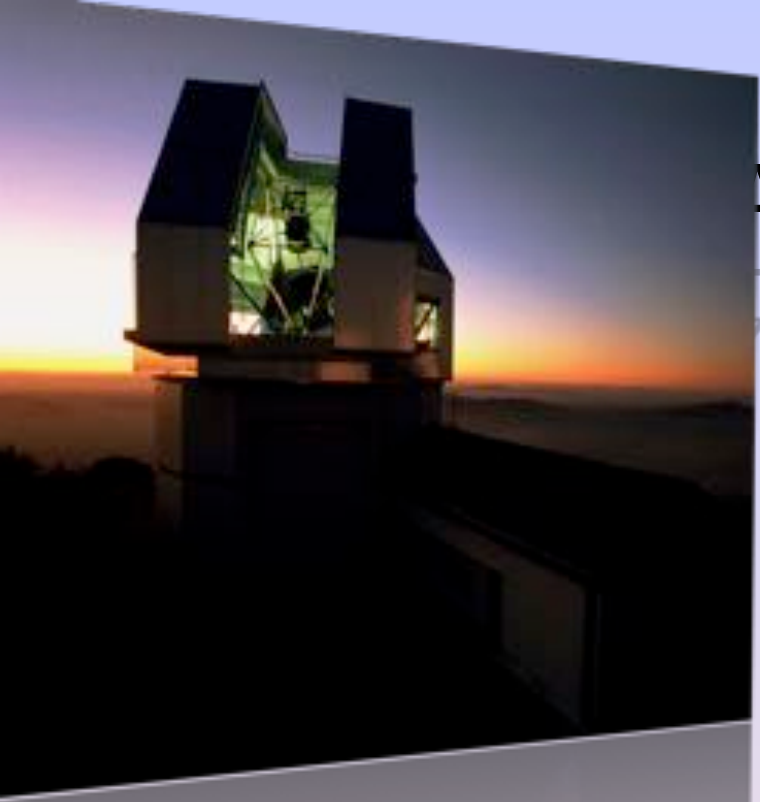


Astro 500

Techniques of Modern *Observational* Astrophysics

Matthew Bershady
University of Wisconsin

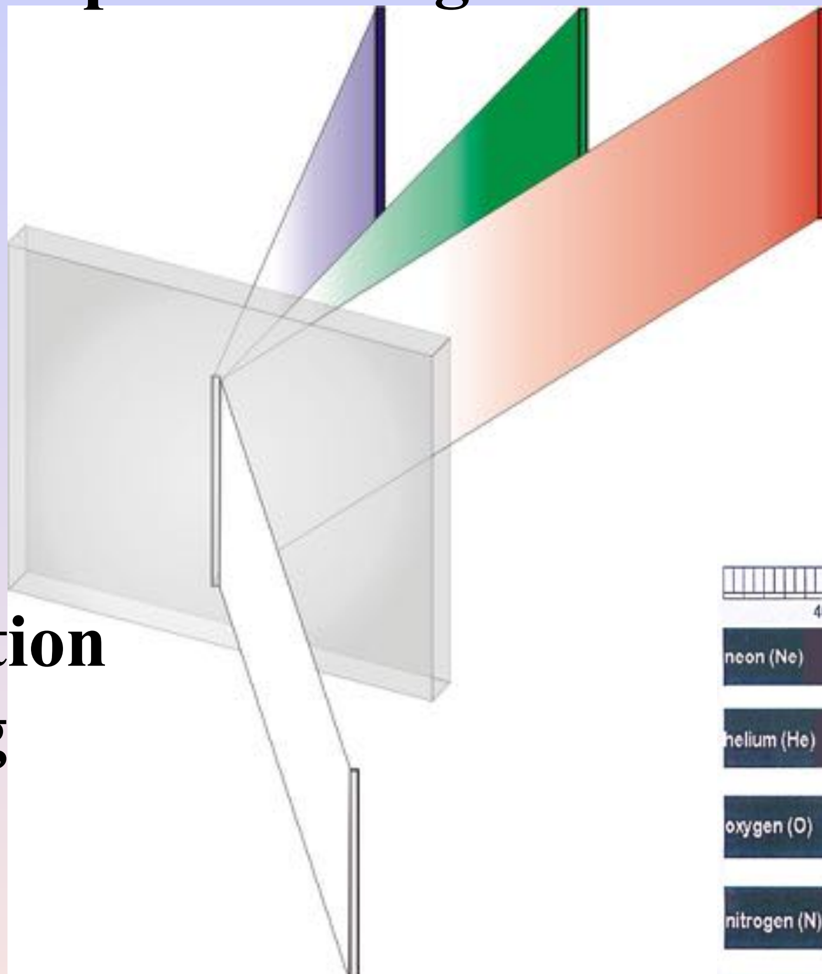
Lecture Outline

Spectroscopy from a 3D Perspective

- Basics of spectroscopy and spectrographs
- Fundamental challenges of sampling the data cube
- Approaches and example of available instruments
  - I: Grating-dispersed spectrographs ← **a lot of material**
  - II: Fabry-Perot interferometry
  - III: Spatial heterodyne spectroscopy

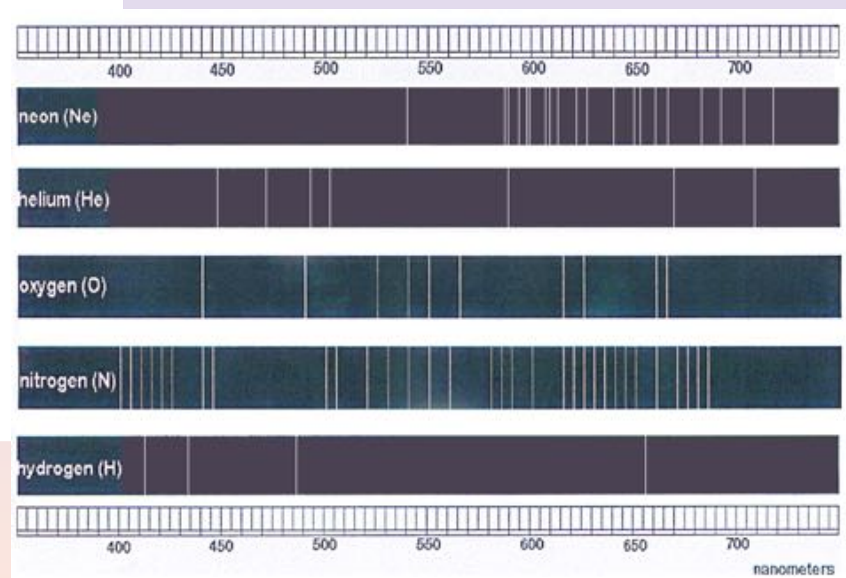
Basics of Spectroscopy:

Dispersed images of entrance slit



Diffraction Grating

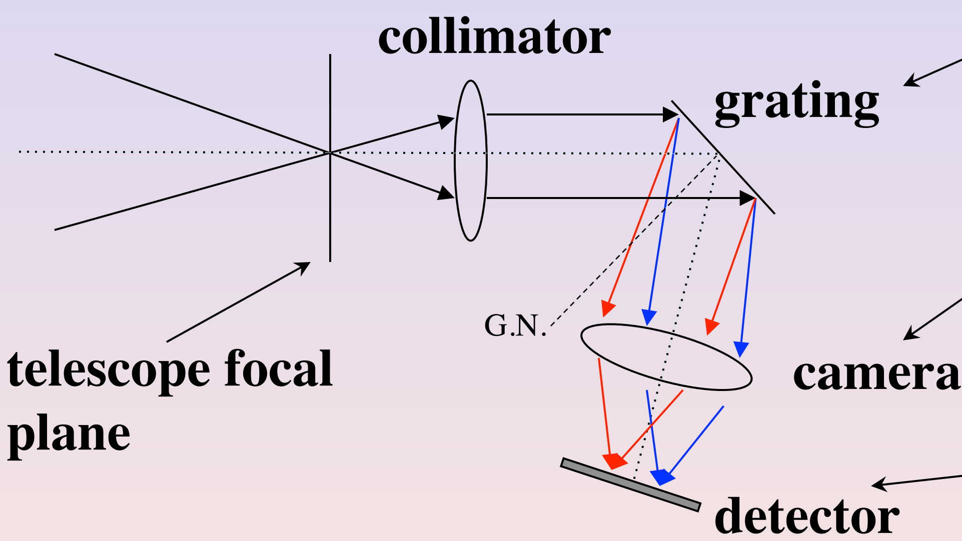
Entrance Slit



But this is only one way to skin the cat…

The Basic Spectrograph

- Gratings do not require but typically are used with collimated light. A basic spectrometer layout:



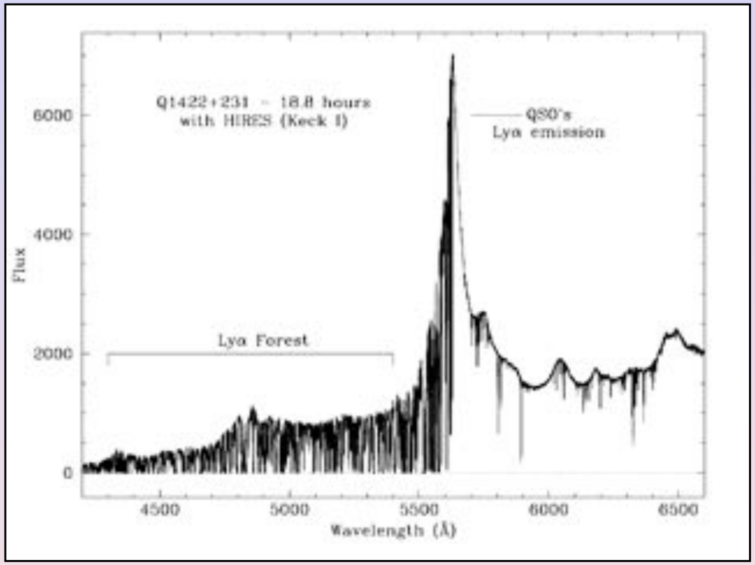
Grating tilt to varies the wavelengths arriving on the detector

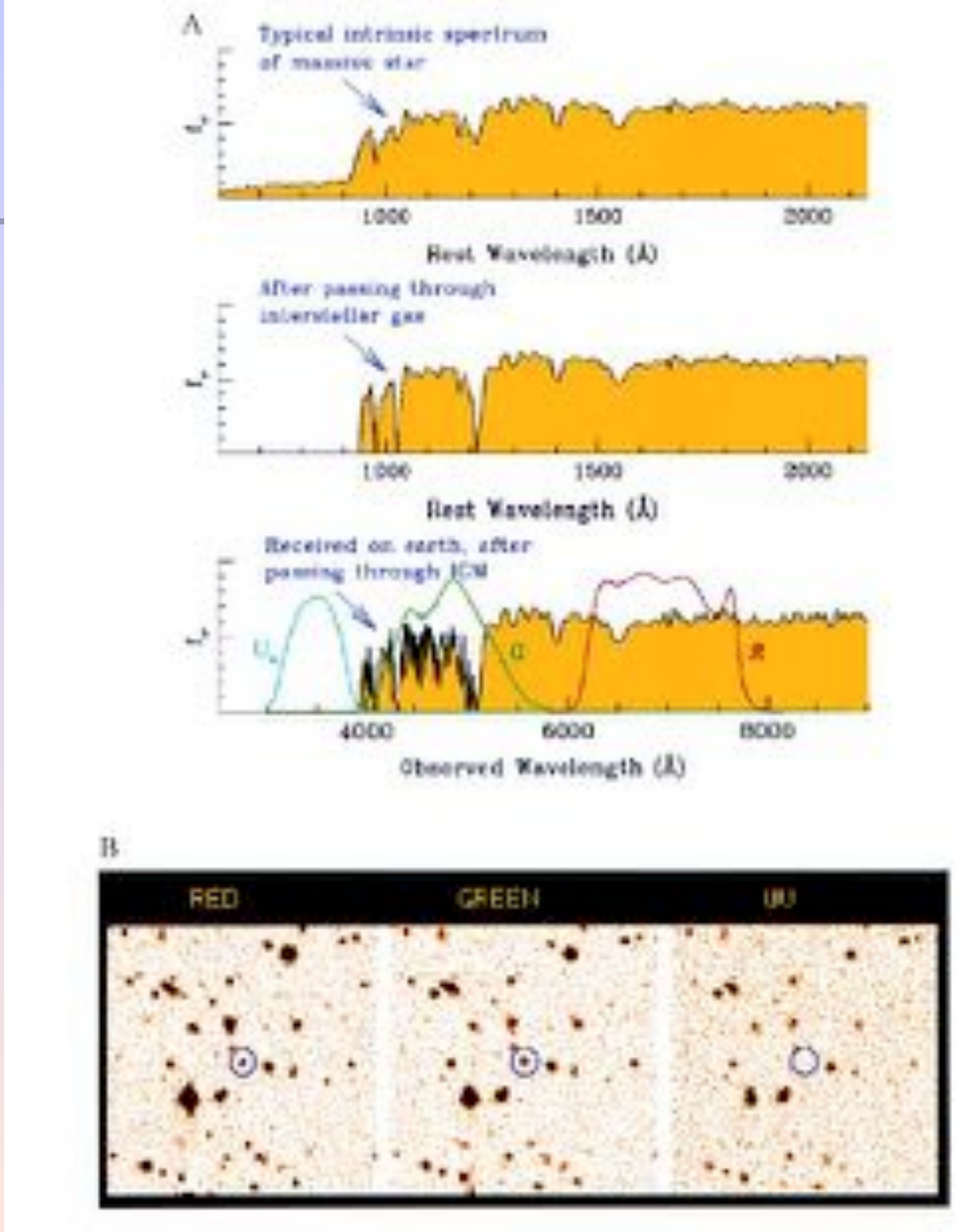
Camera-collimator angle tunes grating efficiency

Detector angle tunes chromatic focus

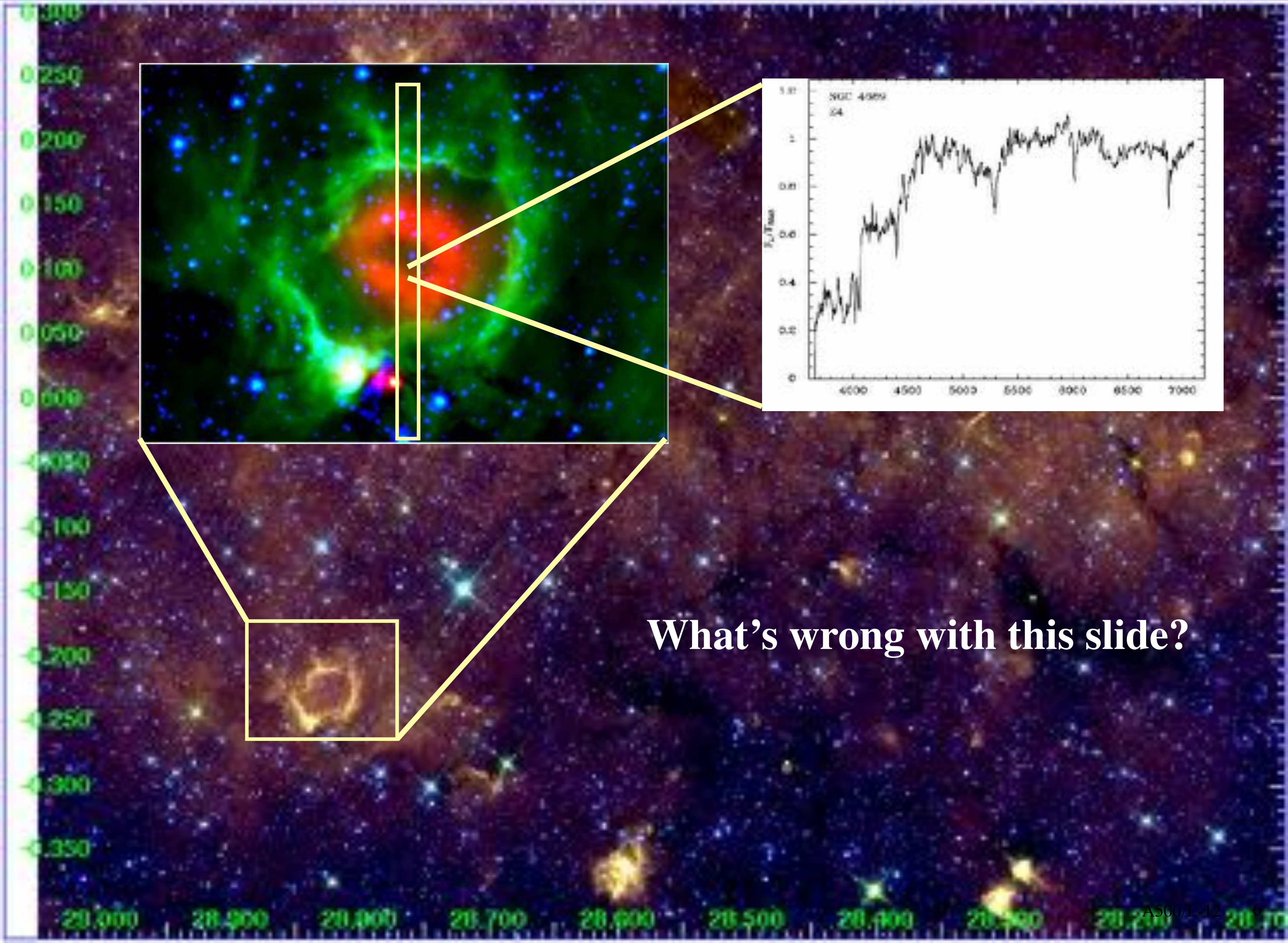
Replace the grating with a mirror and what to you have?
(And how does the camera-collimator angle relate to the grating angle?)

Spectra vs photometry





- Bowen, 1962, Astronomical Techniques, pg 34.
- Pogge, 1992, ASP Conf. Ser.#23, pg.160


0.250
0.200
0.150
0.100
0.050
0.000
-0.050
-0.100
-0.150
-0.200
-0.250
-0.300
-0.350
28.900
28.800
28.700
28.600
28.500
28.400
4000
4500
5000
5500
6000
6500
7000
0
0.2
0.4
0.6
0.8
1
What’s wrong with this slide?

Fundamental challenges:

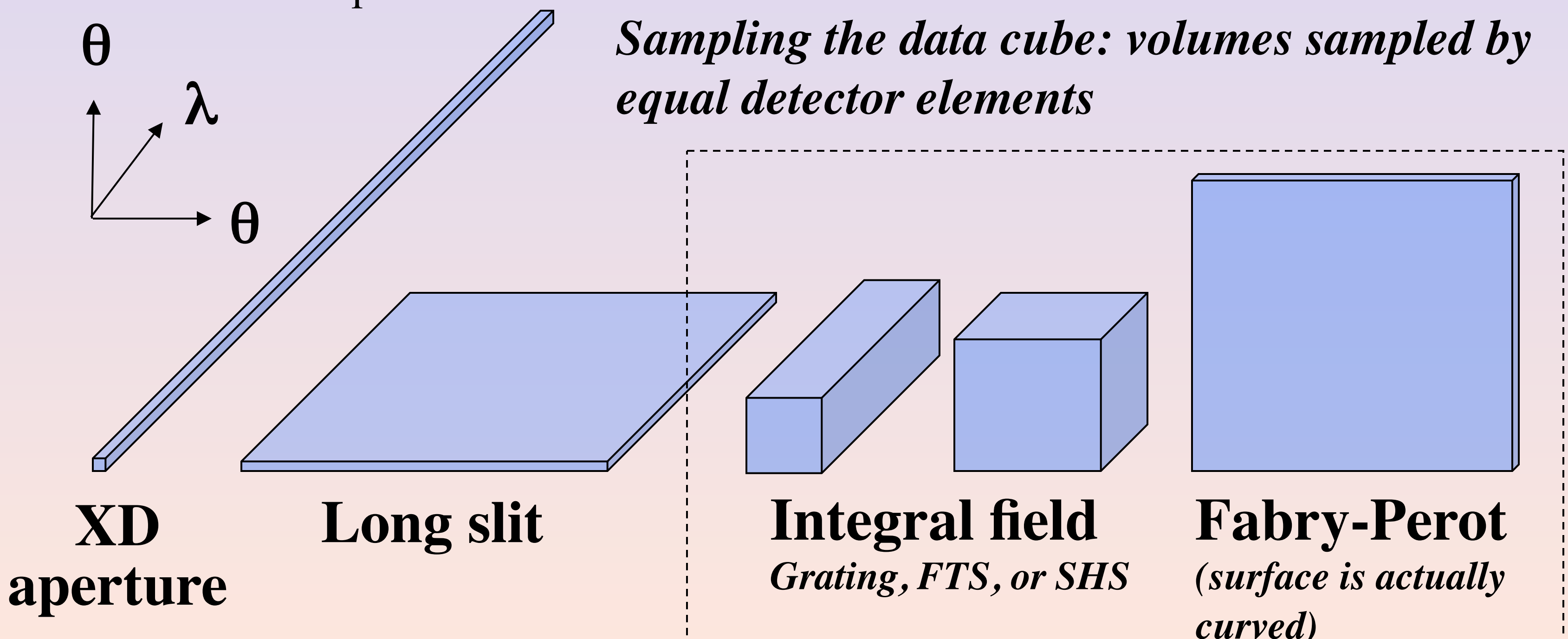
Considerations for sampling the data cube

- The detector limit-I: three into two dimensions
  - spatial vs spectral sampling
  - integral vs sparse sampling
  - coverage vs resolution (spatial and spectral)
  - merit functions: grasp, etendue, R, etc.
- The detector limit-II: read-noise
  - detector vs photon limited
  - background-limited: constraints on the Ω-R sampling unit

The detector limit-I:
Three into two dimensions

- spatial vs spectral sampling and coverage
  - detectors are only 2D today (maybe 3D tomorrow), but data is 6D:
    - **2 spatial dimensions**
    - **1 spectral dimension**
    - 1 temporal dimension
    - 2 polarizations

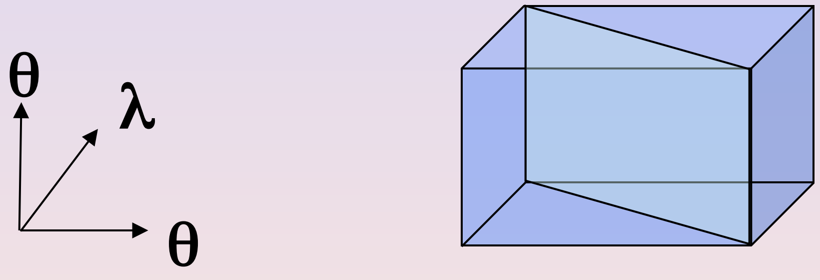
Sampling the data cube: volumes sampled by equal detector elements



The detector limit-I:
Three into two dimensions

- spatial vs spectral sampling and coverage

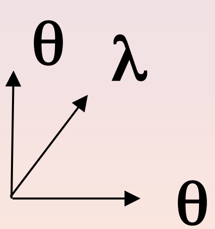
Differential spatial/spectral sampling possible?

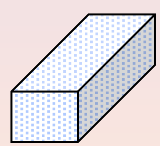


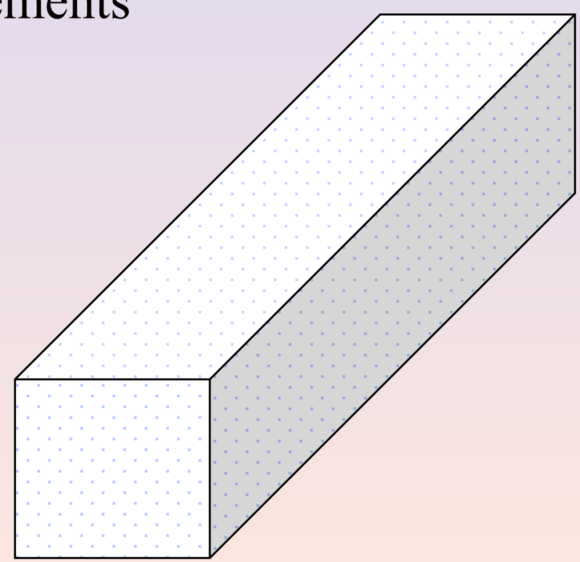
- **Choice is in how data-cube is sliced;**
- **Can't easily rotate a slice within the cube;**
- **Science motivation?**

The detector limit-I:
Three into two dimensions

- Coverage vs resolution (spatial and spectral):
  - Spectral resolution $R = \lambda/d\lambda$
  - N_R = number of spectral resolution elements
  - Spectral coverage = $\Delta\lambda = N_R \times d\lambda$
  - Spatial resolution $d\Omega$
  - N_θ = number of spatial resolution elements
  - Spatial coverage $\Omega = N_\theta\, d\Omega$
  - $N_R x N_\theta \sim$ constant for given detector
  - *Science-drive trades*

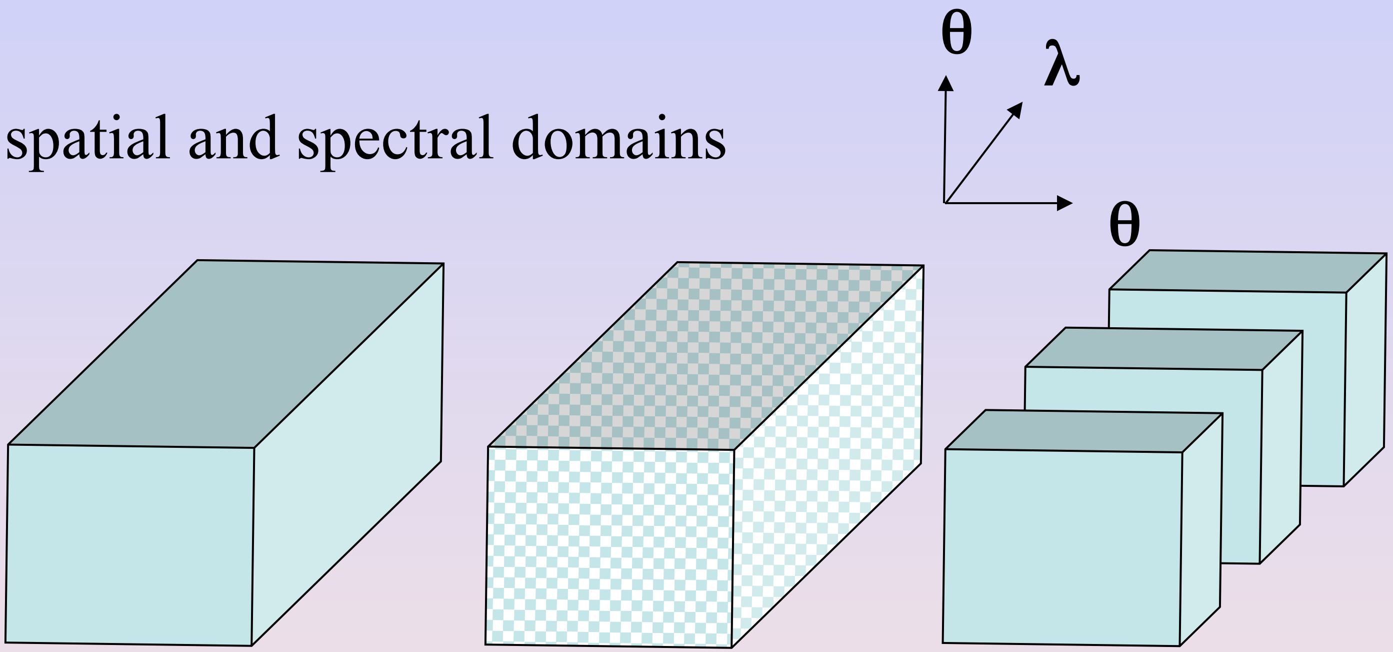






Integral vs sparse sampling

- spatial and spectral domains



Integral
Fibers, lenslets
Slicers, interferometers

Sparse spatial sampling
Fibers or MOS
(fibers or slicers)

Sparse spectral sampling
Multiple exposures with FP, multi-beam spectrograph or <u>notch gratings</u>

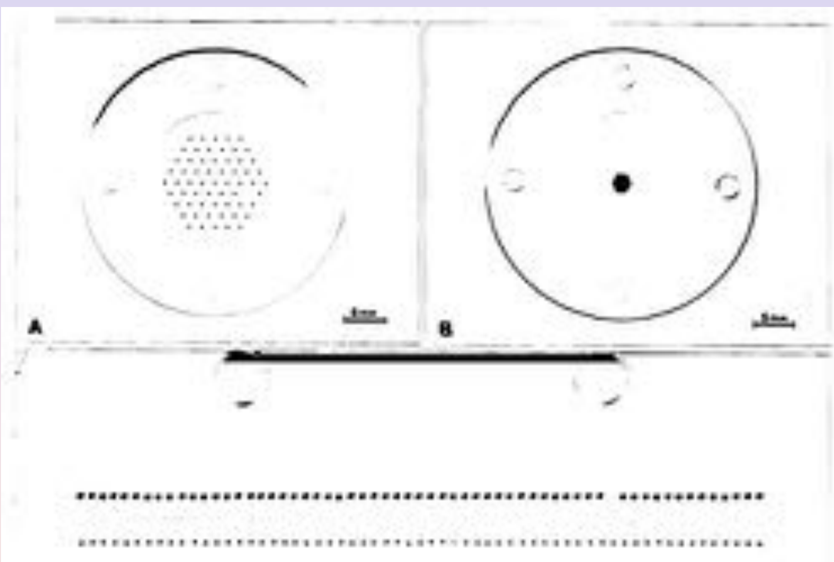
Not all data has equal information content!

Integral vs sparse sampling

- Real sparsely-sampled IFUs: *formatted field units*

60” FoV
7.3” Δ_f
1.4” D_f

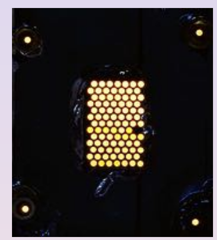
13” FoV
1.5” Δ_f
0.9” D_f



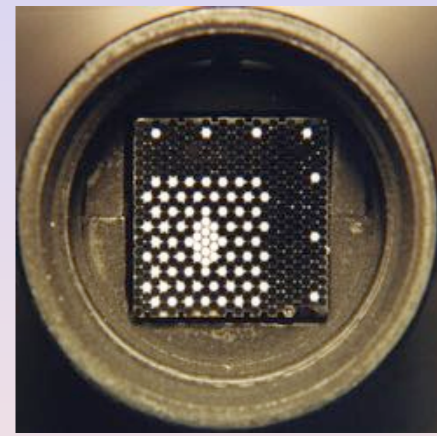
Hexaflex, WHT 4.2m, Flex spectrograph

Arribas, Mediavilla & Rasilla‘91

27x43” FoV
4” Δ_f
2.7” D_f



71” FoV
5.6” Δ_f
4.7” D_f



DensePak and SparsePak
WIYN 3.5m, Bench spectrograph

Barden et al. ‘98 **Bershady et al. ‘04**

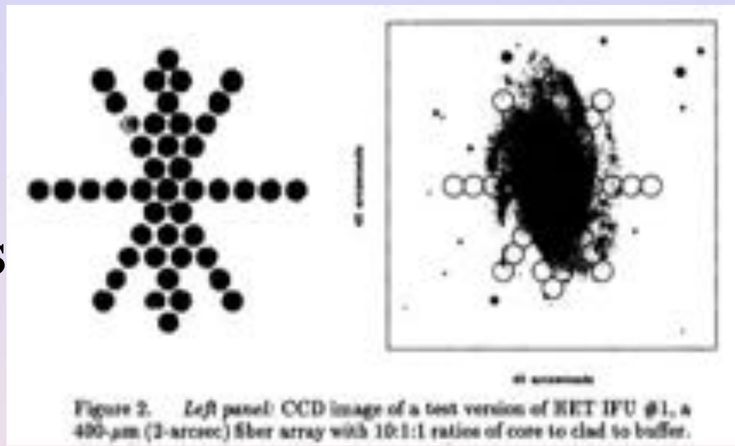
Integral vs sparse sampling

- Sparse sampling is useful when large FoV and spectral sampling is at a premium *and* some regularity and continuity can be assumed in the spatial distribution function.

Verheijen & Bershady '02

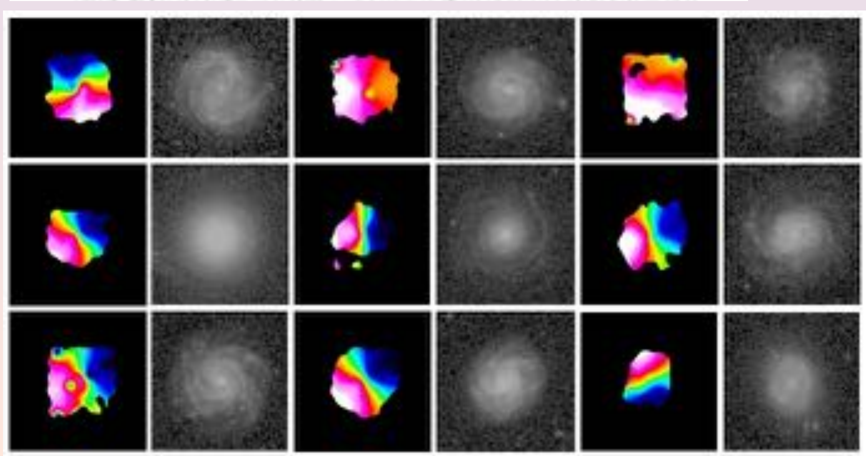
Bershady et al. '98

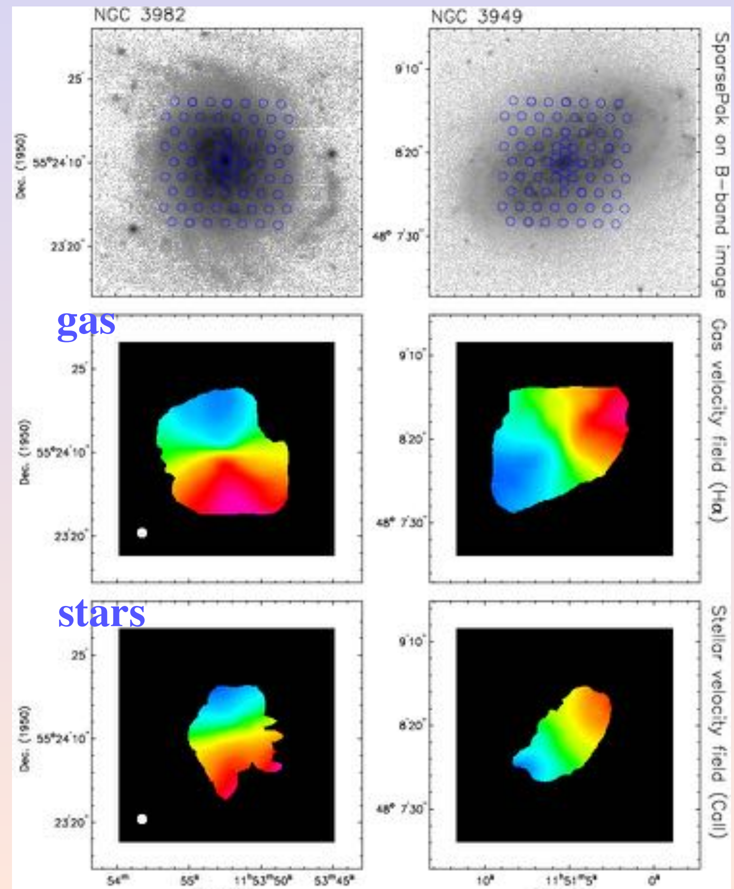
HET MRS prototype



Swaters et al. '06

Hα velocity fields





The detector limit-I:
Three into two dimensions

- Typical merit functions
  - Grasp = A Ω
    - o Ω is slit-width x slit-length for spec and $\pi/4$ x slit-length^2 for FP and FTS.
    - o A = collecting area = $\pi/4\ D_T^2$
    - o Specific grasp = A dΩ
  - Etendue = A Ω ε, where ε = total system efficiency (also specific etendue)
  - Ω R, dΩ R, where $R = \lambda/d\lambda$, i.e. the spectral resolution
  - A Ω R ε, A dΩ R ε
  - Spectral power = R N_R *if there is no premium on spatial information*
  - A $d\Omega^n N_\theta$ = A $d\Omega^{n-1}\ \Omega$ *if there is no premium on spectral information*

    n = 1 for high specific grasp, -1 for high resolution
  - $N_R\ N_\theta$, *if any information will do*

The detector limit-I:
Three into two dimensions

Add terms:

$R^n \, d\Omega^m$

- $n, m = 1$ if resolution is science-critical
- $n, m = -1$ if coverage is science-critical

- A grand merit function (warning: no such thing!)

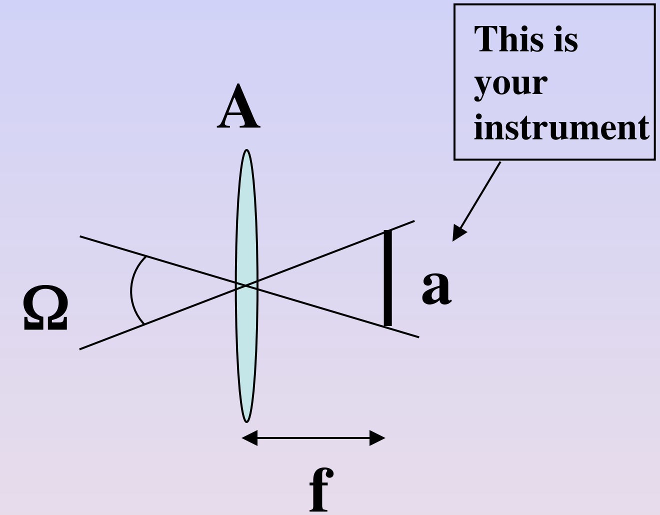
  - F.O.M. $= \varepsilon \; (\Delta\lambda / d\lambda) \; (\Omega / d\Omega) \; A \; \Omega_s \; \$^{-1}$
    $= \varepsilon \; N_R \; N_\theta \; A \; \Omega_s \; \$^{-1}$

    - o $\Delta\lambda$ sampled spectral range
    - o $d\Omega$ = sampling element (fiber, lenslet, or slicer slitlet area or seeing disk).
    - o Ω_s = survey or sample area
    - o \$ = cost

How many resolution elements can be coupled efficiently to the largest telescope aperture (A) covering the largest patrol field (Ω_s) for as little cost as possible?

The detector limit-I:
Three into two dimensions

AΩ is conserved in an optical system.



This means the same instrument has the same AΩ on any telescope *of the same focal ratio.*

$\Omega = a / f^2$

$A\Omega = A\, a / f^2$

$A/f^2 \sim \text{focal-ratio}^2$

What "killer" science would be done with MUSE on a 1m telescope? 4m?

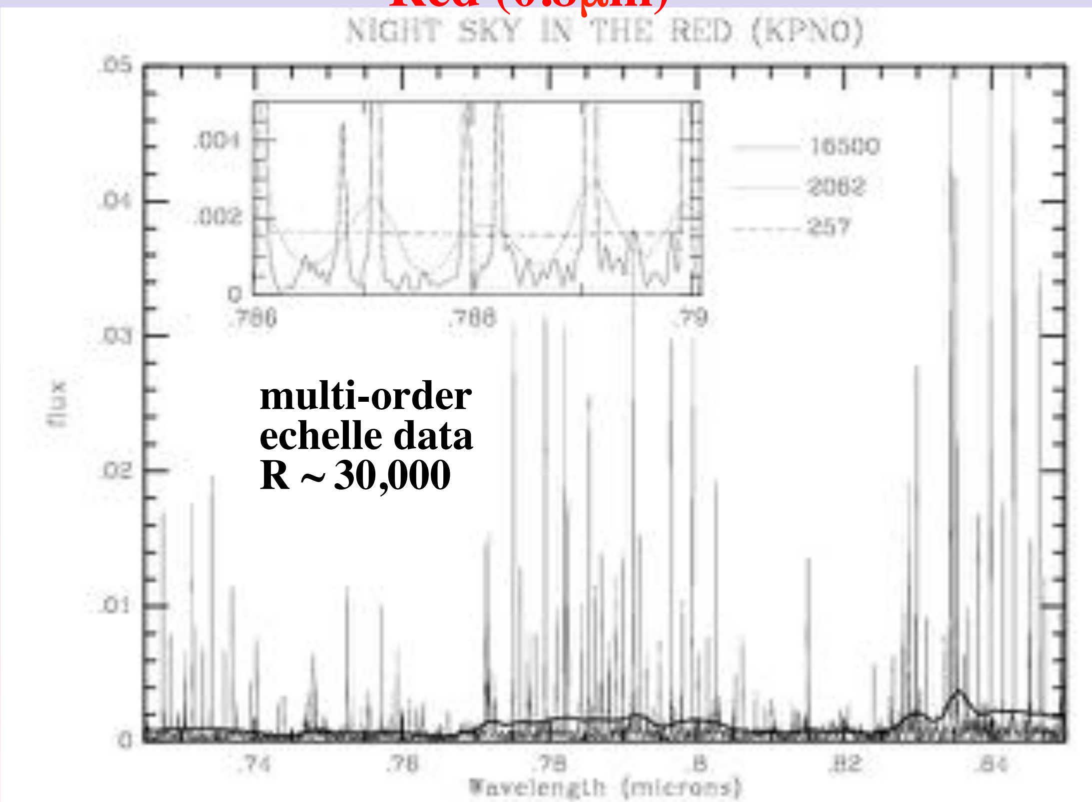
Critical point for diffuse sources of surface brightness S:

signal = S * A Ω

The detector limit-I:
Three into two dimensions

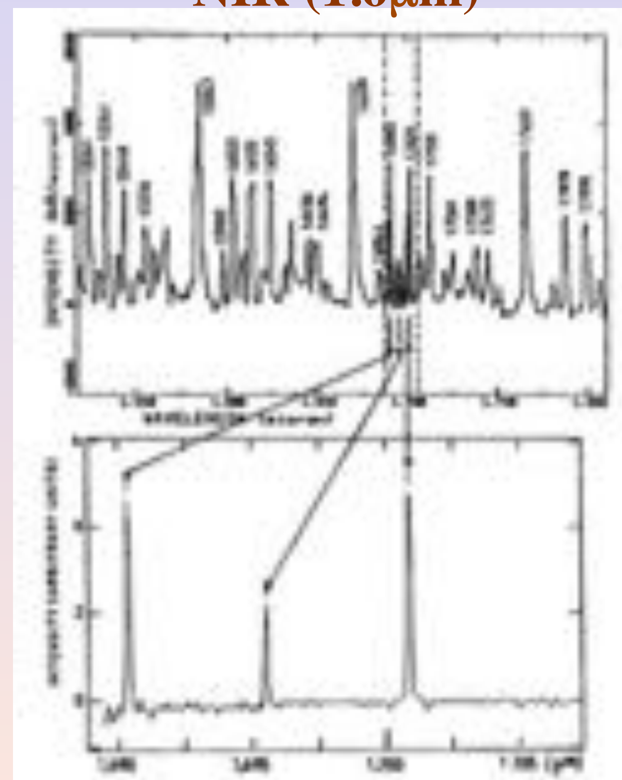
- **Why spectral resolution is so important:**
  - Terrestrial backgrounds, sensitivity, and sky subtraction
  - Situation similar from 0.7-2.2 microns: OH airglow dominates

Red (0.8μm)



MAB using echelle data from York & Lauroesch

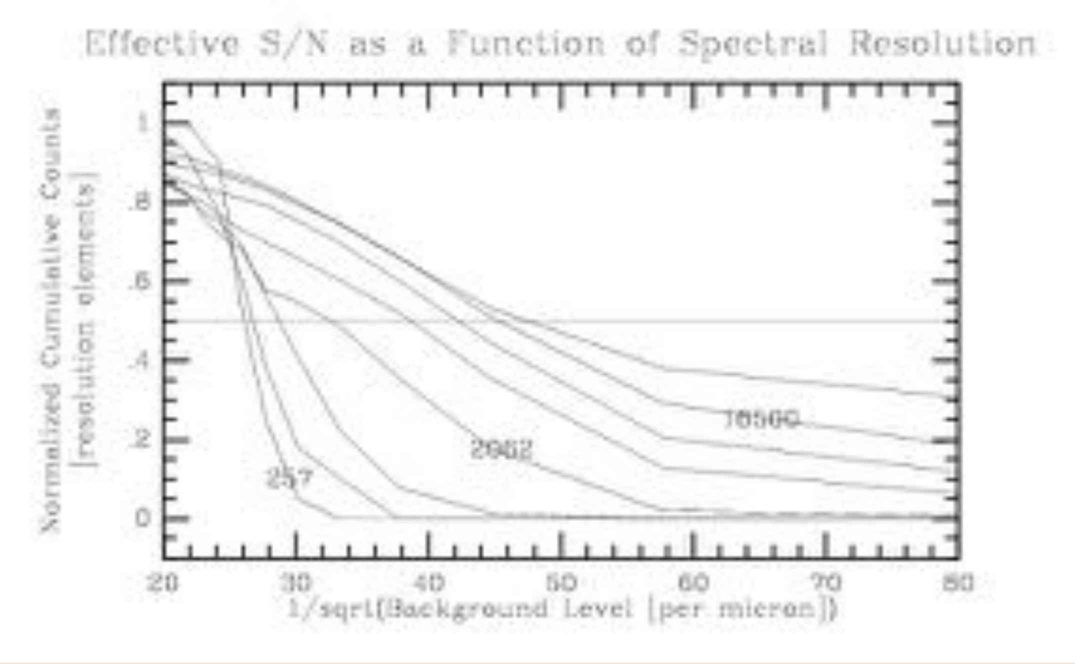
NIR (1.6μm)

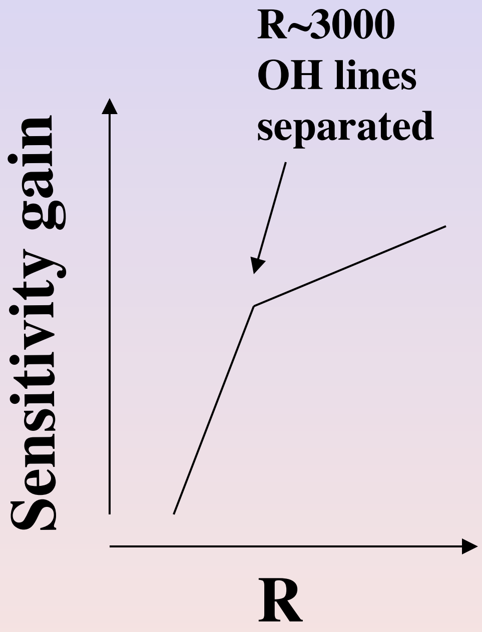


Maihara et al. '93

The detector limit-I:
Three into two dimensions

- Sensitivity implications of increased spectral resolution
  - Significant gains up to R = 2000-4000 as OH lines are separated
  - ***BUT*** linear gains continue up to m/s resolution of atmospheric OH lines

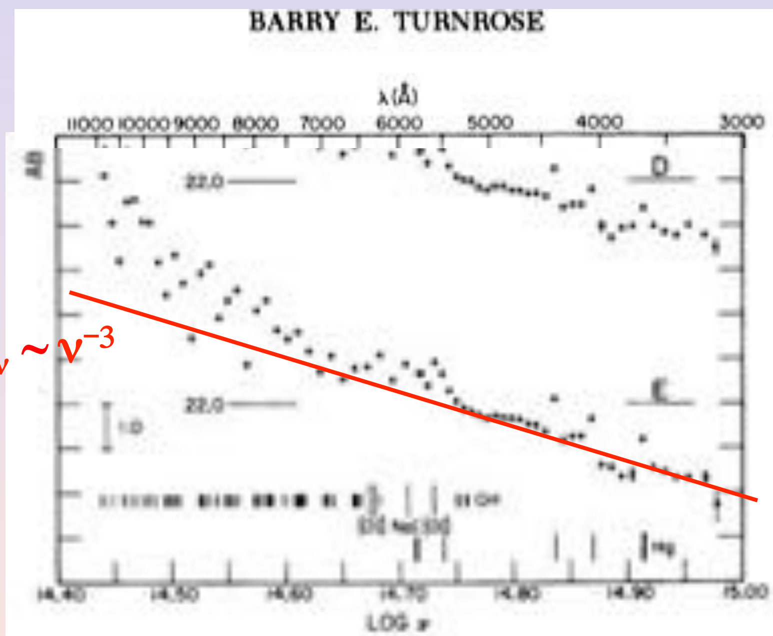




Results will vary slighty depending on exact spectral region

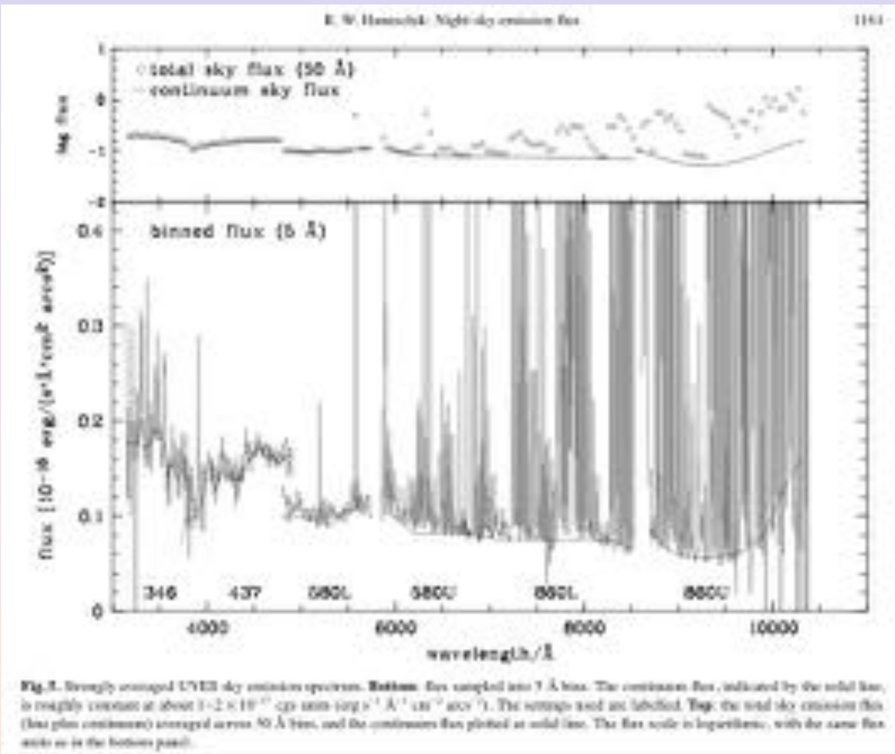
The detector limit-I:
Three into two dimensions

- What is the sky spectral continuum (from the ground) at high resolution?
- Trends with wavelength?
  - ➢ Outstanding, but fundamental issue.



$f_\nu \sim \nu^{-3}$

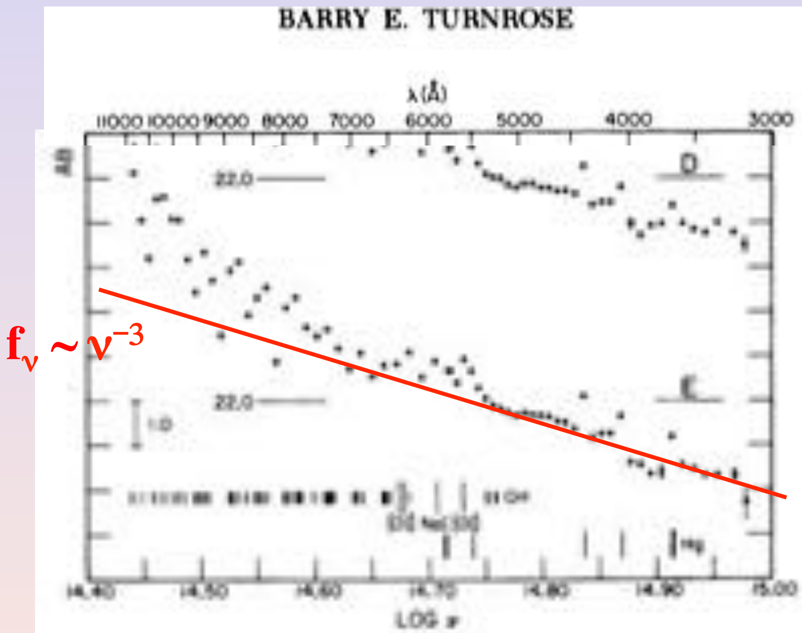
Turnrose '74



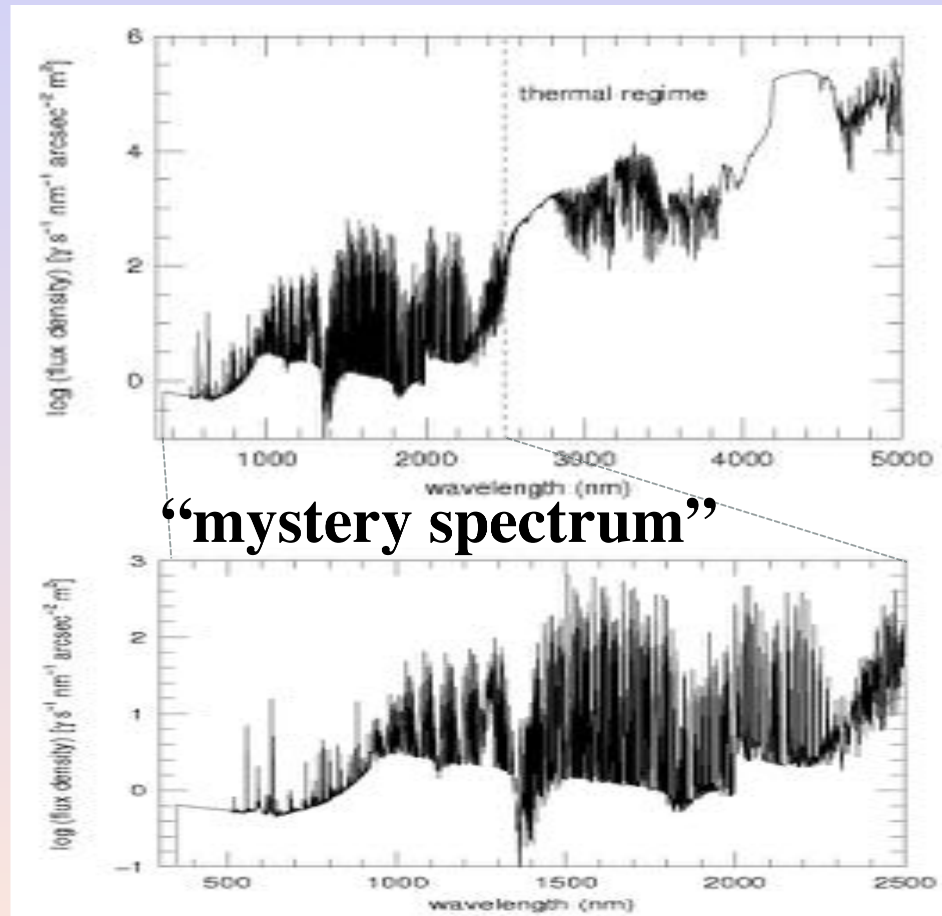
Hanuschik et al. '03

The detector limit-I:
Three into two dimensions

- What is the sky spectral continuum (from the ground) at high resolution?
- Trends with wavelength?
  - Outstanding, but fundamental issue.



Turnrose ‘74



The detector limit-II:
Read-noise

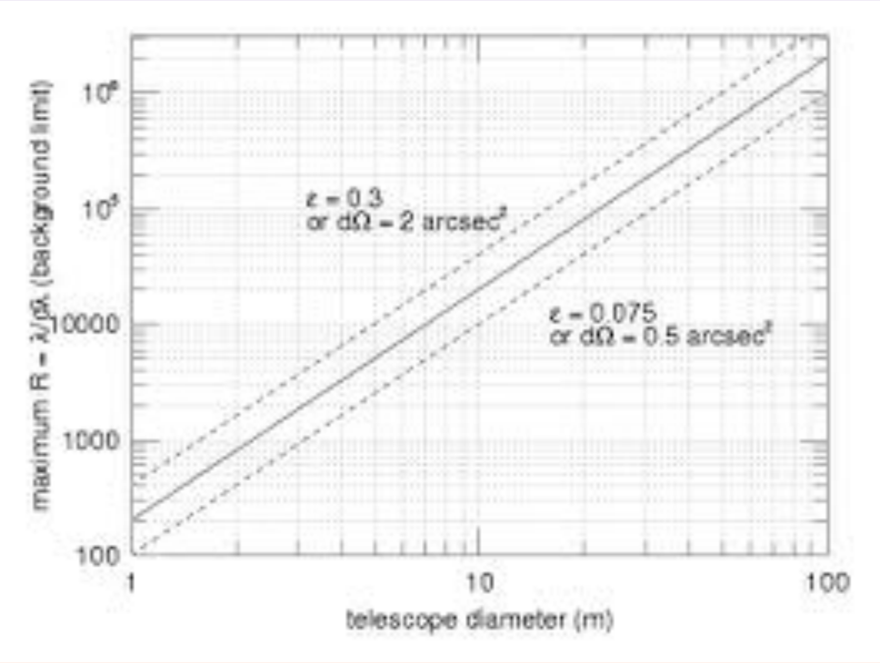
- Detector vs photon limited
  - S/N in different regimes
    - Source limited: $(S\,t)^{1/2}$
    - Background limited: $S\,(t/B)^{1/2}$
    - Detector limited: $S\,t\,(N_A)^{-1/2}\,RN$
      - S = source counts in aperture per unit time
      - B = background counts in aperture dΩ per unit time
      - t = exposure time
      - N_A = pixels in aperture dΩ
      - RN = rms read-noise per pixel
  - Prefer photon-limit (fundamental)
    - S/N is independent of sub-exposure time

photon limited

$d\Omega = \pi(\theta/2)^2$
θ = circular aperture diameter

The detector limit-II:
Read-noise

- Background-limited: constraints on the Ω−R sampling unit
  - spatial and spectral sampling unit can't be too small for given A, ε
- Detector limit (RN) constraint:
  - $R/d\Omega < 16500\,(D_T/9\text{m})^2\ (t/1\text{h})\ (\varepsilon/0.15)\ \text{arcsec}^{-2}$ [8m class]
  - $R/d\Omega < 2500\,(D_T/3.5\text{m})^2\ (t/1\text{h})\ (\varepsilon/0.15)\ \text{arcsec}^{2}$ [4m class]



Approaches

Examples of available instruments

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

Grating-dispersed spectrographs
basic spectrograph design

- **Grating equation**

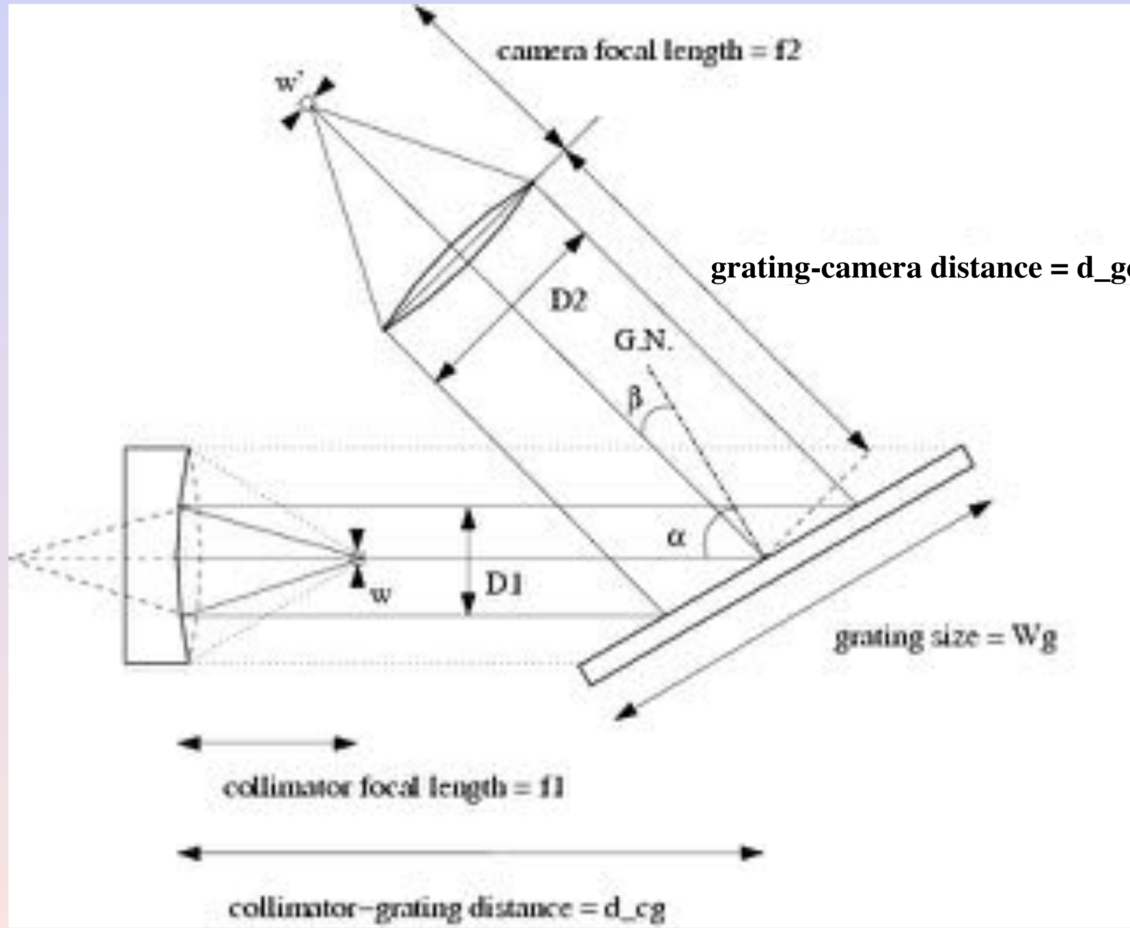
  $m\,\lambda = \sigma\,(\sin\beta \pm \sin\alpha)$

  (reflection or transmission)*
  - σ is groove separation (nm)
  - m is grating order (integer)[§]
- **Angular dispersion**

  $\gamma = d\beta/d\lambda = m / \sigma \cos\beta$

  $= (\sin\beta \pm \sin\alpha) / \lambda \cos\beta$
- **Linear dispersion**

  $dx/d\lambda = f_2\,\gamma$



§ $-\infty < m < \infty$

* Sign convention:
+ for reflection
– for transmission