Overview of Optical/UV Spectroscopic Properties of Quasars

A subjective story of what we know
and how (and how well) we know it.

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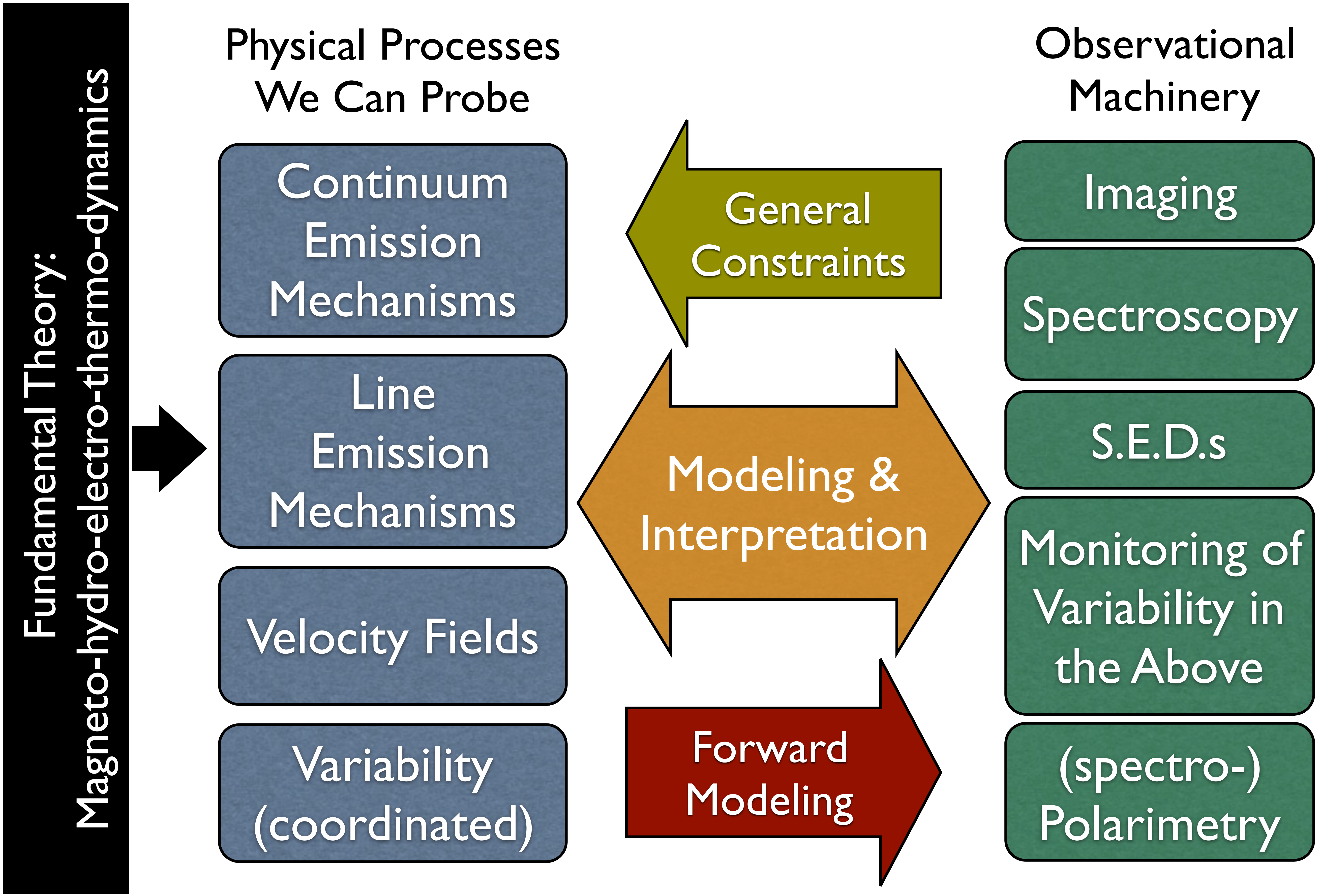
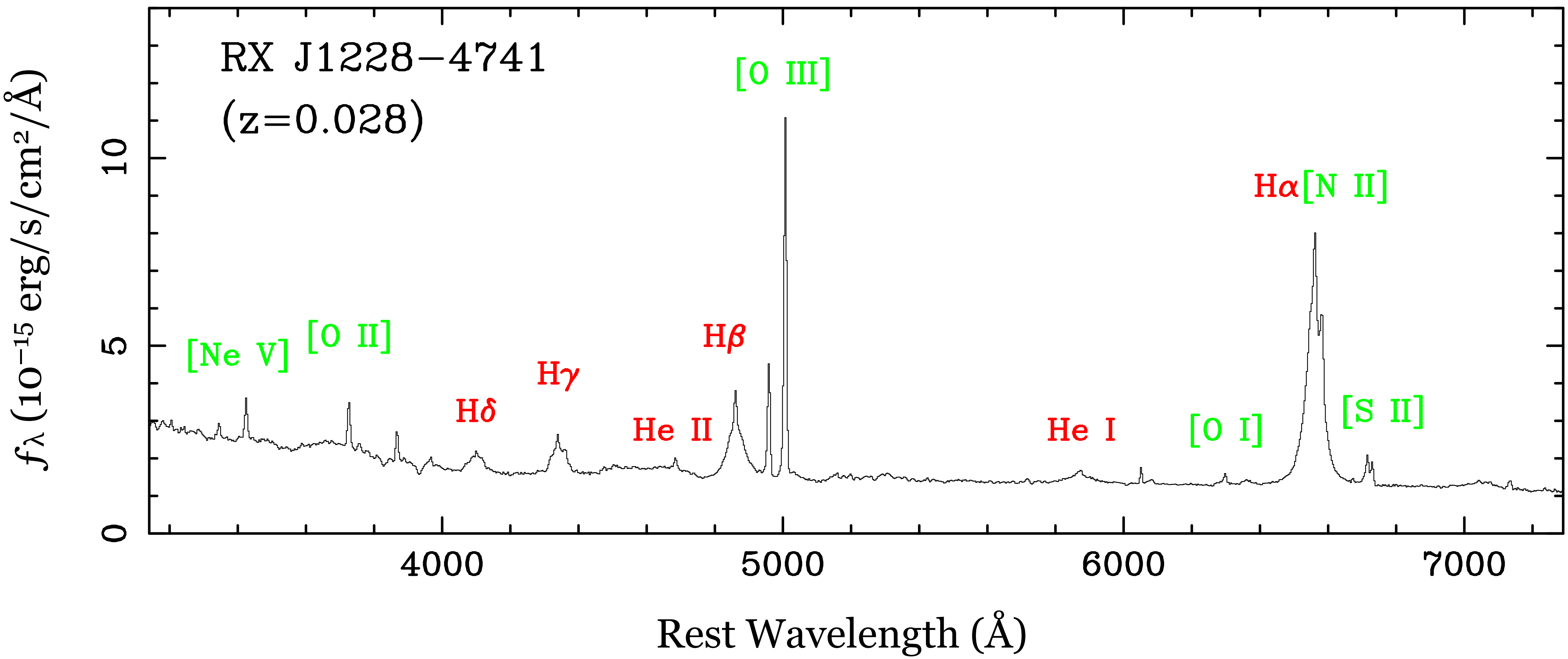
by Mike Eracleous

"Quasars [are] in Crisis" and we are here to comfort them!
Edinburgh, August 5–9, 2019

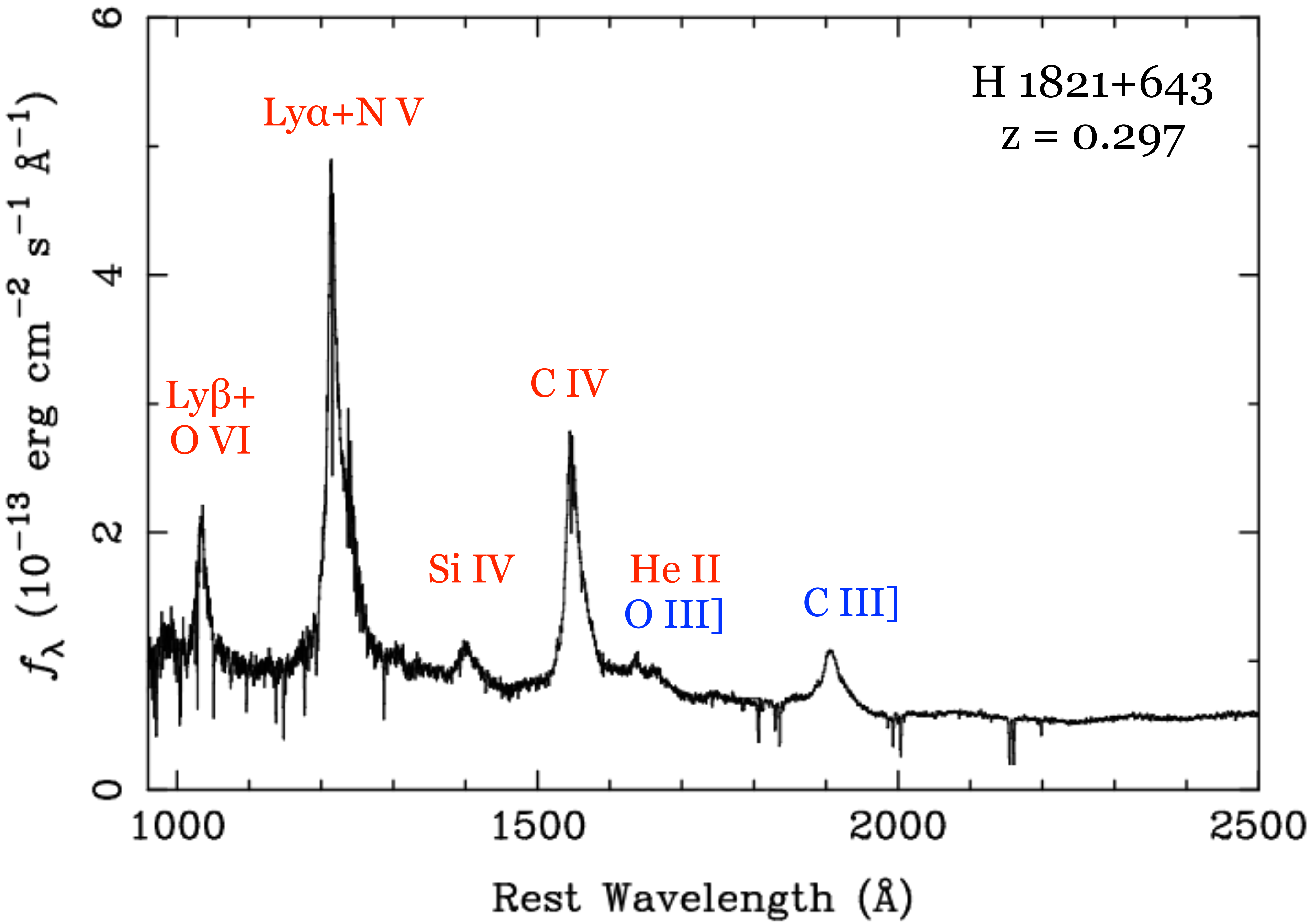

Fundamental Theory:
Magneto-hydro-electro-thermo-dynamics
Physical Processes
We Can Probe
Continuum
Emission
Mechanisms
Line
Emission
Mechanisms
Velocity Fields
Variability
(coordinated)
General
Constraints
Modeling &
Interpretation
Forward
Modeling
Observational
Machinery
Imaging
Spectroscopy
S.E.D.s
Monitoring of
Variability in
the Above
(spectro-)
Polarimetry

Example of an optical spectrum



spectrum kindly provided by Ed Moran

Example of a FUV spectrum



spectrum from the HST archive

Composite FUV + EUV spectrum

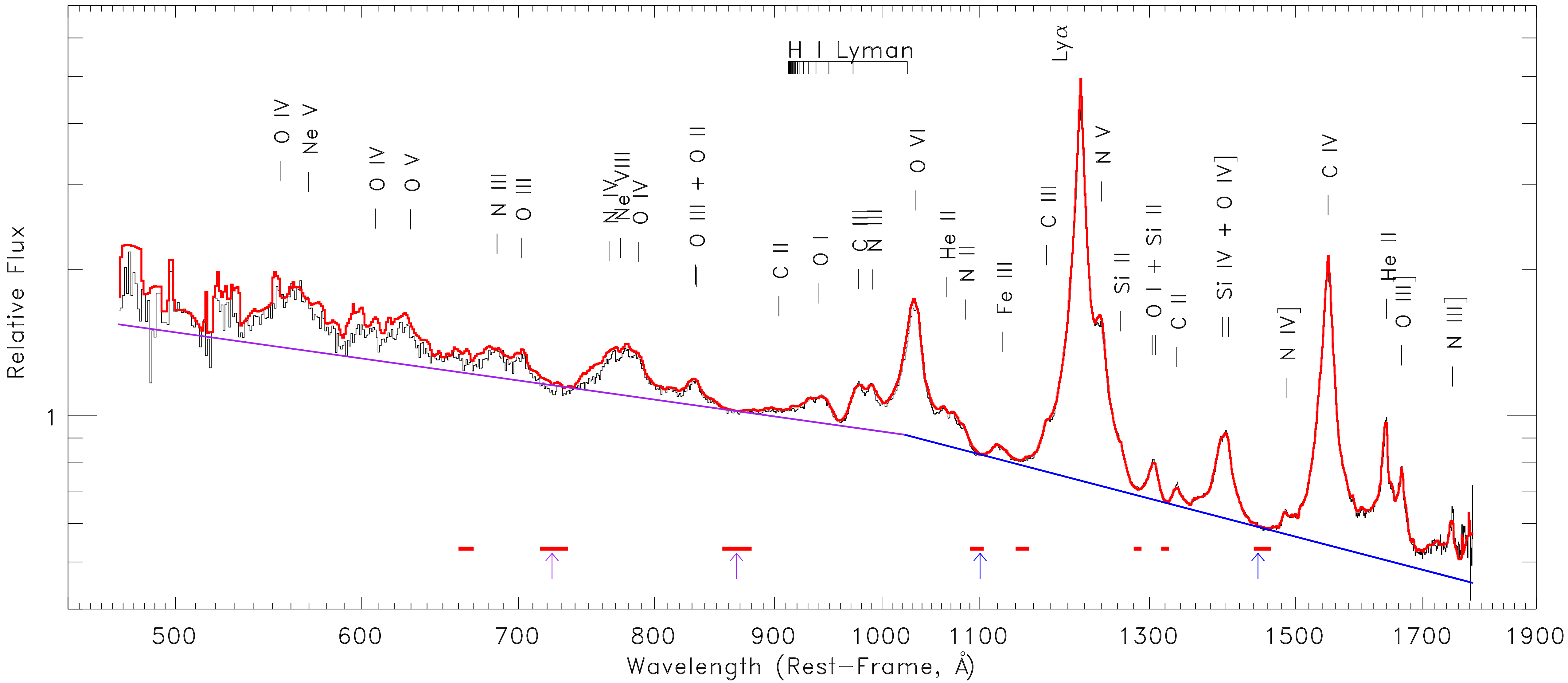


figure from Stevans et al. 2014, ApJ, 794, 75

Blowin' in the Wind

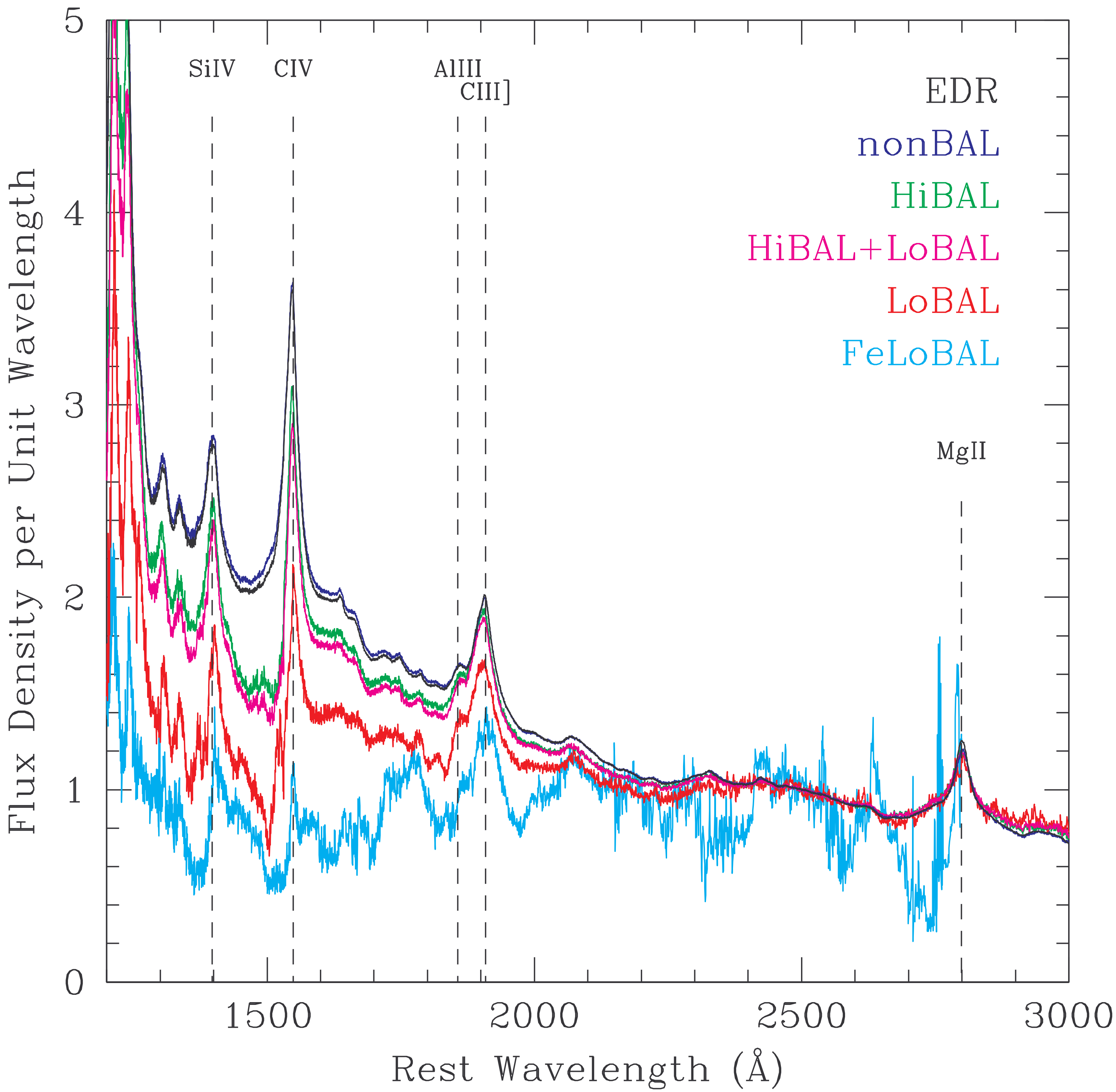


figure from Reichard et al 2003, AJ, 126, 2594

A whirlwind tour of observed continuum properties

Spectral energy distributions and α_{ox}

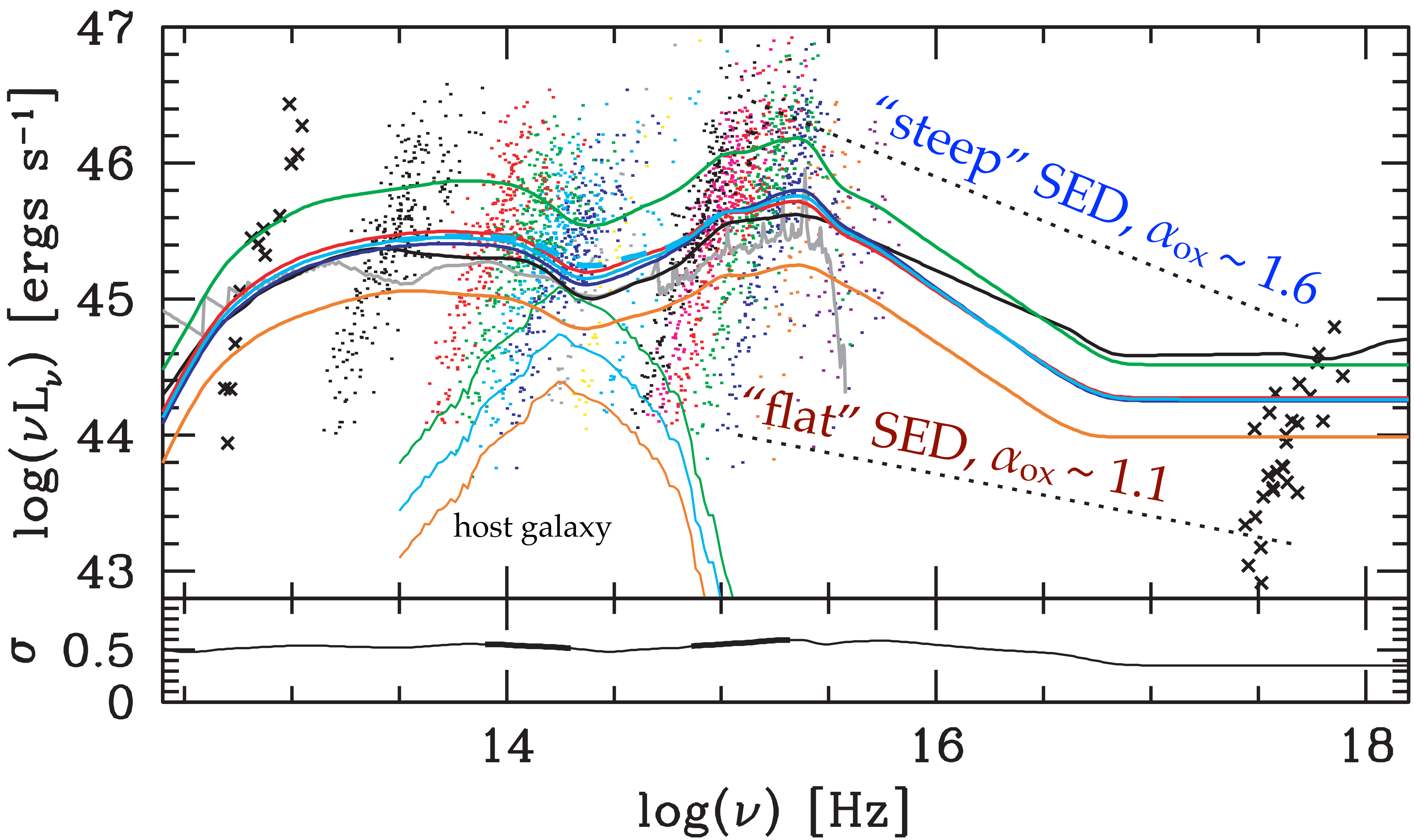
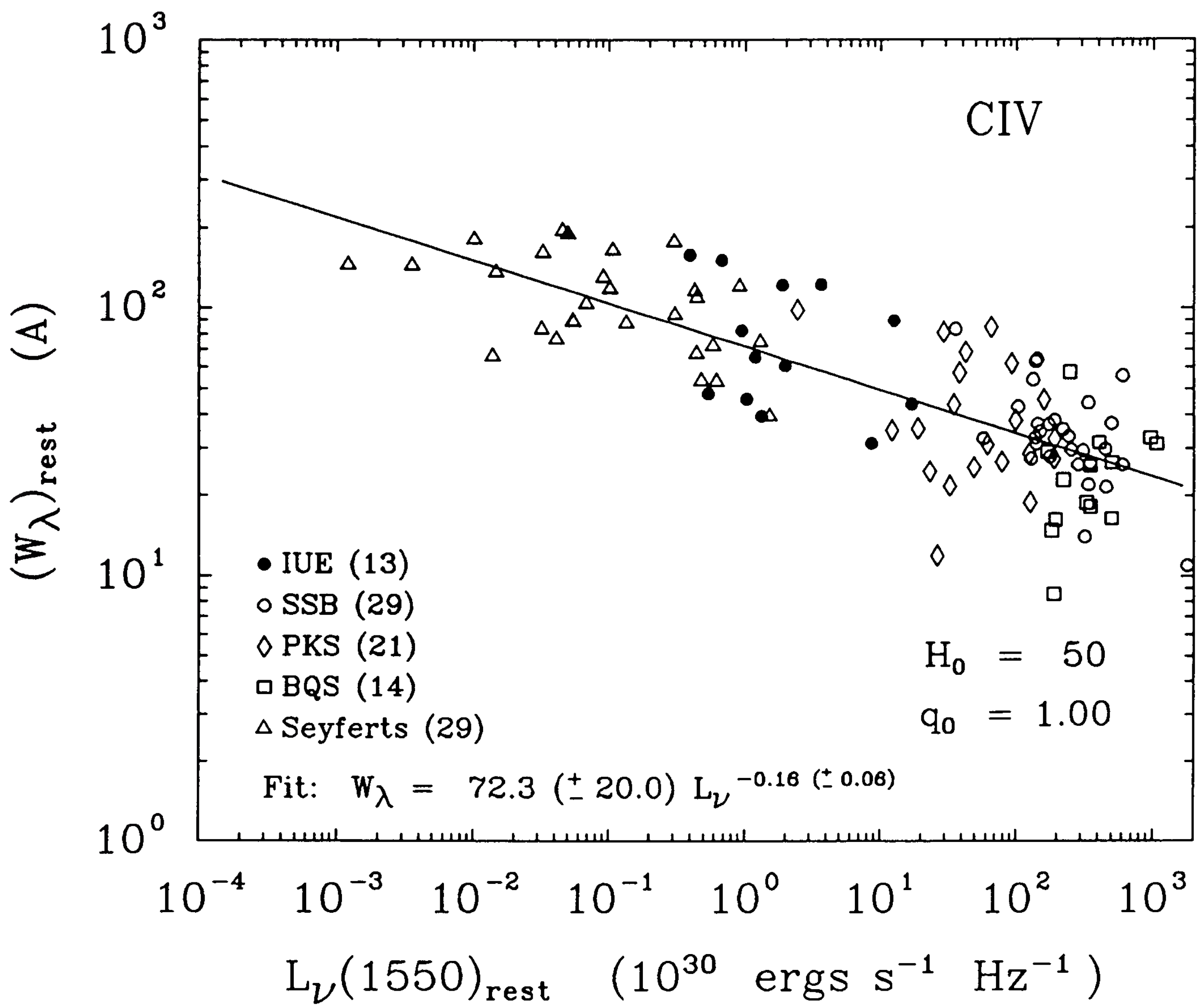


figure from Richards et al 2006, ApJS, 166, 470

The Baldwin effect



- Change of W_λ with L
  - Observed in the UV resonance lines (C IV, Lyα)
- What's the cause?
  - Change in the continuum shape with luminosity?
  - Change of BLR covering fraction with luminosity?
  - Change of BLR ionization state with luminosity?

figure from Kinney et al. 1990, ApJ, 357, 338

In polarized light…

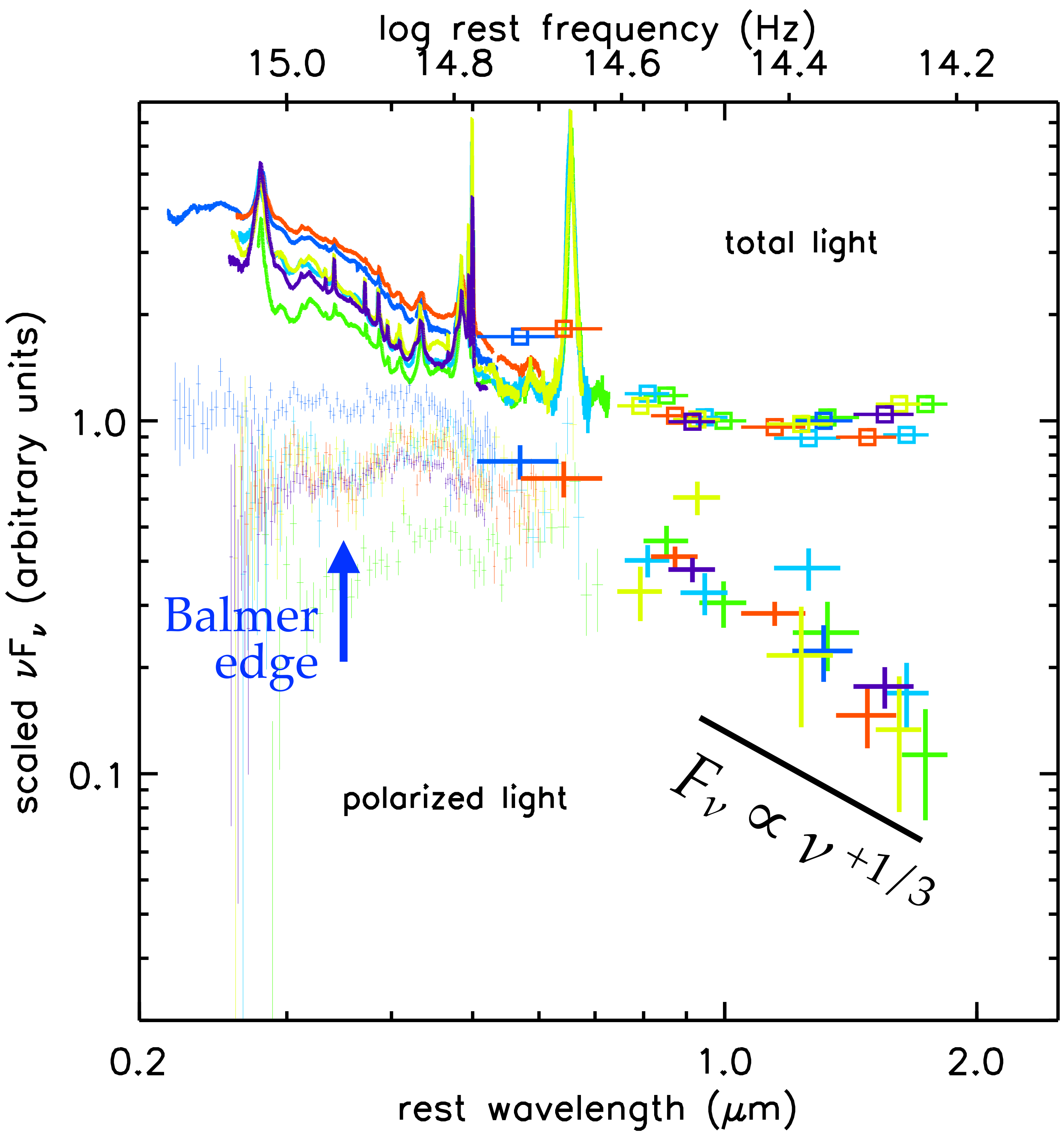
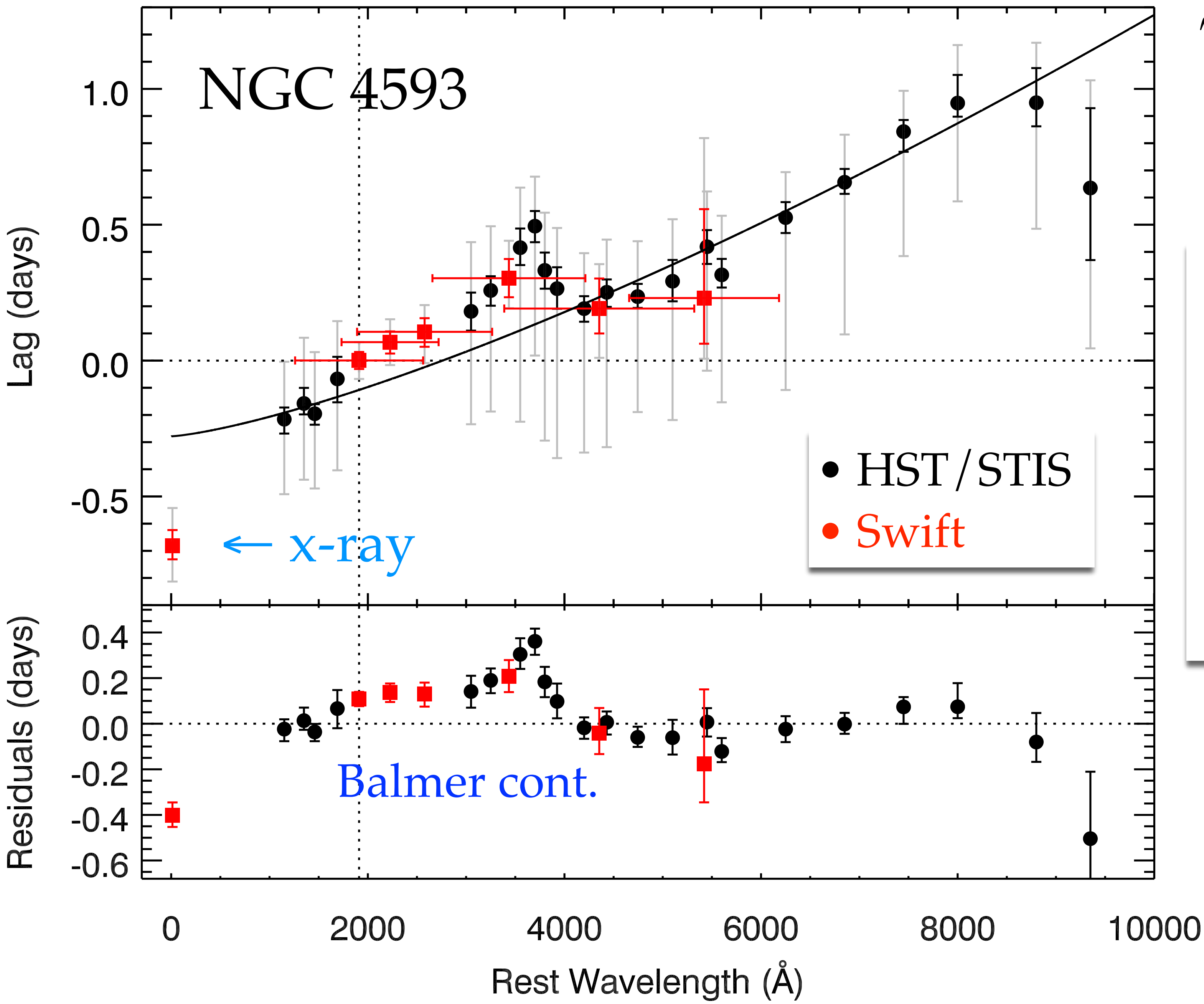


figure from Kishimoto et al. 2008, Nature, 454, 49

- Optical-NIR light probes cooler portions of disk (weak relativity and broadening)
- Polarization via e^- scattering within or interior to the BLR. Polarized light excludes broad emission lines and nebular continuum.
- Polarized-light spectrum reveals "uncontaminated" features of the primary continuum:
  - Balmer edge
  - Tail of thermal emission from multi-*T* disk

Time lags *vs* wavelength



$\tau \propto \lambda^{4/3}$

1.5 days → 2500 R_g / M_7

~ 3200 R_g for NGC 4593

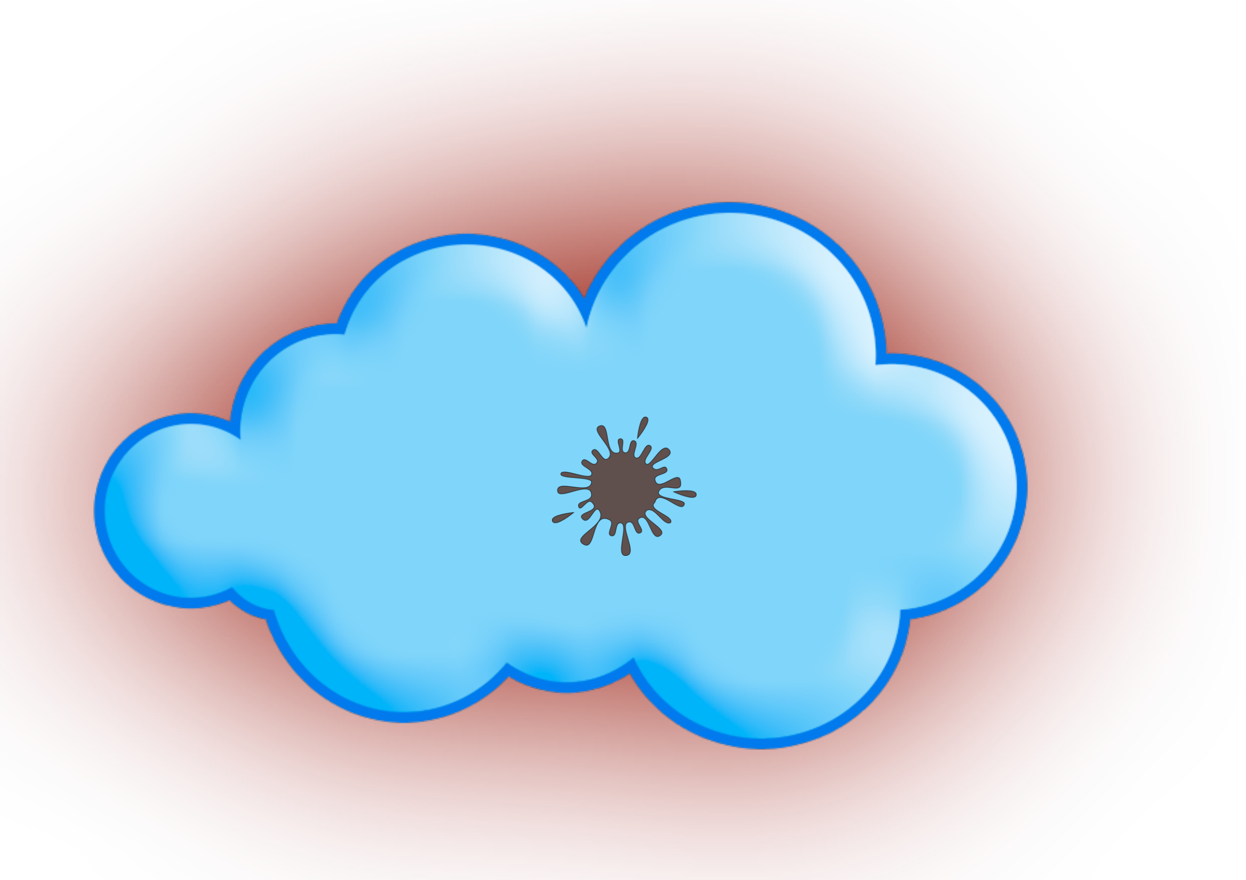
($M_7 = 0.76$)

figure from Cackett et al 2006, ApJ, 857, 53

A general, qualitative picture of the BLR to guide our thinking

m=10

Basic arrangement and properties



Fiducial Configuration

$M \sim 10^8\ M_\odot$ and $L/L_{\rm Edd} \sim 0.1$

$R \sim 10^{17}$ cm $\sim 7000\ R_g$

$T \sim 10^4$ K

$n \sim 10^9$–10^{13} cm^{-3}

- Continuous medium (based on smoothness of line profiles) but with density fluctuations and multiple phases.
- Can get mass and characteristic size from reverberation time combined with line widths
- Dust in the outskirts (from IR continuum reverberation)
- Density stratification but in what sense/direction?
- Hints of disky geometry… (stay tuned for the clues)

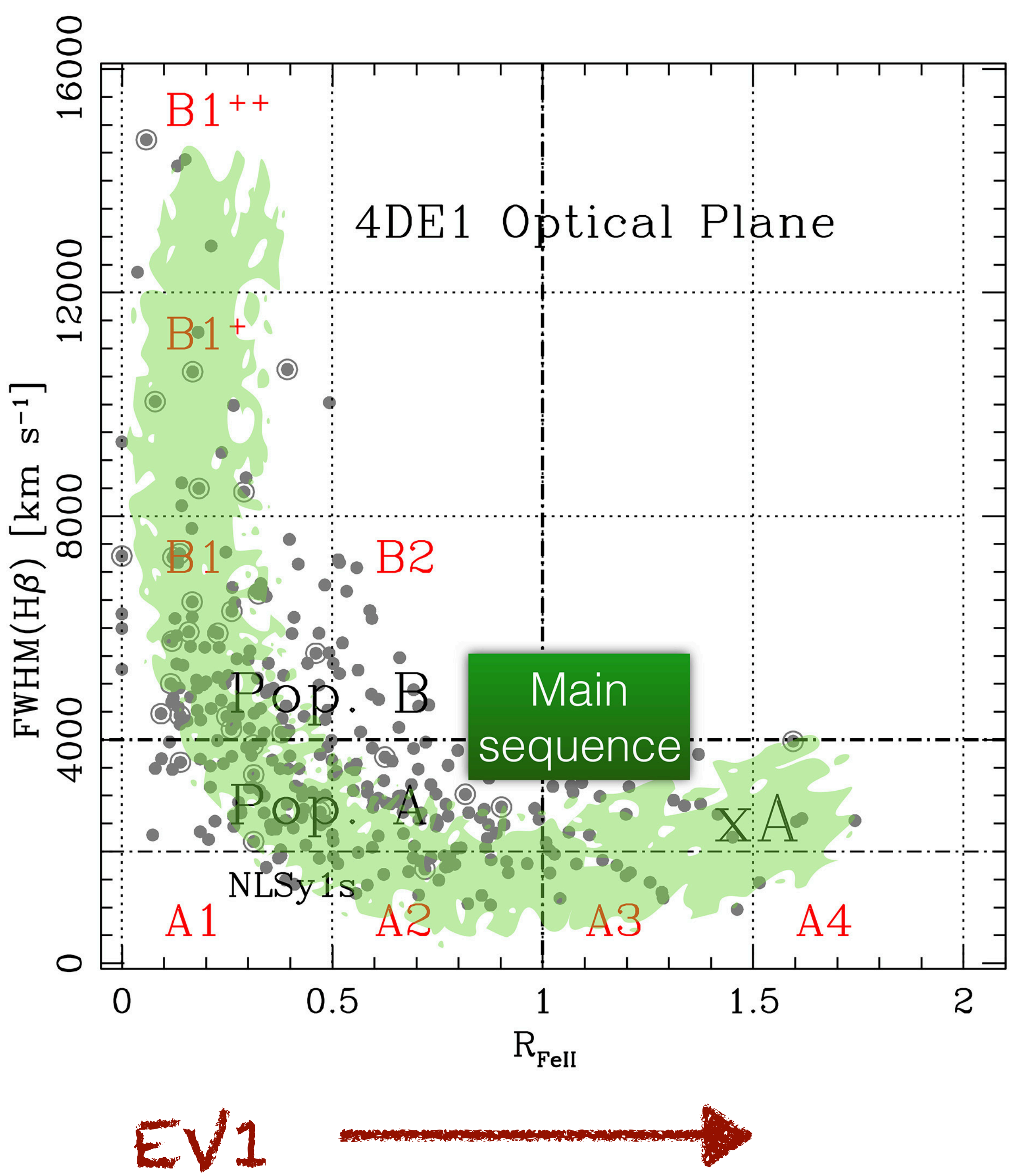
Time scales of interest

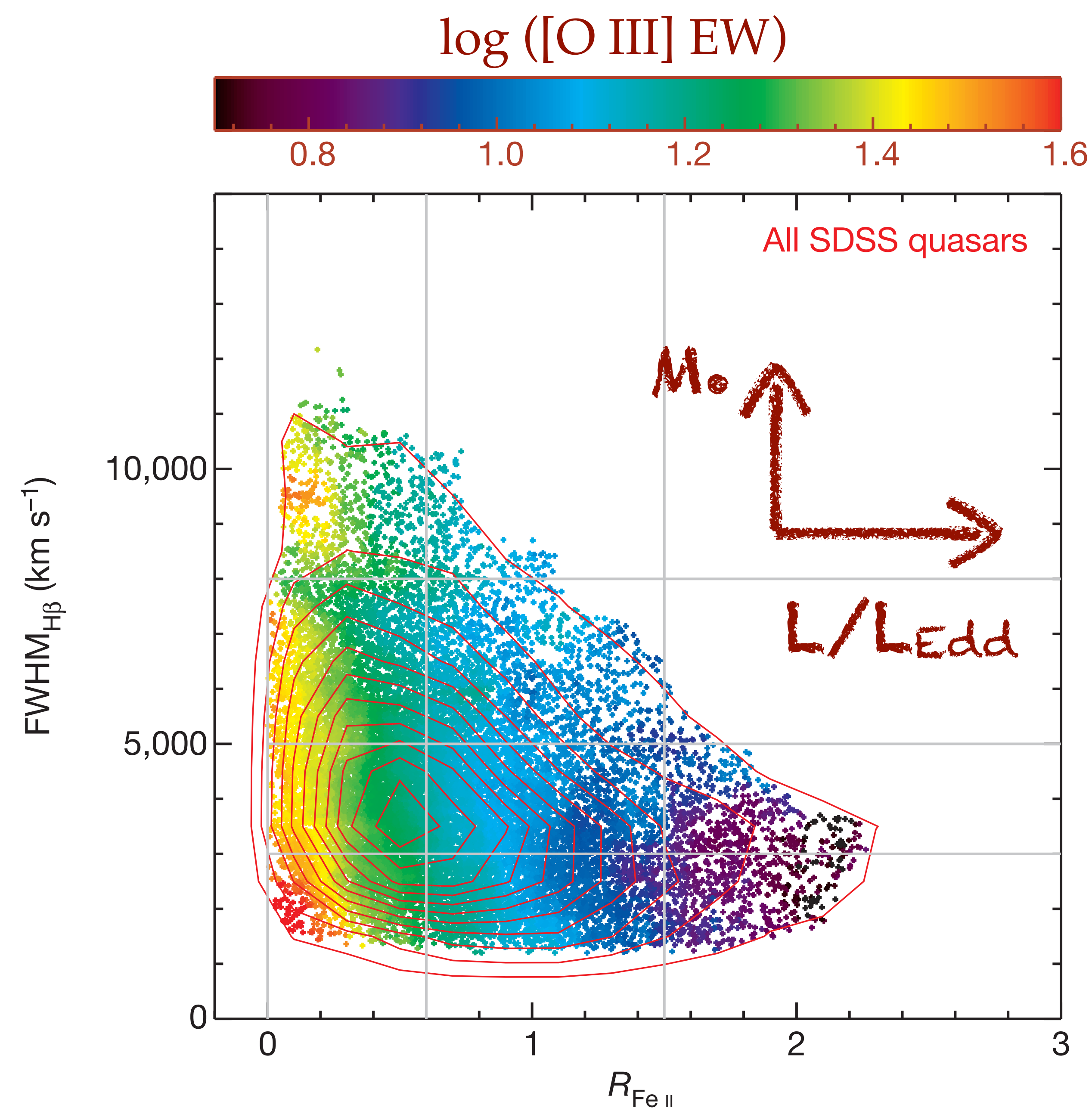
$$t_{\rm light} = \frac{R}{c} \approx \text{(6 weeks)}\ R_{17}$$

$$t_{\rm dyn} = \left(\frac{R^3}{GM}\right)^{1/2} \approx \text{(9 years)}\ R_{17}^{3/2}\, M_8^{-1/2}$$

Lessons from studying samples of quasars and AGNs

Classification via "Eigenvector 1"

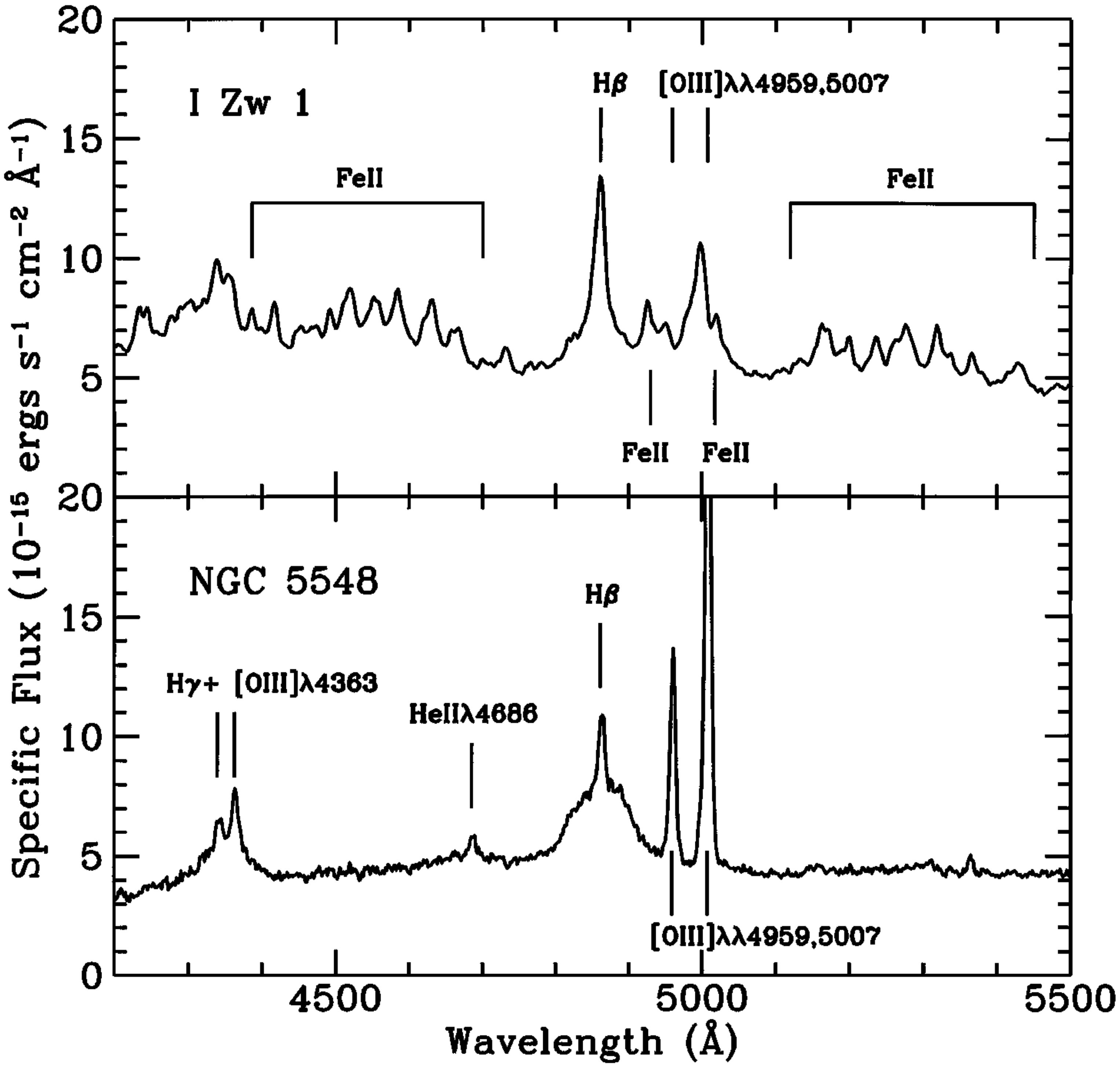




from Marziani et al. 2018, FrASS, 5, 6

from Shen & Ho 2014, Nature, 210, 513

Spectra from opposite ends of EV1

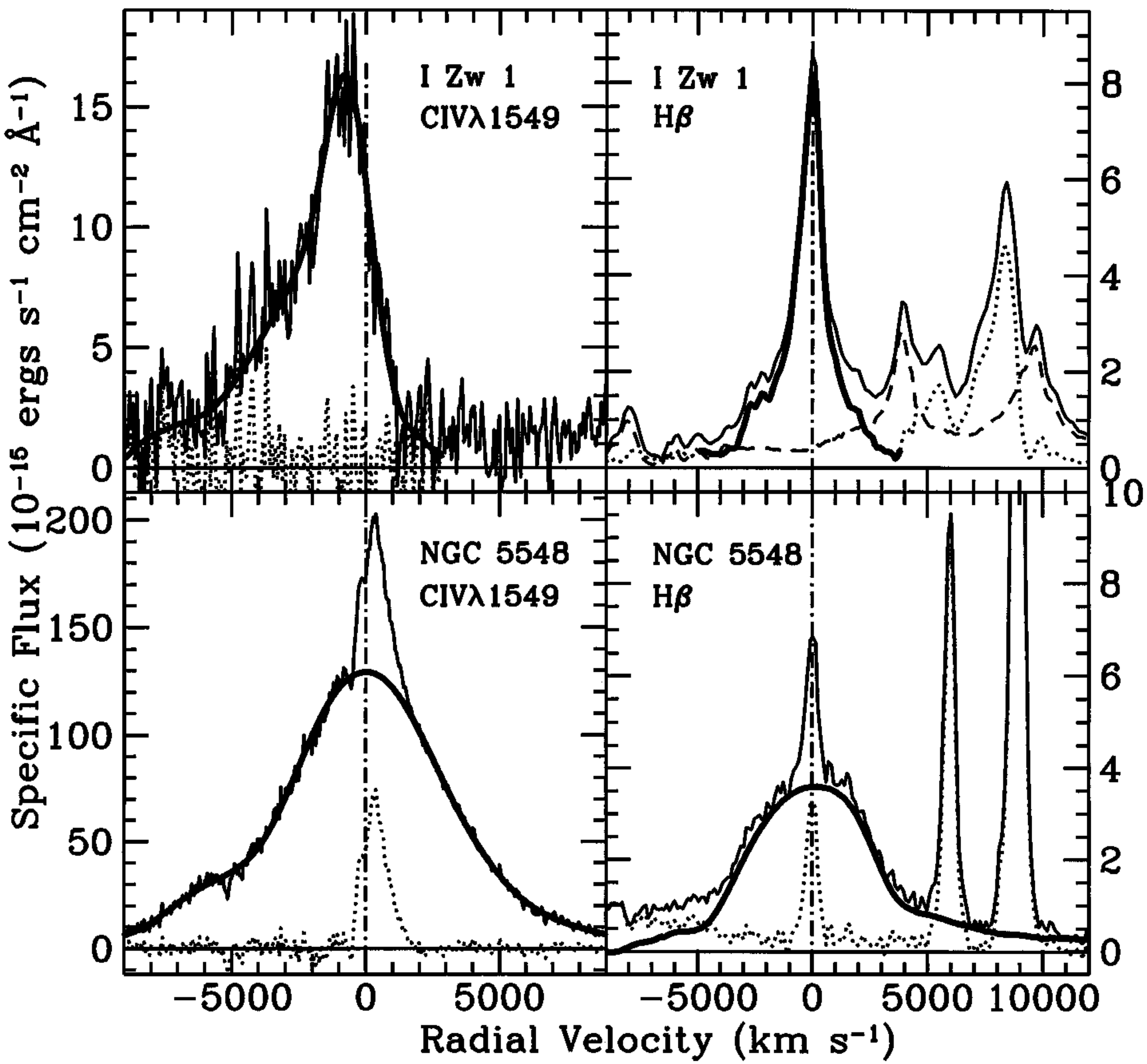


Lower Right
high L/L_{Edd}?

Upper Left
low L/L_{Edd}?

figure from Sulentic et al 2000, ARA&A, 38, 521

Comparison of resonance and recombination line profiles from opposite ends of EV1



Lower Right
high L/L_{Edd}?

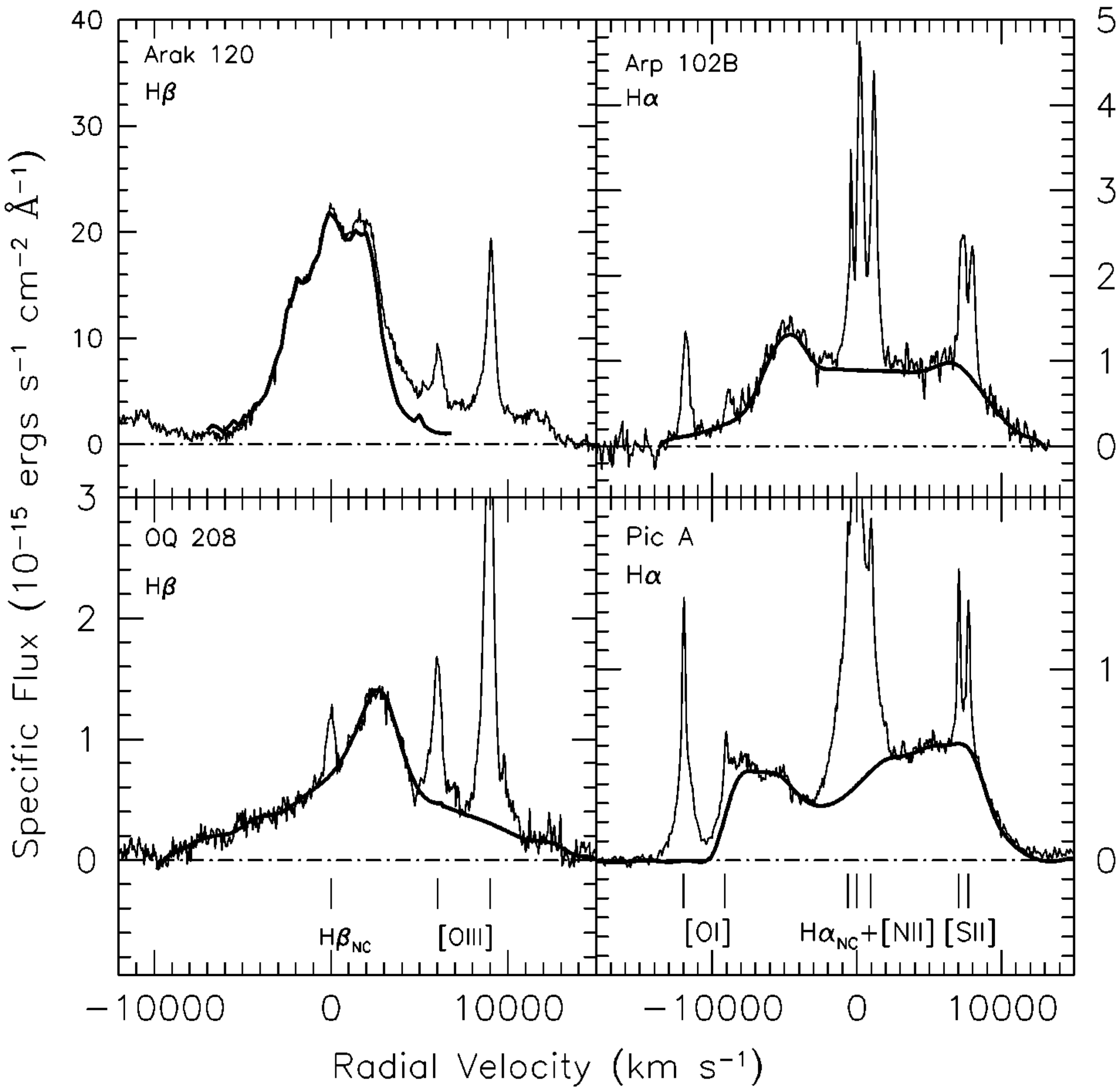
Upper Left
low L/L_{Edd}?

figure from Sulentic et al 2000, ARA&A, 38, 521

Diversity of profile shapes

double shoulders in broad Hβ

redshifted broad Hβ



double-peaked broad Hα

figure from Sulentic et al 2000, ARA&A, 38, 521

Lessons from reverberation mapping of the broad-line region

m=20

What measurements do we get from R.M.?

- The lag between continuum variations and total emission-line flux.

  We convert this to a ``BLR radius'' via

  $$R_{\mathrm{BLR}} = c\,\tau_{\mathrm{lag}}$$

  but we must interpret and treat R_{BLR} **very** carefully; it is not the radius of any physical structure; it is a moment of the responsivity distribution.

- Trends between time lags and line properties (width, luminosity)
  - for ensembles of objects
  - for single lines in same object as they vary
  - for different lines in same object but from ions of different ionization energies

- The lag between continuum and velocity-resolved emission line flux variations (across the line profile)
- Velocity-Delay maps (for sufficiently high S/N)

} for sufficiently high S/N

How big is the BLR? $(c\,\tau) \propto L^{0.5}$

But the BLR does not end at R_{BLR}
and the line-emitting zones are probably fairly wide.

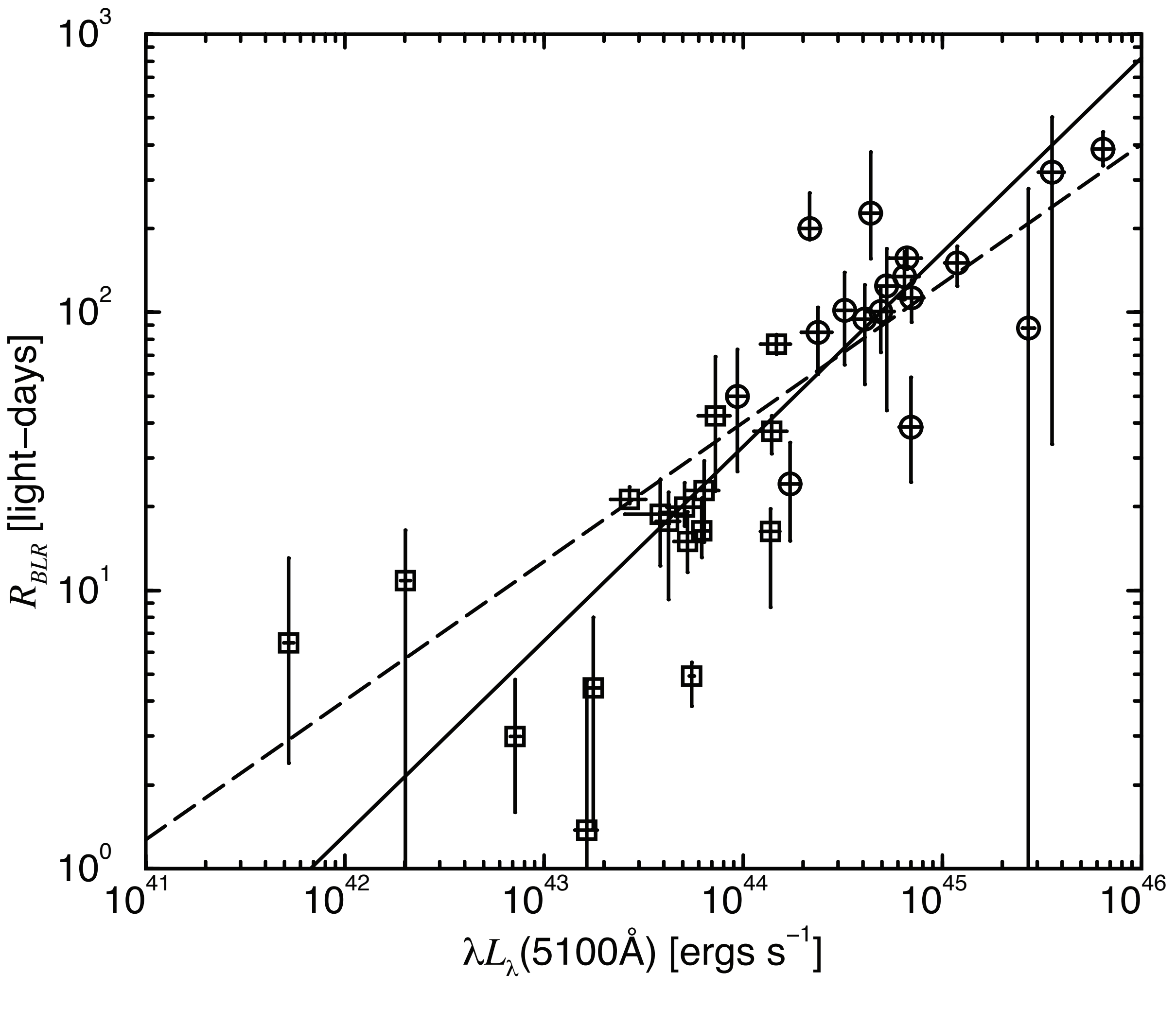


figure from Kaspi et al.
2000, ApJ, 533, 631

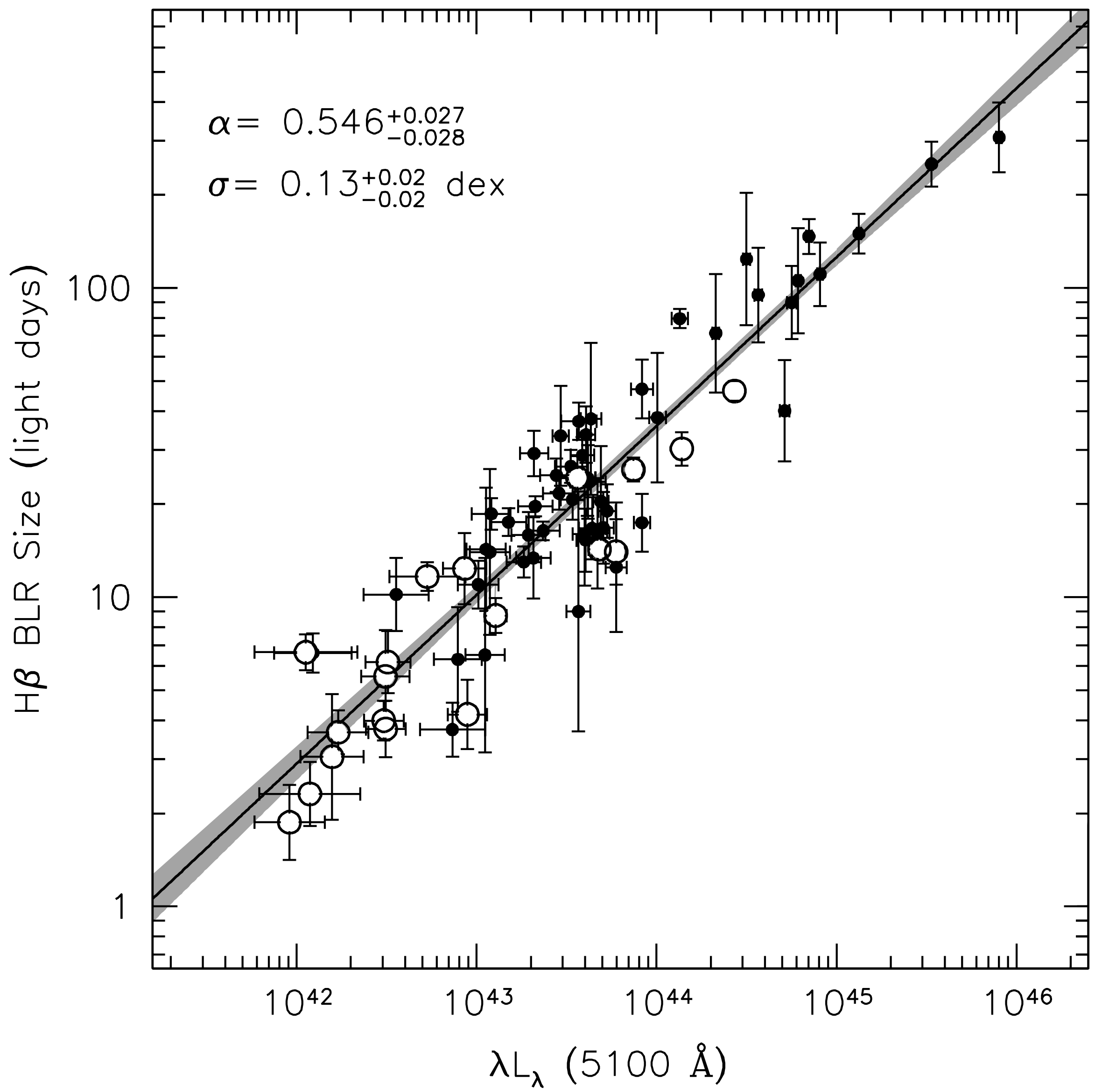


figure from Bentz et al.
2013, ApJ, 767, 149

How big is the BLR? Really....

- Optical Fe II multiplets respond with a longer lag than the Balmer lines. ~ 2–3x
- NIR continuum reverberates with even longer lags. ~4–5x
- There is gas that contributes to the broad lines out to the dust reverberation "radius."
- Prefer the dust radius as the outer boundary of the BLR

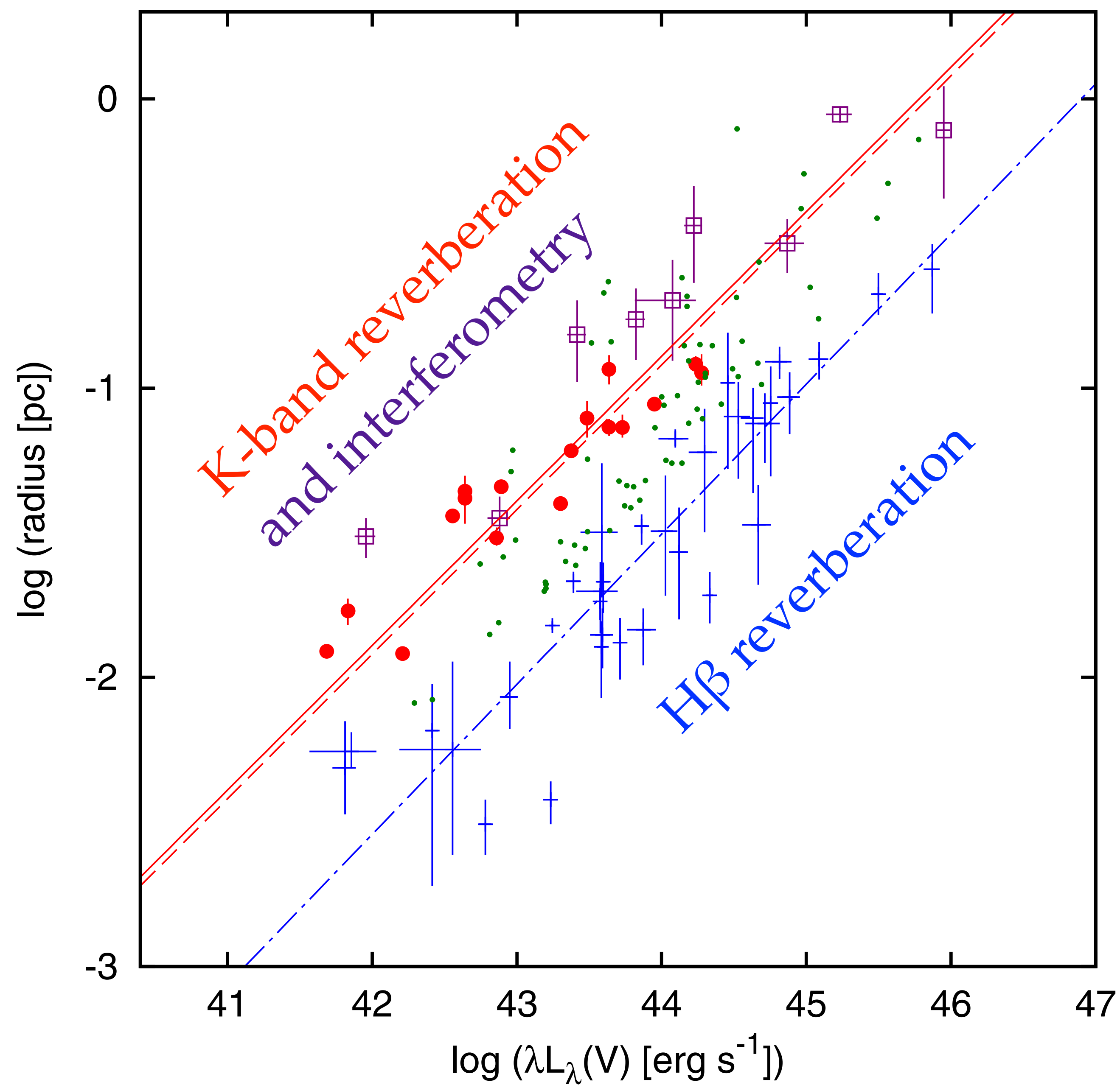
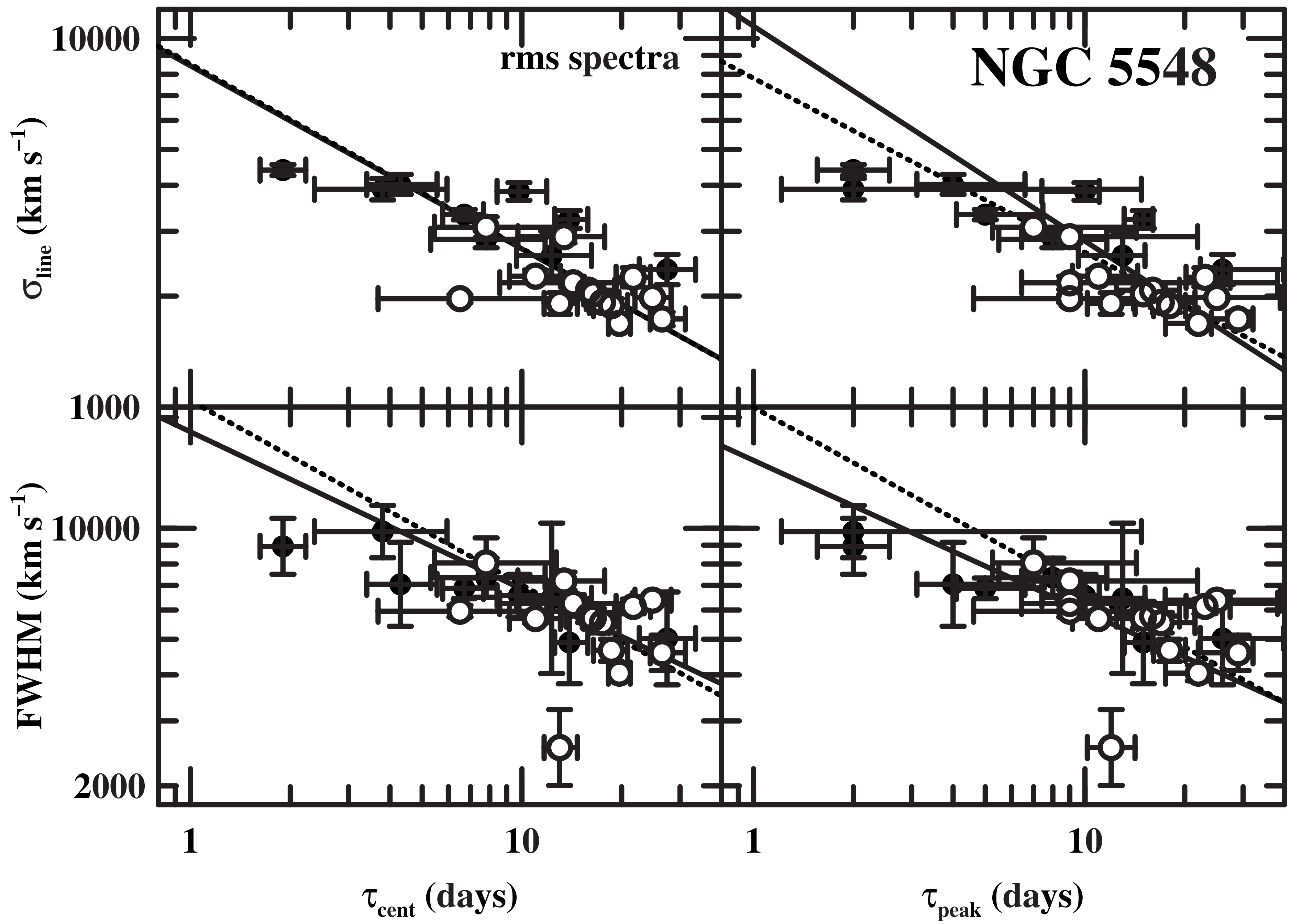


figure from Koshida et al. 2014, ApJ, 788, 159

Line width *vs* lag relation
r.m.s. profiles of various lines in same object



solid line = best fit
dashed line = viral relation, $\Delta v \propto \tau^{-1/2}$

figure from Peterson et al. 2004, ApJ 613, 682

Line width *vs* flux of same line: “Breathing”

Short time scale
Mrk 40

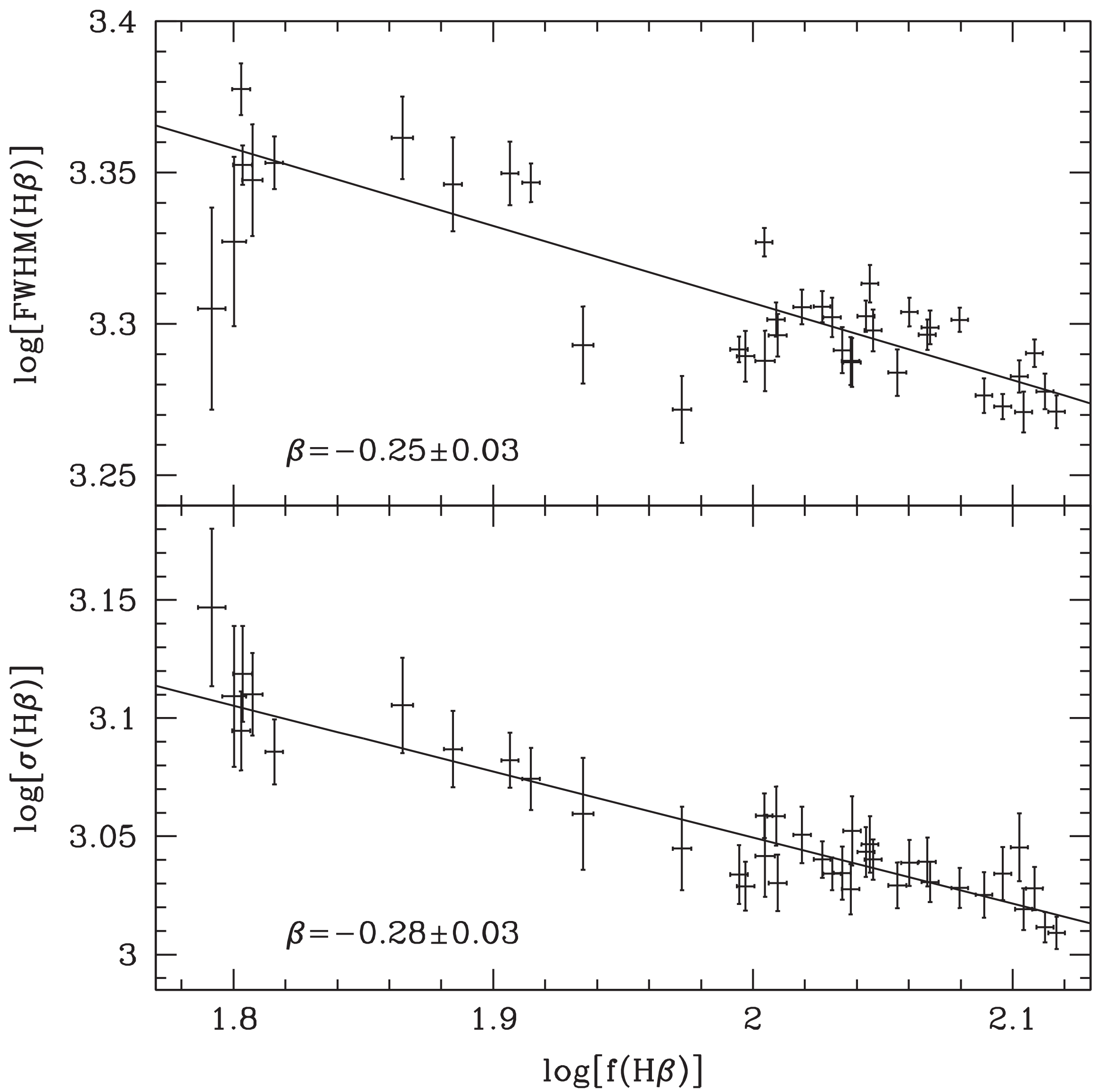


figure from Barth et al 2015, ApJS, 217, 16

Long time scale
NGC 1097

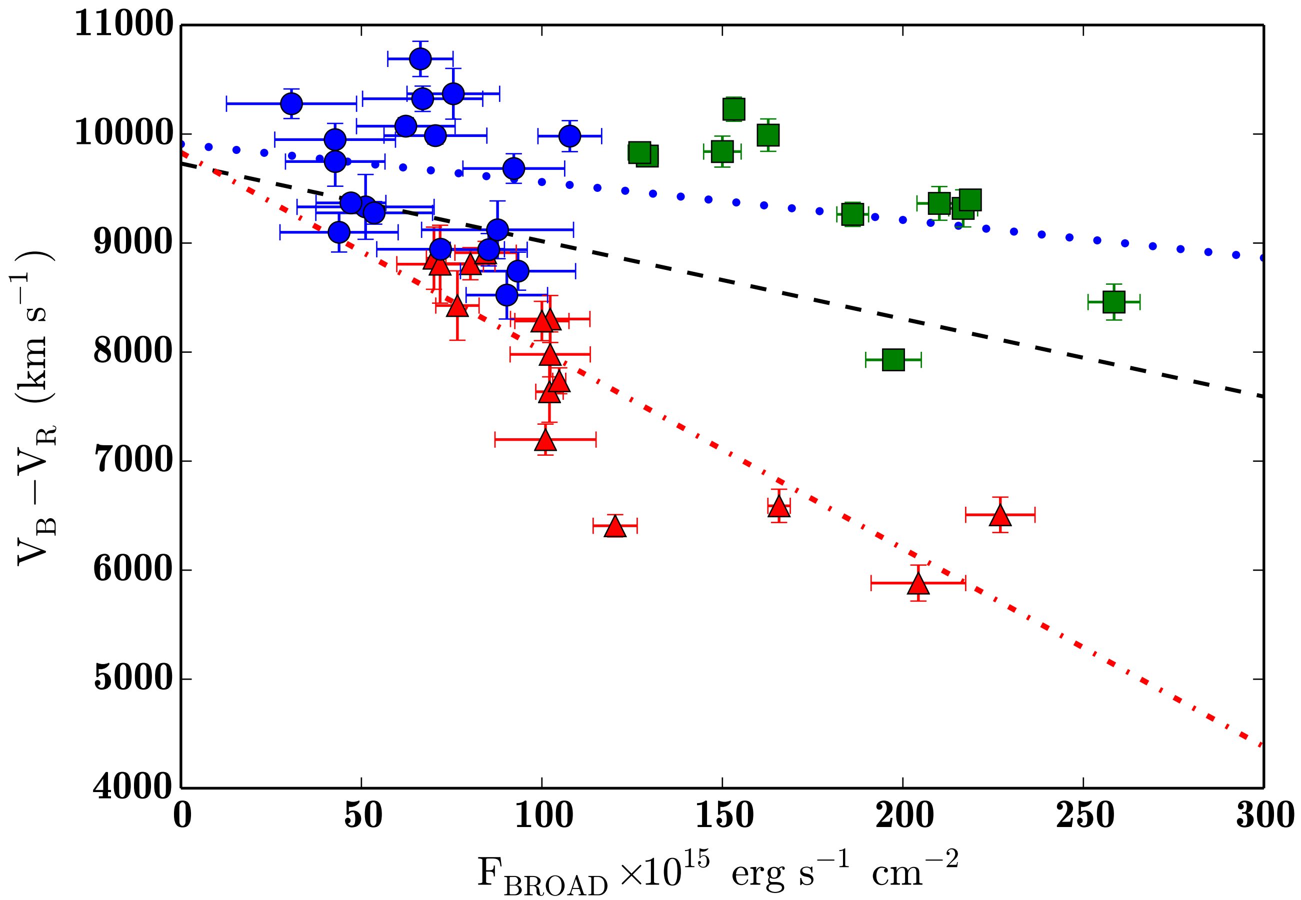
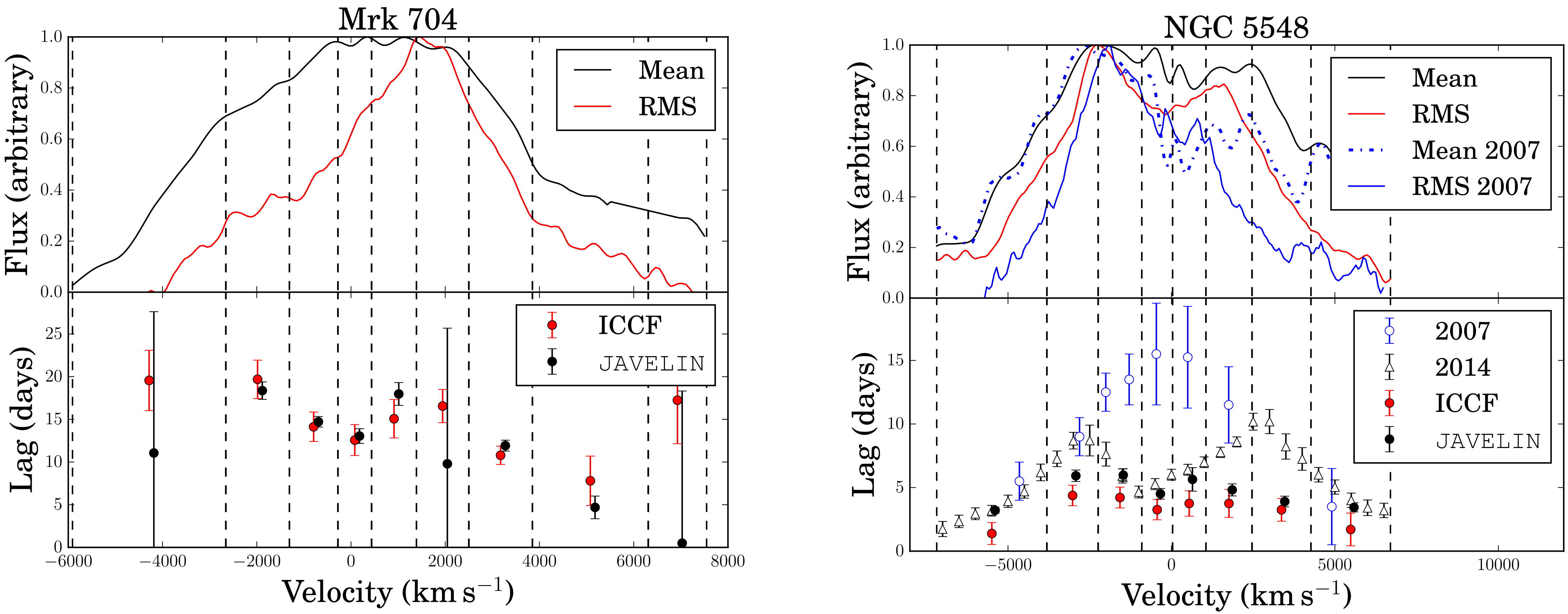


figure from Schimoia et al 2015, ApJ, 800, 63

Velocity-dependent time lags (across the line profile)



- ✦ Many objects show the signature of “rotating” gas. But some do not.
- ✦ The signature for the same object changes from one campaign to the next.

figures from DeRosa et al 2018, ApJ, 866, 133

Velocity-Delay maps (a few examples of optical lines)

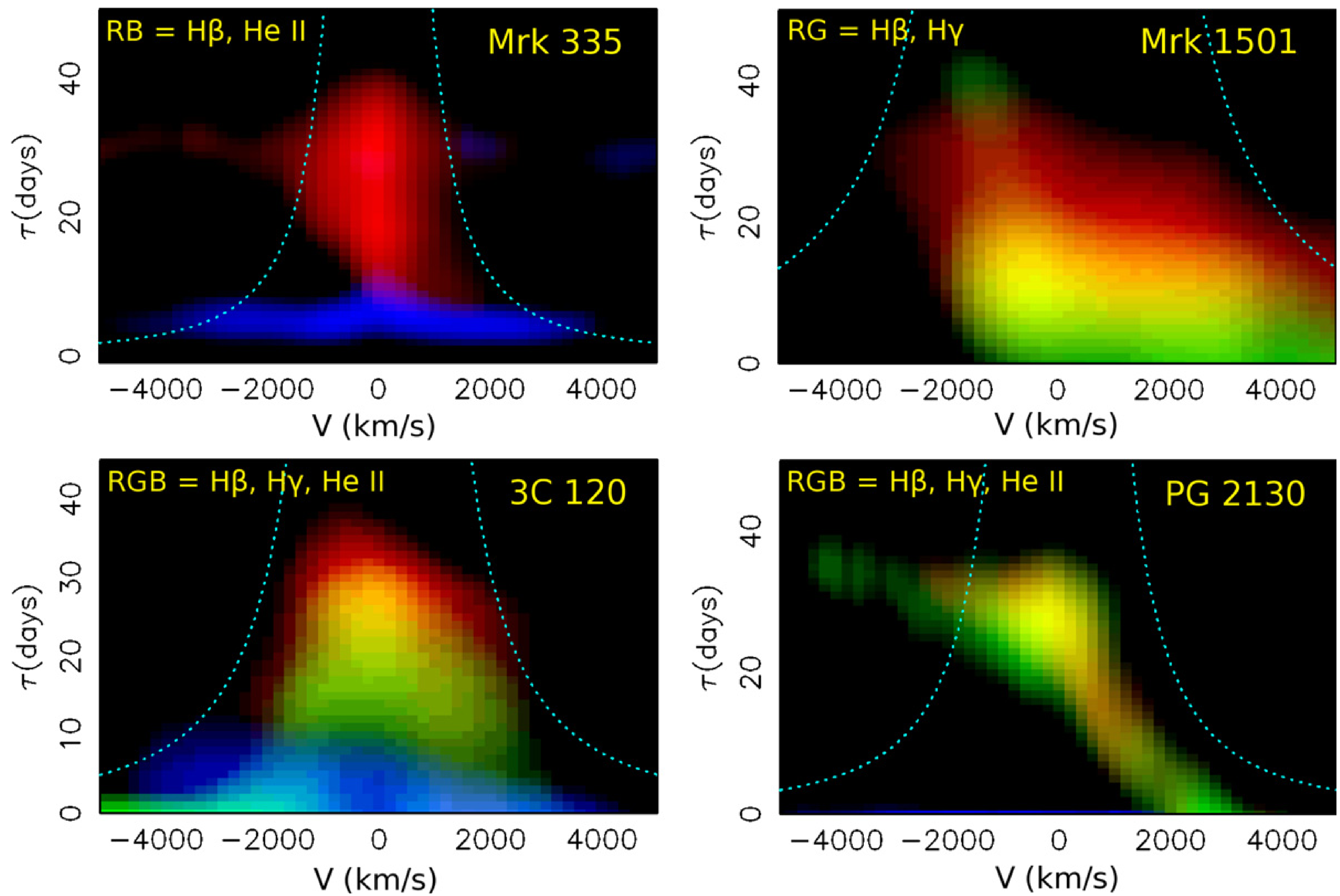


figure from Grier et al 2013, ApJ, 764, 47

Highlights of what we have learned from R.M.

- Line emission from the BLR is driven (largely?) by photoionization

  The flux of the broad lines responds directly to changes in the ionizing continuum

- The BLR is stratified in ionization
  - Higher ionization lines respond faster than lower-ionization lines
  - The lag of a given line depends on the continuum luminosity so as to preserve the ionization parameter of its emission zone

$$c\,\tau_{\mathrm{lag}} \propto L^{1/2}$$

- The gas in the BLR is virialized.
  - Broader lines respond faster, following Keplerian dynamics (more or less).

$$c\,\tau_{\mathrm{lag}} \propto (\mathrm{width})^{-1/2}$$

  - The BLR "breathes:" optimal zone for a given line moves in and out so as to preserve the black hole mass

$$(\mathrm{width})^{-1/2} \propto L^{1/4}$$

Hints of diskiness...

- Widths of Balmer lines of radio-loud quasars depend on jet inclination.
- Virialized gas
  (and basic physical considerations)
- Symmetric velocity-resolved lags
- Double-peaked lines
- The f of the viral relation decreases with increasing FWHM.

Variability of broad lines on long time scales, of order years–decades

m=30

What might happen in a decade or two?

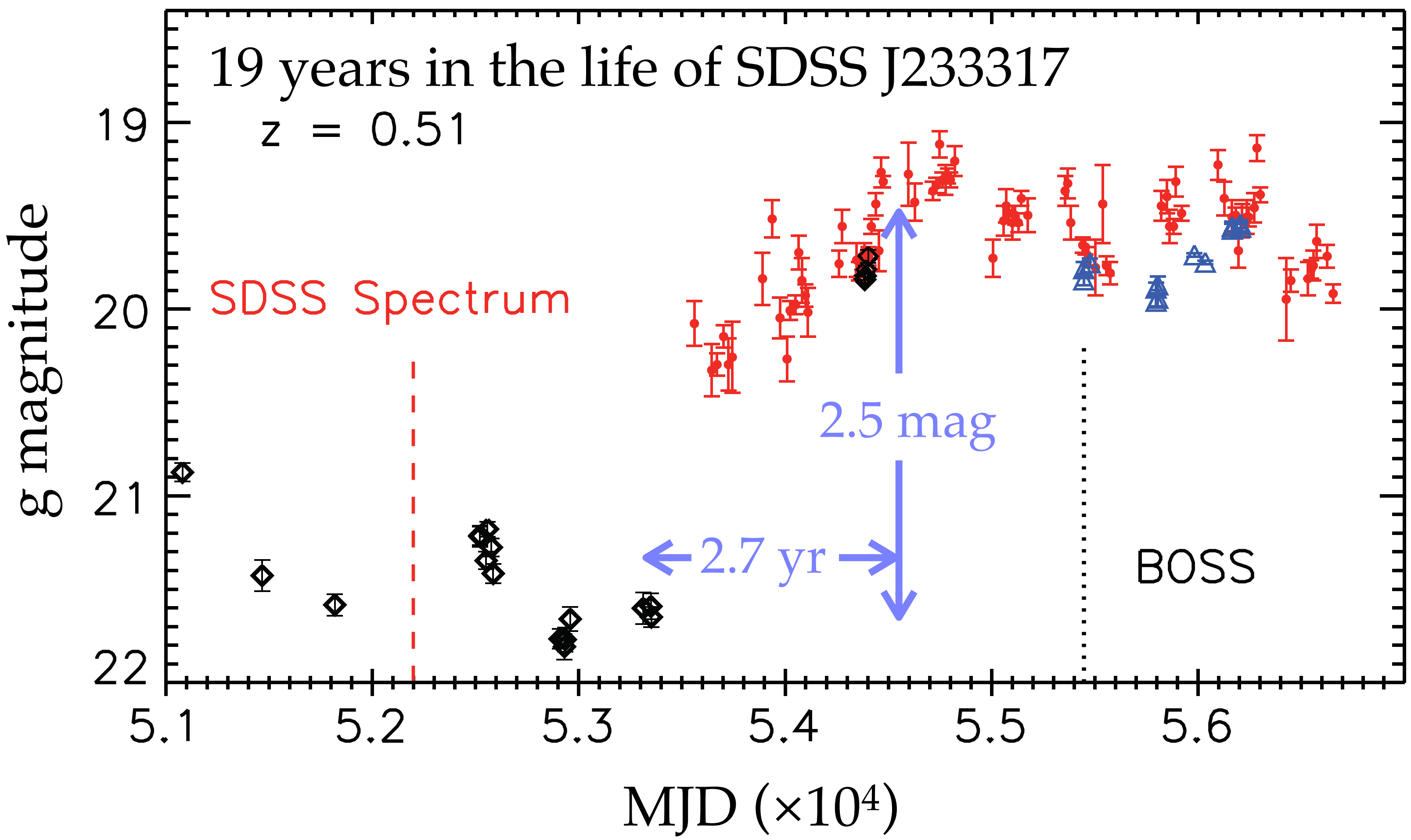
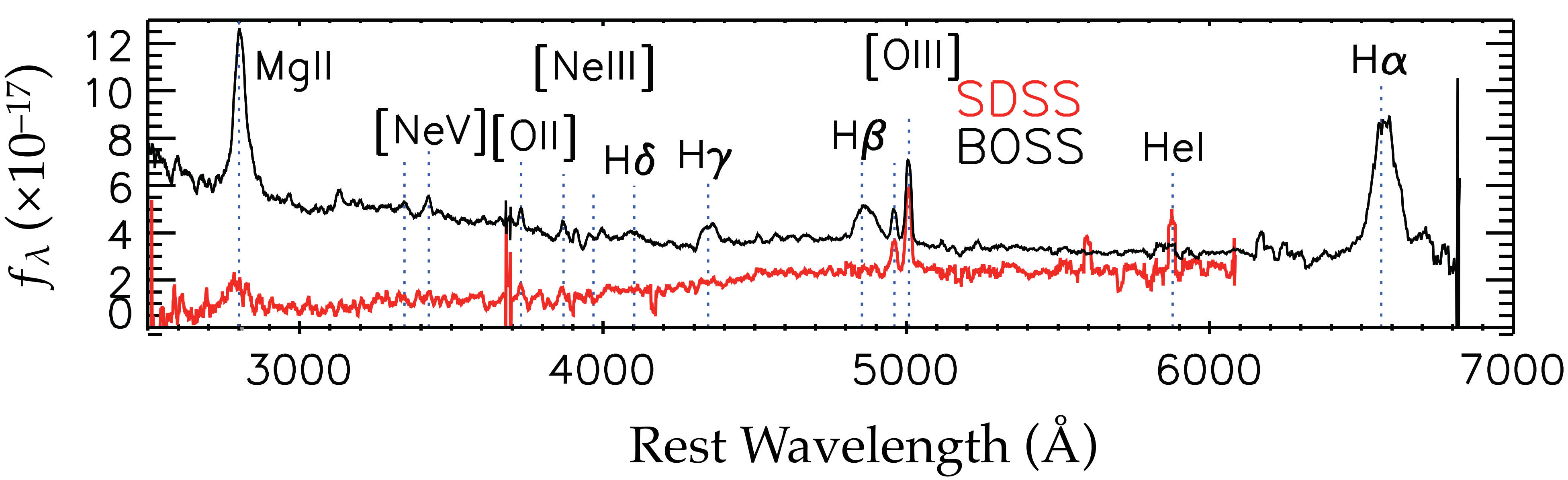


figure adapted from MacLeod et al. 2016, MNRAS,457, 389



Log-term variability of line profiles

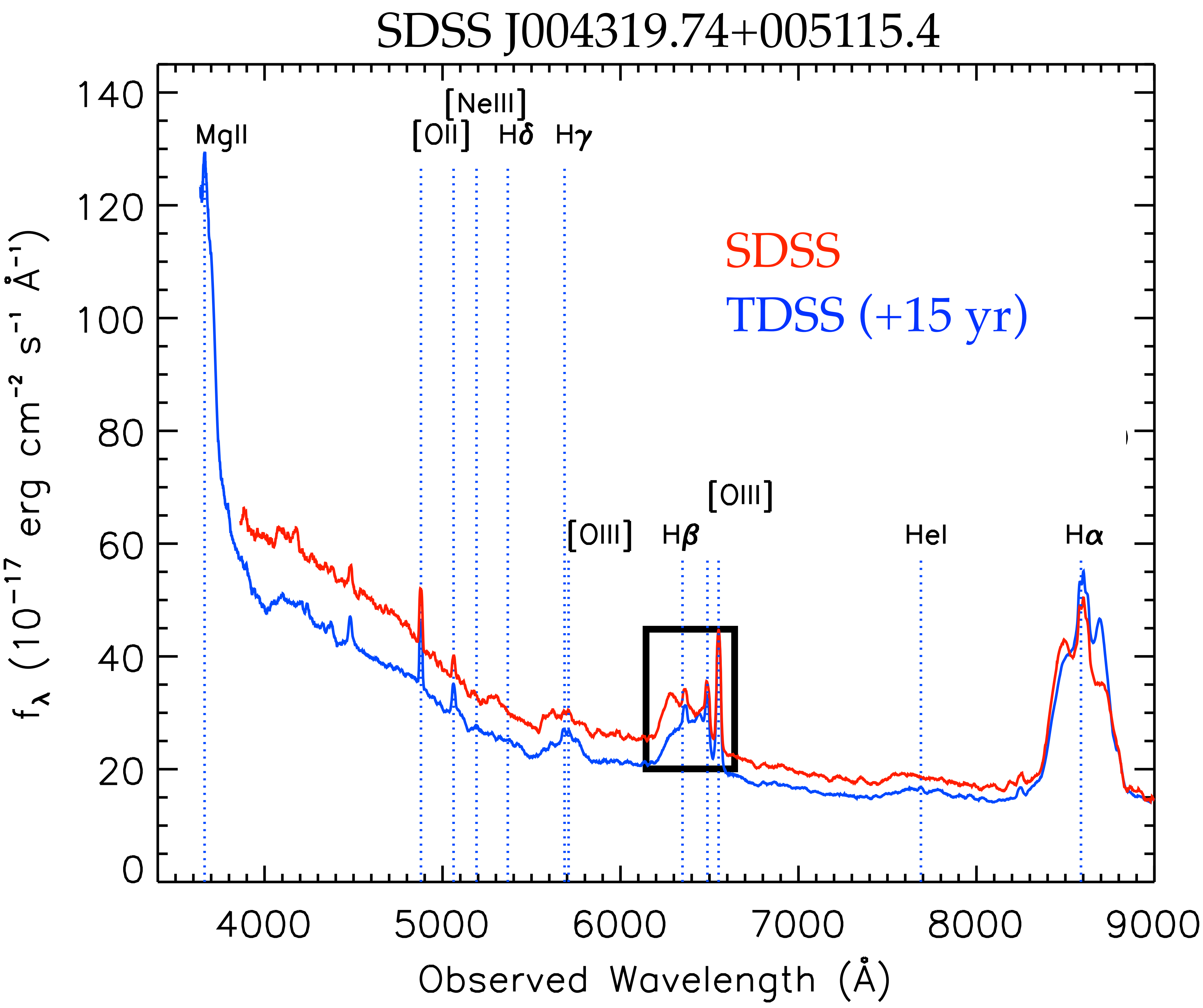


figure from MacLeod et al. 2018, AJ, 155, 6

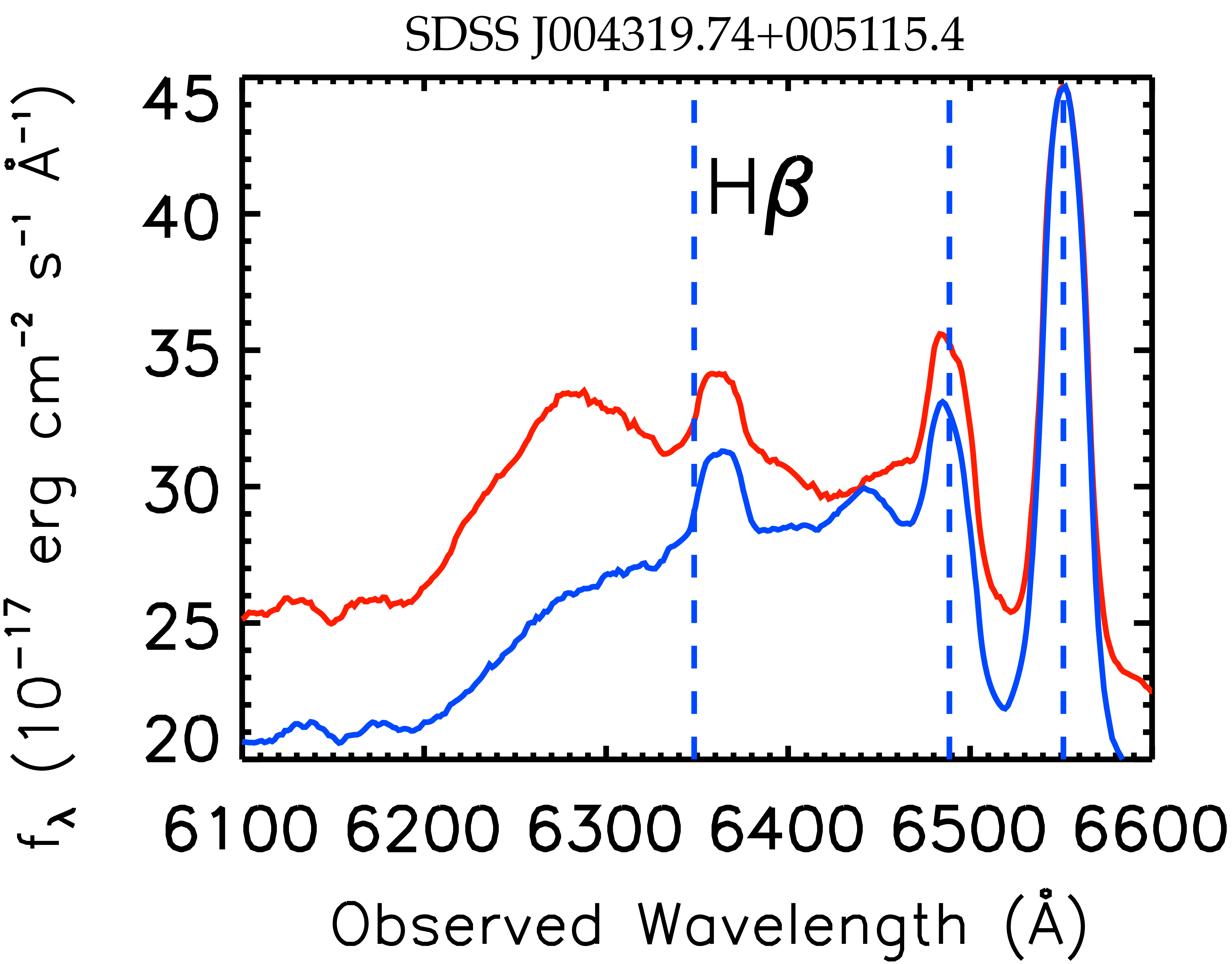
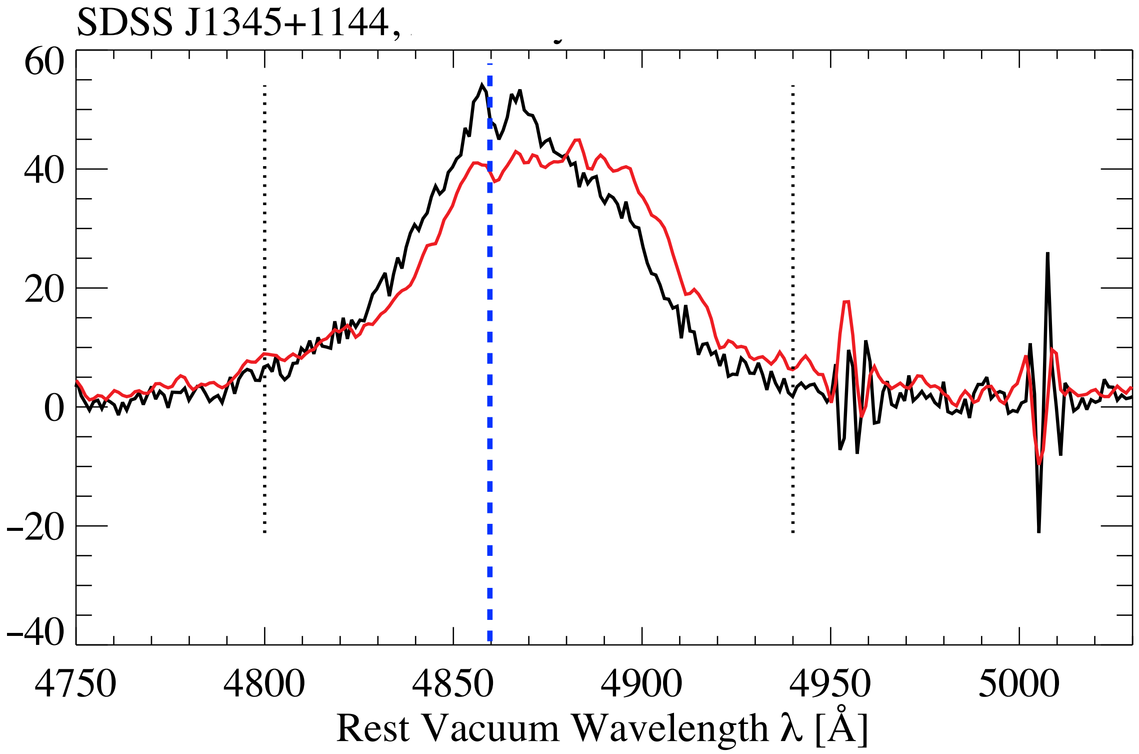
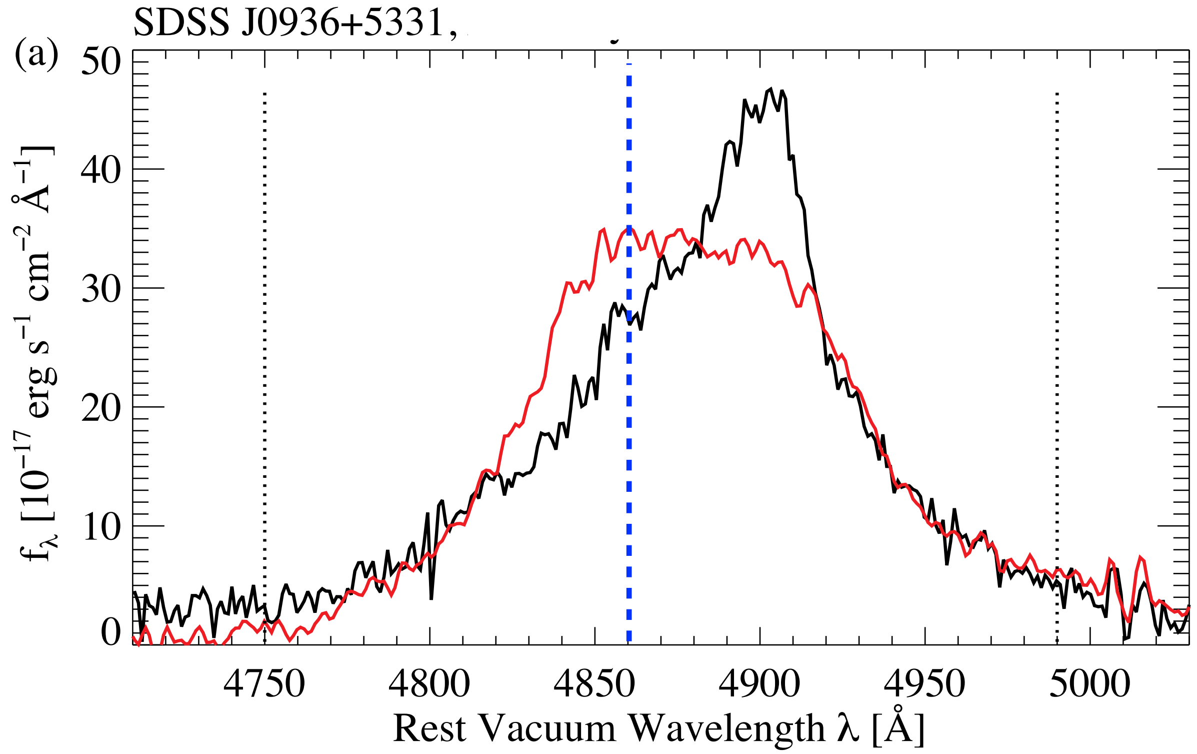


figure from MacLeod et al. 2018, AJ, 155, 6

Shifty Hβ profiles

narrow lines have been subtracted…





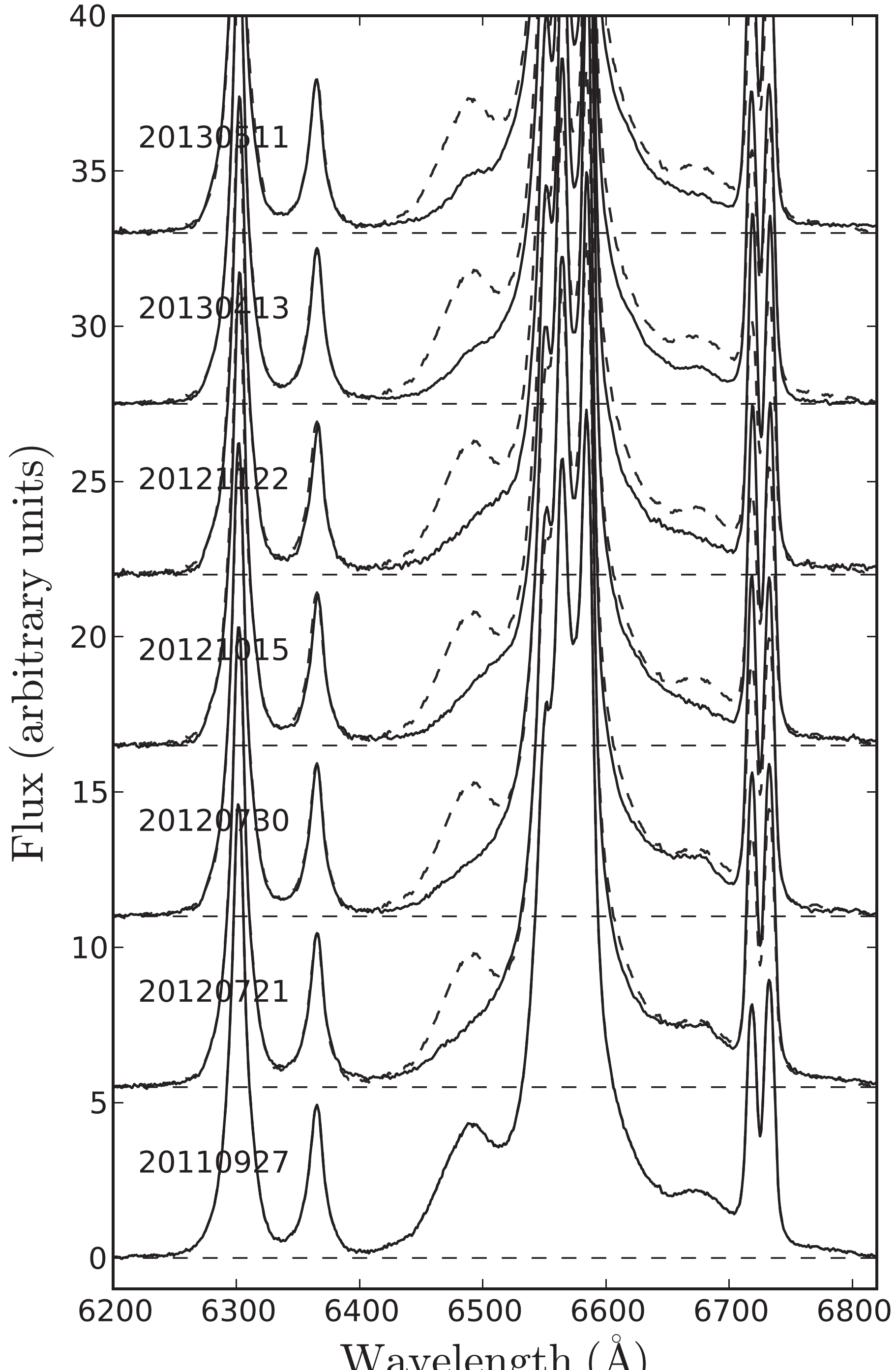
$\Delta t = 7.2$ yr
Apparent shift but the profile has changed too.

$\Delta t = 8.3$ yr
Major change in profile

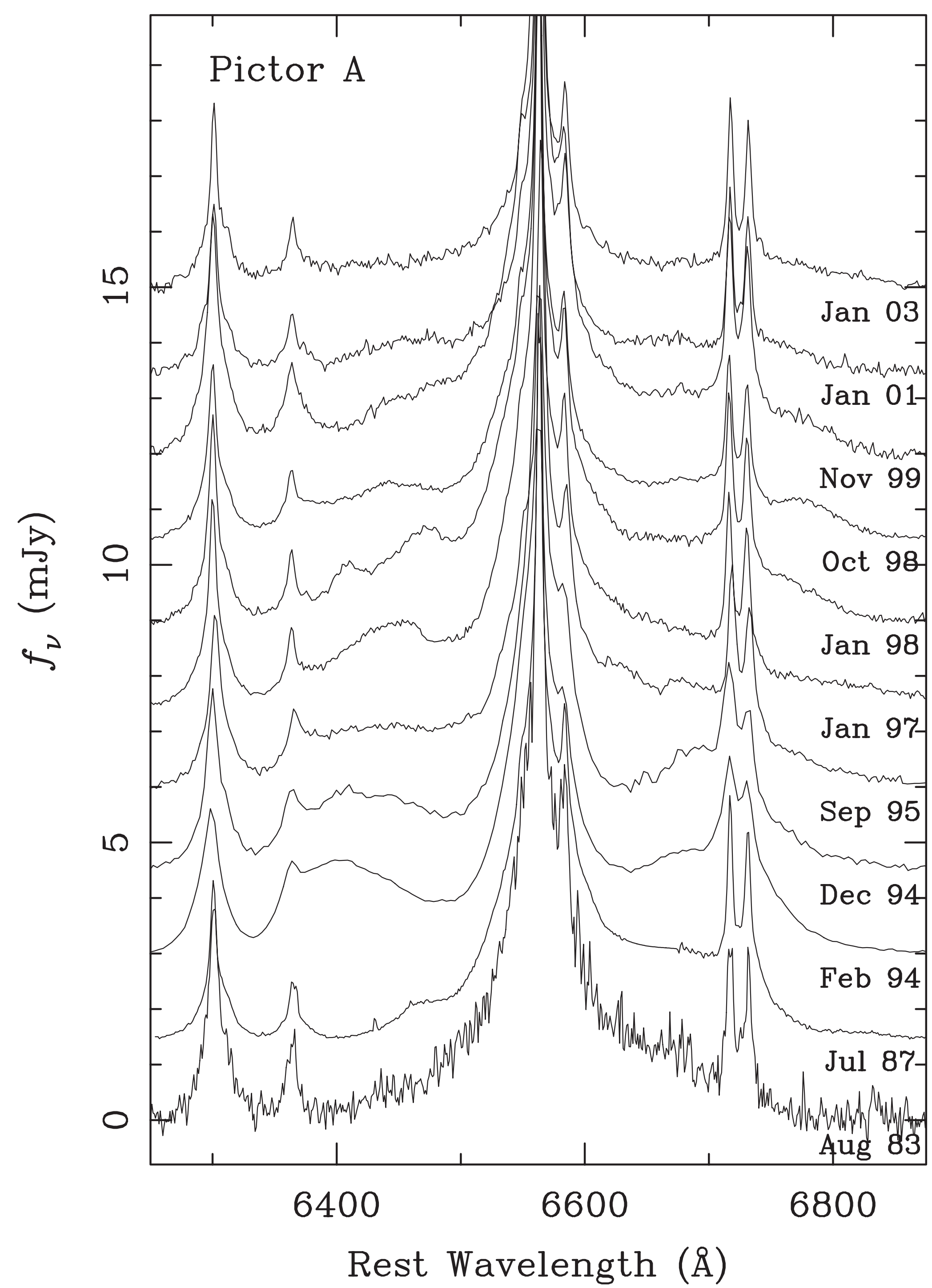
figure from Liu et al. 2014, ApJ, 789, 140

Transient double-peaked-ness (in Hα)

NGC 7469



Pictor A



Schimoia et al. 2017, MNRAS, 472, 2170

Lewis et al. 2010, ApJS, 187, 416

Looking to the future…

What observations might lead to progress, IMHO?

- **Long-term** photometric and spectroscopic variability surveys! We are only starting to appreciate the possible variability modes (e.g., CLQs)
  - Photometry can uncover new variability modes. Combine past surveys (SDSS, PanSTARRs) with LSST for long baseline.
  - SDSS-IV and SDSS-V can reveal variations of the emission lines. Need to understand the range of possibilities in order to use the broad lines as tools and as constraints for models
- Reverberation mapping has been quite productive. Continue!
  - Higher S/N and denser monitoring are desirable
  - Target objects with diverse line profiles
  - More continuum lag measurements needed (good test of disk models!)
- Spectropolarimetry has potential but the signals are not always easy to decipher. Need more observations and comparison to detailed models.

What others can <u>you</u> think of?

Concluding thoughts

The biggest question is "What is going on in quasars?" But in order to answer that question, we need to start with less ambitious ones:

- ✦ Where is the primary continuum from the accretion disk?
- ✦ What is the relation of the accretion disk/flow to the BLR?
- ✦ Do ALL AGNs/quasars have a BLR? If not, why not?
- ✦ What are the phases of the BLR gas? How are they connected to each other?
- ✦ What is the relation of the *absorption* line gas to the *emission* line gas?

and many more…