THE LOCATION AND NATURE OF THE FE II EMITTING REGION IN ACTIVE GALACTIC NUCLEI

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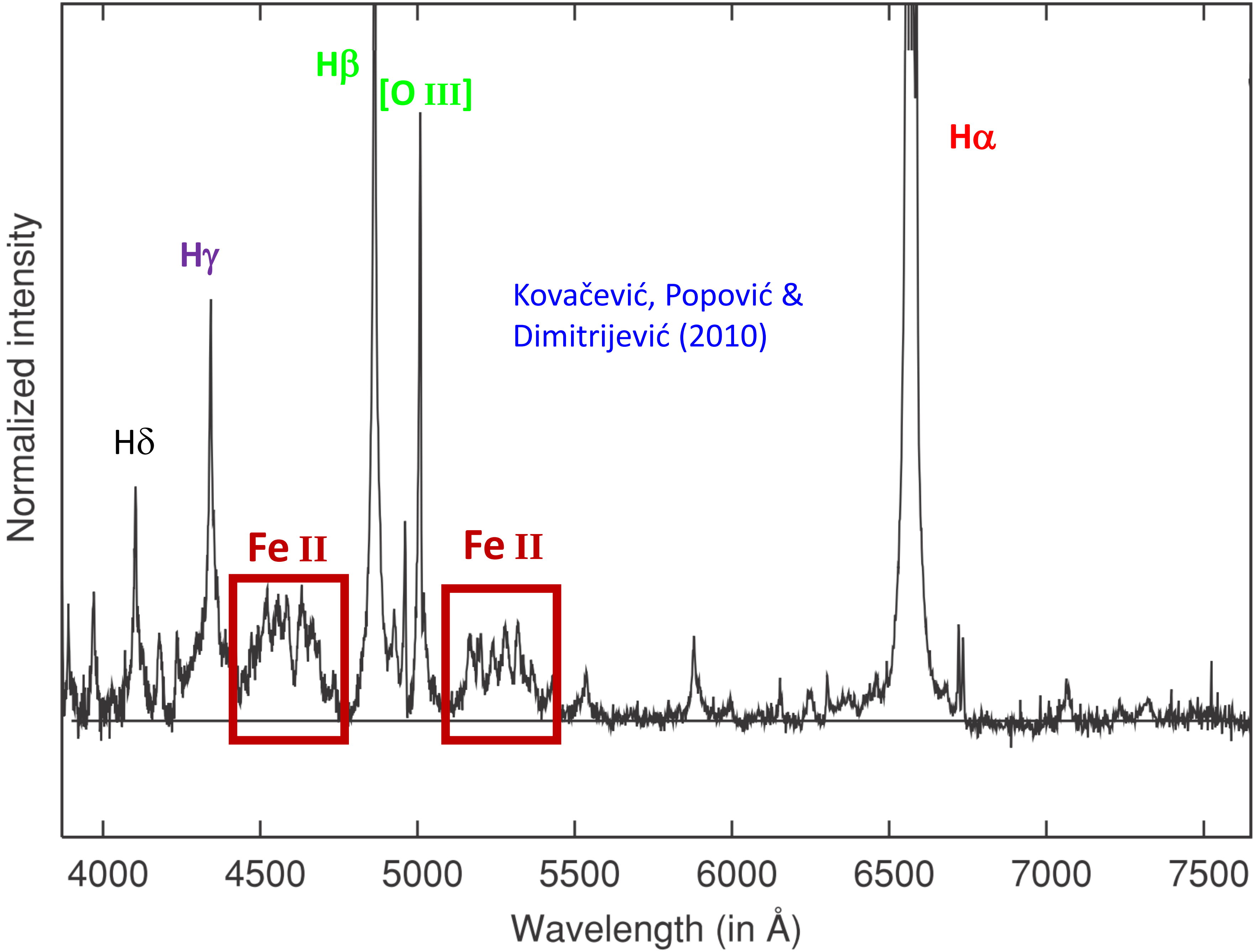
Introduction



Kovačević, Popović & Dimitrijević (2010)

OUTLINE

- Some history [“Those who do not learn history are doomed to repeat it.” ~ George Santayana (1905).]
- Why Fe II is interesting: five remarkable Fe II correlations (“eigenvector 1”)
- The big Fe II questions
- Is Fe II produced by photoionization?
- The GKN model of the BLR
- What the GKN model predicts for Fe II
- Line widths
- Problems with Fe II reverberation mapping results (including a little-known major bias)
- Why Fe II strength varies from object to object
- What drives Fe II emission and eigenvector 1
- (Why Fe II strength appears to vary with radio type)

History

Fe II emission first identified (η Carinae) by Moore & Sanford (1914, *Lick Observatory Bulletin*, **252**)

(also in nova Herculis 1934 and RR Telescopii)

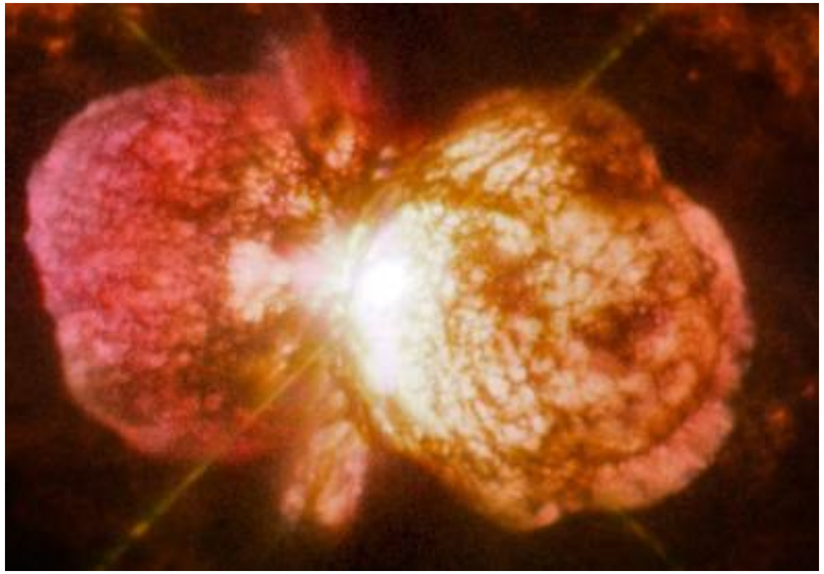
Tells us: strong Fe II does *not* need black holes!

[First spectrum of a Seyfert 1 – Campbell & Moore (1918)]

Point missed in early 20th century: strong Fe II is *not* found in H II regions and planetary nebulae.

Modern insight: what do η Carinae and symbiotic novae like RR Telescopii have in common?

Answer: **strong soft X-rays**



Background: AGN emission line regions as understood in 1967:

Lines being modelled as classical H II regions. Density of narrow-line region (NLR) ~ 10^3 cm^{-3} (Dibai & Pronik 1965; Osterbrock & Parker 1965)

Dibai & Pronik (1967):

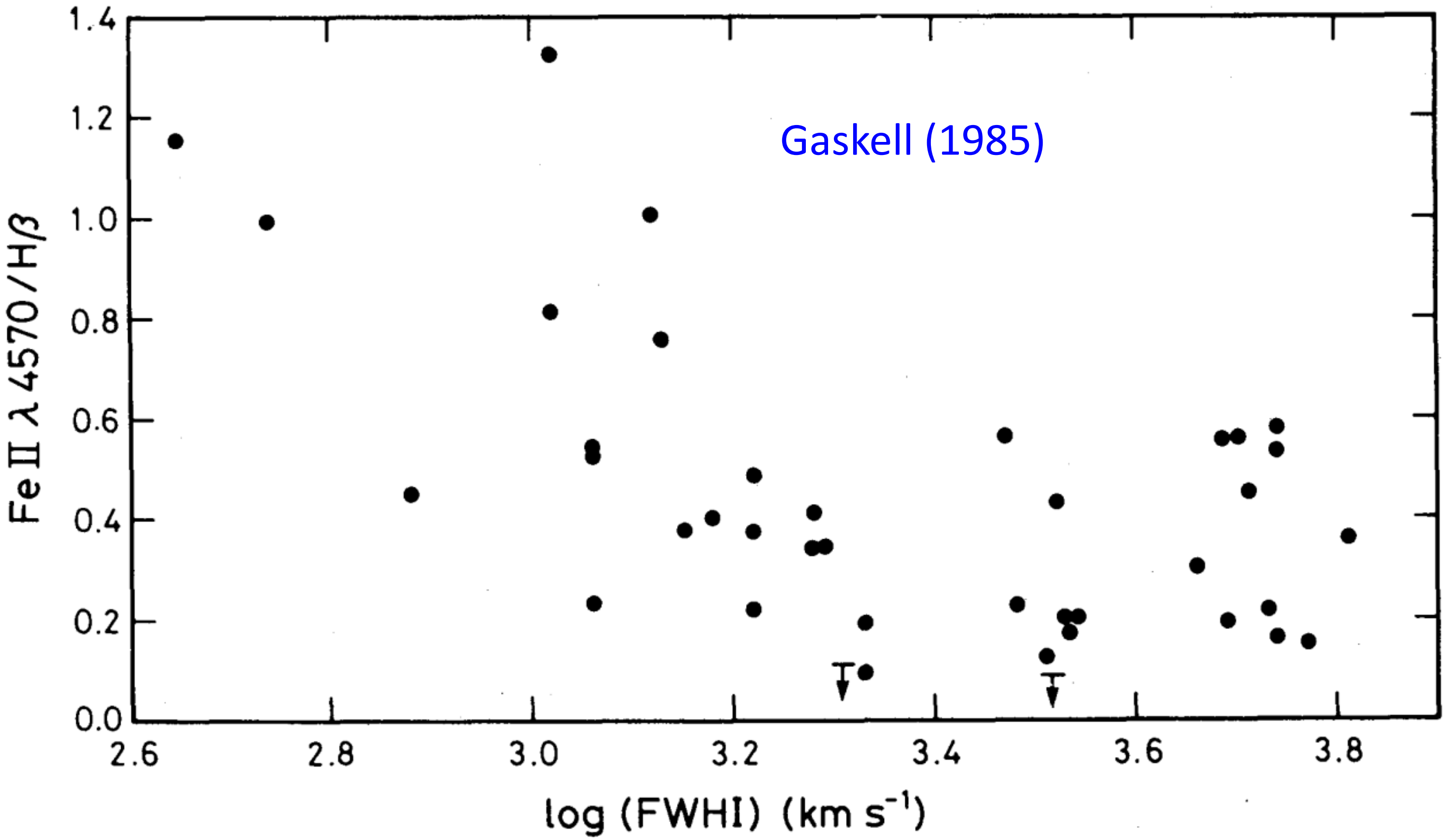
- Recognition of the broad-line region (BLR) / NLR dichotomy.
- Density of BLR: $n_e > 10^6$ cm^{-3}.
- Sizes: NLR: 100s of pc; BLR < 1 pc.

Wampler & Oke (1967):

First identification of Fe II emission in an AGN, 3C 273 (by comparison with Nova Herculis 1934.)

- **Density: Absence of [Fe II] ⇒ $n_e > 10^7$ cm^{-3}.** (*i.e.*, BLR densities)
- **Abundance: Relative strengths of Mg II and Fe II consistent with solar [Mg/Fe].**

Why Fe II emission is interesting: five remarkable correlations



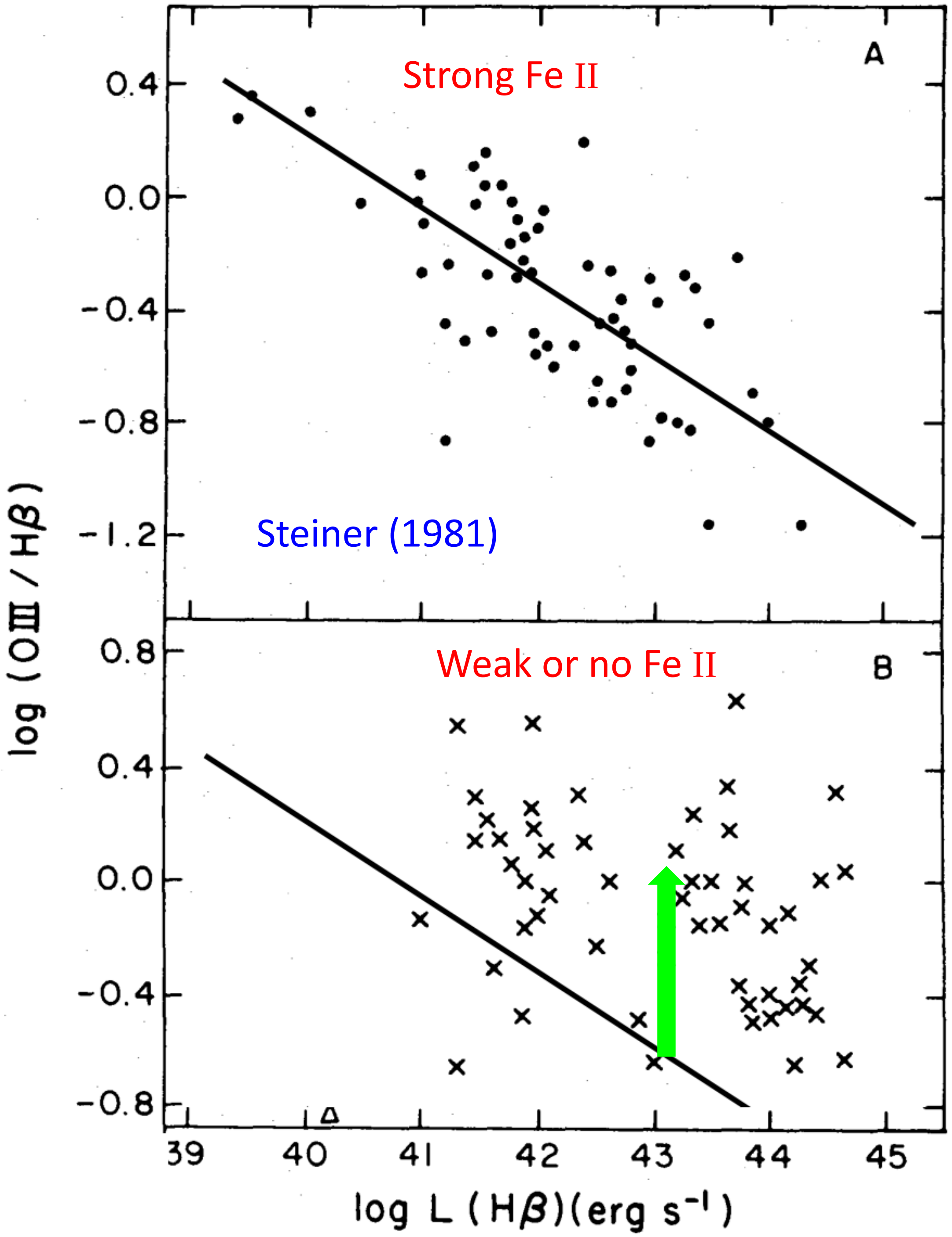
1. Fe II shows more than an order of magnitude variation in relative strength.
2. Fe II/Hβ correlates with line width (weaker in broad-line objects).

[This is the "EV 1 fundamental plane" discussed by Paula Marziani and others at the conference.]

3. Fe II seems to be correlated with the radio type. Weaker in extended radio source selected samples. (Osterbrock 1977; Setti & Woltjer 1977; Miley & Miller 1979)

4. Fe II is correlated with the narrow-line properties. Weak Fe II ⇒ strong [O III] (Steiner 1981).

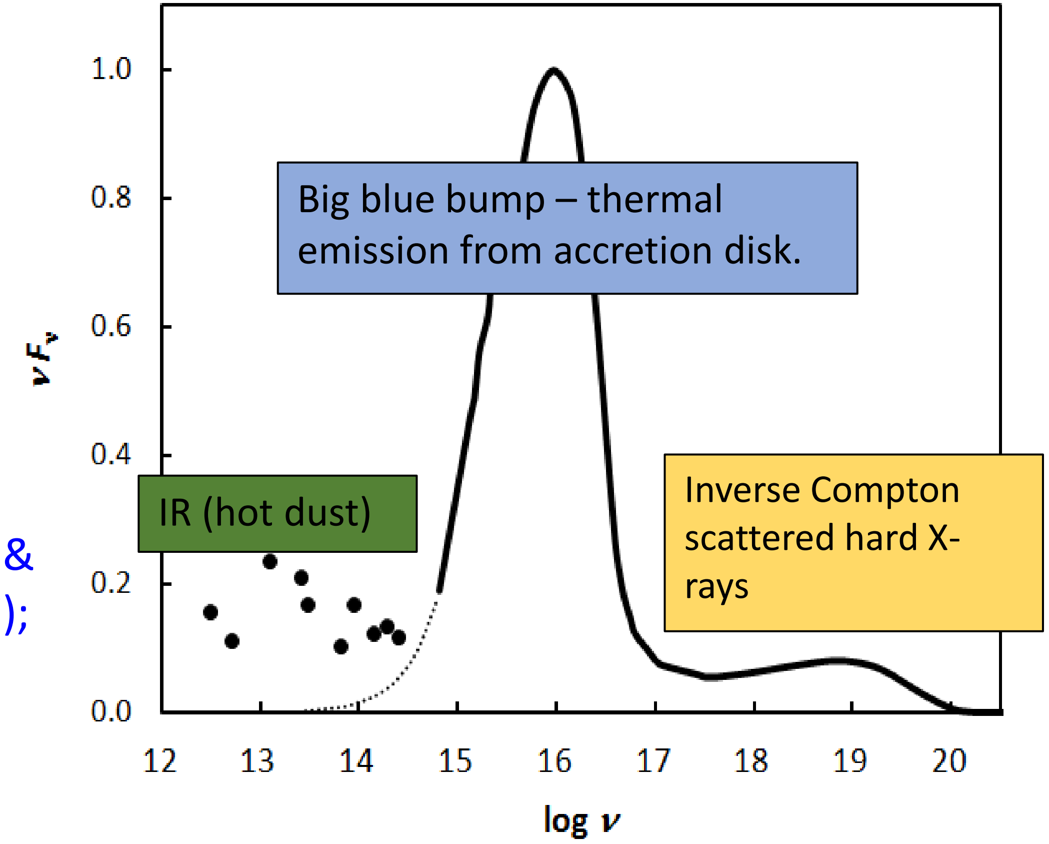
[Correlations (2) and (4) make up "eigenvector 1" = "EV1") of Boroson & Green (1992)]



Steiner (1981)

5. Fe II is correlated with the "soft X-ray excess" (Boller, Brandt & Fink 1996)

The "soft X-ray excess" is so called because it lies above the extrapolation of hard X-rays to lower energies. It is the high-energy tail of the "big blue bump" :

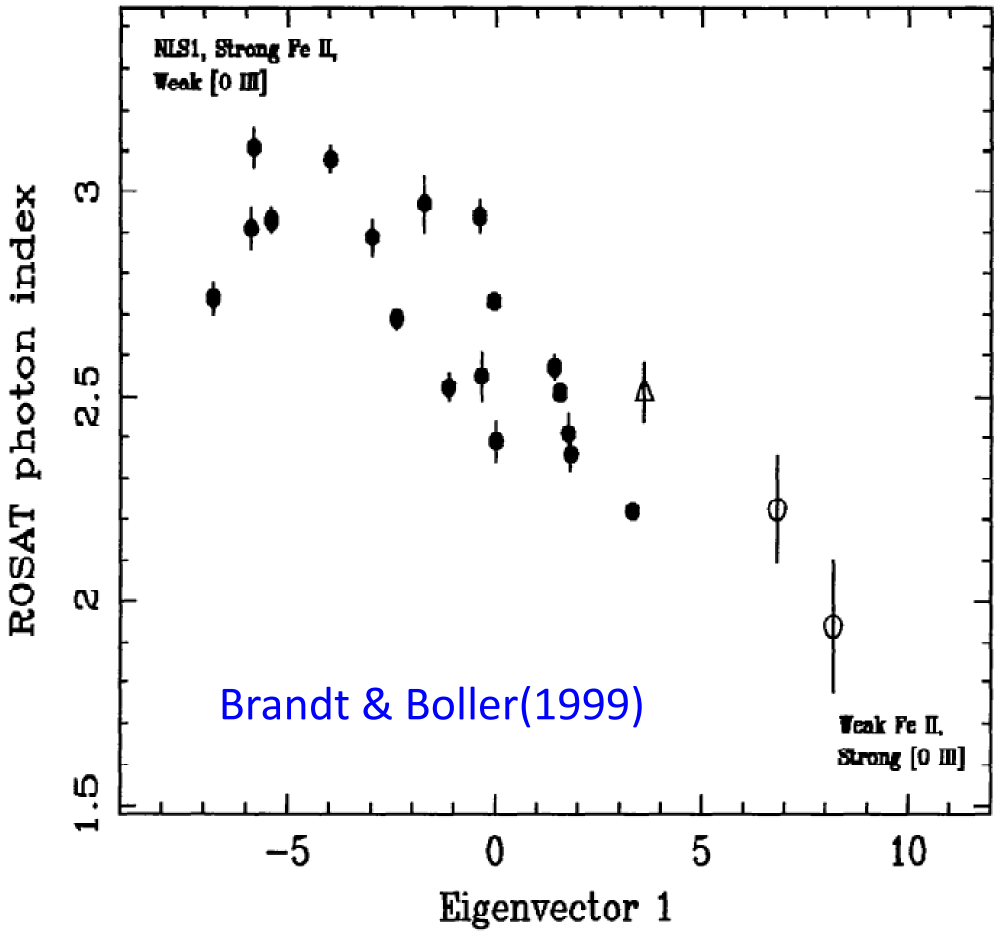


Big blue bump – thermal emission from accretion disk.

IR (hot dust)

Inverse Compton scattered hard X-rays

Gaskell, Klimek & Nazarova (2007); Gaskell (2008)



Brandt & Boller(1999)

The big Fe II questions:

A. ¿What causes those five correlations?

B. ¿How is Fe II emission produced? (Photoionization or something else?)

"The excitation mechanism of Fe II lines is one of the outstanding problems of AGN research." (Boller, Brandt & Finck 1996)

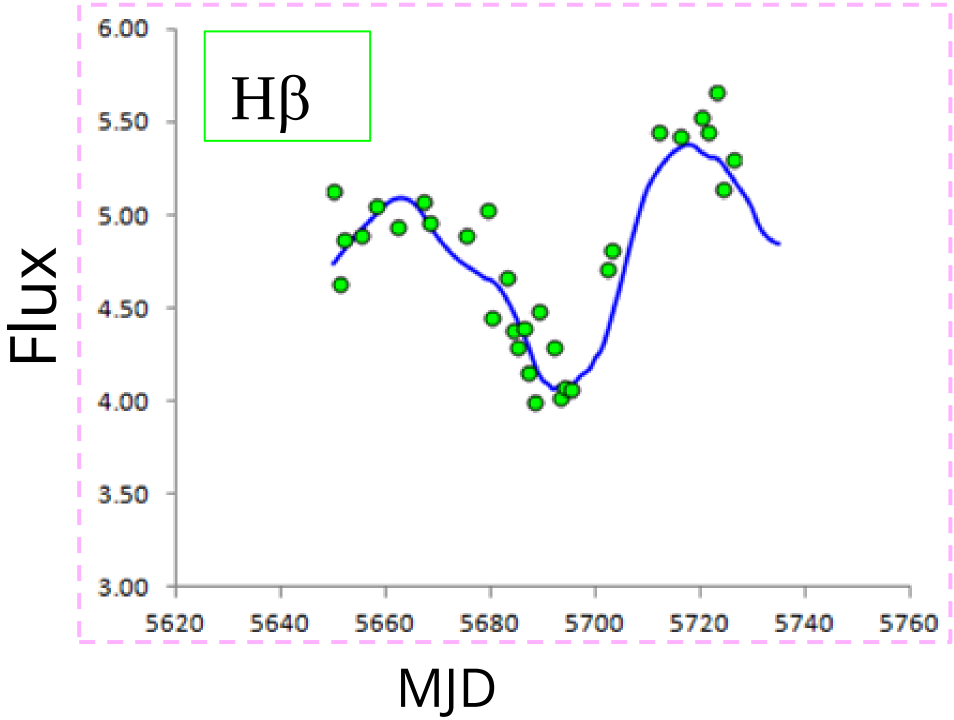
Joly (1991) "**[The correlation with radio emission ⇒] . . . Fe II is closely associated with the jets** responsible for the compact radio source. In this model the heating of the gas is due to internal shocks."

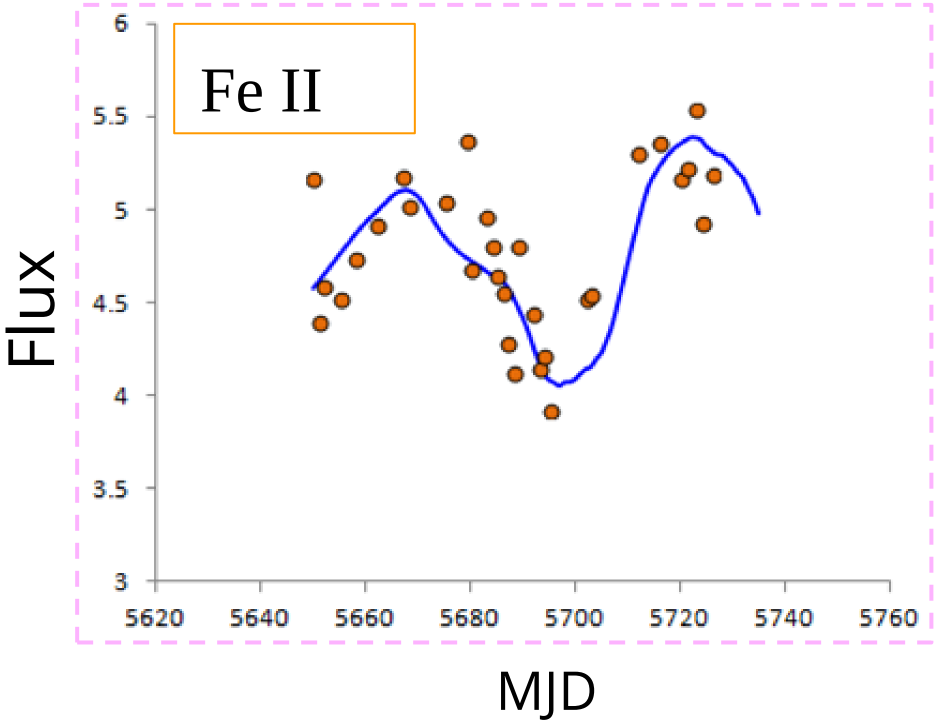
Collin & Joly (2000) review: "… **the strengths of the Fe II lines cannot be explained in the framework of photoionization models."** Strong outflows and shocks?

Joly, Véron-Cetty & Véron (2007) "The region emitting the Fe II lines [is **probably] shielded from the central source of radiation** and mechanically heated."

Is the Fe II emission caused by photoionization?

- ➢ Look at reverberation-mapped AGNs with Fe II measurements
- ➢ Convolve continuum at λ5100 with a response function (blue curves below)
- ➢ Compare with Hβ and Fe II light curves



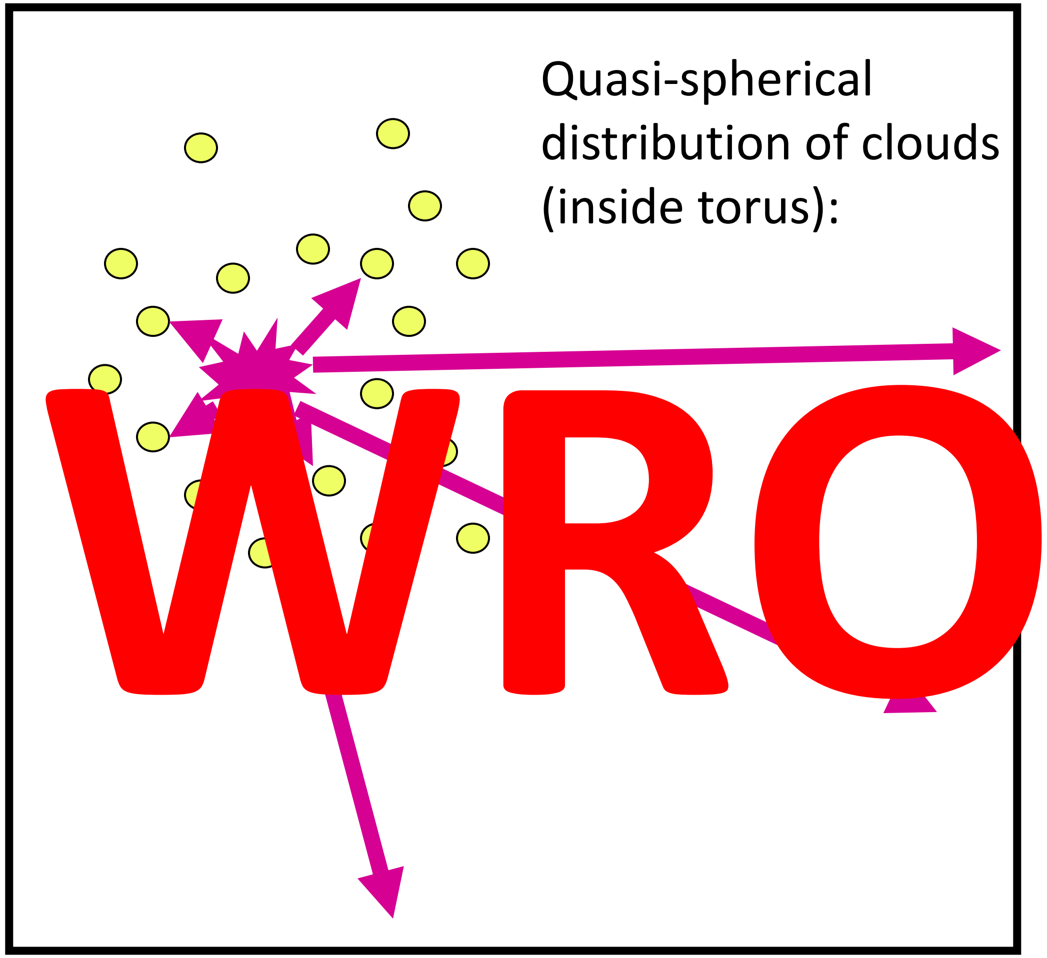


RESULT: Hβ and Fe II vary similarly in all objects ⟶ Fe II is **photoionized**

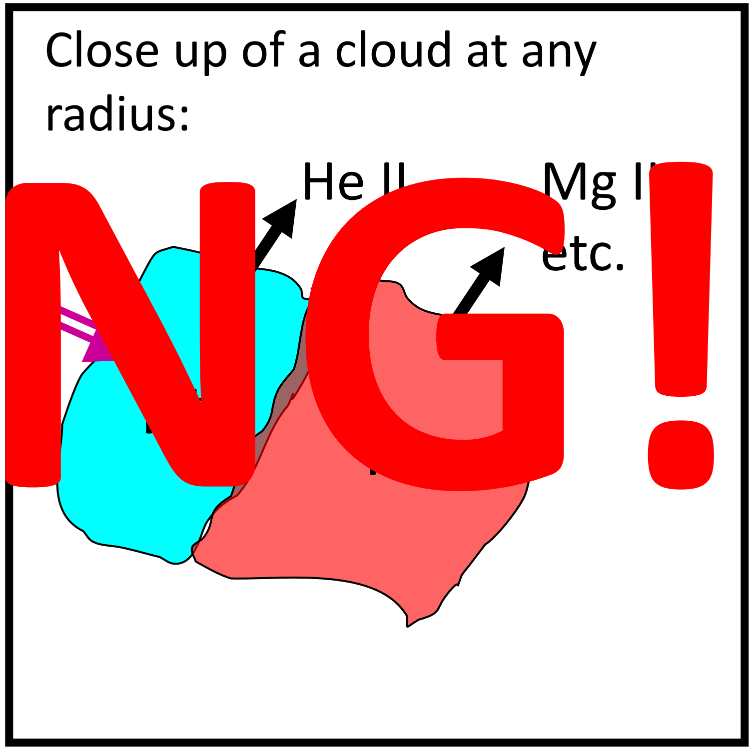
WHAT IS A STANDARD BLR LIKE?

The old “typical cloud”BLR model:

[Figures from Gaskell 2009 BLR review; 7th SCSLSA]



Quasi-spherical distribution of clouds (inside torus):



Close up of a cloud at any radius:

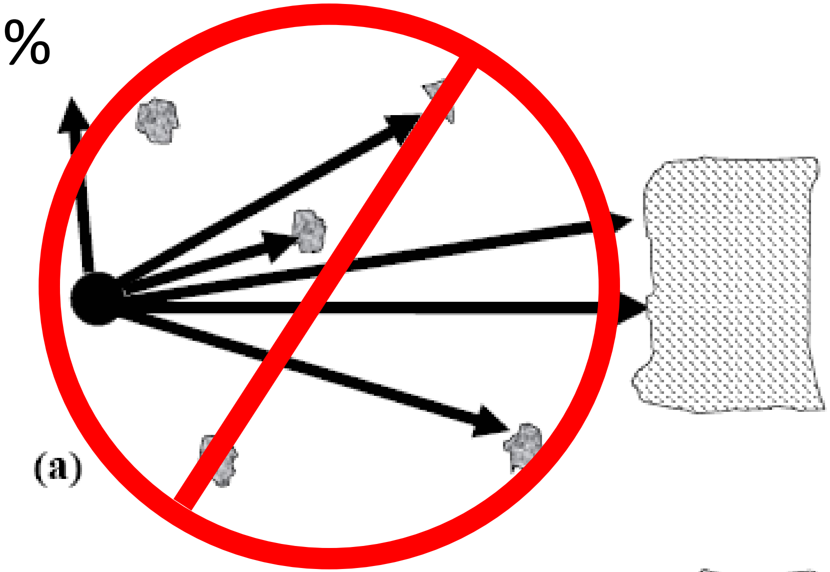
WRONG!

Gaskell, Klimek & Nazarova (2007; “**GKN**”) model. We never see BLR absorption, but a ~20% covering factor is needed to explain line strengths.

∴ (a) BLR is flattened (in the plane of the accretion disc) and

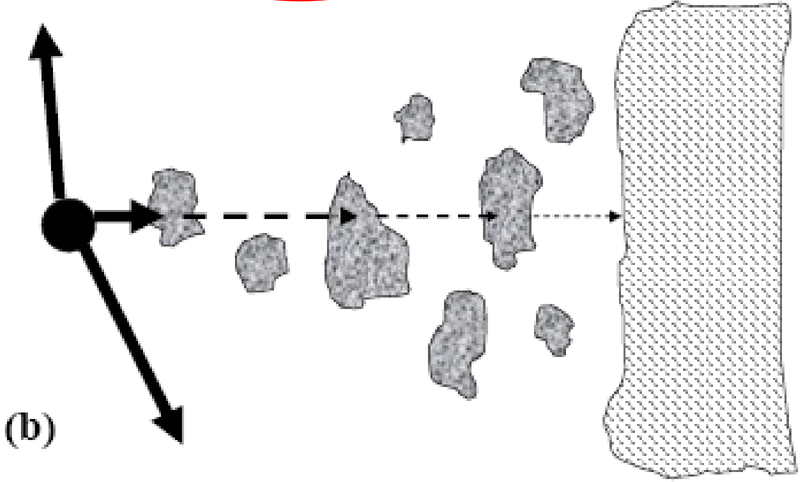
(b) *shielding near equatorial plane* is 100%

not...



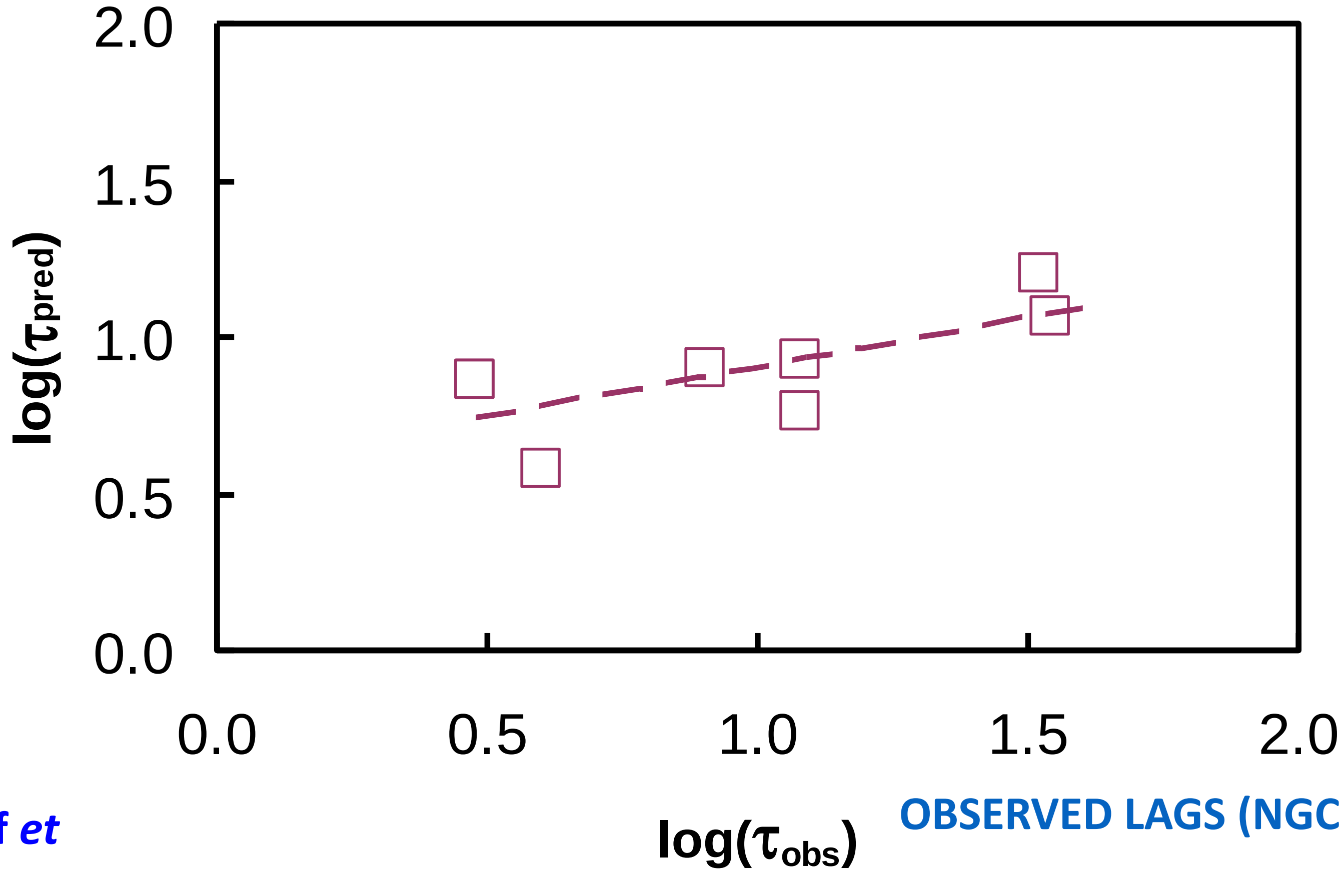
BLR clouds self shield each other!

but...



¿Radial ionization dependence?

Old “typical clouds” model does <u>not</u> explain the range of radii with ionization



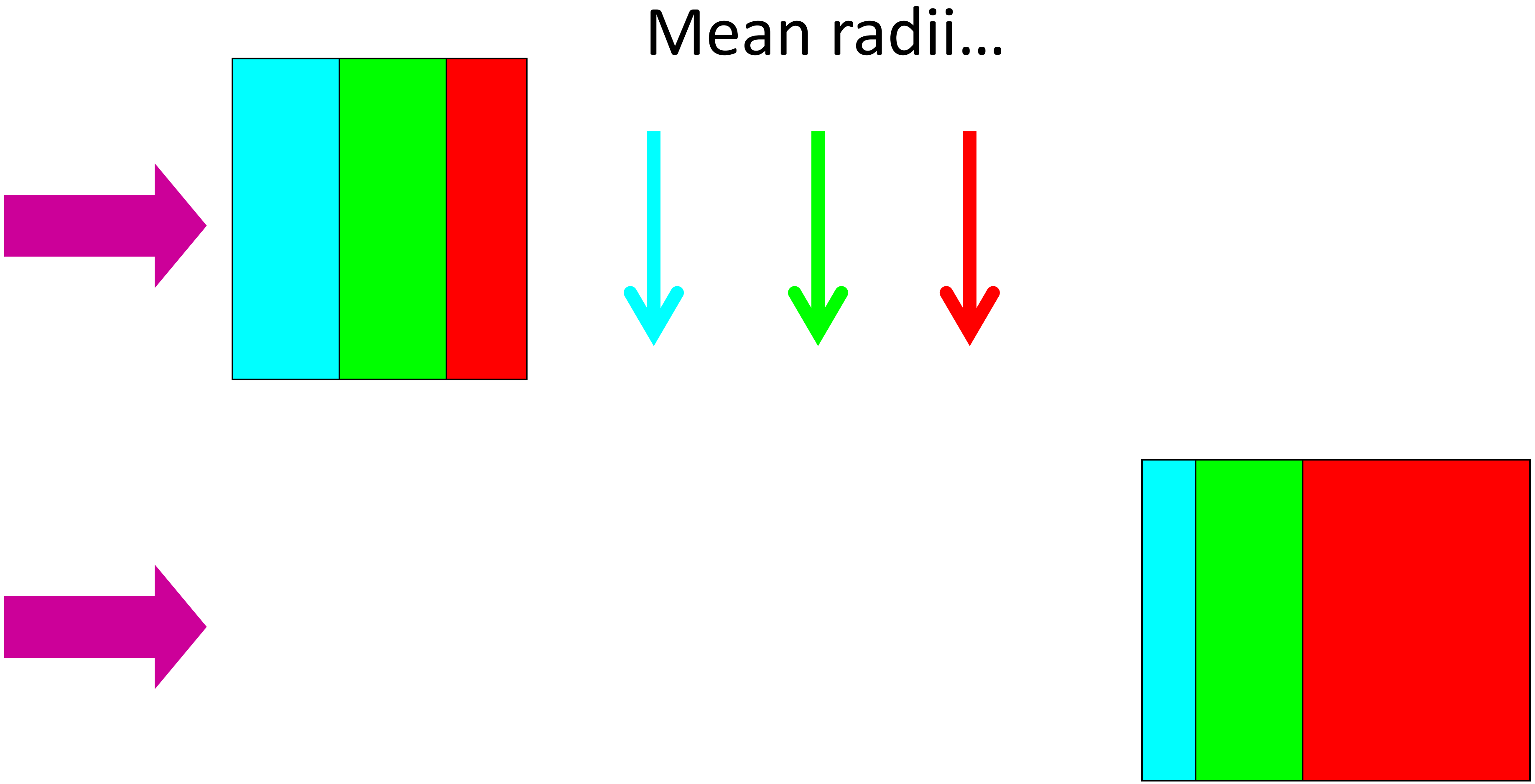
PREDICTED LAGS

Korista & Goad (2000); Bottorff *et al*. (2002)

OBSERVED LAGS (NGC 5548)

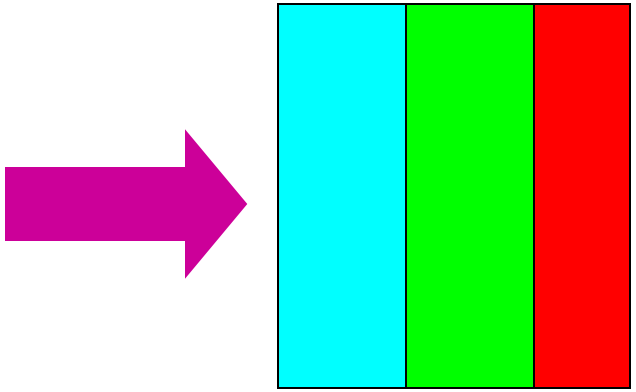
Clavel *et al*. (1991); Peterson *et al*. (1991); Krolik *et al*. (1991); Bottorff *et al*. (2002)

WHY THE OLD “TYPICAL CLOUD(S)” MODEL DOES NOT PREDICT A STRONG RADIAL DEPENDENCE OF IONIZATION

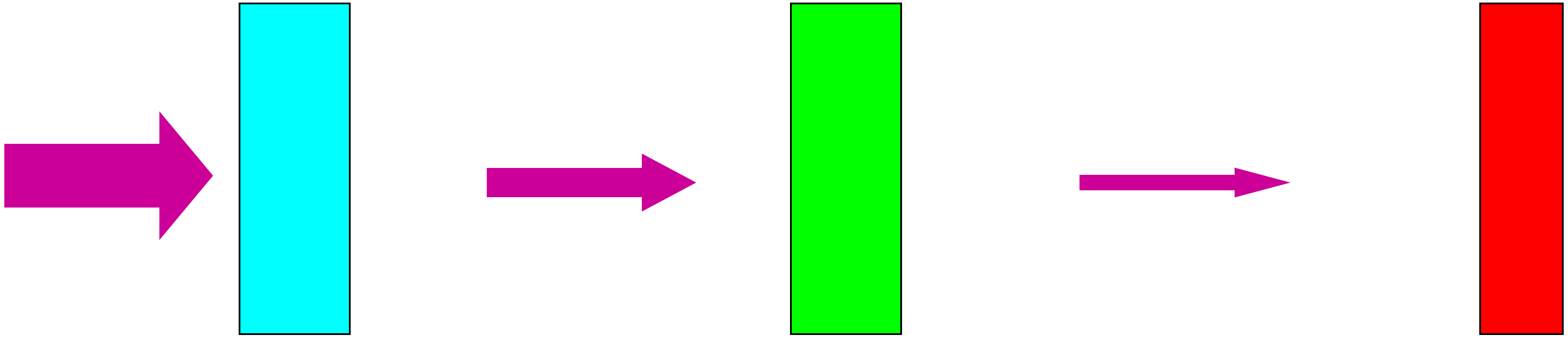


Mean radii…

BASIS OF GKN MODEL (easy!)

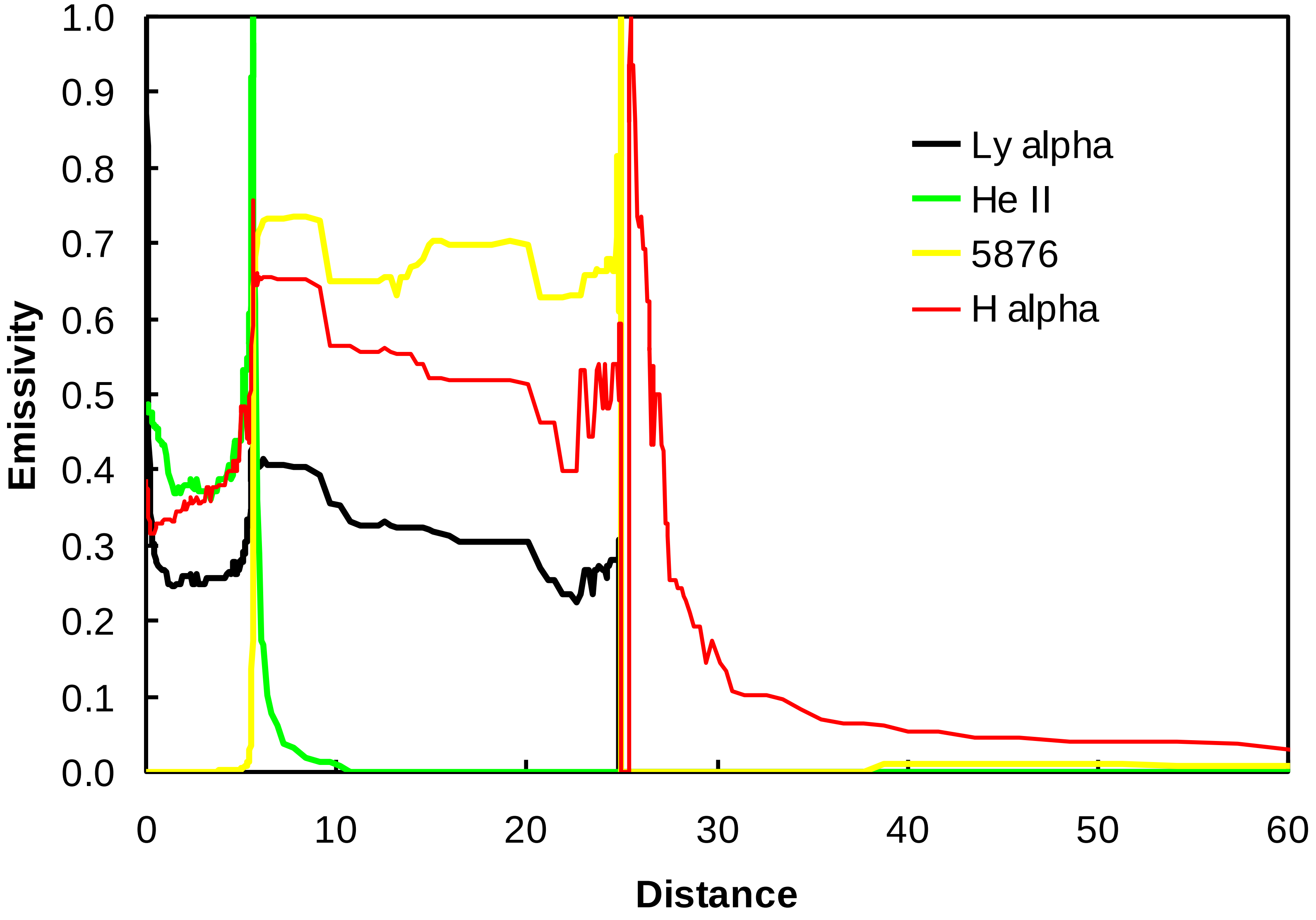


BASIS OF GKN MODEL (easy!)



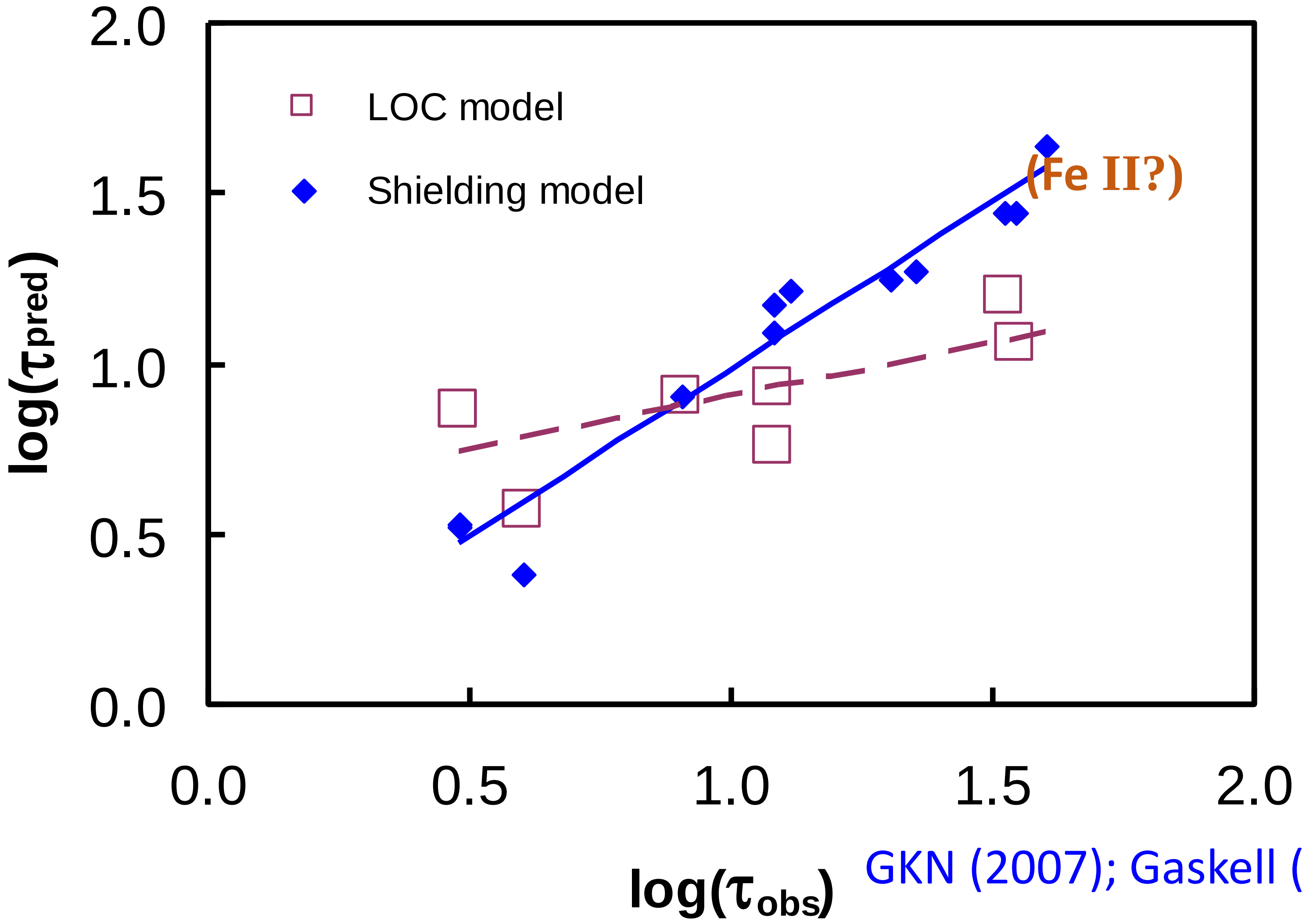
cf. “filling-factor” model of
MacAlpine (1974)

Radial ionization dependence is similar to a single cloud (in *Cloudy*)



GKN model correctly predicts ionization dependence of lags for NGC 5548:

(only *one* free parameter)



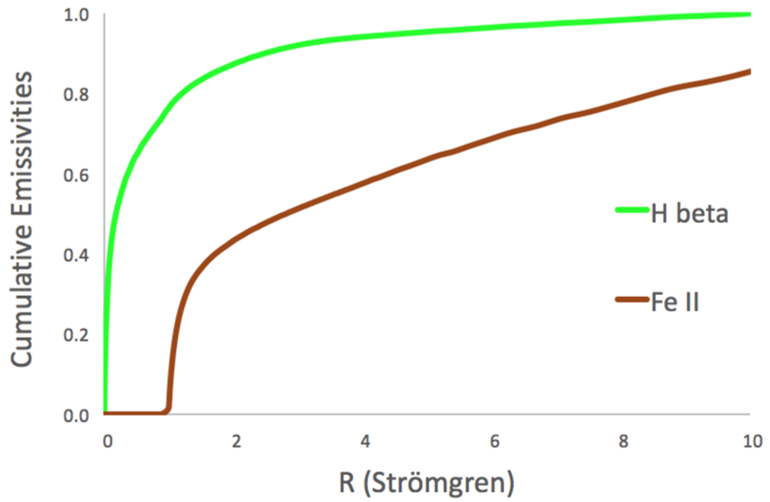
GKN (2007); Gaskell (2009)

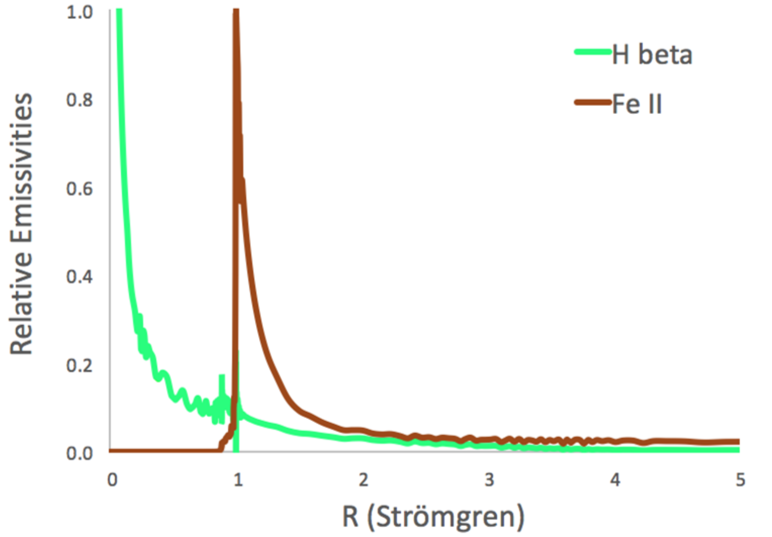
GKN model prediction for Fe II radius

Use Gary Ferland's photoionization code *Cloudy* to predict emission-line intensities as a function of distance.

- Fe II emission increases as distance increases.
- Fe II is produced further out than Hβ.

Prediction: The relative size of the Fe II emitting region is about **twice** that of Hβ





What is the Fe II emitting region radius?

Line widths

For BLR expect:

$$FWHM \propto R^{-1/2}$$

Confirmed by reverberation mapping (Krolik *et al*. 1991)

Expect Fe II radius ~ twice radius of Hβ

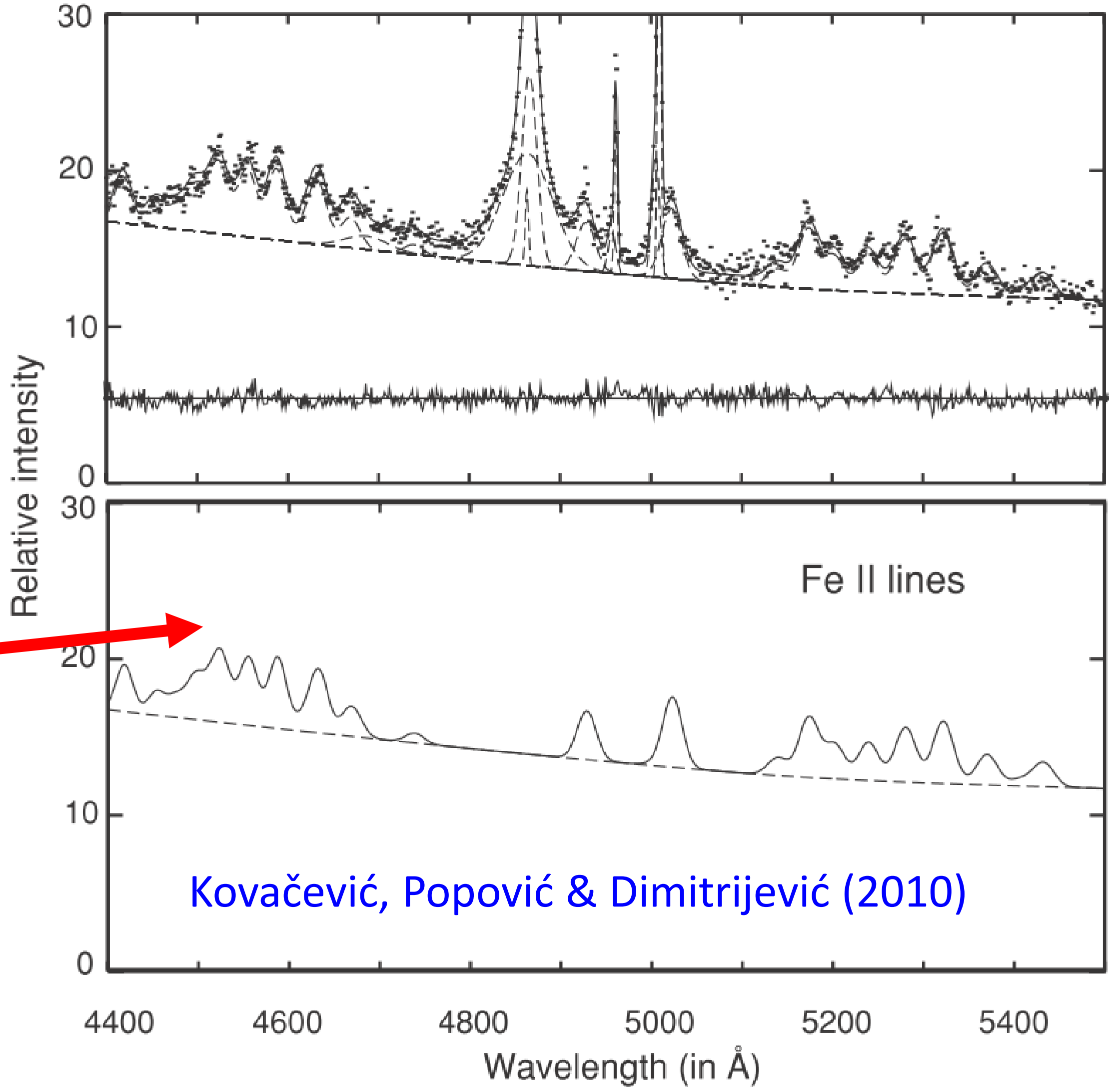
$\Rightarrow FWHM(\text{Fe II}) \sim FWHM(\text{H}\beta)/\sqrt{2}$.

This is indeed the case.

From measurements of Hu *et al*. (2008) of a large SDSS sample

$$\text{FWHM}_{\text{Fe II}} = 0.71\ \text{FWHM}_{\text{H}\beta}.$$

$$\Rightarrow R(\text{Fe II}) \sim 2\,R(\text{H}\beta)$$



Kovačević, Popović & Dimitrijević (2010)

Reverberation mapping

Our best way of measuring radii.

Gaskell (1994) list of reverberation mapping projects that ought to be carried out:

> *"We need to make an optical study of a strong optical Fe II emitter to try to see where the Fe* II *emission is coming from."*

[Had to wait 21 years until the *SEAMBH* collaboration! Hu *et al*. (2015)]

Why Fe II reverberation is difficult:

- Fe II hard to measure (broad blends of many weak lines)
- The optical-UV continua of narrow-line Seyfert 1s (NLS1s) are much less variable that broad-line Seyfert 1s (Klimek, Gaskell & Hedrick 2004).
- Reverberation-mapping campaigns focus on "guaranteed performers" = broad line Seyfert 1s with weak Fe II, esp. NGC 5548 **["Reverberated to death!" – Jack Sulentic at a previous SCSLSA conference]**
- Fe II doesn't vary very much (supported idea of not being photoionized)

PREVIOUS RESULTS:

Hu *et al*. (2015) – *R*(Fe II) “indistinguishable”from *R*(Hβ).
Median *R*(Fe II) /*R*(Hβ) = 1.0
Disagrees with prediction of GKN model (and FWHM results).
Which are wrong??
We checked all the Hu *et al*. analysis. No problems.

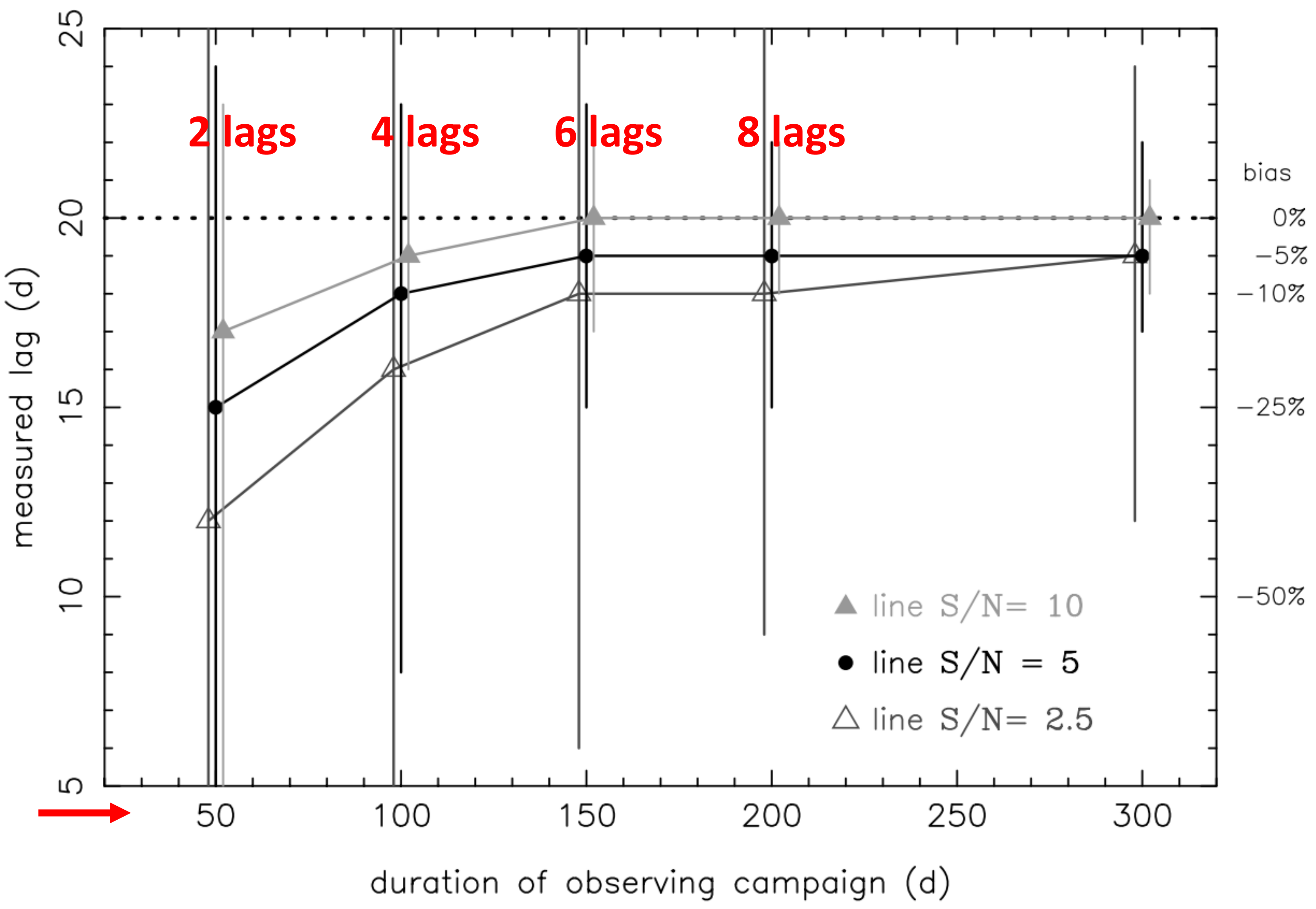
However . . .

Under appreciated fact about reverberation mapping campaigns: *short campaigns with low signal/noise are biased to too small sizes*. (Welsh 1999)

Bias in reverberation mapping

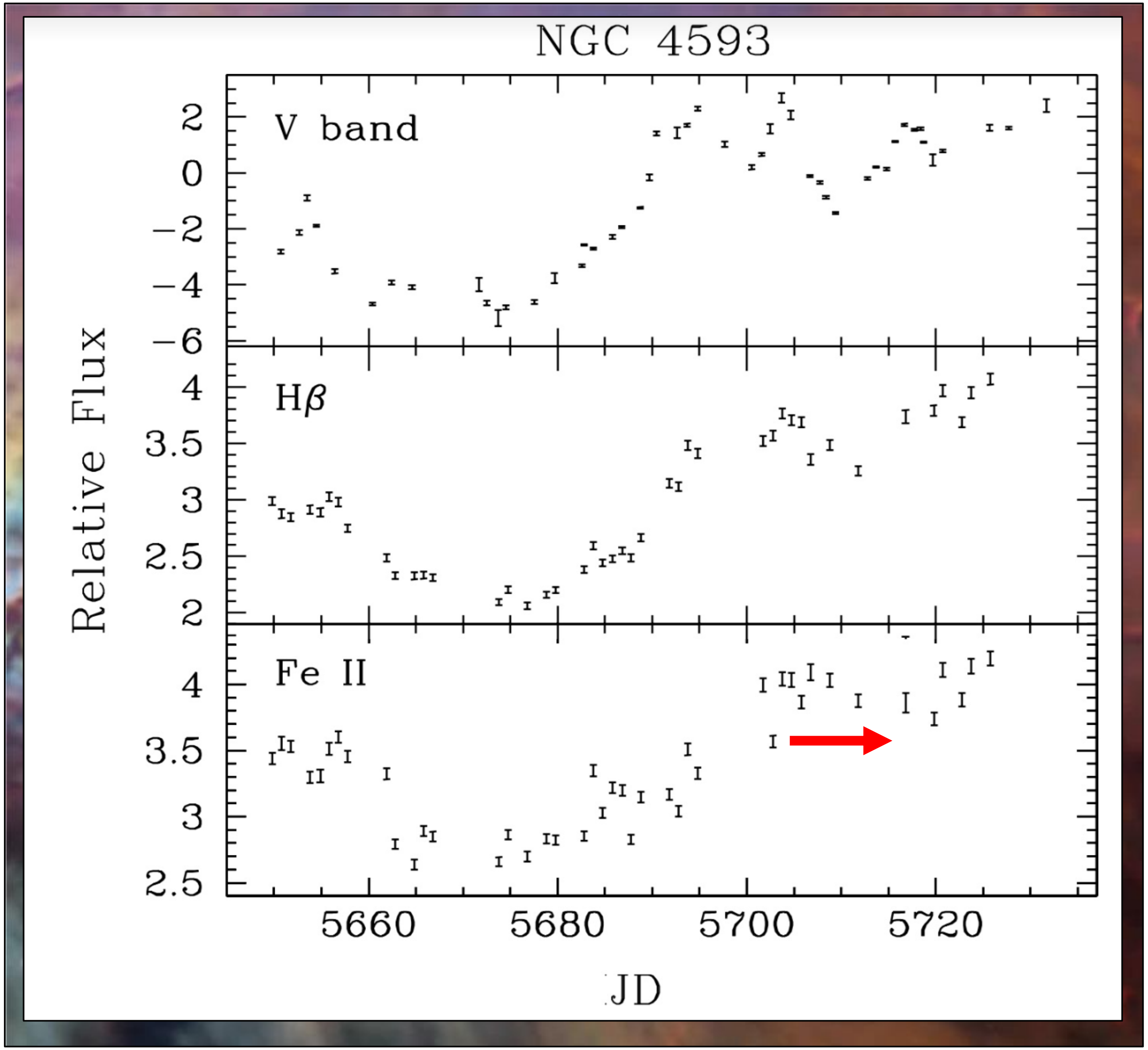
Welsh (1999)

- Observing campaigns that are short compared with the lag (red arrow) produce systematically too small lags.
- This is especially true when the signal/noise ratio is poor.
- Predicts poorer Fe II reverberation sizes too small by up to factor of ~ two.



Example: NGC 4593 (Barth *et al*. 2013)

Campaign duration fairly short compared with Fe II lag and duration of events.



Check: look at R(Fe II) /R(Hβ) *as a function of signal/noise ratio*

Ratio only reported to better than 25% accuracy for three objects:

Mrk 335 (Hu et al. 2015) ⇒ 3.1
3C 273 (Zhang et al.2019) ⇒ 2.2
Mrk 1511 (Barth et al. 2013) ⇒ 1.5

Conclude:

The best reverberation mapping results support the GKN model prediction of R(Fe II) /R(Hβ) $\sim$ 2.

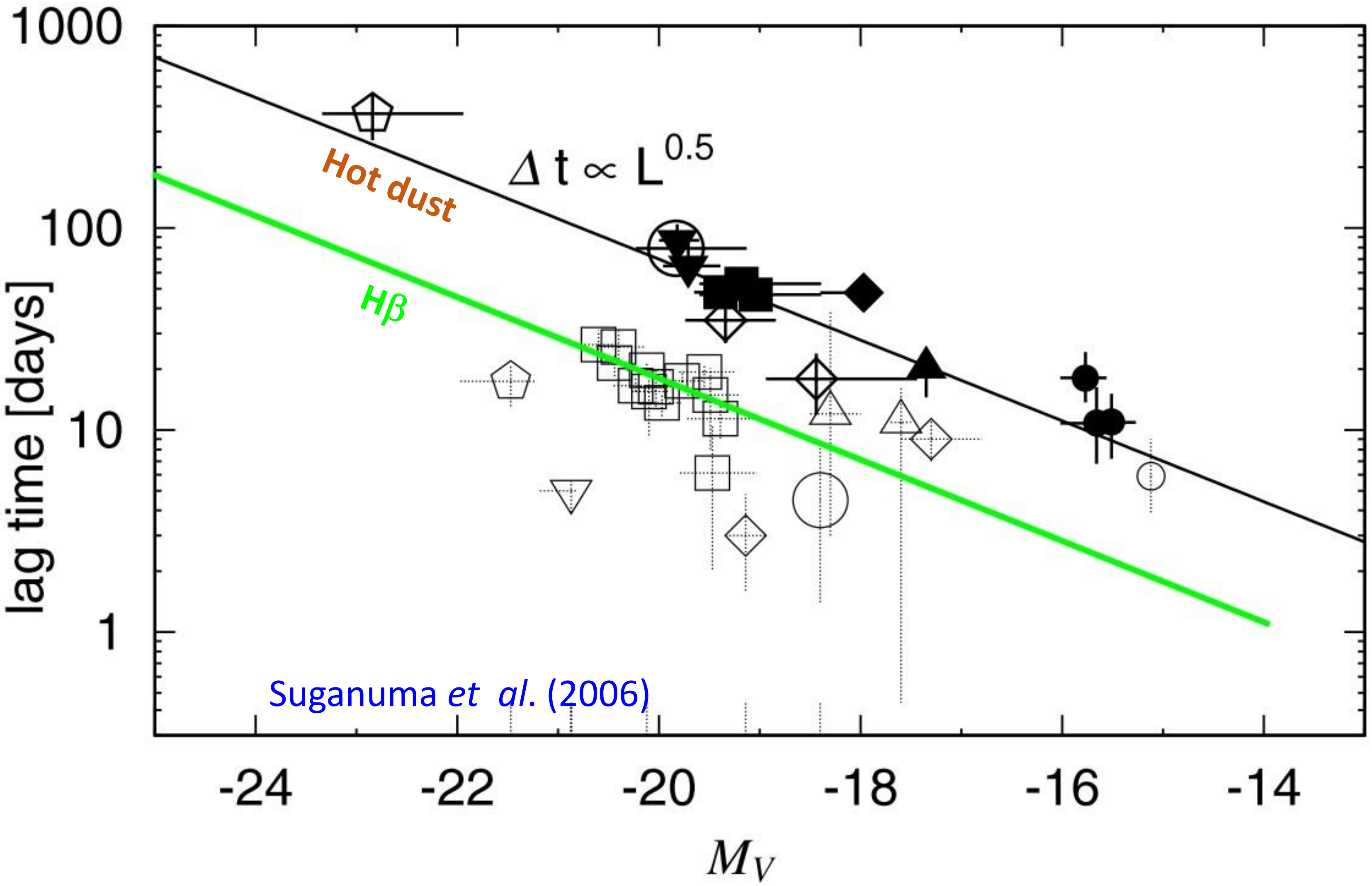
[*Advice: always check results against signal/noise ratio!*]

The Fe II emission region in context

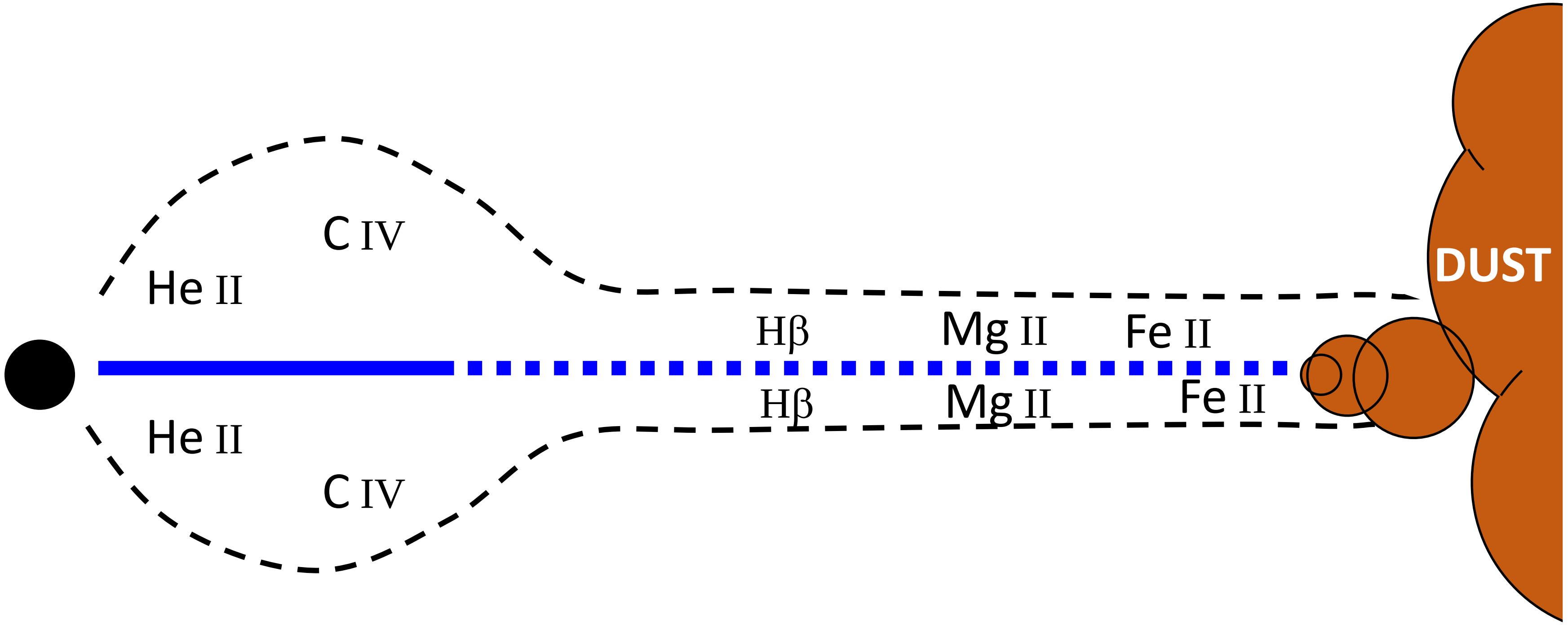
Suganuma *et al.* (2006):
R(dust) ≈ 3.5 *R*(Hβ)

We find here:
R(Fe II) ≈ 2 *R*(Hβ)

∴ Fe II comes from the outer edge of the BLR next to the hot dust.



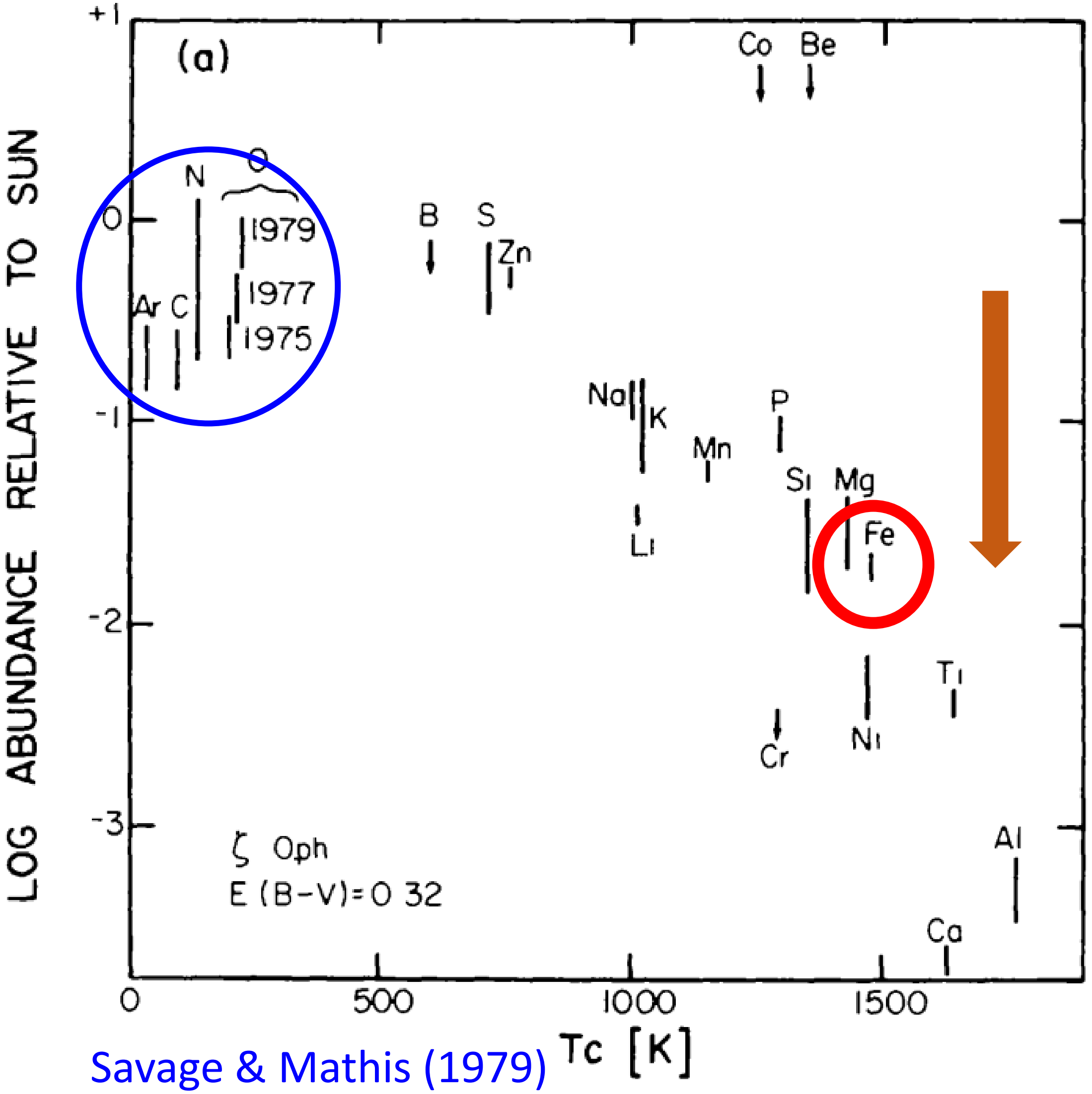
Sketch of GKN BLR model



(Edge-on view. Blue line is the
plane of the accretion disc.)

The cause of very weak Fe II

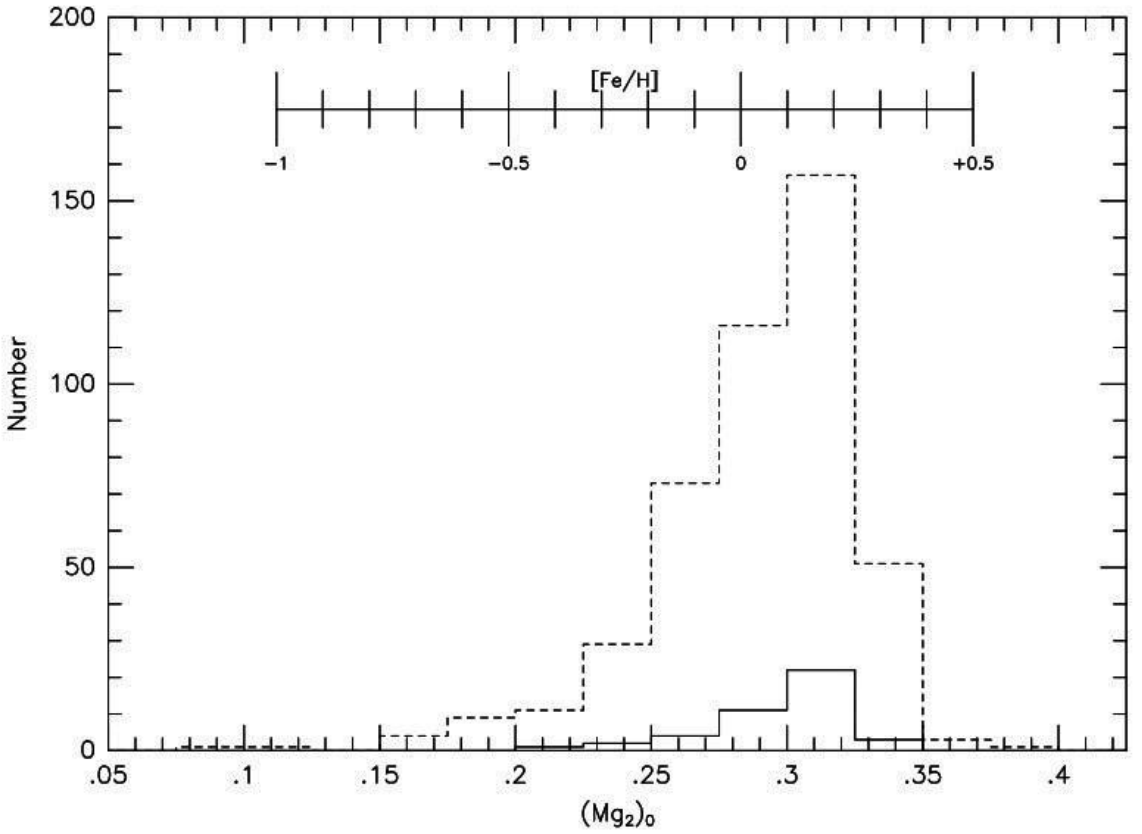
- Gaskell, Shields & Wampler (1981) Lack of depletions of Mg, Si, Al and Fe in the BLR ⇒ **no dust in the inner BLR**
- Conversely, **when there *is* dust in the BLR, Fe II <u>will</u> be weak.**
- [Elements with high condensation temperatures are depleted in the interstellar medium (Morton 1972, 1974, Field 1974).
- Fe depletions in planetary nebulae span *two orders of magnitude* (Delgado Inglada *et al*. 2009).]



Savage & Mathis (1979)

Metallicity?

- Metallicity variations will also affect Fe II strength.
- Mass-metallicity relationship for galaxies as a whole ⇒ up to [Fe/H] ~ +0.3 *for the most massive galaxies* (*i.e.*, twice solar)
- Metallicity-radius relationship ⇒ another +0.2 dex ⇒ up to [Fe/H] ~ +0.5 in the nuclei (*i.e.*, three times solar)
- Perhaps another +0.2 dex going from stellar abundances to gas-phase abundances ⇒ up to [Fe/H] ~ +0.7 (*i.e.*, fives times solar)
- ∴metallicity variations can give factors of several in Fe II strength, but **no evidence to support extremely high metallicities (20 to 80x solar).**



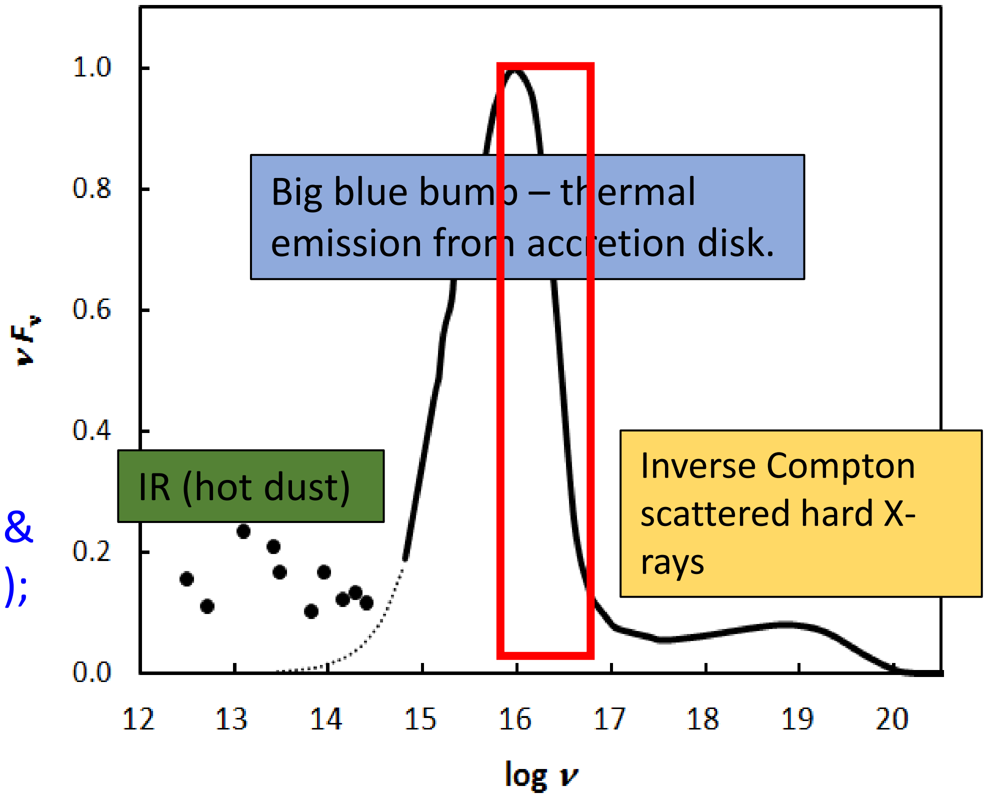
Frequency distribution of Mg_2 at a galaxy center for 572 ellipticals (*dashed line*) taken from Davies et al. (1987) and 46 ellipticals from our sample (*solid line*).

Kobyashi & Arimoto (1999)

What drives Eigenvector 1?

Remember: Boller, Brandt & Fink (1996): eigenvector 1 *correlated with soft X-ray excess*.

AGNs are driven by the extreme-UV/soft X-rays (**red region**). Energetically dominant and the region leading spectral variability.

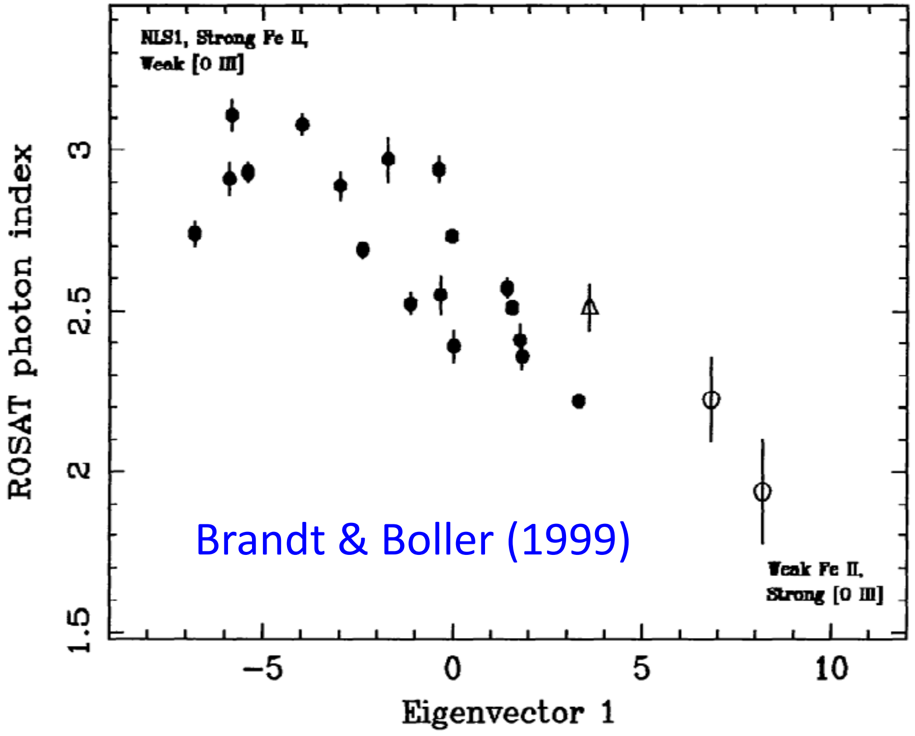


Big blue bump – thermal emission from accretion disk.

IR (hot dust)

Inverse Compton scattered hard X-rays

Gaskell, Klimek & Nazarova (2007); Gaskell (2008)



Brandt & Boller (1999)

⇒ The soft X-ray excess is the driver of eigenvector 1 (and hence of Fe II emission)

HOW DOES THE SOFT EXCESS DRIVE EV1?

Answer: **The Eddington ratio** (Wandel & Boller 1998) [see also Sulentic *et al*. (2000); Marziani *et al*. (2003), *etc*.]

- For a fixed ionization parameter, $R_{\mathrm{BLR}} \propto L^{1/2}$.
  $\therefore$ for a fixed mass, FWHM decreases with increasing L/L_{Edd}. (Wandel & Boller 1998)
- Lower mass and higher L/L_{Edd} gives a higher temperature cutoff (not fully understood) and hence a larger soft X-ray excess.
- Strong soft X-rays destroy dust (*cf*. η Carinae, RR Telescopii, *etc*.)
- Lack of dust produces strong Fe II. (Gaskell, Shields & Wampler 1981)

What about the correlation with the radio?

Answer: **"Downsizing"**. Higher mass BHs now have low L/L_{edd} because their hosts are "red and dead" (*e.g*., M87)
Actively accreting black holes in local universe have lower M and a higher L/L_{Edd}; $\Rightarrow$ stronger soft X-rays and hence strong Fe II. Downsizing predicts stronger Fe II at higher redshift, as found by Kovačević, Popović & Dimitrijević (2010).

CONCLUSIONS

- Fe II emission in AGNs *is* produced by photoionization
- The GKN model of the BLR predicts an effective emission radius ~ twice that of Hβ.
- Line widths ⇒Fe II predominantly comes from twice the radius of Hβ.
- The highest signal-to-noise ratio reverberation mapping is consistent with Fe II coming from twice the radius of Hβ.
- Fe II arises in the outermost part of the BLR between the Hβ radius and the dust radius.
- Strong object-to-object variation of Fe II /Hβ is due to depletion of Fe onto grains.
- The driver of Fe II emission (and EV1 in general) is the soft X-ray excess.
- Correlation with radio properties is a result of downsizing.