Enhancing the value of *Fermi*/LAT catalogs with dedicated radio counterpart searches

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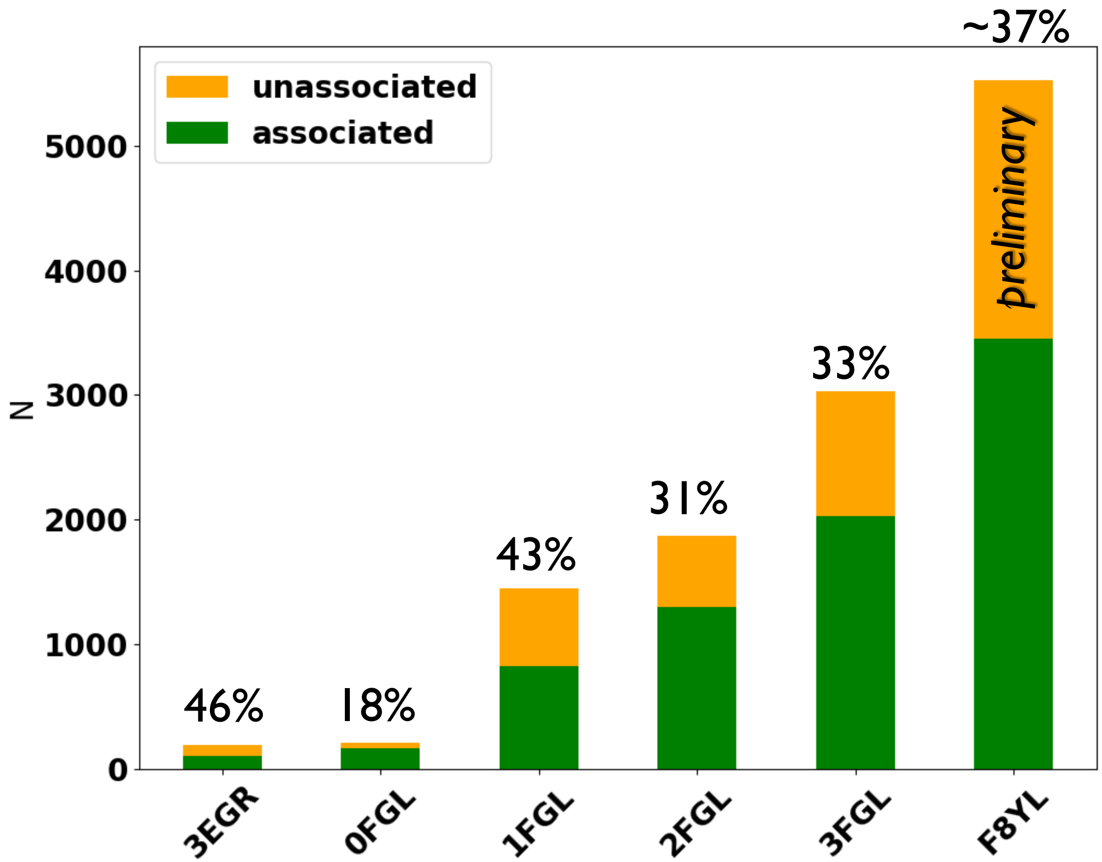
on behalf of the Fermi/LAT collaboration

Gamma-Ray Sources (GeV) w/ no counterpart



1/3 of the gamma-ray sky is still unknown after 10 years of *Fermi*! What are we missing?

Attempts to find counterparts

- Search for Pulsar counterparts (radio, gamma-ray data)
  e.g. *Einstein@home17 new γ-ray Pulsars: Clark et al. (2017); 16 new γ -ray Pulsars: Abdo et al. (2009)*

- Mining existing catalogs (WISE, NVSS, FIRST, TGSS, etc.)
  e.g. *Frail et al. (2016, 2018),* Massaro et al. (2012/2013)

- Machine Learning / Deep Learning
  e.g. *Saz-Parkinson et al. (2016)*

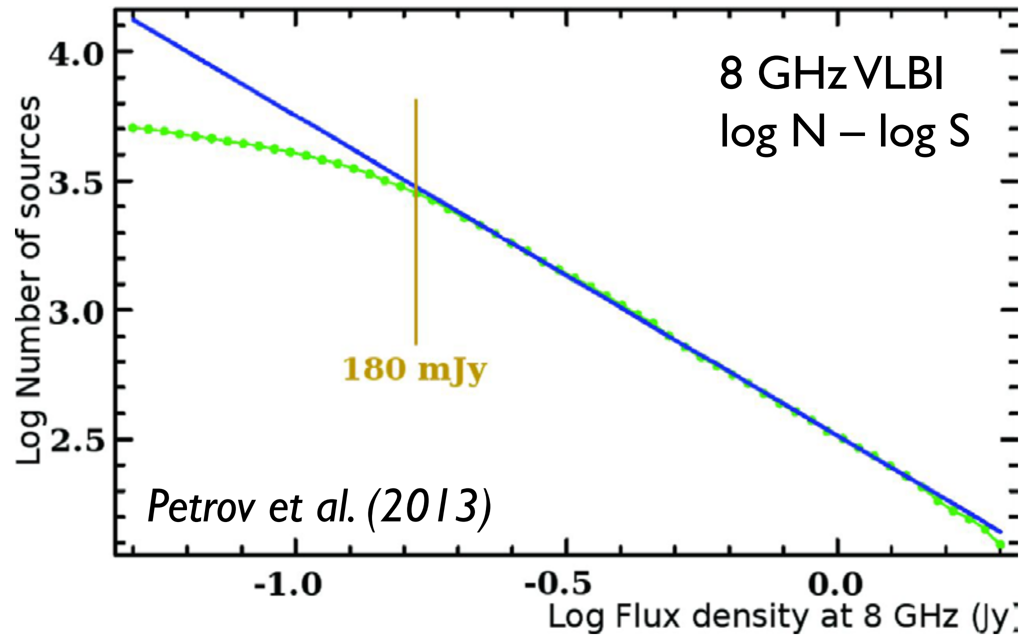
- Multi-wavelength follow-ups:
  – X-ray e.g. *Swift: Falcone & Stroh; Paiano et al. (2017)*
  – Optical, e.g. *Bellm et al.; Paiano et al. (2017)*
  – **Radio surveys (VLA, VLBA, ATCA, LBA, ALMA, SPT)**

Associating new radio-loud AGN

Calculate likelihood ratio that a compact, VLBI, detected source can be associated with a *Fermi/LAT* source.

Depends on: separation, size of error circle, and flux density of compact parsec-scale emission.

Goal: Associate new AGN with *Fermi*/LAT sources that are fainter in the radio by more than an order of magnitude than current completeness limit of catalogs, i.e. are most likely high synchrotron-peaked BL Lac objects.



Missing sources < 180 mJy
VLBI detected source ≈ AGN

Observation Strategy

Started in 2012 with 2FGL, continued with 3FGL, and currently working toward 4FGL.

Two tiered approach:

1. Australia Telescope Compact Array & Very Large Array 5-10 GHz observations of **every** unassociated Fermi source.
   => find all radio sources >1 mJy within Fermi error circles

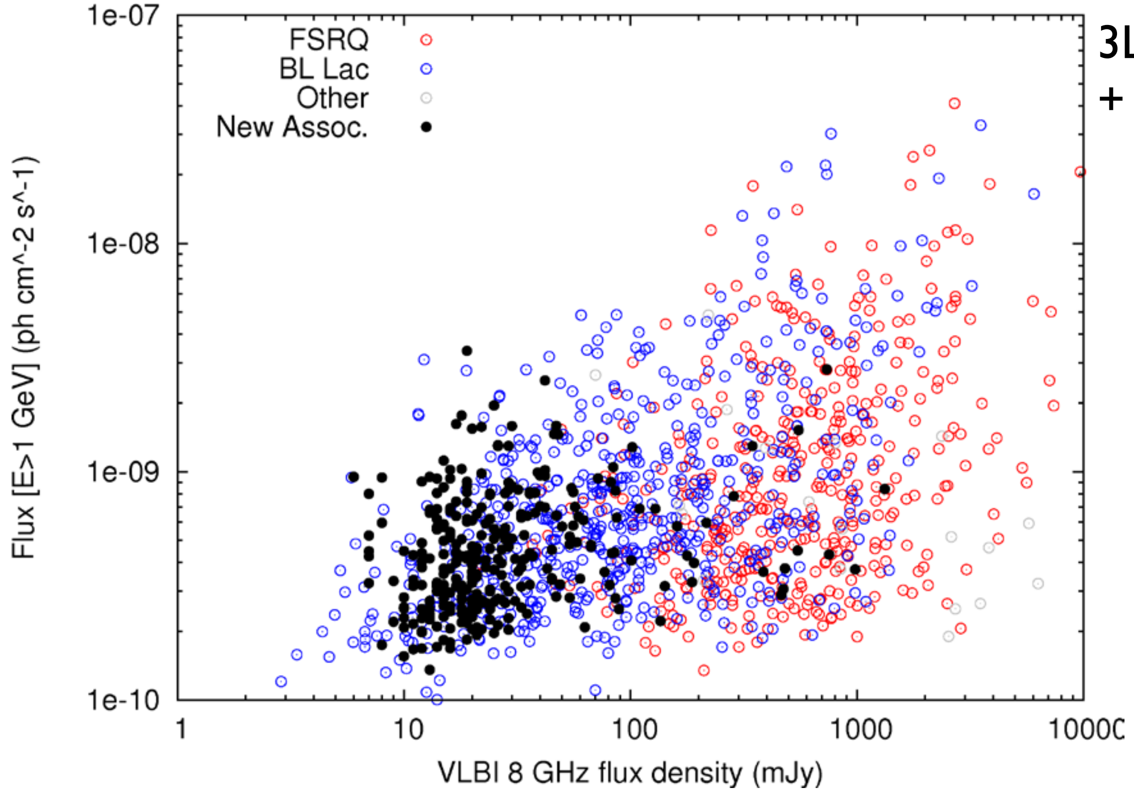
2. Follow-up with Very Long Baseline Interferometers (VLBA, LBA, ad-hoc VLBI) of candidates detected by ATCA and VLA that were brighter than 8 mJy

Will allow associations between *Fermi* -> radio -> optical (esp. Gaia)

Increase of AGN associations

2FGL: 76 new associations – 13% of unassociated sources (Schinzel et al. 2015)

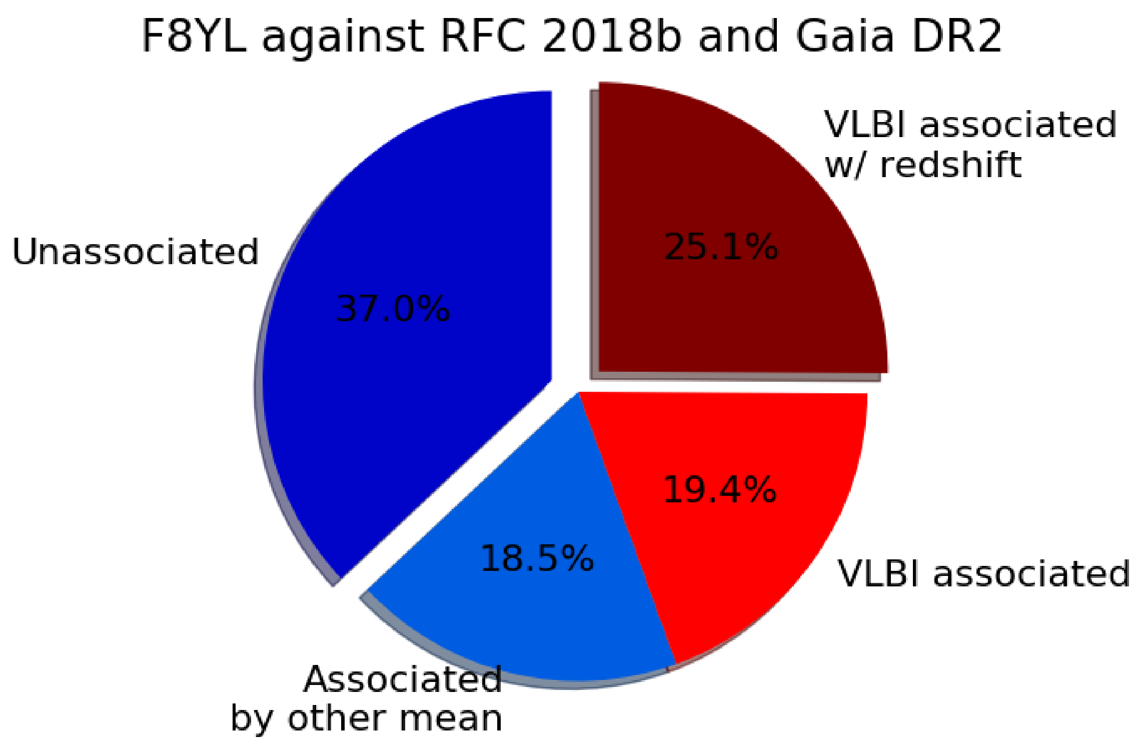
3FGL: 142 new associations – 14% of unassociated sources
improved positions for 144 (Schinzel et al. 2017)



3LAC (Ackermann et al. 2015)
+ new associations

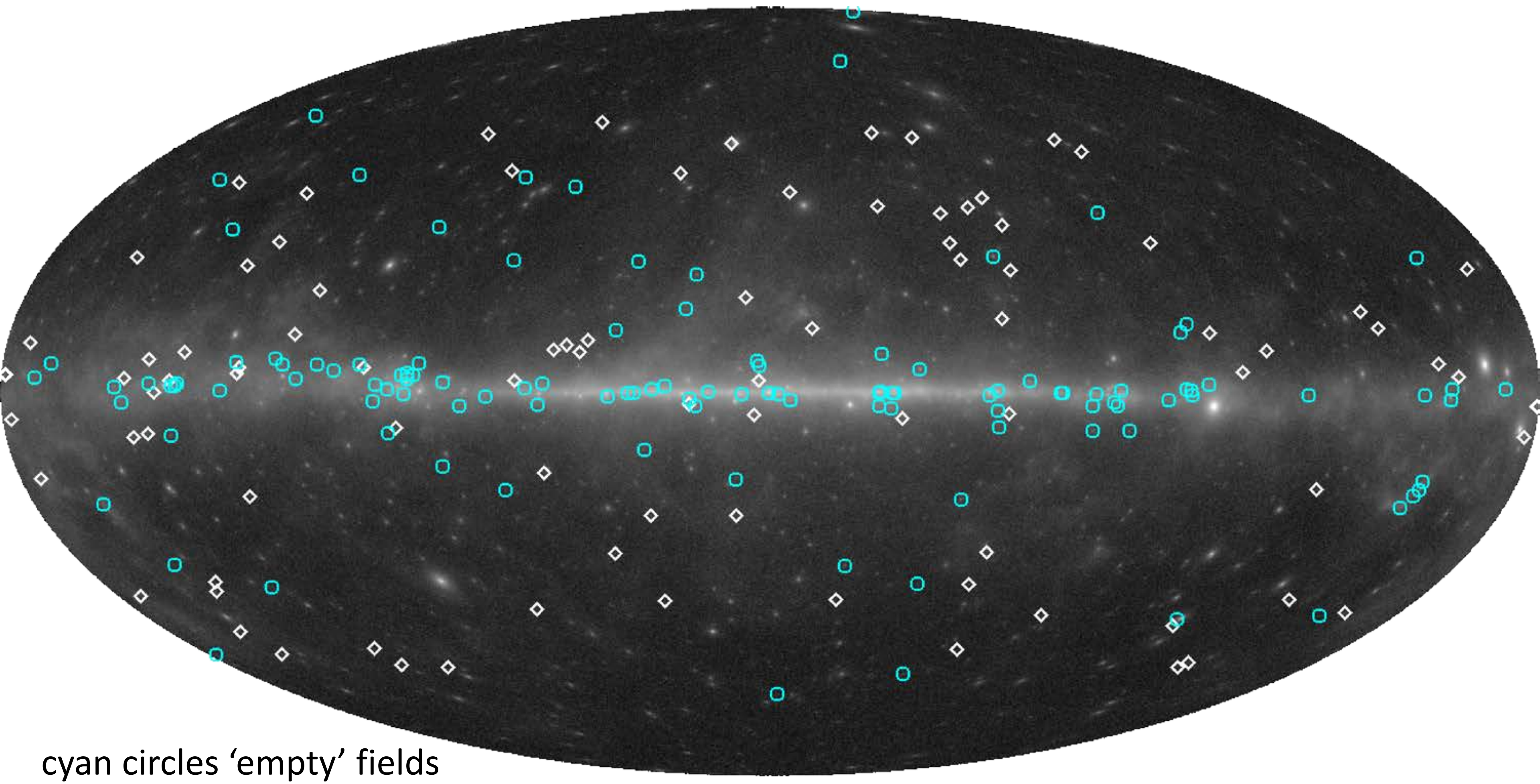
F8YL/4FGL – *Fermi*-radio-Gaia/optical connection

VLBI/Gaia association highly reliable – probability of false association < 0.0002



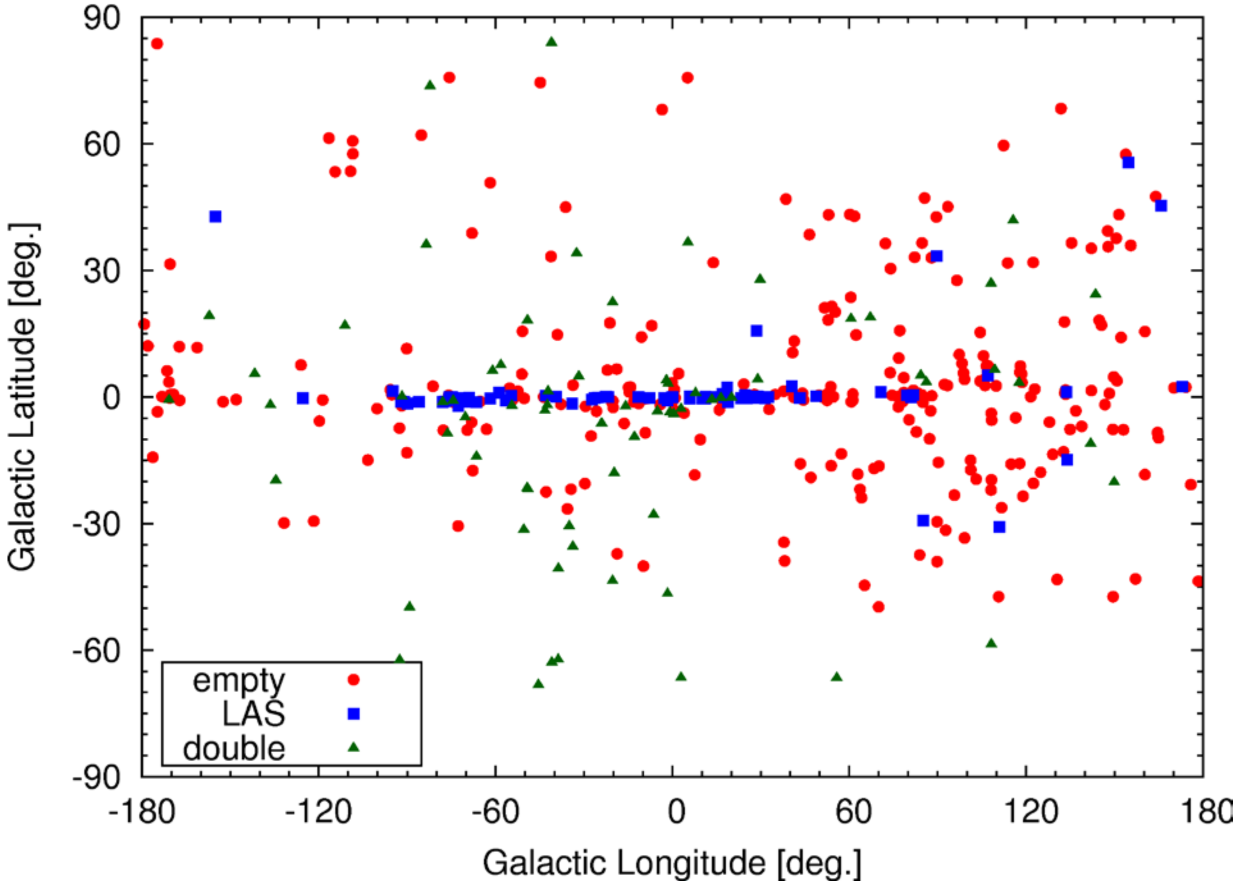
44.5% of F8YL source counterparts localized to 0.74 mas!
Redshifts are known for ¼ of F8YL sources.

Empty fields 2FGL



cyan circles ‘empty’ fields
white diamonds new AGN associations

Empty fields 3FGL



There is a distribution of *Fermi*/LAT sources with no radio counterpart >1 mJy at 5-10 GHz both Galactic and extragalactic

Searching for steep spectrum counterparts

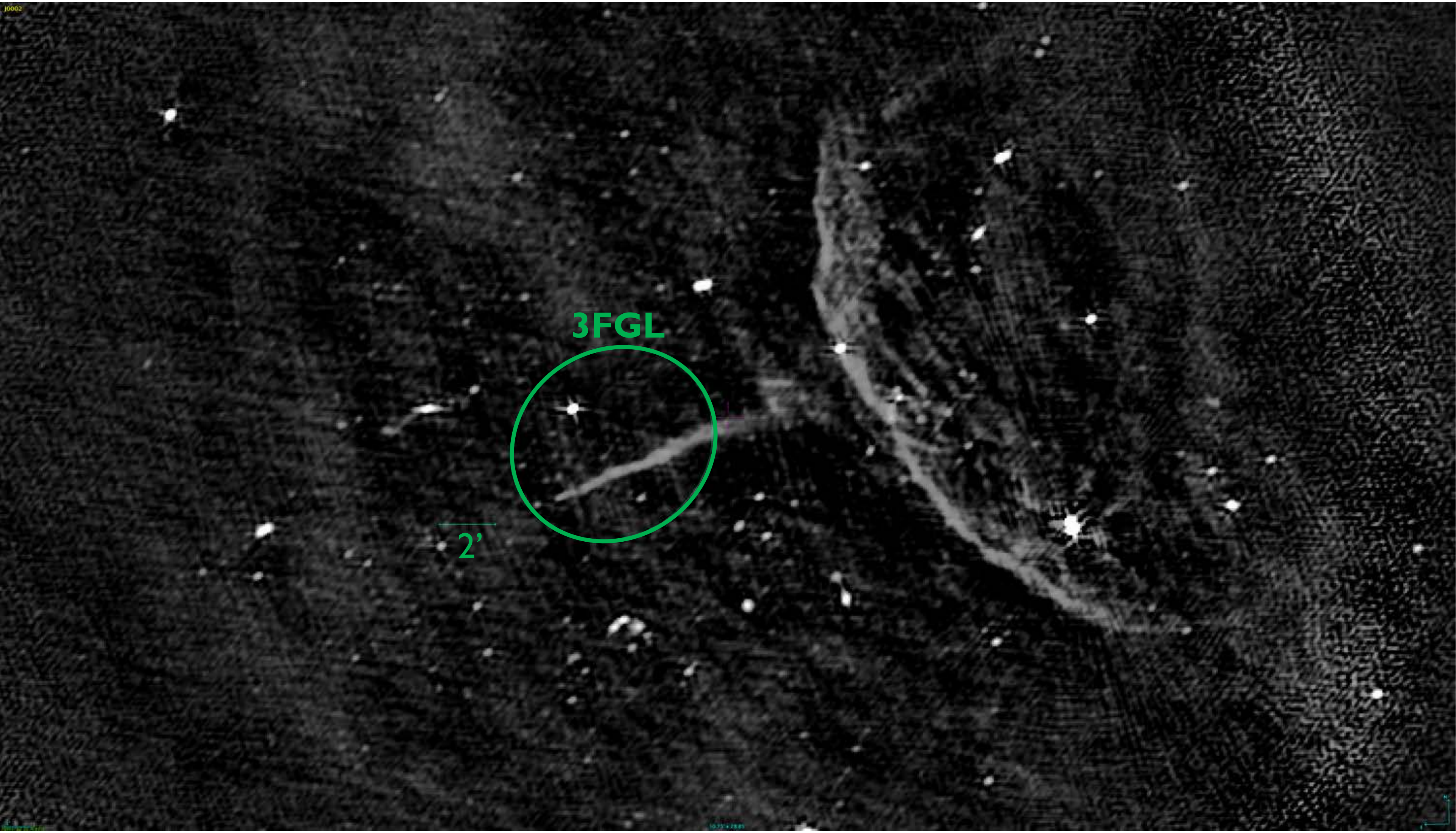
F. Schinzel, D. Frail, S. Bathnagar, U. Rao

Pilot program in 2017 (VLA filler time project) to obtain deeper 1-2 GHz VLA images of empty fields (~18 uJy/beam rms per field) Observed 17 unassociated 3FGL sources.

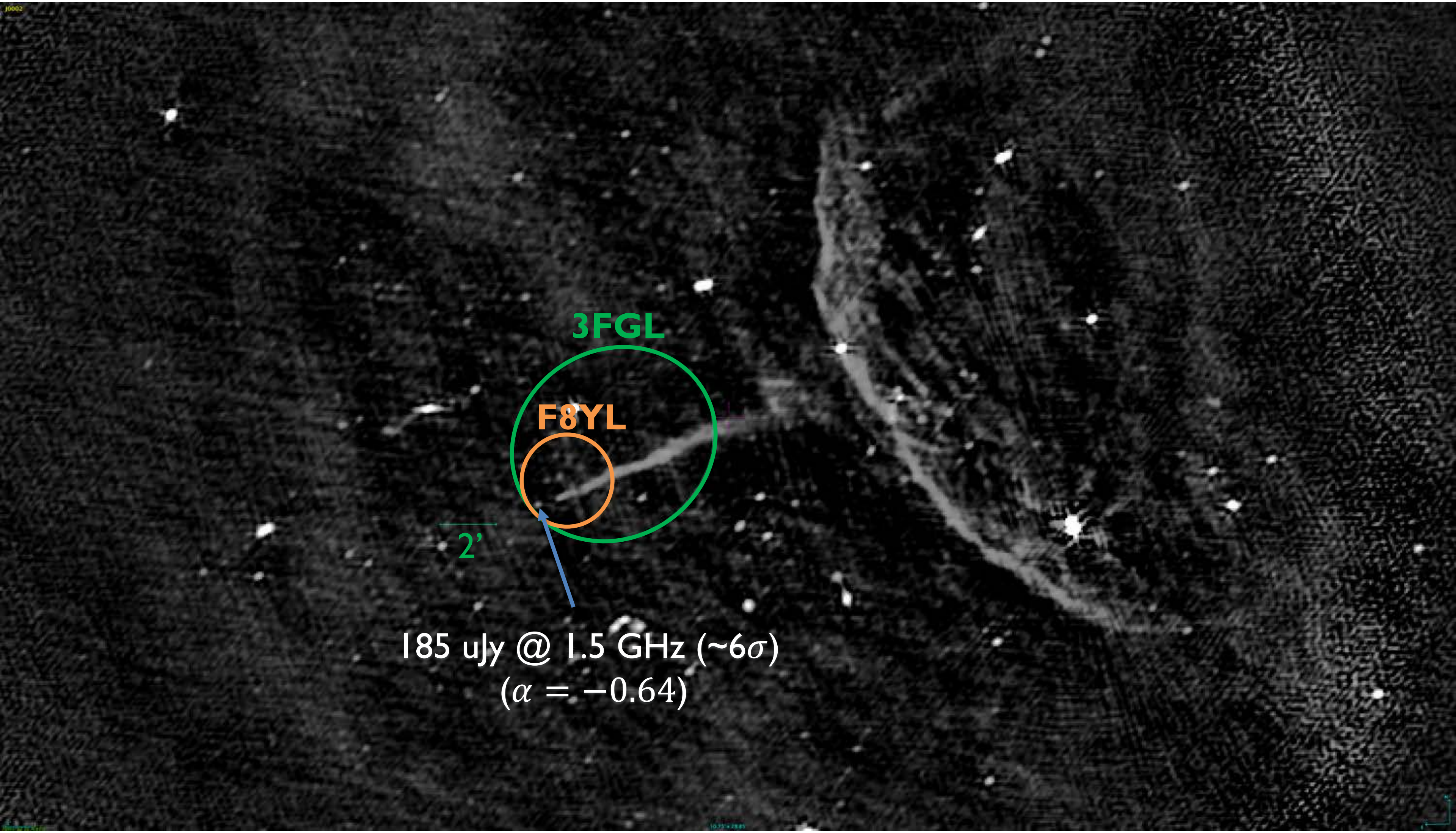
1. Selected fields have no radio source within 3FGL error circle >1 mJy/beam at 5-10 GHz with the VLA or ATCA.
2. Pulsar candidates based on Saz-Parkinson et al. (2016)

Goal: Find faint steep spectrum radio counterparts that could be Pulsars, but were missed in radio pulsation searches due to scattering.

Example deep field 1-2 GHz (rms ~ 30 uJy/beam)



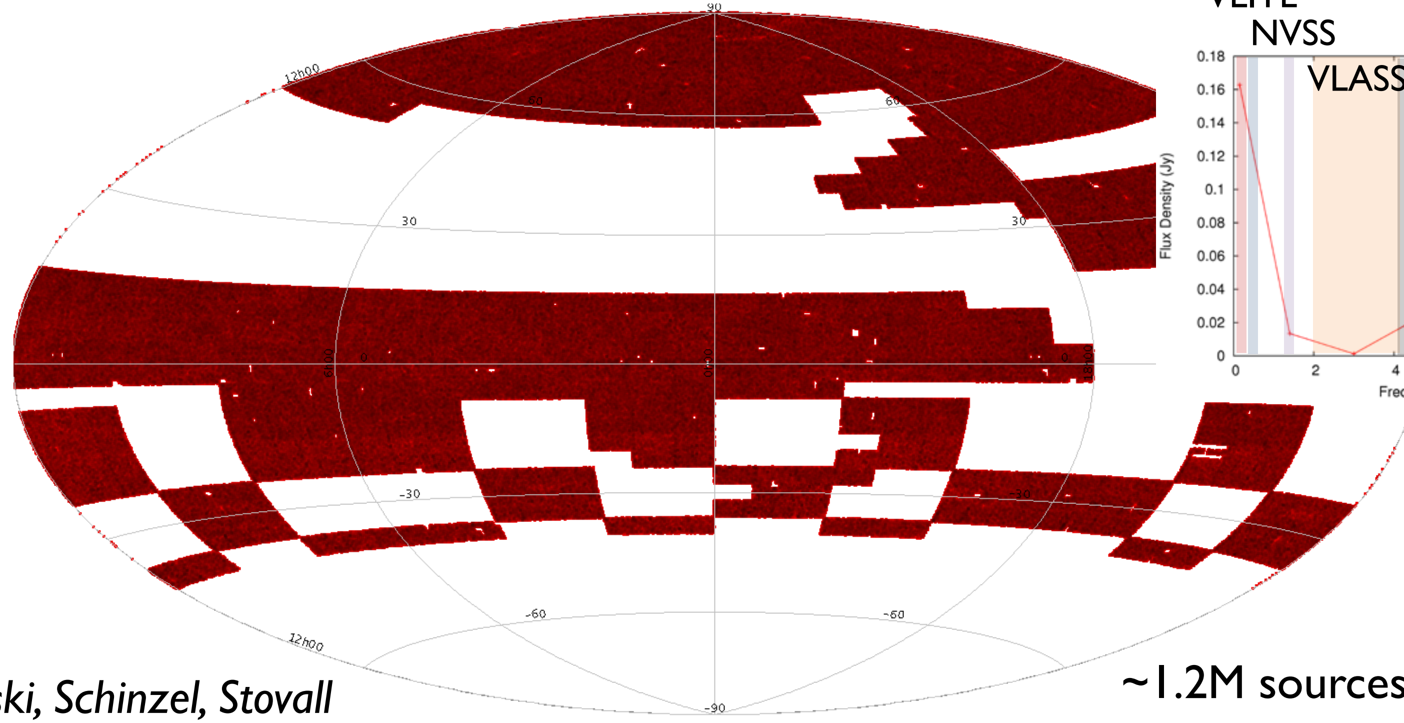
Pulsar candidate?

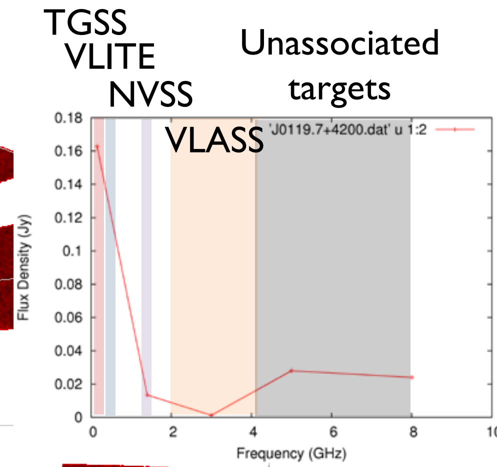


Unexplored Parts: VLA Sky Survey (2-4 GHz)

https://science.nrao.edu/science/surveys/vlass

VLASS1.1 quicklook sources (2017/2018)
VLASS1.2/second half to be observed 2019





Bruzewski, Schinzel, Stovall

~1.2M sources

Will allow compilation of radio spectra for all associations & candidates from 150 MHz – 10 GHz using existing surveys + our observations + VLASS

Summary

- The gamma-ray sky is still one of the most unexplored parts of the electromagnetic spectrum in astronomy.
- Radio observations are an extremely powerful tool to hunt for associations of known and unknown source classes.
- The radio sky with its lower source density provides an excellent stepping stone to make reliable associations between *Fermi*/LAT sources and the optical band.
- The upcoming 4FGL catalog with its improved localizations will be a major step forward for multi-wavelength associations.

Contributors to this work since 2012:

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