AGN astrophysics from radio and optical astrometry

Displaced AGN emission

(Ian Browne, University of Manchester, Jodrell Bank)

Outline

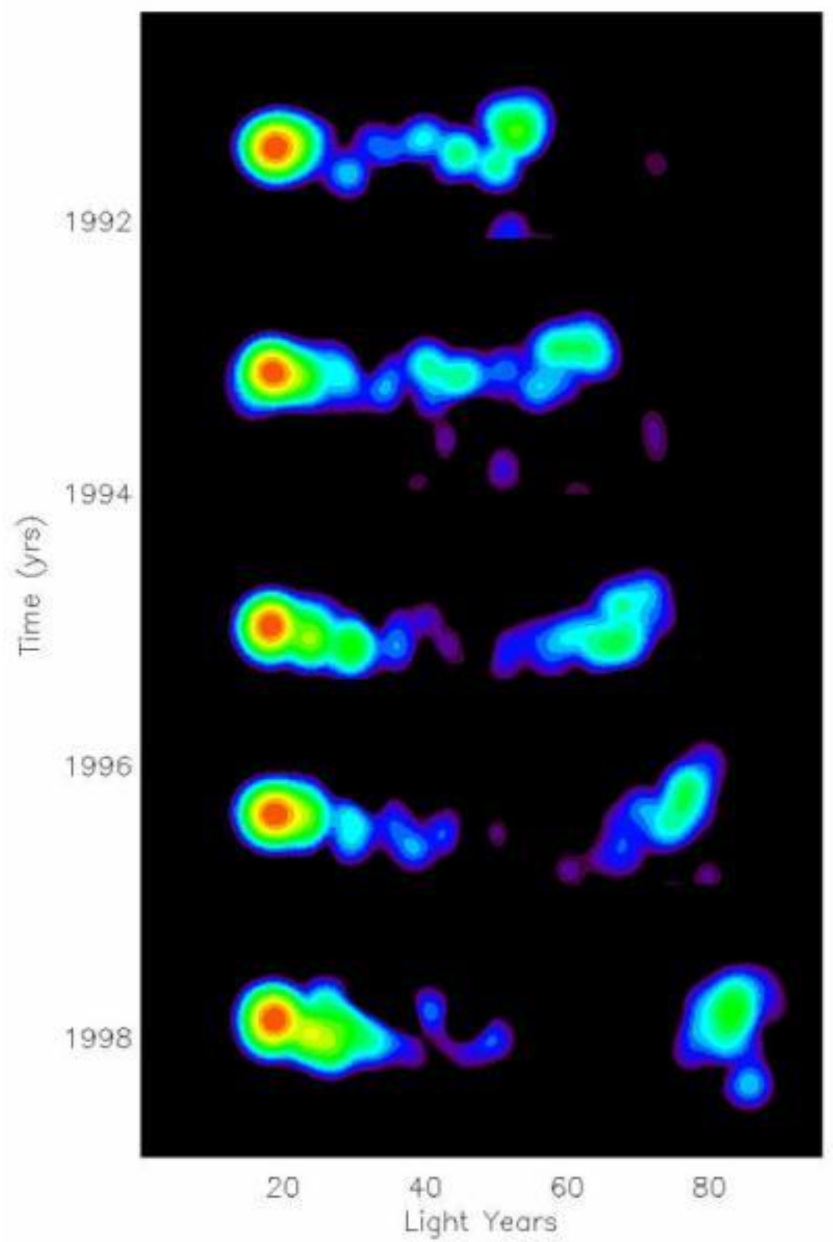
- Brief tour of possible extragalactic astrophysical applications. Then zoom in on:
- Location of blazar emission regions
- Gravitational lensing
- Displaced black holes
  - Binary black holes
  - A search for kicked black holes in early-type galaxies
- Summary

Potential extragalactic applications

- Physics of jets – where does the emission come from?
- Finding new gravitational lens systems
- Studying known lens systems. Time-variable radio-optical displacements. Micro-lensing image wander
- Displaced AGN
  - Binary black holes
  - Kicked black holes

Astrophysics of radio jets

- What do we (think) we know?
  - Symmetric jets with bulk Lorentz factors ~10 are produced by an accreting black hole system
  - Jets flare on timescales of days, weeks to >10 years
  - VLBI we measure superluminal motions (see 3C279, adjacent). The moving blobs are related to flares
  - The same jets emit up to gamma-ray energies. Blazars
  - Much of the optical and Gamma-ray flare emission comes from the same place (correlated variability with no time delay (Stefan Wagner – Fermi conference, May 2011)



Astrophysics of jets (2)

- What we would like to know?
  - The physics of jet production (difficult!)
  - Where do things happen
    - Where is the radio core relative to the optical/gamma-ray emission? (Correlated variability gives us clues)
    - Where does the acceleration occur?
    - Does the blazar optical emission come from the same place as the thermal (disk) emission?

Astrophysics of jets (3)

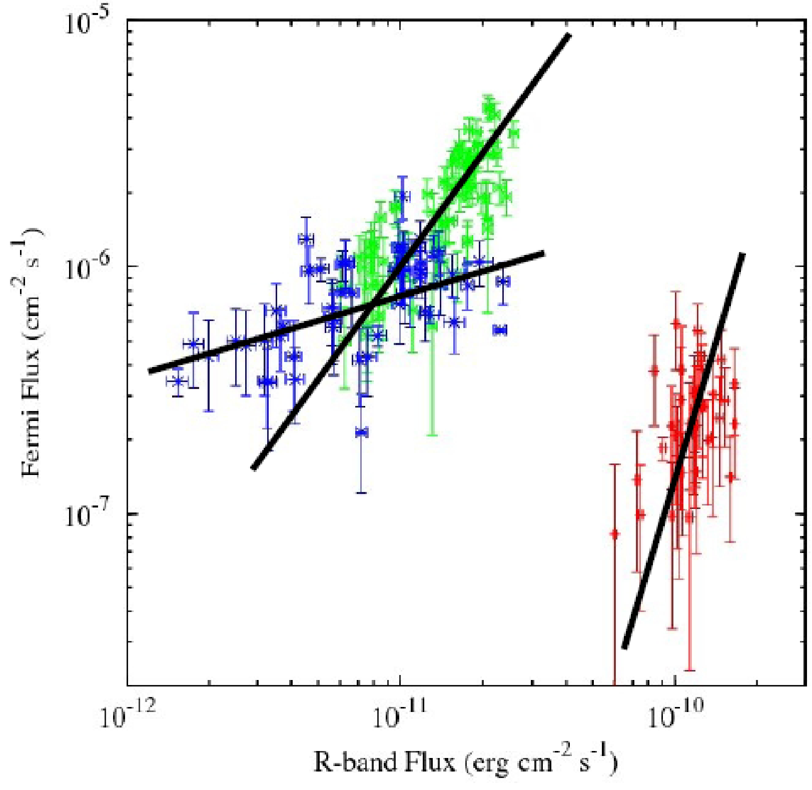
- **Context.** There is an active debate (recent Fermi symposium in Rome) in the Blazar community concerning **the location of the gamma-ray** (and optical/radio) emitting region.
- Is it within the BLR (~0.1pc)?
- Or well outside (~10pc)?

There is evidence both ways

(N.B. 1mas=8pc at z=1)

Results of gamma-ray and optical monitoring (Credit: Stefan Wagner)

F_{GeV} – F_{eV} Relations: Slopes



3C454.3, PKS 0235+164 and PKS 2155-304

Even for Blazars of similar type, slopes and average flux ratios are different.

With fixed observing band, slopes and ratios depend on relative locations of bands w.r.t. peaks within SED.

A Gaia opportunity?

(Absolute image wander)

- **A simple idea**. Imagine a FSRQ with roughly equal contributions of blazar and accretion disk emission. Then let the blazar bit vary.
  - If the blazar light is >1pc away from the disk emission, the centroid will move by an easily detectable >~0.1mas
  - Look for optical centroid motion in blazars and a correlation of positions with optical (or gamma-ray) light curves.
  - Any correlation will support the "well outside" picture and spectroscopy can give the ratio of thermal to non-thermal so that a toy model can be constructed.

Sonia Anton's talk will be relevant

Comparing radio and optical positions

(Relative image wander. Others:Patrick Charlot, Richard Porcas, etc. will talk about this.)

- Components in jets move and thus the radio centroid wanders.
- Even if the optical centroid is stable, this is a pain for ICRF people
- This pain is also an astrophysical opportunity!

Gravitational lensing

- Gaia will find some – (Talk by Francois Finet)
- What can it tell is about known systems?
  - Micro-lensing. Stars in the lensing galaxy will lens compact regions (e.g. the AGN) in the lensed objects giving rise to uncorrelated variations in lensed images. This is seen. Gaia will have right cadence to see the effect in known and new systems.
  - Astrometric micro-lensing. Associated with the variations are position shifts which can be as large a 100μas. Gives extra information about the masses of lensing objects (see review by Schmidt & Wambsganss, 2010, ReGr, 42, 2127)

Lensing continued

- Time delays. Anything that changes in lensed images can be used to obtain a time delay.
  - Image brightness
  - Image positions
  - Image polarizations
  - Etc
- Cadence. Most time delays are days to weeks. Wide separation lens systems with long delays will be of interest to Gaia. Only 0957+561, the first lens, looks suitable (Delay 420 days and magnitude 17).

Searching for displaced black holes

(A semi-serious project)

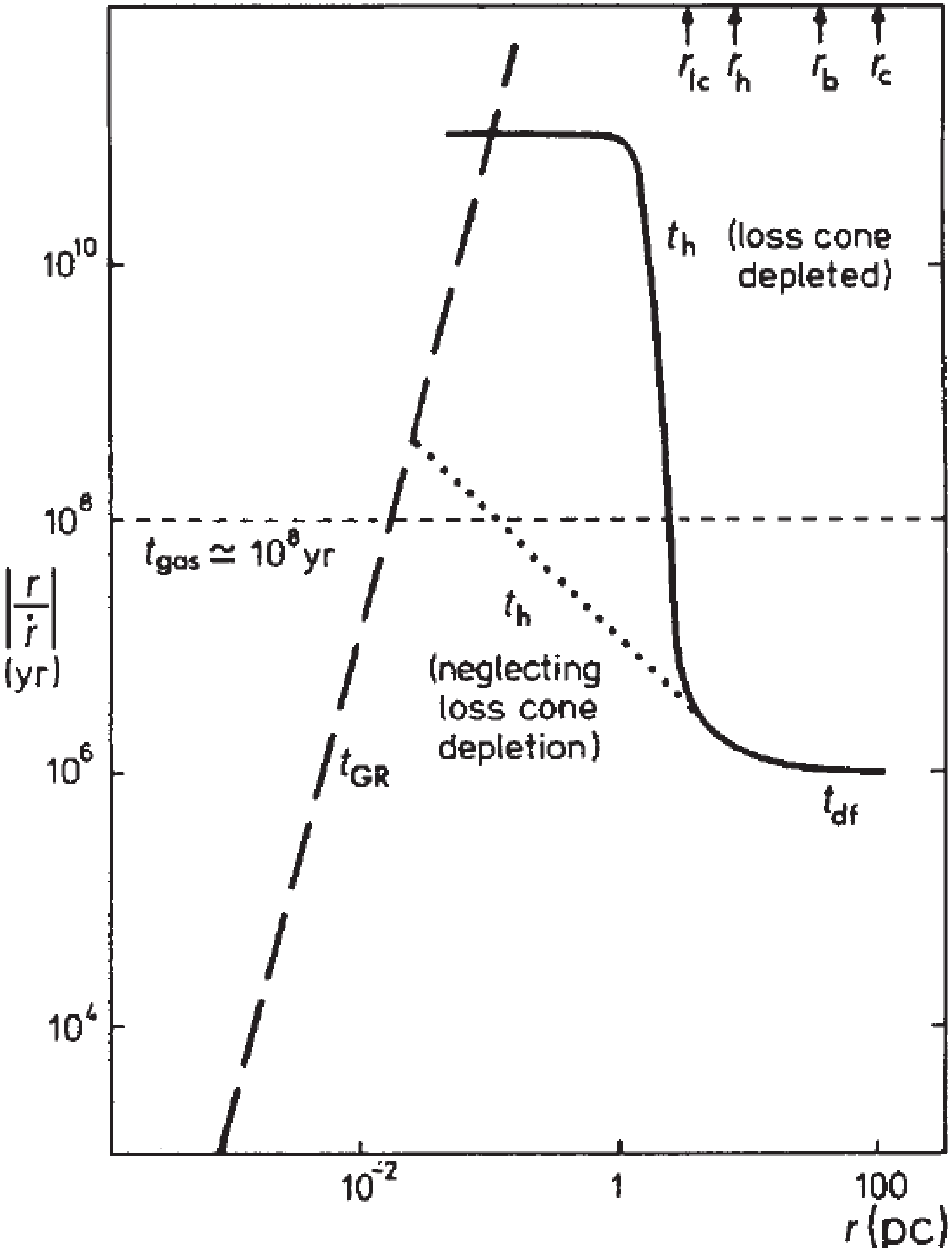
- Look for displacements of radio nuclei from the stellar light in elliptical galaxies.
  - e-MERLIN for radio and Gaia for optical
- Displacements could be due to:
  - Binary BH
  - Kicked BH
  - Lensing of background source
  - Something more prosaic!

Overview; super-massive black hole life histories

- During galaxy building black holes at the centres of a galaxies, grow by accretion
- Galaxies merge and binary BHs are formed
- Binaries evolves rapidly to <1pc orbit
- May "stall" before coalesce. Timescale very uncertain
- Accretion of gas can prevent stalling and may control the binary orbit evolution.
- Coalescence produces burst of gravitational radiation and perhaps gives the resulting BH a large (~1,000km/s) kick

Merging; the Begelman et al. (1980) picture

- Once galaxies merge, nuclei (BH + nuclear stellar cluster) merge rapidly in ~10^6yr
- Dynamical friction of the BHs against the background stars shrinks the orbit in ~10^8 yr
- After this time all stars that contribute to dynamical friction have been depleted and the shrinkage stalls at r<1pc. How long does this stalled phase last? Maybe ~Hubble time but gas accretion may hasten coalescence.



The time evolution of a super-massive binary black hole.

From Begelman, Blandford & Rees, 1980, Nature, 287, 307

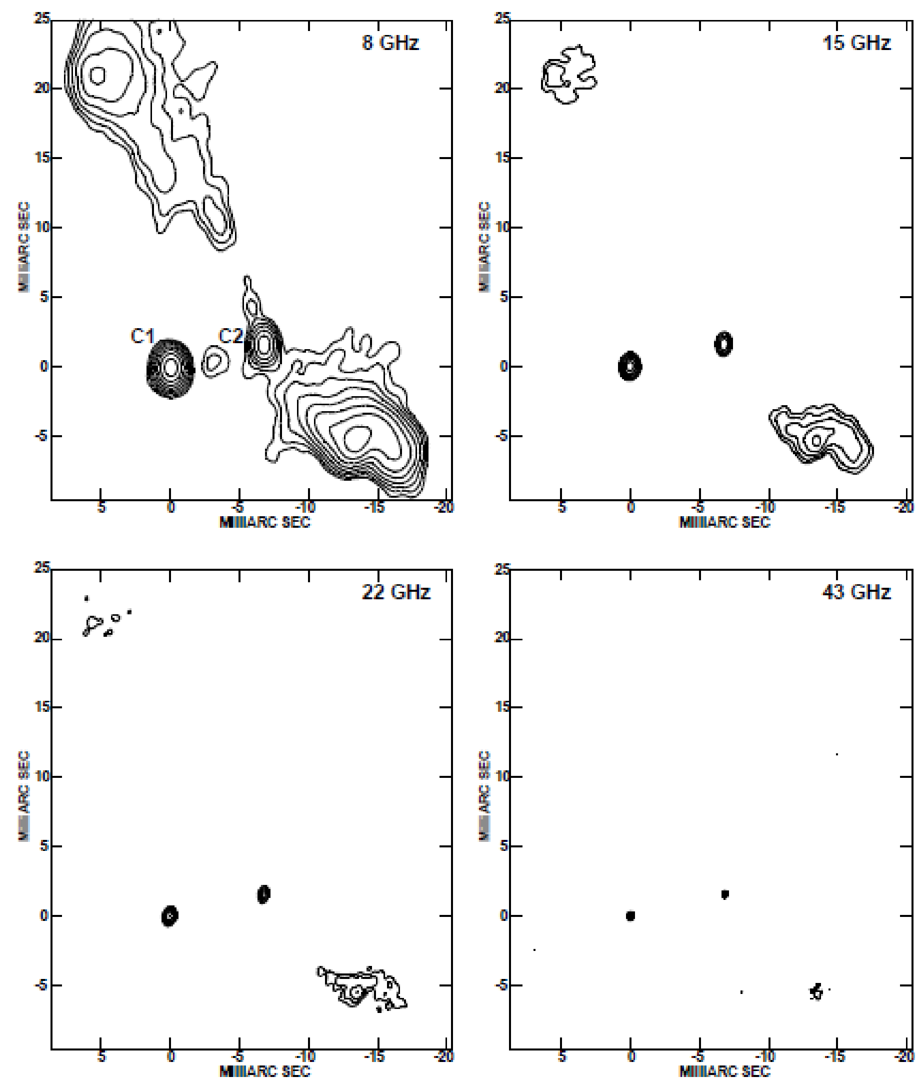
For an update see review by Colpi & Dotti astro-ph: 0906.4339

Binary Black holes

- An inevitable consequence of CDM structure formation.
- The critical observational question is how long do the phases last
- What do we know?
  - A handful of optical binary nuclei with separations of ~kpc are known
  - One convincing 7.3pc radio-loud binary (0402+379)
  - 3C78 and separation ~7kpc
  - Lots of radio failures (and some optical):
    - Burke Spolaor (MN, 410, 211)-- ~2000 vlbi maps and only re-discoverd 0402+379
    - CLASS (Browne et al., MN, 341, 13)-- ~16000 VLA maps. 23 lenses but no binaries

Perhaps binaries are radio quiet

<u>0402+379;</u> a convincing binary black hole system (Rodrigues et al, 646, 49) separation 7.3pc



Will Gaia be able to detect kicked black holes?

- There are several important factors:
  - The timescale for black hole mergers
  - How big are the kicks?
  - How long does a kicked black hole remain displaced from the nucleus?
  - Are kicked black holes active; i.e. are they optical or radio AGN so we can see them?
  - Is there a position reference wrt which the BH position can be measured?

Why does the merger timescale matter?

- Since most galaxy merging happened at z~2, quick merging implies we need to look at high redshift.
- Slow merging (~Hubble time) means that coalescences will be happening in the local universe

Do we look at high z quasars or low z ellipticals?

How big are the kicks and how long do they last?

- Numerical GR has made great progress
- Simulations suggest kicks of ~1000 km/s depending in mass ratios and relative spins
- Large enough to produce kpc displacements and even escape the host
- Simulations suggest that the settling timescale after the kick is ~1% of Hubble time

Are kicked BH active?

- We don’t really know
- There is a claim that the nucleus in M87 is displaced (M87, Batcheldor et al. 2010, ApJ, 717)
- The are examples of multiple AGN; e.g. 3C78, and a convincing BH binary 0402+379 implying that merging BHs on the path to coalescence does not necessarily kill activity

Finding a reference position

- The idea is to use Gaia optical positions for passive ellipticals since the stellar light should be a good indicator of the centre of mass. (In high redshift AGN there is no obvious reference)
- Use the radio to pinpoint the BH

Note that for this to be practical we require the BH coalescence process to take ~Hubble time; i.e. long enough after the (major) merger for the galaxy to settle into boring old age

A straw man proposal

- Target passive radio-loud elliptical galaxies
  - The starlight gives an optical reference position
  - Need to be optically passive otherwise the AGN will dominate the optical position
  - Passive ellipticals often host compact radio sources so radio position can used as marker for the BH position
- Use Gaia for optical and e-MERLIN or vlbi for radio. Aim for ~mas accuracy, but absolute accuracy is probably not critical because systematics like dust will set the true limit

Practicalities

- Measuring radio positions to a few mas accuracy is no problem (e-MERLIN or VLBI)
- Will Gaia detect ellipticals – what do local experts say?
- How many objects?
  - 10,000 radio positions for ellipticals z<0.4 would be an ambitious target (10s of days of observation).
- How many successes?
  - Assume all elliptical underwent a major merger 10Gyr ago and that the timescale for coalescence is also ~10Gyr. If BHs remain kicked for 0.1Gyr this implies ~1% of ellipticals should have kicked BHs
  - Say 10% have detectable radio emission and significant kick we might expect a 0.1% success rate

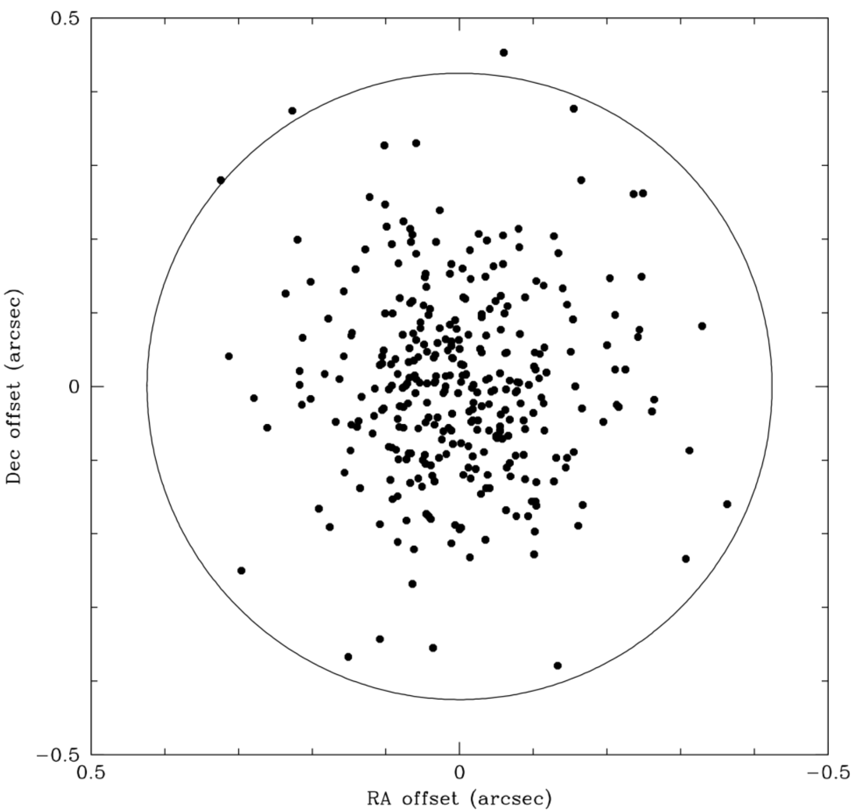
Not out of the question and it might be a good way to find binaries too if one is active.

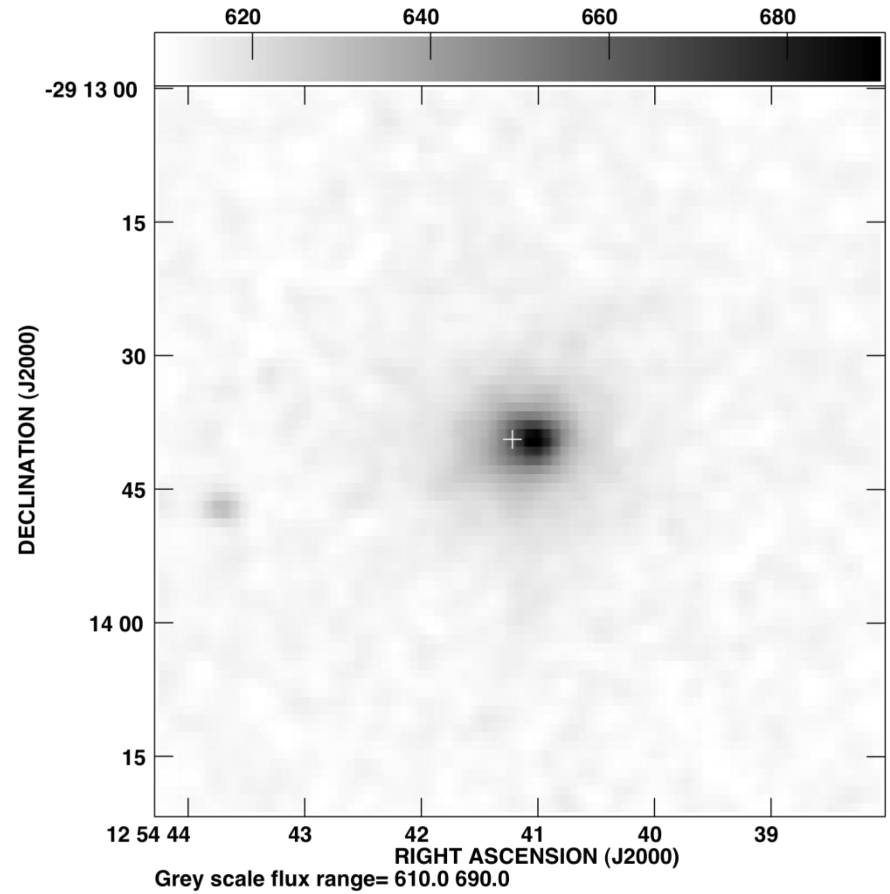
Preliminary studies

- SDSS and FIRST. Two Manchester undergraduates have picked 40 z<0.04 SDSS galaxies. Used GALFIT to measure positions and compared with FIRST
  - Rms position difference ~0.15 arcsec in RA and Dec. Implies ~15mas for z<0.4 (if limited by systematics)
- With the same motivation Jim Condon (NRAO) has used 2MASS and VLBA =>rms 0.11arcsec
  - Our SDSS optical positions are better than 2MASS for the same objects

Conclusion: Not sure what the limitation is – probably systematic, perhaps optical confusion, but <10mas within reach.

First results from Jim Condon





Conclusions

Blazar emission regions

- Gaia has the potential to answer a fundamental question about where the non-thermal emission comes from by looking for image motion in blazars.
- Such image motion might limit ICRF but picking objects where the blazar light dominates (e.g. BL Lacs) may mitigate the problem

Displaced black holes

- Gaia by itself will have to rely on its intrinsic resolution
- Gaia with radio can potentially give mas displacement accuracy, provided the radio and optical measure different things
- Using e-MERLIN to measure positions for ~10,000 elliptical galaxies is a potentially interesting project