

A RADIO SURVEY AT 1-2GHZ IN THE GALACTIC BULGE

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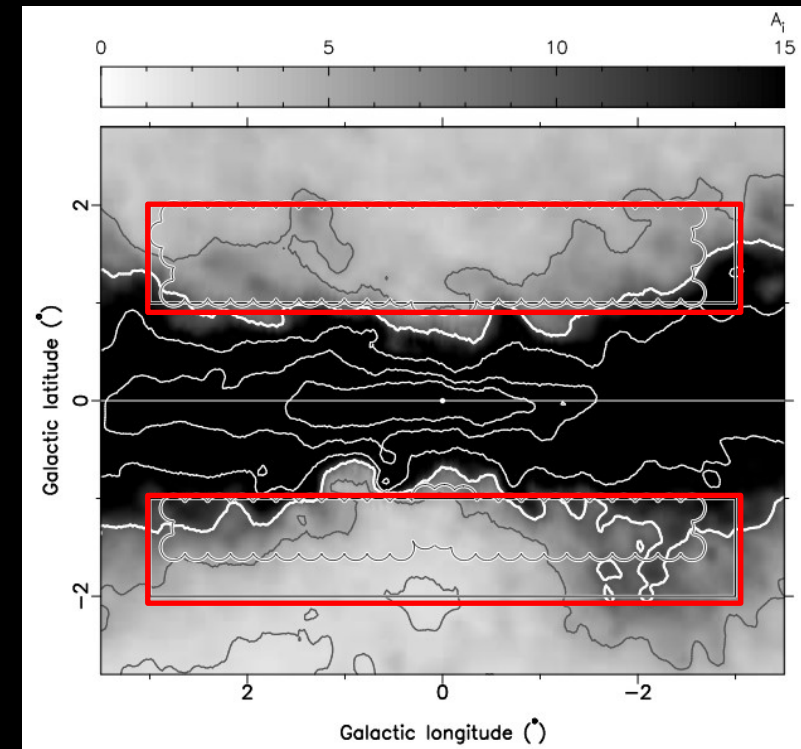
Tom Maccarone (Texas Tech)

THE GALACTIC BULGE SURVEY (GBS)

- *Chandra* X-ray survey (CXOGBS), and optical
- Interested primarily in compact objects
- Covered 12 square degrees

- Jonker et al. 2011

Extinction map
CXOGBS region

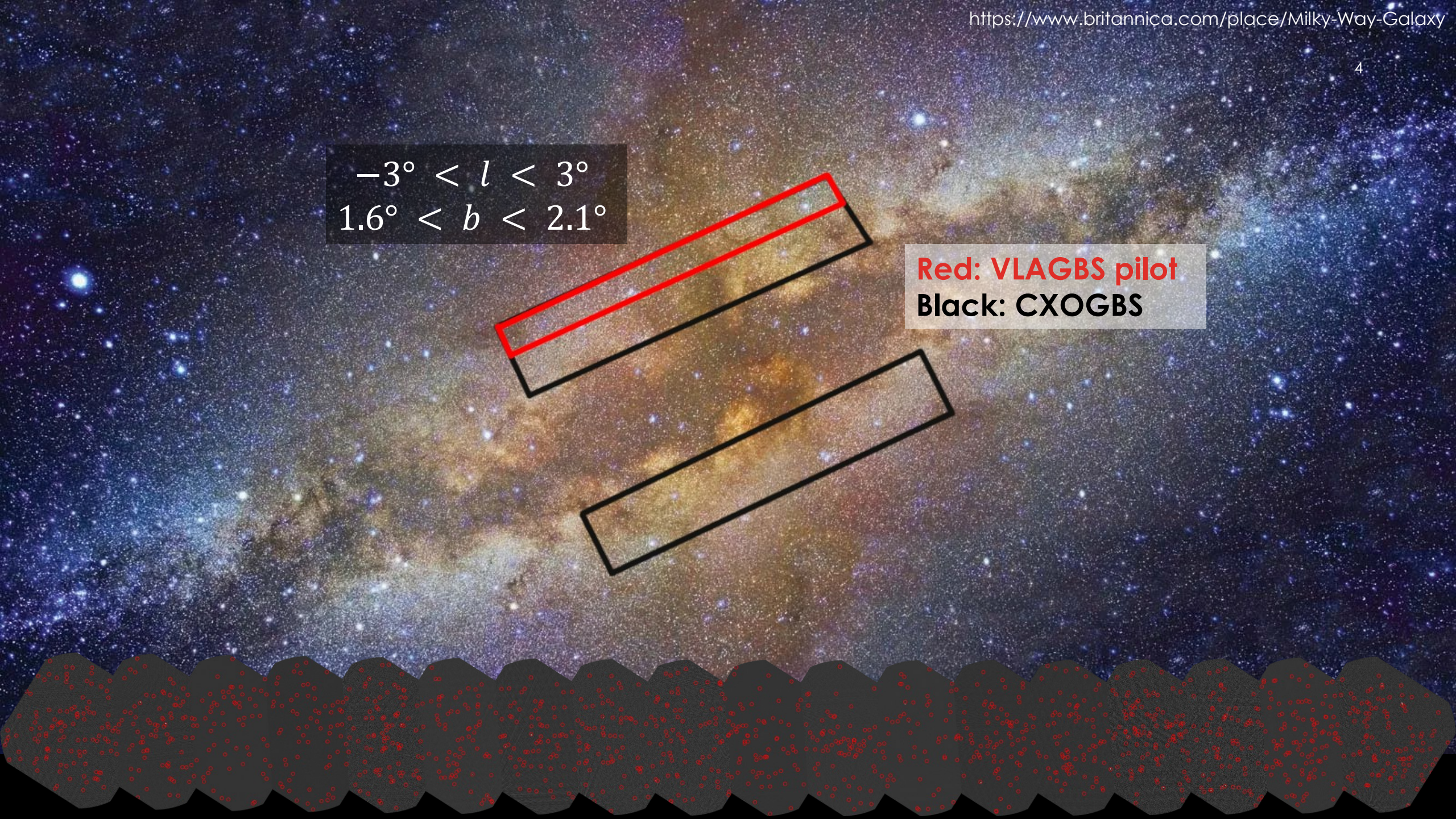


THE VERY LARGE ARRAY GBS

- 1-2GHz 1.1" resolution 0.1mJy sensitivity 3 sq. deg.
- Main goals:
 - Radio counterparts, especially for CXOGBS/X-ray sources
 - Identify possible pulsar population
- Spectral indices calculated within L-band (1-2GHz)
- Matched to RACS, VLASS, infrared, optical, X-ray catalogs

$-3^\circ < l < 3^\circ$
 $1.6^\circ < b < 2.1^\circ$

Red: VLAGBS pilot
Black: CXOGBS



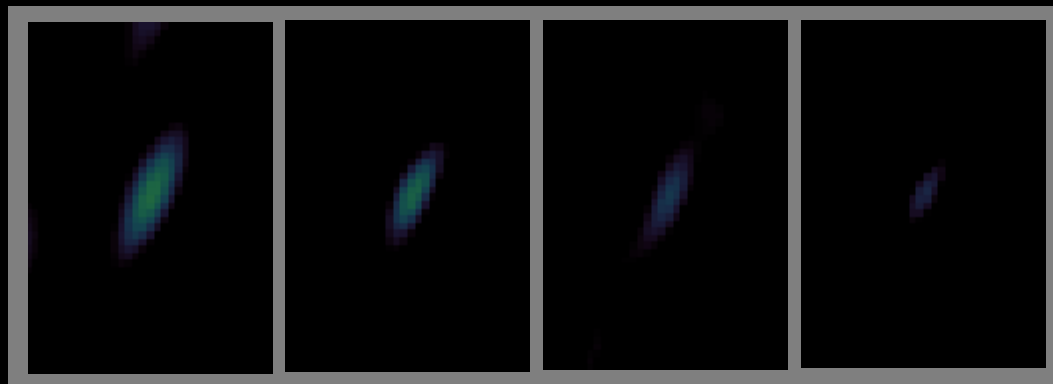
VLAGBS RESULTS OVERVIEW

| Source class | Number |
|----------------------------|-------------|
| Total $>5\sigma$ | 1605 |
| With spectral index | 946 (58%) |
| Point sources (PS) | ~1400 (87%) |
| CXOGBS matches | 24 |
| PS w/ $\alpha < -1$ (-1.4) | 162 (80) |
| Possible transients | 15 |
| AGN/candidates | ~120 |

POSSIBLE PULSAR POPULATION?

- Only 5 known ATNF pulsars in VLAGBS region
- ~100 steep spectrum point sources in VLAGBS
 - Pulsar spectral index $\langle \alpha \rangle = -1.4$
- Suggestive evidence of undiscovered pulsar population?

A known pulsar (J1736-2843, $\alpha = -1.5$):



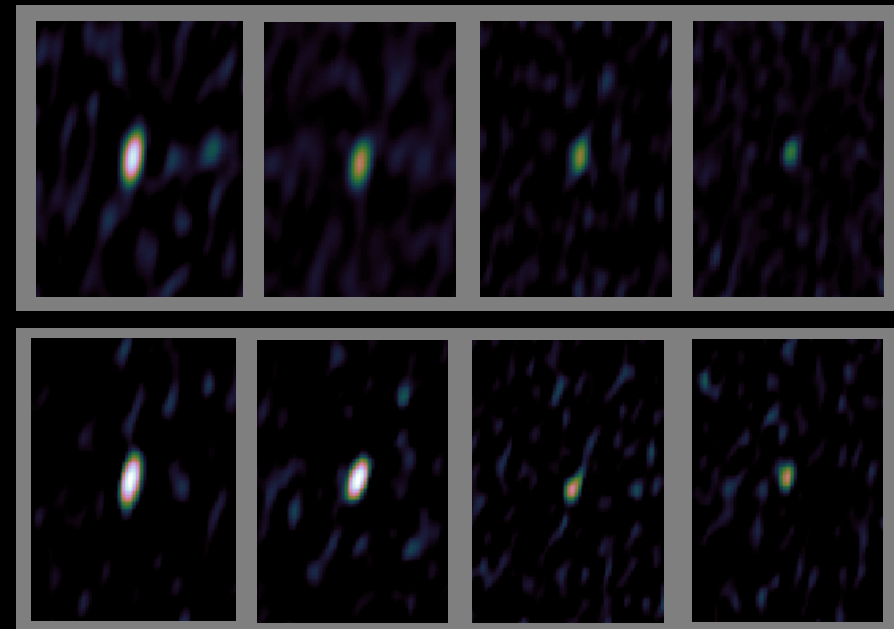
1.12GHz

1.37GHz

1.65GHz

1.87GHz

Subband frequency



$\alpha = -2.8$

Not known
as pulsars

$\alpha = -1.7$

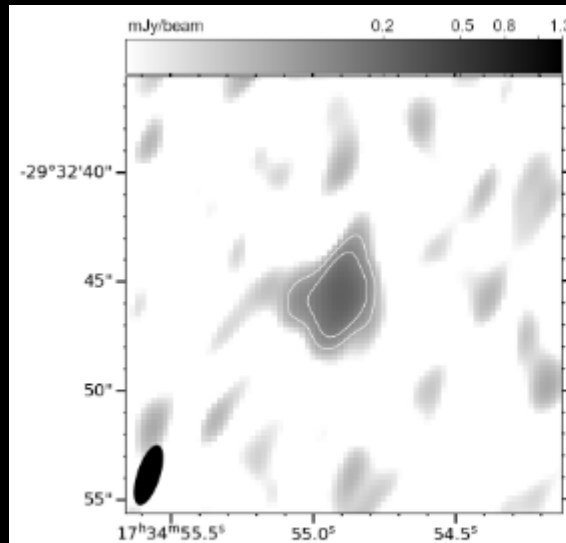
PLANETARY NEBULAE

Known PNe displaying structure

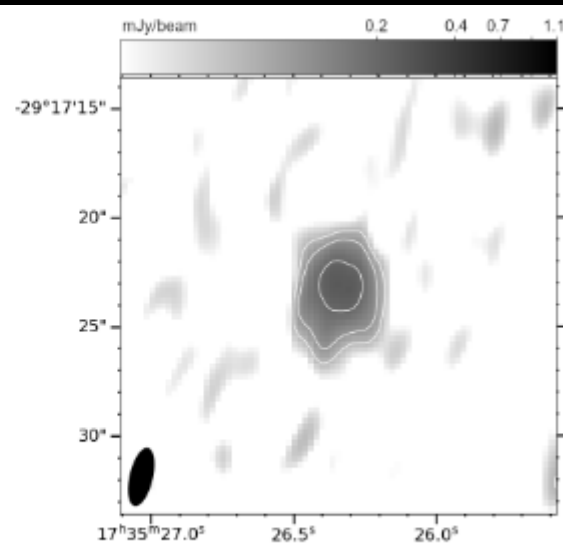
Possible new PNe, based on:

- Radio morphology
- Ratio to MIPS GAL 24 μ m counterpart

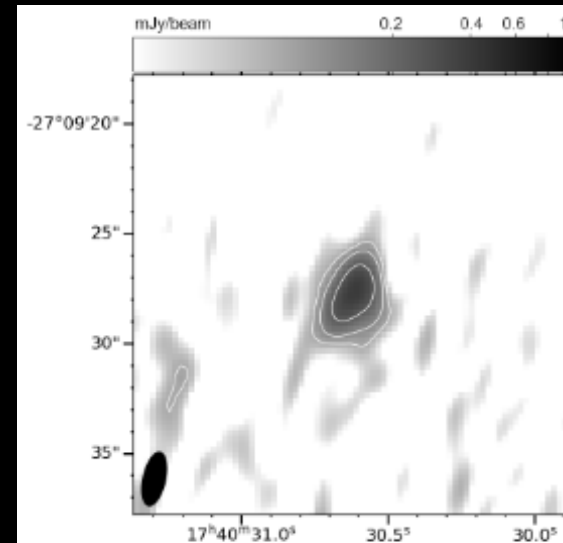
Are fainter in radio and infrared than known PNe



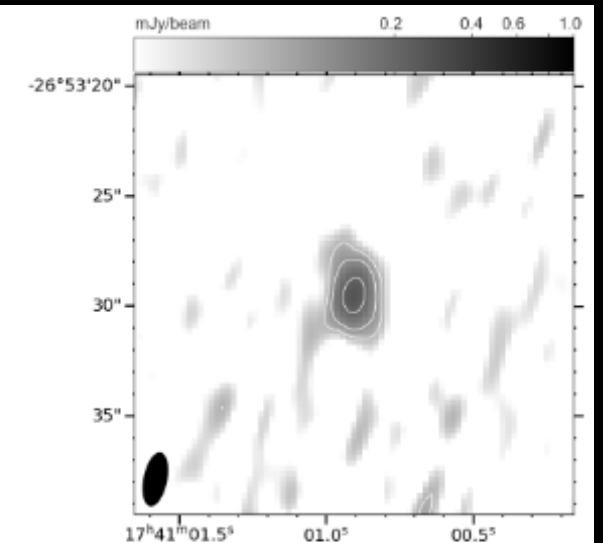
(a) J173454.9-293245
contours: 0.102, 0.170; peak 0.36; total 0.97mJy



(b) J173526.3-291723
contours: 0.068, 0.113, 0.227; peak 0.31; total 1.17mJy



(c) J174030.6-270927
contours: 0.076, 0.127, 0.253; peak 0.46; total 0.95mJy



(d) J174100.9-265329
contours: 0.068, 0.113, 0.226; peak 0.31; total 0.52mJy

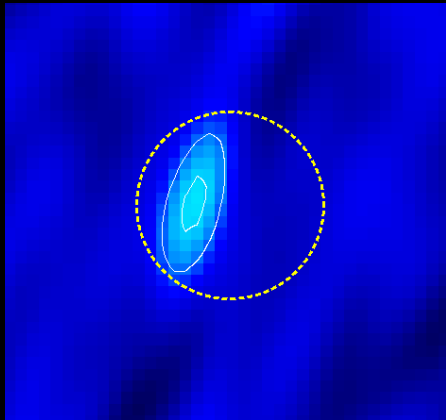
| CXOGBS source | 0.3-8keV flux 10^{-14} erg s $^{-1}$ [counts] | VLAGBS source | S $_{1.5\text{GHz}}$ mJy | α | log(L $_R$ /L $_X$) | RS | Notes |
|---------------|--|------------------|-----------------------------|------------------|----------------------|----------------|-----------------------------------|
| CX40 | 27.16 [35] | J174404.3-260925 | 17.58 \pm 0.91 | 0.36 \pm 0.14 | -12.2 | RNV † | AGN |
| CX49 | 23.28 [30] | J173146.8-300308 | 62.40 \pm 3.15 | 0.23 \pm 0.13 | -11.6 | RNV † | AGN |
| CX51 | 22.50 [29] | J174000.6-274859 | 0.97 \pm 0.09 | -2.31 \pm 0.54 | -13.4 | – | *radio transient, tMSP candidate? |
| CX63 | 20.17 [26] | J173411.3-293117 | 0.27 \pm 0.05 | -0.80 \pm 0.91 | -13.9 | – | *CV, now BHXB candidate |
| CX68 | 18.62 [24] | J173204.6-295220 | 2.61 \pm 0.17 | 0.45 \pm 0.26 | -12.9 | RV | |
| CX78 | 17.85 [23] | J173354.1-292138 | 0.36 \pm 0.06 | 0.27 \pm 0.78 | -13.7 | – | |
| CX101 | 14.74 [19] | J173353.1-300131 | 0.80 \pm 0.10 | -0.20 \pm 1.51 | -13.3 | – | |
| CX233 | 7.76 [10] | J174206.1-264115 | 6.31 \pm 0.34 | -0.79 \pm 0.14 | -12.1 | RNV † | AGN |
| CX278 | 6.98 [9] | J174044.5-265913 | 0.26 \pm 0.04 | – | -13.4 | – | |
| CX293 | 6.98 [9] | J174000.6-274816 | 174.77 \pm 8.78 | -0.92 \pm 0.14 | -10.6 | RNV † | AGN |
| CX330 | 6.21 [8] | J173643.8-282121 | 0.73 \pm 0.07 | 0.87 \pm 0.38 | -12.9 | – | *infrared transient, YSO? |
| CX392 | 5.43 [7] | J173551.3-285646 | 0.16 \pm 0.03 | – | -13.5 | – | |
| CX455 | 4.66 [6] | J174442.9-254932 | 0.43 \pm 0.05 | 0.07 \pm 0.52 | -13.0 | – | |
| CX480 | 4.66 [6] | J173801.2-281351 | 0.25 \pm 0.04 | -1.56 \pm 0.83 | -13.3 | – | Possible pulsar + M dwarf binary |
| CX488 | 4.66 [6] | J173605.2-283238 | 122.31 \pm 6.15 | -1.25 \pm 0.13 | -10.6 | RNV † | likely AGN |
| CX498 | 4.66 [6] | J173419.6-294549 | 0.37 \pm 0.07 | – | -13.1 | – | |
| CX597 | 3.88 [5] | J174239.6-262655 | 1.08 \pm 0.10 | -0.82 \pm 0.21 | -12.6 | R | |
| CX639 | 3.88 [5] | J173242.3-295039 | 1.90 \pm 0.14 | -0.11 \pm 0.22 | -12.3 | RV | AGN |
| CX875 | 3.10 [4] | J173650.8-284539 | 0.15 \pm 0.04 | – | -13.3 | – | |
| CX1146 | 2.33 [3] | J173832.3-280823 | 0.11 \pm 0.03 | – | -13.3 | – | |
| CX1215 | 2.33 [3] | J173340.4-293332 | 0.16 \pm 0.04 | – | -13.2 | – | |
| CX1222 | 2.33 [3] | J173239.3-300701 | 0.17 \pm 0.04 | – | -13.1 | – | |
| CXB163 | 4.66 [6] | J173228.3-302534 | 0.39 \pm 0.05 | 1.30 \pm 0.72 | -13.1 | RN † | AGN? |
| CXB290 | 3.10 [4] | J173138.5-302946 | 0.20 \pm 0.04 | -1.24 \pm 2.32 | -13.2 | – | |

CXOGBS MATCHES

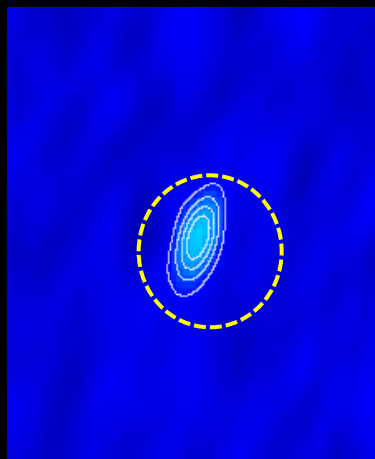
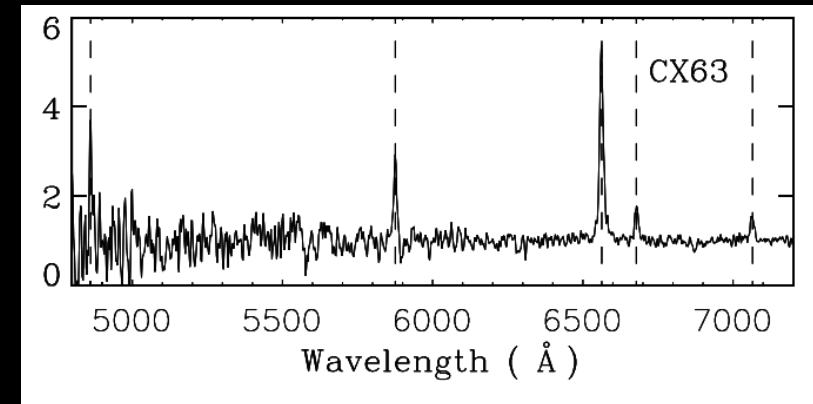
- **24 matches total**
- 7 AGN
- 1 previously classified young stellar object
- 1 previously classified accreting white dwarf binary
- 2 particularly interesting sources with VLAGBS counterparts

SOME INDIVIDUAL SOURCES I

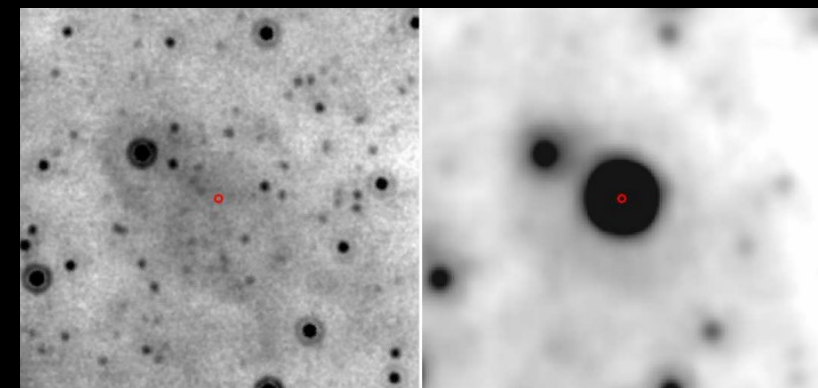
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- CXOGBS “CX63”
- Accretion disk optical spectrum
 - Torres et al. 2014
- May be a faint XRB or one of the radio-brightest CVs
 - Radio-bright on L_R - L_X



- CXOGBS “CX330”
- Bright infrared outburst, variable
- Likely young stellar object
- Though, not in a star-forming region
- Britt et al. 2016

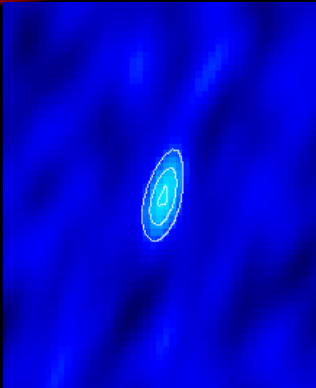


2006 MIPS GAL

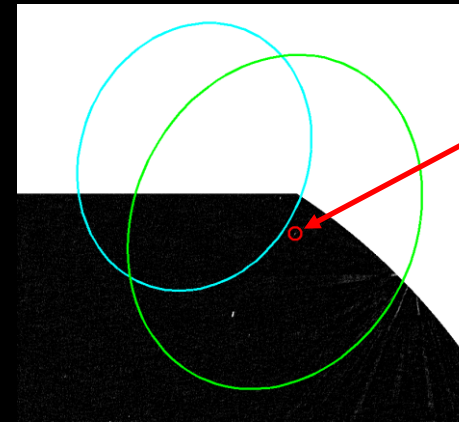
2010 WISE

SOME INDIVIDUAL SOURCES II

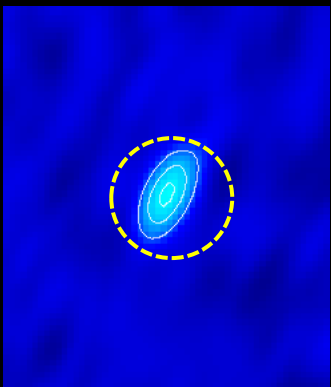
10



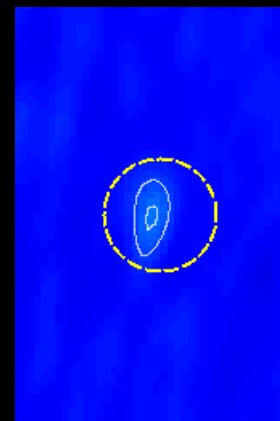
- Transient ~ 1 mJy (no R/V)
- Next to MSP-spectrum Fermi source (unassoc.)
- Potential tMSP candidate?



Radio source
3FGL
4FGL



- CXOGBS "CX51"
- $\alpha = -2.3$
- Transient ~ 1 mJy (no R/V)
- Bright infrared counterpart



- CXOGBS "CX480"
- $\alpha = -1.6$
- Very red OIR counterpart
- Pulsar + late K star?

- 1600 sources in VLAGBS (1.5GHz, ~ 0.1 mJy sens.) (2015)
- 430 in RACS (0.887GHz, ~ 1.5 mJy)
- 200 in VLASS (3GHz, ~ 0.5 mJy)

TRANSIENT OR VARIABLE

- Sources in RACS but not VLAGBS:

| RACS Source | S_{peak} | VLAGBS 3σ | RACS/VLAGBS 3σ | α lim. |
|----------------|-------------------|------------------|-----------------------|------------------|
| J173218-301236 | 1.504 | $\lesssim 0.08$ | 19.39 | $\lesssim -5.65$ |
| J173241-302831 | 1.799 | $\lesssim 0.17$ | 10.68 | $\lesssim -4.51$ |
| J173246-301850 | 1.810 | $\lesssim 0.14$ | 12.86 | $\lesssim -4.87$ |
| J173611-281740 | 1.915 | $\lesssim 0.15$ | 12.76 | $\lesssim -4.85$ |
| J173933-270755 | 1.452 | $\lesssim 0.14$ | 10.57 | $\lesssim -4.49$ |
| J174400-254540 | 1.734 | $\lesssim 0.08$ | 22.79 | $\lesssim -5.96$ |
| J174431-262415 | 2.784 | $\lesssim 0.30$ | 9.33 | $\lesssim -4.26$ |
| J174627-254425 | 2.278 | $\lesssim 0.29$ | 7.83 | $\lesssim -3.95$ |

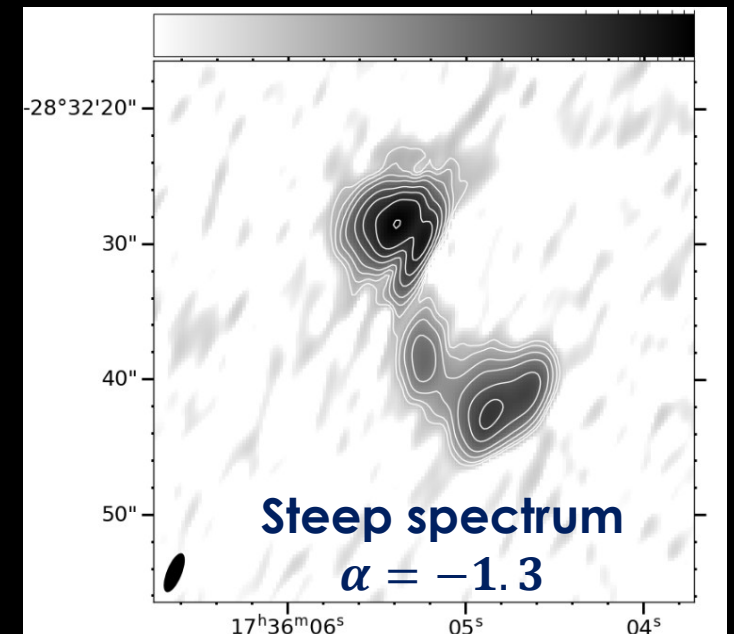
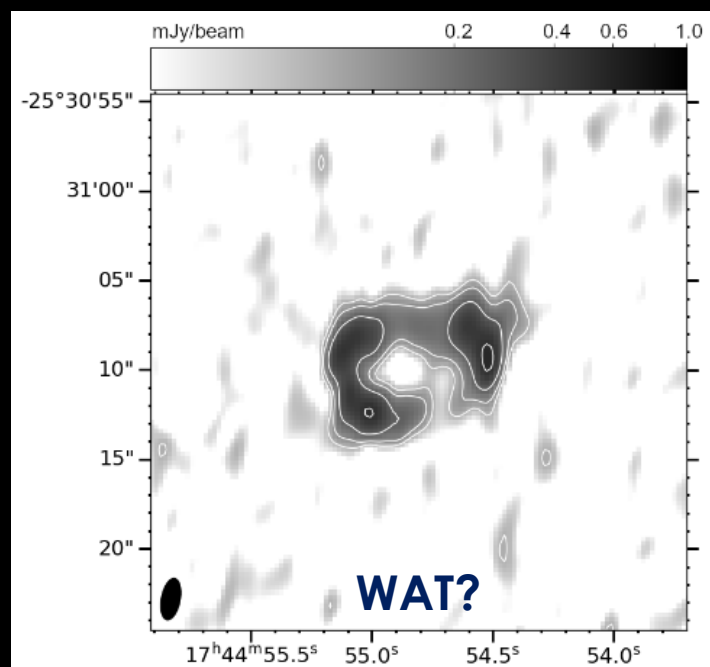
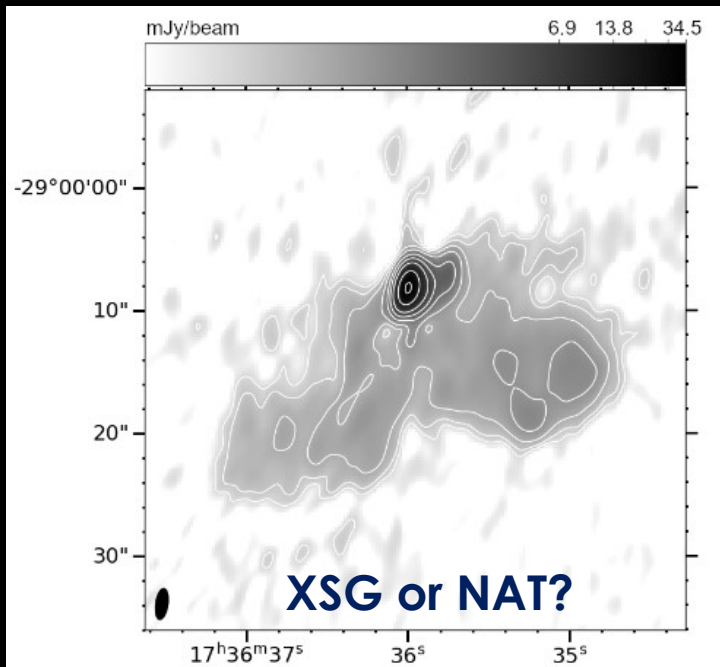
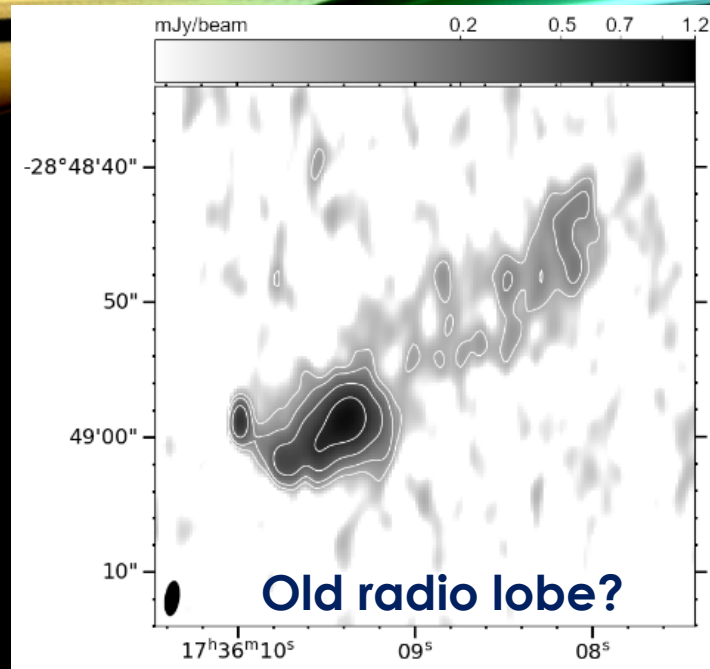
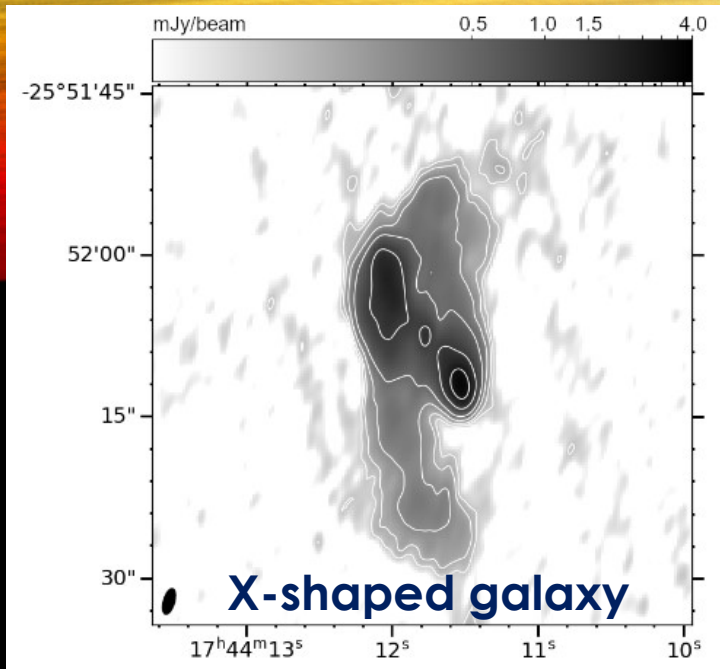
- All VLASS sources are recovered in VLAGBS

- Sources in VLAGBS but not RACS & VLASS:

| VLAGBS radio source | $S_{1.5\text{GHz}}$ (mJy) | α |
|---------------------|---------------------------|------------------|
| J173155.5-302304 | 0.94 ± 0.07 | -0.42 ± 0.28 |
| J173454.9-293245 | 0.97 ± 0.09 | -1.10 ± 0.38 |
| J173630.7-285210 | 1.25 ± 0.10 | -0.85 ± 0.33 |
| J174000.6-274859 | 0.97 ± 0.09 | -2.31 ± 0.54 |
| J174029.9-264305 | 1.00 ± 0.12 | -0.77 ± 0.99 |
| J174110.2-271300 | 1.02 ± 0.08 | 0.44 ± 0.44 |
| J174248.1-264958 | 1.06 ± 0.08 | -0.44 ± 0.32 |

- None show significant variability

AGN



SUMMARY

- 1600 radio sources found
- Several interesting sources to follow up on
- Evidence of missing pulsar population?
- Preliminary talks of completing the VLAGBS for full 12 sq. deg.

| Source class | Number |
|----------------------------|-------------|
| Total $>5\sigma$ | 1605 |
| With spectral index | 946 (58%) |
| Point sources (PS) | ~1400 (87%) |
| CXOGBS matches | 24 |
| PS w/ $\alpha < -1$ (-1.4) | 162 (80) |
| Possible transients | 15 |
| AGN/candidates | ~120 |

