Using Low Density Gas to Ferret Out Black Holes in SDSSJ092712.65+294344.0

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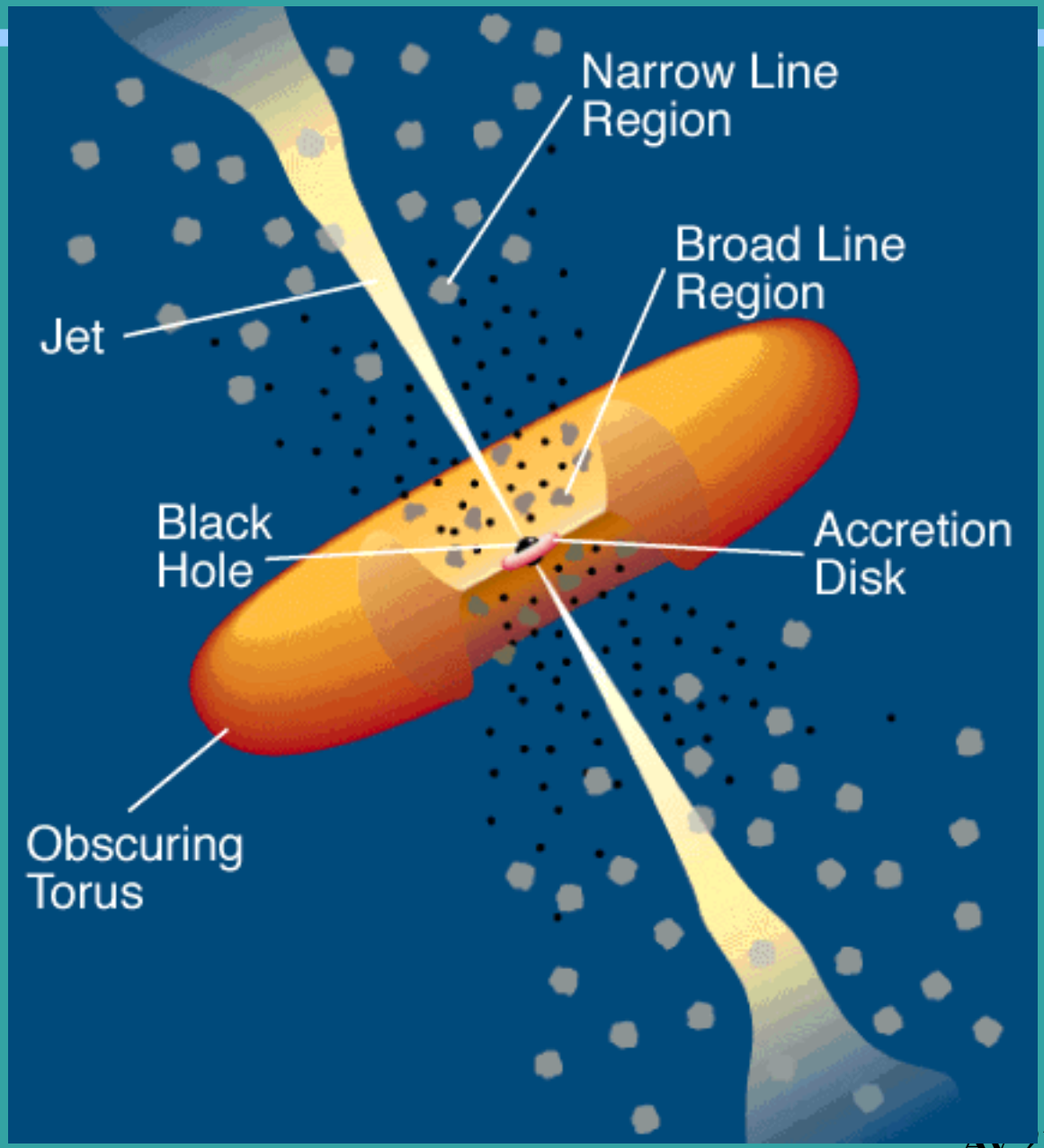
Intro to BH Thermodynamics

- Accretion disk radiates in x-rays
- Photoionization of gas around the BH/disk system: e.g. [O III], [O II], [Ne V], Balmer lines
  - "broad line region": broad emission lines from high-velocity material inside sphere of influence
  - "narrow line region": narrow emission lines from lower-velocity material further away
- Jets may exist, observed in radio
- IR observations show reprocessing of emission by dusty torus

Helpful Cartoon



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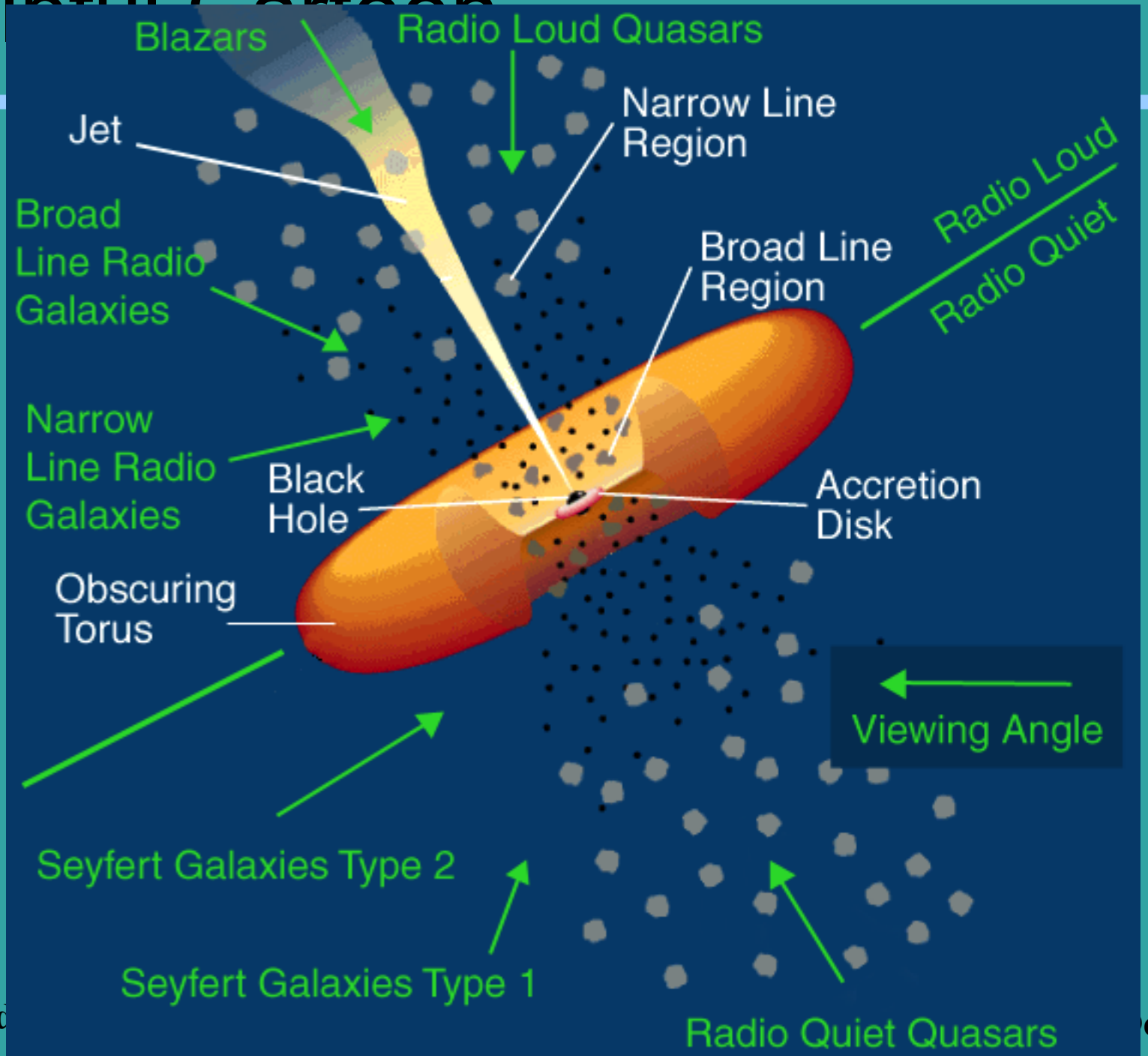


The System: J092712.65+294344.0

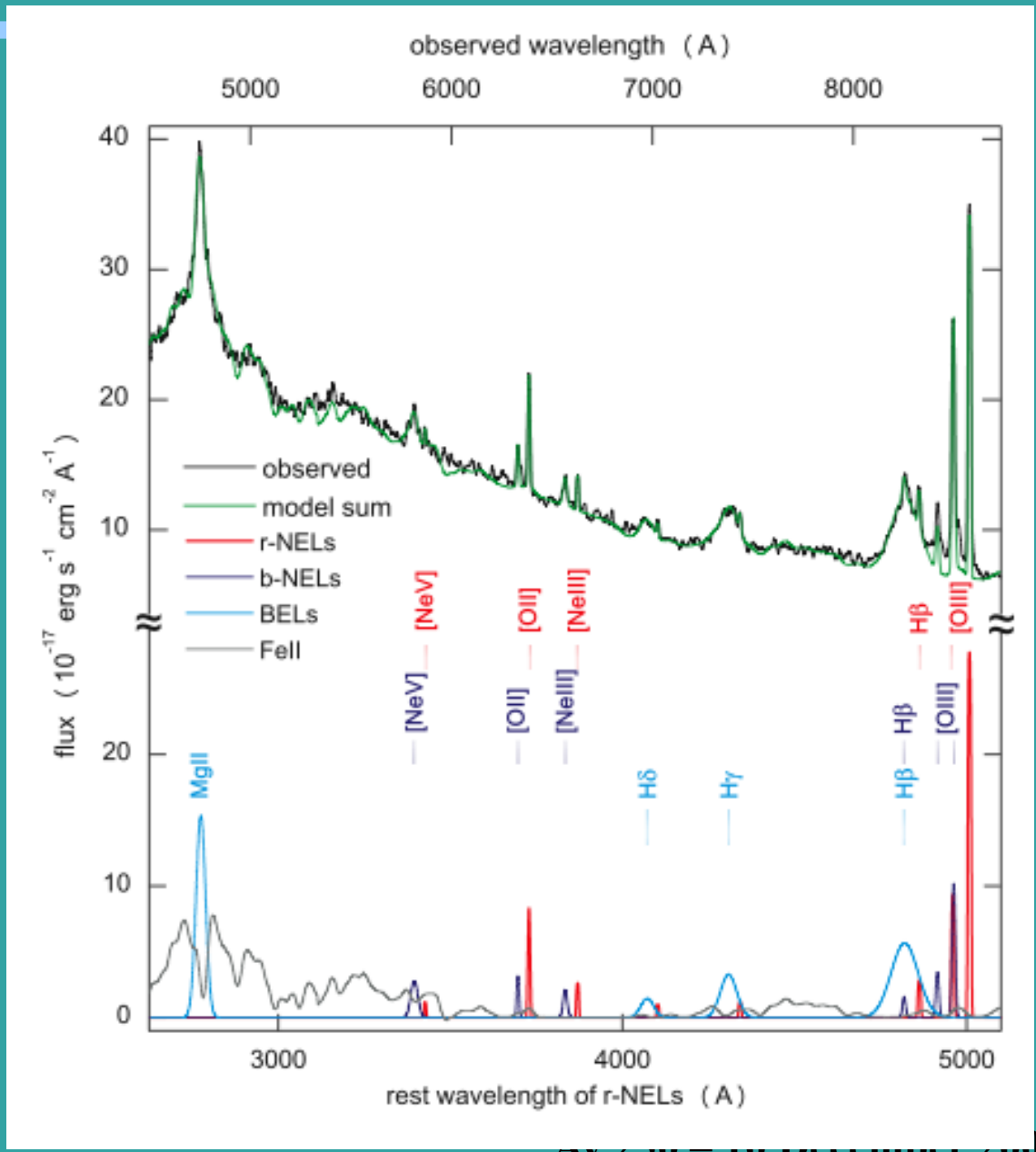
- luminous quasar in SDSS
- presented by Komossa et al. 2008 as peculiar
  - exhibits narrow-line emission at z=0.713 (identified as quasar host galaxy)
  - also has narrow- and broad-line emission blueshifted by 2650 km/s
- what's going on in this gas?

Using Line Ratios

- [Ne III]/[O II] ratios imply that the blue-shifted NLR is 1-2 orders of magnitude more dense than the 'rest frame' NLR
- [O III]/Hβ and [Ne III]/[Ne V] suggest higher ionization parameter in blue-shifted gas

The System: J092712.65+294344.0

- Red narrow emission lines
- bluer narrow and broad emission lines
- what gives?



The Recoiling Black Hole

Komossa, Zhou, & Lu 2008

Option 1: Recoiling Black Hole

- in a single, traditional BH, we expect to see one set of narrow lines and one set of broad lines, centered at redshift of galaxy
- if BH was rocketing away from center of the galaxy, could explain broad+narrow lines
  - requires taking gas near accretion disk and gas that's more dynamically relaxed with it
- second set of narrow lines is still in galactic nucleus --> still being photoionized

What would kick a BH out?

- when galaxies merge, eventually their two BHs are thought to also
  - not clear how this happens (ie we've never seen it)
  - 'last parsec problem'
    - in simulations, BHs eject all material before angular momentum is entirely gone
    - may be 'stuck forever' at the last parsec as a BH binary system
    - now thought to be resolved by adding gas

What would kick a BH out?

- during BH merging process, they emit gravitational radiation anisotropically
- depending on initial spins, could end up kicking the final merged BH in velocity by hundreds or thousands of km/s
- could explain offset in velocity

Option 1: Rehash

- in the past, two galaxies with SMBHs merged
- their BHs merged, got kicked out at high velocity
  - taking some gas with it
- BH is now moving towards us relative to galaxy
  - still accreting mass --> emitting radiation
  - photoionizes gas
    - both what comes with it AND gas that stays behind

Option 1: Issues

- quite the fortuitous observation
  - average recoil velocities much lower
  - BH would only shine for so long before using up all the fuel
- could BH really be photoionizing gas left behind?
  - would have to be 3-8 kpc based on flux/equiv widths
- would recoiling BH really take a narrow-line region with it?
  - supposed to be 'outside sphere of influence'

Binary Black Hole System

Bogdanović, Eracleous, & Sigurdsson 2008

Dotti, Montuori, Decarli, Volonteri, Colpi & Haardt 2008

Option 2: Binary Black Holes

- similar to before, two galaxies are merging/have merged
  - BHs have not yet merged, are still spinning
- more massive BH is at center, less massive orbits around it
- then surrounded by gap in the gas
- stream of low-density gas accretes onto secondary BH

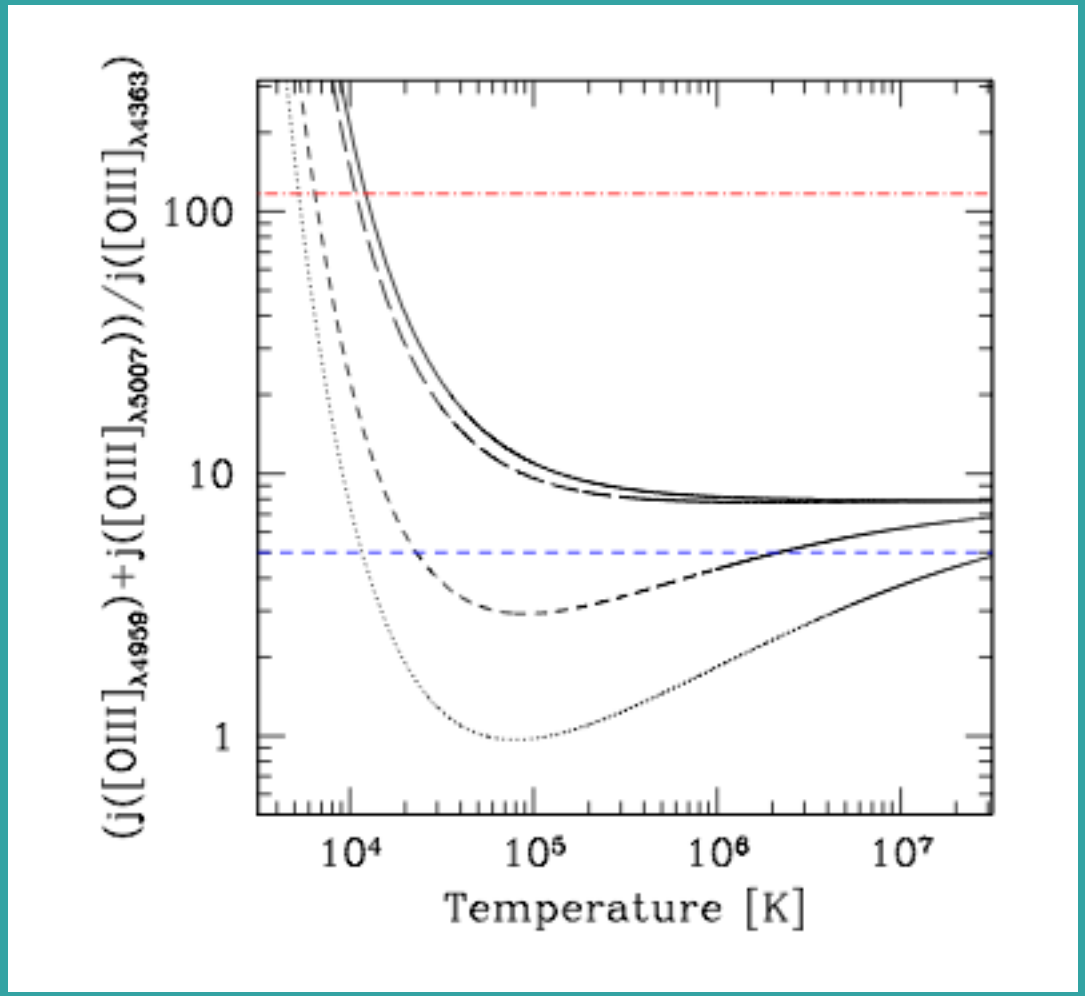
Option 2: Binary Black Holes

- accretion onto secondary BH creates the ionizing radiation
- ionizes gas around BH (broad line region) and tidal stream (narrow line region) at orbital velocity of secondary (hence the 2650 km/s offset)
- also ionizes gas in circumbinary disk, at orbital velocity of primary (narrow lines with no offset)

Option 2: Binary Black Holes

- Use luminosity of Balmer lines with assumption that gas in gap is ionized to get density
- $$L_{\mathrm{H}_\beta} = 4\pi D_L^2 F_{\mathrm{H}_\beta} = h\nu_{\mathrm{H}_\beta} n_p n_e \alpha_{\mathrm{H}_\beta} V_{\mathrm{gap}},$$
- higher than typical for NLR
  - supports claim that it's not a normal AGN

Option 2: Binary Black Holes



- For consistency, check temperature in this gas from [O III] lines
- red set of lines consistent with standard low density gas at 10^4 K

Option 2: Issues

- still a fortuitous observation
  - orbit of BH binary is constrained
  - we've never seen a BH binary before; not sure how long it would last before merging
- hard to imagine the broad line region wouldn't be disturbed by a SMBH nearby
- characteristics of red narrow system does not demand a binary BH system
  - could be ISM/halo gas lit up by recoiling BH

Option 2: Issues

- simulations show that circumbinary disk and stream should be denser or at least have highly-dense clumpy regions
  - [O III] 5007 should be partially suppressed (and [O III] 3727 moreso) by collisional deexcitation
  - they aren't

Two Galaxies Interacting

Heckman, Krolik, Moran, Schnittman, & Gezari 2008

Option 3: Interacting Galaxies

- in a rich cluster, not unreasonable to imagine large galaxy (with QSO) might interact with smaller galaxy (no QSO)
  - large galaxy with QSO excites gas around the nucleus --> excites narrow + broad lines
    - 'typical AGN activity' in host galaxy
  - QSO in large galaxy might irradiate cold HI clouds in ISM of smaller galaxy --> single narrow set of lines

Option 3: Interacting Galaxies

- flux ratio of [O II]3726,3729 is 1+/- 0.1
  - electron density of 300 /cm^3
  - this would be gas in cold HI clouds in ISM of normal galaxy
- Hβ luminosity and continuum flux implies gas mass is 10^7 Msun
  - plausible for irradiated clouds in hypothesized infalling galaxy

Option 3: Interacting Galaxies

- for photoionization of second galaxy, needs to be 3-8 kpc away
  - inferred from [O III]5007/Hβ and [O II]/[O III] ratios
- density of other galaxies in the field imply that it could be a rich cluster
  - and thus ~8 kpc is a reasonable distance for interaction

Option 3: Issues

- other galaxies in field don't have good redshifts
  - no clear evidence of a “rich cluster”
- is 2650 km/s a reasonable velocity for an infalling galaxy?

Superposition of Two AGN

Shields, Bonning, & Salviander 2008

Option 4: Superposition of Two AGN

- observations with HET reveal a third set of weak, narrow [O III] and [O II] emission lines at intermediate velocity
  - new system could be gas ejected from QSO or different host candidate, or due to star formation somewhere
- chance superposition of two AGN, third is a passing galaxy in cluster that happens to be photoionized by closer AGN

Option 4: Issues

- seems a bit contrived to me!
- primary reasoning is 'other ideas have more problems'
- also, still don't have redshifts to prove that our system sits in a rich cluster

Recap of Possibilities

- recoiling black hole bringing gas along with it, also photoionizing host galaxy
- binary black hole system with secondary BH accreting and photoionizing also accretion stream and circumbinary disk
- two galaxies interacting in a cluster, normal QSO photoionizes other galaxy
- chance superposition of AGN, third system is photoionized by one of them

How to decide?

- obviously, need more data!
- wait a few years, take more spectra
  - resolve change in velocity offsets if it's a binary BH system
- high-res images or integral-field spectroscopy
  - distinguish offset point sources
  - reveal morphologies / signs of merger or interactions

How to decide?

- deeper spectra searching for stellar absorption features
  - confirm presence of galaxy in one or more velocity spaces
- images or better redshifts
  - confirm presence of cluster
- NIR spectroscopy for other lines
  - ie density-sensitive [S II] might determine if redder narrow-line region is where BH was or ISM/halo gas of host