Reverberation Mapping

and everything you ever wanted to know about it

Motivation

- AGN and quasars appear to be powered by BHs ➠ most galaxies probably have BH at center
- We've established that we can measure BH mass from stellar/gas dynamics near center (i.e. Galactic Center)
- This is OK for normal galaxies, where nucleus is not too bright
- AGN and quasars are problematic, however, since bright nuclei swamp out stellar light
- "The ironic result is that the bright Seyfert nuclei and quasars that motivate the BH search are conspicuously rare in the dynamical BH census" (Gebhardt et al. 2000)
- Reverberation mapping saves the day

Basic Idea

- Observationally, spectrum from AGN/quasar is a strong continuum + broad emission lines (+ other unimportant stuff)
- Continuum due to accretion onto BH, thus is produced essentially at center
- Emission lines arise from gas located farther out, excited by continuum radiation
- Gas is still near BH and therefore has high Doppler motions ➠ hence broad lines (Broad Line Regions or BLRs)

Basic Idea cont.

- Any change in continuum level takes time to reach BLR
- Observationally, there is a time delay (τ) between continuum changes and emission line changes ➠ gives $R_{BLR} = c\tau$
- Width of line (ΔV) is a measure of velocity of gas at R_{BLR}
- BH mass is thus ➠ $M_{BH} \approx f\, R_{BLR}\, \Delta V^2 / G$ (assuming gravity dominates motion)

Assumptions and Complications

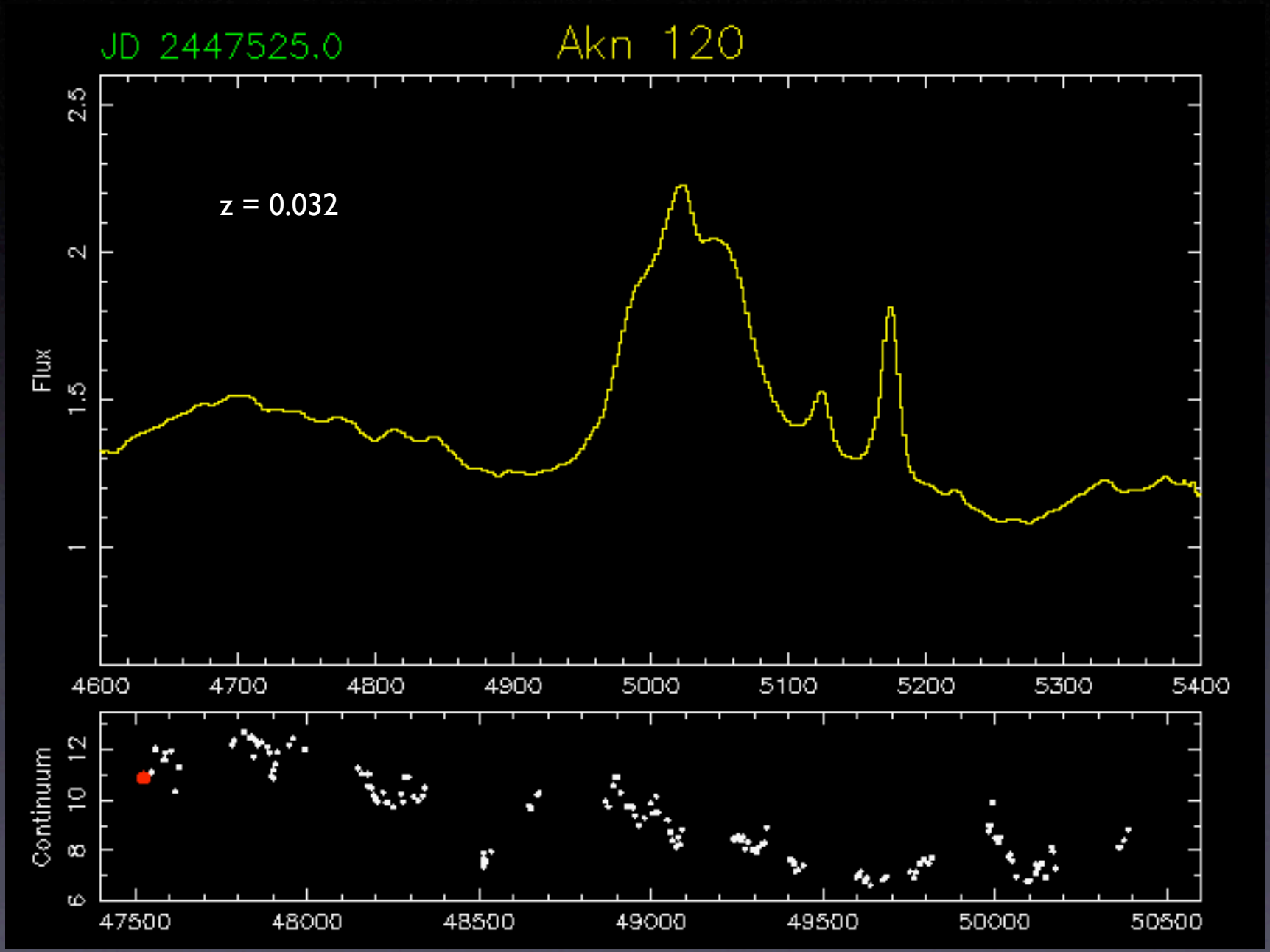
- Is assumption of virialized motions OK? (outflows, jets, winds, radiation pressure....)
- Unknown geometric factor f of BLR (thin/thick disk, inclination, multiple ionization regions, etc....)
- Adequate sampling to accurately measure time lag
- Contamination of broad lines by non-varying (or slowly varying) narrow line regions ➠ use rms spectrum
- Line blending (with different)
- Absorption along line of sight (especially at high z)

Best Case

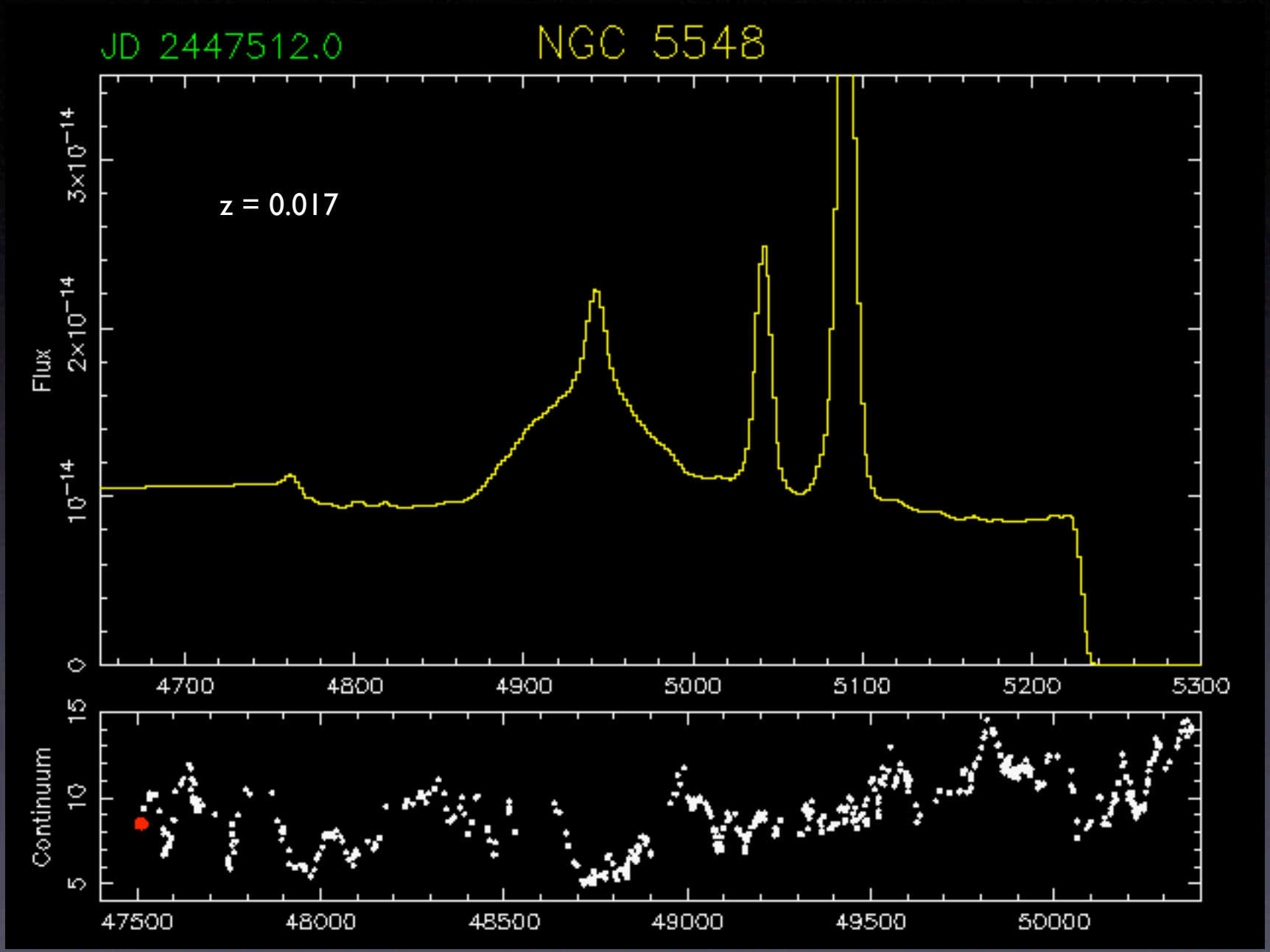
Peterson & Wandel, 2000

- Multiple ionization regions and lines ➠ ionization stratified structure
- M_{BH} from R_{BLR} and □ consistent for each line
- Motion appears Keplerian based on multiple lines and their profiles ➠ virialized assumption OK (most outflow models have at least □ ∝ constant)
- $L_{bol} < L_{Edd}$ ➠ gravity dominates

Other Examples...



http://www-astronomy.mps.ohio-state.edu/~peterson/AGN



http://www-astronomy.mps.ohio-state.edu/~peterson/AGN

Does it fit with other BH mass estimates?

Gebhardt et al., 2000

- Obviously difficult to compare reverberation mapping and stellar dynamics directly with same object
- Initially there existed a discrepancy in M_{BH} - L_{bulge} relation between dynamical and rev. map. BH masses
- Obviously (I think) L_{bulge} not well measured for AGN
- M_{BH} - σ_* much better correlation ➠ reverberation mapping appears to work (note: σ_* quite difficult to measure in AGN) ➠ can cross check (info on f ?)

Onwards to Higher Redshifts

- Ideally, we'd like to extend this method to quasars, where stellar/gas dynamical studies are impossible
- Unfortunately, higher (and harder) luminosity implies larger R_{BLR}
  - ➠ τ ~ days/months, up to a year
  - ➠ real changes in BLR size/geometry ?
- Monitoring campaign very difficult
- Can perhaps calibrate a scaling relationship to be used at high z ??

Reverb Mapping with Quasars

Kaspi et al., 2000

- LONG study (~8 years), monitoring H□ and H□ time delays and line widths in 17 quasars
- Mean redshift z ~ 0.1-0.2
- In principle, Balmer lines all come from same BLR, so should give same R_{BLR} and □ (and indeed they do)
- FWHM from mean spectra vs. rms spectra
- Hence M_{BH} for each quasar

Reverb Mapping with Quasars cont.

Kaspi et al., 2000

- Now attempt to calibrate scaling relationship
- Need luminosity measurement (not always easy)
  ➠ monochromatic + corrections, based on SEDs
- R_{BLR} vs. L
- □ vs. L
- M_{BH} vs. L (larger scatter...)
- ➠ Hence maybe □ vs. M_{BH} ? Or just use R_{BLR} vs. L ?

Higher and Higher Redshifts

Vestergaard, 2004

- Scaling relationships extendable to $z \geq 3$?
- Seems OK ➠ X-ray/UV/optical/radio data suggests similar line flux ratios, line EWs, and SEDs at low and high z (likely accurate to factor of ≤ 4)
- Virial assumption still OK from 2+ lines and similarity with known AGN with virial BLRs
- Can use C IV transition as standard line

Higher Redshifts cont.

Vestergaard, 2004

- Reverb mapping BH mass estimates agree with earlier estimates based on Eddington luminosity arguments (10^9-10^{10} $M_\odot$)
- ➠ Reverb mapping at high z is OK
- Max BH mass of 10^{10} $M_\odot$ at all redshifts (limits on dark matter potentials, accretion timescales...)
- Complications: gravitational lensing, non-virial motions, selection effects, beaming
- Even so, mass estimates likely accurate to factor of 3-4

BH Evolution

Vestergaard, 2004

- Extremely massive BHs already exist at z=6
- Host galaxies do not appear fully formed
- Evidence: high SFR, huge amounts of molecular gas, young stellar populations, host galaxy morphologies
- Supermassive BHs form first
- Given that host galaxies are not dynamically relaxed at high z, does M_{BH} -□$_*$ relation hold?

  Does it change vs. z?

Conclusions

- Reverberation mapping is an effective way of measuring BH masses for AGN without stellar dynamics
- Things get a little tricky for higher luminosity quasars (large □ extending scaling relationships...)
- Possibility of calibrating line width - BH mass relation or luminosity - size relation (for a given line) ➠ quasar BH masses are now feasible
- Can begin to trace typical BH mass vs. z
  ➠ cosmological BH evolution !
- Early massive BHs ➠ BHs appear to form before galaxies ➠ How ???