VLBI associations of Fermi sources

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Populations of γ-ray and compact radio sources: what is common?

VLBI provides us insight on emission from parsec-scales.

γ-ray dataset:	Fermi **2FGL** catalogue
VLBI datasets:	positions and images from **surveys**.

From VLBI observations we can get

- Positions with sub-mas accuracy;
- maps with parsec-scale resolution;
- polarization properties.

Scope of this talk: data from absolute astrometry surveys.

Major geodesy/absolute astrometry programs

	Dur (h)	C	X/S	X	K
IVS*	115,000		**946** (1060)		
VCS	504		**3497** (3800)	**3516** (3800)	
RDV*	3,024		**1045** (1073)	**1043** (1073)	
LCS*	216			**845** (1014)	
V2M*	338			**1162** (1621)	
NPCS	72		**177** (521)	**133** (521)	
OBRS*	48		**115** (115)		
KQ	288				**329** (340)
VGAPS	72				**384** (543)
EGAPS	48				**178** (437)
BESSEL	155			**354** (1535)	
VIPS	176	**857** (858)			
VIPS+	48	**193** (193)			
FAPS*	72			**279** (283)	
Total		**1167** (1171)	**4150** (4904)	**5751** (8193)	**817** (1225)

$*$ — ongoing.
the number of **detected** (observed) sources.

Grand total: **6547 (9211) sources**. **Statistics are computed on 2011.11.01**

The catalogues and $\sim 30,000$ images are available at **http://astrogeo.org/rfc**

Fermi/VLBI association

Preliminary VLBI/Fermi associations: sources that are within 2σ of $\mathrm{Err}_{\mathrm{maj}}$.

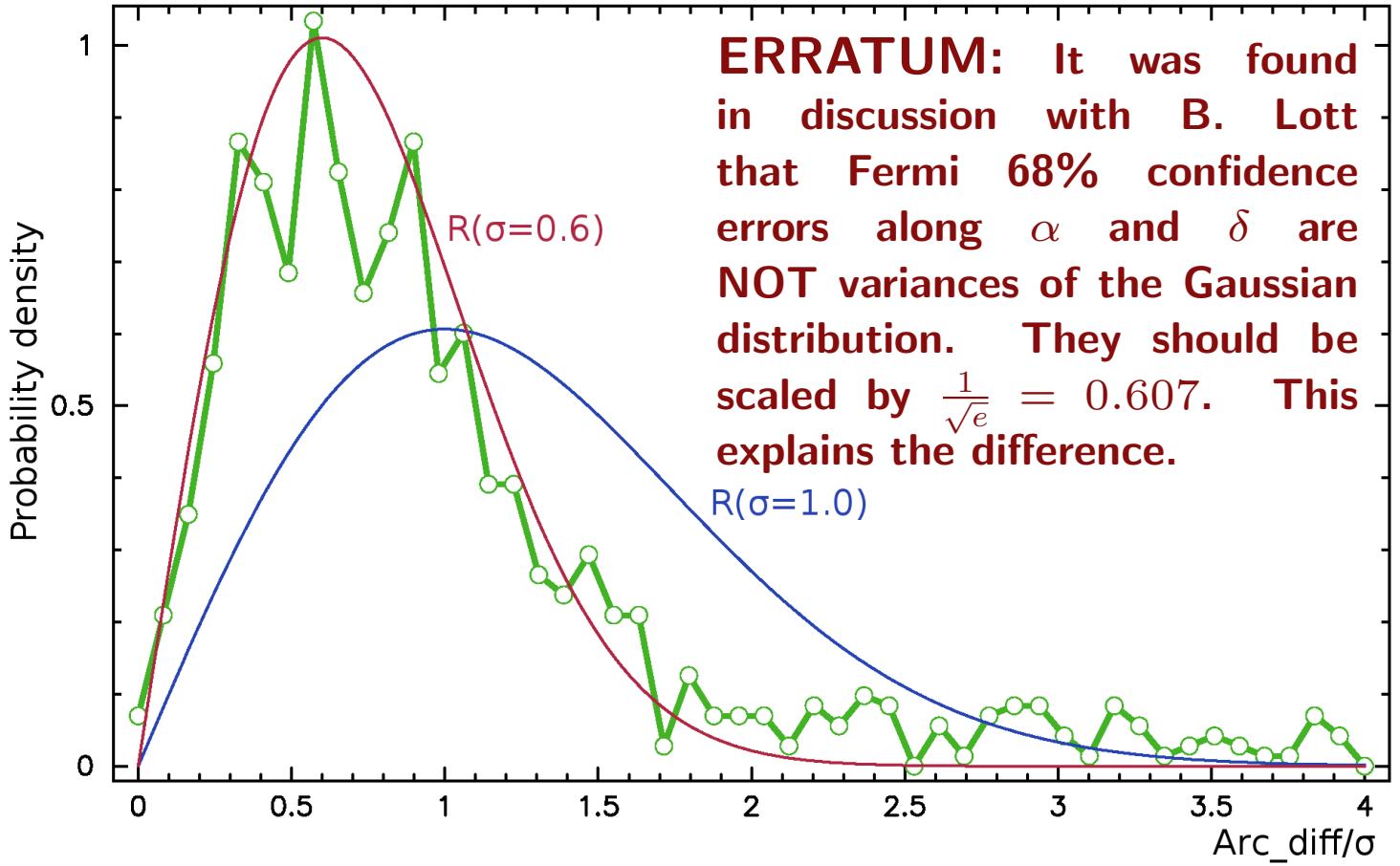
Zone	Fermi	VLBI	share
$\delta > -30^\circ,\ \ \lvert b\rvert > 10^\circ$	**1009**	**648**	64%
$\delta < -30^\circ,\ \ \lvert b\rvert > 10^\circ$	**308**	**128**	42%
all sky	**1872**	**880**	47%

As a rule of thumb, 1/2 of Fermi sources from 2FGL have been observed with VLBI.

Can physically unrelated Fermi and VLBI sources be associated by chance?

How accurate are 2FGL Fermi position errors?

The histogram of **normalized position differences**
VLBI–2FGL (arc/σ arc)

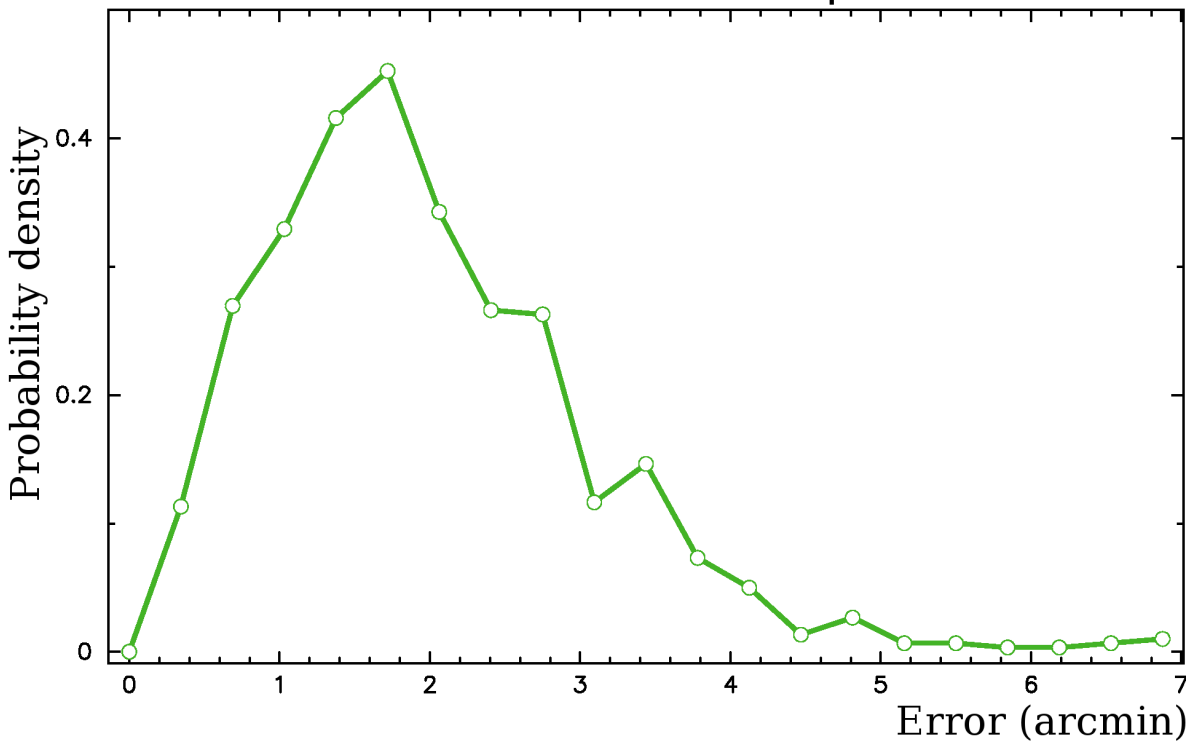


ERRATUM: **It was found in discussion with B. Lott that Fermi 68% confidence errors along α and δ are NOT variances of the Gaussian distribution. They should be scaled by $\frac{1}{\sqrt{e}} = 0.607$. This explains the difference.**

In total, 880 sources (47% of 2GFL) were used.
Conclusion: Fermi position errors are **overestimated by 67%**.

Fermi position errors

The distribution of rescaled Fermi position errors.

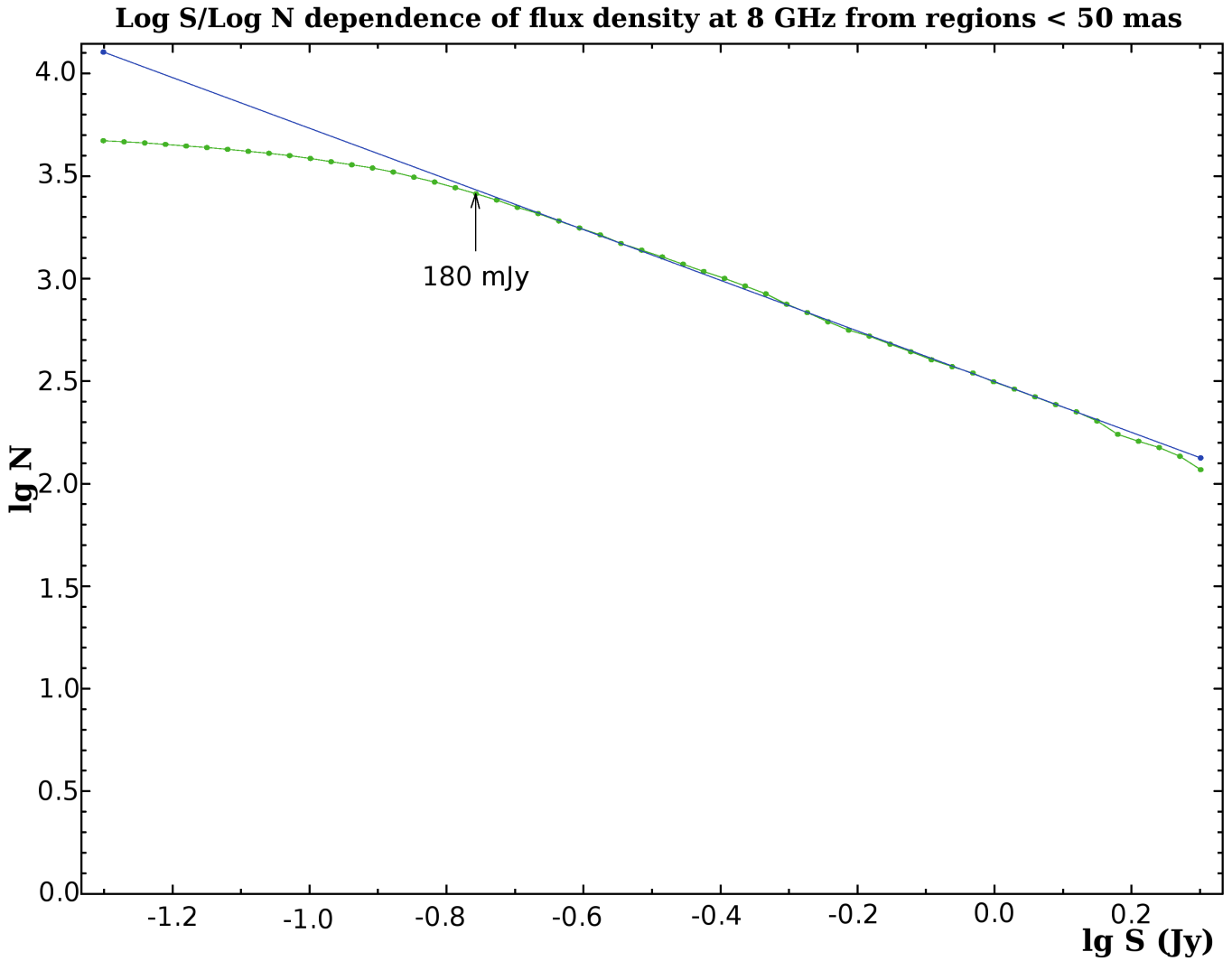


2FGL position errors were scaled by a factor of 0.60

The 2FGL semi-major position error axes
50% objects $< 1'.7$
80% objects $< 2'.7$
95% objects $< 3'.5$

Rotation angles from differences VLBI–Fermi	
R_x	$3''.1 \pm 5''.8$
R_y	$7''.9 \pm 5''.6$
R_z	$12''.1 \pm 4''.1$

Completeness of the cumulative VLBI catalogue at $\delta > -30°$



The completeness of the catalogue at correlated flux density 180 mJy is 95%.

$N = 311 \cdot 10^{-1.236 \ \lg S}$ where S is in Jansky

Using this source count and assuming

1) log N/log S dependence can be extrapolated down to 1 mJy;
2) Source distribution is isotropic.

We can compute the probability to detect a VLBI source in an area of a given radius:

R	1 mJy	5 mJy	10 mJy	20 mJy	50 mJy	100 mJy
$4'$	0.418	0.073	0.032	0.014	0.004	0.002

The probability grows quadratically with the growth of the search area.

The probability to find an unrelated VLBI source as a function of Fermi semi-major position error, and X-band correlated flux density:

Err	1 mJy	2 mJy	5 mJy	10 mJy	20 mJy	50 mJy	100 mJy
$1'.7$	0.1638	0.0774	0.0266	0.0116	0.0050	0.0016	0.0007
$2'.6$	0.3142	0.1620	0.0601	0.0270	0.0118	0.0038	0.0016
$3'.5$	0.4536	0.2623	0.1039	**0.0473**	0.0208	0.0069	0.0029
$10'$	0.8714	0.7437	0.4862	0.2883	0.1479	0.0535	0.0236

Final VLBI/Fermi associations with identification significance 99%:

1. The probability that the arc-length VLBI–γ is due to random errors > 0.01
2. The probability of association with an unrelated source < 0.01

Zone	Fermi	VLBI	share
$\delta > -30^\circ,\ \ \lvert b\rvert > 10^\circ$	**1009**	**563**	56%
$\delta < -30^\circ,\ \ \lvert b\rvert > 10^\circ$	**305**	**109**	34%
$\lvert b\rvert < 10^\circ$	**554**	**75**	14%
all sky	**1872**	**745**	40%

There are 35 outliers: Arc $< 15'$, P(VLBI–γ)< 0.01

For instance,

J1041+0610 F(8.6 GHz)= 1.174 Jy, Arc: $9'.4$
J1127−1857 F(8.6 GHz)= 1.407 Jy, Arc: $6'.1$
J1635+3808 F(8.6 GHz)= 1.954 Jy, Arc: $2'.2$

Are there weak (F $<$ 150 mJy) VLBI associations?

We ran a dedicated VLBA+GBT experiment in 2009/2010 at 8 GHz.

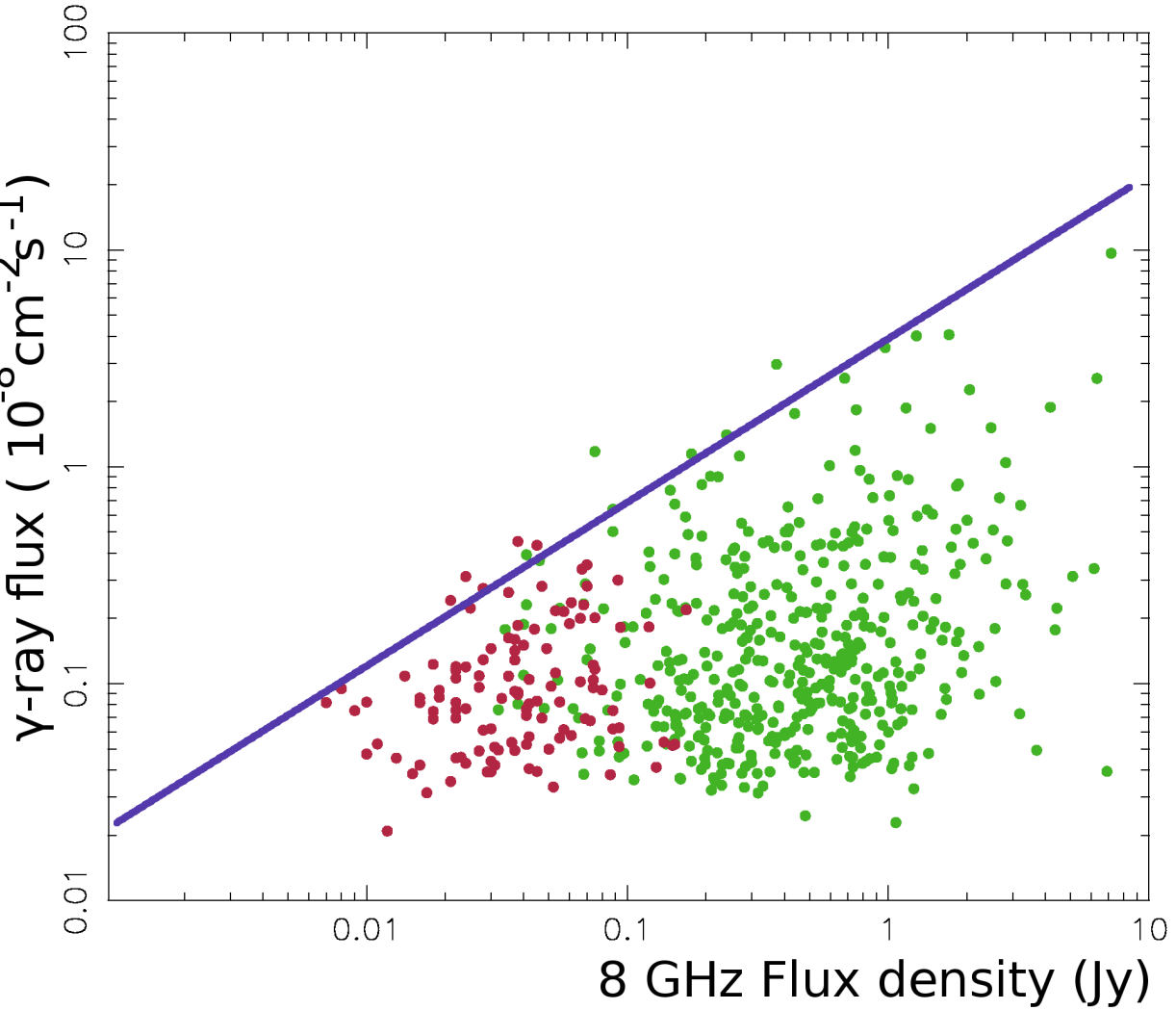
169 targets associated with flat-spectrum sources, not previously observed with VLBI.

Targets are 1FGL identifications.

Result: 168 out of 169 targets have been detected.

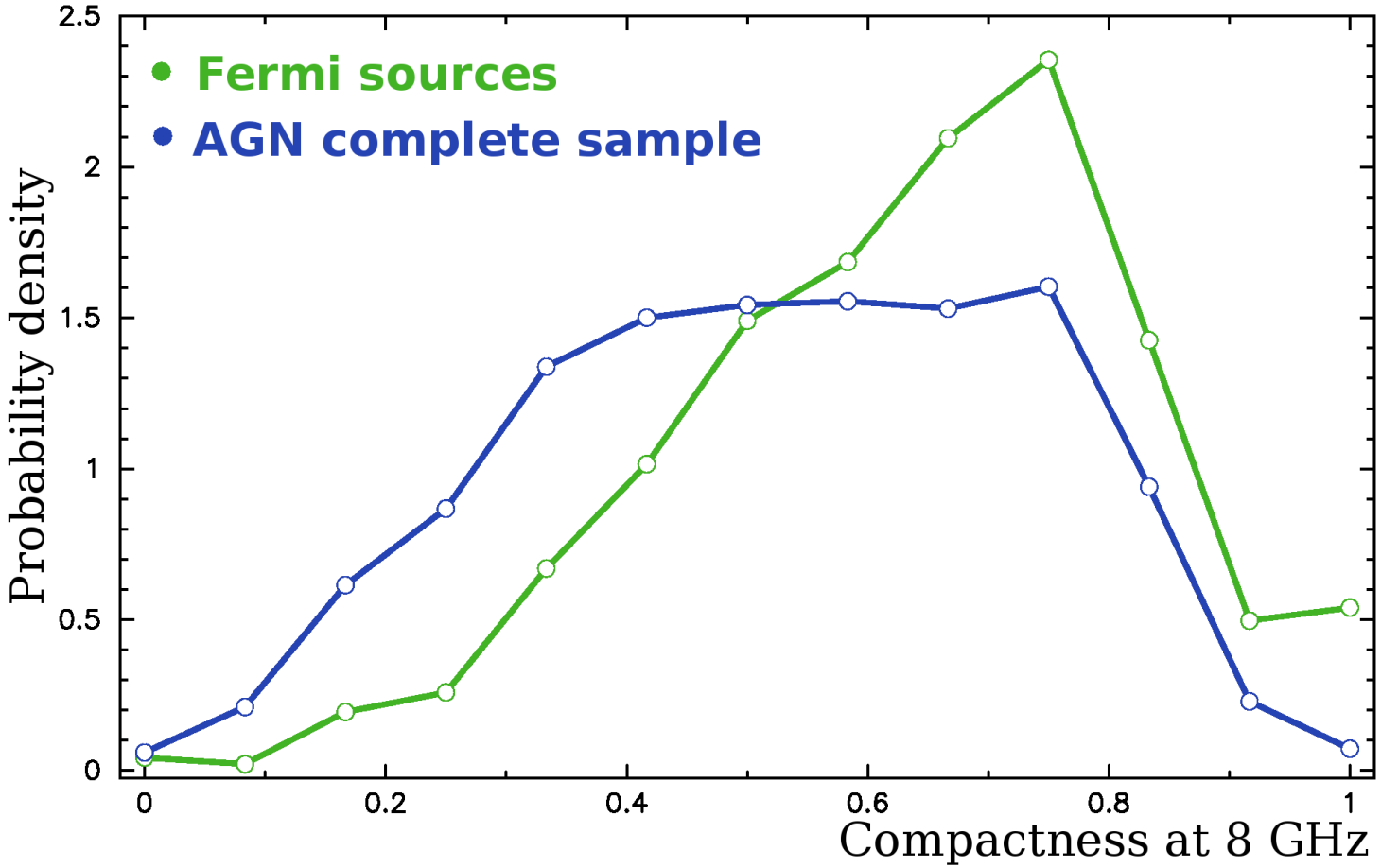
Detection limit 4 mJy.

Direct correlation of γ-ray and radio fluxes at 1–100 Gev for 2FGL associations with $\delta > -30^\circ$



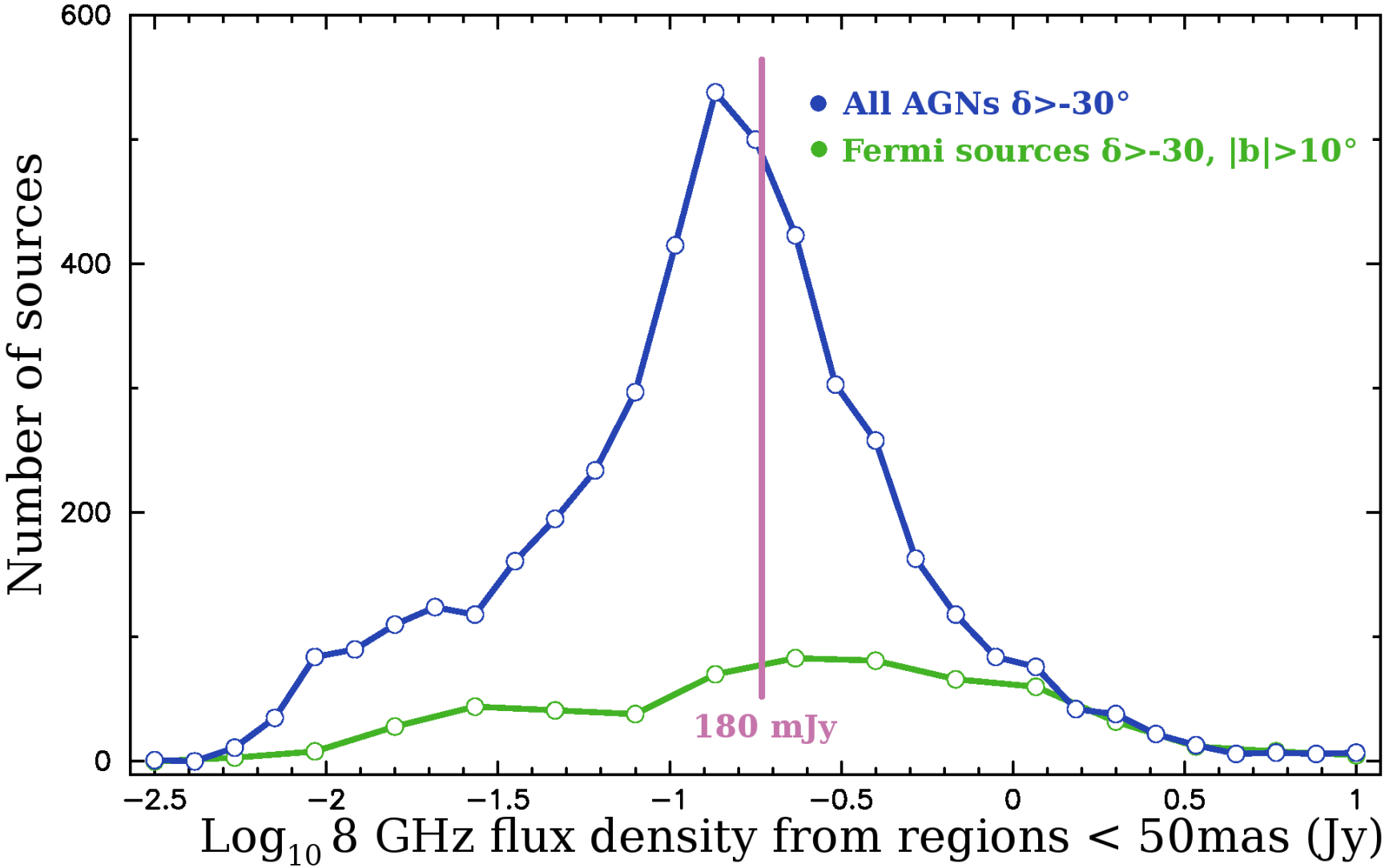
- — results from a dedicated VLBA+GBT experiment.
- — other experiments.

Compactness of Fermi sources and the AGN complete sample

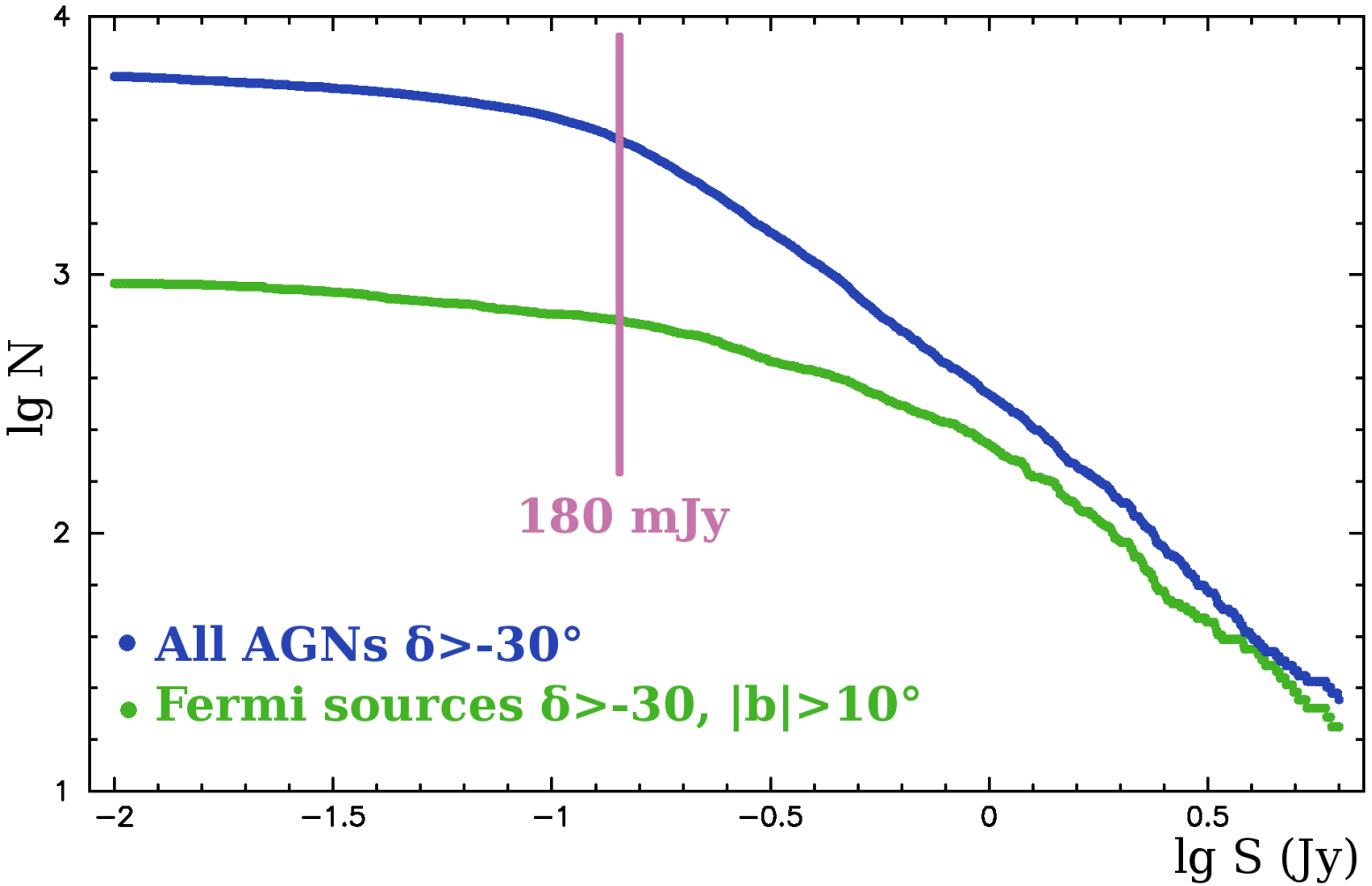


$$\text{Compactness} = \frac{\text{Median } F_{\text{corr}} \text{ at baseline projection lengths [5000, 8600] km}}{\text{Median } F_{\text{corr}} \text{ at baseline projection lengths [0, 900] km}}$$

The histogram of parsec-scale flux densities of Fermi sources and the AGN complete sample



Log N/Log S curve for Fermi sources and the AGN complete sample using correlated flux density from regions < 50 mas



40% sources with $F_{\rm corr}(8\ {\rm GHz}) > 1$ Jy have a Fermi association
20% sources with $F_{\rm corr}(8\ {\rm GHz}) > 0.2$ Jy have a Fermi association

Conclusions

- $\sim 1/2$ Fermi sources at $\delta > -30^\circ$ and $|b| > 10^\circ$ are associated with VLBI sources and **have position accuracy < 1 mas**;
- Fermi position errors should be scaled by 0.60 **(ERRATUM: rescaling factor $0.6 = \frac{1}{\sqrt{e}}$ stems from the definition of 68% confidence errors)**;
- Position errors of $\sim 5\%$ Fermi objects significantly exceed reported error bars;
- There is **a positive correlation** between γ-ray and parsec-scale radio fluxes. The upper envelop of γ-ray/radio flux diagram has been confirmed;
- Fermi sources are significantly **more compact** than the general AGN population;
- Log N/Log S diagram shows that the share of Fermi detections among all VLBI sources is gradually **reduced** at low correlated flux density at 8 GHz.

What's next?

- VLBI observations of sources at $\delta < -30^\circ$ with LBA ($observed\ right\ now$)
- VLBA+GBT observations of weak radio-γ 2FGL associations ($approved$)