The Puzzle of LINERs and the Warm Ionized Gas in Early-type Galaxies

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Yan & Blanton (2011) arXiv:1109.1280

Outline

- Introduction to LINERs
- How can we solve the puzzle about its ionization and what do the data show?
- Gas-phase metallicity in early-type galaxies

Why study the line emission?

- The emission lines probe the warm ionized phase in the ISM. They can reveal the density, temperature, excitation state, kinematics, and metallicity of the gas.

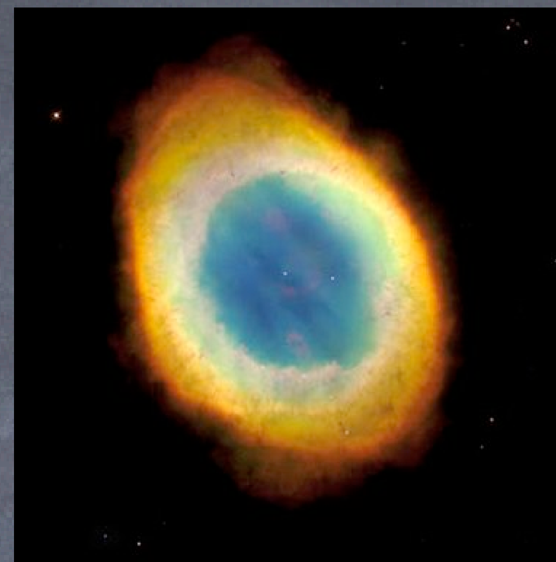
- We can learn about the ionizing source, be it AGN or stars.

- Where does the gas come from? Mass-loss from stars or accreted from the outside?

- Combining this with other components of the ISM may reveal the heating processes in these early-type galaxies, which has short cooling time in the center but little star formation.

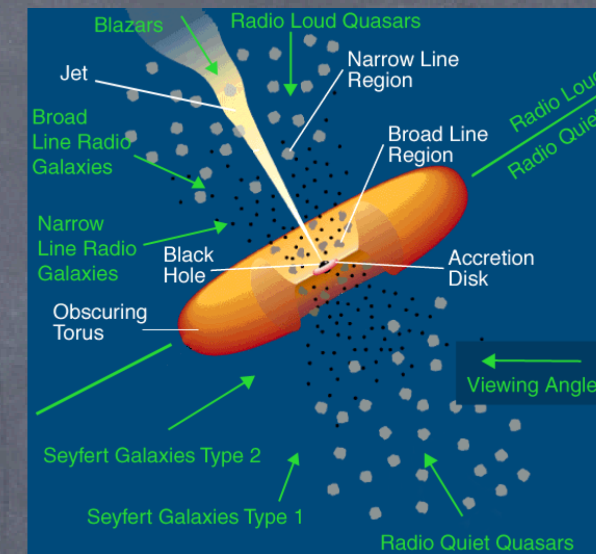
Line Emitting Objects in Galaxies

Star-forming HII region

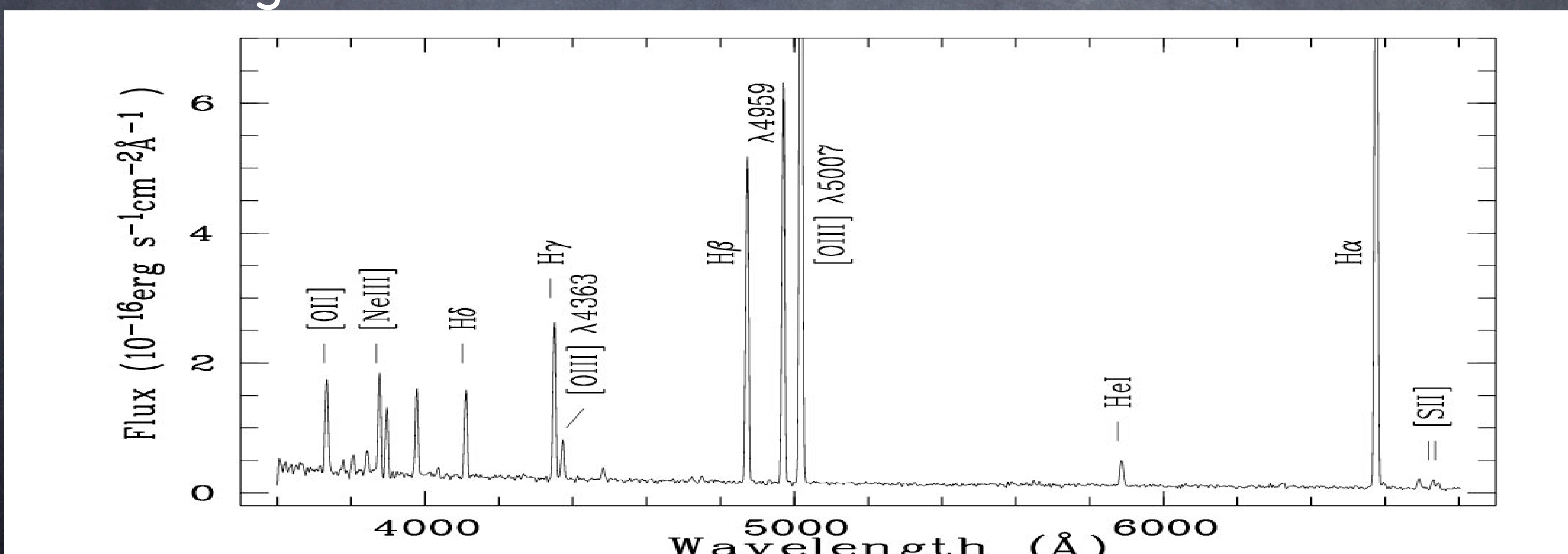


Planetary Nebula

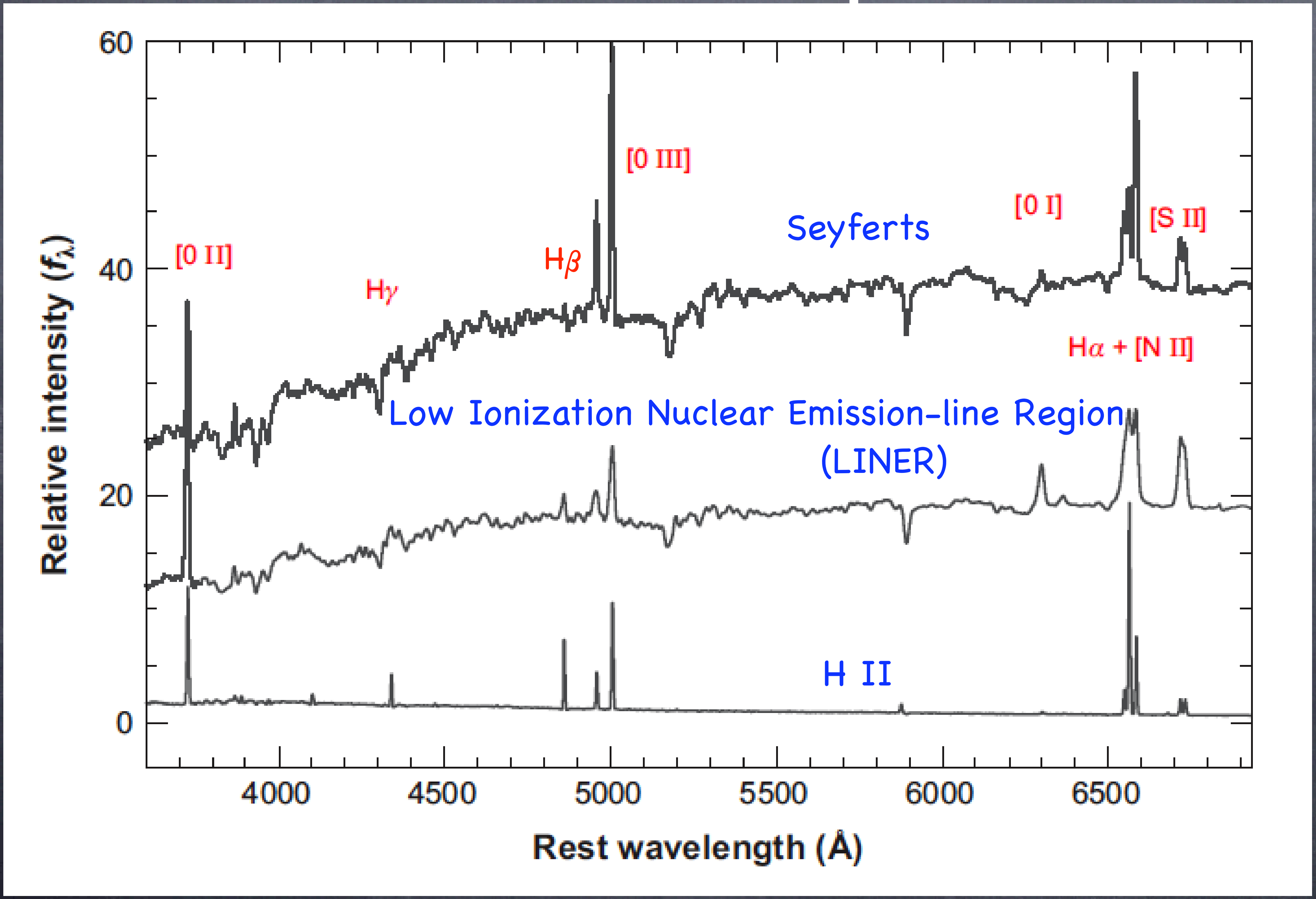
Supernova Remnant



Active Galactic Nucleus

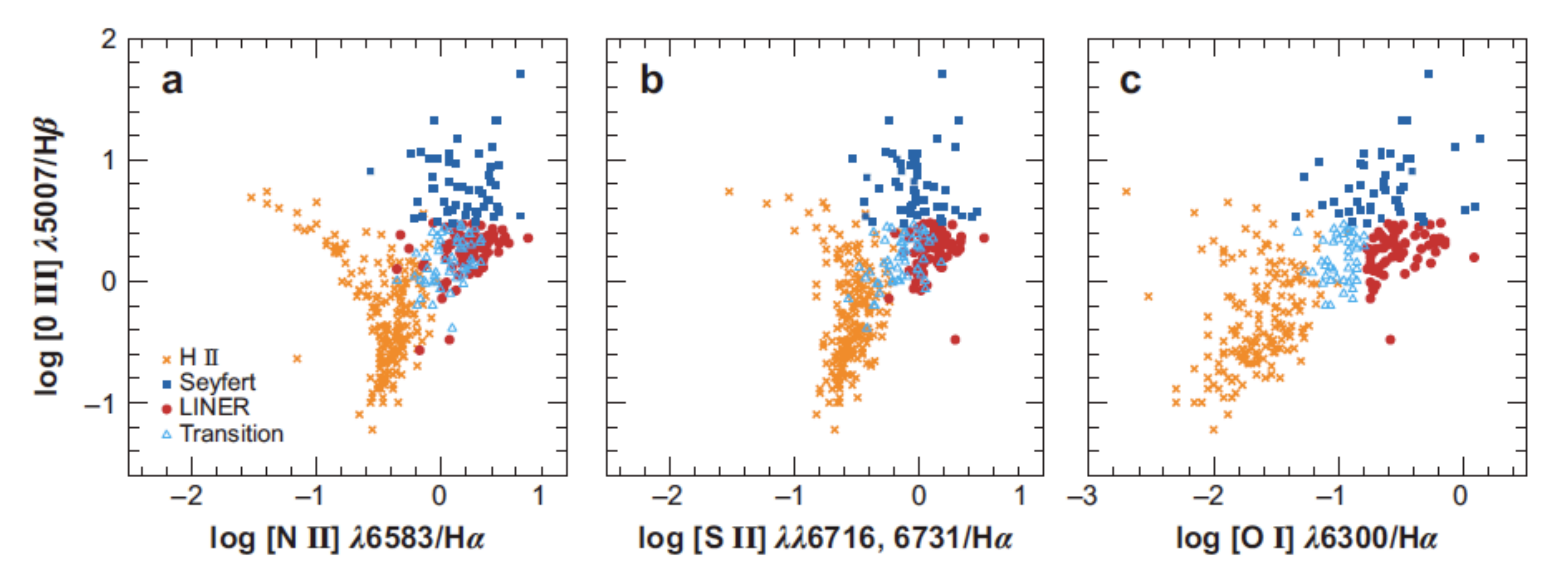


Line Ratio Diagnostics for Nuclear Spectra



Palomar Survey by Ho, Filippenko, & Sargent

Line Ratio Diagnostics for Nuclear Spectra



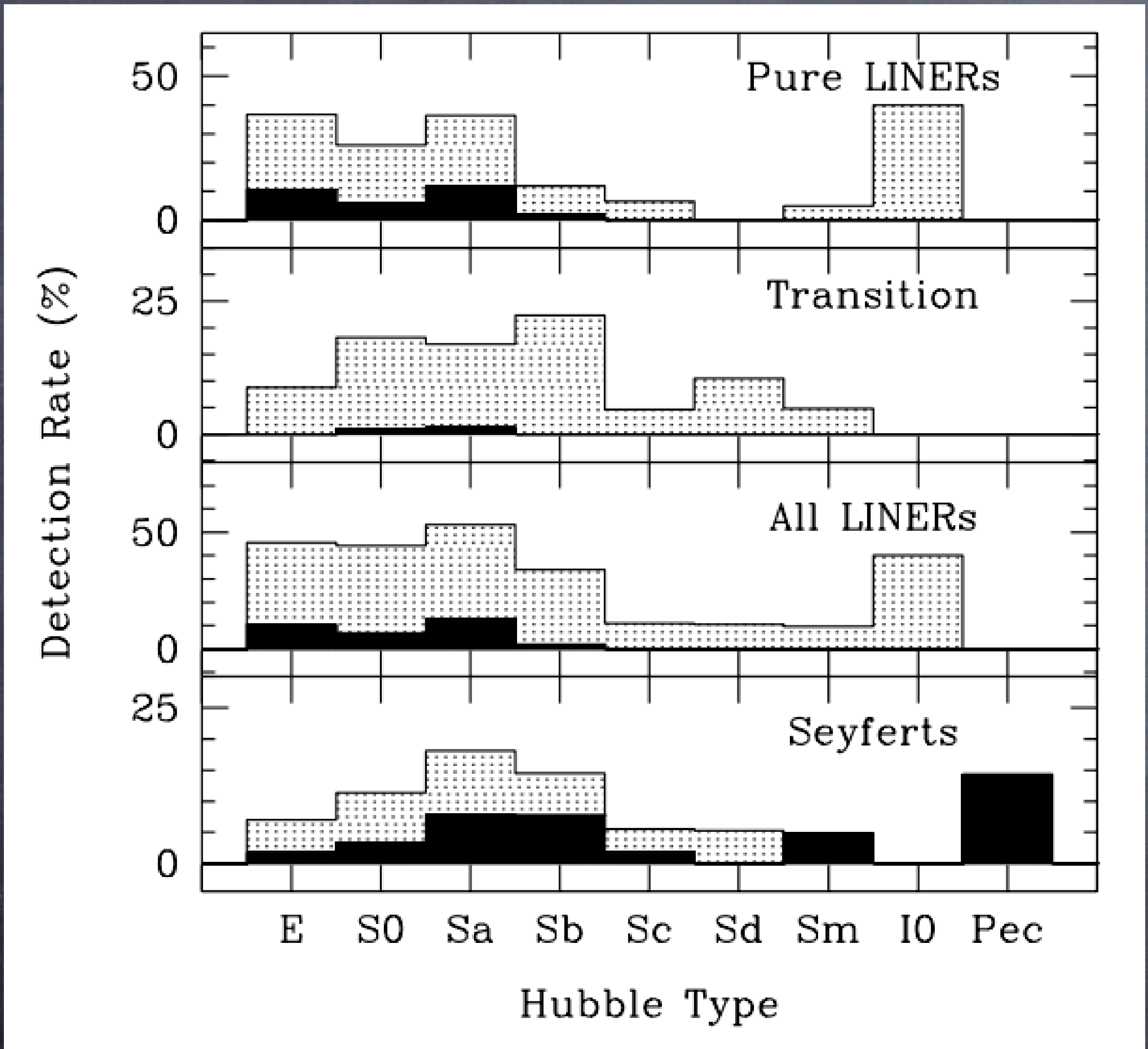
Ho (2008)

Palomar Survey (r< 200pc)

Potential Ionization Mechanisms for LINERs

- Photoionization by an AGN (Ferland & Netzer 1983, Halpern & Steiner 1983)
- Photoionization by hot evolved stars, e.g. post-AGBs (di Serego Alighieri et al. 1990, Binette et al. 1994)
- Photoionization by hot X-ray emitting gas (Voit & Donahue 1990, 1991; Kim 1989)
- Collisional ionization by fast shocks (Heckman et al. 1989, Dopita & Sutherland 1995)

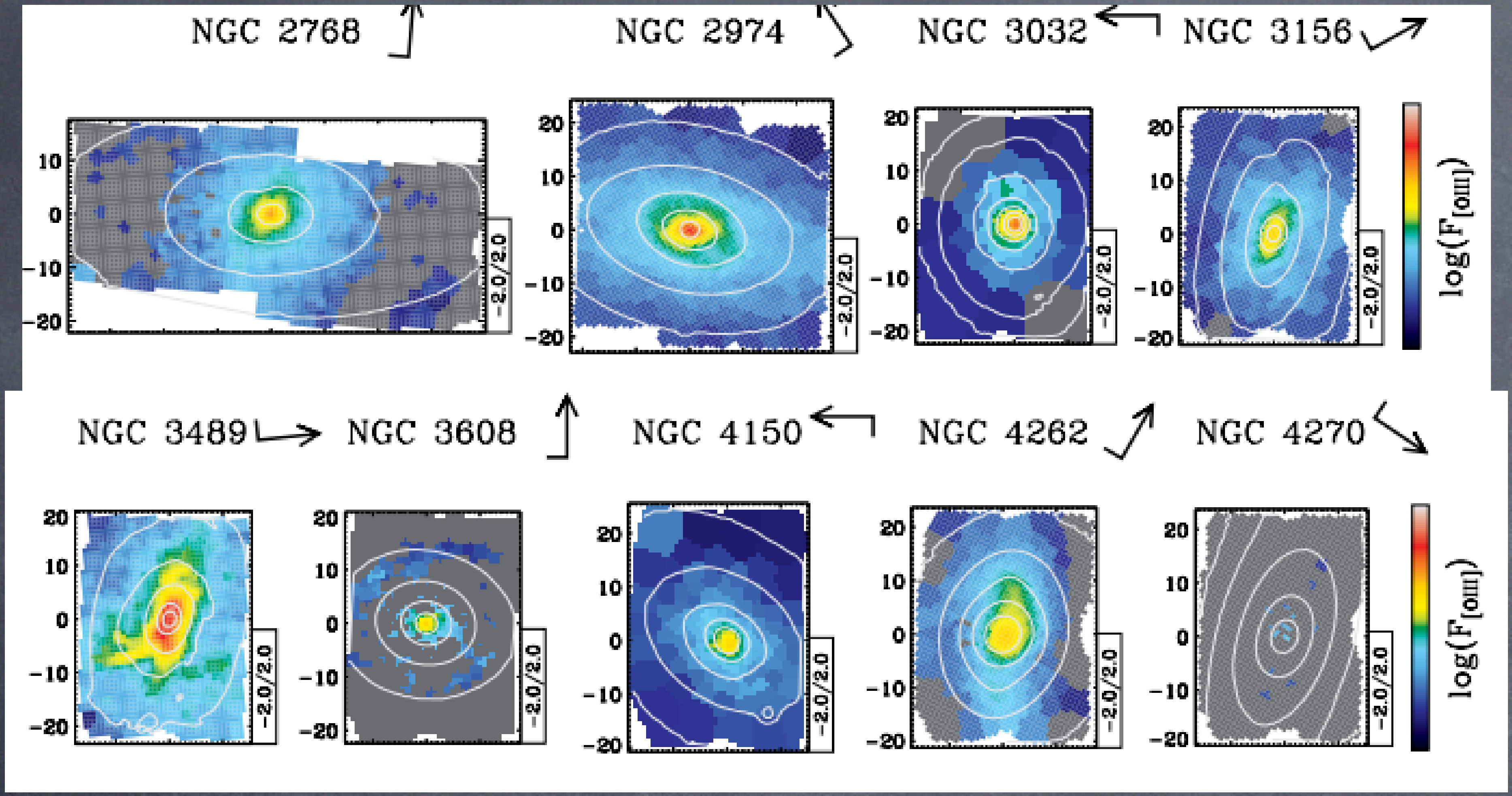
Nuclear LINERs



LINER is the most common spectral type found in the nuclei of early-type galaxies, comprising ~50% of all early-types.

Ho et al. (1997)

Extended LINER-like Emission



SAURON project

Sarzi et al. (2006)

75% of early-type galaxies display line emission, often spatially extended. The line ratio pattern is LINER-like.

(Phillips et al. 1986, Kim 1989, Buson et al. 1993, Goudfrooij et al. 1994, Macchetto et al. 1996, Zeilinger et al. 1996, Eisenstein et al. 2003, Yan et al. 2006)

Definition of LINER

Low Ionization Nuclear Emission-line Region

Definition of LINER

Low Ionization Nuclear Emission-line Region

- Spectral definition based on line ratios

Definition of LINER

Low Ionization Nuclear Emission-line Region

- Spectral definition based on line ratios
- Morphological definition --- Never Quantified!

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Nuclear LINER vs. Extended LINER

Definition of LINER

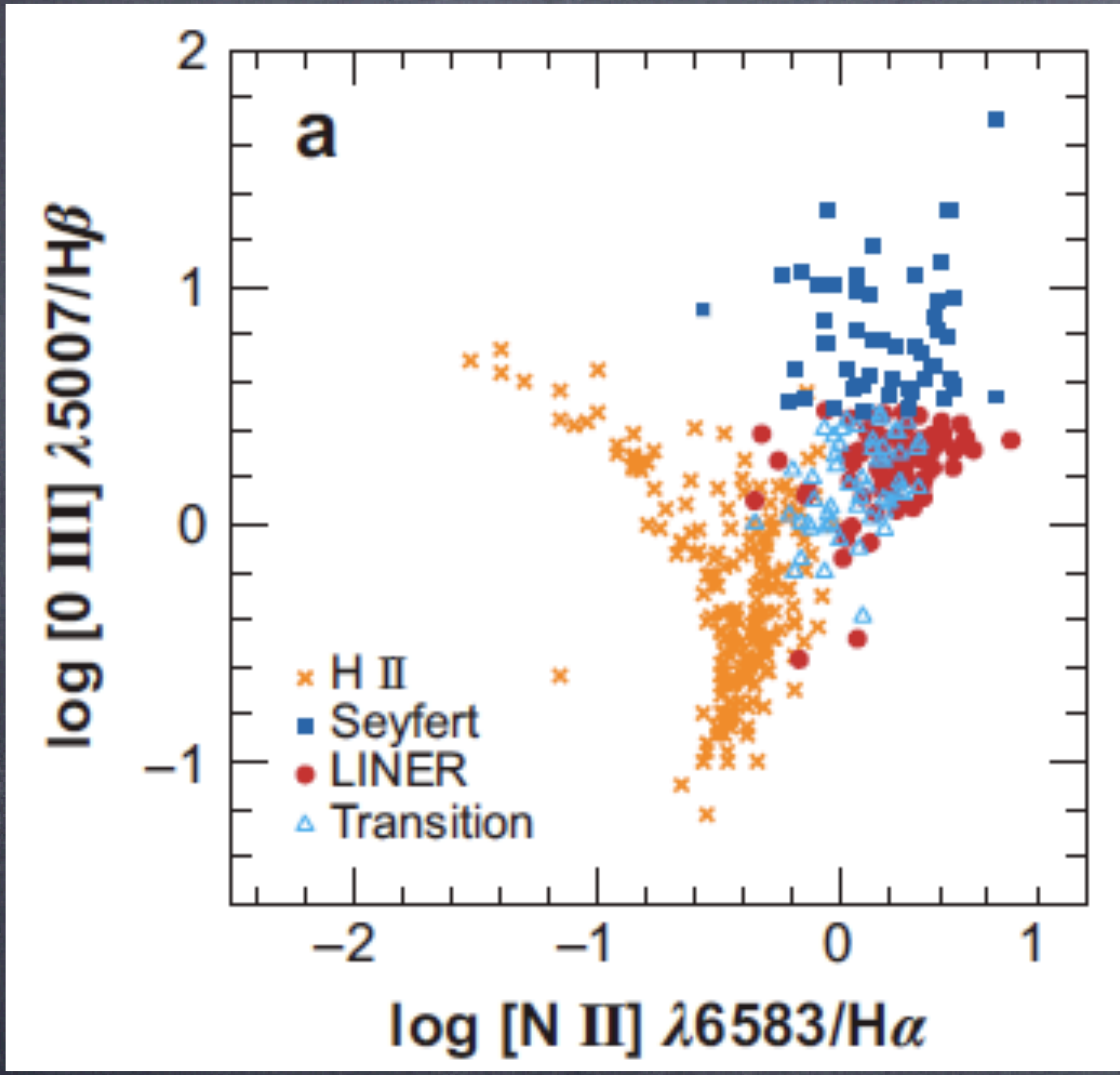
Low Ionization Emission-line Region

- Spectral definition based on line ratios
- Morphological definition --- Never Quantified!

Nuclear LINER vs. Extended LINER

In SDSS Spectra

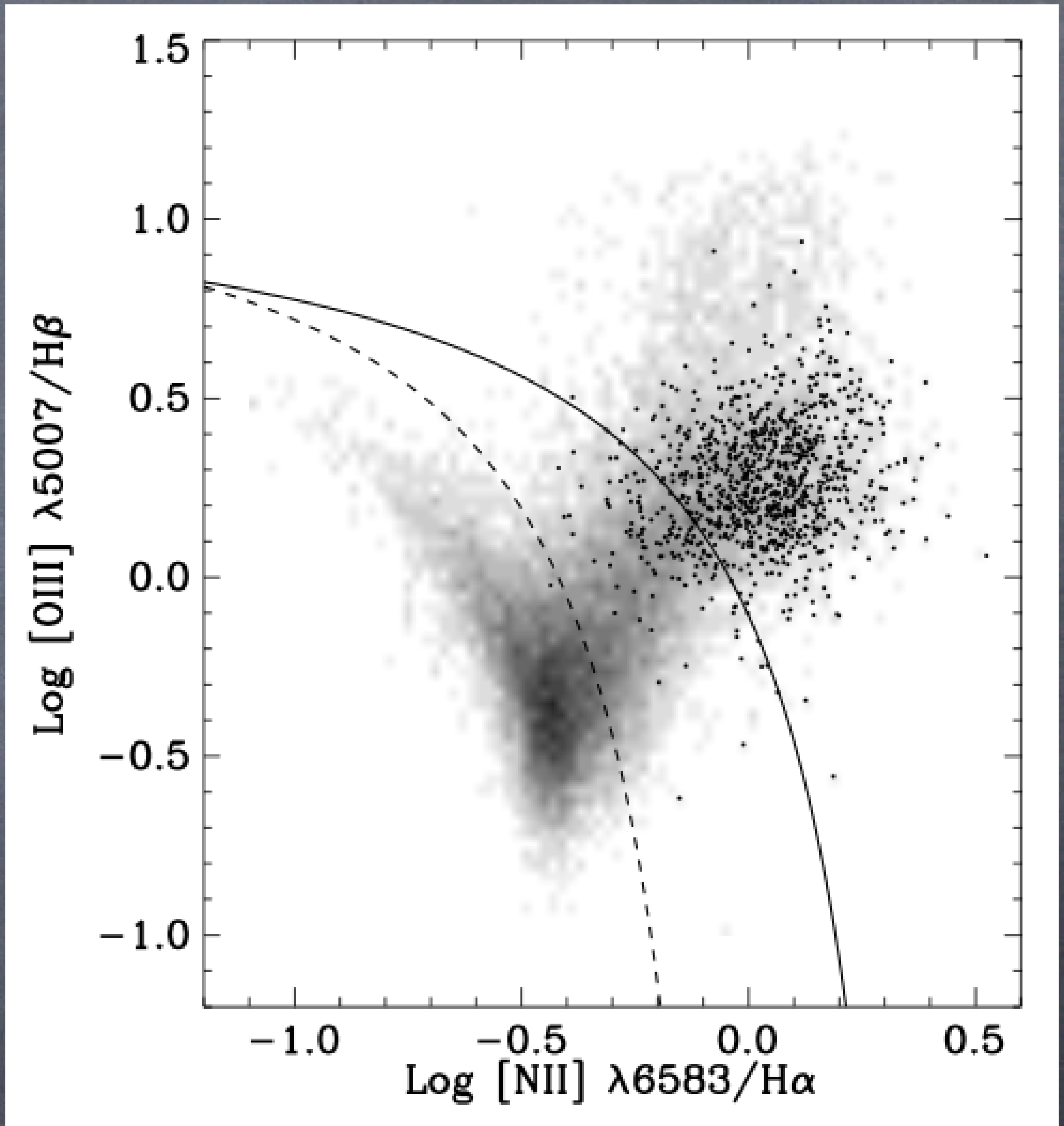
Palomar Survey



Ho (2008)

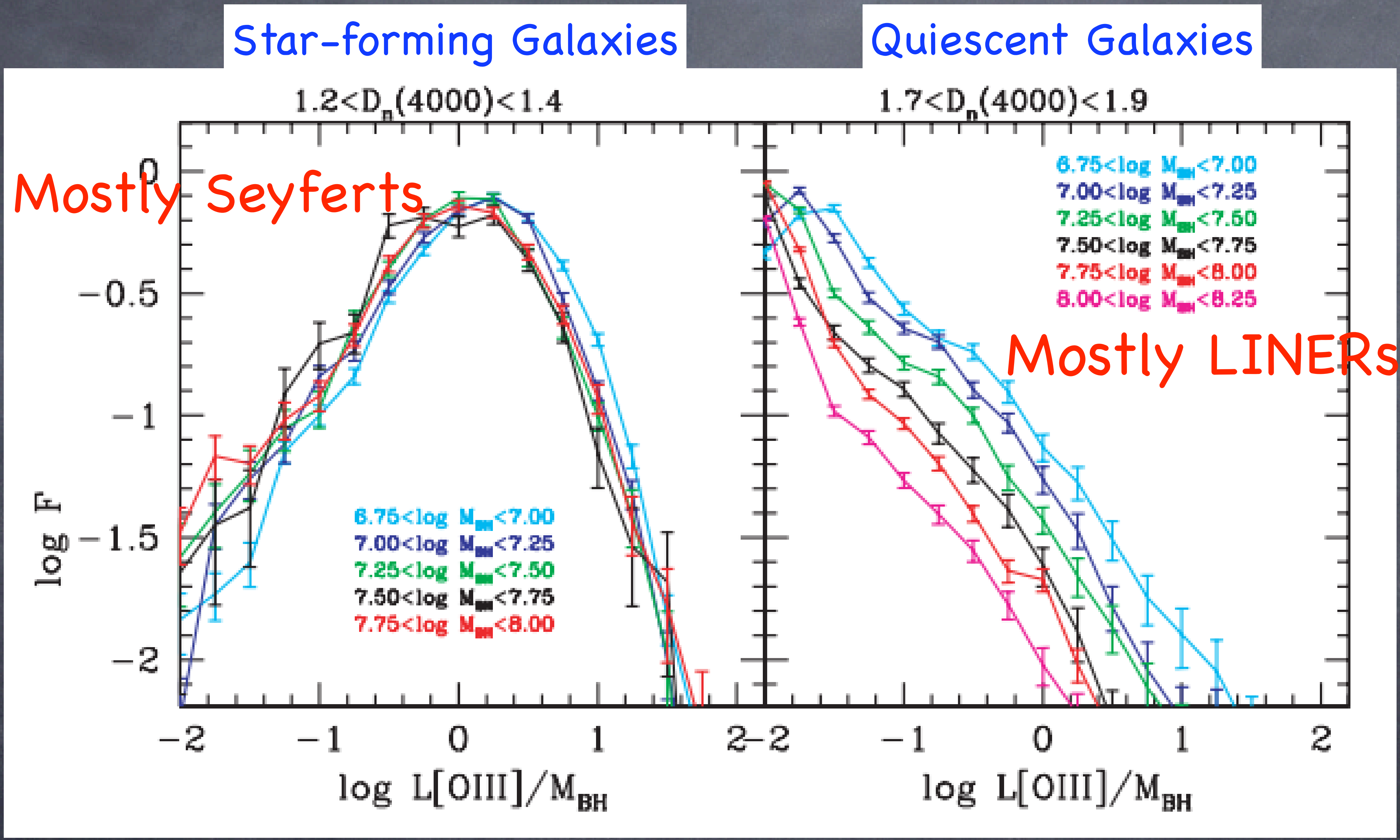
Nuclear Spectra
(r< 200pc)

SDSS



Bulge/Center Spectra
(r~2.5kpc at z~0.1)

Using [OIII] as AGN indicator?

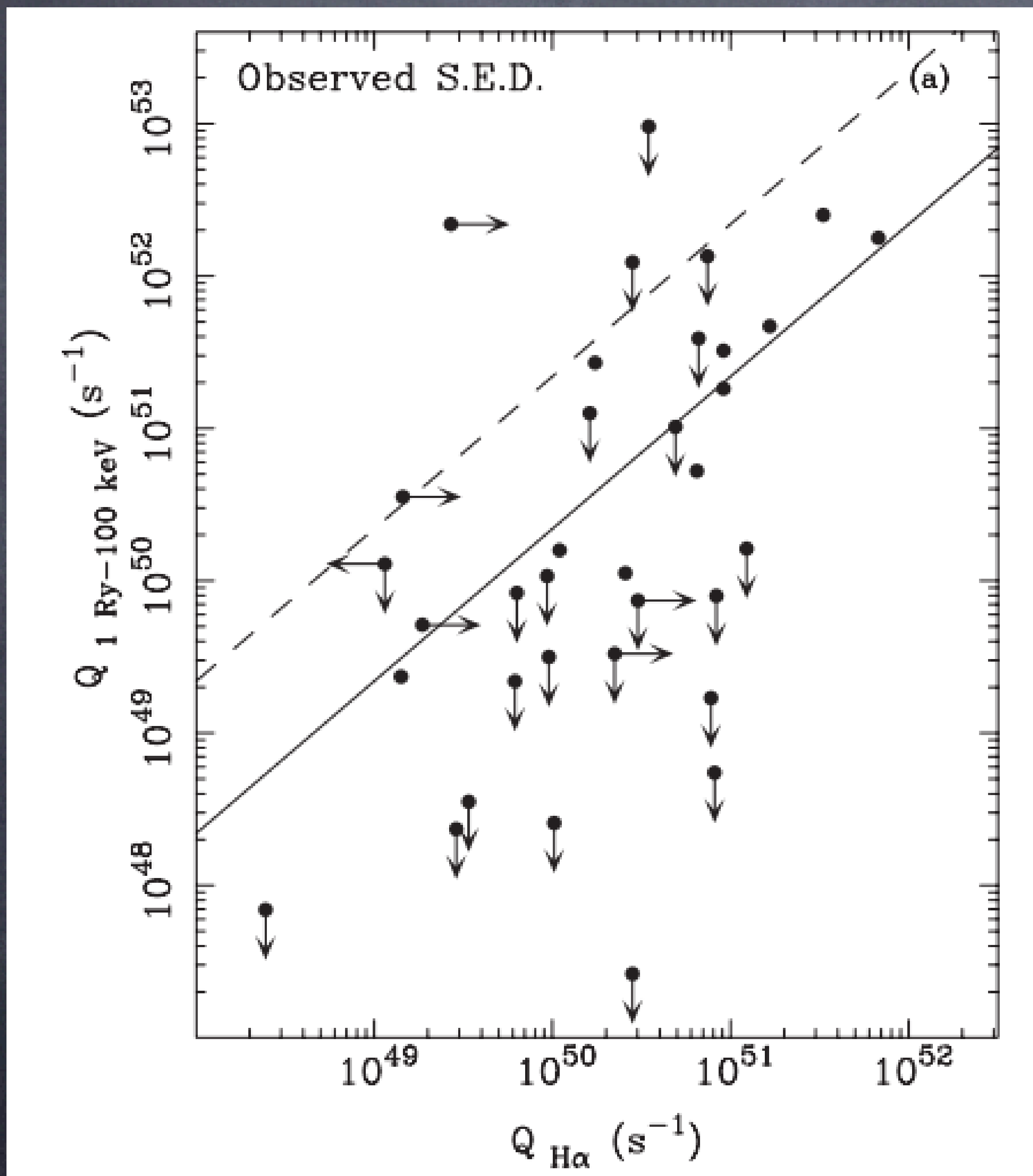


Kauffmann & Heckman (2010)

Nuclear LINER's Nature --- Evidences for AGN

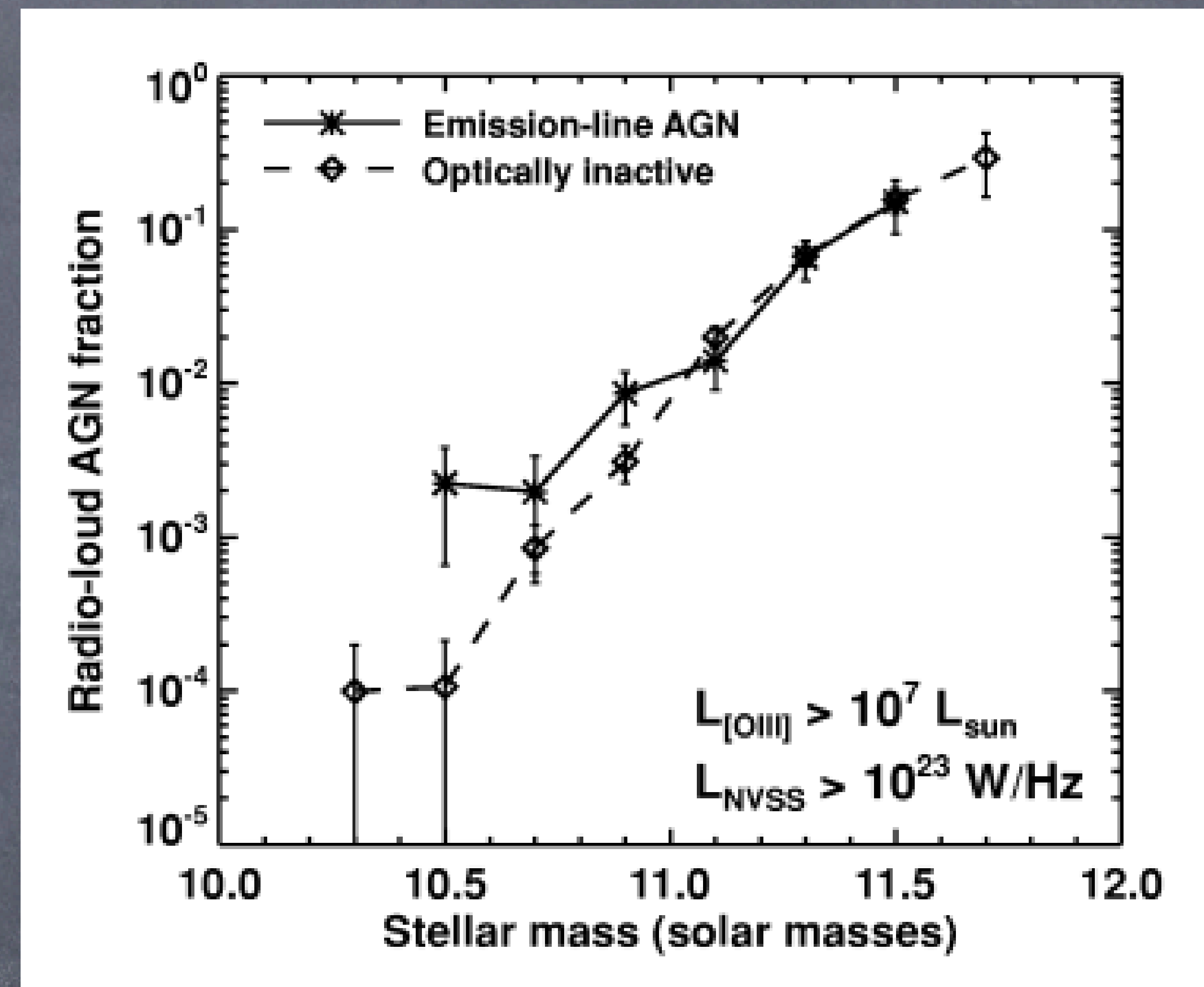
- X-ray cores (70% in LINERs vs. 30% in line-less galaxies)
- Radio cores (similar detection rate in LINERs as in Seyferts)
- Broad-line components (25% of LINERs)
- UV variability

Nuclear LINER's Nature
--- Problems w/ AGN scenario



Energy Budget Deficit

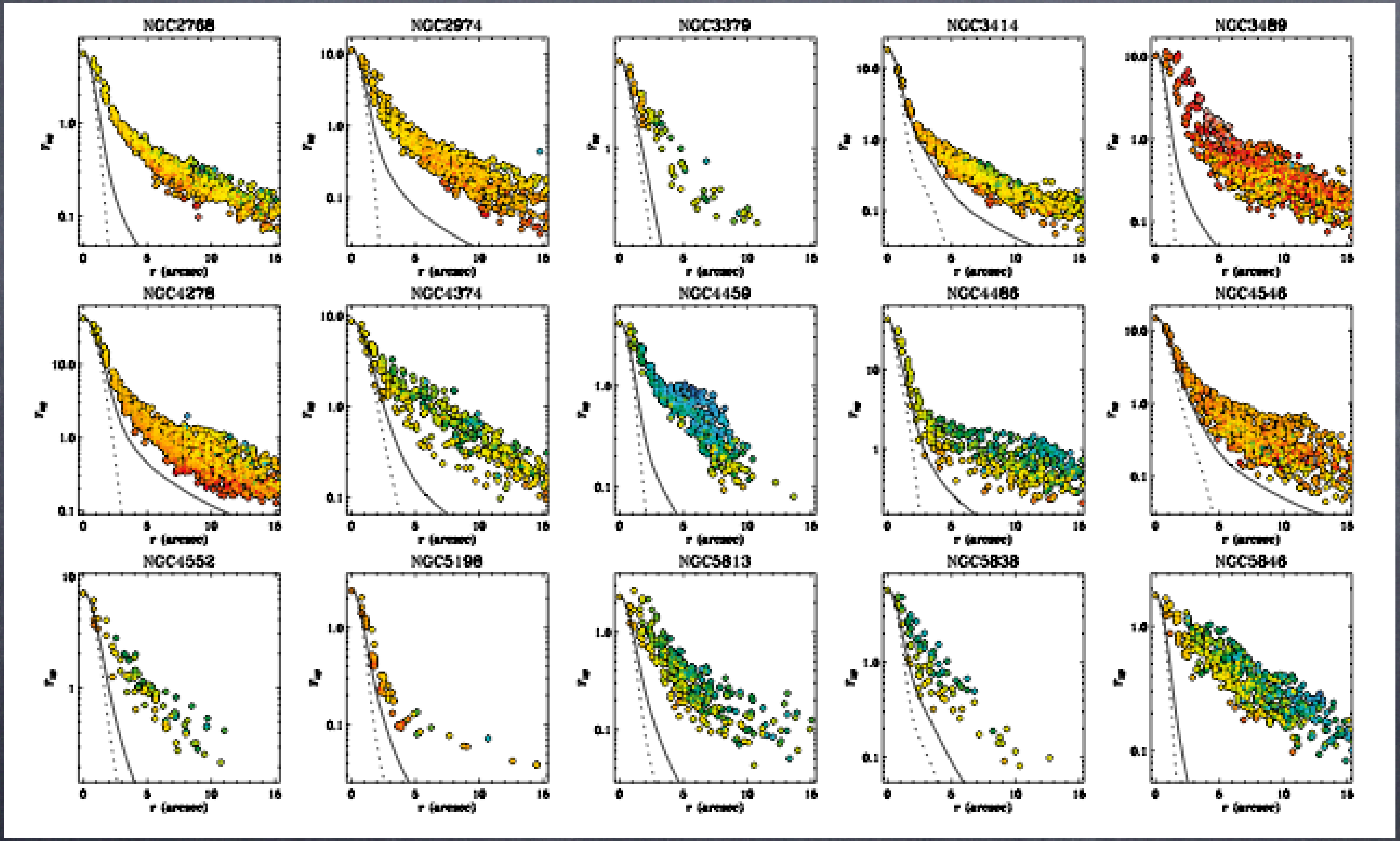
Eracleous et al. (2010)



Best et al. (2005)

No Correlation with radio

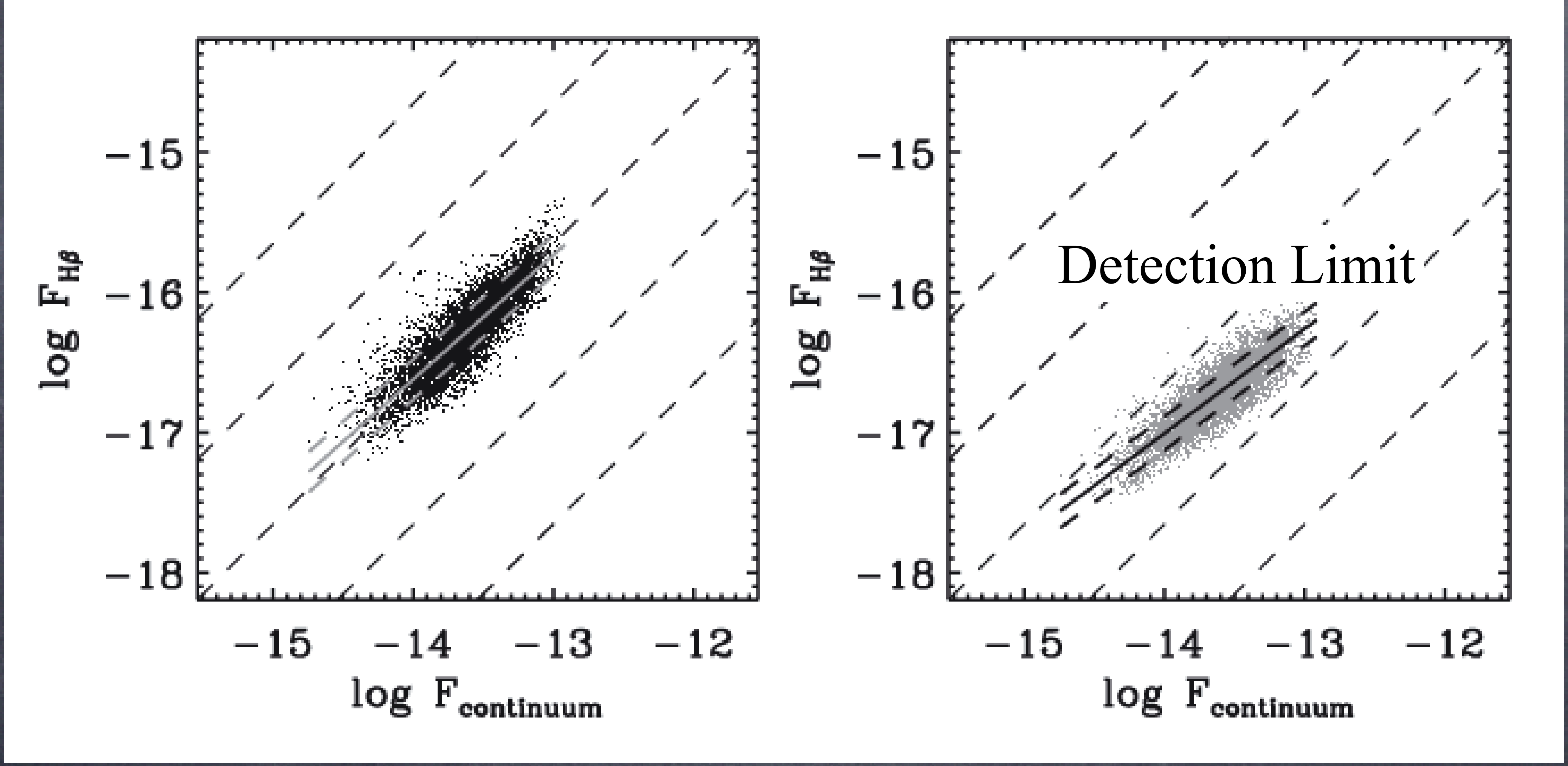
Extended LINER's Nature --- Evidences against AGN



Sarzi et al. (2010)

- Flux profile decline slower than 1/r^2.

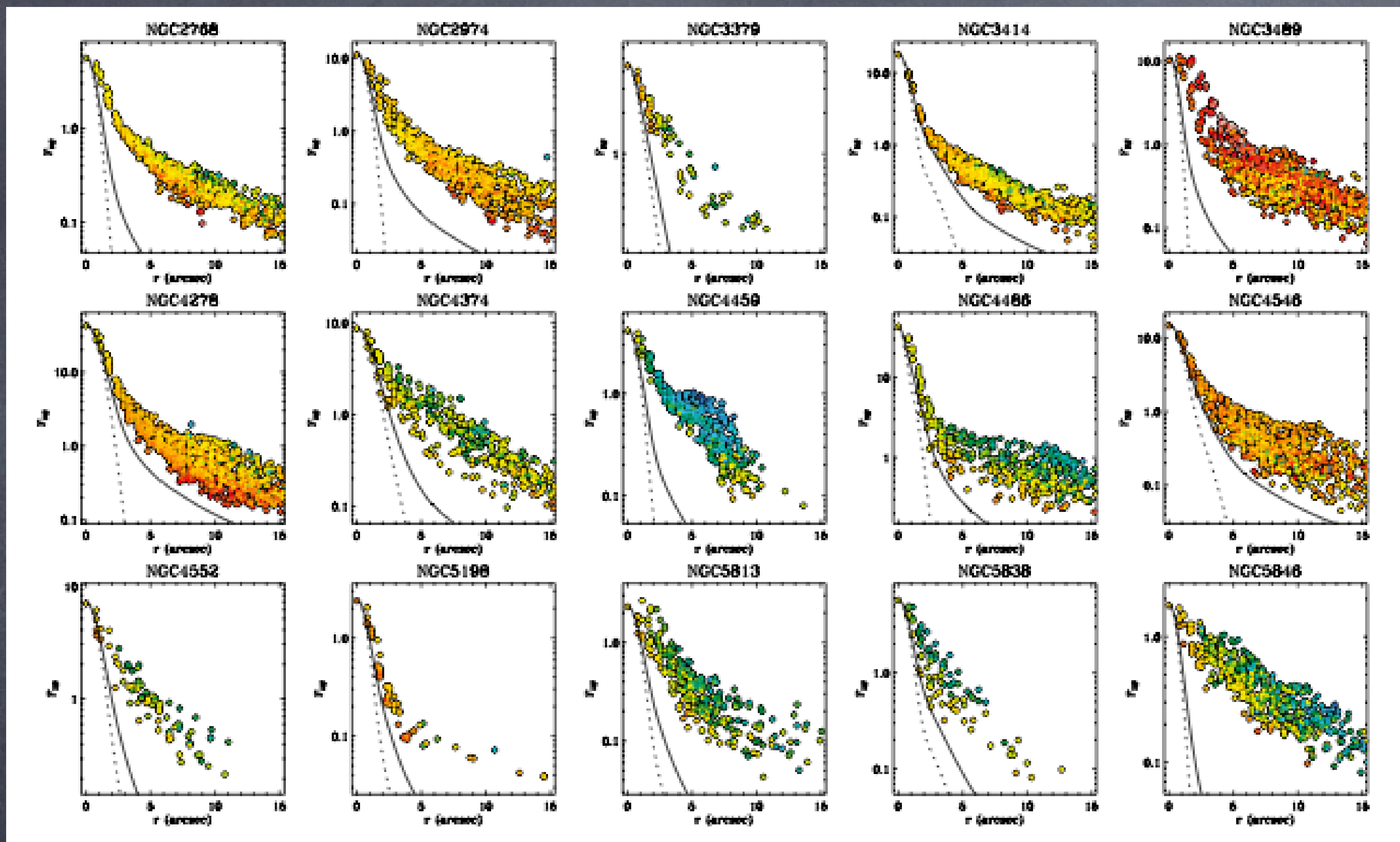
Extended LINER's Nature --- Evidences against AGN



Sarzi et al. (2010)

- Line flux correlates with stellar continuum.

Why was I unconvinced?



- AGN can generate extended emission regions.
- It also can correlate with stellar luminosity.

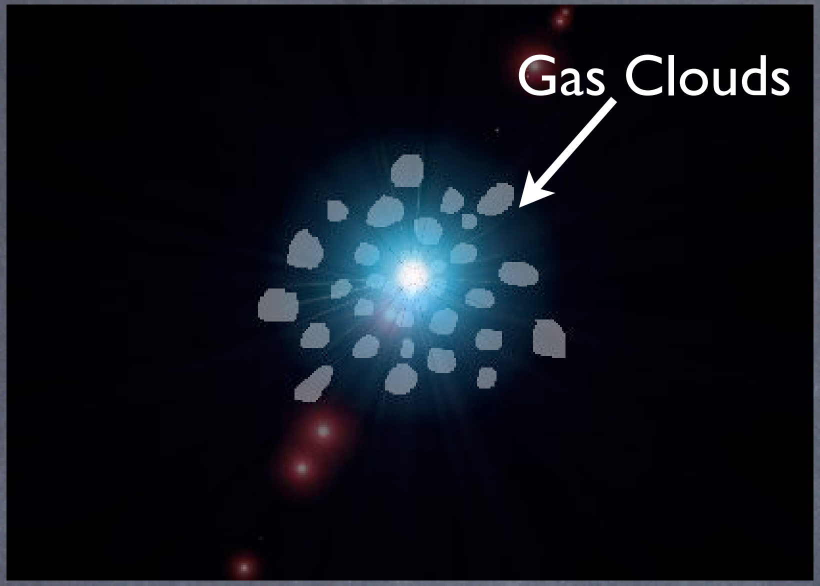
Luminosity density $$j(r) = F(r) f_g(r) \frac{\langle A \rangle}{\langle V \rangle}$$

Surface brightness (assuming gas clouds in disk) $$\Sigma(r) = F(r) f_g(r) H(r) \frac{\langle A \rangle}{\langle V \rangle}$$

$$= F(r) f_g(r) H(r) n^{1/3}$$

How to distinguish?

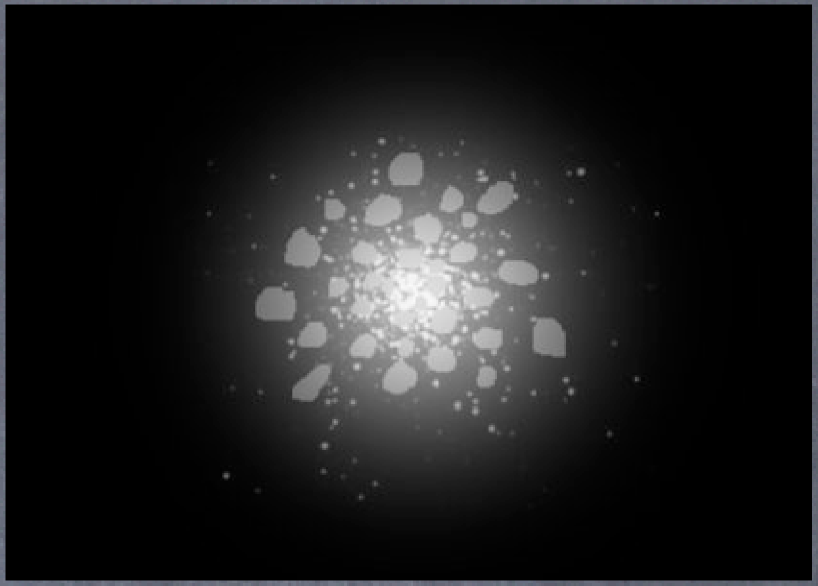
A central point source



AGN

vs.

Distributed ionizing sources



e.g. Post-AGB stars

How to distinguish?

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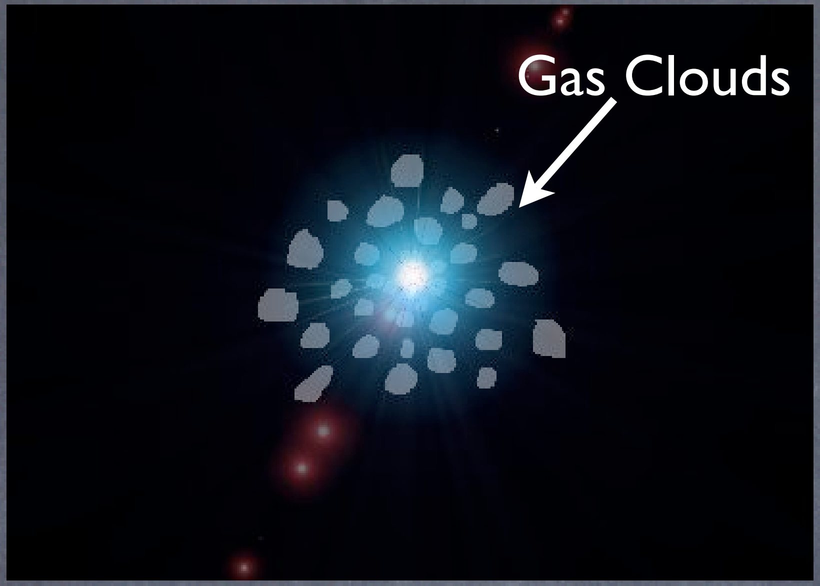

AGN

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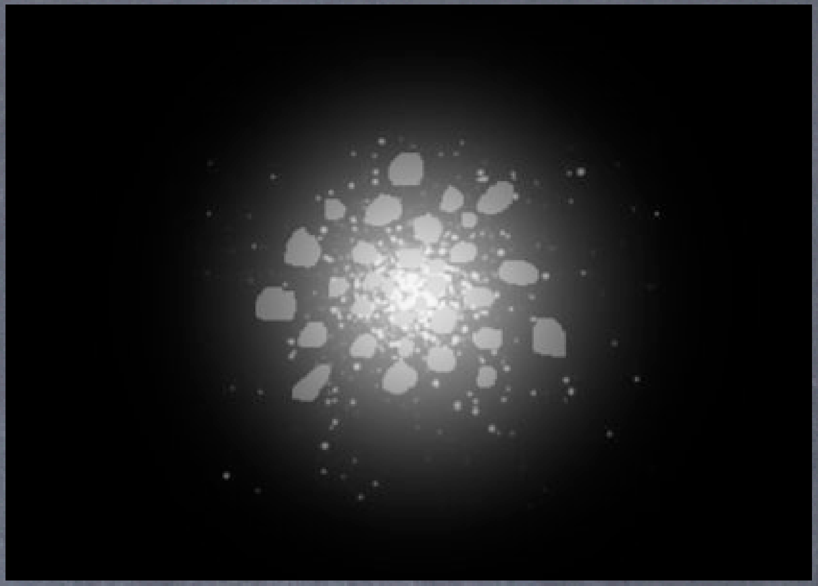


e.g. Post-AGB stars

Different ionizing flux profile

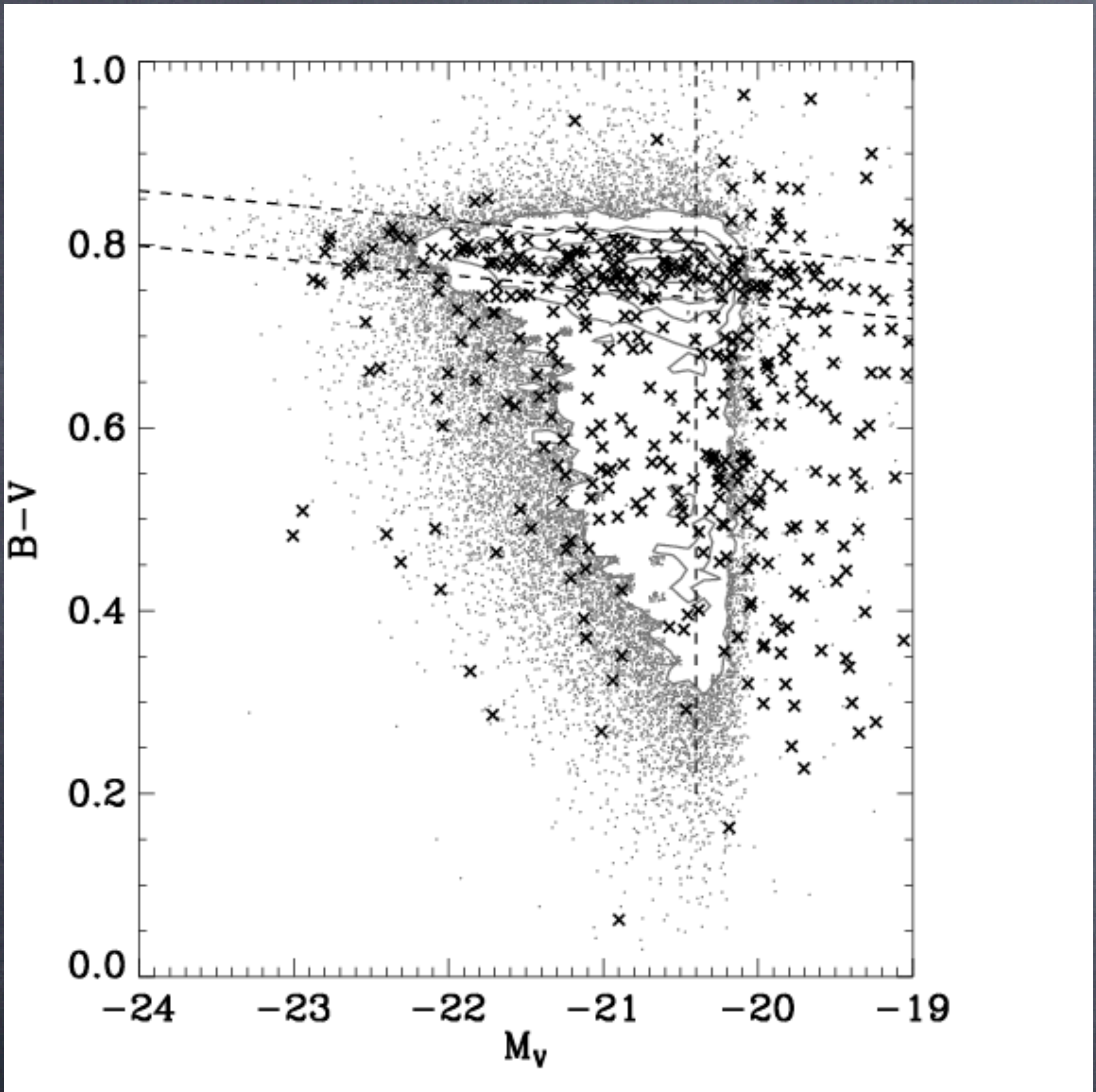
=> Different line ratio gradient with radius

=> Different widths for different lines if there is kinematic structure

Are there data to do this?

- SAURON/ATLAS3D cannot.
- What can I do? SDSS + Palomar

Idea: Palomar vs. SDSS



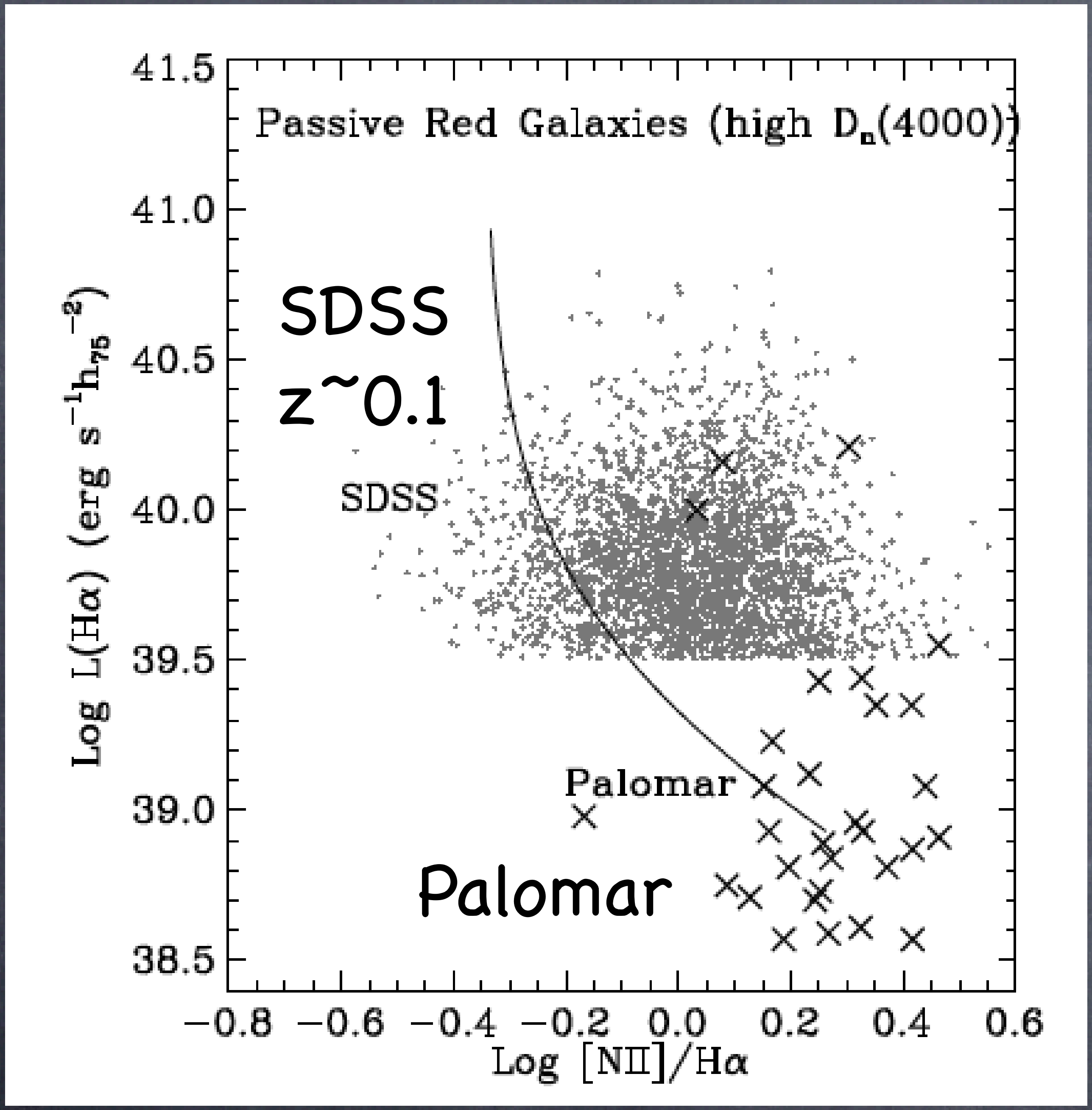
Select only red galaxies and remove the 30% with the lowest D4000

Palomar: 2″ x 4″ slit
radius < 300pc

SDSS: 3″ fiber
600pc at z~0.02
1.3kpc at z~0.05
2.5kpc at z~0.1

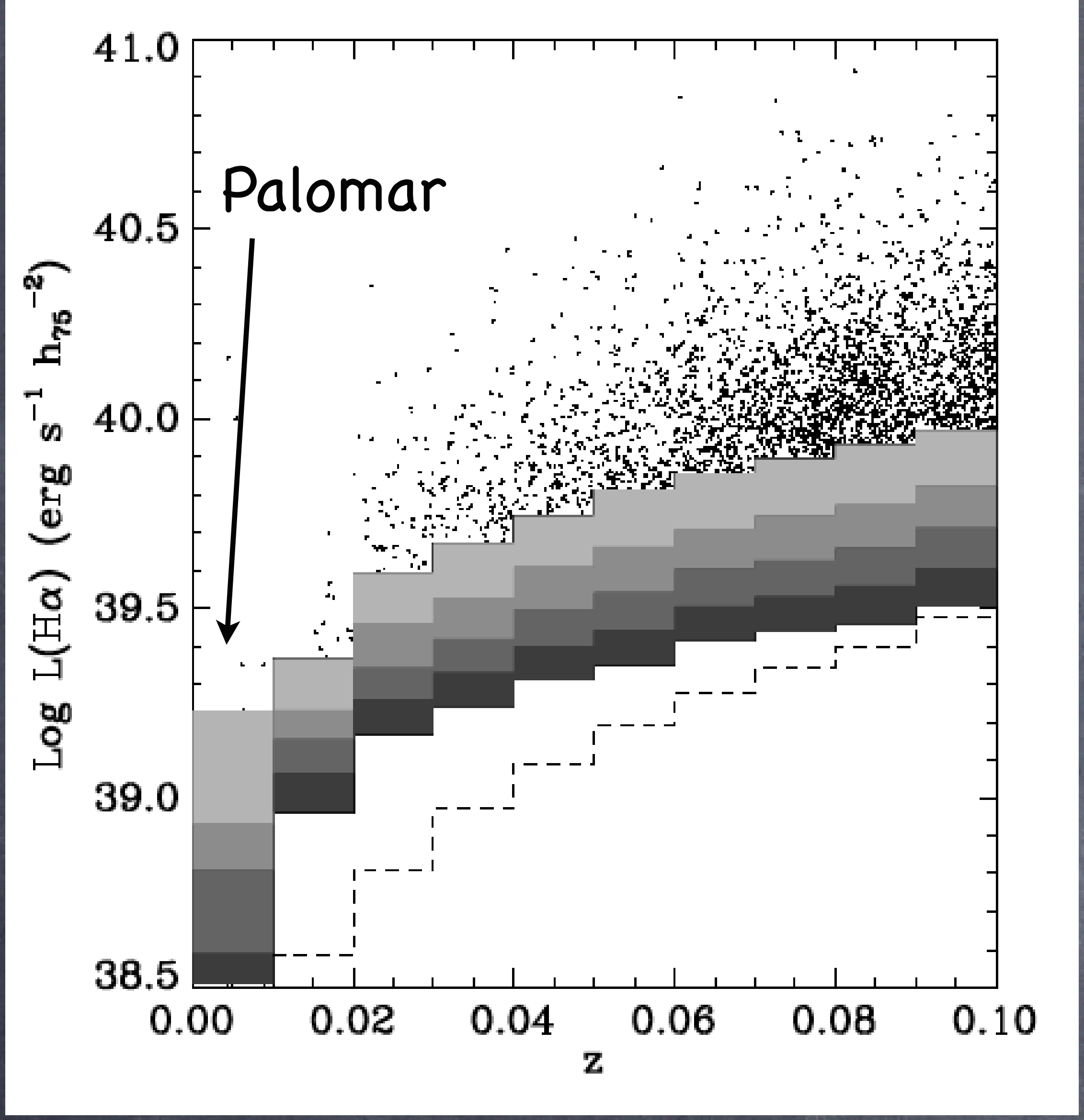
Identify the same population of galaxies at different redshifts. The same apertures correspond to different scales.

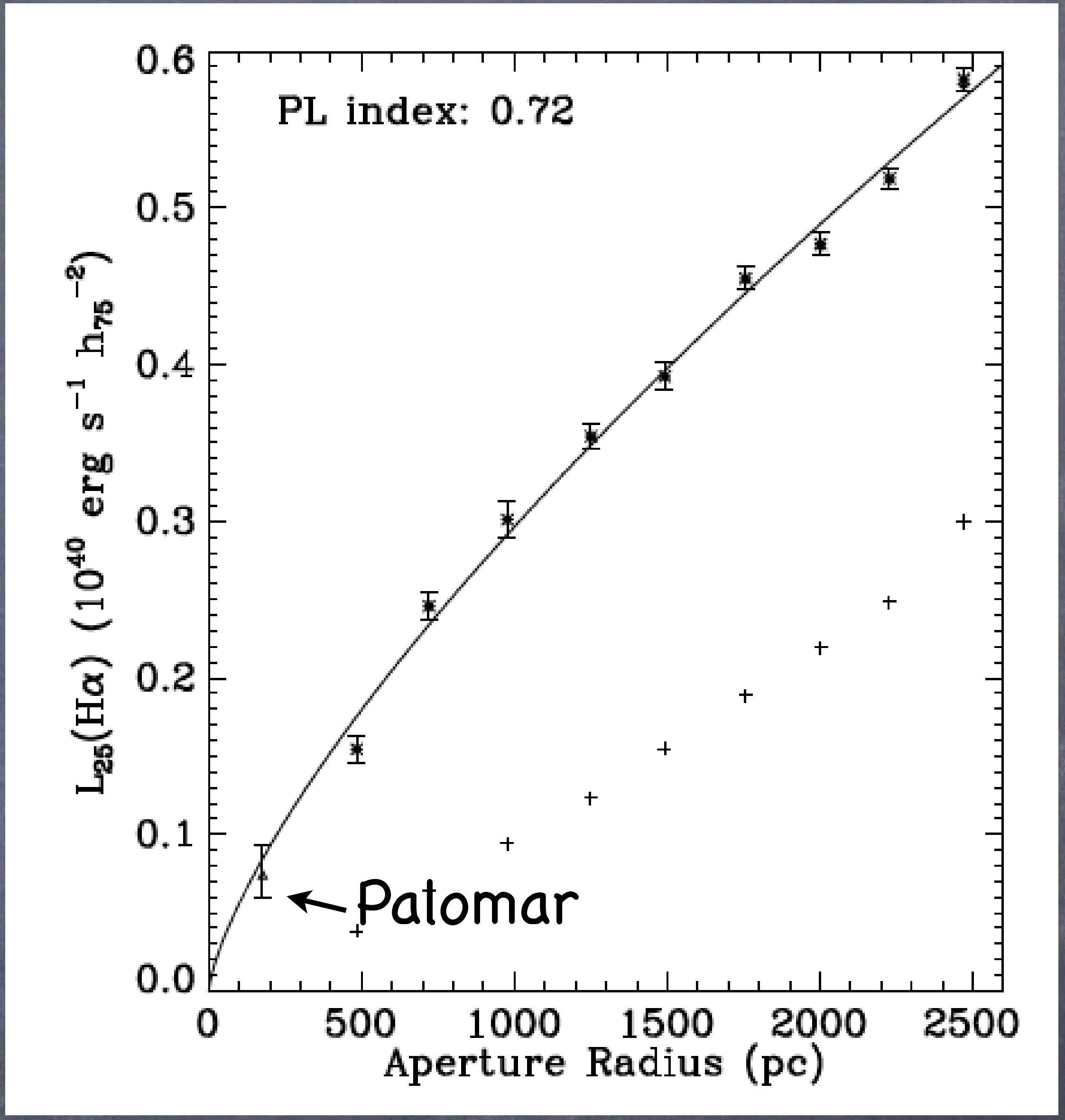
Nuclear vs. Extended Emission



- The emission in SDSS red galaxies at z~0.1 has to be spatially extended.
- The Palomar nuclear LINERs have to be just the central part of these extended LINER-like emission.

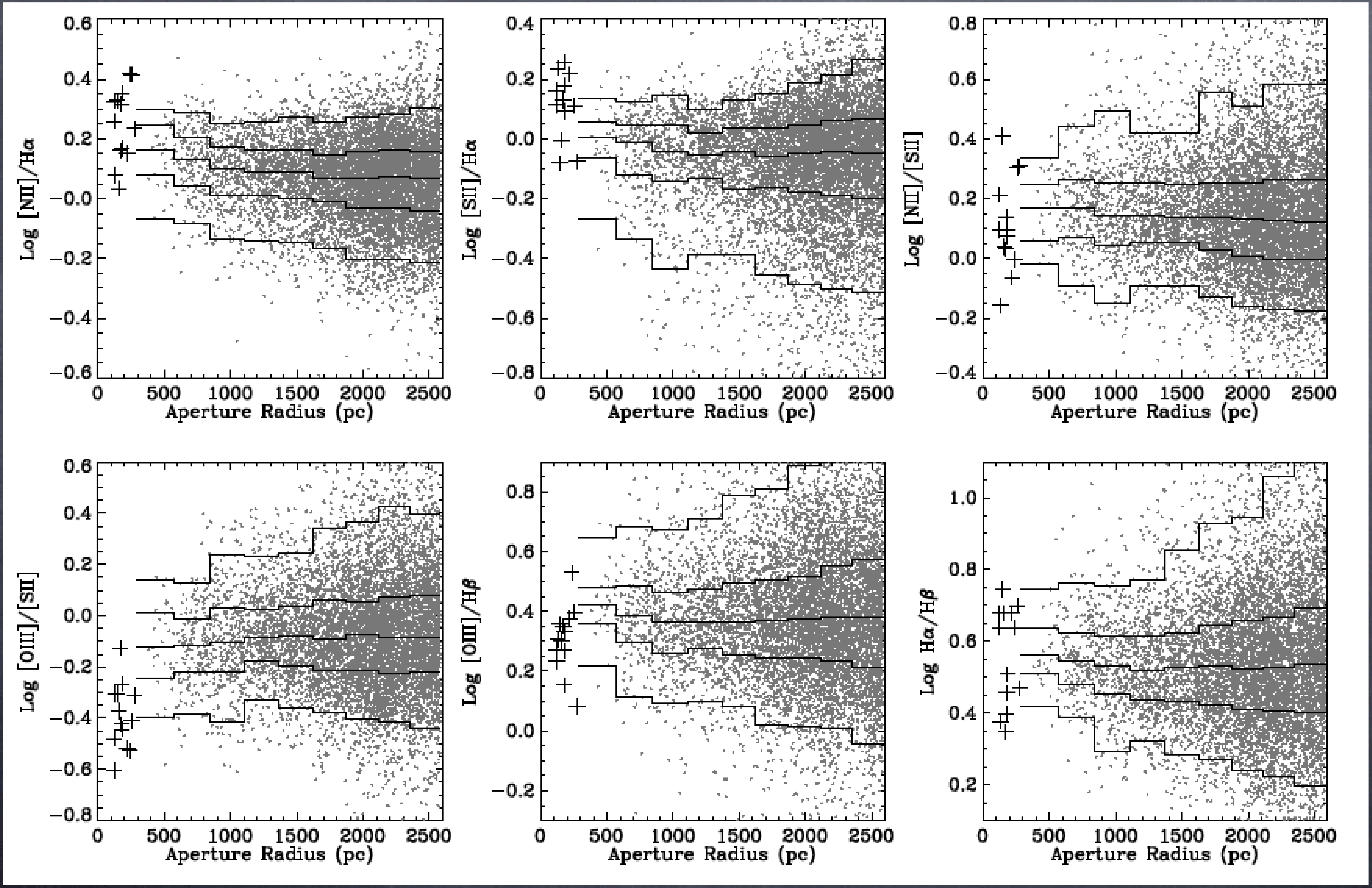
Luminosity Profile



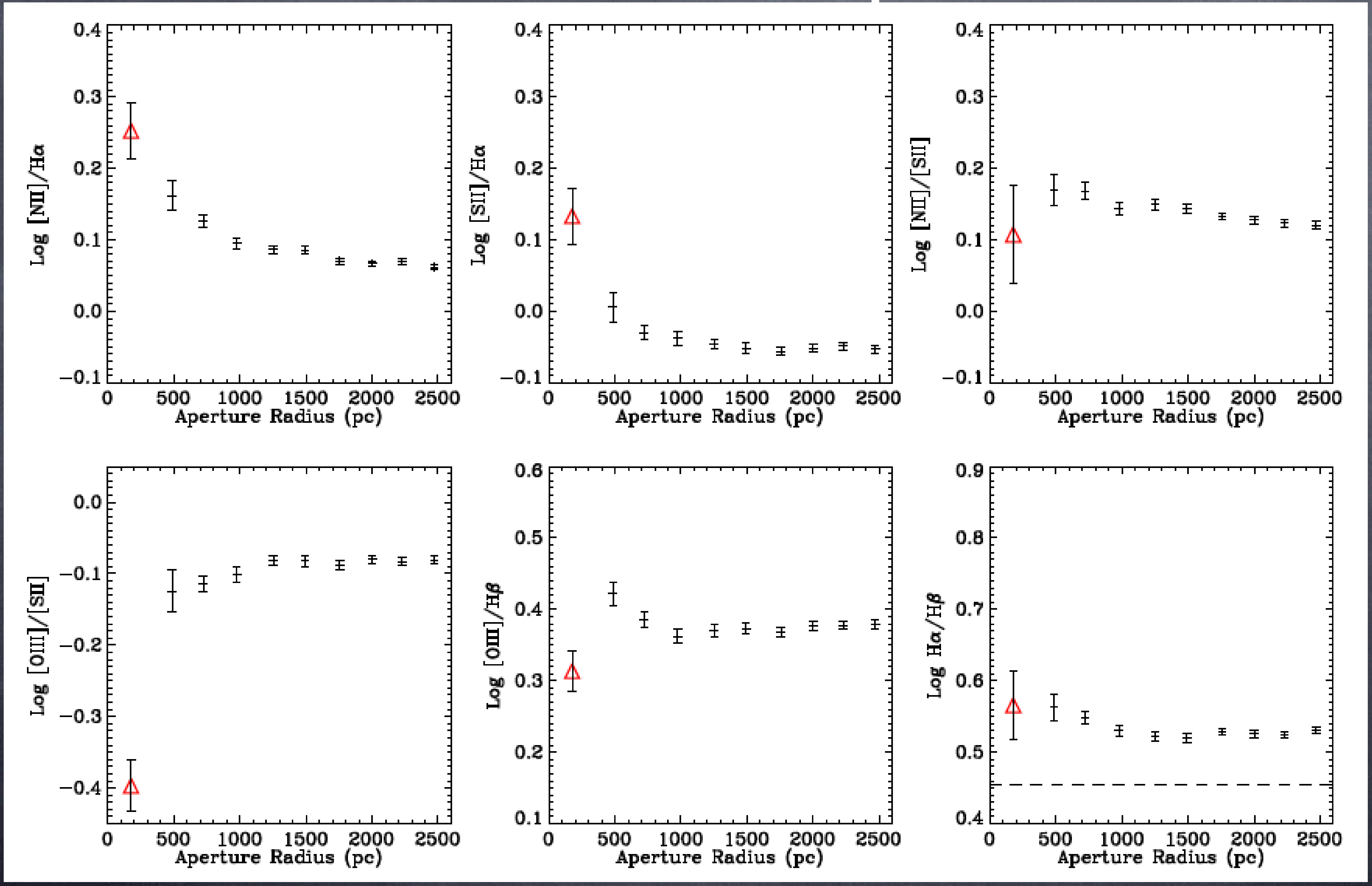


- Nuclear LINERs, in most cases, are just the central part of extended LINERs.
- Average surface brightness profile $\Sigma(r) \propto r^{-1.28}$.

Line Ratio Distribution vs. Scale



Median Line Ratio in Aperture (r<R)



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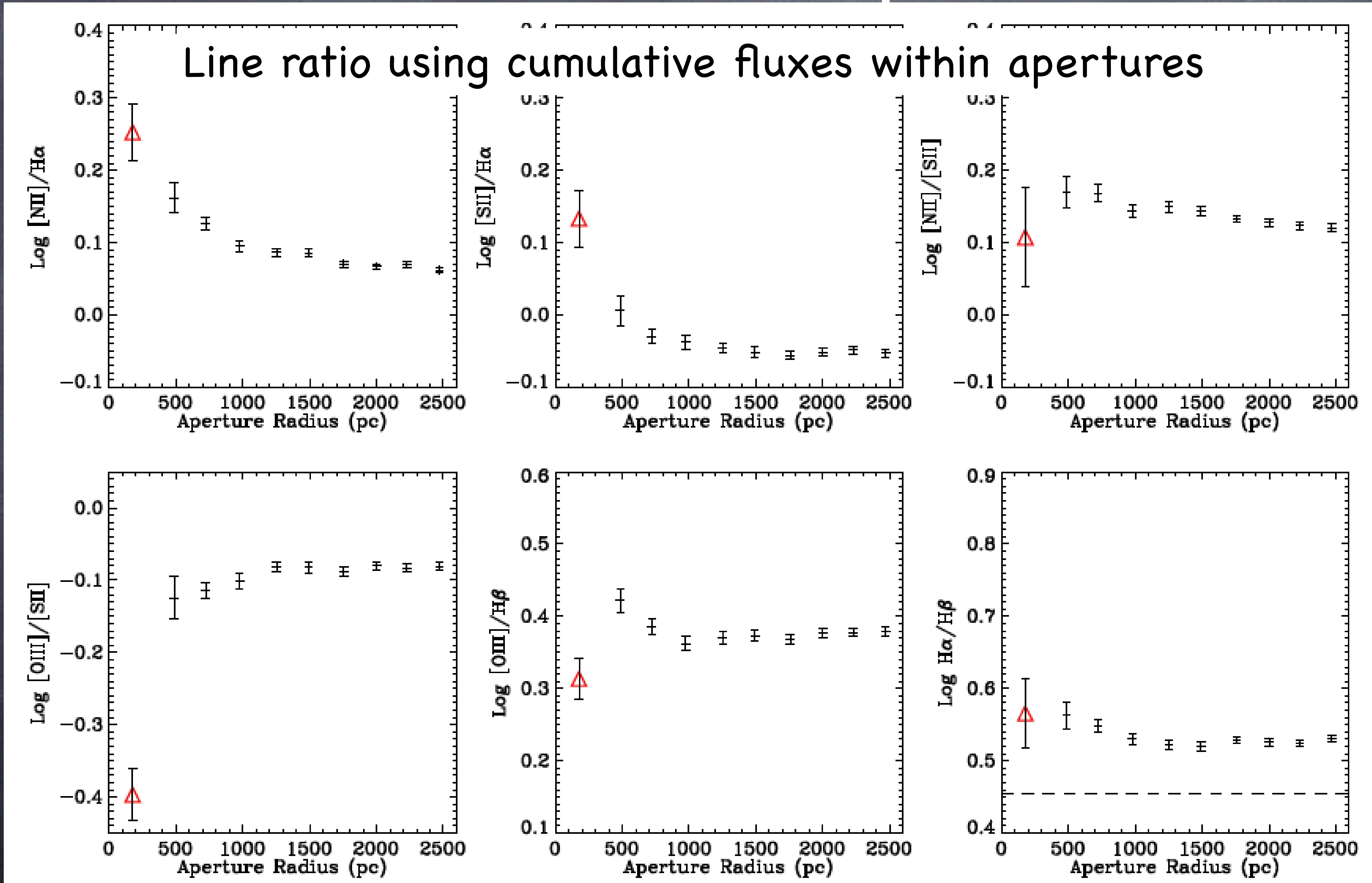
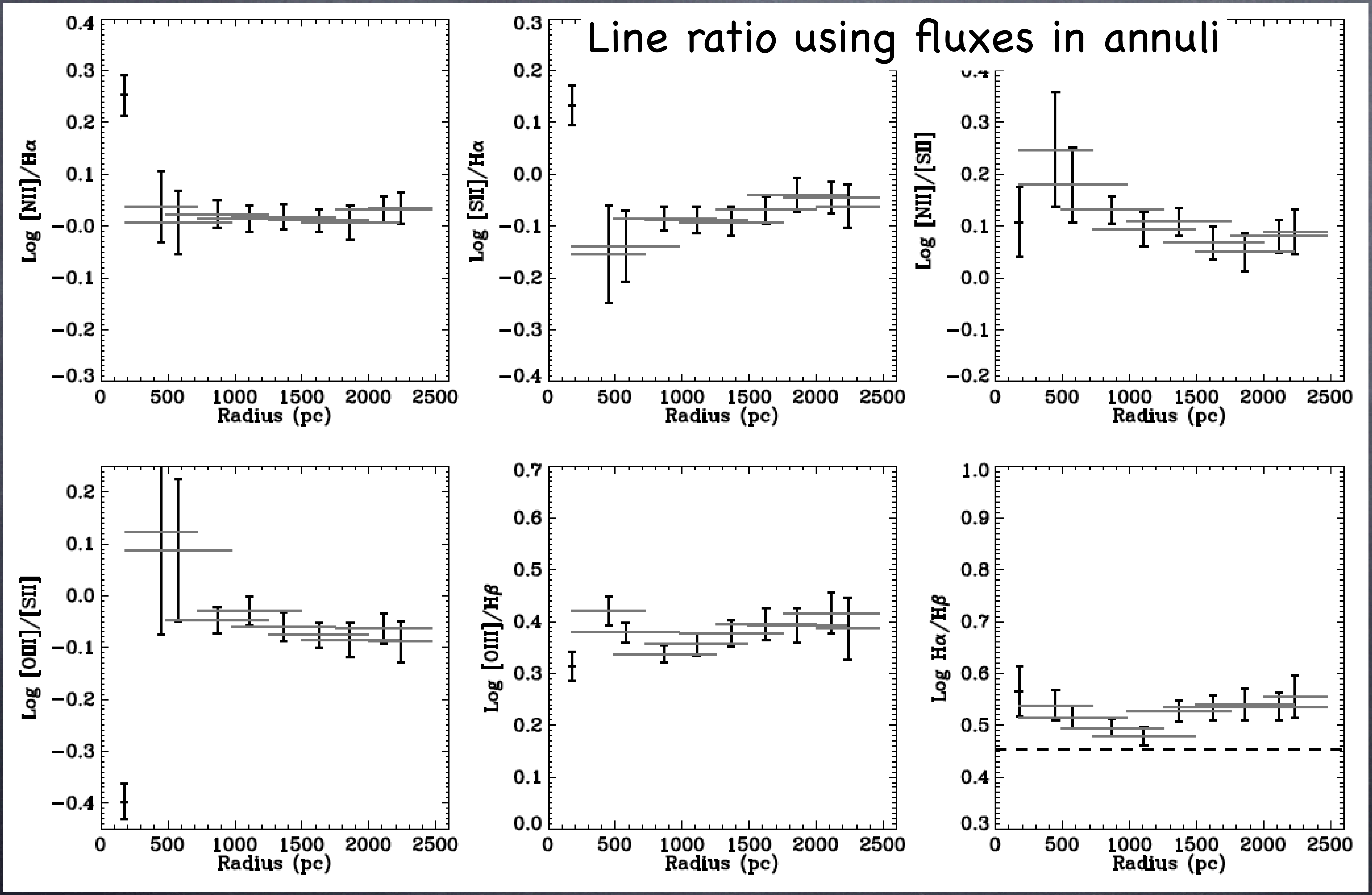


Line Ratio Profiles

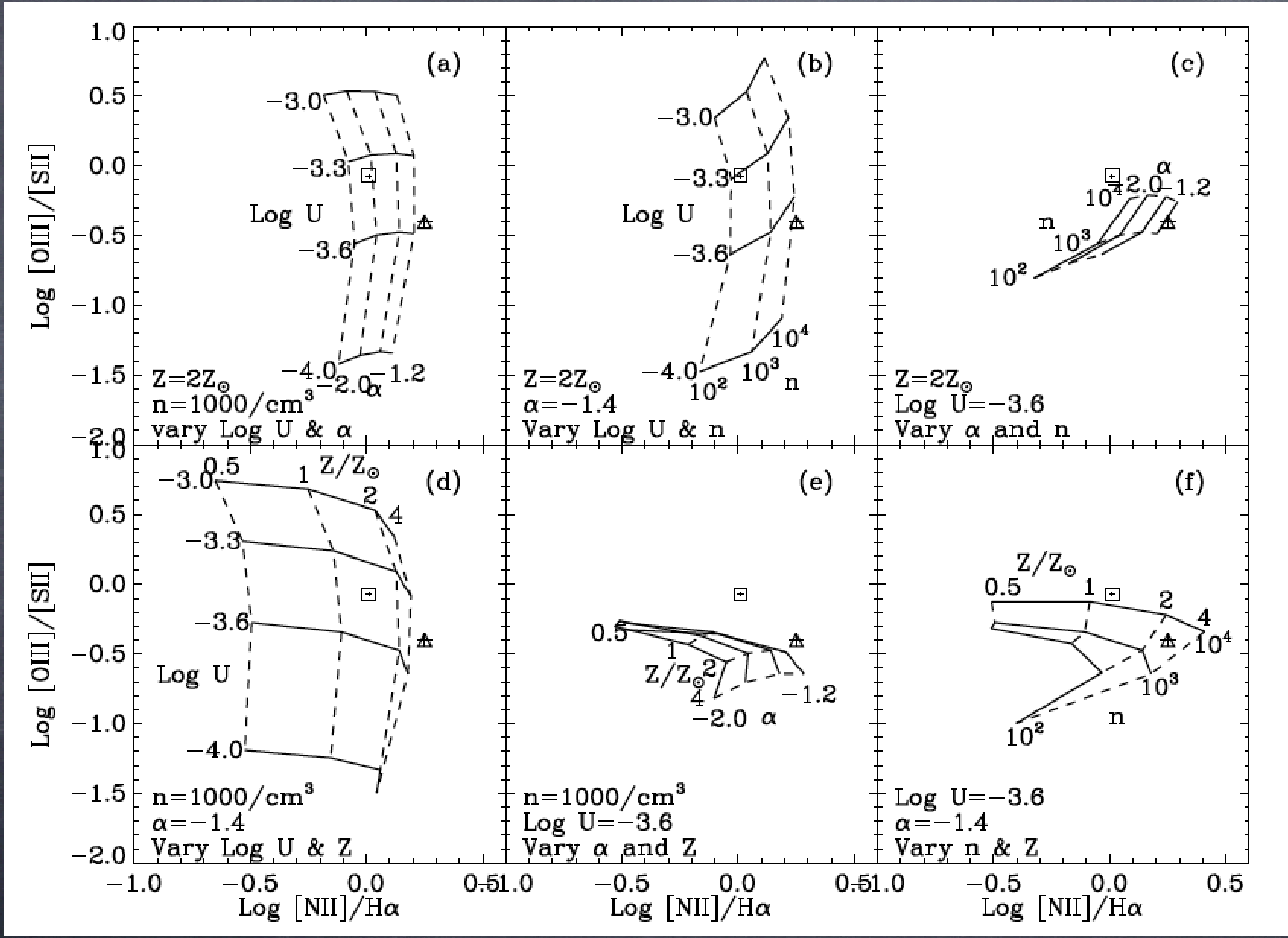


Production of the line ratio gradient by Photoionization

- Line ratios are determined by four factors:
  - ionization parameter (U)

    U $\equiv$ Ionizing Flux/gas density
  - hardness of the spectrum
  - metallicity (Z)
  - density (n)

Explore the Possibilities



Based on Groves et al. (2004) model grids for AGN photoionization

Gradient in physical conditions

From Center to Outskirts

- [NII]/Hα $\searrow$ requires Z $\searrow$ or n $\searrow$ or spectrum to soften
- [OIII]/[SII] $\nearrow$ requires U $\nearrow$ or n $\nearrow$

Gradient in physical conditions

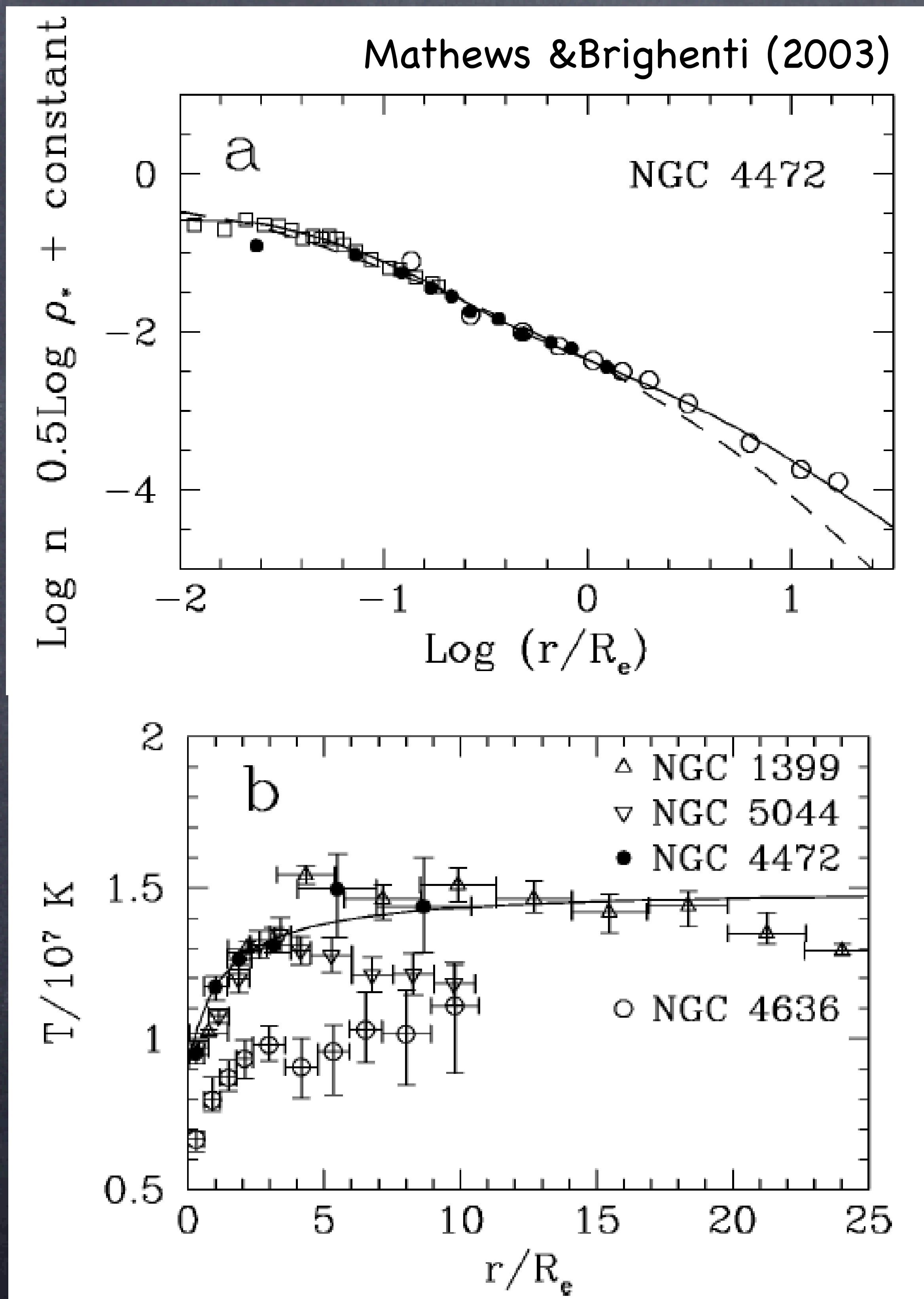
From Center to Outskirts

[NII]/Hα ↘ requires Z ↘ or n ↘ or spectrum to soften

[OIII]/[SII] ↗ requires U ↗ or n ↗

- Ionization parameter (U) increases outwards!
- In the case of the AGN, $F(r) \propto 1/r^2$
  Gas density has to fall faster. Does it?

Gas Density Profile



Assuming $P_{\rm hot} = P_{\rm warm}$

$$n_{\rm hot} T_{\rm hot} = n_{\rm warm} T_{\rm warm}$$

$$n_{\rm hot} \propto \rho_{\rm star}^{1/2}$$

$$T_{\rm hot} \sim {\rm Const}$$

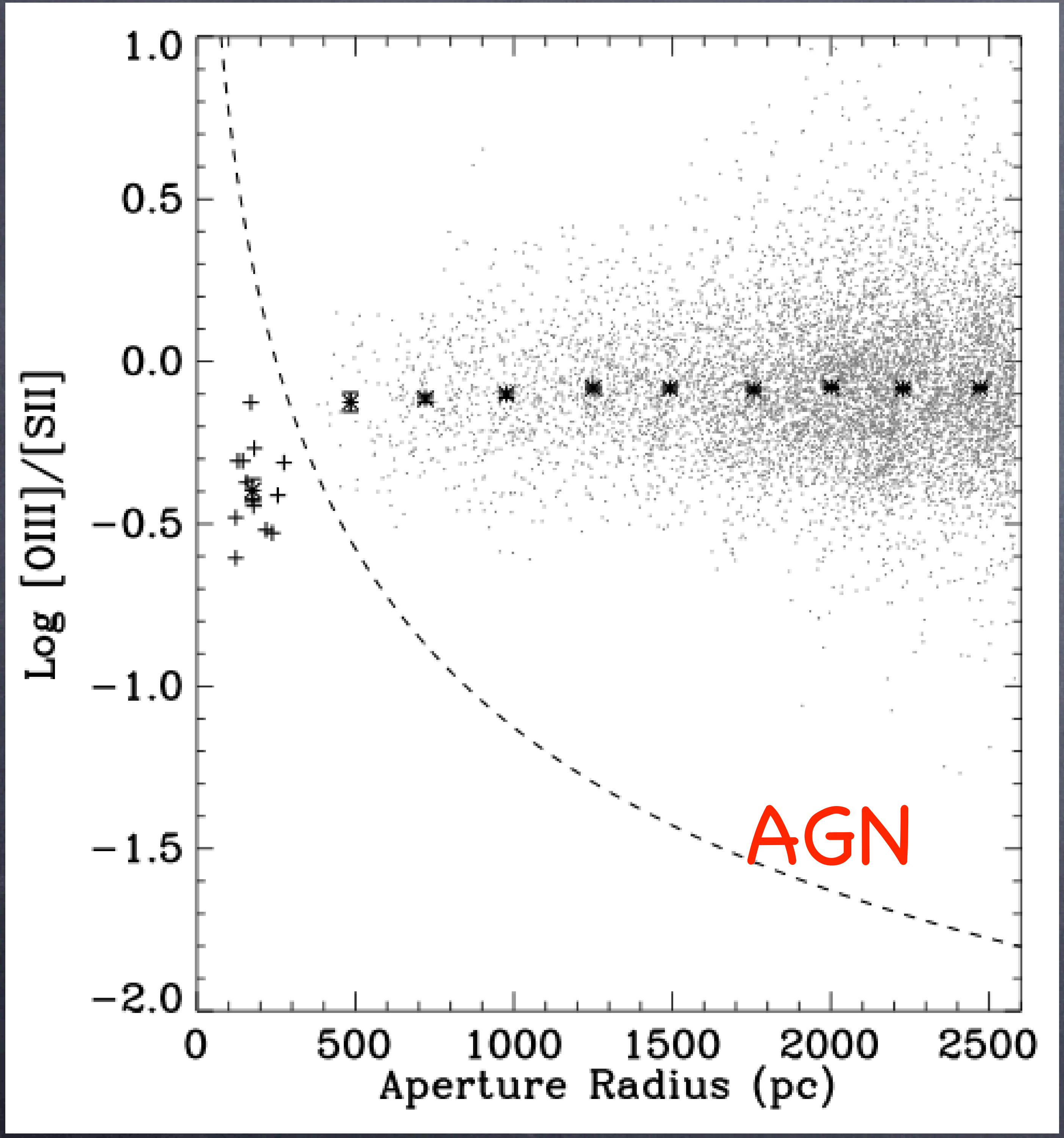
$$T_{\rm warm} \sim {\rm Const}$$

=> $n_{\rm warm} \propto \rho_{\rm star}^{1/2}$

$$n_{\rm warm} \propto r^{\alpha}$$

where $-1 < \alpha < -0.5$

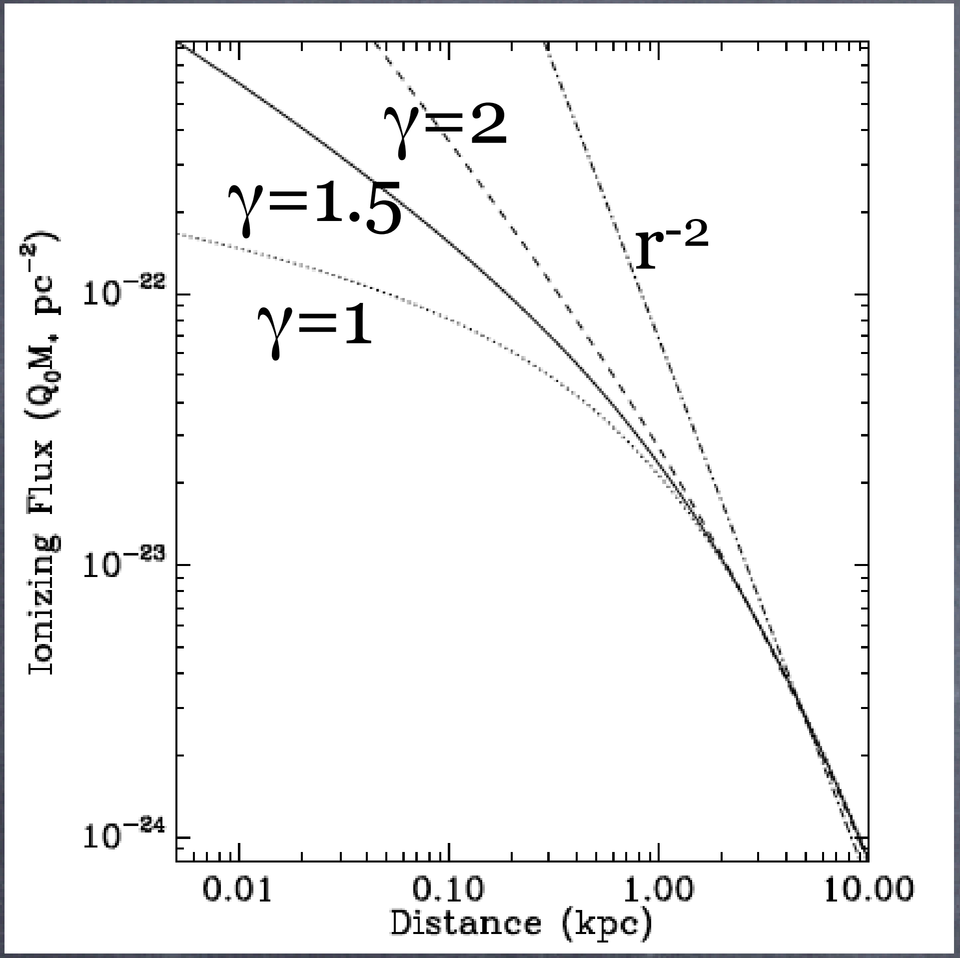
AGN is ruled out



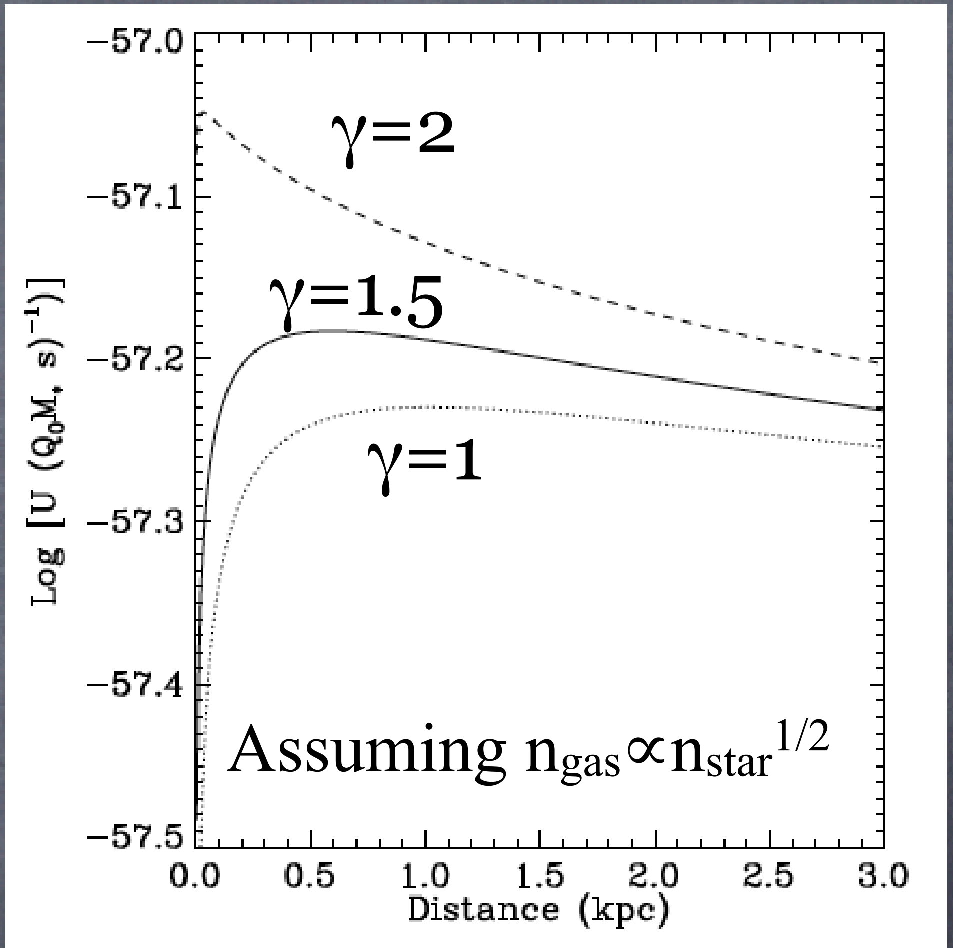
- AGN will produce an outward decreasing ionization parameter, opposite to what we see!
- AGN alone cannot explain the line ratio gradient.

Production of Line Ratio Gradient by Distributed Ionizing Sources

Flux Profile



Ionization Para. Profile



$$F(D) = \int_0^\infty \mathrm{d}r \int_0^{2\pi} \mathrm{d}\phi \int_0^\pi \frac{Q_0 \rho(r) r^2 \sin\theta}{4\pi(D^2 + r^2 - 2Dr\cos\theta)} \mathrm{d}\theta$$

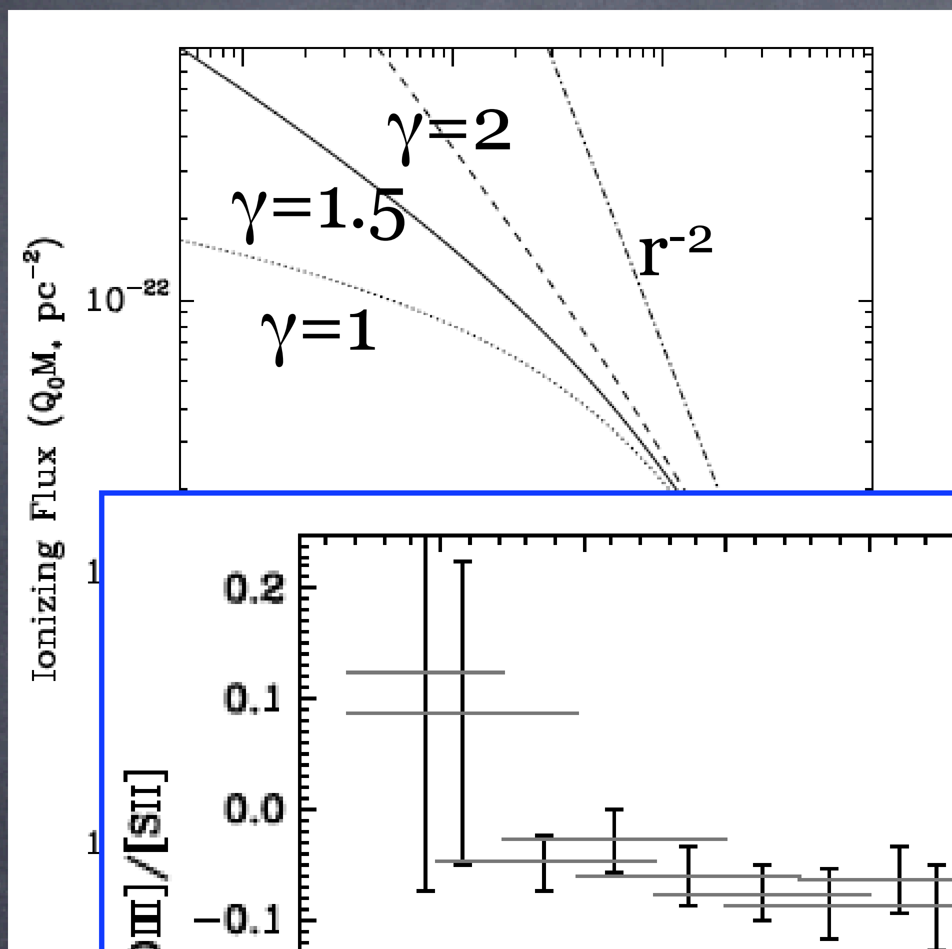
$$= \frac{Q_0}{2} \int_0^\infty \rho(r) \frac{r}{D} \ln \frac{D+r}{|D-r|}$$

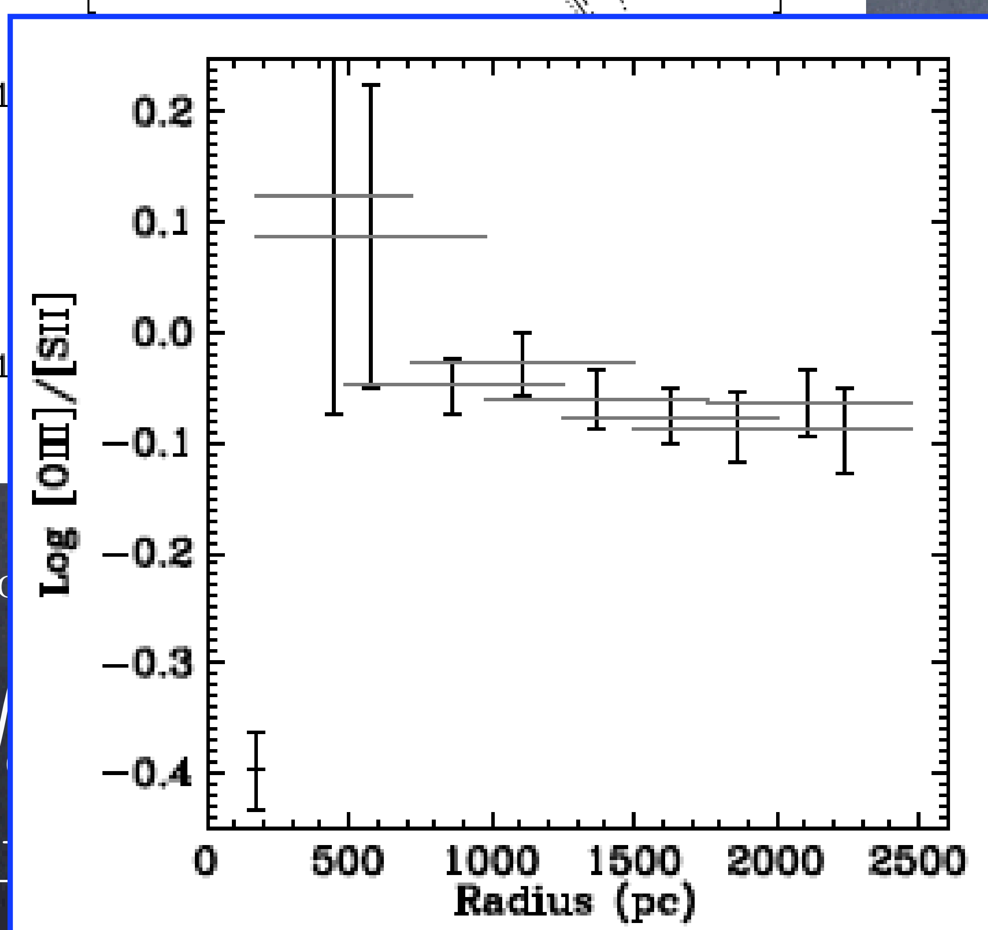
$$\rho(r) = \frac{(3-\gamma)M}{4\pi} \frac{a}{r^\gamma (r+a)^{4-\gamma}} \qquad \text{(Dehnen 1993)}$$

- Ionizing sources following the stellar density profile can produce the observed trends in ionization parameter.
- It predicts a luminosity-dependence.

Production of Line Ratio Gradient by Distributed Ionizing Sources

Flux Profile



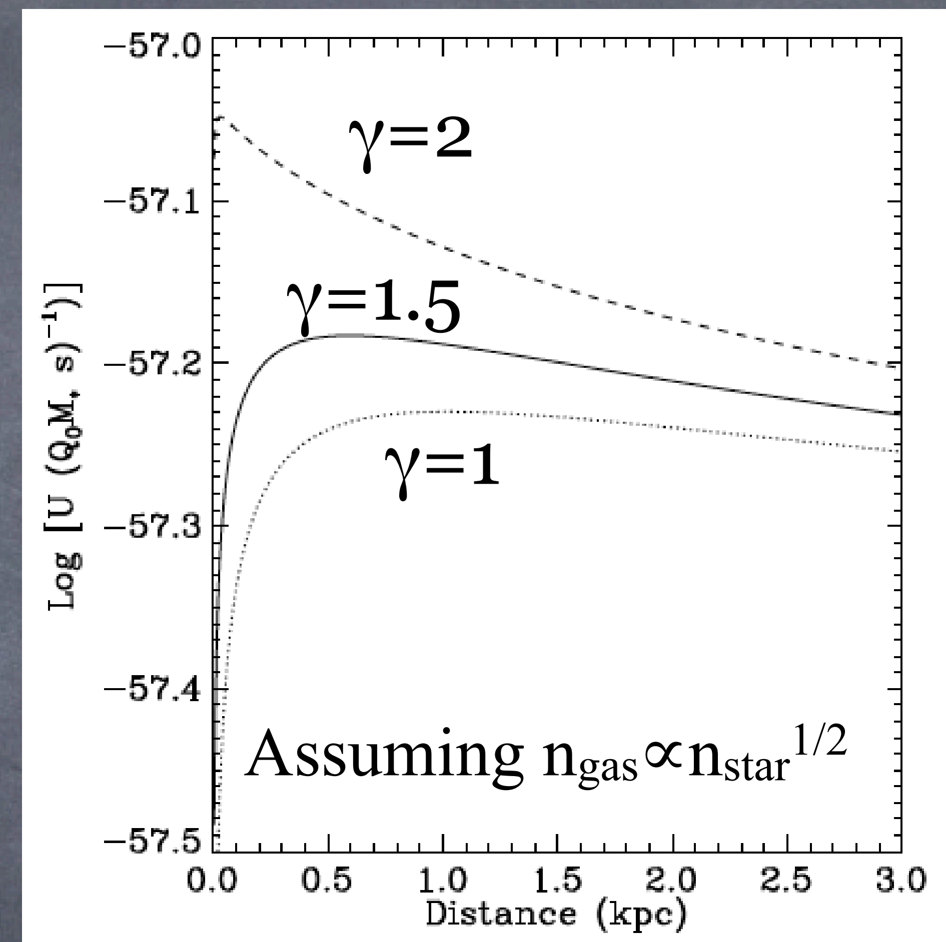


$F(D) = \int_0^\infty$ …

$= \frac{Q_0}{2} \int$ …

$\rho(r) = \frac{(3}{}$ …

Ionization Para. Profile



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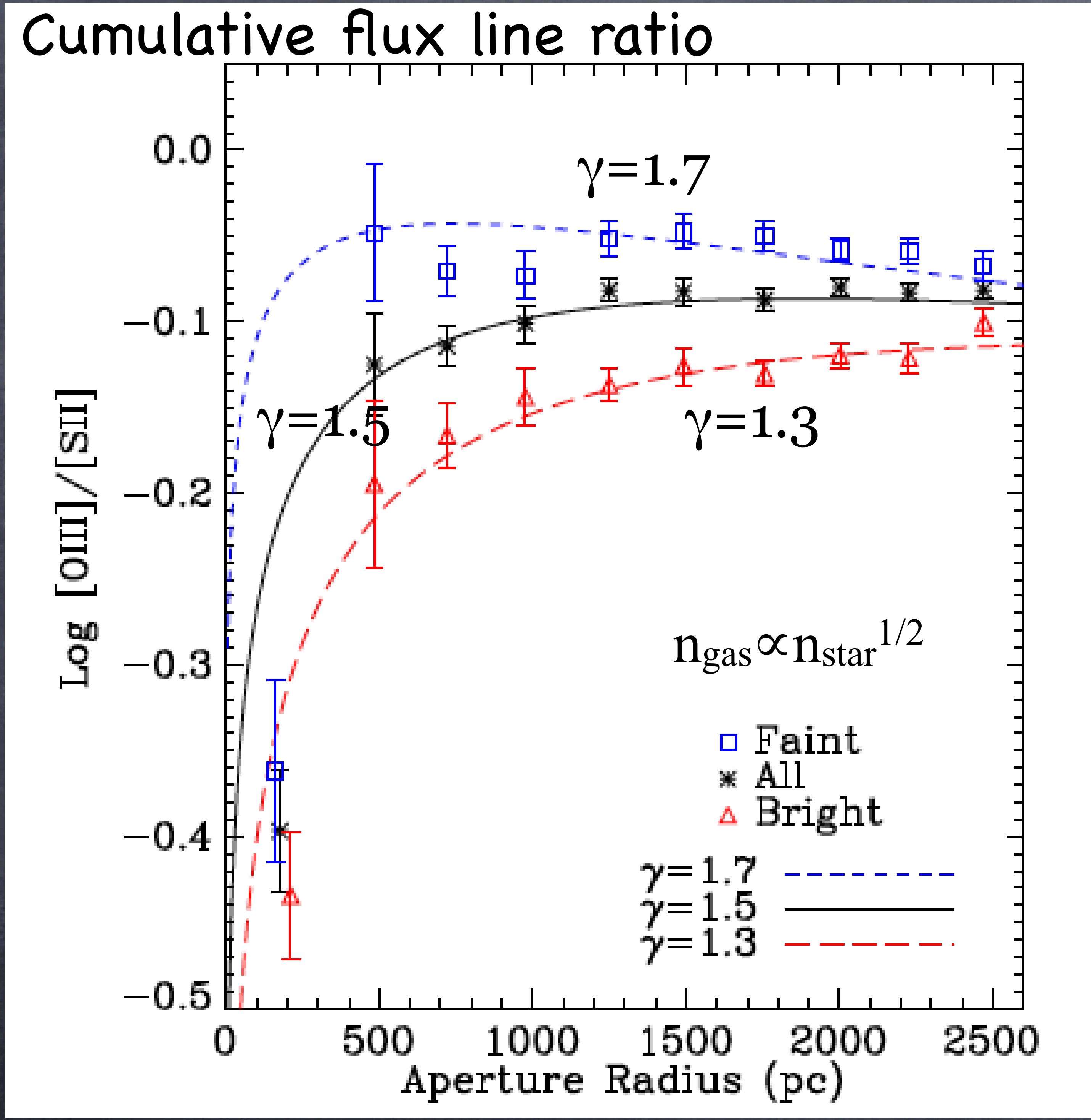
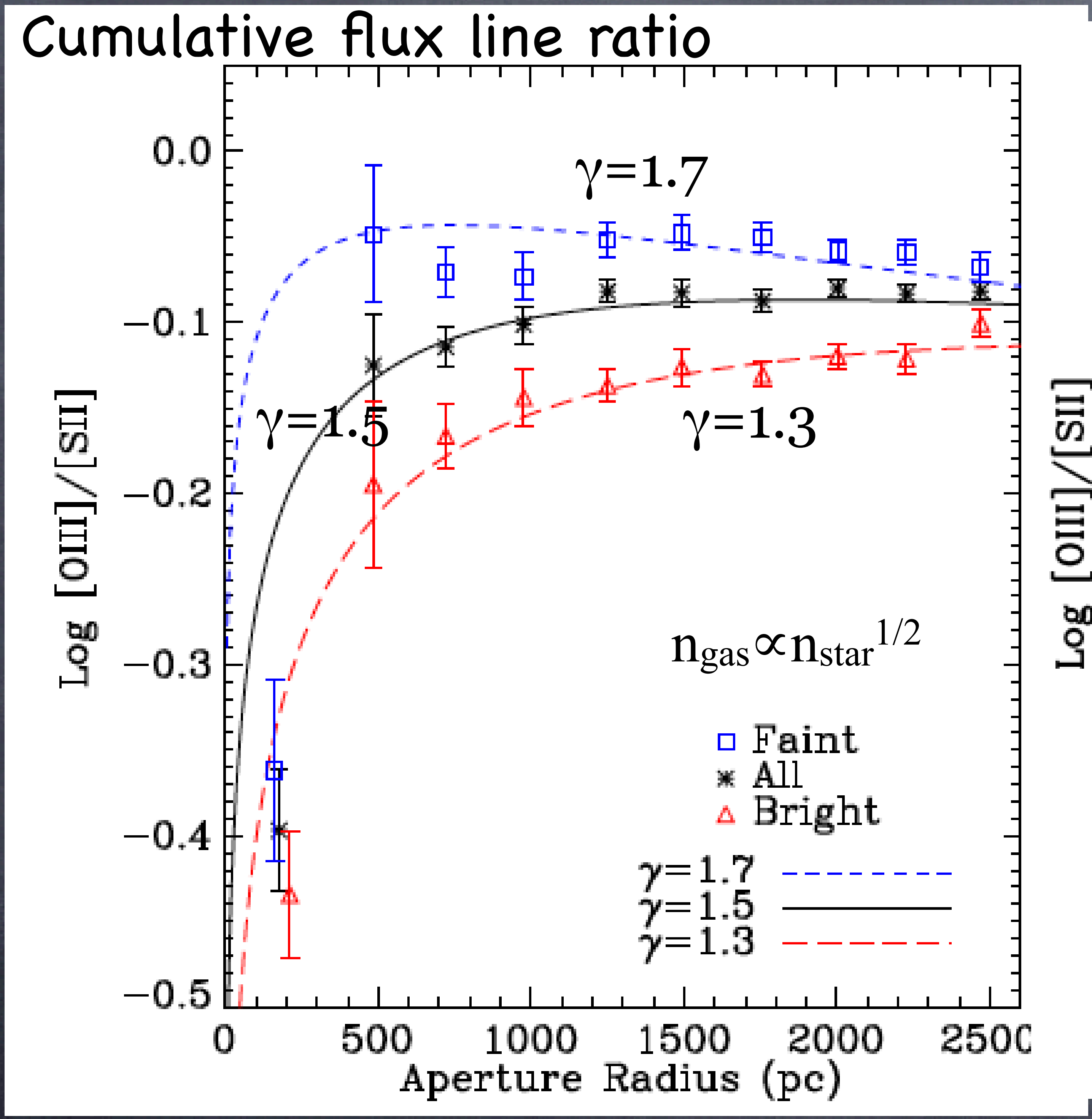
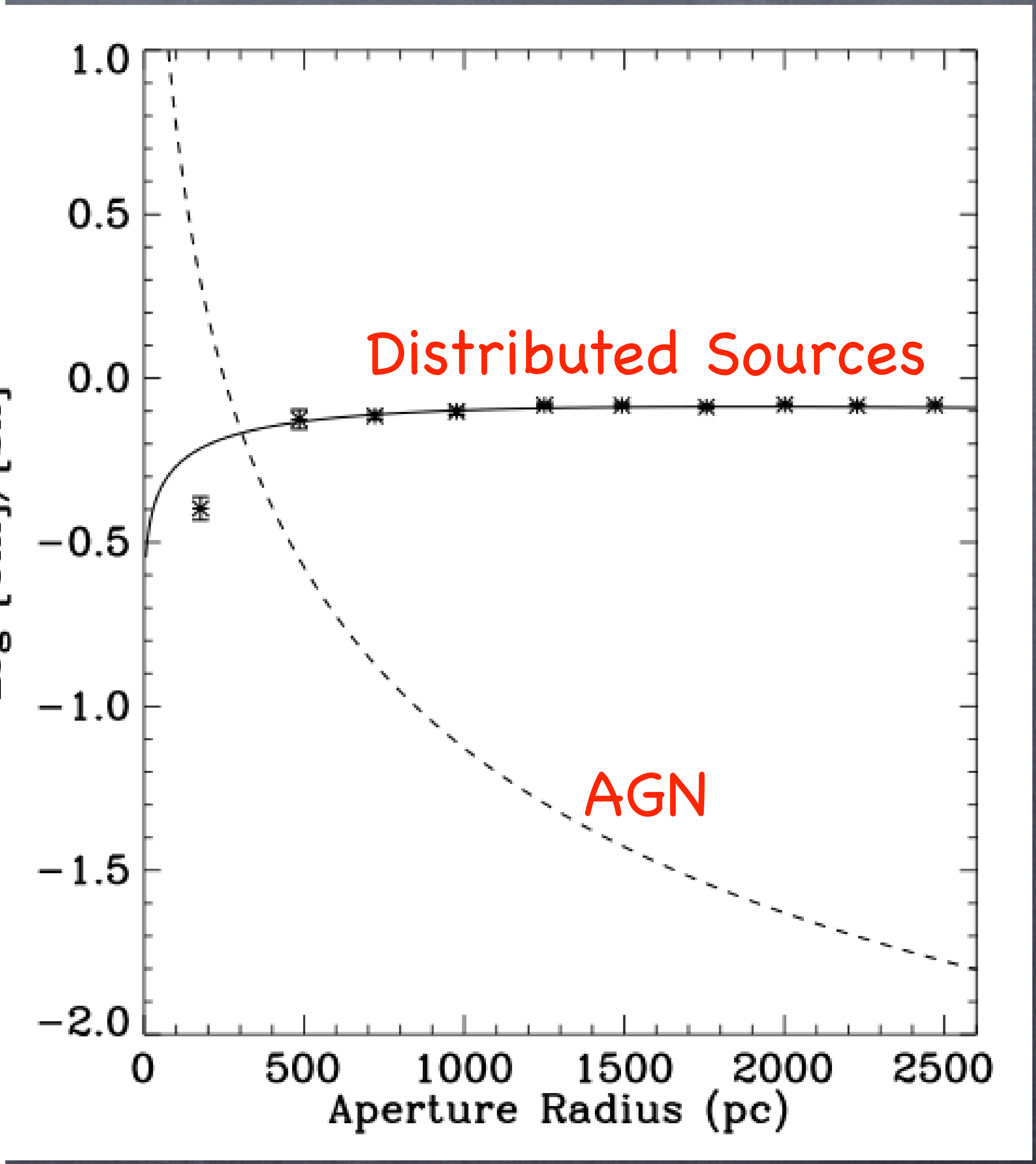
Luminosity Dependence



The observed luminosity dependence in line ratio gradient matches the general trends predicted by distributed ionizing sources following the stellar density profile.

Luminosity Dependence

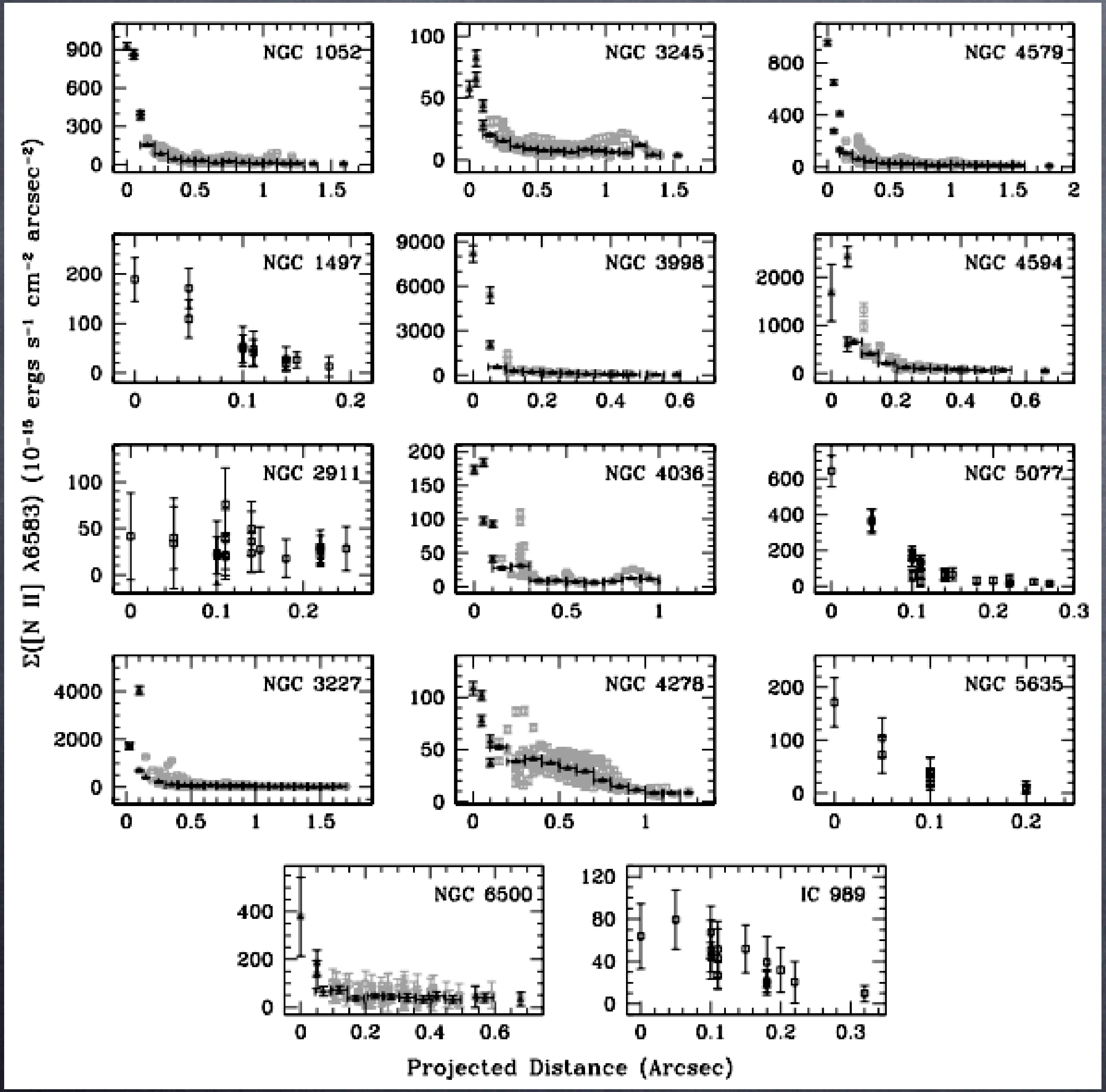




What about those supporting evidence for AGN?

- What about LINER's higher X-ray detection rate?
- What about the broad line components?
- What about UV variability?

Narrow Line Region of the weak AGN in LINER

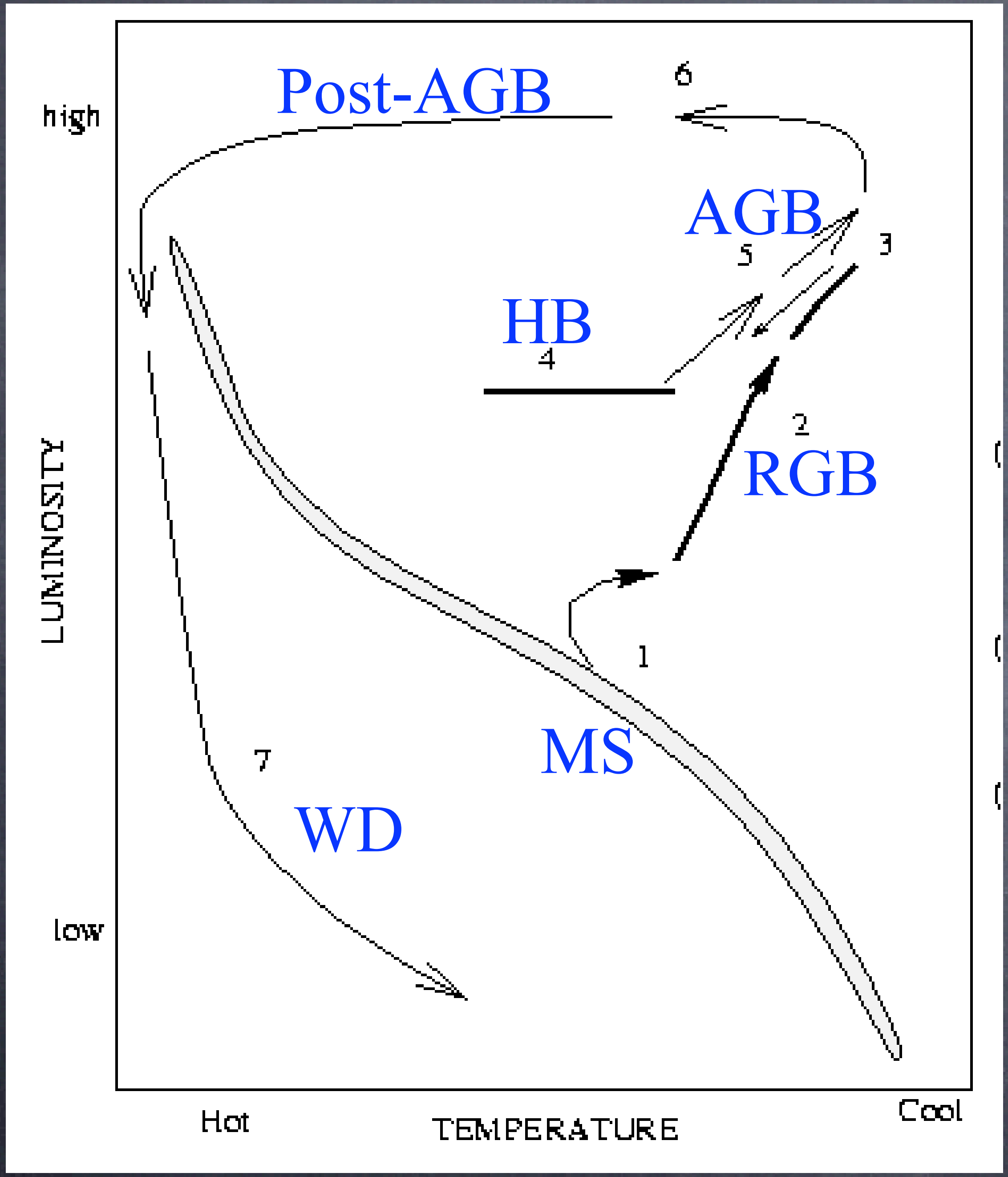


LINER NLR
Scale < 10~20 pc

LINER-like line emission, when measured using apertures larger than 100pc, is not primarily powered by AGN.

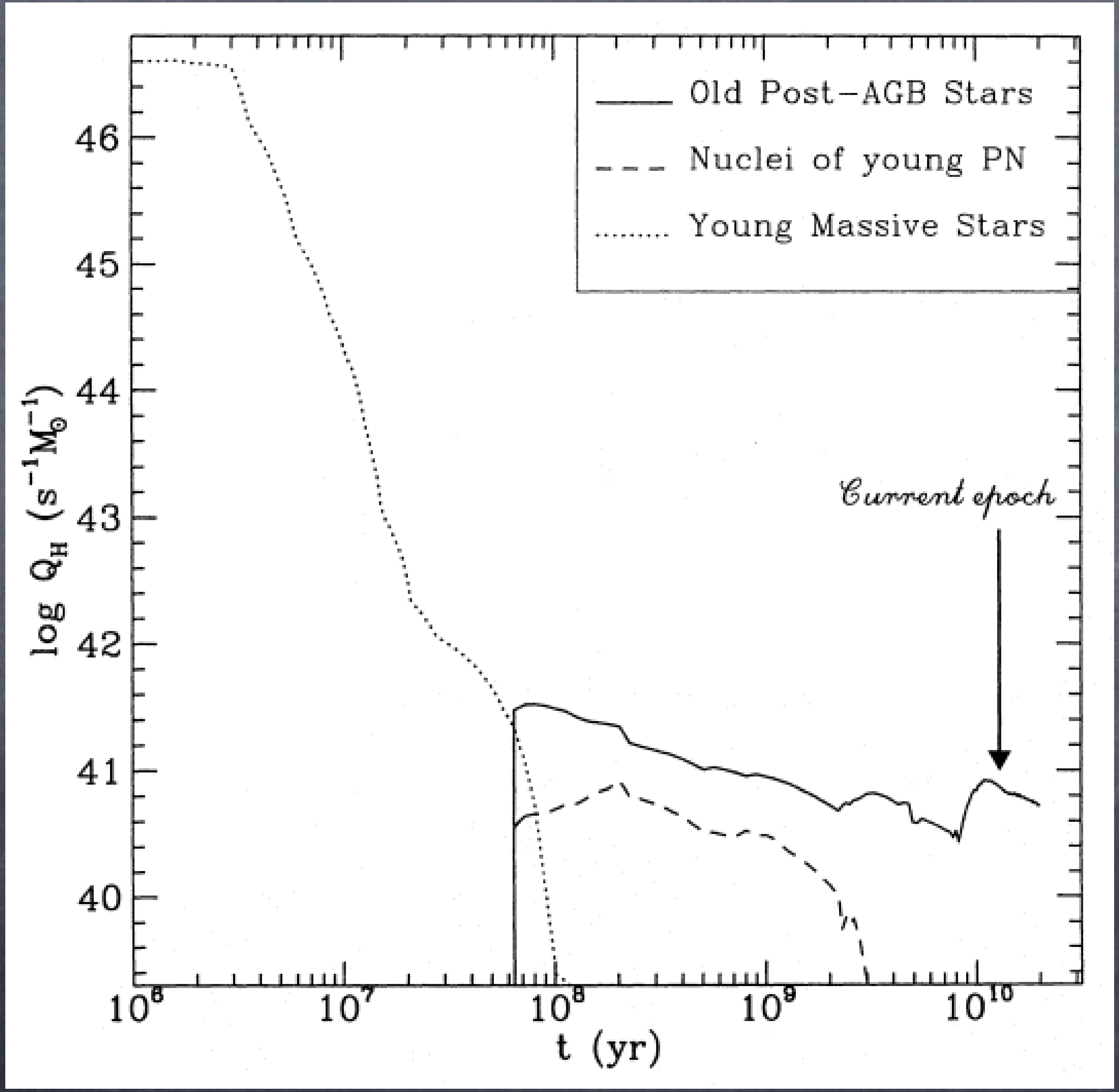
Walsh et al. (2008)

Post-AGB stars



- A short-lived phase between AGB and WD.
- Often accompanied by planetary nebulae.
- The lifetime of PN depends strongly on the core mass of the star.
- Some low-mass post-AGB stars will be naked, forming a diffuse ionizing field.

Planetary Nebulae vs. Diffuse Ionizing Radiation



Binette et al. (1994)

Ionization para deficit

- Total ionizing photons from post-AGB is roughly enough to account for the observed line luminosity (if they are absorbed by the gas).
- However, if one assumes the gas clouds are randomly distributed relative to the stars, the ionization parameter would be too small, by a factor of 10.

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Solutions

- Increase the number of post-AGBs.
- Gas originated from mass loss from AGBs, but got carried away by the ambient hot medium.

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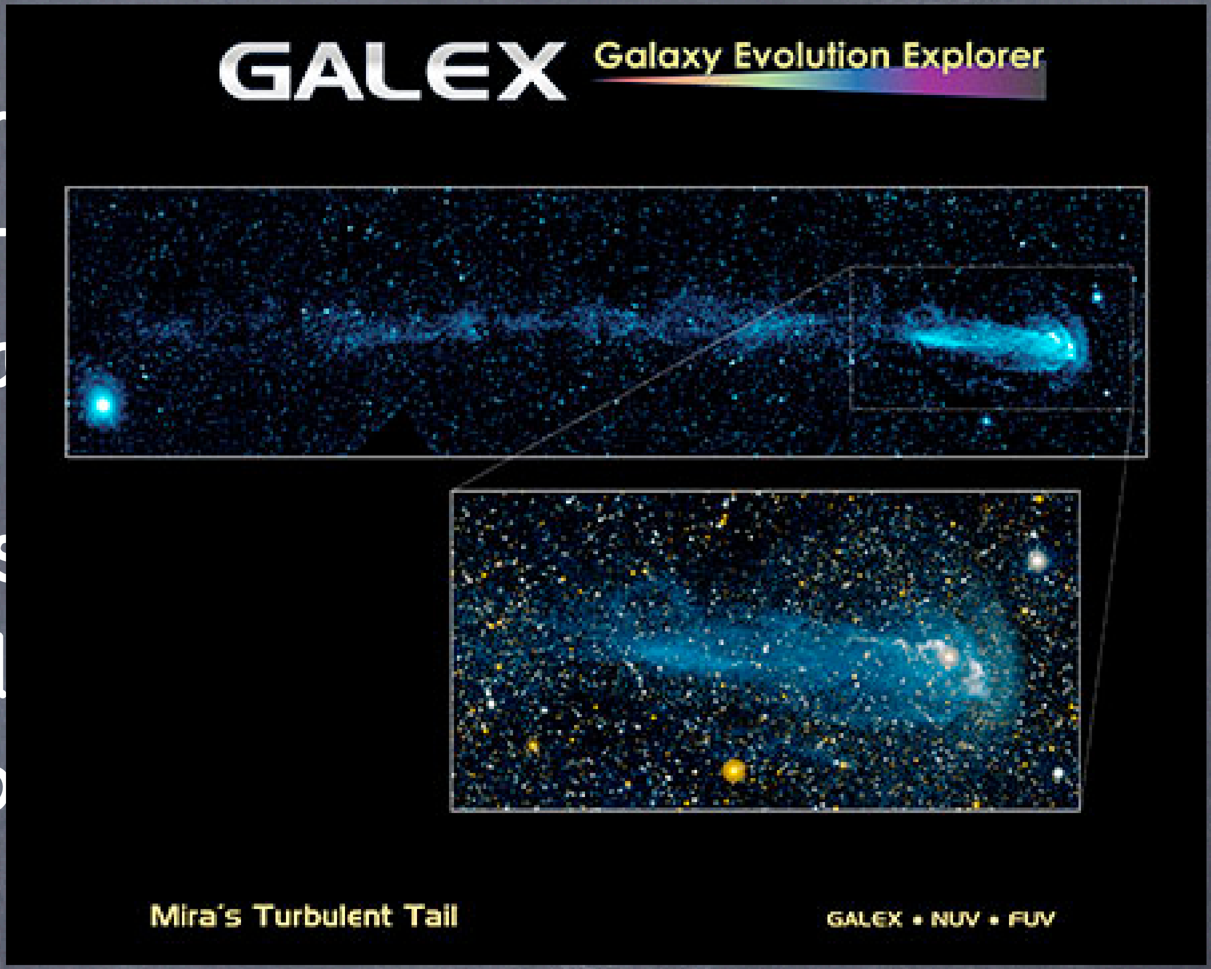

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Solutions

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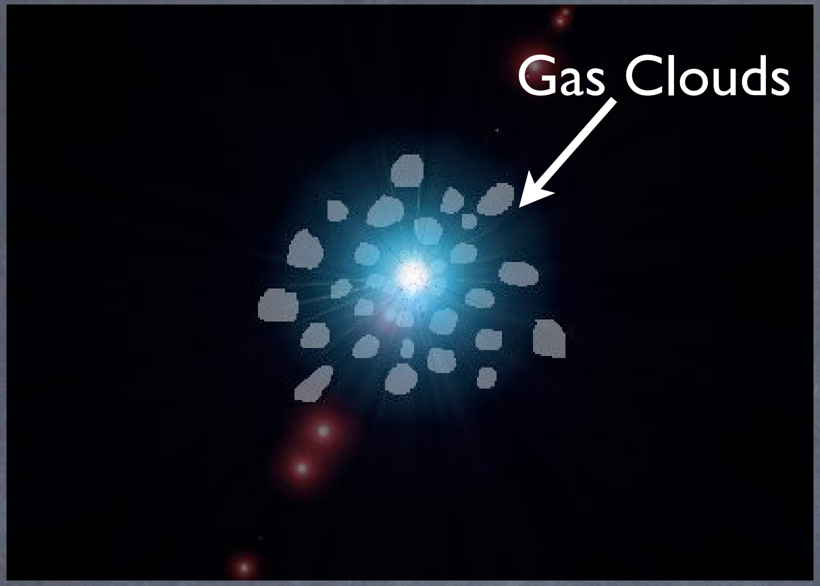
- Gas originated from mass loss from AGBs, but got carried away by the ambient hot medium.

Other sources

- Extreme Horizontal Branch Stars
- X-ray binaries
- Hot gas

How to distinguish?

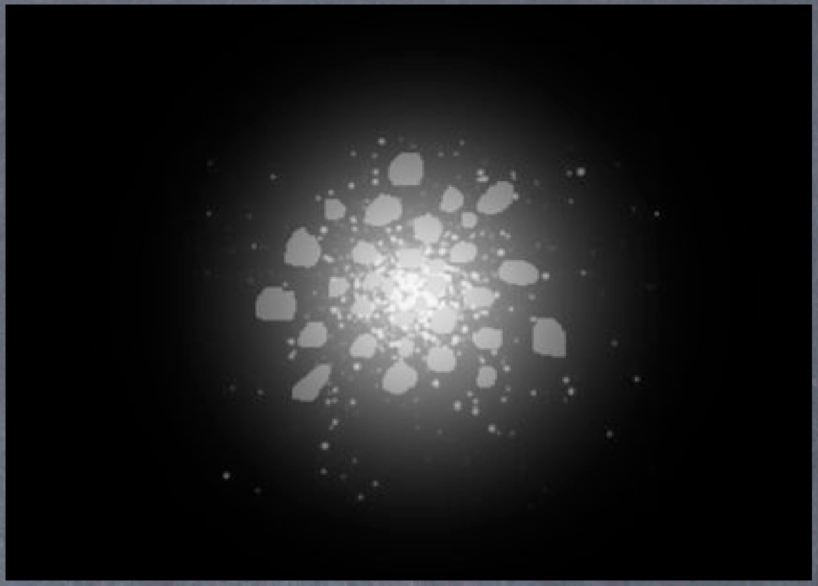
A central point source



AGN

vs.

Distributed ionizing sources



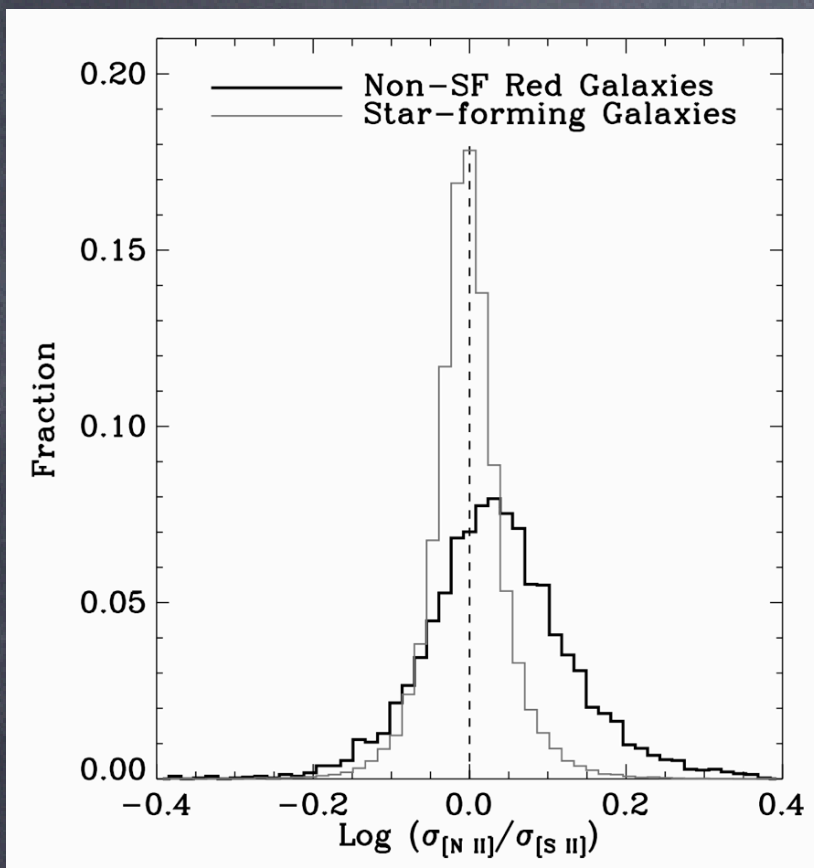
e.g. Post-AGB stars

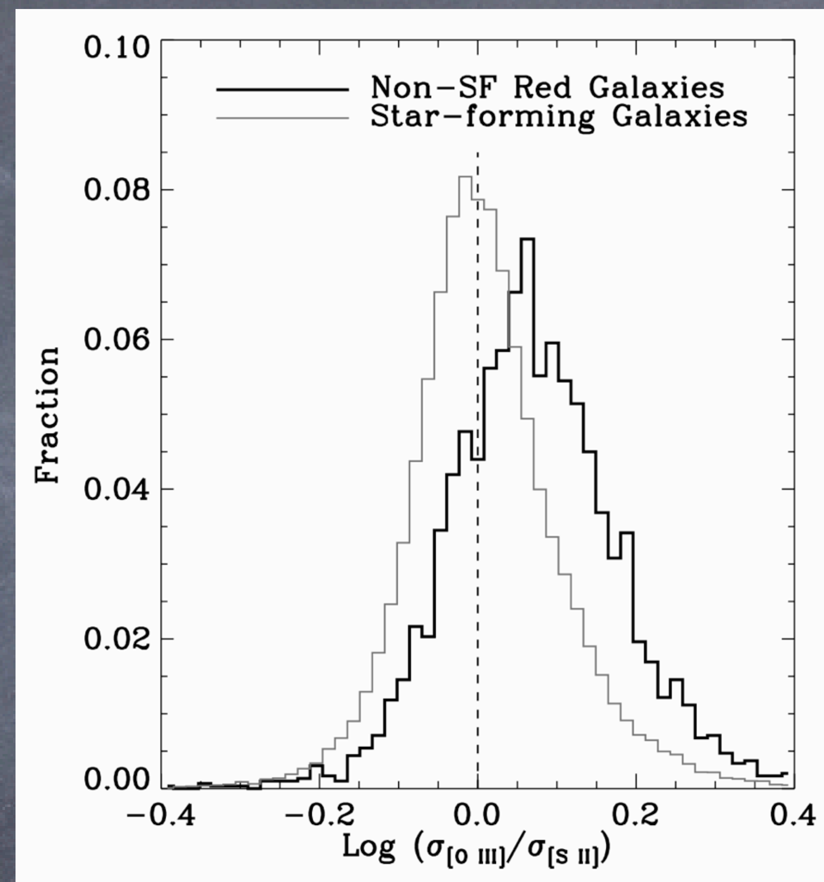
Different ionizing flux profile

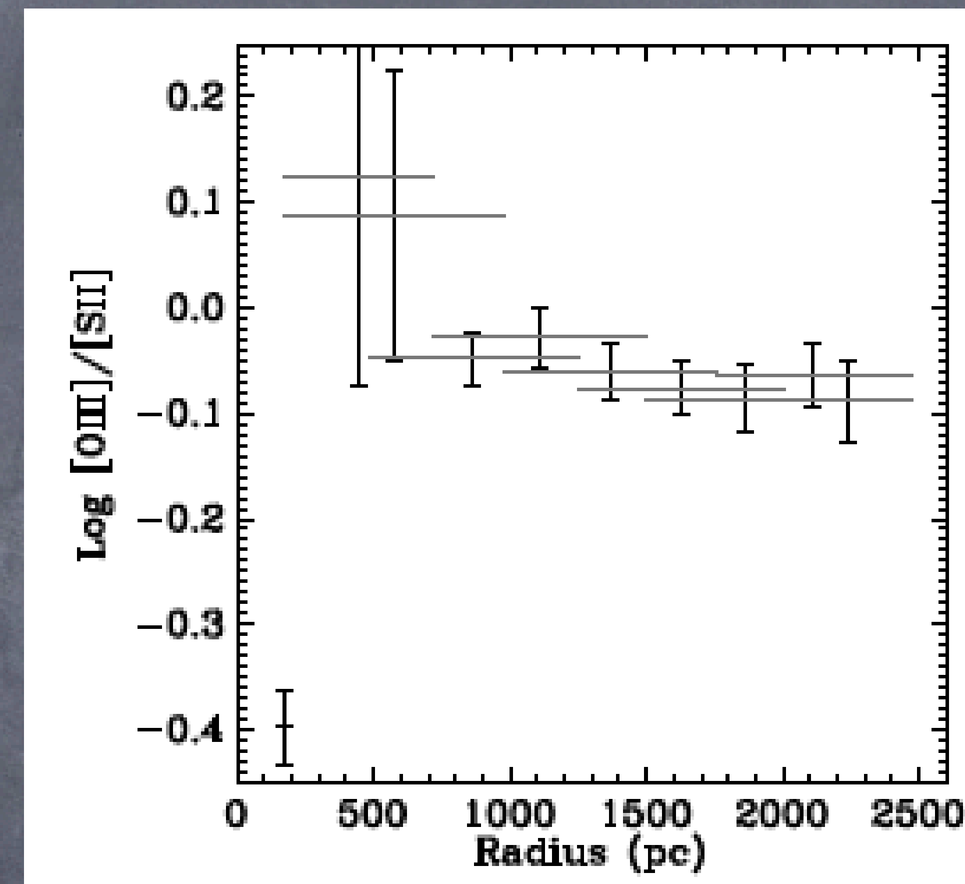
=> Different line ratio gradient with radius

=> Different widths for different lines if there is kinematic structure

Kinematic Evidence for Line Ratio Gradient?



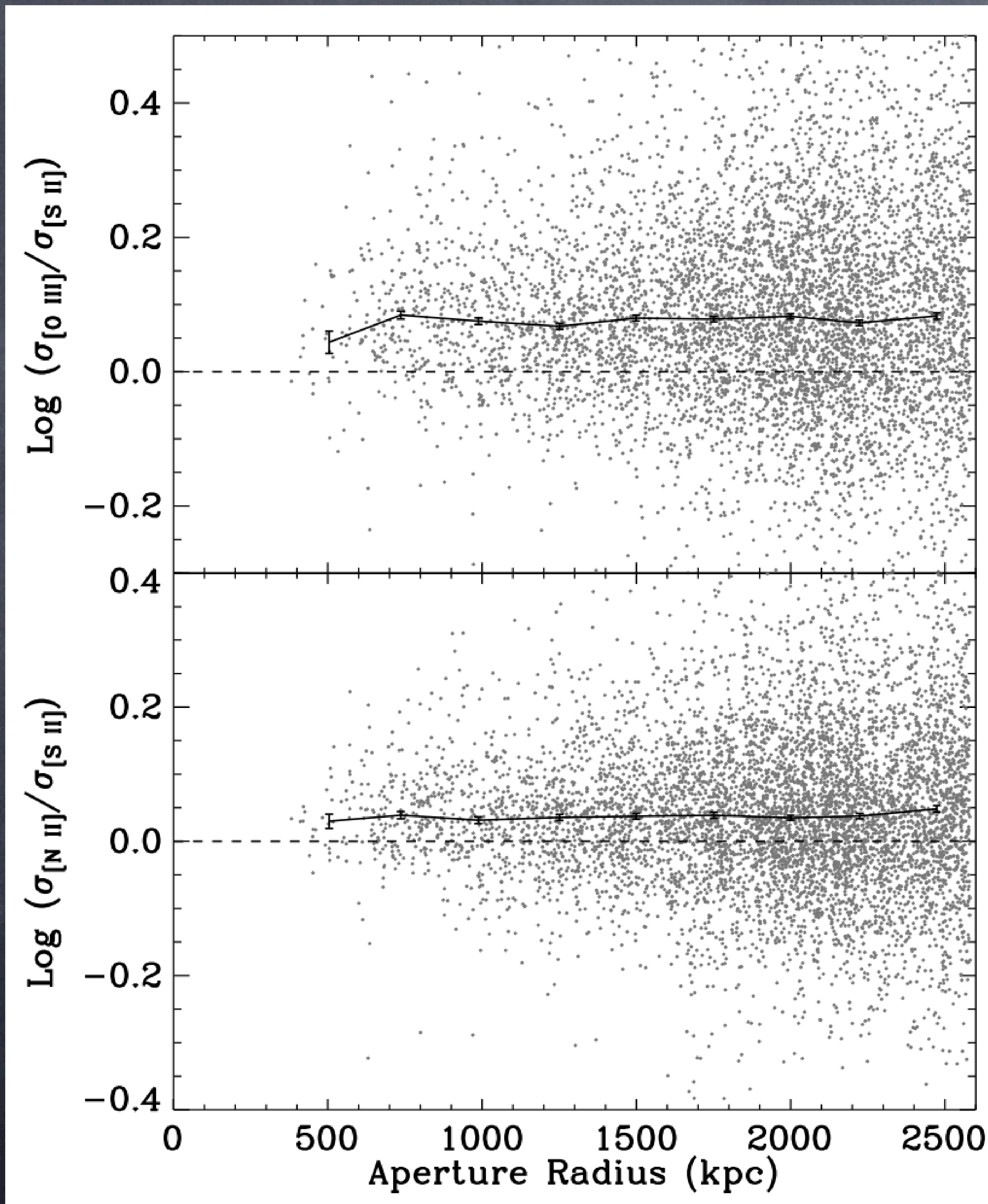




On average, Hα and [NII] are wider than [SII] by 8%, and [OIII] is wider than [SII] by 16%. This requires velocity broadening increases with [OIII]/[SII] ratio. Does velocity broadening increases with radius?

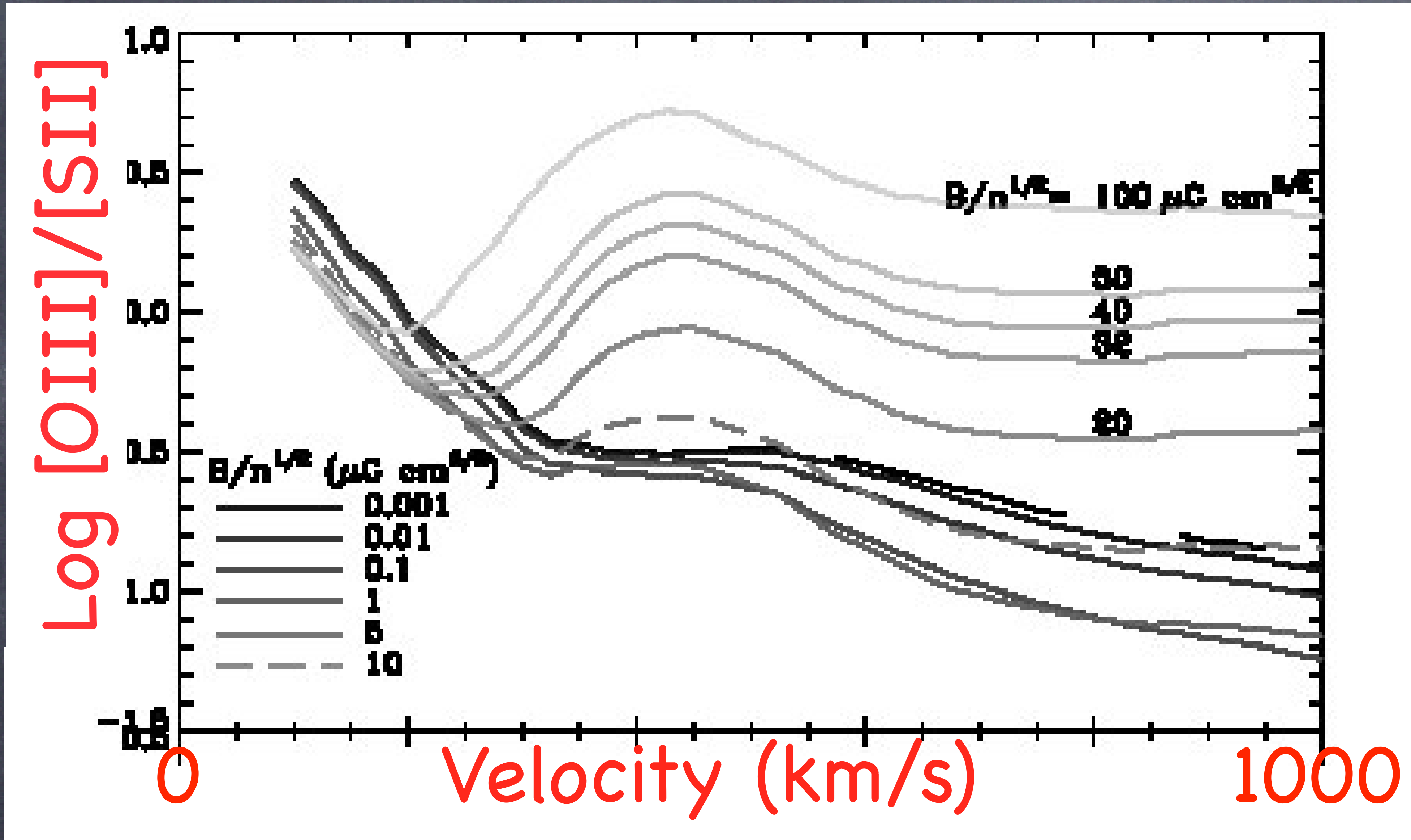
It does. However, the difference should go away at large apertures.

Vel. Difference w/ Aperture



- Line width difference stays flat with aperture radius. So, it is not due the large scale kinematic structure.
- Instead, the warm ISM must have multiple components. Low density components have larger velocity dispersion than high density components.

Shocks



- Shocks produce the opposite line ratio - velocity correlation to what's observed. Therefore, shocks cannot be the dominant source.

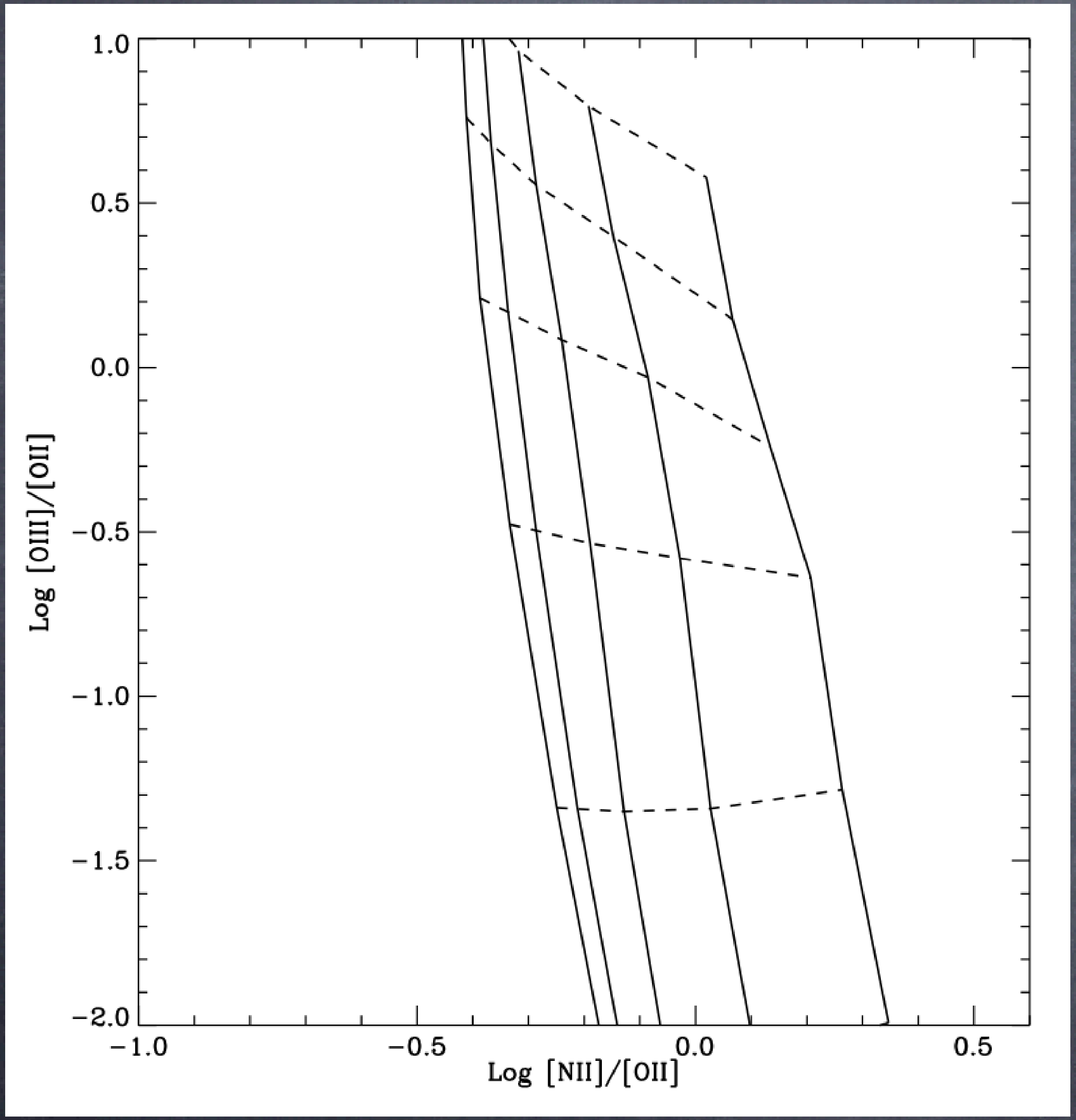
Summary

- Most LINER-like emission regions are spatially extended. Nuclear LINERs are just their central parts.
- AGN is not the dominant ionizing source for the LINER-like line emission commonly found in early-type galaxies, neither are shocks.
- The dominant ionizing sources are probably distributed like the stars.
- The warm phase of the ISM has multiple components.
- Line strength in LINERs found with large aperture (>100pc) spectra cannot be used to trace AGN luminosity, but can be used to trace the warm/cold gas.

Metallicity Measurement

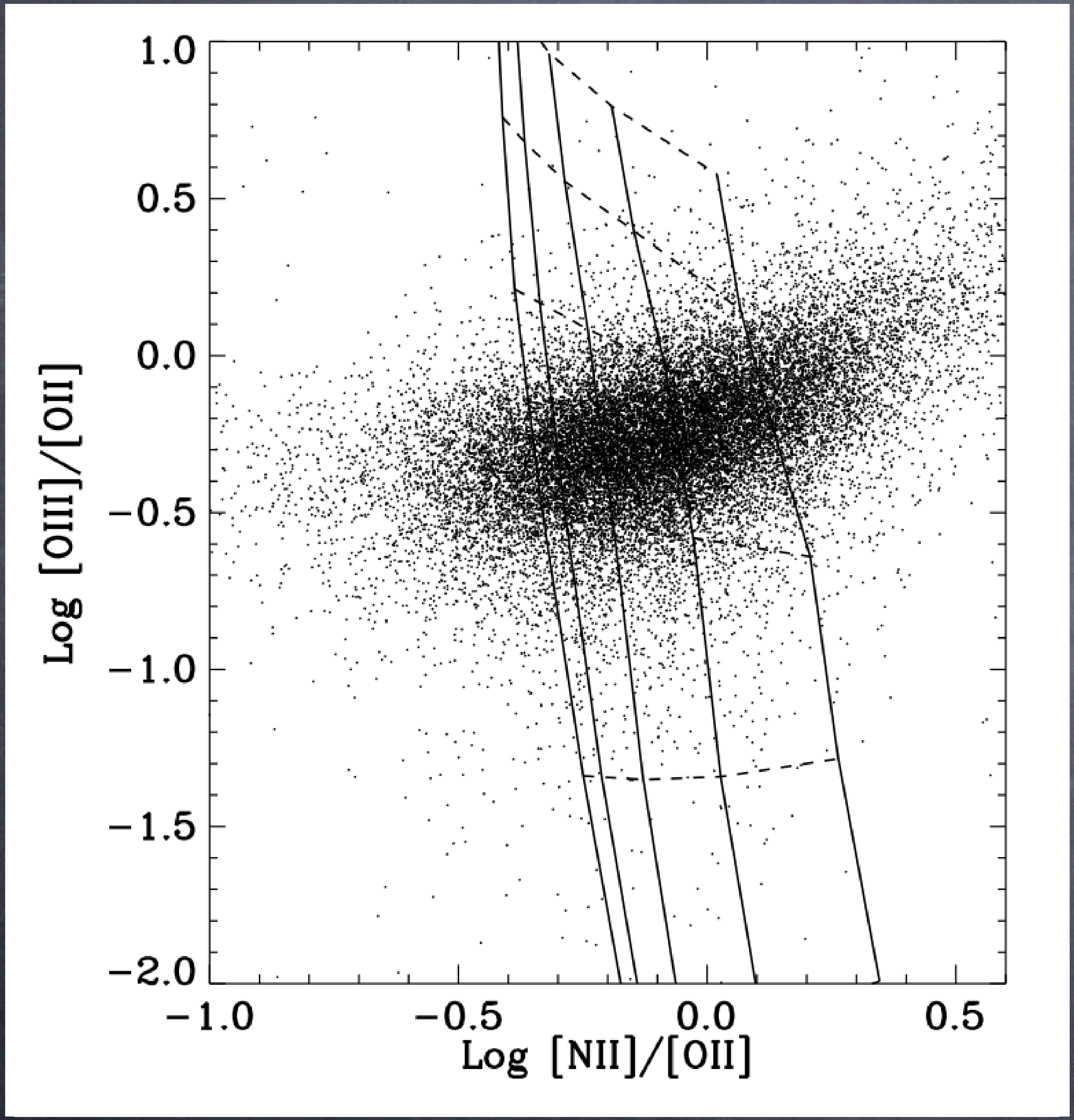
- Stellar metallicity from stars
- Hot-gas metallicity from X-ray spectra.
- Warm-gas metallicity from HII regions (not applicable in these old galaxies!)
- There is line ratio gradient. So, use large apertures.

CLOUDY model grids



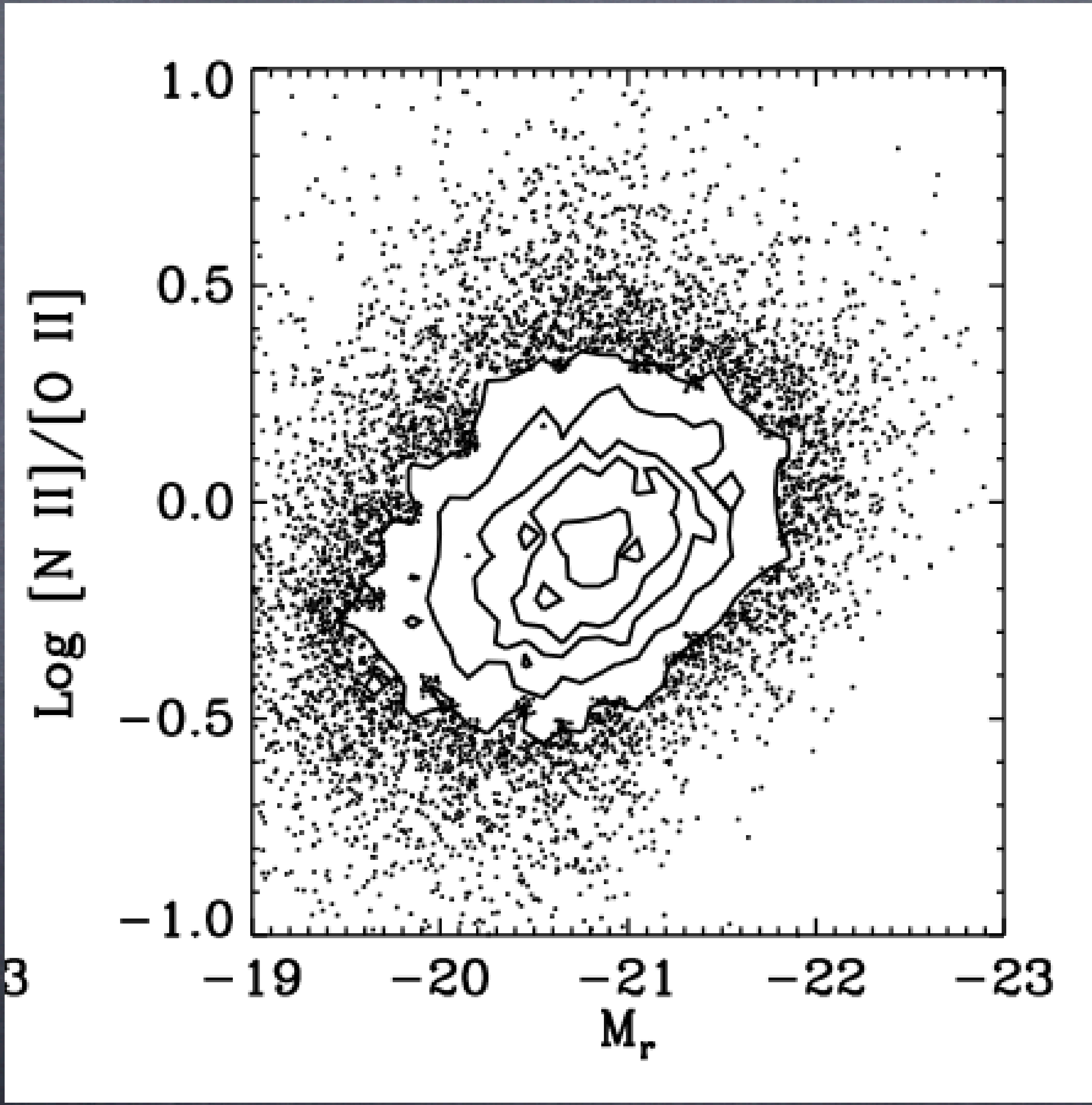
[OIII]/[OII] --- ionization parameter
[NII]/[OII] --- metallicity

CLOUDY model grids

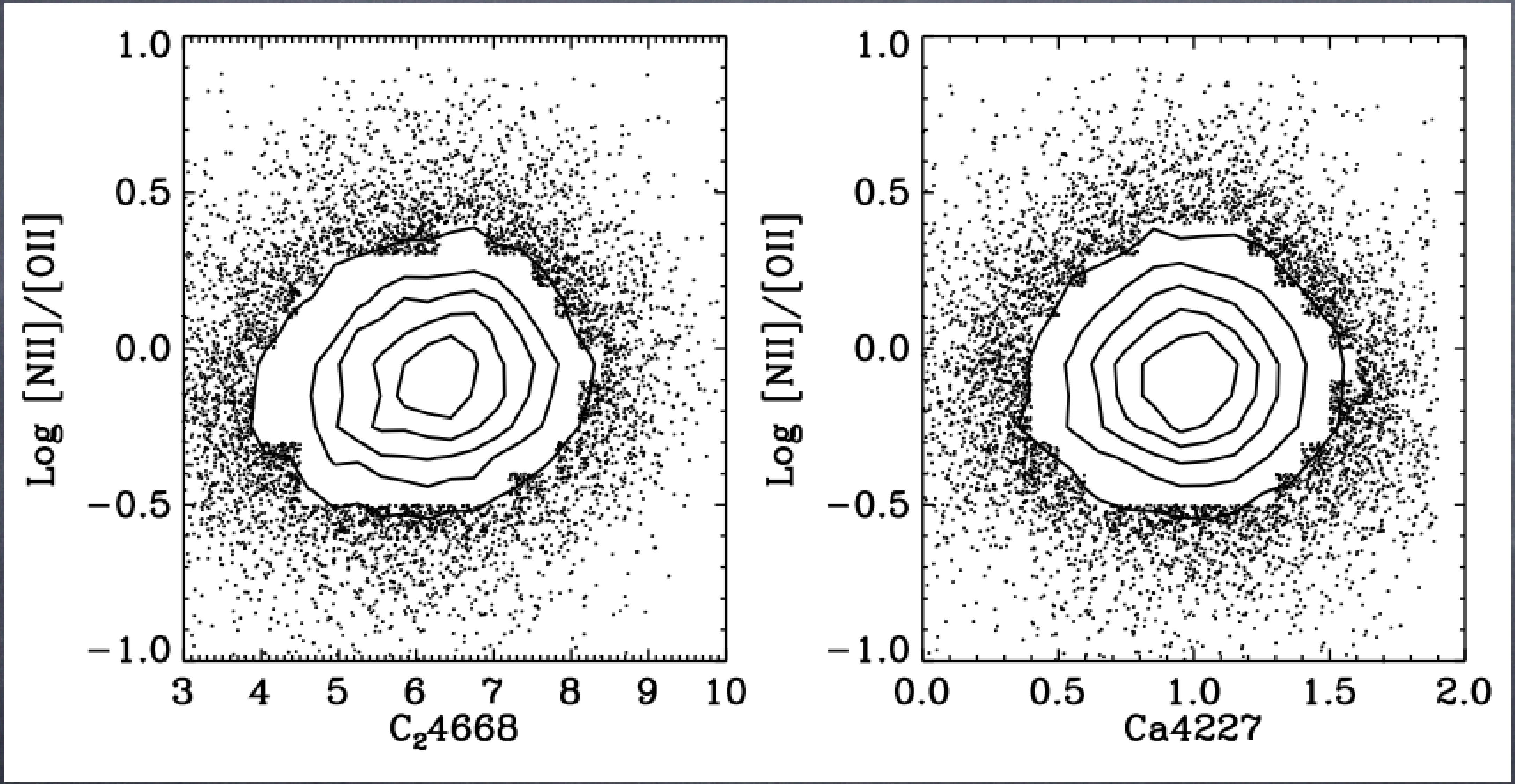


[OIII]/[OII] --- ionization parameter
[NII]/[OII] --- metallicity

Metallicity vs. Luminosity

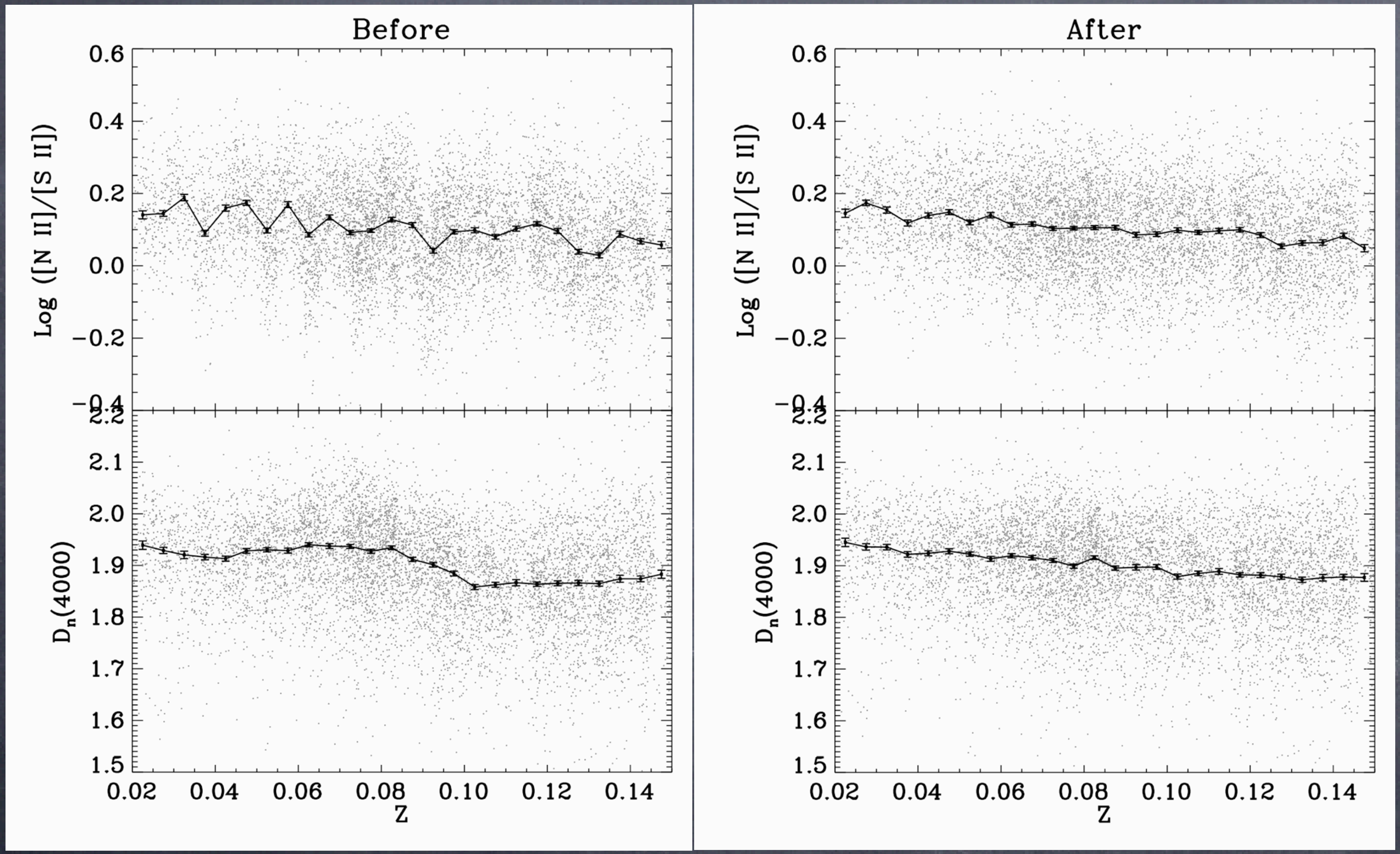


Gas Metallicity vs. Stellar Metallicity



- Origin of the gas is likely external

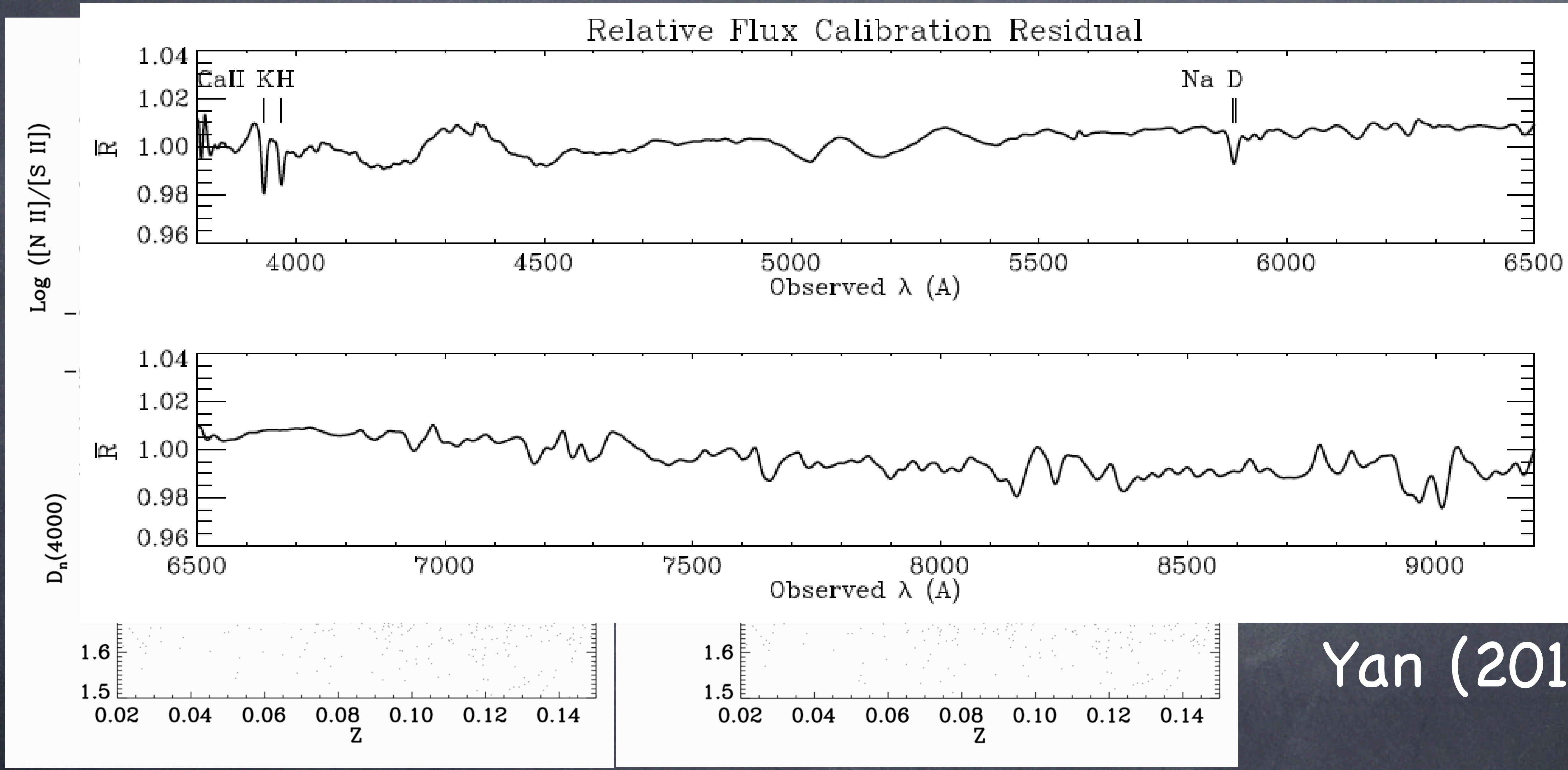
Precision Spectrophotometry at the 0.1% level



Yan (2011)

- For weak spectral features, small scale flux calibration need to be accurate at subpercent level .

Precision Spectrophotometry at the 0.1% level



Yan (2011)

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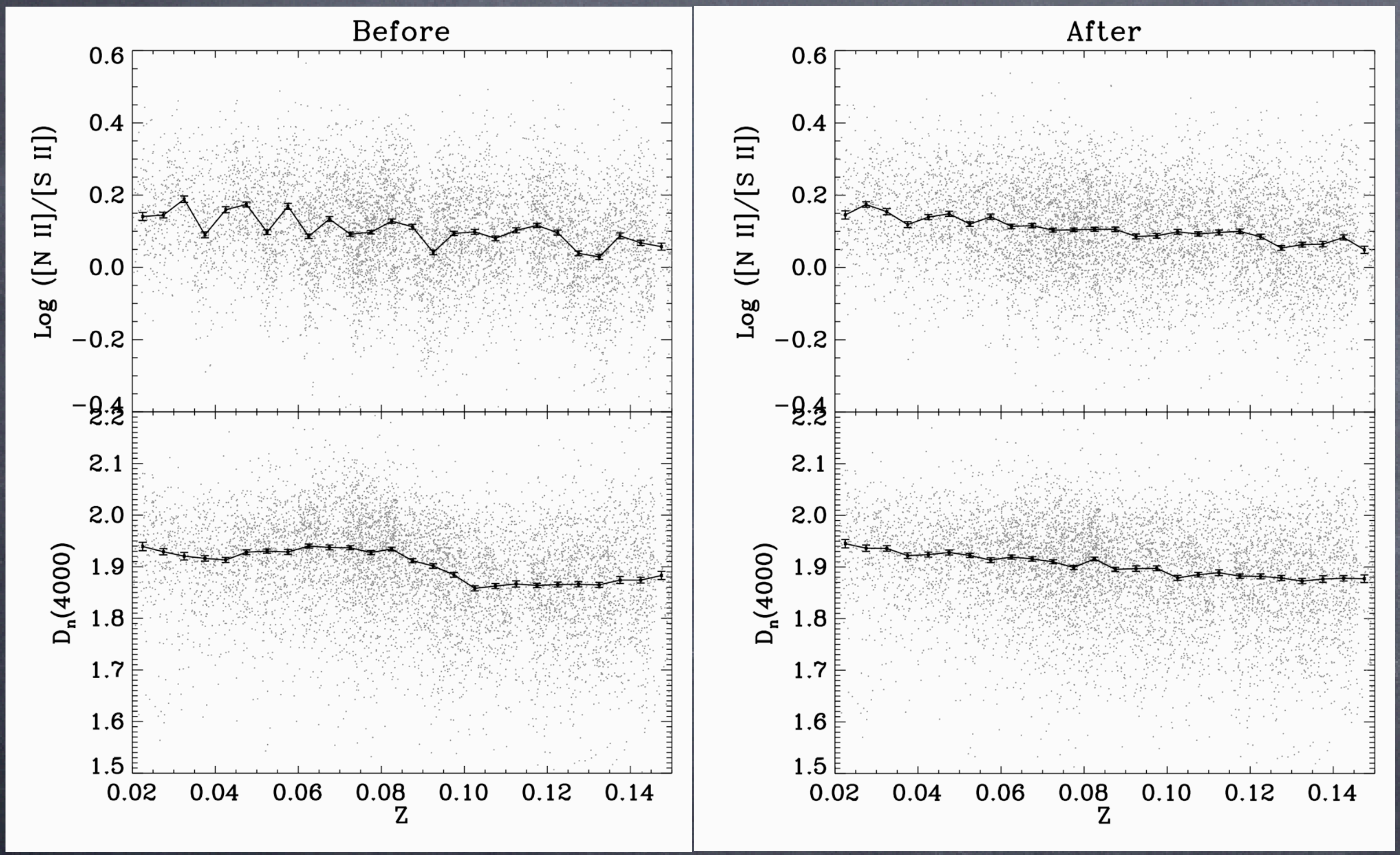
Precision Spectrophotometry at the 0.1% level



Yan (2011)

- For weak spectral features, small scale flux calibration need to be accurate at subpercent level .

- Thank you!