New Paradigms for the Nature of the Line- and Continuum-Emitting Regions of Active Galactic Nuclei.

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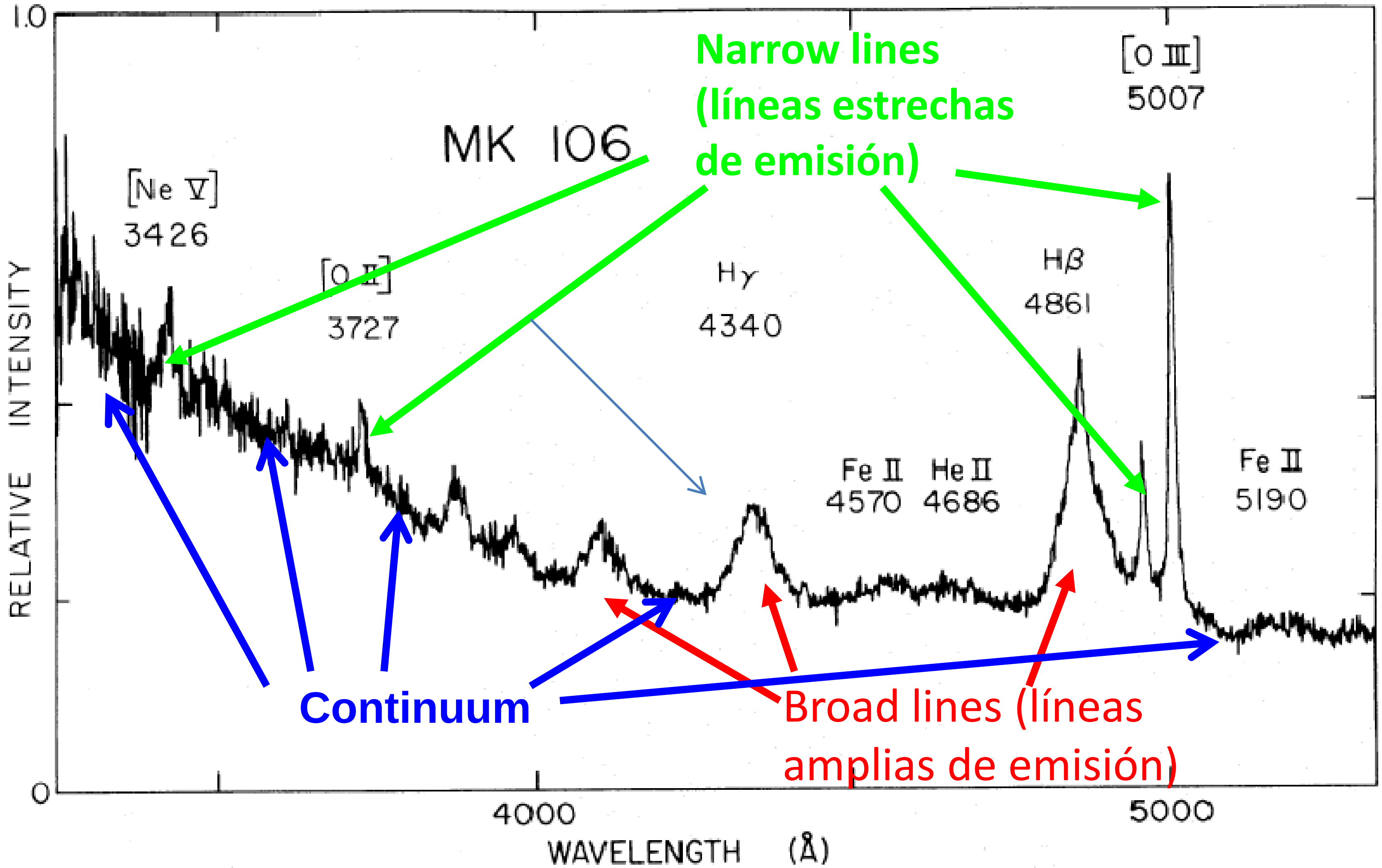
DEPARTAMENTO FISICA Y Astronomía

… Line and Continuum Emission…



… the Nature of …

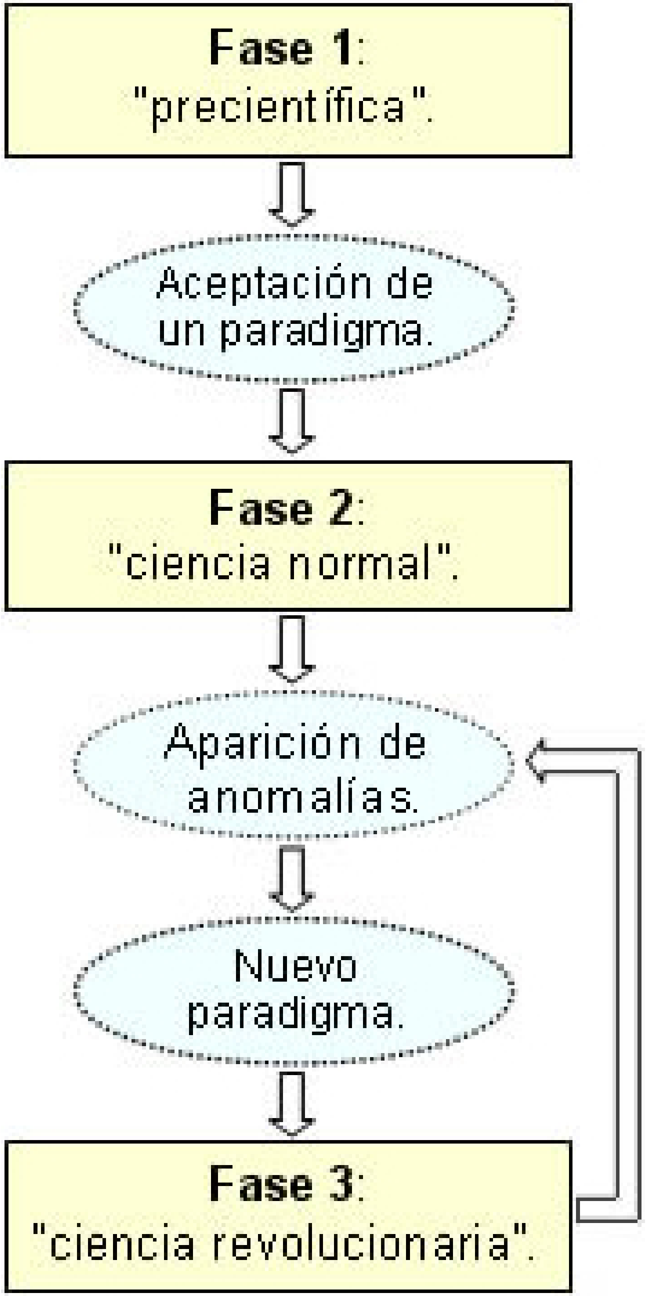
- What something is like
- How it works

Focus here only on the most basic things:

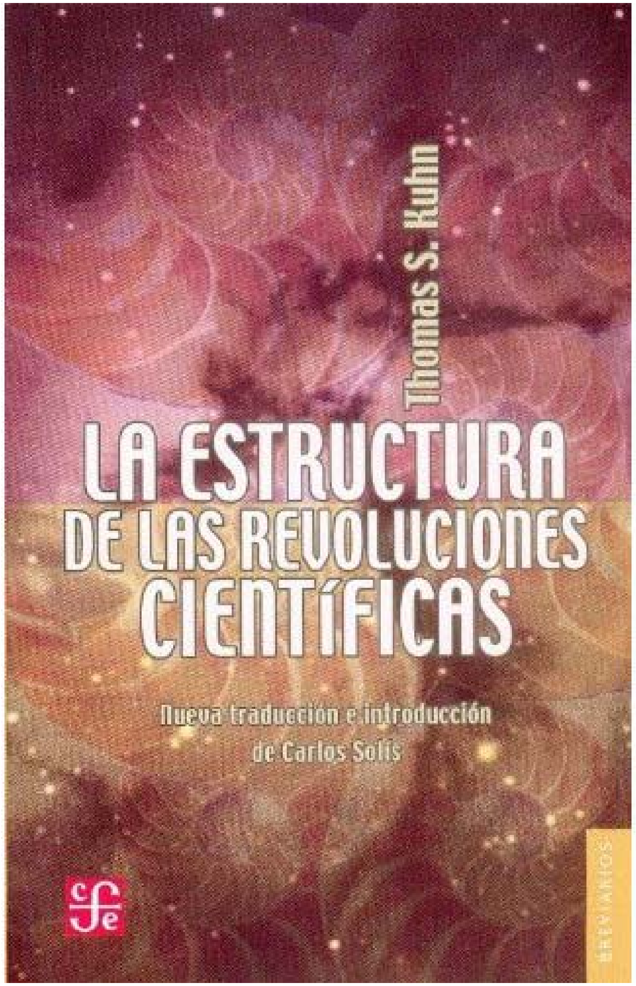
- What things <u>look like</u>
- How things <u>move</u>

Paradigms

- Thomas S. Kuhn (1962) *The Structure of Scientific Revolutions*



Today: how my understanding of AGNs has gone through a Kuhnian revolution



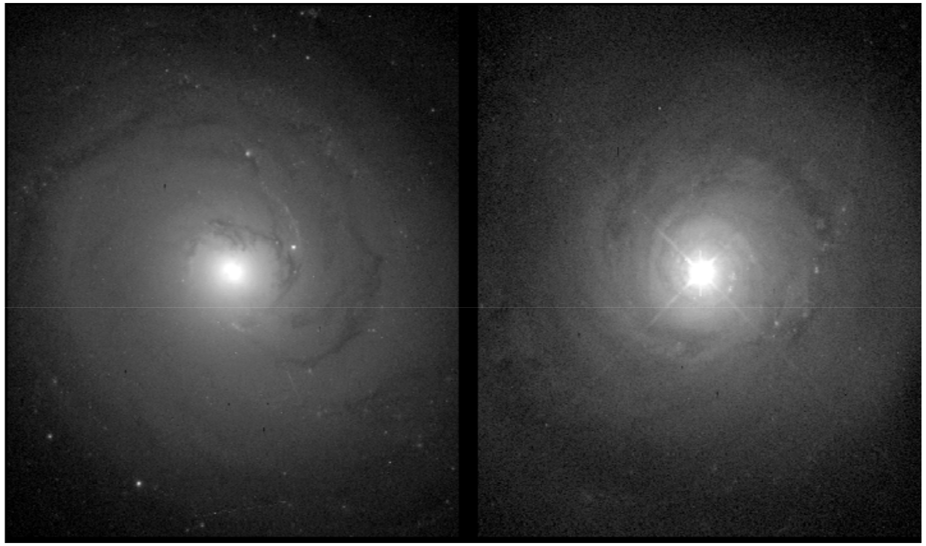
OUTLINE

1. The 2009 AGN paradigm
2. The crisis – a lot of weird observations
3. The new paradigm and how it explains the weird things

Where to read more about this:

- Review of the broad line region (the 2009 paradigm): - Gaskell 2009, *New Ast. Rev*. **53**, 140
- Review of continuum and continuum variability – Gaskell 2008, *Rev. Mex. A & A (Ser. de Conf.)*, **32**, 1
- The new paradigm – Gaskell 2010, *ApJ.,* submitted [arXiv:1008.1057]

AGN basics – I.



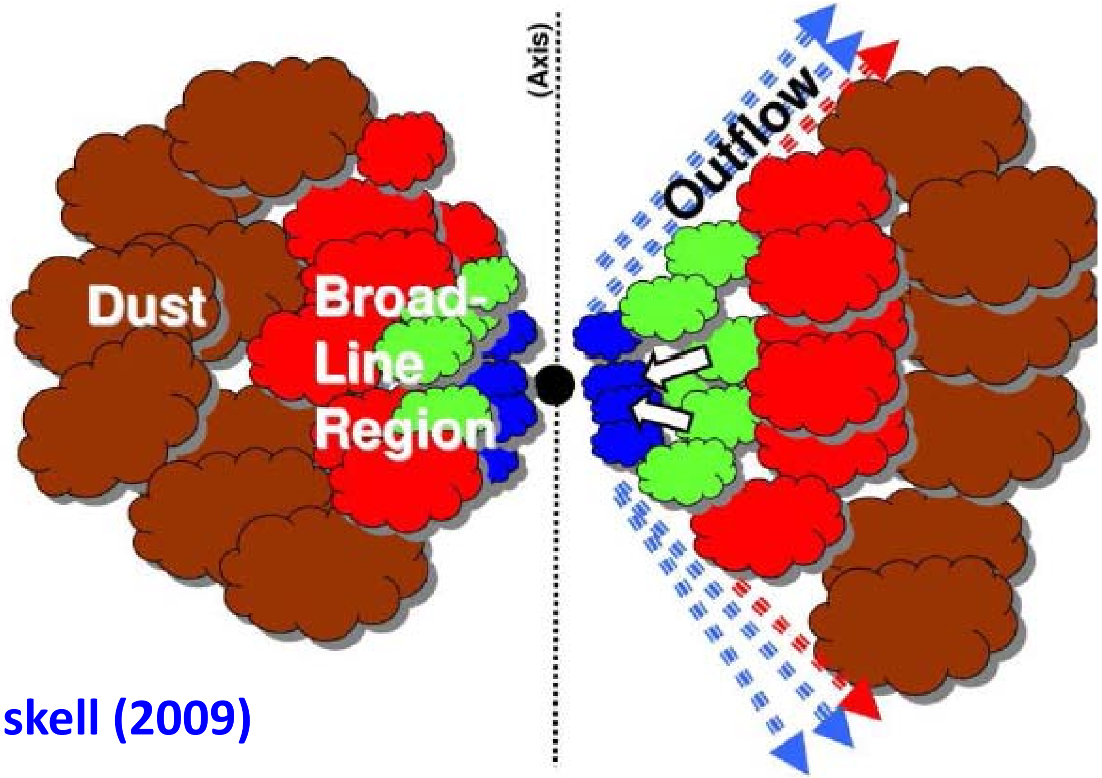
- Molecular gas driven into center of a galaxy
- Forms dusty torus (like donut)
- Material spirals inwards (magneto-rotational instability provides viscosity)
- Potential energy converted to thermal energy

AGN basics – II.

Gaskell, Klimek & Nazarova (2007) (“GKN”) picture:

- Dust sublimates when $T = T_{sub}$
- Remaining material is “Broad-Line Region”(BLR)
- Accretes onto BH
- (Some material comes off as a wind)

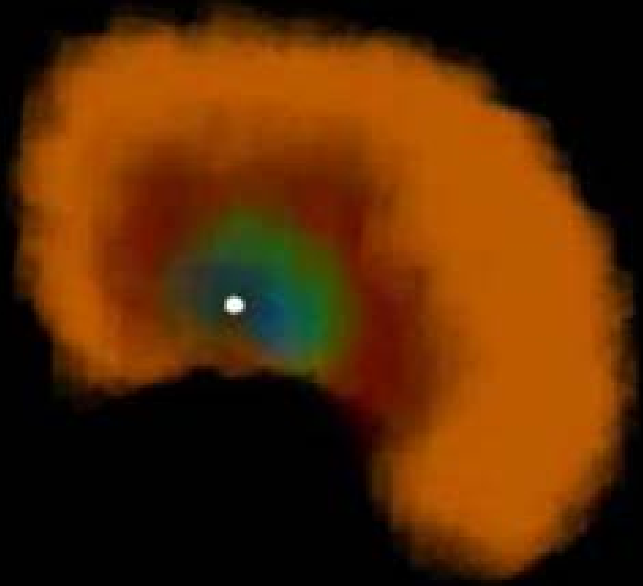
What this looks like:

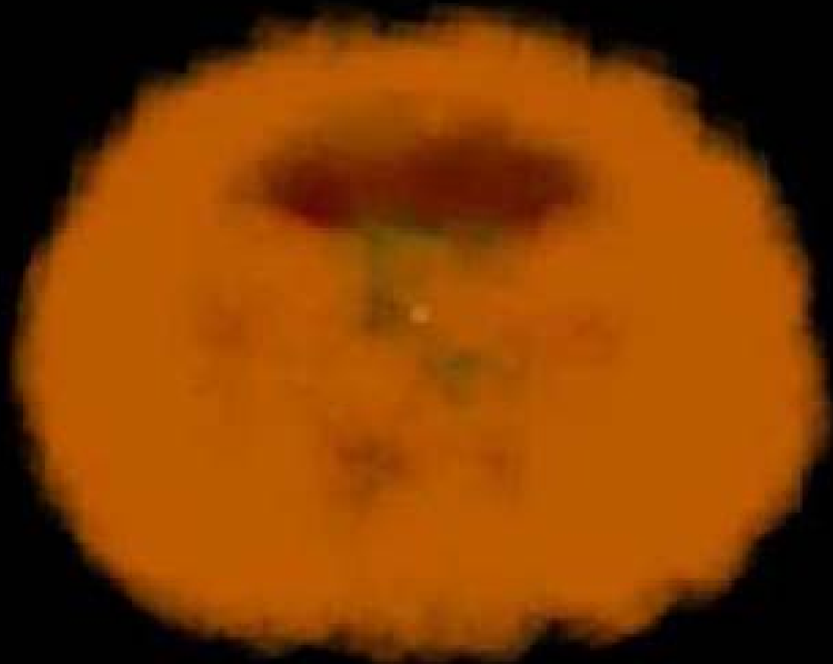


Gaskell (2009)

- High BLR covering factor (to explain line strengths)
- Hole at the pole (to avoid seeing absorption)
- Self-shielding – highly stratified

Computer-generated images:





"BIRD'S NEST"

Gaskell (2009)

Images by Daniel Gaskell

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!)

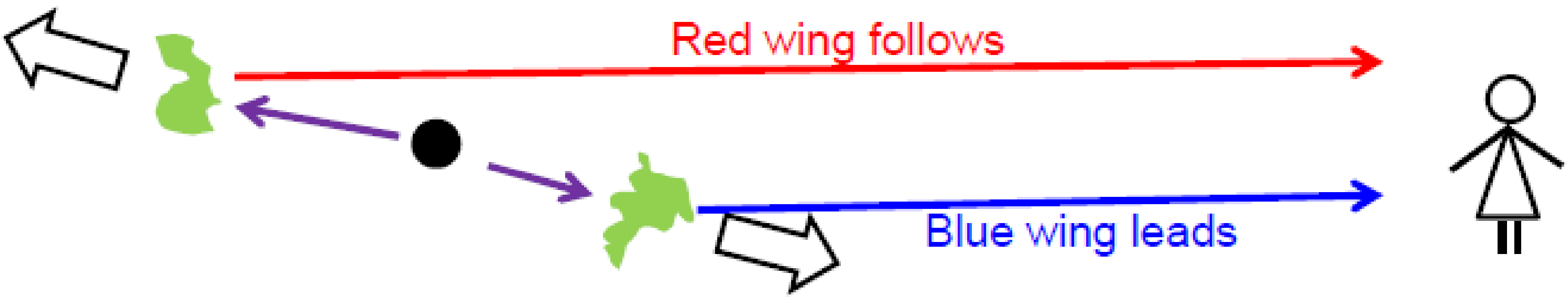
Now add inflow:

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

[Show MHD movie]

Important point: the BLR is not outflowing: velocity-resolved reverberation mapping

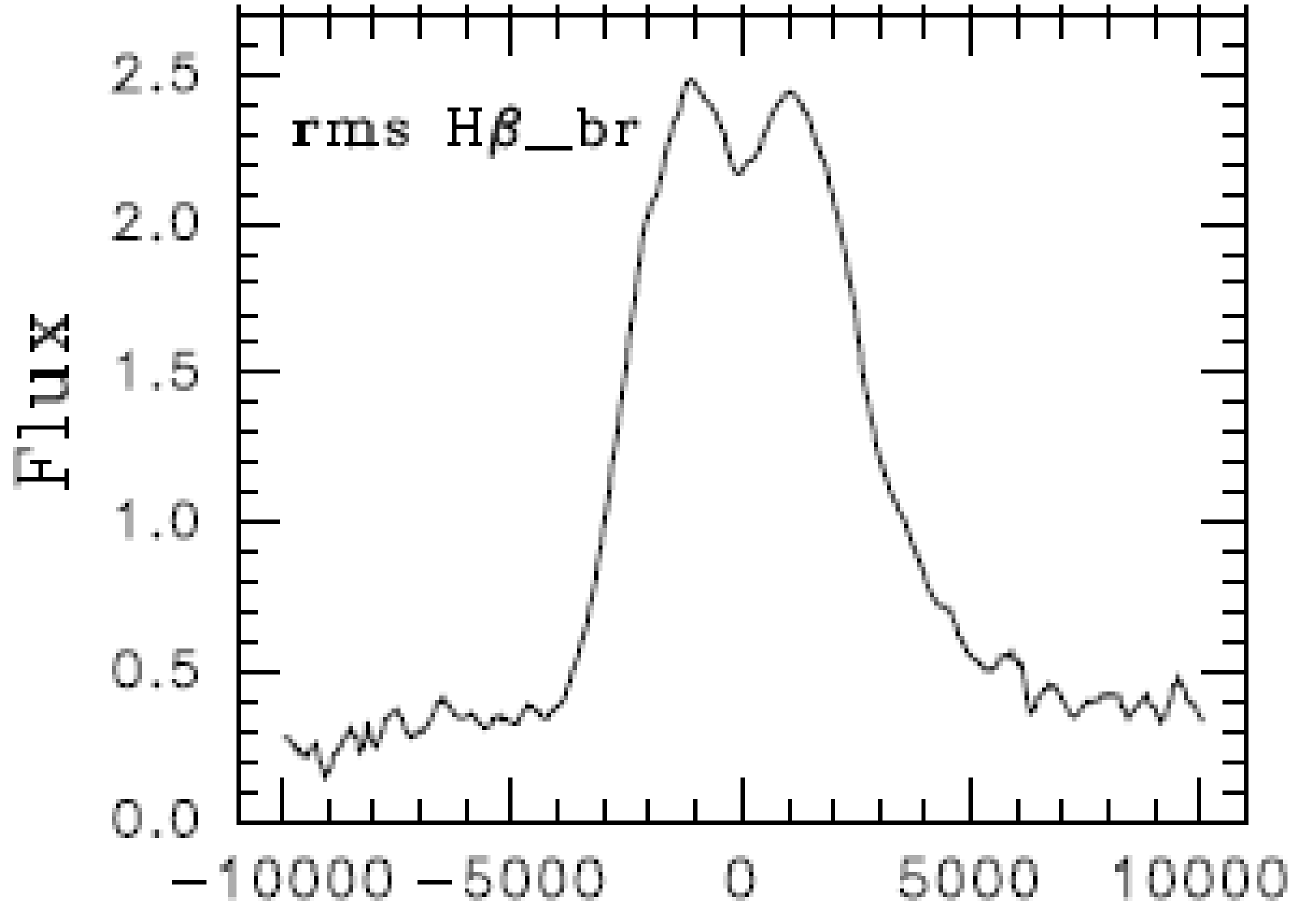
For outflow, blue wing (near side) would show shortest lag (Gaskell 1988).



We observe the opposite (slight inflow)

WHAT THE MODEL EXPLAINS

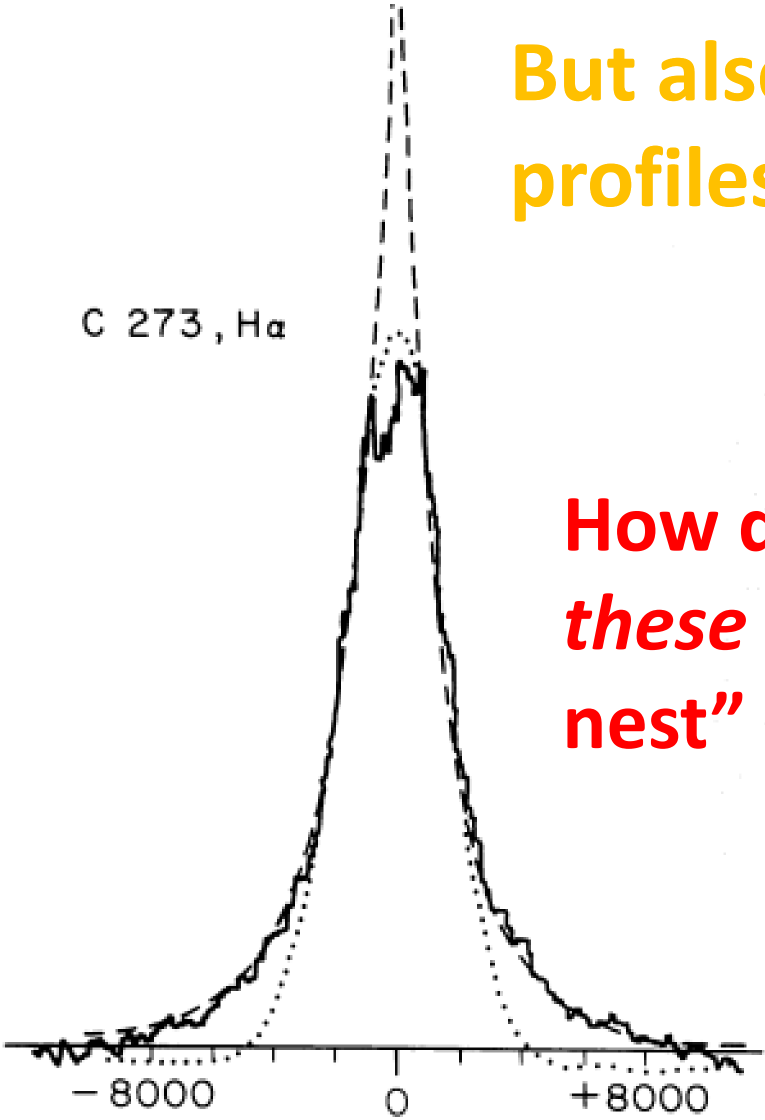
GKN model explains disc-like profiles



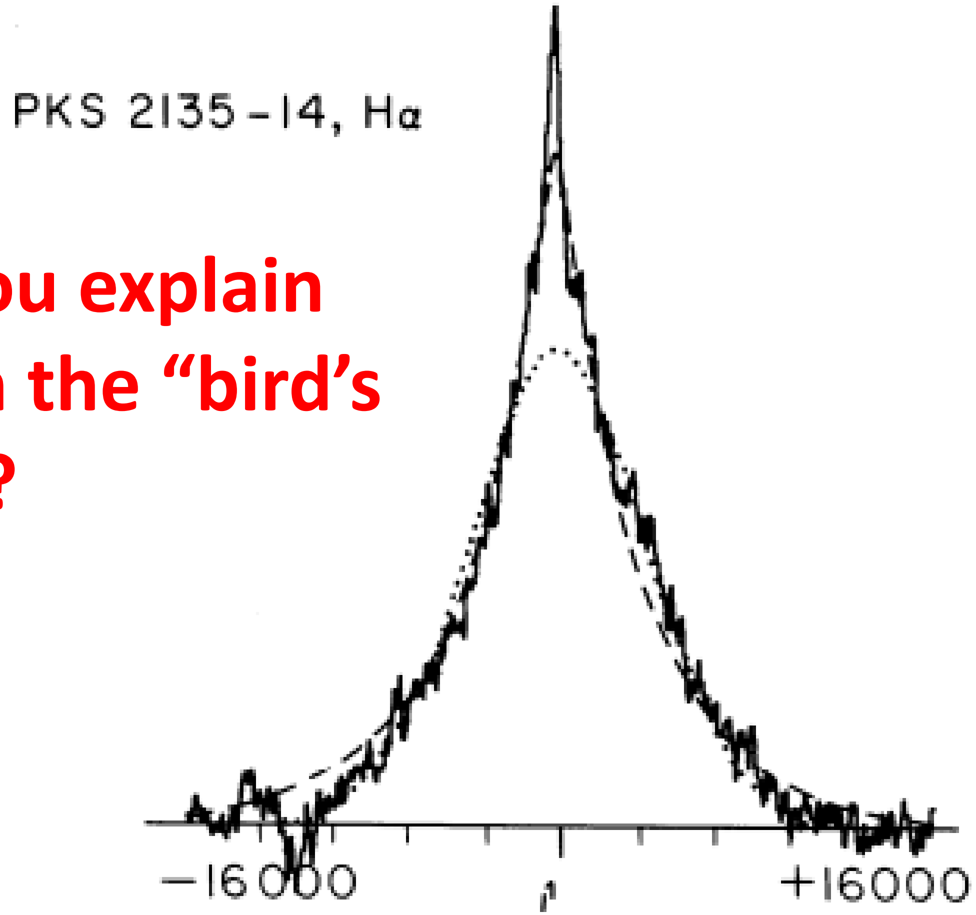
NGC 5548

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)

Models – “logarithmic” profiles from Blumenthal & Mathews (1975)

New (since 2009) – a new code for modelling the BLR: *BL-RESP*

- *[**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
  - Polarizations
- **What *BL-RESP* does not do:**
  - Multiple scattering (use the *STOKES* program - publically-available)
  - Line transfer (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.)

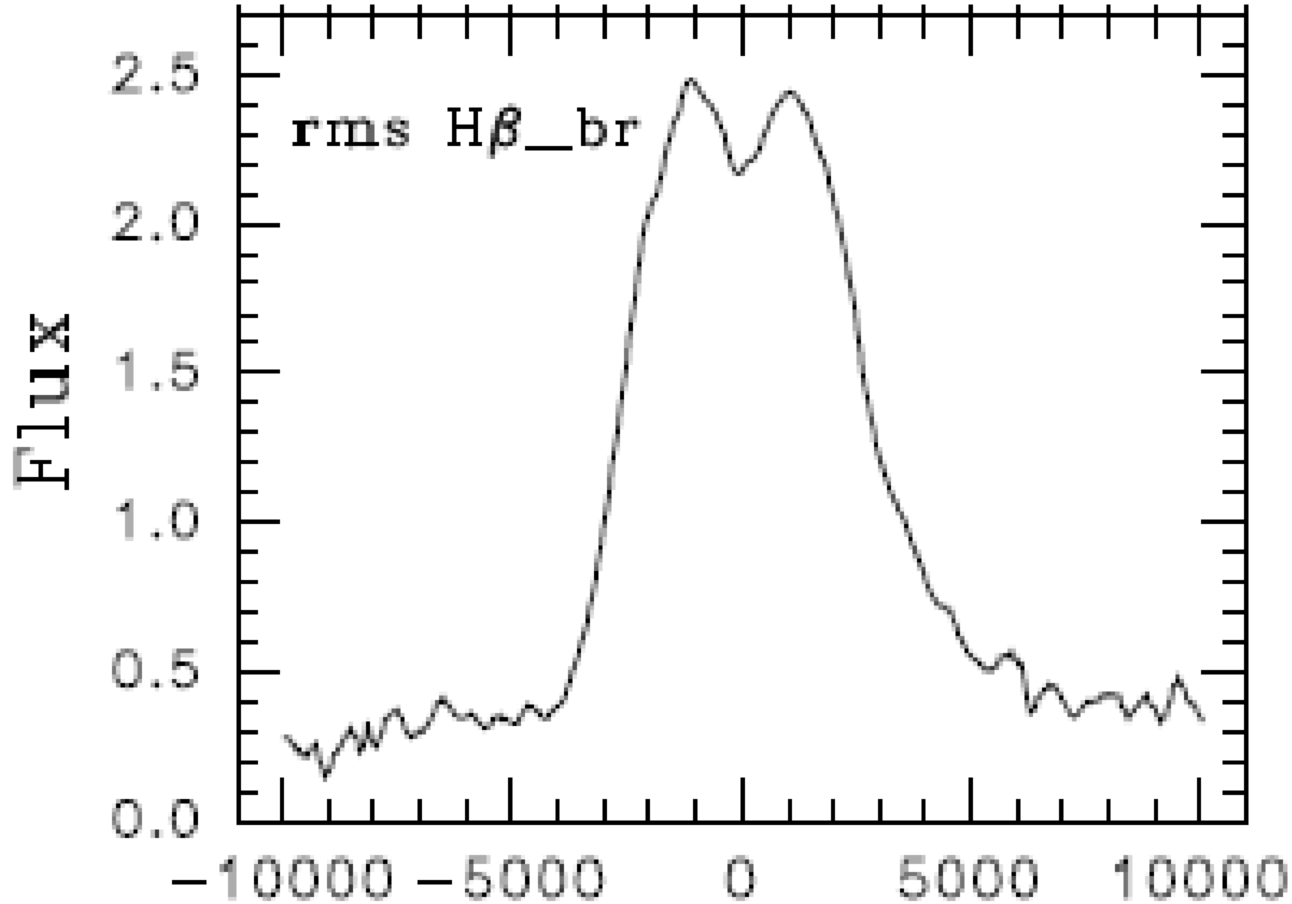
What is looks like

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

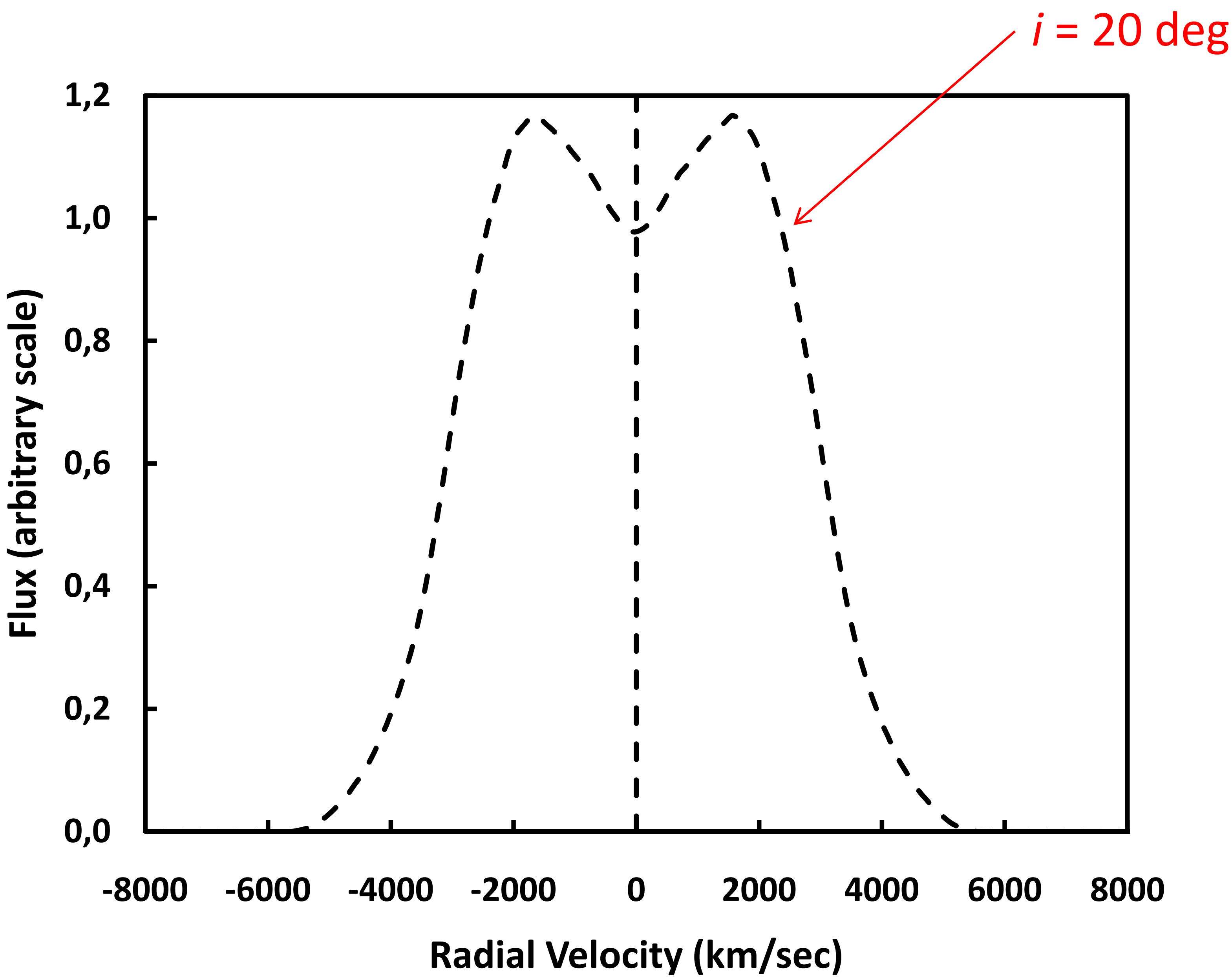
[Hit ESC to terminate movie – if that doesn't work close the command window.

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

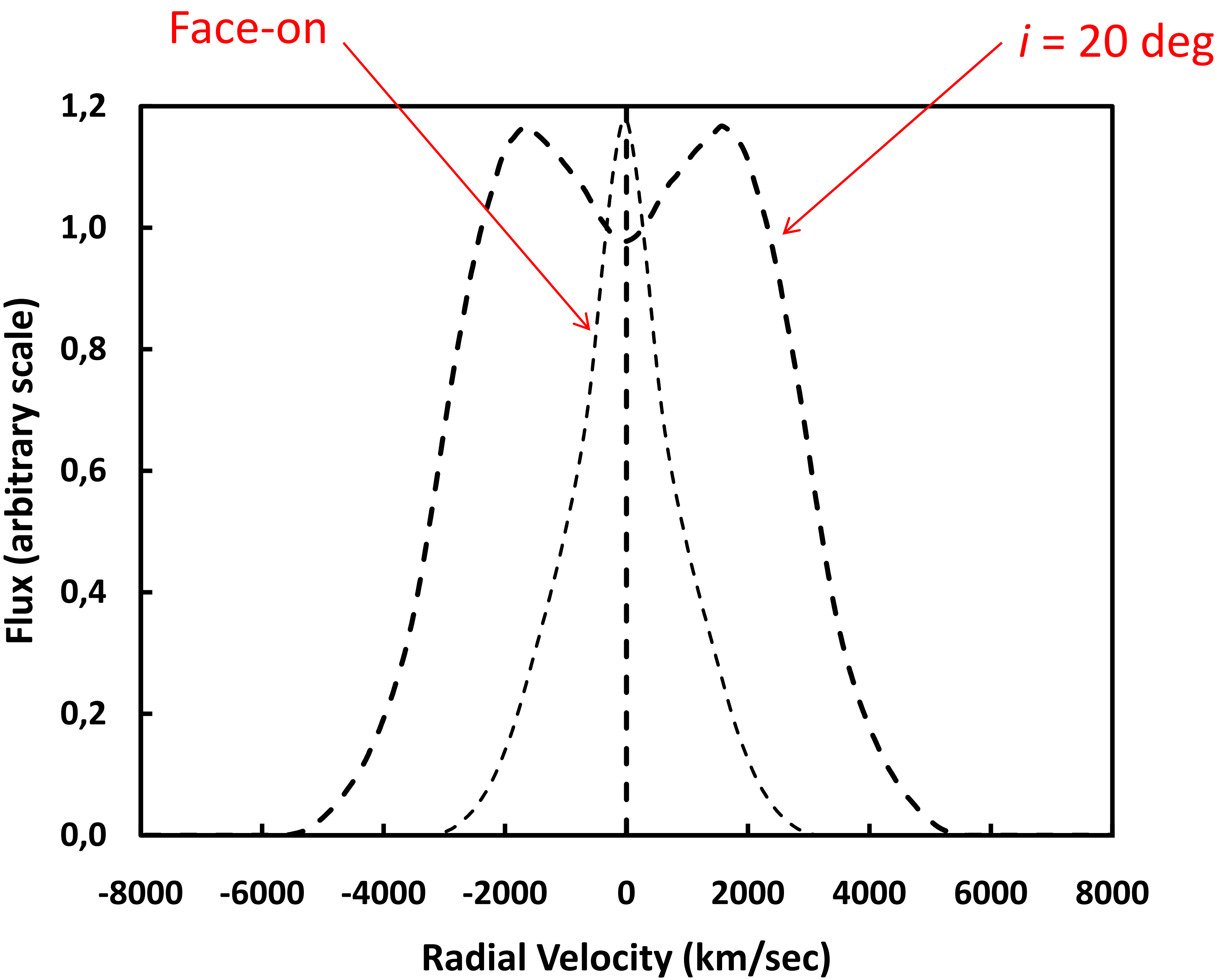
Typical disc:



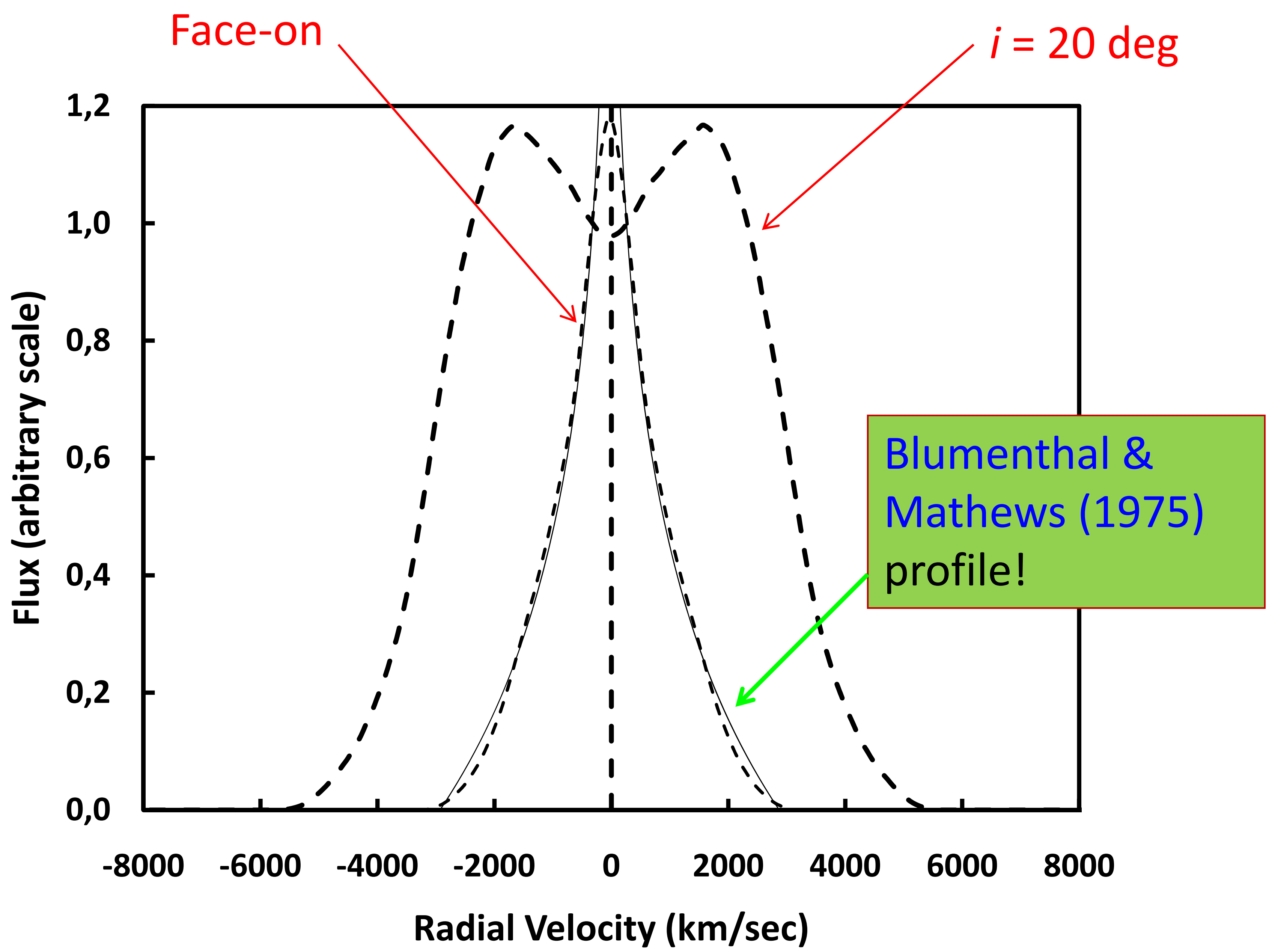
NGC 5548
Shapovalova *et al*. (2004)



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
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)

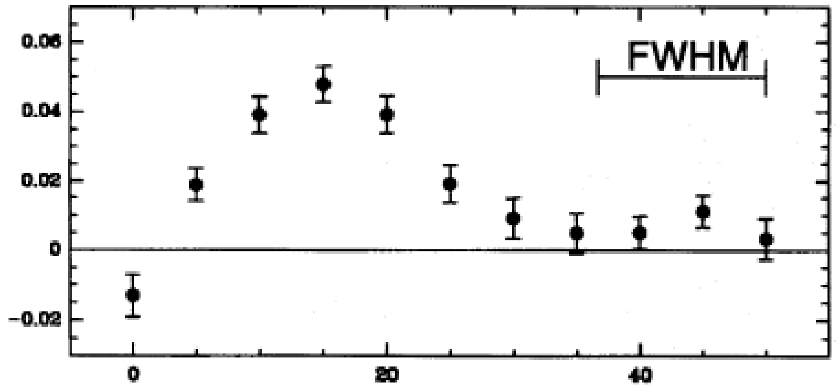

Face-on
i = 20 deg
Blumenthal & Mathews (1975) profile!
1,2
1,0
0,8
0,6
0,4
0,2
0,0
Flux (arbitrary scale)
-8000
-6000
-4000
-2000
0
2000
4000
6000
8000
Radial Velocity (km/sec)

Results

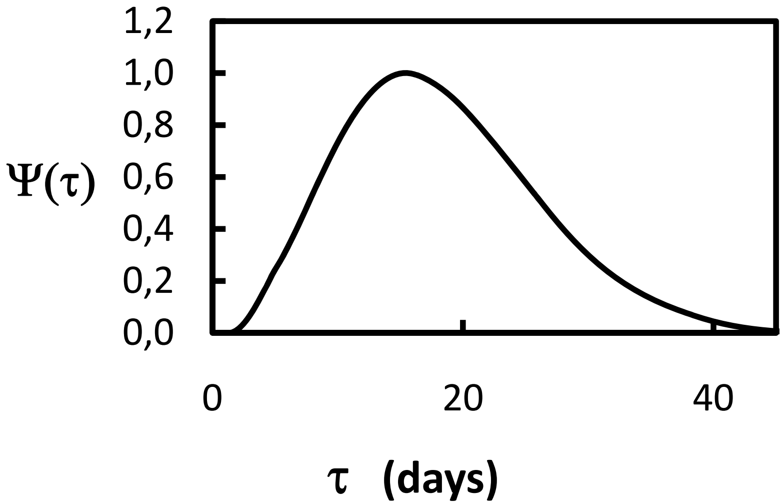
- The *same* GKN model explains line profiles ranging from the “logarithmic” profile (Blumenthal & Mathews 1975) to “disc-like” emitters!
- “Disc-like” emitters **not** fundamentally different from “normal” AGNs – just seen at a higher inclination.

Transfer Functions [$\Psi(\tau)$] *("room reverberation")*

NGC 5548 - Hβ
(Pijpers & Wanders 1994)



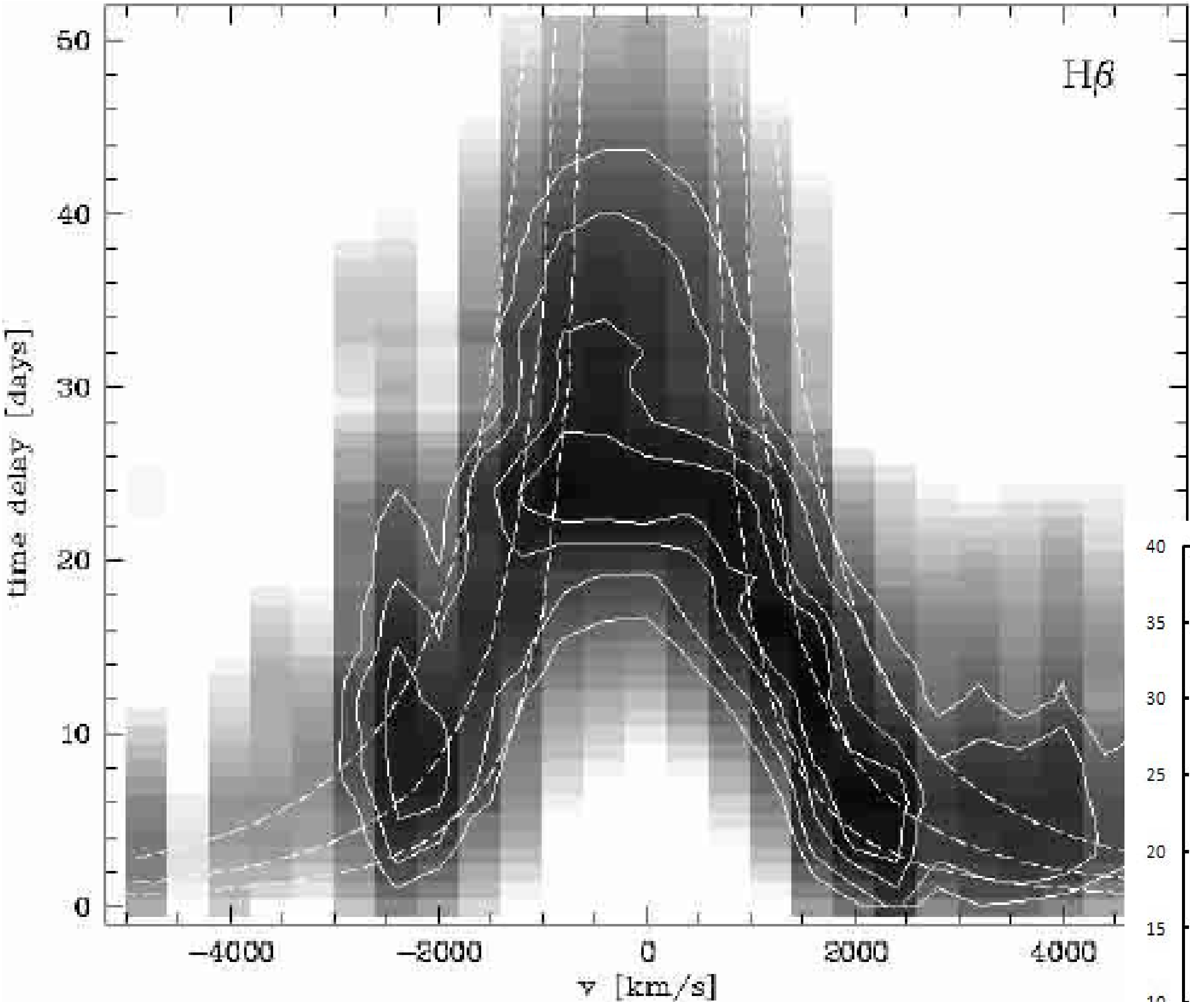
1990



(*BL-RESP* model)

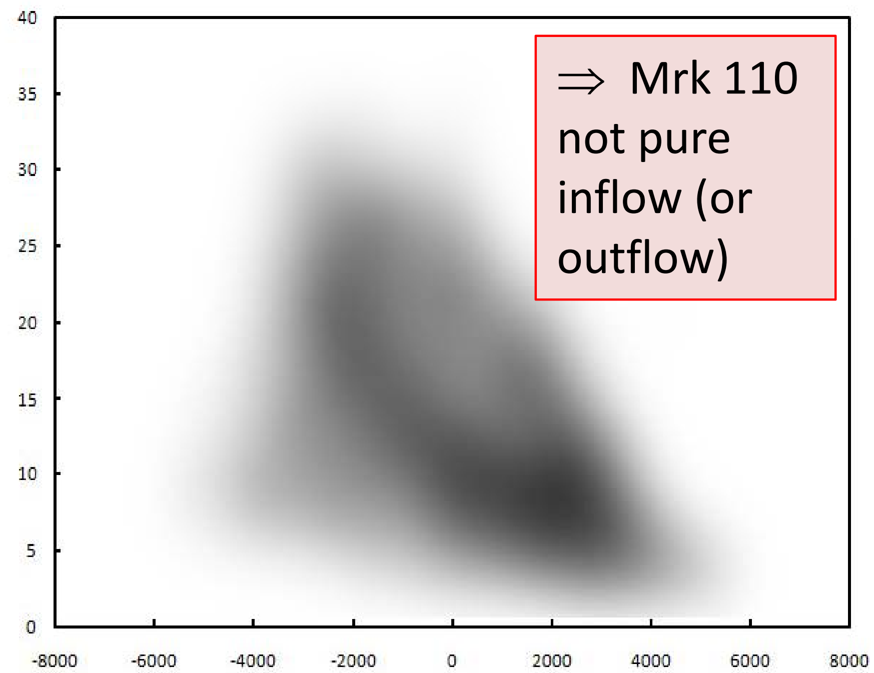
Note: observed $\Psi(\tau)$ supports Hβ mostly coming from within a factor of ~ 4 in radius as in GKN.

Velocity-delay diagrams



Best example to date: Mrk 110 (Kollatschny 2003)

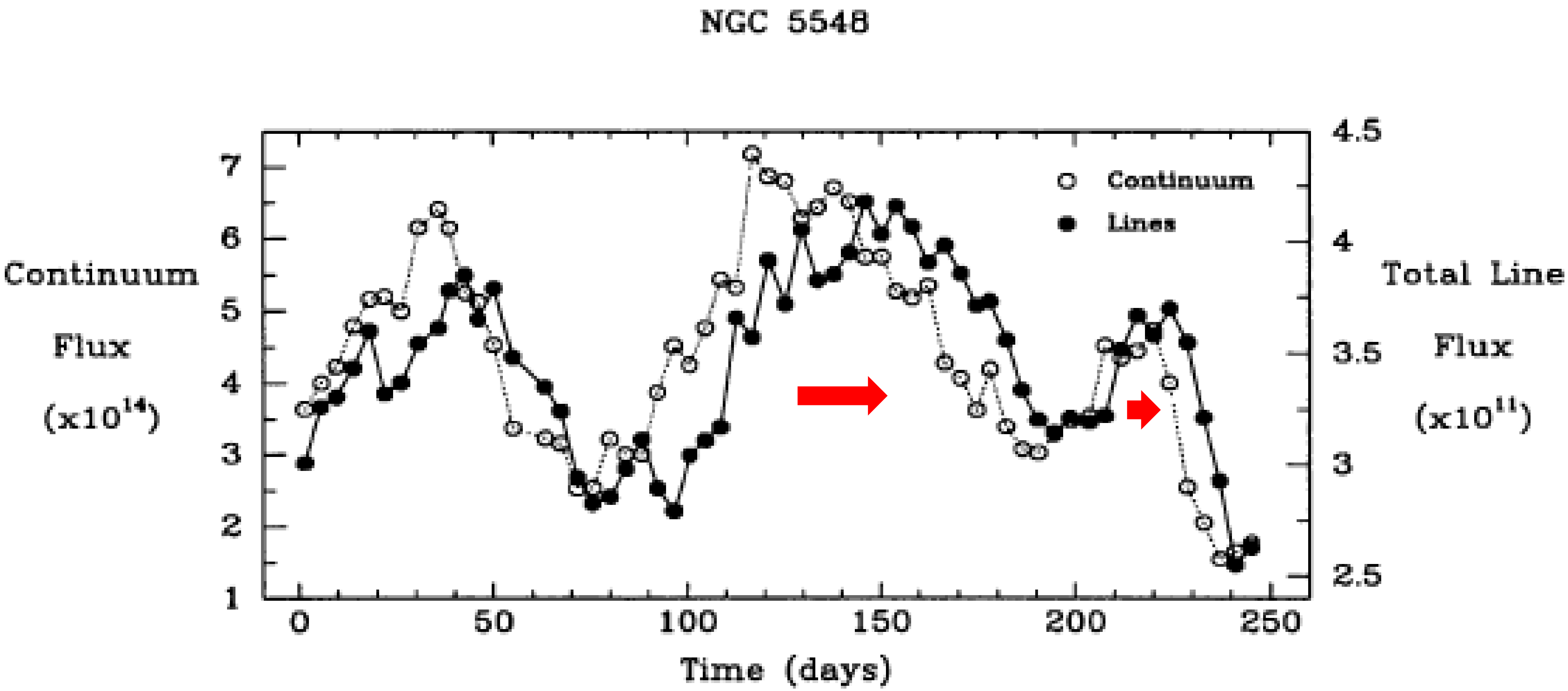
Sample *BL-RESP* velocity-delay diagram (pure inflow):



The growing crisis …

(problems we've swept under the carpet!)

Lag can change in a couple of months!

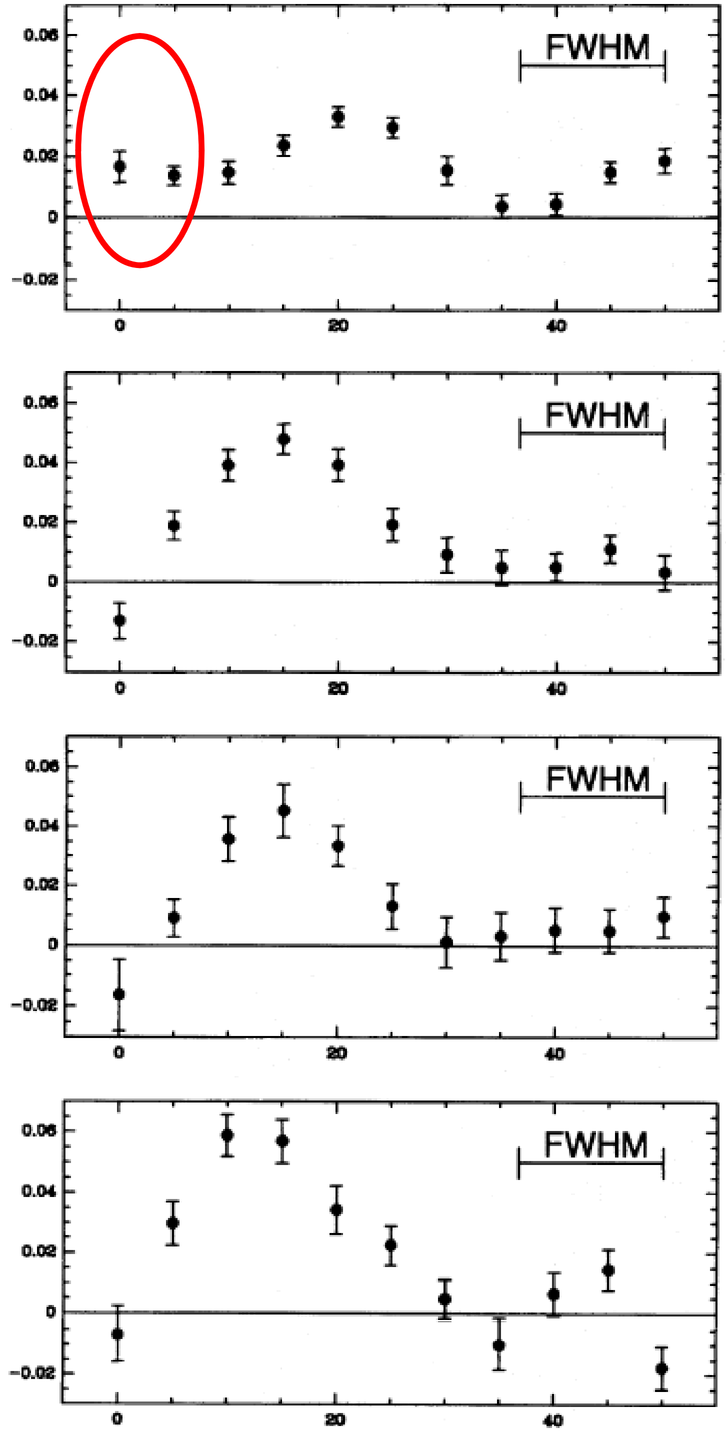


Maoz (1994)

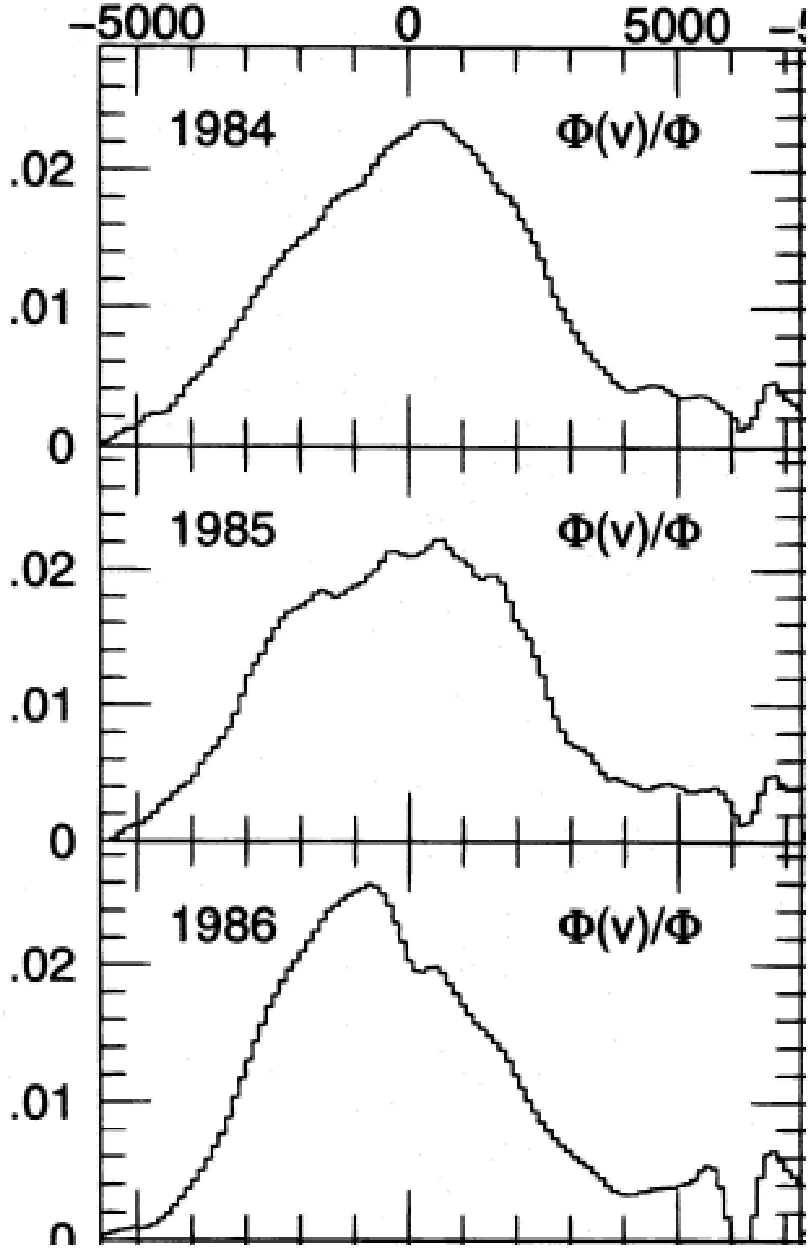
Lag changes by factor of 1.5!

Transfer function can change from year to year!

Pijpers & Wanders (1994)

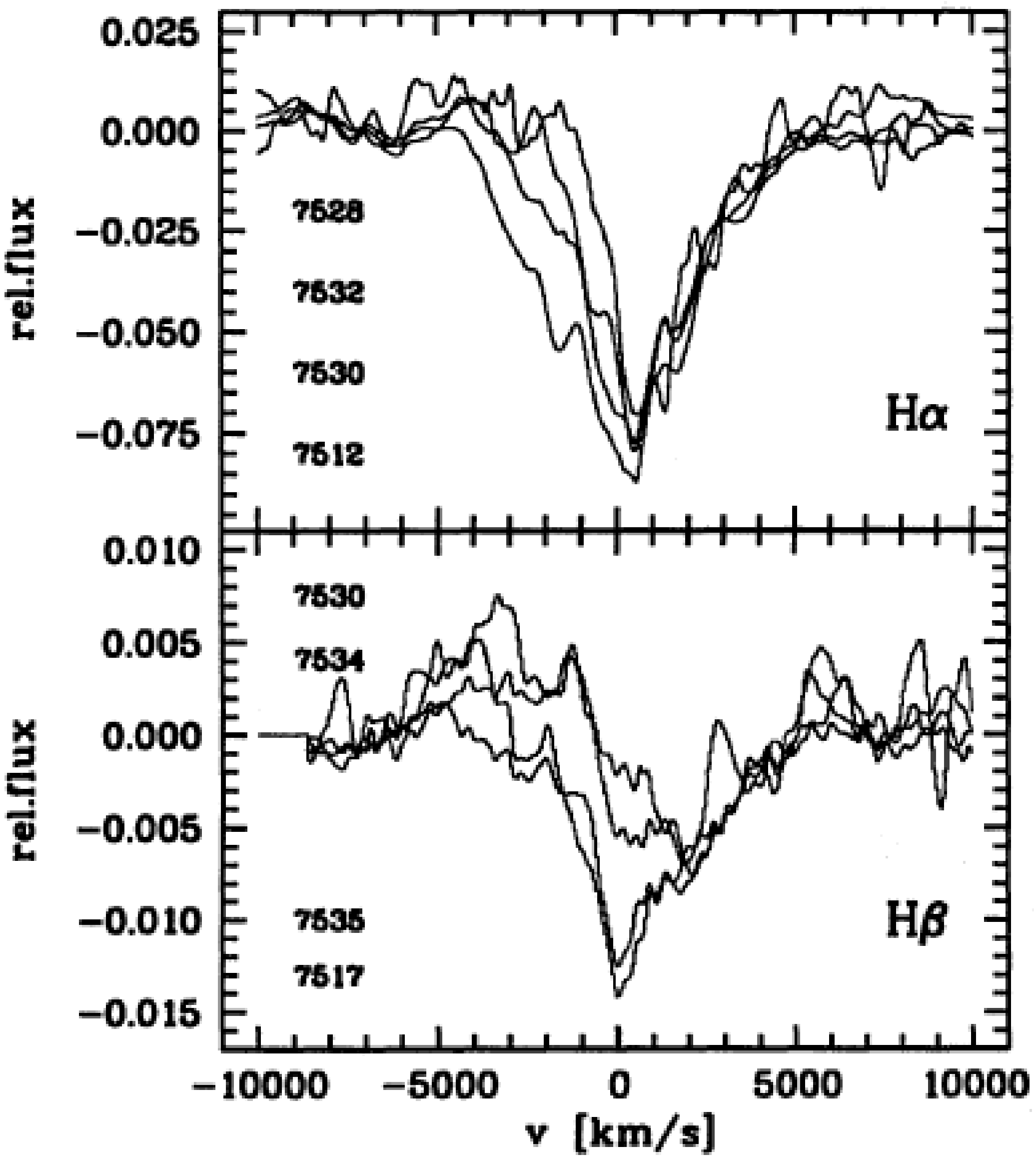


Profiles change with time



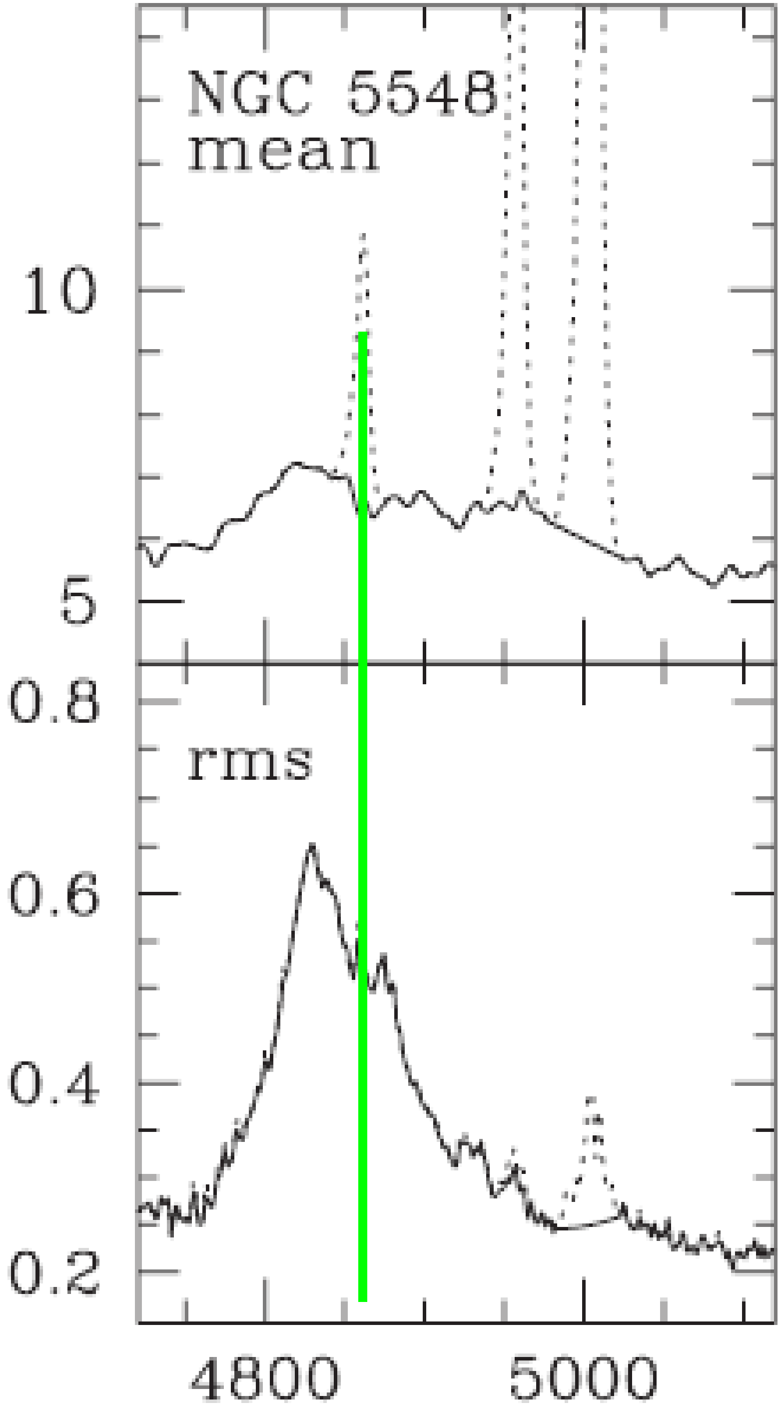
Wanders & Peterson (1996)

Sometimes only parts of profile vary . . .



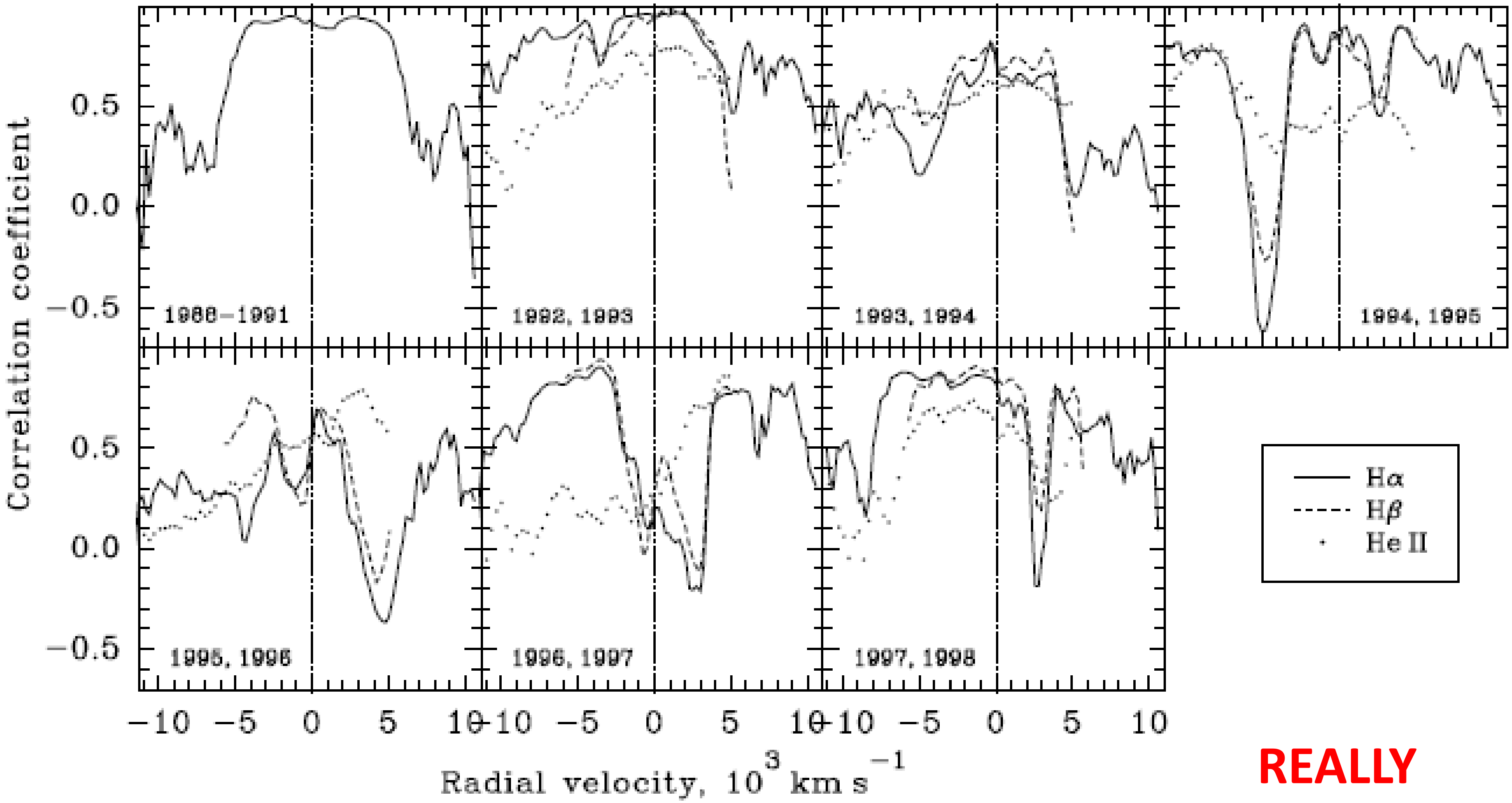
Kollatschny & Dietrich (1996)

Profiles change in odd ways!



Denney *et al*. (2009)

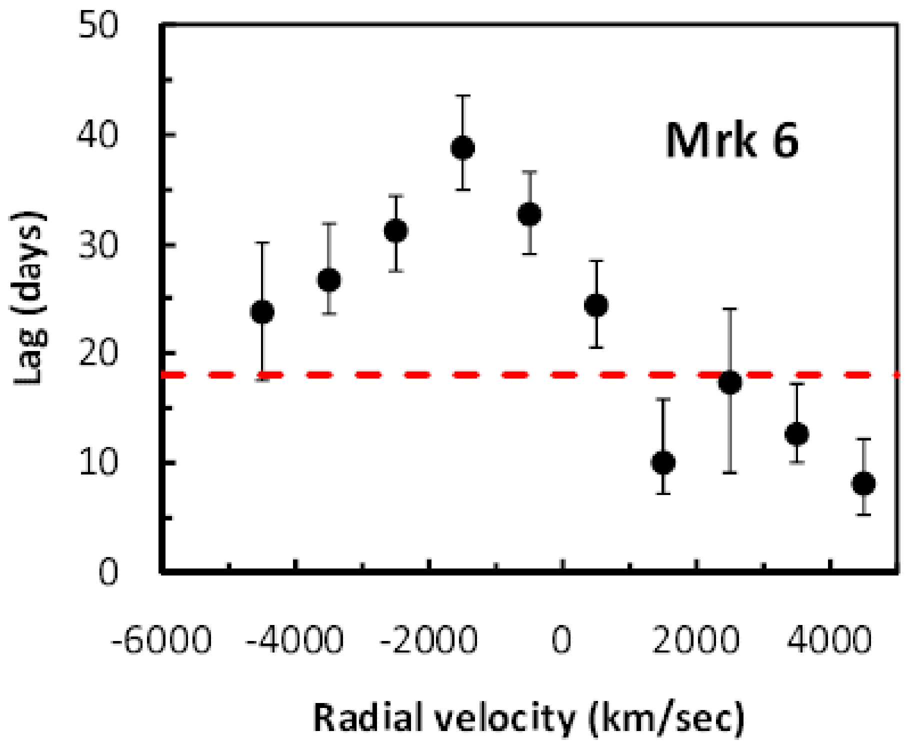
Sometimes narrow velocity regions do <u>not</u> correlate with the continuum variability!



Sergeev *et al.* (2001)

REALLY WEIRD!!

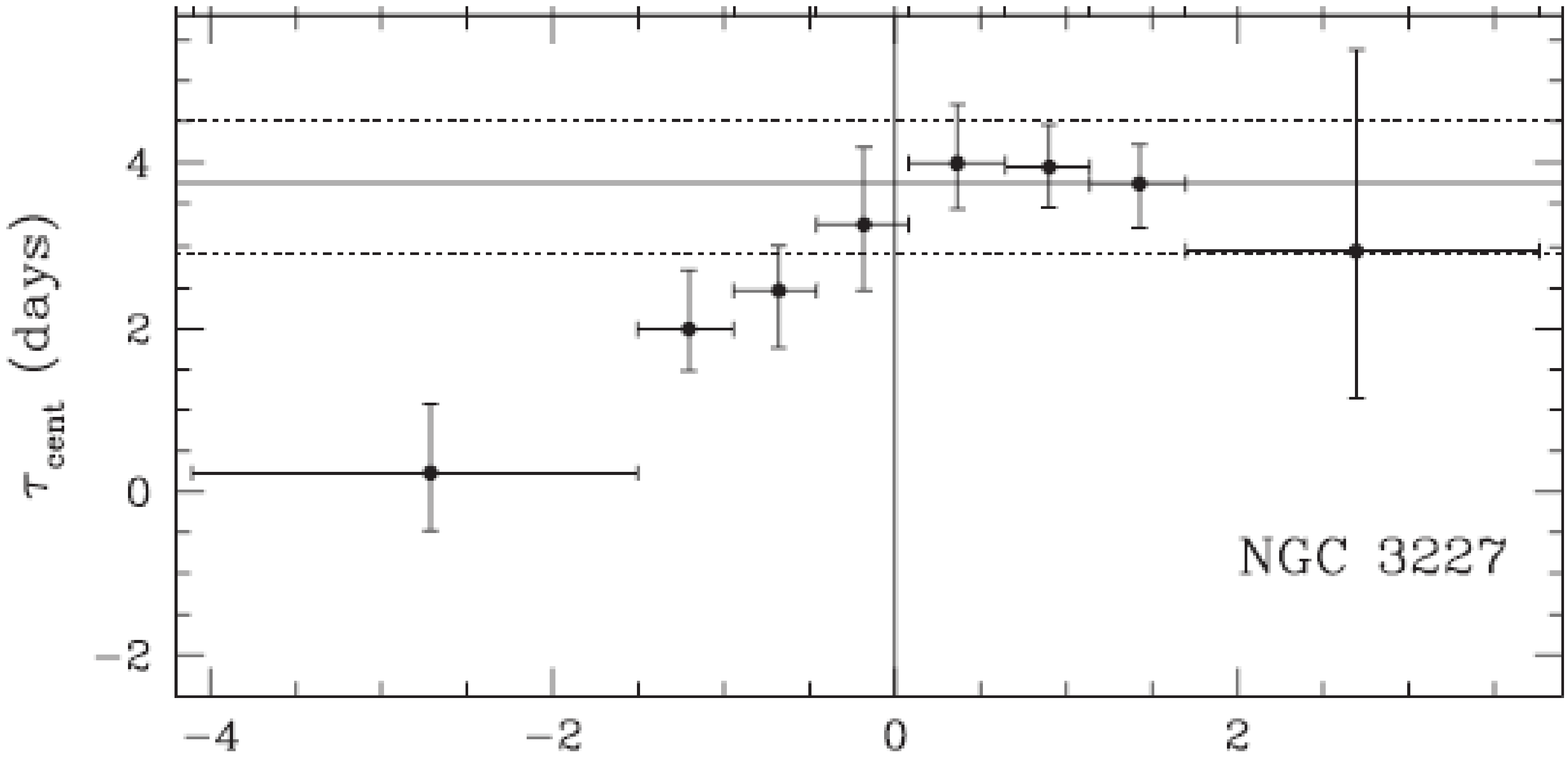
Conflicting inflow/outflow kinematic signatures



OK?

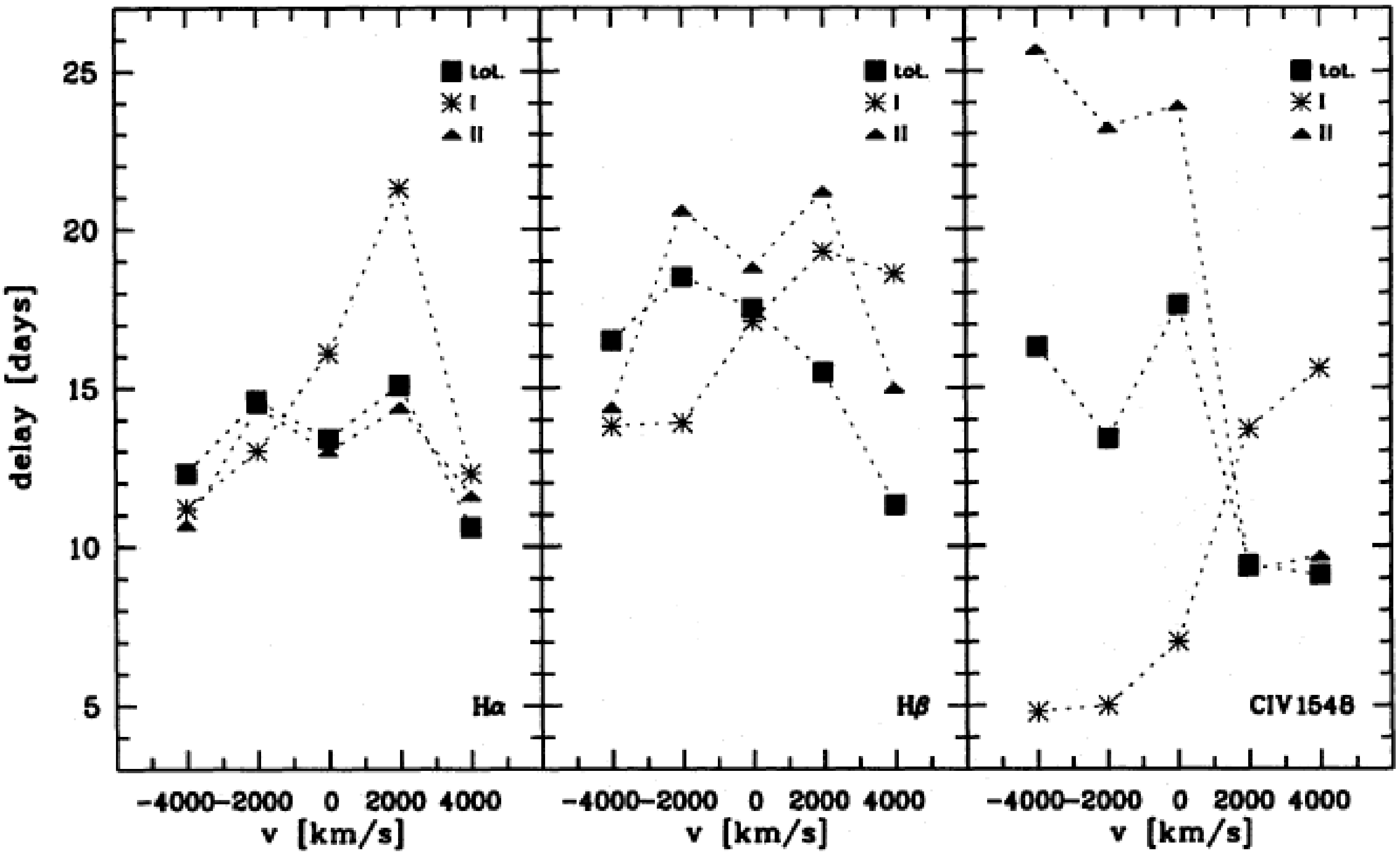
Gaskell (2010) (Adapted from Sergeev, Pronik, & Sergeeva (1999))

Reverberation mapping signature of outflow??!!



Denney *et al*. (2009)

Whole kinemetic signature can change in 2 months!!!

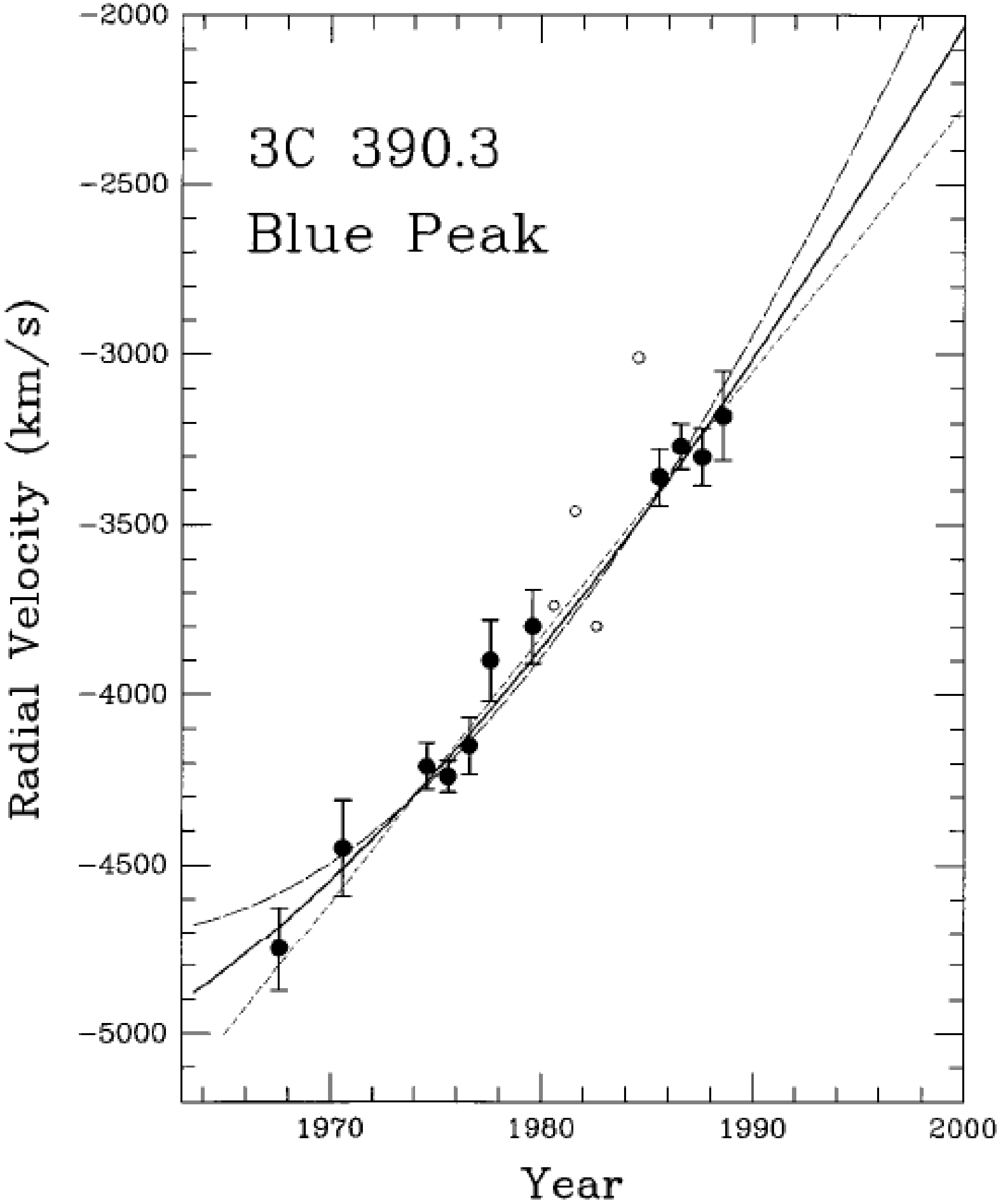


Kollatschny & Dietrich (1996)

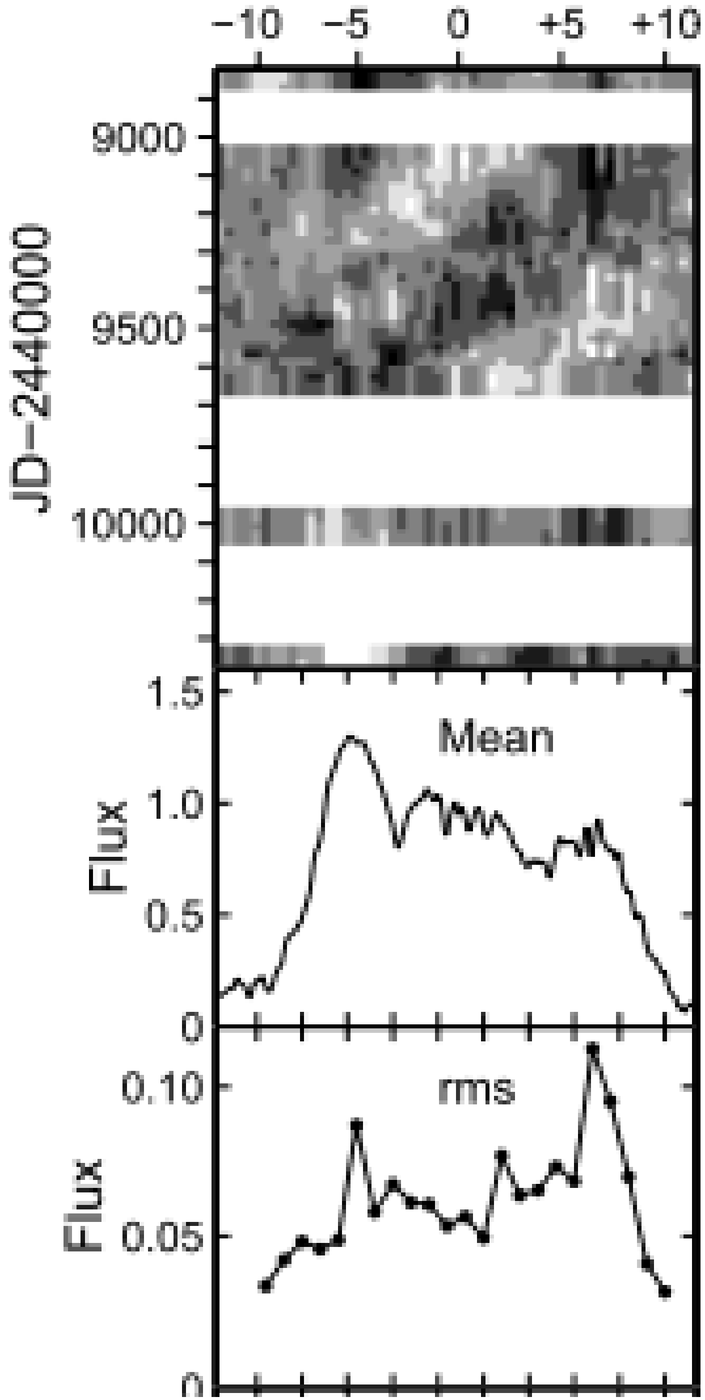
How the kinematics appear to change in 2 months

- Outflow
- Inflow

Peaks appear to orbit

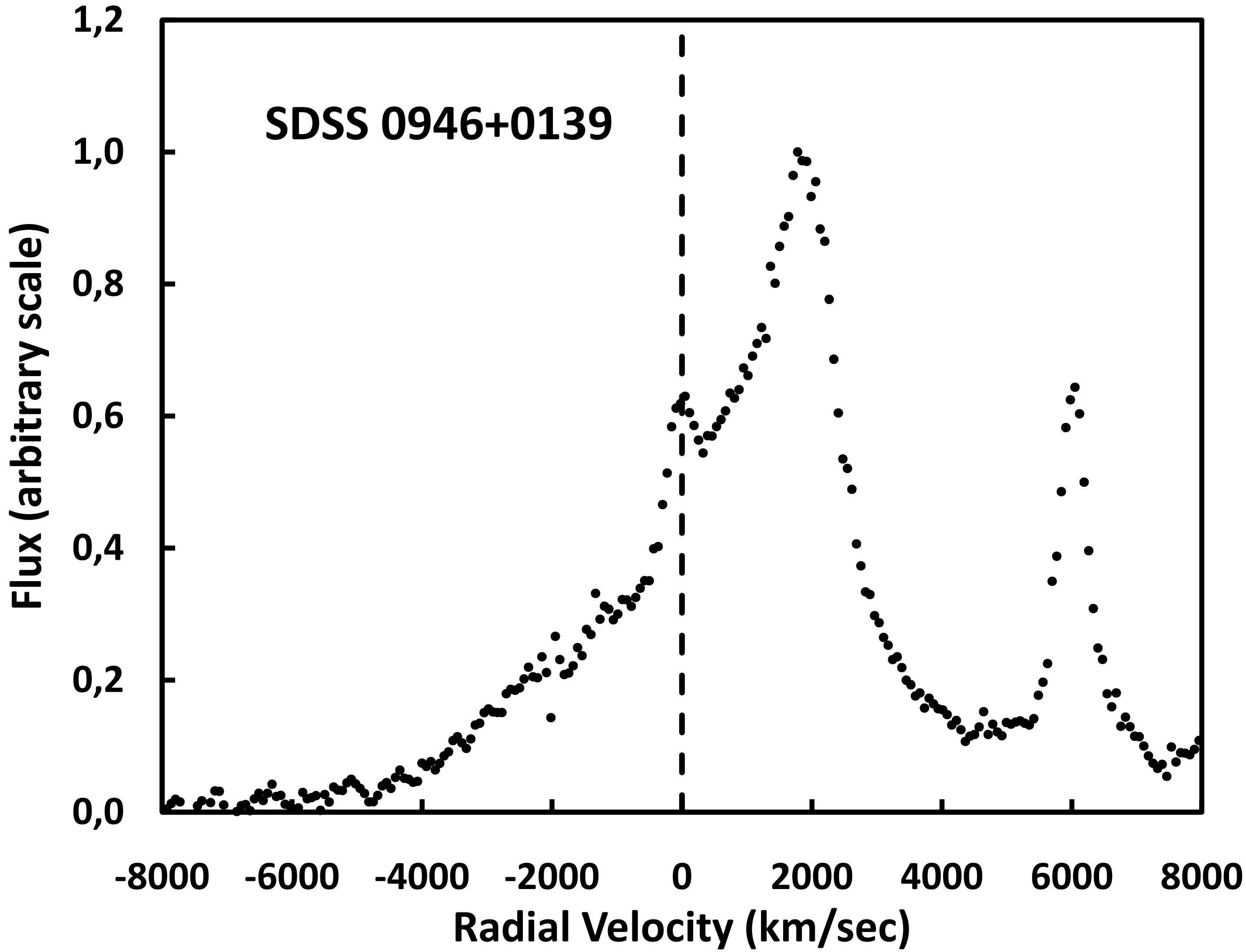


Gaskell (1996)



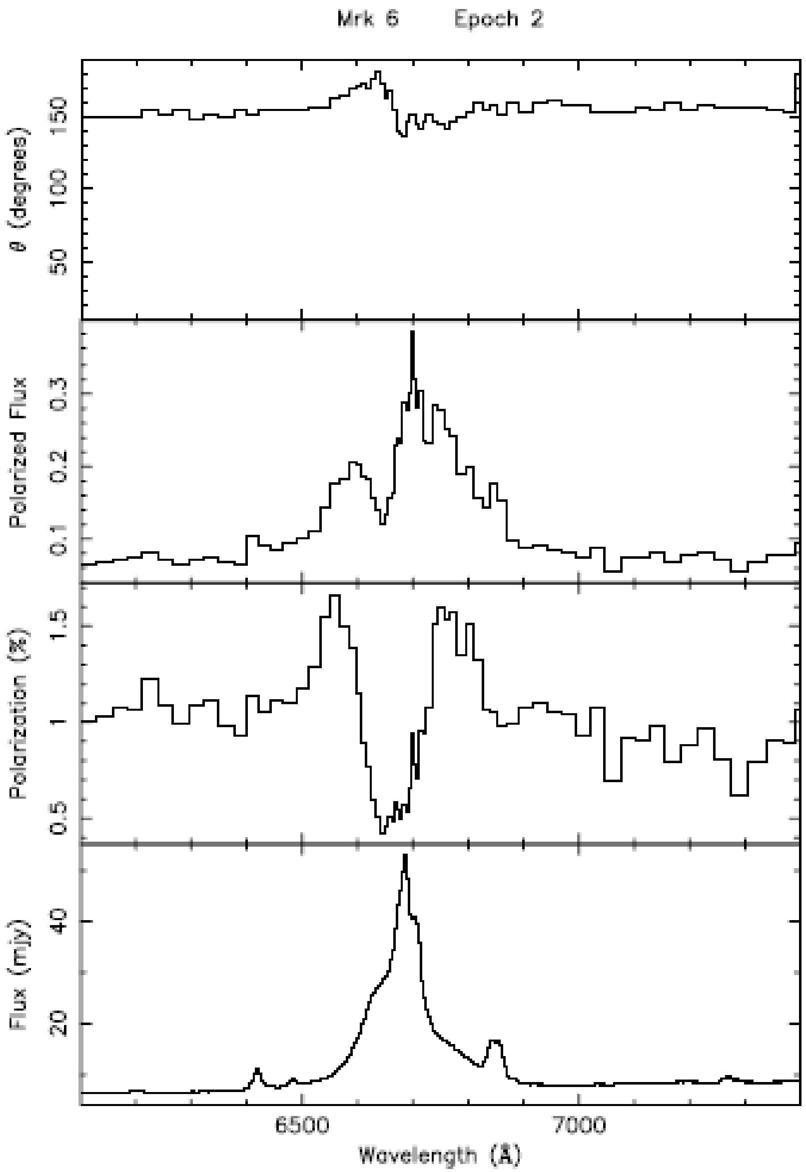
Sergeev *et al*. (2001)

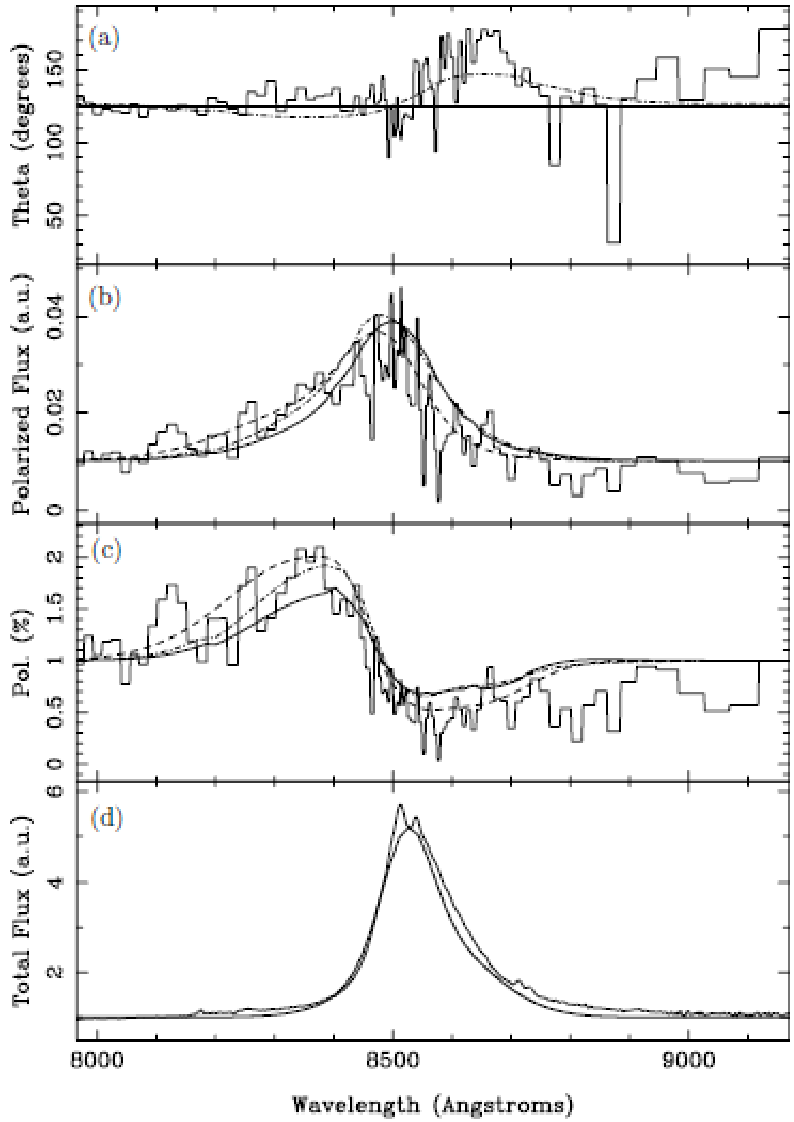
Can we explain a profile this extreme?



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

Spectropolarimetry (and spectropolarimetric variability)





A NEW AGN VARIABILITY PARADIGM

First: basic theory of how “thermal” AGNs are powered

- Energy mostly arises from accretion “disc”
- Temperature structure well understood (see Gaskell 2008)

Classical disc (Pringle & Rees 1972; Shakukra & Sunyaev 1973)

Assume all energy is generated and release on the spot.

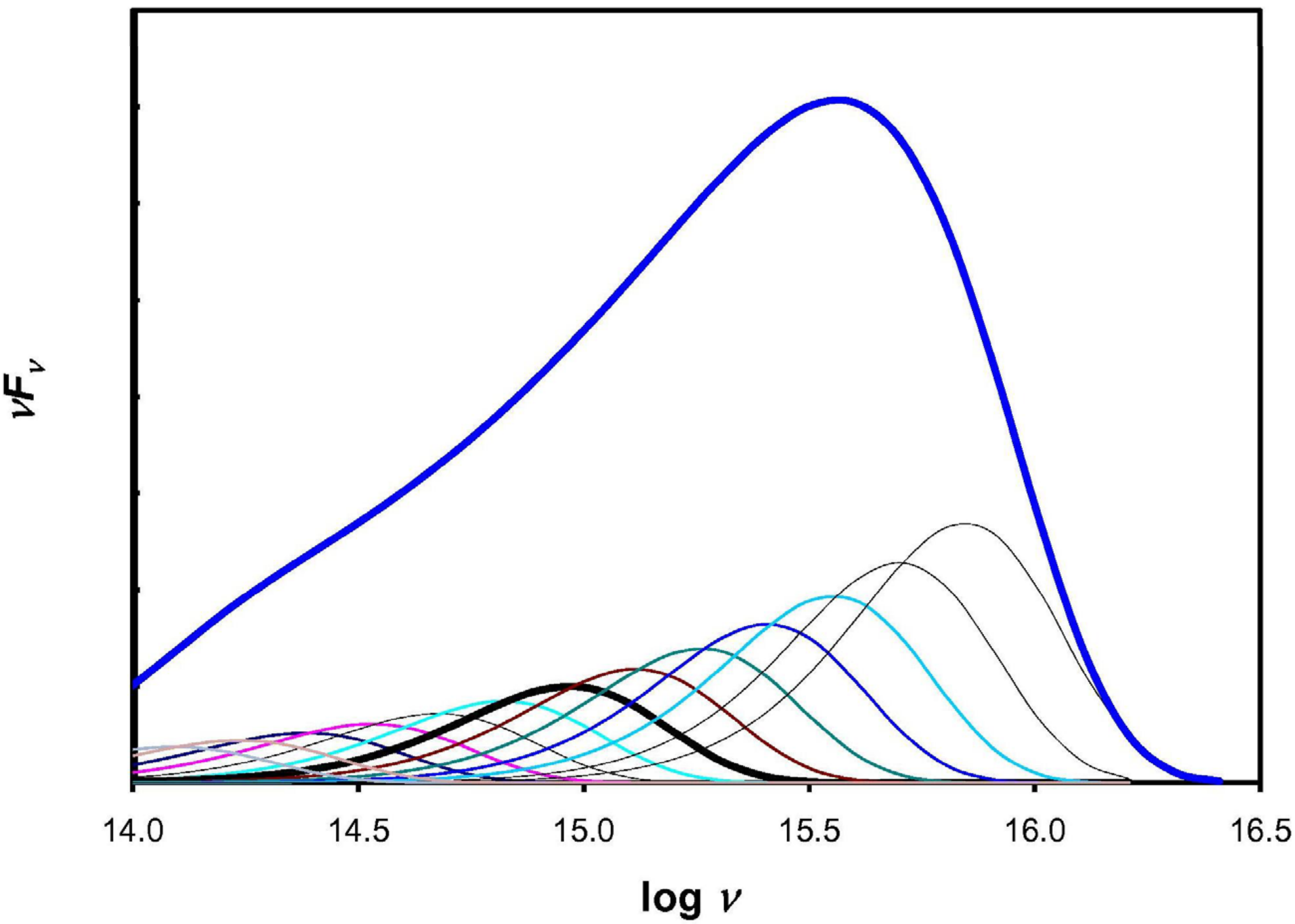
Easy to show (see Gaskell 2008)

$$T \propto R^{-0.75}$$

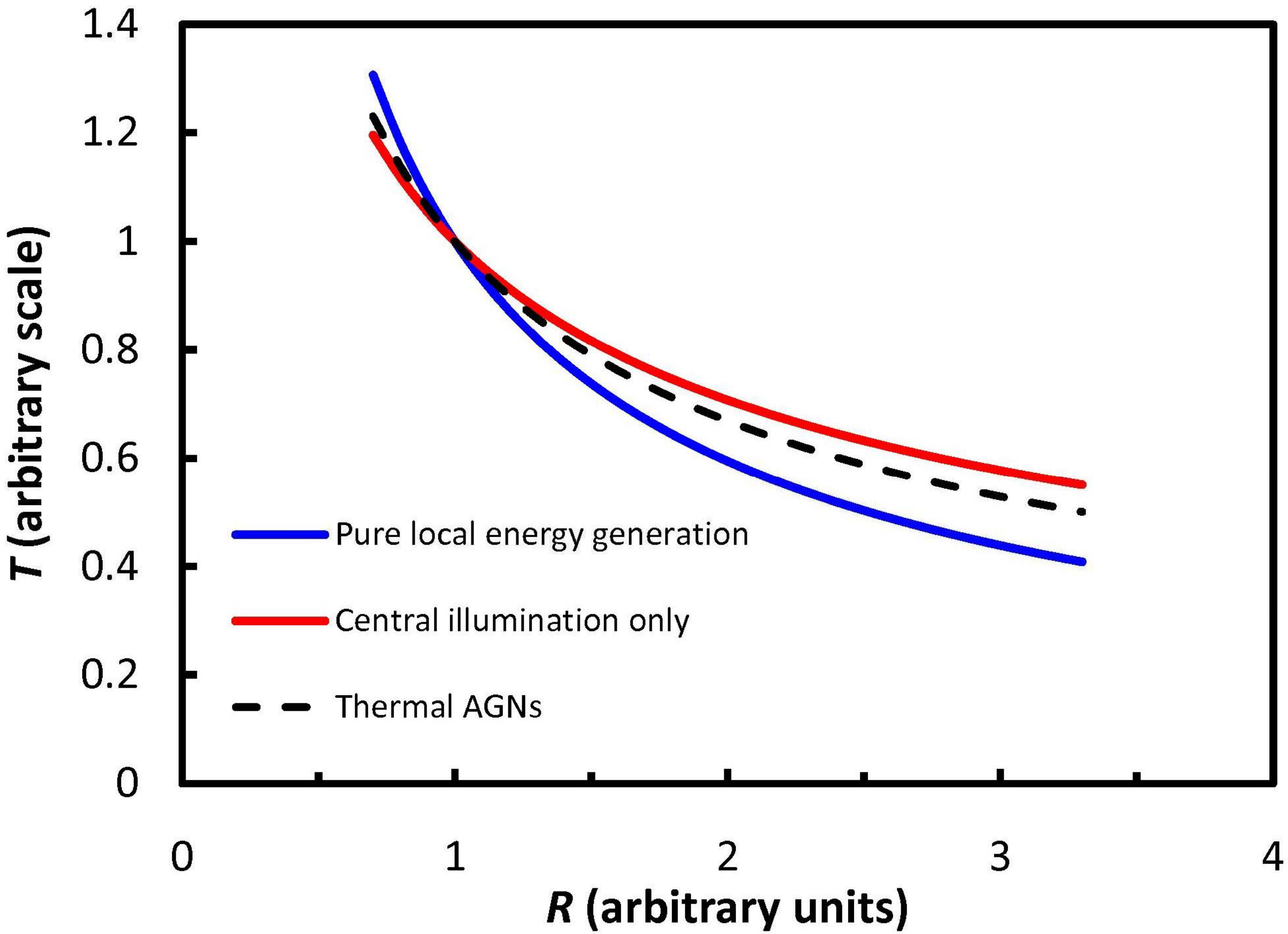
Other extreme: *complete reprocessing* of energy from a central point source

$$T \propto R^{-0.5}$$

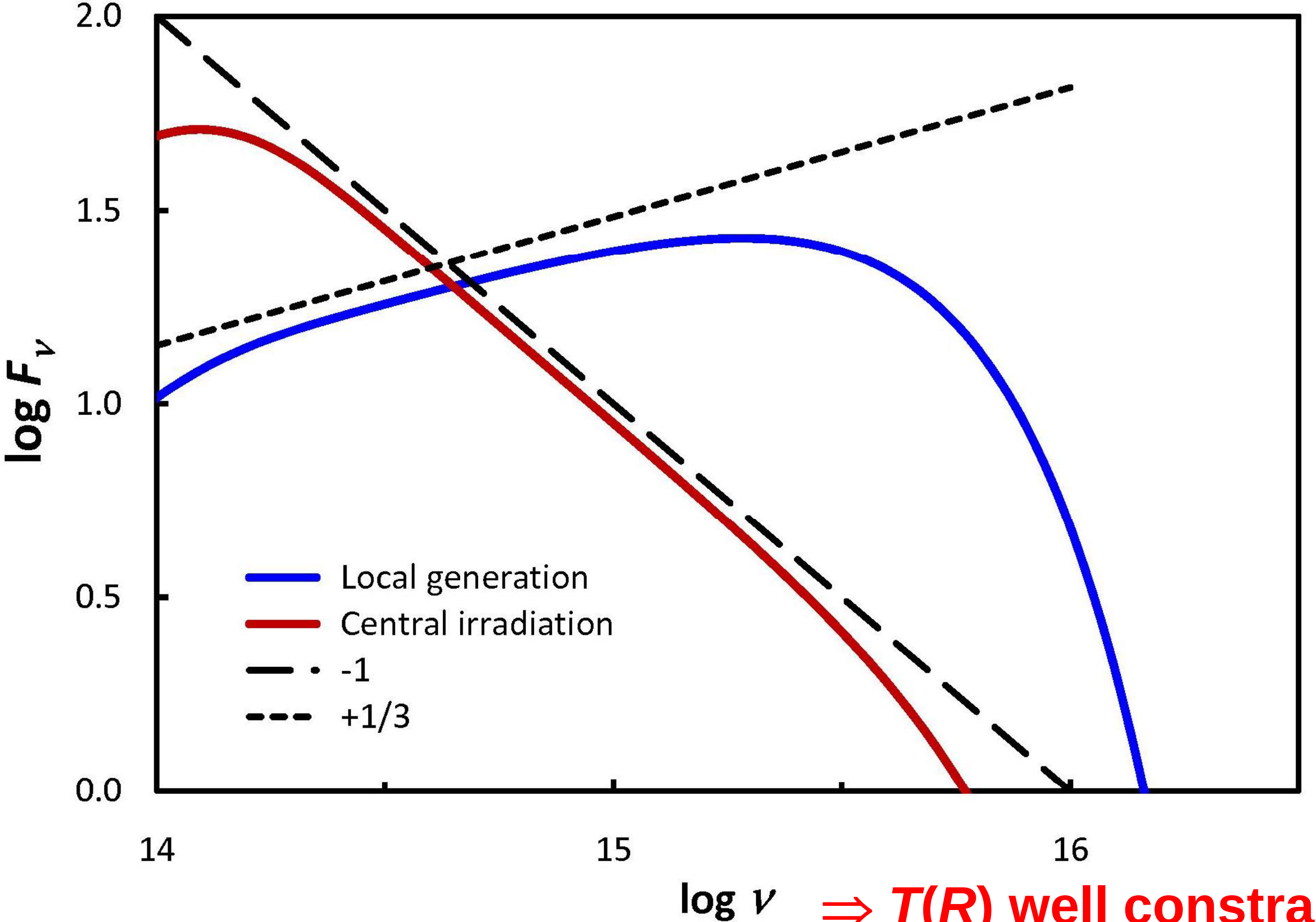
Spectral Energy Distribution (SED) Result of summing Planck curves at different temperatures:



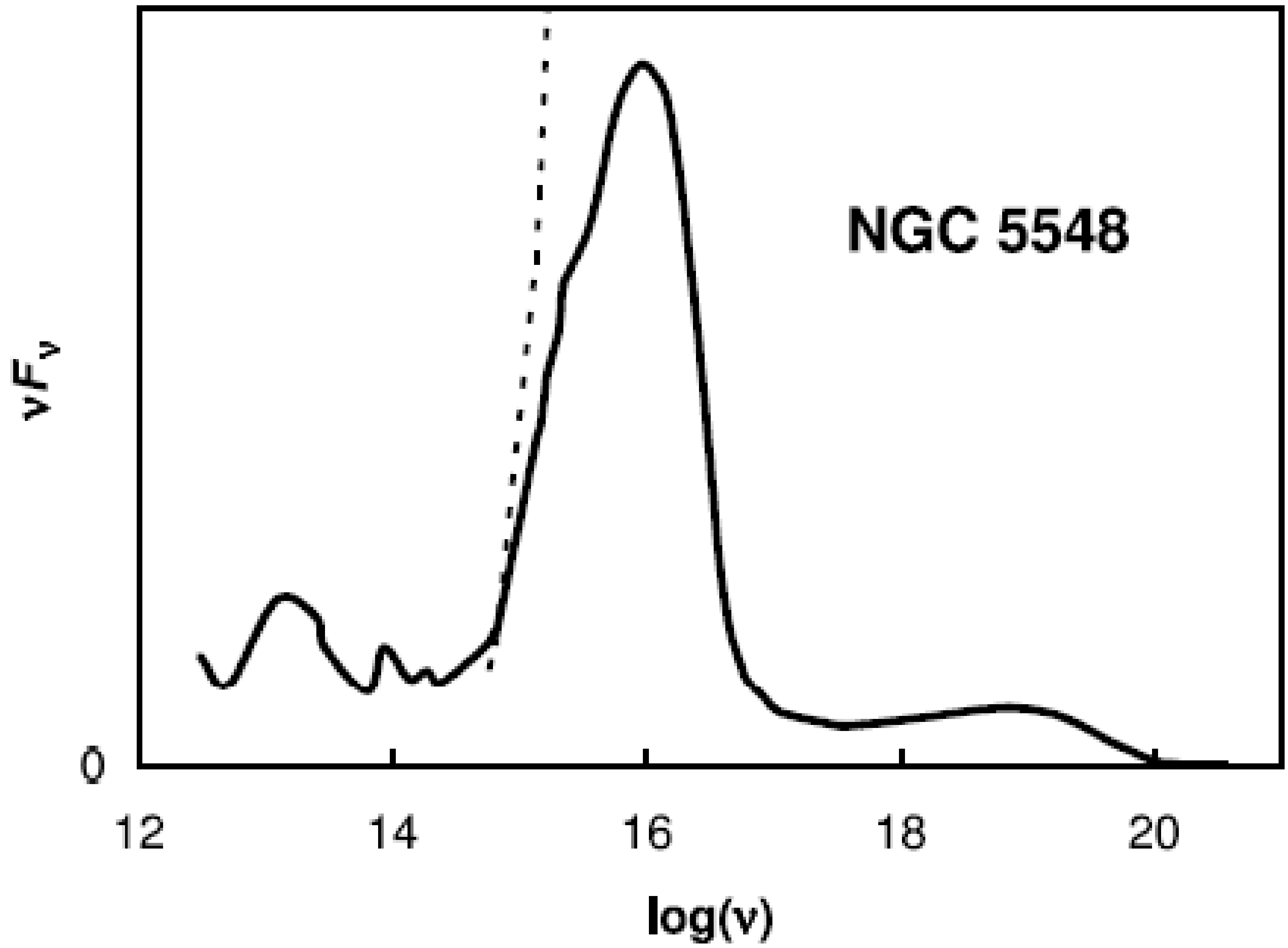
SMALL change in temperature gradient: $T \propto R^{-0.5}$ vs. $R^{-0.75}$



⇒ *BIG* change in spectral shape: $F \propto \nu^{-1}$ vs. $\nu^{+1/3}$

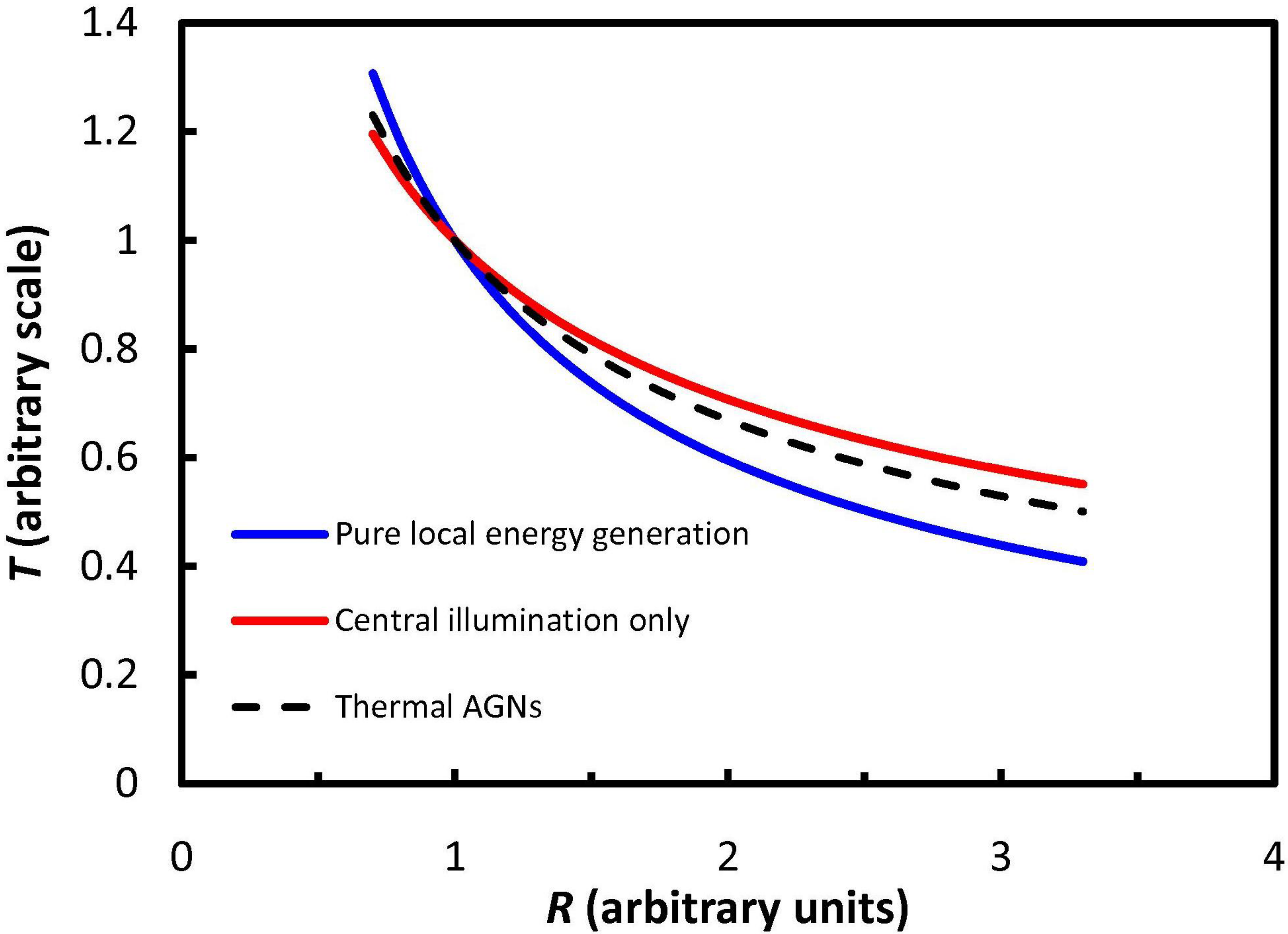


⇒ $T(R)$ well constrained by observations

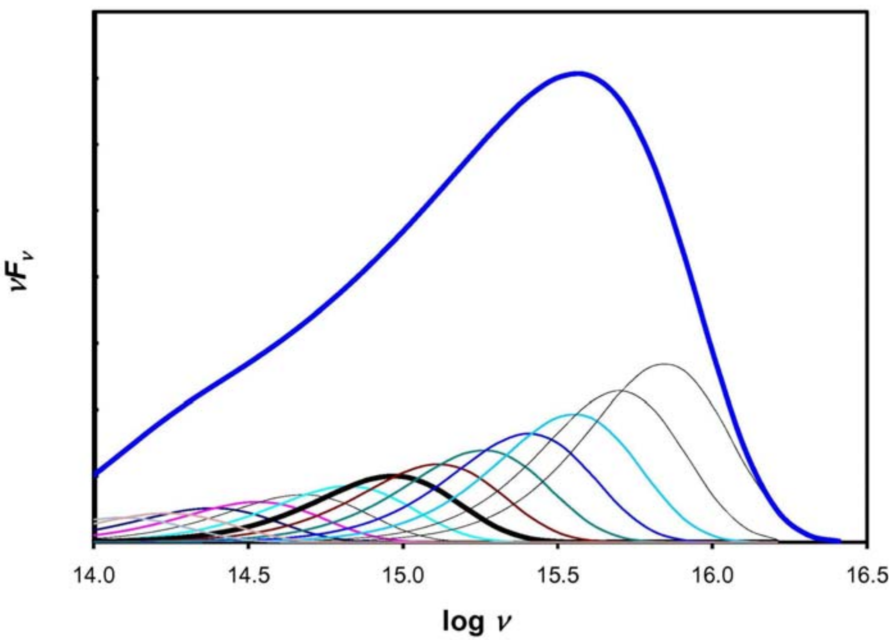


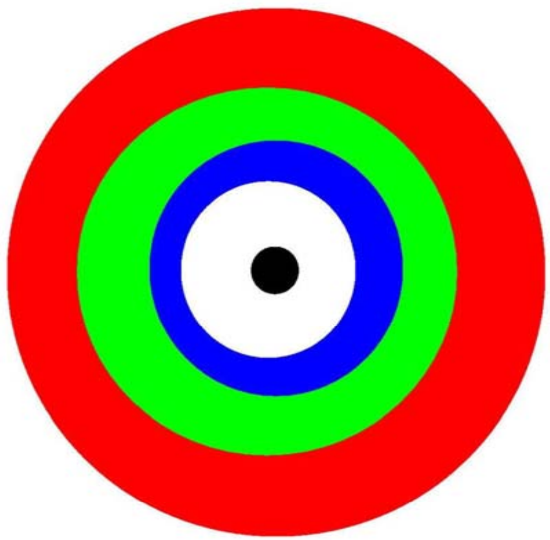
Gaskell (2008)

⇒ Mostly local energy generation, but some reprocessing

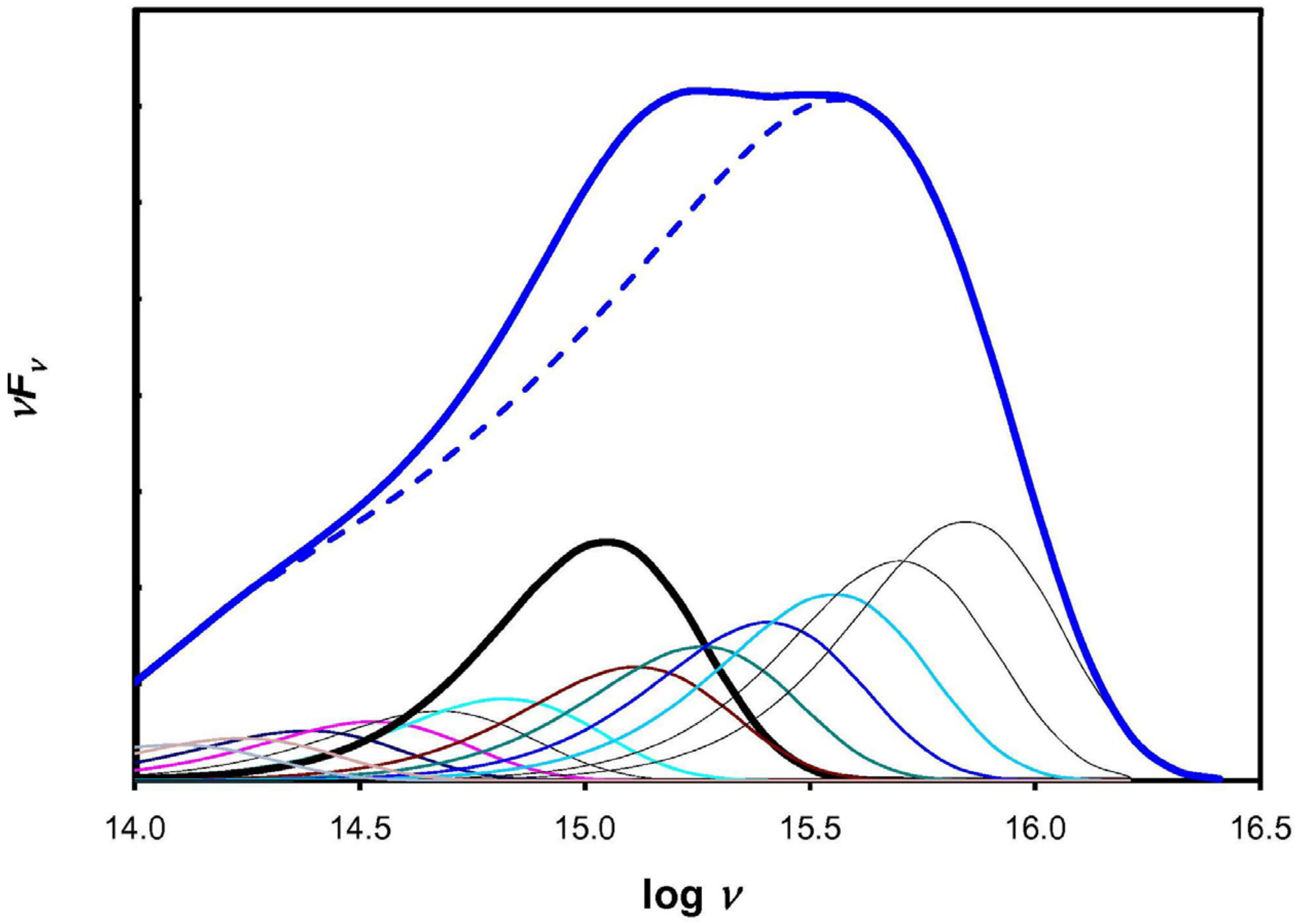


- Photons in each observed spectral region *come mostly from where the Plank curve peaks*.
- $\therefore$ each spectral region comes *from within an annulus*.

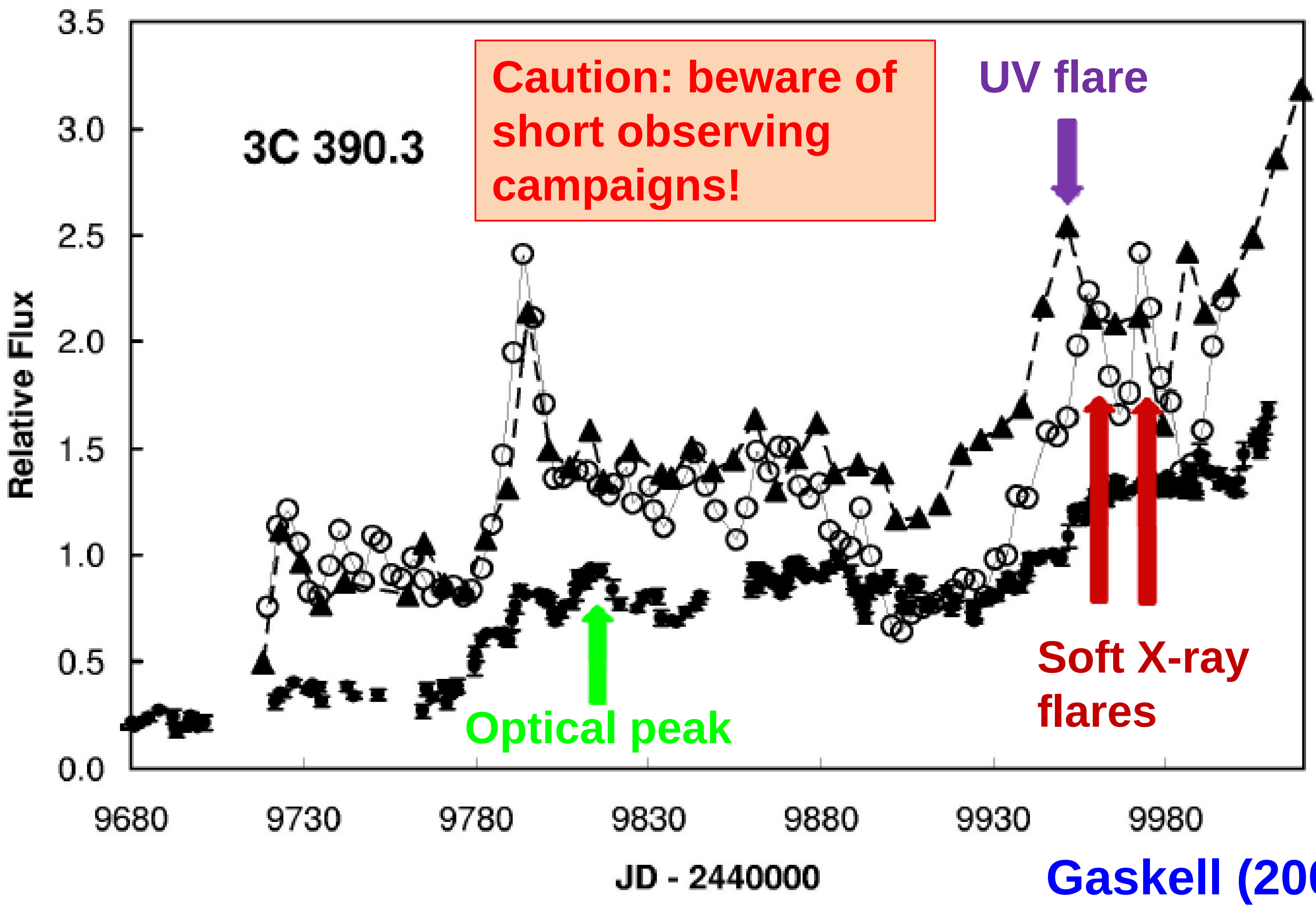




When we see a spectral region varying – we are seeing *an annulus* varying.



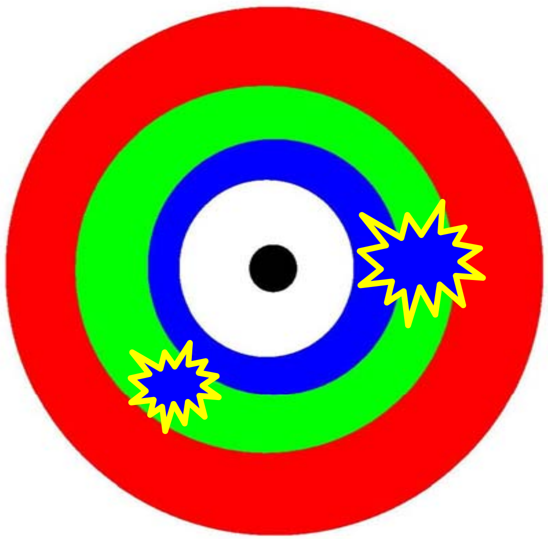
Variability at lower energies is *not* reprocessing of variability at higher energies.



Gaskell (2006)

Monitoring $\Rightarrow$ annuli of very different radii vary **independently**

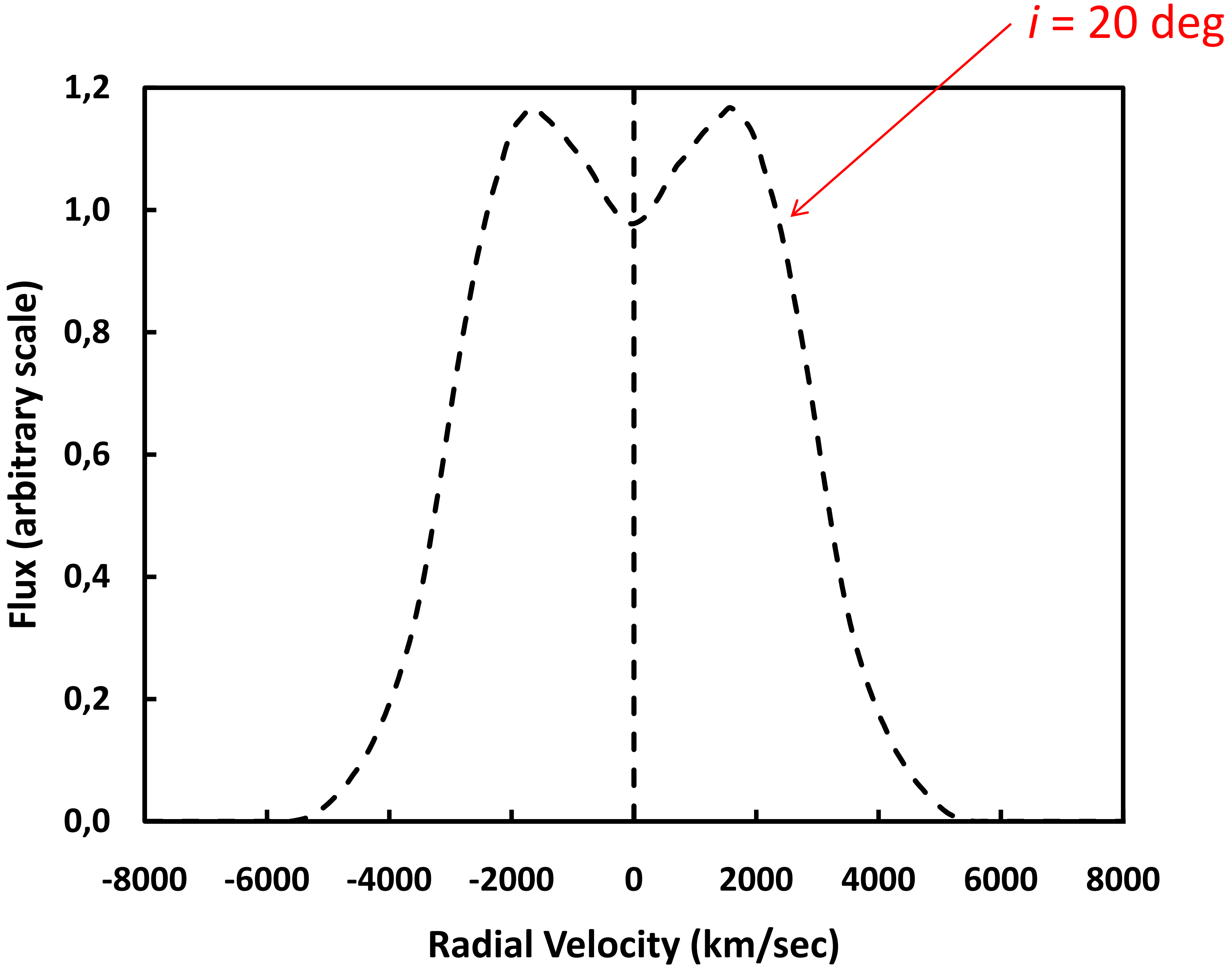
THE IMPORTANT POINT:
When a spectral region varies – the whole annulus cannot vary at once.

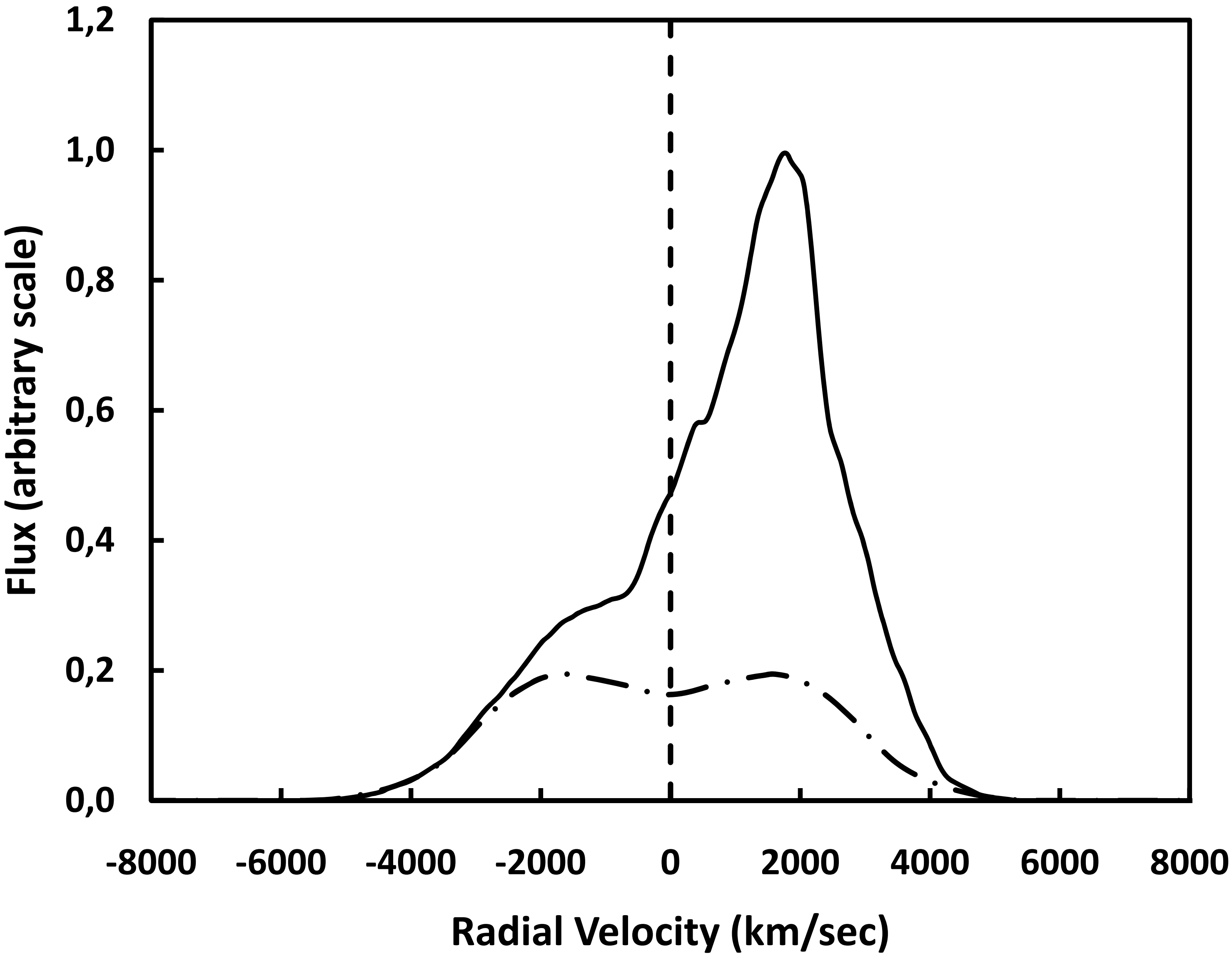


∴ **Variations have to be asymmetric**

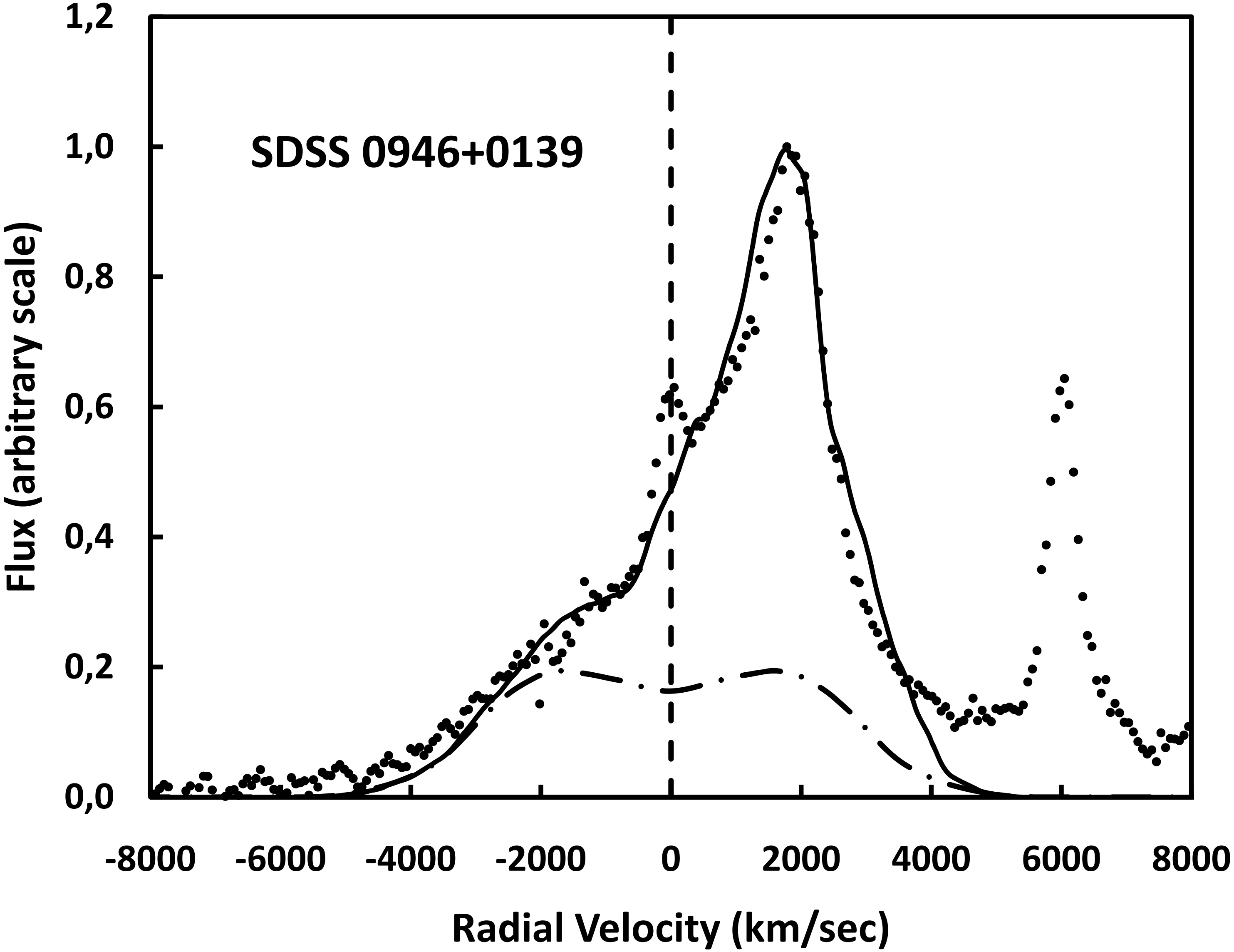
- Off-axis illumination

Basic profile for central illumination:

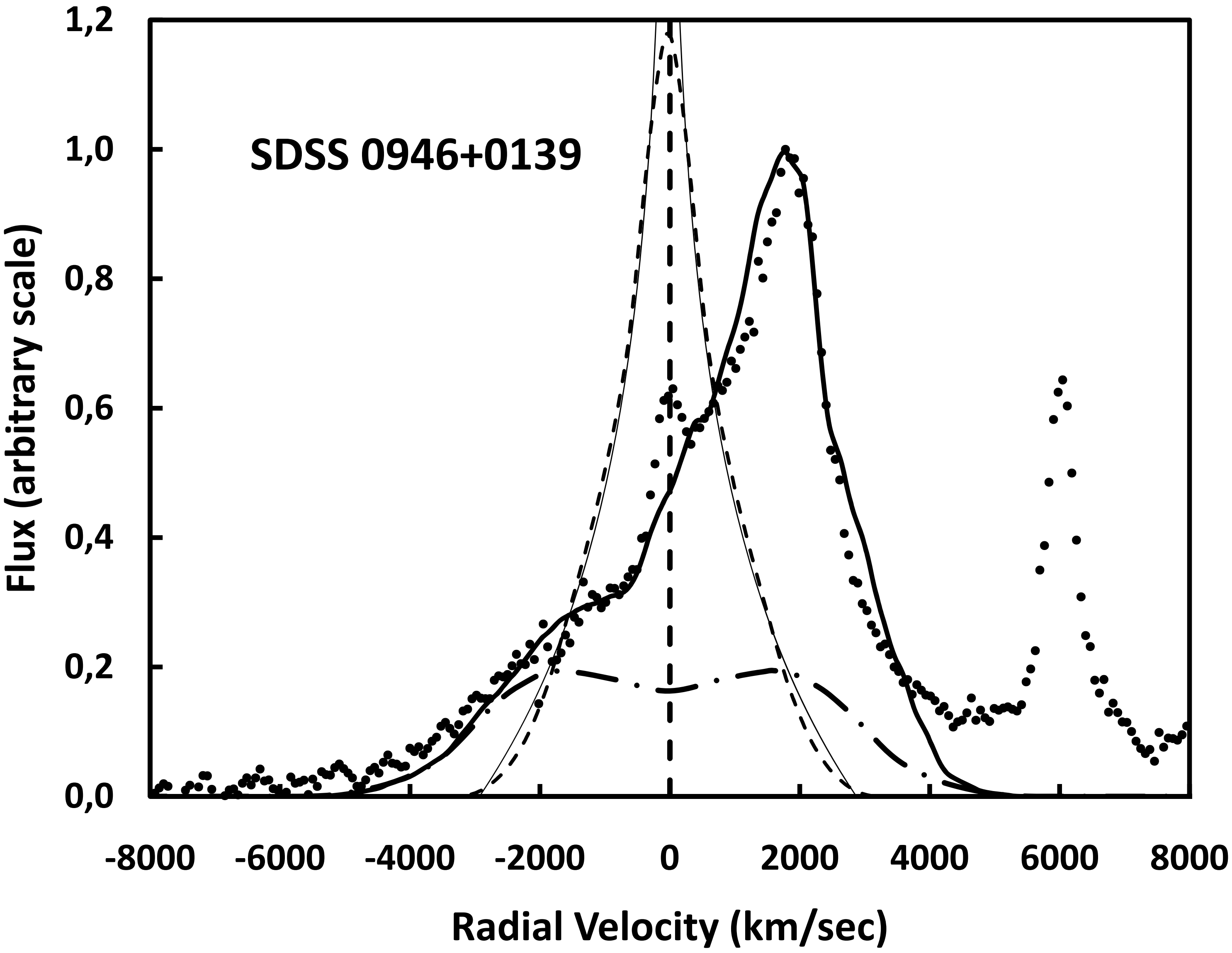




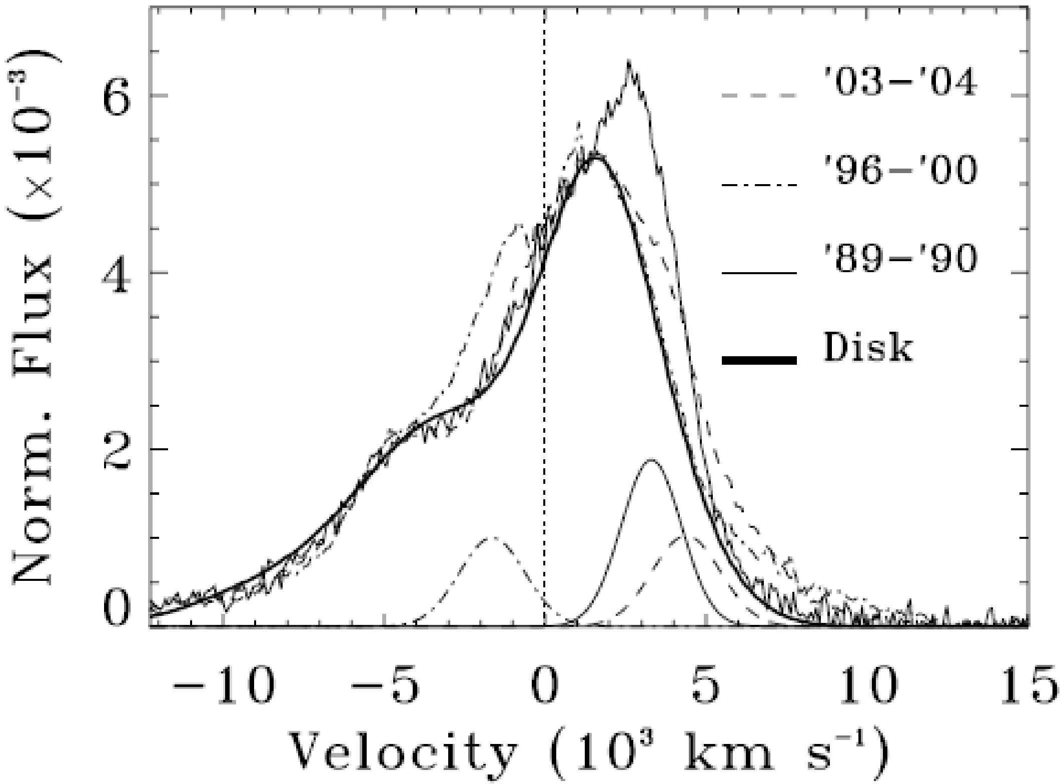
Flux (arbitrary scale)
1,2
1,0
0,8
0,6
0,4
0,2
0,0
-8000
-6000
-4000
-2000
0
2000
4000
6000
8000
Radial Velocity (km/sec)



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)


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

Consistent with profile variability



Gezari *et al.*

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.

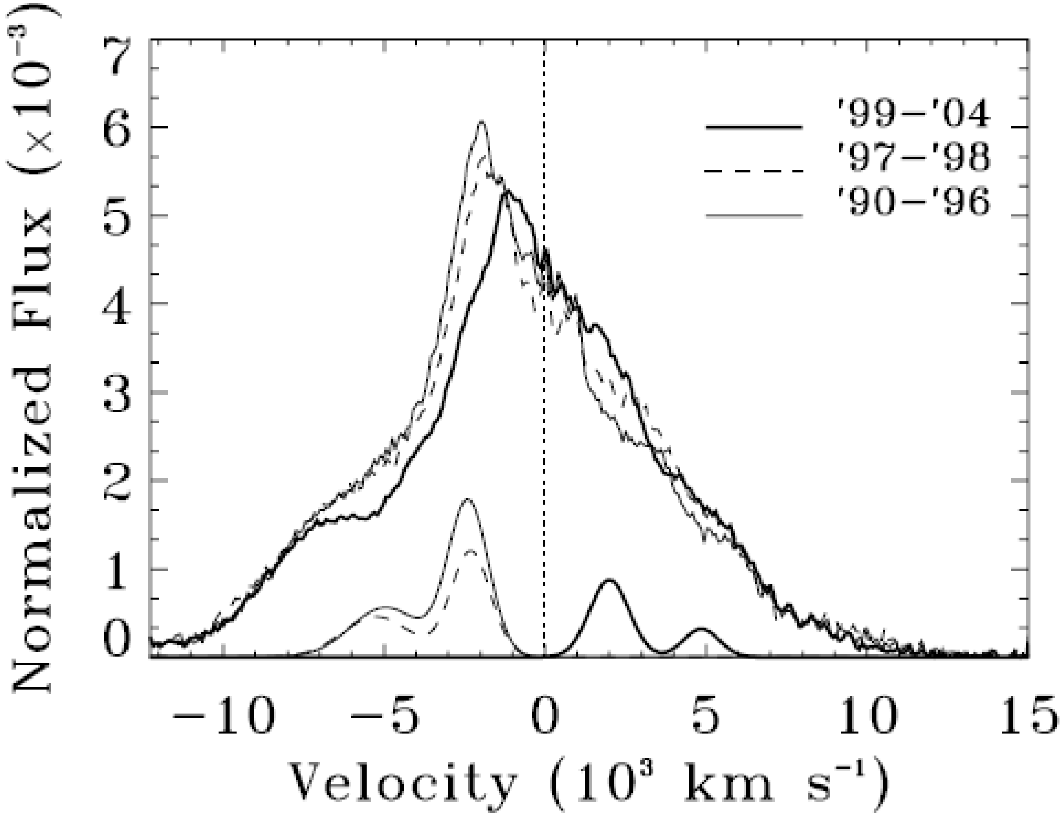
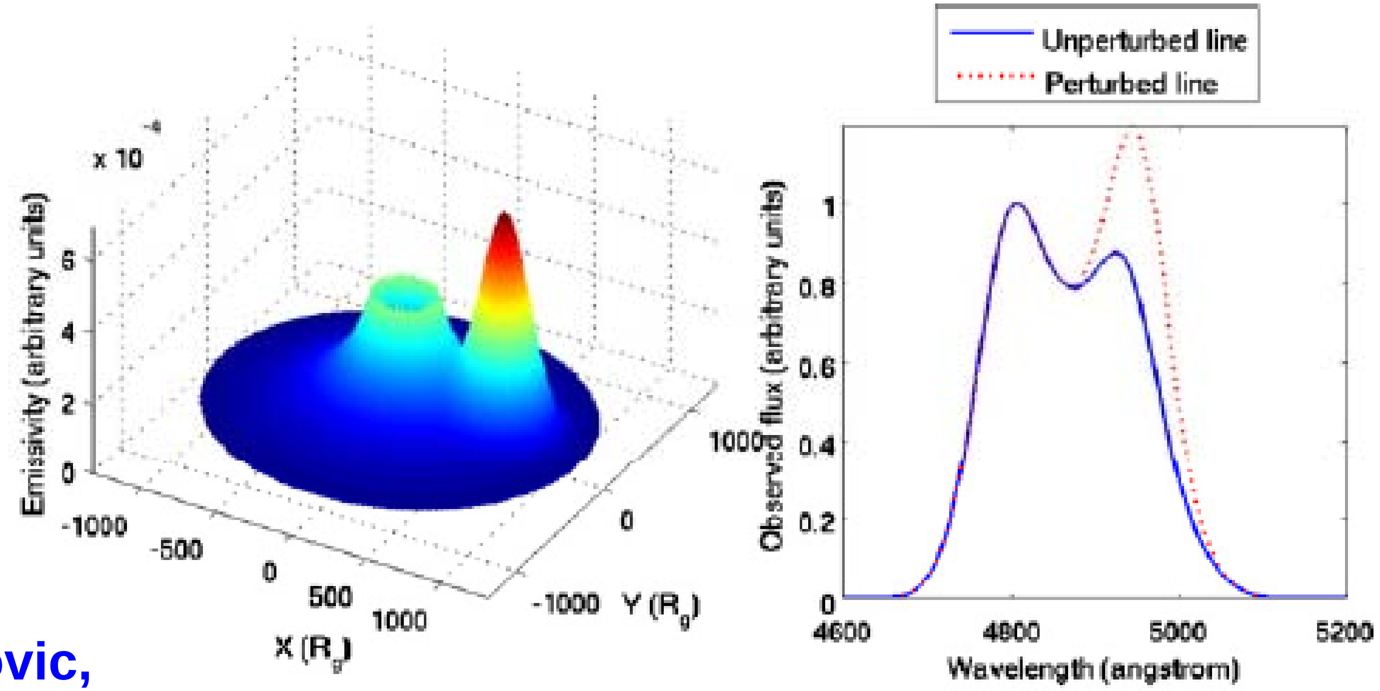
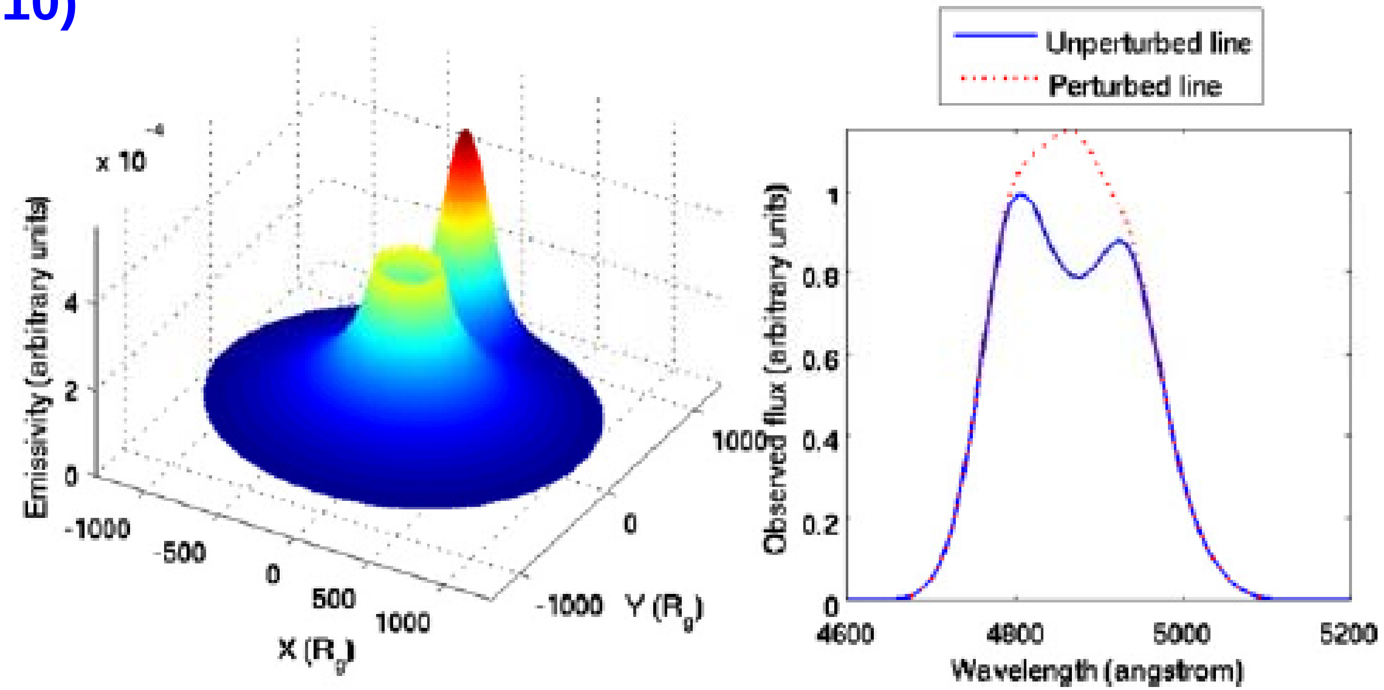


FIG. 32.—3C 227: Averaged broad Hα profiles that demonstrate the dramatic changes in the blue peak. Gaussian fits to the excess that appears to traverse from the blue to the red side of the profile are also shown, following the line style convention of the legend.

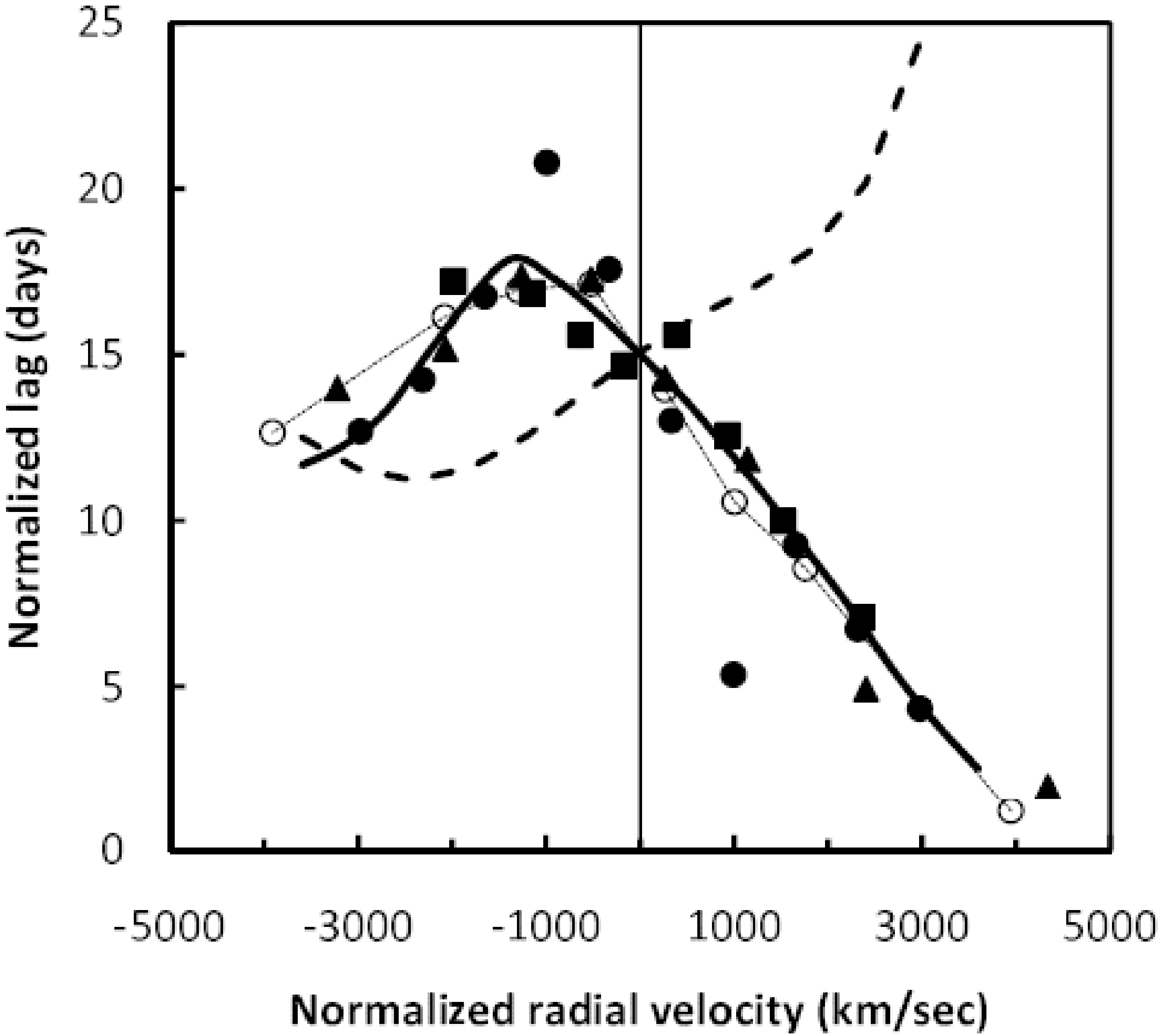
Gezari *et al.*



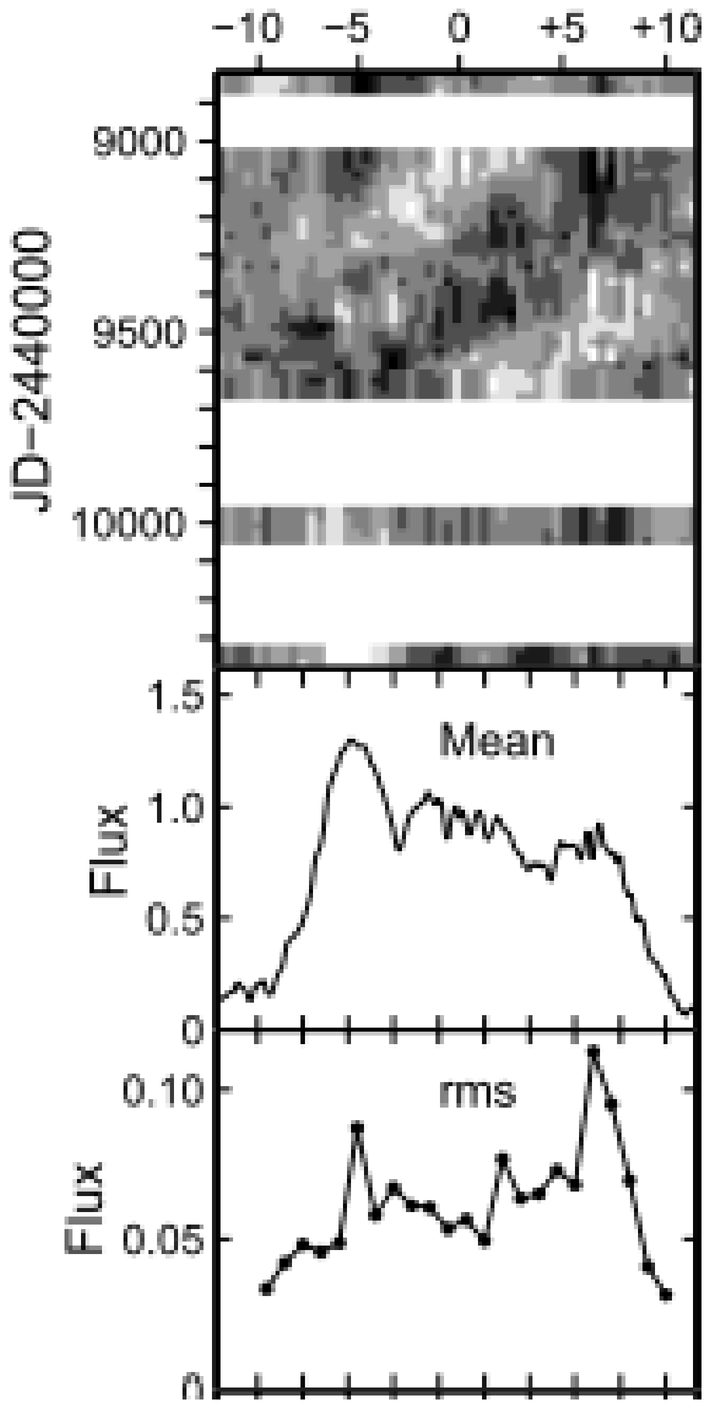
Jovanovic, Popovic, Stalevski, & Shapavalova (2010)



Explains diverse kinematic signatures

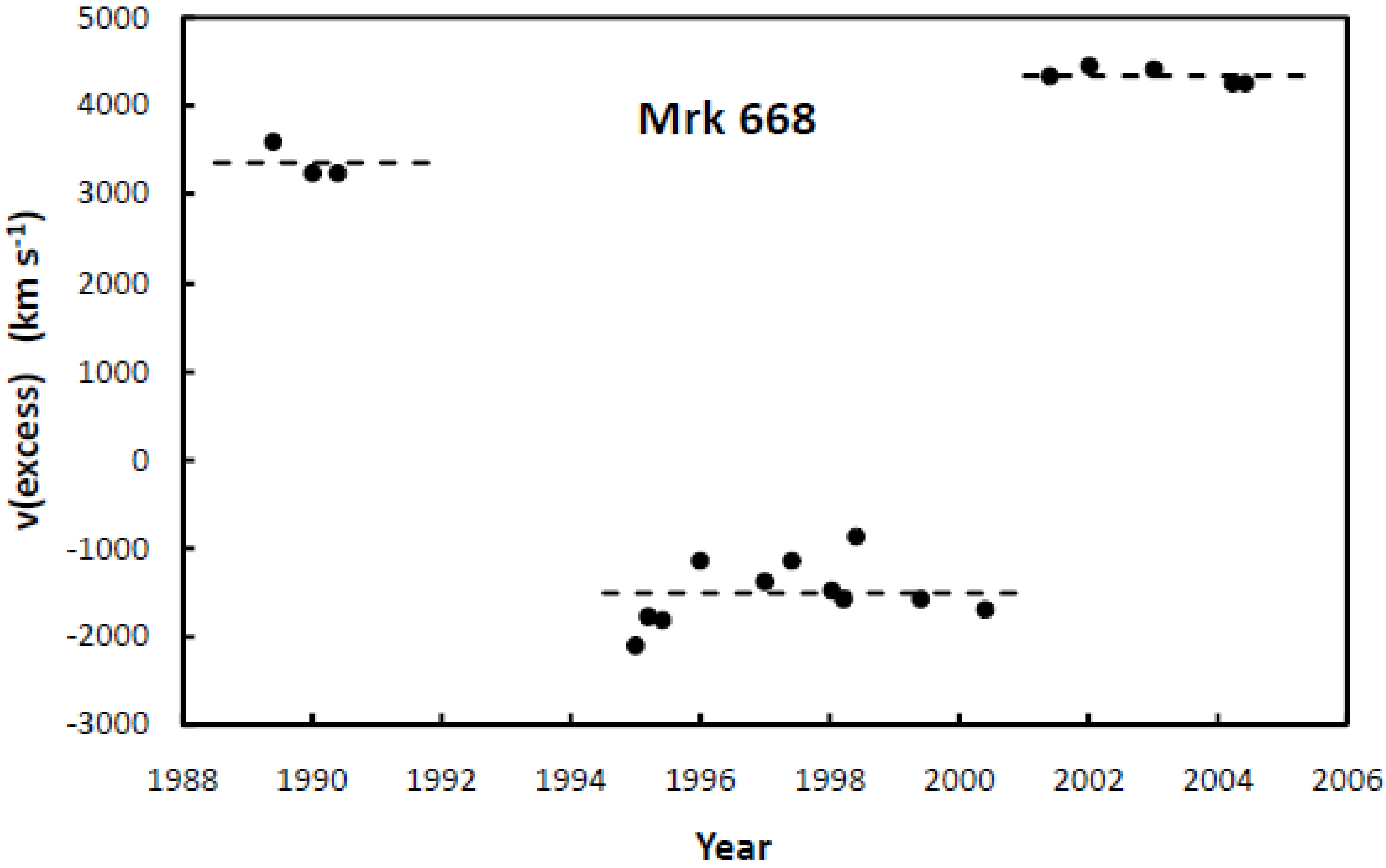


- It’s the **continuum flares** that are orbiting, not blobs in the BLR.
- Solves speed problem
- Solves Keplerian shear problem

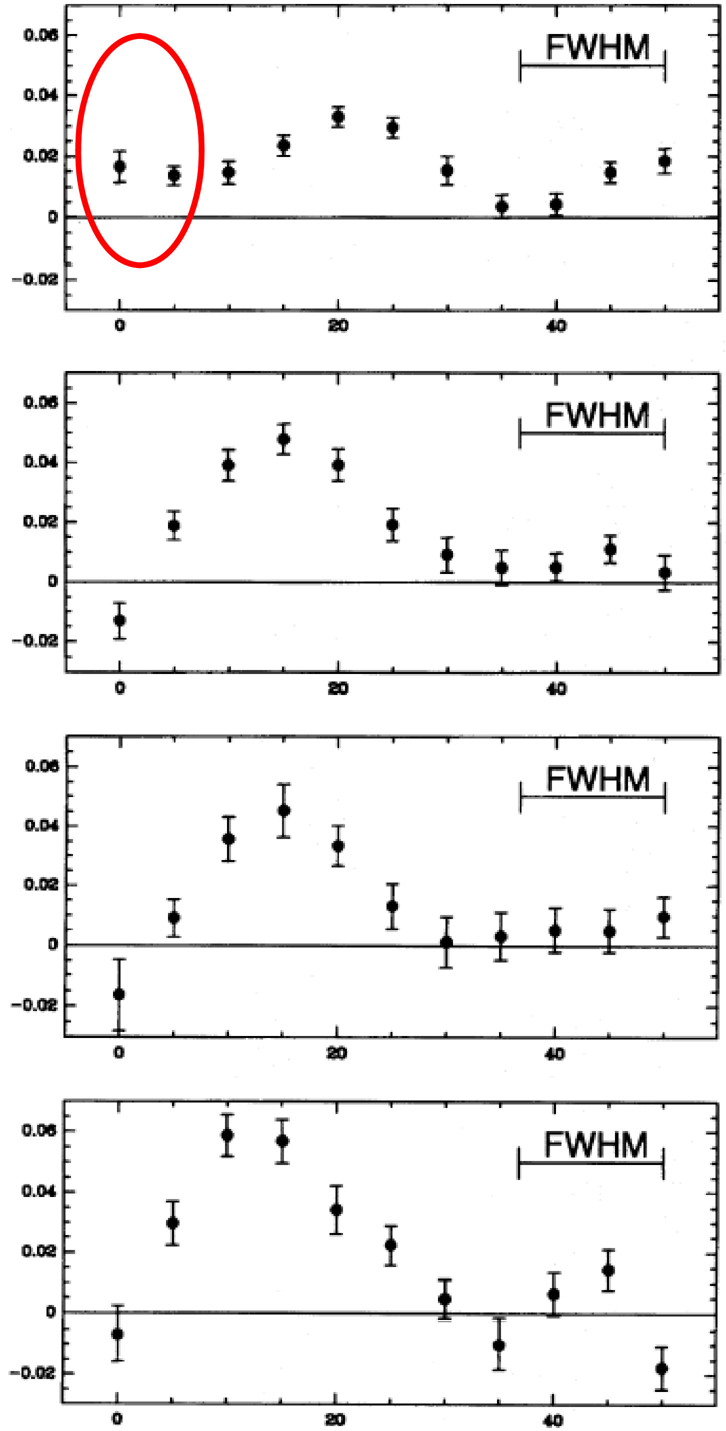


Sergeev et al. (2001)

Flares turn off and on in different parts of the disc – can give illusion of orbital motion:

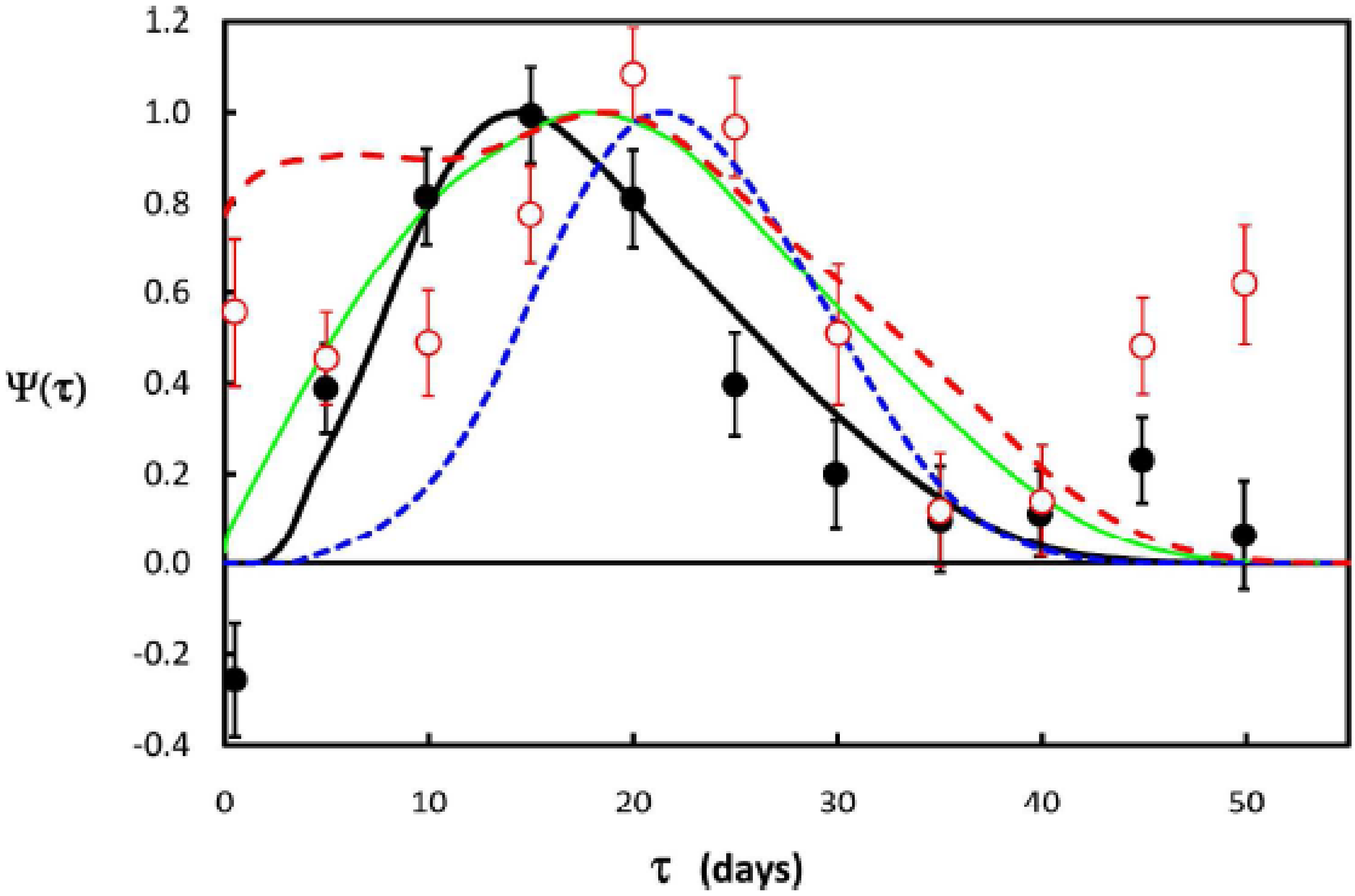


Off-axis variability solves problem of transfer function changing from year to year

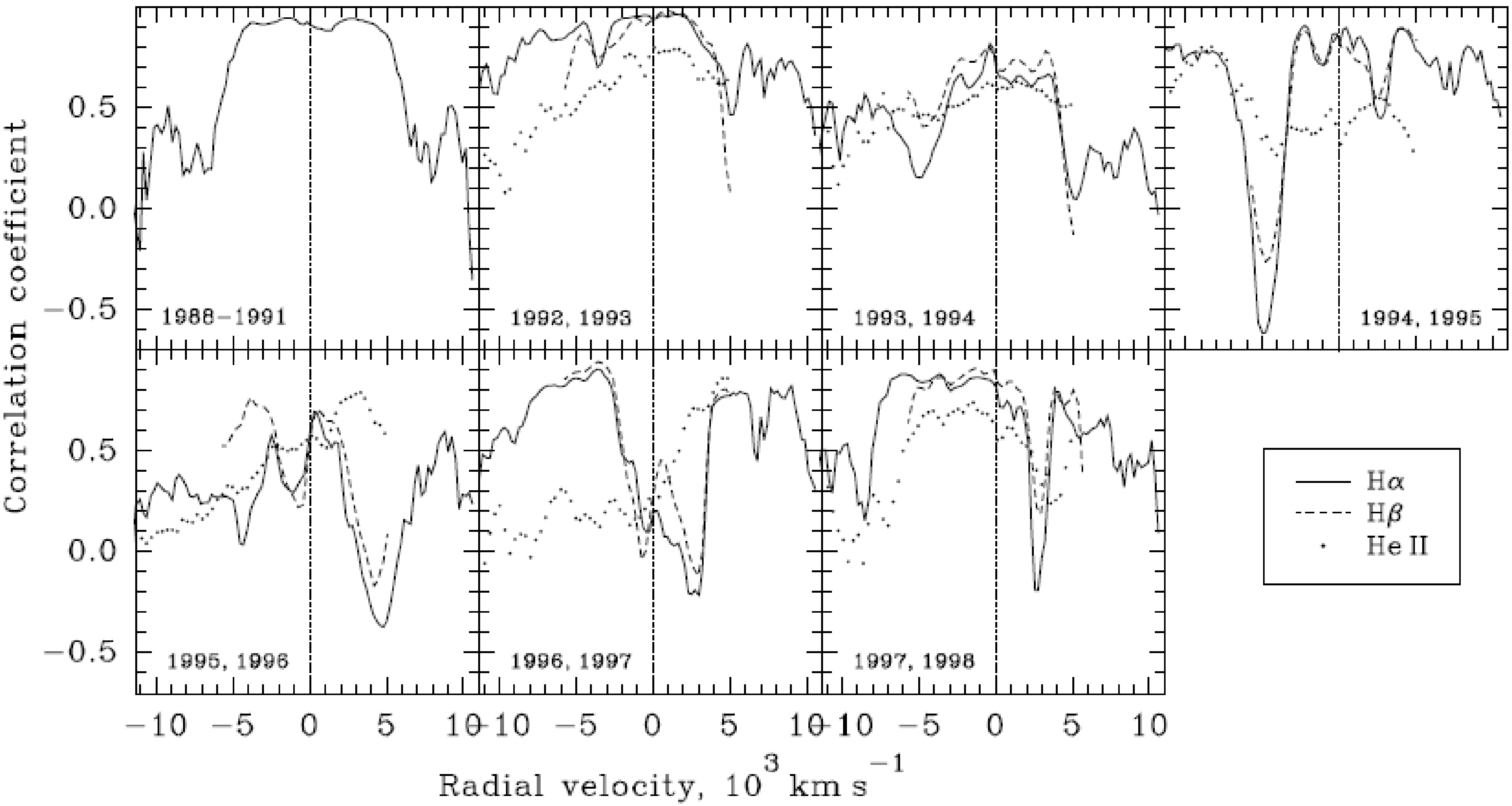


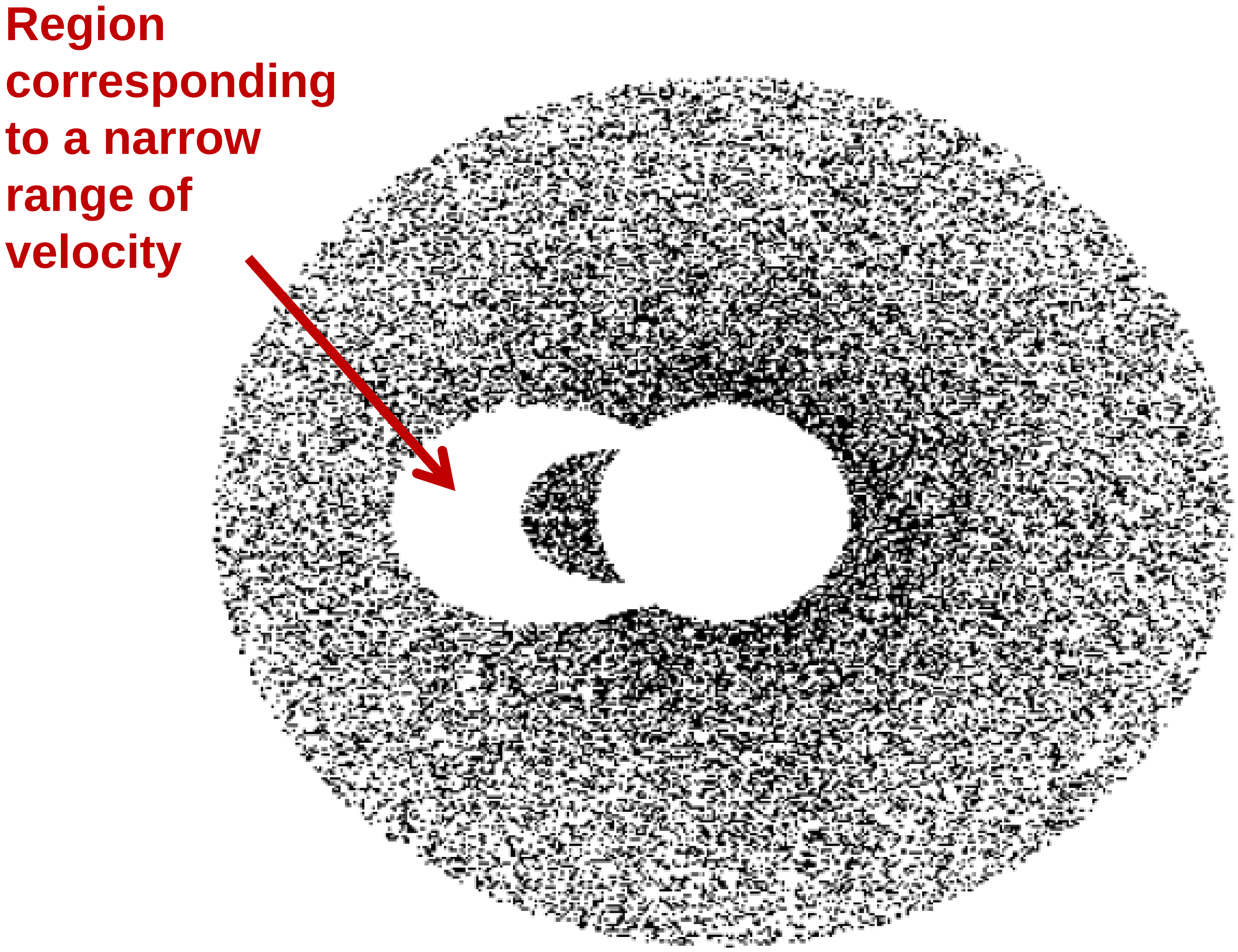
Pijpers & Wanders (1994)

Theoretical transfer functions for different position flares.

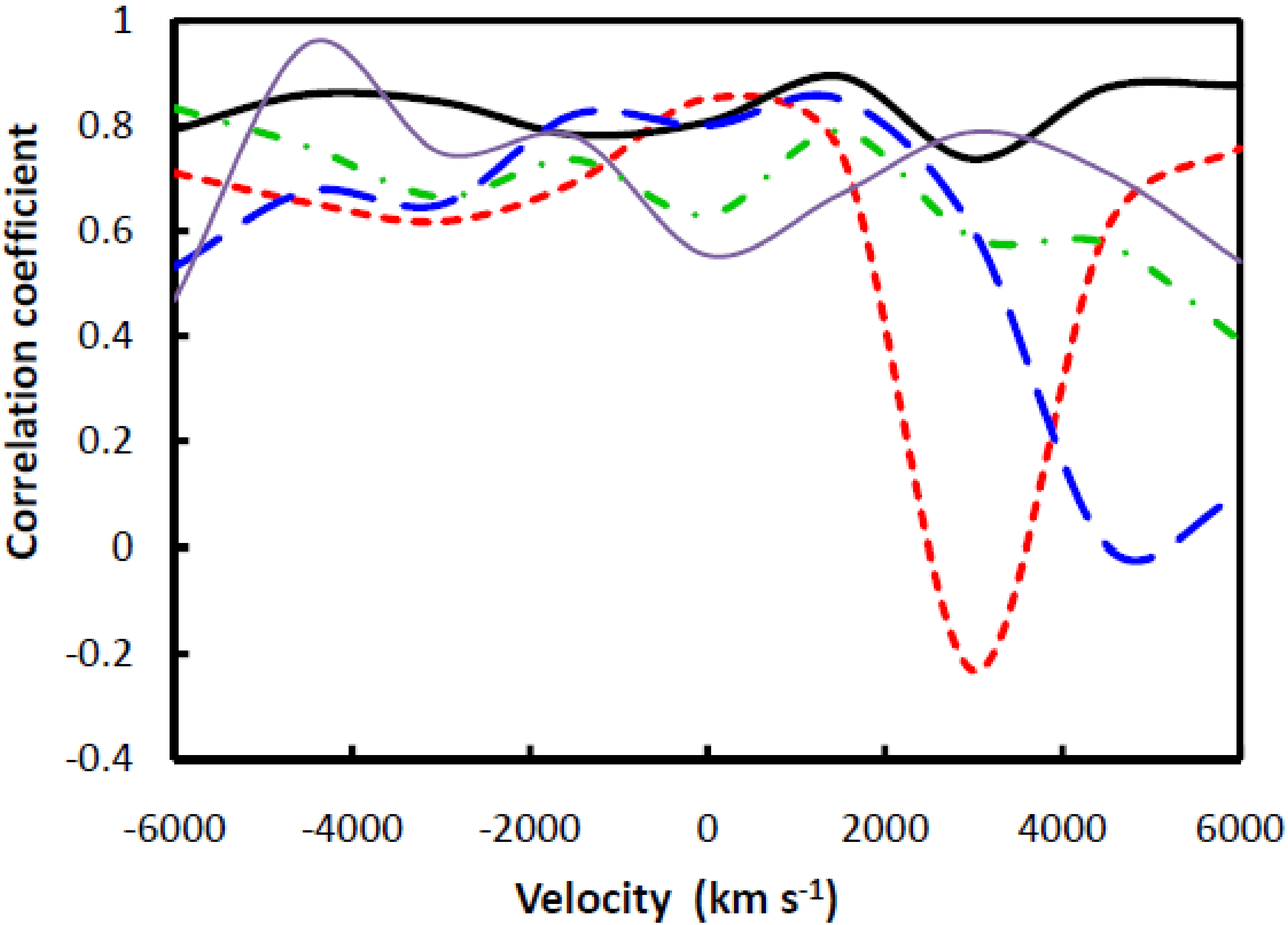


Explains why narrow velocity regions do or don't respond.

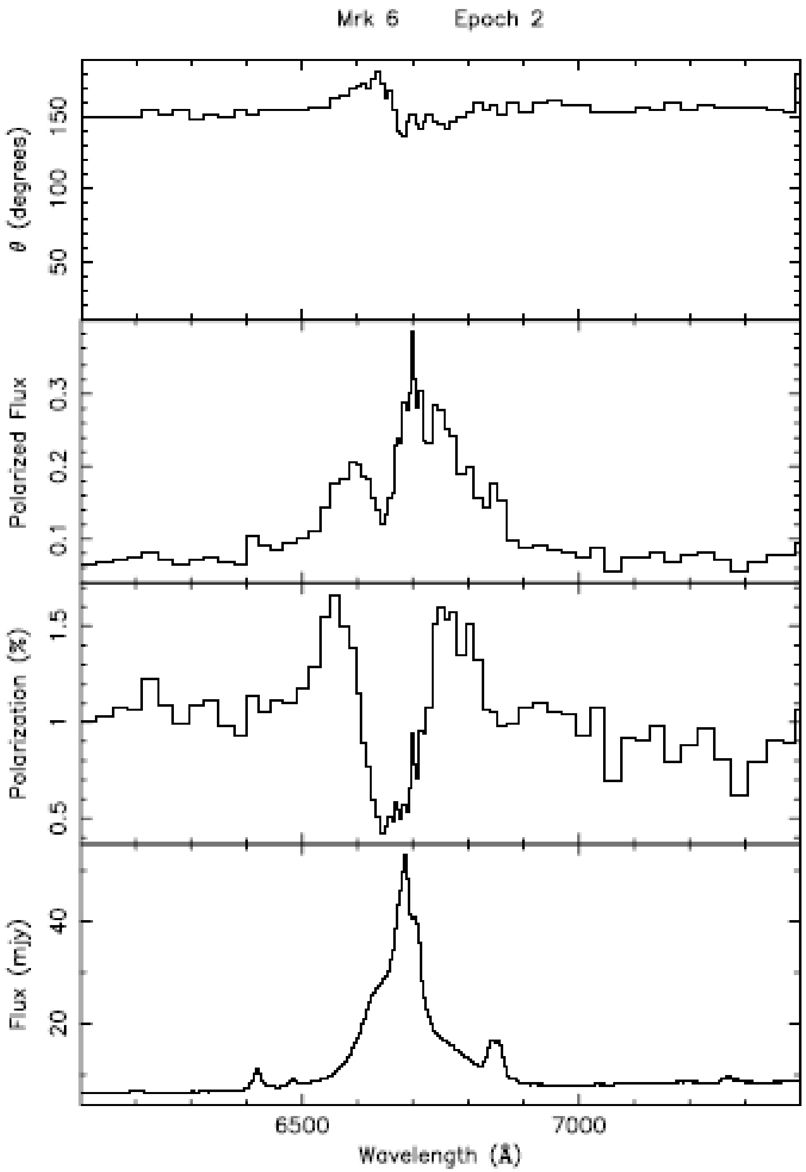


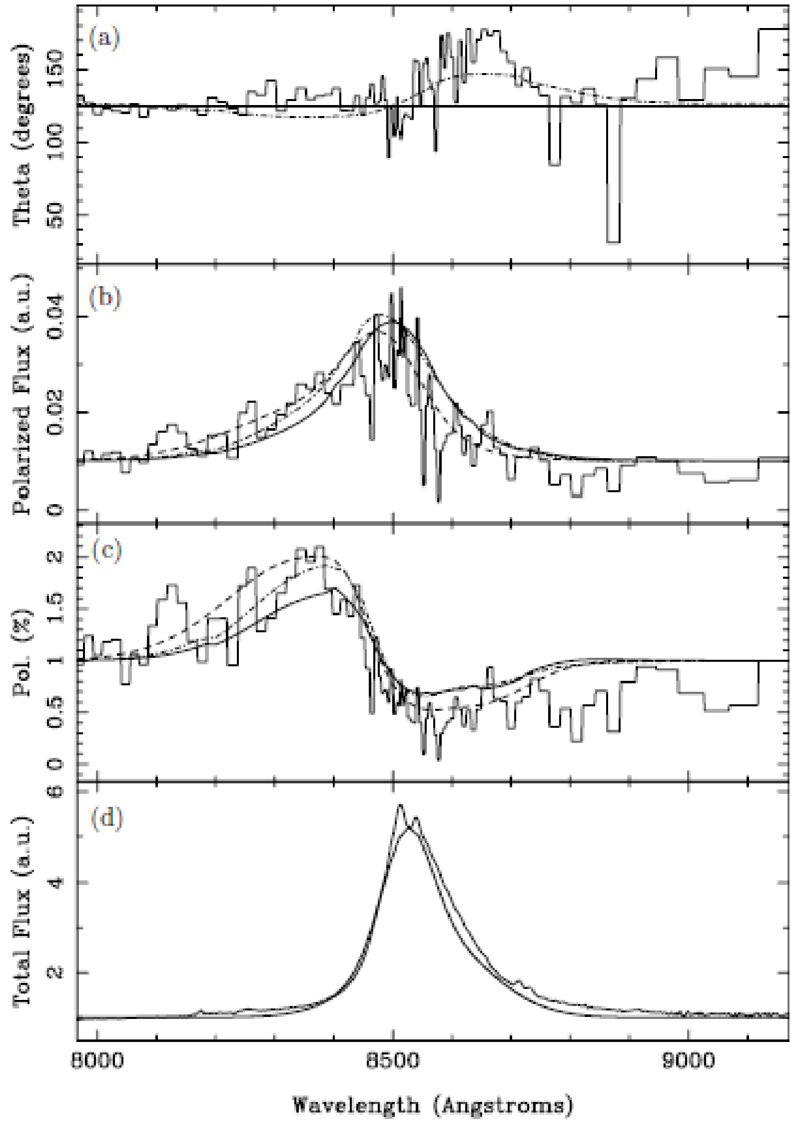

Region corresponding to a narrow range of velocity

Active regions in different places in different years producing a lack of correlation between the observed continuum and the line flux in narrow velocity ranges.

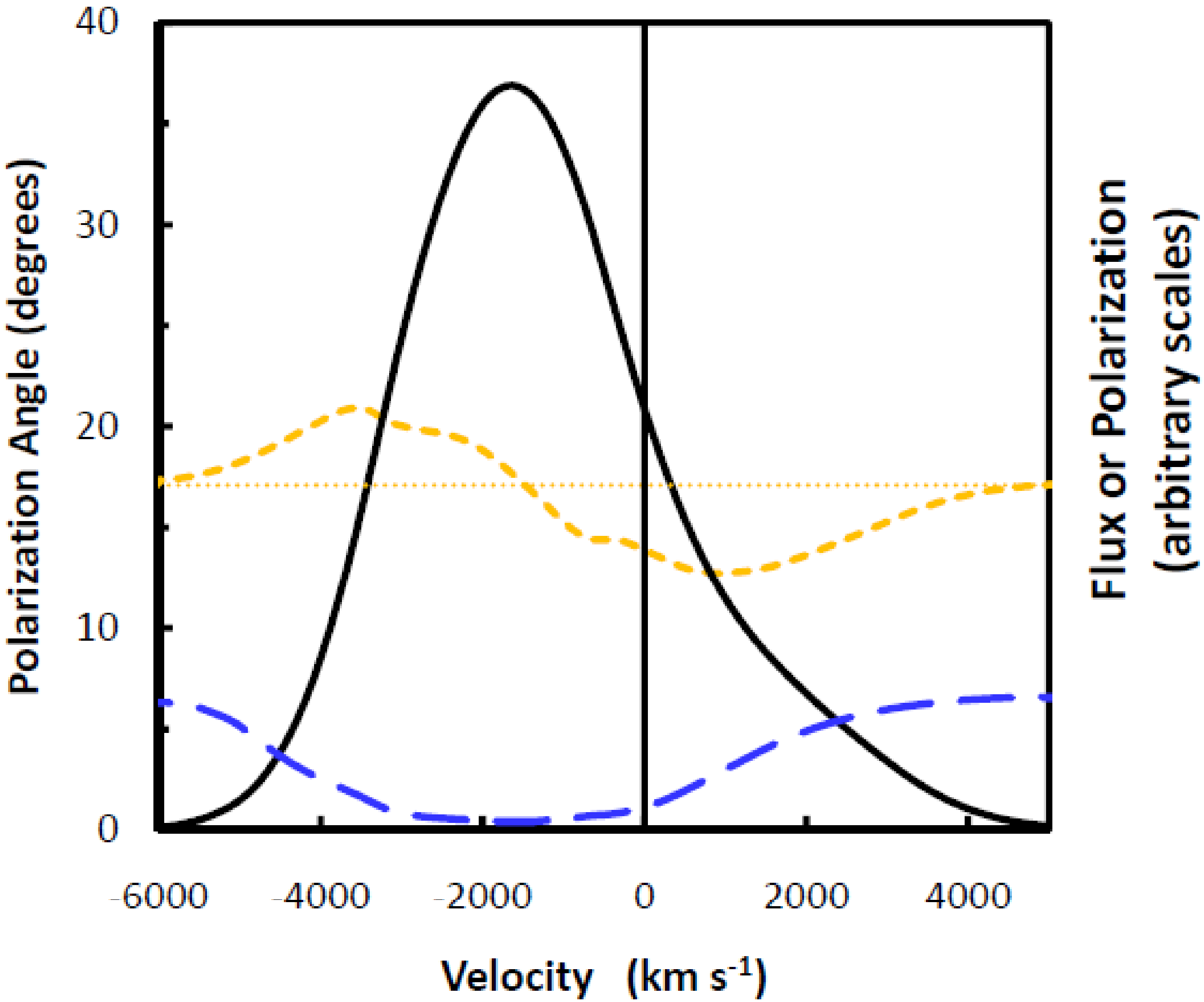


Spectropolarimetry (and spectropolarimetric variability)





Polarization percentage (blue) and position angle (yellow) arising from an off-axis illumination contribution.



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, spectropolarimetric variability
- 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