



Astro 500

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Techniques of Modern Observational Astrophysics

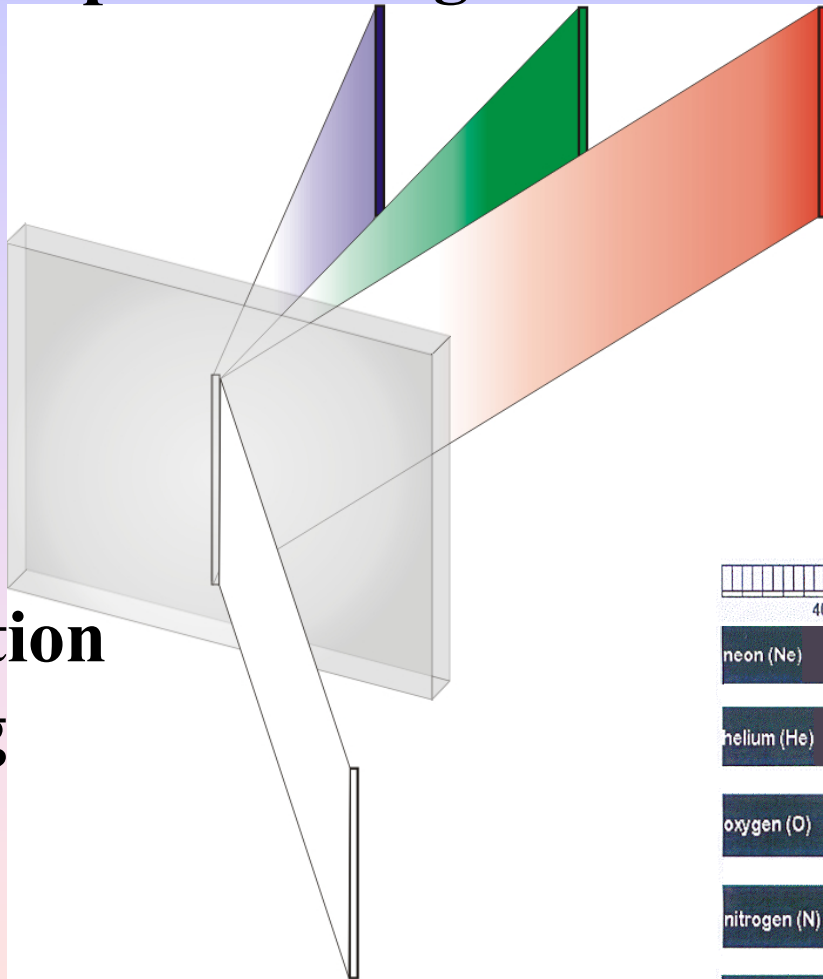
*Matthew Bershady
University of Wisconsin*

Lecture Outline

Spectroscopy from a 3D Perspective

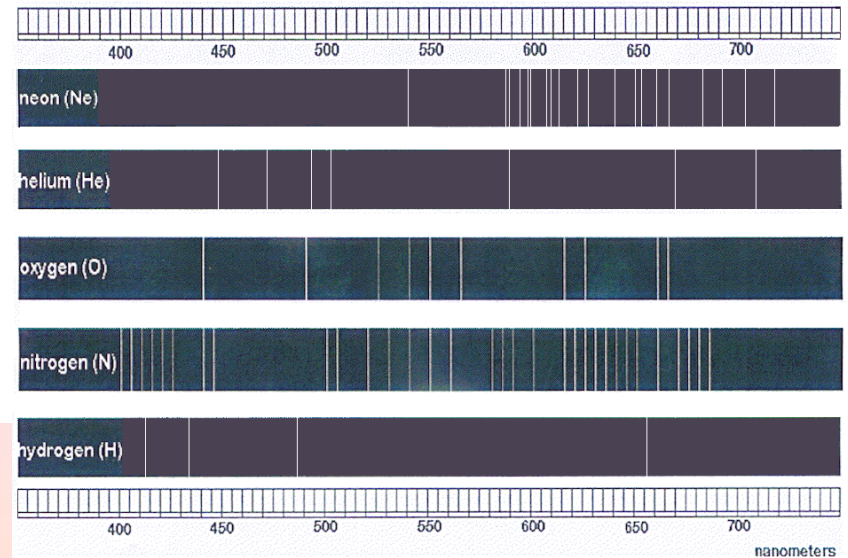
- 
- Basics of spectroscopy and spectrographs
 - Fundamental challenges of sampling the data cube
 - Approaches and example of available instruments
 - I: Grating-dispersed spectrographs ← **a lot of material**
 - II: Fabry-Perot interferometry
 - III: Spatial heterodyne spectroscopy

Basics of Spectroscopy: Dispersed images of entrance slit



**Diffraction
Grating**

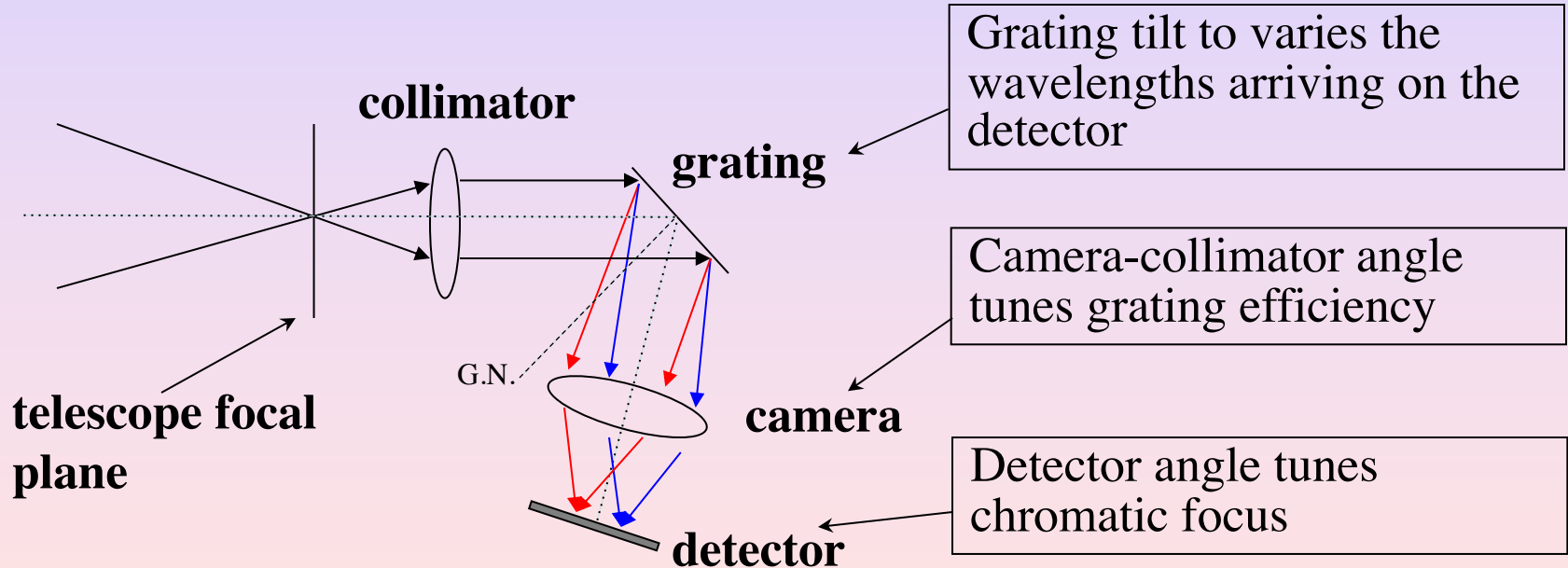
Entrance Slit



What's wrong with this slide?

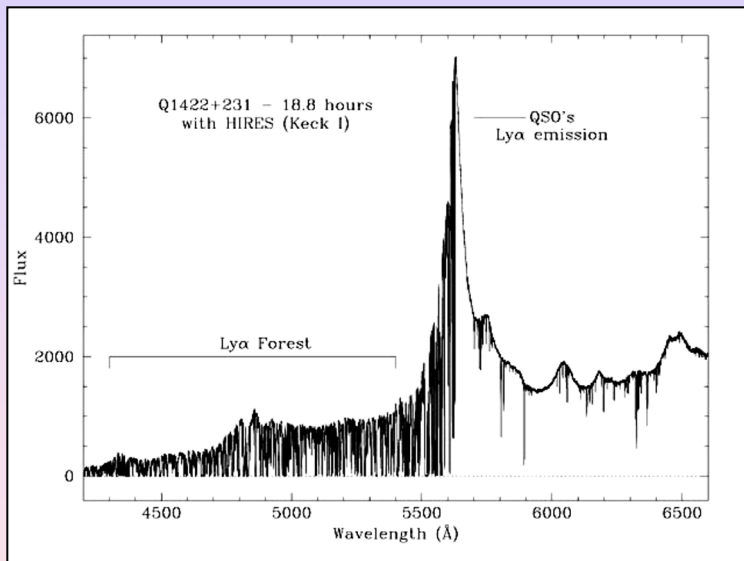
The Basic Spectrograph

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

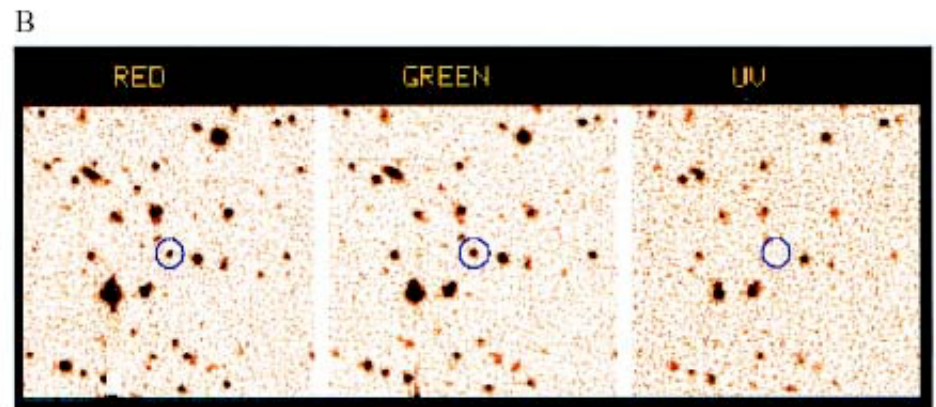
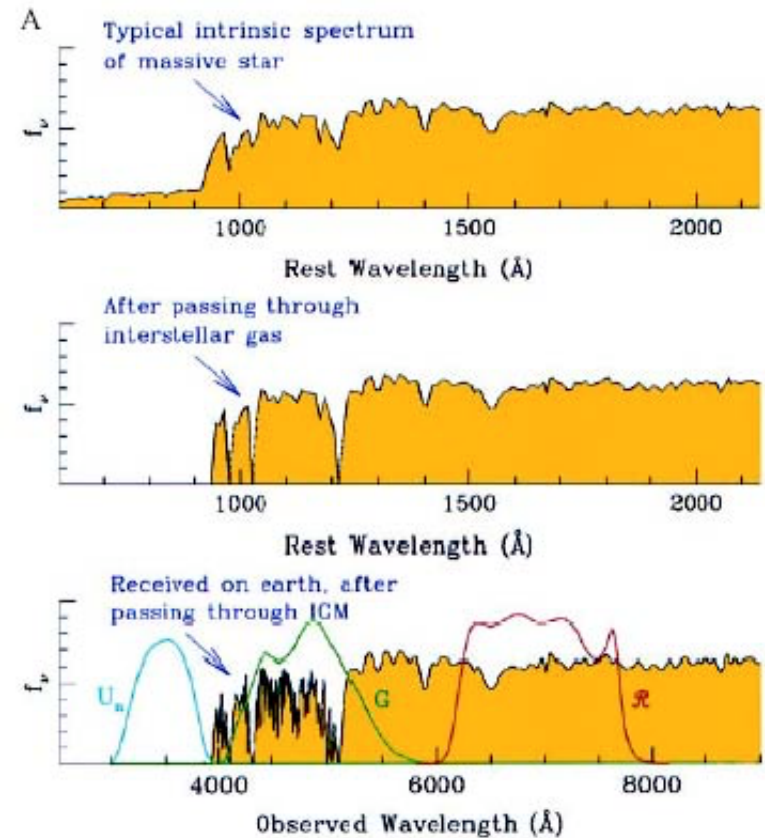


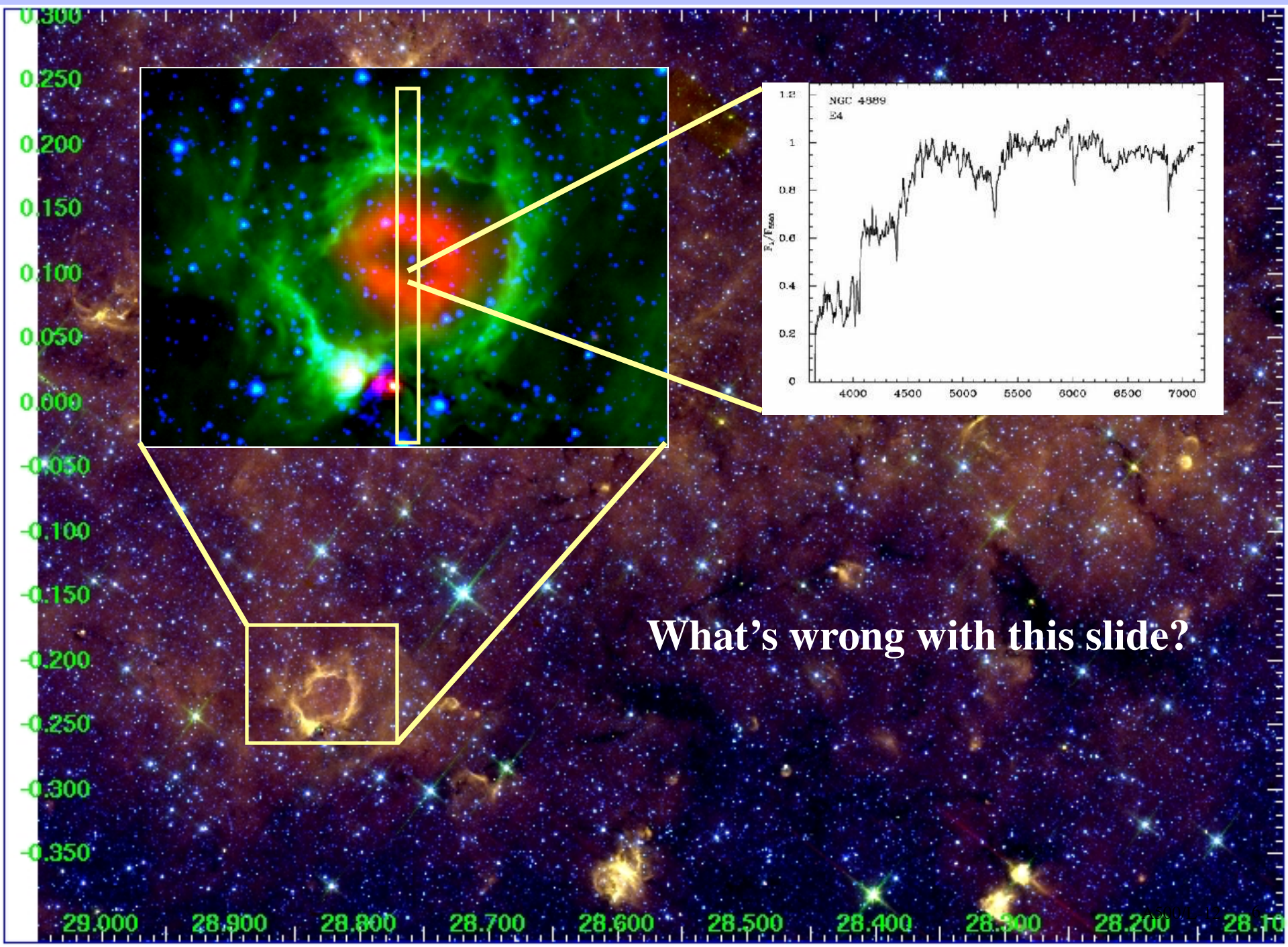
**Replace the grating with a mirror and what to you have?
(And how does the camera-collimator angle relate to the grating angle?)**

Spectra vs photometry



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





What's wrong with this slide?

Fundamental challenges:

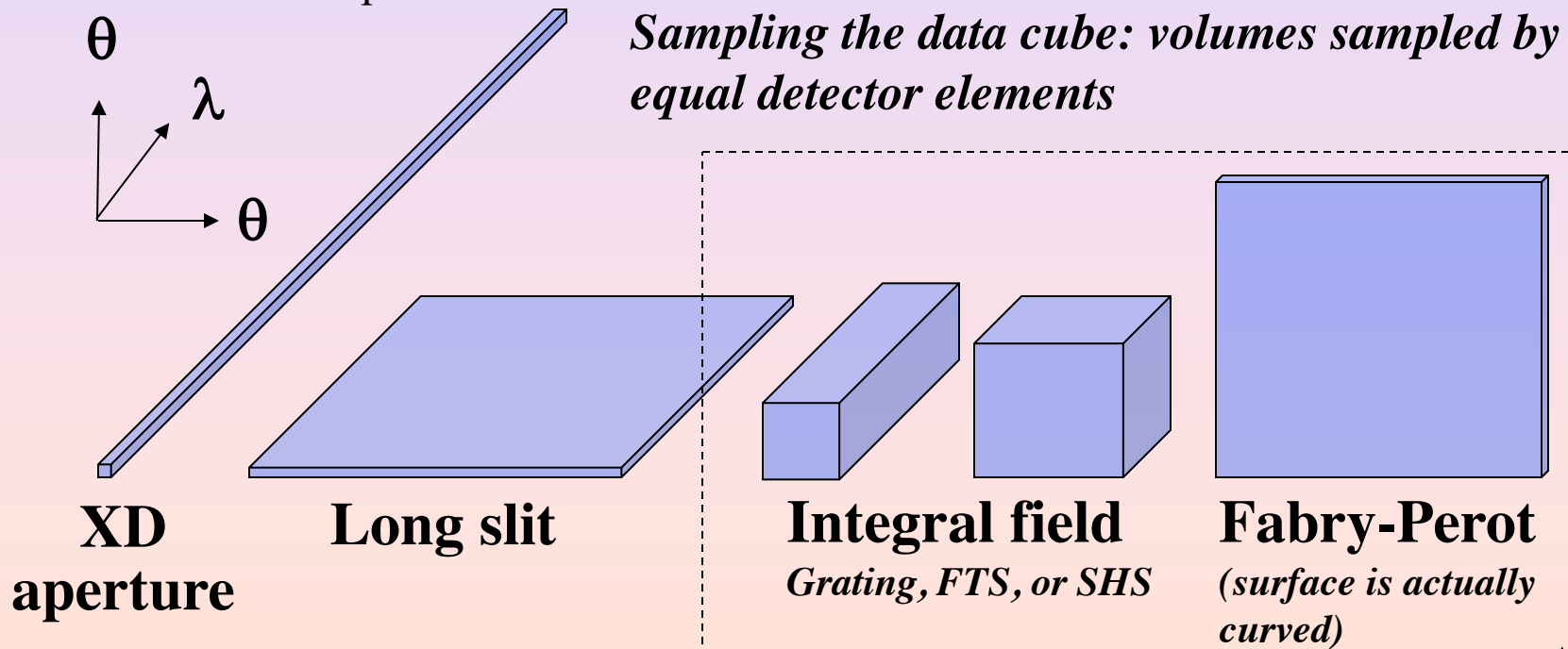
Considerations for sampling the data cube

- 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

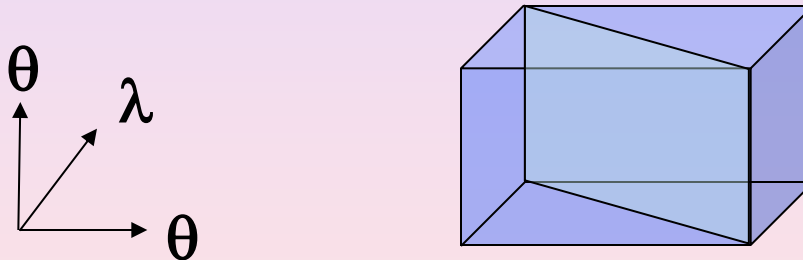


The detector limit-I:

Three into two dimensions

- spatial vs spectral sampling and coverage

Differential spatial/spectral sampling possible?

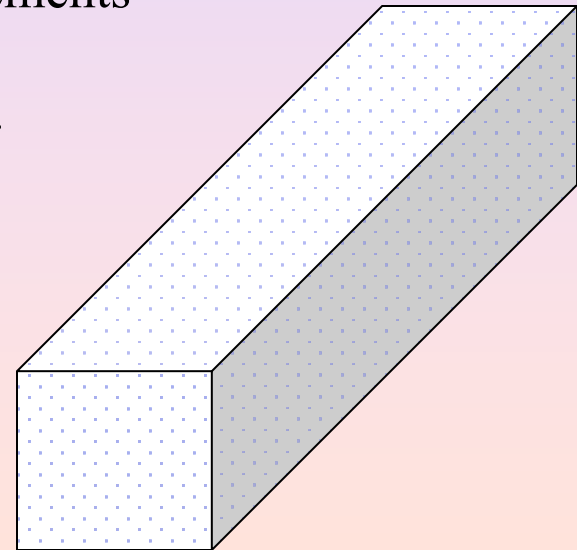
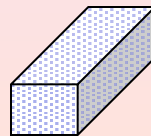
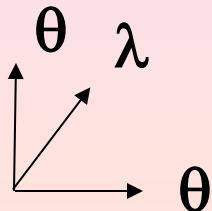


- **Choice is in how data-cube is sliced;**
- **Can't easily rotate a slice within the cube;**
- **Science motivation?**

The detector limit-I:

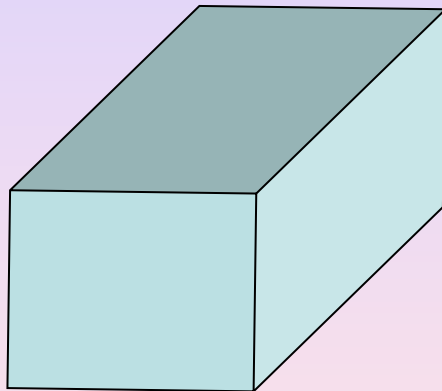
Three into two dimensions

- 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 $\Omega = N_\theta d\Omega$
 - $N_R \times N_\theta \sim$ constant for given detector
 - *Science-drive trades*



Integral vs sparse sampling

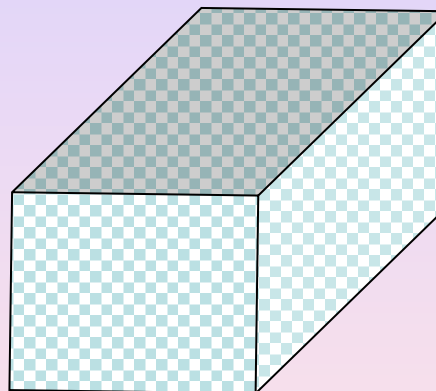
- spatial and spectral domains



Integral

Fibers, lenslets

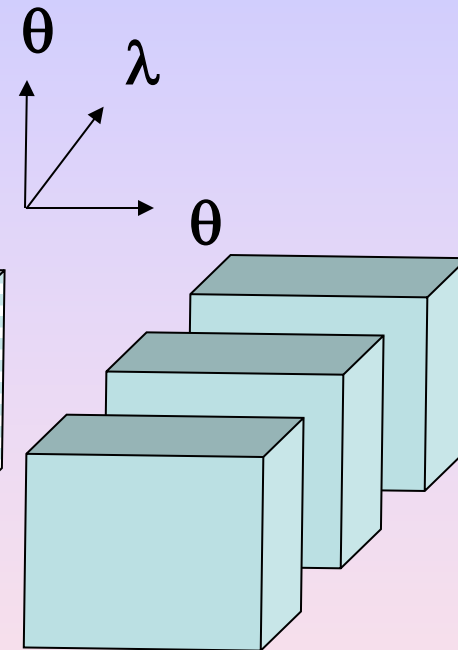
Slicers, interferometers



Sparse spatial sampling

Fibers or MOS

(fibers or slicers)



Sparse spectral sampling

Multiple exposures with FP, multi-beam spectrograph or notch gratings

Not all data has equal information content!

Integral vs sparse sampling

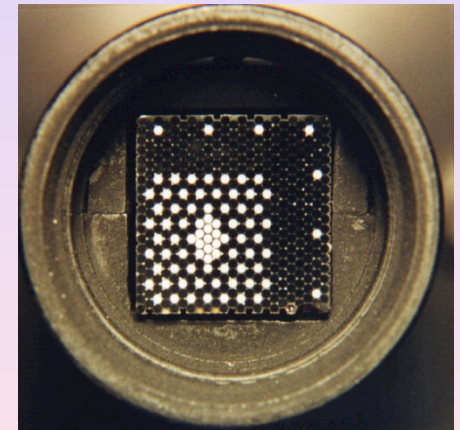
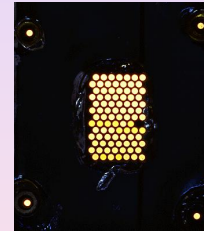
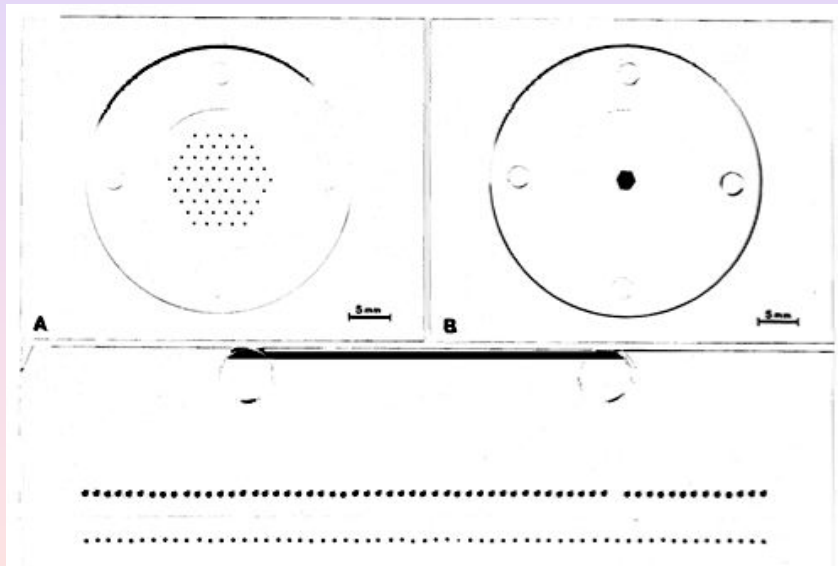
- Real sparsely-sampled IFUs: *formatted field units*

60" FoV
7.3" Δ_f
1.4" D_f

13" FoV
1.5" Δ_f
0.9" D_f

27x43" FoV
4" Δ_f
2.7" D_f

71" FoV
5.6" Δ_f
4.7" D_f



Hexaflex, WHT 4.2m, Flex spectrograph

Arribas, Mediavilla & Rasilla '91

DensePak and SparsePak

WIYN 3.5m, Bench spectrograph

Barden et al. '98

Bershady et al. '04

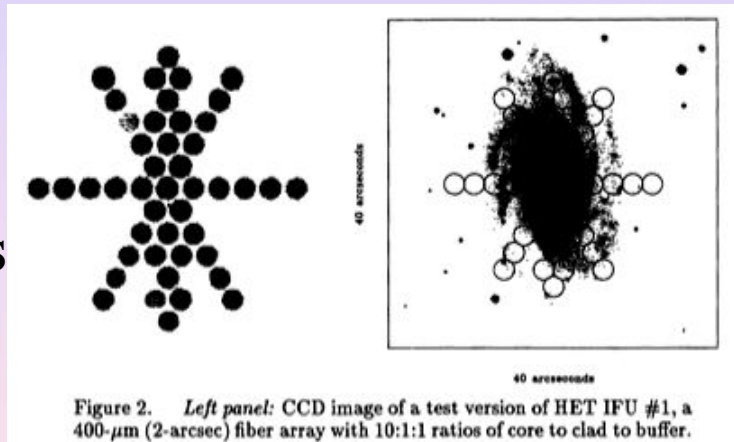
Integral vs sparse sampling

- 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

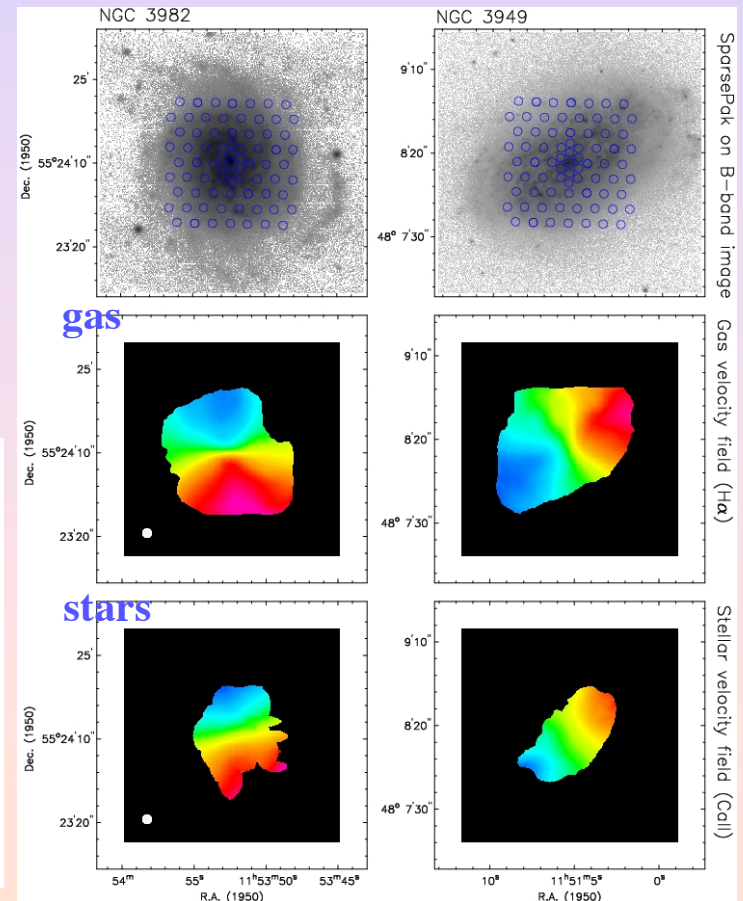
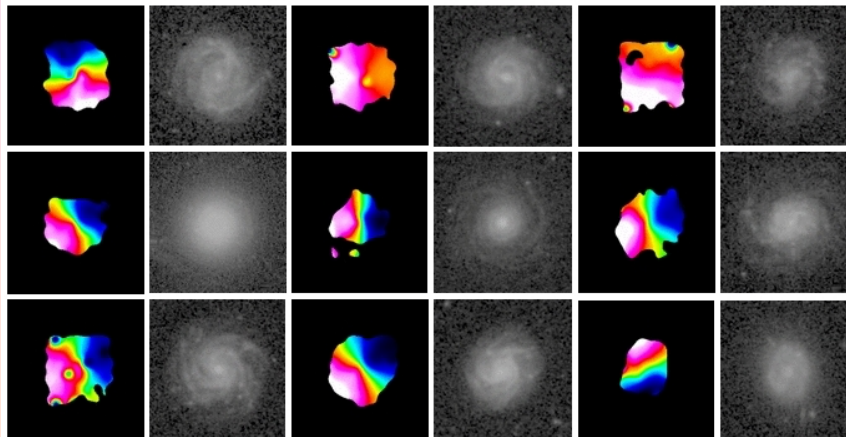
Bershady et al. '98

HET MRS prototype



Swaters et al. '06

H α velocity fields



The detector limit-I:

Three into two dimensions

- Typical merit functions

- Grasp = $A \Omega$

- Ω is slit-width x slit-length for spec and $\pi/4$ x slit-length² for FP and FTS.

- A = collecting area = $\pi/4 D_T^2$

- Specific grasp = $A d\Omega$

- Etendue = $A \Omega \varepsilon$,

where ε = total system efficiency (also specific etendue)

- ΩR , $d\Omega R$,

where $R = \lambda/d\lambda$, i.e. the spectral resolution

- $A \Omega R \varepsilon$, $A d\Omega R \varepsilon$

- 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

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

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

- 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

Add terms:

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

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

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

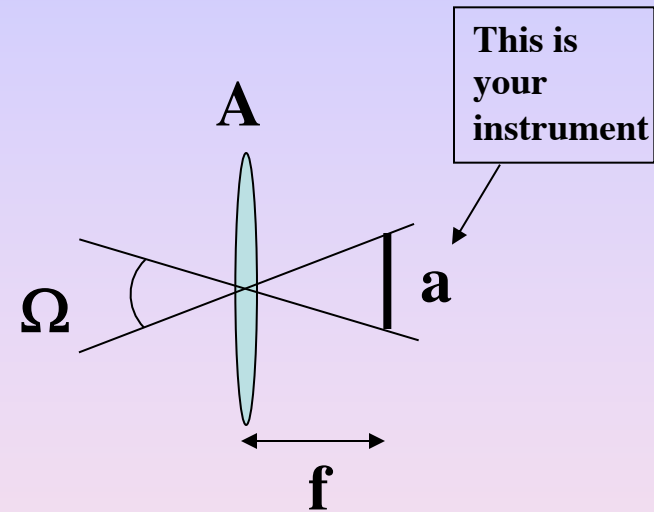
$A\Omega$ is conserved in an optical system.

This means the same instrument has the same $A\Omega$ on any telescope *of the same focal ratio*.

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

Critical point for diffuse sources
of surface brightness S :

$$\text{signal} = S * A \Omega$$



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

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

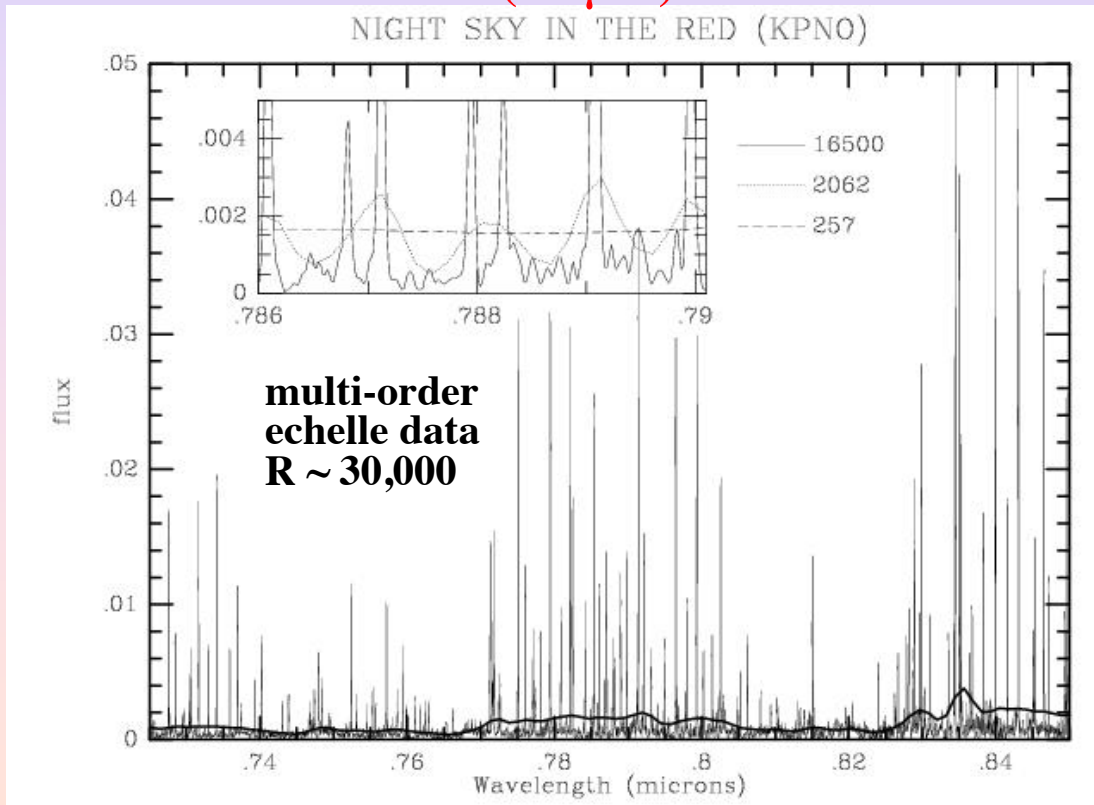
$$A/f^2 \sim \text{focal-ratio}^2$$

The detector limit-I:

Three into two dimensions

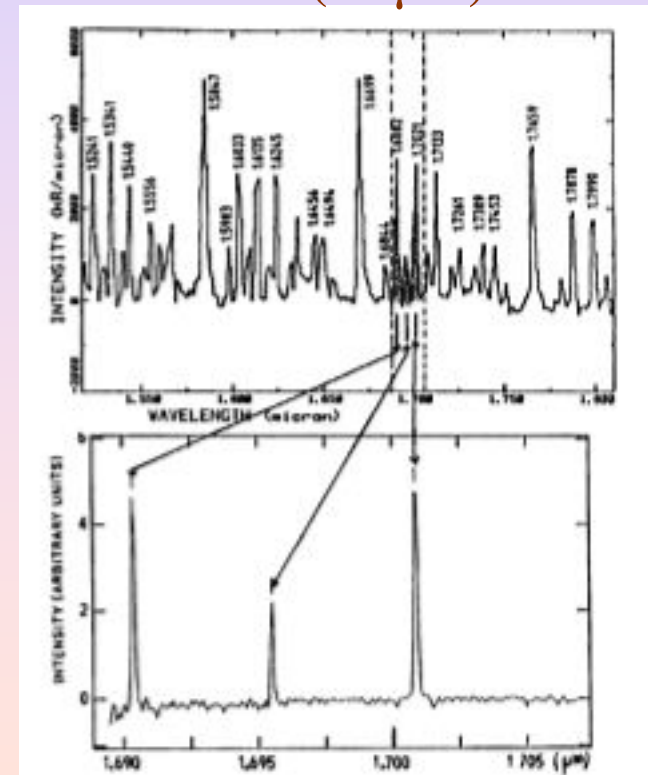
- **Why spectral resolution is so important:**
 - Terrestrial backgrounds, sensitivity, and sky subtraction
 - Situation similar from 0.7-2.2 microns: OH airglow dominates

Red ($0.8\mu\text{m}$)



MAB using echelle data from York & Lauroesch

NIR ($1.6\mu\text{m}$)

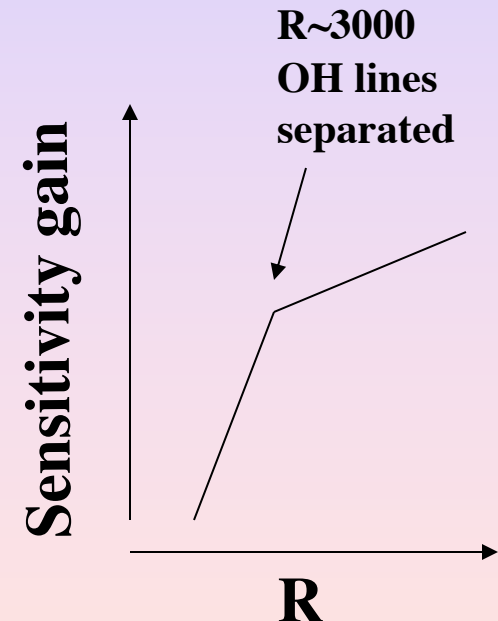
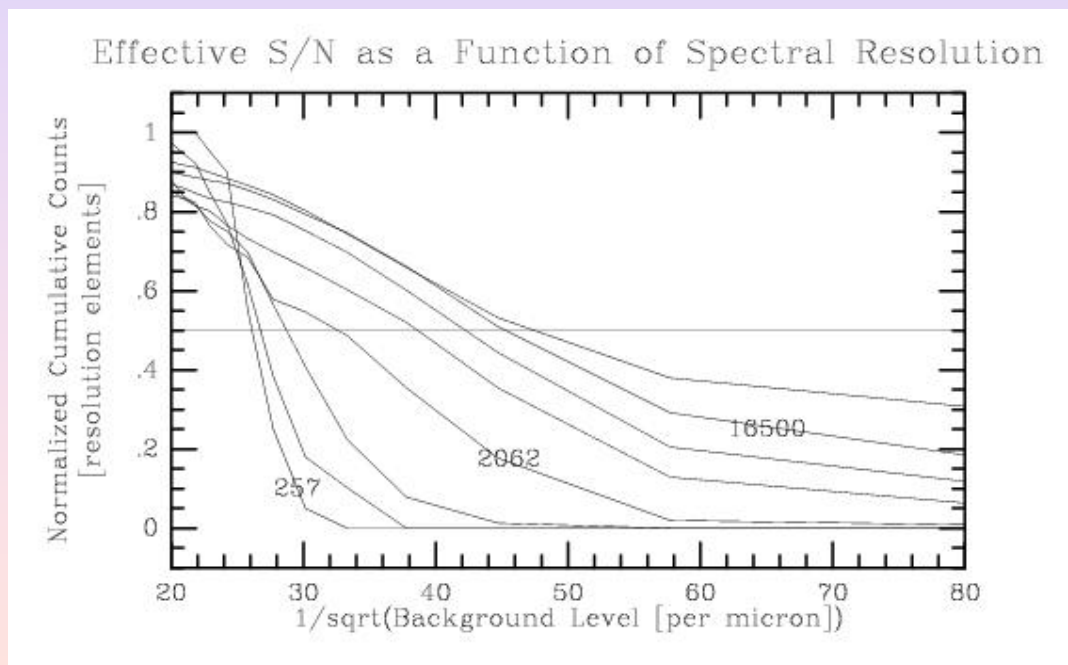


Maihara et al. '93

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

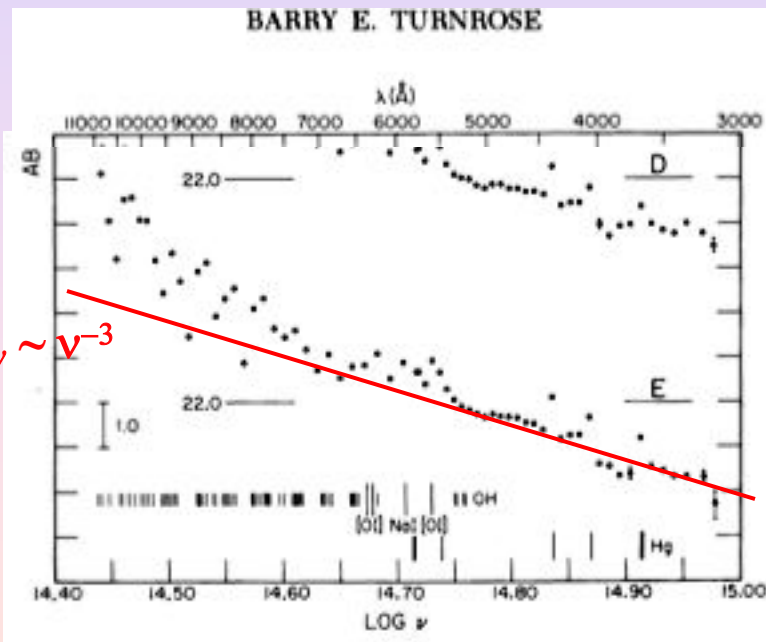


Results will vary slightly depending on exact spectral region

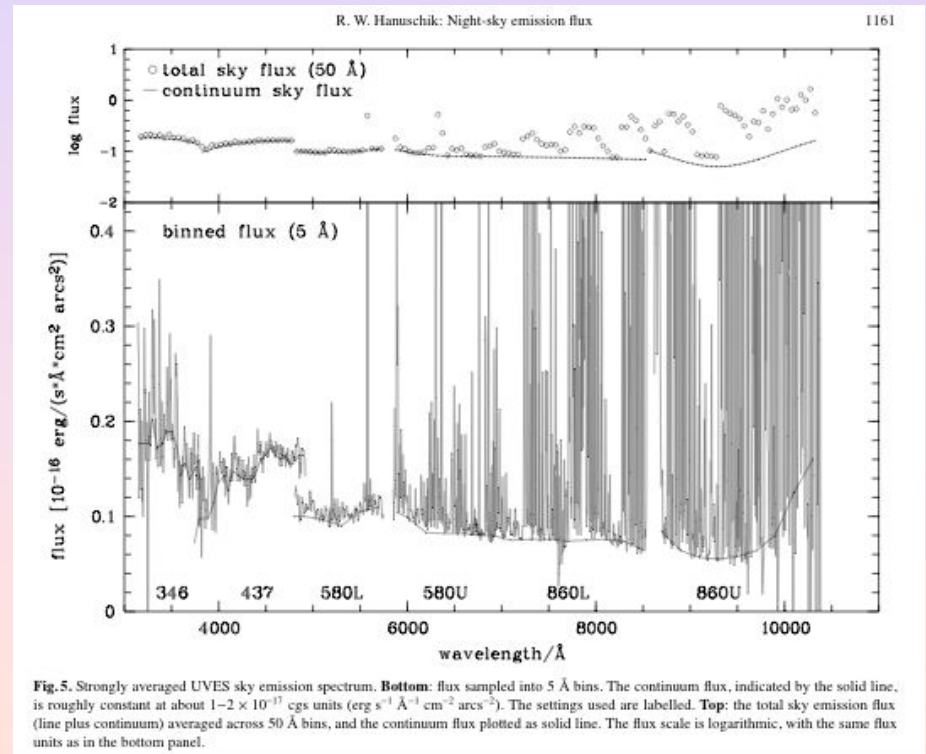
The detector limit-I:

Three into two dimensions

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



Turnrose '74

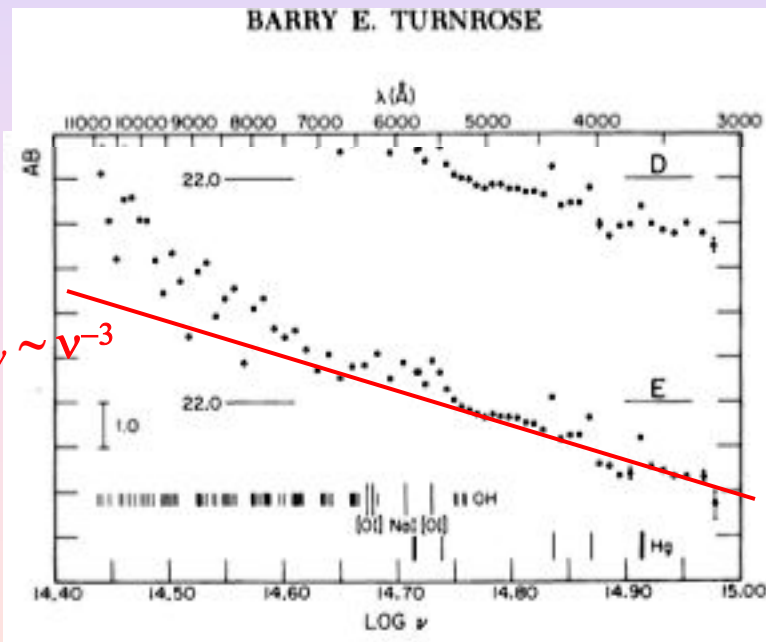


Hanuschik et al. '03

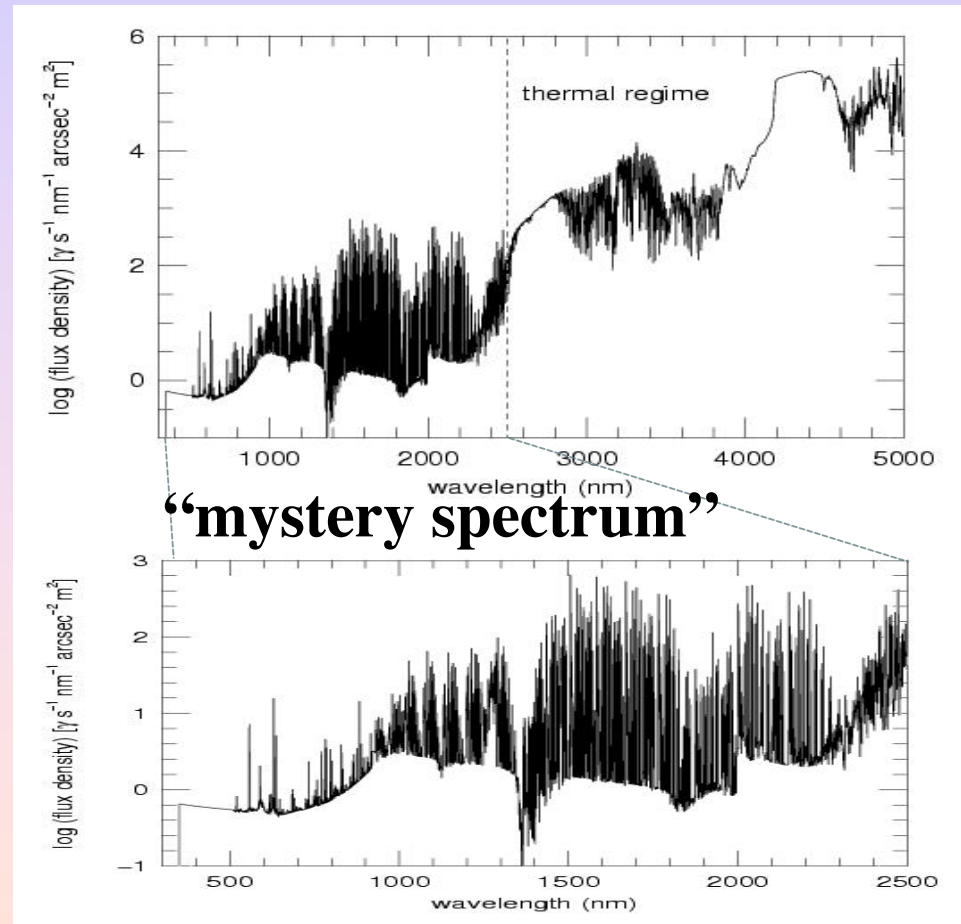
The detector limit-I:

Three into two dimensions

- What is the sky spectral continuum (from the ground) at high resolution?
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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 $d\Omega$ per unit time
- t = exposure time
- N_A = pixels in aperture $d\Omega$
- RN = rms read-noise per pixel

- Prefer photon-limit (fundamental)

- S/N is independent of sub-exposure time

**photon
limited**

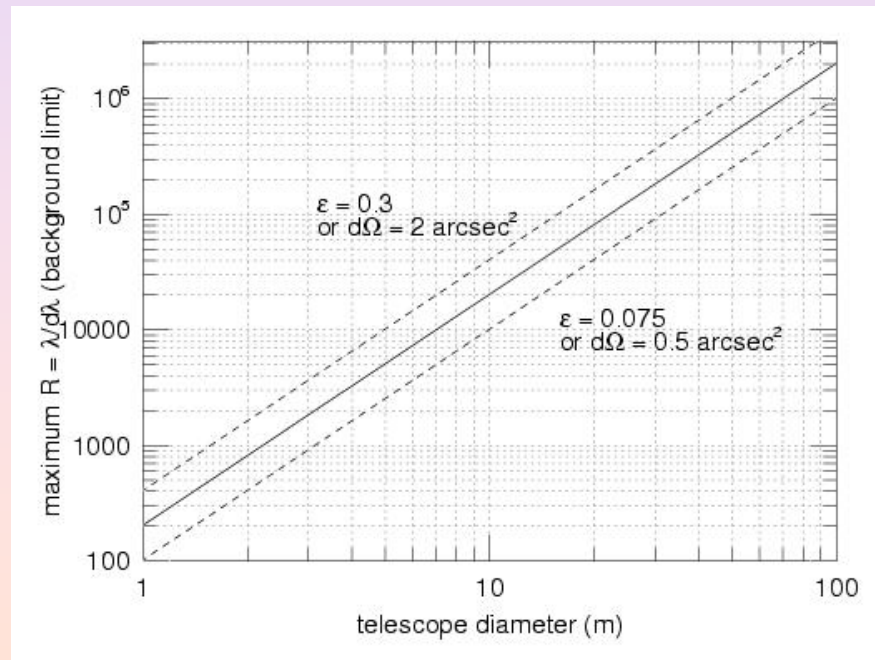
$$d\Omega = \pi(\theta/2)^2$$

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:
 - $R/d\Omega < 16500 (D_T/9\text{m})^2 (t/1\text{h}) (\epsilon/0.15) \text{ arcsec}^{-2}$ [8m class]
 - $R/d\Omega < 2500 (D_T/3.5\text{m})^2 (t/1\text{h}) (\epsilon/0.15) \text{ arcsec}^{-2}$ [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
 - o Fiber
 - o Fiber+lenslet
 - o Slicer
 - o Lenslet
 - o 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**

$$\begin{aligned} \gamma &= d\beta/d\lambda = m / \sigma \cos \beta \\ &= (\sin \beta \pm \sin \alpha) / \lambda \cos \beta \end{aligned}$$

- **Linear dispersion**

$$dl/d\lambda = f_2 \gamma$$

§ $-\infty < m < \infty$

* Sign convention:

+ for reflection

– for transmission

