Radio-loud Broad Absorption Line Quasars

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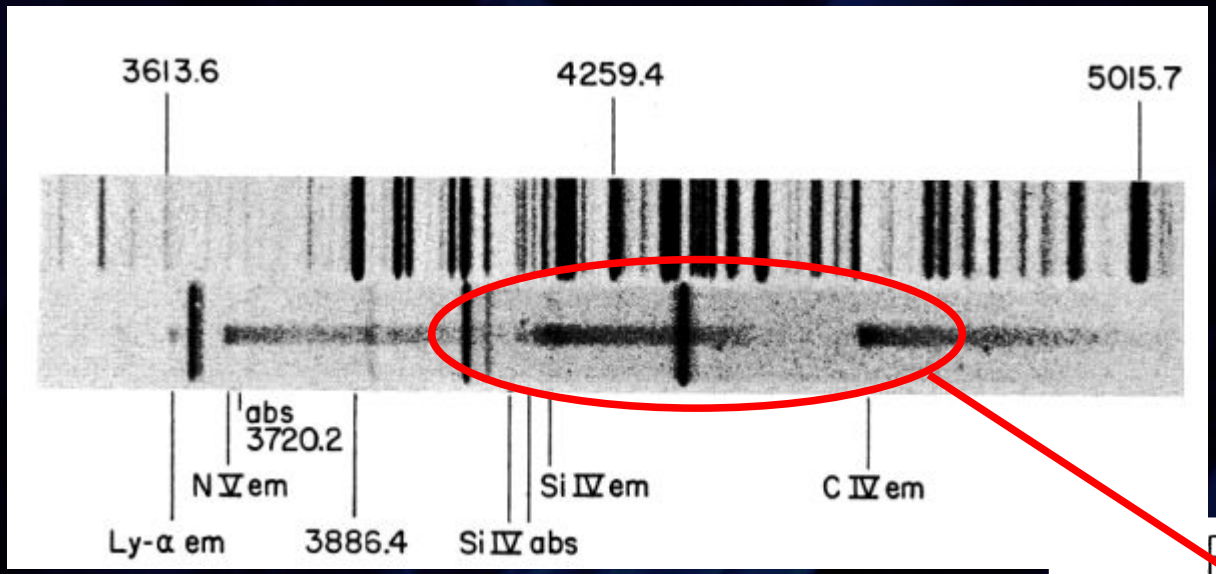
Outline:

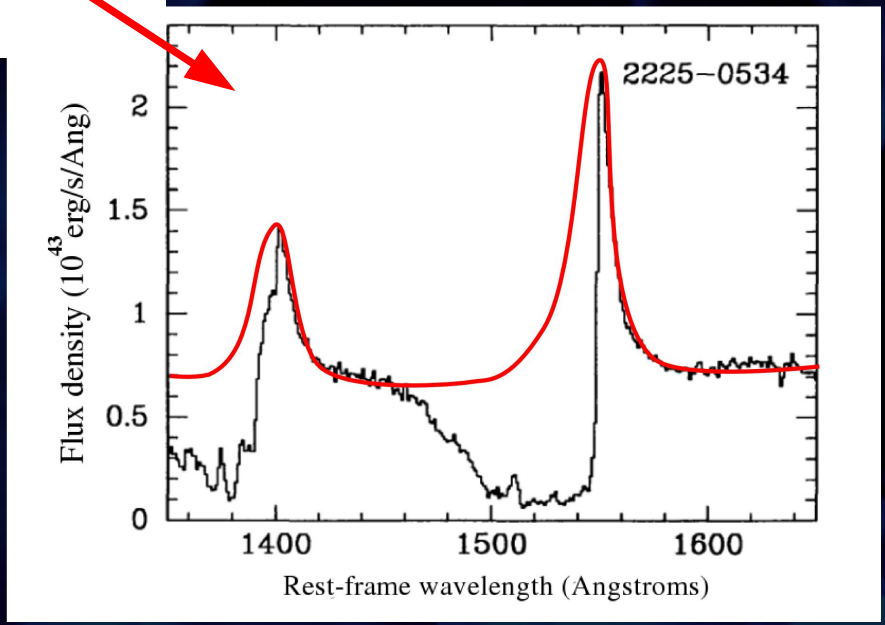
- BAL QSOs in a nutshell
- Radio spectra and polarisation properties
- Spectral ageing
- pc-scale morphology
- H I in absorption (J1624+3758)
- Conclusions

BAL QSOs in a nutshell...



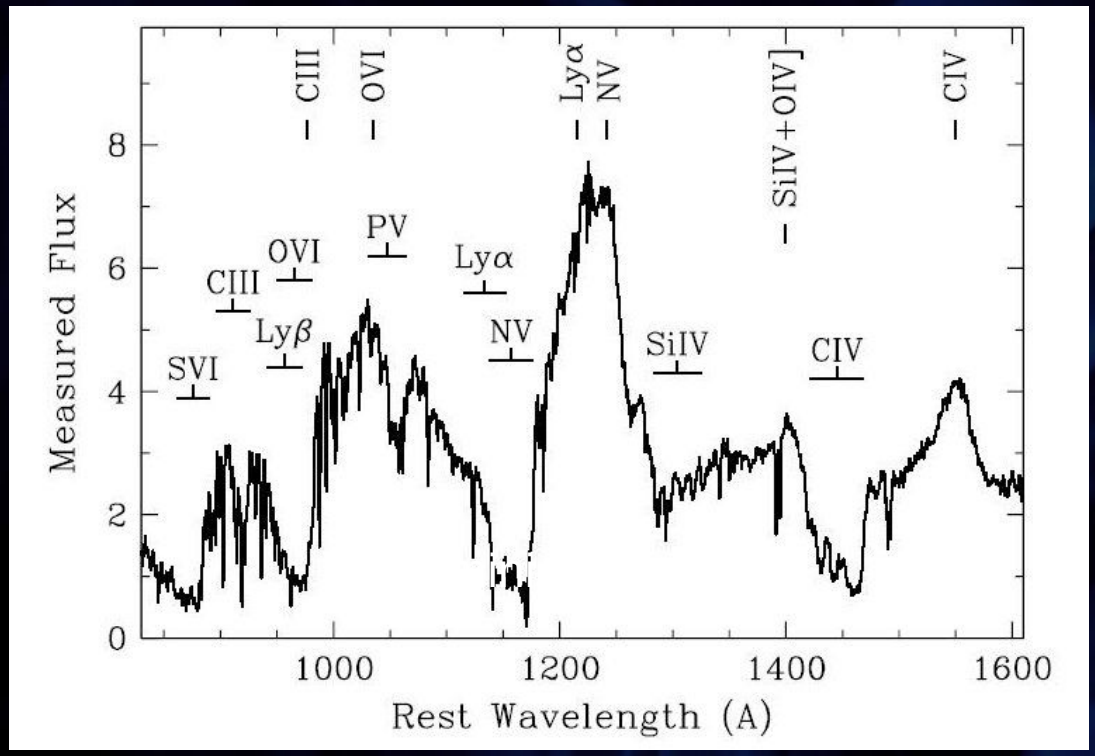
PHL 5200. Burbidge (1968)

Wide absorptions towards the blue wings of some resonant lines: C IV, Si IV, N V, O VI, Mg II, Al III, ...



PHL 5200. Korista et al. (1993)

BAL QSOs in a nutshell...



Broad Absorption Lines

$\Delta v \geq 3000$ km/s

$v_{max} \sim 5000$ km/s up to 20% c

mini-BAL

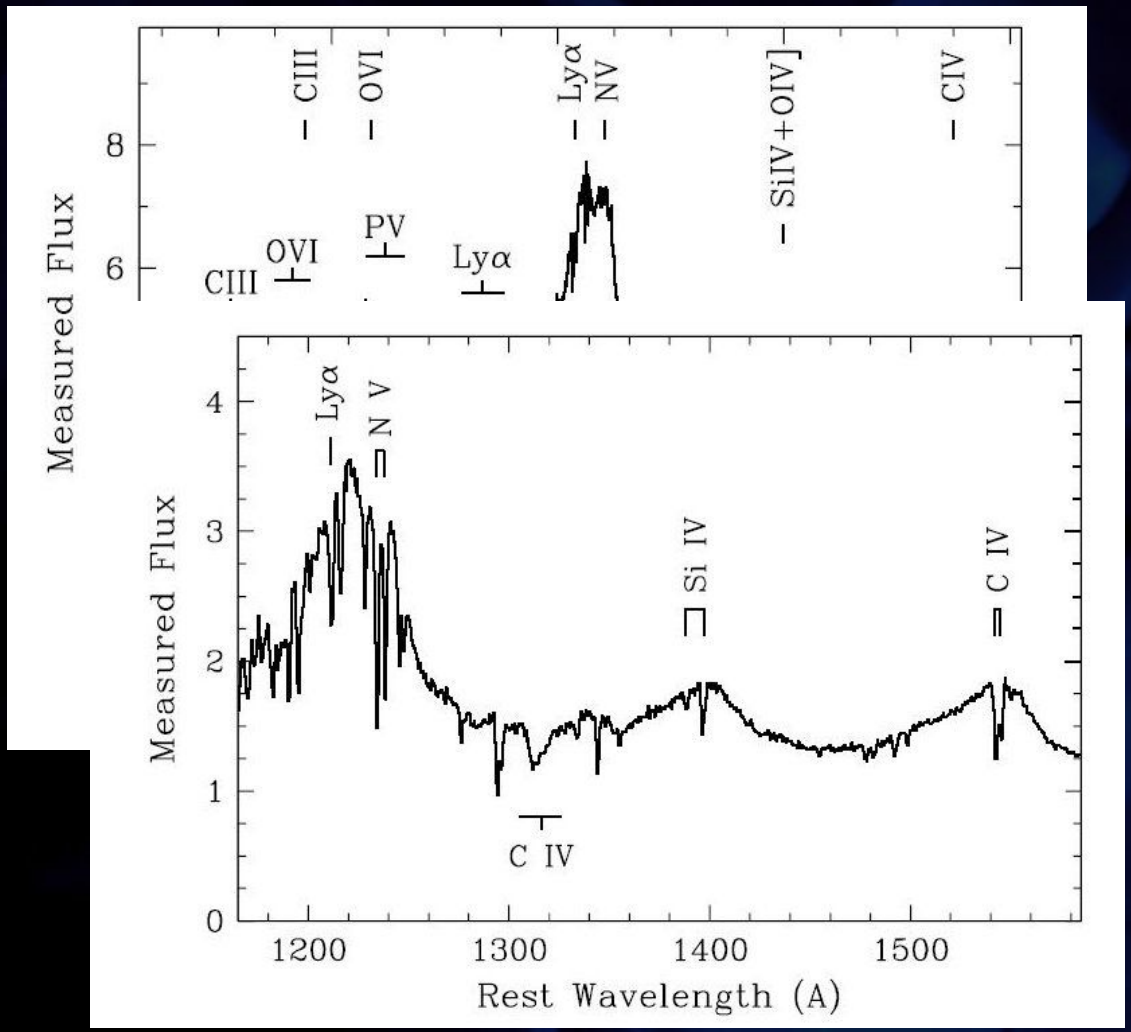
$500 \geq \Delta v \geq 3000$ km/s

Narrow Absorption Lines

$\Delta v \leq 500$ km/s

Associated or intervening

BAL QSOs in a nutshell...



Broad Absorption Lines

$\Delta v \geq 3000$ km/s

$v_{max} \sim 5000$ km/s up to 20% c

mini-BAL

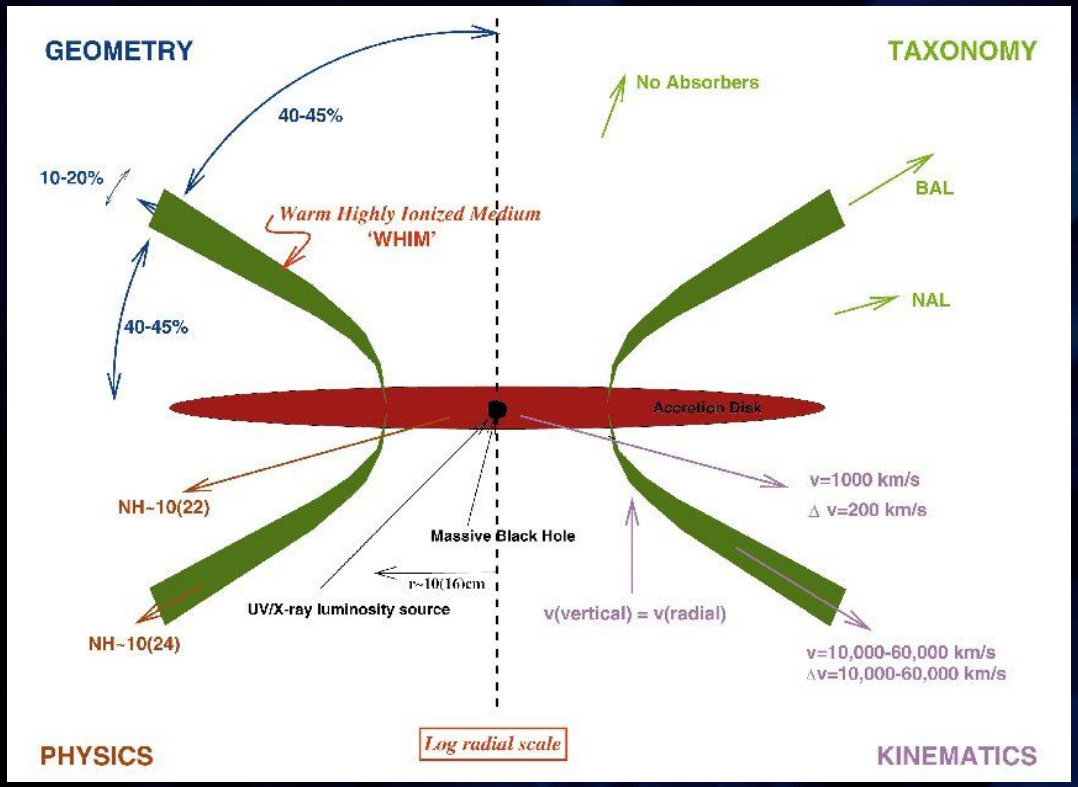
$500 \geq \Delta v \geq 3000$ km/s

Narrow Absorption Lines

$\Delta v \leq 500$ km/s

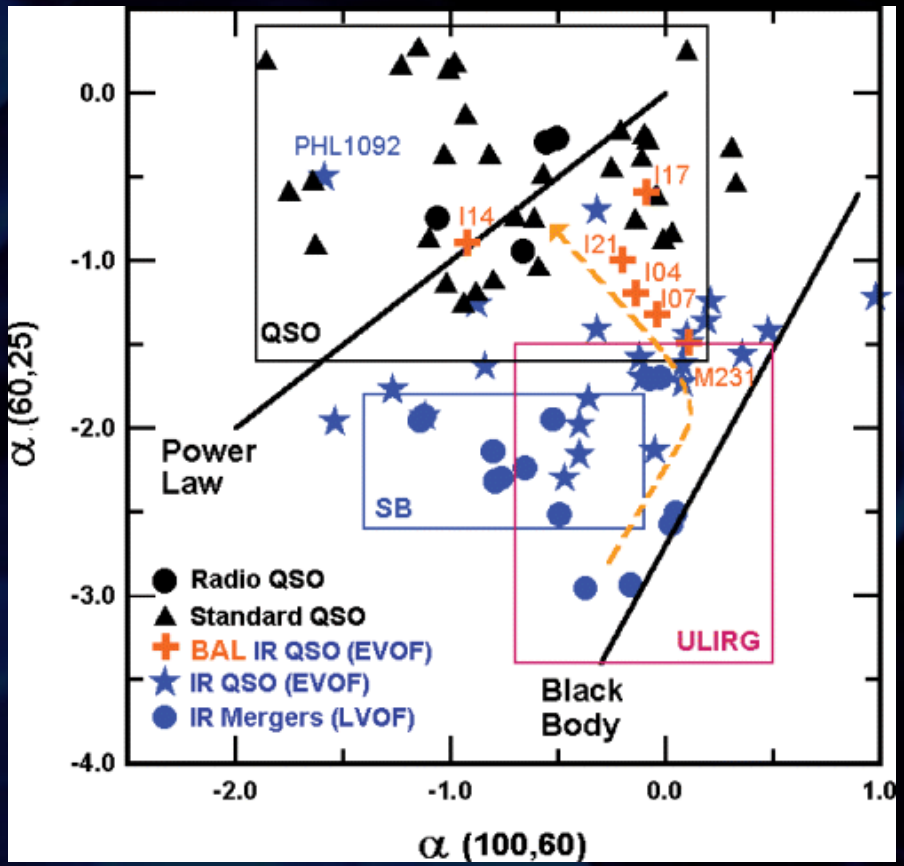
Intrinsic or intervening

BAL QSOs in a nutshell... orientation or evolution?



Elvis, 2000

Radiation pressure?
Gas pressure?
Magneto-centrifugal forces?

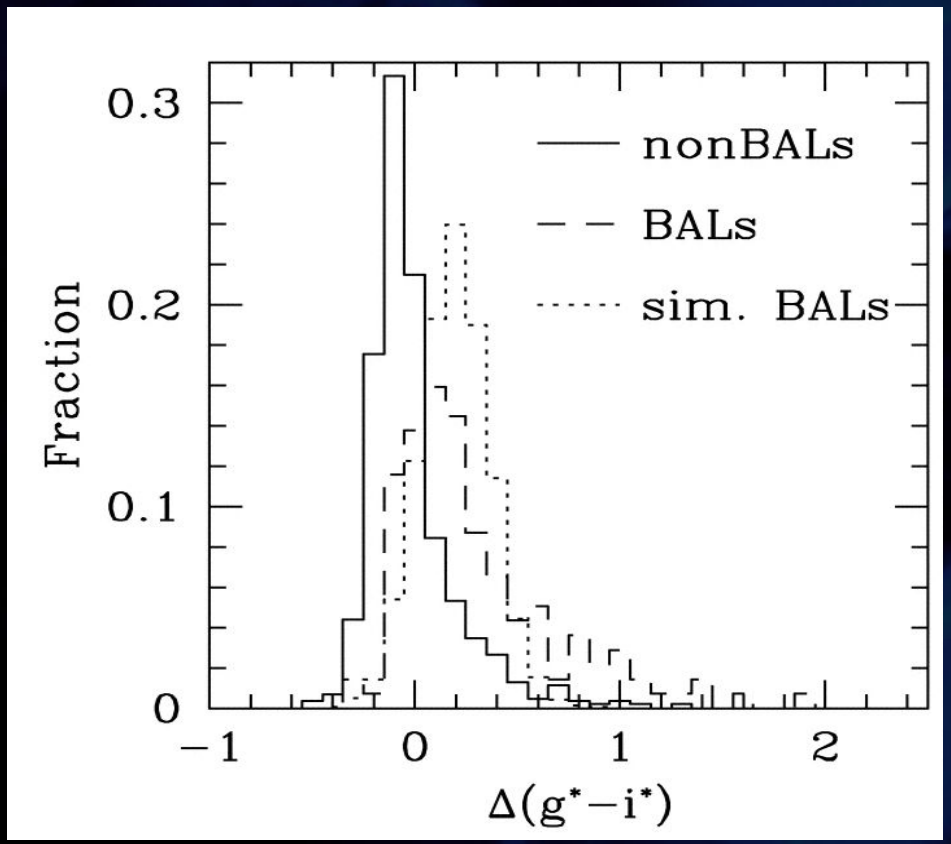


Lípari & Terlevich, 2006

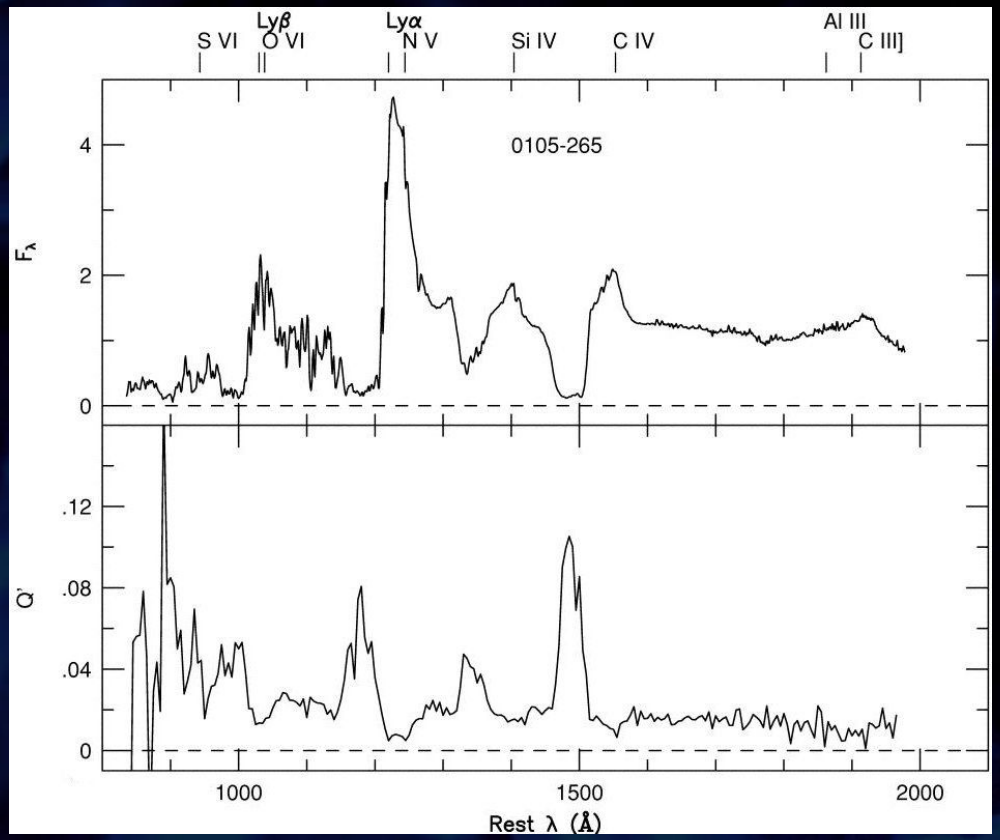
BAL QSOs in a nutshell...

Optical: Quite similar to non-BAL QSOs but...

Both may suggest a more edge-on orientation



Reichard et al. 2003



Ogle et al. 1997

BAL QSOs in a nutshell...

X-Rays: BAL QSOs are weaker in X-rays
More absorbed, emission intrinsically similar.
(Green et al. 2001, Gallagher et al. 2007)

Mid-IR: Similar continuum emission (MIPS 24, 70 & 160 micron)
(Gallagher et al. 2007)

Sub-mm, mm: No differences in samples of radio-quiet BAL QSOs
(Lewis et al. 2003, Willott et al. 2003, Priddey et al. 2007)

Radio: Radio-loud BAL QSOs are rare (not much was known)
Compact radio sources
Mixture of steep and flat spectral indices (Becker et al. 2000)

BAL QSOs in a nutshell...

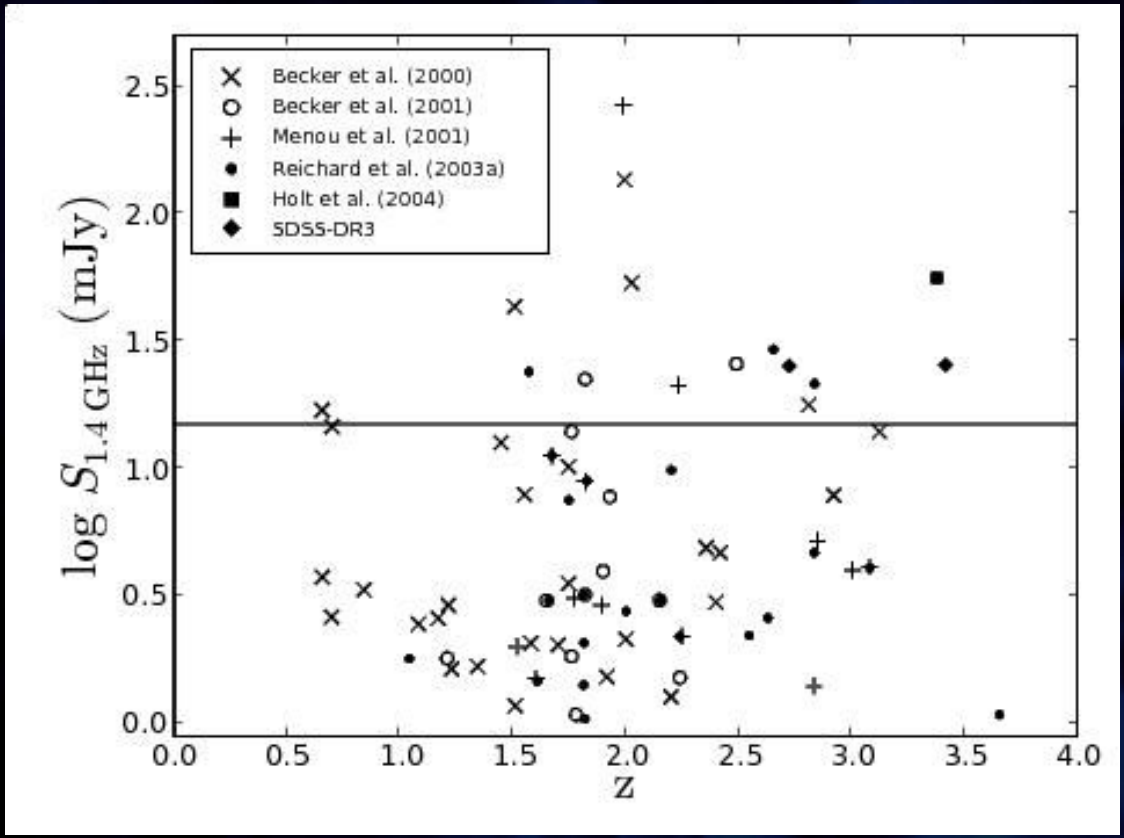
- Characterisation of the radio properties of radio BAL QSOs:
  - Radio spectral shape
  - Polarisation properties
  - Radio morphology at smaller scales
  - Flux density variability
  - Spectral ageing analysis

- Multi-frequency radio observations:

  Effelsberg + VLA(A) + literature (74 MHz up to 43 GHz)
  2.6, 4.8, 8.3, 10.5; 8.4, 15, 22, 43 GHz

  VLBA observations
  4.8, 8.4 GHz

Sample of radio BAL QSOs



Montenegro-Montes et al. 2008

- Existing samples of BAL QSOs
- Redshift: 0.5 – 3.5
- S (1.4 GHz) > 15 mJy
- 15 objects
- Some with BI = 0 but AI > 0

- SDSS-DR5 BAL QSO sample defined for future studies (Ph.D. thesis of G. Bruni)

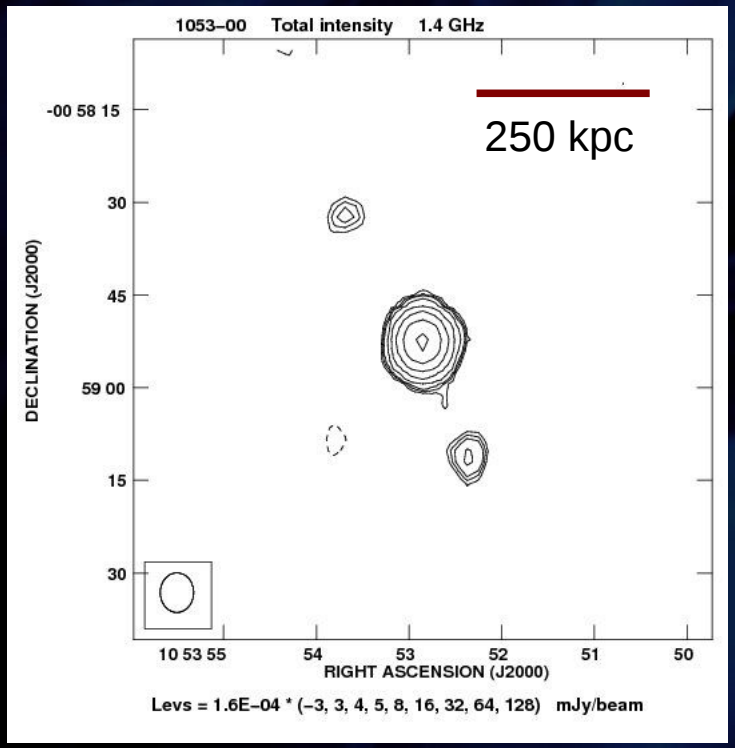
Radio spectra and polarisation properties...

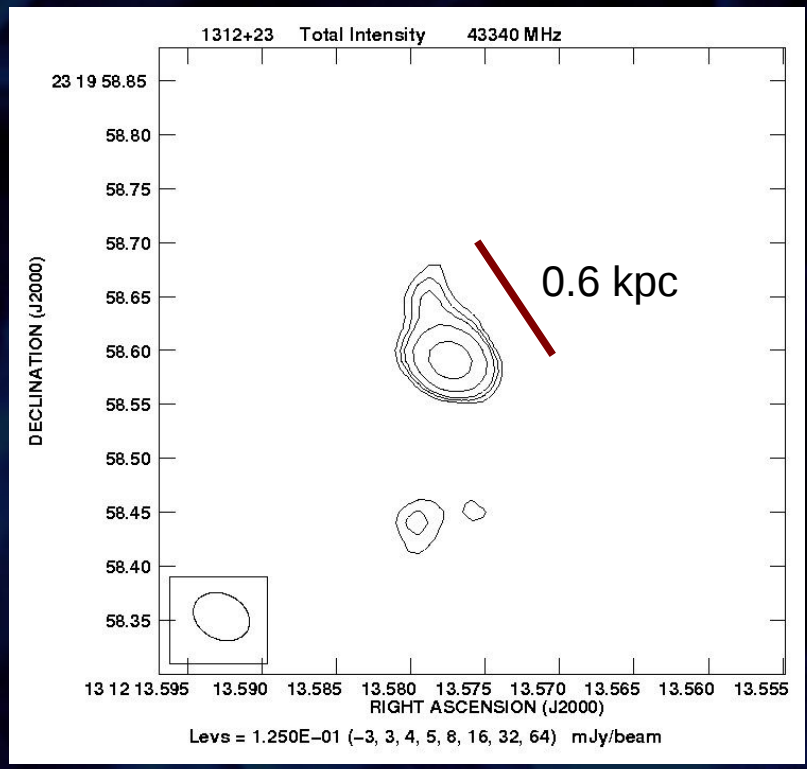
Morphology: BAL QSOs are compact radio sources

5 / 15 unresolved @ 22 GHz (beam ~ 80 mas)

8 / 15 slightly resolved at 22 GHz. Θ_{dec} ~ 10 – 70 mas

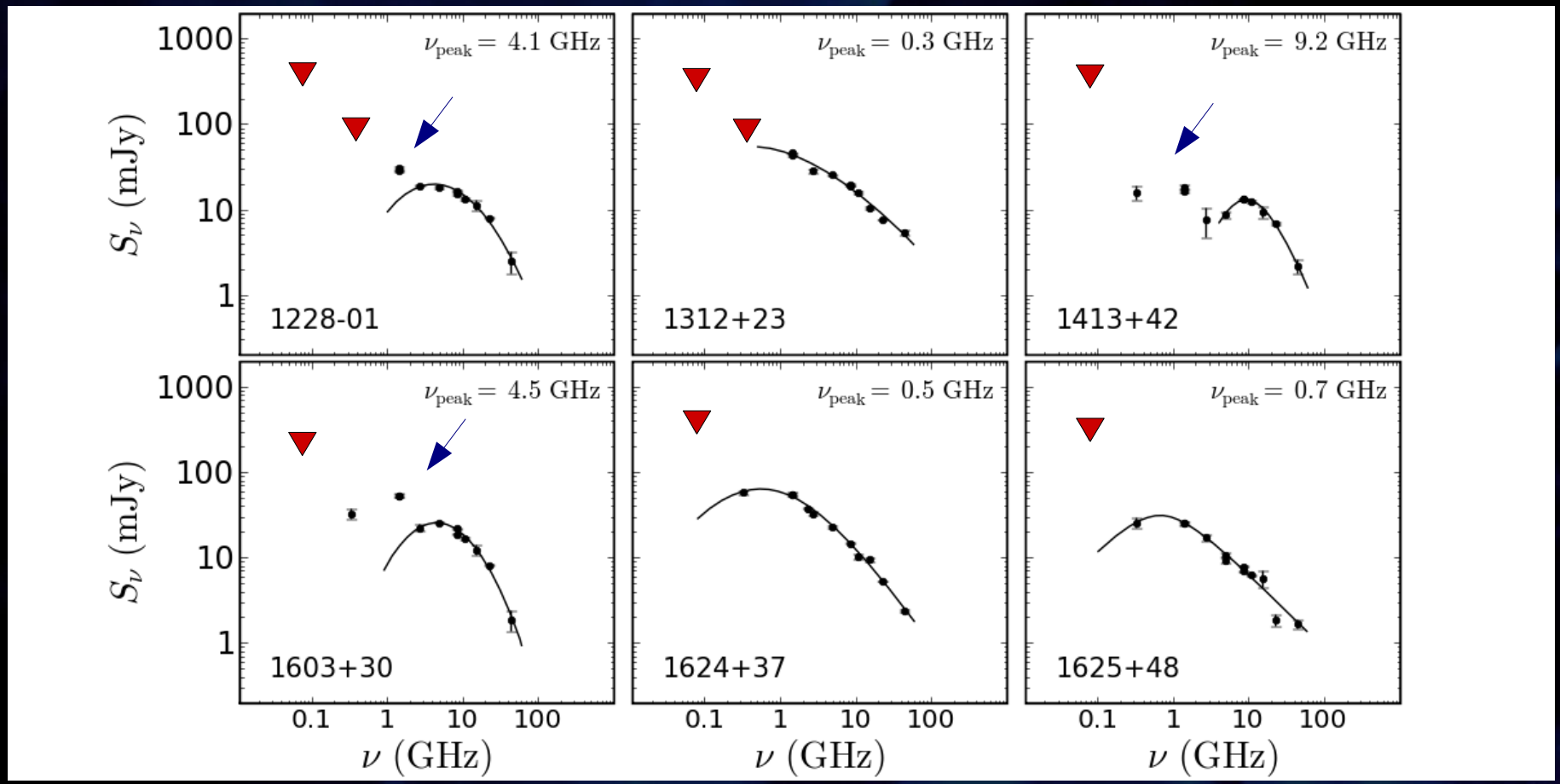
2 / 15 clearly resolved



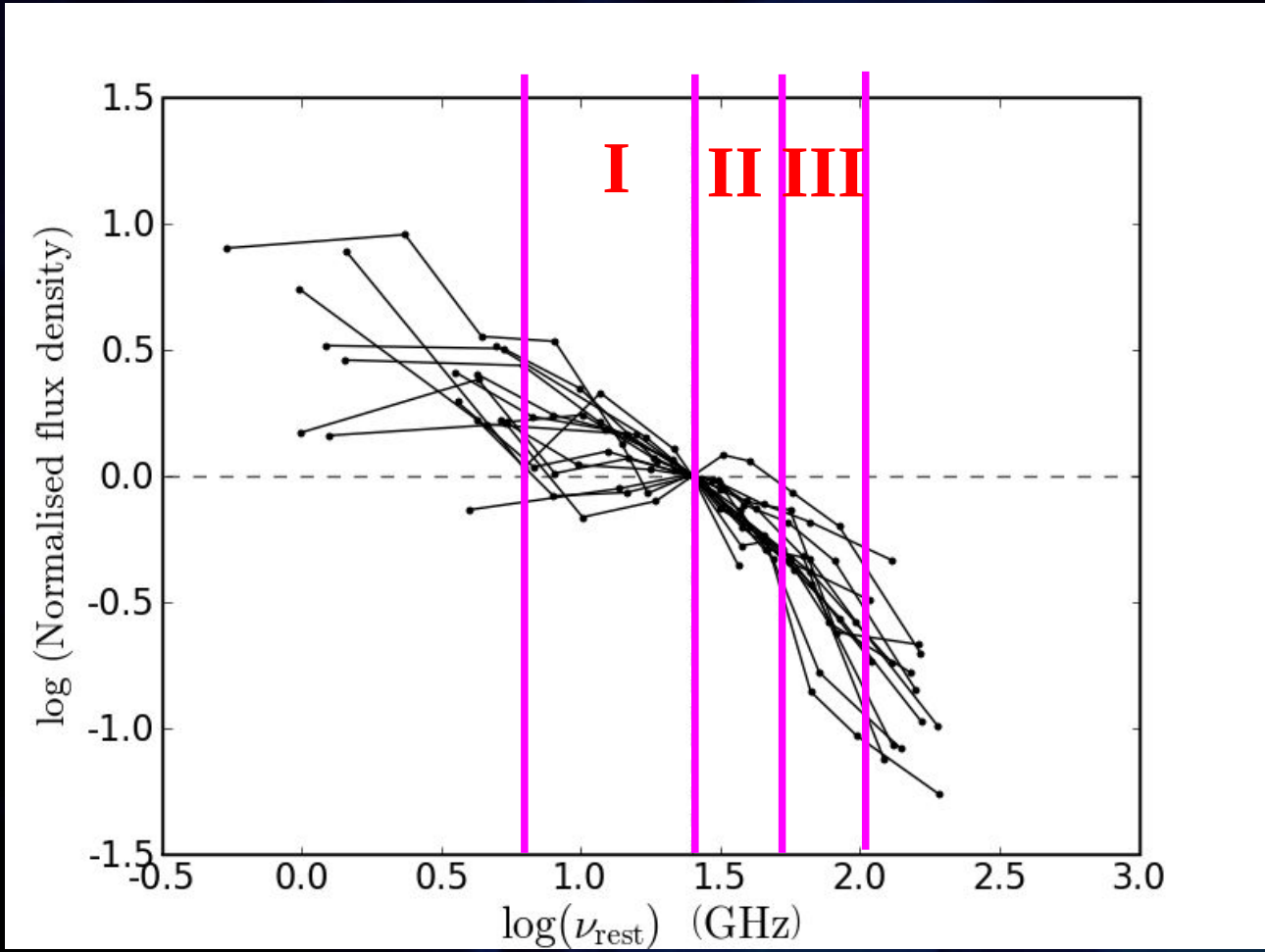


Radio spectra and polarisation properties...

- Convex radio spectra, some with two radio components



Radio spectra and polarisation properties...



α_m(I) ~ – 0.32

α_m(II) ~ – 0.92

α_m(III) ~ – 1.24

Radio spectra and polarisation properties...

Variability (only 2 epochs):

1.4 GHz: FIRST – NVSS epochs, 14 objects

8.4 GHz: Becker et al. 2000 – This work, 5 objects

$$Var_{\Delta S} = \frac{S_{max} - S_{min}}{S_{min}} \qquad \sigma_{Var} = \frac{|S_2 - S_1|}{\sqrt{\sigma_2^2 + \sigma_1^2}}$$

No strong variability for genuine GPS sources $Var_{\Delta S} << 3$

(Torniainen et al. 2005)

Source	Freq (GHz)	S_1 (mJy)	S_2 (mJy)	$Var_{\Delta S}$	σ_{Var}
0256−01	1.4	22.3±0.8 D	27.5 B	0.23	3.2
1213+01	1.4	27.5±0.9 D	22.9 B	−0.20	3.2
1312+23	8.4	12.6 A	19.4±0.2 A	0.54	10.3
1413+42	8.4	11.3 D	13.4±0.1 A	0.19	3.7
1603+30	8.4	18.1 A	22.1±0.3 A	0.22	4.2

2 / 14 variable

3 / 5 variable

Radio spectra and polarisation properties...

Polarisation: VLA @ 8.4 GHz sensible rms

10 / 15 unpolarised $m_{8.4} < 1\%$

5 / 15 significantly polarised $m_{8.4}$ (median) = 1.3 %

As a comparison, Stanghellini et al. (2003):

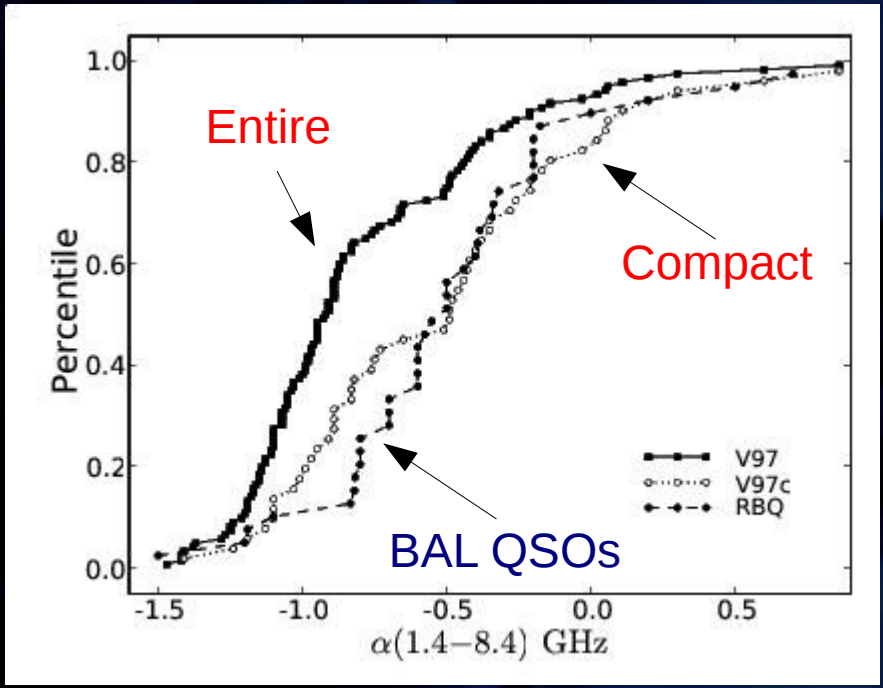
Flat-spectrum quasars: $m_{5\ GHz} = 1.8\ \%$
GPS quasars: $m_{5\ GHz} = 1.2\ \%$
GPS galaxies: $m_{5\ GHz} < 0.3\ \%$

2 RM: 1159+01 RM = (–72 ± 2) rad/m^2 (–644 ± 12) rad/m^2
1624+37 RM = (–960 ± 30) rad/m^2 (–18350 ± 760) rad/m^2

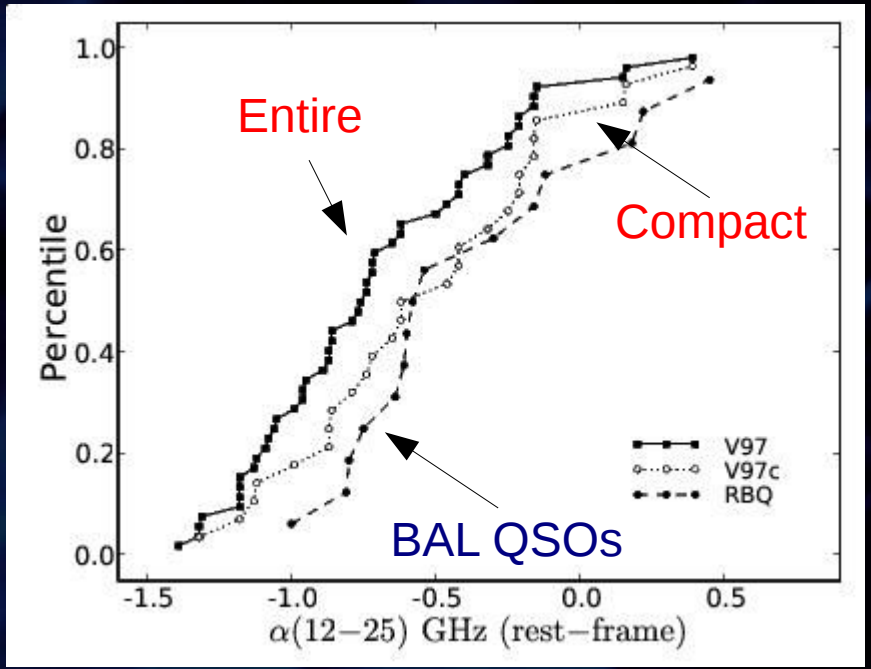
Radio spectra and polarisation properties...

Spectral indices: Test on orientation

BAL QSOs vs. non-BAL QSOs (B3-VLA, Vigotti et al. 1997)



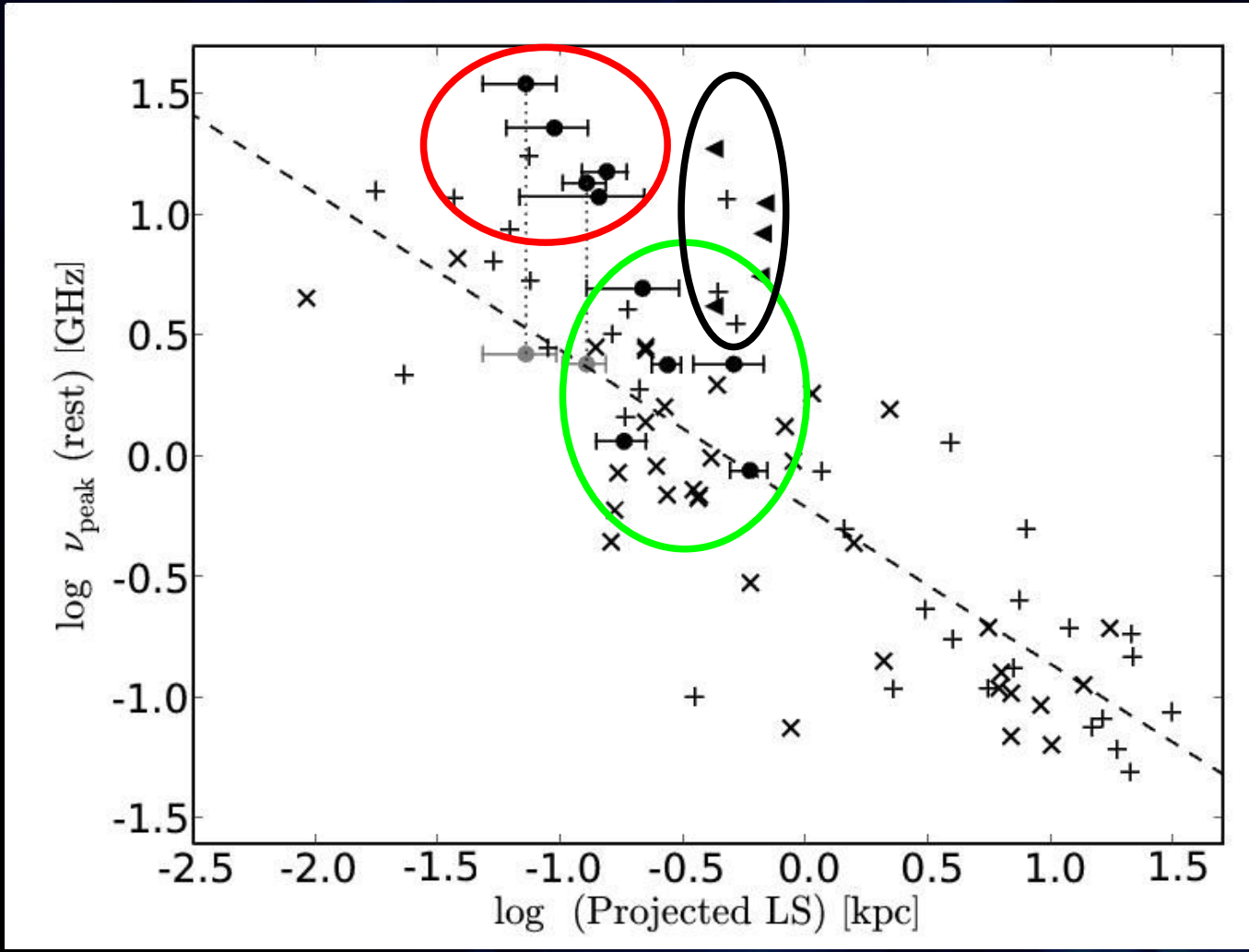
Observer's frame



Rest frame

Radio spectra and polarisation properties...

Spectral indices: Test on CSS/GPS sources



Anticorrelation:
ν_{peak} vs LS

Fanti et. al 1990
O'Dea & Baum, 1997

Spectral ageing...

- SYNAGE software (M. Murgia): CI, JP models -> ν_{br}
- Equipartition conditions -> B (dimensions)

$$\tau_{syn} = 1610 \frac{B^{1/2}}{B^2 + B^2_{\rm CMB}} \frac{1}{[\nu_{\rm break}(1+z)]^{1/2}}$$

- Define an expansion velocity:

$$v_{\rm exp} \sim c\ell / 2\tau^{-1}_{\rm syn}$$

Spectral ageing...

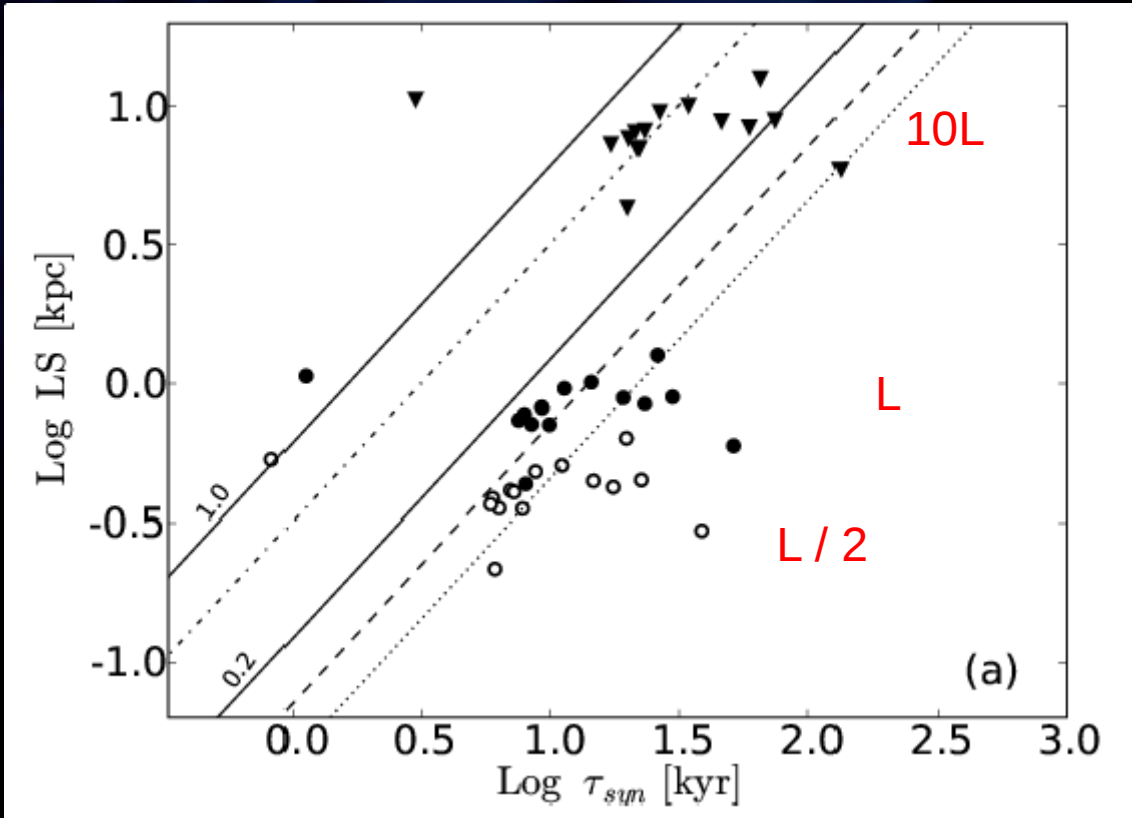
Table 6.1: Parameters from the SYNAGE fits.

ID (comp)	Best Fit Model	α_{inj}	ν_{br} [GHz]	$\nu_{br}(1+z)$ [GHz]	ℓ_k [kpc]	B_{eq} [μG]	τ_{syn} [kyr]	v_{exp}/c
0039−00	JP	0.467	25.5	82.6	0.715	715	9.2	0.15
0135−02	JP	0.375	18.0	50.7	0.816	735	11.3	0.14
0256−01	CI	0.475	6.2	21.9	0.794	510	29.8	0.05
0728+40	CI	0.542	2.4	4.0	0.551	625	51.0	0.02
0837+36	CI	1.000	22.5	99.5	0.676	640	9.9	0.12
0957+23	CI	0.375	6.0	18.1	0.672	1260	8.4	0.14
1053−00	CI	0.809	26.6	67.9	0.856	570	14.4	0.11
1159+01	CI	0.375	94.1	281.3	0.892	1950	1.1	1.55
1213+01	CI	0.622	11.2	43.0	0.744	545	19.2	0.08
1228−01	JP	0.375	30.1	110.0	0.694	720	7.9	0.16
1312+23	CI	0.375	6.1	15.4	0.817	680	23.2	0.06
1413+42	JP	0.375	28.9	109.9	0.644	745	7.5	0.16
1603+30	JP	0.375	22.3	67.4	0.706	765	9.3	0.14
1624+37	CI	0.577	7.8	34.1	0.368	1055	8.0	0.09
1625+48	CI	0.521	9.3	34.3	0.921	480	26.1	0.08

1 - 50 0.12

Spectral ageing...

- Several important uncertainties:
  - Size estimates from unresolved sources
  - B can be different from the equipartition value
  - Beaming -> changes the apparent size and B



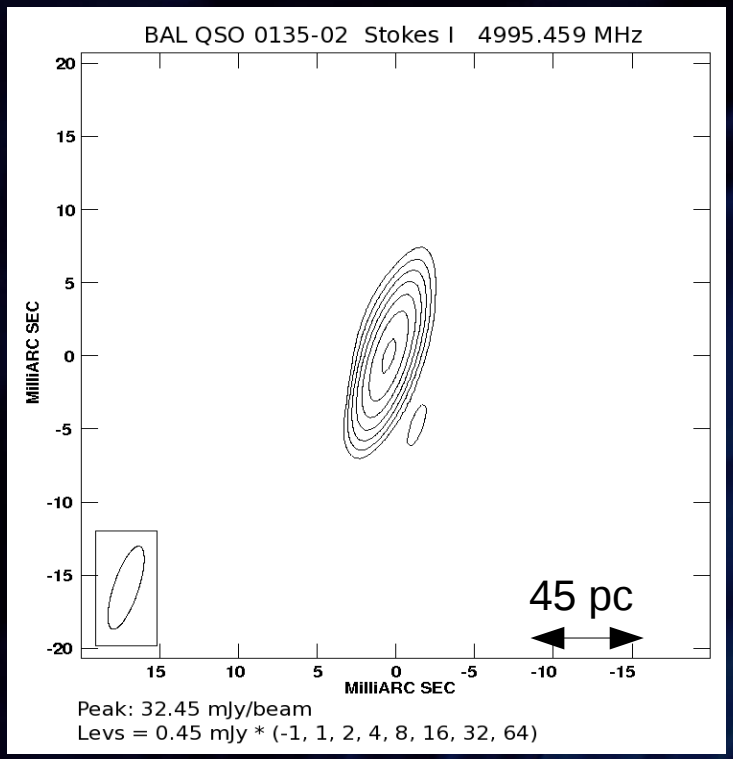
- Indications of small synchrotron ages of the dominant component
- Consistent expansion velocities

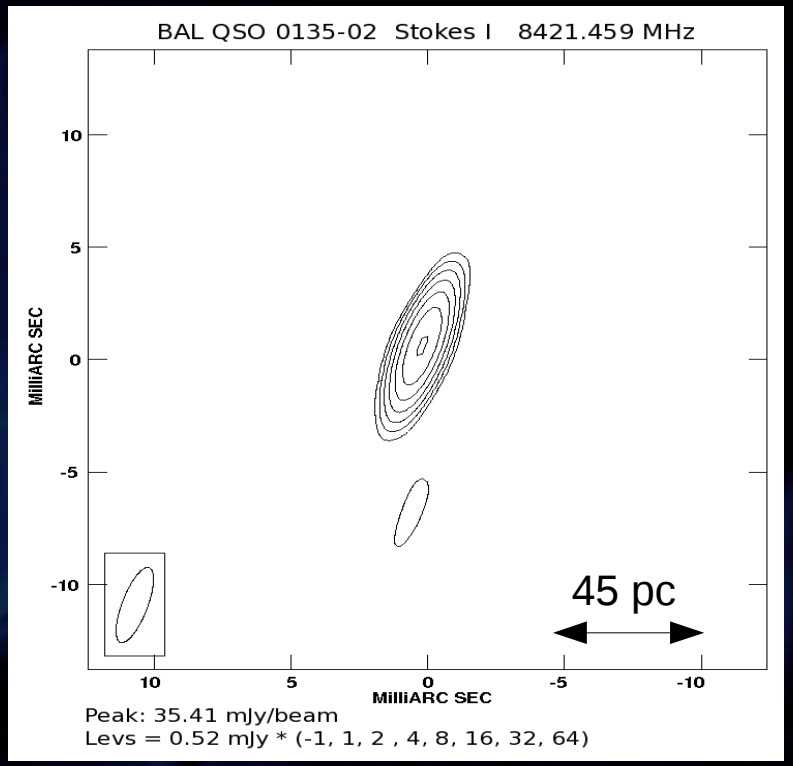
Pc-scale morphology...

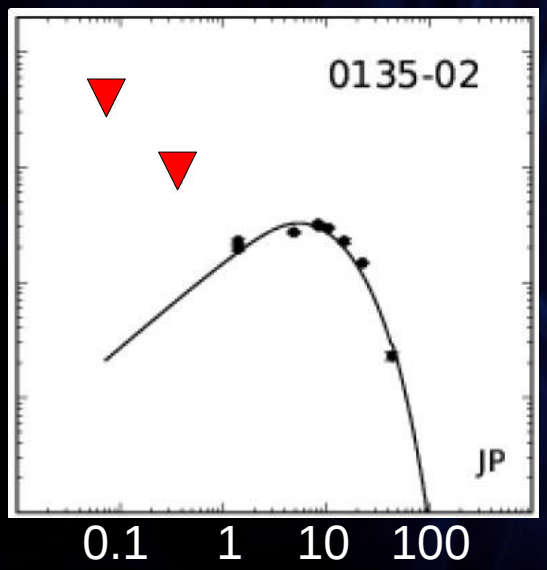
- Subsample of 5 BAL QSOs
- VLBA observations at 4.8 and 8.4 GHz (phased reference)

Source	z	Type	S(5 GHz) [mJy]	log L(5 GHz) [W/Hz]
0135-02	1.82	HiBAL	27.2 ± 0.6	26.3
0837+36	3.42	LoBAL	30.2 ± 2.3	26.7
1159+01	1.99	HiBAL	137.8 ± 1.7	27.3
1537+58	3.06	LoBAL	40.6 ± 0.8	27.3
1624+37	3.38	HiBAL	23.3 ± 1.1	27.1

Montenegro-Montes et al. 2009

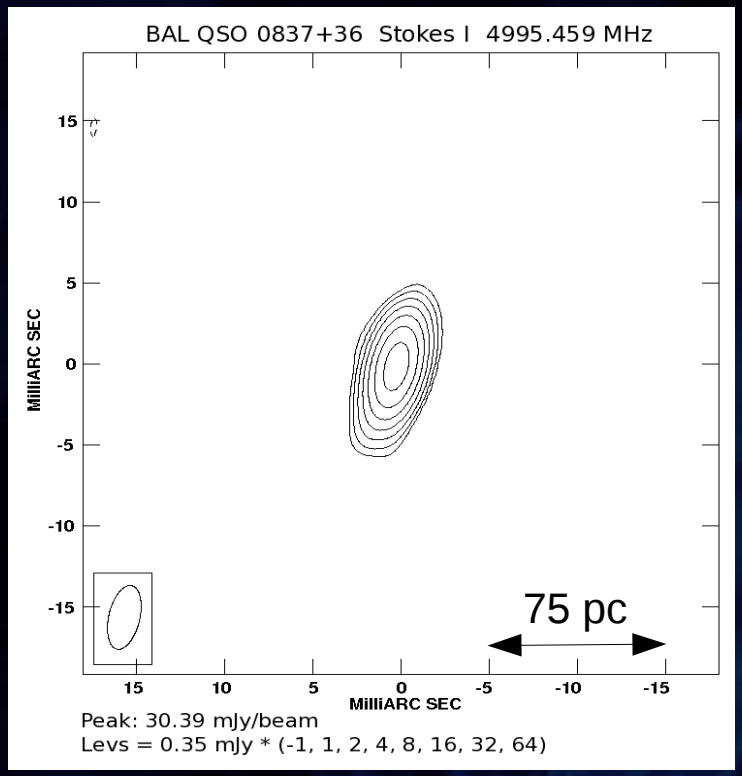


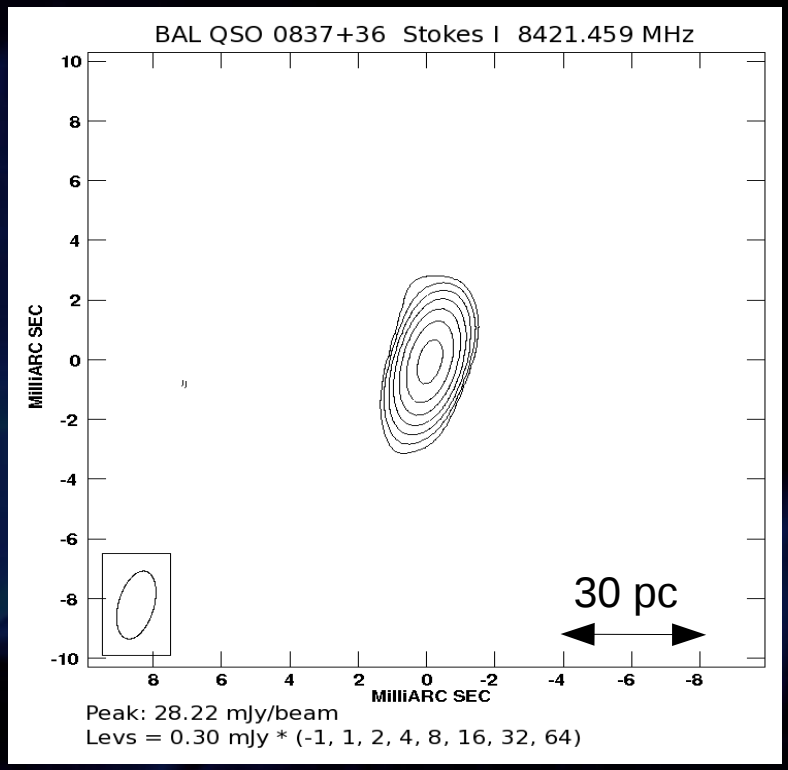


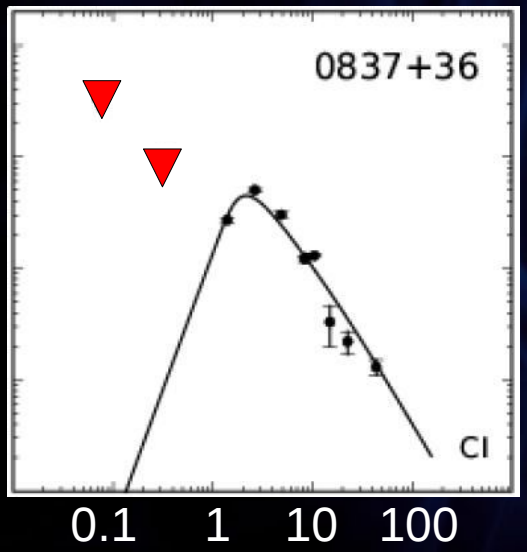


- Compact GPS / HFP quasar
- m(8.4 GHz) < 0.84%, m(22 GHz) < 1.7%
- Maybe some variability (15%) but below $3\sigma_{var}$

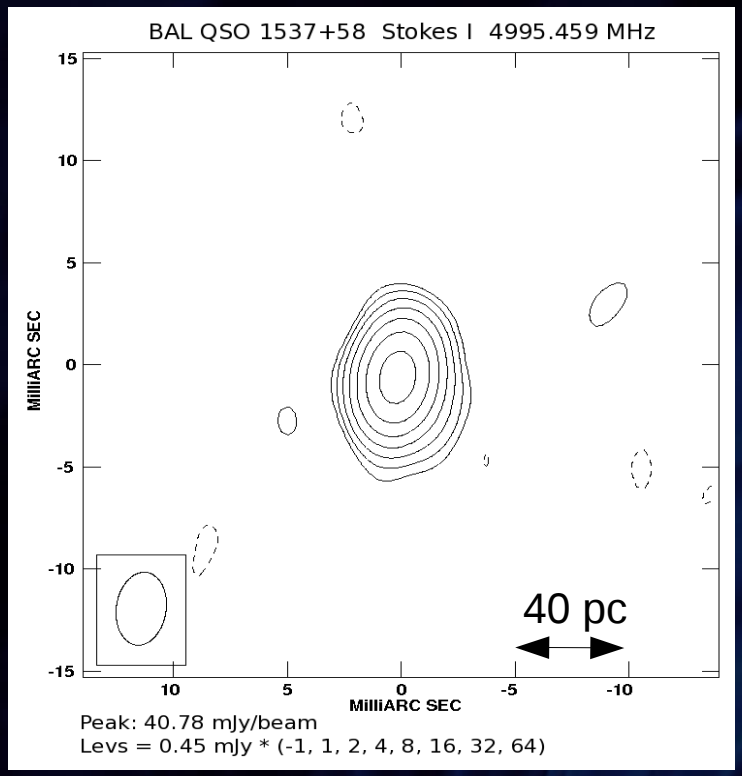
Further follow-up

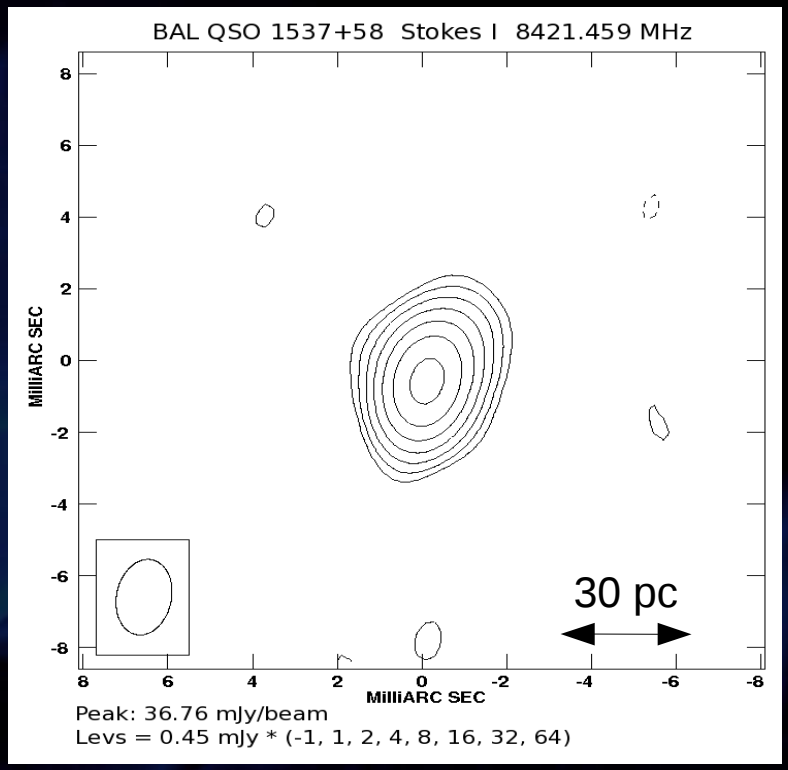


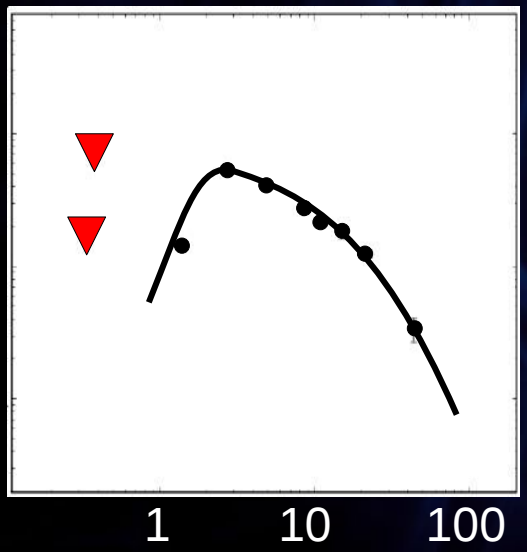




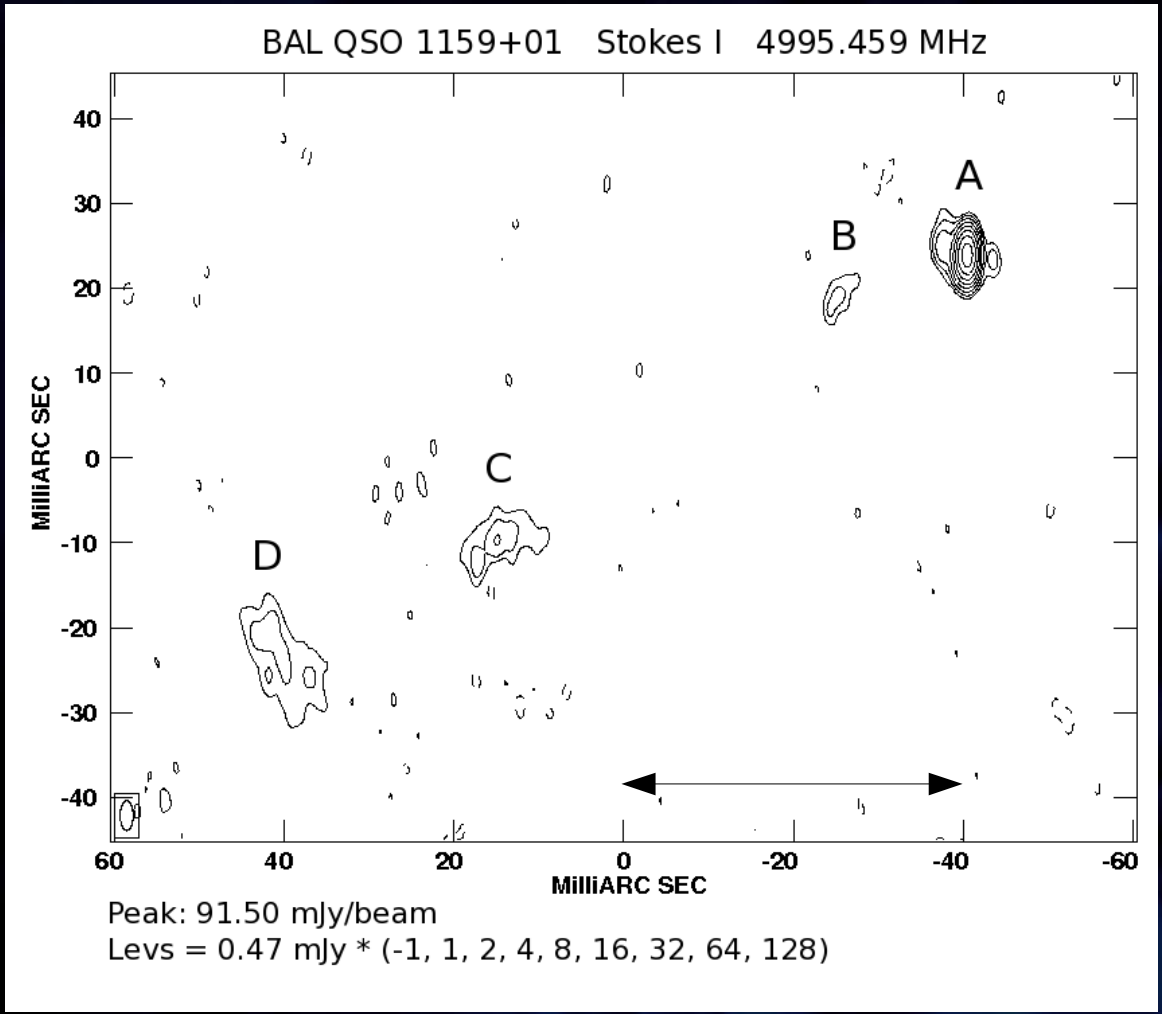
- Compact GPS quasar
- m(8.4 GHz) < 0.60%
- Variable at level ~ 5 σ_{var}
  Change in spectra shape?



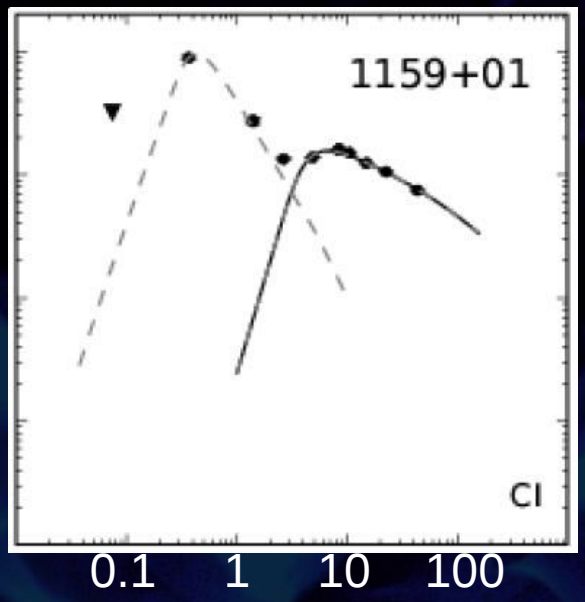


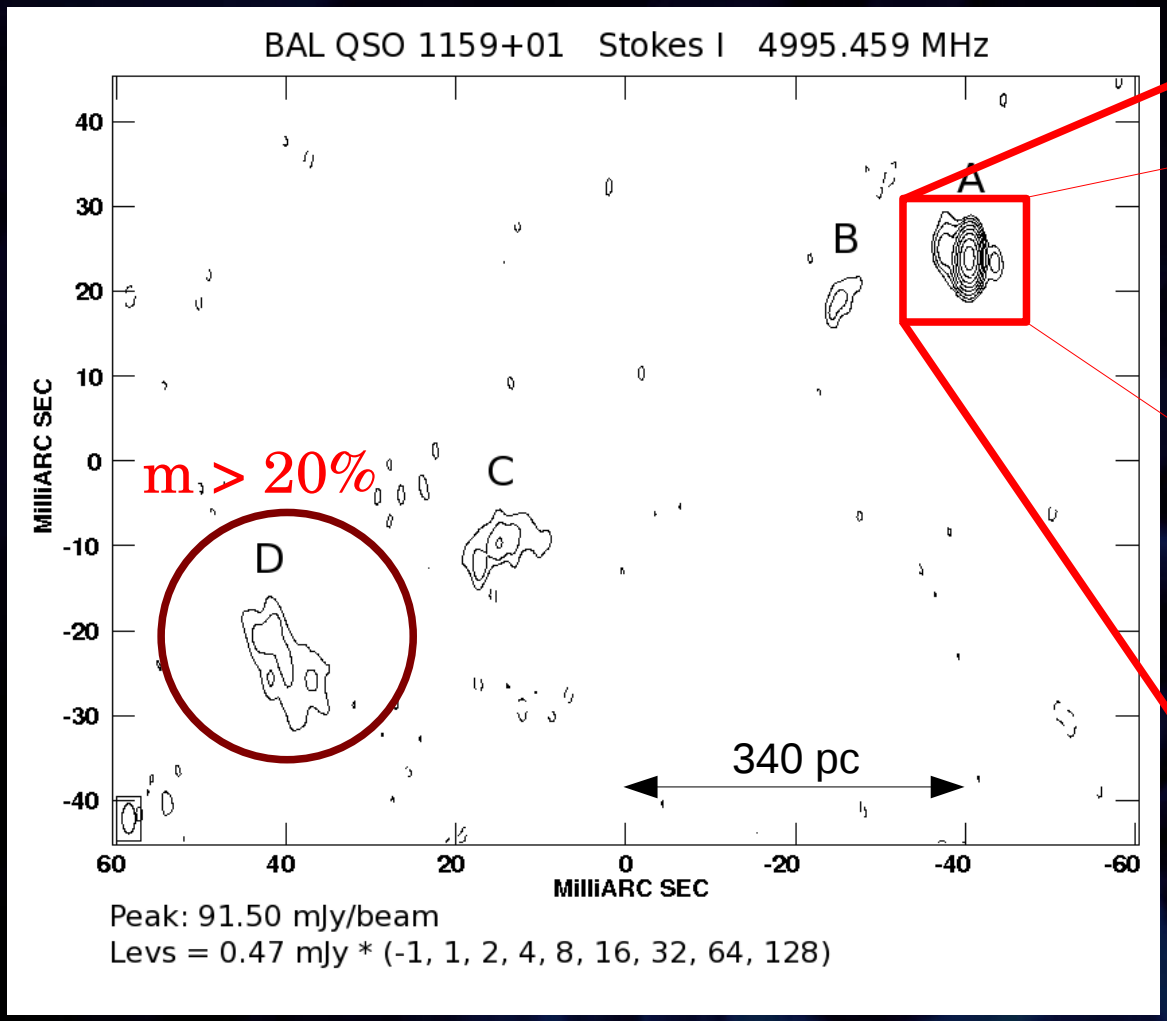


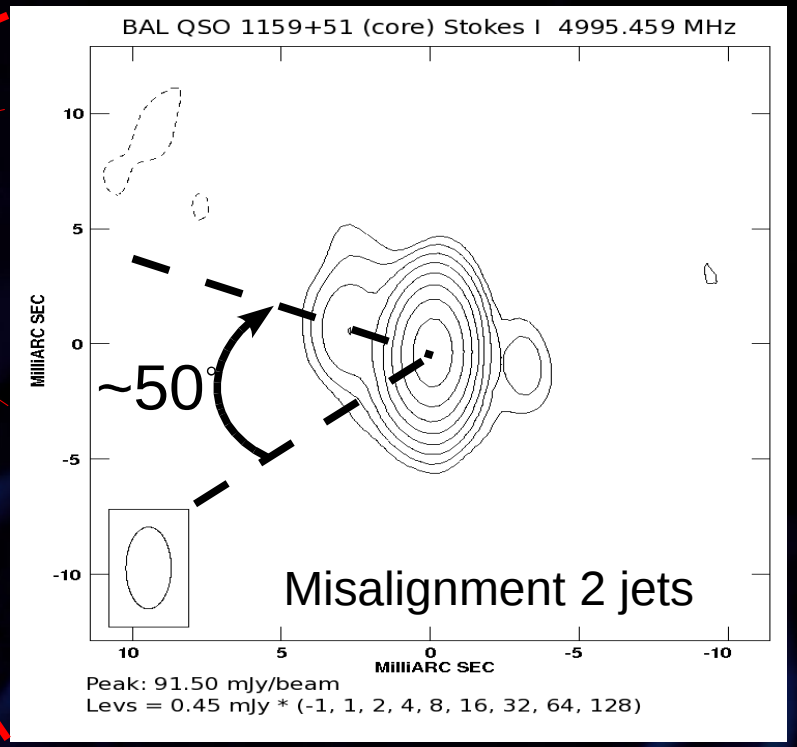
- Compact GPS quasar
- m(8.4 GHz) < 0.60%
- Variable (30%) at a level ~ 3 σ_{var}

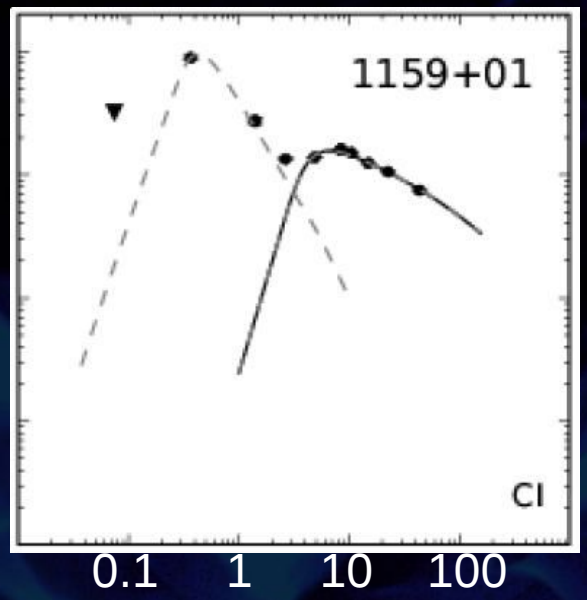


Much more interesting !!





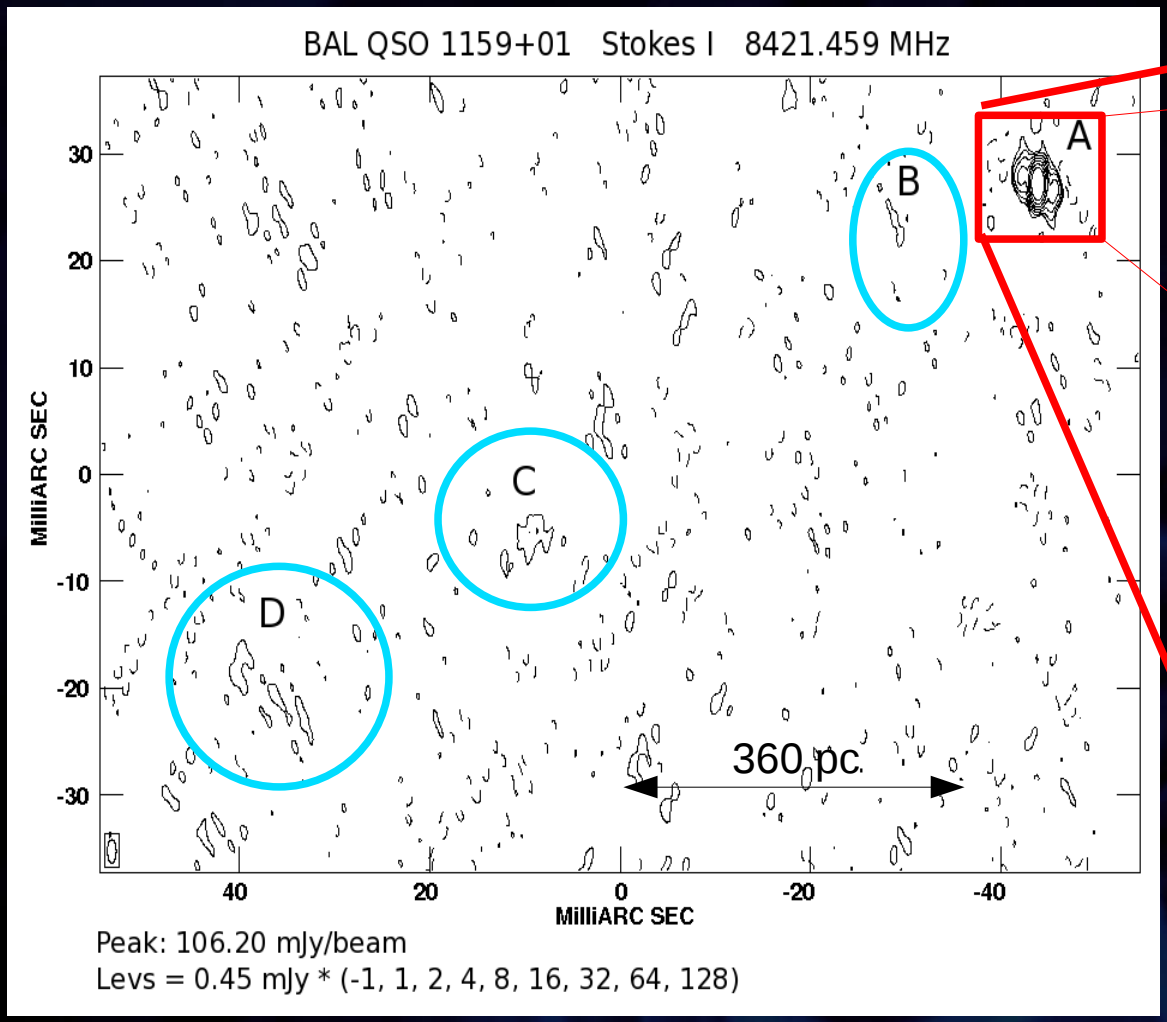


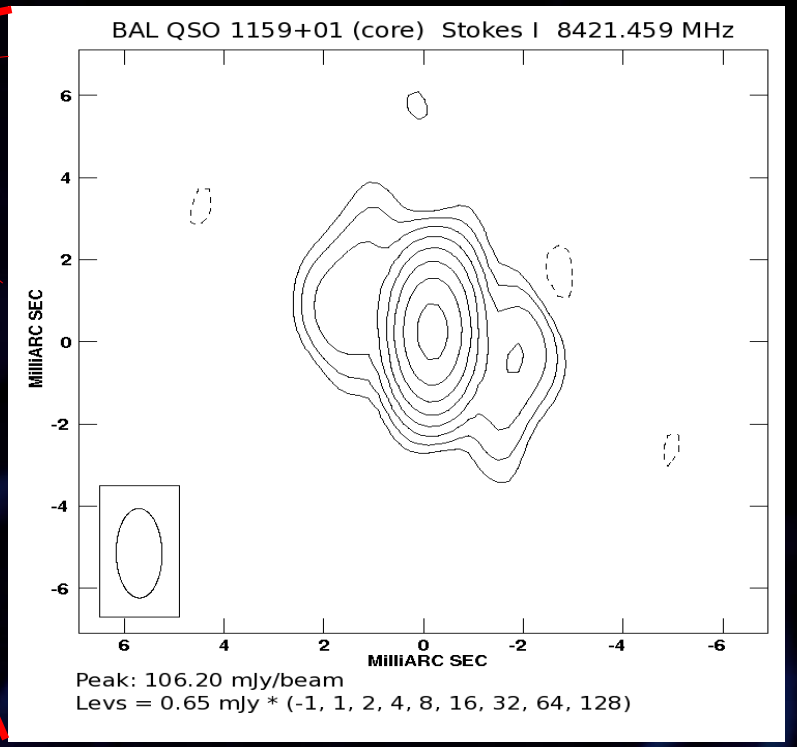


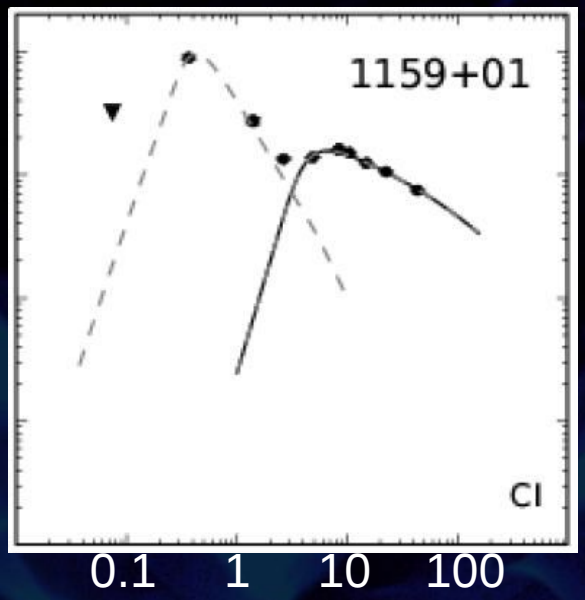
Residual/faint lobe emission (no hot-spot)

"Core": CSO morphology (?)

- Bright core
- Asymmetry in flux density



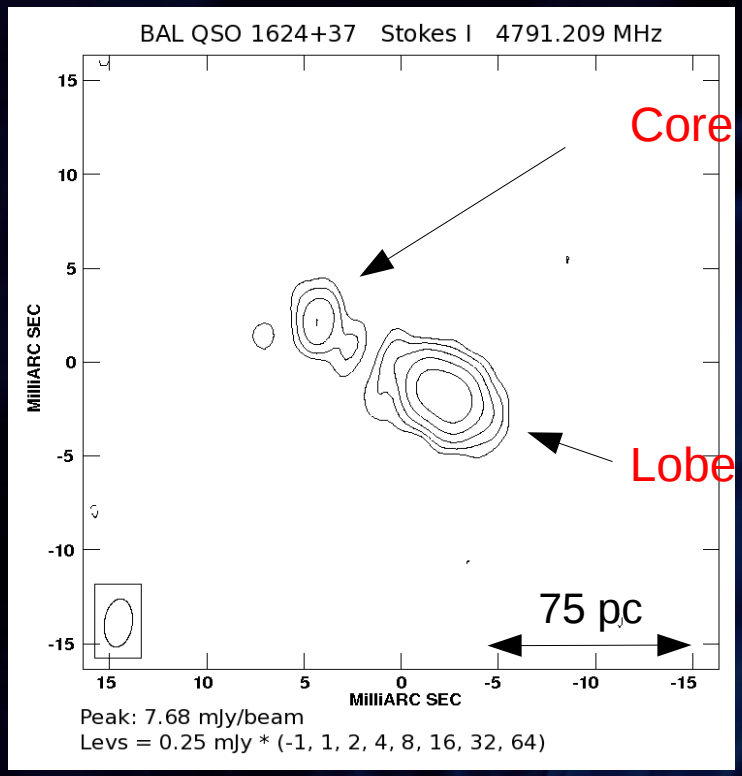




Very faint extended emission at 8.4 GHz

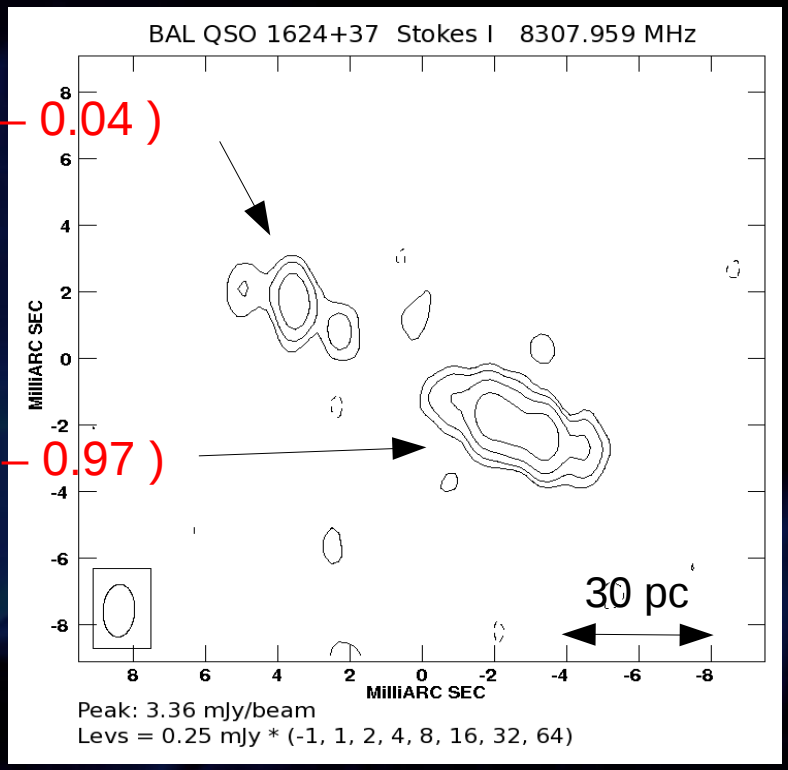
Spectral indices: "core" $\alpha = +0.3$ (inverted)

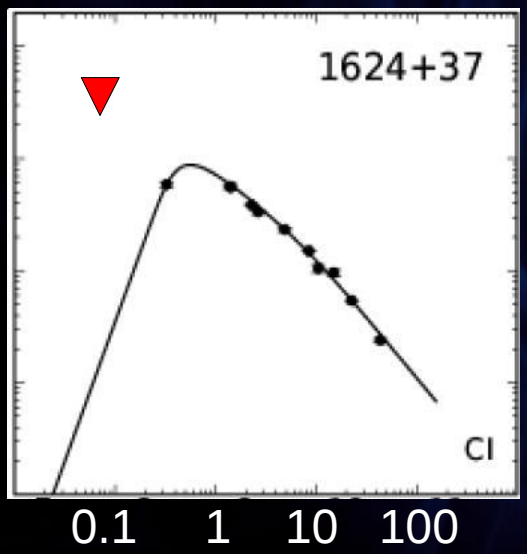
"extended (D+C)" $\alpha = -1.6$ (steep)



Core (α = – 0.04)

Lobe (α = – 0.97)





- Unusual BAL QSO (Benn et al. 2005)
- CSS quasar: Core-jet morphology
- No polarisation detected in VLBA (?)
- Jet / counterjet gives $\theta < 37^{o}$

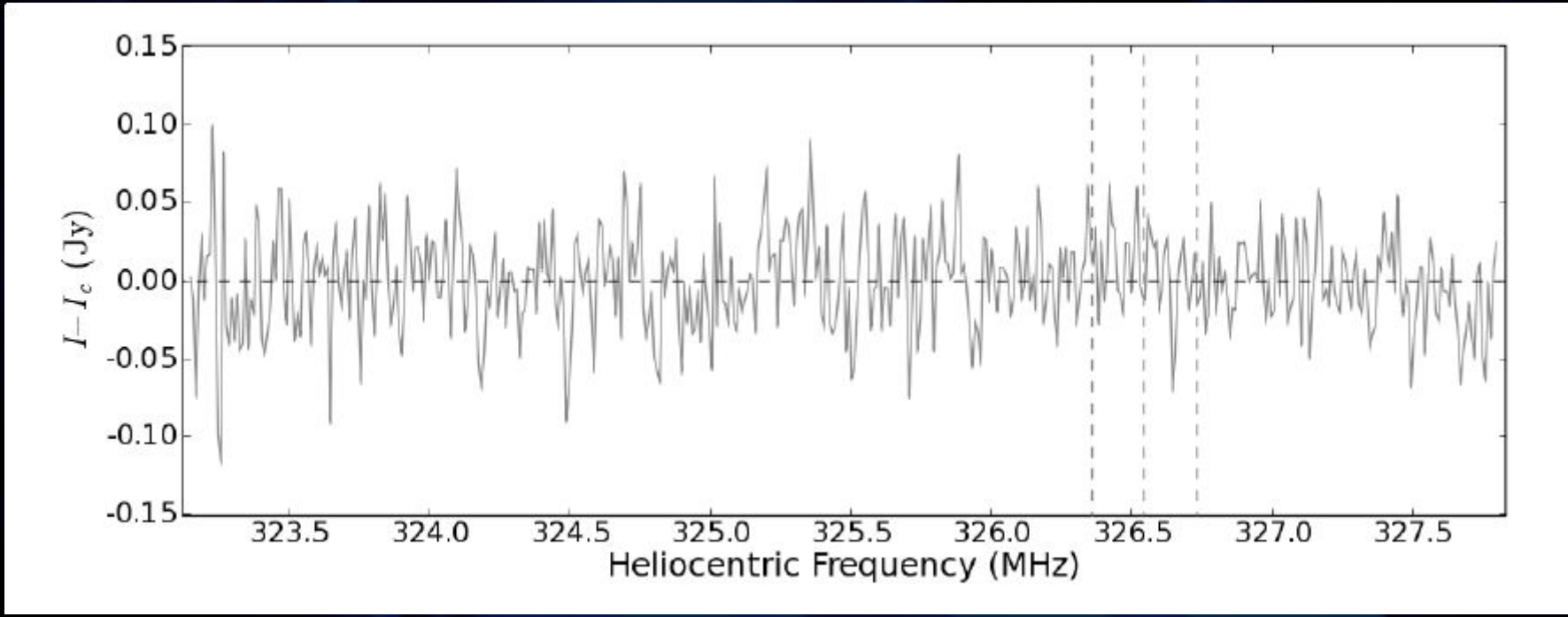
Pc-scale morphology...

Total of 17 BAL QSOs with VLBI in literature
(Jiang & Wang, 2003; Kunert-Brajraszewska & Marecki, 2007;
Liu et al., 2008; This work)

- **7** unresolved (41%)
  Polar BAL QSOs / intrinsically compact / very faint jet-lobe
- **6** core-jet (35%)
  Intermediate orientation. If bright enough, θ can be determined
- **2** "compact symmetric objects" (12%)
  Jet not aligned to the line of sight.
- **2** complex morphology (12%)
  possible signs of restarting radio activity *(Marecki et al. 2006)*

Detection experiment: H I in absorption J1624+3758...

- Very high rotation measure (large amount of matter?)
- Indications of an absorber in the optical
- z ~ 3.38 (most sensitive part of WSRT receiver at 327 MHz)



$N(HI) < 9 \times 10^{18} T_s \text{ cm}^{-2}$ $n(HI, 140K) < 2.7 \text{ cm}^{-3}$ $B_{||} > 60 \ \mu G$

Conclusions about radio-loud BAL QSOs

Hints on evolution (properties of young sources):

- BAL QSOs very compact in the radio (mostly unresolved with VLA)
- They show convex radio spectra (losses + SSA)
- Little linear polarisation
- Little flux density variations (so far)
- Anticorrelation LS vs ν_{br} nicely holds
- Synchrotron ages derived from the spectra are small

Hints against orientation:

- No different α distribution between BAL/non-BAL QSOs
- Variety of pc-scale morphologies: unresolved, core-jet, CSO-like


Thanks!