Synchrotron emission in protostellar jet shocks revealed by metre wavelength observations

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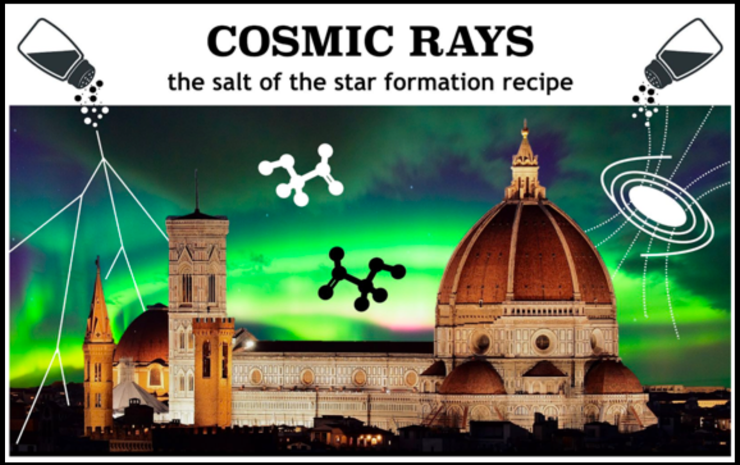
Collaborators:
Anna Scaife (UoM), Tom Ray (DIAS), David Green (Cambridge),
Andrew Taylor (DESY), Simon Purser (DIAS)



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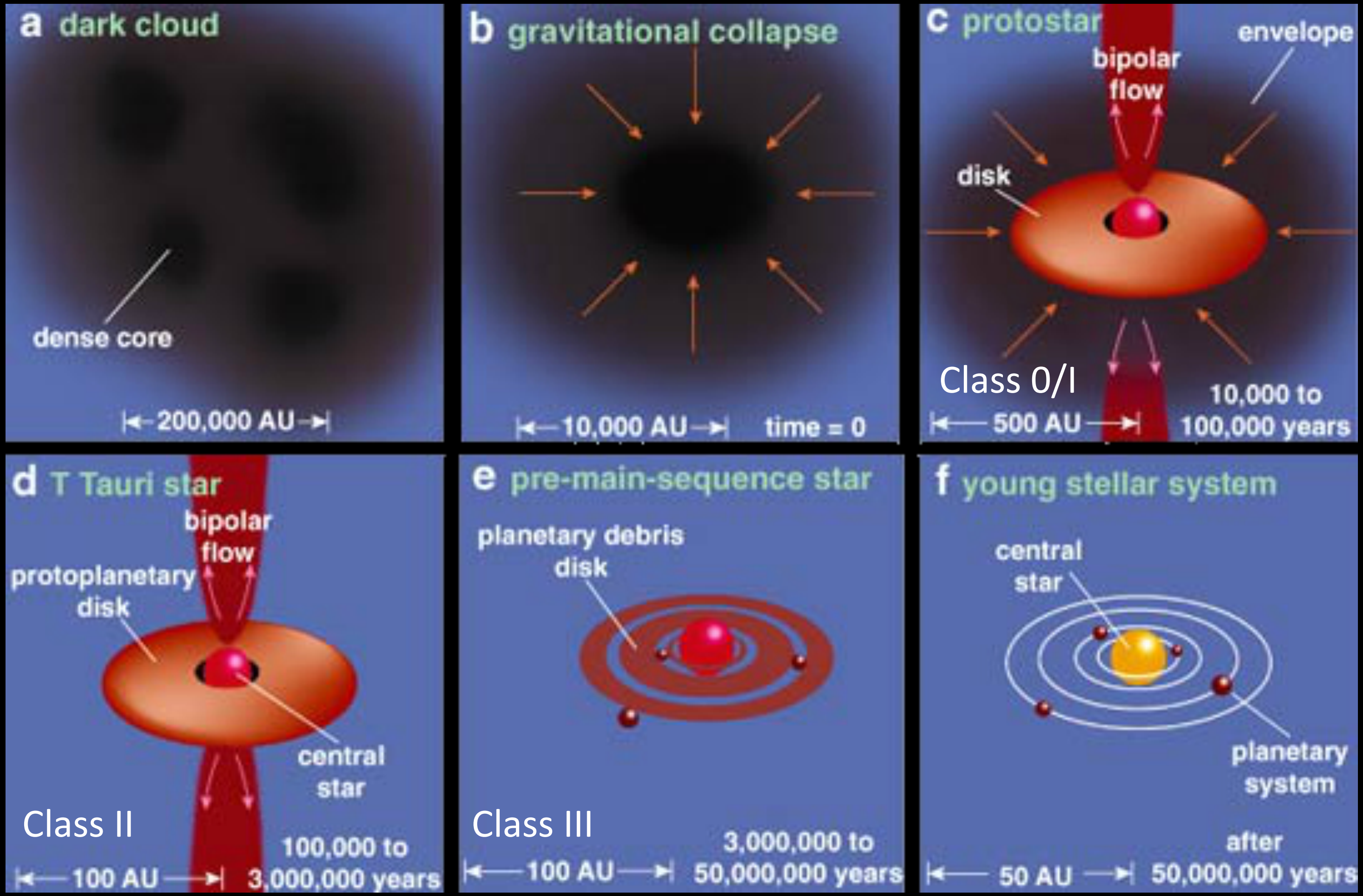
Low mass star formation



Green, T., 2001, AS, 89, 316.

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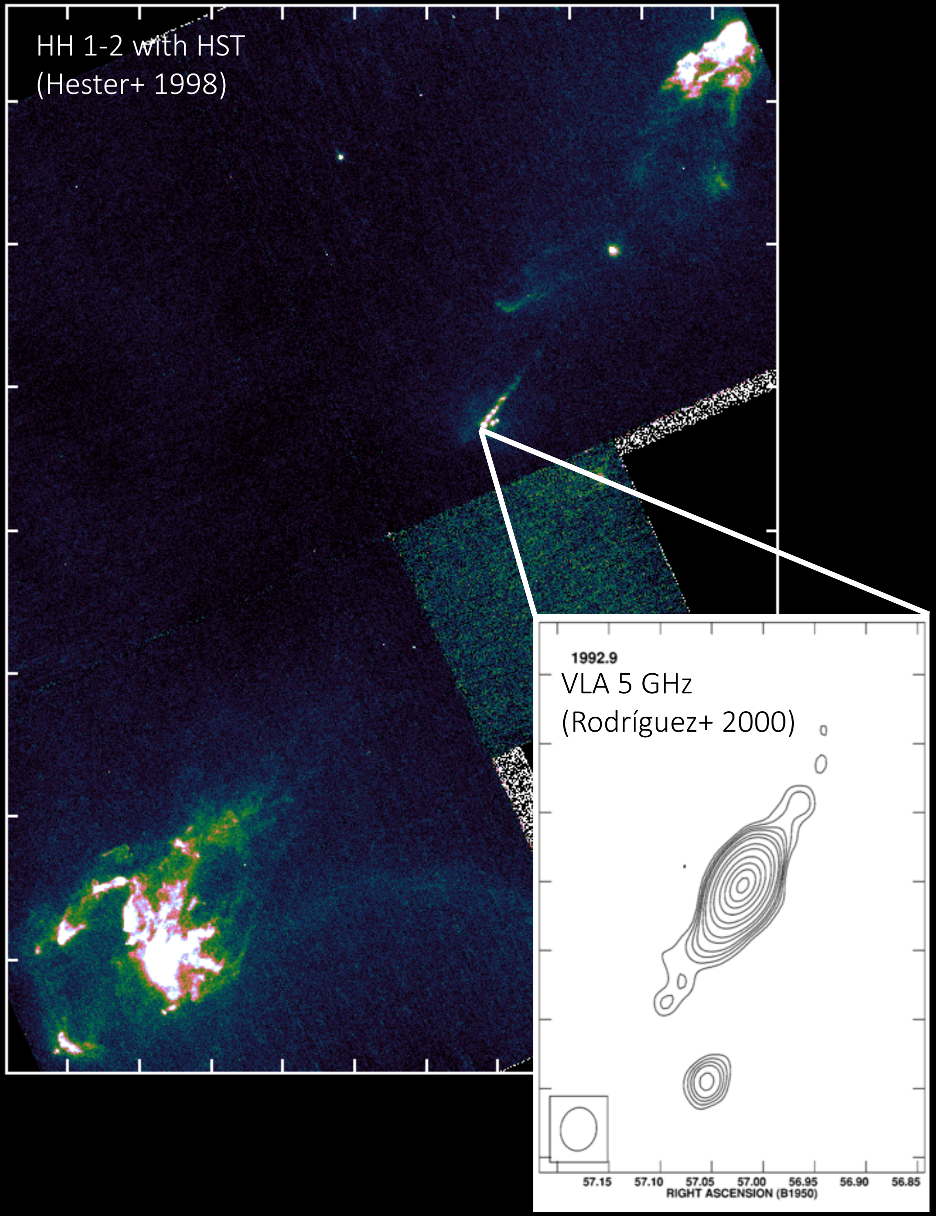
Radio emission from YSOs: free-free

- λ > 1 cm (ν < 30 GHz)
- Class 0-II YSO jets
- Flux density ~ 1 mJy
- Traces outflow



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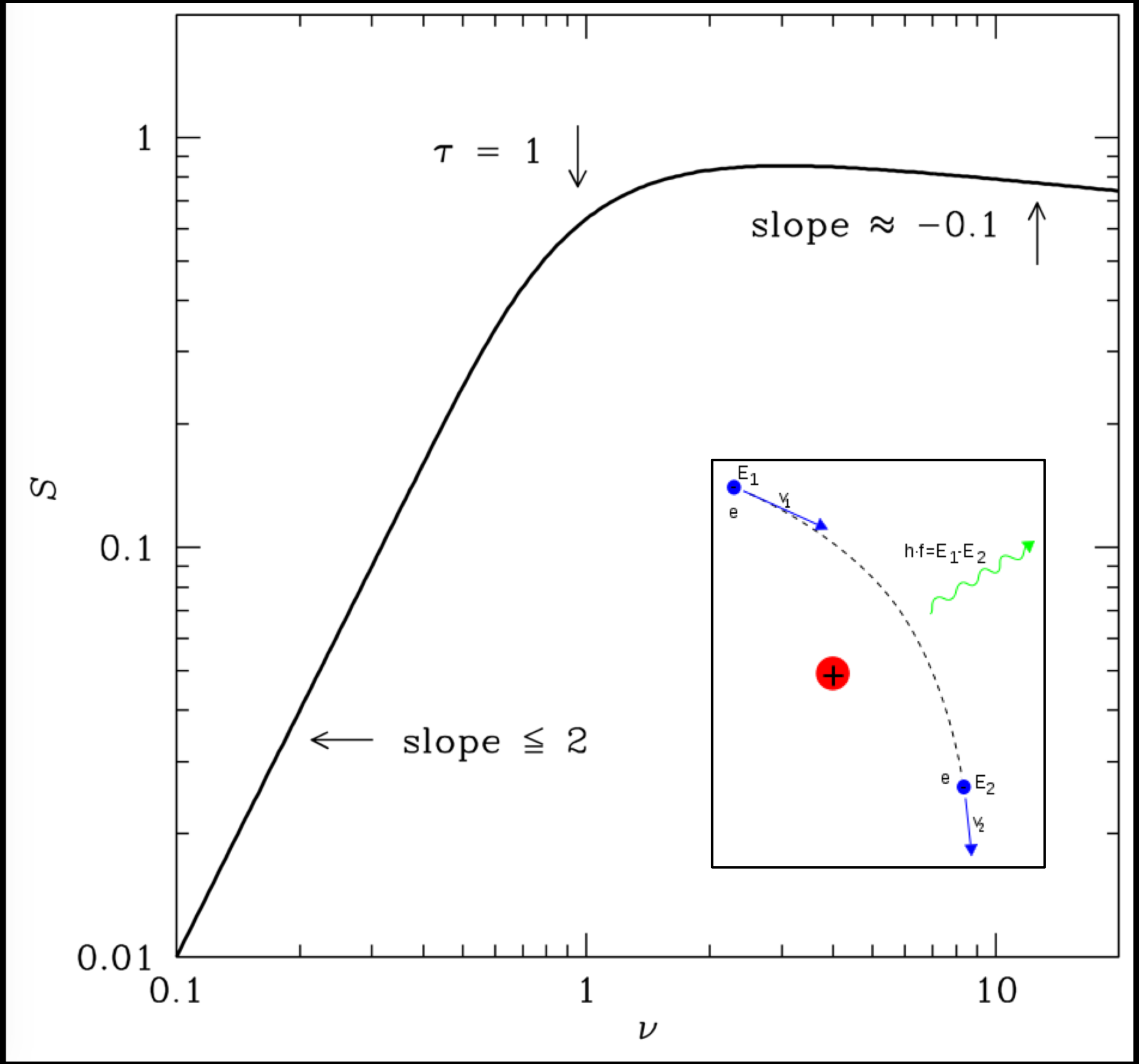
- $S_\nu \propto \nu^\alpha$, where $-0.1 < \alpha < 2$
  - $\alpha = 0.6$ “standard” spherical stellar wind (e.g. Panagia & Felli 1975)
  - $\alpha = 0.25$ “standard” collimated jet (Reynolds 1986)



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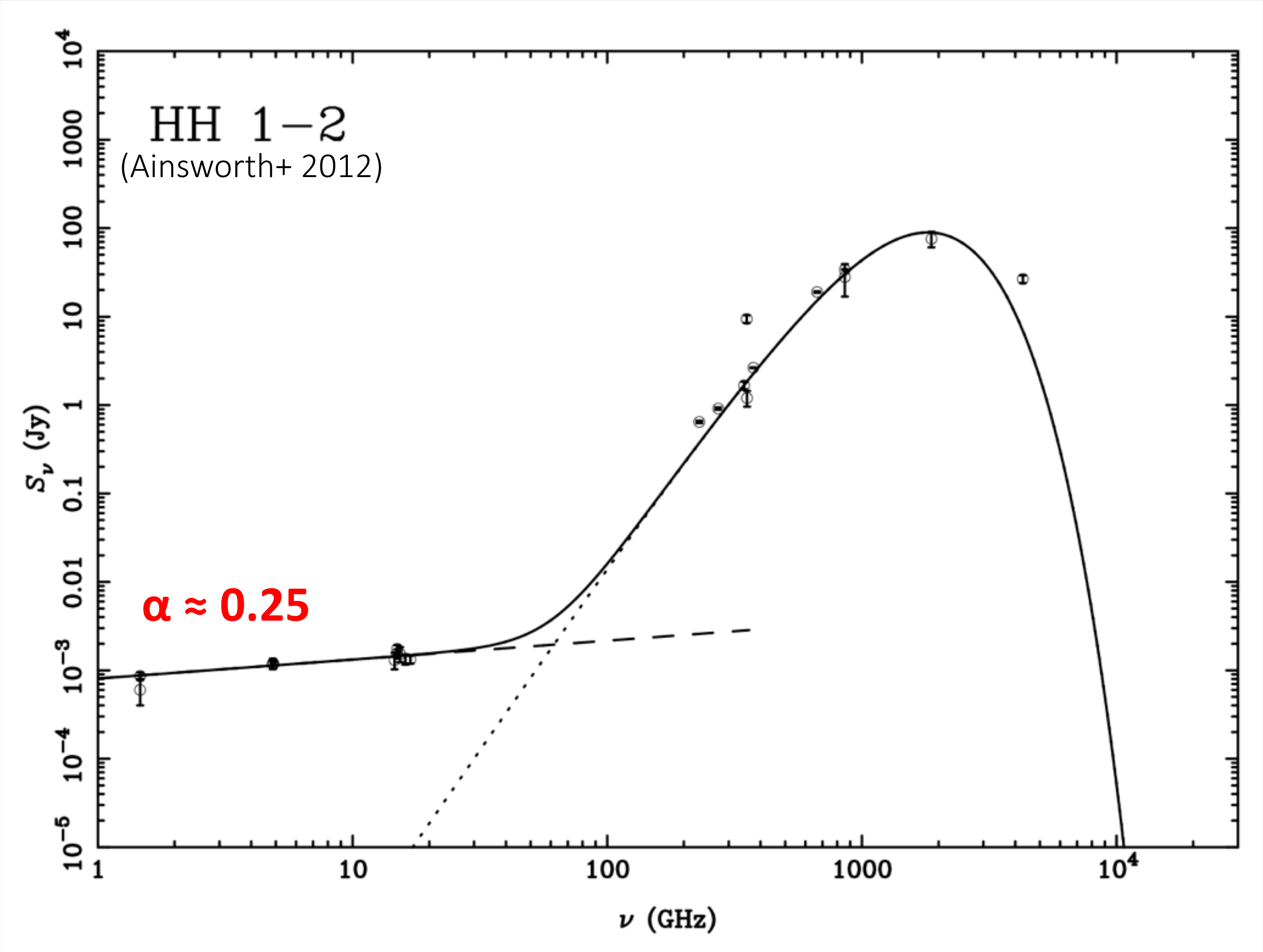
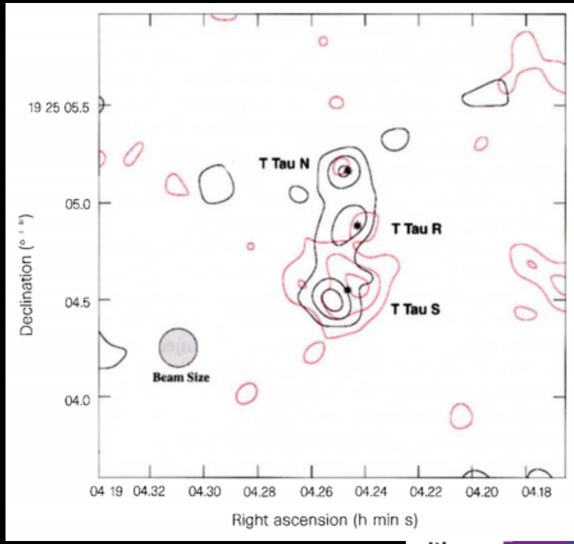
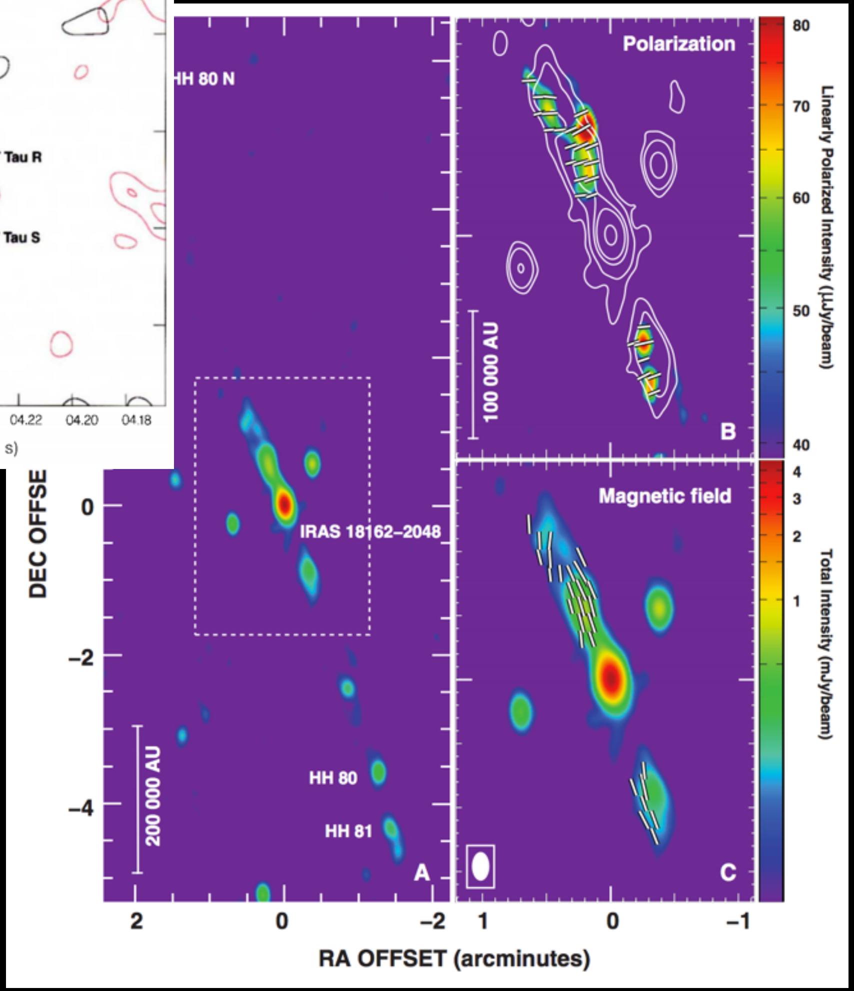


Radio emission from YSOs: non-thermal

- 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





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Motivation for metre wavelengths

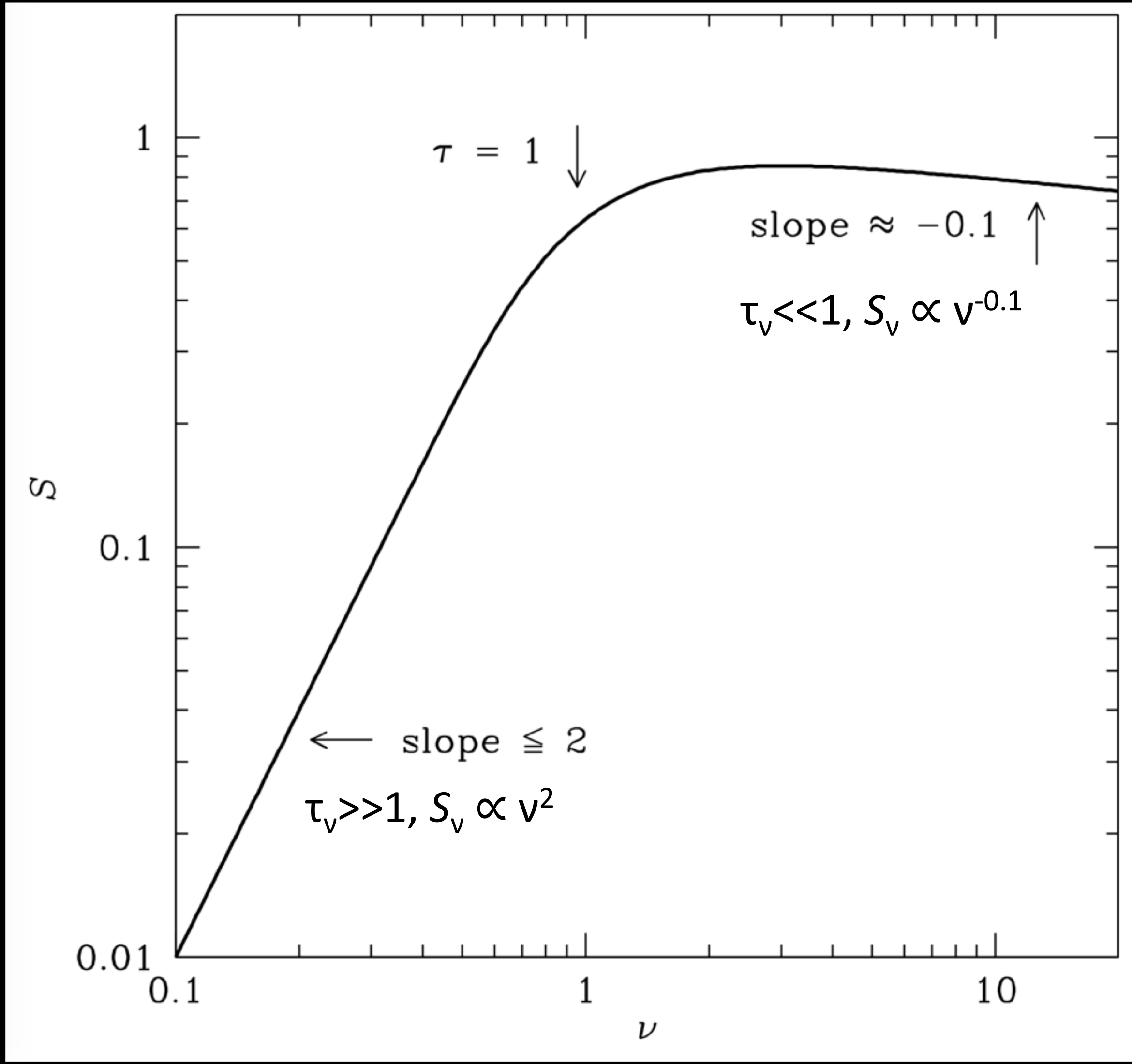
- New territory!
- Detect optically thick surface (free-free)

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

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

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

- Detect Synchrotron emission



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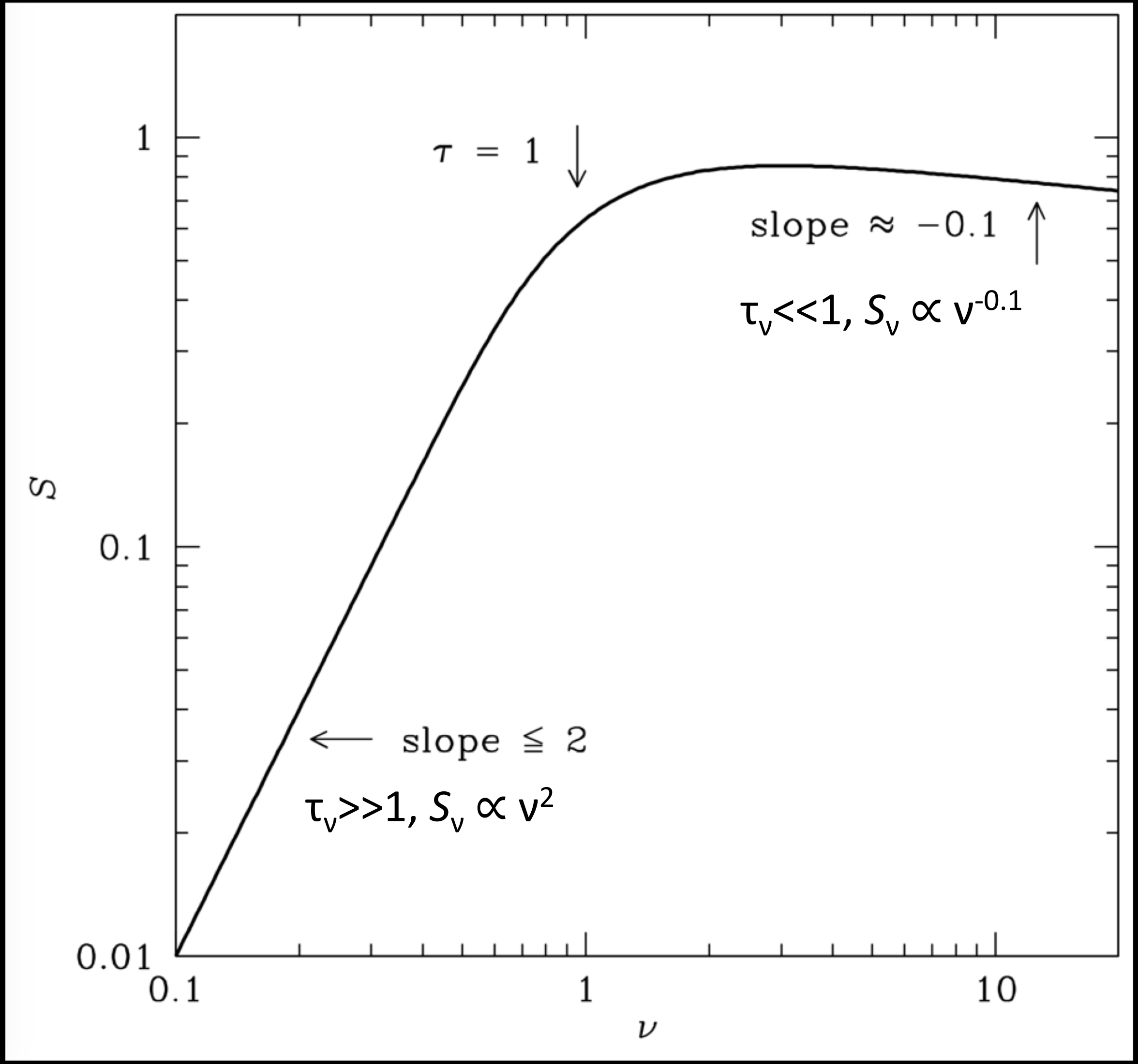
✓ Detected free-free spectral turnover of T Tau with LOFAR at 150 MHz (2 m), see Coughlan+ (2017)

- Detect Synchrotron emission



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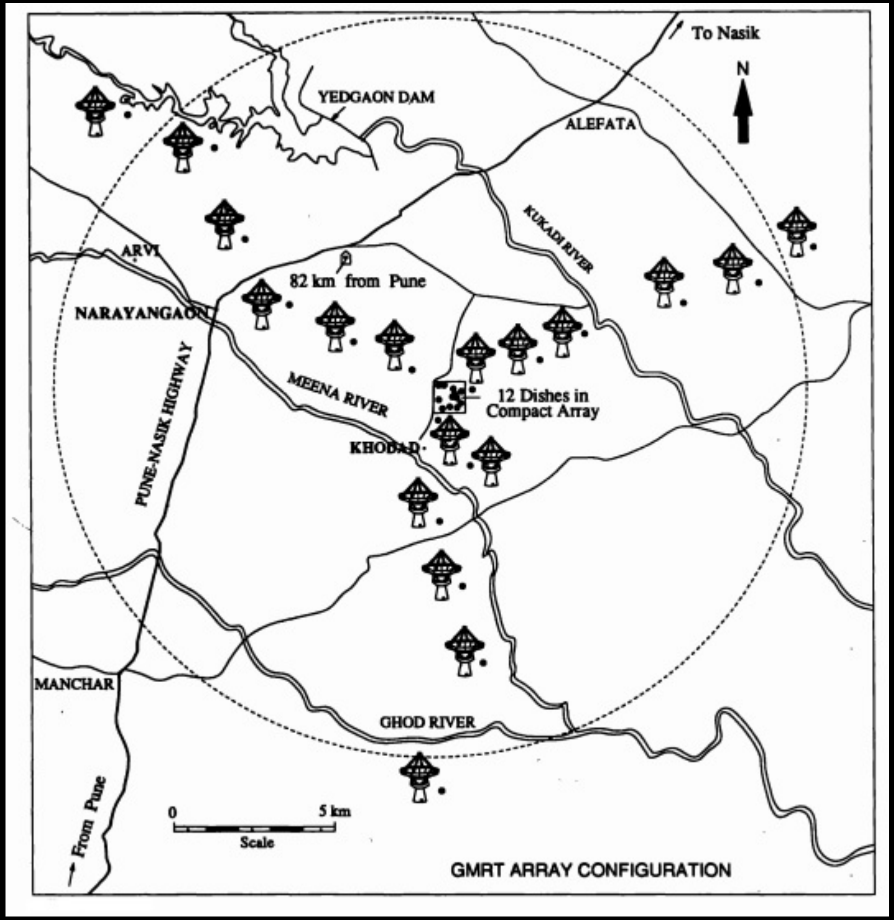
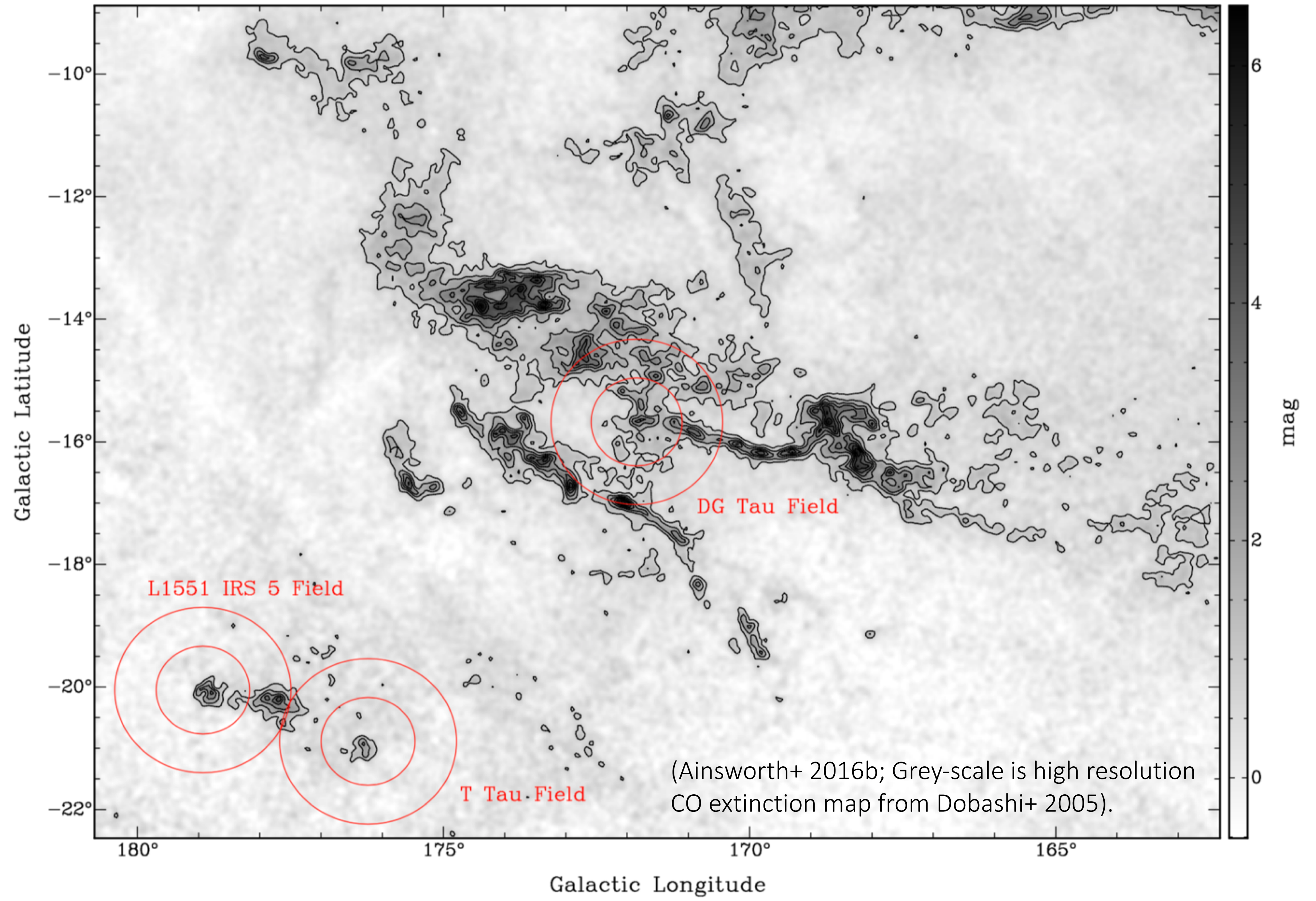
Giant Metrewave Radio Telescope (GMRT)



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

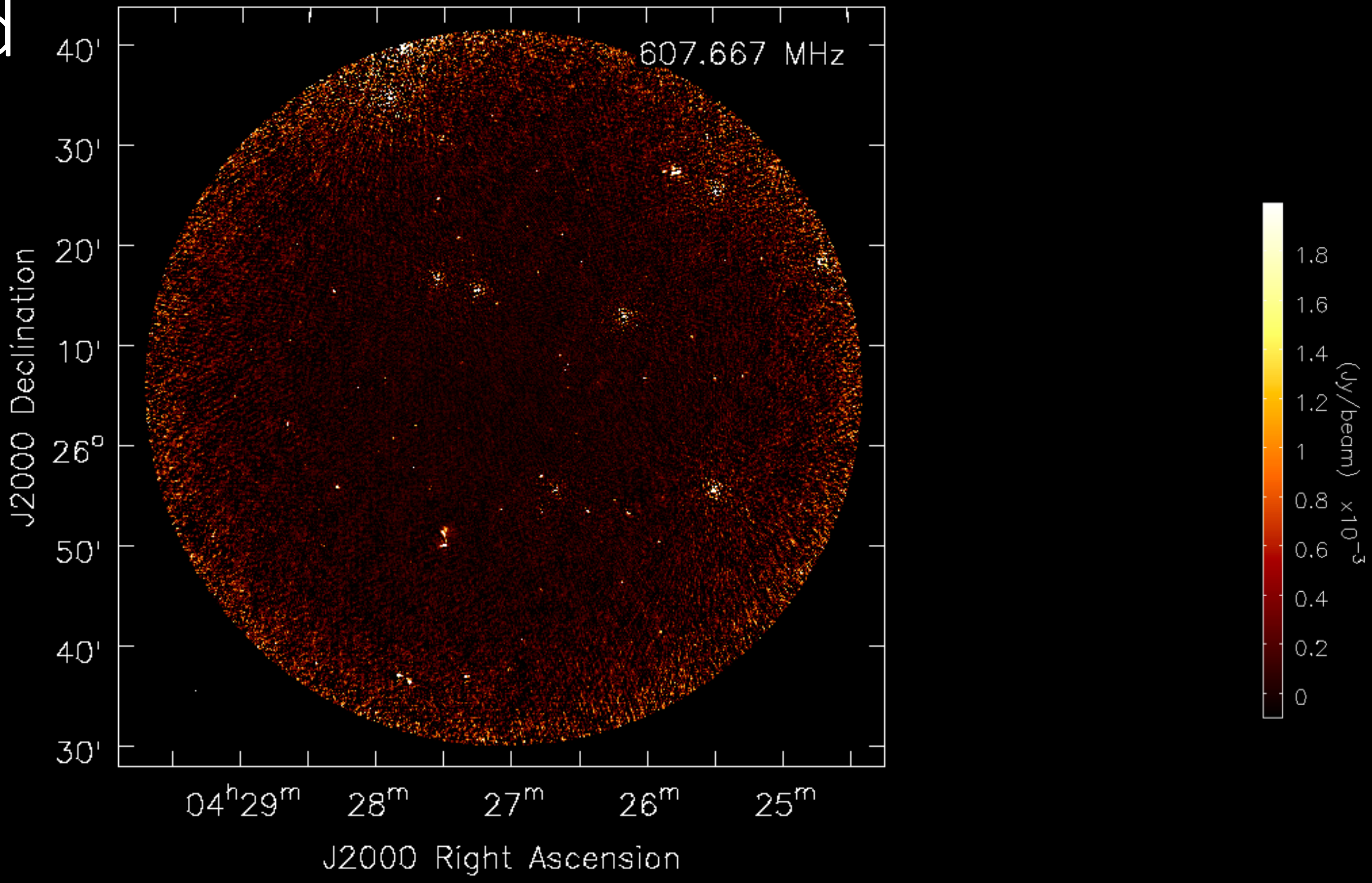
(Ainsworth+ 2016a,b)



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

(Ainsworth+ 2016b)

DG Tau field with GMRT



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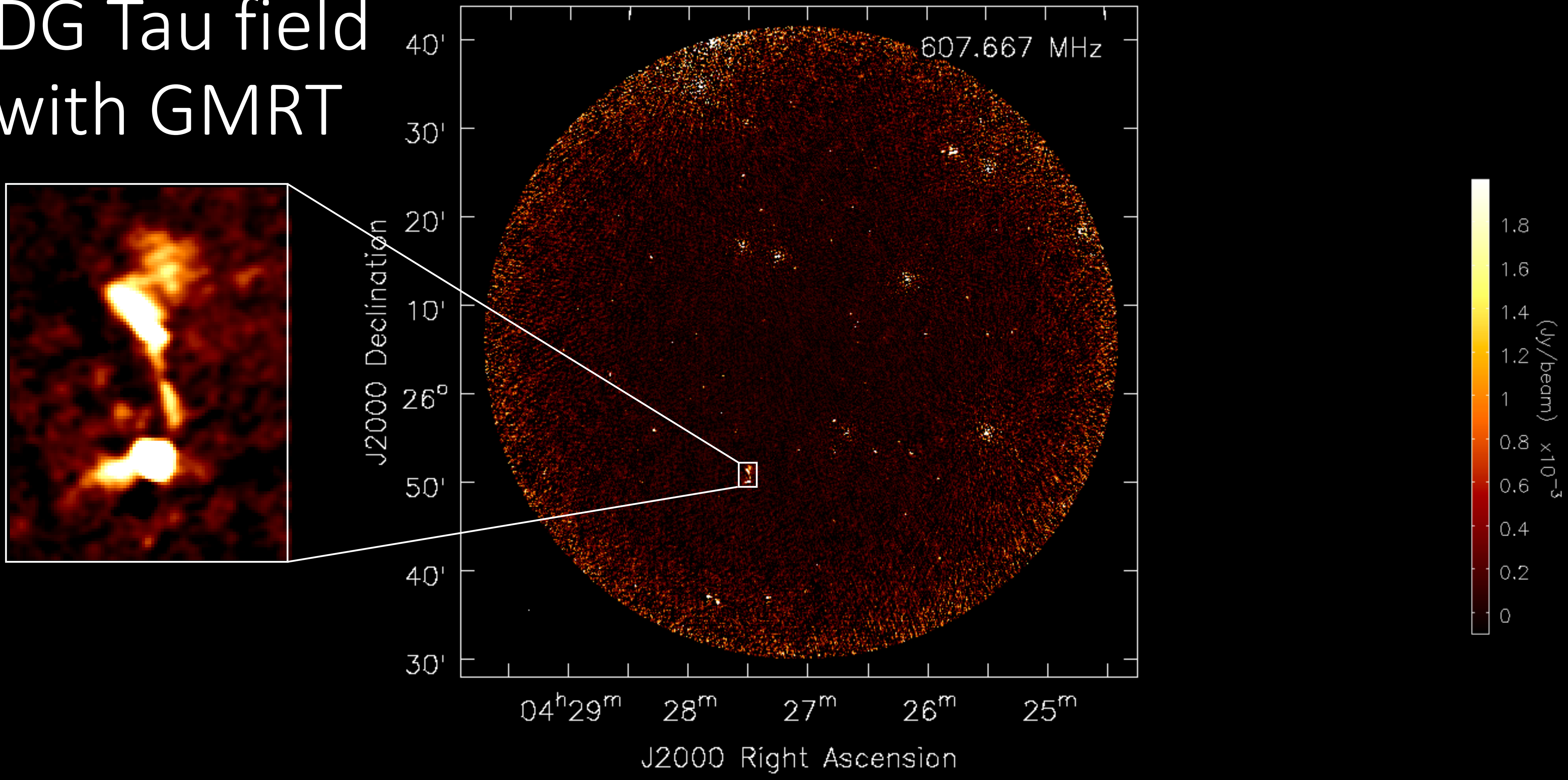
(Ainsworth+ 2016b)

DG Tau field with GMRT



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(Ainsworth+ 2016b)

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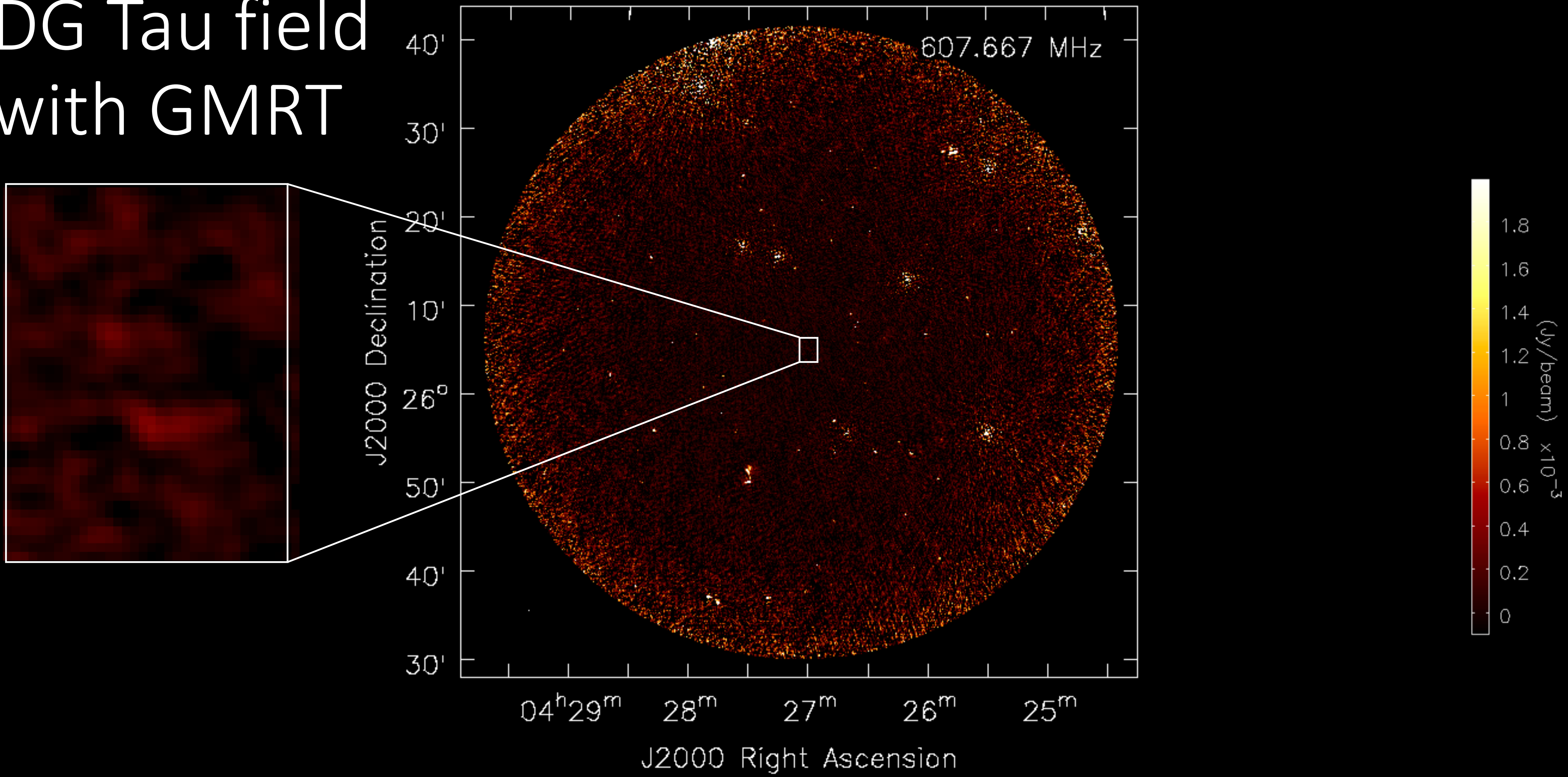

(Ainsworth+ 2016b)

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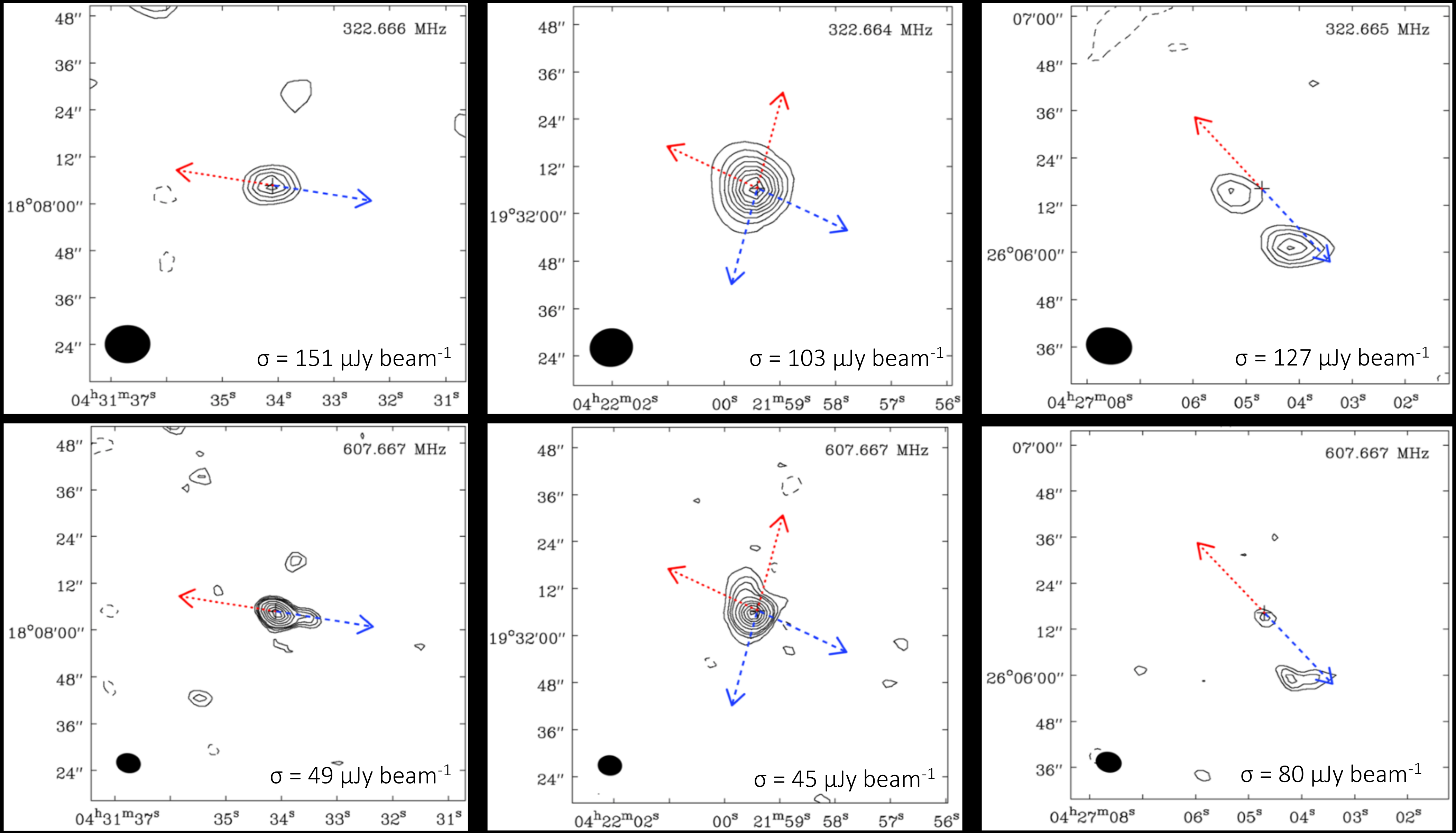
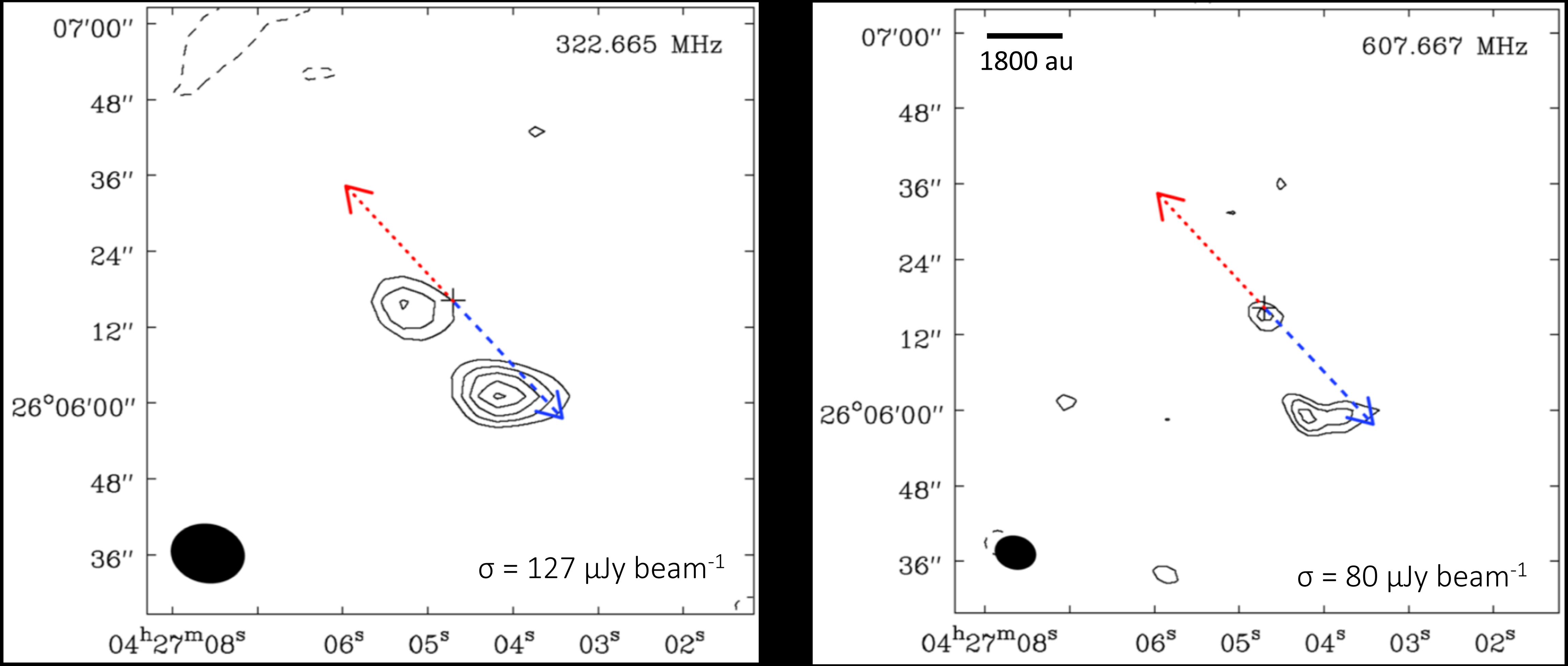
L1551 IRS 5 | T Tau | DG Tau



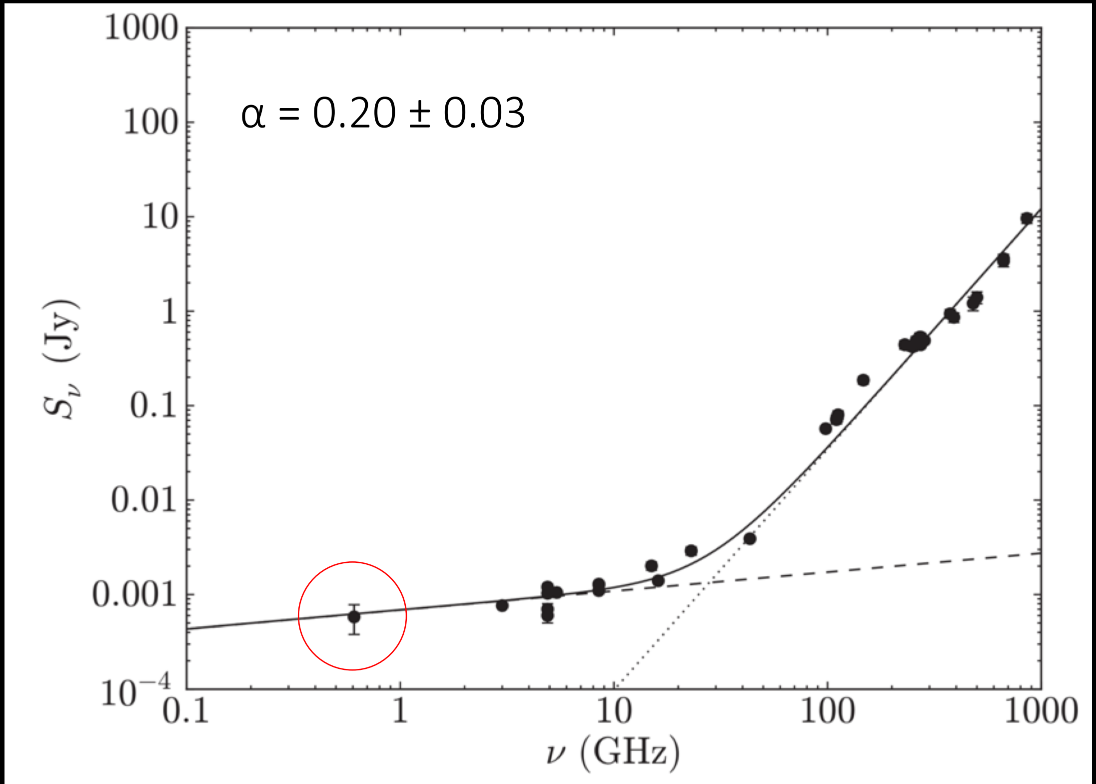
(Ainsworth+ 2016a)

DG Tau with GMRT



(Ainsworth+ 2016a)

DG Tau Spectral Energy Distribution



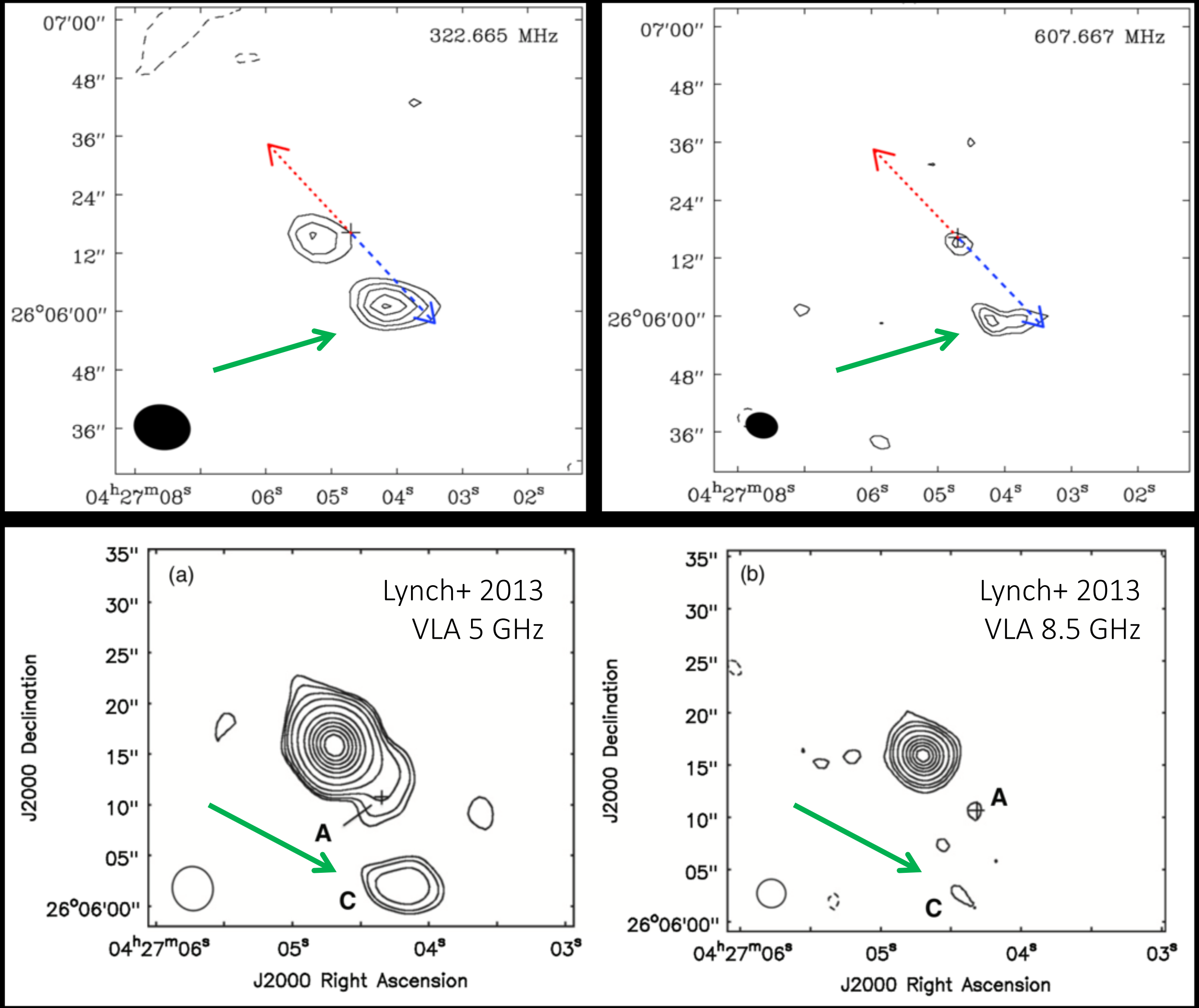
- GMRT data combined with data from the literature
- SED traces disk at high frequencies and jet at low frequencies
  - Fitted with 2 power-laws using a joint likelihood MCMC method

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

- GMRT measurements are consistent with the free-free power-law associated with optically thin/partially optically thick emission extrapolated from cm wavelengths.

(Ainsworth+ 2016a)

DG Tau



(Ainsworth+ 2014)

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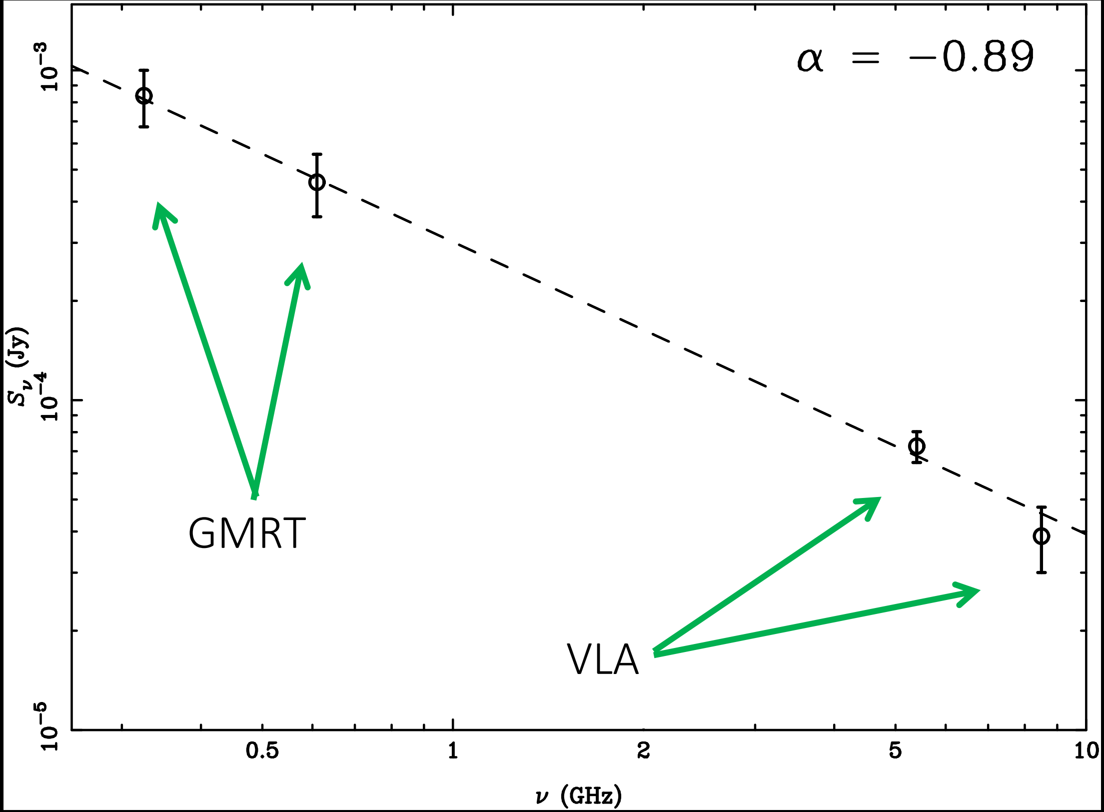
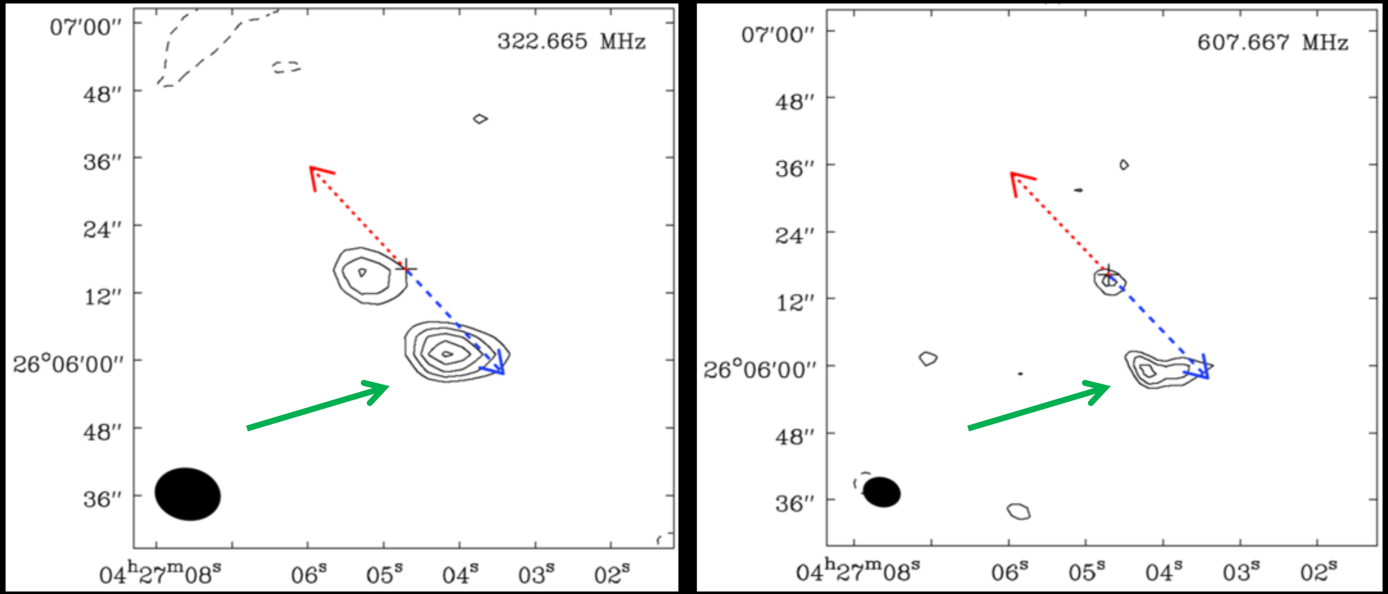
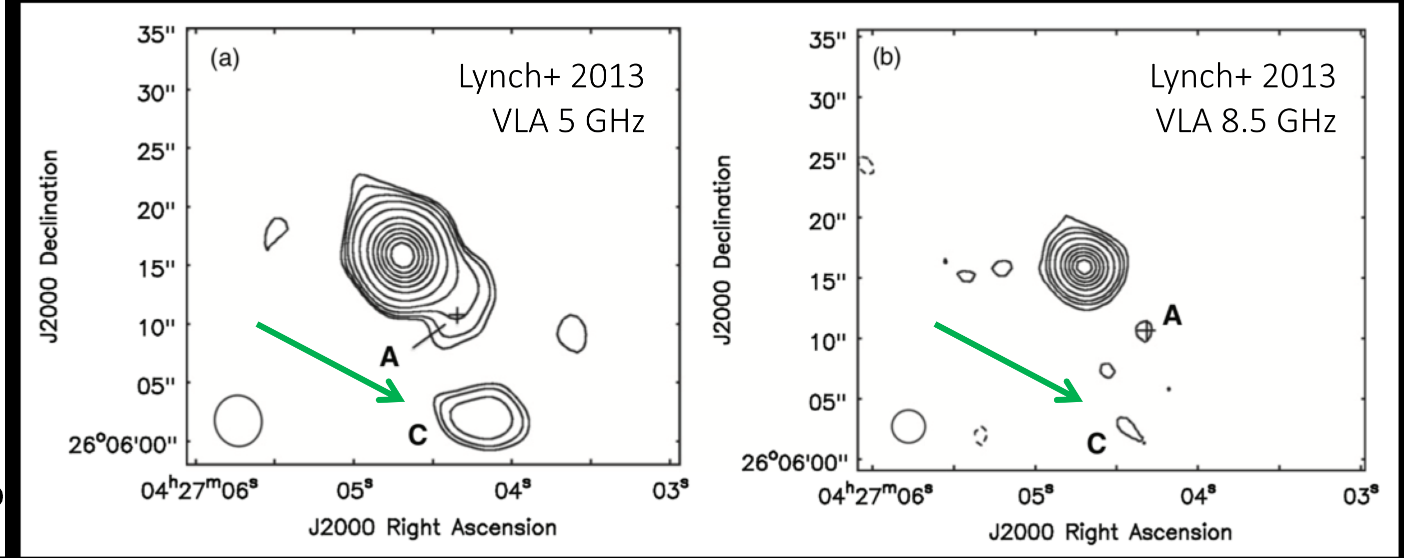
DG Tau







(Ainsworth+ 2014)

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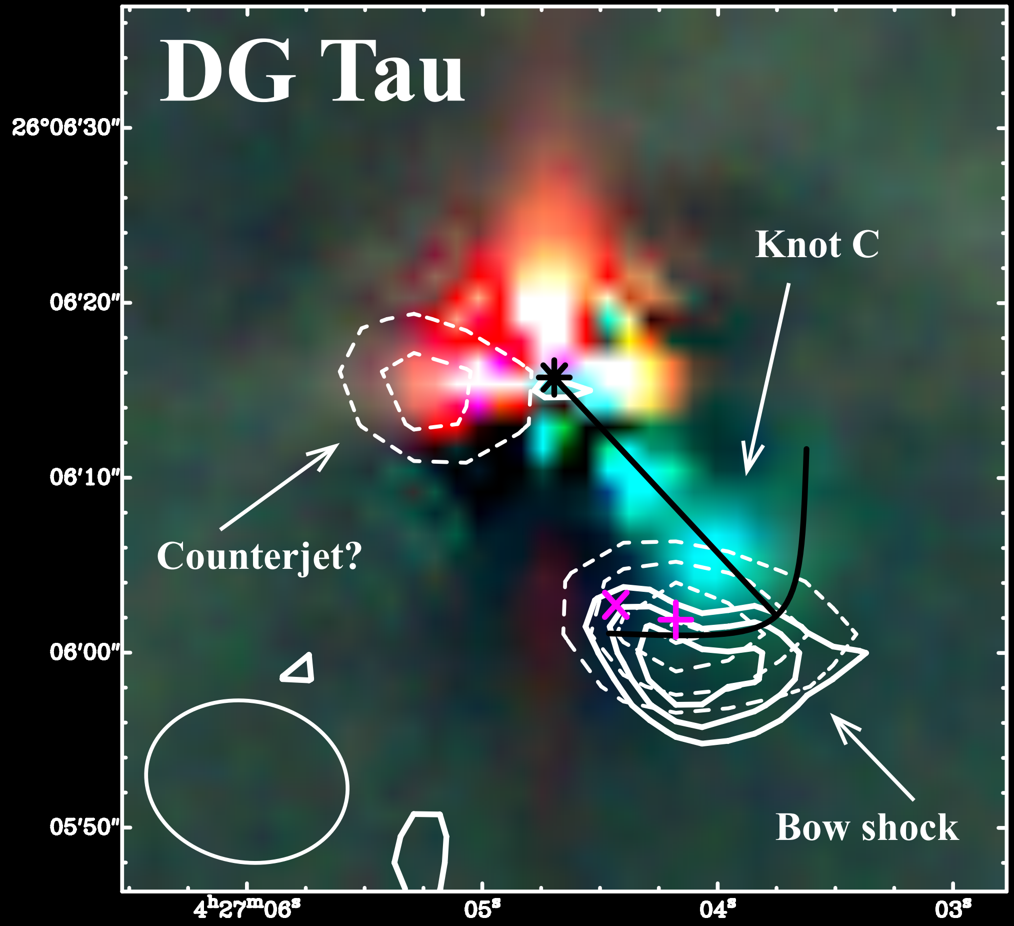
DG Tau bowshock



- 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)

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(Ainsworth+ 2014)

Equipartition magnetic field strength & minimum energy

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

$$\simeq 0.11\,\mathrm{mG}$$

$$E_{\min} = \frac{7}{6\mu_0}(Vf)^{3/7}\left[\frac{3\mu_0}{2}G(\alpha)(1+k)L_\nu\right]^{4/7}$$

$$\simeq 4\times 10^{40}\,\mathrm{erg}$$

(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).

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(Ainsworth+ 2014)

Cosmic rays from the young Sun? (1)

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

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

➔ Low energy cosmic ray electrons

$$r_{\rm L} = \frac{E_{\rm e}}{ecB_{\rm min}} \approx 2 \times 10^{-3}\,{\rm au}$$

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

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

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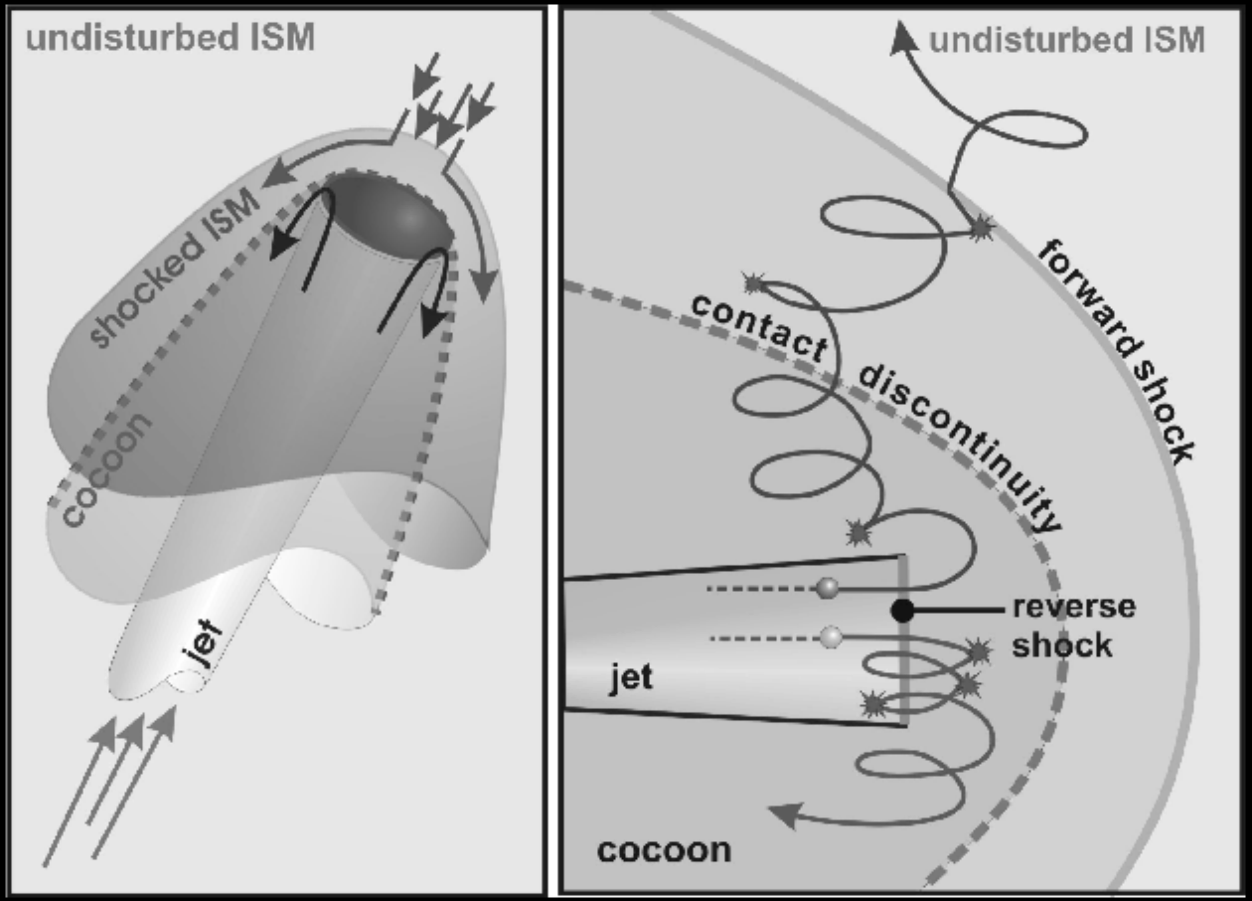
(Ainsworth+ 2014)

Cosmic rays from the young Sun? (2)



(Heinz & Sunyaev 2002)

- 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; see talk by A. Marcowith)
- Observations
  - Synchrotron emission from jets of high mass (e.g. HH 80-81: Carrasco-González+ 2010, Rodríguez-Kamenetzky+ 2017, Vig+ 2018), intermediate mass (e.g. Serpens: Rodríguez-Kamenetzky+ 2016; HOPS 370: see talk by M. Osorio) 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; see talk by L. Podio)

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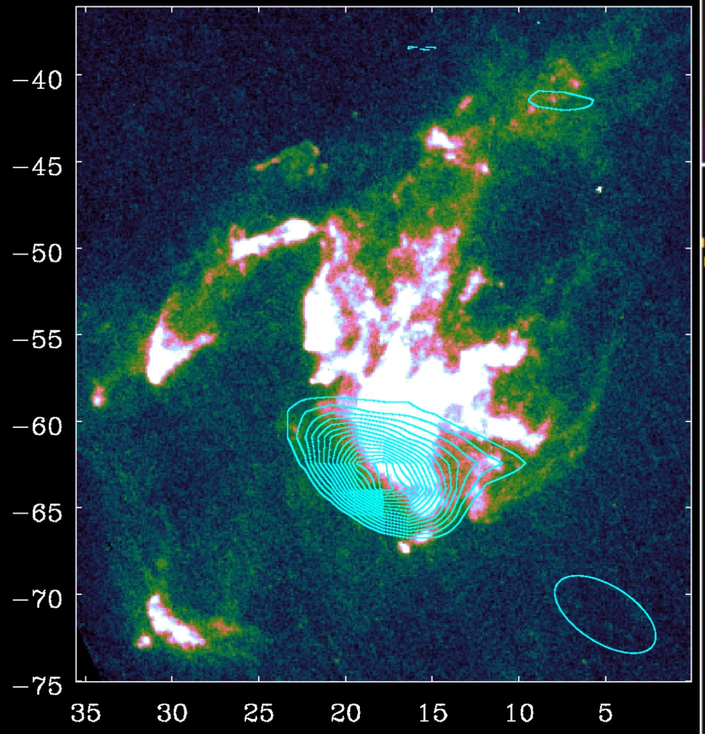
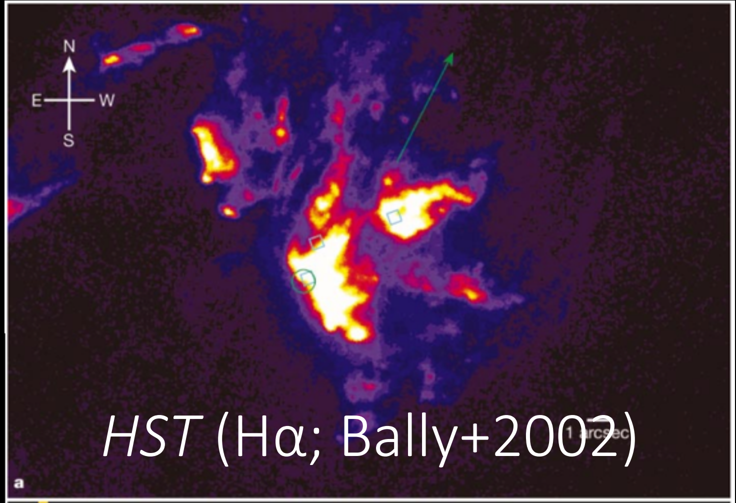
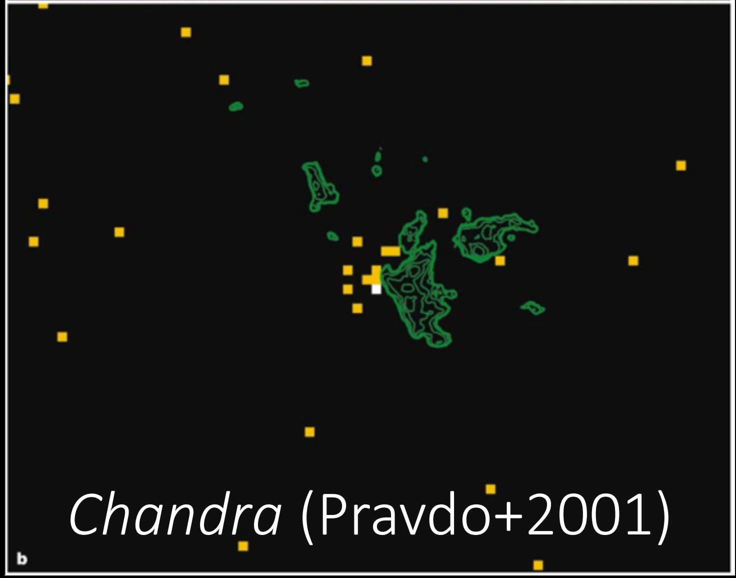
HH 1-2

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

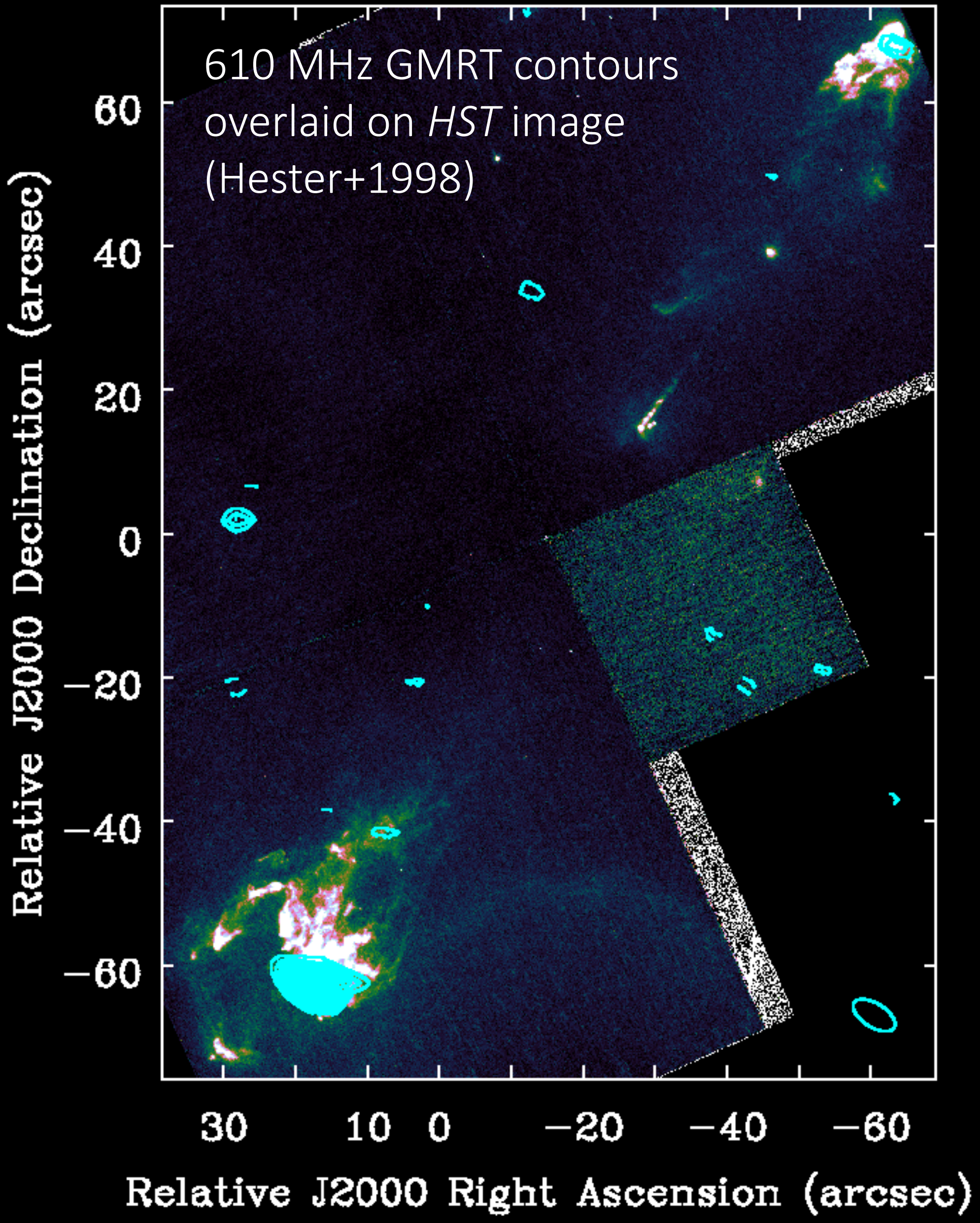




HST (Hα; Bally+2002)



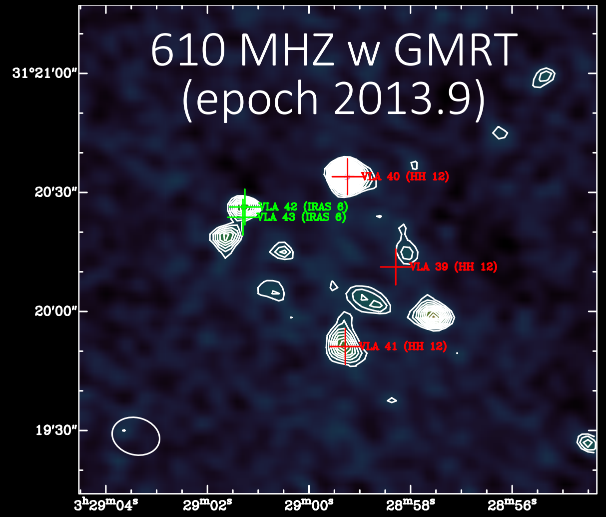
Chandra (Pravdo+2001)

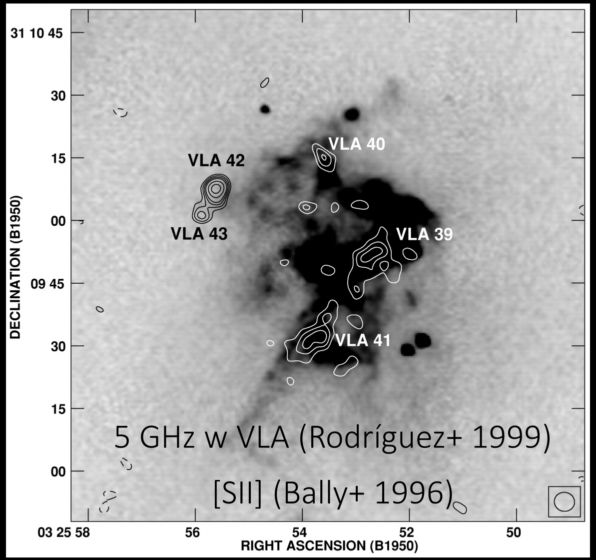


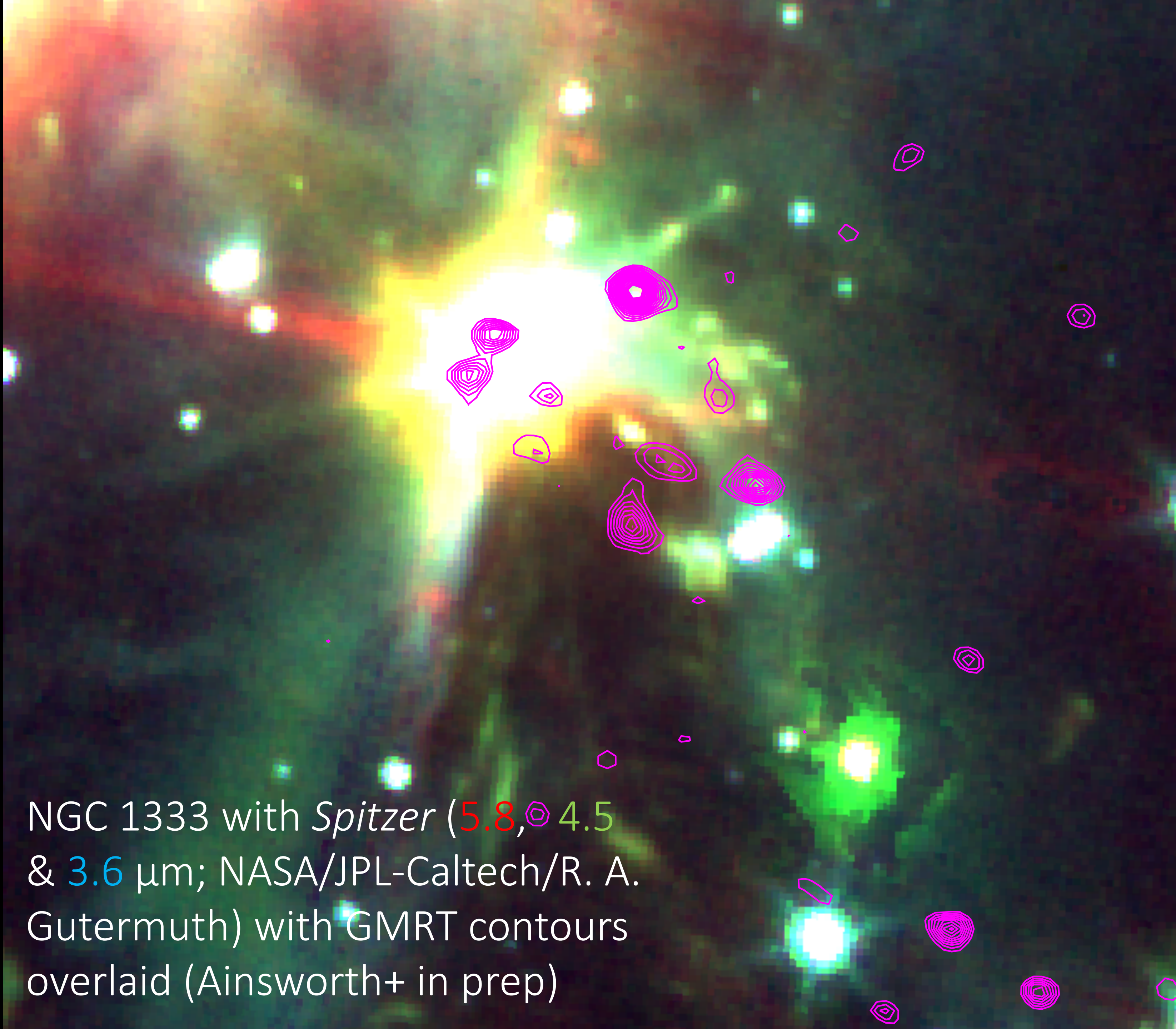
610 MHz GMRT contours overlaid on *HST* image (Hester+1998)

Ainsworth + in prep.

HH 12







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

Summary & current work

- Increasing number of observations of synchrotron emission in outflows from (low to high mass) young stars
  - Metre-wavelength observations are ideal to disentangle competing emission mechanisms in young stellar systems & better detect synchrotron emission
  - Jets from young stars could potentially provide a new laboratory to test the theory of Galactic CR production
- VLA follow-up of DG Tau to confirm nature of radio emission (Purser+ in prep)
- Characterise YSOs at very low radio frequencies (< 1 GHz)
  - Observations of more YSOs with GMRT at 610 MHz (Ainsworth+ in prep)
    - Class 0 sources: L1448, L723, Serpens, HH 1-2
    - Blind survey of NGC 1333

Acknowledgements & contact info

- Collaborators: Anna Scaife (UMAN), Tom Ray (DIAS), Dave Green (Cambridge), Andrew Taylor (DESY), Simon Purser (DIAS)

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