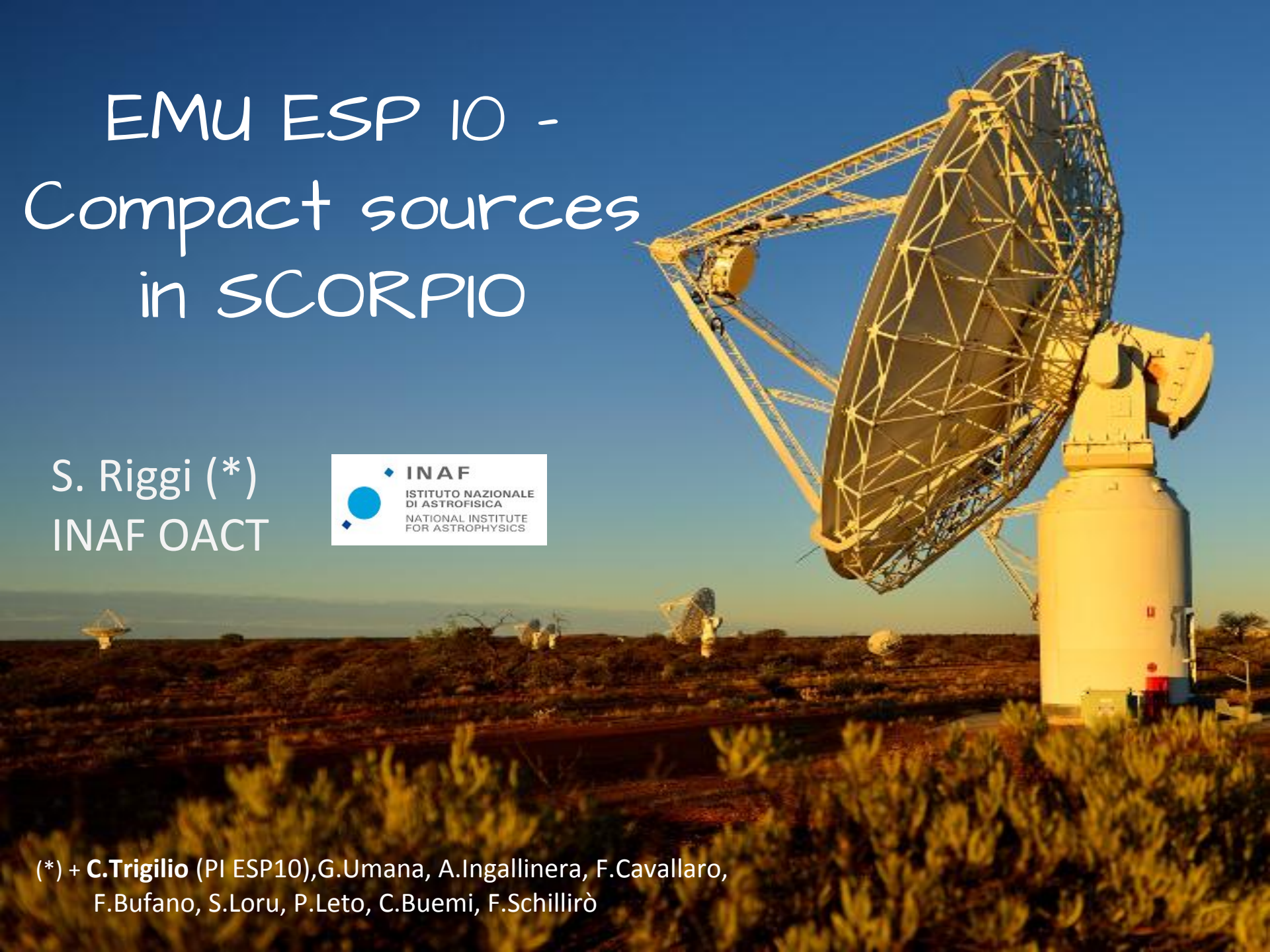
EMU ESP 10 - Compact sources in SCORPIO



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Outline

- **Goals of the SCORPIO Early Science Project**
- **Observations of the SCORPIO field**
  - Summary and status of the data reduction
  - Processing issues
  - Maps obtained
- **Source extraction**
  - Methodology
  - Performance validation
- **Source catalog analysis**
  - Source counts
  - Spectral indices
  - Extended/resolved source fraction
- **Comparison with other catalogues**
  - Validation studies by cross-match with MGPS-II
  - Search for galactic object associations in astronomical databases
- **Summary**
  - Ongoing analysis
  - Paper organization

The SCORPIO Early Science Project

PI: C. Trigilio (INAF-OACT)

First blind survey of the Galactic plane at this frequency with a planned sensitivity of 30 μJy/beam.

Scientific goals:

- unbiased search for radio stellar emission
- insights on the physics of particular classes of stellar systems
- search for coherent radio emission from stellar systems
- study the occurrence of different Galactic objects (e.g. PNs, HIIs, SNR)
- provide us with a clear forecast on the potential of SKA and its precursors in the field of Galactic radio astronomy

Technical goals:

- Test of ASKAP pipeline on the Galactic plane (extended objects, diffuse emission, ...)
- Development of imaging and analysis techniques suited for the Galactic plane

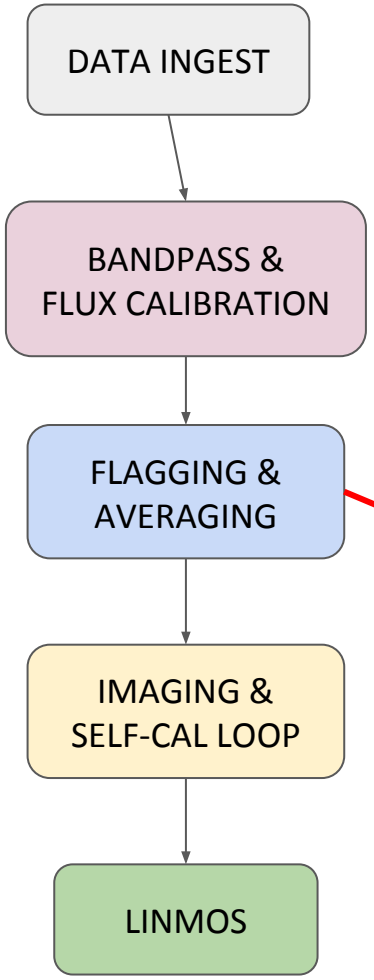
Observations of the SCORPIO field

Available observations of the SCORPIO field. Using #1 and #3 for this analysis.
ISSUE: Data reduction of observations #4, #5, #6 was not completed by processing staff
--> see Umana's talk

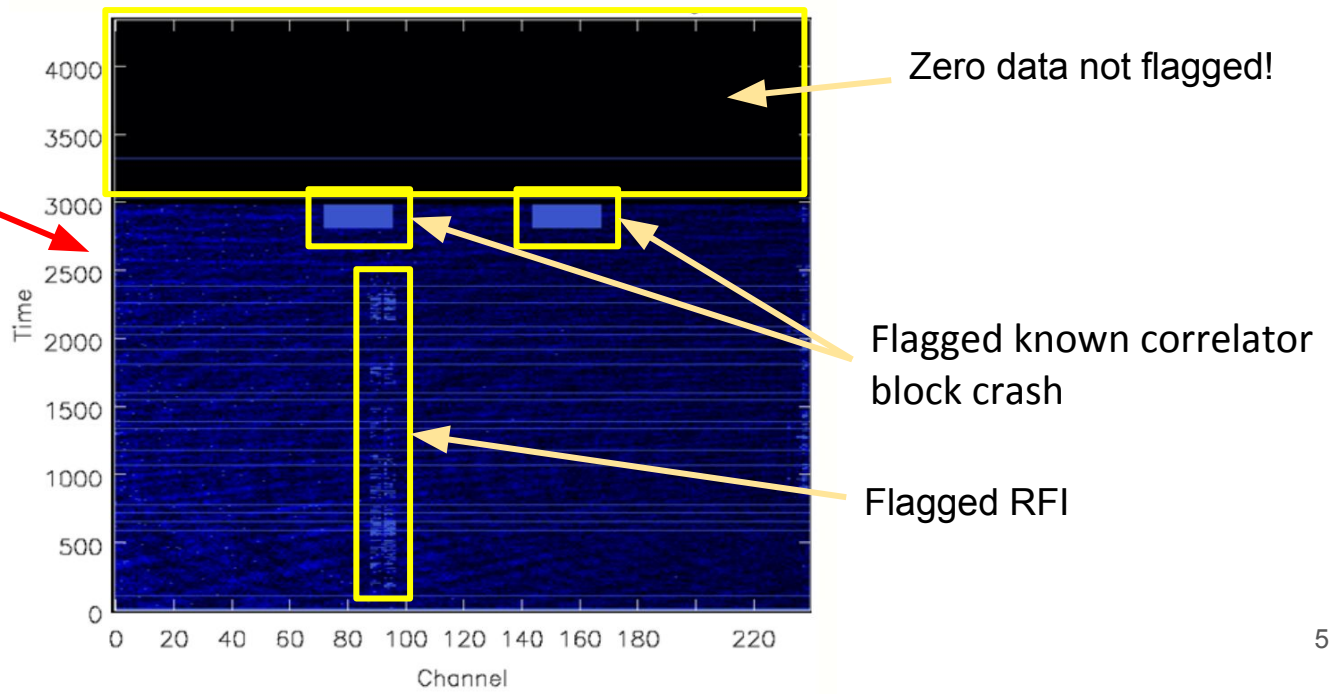
ID	Telescope	Freq. (MHz)	Config.	#Ant.	Area (deg^2)	RMS (μJy/b)	Obs. Date	Data reduction Status	Refs.
1	ATCA	2100	6A 6B	6	8.4	30/ 40	2011 2012	Completed	Umana+15 Cavallaro+18
2	ATCA	2100	EW367 EW352 H214	6	6.7	100	2014 2016	Completed	Riggi+16 Ingallinera+19
3	ASKAP	912	closepack36	15	40	300/ 500	2018	Completed	
4	ASKAP	920	closepack36	36	40	?	2019	Not completed	
5	ASKAP	1296	closepack36	36	40	?	2019	Not completed	
6	ASKAP	1630	closepack36	36	40	?	2019	Not completed	

SCORPIO data reduction & issues

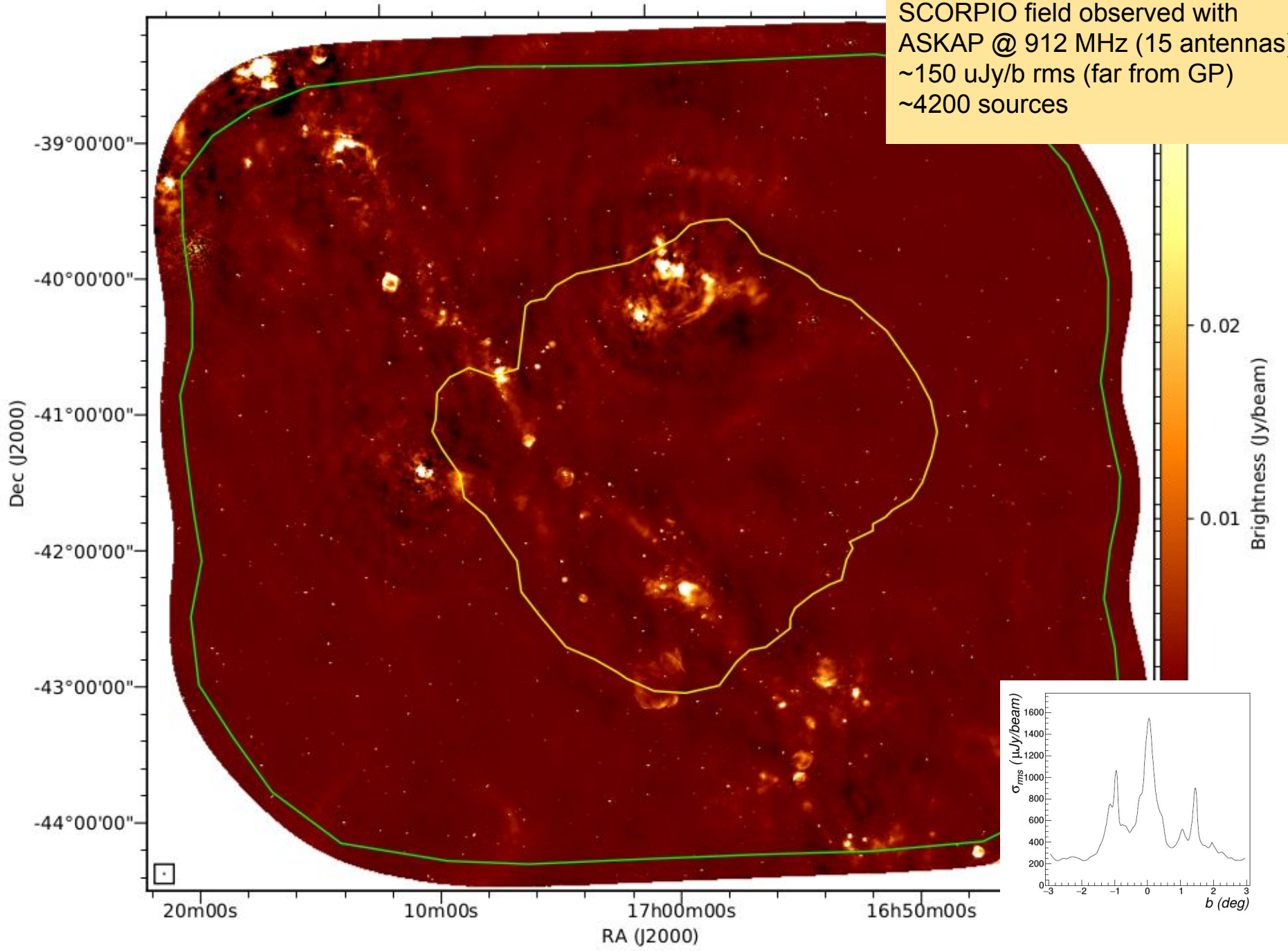
Tweaking ASKAPsoft pipeline for Galactic data...

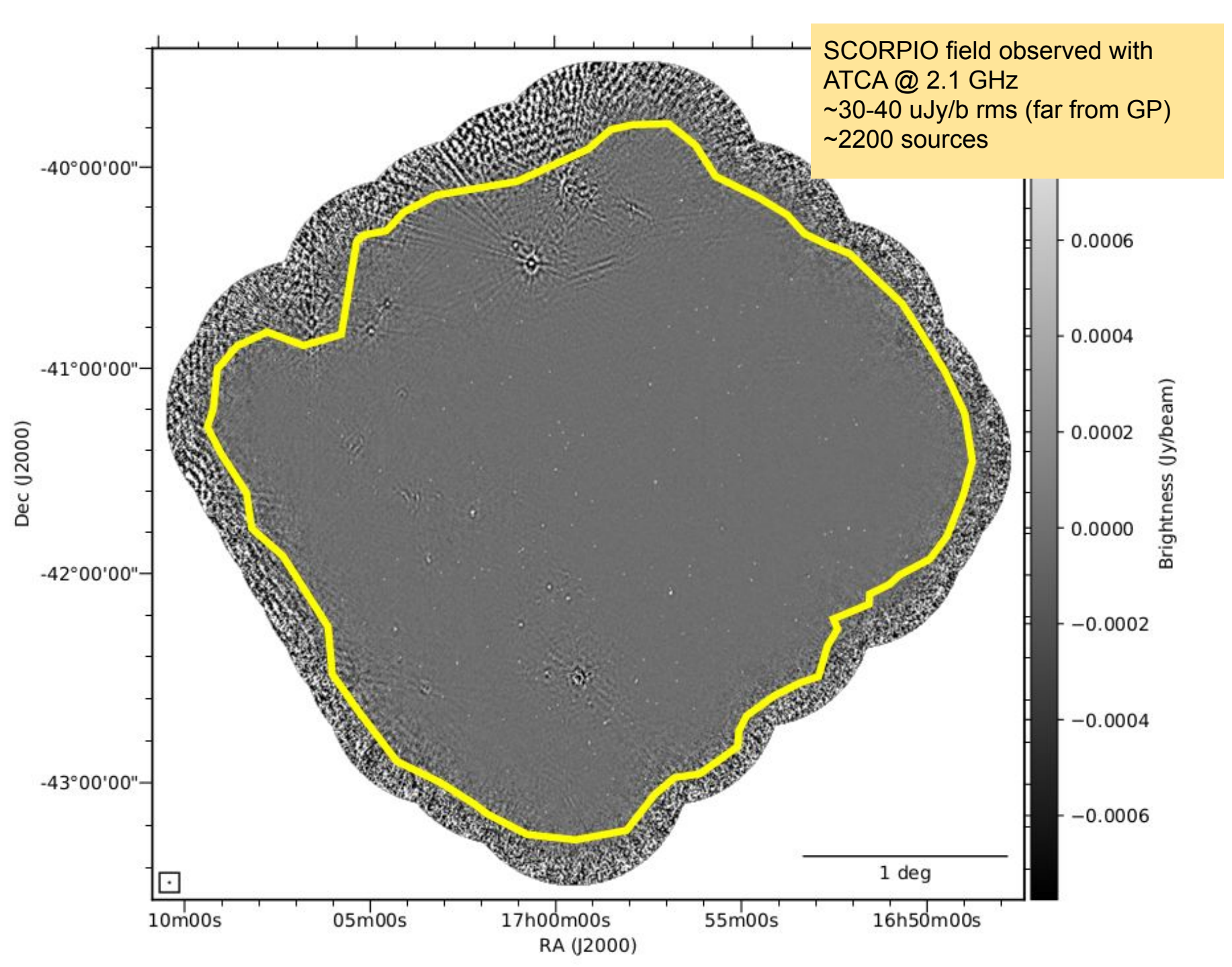


- User congestion, job failures (scratch space filling up, long queuing times, timeouts, ...). Mostly solved by centralizing data reduction
- Some bad data not flagged (using default flagger parameters)
- Excluding short baselines from self-cal due to extended sources



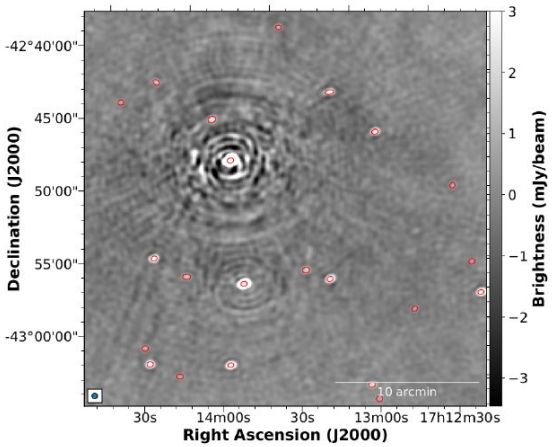
SCORPIO field observed with ASKAP @ 912 MHz (15 antennas)
~150 uJy/b rms (far from GP)
~4200 sources




SCORPIO field observed with
ATCA @ 2.1 GHz
~30-40 uJy/b rms (far from GP)
~2200 sources
-40°00'00"
-41°00'00"
-42°00'00"
-43°00'00"
Dec (J2000)
10m00s
05m00s
17h00m00s
55m00s
16h50m00s
RA (J2000)
1 deg
0.0006
0.0004
0.0002
0.0000
−0.0002
−0.0004
−0.0006
Brightness (Jy/beam)

Compact source extraction

Sources extracted from both maps with CAESAR source finder



Main finder parameters

Par. Type	Parameter	CAESAR
Detection	σ_{seed}	5*
	σ_{merge}	2.5
	n_{pix}	5
Bkg/Noise	method	local
	bkg	median
	rms	mad
	box size	10×beam
	grid step	20%box
Deblending	method	peak search+ blob detection †
Fitting	method	N-gaus fit‡

Pre-selection cuts

CAESAR
Fit converged, $\tilde{\chi}^2$ <10
Component peak flux positive
Component centroid inside the source island and inside a mosaic boundary region
Separation between any pair of source components larger than 2 pixels

ASKAP catalogue

# components	Selection		
	NO SEL	SEL	SEL+VIS SEL
0	250	0	0
1	4754	3857	3812
2	440	308	195
3	131	59	6
>3	88	38	0
All	5663	4262	4013

ATCA catalogue

# components	Selection		
	NO SEL	SEL	SEL+VIS SEL
0	146	0	0
1	3021	2104	2096
2	465	188	120
3	158	53	11
>3	102	30	0
All	3892	2375	2227

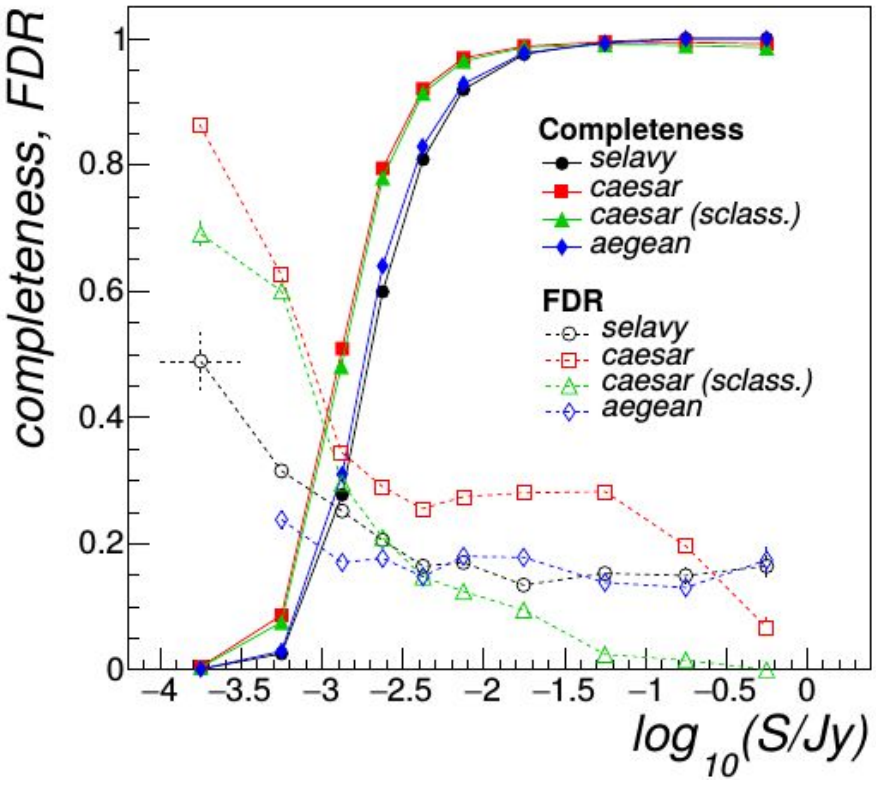
Visual inspection to reject spurious and artefacts.

Need automation + improved quality cuts/classification algorithm

Catalog completeness & reliability

Evaluated with simulations for 3 different finders (Caesar, Selavy, Aegean)

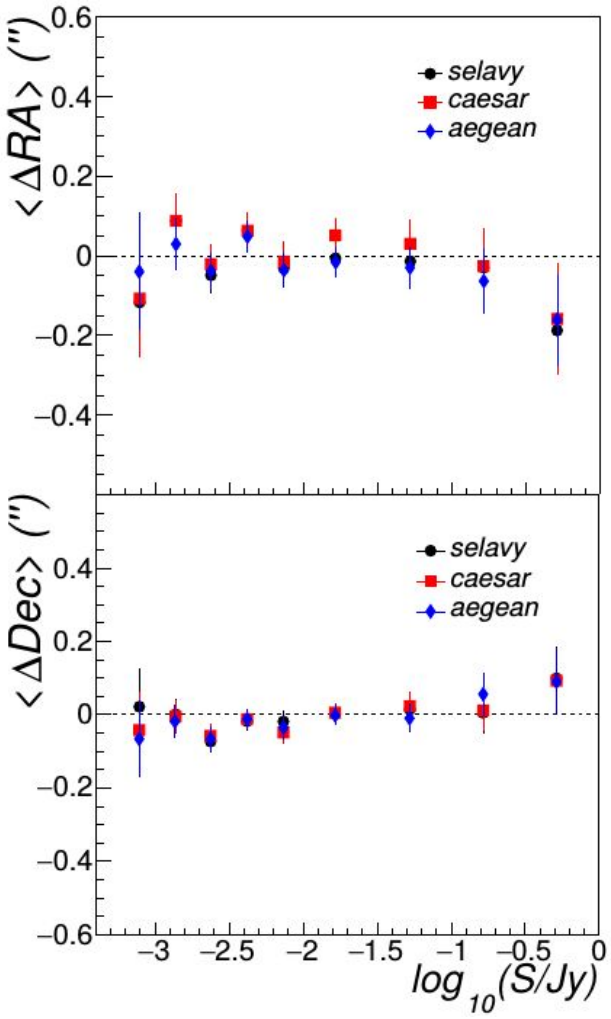
- 20 mosaics drawn from the data with real compact source subtracted (down to 2σ) and artificial point sources added (similar source density, flux distribution of the real data)
- Used default parameters for all finders
- PyBDSF tried also but hanging on extended source fitting (at least with default parameters)

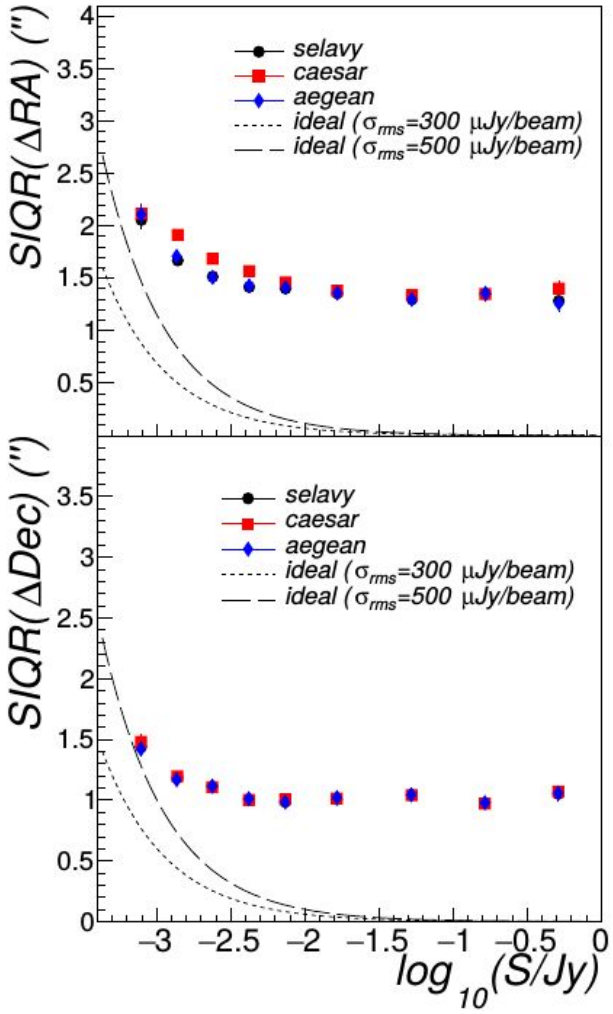


- Completeness >90% above 5 mJy
- Low reliability (>20%) for all finders --> *Welcome to the Galactic Plane!*
- Difference among finders due to different detection thresholds and quality cuts
  - Deliberately used a lower detection threshold in Caesar to create a training sample with more visually identified spurious sources.
  - Selavy pre-defined cuts are more stringent than in Caesar, Aegean does not report quality cuts. Caesar/Selavy comparable when using the same cuts
- Aegean wrt Selavy are quite comparable overall
- Caesar outperforming when using predefined cuts + a neural network classifier to identify good/bad source components

Source position accuracy

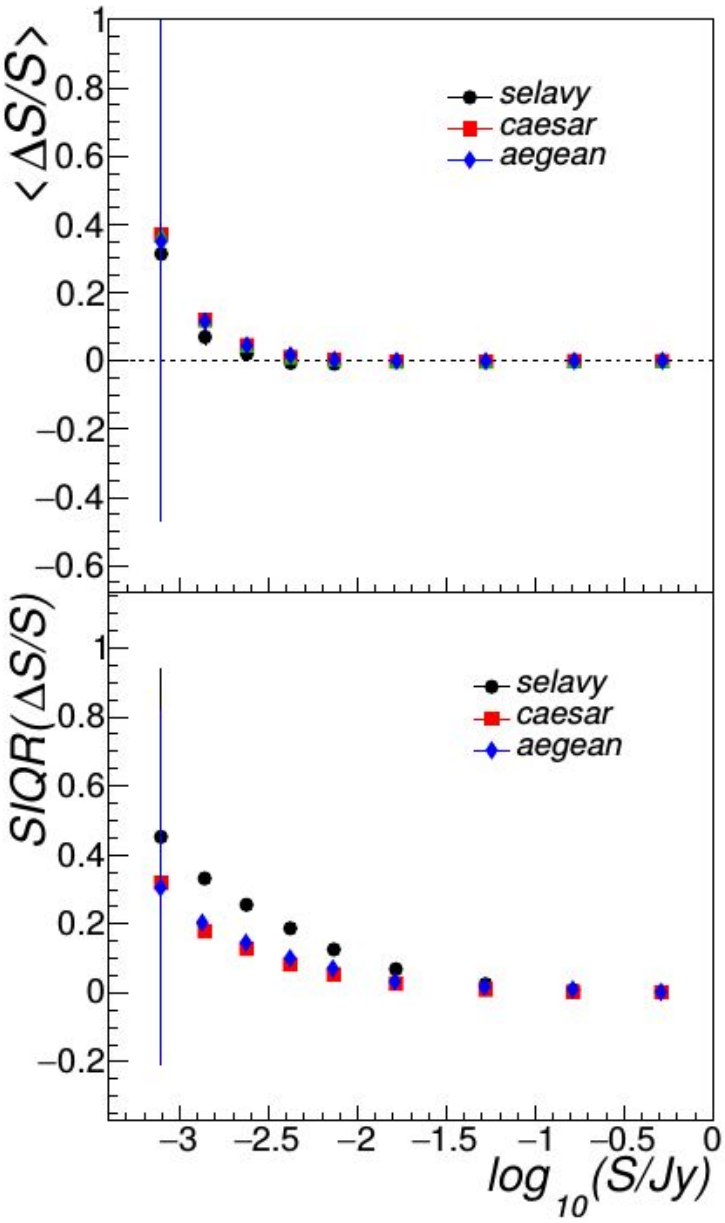
Accuracy evaluated on the same set of sources (e.g. detected by all finders) due to the different completeness





- No significant biases found in all finders
- Position resolution comparable in all finders (slightly worse in RA for Caesar)

Source flux density accuracy

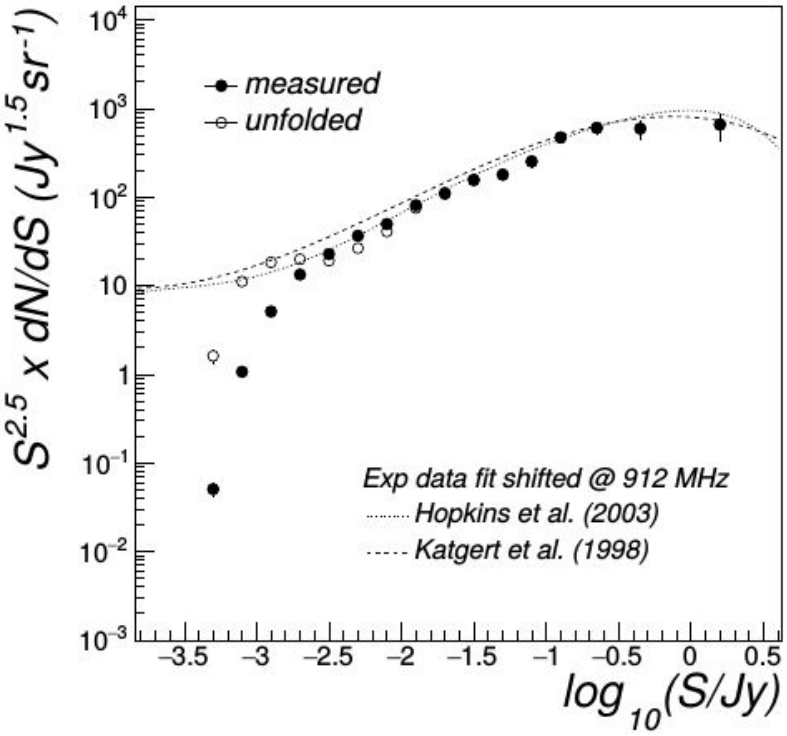


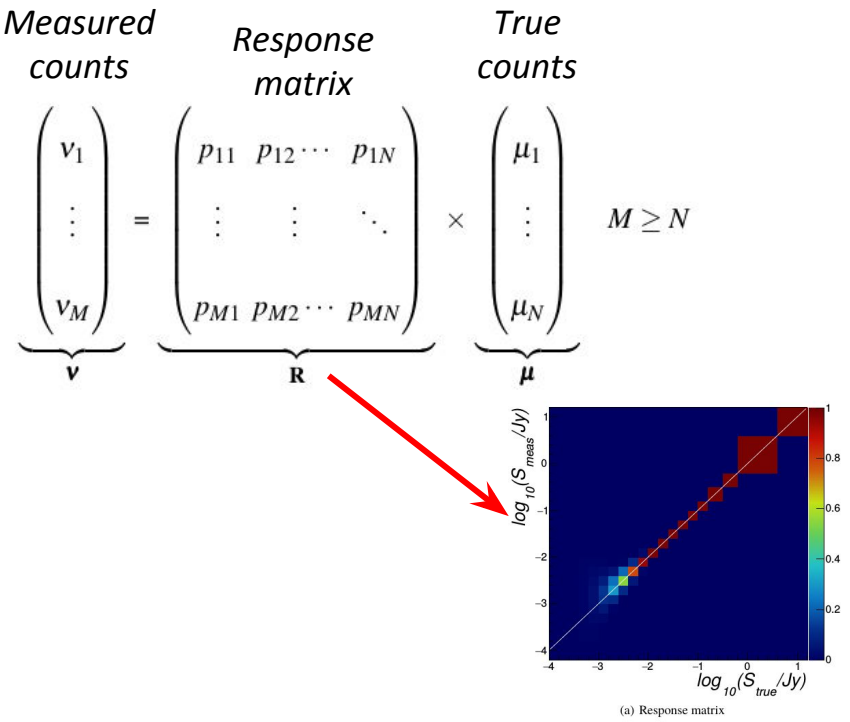
Accuracy evaluated on the same set of sources (e.g. detected by all finders) due to the different completeness

- Biased measurement in the low S/N
  - <5% at the detection threshold, >20% below
  - Common issue in many other finders
  - Slightly better in Selavy
- Comparable flux density resolution for Caesar and Aegean
  - ~10% at the detection threshold, larger for Selavy
- Bias and resolution were parameterized in Caesar vs lgS for source counts correction (see next slides)

Source counts

Source counts derived from ASKAP source catalog



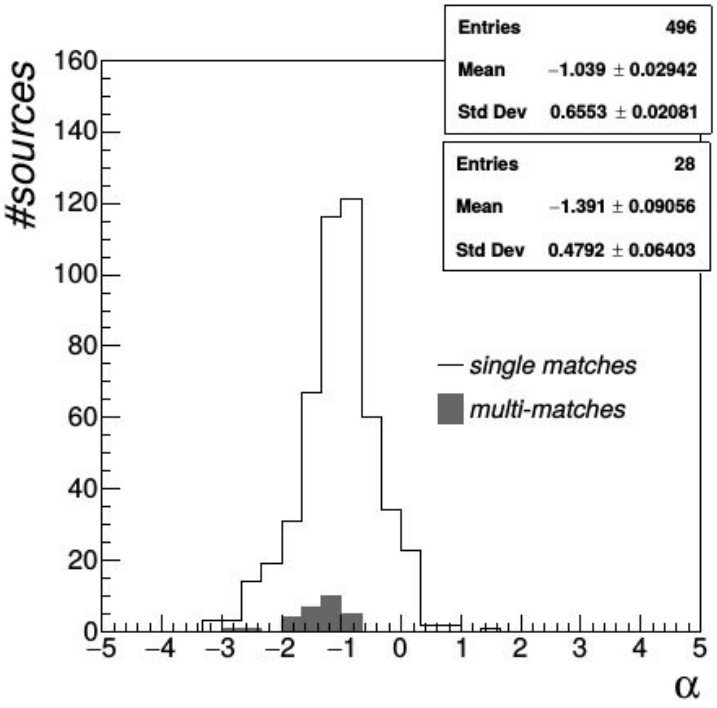


- Source counts corrected for measurement effects (completeness, flux bias/resolution) using a forward-folding technique
  - Model true source counts (e.g. with a power-law)
  - Fit model (folded with a response matrix) to data with maximum log-likelihood method --> correction parameters
- Differential counts found in agreement with literature data at 1.4 GHz

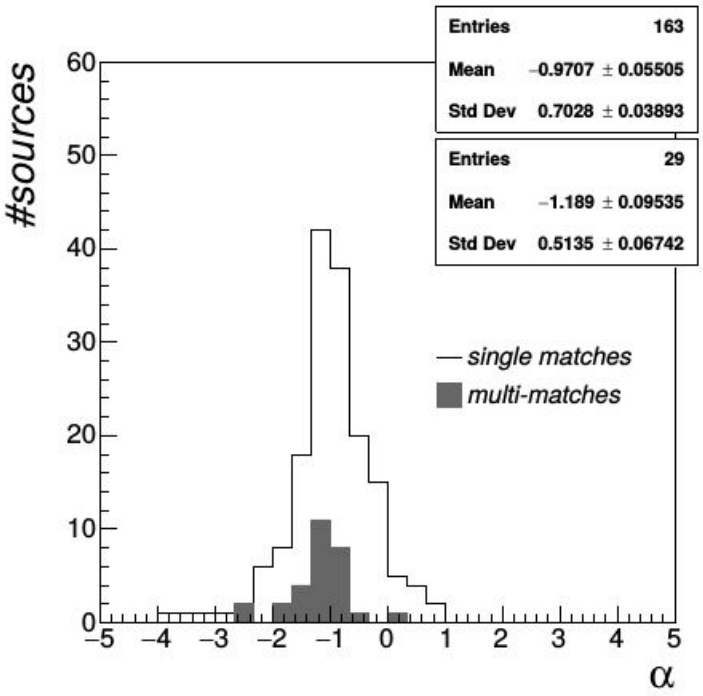
Spectral indices

Average spectral indices can be obtained for a portion of ASKAP map by cross-match with ATCA catalogue

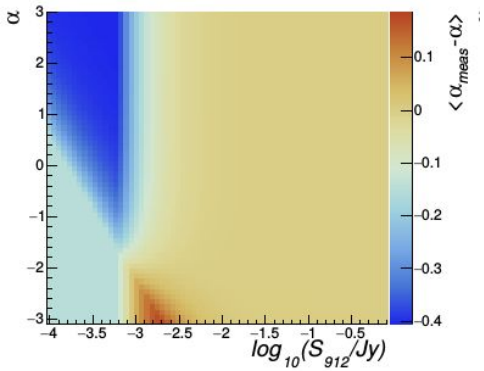
- 716 ASKAP source components matched to ATCA (out of 856 inside ATCA region)
  - #659 one-to-one matches
  - #57 one-to-many matches (NB: ATCA map has ~10”x6” resolution wrt to ASKAP 24”x20”)
  - ~3.8 matches found by chance in randomized catalogues



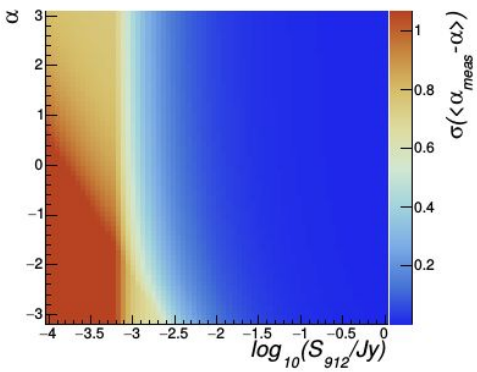
(a) Spectral indices (S_{912} <10 mJy)



(b) Spectral indices (S_{912} >10 mJy)

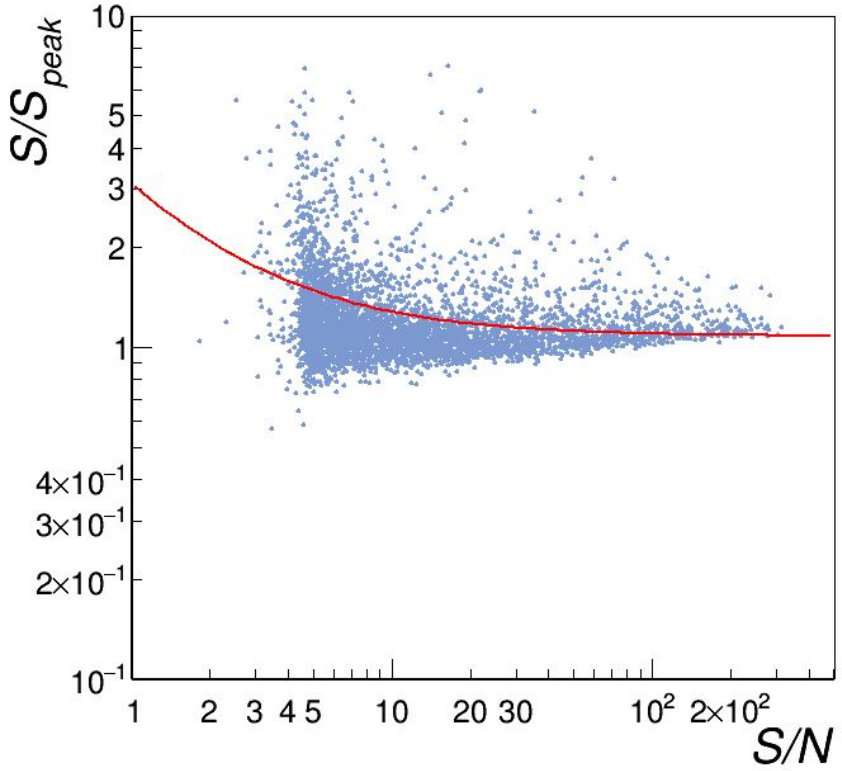


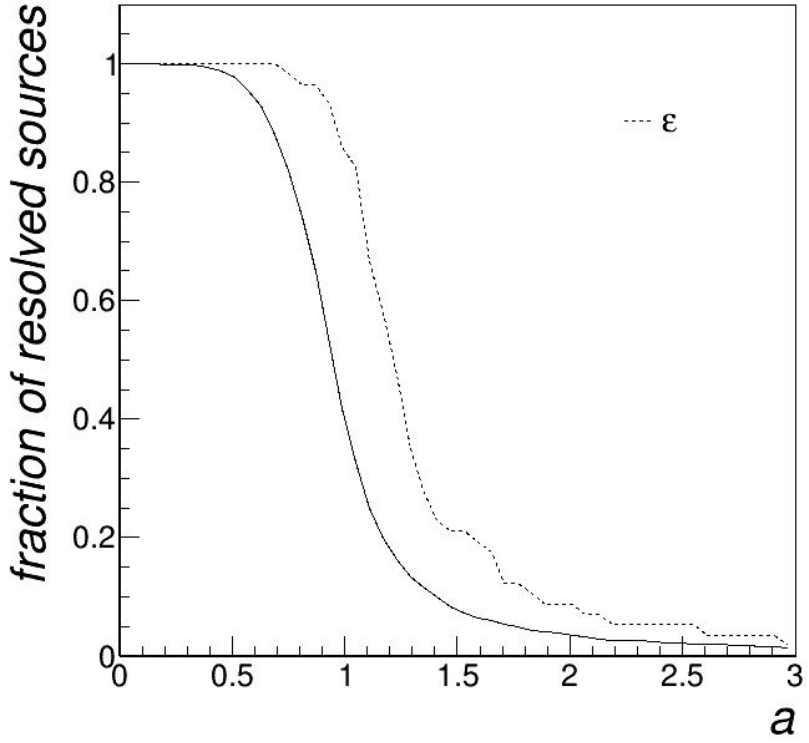
(b) Spectral index bias



(c) Spectral index uncertainty

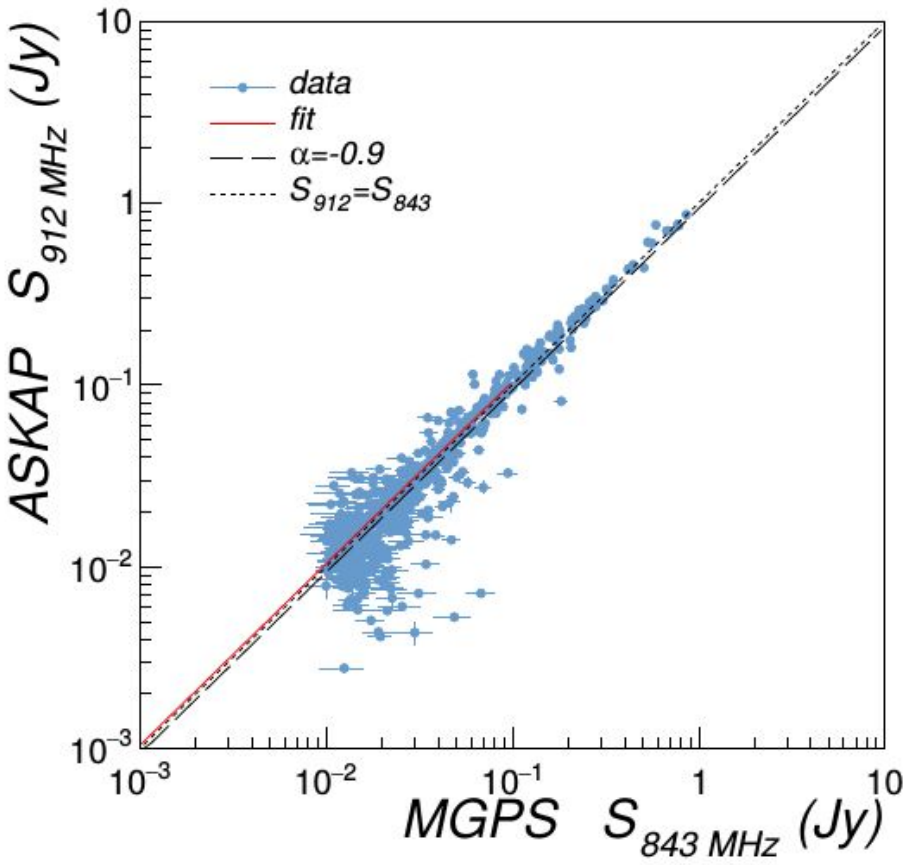
Resolved source fraction





- Resolved source if S/Speak>thr, thr= a + b/SN (e.g. a=1.08, b=2.03 in XLL survey)
- Computed the fraction of resolved sources as a function of a
  - ~30% resolved sources extended in the catalogue from S/Speak criterion
  - ~8% of truly resolved sources obtained from ATCA cross-matches, ~80% identified with S/Speak criterion

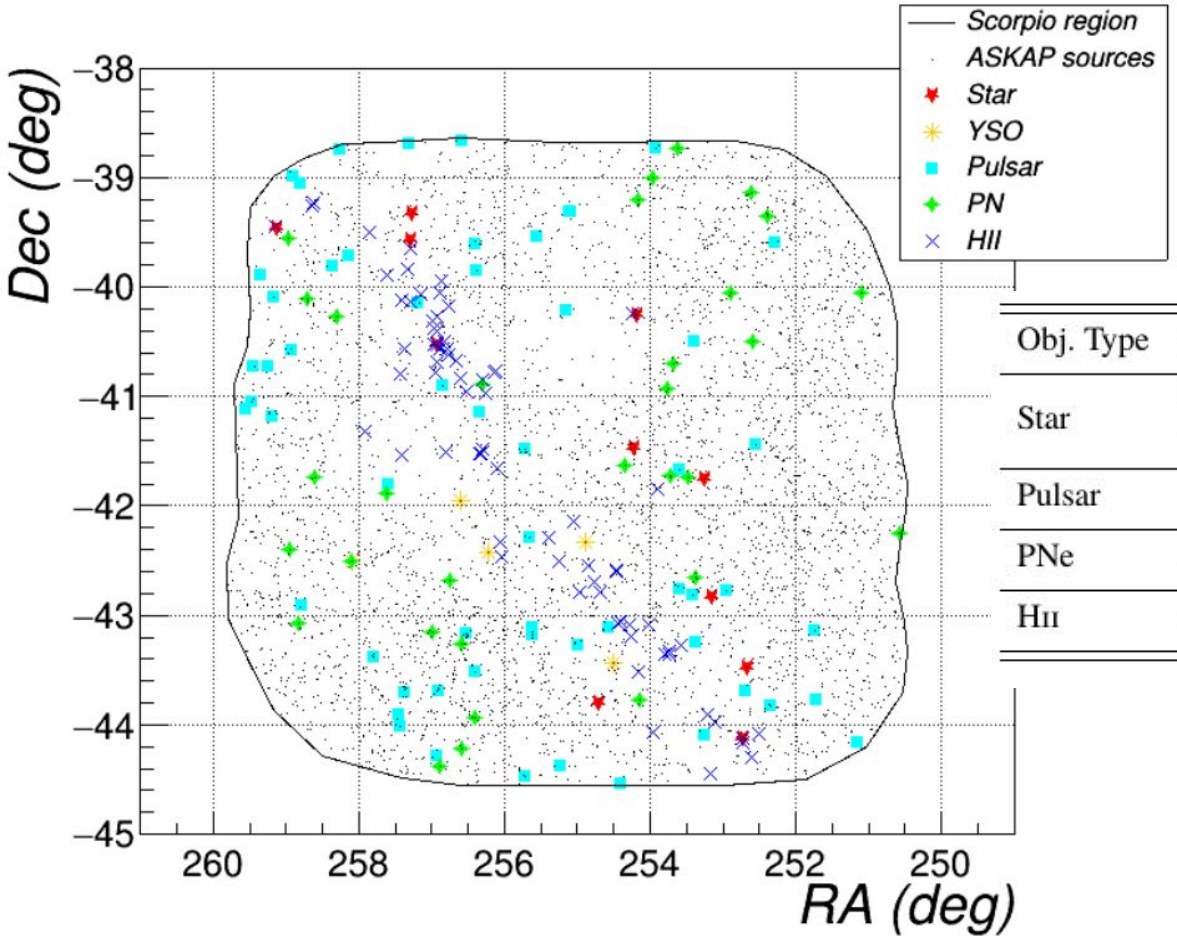
Comparison with MGPS catalogue



- 765 source matches with MGPS-II catalog (out of 799 MGPS sources present in ASKAP map)
- 594 matches left after removal of multi-match and visual inspection (unreliable MGPS fluxes, etc)
- No significant flux density scale issues (i.e. data are strongly correlated)
- Fitted slope (1.040±0.003) indicating an excess in ASKAP fluxes compared to MGPS --> potential flux scale offset at the level of 9-10% to be investigated with full array data

Cross-matches with astronomical catalogues

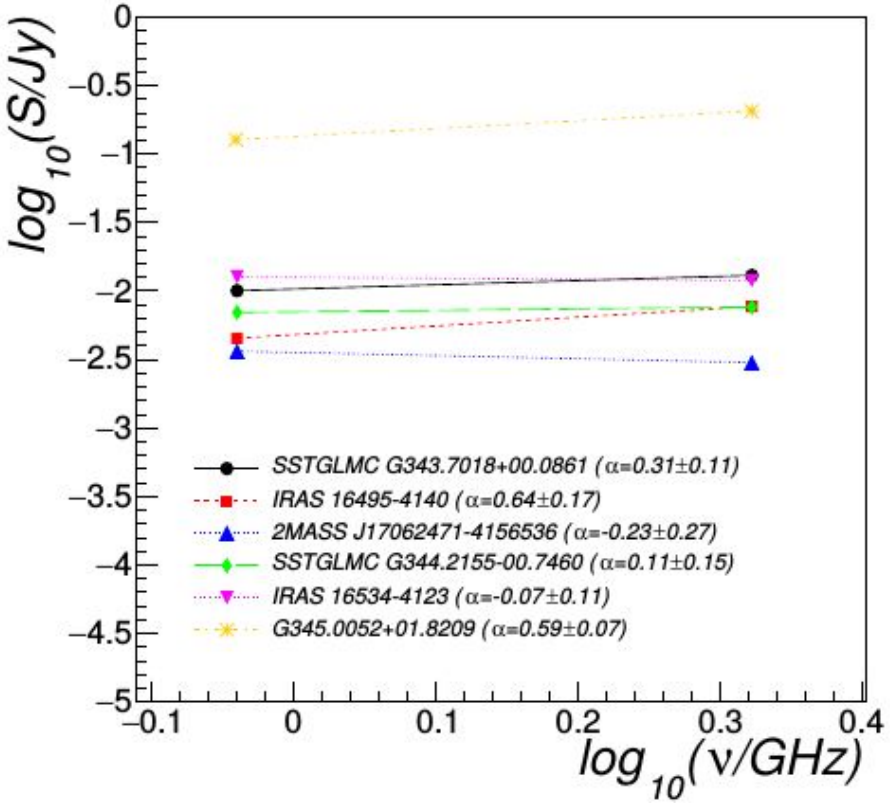
- ~150 known Galactic compact objects (stars, HII, pulsars, PNe) associated to ASKAP sources
- Extended objects not analyzed in this work --> see S.Loru's talk for SNR in SCORPIO
- ~96% ASKAP sources not classified yet

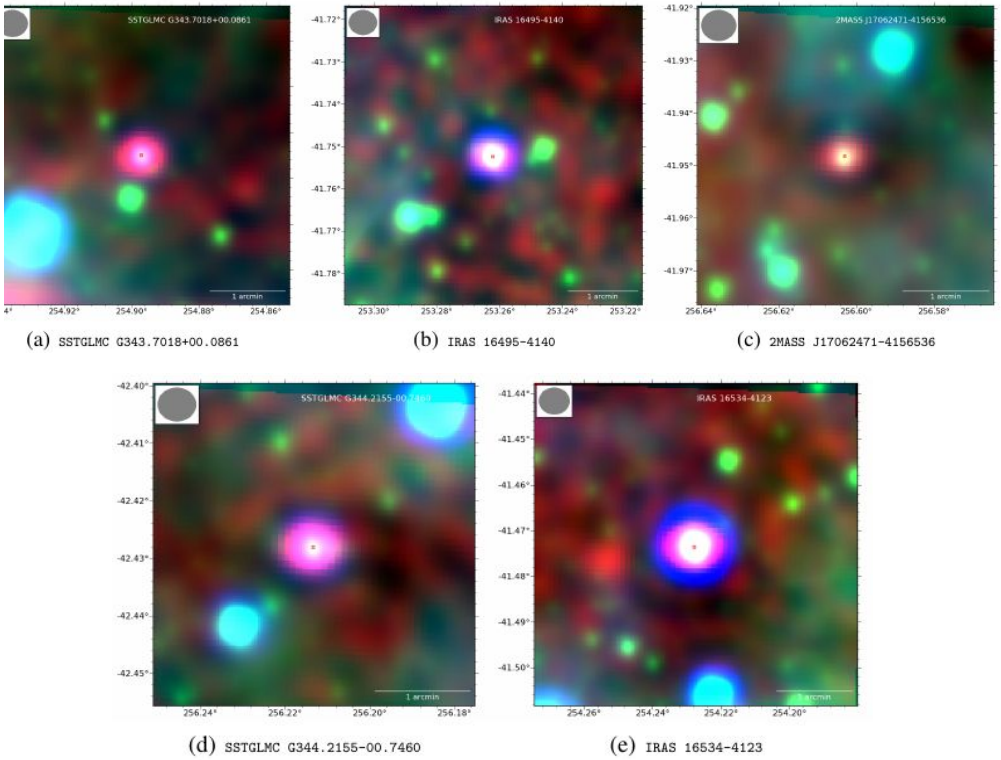


Obj. Type	Catalogue	r_{match} (")	$n_{matches}$	confirmed objs.
Star	SIMBAD	4	20	13
	WR Cat.	4	0	0
Pulsar	ATNF Cat.	8	21	21
PNe	HASH	12	32	27
HII	Wise	32	83	46

Stars in SCORPIO

- 20 stars (7 candidates, 13 confirmed) associated to ASKAP sources out of 10628 SIMBAD entries --> sample including 7 YSO (6 candidates, 1 confirmed)
- Spectral index measurement for 6 sources (4 YSO, 2 STARS)



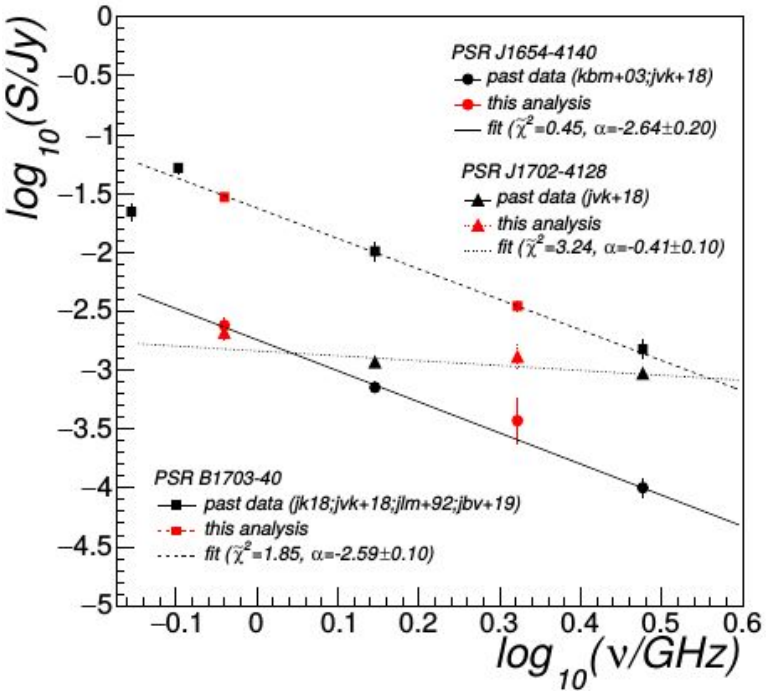


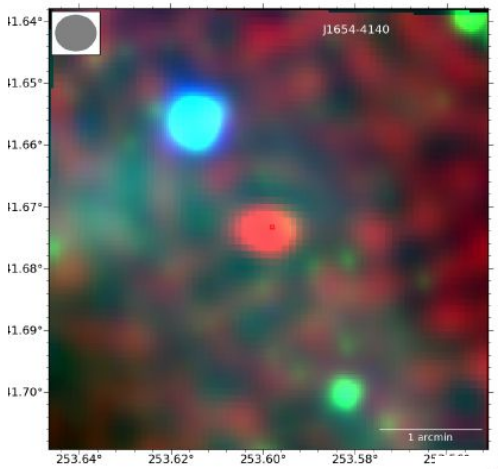
- First spectral index measurement provided
- Infrared emission (co-spatial with the radio) observed at 12 & 22 um

Red: radio ASKAP 912 MHz
Green: IR WISE 12 um
Blue: IR WISE 22 um

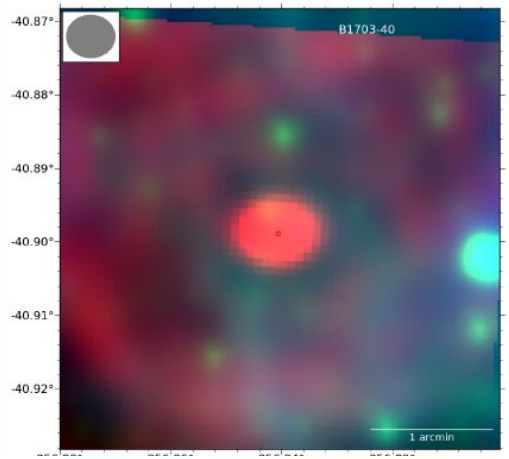
Pulsars in SCORPIO

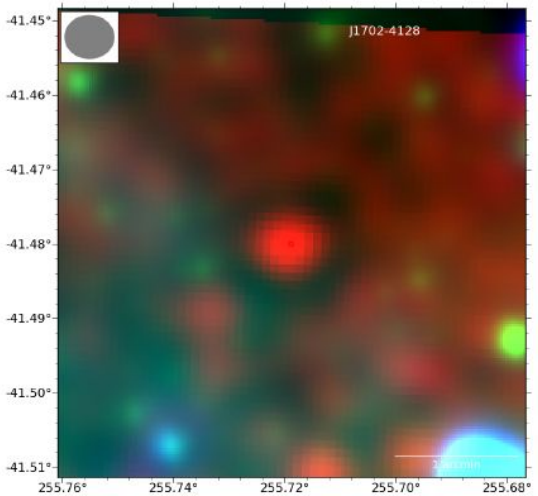
- 21 pulsars (all confirmed objects) associated to ASKAP sources out of 58 ATNF entries
- Spectral index measurement for 4 sources (1 resolved in ASKAP)





(a) J1654-4140



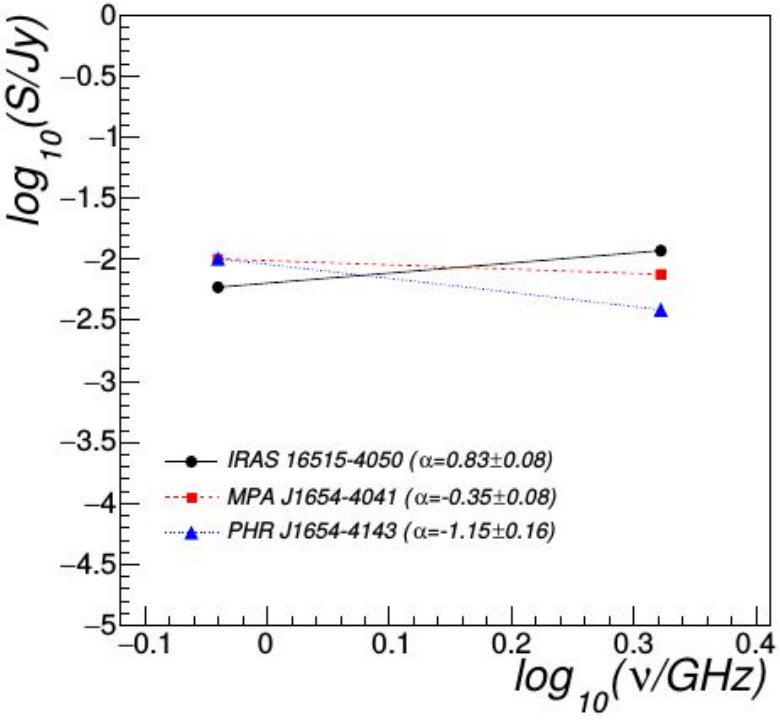


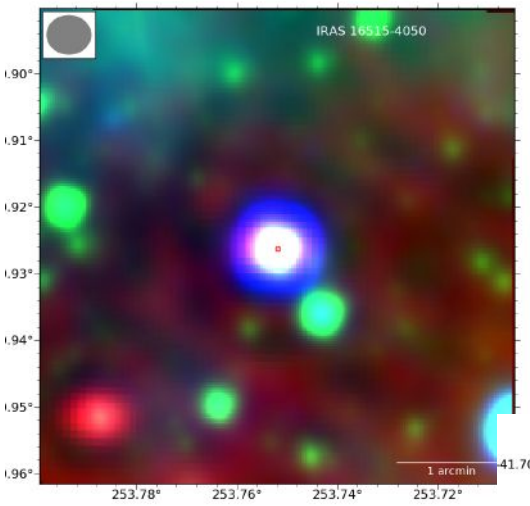
(c) J1702-4128

- ASKAP & ATCA data filling the gaps of existing measurements and nicely following the spectral trend
  ==> New spectral index measurement!
- No infrared emission observed at 12 & 22 um
- PSR J1702-4128 radio emission possibly originating from a PWN (still debated in the literature)

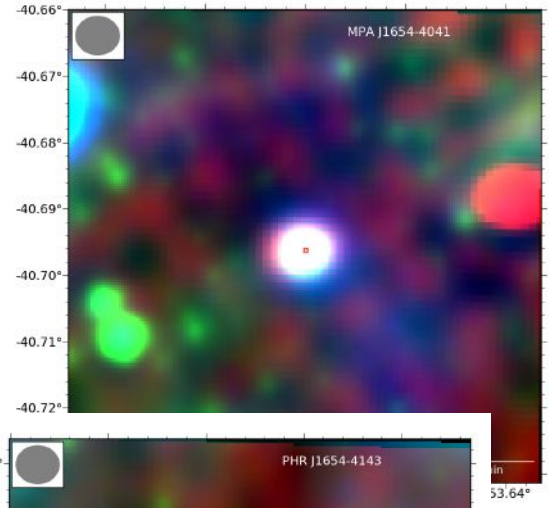
PNe in SCORPIO

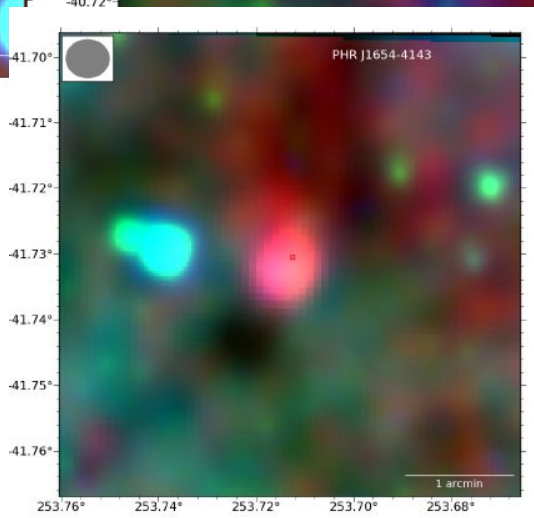
- 32 PNe (27 confirmed, 5 candidates) associated to ASKAP sources out of 45 HASH entries
- Spectral index measurement for 3 sources (1 confirmed, 2 candidates)





(a) IRAS 16515-4050



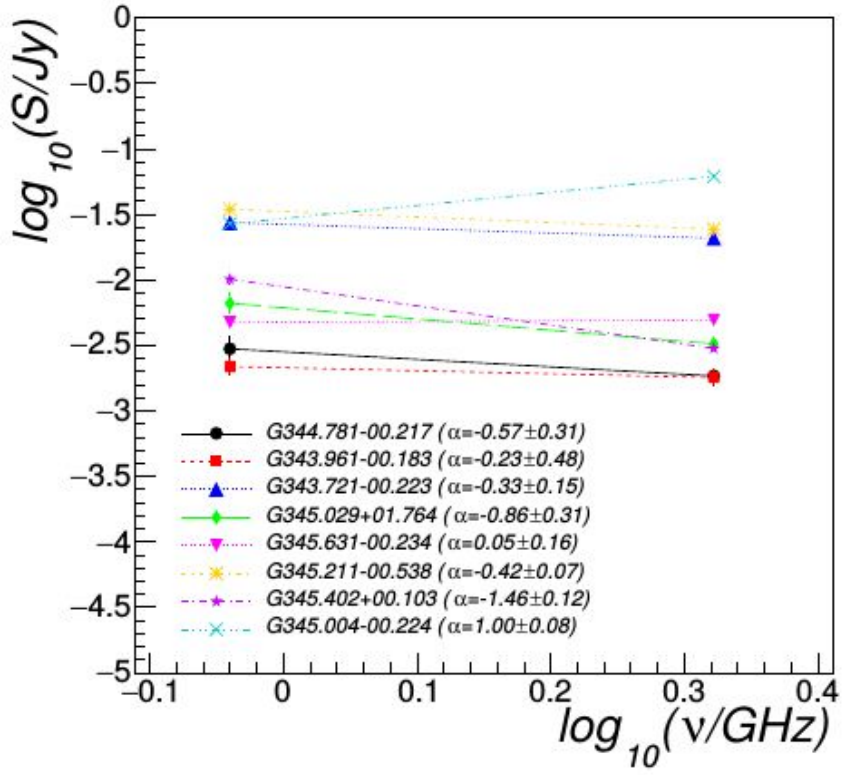


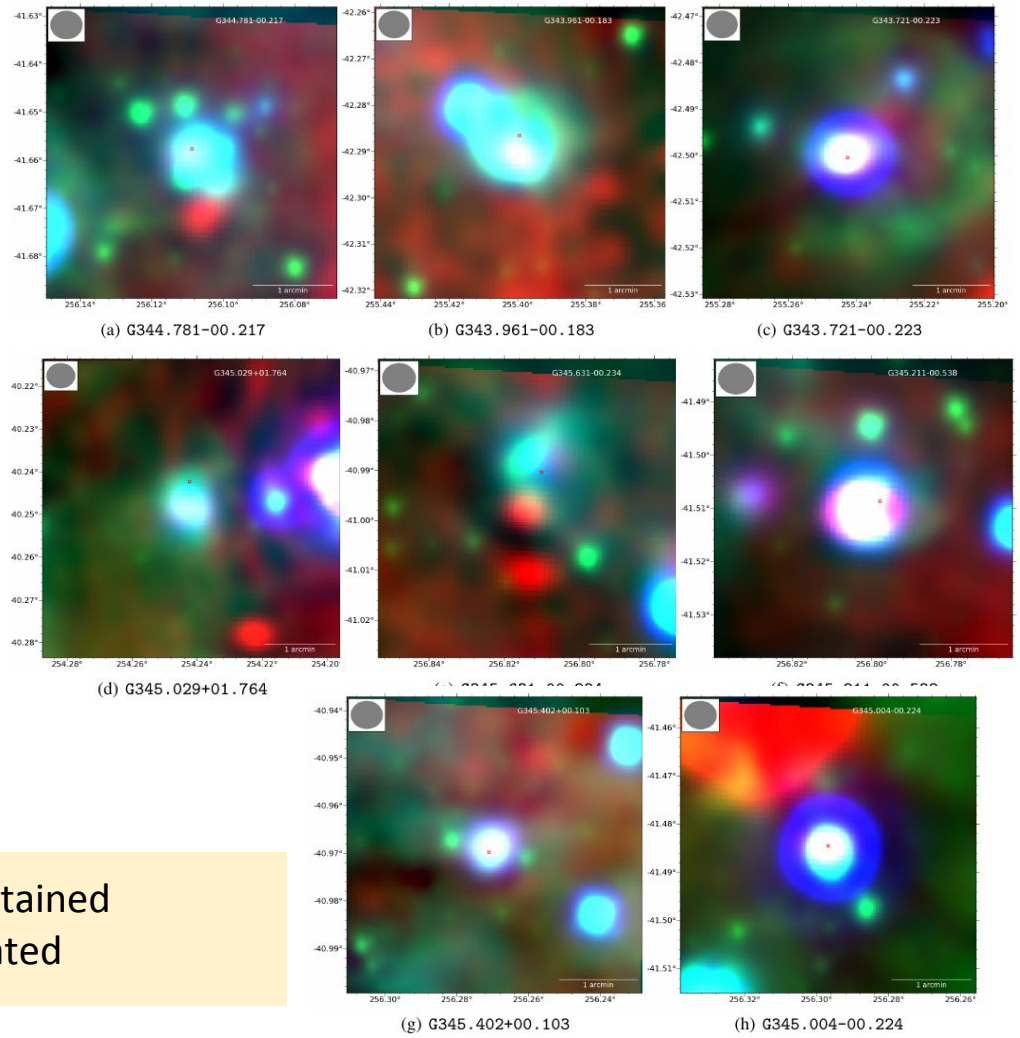
(c) PHR J1654-4143

- First spectral index measurement provided
- Infrared emission (co-spatial with the radio) observed at 12 & 22 um
- Radio spectral index + IR suggesting a thermal free-free emission from an optically-thin nebula as the origin of the radiation ==> need more analysis

HII regions in SCORPIO

- 83 HII (46 confirmed, 37 candidates) associated to ASKAP sources out of 356 WISE entries
- 10 detected in both ASKAP and ATCA, 8 (4 candidates) with spectral index measurement





- First measurement of the spectral index obtained
- Associations and candidates to be investigated

Results & lessons learnt from SCORPIO ESP

Scientific results (even with an incomplete array!)

- 4220 sources catalogued at 912 MHz with fluxes ranging from 3.9 Jy down to 0.4 mJy
  - ✓ ~87% of the sources detected with significance higher than 5 sigmas
  - ✓ >90% completeness above 5 mJy
  - ✓ >8% resolved sources
  - ✓ ~4% associated to catalogue objects, ~96% still unclassified
- Differential source counts in agreement with existing data at 1.4 GHz
- Spectral index measurement provided for ~17% of the source sample
- New spectral index measurements for some known and candidate objects present in SCORPIO (stars, pulsars, PNe)

Technical results

- Optimization of pipeline parameters for Galactic fields
- Improvements and testing of CAESAR source finder performances for both compact and extended sources (e.g. S. Riggi et al, PASA 2019)
- Comparable source finding performances found from different tools
- Development of post-processing algorithms for value-added catalogue (spectral indices, cross-matches, classification, etc) under way

Ongoing and future analysis

Ongoing activities

- Complete census of SCORPIO sources using additional catalogues
- Study of classification parameters on pre-classified sources
- Unsupervised classification of the full source sample

Future activities

- Exploitation of new ASKAP SCORPIO data (B1, B2, B3) with full array
- Benefits expected
  - ✓ An increase in catalogue size, due to the lower detection threshold reached, and a better source flux density characterization (bias and resolution) for the already catalogued sources
  - ✓ A more accurate and automated identification of extended and spurious sources for the entire field, by cross-matching results found at different frequencies
  - ✓ A more robust source counts estimate around and below 1 mJy
  - ✓ A first and more robust spectral index measurement for sources currently lacking a spectral information, e.g. sources located outside the Scorpio ATCA region and near the detection threshold

Paper on SCORPIO Compact Sources

- **New paper announced recently on EMU/ASKAP mailing list**
- **What is expected to be included in the paper?**
  - ✓ Brief description of the data reduction (described more in detail in Umana's paper in preparation)
  - ✓ Source extraction methodology and performances
  - ✓ Cross-checks and analysis with the extracted catalogues (e.g. source counts, spectral index, etc)
  - ✓ Census of SCORPIO compact sources by cross-match with astronomical catalogues and first measurements for selected sources
- **What is expected to be left for future papers?**
  - ✓ Inclusion of B1, B2, B3 ASKAP SCORPIO data with 36 antennas (long times expected for data reduction so left for a second release of the catalogue)
  - ✓ Classification studies on the catalogued source sample (still working on this)
  - ✓ Deep studies on selected/interesting sources (interested people are welcome)
  - ✓ Study of existing and new supernova remnants (keep in touch with Milena, Sara, and Adriano)