The Swift AGN Accretion Disk Reverberation Mapping Survey (made possible by Neil)

R. Edelson
University of Maryland

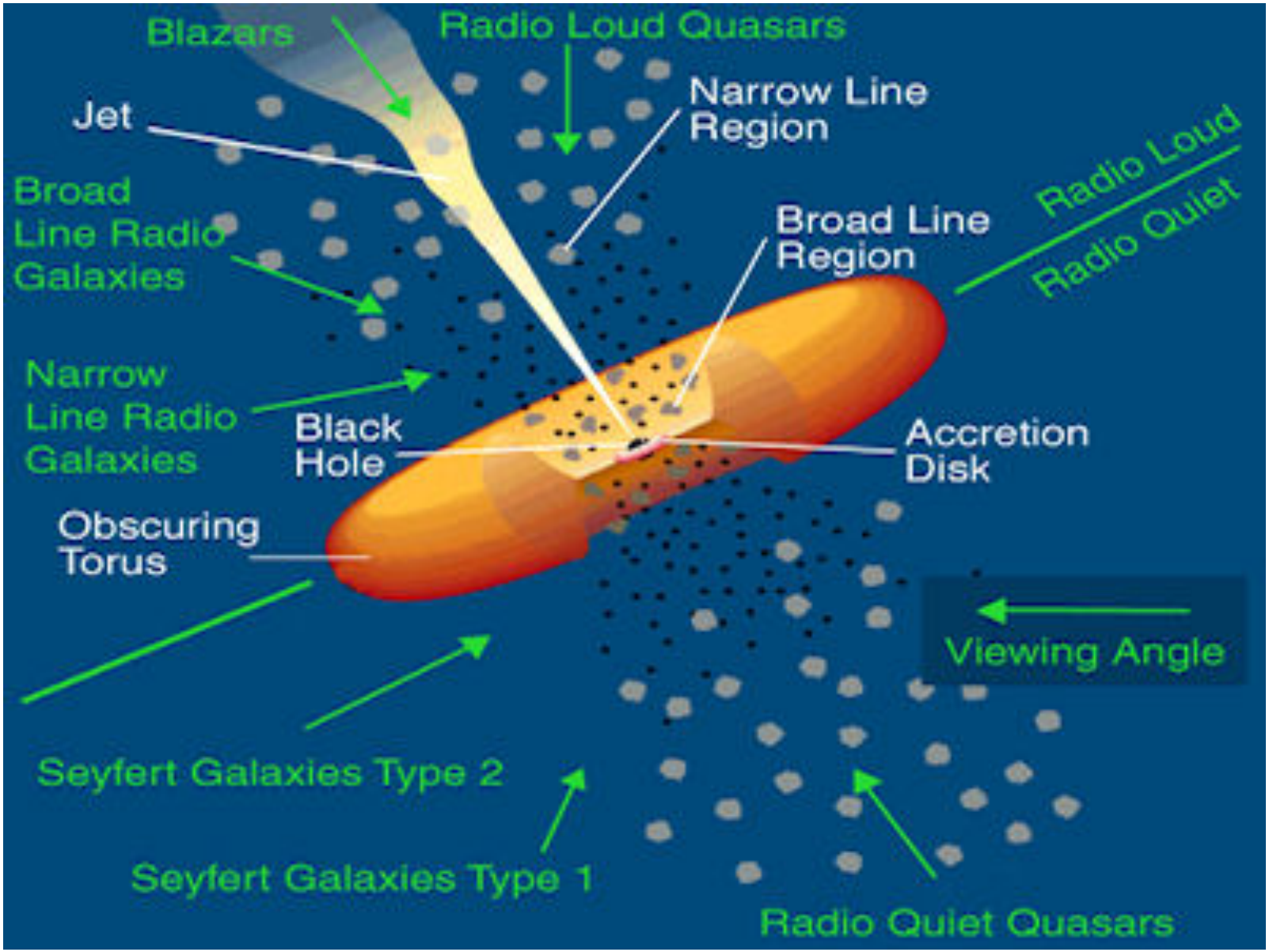
Background

- AGN are so distant we cannot image central engine, must use indirect methods like variability or lensing
  - Key tool is reverberation mapping (RM), which uses "light echoes" to determine broad-line region (BLR) component sizes and structures
  - Has now been applied to >100 AGN, yielding BLR sizes and black hole mass estimates
  - Started trying to use RM to map accretion disk in '90s

    But hit a roadblock, couldn't measure clear lags

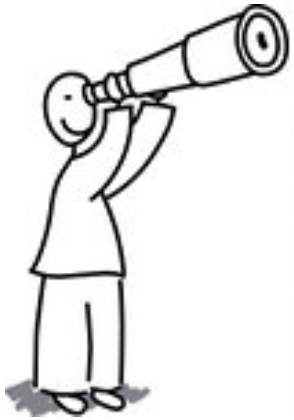
- **Neil's involvement and contributions were *crucial* for making progress on this long-standing problem.**

Artist's conception of an AGN central engine



The BLR Reverberation Mapping technique

- Central disk/corona emits continuum, powers BLR
- Continuum variations "echoed" by the emission lines; delayed, broadened by transfer function
- Invert transfer function to get information about the BLR size, geometry, structure



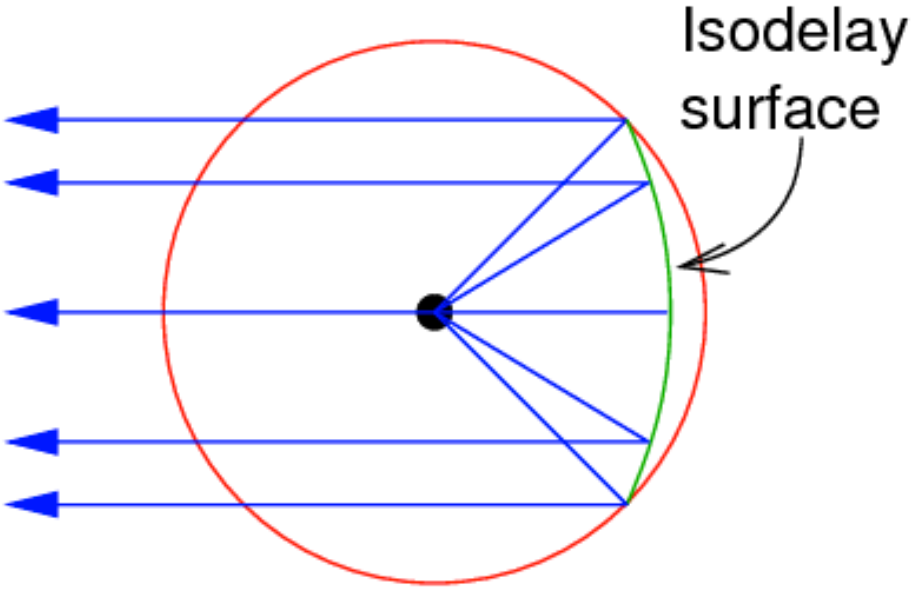
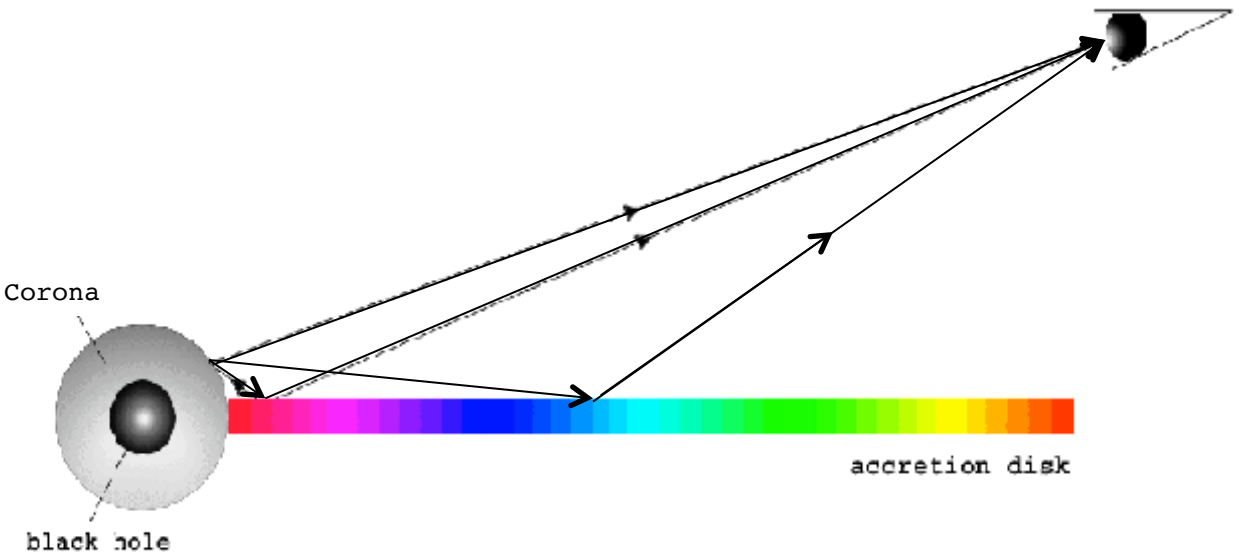


image from Jorn Wilms' website

Reverberation mapping the accretion disk

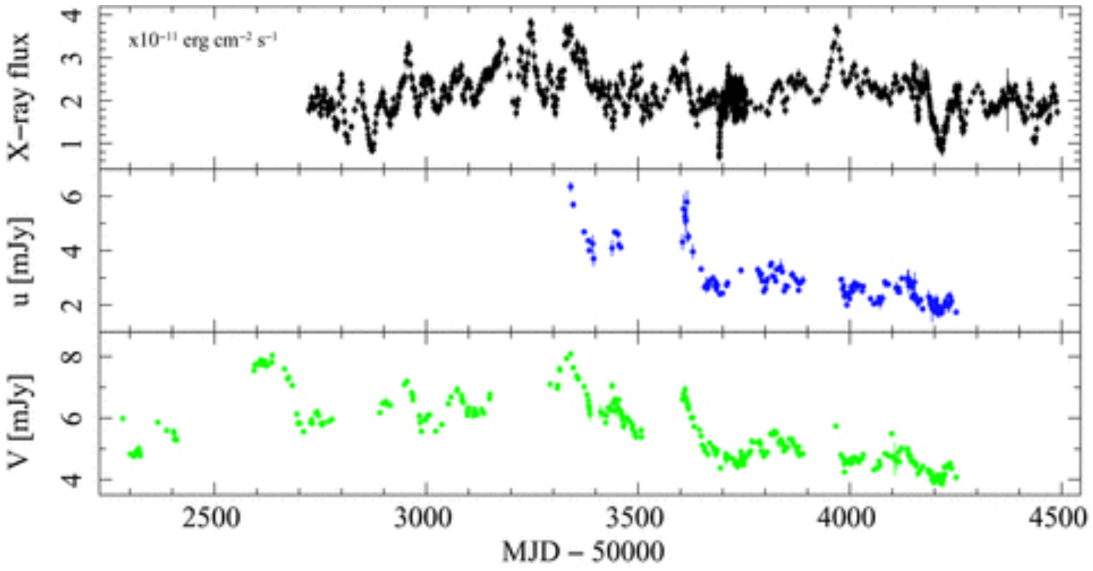
- Can also use RM principle to map accretion disk
- Reprocessing: corona illuminates, heats larger disk
  - Thus should expect variability to be correlated, with X-rays leading UV leading optical on day-hours timescale
- We have been searching for decades for expected lags
  - Lags will go as $\tau = R/c \propto (M\dot{M})^{1/3}\ T^{-4/3} \propto (M\dot{M})^{1/3}\ \lambda^{4/3}$

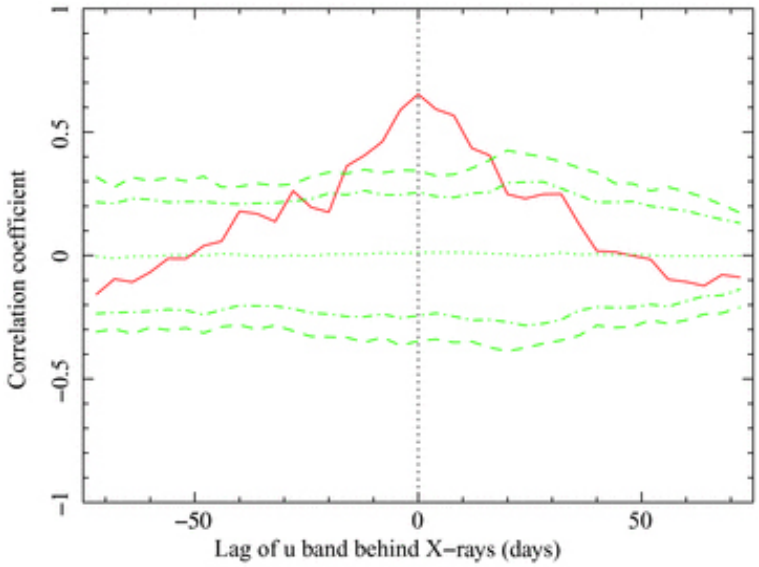


(My modification of an artist's conception of a galactic transient, GRS 1915+105; Rau & Greiner 2013. The physical picture is pretty much the same for AGN.)

Early (pre-Swift) campaigns: Mrk 79

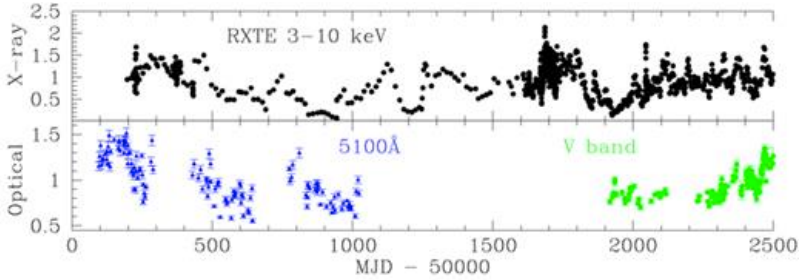
- Breedt et al. 2009, MNRAS, 394, 427
- 5 years of monitoring with RXTE, ground-based
- X-ray, u, V all strongly correlated, consistent with zero lag

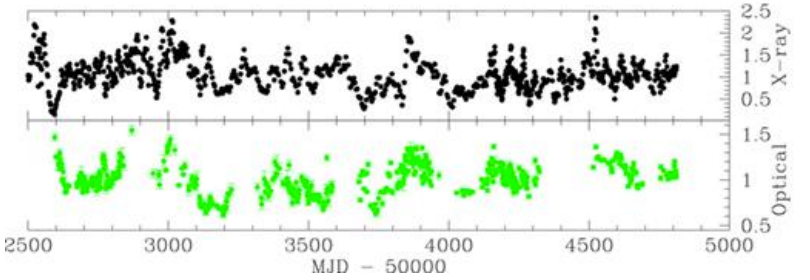


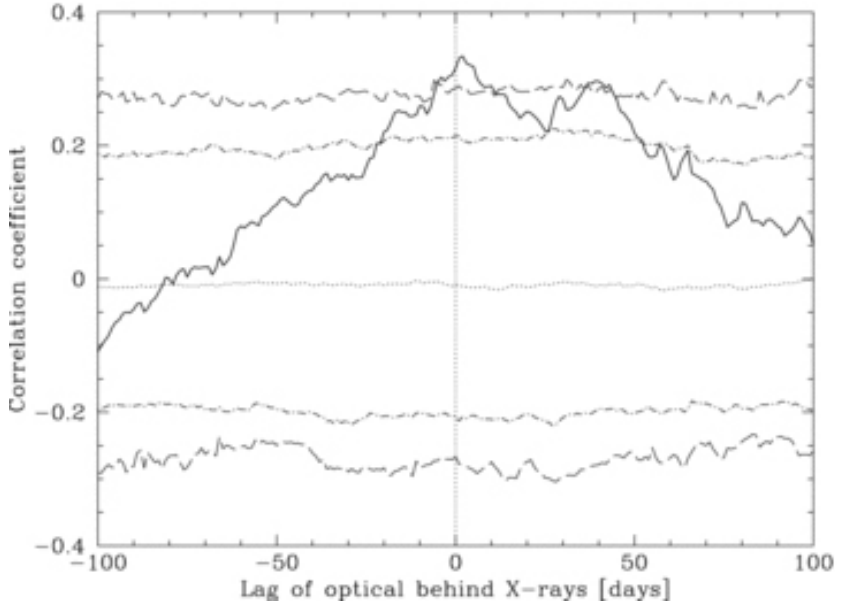


Early campaigns: NGC 4051

- Breedt et al. 2010, MNRAS, 403, 605
- 12 years of data, again combining RXTE, ground-based
- Optical shows a lag of +1.2 (+1.0/-0.3) days behind X-rays
- Note relatively low peak correlation coefficient ($r_{max} \sim 0.3$)

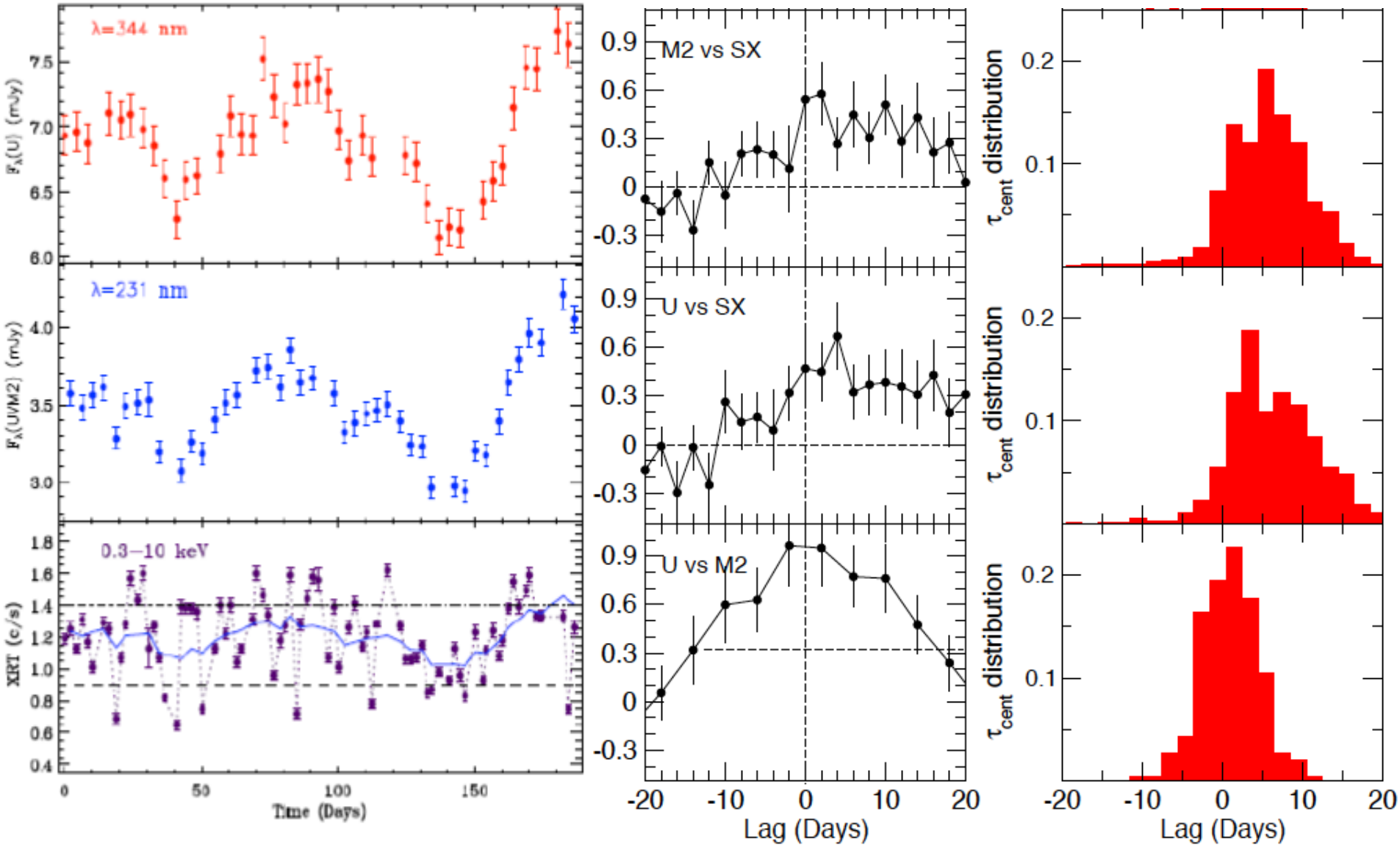






Typical early Swift AGN disk RM campaign

Ark 120 (Gliozzi et al. 2017, MNRAS, 464, 3955)

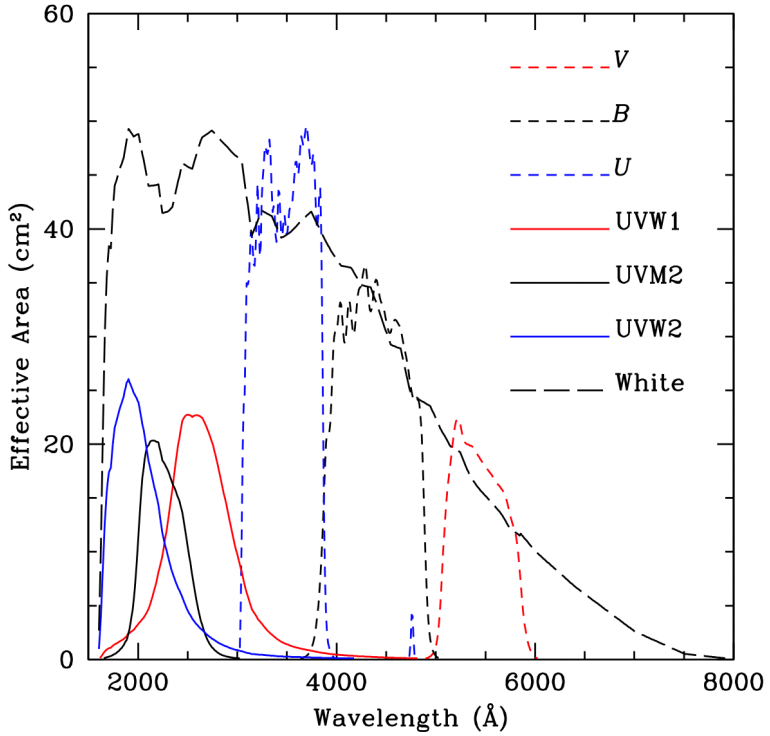


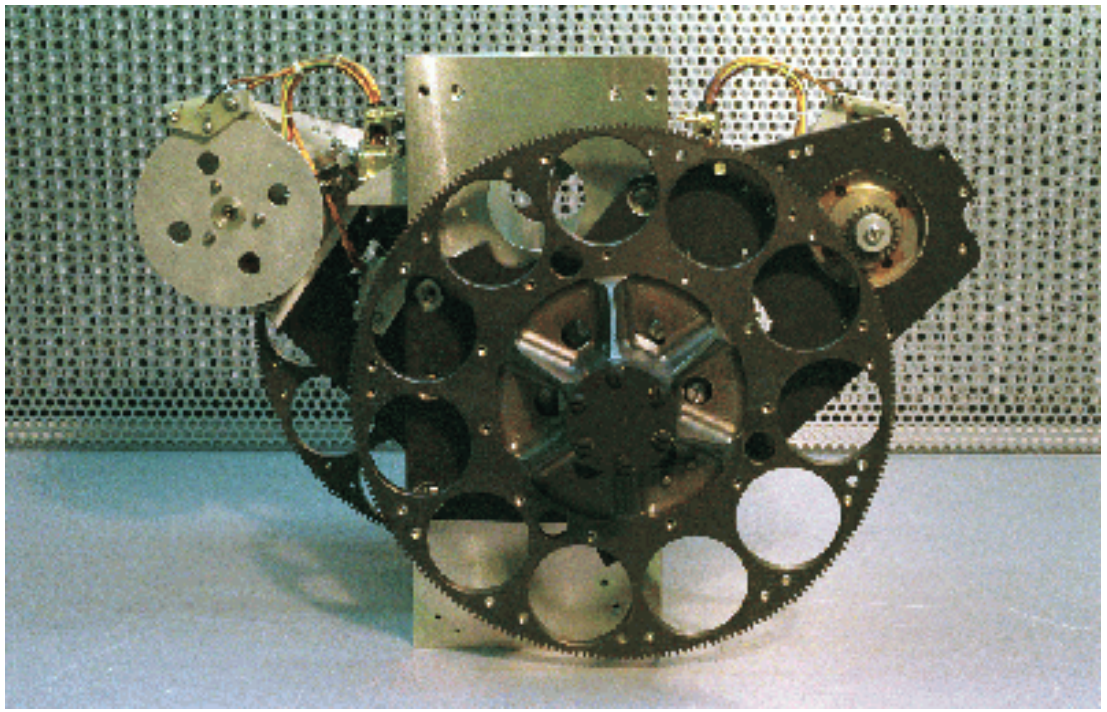
The breakthrough 2012 NGC 5548 campaign

- Suggested to Neil a new, two-pronged approach
  1. Intensive sampling, esp on short timescales
  2. Use all six UVOT filters instead of filter of day
- Neil immediately grasped this, approved on the spot
  - I then discussed with other community members, we arrived at joint Swift/HST/LCO campaign on 5548
  - We now call this Swift technique "IDRM" (Intensive accretion Disk Reverberaton Mapping)
- This created a new way for us to probe and understand AGN central engines that ***simply would not have happened if not for Neil's support, insight and courage***

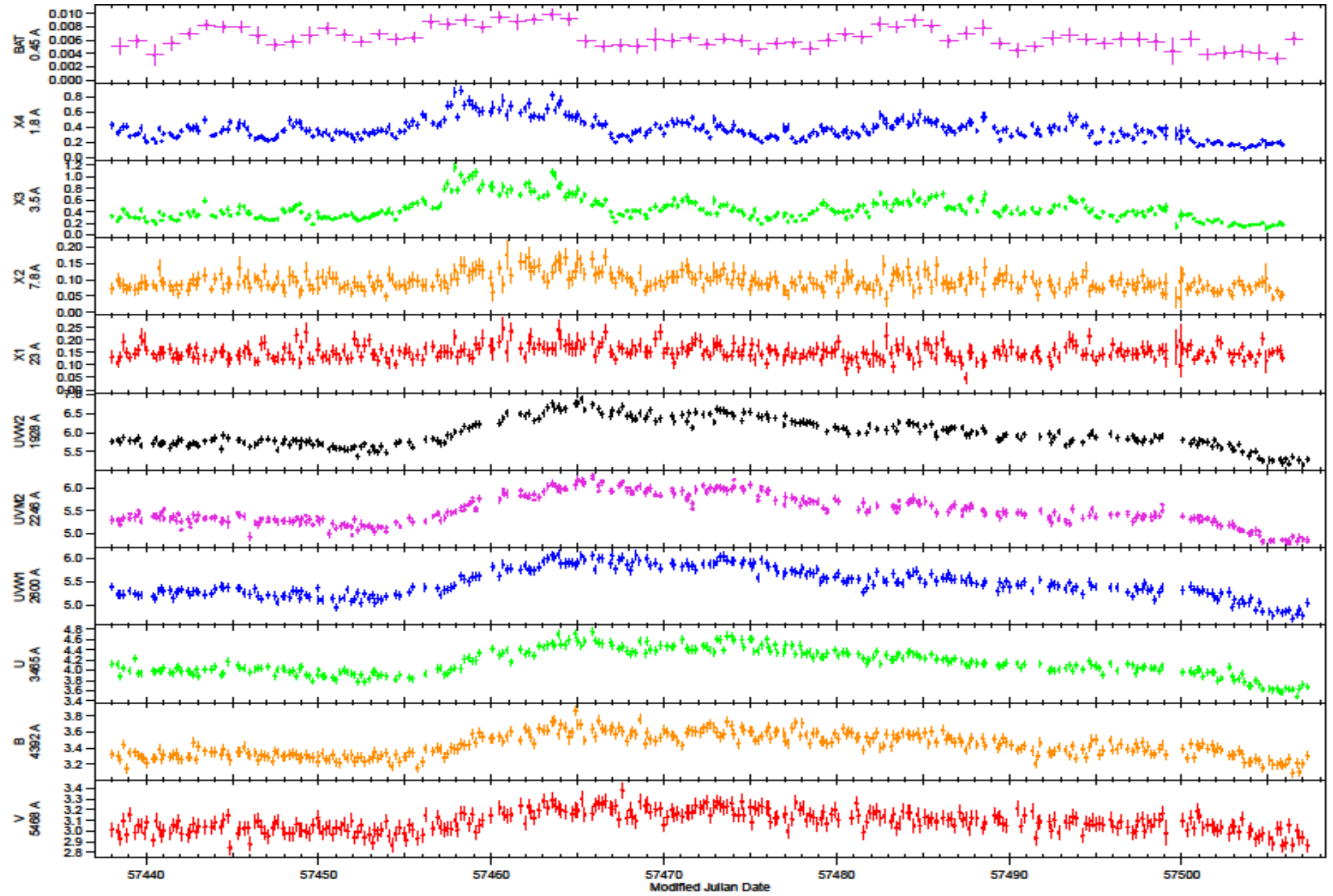
Swift UVOT

- Filter wheel has 6 filters covering 1800-5800 A
  - The key to this experiment was Swift PI's decision to allow filter changes well in excess of design lifetime
  - This demonstrated **real courage** from Neil Gehrels
  - Note for instance that XMM makes opposite decision



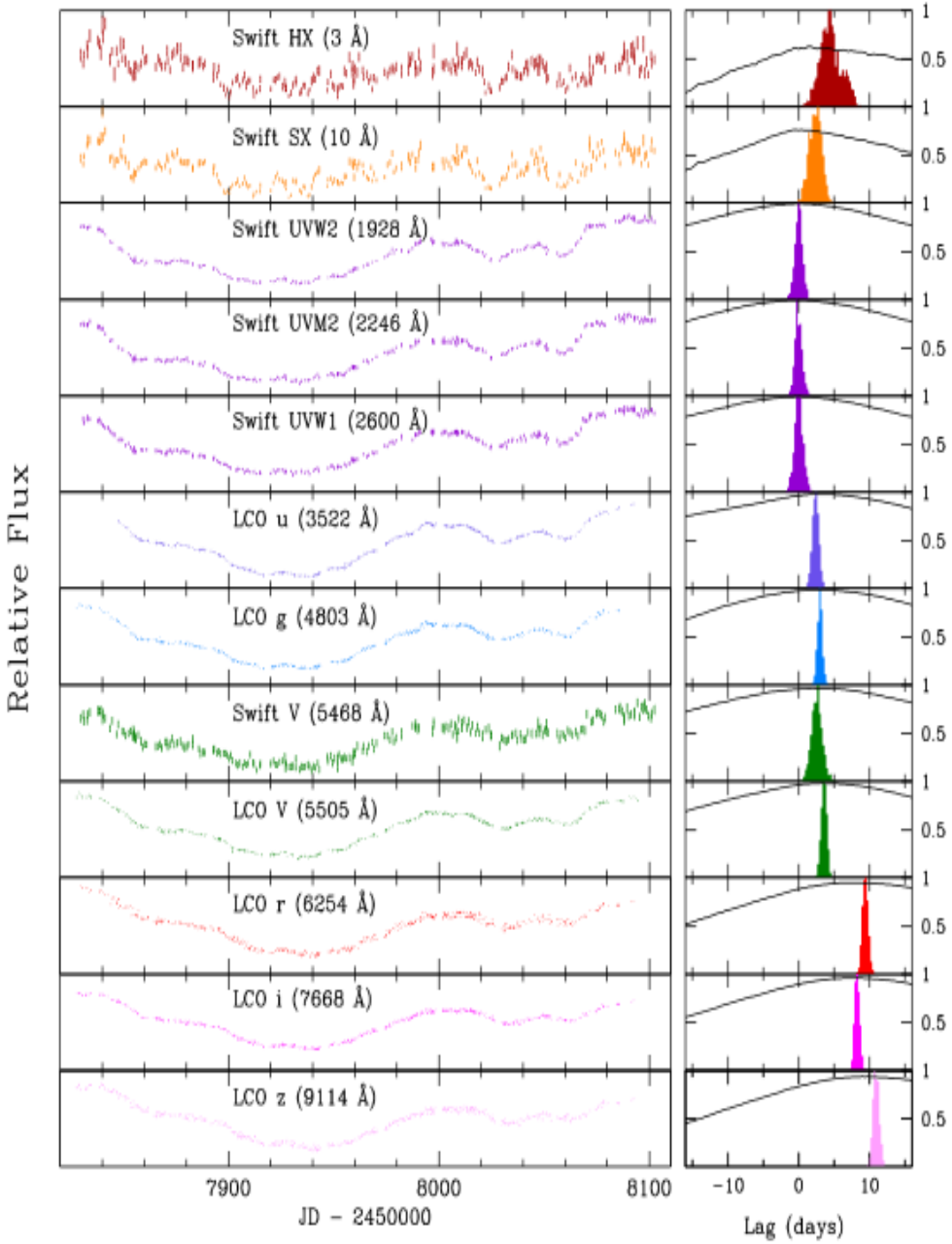


NGC 4151 (Swift only) light curves



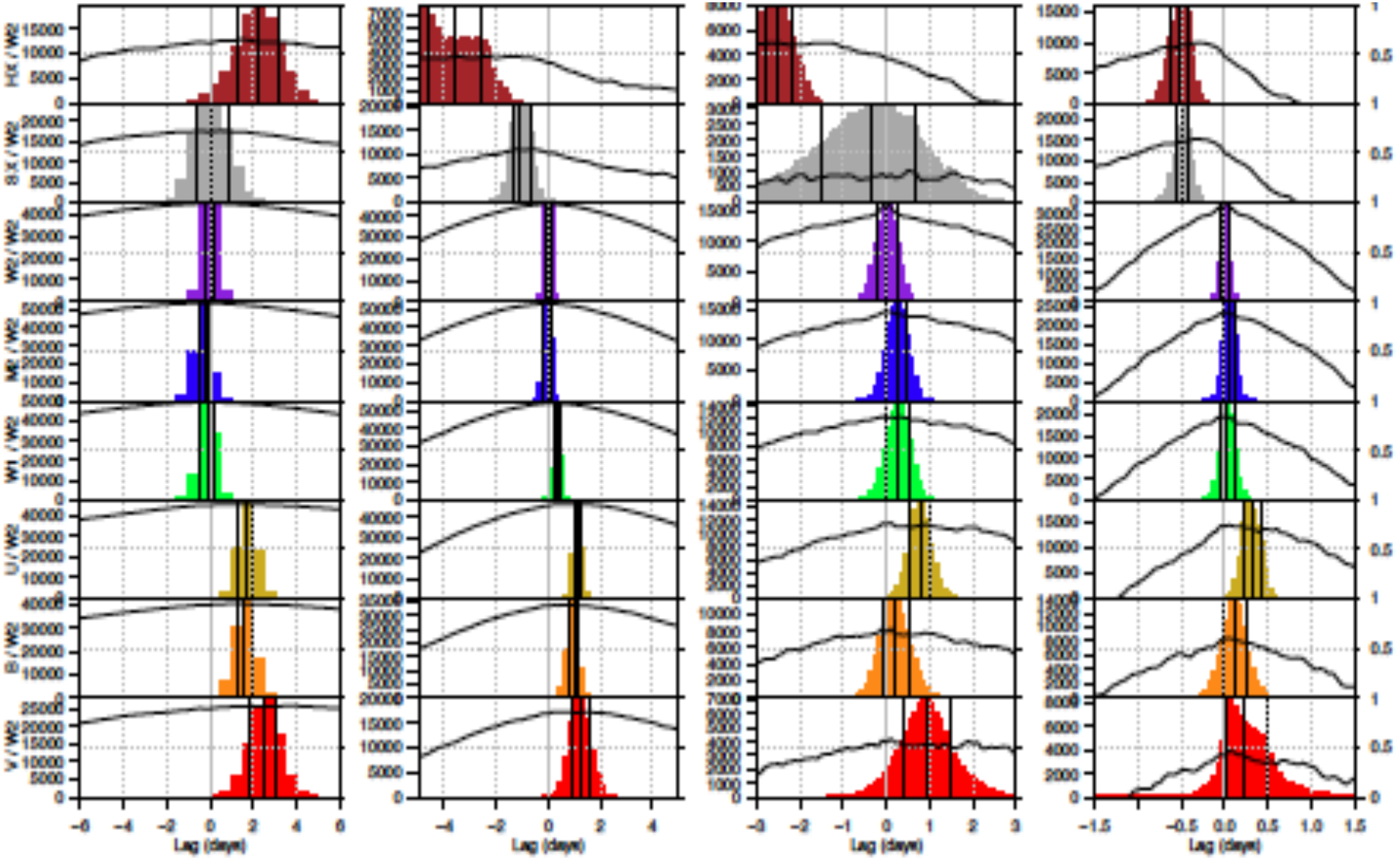
Most recent IDRM result: Mrk 509

- Latest (4th) target
- Plot shows both Swift and LCO data
  - Note very clear lag vs wavelength trend
  - But X-rays **lag** UV (!!)
  - two instruments have great synergy, large sky coverage needed for AGN IDRM
- NICER: another satellite with large sky coverage



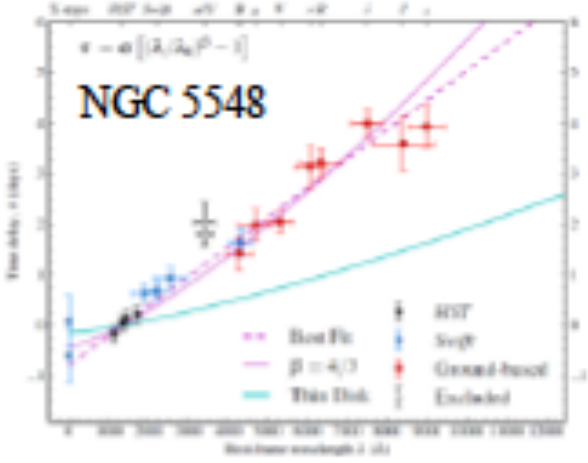
4 AGN subjected to IDRM to date

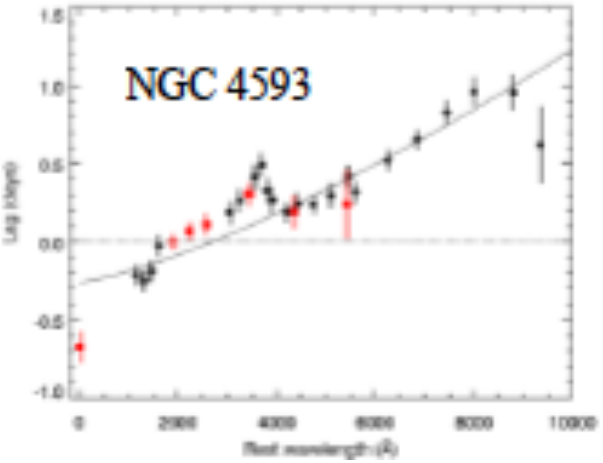
Mrk 509 NGC 5548 NGC 4151 NGC 4593

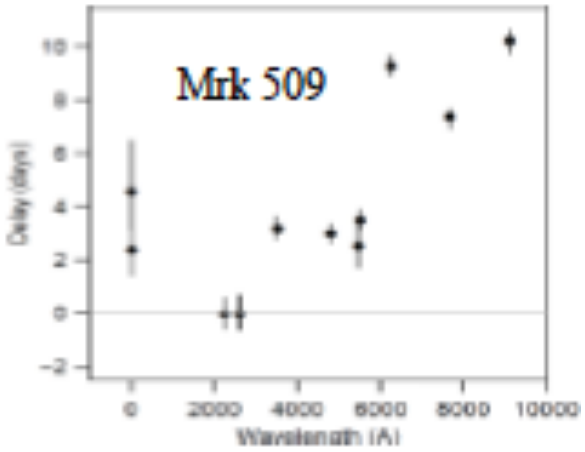


Lag vs Wavelength

- Initial (pre-Swift and pre-Neil) AGN disk RM campaigns focused on X-ray correlations with lower energies
- Thanks to the aggressive use of UVOT, we now see the real action is within the UV/optical
  - Fits show Shakura-Sunyaev disk relation $\tau \propto \lambda^{4/3}$
  - Excess in U band due to diffuse continuum from BLR
  - Observed X-rays showed wide diversity of behaviors







IDRM Survey findings

- Now have completed IDRM monitoring on four AGN
  - NGC 5548, NGC 4151, NGC 4593, Mrk 509
  - All show similar lag structure within UV/optical
  - However wide variety of UV/X-ray behaviors
- This supports the basic accretion disk picture, although sizes appear a factor of a few larger than expected
- However the puzzling disconnectedness with the X-rays calls the entire reprocessing picture into question
  - First 3 results suggest driver may be at harder energies
  - However, there is no obvious way to explain Mrk 509
  - It looks like the whole reprocessing picture is wrong

Summary of current/future IDRM campaigns

- IDRM has now "graduated" from ToO to GI programs
- Two more targets have data gathered, not fully analyzed
  - Mrk 1220: simultaneous with Kepler
  - Mrk 110: high L/L_{Edd} target, Ian McHardy PI
- One new campaign currently underway on Fairall 9
- Two future campaigns: Mrk 142 (another high L/L_{Edd} target, Ed Cackett PI), Mrk 876 (simultaneous w/ TESS)
- IDRM results are causing fundamental reassessment of the >30 yr old reprocessing model
- **This would not have happened w/o Neil's courageous decision to make full use of UVOT capabilities.**

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Swift Monitoring of NGC 4151: Evidence for a Second X-Ray/UV Reprocessing

R. Edelson[1], J. Gelbord[2], E. Cackett[3], S. Connolly[4], C. Done[5], M. Fausnaugh[6], E. Gardner[5], N. Gehrels[7,35], M. Goad[8], K. Horne[9], I. McHardy[4], B. M. Peterson[6,10,11], S. Vaughan[8], M. Vestergaard[12,13], A. Breeveld[14], A. J. Barth[15], M. Bentz[16], M. Bottorff[17], W. N. Brandt[18,19,20], S. M. Crawford[21], E. Dalla Bontà[22,23], D. Emmanoulopoulos[4], P. Evans[8], R. Figuera Jaimes[9], A. V. Filippenko[24], G. Ferland[25], D. Grupe[26], M. Joner[27], J. Kennea[18], K. T. Korista[28], H. A. Krimm[7,29], G. Kriss[10], D. C. Leonard[30], S. Mathur[5], H. Netzer[31], J. Nousek[18], K. Page[8], E. Romero-Colmenero[21,32], M. Siegel[15], D. A. Starkey[9], T. Treu[33], H. A. Vogler[15], H. Winkler[34], and W. Zheng[24]

We dedicate this paper to the memory of Neil Gehrels, the P.I. of Swift and a leading author of this paper. Neil was a great scientist who also brought out the best in others. He led the Swift team with enthusiasm and expertise, always happy and eager to take the satellite in new directions. For example, his strong and unwavering support is what allowed Swift to gather these unprecedented data on NGC 5548 and NGC 4151, providing a powerful method that should continue to inform our understanding of AGN physics for years to come. Specifically, without his courageous approval of increased UVOT filter changes well beyond the design lifetime of the filter wheel, the extraordinary 11-band light curve in Figure 3, which forms the basis of this work, could not have been gathered. This is but one tiny piece of the rich legacy that he leaves us.