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)
Any change in continuum level takes time to reach BLR

Observationally, there is a time delay ($\tau$) between continuum changes and emission line changes gives $R_{BLR} = c\tau$

Width of line ($\sigma$) is a measure of velocity of gas at $R_{BLR}$

BH mass is thus $M_{BH} \approx f R_{BLR} \sigma^2 / G$

(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 $\tau$)

- 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 $\sigma$ consistent for each line

• Motion appears Keplerian based on multiple lines and their profiles → virialized assumption OK (most outflow models have at least $\sigma \propto$ constant)

• $L_{bol} < L_{Edd}$ → gravity dominates
Other Examples...
$z = 0.032$
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
- $M_{BH} - \sigma_*$ much better correlation \* reverberation mapping appears to work (note: $\sigma_*$ 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 $R_{\text{BLR}}$
  - $\tau \sim$ 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\(\alpha\) and H\(\beta\) time delays and line widths in 17 quasars
- Mean redshift \(z \sim 0.1-0.2\)
- In principle, Balmer lines all come from same BLR, so should give same \(R_{\text{BLR}}\) and \(\sigma\) (and indeed they do)
- FWHM from mean spectra vs. rms spectra
- Hence \(M_{\text{BH}}\) 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
- $R_{\text{BLR}}$ vs. $L$
- $\sigma$ vs. $L$
- $M_{\text{BH}}$ vs. $L$ (larger scatter...)
- Hence maybe $\sigma$ vs. $M_{\text{BH}}$ ? Or just use $R_{\text{BLR}}$ 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 $\leq 4$)
• 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 \((10^9-10^{10} \text{ M}_\odot)\)

- Reverb mapping at high z is OK

- Max BH mass of \(10^{10} \text{ M}_\odot\) 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 $M_{\text{BH}} - \sigma_*$ 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 $\tau$, 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???