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# Extragalactic Astrophysics

# What did we learn?

# What did we learn?

1. Galaxies are not isolated system: usually, they are bounded in groups, clusters, or interacting systems
2. Specific physical processes act on galaxies within denser environments and can modify their shape
3. Galaxies in clusters have less star formation, are more gas-poor and a correlation exists between morphology and the density
4. These mechanisms can be studied via spectral and/or SED analysis

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# Highlights

**A phase-space view of cold-gas properties of Virgo-cluster galaxies: multiple quenching processes at work?**

Kana Morokuma-Matsui,[1,2,3,*] Tadayuki Kodama,[4] Tomoki Morokuma,[1] Kouichiro Nakanishi,[5,6] Yusei Koyama,[7] Takuji Yamashita,[5,8] Shuhei Koyama,[5,8] and Takashi Okamoto[9]

We investigate the cold-gas properties of massive Virgo galaxies ($> 10^9$ $M_\odot$) at $< 3R_{200}$ ($R_{200}$ is the radius where the mean interior density is 200 times the critical density) on the projected phase-space diagram (PSD) with the largest archival dataset to date to understand the environmental effect on galaxy evolution in the Virgo cluster. We find: lower H I and $H_2$ mass fractions and higher star-formation efficiencies (SFEs) from H I and $H_2$ in the Virgo galaxies than the field galaxies for matched stellar masses; the Virgo galaxies generally follow the field relationships between the offset from the main sequence of the star-forming galaxies [$\Delta$(MS)] with gas fractions and SFEs but slightly offset to lower gas fractions or higher SFEs than field galaxies at $\Delta(\mathrm{MS}) \lesssim 0$; lower gas fractions in galaxies with smaller clustocentric distance and velocity; lower gas fractions in the galaxies in the W cloud, a substructure of the Virgo cluster. Our results suggest the cold-gas properties of some Virgo galaxies are affected by their environment at least at $3R_{200}$ maybe via strangulation and/or pre-processes and H I and $H_2$ in some galaxies are removed by ram pressure at $< 1.5R_{200}$. Our data cannot rule the possibility of the other processes such as strangulation and galaxy harassment accounting for the gas reduction in some galaxies at $< 1.5R_{200}$. Future dedicated observations of a mass-limited complete sample are required for definitive conclusions.

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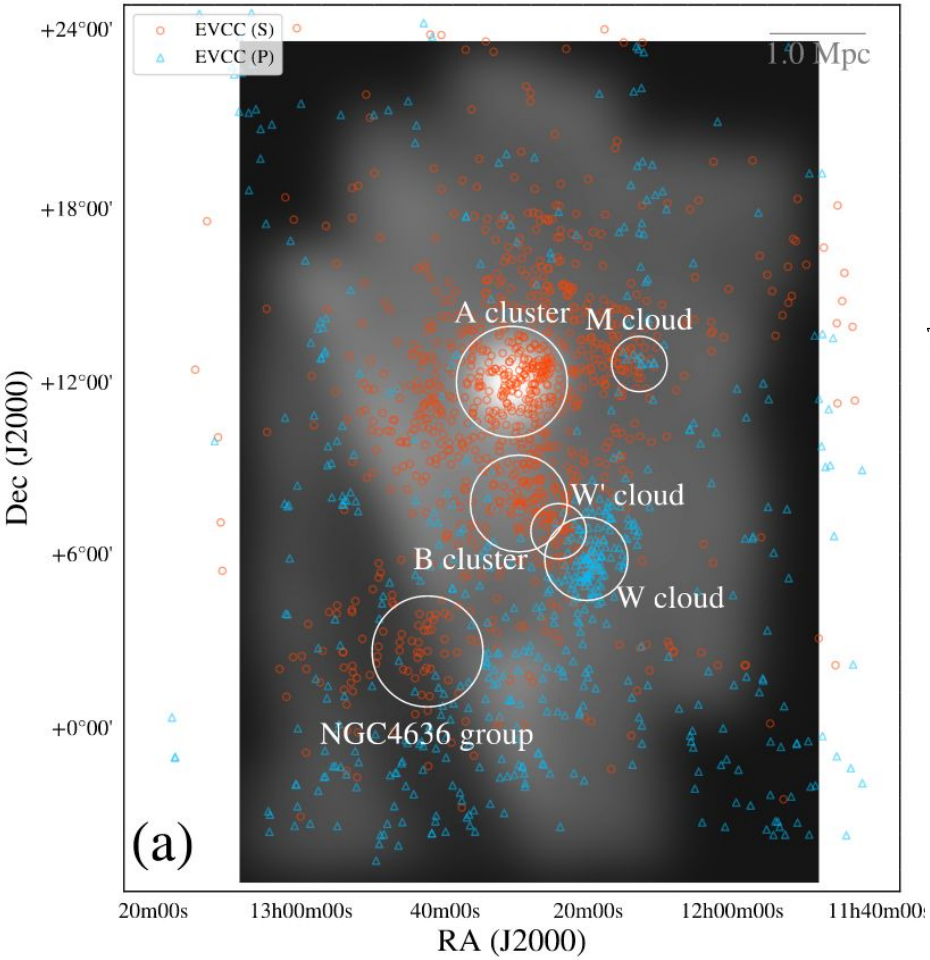
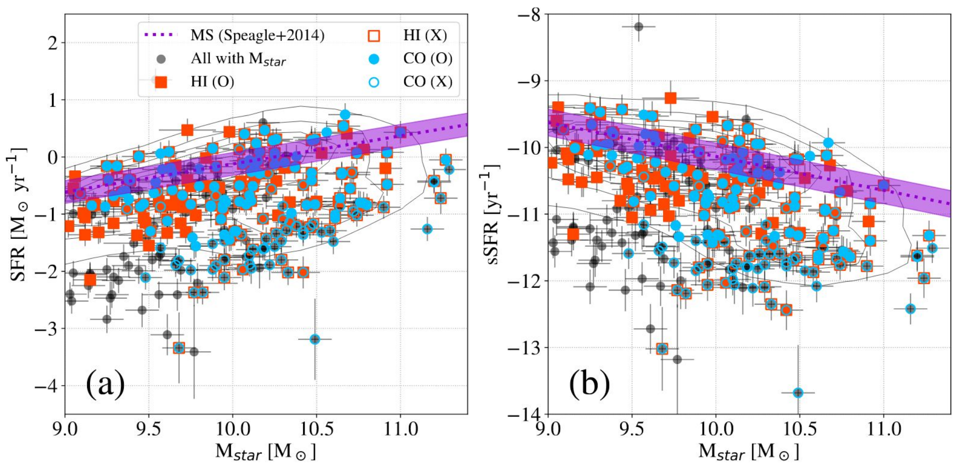


# Outline of the course

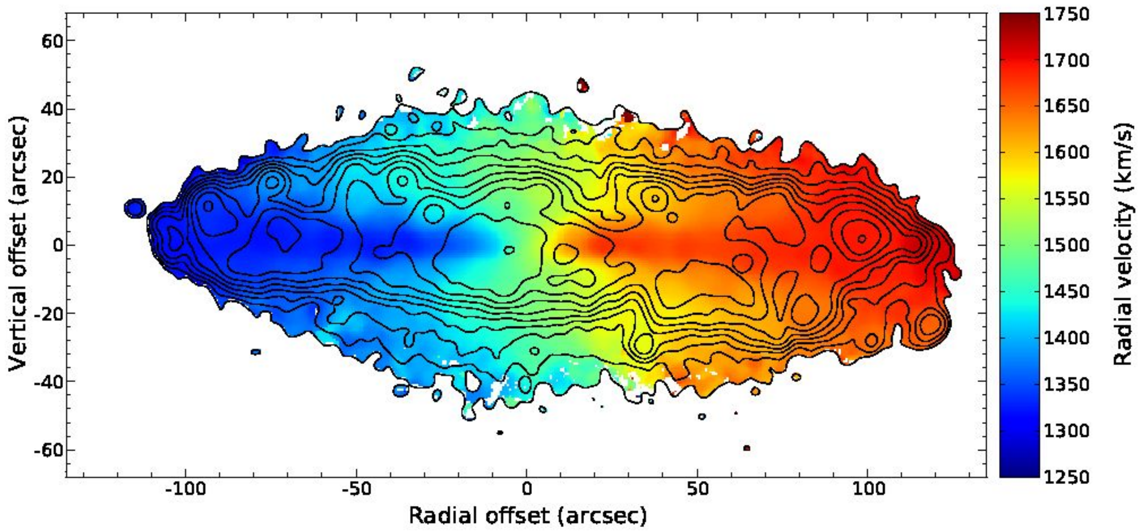
1. History
2. General concepts review
3. Galaxies in the local Universe
4. **Galaxies kinematics and scaling relations**
5. Star formation
6. Interstellar Medium
7. Distances and redshift
8. High redshift Universe
9. Final remarks and open debate

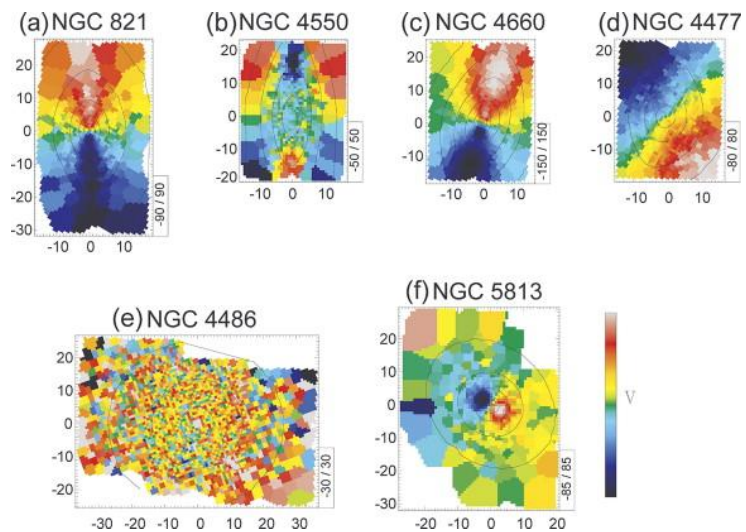
# Galaxy kinematics

Goal: To measure the motions of gas and stars providing relevant hints about galaxy evolution.
Examples:

a) dynamical mass within galaxies → gravitational potentials

b) dynamical state of baryons → angular momentum and the ratio of kinetic energy in random motion vs. ordered rotation



# Rotation Curve

Galaxies form via collapse due to gravity. In this phase, the rotation increases because of the conservation of angular momentum. When the equilibrium is reached the gravitational force (which would collapse everything in an enormous black hole) must equal the centrifugal force due to the galaxy rotation.

$$F = G\frac{Mm}{r^2}$$

+

$$F = \frac{mv^2}{r}$$

⬇

$$G\frac{Mm}{r^2} = \frac{mv^2}{r}$$

$$v = \sqrt{\frac{GM}{r}}$$

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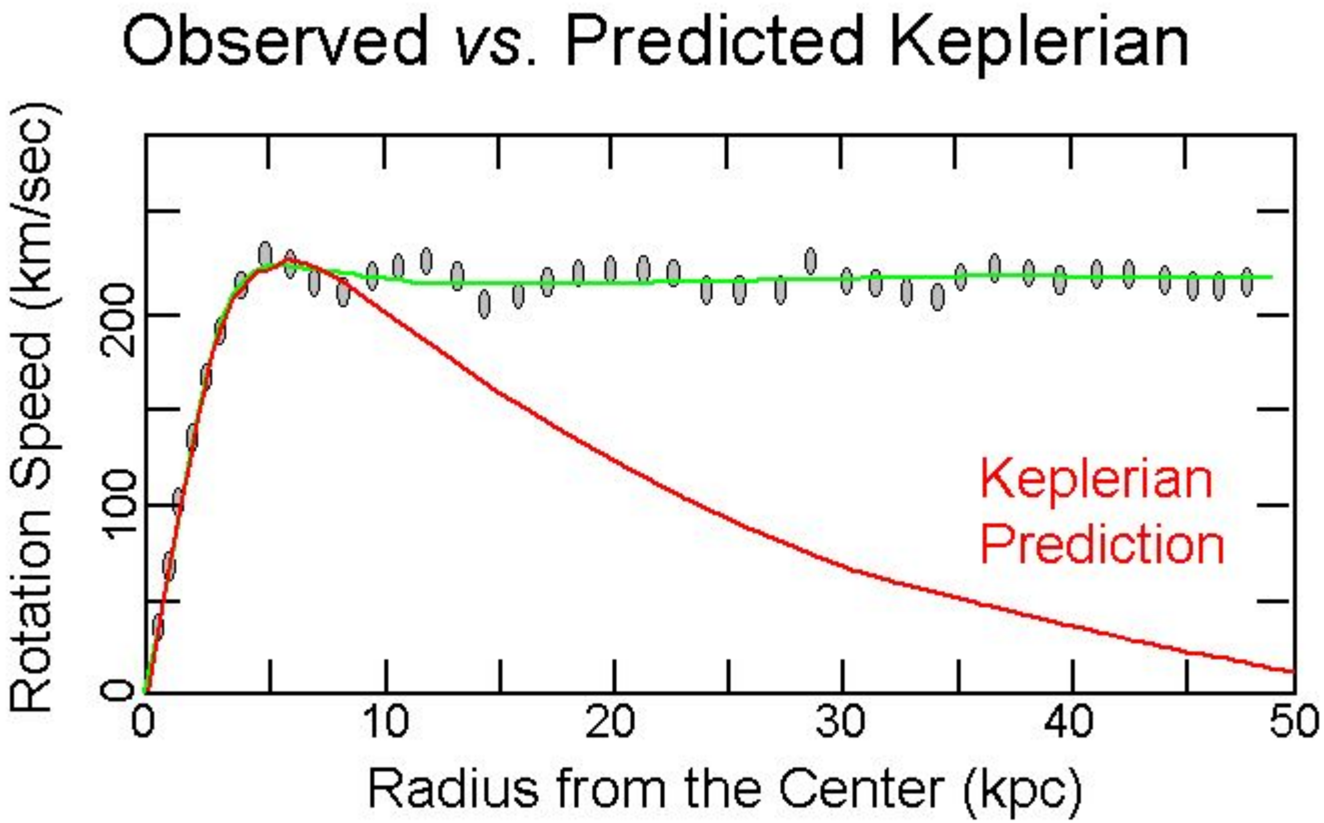

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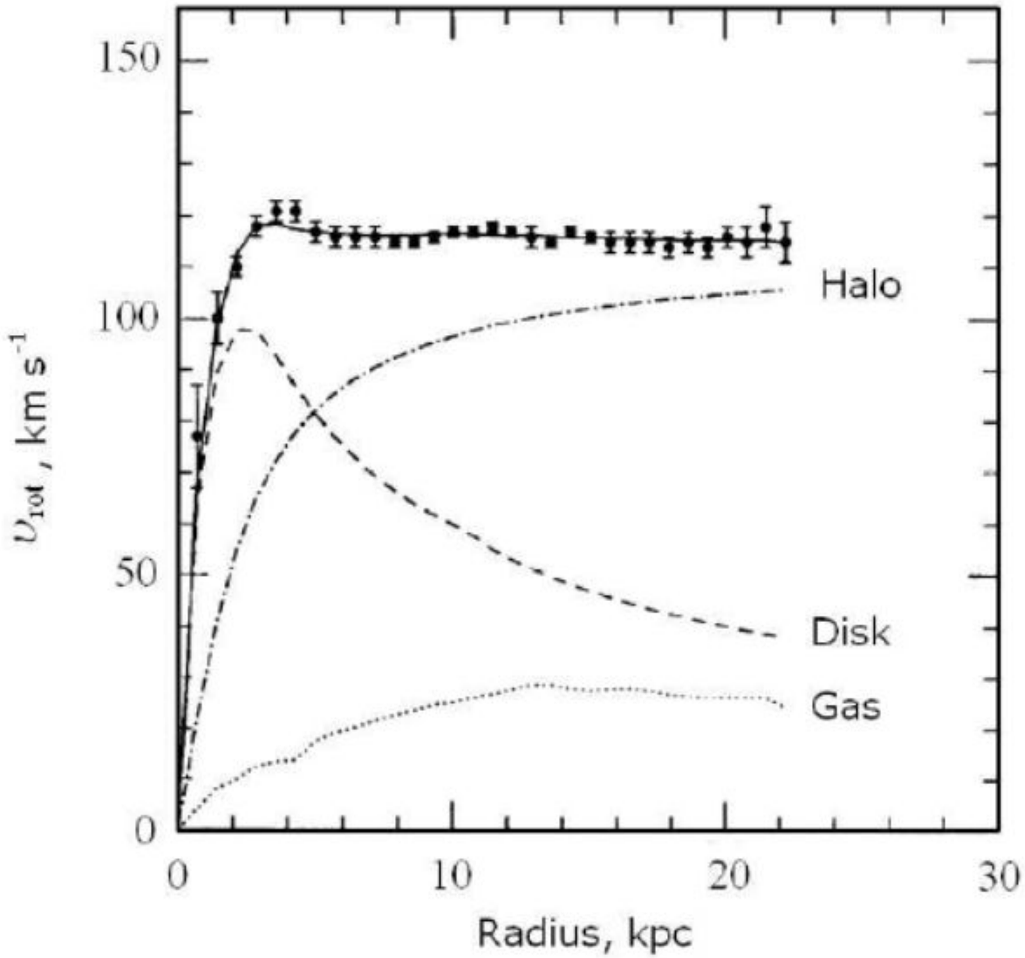
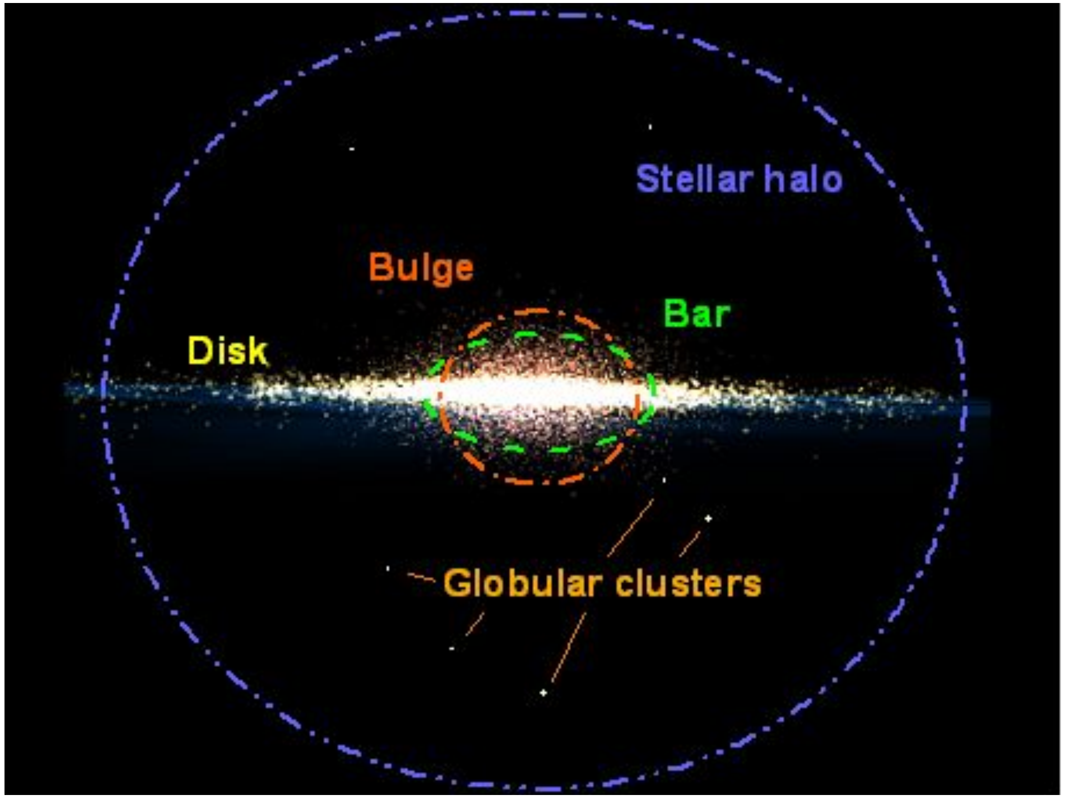


# Galaxy halo

At high R the velocity of two stars is similar and from: $$M = \frac{v^2}{G} \cdot R$$

Derives that: $$M \propto R$$

Isothermal Sphere $$\rho \propto \frac{M}{V} = \frac{R}{R^3} = \frac{1}{R^2}$$



# Galaxy Formation



**PHASE 1**

**Age:** Before the recombination of the Universe (~380,000 years after the Big Bang)

- Baryons are ionized and interacts with photons
- DM does not interact with the photons → collapse once matter dominates over radiation

**PHASE 2**

**Age:** During recombination

- Baryons decouple from the photons → can fall into the DM halo potential well

Hydrogen 75% - Helium 24%

Gas dissipates → rotating discs (angular momentum due to tidal torques in the halo is concerved)

Local gravitational instability → gas forms stars

# Galaxy Formation

**Hierarchical model:** galaxies form and evolve through successive mergers of smaller bodies and their fate is dependent on the environment which they inhabit.

Pros

– Mergers are seen

– Ellipticals in high density environments

– Irrs isolated

Cons

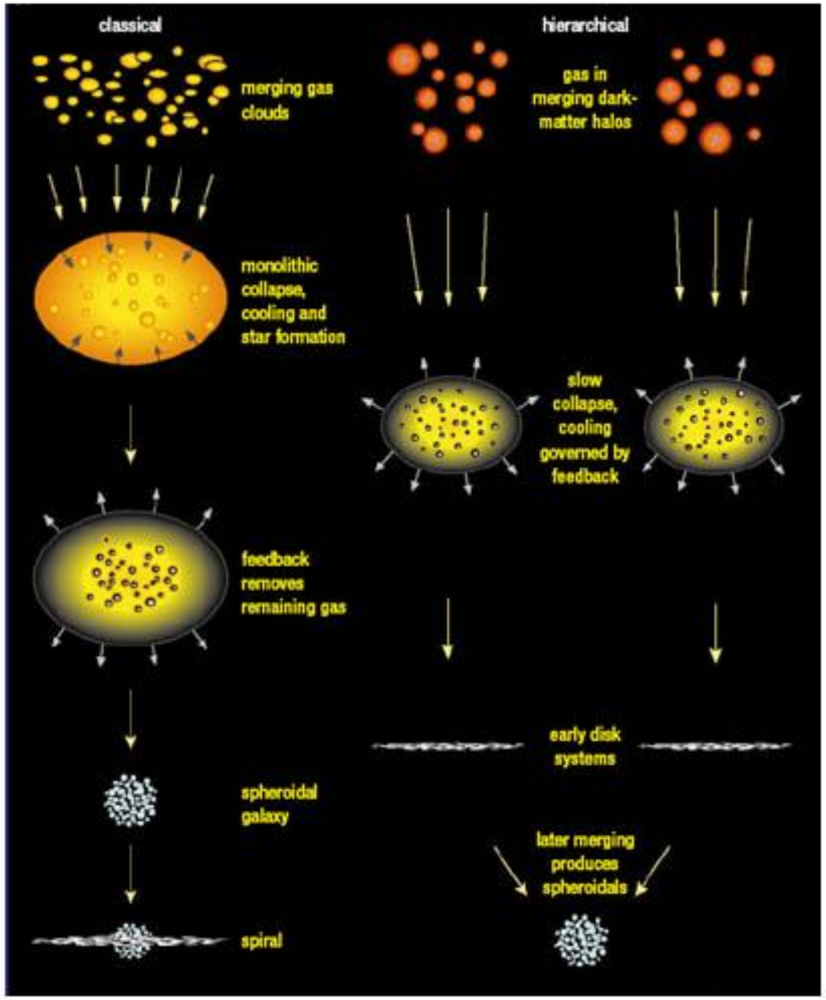
– Ellipticals saw at early epochs

– Irregulars forming today

Merging of 2 discs with randomly oriented angular momenta → lower angular momenta

Multiple minor mergers → massive bulges

Major mergers (mass ratio close to 1) → elliptical galaxies (spheroid)



# Galaxy Formation

**Monolithic scenario**: galaxies form and evolve as relatively isolated bodies. Their physical properties are determined by the initial condition.

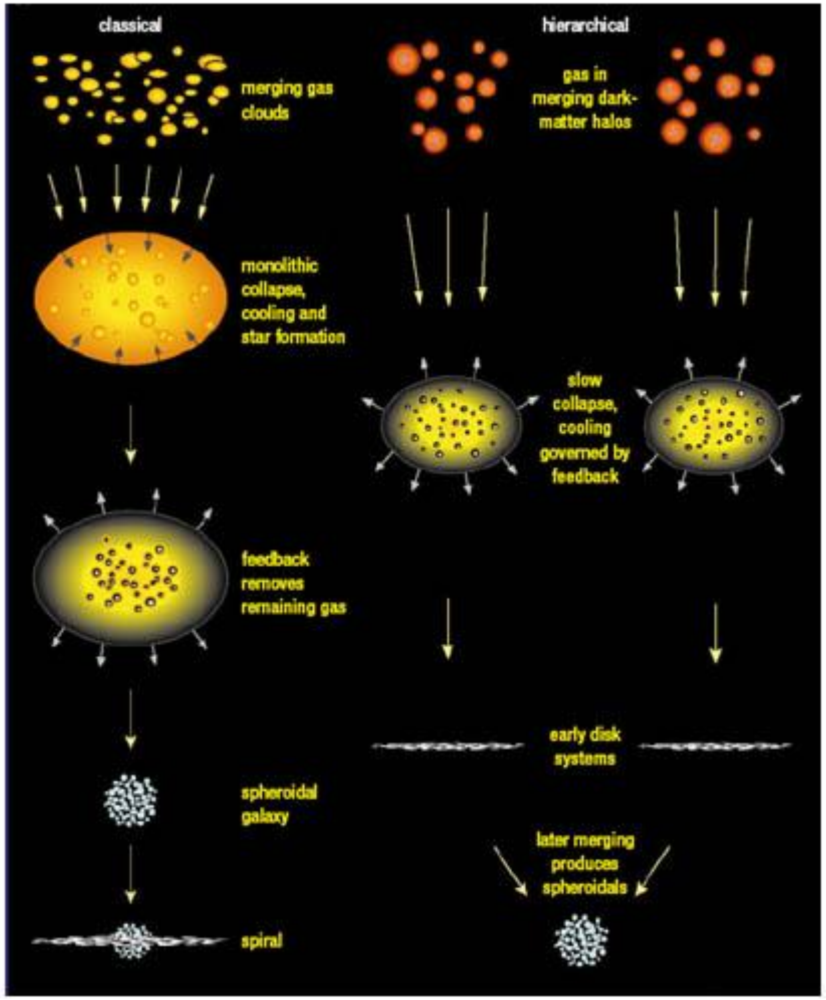
Pros:

- Ellipticals are old
- Ellipticals are seen at high z
- Spirals/Irrs rotating
- Irregulars forming today

Cons:

- Mergers are seen

If star formation occurs more quickly than the collapse time → spheroid forms first → disc forms later through gas accretion



# Galaxy Formation



Hybrid Hierarchical Model: a combination of the two models. The small variations in CMB show that the distribution of matter in the early universe was slightly clumped. These clumps formed the cores of the first protogalaxies.

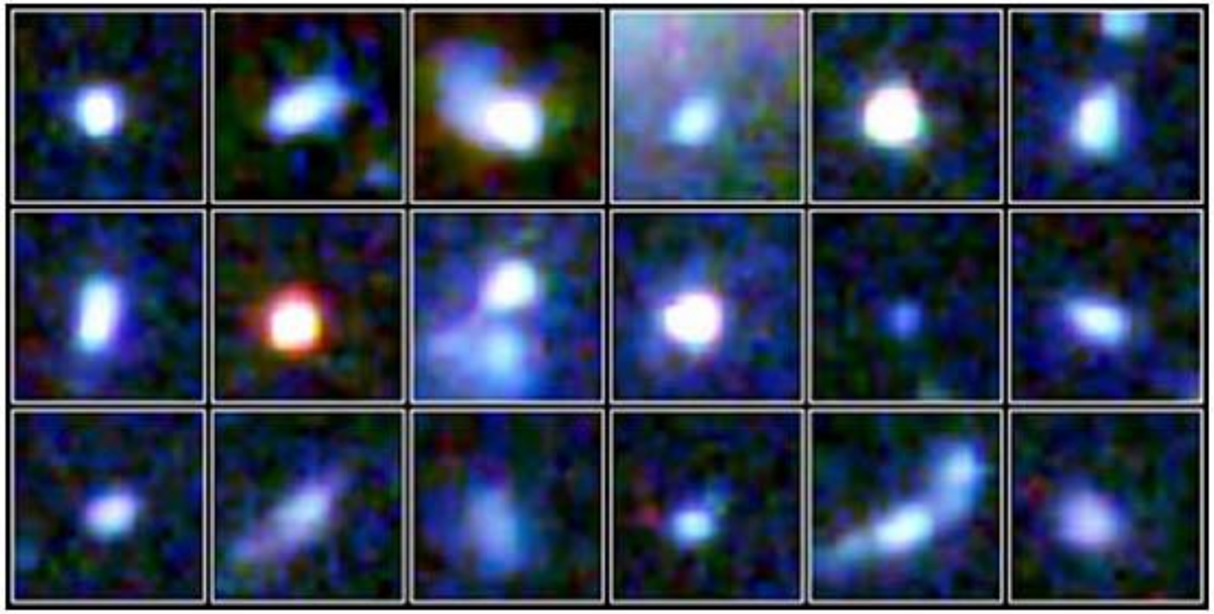
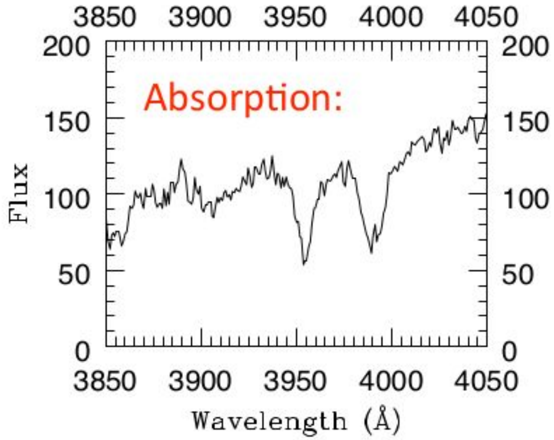


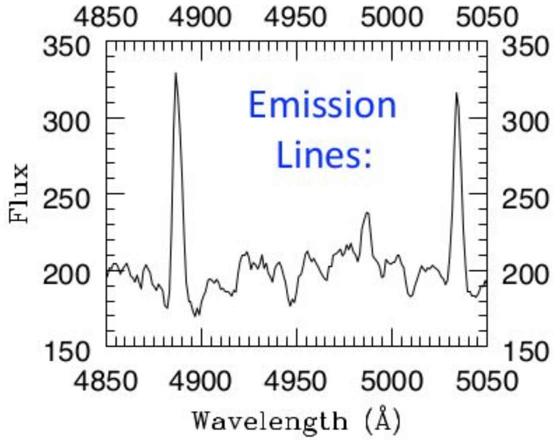
**Figure 5:** These 18 small blue objects imaged by the HST could be the precursors to galaxies we see in the universe today.

# Spectrum



Example galaxy spectrum:



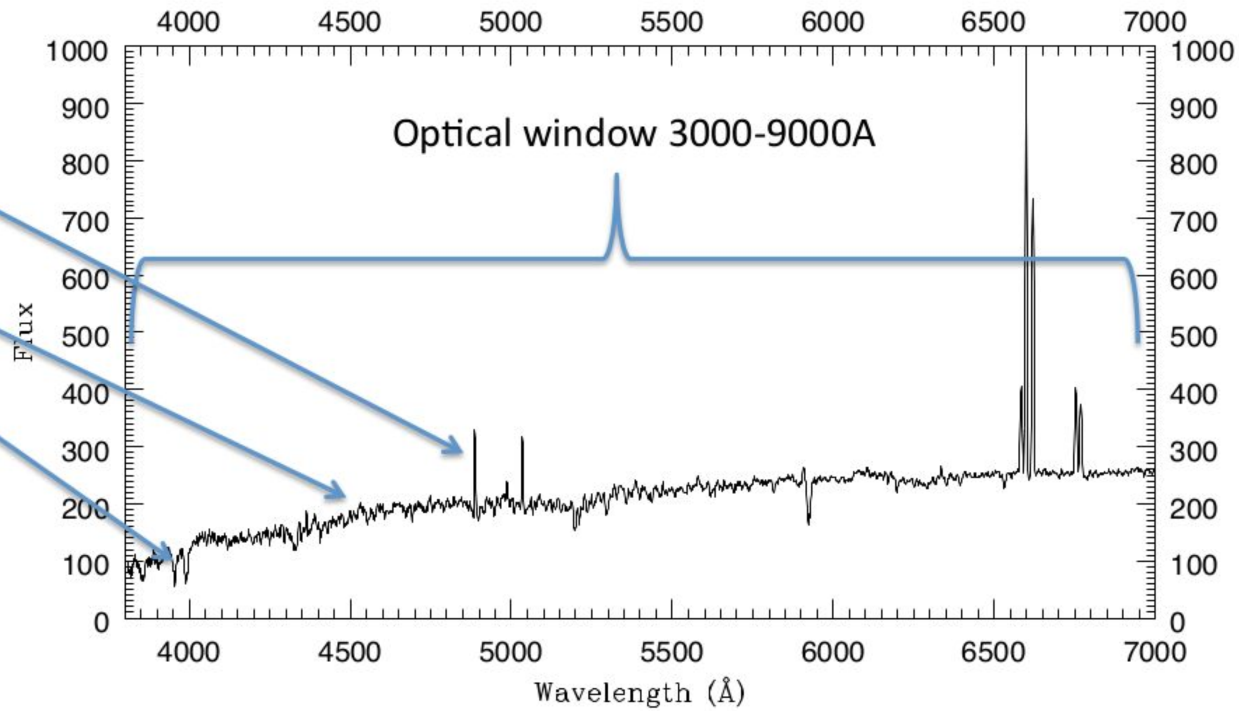




Features:

Emission lines

Continuum

Absorption lines



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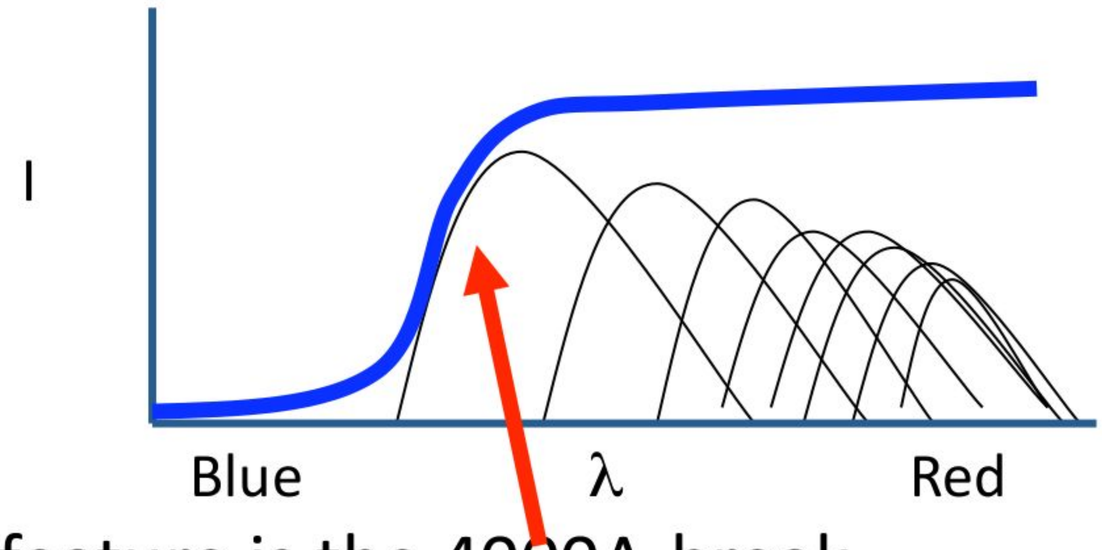
# Continuum

- The combination of many Black-Body spectra spanning a range in temperatures
- This produces a fairly flat overall spectrum




- The main feature is the 4000A-break

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# $D_n4000$

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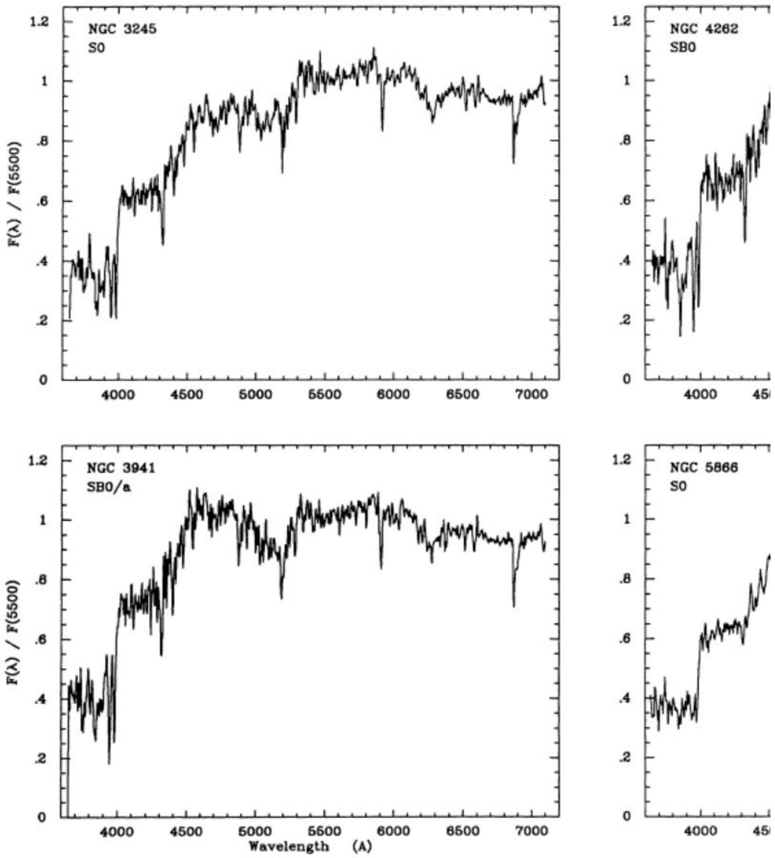
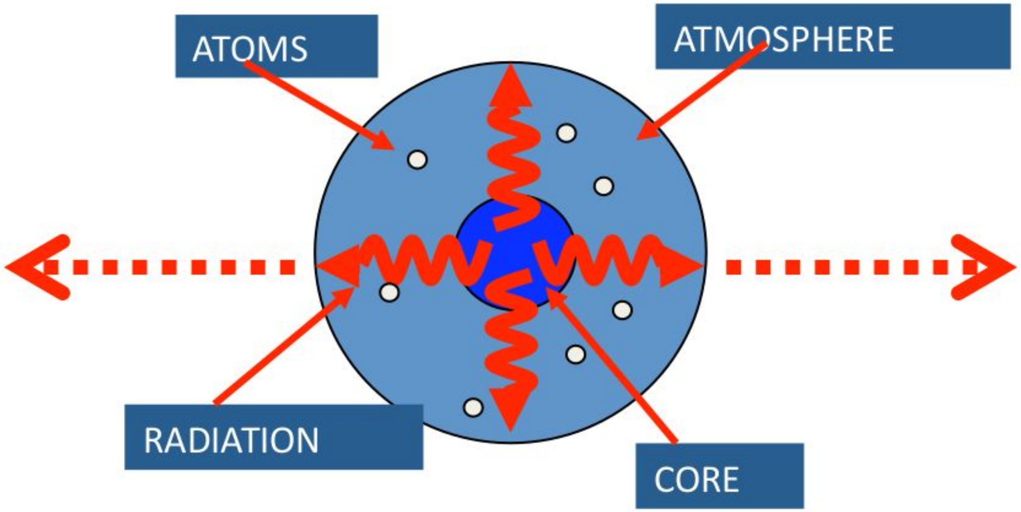



## The 4000A-break

- Caused by:
  - blanket absorption of high energy radiation from metals in the stellar atmospheres
  - the lack of hot blue stars
- Hence:
  - Ellipticals => A strong 4000A-Break
  - Spirals => A weak 4000A-Break
  - Irregulars => No 4000A-Break

# Absorption Lines

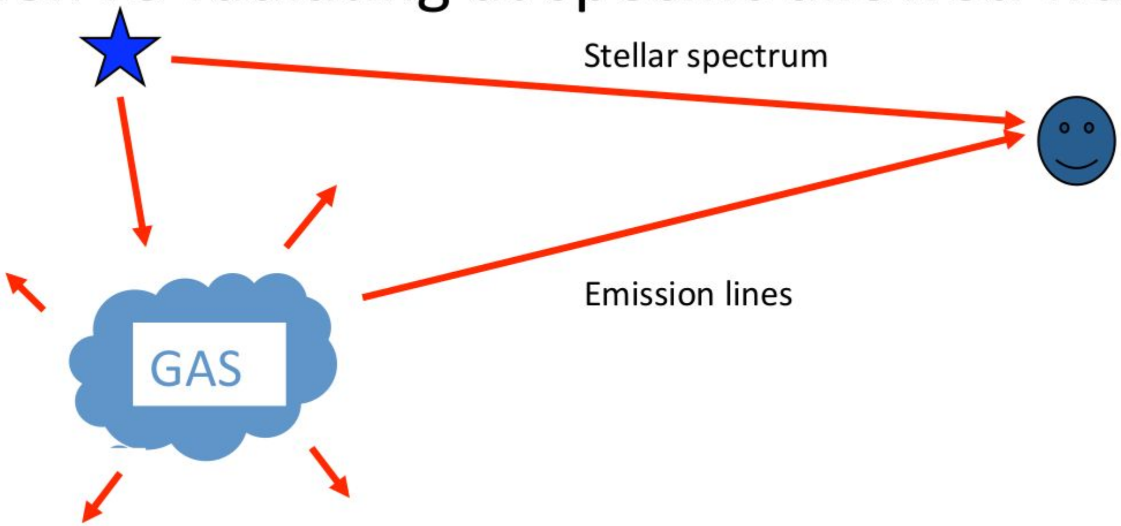
- Caused by Atoms/Molecules in a star's atmosphere that absorb specific wavelengths




- Can also be due to COLD gas in the interstellar medium which can EXTRACT energy from the passing radiation

# Emission Lines

- Caused by gas being ionized and heated and then re-radiating at specific allowed wavelengths




- Stars form from gas so are often embedded
- Young stars ionise gas which releases radiation at a specific wavelength as it recombines

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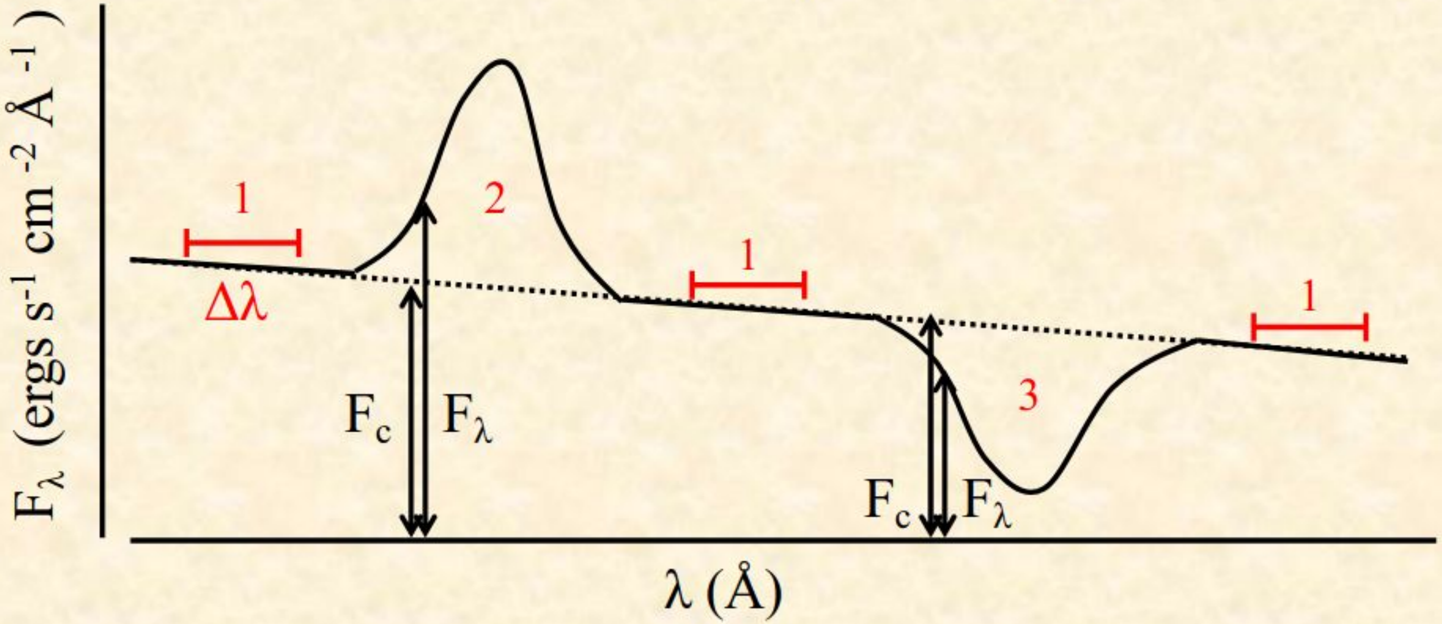
# Absorption / Emission Lines

- Absorption Lines
  - Need metals in stellar atmospheres or cold gas in the interstellar medium
- Implies
  - Old stellar population = old galaxy
- From
  - Ellipticals
  - Spiral Bulges

- Emission Lines
  - Need very hot gas and O and B type stars
- Implies
  - Newly formed stars = star-forming/young galaxy
- From
  - Spiral Disks
  - Irregulars

# Basics of Spectroscopy




Units:

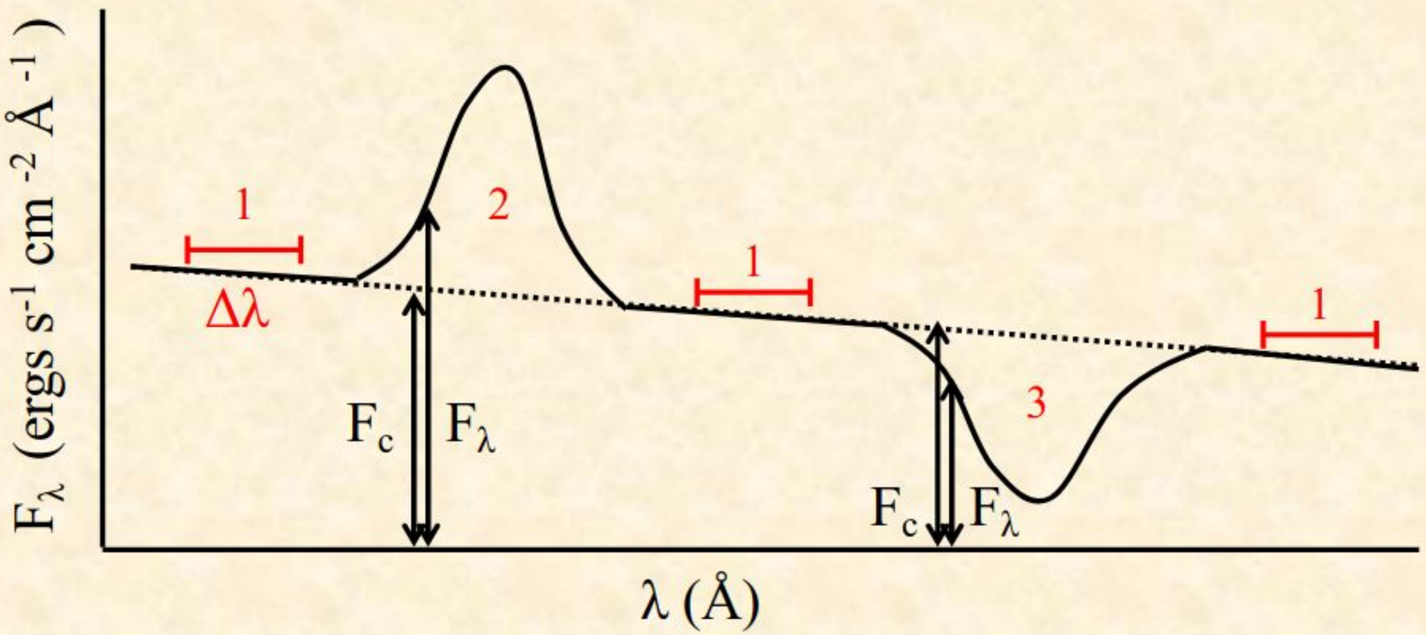
1. Continuum Flux: $F_c = \dfrac{\int F_\lambda \, d\lambda}{\Delta\lambda} = \langle F_\lambda \rangle$ (ergs $s^{-1}$ cm $^{-2}$ Å $^{-1}$ )

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

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

# Basic of Spectroscopy

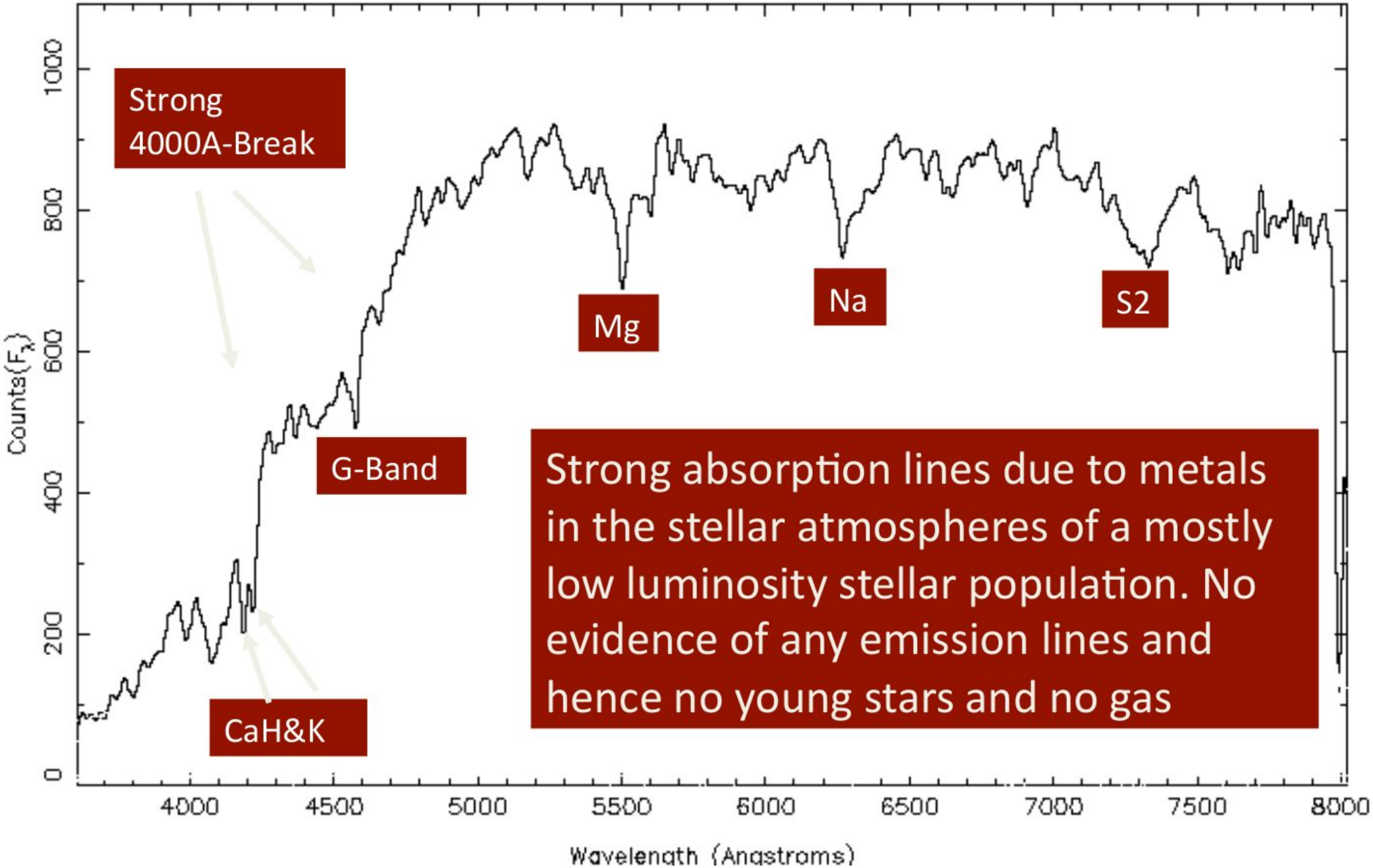




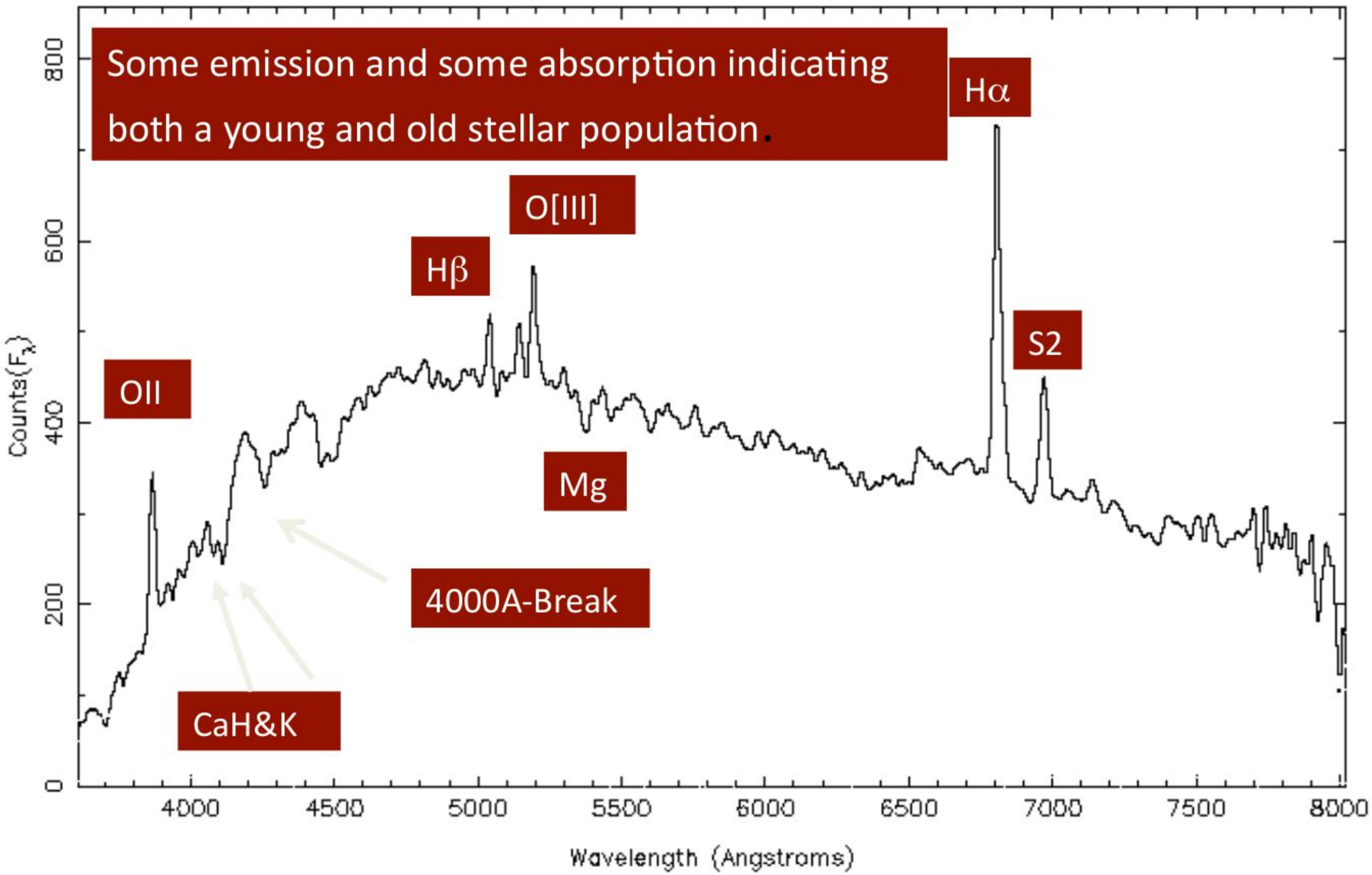

3b. Absorption-Line Centroid: $$\lambda_c = \frac{\int \lambda (F_c - F_\lambda) d\lambda}{\int (F_c - F_\lambda) d\lambda}$$ (Å)

3c. Radial Velocity Centroid: (nonrelativistic) $$v_r = \frac{\lambda_c - \lambda_{lab}}{\lambda_{lab}} c$$ (km s$^{-1}$)

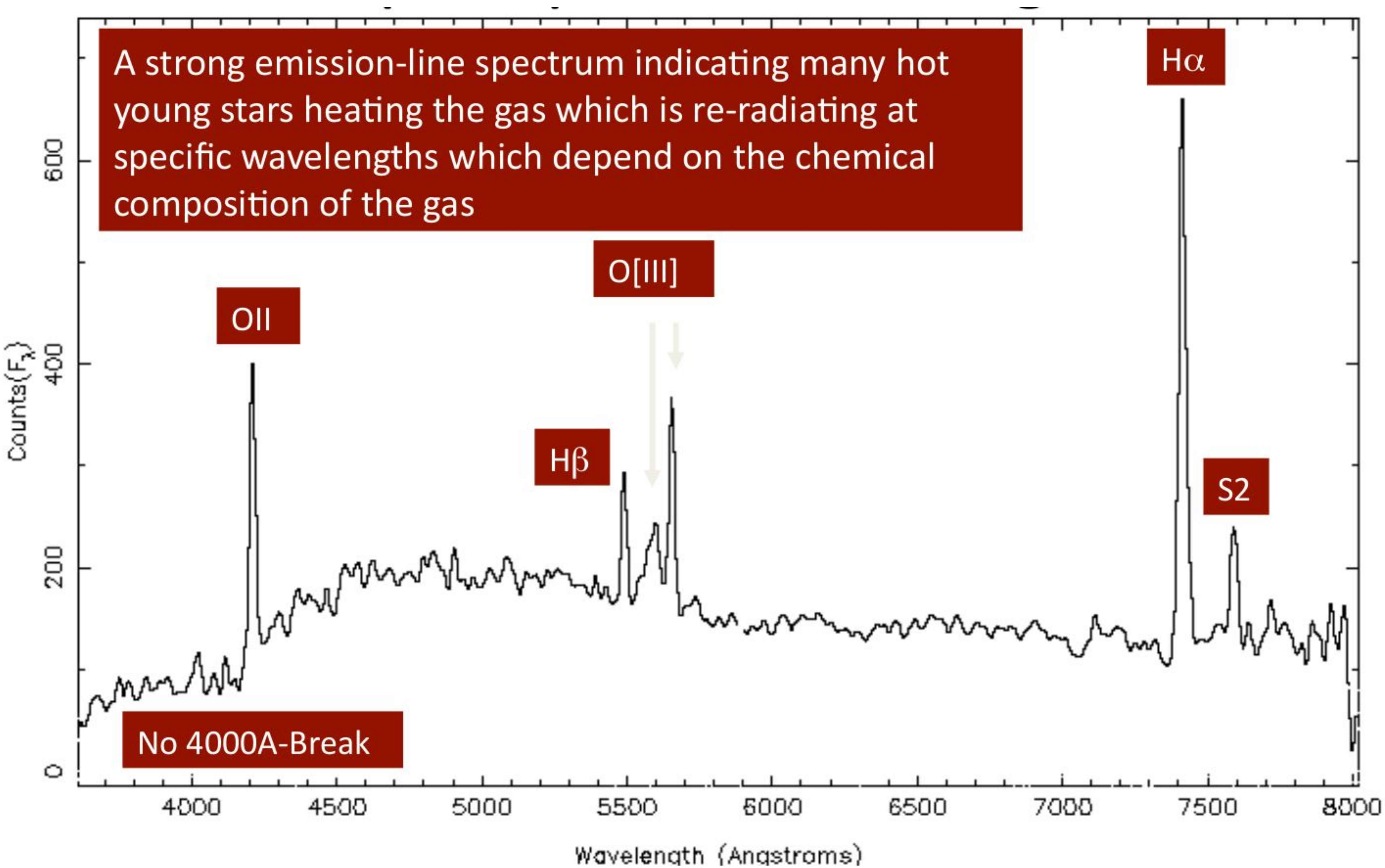
# Example: Elliptical



# Example: Spiral

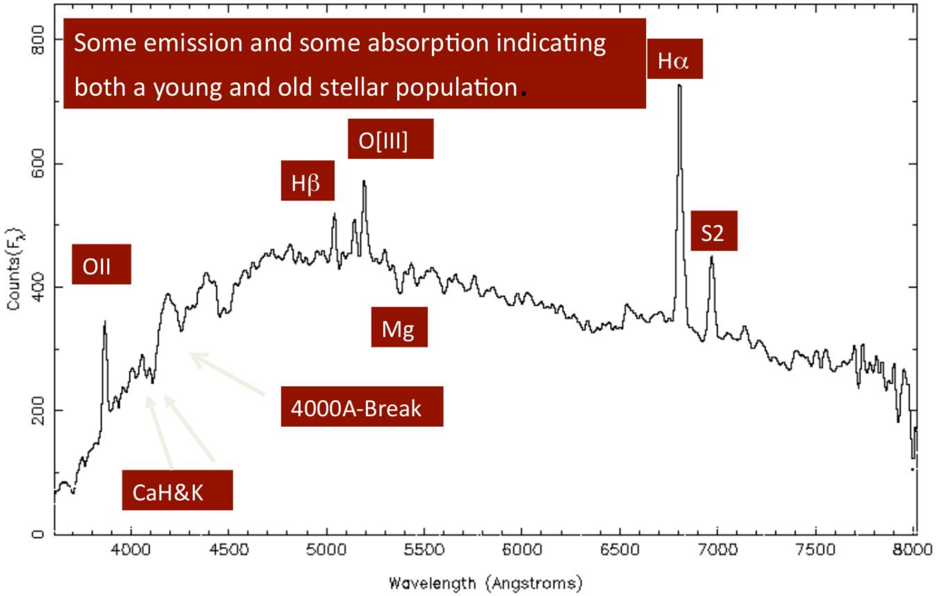


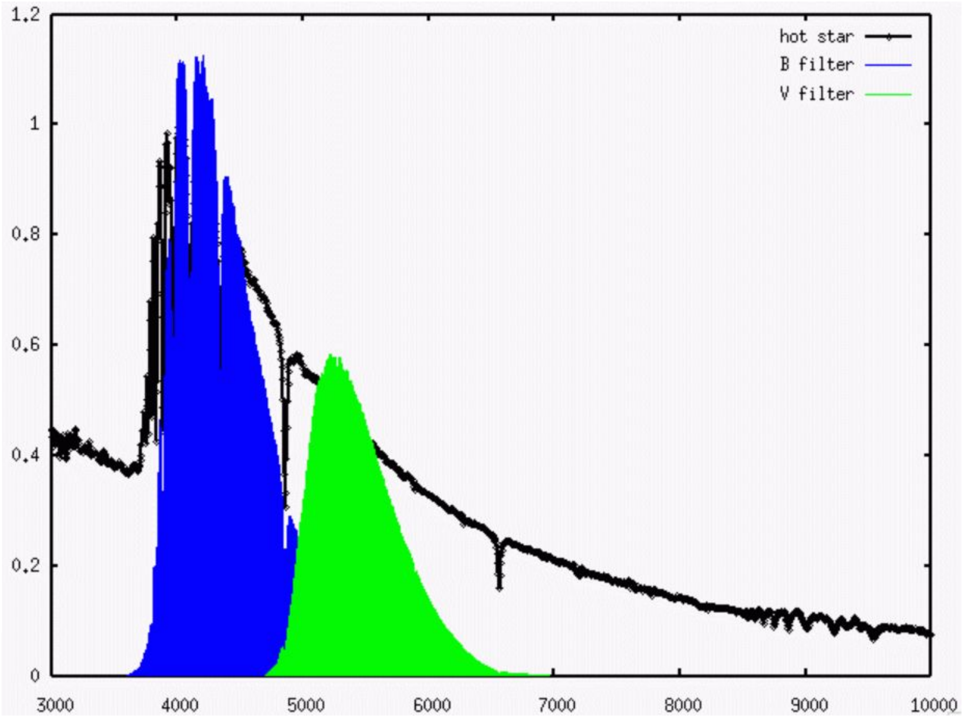
# Example: Irregular



# Spectrum: S0 & Spirals

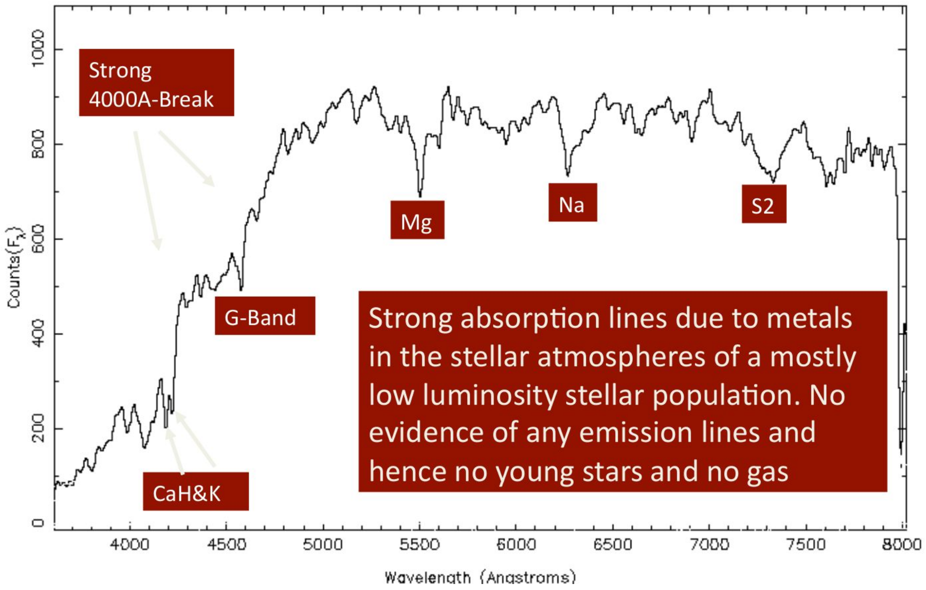
- SO similar to E in terms of old stellar populations
- Sa/Sb have stronger Balmer lines (A, F stars) and bluer continua
- Sc have emission lines from H II regions (young hot stars)
- Starburst galaxies have very strong emission lines and blue continua

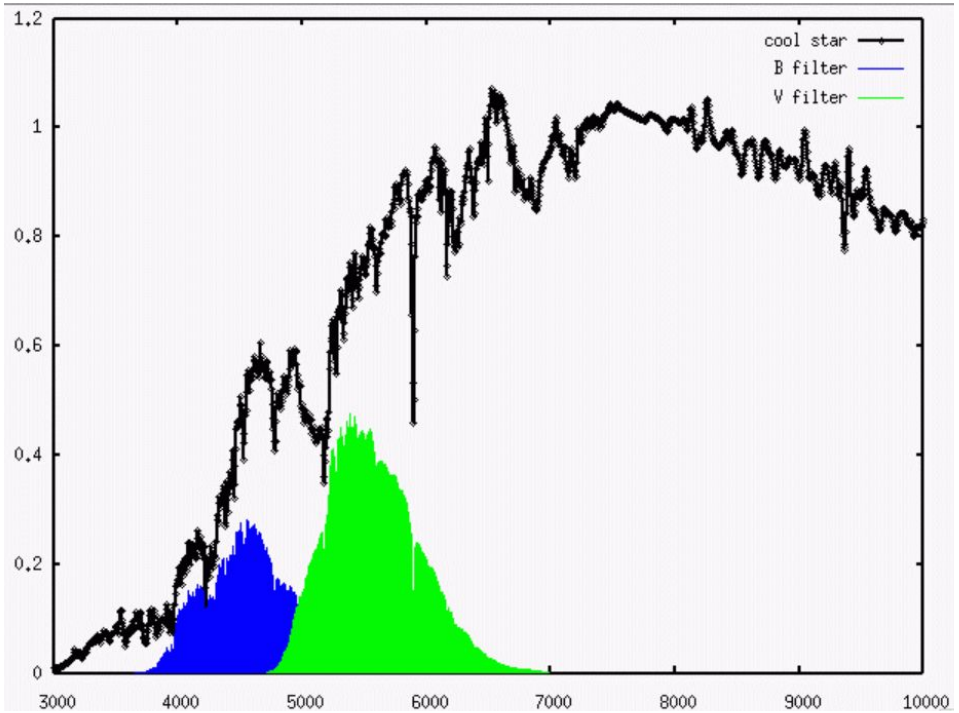


# Spectrum: Ellipticals

- Features from giant G and K stars
- In the optical stellar absorption
- Ca II H, K and NaI D can come from ISM as well (but not much in Ellipticals)
- Lines are broadened from stellar motions
- CaII triplet lines at ~8500 Å are good for kinematics (well separated, uncontaminated)



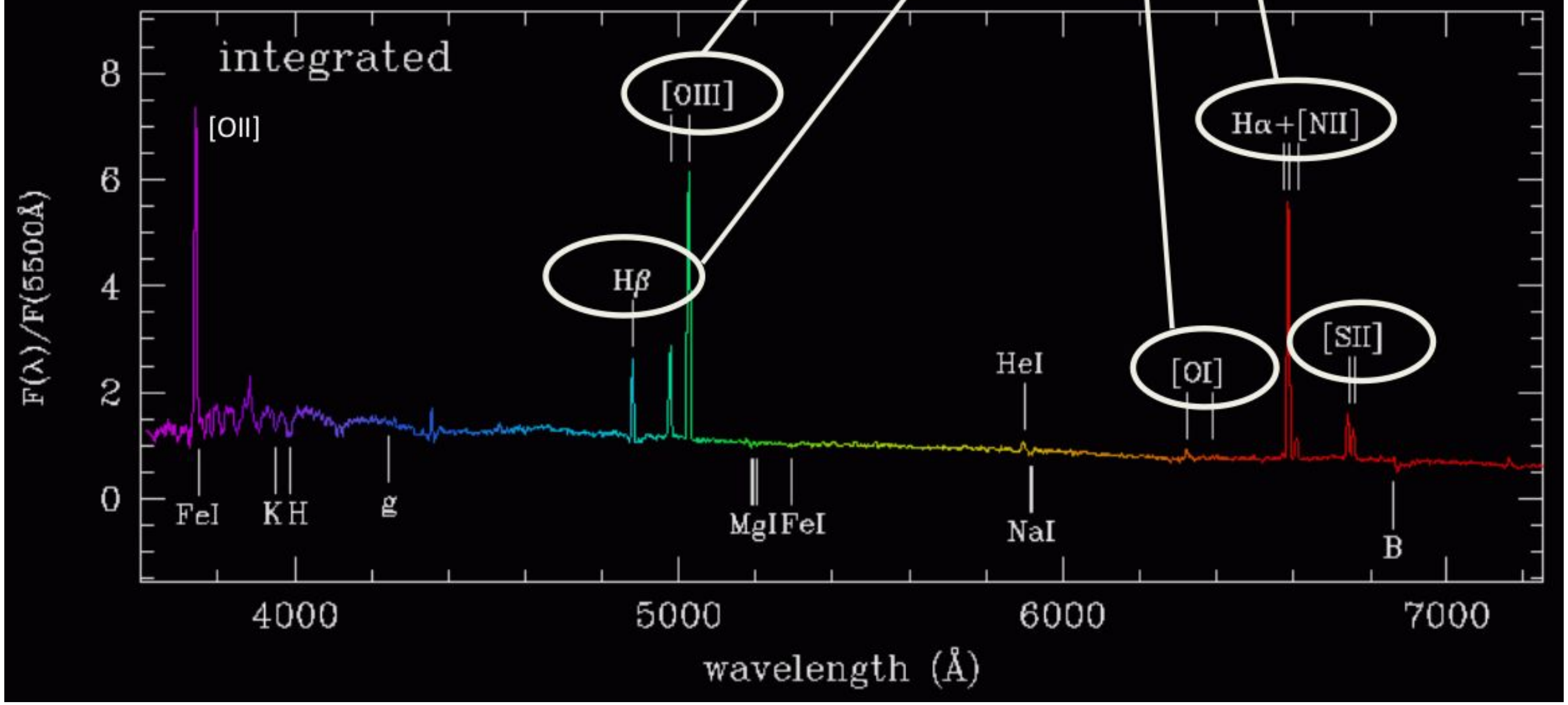



# Typical Spectral features

- Absorption
  - Ca(H) = 3933.7A
  - Ca(K) = 3968.5A
  - G-band = 4304.4A
  - Mg = 5175.3A
  - Na = 5894.0 A
- Emission
  - O[II] = 3727.3A
  - Hδ = 4102.8A
  - Hγ = 4340.0A
  - Hβ = 4861.3A
  - O[III] = 4959.0A
  - O[III] = 5006.8A
  - Hα = 6562.8A
  - S2 = 6716.0A

# Spectral Diagnostics

- Metallicity
- Star Formation Rate
- Electron Density
- Ionizing Source

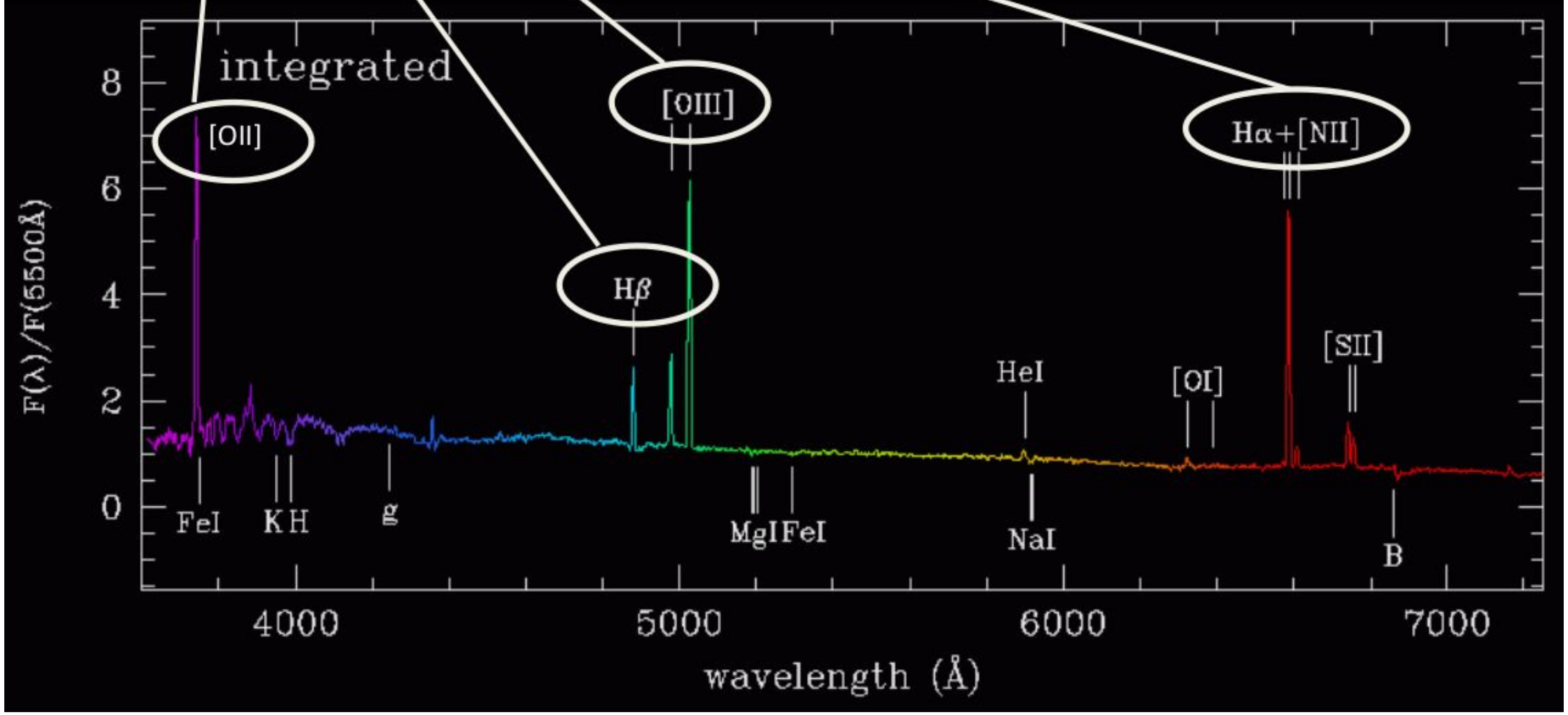


# Spectral diagnostics

- Metallicity (amount of metals)

$Z = \log(O/H)+12$

Solar = 8.69 (Asplund)



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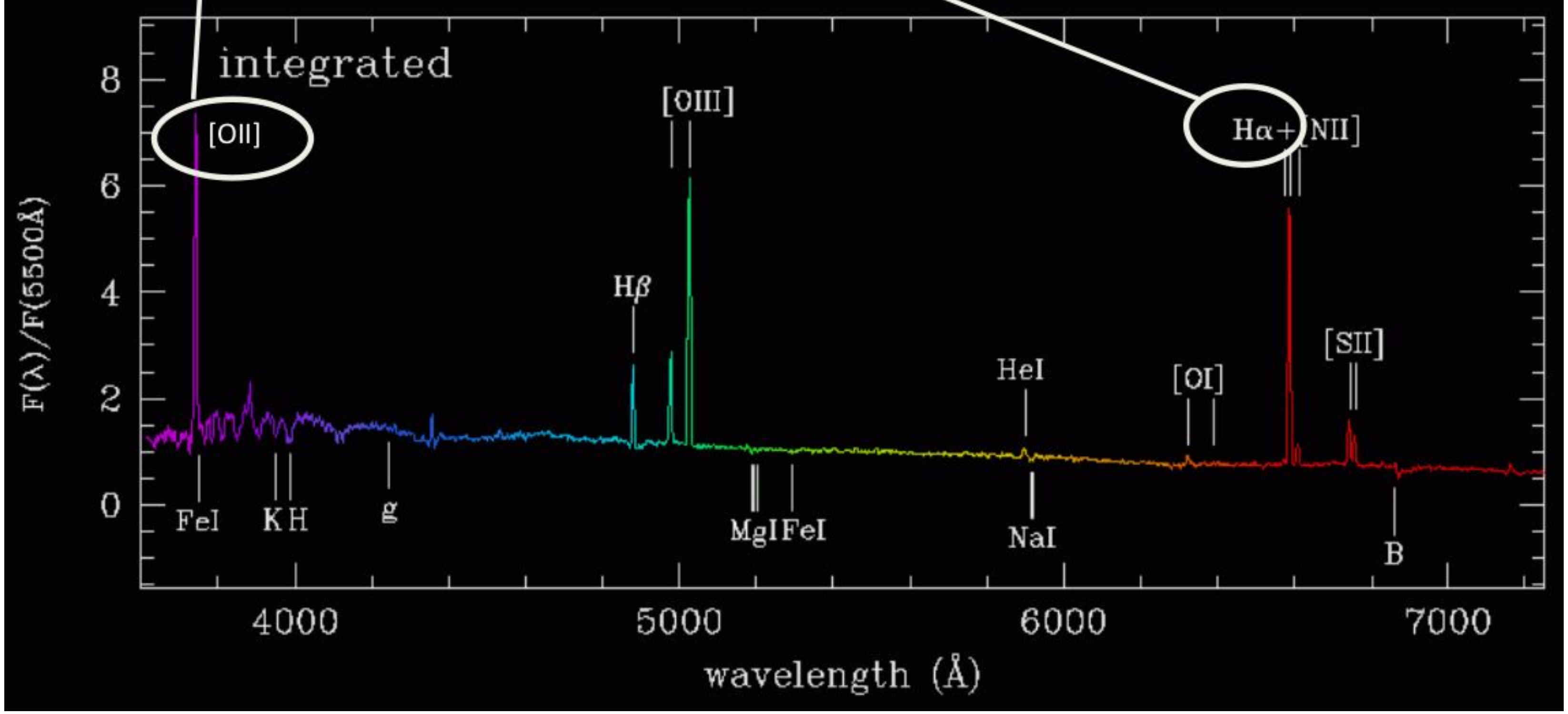

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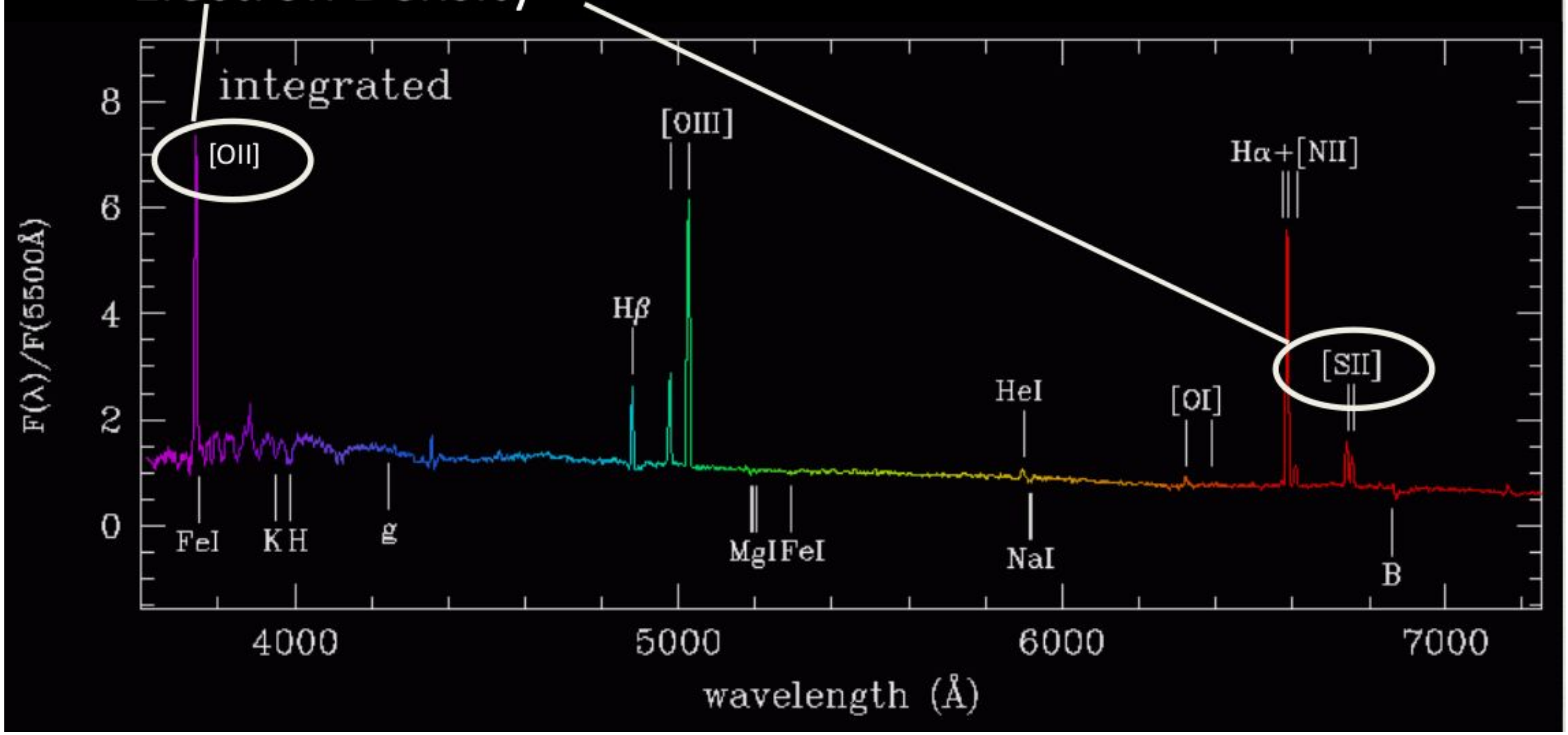

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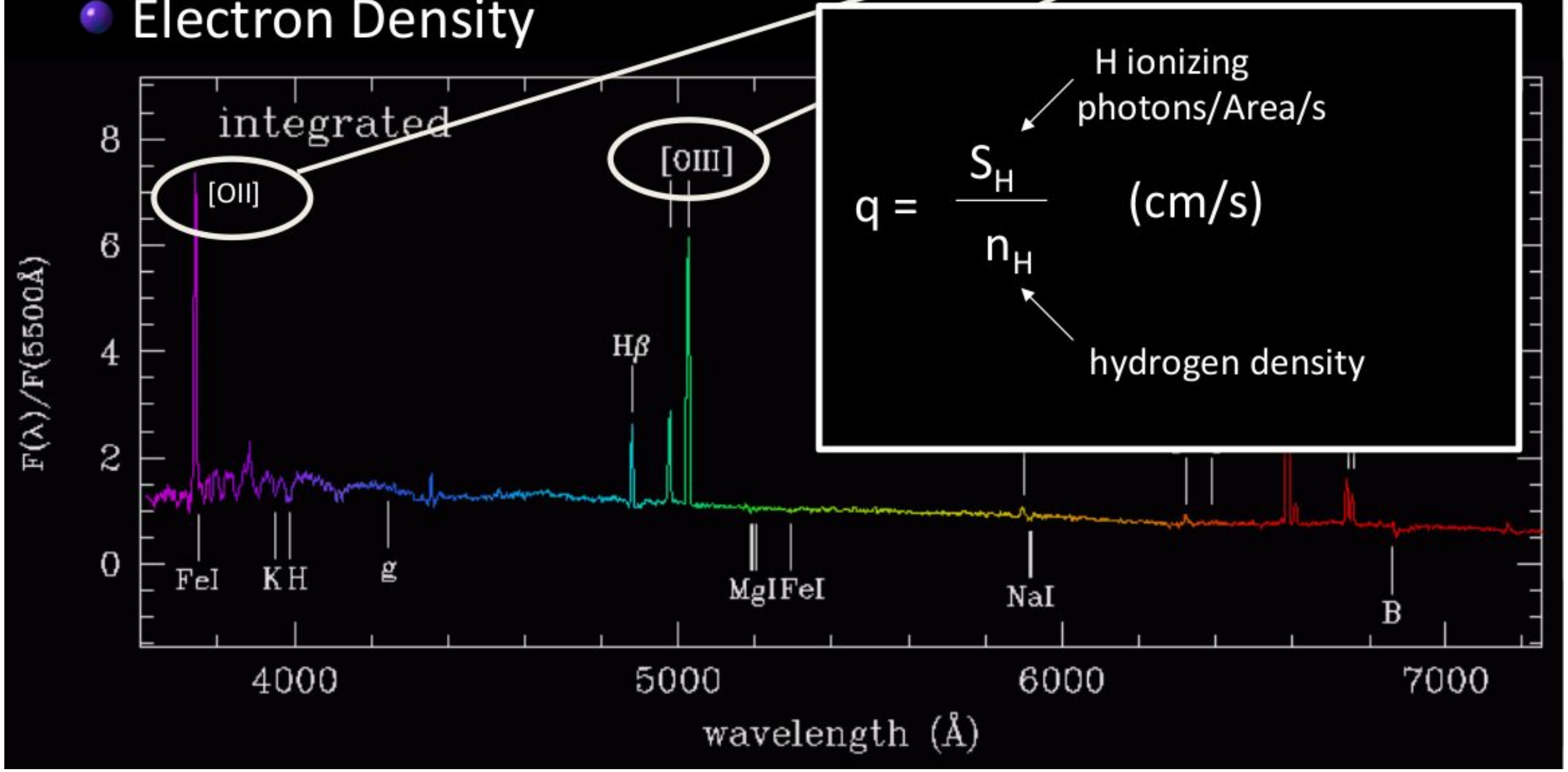
# Spectral Diagnostics

- Metallicity
- Star Formation Rate
- Electron Density
- Ionizing Source
- Ionization Parameter



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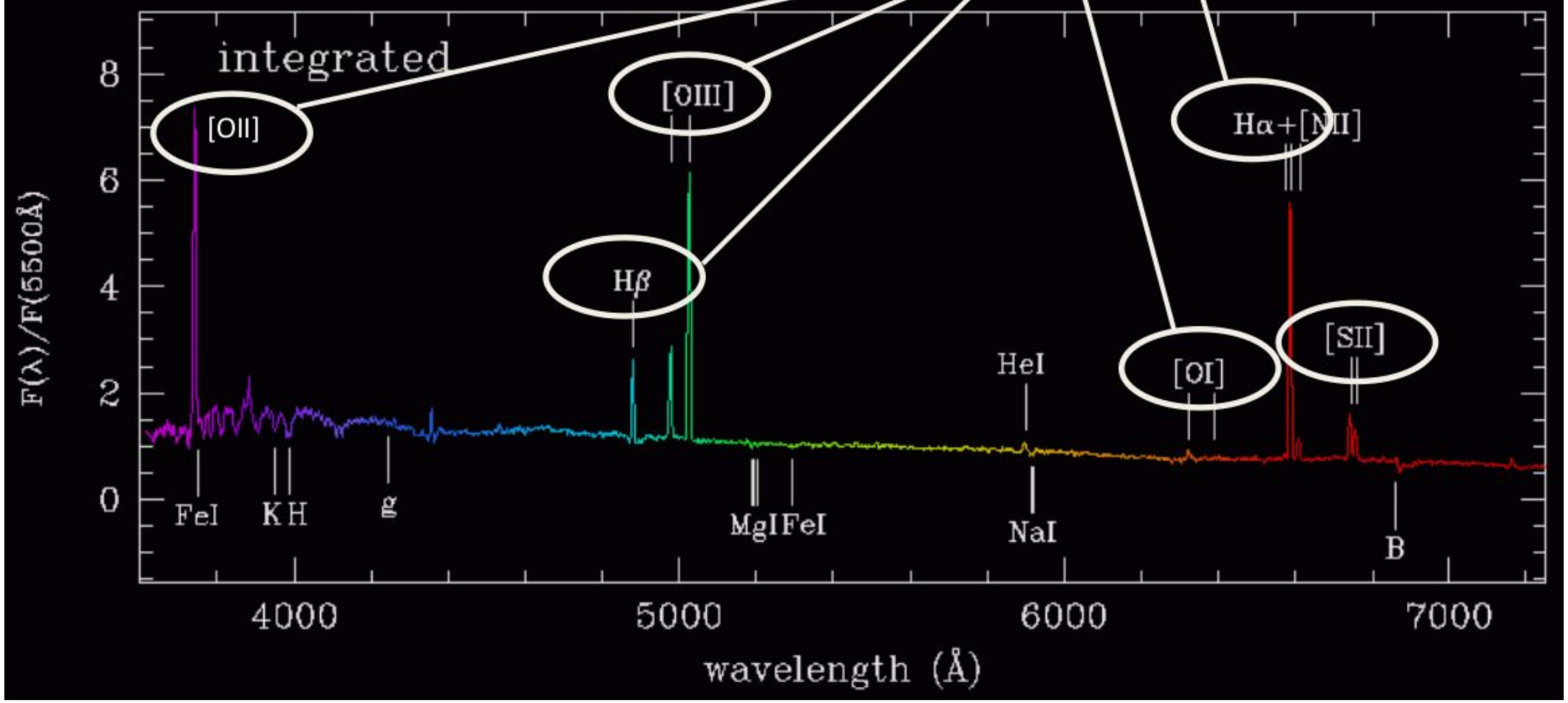
# Spectral Diagnostics

- Metallicity
- Star Formation Rate
- Electron Density
- Ionizing Source
- Ionization Parameter
- Shock properties



# What did we learn?

1. What is galaxy kinematics
2. How DM was discovered
3. Galaxy Formation theory
4. Physical parameters from spectral analysis