Black Hole Twins in the BCG of RBS 797

(..and A2626 ?)

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- Gitti, Giroletti, Giovannini, Feretti, Liuzzo 2013, A&A, 557, L14
- Gitti 2013, MNRAS Letters in press, arXiv:1308.5825

OABO & DIFA Seminar, 17 October 2013, Bologna

Introduction: SMBBHs

The production and coalescence of **SuperMassive Binary Black Holes** (**SMBBHs**) seem to be a natural consequence of galaxy mergers during the formation of structures

➔ SMBBH systems should be common
(e.g., Begelman, Blandford & Rees 1980; Volonteri, Haardt, Madau 2003; review by Colpi & Dotti 2011)

Important for galaxy formation and evolution!

Introduction: SMBBHs

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(e.g., Begelman, Blandford & Rees 1980; Volonteri, Haardt, Madau 2003; review by Colpi & Dotti 2011)

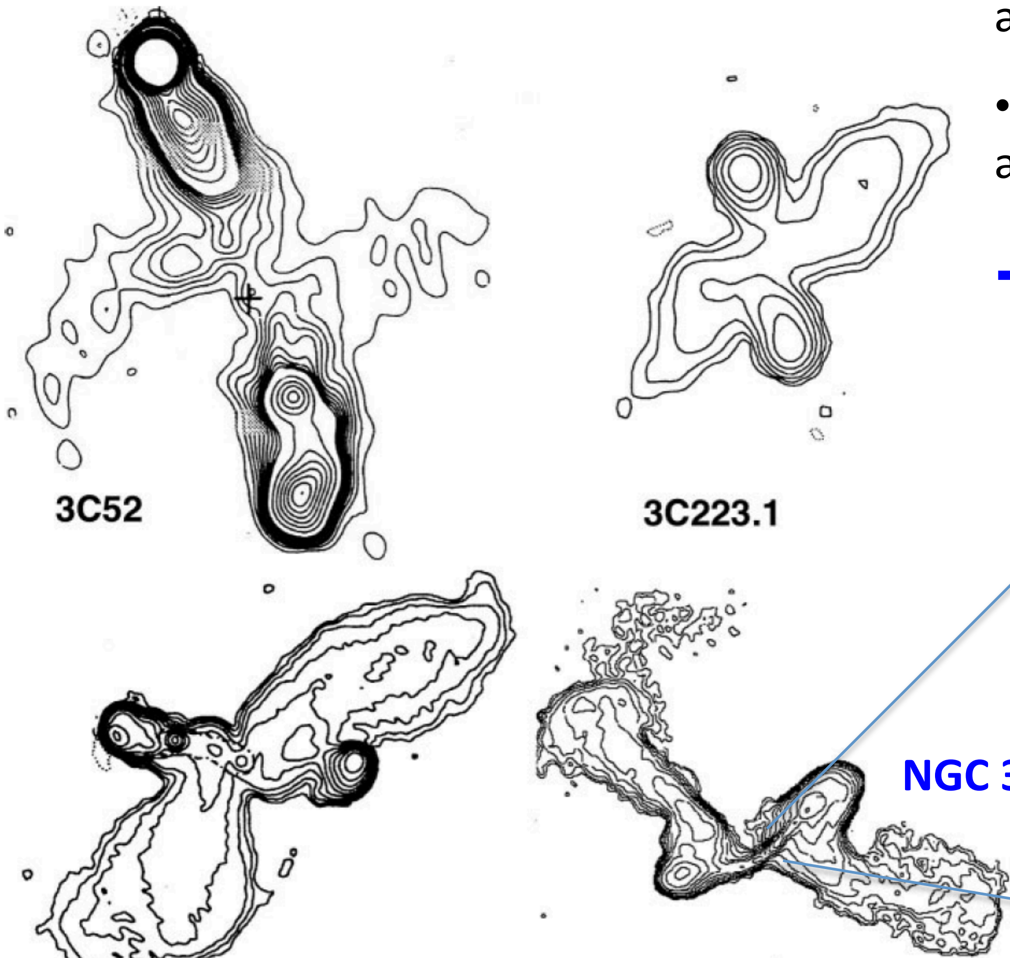
However, observational cases where ***both SMBHs*** in a merging system are accreting as AGNs are rare, and there have only been a few *confirmed* **kpc-scale** binary AGNs detected via various techniques

The detection of dual compact radio or X-ray sources in an active galaxy provides the most unambiguous evidence that a system hosts SMBBHs

(optical data alone, i.e. double-peaked narrow emission line signatures, are not conclusive, e.g., Blecha et al. 2013)

Introduction: SMBBHs *(class of likely candidates)*

X-shaped radio sources

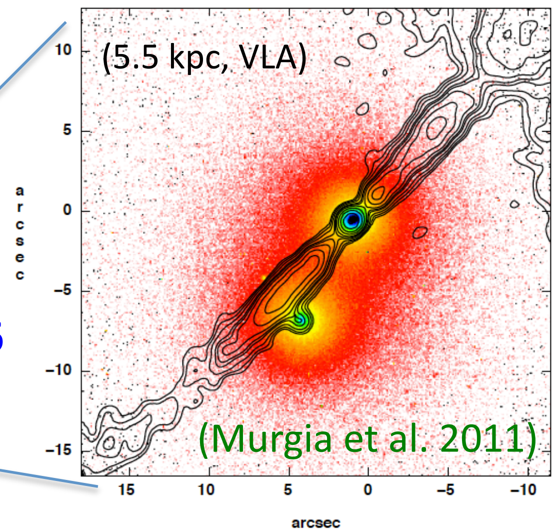


NGC 326

(Merritt & Ekers 2001)

- The jet points in the same direction as the spin axis of the central SMBH
- The merger with a second SMBH can alter the spin axis of the primary SMBH (*spin-flip*)

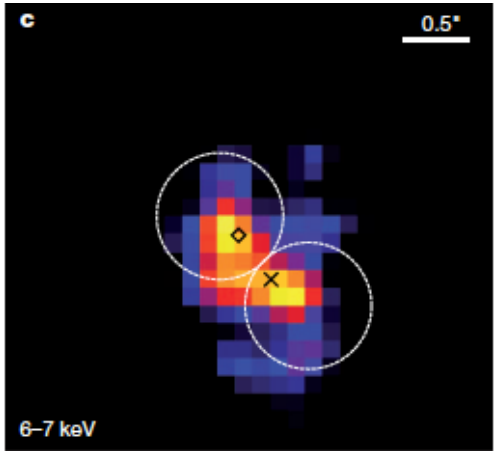
➔ sudden change in the jet direction
+ new radio lobe ad different P.A



(Murgia et al. 2011)

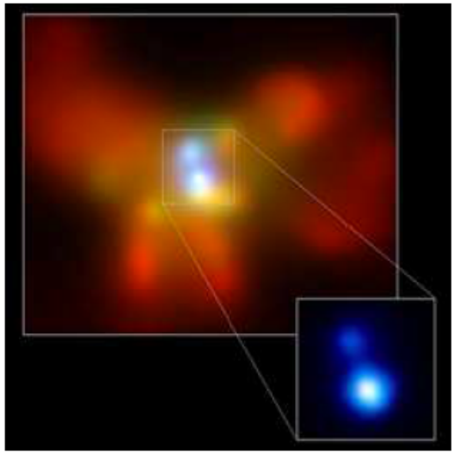
Introduction: SMBBHs *(confirmed dual AGNs)*

NGC 3393 (150 pc, CHANDRA)



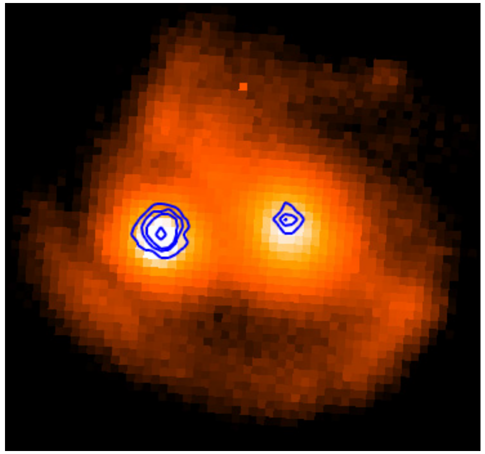
(Fabbiano et al. 2011)

NGC 6240 (700 pc, CHANDRA)



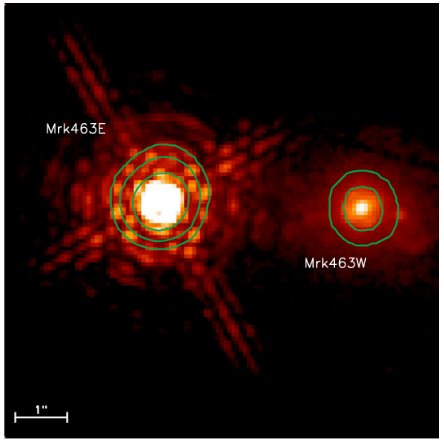
(Komossa et al. 2003)

Mrk 739 (3.4 kpc, CHANDRA)



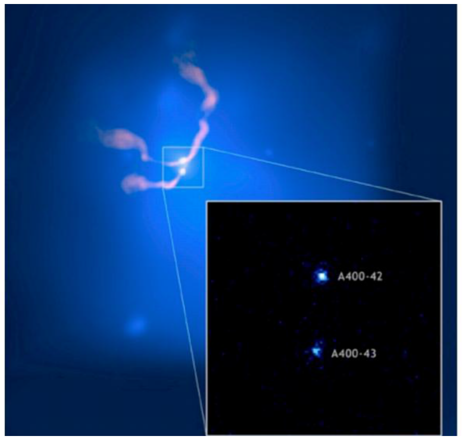
(Koss et al. 2011)

Mrk 463 (3.8 kpc, CHANDRA)



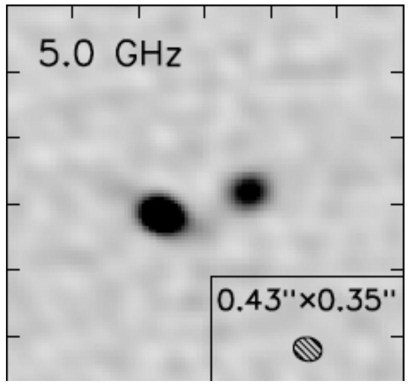
(Bianchi et al. 2008)

3C 75/A400 (7 kpc, VLA/CHANDRA)



(Owen et a. 1985, Hudson et al. 2006)

SDSS J150243.1+111557
(7 kpc, EVLA)



(Fu et al. 2011)

Introduction: SMBBHs

- On the other hand, the longest timescale *(several Gyr)* in the evolution of SMBBHs leading up to coalescence *(GW emission)* is when the binary is closely bound, **~0.1-10 pc separation** (Milosavljević & Merritt 2001, Yu 2002)

The merging of the two SMBHs proceeds in three stages:

1. Dynamical friction

separation ≥ 10 kpc

~ 10-100 Myr

?

2. - stellar slingshot
- interaction with gas
- ...

not very efficient!

SMBBH system stalls at separation ~0.1-10 pc

~several Gyr

3. Gravitational wave (GW) emission

separations ≤ 10^{-3} pc

(~ 100 s)

Introduction: SMBBHs

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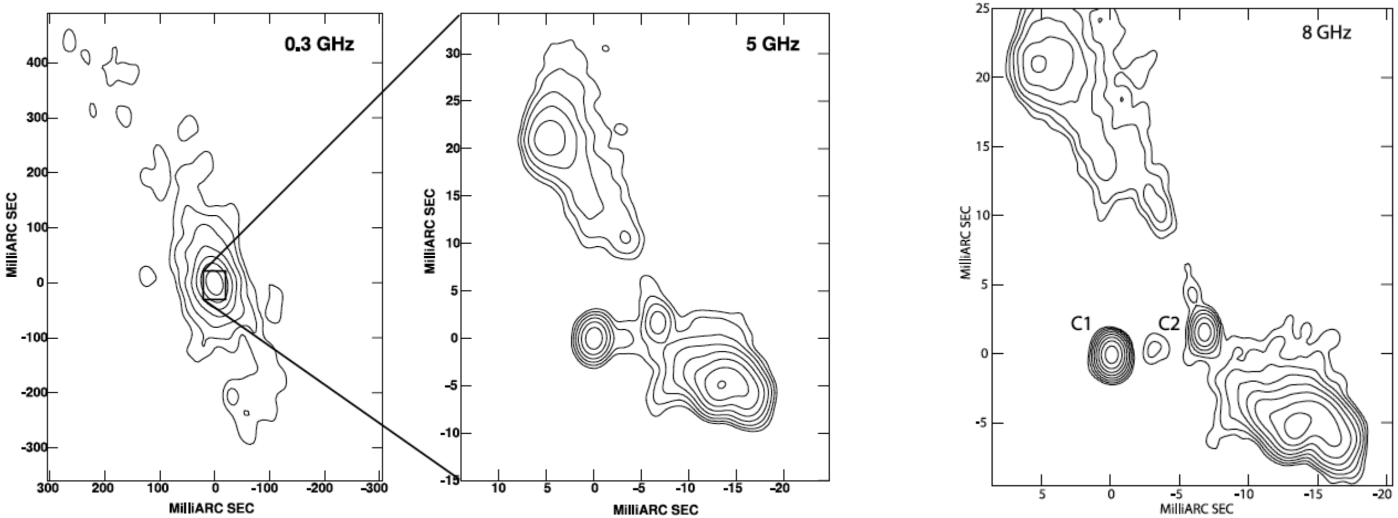
➔ the (radio-loud) SMBH pair in these compact systems can only be resolved by VLBI observations

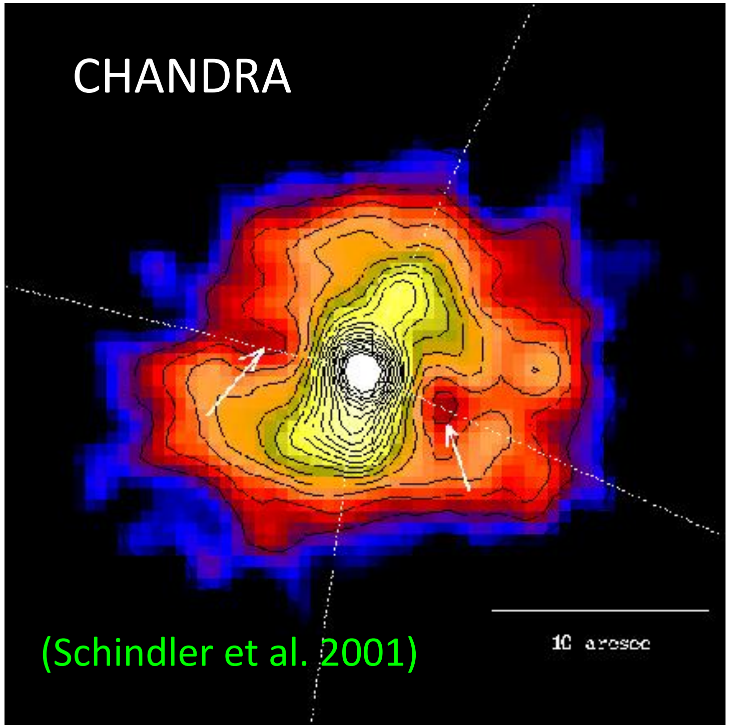
- At present, there is only one confirmed **pc-scale** SMBBH system with separation=7.3 pc

0402+379 (VLBA, Rodriguez et al. 2006)

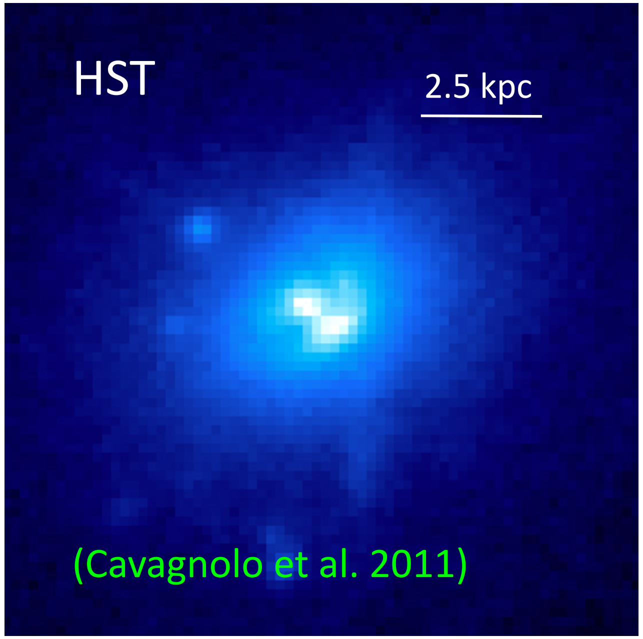


The galaxy cluster RBS 797

- Cool core, first distant (z=0.35) cluster in which two pronounced X-ray cavities have been discovered (size ~20 kpc)
- X-ray point source in the center which coincides with the Brightest Cluster Galaxy (BCG)



(Schindler et al. 2001)

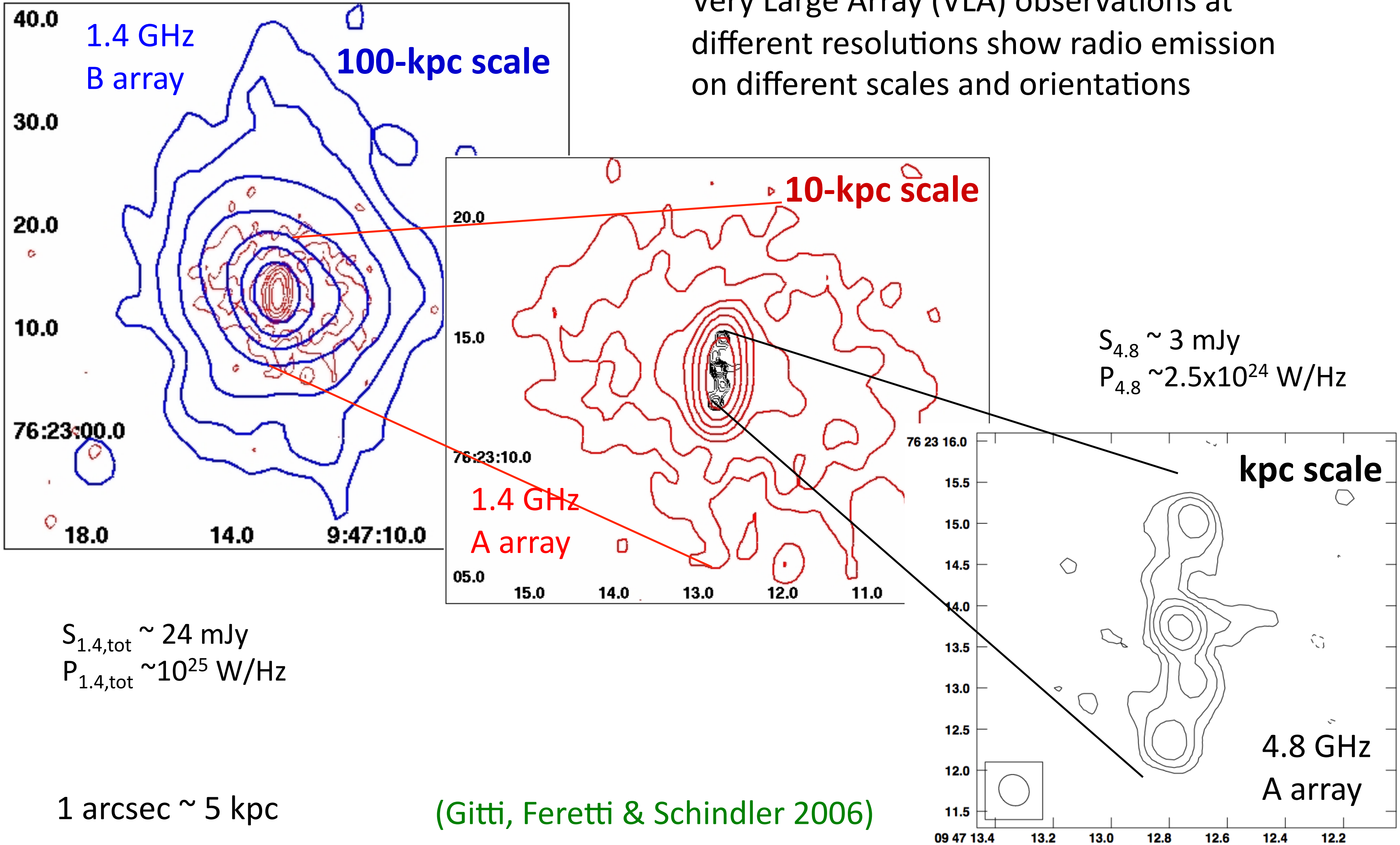


(Cavagnolo et al. 2011)

- The optical BCG shows emission lines typical of AGNs and has the appearance of being bifurcated (dust lane?)

RBS 797: radio properties

Very Large Array (VLA) observations at different resolutions show radio emission on different scales and orientations



$S_{4.8}$ ~ 3 mJy
$P_{4.8}$ ~$2.5\text{x}10^{24}$ W/Hz

$S_{1.4,tot}$ ~ 24 mJy
$P_{1.4,tot}$ ~10^{25} W/Hz

1 arcsec ~ 5 kpc

(Gitti, Feretti & Schindler 2006)

RBS 797: radio properties

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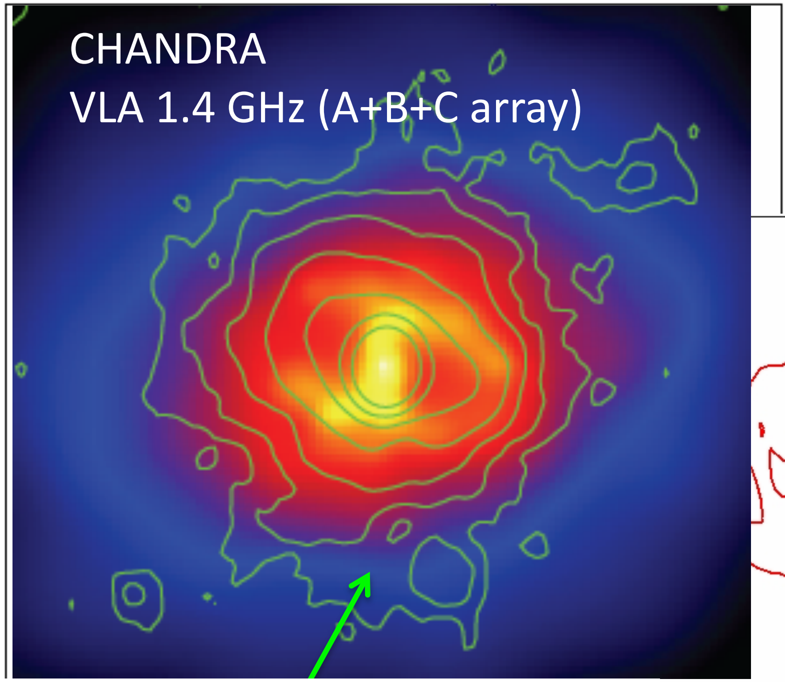
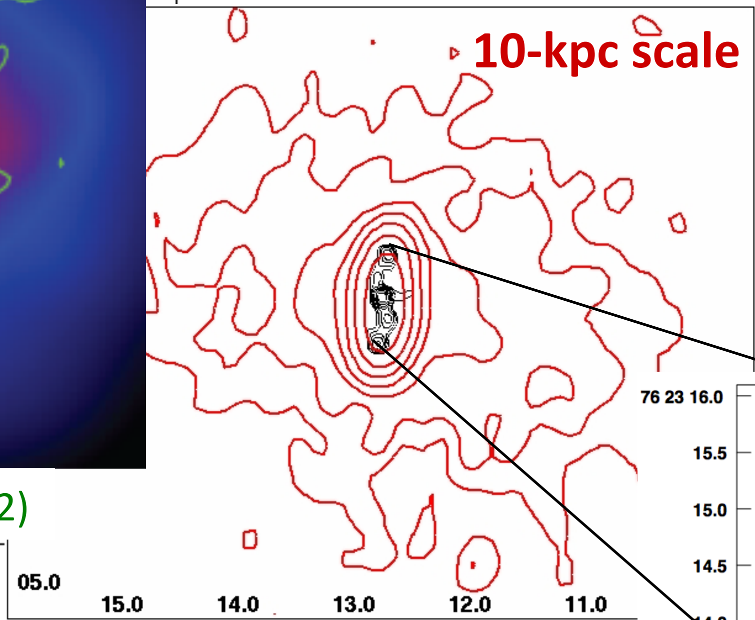
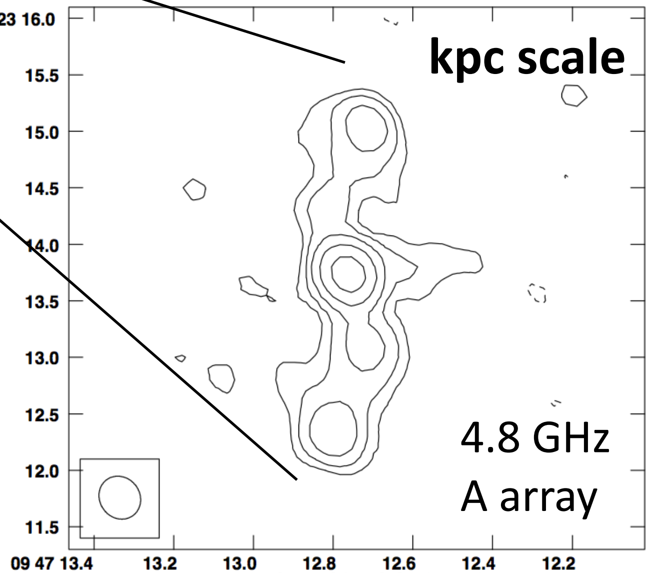


(Gitti, Brighenti & McNamara 2012)





$S_{4.8}$ ~ 3 mJy
$P_{4.8}$ ~2.5×10^{24} W/Hz

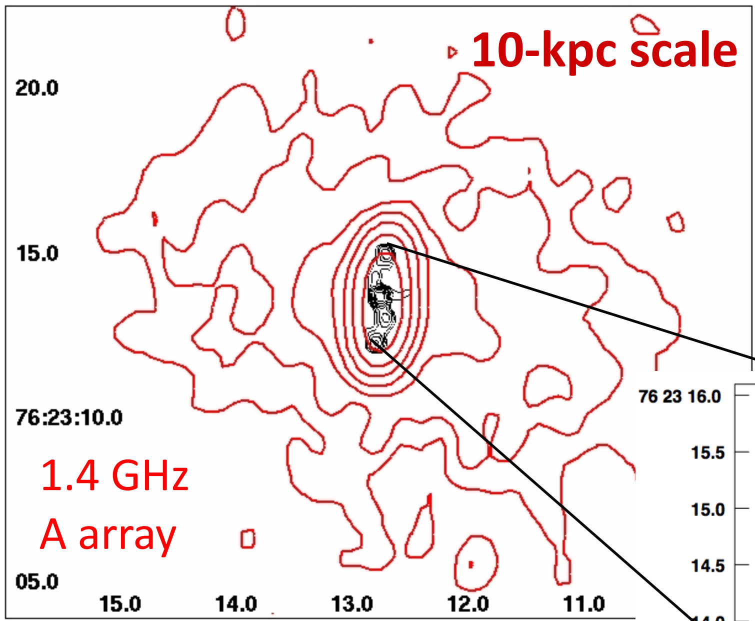
Diffuse emission:
radio mini-halo
(Doria, Gitti et al. 2012)

$S_{1.4,mh}$ ~ 12 mJy
$P_{1.4,mh}$ ~4.8×10^{24} W/Hz

(Gitti, Feretti & Schindler 2006)

RBS 797: radio properties

Very Large Array (VLA) observations at different resolutions show radio emission on different scales and orientations



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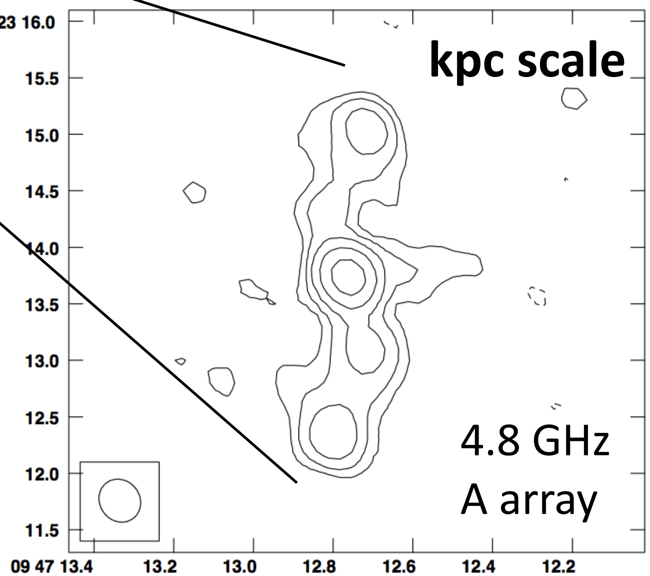
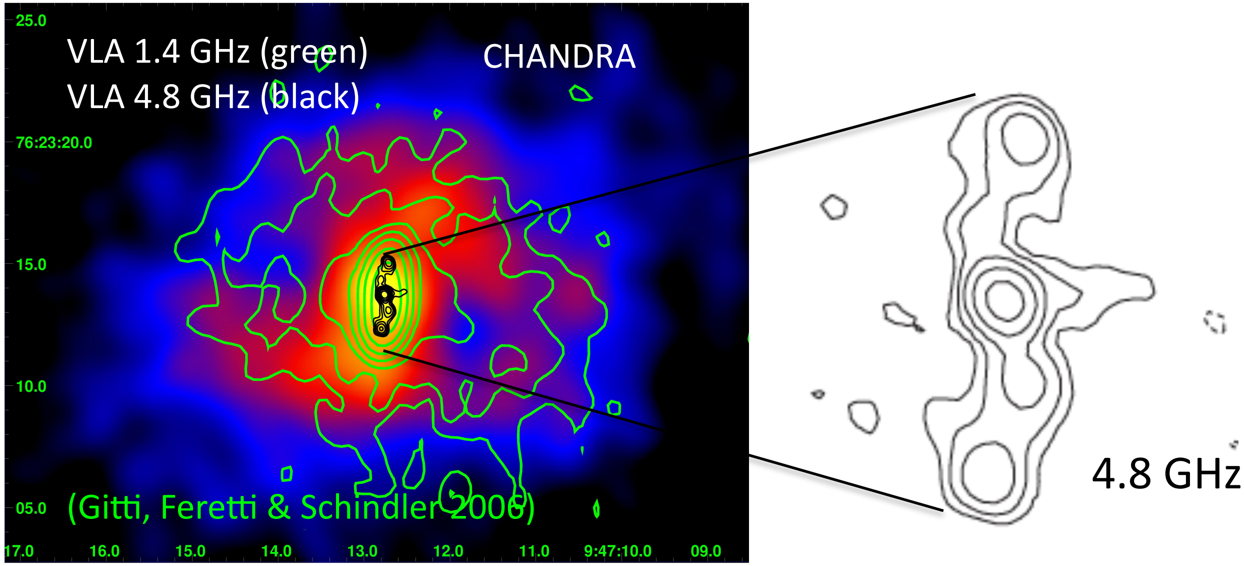


Remarkably, the kpc-scale jets are almost *orthogonal* to the ten-kpc-scale radio emission!

(Gitti, Feretti & Schindler 2006)

RBS 797: indirect evidence of SMBBHs

Radio lobes in active galaxies provide a fossil record of the orientation history of the jets



The kpc-scale jets (N-S) are almost *orthogonal* to the ten-kpc-scale radio emission (E-W) filling the X-ray cavities

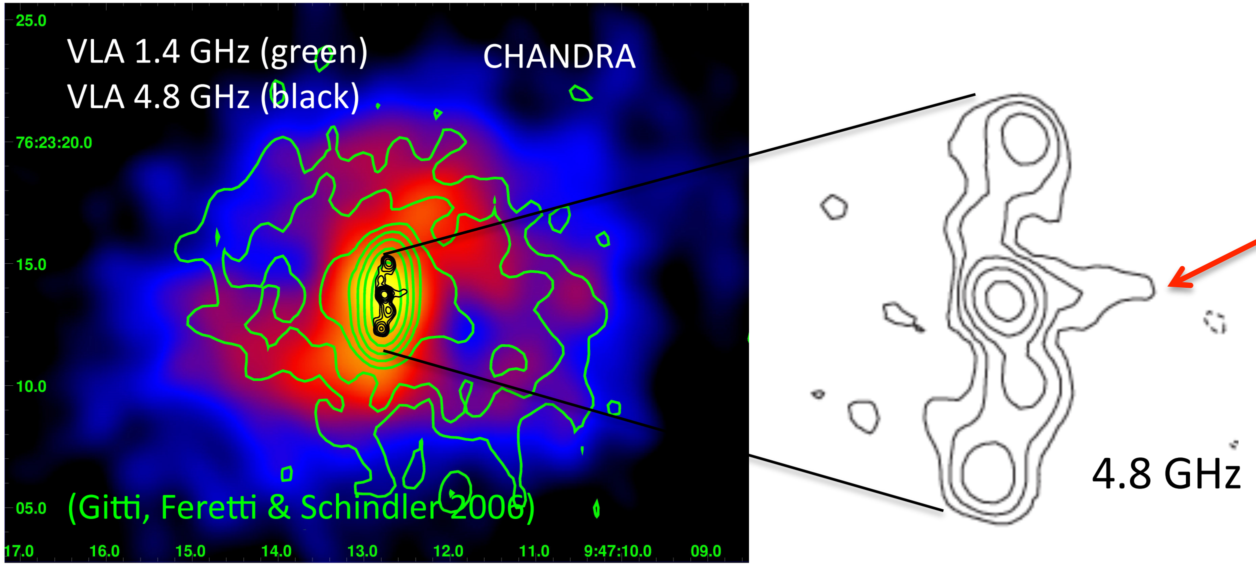
- not slowly precessing jet, but real difference in radio emission P.A.
- no large influence by galaxy motion (BCG)

➔ **Recurrent activity where the jet orientation has changed due to SMBBH effects**

The change in the jet P.A. may be originated by a spin-flip of the primary SMBH caused perhaps by capture of a second SMBH (Merritt & Ekers 2001)

RBS 797: indirect evidence of SMBBHs

Radio lobes in active galaxies provide a fossil record of the orientation history of the jets



Is this feature real?

If confirmed, it may indicate ejecta from a secondary SMBH

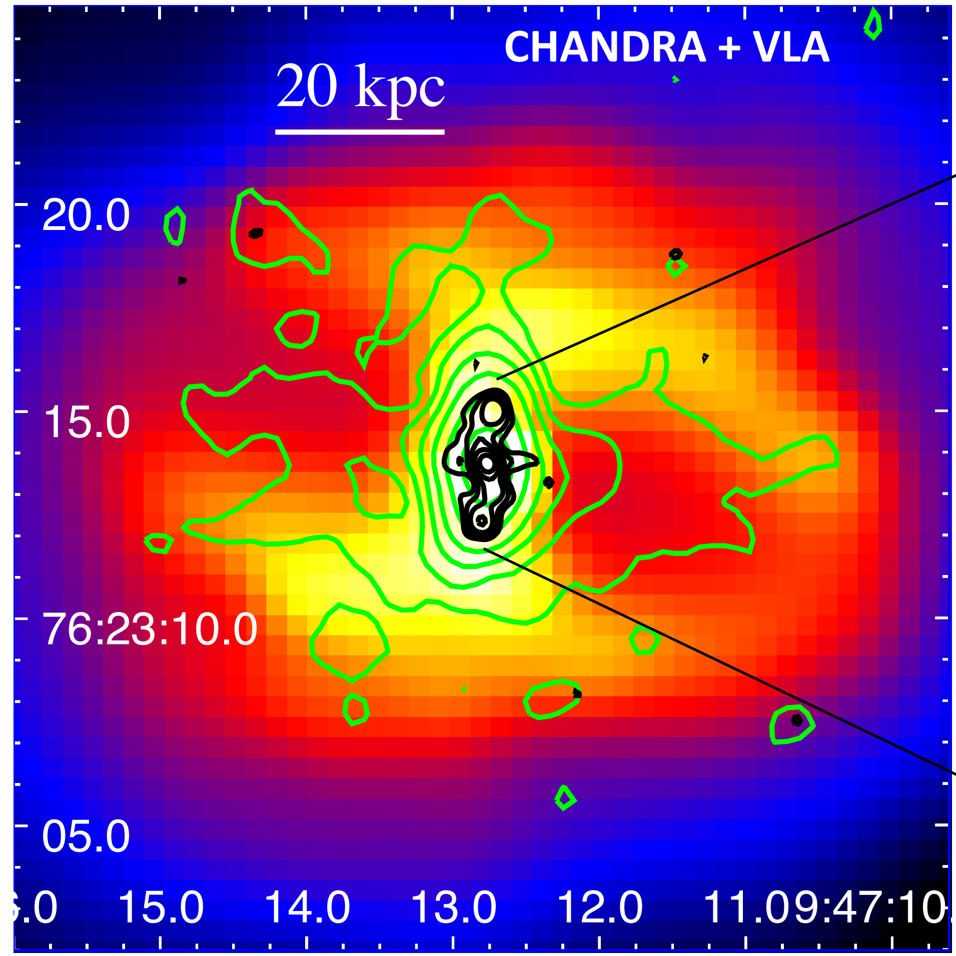
- not slowly precessing jet, but real difference in radio emission P.A.
- no large influence by galaxy motion (BCG)

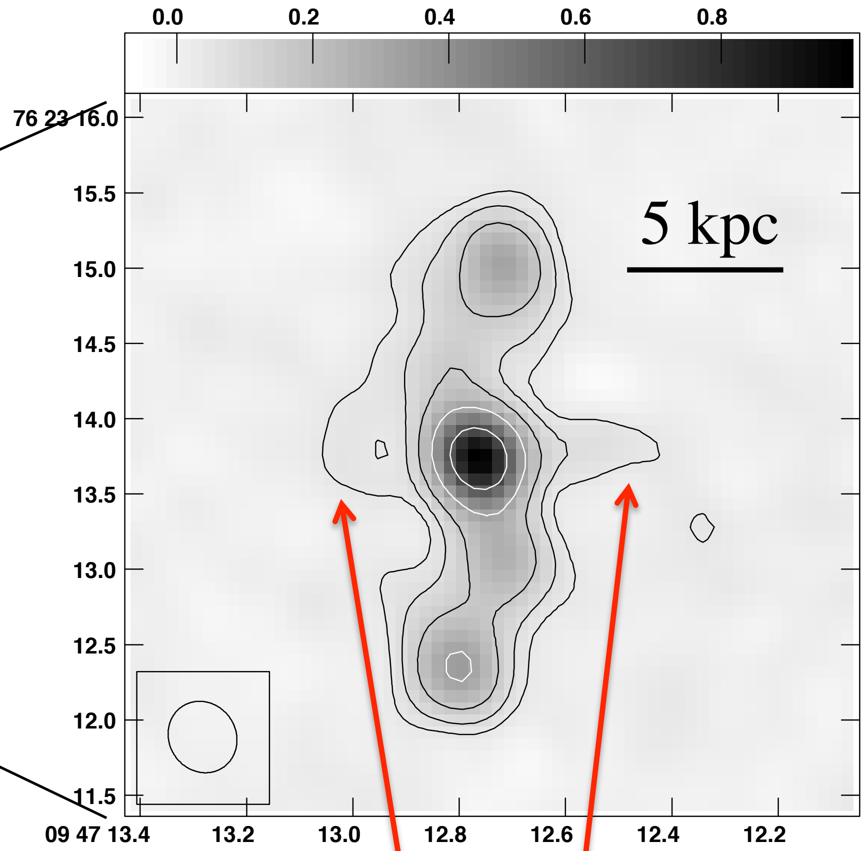
➔ Recurrent activity where the jet orientation has changed due to SMBBH effects

The change in the jet P.A. may be originated by a spin-flip of the primary SMBH caused perhaps by capture of a second SMBH (Merritt & Ekers 2001)

..or two pairs of radio jets ejected in different directions by two active SMBHs ?

RBS 797: re-analysis of VLA data





VLA 4.8 GHz (A+B array)
Green: 1".4 res.
Black: 0".5 res.

The jet-like features are real

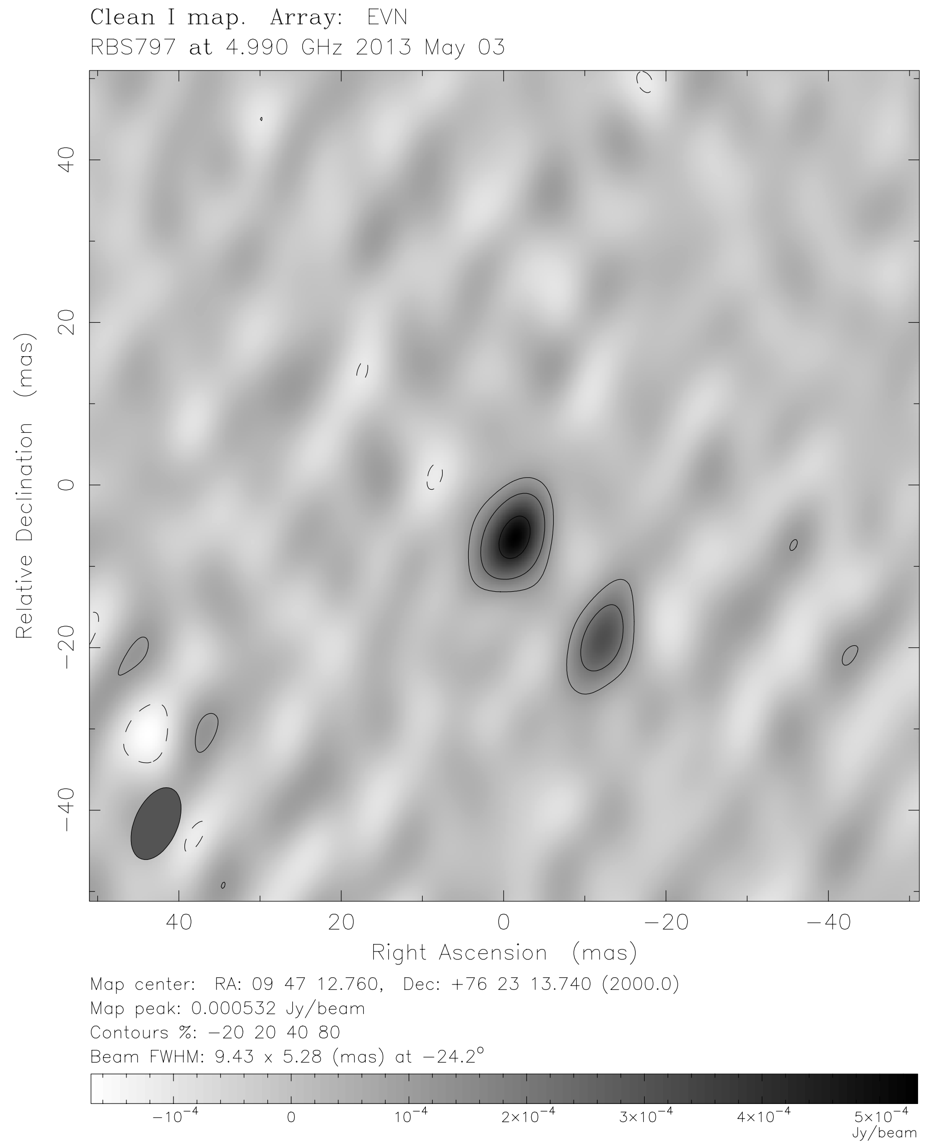
➔ **presence of kpc-scale jets also in the E-W direction!**

(Gitti et al. 2013, A&A, 557, L14)

RBS 797: new EVN observations

- Test observations with the **European VLBI Network (EVN)** on 3 May 2013 (PI Gitti)
- Frequency: 5 GHz
- **Angular resolution: 9 x 5 mas^2**
- Time on source ~ 1 hour
- Sensitivity ~ 36 μJy / beam

➔ **We clearly detected two compact components !**



Nature of the EVN double source

C1 : flux density 0.61 mJy

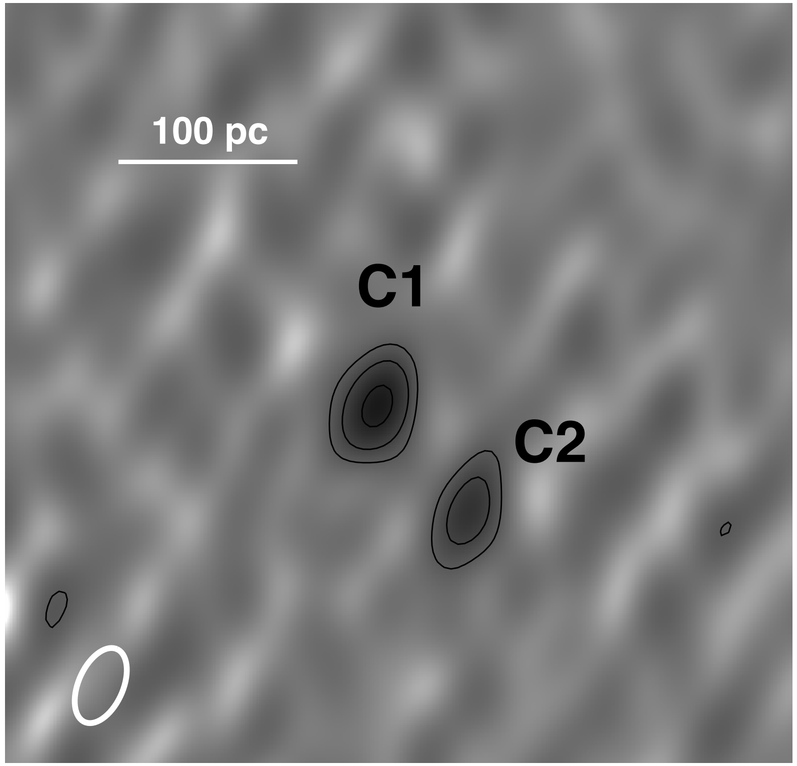
C2 : flux density 0.54 mJy

Separation ~ 16 mas ~ 77 pc

Two scenarios are possible:
the components C1 and C2 are

(1) two different nuclei in a close binary system; or

(2) the core and a knot of its jet



Two compact components separated by ~77 pc

(Gitti et al. 2013, A&A, 557, L14)

(1) Two nuclei in a binary system

This scenario is favored by the compactness of the two VLBI components and by the large-scale VLA radio properties

- The EVN detection of two compact components is remarkable

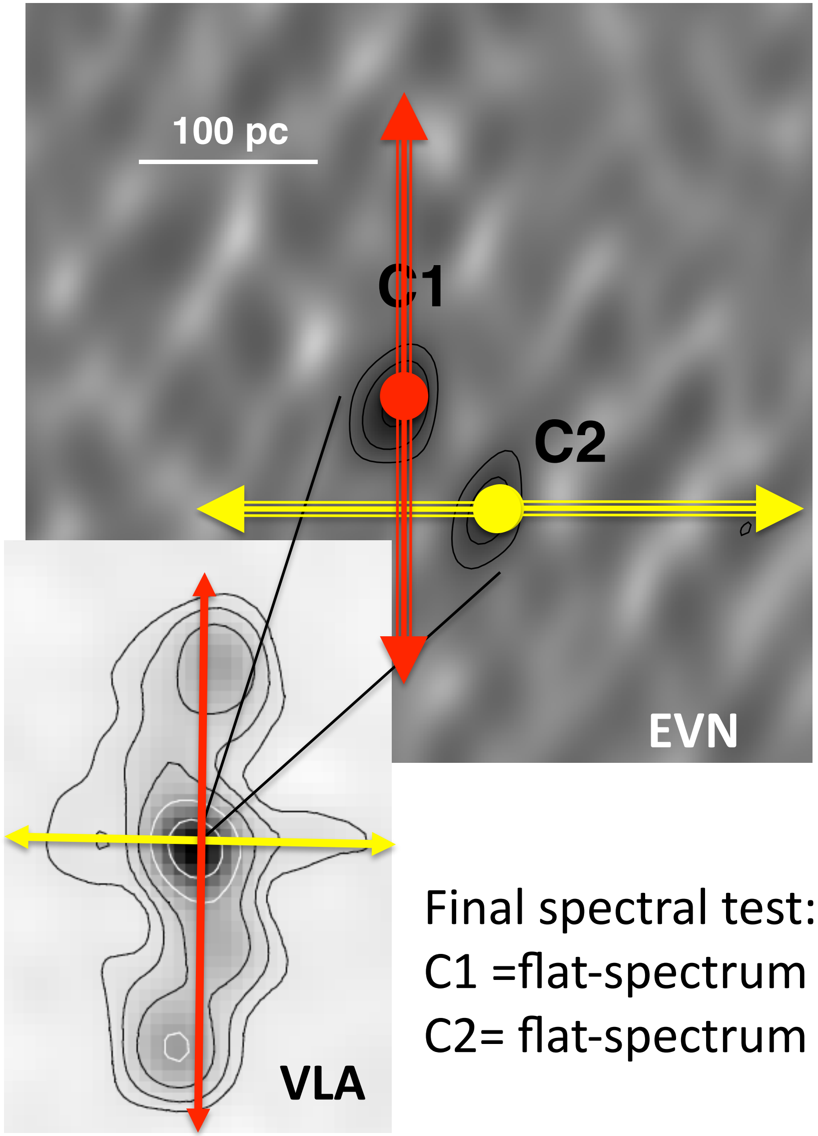
(5 GHz VLBI detection rate in a complete sample of BCGs ~68%, only 1 double source, Liuzzo et al. 2010)

- VLA data show **two pairs of radio jets**, misaligned by ~90°, ***on the same kpc scale***

➔ two outbursts almost contemporaneous

➔ ***two active SMBHs*** **with different ejection orientation**

(radio nuclei unresolved with the VLA)



Final spectral test:
C1 =flat-spectrum
C2= flat-spectrum

(2) Core-Jet structure

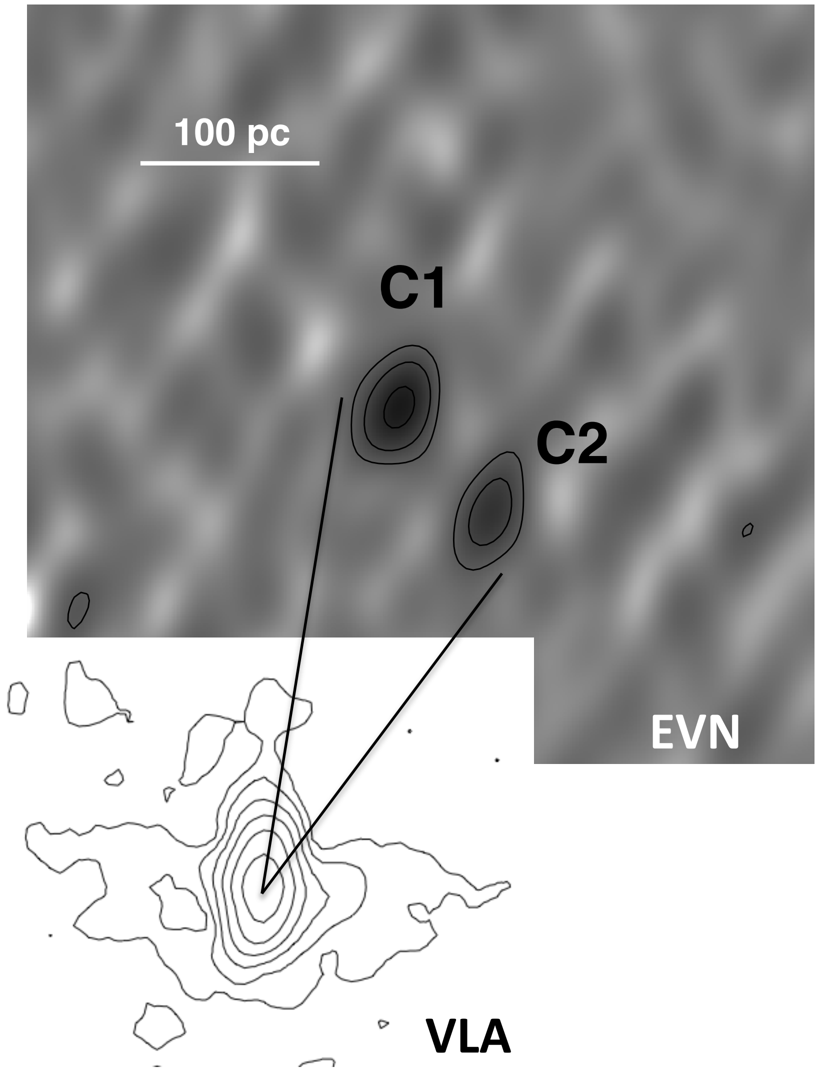
C1 is the most likely main core candidate
(more compact and brighter)

The presence of SMBBHs is possible also in this scenario:

VLA data show a misalignment by ~90° of inner N-S jets and extended E-W emission

➔ recurrent activity from a single SMBH that has changed ejection orientation because of the interaction with a *secondary (undetected) SMBH*

➔ VLBI double source:
core-jet structure of the *primary (active) SMBH*



(2) Core-Jet structure

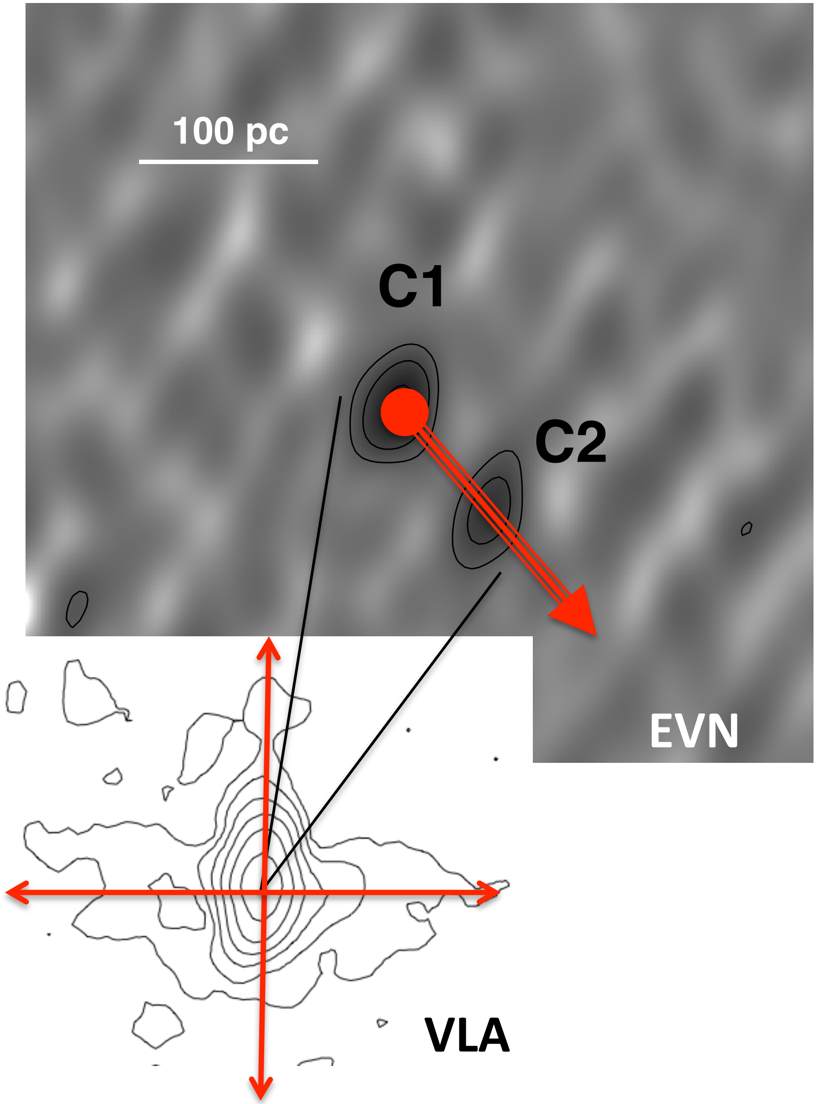
However, this scenario is disfavored by the orientation of the C1-C2 vector:

the pc-scale jet flow would not be aligned with any of the directions seen at kpc-scale in the VLA images

Final test only through a multi-frequency space-resolved spectral study:

C1 = flat-spectrum core
C2 = steep-spectrum jet knot

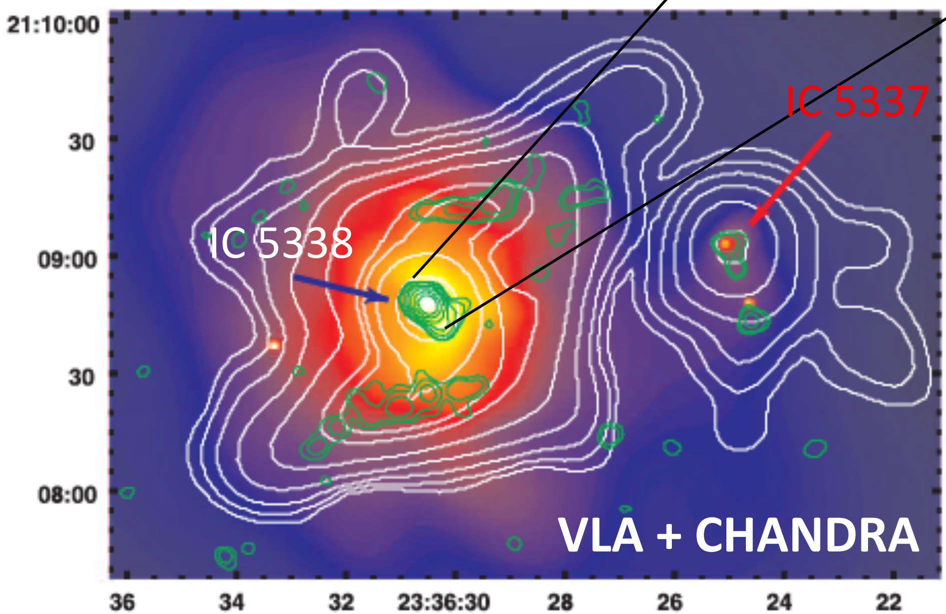
+ deep search for extended jet emission connecting C1-C2

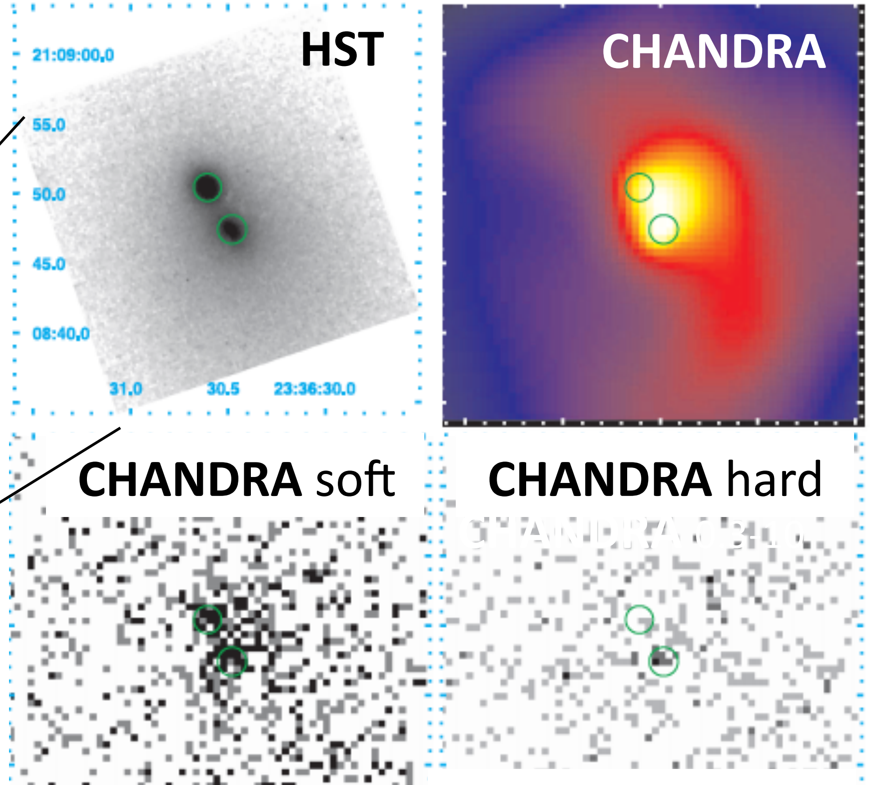


The galaxy cluster Abell 2626

- Cool core, included in the first mini-halo cluster sample (Gitti et al. 2004)

- No obvious correlation between radio and X-ray features (Wong et al. 2008)





(Wong et al. 2008)

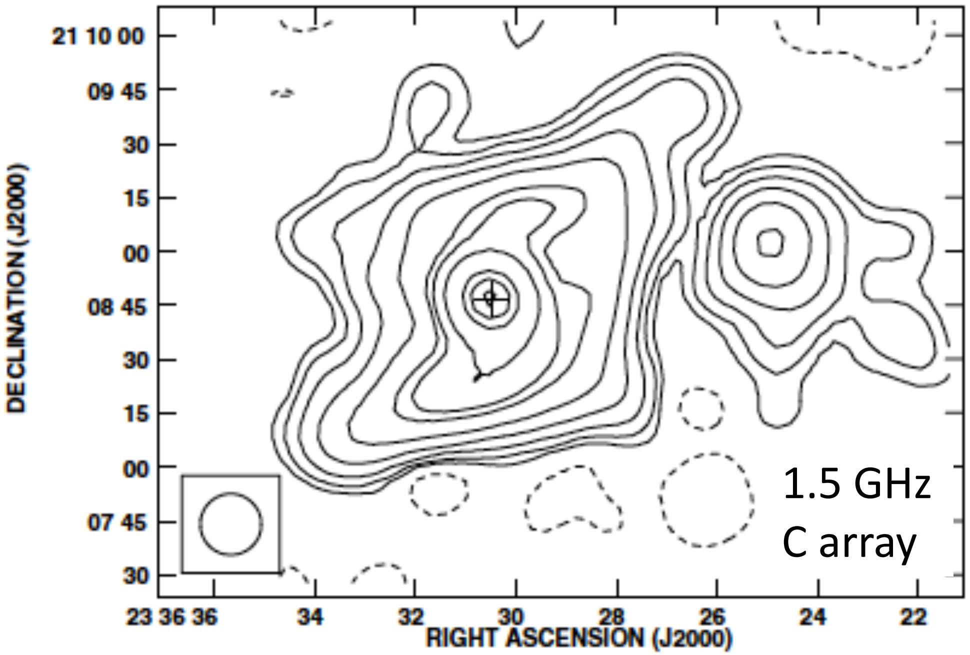
- Double-nuclei cD elliptical galaxy (IC 5338), separation 4 kpc

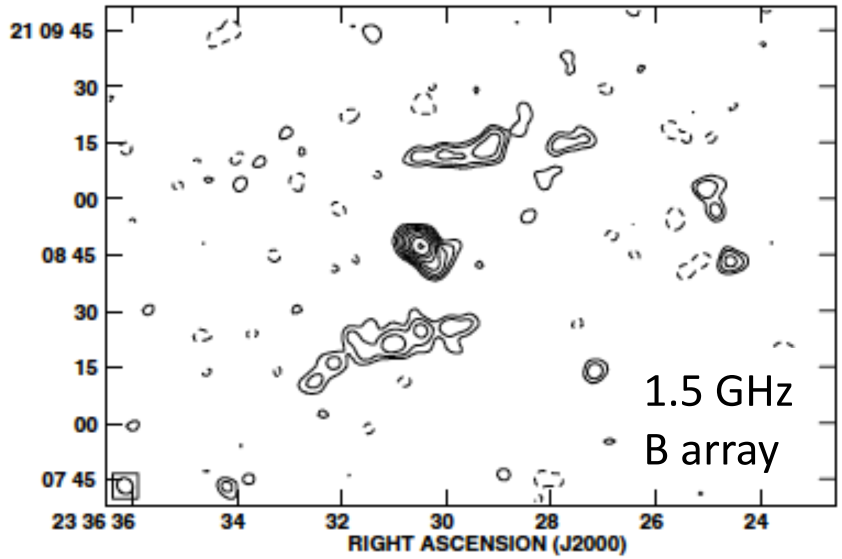
- Only SW nucleus is active

A2626: radio properties

- Diffuse, diamond–shaped radio emission
- Two parallel radio "bars" seen at higher resolution

➔ **origin unclear**
(no X-ray cavities associated)





1 arcsec ~ 1 kpc

Interpretation (Gitti et al. 2004):

The two radio bars are distinct from and embedded in the diffuse emission, which is classified as a **radio mini-halo** and successfully modeled as syn. emission from relativistic electrons reaccelerated by MHD turbulence in the cool core region

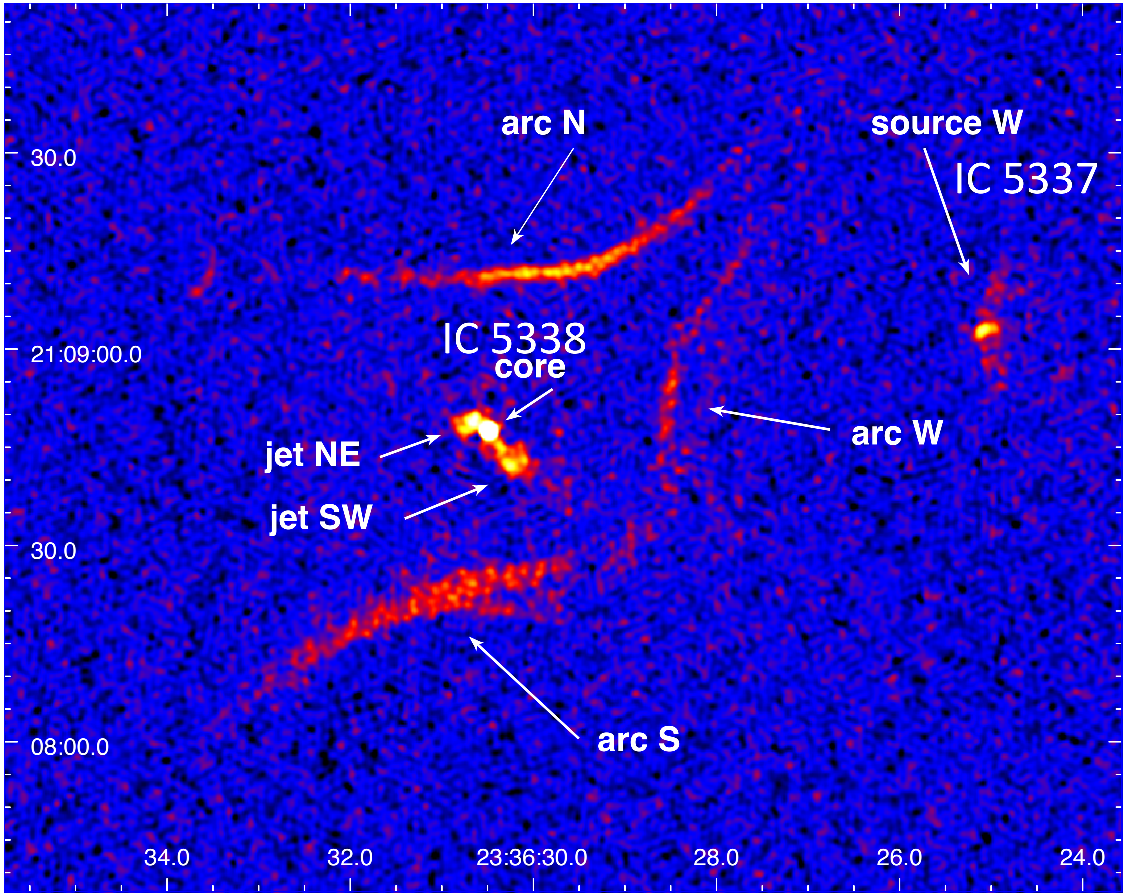
A2626: new VLA observations

- 12 hours at 1.4 GHz array A+B (PI Gitti)
- Sensitivity improved by a factor ~3
- Full resolution: 1.2”

✓ Core-jets resolved (S~18 mJy, P~1.4x10^{23} W/Hz)

✓ Bars ➔ narrow arcs

✓ **New arc to the W**



(Gitti 2013, MNRAS Letters in press, arXiv:1308.5825)

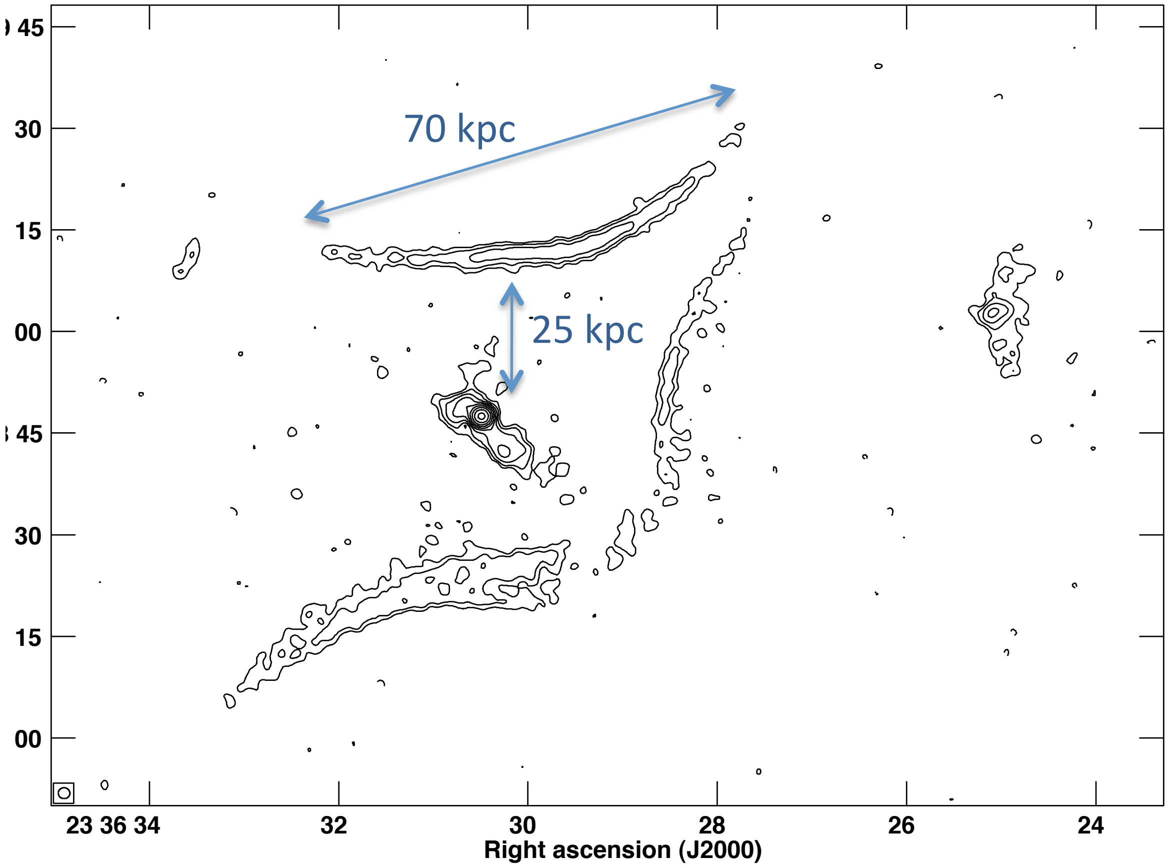
A2626: new VLA observations

- 12 hours at 1.4 GHz array A+B (PI Gitti)
- Sensitivity improved by a factor ~3
- Resolution: 1.6”

✓ Core-jets resolved (S~18 mJy, P~1.4x10^{23} W/Hz)

✓ Bars ➔ narrow arcs

✓ **New arc to the W**



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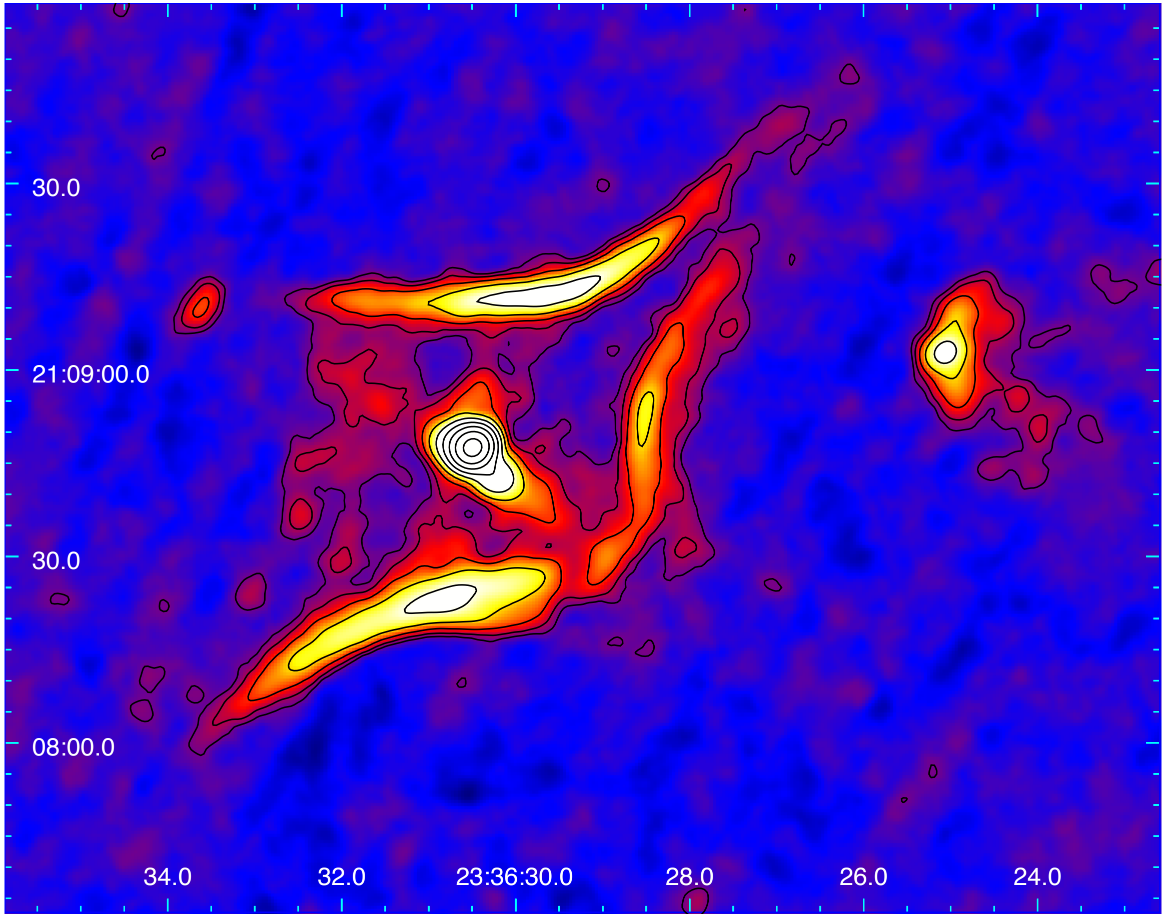
A2626: new VLA observations

- 12 hours at 1.4 GHz array A+B (PI Gitti)
- Sensitivity improved by a factor ~3
- Resolution ~ 4”

✓ Bars ➔ narrow arcs

✓ **New arc to the W**

✓ Diffuse emission

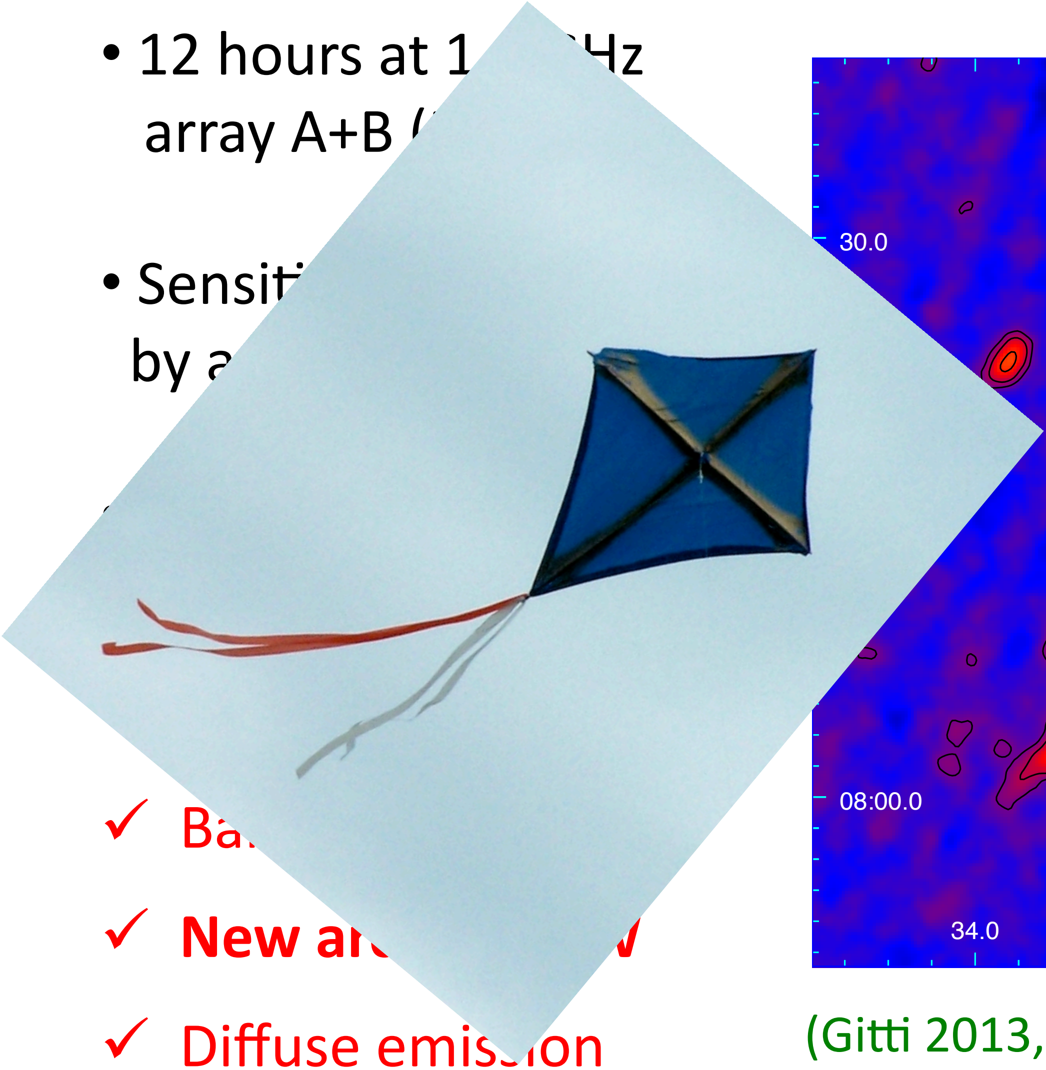


(Gitti 2013, MNRAS Letters in press, arXiv:1308.5825)

A2626: the “Kite” radio source

• 12 hours at 1 … Hz
array A+B (

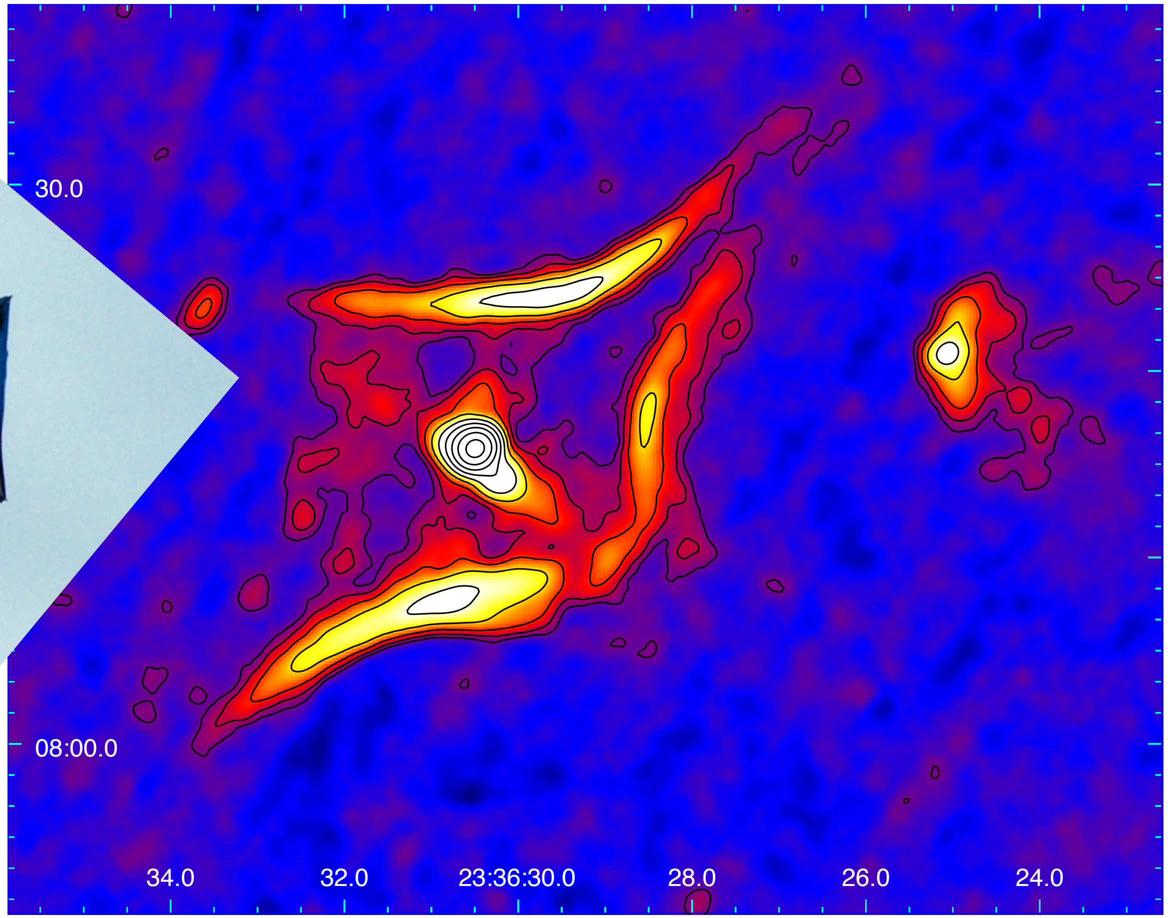
• Sensit…
by a…



✓ Ba…

✓ **New ar… v**

✓ Diffuse emis…ion



(Gitti 2013, MNRAS Letters in press, arXiv:1308.5825)

A2626: diffuse emission

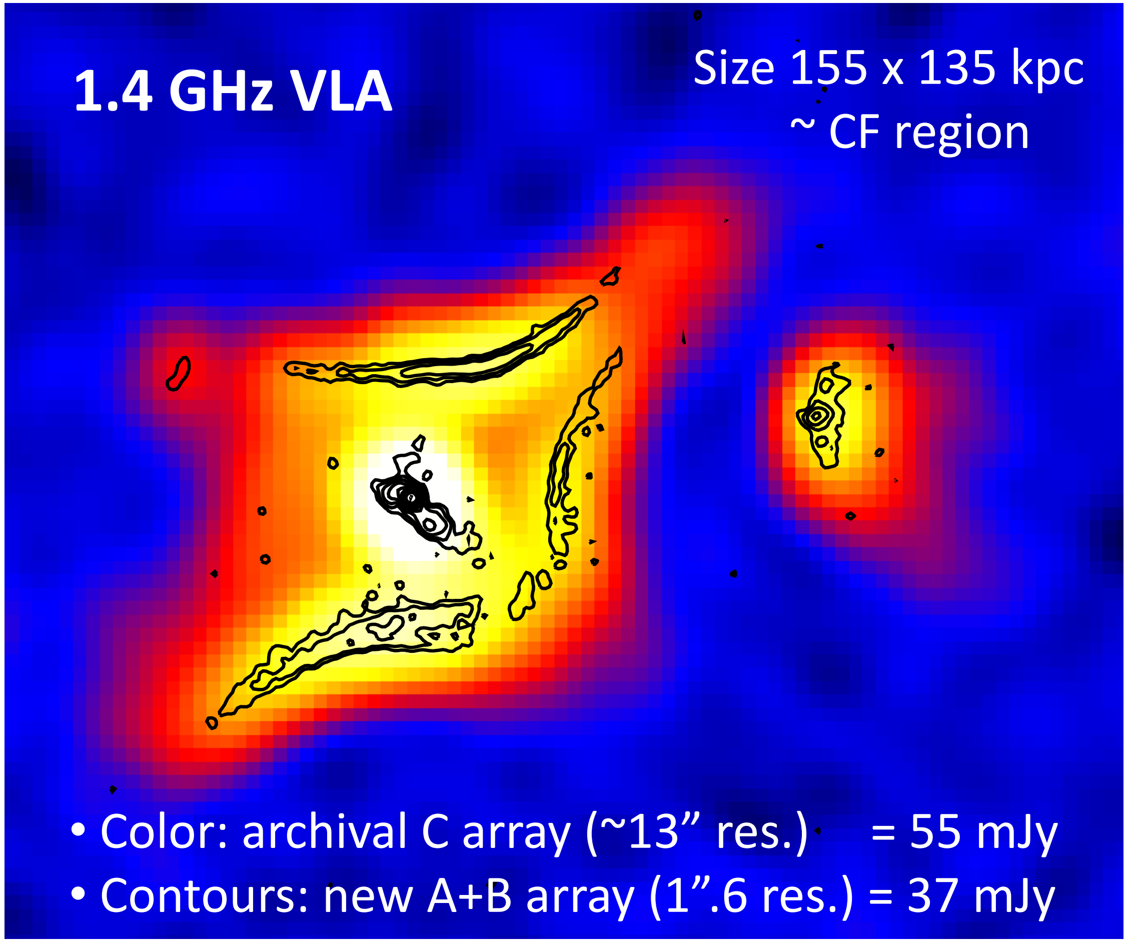
Subtraction of discrete features:
residual 18 mJy of diffuse em.

$P_{1.4}$ = 1.4 x 10^{23} W/Hz

(previous estimate: 2.3x10^{23} W/Hz)

The radio power still follows the trend with the power of cooling flows ($\dot{M}kT/\mu m_p$) expected by the reacceleration model

(Gitti, Brunetti & Setti 2002; Gitti et al. 2004)



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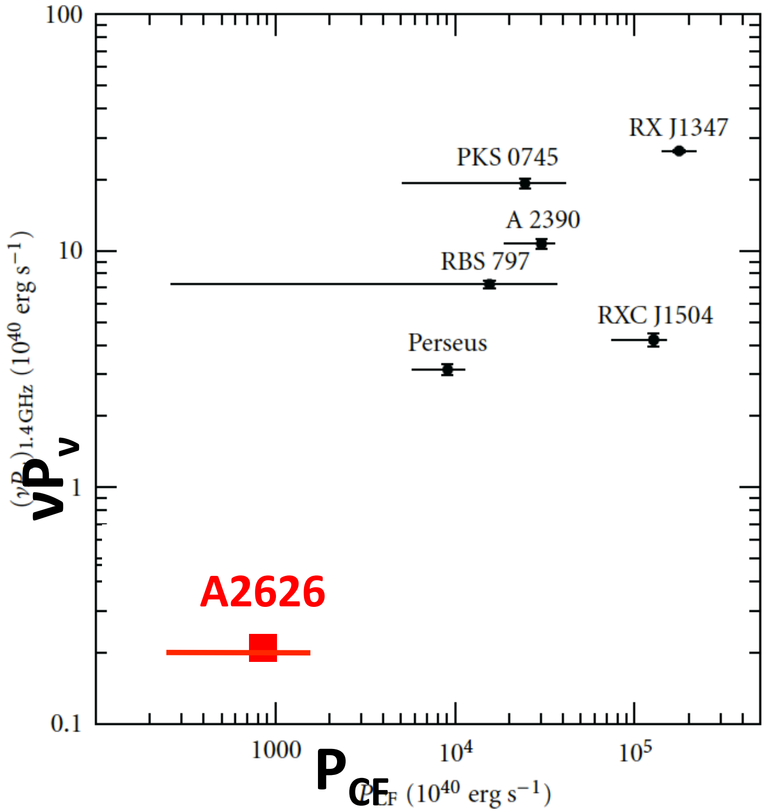
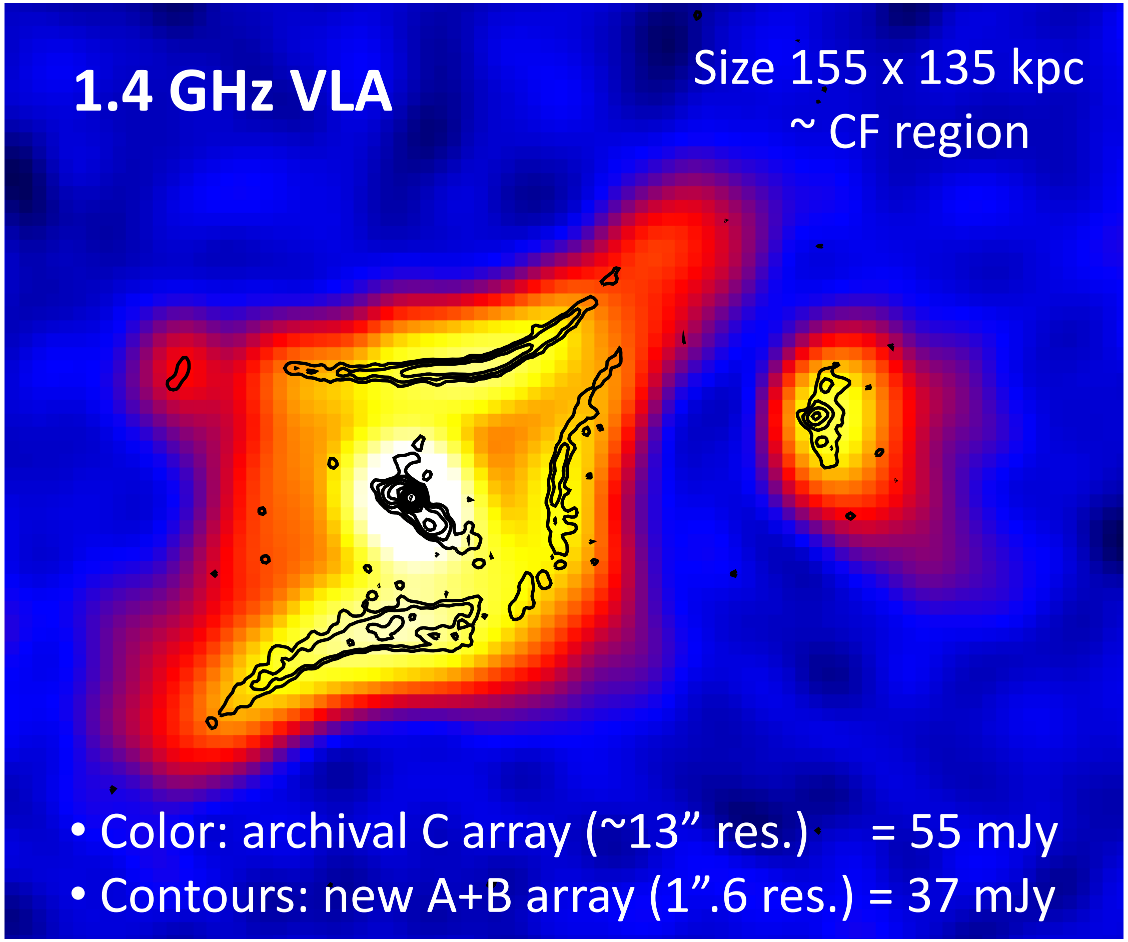
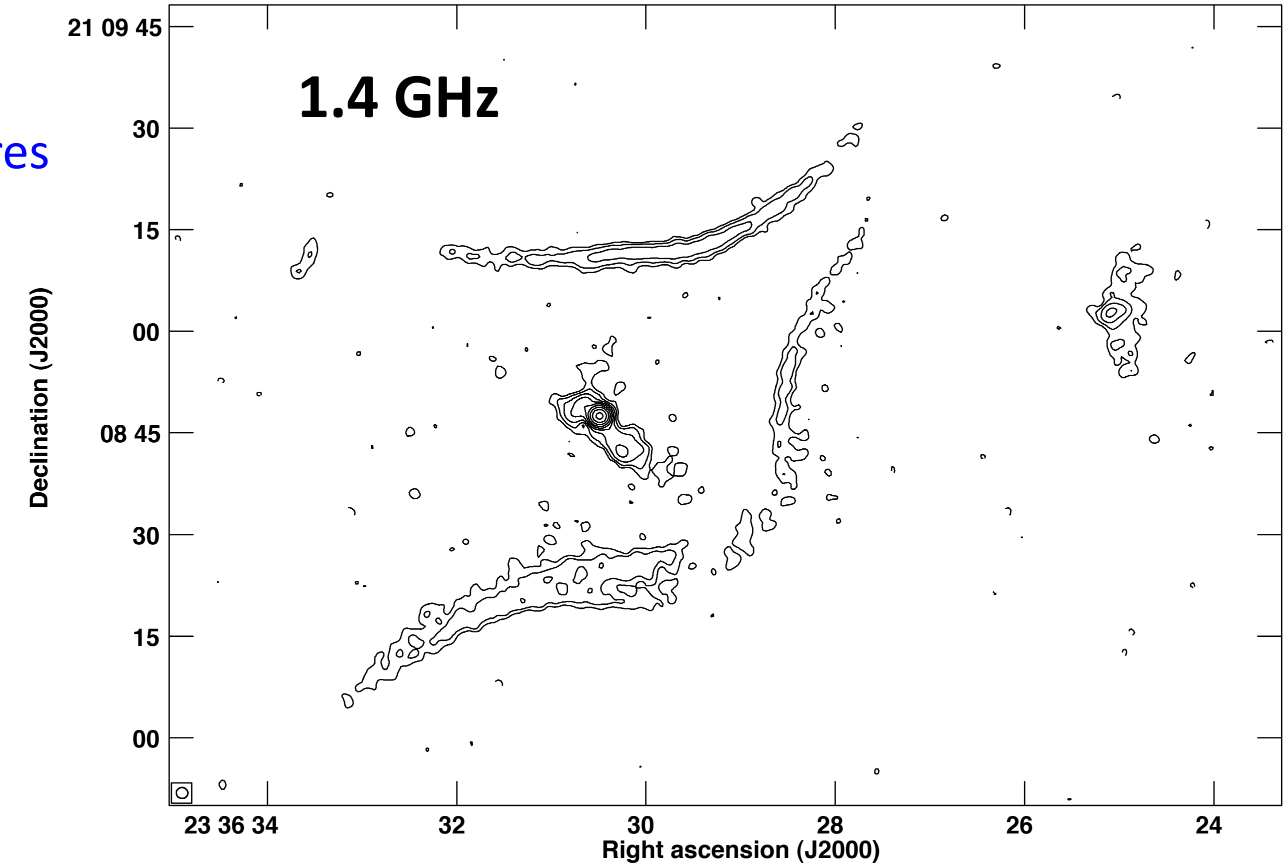




may still be classified as a radio mini-halo

A2626: radio arcs

• Elongated morphology not common to typical jet-lobe bubbles in cool cores
(no X-ray cavities associated
+ no torus-like concavity)



A2626: radio arcs

- Elongated morphology not common to typical jet-lobe bubbles in cool cores
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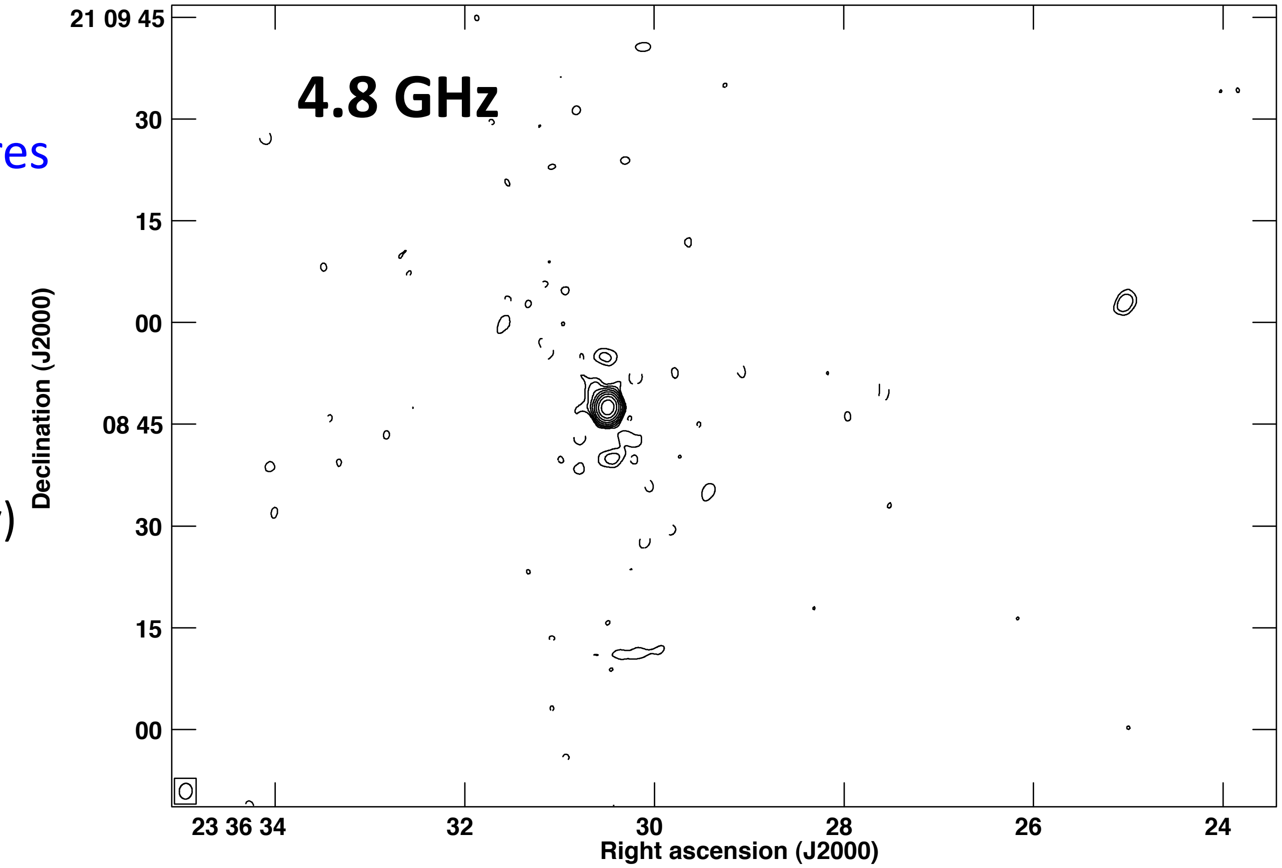
- Steep spectrum, α >1
  (not detected in our new 7h obs. at 4.8 GHz, A+B array)



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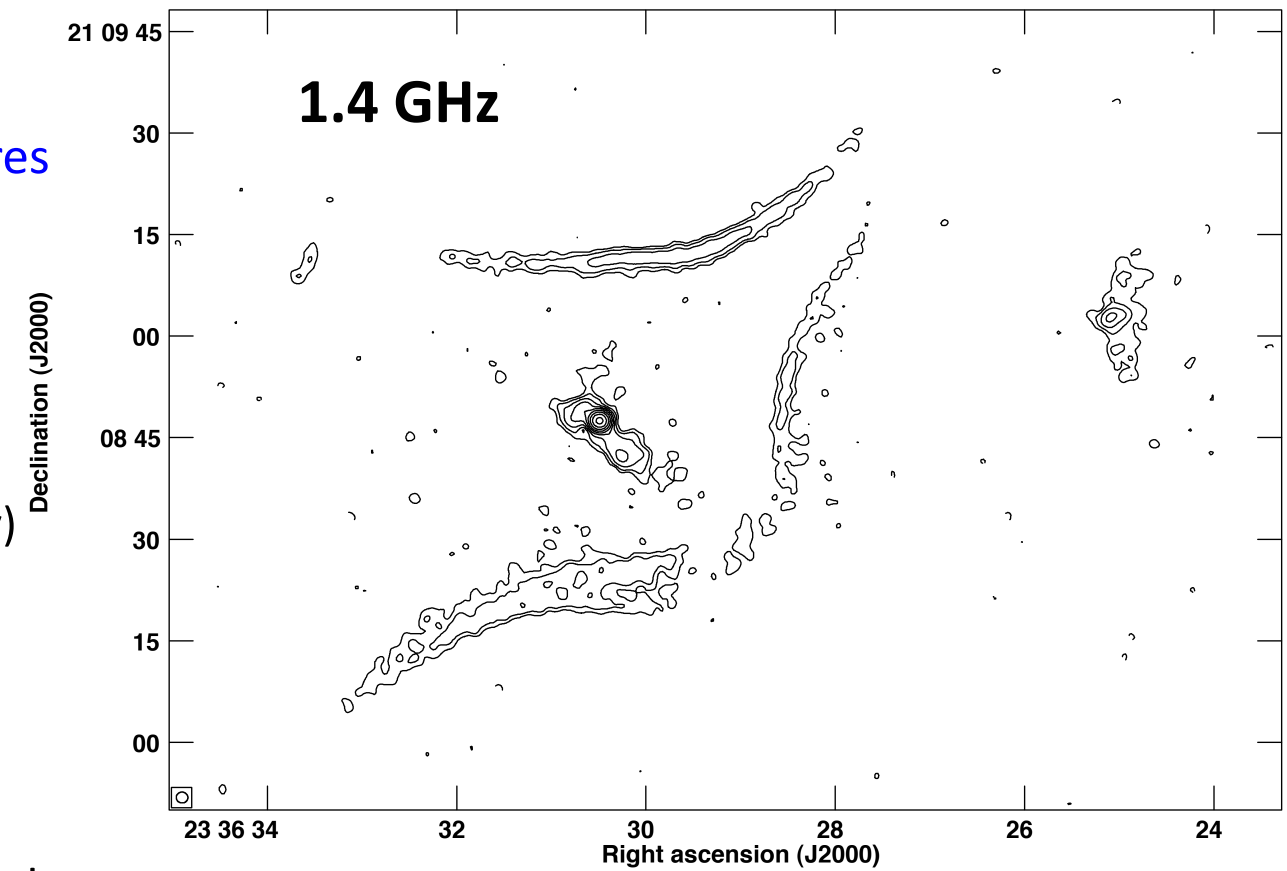
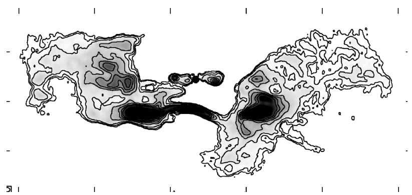
➔ each radio arc is similar to **cluster radio relics** associated with particle reacceleration due to shocks (e.g., Feretti et al. 2012)



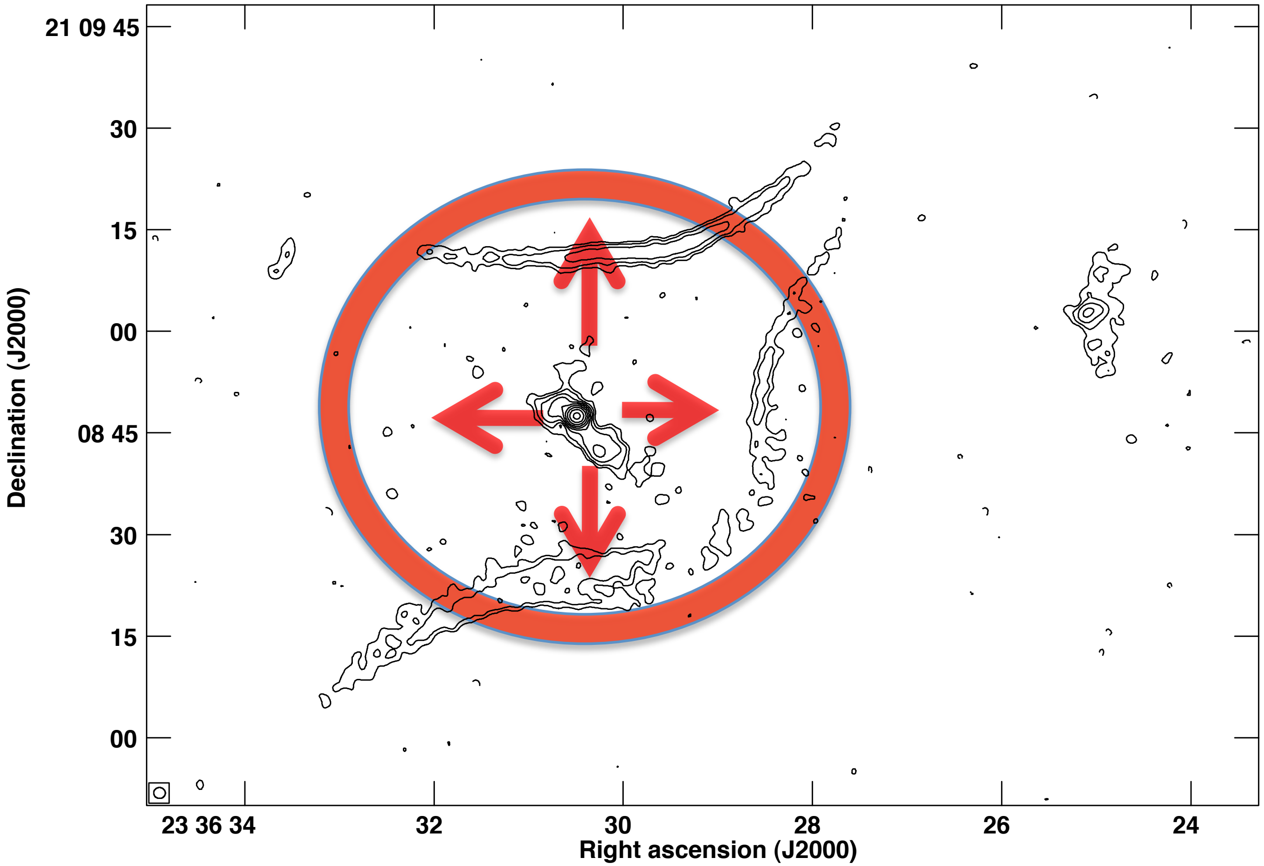


← .. see also 3C 338 (Giovannini et al. 1998)

A2626: radio arcs

Relics due to shocks?

1. One single shock propagating *from* the center ?



BUT..

wrong concavity

+ no polarization..

A2626: radio arcs

Relics due to shocks?

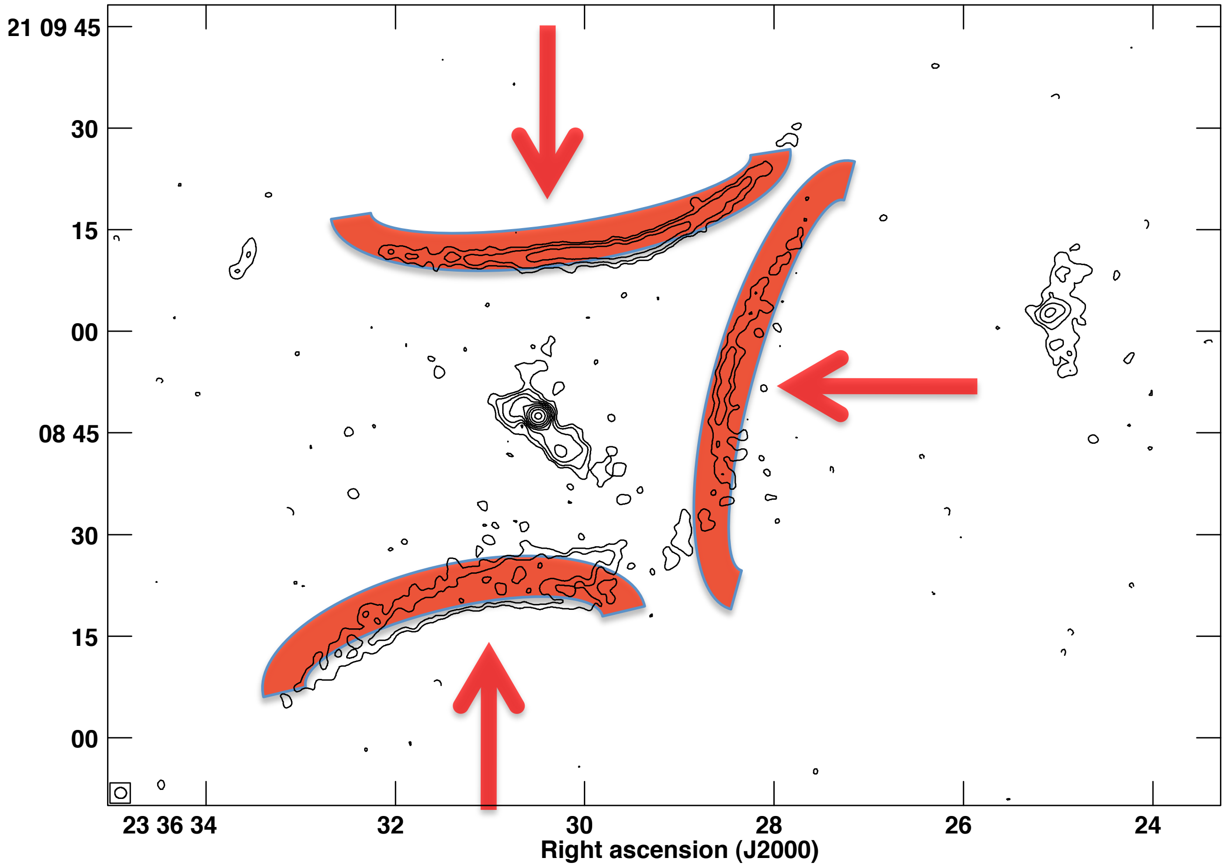
1. ~~One single shock propagating *from* the center ?~~

2. **Three distinct shocks** propagating *toward* the center?

Unlikey..

(relaxed cluster, no X-ray edges seen in Chandra data)

+ no polarization..



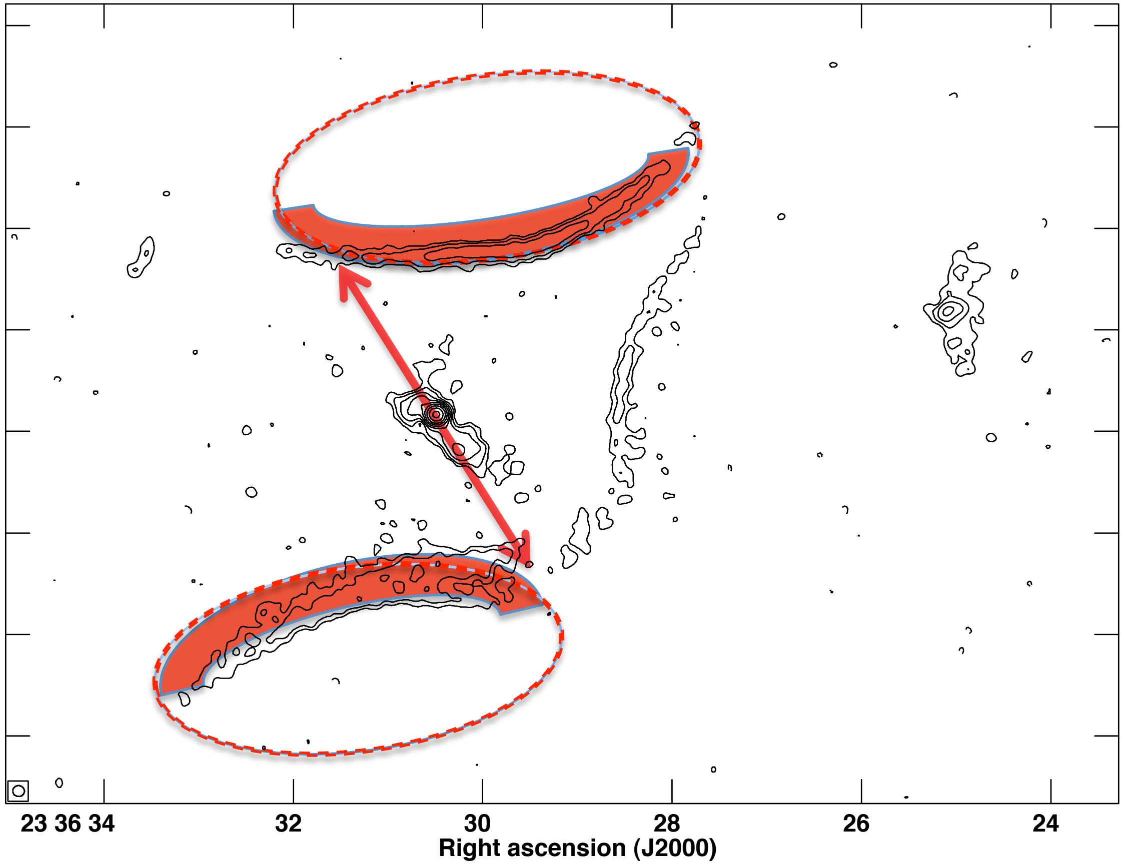
A2626: radio arcs

Precessing jets ?

- Particle acceleration by N-S precessing jets stopped at a "working surface" (Wong et al. 2008)

  ✓ Shape consistent with segment of circles seen at high inclination angle

  ✓ Radiative lifetime of the radio-emitting electrons ~1/3 of the precessing period of the jets



A2626: radio arcs

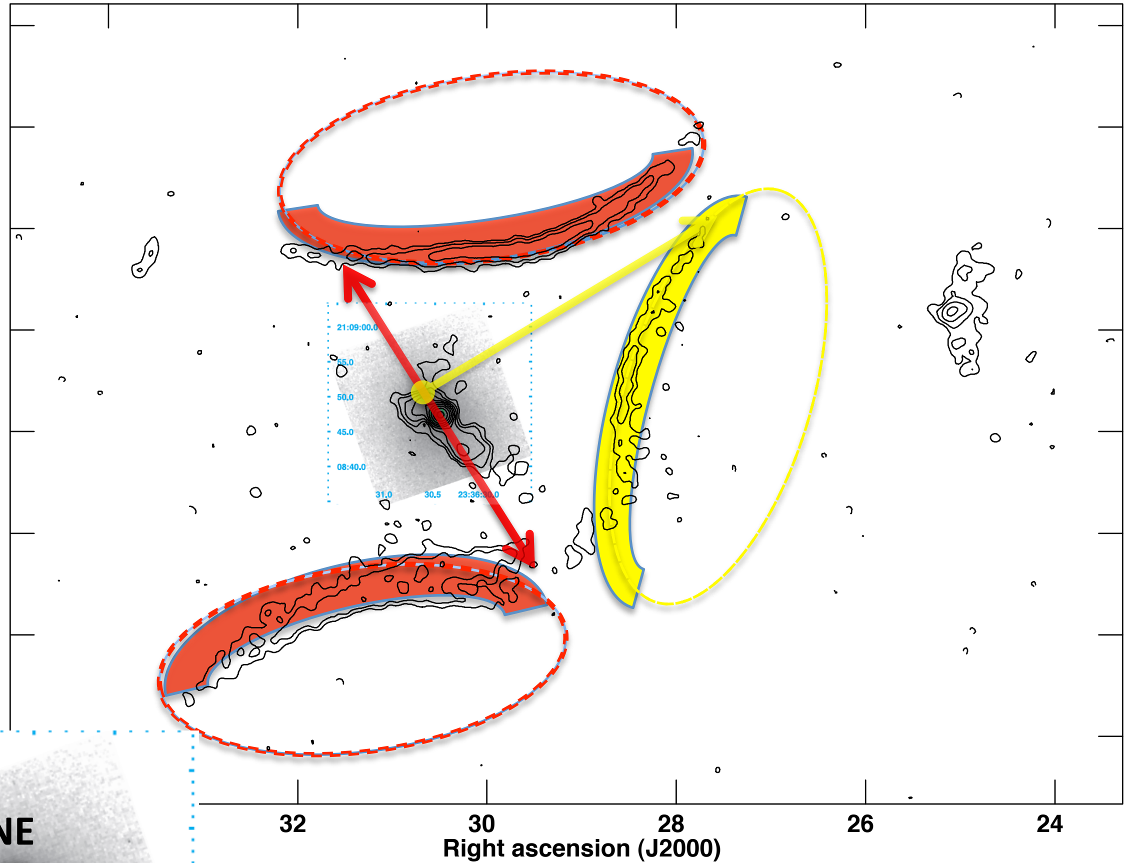
Precessing jets ?

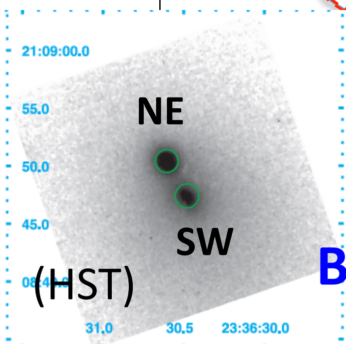
- Particle acceleration by N-S precessing jets stopped at a “working surface” (Wong et al. 2008)

- **New Arc W**: another precessing jet ejected also from the NE nucleus of IC 5338?

↓

SMBBHs





BUT.. NE does not show a radio core..

Conclusions and future work

RBS 797

- Two pairs of radio jets at kpc-scale (N-S / E-W dir.)
- **New EVN observations: two compact components separated by 77 pc**
- Possible scenarios:

(1) Nuclei of two active SMBHs

(2) Core-jet of primary SMBH

(Gitti et al. 2013, A&A, 557, L14)

✔ Approved **16 EVN hours** at 18 and 6 cm to study the spectral properties (PI Gitti)

A2626

- "Kite" radio source unlike typical bubbles/cavities in cool cores
- **New VLA observations: three symmetric radio arcs + diffuse emission (mini-halo)**
- Possible scenarios:

(1) Relics due to shock acceleration

(2) Two pairs of precessing jets

(Gitti 2013, MNRAS in press)

✔ Approved **120 ks CHANDRA** (PI Sarazin) + will request new EVLA obs. at 13 cm (PI Gitti)

Future prospects

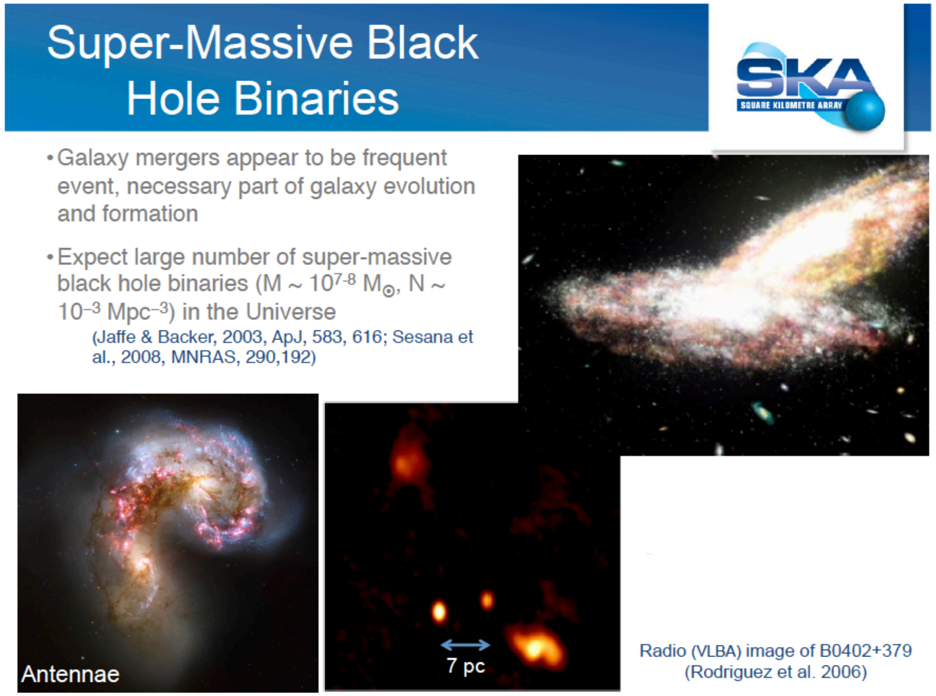
Caveat: very small-number statistics of observed SMBBHs

systematic study of 3114 radio-luminous AGNs using VLBI archival data: ***only one binary AGN detected*** (Burke-Spolaor 2011)

Little possibility to assess the physical mechanism responsible for driving binary system into the phase when GW emission dominates (➔ LISA)

✔ Definitive SMBBH studies for large number of radio AGNs will become possible with the large collecting area, dense instantaneous *u*-*v* coverage and long baselines of **SKA**

SKA Key Science!



(Slide credit: J. Lazio SKA presentation)