AGN STORM: A Leap Forward in Reverberation Mapping

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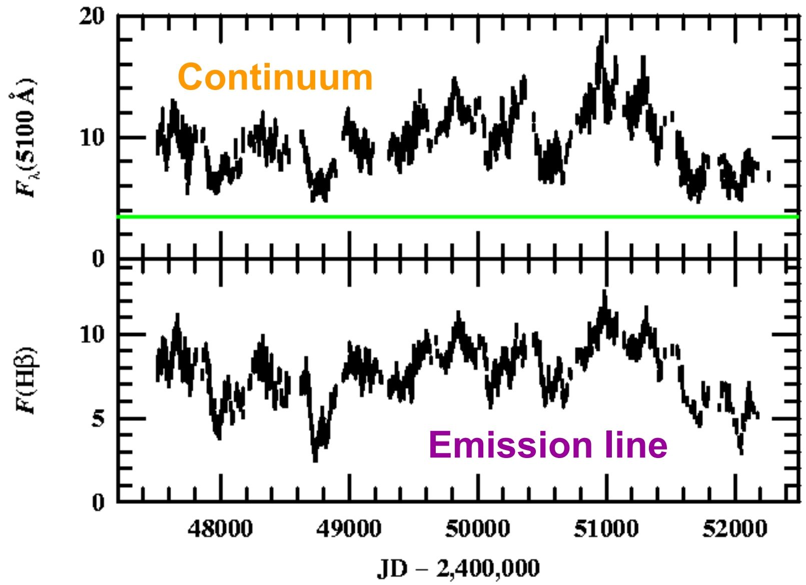
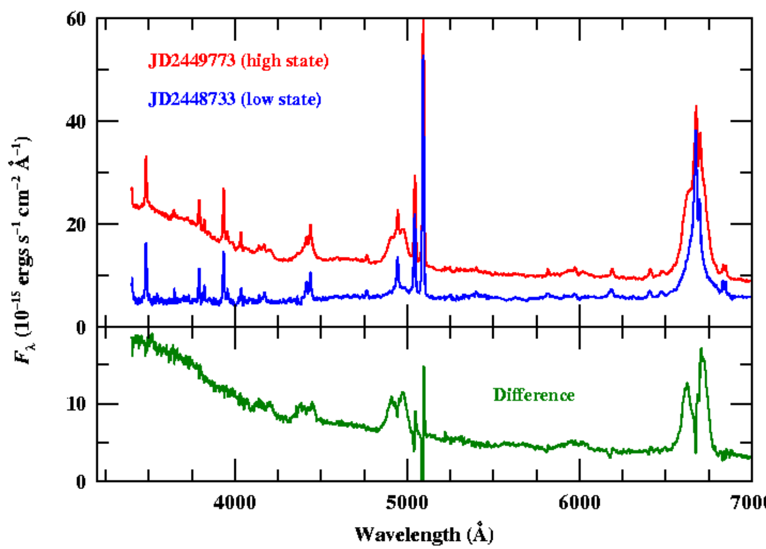
Reverberation Mapping

- Kinematics and geometry of the BLR can be tightly constrained by measuring the emission-line response to continuum variations.
- Size of the BLR can be measured simply by timescale for response.

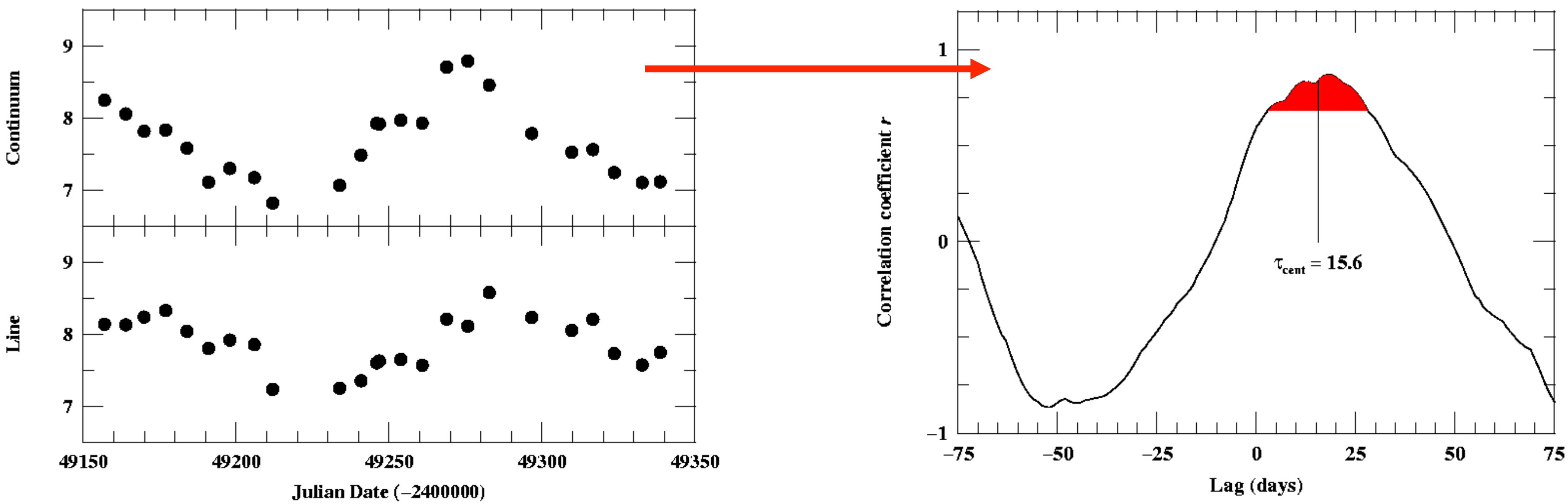


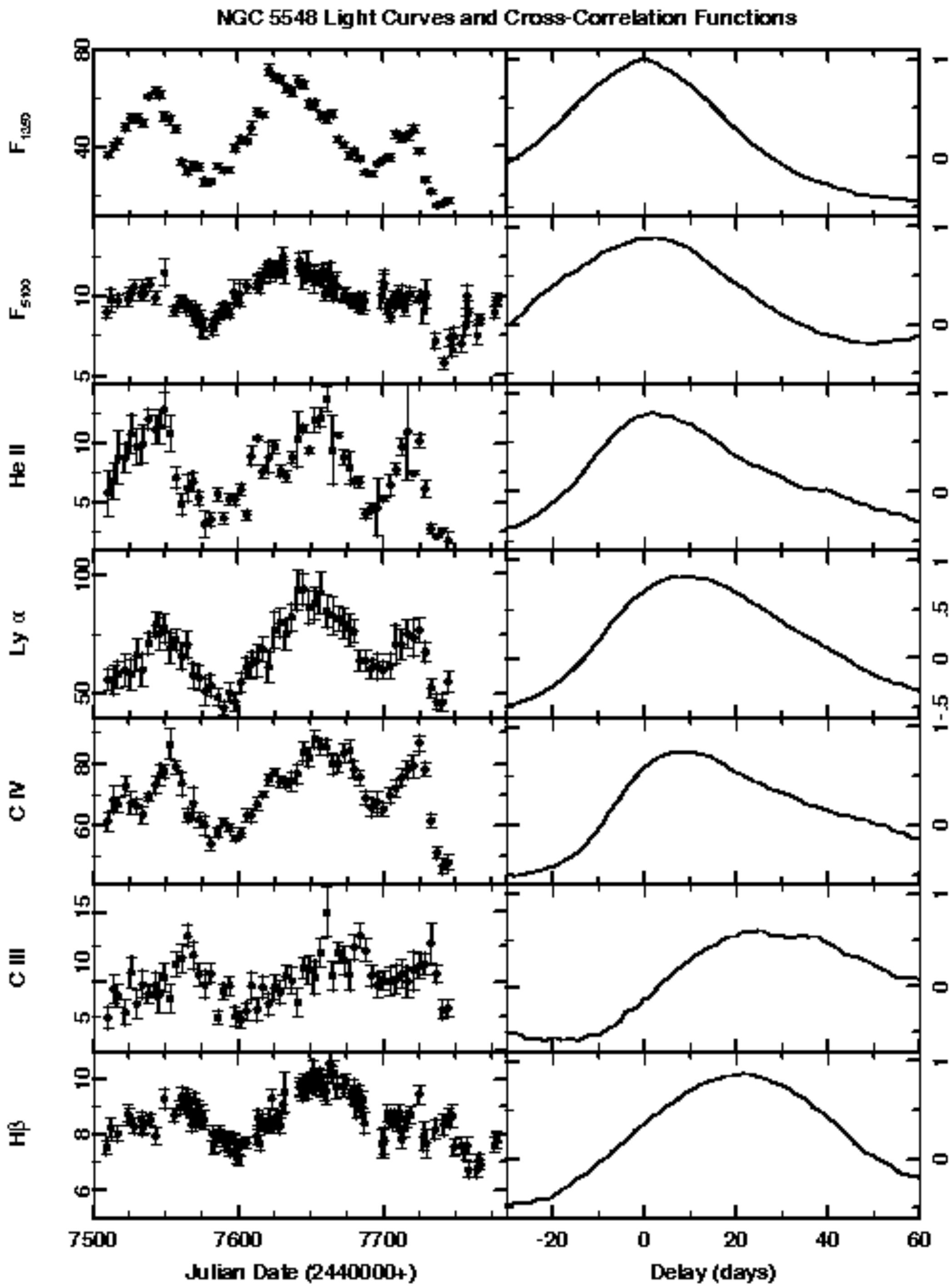


NGC 5548, the most closely monitored Seyfert 1 galaxy

Emission-Line Lags

- Because the data requirements are *relatively* modest, it is most common to determine the cross-correlation function and obtain the “lag” (mean response time). For an axisymmetric, isotropically emitting system, the lag is a measure of the size, $R = c\tau$





Reverberation Mapping Results

- Reverberation lags have been measured for ~50 AGNs, mostly for Hβ, but in some cases for multiple lines.
- AGNs with lags for multiple lines show that highest ionization emission lines respond most rapidly ➔ ionization stratification

Reverberation-Based Masses

"Virial Product" (units of mass)

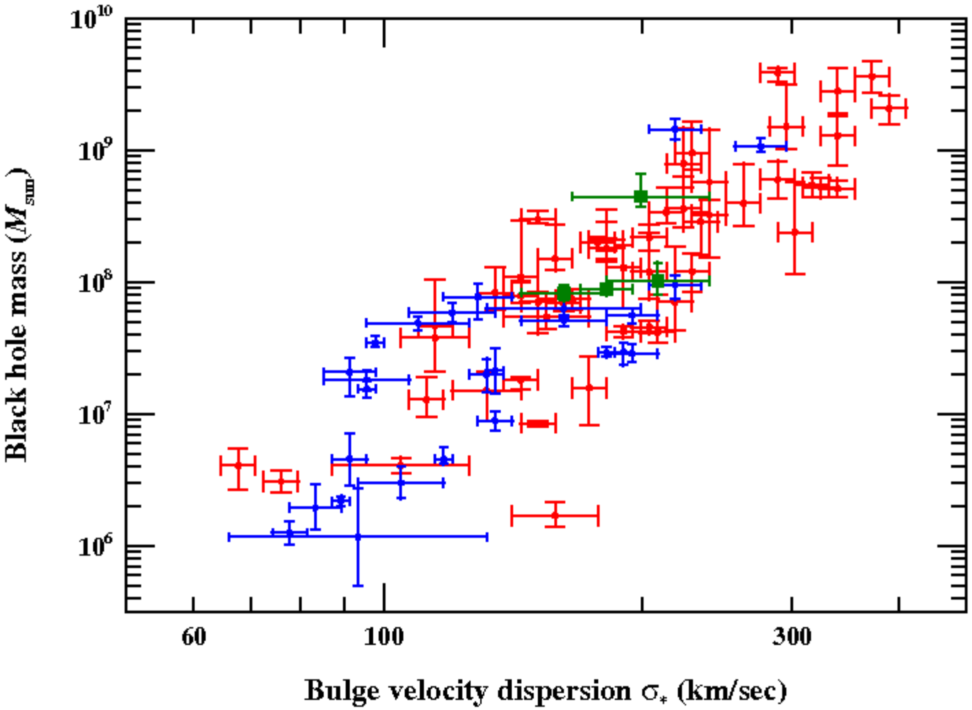
$$M_{\mathrm{BH}} = f\, \boxed{\underline{r\,\Delta V}^{2} / G}$$

Observables:
r = BLR radius (reverberation)
ΔV = Emission-line width

Set by geometry and inclination
(subsumes everything we don't know)

If we have independent measures of M_{BH}, we can compute an ensemble average $\langle f \rangle$

The AGN M_{BH}– σ_* Relationship



- AGN
- AGN, new *H*-band σ_*
- Quiescent galaxy

Grier+ 2013, ApJ, 773:90

- Assume zero point of most recent quiescent galaxy calibration.

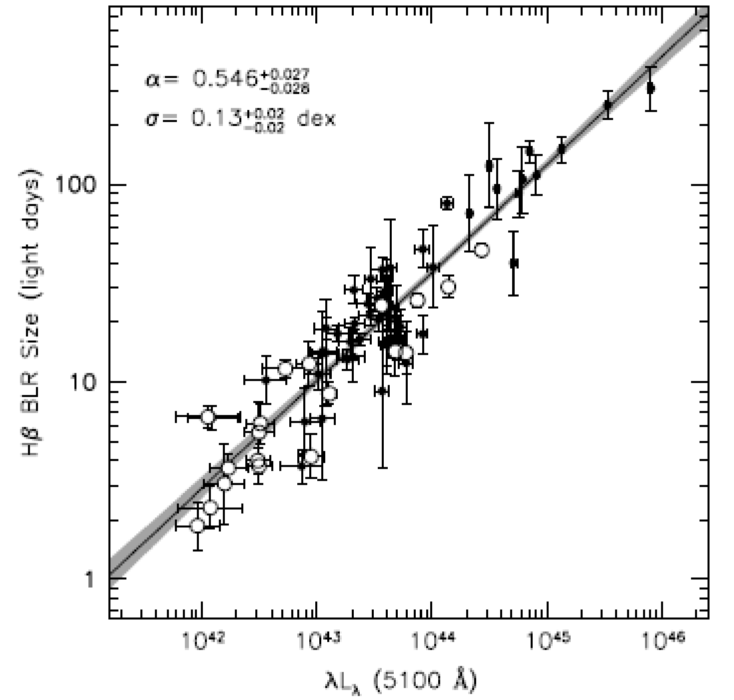
  $\langle f \rangle = 4.19 \pm 1.08$

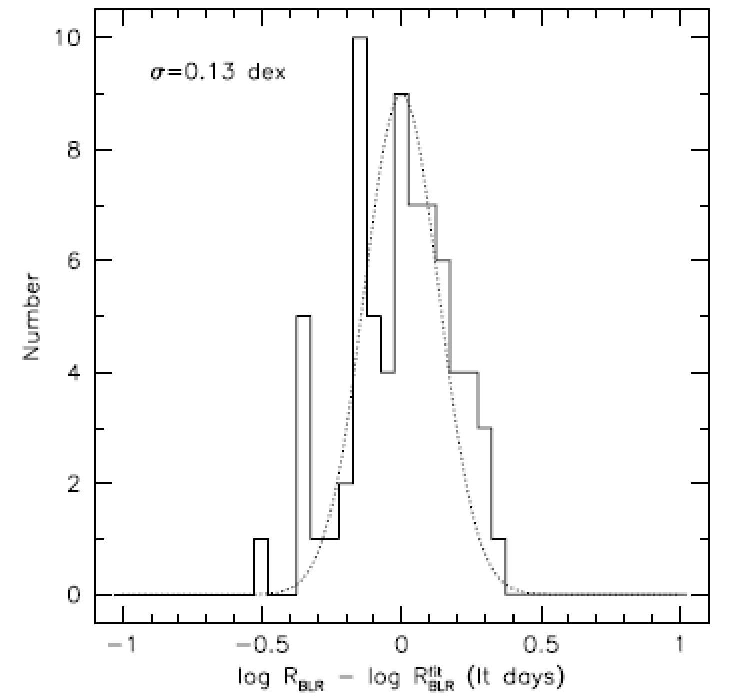
- Maximum likelihood places an upper limit on intrinsic scatter

  $\Delta \log M_{BH} \sim 0.40$ dex.
  - Consistent with quiescent galaxies.

The *R–L* Relation

- Empirical slope ~0.55 ± 0.03
- Intrinsic scatter ~0.13 dex
- Typical error bars on best reverberation data ~0.09 dex
- Conclusion: for Hβ over the calibrated range ($42 \leq \log L_{5100}$ (ergs s^{-1}) ≤ 46 at $z \approx 0$), *R-L* is nearly as effective as reverberation.





Bentz+ 2013, ApJ, 767:149

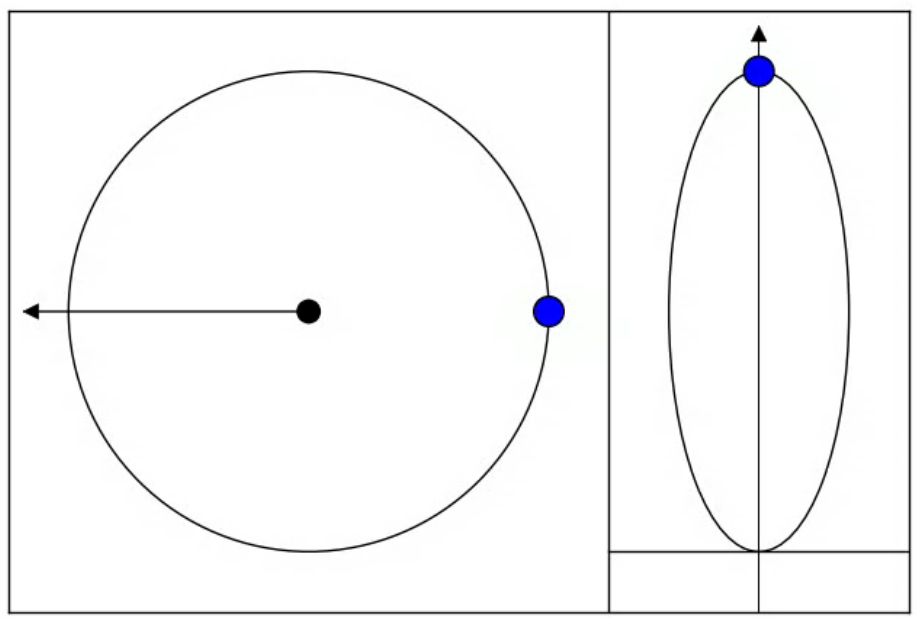
Velocity-Resolved Reverberation Mapping

- By measuring the line response as a function of Doppler velocity, we can determine the kinematics of the BLR.
- Requirements:
  - Good temporal sampling (~1 spectrum/day)
  - High S/N (~100) spectra
  - Moderate spectral resolution (~100s km s^{-1})
  - Long duration (several times *r/c*)

Horne+ 2004

Velocity-Delay Map

Configuration space　　Velocity-delay space



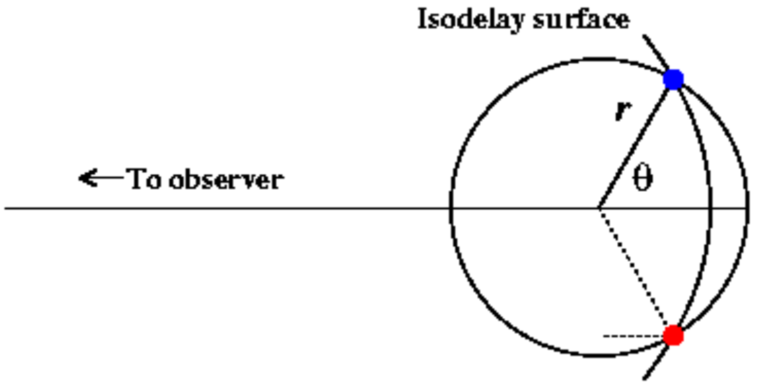
To observer

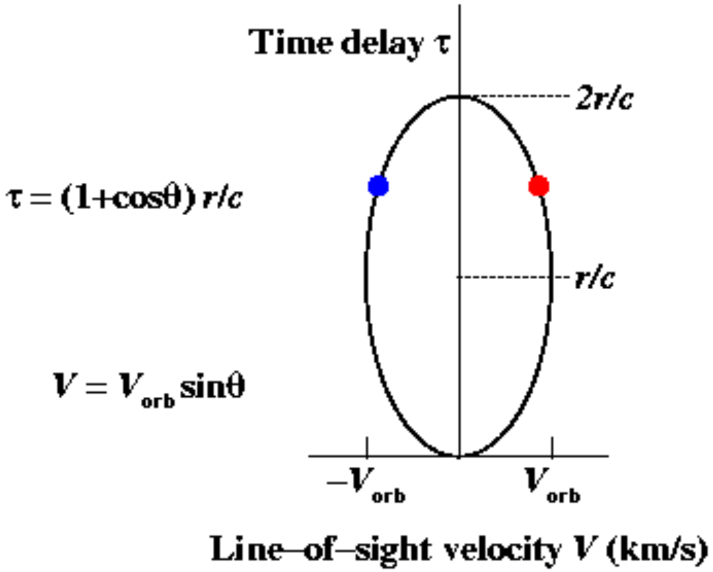
Time delay

Doppler velocity

Velocity-Delay Map for an Edge-On Ring

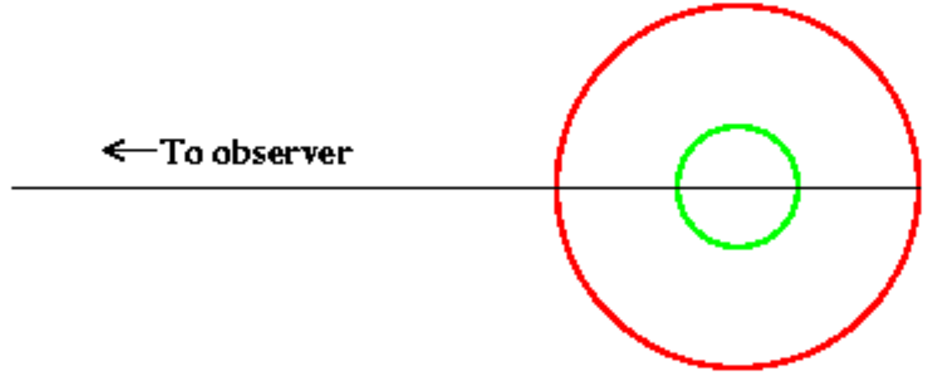
- Clouds at intersection of isodelay surface and orbit have line-of-sight velocities $V = \pm V_{orb} \sin \theta$.
- Response time is $\tau = (1 + \cos \theta) r/c$
- Circular orbit projects to an ellipse in the (V, τ) plane.

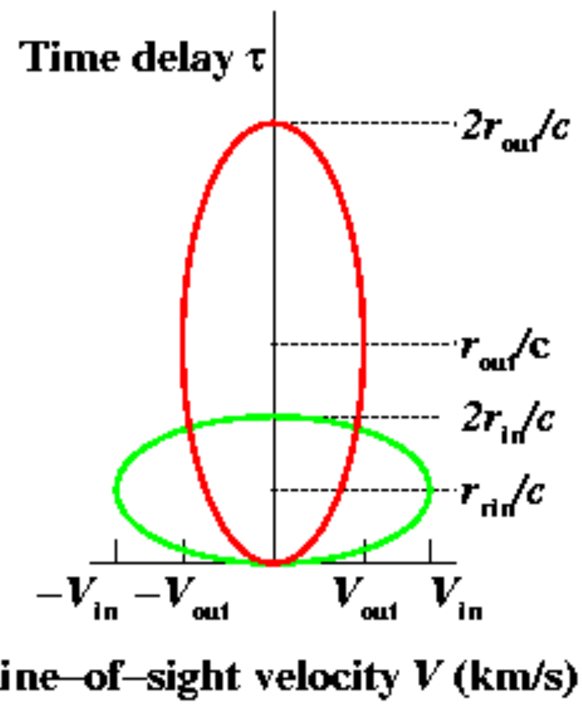


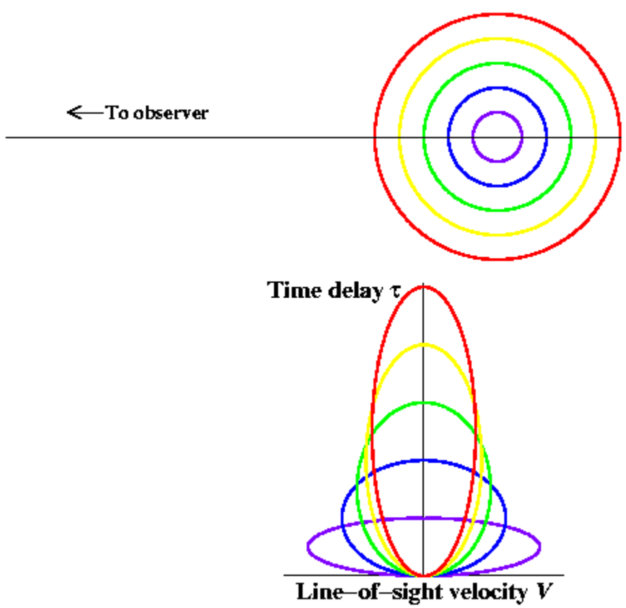


Thick Geometries

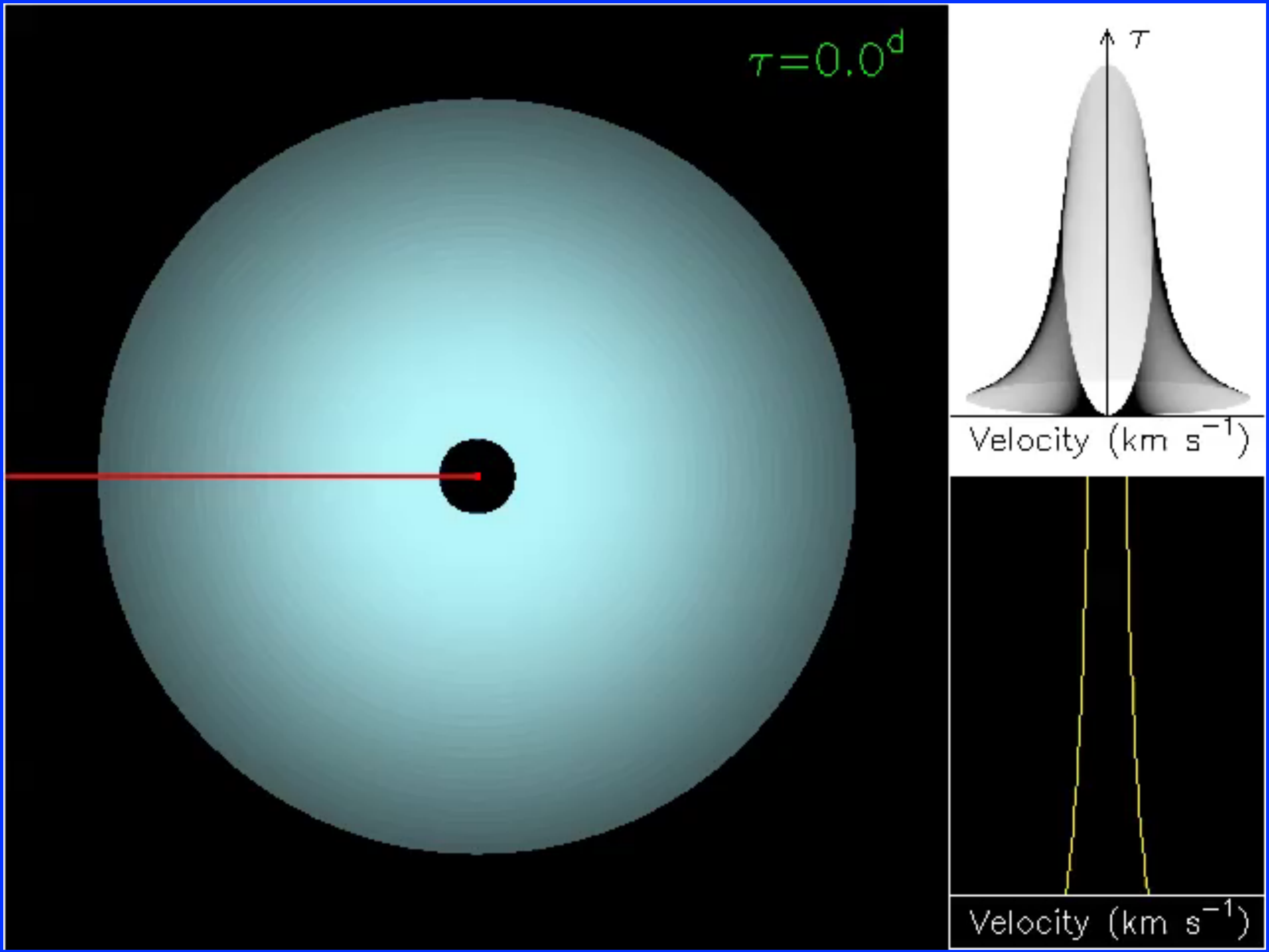
- Generalization to a disk or thick shell is trivial.
- General result is illustrated with simple two ring system.







A multiple-ring system



$\tau=0.0^d$
τ
Velocity (km s^{-1})
Velocity (km s^{-1})

Reverberation Response of an Emission Line to a Variable Continuum

The relationship between the continuum and emission can be taken to be:

$$L(V,t) = \int \Psi(V,\tau)\, C(t-\tau)\, d\tau$$

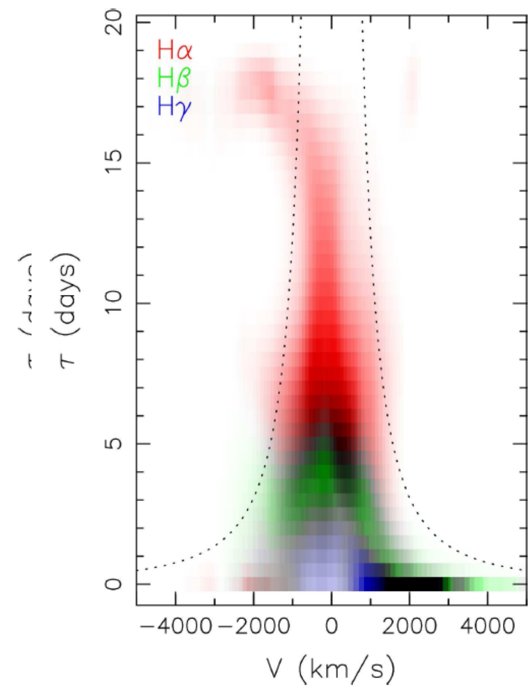
Velocity-resolved emission-line light curve

"Velocity-delay map"

Continuum light curve

Velocity-delay map is observed line response to a δ-function outburst

Required time sampling, duration, and *S/N* makes velocity-delay map recovery very difficult.

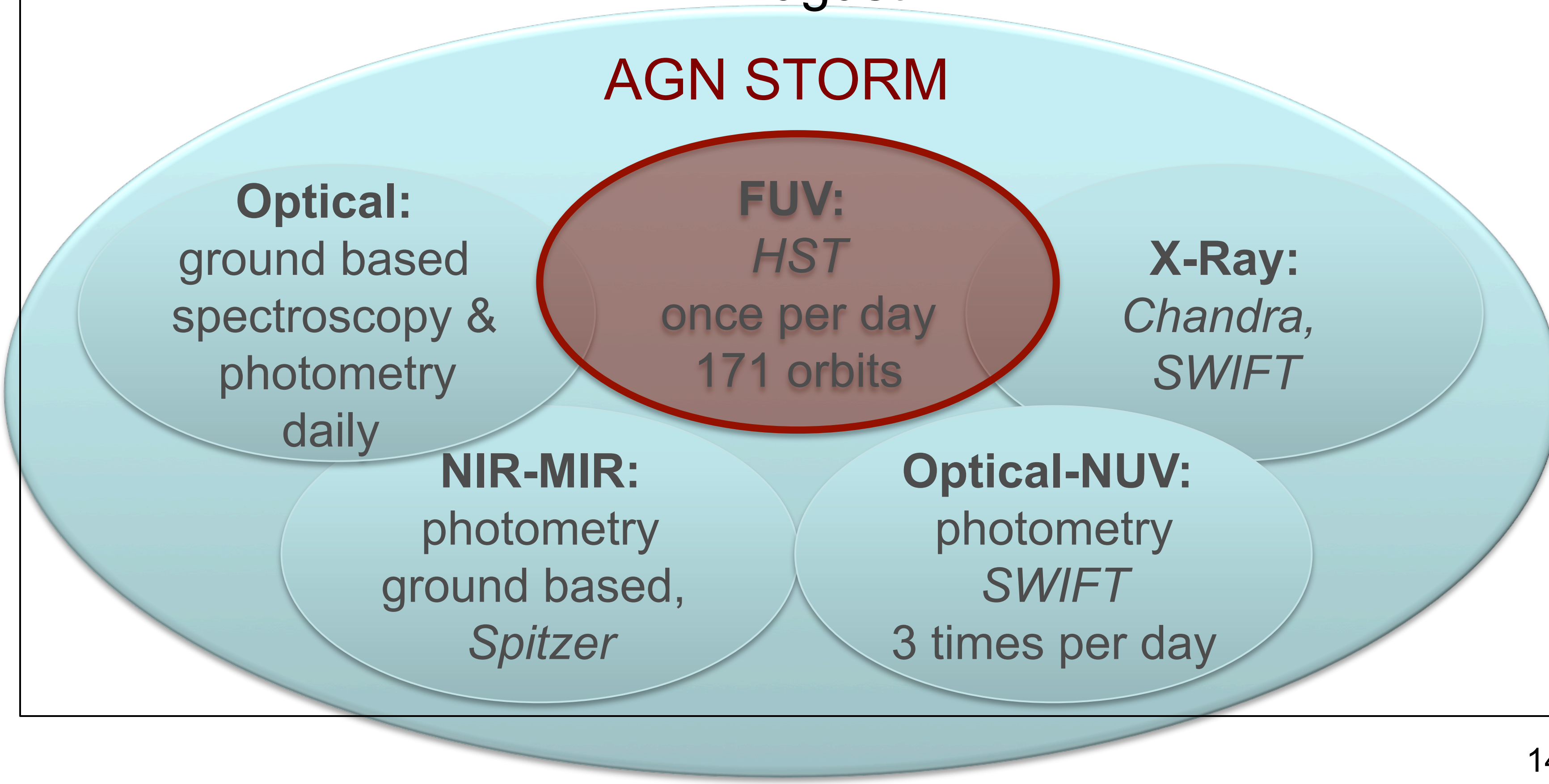


Arp 151

LAMP: Bentz+ 2010

AGN Space Telescope and Optical Reverberation Mapping (STORM) Program

Multiwavelength reverberation mapping monitoring program to study the Seyfert 1 galaxy NGC 5548, 2014 January - August



AGN STORM *HST* program challenges

Broad UV absorption gradually varying during the campaign

(**Kriss+ in prep**)

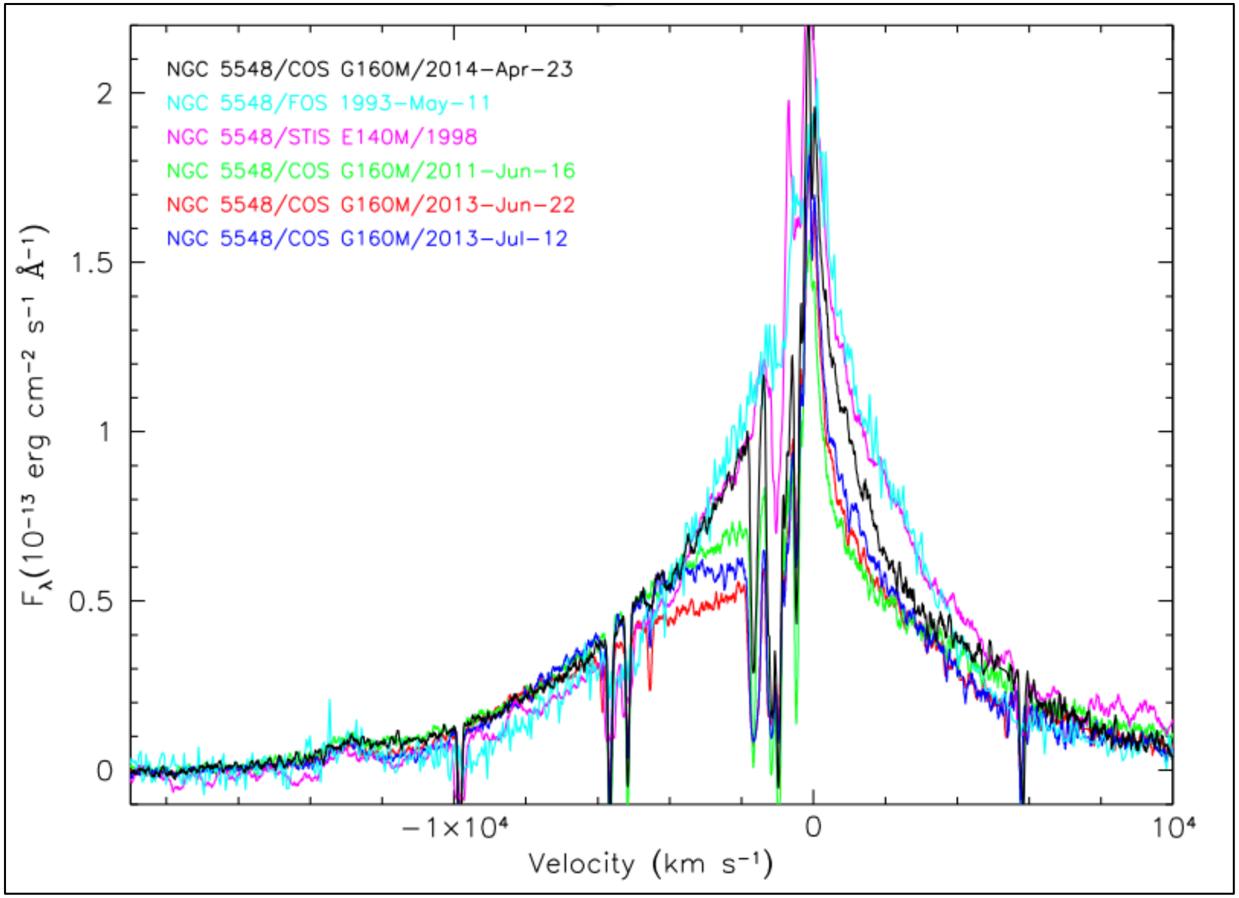
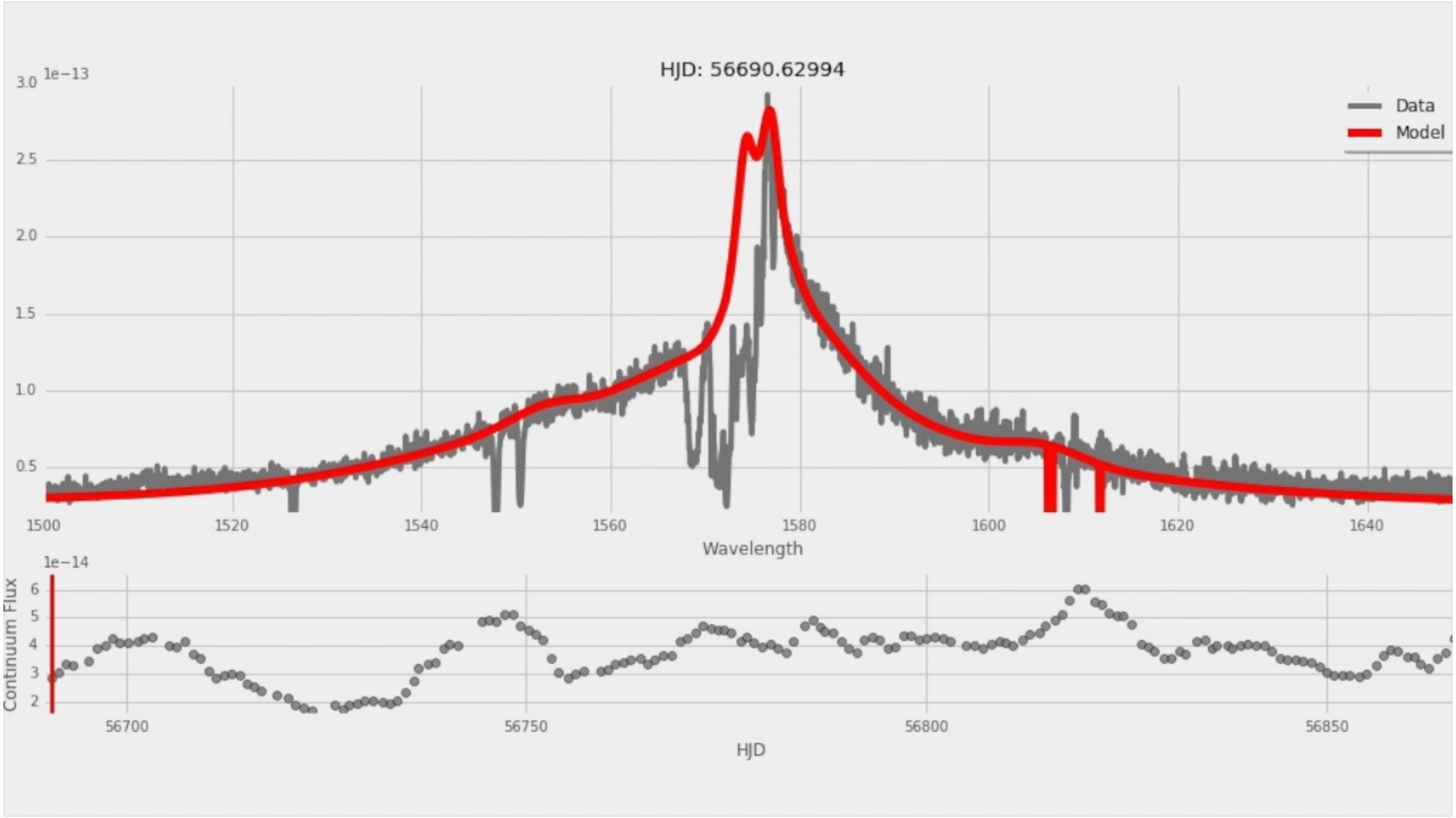
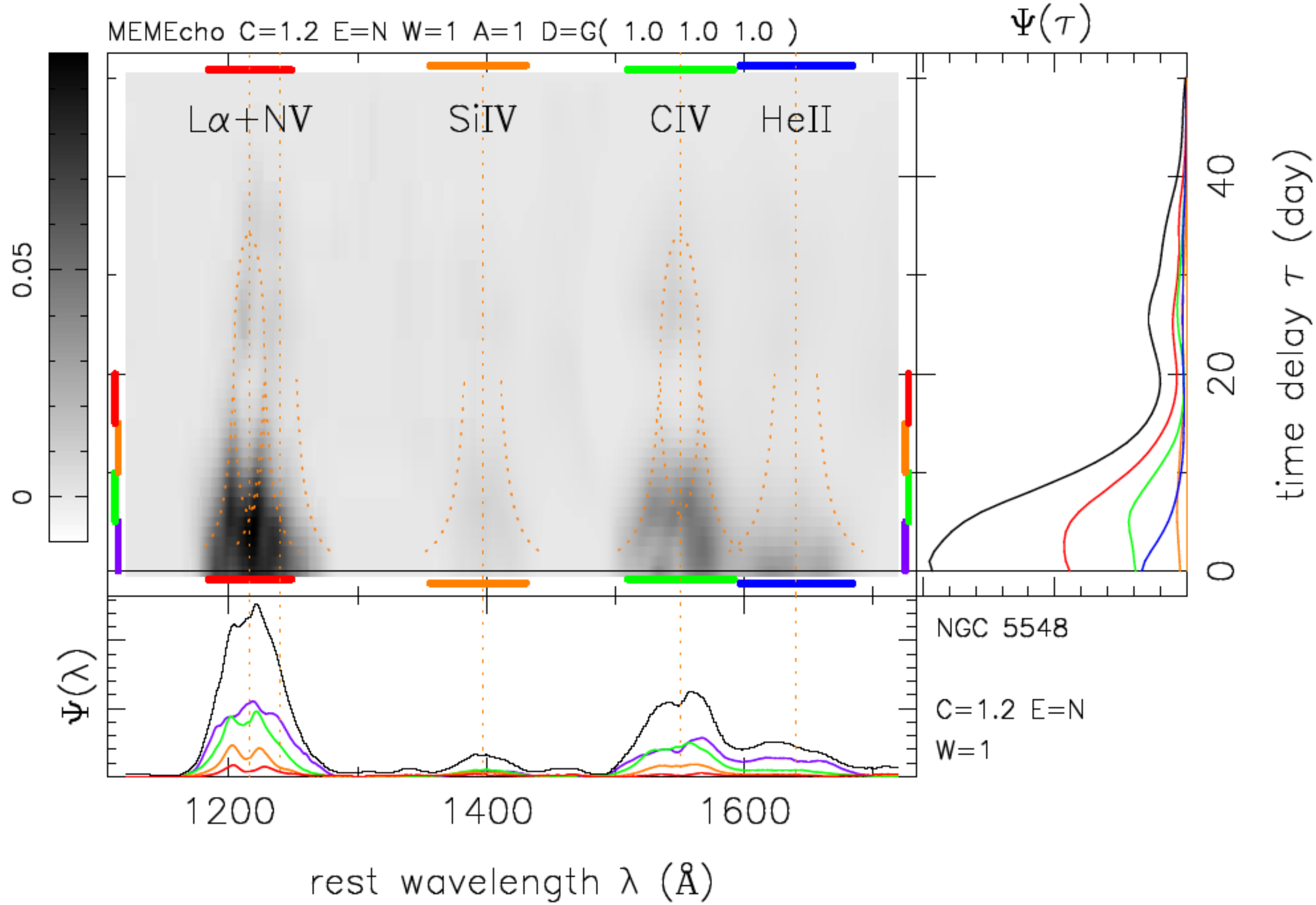


Figure courtesy of G. Kriss

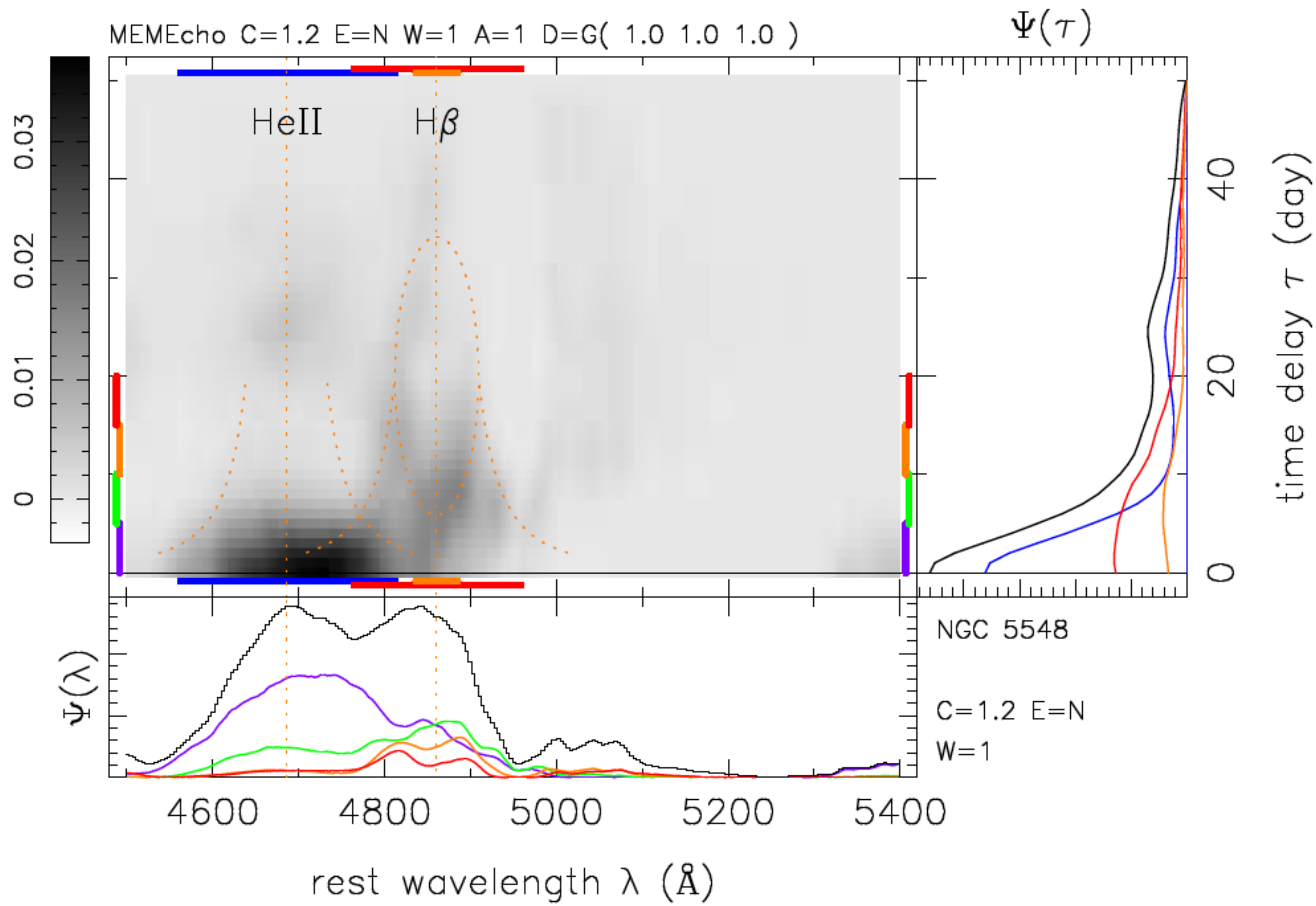
C IV Variations



UV Velocity-Delay Maps



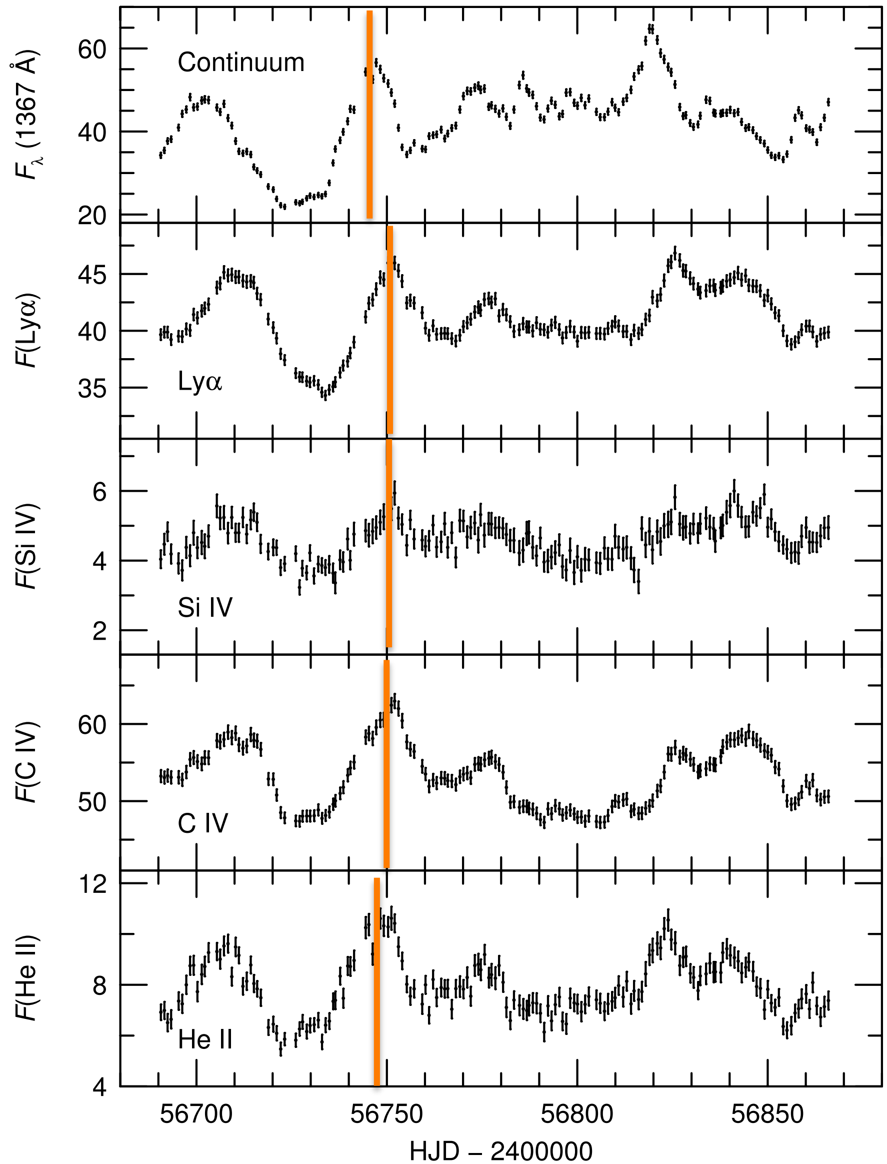
Optical Velocity-Delay Maps



AGN STORM
HST program

Mean lags relative to 1367 Å continuum

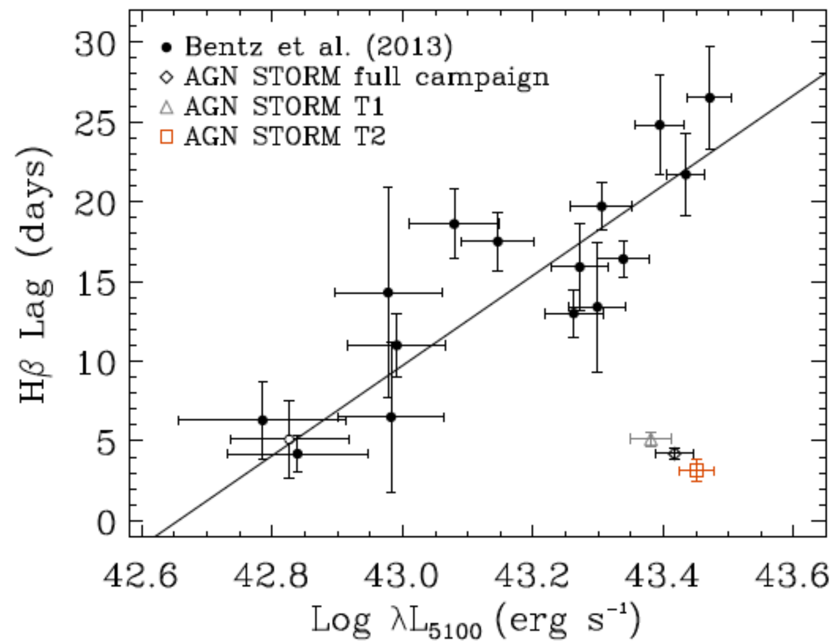
Ly α	6.19 ± 0.27 days
Si IV	5.44 ± 0.70 days
C IV	5.33 ± 0.46 days
He II	2.50 ± 0.33 days

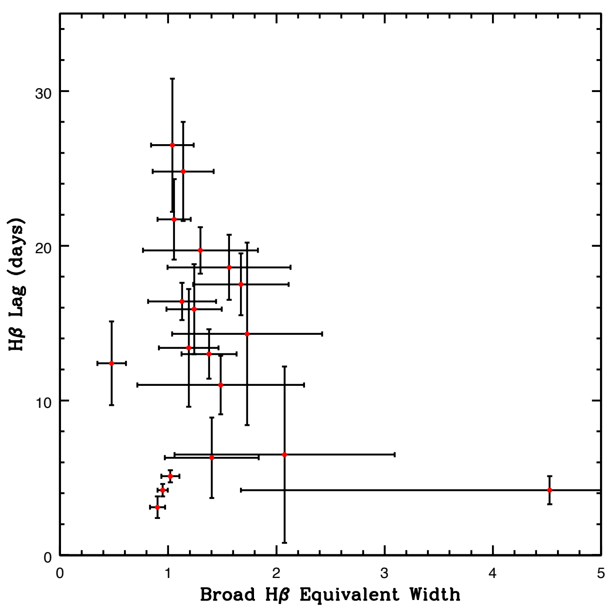


De Rosa+ 2015

Why Are the Emission-Line Lags So Small?

- Given high luminosity in 2014, Hβ lag should be ~20 days.
- Measured lag ~6 days

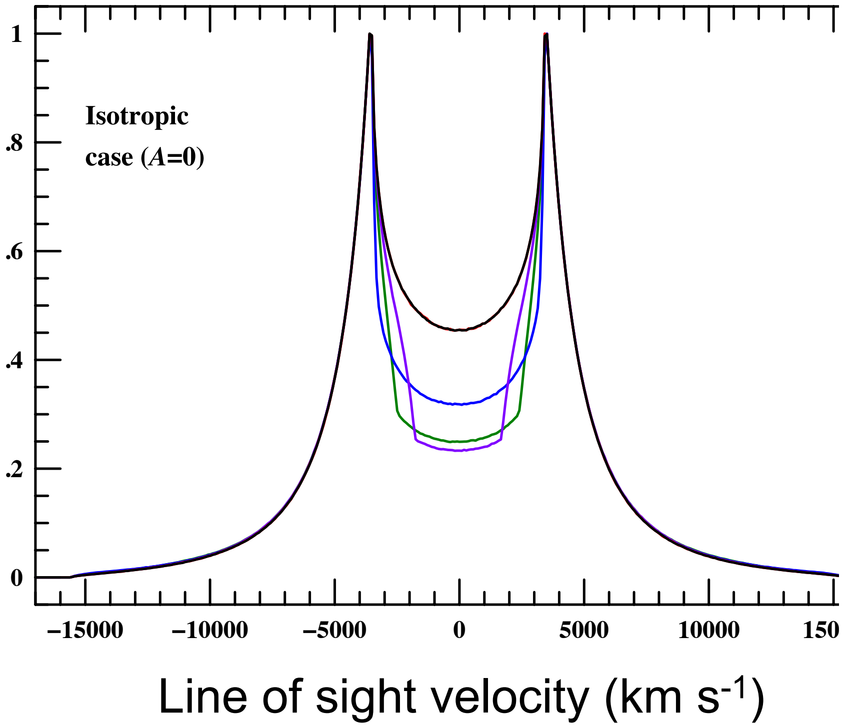


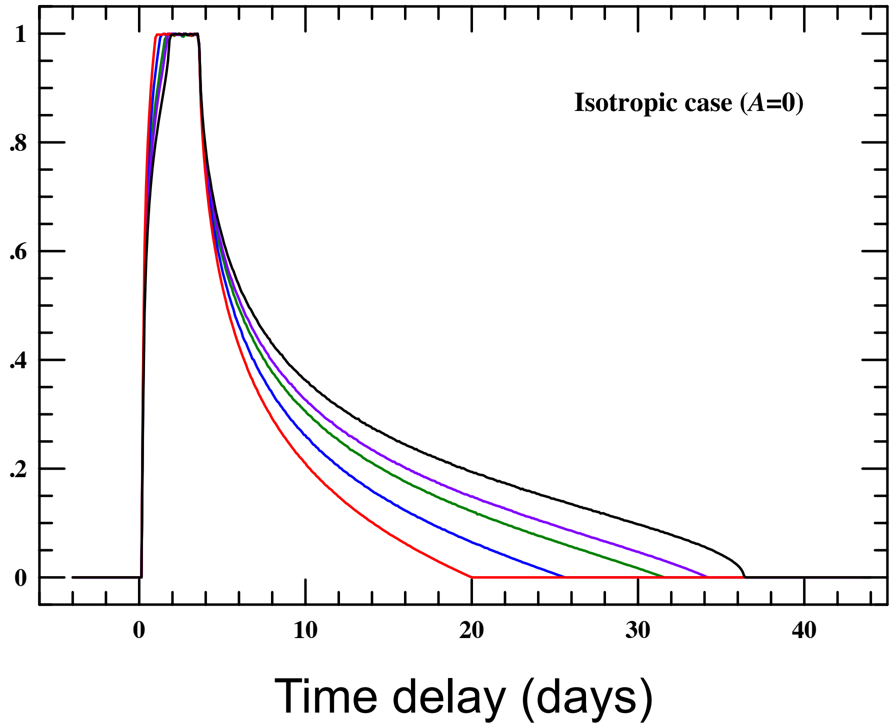


The equivalent width of Hβ (line to continuum ratio) is also very low

➔Is some BLR gas shielded?

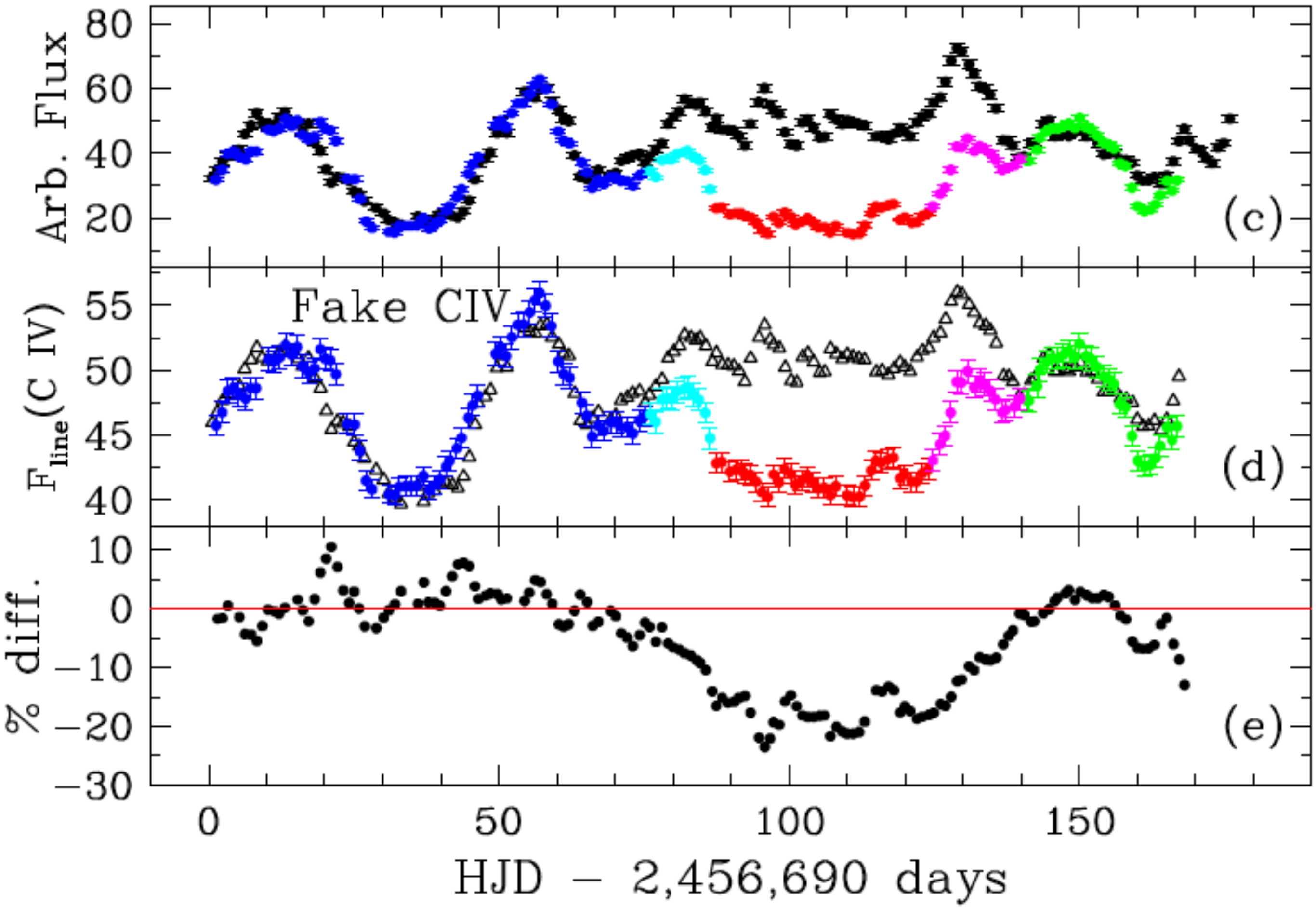
What Happens If You Shield the Far Side of the BLR from the Ionizing Source?





Profiles don't change much, but mean time delays do.

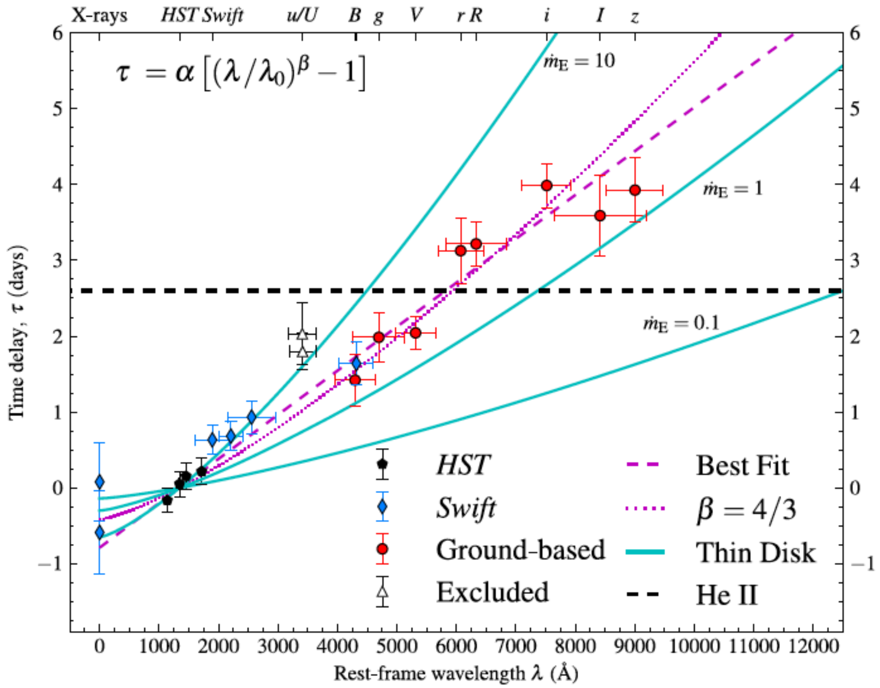
Line Responses "De-cohere" 60 Days into STORM Campaign



Goad+ 2016

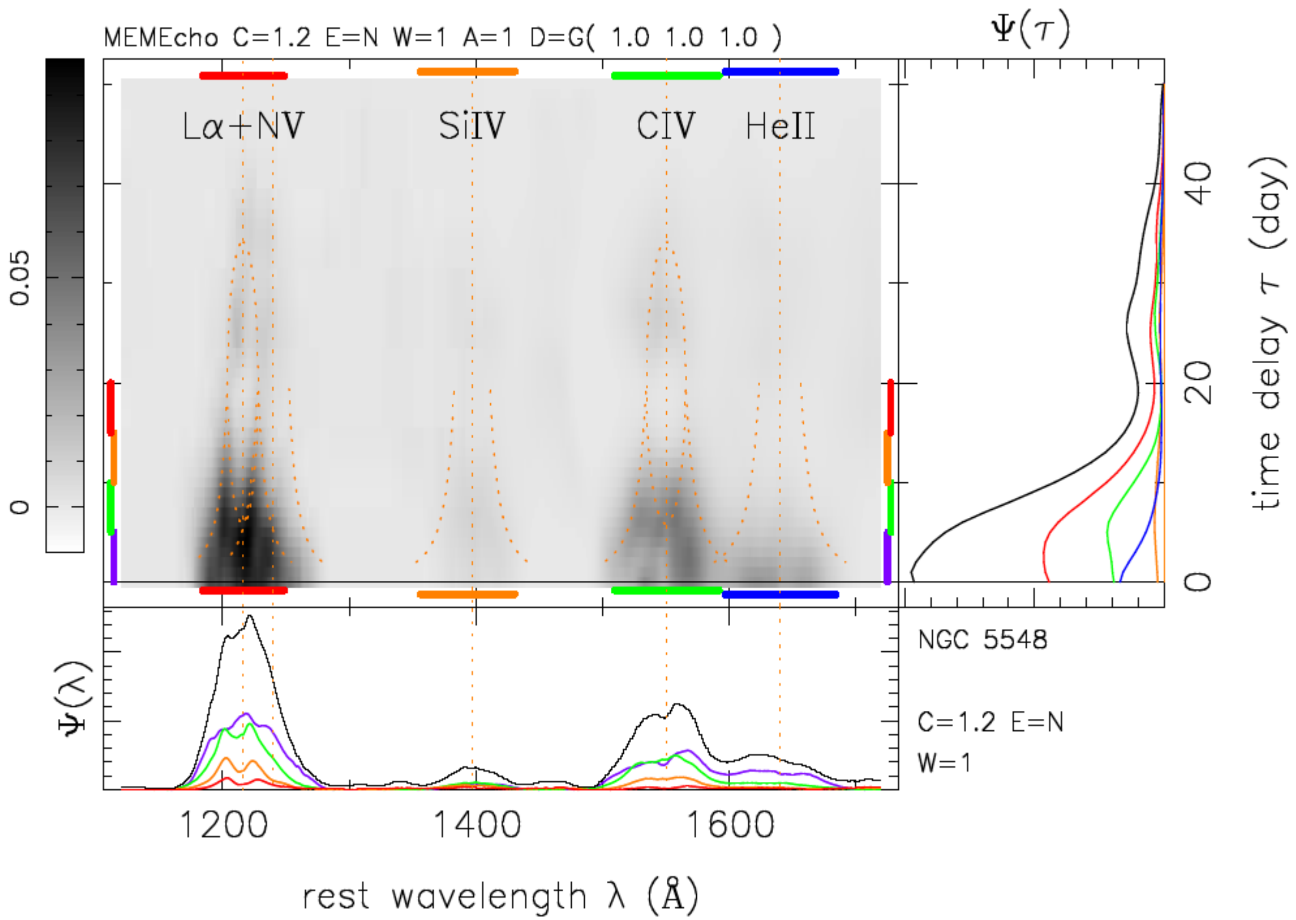
What We Learned About NGC 5548

- Interband continuum lags at high confidence
  - Hard X-ray through *z*-band
    - X-ray light curves don't look much like UV/optical (Gardner & Done 2016)
  - Disk larger than expected



What We Learned About NGC 5548

- Much of BLR is an inclined disk ($i \sim 50^o$), farside unexpectedly weak relative to nearside



AGN STORM: publication plan

Published or nearly complete:

I: *HST*-COS observations – De Rosa+ 2015 ApJ 806:128

II: *Swift-HST* continuum observations.– Edelson+ 2015 ApJ 806:129

III: Continuum interband lags, FUV through *z* – Fausnaugh+ 2016 ApJ 821:56

IV: Anomalous behavior of UV emission lines – Goad+ 2016 ApJ 824:1

V: Optical emission line variations – about to submit, Pei+

VI: Accretion disk modeling – about to submit, Starkey+

In progress or planned:

Heuristic models of the UV emission lines – Kriss+

Chandra X-ray observations – Mathur+

Velocity-delay maps – Horne+

Dynamical modeling – Pancoast+

Absorption line variations – Kriss+

Photoionization modeling – TBD

NIR and *Spitzer* observations – TBD