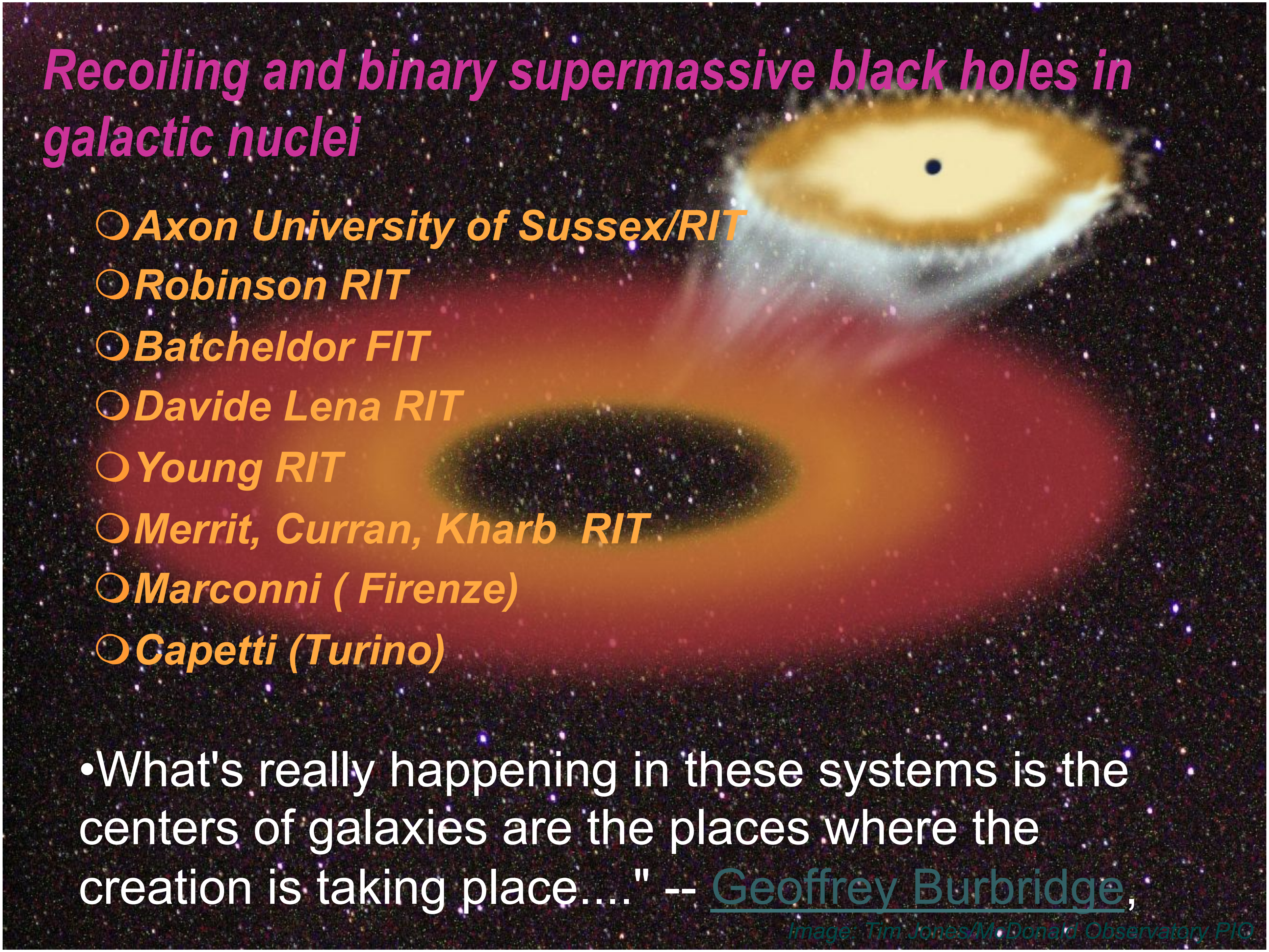
Recoiling and binary supermassive black holes in galactic nuclei
Axon University of Sussex/RIT
Robinson RIT
Batcheldor FIT
Davide Lena RIT
Young RIT
Merrit, Curran, Kharb RIT
Marconni (Firenze)
Capetti (Turino)
•What's really happening in these systems is the centers of galaxies are the places where the creation is taking place...." -- Geoffrey Burbridge,
Image: Tim Jones/McDonald Observatory PIO

Outline

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- Motivation- Gravitational Recoil of Massive Black Hole from binary BH merger
- Search for BH Recoils
  - Displaced AGN
    - *The Case of M87*
    - *Active Core Ellipticals*
  - Radial velocity Shifts of the BLR
  - Spectropolarimetry: a refined approach to finding gravitational recoiling MBH
    - *The Case of E1821+643*
    - *Recoil or Binary?*
- Summary

Many Galactic Nuclei should

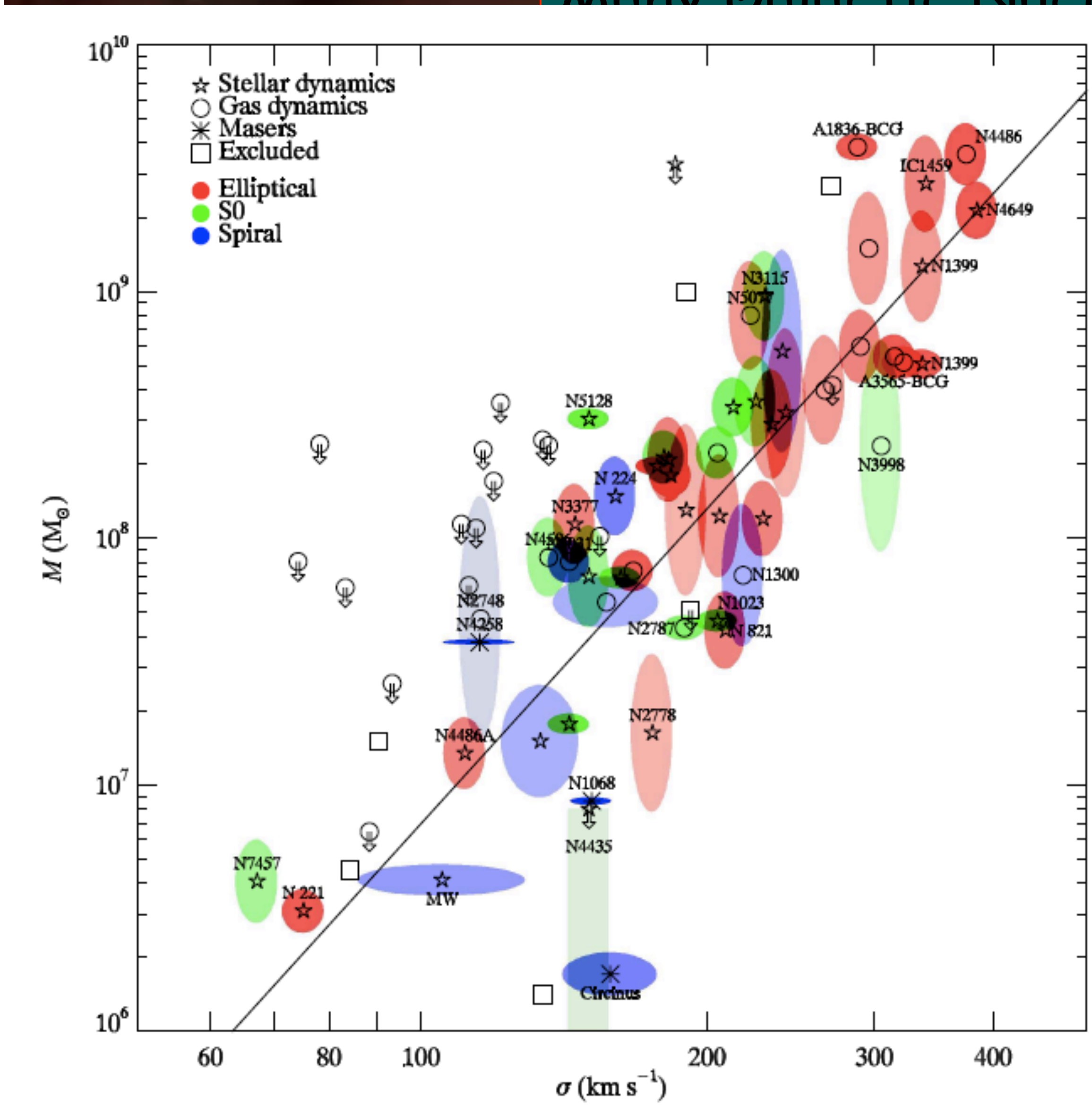

Image: NASA / CXC / A. Hobart

NGC6240: double AGN

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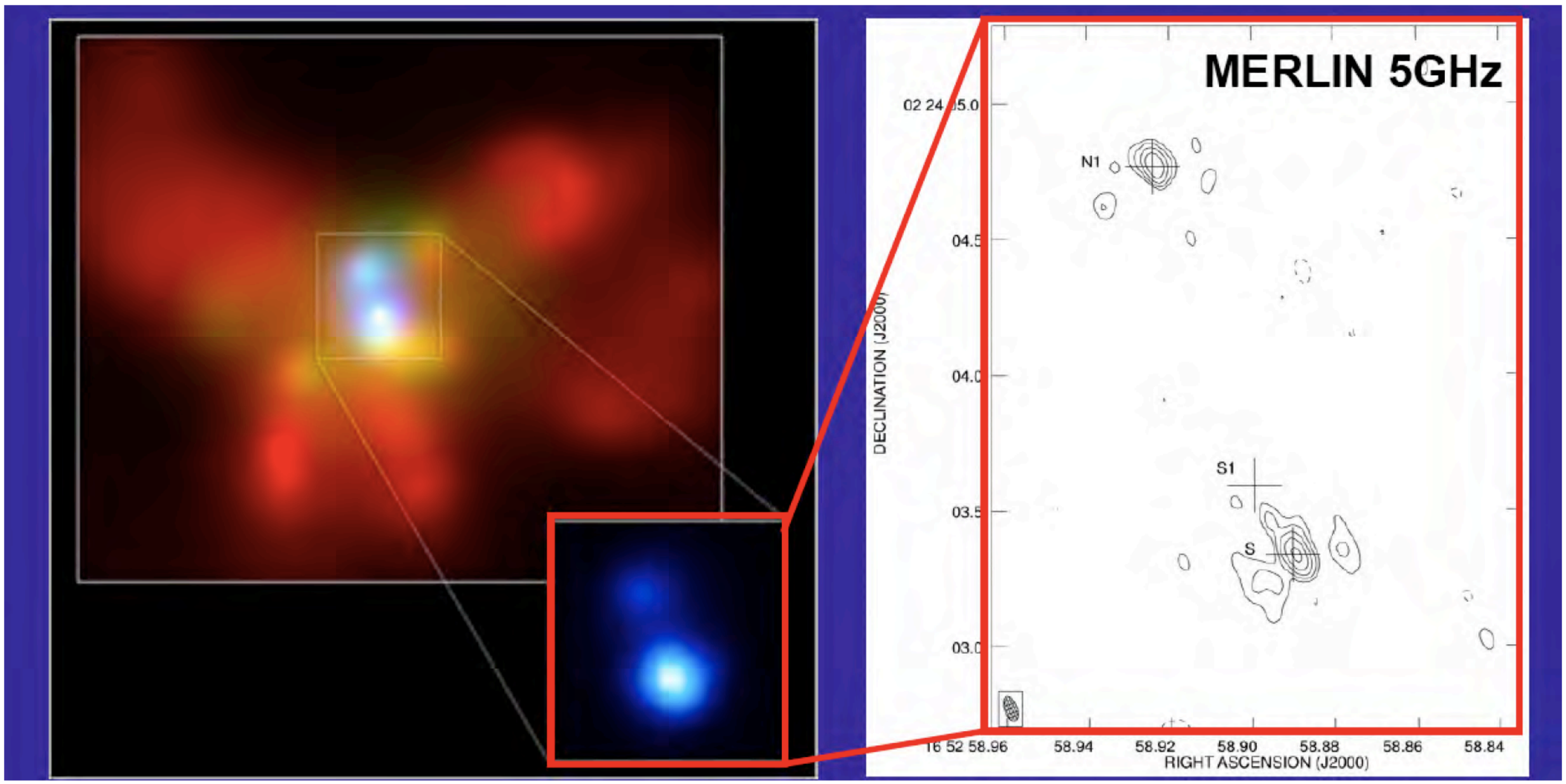
Recent merger, AGN separated by ~ 1 kpc – not (yet) a bound system

X-rays

Radio



(Komossa et al 2003)

Beswick et al 2001

Gallimore& Beswick2004

0402+379: twin radio cores

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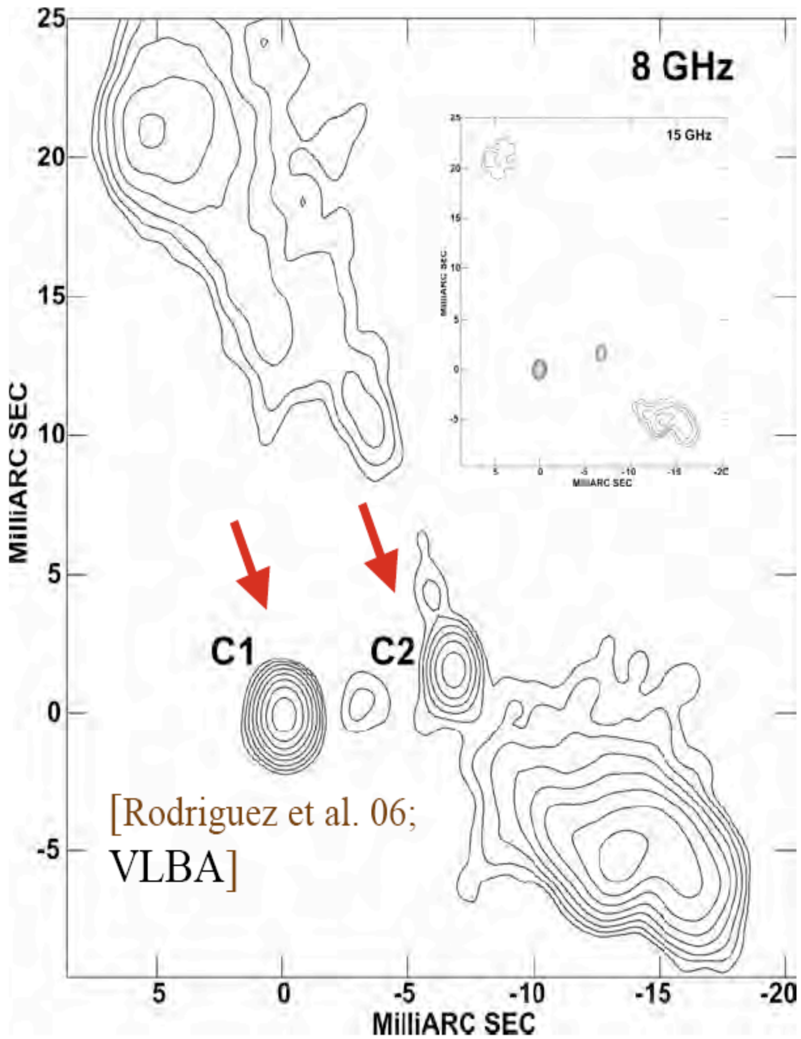

- nearby radio galaxy (4C37.11) at z=0.06
- two radio cores C1,C2
- Both compact, variable & flat spectrum, suggesting separate nuclei rather than knots in jet
- projected separation: 7.3 pc !

Best candidate for a bound SMBH system

Gravitational wave recoil

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- Final coalescence of binary BH driven by emission of gravitational waves
  - carry linear momentum from binary system
  - radiation field is typically asymmetric
- Center of mass must recoil in order to enforce global conservation of momentum
- Recent development: numerical relativity codes can follow coalescence of spinning BH recoil velocities can reach 4000 km/s

Caveat: Not clear how binary orbit decays from ~ 1pc to GW regime ("final parsec problem")

[e.g., Baker+ 06,07,08, Campanelli+ 06, 07a,b, Dain+08, Gonzales+ 06, 07a,b, Herrman+ 07a,b, Koppitz+ 07, Pretorius 05, 07,, Schnittman+ 07, 08,Healy+08 ...]

Recoil (“kick”) velocities

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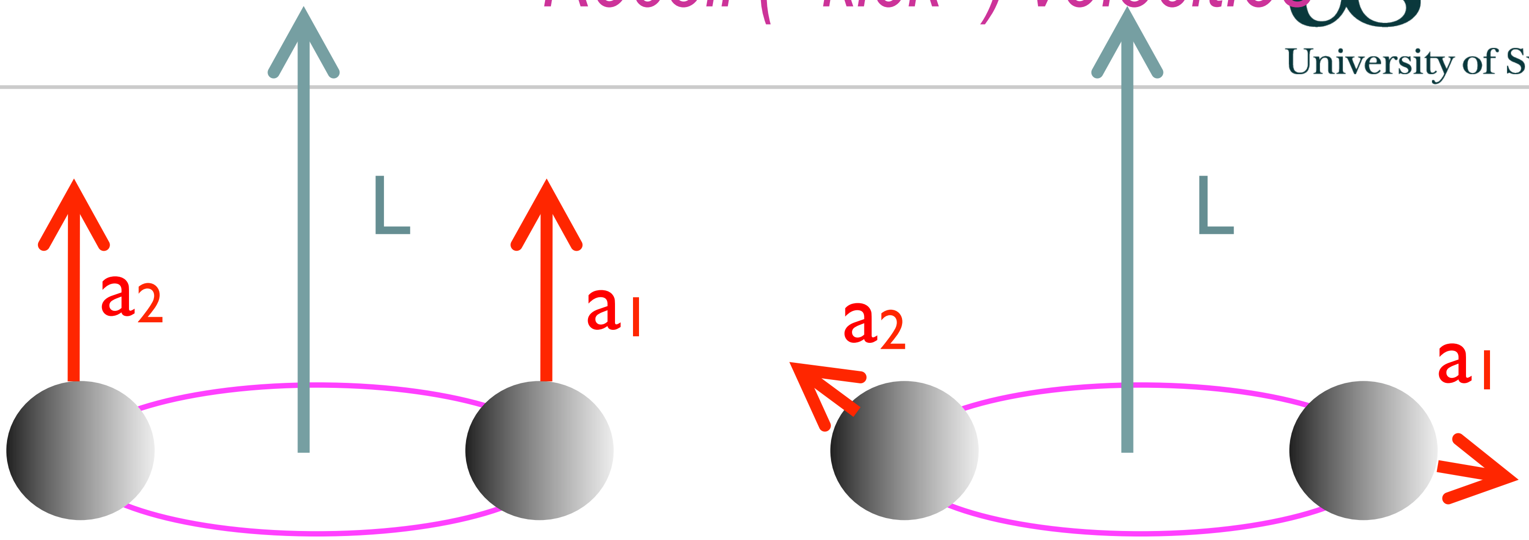
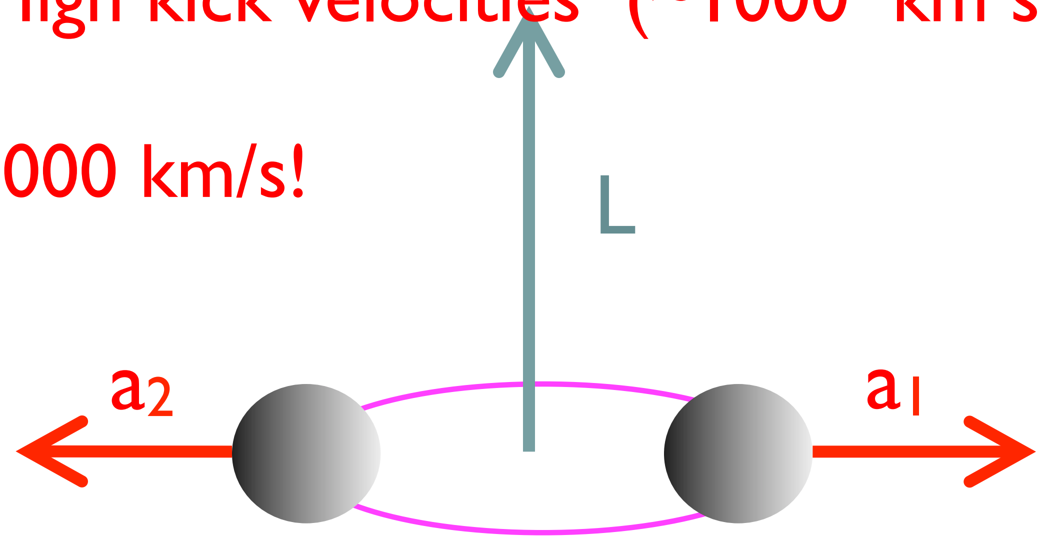


Low kick velocities (~100 km s^{-1})

High kick velocities (~1000 km s^{-1})

up to 4000 km/s!



Galaxy Escape Velocities

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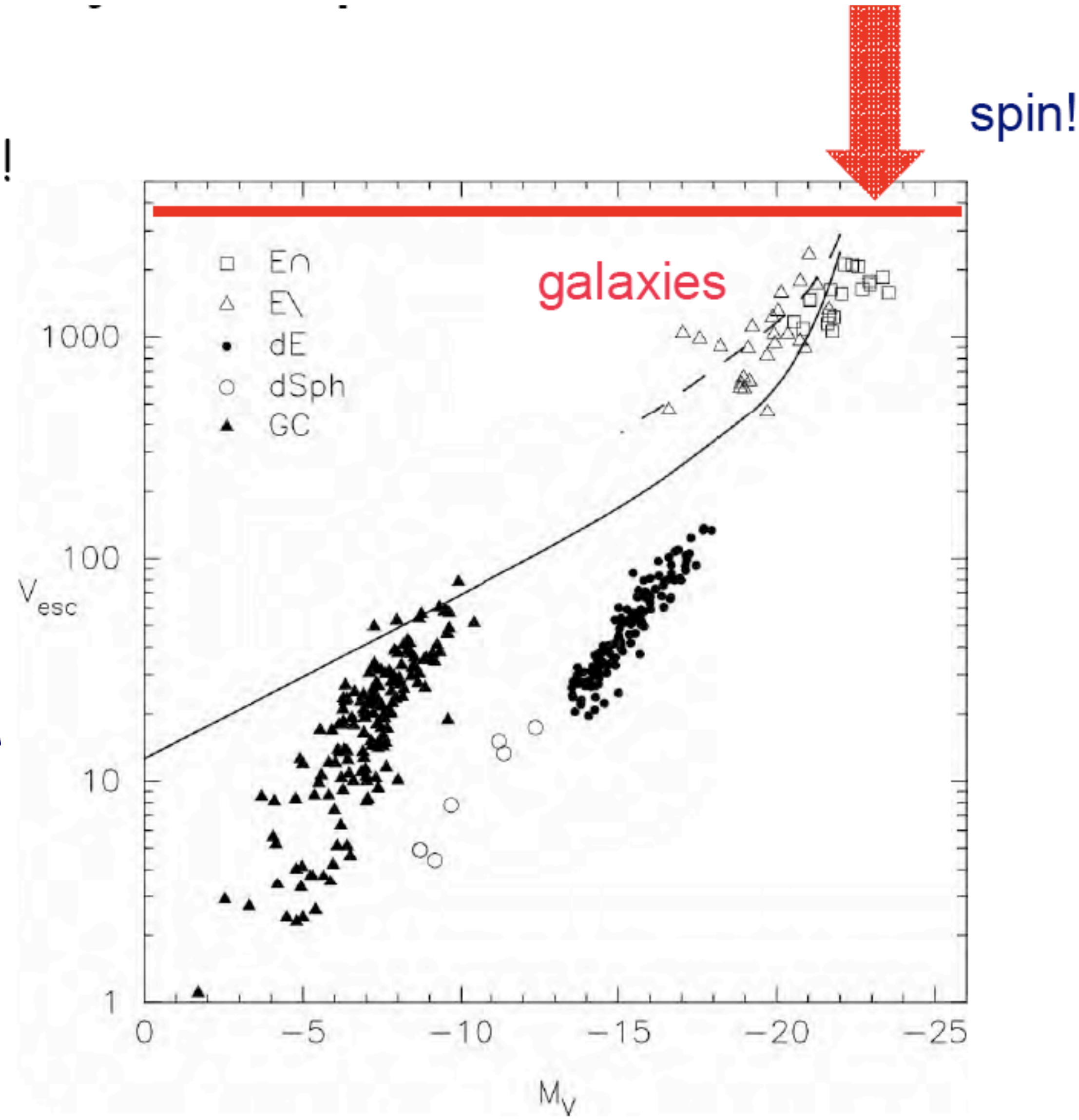
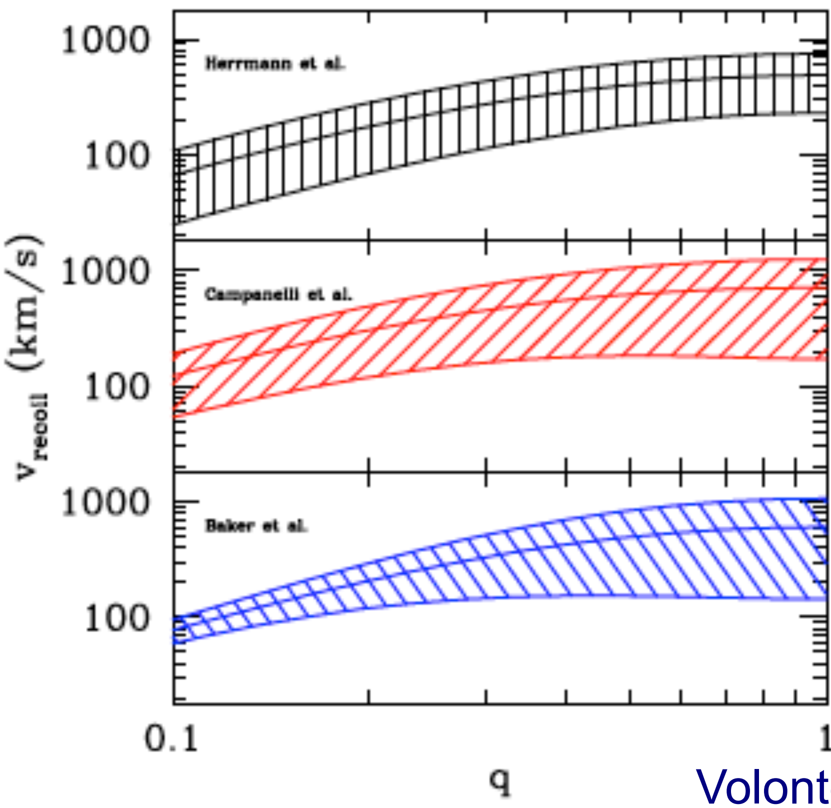
$V_{recoil}^{max} \sim 4000$ km/s !



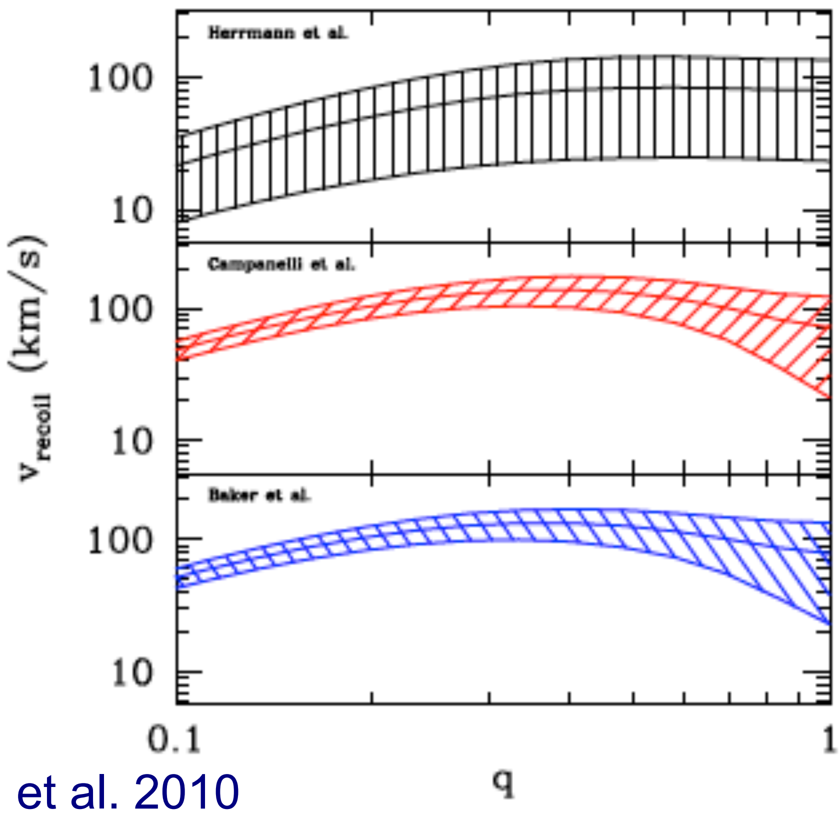
Kicks of ~4000 km/s are large enough to eject SMBHs even from the brightest galaxies!

Recoil velocities from NR simulations

Isotropic spins



Aligned spins



Volonteri et al. 2010

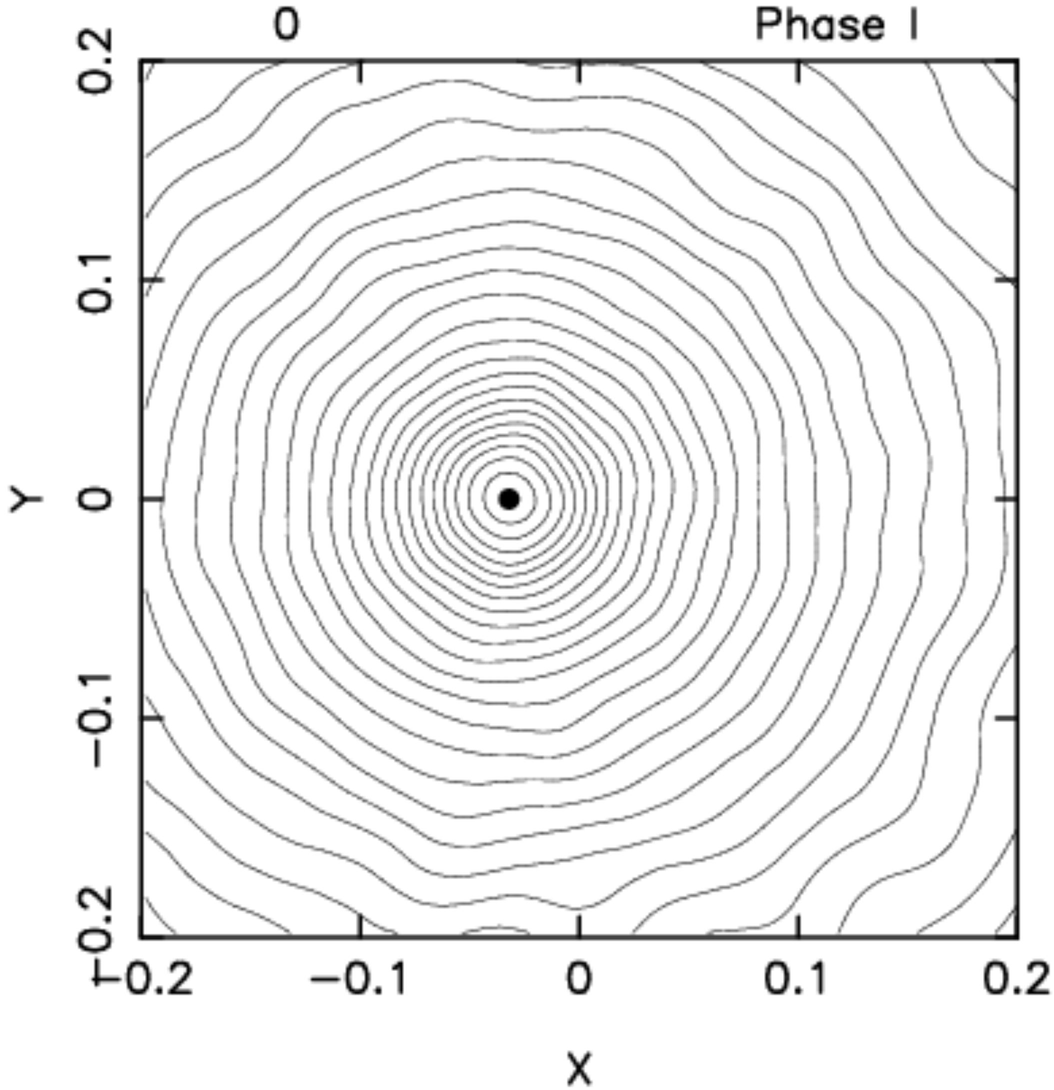
- Spins can be aligned by circum-nuclear gas disks
  - Bogdanovich et al. 2007
  - Dotti et al. 2009

- Recoil velocities reduced by factor 10 when spins aligned with orbital angular momentum

Oscillating BH at low V_{recoil}

Gualandris & Merritt 2007

Sculptures
In part of
bulge



Observational consequences of recoil

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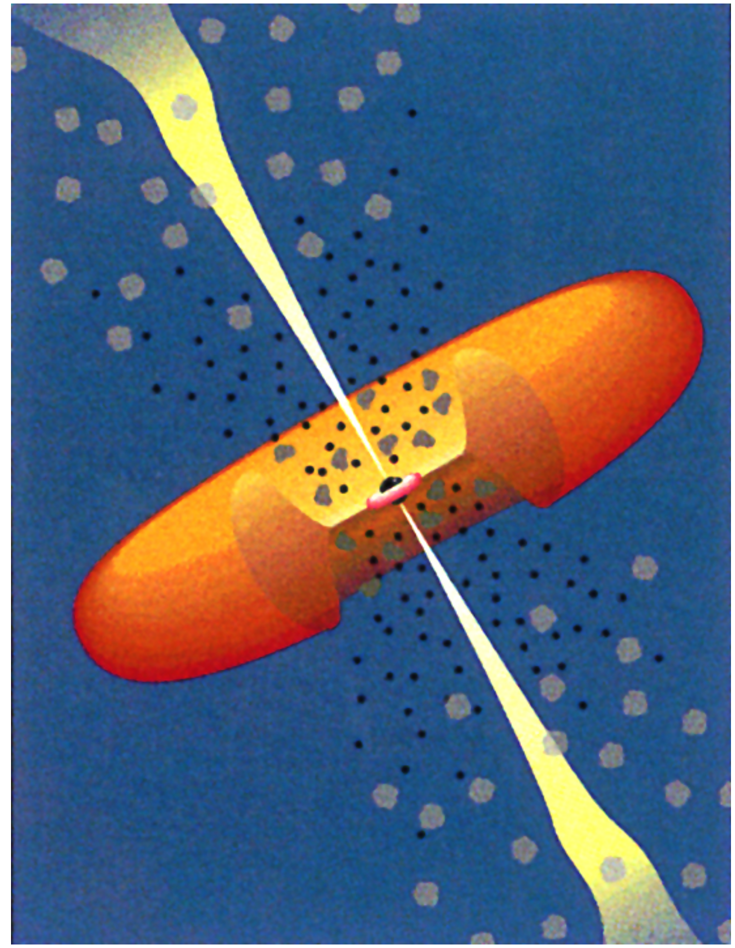
- Gas whose $V_{Keplerian} > V_{recoil}$ remains bound to SMBH
- Recoiling BH retains gas within radius

$$r_G = (0.43\ \text{pc})\left(v_{recoil}/10^3\ \text{km s}^{-1}\right)^{-2}\left(M_\bullet/10^8 M_\odot\right)$$

- $V_{recoil} \geq 1000$ km s^{-1}, bulk of accretion disk, BLR retained
- NLR, torus left behind

- "Displaced" (naked) quasar?
- Spectroscopically, broad-lines shifted relative to narrow-lines



[e.g. Madau & Quataert 04, Magain+06, Merritt+ 04, 06, Milosavljevic & Phinney 05, Bonning+ 07, Loeb 07, Gualandris & Merritt 08, Blecha & Loeb 08, Kornreich & Lovelace 08, Devecchi+ 08, Lippai+ 08, Shields & Bonning 08, Schnittman & Krolik 08]

Observational challenges

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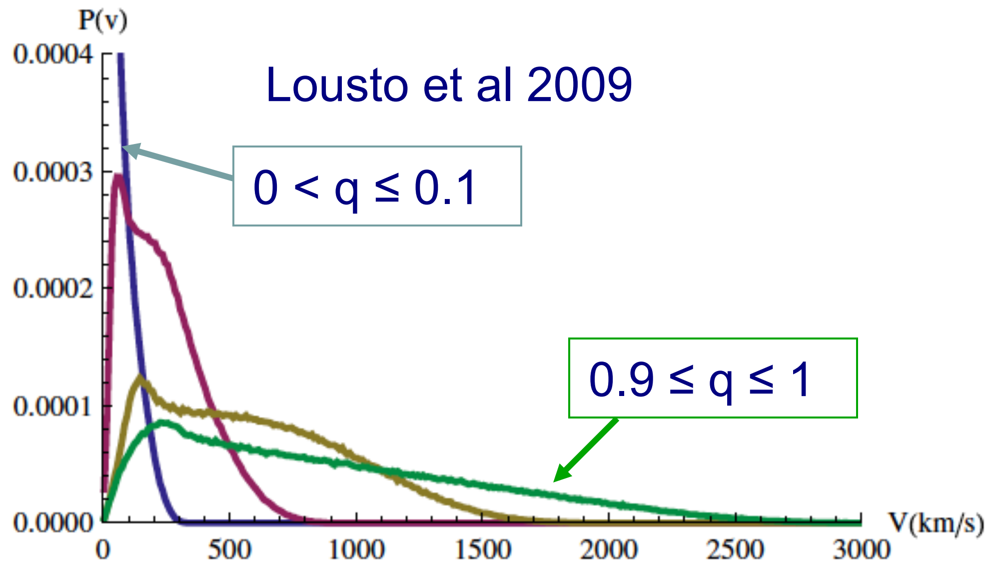
- Large kicks ($V_{recoil} \geq V_{escape}$)
  - Rare (special configuration, even without gas)
  - Large amplitude oscillations decay relatively quickly
- Small kicks $V_{recoil} \ll V_{escape}$)
  - Should occur frequently
  - Small displacements
  - Small velocity shifts
- Recoiling SMBH can only be detected by accretion activity
  - Requires gas, which may inhibit large kicks

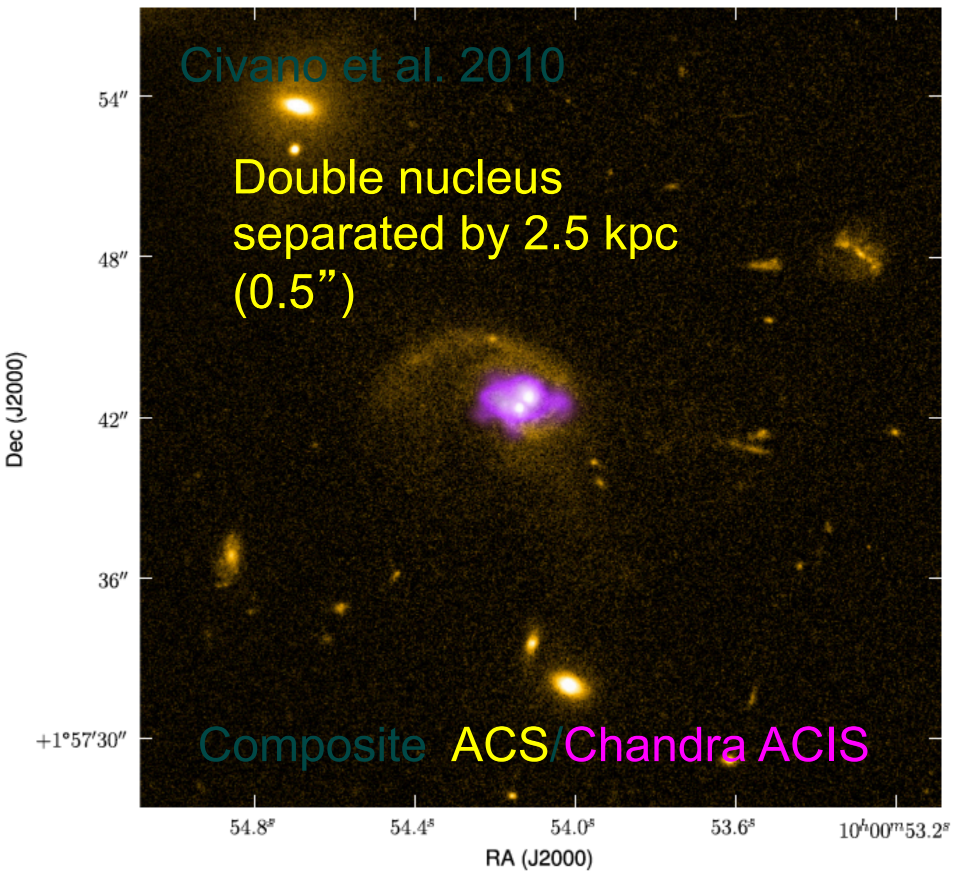


Distribution of recoil velocities for different values of BH mass ratio (isotropic spin distributions)

Hunting Displaced SMBH

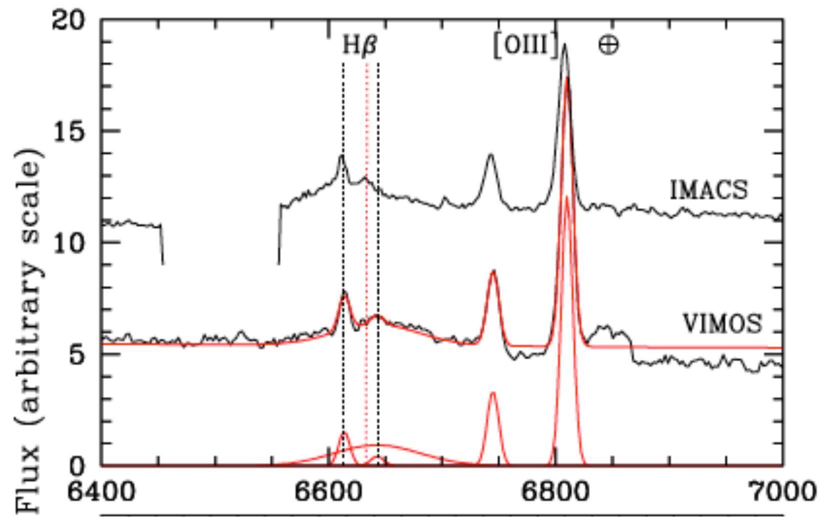
Direct Imaging

CXOC J100043.1+020637



X-ray spectrum -> Redshifted Fe K absorption line, variable energy

Broad - narrow line shift Δv≈1000 km/s



- Gravitational recoil?
  - BL gas bound to recoiling BH
- Slingshot ejection
  - Binary MBH + ejected tertiary

QSO HE0450–2958 Ejected Black Hole?

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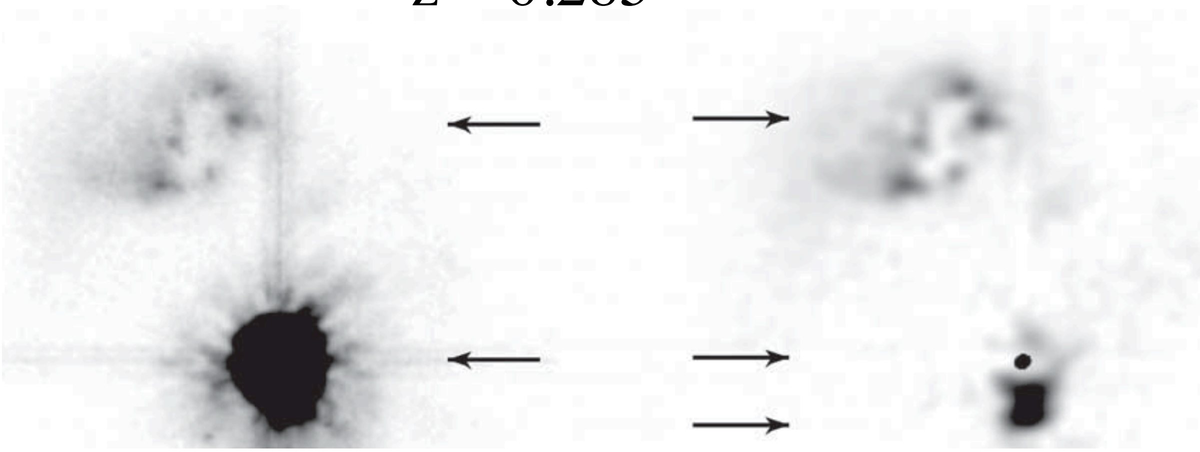
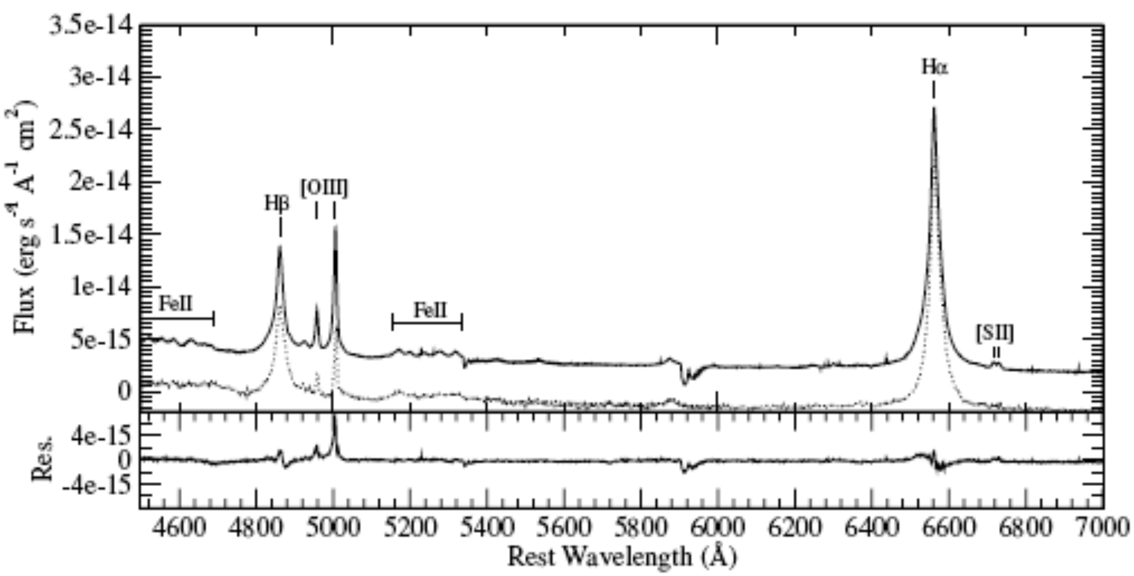
z = 0.285



Magain et al 2005



Merritt et al 2006

Probably not!

An HST archive search

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- Several mechanisms can displace SMBH from center of mass
  - Gravitational recoil
  - Asymmetric radio jets
  - Orbital motion of binary SMBH
  - Massive perturbers
- Look for offsets between AGN and galaxy photocenter in active early-type galaxies
  - AGN locates SMBH
  - Isophote fitting photocenter
- Initial results for M87, sample of low-z radio galaxies
- Defining the “center” is the big challenge

Do SMBH really live at the centers of their hosts ?

Galaxy (photo)centers & AGN positions

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- Measure galaxy centers of mass (light):
  - cannot compute photocenters by pixel weighting (noise, foreground stars, blemishes, bad pixels, cuts in field of view, etc.)
  - cannot do 2D fitting with, e.g, GALFIT or similar software (one 2D component usually not enough, isophote twisting, etc.)
  - can do ellipse fitting of isophotes and find ellipse centers for different surface brightness levels;

    iterative process to mask out bright stars, dust lanes, peculiar features (e.g. jets), residual bad pixels
  - minimum radius r_{min}:

    $r_{min} > r_b$ break radius
    (strong isophote twisting for $r=r_b$, Lauer et al. 2004)

    $r_{min} >$ 3 FWHM from the AGN
    (avoid contamination by AGN PSF)

    $r_{min} > r_g$ gravitational sphere of influence of BH

$$r_g = \frac{GM_\bullet}{\sigma_\star^2}$$

  - maximum radius set by field of view: only consider entire ellipses (centers from partial ellipses are usually shifted (Jedrzejewski 1987)

Galaxy (photo)centers & AGN positions

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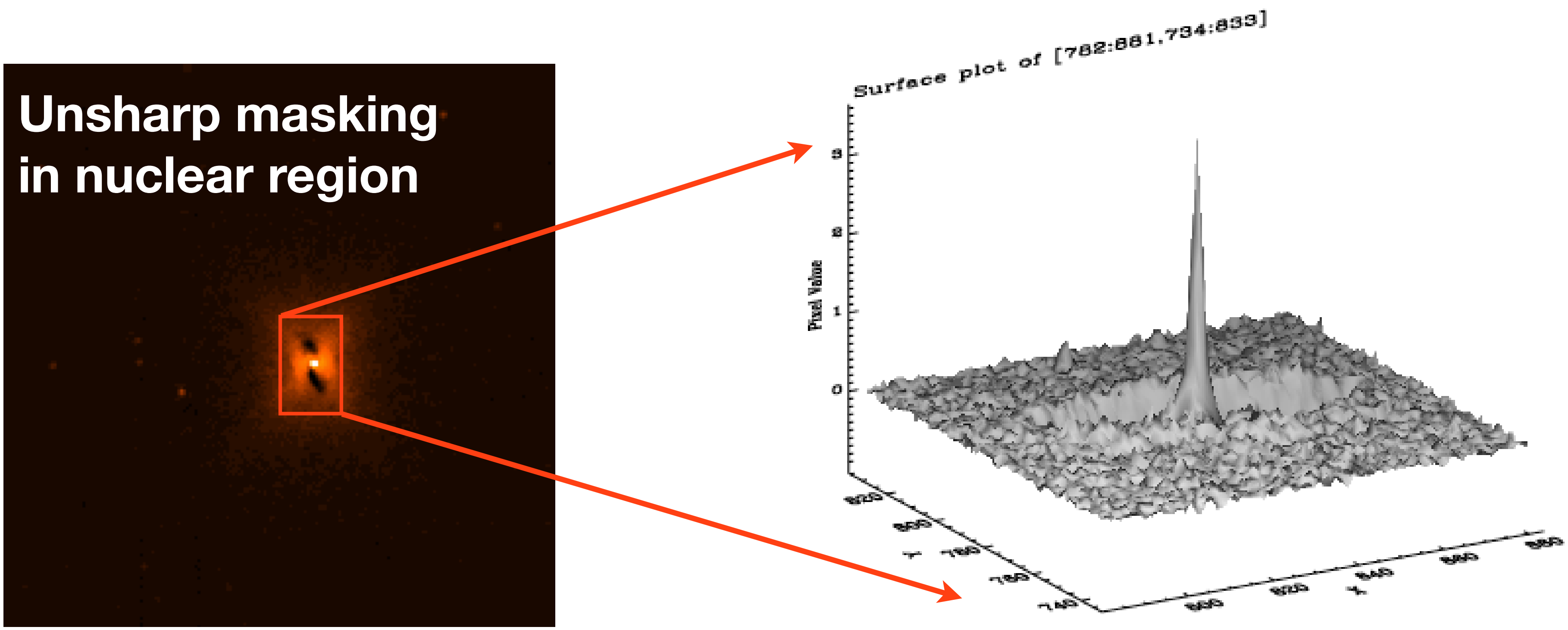
- Simulations: can locate ellipse center down to 0.05 pix (e.g., ~0.003 arcsec for ACS), photocenter (weighted average) down to 0.1 pix

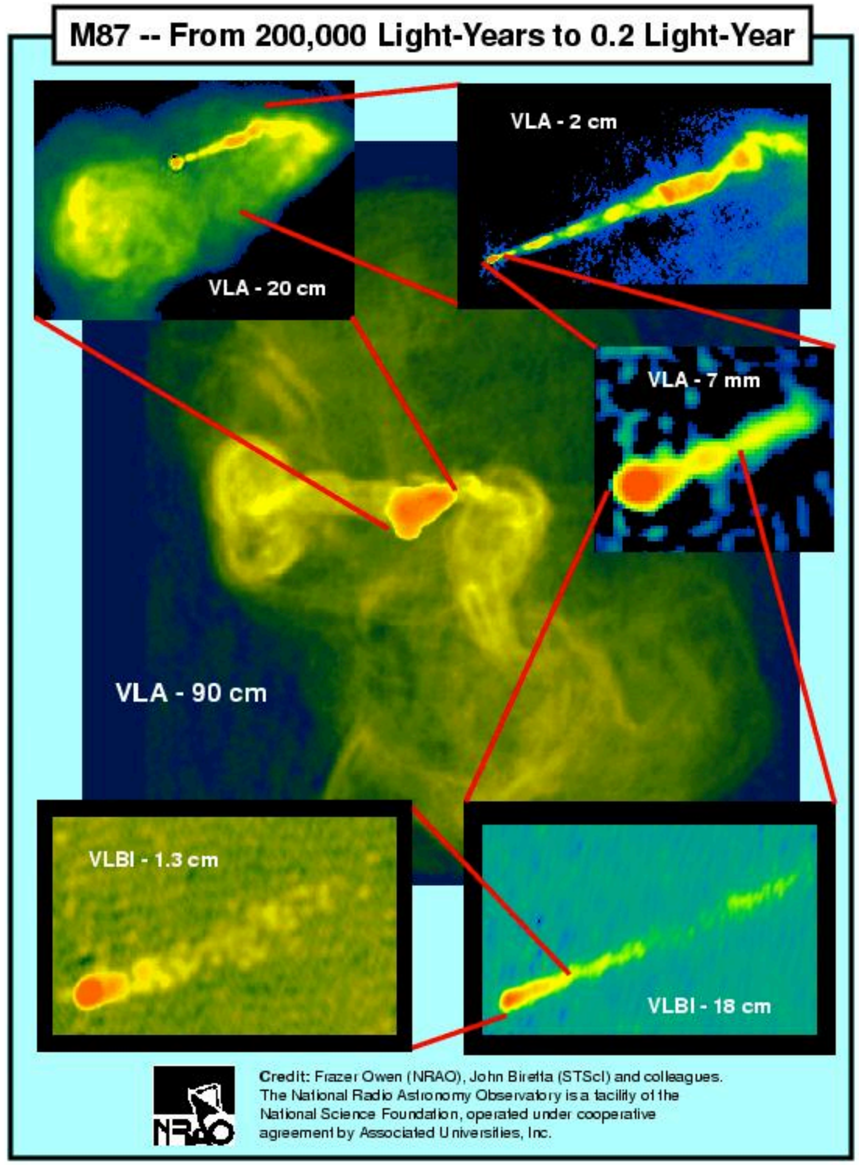
AGN position: simple centering after unsharp masking in nuclear region accuracy 0.1 pix

Minimum significant offset 0.4±0.1 pix (3σ level)



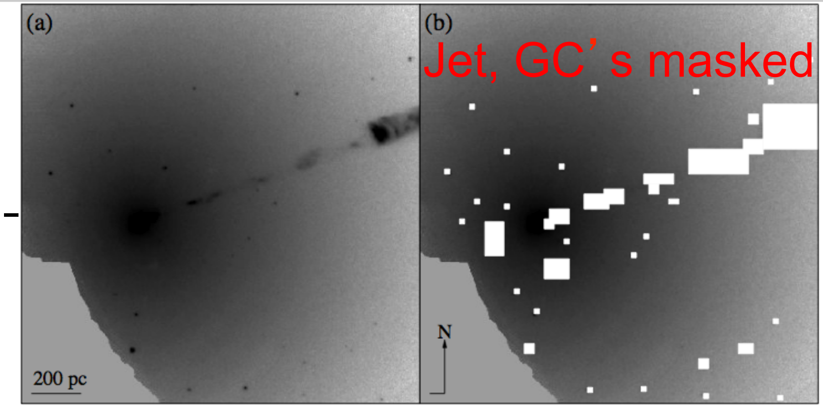
M 87

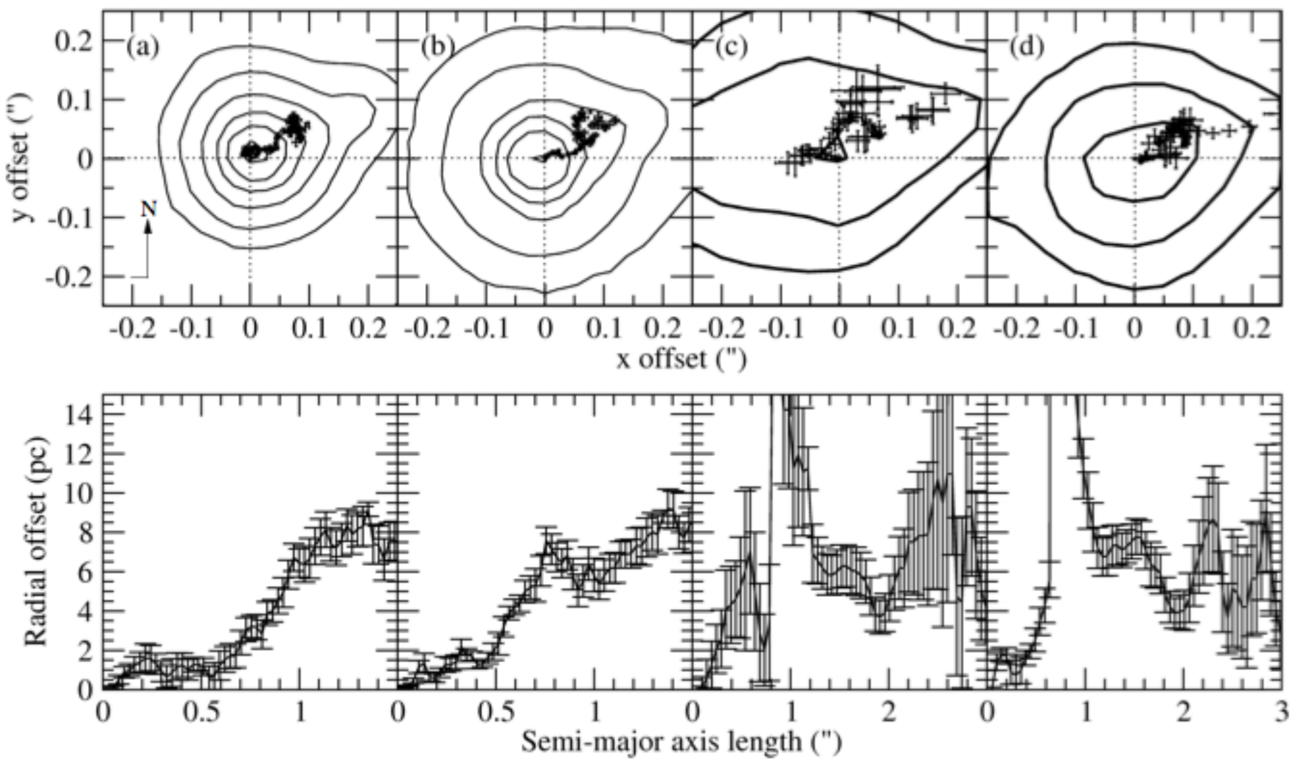
- $M_{BH} = 3\text{–}6 \times 10^9\ M_\odot$
- Distance 17.9 Mpc



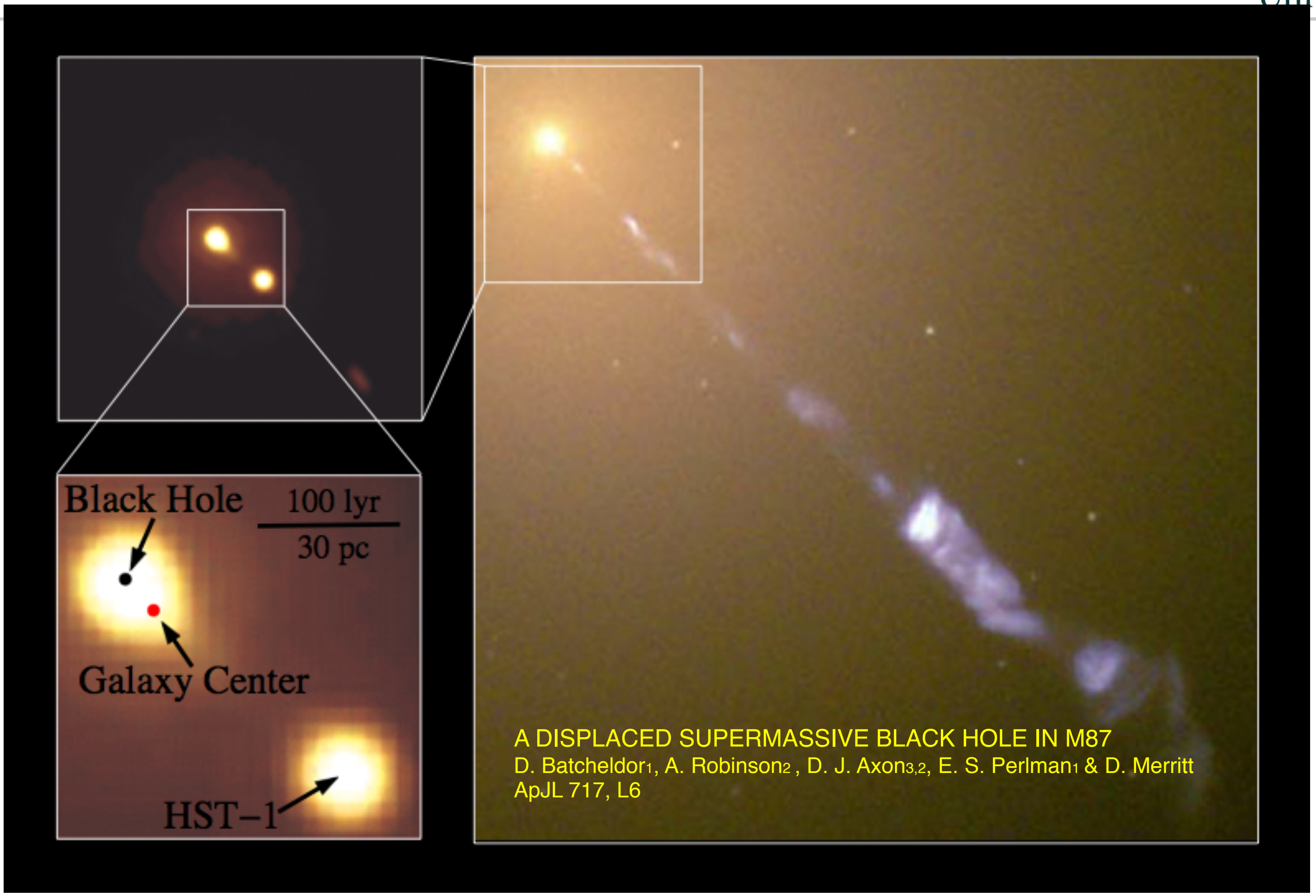
The displaced black hole in M87

- Ellipses of progressively increasing semi-major axis fitted to isophotes
- Determine x,y co-ordinates of photo-centre as a function of SMA
- **Photocenter is mean position of ellipse centers**
- Simulations ➔ artificial offsets recovered to ≈0.2 pixels
  - With or without mask





The displaced black hole in M87



- BH is displaced from galaxy photocenter by 6.8±0.8 pc (≈0.1”) in counter-jet direction
- Physical displacement 10–26 pc (depending on jet inclination)

Asymmetric Jets?

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- If radio jet is intrinsically one-sided (or asymmetric) BH will be accelerated in opposite direction
- Naturally explains alignment

- Jet acceleration

$$a_{jet} \propto f_{jet} \dot{m}$$

jet asymmetry as fraction of accretion luminosity

accretion rate (units of Eddington rate) ≈ 10^{-4} in M87 (di Matteo et al, 2003)

- No restoring force (sparsely populated core)
  - f_{jet} >> 1 for young jet (inner lobes ~ 1 Myr)
  - f_{jet} ≈ 0.03 for old jet (outer lobes 0.1 Gyr)

- With restoring force due to (fixed) galaxy potential
  - SMBH comes to rest where gravitational force balances jet acceleration
  - Require m ≈ 0.02 even for f_{jet} =1

Shklovski (1982), Wang et al. (1992), Tsygan (2007), Kornreich & Lovelace (2008)

Gravitational recoil?

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- Recent kick $V_{recoil} \approx 500$ km/s
  - Early, large amplitude (~1 kpc) oscillations within core
  - Expect shock signatures in retained gas disk

- Decayed large kick

Damping time for SMBH-core oscillations (Gualandris & Merritt)

$$T_{\rm damp} \approx 15 \frac{\sigma^3}{G^2 \rho M_\bullet} \approx 2 \times 10^9 {\rm yr}\ \sigma_{300}^{-3.86} r_{500}^2$$

→ recoil consistent with observed displacement could have been generated by a major merger at any time during formation of galaxy

Criteria for ideal targets

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High probability of a past merger, with subsequent formation of BH binary → Luminous ellipticals with flat cores perhaps due to scouring by binary BH

Unambiguously identify BH position → AGN with low L (well defined nuclear PSF but so strong as to compromise galaxy photometry)

Ability to resolve linear displacements ≤ 100 pc → Low z galaxies with HST images

Nearby Radio Galaxies (D < 100 Mpc) from the well studied sample of Balmaverde & Capetti (2006)

The sample

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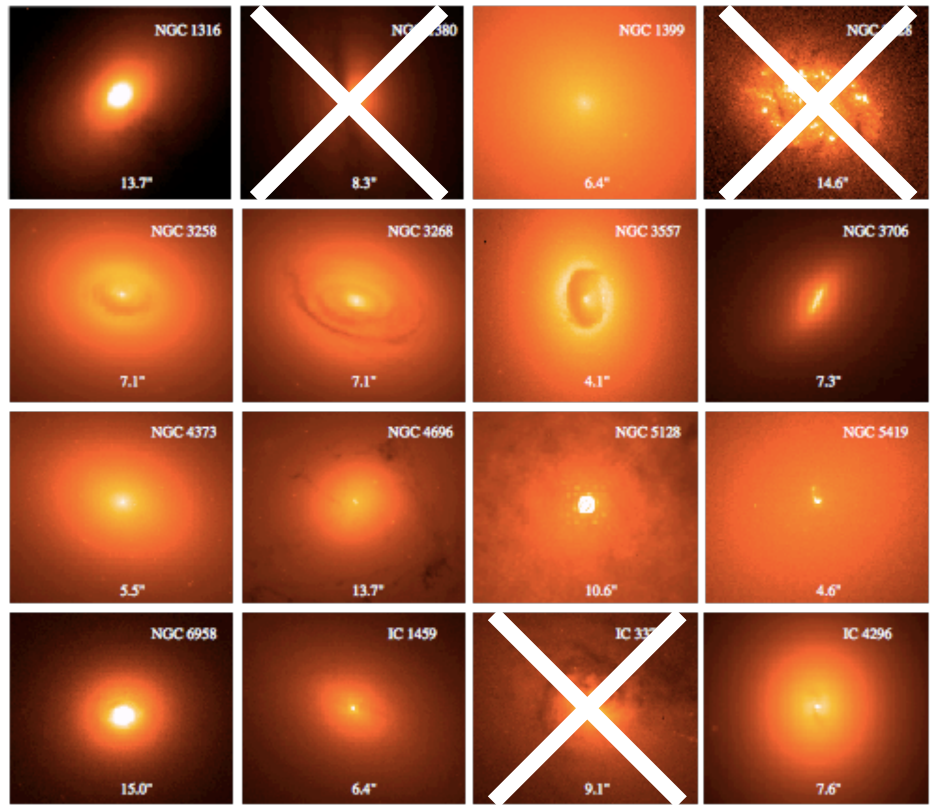
- Properties of the Balmaverde & Capetti sample:
  - Radio flux limited sample ~330 sources with F(5 GHz) > 1 mJy (L(5GHz)> 10^{36} erg s-1)
- ≈150 galaxies after discarding
  - objects without obvious nuclear point source
  - objects with heavy obscuration or irregular morphologies



- 14 analysed so far, 3 displaced BH candidates identified
  - Offsets 3 – 20 pc

Davide Lena PhD project

Example: Abell 3565

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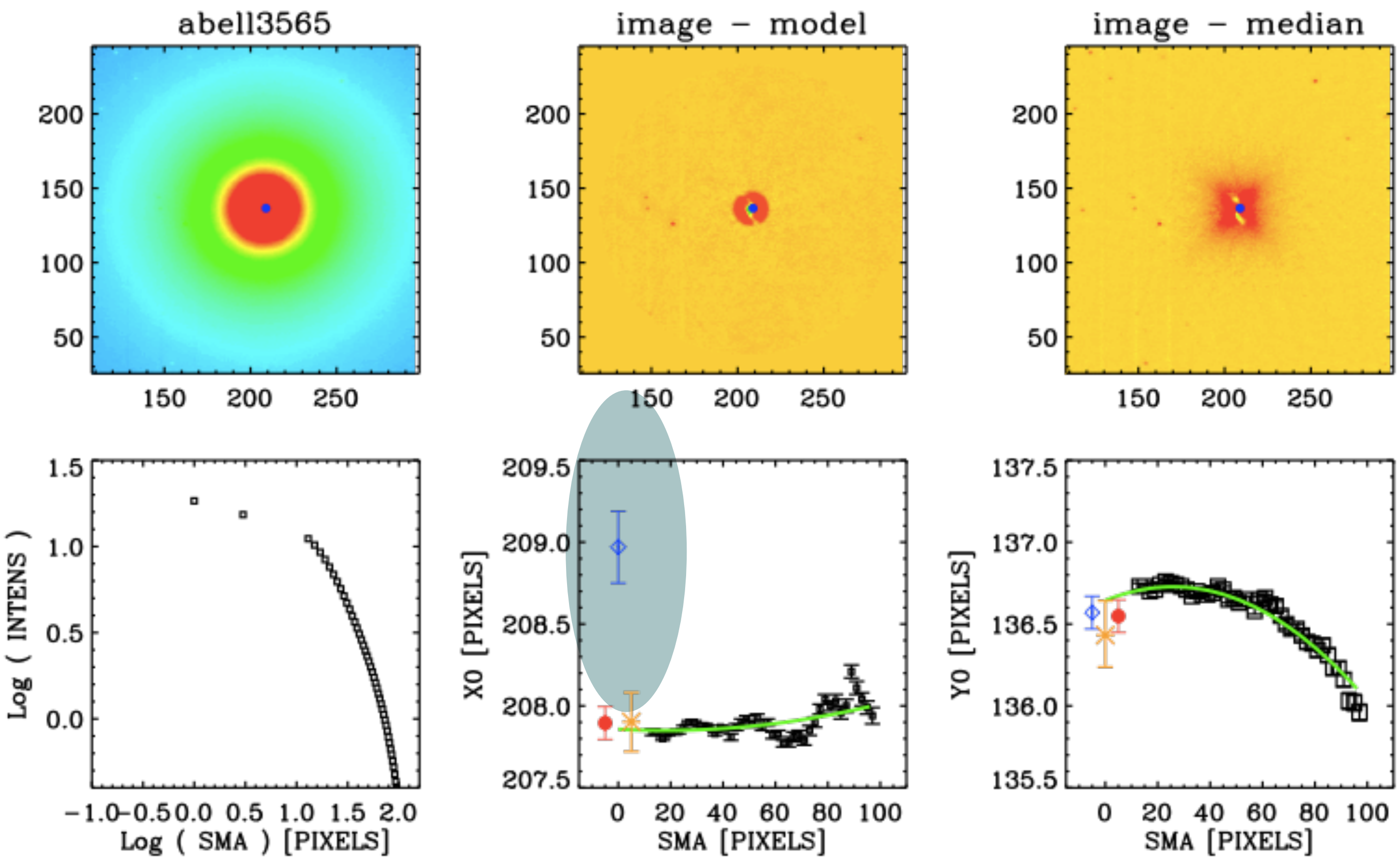


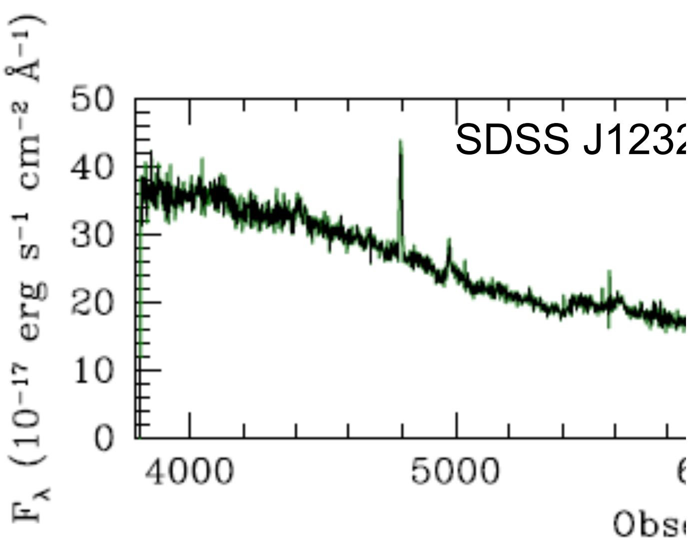
Offset: 19±5 pc (S-SE)
NICMOS 2

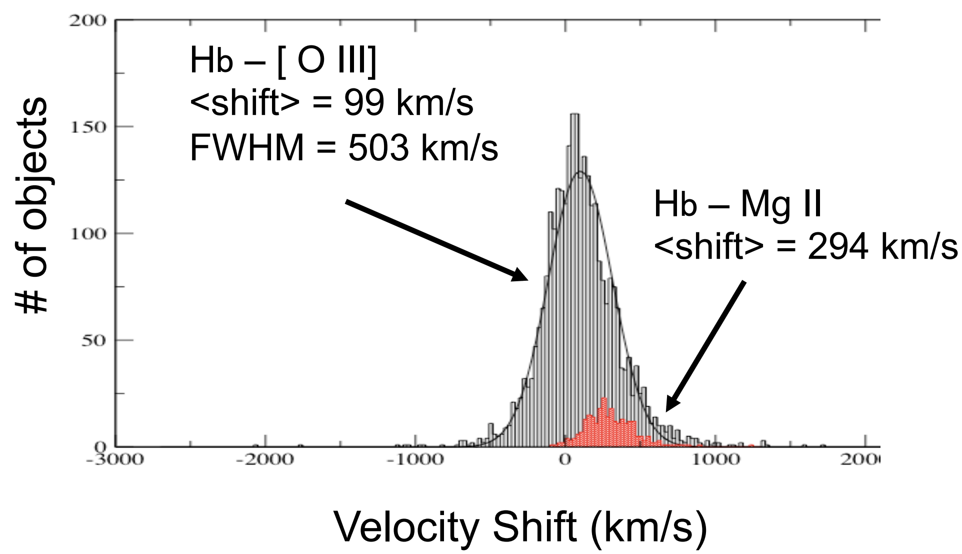
Hunting Kicked SMBH

Broad Line Region Radial Velocity Shifts

Hunting for kicks in the SDSS

- Bonning et al (2007): searched 2600 QSOs from SDSS Data Release 5 (DR5) in the redshift range 0.1 < z < 0.81 for shifts > 500 km/s between Hβ and [O III] peak
- <4% have Δv > 500 km/s; <0.04% have Δv > 1000 km/s
- Exclude objects with strongly asymmetric lines
- Conclude "shifts" most likely due to BLR physics





What you might actually expect (to 0th order)

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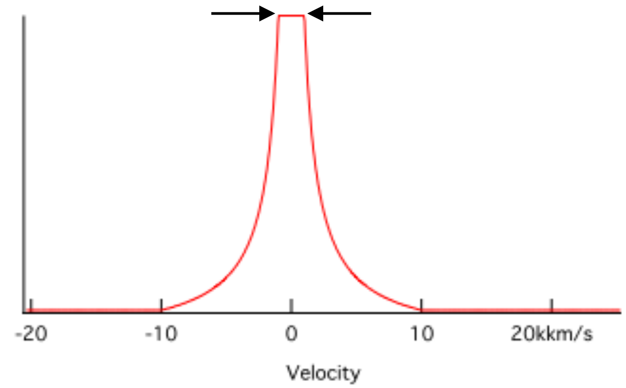
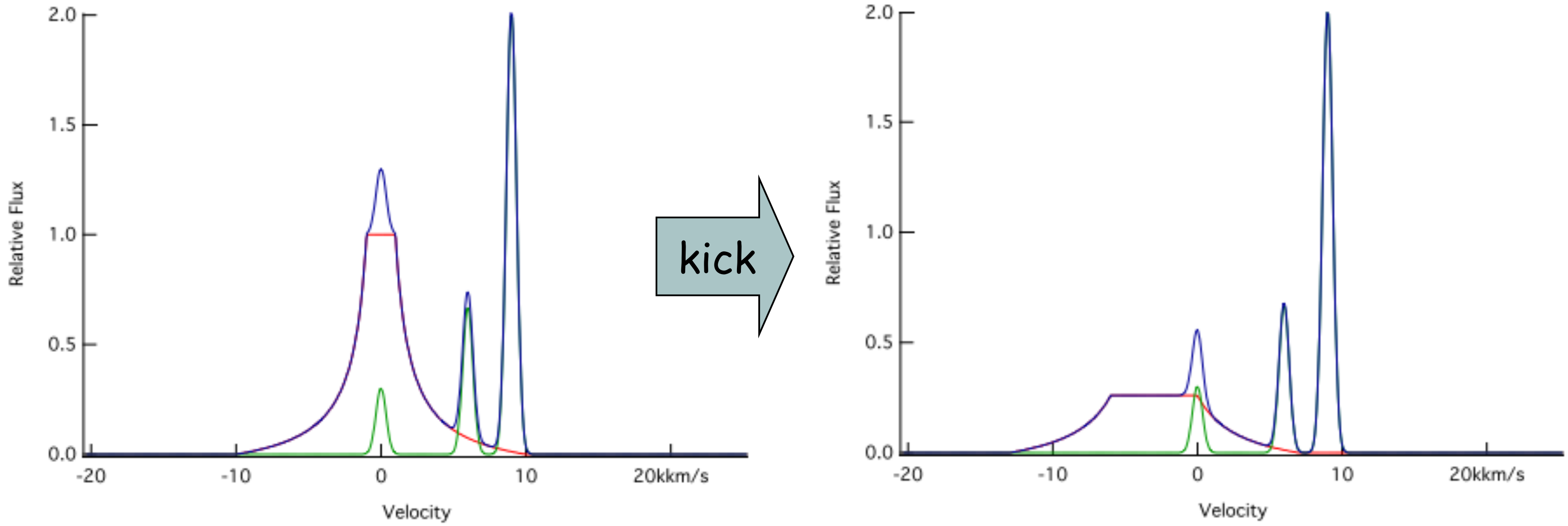
"We have no reason to expect recoils to prefer larger FWHM." Bonning et al.

Spherical shell BLR with $v(r) \propto r^p$

Profile core width determined by $v_{min} = v(r_{outer})$, if $p < 0$



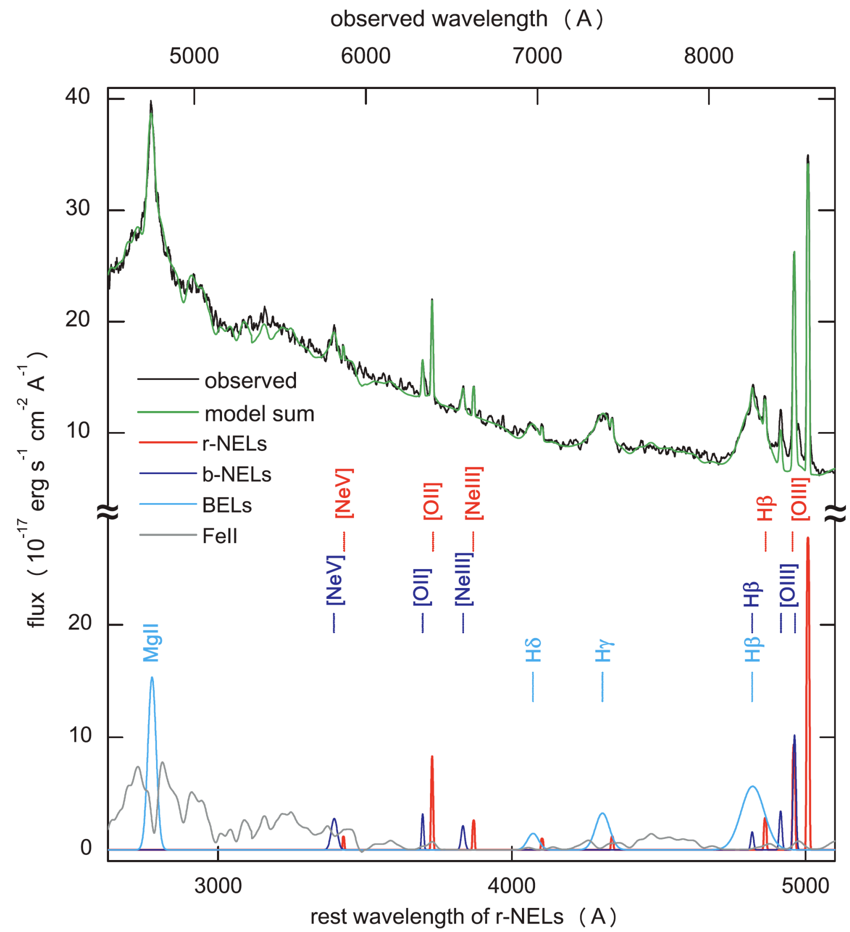


Transient asymmetries may arise from "left behind" gas

SDSS J0927+2943

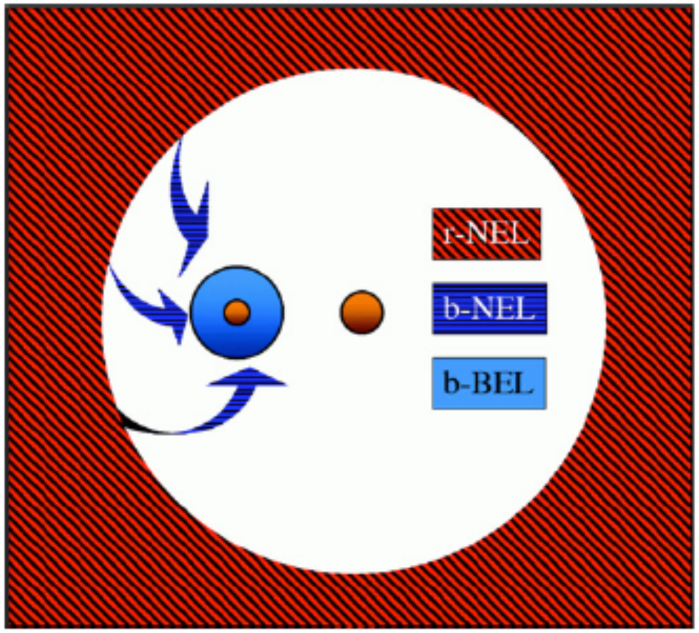
Komossa et al. 2008

- Two very unusual emission-line systems
- Emission-line signature characteristic of recoiling SMBH
- High-velocity gas bound to BH, in form of broad emission lines ("blue system"); blueshifted by **2650** km/s,
- Low-velocity gas left behind, in form of narrow emission lines ("red system")



SDSS J0927+2943: Alternatives

- Sub-parsec MBH binary Bogdanovic, Eracleous & Sigurdsson (2009); Dotti et al. (2009)
  - Period ~100 yr
  - relative velocity shift unchanged over 4 yrs (Vivek et al. 2009) ➔binary model unlikely



- Chance superposition in rich cluster (Shields et al. 2009)
  - Existence of massive cluster disputed by Decarli et al. (2009)
- NGC1275-like system (Heckman et al. 2009)

Recoil candidate: SDSS J1050+3456

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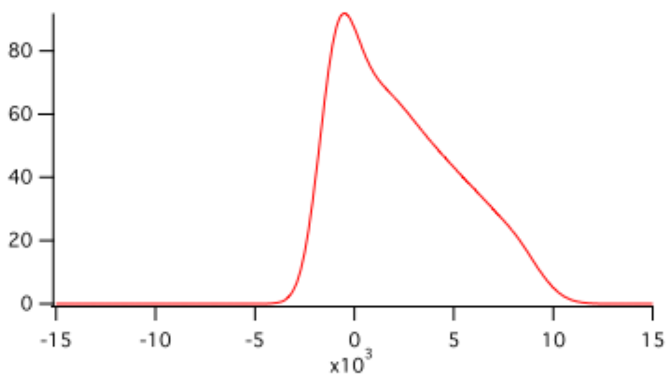
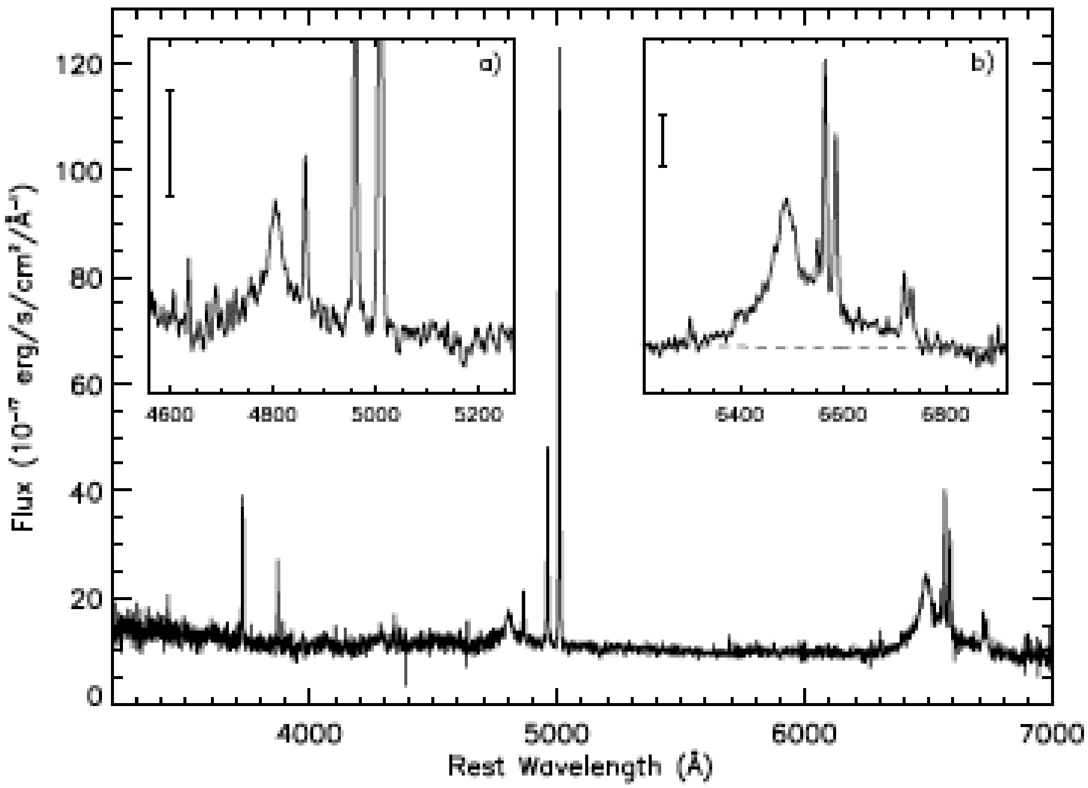
Shields et al. 2010

- Broad Hα, Hβ blueshifted by 3500 km s^{-1} relative to narrow lines
  - z = 0.272
- Or,
  - Extreme "double peak" emitter?





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Spectropolarimetry of E1821+643: gravitational recoil, SMBH binary or superwind?

SPECTROPOLARIMETRIC EVIDENCE FOR A KICKED SUPERMASSIVE BLACK HOLE IN THE QUASAR E1821+643
Andrew Robinson, Stuart Young, David J. Axon, Preeti Kharb, and James E. Smith
2010, ApJ 717, L122

Properties of E1821+643

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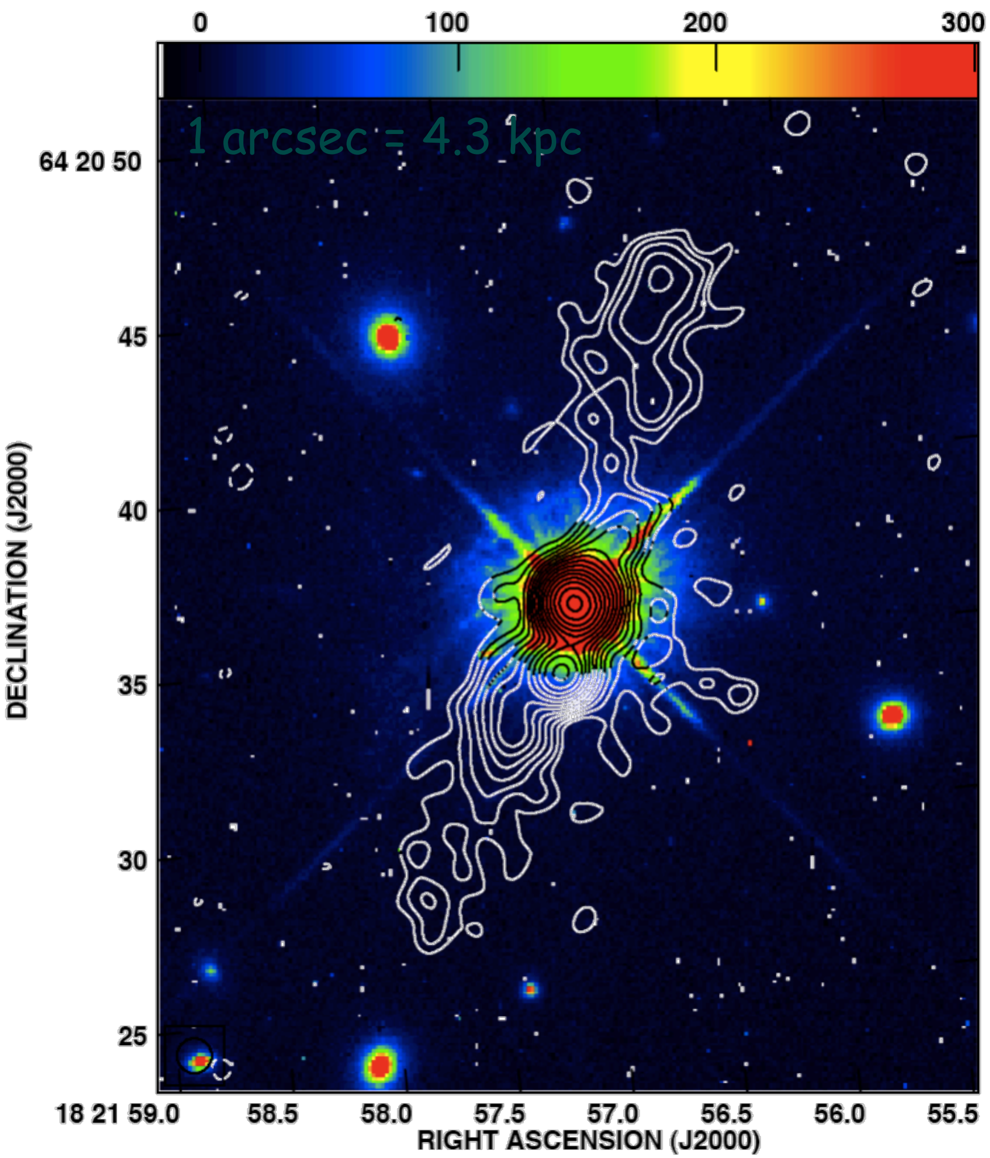


- Large CD galaxy at center of large X-ray cluster (Shneider et al 1992, Hall 1997) (Abell class 2)
- One of most luminous AGN in local universe (M_V=-27.1)
- "Radio-Quiet" but has 250 kpc FRI radio source (Blundell & Rawlings 2001).

M_{BH} = 5–40×10^8 $M_\odot$

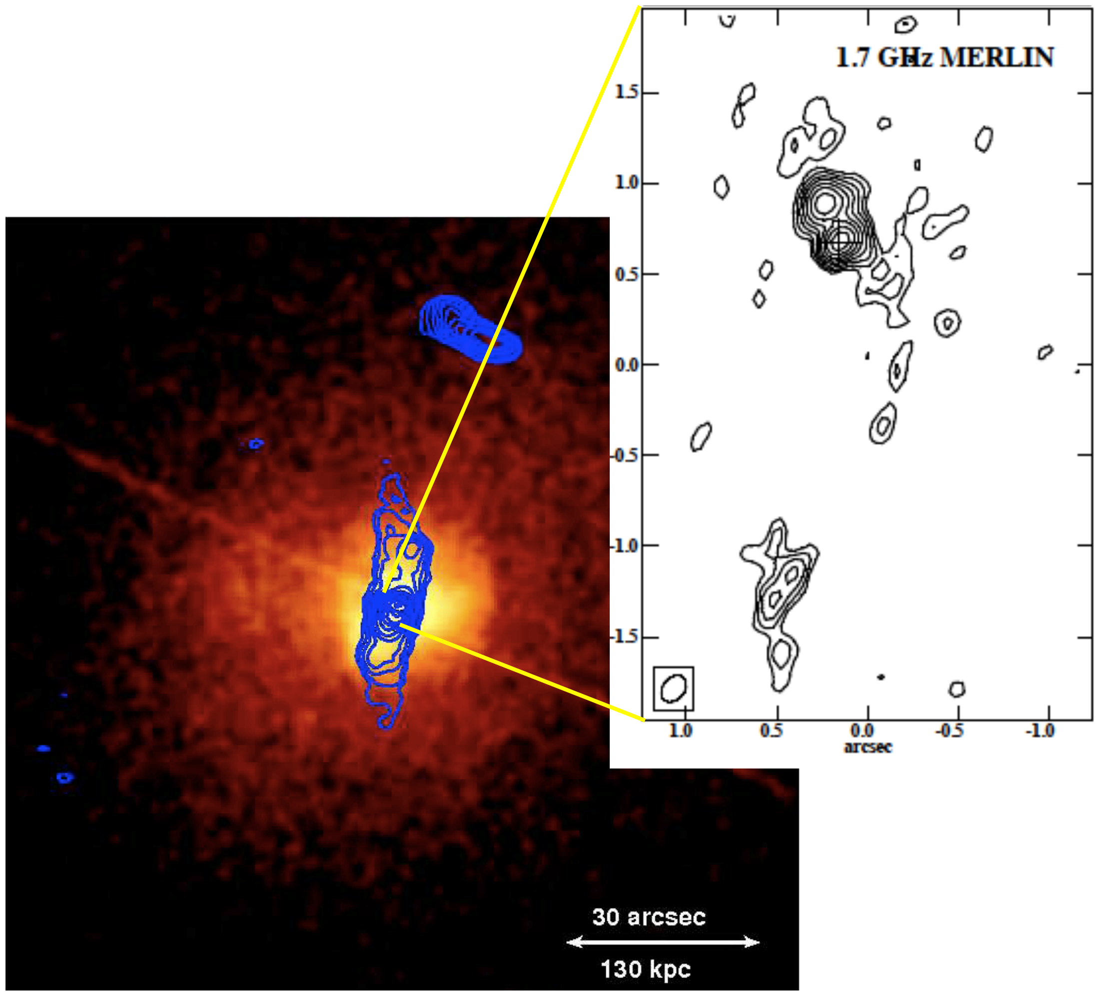
e.g. Kelly & Bechtold 2007

host galaxy,
M_V = –24.3; $R_{1/2}$≈10.5 kpc;
Total mass ~2×10^{12} $M_\odot$

Floyd et al 2004

E1821+643: gravitational recoil, SMBH binary or superwind?

- Jet bends through ~90° on ~ arcsec scales (Blundell et al 1996)
  - Precession in binary SMBH?
  - Re-orientation of spin axis following SMBH coalescence? (Merritt & Ekers 2002)



z = 0.297   1 arcsec = 4.3 kpc

Spectropolarimetry of E1821+643

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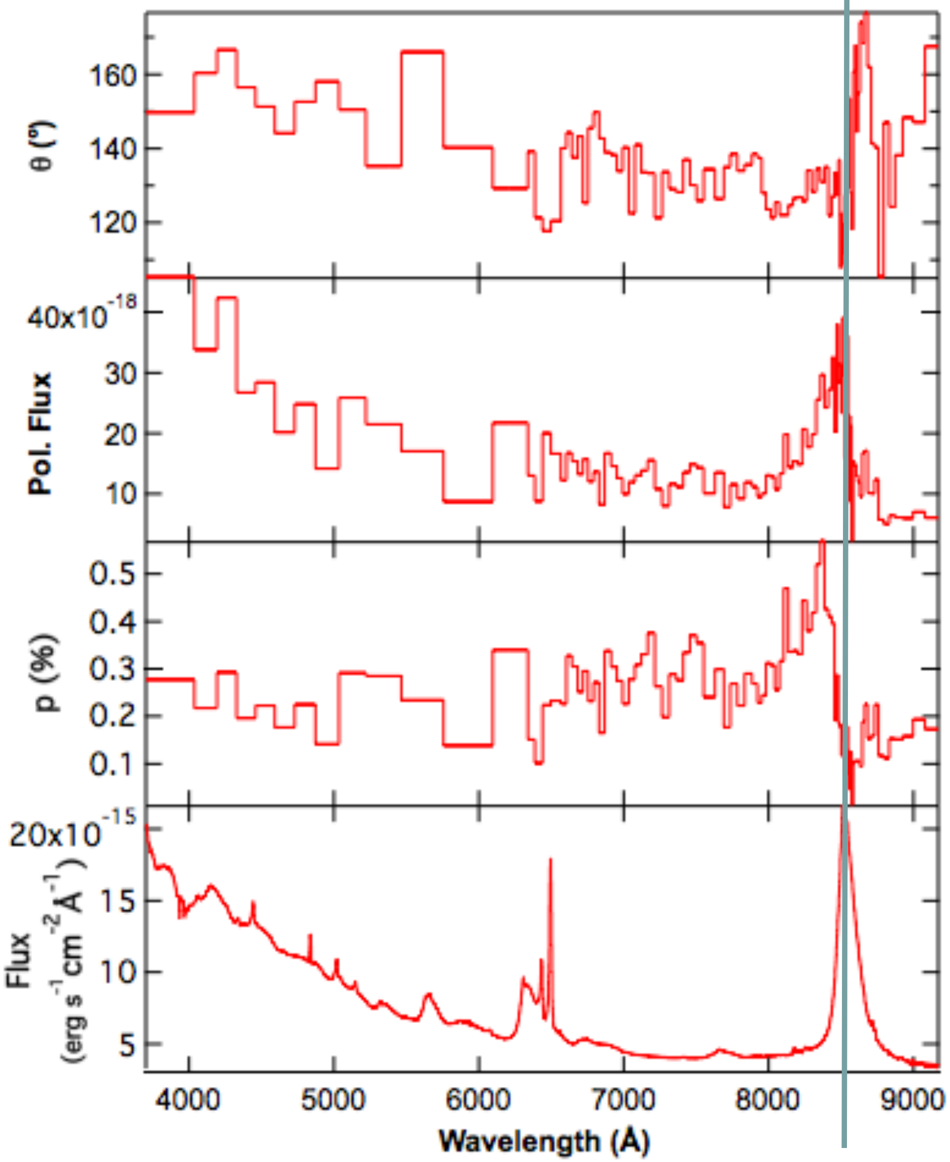
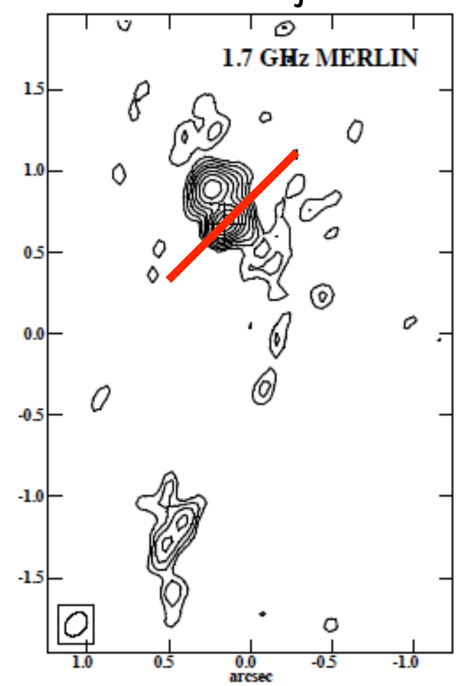


- Broad Hα, Hβ redshifted & red asymmetric in total flux
- Broad Hα blueshifted & blue asymmetric in polarized flux
- Average pol PA ~ perpendicular to 1" jet



E1821+643: a “kicked” SMBH?

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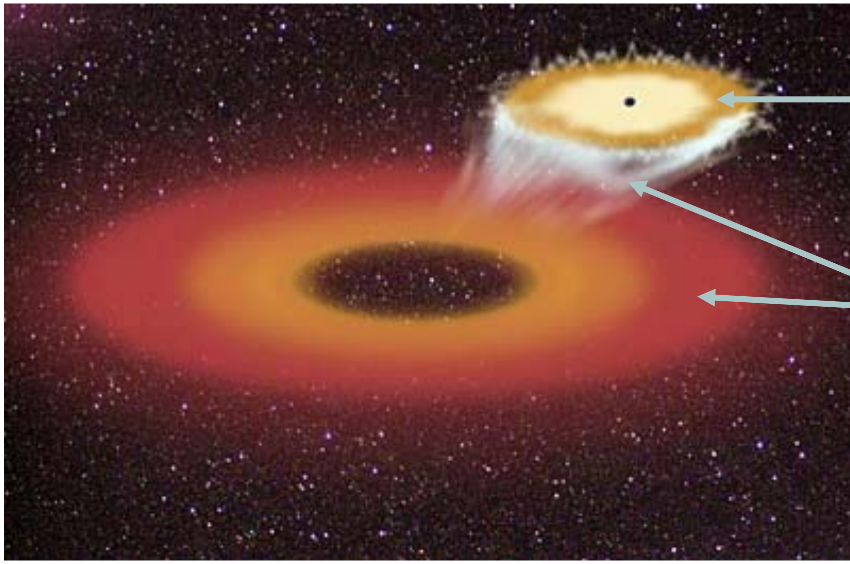


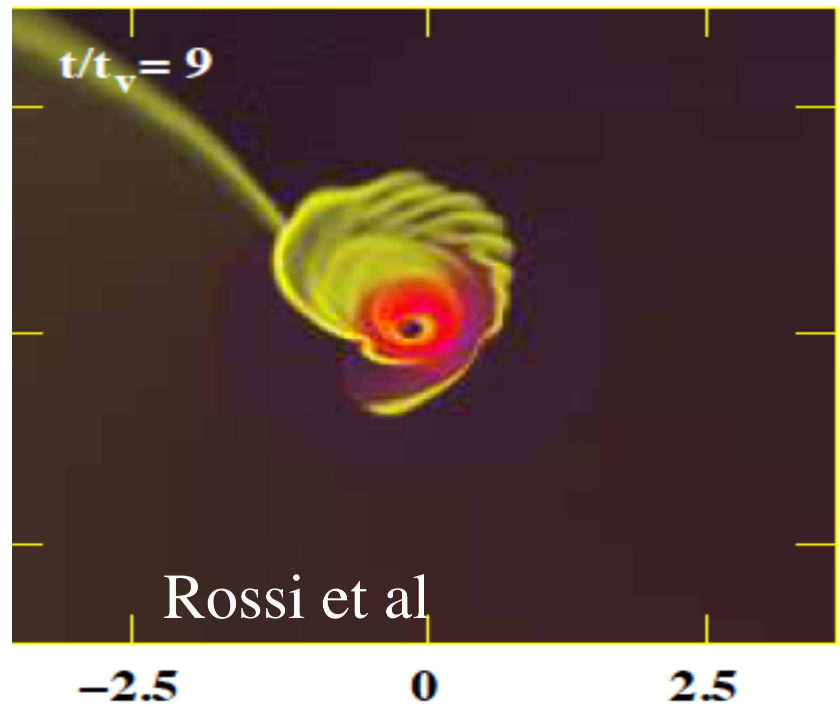
R2: inner BLR retained by recoiling SMBH ($v_{Kepler} > v_{recoil}$)

R1: outer BLR/circumbinary disk left in wake of recoiling SMBH ($v_{Kepler} < v_{recoil}$)

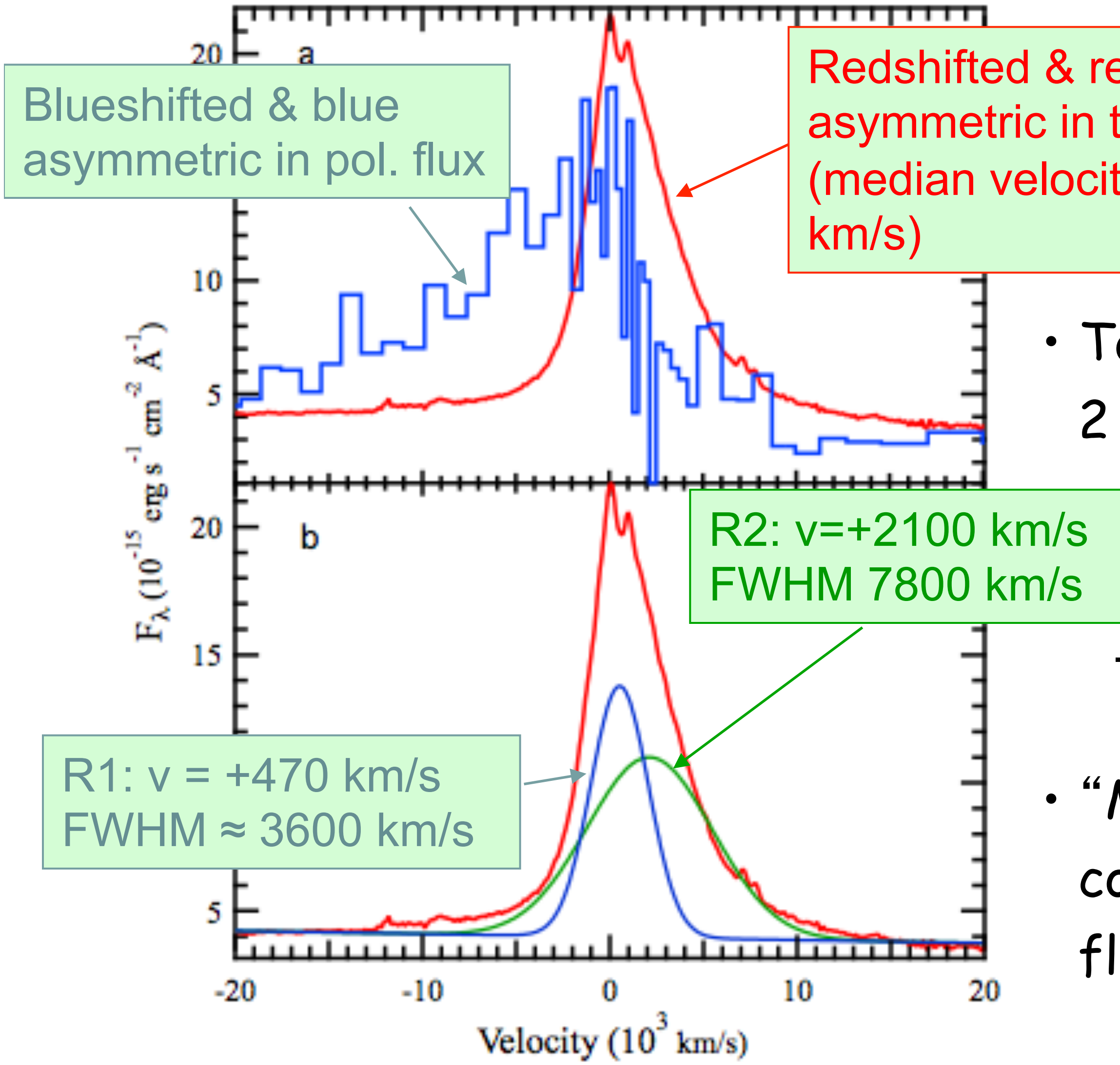
- R2 gives recoil velocity:

  $2100 < V_{recoil} < 4000$ km/s ($\alpha = 120°$)

- Assume $\alpha = 170°$ (most conservative): $V_{recoil} \approx 2000$ km/s

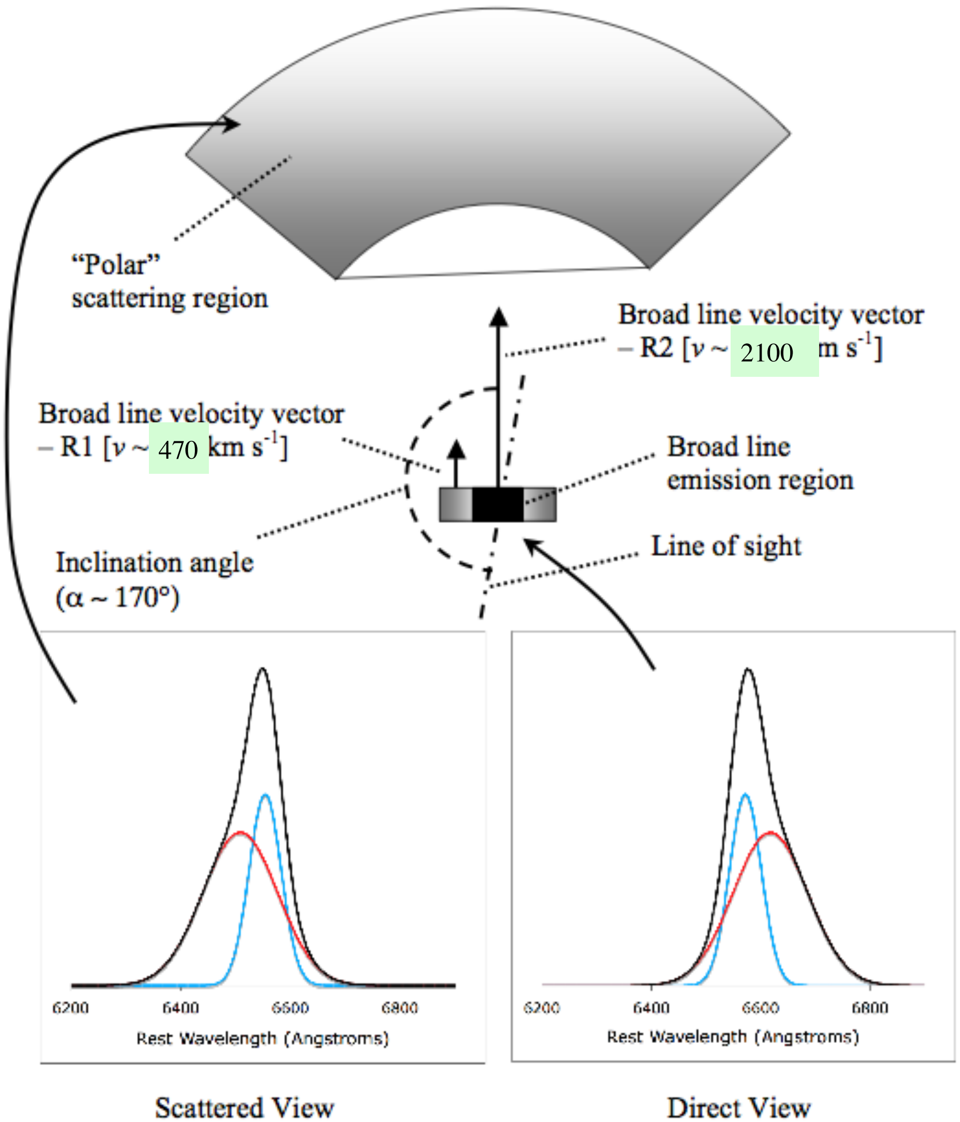


E1821-643: Hα in total & polarized flux



- Total flux profile described by 2 Gaussian components:
  - R1: low velocity, low velocity dispersion
  - R2: high velocity; high velocity dispersion
- "Mirroring" of these components explains polarized flux profile

E1821+643: scattering model



Both BLR components move

- away from observer ➔redshifts in direct light
- towards scattering region ➔blueshifts in scattered (polarized) light

Shift & asymmetry reversal

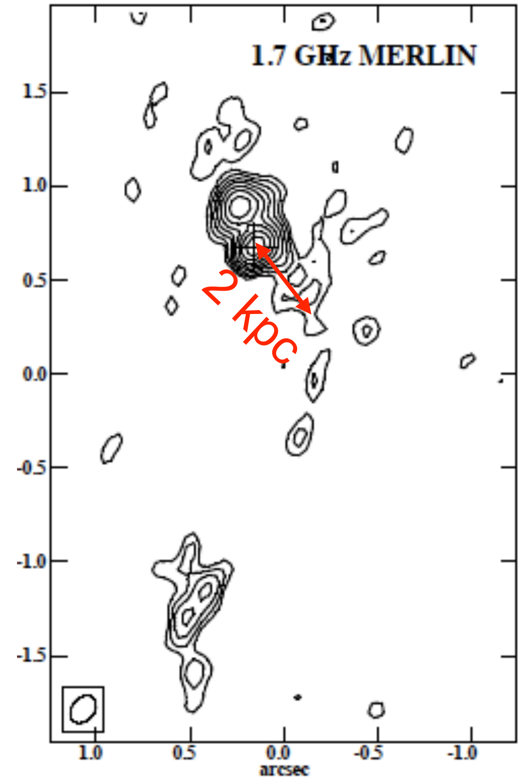
Relation to radio jet

- Assuming inner jet (1” scale) emitted post coalescence, jet lifetime -> lower limit on time elapsed since recoil

$$t_{jet} \sim 7000 \ \ yr / \left(\beta_{jet} \sin i \right)$$

  - β_{jet} = jet advance speed in units of c
  - i = jet inclination
- β_{et} sin i ≤ 1, so displacement ≥ 18 pc
- If β_{jet} ≤ 0.1 c, T_{jet} ≥ 10^5 yr and d ≥ 180 pc

- SMBH has moved 20 – 200 pc (but almost along line of sight)



- Scattering model ➔ recoil approximately along jet axis
- Recoil velocity & spin of merged BH tend to align with binary angular momentum axis
  - Lousto et al (2009

Spectroastrometry of E1821+643

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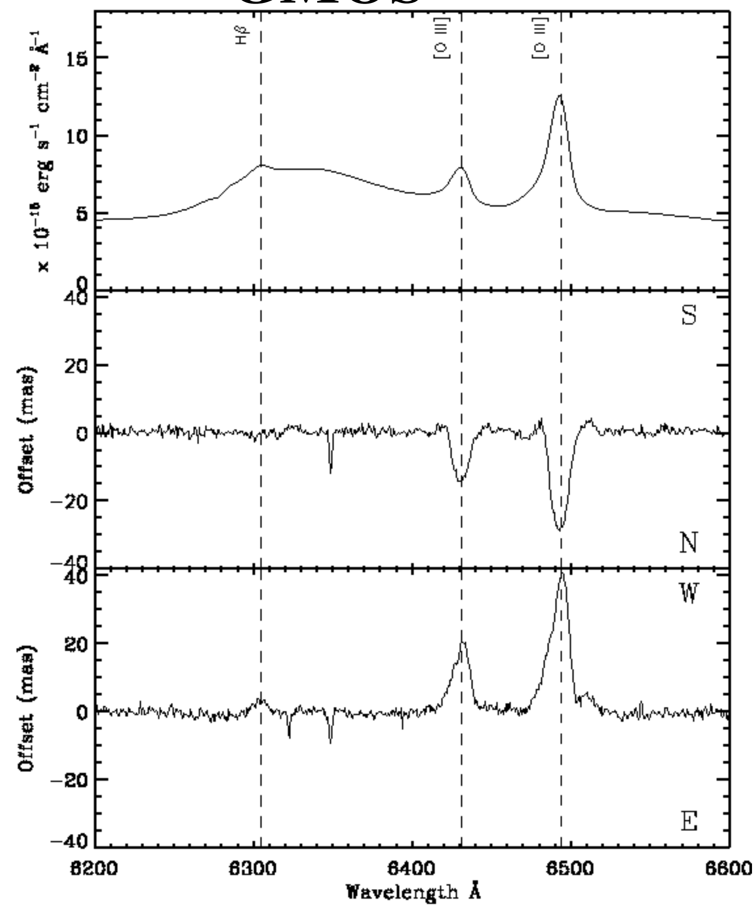
- Measure position as function of wavelength in long slit spectrum
- Yields relative position of spectral features to mili-arcsecond (mas) scales

- Narrow lines (Hα, Hβ, [OIII]) displaced relative to broad lines & continuum (i.e. quasar nucleus) by ≈20–40 mas ➔100–200 pc

Consistent with inferred SMBH displacement …

GMOS



Curran et al 2011 in prep

“Were you so lucky?”

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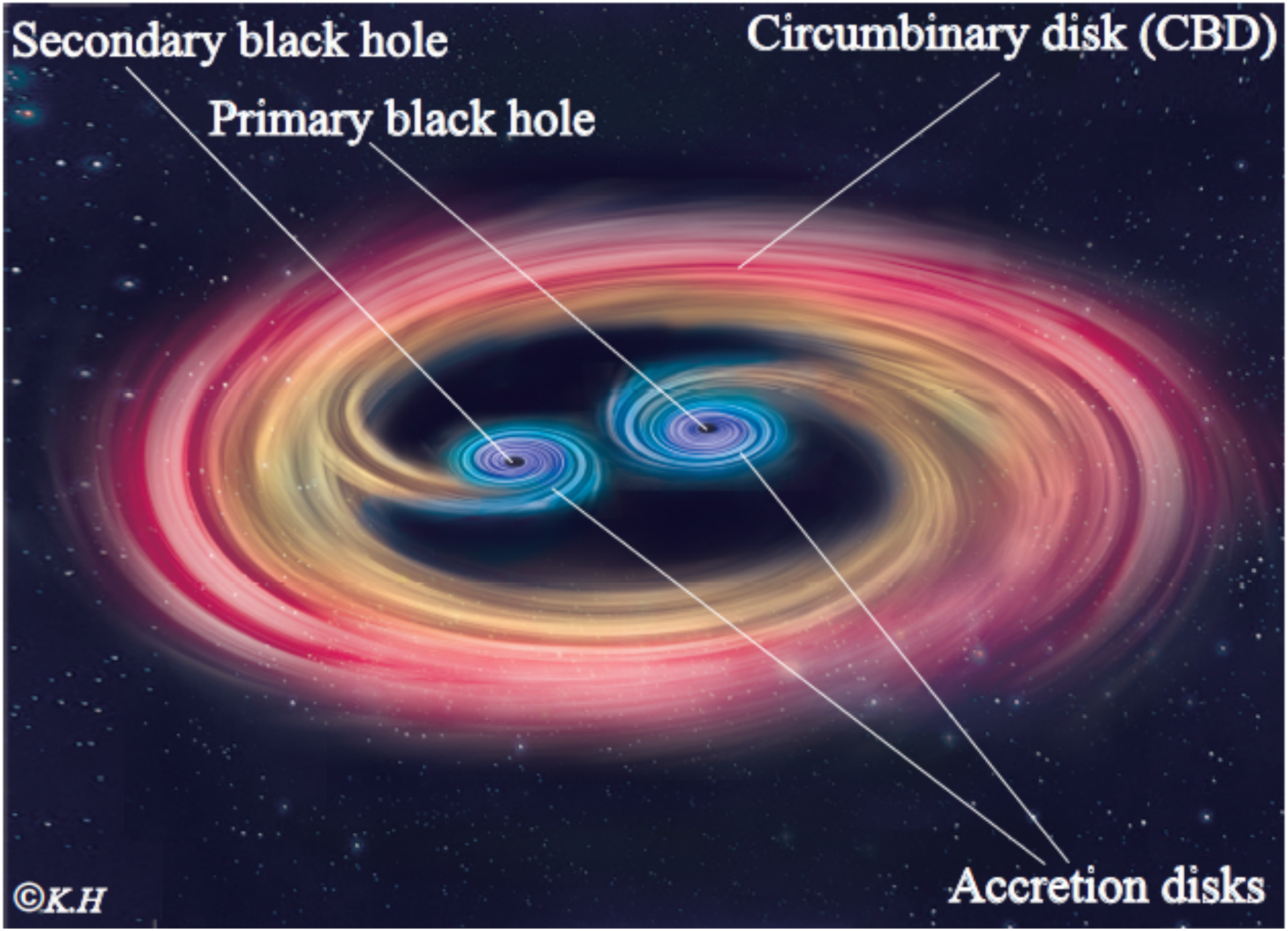
- Large recoils rare
  - Entirely suppressed in gas rich systems?
- Observed at special point in time
  - Shortly after coalescence
  - Or during early pericenter passage
- Alternative models
  - Wind models
  - Binary black hole

Accretion flow around Binary BH



Rotating disk secondary

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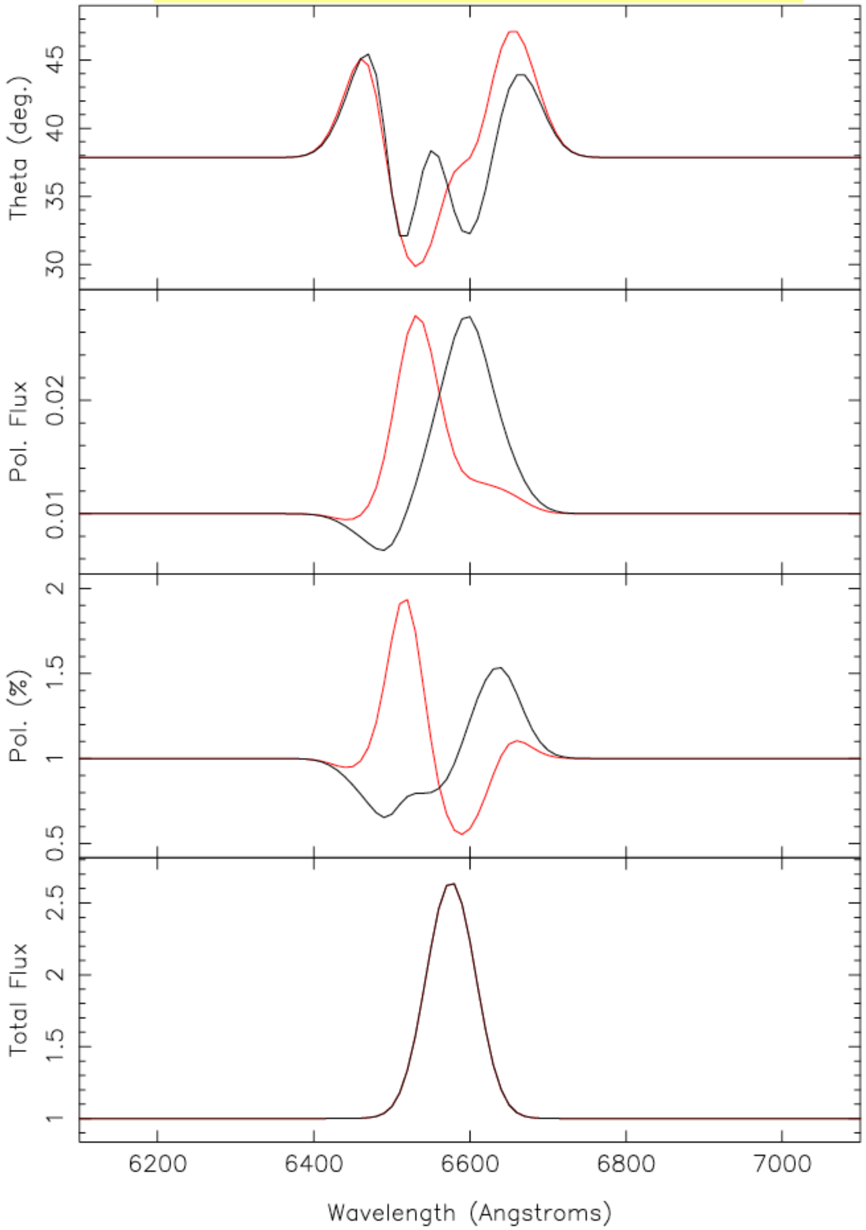
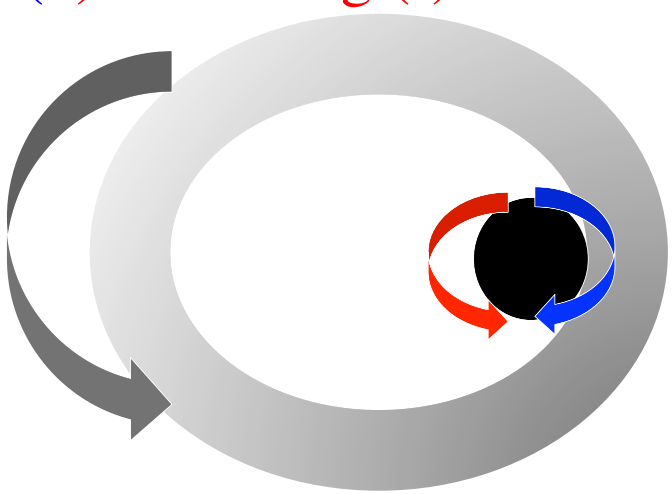


r(secondary)/r(inner-ESR) = 0.25

ESR=Equatorial Scattering Region

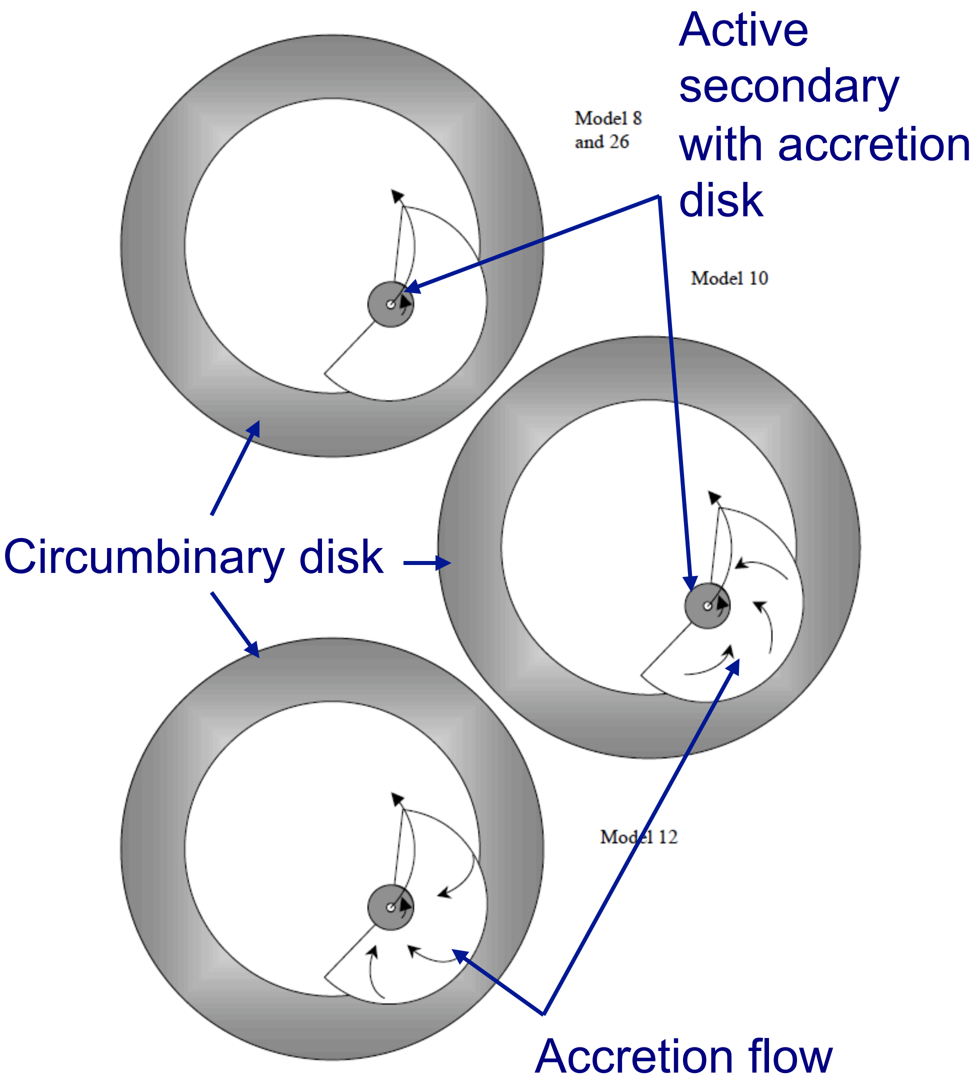
inclination - 22.5

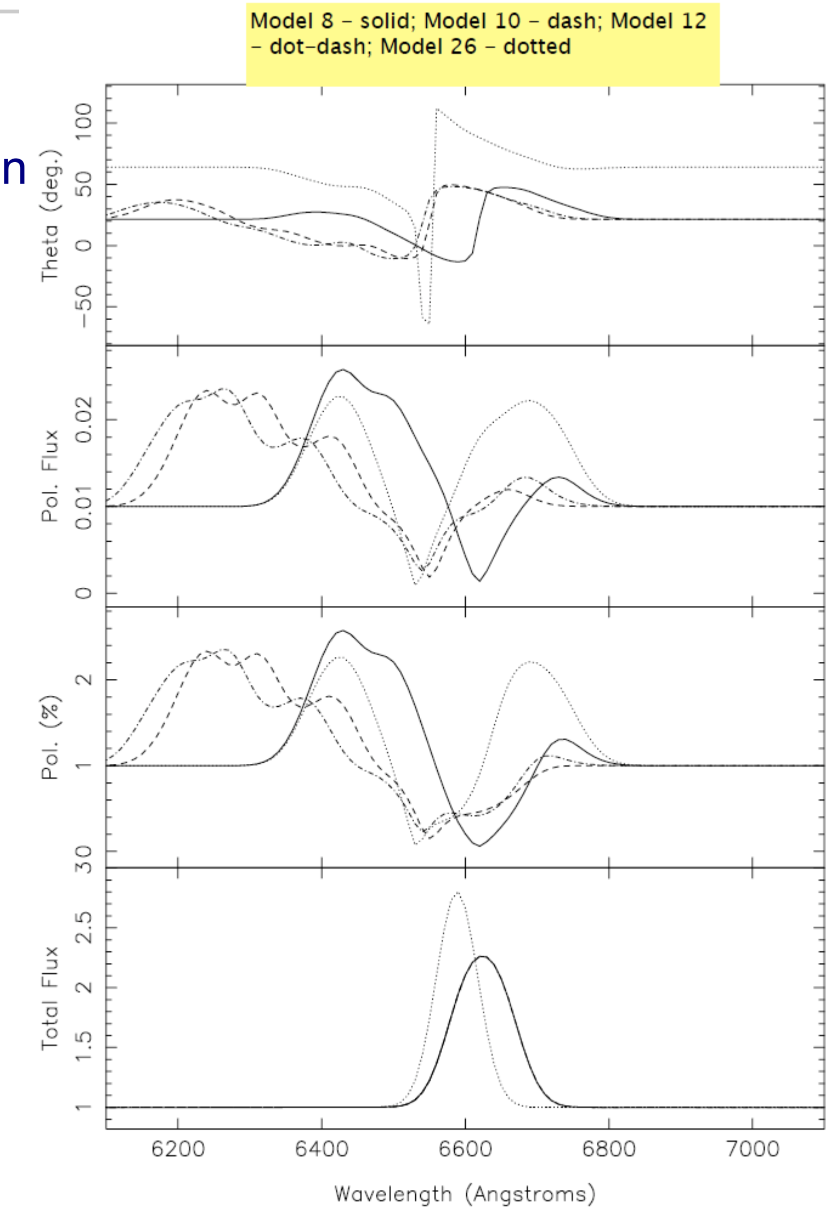
disk counter-rotating (b) corotating (r)



Young, Axon Robinson 2011 in prep

Scattering models for BH binaries





NGC 7603(Mrk530)

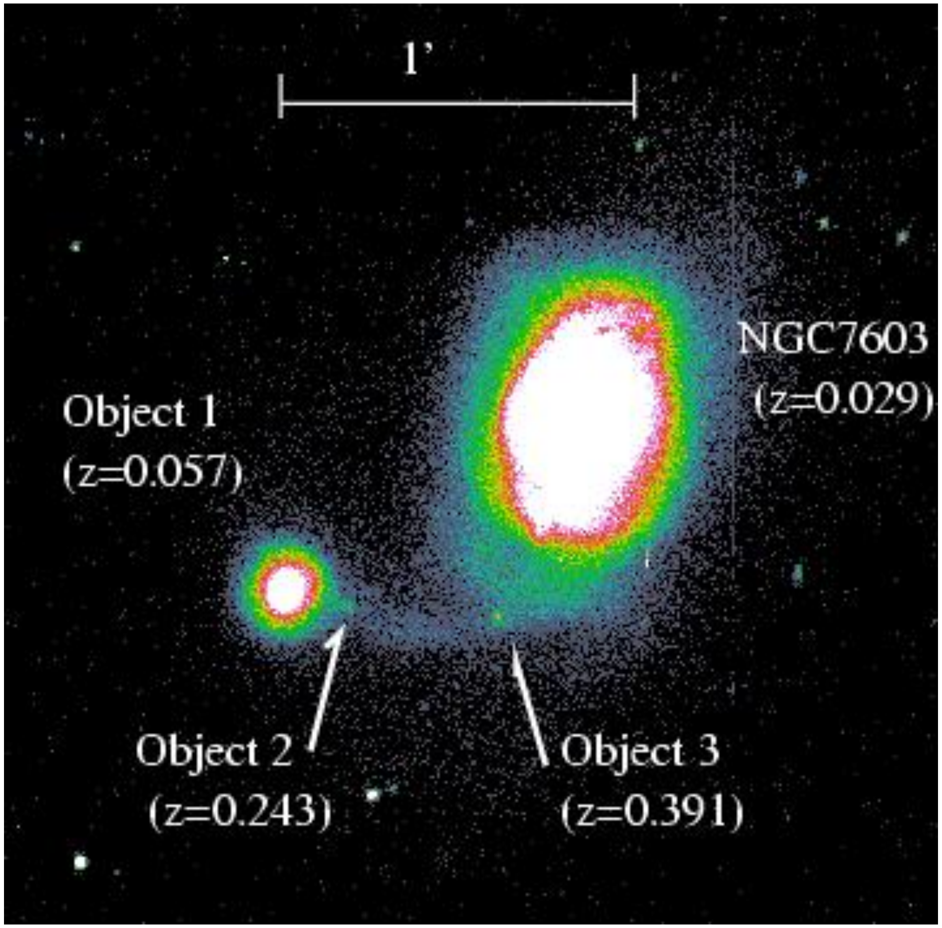
- Has been described as "the most impressive case of a system of anomalous redshifts discovered so far"

Arp 1971

ROSAT/SWIFT source

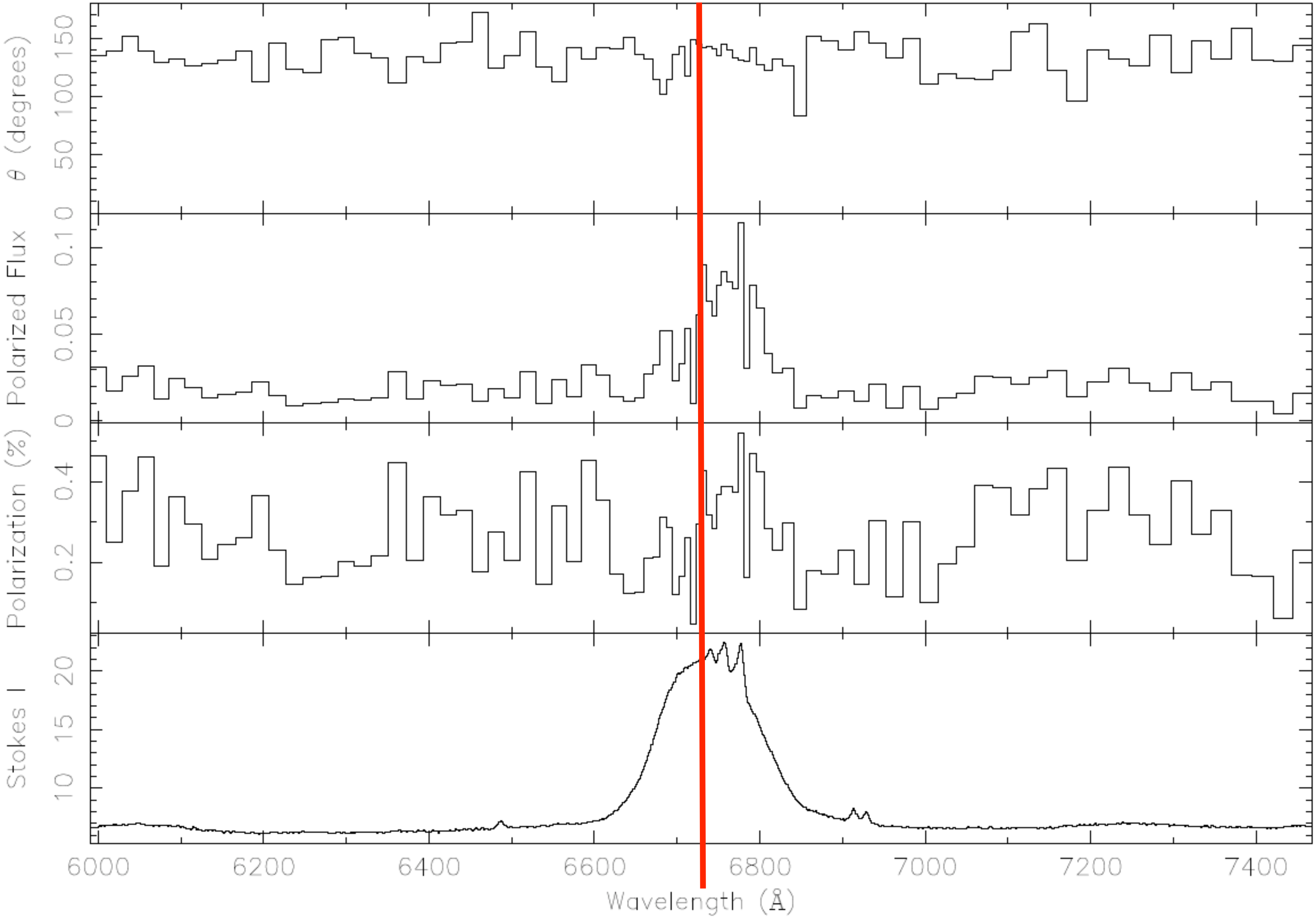
In Cluster

Lopez-Corredoira & Gutierrez 2002, 2004



Outer regions show boxy Isophotes
Tidal tails to SE and NW

Spectopolarimetry



Summary

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- LCDM structure formation ➔ BH binaries & subsequent mergers common
- Recoil kicks can be large & damped oscillations long-lived
- Direct measurement of physical displacements challenging but expected in large galaxies (arguably)
  - Possible detection in M87 and in 3 further radio ellipticals
- Radial velocity shifts easier but hampered by our lack of understanding of BLR geometry/dynamics
  - Two interesting candidates
- Spectropolarimetry provides us with a unique probe of the kinematics of material inside - can reveal moving BLR
  - Large kick detected in E1821+643?
  - NGC7603+ 2 other spectropolarimetric candidates