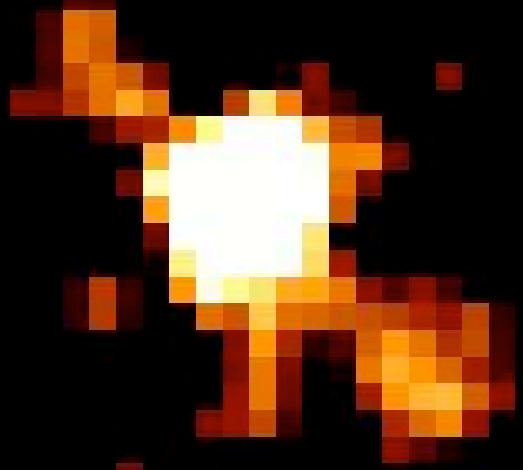
X-Rays from Young Stellar Jets

Manuel Güdel (ETH Zürich, Switzerland)



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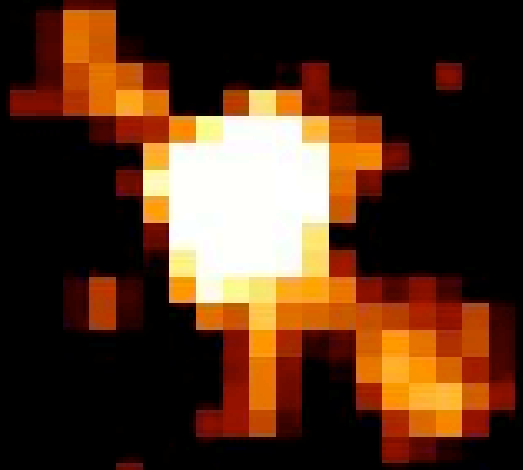
Roland Gredel (MPIA, Germany), **Kevin Briggs** (ETH Zürich, Switzerland)

Jets in Context, Rhodes, July 2008

Outline

1) Introduction: X-rays and YSO outflows
2) X-ray jets from classical T Tauri stars

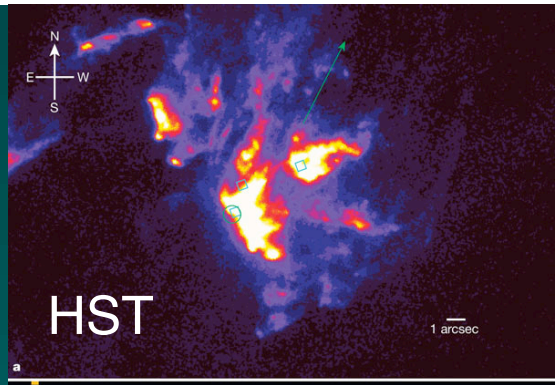


3) Physical parameters
4) Conclusions

HH 2 (Orion): at HH bow shock
10^6 K, $L_X \approx 5 \times 10^{29}$ erg s^{-1}

V_{shock} = 200 km s^{-1} sufficient for heating

measured flow speed: 230 km s^{-1}

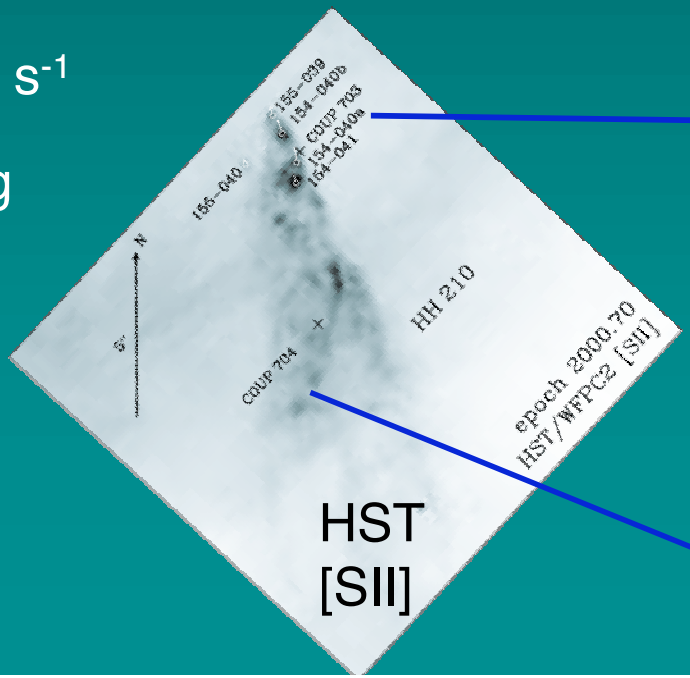


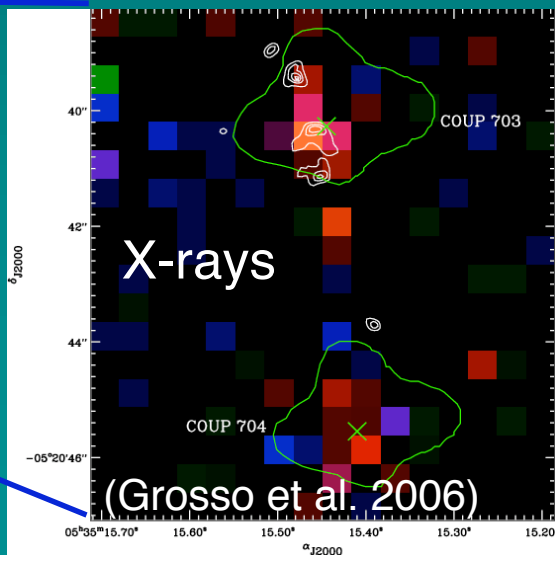
HH210 (Orion): 0.8 MK in fastest HH feature:

V_{shock} = 170-240 km s^{-1}

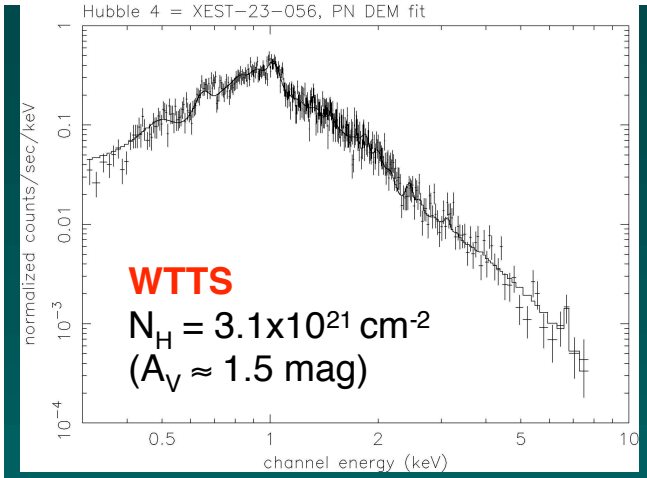
sufficient for heating

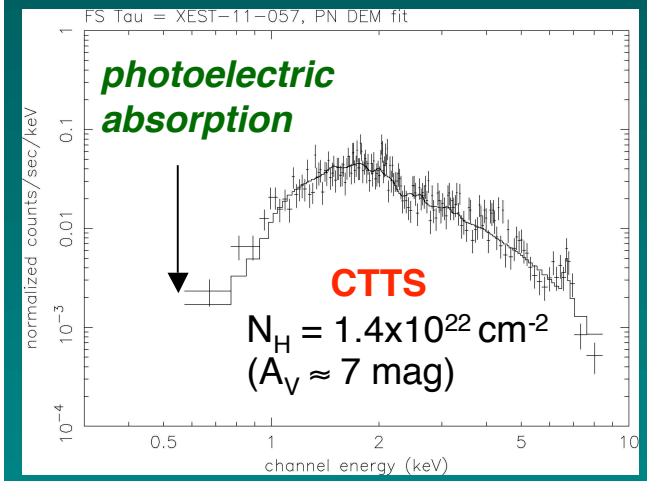
$L_X \approx 10^{30}$ erg s^{-1}

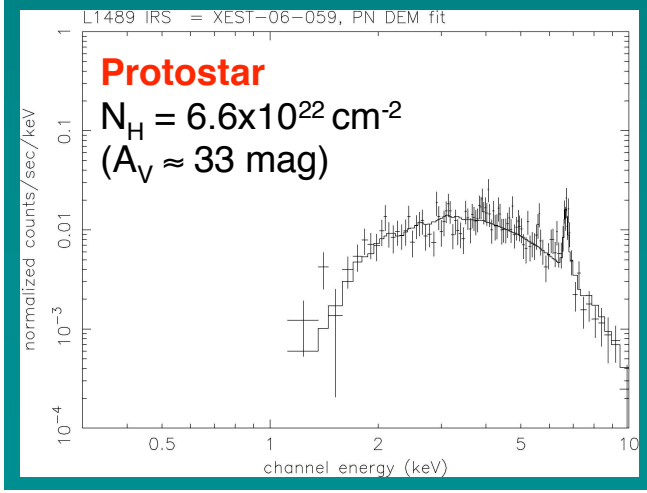


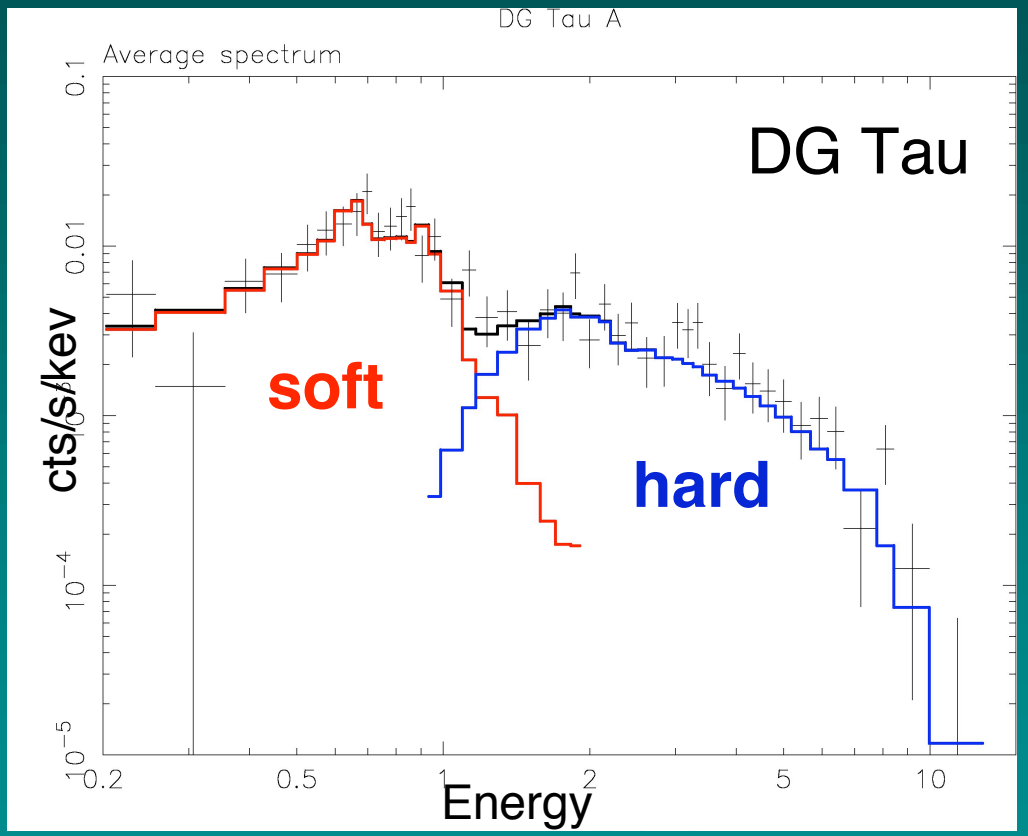


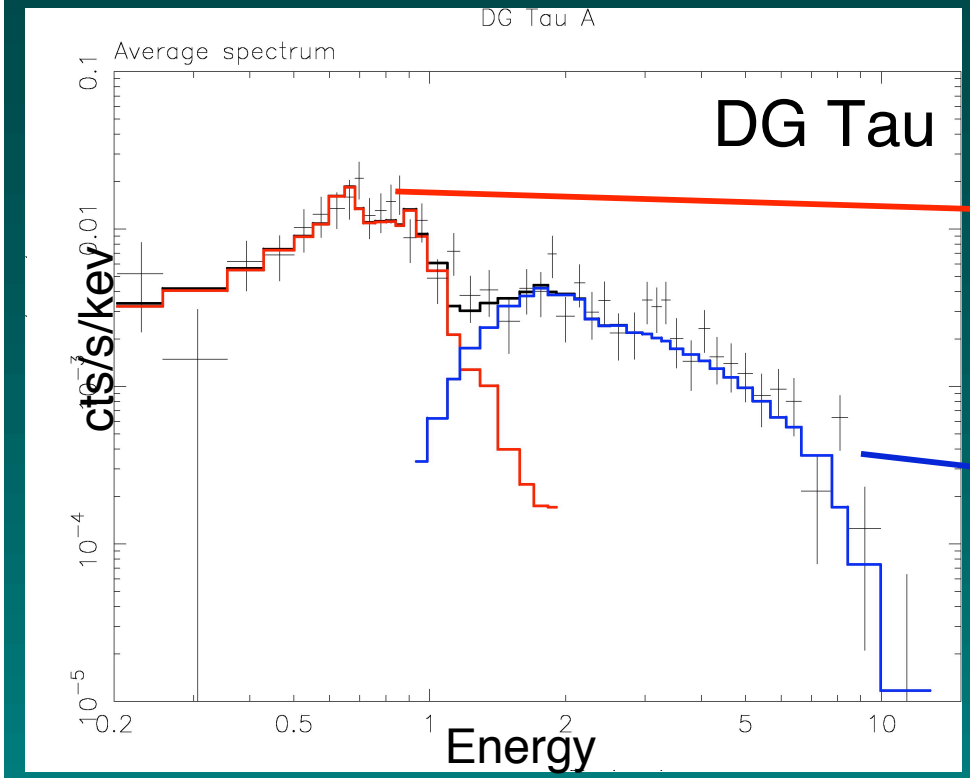
X-ray spectroscopy of T Tauri stars

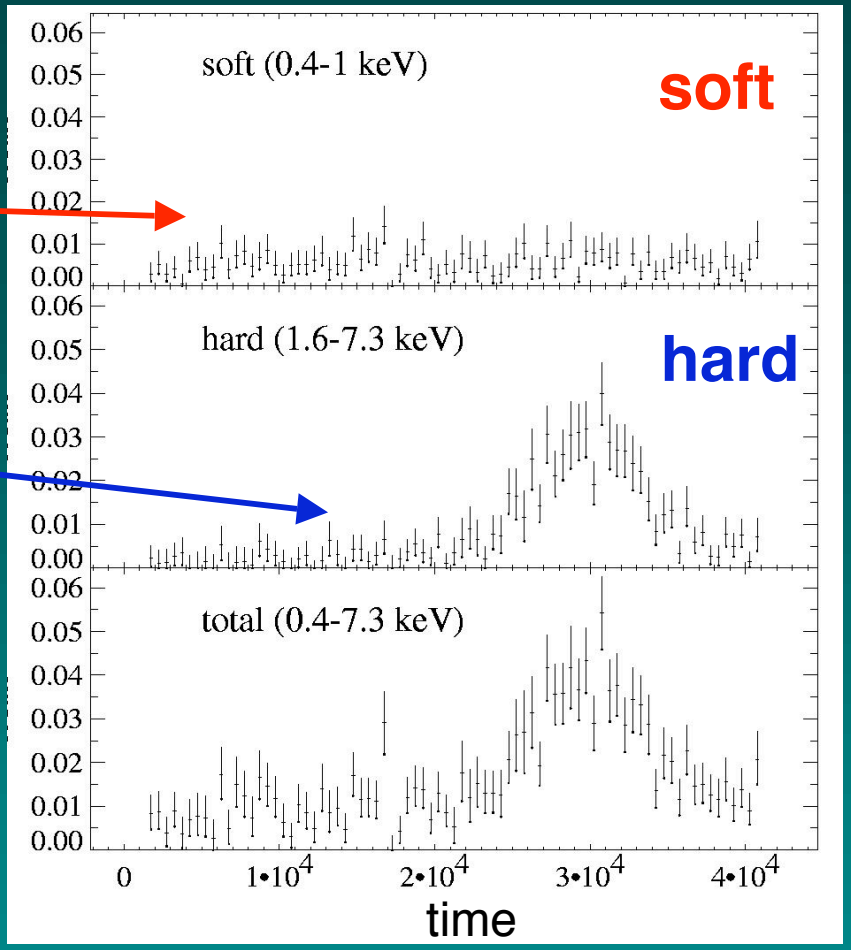








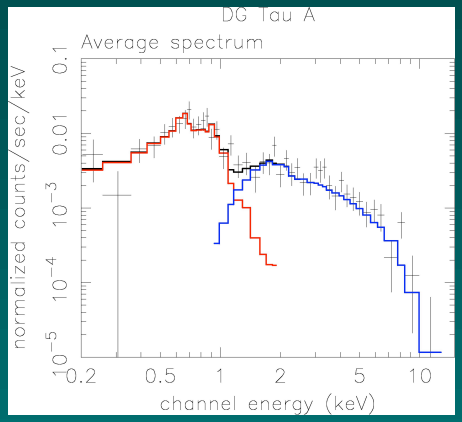


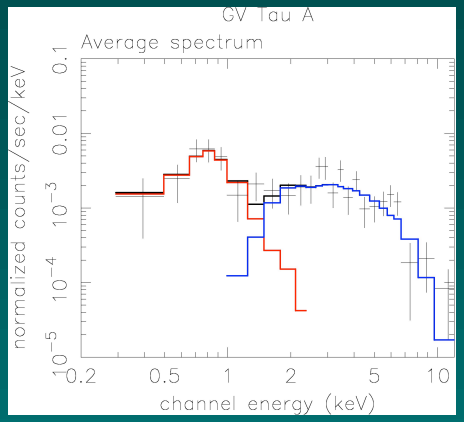


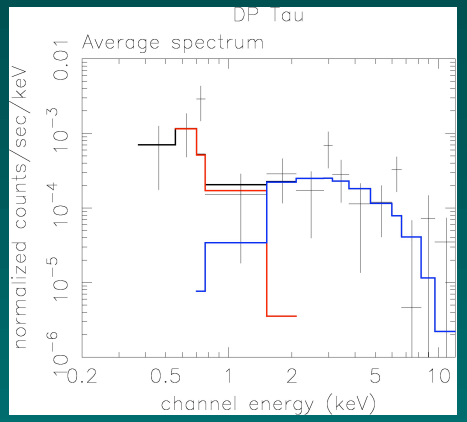
(Güdel et al. 2007)

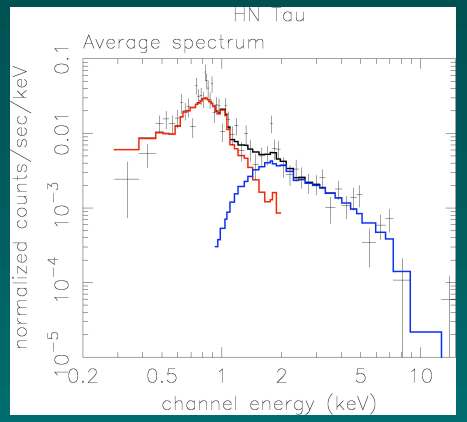
soft/cool component: low N_H, constant
hard/hot component: high N_H, flaring

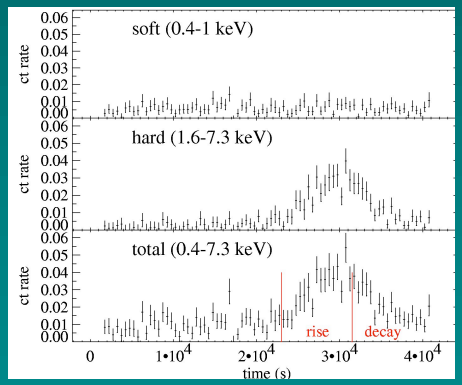
Two-Absorber X-Ray Spectra (TAX)

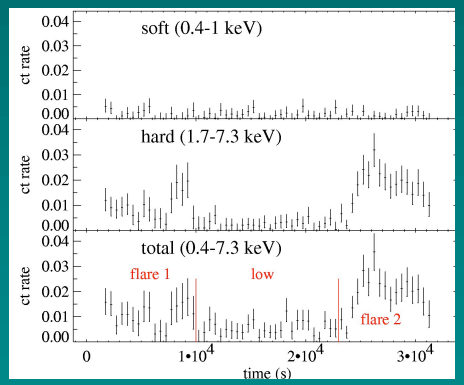


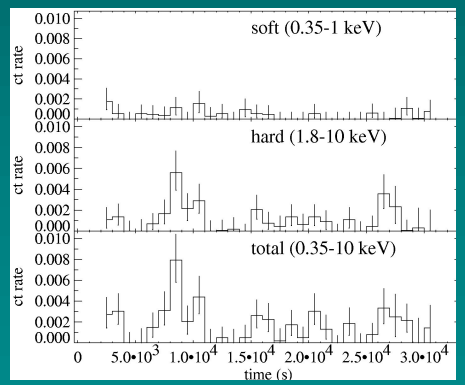












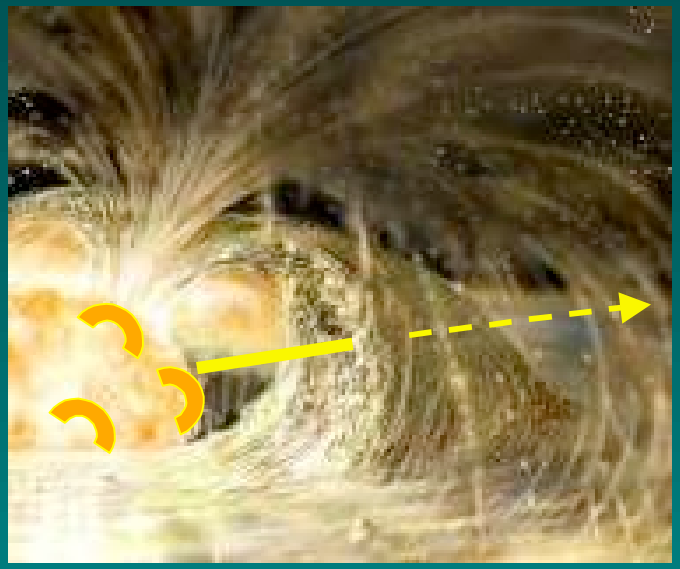
not variable

DG Tau GV Tau DP Tau HN Tau

TAX:

+ one case in Orion Nebula (Kastner et al. 2005)
+ FU Ori? (Skinner et al. 2006)

The hard spectral component: coronal



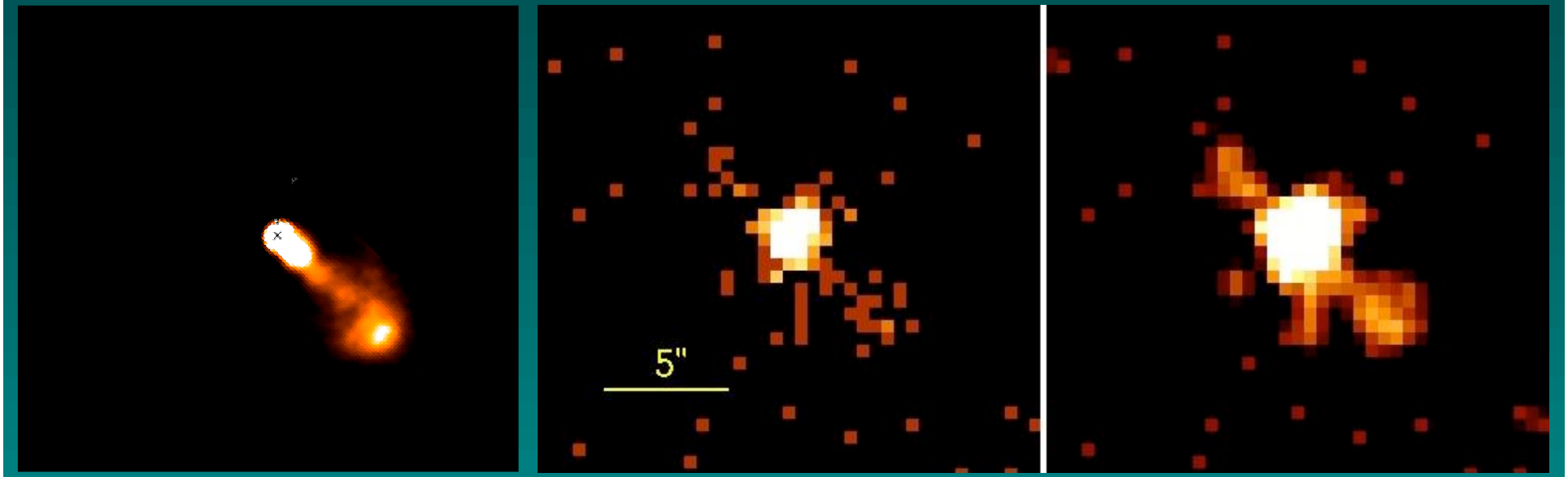
Hard emission:
Excessive absorption by dust-depleted accretion flows

compatible with absorption from spherically symmetric infall with observed dM/dt

The soft spectral component: *not* coronal

Soft emission: $N_H < N_H(\text{star})$ → "in front" of star?

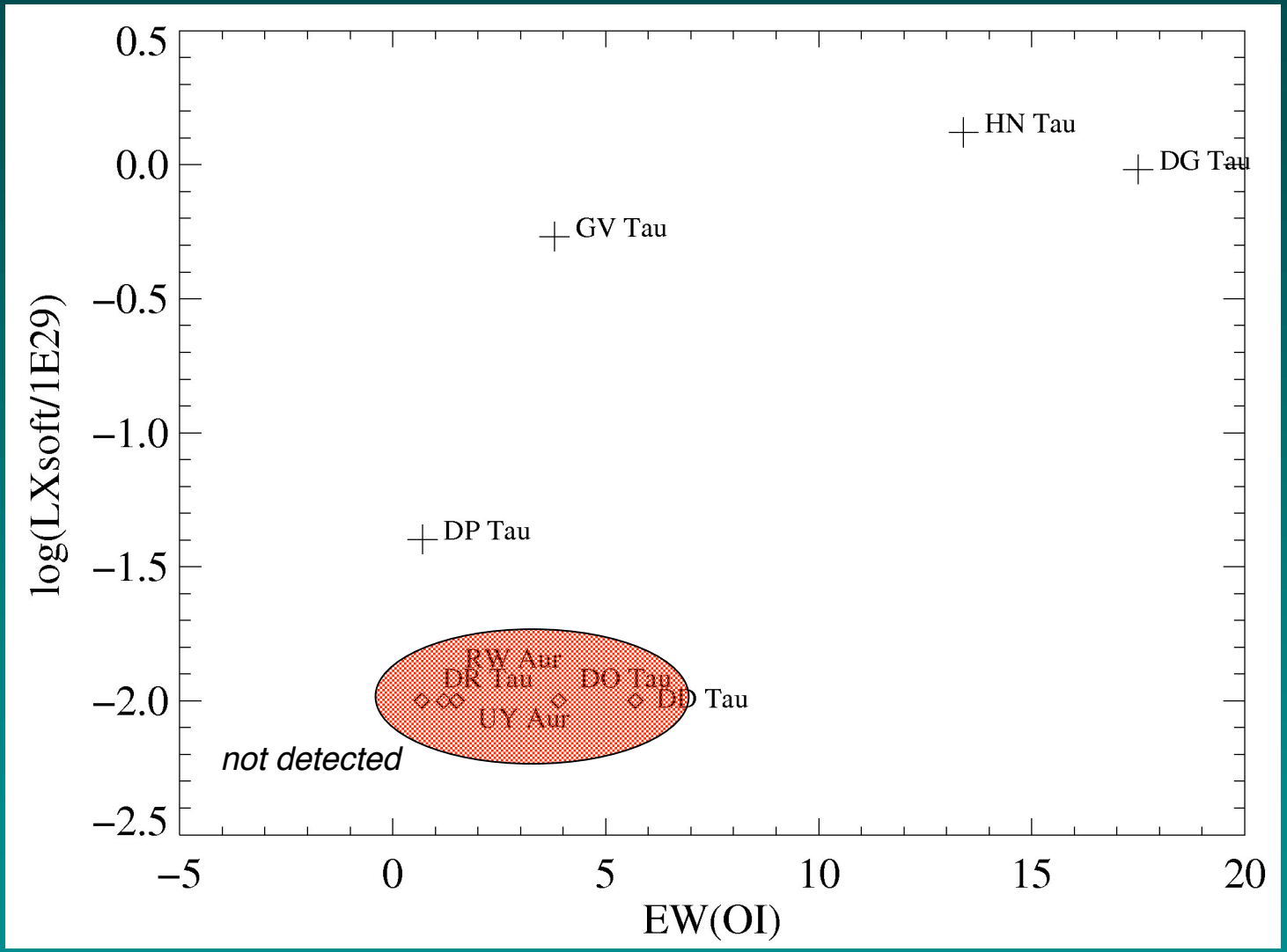
[OI] and Chandra high-resolution image of DG Tau



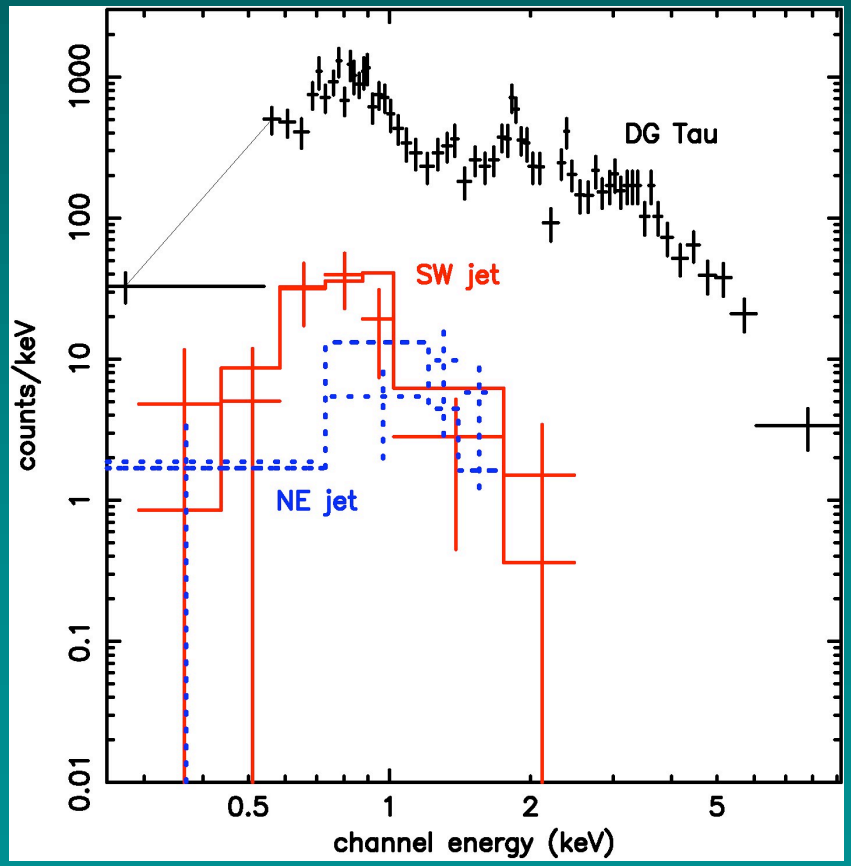
[OI] [1997] (Dougados et al. 2002)

Güdel et al. (2007); from Chandra

All TAX sources drive strong jets


0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
log(LXsoft/1E29)
−5
0
5
10
15
20
EW(OI)
HN Tau
DG Tau
GV Tau
DP Tau
RW Aur
DR Tau
DO Tau
UY Aur
Tau
not detected

	soft PSF	SW Jet	Star
T (MK)	3.7(3.2-4.6)	3.4(2.3-8.6)	
N_H (cm^{-2})	1.1(0.3-2.5)x10^{21}	3(0-6)x10^{21}	
N_H (A_V)(cm^{-2})	...	...	≈5x10^{21}
L_X (erg s^{-1})	10^{29}	1.2x10^{28}	

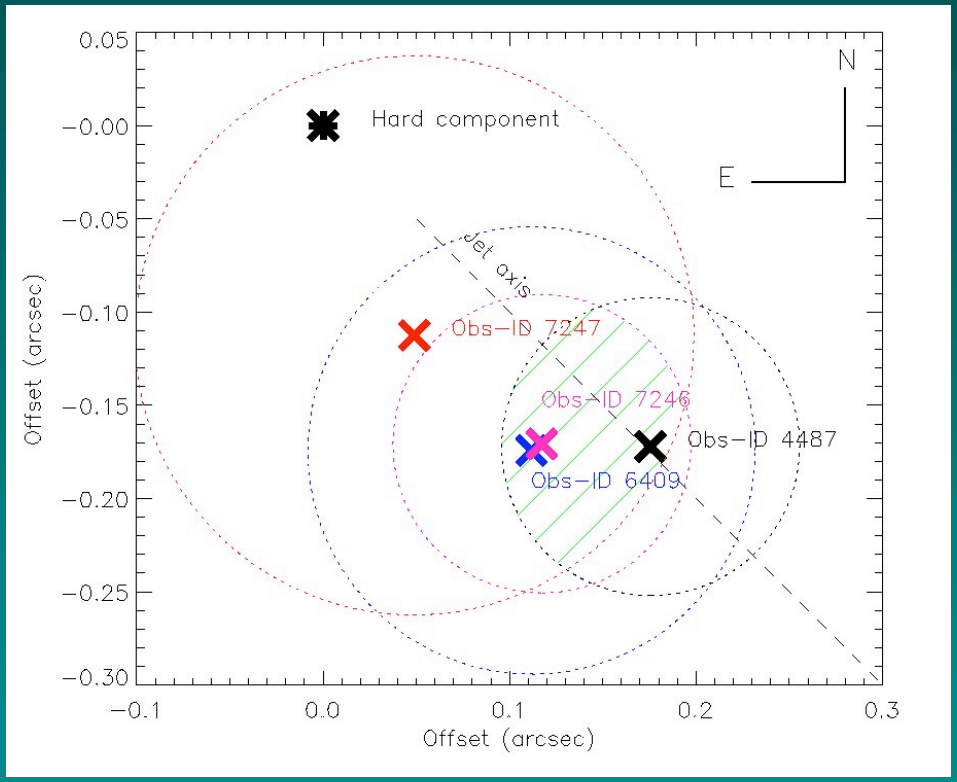


Soft spectral component is continuation of X-ray jet within PSF

Positional Analysis within PSF

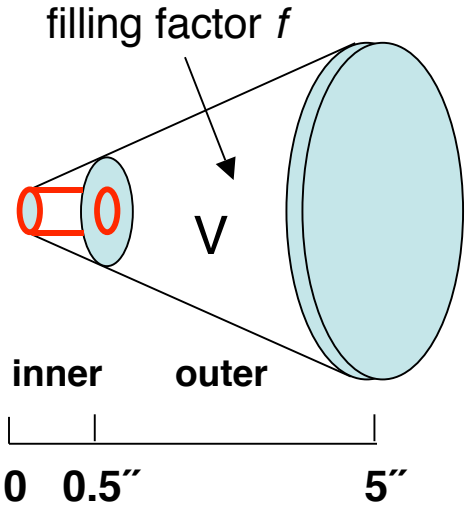
Soft component is displaced from hard component:

by 0.2″ along jet direction!



see poster #42 by Schneider & Schmitt

Radiative Cooling



required cooling time Δt → **2 yr** **20 yr**

see also poster #37 by Günther et al.

$EM = n_e n_H V = 0.83\, n_e^2 V$	set $\dot{E}_{th} = L$:
$M = 1.28\, m_p (EM\, Vf)^{1/2}$	$f^{1/2} = 0.32\, L\, \Delta t\, (EM\, V)^{-1/2} (kT)^{-1/2}$
$\dot{E}_{th} = 3.15 (EM\, Vf) kT$	$n_e = 3.4 EM\, kT/(L\Delta t)$

Jet	Outflow rate ($M_\odot \mathrm{yr}^{-1}$)	Heating rate ($\mathrm{erg\ s}^{-1}$)	Electron density (cm^{-3})	Filling factor	Cooling time (yr)
Outer	3.6×10^{-13}	1.7×10^{28}	1.7×10^{5}	2.3×10^{-6}	20
Inner (conical)	3.0×10^{-12}	1.4×10^{29}	1.7×10^{6}	1.9×10^{-4}	2
Inner (linear)	3.0×10^{-12}	1.4×10^{29}	1.7×10^{6}	3.1×10^{-3}	2

10^{-5}-10^{-4} times optical

compares well with optically derived densities

Cooling by Radiation and Expansion

1st law of TD: $dU + \delta W = \delta Q$

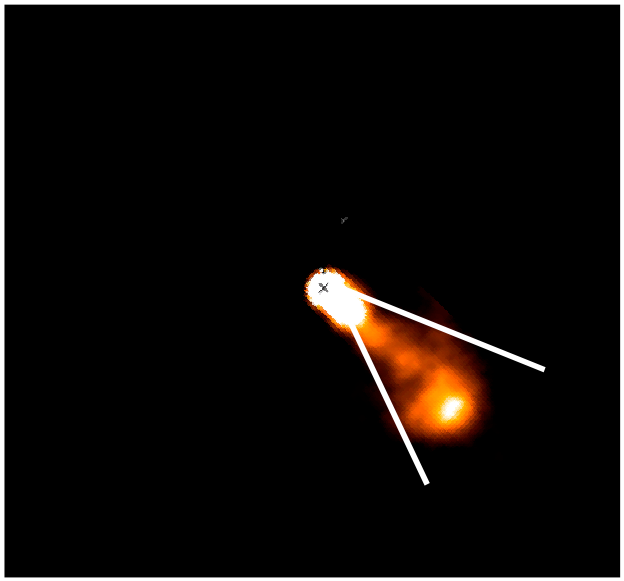
$U = 2\alpha N_e kT$ $\quad \delta W = pdV$

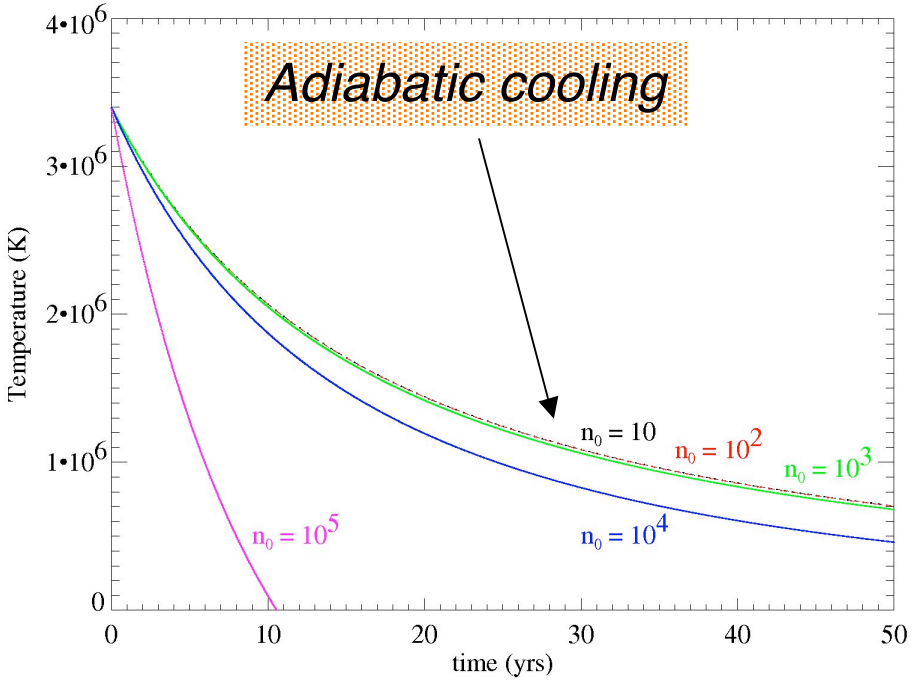
$$\delta Q = -n_e(t)^2 V(t) \Lambda(T) dt$$

$$\alpha \frac{dT}{T(t)} + \frac{dV}{V(t)} = -\frac{n_e(t)\Lambda(T)}{2kT(t)} dt.$$

linear jet expansion in time: dV → dt

$$\alpha \frac{dT}{T(t)} = -\left[\frac{2v}{r(t)} + \left(\frac{r_0}{r(t)} \right)^2 \frac{n_0 \Lambda(T)}{2kT(t)} \right] dt.$$





Pressure in the Plasma

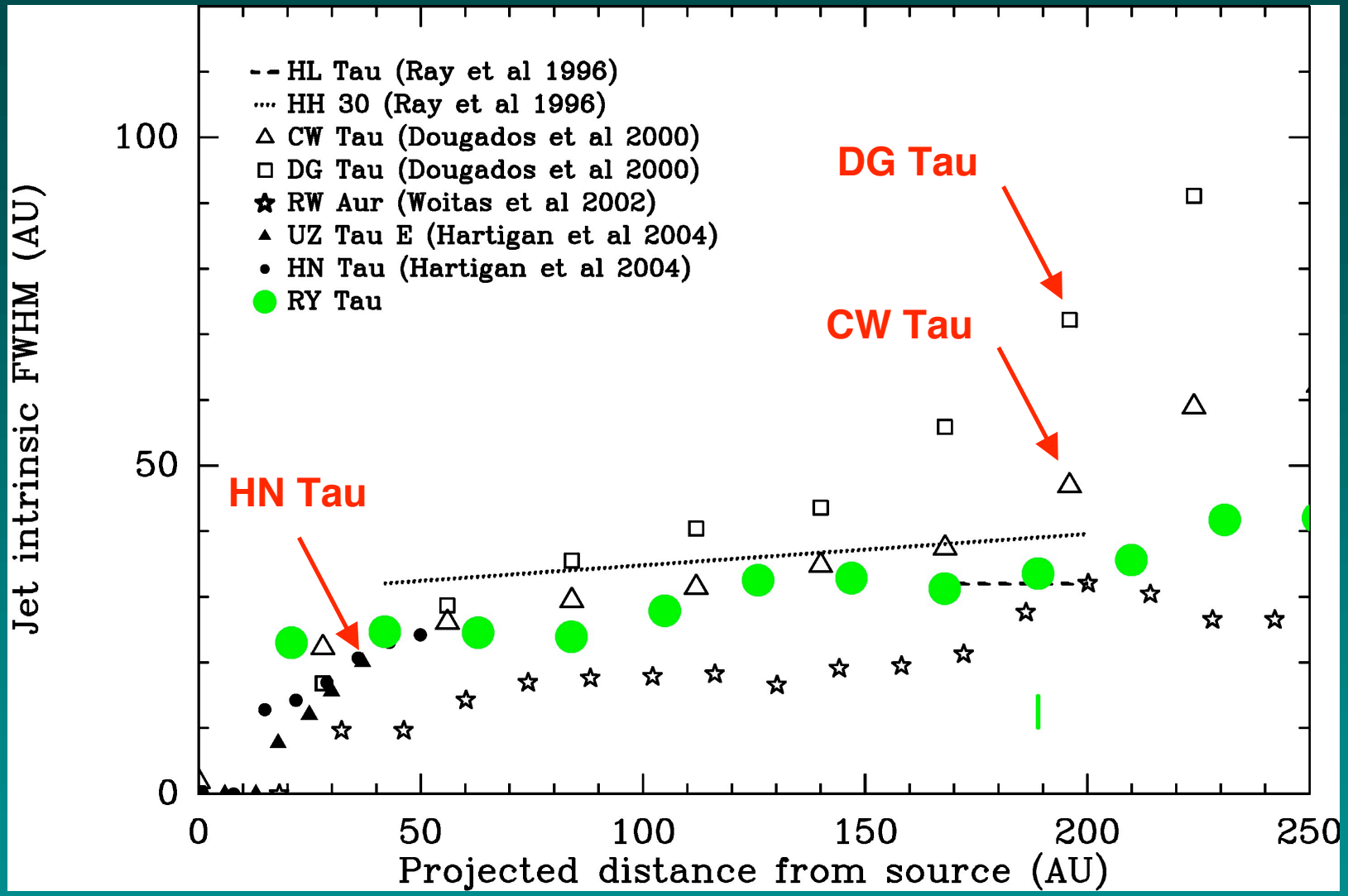
$$n_e = \left(\frac{EM}{fV}\right)^{1/2}$$

(Lavalley-Fouquet et al. 2000)

optical (warm) outer jet:	$n \approx 10^3$ - 10^4 cm^{-3}	$T \approx 10^4$ K
X-ray (hot) outer jet:	$n_e = 1.6 \times 10^5$ cm^{-3}	$T \approx 3.7 \times 10^6$ K
	>1.2 dex	2.6 dex (*f=1*: 1 dex)

optical (warm) inner jet:	$n \approx 10^6$ cm^{-3}	$T \approx 10^4$ K
X-ray (hot) inner jet	$n_e = 1.6 \times 10^6$ cm^{-3}	$T \approx 3.7 \times 10^6$ K
	0 dex	2.6 dex

Hot gas contributes to jet expansion if not located at surface of jet

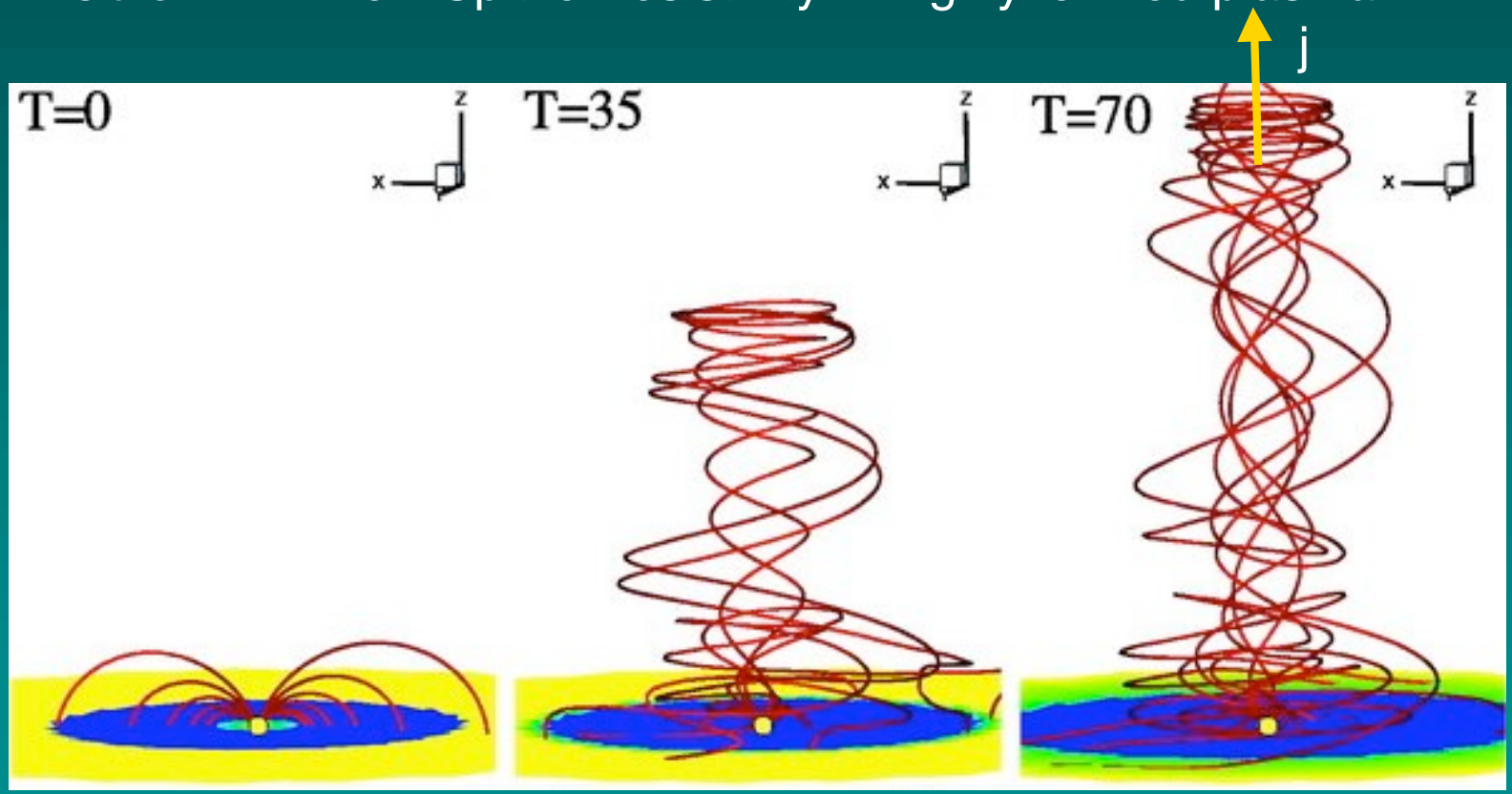


(Dougados et al. 2008)

T = 3.7 MK - How are the jets heated?

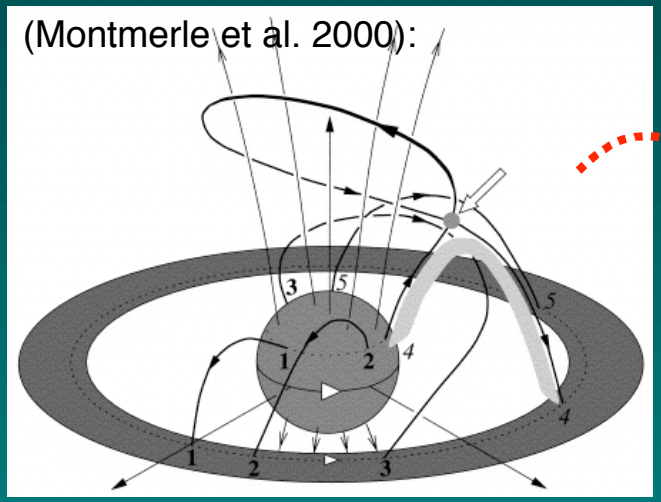
Magnetic jet acceleration: winding-up magnetic fields → $\nabla \times \mathbf{B} \rightarrow \mathbf{j}$

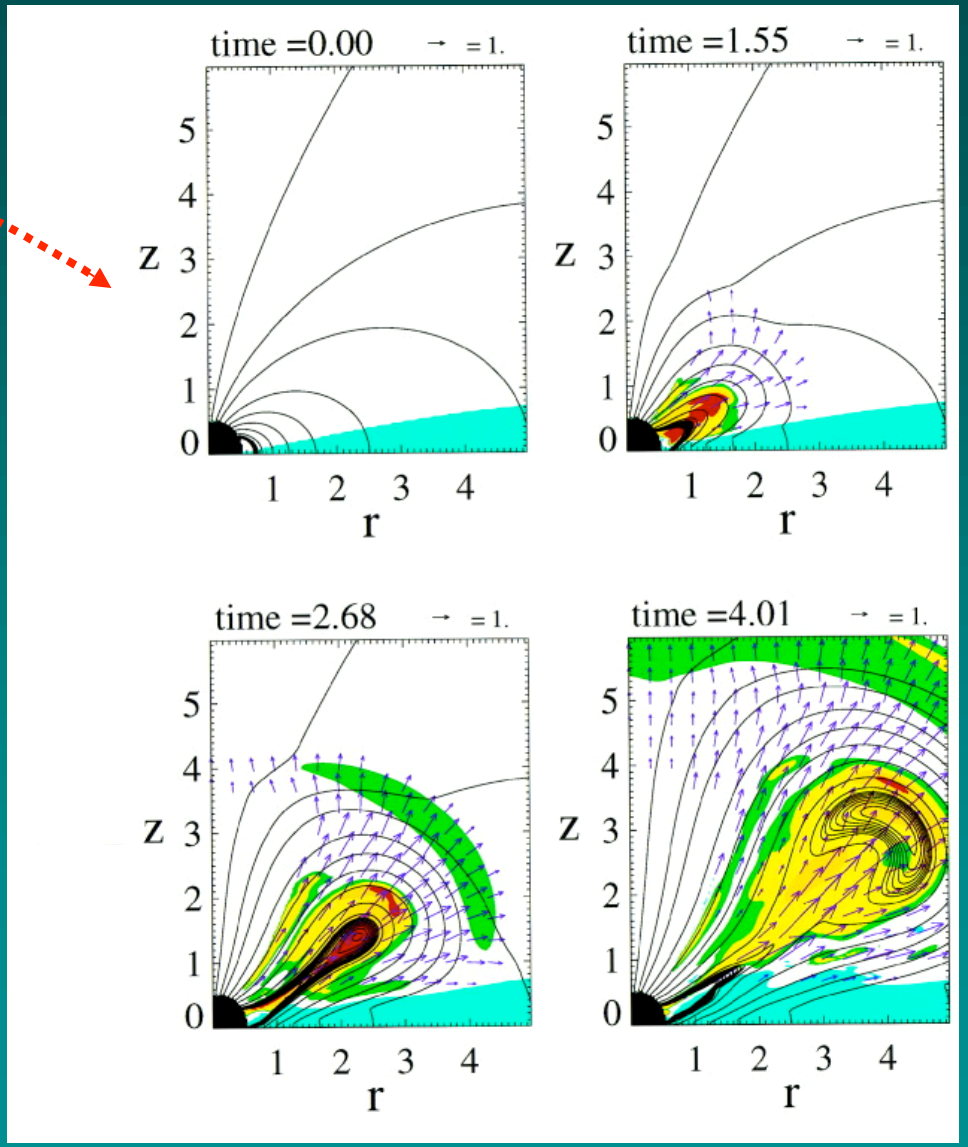
Problem: low Spitzer resistivity in highly ionized plasma



(Romanova et al. 2004)

Reconnection





(Hayashi et al. 1996)

Winding up star-disk fields

→ Antiparallel fields
→ Heating and Reconnection
→ Ejection of hot plasmoids
→ Jets?

→talk by R. Matsumoto (Tues)

Conclusions

1) Some jets of T Tauri stars are luminous X-ray sources:

- close to the star (<100 AU)
- at levels of 10^{29} erg s^{-1}

2) Plasma thermal pressure very high:

- influence on jet kinematics and expansion

3) Electron temperatures are high:

- small fraction of gas with very high velocities?
- magnetic heating?

END