Blazars in LOFAR Surveys

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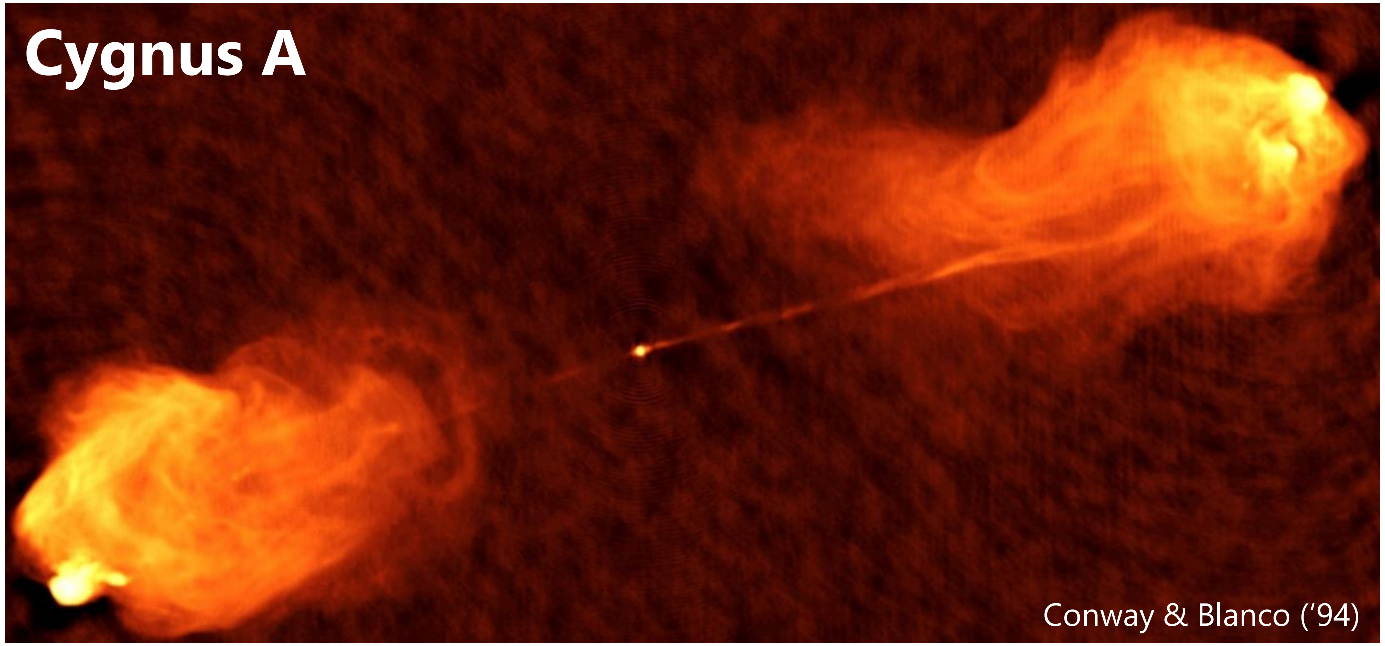
RADIO-LOUD UNIFICATION

Blazars (BL Lacs, FSRQs) are end-on radio galaxies (LERGs, HERGs)

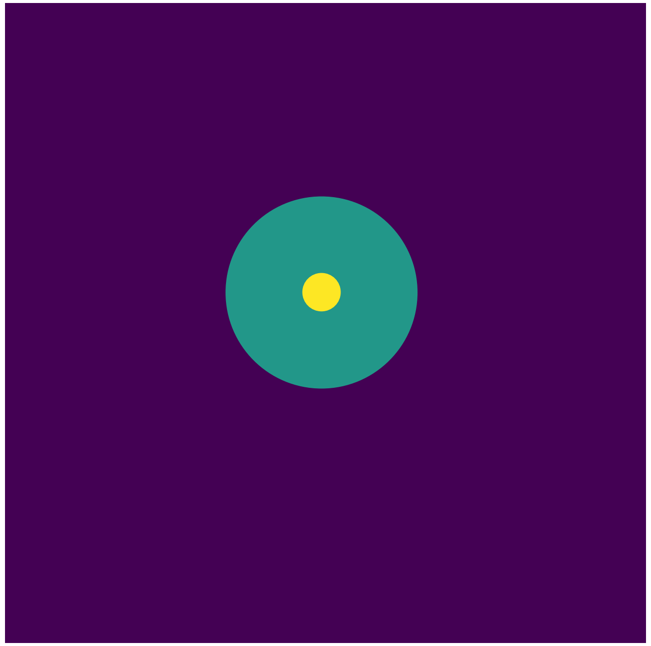


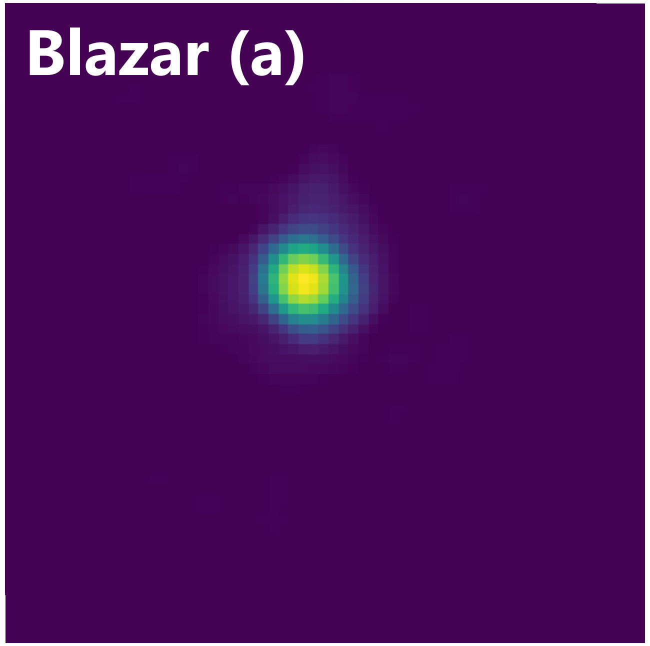
Radio-Loud Unification

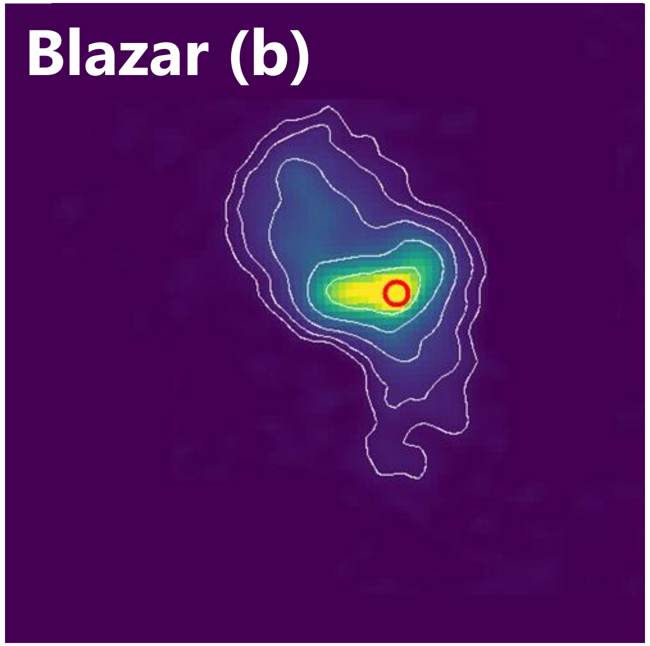
COMPONENTS OF THE MHZ EMISSION

1. <u>Unbeamed</u> steep-spectrum diffuse emission from the optically thin extended jet/lobe

2. <u>Beamed</u> flat-spectrum compact emission from the optically thick core







BLAZAR DIFFUSE EMISSION

TO DETECT THE DIFFUSE EMISSION, WE NEED...

- **Resolution** to separate the 2 components
- **Sensitivity** to detect low surface brightness emission
- **Low frequencies** to increase contrast between the components

AND IT HAS BEEN DONE, E.G....

- **Wardle (‘78)** detected extended emission around blazars
- **Kharb+ (‘10)** detected extended emission around 93% blazars

BUT OFTEN STUDIES HAVE LIMITATIONS

- **Mostly at GHz** or at MHz, trading off sensitivity or resolution
- **Tens of objects** blazars are rare by definition; incomplete samples

SCIENCE CASE

COMPARISON OF BLAZAR TYPES

- Do FSRQs and BL Lacs have diffuse halos?
- Set strong upper limits on core-only blazars

FRACTION OF DIFFUSE EMISSION

- Core dominance parameter, Lorentz factor, orientation, jet kinetic power
- Episodic jet activity

TESTING UNIFICATION

- Does the diffuse emission around BL Lacs qualify them as FR-IIs for large θ?
- Expect $N_{\text{radio galaxies}}$ to scale up from N_{blazars}

Datasets

Dataset	Area	Sensitivity	N_{blazar}
	deg^2	$\mu\mathrm{Jy}\cdot\mathrm{beam}^{-1}$	
LoTSS DR1	424	70	98
Deep Fields	25	22–40	23
LoTSS DR2	>2000	~70	~800

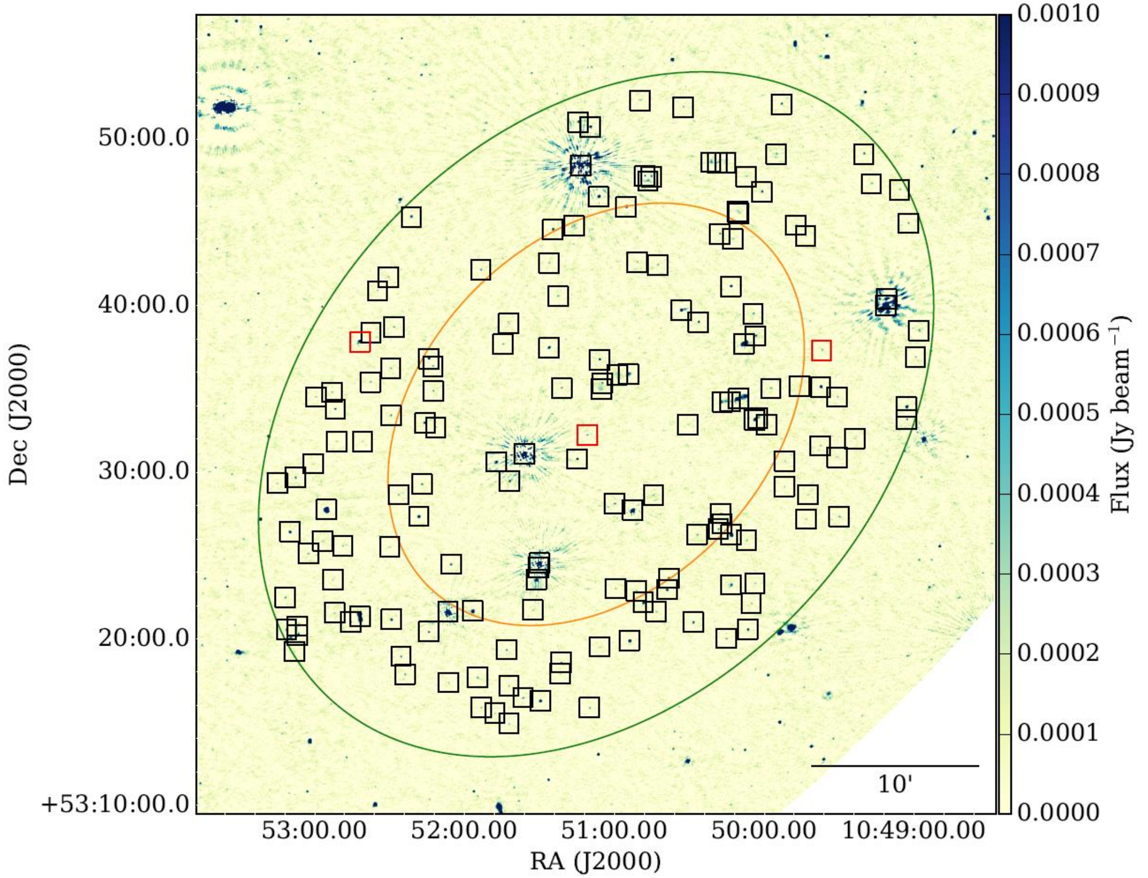
+ not many artefacts

- Blazars defined using BZCAT
- $\nu \approx 150$ MHz
- Resolution ≈ 6″

Key results from LoTSS DR1 study

- Sample defined by BZCAT ($N \approx 98$)
- 30% were γ-ray detected
- All blazars detected in LoTSS DR1
- $\alpha_{\text{MHz–GHz}} = -0.15 \pm 0.17$
- S_{MHz} & S_{GeV} mildly correlated ($r = 0.45$, $p = 0.06$, $N = 30$)
- Cut down likely matches for UGS

UNIDENTIFIED γ-RAY SOURCE

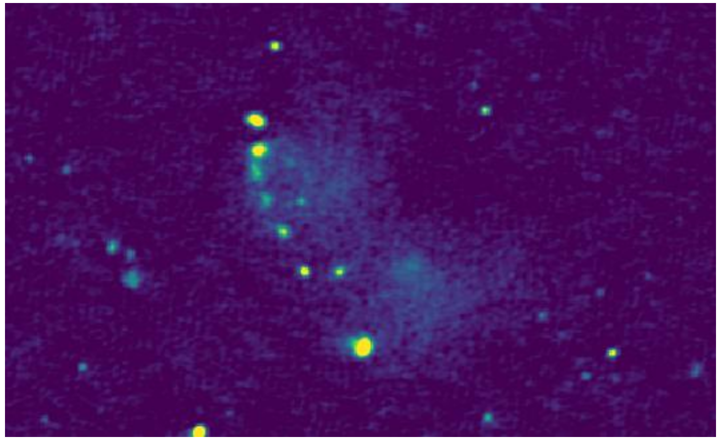


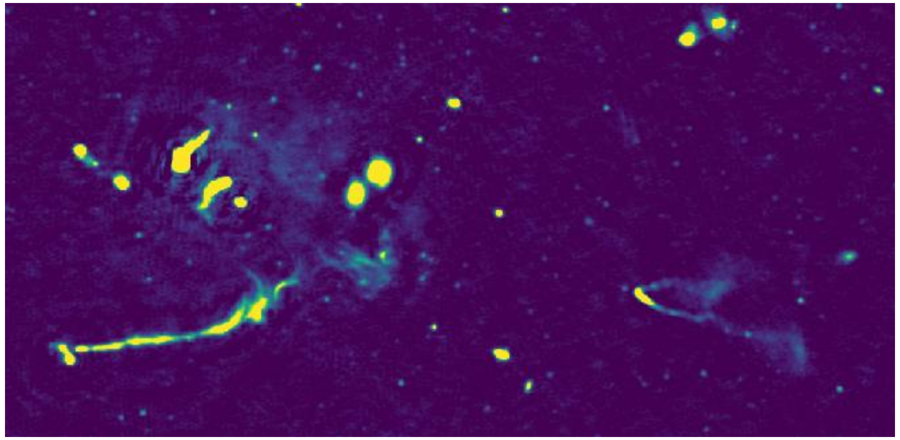
DEEP FIELDS

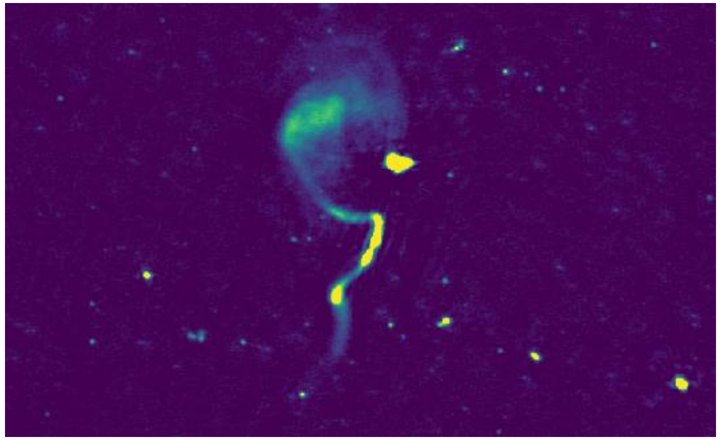
Images of Boötes (80h), Elais-N1 (180h), Lockman Hole (112h)

+ lots of value-added information

E.G. PRETTY SOURCES:







Methods

CHALLENGE

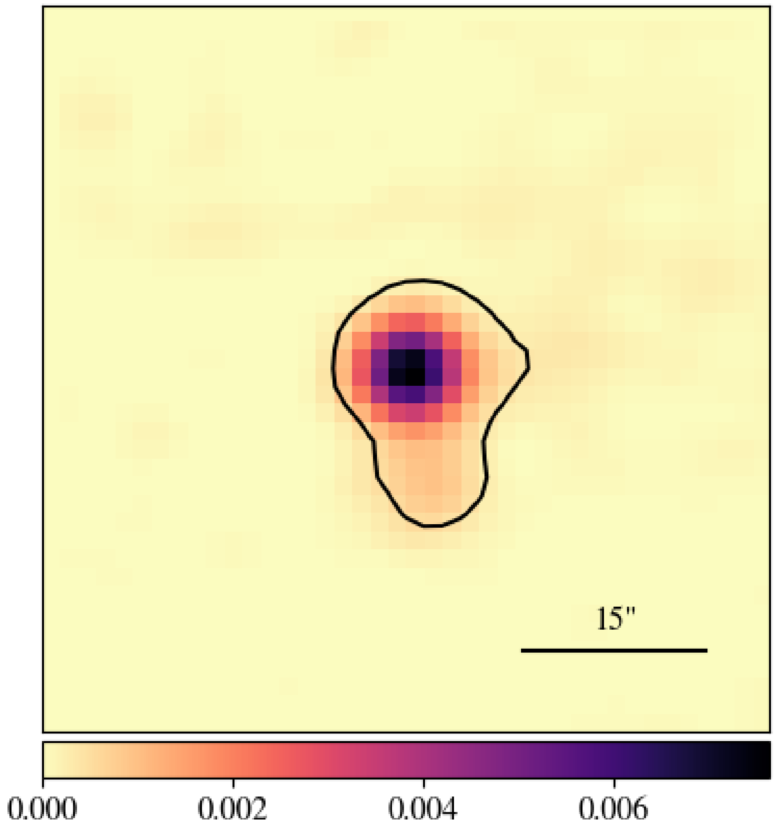
Accurately measure diffuse emission

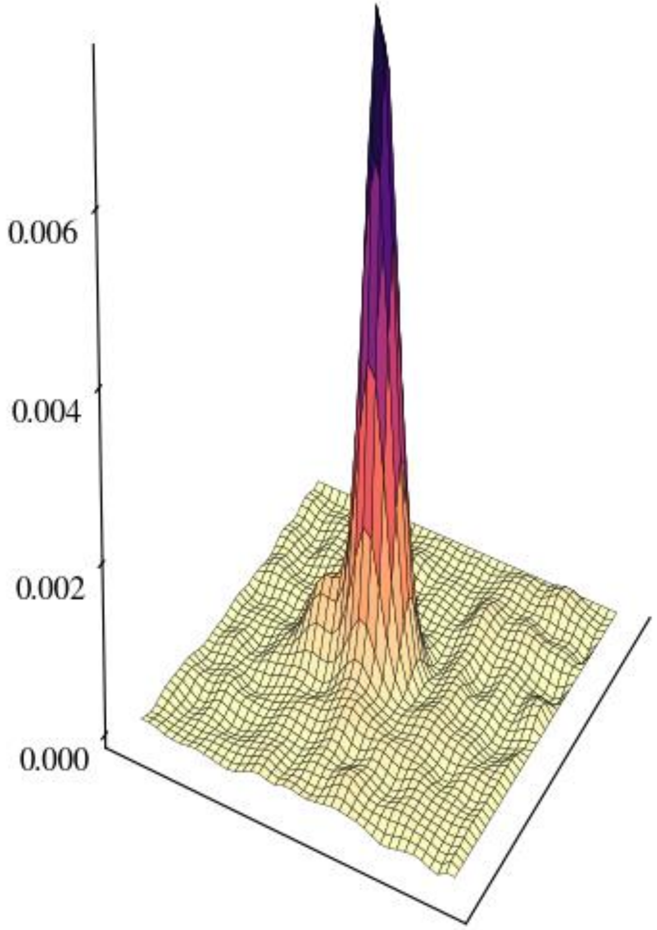
METHODS

1. Gaussian subtraction
2. Component summation
3. Total and peak flux density difference
4. Signal threshold
5. Spectral index cut-off
6. Manual regions

GAUSSIAN SUBTRACTION

With core





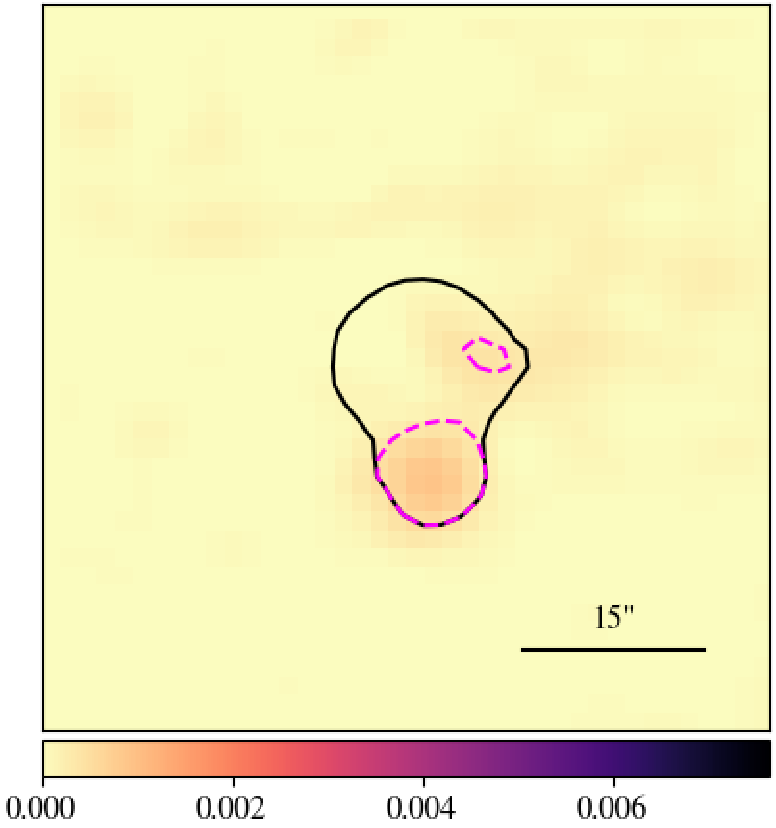
Lower limit

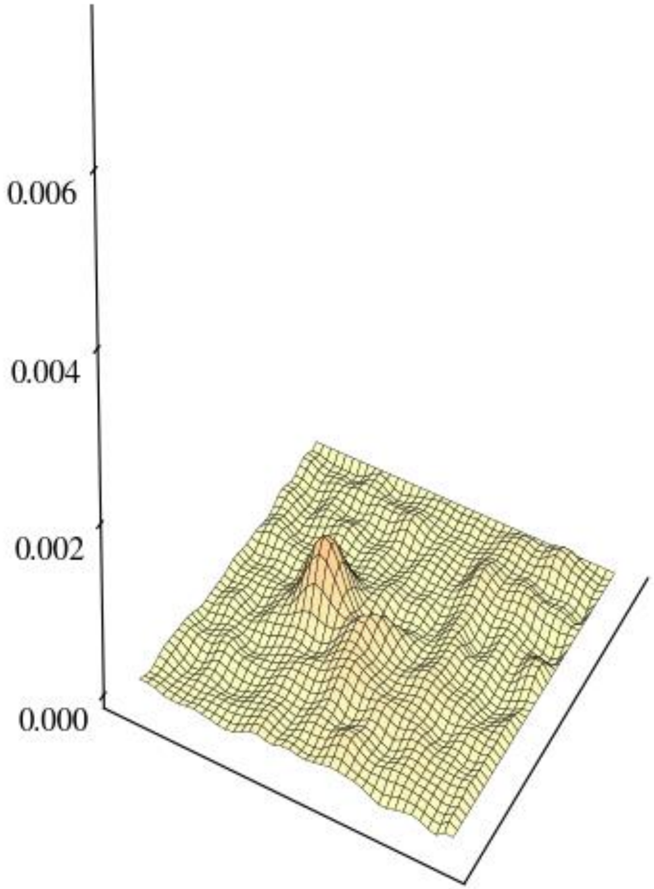
2D

3D

GAUSSIAN SUBTRACTION

Without core



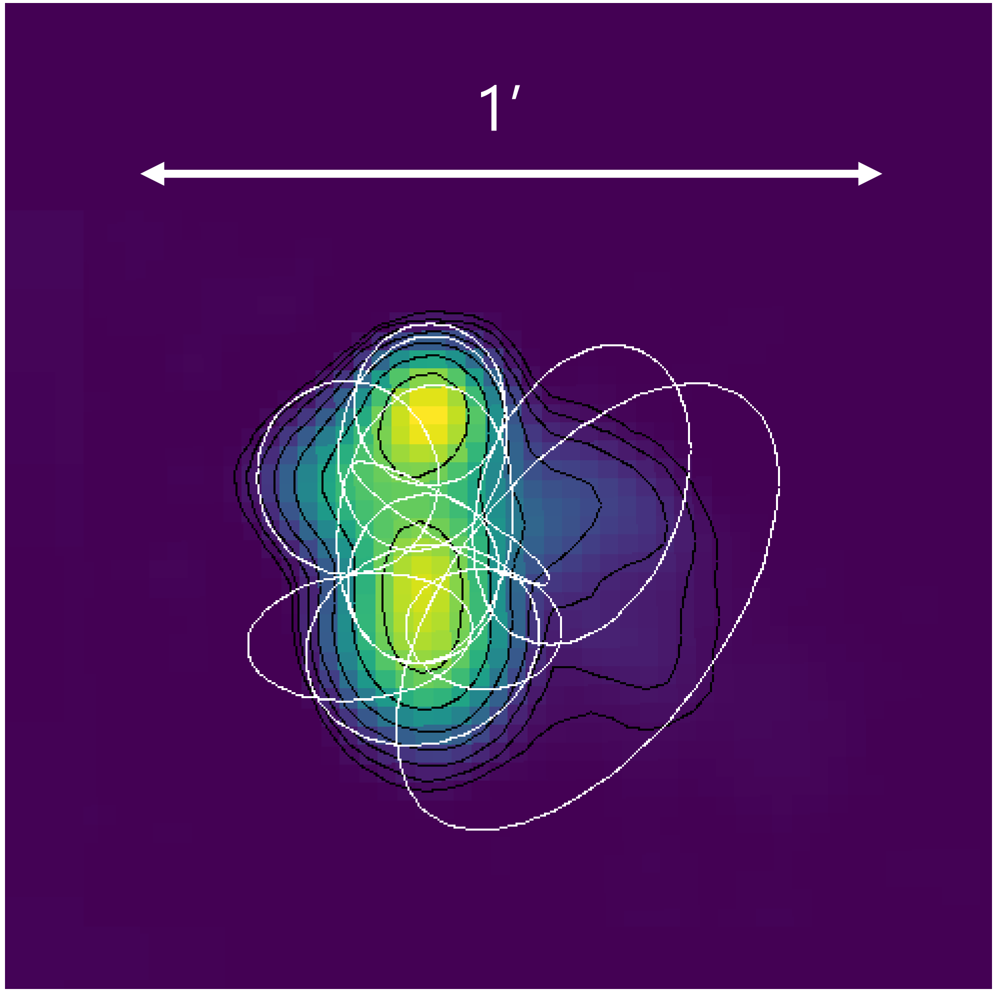


Lower limit

2D

3D

Component Summation



- PyBDSF fits components to a source
- Often a dominant component for the core
- Classify each component as diffuse or core/jet

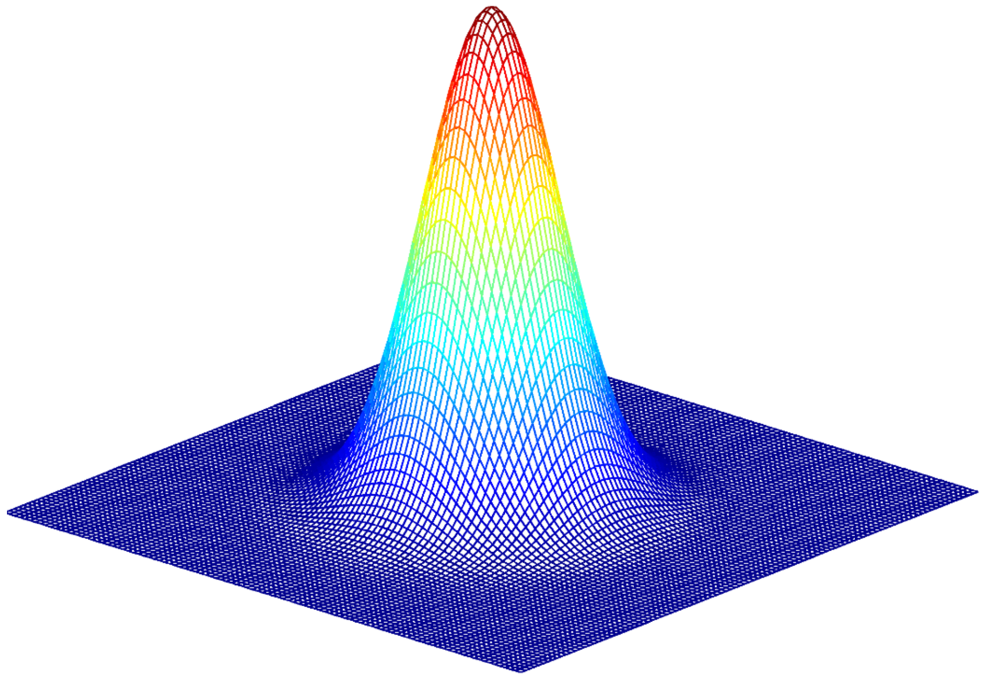
Acts as upper limit of S_{diffuse}

(diffuse components overlap core regions)

Pro: Easy

Con: Requires manual inspection

TOTAL AND PEAK FLUX DENSITY DIFFERENCE



In idealized scenario,

- $S_{total} = S_{peak}$ for point sources
- $S_{diffuse} = S_{total} - S_{peak}$ for blazars

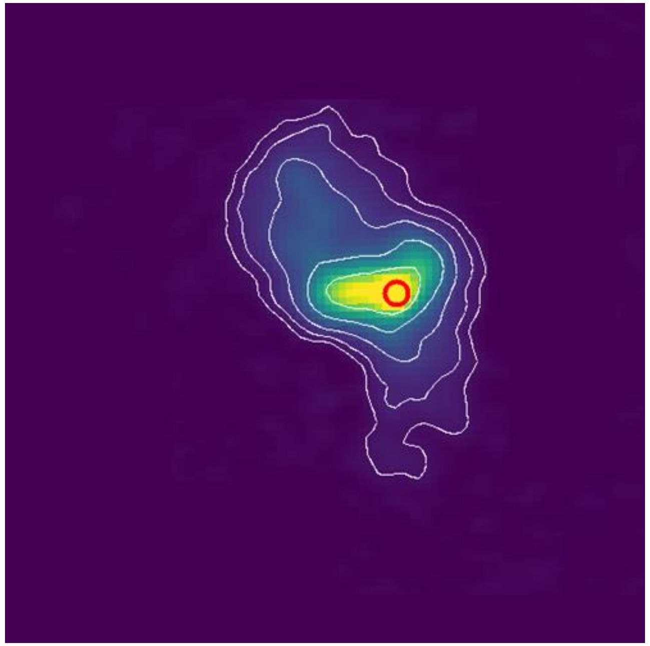
Acts upper limit of $S_{diffuse}$ (spread of flux by resolution element classified as diffuse emission)

Pro: Fast & easy

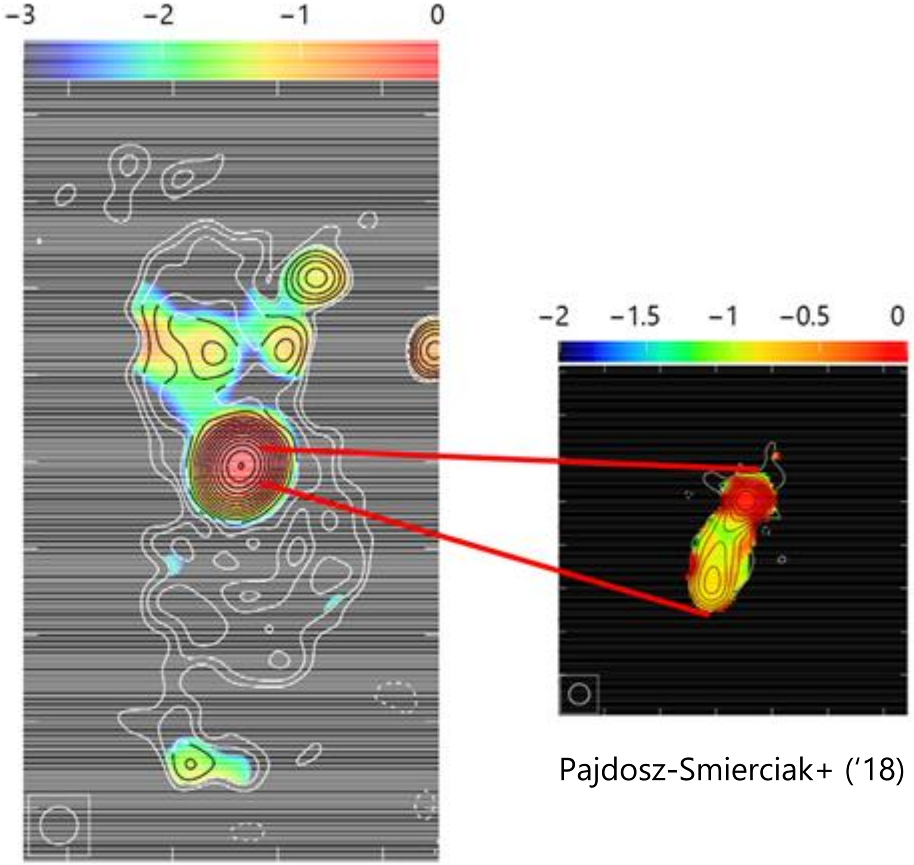
Con: Blunt

σ, α, OR MANUAL DEMARCATION

$5\sigma, 10\sigma, \ldots, 160\sigma$



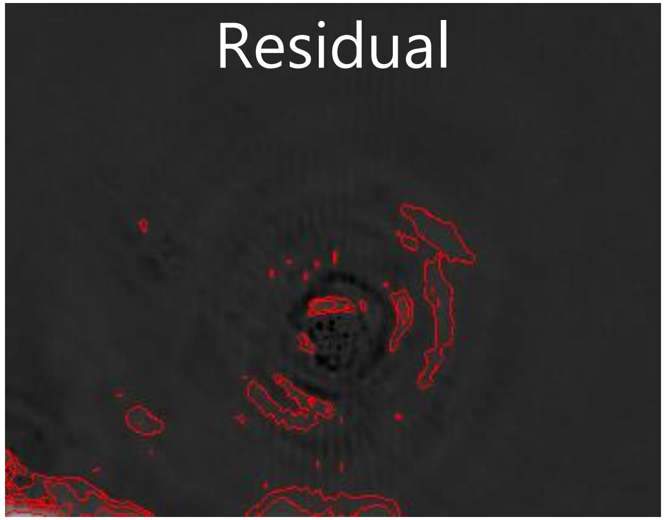
SBS B1646+499, $\alpha_{\mathrm{GMRT}}^{\mathrm{VLA}}$



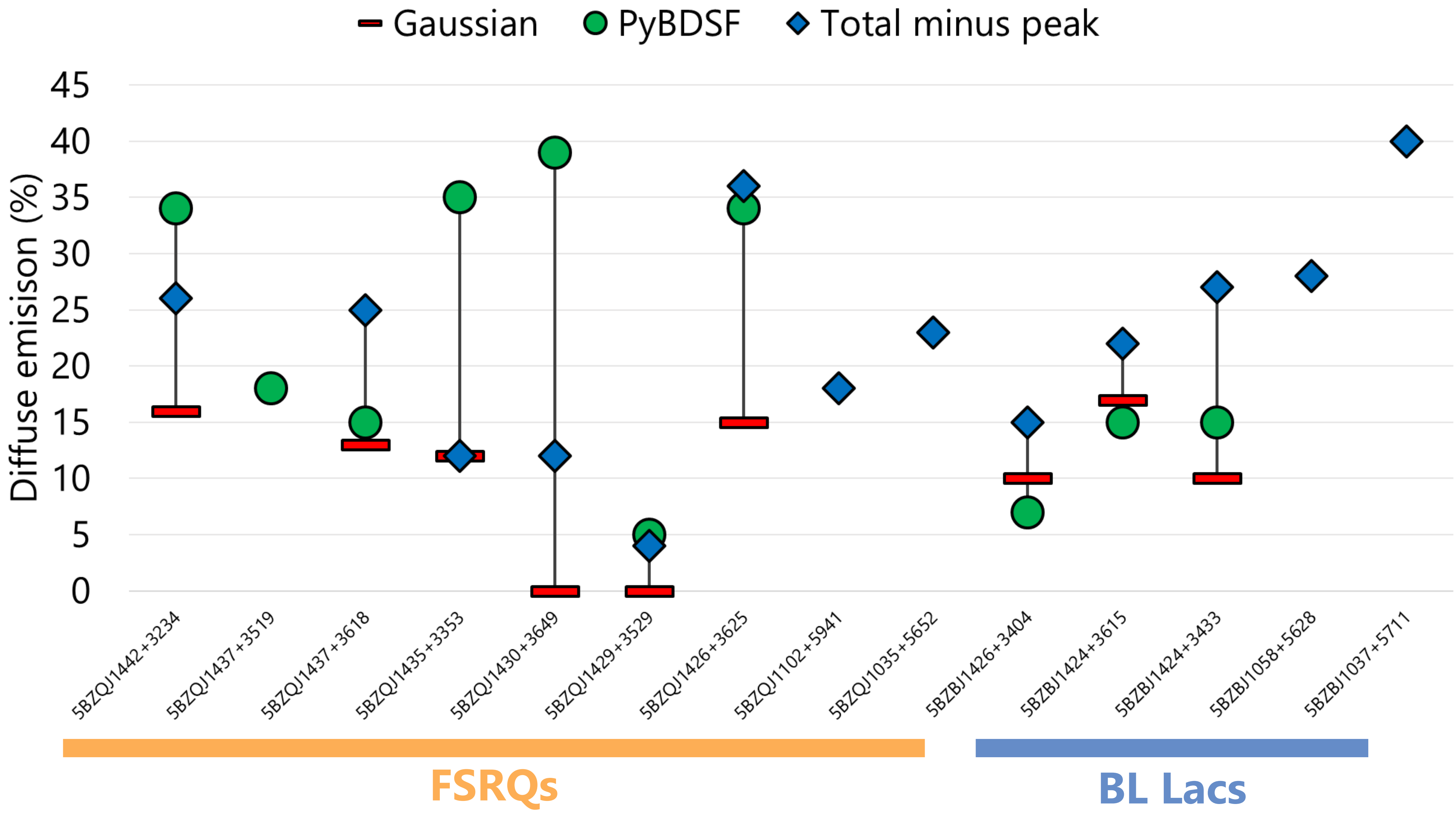
Pajdosz-Smierciak+ ('18)

Preliminary results

- Blazars in the Boötes field analysed using methods 1, 2, 3
- Methods broadly agree; automated methods may prove reliable for large samples
- ~20 (±10) % of the emission can be attributed to diffuse component
- $\left\langle \frac{S_{\text{total}}}{S_{\text{core}}} \right\rangle = 1.27$ ($\sigma = 0.14$), in agreement with $\alpha_{\text{MHz}} \approx -0.15 \pm 0.17$
- Inspection of LoTSS DR2 residual maps for artefacts (~800 blazars)



Preliminary results



Preliminary results

Source	Total (mJy)	Core (mJy)	Diffuse (mJy)	Diffuse (%)
FSRQ	1246	960	286	23
FSRQ	1237	926	311	25
FSRQ	512	366	146	29
FSRQ	419	344	75	18
FSRQ	410	335	75	18
FSRQ	80	67	13	16
FSRQ	23	22	1	4
FSRQ	21	17	4	19
FSRQ	11	9	2	18
BL Lac	172	124	48	28
BL Lac	154	127	28	18
BL Lac	68	41	27	40
BL Lac	61	54	6	10
BL Lac	10	9	2	20

Future

Short term

- Blazars in Elias-N1 & Lockman Hole
- Methods using σ, α, and manual demarcation (and how to combine them!)
- Use α, z, optical ID, etc to constrain kinetic power, B, etc

Medium term

- Publish in Deep Fields paper splash (autumn 2019)
- Look for new blazars in Deep Fields
- Collaborate with LOFAR blazar community on LoTSS DR2

Long term

- Polarisation, WEAVE, LBA survey
- Single object long-baseline studies of blazars (3C 273, OJ 287)

SUMMARY

1. LOFAR Surveys well-suited to this work

2. Blazars are not point sources at MHz frequencies

   (diffuse component and core component both play a role)