Observing Young Stellar Objects at 150 MHz with LOFAR

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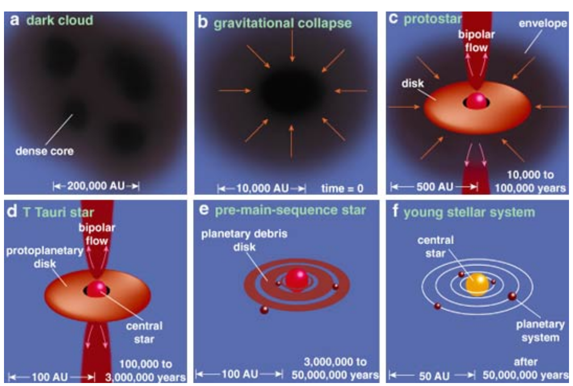
YSOs at Radio Frequencies

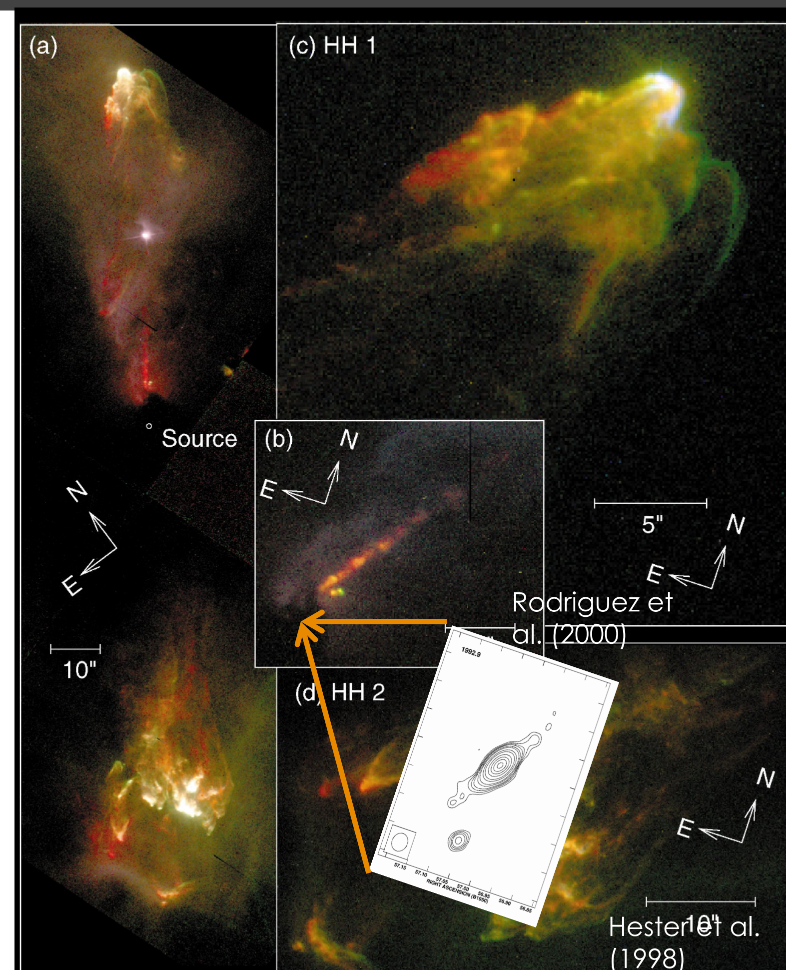
Jets from protostars impacting into the surrounding medium produce Herbig-Haro objects in the optical

Radio companions to these outflows can be detected

Emission mechanism: Free-free emission



Spitzer Science Centre



Rodriguez et al. (2000)

Hester et al. (1998)

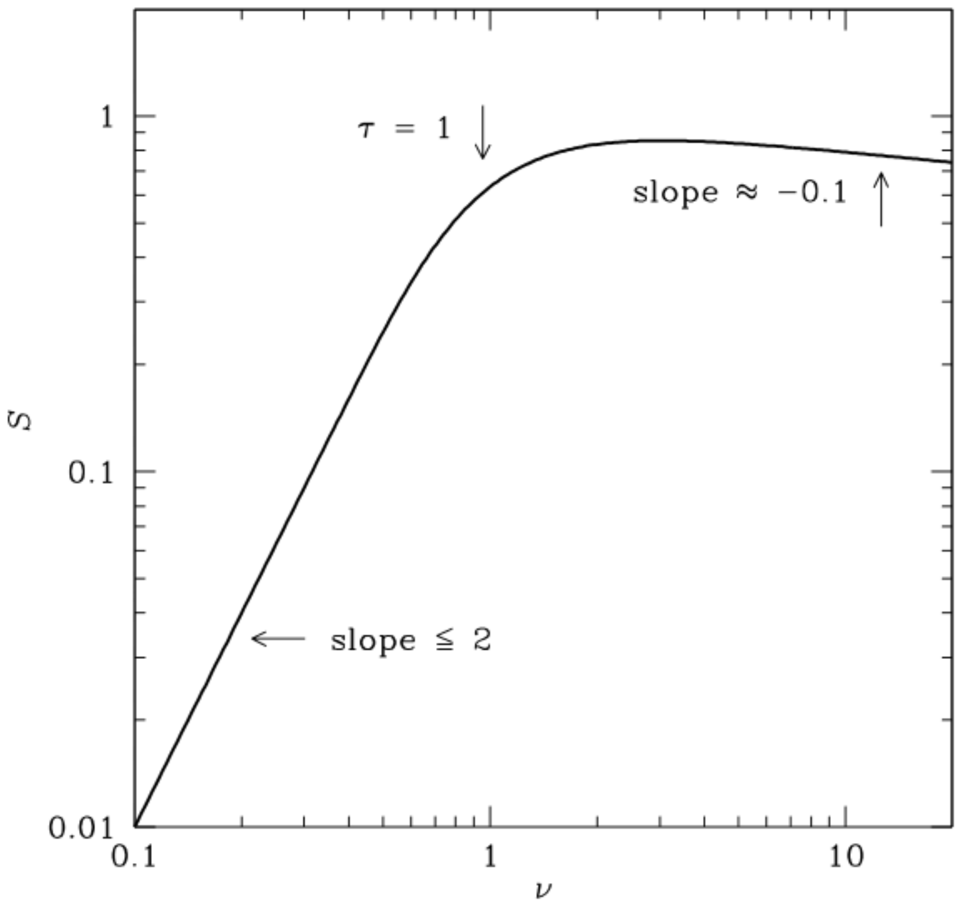
YSO spectral energy distribution

Free-free emission detected from the jets of YSOs at low frequencies

Detection of the turnover frequency would allow important system parameters to be constrained:

- Ionised mass
- Electron density
- Emission measure

Need to study YSOs at low frequencies



GMRT observations

Giant Metrewave Radio Telescope, Pune, India

3 target YSOs: T Tau, DG Tau, L1551 IRS 5

30 45m dishes

Observations at 325 and 610 MHz

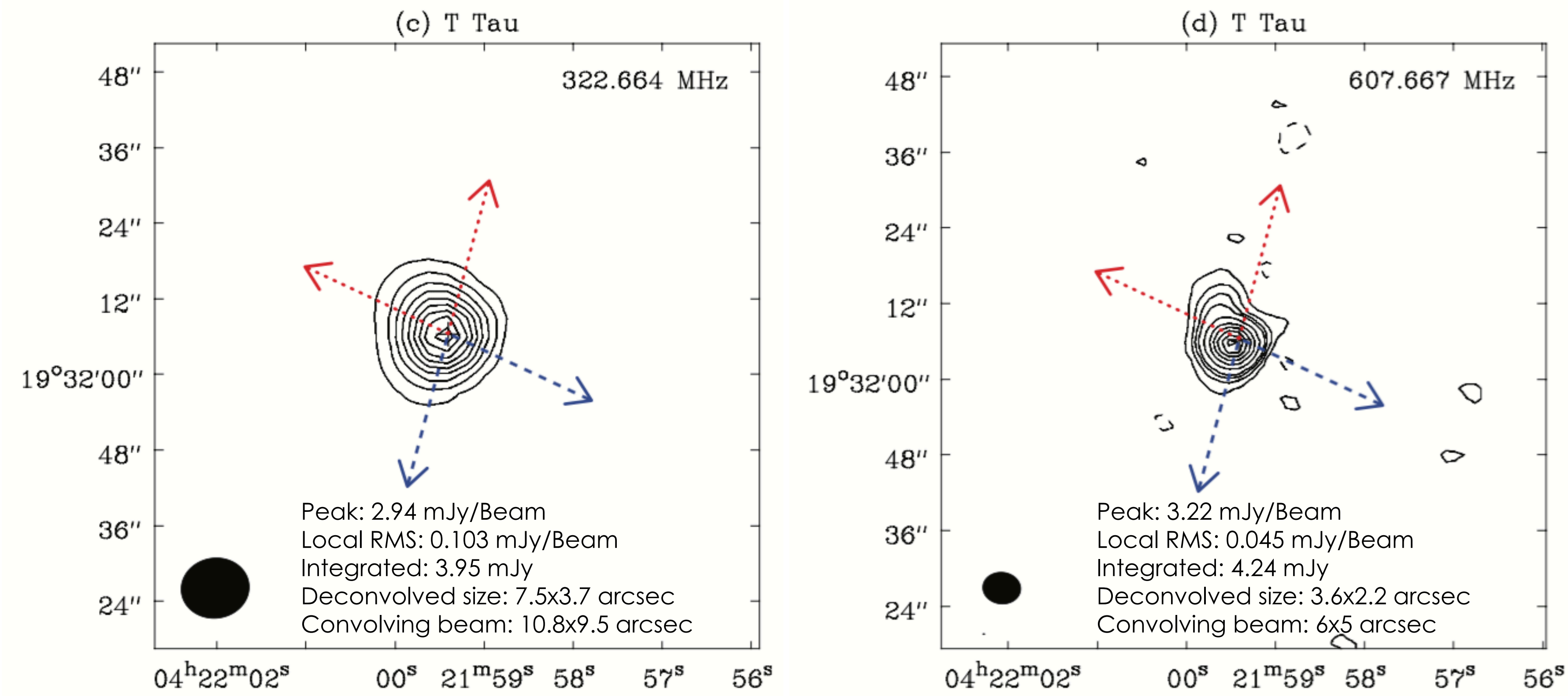
Resolution ~ 5-6 arcsec at 610 MHz

Ainsworth et al. (2016)

Source	Class	J2000.0 Coordinates α ($^{h\ m\ s}$)	δ (° ′ ″)	ν (MHz)	λ (cm)	Obs. time (hrs.)	FWHM, PA (″×″, °)	σ_{rms} (μJy beam^{-1})
L1551 IRS 5	I	04 31 34.1	+18 08 04.8	325	90	6.0	11.4 × 9.5, −88.5	151
				610	50	2.2	6.2 × 4.9, 76.5	49
T Tau	II	04 21 59.4	+19 32 06.4	325	90	3.3	10.8 × 9.5, −81.6	103
				610	50	2.2	6.0 × 5.0, 83.8	45
DG Tau	II	04 27 04.7	+26 06 16.3	325	90	6.0	11.6 × 9.2, 79.6	127
				610	50	2.2	6.5 × 5.2, 74.0	80

T Tau at 323 and 608 MHz

Ainsworth et al. (2016)



Spectral Energy Distribution

GMRT data combined with data from literature

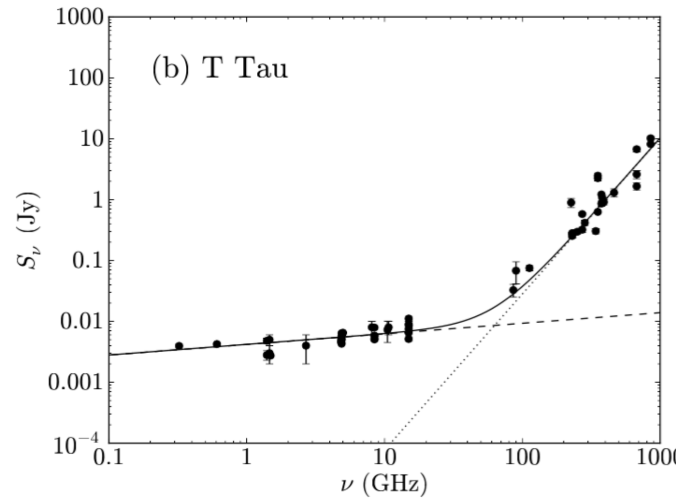
SED traces both the disk and outflow

- Disk at high frequency
- YSO jet at low frequency

SED fitted with two power laws using a joint likelihood Markov Chain Monte Carlo method

$$\left(\frac{S_\nu}{\text{mJy}}\right) = K_{323\,\text{MHz}}\left(\frac{\nu}{323\,\text{MHz}}\right)^{\alpha} + K_{100\,\text{GHz}}\left(\frac{\nu}{100\,\text{GHz}}\right)^{\alpha'}$$

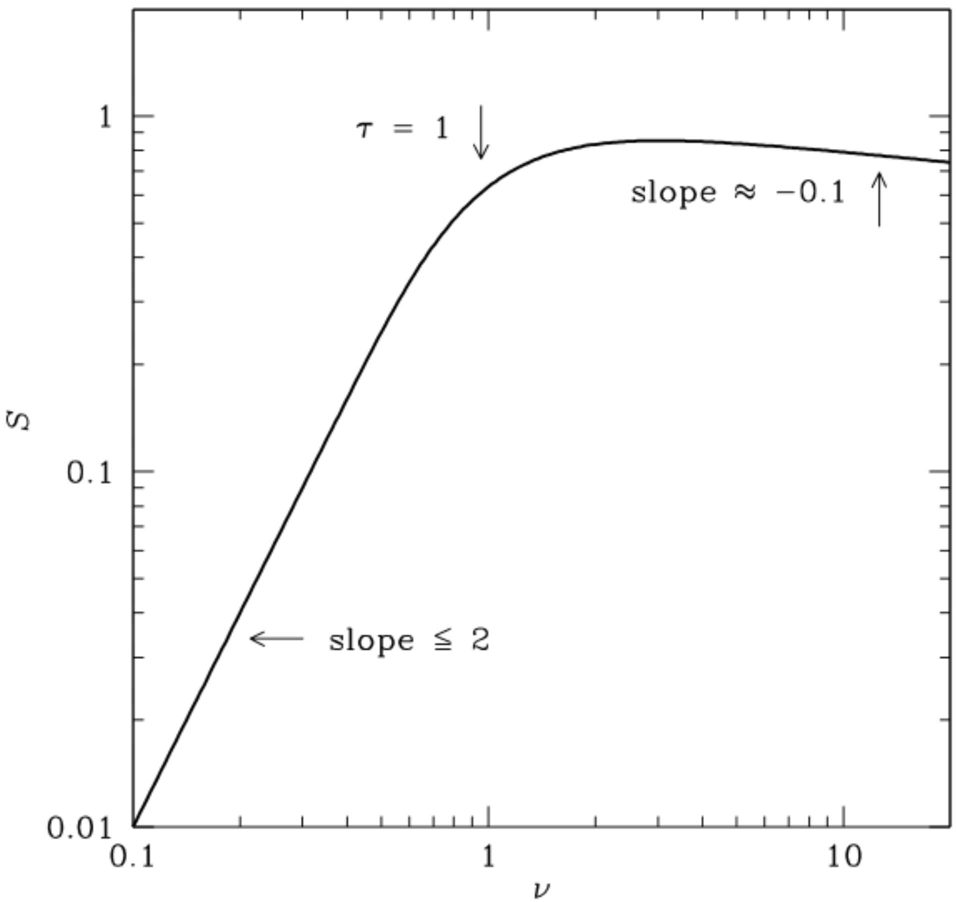
Source	$K_{323\,\text{MHz}}$ (mJy)	α	$K_{100\,\text{GHz}}$ (mJy)	β
L1551 IRS 5	1.61 ± 0.10	0.23 ± 0.02	120.58 ± 3.63	1.31 ± 0.05
T Tau	3.43 ± 0.08	0.17 ± 0.01	28.16 ± 1.15	0.56 ± 0.03
DG Tau	0.55 ± 0.05	0.20 ± 0.03	34.54 ± 1.08	0.55 ± 0.03



Ainsworth et al. (2016)

Free-free spectrum still has not turned over

Modeling YSO free-free emission



$$\left(\frac{n_e}{\mathrm{cm^{-3}}}\right) = 7.2\times10^3 \left(\frac{T_e}{10^4\,\mathrm{K}}\right)^{0.175} \left(\frac{\nu}{\mathrm{GHz}}\right)^{0.05} \left(\frac{S_\nu}{\mathrm{mJy}}\right)^{0.5} \times \left(\frac{D}{\mathrm{kpc}}\right)^{-0.5} \left(\frac{\theta}{\mathrm{arcsec}}\right)^{-1.5}.$$

$$\left(\frac{M_{\mathrm{ion}}}{\mathrm{M_\odot}}\right) = 3.4\times10^{-5} \left(\frac{T_e}{10^4\,\mathrm{K}}\right)^{0.175} \left(\frac{\nu}{\mathrm{GHz}}\right)^{0.05} \left(\frac{S_\nu}{\mathrm{mJy}}\right)^{0.5} \times \left(\frac{D}{\mathrm{kpc}}\right)^{2.5} \left(\frac{\theta}{\mathrm{arcsec}}\right)^{1.5}.$$

$$\left(\frac{EM}{\mathrm{pc\,cm^{-6}}}\right) = 7.1\times10^{-3} \left(\frac{D}{\mathrm{kpc}}\right) \left(\frac{\theta}{\mathrm{arcsec}}\right) \left(\frac{n_e}{\mathrm{cm^{-3}}}\right)^2.$$

Mezger & Henderson

Modeling YSO free-free emission

Model parameters derived using fit to SED

SED still optically thin

- Derived parameters not necessarily well-constrained

Can estimate the turnover frequency:

$$\tau_\nu = 8.235 \times 10^{-2} \left(\frac{T_e}{K}\right)^{-1.35} \left(\frac{\nu}{GHz}\right)^{-2.1} \left(\frac{EM}{pc\,cm^{-6}}\right)$$

Ainsworth et al. (2016)

Source	$K_{323\,MHz}$ (mJy)	α	$K_{100\,GHz}$ (mJy)	β	θ ($''$)	n_e (cm^{-3})	M_{ion} ($M_\odot$)	EM ($pc\,cm^{-6}$)	ν_0 (MHz)
L1551 IRS 5	1.61 ± 0.10	0.23 ± 0.02	120.58 ± 3.63	1.31 ± 0.05	4.8	2.2×10^3	3.1×10^{-6}	2.3×10^4	105
T Tau	3.43 ± 0.08	0.17 ± 0.01	28.16 ± 1.15	0.56 ± 0.03	2.9	6.8×10^3	2.2×10^{-6}	1.3×10^5	226
DG Tau	0.55 ± 0.05	0.20 ± 0.03	34.54 ± 1.08	0.55 ± 0.03	5.3	1.1×10^3	2.1×10^{-6}	6.4×10^3	59

LOFAR Observations

Data from LOFAR cycle one (November 2013)

8 hours of high band observations

3C147 as flux calibrator ("bookend")

Averaged to 5 sec, 4 ch per SB.

Reduced core and remote data on local (DIAS and ICHEC) resources

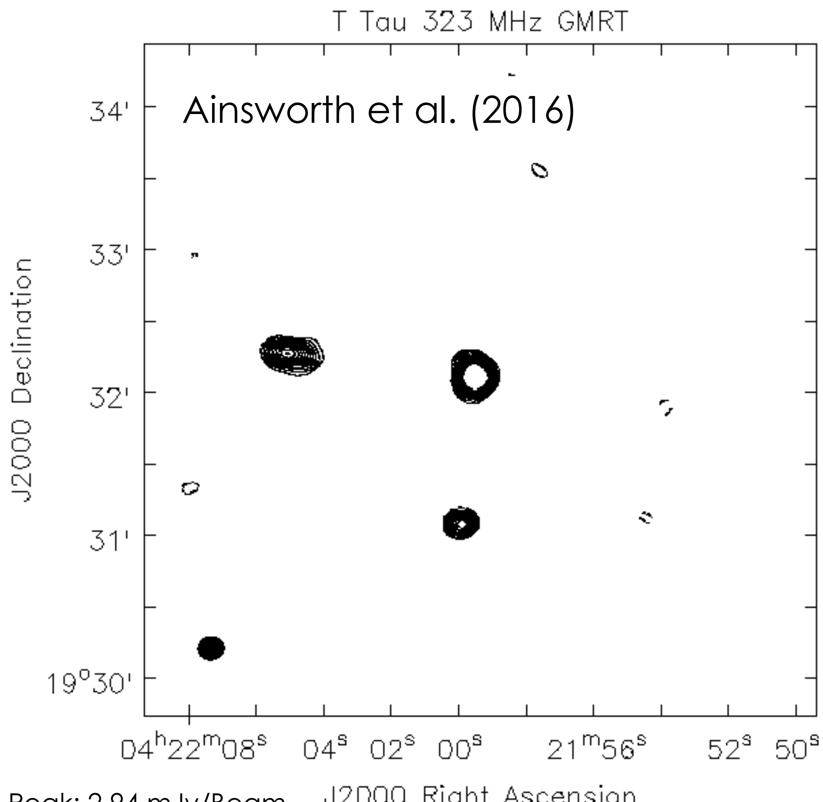
T Tau LOFAR reduction strategy

250 subbands centred on 149 MHz ~ 2 TB

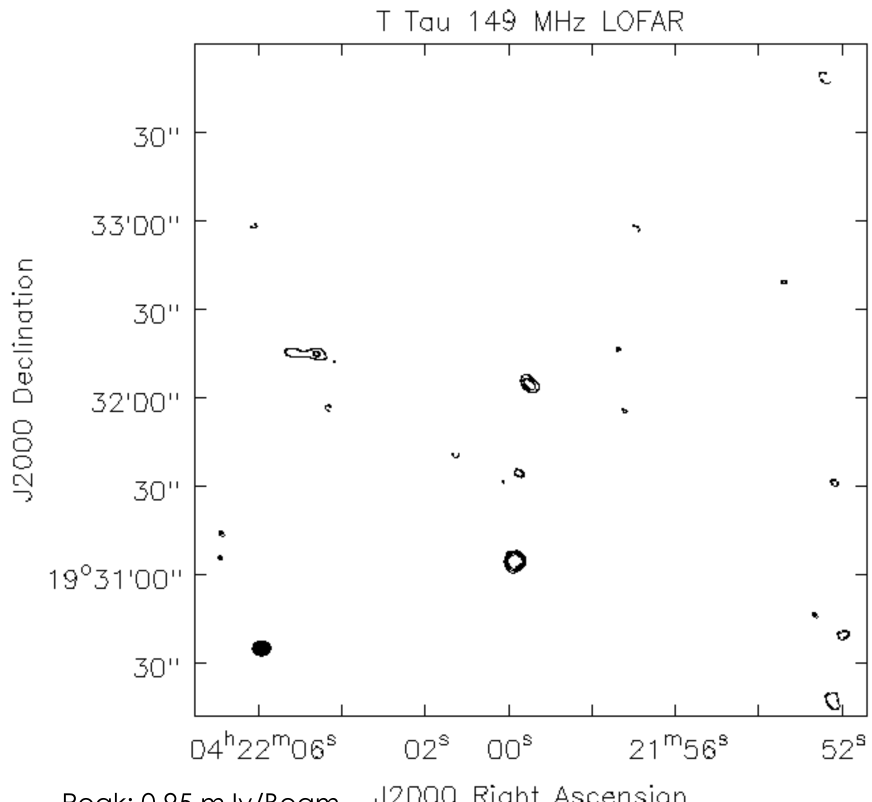
- Pre-facet calibration (prefactor)
    - Flux calibration (ignoring core-core baselines)
    - Clock – TEC separation
    - Phase calibration with initial GSM
- Phase only direction-independent self-calibration
    - Image 5 10SB (2 MHz) chunks at regular intervals
    - Build multi-frequency model of the sky
    - Apply direction independent phase calibration
- SAGECal source subtraction
    - Bright sources subtracted using SAGECal (robust mode)

Wide-band, wide-field imaging in CASA

T Tau at 149 MHz



Peak: 2.94 mJy/Beam
Local RMS: 0.103 mJy/Beam
Integrated: 3.95 mJy
Deconvolved size: 7.5x3.7 arcsec
Convolving beam: 10.8x9.5 arcsec



Peak: 0.95 mJy/Beam
Local RMS: 0.2 mJy/Beam
Integrated: 1.9 mJy
Deconvolved size: 8.13x2.15 arcsec
Convolving beam: 6.01x4.90 arcsec

T Tau at 149 MHz

4.75 sigma detection

Partially resolved – seems to agree with 608 MHz GMRT extension

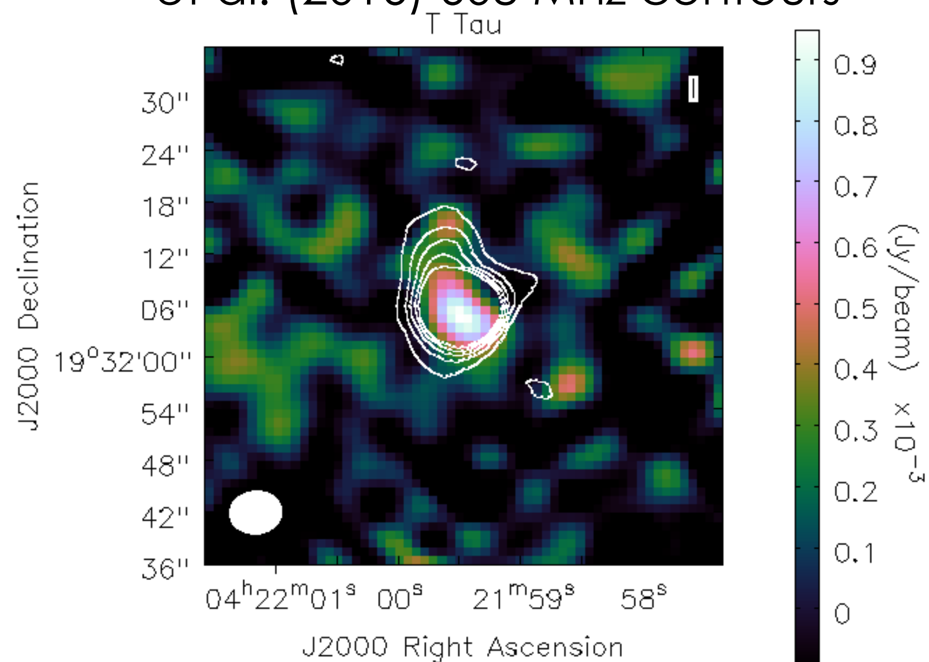
Need good estimates of systematic error in flux scale due to beam effects

Compared first and last 3C147 scans to estimate errors: ~ 12% error

Final integrated flux:

1.90 +- 0.47 mJy

LOFAR (colour) with Ainsworth et al. (2016) 608 Mhz contours



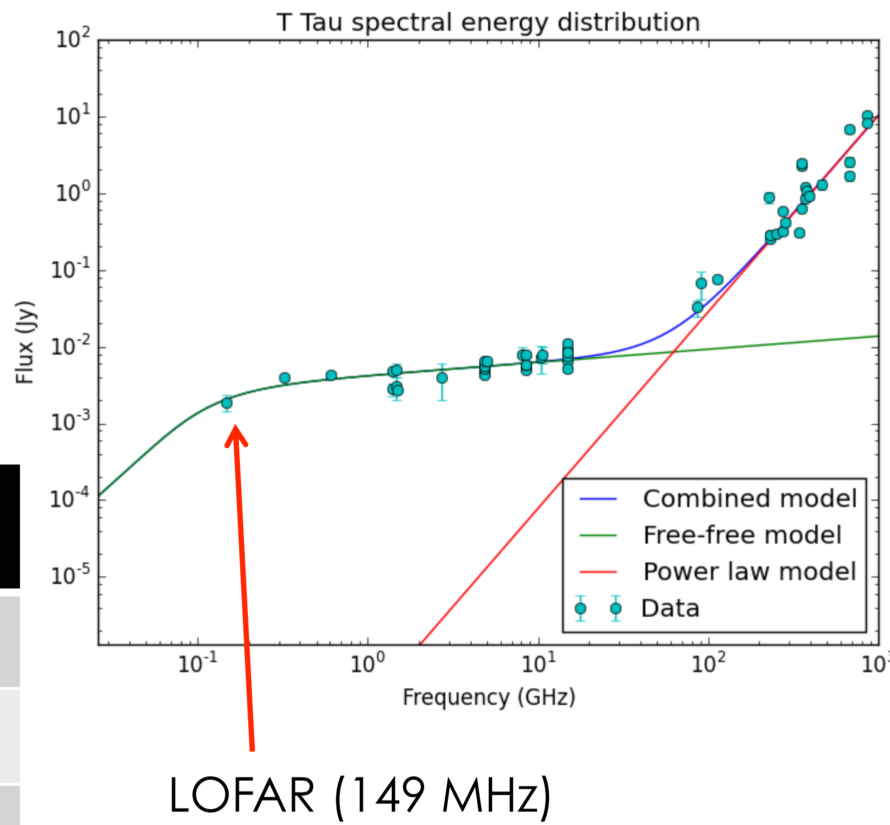
Peak: 0.95 mJy/Beam
Local RMS: 0.2 mJy/Beam
Integrated: 1.9 mJy
Deconvolved size: 8.13x2.15 arcsec
Convolving beam: 6.01x4.90 arcsec

Improved spectral modeling

Turnover in free-free spectrum has been detected

Improved estimates of key YSO parameters

	Ainsworth et al. (2016)	With LOFAR data
Turnover Frequency (MHz)	<323	174
Emission Measure (pc cm^-6)	1.3x10^5	7.8x10^5
Ionised gas mass (solar masses)	2.2x10^-6	3.0x10^-6
Electron density (cm^-3)	6.8x10^3	3.1x10^3



Summary

- Low frequency observations of YSO jets help constrain important jet parameters
- Ideally need to resolve the YSO, as well as estimate its turnover frequency
- LOFAR offers a unique opportunity to do both
- T Tau is the first YSO to be detected with LOFAR
- Low frequency data is improving quality of modeled parameters