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RESEARCH CENTER FOR
SPACE AND COSMIC EVOLUTION

Near-infrared spectroscopy of Seyfert galaxies for examining the ionization mechanism of narrow-line regions

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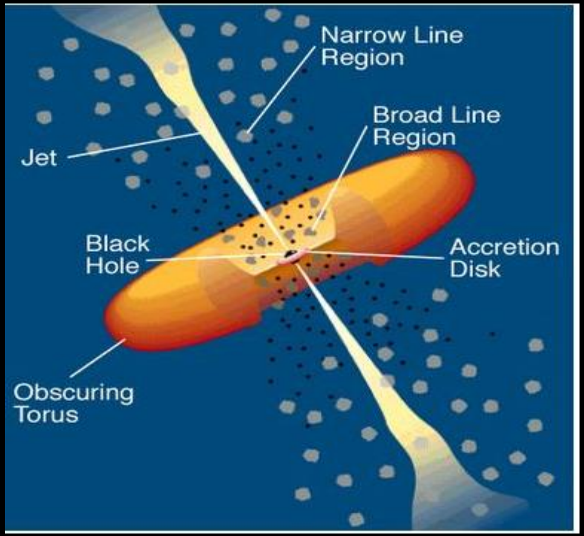
Active Galactic Nucleus (AGN)

- Vast radiative energy from AGNs
  ➔ various influence on the surrounding environment
  ✓ star formation in host galaxies
  ✓ accretion onto super-massive black holes (SMBHs)

could be prevented by AGN activities

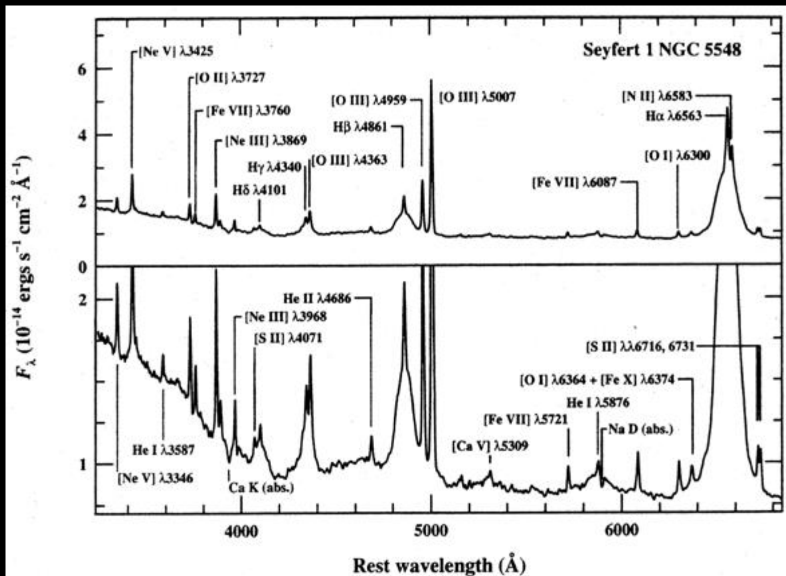


AGN unified model (Urry & Padovani 95)

AGN feedback

- possibly taking an important role in the galaxy-SMBH co-evolution

Emission lines from AGNs



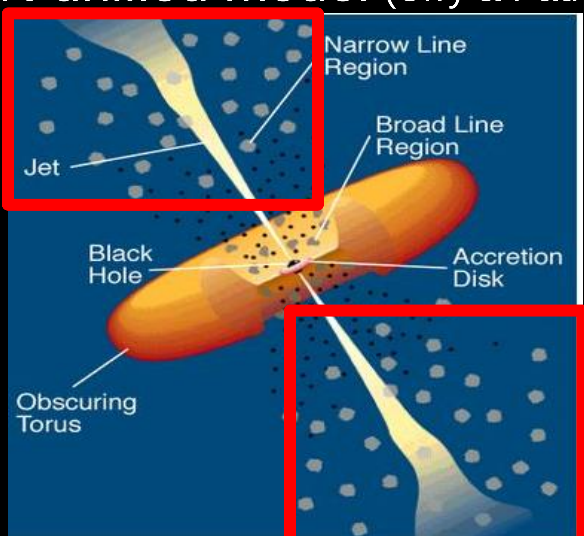
(Peterson+94)

- Broad emission lines
  - ✓FWHM > 2000 km/s
  - ✓from broad-line region (BLR)
  - ✓spatial scale: < 1 pc

- Narrow emission lines
  - ✓FWHM ~ a few 100 km/s
  - ✓from narrow-line region (NLR)
  - ✓spatial scale: ~ 10^{2-4} pc

↑ comparable to host galaxies

AGN unified model (Urry & Padovani 95)



We can study the influence of the AGN feedback for the ISM in host galaxies

Ionization mechanisms of NLRs

- **Photoionization by the ionizing photon from the AGN central engine**
  (e.g., Osterbrock 89, Binette+96, Groves+04, Bianchi+06)
- **Collisional ionization by the fast shock associated with outflows**
  (e.g., Knop+96, Wilson & Raymond 99, Fu & Stockton 07)

Discriminating the ionization mechanism of NLRs is a key to understand the radiative and kinetic contributions of the AGN feedback.

Previous studies: Emission-line diagnostics based on rest-frame optical and/or UV spectra

➔ Unsuccessful because different models predict similar flux ratios
(e.g., Dopita & Sutherland 95, 96, Groves+04, Allen+08, Kewley+13)

Ionization mechanisms of NLRs

The goal of this work:

Discrimination of ionization mechanisms of the NLR

We focus on a **near-infrared** flux ratio of forbidden emission lines seen in the *J*-band,

[FeII]1.257 μm/[PII]1.188 μm

(Oliva+01)

The reason for using the [FeII]/[PII]

① Similarity of parameters of two transitions

	[FeII]1.257	[PII]1.188
critical density	$3.5 \times 10^4\ \mathrm{cm}^{-3}$	$5.3 \times 10^4\ \mathrm{cm}^{-3}$
ionization potential	7.9 eV	10.5 eV

(e.g., Storchi-Bergmann+09, Koo+13)

Very similar

↓

The two lines arise at a similar location in the NLR

The reason for using the [FeII]/[PII]

② behavior toward dust grains

- Fe: a refractory species ➔ depleted into dust grains
- P: a non-refractory species ➔ exist in the gas phase

photoionization dominated ➔ no destruction of dust grains ➔ iron is remaining into dust grains ➔ weak [FeII] emission

[Fe II]/[P II] ~ **2** e.g., HII region

shock dominated ➔ destruction of dust grains ➔ gas-phase iron abundance increases ➔ strong [FeII] emission

[Fe II]/[P II] ~ **20** e.g., supernova remnant (Oliva+01)

➔ **The [FeII]/[PII] flux ratio is a powerful tool to examine the presence of shocks**

Problem

only a few [FeII]/[PII] measurements for AGNs

➔ insufficient for various statistical discussions

Our approach

Near-infrared spectroscopic observations of nearby Seyfert galaxies

Purpose

Investigation of the ionization mechanism of the NLR and the origin of shocks through the [FeII]/[PII] ratio

Observations

- site: Okayama astrophysical observatory
- telescope diameter: 188 cm
- instrument: ISLE (near-infrared spectrometer)
- date: Aug. 2010 to Apr. 2011 (19 nights)
- band: *J*-band (1.11 − 1.32 μm)
- slit width: $2''.0$
- resolution: $\sim$ 1300
- pixel scale: $0''.25$ pixel^{-1}
- seeing size: $1''.0 - 2''.0$

ISLE boarded on the OAO 188 cm telescope

The targets

- 26 nearby ($z < 0.05$) Seyfert galaxies
  - ✓ Clear detections of both [FeII] and [PII] in 6 objects
  - ✓ Only [FeII] detection in 13 objects
    - ➔ 3σ lower limit of the [FeII]/[PII] ratio

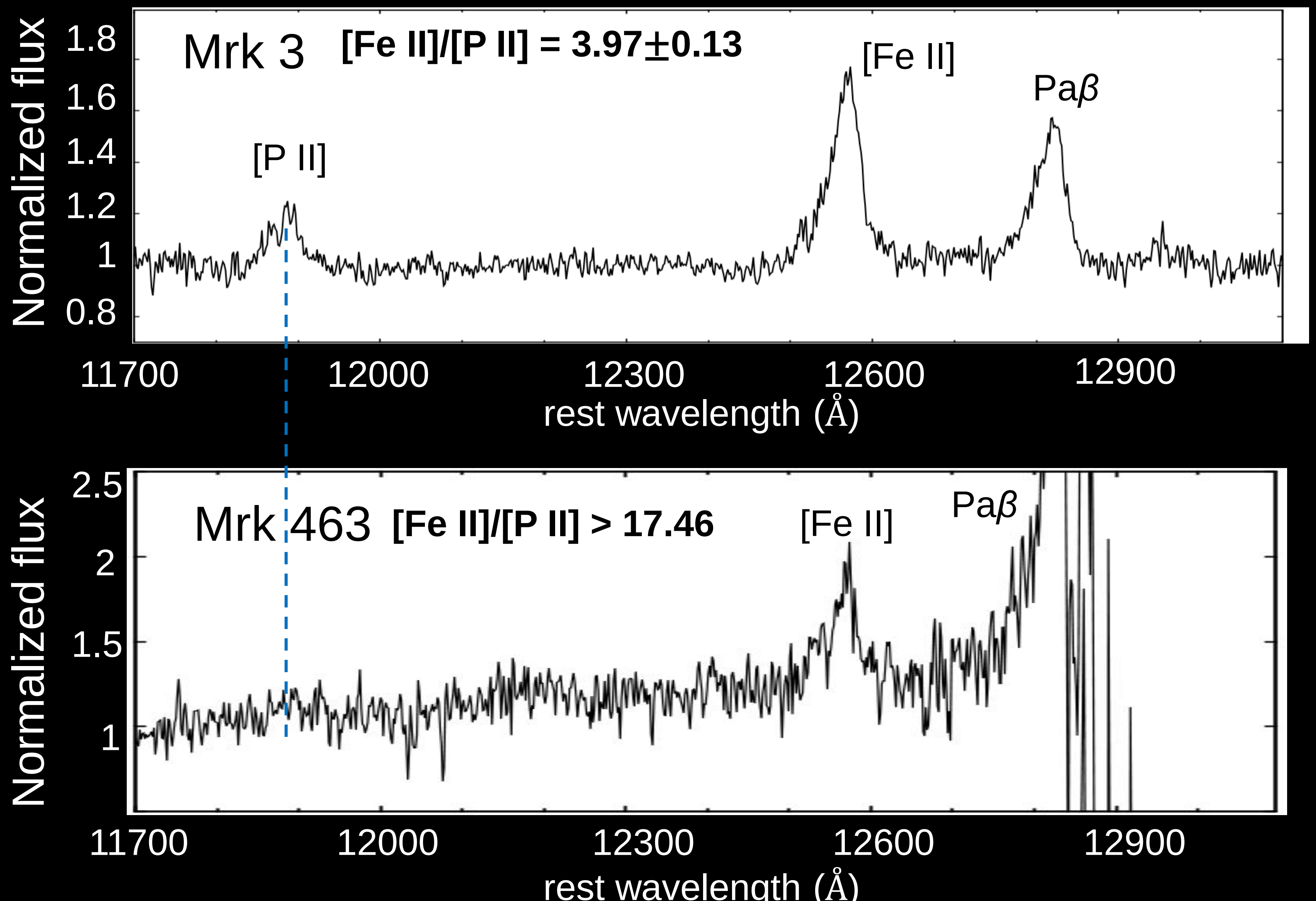
Our observations measured the [FeII]/[PII] ratio or its lower limit for 19 objects in total

- Additional 22 objects are collected from the literature

⬇

Our [FeII]/[PII] sample: 41 objects

Examples of the obtained spectra



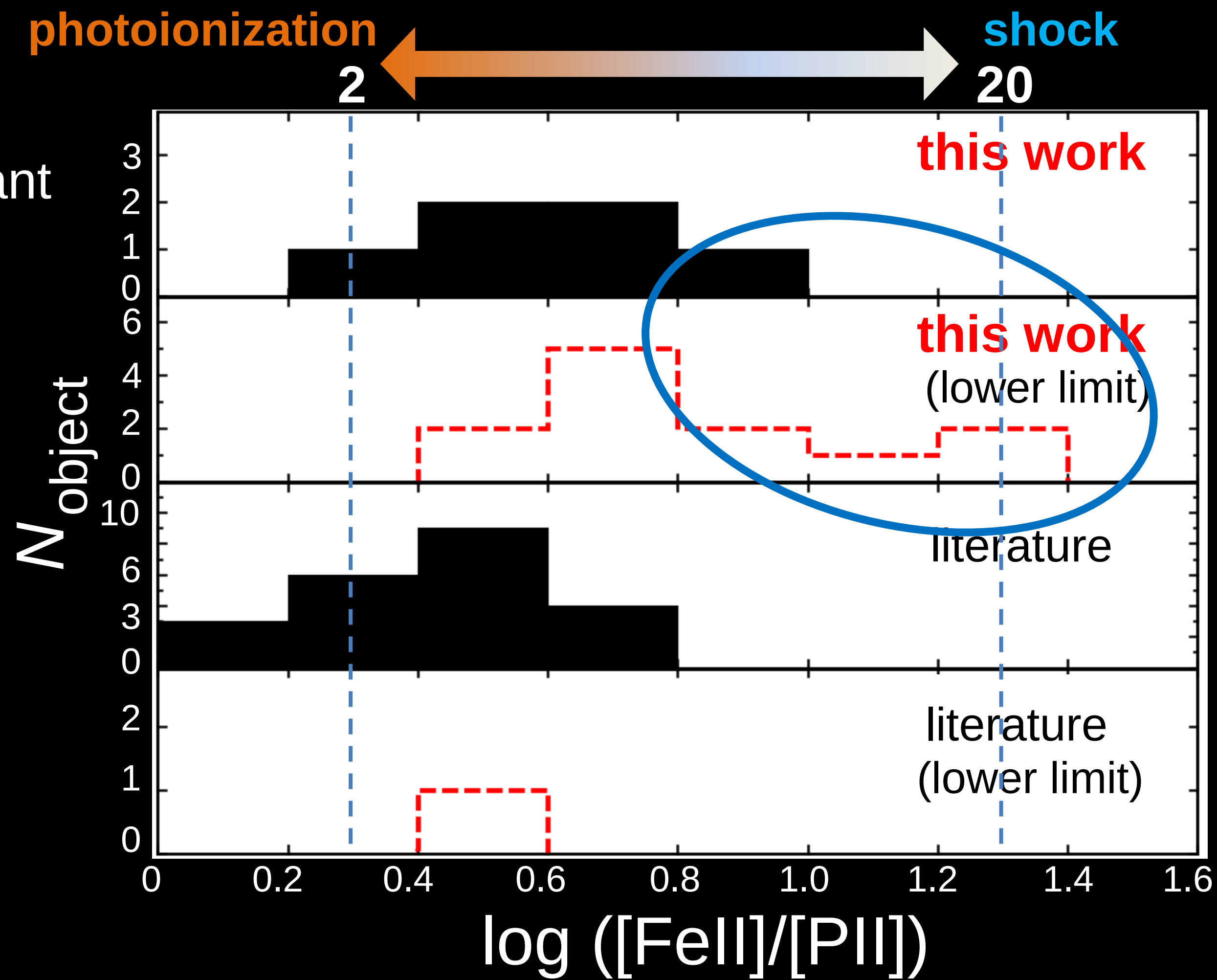
Results

The [FeII]/[PII] flux ratios

- Photoionization is dominant in NLRs of many objects

- Some objects show high flux ratio (blue circle)

The NLR in those objects are significantly affected by shocks



The [FeII]/[PII] flux ratios

- Photoionization is dominant in NLRs of many objects

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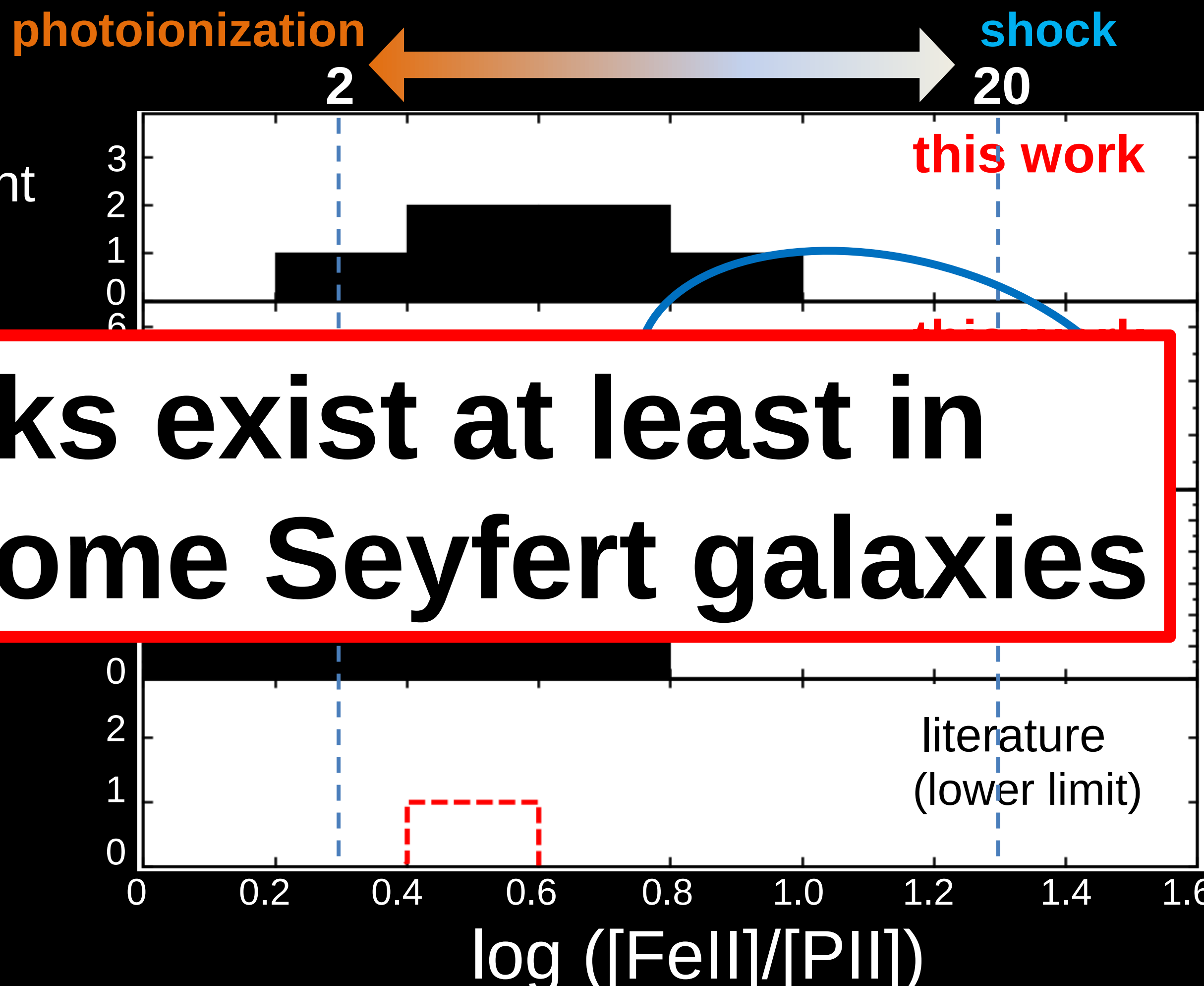
Fast shocks exist at least in NLRs of some Seyfert galaxies

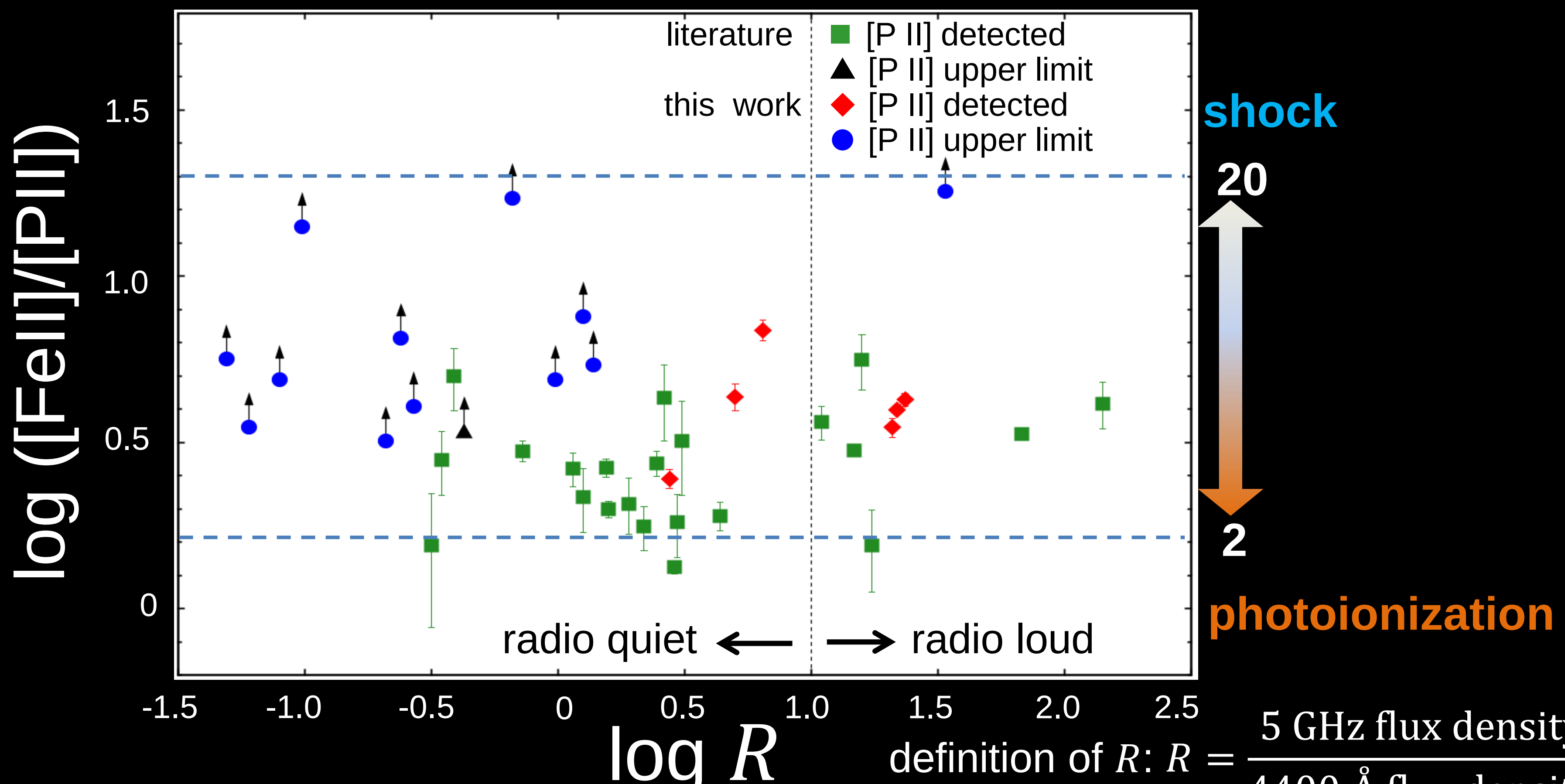
The NLR in those objects are significantly affected by shocks



The origin of fast shocks: radio jet?

radio loudness (R): an indicator of the jet power

- The [FeII]/[PII] shows no clear correlation with the radio loudness
- The high [FeII]/[PII] objects show various radio loudness



definition of R: $R = \frac{\text{5 GHz flux density}}{\text{4400 Å flux density}}$

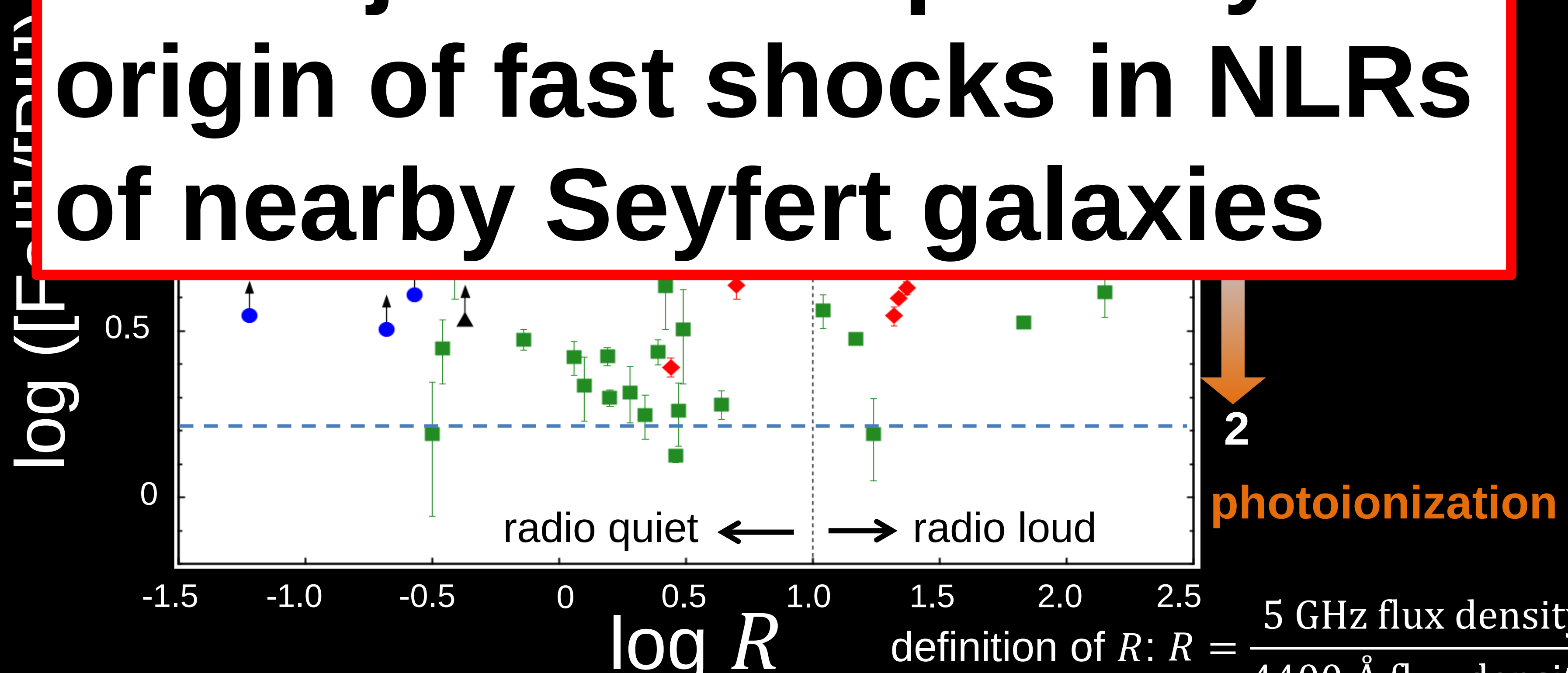
Discussion

The origin of fast shocks: radio jet?

radio loudness (R): an indicator of the jet power

- The [FeII]/[PII] shows no clear correlation with the radio loudness
- The high [FeII]/[PII] objects show various radio loudness

Radio jet is not a primary origin of fast shocks in NLRs of nearby Seyfert galaxies



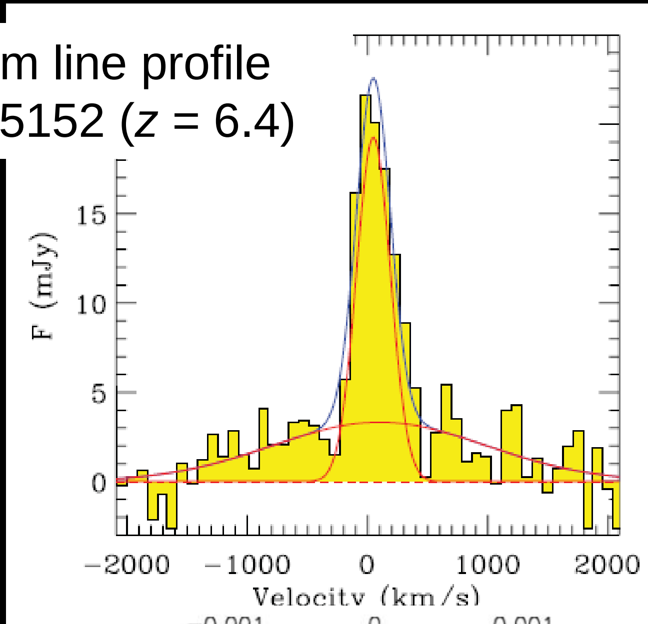
definition of R: $R = \frac{\text{5 GHz flux density}}{\text{4400 Å flux density}}$

The other origin of fast shocks

AGN-driven outflows

- The high velocity (> 1000 km/s) outflowing gas is observed by broad and/or blueshifted emission (absorption) lines
- The extension is kpc-scale (bottom figure)
- With a wide opening angle

Maiolino+12



[CII]158 μm line profile of J1148+5152 (z = 6.4)

Observed examples

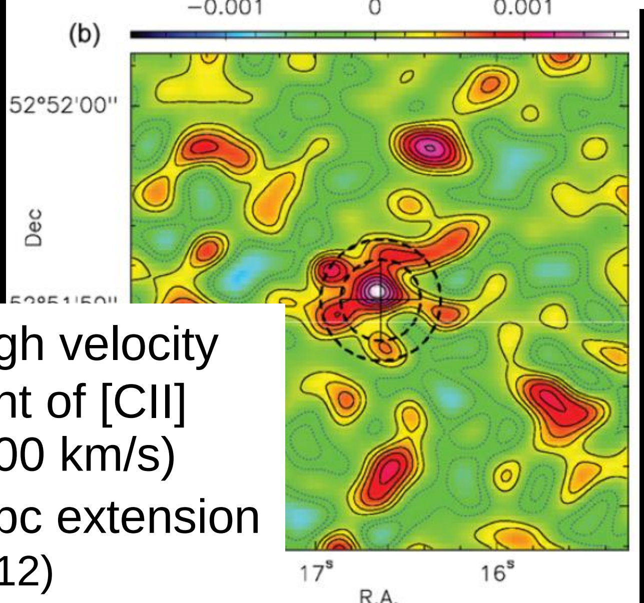
○ J1148+5152 (z = 6.4)

- ~ 1300 km/s velocity component
- mass outflow rate > 3500 $M_{\odot}\ \mathrm{yr}^{-1}$

○ Mrk 231 (z=0.042)

- ~ 1000 km/s velocity component

(e.g., Rupke+11, Feruglio+15)

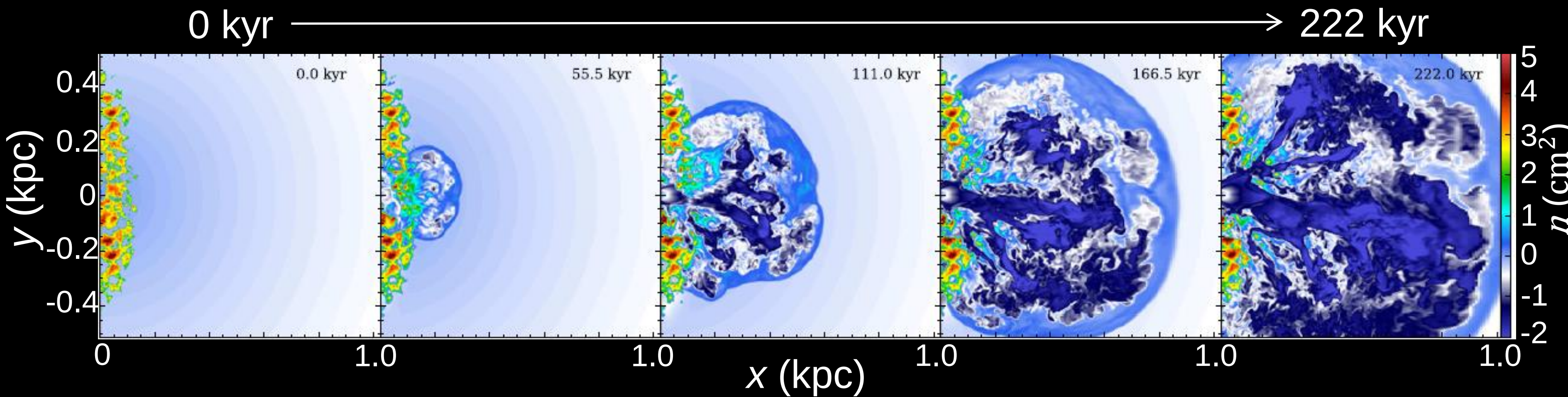


Map of high velocity component of [CII] (300 – 1300 km/s)
➔ ~ 16 kpc extension
(Maiolino+12)

AGN-driven outflows from theoretical study

Ultra Fast Outflow (UFO): Observed as absorption lines in X-ray by high velocity outflowing gas (~ 10000 km/s)

➔ UFOs can affect the ISM even at ~1 kpc scales



(Wagner+13)

<u>A possible origin of fast shocks in NLRs</u>

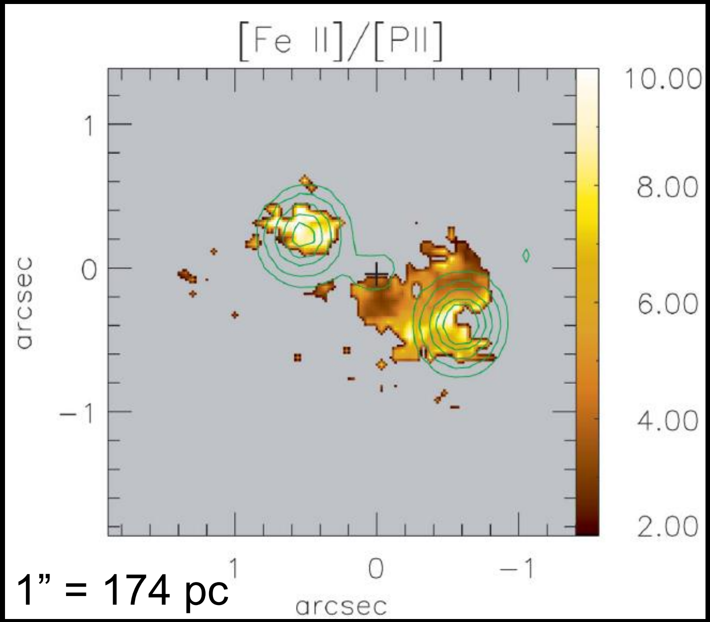
Future works

[FeII]/[PII] ratio maps obtained from IFU observations

The comparison of the [FeII]/[PII] maps with radio images will tell us the possible origin of fast shocks in NLRs

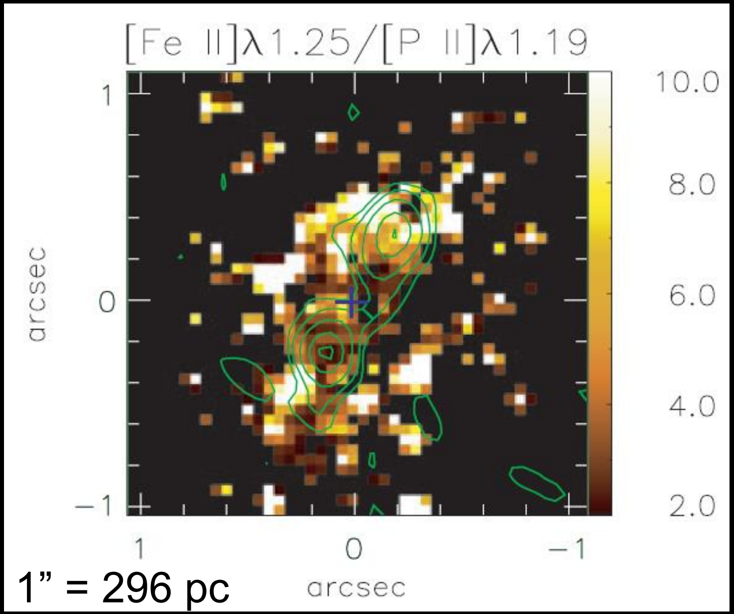
- In NGC 5929 shows high [FeII]/[PII] in radio knots
  - ➔ radio jet is the primary origin of fast shocks
- In Mrk 1157 shows no correlations [FeII]/[PII] maps with radio images
  - ➔ AGN-driven outflow is the primary origin of fast shocks

NGC 5929 (Gemini/NIFS+AO; Riffel+15)



green contours: 6.0 cm radio image

Mrk 1157 (Gemini/NIFS+AO; Riffel & Storchi-Bergmann+11)



green contours: 3.6 cm radio image

Summary

- The **Near-infrared [FeII]1.257 *μ*m/[PII]1.188 *μ*m flux ratio** can be used as an indicator of fast shocks
- More than half of Seyfert galaxies in our samples show pure photoionization in NLRs.
- Some objects show contribution by fast shock in NLRs.
- [FeII]/[PII] flux ratio shows no correlation with the radio loudness, thus radio jet is not the primary origin of fast shocks in NLRs of Seyfert galaxies.
- The AGN-driven outflow is a possible candidate of the origin of fast shocks in Seyfert galaxies.