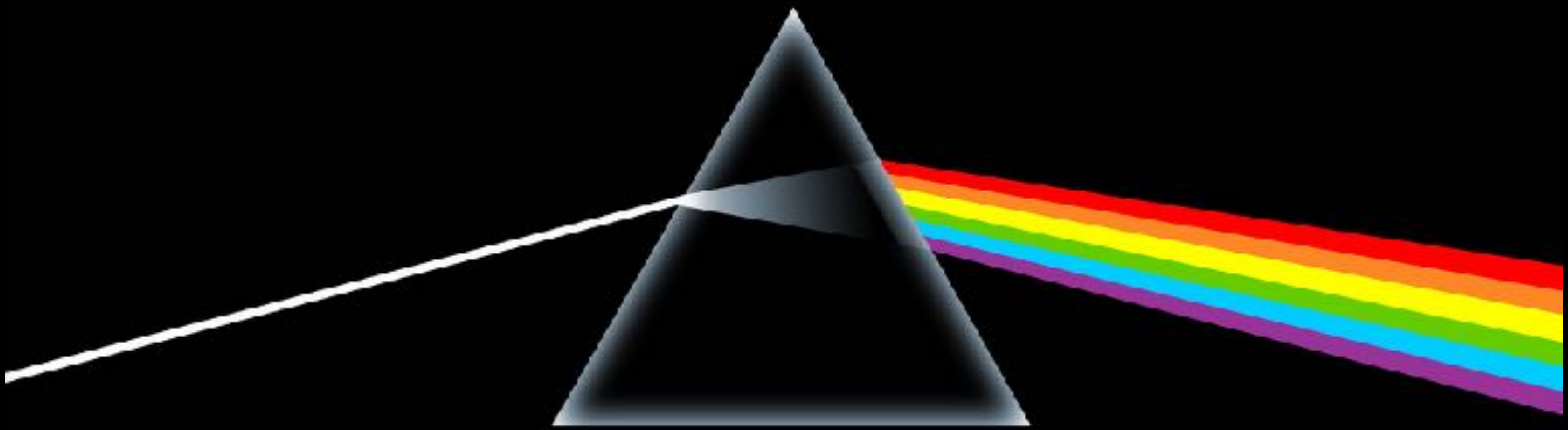
Astronomy 503
Observational Astronomy

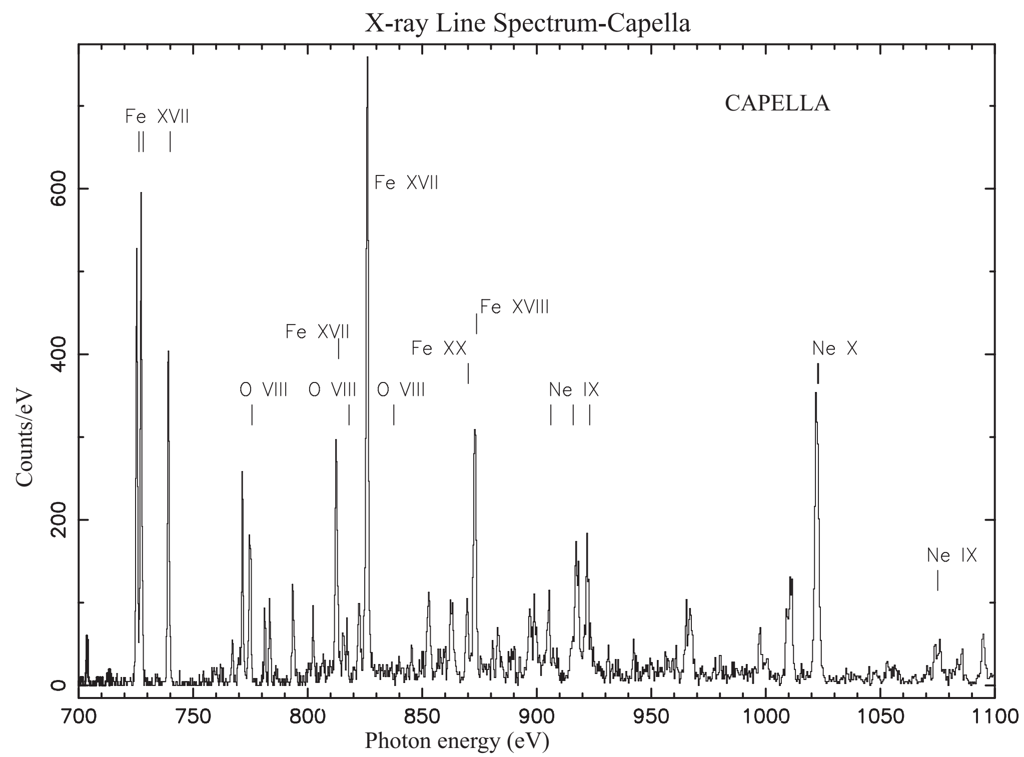


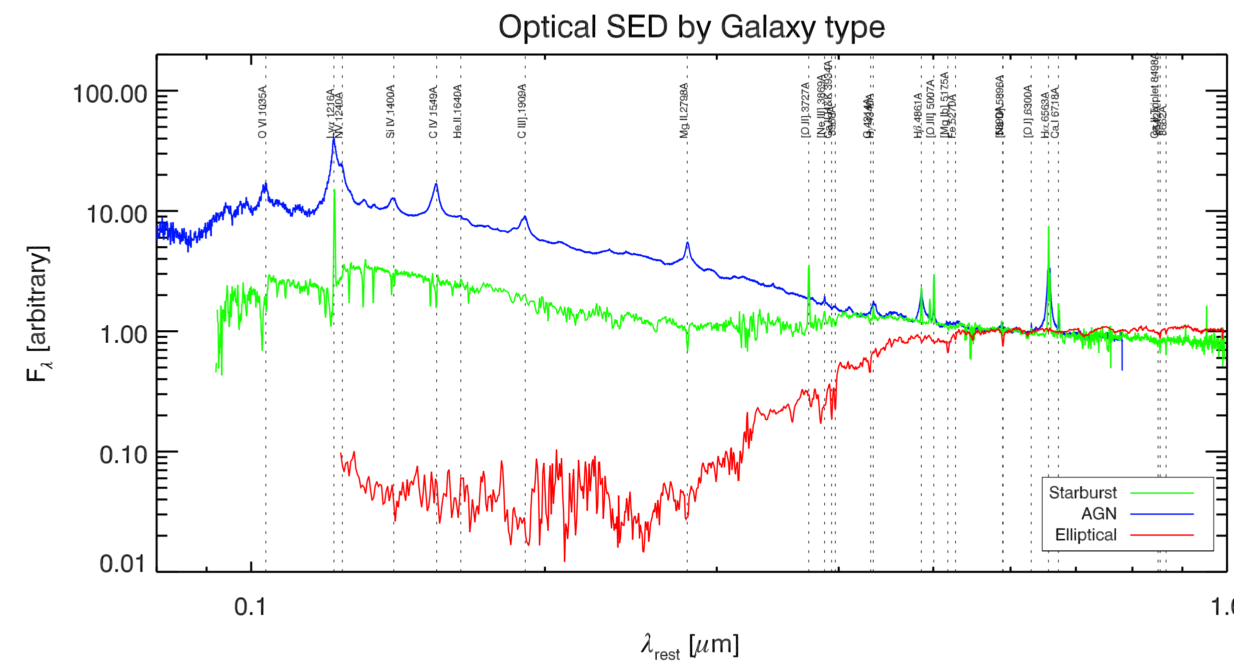
Gautham Narayan

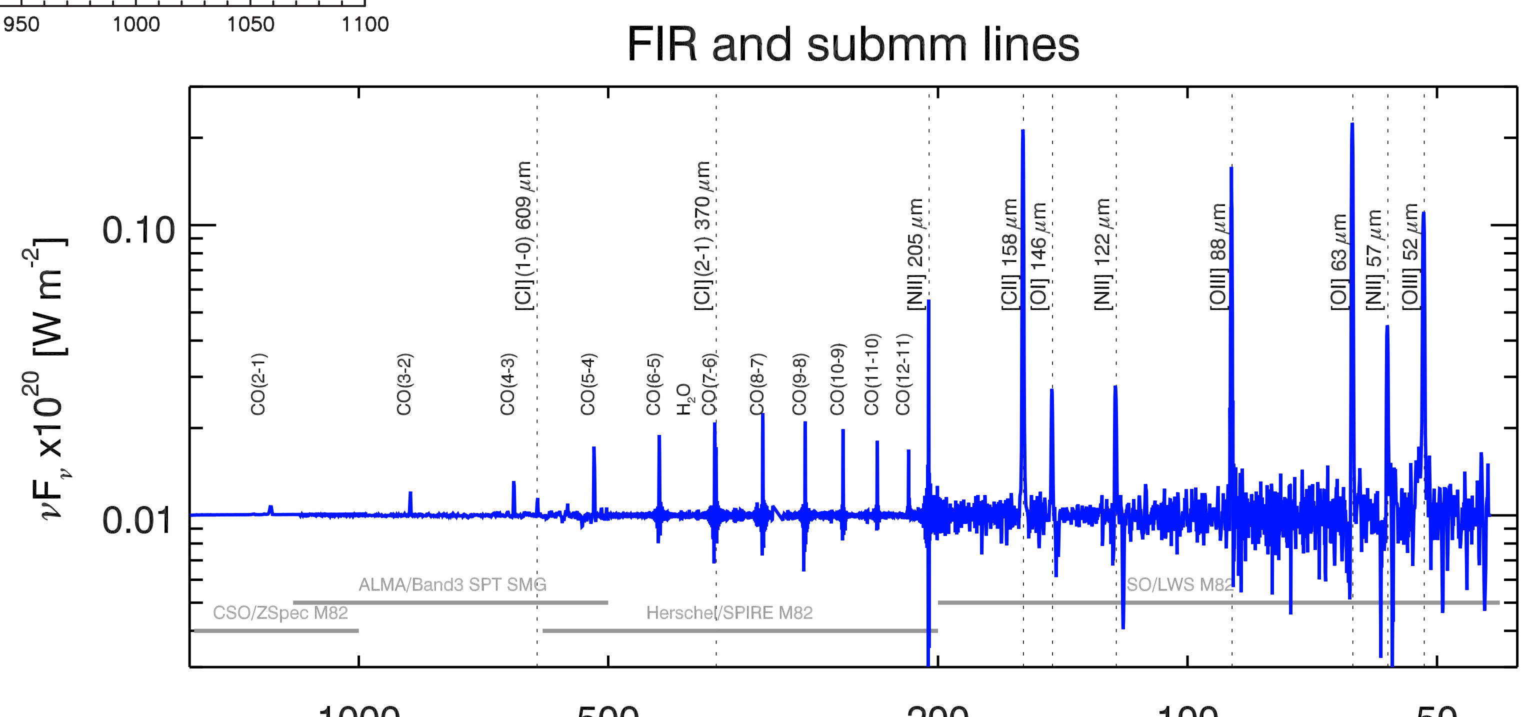
Lecture 10: Spectroscopy and Spectrometers

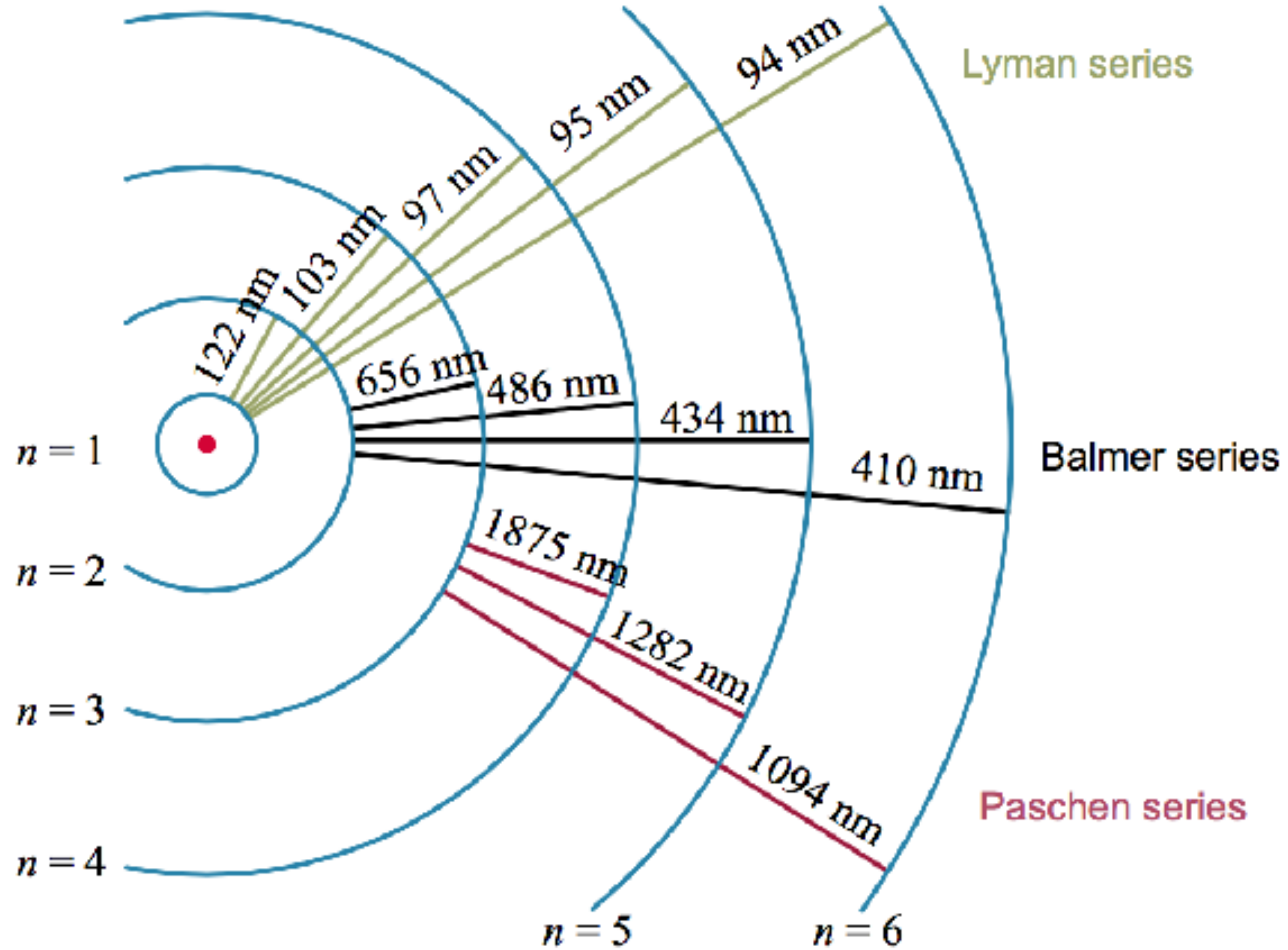
Spectroscopy — Why?

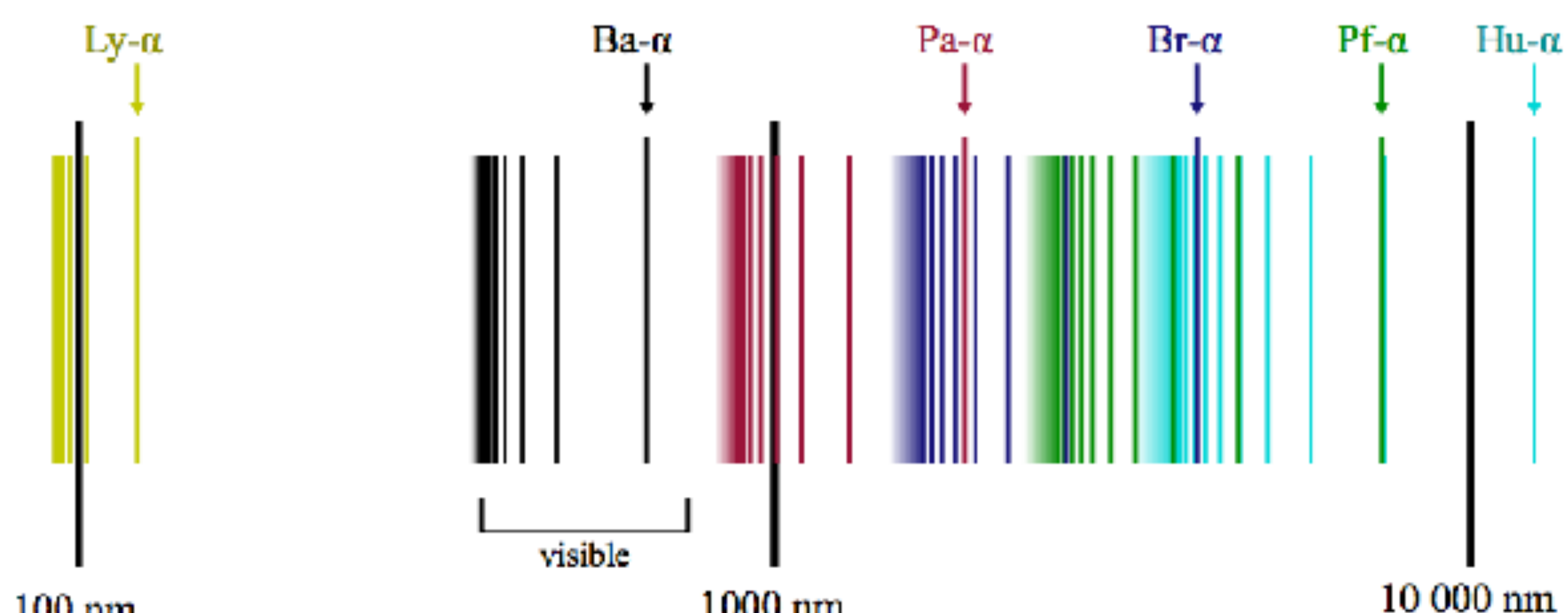
Spectroscopy is the link between astronomy and physics —> astrophysics



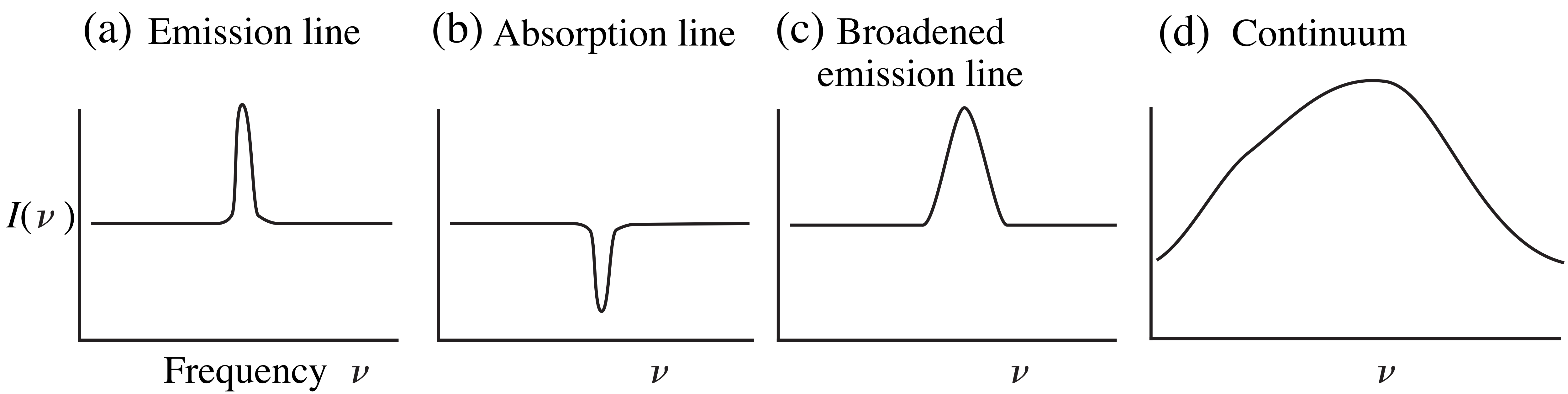


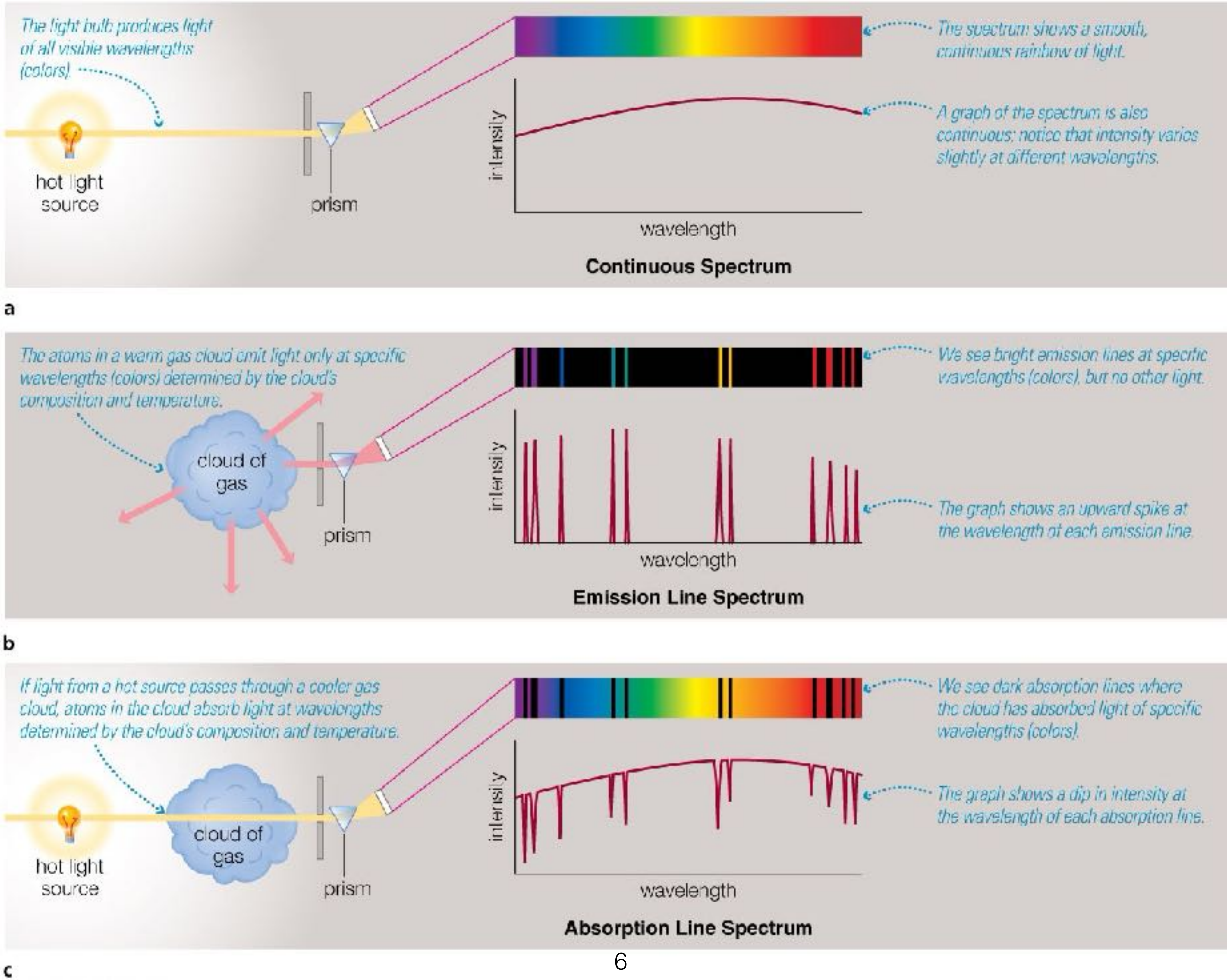



Lyman series
94 nm
95 nm
97 nm
103 nm
122 nm
656 nm
486 nm
434 nm
410 nm
Balmer series
1875 nm
1282 nm
1094 nm
Paschen series
n = 1
n = 2
n = 3
n = 4
n = 5
n = 6


Ly-α
Ba-α
Pa-α
Br-α
Pf-α
Hu-α
visible
100 nm
1000 nm
10 000 nm

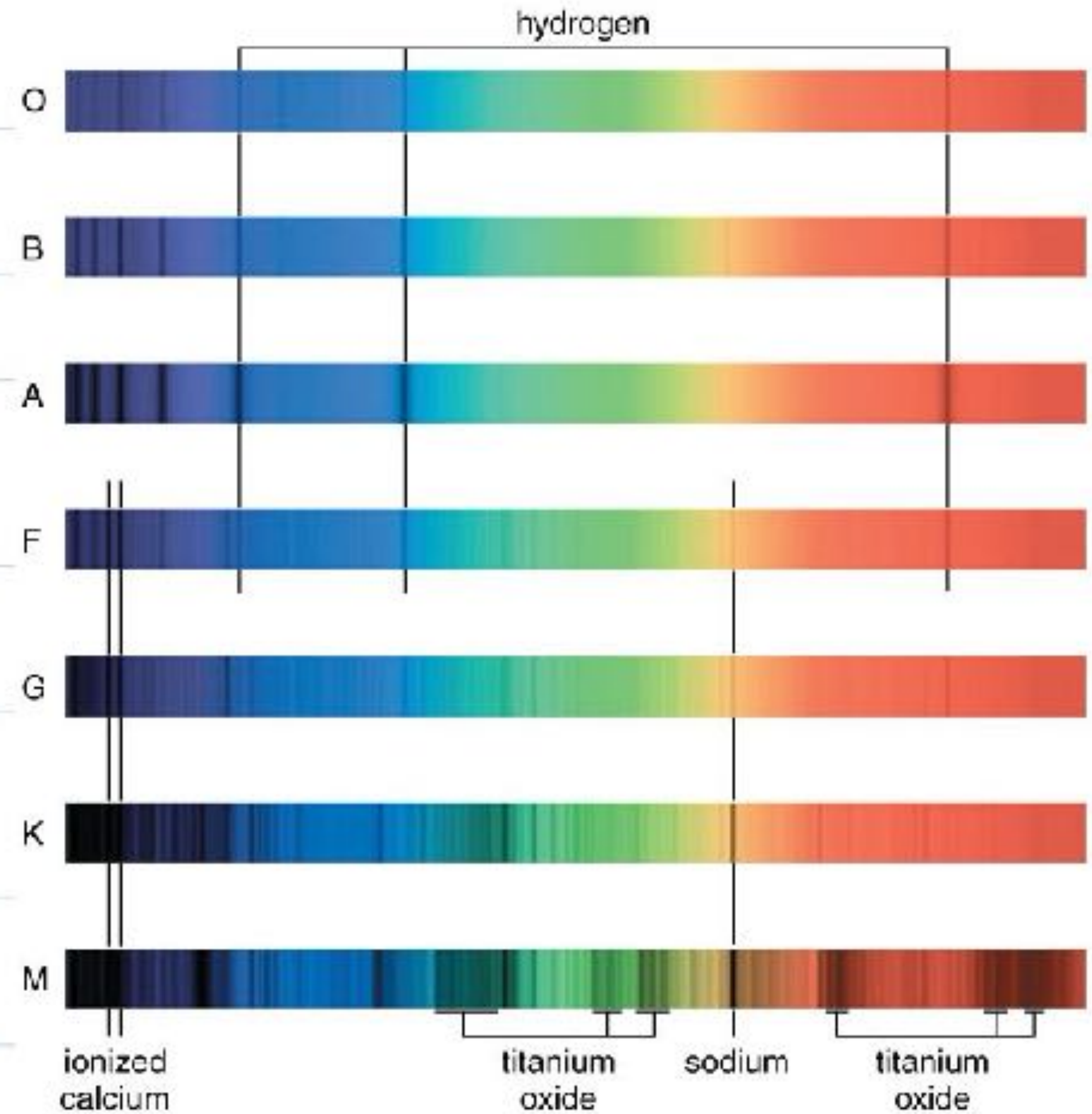
Spectral Lines and Continuum




The light bulb produces light of all visible wavelengths (colors).
hot light source
prism
The spectrum shows a smooth, continuous rainbow of light.
A graph of the spectrum is also continuous; notice that intensity varies slightly at different wavelengths.
intensity
wavelength
Continuous Spectrum
a
The atoms in a warm gas cloud emit light only at specific wavelengths (colors) determined by the cloud's composition and temperature.
cloud of gas
prism
We see bright emission lines at specific wavelengths (colors), but no other light.
The graph shows an upward spike at the wavelength of each emission line.
intensity
wavelength
Emission Line Spectrum
b
If light from a hot source passes through a cooler gas cloud, atoms in the cloud absorb light at wavelengths determined by the cloud's composition and temperature.
hot light source
cloud of gas
prism
We see dark absorption lines where the cloud has absorbed light of specific wavelengths (colors).
The graph shows a dip in intensity at the wavelength of each absorption line.
intensity
wavelength
Absorption Line Spectrum
c

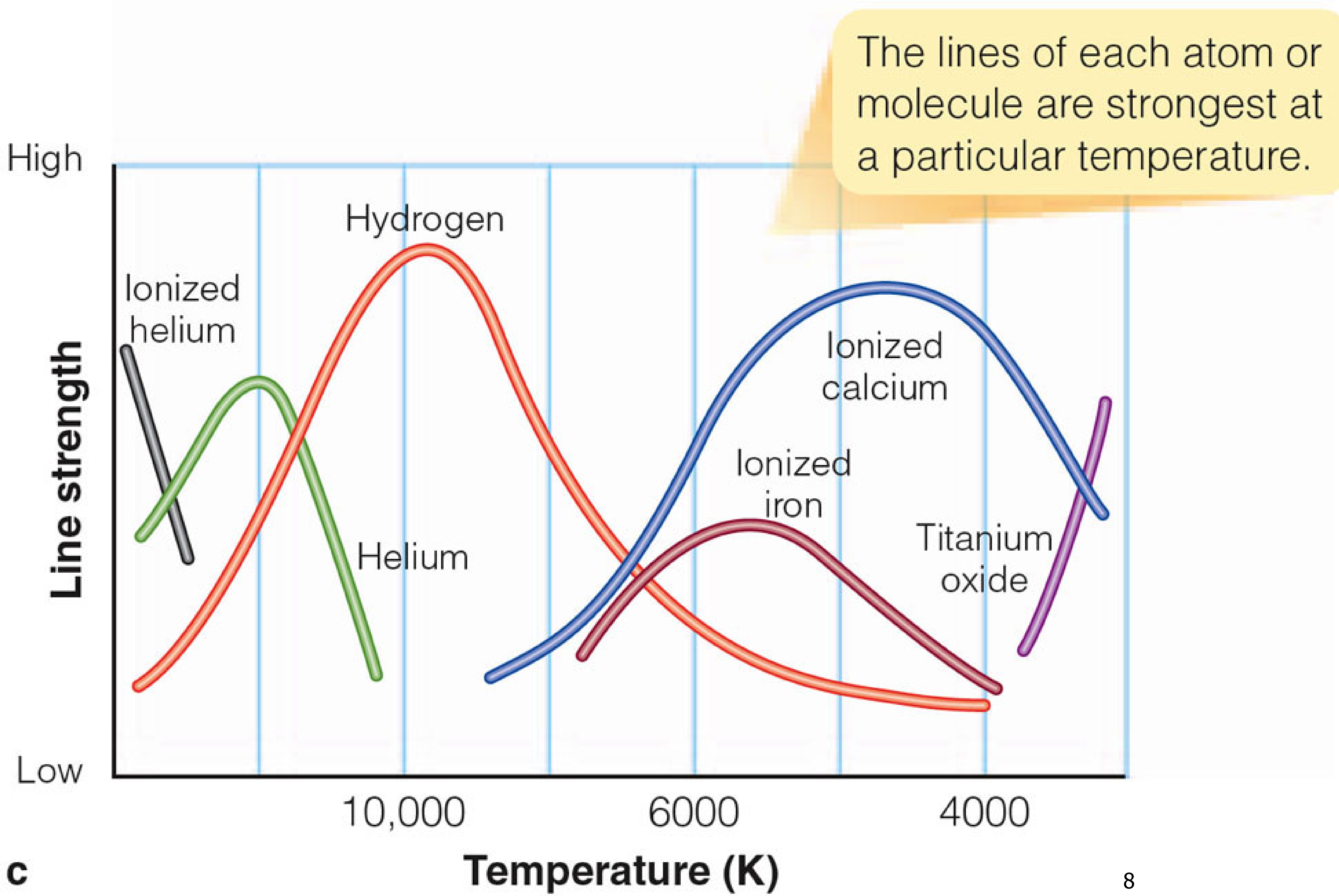
Spectral Type	Example(s)	Temperature Range	Key Absorption Line Features	Brightest Wavelength (color)
O	Stars of Orion's Belt	>30,000 K	Lines of ionized helium, weak hydrogen lines	>97 nm (ultraviolet)*
B	Rigel	30,000 K–10,000 K	Lines of neutral helium, moderate hydrogen lines	97–290 nm (ultraviolet)*
A	Sirius	10,000 K–7500 K	Very strong hydrogen lines	290–390 nm (violet)*
F	Polaris	7500 K–6000 K	Moderate hydrogen lines, moderate lines of ionized calcium	390–480 nm (blue)*
G	Sun, Alpha Centauri A	6000 K–5000 K	Weak hydrogen lines, strong lines of ionized calcium	480–580 nm (yellow)
K	Arcturus	5000 K–3500 K	Lines of neutral and singly ionized metals, some molecules	580–830 nm (red)
M	Betelgeuse, Proxima Centauri	<3500 K	Strong molecular lines	> 830 nm (infrared)

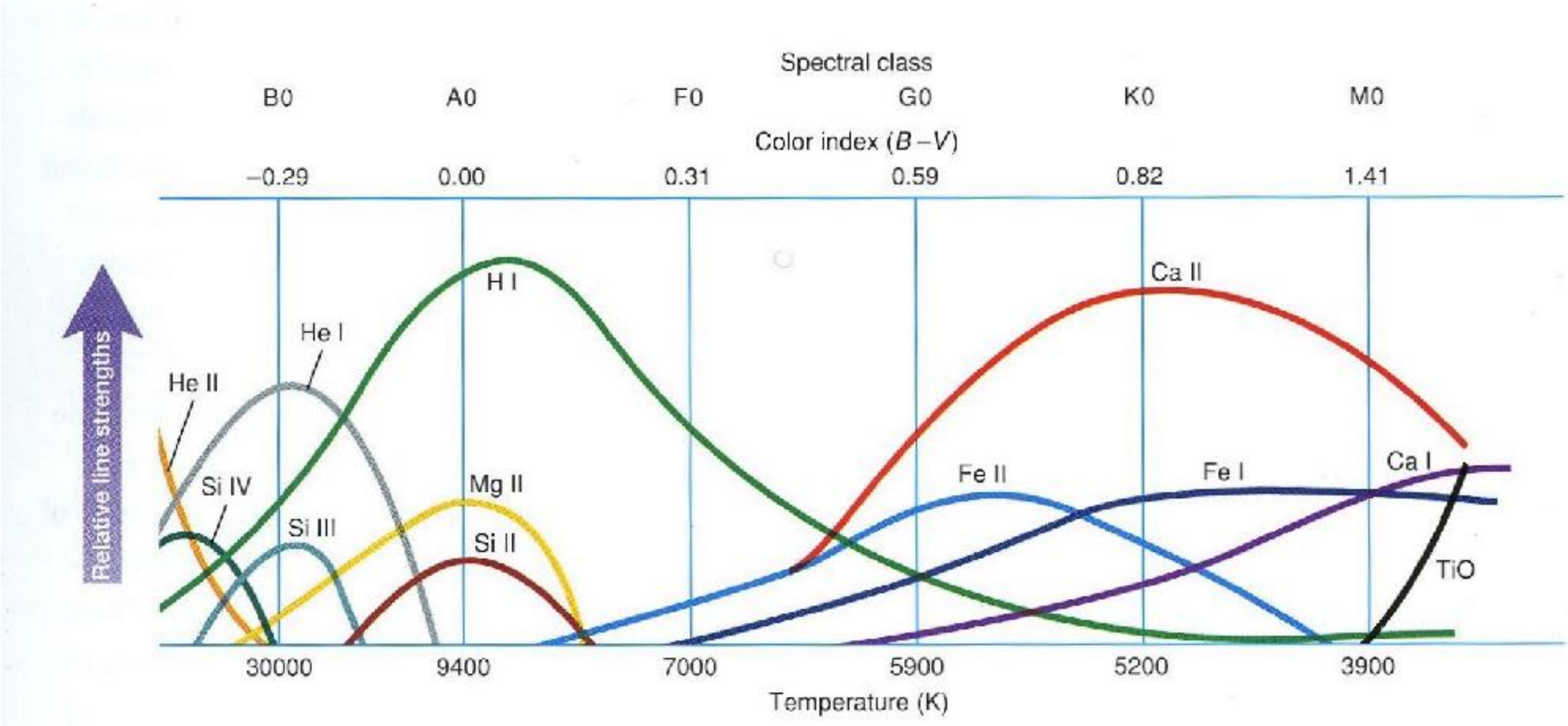
Typical Spectrum

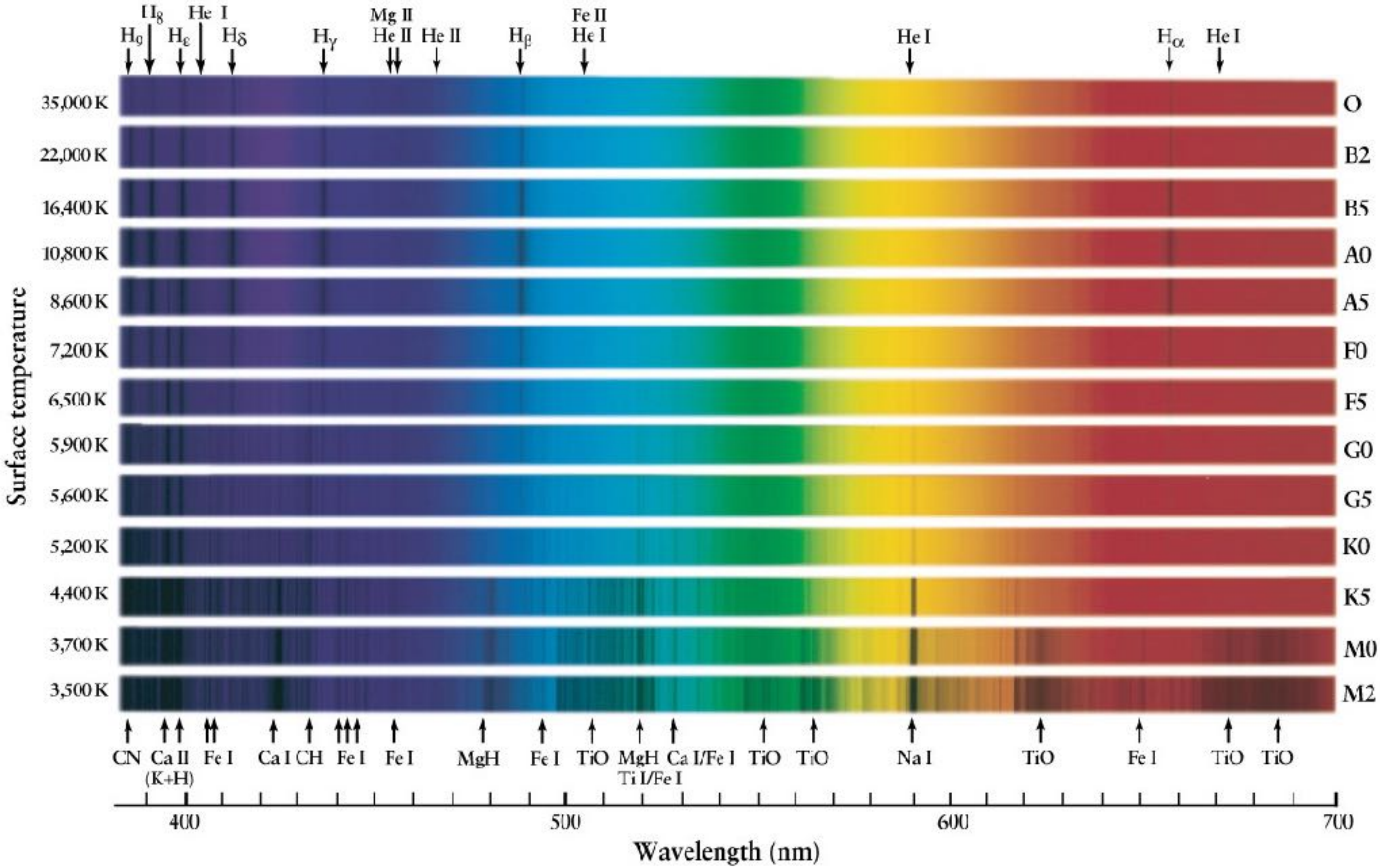


*All stars above 6000 K look more or less white to the human eye because they emit plenty of radiation at all visible wavelengths.

Strength of spectrum lines varies with temperature

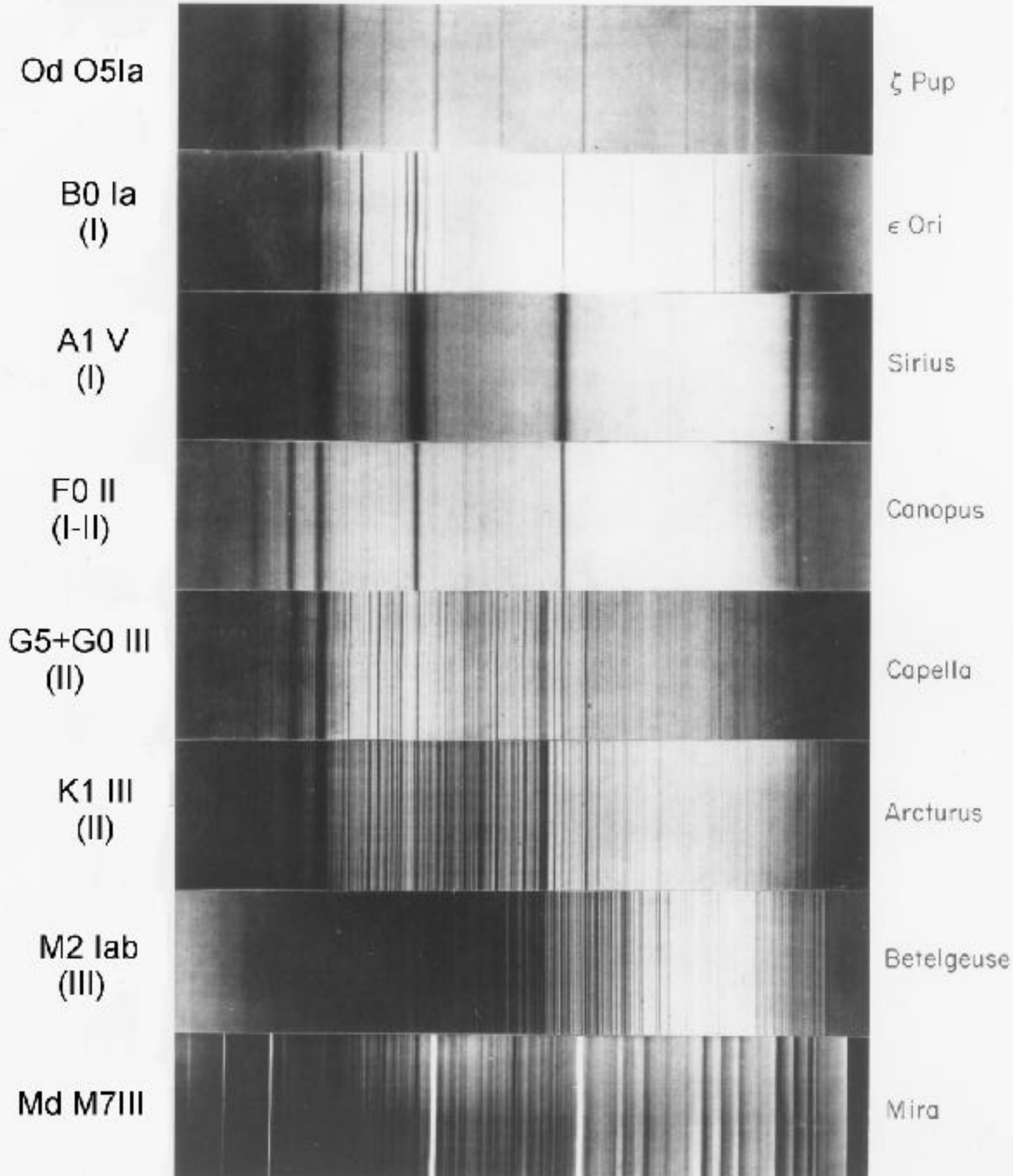


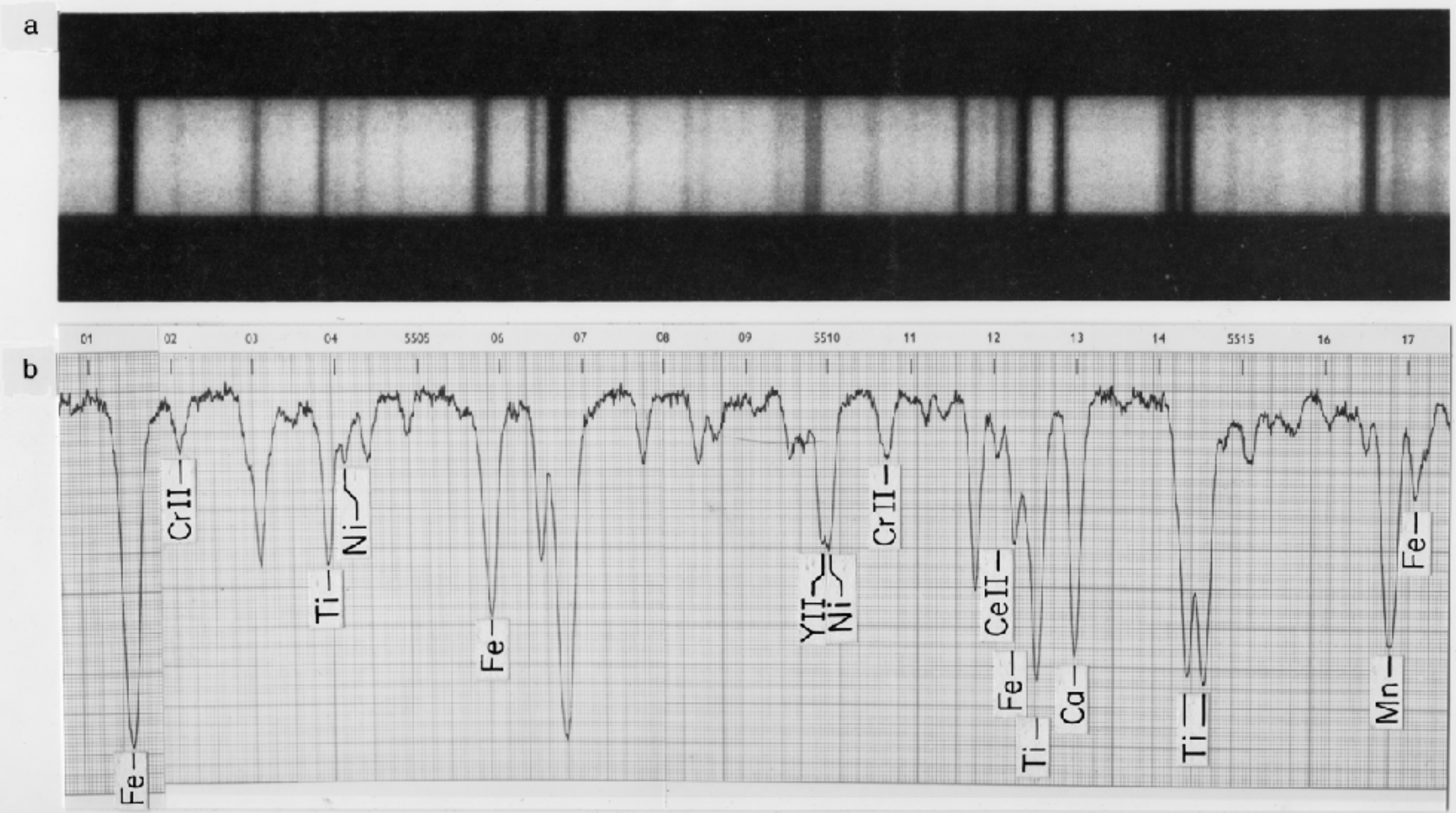

Spectral class
B0
A0
F0
G0
K0
M0
Color index (B – V)
–0.29
0.00
0.31
0.59
0.82
1.41
Relative line strengths
H I
Ca II
He I
He II
Si IV
Si III
Mg II
Si II
Fe II
Fe I
Ca I
TiO
30000
9400
7000
5900
5200
3900
Temperature (K)

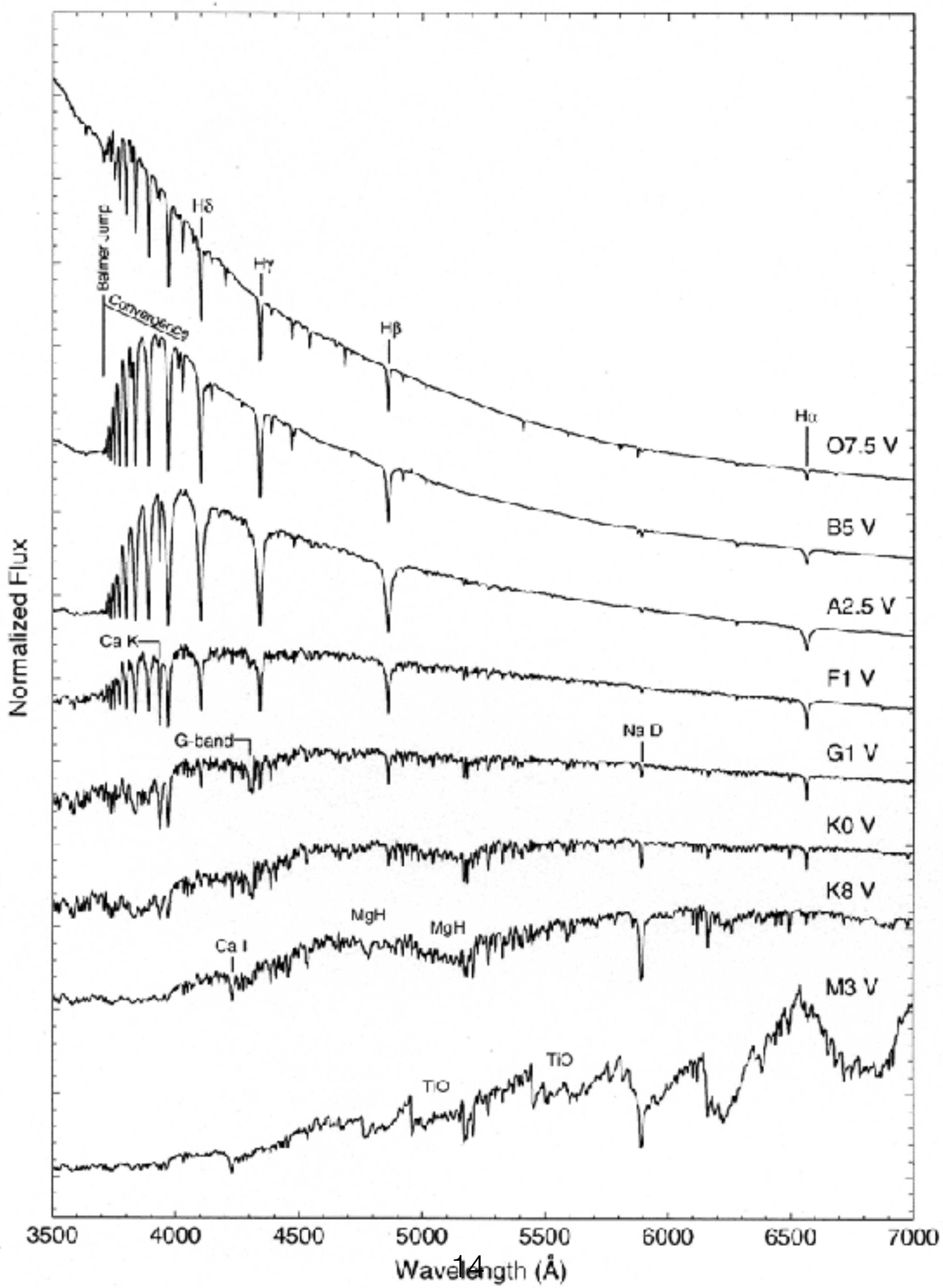


Surface temperature
35,000 K
22,000 K
16,400 K
10,800 K
8,600 K
7,200 K
6,500 K
5,900 K
5,600 K
5,200 K
4,400 K
3,700 K
3,500 K
O
B2
B5
A0
A5
F0
F5
G0
G5
K0
K5
M0
M2
Wavelength (nm)
400
500
600
700

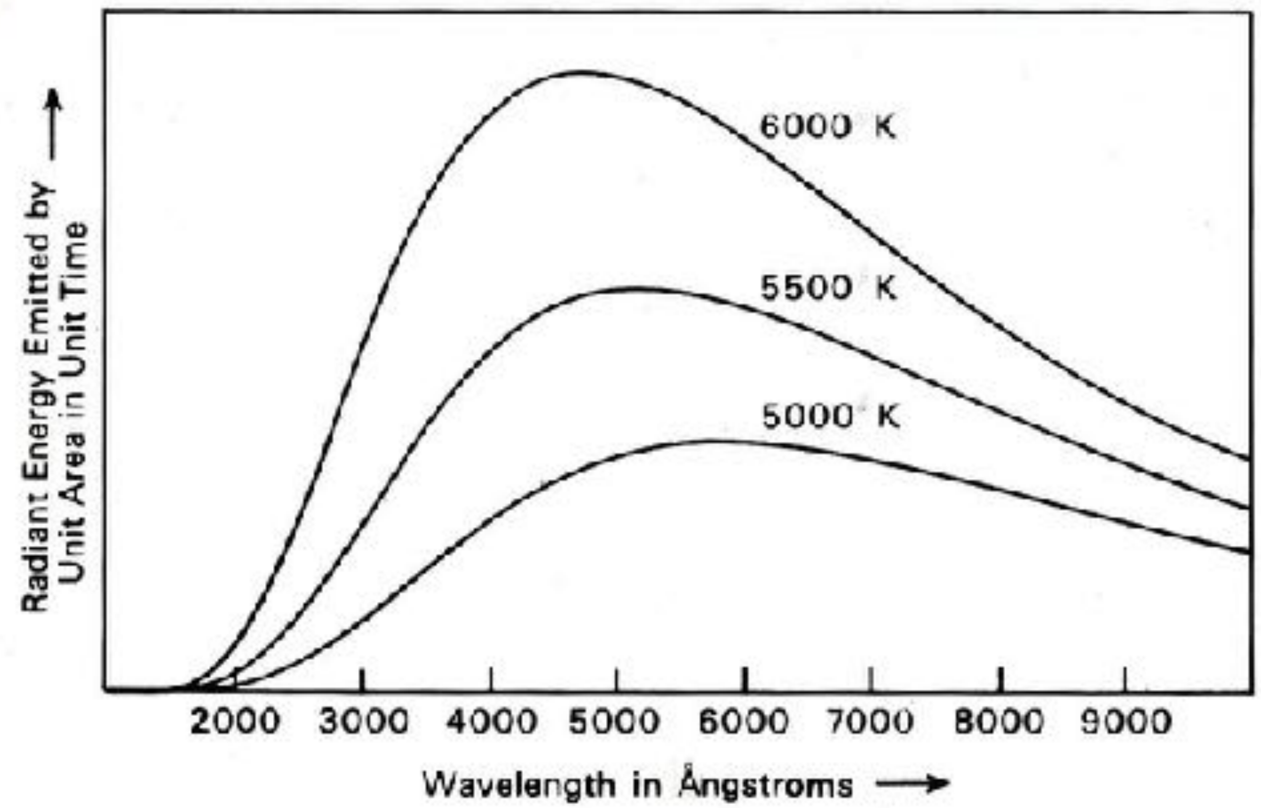

Ca II K
He I 4026
Hδ
Si II 4129
Fe II 4233
Hγ
4385
He I 4471
Mg II 4481
HR 1040
13 Mon
α Lyr
A0 I
A0 II
A0 V


Od O5Ia
B0 Ia
(I)
A1 V
(I)
F0 II
(I-II)
G5+G0 III
(II)
K1 III
(II)
M2 Iab
(III)
Md M7III
ζ Pup
ϵ Ori
Sirius
Canopus
Capella
Arcturus
Betelgeuse
Mira

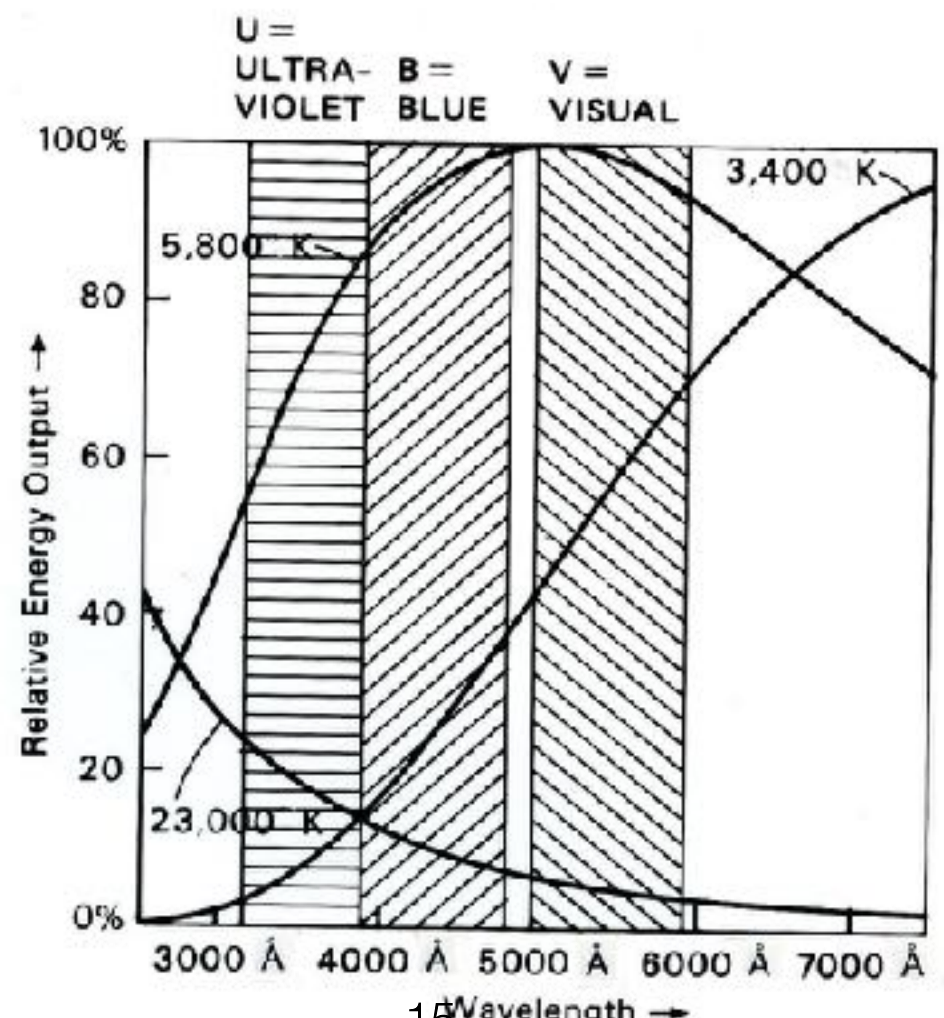

a
b
01
02
03
04
5505
06
07
08
09
5510
11
12
13
14
5515
16
17
Fe
CrII
Ti
Ni
Fe
YII
Ni
Cr II
CeII
Fe
Ti
Ca
Ti
Mn
Fe

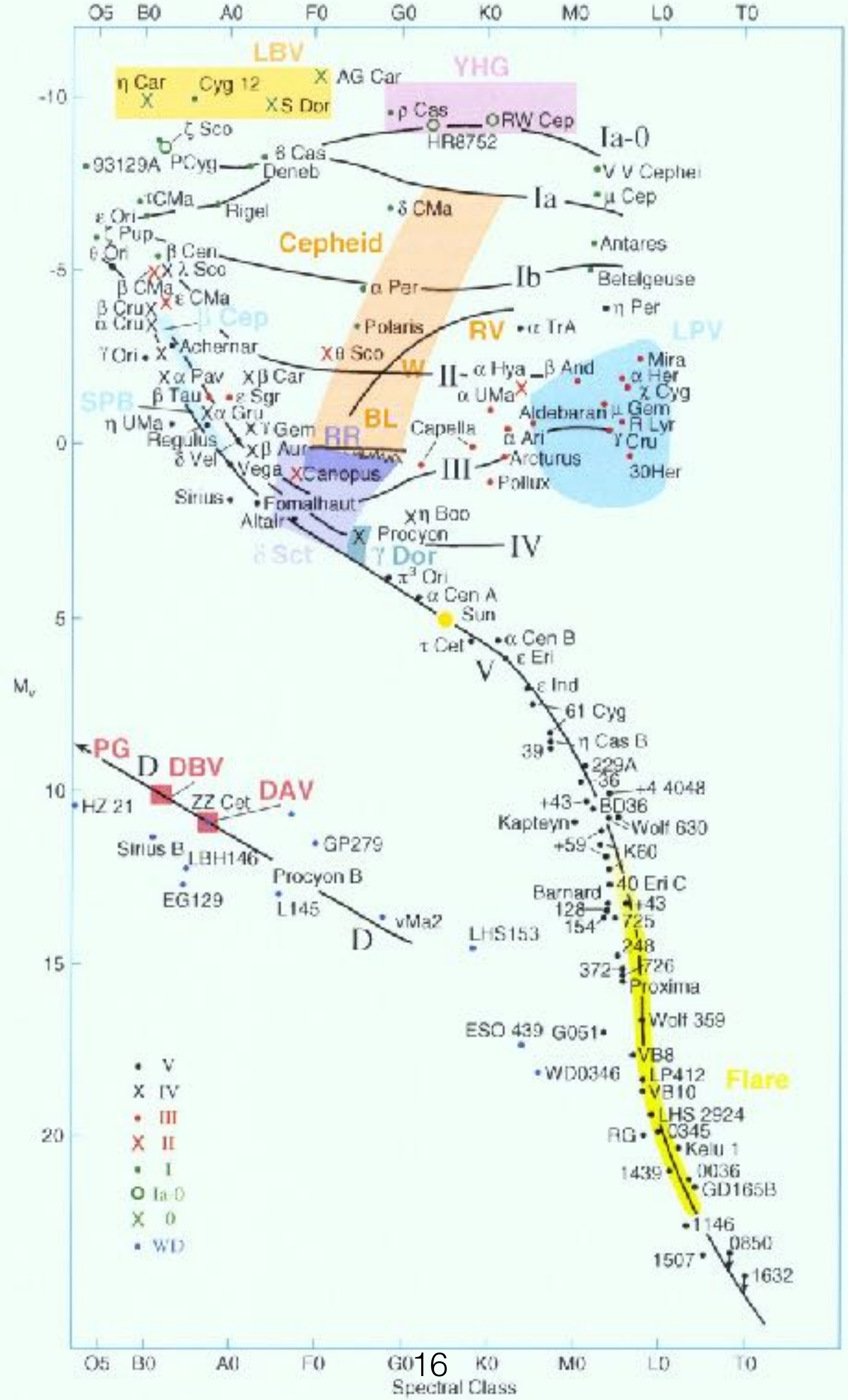

Balmer Jump
Convergence
Hδ
Hγ
Hβ
Hα
O7.5 V
B5 V
A2.5 V
Ca K
F1 V
G-band
Na D
G1 V
K0 V
K8 V
MgH
MgH
Ca I
M3 V
TiO
TiO
Normalized Flux
3500
4000
4500
5000
5500
6000
6500
7000
Wavelength (Å)

a

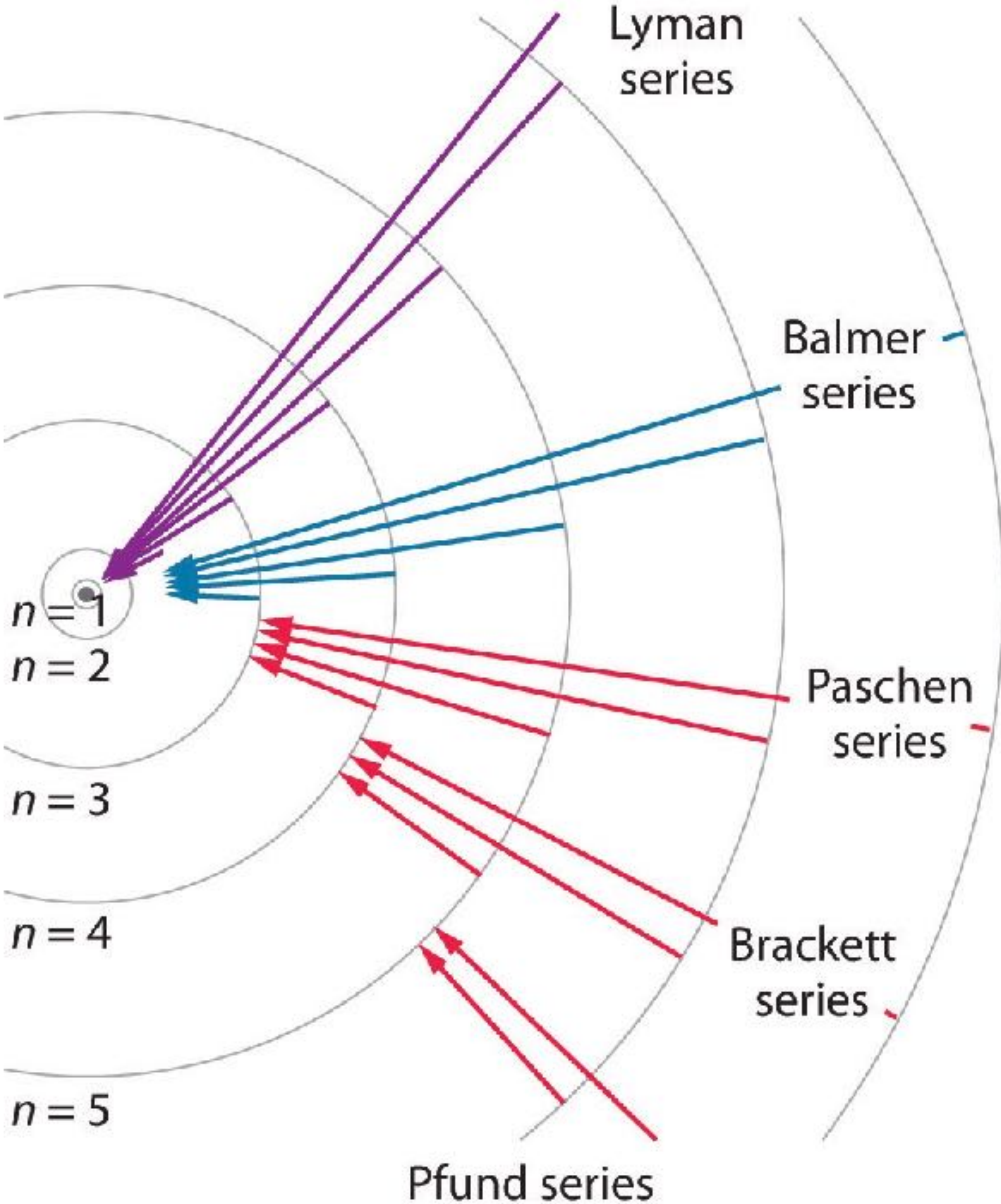

6000 K
5500 K
5000 K
Radiant Energy Emitted by Unit Area in Unit Time
2000 3000 4000 5000 6000 7000 8000 9000
Wavelength in Ångstroms

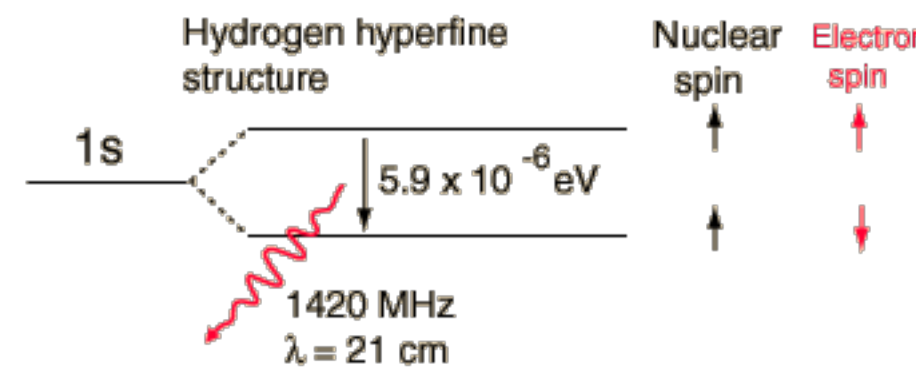
b

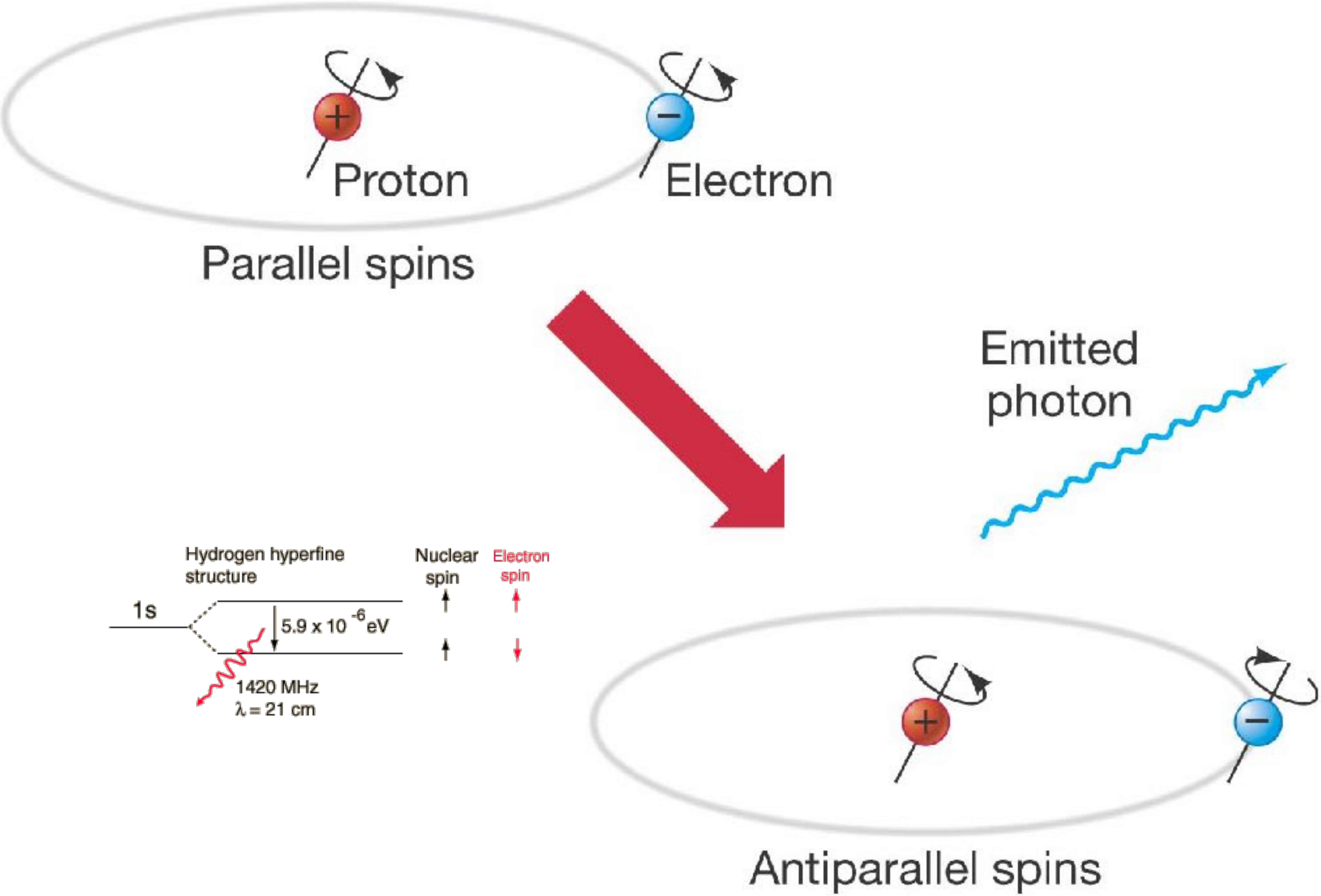

U = ULTRA-VIOLET
B = BLUE
V = VISUAL
100%
80
60
40
20
0%
3,400 K
5,800 K
23,000 K
Relative Energy Output
3000 Å 4000 Å 5000 Å 6000 Å 7000 Å
Wavelength


O5 B0 A0 F0 G0 K0 M0 L0 T0
LBV
η Car
Cyg 12
AG Car
S Dor
YHG
ρ Cas
HR8752
RW Cep
Ia-0
ζ Sco
P Cyg
93129A
δ Cas
Deneb
V V Cephei
τ CMa
Rigel
Ia
μ Cep
ε Ori
δ CMa
ζ Pup
δ Ori
β Cen
λ Sco
Cepheid
Antares
β CMa
ε CMa
α Per
Ib
Betelgeuse
β Cru
α Cru
β Cep
η Per
Polaris
RV
α TrA
LPV
γ Ori
Achernar
θ Sco
W
II
α Hya
β And
Mira
α Pav
β Car
α UMa
α Her
χ Cyg
SPB
β Tau
ε Sgr
α Gru
Aldebaran
μ Gem
R Lyr
η UMa
γ Gem
BL
Capella
Regulus
β Aur
RR
α Ari
γ Cru
δ Vel
Arcturus
30Her
Vega
Canopus
III
Pollux
Sirius
Fomalhaut
η Boo
Altair
Procyon
IV
δ Sct
γ Dor
π³ Ori
α Cen A
Sun
α Cen B
τ Cet
ε Eri
V
ε Ind
61 Cyg
39
η Cas B
229A
36
+4 4048
+43
BD36
Kapteyn
Wolf 630
+59
K60
40 Eri C
Barnard
128
+43
725
154
248
372
726
Proxima
Wolf 359
ESO 439
G051
VB8
WD0346
LP412
VB10
Flare
LHS 2924
RG
0345
Kelu 1
1439
0036
GD165B
1146
0850
1507
1632
PG
D
DBV
DAV
HZ 21
ZZ Cet
Sirius B
LBH146
GP279
EG129
Procyon B
L145
vMa2
D
LHS153
-10
-5
0
5
10
15
20
M_v
V
IV
III
II
I
Ia-0
0
WD
Spectral Class

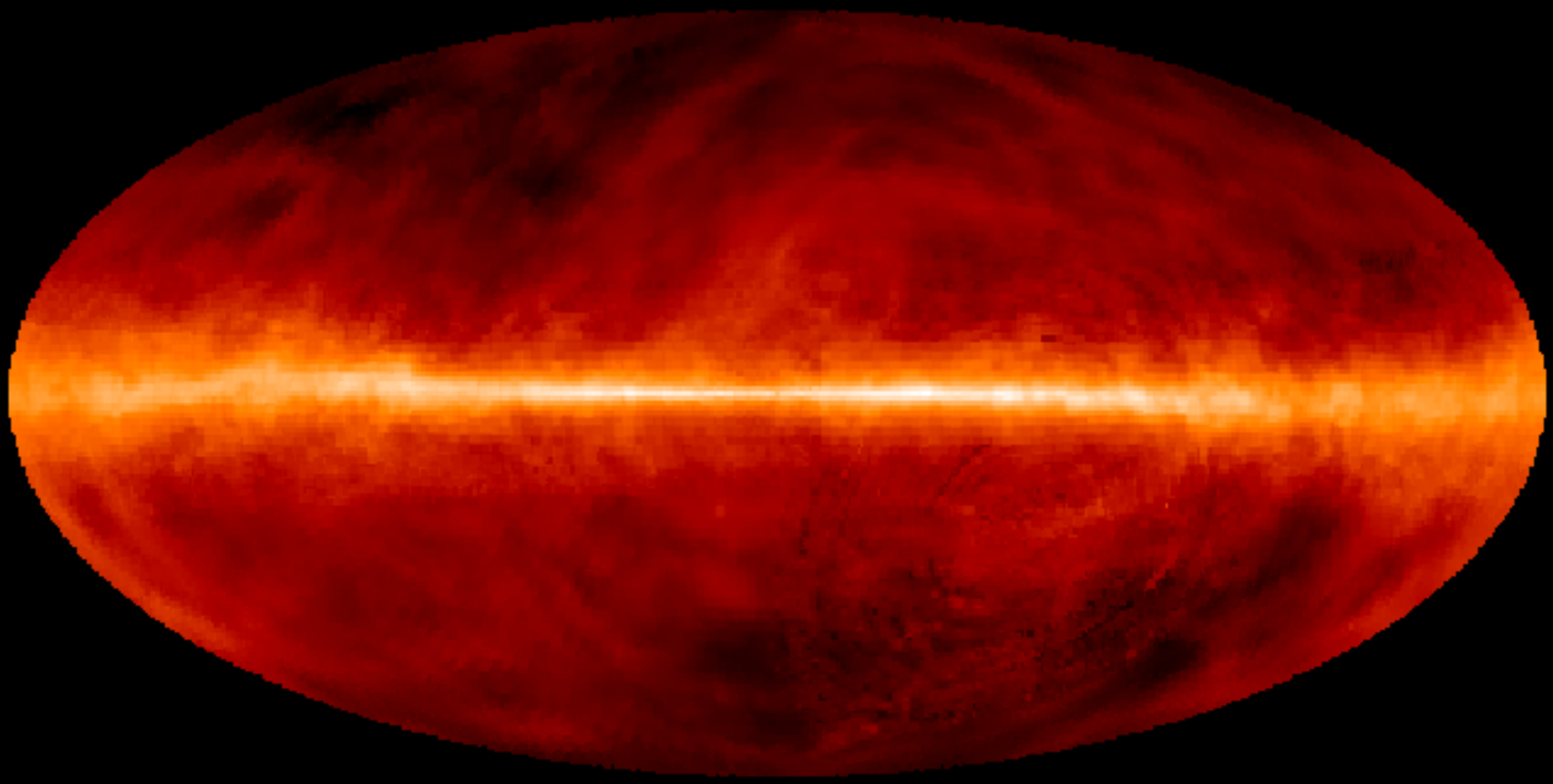
Hydrogen Atom

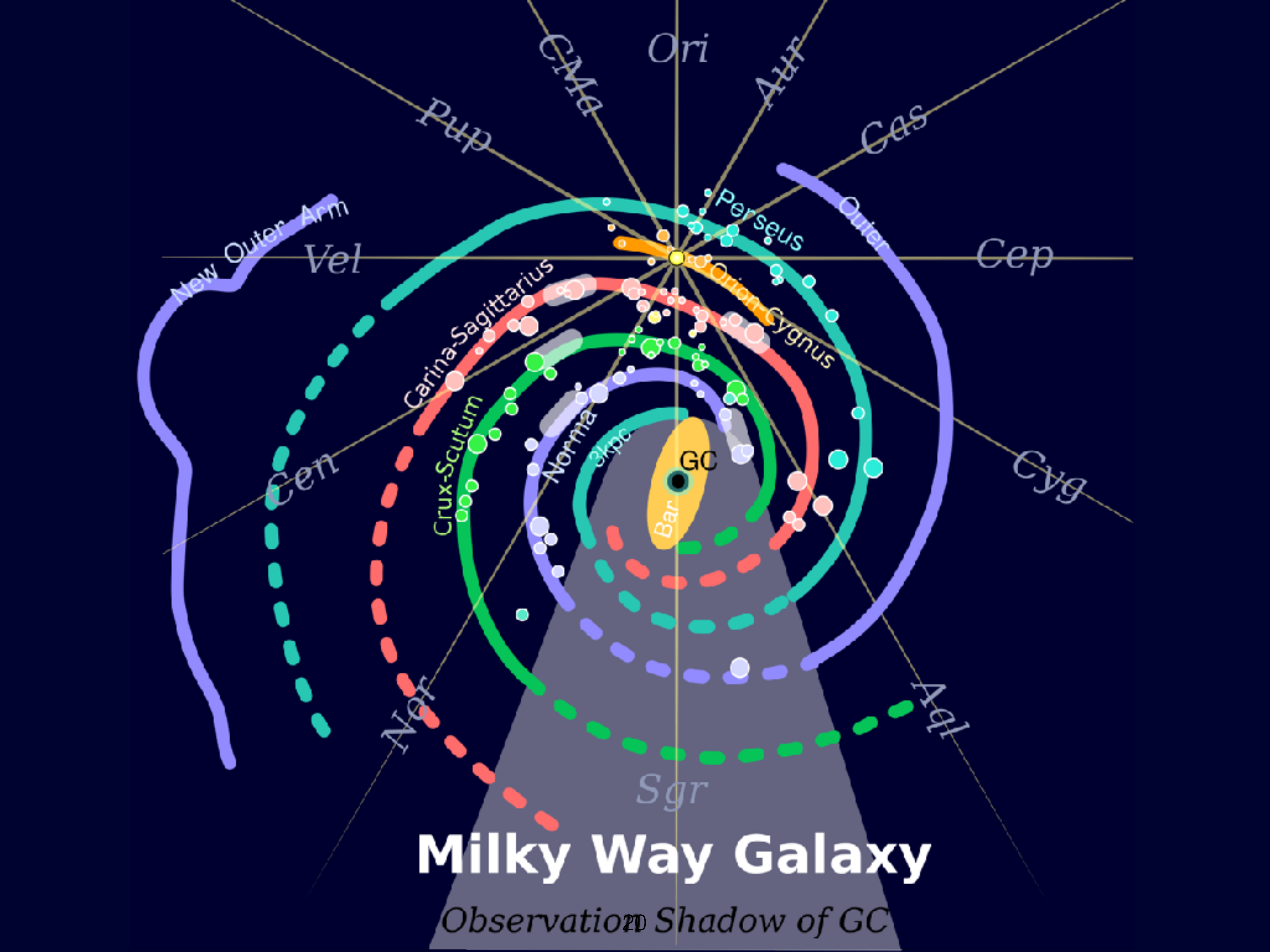


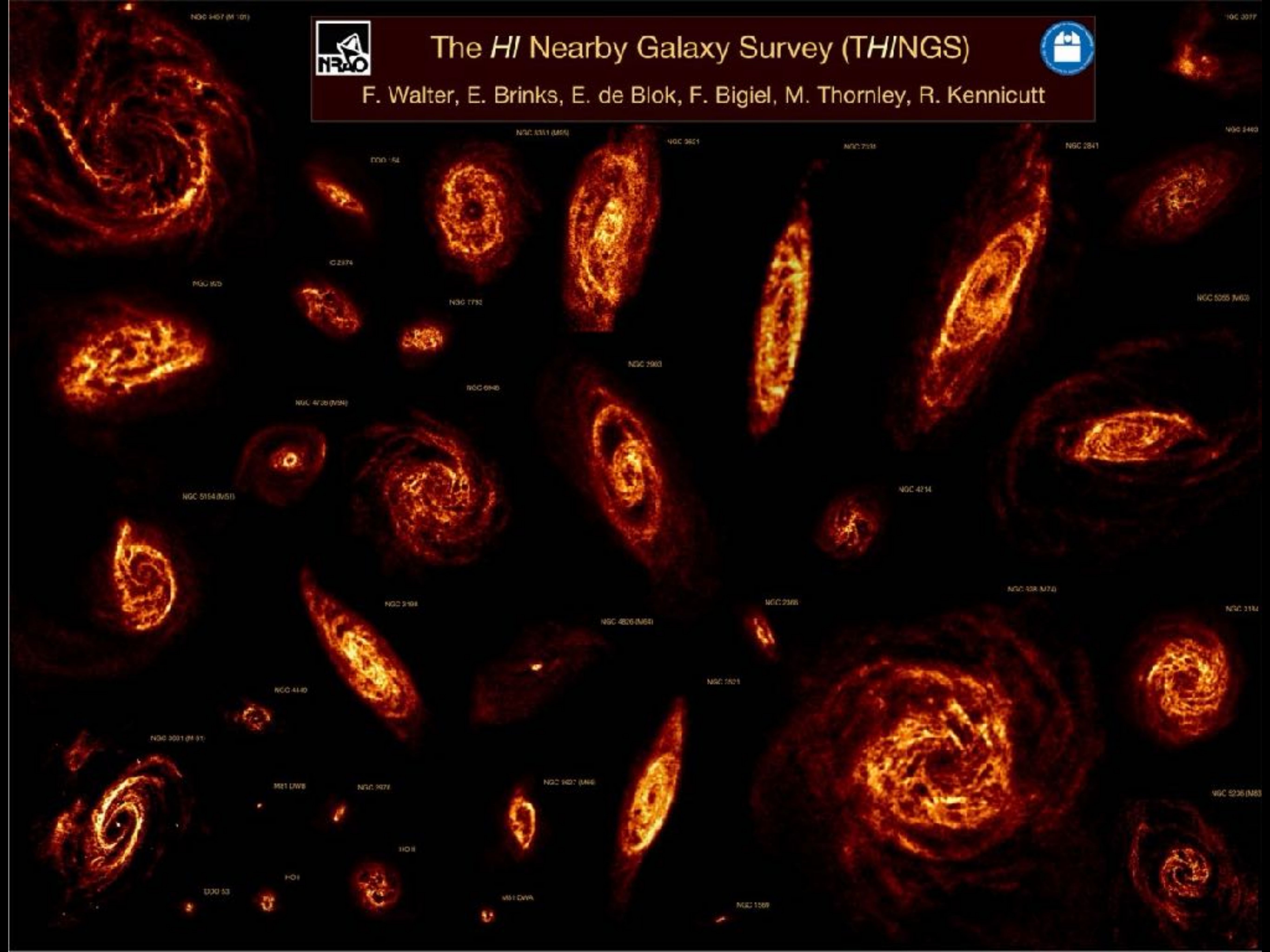



Proton
Electron
Parallel spins
Emitted
photon
Hydrogen hyperfine
structure
Nuclear
spin
Electron
spin
1s
5.9 x 10 -6 eV
1420 MHz
λ = 21 cm
Antiparallel spins

The Milky Way in HI 21 cm

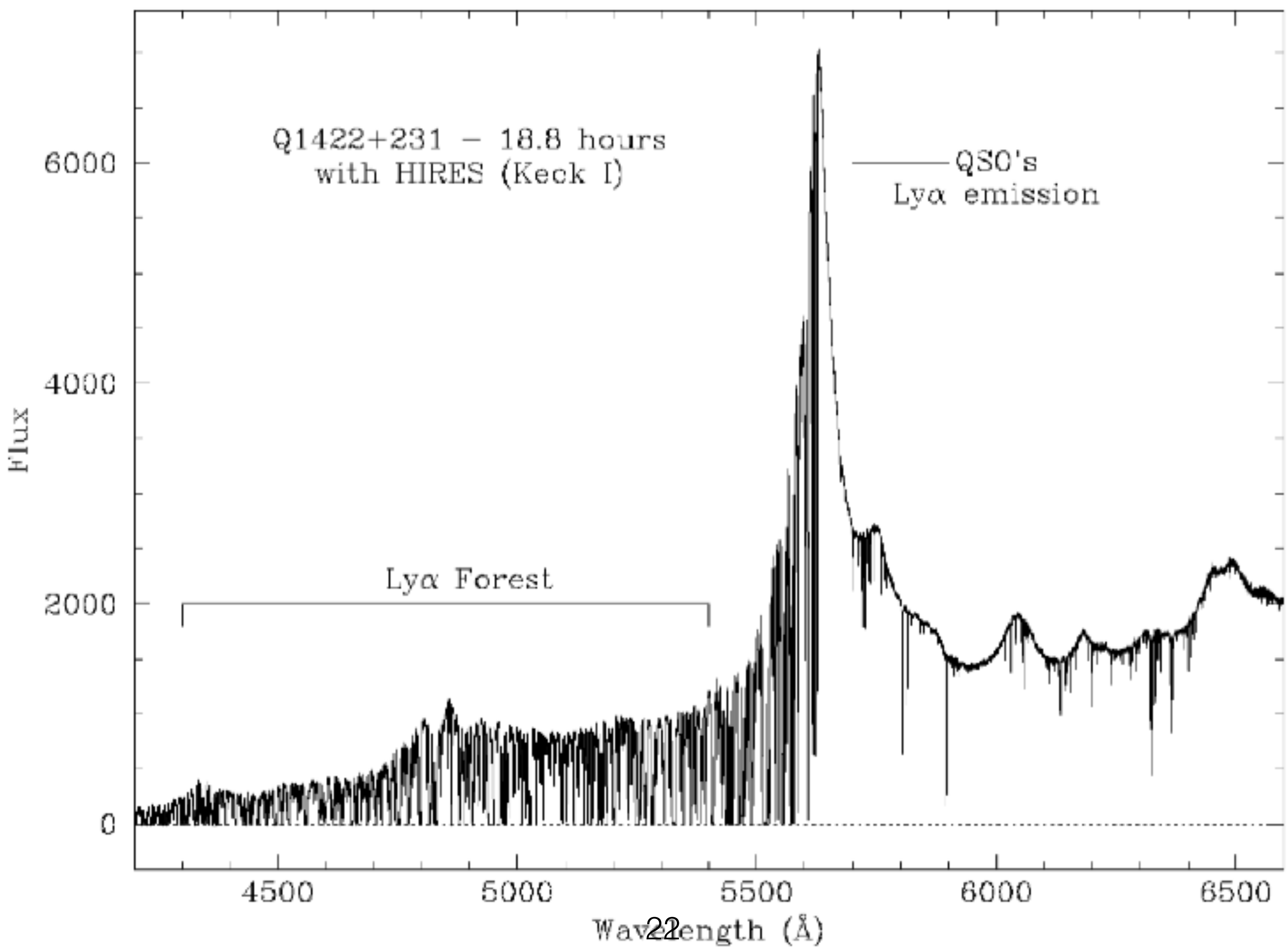


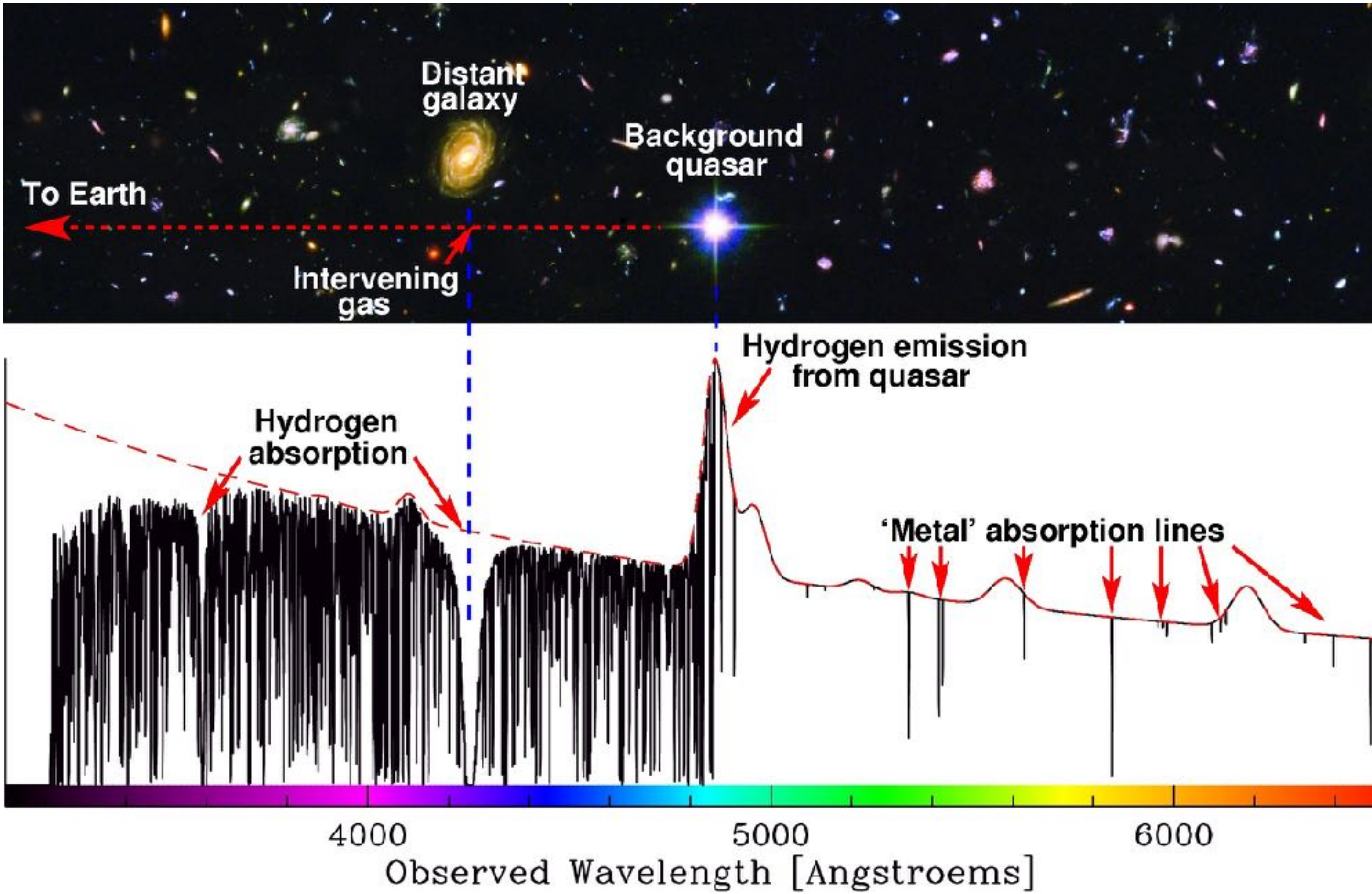

Ori
CMa
Aur
Pup
Cas
Perseus
Outer
New Outer Arm
Vel
Cep
Carina-Sagittarius
Orion-Cygnus
Crux-Scutum
Norma
3kpc
GC
Bar
Cen
Cyg
Nor
Aql
Sgr
Milky Way Galaxy
Observation Shadow of GC


The HI Nearby Galaxy Survey (THINGS)
F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt

Lyα 1216Å

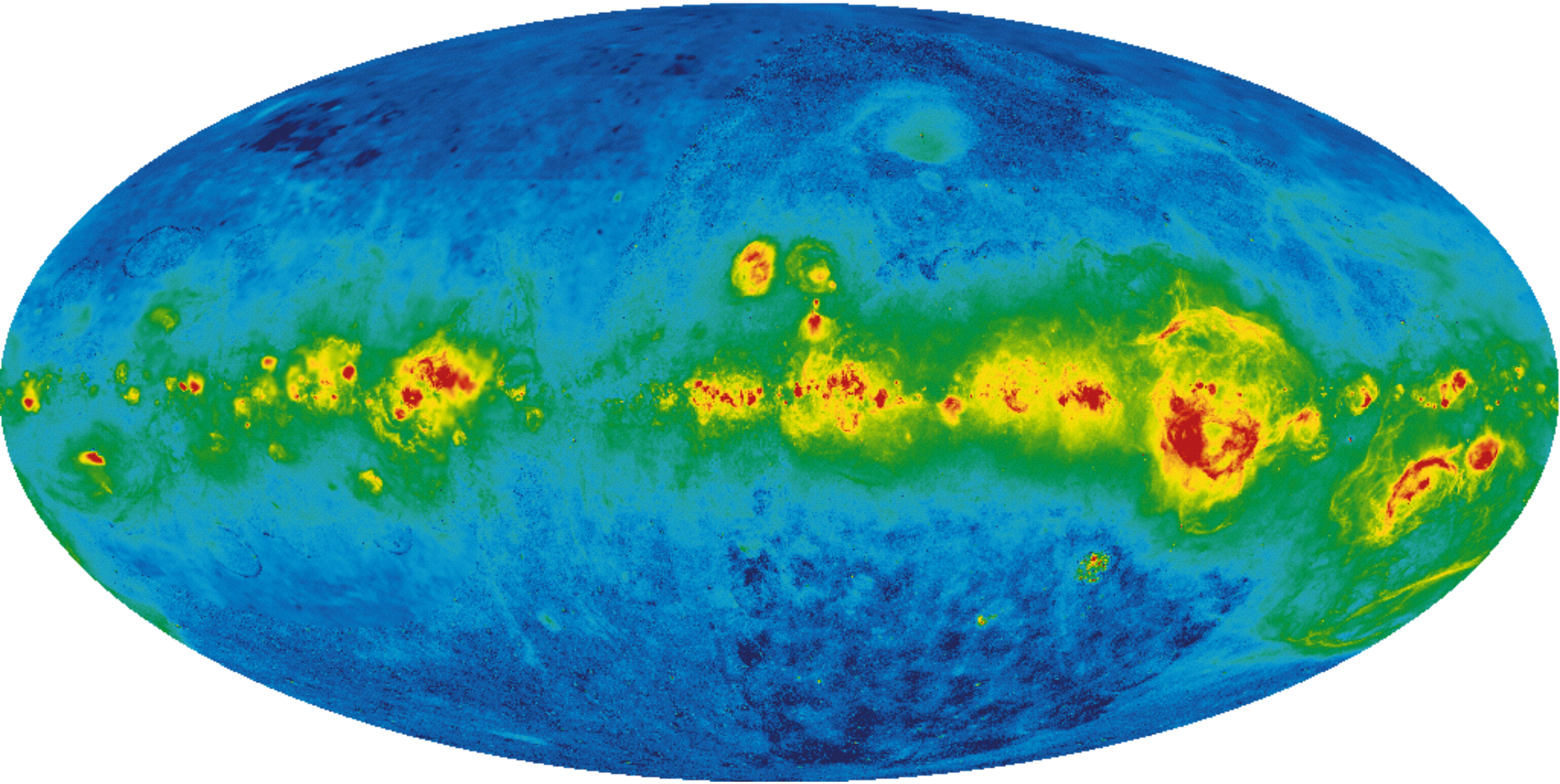
Brightest line





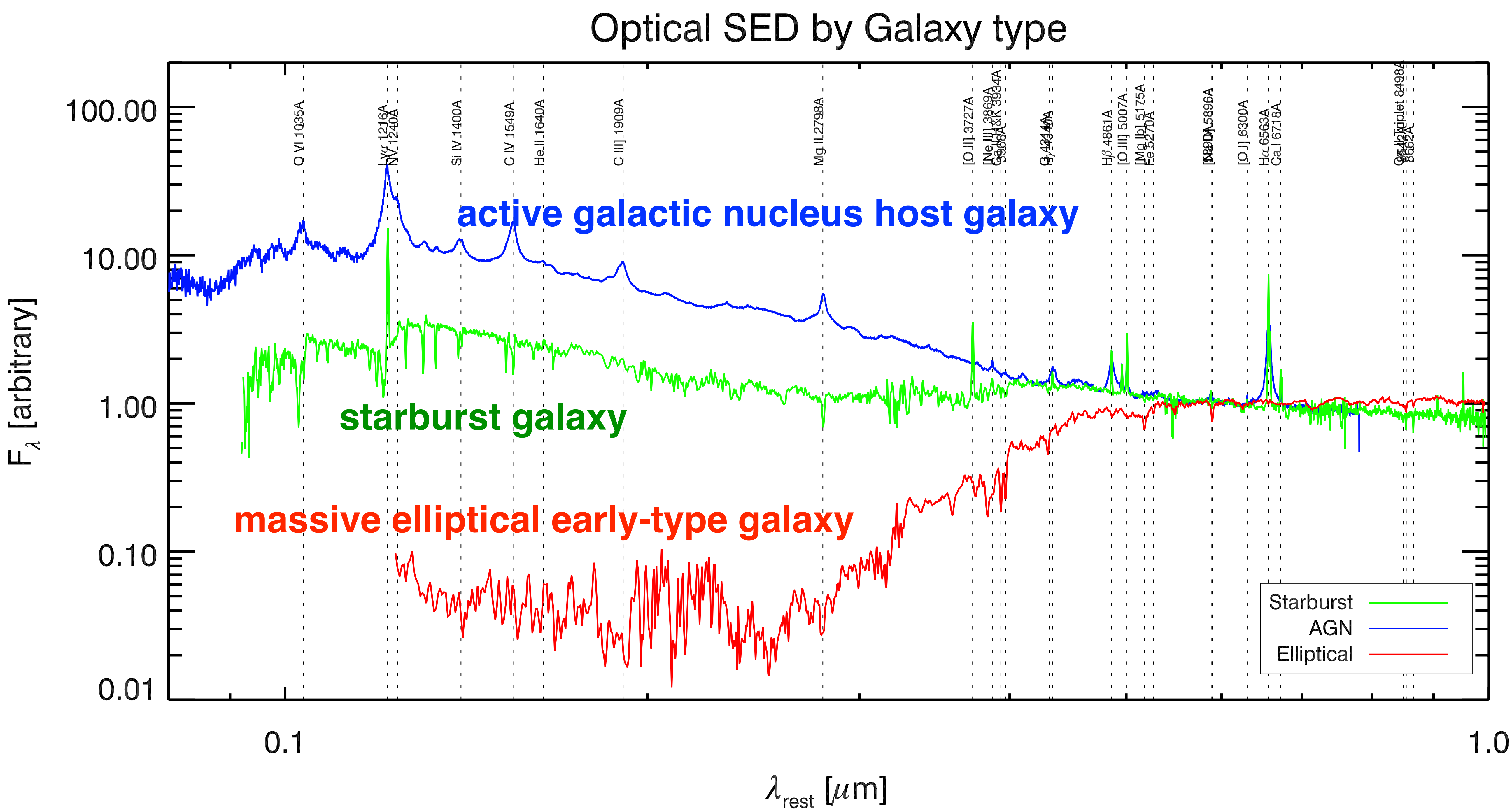
Distant galaxy
Background quasar
To Earth
Intervening gas
Hydrogen emission from quasar
Hydrogen absorption
'Metal' absorption lines
4000
5000
6000
Observed Wavelength [Angstroems]

Hα 6563Å



Hα 6563Å

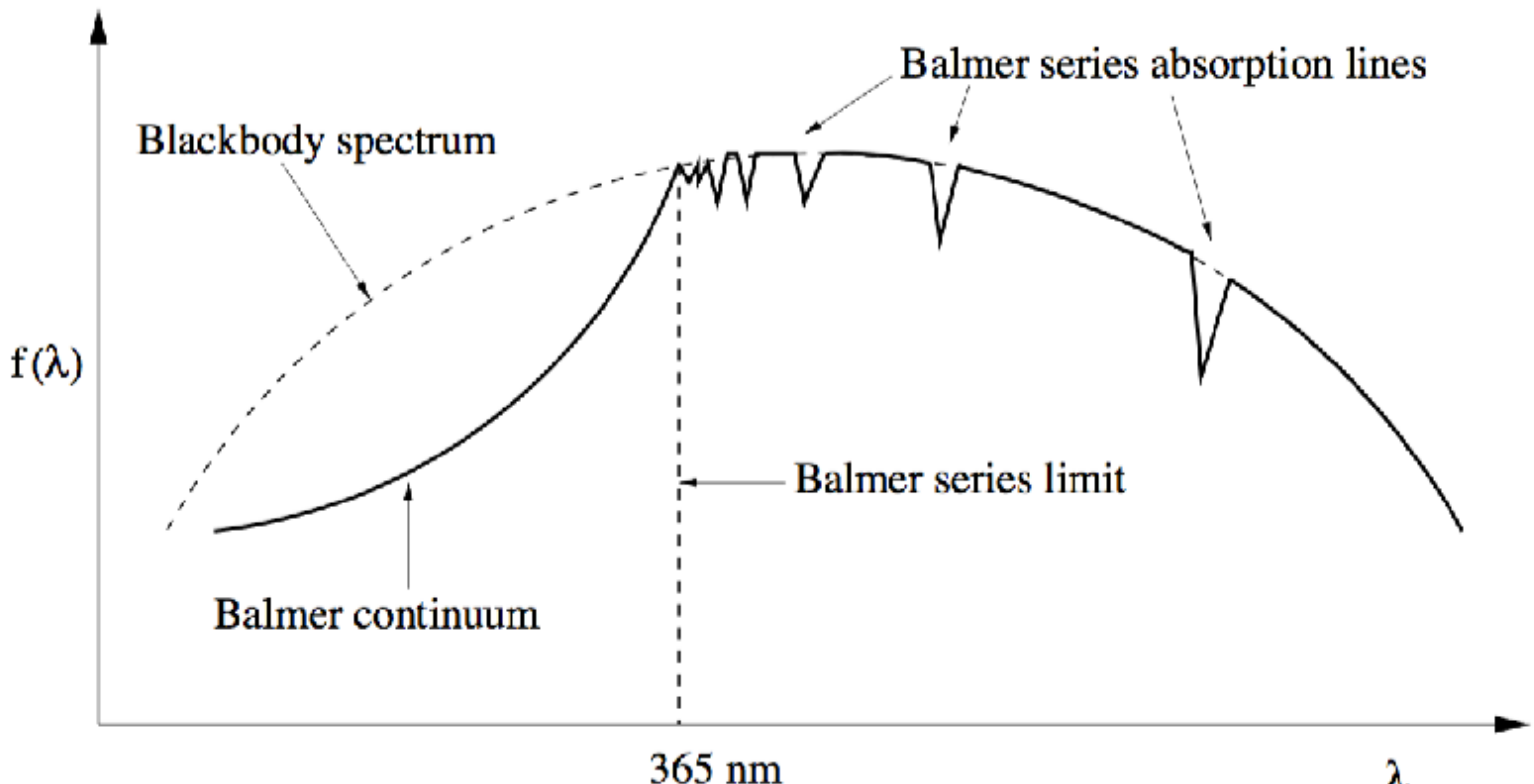
- The most commonly used emission line is therefore the first is the Balmer series, Hα, as it is the most luminous. So the Hα line occurs when the electron cascades down from $n = 3$ to $n = 2$ and emits a photon of wavelength 6562.8Å.
- This line also occurs in the optical, so historically, Hα is the most studied line in astronomy.
- Since only massive stars with lifetimes < 20Myr contribute significantly to the ionizing flux, Hα 6563Å emission lines give you a direct measure of the instantaneous SFR.
- For an ionisation-bounded region of HII gas the Balmer emission series directly scales with the ionising flux of the stellar population within.
- Another major advantage of the Hα line is that it is sensitive to all types of stellar population and is independent of temperature and ionization level of the gas.
- Often when you measure the EW of the Hα line you are measuring the EW of the Hα+NII as these often can not be resolved.

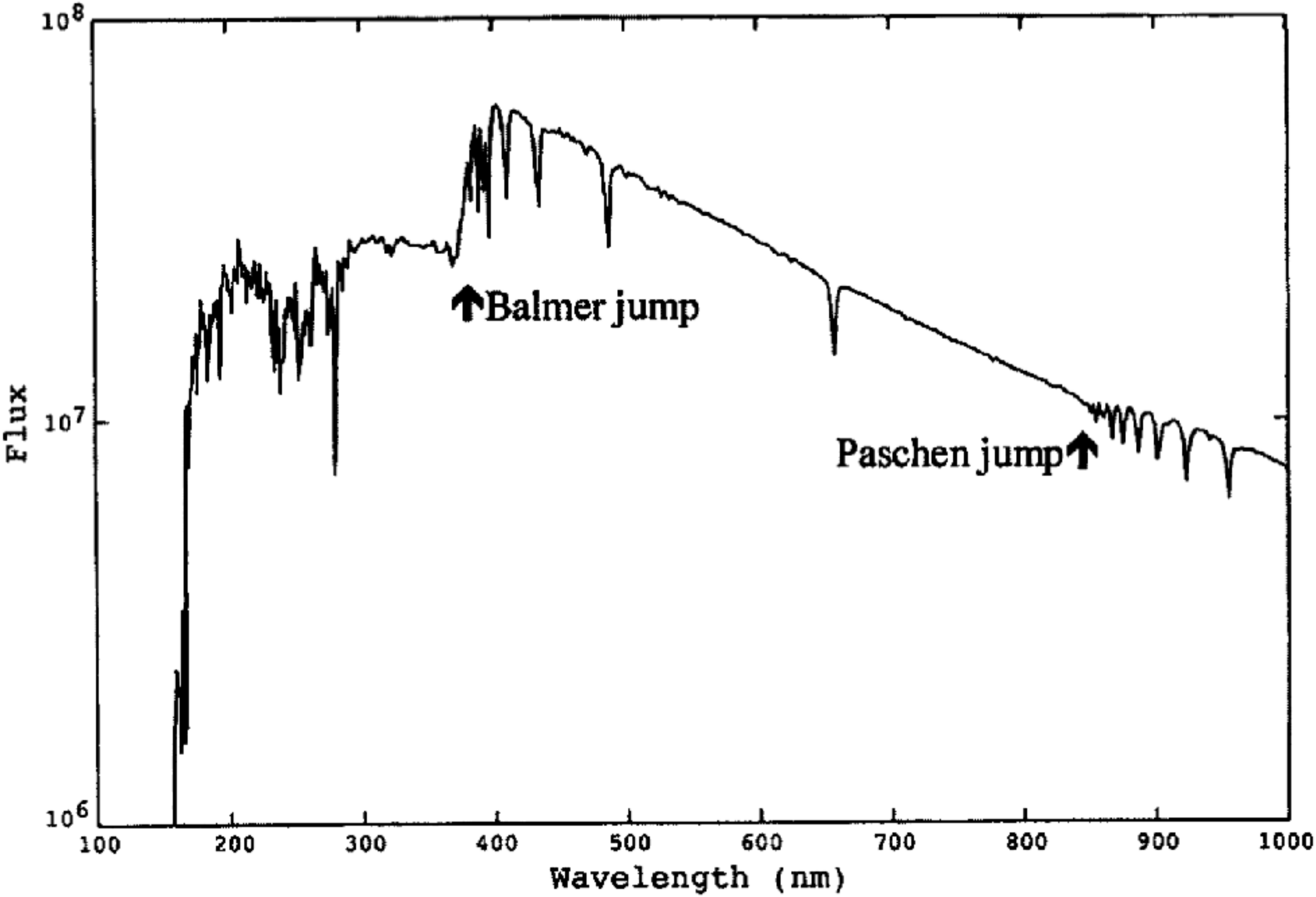


Optical SED by Galaxy type
active galactic nucleus host galaxy
starburst galaxy
massive elliptical early-type galaxy
100.00
10.00
1.00
0.10
0.01
0.1
1.0
F_λ [arbitrary]
λ_rest [μm]
O VI 1035A
Lyα 1216A
NV 1240A
Si IV 1400A
C IV 1549A
He II 1640A
C III] 1909A
Mg II 2798A
[O II] 3727A
[Ne III] 3869A
Ca K 3934A
Hβ 4861A
[O III] 5007A
Hα 6563A
Starburst
AGN
Elliptical

Balmer Break

- The 4000Å break is the accumulation of ionized metal absorption lines in the atmosphere of the stars (two of the strong feature being CaII H & K). As the stellar temperature decreases the opacity of the star increase and the so does the strength of the break.
- The strength of the break in the spectra of stellar systems at 4000Å gives you an indication of the cumulative star formation history which in turn gives you an idea of the age of the system.
- The understanding of how this break evolves with time is looked at using evolutionary models of galaxies. These models take stellar libraries, a star formation rate and an IMF and try to predict how the spectra of stellar systems will evolve.

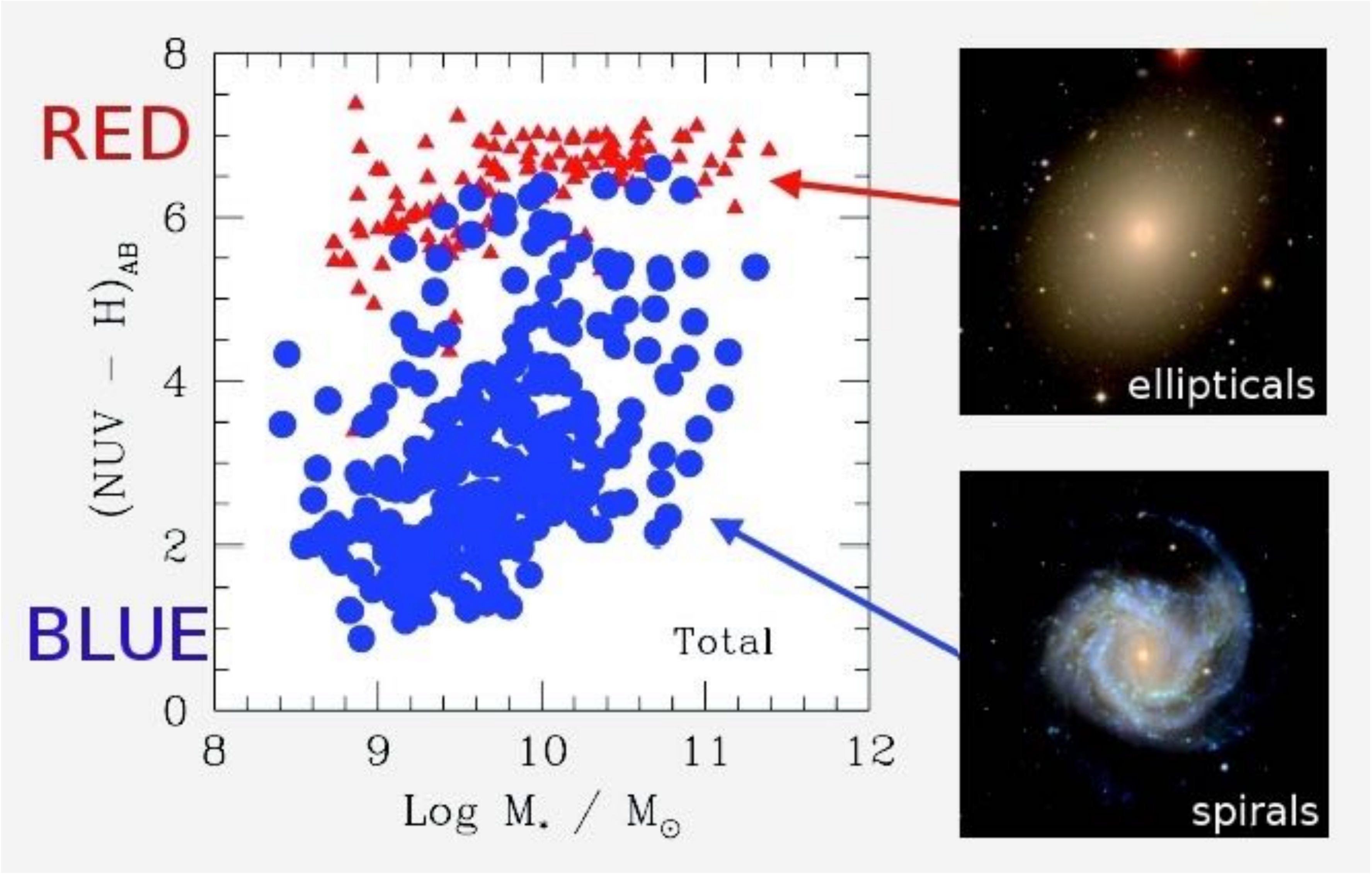




10^8
10^7
10^6
Flux
Balmer jump
Paschen jump
100
200
300
400
500
600
700
800
900
1000
Wavelength (nm)

Balmer Break

- This spectral feature defines what we call the “red-sequence” and is how we get photometric redshifts and find galaxy clusters in the optical.



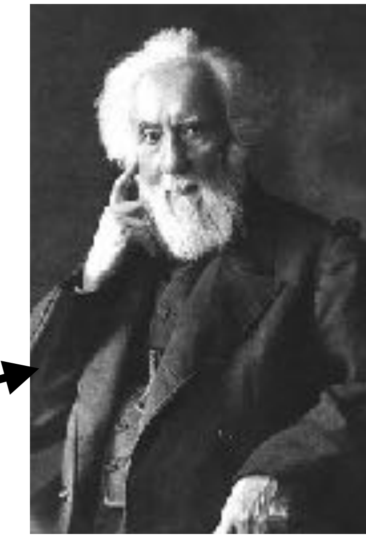
Spectroscopy — Why?

- composition, ionization, temperature, densities —> composition and physical conditions of astronomical objects at cosmic distances
- velocities, redshifts, rotations —> distances, 3D structure and kinematics of the Universe, and dynamics of structures

Cosmic Discoveries Enabled by Spectroscopic Technology

Past:

- Atomic composition of the stars and nebulae (ie, they are made of the same stuff as on Earth) (Fraunhoffer—> Higgins—> Draper~1840-1870)
- Stellar Classification (Annie Jump Cannon ~1900), H-R diagram (1910), and stellar evolution
- Velocities of nebulae (galaxies) (Vesto Slipher ~1912)
- Chemical composition of stars (Ceclia Payne) ~1925
- Expansion of the universe (Hubble ~1929)
- Dynamical masses and dark matter (Zwicky ~1933)
- galaxy rotation curves (dark matter) (Babcock—> Vera Rubin ~1940–1970s)





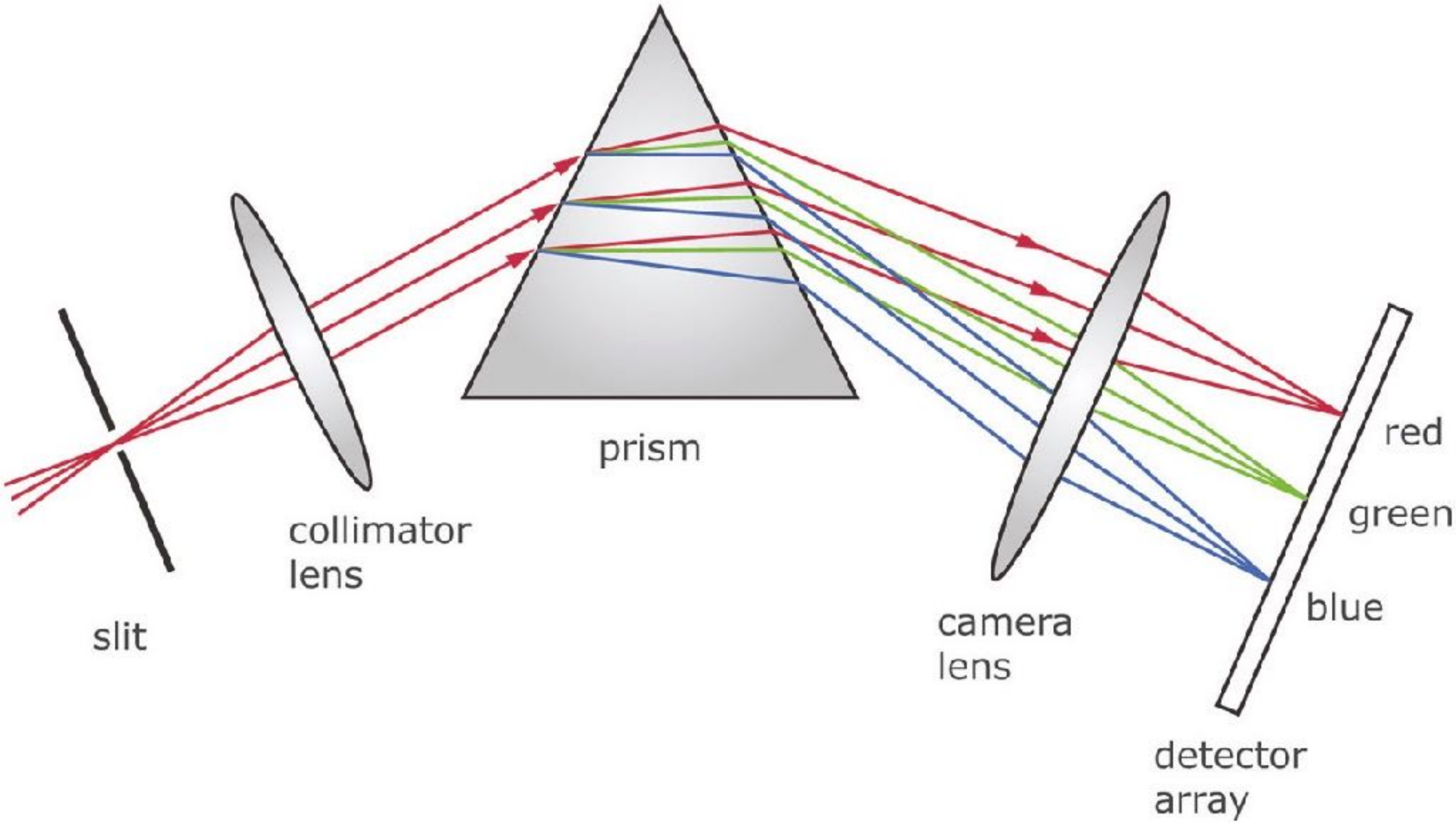

Spectrometers — How?

Types of Dispersers

- prism
- grating
- grism
- narrow band imagers
- coherent detection

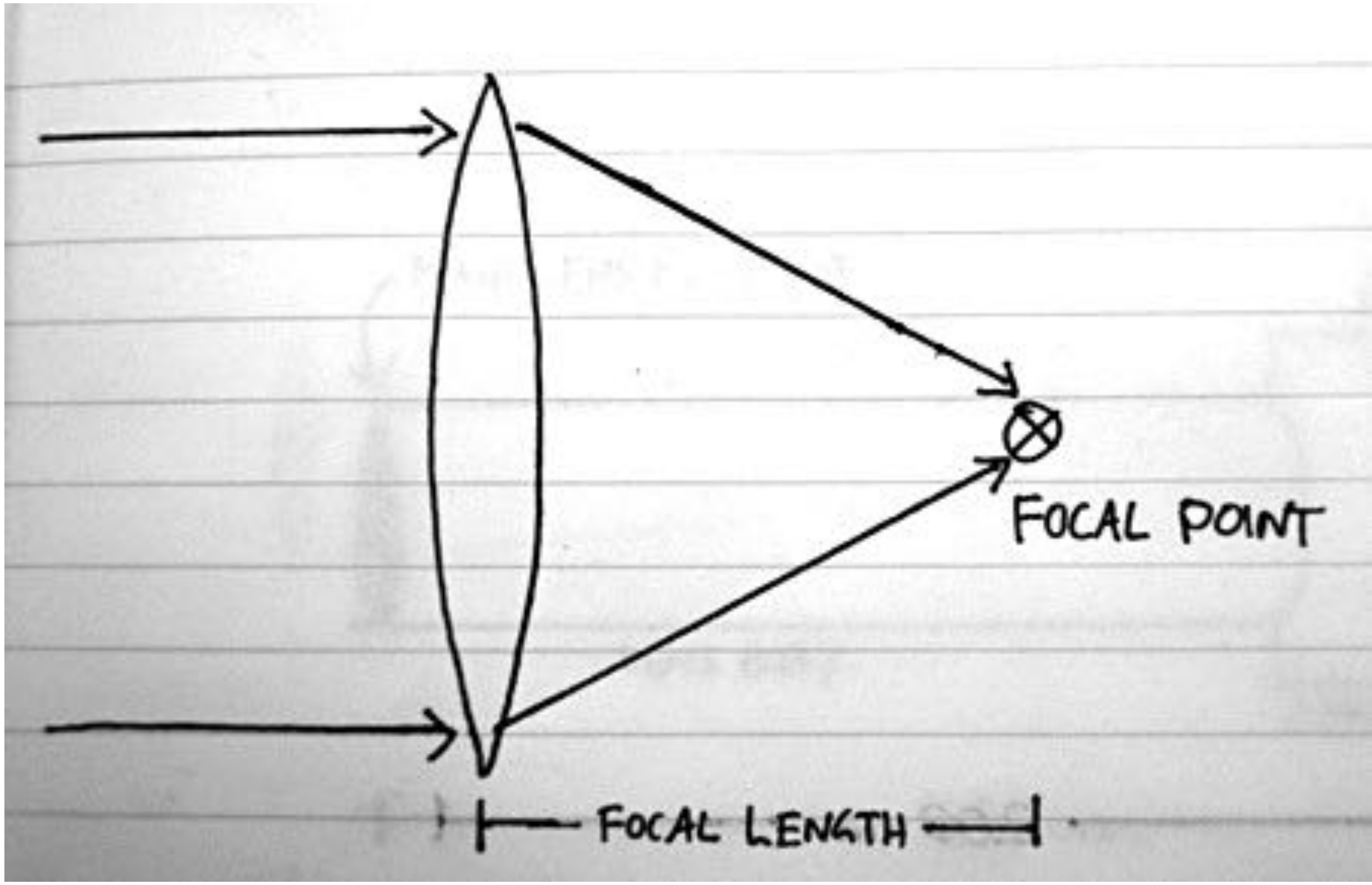
Types of Instruments

- objective prisms
- slits
- fibers
- IFUs
- tunable imagers (Fabry-Perot)
- interferometers


prism
slit
collimator
lens
camera
lens
red
green
blue
detector
array

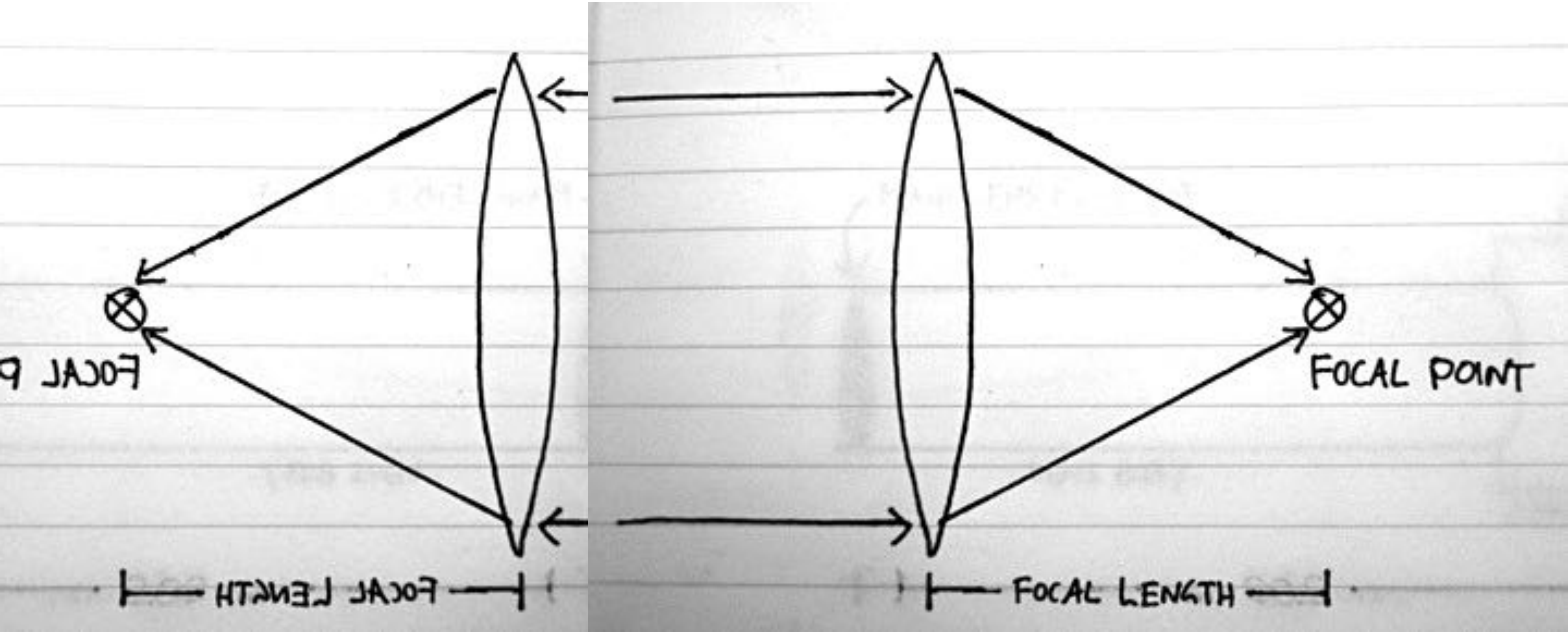
Consider the two lenses separately. The second one is the camera – it works just like a camera!

camera



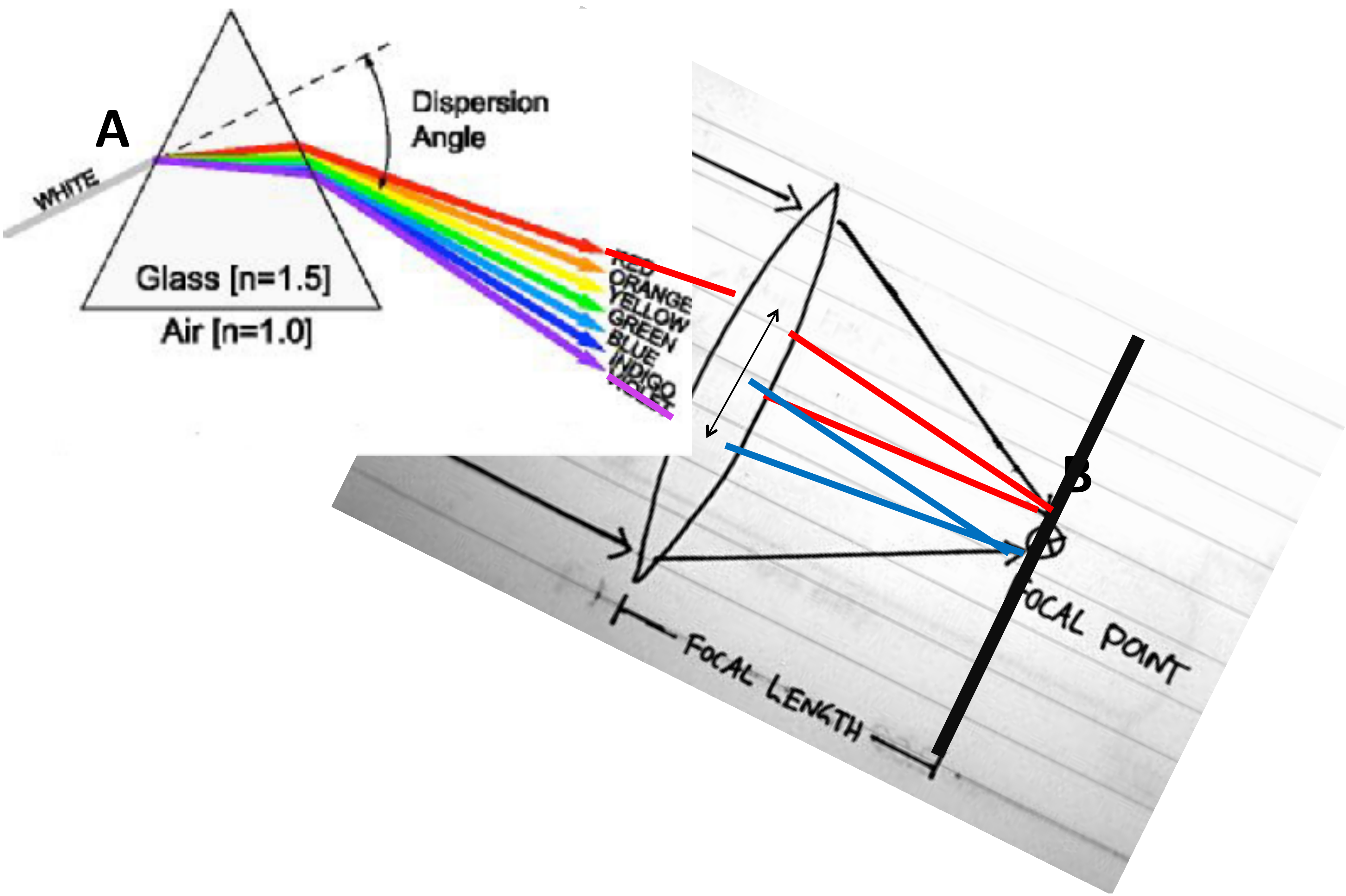
The first one is the collimator.

collimator **camera**



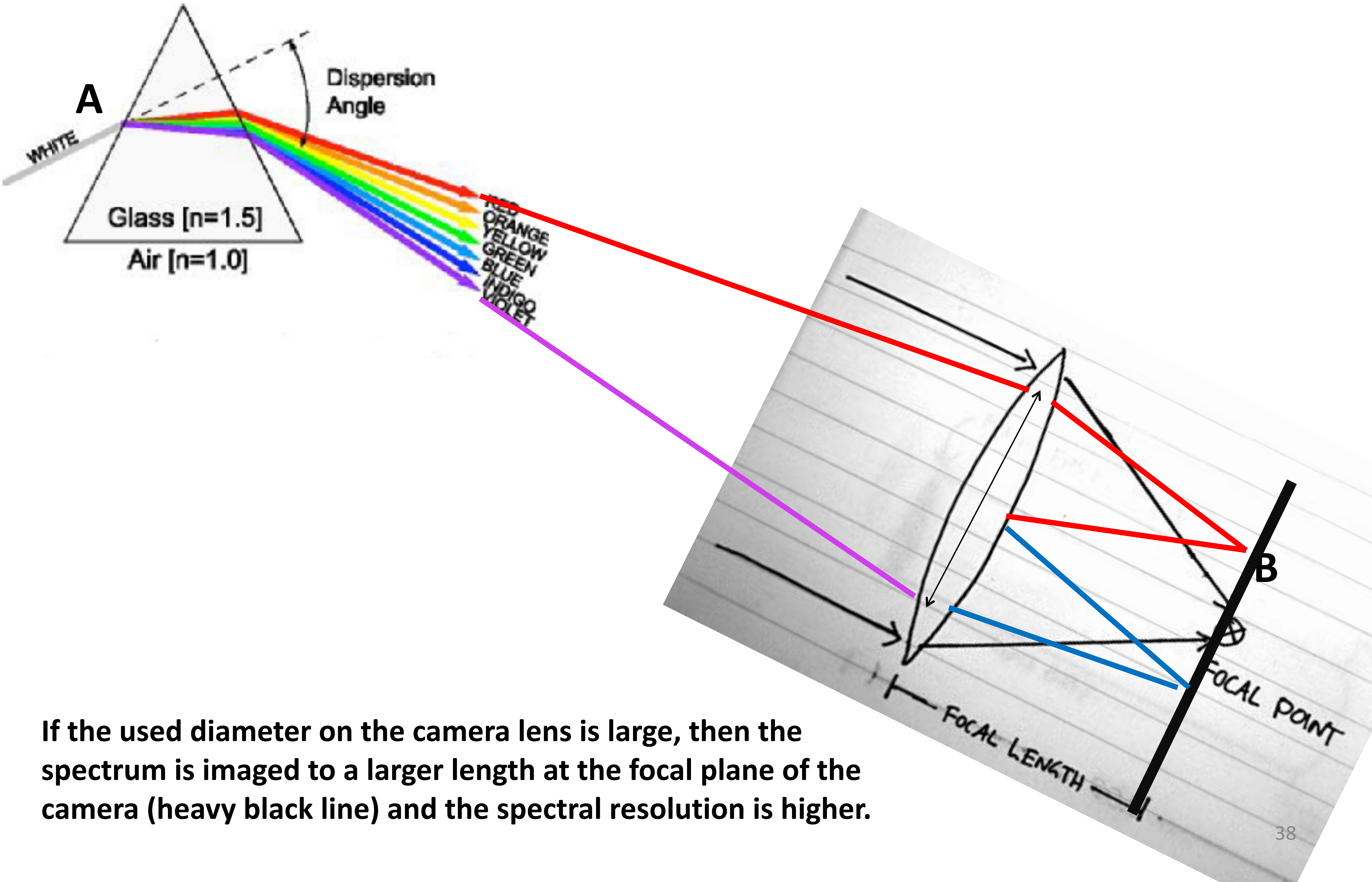
Together they just reimage the telescope focal plane (to left) onto the detector array (to right). The focal lengths of the lenses determine the scale of the image, input compared with output.

What determines the spectral resolution?



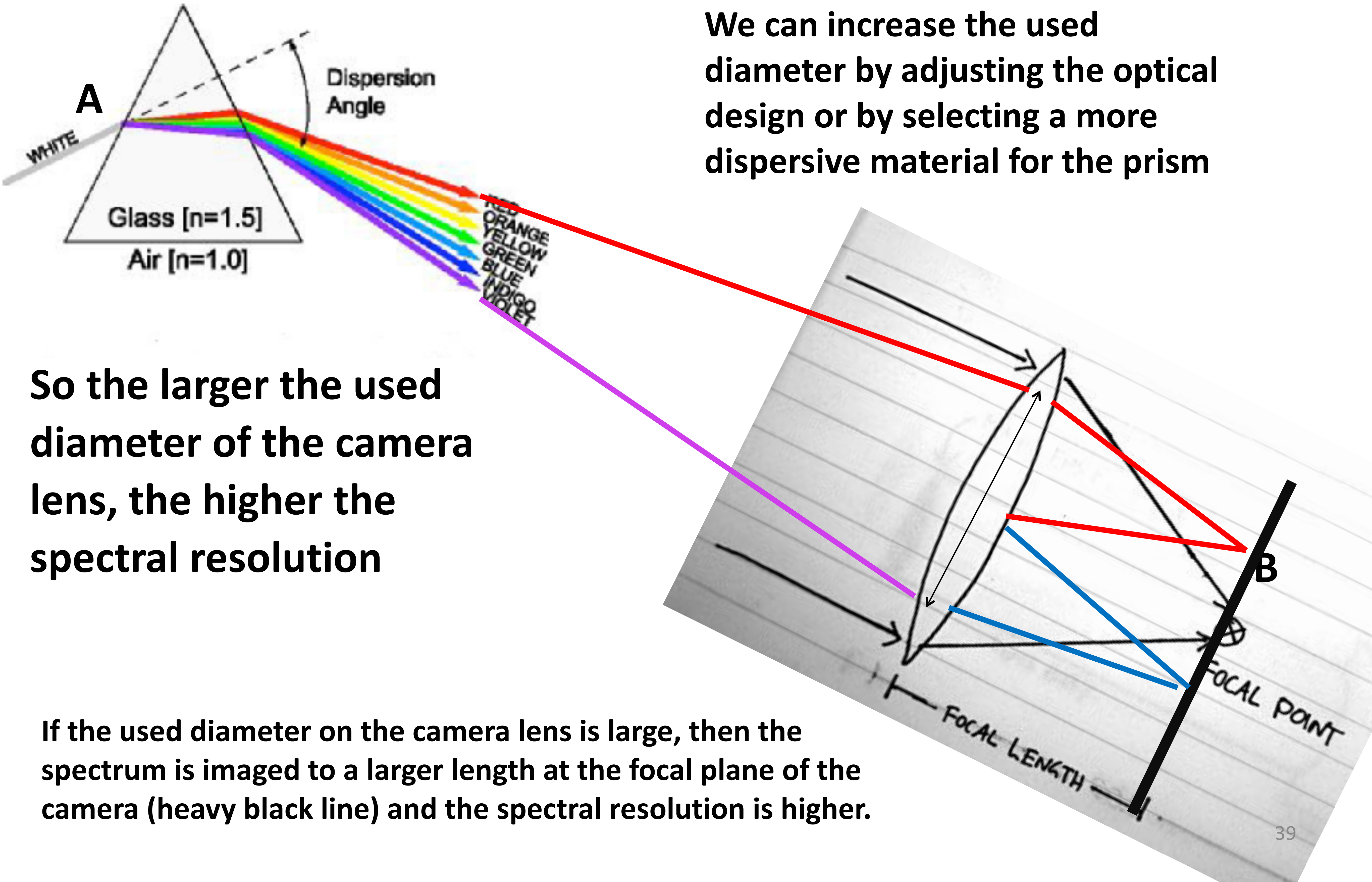
If the used diameter on the camera lens is small, then the spectrum is imaged to a short length at the focal plane of the camera (heavy black line) and the spectral resolution is low.

What determines the spectral resolution?



If the used diameter on the camera lens is large, then the spectrum is imaged to a larger length at the focal plane of the camera (heavy black line) and the spectral resolution is higher.

What determines the spectral resolution?

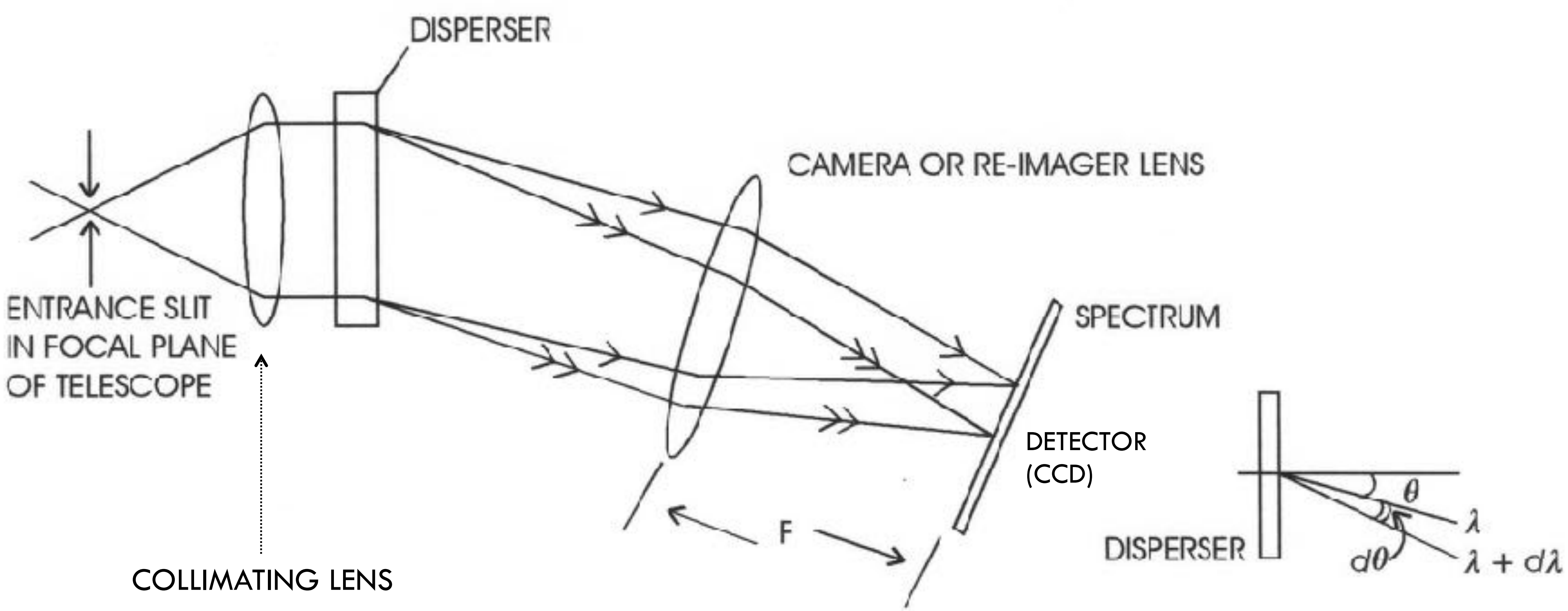


We can increase the used diameter by adjusting the optical design or by selecting a more dispersive material for the prism

So the larger the used diameter of the camera lens, the higher the spectral resolution

If the used diameter on the camera lens is large, then the spectrum is imaged to a larger length at the focal plane of the camera (heavy black line) and the spectral resolution is higher.

Spectrometers: general principles

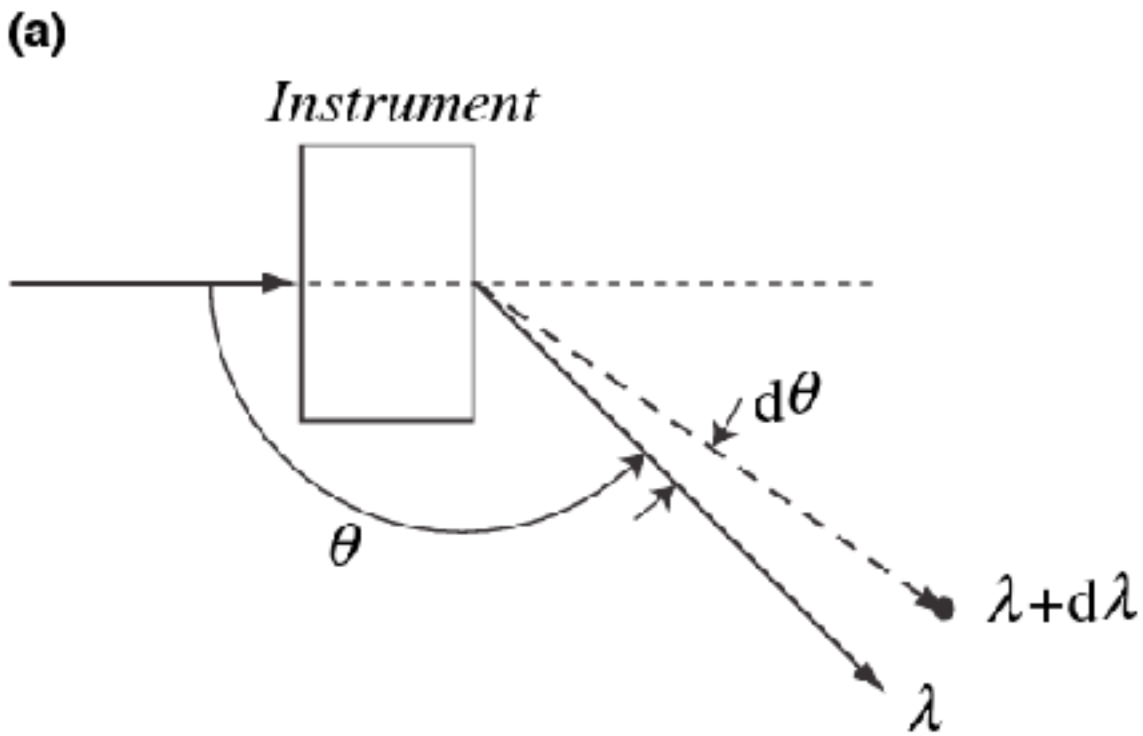


(McLean 2008)

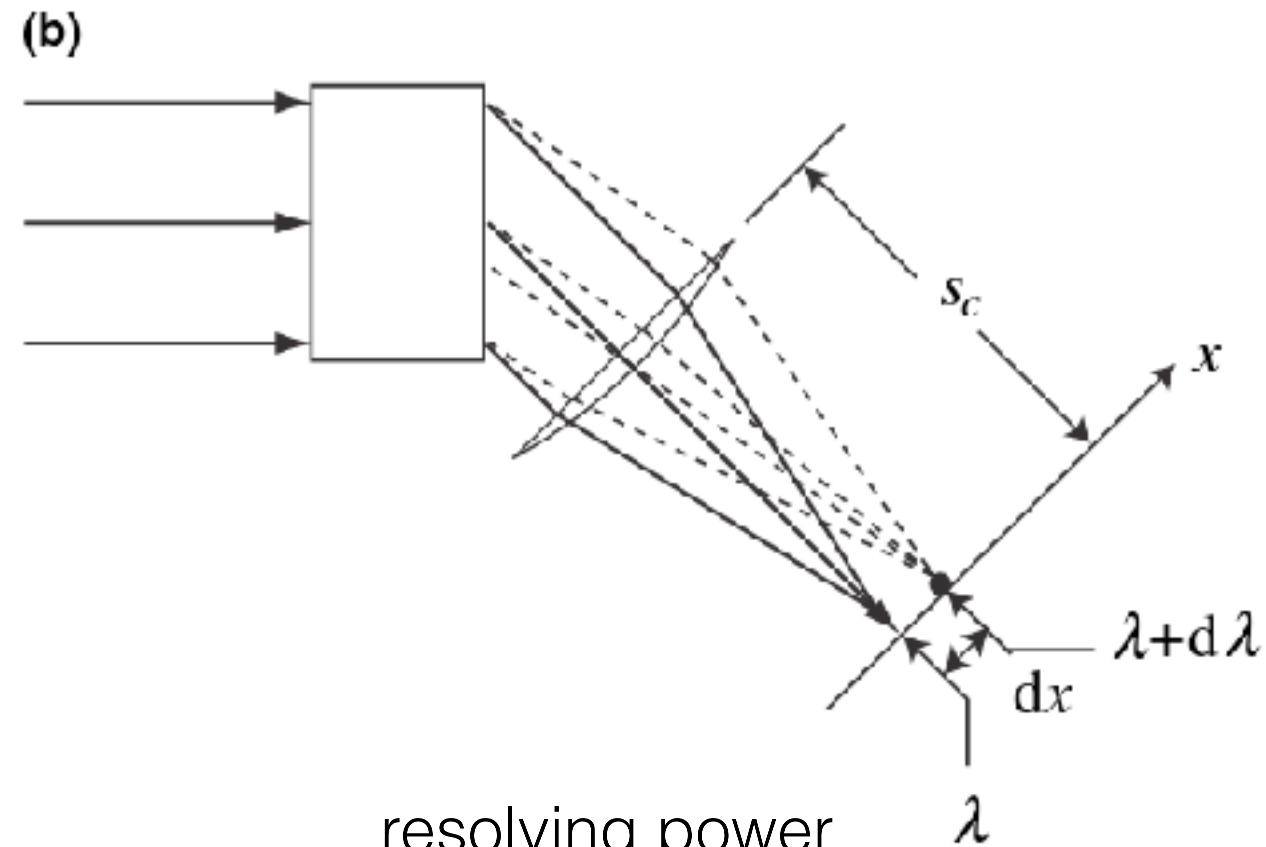
- ***Disperser:***
  - Angular dispersion of light into constituent wavelengths.
  - Dispersive elements: ***prisms***, ***gratings***, or ***grisms***.
  - Some may operate in either *reflection* or *transmission* mode.

Dispersive Spectrometer

Angular dispersion



linear dispersion



$$\frac{\mathrm{d}x}{\mathrm{d}\lambda} = s_{\mathrm{c}} \frac{\mathrm{d}\theta}{\mathrm{d}\lambda}$$

plate factor

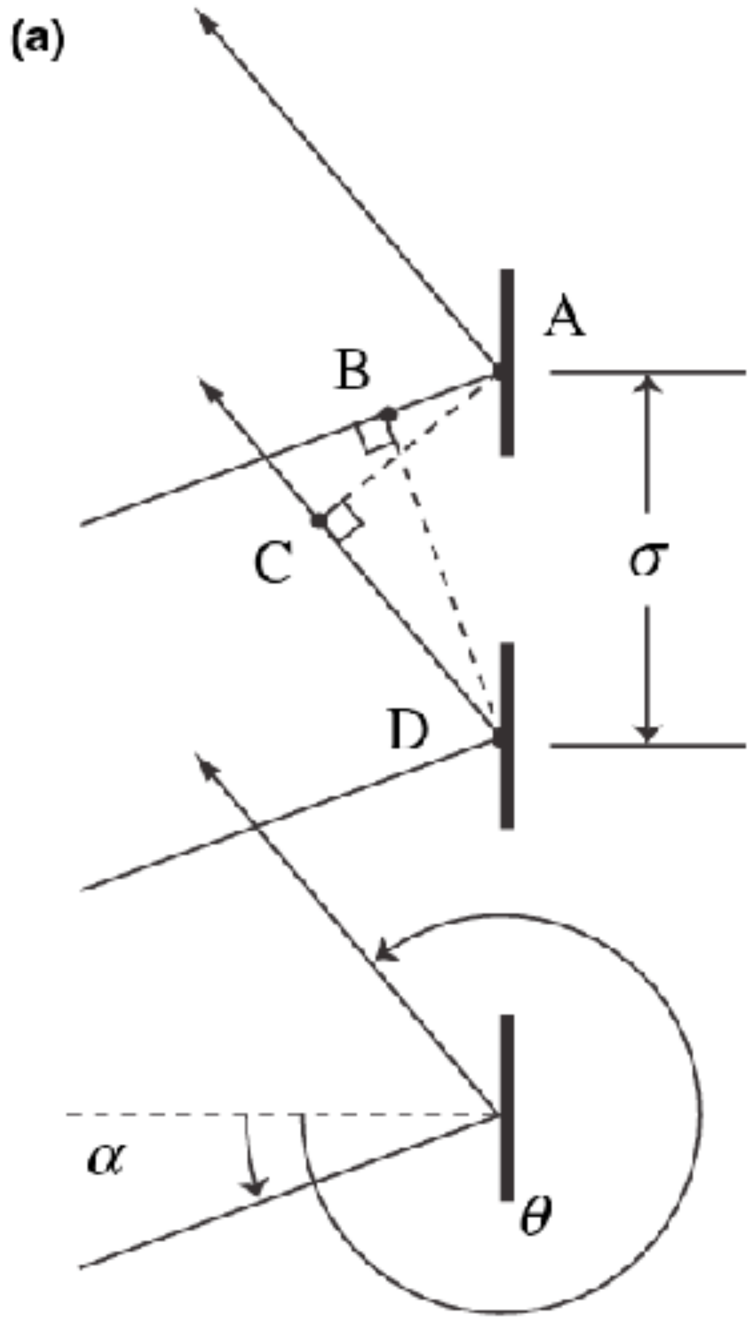
$$p = \frac{\mathrm{d}\lambda}{\mathrm{d}x} = \left[s_{\mathrm{c}} \frac{\mathrm{d}\theta}{\mathrm{d}\lambda} \right]^{-1}$$

resolving power

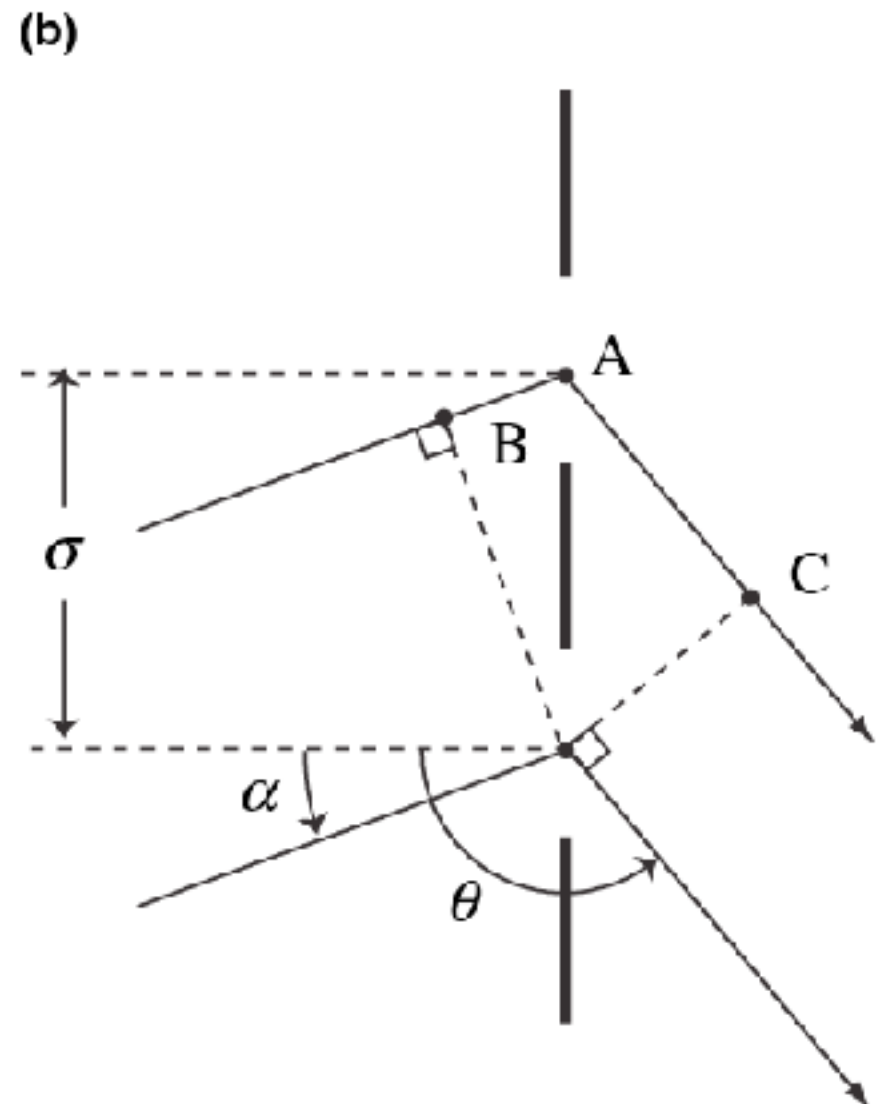
$$R = \frac{\lambda}{\delta\lambda}$$

Diffraction Grating

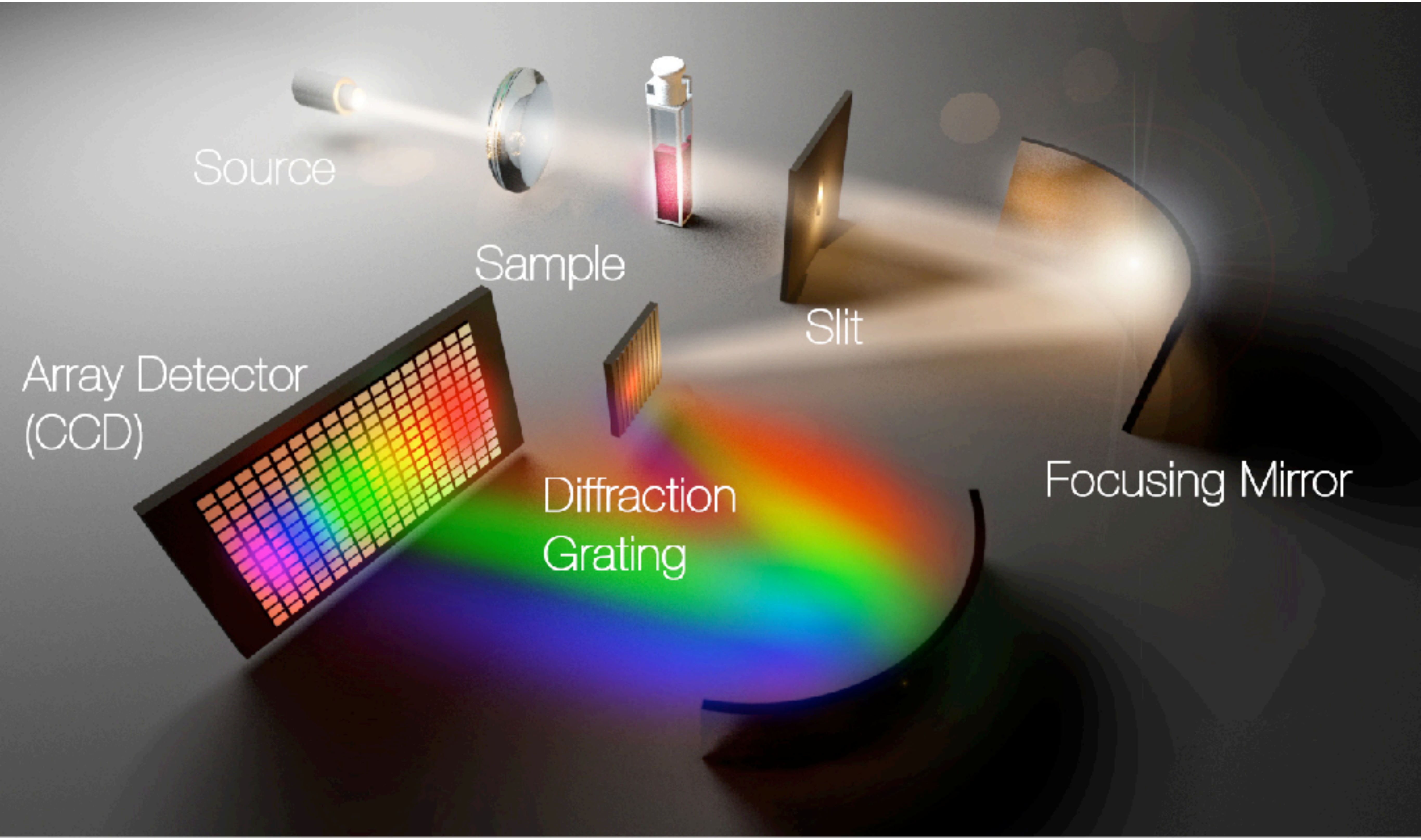
Reflection grating



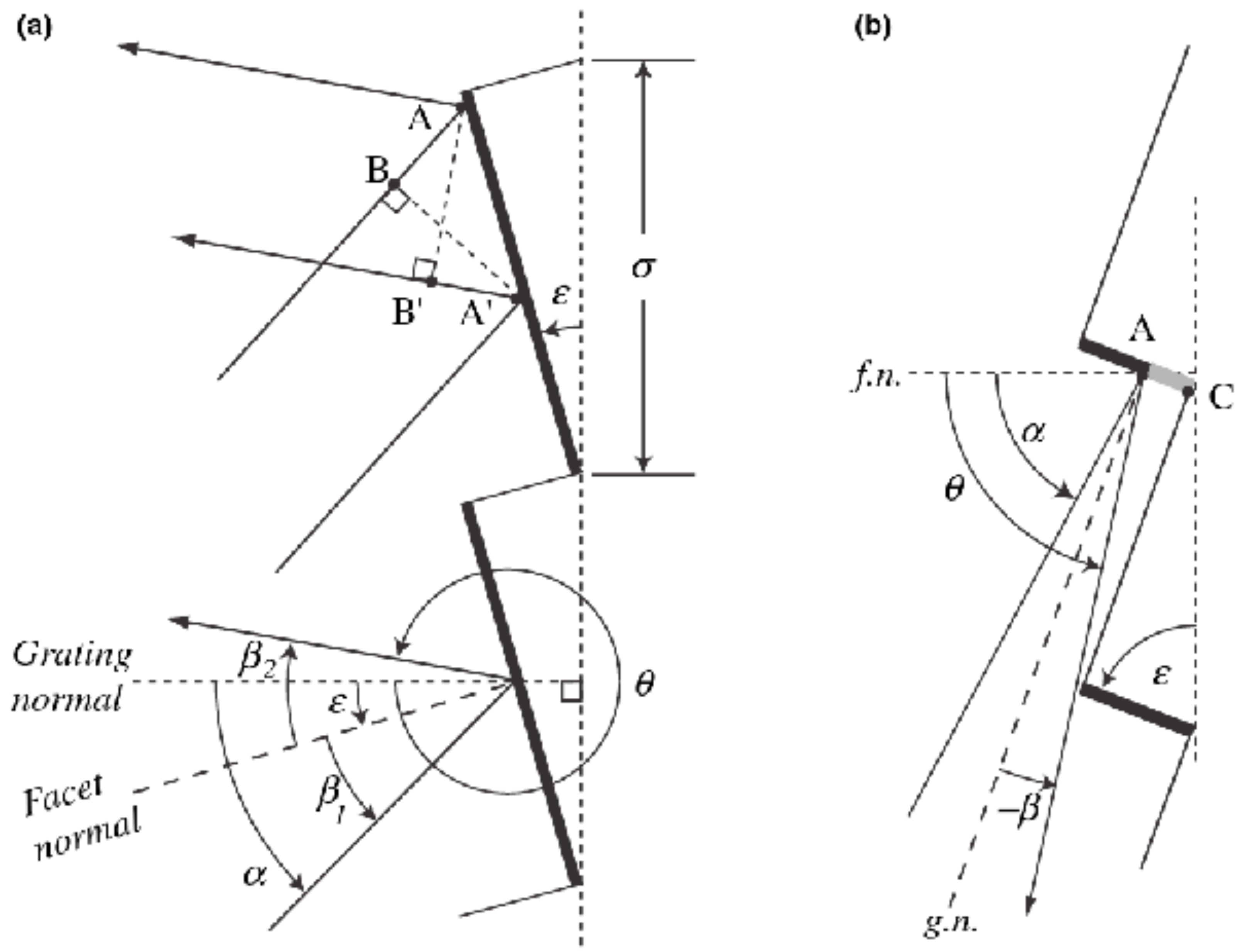
Transmission grating



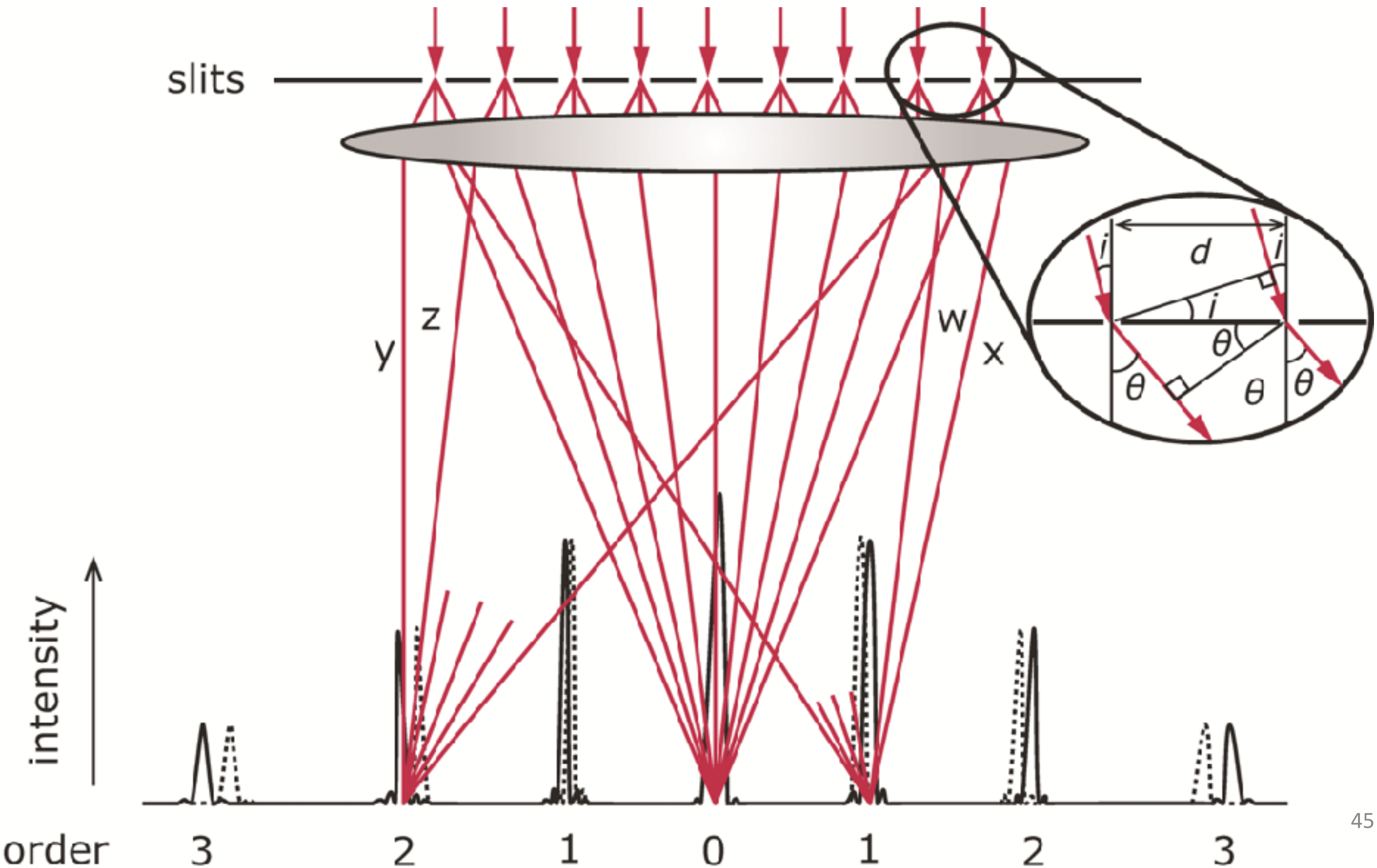
$$\sin\theta + \sin\alpha = \frac{m\lambda}{\sigma}$$


Source
Sample
Slit
Array Detector
(CCD)
Diffraction
Grating
Focusing Mirror

Blazed Diffraction Grating



How a grating works. Consider a series of slits illuminated by parallel light. The interference pattern that results will have an envelope due to the diffraction pattern of a slit, and within it will have constructive interference peaks at orders 0, 1, 2, etc. corresponding to 0, 1, 2 etc. wavelengths of retardation



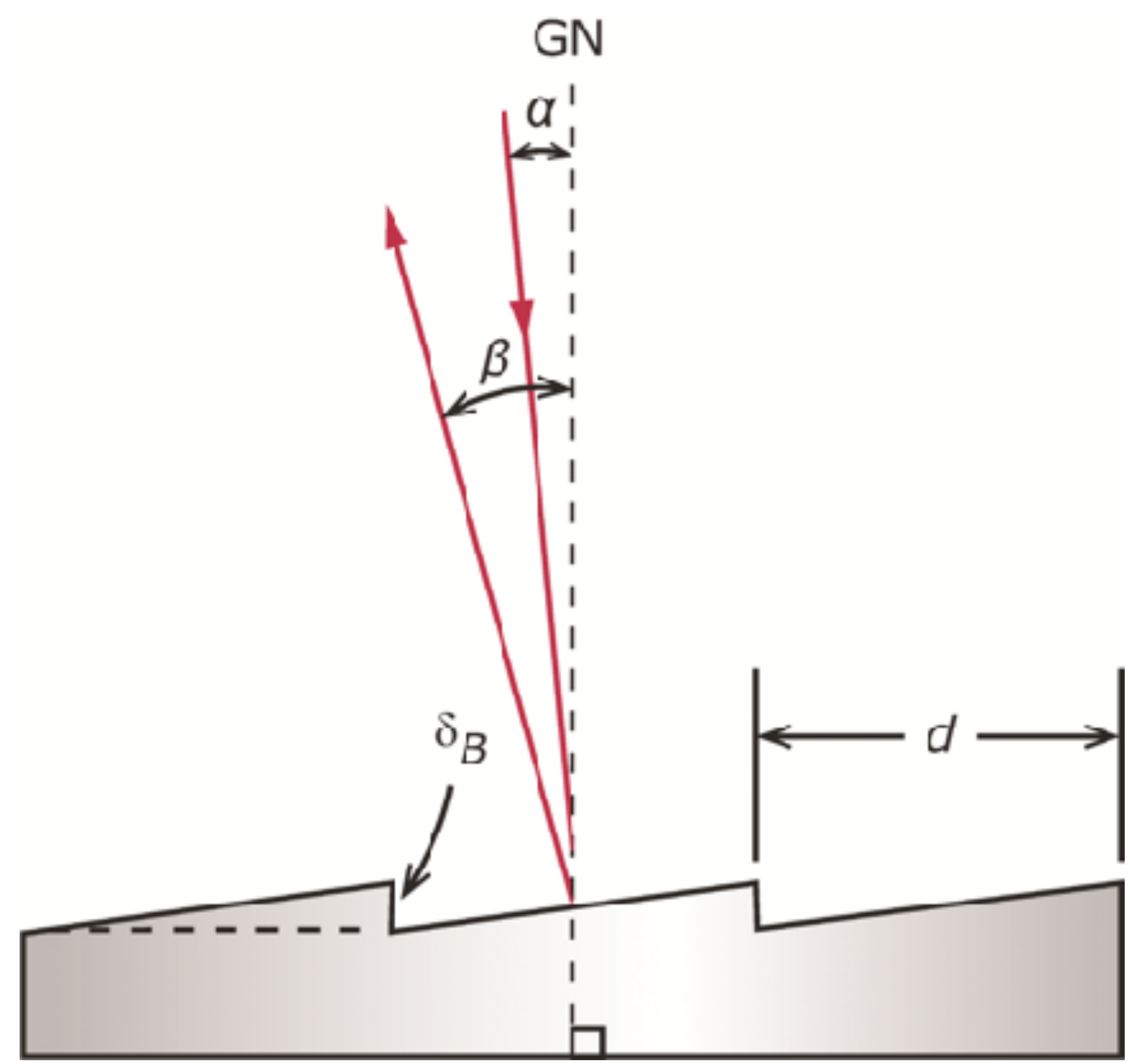
Diffraction Gratings

To use this effect as a spectrometer, we want $\theta >> 0$, that is we want to work at an order > 0. The problem is that as the order increases, the intensity drops (see previous slide)

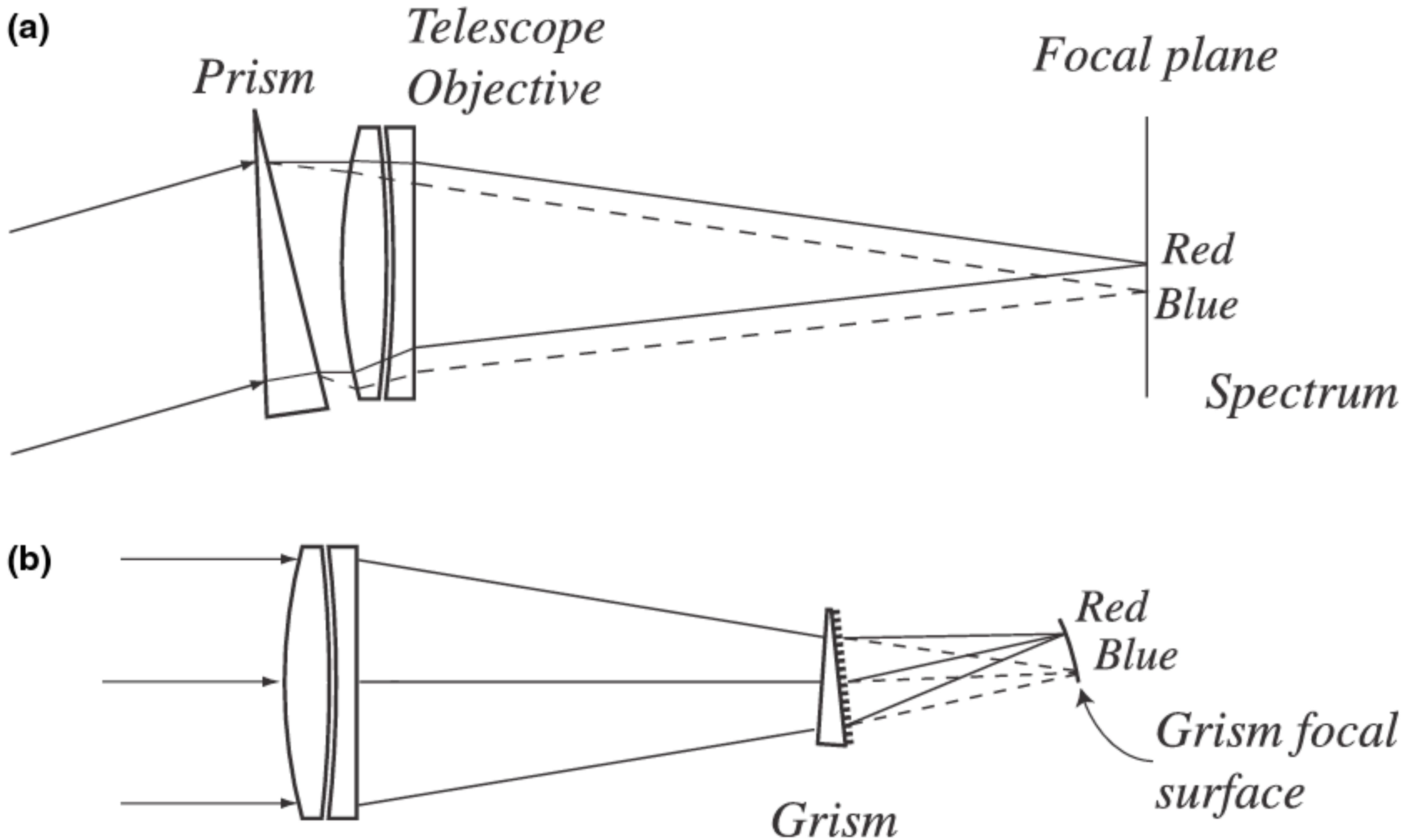
To solve this problem, we replace the slits with a bunch of little tilted mirrors, all arranged parallel to each other.

We now have a reflective diffraction grating!

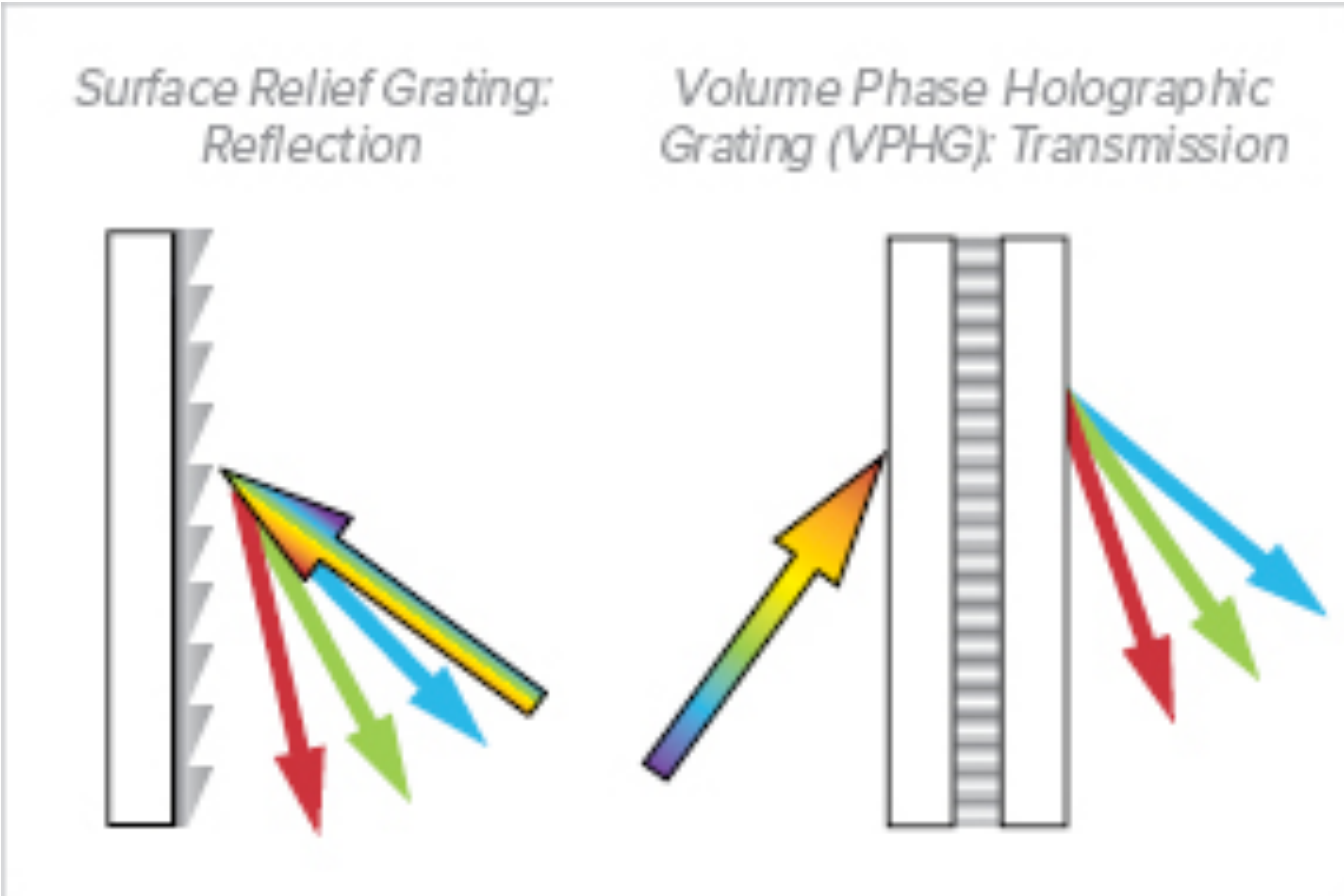
$$m\lambda = d(\sin\alpha + \sin\beta) \qquad (8)$$

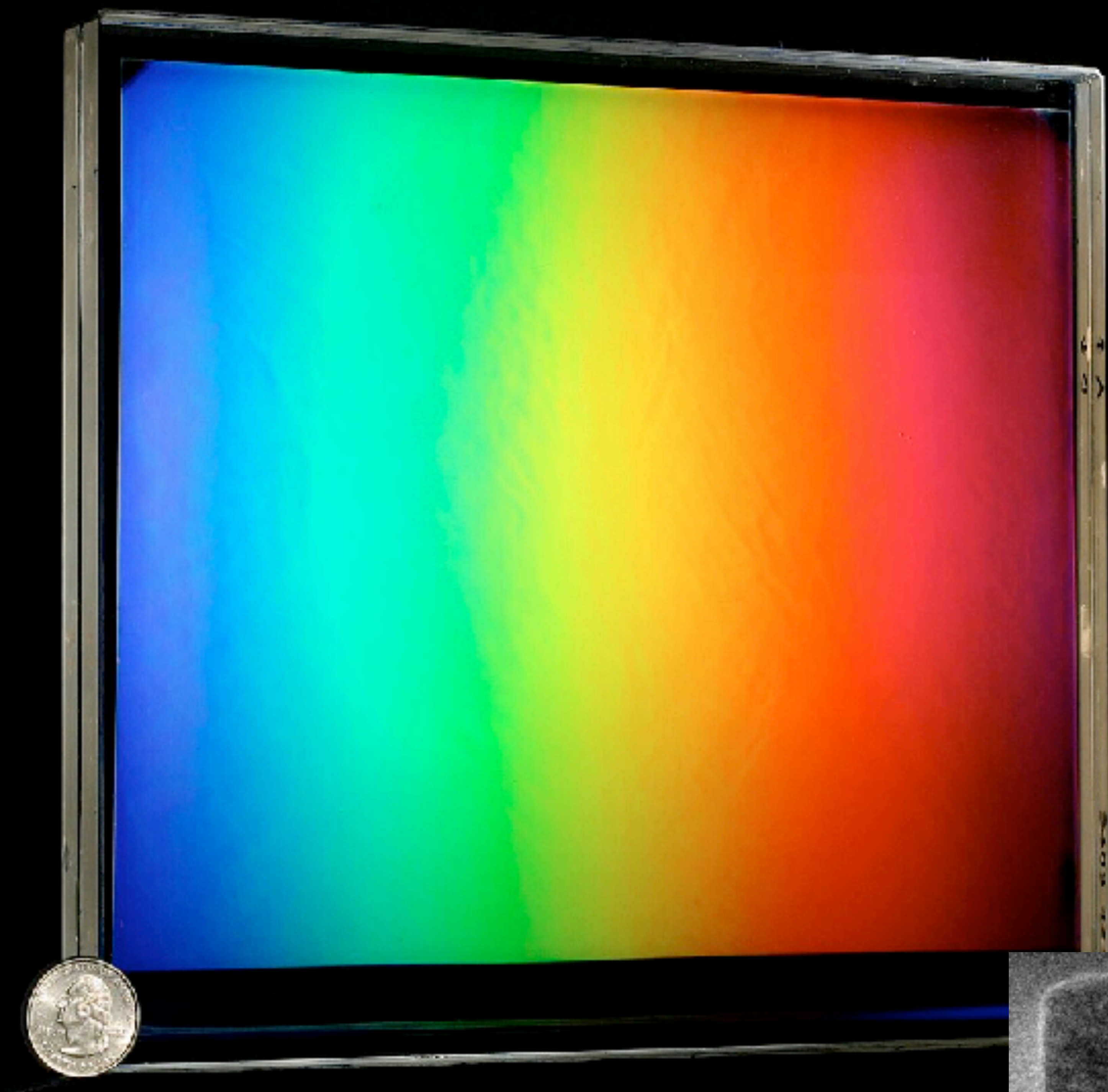


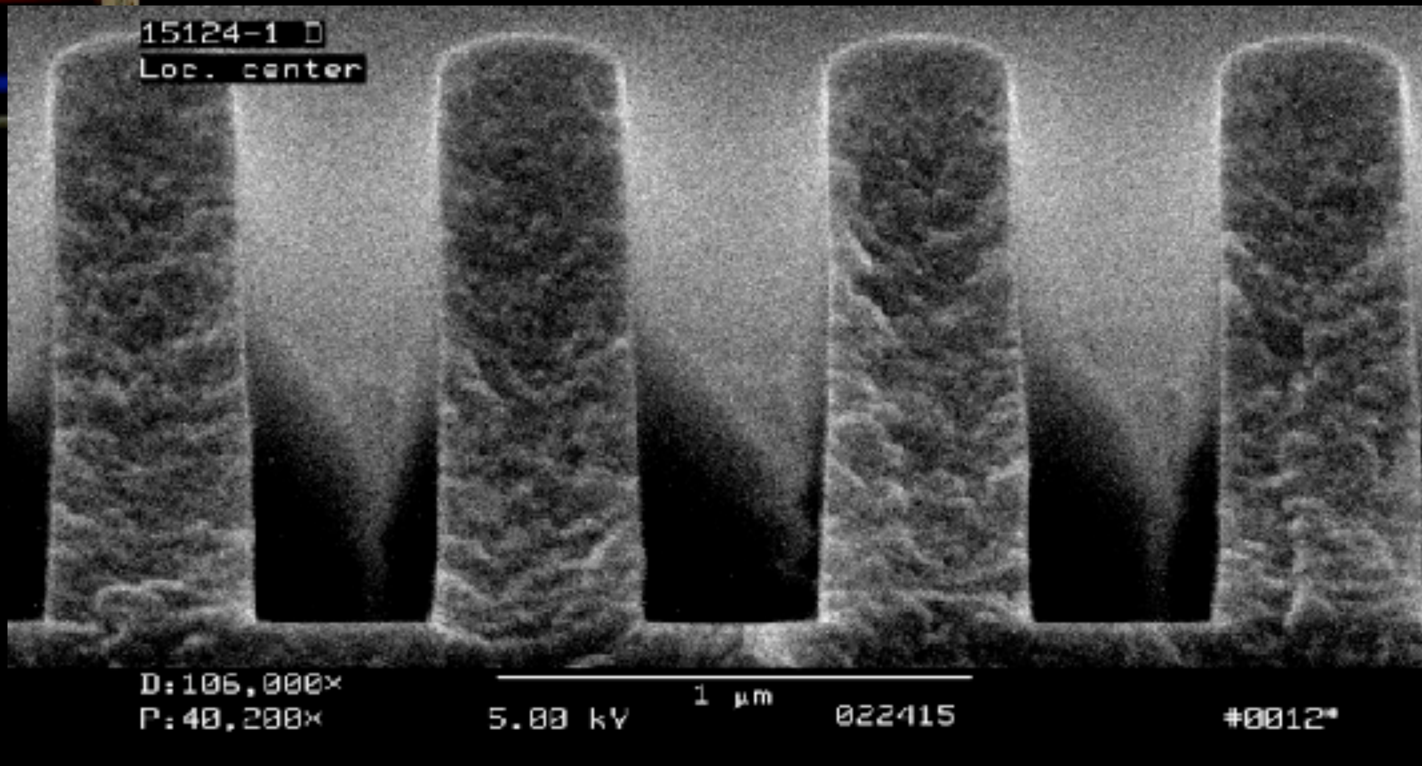
Objective prism



Volume Phase Holographic Gratings (VPH)

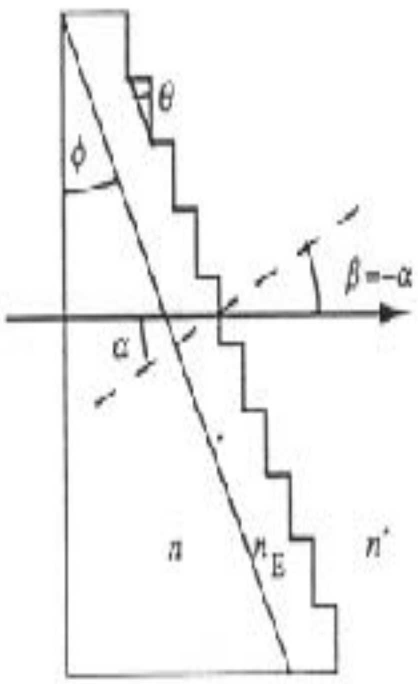





15124-1
Loc. center
D:106,000×
P:40,200×
1 µm
5.00 kV
022415
#0012

Grisms

- A popular way to convert a camera into a spectrograph is to deposit a transmission grating on the hypotenuse of a right-angled prism and use the deviation of the prism to bring the first order of diffraction on axis. Such a device is called a "grism" (not to scale). The advantage of a grism is that it can be placed in a filter wheel and treated like another filter.



- R~500-2000 is practical.

(McLean 2008)

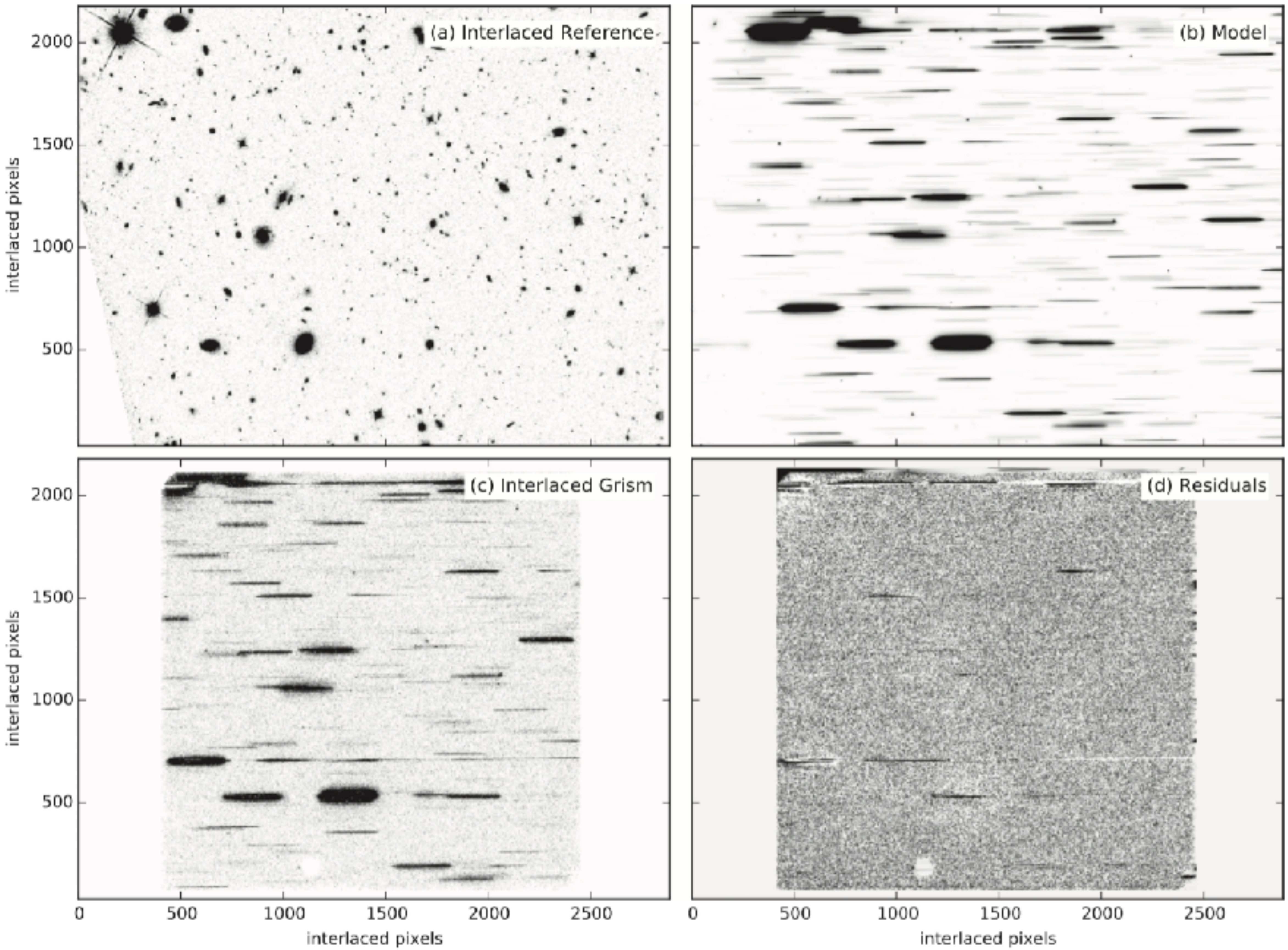
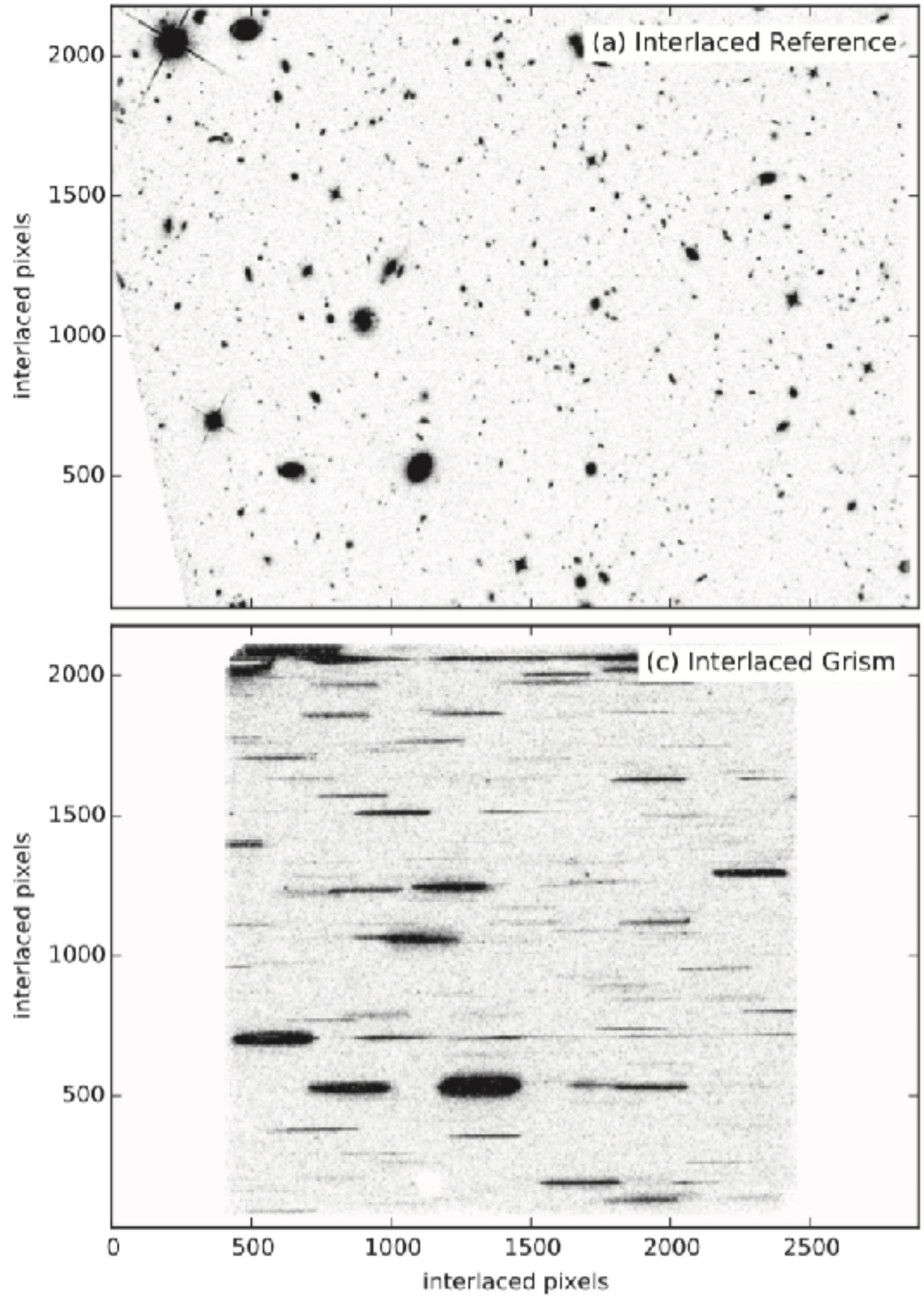
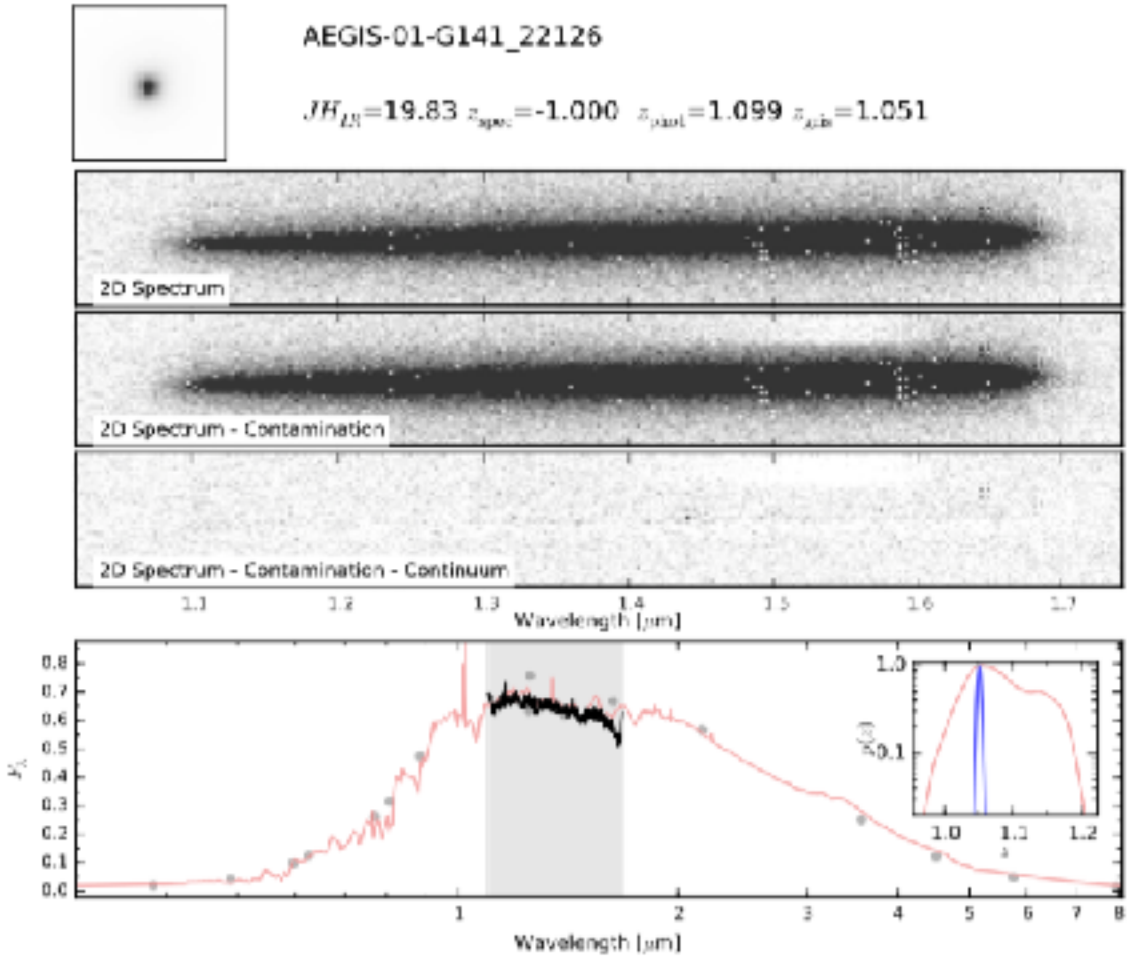
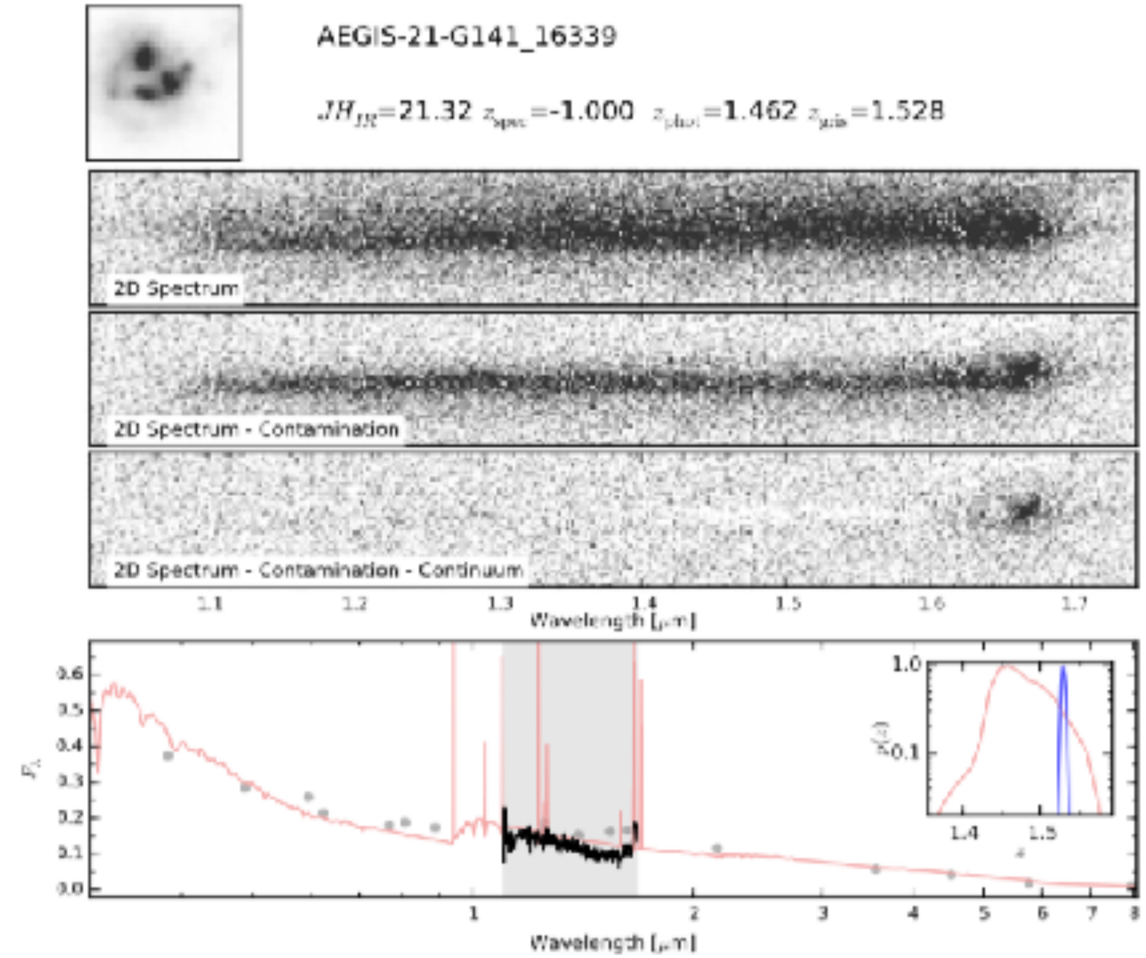


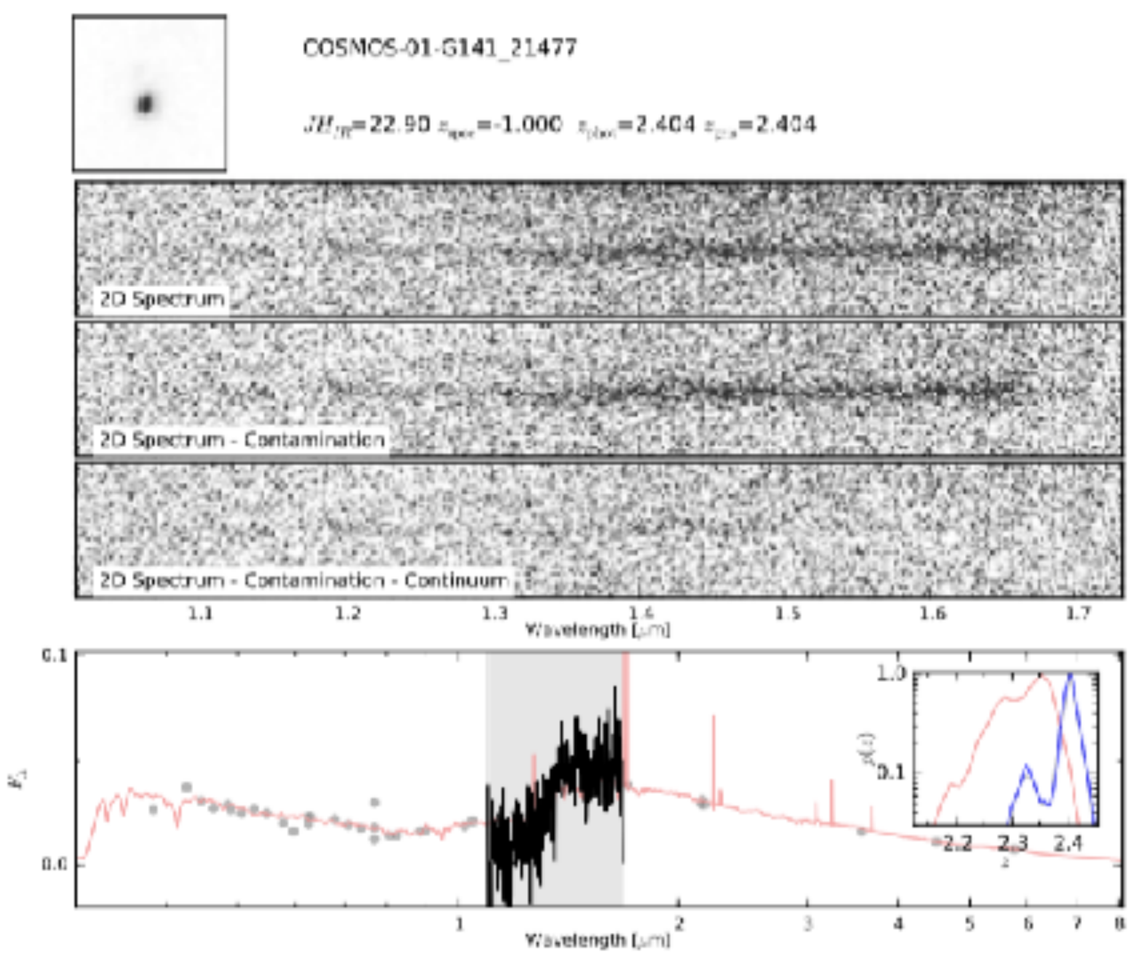
Figure 7. Full contamination model of the COSMOS-04 pointing. The panels show (a) the interlaced direct reference image, created from the CANDELS+3DHST $J_{IR} = J_{125} + JH_{140} + H_{160}$ mosaic of the COSMOS field; (b) the contamination model created using the direct image and model spectra for all the objects; (c) the observed interlaced grism image; and (d) the residuals after subtracting the contamination model from the interlaced grism image.

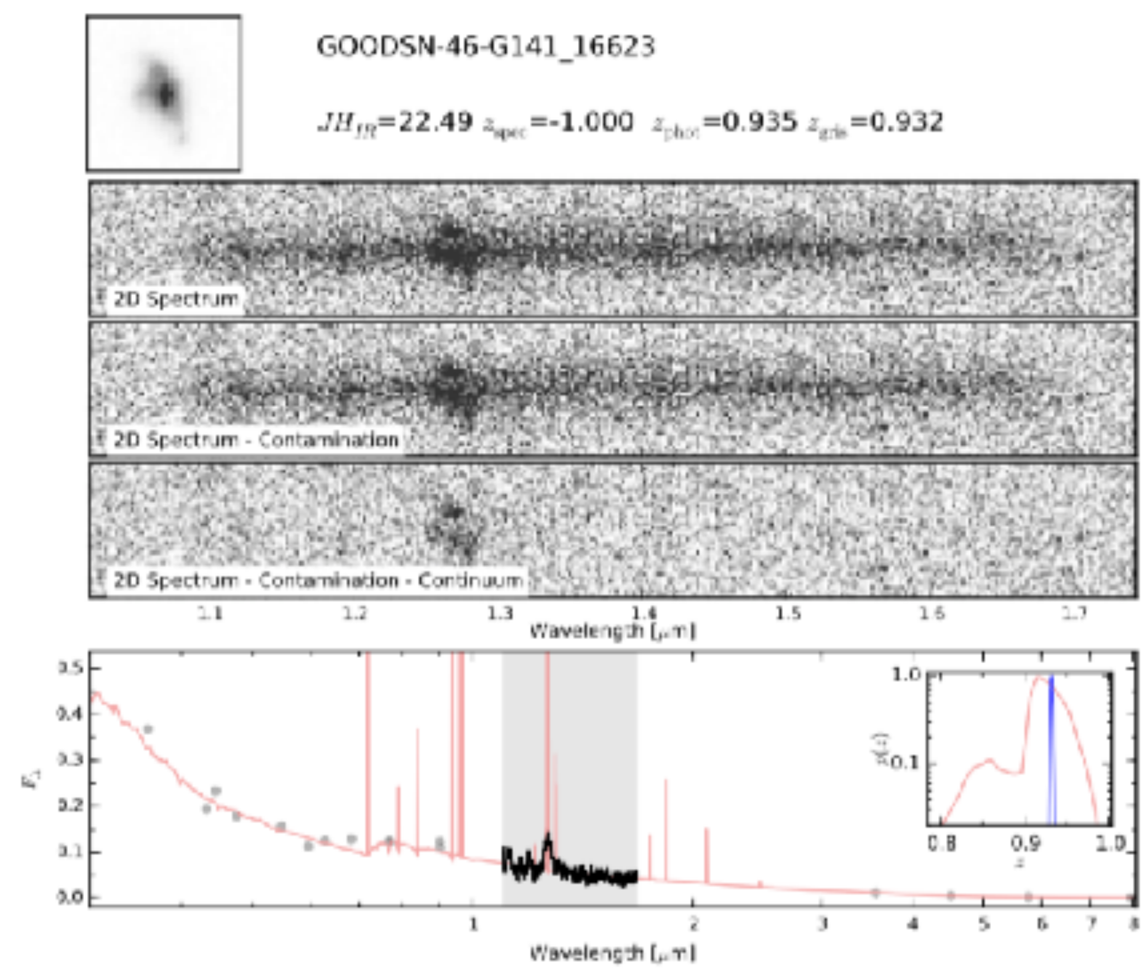


(a) Interlaced Reference
(c) Interlaced Grism
interlaced pixels
interlaced pixels
interlaced pixels
2000
1500
1000
500
0
500
1000
1500
2000
2500


AEGIS-01-G141_22126
JH_{IR}=19.83 z_{spec}=-1.000 z_{phot}=1.099 z_{gris}=1.051
2D Spectrum
2D Spectrum - Contamination
2D Spectrum - Contamination - Continuum
Wavelength [μm]
F_λ
$p(z)$
Wavelength [μm]


AEGIS-21-G141_16339
JH_{IR}=21.32 z_{spec}=-1.000 z_{phot}=1.462 z_{gris}=1.528
2D Spectrum
2D Spectrum - Contamination
2D Spectrum - Contamination - Continuum
Wavelength [μm]
F_λ
$p(z)$
Wavelength [μm]


COSMOS-01-G141_21477
JH_{IR}=22.90 z_{spec}=-1.000 z_{phot}=2.404 z_{gris}=2.404
2D Spectrum
2D Spectrum - Contamination
2D Spectrum - Contamination - Continuum
Wavelength [μm]
F_λ
$p(z)$
Wavelength [μm]


GOODSN-46-G141_16623
JH_{IR}=22.49 z_{spec}=-1.000 z_{phot}=0.935 z_{gris}=0.932
2D Spectrum
2D Spectrum - Contamination
2D Spectrum - Contamination - Continuum
Wavelength [μm]
F_λ
$p(z)$
Wavelength [μm]

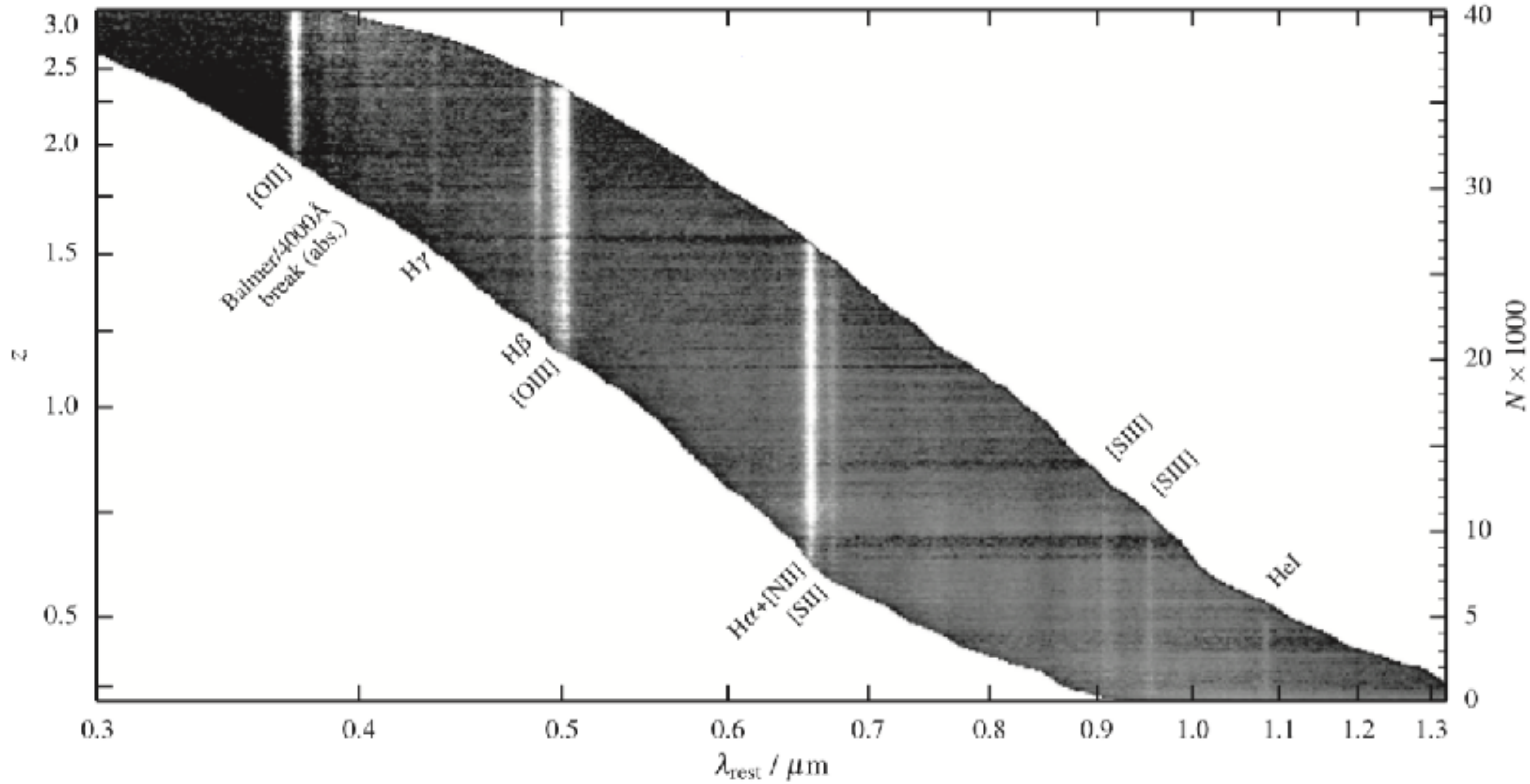


Figure 25. Overview of ~40,000 3D-HST G141 grism spectra with $H_{160} < 25$. Each pixel row shown is the median of 100 individual 1D spectra sorted by redshift and shifted to the rest frame; ticks on the right axis mark every 1000 galaxies, and tick labels on the left axis indicate the corresponding redshift. Each spectrum is normalized by the object's JH_{140} flux. Absorption and emission lines that move through the G141 passband at different redshifts are indicated.

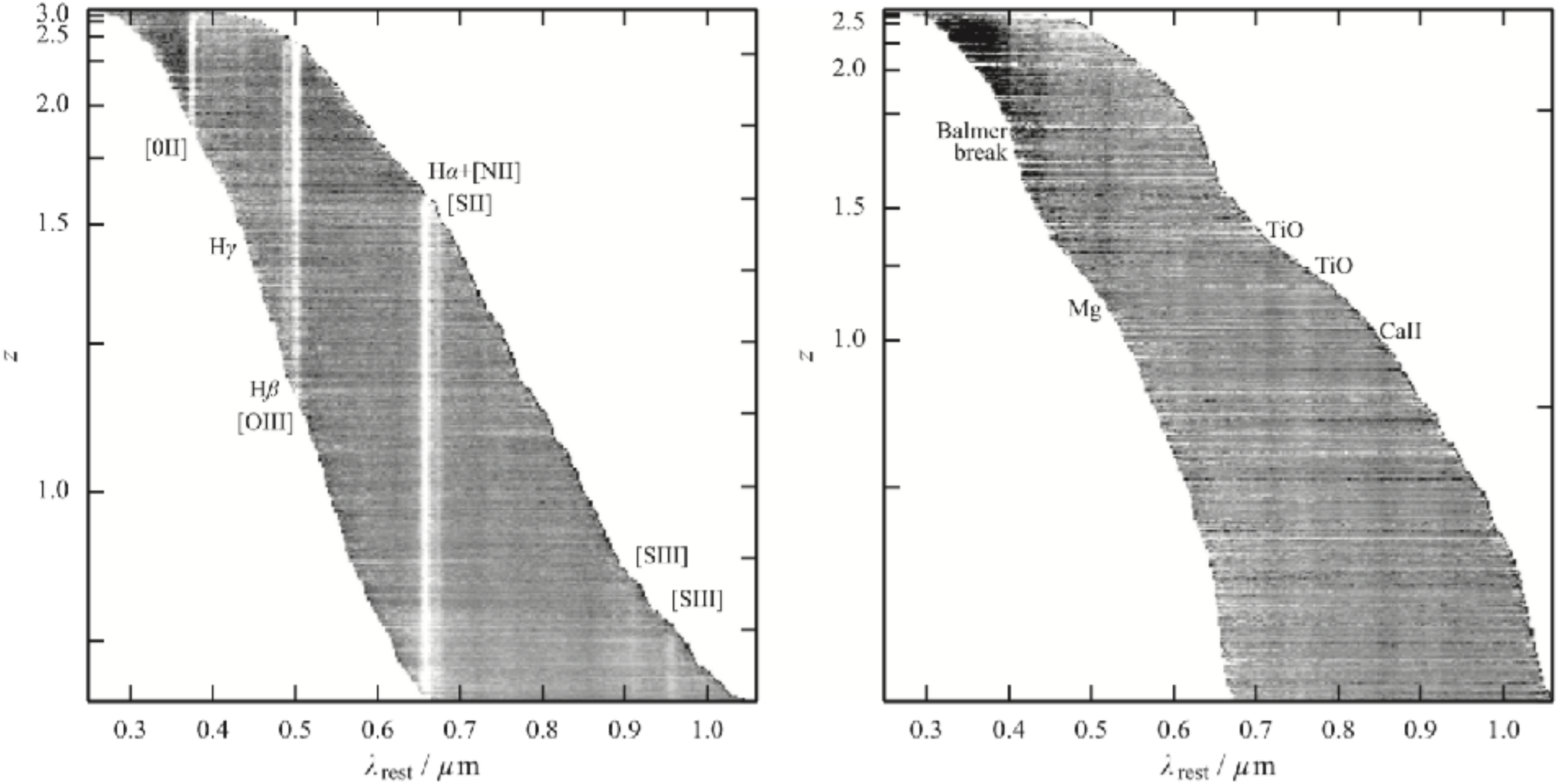


Figure 27. Same as Figure 25, but split by emission line properties and only showing galaxies with $z > 0.605$. Galaxies in the left panel have at least one emission line with an S/N greater than three. Galaxies in the right panel have a relatively bright magnitude limit ($H_{160} < 23$) and no detected emission lines with an S/N greater than two. As in Figure 25, each tickmark on the right vertical axis corresponds to 1000 spectra. The survey contains >2000 spectra of relatively bright quiescent galaxies.

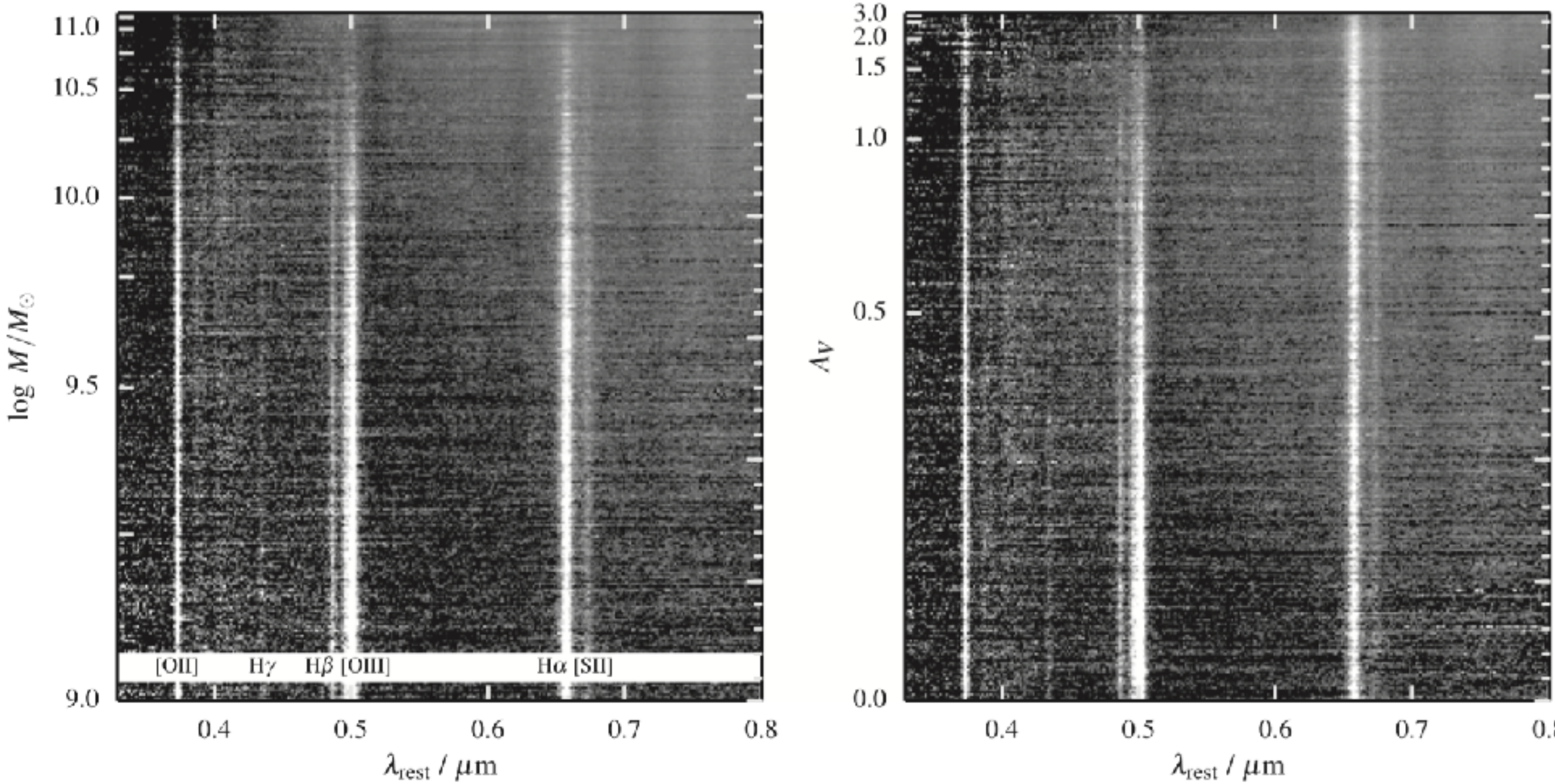
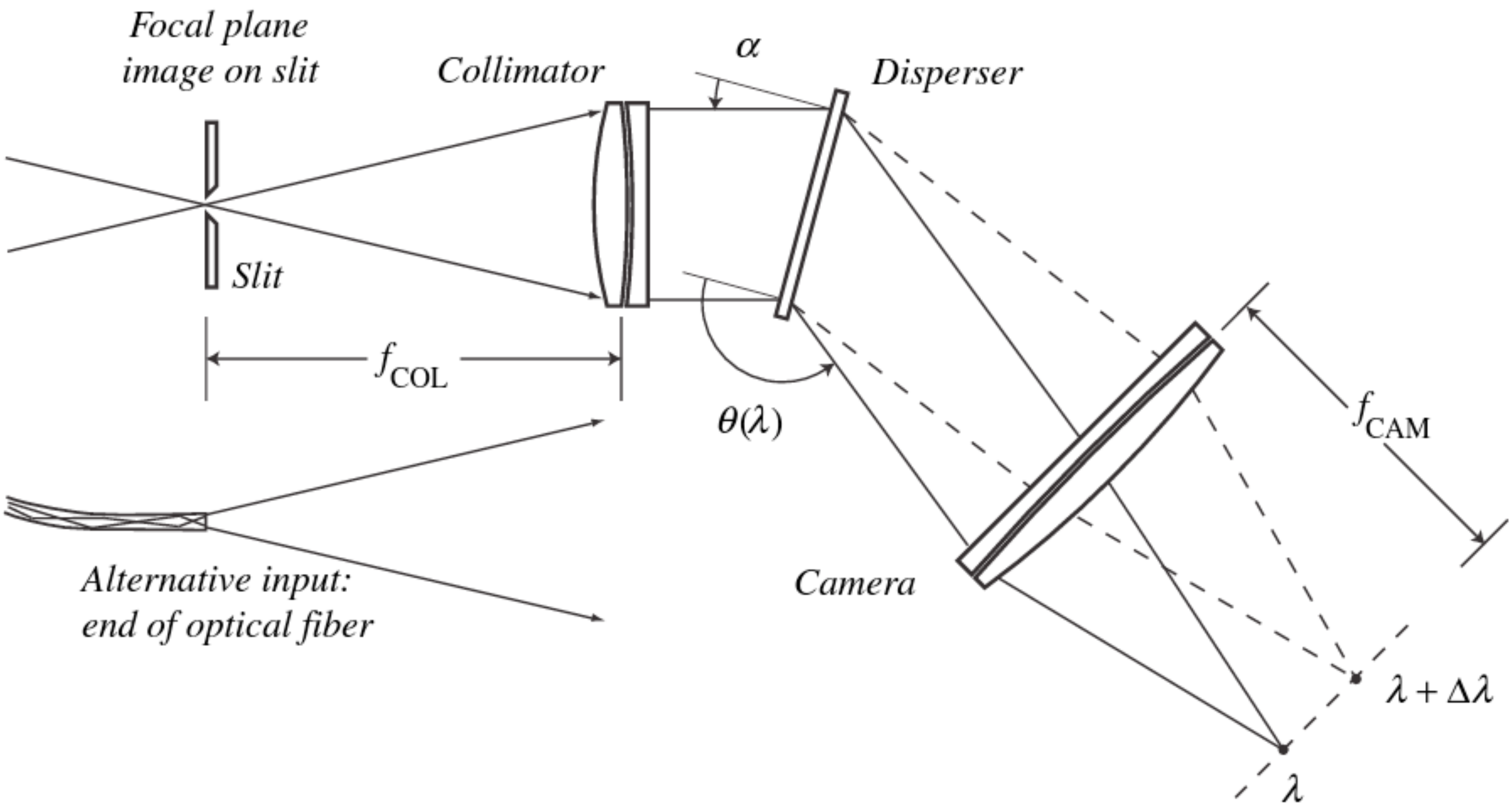
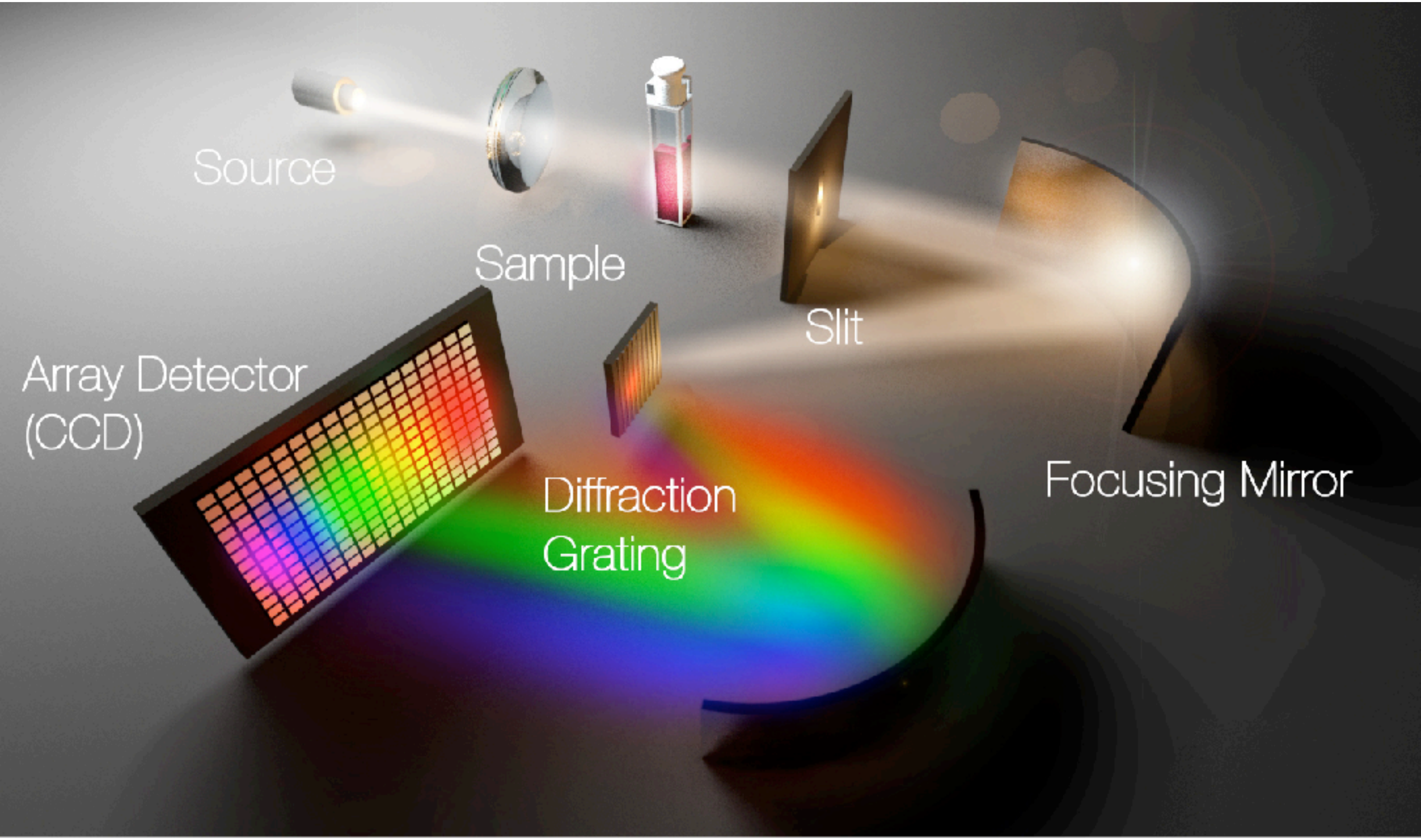


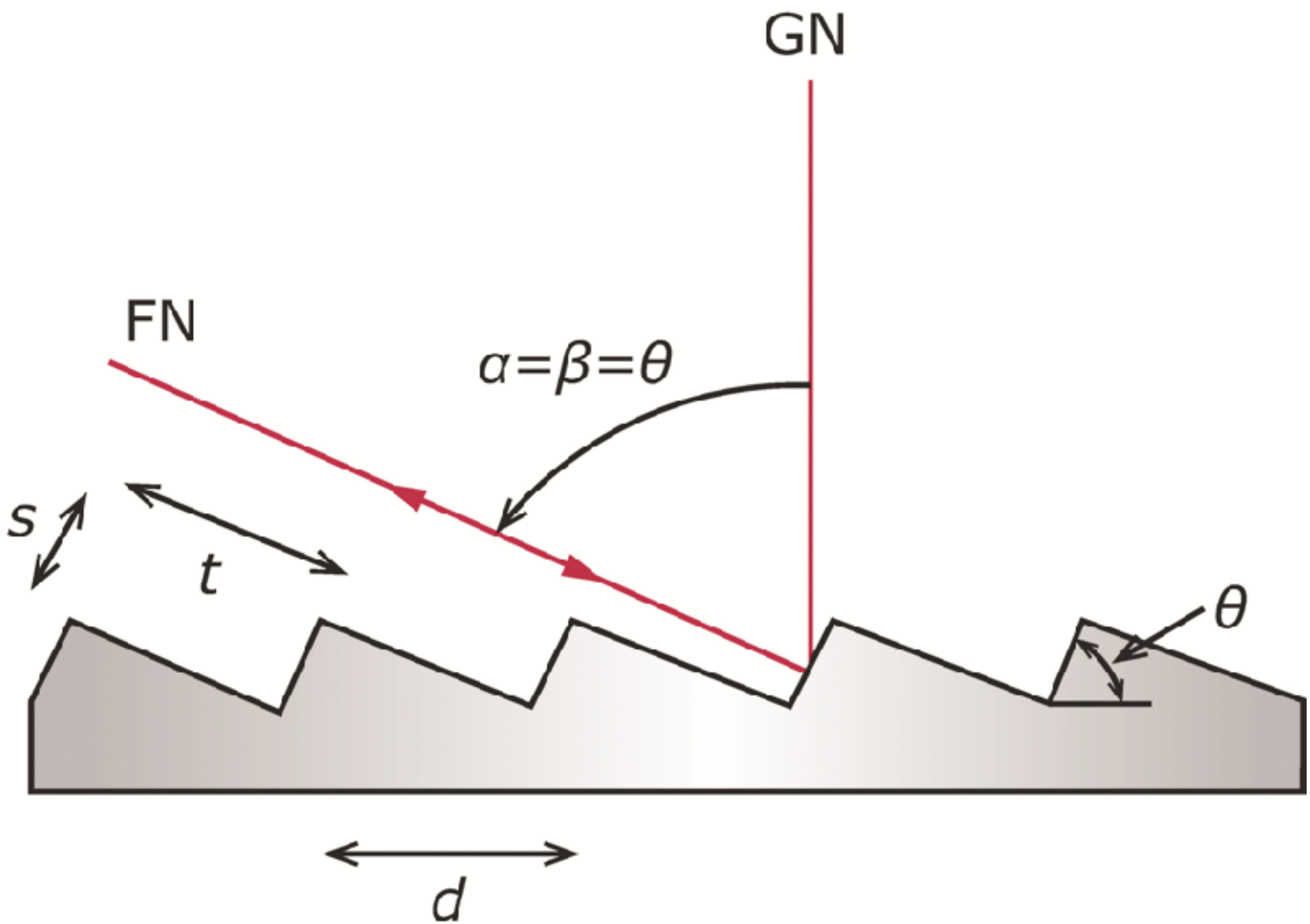
Figure 28. Same as Figure 25, but with objects sorted by M_* (left panel) and continuum dust extinction (A_V, right panel), both determined from stellar population synthesis fits to the broadband photometry. Here galaxies with a range of redshifts contribute to each row, providing rest-frame spectra from 3300 to 8000 Å. There are clear trends: higher mass galaxies have weaker emission lines and stronger absorption lines, and galaxies with higher continuum extinction have stronger Balmer decrements (see the text).

Slit spectrometer



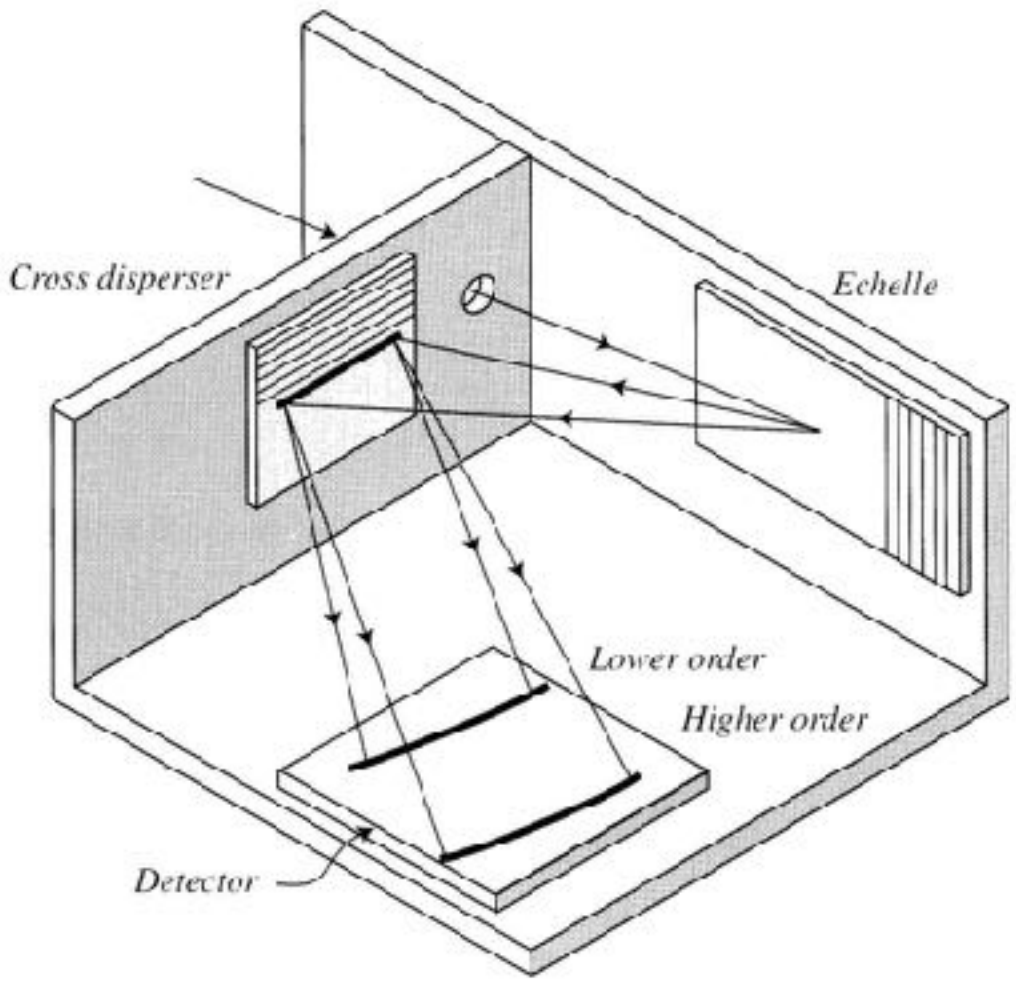

Source
Sample
Slit
Array Detector
(CCD)
Diffraction
Grating
Focusing Mirror

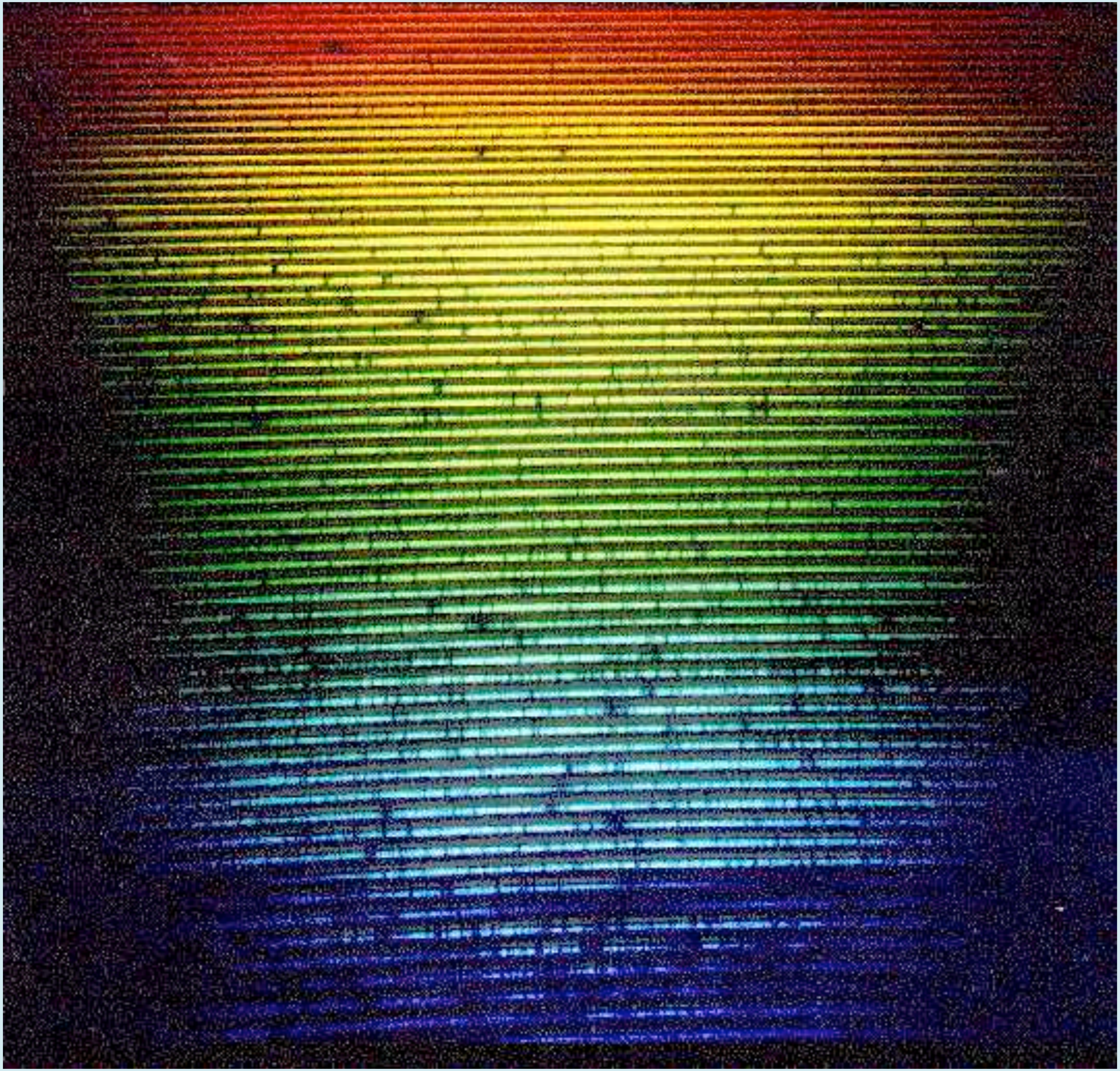
Echelle gratings are another useful variant. They operate at high incidence angle and high order (50 – 100). They are commonly used in high spectral resolution instruments, and usually with some kind of cross disperser to get more than one order on the detector at a time.



Echelle spectrometers

- Echelle spectrometer
- Cross-disperser addresses problem of overlap in high-order of Echelle grating.



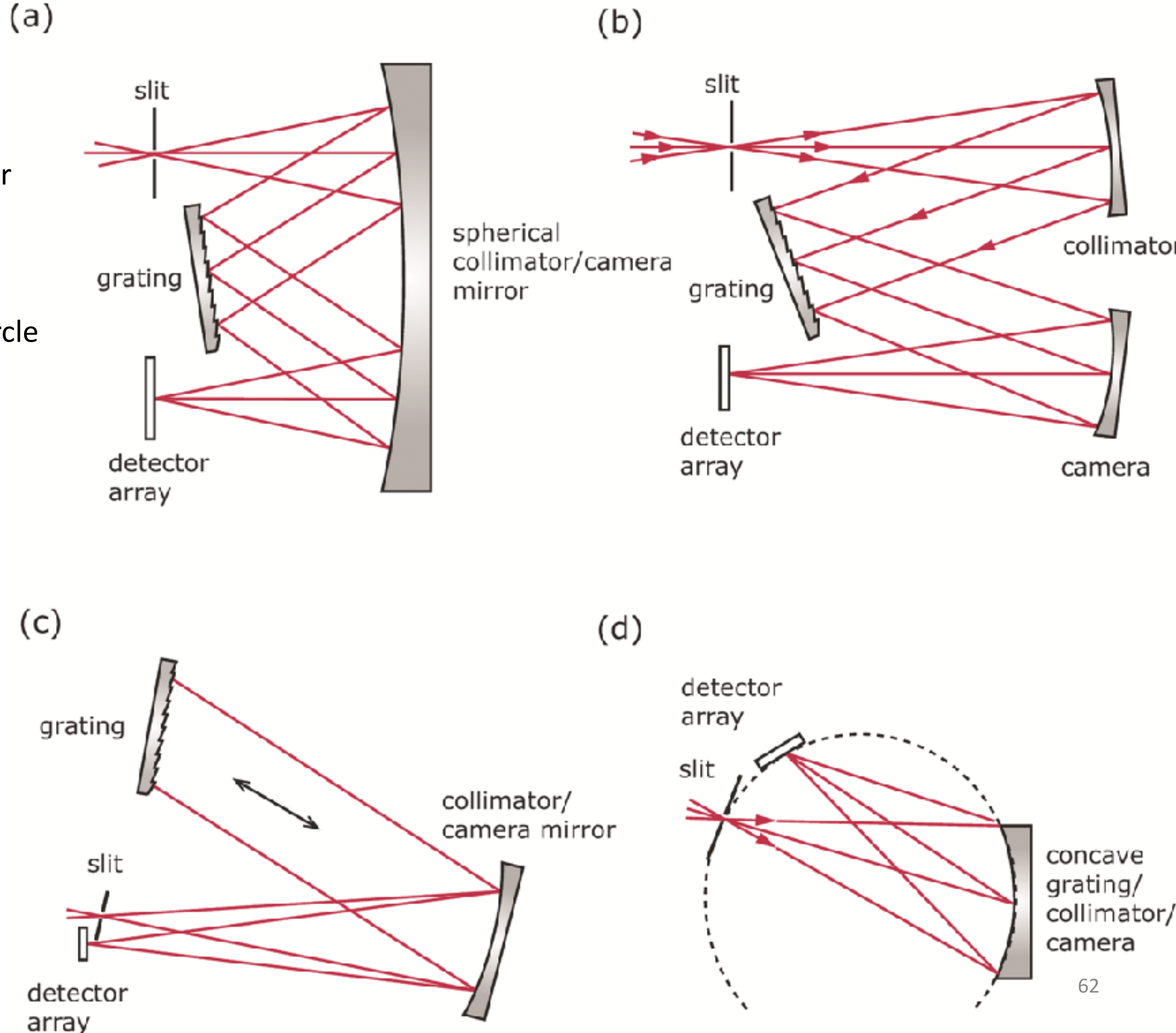


(a) Ebert-Fastie

(b) Czery-Turner

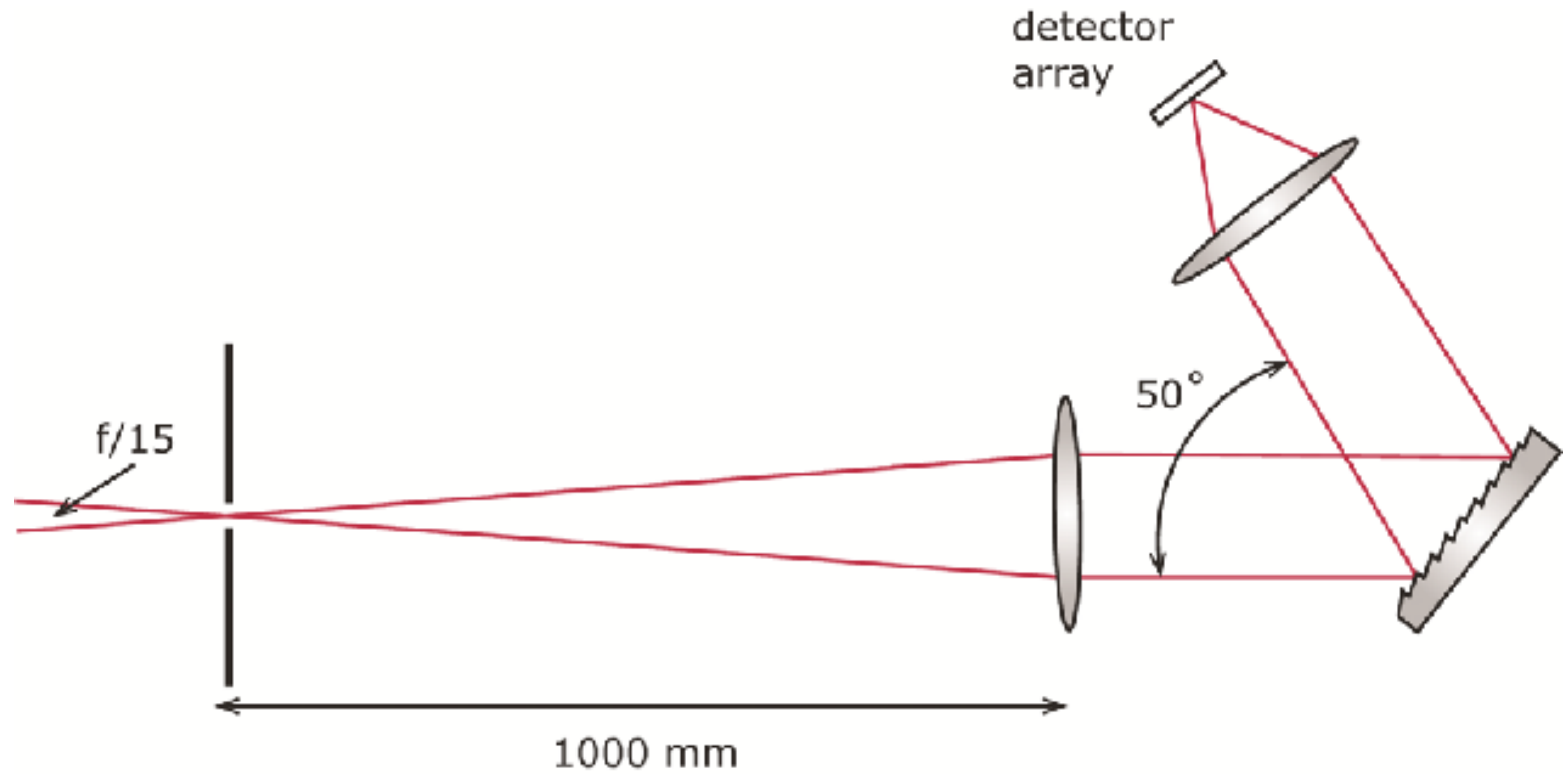
(c) Littrow

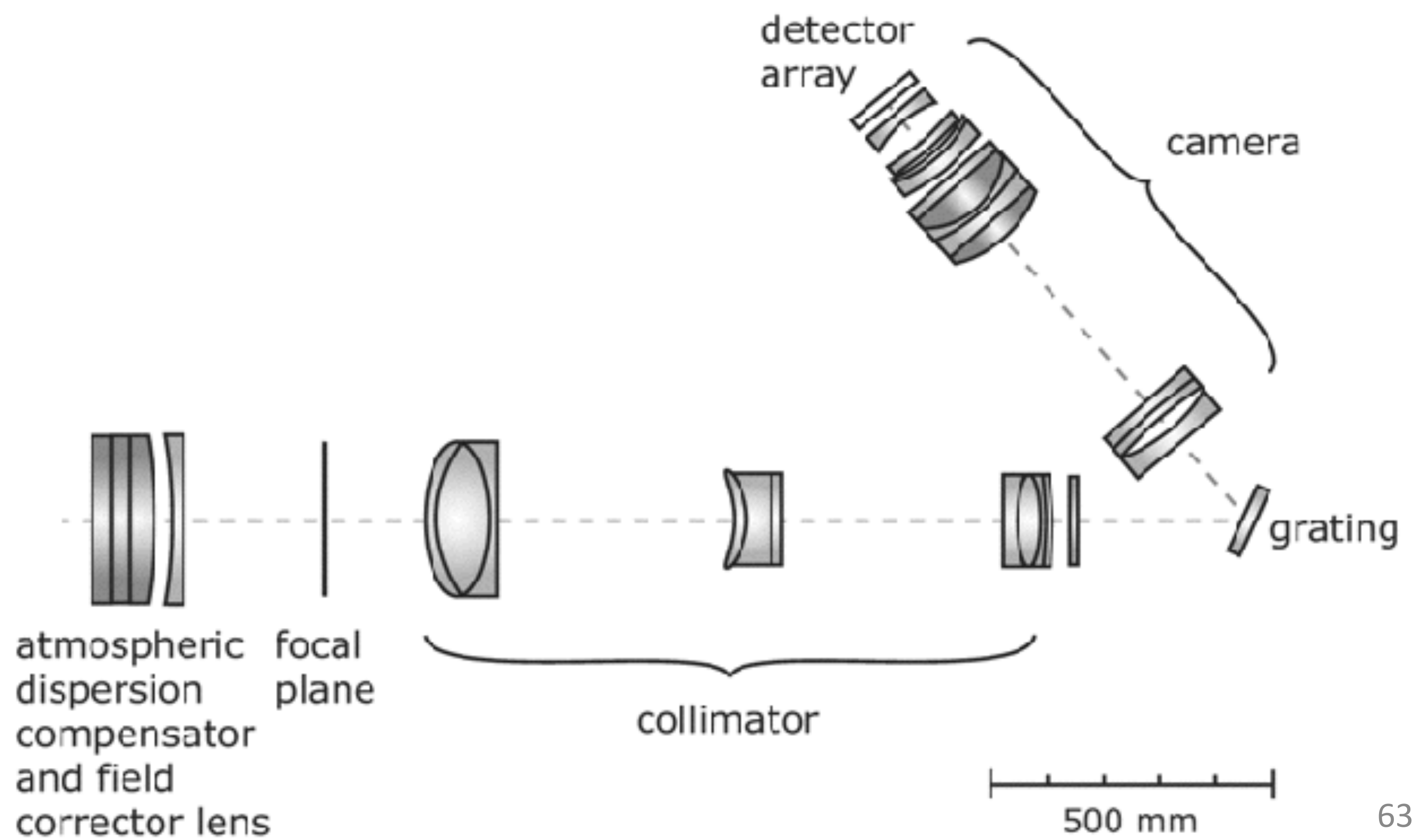
(d) Rowland Circle



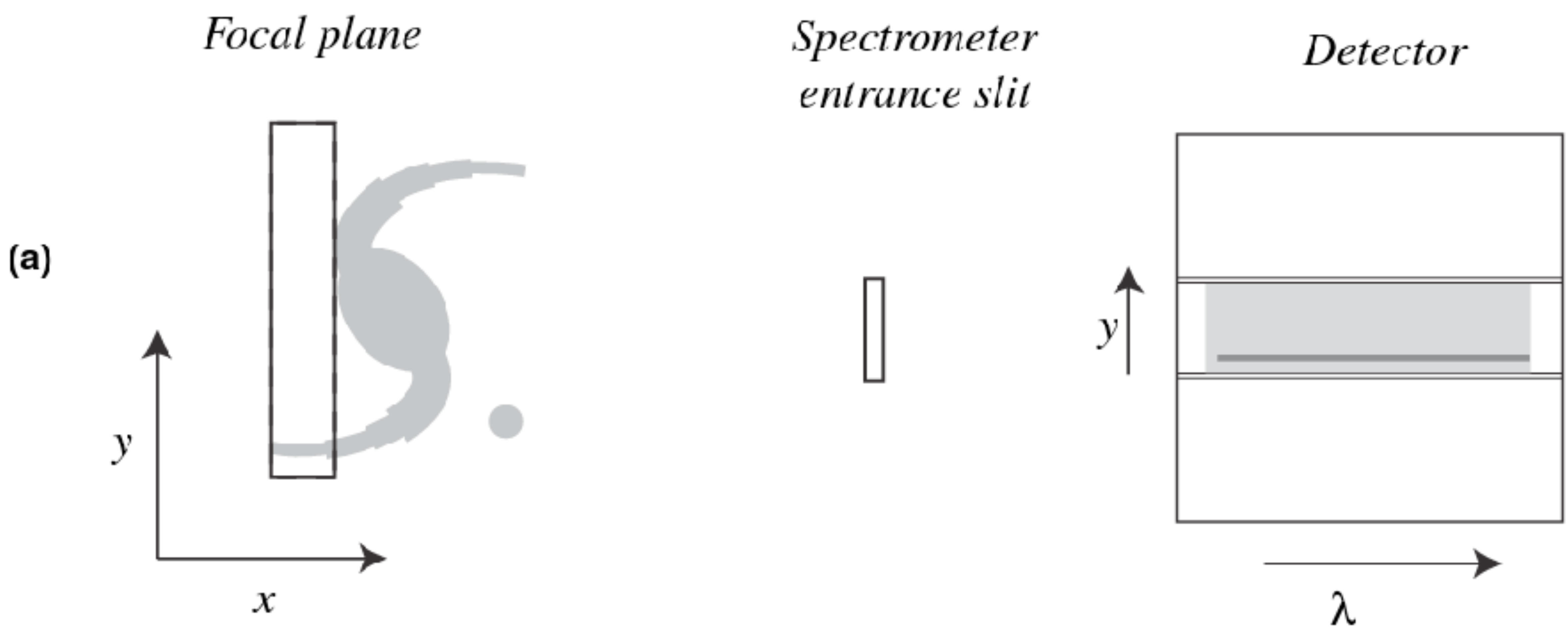
Top: simple spectrometer

Bottom: GMOS optical train (Gemini Multi-Object Spectrograph)

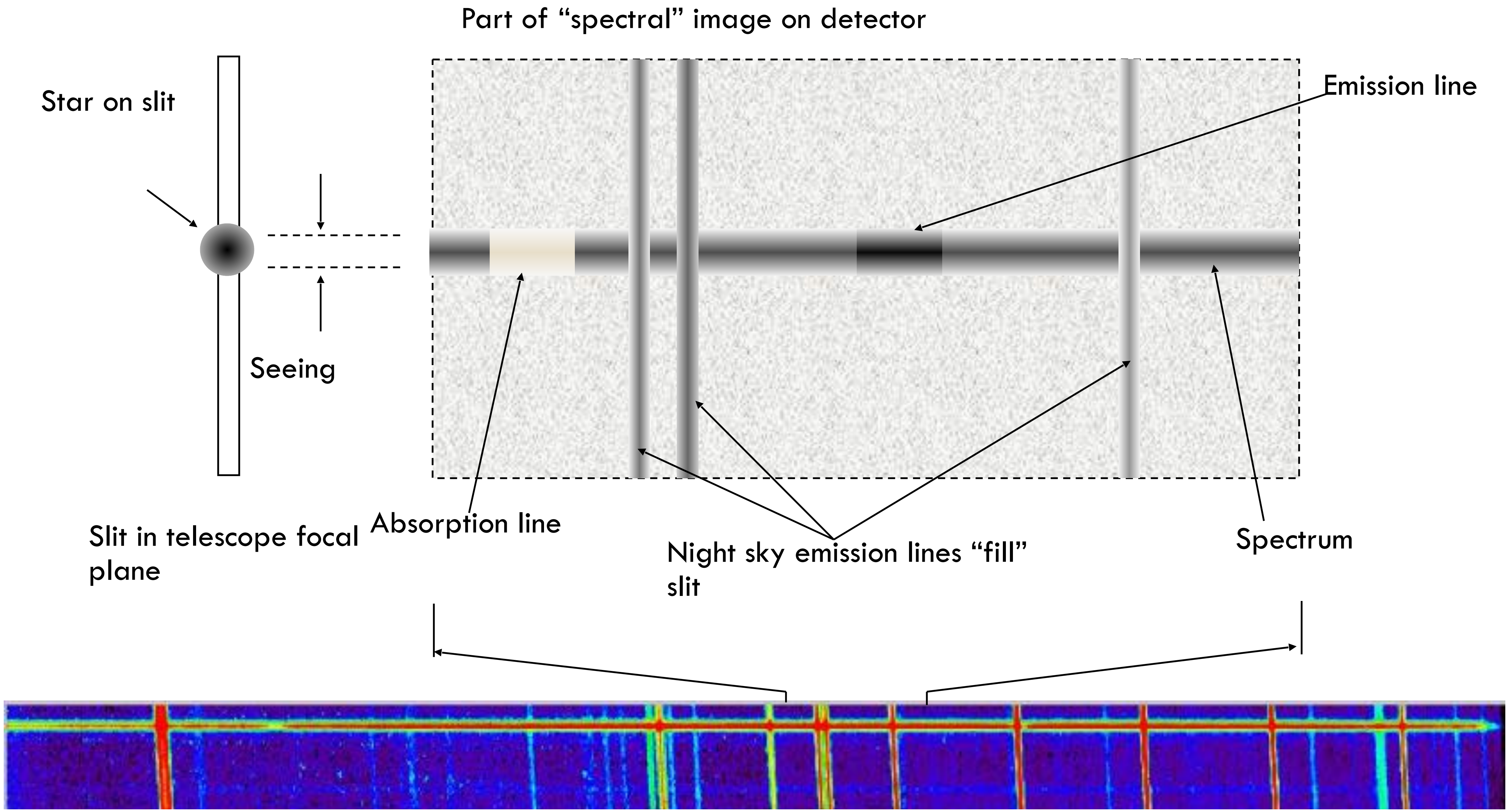




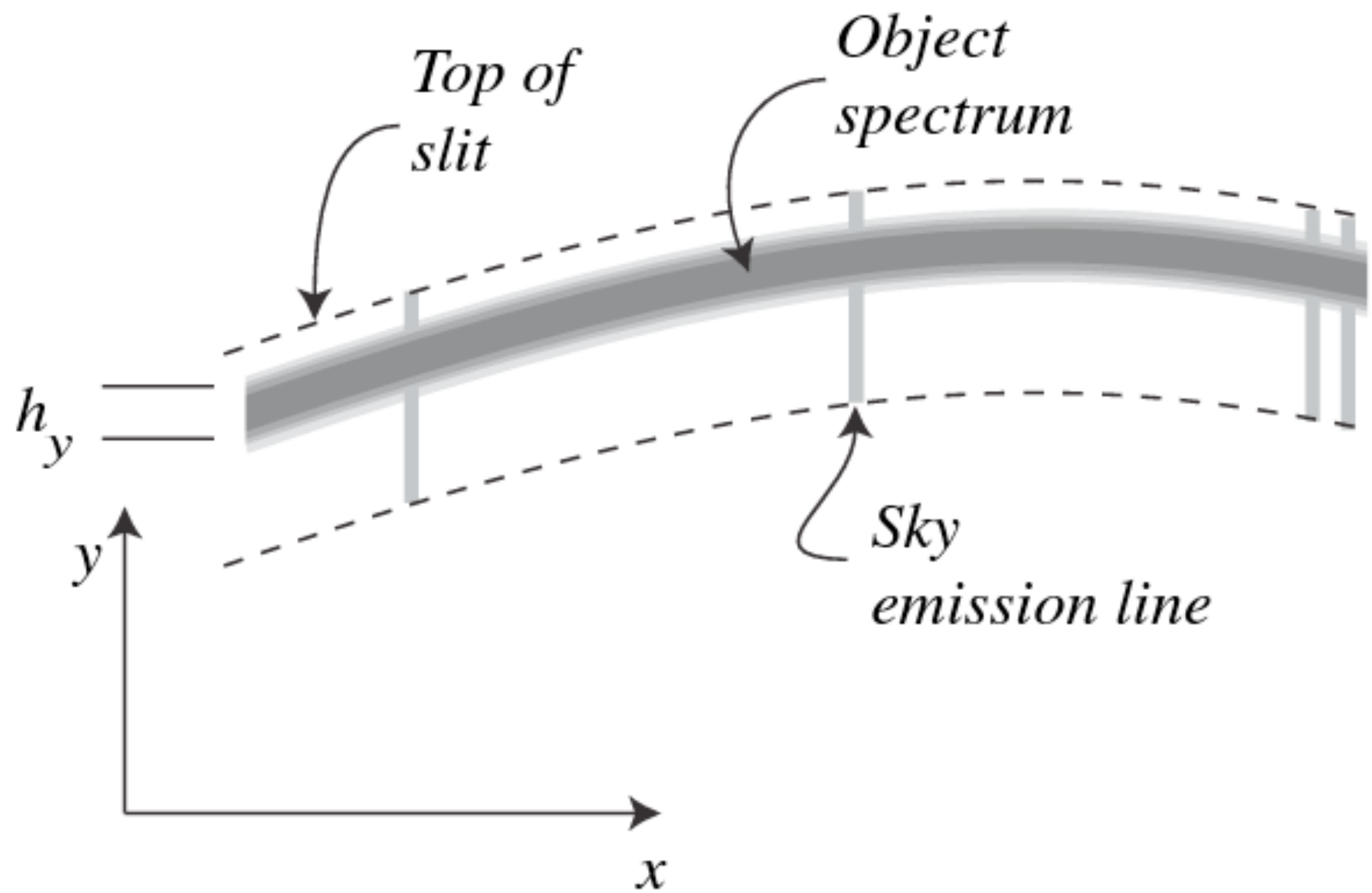
long slit spectroscopy



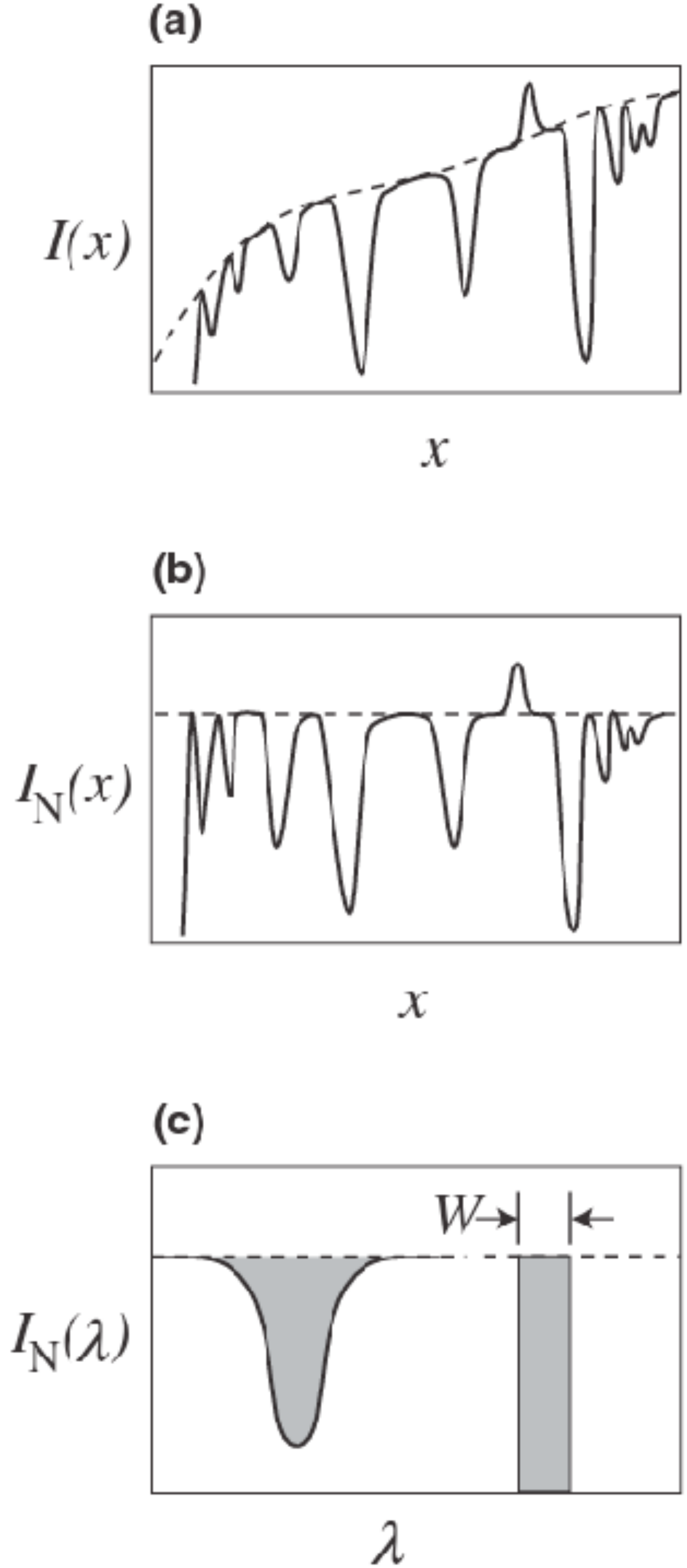
Spectrum on an array detector



(McLean 2008)

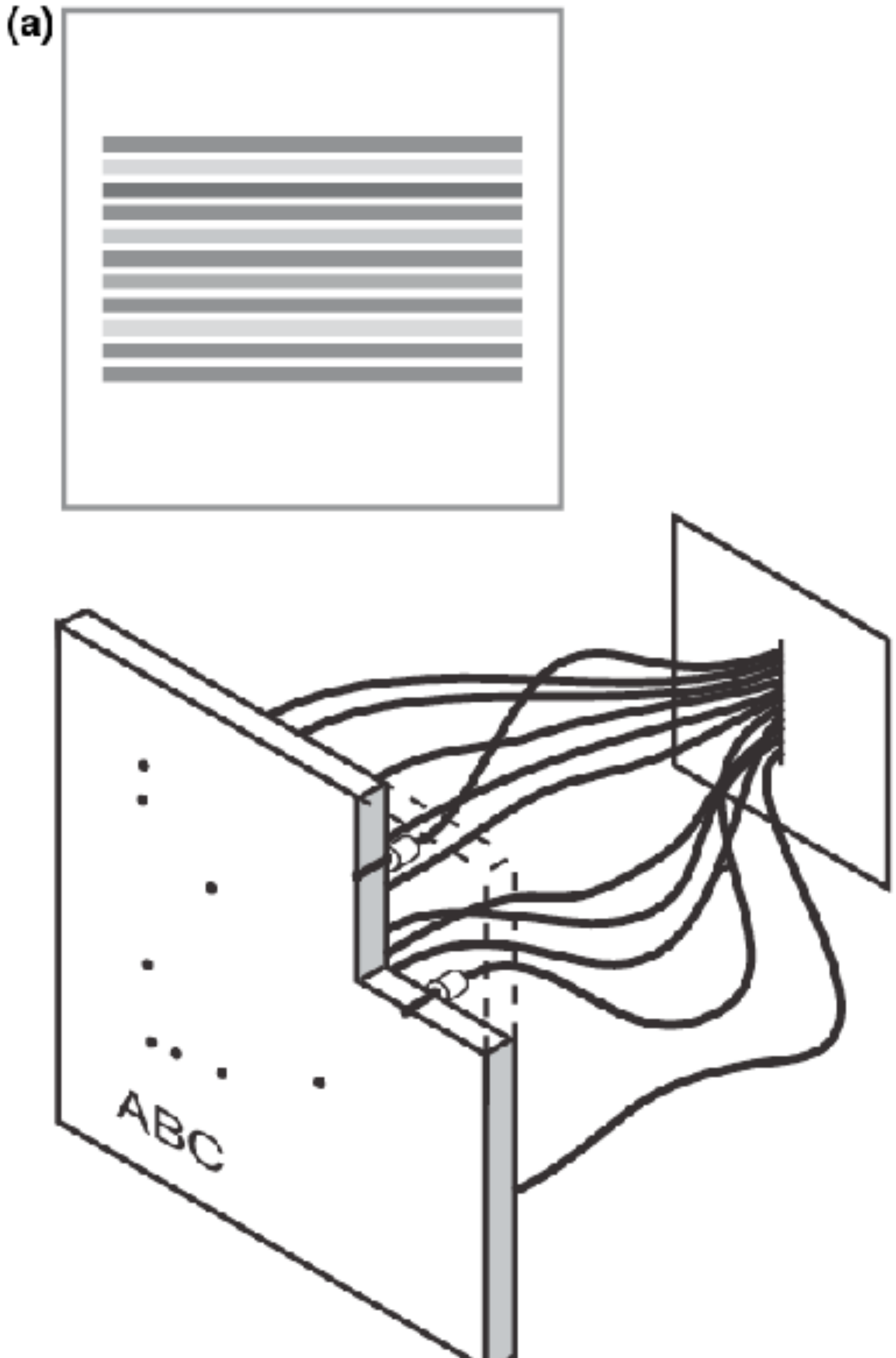

Top of
slit
Object
spectrum
h_y
y
Sky
emission line
x

Equivalent Widths

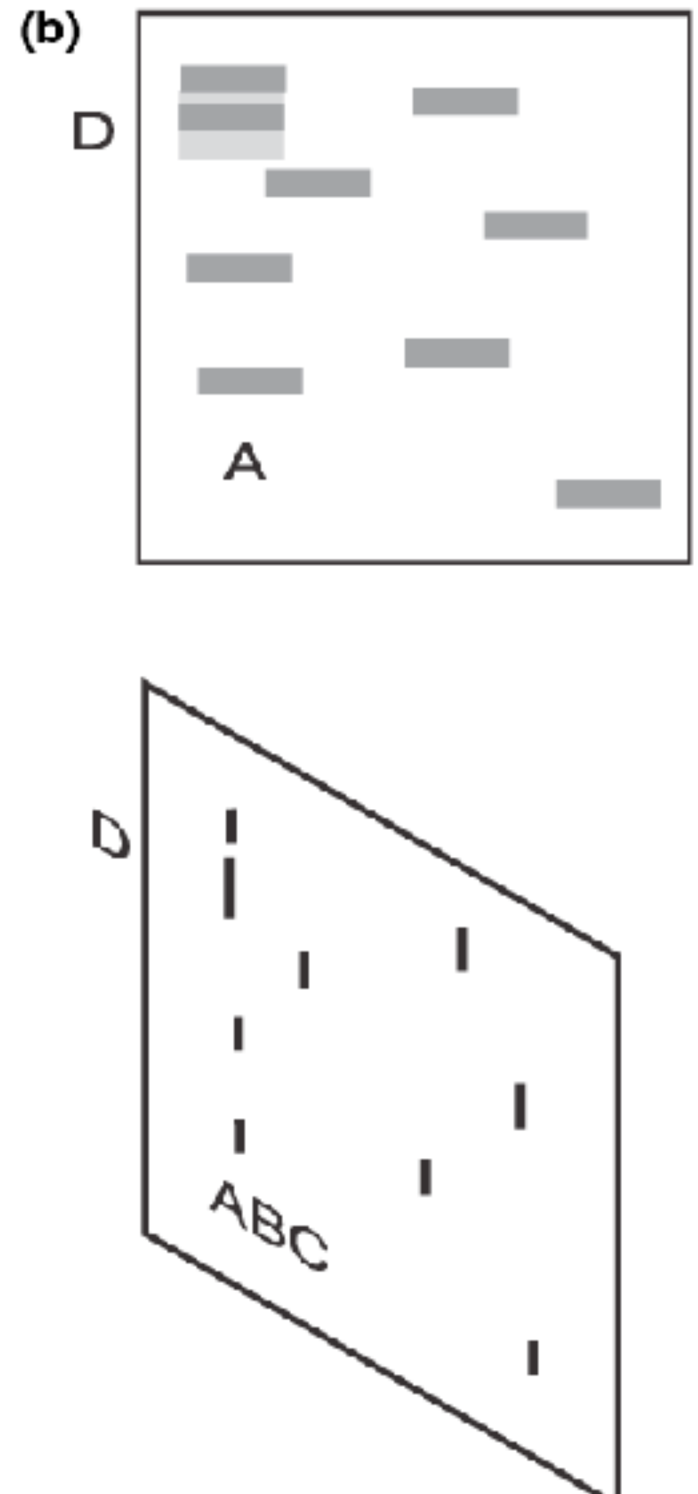


Multi Object Spectrometer (MOS)

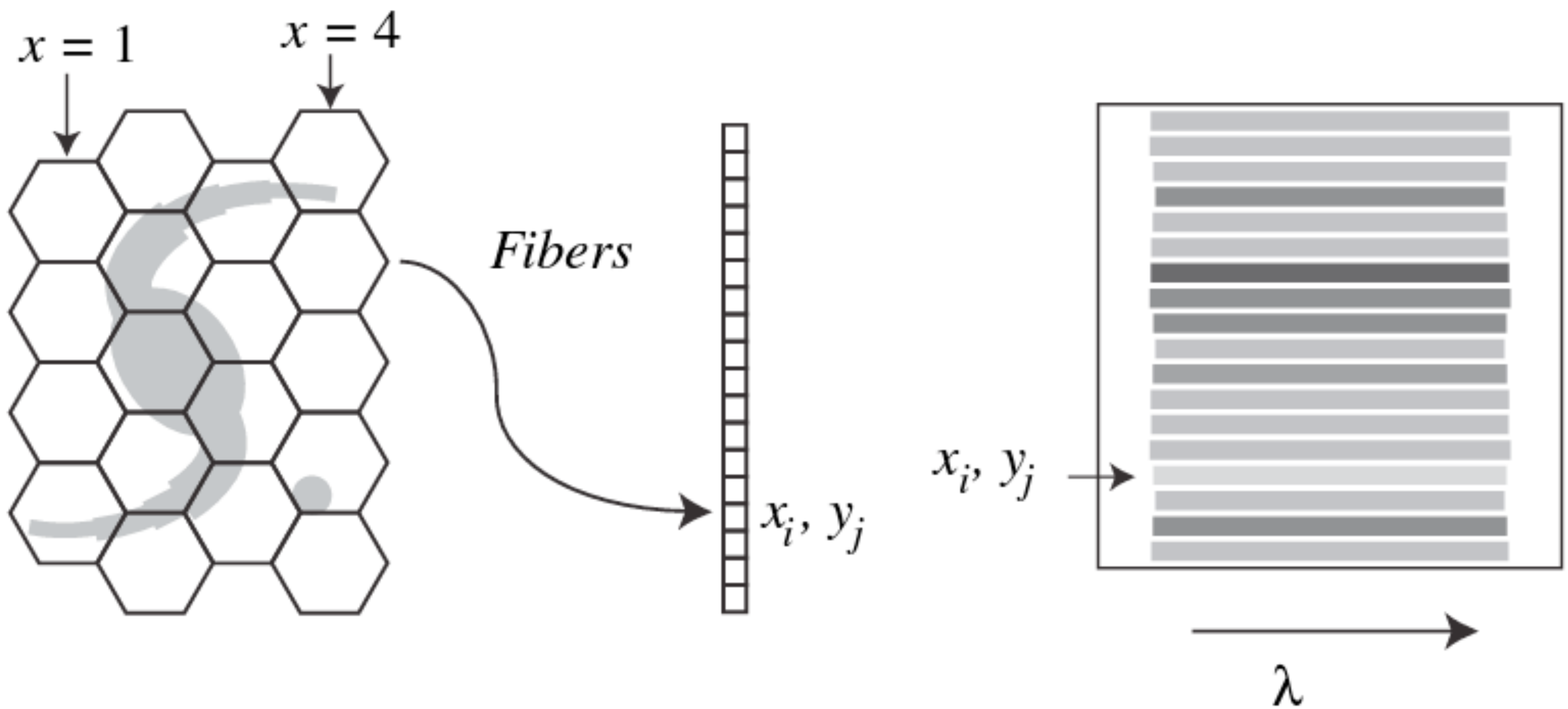
fiber

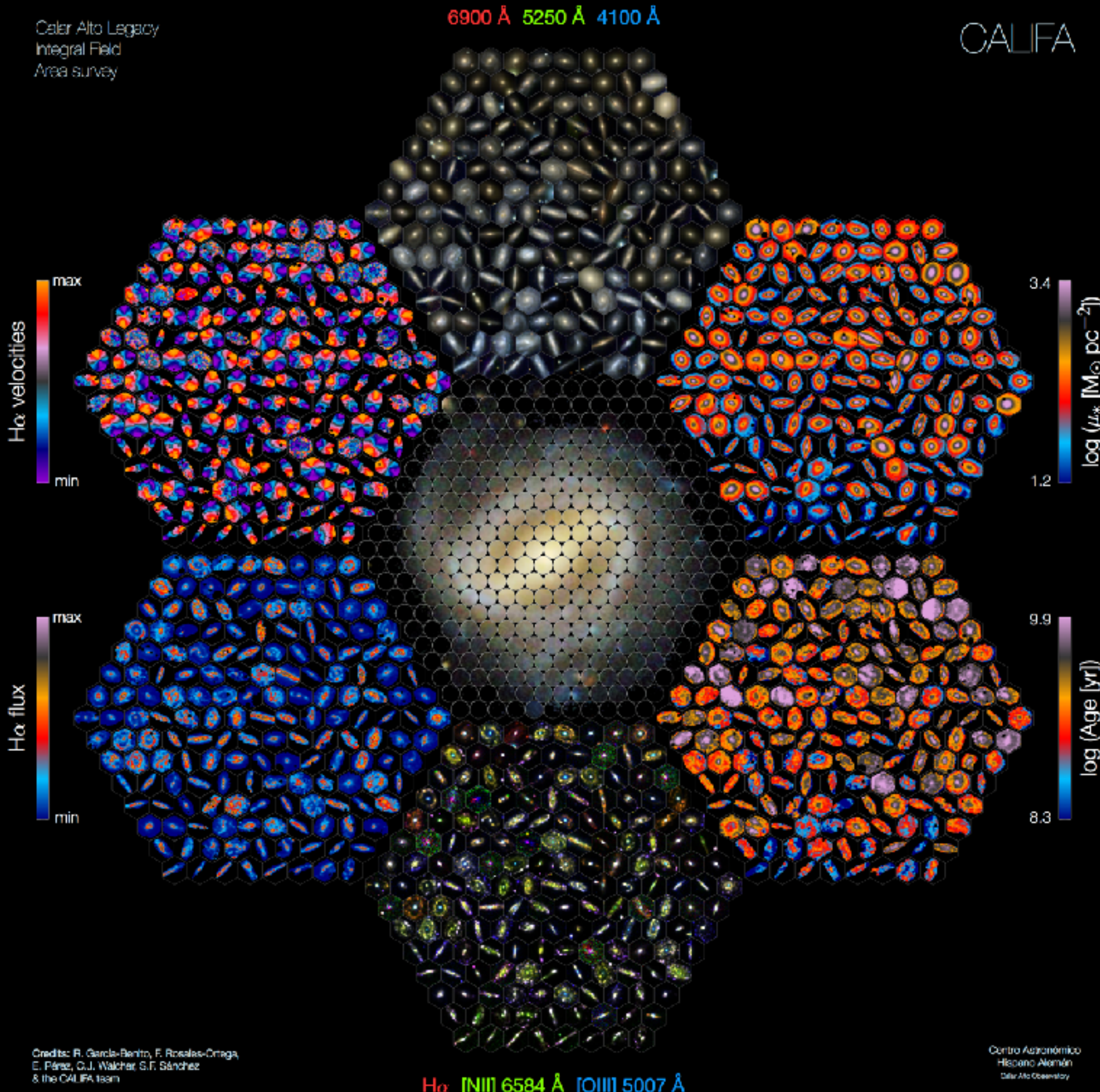


mask

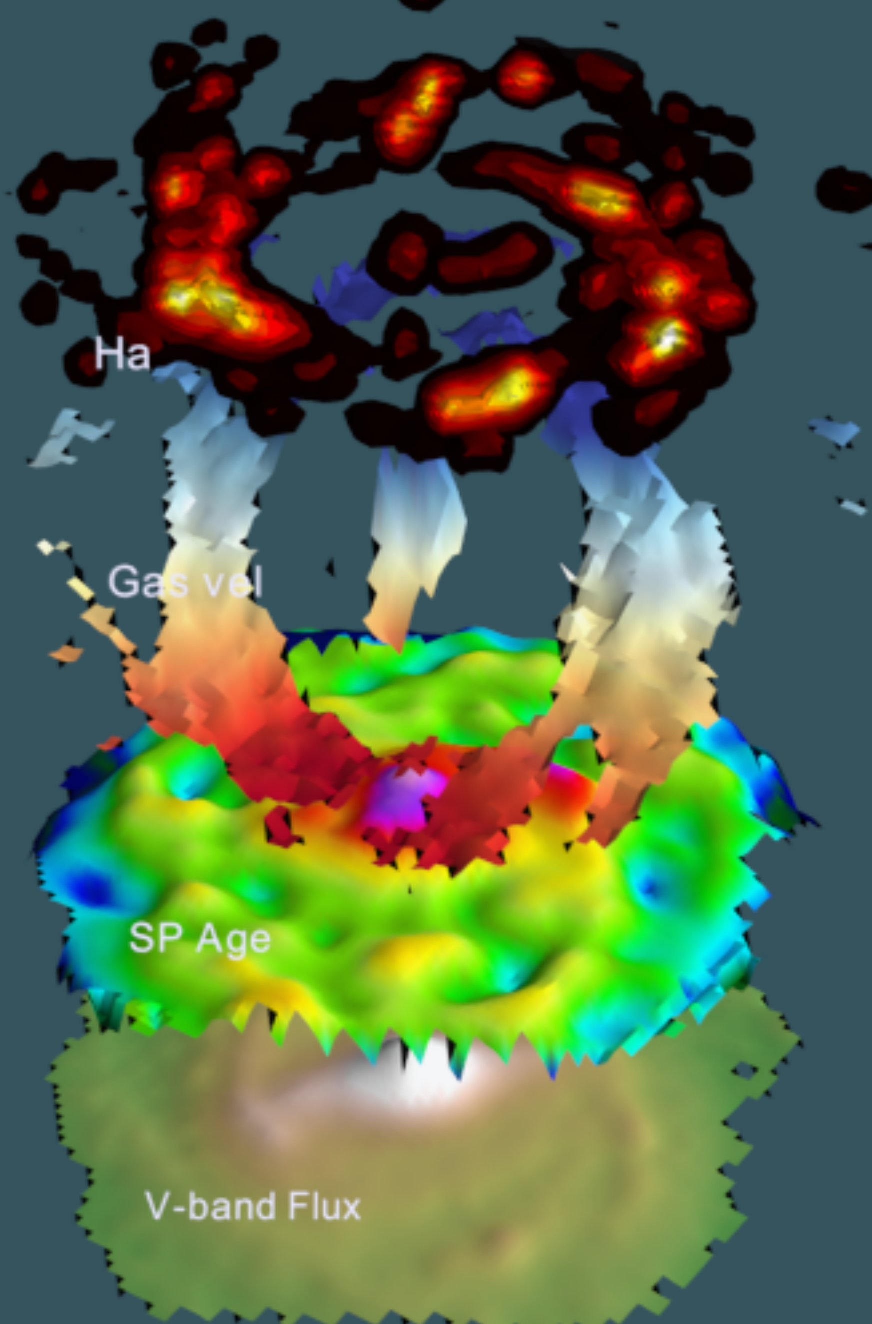


Integral Field Unit (IFU) Spectroscopy

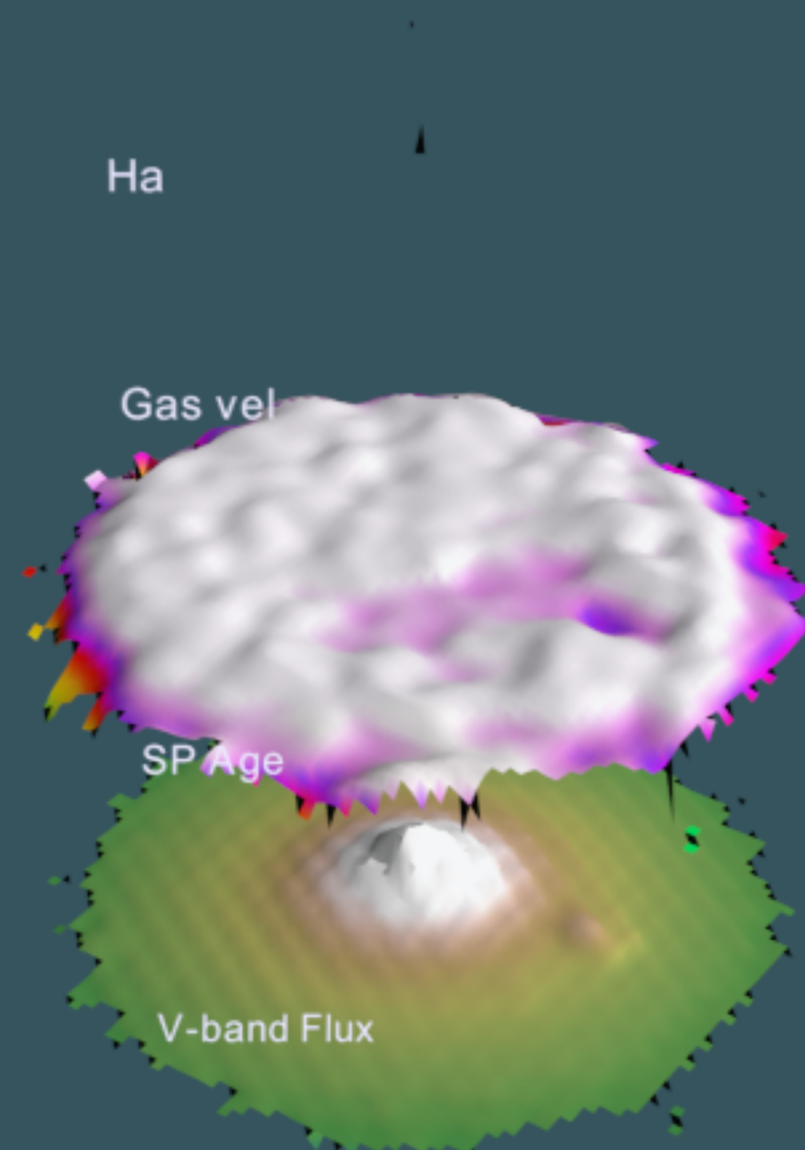


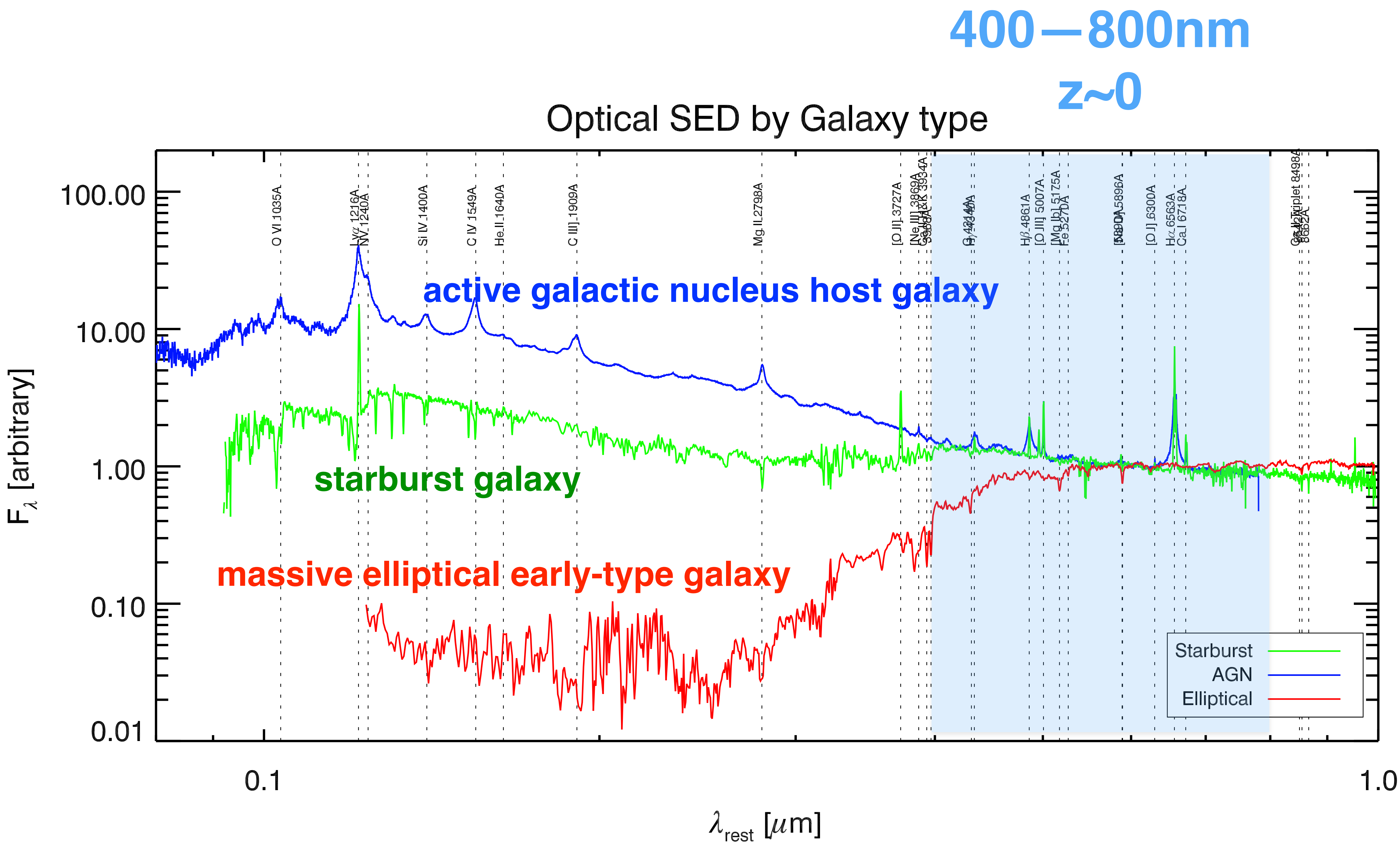

6900 Å 5250 Å 4100 Å
Calar Alto Legacy
Integral Field
Area survey
CALIFA
Hα velocities
max
min
Hα flux
max
min
log (μ_* [M$_\odot$ pc^{-2}])
3.4
1.2
log (Age [yr])
9.9
8.3
Credits: R. García-Benito, F. Rosales-Ortega,
E. Pérez, C.J. Walcher, S.F. Sánchez
& the CALIFA team
Hα [NII] 6584 Å [OIII] 5007 Å
Centro Astronómico
Hispano Alemán

NGC5406

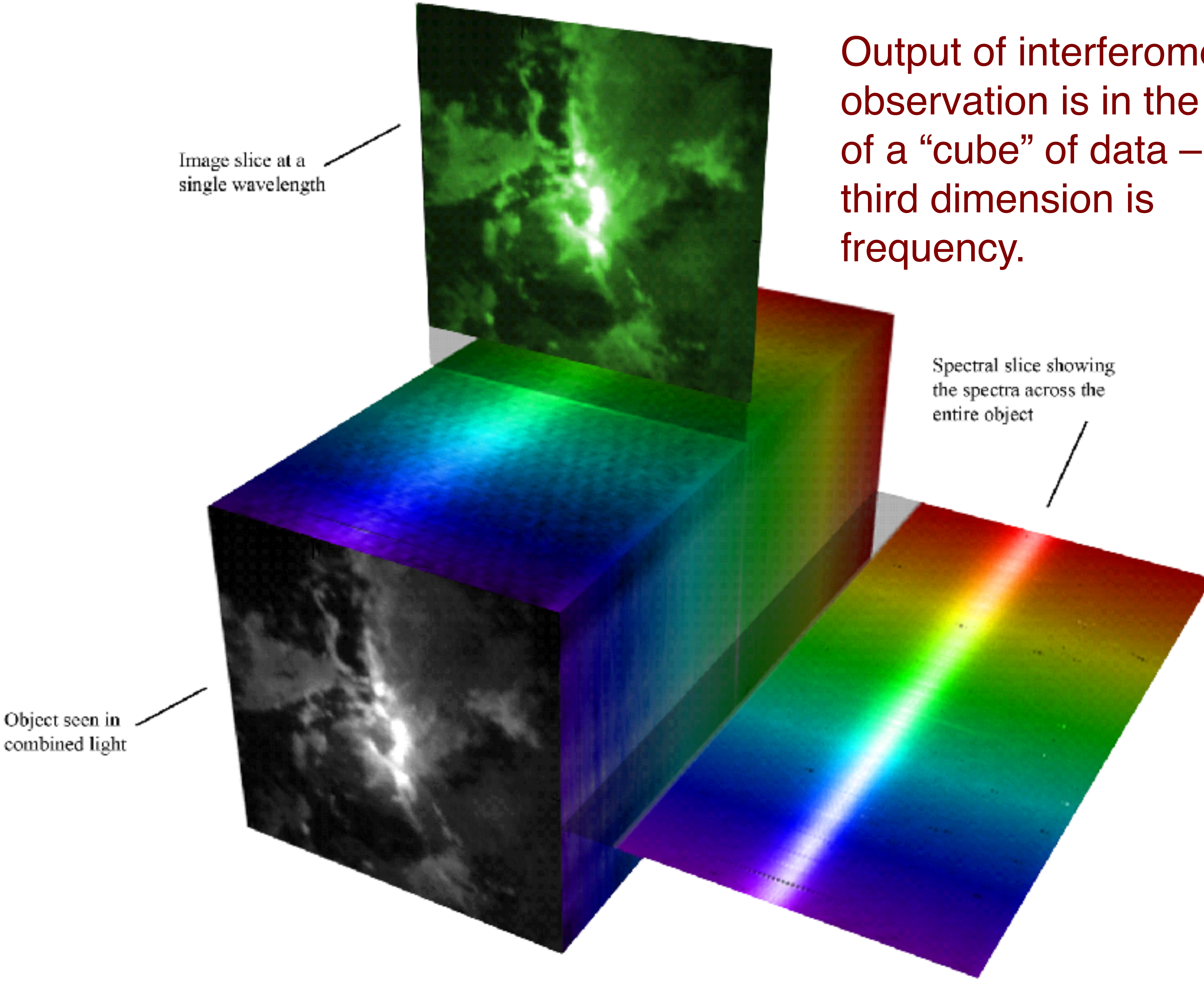


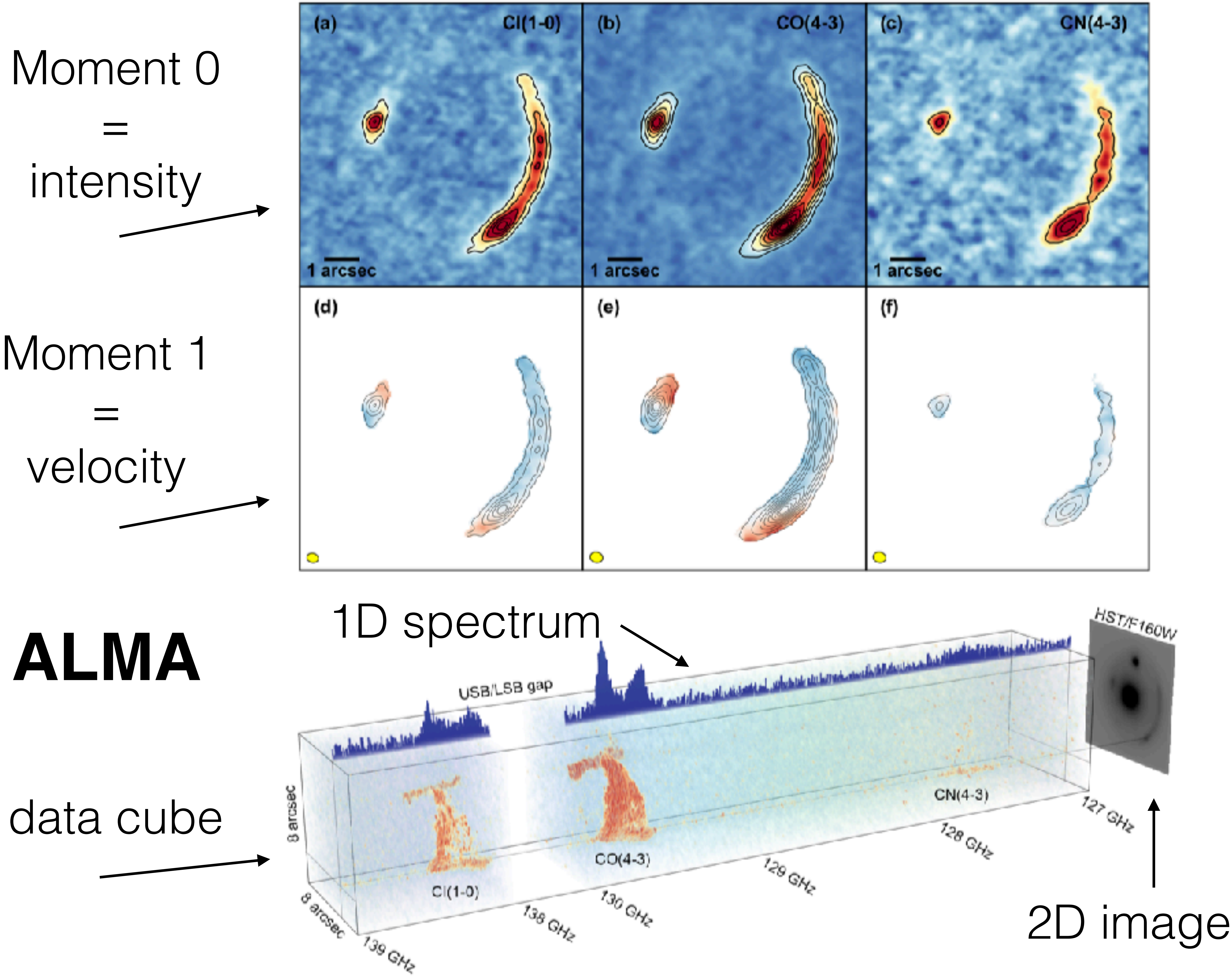
NGC6125




400—800nm
z~0
Optical SED by Galaxy type
active galactic nucleus host galaxy
starburst galaxy
massive elliptical early-type galaxy
Starburst
AGN
Elliptical
100.00
10.00
1.00
0.10
0.01
0.1
1.0
F$_\lambda$ [arbitrary]
λ_{rest} [μm]

Output of interferometric observation is in the form of a “cube” of data – the third dimension is frequency.





Moment 0
=
intensity
Moment 1
=
velocity
ALMA
data cube
1D spectrum
2D image
(a)
CI(1-0)
(b)
CO(4-3)
(c)
CN(4-3)
1 arcsec
1 arcsec
1 arcsec
(d)
(e)
(f)
USB/LSB gap
HST/F160W
8 arcsec
8 arcsec
CI(1-0)
CO(4-3)
CN(4-3)
139 GHz
138 GHz
130 GHz
129 GHz
128 GHz
127 GHz

Cosmic Discoveries Enabled by Spectroscopic Technology

More Recent:

- MOS has enabled astronomers to map out the large scale structure (LSS) of the Universe and it's evolution over 95% of it's history.
- Dark Matter and Dark Energy from (LSS)
- The Epoch of Reionization (EoR)
- The dawn of galaxy formation and evolution at $z>6$

THE ASTROPHYSICAL JOURNAL, 242:L69–L72, 1980 December 1

MULTIPLE OBJECT SPECTROSCOPY: THE MEDUSA SPECTROGRAPH

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AND

PAUL HINTZEN
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Received 1980 August 4; accepted 1980 August 28

ABSTRACT

We have built and tested an instrument to obtain simultaneous spectra of many objects in the field of view of the Steward 90 inch (2.29 m) telescope. Short lengths of fused silica fiber 300 μm in diameter are used to bring the light from galaxy images at the Cassegrain focus into a line along the spectrograph slit. From a single exposure of the cluster Abell 1904, which has a redshift of $\sim$20,000 km s^{-1}, we have determined the redshifts of 26 individual galaxies, each with a precision of $\sim$100 km s^{-1}. The present device, while already giving a sixfold reduction in the mean telescope time per galaxy, has significant light losses because it is not ideally matched to the telescope. An instrument being designed for the prime focus will transmit light from each object as efficiently as a conventional spectrograph.

Subject headings: galaxies: redshifts — instruments

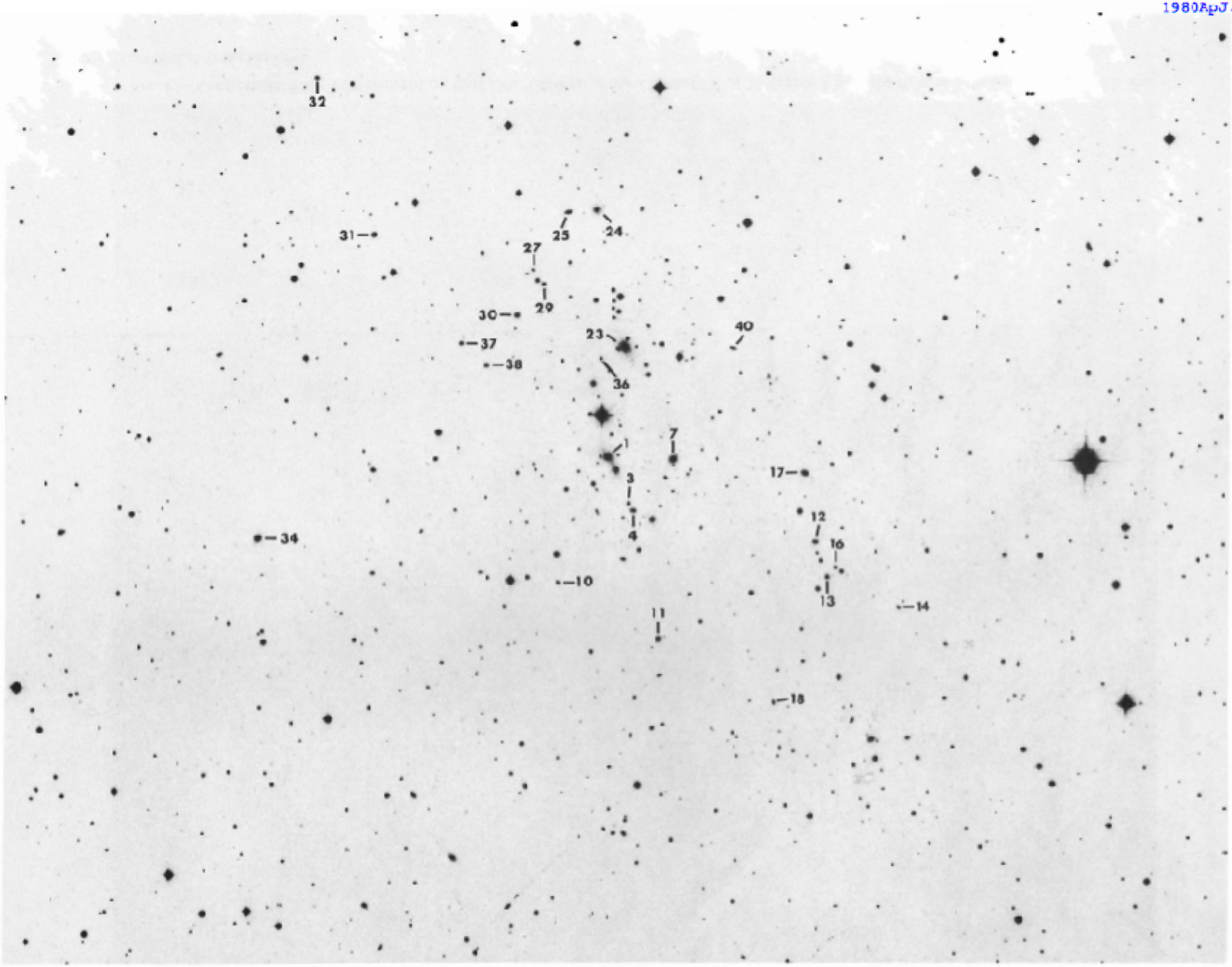


FIG. 4.—Finding chart for the galaxies in Abell 1904 and listed in Table 1. North is at the top, and east is to the left of north.

PLATE L7

HILL *et al.* (*see* page L70)

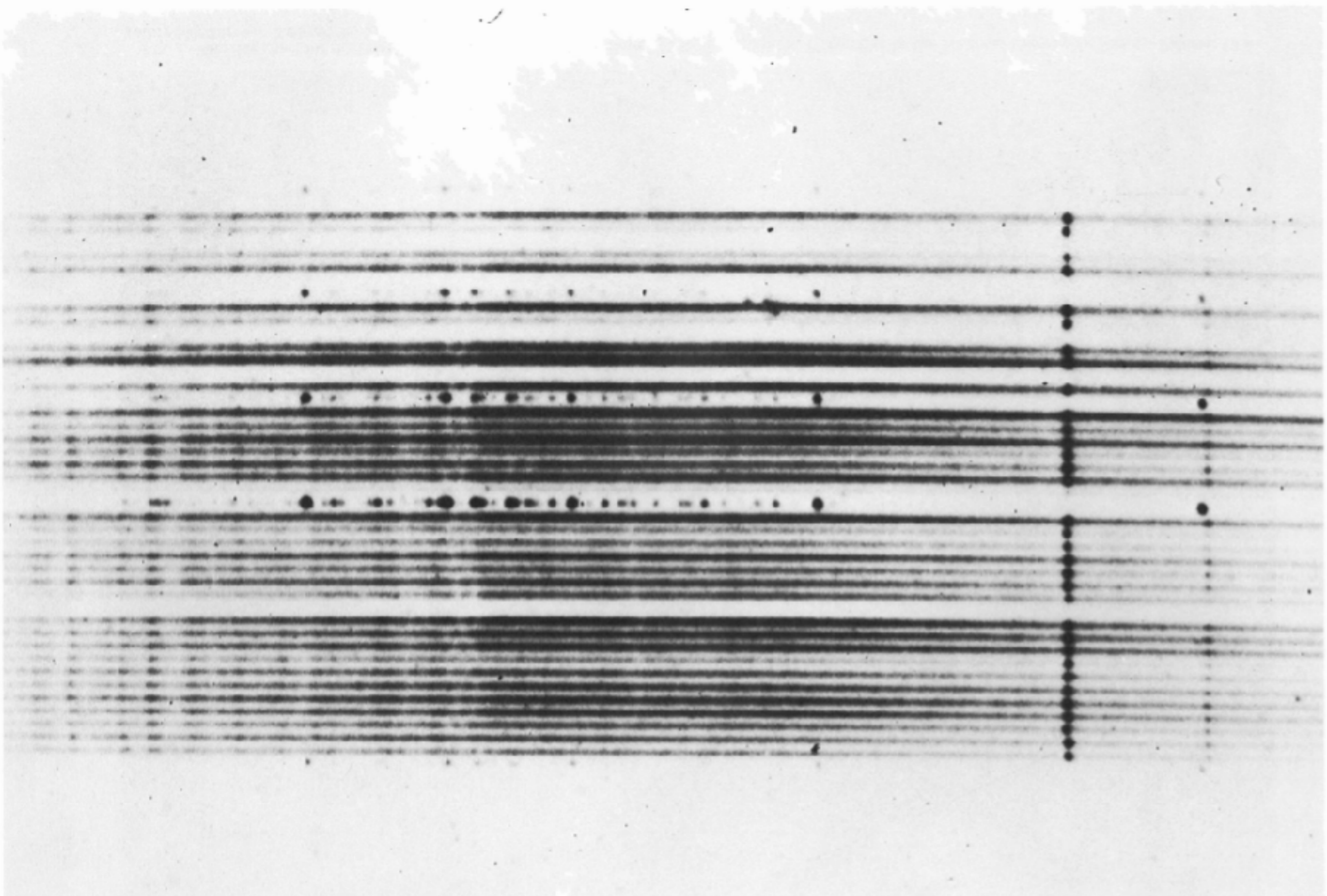


FIG. 1.—Twenty-six measurable spectra obtained for A1904. H and K and G-band are plainly visible.

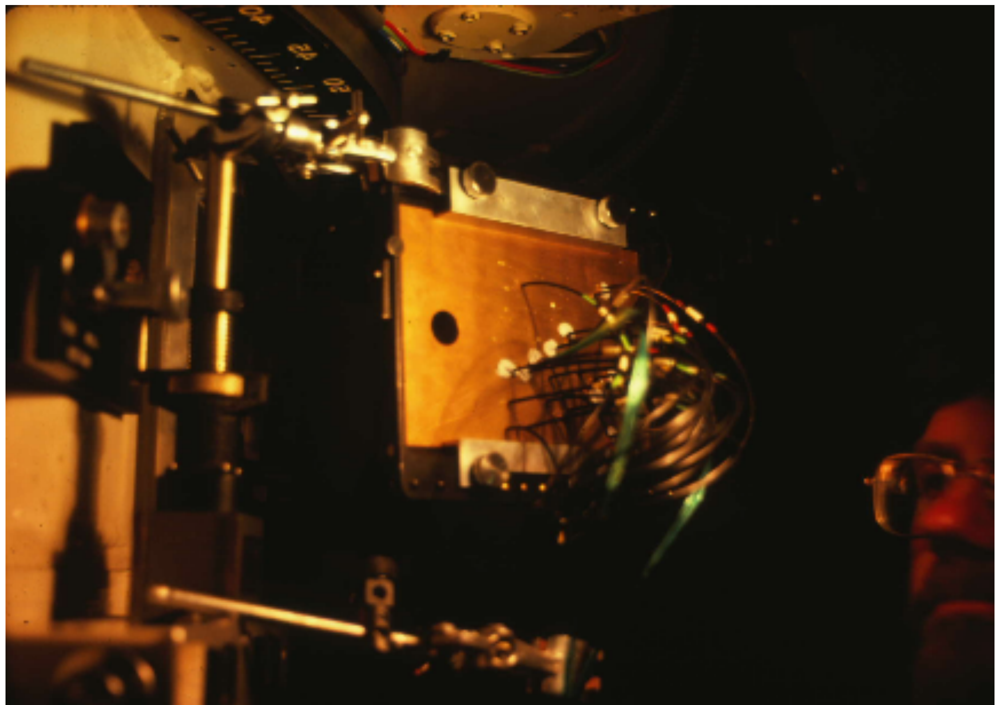
HILL *et al.* (*see* page L70)

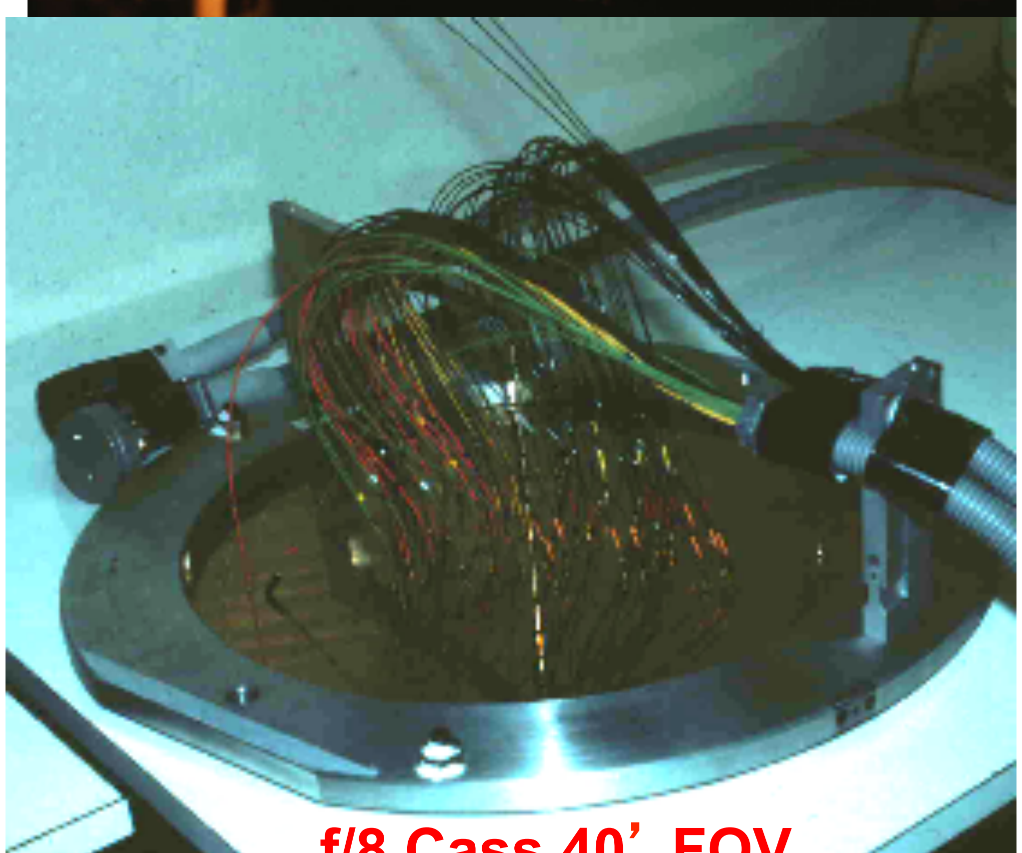
Anglo-Australian Telescope FOCAP

(Fibre Optic Coupled Aperture Plate)

Gray

Auxiliary f/8 Cass 12' FOV





f/8 Cass 40' FOV

Mon. Not. R. astr. Soc. (1984) **206,** 285–292

Multi-object spectroscopy using fibre optics at the Anglo-Austrialian telescope – an application to the IC 2082 galaxy cluster

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P. M. Gray *Anglo-Australian Observatory, PO Box 296, Epping, NSW 2121, Australia*

D. Carter *Mount Stromlo and Siding Spring Observatory, Private Bag, Woden PO, ACT 2606, Australia*

J. Godwin *Oxford University, South Parks Road, Oxford OX1 3RQ*

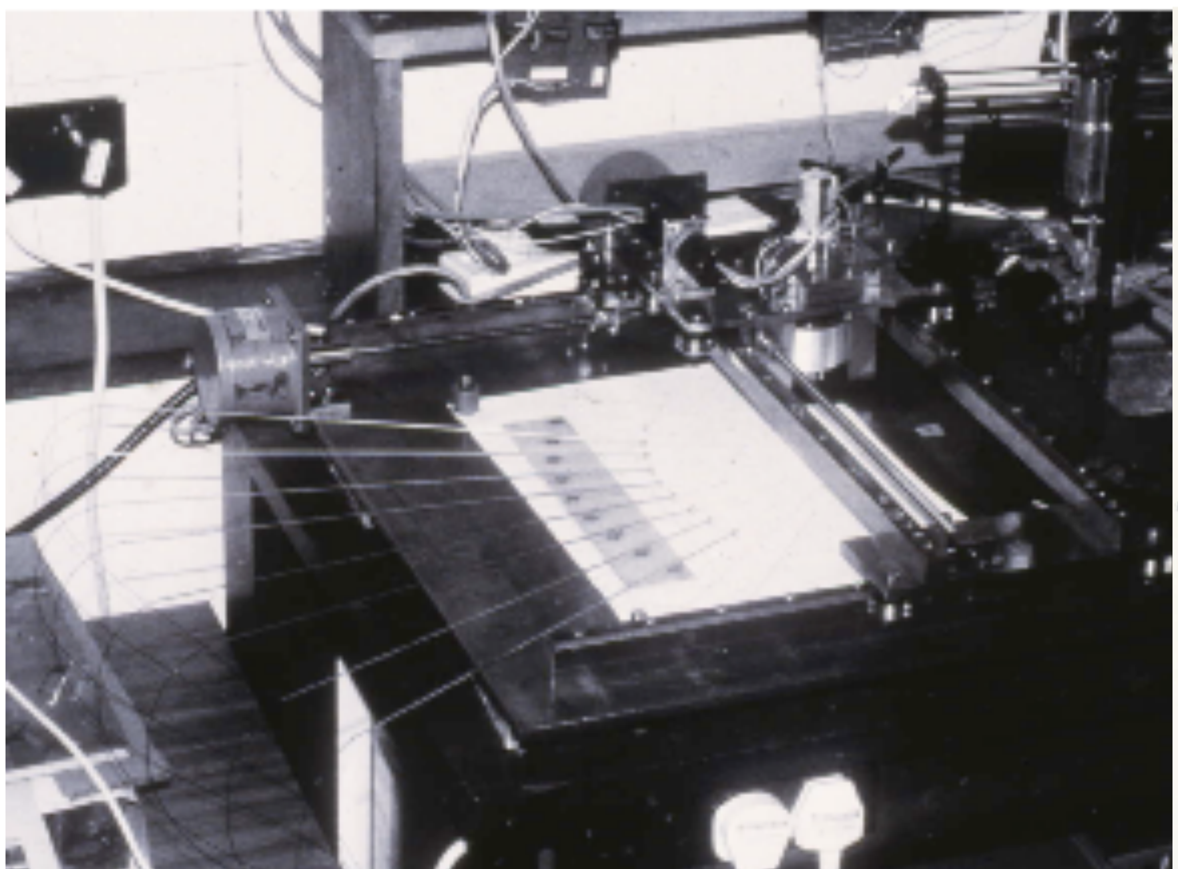
Received 1983 May 16; in original form 1983 January 27

Summary. We describe a multi-object fibre optic coupler we have developed for the Cassegrain focus of the Anglo-Australian telescope. The results of a test run on the southern cluster containing the dumb-bell galaxy IC 2082 are presented. Where comparisons with previous work can be made the radial velocities determined using the coupler show no signs of any systematic errors. The new results are briefly discussed in terms of earlier claims for galactic cannibalism in the cluster.

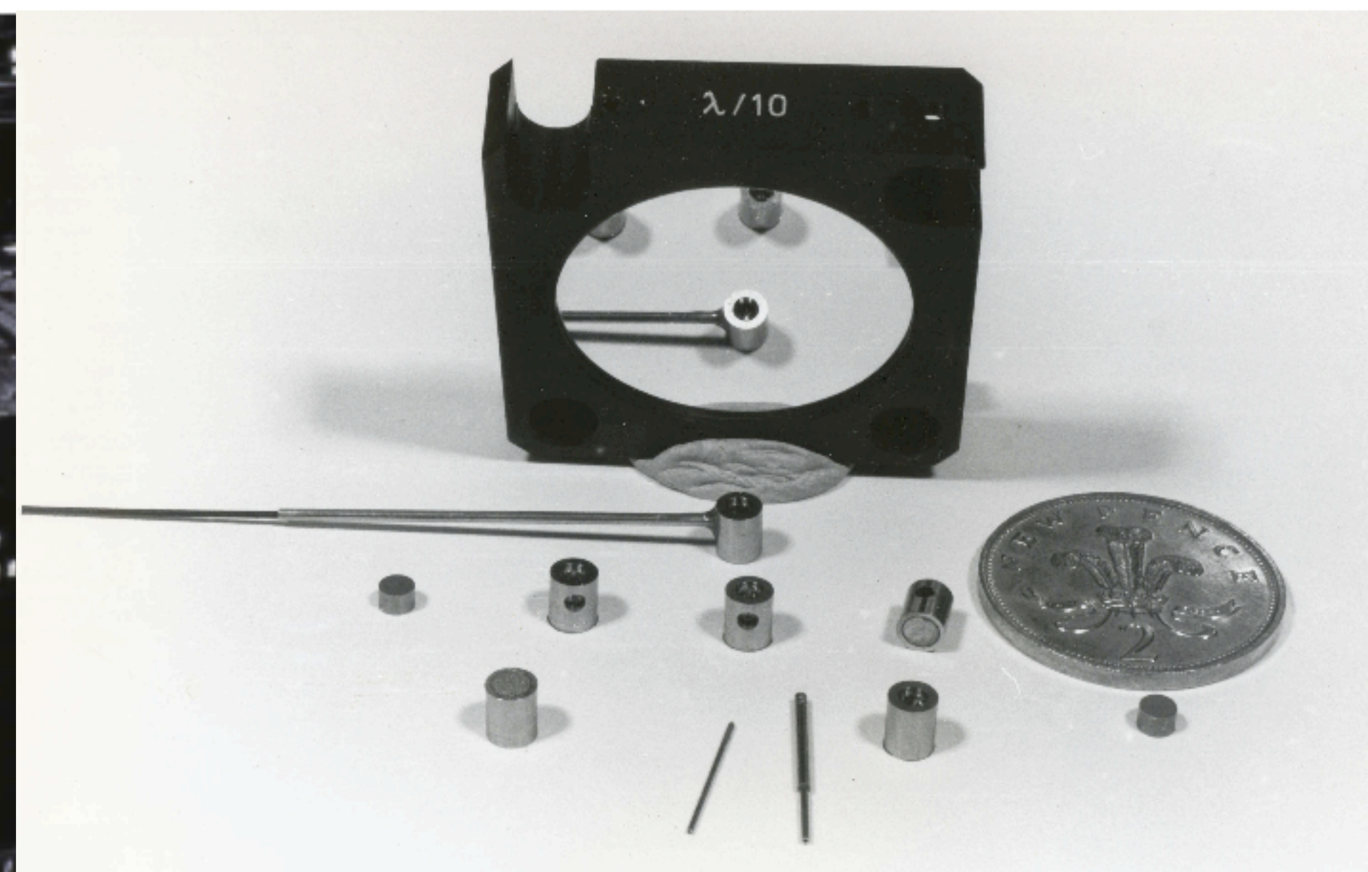
Automated Fiber Positioning

- FOCAP was a big success: 30% of all spectroscopic time!
- Aperture plates inflexible to target changes/atmospheric effects
- Automation ensures better placement, more uniform transmission
- Aug 1984: Parry et al proposes *prototype robotic positioner*
- May 1985: Autofib-1 commissioned in March 1987
- Total cost £20K + manpower

Parry

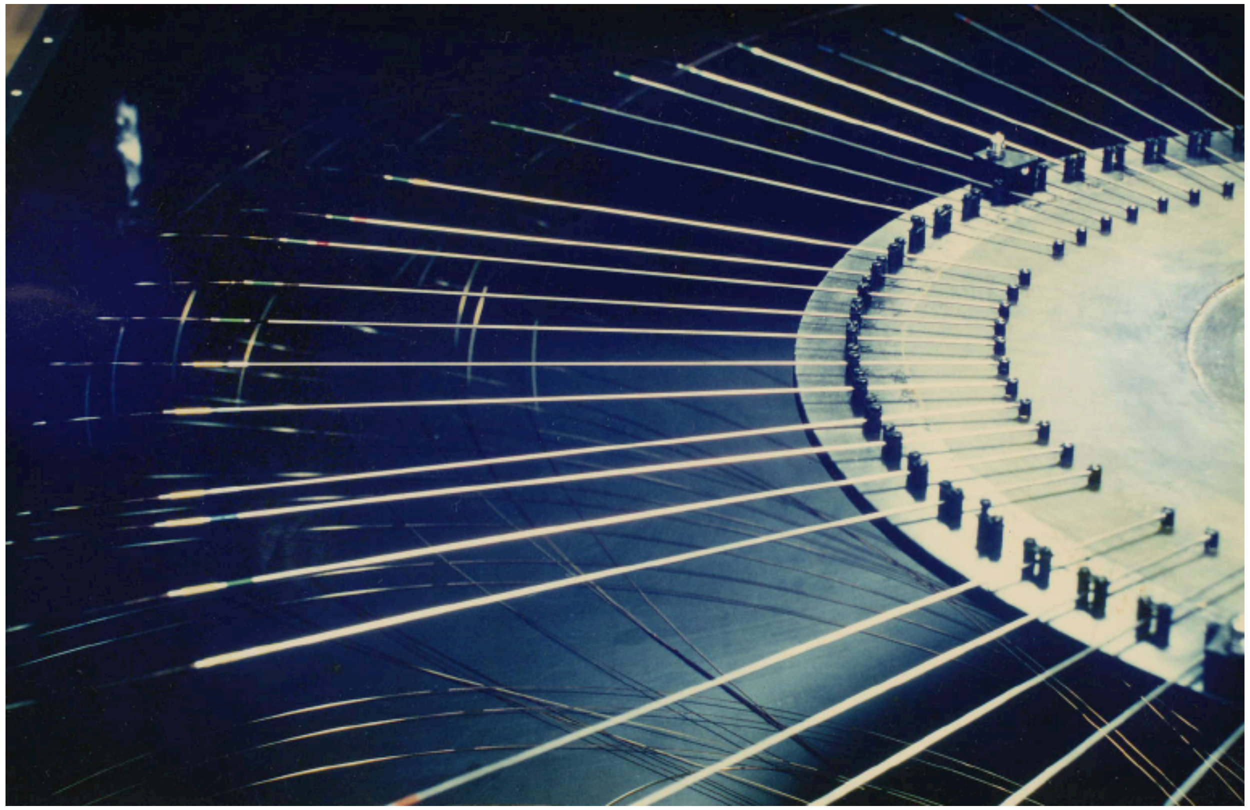


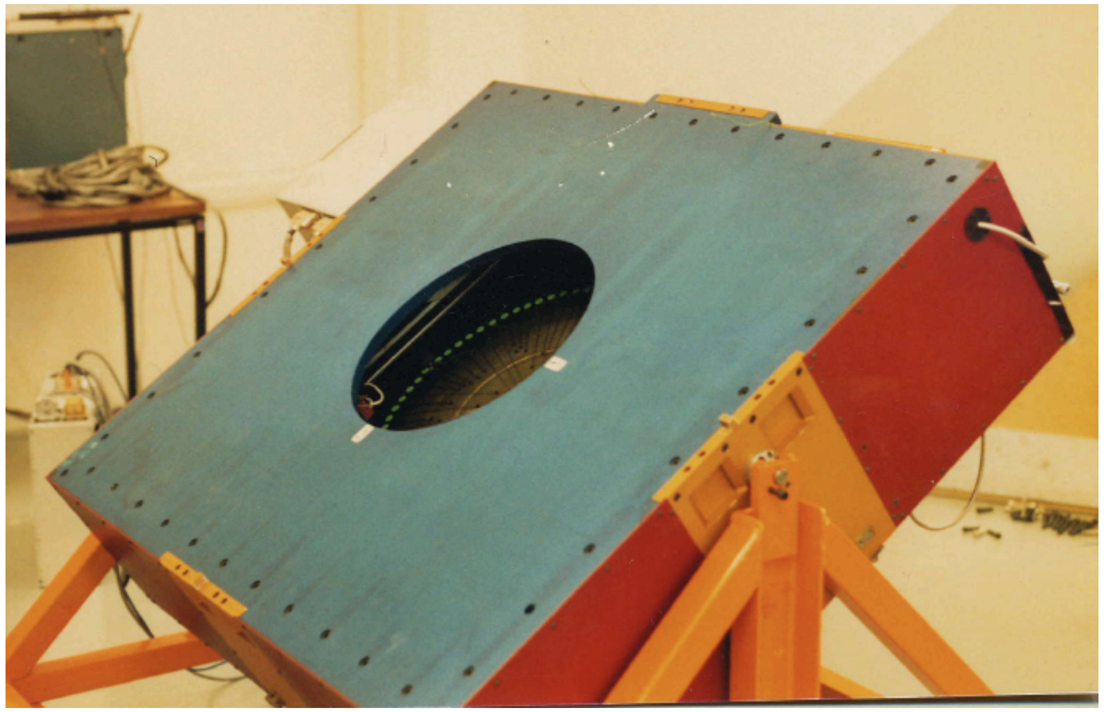
Laboratory protype (Durham U)



Fiber end (SmCo magnets & 90° prisms)

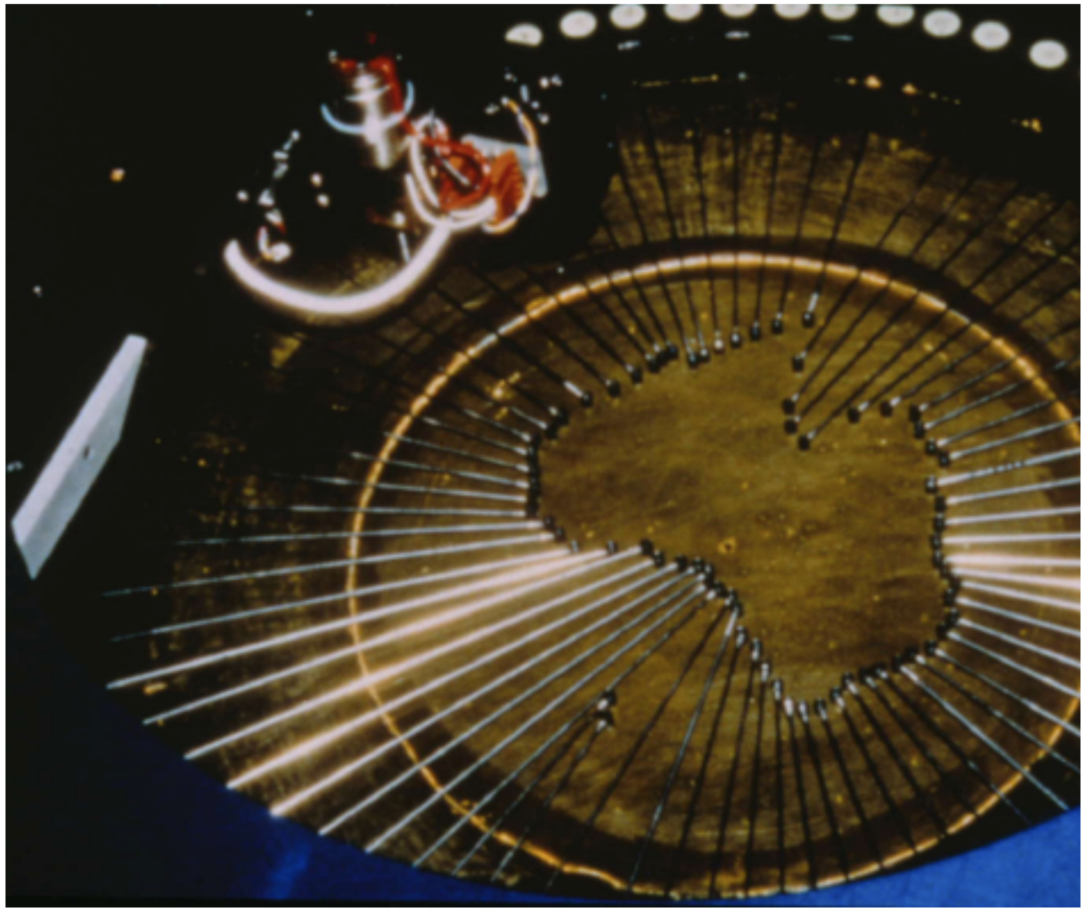
Autofib-1 @ AAT (1986 – 1994)



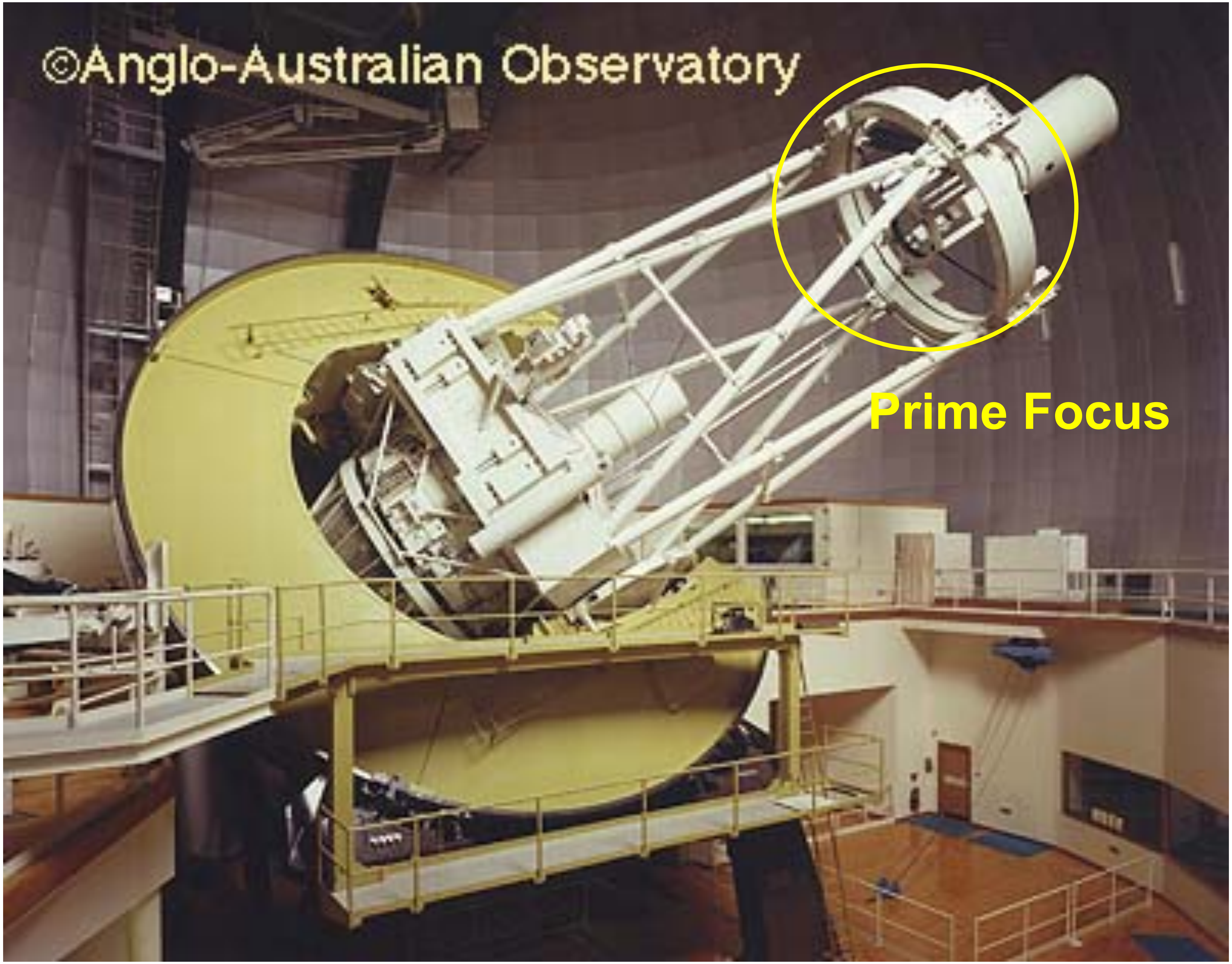


The Autofib concept (Parry) was pioneering and rapidly became the standard robotic option. It led to enquiries for cloned versions from:

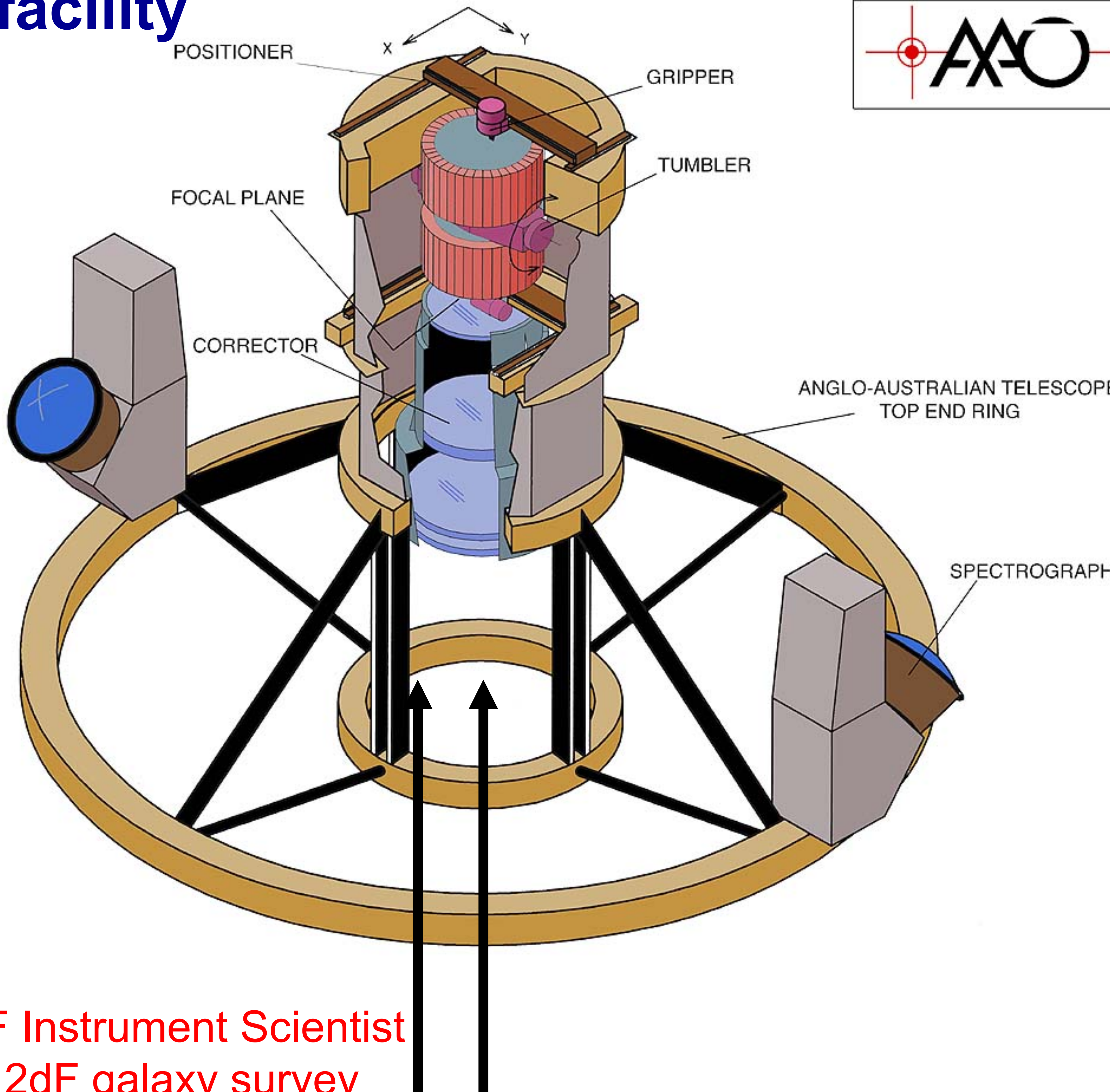
UH 2.2m, MDM 2.4m, CFHT 3.5m, ESO, NOAO & China (but not SDSS!)



The 2 degree Field (2dF) Project (1994 -)

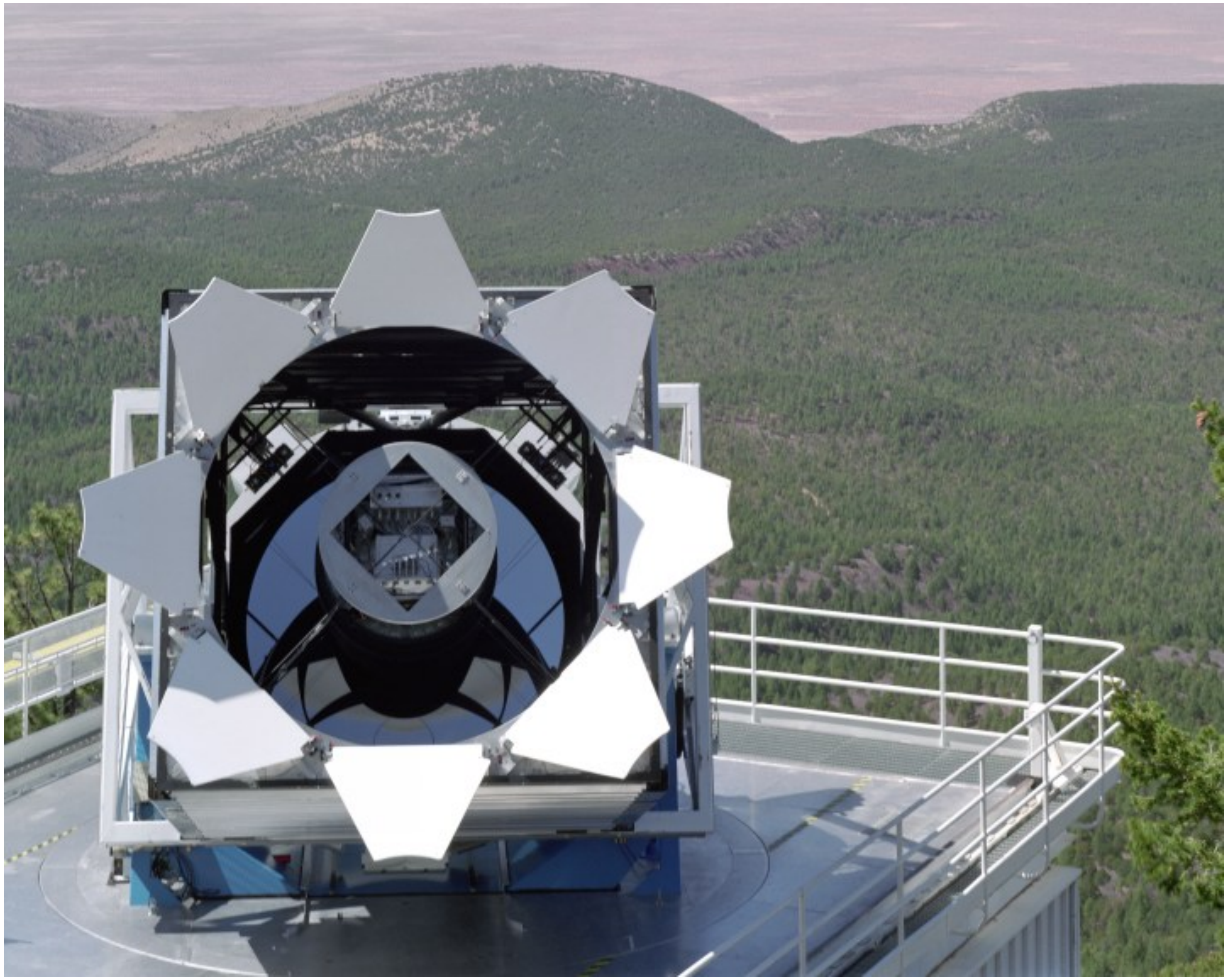


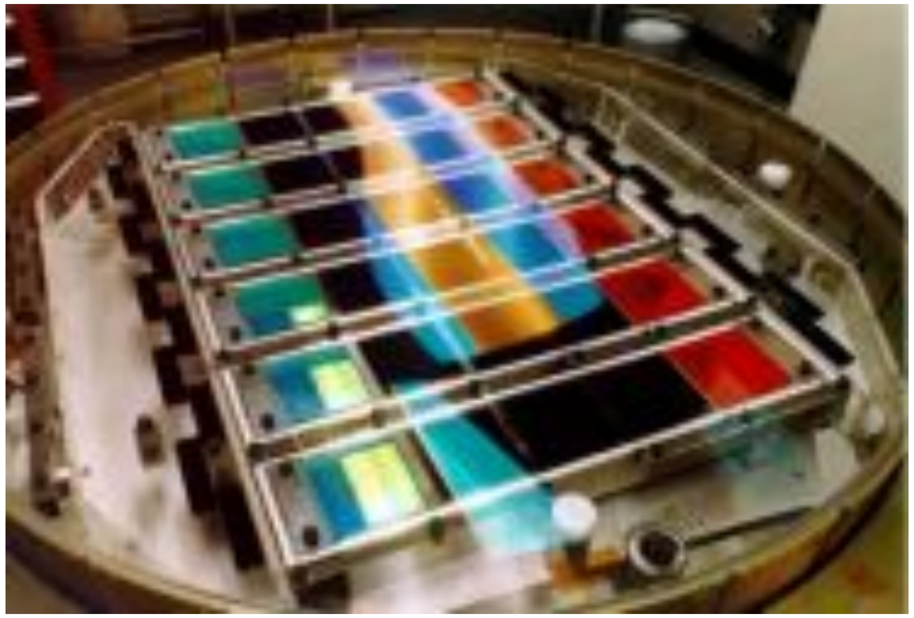
The 2dF facility



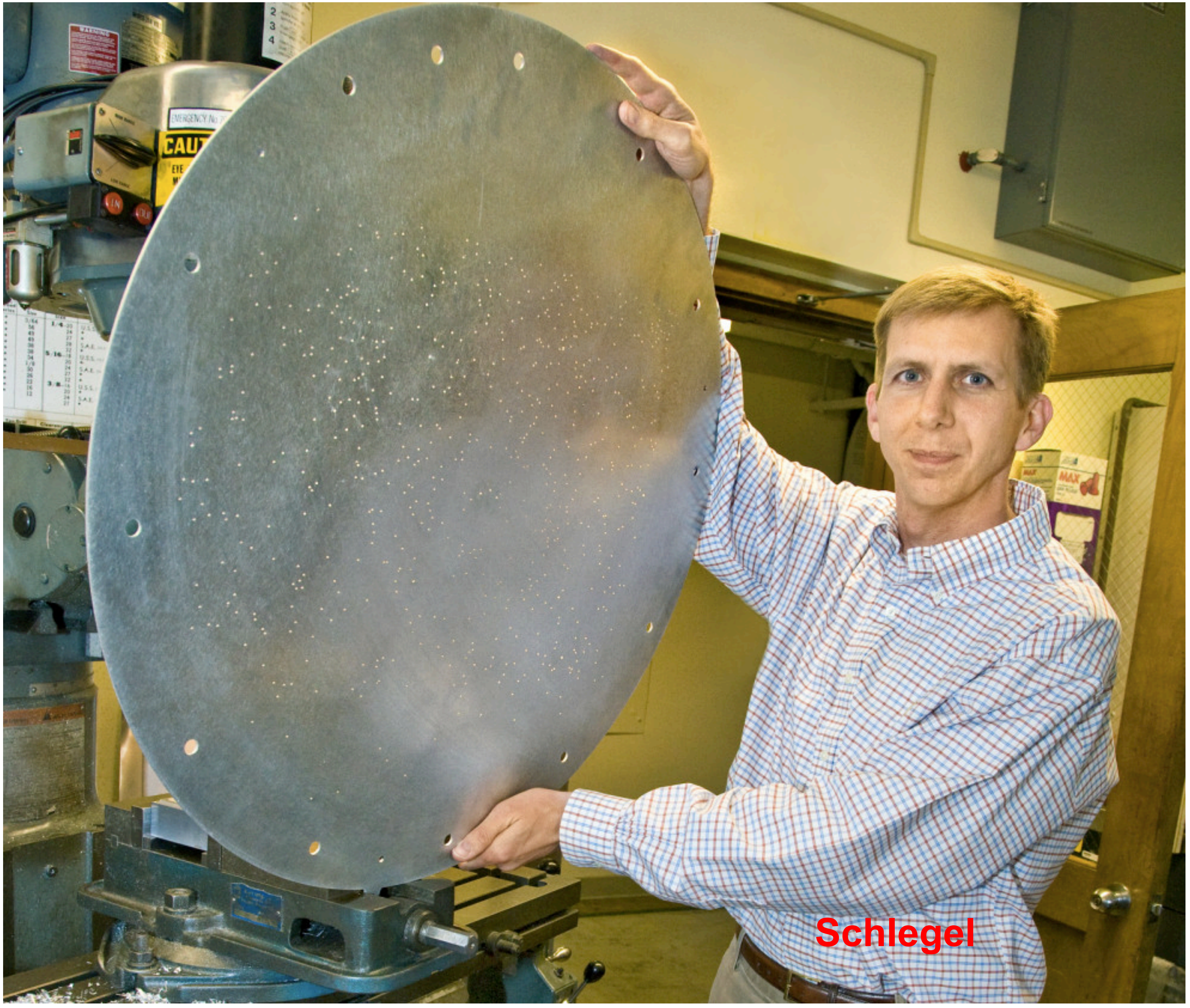
Glazebrook: 2dF Instrument Scientist
Peacock: UK PI 2dF galaxy survey

Sloan Digital Sky Survey





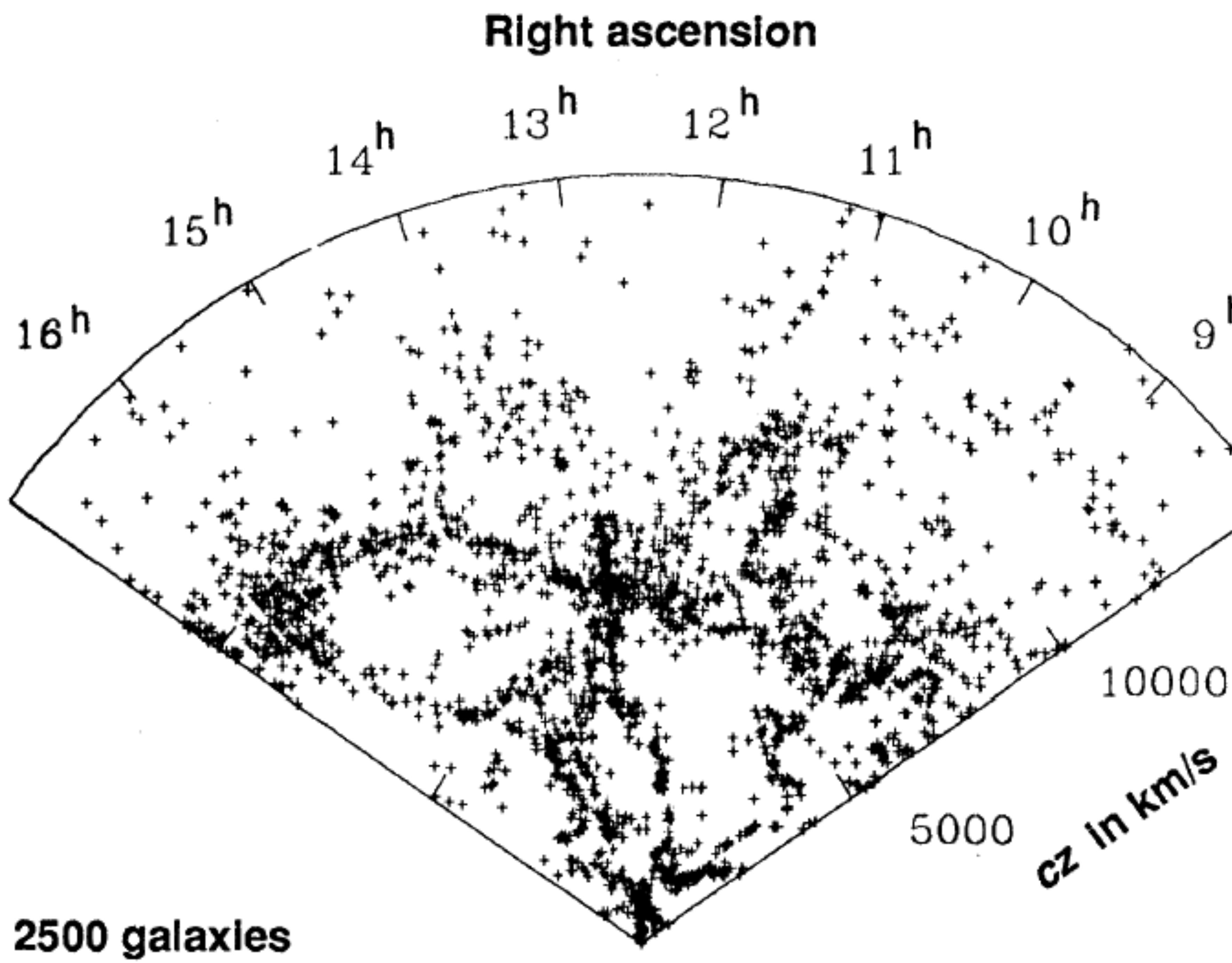
SDSS Aperture Plate



Discoveries with Multi-fiber Galaxy Surveys

- Is the Universe homogeneous on large scales?
- What is the mean mass density of the Universe? Is it suficient to halt the cosmic expansion
- What is the expansion history and ultimate fate of the Universe?

The Great Wall - "Largest Known Structure"



Geller & Huchra (1990) Science 246, 897

Las Campanas Redshift Survey

Pioneering multi-fiber survey at the 2.5m Du Pont telescope charted galaxy distribution to 50,000 km/s (c.f. 10,000 km/s in CfA survey)

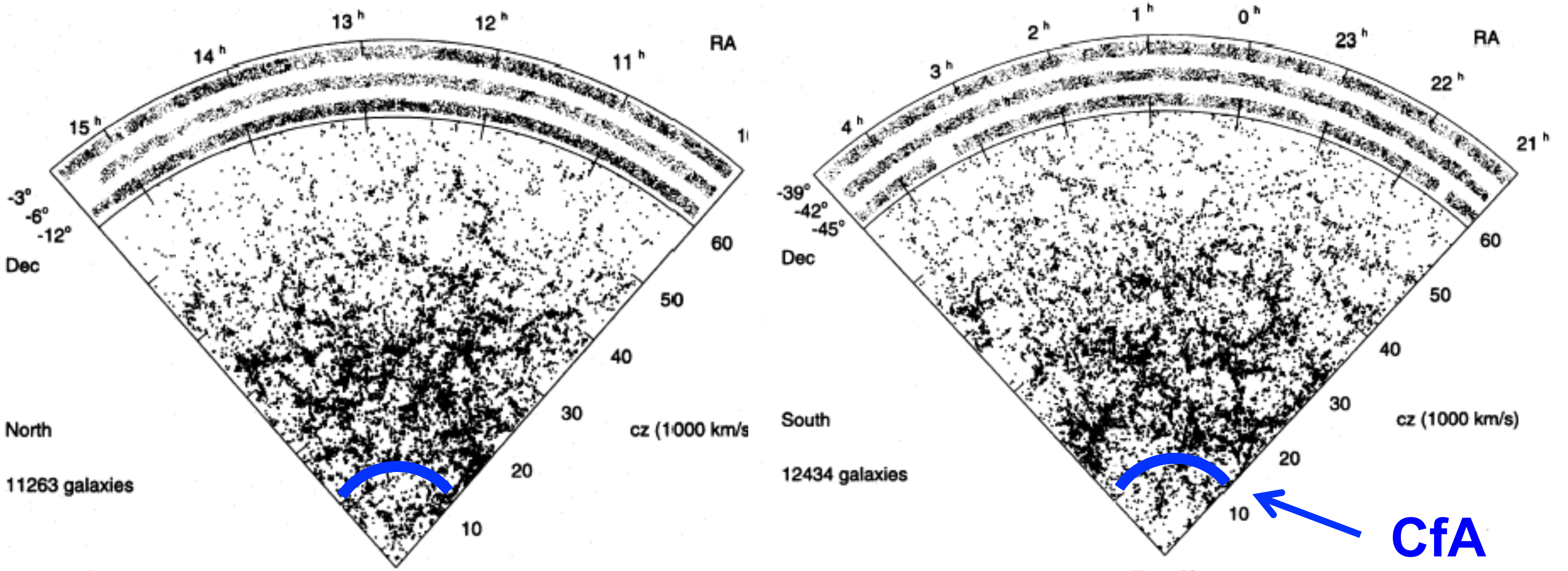


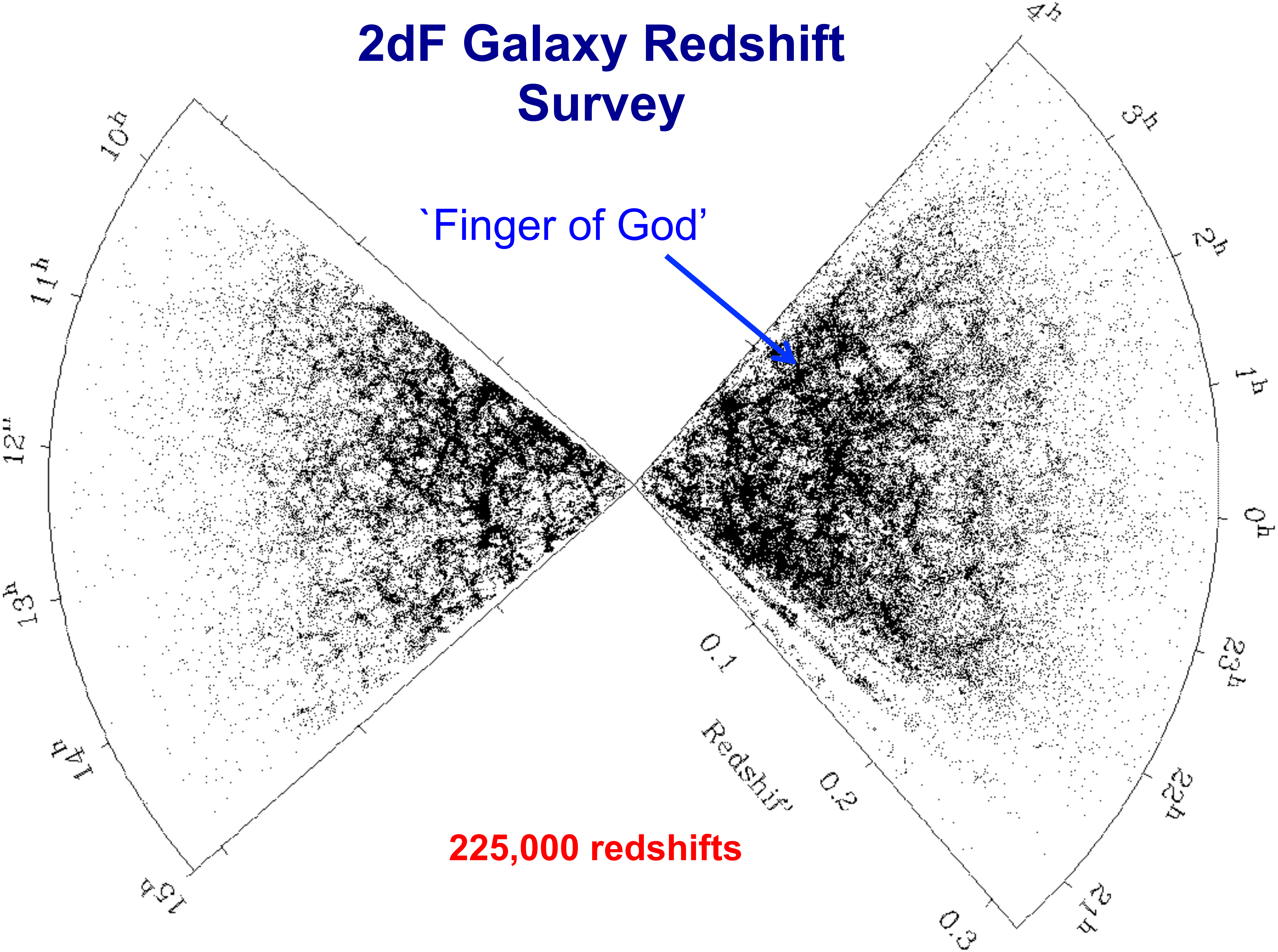
FIG. 8g

FIG. 8h

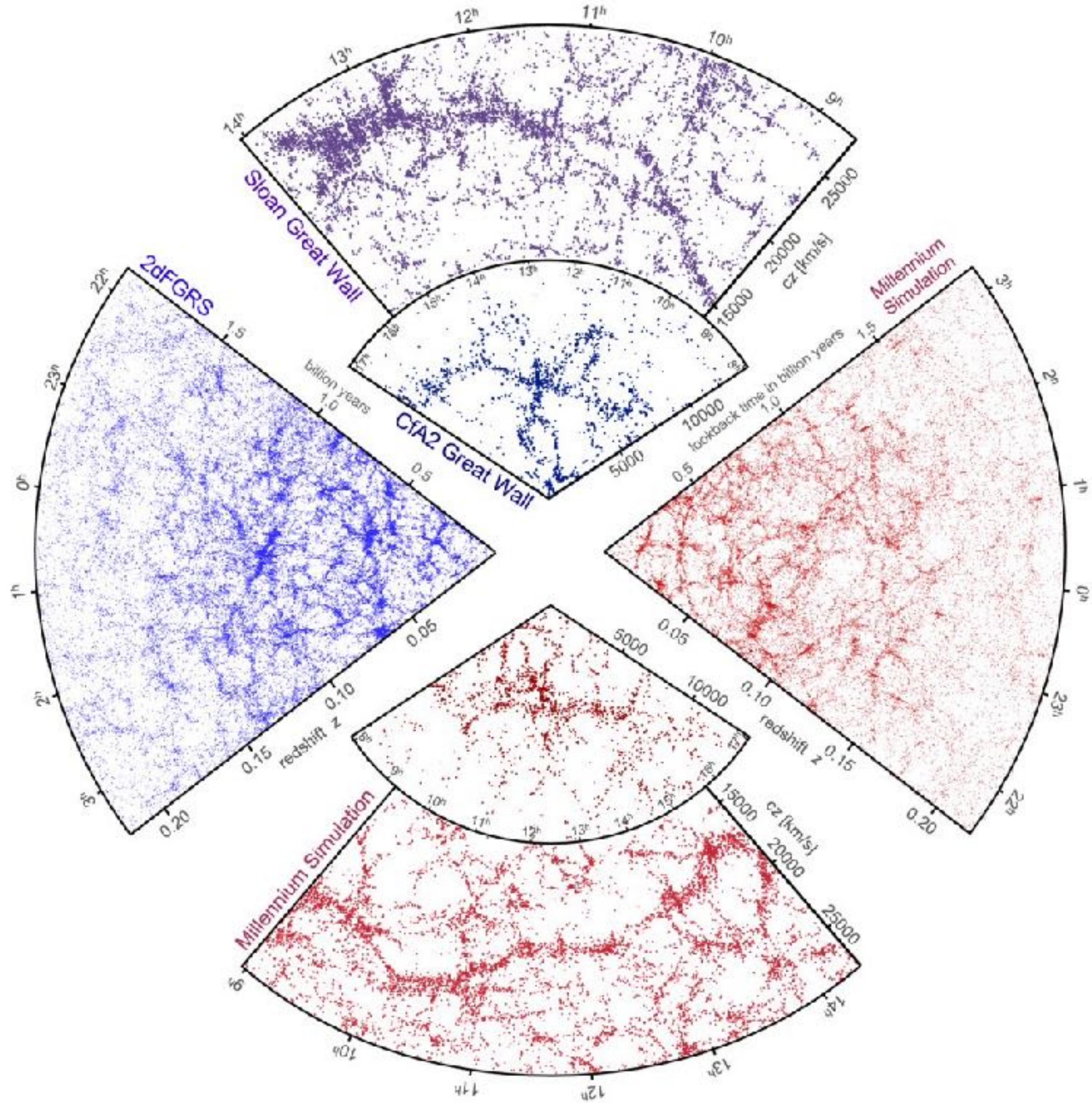
26412 gals R <17.7

Shectman et al 1996 Ap J 470, 172

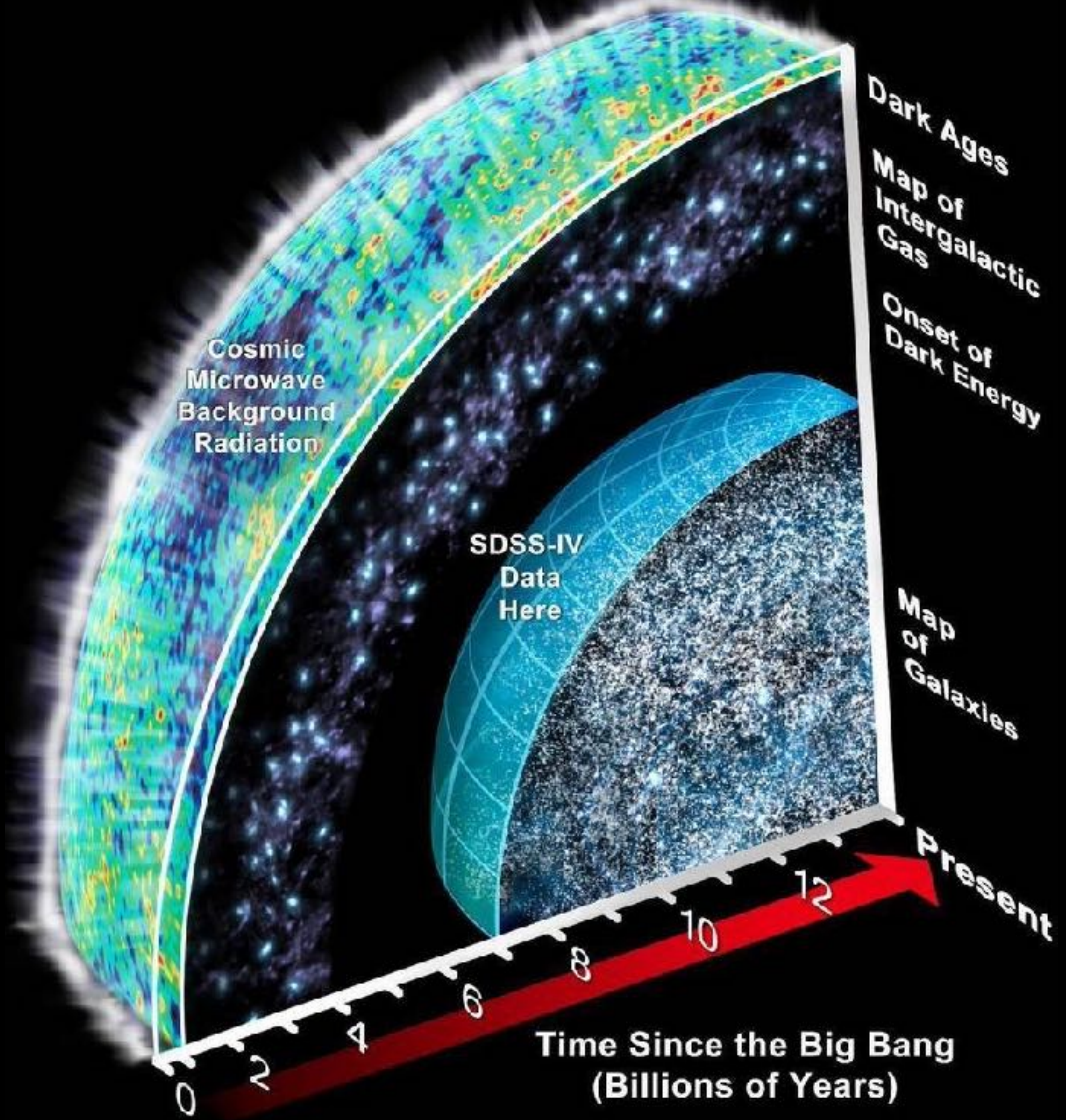
2dF Galaxy Redshift Survey



225,000 redshifts

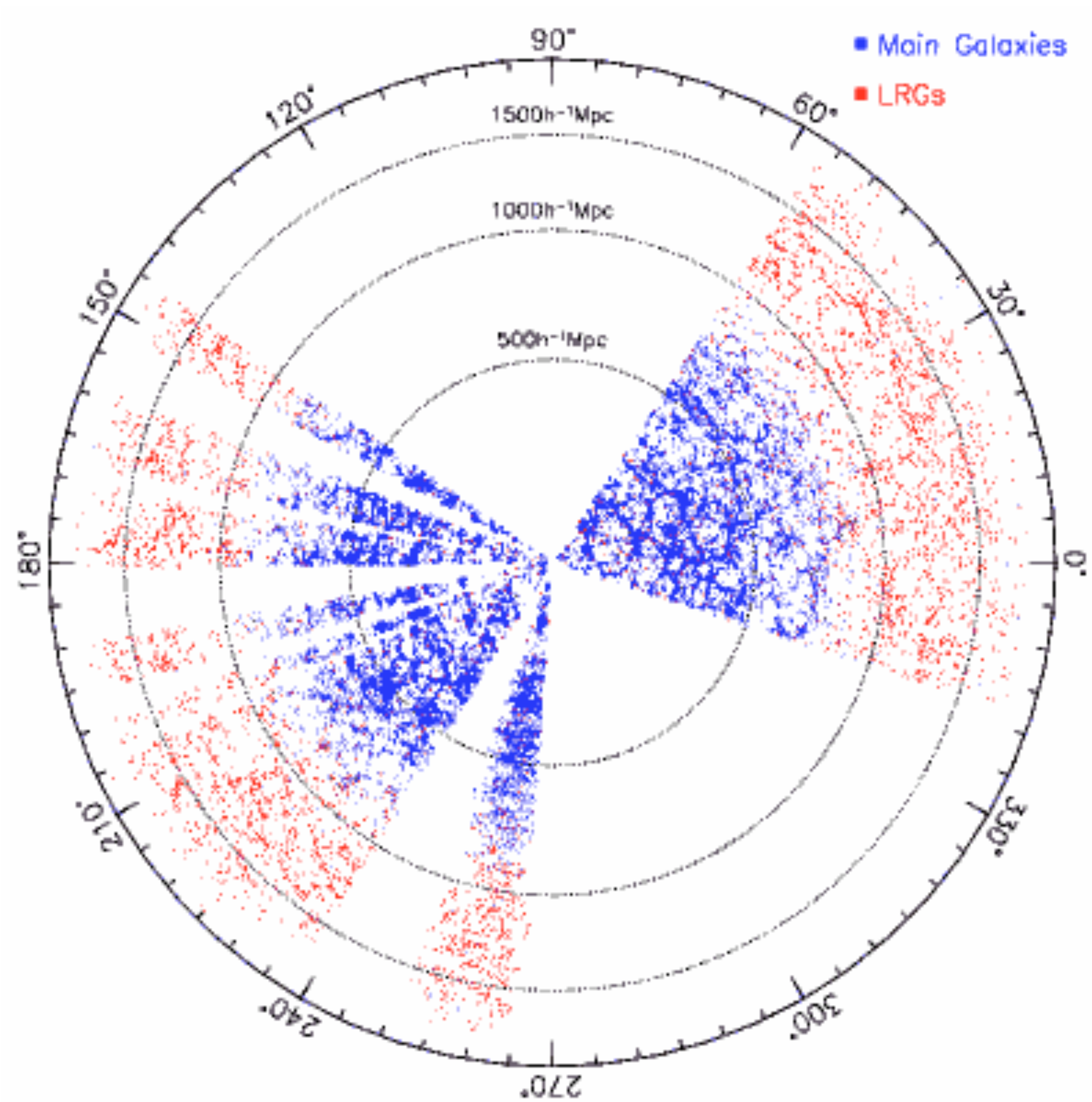


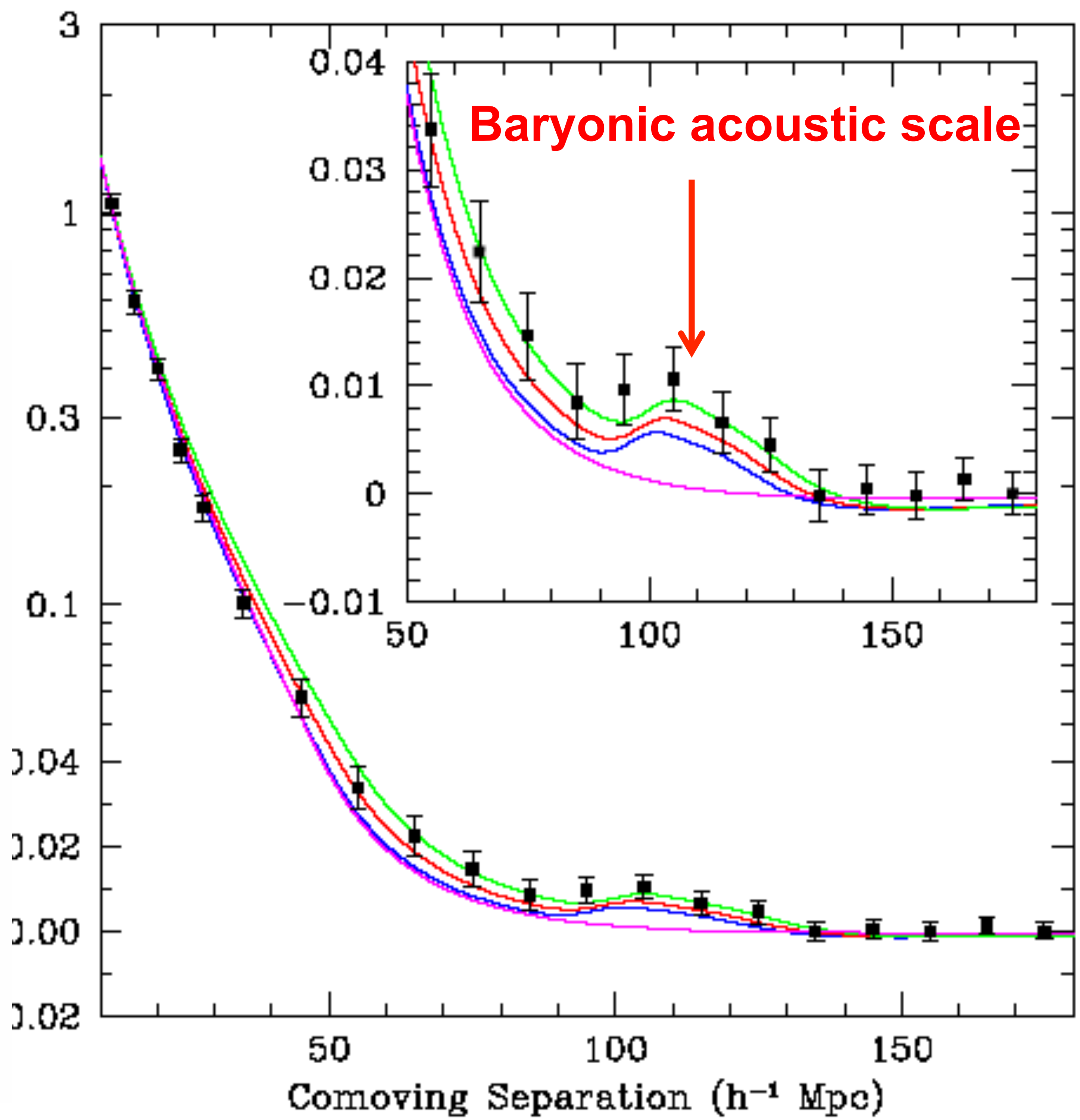
Sloan Great Wall
2dFGRS
CfA2 Great Wall
Millennium Simulation
Millennium Simulation
billion years
lookback time in billion years
redshift z
redshift z
cz [km/s]
cz [km/s]


Dark Ages
Map of Intergalactic Gas
Onset of Dark Energy
Map of Galaxies
Cosmic Microwave Background Radiation
SDSS-IV Data Here
0
2
4
6
8
10
12
Present
Time Since the Big Bang (Billions of Years)

Clustering of SDSS red galaxies

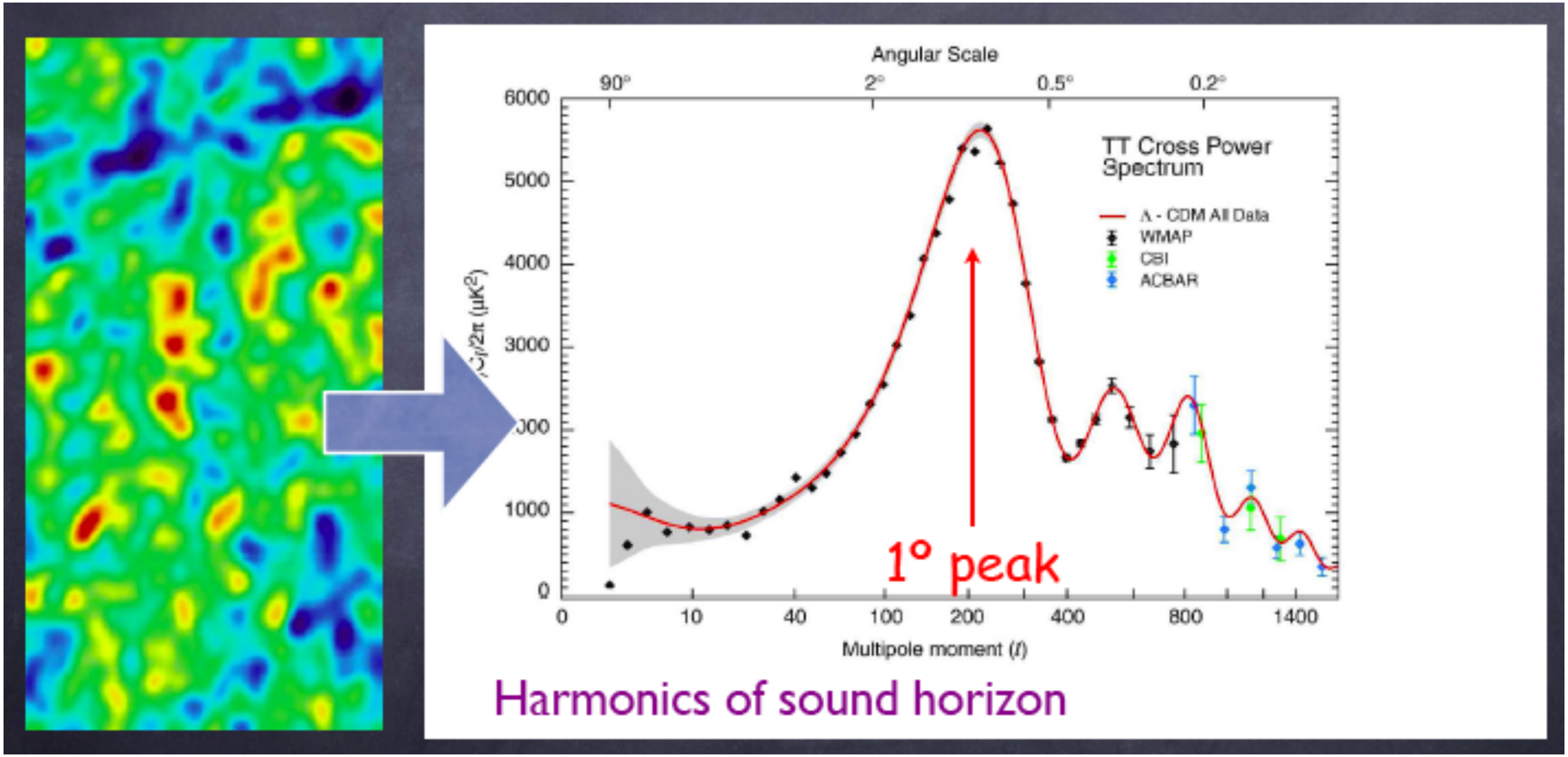
SDSS (and 2dF) discovered a coherent pattern in the distribution of galaxies on very large scales (120 Mpc)





Eisenstein et al (2005) Ap J 633, 560; also Cole et al (2005) MNRAS 362, 505

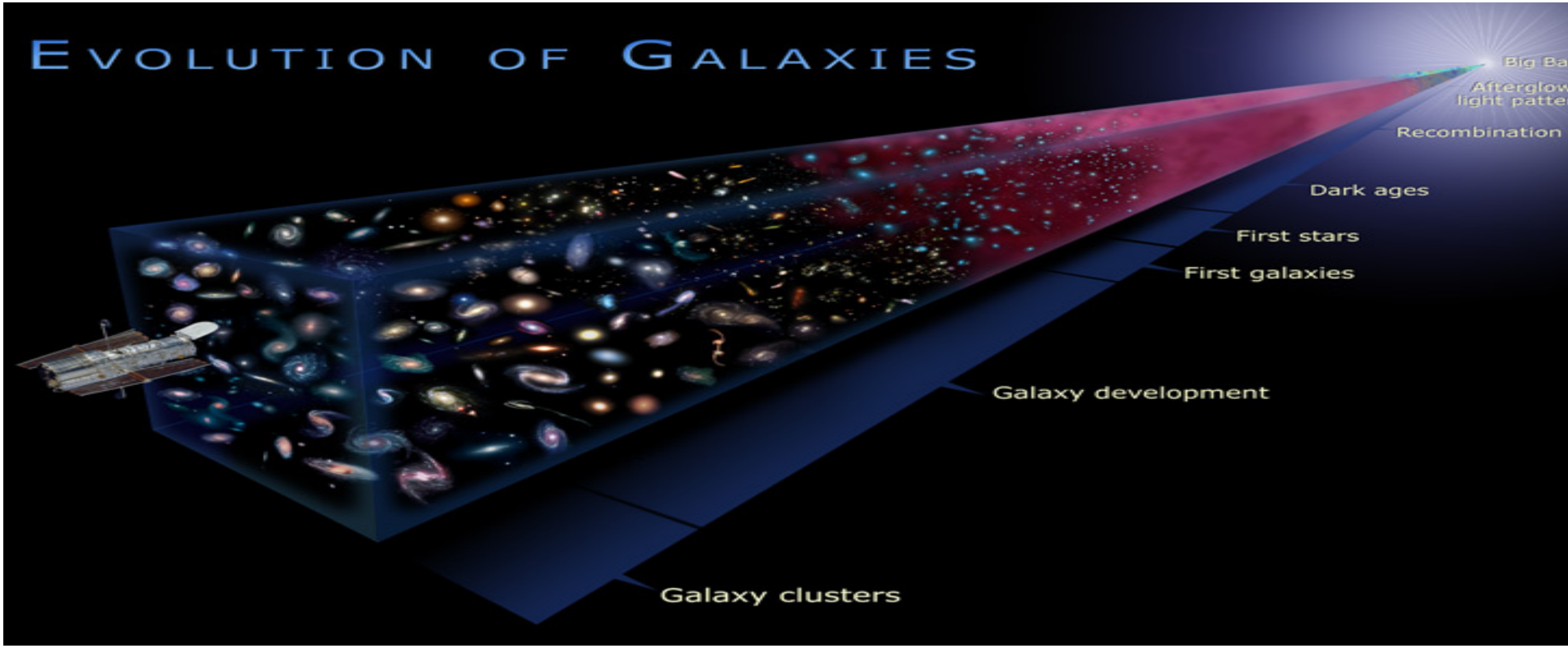
Origin of the Baryonic Acoustic Scale



Relic of primary acoustic peak seen in cosmic microwave background radiation which has freely expanded with Universe since it was 300,000 yrs old. Its measurement at various look-back times offers a way to directly trace the history of the expansion

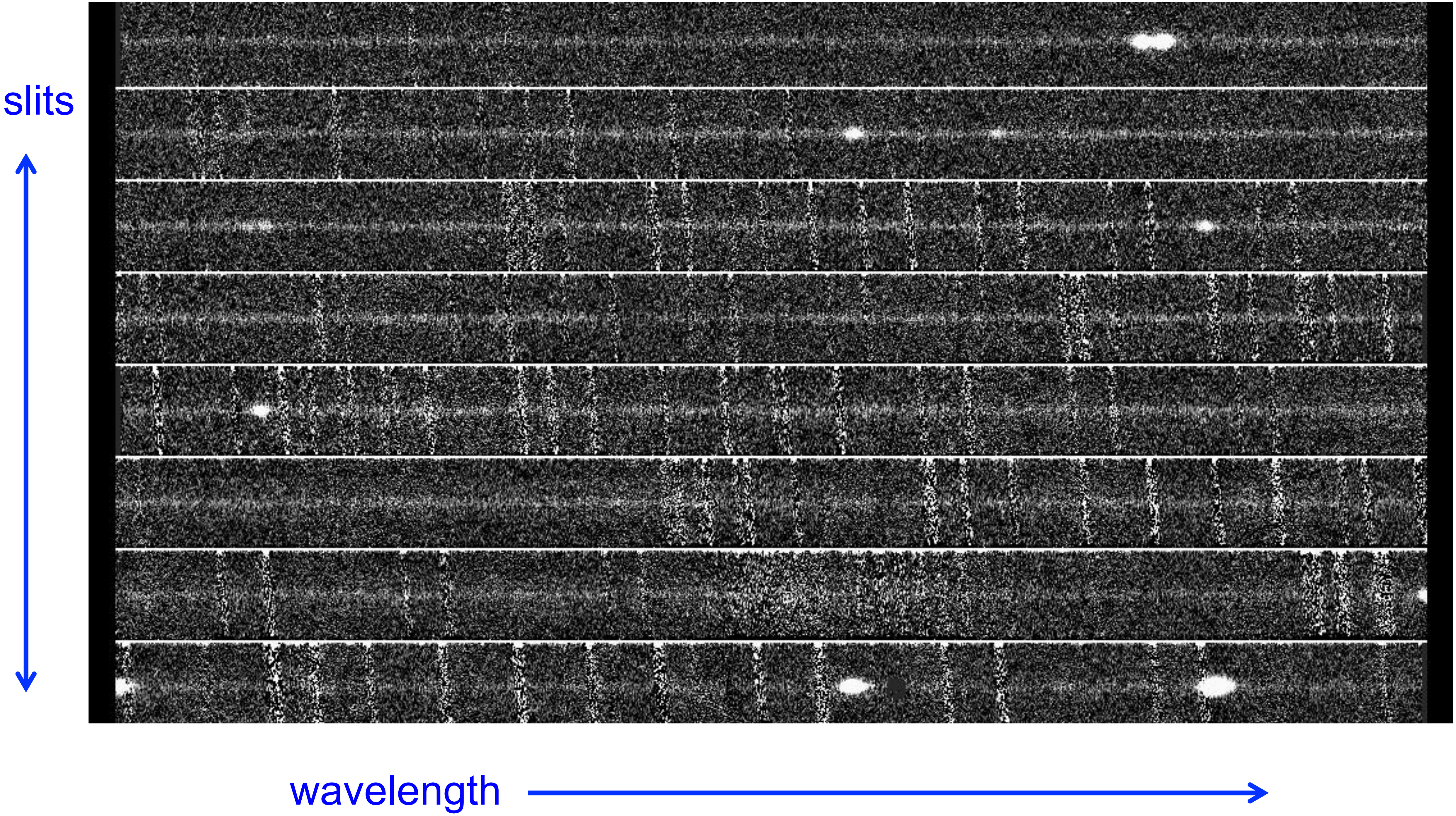
Predicted theoretically by Peebles & Yu 1970; Sunyaev & Zel'dovich 1970

Multi-Slit Technologies: Looking Back in Time



Galaxy redshift surveys have also been influential in charting the ***evolving properties of galaxies over cosmic time*** – determining the mass assembly history, origin of the Hubble sequence of morphological types and searching for the earlier systems

Advantages of Multi-slit Spectroscopy

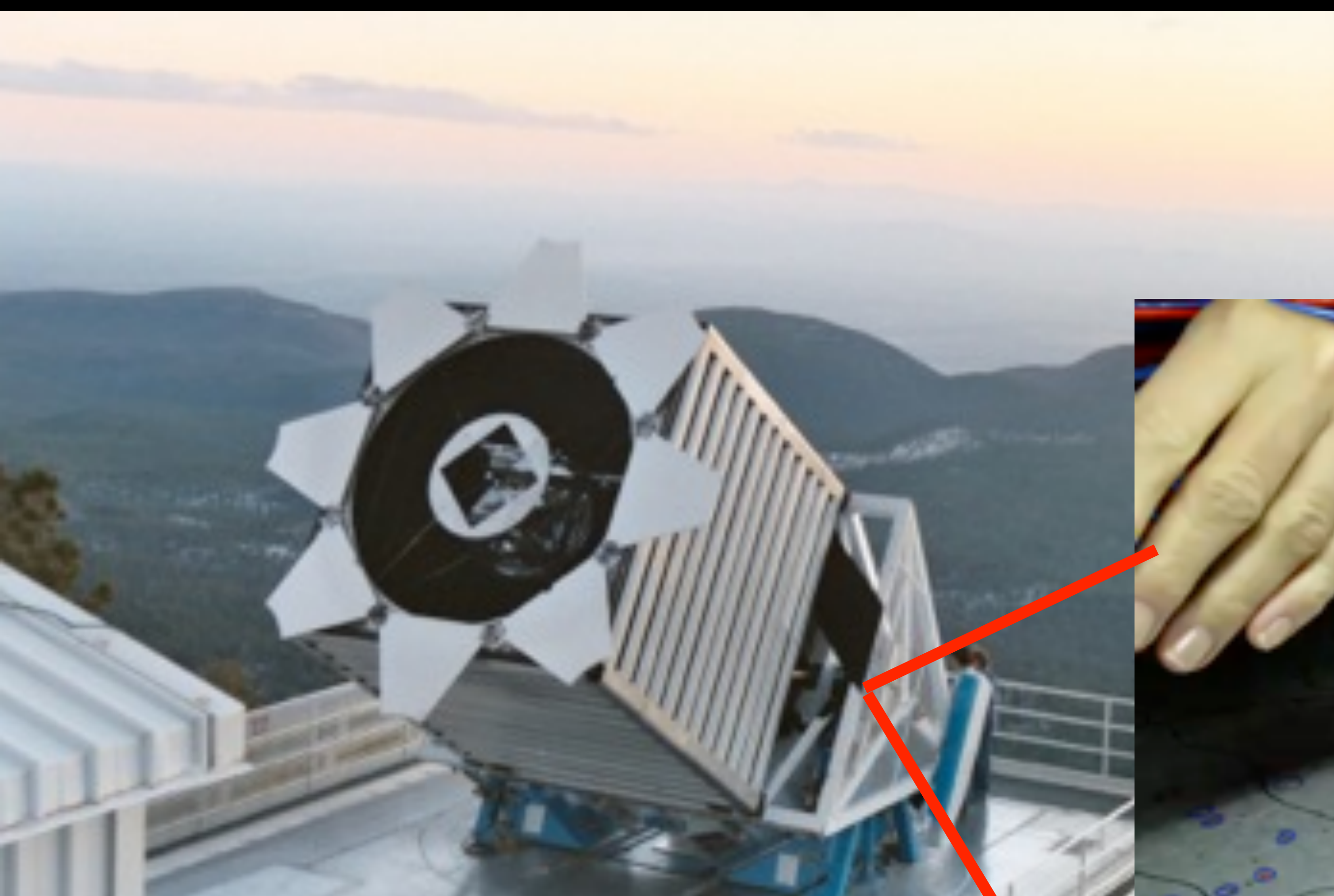


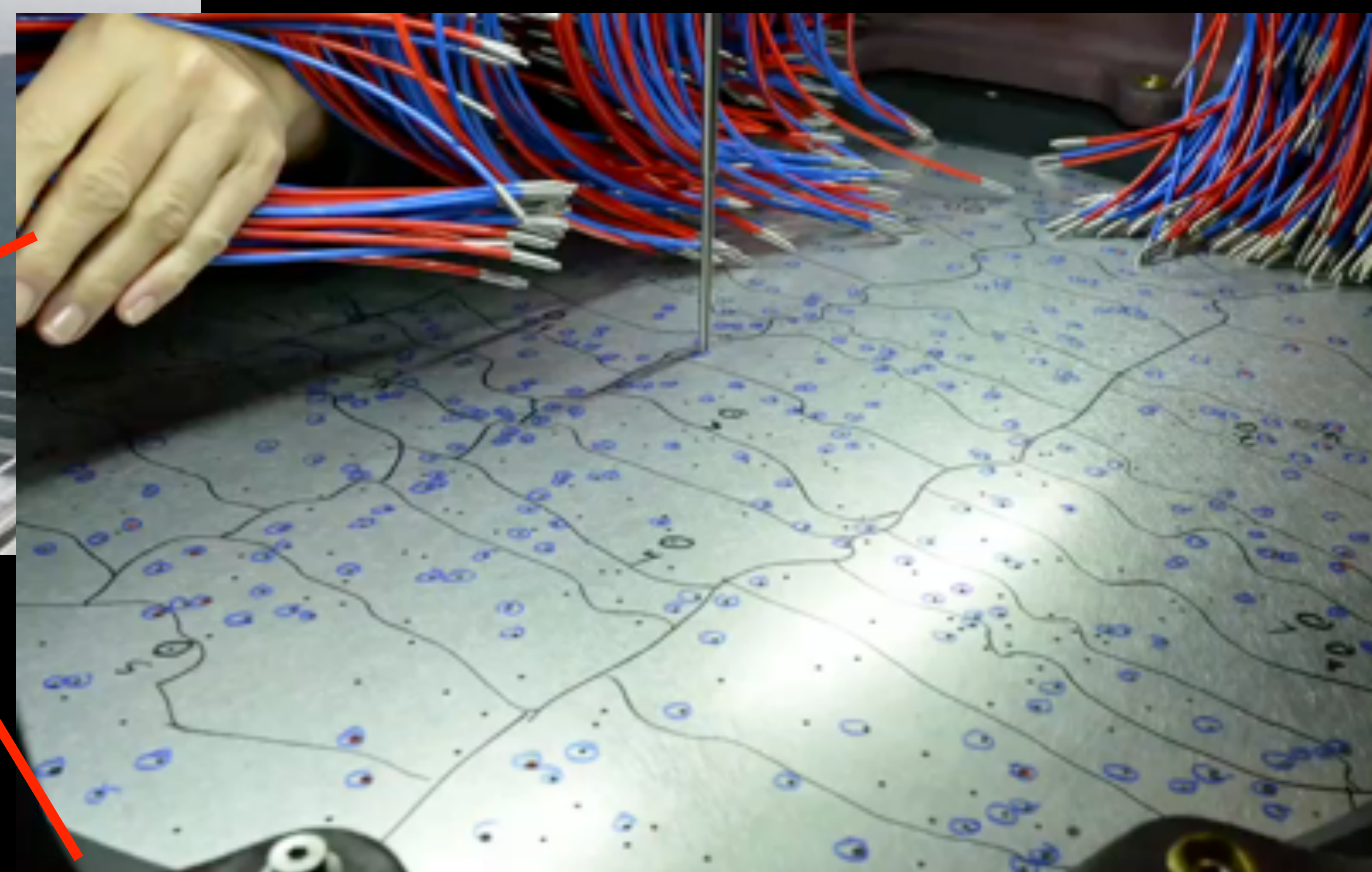
With a 2-D detector each `mini-slit’ produces a spectrum of the galaxy and an adjacent portion of the night sky. The initial challenge was the limited field of view c.f. fiber-fed spectrographs

BOSS limitation using hand-plugged “plates”

Not possible to plug >2 million galaxies

1000 fibers

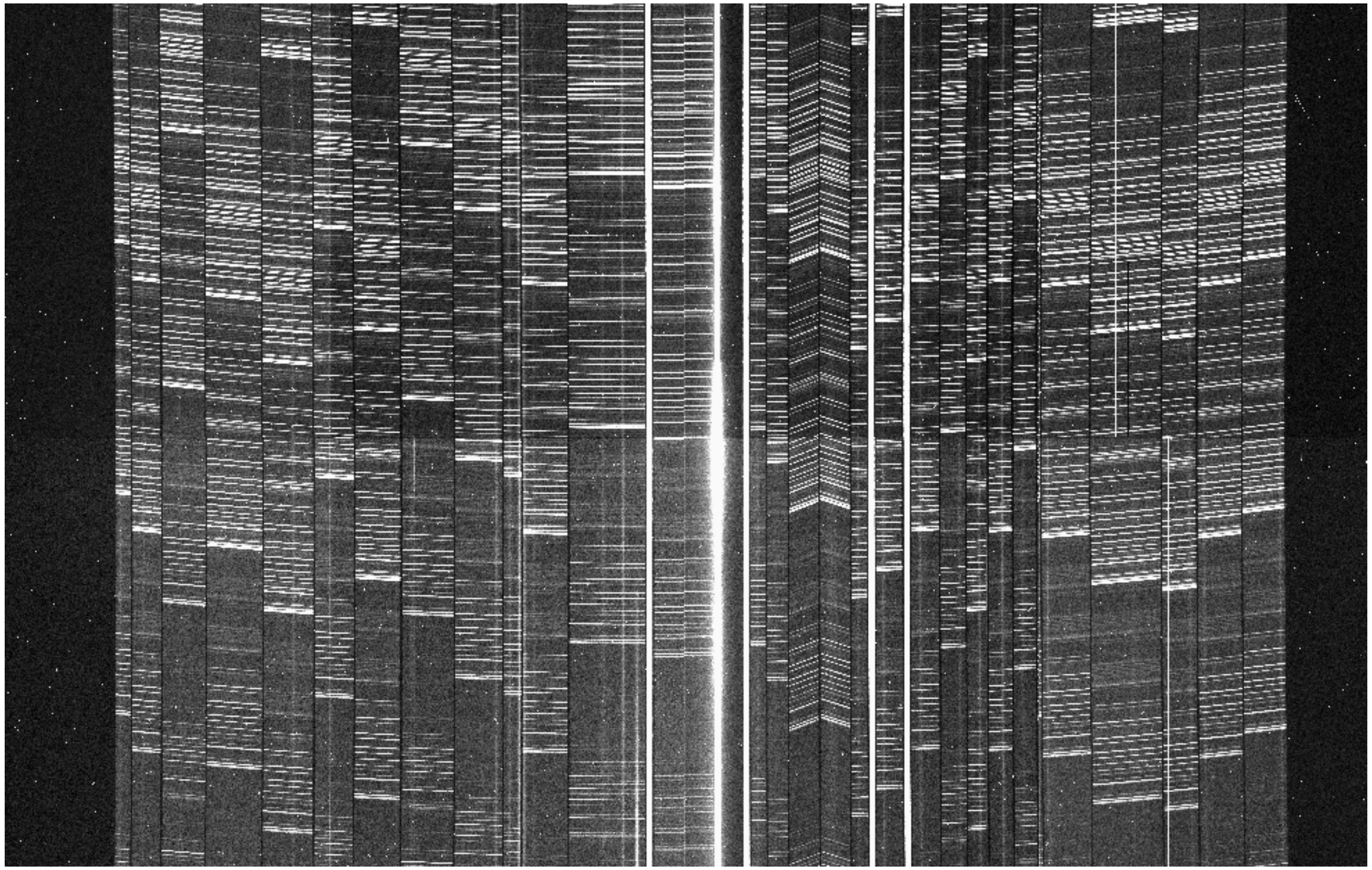


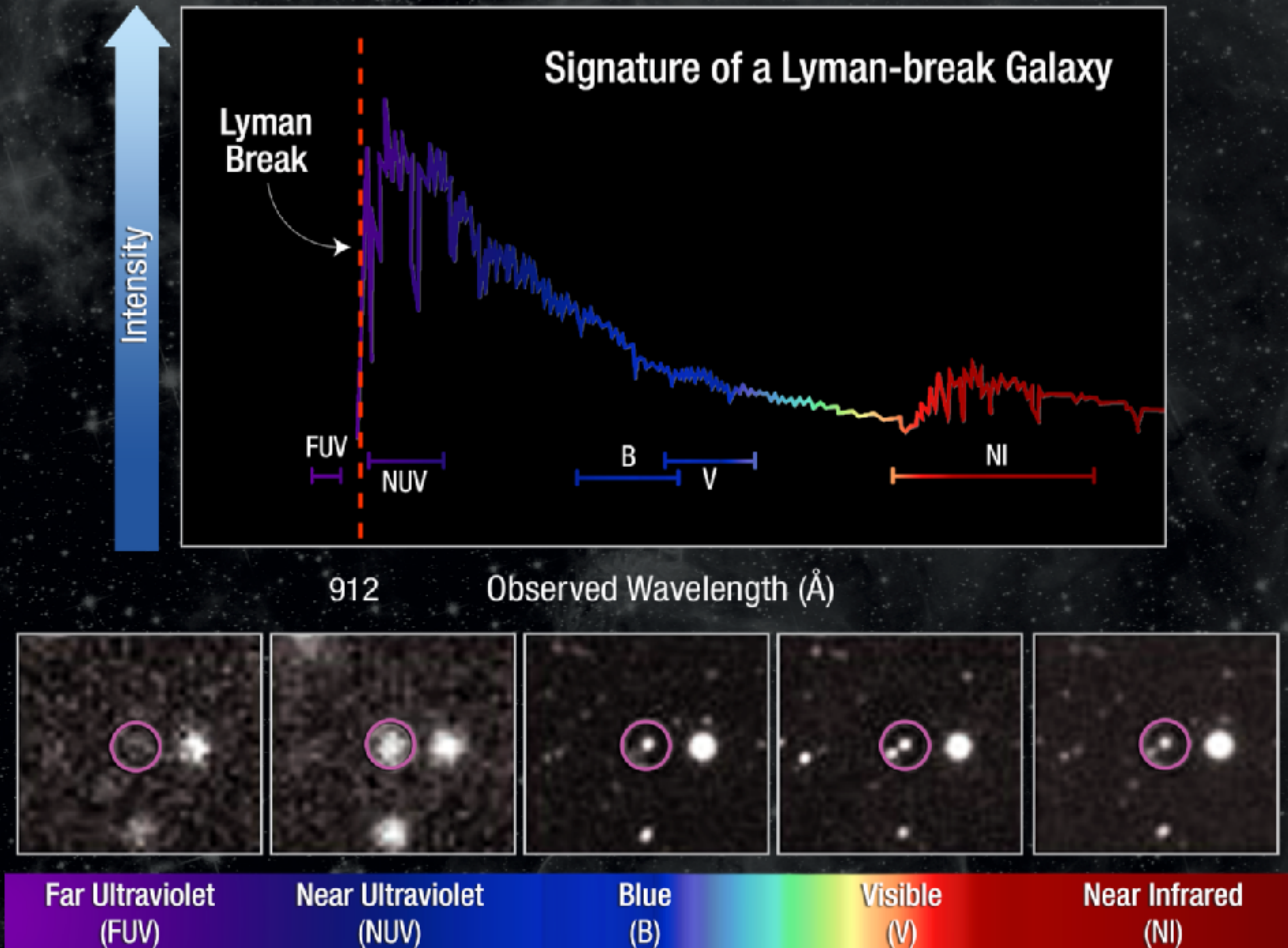


DEIMOS at Keck Observatory

Faber

DEIMOS provided a large field (15 × 5 arcmin) via a mosaic of CCD detectors on a 10 meter aperture enabling surveys of ~30,000 faint galaxies to m~24 and a detailed understanding of galaxy evolution since z~1.5 (9 Gyr ago)




Signature of a Lyman-break Galaxy
Lyman Break
Intensity
FUV
NUV
B
V
NI
912
Observed Wavelength (Å)
Far Ultraviolet (FUV)
Near Ultraviolet (NUV)
Blue (B)
Visible (V)
Near Infrared (NI)

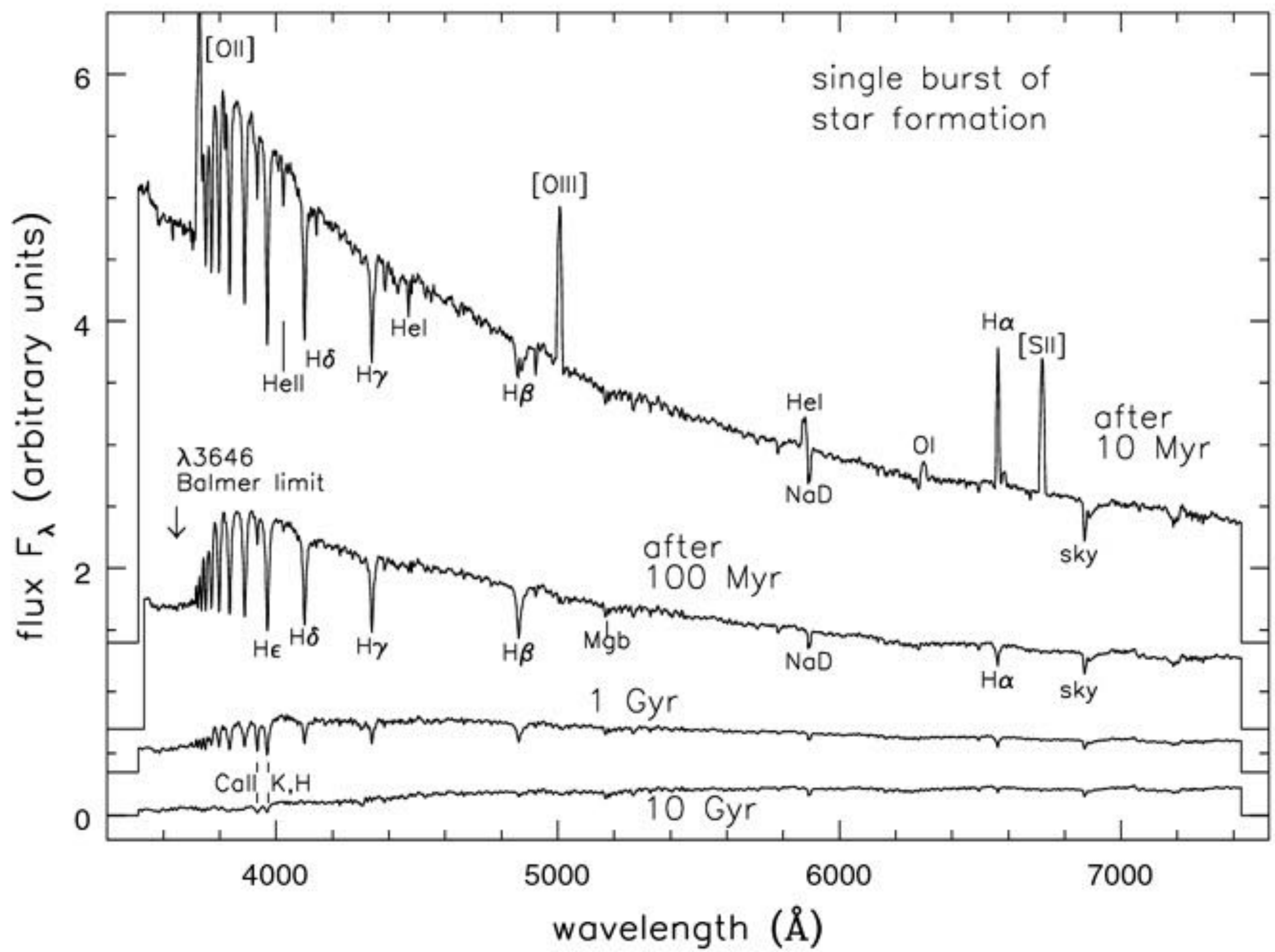
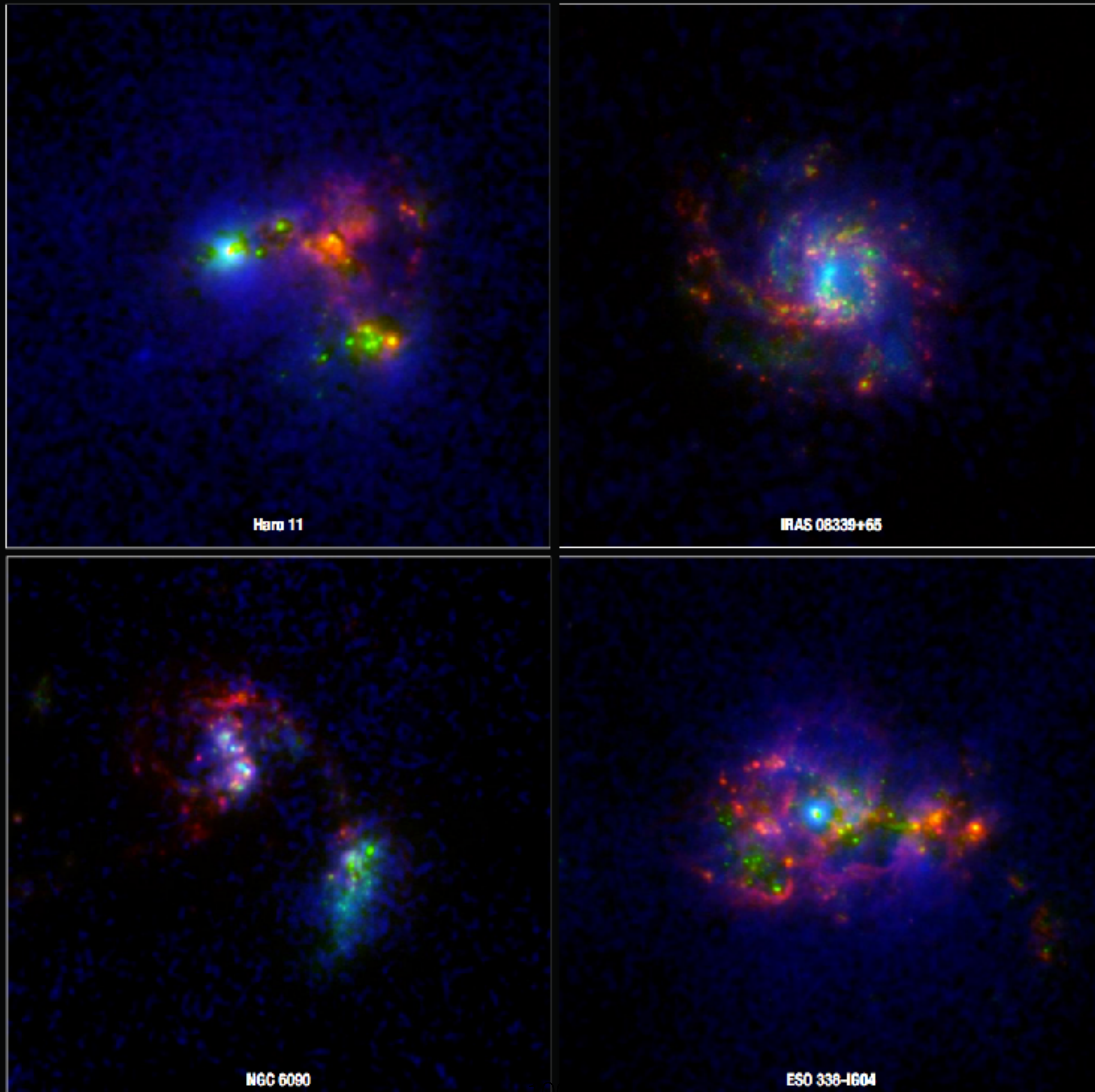
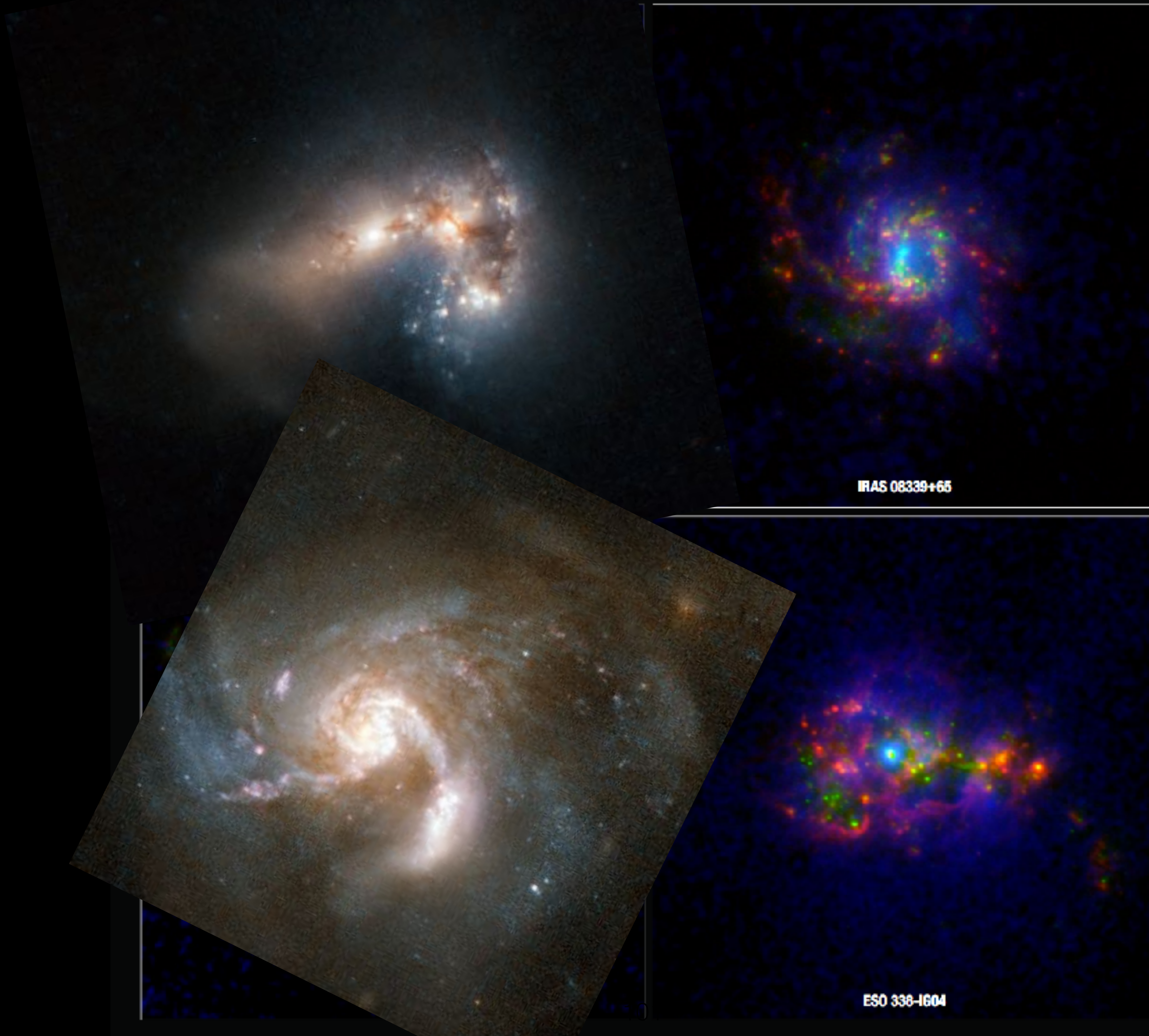


Fig 6.18 (B. Poggianti) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

R = H-α
G = UV
B = Ly-α



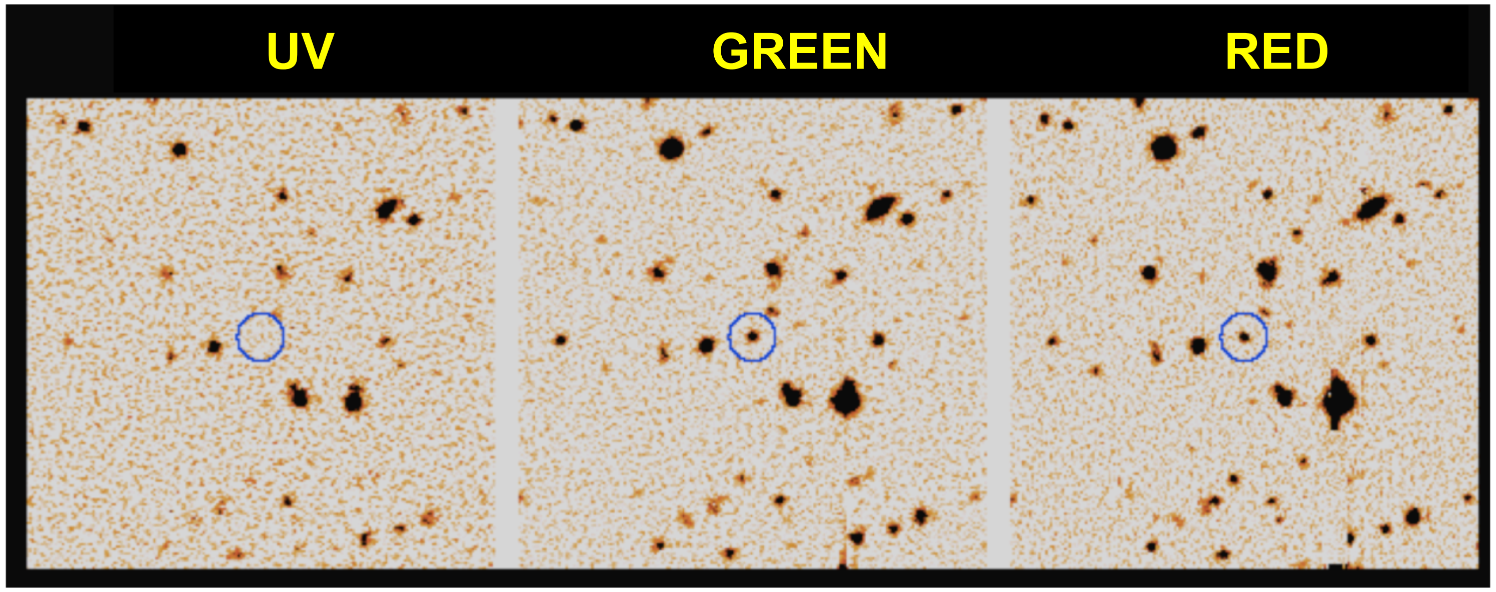
HUBBLE 2012: SCIENCE YEAR IN REVIEW


IRAS 08339+65
ESO 338-IG04

Lyman Alpha Emitters

- Partridge & Peebles 1967 predicted Ly-α could account for ~5% of total luminosity of galaxies.
- A hunt started to detect these high redshift “primeval” galaxies for two decades.
- Finally detected in narrow-band imaging by Cowie & Hu 1998 using Hubble Deep Field to select sources and Keck/LRIS as a narrow band imager. z=3.4
- Perfected to cosmology by Steidel et al 1999
- Now done all the time at high redshift with HST and more and more with JWST …

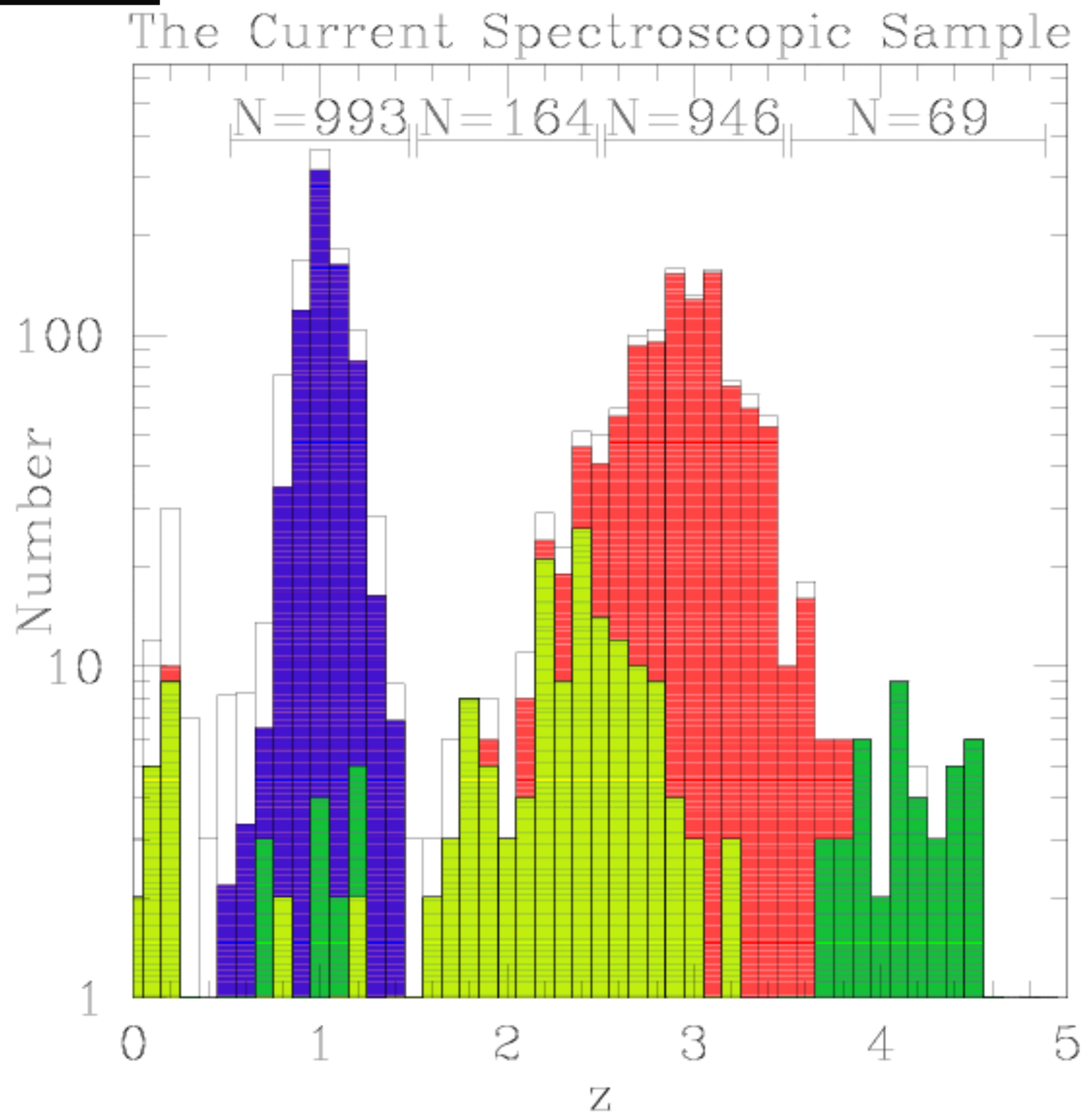
Star-forming galaxies at higher z



Steidel

Via a novel 2 color-selection technique, Steidel et al located the first convincing population of star-forming galaxies at redshift 3 (when the Universe was only 2 Gyr old – 15% of its present age).

Over 1996-2003 they secured ~1000 redshifts at z~3



Steidel et al 1999 Ap J 462, L17
Steidel et al 1999 Ap J 519, 1
Steidel et al 2003 Ap J 592 728

1. Luminous Red Galaxies (LRGs)

These are the most massive galaxy halos
LRGs have been the workhorse of BAO surveys (SDSS, BOSS)
All LRG spectra look nearly identical to z~1

Entire spectrum used for redshift,
dominant features are “4000 Angstrom break” and “Ca H+K lines” to z=1.2

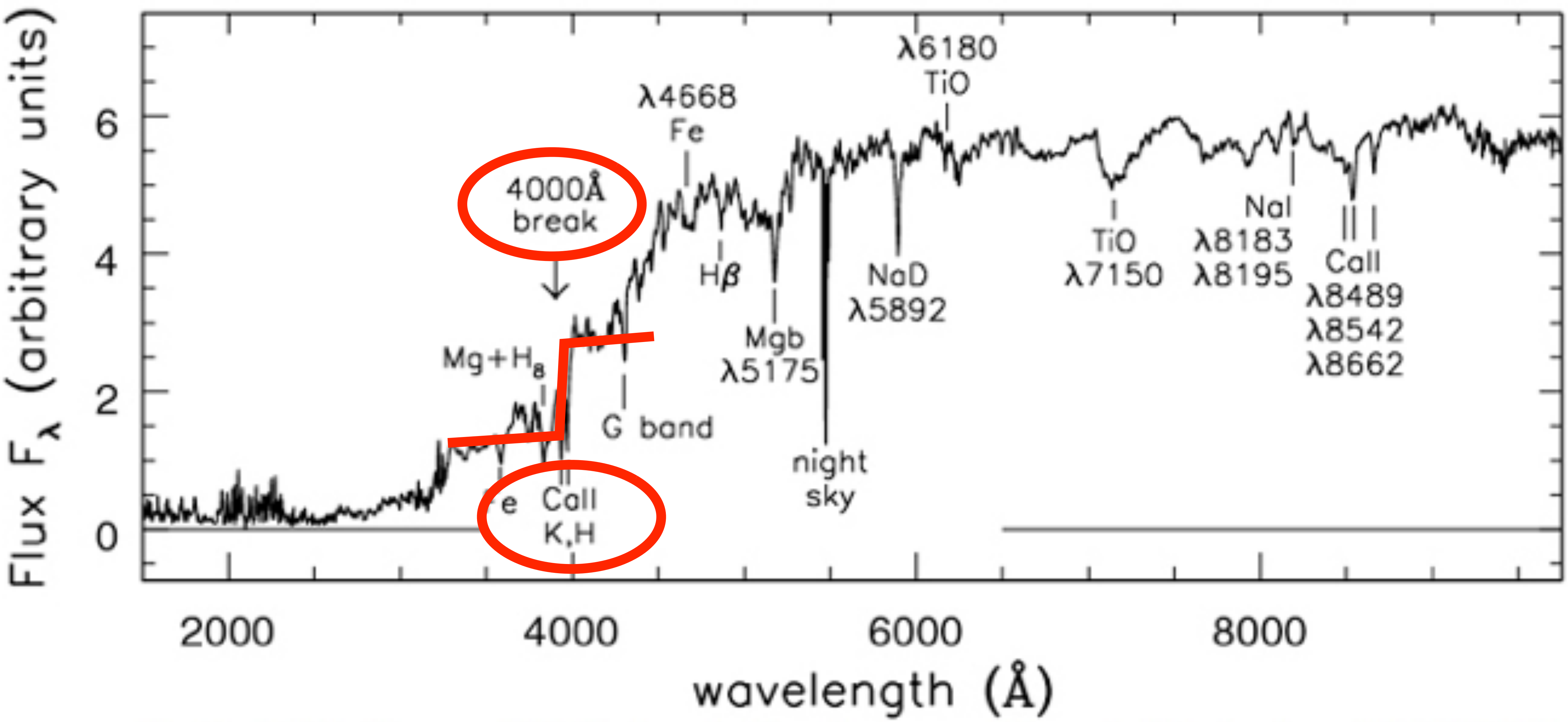


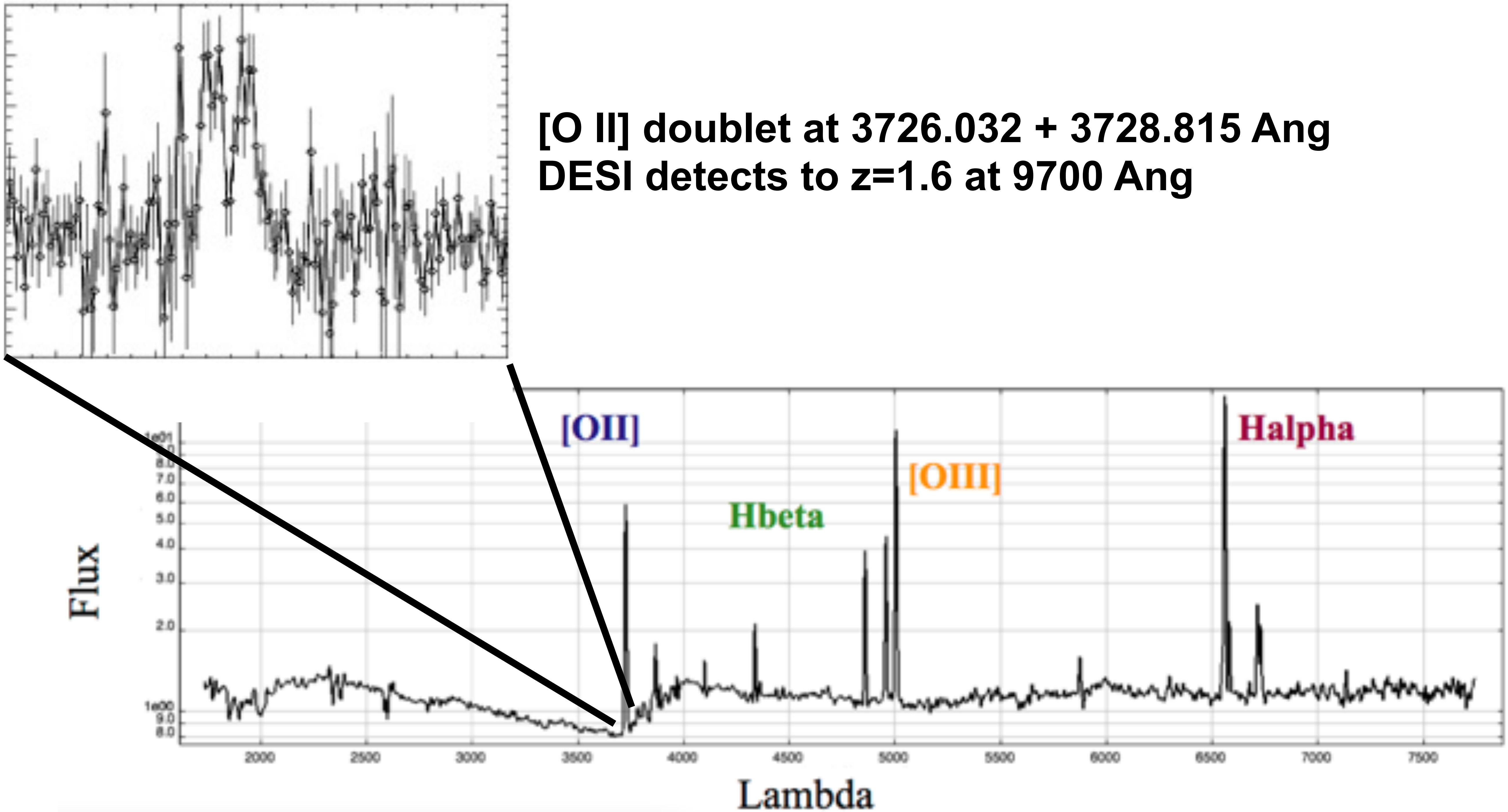
Fig 6.17 (A. Kinney) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

2. Emission Line Galaxies (ELGs)

At z~1, galaxies were forming many more stars, easy to see

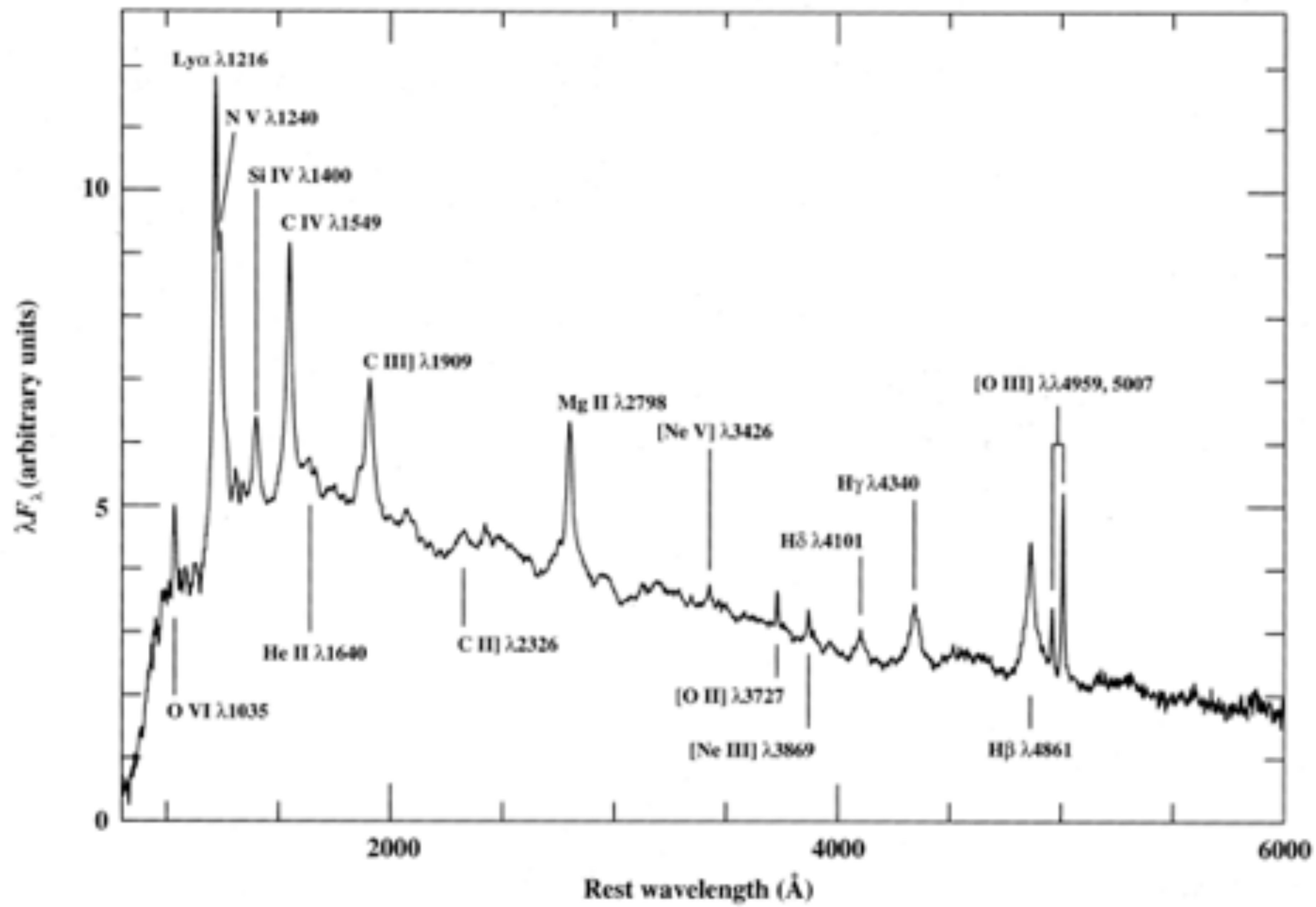
ELGs unique signature of [O II] doublet, detectable from z=0 to z=1.7

[O II] doublet at 3726.032 + 3728.815 Ang
DESI detects to z=1.6 at 9700 Ang



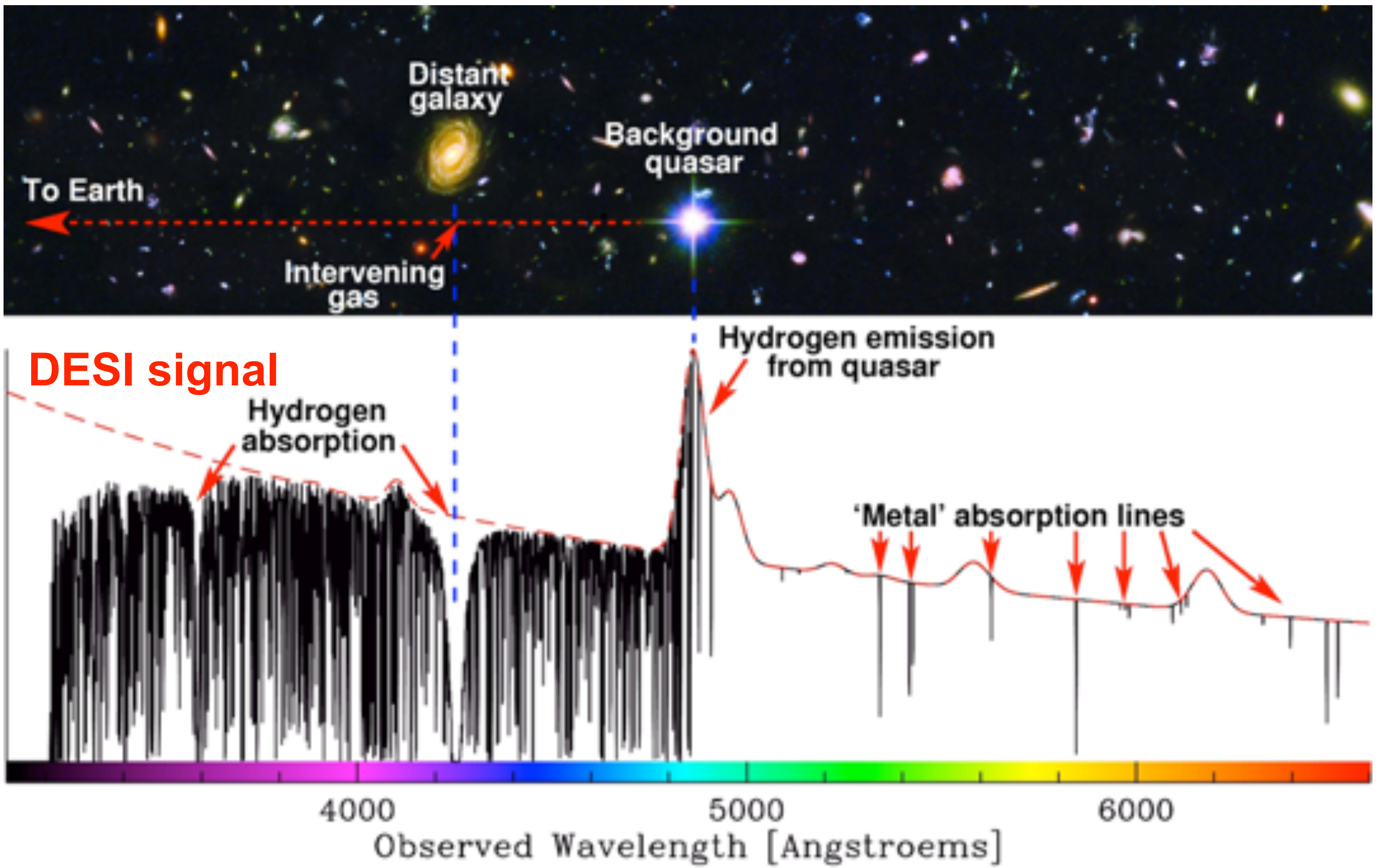
3. QSOs as tracers

QSO spectra are obvious even at very faint S/N
BOSS survey easily identifies to g=22, DESI extends to r=23



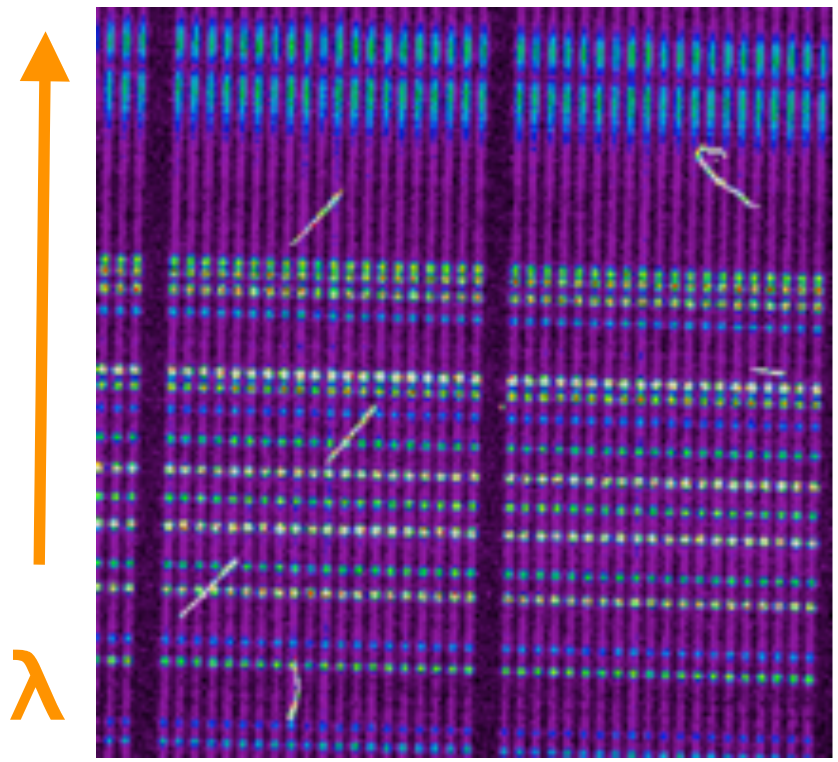
4. Lyman-alpha forest from QSOs

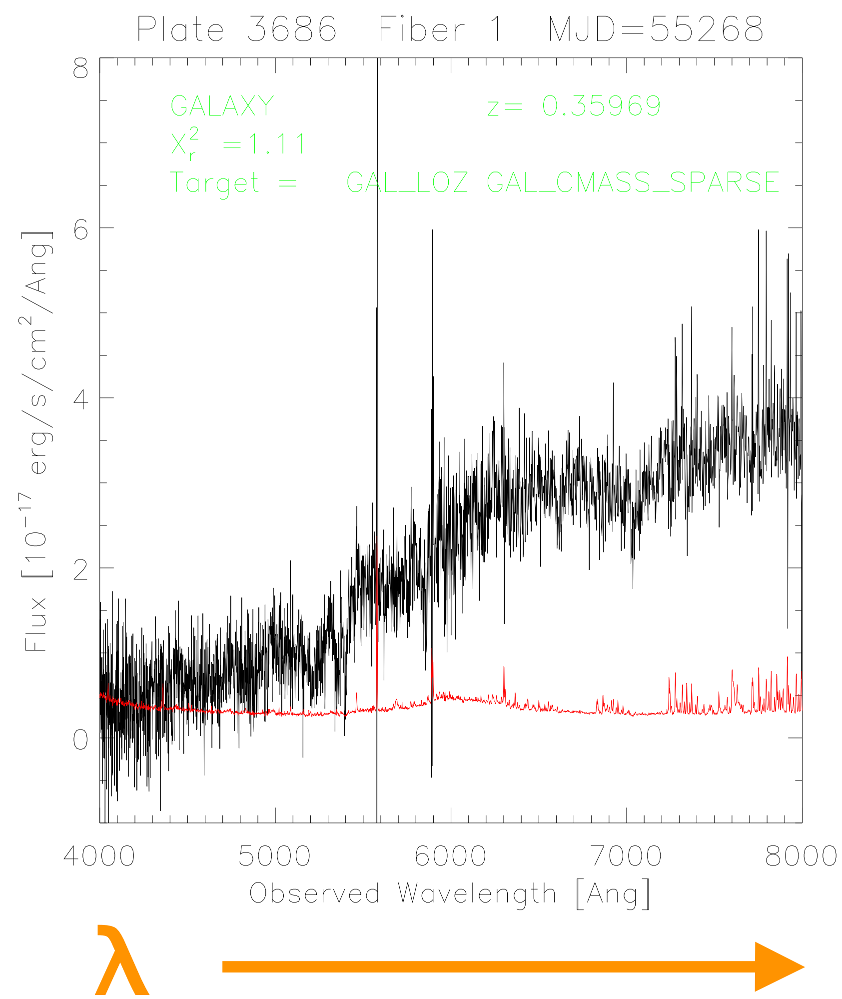
QSOs at z < 2.2 will be observed once → "tracer QSOs"
QSOs at z > 2.2 will be observed 5X for high S/N for "Lyman-alpha forest"

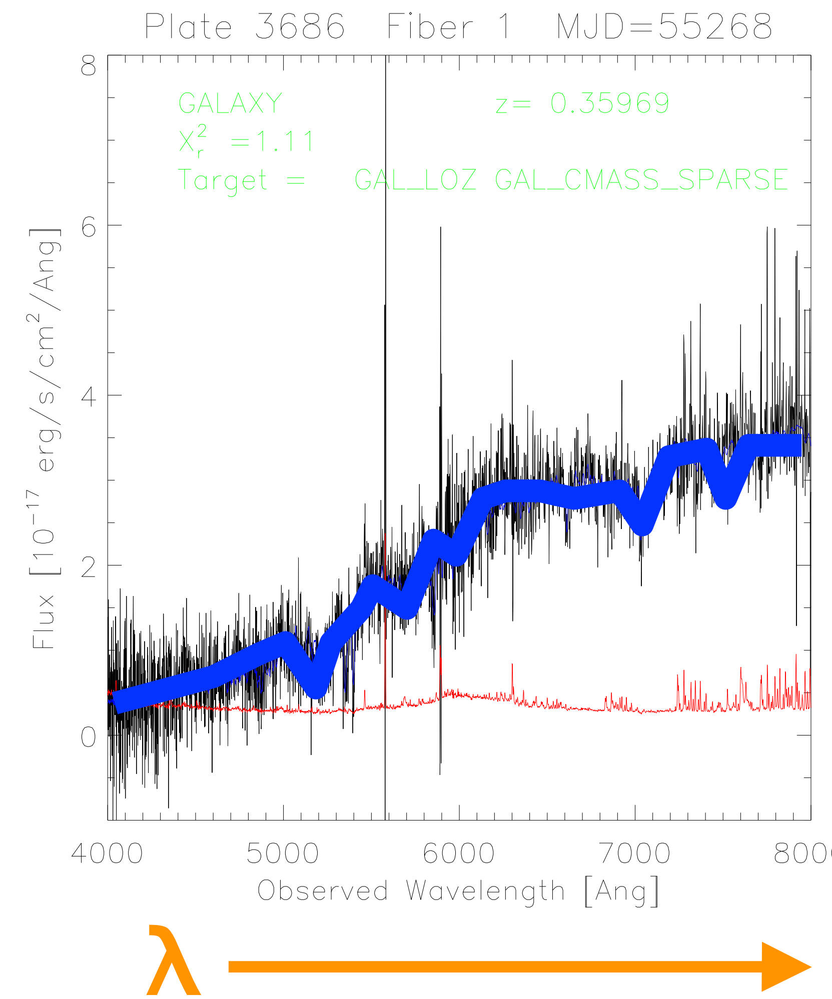


Spectrum → classification + redshift

Raw image → Spectrum + errors → Classify as galaxy z=0.3597

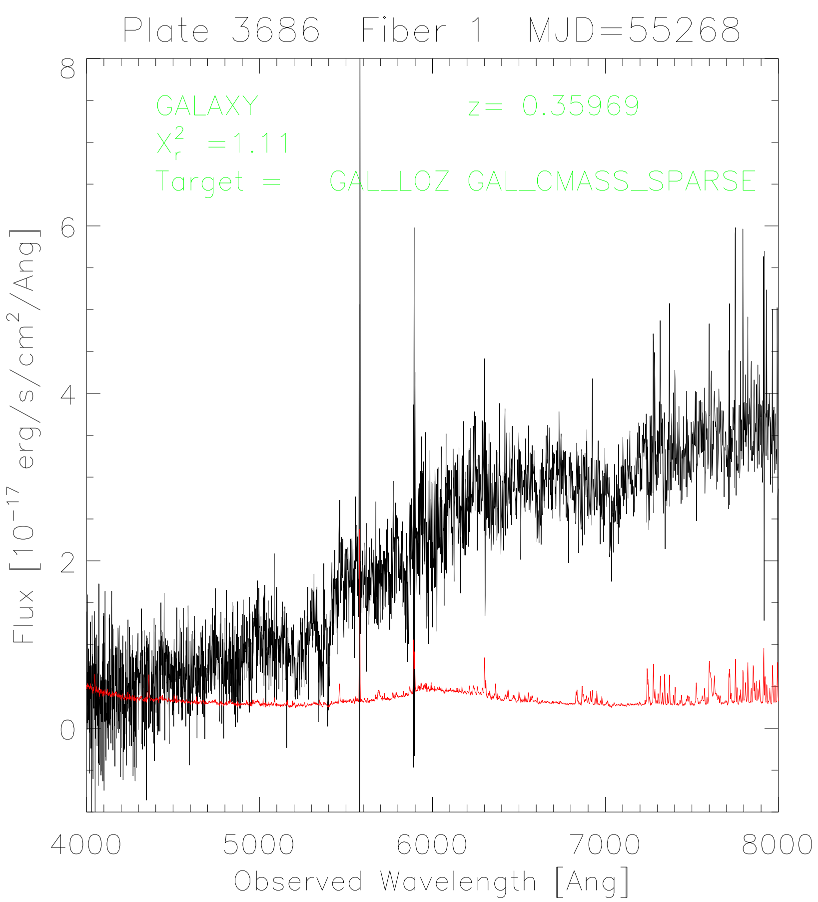




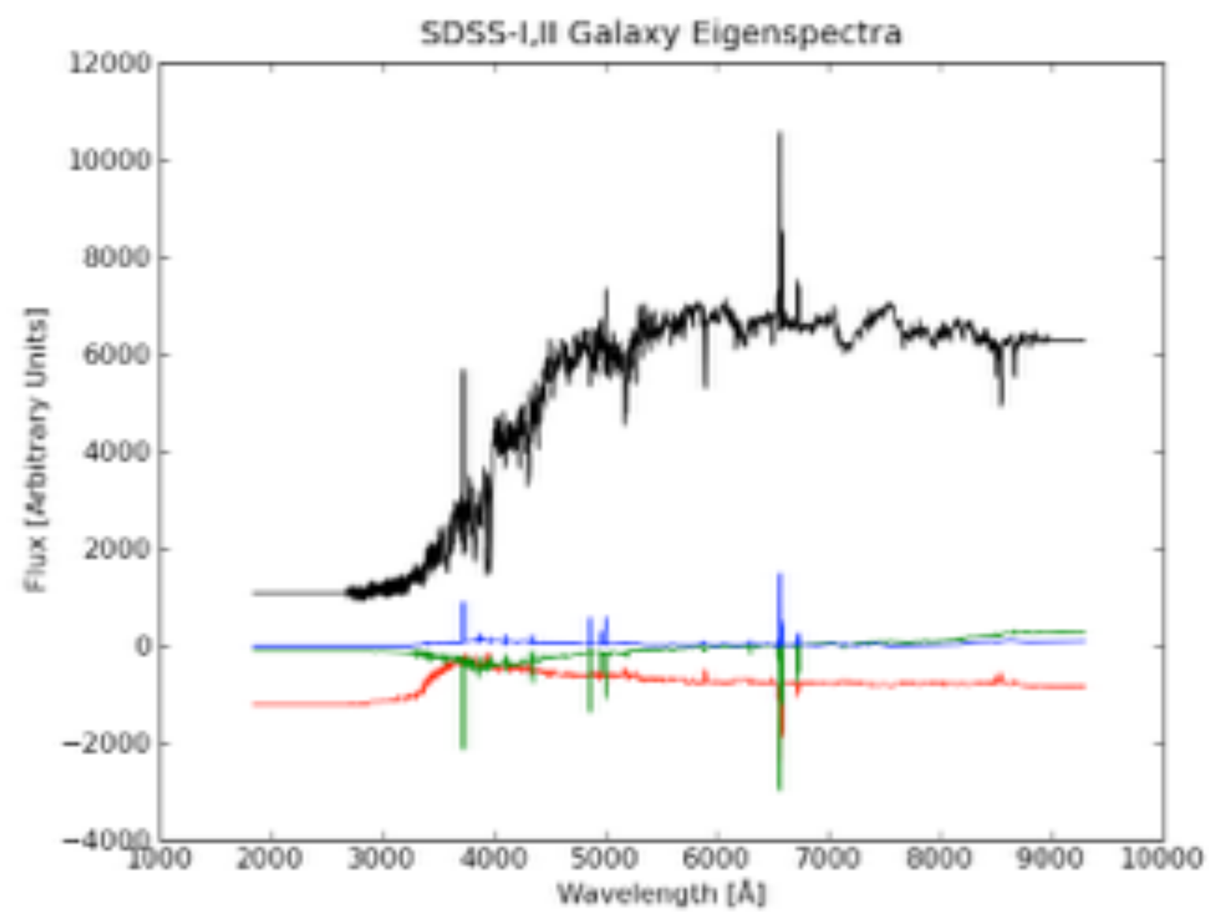


Spectrum → classification + redshift

Hypothesis testing
Given: Galaxy spectrum templates
Compute: X^2 of each template at each redshift



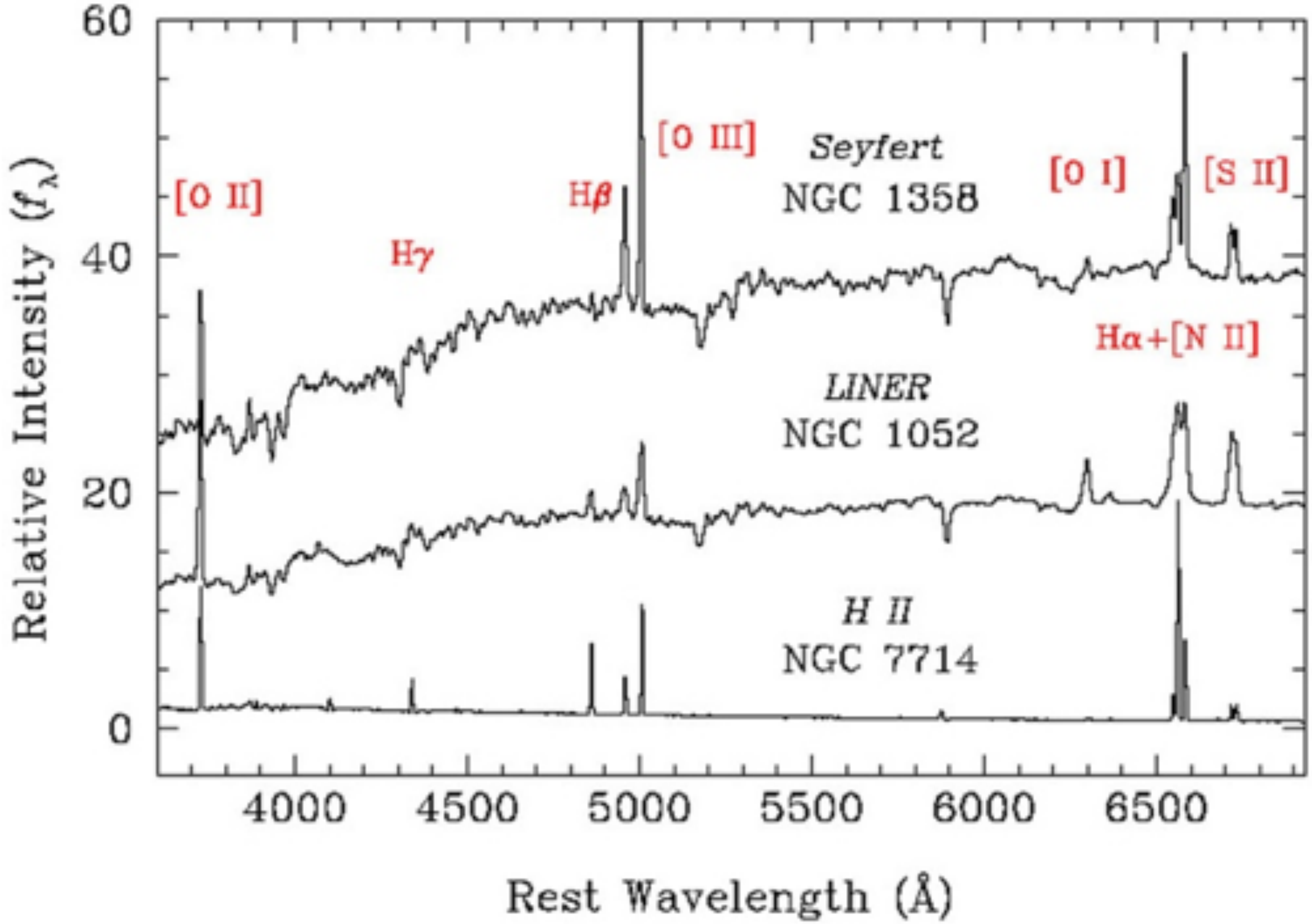
=



Compute-intensive: Search all possible z's for all templates (very little code)

Spectrum → classification + redshift

Galaxy spectra well-described by linear combinations of a small set of "eigenspectra"

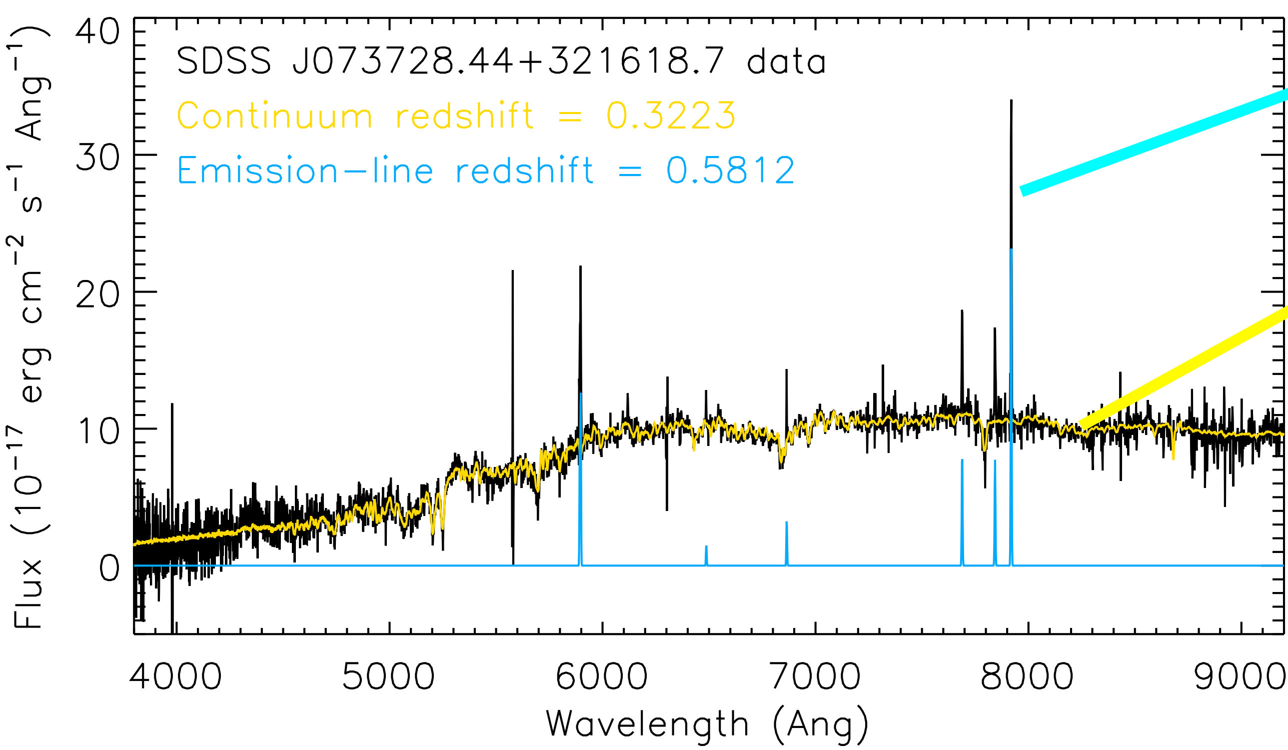


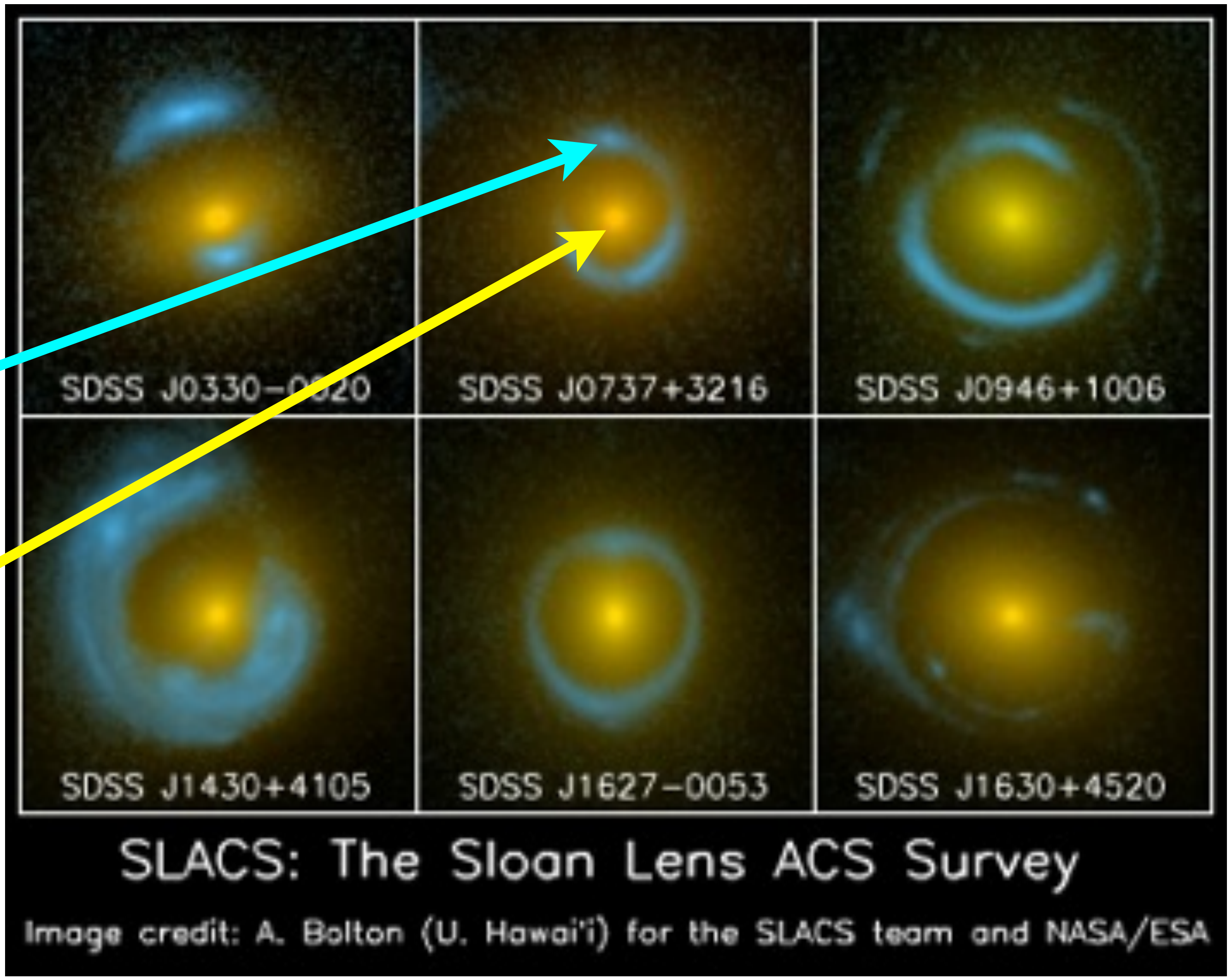
Spectrum → classification + redshift

An interesting example of where this did not work...

Strong lenses discovered ***spectroscopically***,from rogue emission lines
(Requires very good noise model at the pixel level)

10-σ outliers from single pixels





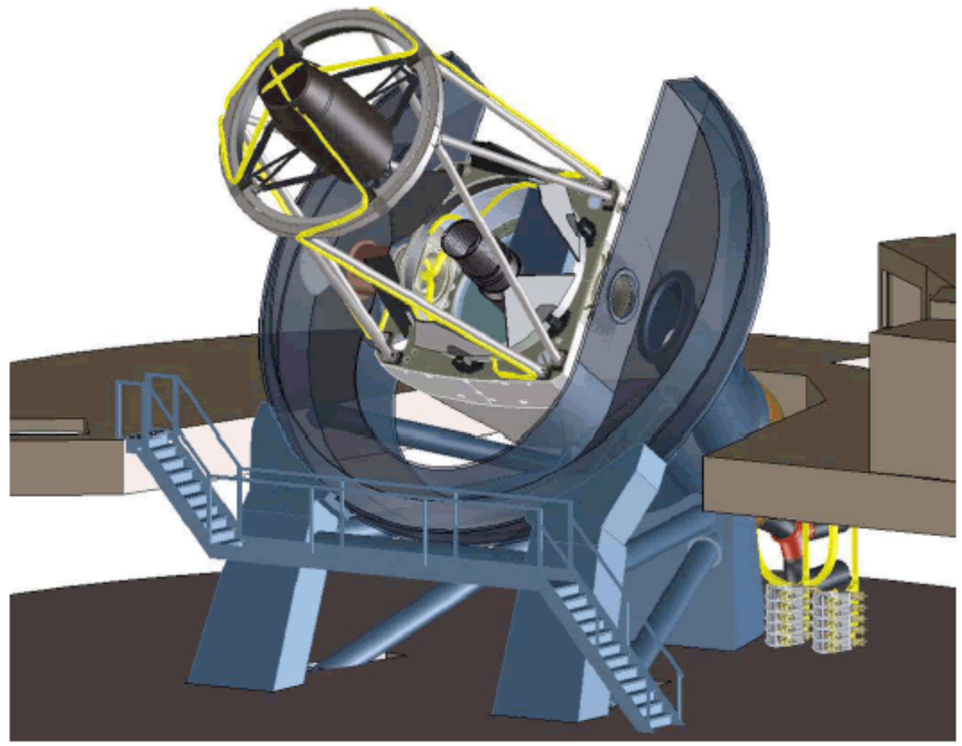
Next Generation Galaxy Surveys

4MOST

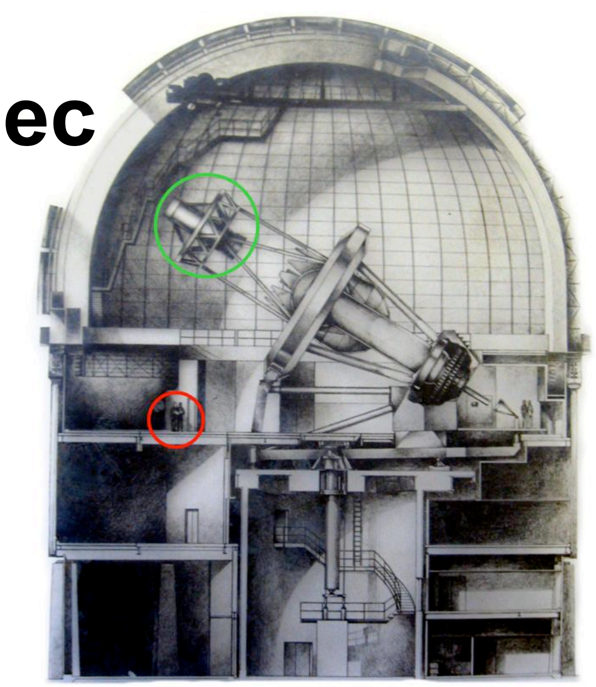
4-meter Multi Object Spectroscopic Telescope

Proposal for a Conceptual Design Study for ESO

BigBOSS



DESpec

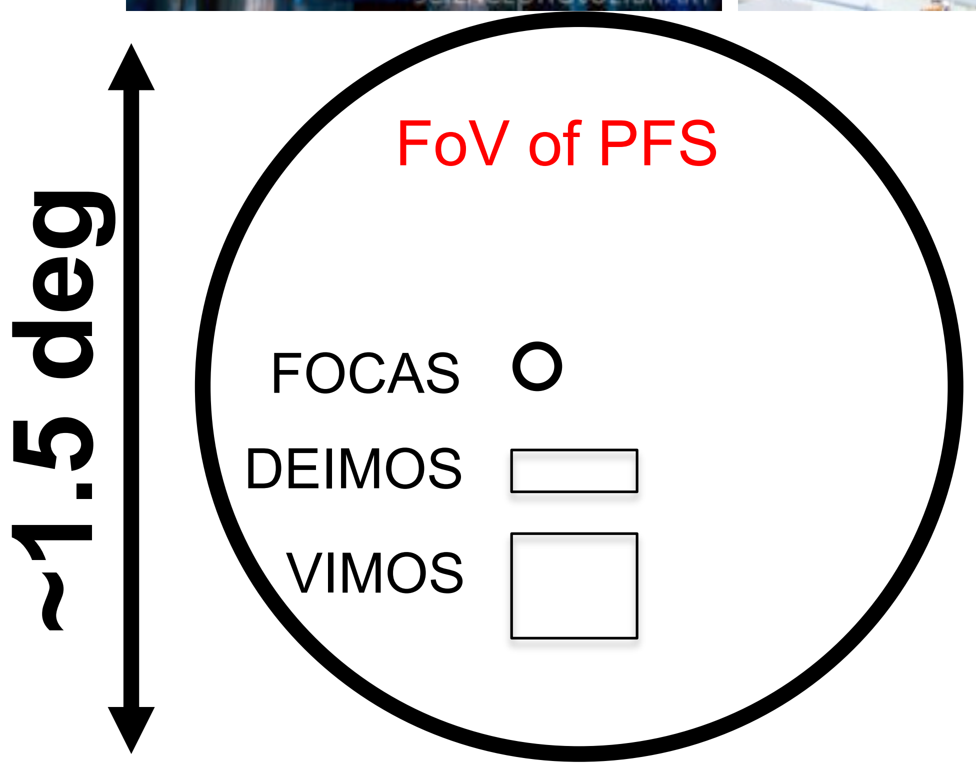


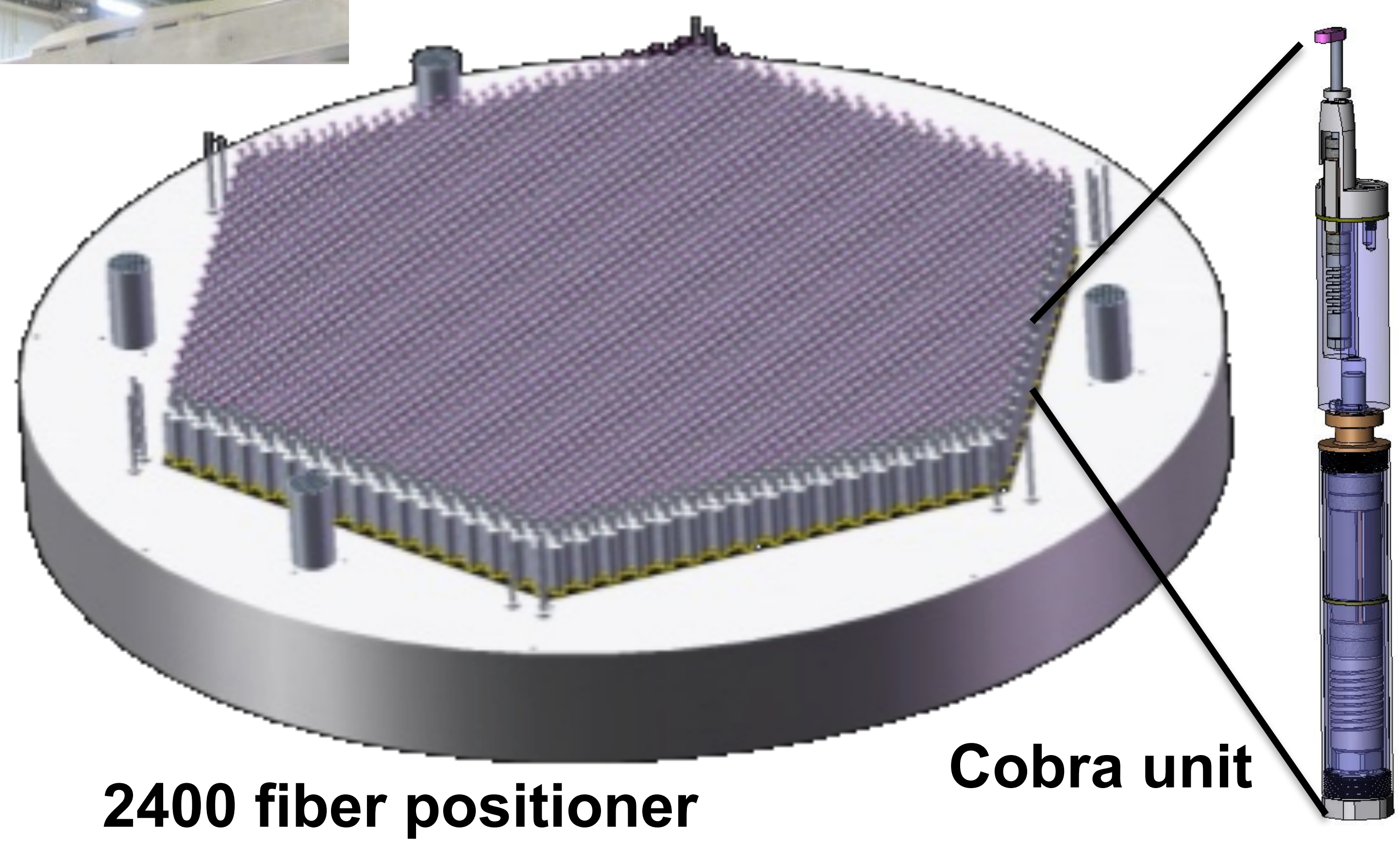
A new generation of massively-multiplexed spectroscopic surveys motivated by the need to measure the baryonic acoustic scale over the past 10 billion years.

A valuable probe of dark energy (in addition to other measures)

Subaru Prime Focus Spectrograph (PFS)

PFS is a collaboration between Caltech/JPL, Princeton, JHU and Japan) addressing the expansion history over the past 10 billion years through measures of the baryonic acoustic scale at various `look-back times'. A survey of 4 million galaxies to z~2.4 is proposed (2017-2022)

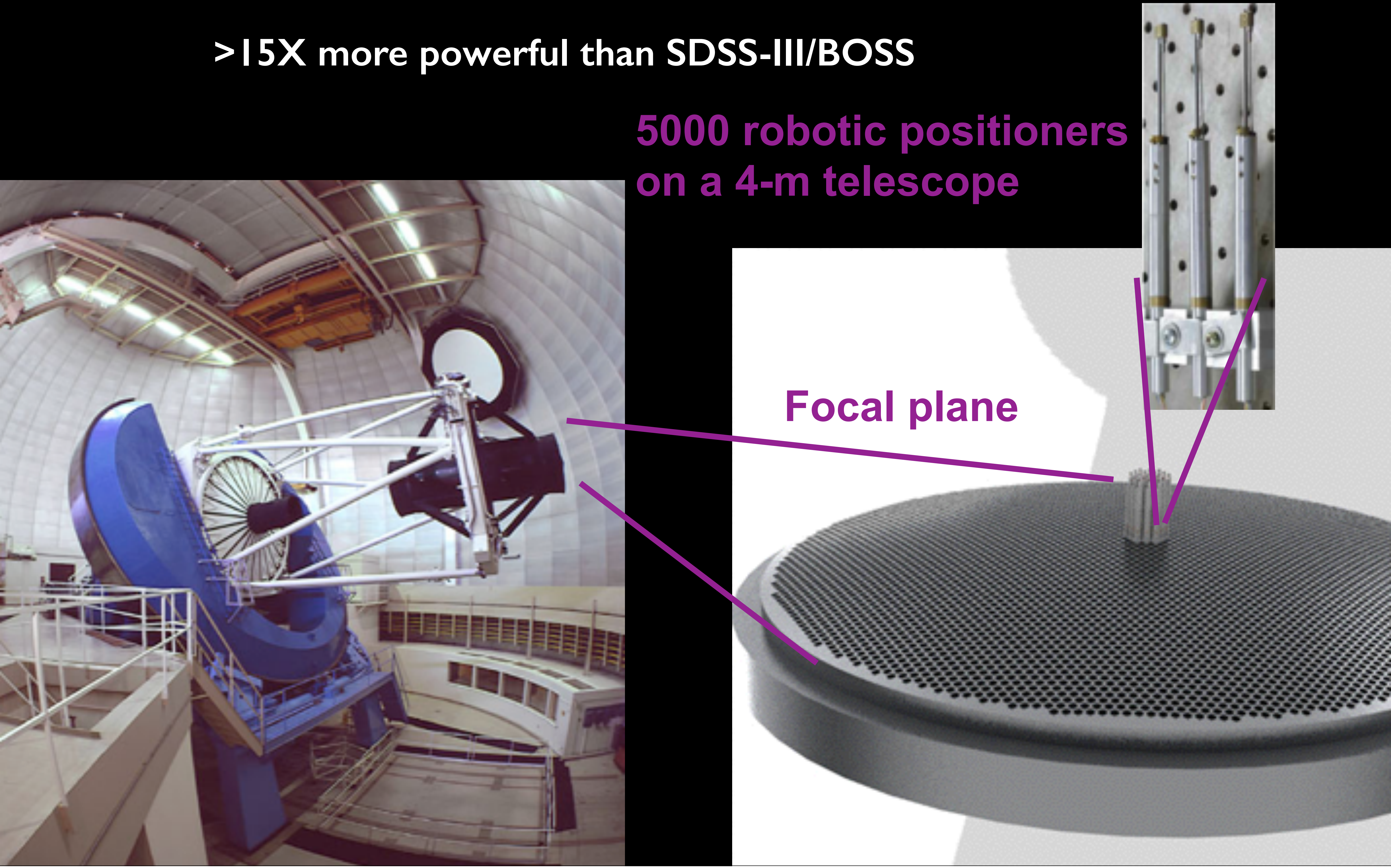




DESI is the next big step in mapping the Universe

>15X more powerful than SDSS-III/BOSS

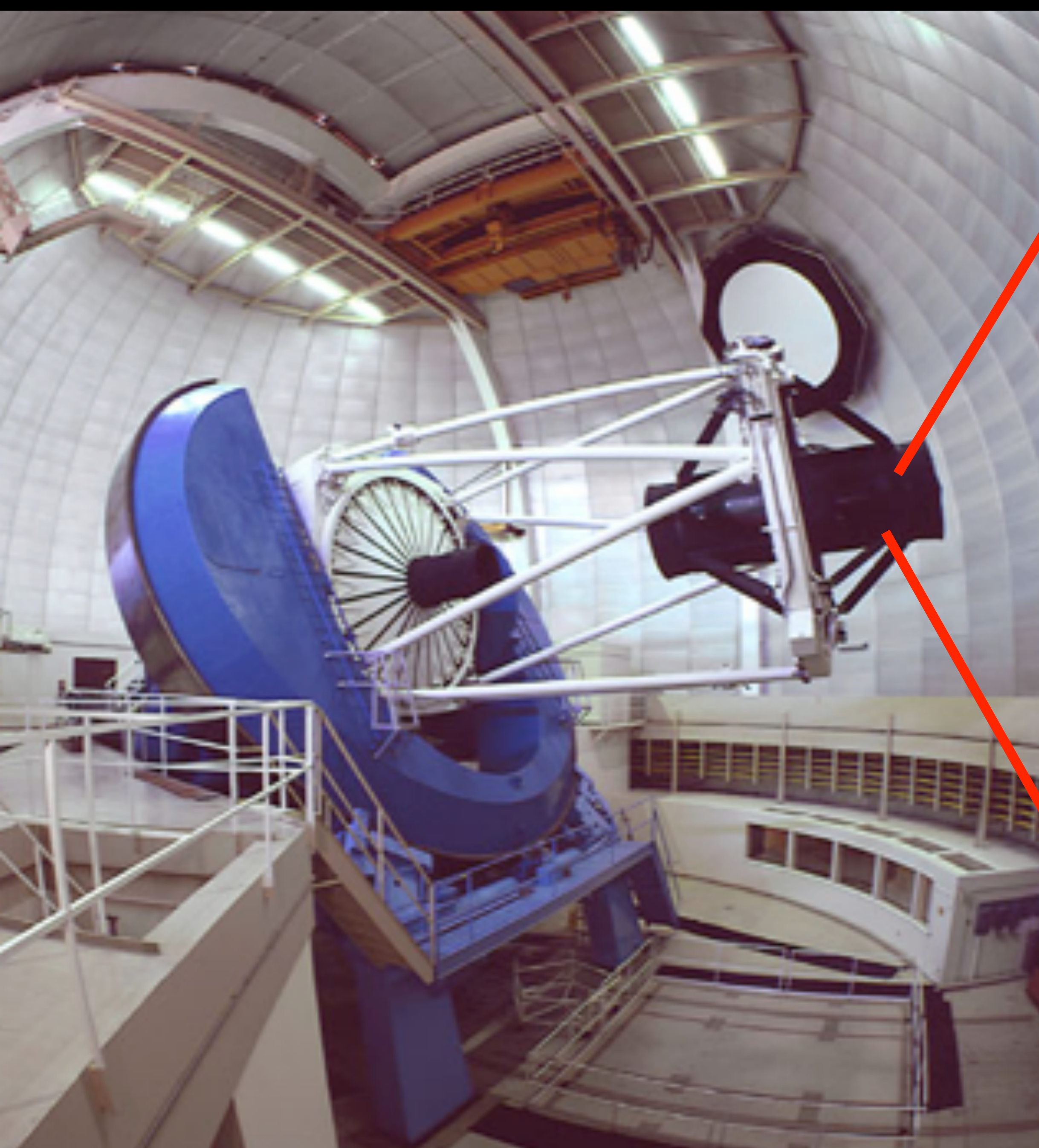
5000 robotic positioners on a 4-m telescope

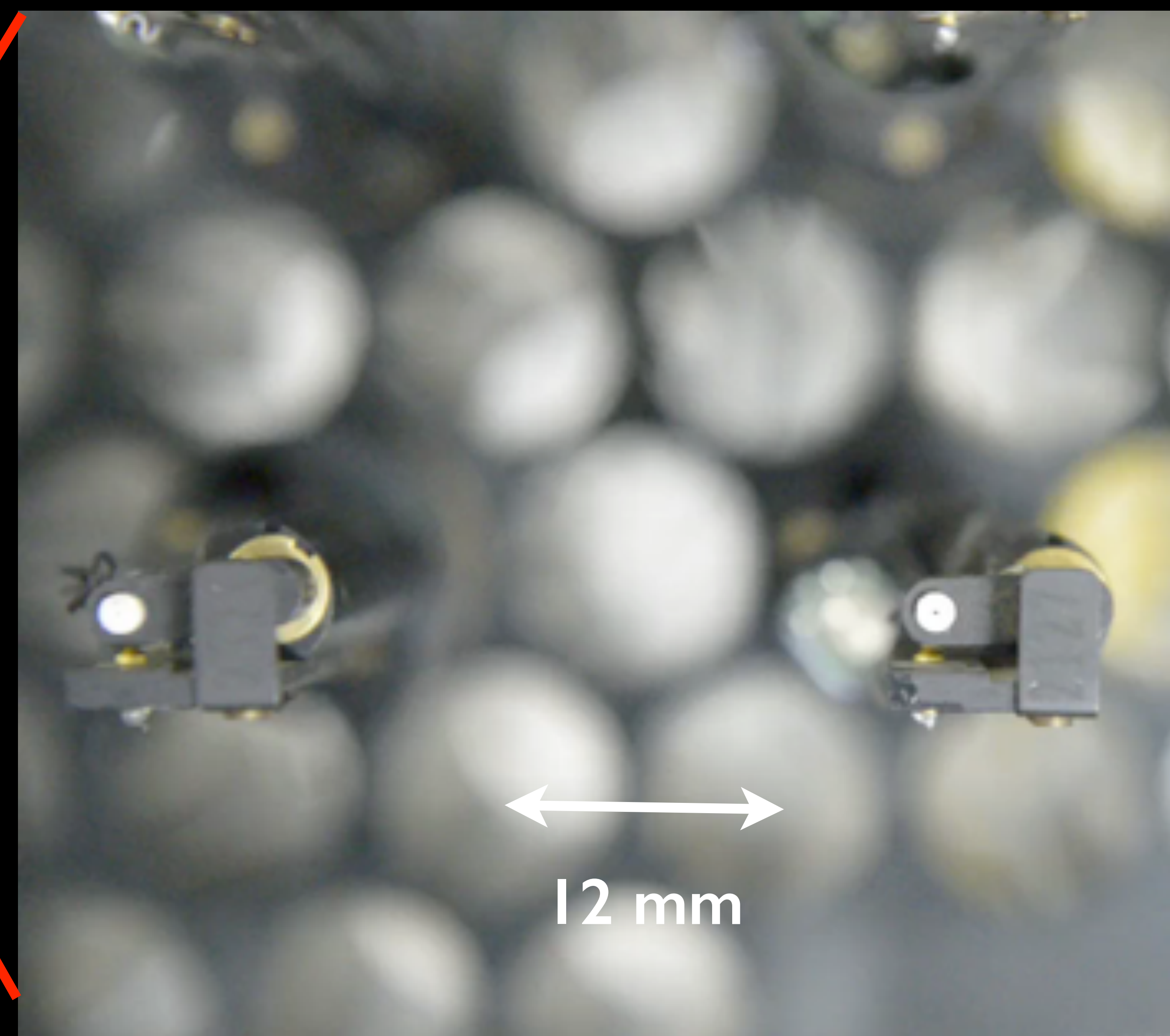


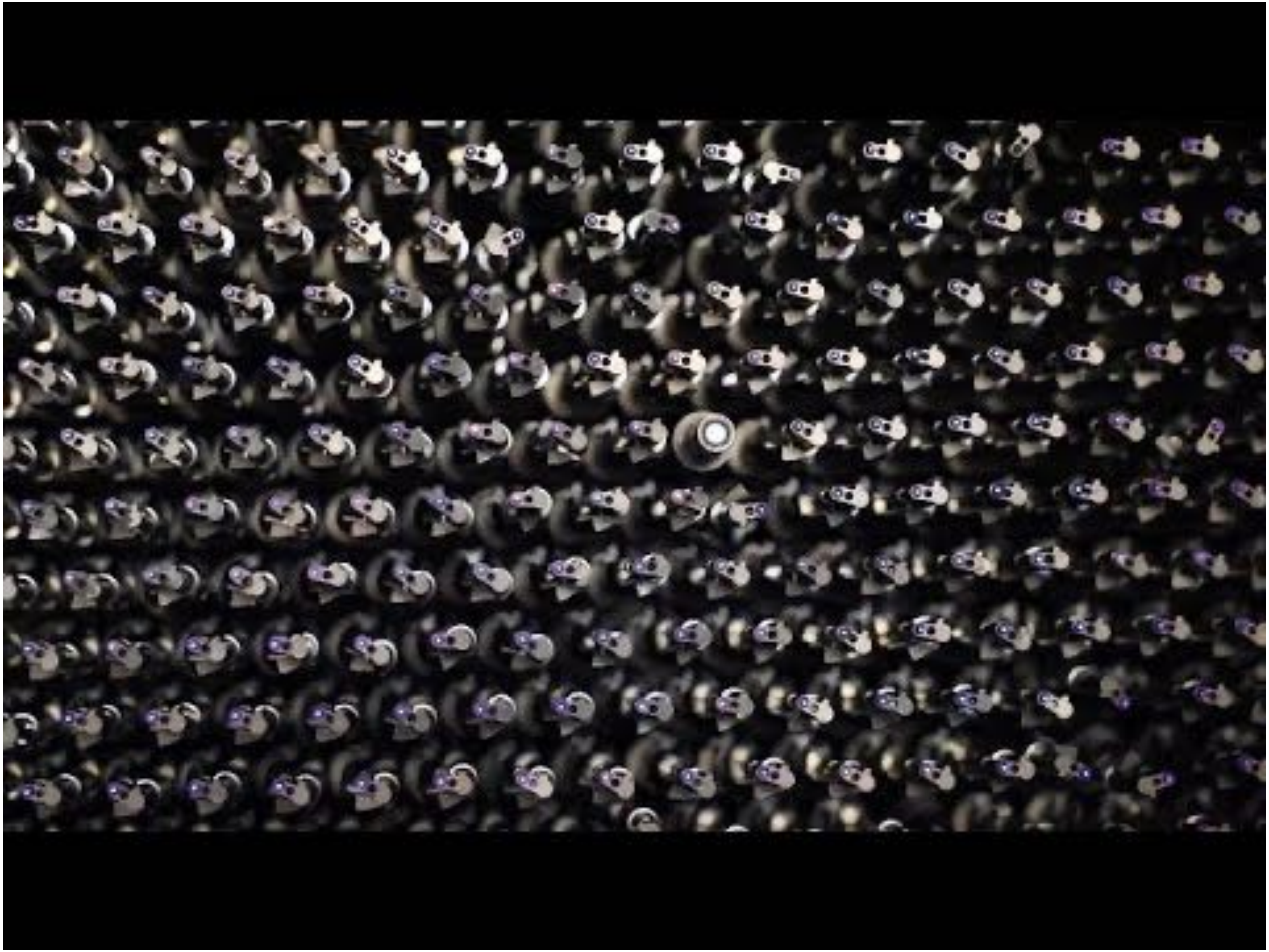
DESI using robotically-positioned fibers

Map of 50 million galaxies possible

5000 fibers
robotically move in 1 minute

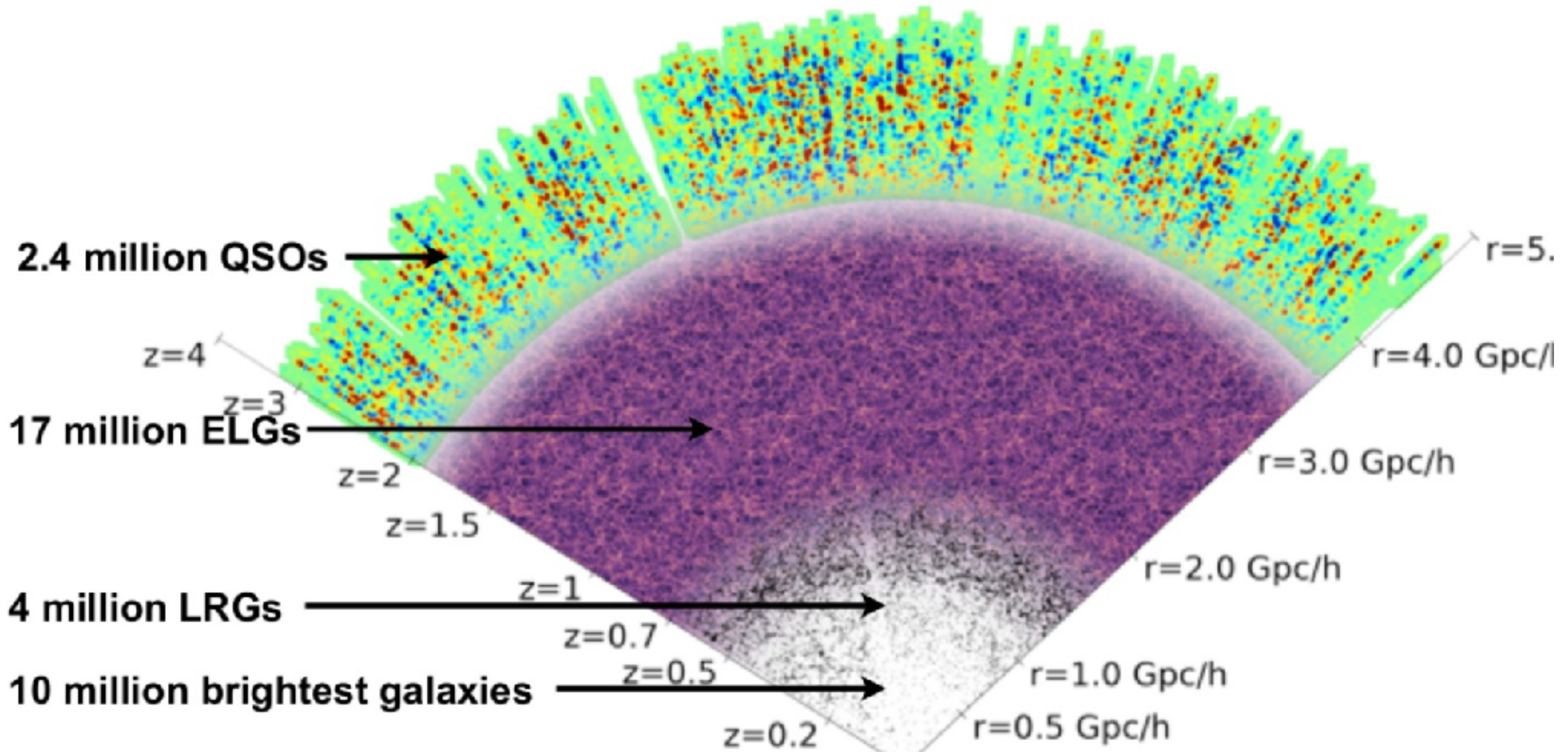


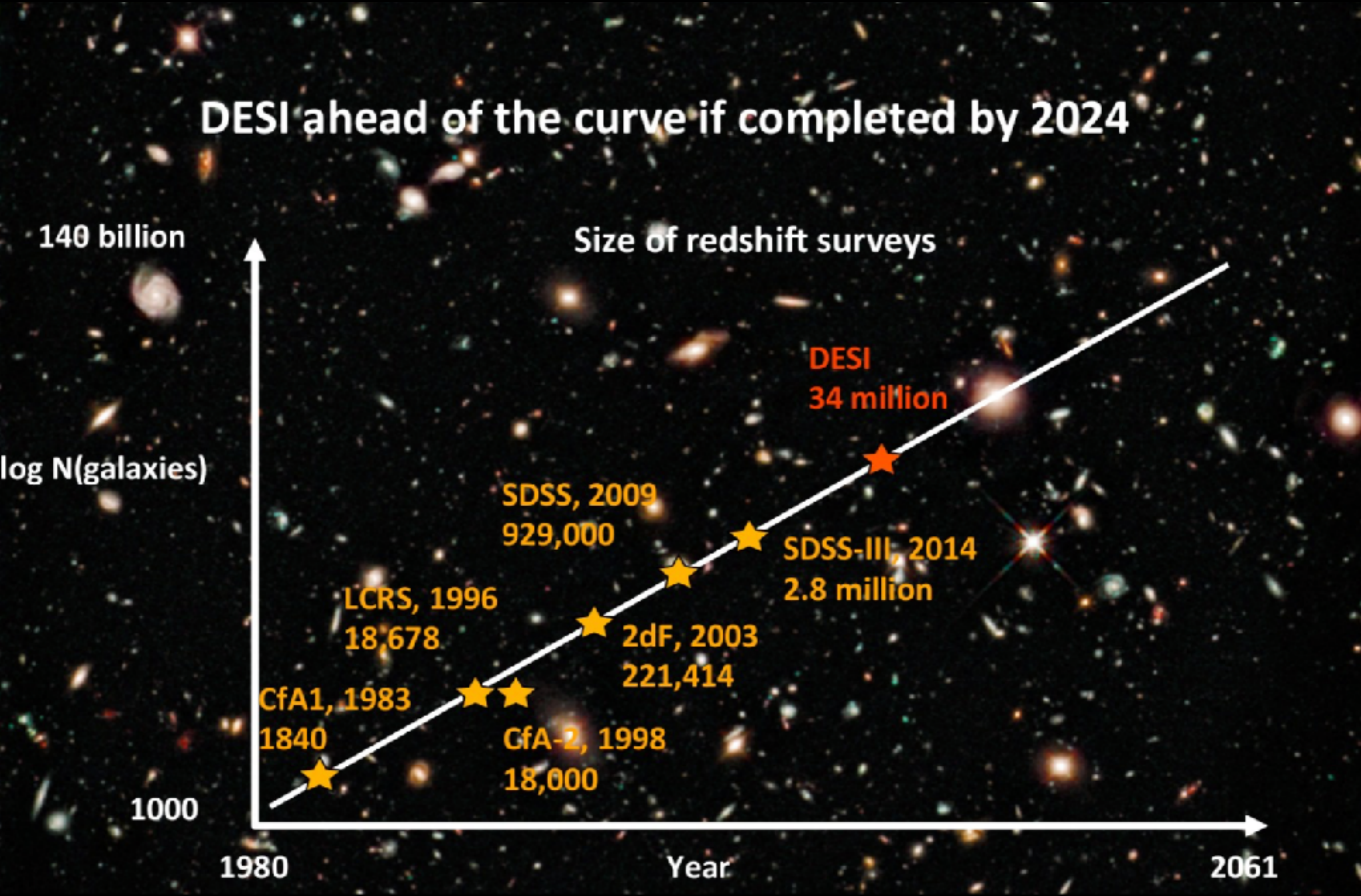




DESI spectroscopic survey 14000 deg2

SDSS ~2h^{-3}Gpc^3 ⇨ BOSS ~6h^{-3}Gpc^3 ⇨ DESI 50h^{-3}Gpc^3

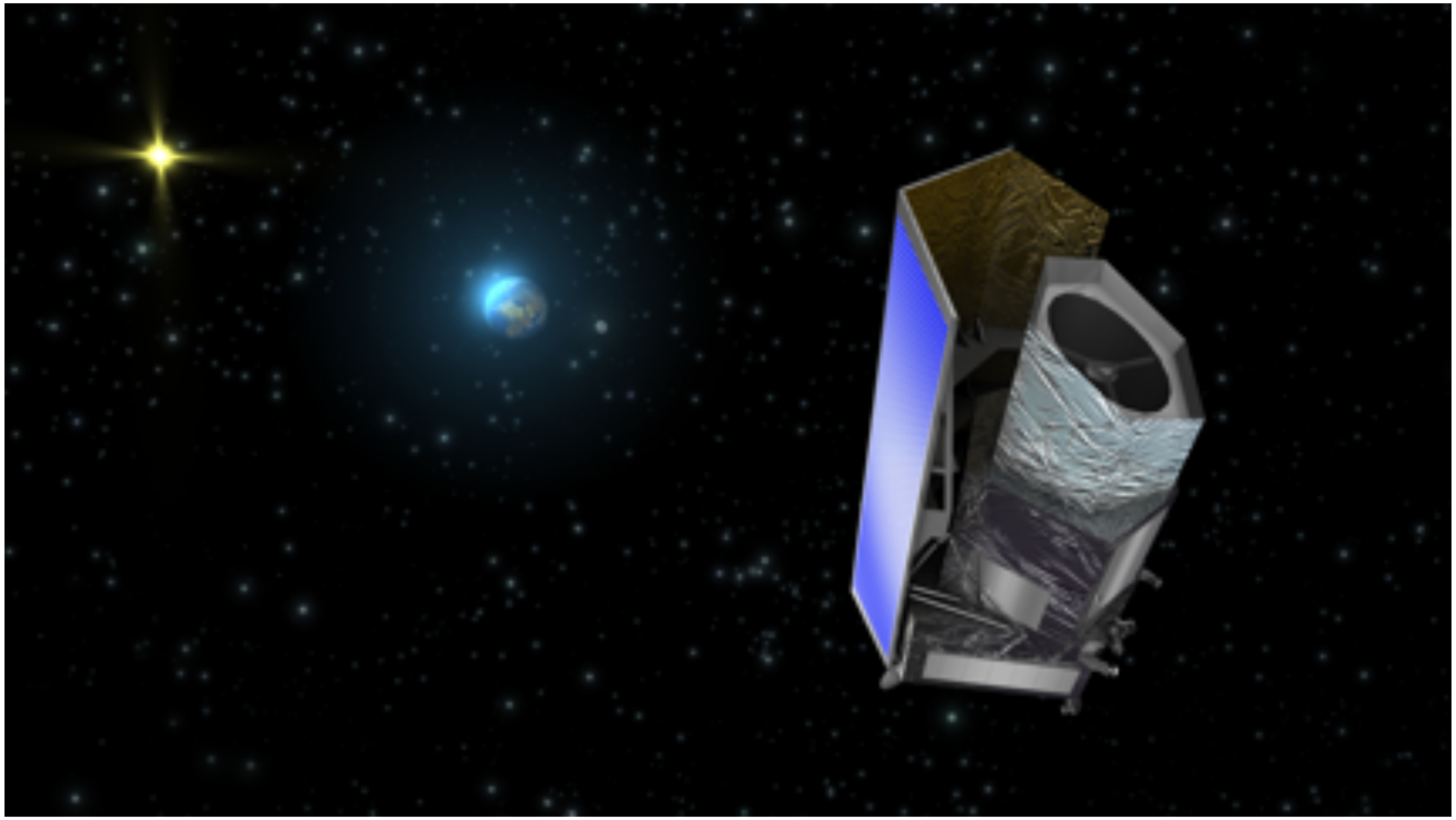



DESI ahead of the curve if completed by 2024
140 billion
Size of redshift surveys
log N(galaxies)
1000
1980
Year
2061
DESI
34 million
SDSS, 2009
929,000
SDSS-III, 2014
2.8 million
LCRS, 1996
18,678
2dF, 2003
221,414
CfA1, 1983
1840
CfA-2, 1998
18,000

Euclid satellite redshift survey

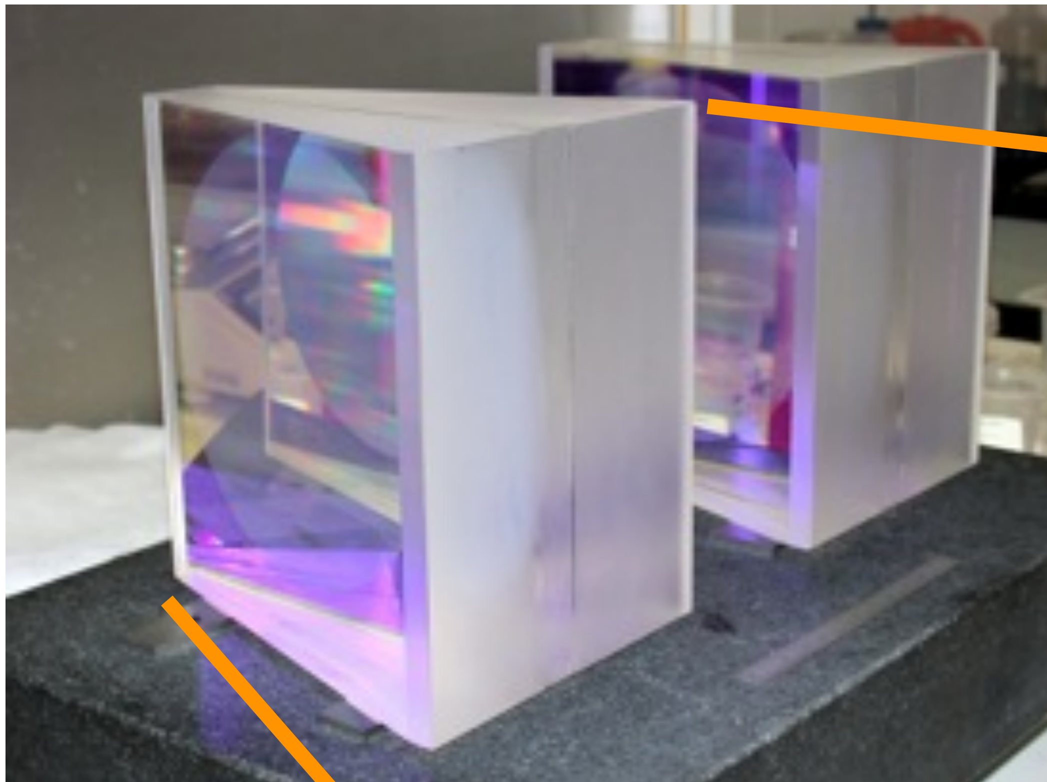
Technique of slit-less spectroscopy ("objective prism") pioneered by Edward Pickering in 1882 to classify stars

Used very little for the past ~70 years
… never used for galaxy redshift surveys

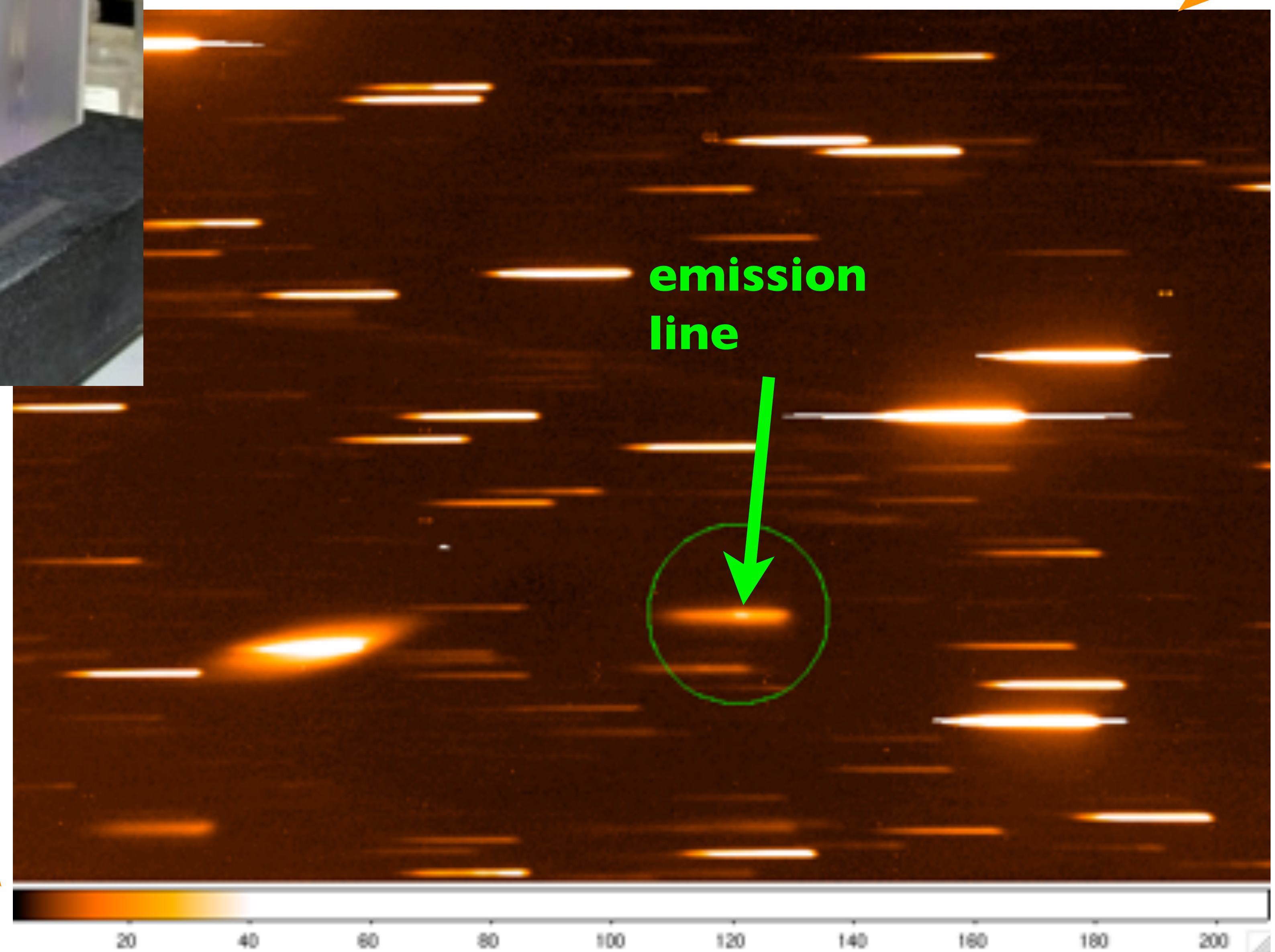


Euclid satellite redshift survey

Disperse all the light for all objects in your field-of-view



Complicated: Mixes spatial + spectroscopic info



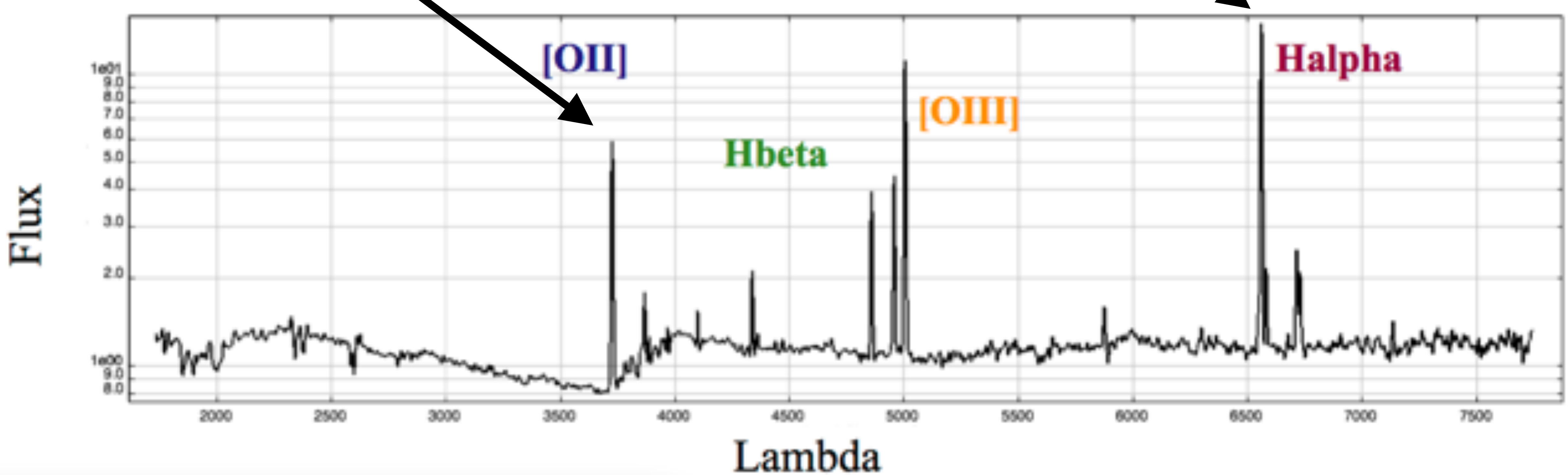
Real grism data from duPont telescope 2.5-m 0.64-0.75 micron (Nick Mostek)

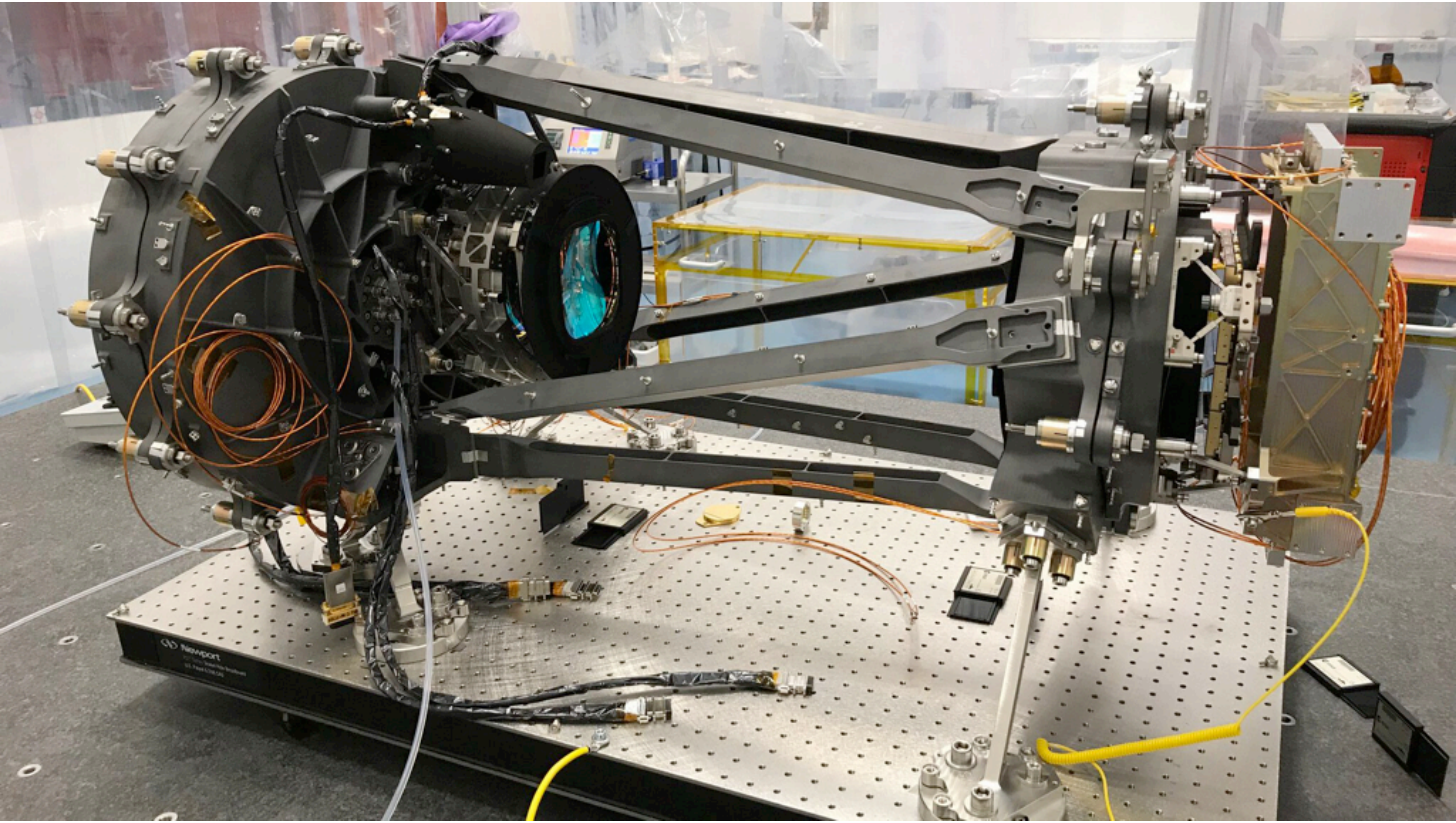
Euclid satellite redshift survey

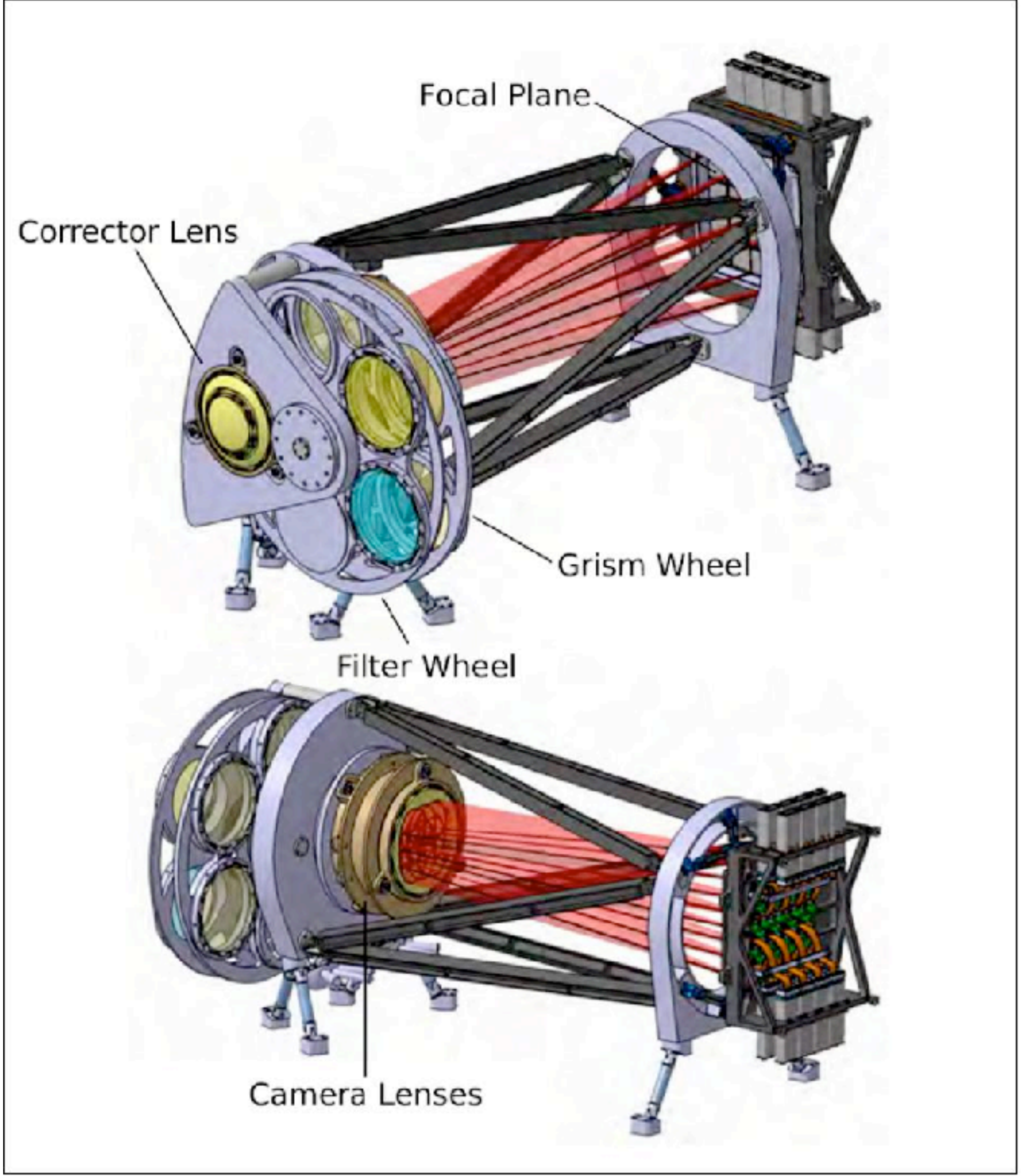
Why do this crazy prism survey?

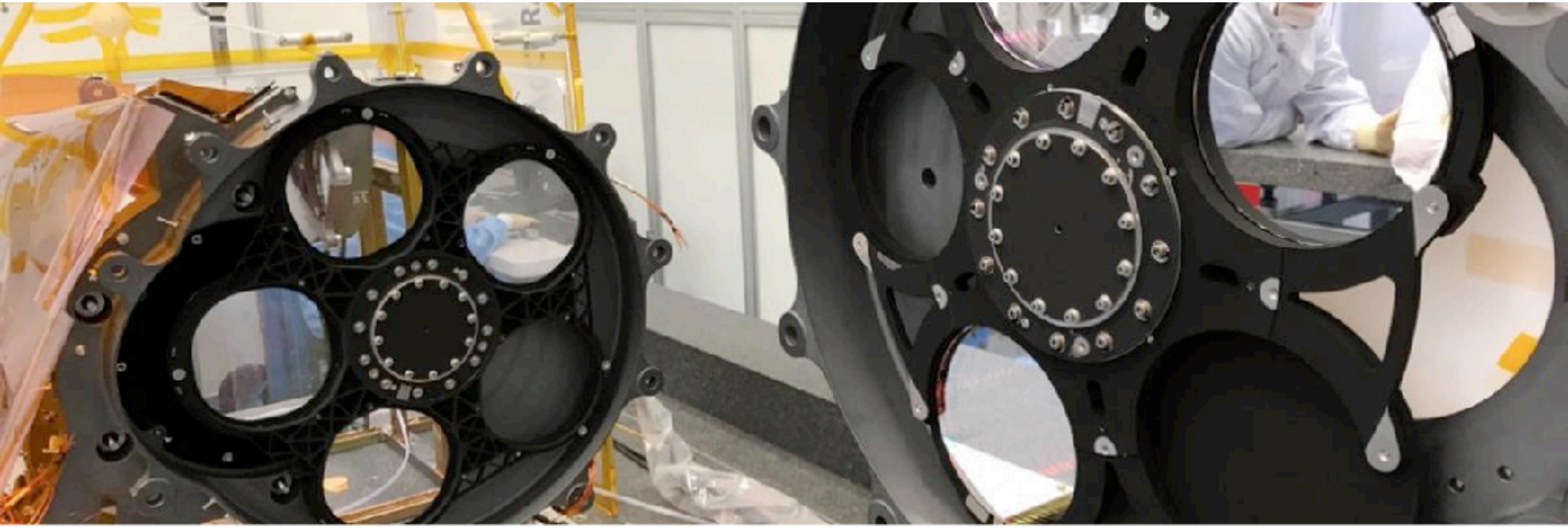
1. **Almost no moving parts**
2. **Can observe the brightest H-alpha (H 3-2 transition) from z=1-2**

DESI uses this signature from O^{+}

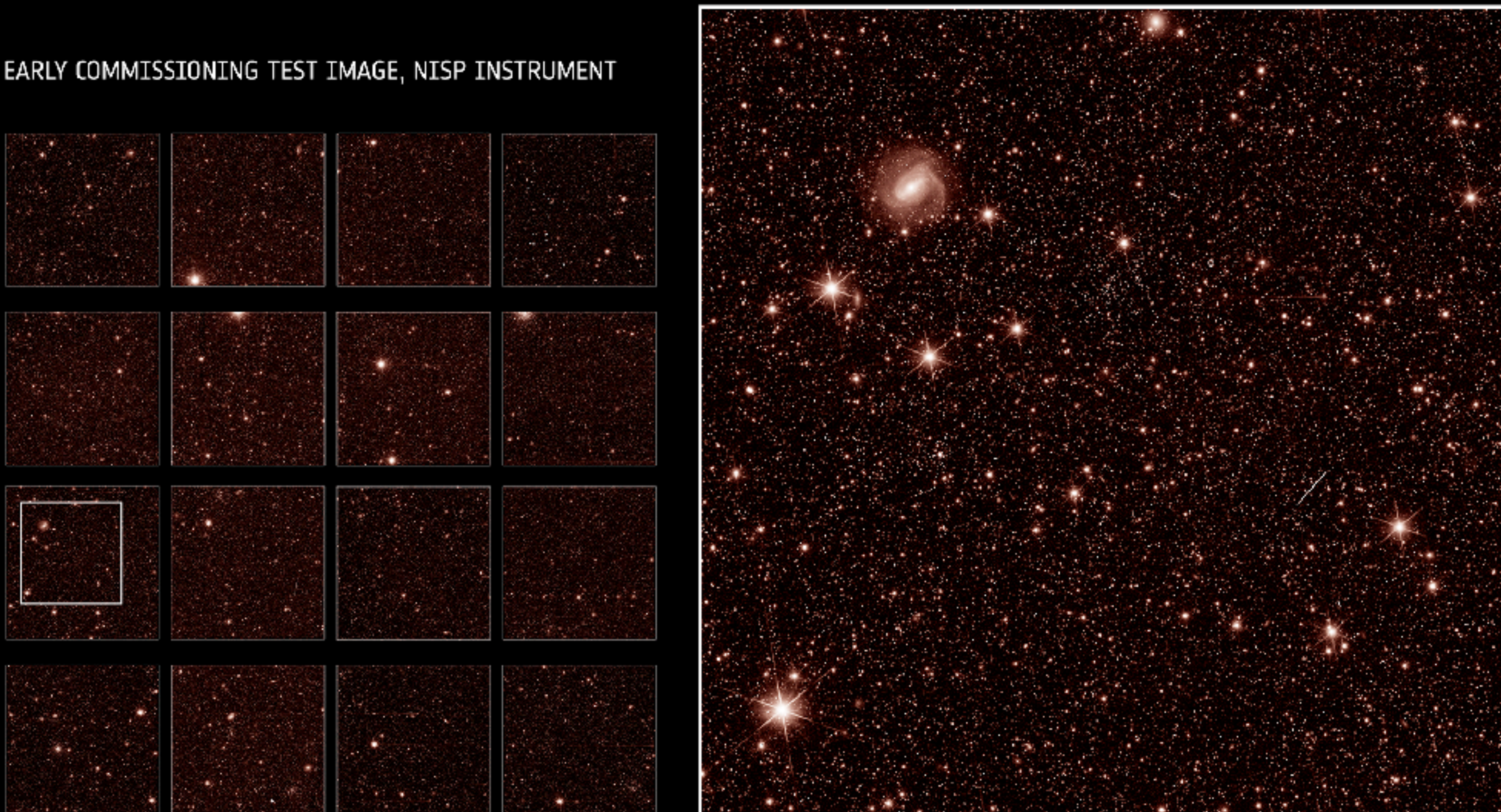


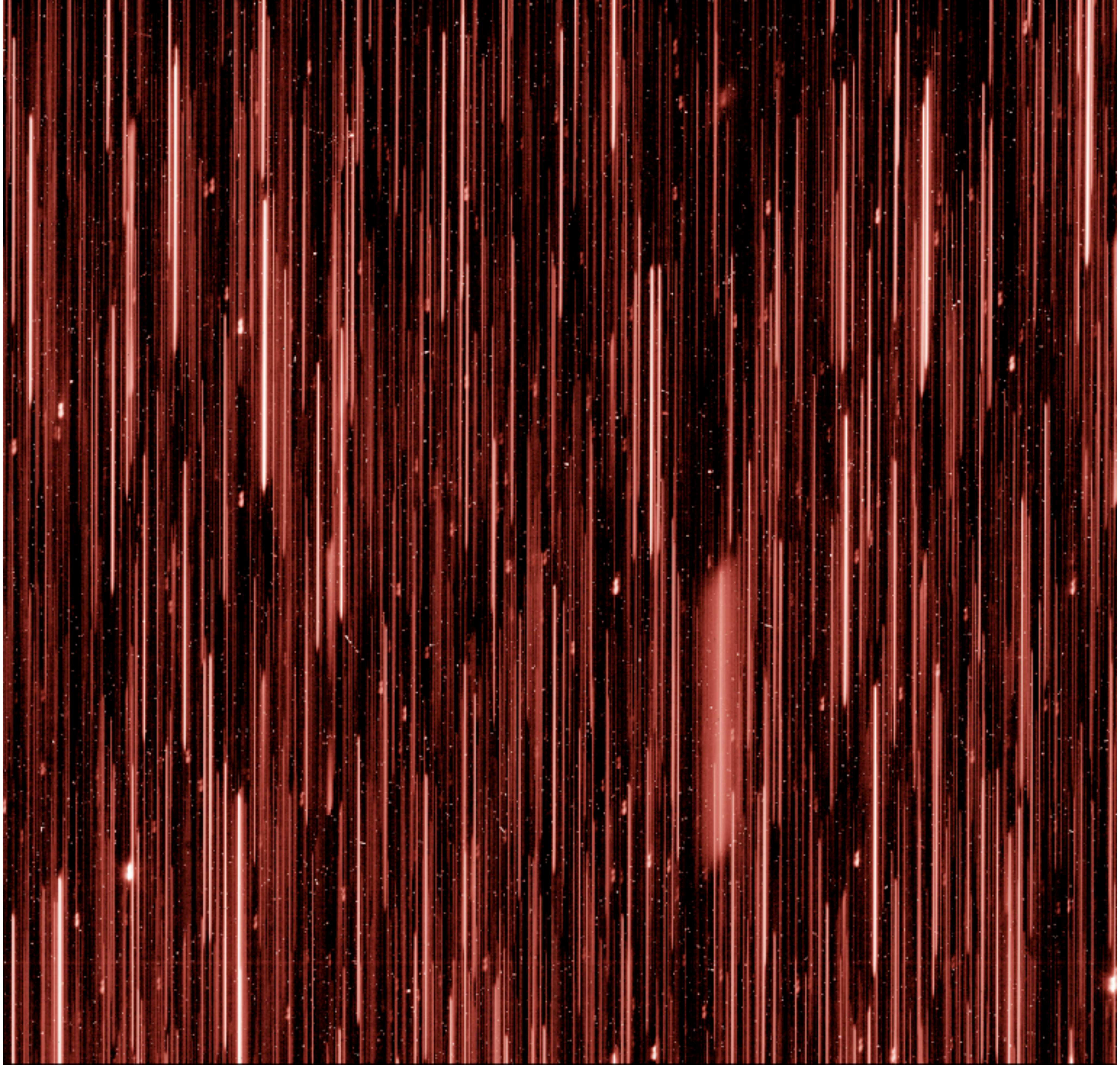

Newport


Focal Plane
Corrector Lens
Grism Wheel
Filter Wheel
Camera Lenses



EARLY COMMISSIONING TEST IMAGE, NISP INSTRUMENT





Early commissioning test image, NISP instrument (grism mode)