Surveying cosmic ray production in molecular clouds

A low-frequency radio survey of Perseus and Taurus

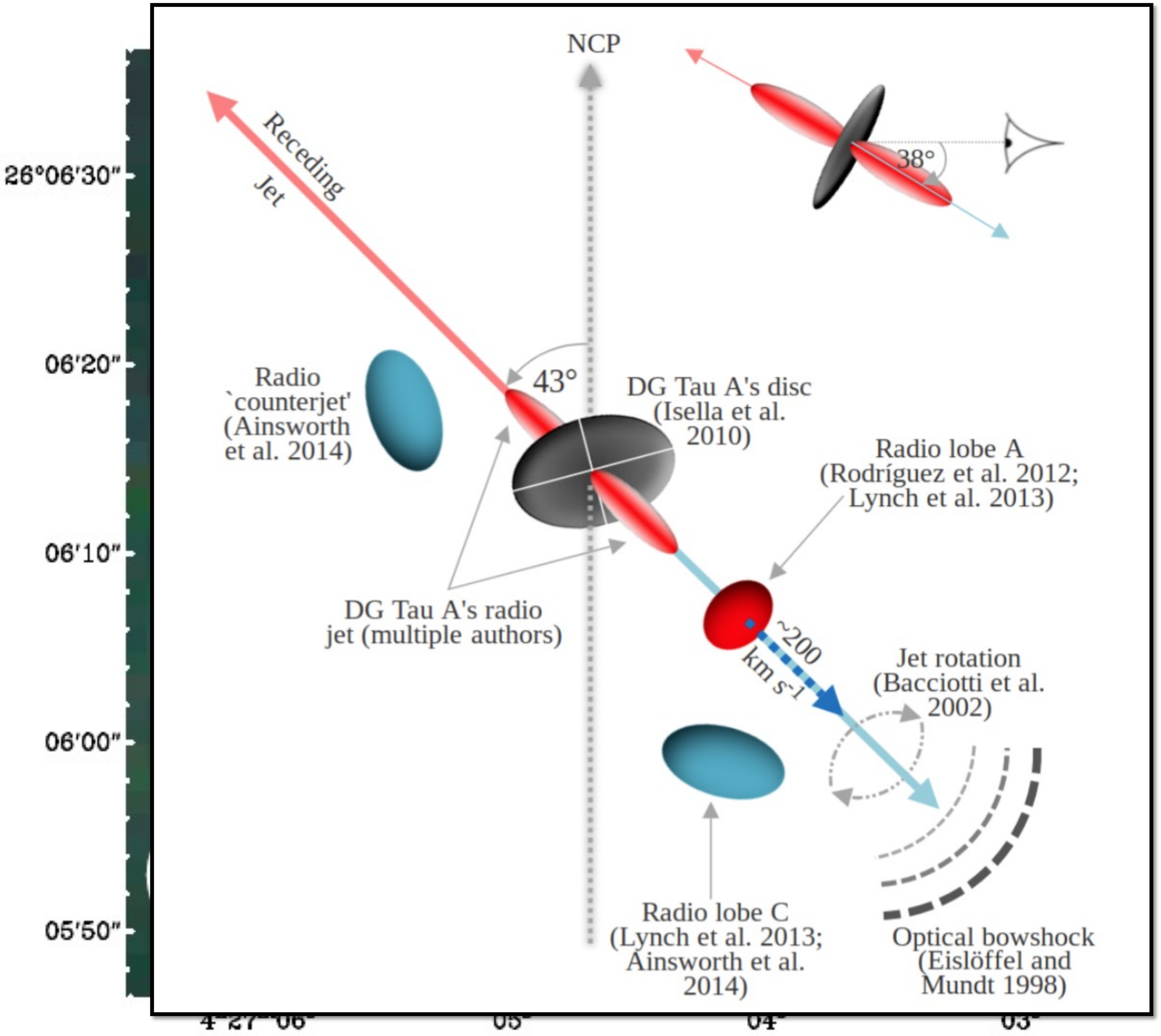
Simon Purser, 09:40 - 10:00, Wednesday 9th November 2022

YSOs, Jets, and Radio Emission

Jets

Feedback into the environment

- Natural consequence of accretion
- Collimated/launched by stellar and/or disc magnetic fields
- Many types of radio emission
- Can drive CR production in the environment
- To what degree does this impact the SF paradigm?



Ainsworth et al (2014)

Introduction

Radio emission from YSOs

Emission Mechanism	Physical Origin	YSO spatial coincidence?	α ($S_\nu \propto \nu^\alpha$)	T_B [K]	Polarisation [%]	Short-term Variability
Thermal Bremsstrahlung	Ionised jets	✓	-0.1 - 2.0 (~0.6)	~10^4	0	✗
Synchrotron	Jet shocks	✗	~-0.5	≤10^{12}	~10	✗
Electron-Cyclotron Maser	Coronal loops, Exoplanets, Aurorae	✓	0	≤10^{15}	≤100	✓
Plasma Emission	Coronal plasma, Exoflares	✓	0 (Complicated)	≤10^{15}	<50	✓

Motivation

- Contribution to low-energy cosmic ray flux in SF environments from jets (Ainsworth et al, 2014; Purser et al. 2016, 2021)
- Constraining jet launch/collimation regions (Reynolds 1986)
- How common are exosolar ‘aurorae’ (Feeney-Johansson et al. 2021)
- Exoflares and their prevalence in YSOs (e.g. Lynch et al, 2013)
- Exoplanets and their magnetic and orbital properties (e.g. Vedantham et al. 2020, Feeney-Johansson et al. 2021)

Non-thermal Radio Emission

Thermal Radio Emission

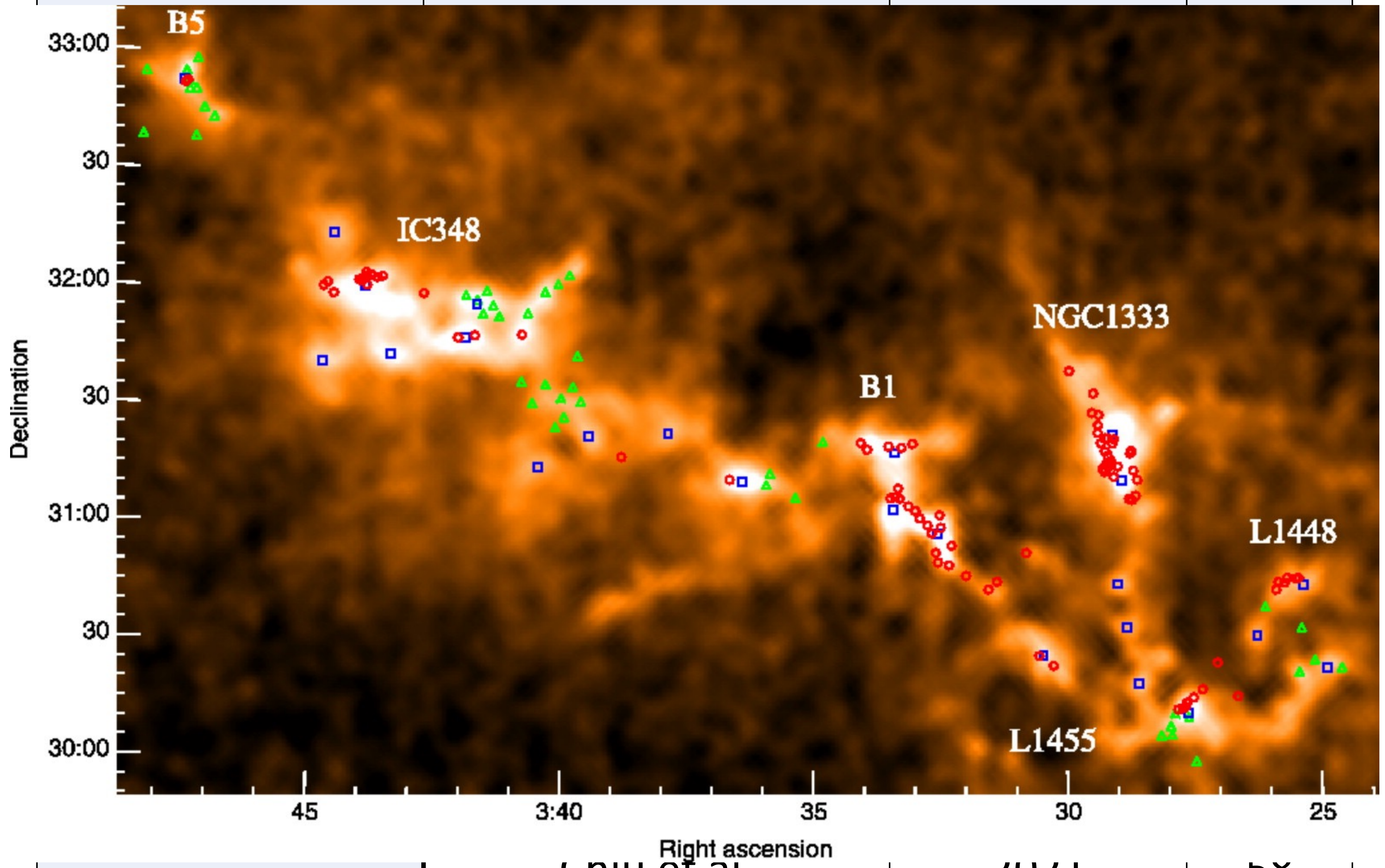
Variable Radio Emission

YSO Sample

YSO Sample

Perseus

	Authors	Year	$N_{objects}$
	Chiu et al.	2021	58

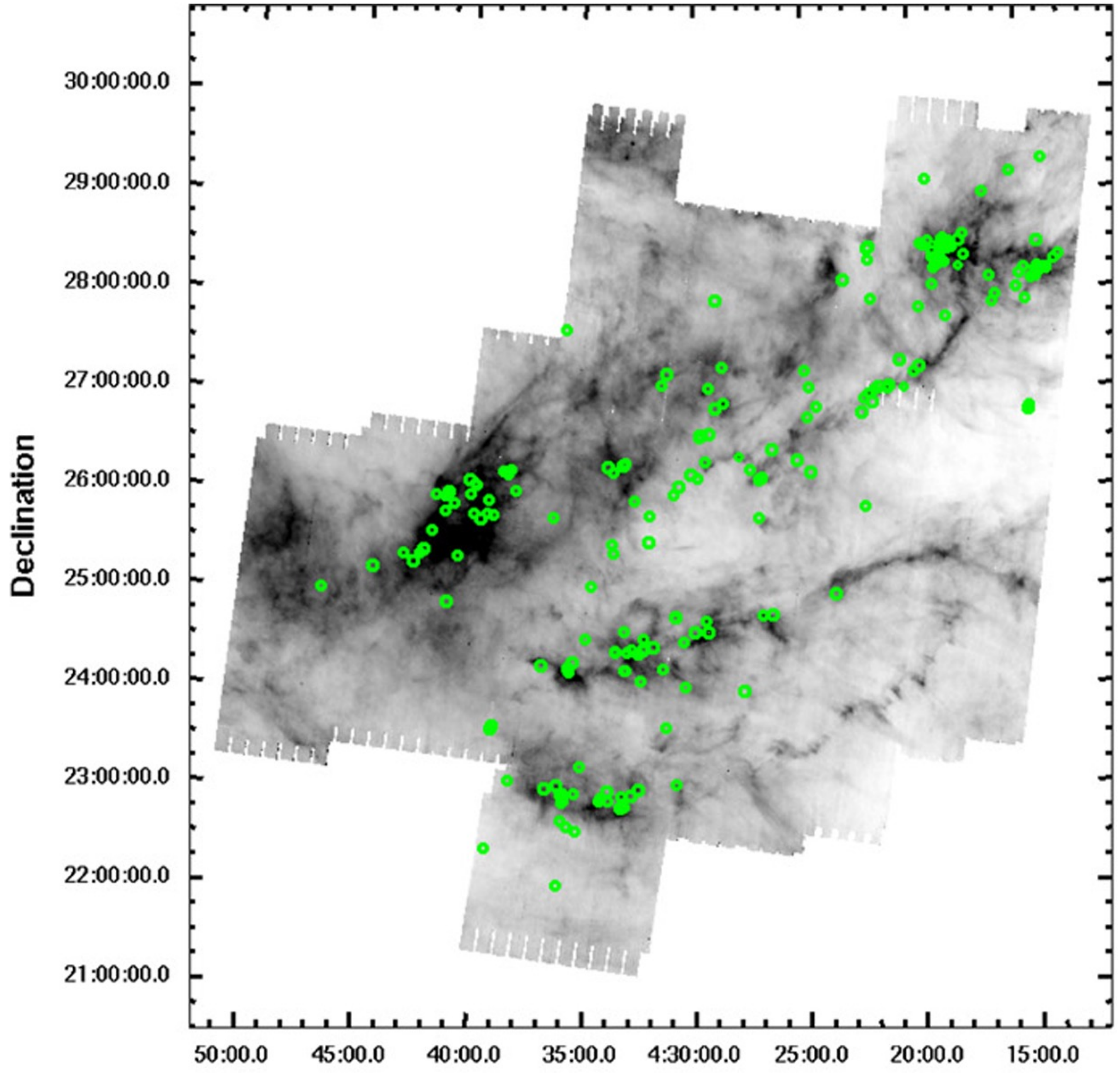


Kirk et al (2007)

- Multiple YSO catalogues present in literature
- SIMBAD database searched for object with classification of either ‘Y*?’ or ‘Y*O’
- Compare positions of all catalogues’ YSOs and associate sources with each other for Δx < 3 arcsec
- Resulting catalogue of 2365 potential YSOs
- Concentrate on well established Spitzer c2d sample (~385 objects)

YSO Sample

Taurus



Rebull et al (2010)

	$N_{objects}$
	119
	414
	610
	1498
	363
	272
	60

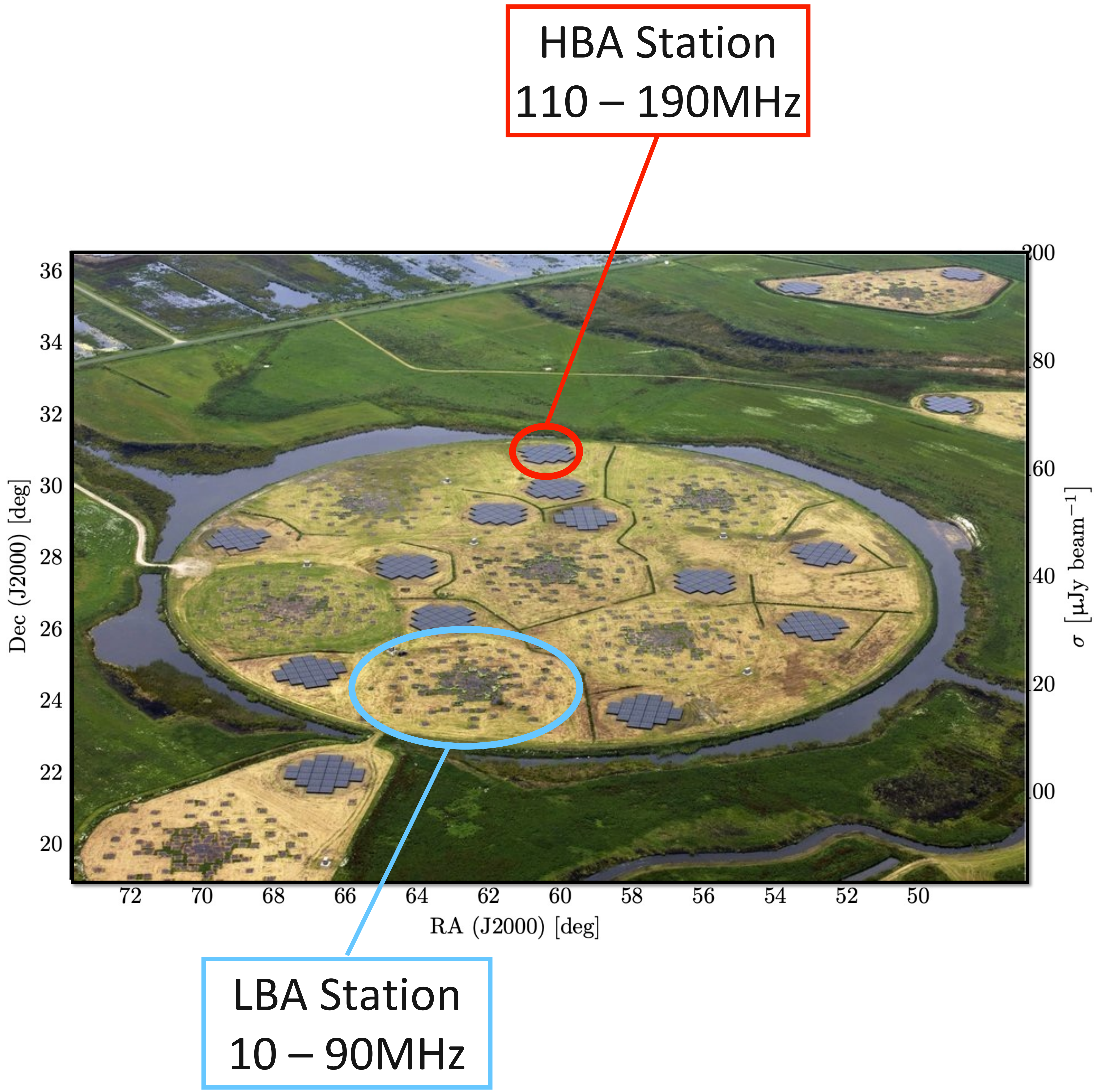
- Multiple YSO catalogues present in literature
- SIMBAD database searched for object with classification of either ‘Y*?’ or ‘Y*O’
- Compare positions of all catalogues’ YSOs and associate sources with each other for Δx < 3 arcsec
- Resulting catalogue of 515 potential YSOs
- Concentrate on ‘reliable’ sample (~411 objects)

LOFAR Observations

LOFAR Observations

Details

- Low-frequency radio survey of two, nearby star formation complexes: Perseus and Taurus
- LOFAR (120-168 MHz) observations covering ~150deg^2 conducted in partnership with LoTSS
- 8 hour integrations towards 20 pointings forming two mosaics
- Sensitivities of $\gtrsim$ 85 μJy beam^{-1} (pretty good at these frequencies!)
- 6 arcsecond resolution

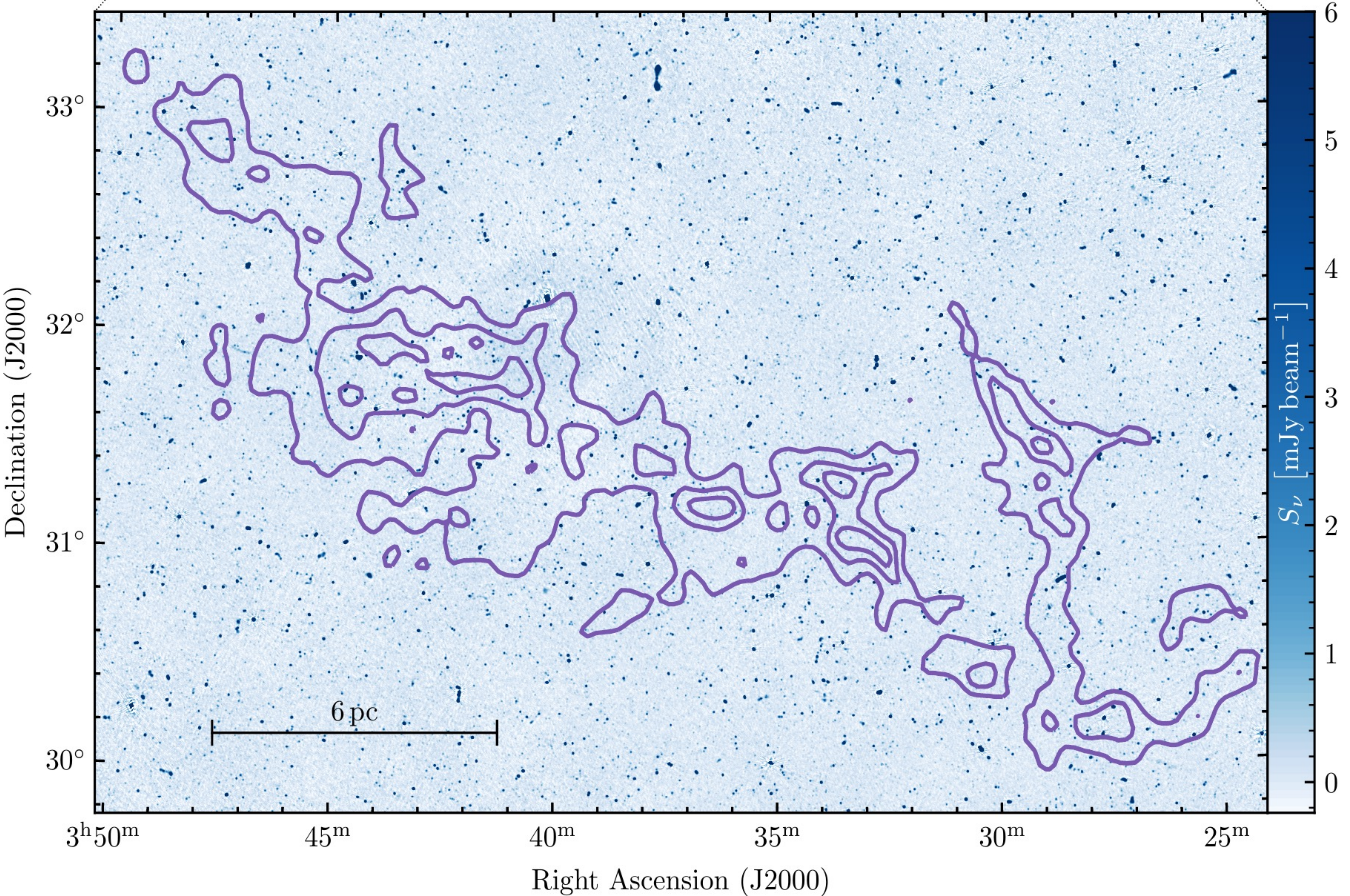


Imaging

Polarisation, 24 epochs, multiple bandwidth selections

- Full-bandwidth, full-integration mosaic image (1)
- Full-bandwidth, single epoch, single hour images (24) [Perseus only]
- Full-integration, single band (128, 144, 160 MHz) images (3) [Perseus only]
- Stokes-V full-bandwidth, full-integration mosaic image (1) [Perseus only]
- Stokes-V full-bandwidth, single epoch, single hour images (24)
- Stokes-V full-integration, single band (128, 144, 160 MHz) images (3)

Results



6 pc
Declination (J2000)
33°
32°
31°
30°
Right Ascension (J2000)
3^h50^m
45^m
40^m
35^m
30^m
25^m
S_ν [mJy beam^{-1}]
6
5
4
3
2
1
0

Results

PyBDSF Catalogues

- Run PyBDSF:
  - Adaptive RMS boxes (40, 10) → (20, 4)
  - Adaptive threshold 100σ
  - Source threshold at 5σ
- Source catalogues for Stokes I and V, epoch, band and the full mosaic

BW	Stokes	Epoch	Catalogue		$N_{sources}$	
			Taurus	Perseus	Taurus	Perseus
Full	I	Full	✓	✓	36771	31260
Band 0	I	Full	✗	✓	?	17333
Band 1	I	Full	✗	✓	?	16988
Band 2	I	Full	✗	✓	?	15051
Full	I	E1	✓	✓	8195	8401
Full	I	…	✗	✓	?	…
Full	I	E_{last}	✗	✓	?	14255
Full	V	Full	✗	✗	?	?
Band 0	V	Full	✗	✗	?	?
Band 1	V	Full	✗	✗	?	?
Band 2	V	Full	✗	✗	?	?
Full	V	E1 0-1h	✗	✗	?	?
Full	V	□	✗	✗	?	?
Full	V	E3 7-8h	✗	✗	?	?

Sample

Spectral index and variability

$$\alpha = \frac{\log_{10}\left(\frac{S_{\nu_1}}{S_{\nu_2}}\right)}{\log_{10}\left(\frac{\nu_1}{\nu_2}\right)} \qquad (1)$$

$$S^2 = \frac{\Sigma\left(S_{144,E_i} - S_{144}\right)}{n} \qquad (2)$$

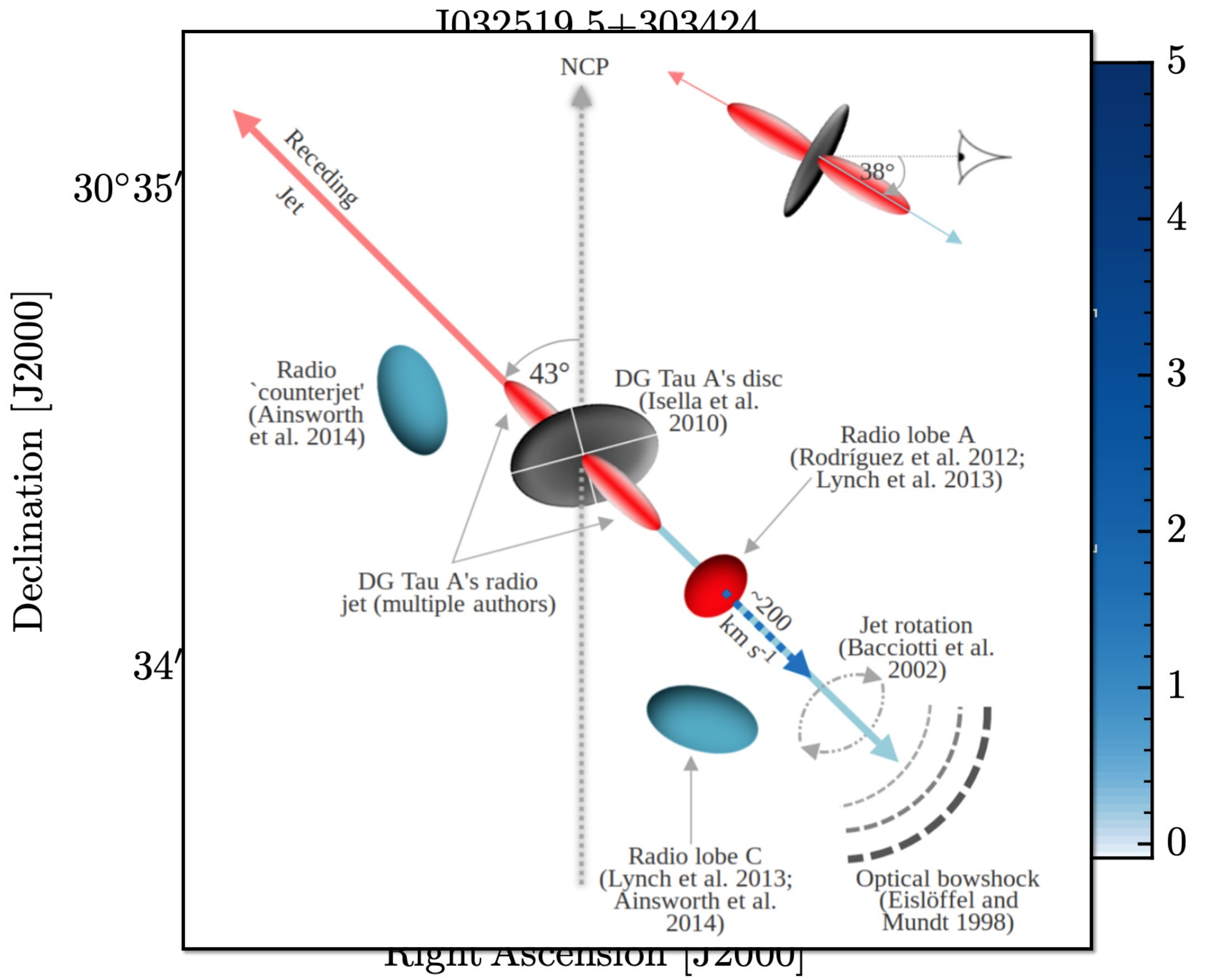
- Derive spectral index by:
  - LSQ fitting (detection in 3 bands)
  - Equation (1) (detection in 2 bands)
- Calculate variability via Equation 2 where:
  - S_{144} is either the measured full-BW, full-mosaic flux, or its upper-limit
  - S_{144,E_i} is flux in epoch *i*, or its upper-limit IF below S_{144}
  - N is the number of measured epochs and upper-limits below S_{144}

Analysis

YSO association

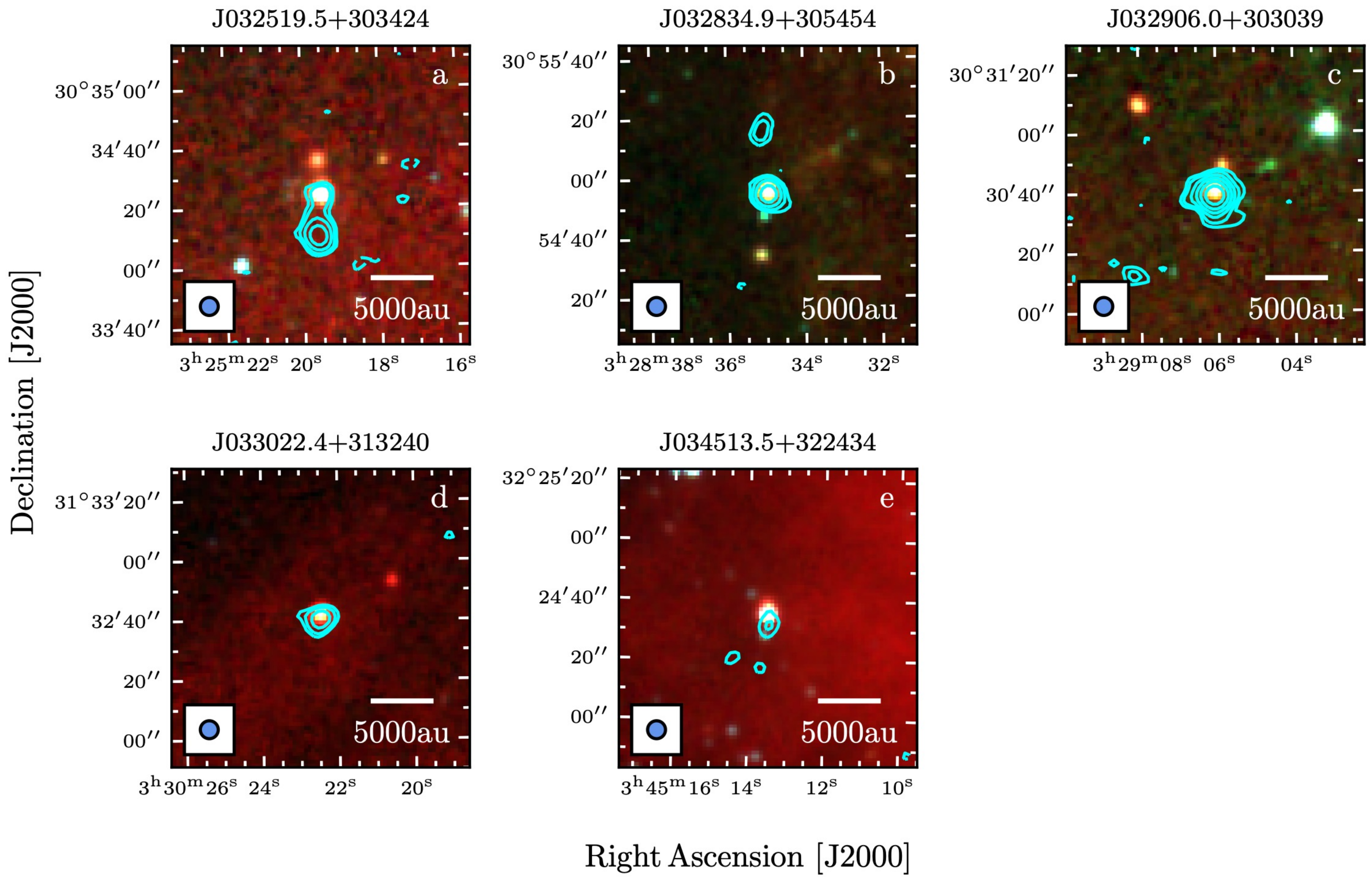
Spatial coincidence

- Define two categories of associated emission:
  - $\boxed{\Delta s \leq 3'' \text{ (YSO)}}$
  - $\boxed{\Delta s \leq 15'' \text{ (YSO-associated)}}$
- Extragalactic considerations (using T-RECs):
  - 0.2±0.4 false ‘YSO’ per 100 YSO
  - 4.5±2.1 false ‘YSO-associated’ per 100 YSO
- Assuming YSO catalogues are 100% Galactic!



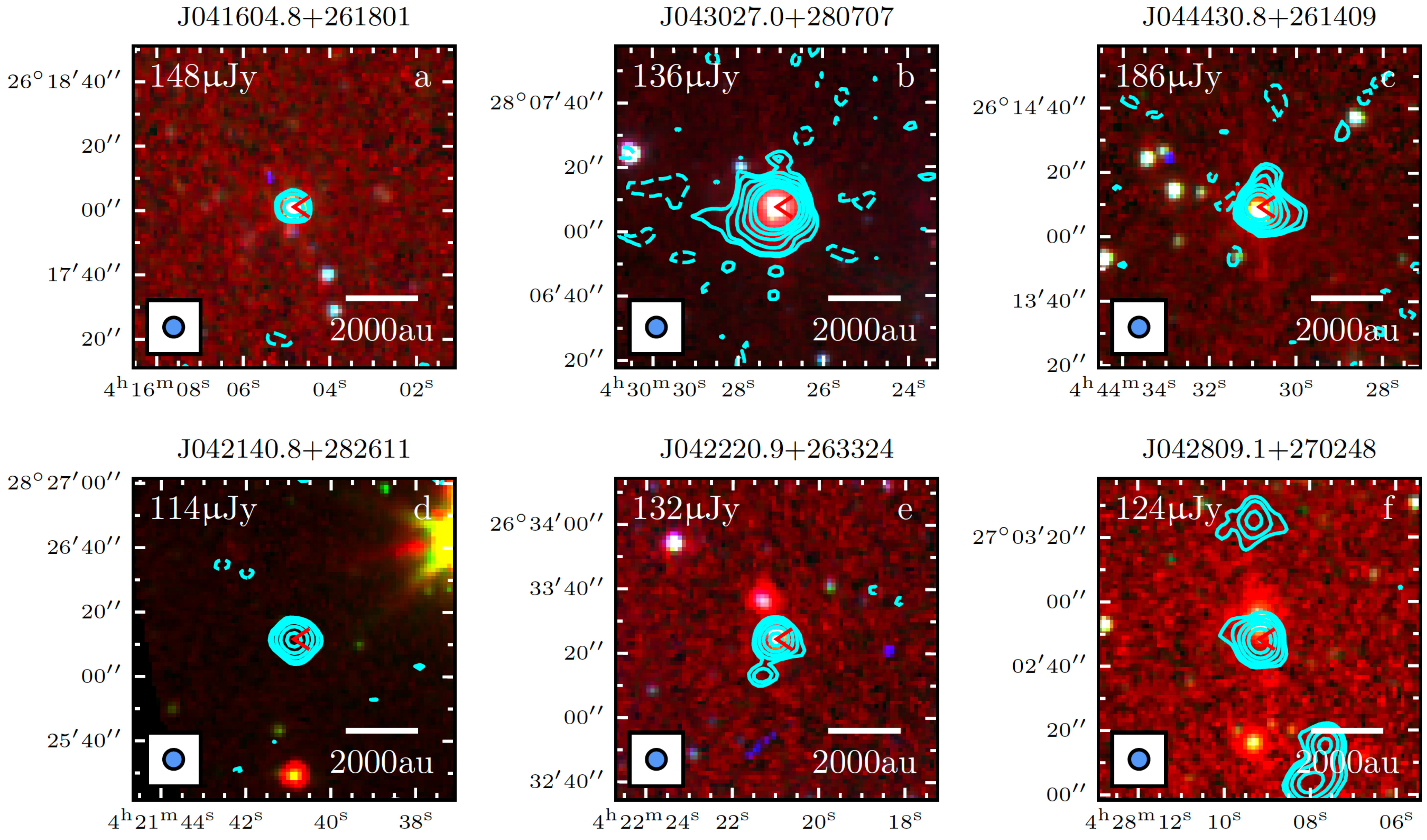
Detected YSOs - Perseus

Coincident radio emission (<3 arcsec)



Detected YSOs - Taurus

Coincident radio emission (<3 arcsec)



+ 23 other coincident detections

Perseus YSOs coincident with 144 MHz emission

JID	L_{bol} ($L_\odot$)	Class	S_{144} (mJy)	α	c_V	X_V (%)
J032519.5+303424	0.010	Flat	2.04±0.34	-1.9±1.6	0.25±0.15	<16±3%
J032834.9+305454	0.008	Flat	3.34±0.17	-1.1±0.6	0.18±0.05	<10±1%
J032906.0+303039	0.018	O/I	15.05±0.21	-0.4±0.2	0.10±0.04	<2±1%
J033022.4+313240	0.009	Flat	1.91±0.17	-0.9±1.1	0.75±0.29	<17±2%
J034513.5+322434	0.017	II	0.73±0.22	-	-	<45±13%

Taurus YSOs coincident with 144 MHz emission

JID	L_{bol} ($L_{\odot}$)	Class	S_{144} (mJy)	α	c_V	X_V (%)
J041604.8+261801	-	Flat	2.37±0.29	-	-	-
JH 56	0.5	III	3.34±0.17	-	-	-
LkCa 4	1.0	III	15.05±0.21	-	-	-
T Tau	7.3	II	1.91±0.17	-	-	-
J043233.4+274409	…	…	1.75±0.21	…	…	…

+ 24 other coincident detections

YSO association - Perseus

Associated radio emission (<15 arcsec)

- 14 YSOs with 'associated' radio emission, but expect 17±8 'pollutant' sources
- Likely that most, if not all, are attributable to AGN or SF galaxies

YSO association - Taurus

Associated radio emission (<15 arcsec)

- 7 YSOs with ‘associated’ radio emission, but expect 18±9 ‘pollutant’ sources
- Likely that most, if not all, are attributable to AGN or SF galaxies

YSO association - c2d Sample

Associated radio emission (<15 arcsec)

- Upper-limit to equipartition energy attributable to shocks from YSO jets of $\sim 7\times10^{39}$ erg

- Assuming a modest lifetime for shocks of ~100 yr (i.e. DG Tau A), $L_e \sim 6\times10^{28}$ erg/s

- For the PMC, this equates to $\sim 2\times10^{-5}$ eV / cm^{-3} per YSO over its outflow stage (~1 Myr)

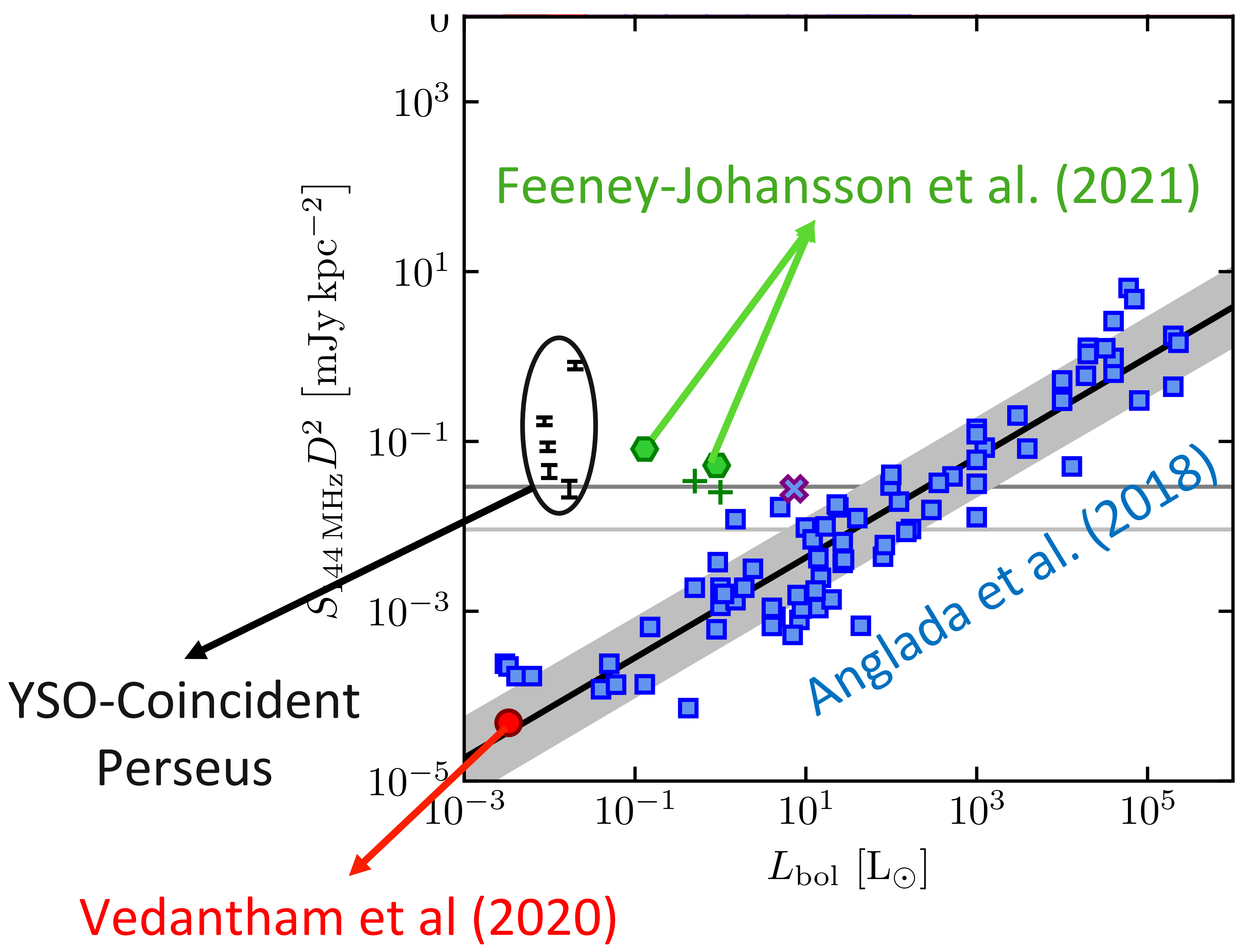
- Over cloud lifetime of 10 MYr, SF rate of 5×10^{-5} Msol / yr -> **$U_e < 2x10^{-2}$ eV cm^{-3}** (same as Galactic CR energy density)

$$E_{\min} = c_{13}\left(\nu_1, \nu_2, \alpha\right)\left(fr^3\right)^{\frac{3}{7}}\left(\left(1+k\right)L_\nu\right)^{\frac{4}{7}}$$

Pachoczyk (1970)

YSO emission

Nature of the Emission



- Just consider the sources coincident with the YSO sample of Evans et al. (2009)
- Are they Jets? No! (Apart from T Tau, Coughlan et al. 2017)
- Are they Star-Planet Interactions? Going off Vedantham et al. (2020), no (but that's one object)
- ECM emission? Maybe! Going from Feeney-Johansson et al. (2021) and emission properties for co-rotation breakdown

Conclusions

Conclusions

- Detection of radio emission coincident with 5 of 385 Perseus YSOs, 29 of 411 Taurus YSOs, with 1±2 expected extragalactic contaminant sources
- Detection of 'YSO-associated' non-thermal emission with 14 of 385 Perseus YSOs, 7 of 411 Taurus YSOs, with 18±9 expected extragalactic sources
- YSO-coincident radio emission inconsistent with jets, ECM emission (exoplanets) and shocks
- YSO radio emission consistent with plasma emission from 'coronae' and exoflares, however low-polarisation is a potential issue
- Upper-limit on low-energy CR contribution for YSO jets of $< 2\times10^{-2}$ eV cm^{-3} based on lack of shocked emission, same as Galactic LE CR rate. Need more TMC analysis to constrain further!