Astr 8300
Resources

- Web page: http://www.astro.gsu.edu/~crenshaw/astr8300.html
- Electronic papers: https://ui.adsabs.harvard.edu/
  (ApJ, AJ, MNRAS, A&A, PASP, ARAA, etc.)
- General astronomy-type numbers (Ionization Potentials, etc.): Allen, C.W. **Astrophysical Quantities**
- ISM Spectral Lines:
  Morton et al. 1988, ApJS, 68, 449
  Morton, 1991, ApJS, 77, 119
- Cloudy web page: http://www.nublado.org/
- Atomic Line List: http://www.pa.uky.edu/~peter/atomic/

Astronomy 8300
The Interstellar Medium (ISM)

- Cold gas in the ISM
- Warm diffuse gas in the ISM
- H II regions
- Planetary nebulae
- Novae, Supernova remnants
- Active Galactic Nuclei (AGN) – emission and absorption line regions
- Intergalactic Medium

What do these things have in common?

-characterized by low densities ($n_H < 10^{10}$ cm^{-3}), non-LTE

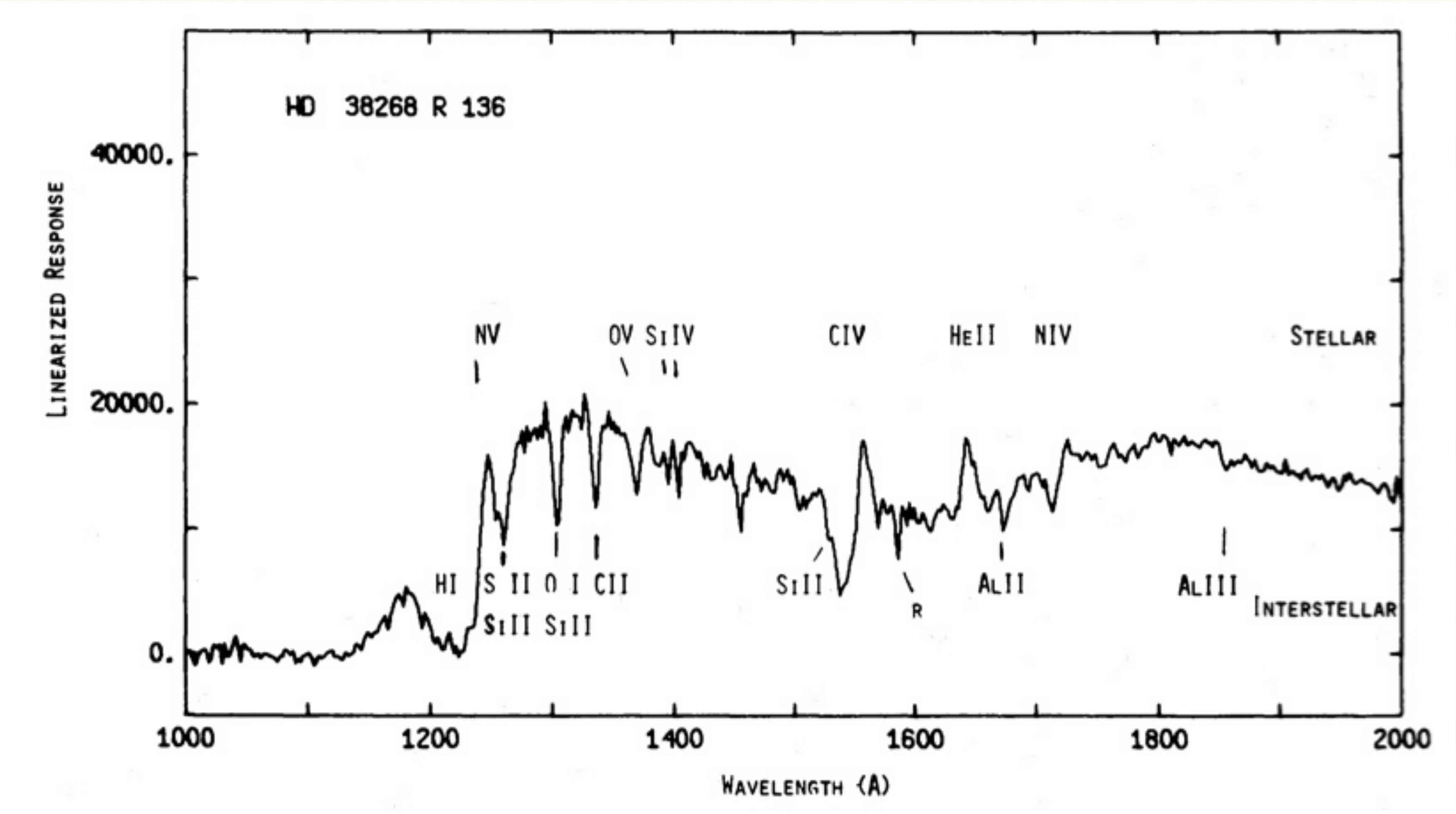
- most are photoionized by UV, EUV, and sometimes X-ray radiation (although collisional ionization important in some)

Cold Gas in the ISM

- neutral H (H I), low-ionization species (e.g., Mg II, C II, Si II), molecules (e.g., H_2, CO, H_20)
- revealed through resonance absorption lines, mostly in UV
  (why resonance?)
- also H I 21-cm line (emission and absorption)
  (what transition?)
- also molecular transitions, mostly in the radio and IR
- $T \approx 100$ K, $n_H \approx 1 - 10$ cm^{-3}, concentrated in spiral arms
- ISM cloud velocities from spectral lines: $v_r \approx 50$ km s^{-1}
- Scale height of H I for the Galactic disk (order of magnitude):

$$h = \frac{N(HI)}{n_{HI}} \approx \frac{10^{21}\ \mathrm{cm}^{-2}}{1\ \mathrm{cm}^{-3}} \approx 100\ \mathrm{pc}$$

UV Spectrum of the ISM



(de Boer, et al. 1980, ApJ, 236, 769)

Note: There are only a few strong **optical** resonance lines:
Ca II λλ3393, 3968 ; Na I λλ5890, 5896

Warm/Hot Diffuse Gas in the ISM

- Typically found in high velocity (v_r = 50 to 200 km s^{-1}), high Galactic latitude clouds
- Revealed through high-ionization absorption lines (C IV, N V, O VI
- May also be detected by diffuse Hα or even X-ray emission, where no obvious hot stars are present

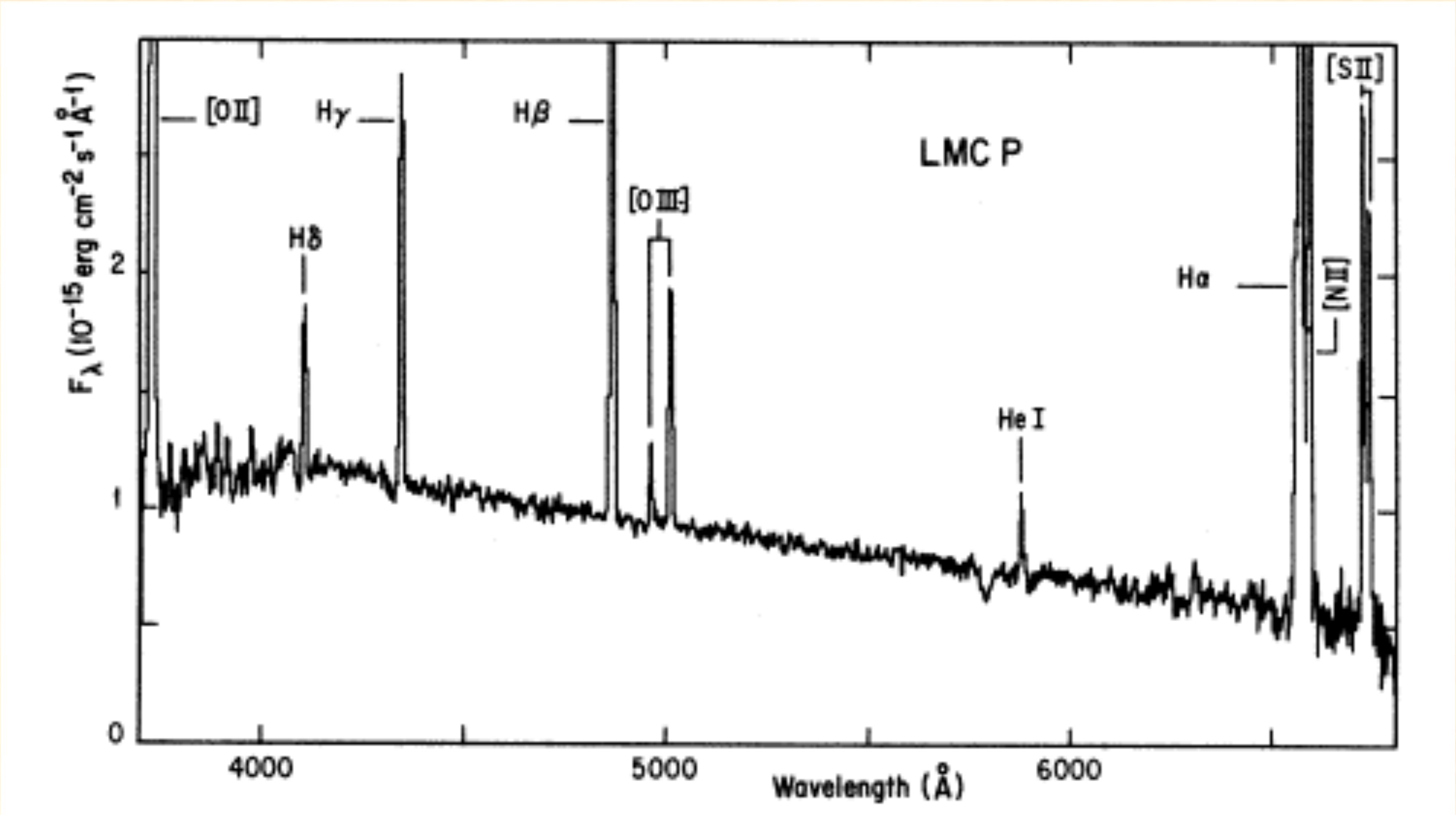
H II Regions

- Surround hot (O and B) stars with temperatures 30000 - 50000 K (why not cooler stars?)
- Detected through emission lines (Hα, [O III], etc.)
- Densities: $n_H = 10 – 10^4$ cm^{-3}
- Temperatures: T ≈ 10,000 K
- Outline spiral arms, typical masses = 10^2 - 10^4 $M_\odot$
- "Ionization fronts" are found at the edges of H II regions.

H II Region Image

Orion Nebula (HST image)

H II Region Spectrum



(Pena, et al. 1987, RMxAA, 14, 178)

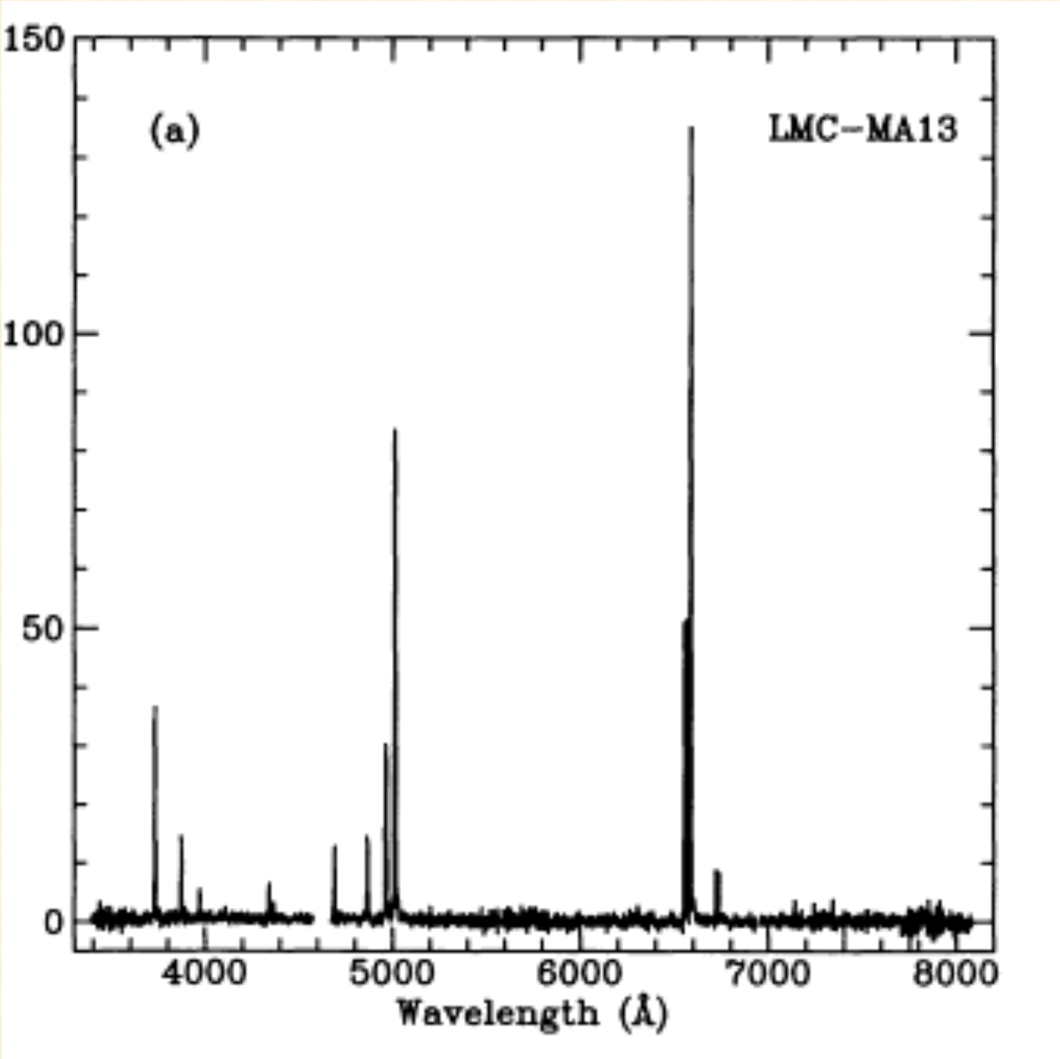
Planetary Nebulae

- Ejected during later stages of stellar evolution from stars with *original* masses $\leq 8\ M_{\odot}$
- Central stars have temperatures ≈ 50,000 to 100,000 K
- Typical densities: $n_H = 10^2 - 10^4\ cm^{-3}$
- Typical masses = $0.1 - 1.0\ M_{\odot}$
- High-ionization emission lines (e.g., He II, [Ne V]) typically stronger than in H II regions (why?)
- Typical lifetimes ~ 50,000 years
- Expansion velocities ≈ $30\ km\ s^{-1}$

Planetary Nebula Image

“Southern Ring Nebula” (JWST NIRCam)

Planetary Nebula Spectrum

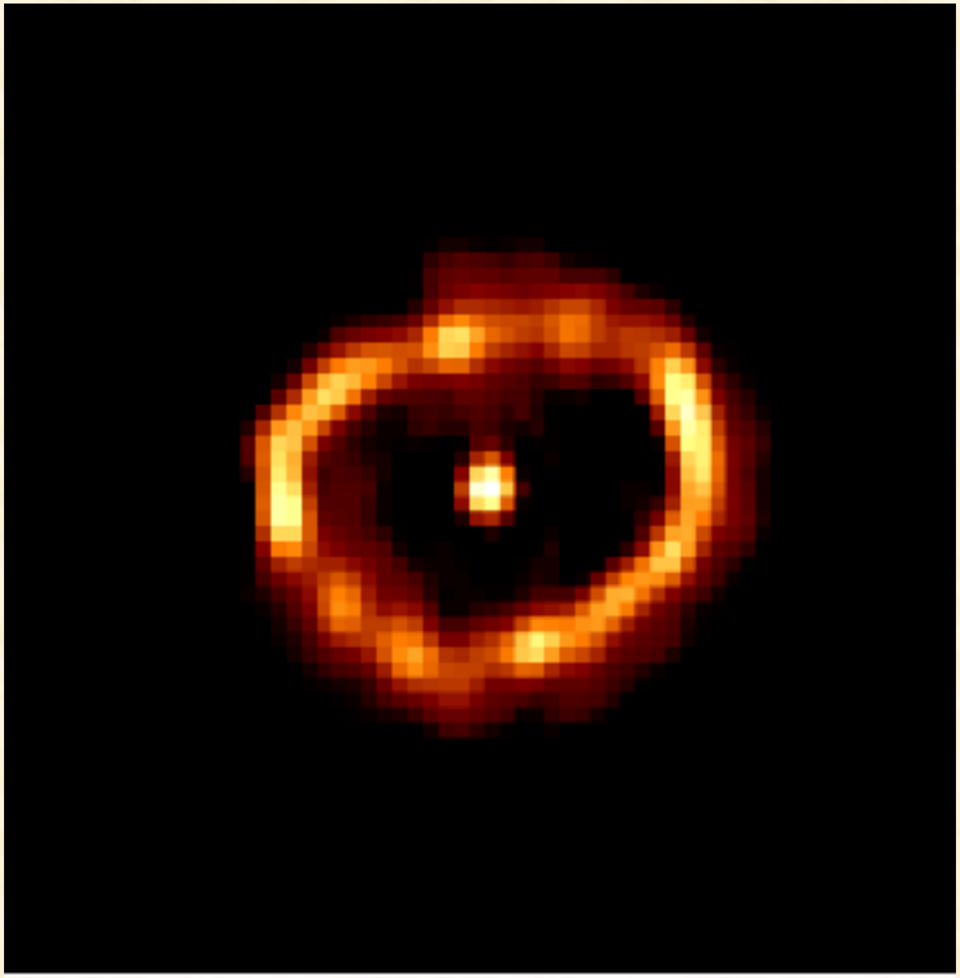


(Vassiliadis, et al. 1992, ApJS, 83, 87)

Novae

- Low mass (~10^{-4} $M_\odot$) shell surrounding binary white dwarf + red M.S. star or subgiant
- Red star overflows its Roche lobe, producing an accretion disk around the white dwarf
- H-rich gas builds up on surface, and eventually explodes outward in a thermonuclear runaway
- Expansion velocity ≈ 10^3 km s^{-1}
- After initial absorption-line spectrum, emission lines become strong
- Shell is ionized by initial outburst, subsequently by UV radiation from the accretion disk
- $n_H \approx 10^2$ cm^{-3} , T ≈ 1000 - 3000 K

Nova Image



Nova Cygni 1992 (HST)

Supernova Remnants

- Expanding shell from Type I or Type II Supernovae
- Expansion velocity ≈ 10^4 km s^{-1}
- Initial ionization caused by thermonuclear explosion, subsequent ionization by collision with ambient ISM (via shock fronts)
- Just behind the shock front, temperatures reach ~10^5 K
- Evidence for photoionization in Crab Nebula – from synchrotron radiation produced by fast electrons in B field
- High temperatures lead to extended X-ray emission

Supernova Image

SN 1987A (JWST)

Active Galactic Nuclei (AGN)

"Clouds" of photoionized gas surrounding "central engine" (Supermassive Black Hole + accretion disk + X-ray corona)

- Broad-line region (BLR): Velocities ~ 5000 km/sec (full width at half-maximum [FWHM]), $n_H \sim 10^8 - 10^{11}$ cm^{-3}
- Narrow-line region (NLR): Velocities ~ 500 km/sec (FWHM), $n_H \sim 10^3 - 10^6$ cm^{-3} , T ~ 10,000 – 20,000 ºK
- UV and X-ray absorption-line regions: more diffuse, highly ionized gas with temperatures up to T ~ 100,000 ºK
- These regions give clues to the source of ionizing radiation, dynamical forces around SMBH, etc.
- Some evidence for shock fronts in localized regions as well.

AGN "Unified Model"

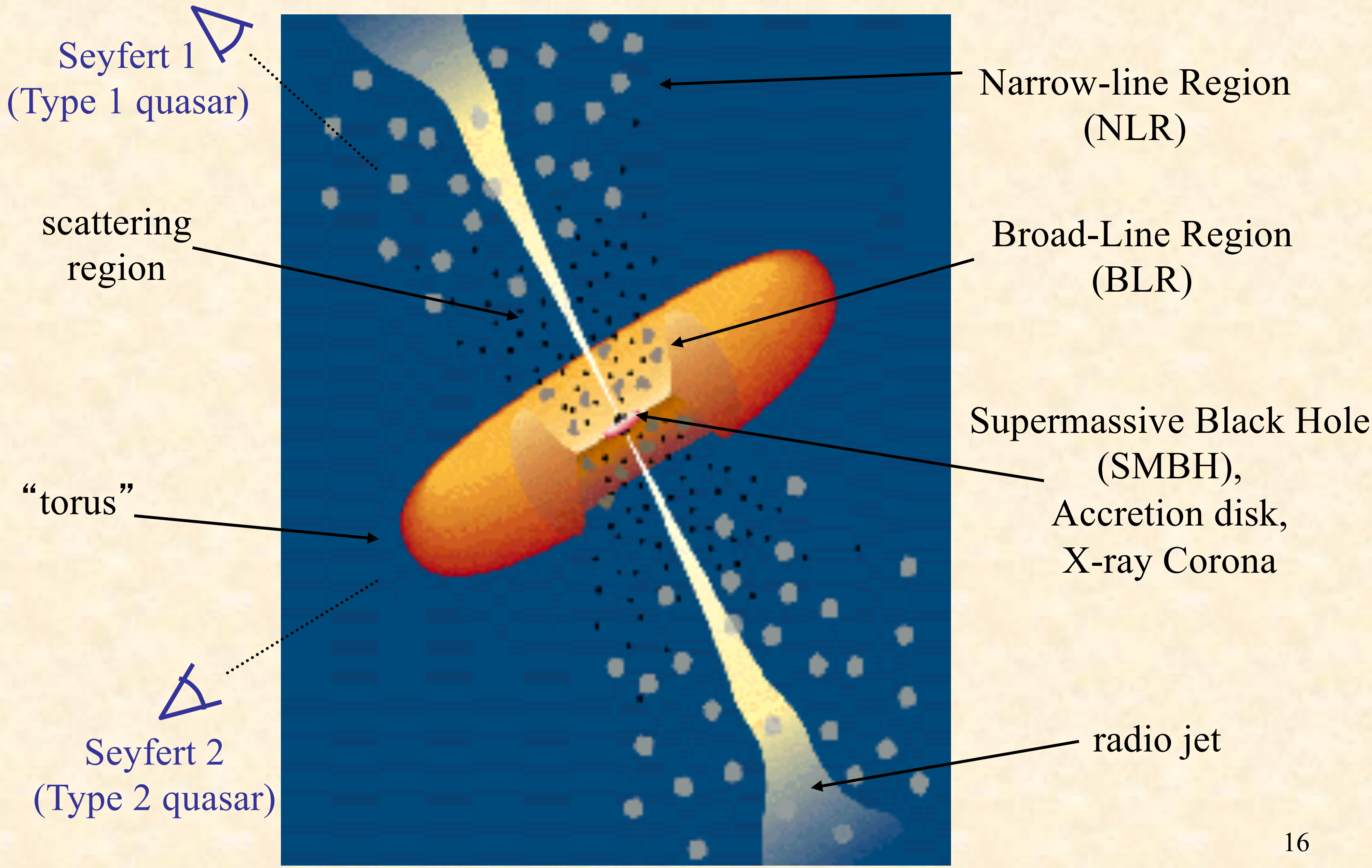
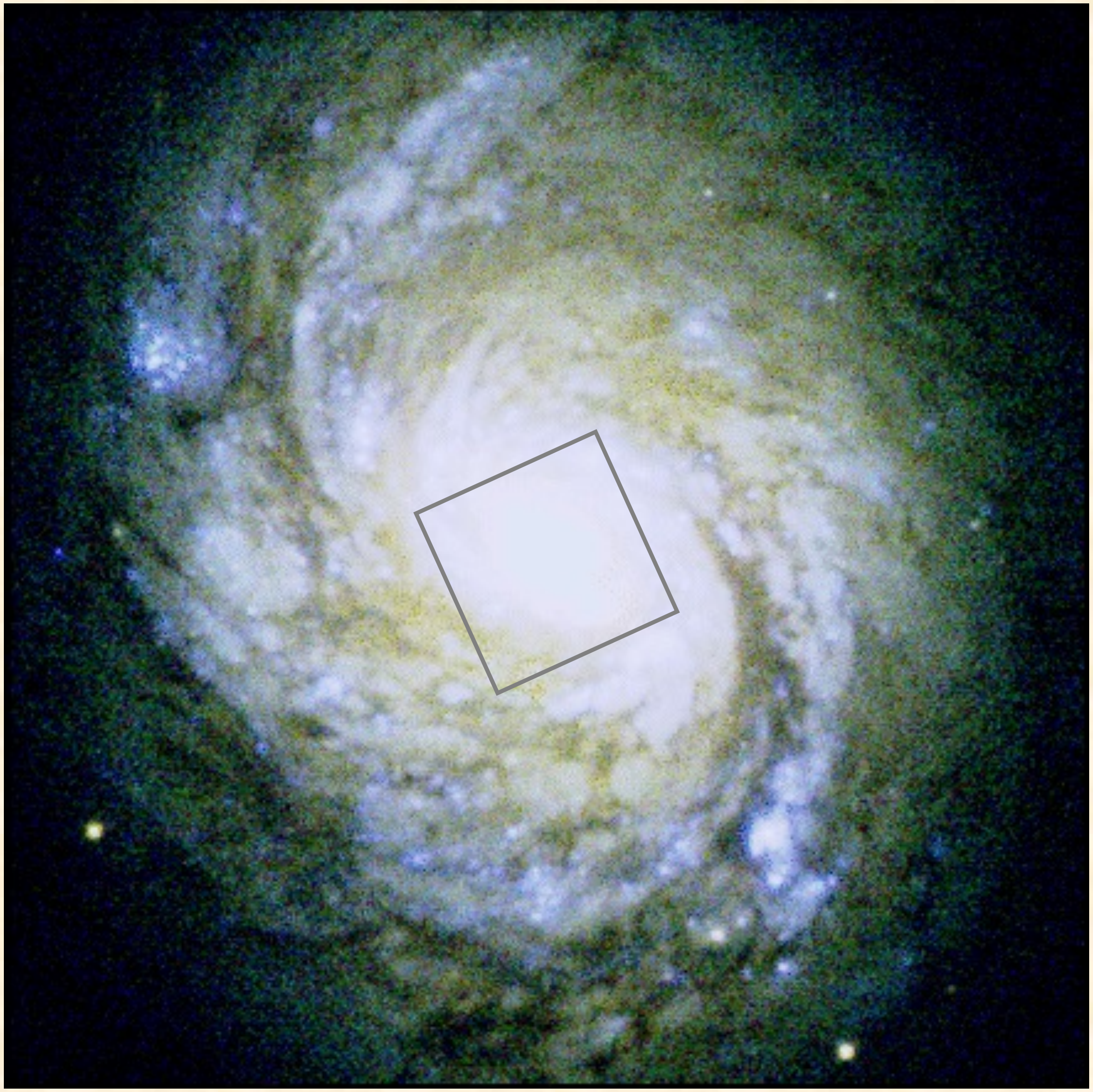


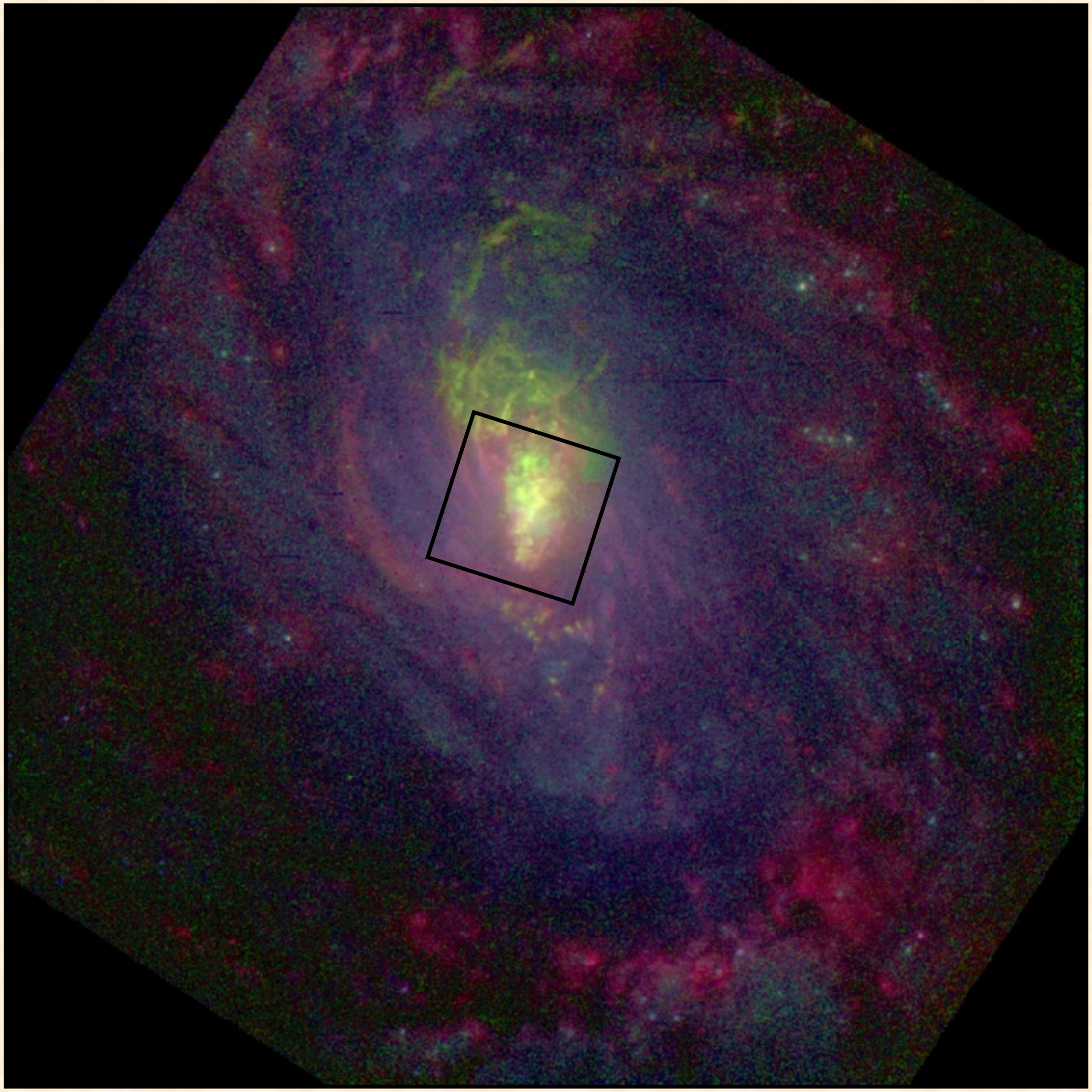
Image of Active Galaxy

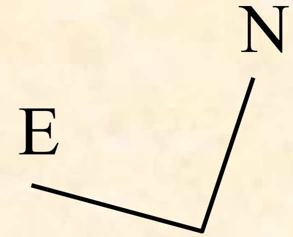


NGC 1068 (Seyfert 2 galaxy)

NGC 1068 – HST/WFPC2 Image

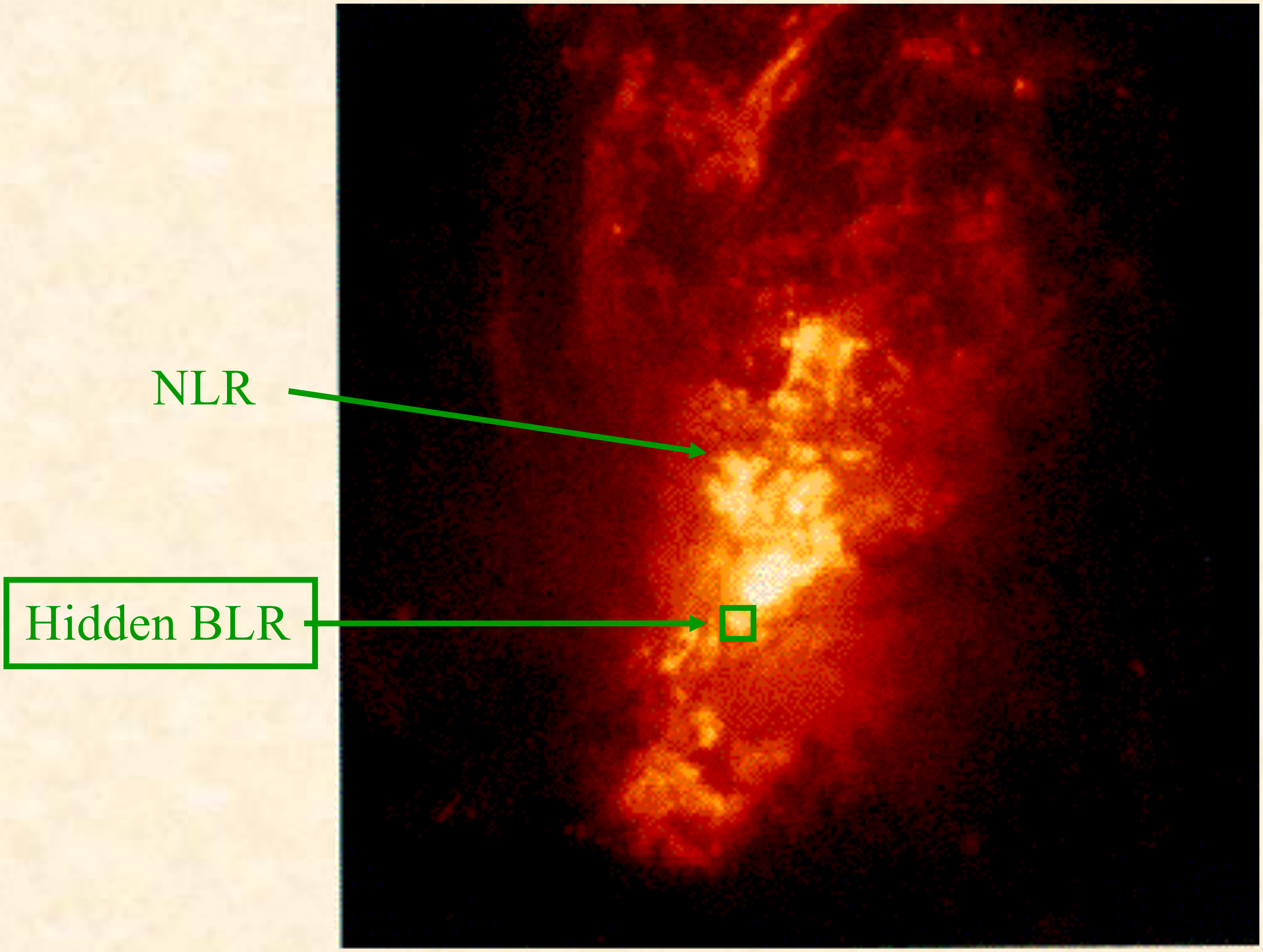
(Bruhweiler et al. 2001, ApJ, 546, 866)



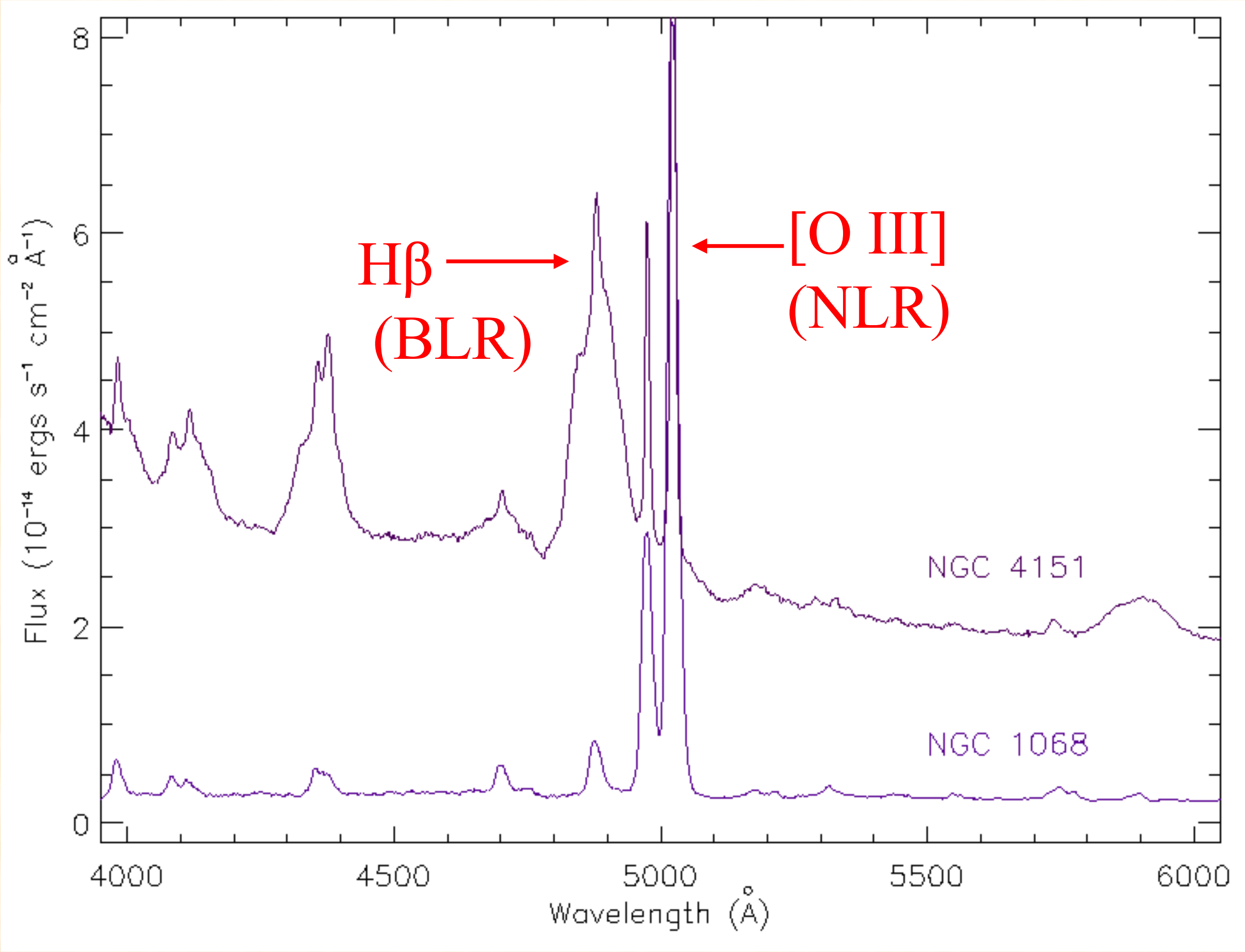


blue - stellar
red - Hα
green - [O III]

NGC 1068 – [O III] image (false color)

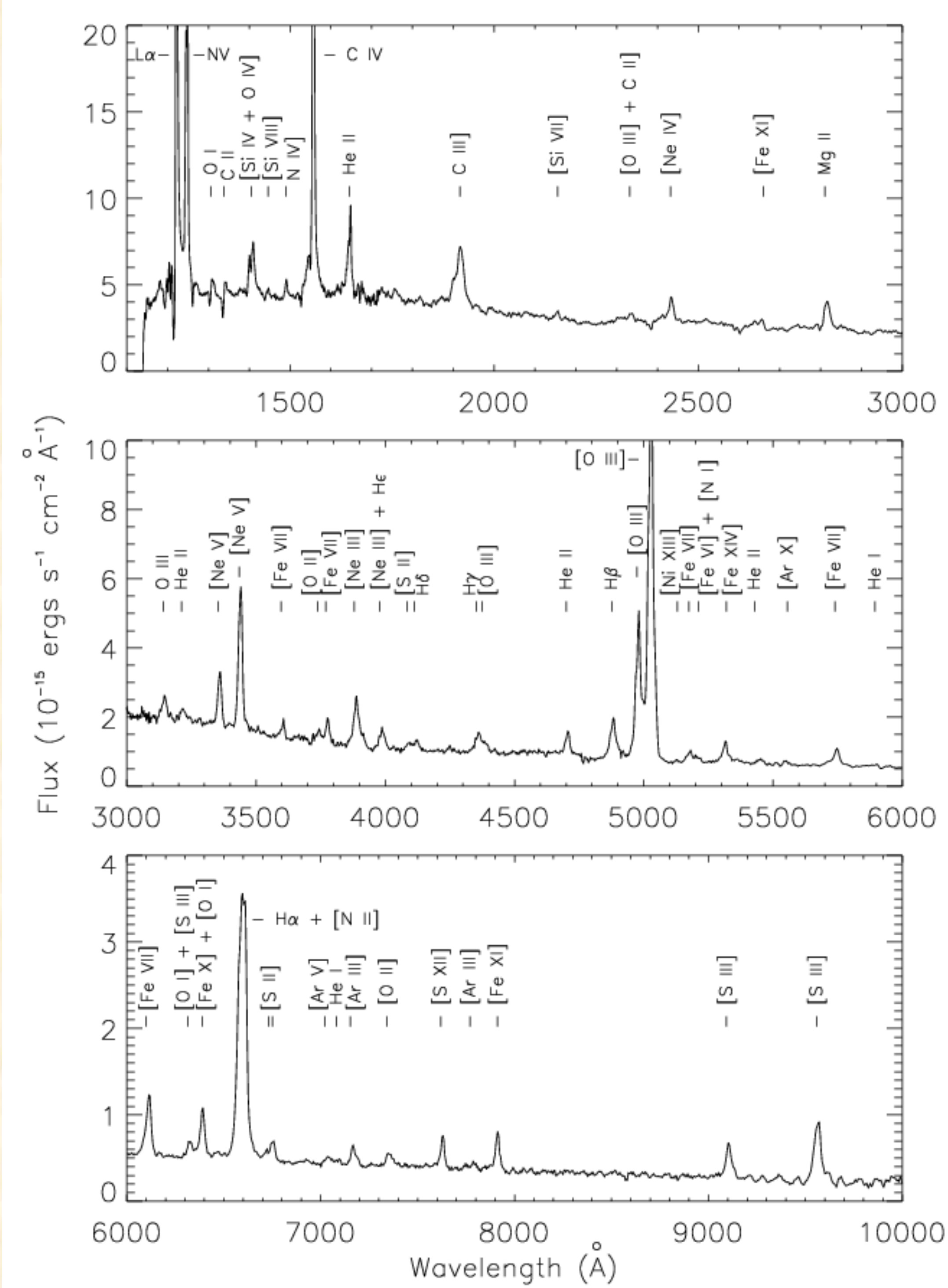


Optical Spectra of Seyfert Galaxies



Seyfert 1

Seyfert 2



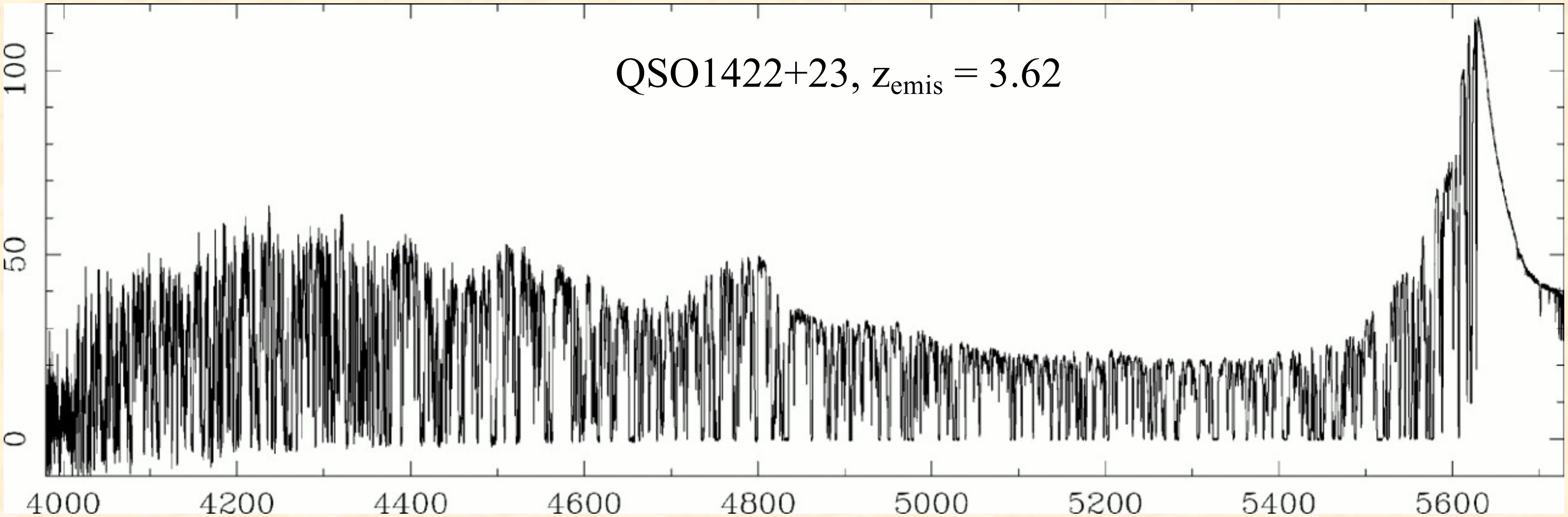
NGC 1068

- huge range in ionization ([O I] to [S XII])
- X-rays penetrate deeply into clouds to create low-ionization lines

(Kraemer & Crenshaw 2000, ApJ, 532, 256)

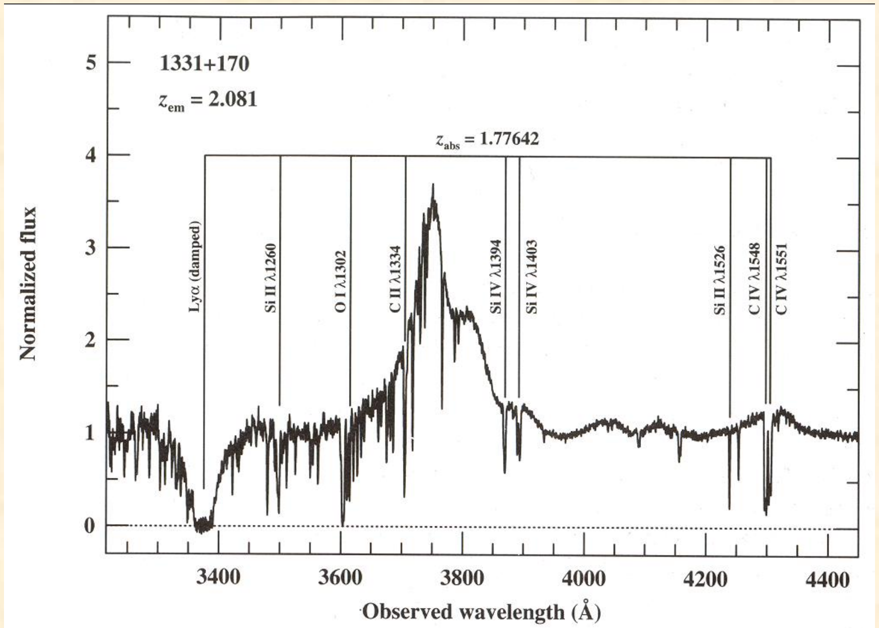
Intergalactic Medium

Lyα Forest - intervening clouds in the intergalactic medium



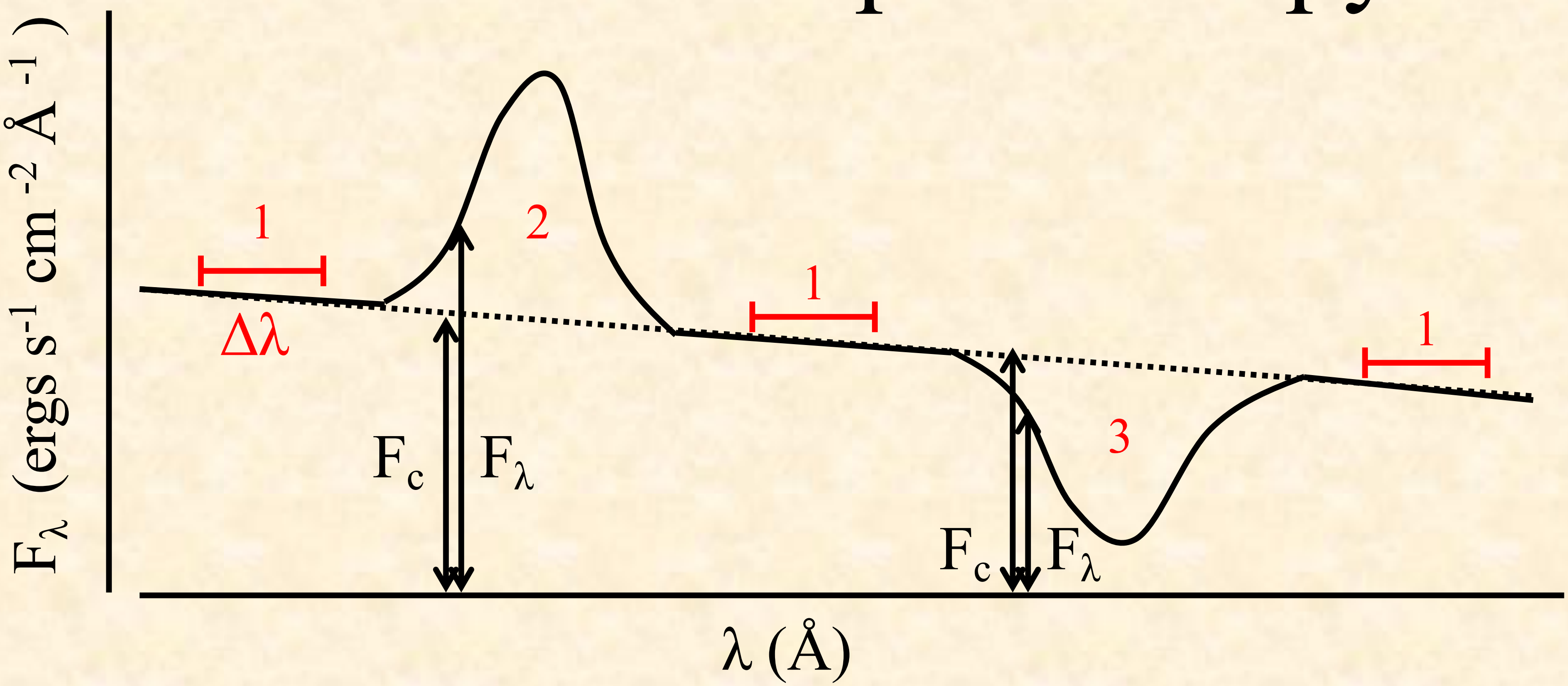
(Rauch, 1998, ARAA, 36, 267)

"Metal-line" systems - intervening galaxies and their halos



(Peterson, 1997, An Introduction to AGN, p. 201)

Basics of Spectroscopy

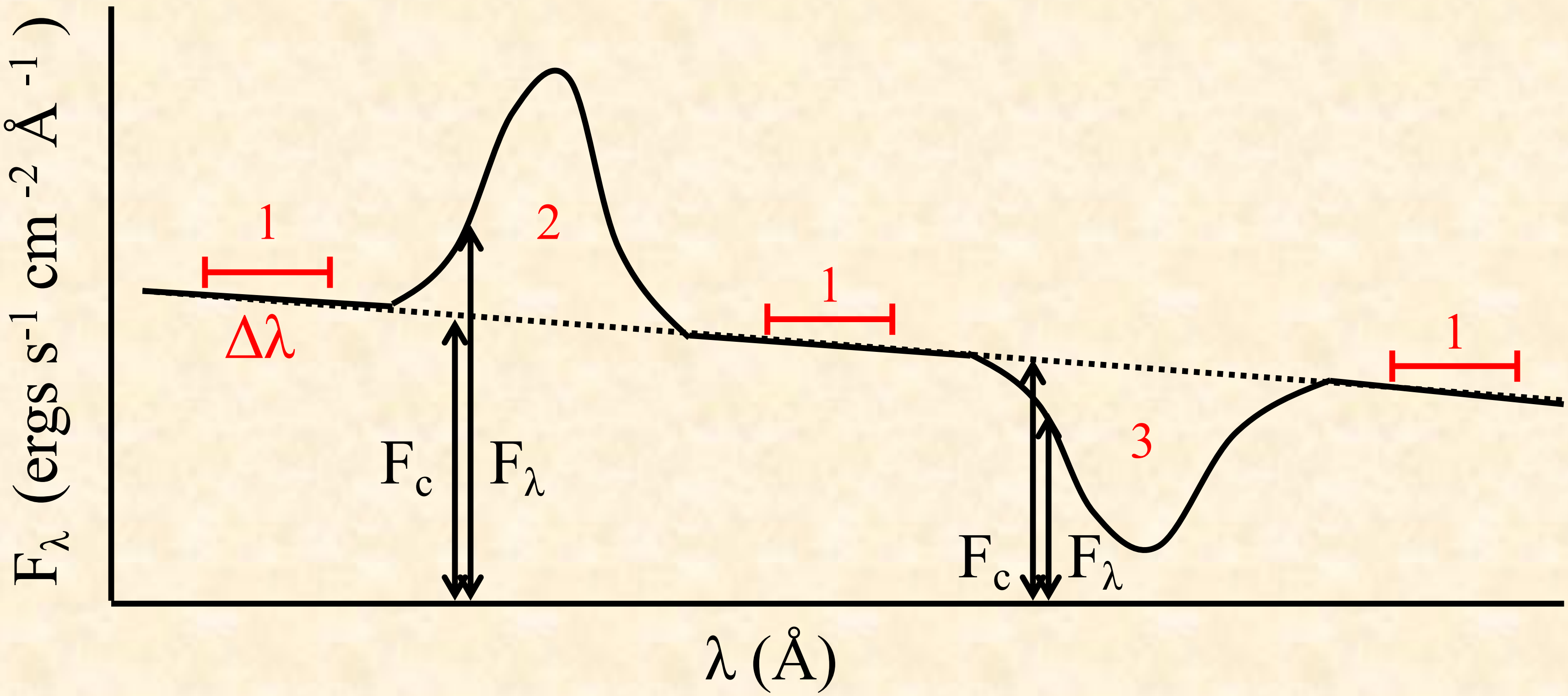


Units:

1. Continuum Flux: $F_c = \dfrac{\int F_\lambda \, d\lambda}{\Delta\lambda} = \langle F_\lambda \rangle$ (ergs s^{-1} cm^{-2} $Å^{-1}$)

2. Emission Line Flux: $F = \int (F_\lambda - F_c)\, d\lambda$ (ergs s^{-1} cm^{-2})

3. Equivalent Width: $W_\lambda = \int (1 - F_\lambda / F_c)\, d\lambda$ (Å)



4. Line Centroid:

$$\lambda_c = \frac{\int \lambda \left(F_\lambda - F_c\right) d\lambda}{\int \left(F_\lambda - F_c\right) d\lambda} \qquad \text{(Å)}$$

5. Radial Velocity Centroid:
(nonrelativistic)

$$v_r = \frac{\lambda_c - \lambda_{lab}}{\lambda_{lab}} c \qquad (\text{km s}^{-1})$$