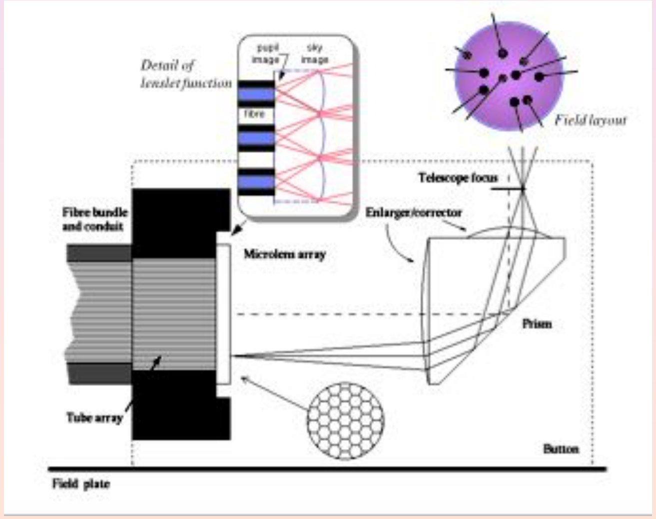
- This is a major path for the future
  - ➢ How to feed?
    - o Fiber, fiber+lenslet, slicer+ relay optic

Relatively easy; many existing MOS could be upgraded

More challenging; many surfaces



Sharples et al. ‘04: KMOS



Allington-Smith & Content ‘98

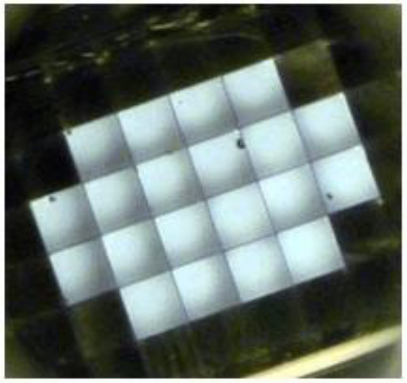
Grating-dispersed spectrographs
Multi-object configurations

- This is a major path for the future
  - How to feed?
    - Fiber, fiber+lenslet, slicer+ relay optic

Relatively easy; many existing MOS could be upgraded (Fiber, fiber+lenslet)

More challenging; many surfaces (slicer+ relay optic)

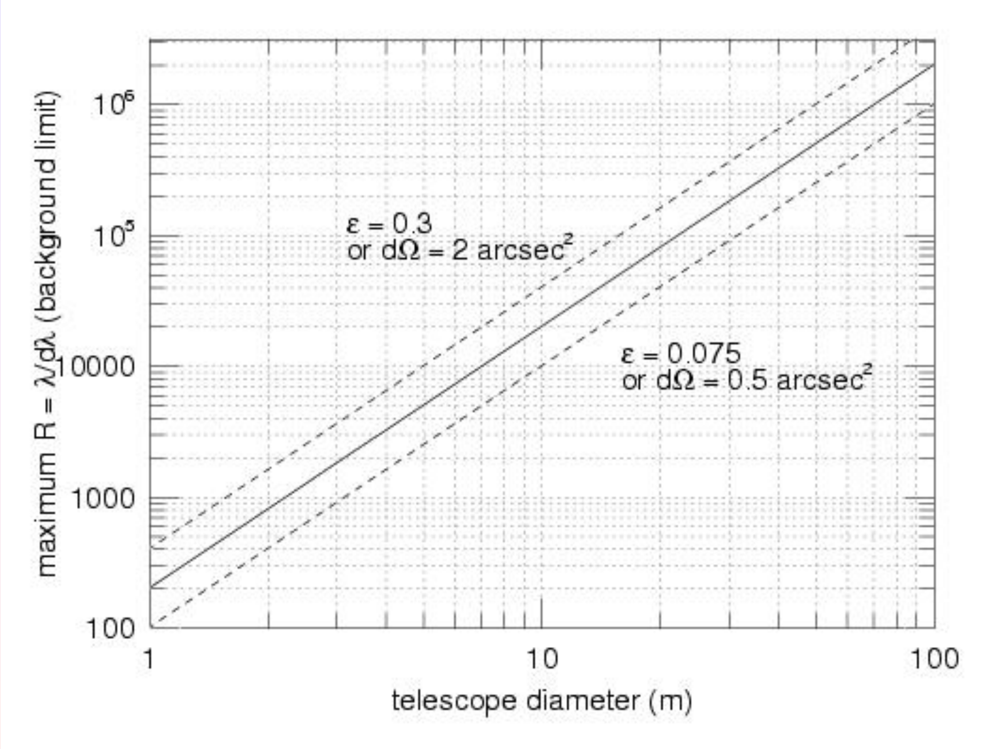
- 10 years ago: only one existing instrument
  - FLAMES/GIRAFFE
    - Fiber+lenslet
    - 15 units + 15 sky fibers
    - Each unit is 2 x 3 arcsec of 20 rectangular microlenses sampling 0.52 x 0.52 arcsec



Credit: ESO web page

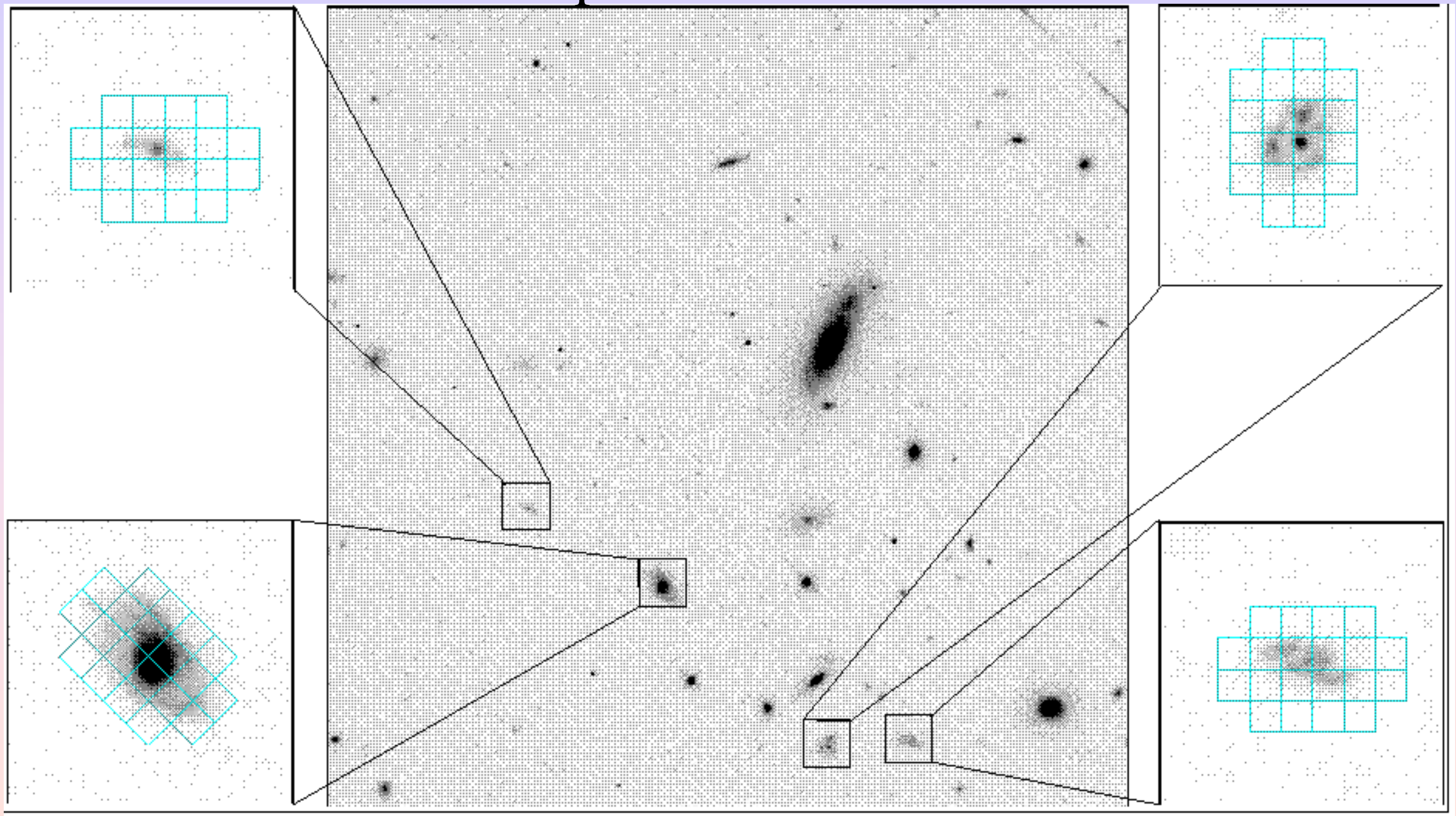
Grating-dispersed spectrographs
Multi-object configurations

- Background limited?
  - FLAMES/GIRAFFE
    - Each unit is 2 x 3 arcsec of 20 rectangular microlenses sampling 0.52 x 0.52 arcsec
  - Equivalent to 1 arcsec fiber on 3.5m telescope.
  - Great for emission-line work, particular if line emission is clumpy.
  - Tough for diffuse gas or stellar continuum in resolved sources.



Grating-dispersed spectrographs
Multi-object configurations

This is a powerful instrument:



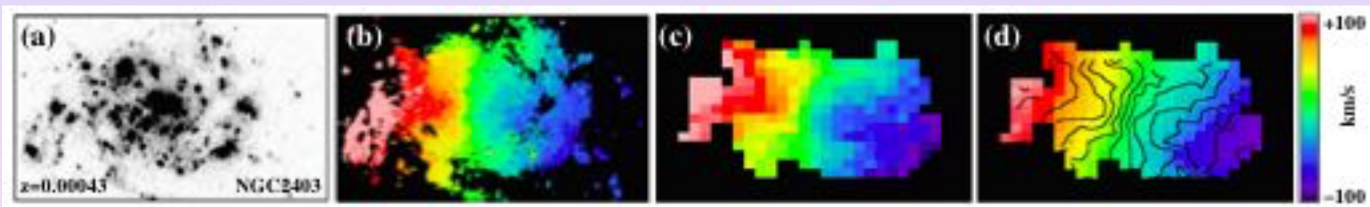
VLT / GIRAFFE

Grating-dispersed spectrographs

Multi-object configurations

- FLAMES/GIRAFFE science: emission-line kinematics of distant galaxies.

Hα image — high-res. FP map — z~0.2 simulation — deconvolution using Hα map

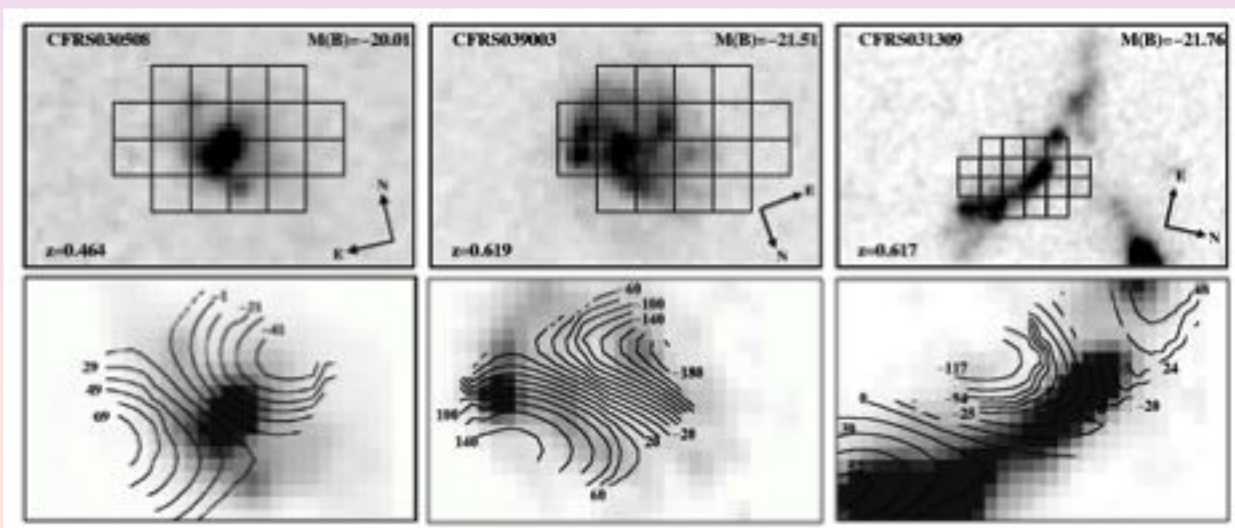


simulation: DisGal3D

Flores et al.'04

HST+ overlay

DisGal3D deconvolutions



Note: isovels heavily smoothed

Grating-dispersed spectrographs
summary of considerations

- Information packing: format-driven trades
  - Lenslets and filtered-multi-slit have limited spectral sampling.
  - Pure fiber systems have at best 65% integral coverage.
  - Fiber+lens, slicers, and lenslets yield comparable sampling of telescope focal plane.
  - Slicers give most efficient packing on detector.
  - Only slicers preserve full spatial information.
- Coverage vs purity: scattered light and cross-talk
  - science-driven trade-off -- *in what way are you greedy?*
  - pure fiber systems are the cleanest
- Sky subtraction
  - Fiber-based systems offer the most mapping flexibility.
  - Slicers preserve spatial information.

Grating-dispersed spectrographs

Sky Subtraction

- Issues and root causes of problems:
  - *Low dispersion*: sky-lines contribute overwhelming shot-noise.
  - *Aberrations and non-locality*: sky-line profiles vary with field angle (spectral and spatial).
  - *Stability*: instrument-flexure and detector fringing.
  - *Under-sampling*: compounds problems of field-dependent aberrations and flexure.
- Solutions / algorithms
  - Well-sampled, high-resolution data on a stable spectrograph is a premium (you get what you pay for).
  - *Beam-switching*: interleave object and sky exposures (50% efficiency).
  - *Nod-and-shuffle:* shuffle charge and nod telescope between object and sky positions (50% efficiency).
  - *Aberration modeling:* treat IFU data as long-slit.
    - example of telescope-time-efficient algorithm.

Grating-dispersed spectrographs
sky subtraction

- Example: wave-calibrated fiber data in pseudo-longslit format

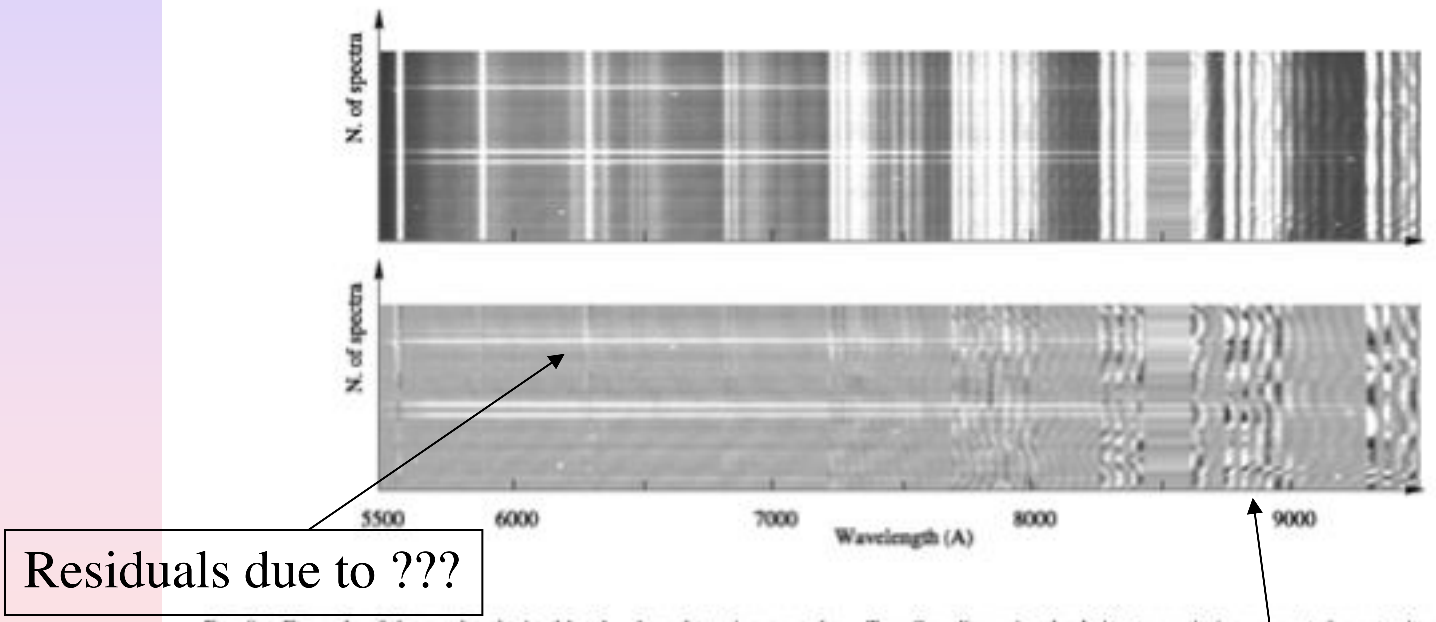


FIG. 8.—Example of the results obtained by the sky subtraction procedure. *Top:* One-dimensional relative transmission–corrected spectra in an exposure taken with the low-resolution red grism. *Bottom:* Same spectra after sky subtraction. The 5892 Å sky line has been used to group spectra before "average" sky spectrum computation. In the ~8500 Å region, the zero order due to a nearby pseudoslit has been clipped, creating a "flat" intensity distribution.

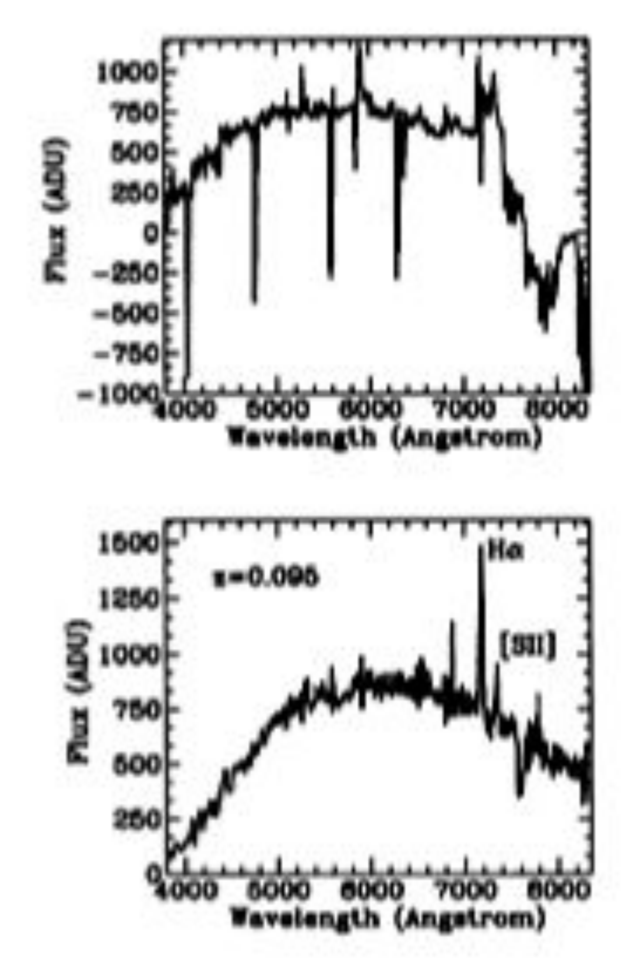
Zanichelli et al. '05
VIMOS, VLT 8m

Grating-dispersed spectrographs
sky subtraction

- Lissandrini et al. ‘94
  - ➢ Use sky-lines for 2nd-order flux calibration.
    - o Flat-fields aren’t good enough.
  - ➢ Model scattered light from neighboring fibers.
  - ➢ Map image distortions in pixel space to obtain accurate wavelength calibration

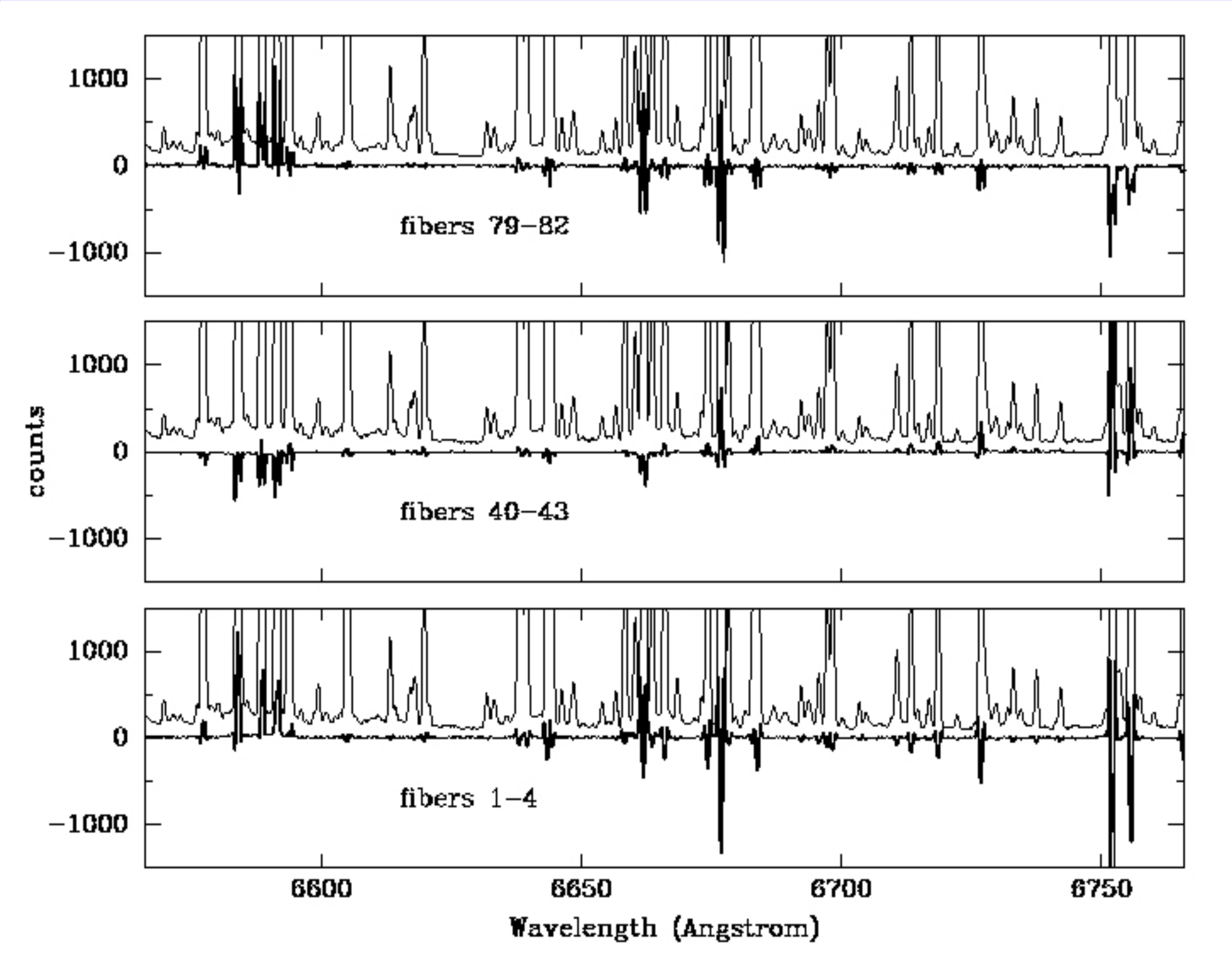
before

after



Grating-dispersed spectrographs
sky subtraction

- Higher-order aberrations are important
  - Wavelength calibration is critical, but this is only the first moment, i.e., centroid
  - 2nd-moment and higher-order aberrations are important for defining line width and shape (skew, kurtosis)

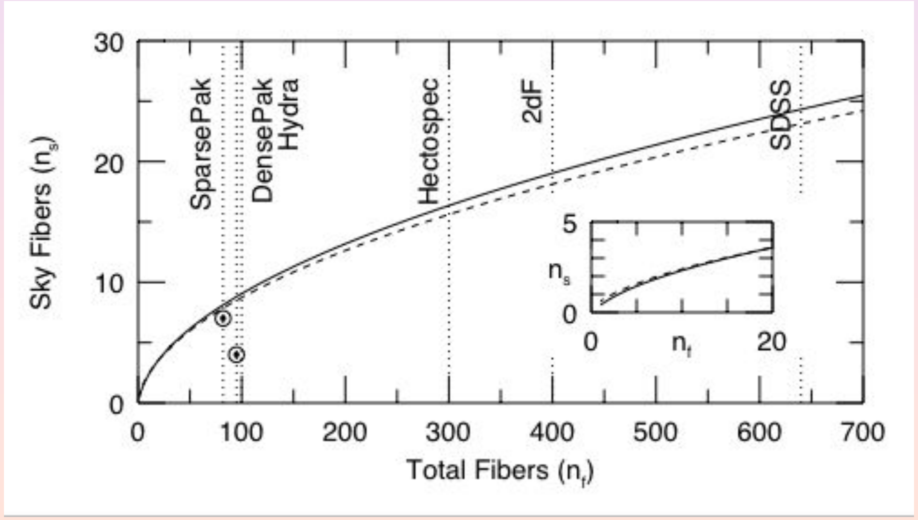


Bershady et al. ‘05: SparsePak line-lamp spectra

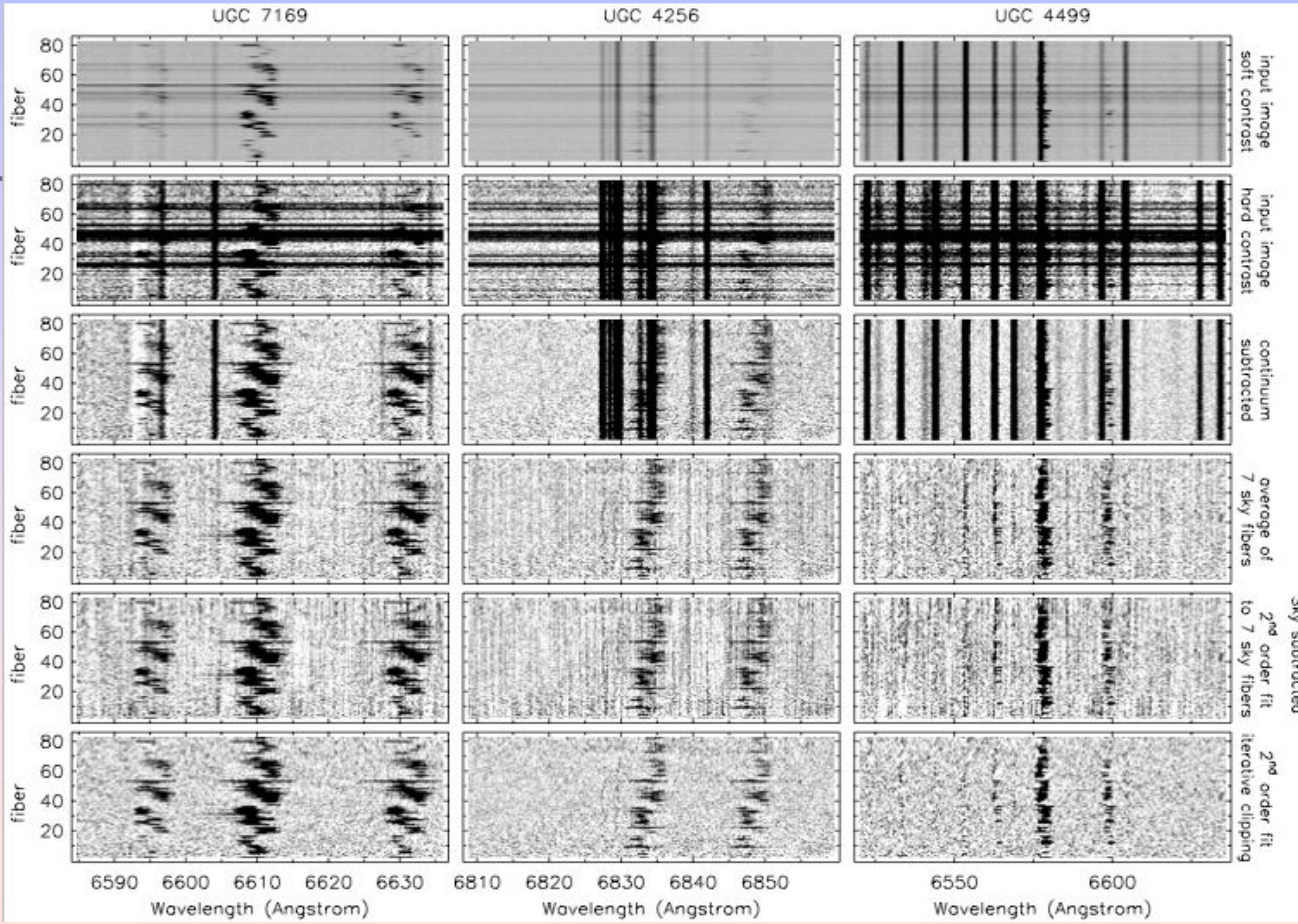
Grating-dispersed spectrographs
sky subtraction

- Solution w/o beam-swithing or nod-and-shuffle
  - Treat multi-fiber data as long-slit
    - Wavelength calibrate and register
  - Subtract spectral continuum (object+sky) from each fiber (spatial) channel via low-order fit with clipping-rejection of lines.
  - Fit and subtract low-order function to each spectral channel with clipping rejection.
  - Replace object spectral (difference of sky-fiber and source fiber continua fits).
  - 100% efficient!

- Works well for narrow source line-emission with significant spectral-channel offsets (e.g., high-dispersion or intrinsically large velocity range).
- For other instrument or source cases (low dispersion, broad lines, small velocity range): If aberrations are significant, need more sky fibers.



Bershady et al. '04

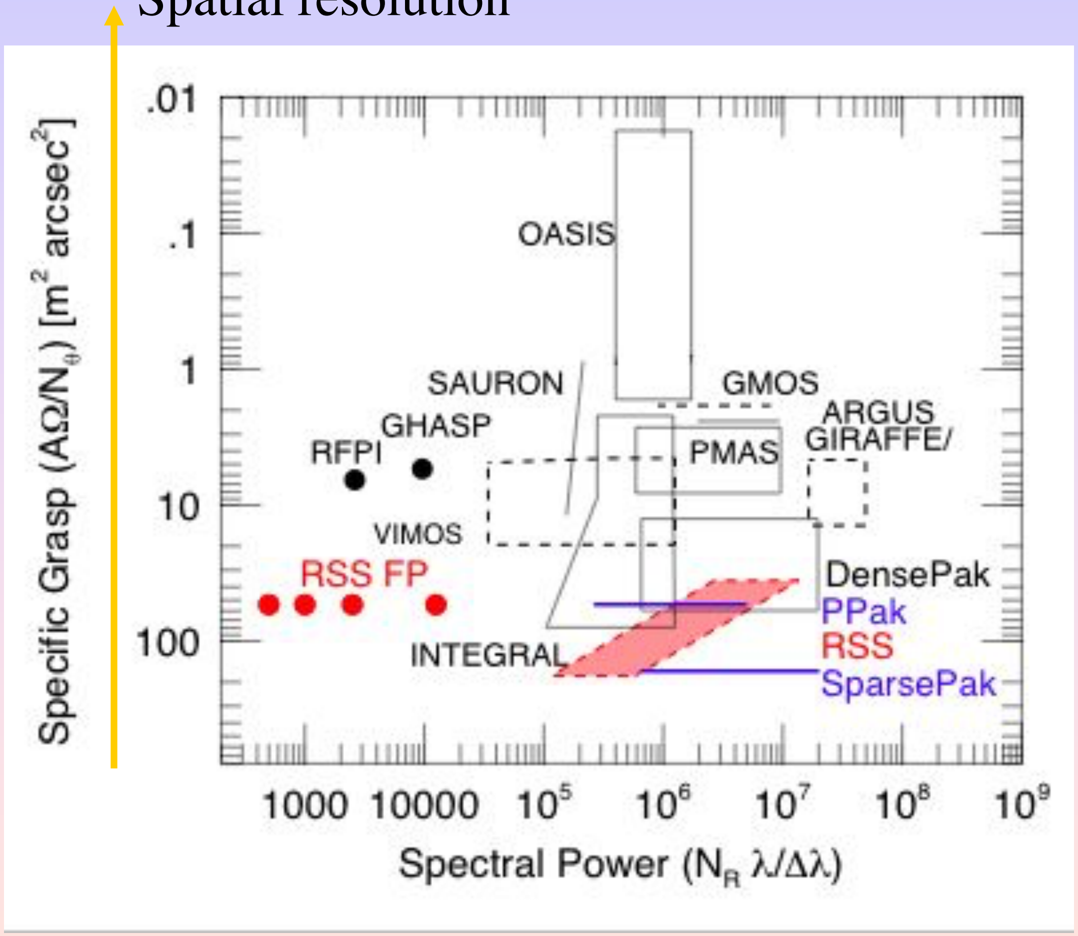


Bershady et al. '05: SparsePak

Existing instruments
Summary of sampled parameter space circa 2010

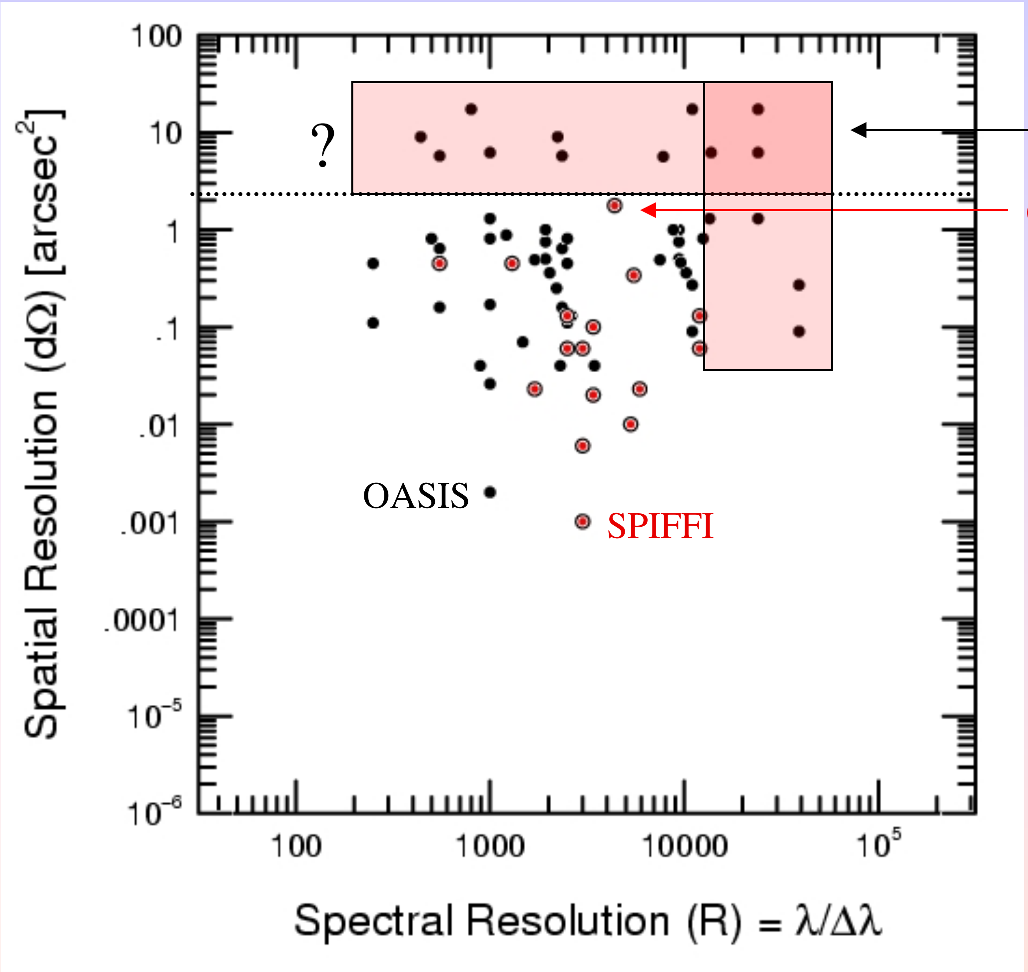
- Spatial vs spectral / coverage vs resolution
  - ➢ reliable, consistent ε measurements unavailable for most instruments
  - ➢ use grasp instead of etendue (warning: really want etendue)
  - ➢ many merit functions - start with grasp and spectral power

Spatial resolution



Bershady et al. '04 *(revised)*

Existing instruments
summary of sampled parameter space circa 2010



Fiber IFUs
- Integral
- DensePak
- SparsePak
- PPak

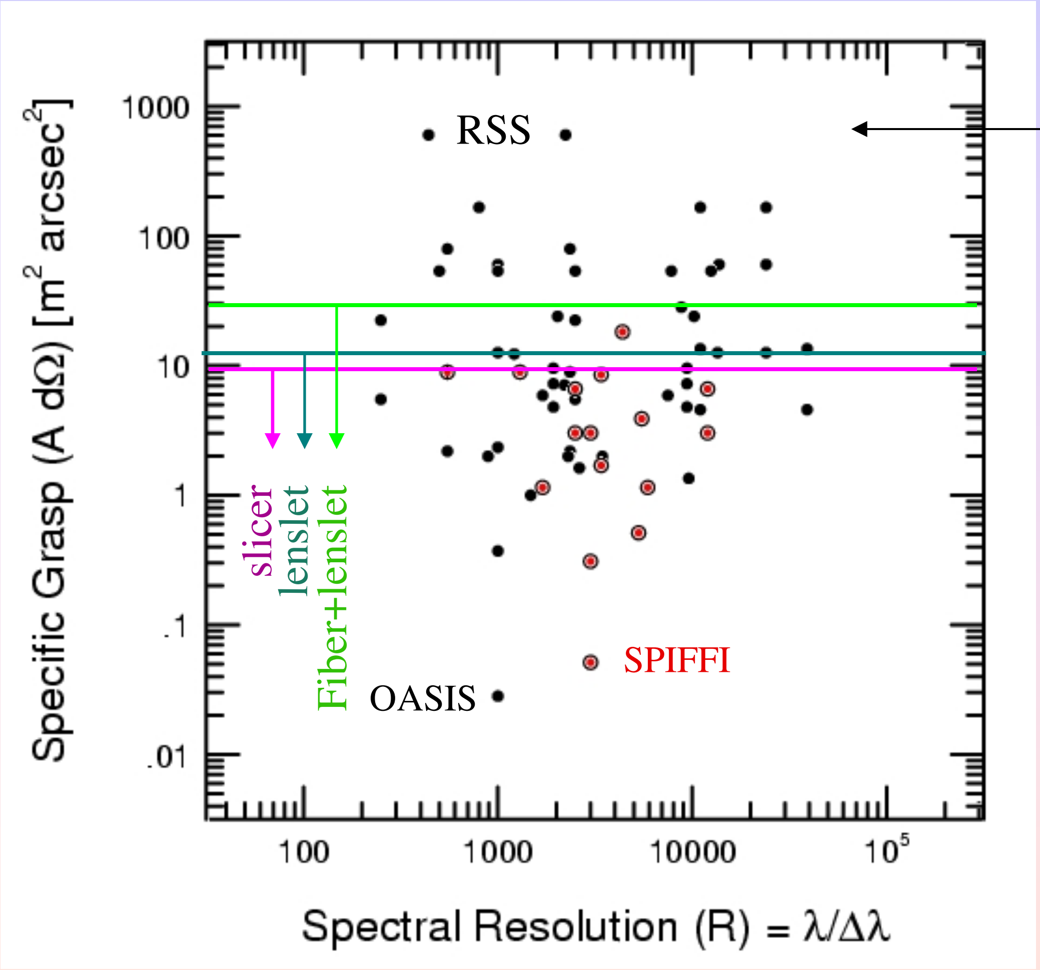
and FMS
- RSS

Spatial resolution:
- higher in NIR on average

Spectral resolution:
- higher in optical

optical ● infrared ◉

Existing instruments
summary of sampled parameter space circa 2010



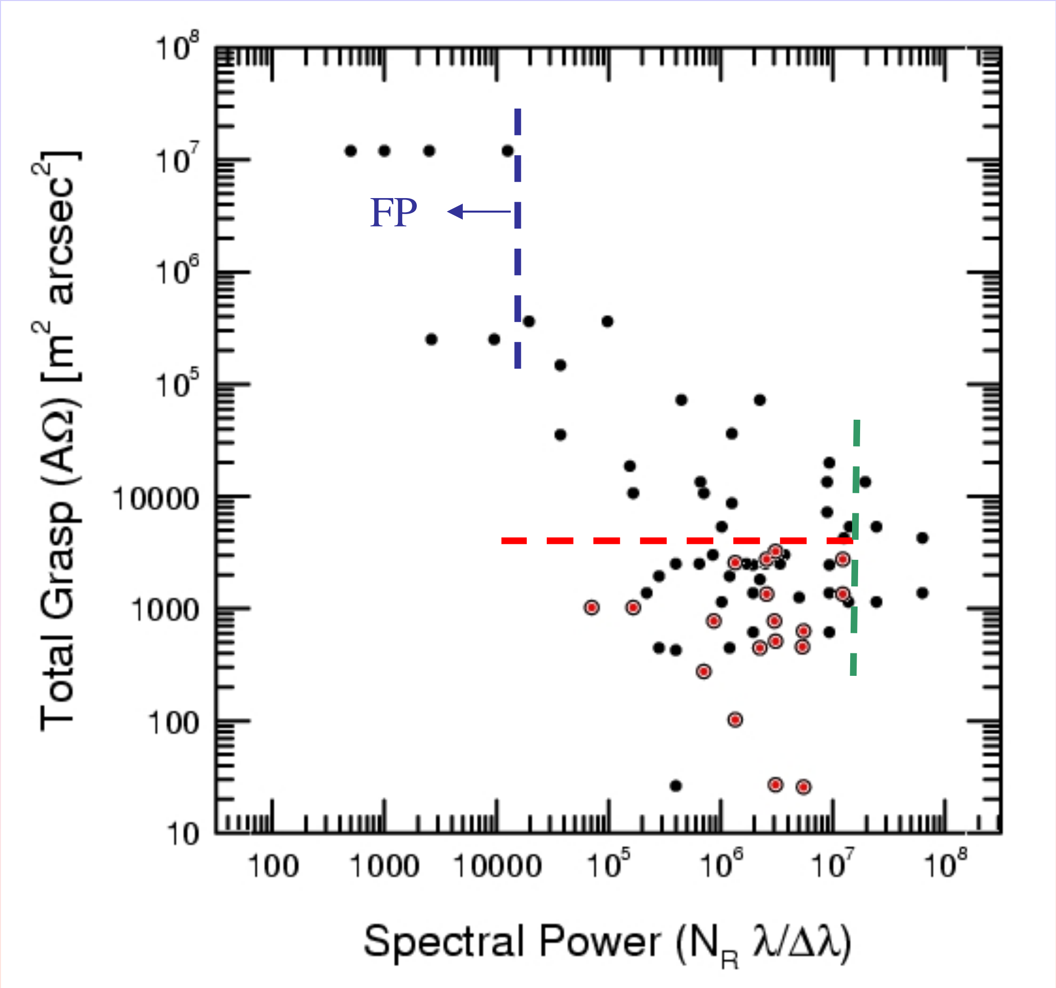
Fiber IFUs
- Integral
- DensePak
- SparsePak
- PPak

and FMS
- RSS

Specific grasp:
- higher in optical
- highest in fiber systems and FMS

optical ● infrared ◉

Existing instruments
summary of sampled parameter space circa 2010



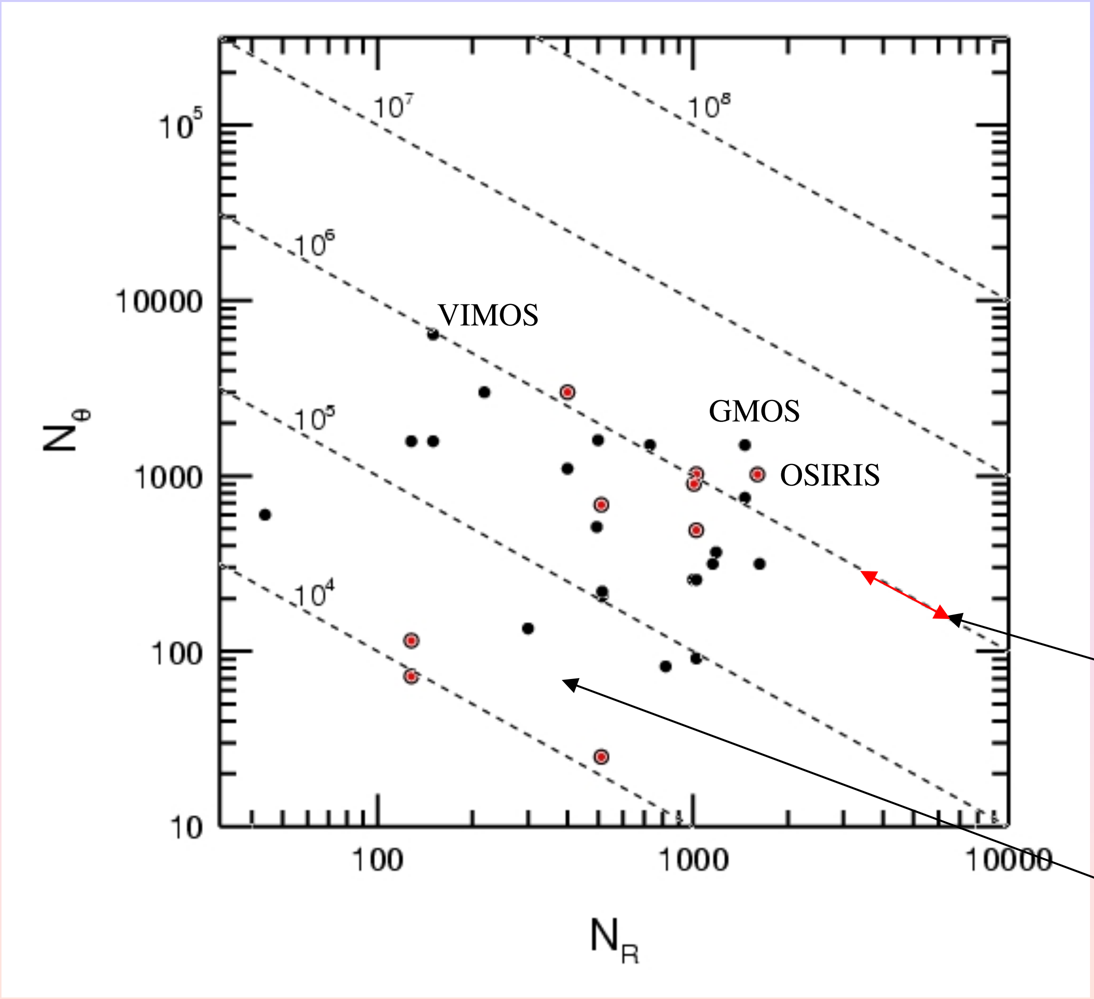
optical ● infrared ◉

Optical/NIR instruments trade spatial resolution for grasp.

No high-grasp NIR instruments.

Highest spectral power instruments are optical.

Existing instruments
summary of sampled parameter space circa 2010



optical ● infrared ◉

Optical and NIR instruments sample comparable total information.

Optical instruments offer broader range of trades: spectral vs spatial.

Lines of constant total information: $N_R x N_\theta$

Older NIR instruments detector limited (early arrays were much smaller than CCDs).