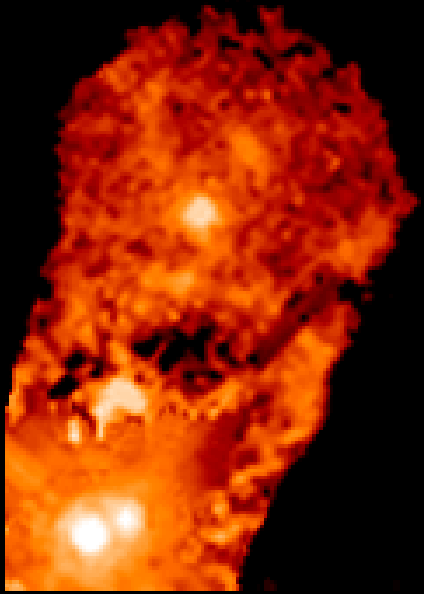
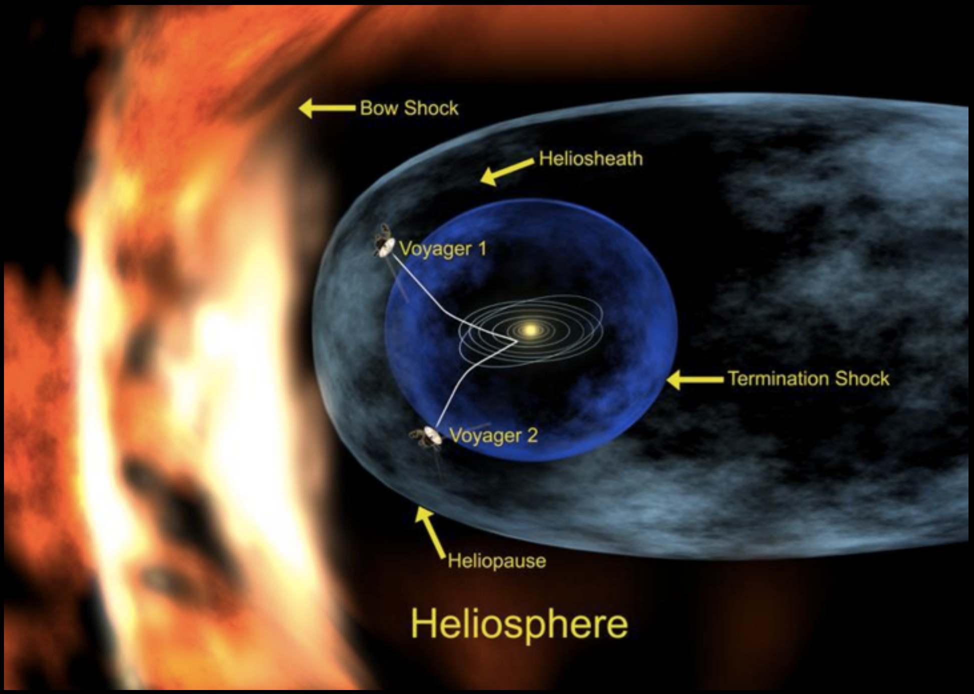
Cosmic Rays from Stellar Birth?





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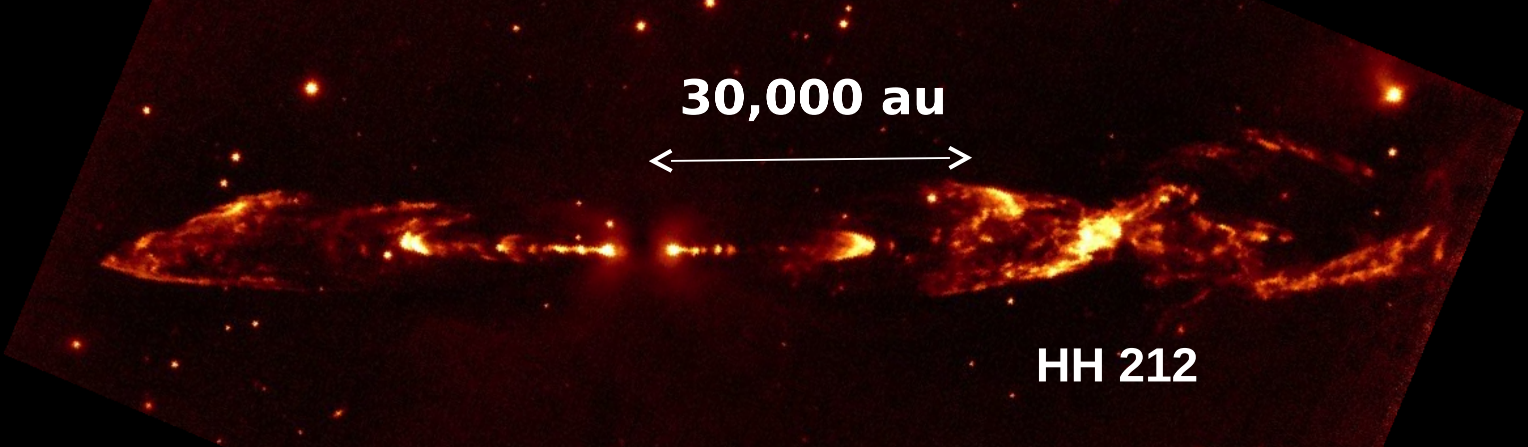
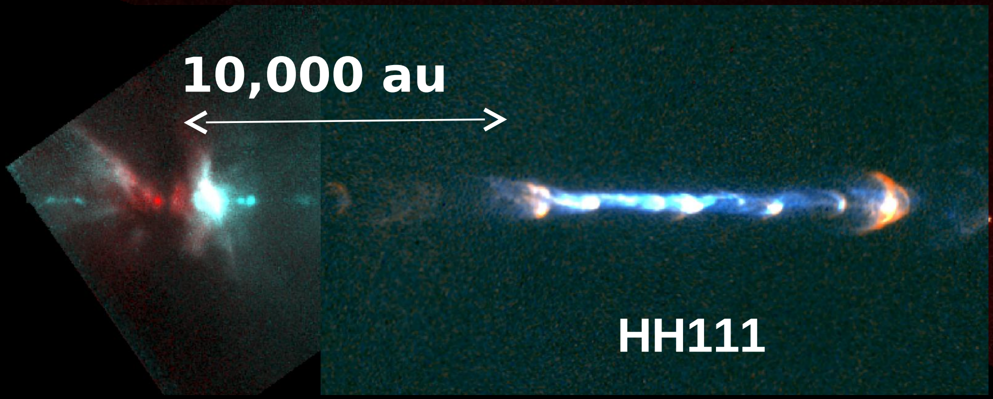
Outline

- Some introductory remarks on outflows & why they are important
- High energy emission: the X-ray regime
- Thermal radio emission from YSO jets
- Non-thermal emission
- Are non-thermal particles from YSO jets important for cloud ionization?

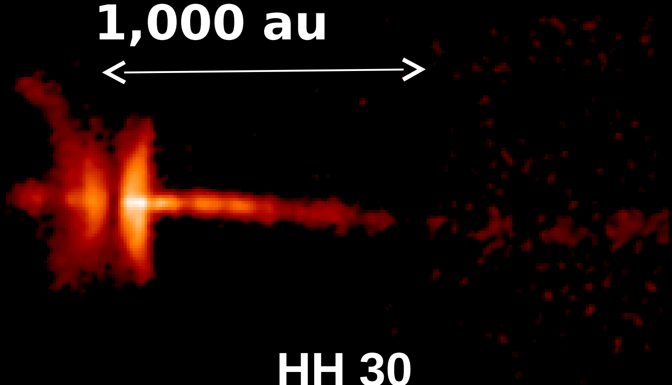
Where Do We See Jets ?



Class 0 Protostars



Evolved Class 1 Protostars



Class 2 Disk (No Envelope)

Universal across evolutionary stage

$$\dot{M}_{Jet} / \dot{M}_{Acc} \approx 0.1$$

Accretion-powered

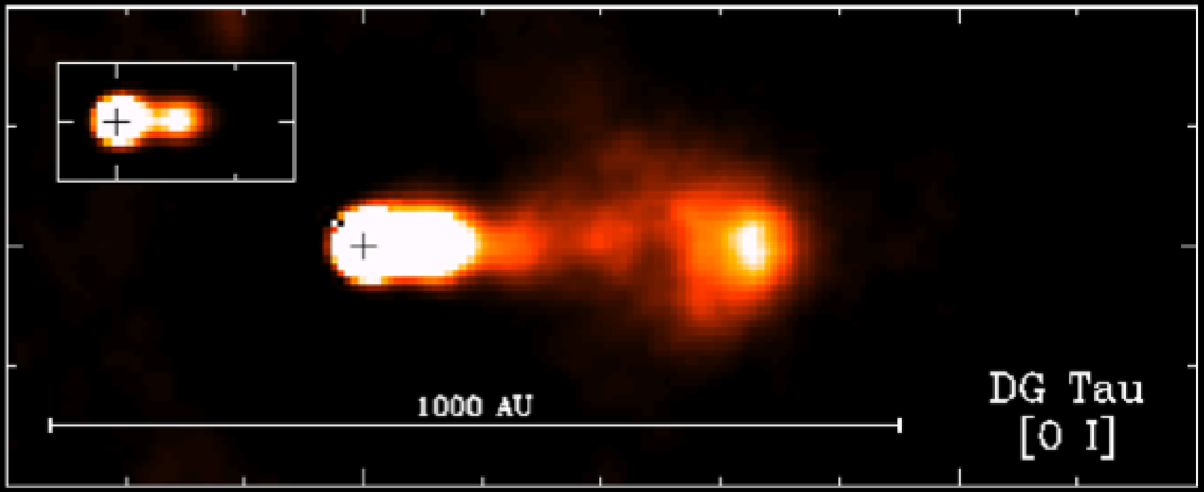
Universal in M_*: from 24 M_{Jup} to 10 M

Why Are Jets Important ?

- Invoked to solve several major issues in SF:
  - Low SFE and SFR in turbulent clouds
  - 30% Core to Star efficiency
  - Removal of star/disk angular momentum
  - Possible cloud support?

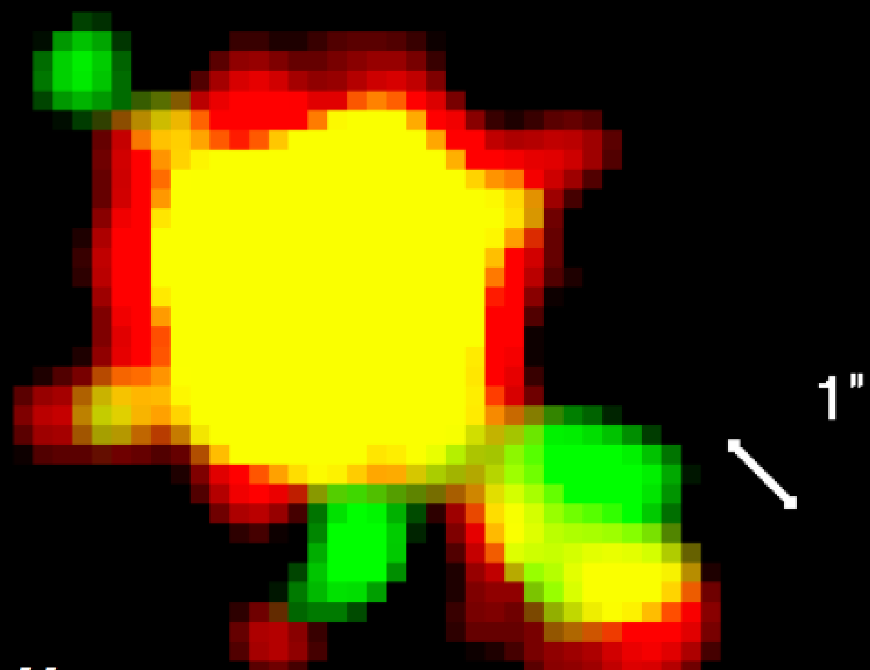
- Also:
  - May affect planet formation and photo-evaporation
  - Unique information on source binarity, variability, axis precession

X-Ray Emission: DG Tau



- Classical T Tauri Star (solar analogue ≈1 Myr old)
- Spectral Energy Distribution (SED) implies a disk is present
- Optical bipolar jet - several knots
- Known X-ray source Jet was detected in X-rays in 2004 (Very faint!)

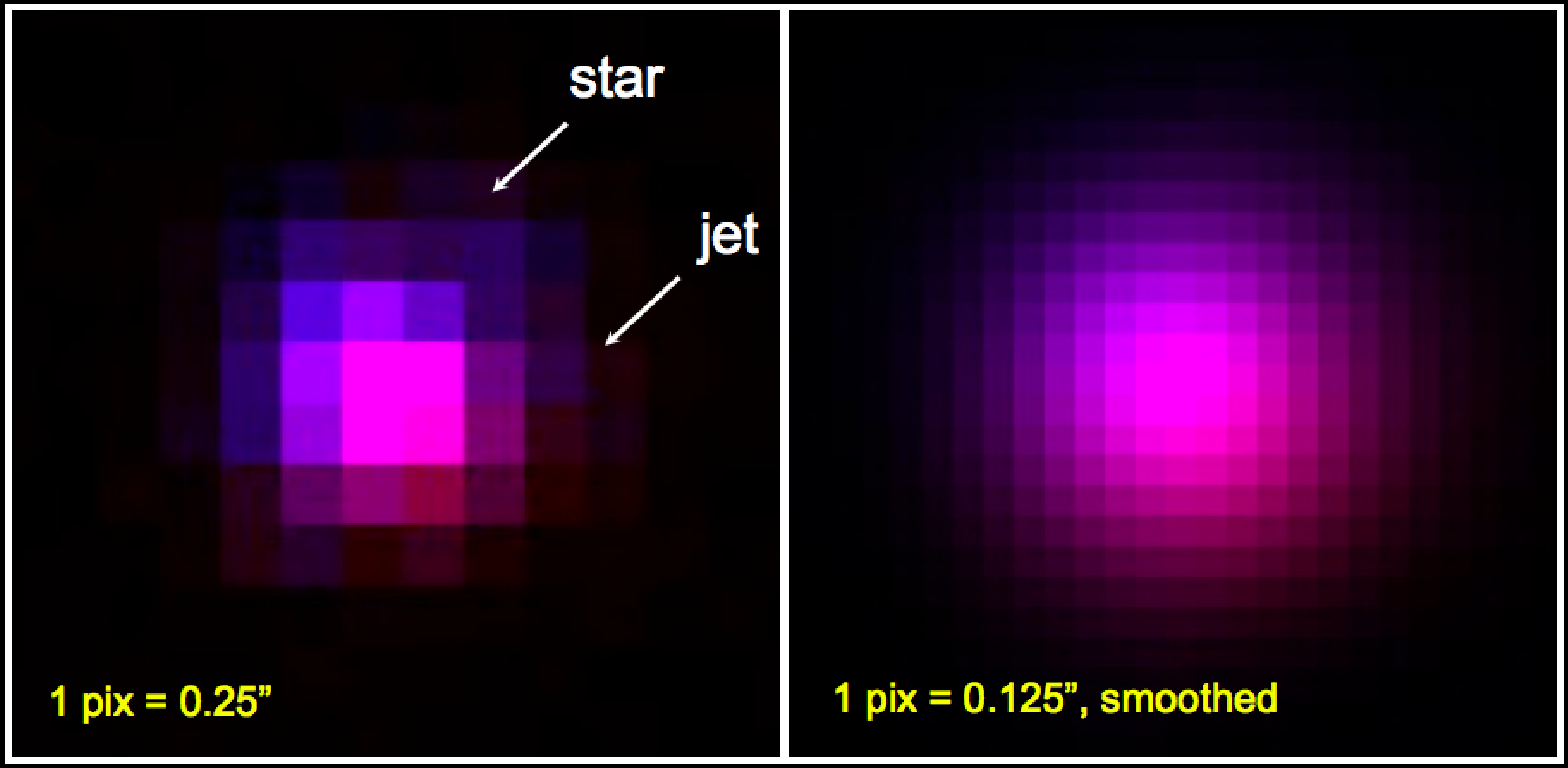
Winter 2004/5 Green
Winter 2010 Red



- Motion of 0.2′′/yr - consistent with optical proper motion
- SW Jet has faded (factor ≈ 2)

The X-ray Components

- Soft component comes from the inner jet T≈ 3.7 MK
- Column density (N_H) is 2-3 times less than expected from stellar extinction - again suggests inner jet
- Also a soft/hard offset present in peak emission


star
jet
1 pix = 0.25”
1 pix = 0.125”, smoothed

What Does the X-ray Observations Tell Us?

- Hard X-ray emission is chromospheric in origin
- Soft X-ray emission is from the jet but is not expected from internal working surfaces (internal shocks)
- Jet must be impacting on virtually stationary media (knots? walls?)
- Cooling will occur rapidly (for $n_e \approx 10^5$) - we are seeing sparks!

Radio Emission from YSO Jets

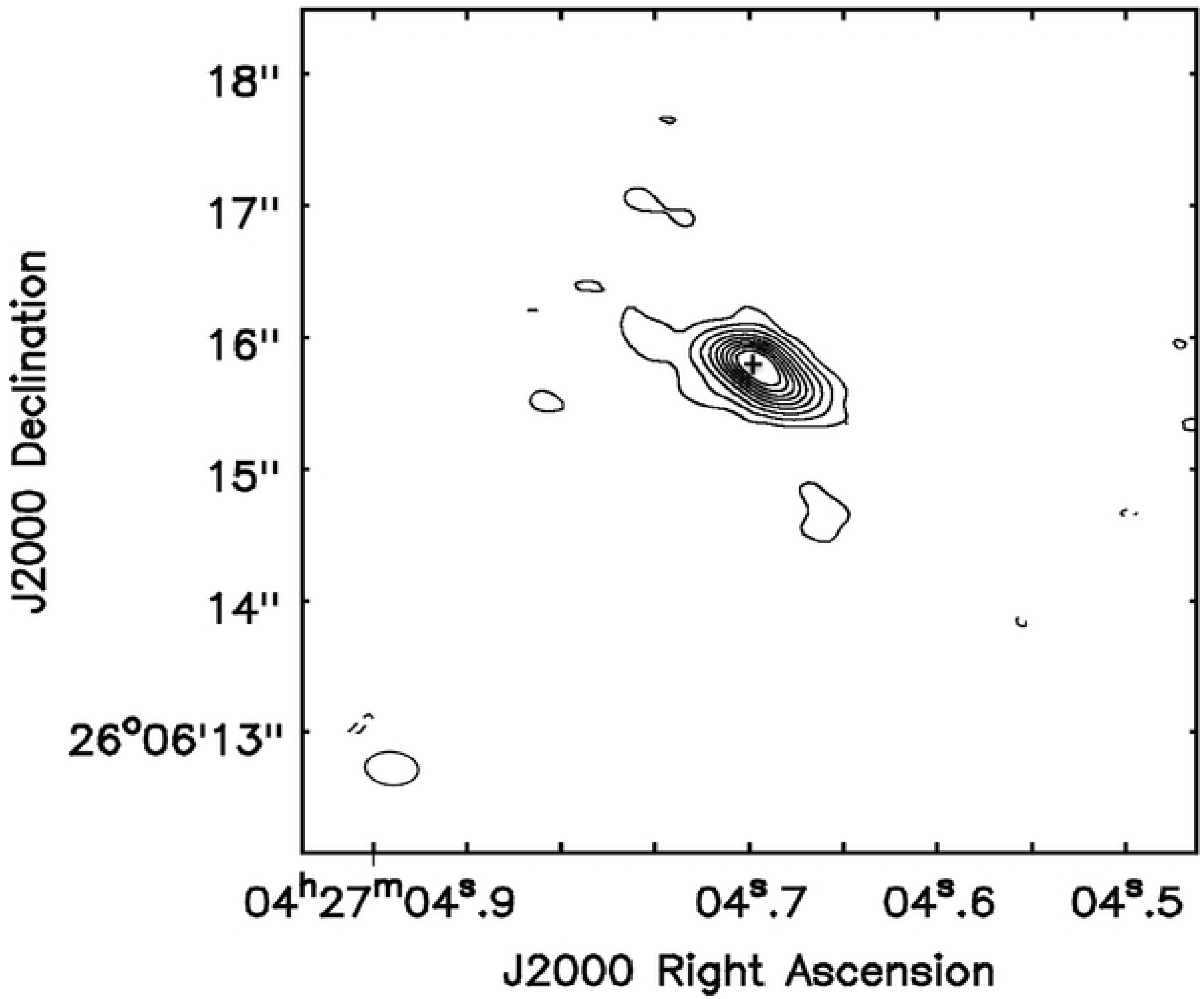
- Continuum usually thermal bremsstrahlung
- Power-law spectral index α, where the flux density ⌫ ⌫↵

$$S_\nu \propto \nu^{\alpha}$$

at frequency ν⌫, varies from α = 2 (optically thick) to α = −0.1 (optically thin)

- Radio observations for a handful of low mass Class 0-II objects imply non-thermal processes (e.g. gyro-synchrotron

DG Tau 8 GHz JVLA (2011.4)



From Lynch et al. 2013

Advantages of Radio Observations

Assuming V_{Jet} similar to optical/NIR jet

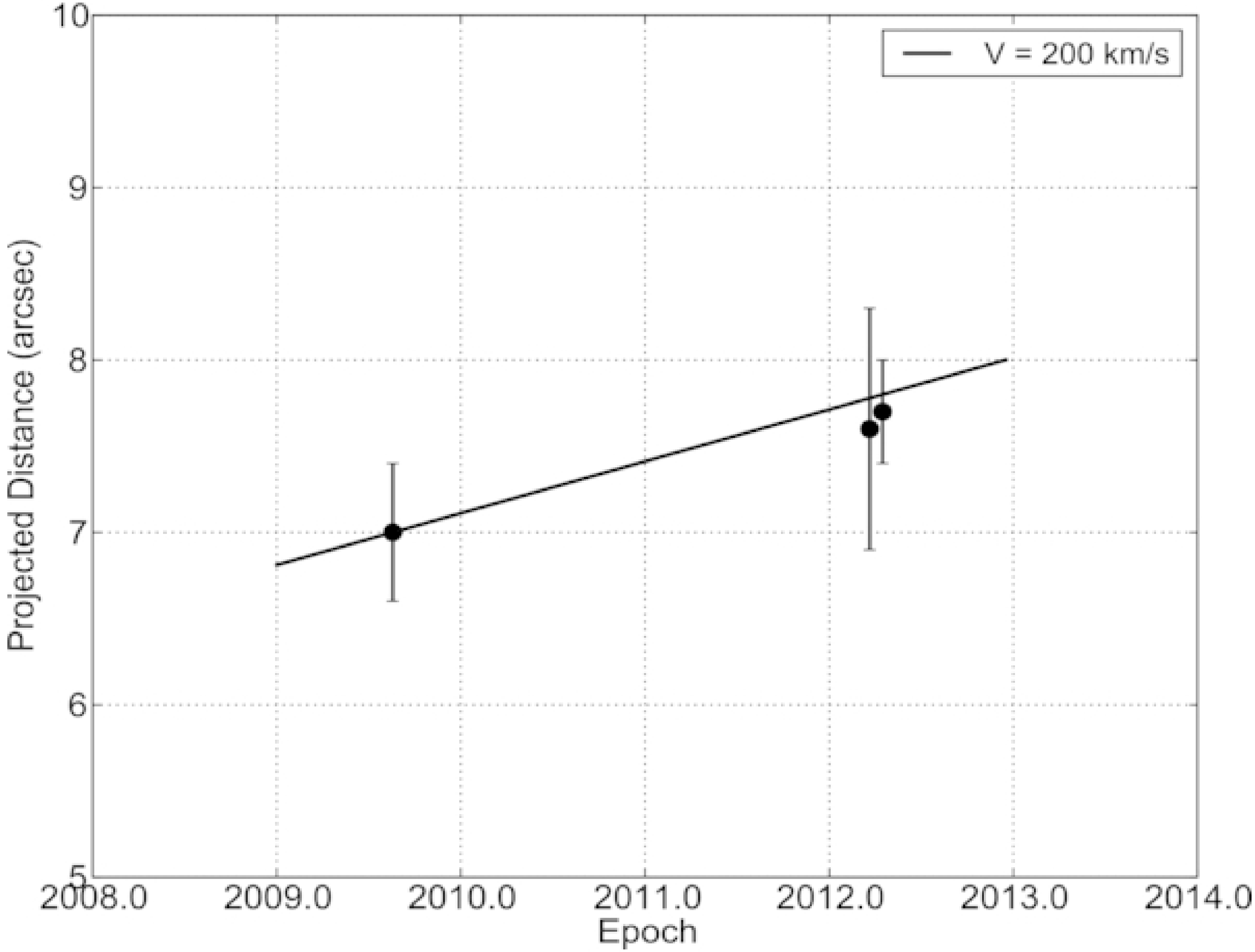
$\dot{M}_{Jet,ion}$ may be estimated

Values close to those from optical/NIR line ratios are found

Possible to probe ionized wind launch region at high spatial resolution

 Facilities such as the Jansky Array and e-MERLIN are opening this field up

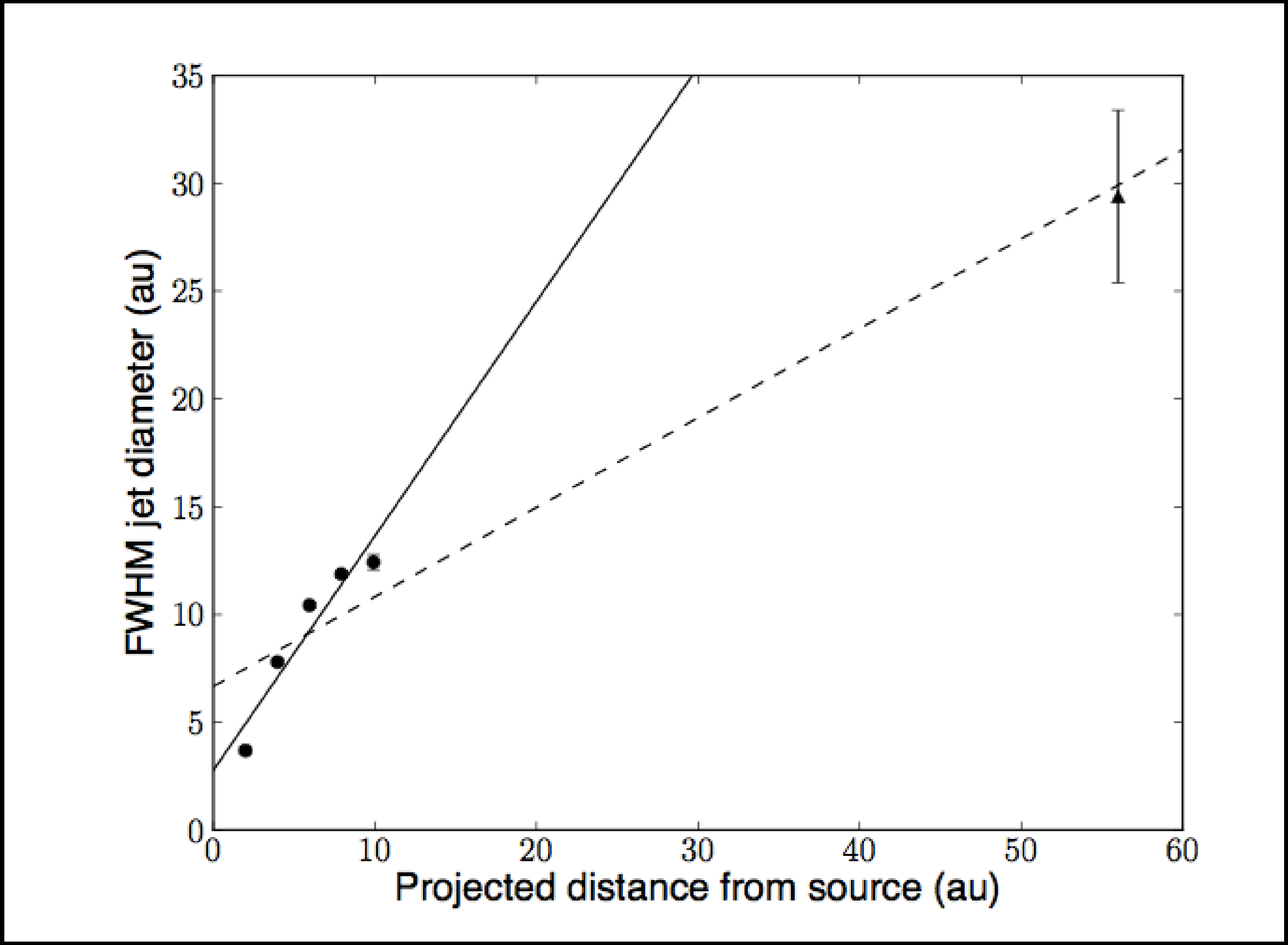
Proper Motion of DG Tau Knot A



Lynch et al. 2013

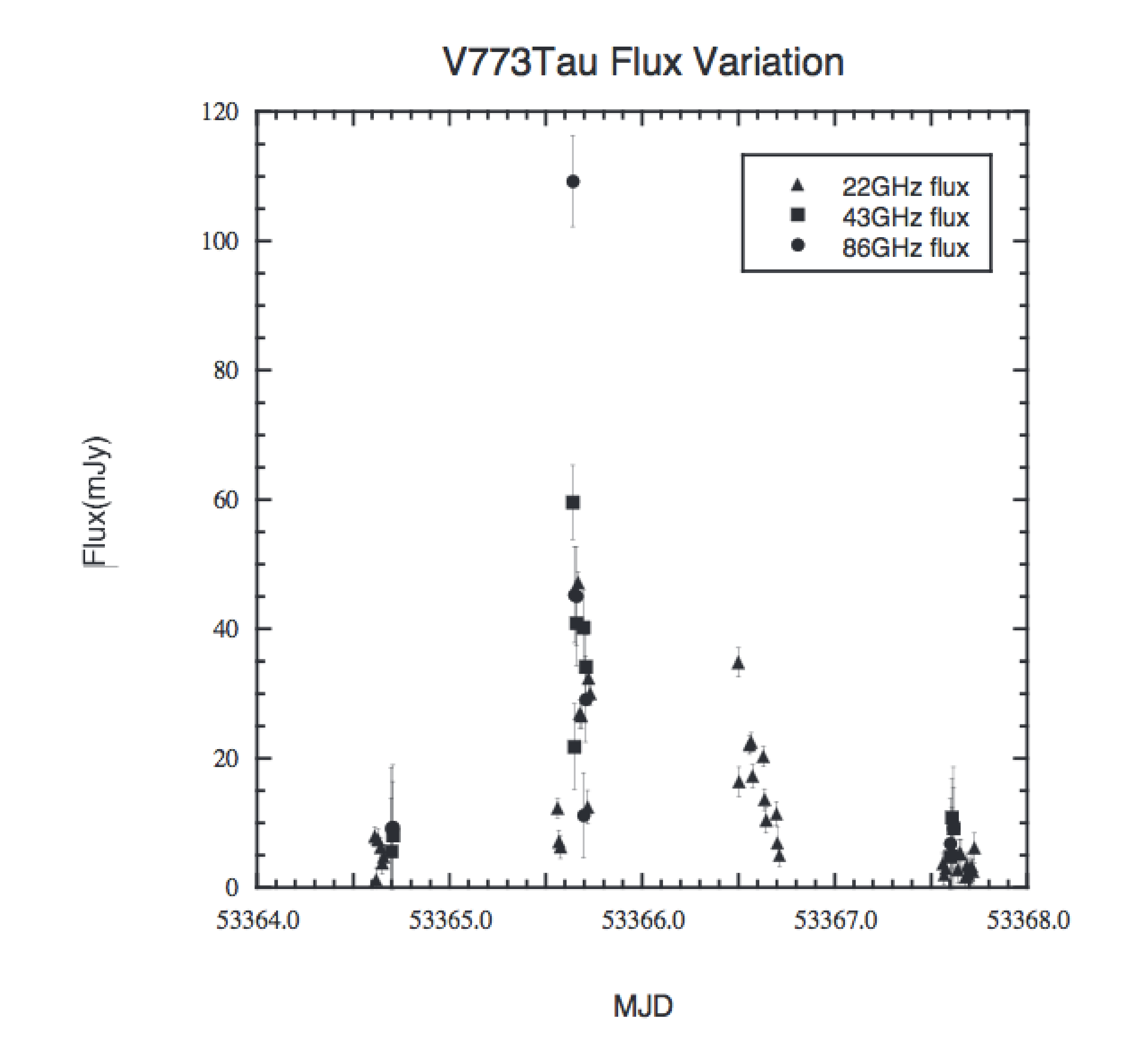
Probing Launch Zone at Radio Frequencies

5 GHz Beam Size ≈ 0.1”



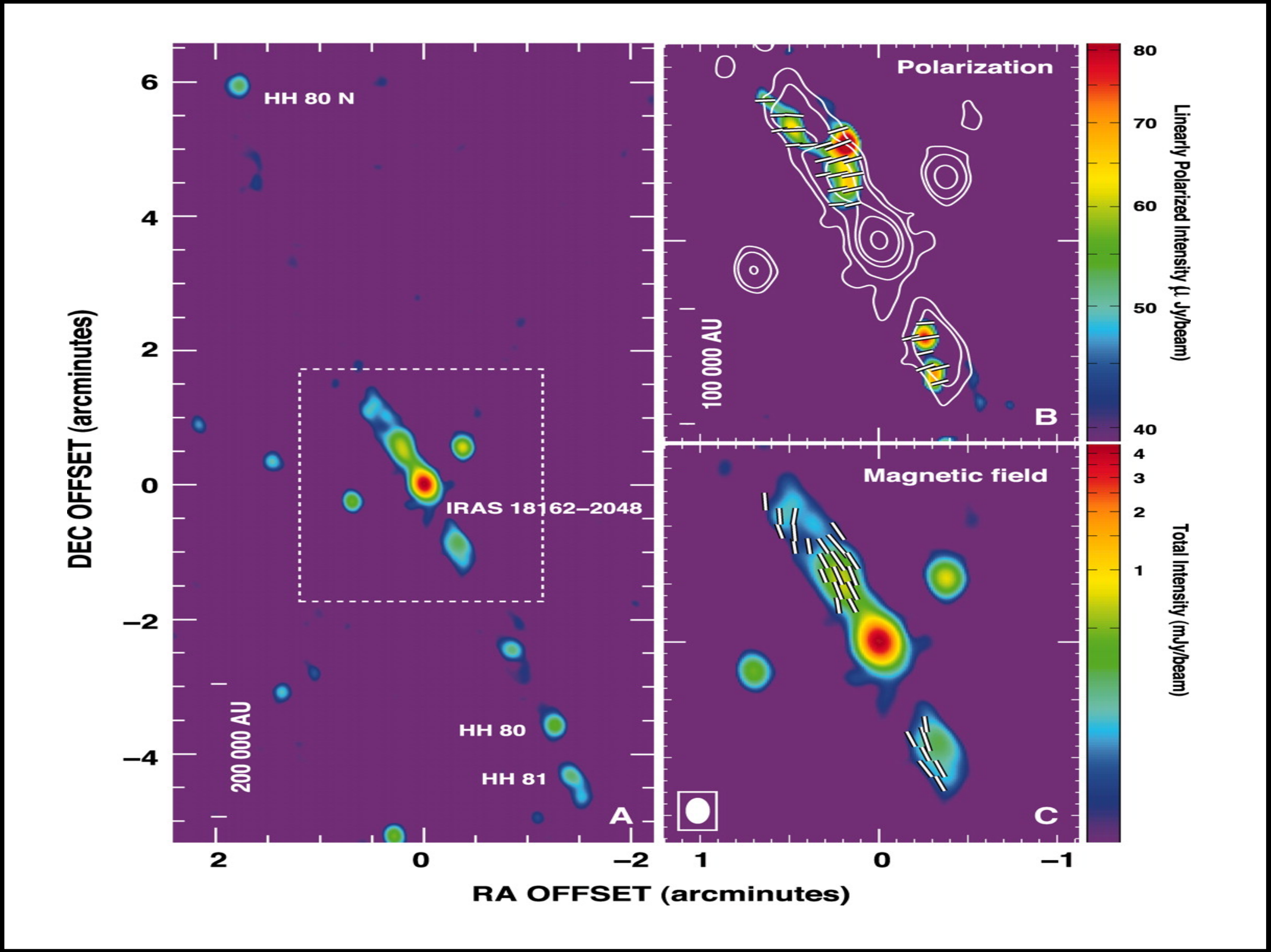
DG Tau A (e-MERLIN)
Ainsworth et al. 2013

Non-thermal Processes in Weak Line T Tauri Stars



Flaring Activity: Non-thermal Particles Present

Most YSO Jets Are Thermal at Radio Wavelengths but … HH 80-81 jet (IM Protostar) at 6 cm

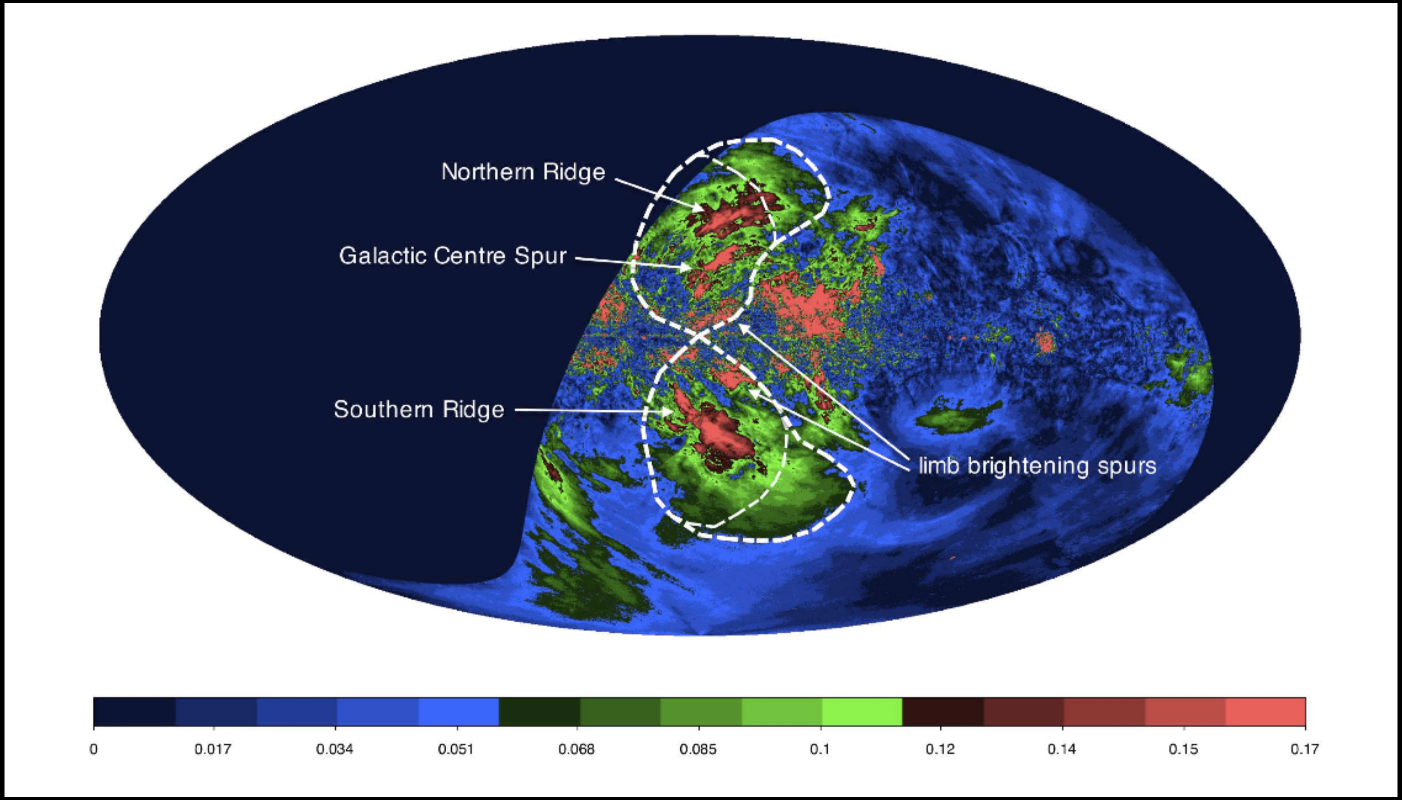


C Carrasco-González et al. 2010

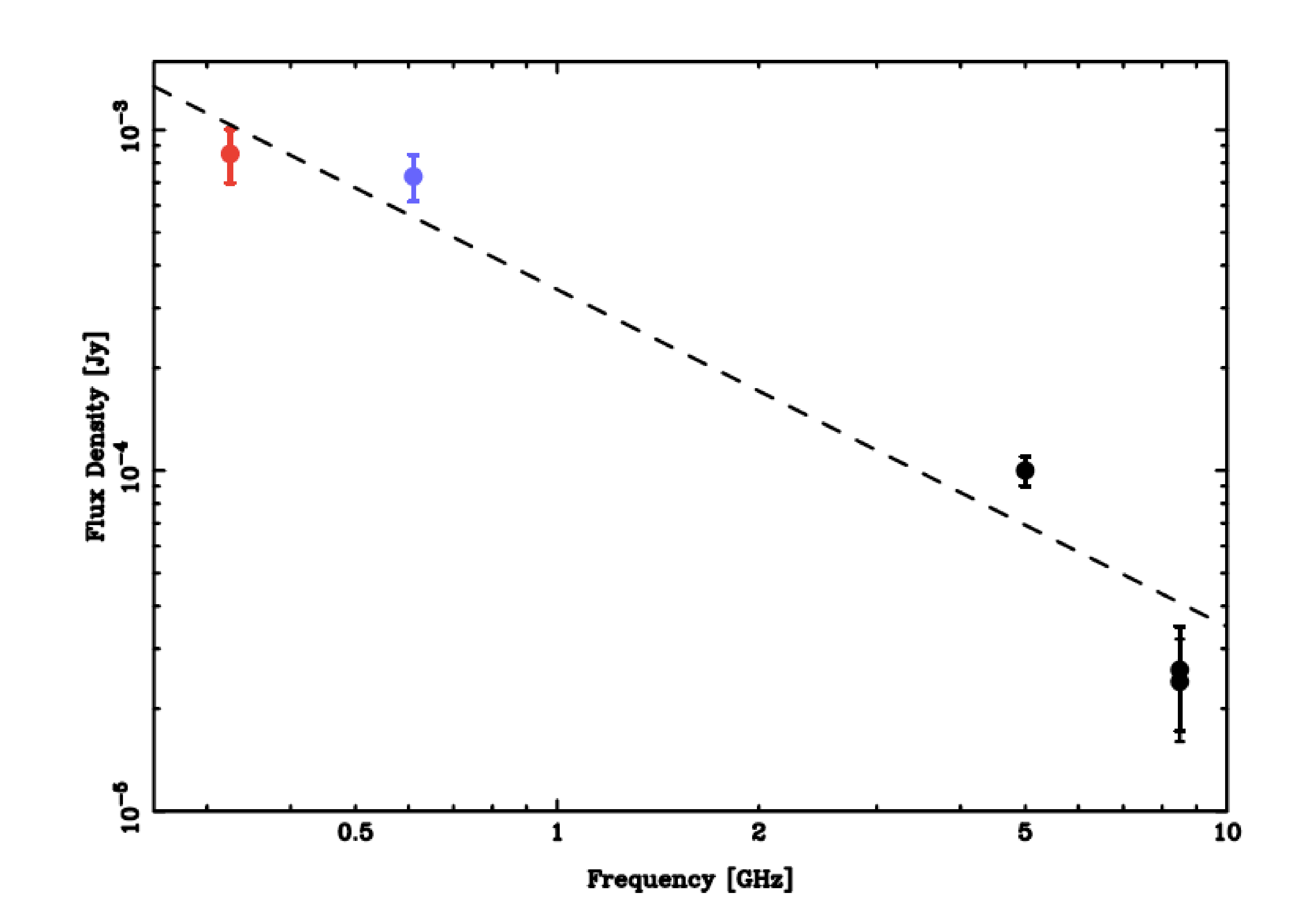
Giant Metrewave Radio Telescope, India

CR electrons associated with SFRs at Galactic Centre
Closely Correspond with Fermi Bubbles

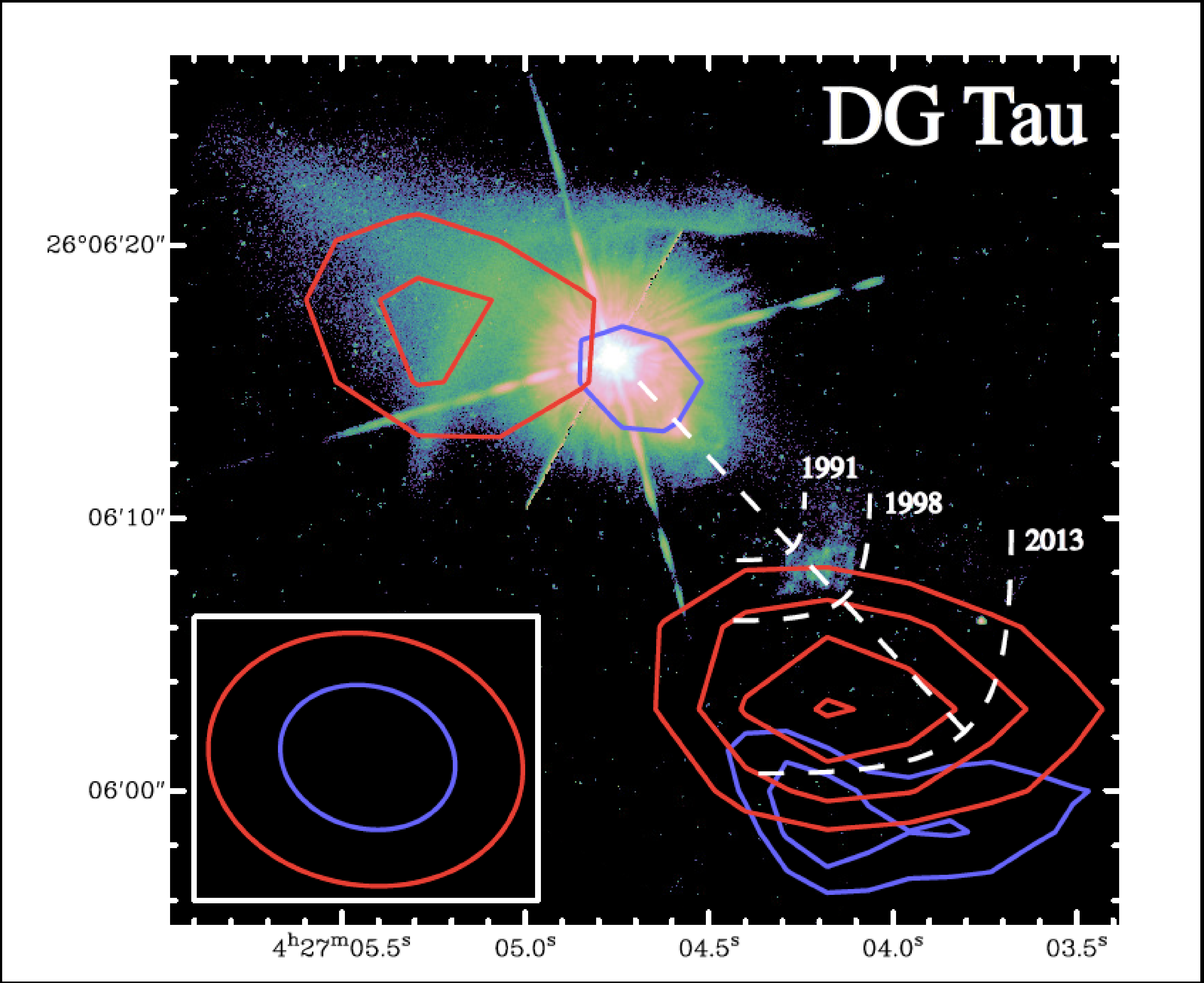
Parallel radio & γ-ray data suggest GeV excess (below SM limit) (Orlando & Strong 2013)



Ettore Carretti et al. 2013



Flux Density [Jy]
10^{-3}
10^{-4}
10^{-5}
0.5
1
2
5
10
Frequency [GHz]



GMRT Data: 325MHz (red contours) and 610MHz (blue contours)

Minimum Magnetic Field Strength and Energy

α (8.5GHz-325 MHz) = -0.99 ± 0.05 for the bow shock

$\mathbf{B}_{min} = [(3\boldsymbol{\mu}_0/2)\mathbf{G}(\alpha)(1+\mathbf{k})\mathbf{L}_{\nu}$⌫$/\mathbf{V}\ \mathbf{f}\ ]^{2/7}$ T

$\mathbf{E}_{min} = (7/6\boldsymbol{\mu}_0)(\mathbf{V}\ \mathbf{f}\ )^{3/7}[(3\boldsymbol{\mu}_0/2)\mathbf{G}(\alpha)(1+\mathbf{k})\mathbf{L}$⌫$]^{4/7}$ J

$\mathbf{B}_{min} \approx 150\ \mu G$ and $\mathbf{E}_{min} \approx 10^{40}$ erg

Electron energy of ≈ 600 MeV ≈ GeV

Larmor Radius $\mathbf{r}_L \approx 10^{-3}$ au □

e-folding $\tau \approx 15$ days

What is the CR Energy Density?

$\mathbf{E}_{min}$ released over τ_{Dyn} (bow shock) ≈ 100 yrs

Luminosity in low energy cosmic rays (CRs) is

$\mathbf{L_e} \approx 8 \times 10^{28}$ erg s^{-1}

$\mathbf{U_e}$ **(1 YSO)** = $\mathbf{W_e}/\mathbf{V}_c$ = $\mathbf{L_e}$☒$/\mathbf{V}_c \approx 5 \times 10^{-5}$ eV cm^{-3}

$\mathbf{U_e}$ **(300 YSOs)** ≈ 1.5×10^{-2} eV cm^{-3}

Galactic CR electron energy density ≈ 10^{-2} eV cm^{-3}

Summary

- Low energy CRs may be generated by YSOs
- Energy Density comparable to Galactic CR Energy Density in clouds
- Source is presumably diffusive (1^{st} Order Fermi) shock acceleration
- Further observations have been made with LOFAR – awaiting analysis