Low Mass Young Stars at Metre Wavelengths

Radio Stars from kHz to THz - MIT Haystack Observatory Workshop

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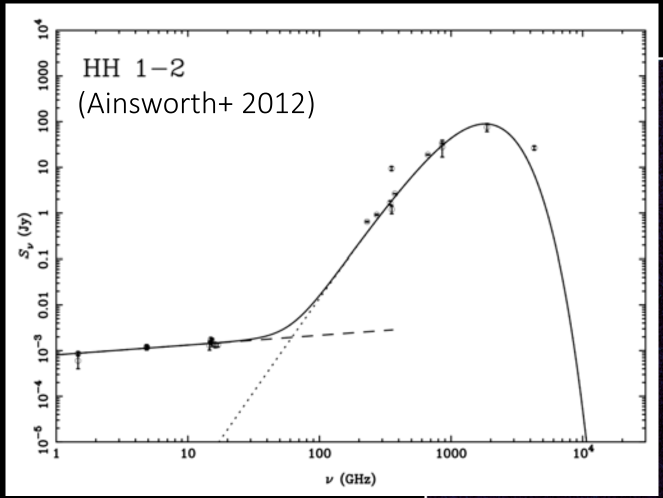
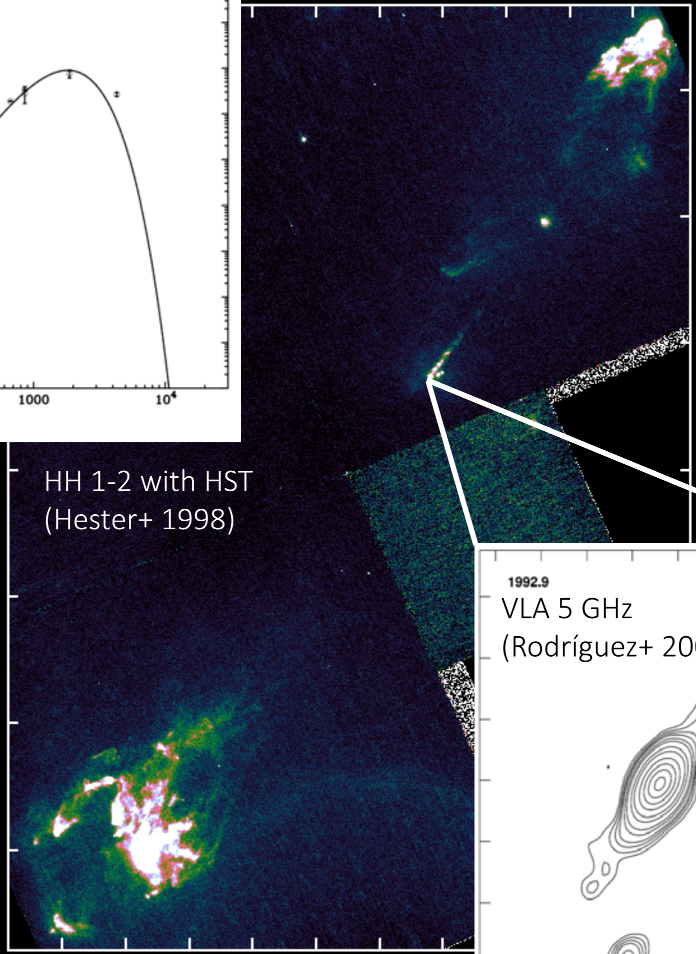
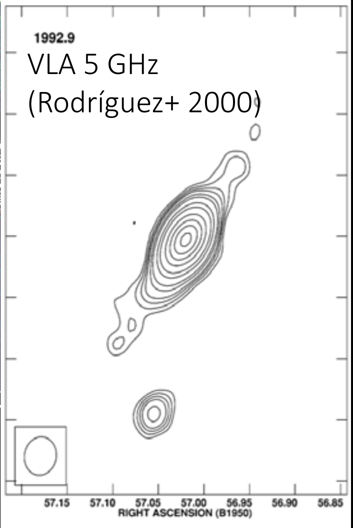
Radio emission from YSOs: free-free

- cm wavelengths
- Class 0-II YSO jets
- Flux density ~ 1 mJy
- Traces outflow
- $S_\nu \propto \nu^\alpha$, where $-0.1 < \alpha < 2$
  - $\alpha = 0.6$ “standard” spherical stellar wind (e.g. Panagia & Felli 1975)
  - $\alpha = 0.25$ “standard” collimated jet (Reynolds 1986)

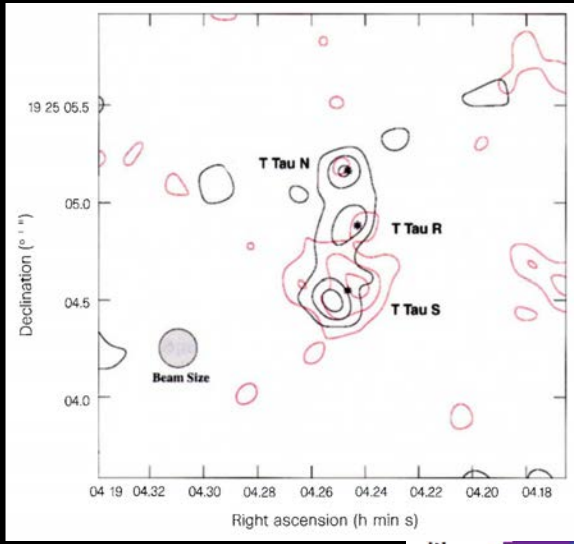


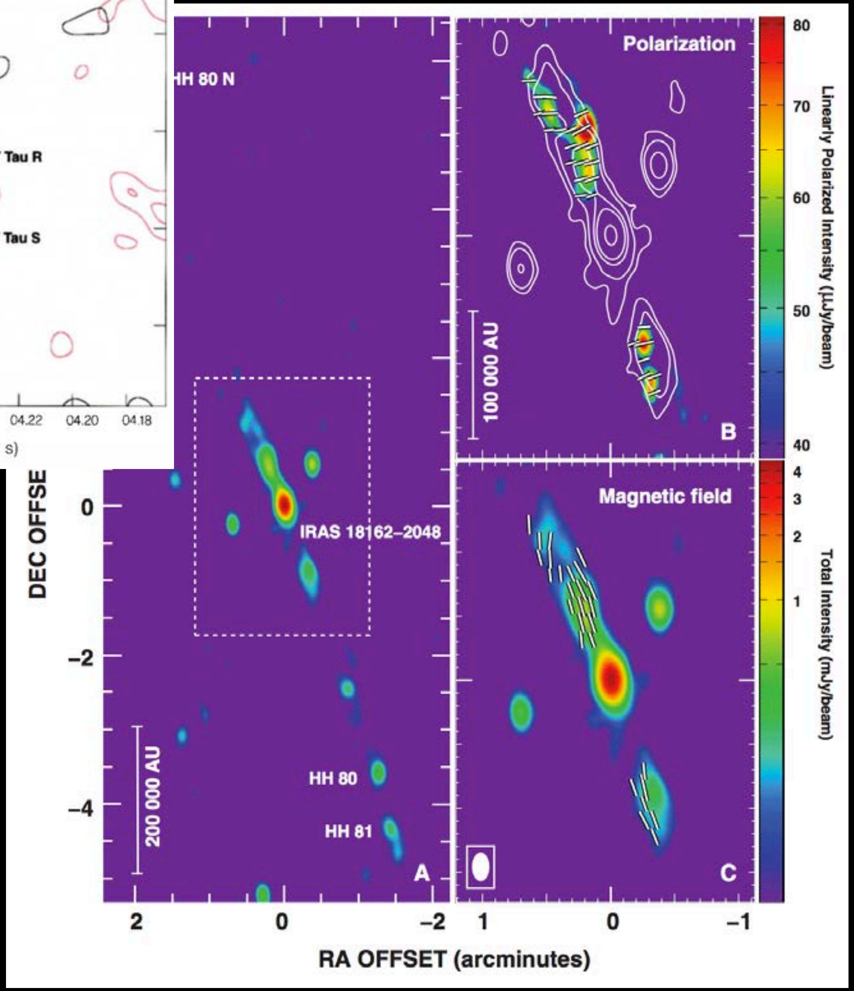




Radio emission from YSOs: non-thermal

- Class II-III coronae
  - e.g. GBS-VLA Dzib+ 2013, 2015
- Gyro-synchrotron from T Tau
  - e.g. Ray+ 1997
- Synchrotron from a <u>high-mass</u> YSO jet (α ~ -0.7)
  - Carrasco-González+ 2010
- VERY FEW <u>low-mass</u> Class 0-II jets have α << -0.1 indicative of non-thermal emission
  - e.g. Curiel+ 1993; Girart+ 2002





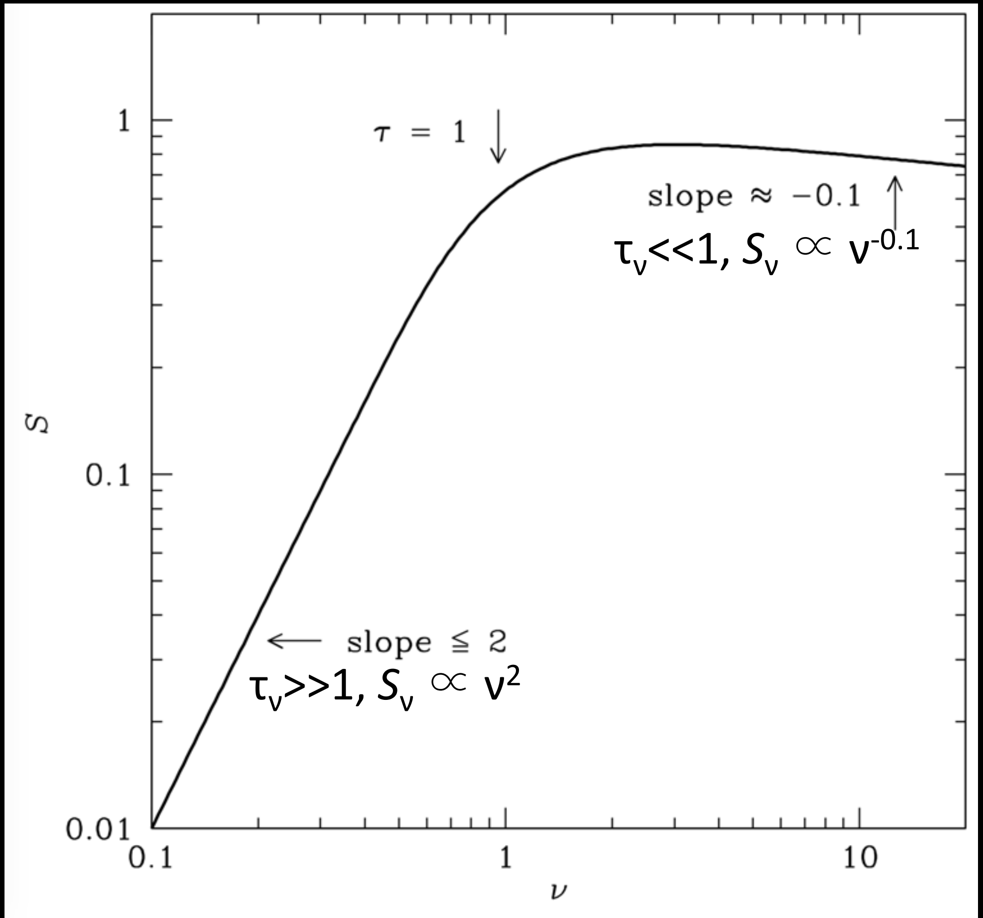
Motivation for metre wavelengths

- New territory!
- Detect optically thick surface
- Detect non-thermal emission

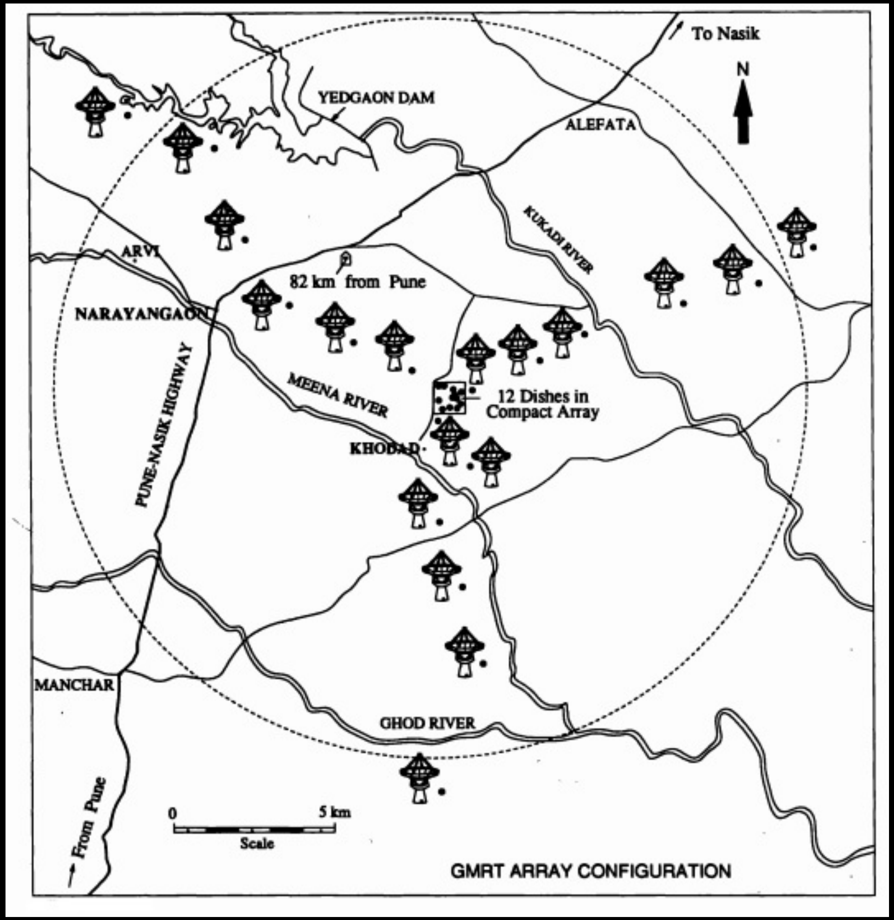
$$\left(\frac{S_\nu}{\mathrm{Jy}}\right) = 3.07 \times 10^4 \left(\frac{T_\mathrm{e}}{\mathrm{K}}\right)\left(\frac{\nu}{\mathrm{GHz}}\right)^2 (1 - e^{-\tau_\nu})\left(\frac{\Omega}{\mathrm{sr}}\right)$$

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

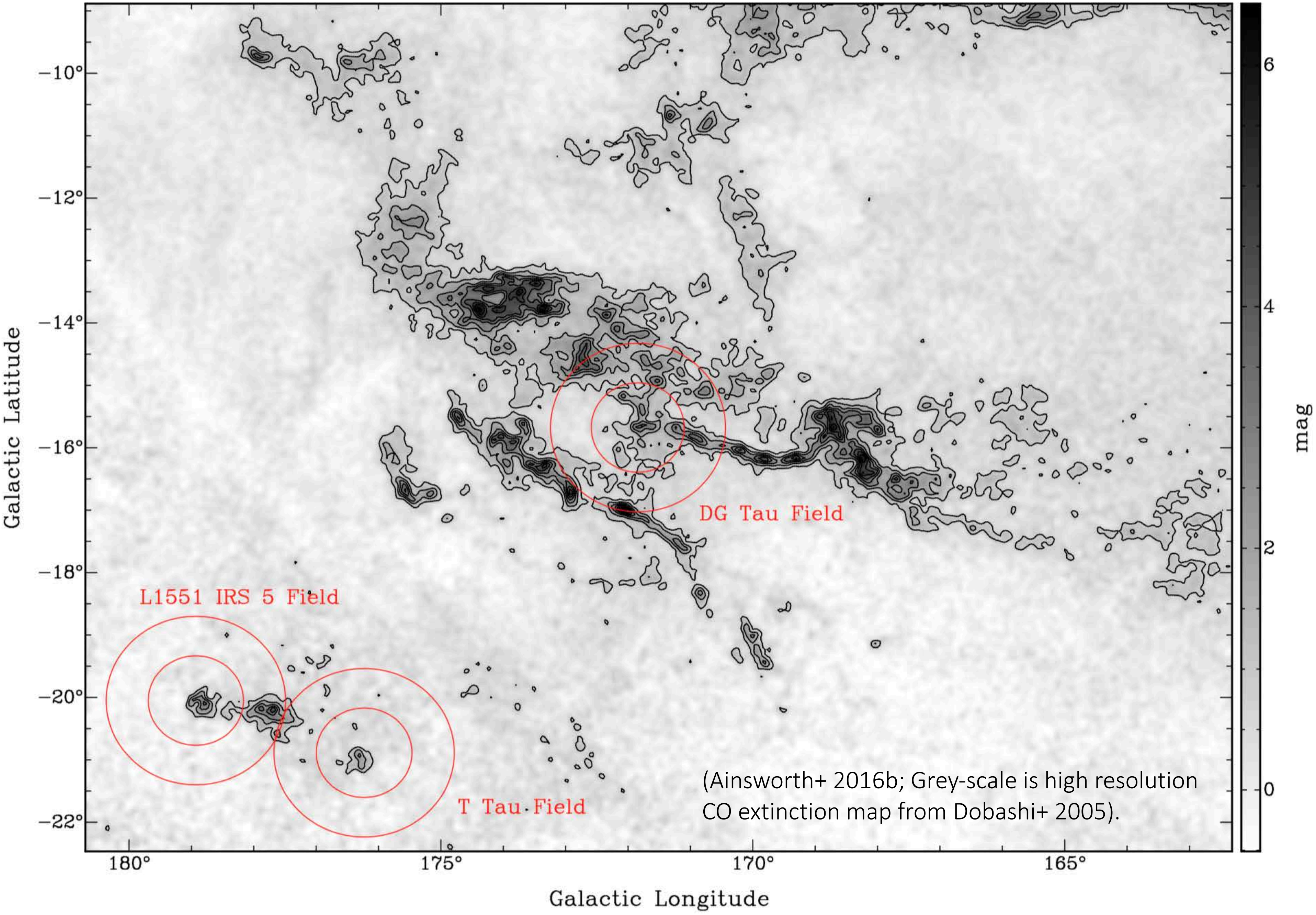
$$\left(\frac{EM}{\mathrm{pc\,cm^{-6}}}\right) = \int_0^{s/\mathrm{pc}} \left(\frac{n_\mathrm{e}}{\mathrm{cm^{-3}}}\right)^2 d\left(\frac{s}{\mathrm{pc}}\right)$$



Giant Metrewave Radio Telescope (GMRT)

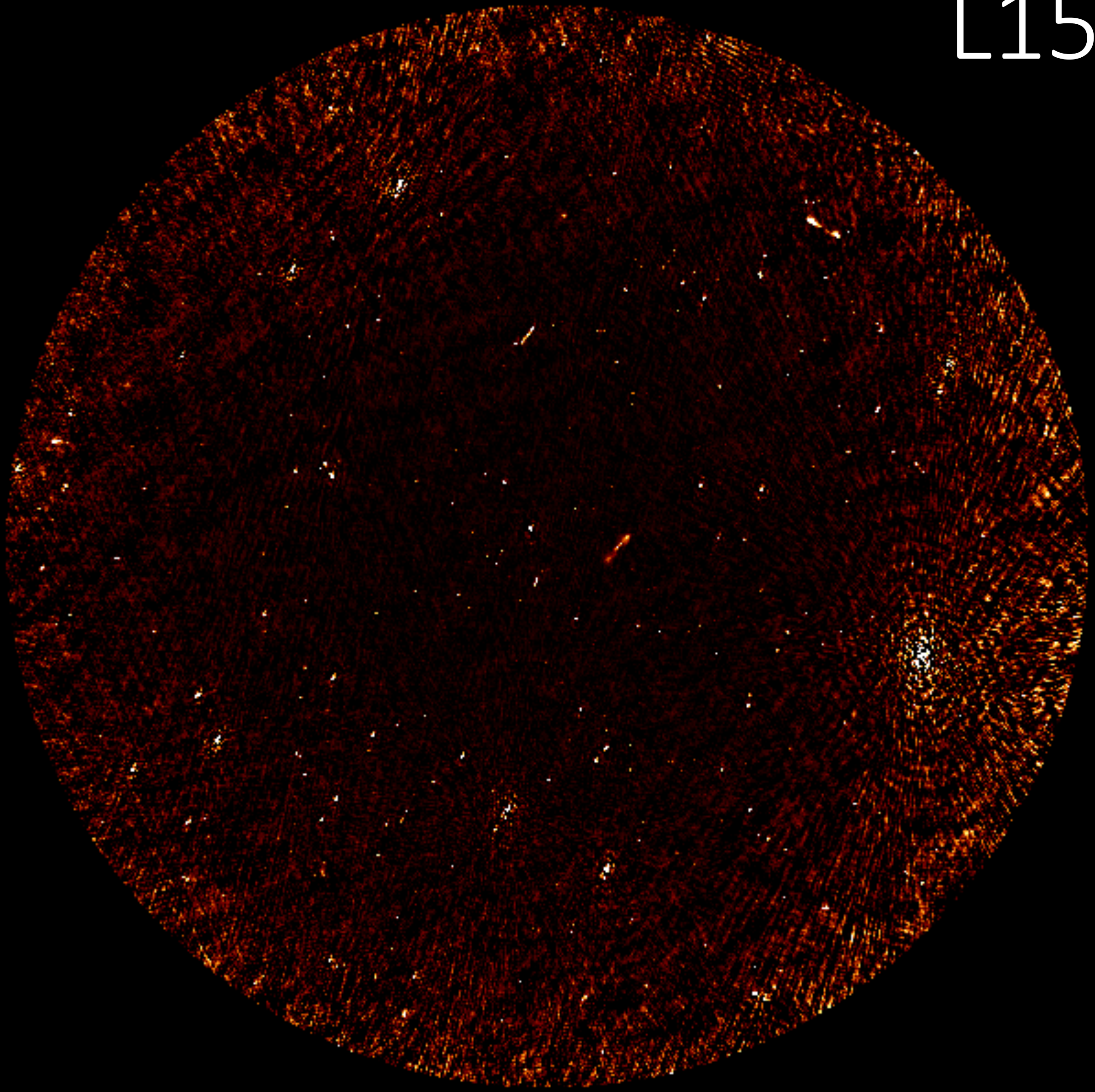


- 30, 45 m dishes
- 610 MHz (50 cm)
  - Resolution ~ 5’’
  - FoV ~ 43’
- 325 MHz (90 cm)
  - Resolution ~ 9’’
  - FoV ~ 81’
- Target sample: L1551 IRS 5, T Tau & DG Tau
- Epoch: December 2012



(Ainsworth+ 2016b; Grey-scale is high resolution CO extinction map from Dobashi+ 2005).

L1551 field @ 325 MHz



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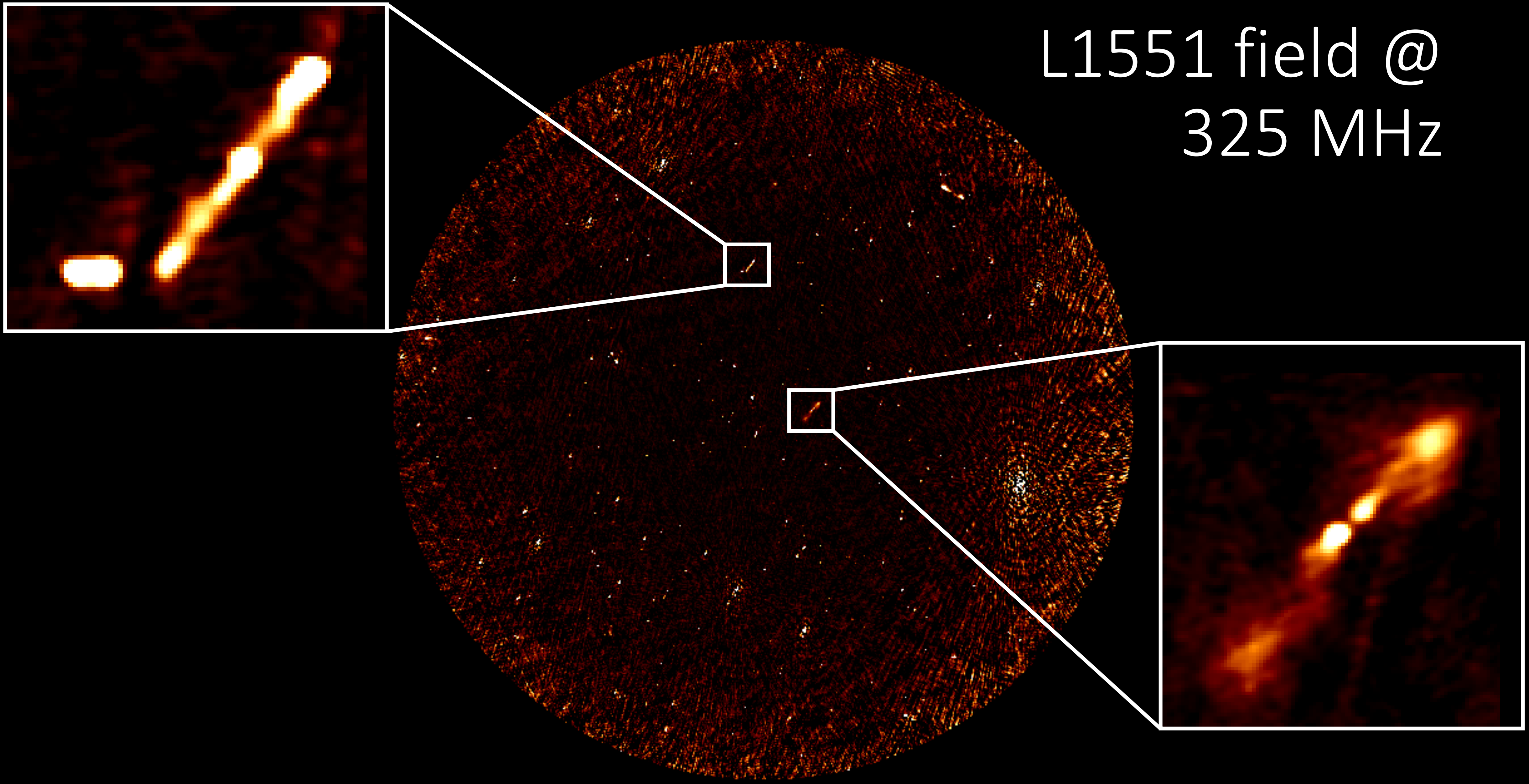
(Ainsworth+ 2016b)



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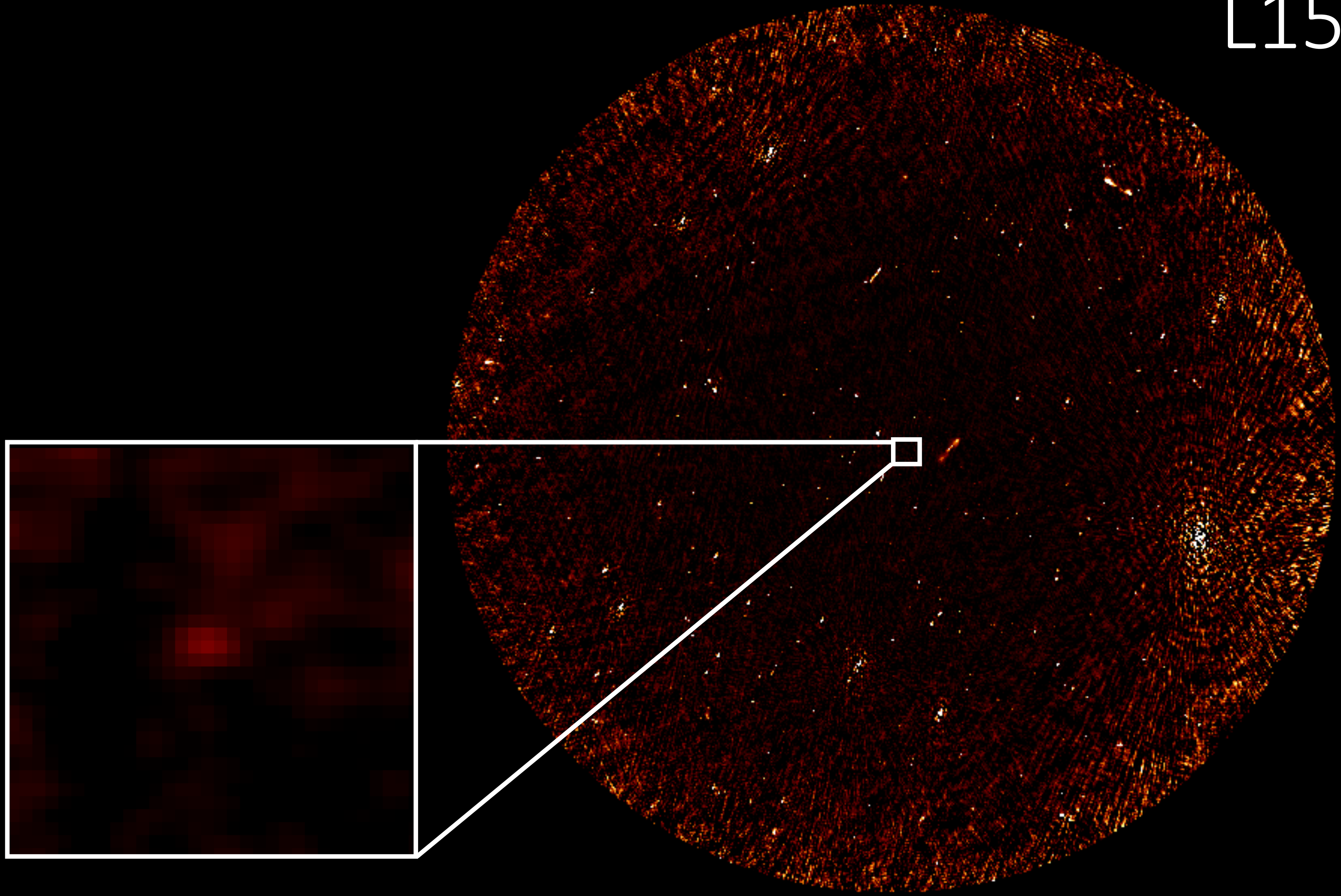
(Ainsworth+ 2016b)

L1551 field @ 325 MHz



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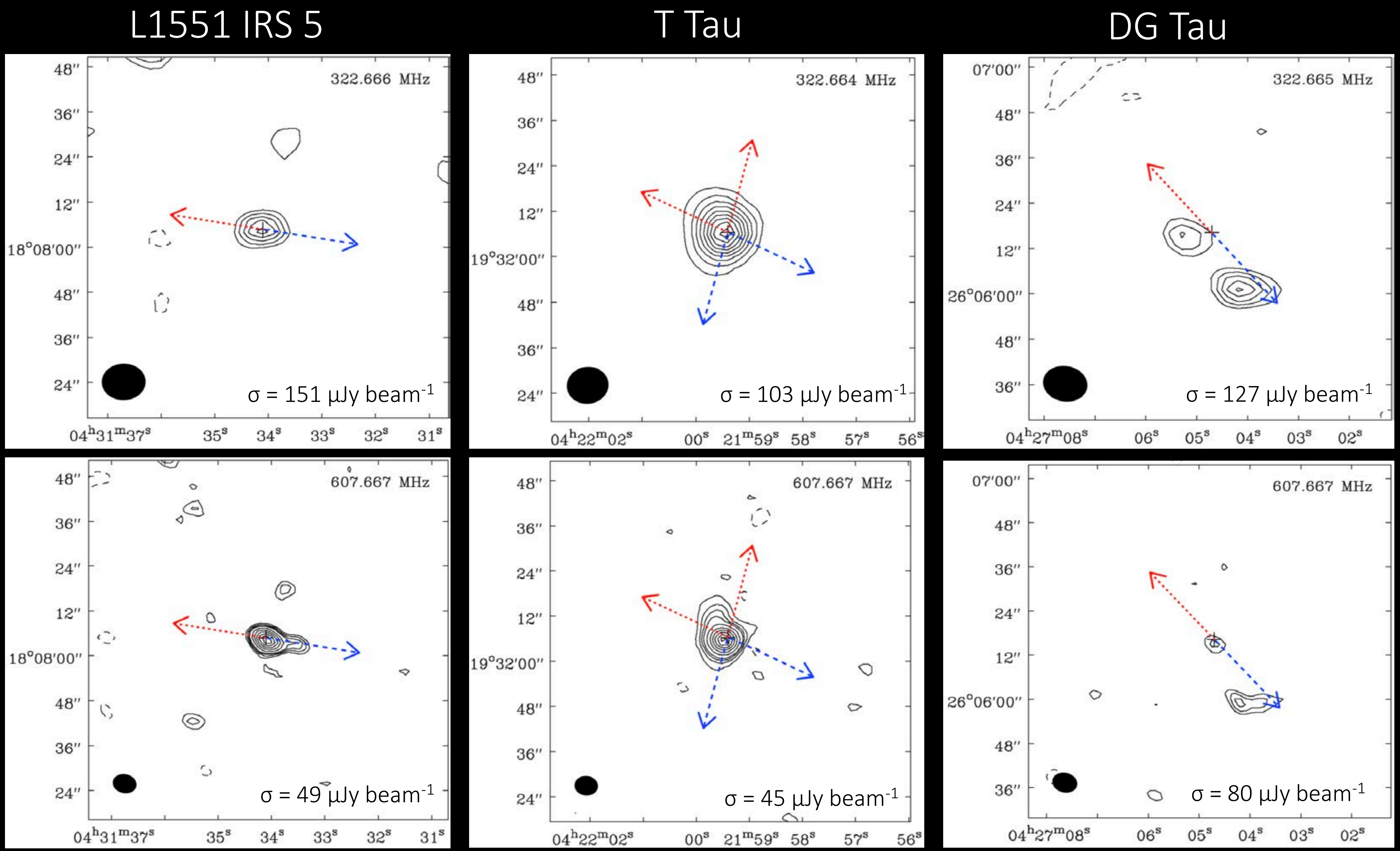
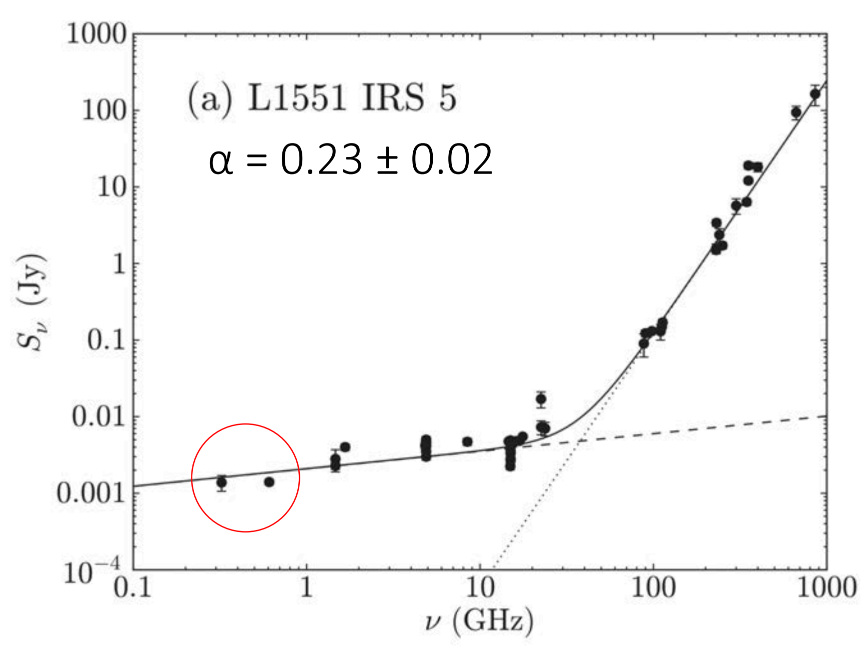
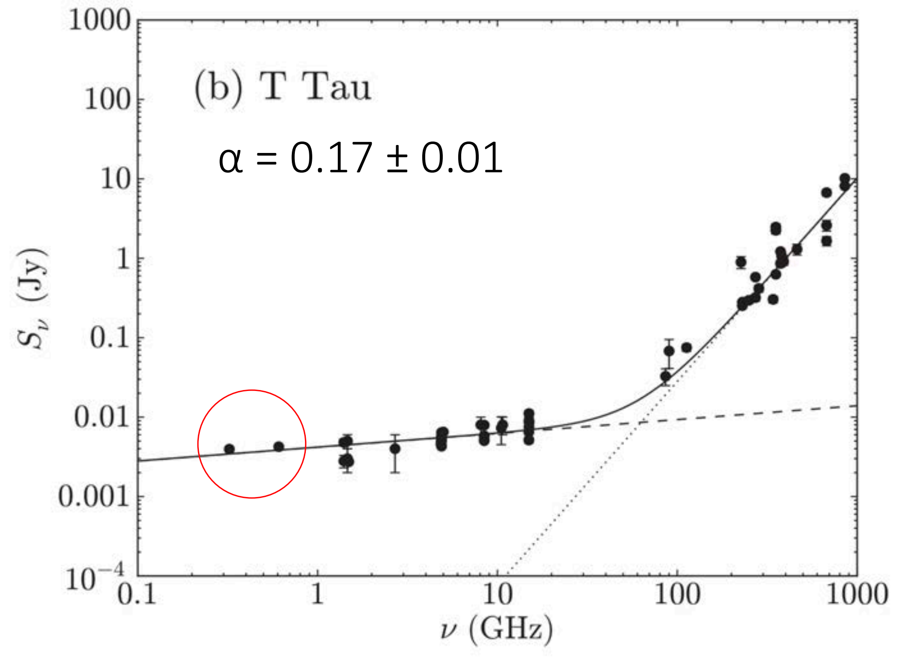
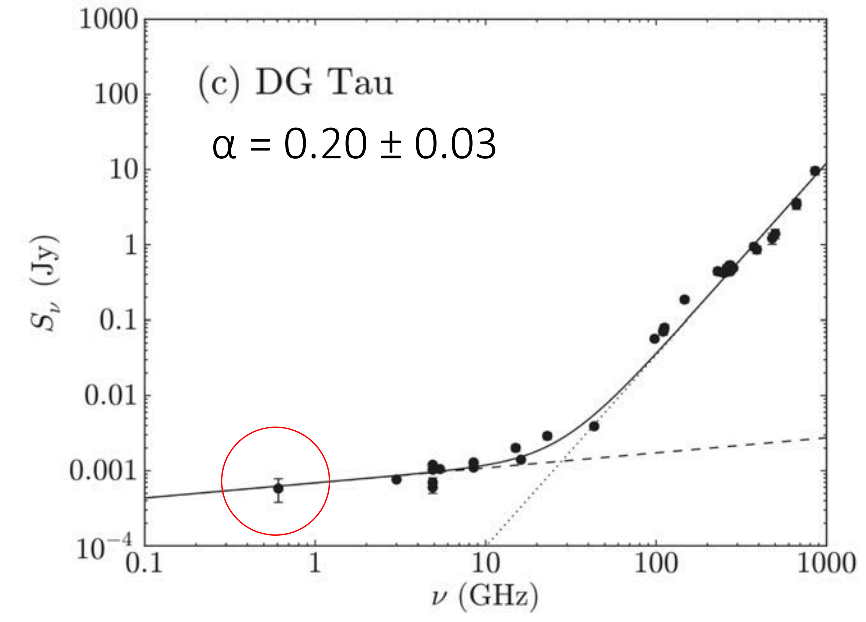
(Ainsworth+ 2016b)



(Ainsworth+ 2016a)







Spectral Energy Distributions

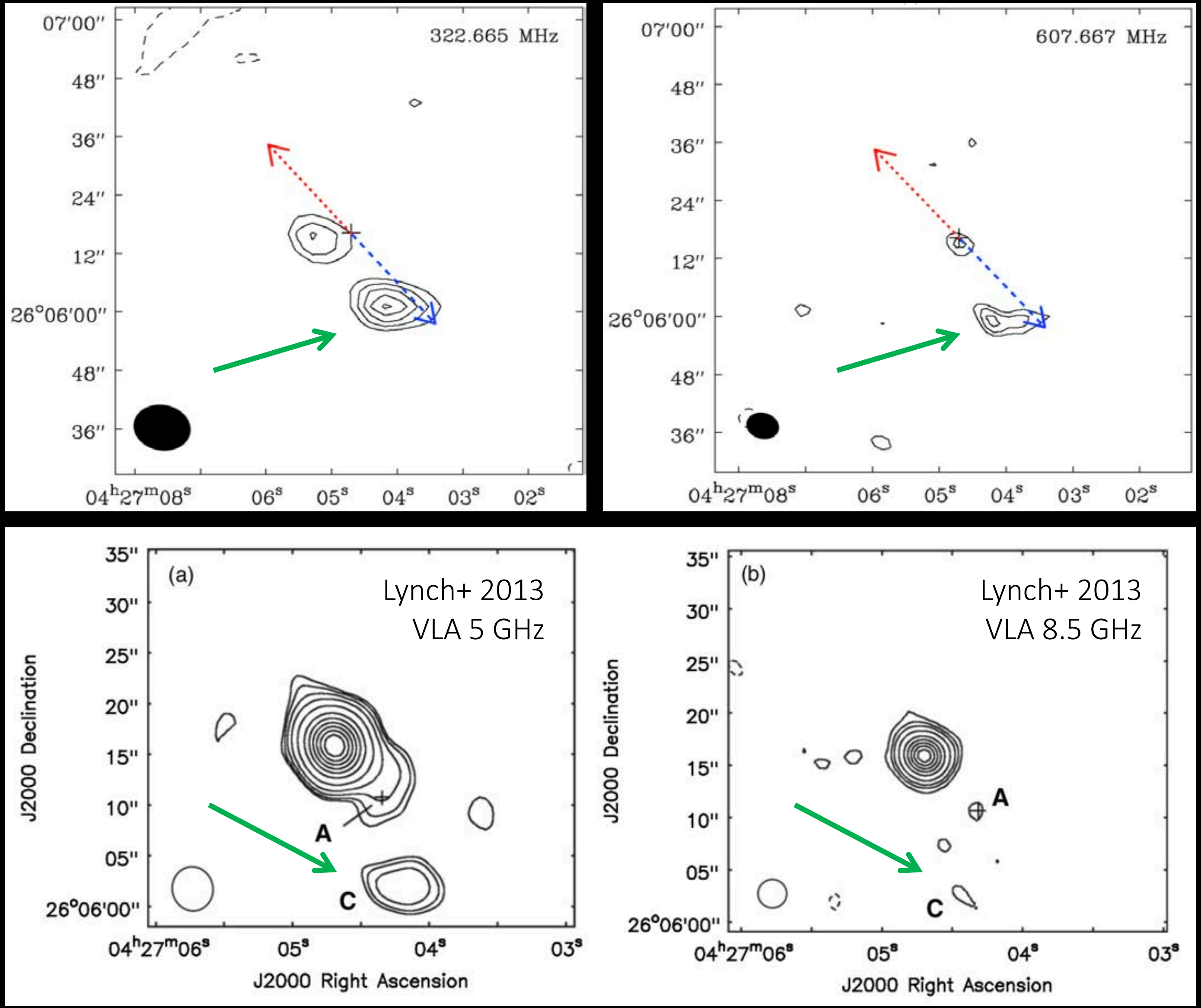
The GMRT measurements at 325 and 610 MHz are consistent with the free-free power-law associated with partially optically thin emission extrapolated from higher frequencies for each target source.

Still haven't detected spectral turnover.

DG Tau is doing something funny.

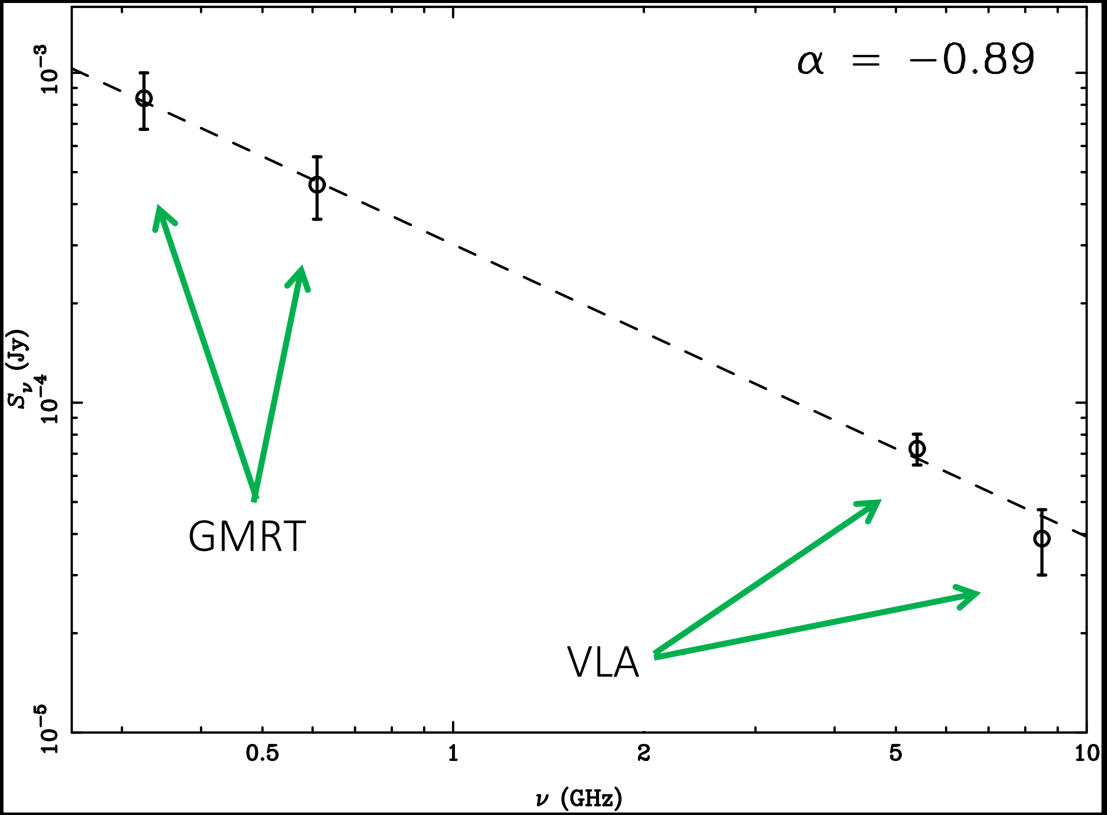
(Ainsworth+ 2016a)

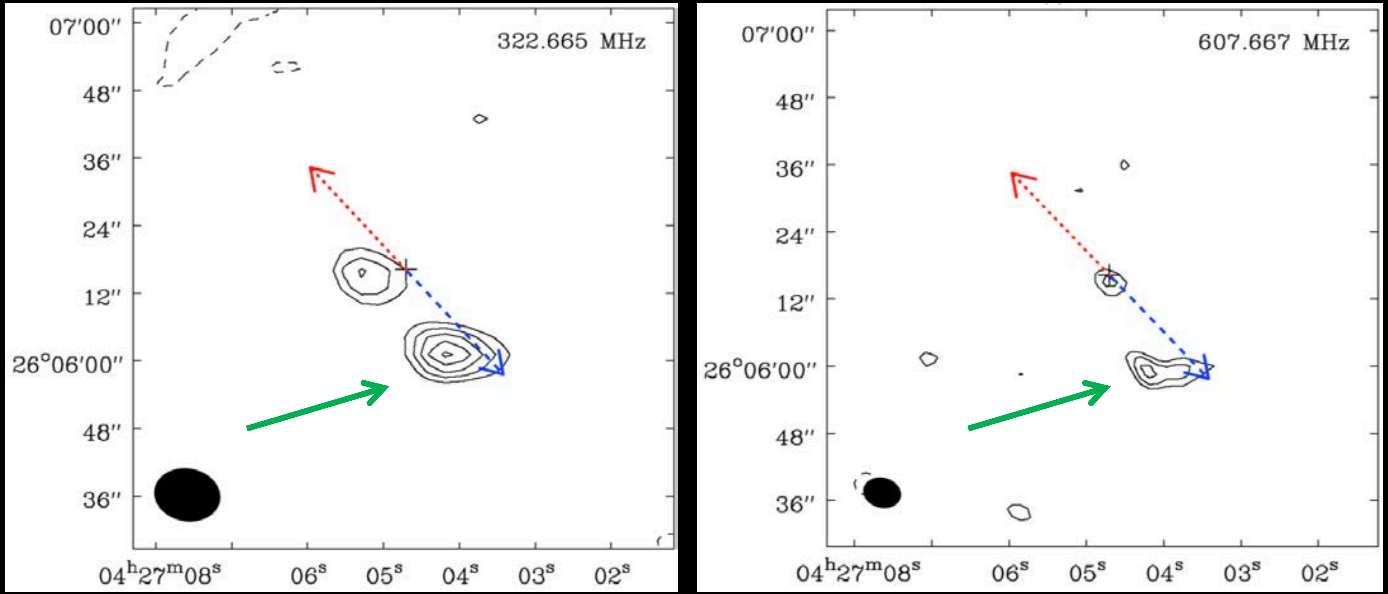
DG Tau

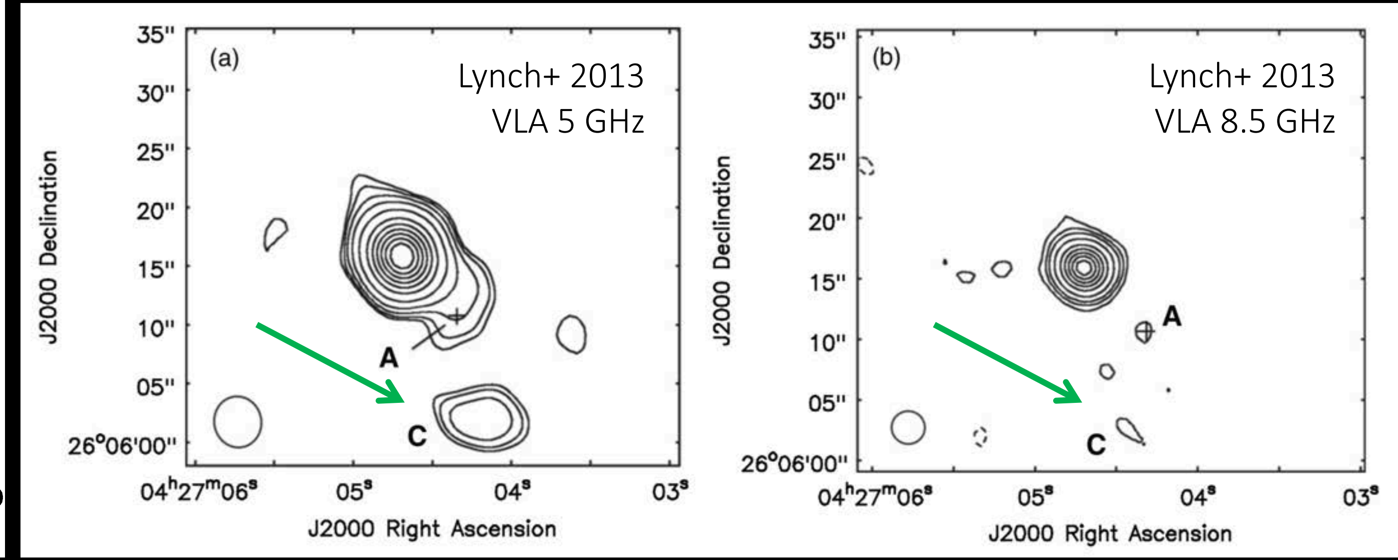


(Ainsworth+ 2014)

DG Tau

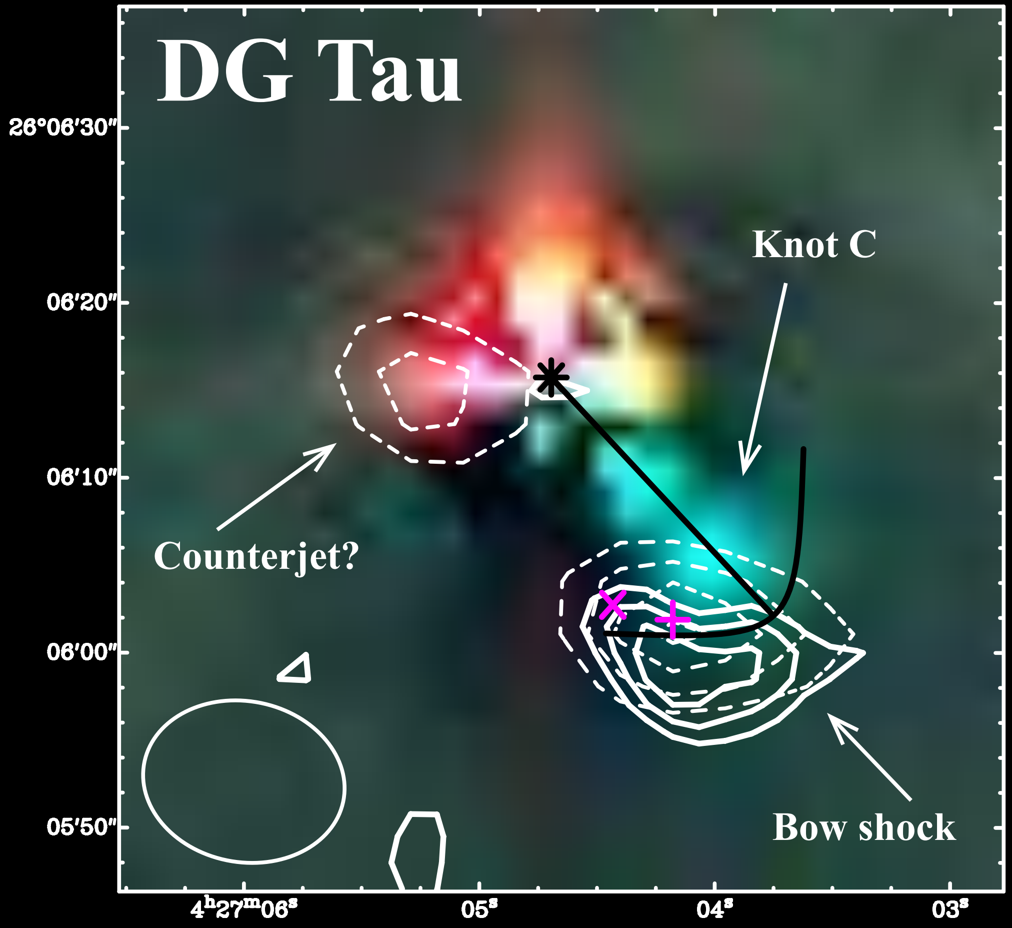






(Ainsworth+ 2014)

DG Tau bowshock



- Dashed contours = 325 MHz with GMRT
- Solid contours = 610 MHz with GMRT
- Black * = optical stellar position
- Optical image: R = I, G = Hα; B = [SII] (TLS Schmidt, B. Stecklum, priv. com.)
- Magenta + = 5 GHz VLA position (Lynch+ 2013)
- Magenta x = 8.5 GHz VLA position **(Lynch+ 2013)**

(Ainsworth+ 2014)

Equipartition magnetic field strength & minimum energy

$$B_{\text{min}} = \left[\frac{3\mu_0}{2}\frac{G(\alpha)(1+k)L_\nu}{Vf}\right]^{2/7}$$
$$\simeq \boxed{0.11\,\text{mG}}$$

$$E_{\text{min}} = \frac{7}{6\mu_0}(Vf)^{3/7}\left[\frac{3\mu_0}{2}G(\alpha)(1+k)L_\nu\right]^{4/7}$$
$$\simeq \boxed{4 \times 10^{40}\,\text{erg}}$$

(Longair 2011)

➔ These values of B_{min} and E_{min} are needed to account for the observed radio luminosity.

➔ Consistent with magnetic field values obtained from Zeeman observations toward star-forming cores (Crutcher 1999).

(Ainsworth+ 2014)

Cosmic rays from the young Sun? (1)

$$\gamma = \left[\left(\frac{h\nu}{m_\mathrm{e}}\right)\left(\frac{B_\mathrm{crit}}{B_\mathrm{min}}\right)\right]^{1/2} \approx 1400$$

$$E_\mathrm{e} = \gamma m_\mathrm{e} \approx 700\,\mathrm{MeV} \sim 1\,\mathrm{GeV}$$

➔ Low energy cosmic ray electrons

$$r_\mathrm{L} = \frac{E_\mathrm{e}}{ecB_\mathrm{min}} \approx 2\times10^{-3}\,\mathrm{au}$$

$$t_\mathrm{acc} = \frac{r_\mathrm{L}}{c\beta_\mathrm{sh}^2} \approx 10-100\,\mathrm{days}$$

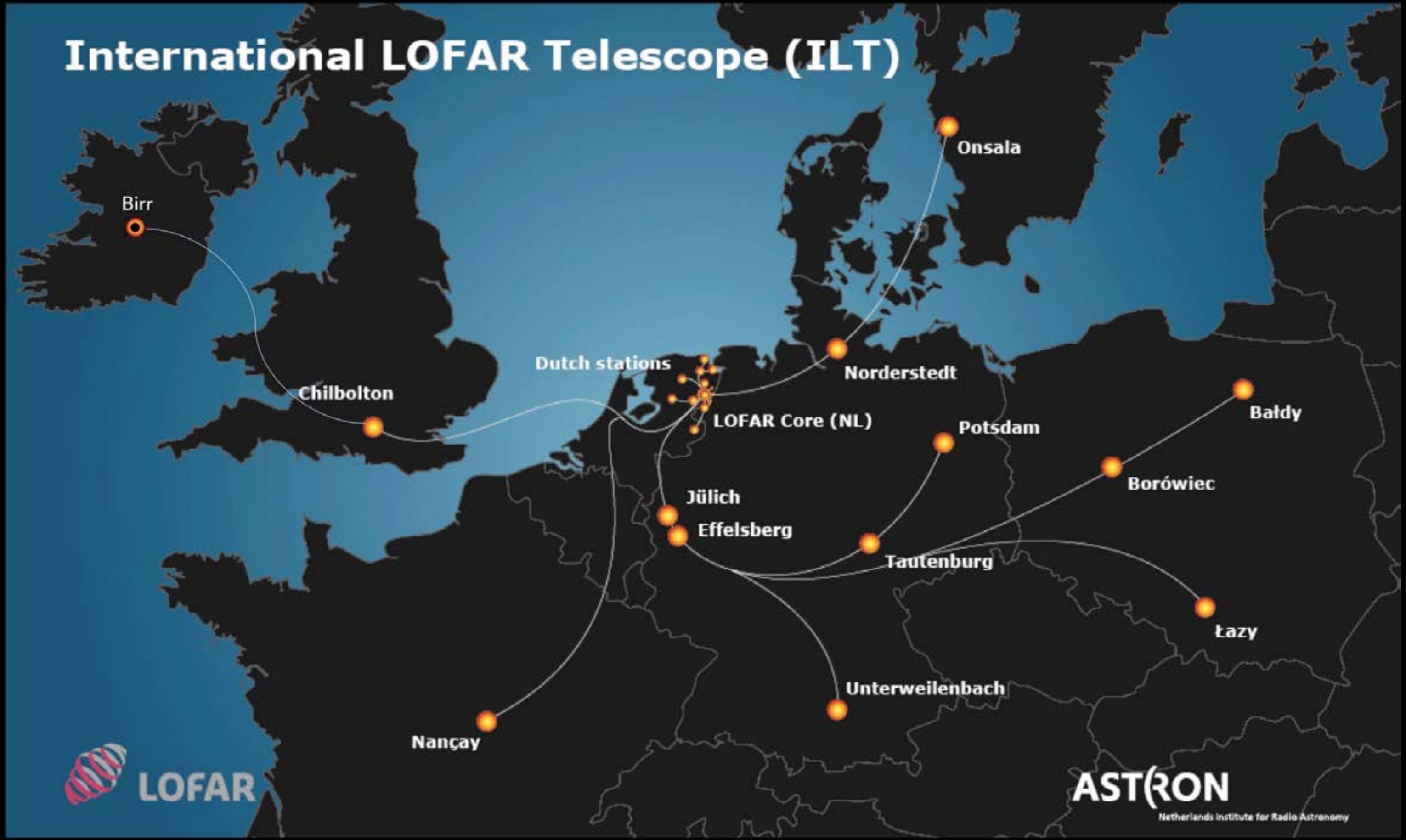
$$\tau_\mathrm{bow} \approx 50-100\,\mathrm{yr},\;\; t_\mathrm{cool} \sim 10^6\,\mathrm{yr}$$

(Ainsworth+ 2014)

Cosmic rays from the young Sun? (2)

- Observations
  - Synchrotron emission from jets of high mass (e.g. Carrasco-González+ 2010), intermediate mass (e.g. Rodríguez-Kamenetzky+ 2016) and low mass (e.g. Ainsworth+ 2014) YSO systems
  - Herschel observations reveal the necessity of energetic particles to produce the chemistry observed in young protostellar systems (e.g. Ceccarelli+ 2014, Podio+ 2014)
- Theory
  - Jet shocks are possible accelerators of particles that can be easily boosted up to relativistic energies through diffusive shock acceleration (Padovani+ 2015, 2016, 2017)

Low Frequency Array (LOFAR)



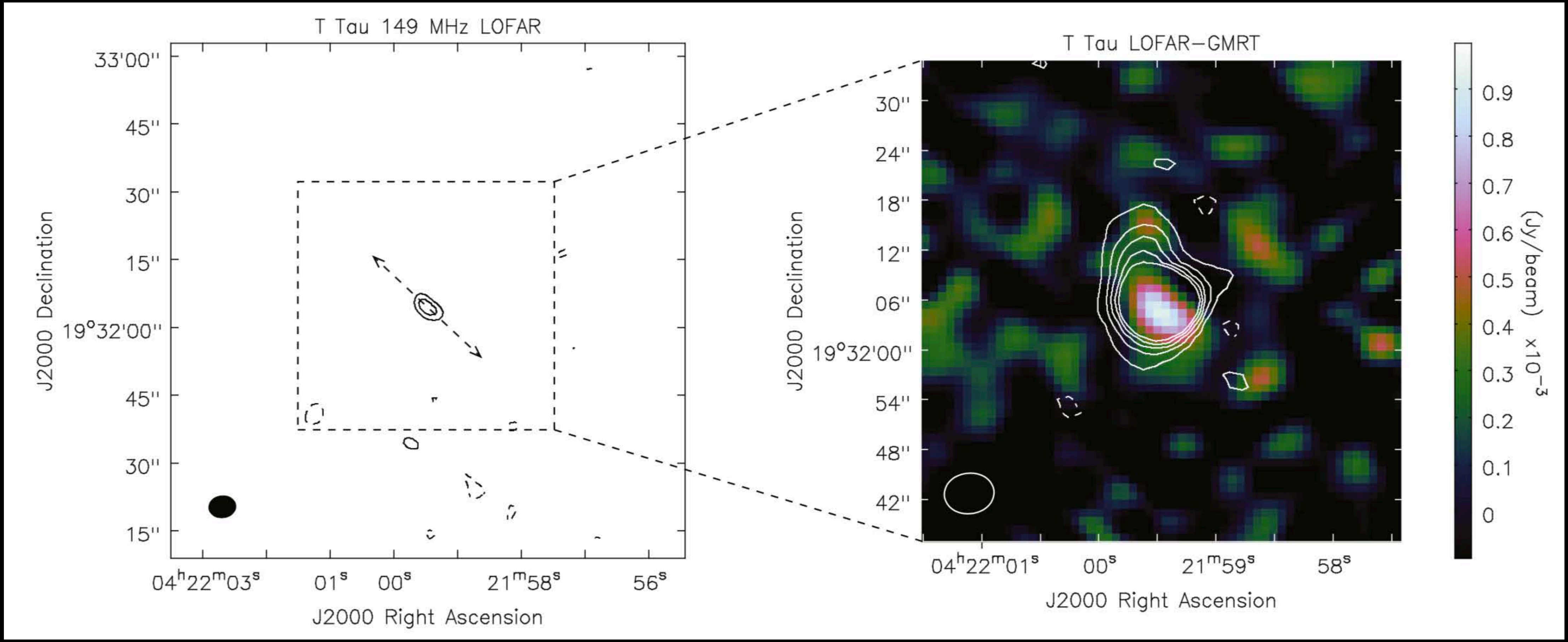
LOFAR Cycle 1 data: November 2013

HBA (high band) observations at 150 MHz of T Tau & DG Tau

Reduced data from core & remote stations using the computing facilities at the Dublin Institute for Advanced Studies (DIAS) & the Irish Centre for High End Computing (ICHEC)

Coughlan, Ainsworth + 2017

T Tau with LOFAR



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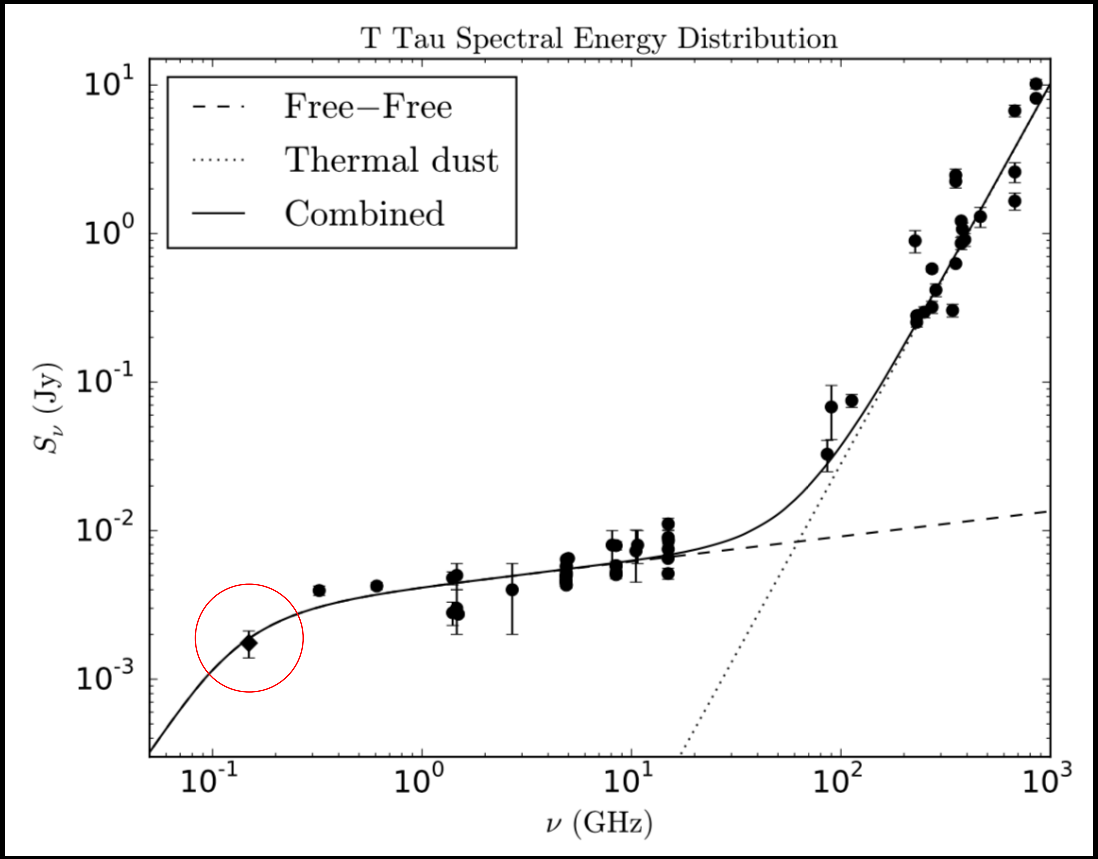
T Tau with LOFAR



$$\left(\frac{S_\nu}{\mathrm{mJy}}\right) = 7.2 \times 10^{-4} \left(\frac{T_e}{\mathrm{K}}\right)\left(\frac{\nu}{\mathrm{GHz}}\right)^2 (1 - e^{-\tau_\nu}) \left(\frac{\Omega_s}{\mathrm{arcsec}^2}\right) + K_{100\,\mathrm{GHz}} \left(\frac{\nu}{100\,\mathrm{GHz}}\right)^{\alpha_{\mathrm{dust}}}$$

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

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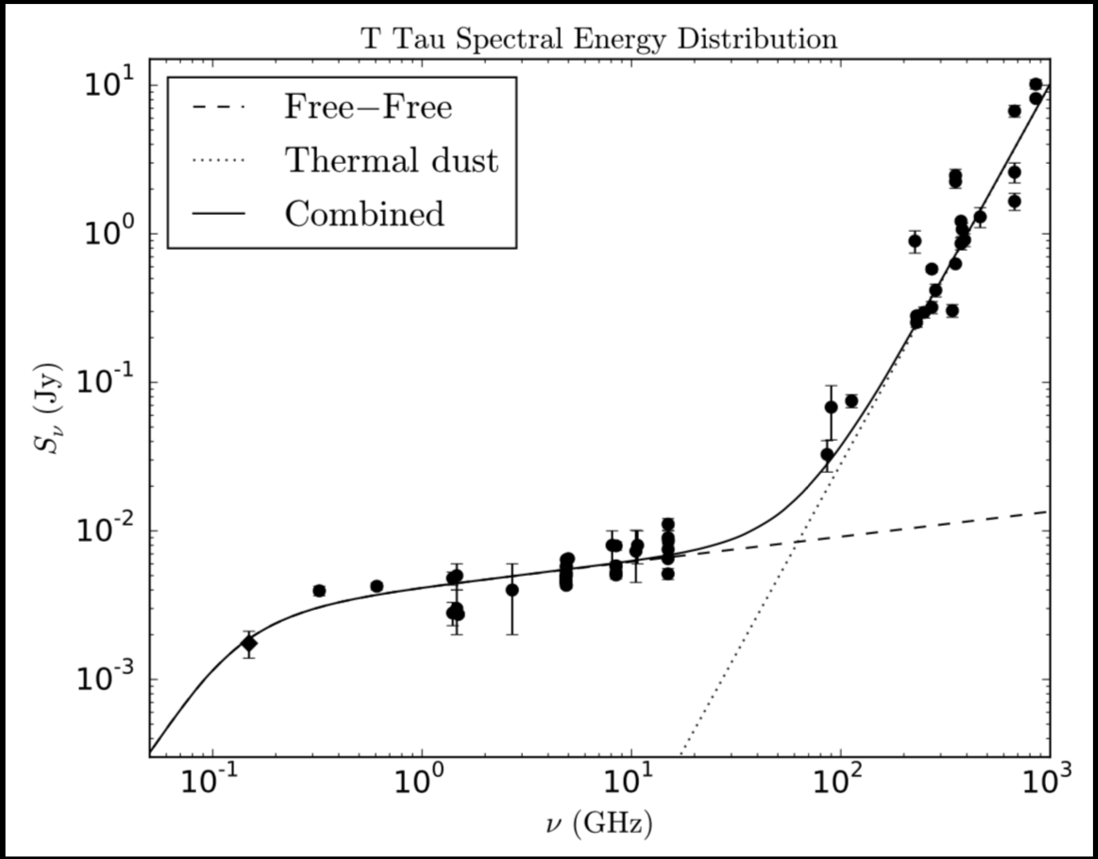
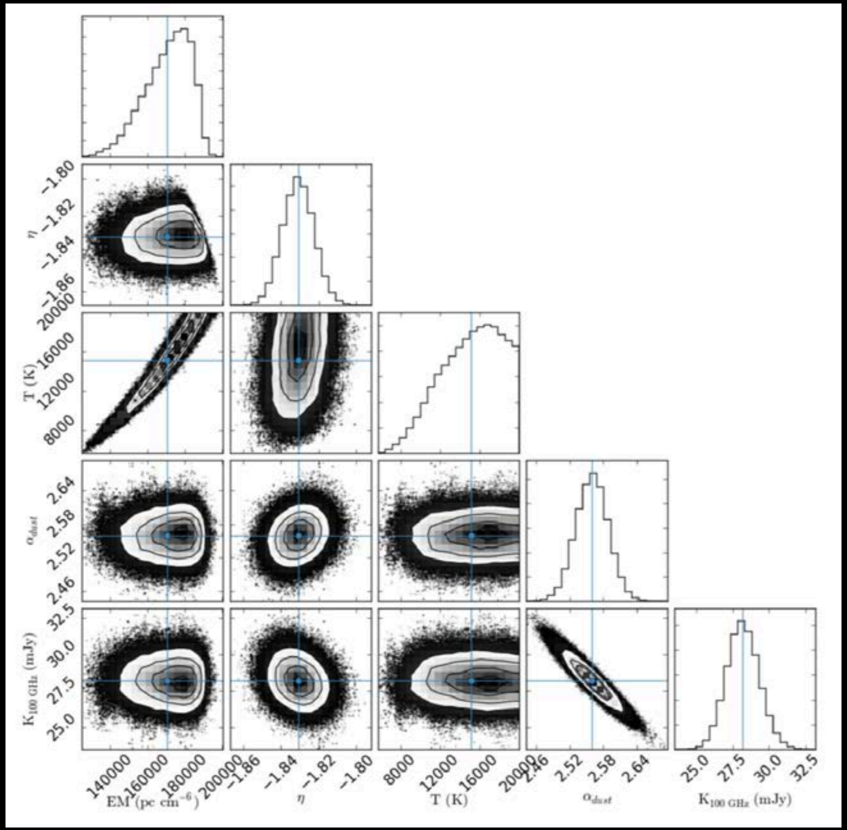
T Tau with LOFAR





$$\theta = 3.''27, D = 148\,\mathrm{pc}$$

$$\mathrm{EM} = (1.67 \pm 0.14) \times 10^5\,\mathrm{pc\,cm^{-6}}$$

$$T_e = (1.4 \pm 0.3) \times 10^4\,\mathrm{K}$$

$$\eta = -1.83 \pm 0.01 \longrightarrow S_\nu \propto \nu^{0.17}$$

$$\tau_\nu = 1 \longrightarrow \nu = (157 \pm 27)\,\mathrm{MHz}$$

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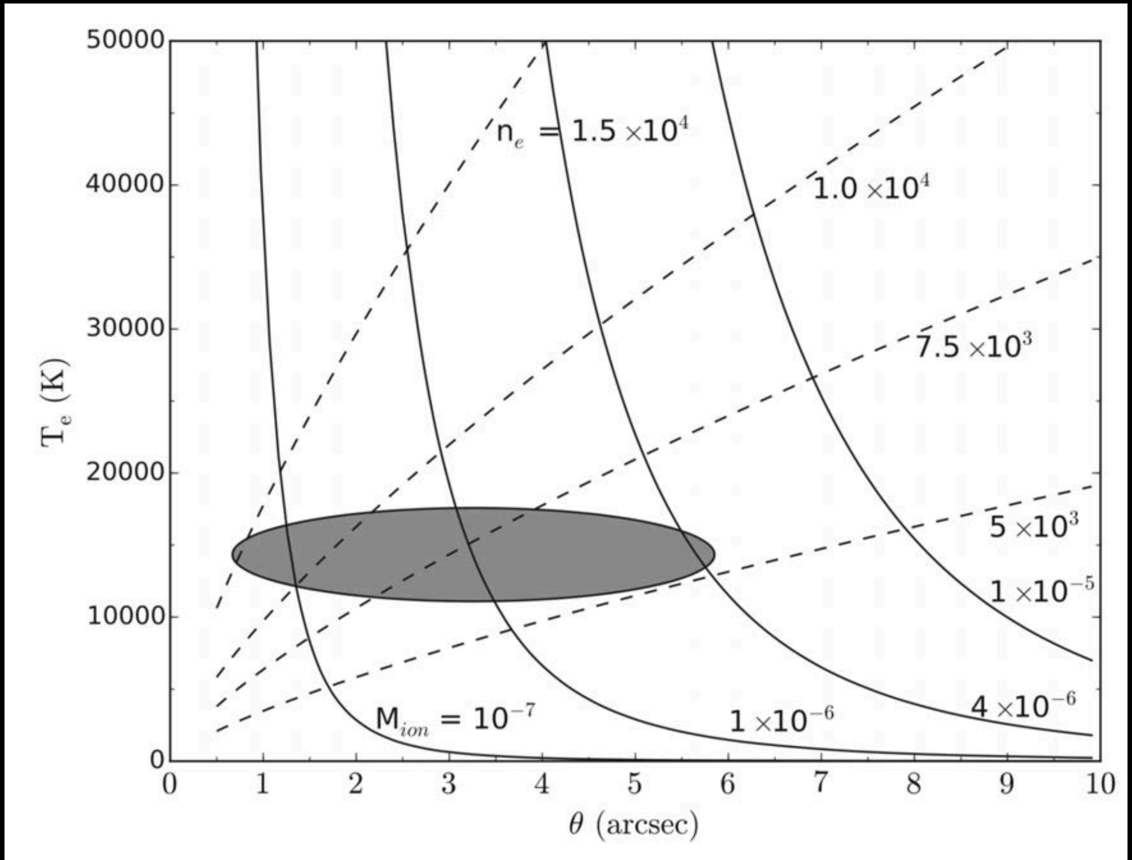
T Tau with LOFAR

$$\mathrm{EM} = (1.67 \pm 0.14) \times 10^5\,\mathrm{pc\,cm^{-6}}$$
$$= 7.1 \times 10^{-3} \left(\frac{D}{\mathrm{kpc}}\right) \left(\frac{\theta}{\mathrm{arcsec}}\right) \left(\frac{n_e}{\mathrm{cm^{-3}}}\right)^2$$
$$\theta = 3.''27,\ D = 148\,\mathrm{pc}$$
$$n_e = (7.2 \pm 2.1) \times 10^3\,\mathrm{cm^{-3}}$$
$$M_{\mathrm{ion}} = \frac{4}{3}\pi r_{\mathrm{gas}}^3 m_{\mathrm{H}} n_e = (1.0 \pm 1.8) \times 10^{-6}\,M_\odot$$

- Selected values of electron density (n_e in cm^{-3}) and total ionized mass (M_{ion} in solar masses) plotted against electron temperature (T_e) and source size (θ) using assuming a spherical cloud of constant density.
- The shaded region indicates the area within 1σ of the geometric mean of the deconvolved angular source size and fitted temperature
  $\theta = 3.''27 \pm 2.''59$
  $T_e = (1.4 \pm 0.3) \times 10^4$ K



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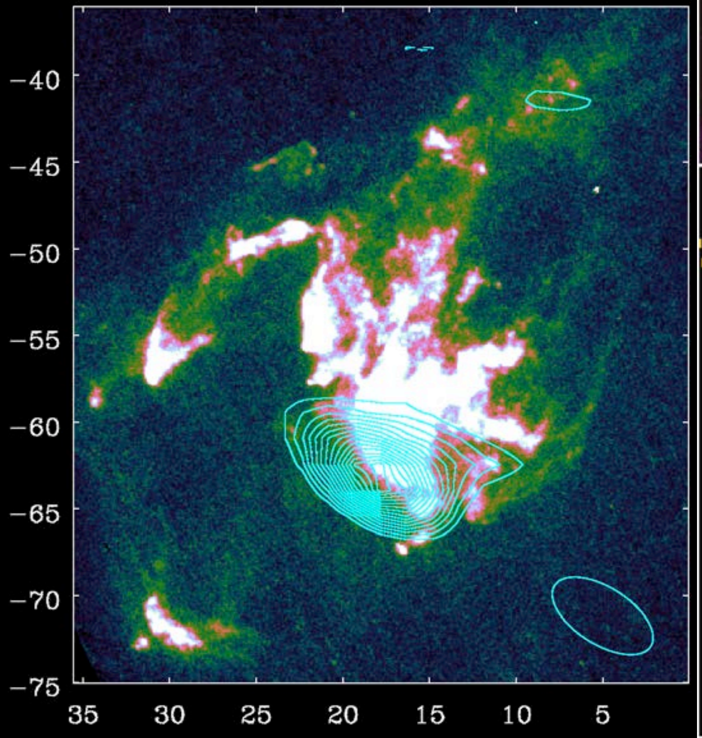
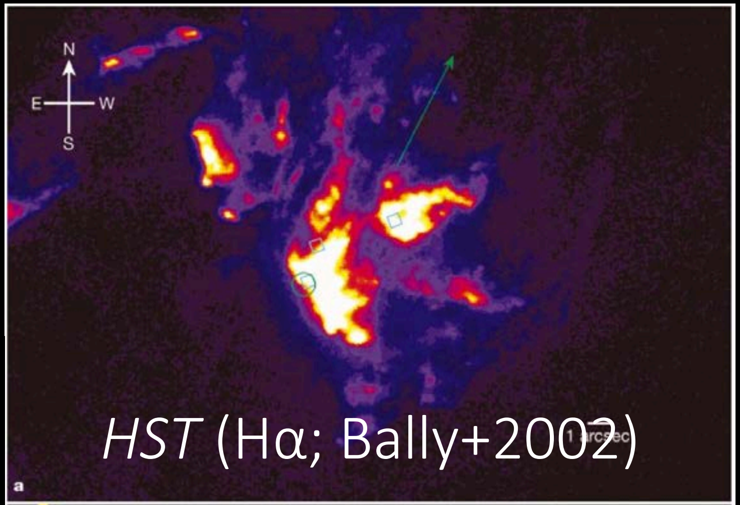
Current & future work

- Characterise YSOs at very low radio frequencies (< 1 GHz)
  - Observations of more YSOs with GMRT
    - Class 0 sources: L1448, L723, Serpens, HH 1-2 (610 MHz)
    - Blind survey of NGC 1333 (610 MHz)
  - VLBI Observations of T Tau and DG Tau with LOFAR HBA (150 MHz)
    - Measure jet opening close to the source with international baselines
    - Insight into the magnetic collimation of the jets

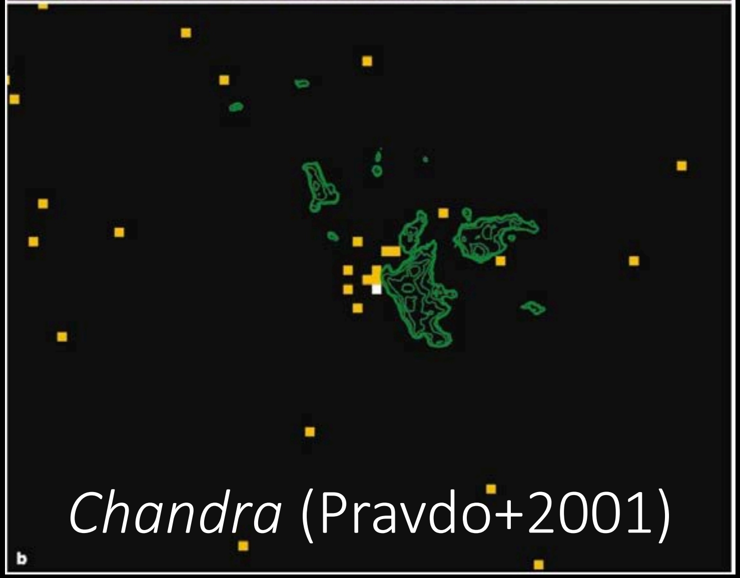
HH 1-2

HH 2: 610 MHz GMRT contours overlaid on *HST* image (Hester+1998)

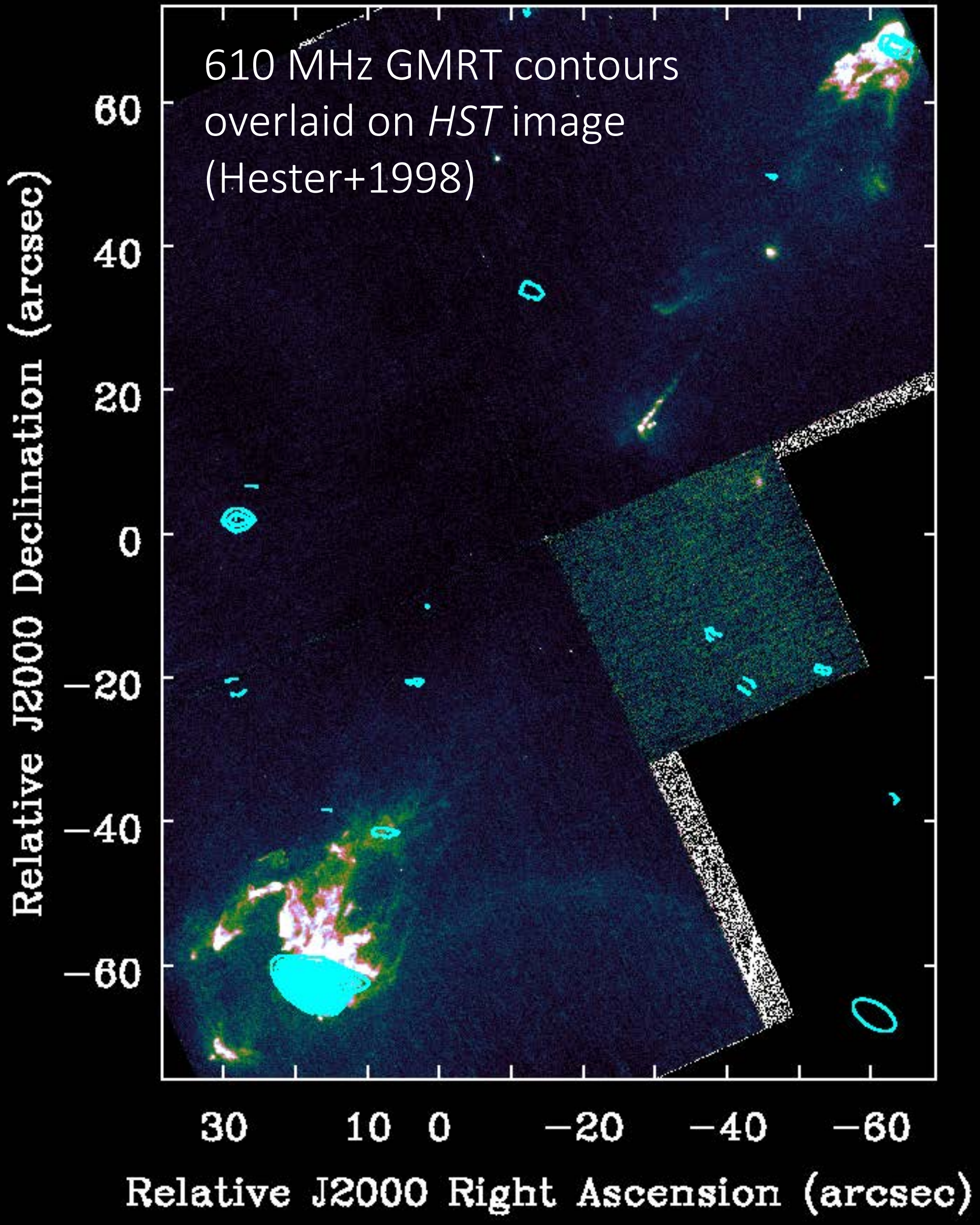




HST (Hα; Bally+2002)



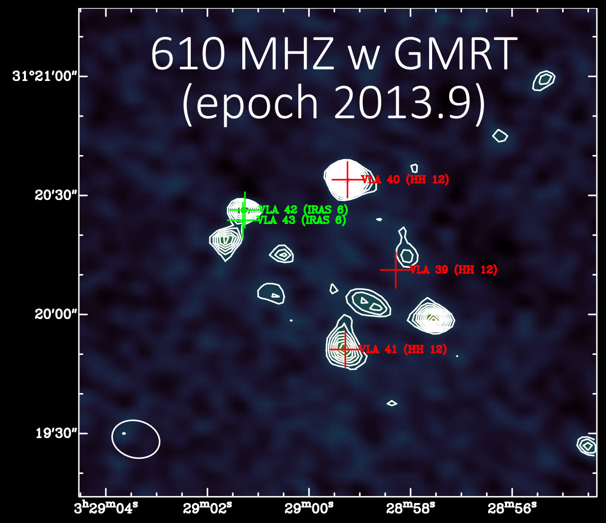
Chandra (Pravdo+2001)

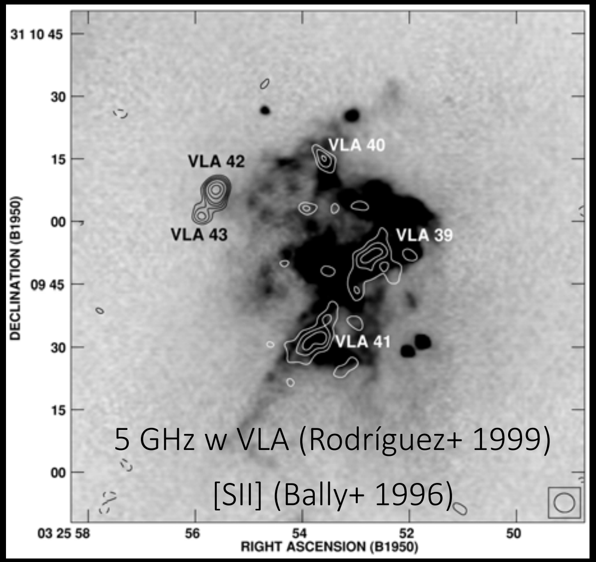


610 MHz GMRT contours overlaid on *HST* image (Hester+1998)

Ainsworth + in prep.

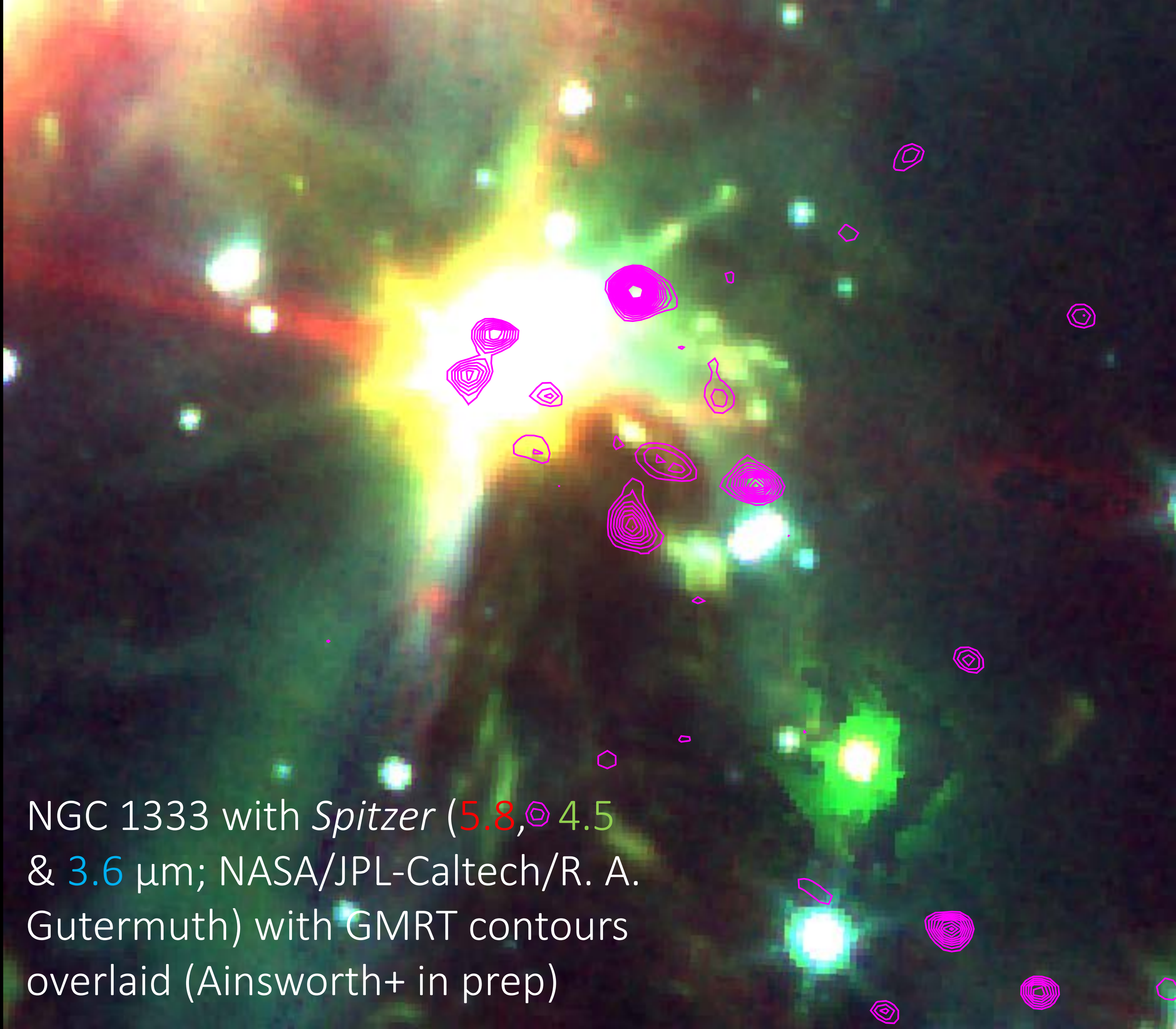
HH 12





5 GHz w VLA (Rodríguez+ 1999)

[SII] (Bally+ 1996)



NGC 1333 with *Spitzer* (5.8, 4.5 & 3.6 μm; NASA/JPL-Caltech/R. A. Gutermuth) with GMRT contours overlaid (Ainsworth+ in prep)

Thank you! Questions?

- Collaborators: Prof. Anna Scaife (UMAN), Prof. Tom Ray (DIAS), Dr. Dave Green (Cambridge), Dr. Andrew Taylor (DESY), Dr. Colm Coughlan (DIAS), Dr. Jochen Eislöffel (TLS)
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