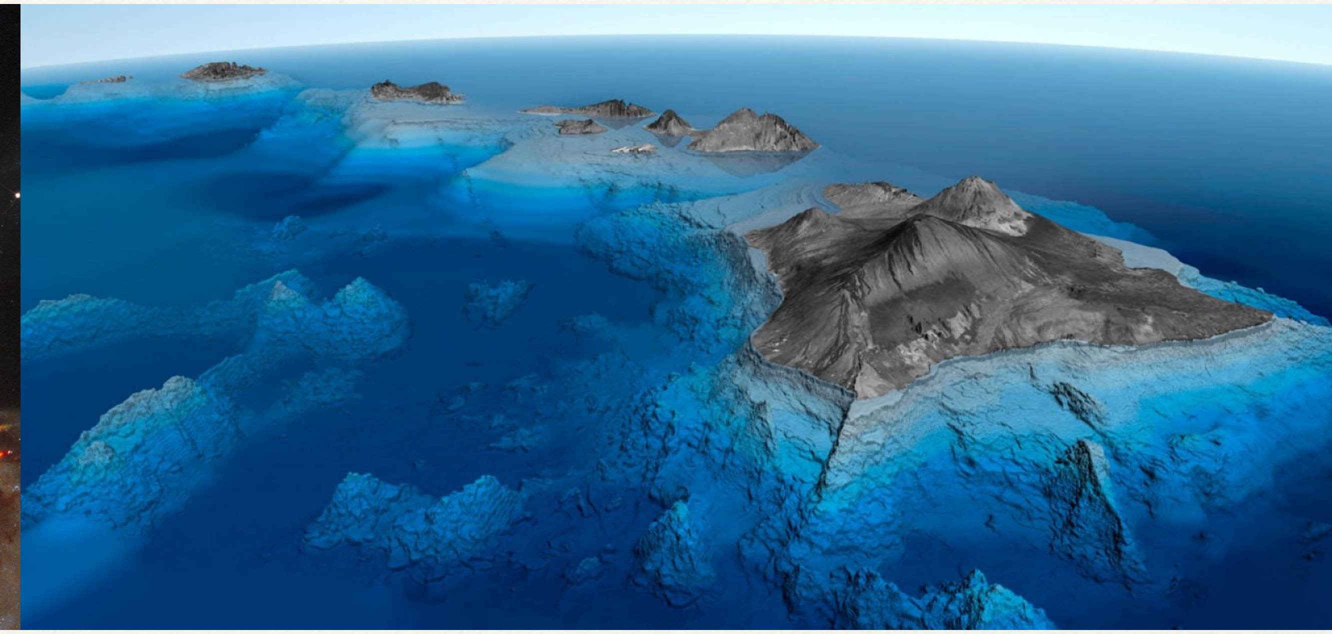


Getting to know the "island universes" out there.

Galaxies I

ASTR 555
Dr. Jon Holtzman

Outline for Today

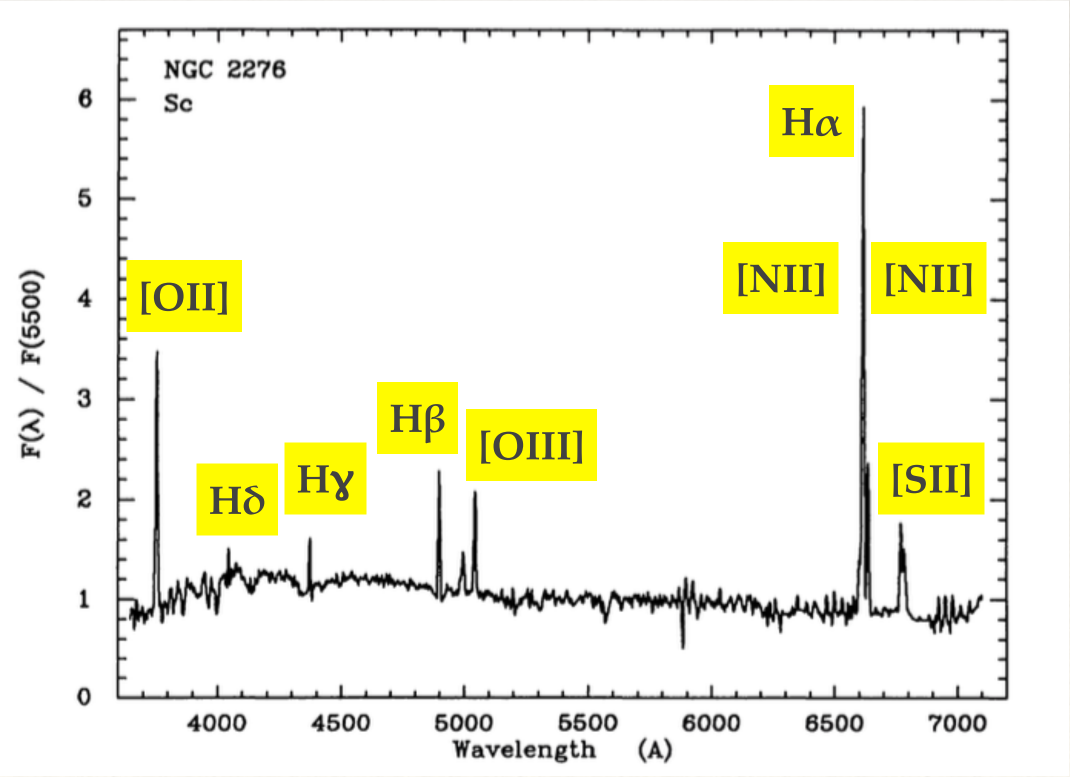
- Building Blocks - Gas:
    - Denser Ionized Gas
        - BPT Diagrams

- Building Blocks - Interactions between Gas and stars
    - star formation
    - feedback

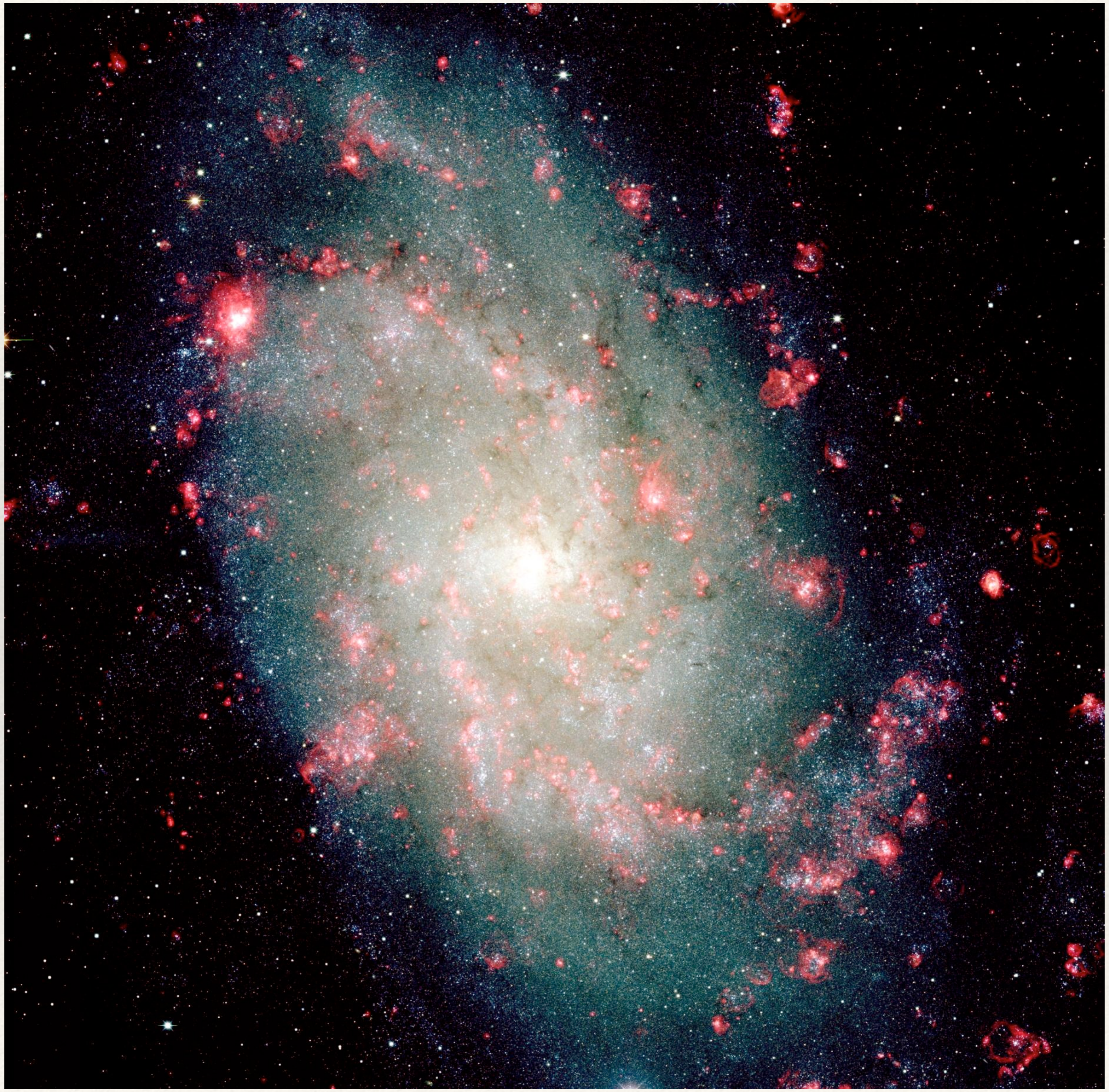
NGC 6240 (Credit: Hiroshima University / NAOJ)

Gas : dense ionized gas

- **Denser Ionized Gas (e.g., HII regions)**
  - Lots of strong emission lines
  - Opportunity to
    - study gas inside galaxies (and outside!) in detail



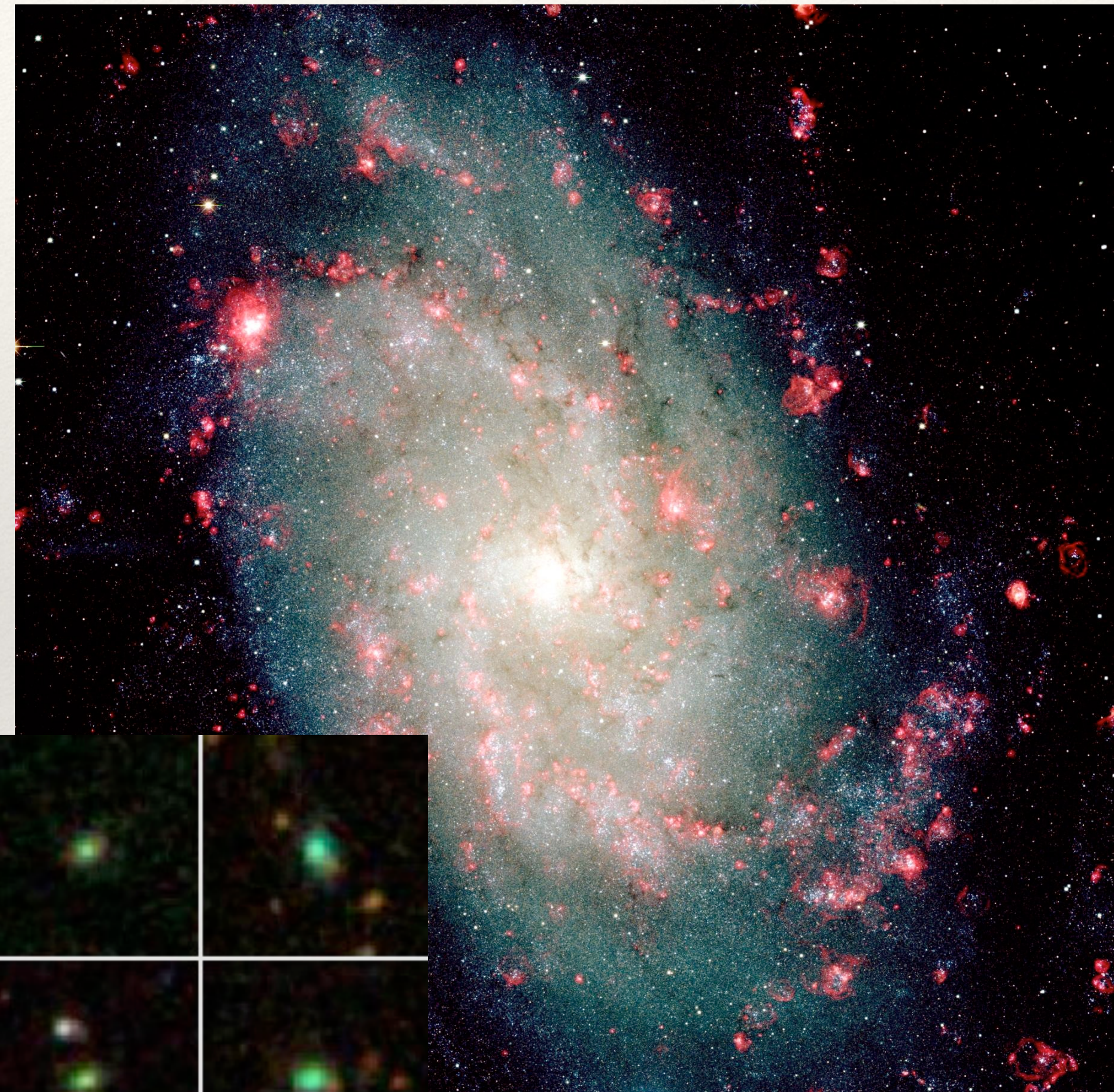
Kennicutt 1992b



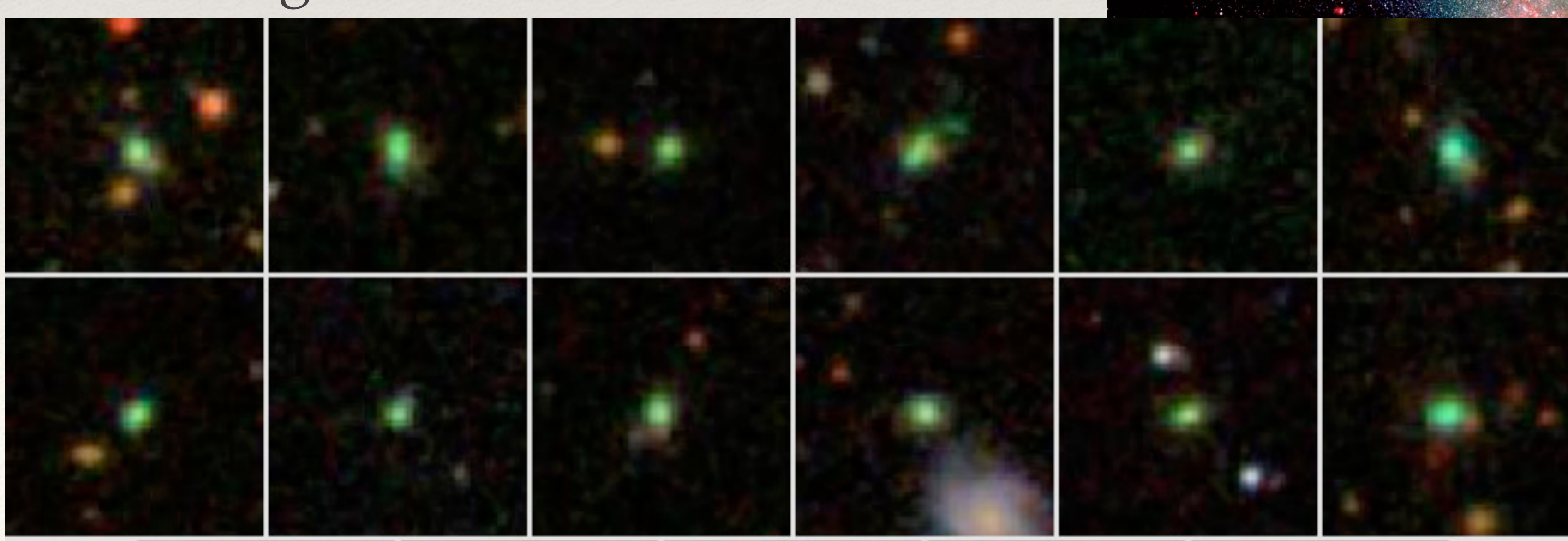
M33 (Credit: Lowell Observatory)

Gas

- **Denser Ionized Gas (e.g., HII regions)**
  - Lots of strong emission lines
  - Opportunity to
    - study gas inside galaxies (and outside!) in detail
    - constrain powering mechanism, even in distant galaxies



Credit: Lowell Observatory)



Schirmer et al. 2013

Gas

- Use **diagnostic diagrams** of emission line ratios to separate differing powering mechanisms:
  - use emission lines that are easy to observe
  - minimize complicating effects of dust reddening

PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC
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PUBLICATIONS OF THE
ASTRONOMICAL SOCIETY OF THE PACIFIC

Vol. 93 February 1981 No. 551

CLASSIFICATION PARAMETERS FOR THE EMISSION-LINE SPECTRA OF EXTRAGALACTIC OBJECTS

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AND

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Institute of Astronomy, Madingley Road, Cambridge, England CB3 0HA

Received 1980 August 21

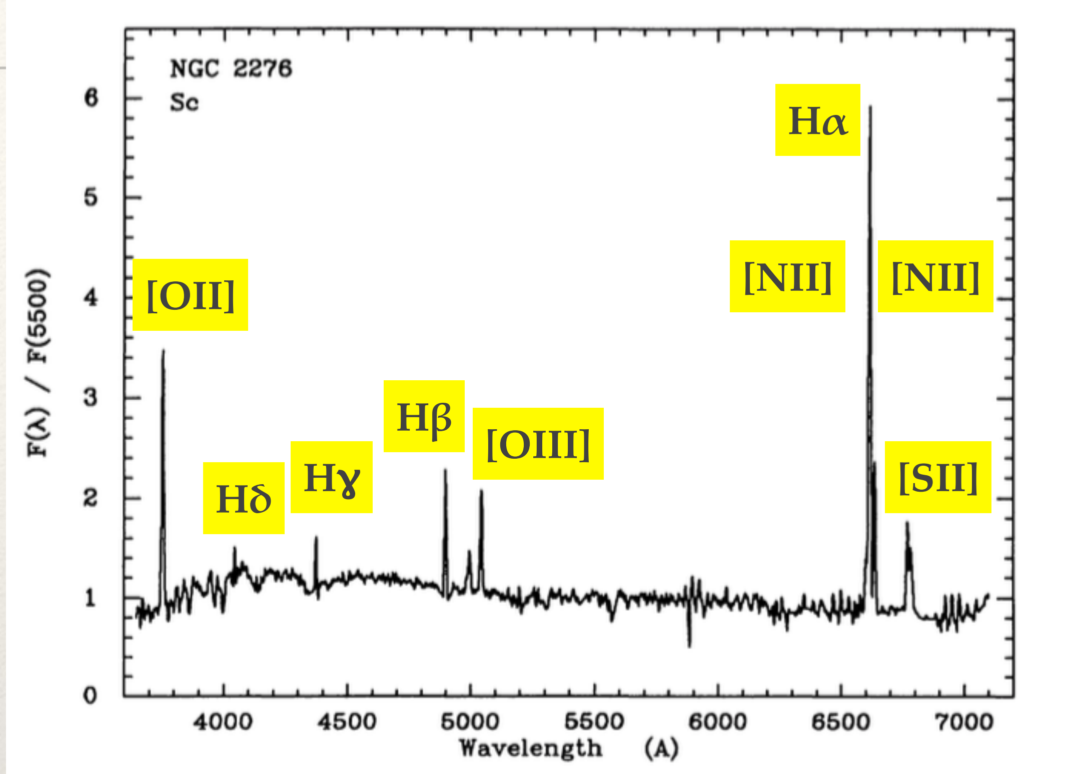
An investigation is made of the merits of various emission-line intensity ratios for classifying the spectra of extragalactic objects. It is shown empirically that several combinations of easily-measured lines can be used to separate objects into one of four categories according to the principal excitation mechanism: normal H II regions, planetary nebulae, objects photoionized by a power-law continuum, and objects excited by shock-wave heating. A two-dimensional quantitative classification scheme is suggested.

Key words: H II region—Seyfert galaxies—quasars—spectral classification

- Often called **BPT diagrams** after original paper that proposed them (Baldwin, Phillips, & Terlevich 1981)

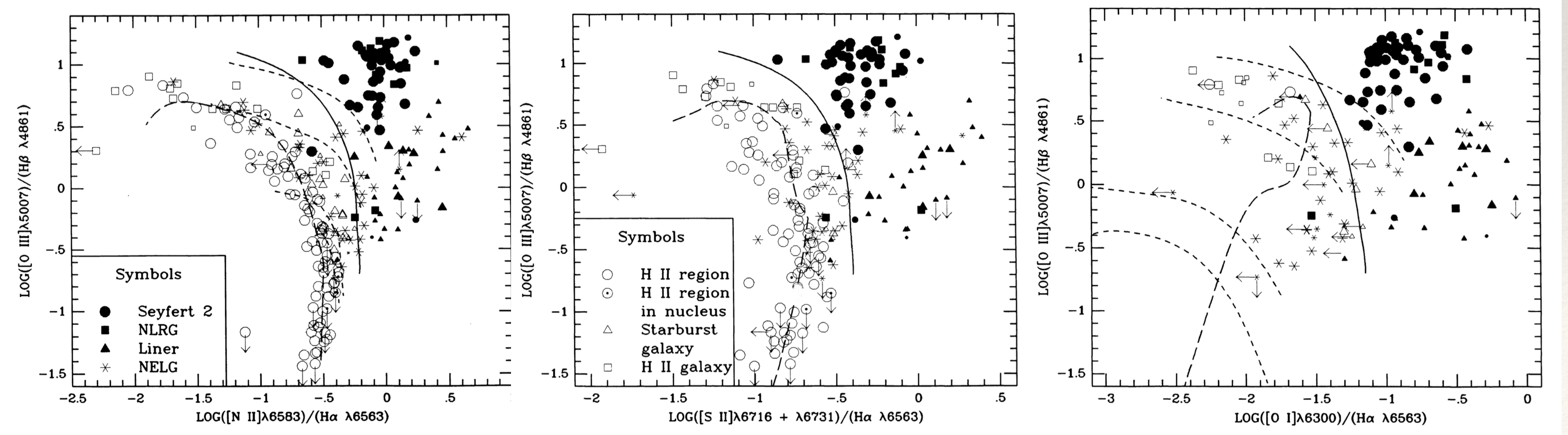
Gas

- Use **strong** emission lines — Hα, [OIII]5007, etc.
- Choose **ratios** of lines **close in wavelength** so reddening roughly cancels:
  - [NII]6583 / Hα vs. [OIII]5007 / Hβ
  - [SII]6716+6731 / Hα vs. [OIII]5007 / Hβ
  - [OI]6300 / Hα vs. [OIII]5007 / Hβ



Kennicutt 1992b

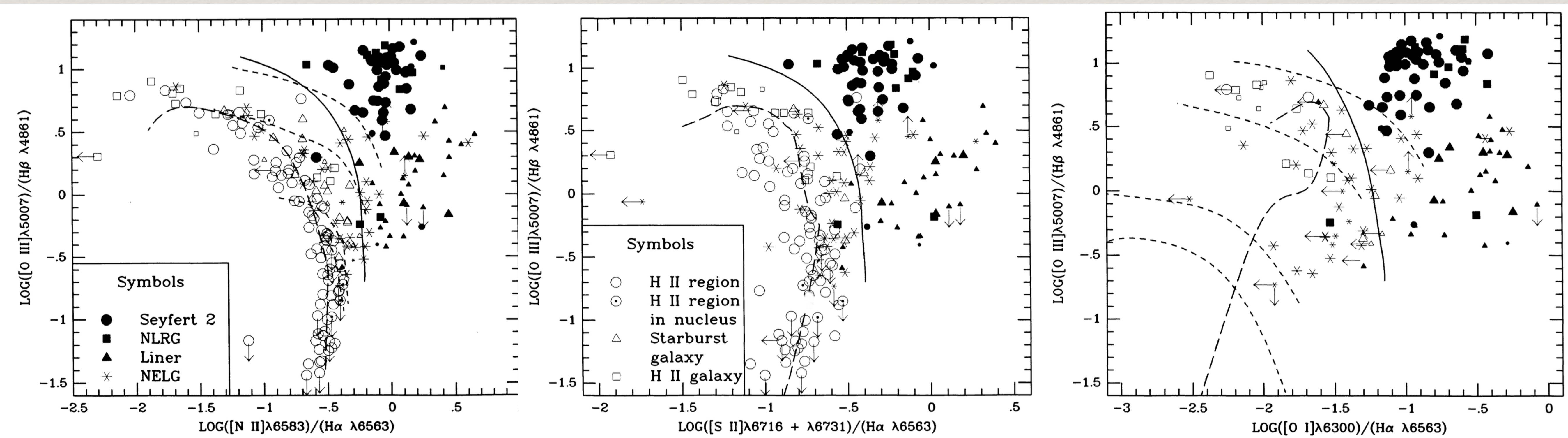
Veilleux & Osterbrock 1987



Thought Questions

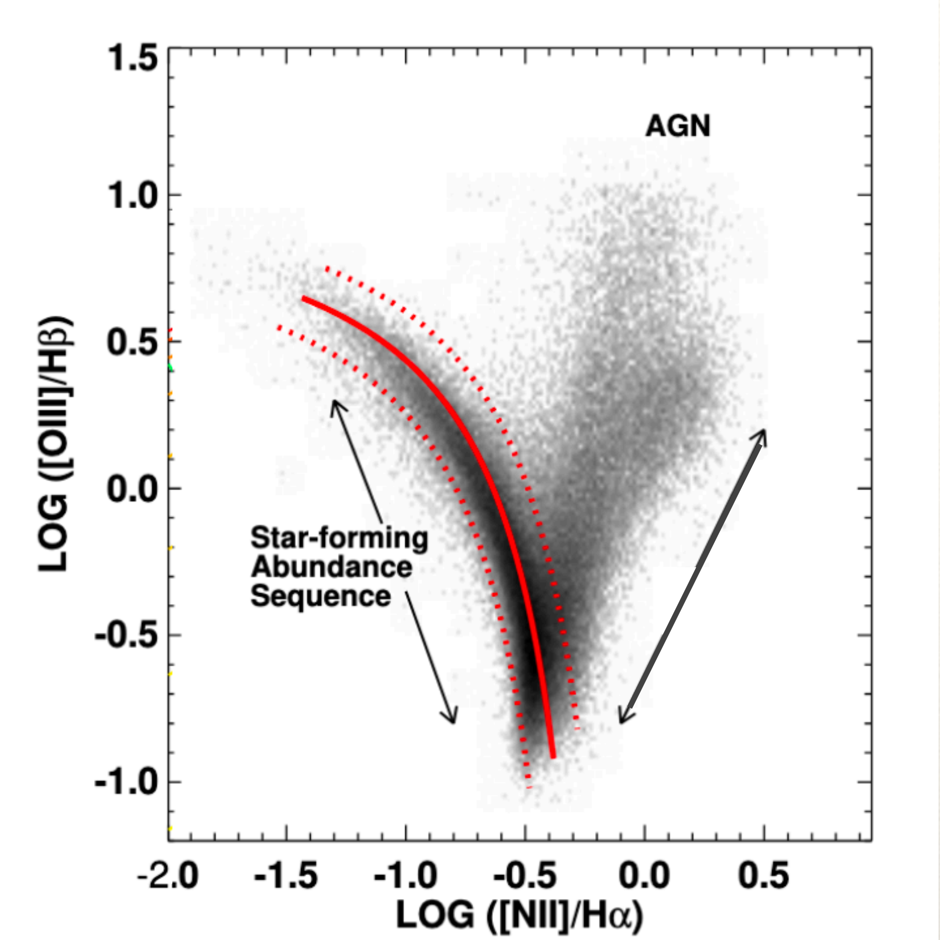
- Take a closer look at the location of different kinds of objects in these diagnostic diagrams. What do you notice?
- Why might this be the case?

Veilleux & Osterbrock 1987



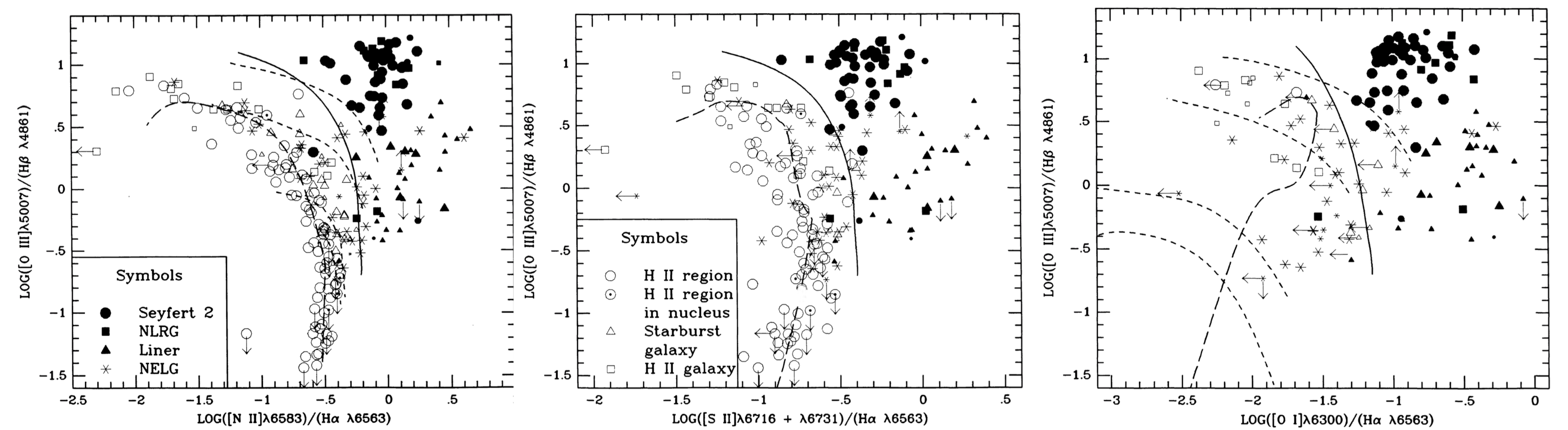
Gas

- Star-formation galaxies separate from AGN in BPT diagrams
- Star-forming "metallicity (or abundance) sequence"



Kewley 2019

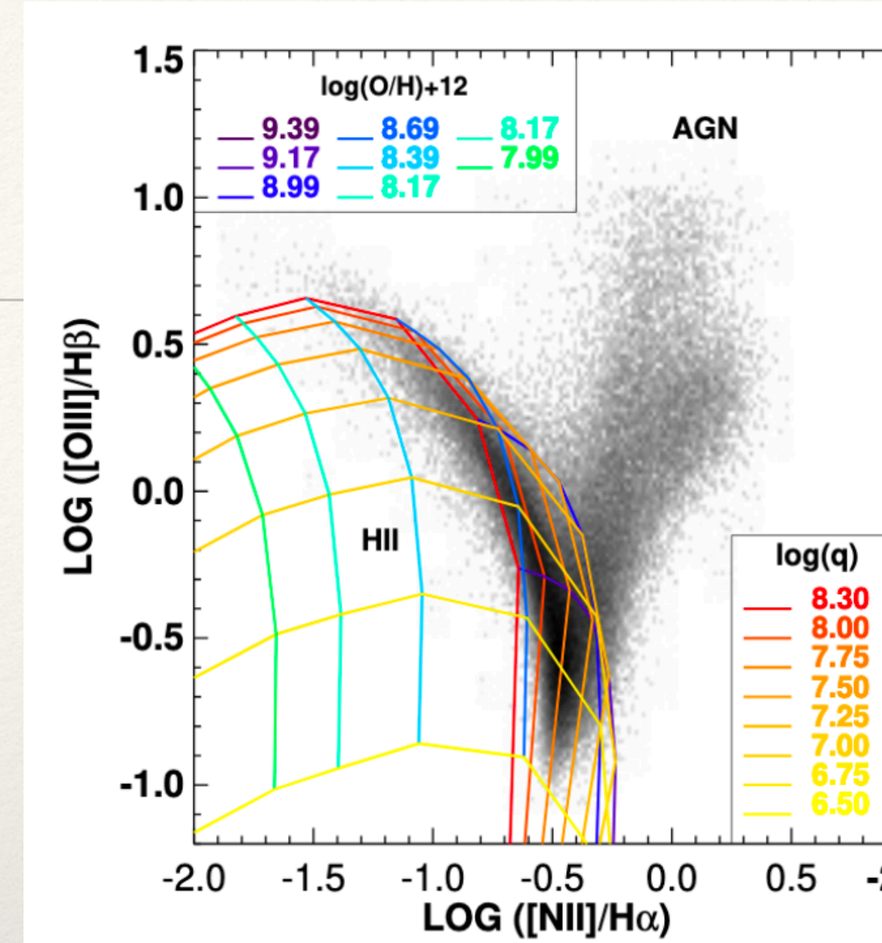
Veilleux & Osterbrock 1987



Gas

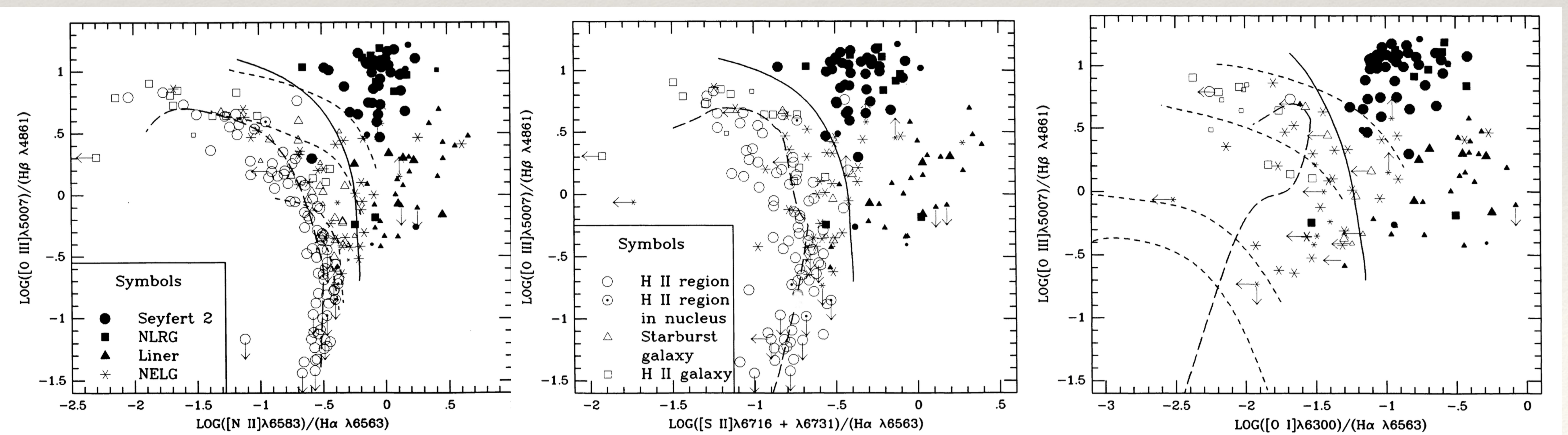
- Star-formation galaxies separate from AGN in BPT diagrams
- Star-forming "metallicity (or abundance) sequence"

But what about the AGN?



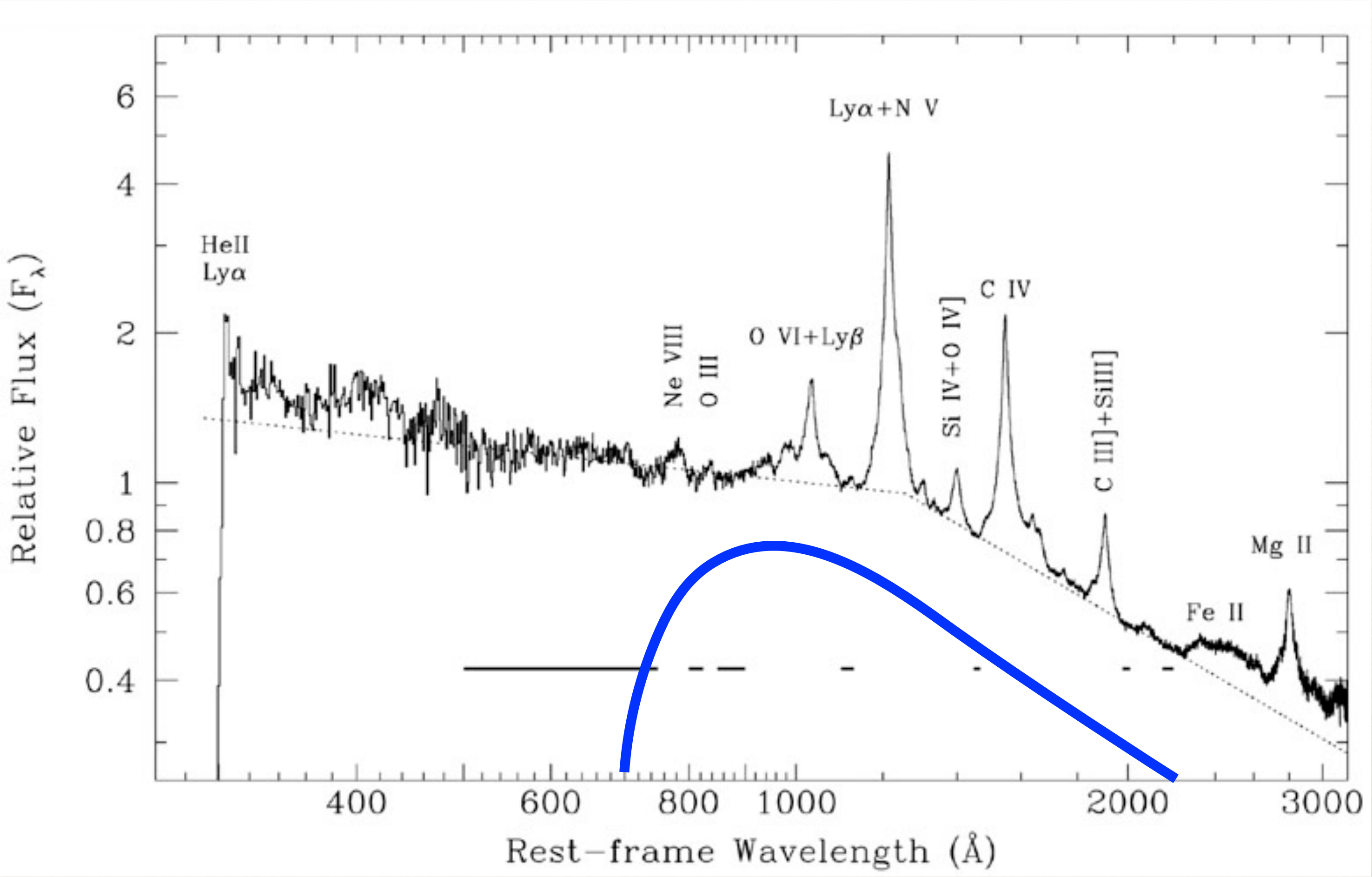
Kewley 2019

Veilleux & Osterbrock 1987



Gas

- Hot stars and AGN have very different spectra:
  - Blackbody vs. power-law ($\nu^{-\alpha}$) ionizing continuum
  - Lots of higher energy (UV, X-ray) photons from AGN
    - More high ionization species, e.g., OIII



Telfer et al. 2002

	Ionization Potential (eV)
H I → H II	13.60
O I → O II	13.62
O II → O III	35.12
S I → S II	10.36
N I → N II	14.53

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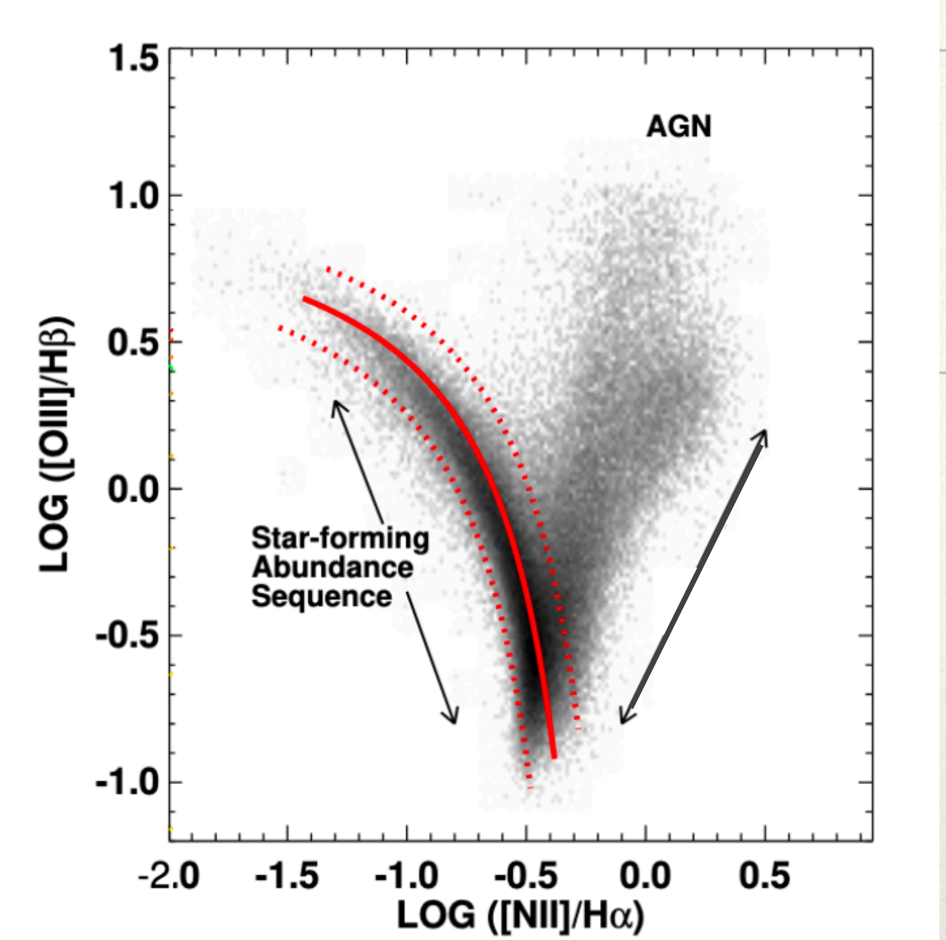

Kewley 2019

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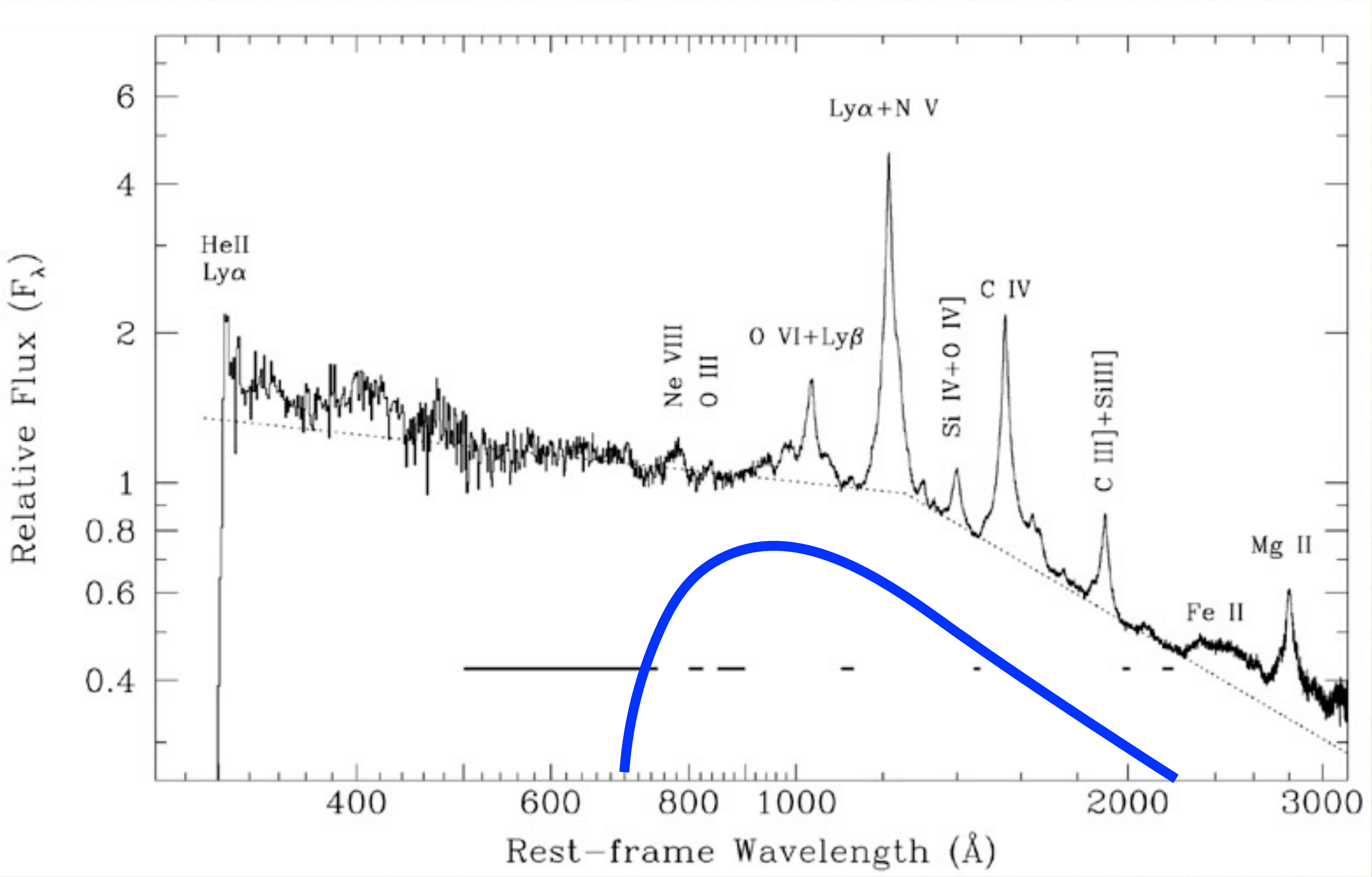
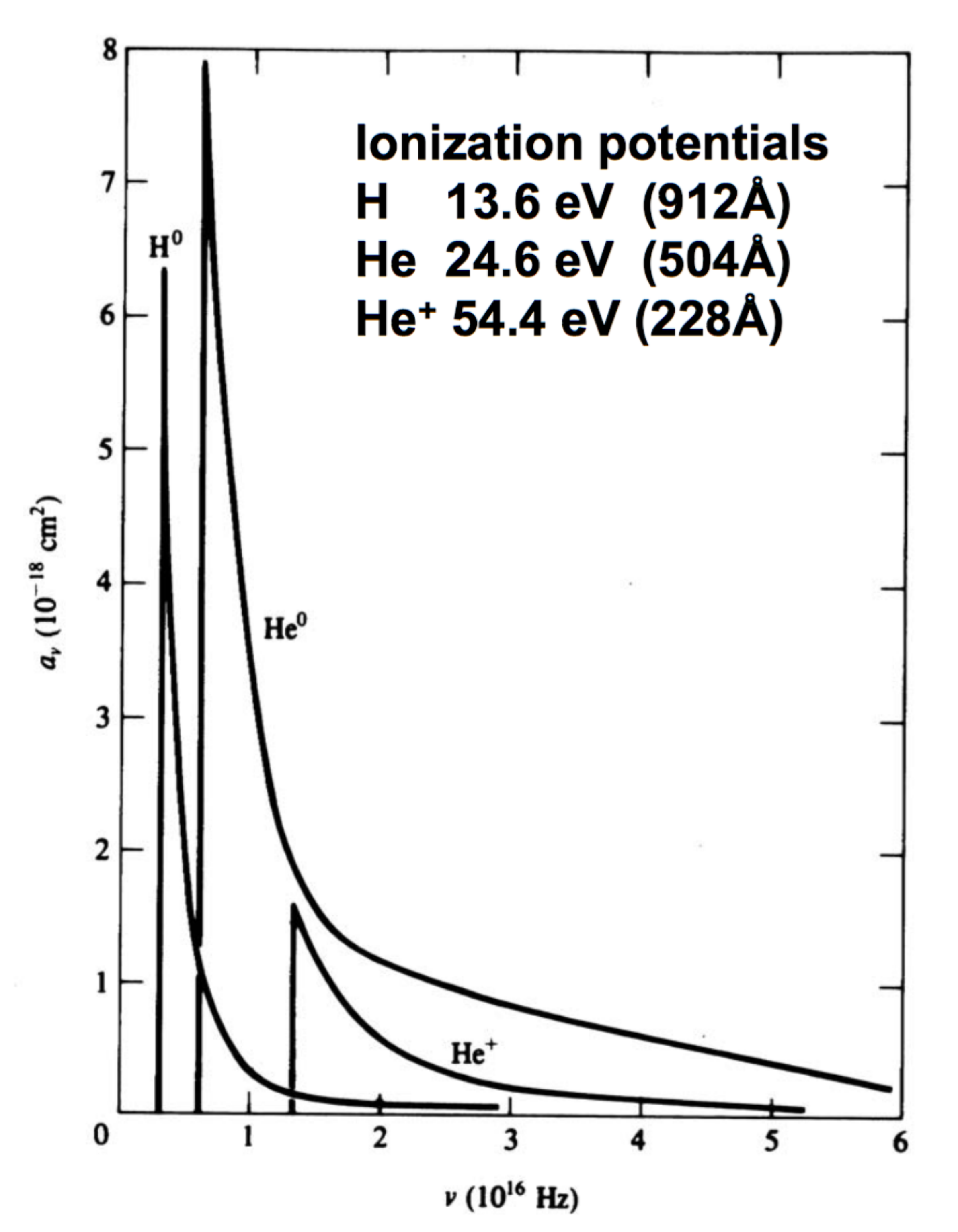
Gas

- Hot stars and AGN have very different spectra:
  - Blackbody vs. power-law ($\nu^{-\alpha}$) ionizing continuum
  - Lots of higher energy (UV, X-ray) photons from AGN
    - Large partially ionized zone



Telfer et al. 2002

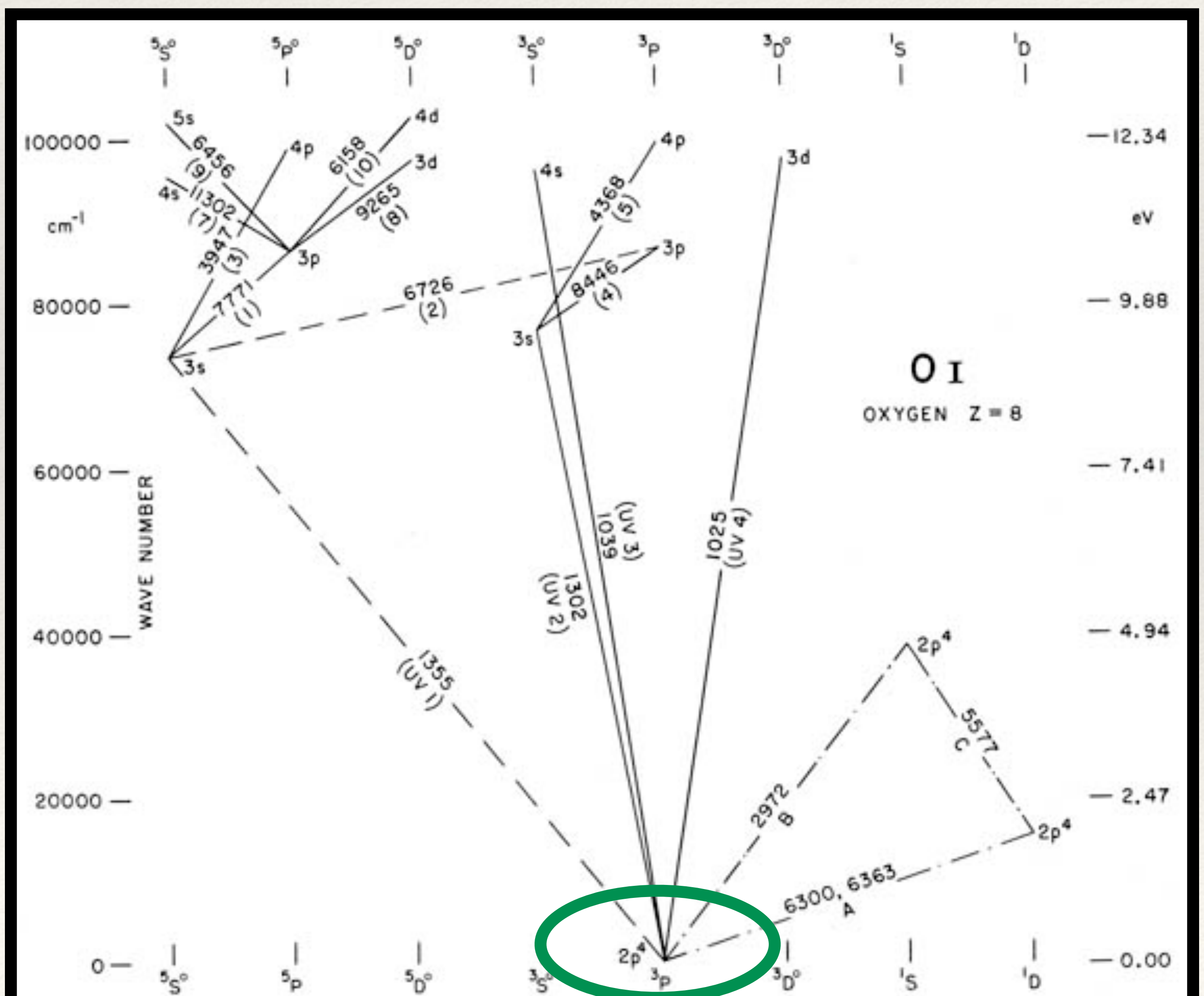
Gas

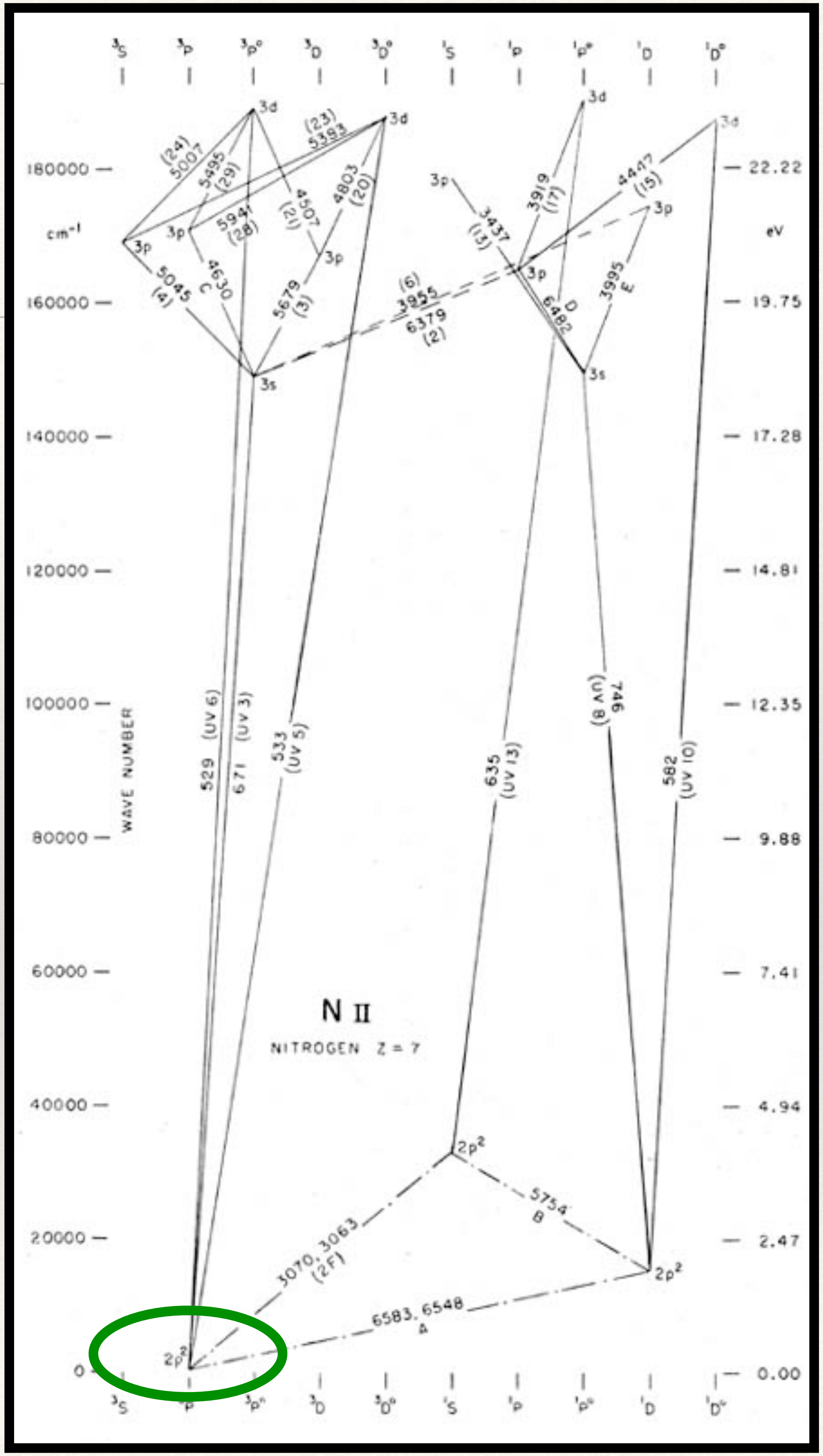


- Photoionization cross-section goes as $\sim\nu^{-3}$ — most H ionized by photons with ~13.6 eV
- Higher energy photons penetrate further into the neutral gas before being absorbed
    - Hot stars — sharp HII/HI transition
    - AGN — partly ionized zone (HII/HI ~ 0.2-0.4) outside fully ionized central region

Gas

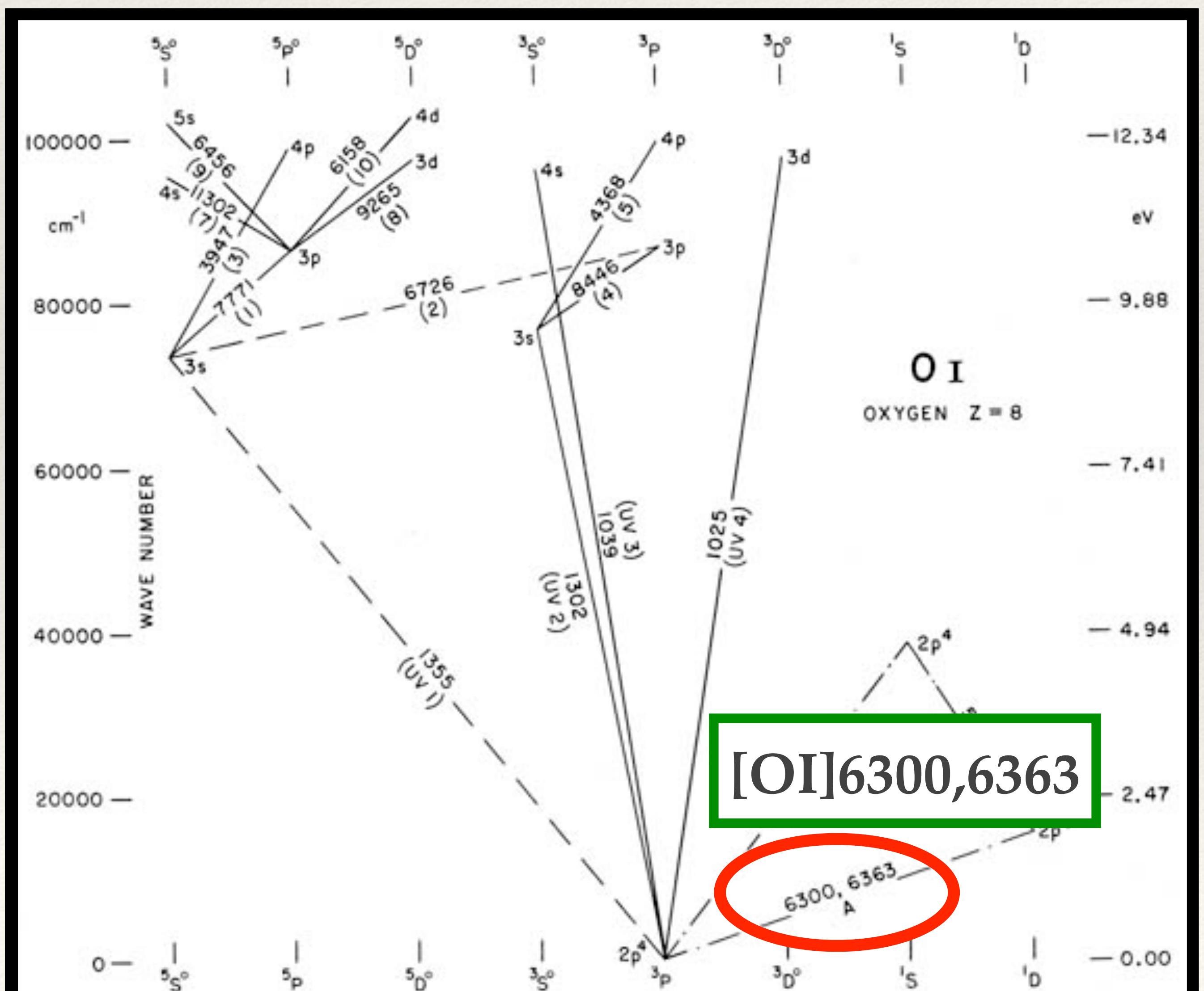
- In partially ionized zone:
  - HI, HII, hot free electrons
  - other neutrals & ions (OI, SII, NI, some NII, OII)

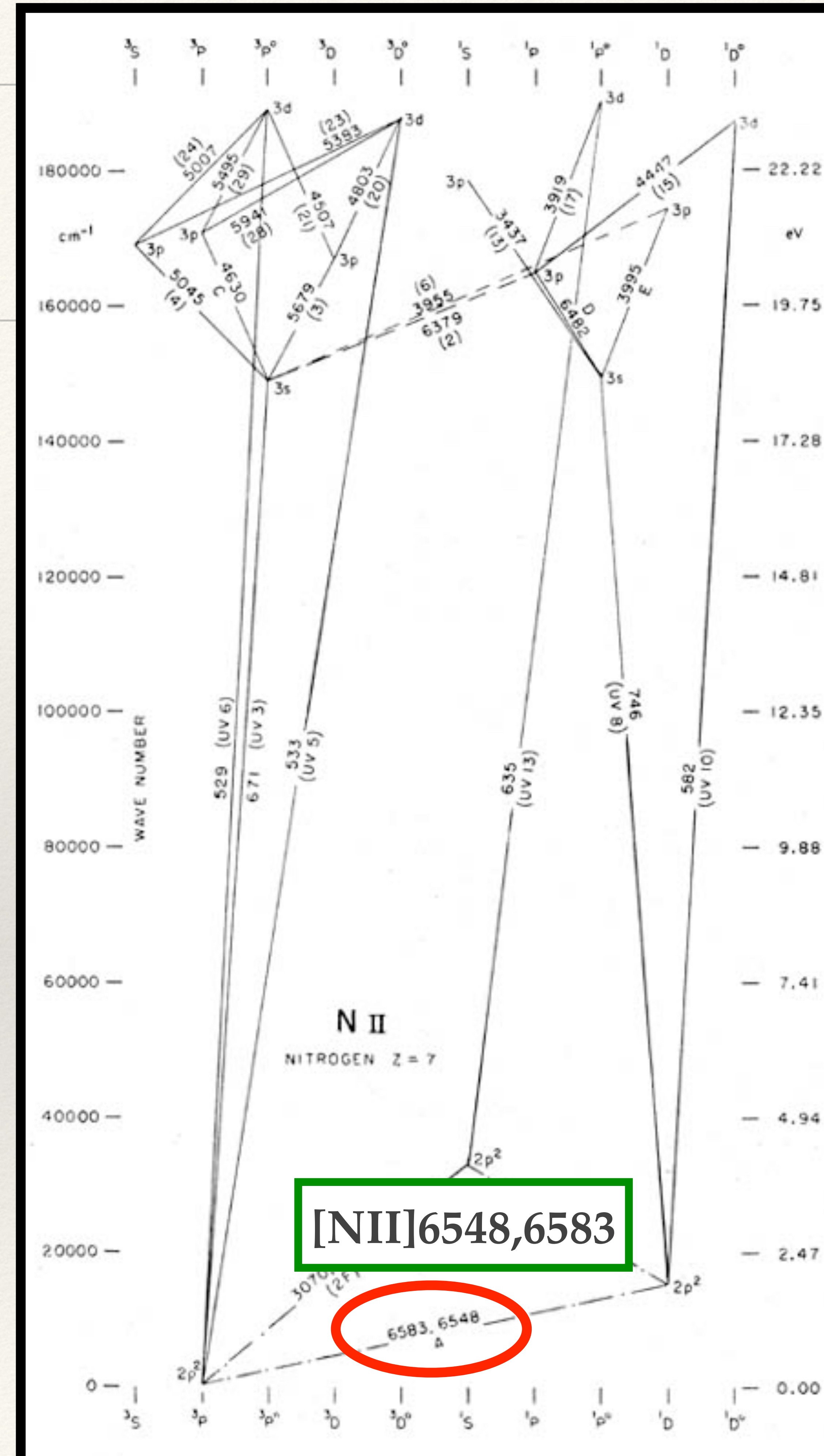




Gas

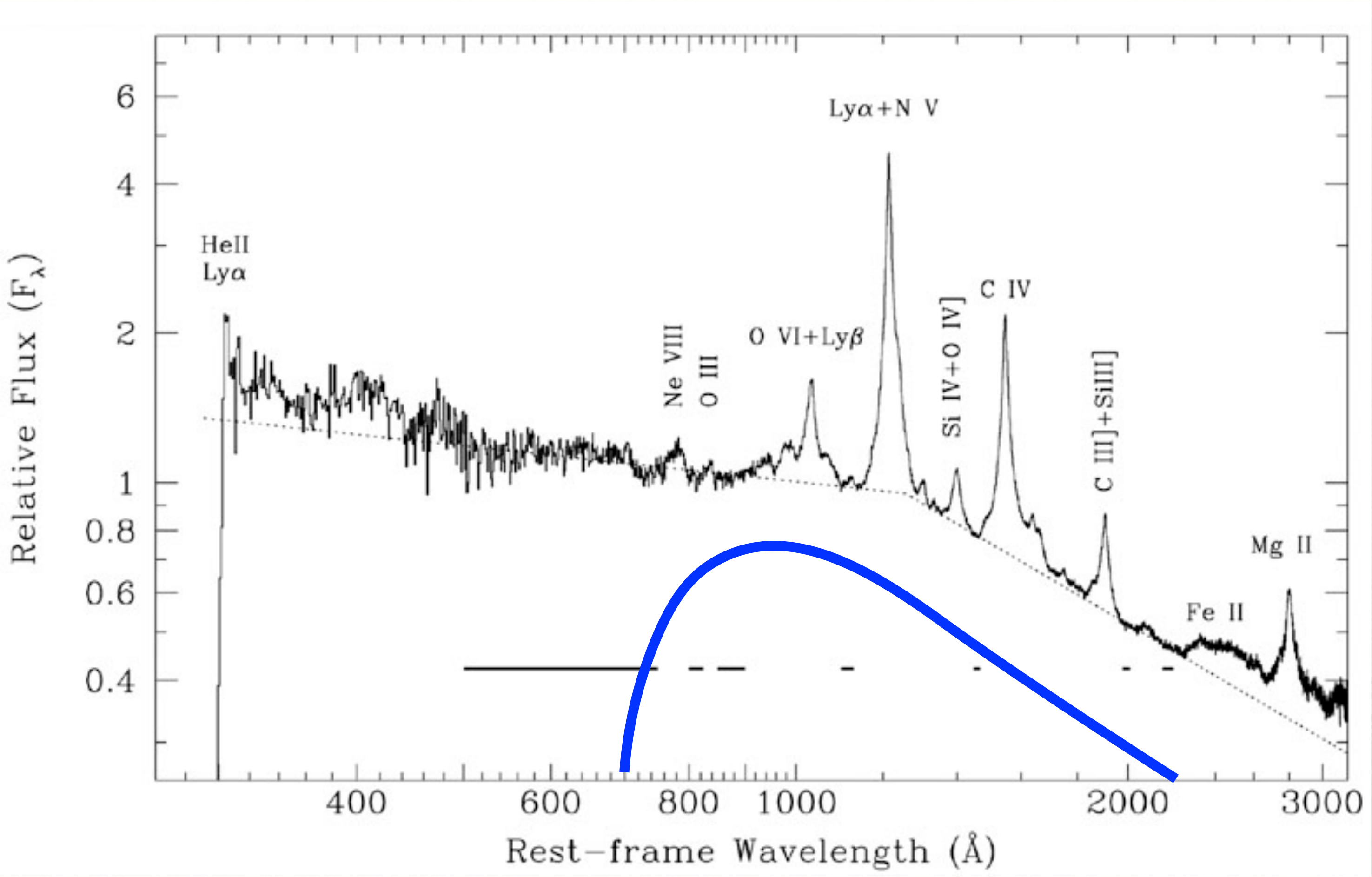
- Hot free electrons have about right energy to **collisionally excite** atoms/ions into low level (sometimes **forbidden**) transitions

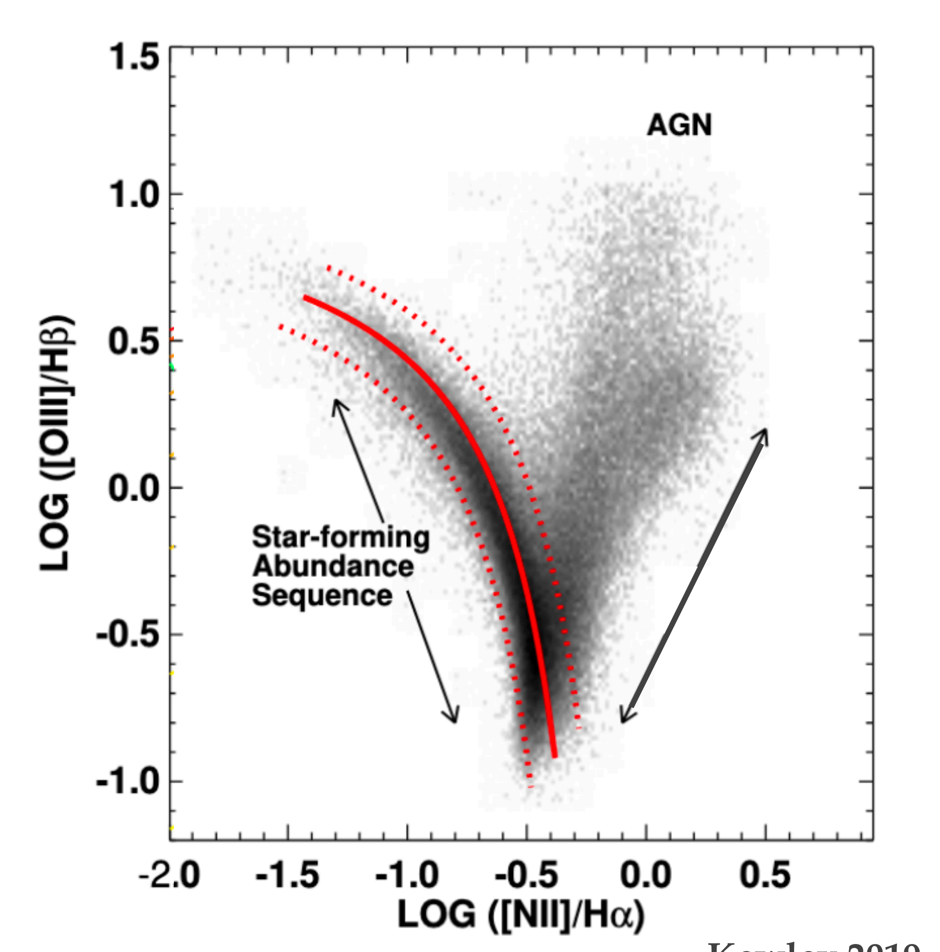




Gas

- Hot stars and AGN have very different spectra:
  - Blackbody vs. power-law ($\nu^{-\alpha}$) ionizing continuum
  - Lots of higher energy (UV, X-ray) photons from AGN
    - Large partially ionized zone — **more collisional excitation of species like NII, SII, OI**

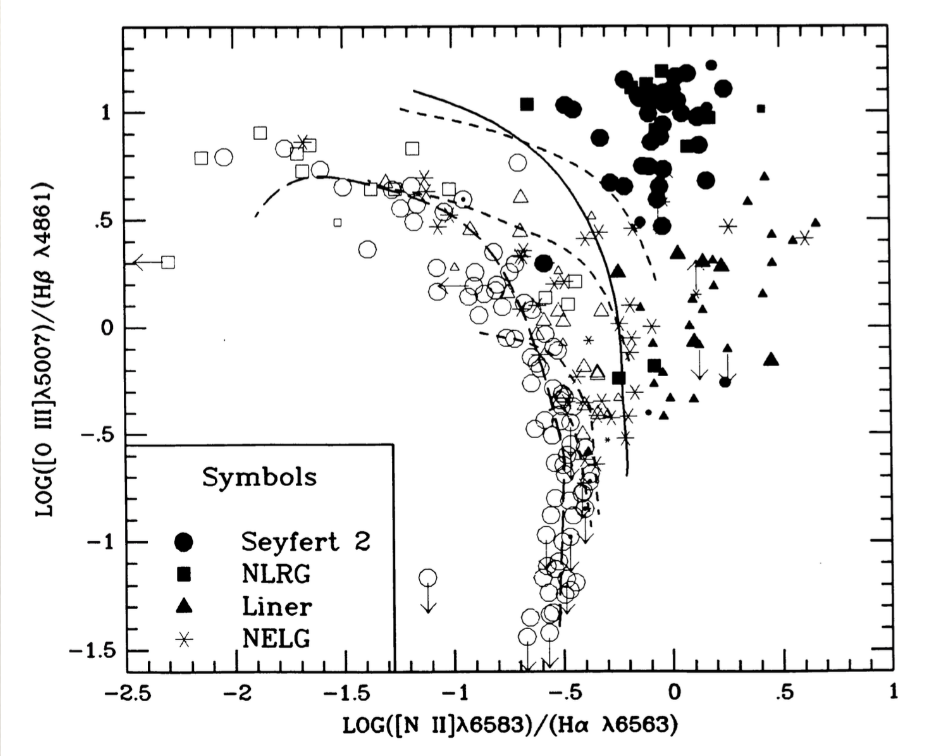




Kewley 2019

Review

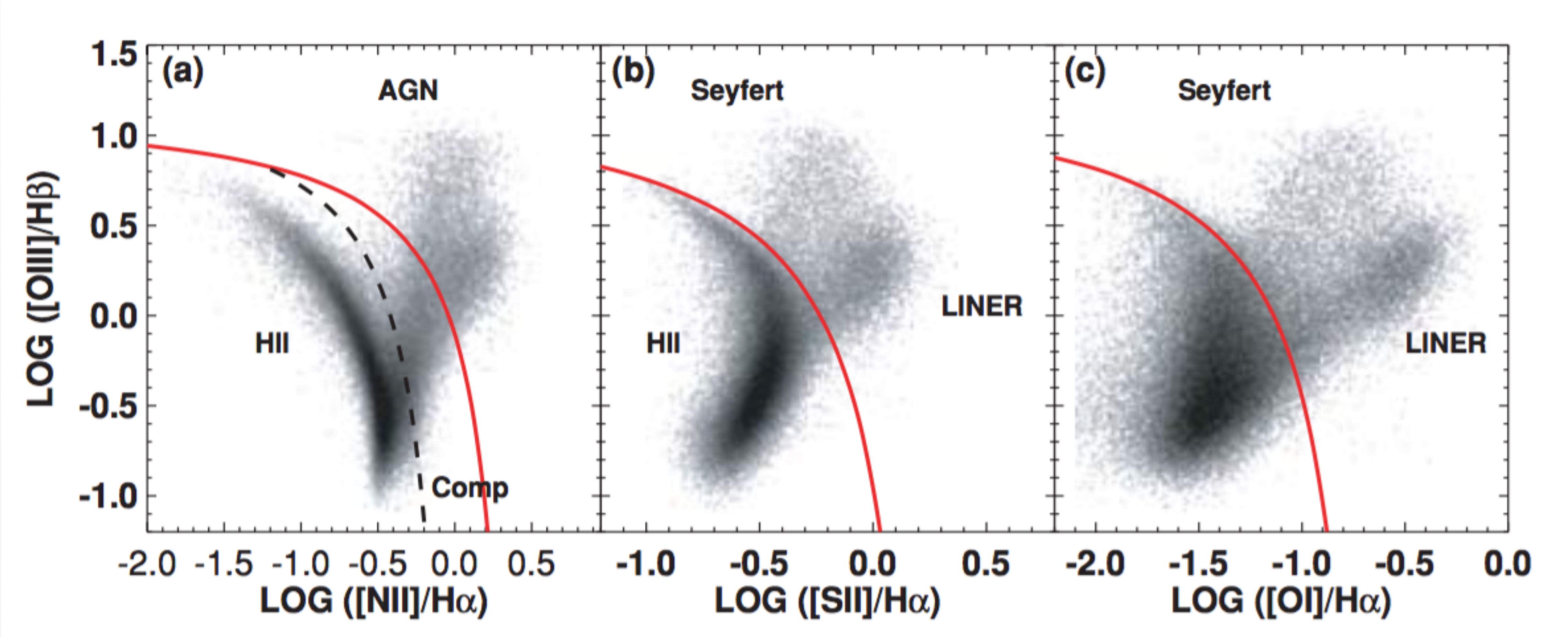
- What makes BPT diagnostic diagrams particularly useful to astronomers?



Veilleux & Osterbrock 1987

- What is the logic that allows us to estimate star formation rates using observations of HII regions in galaxies?

Building Blocks - Gas

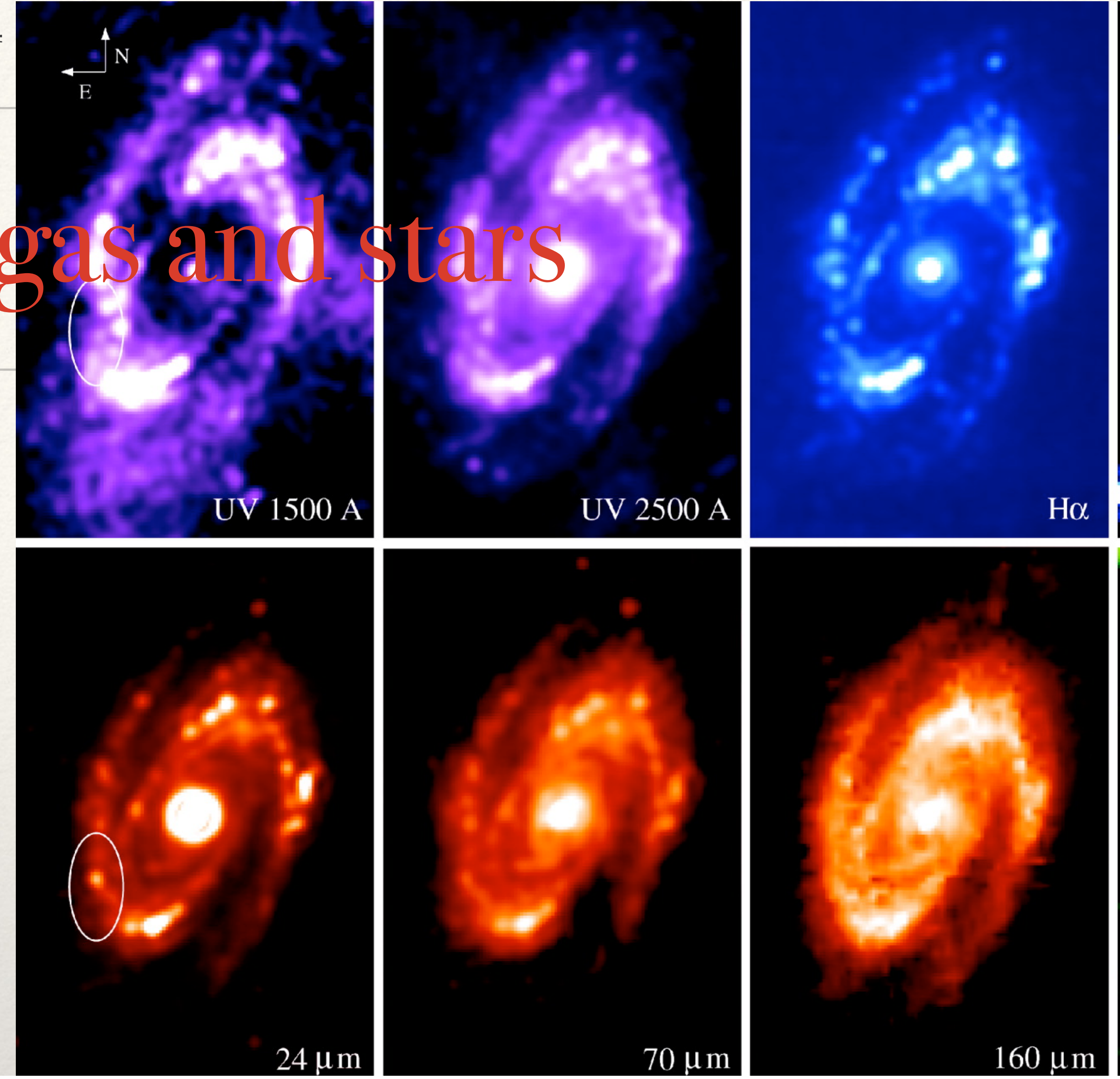


Kewley et al. 2006

- Theoretical "maximum star formation" line and empirical "pure star formation" line, separates **AGN**, **star forming**, and **composite** sources.

Gordon et al. 2004

Interactions between gas and stars



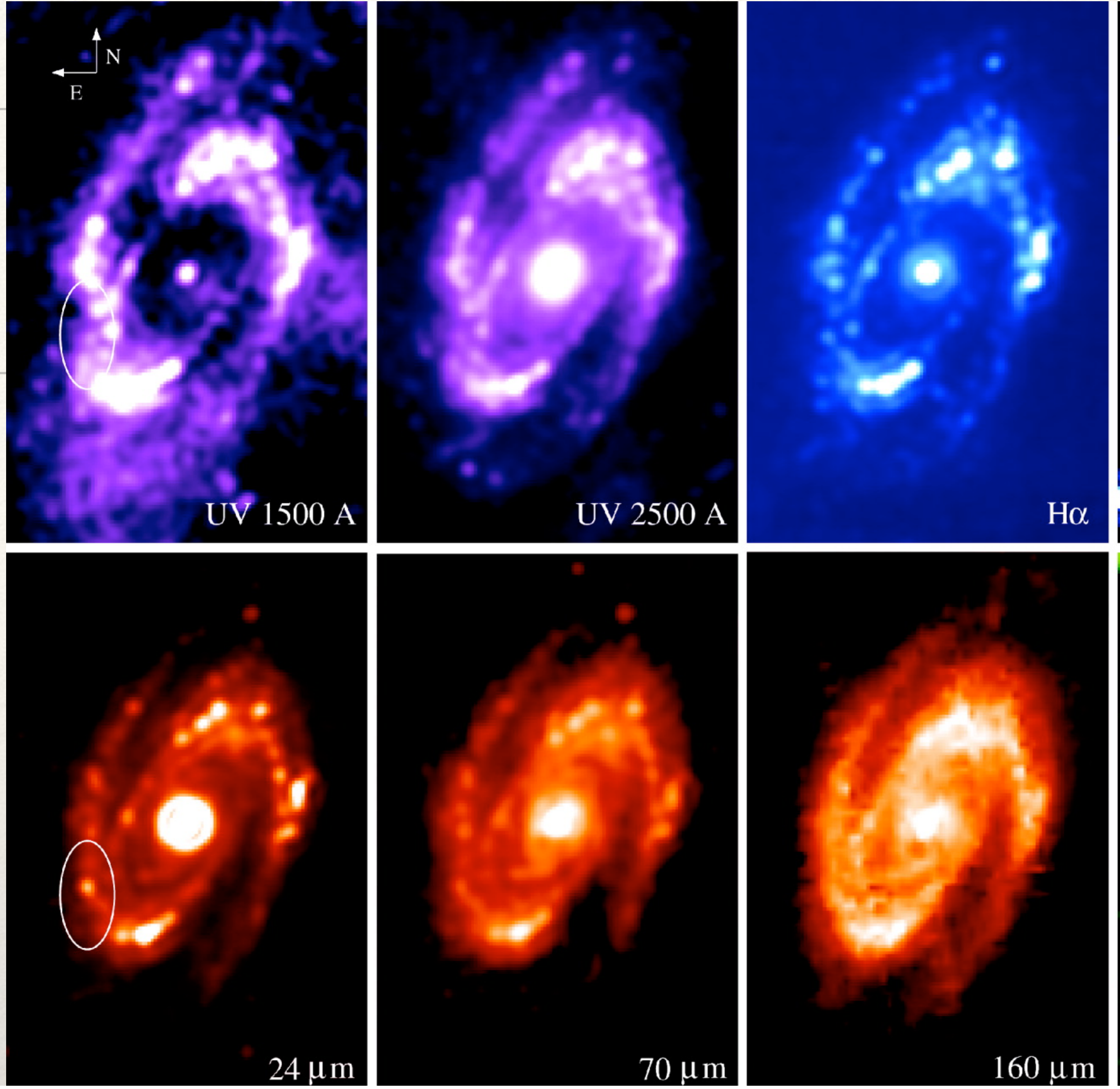
- Interaction between gas and stars—measuring Star Formation Rates
- Main Methods:
  - Hα emission — starlight reprocessed by interstellar gas (challenge: IMF, leakage of ionizing photons)
  - UV continuum — photospheric emission from recently formed stars (challenge: du
  - **IR emission** —dust heated by young stars — (challenge: additio nal heating by evolved stars, need for dust)

Kennicutt 2012

$$\log \dot{M}_*(\mathrm{M}_\odot\ \mathrm{yr}^{-1}) = \log L_x - \log C_x$$

Band	Age Range (Myr)[a]	L_x Units	$\log C_x$	$\dot{M}_\star/\dot{M}_\star$(K98)	References
FUV	$0-10-100$	$\mathrm{ergs\,s^{-1}}$ (νL_ν)	43.35	0.63	1, 2
NUV	$0-10-200$	$\mathrm{ergs\,s^{-1}}$ (νL_ν)	43.17	0.64	1, 2
Hα	$0-3-10$	$\mathrm{ergs\,s^{-1}}$	41.27	0.68	1, 2
TIR	$0-5-100^b$	$\mathrm{ergs\,s^{-1}}$ (3–1100 µm)	43.41	0.86	1, 2
24 µm	$0-5-100^b$	$\mathrm{ergs\,s^{-1}}$ (νL_ν)	42.69		3
70 µm	$0-5-100^b$	$\mathrm{ergs\,s^{-1}}$ (νL_ν)	43.23		4
1.4 GHz	$0-100$:	$\mathrm{ergs\,s^{-1}\,Hz^{-1}}$	28.20		1
2–10 keV	$0-100$:	$\mathrm{ergs\,s^{-1}}$	39.77	0.86	5

Gordon et al. 2004



Star Formation

- Other Methods:
  - **Radio Free-Free** — from ionized gas
  - **Radio Synchrotron** — from charged particles produced in supernovae
  - **X-ray emission** — from massive X-ray binaries, supernovae, supernova remnants

- These methods are more indirect, but correlate with SFR

Kennicutt 2012

$$\log \dot{M}_*(\mathrm{M}_\odot\ \mathrm{yr}^{-1}) = \log L_x - \log C_x$$

Band	Age Range (Myr)[a]	L_x Units	$\log C_x$	$\dot{M}_\star/\dot{M}_\star$(K98)	References
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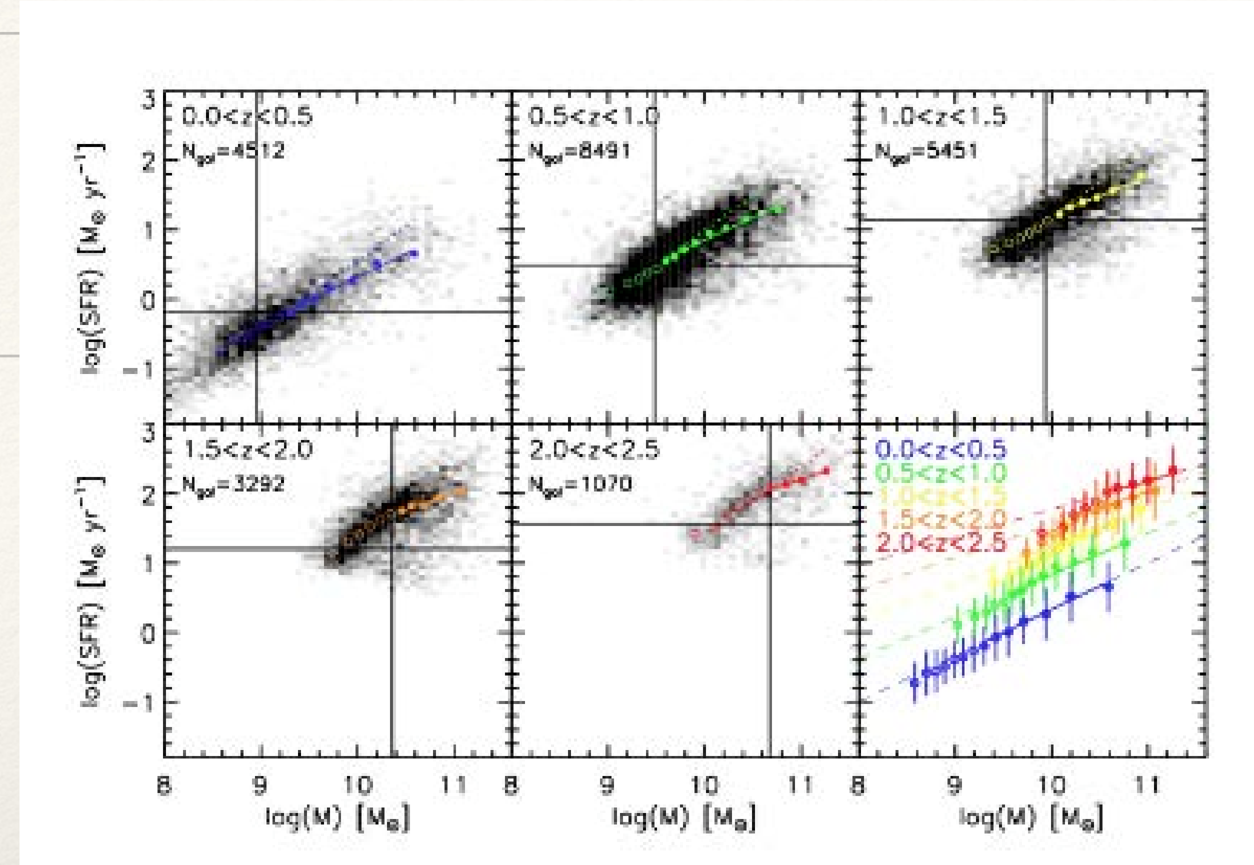
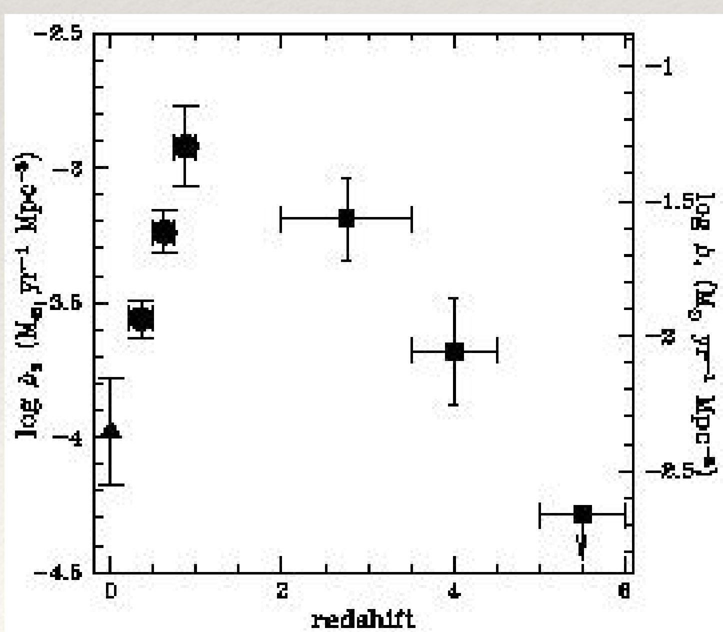
1.4 GHz	0 – 100 :	ergs s^{-1} Hz^{-1}	28.20		1
2–10 keV	0 – 100 :	ergs s^{-1}	39.77	0.86	5

Star Formation results

- Results from measuring star formation:
  - the galaxy "main sequence": SF proportional to stellar mass
  - star formation as a function of redshift: the Madau plot and cosmic noon





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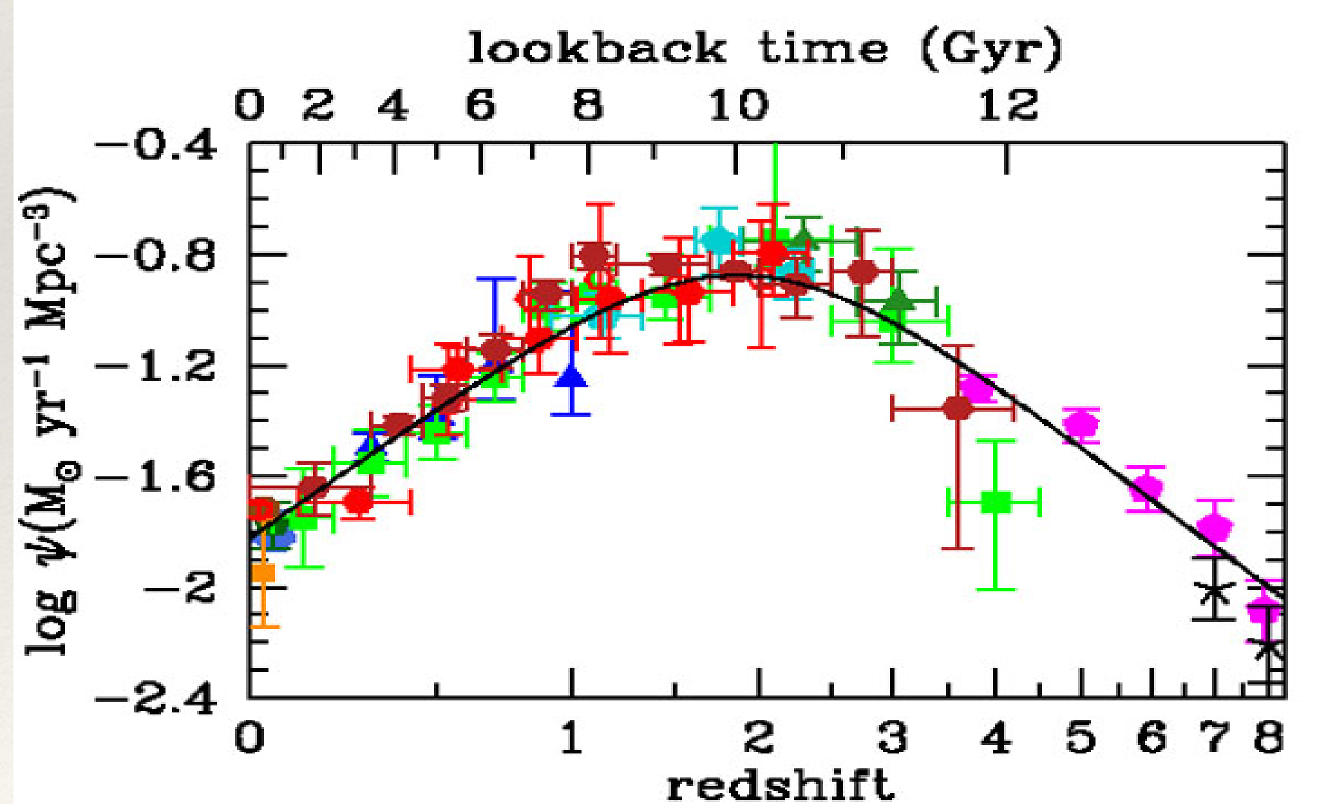

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Star formation parameterizations

- But what causes stars to form? Need to know to be able to model galaxies, but not known, and even if it was, probably don't have resolution
- Need to parameterize star formation: likely related to gas properties:

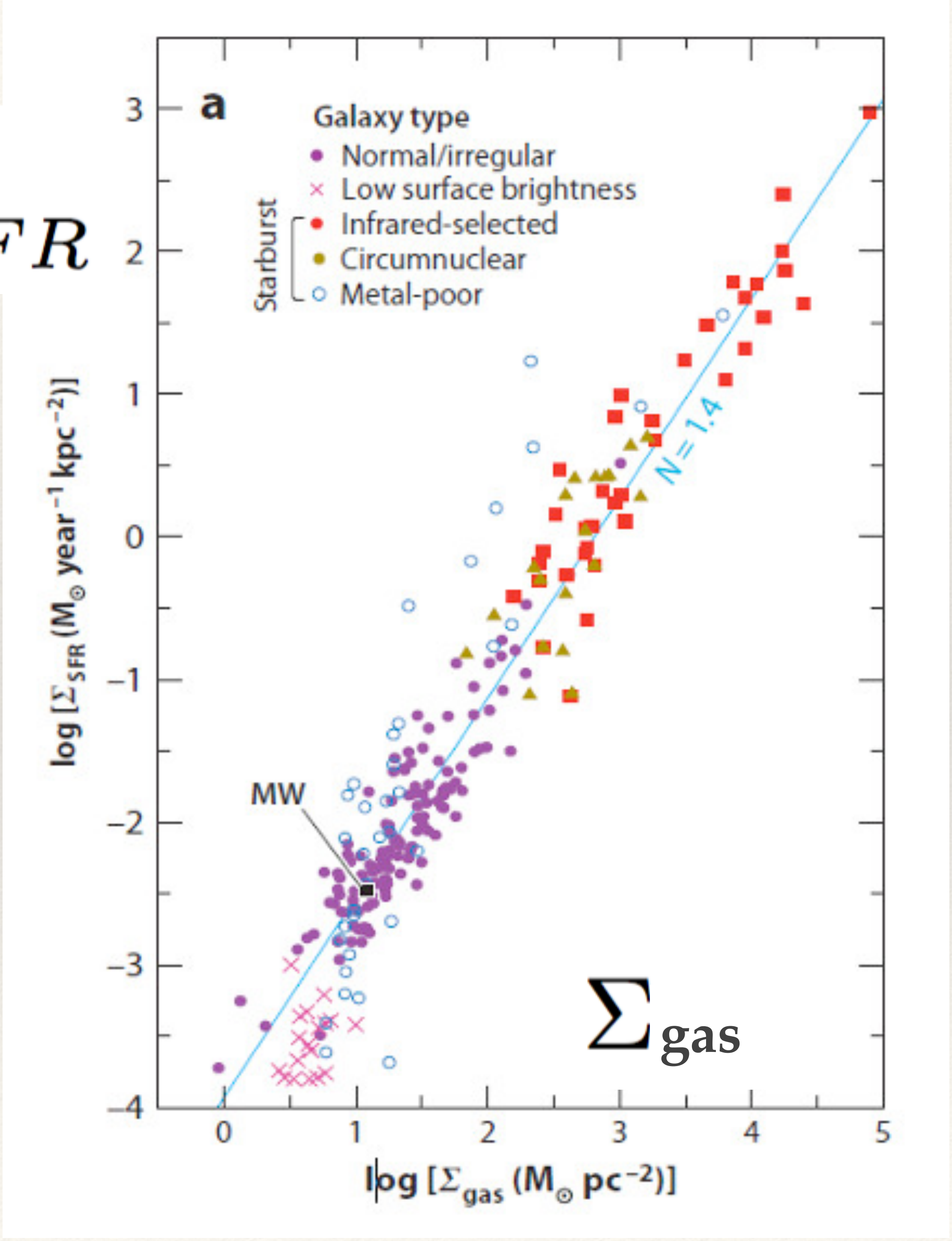
Schmidt Law: $SF \propto \rho^n$

$$\Sigma_{SFR} = A\,\Sigma^N{}_{gas}$$

- Globally, this seems to predict star formation rates fairly well over a large range of surface gas densities

- But star formation is local, not global

Σ_{SFR}



Σ_{gas}

Gao & Solomon 2004

Star formation parameterization

- Locally, may be more complex: proprotional to surface density but only above some critical surface density
- Kennicutt-Schmidt law parameterizes this
- But also some question about whether star formation is related to total gas surface density, or molecular gas:

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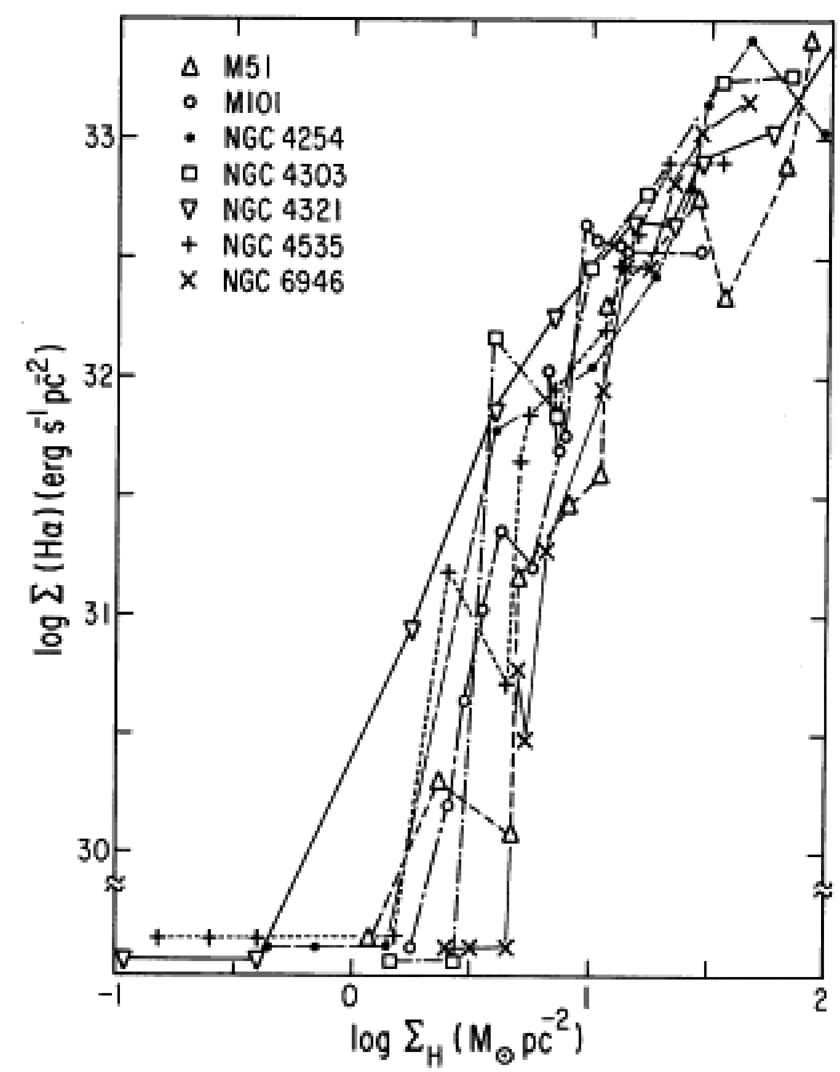


FIG. 8.—Dependence of Hα surface brightness on total (H I + H_2) hydrogen surface density, for seven giant Sc galaxies. Each point represents the Hα and gas densities averaged at a given galactocentric radius, and lines connect points at adjacent radii. The points at the bottom denote regions where no Hα emission was detected.

9.5 Empirical Star-Formation Laws 437

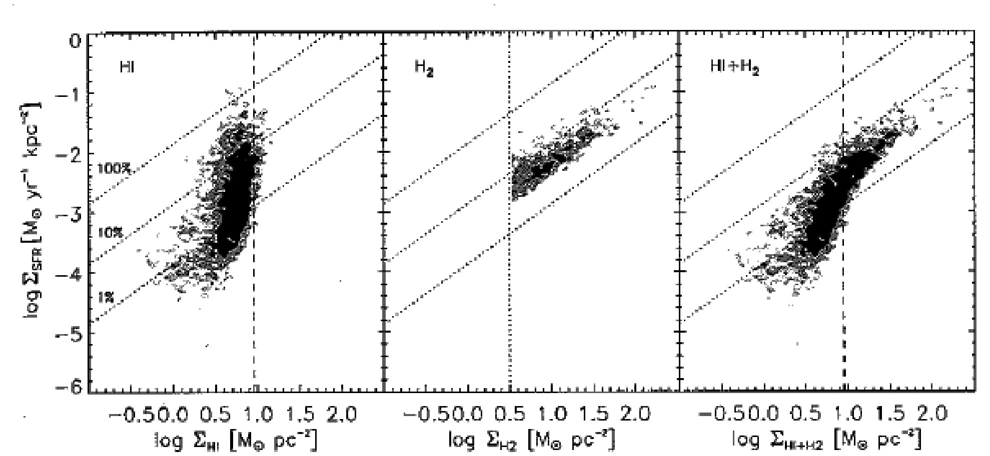
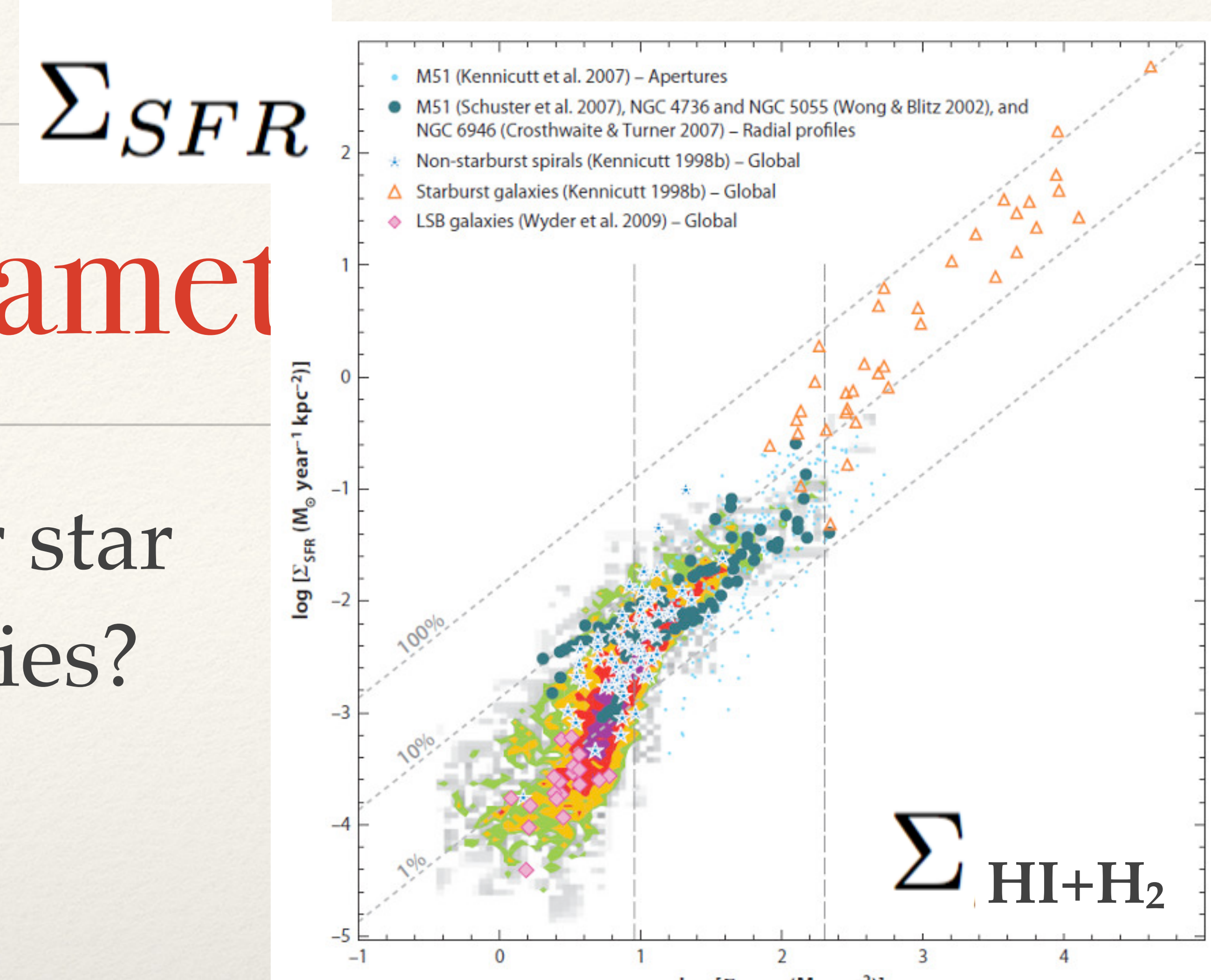


Fig. 9.4. Local star-formation rate per unit area (measured on a scale of ~ 750pc) as a function of the local atomic gas density (left-hand panel), molecular gas density (middle panel), and total gas density (right-hand panel). The grayscale is proportional to the number of independent data points (resolution elements) obtained from a sample of 18 nearby galaxies. The diagonal dotted lines show lines of constant star-formation efficiency, indicating the level of Σ_* needed to consume 1%, 10% and 100% of the gas reservoir (including helium) in 10^8 yr. Dashed vertical lines in the panels on the left and right show the surface density at which HI saturates. The dotted vertical line in the middle panel indicates the typical sensitivity of the CO data used to infer the molecular gas densities. [Kindly provided by F. Bigiel, based on data published in Bigiel et al. (2008)]

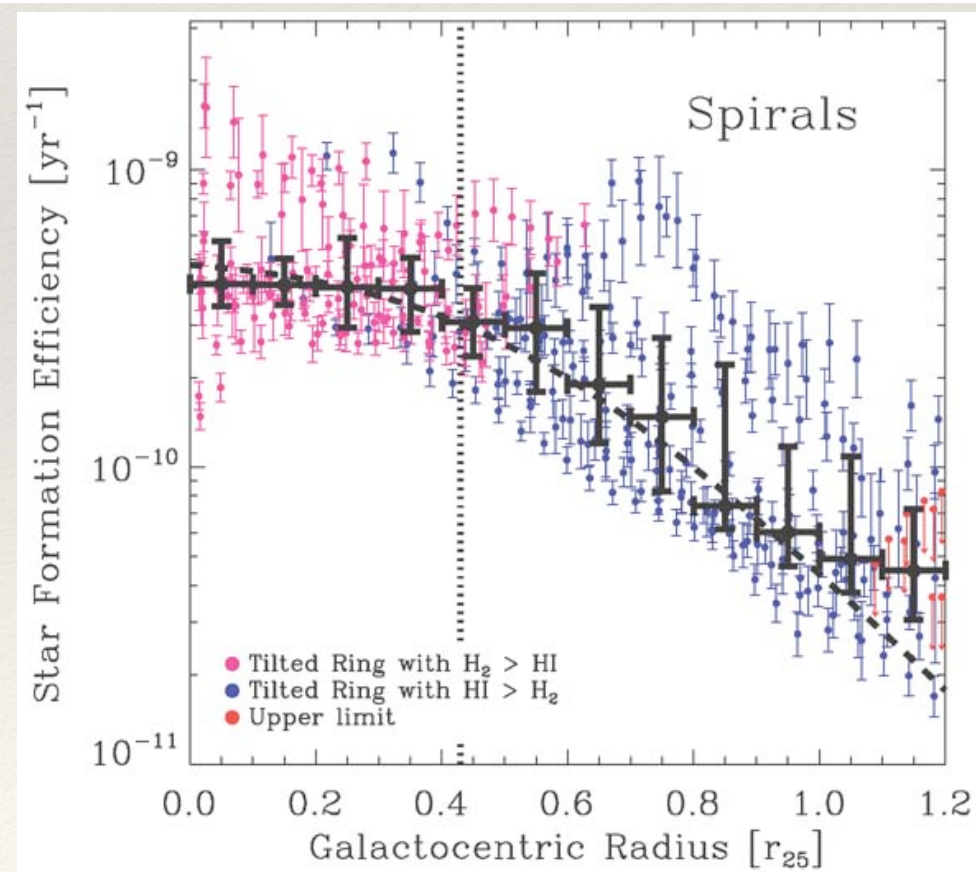
e l e a e a h ee
e g e e al

Star formation paramet

- A turnover or **threshold** for star formation at low gas densities?
- Declining star formation efficiency in outer regions
- Possible reasons —
  - disk more stable
  - molecular cloud formation more difficult
  - variations in X(CO)



Bigiel et al. 2008



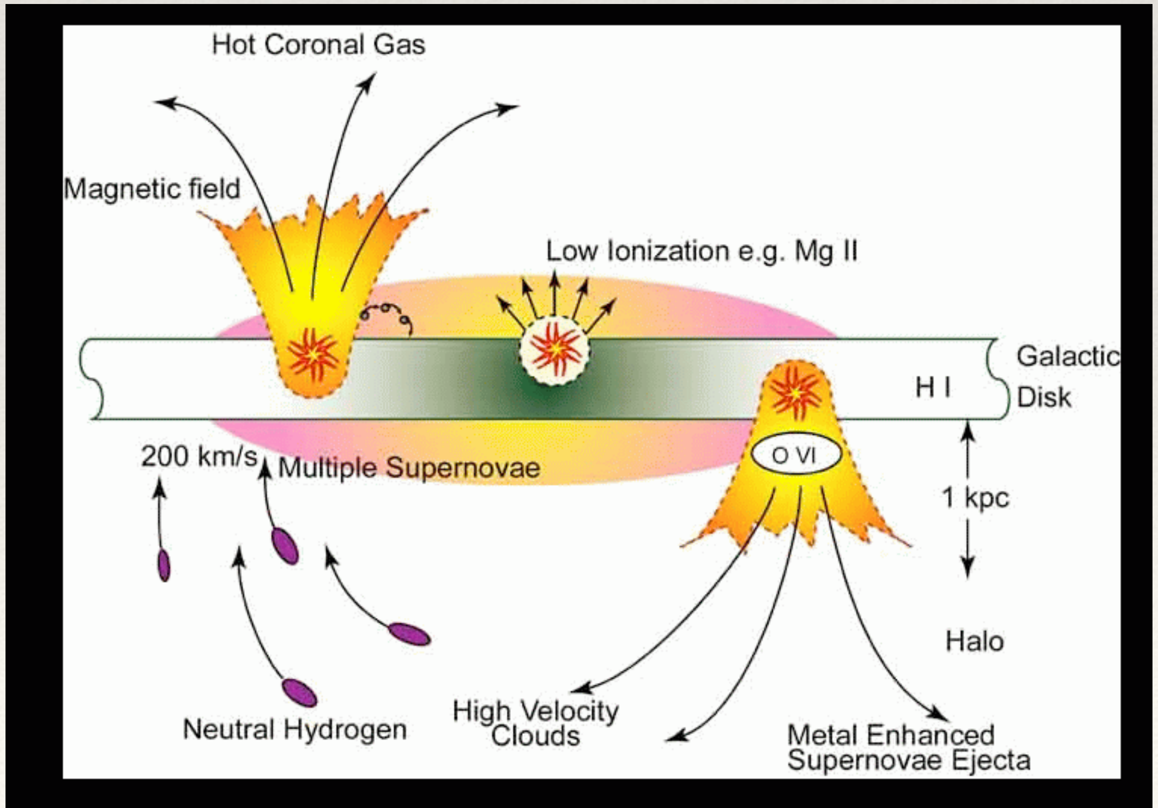
Leroy et al. 2008

Star - Gas interaction

- Interaction between stars and gas:
  - Shocks from supernovae may compress gas clouds — **triggered star formation**
  - Supernovae clear out "superbubbles" in the ISM — **galactic outflows / winds**
  - Gas may fall back down onto the disk — **galactic fountains / chimneys**
- Part of the "gas cycle" in galaxies

M82 (Credit: Ken Crawford, Rancho Del Sol Obs.)

N44 in LMC (Credit: X-ray: NASA/CXC/U.Mich./ S.Oey, IR: NASA/JPL, Optical: ESO/WFI/)2.2-m



Galactic Fountain Model

Star - Gas interaction