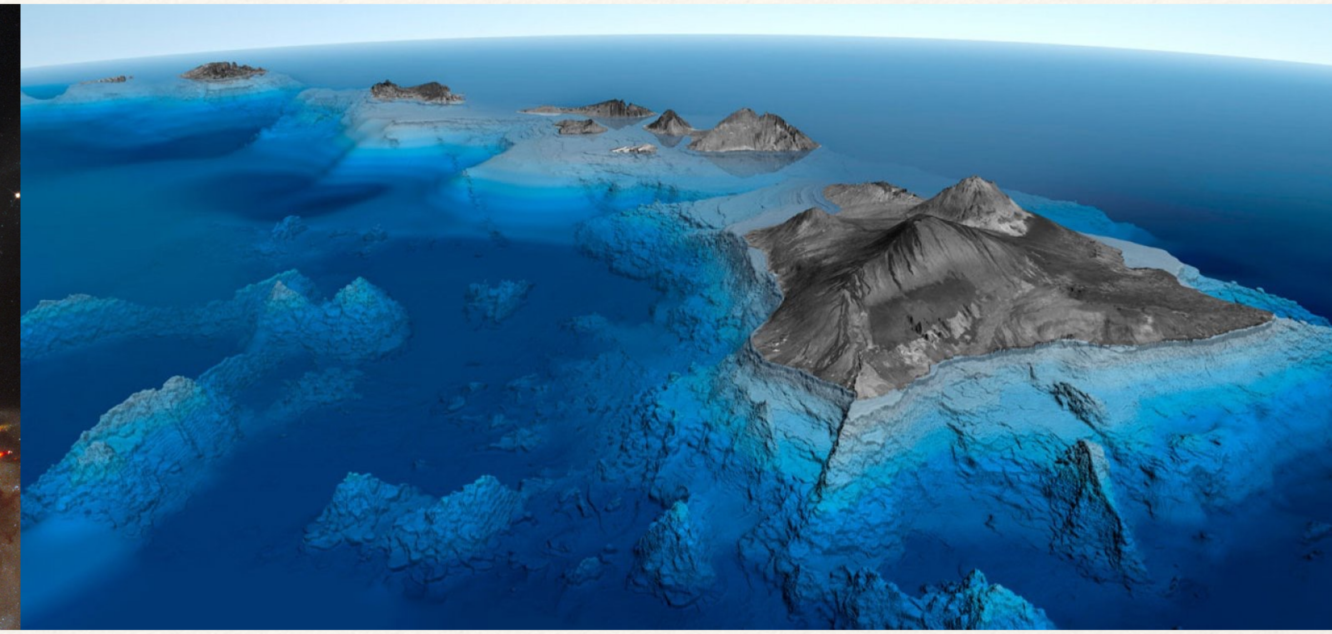


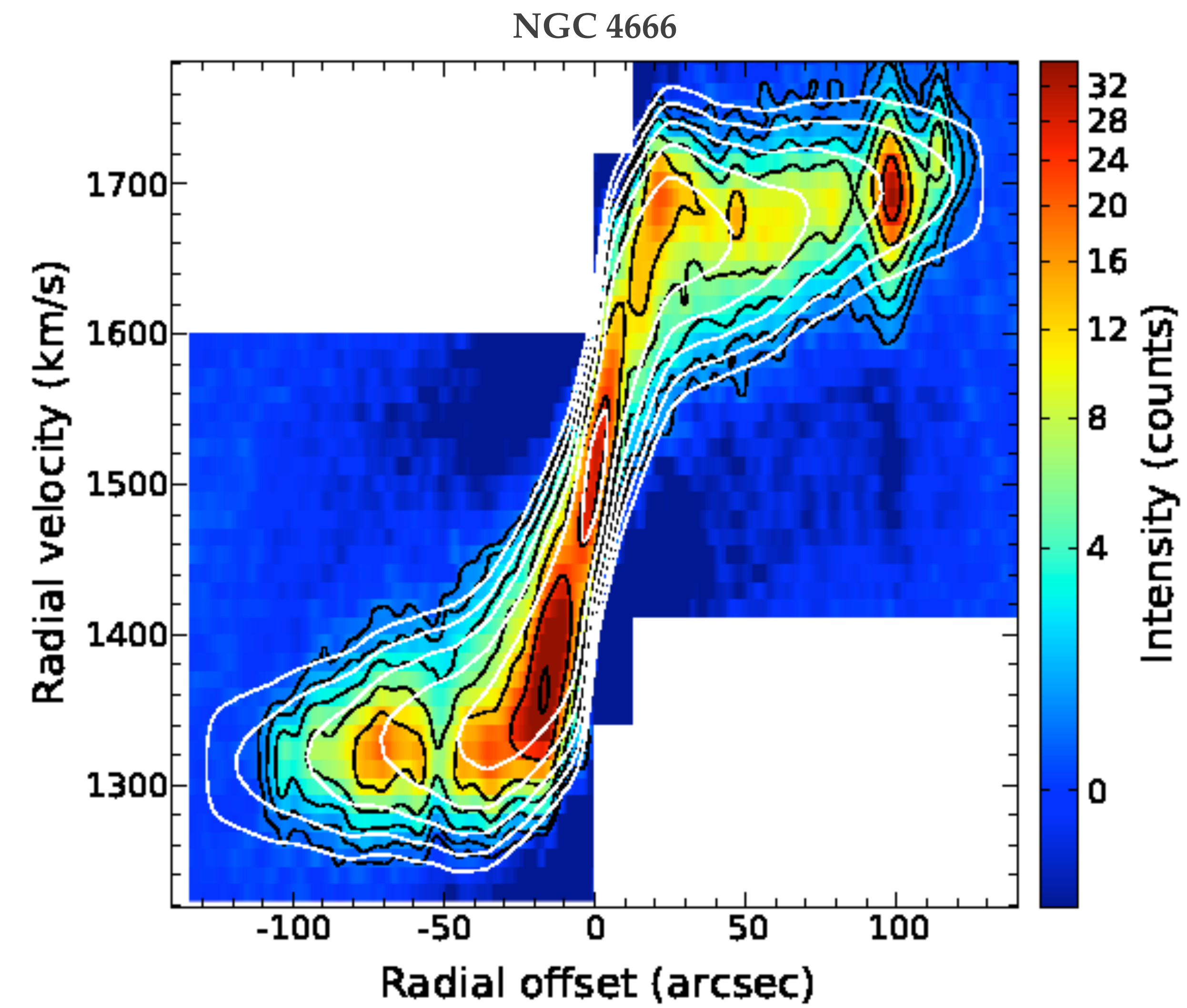
Getting to know the "island universes" out there.

Galaxies I

ASTR 555
Dr. Jon Holtzman

Warm-up

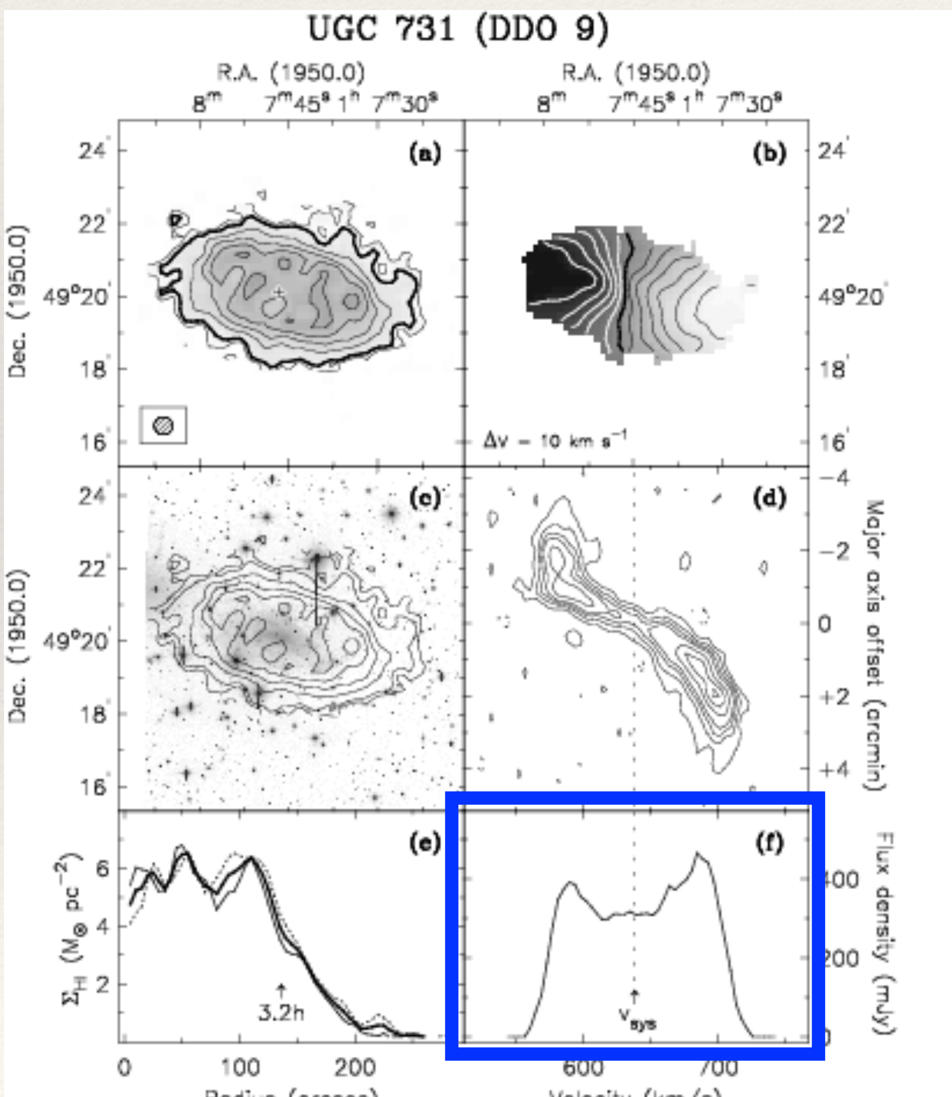
- Consider the PV diagram for NGC 4666.
  - How would you estimate the dynamical mass of this galaxy?
  - What kinematic observation could you make even if your telescope couldn't spatially resolve this galaxy?



Voigtländer et al. 2013

Galaxy Population - Spirals/Disks: Kinematics

- **Unresolved HI profiles** — rotation characterized by line widths, e.g. W_{50}, W_{20} (width at 50%, 20% of peak line flux)



Swaters et al. 2002

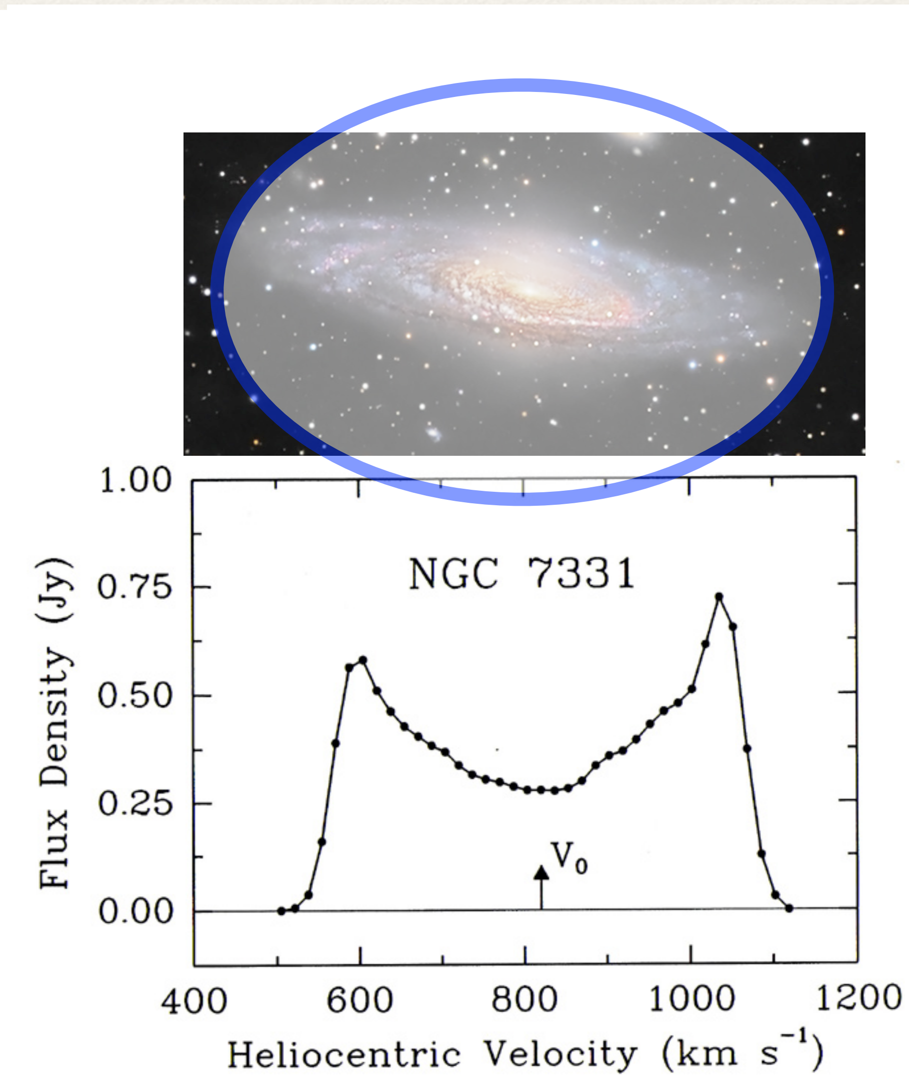
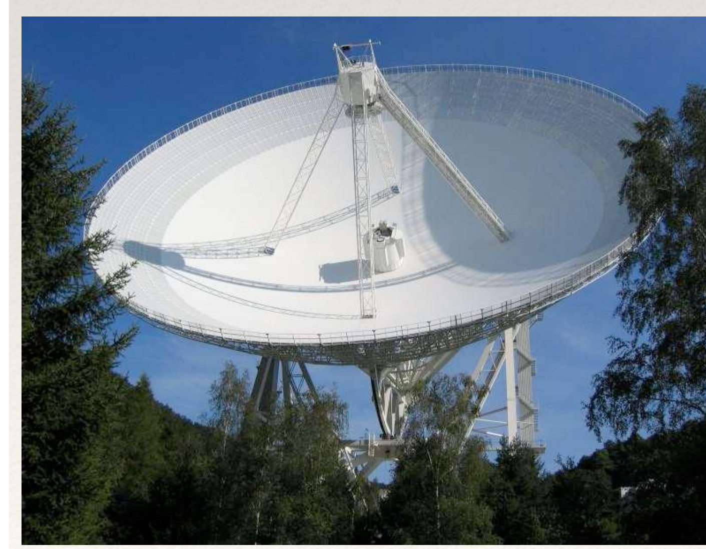


Fig5.22 (K. Begeman) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007



Effelsberg 100m

Outline for Today

- Galaxy Population - Spirals/Disks:
  - Scaling Relations
  - Spectral Energy Distributions (SEDs)
  - Interstellar Medium (ISM)

NGC1232 (ESO)

Spirals/Disks: Scaling Relations

- **Size-Luminosity Relation** & **Surface Brightness-Luminosity Relation**:
  - more luminous spirals are larger **and** have higher surface brightness at the effective radius

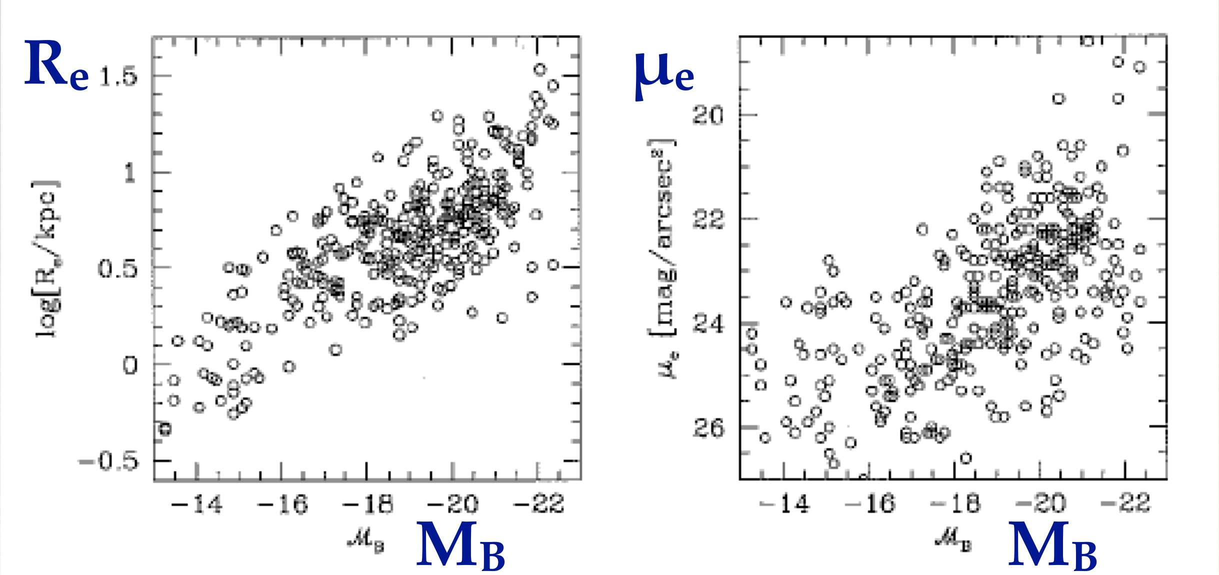
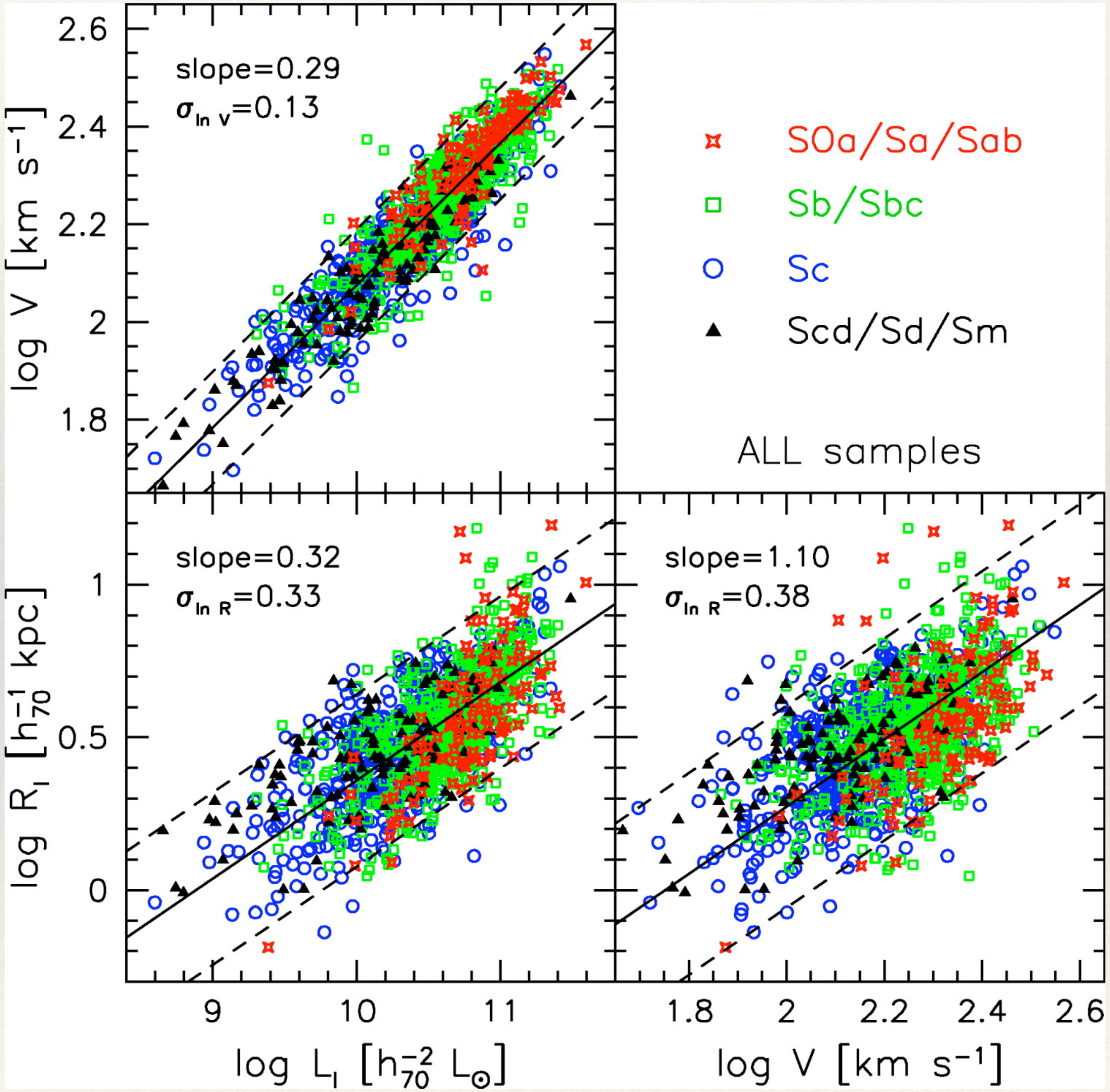


Fig. 2.20. The effective radius (left panel) and the surface brightness at the effective radius (right panel) of disk dominated galaxies plotted against their absolute magnitude in the B-band. [Based on data published in Impey et al. (1996b)]

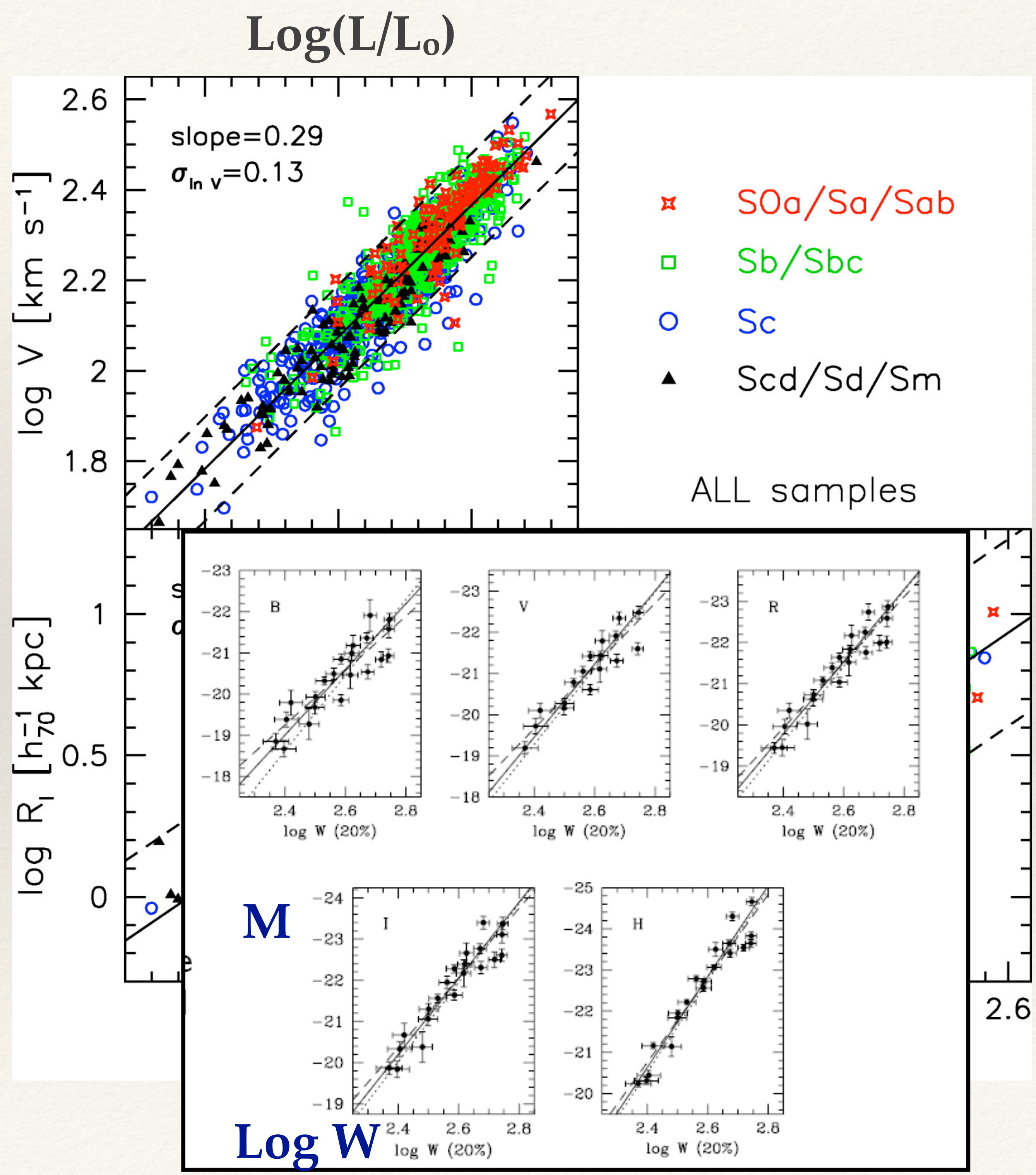
Log(L/Lo)



Courteau et al. 2007

Spirals/Disks: Scaling Relations

- **Tully-Fisher Relation**:
  - Correlation between maximum rotation velocity (or HI linewidth **W**) and luminosity:
    - **L α v$^{3\text{-}4}$**
    - Slope depends on wavelength, definition of velocity, etc.
  - Small scatter — useful distance indicator!
  - Various "explanations" similar to Fundamental Plane with same caveats



Courteau et al. 2007

Virial theorem:

$$-<U>=2<K>$$

$$\frac{GM}{<R>}=<v^2>$$

Note that this is the same that we get from simple rotation, so for disks, it's easier than for ellipticals.

$$L \propto IR^2$$

Therefore we have

$$\frac{GM}{R} \propto v^2$$

$$L \propto IR^2$$

With a mass-to-light ratio:

$$M = L(M/L)$$

We then derive:

$$R \propto (\frac{M}{L})^{-1} v^2 I^{-1}$$

$$L \propto (\frac{M}{L})^{-1} v^4 I^{-1}$$

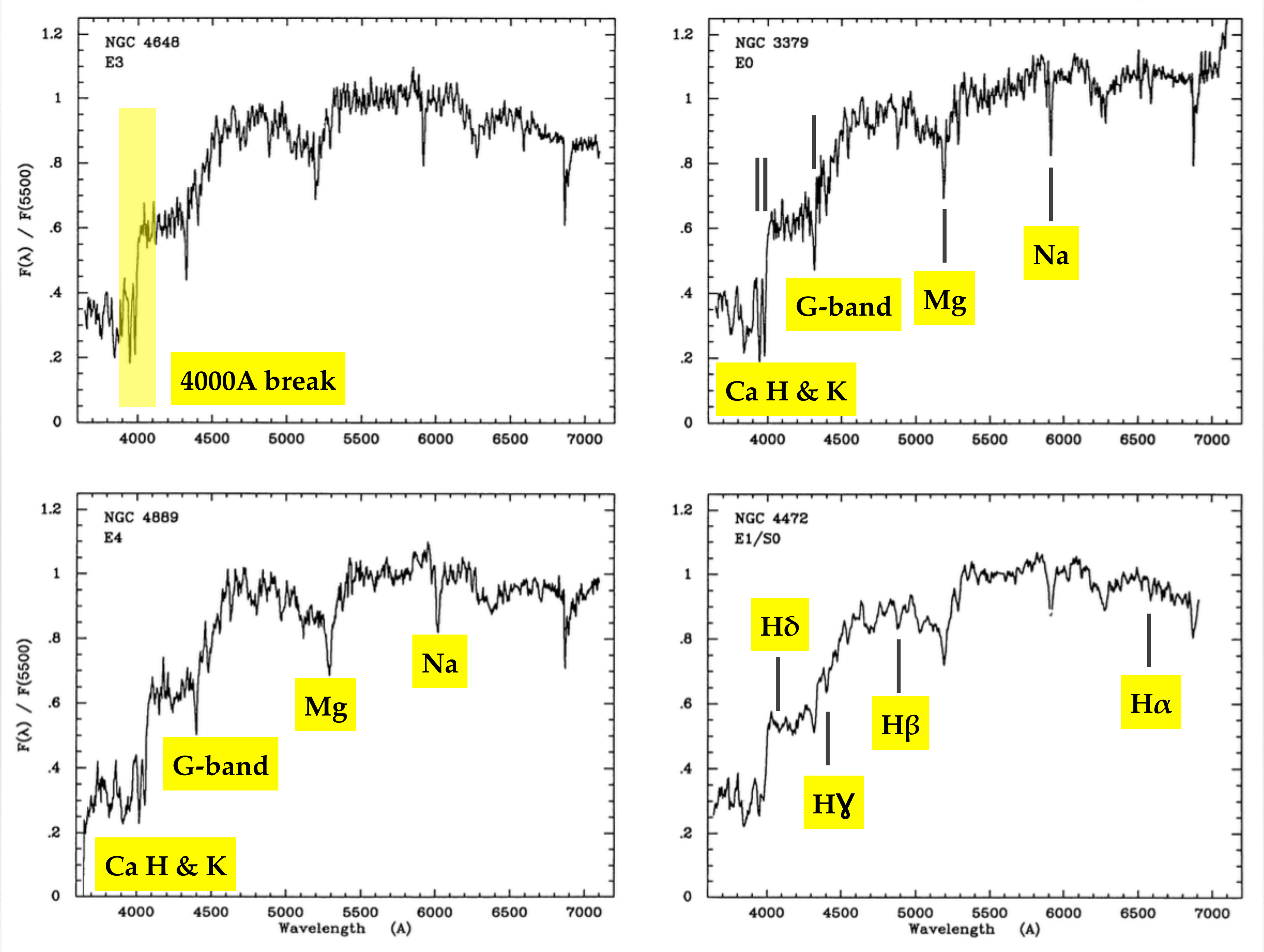
Spiral/disks: SEDs Thought Question

- Sketch a typical elliptical galaxy spectrum and a typical spiral galaxy spectrum, labeling a few spectral features on each (with wavelengths if you can).
- Where are these spectral features coming from?

Ellipticals/Spheroids: SEDs

Reminder

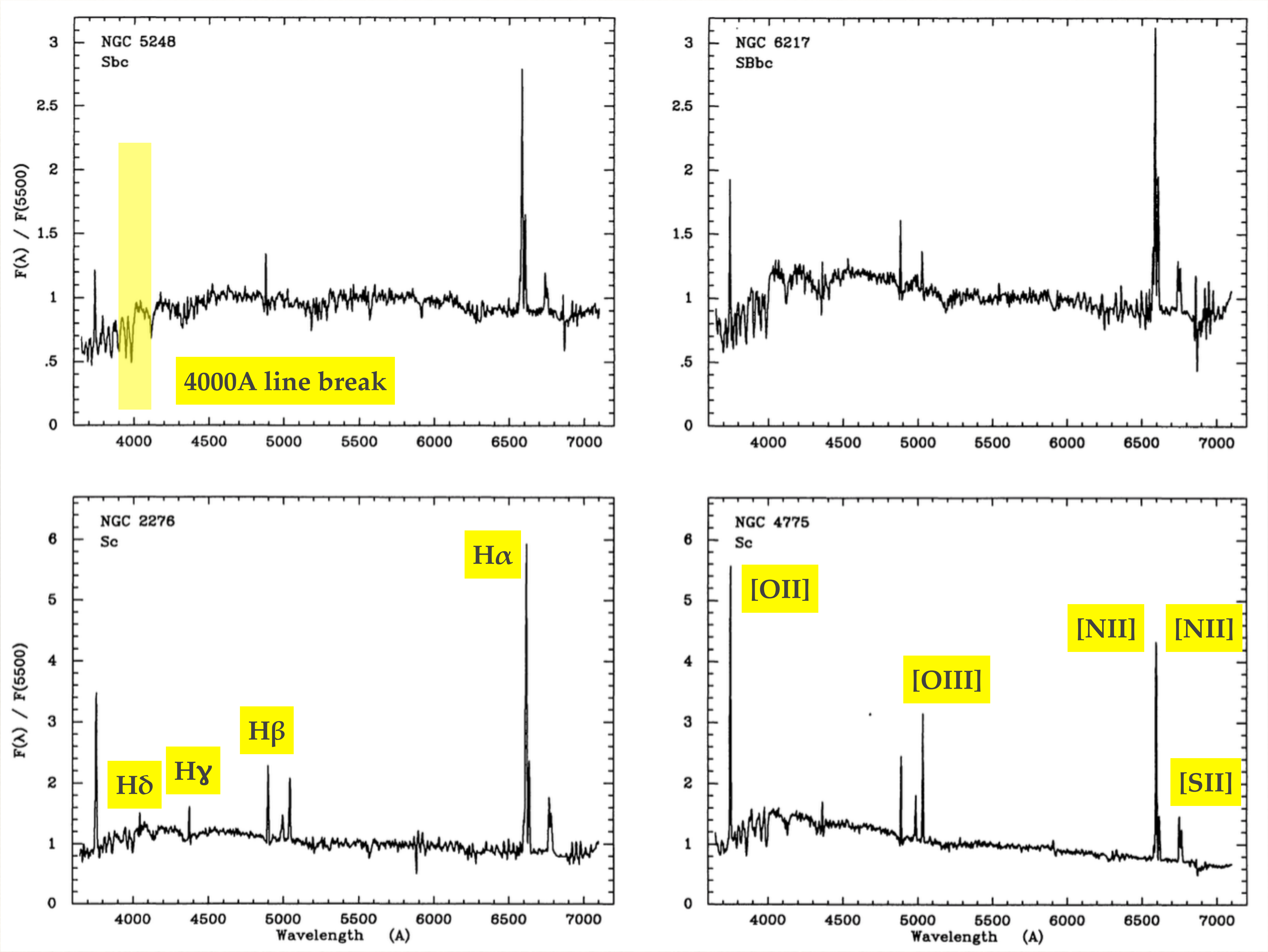
- Elliptical spectra energy distributions (SEDs):
- Typical features:
- 4000A break
- Stellar absorption lines:
  - Ca H & K (~3934A,3969A)
  - Fe & CH G-band (~4304A)
  - Mg (~5175A)
  - Na D doublet (~5894A)



Kennicutt 1992

Spirals/Disks: SEDs

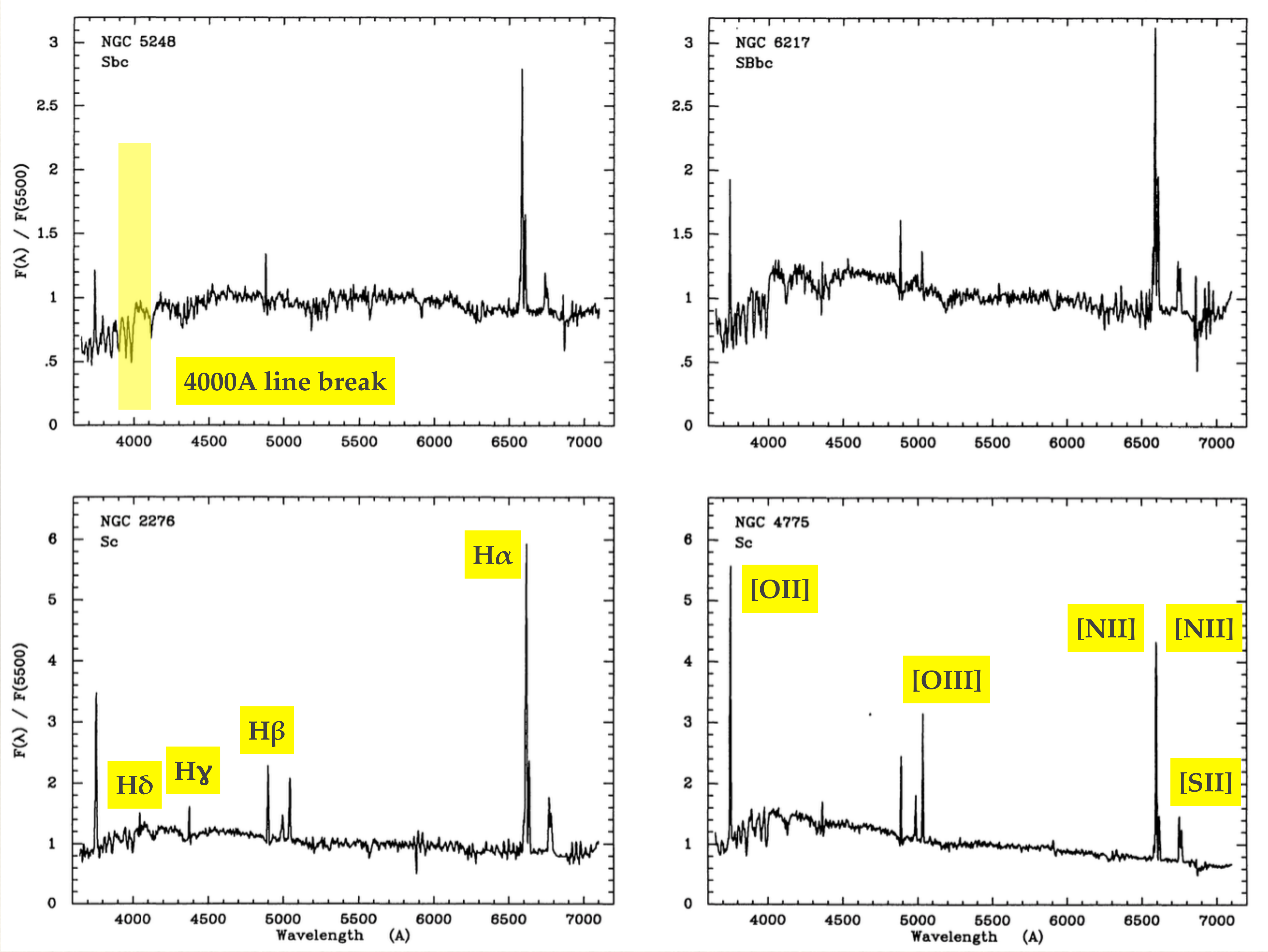
- Spiral spectra energy distributions (SEDs):
- Typical features:
  - blue continuum
  - emission lines from HII regions
  - [OII] (3727A)
  - Hβ (4861A)
  - [OIII] (4959A,5007A)
  - Hα (6563A)



Kennicutt 1992b

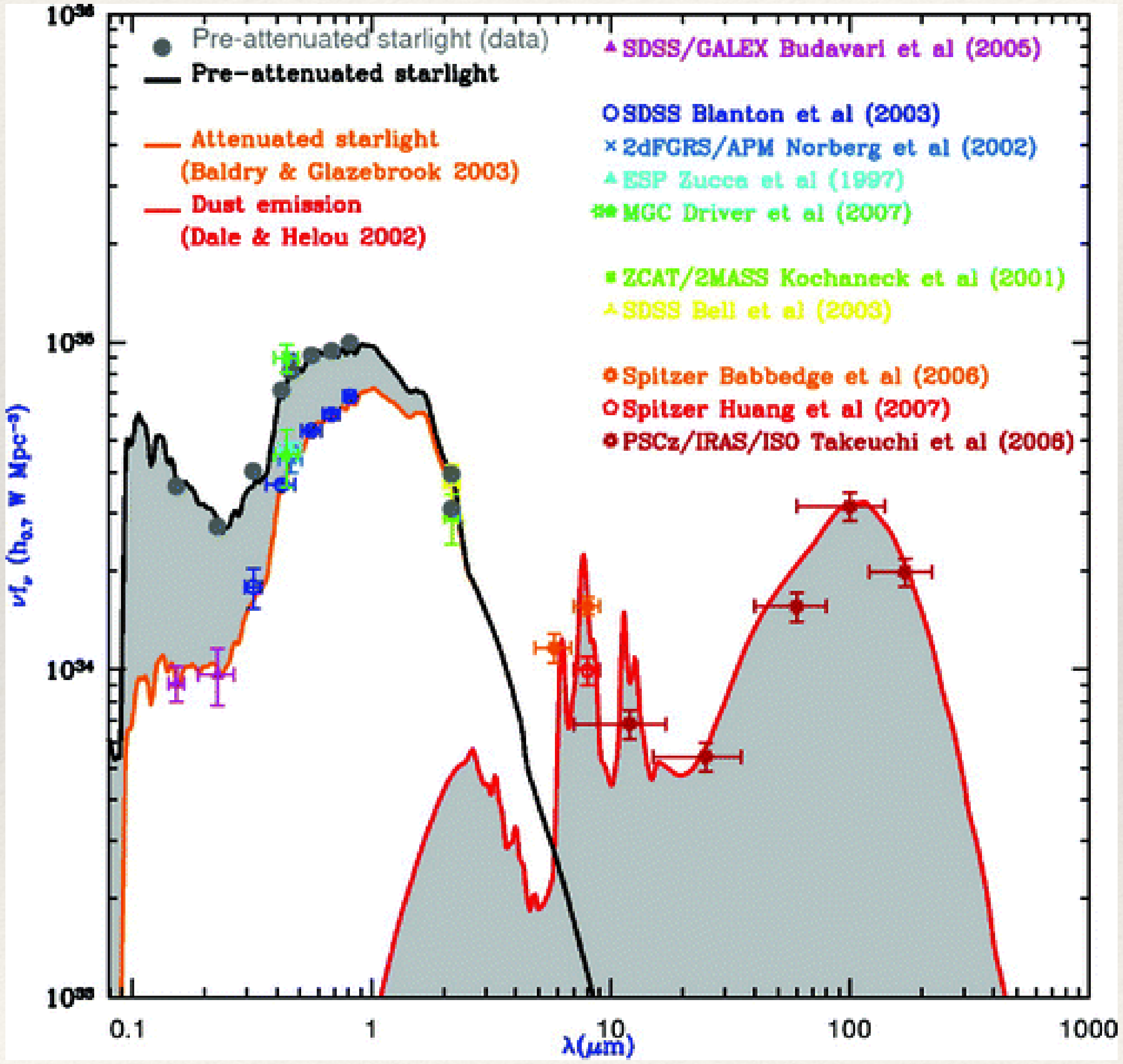
Spirals/Disks: SEDs

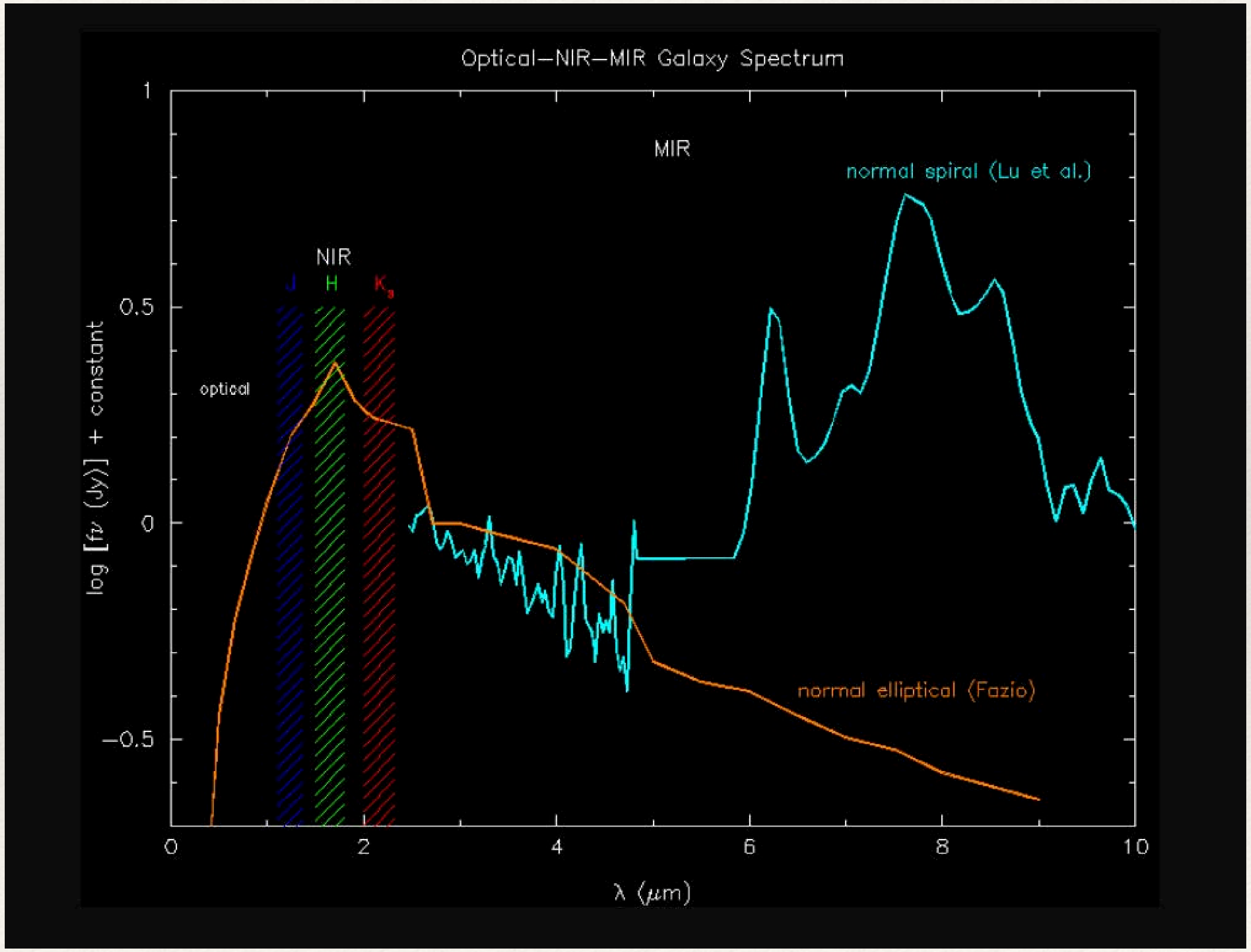
- Strong emission lines like Hα used to estimate star formation rate (**SFR**)
- As star formation proceeds, a galaxy will turn gas into stars and build up stellar mass (**M**$_*$)



Kennicutt 1992b

Spiral / disk SEDs: Multiwavelength



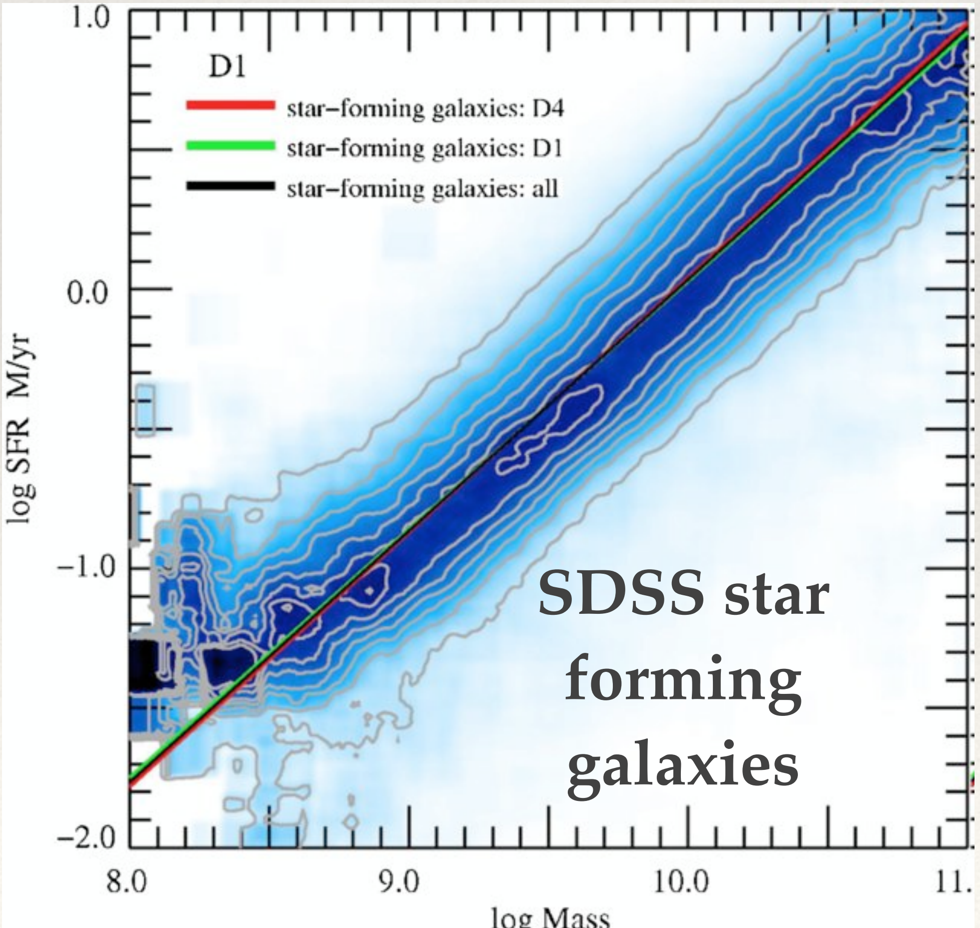


Spiral/disks : Star formation rate

- Defining feature of blue cloud galaxies: star forming!
- Can observationally estimate star formation rate:
  - from emission lines in regions of star formation
  - from UV emission
  - from dust emission
- In principle, as time passes a galaxy may:
  - form stars until it runs out of gas
  - accrete more gas and form more stars
  - blow out material in supernova-driven winds
  - interact/merge with another galaxy, triggering star formation
  - experience periods of higher AGN activity/outflows
- How does star formation rate depend on stellar mass?

Spirals/Disks: Scaling Relations

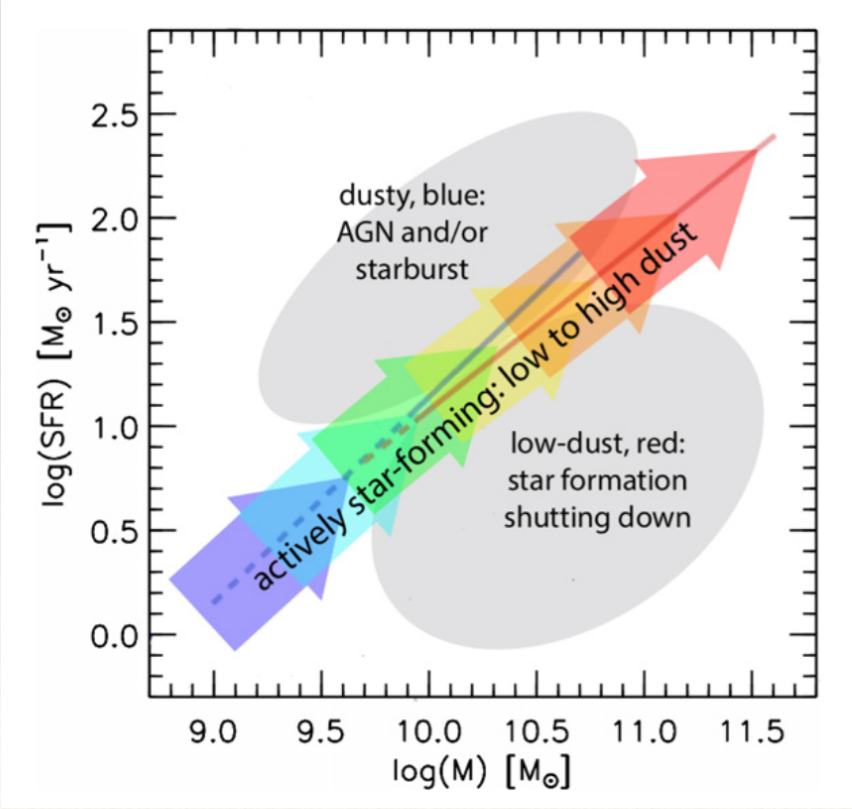
- **Star Formation Rate - Stellar Mass Relation** — the "**Galaxy Main Sequence**":
  - tight empirical relation between SFR and stellar mass
  - Note typical SFRs: ~1 solar mass per year for L* galaxy
  - specific star formation rate (**sSFR = SFR/M***, the star formation per unit mass) is ~independent of stellar mass



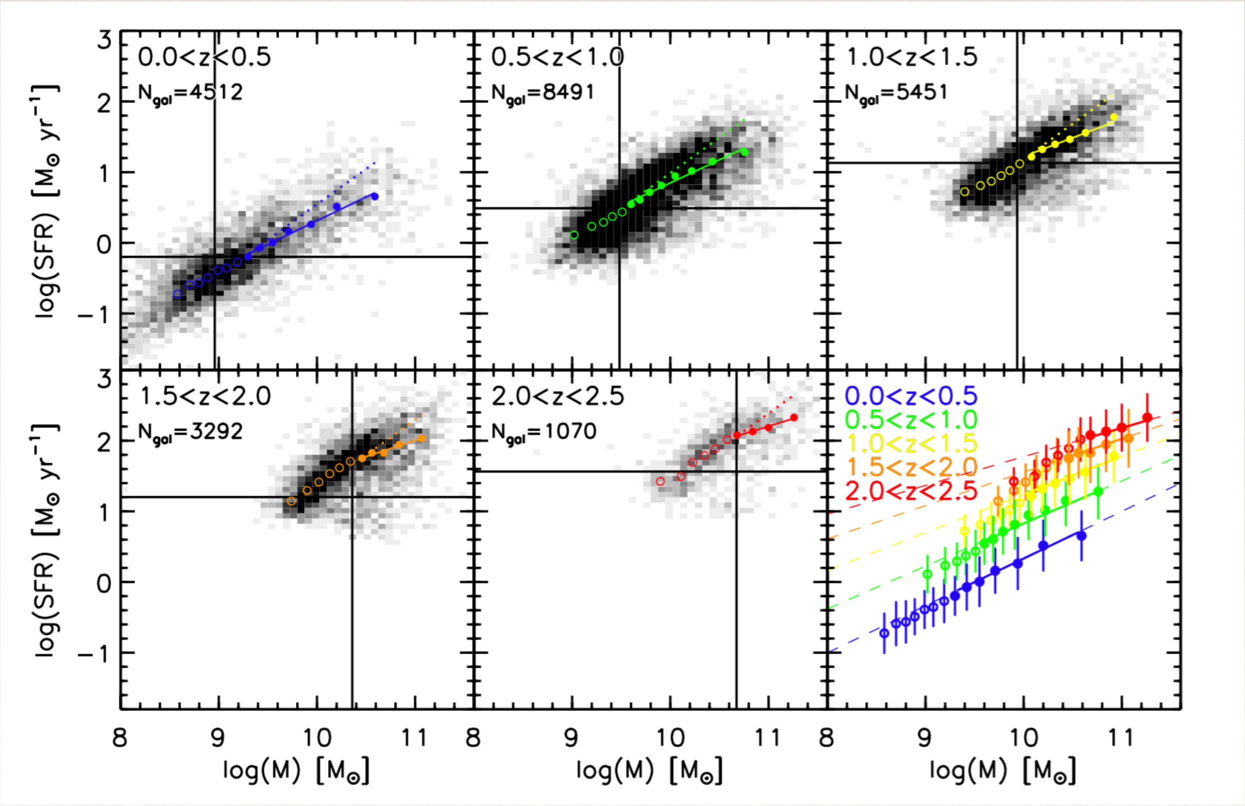
Peng et al. 2010

Spirals/Disks: Scaling Relations

- **Star Formation Rate - Stellar Mass Relation** — the "**Galaxy Main Sequence**":
  - Outliers:
    - galaxies undergoing a burst of star formation after a merger/interaction
    - galaxies that have been "quenched" (star formation has shut down)
  - Normalization shifts with redshift due to change in cosmic SFR over time



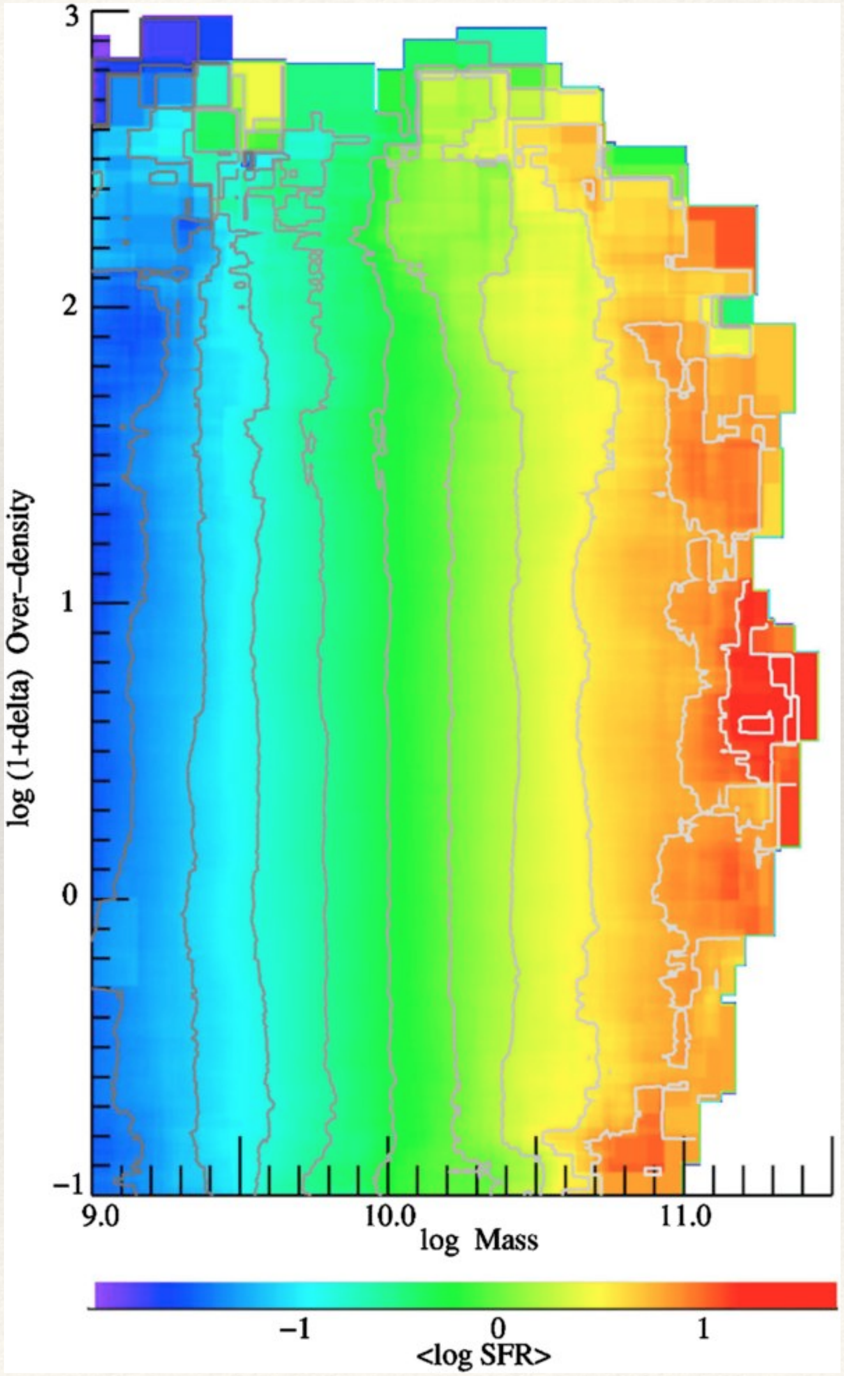
Whitaker et al. 2012



Whitaker et al. 2012

Spirals/Disks: Scaling Relations

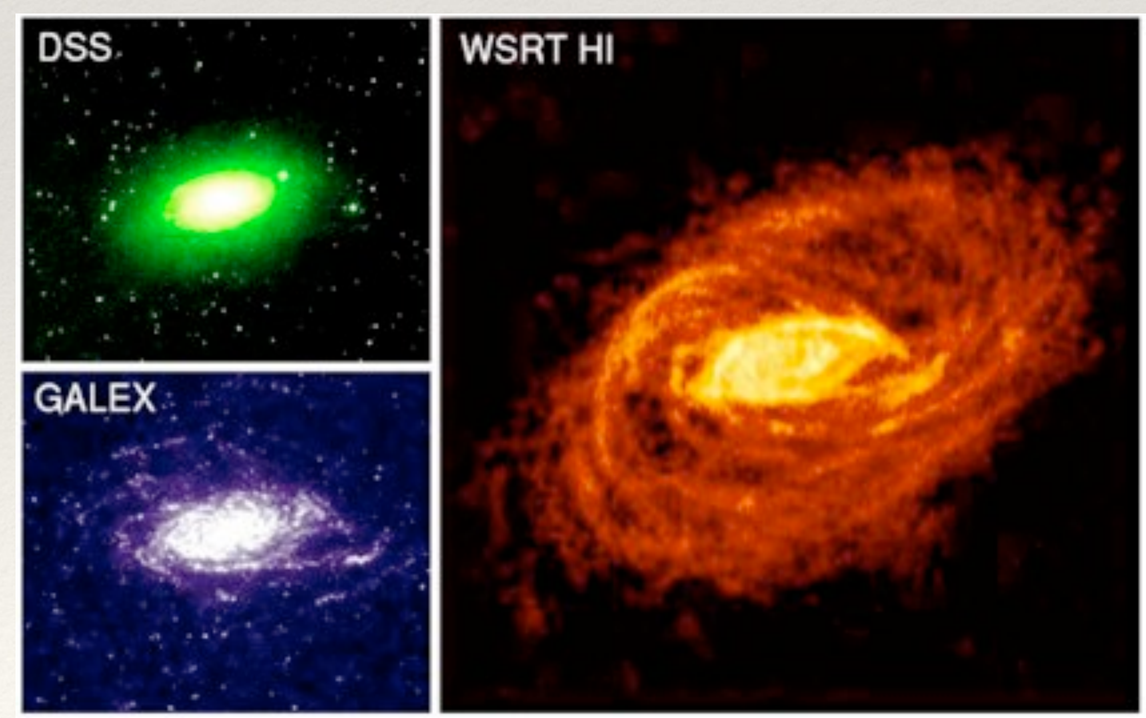
- **Star Formation Rate - Stellar Mass Relation** — the "**Galaxy Main Sequence**":
  - ~independent of environment
  - Note: **fraction** of galaxies that are star-forming **is lower** in high density environments, particularly at later times
  - Suggests transition of a galaxy from star-forming to passive is sharp (either forming stars or not)



Peng et al. 2010

Spirals/Disks: ISM

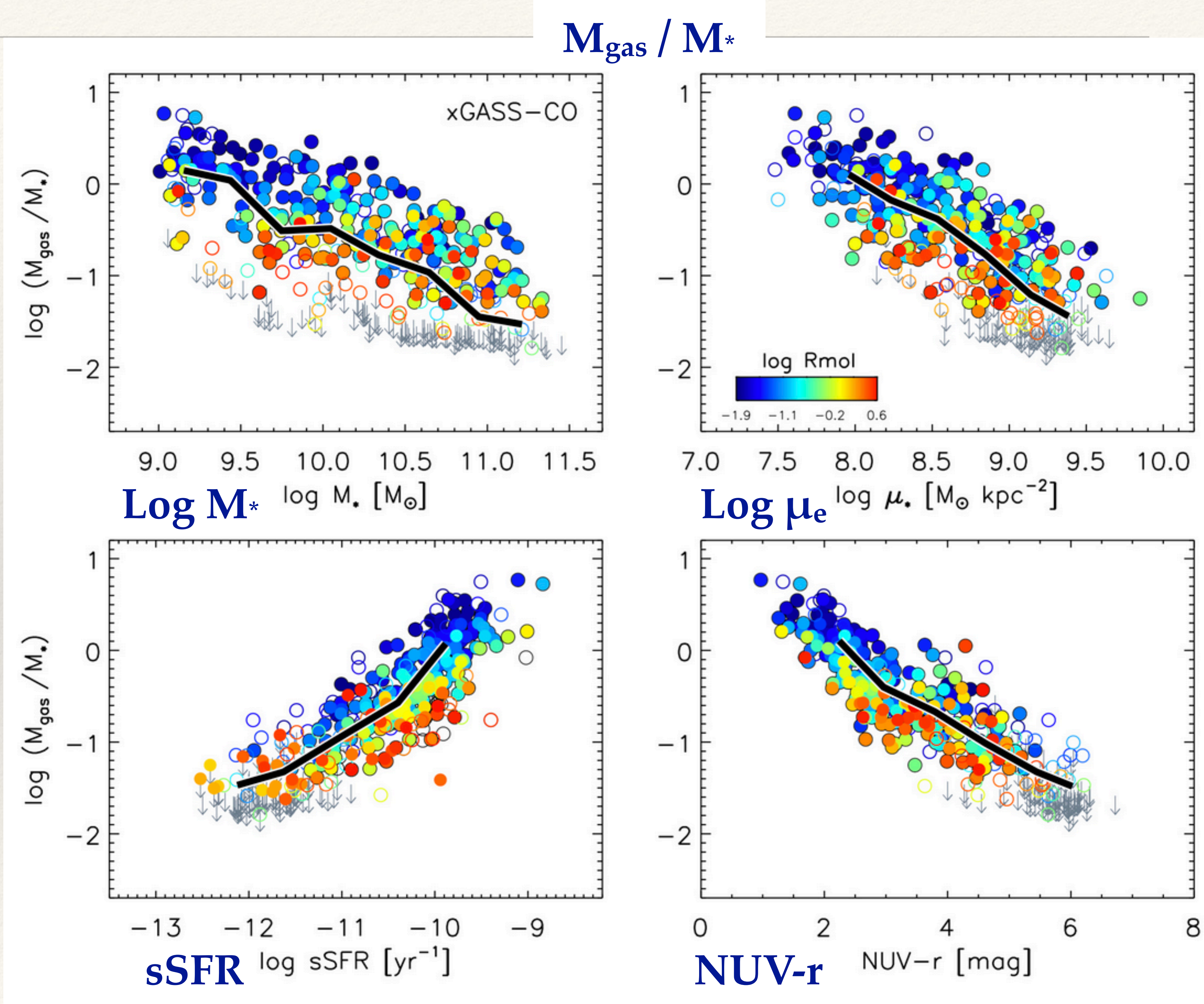
- Interstellar medium (ISM) in disk galaxies:
  - Gas and dust strongly confined to plane of galaxy
  - Most of the gas is neutral hydrogen, observed in HI
  - HI disks are very extended, often well past starlight



Battaglia et al. 2006; Sancisi et al. 2008

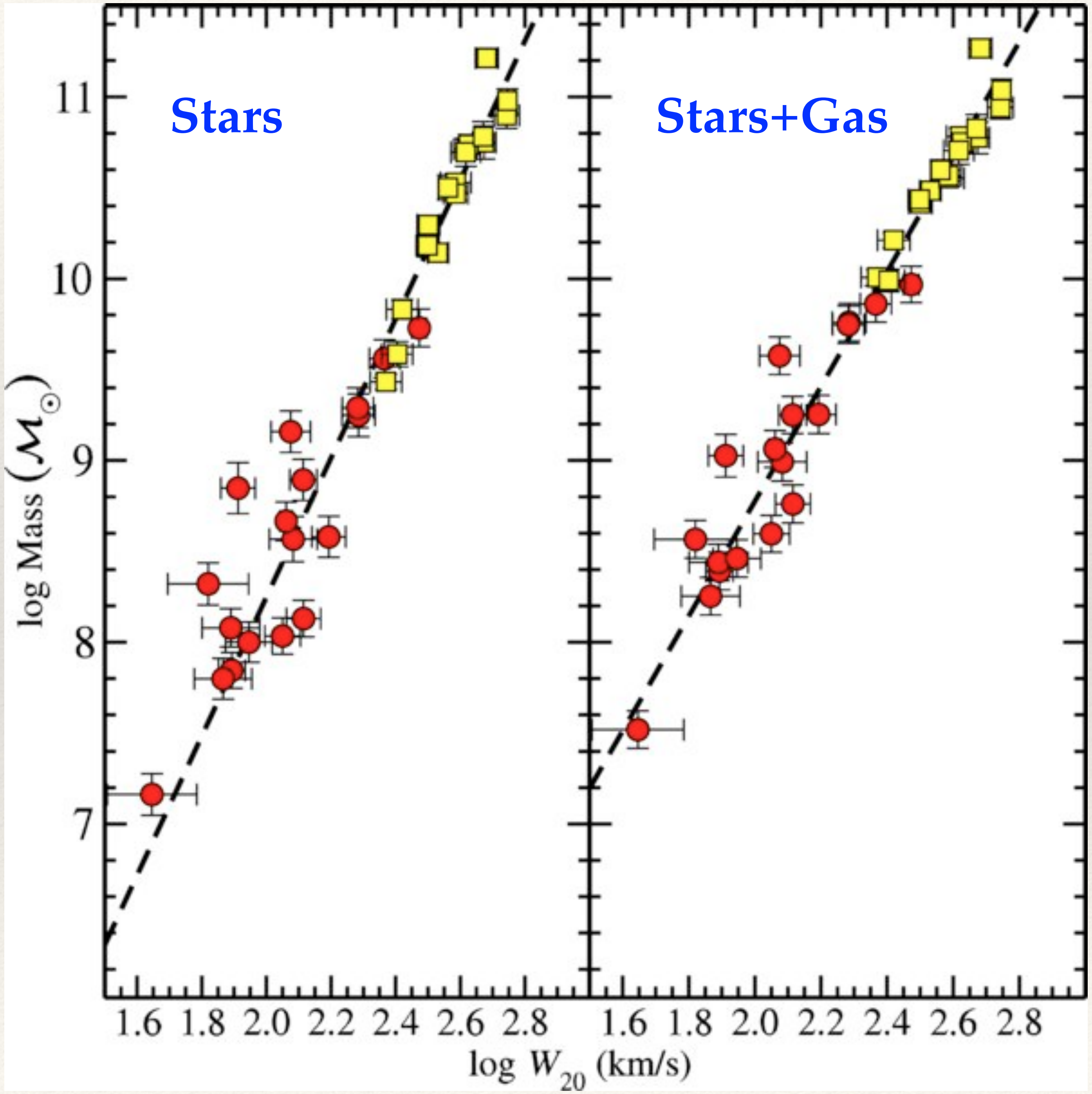
Spirals/Disks: ISM

- Gas mass fractions can be significant (~5 - 80%)!
- Total gas mass fractions higher for:
  - 1) lower stellar mass
  - 2) lower stellar mass surface density
  - 3) higher sSFR
  - 4) bluer color



Spirals/Disks: ISM

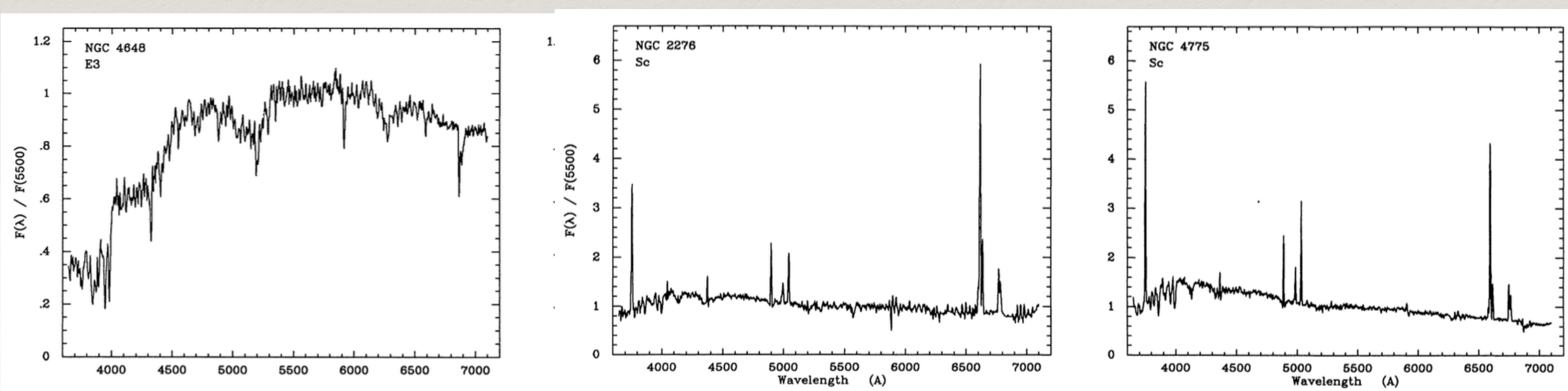
- Gas can be a significant component of mass, especially for lower mass/ luminosity galaxies
- **Baryonic Tully-Fisher Relation** — relation between baryonic **mass** and **rotation velocity** (or HI linewidth):
  - requires estimate of stellar mass from luminosity
  - even less scatter than the **stellar Tully-Fisher Relation**



Gurovich et al 2010

Spiral/disk SEDs: Thought Question

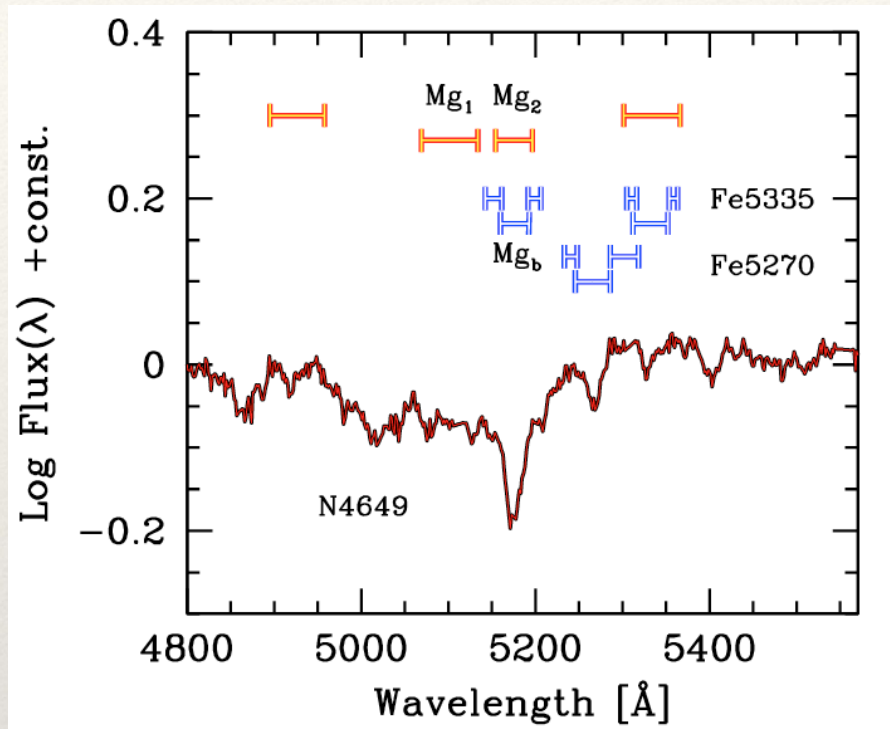
- Given a spiral galaxy spectrum, what are some different ways you might think of to measure metallicities?
- What might the metallicities you measure depend on?

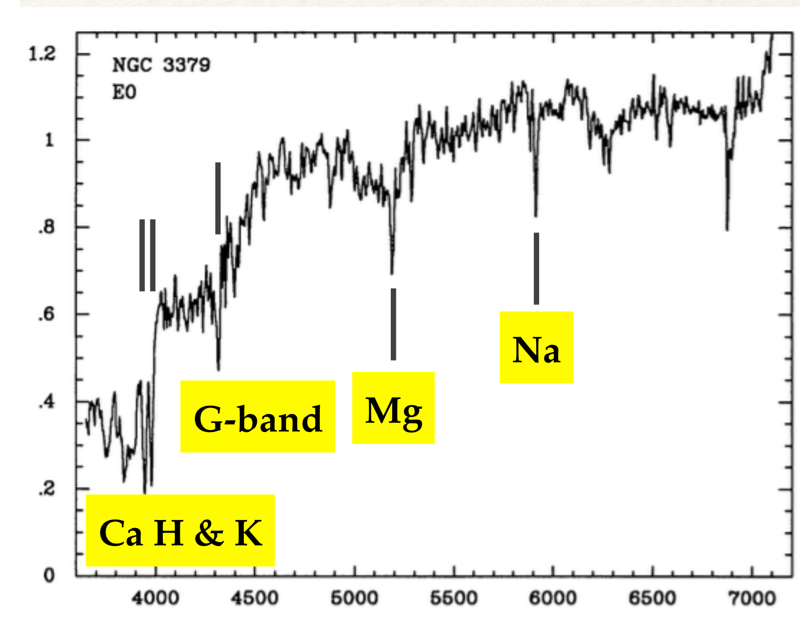


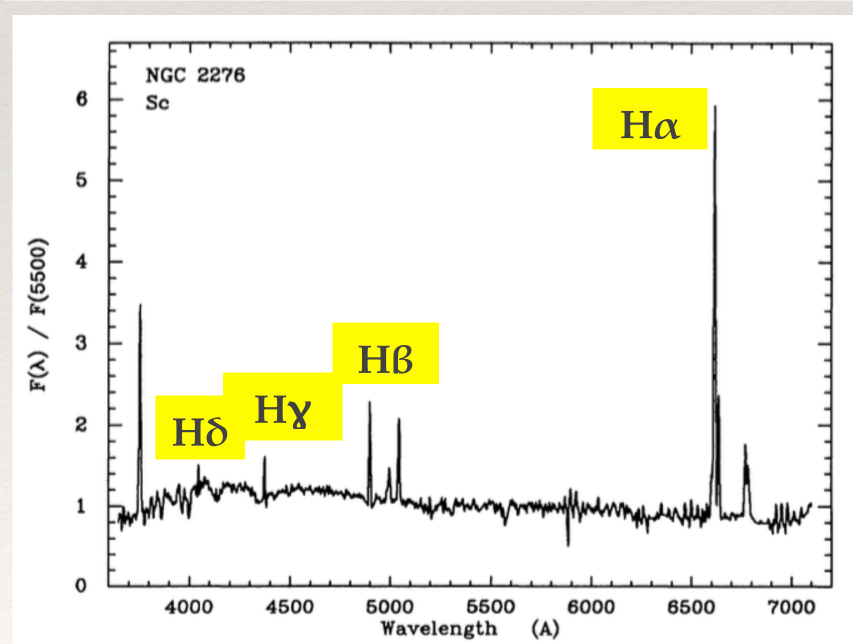
Spirals/Disks SEDs : Thought question

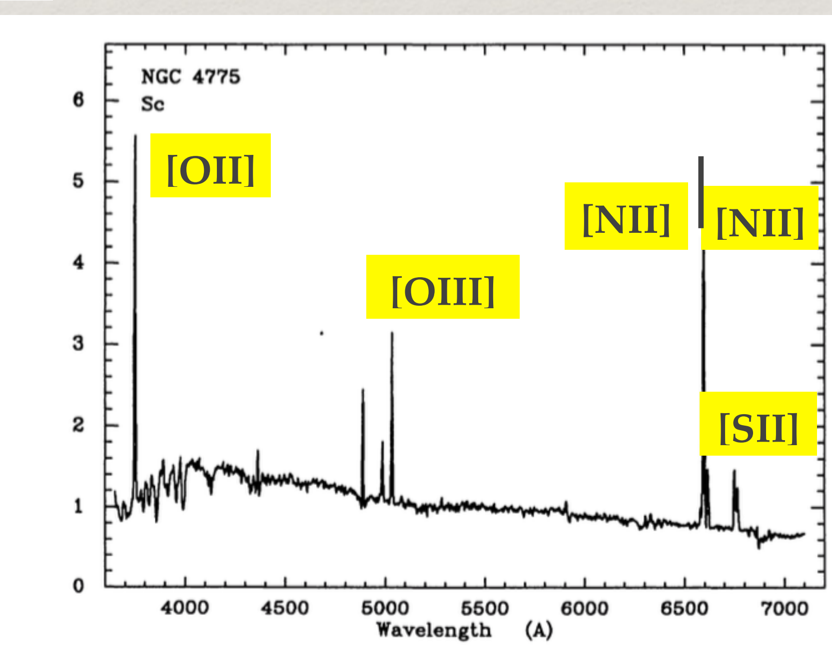
- Given a spiral galaxy spectrum, what are some different ways you might think of to measure metallicities?
- What might the metallicities you measure depend on?

Buzzoni et al. 2015







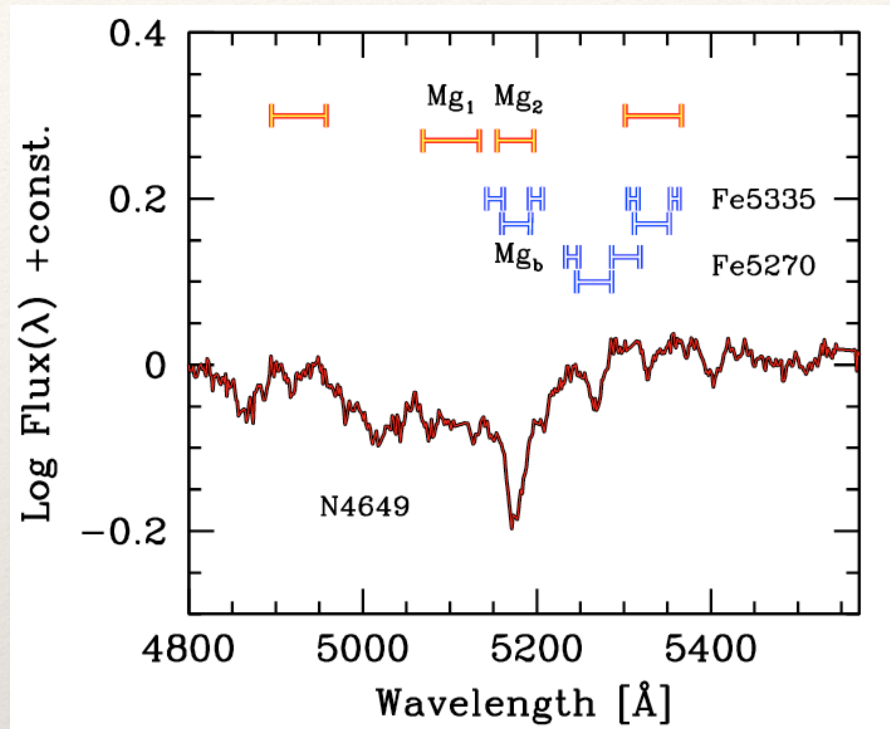


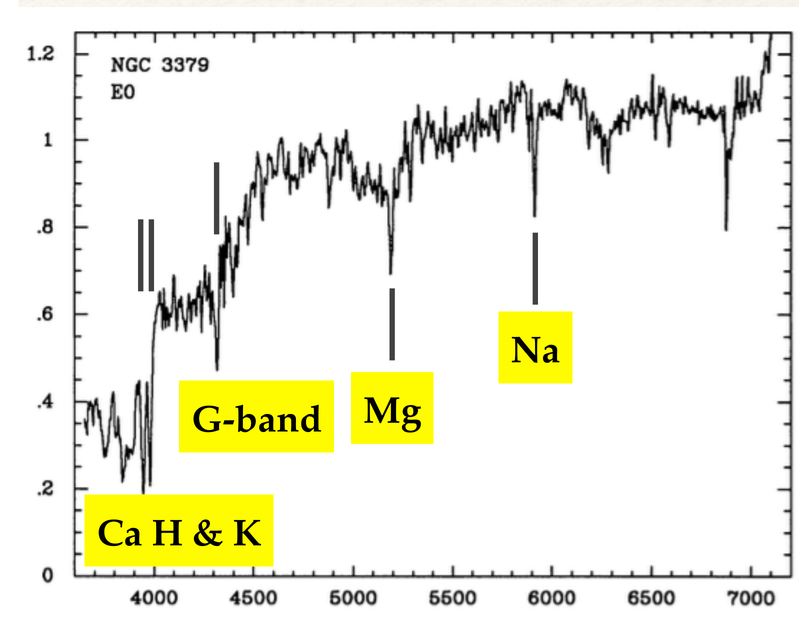
Kennicutt 1992b

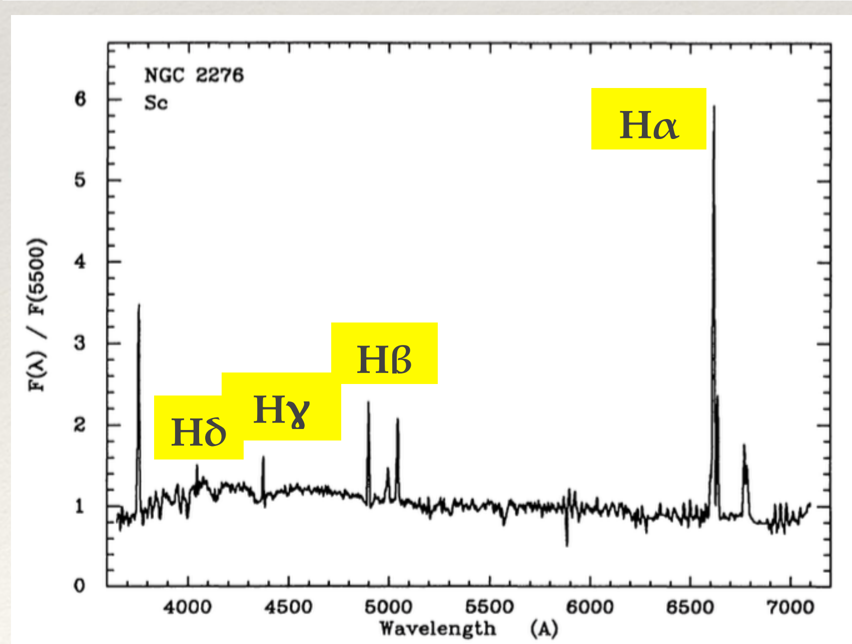
Spirals/Disks: Metallicity

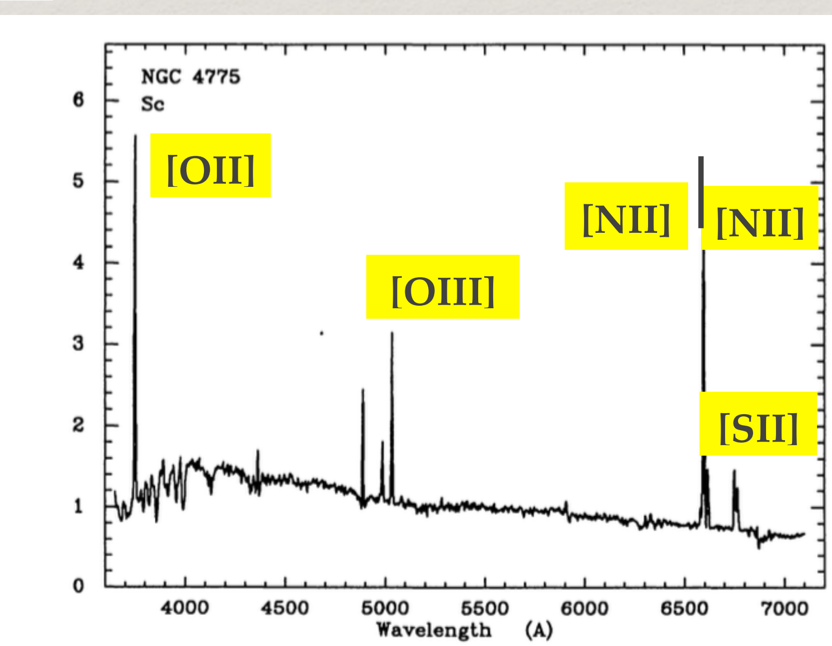
- **Stellar metallicities** - from stellar absorption lines
- **Gas phase metallicities** - from emission lines (or gas absorption of stellar light)

Buzzoni et al. 2015







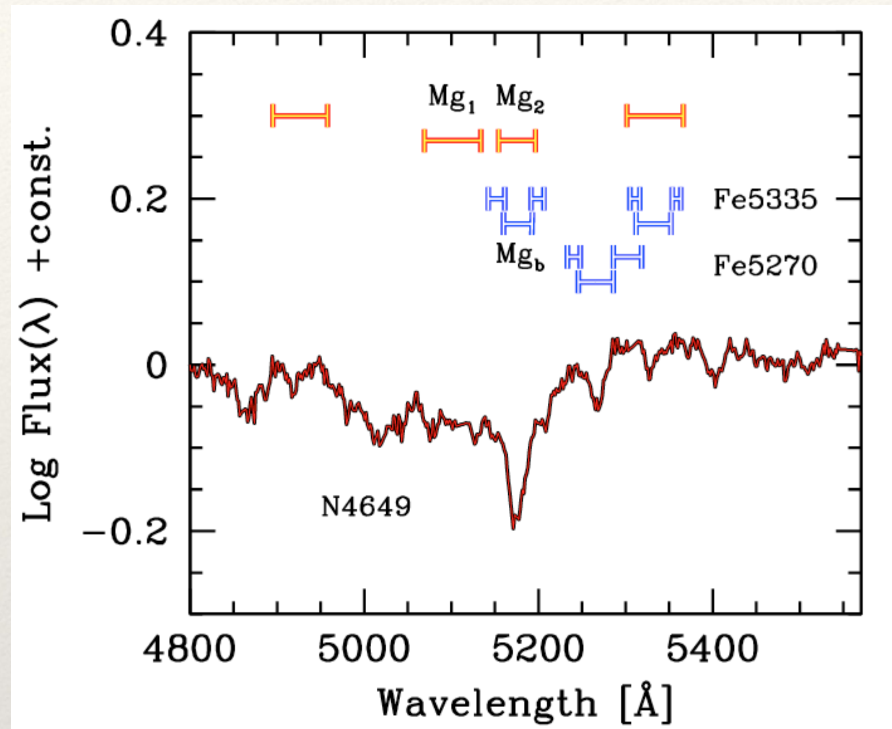


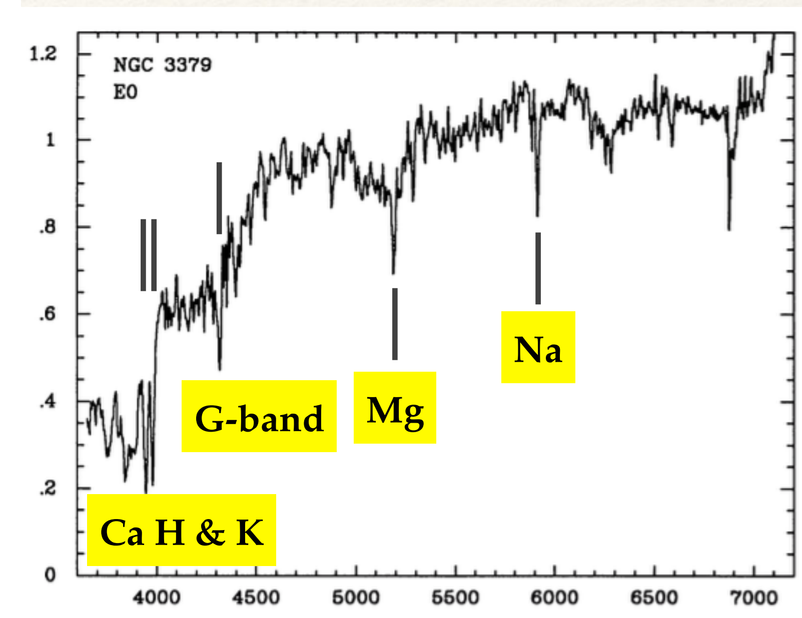
Kennicutt 1992b

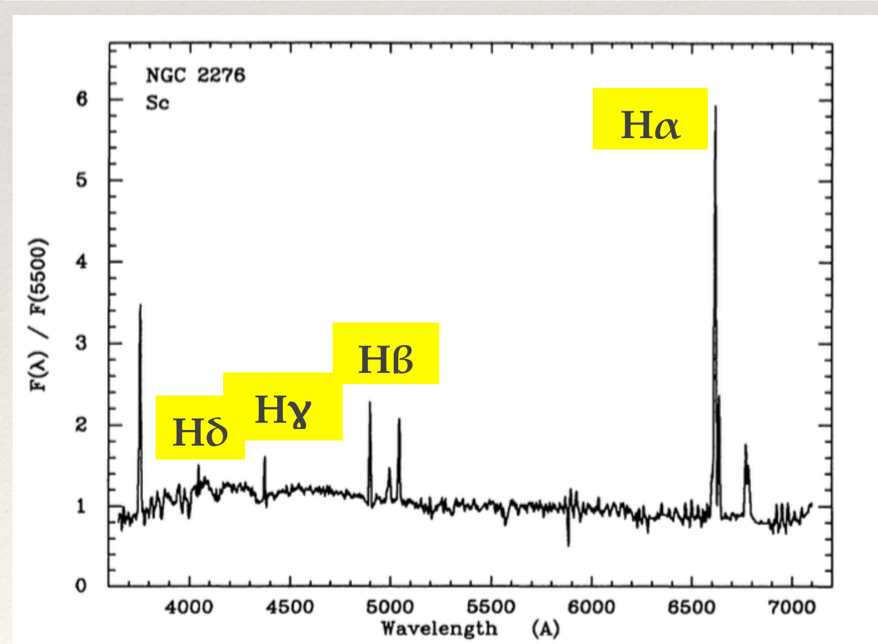
Galaxy Population - Spirals/Disks: Metallicity

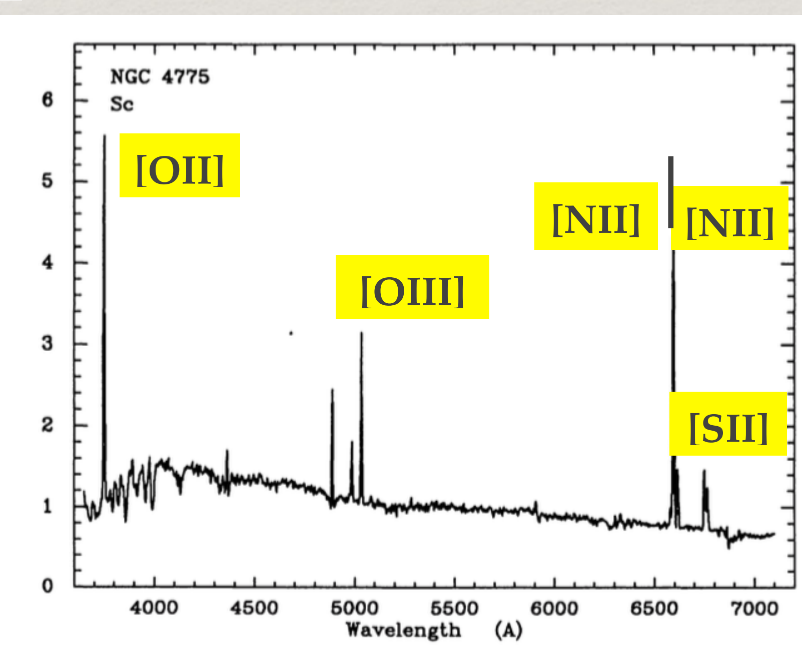
- Galaxy stellar metallicity:
  - varies over time, depending on metallicity of the gas stars are forming out of
  - spectrum is luminosity-weighted average
- Gas metallicity gives present-day metallicity
- Galaxy metallicity affected by:
  - star formation producing metals
  - feedback/outflows expelling enriched material
  - fresh (unenriched) gas infall

Buzzoni et al. 2015





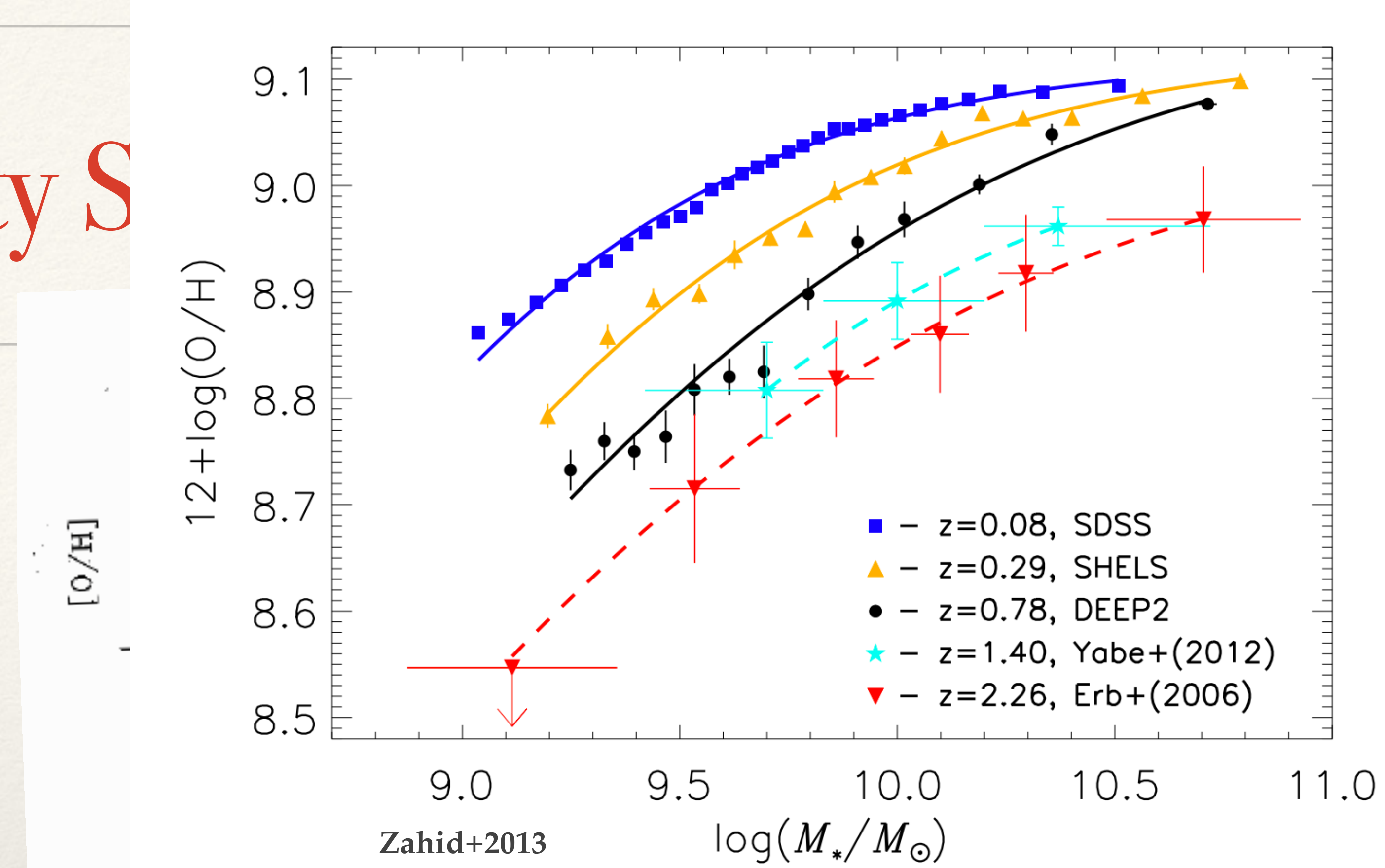




Kennicutt 1992b

Spirals/Disks: Metallicity S

- **Luminosity-Metallicity Relation** or **Mass-Metallicity Relation**
  - more luminous/massive galaxies generally are more metal-rich
- Related to
  - Efficiency of forming stars (and metals)
  - How well the galaxy holds onto those metals given outflows



Zahid+2013

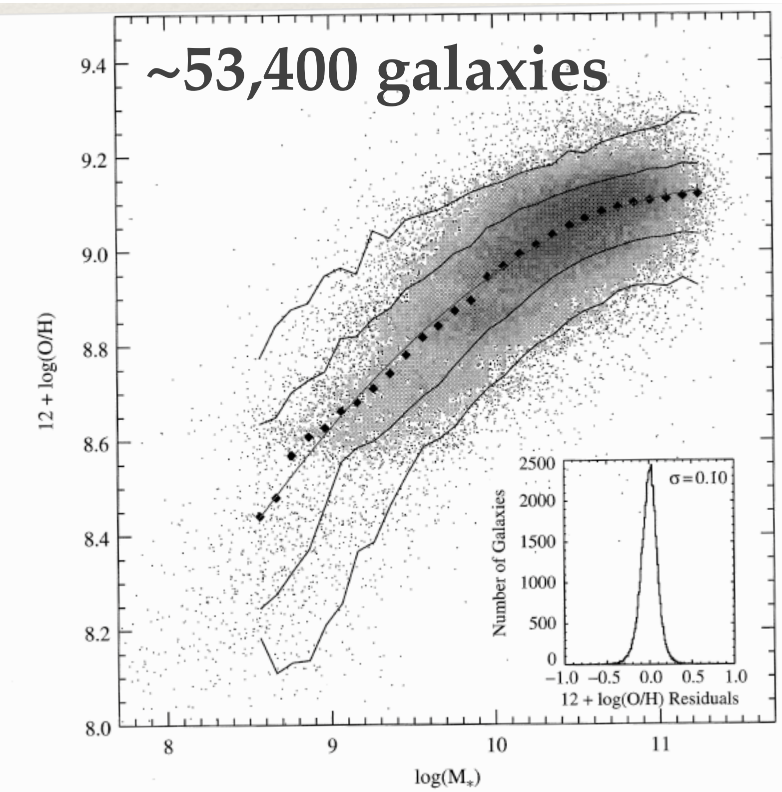


Fig. 2.28. The relation between stellar mass, in units of solar masses, and the gas-phase oxygen abundance for ~53,400 star-forming galaxies in the SDSS. For comparison, the Sun has $12+\log[(O/H)] = 8.69$. The large black points represent the median in bins of 0.1 dex in mass. The solid lines are the contours which enclose 68% and 95% of the data. The gray line shows a polynomial fit to the data. The inset shows the residuals of the fit. [Adapted from Tremonti et al. (2004) by permission of AAS]

Tremonti et al. 2004