Active Galactic Nuclei: Progress and Problems

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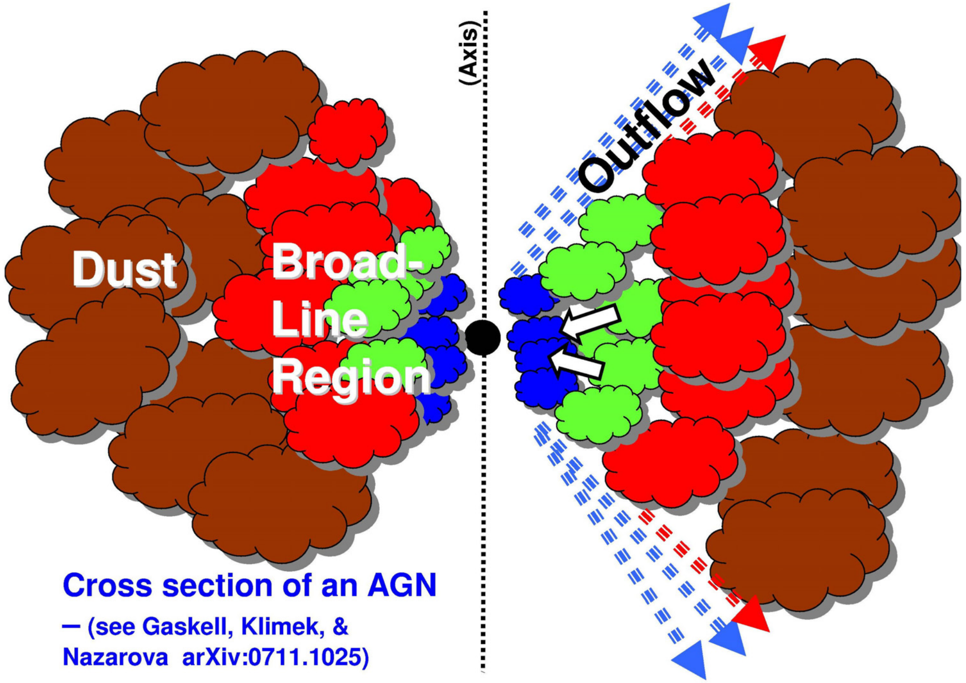
[45 min + 15 min]

Last Year: A Mystery Story!
(a “who-dun-it”)

Elements:

1. Some mysterious happening(s)
2. Lots of interesting “suspects”
3. Lots of pieces of evidence (“clues”)
4. As the story goes on, evidence points to different suspects
5. At the climax, the real culprit is revealed
6. All puzzles are explained

LAST YEAR: “WITH AGNs - WE ARE AT STAGE 5!”



LAST YEAR'S CONCLUSIONS:

Now plenty of good clues to what an AGN looks like, and how it works.

We needed to do two things to complete the story:

1. Convict the culprit!

   (*I.e.*, convince the judge and jury)

2. Wrap up the (many!) loose ends in the plot of the book/movie.

Now, follow the example of popular writers and movie producers:

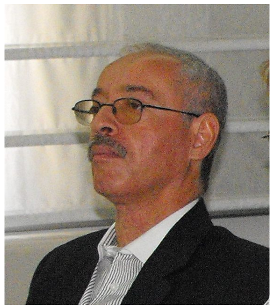
A sequel!

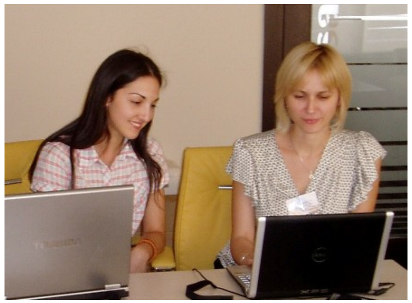
(The same cast of characters gathers in another exotic location in the Balkans to solve further BLR mysteries!)











The Serbian Astronomical Society and Belgrade Astronomical Observatory present…

WHAT SPECTRAL LINE SHAPES TELL US ABOUT HOW AGNS WORK. PART II

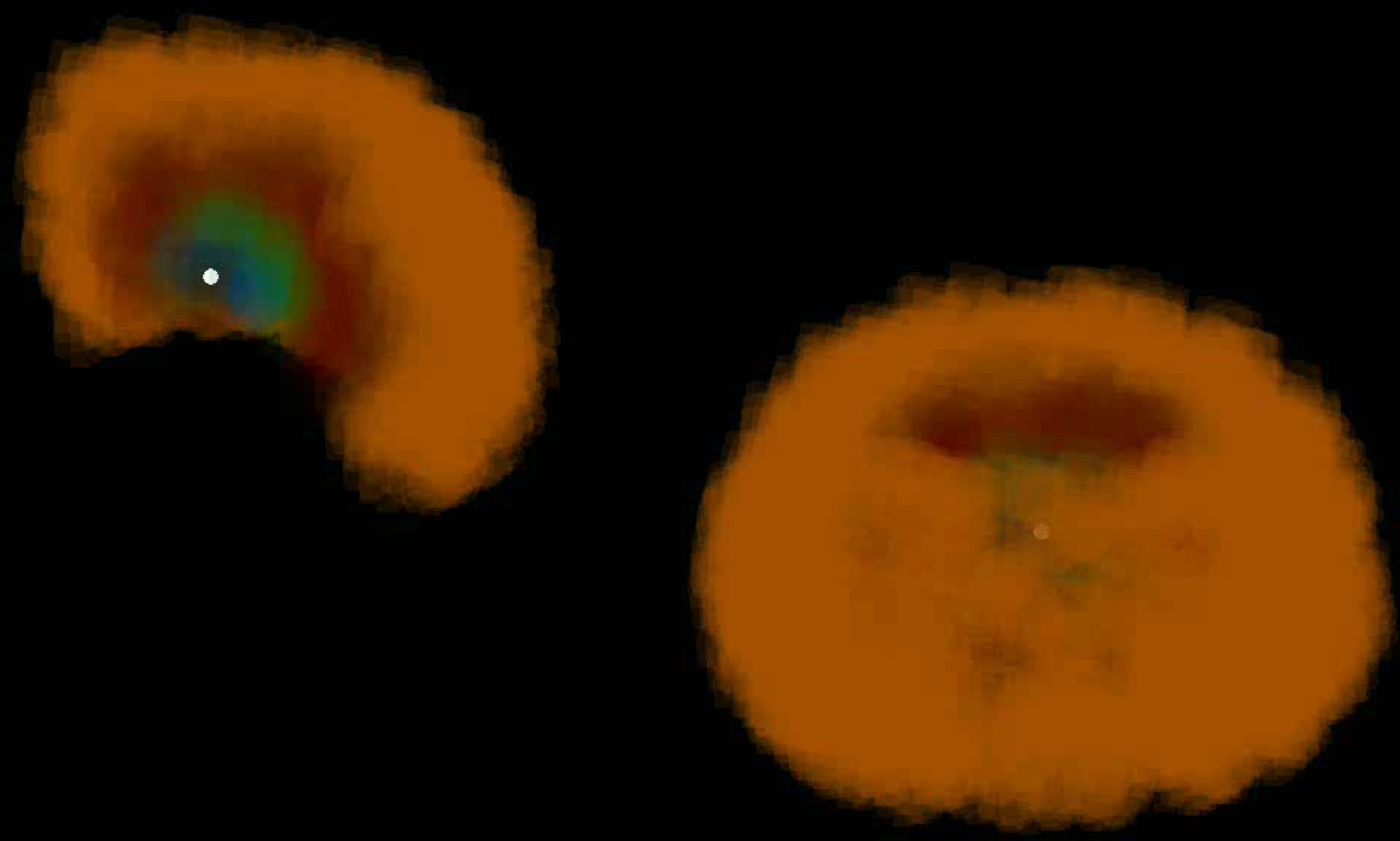
- THE BLR STRIKES BACK!

But first, another idea from network TV:

A re-run!

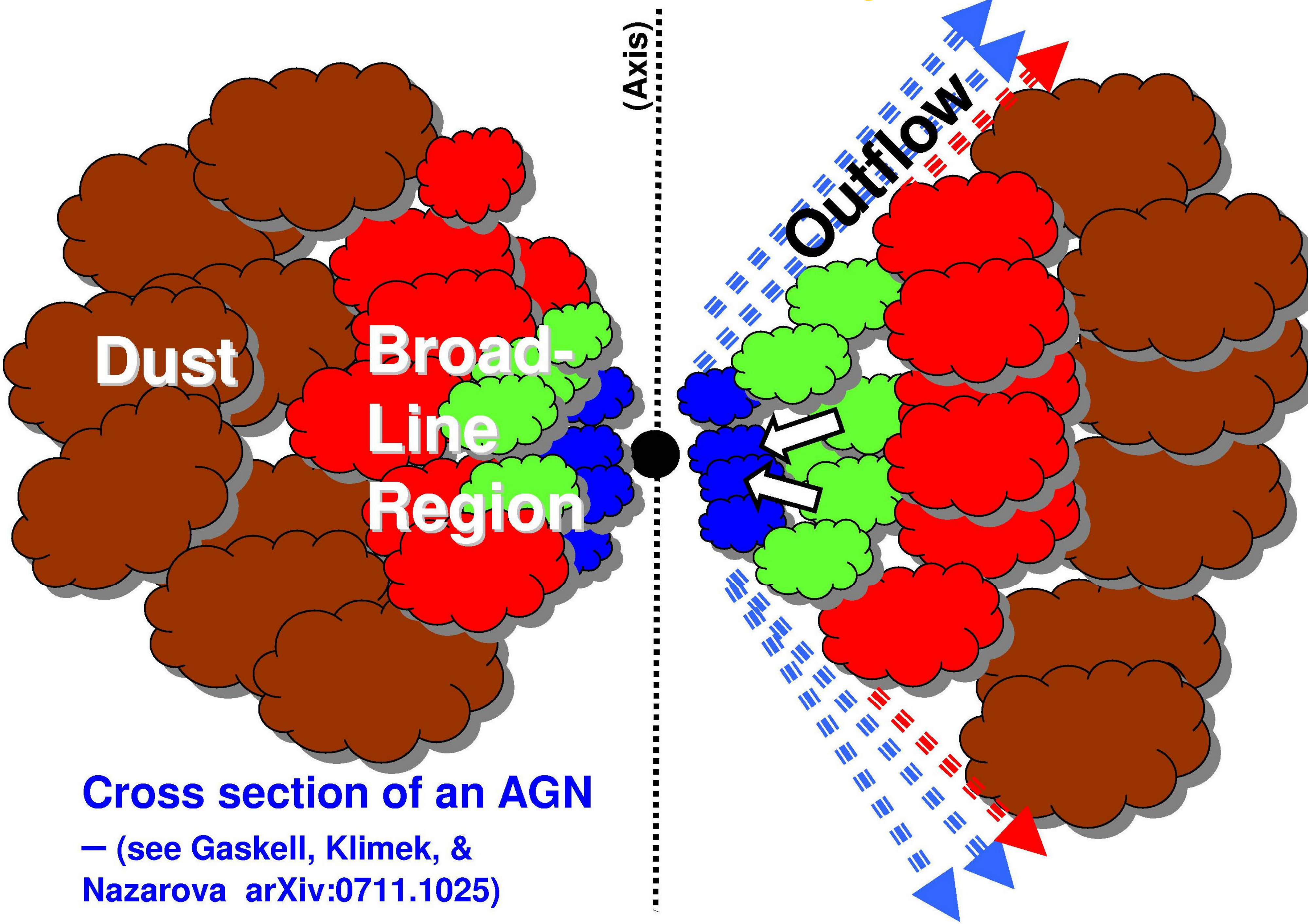
(a review of some of last year’s talk)

Computer-Generated Images of the Culprit:



(Rendering by Daniel Gaskell)

Sketch of the Culprit



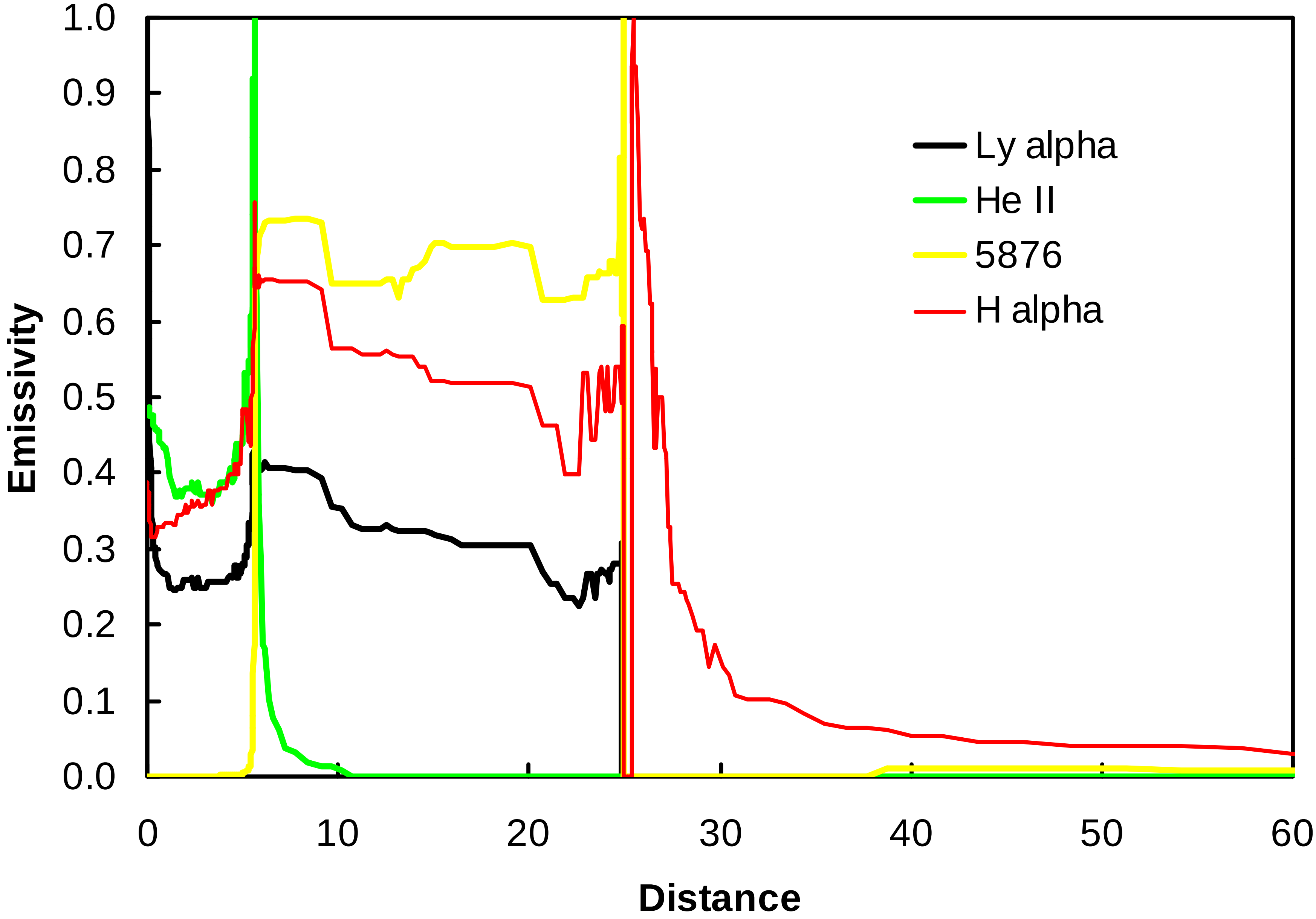
Cross section of an AGN

– (see Gaskell, Klimek, & Nazarova arXiv:0711.1025)

The Description of the Culprit

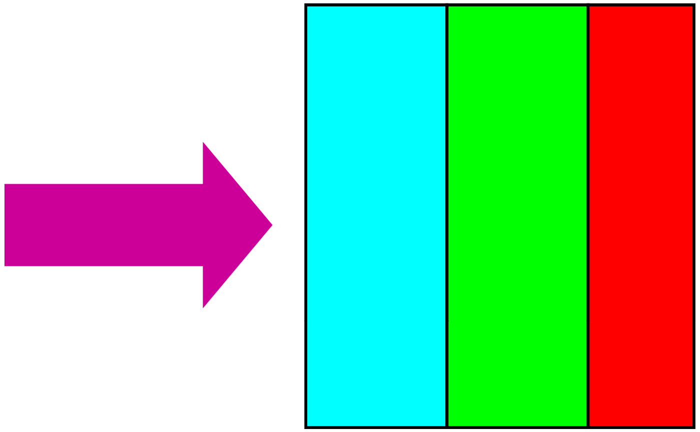
- Outer edge of the BLR is the radius of the torus.
- Outer boundary of BLR is dust sublimation radius (Netzer & Laor 1993) (hence $R_{BLR} \propto L^{1/2}$ from inverse-square law)
- $\Omega_{\rm BLR} = \Omega_{\rm dust}$
- $\Omega \approx 50\%$ (actually luminosity dependent)
- Flattened BLR
- Hole in middle
- We see BLR within $\approx$ 45 deg of face-on
- Strong ionization stratification

Ionization structure of a single cloud:



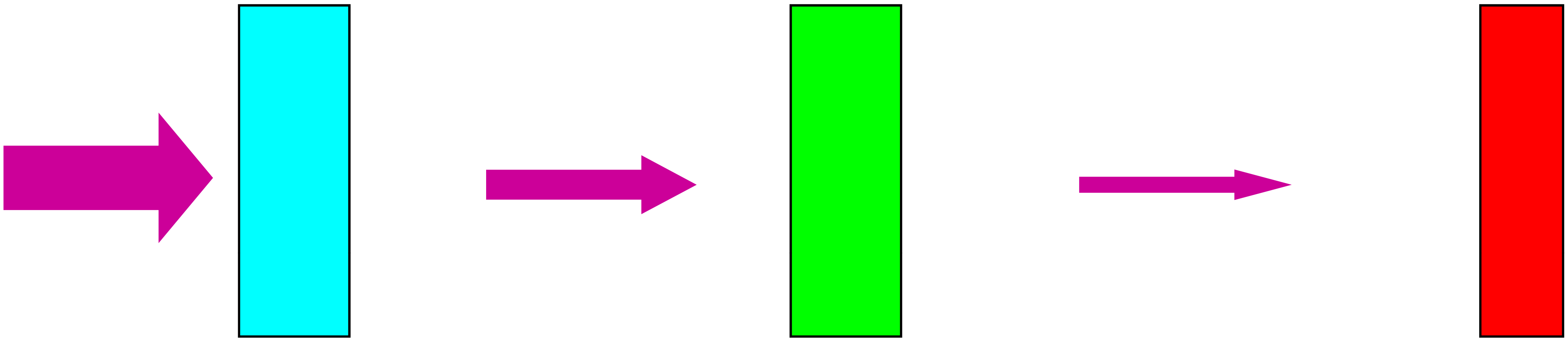
Ionization structure:

SELF-SHIELDING MODEL

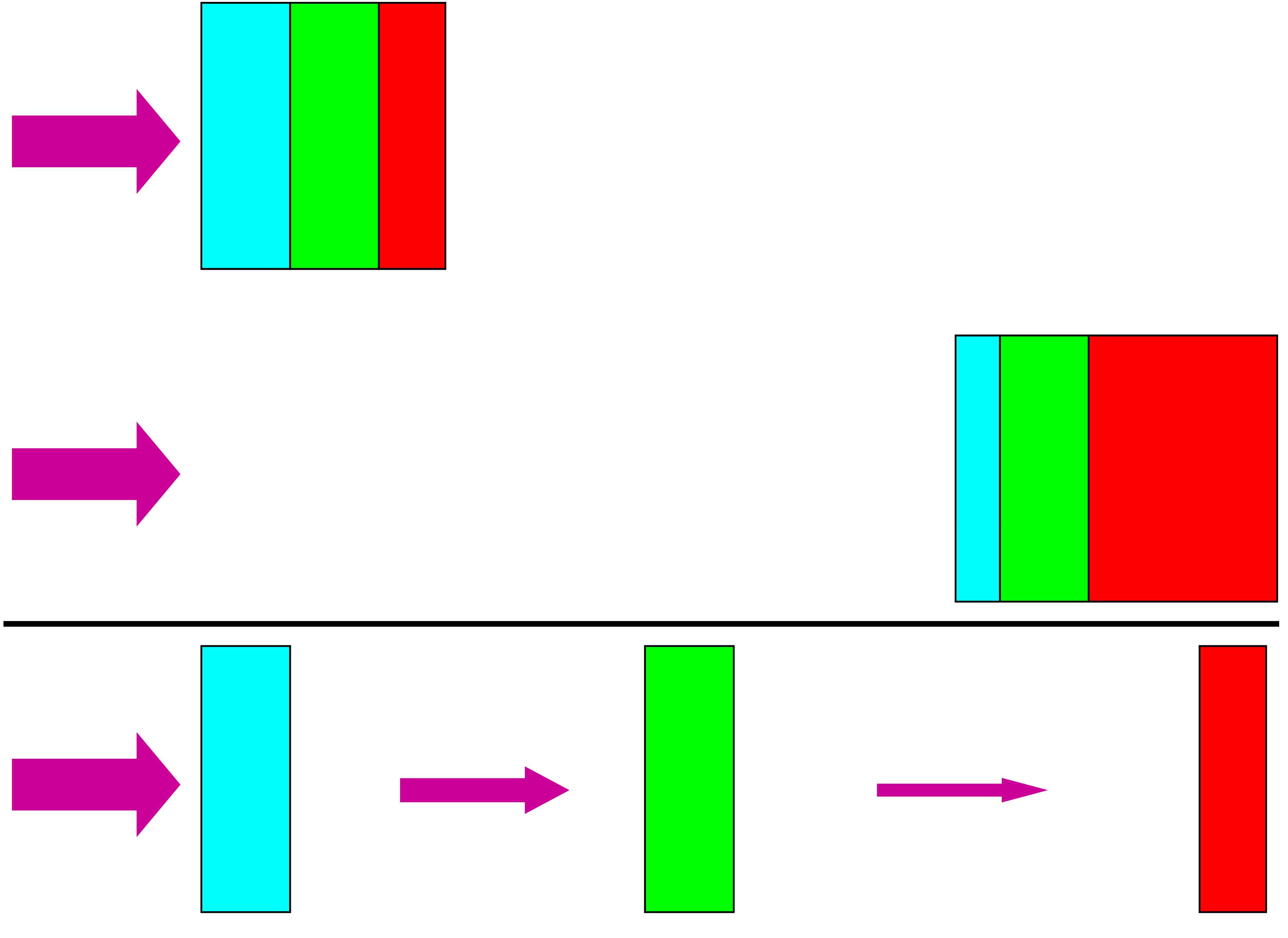


Ionization structure:

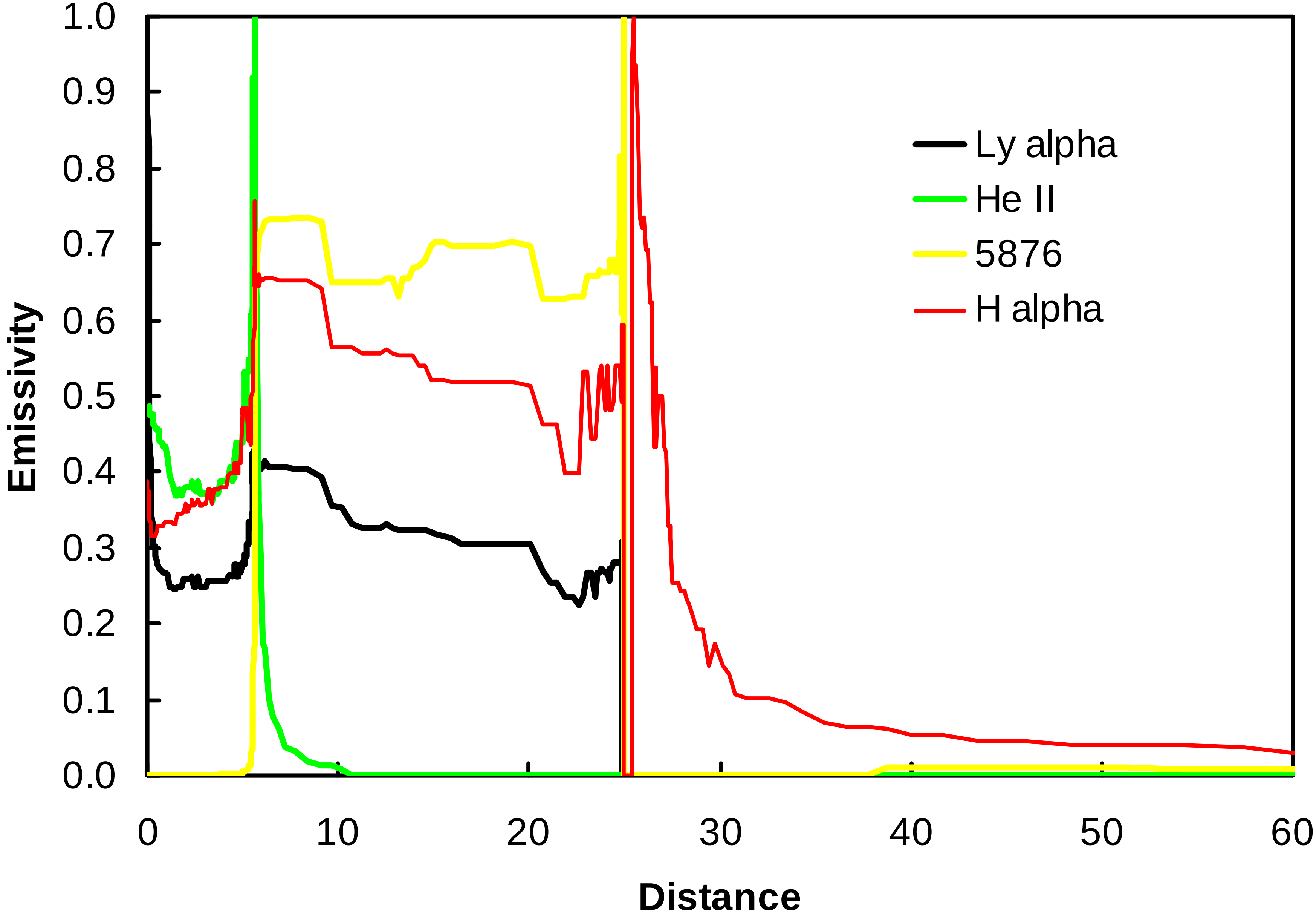
SELF-SHIELDING MODEL

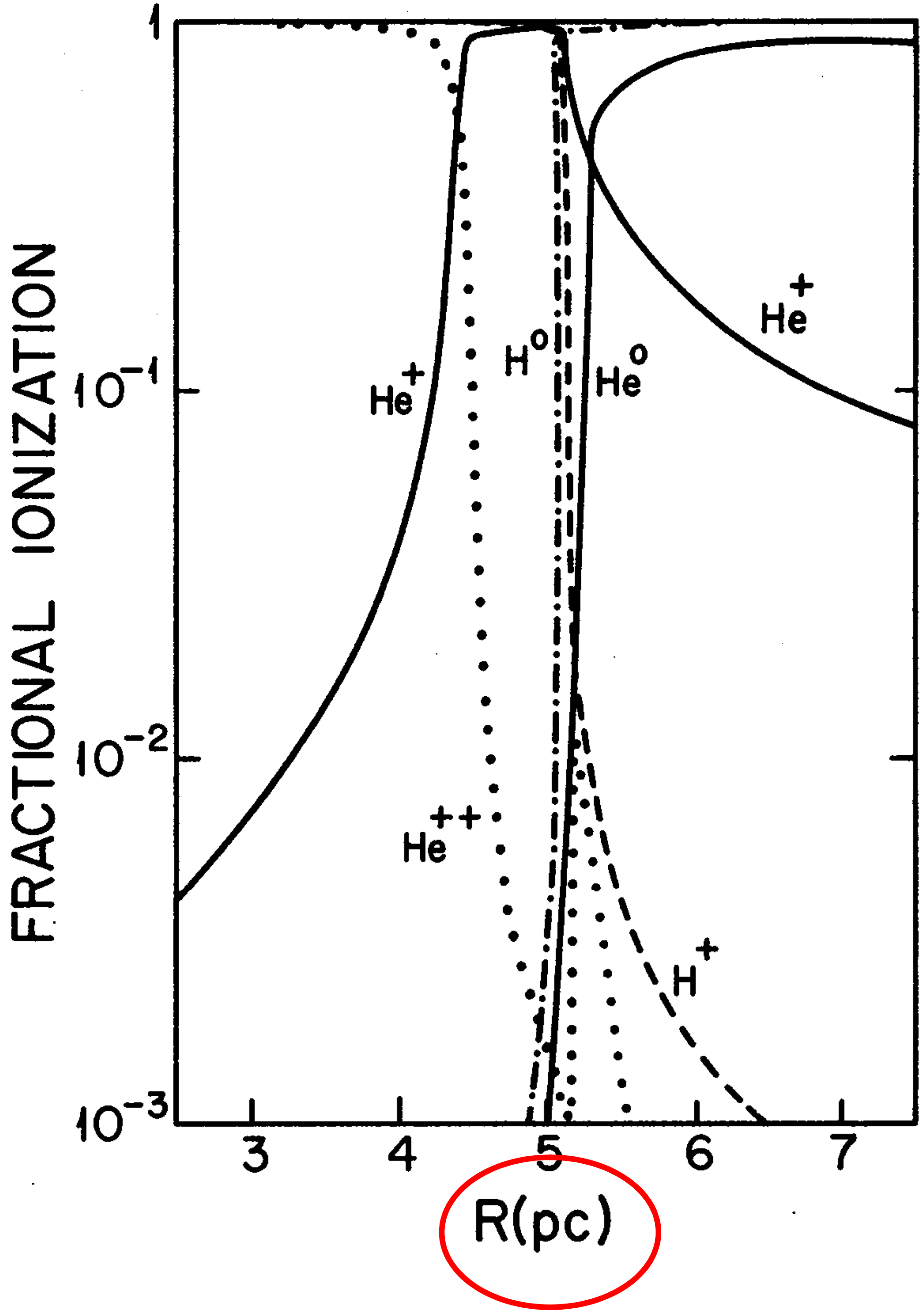


***cf*. "filling-factor" model of MacAlpine (1974)**



Overall ionization structure like a single cloud!

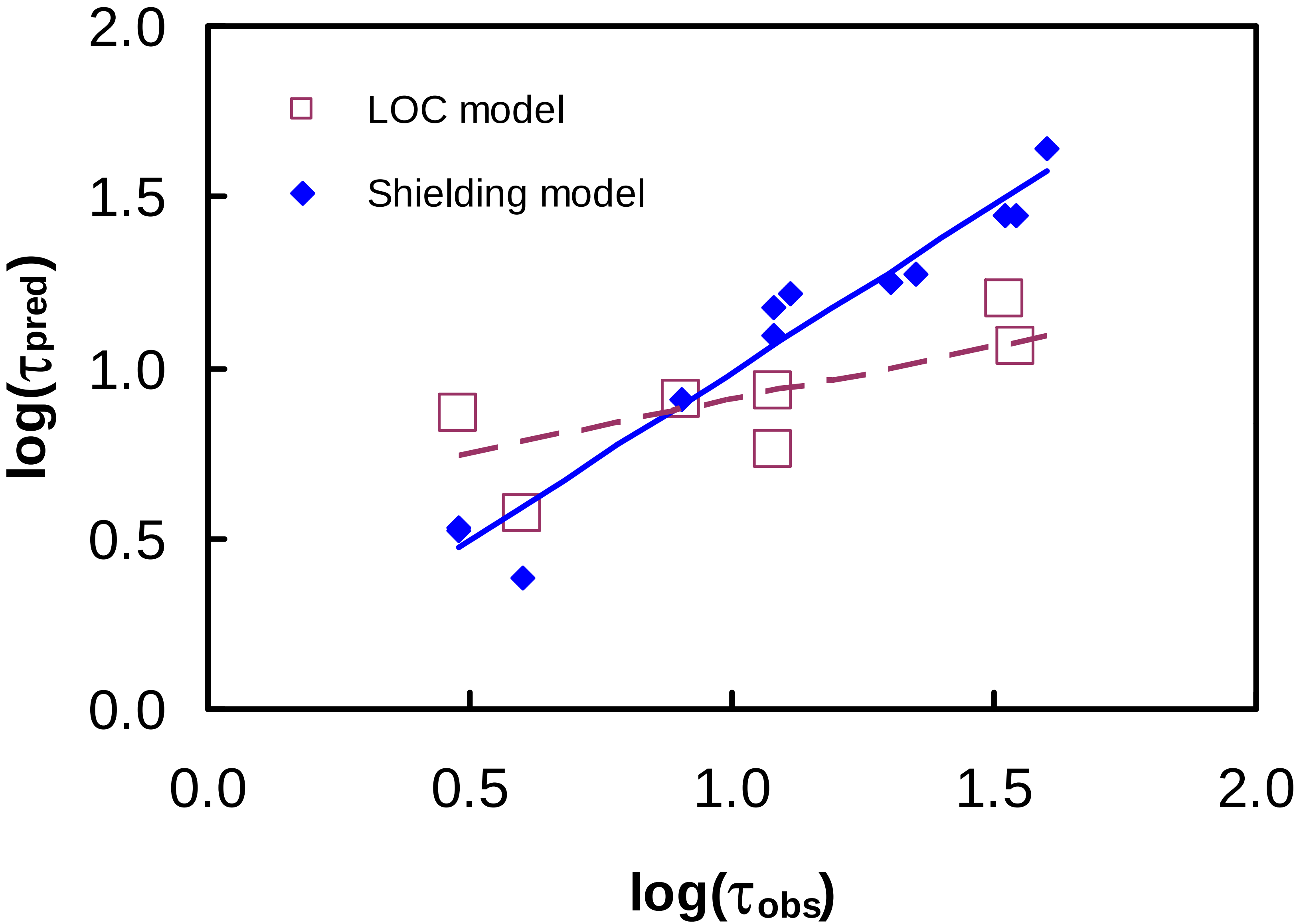




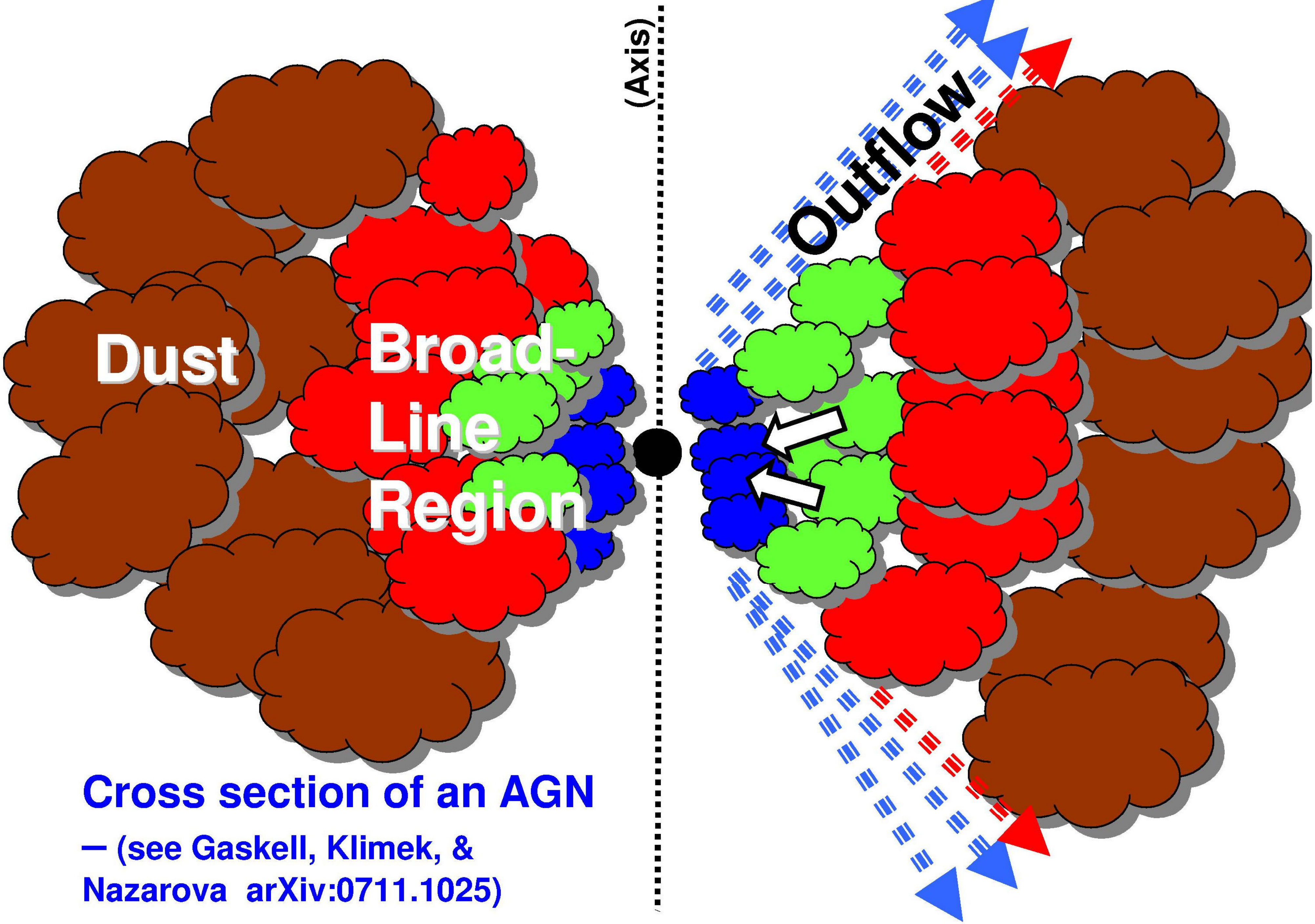
MacAlpine (1972)

Predicts lags for NGC 5548:

(only *one* free parameter!)



Sketch of the Culprit



How was the crime committed? - motions of the culprit

Overall motion of the gas:

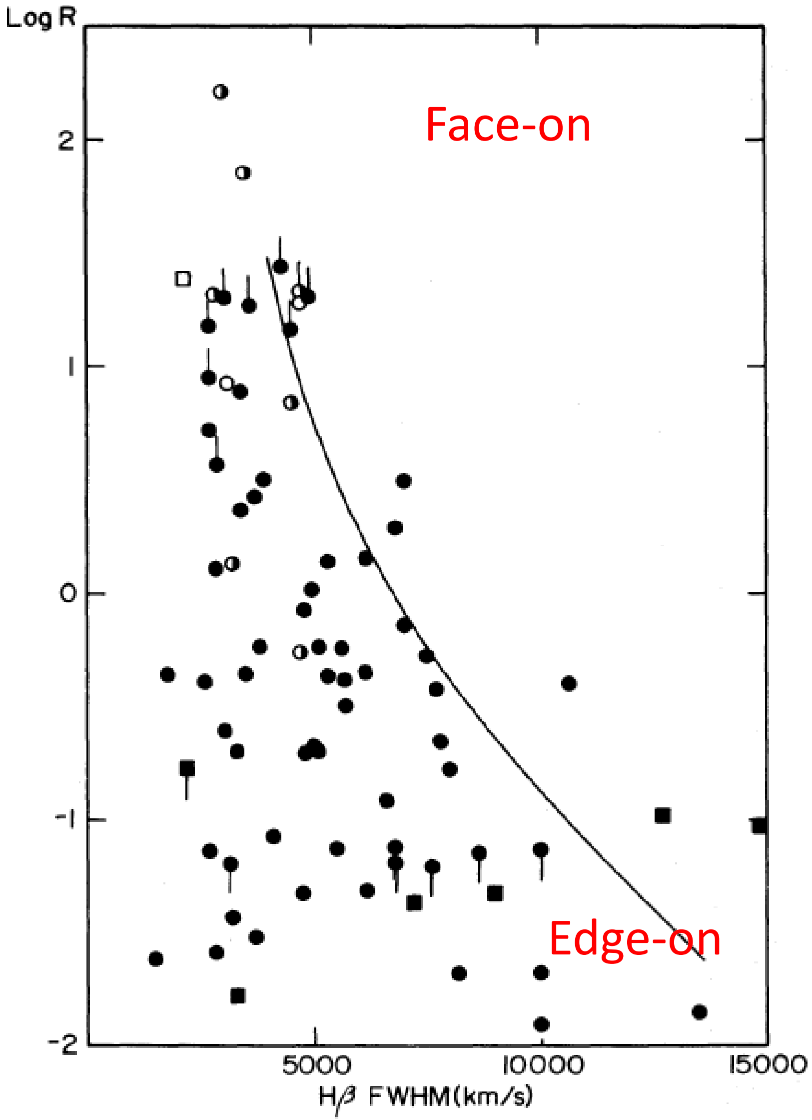
Predominantly Keplerian motion + "turbulence" (random vertical motions) Osterbrock (1978)

- Need the vertical motions to get the necessary thickness
- (if we didn't have vertical motions we couldn't get virial masses since we view AGNs face on!)

Now add inflow:

$$\boxed{v_{\mathrm{Keplerian}} > v_{\mathrm{turb}} > v_{\mathrm{inflow}} \sim 0.1 - 0.2\ v_{\mathrm{Keplerian}}}$$

Evidence for disc BLRs in all AGNs



Wills & Browne (1986)

Disc components present in *all* low-ionization BLR lines

See:

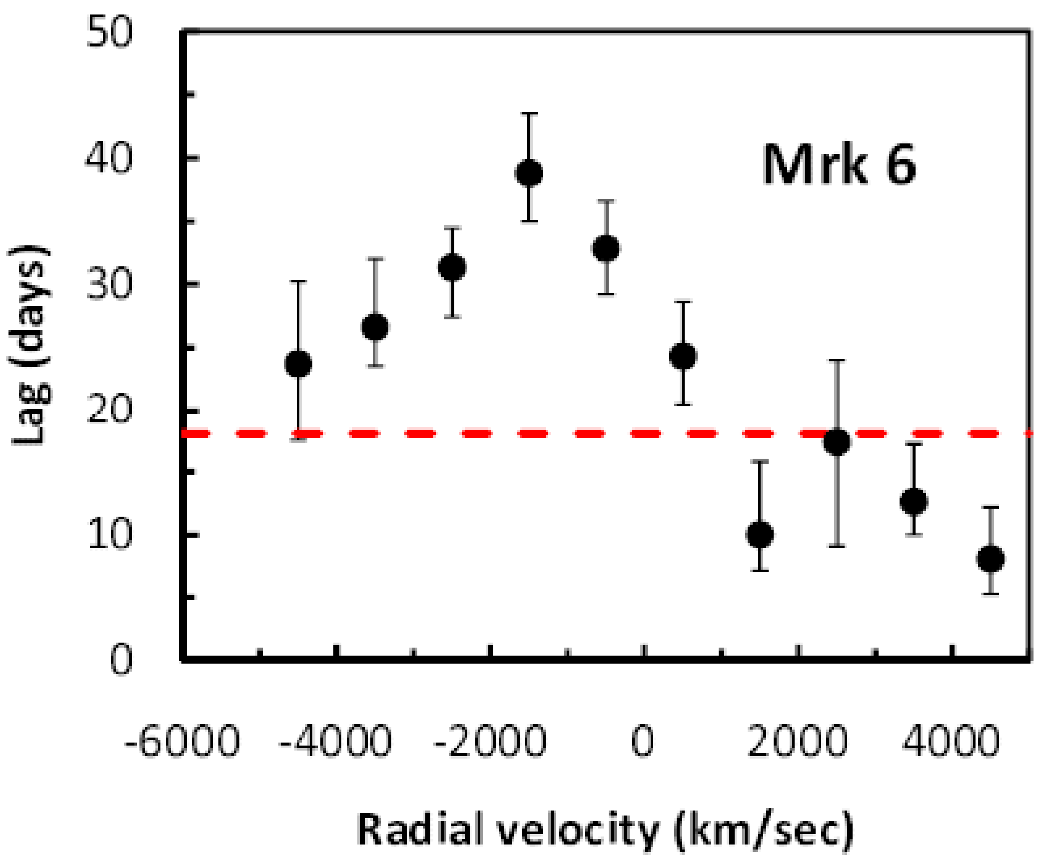
Gaskell & Snedden (1999)
Bon, Popović, Ilić, & Mediavilla (2006)
Popović, Bon, & Gavrilović (2008)

Profile Type **Radio-quiet**	Percentage
No obvious displaced peaks	40%
Single displaced peak	25%
Two displaced peaks	35%
Blue peak strongest	29%
Red peak strongest	25%
Peaks approximately equal	6%

Profile Type **Radio-loud**	Percentage
No obvious displaced peaks	30%
Single displaced peak	32%
Two displaced peaks	38%
Blue peak strongest	26%
Red peak strongest	28%
Peaks approximately equal	16%

Evidence for inflow: 1. Velocity-resolved reverberation mapping

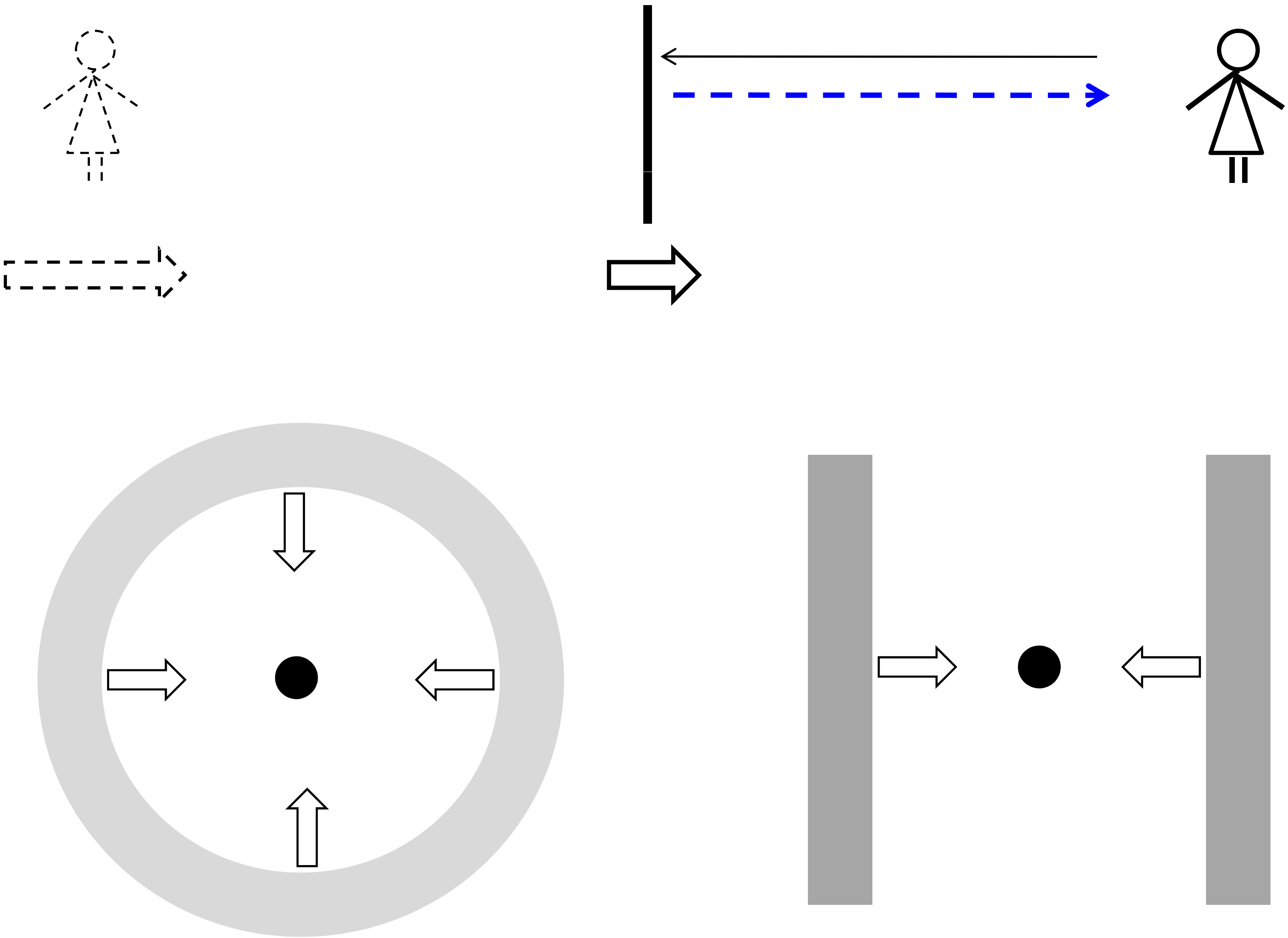
- For inflow, red wing (near side) shows shortest lag (Gaskell 1988).

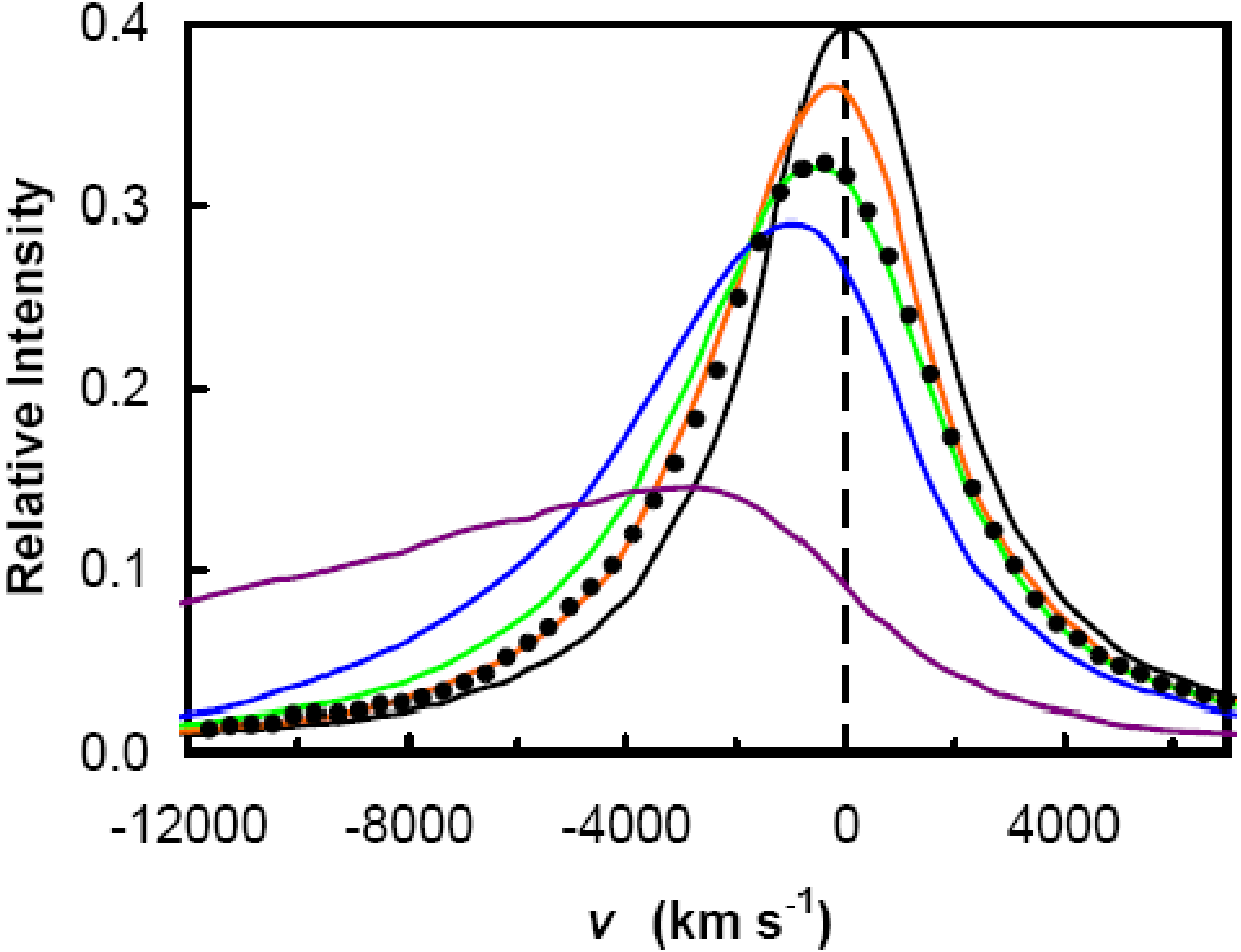


Gaskell (2010) (Adapted from **Sergeev, Pronik, & Sergeeva (1999)**)

Evidence for inflow: 2. Blueshifting of high-ionization lines because of scattering

- High-ionization BLR lines blueshifted relative to low-ionization lines (Gaskell 1982).
- [Popular "wind+disc" model with disc blocking wind on far side (Gaskell 1982) ruled out by velocity-resolved reverberation mapping (Gaskell 1988).]
- Due instead to scattering off infalling material (Gaskell & Goosmann 2008).





[Modelled using *STOKES* (Goosmann & Gaskell 2007)]

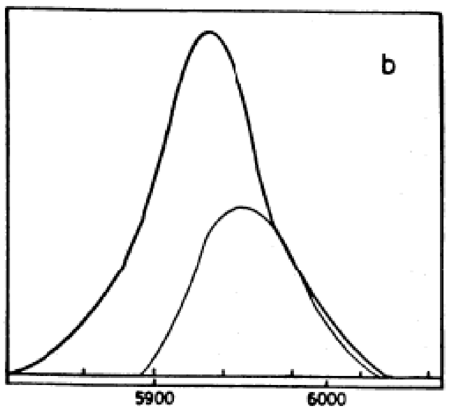
(Gaskell & Goosmann 2008)

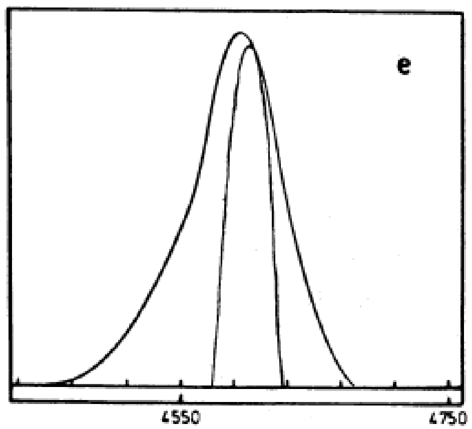
v_{infall} = 1000 km/s

Solid curves: Shell, (τ = 0, 0.5, 1, 2, 10)

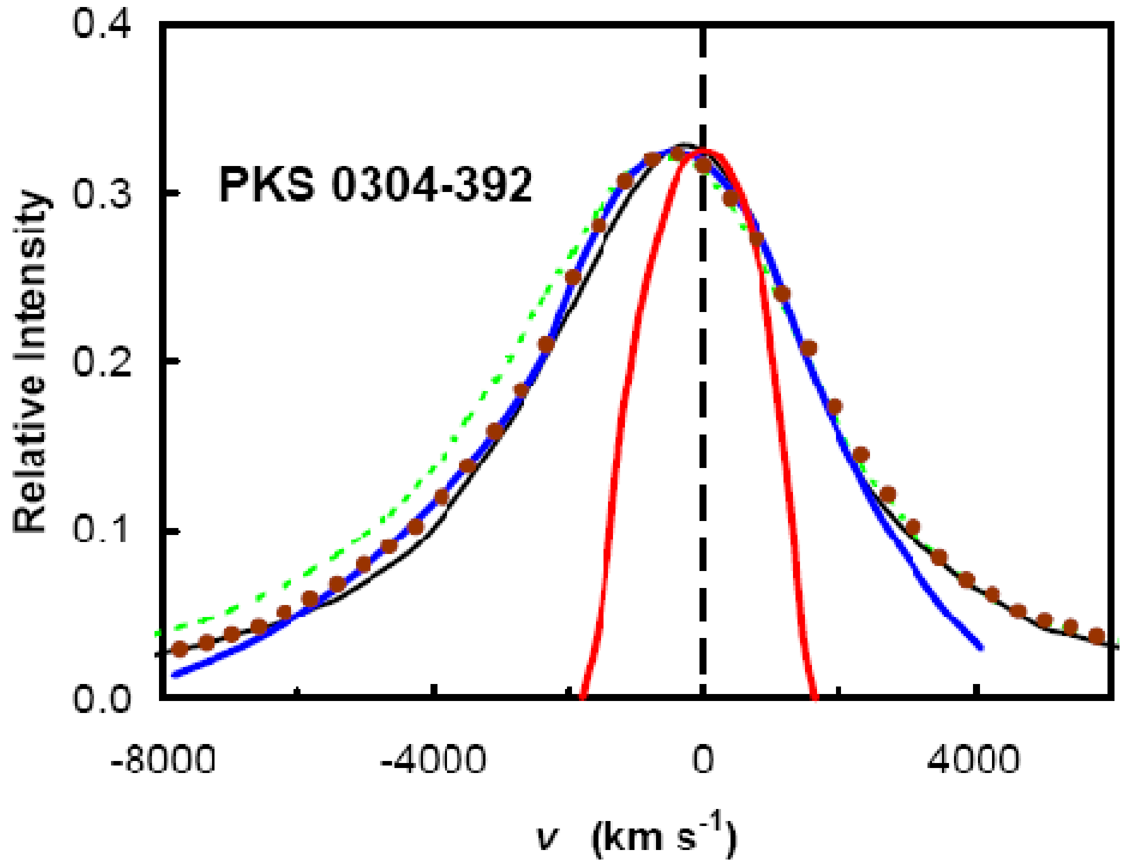
Dots: Torus, τ = 20

Example:





Wilkes (1984)



Gaskell & Goosmann (2008)

MASS ACCRETION RATE OF BLR
(easy calculation!)

- Already noted long ago that if BLR motion is radial, mass flow rate ~ accretion rate needed (*e.g.*, Padovani & Rafanelli 1988)
- $\Rightarrow$ **Mass inflow rate = rate needed to provide observed luminosity!** (If efficiency =10% and n_H = 10^{10} cm^{-3})
- **THE MASS INFLOW OF THE BLR <u>IS</u> THE ACCRETION ONTO THE AGN!**

End of re-run

(on to the sequel…)

What next?

To complete the story we needed to:

1. Convict the culprit

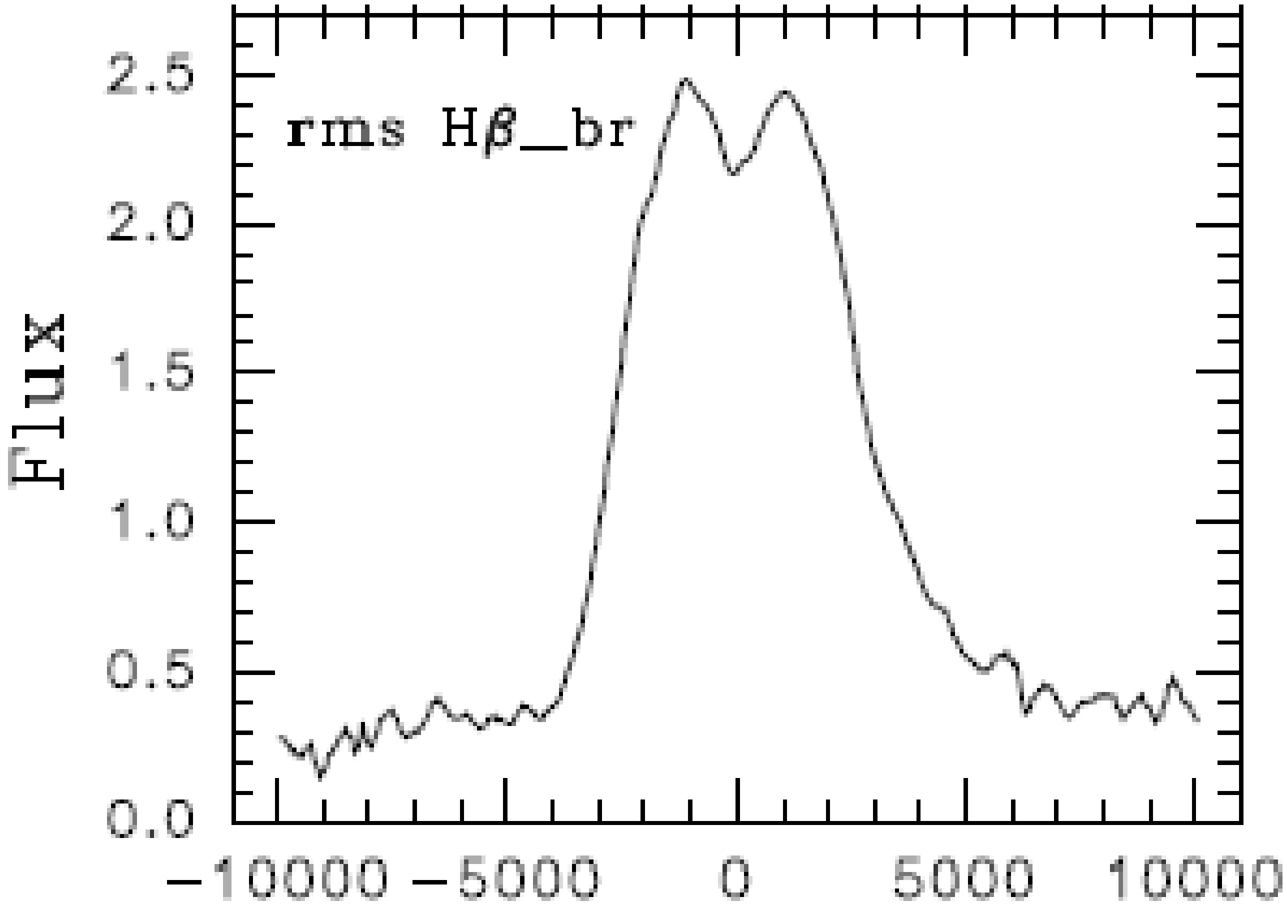
   (*I.e.*, convince the judge and jury of our peers)

2. Wrap up the loose ends in the plot of the book/movie.

Next: focus on convincing our peers about our ability to explain *line profiles* and *profile variability.*

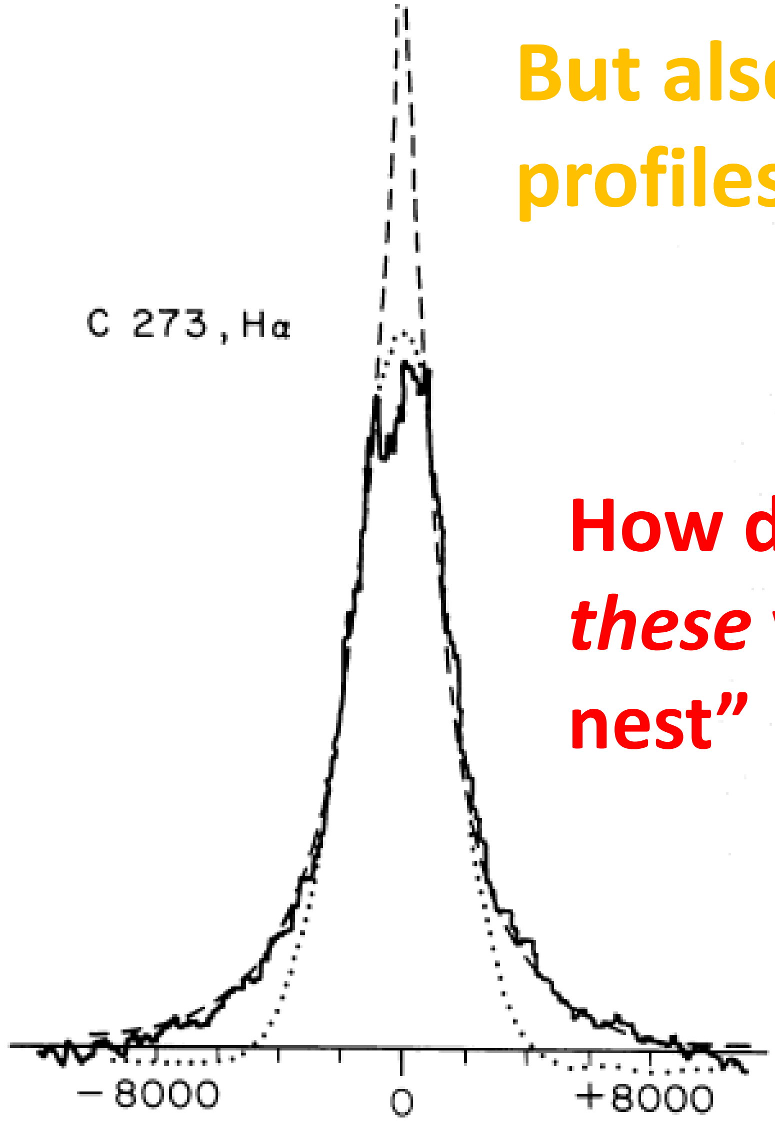
(Will give us new mysteries for the sequel!)

There are disc profiles

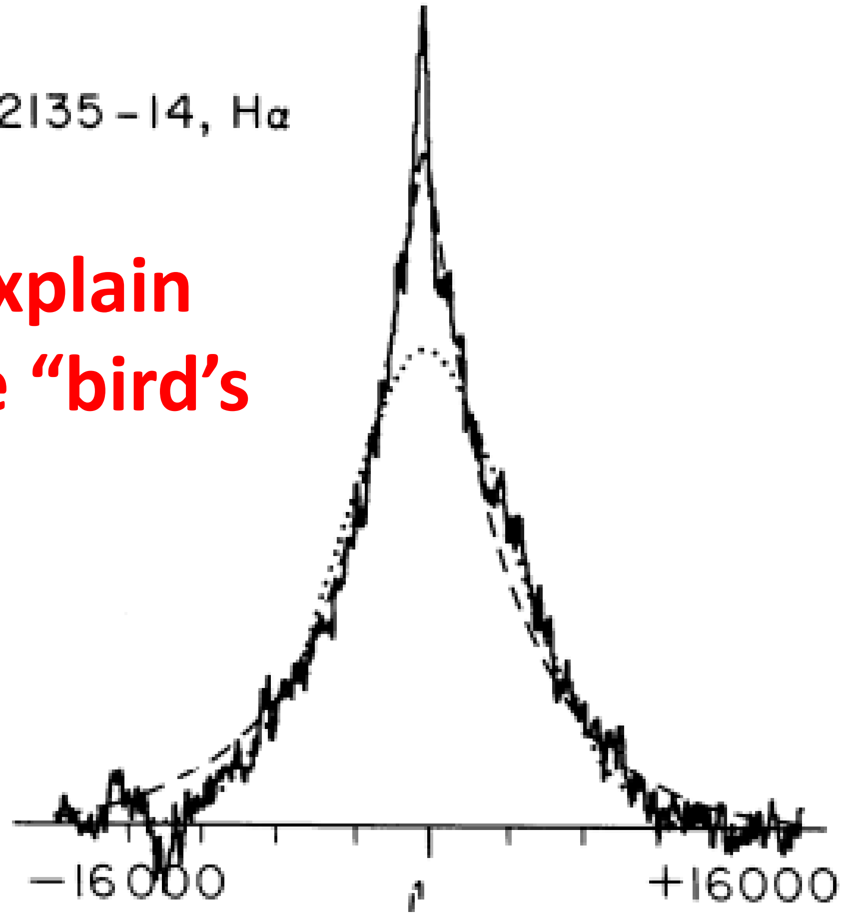


NGC 5548
Shapovalova *et al*. (2004)

But also "normal" AGN line profiles – "logarithmic" profiles



How do you explain *these* with the "bird's nest" BLR?



Obs. – Baldwin (1975) – Lick Observatory (Robinson Wampler IDS)

Models – "logarithmic" profiles from Blumenthal & Mathews (1975)

BL-RESP – a new code for modelling the BLR

- *[**Remark:** Not ready for a public release yet, but I'd be delighted to collaborate with anyone who wants to use BL-RESP to model BLR data.]*
- Takes basic parameters of the GKN (Gaskell, Klimek, & Nazarova) model for each line (or winds, or anything else you want)
- **What *BL-RESP* produces:**
  - movies of the BLR
  - BLR profiles for any line
  - The reverberation mapping lag
  - Reverberation transfer function, $\Psi(\tau)$
  - Velocity-resolved lags
  - 2-D "velocity-delay" maps
  - Correction factor (*f*) for virial black hole mass estimates
- **What *BL-RESP* does <u>not</u> do:**
  - Include scattering (use the *STOKES* program – publically available)
  - Give polarizations (use *STOKES* instead)

BL-RESP – a few details

- BLR modelled as discrete clouds – just for computational convenience (probably really fractal – Bottorff & Ferland 2002)

For GKN model:

- Keplerian motion (simple)
- Vertical motions (MAJOR THEORETICAL PROBLEM!) modelled as tilted orbits. Known physics and physically consistent (conserves energy and ang. mom.) but vertical motions must really be *magnetically driven* (else clouds destroyed in collisions).
- (Other details – ask questions.)

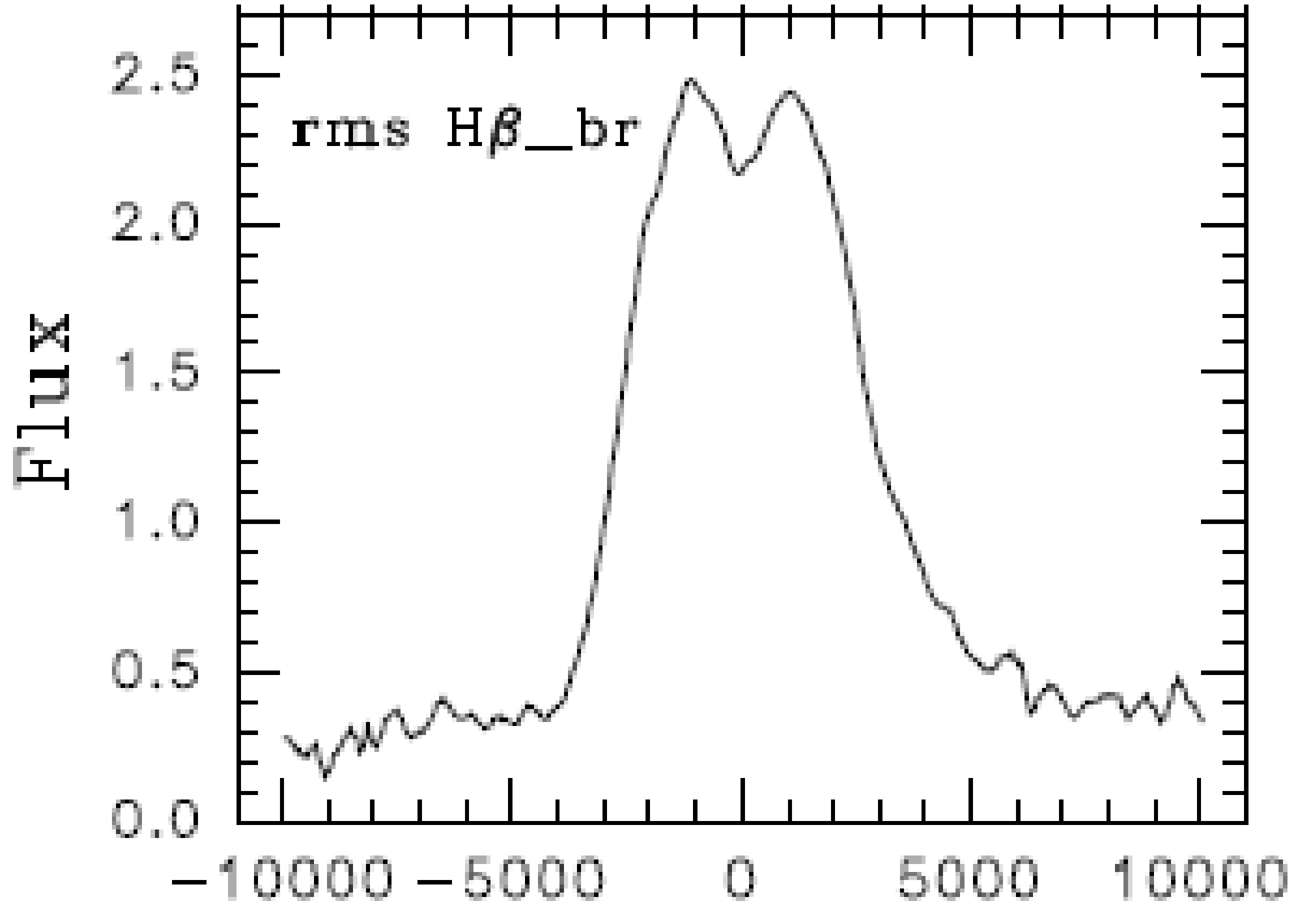
What is looks like

- Face-on
- Edge-on
- i = 30 deg

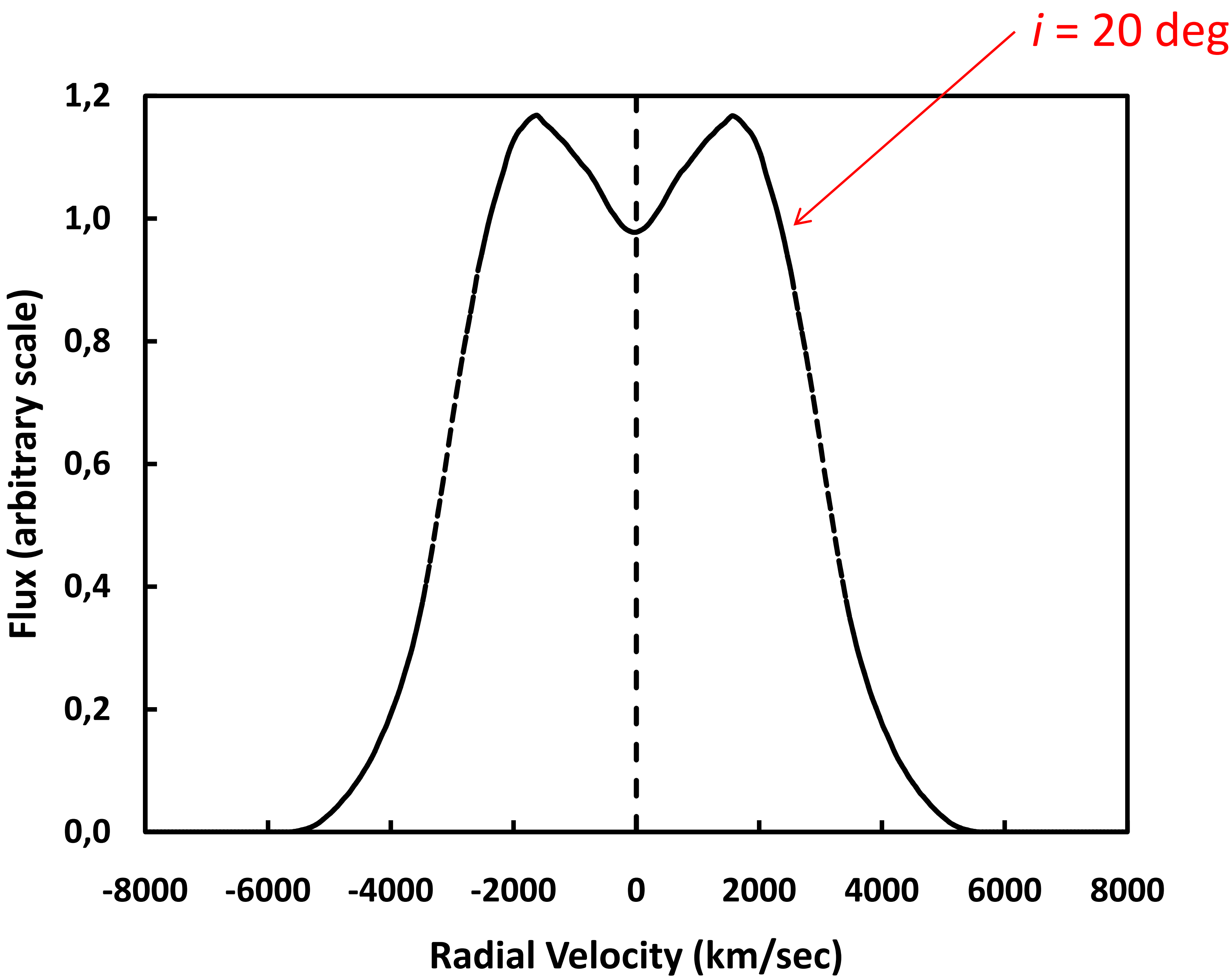
[Hit ESC to terminate movie – if that doesn't work close the command window.

Click on this page when you are done before you move on.]

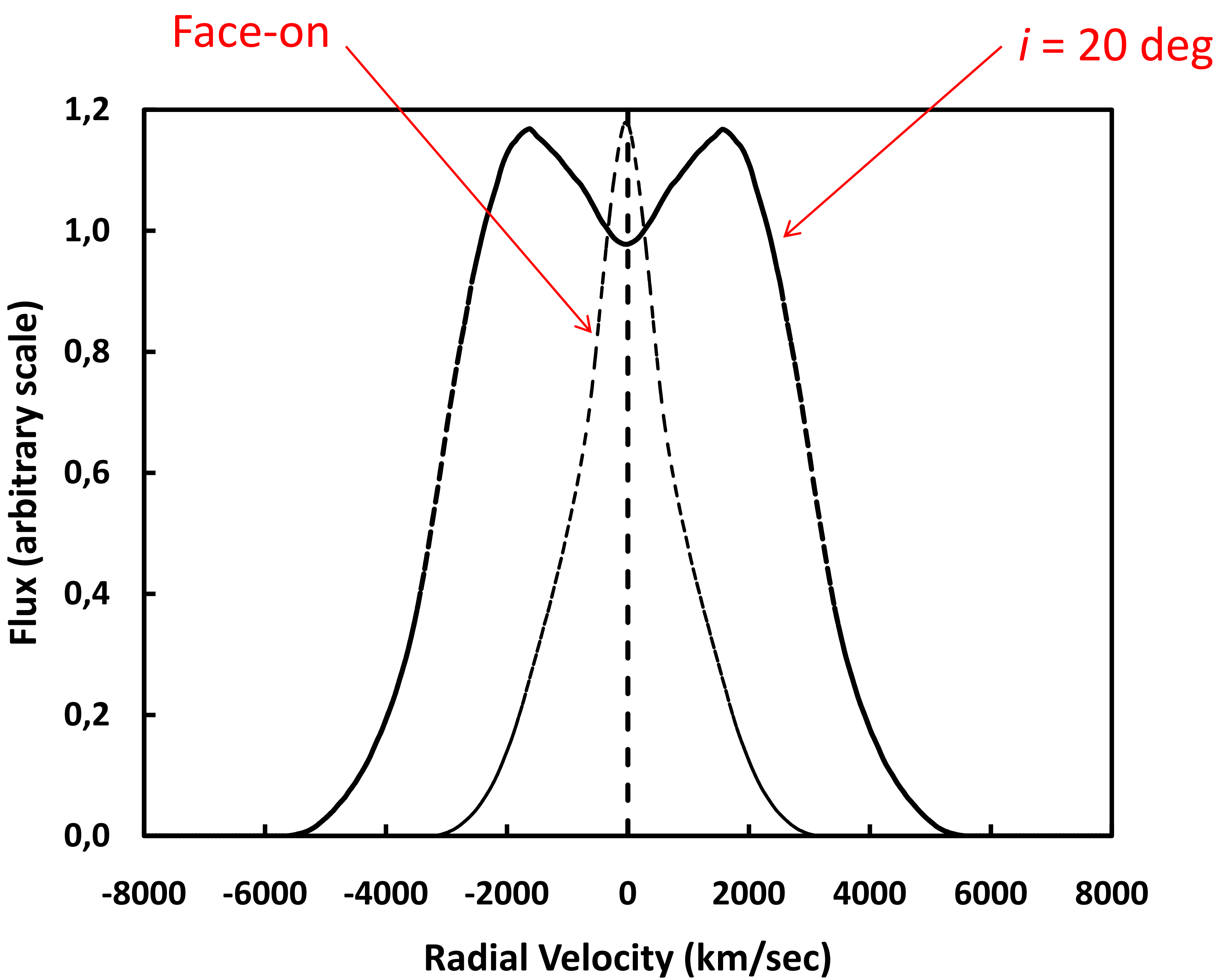
Typical disc:



NGC 5548
Shapovalova *et al*. (2004)



i = 20 deg
1,2
1,0
0,8
0,6
0,4
0,2
0,0
Flux (arbitrary scale)
-8000
-6000
-4000
-2000
0
2000
4000
6000
8000
Radial Velocity (km/sec)


Face-on
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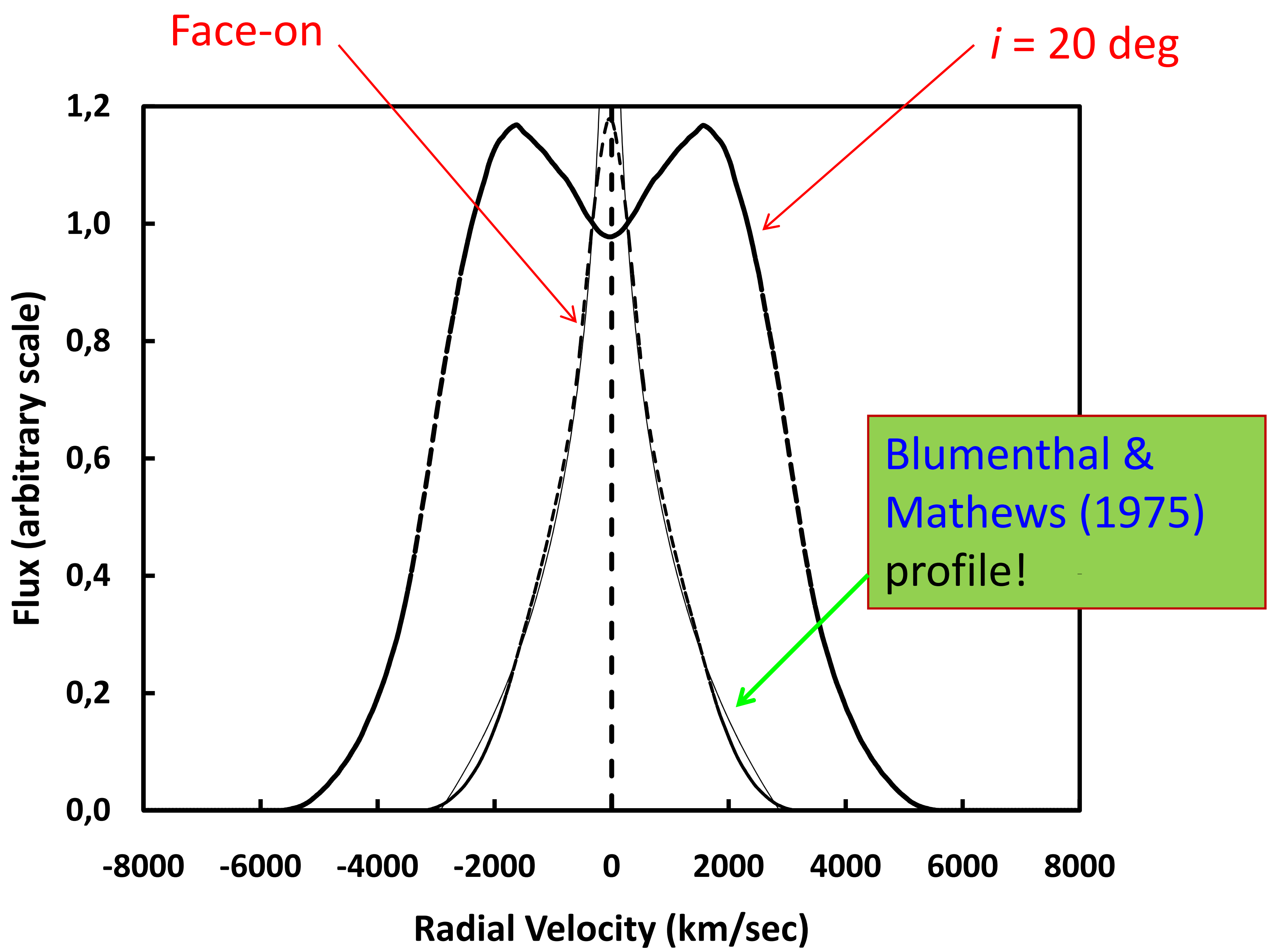
1,2
1,0
0,8
0,6
0,4
0,2
0,0
Flux (arbitrary scale)
-8000
-6000
-4000
-2000
0
2000
4000
6000
8000
Radial Velocity (km/sec)

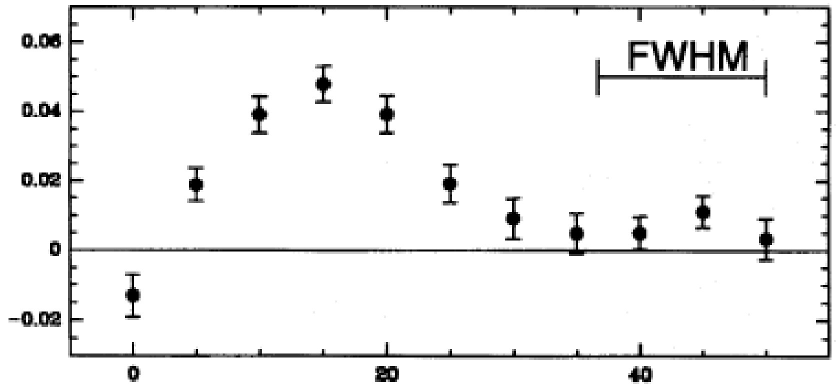

Face-on
i = 20 deg
1,2
1,0
0,8
0,6
0,4
0,2
0,0
Flux (arbitrary scale)
-8000
-6000
-4000
-2000
0
2000
4000
6000
8000
Radial Velocity (km/sec)
Blumenthal & Mathews (1975) profile!

New results

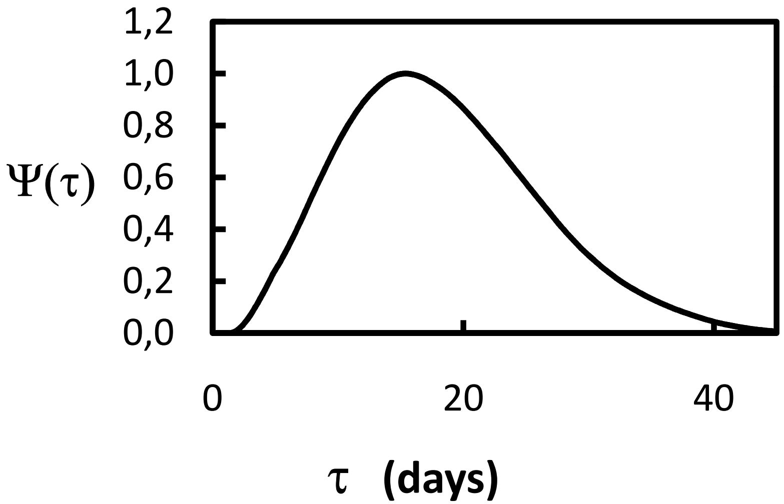
- The *same* GKN model explains line profiles ranging from the “logarithmic” profile (Blumenthal & Mathews 1975) to “disc-like” emitters!
- “Disc-like” emitters **not** fundamentally different from “normal” AGNs – just seen at a higher inclination.
- [What about other claimed differences between disc-like emitters and “normal” AGNs? – differences due to internal reddening (Gaskell *et al*. 2004)]

Transfer Functions [$\Psi(\tau)$]

NGC 5548 - Hβ
(Pijpers & Wanders 1994)



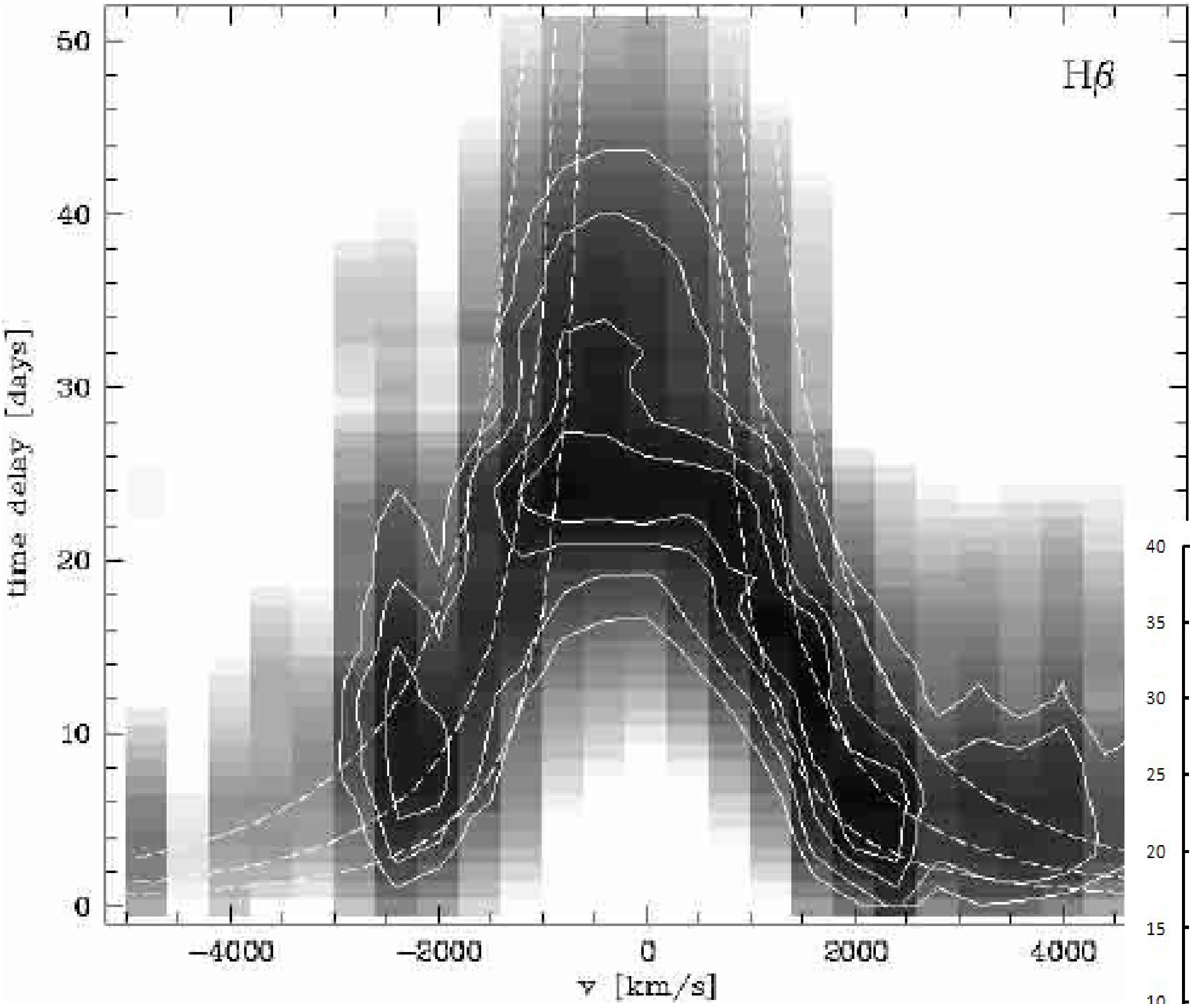
1990



(BL-RESP model)

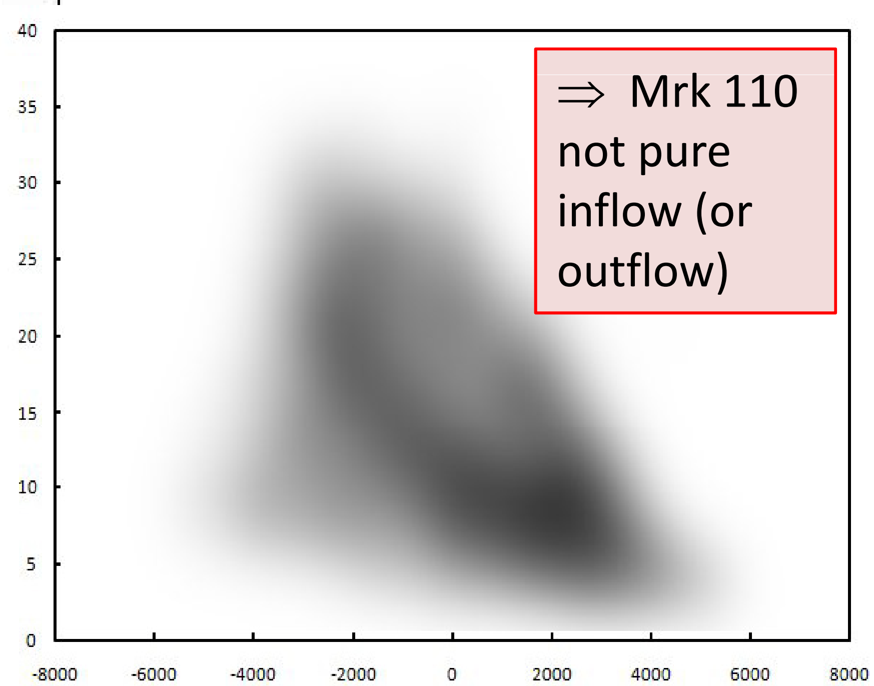
Note: observed $\Psi(\tau)$ supports Hβ mostly coming from within a factor of ~ 4 in radius as in GKN.

Velocity-delay diagrams



Best example to date: Mrk 110 (Kollatschny 2003)

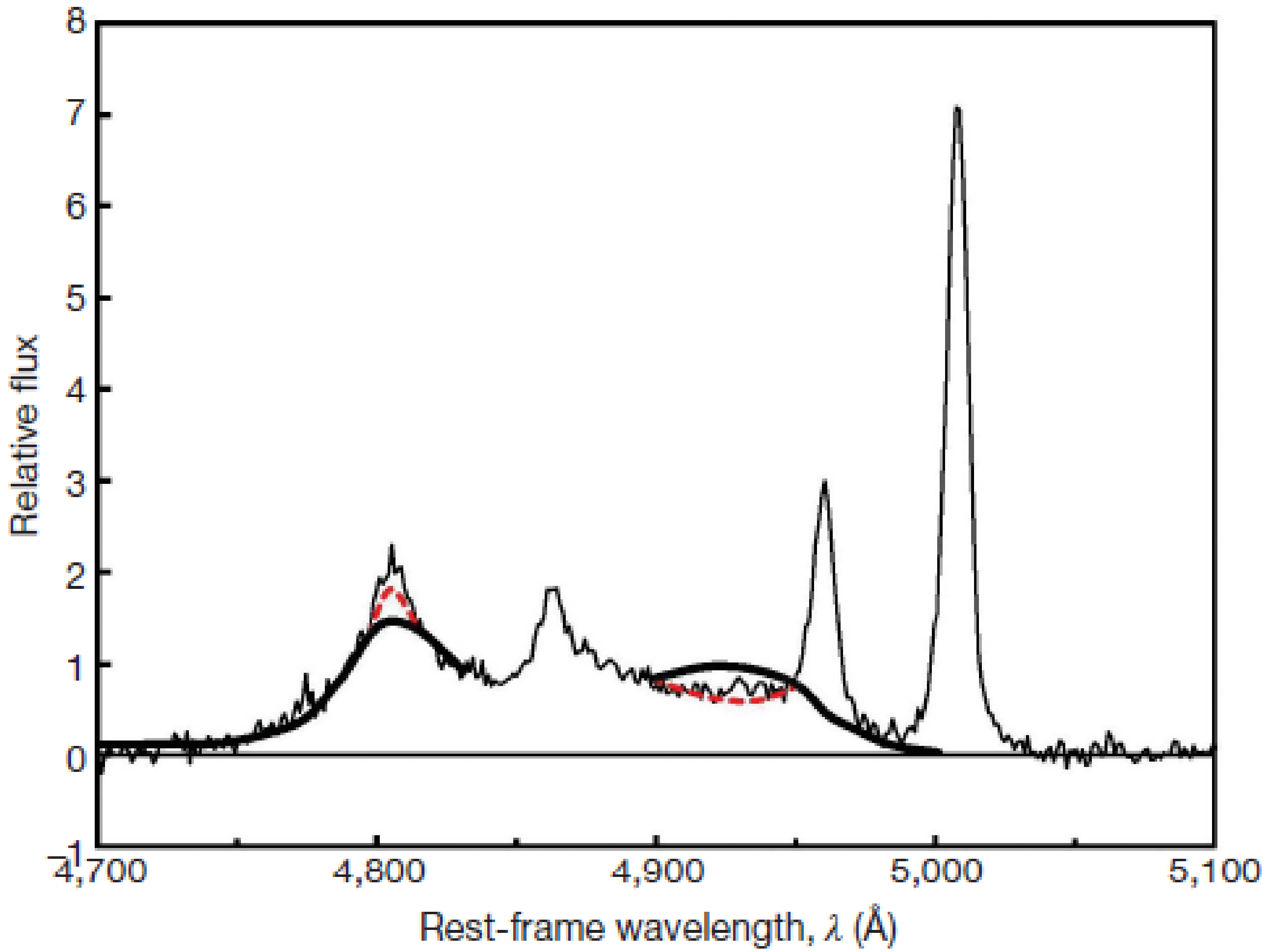
Sample *BL-RESP* velocity-delay diagram (pure inflow):



⇒ Mrk 110 not pure inflow (or outflow)

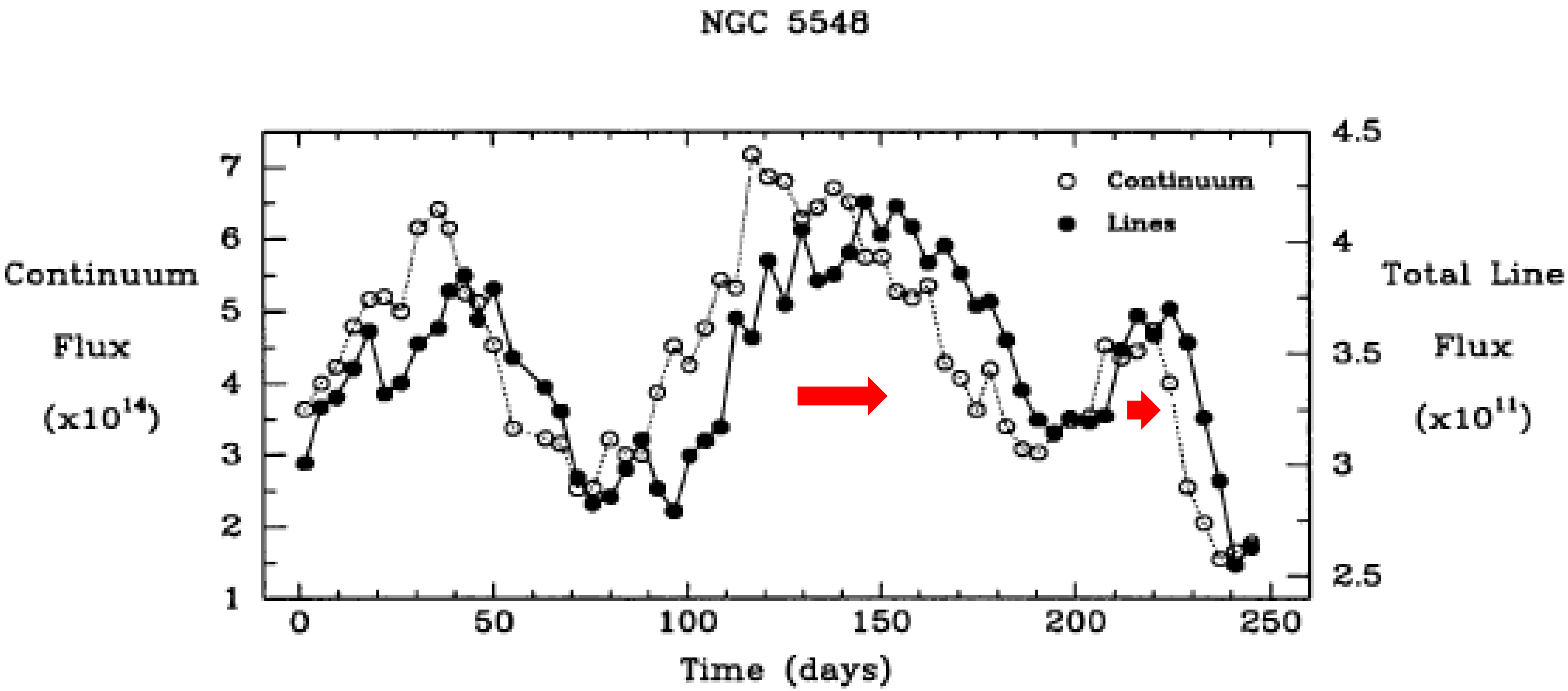
Further mysteries

- OK *on average*, but BLRs are not that simple...



Boroson & Lauer binary BH candidate **(Gaskell 2010)**

Lag can change in a couple of months!

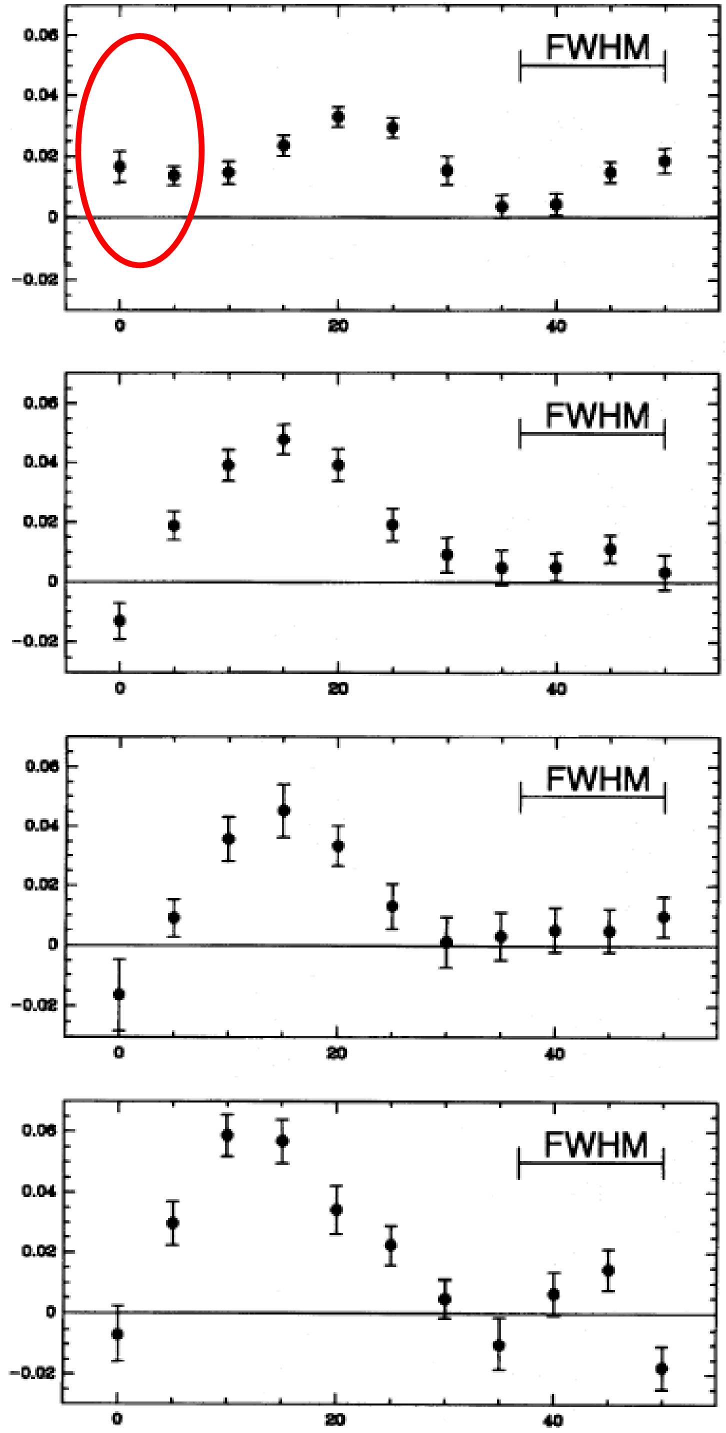


Maoz (1994)

Lag changes by factor of 1.5!

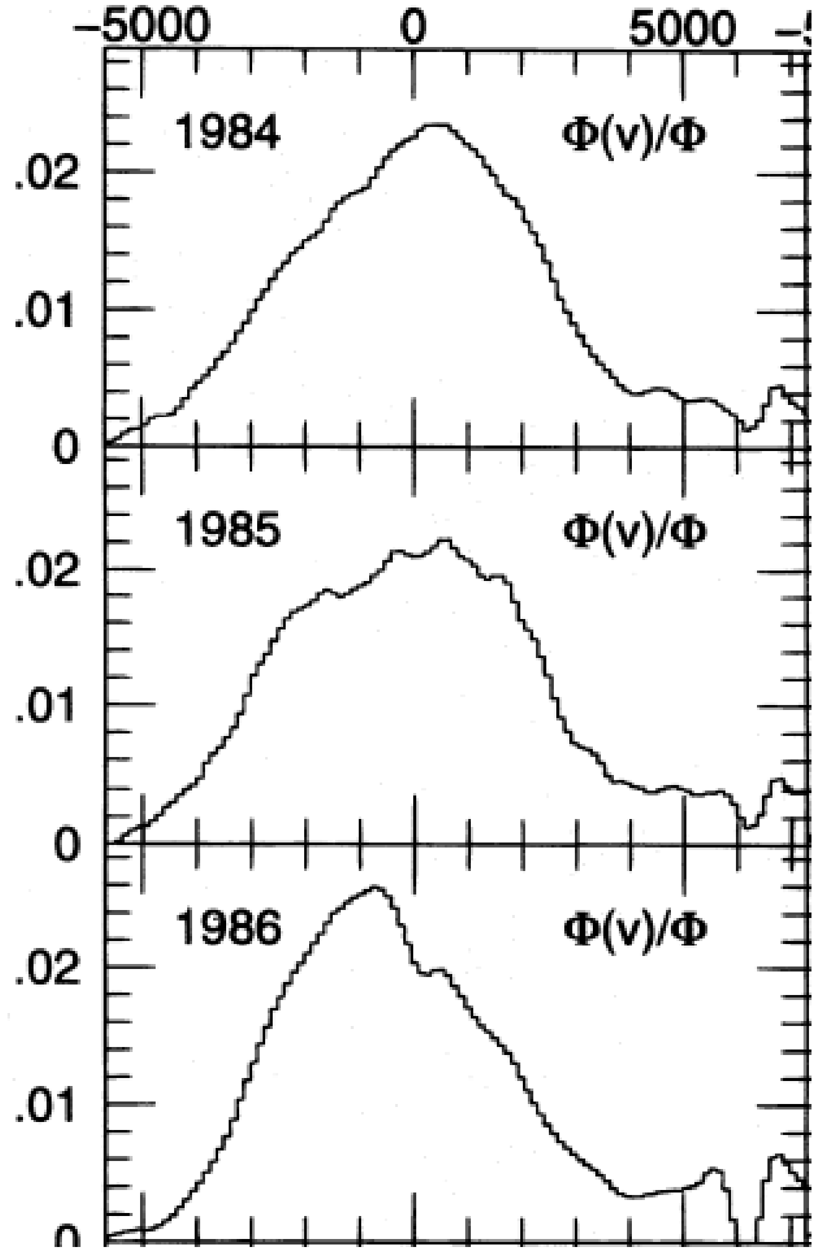
Transfer function can change from year to year!

Pijpers & Wanders (1994)

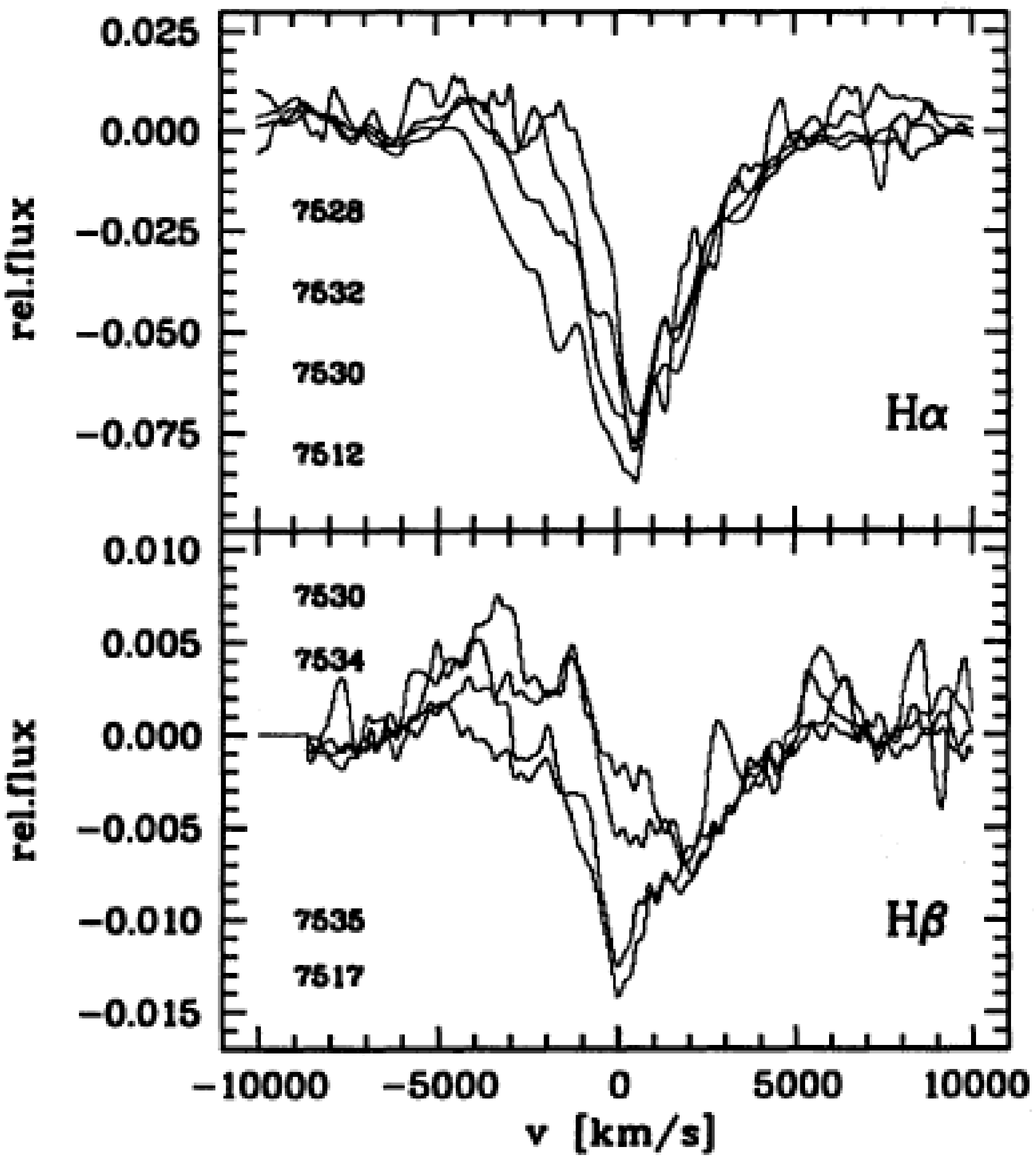


Profiles change with time

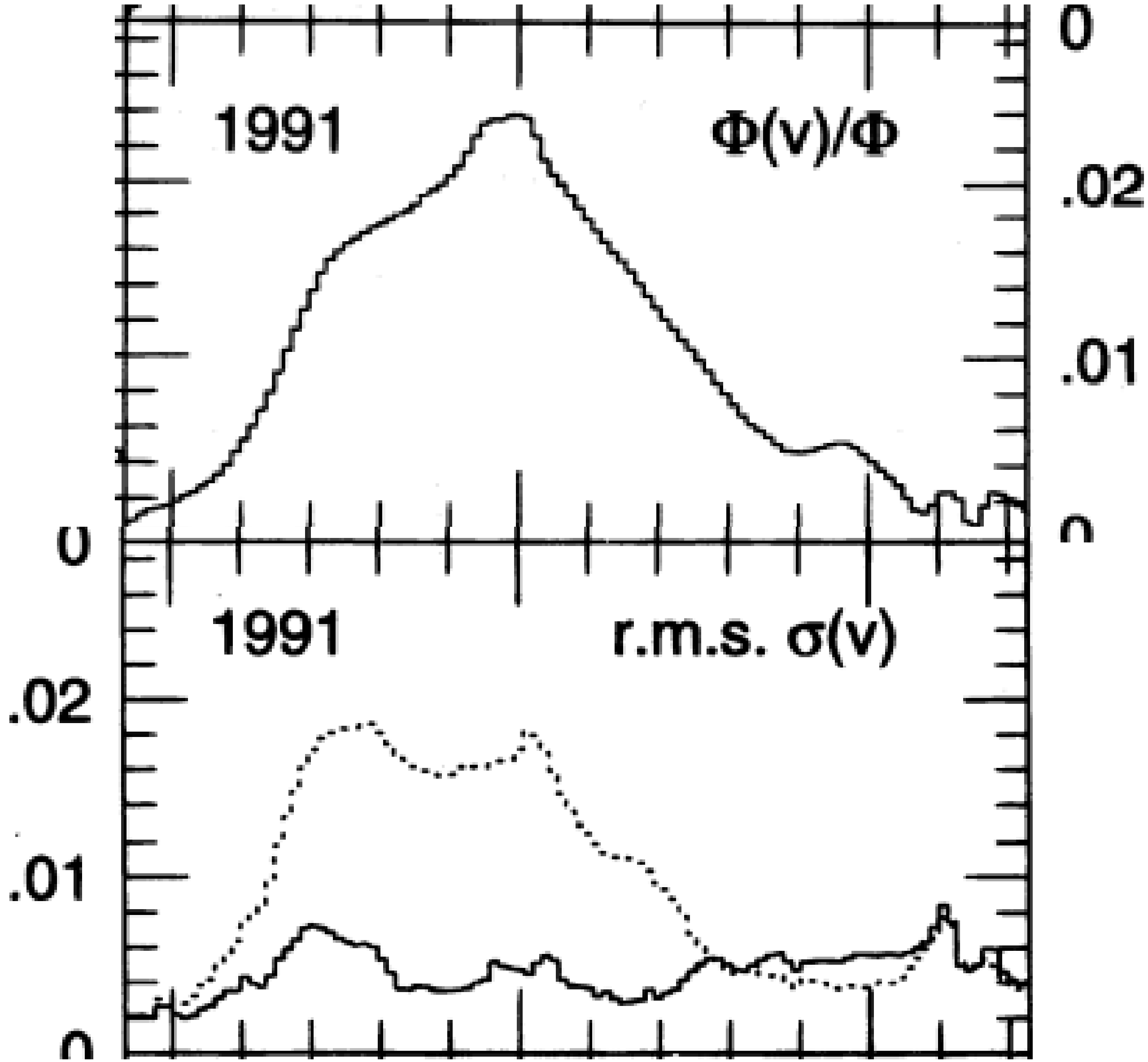
Wanders & Peterson (1996)



Sometimes only parts of profile vary . . .

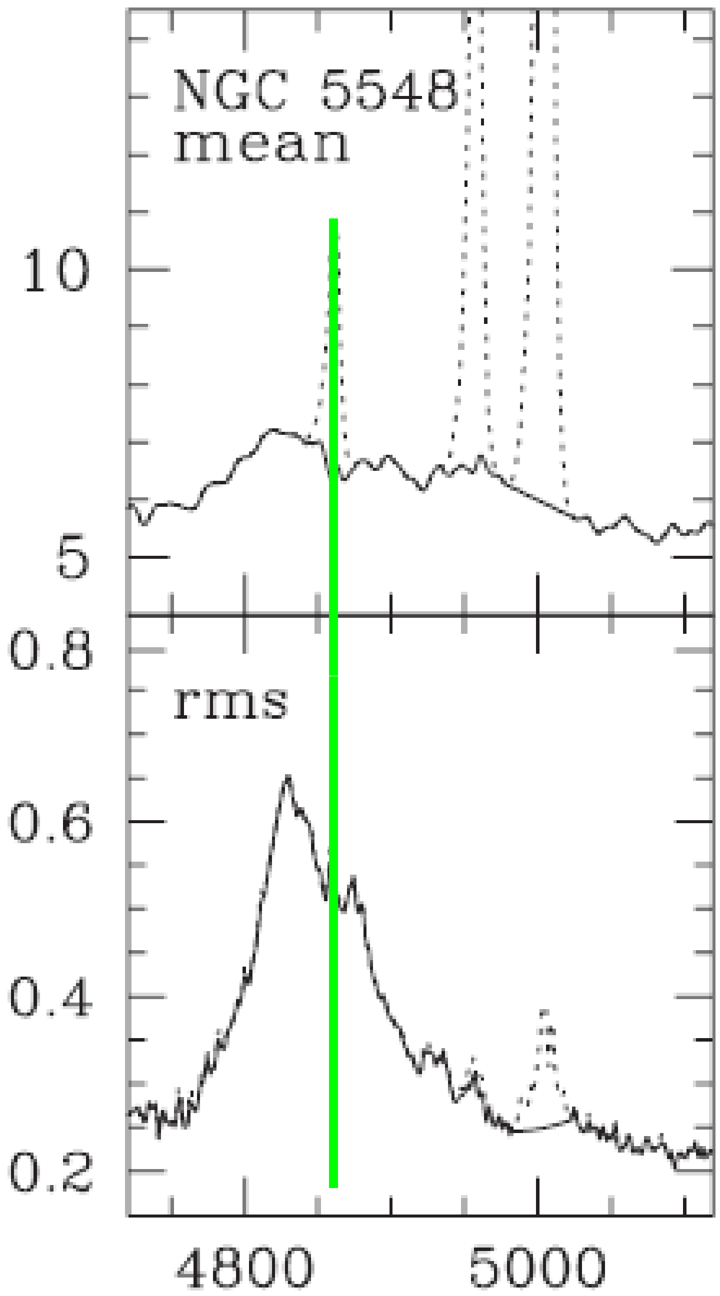


Kollatschny & Dietrich (1996)



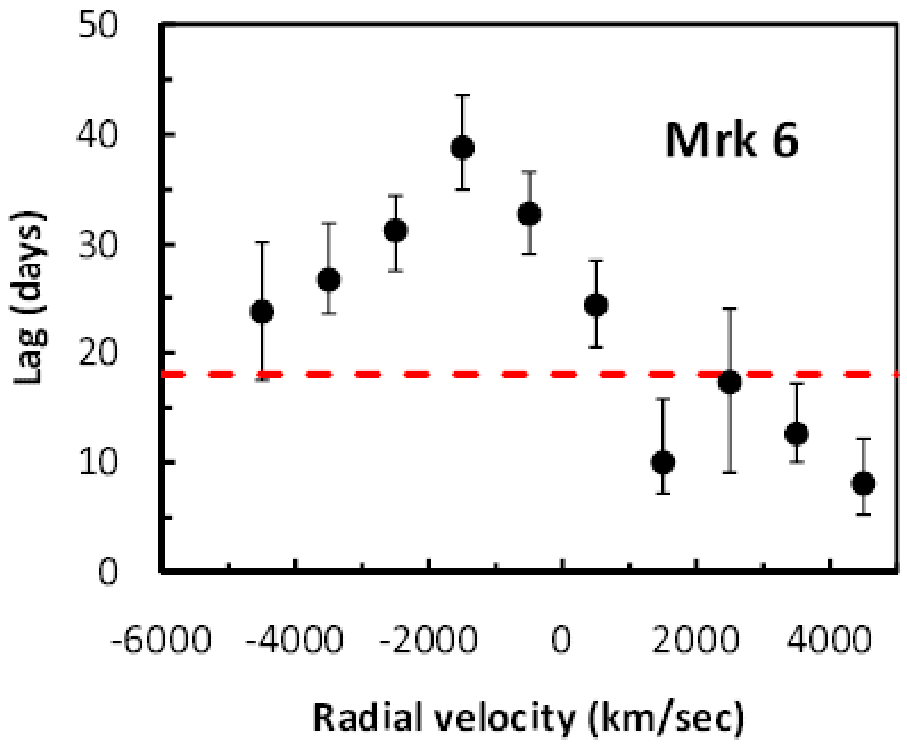
Wanders &
Peterson (1996)

Profiles change
in odd ways!



Denney *et al*. (2009)

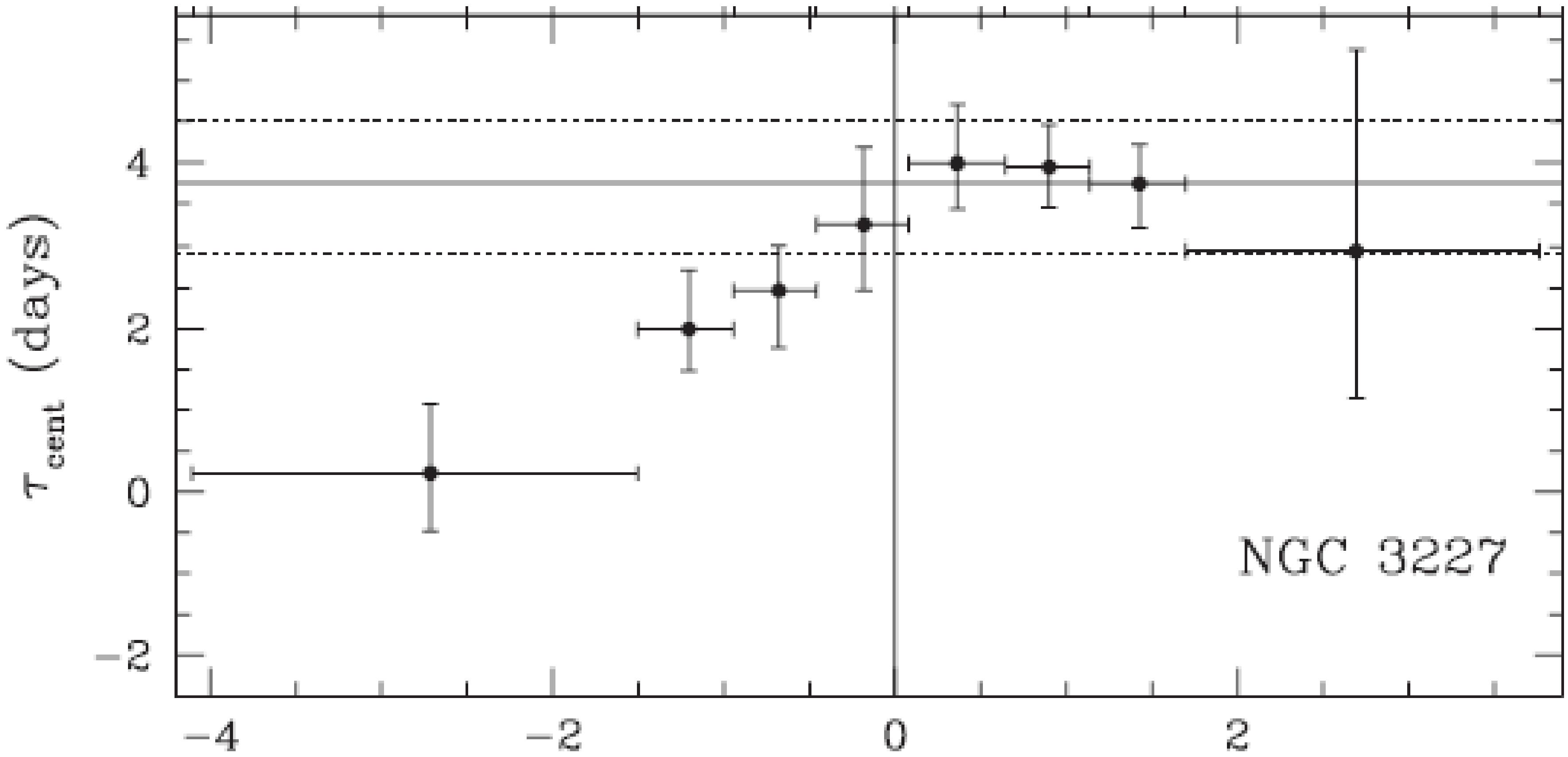
Conflicting inflow/outflow kinematic signatures



OK?

(Adapted from Sergeev, Pronik, & Sergeeva (1999))

Reverberation mapping signature of outflow??!!

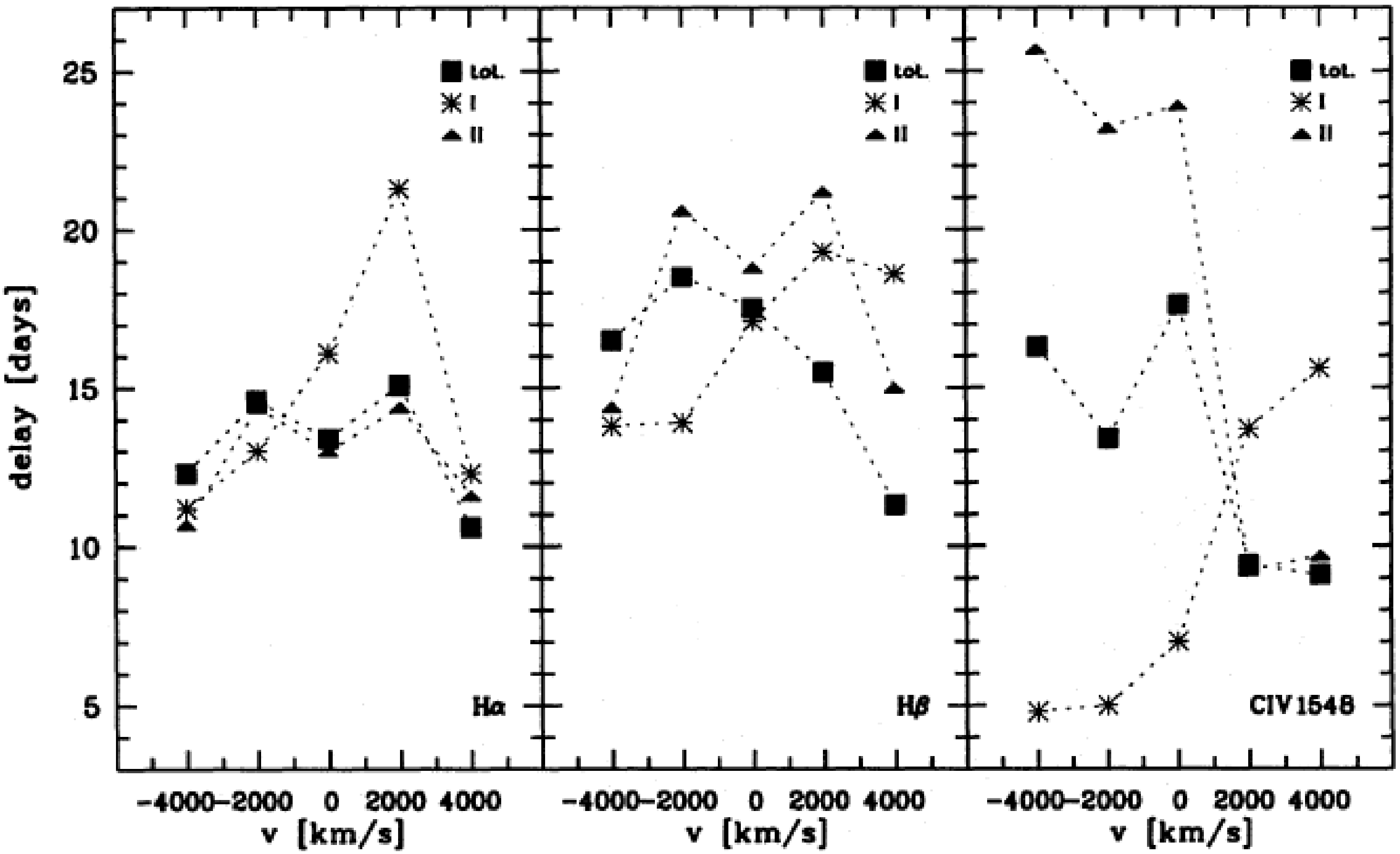


Denney *et al*. (2009)

What an outflow looks like:

- Outflow

Whole kinemetic signature can change in 2 months!!!

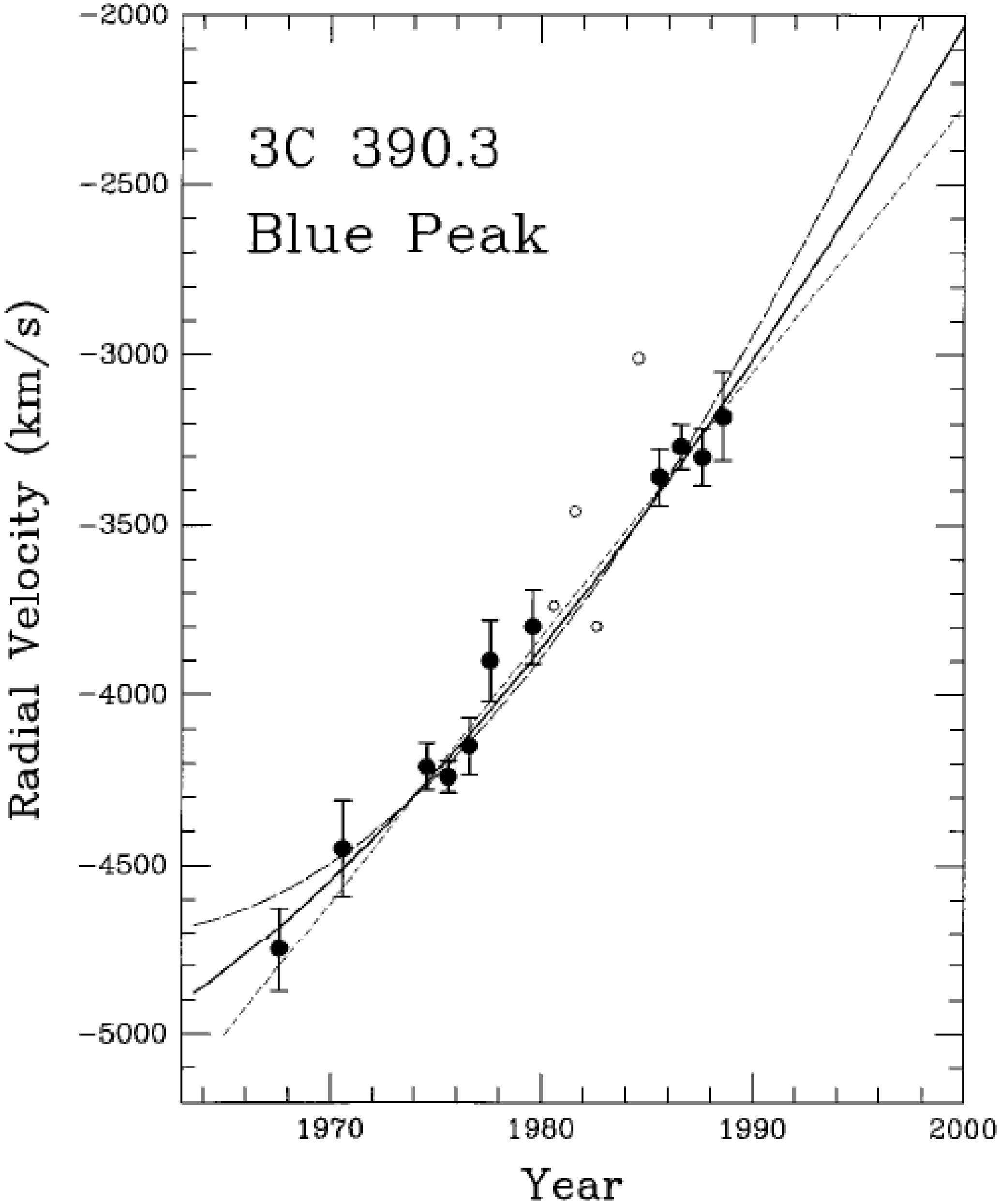


Kollatschny & Dietrich (1996)

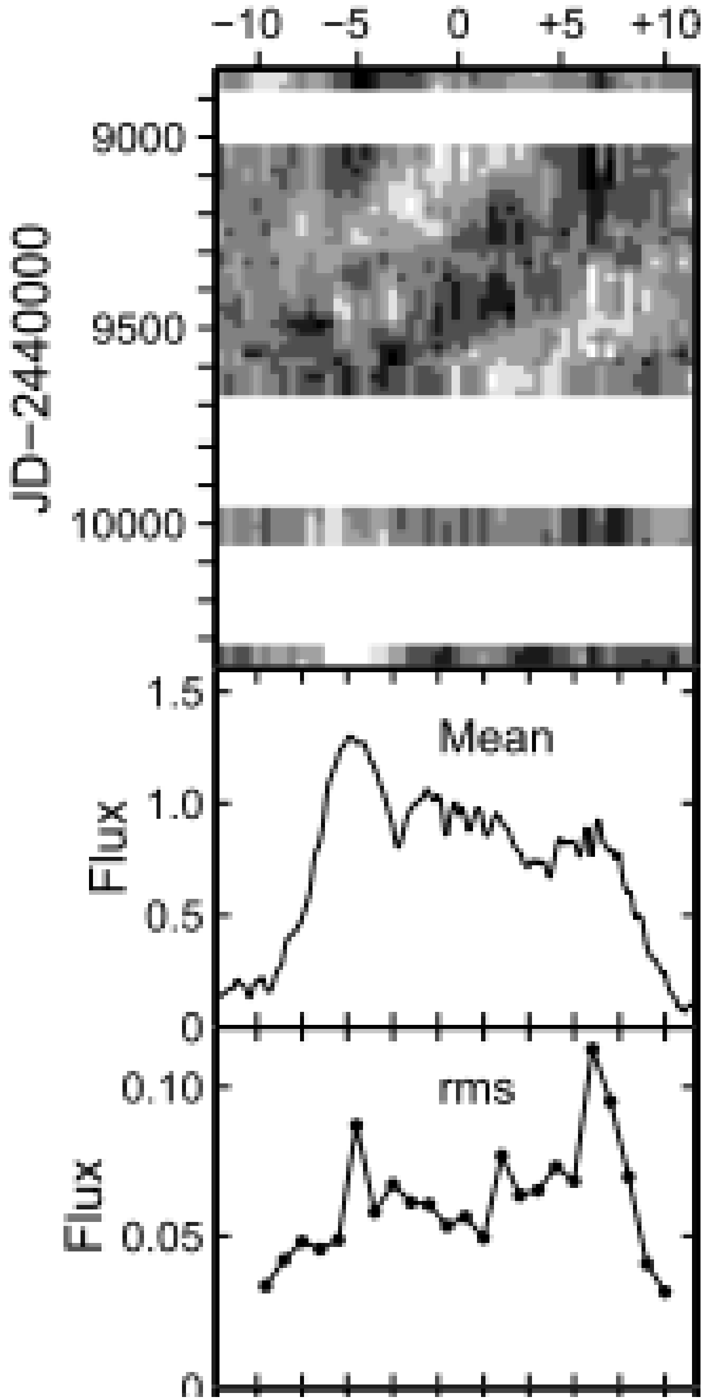
How the kinematics appear to change in 2 months

- Outflow
- Inflow

Peaks appear to orbit

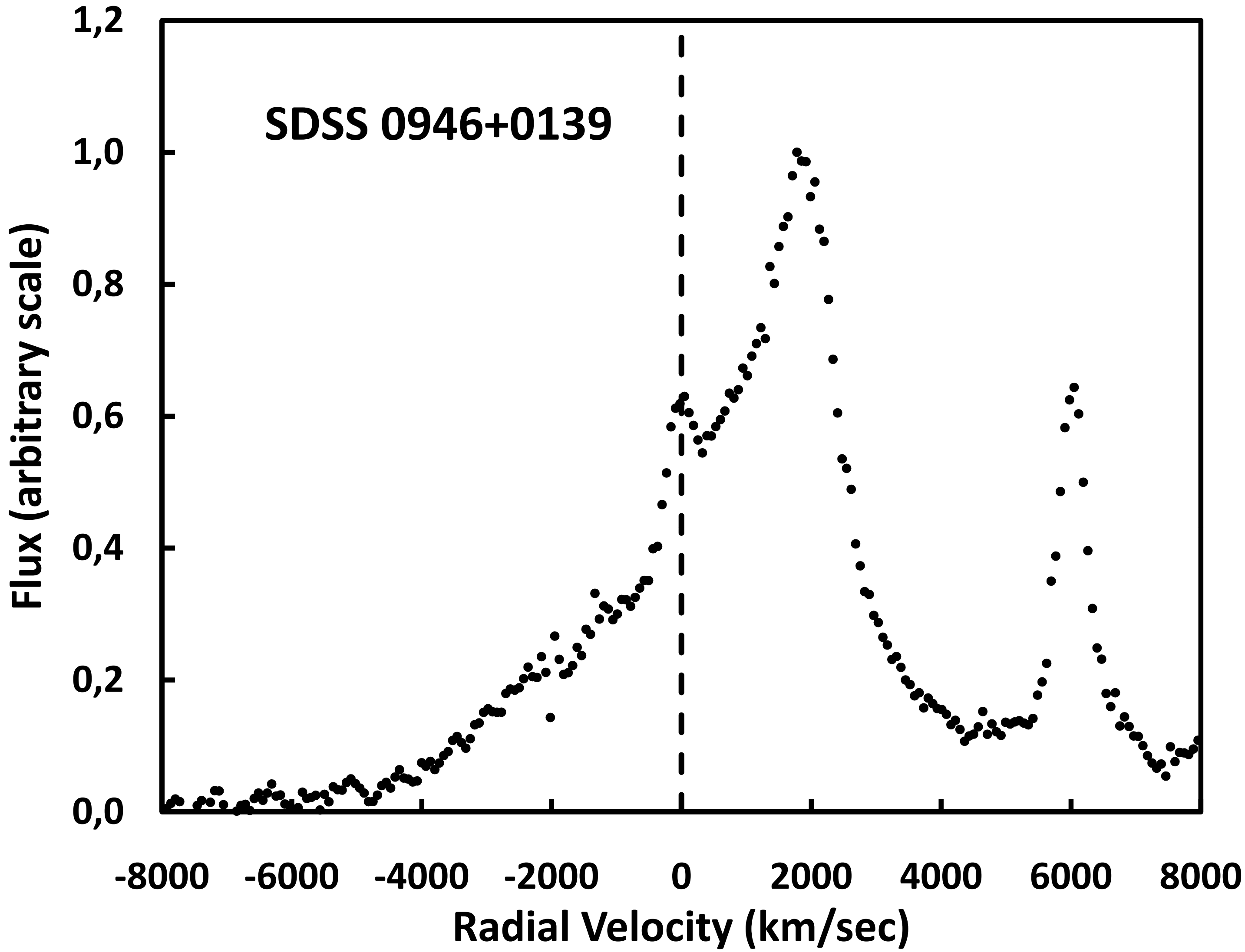


Gaskell (1996)



Sergeev et al. (2001)

Can we exlain a profile this extreme?



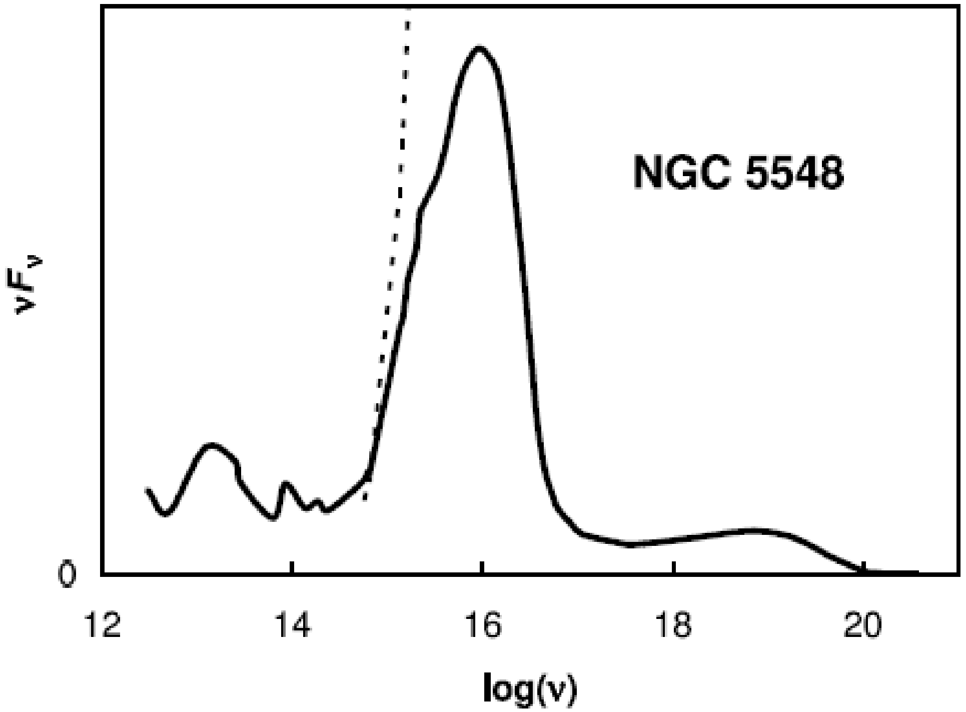
(The most extreme of ~ 10,000 SDSS spectra in **Boroson & Lauer 2010**)

A NEW AGN VARIABILITY PARADIGM

Details in **Gaskell (2008)**

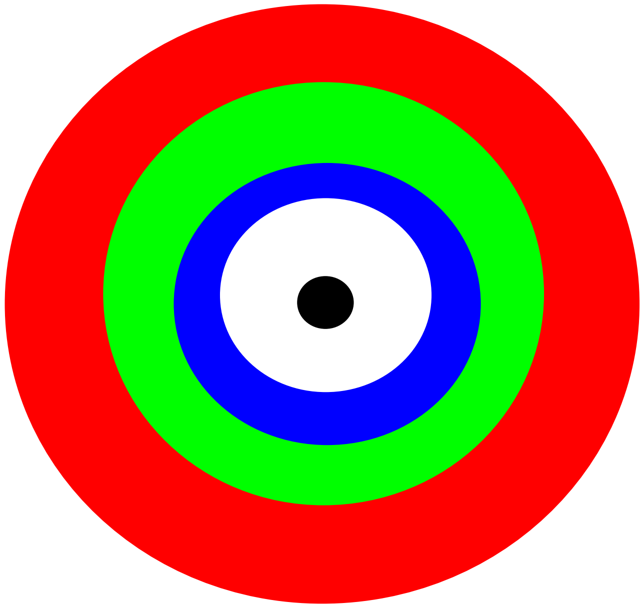
How AGNs are powered

- Energy mostly arises from accretion "disc"
- Temperature structure well understood (see Gaskell 2008)
- SED is the result of summing Planck curves at different temperatures (Pringle & Rees 1972; Shakukra & Sunyaev 1973)
- However, steady disc picture totally wrong – variations are VERY strong $\Rightarrow$ **the variability IS the energy generation** (Gaskell 2007, 2008)



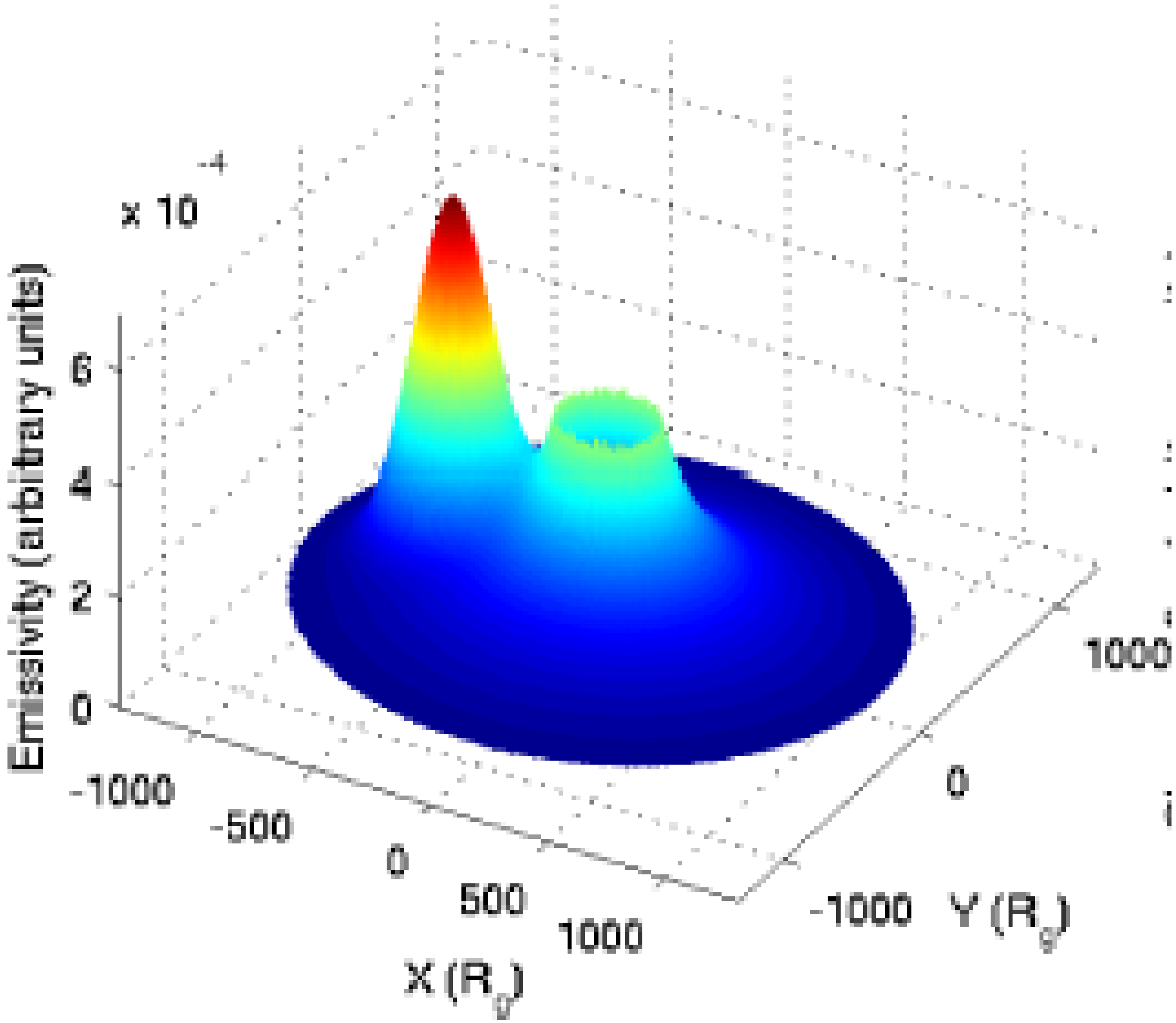
- Photons in each observed spectral region come mostly from where the Plank curve peaks.
- $\therefore$ each spectral region comes *from within an annulus*.

- Photons in each observed spectral region come mostly from where the Plank curve peaks.
- ∴ each spectral region comes *from within an annulus*.



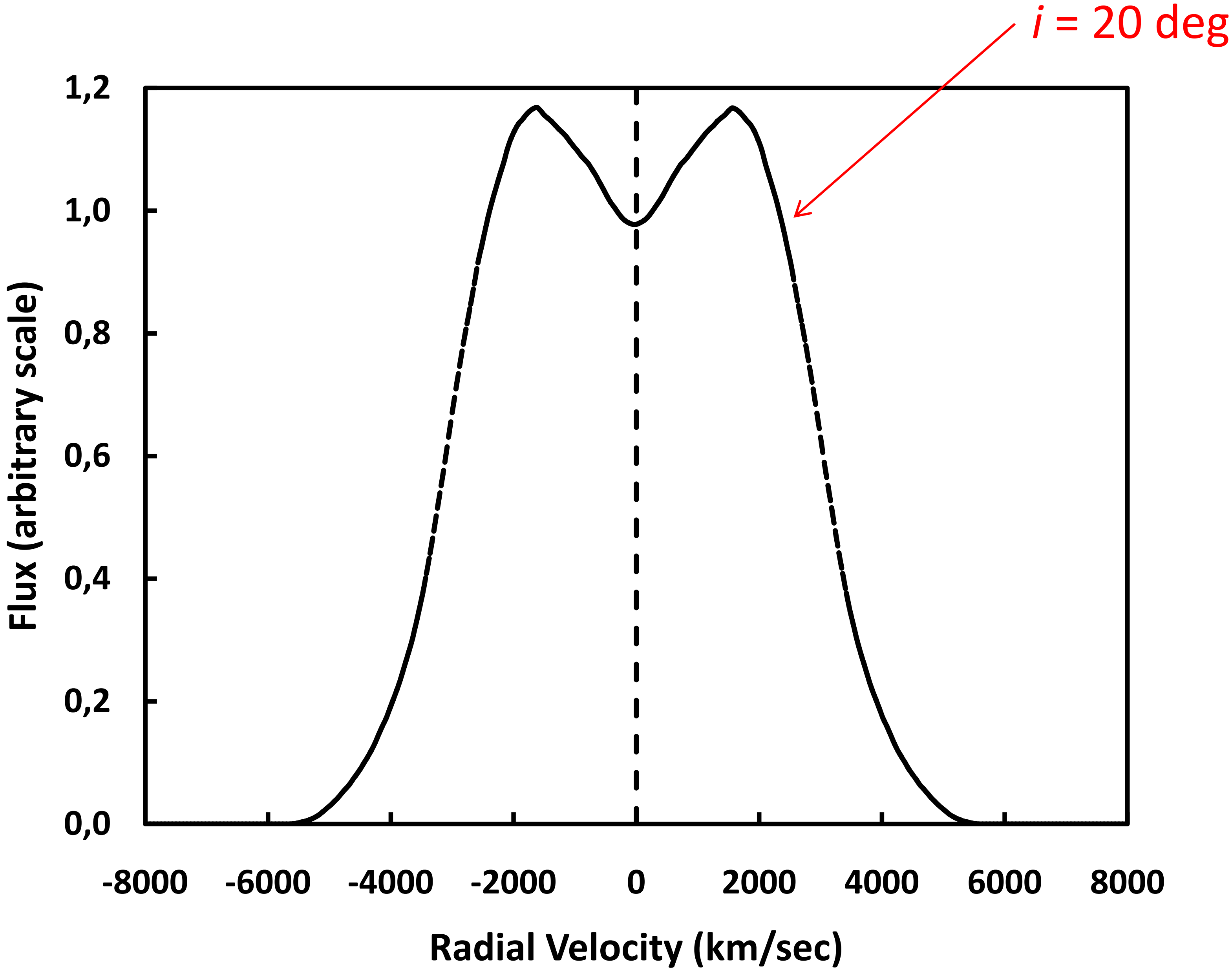
- When a spectral varies – the annulus cannot vary simultaneously.
- **∴ Variations have to be asymmetric**

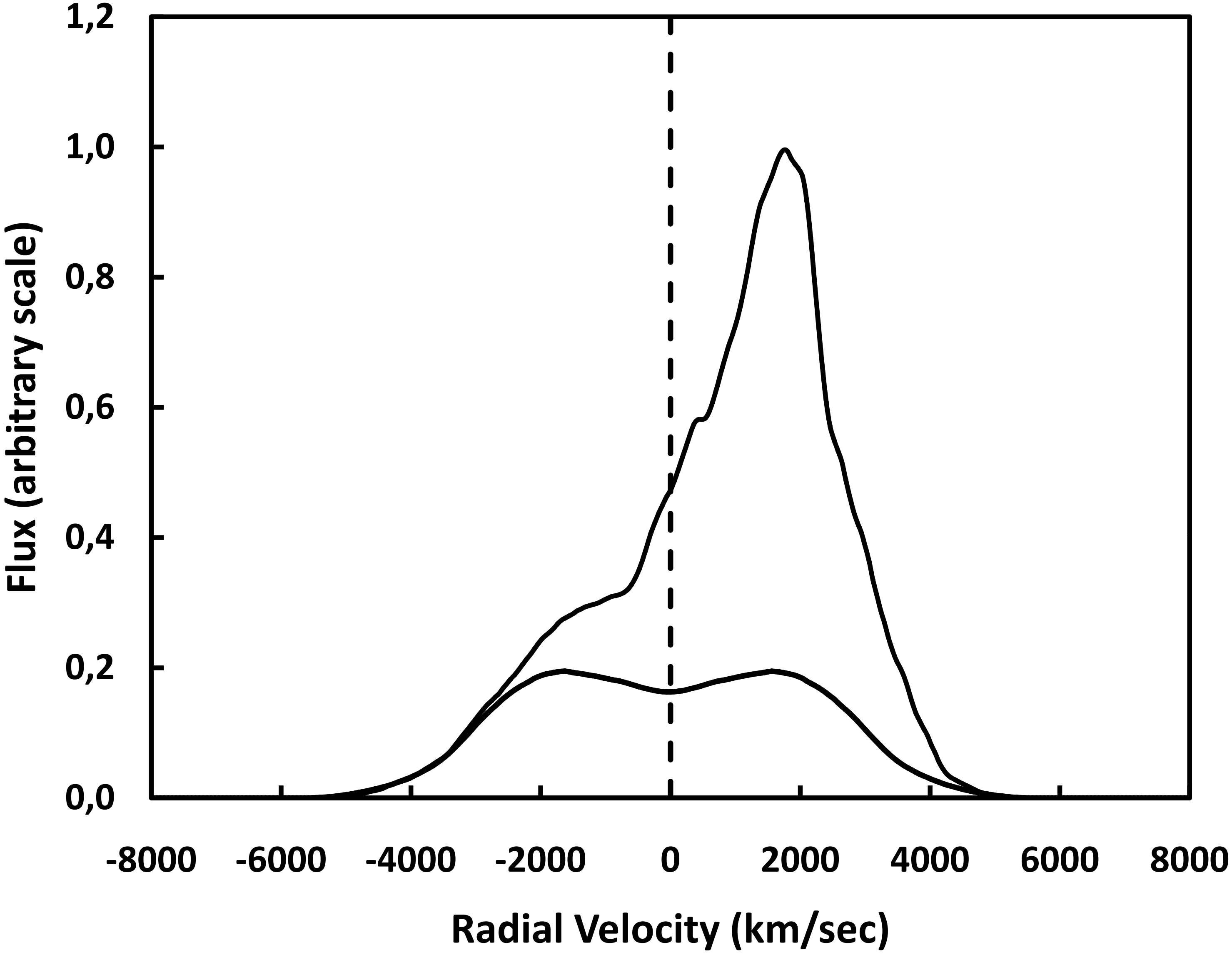
Jovanovic *et al.* (2010)



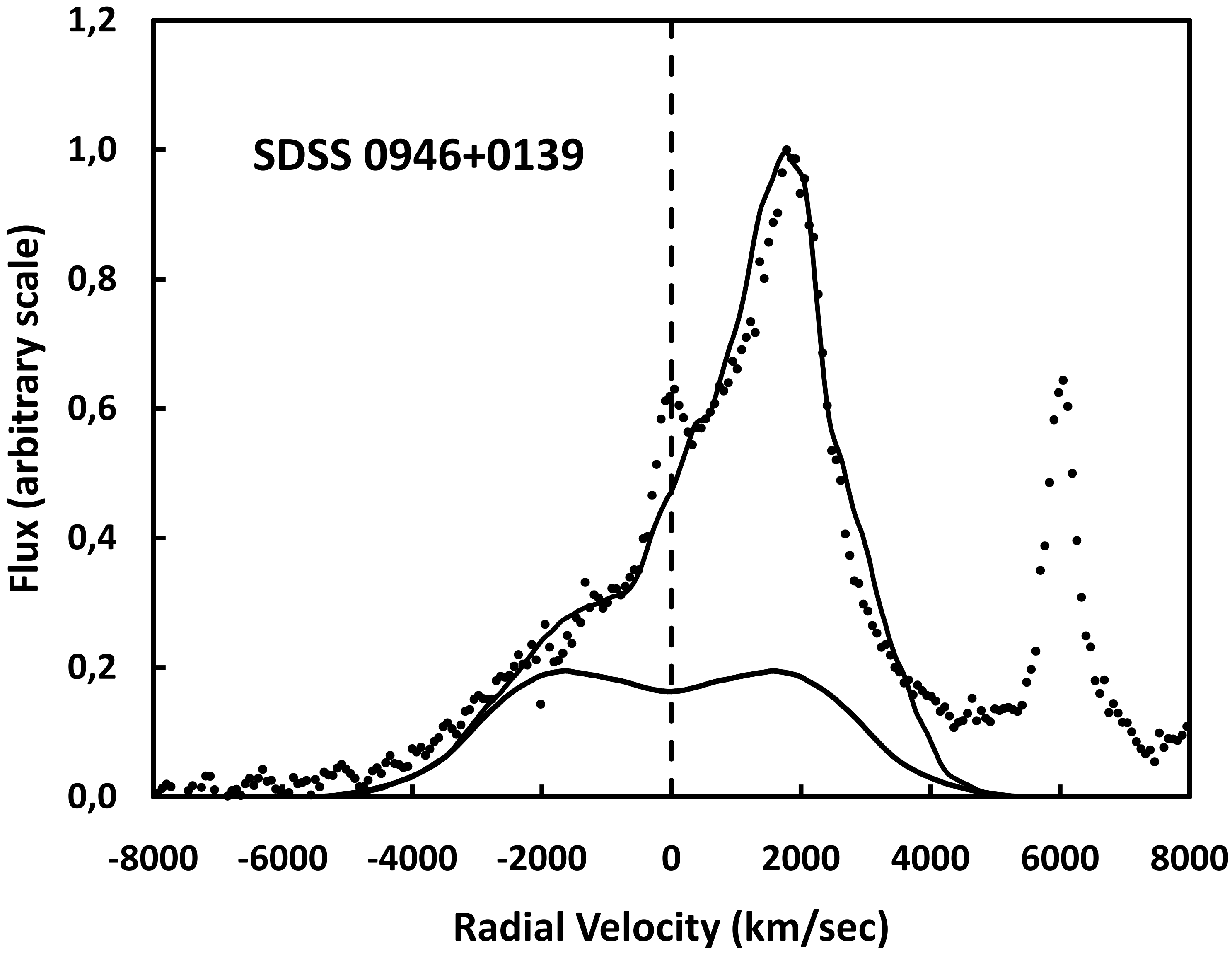
- Off-axis illumination

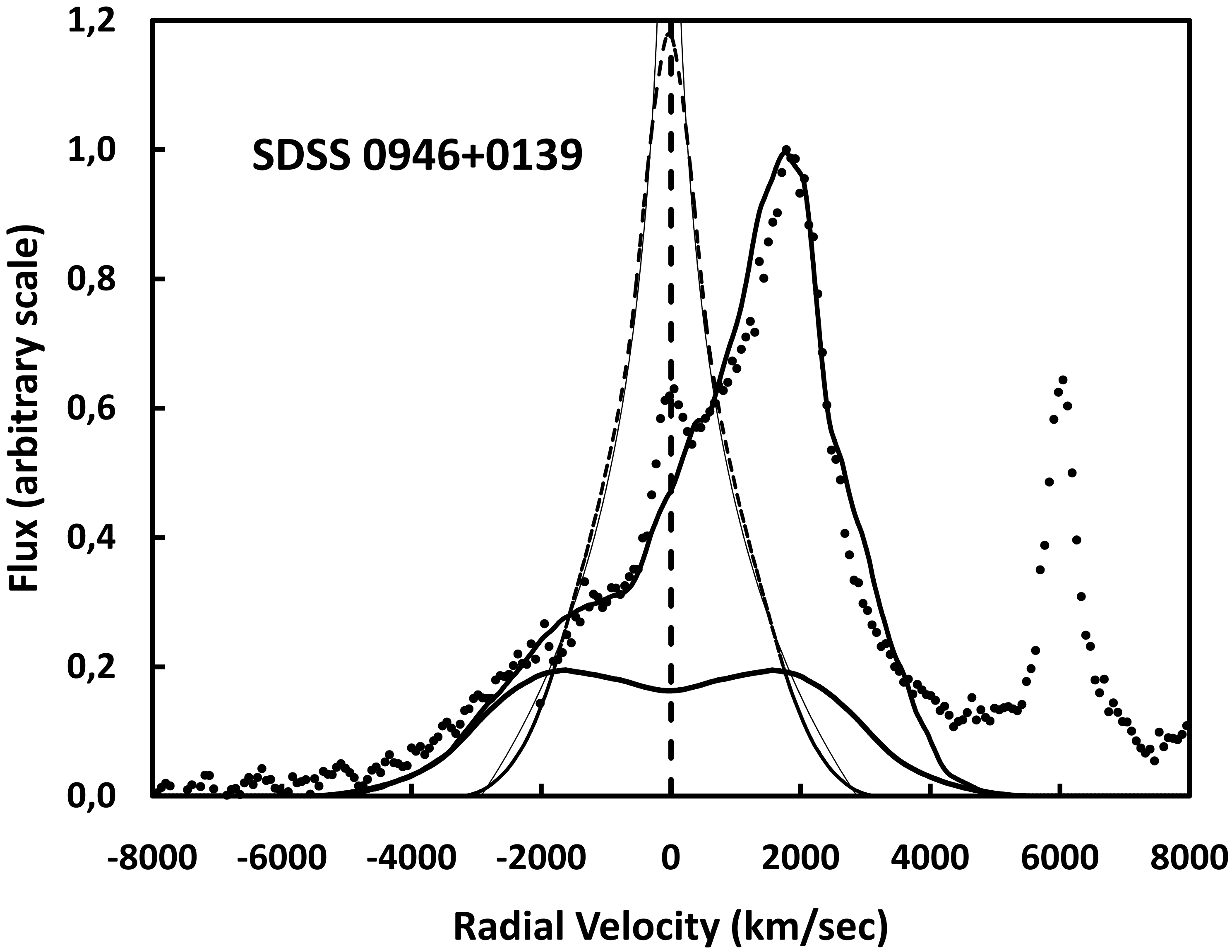
Basic profile for central illumination:





1,2
1,0
0,8
0,6
0,4
0,2
0,0
Flux (arbitrary scale)
-8000
-6000
-4000
-2000
0
2000
4000
6000
8000
Radial Velocity (km/sec)


SDSS 0946+0139
Flux (arbitrary scale)
Radial Velocity (km/sec)
1,2
1,0
0,8
0,6
0,4
0,2
0,0
-8000
-6000
-4000
-2000
0
2000
4000
6000
8000



SDSS 0946+0139
Flux (arbitrary scale)
1,2
1,0
0,8
0,6
0,4
0,2
0,0
-8000
-6000
-4000
-2000
0
2000
4000
6000
8000
Radial Velocity (km/sec)

Consistent with profile variability

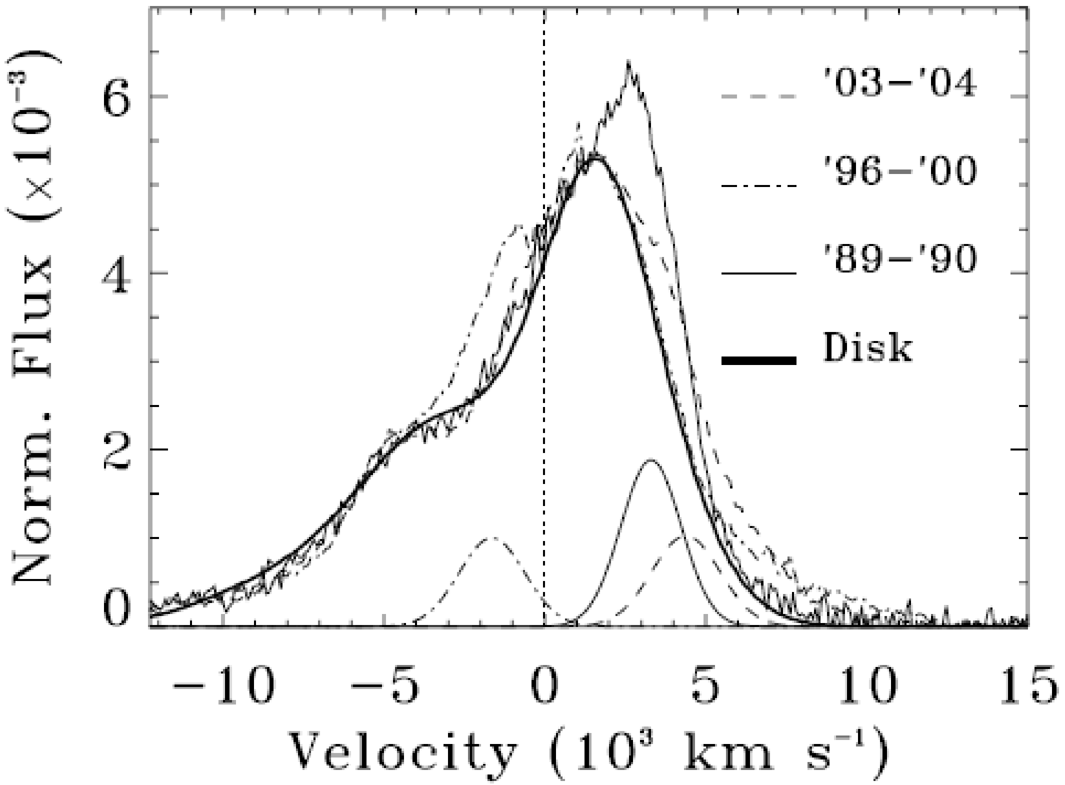
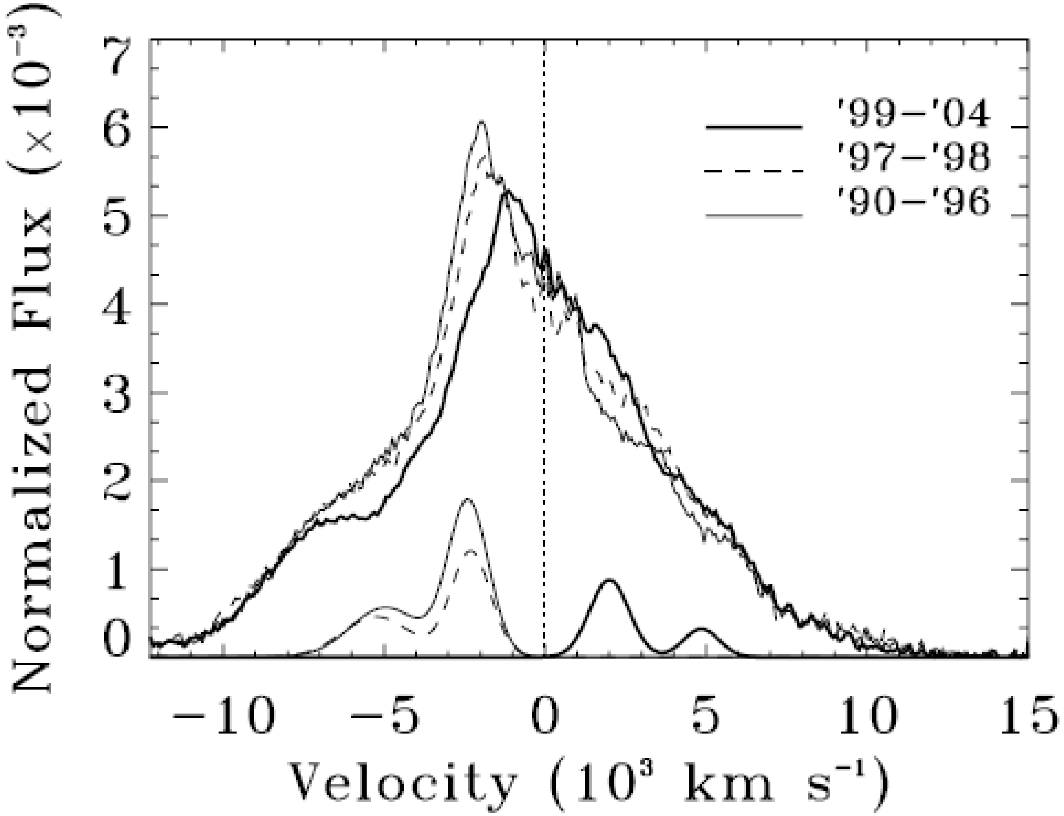


FIG. 30.—Mrk 668: Averaged broad Hα profiles that demonstrate the dramatic changes in the red central peak. The thick solid line shows the eccentric disk fit to the nonvarying portion of the profile. The variations in the profile are modeled with Gaussian excesses superposed on the eccentric disk profile that drift from the red side to the blue side of the profile and back. These are shown at the bottom of the figure, following the line style convention of the legend. See also the discussion in § 4.5.3.

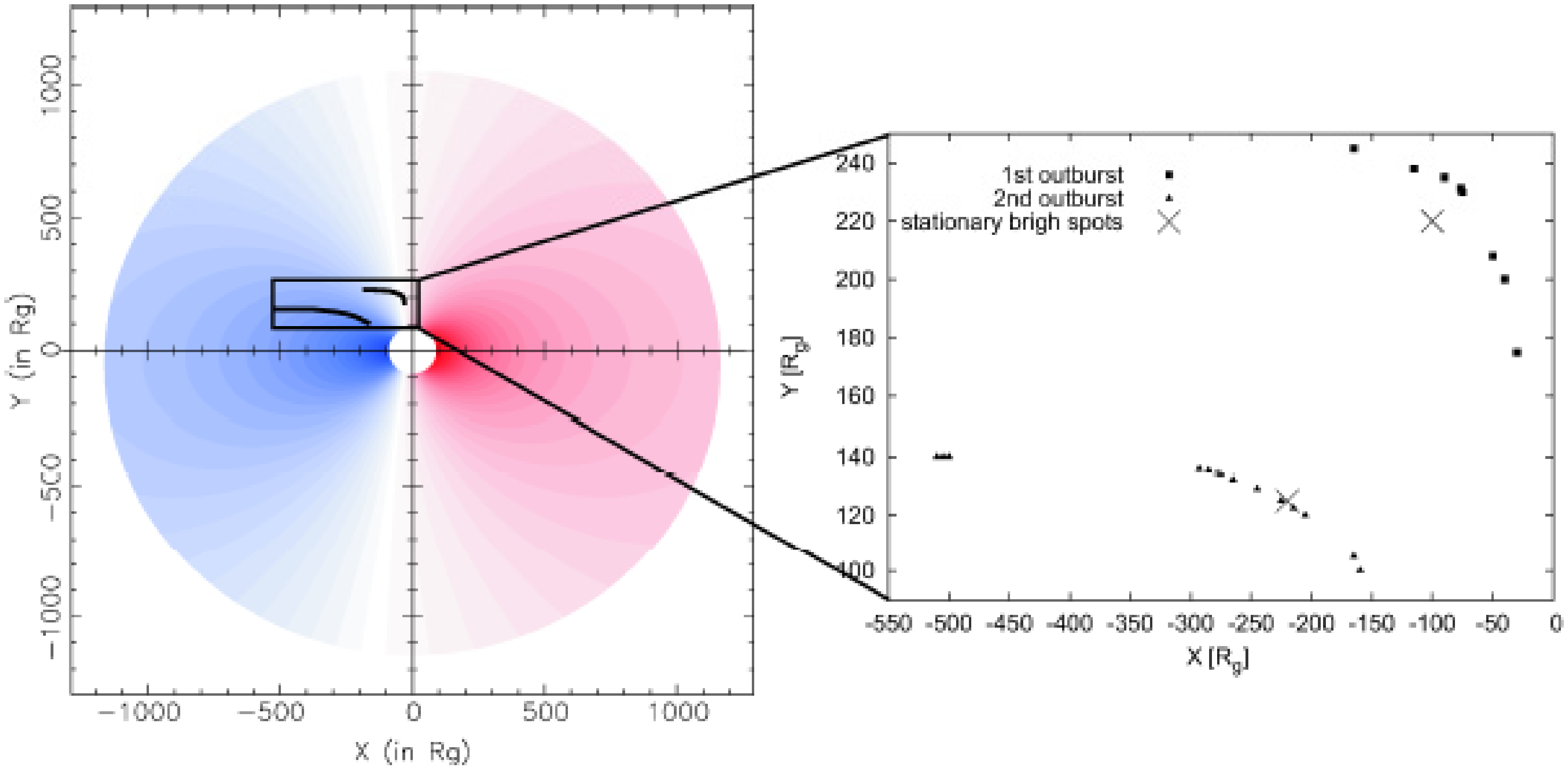
Gezari *et al.*



Gezari *et al.*

FIG. 32.—3C 227: Averaged broad Hα profiles that demonstrate the dramatic changes in the blue peak. Gaussian fits to the excess that appears to traverse from the blue to the red side of the profile are also shown, following the line style convention of the legend.

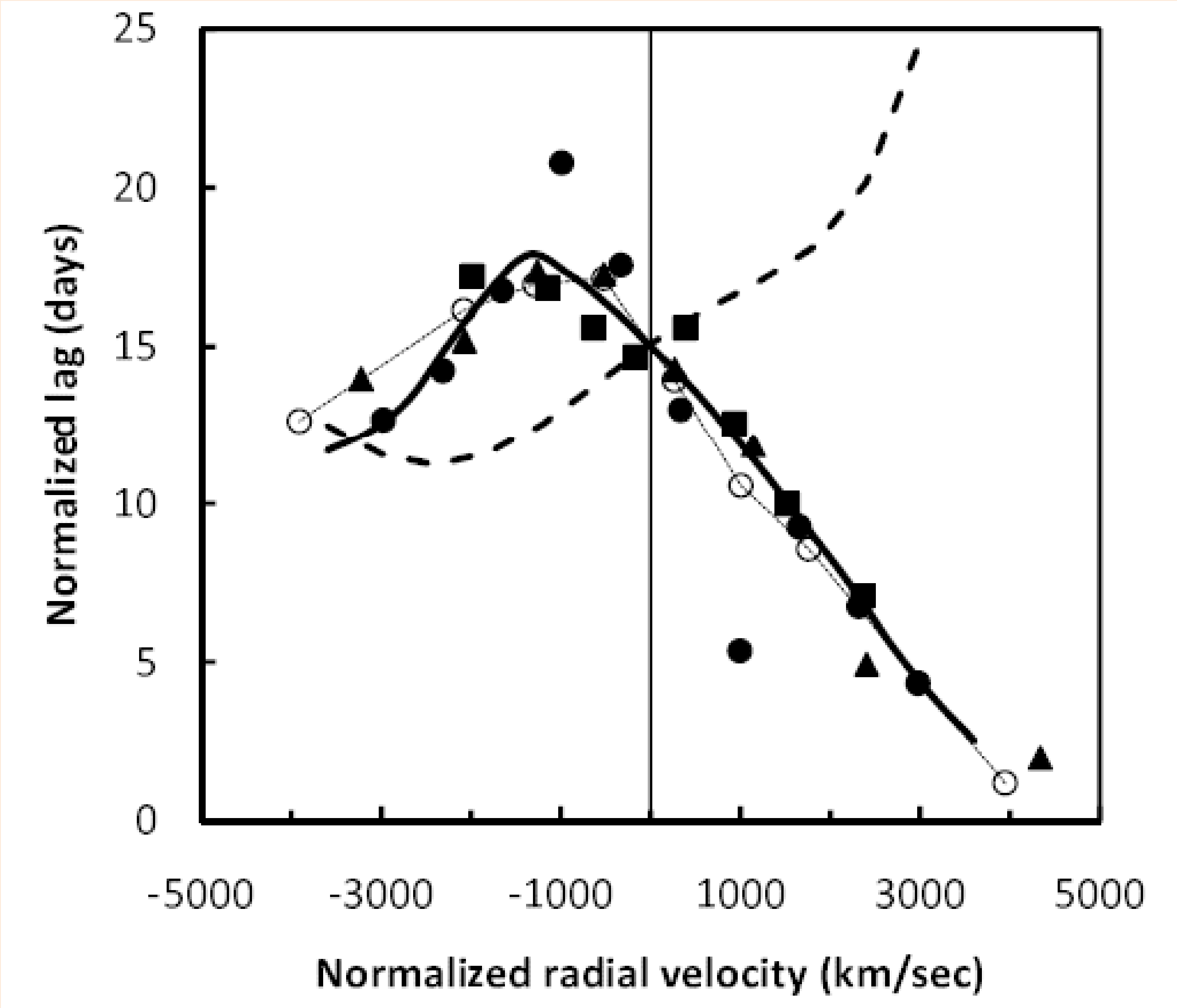
You can model flare motion!



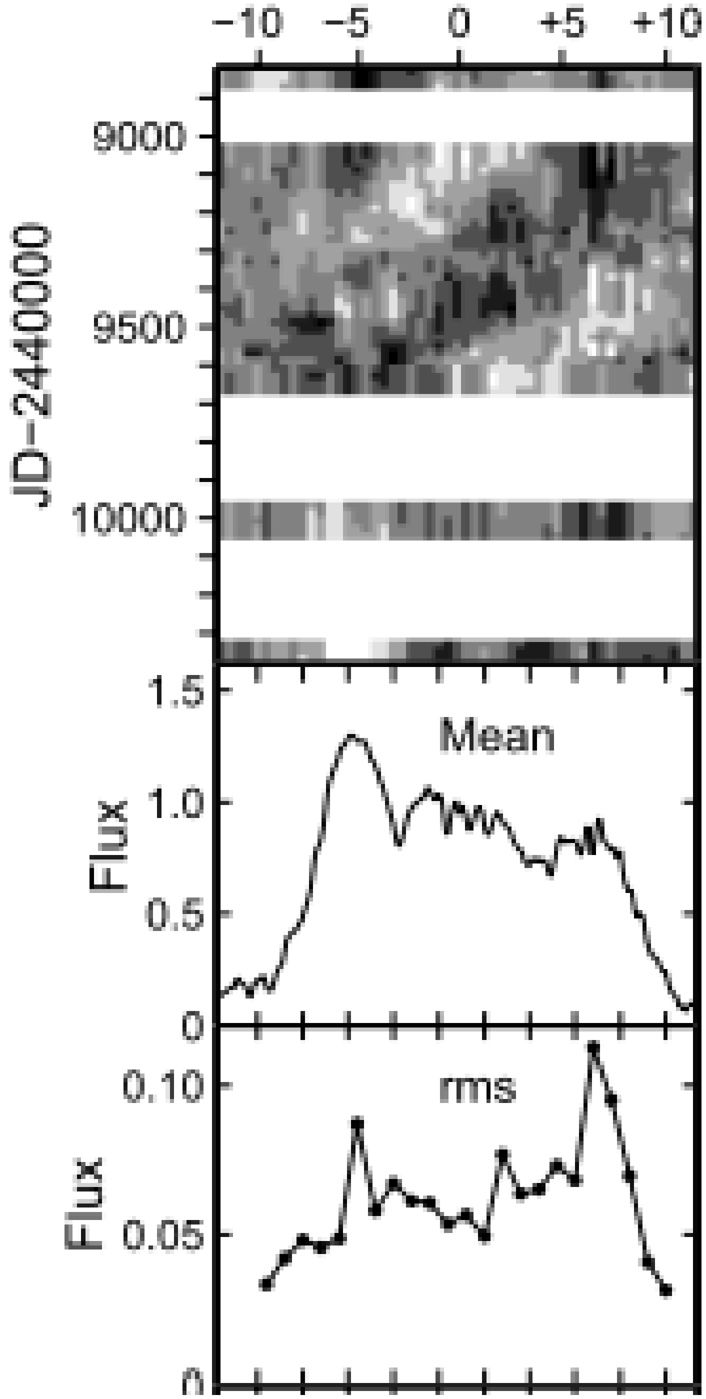
Jovanovic *et al*. (2010)

Explains diverse kinematic signatures

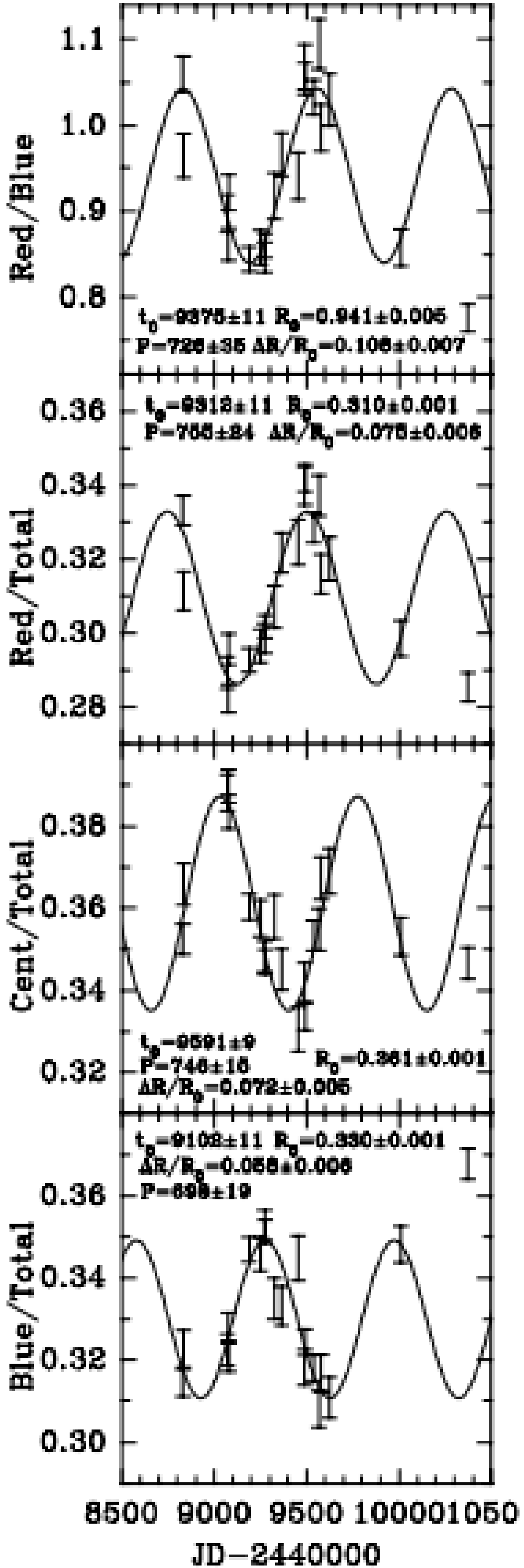
- Outflow?
- Inflow?
- Off-axis illumination
- OFF-AXIS ILLUMINATION EXPLAINS ALL VELOCITY DEPENDENCE OF LAGS



- It’s the **continuum flares** that are orbiting, not blobs in the BLR.
- Solves speed problem
- Solves Keplerian shear problem



Sergeev et al. (2001)



Shapovalova *et al.*

CONCLUSIONS

- The GKN picture works well – **AGN BLRs very similar**
- A new AGN variability paradigm: **VARIABILITY IS STRONGLY OFF AXIS**
- Explains profiles, profile variability, lags, transfer functions, velocity-delay diagrams
- Means that **we have reached the limits of reverberation mapping** (can't get perfect knowledge with infinite observing).
- Makes it hard to find evidence of supermassive BH binaries
- Makes modelling more complicated.
- We can learn a lot about where flares are happening
- Can learn **a lot more** about BLR structure
- **STAY TUNED FOR THE NEXT SEQUEL!**