A new method to measure magnetic fields in jets from young stars using LOFAR

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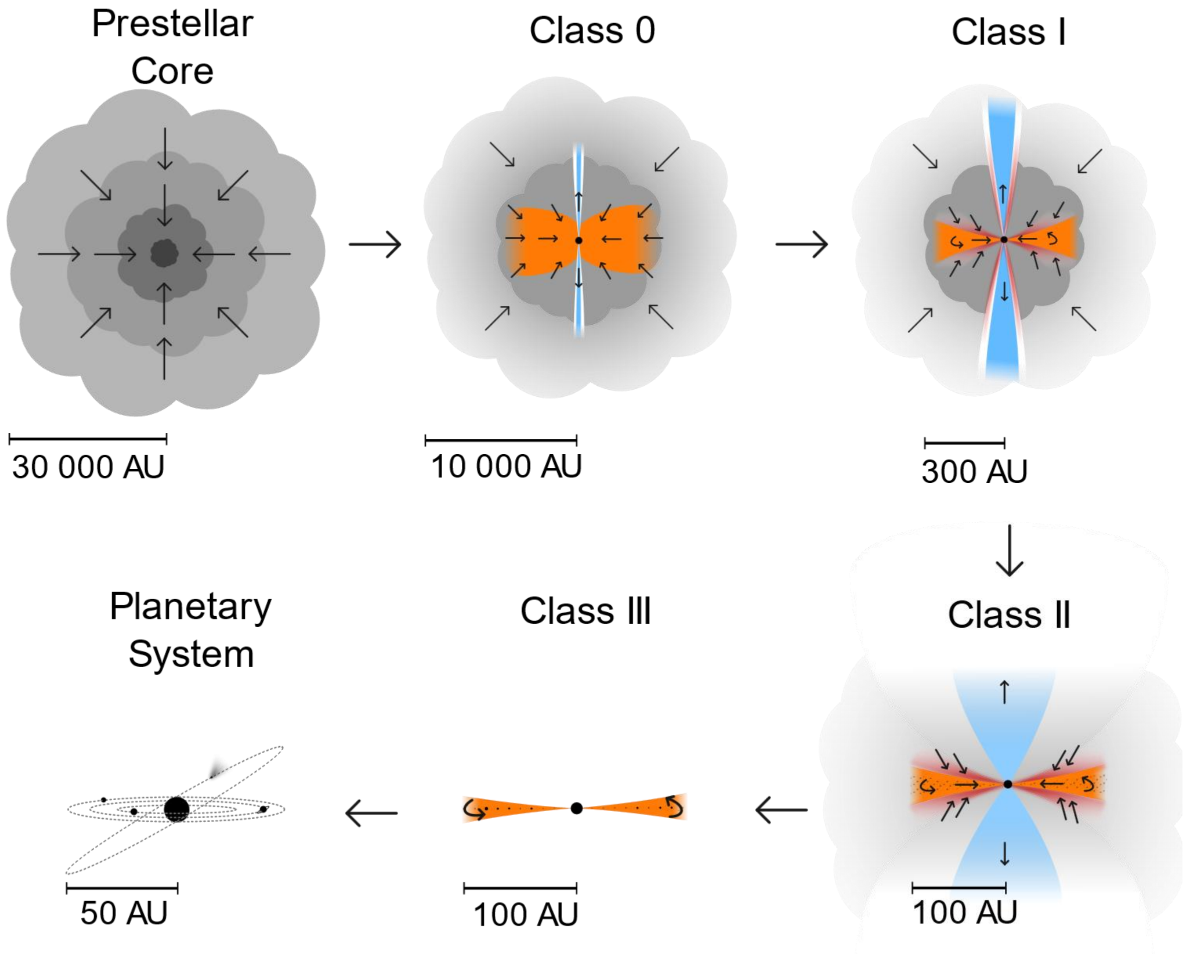
Introduction - Jets

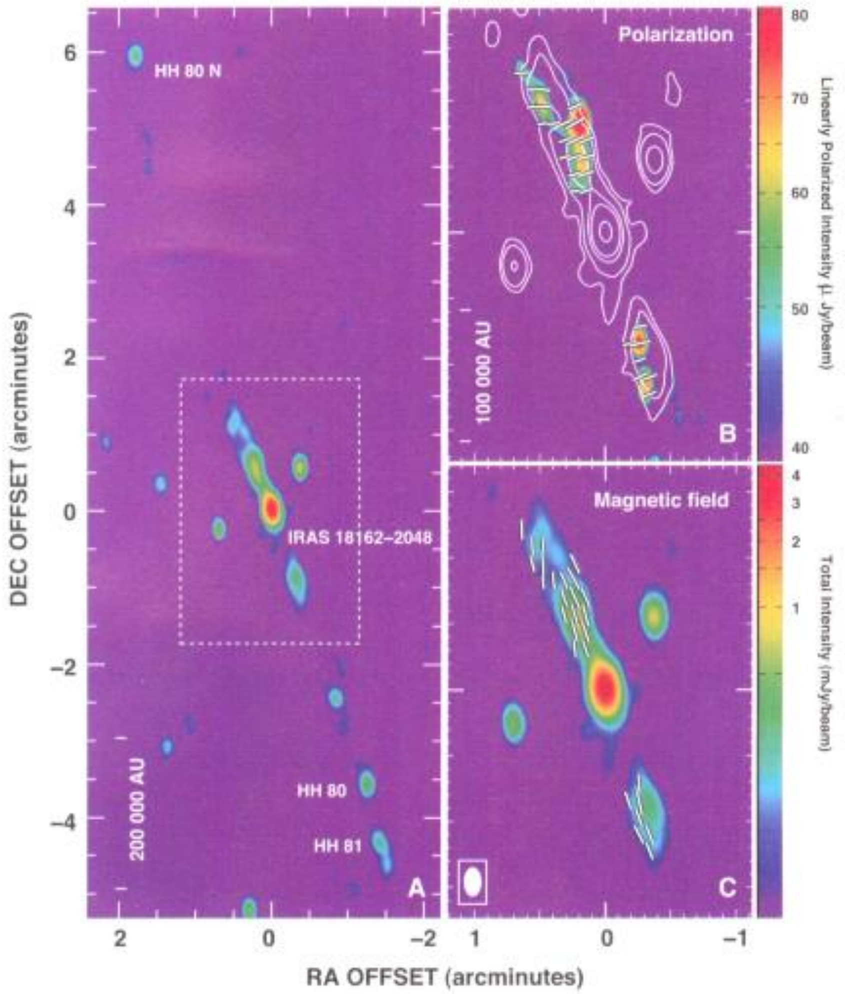
- Young stellar object (YSOs), i. e. stars in the process of formation, are commonly associated with bipolar jets
- Jets play important role
  - Extract mass and angular momentum
  - Drive turbulence in molecular cloud
- Launching mechanism known to involve magnetic field
  - Magnetocentrifugal acceleration
  - Collimated by toroidal component



Star Formation Process (Persson, 2014)

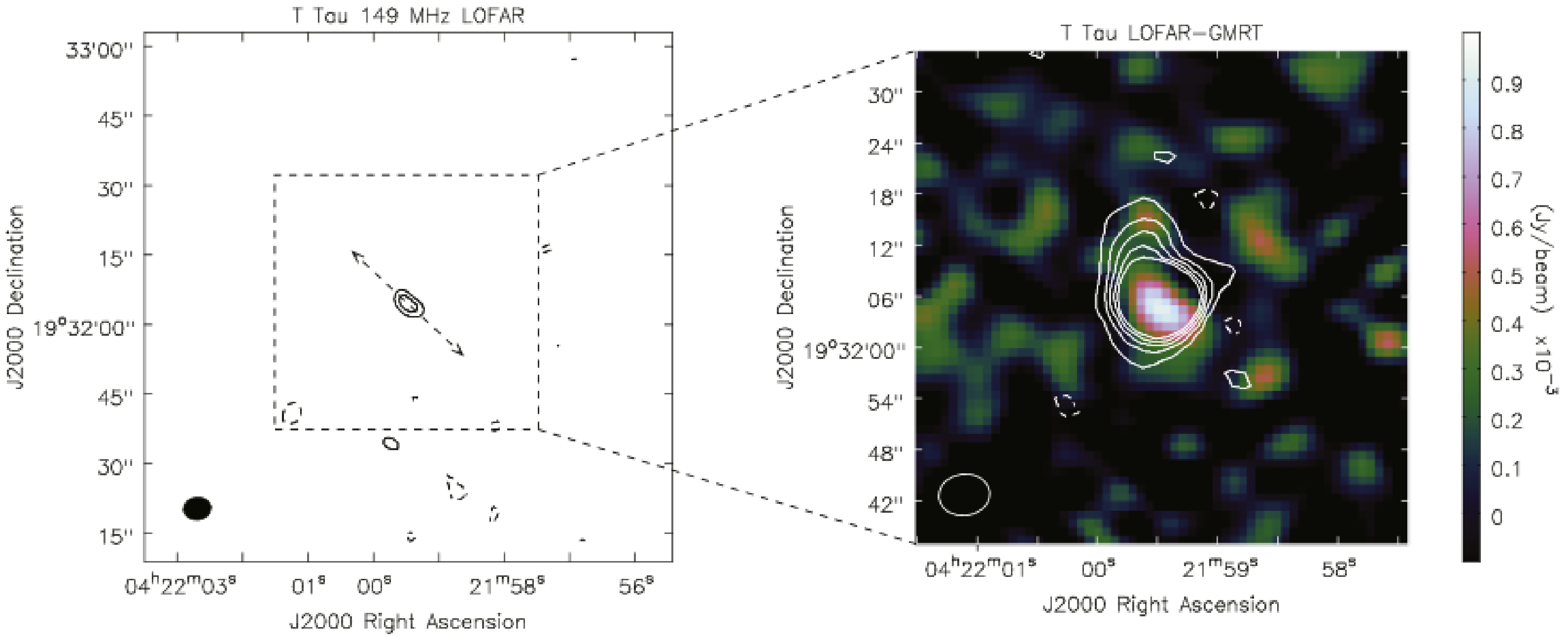
Introduction - Radio Emission from YSOs

- Most radio emission from YSOs is thermal
  - Free-free emission from thermally ionized jets
- Non-thermal emission less well studied
  - Quite weak
  - Synchrotron emission from relativistic electrons in shocks
  - Can study magnetic field
  - Ideal for studying at low frequencies



HH80-81 (Carrasco-Gonzalez et al., 2010)

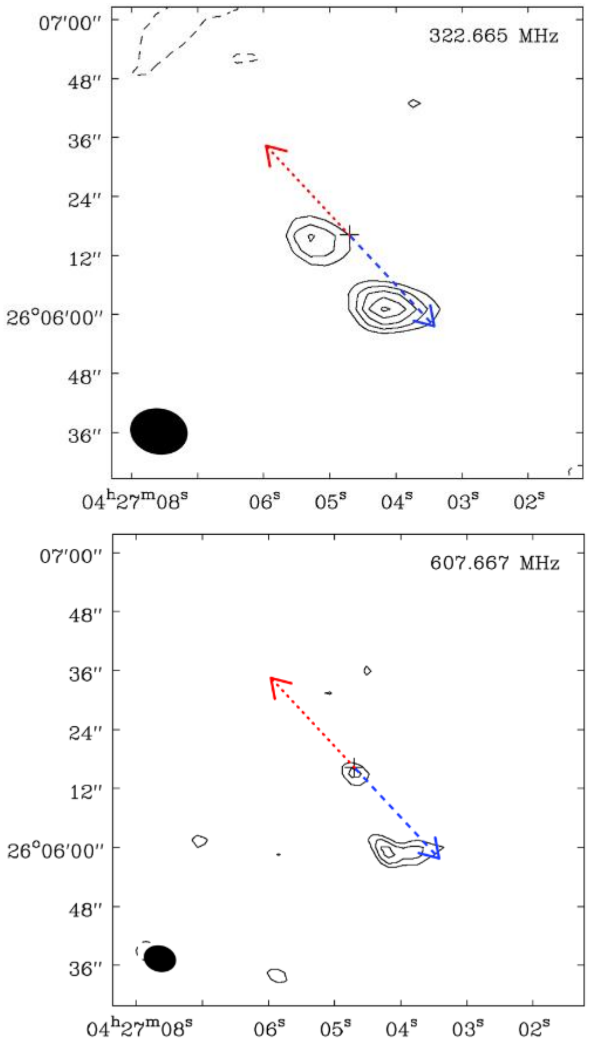
Observing YSOs at low frequencies



- Most study of radio emission from YSOs at higher frequencies (> 1 GHz)
- T Tau previously observed with LOFAR (Coughlan et. al, 2017)
  - Thermal emission from jet observed

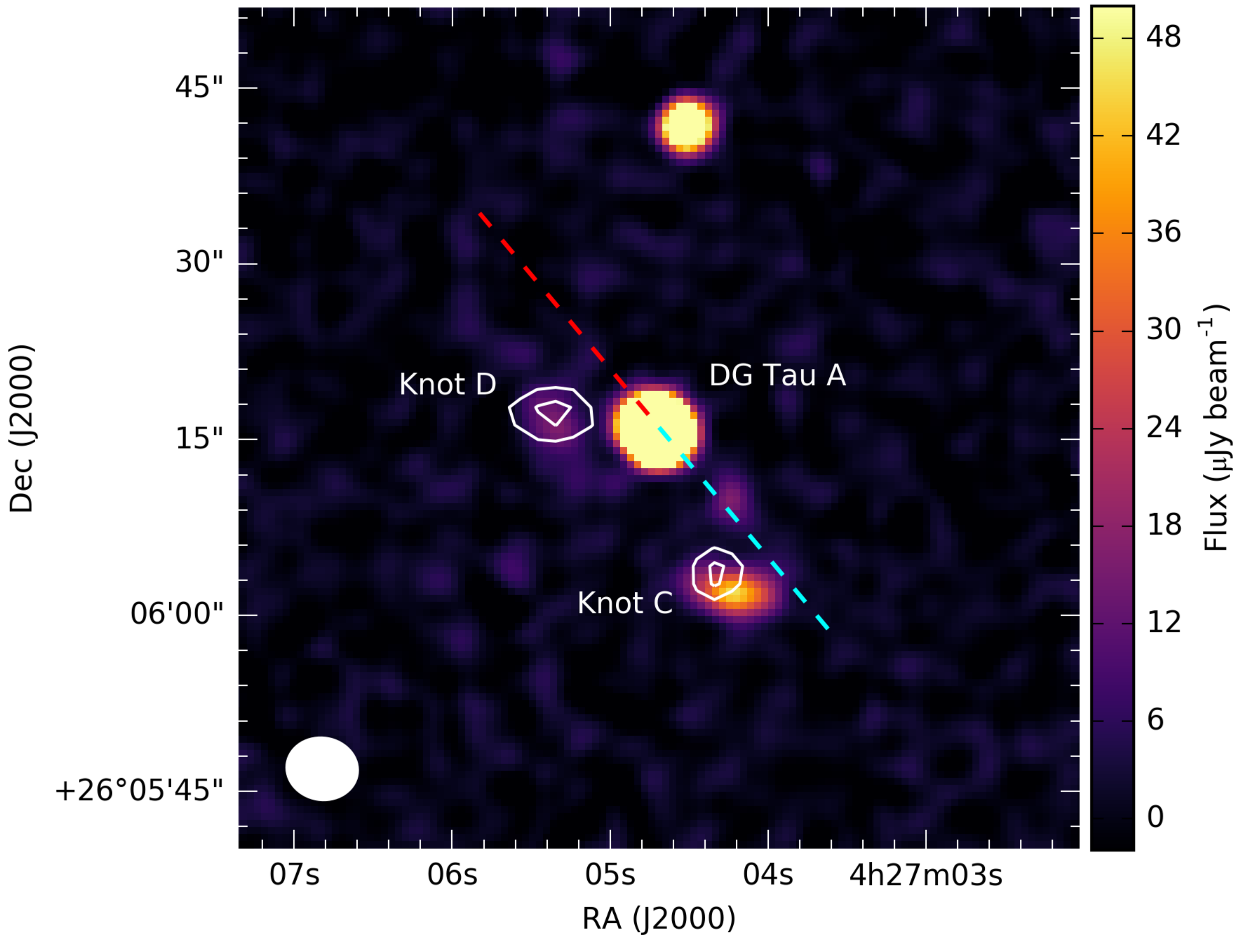
Observing YSOs at low frequencies

- DG Tau A: Low-mass YSO located in the Taurus Molecular Cloud at distance of 120.8 pc
- Observed with Giant Metrewave Radio Telescope (GMRT) at 323 MHz and 608 MHz (Ainsworth et. al, 2016)
- 2 non-thermal (synchrotron) emission knots detected in DG Tau A
  - Knot C SW of DG Tau in approaching jet (blue-shifted)
  - Knot D NE of DG Tau in receding jet (red-shifted)



LOFAR Observation of DG Tau A

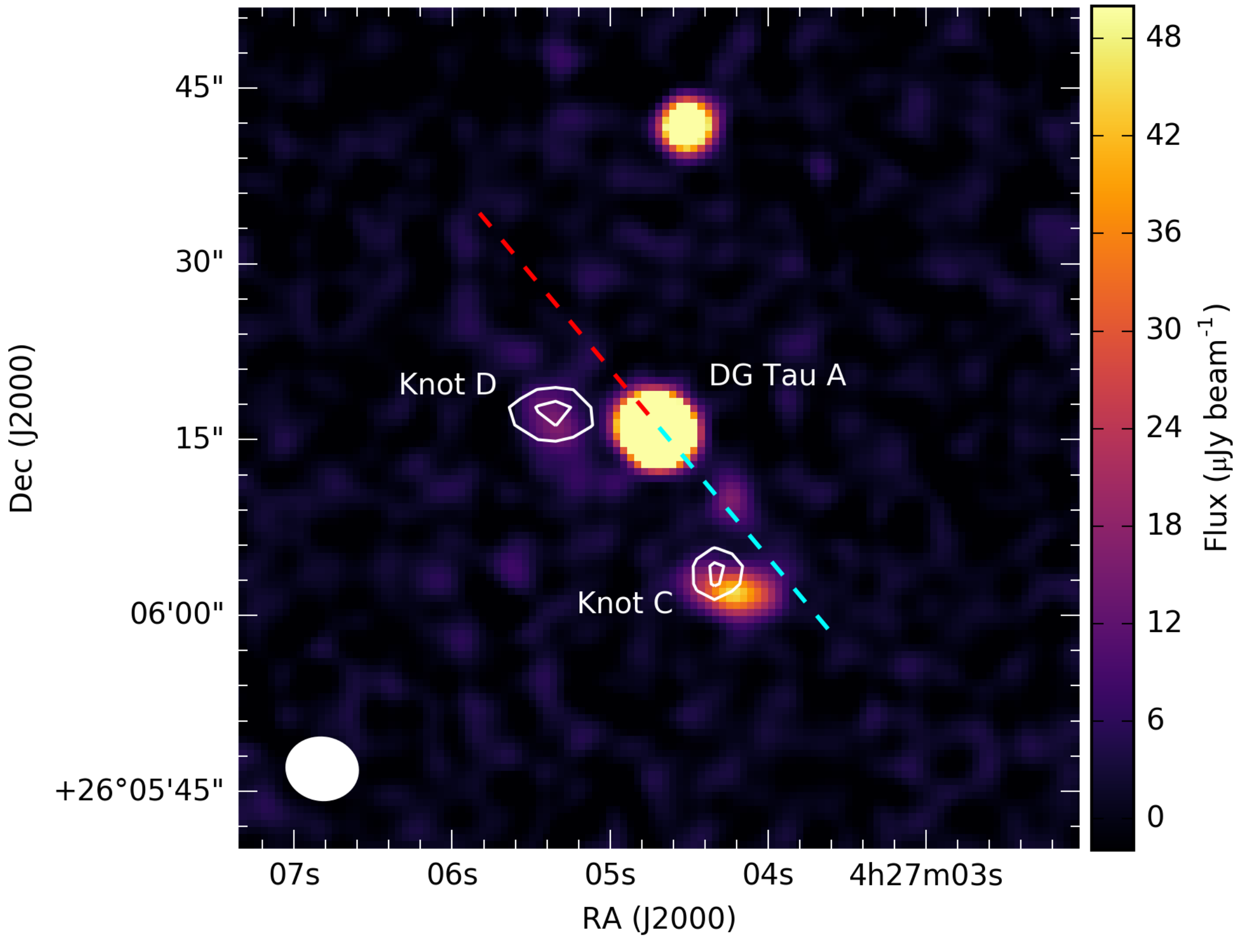
- Observed DG Tau A in November 2013
- With HBA core and remote stations at 110 – 190 MHz
- Time-on-source: 8 hours
- Processed using Prefactor and Factor
- Achieved sensitivity of σ =90 μJy $beam^{-1}$
- Beam Size: 6.0" x 5.2"



LOFAR HBA image (contours) on 6 GHz VLA image (colorscale) (Feeney-Johansson et al., submitted, 2019)

LOFAR Observation of DG Tau A

- Detected both knot C and D at 4σ level
- Did not detect thermal jet (3σ upper limit of S_ν < 270 μJy)



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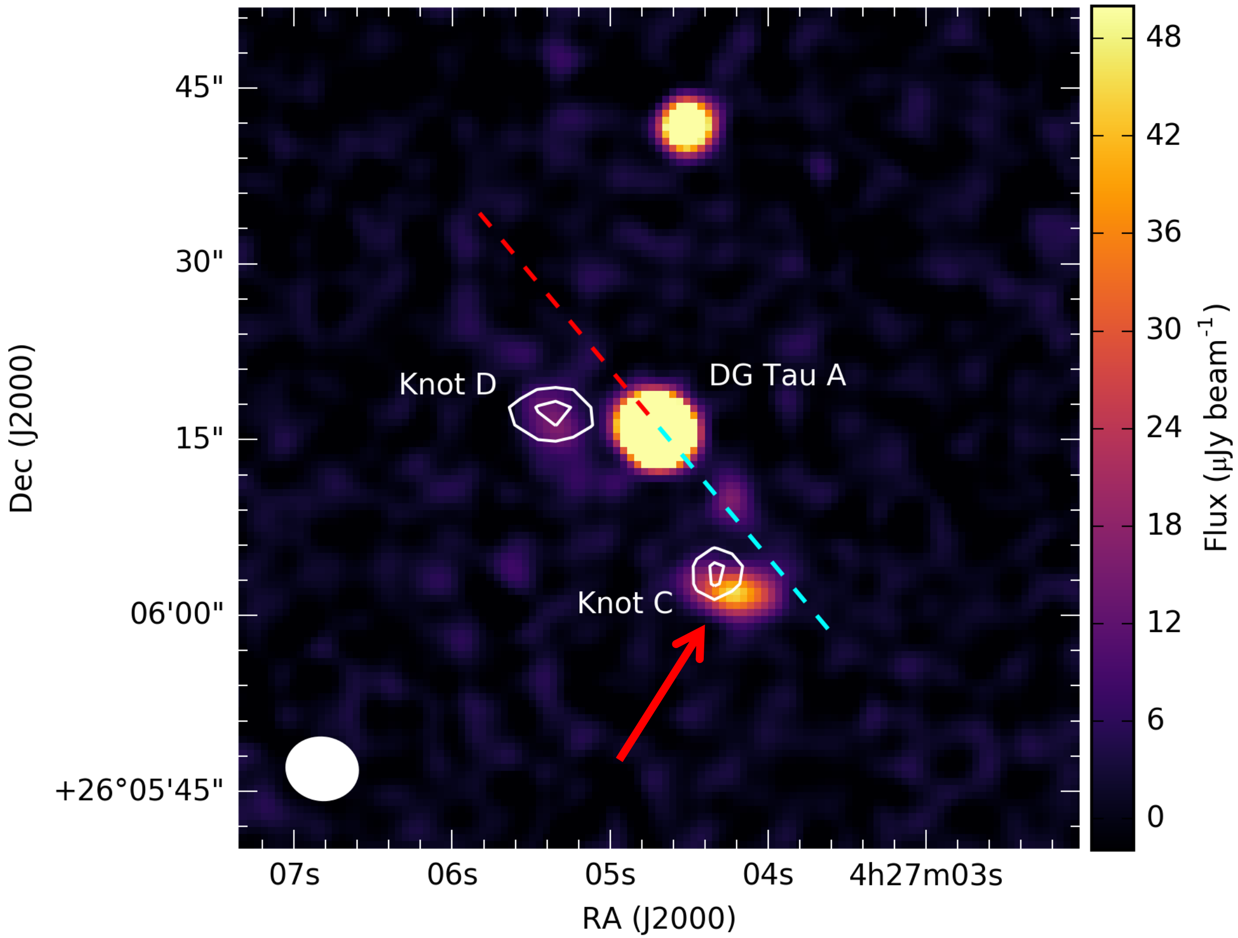
LOFAR Observation of DG Tau A

- Detected with flux density of 490±145 μJy
- Significantly lower than predicted for non-thermal emission
- Low-frequency turnover clearly detected



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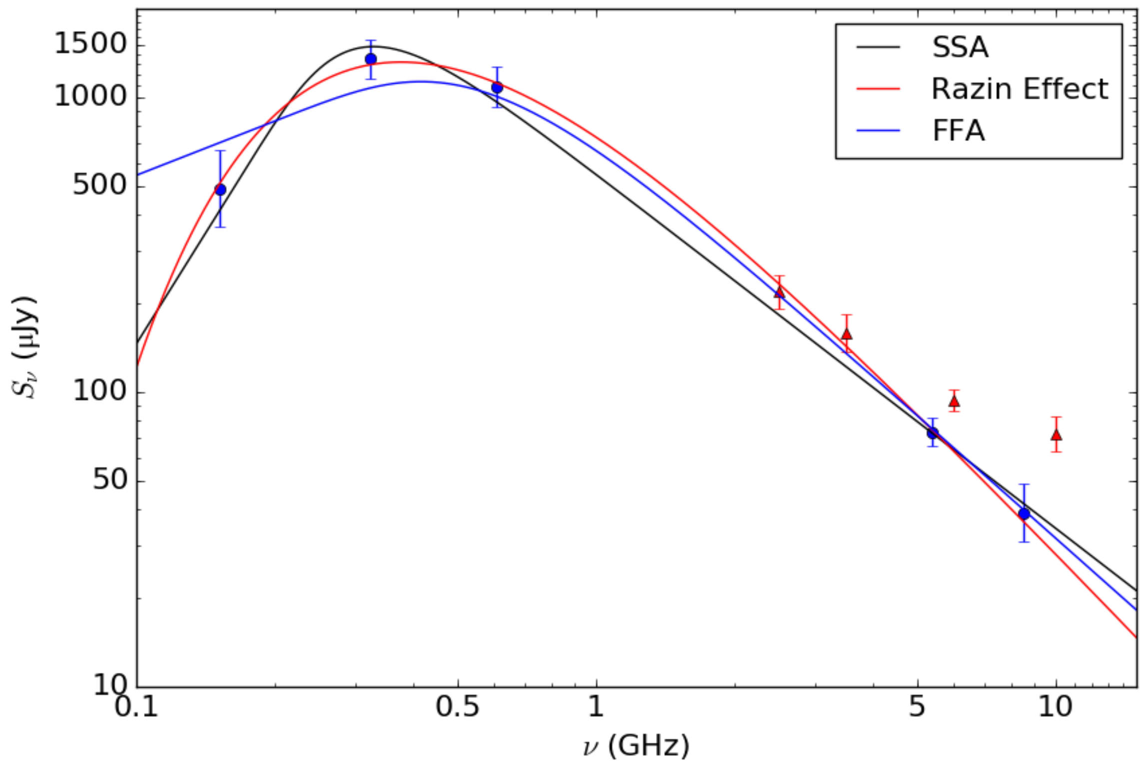
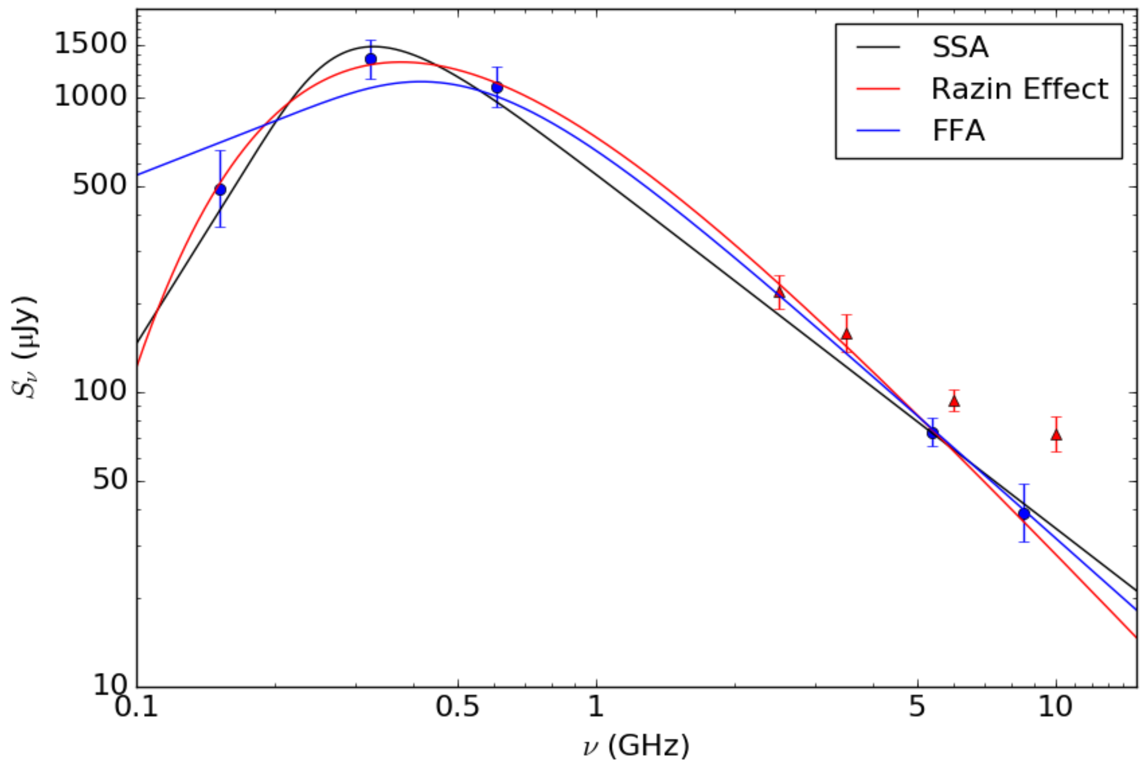


Spectrum of Knot C (Feeney-Johansson et al., submitted, 2019)

Knot C

- Several possible mechanisms for turnover:
  1. Synchrotron Self-Absorption (SSA)
  2. Free-free Absorption (FFA)
  3. Energy Spectrum Cut-off
  4. Razin Effect
- Fitted models to the LOFAR, GMRT and 2012 VLA measurements for each possible mechanism



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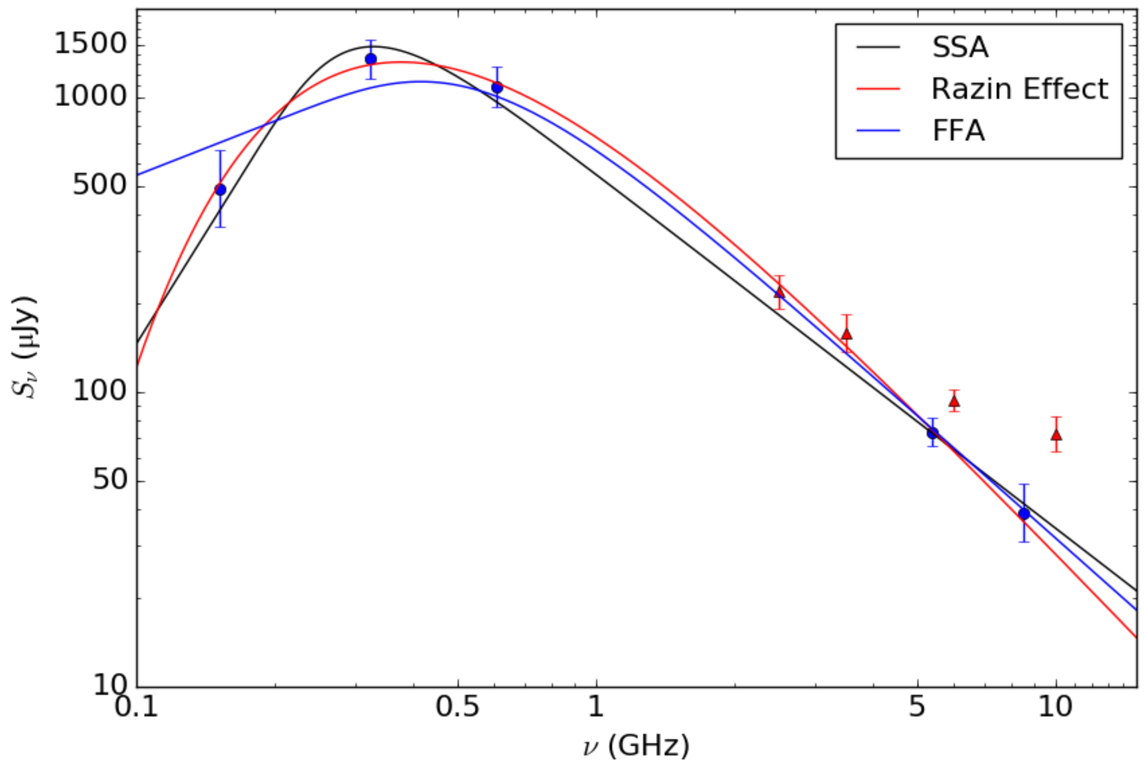
Knot C

- SSA would require unrealistically high magnetic field strength (B ~ 10^{14} G)
- FFA unlikely as electron density required higher then observed (n_e ~ 10^4 cm^{-3})
- Energy spectrum cut-off predicts shallow slope which is not seen



Spectrum of Knot C (Feeney-Johansson et al., submitted, 2019)

Magnetic field strength

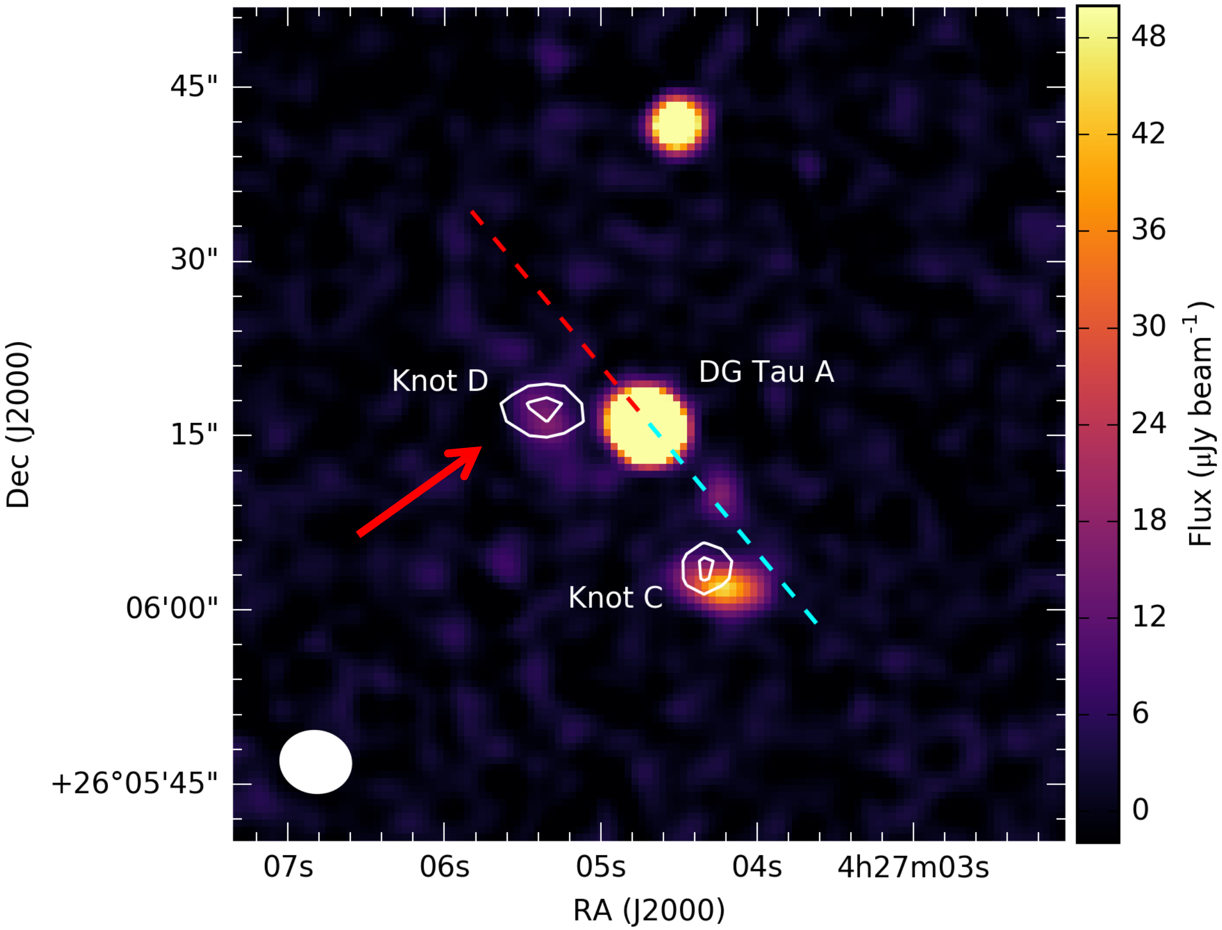
- Razin effect seems most likely based on physical parameters
- Gives simple formula for turnover frequency:

$$\nu = 20\,\frac{n_e}{B}$$

- n_e= 500 cm^{-3} at 14'' from central source (Oh et. al, 2015)
- B ~ 20 μG
- First time magnetic field strength measured in jet with this method
- Comparisons:
  - B ~ 200 μG in high-mass YSO HH80-81 (Carrasco-Gonzalez et al., 2010)
  - B ~ 20 – 30 μG in HH31 and HH111 (Morse et. al, 1992, 1993)

Knot D

- Detected with flux density of 860±205 μJy
- Only 3 measurements at higher frequencies, separated in time
- Tentatively shows a turnover
- Razin effect is plausible explanation
- Lower turnover frequency than knot C
- Could indicate different magnetic field strengths or electron densities



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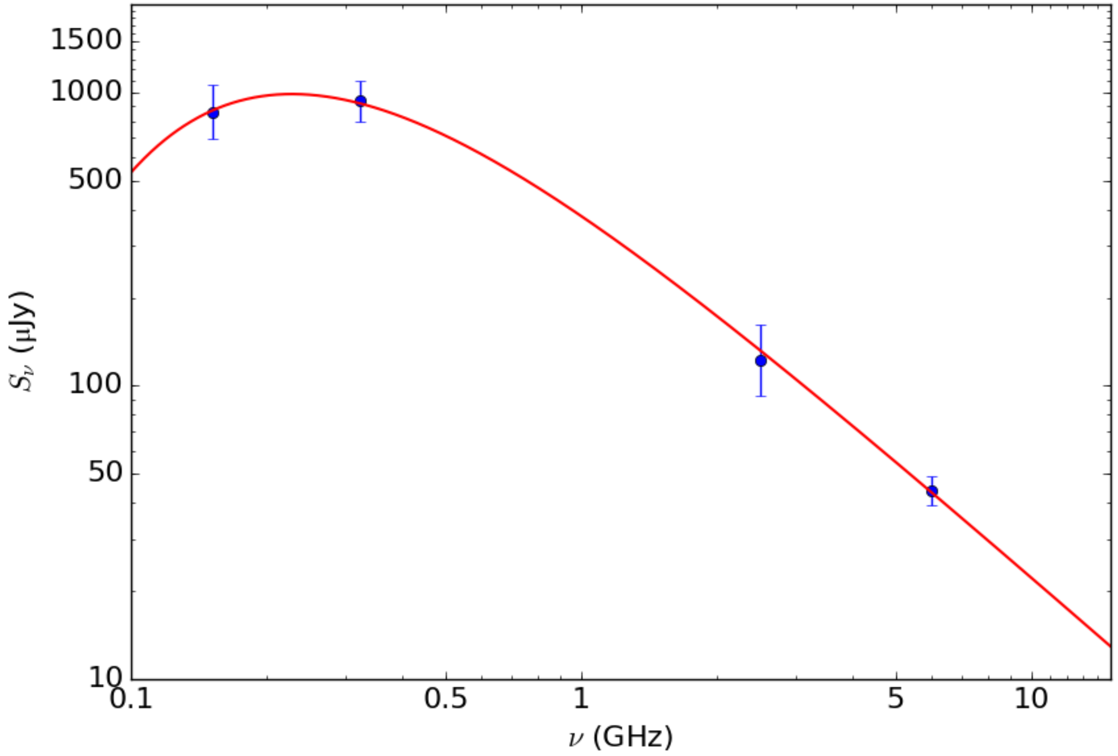
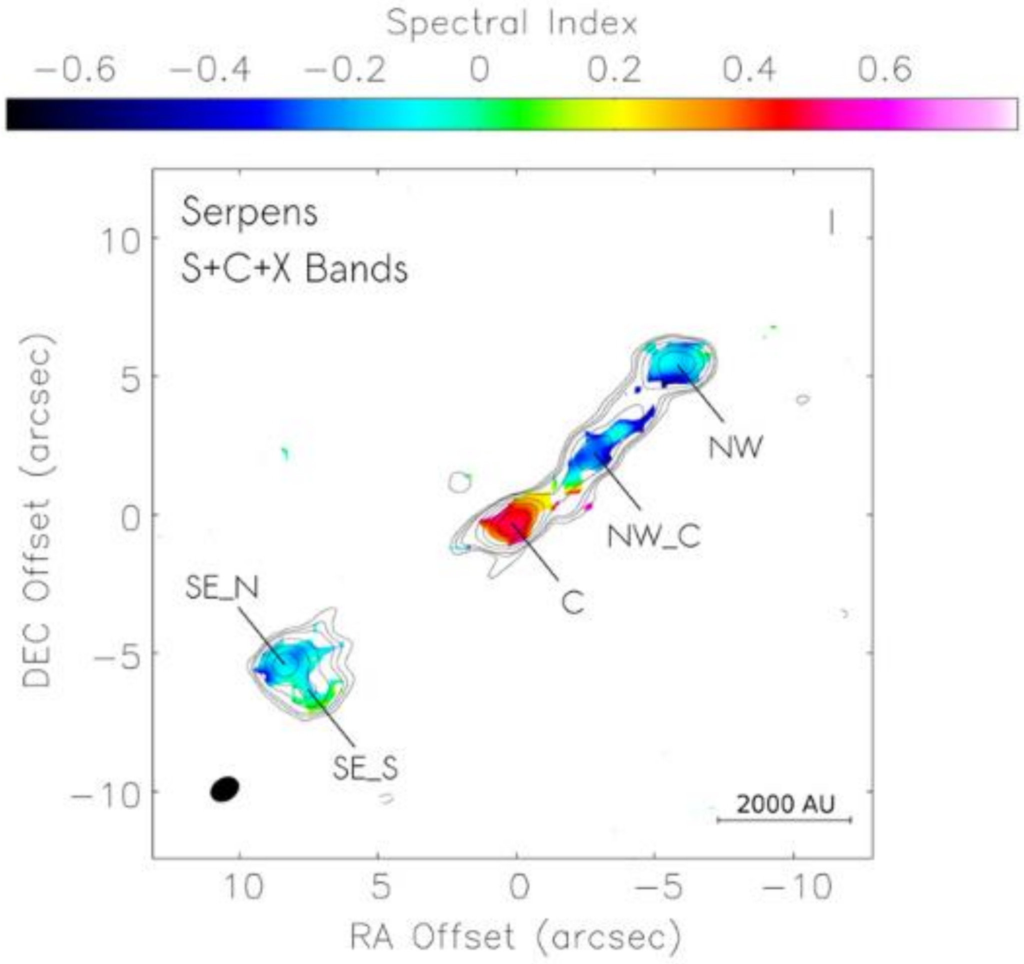


Spectrum of Knot D (Feeney-Johansson et al., submitted, 2019)

Future Work

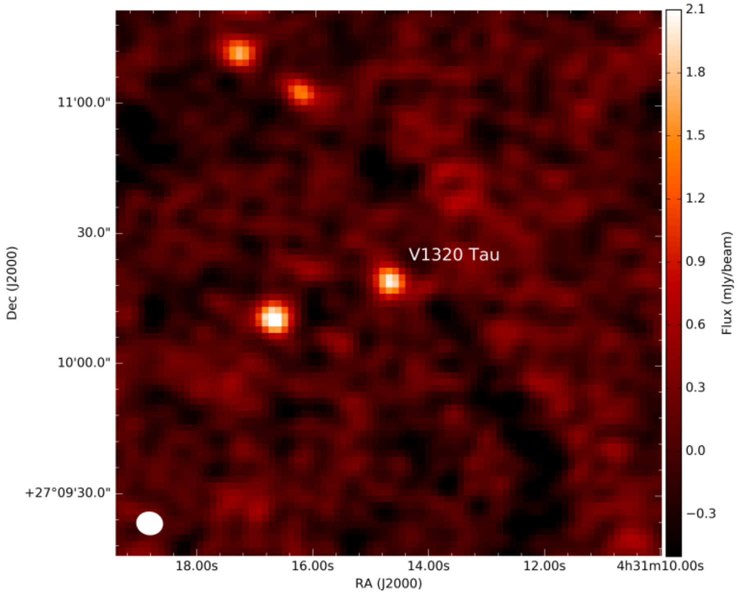
- Search for emission at low frequencies from other YSOs
  - Non-thermal emission in particular
  - Serpens SMM1
    - LOFAR long-baseline observations approved for Cycle 12
    - PI: A. Feeney-Johansson
    - Have GMRT observations as well
  - Molecular cloud survey
    - LOFAR observations to map Taurus Molecular Cloud approved for Cycle 12 co-observing with LoTSS
    - PI: S.. D. Purser

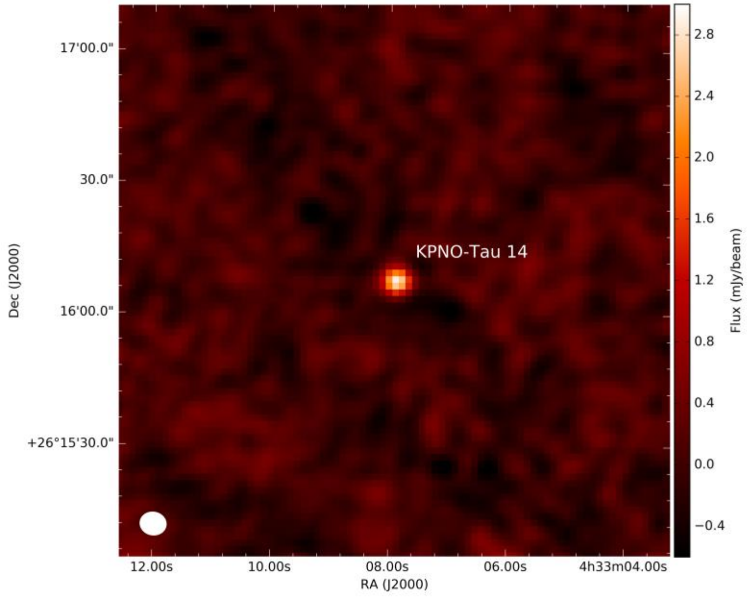


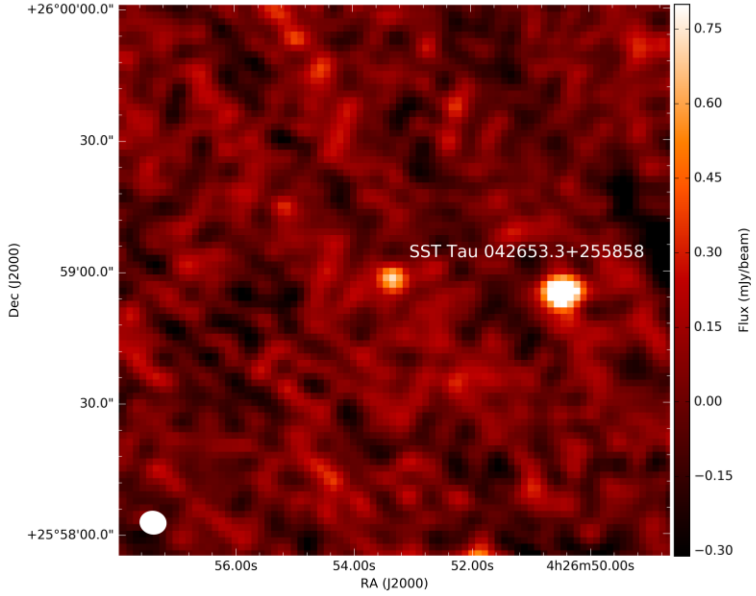
Serpens SMM1 (Rodriguez-Kamenetzky et al., 2016)

Future Work: Other YSOs in field

- Potentially found 3 other YSOs in DG Tau A field
  - V1320 Tau
  - KPNO-Tau 14
  - SST Tau 042653.3+255858







Publications

A. Feeney-Johansson, S. J. D. Purser, T. P. Ray, J. Eislöffel, M. Hoeft, A. Drabent, R. E. Ainsworth, *A new method to measure magnetic fields in jets from young stars using LOFAR,* Astrophysical Journal Letters, submitted, 2019.

Conclusions

- DG Tau A successfully observed with LOFAR HBA for first time
  - Second observation of a YSO with LOFAR
- Turnover detected in spectrum of emission knot in jet
- Razin effect most likely turnover mechanism
- Magnetic field strength in YSO jet derived using spectral turnover for the first time
- Potentially valuable method of measuring magnetic field in YSO jets