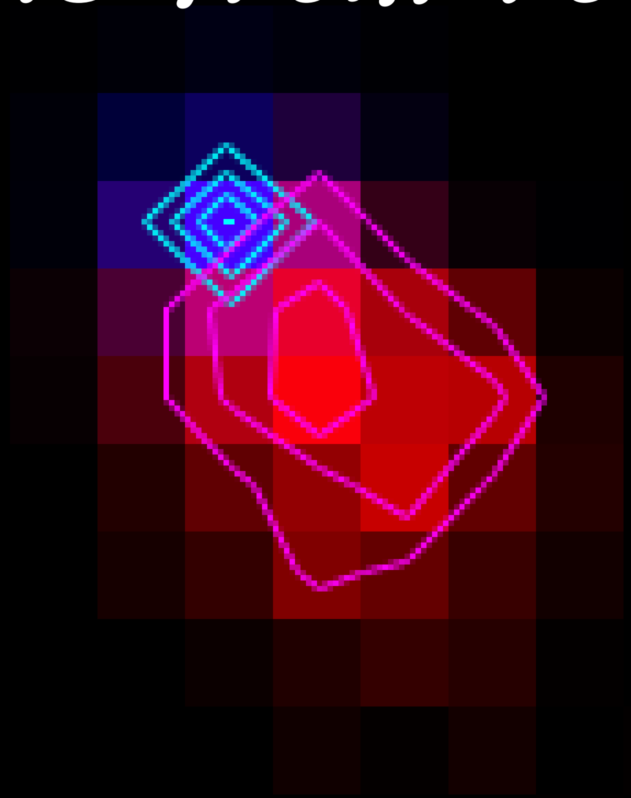
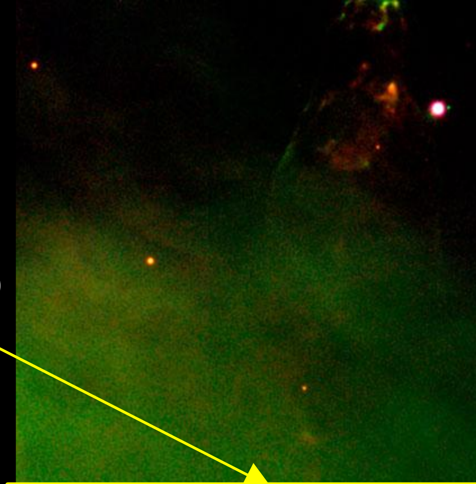
X-Ray Jets from Young Stars



Manuel Güdel   University of Vienna



Outline

- Herbig-Haro Objects
- Inner Jets
- Cooling
- Heating
- Conclusions

Shocks against ISM

Shock temperature

$$T_s = 1.5 \times 10^5 \text{ K} \left(v_{100}\right)^2 ,$$

(Raga et al. 2002) requires a few 100 km s^{-1}: OK

Luminosity for radiative or non-radiative shock:

$$\begin{aligned} L^{\mathrm{r}} &= 4.1 \times 10^{-6} n_{100} \left(r_{16}\right)^2 \left(v_{100}\right)^{5.5} L_\odot \\ L^{\mathrm{nr}} &= 4.5 \times 10^{-5} \left(n_{100}\right)^2 \left(r_{16}\right)^3 v_{100} L_\odot \end{aligned}$$

(Raga et al. 2002) typically works OK ($L_X \approx 10^{29-31}$ erg s^{-1}).

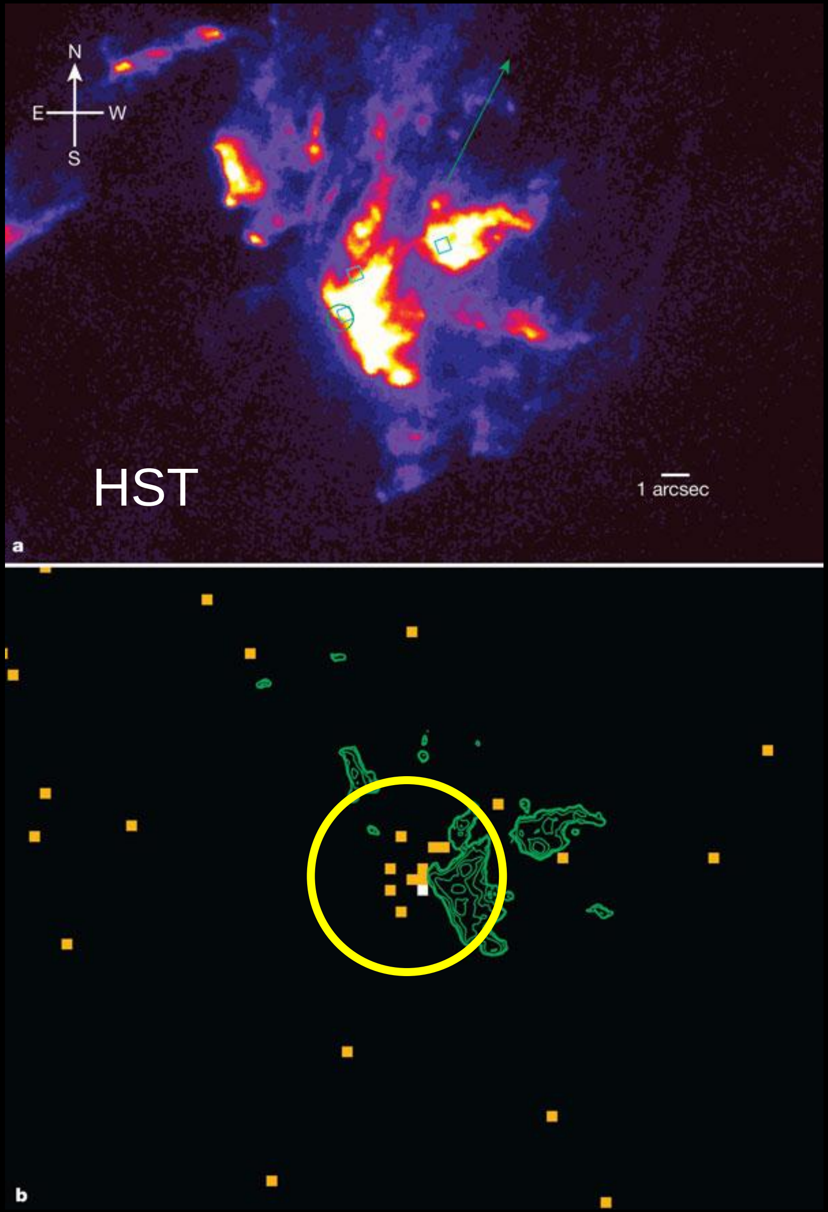
HH 2 (Orion): at bow shock of HH object, 10^6 K, $L_X \approx 5 \times 10^{29}$ erg s^{-1}

$V_{shock} = 200$ km s^{-1}

required for heating

measured motion: 230 km s^{-1}

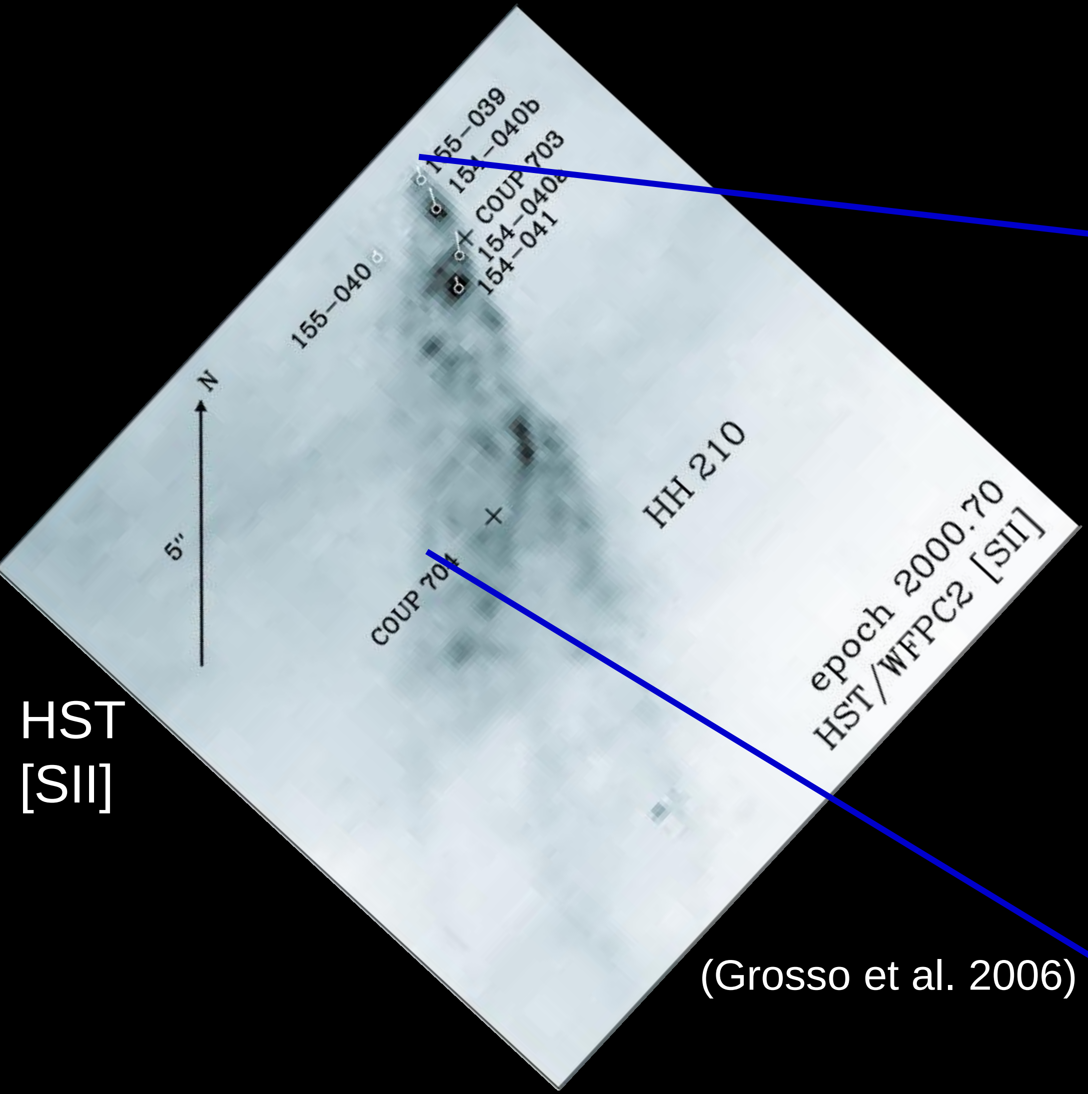
(Pravdo et al. 2001)



HH210 (Orion): T = 0.8 MK in fastest HH feature, $L_X \approx 10^{30}$ erg s^{-1}:

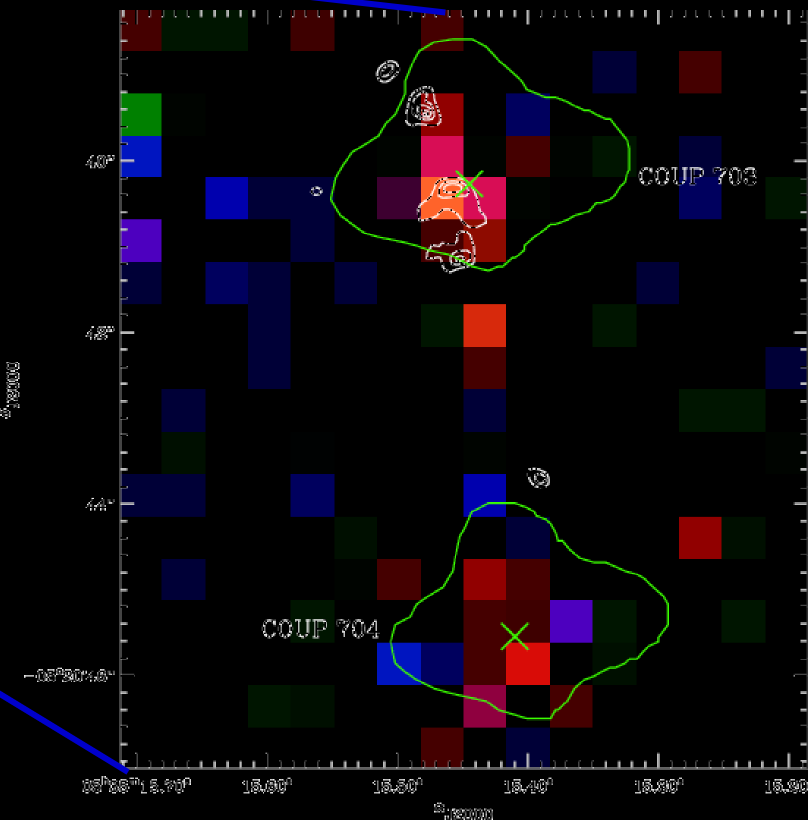
V_{shock} = 170-240 km s^{-1} required

observed bow-shock velocity 133-425 km s^{-1}



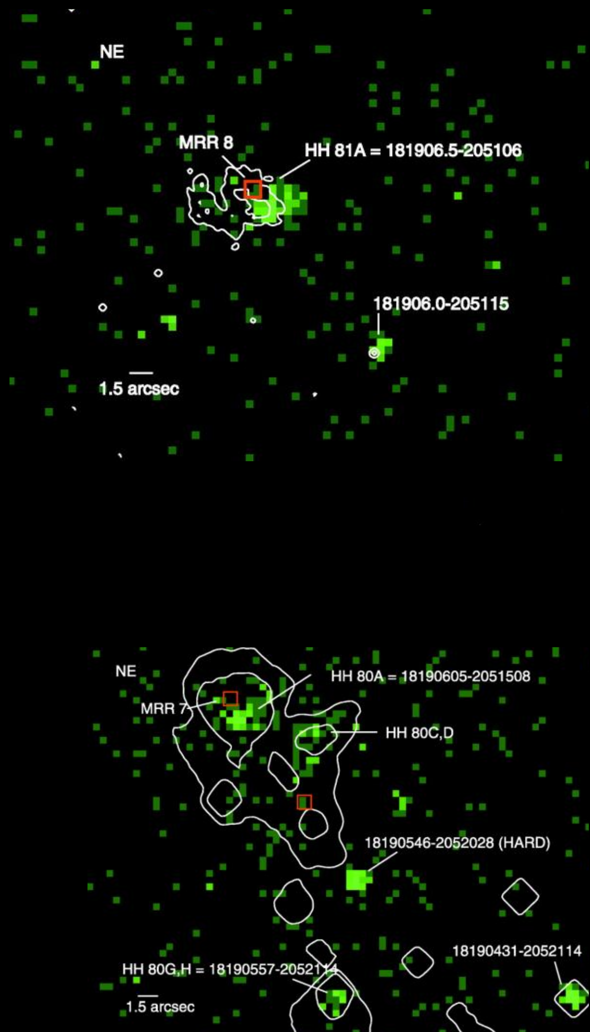
HST
[SII]

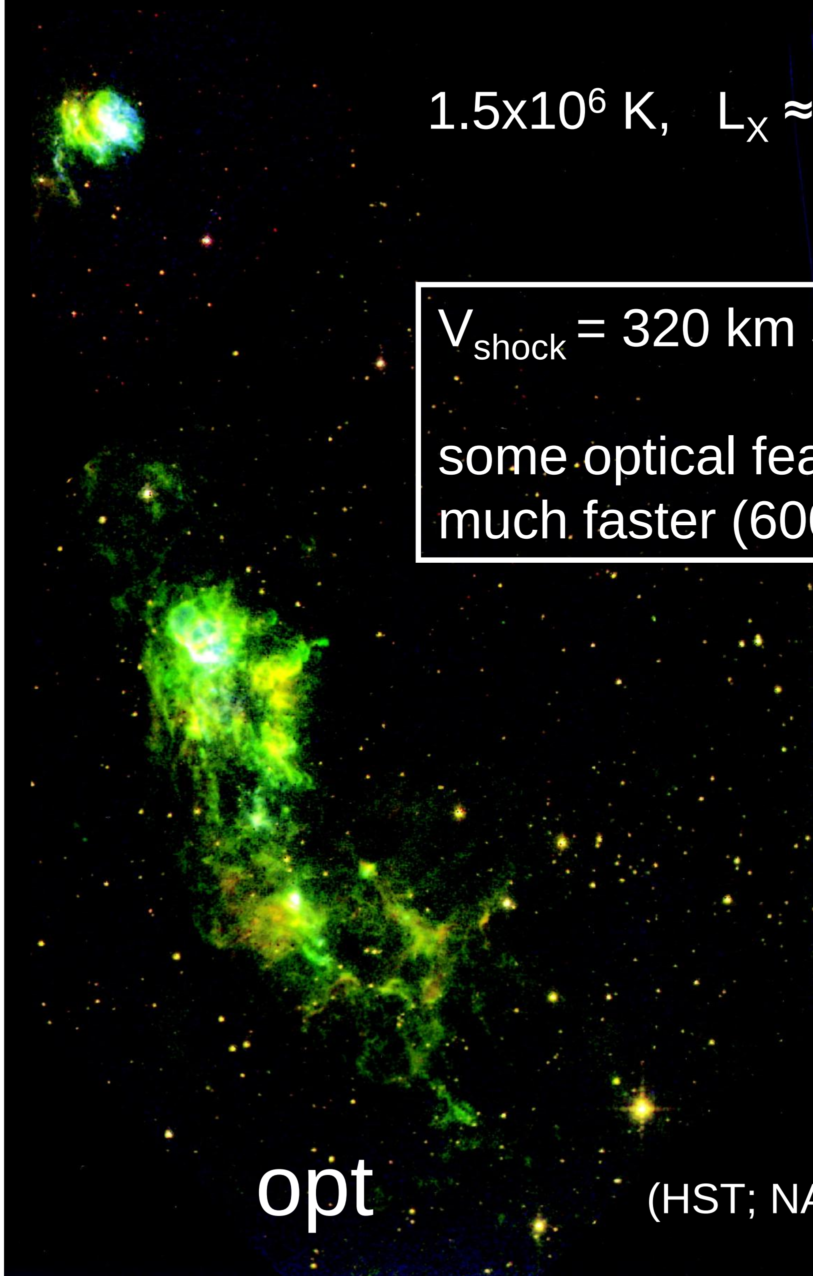
X-rays



(Grosso et al. 2006)

HH 80/81 (from very luminous source)





1.5×10^{6} K, $L_X \approx 4.5 \times 10^{31}$ erg s^{-1}

V_{shock} = 320 km s^{-1} required

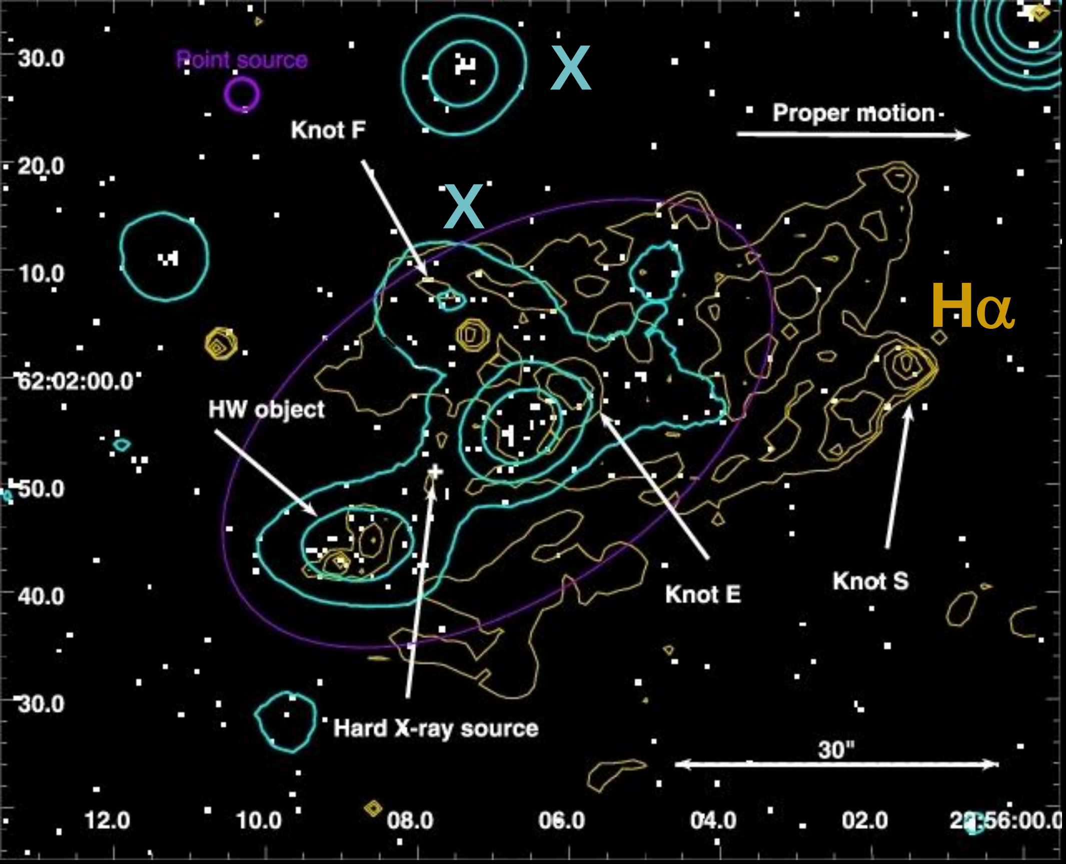
some optical features are much faster (600-1400 km s^{-1})

(Pravdo et al. 2004; contours: HST Hα)

X

opt

(HST; NASA/ESA)



Cepheus A East & West: HH168

6.4×10^6 K, $L_X \approx 1.7 \times 10^{30}$ erg s^{-1}

X-rays behind Hα:

cooling post-shock gas?

V_{shock} = 280-680 km s^{-1} sufficient

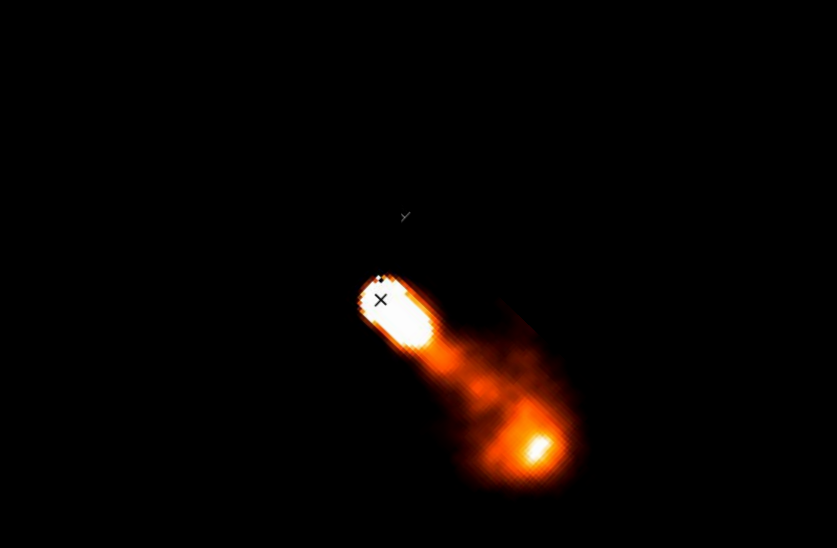
~consistent with optical line width in some places (200-600 km s^{-1})

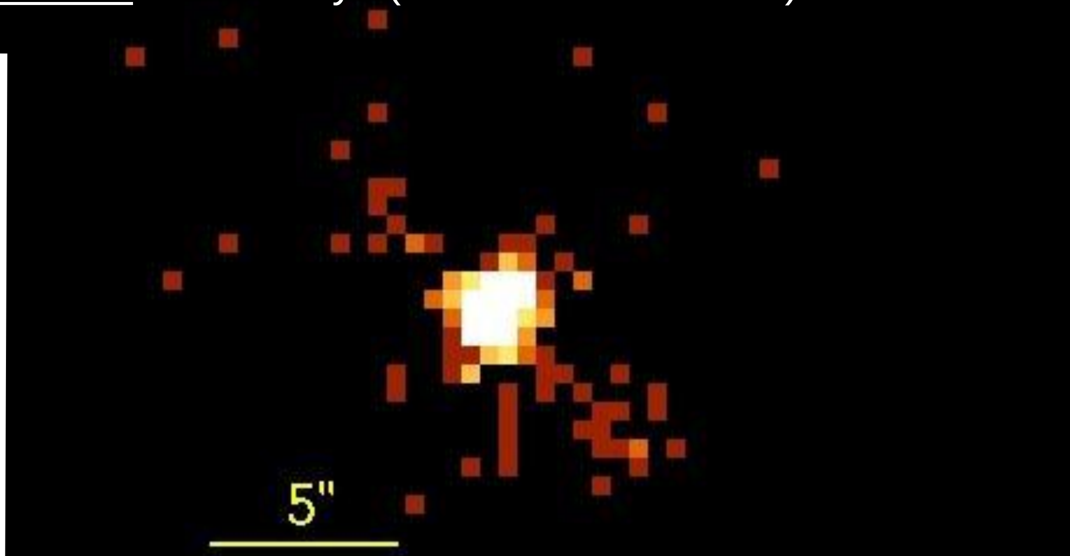
(Pravdo et al. 2005, Schneider et al. 2009)

[OI] (Dougados et al. 2000)

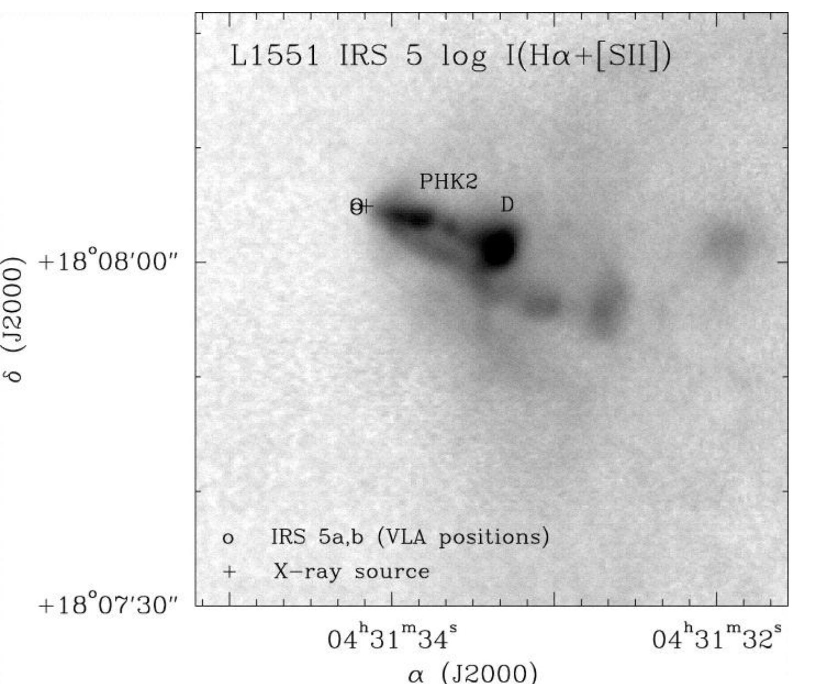
DG Tau

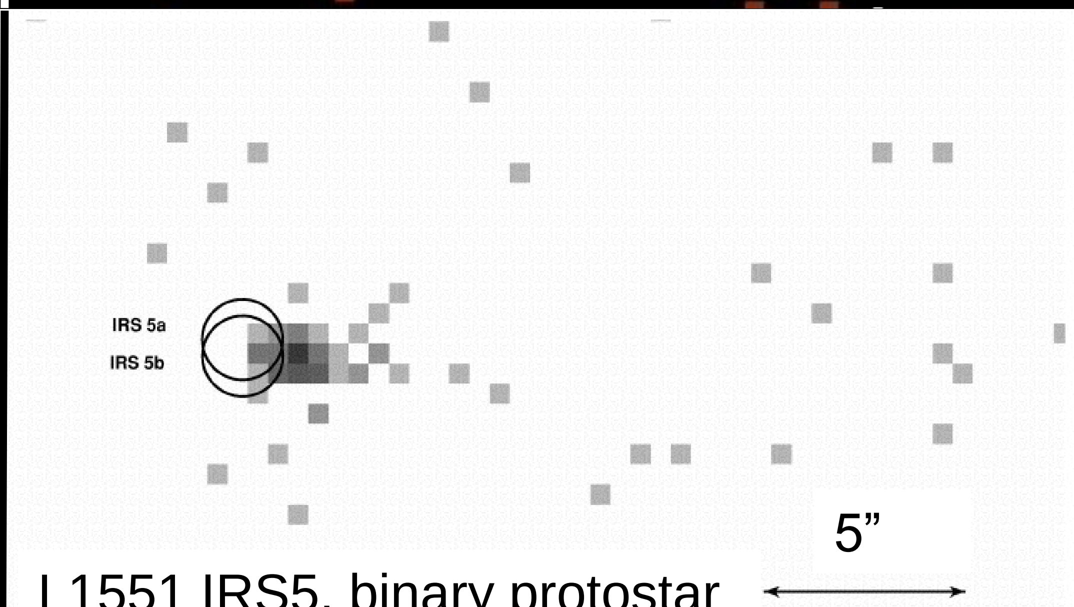
X-Rays (Güdel et al. 2005/08)





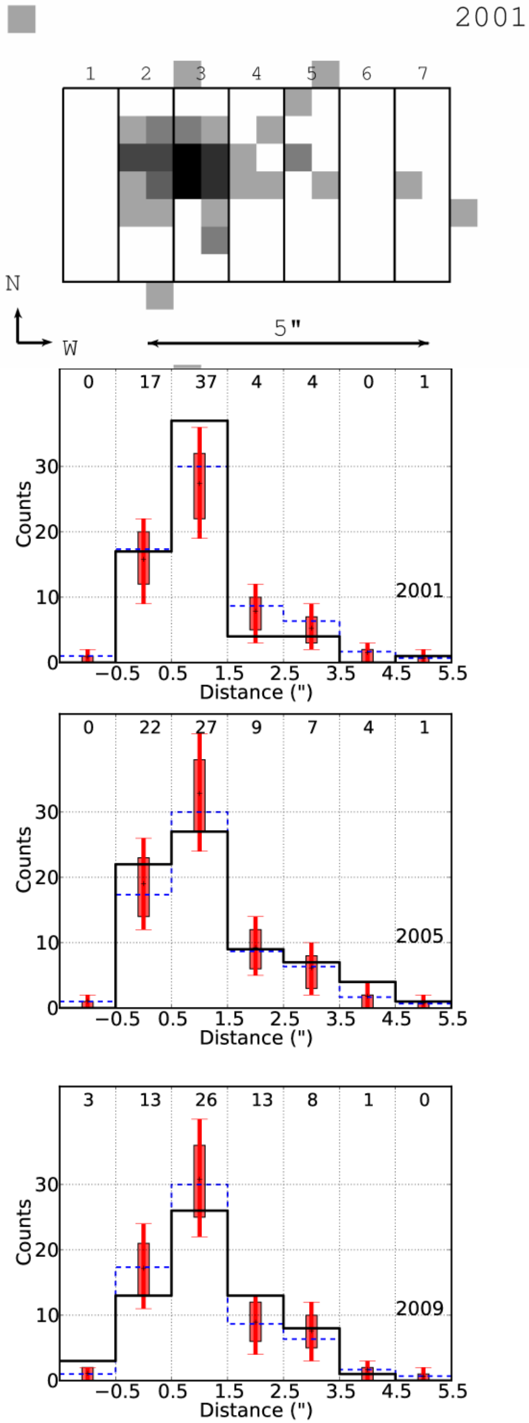
X-rays located *close to jet base:* Internal shocks, or collimation shocks?





L1551 IRS5, binary protostar

(Favata et al. 2002, Bally et al. 2003)

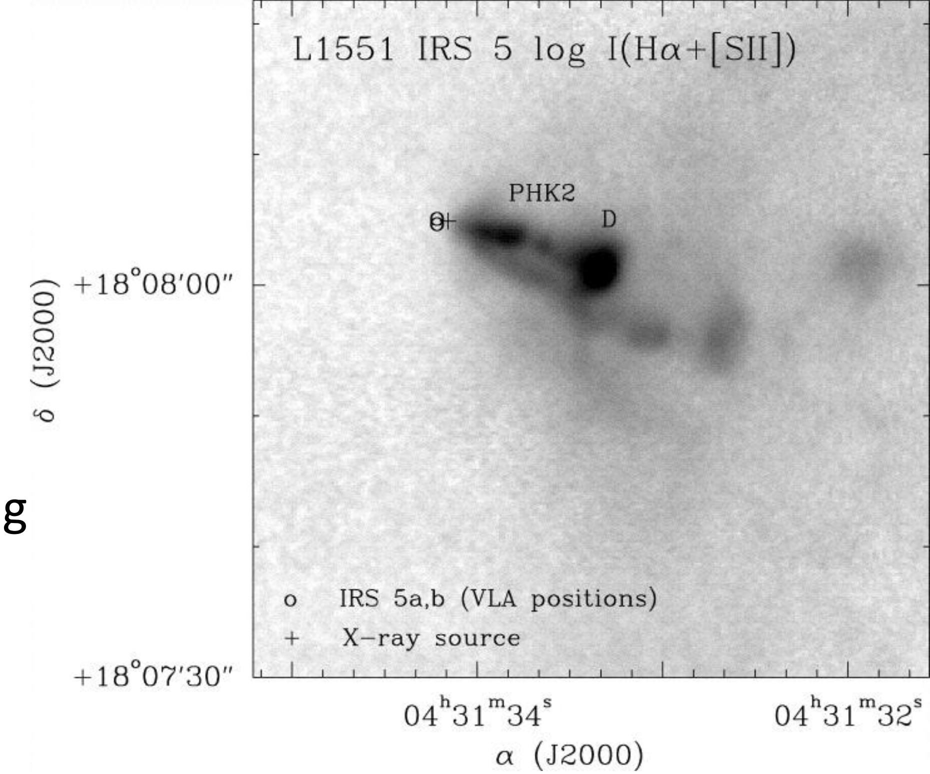


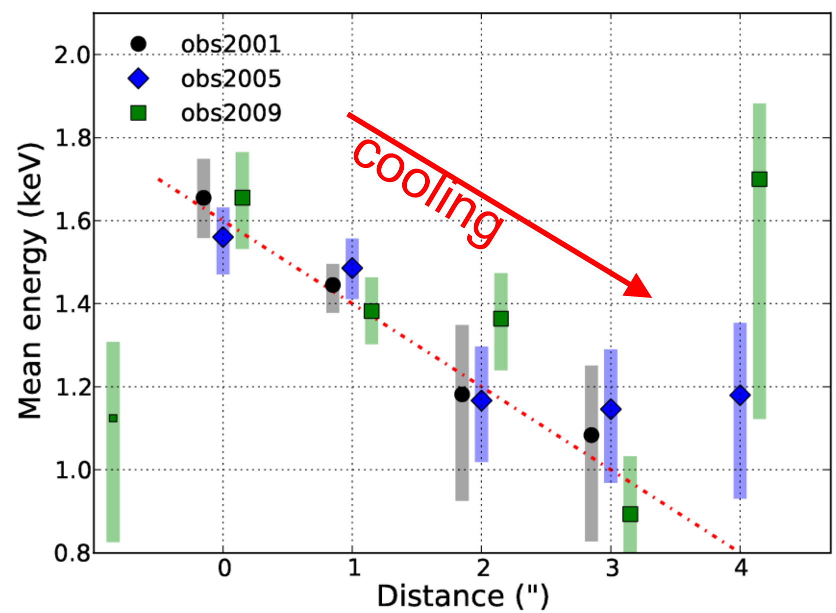
Jet Base?

L1551 IRS 5
Star absorbed,
inner jet X-ray strong

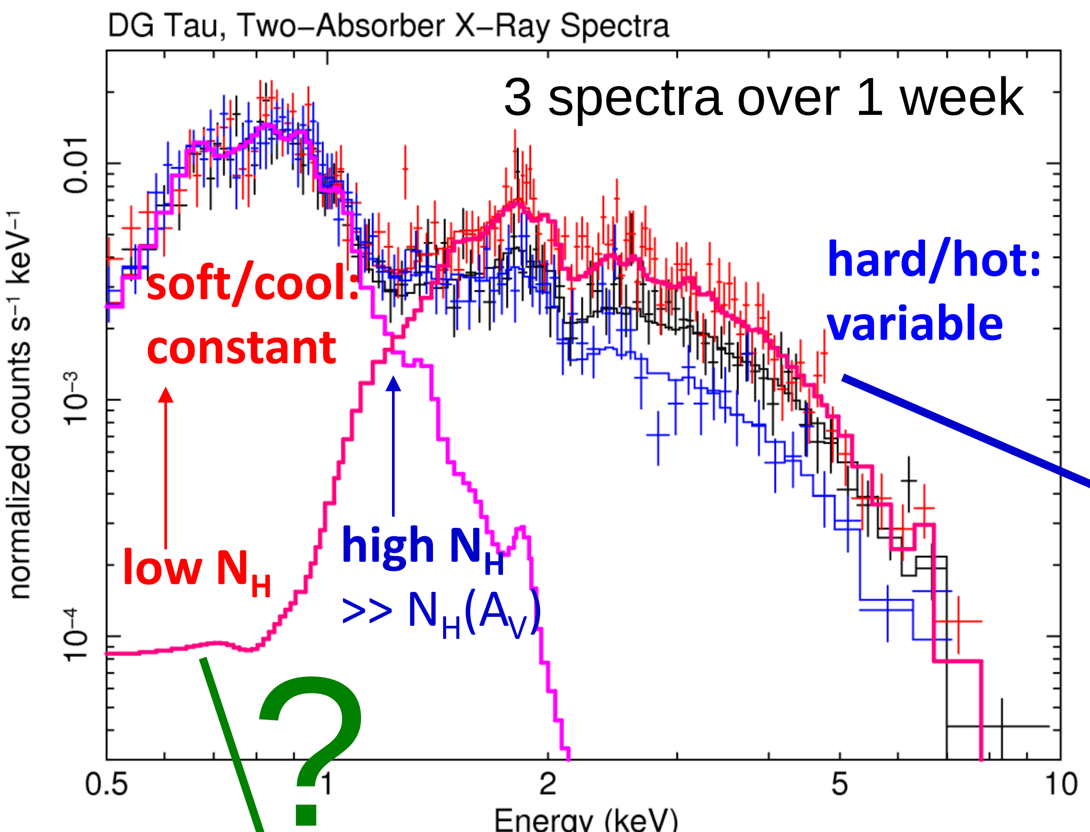
- Cooling jet due to expansion
- standing structure at 0.5-1”

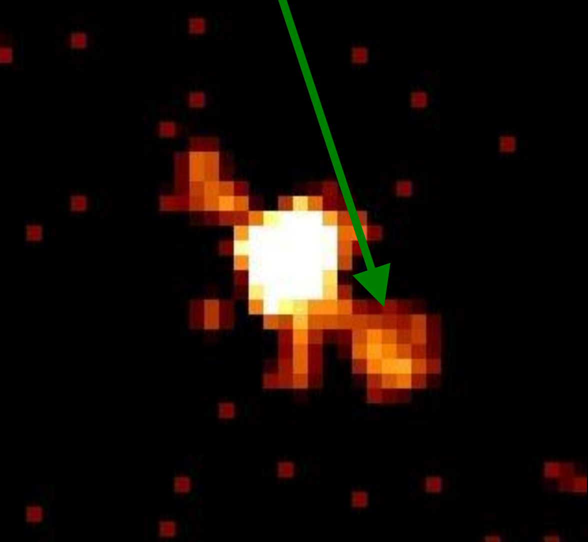
(Schneider+ 2011)



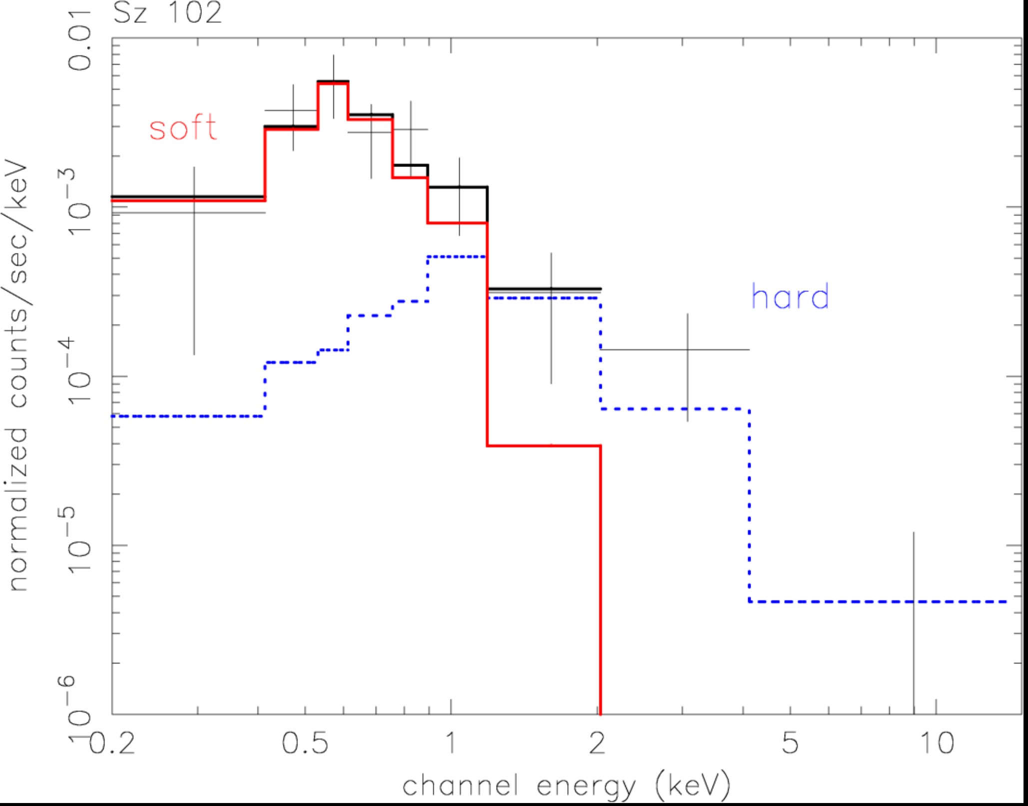


Spectroscopic X-Ray Jets



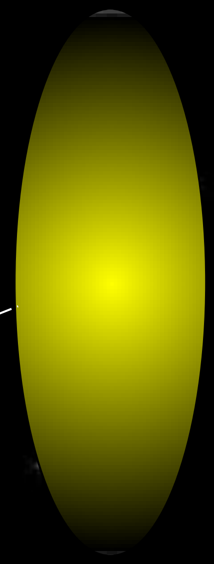


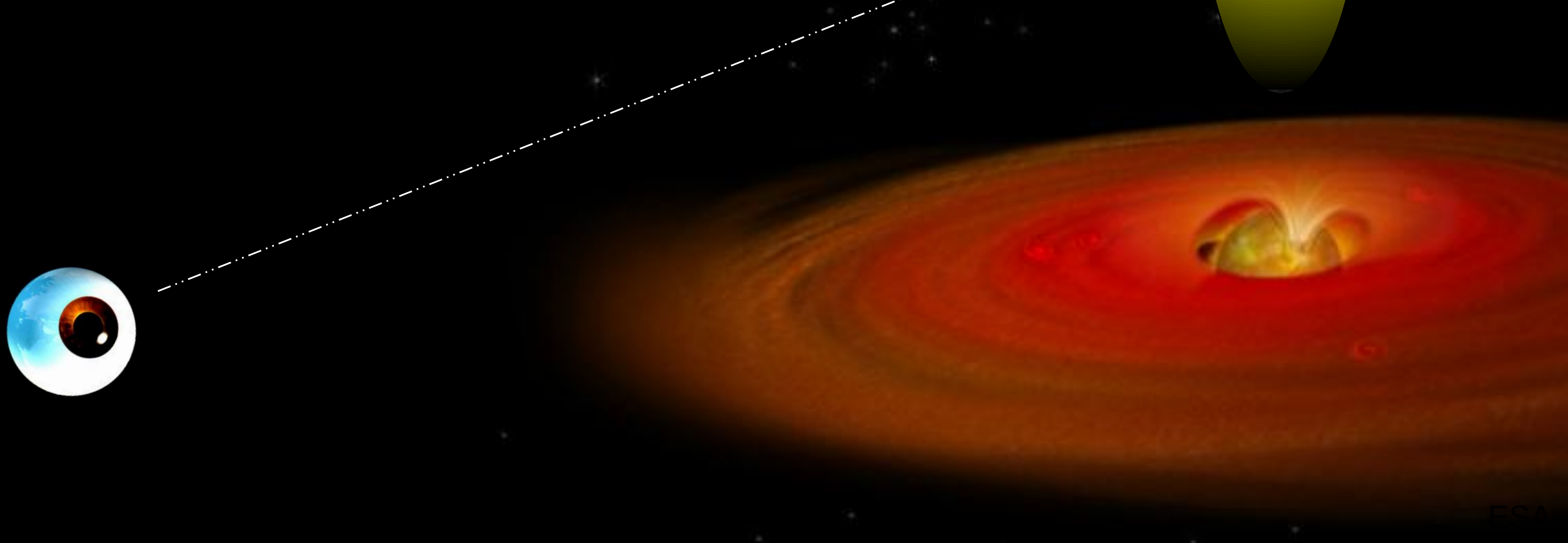
Coronal (hard) emission *absorbed by dust-depleted accretion flows with $N_H > 10^{22}$ cm^{-2}*

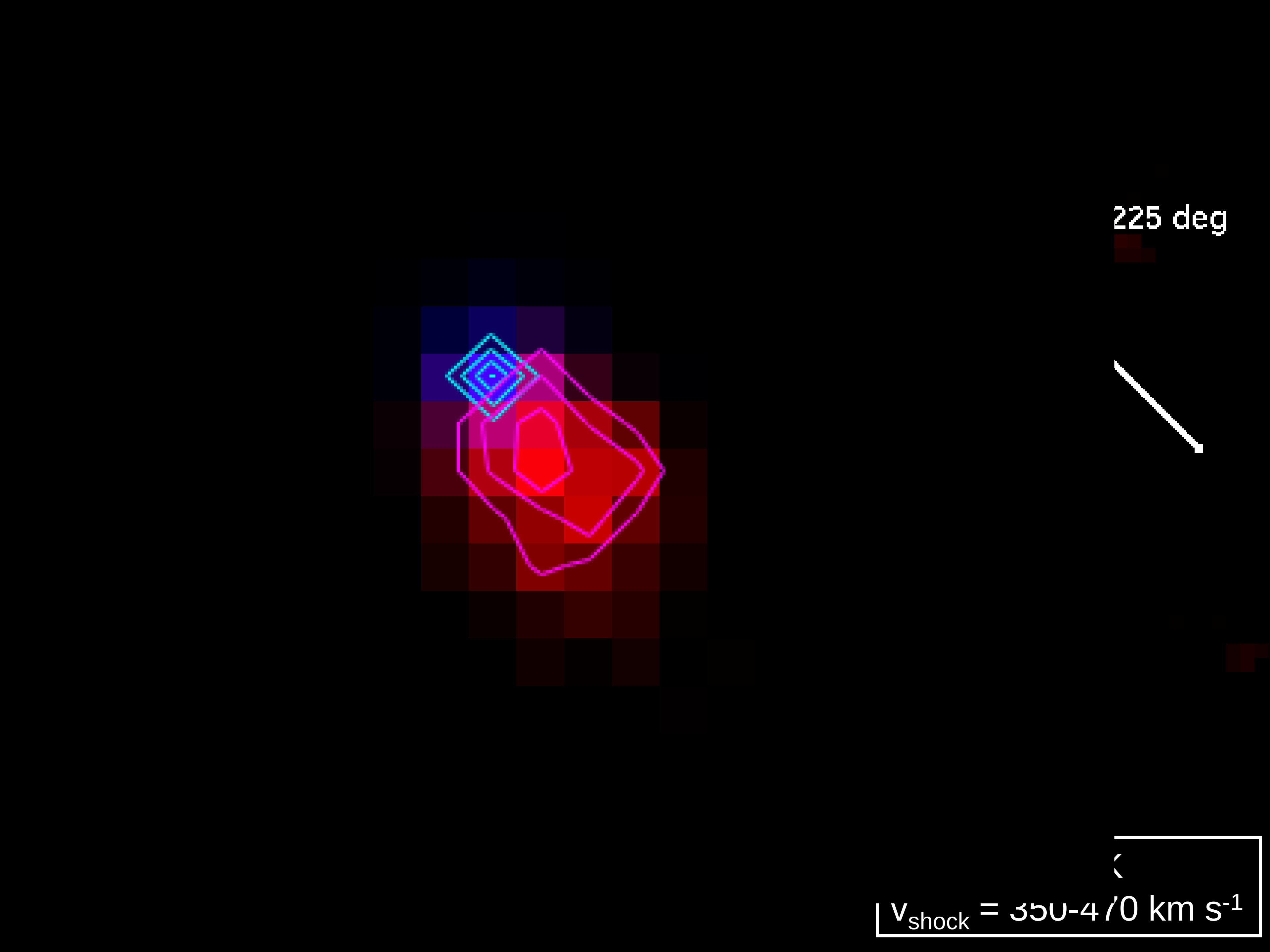


Extreme case: edge-on Sz 102

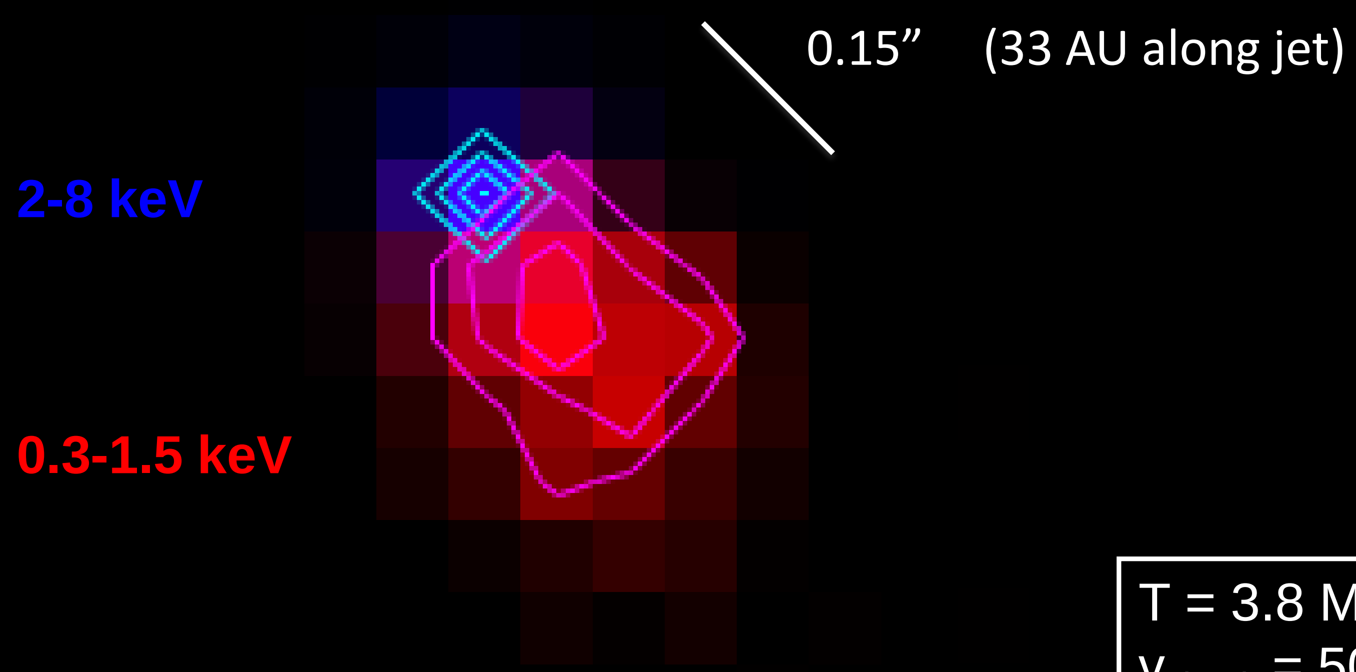
Spectrum very soft, T = 2.1 MK
star absorbed,
see only jet?






225 deg
v_{shock} = 350-470 km s^{-1}

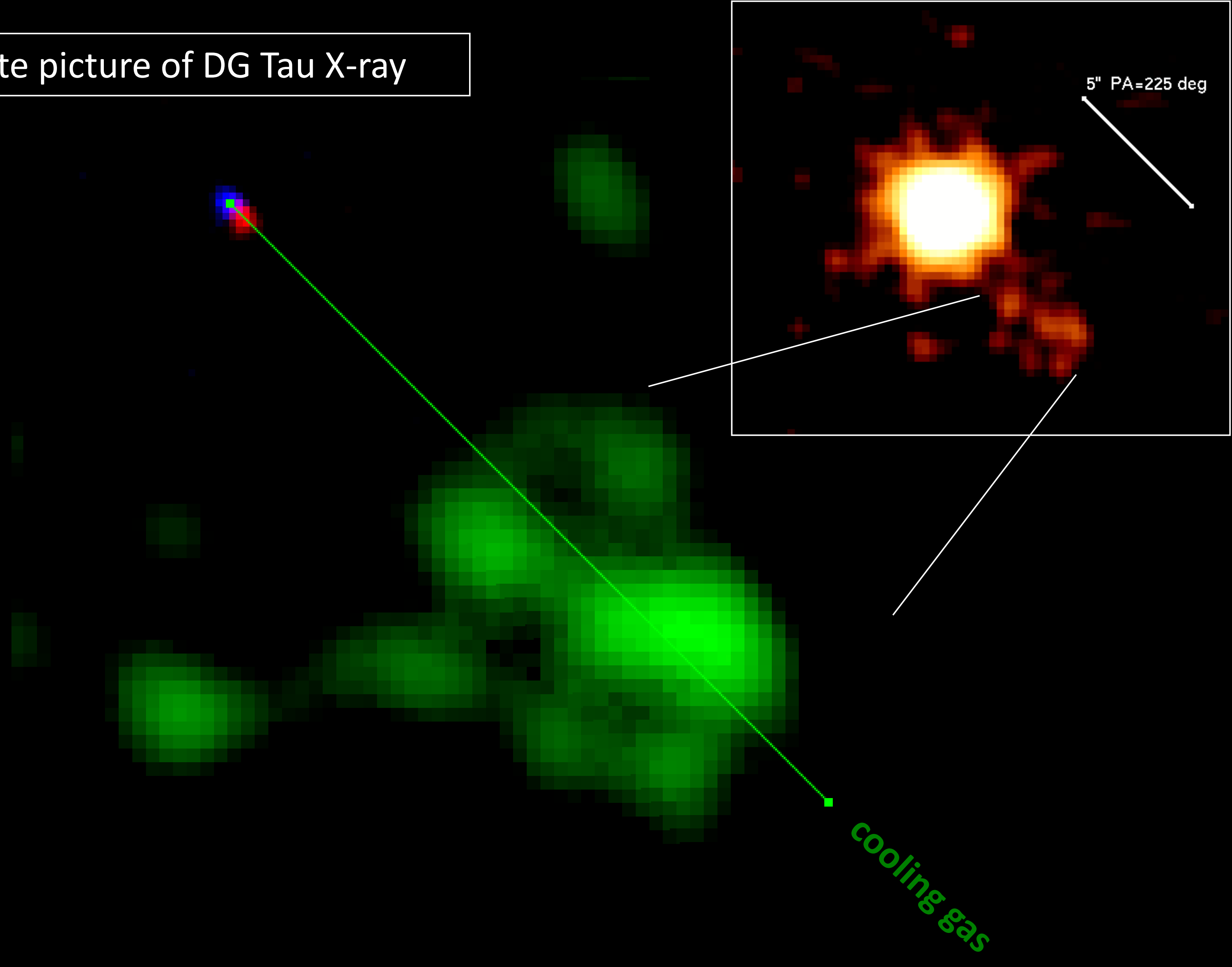
Deconvolution of SER-treated ACIS data (Güdel+ 2012) 1pixel = 0.0615”



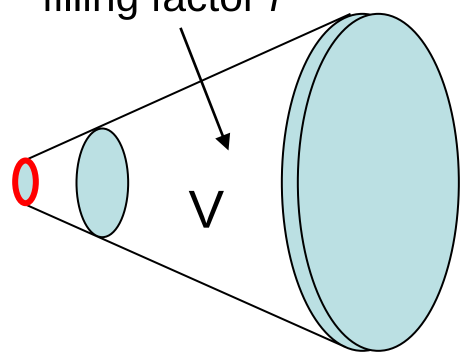
T = 3.8 MK
v_{shock} = 500 km s^{-1}

Offset in 2010 approx. identical to 2005/06 (Schneider et al.: POSTER P47): standing structure; collimation region!

Complete picture of DG Tau X-ray jet



Radiative Cooling



$$\mathrm{EM} = 0.83 n_\mathrm{e}^2 V f$$
$$\tau = 3kT/(n\Lambda)$$

$\longrightarrow$

$$f^{1/2} = (\mathrm{EM}/V)^{1/2} \tau \Lambda/(3kT)$$
$$n_\mathrm{e} = 3kT/(\tau\Lambda)$$

DG Tau: EM = 1.39×10^{52} cm^{-3}
V = 1.77×10^{43} cm^{-3}
T = 3.7×10^{6} K
τ = 0.6 yr
L_X = 1.8×10^{29} erg s^{-1}

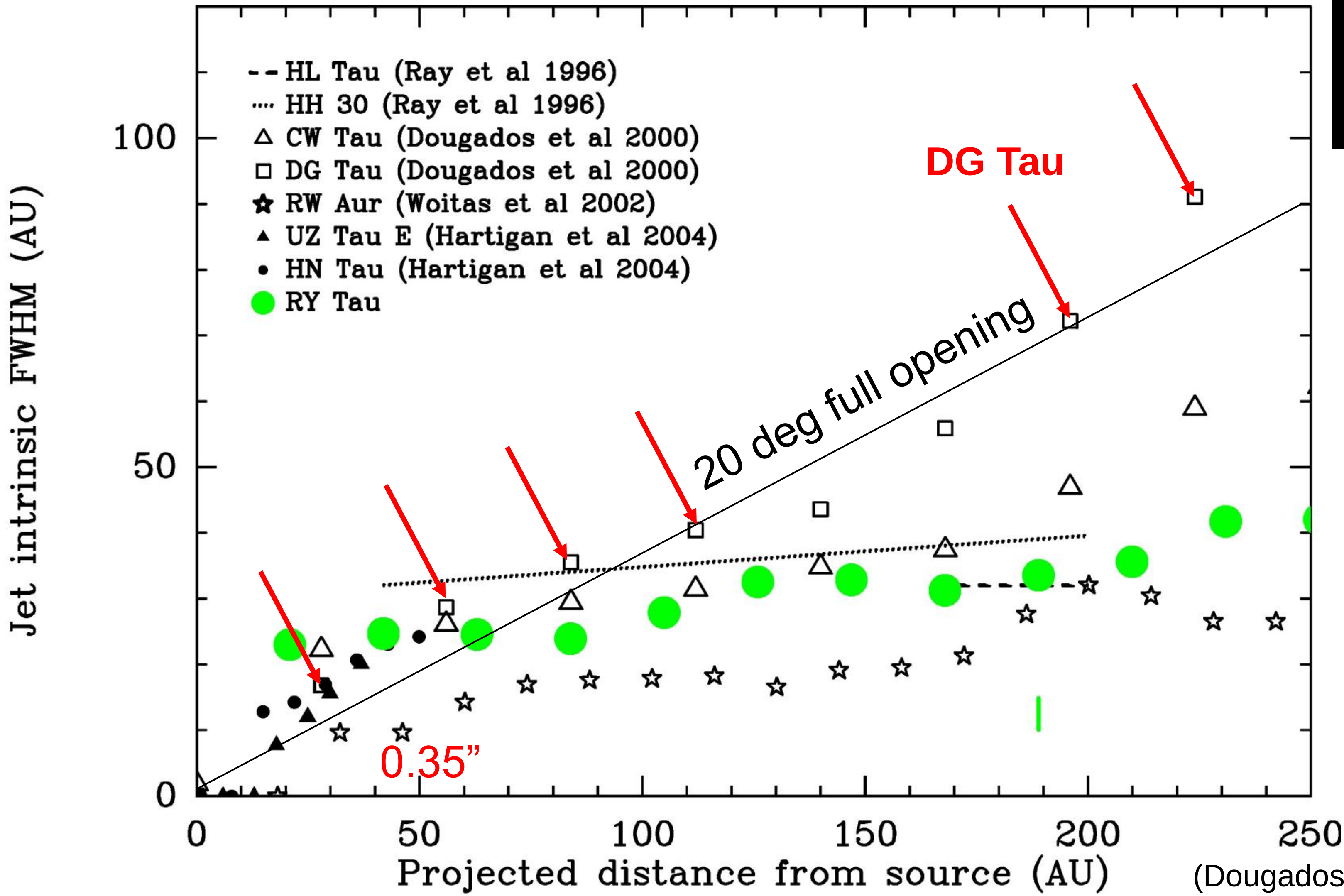
$\longrightarrow$

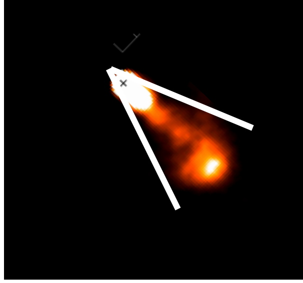
f = 3.5×10^{-5}
n_e = 4.8×10^{6} cm^{-3}

IRS 5: EM = 8.0×10^{51} cm^{-3}
V = 5×10^{45} cm^{-3}
T = 7.0×10^{6} K
τ = 15 yr
L_X = 8.0×10^{28} erg s^{-1}

$\longrightarrow$

f = 1.23×10^{-5}
n_e = 3.6×10^{5} cm^{-3}





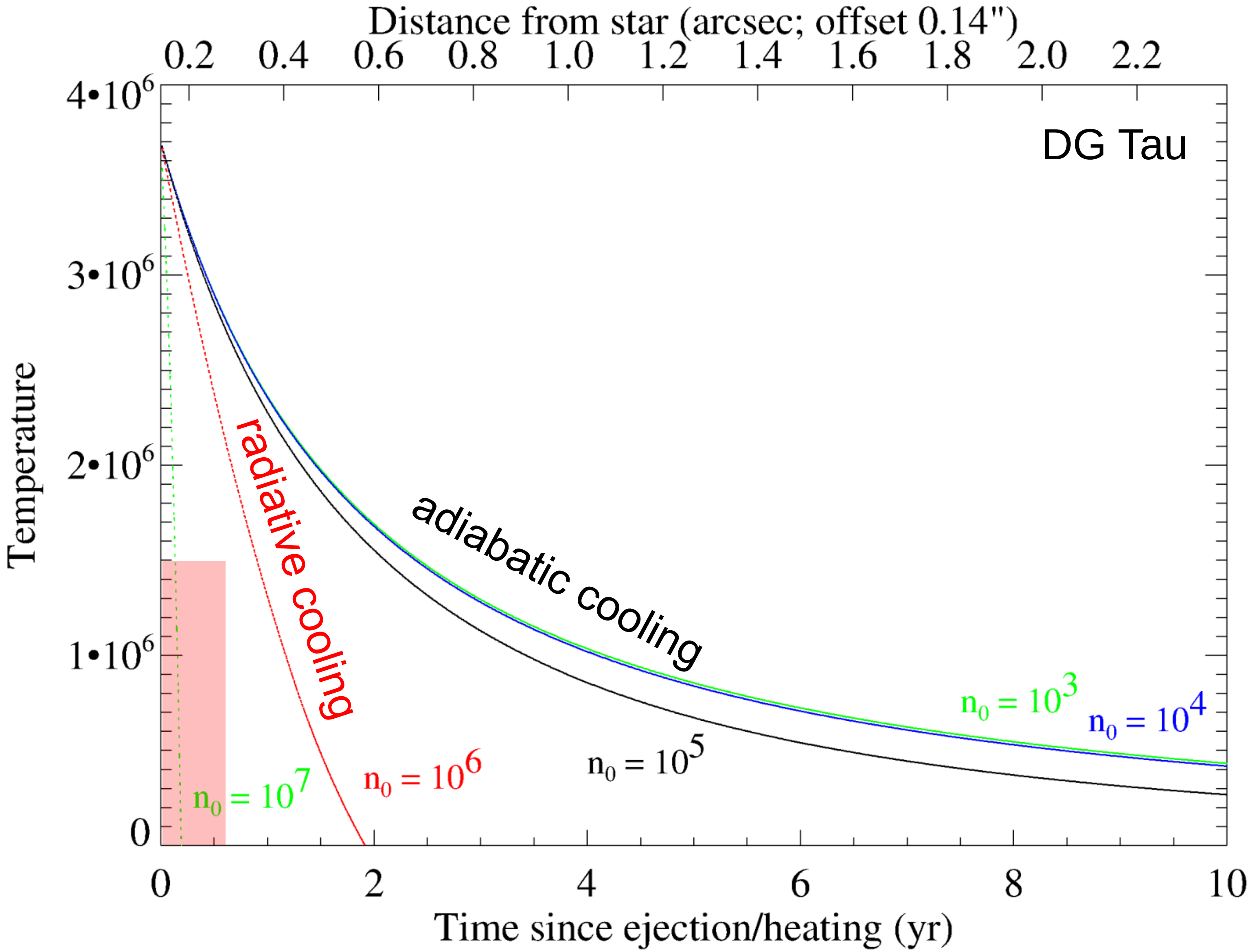
(Dougados et al. 2008)

half opening angle for DG Tau ≈ 10 deg

(Agra-Amboage+ 2011: possibly smaller)

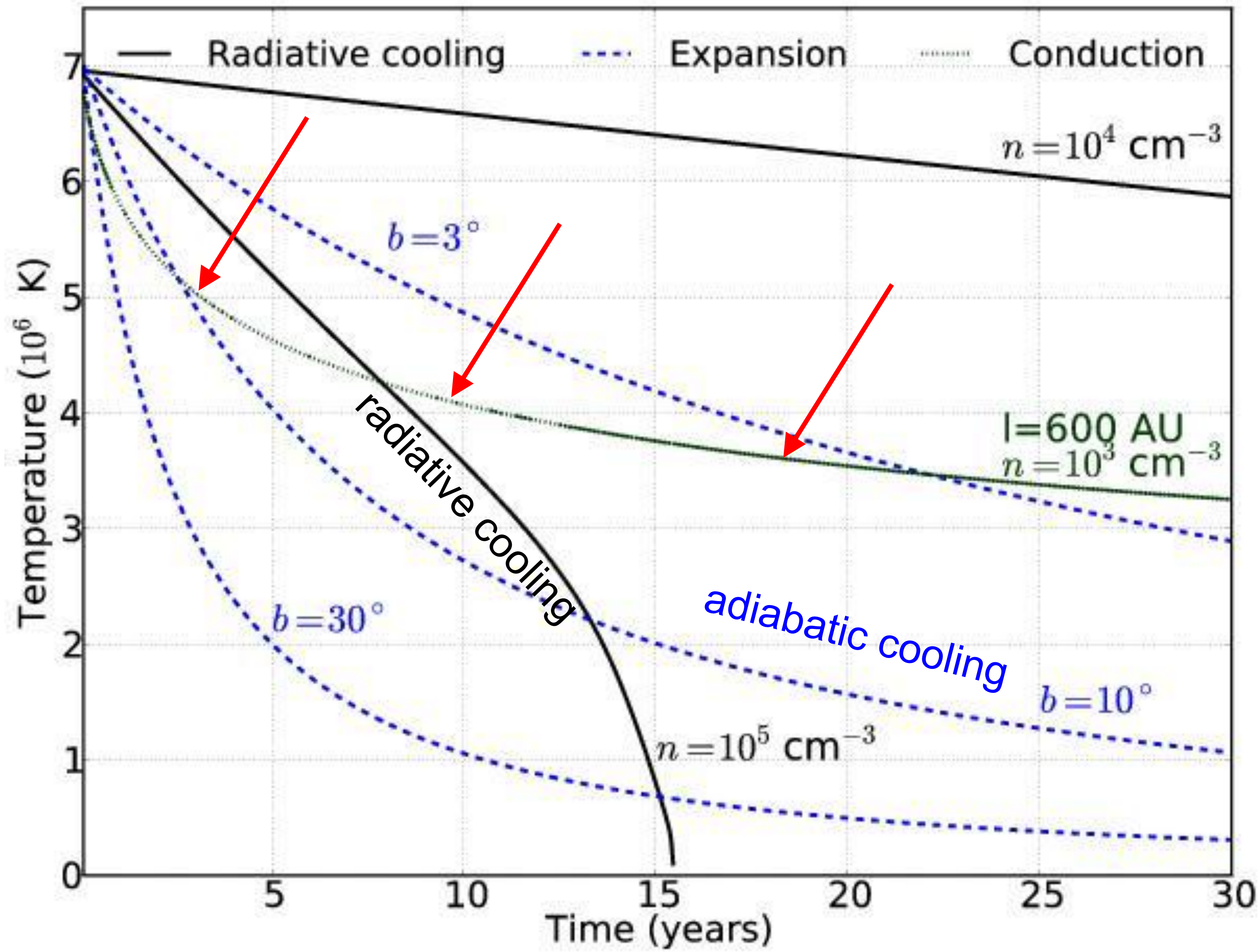
Cooling of inner source including expansion

initial radius: 0.1”
half opening: 10 deg



Requirement: Cooling time ~0.6 yrs: $n_0 > 10^6$ cm^{-3}

L1551 IRS5



(Schneider et al. 2011)

Pressure in the Plasma: Stationary Source

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

(Lavalley-Fouquet et al. 2000)

DG Tau

optical	$n \approx 10^{6}$ cm^{-3}	$T \approx 10^{4}$ K	$nT = 10^{10}$ K cm^{-3}
X-ray	$n_e = 4.8 \times 10^{6}$ cm^{-3}	$T \approx 3.7 \times 10^{6}$ K	$nT = 1.8 \times 10^{13}$ K cm^{-3}

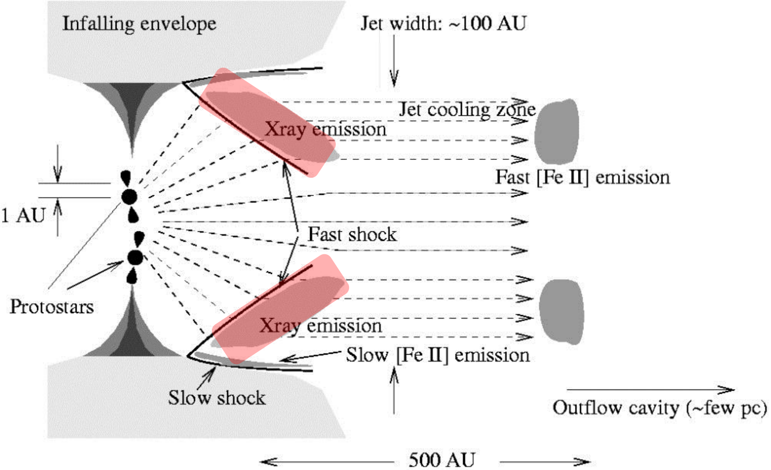
(Itoh et al. 2000)

IRS 5

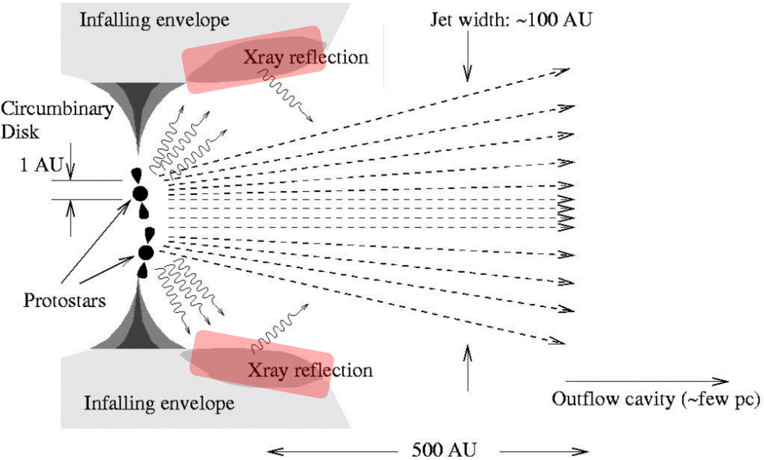
optical	$n \approx 10^{6}$ cm^{-3}	$T \approx 10^{4}$ K	$nT = 10^{10}$ K cm^{-3}
X-ray	$n_e = 3.6 \times 10^{5}$ cm^{-3}	$T \approx 7 \times 10^{6}$ K	$nT = 2.5 \times 10^{12}$ K cm^{-3}

Hot gas contributes to jet expansion if not located at surface of jet or confined by magnetic fields

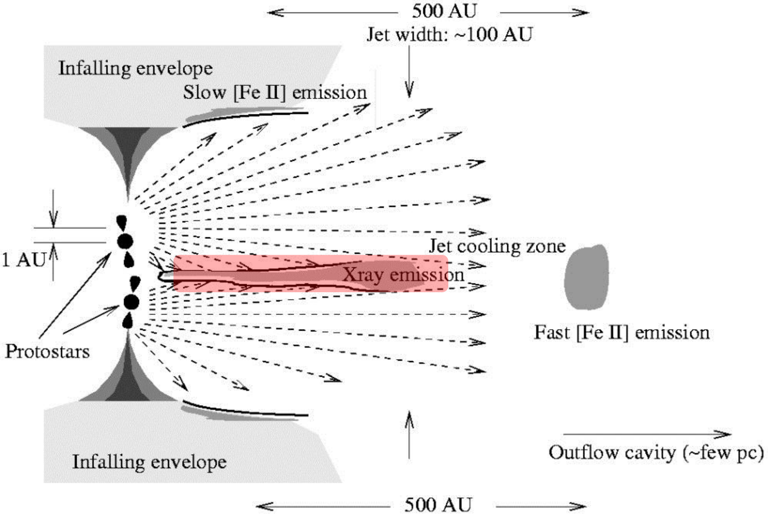
Origin of X-Ray Sources



X-ray shocks in collimation region



X-ray scattering



Colliding winds/jets from the two components

(Bally et al. 2003)

Shocks

For high-T plasma close to star (L1551 IRS5, DG Tau)
measured shock speeds 50-100 km/s
(Agra-Amboage et al. 2009, Lavalley-Fouquet et al. 2000)

Even bulk flow speeds often < 300 km s^{-1}

But then, shock temperatures

$$T_s = 1.5 \times 10^5 \text{ K} \left(v_{100}\right)^2 ,$$

(Raga et al. 2002) too low.

Plasma Mass Loss Rate

DG Tau: radiative heating dominates in center

$$\tau = \frac{3kT}{n_e \Lambda}$$ radiative decay time

$$d = \tau v$$ cooling distance

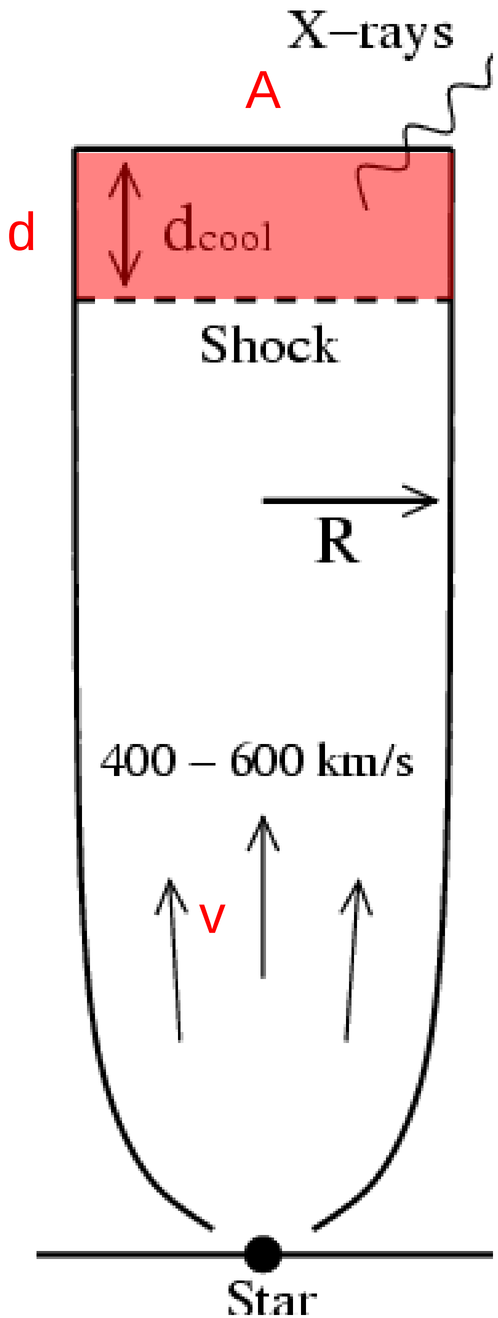
$$\mathrm{EM} = f n_e^2 A d$$ emission measure

$$\dot{M}_X = m_H n_e f r^2 \pi v = \frac{m_H \Lambda(T) \mathrm{EM}}{3kT}$$

$$\boxed{\begin{aligned} \dot{M}_X &= 4.1 \times 10^{-12}\ M_\odot\ \mathrm{yr}^{-1} \\ \ll M_{\mathrm{opt}} &= 3.3 \times 10^{-8}\ M_\odot\ \mathrm{yr}^{-1} \end{aligned}}$$

(Agra-Amboage+ 2011)

Small amount of high-velocity gas that has escaped detection in the optical?
(Günther et al. 2009)



Pulsed jets

- Periodically ejected blobs
- Random velocity

Collisions between blobs and environment: knots

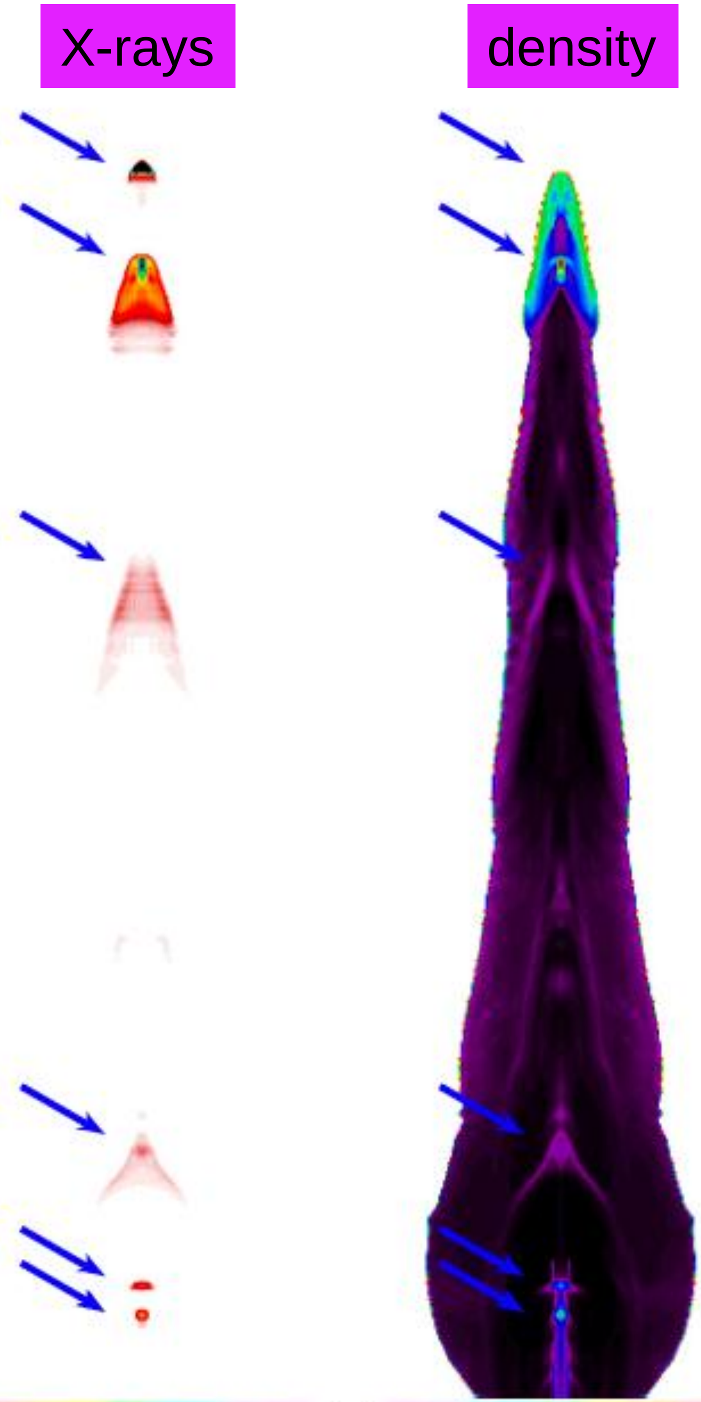
Depending on shocks, chains of X-ray knots

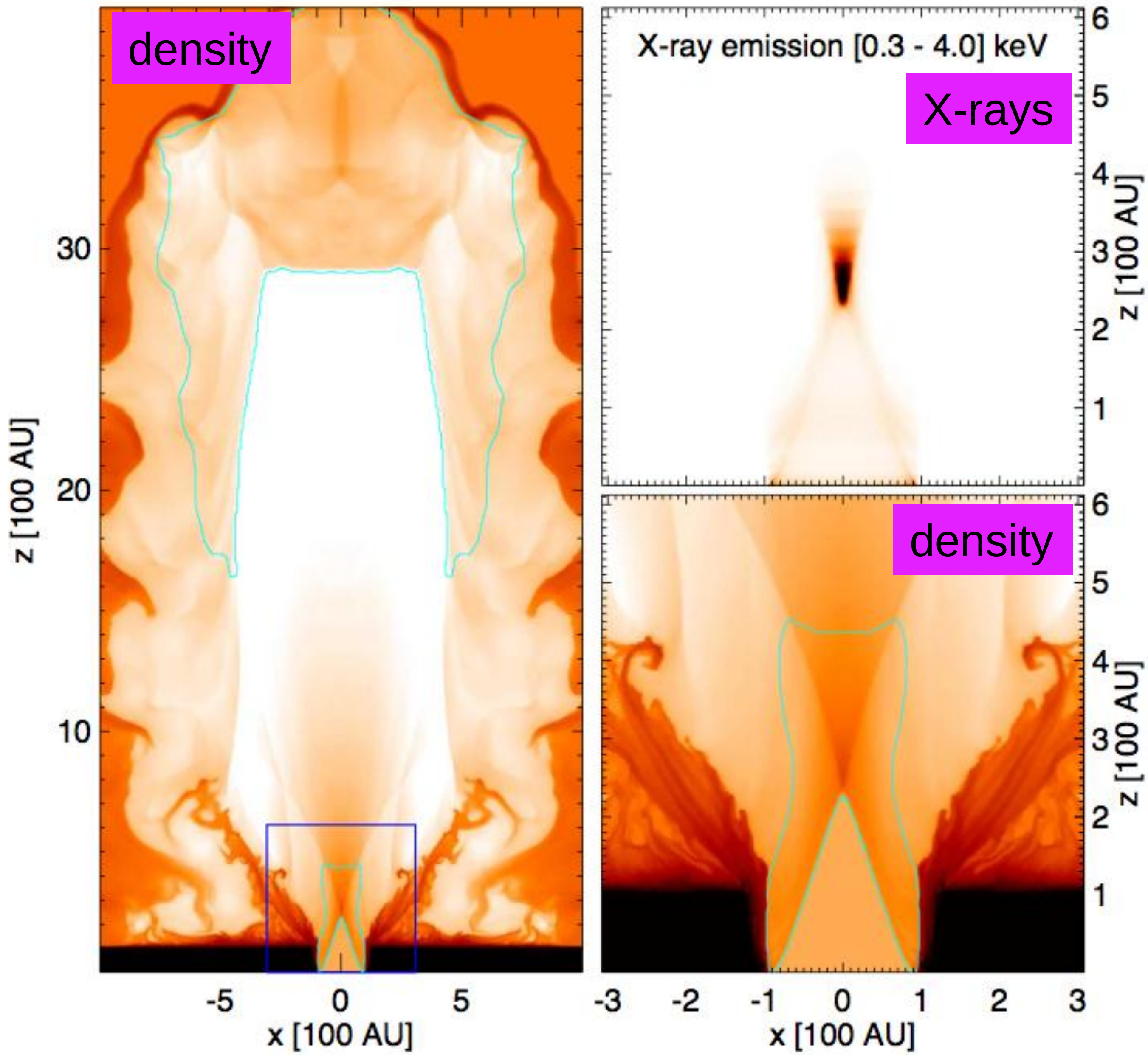
especially in low-density jets

mostly at jet base

Higher ejection rate → higher L_X

(Bonito et al. 2010)

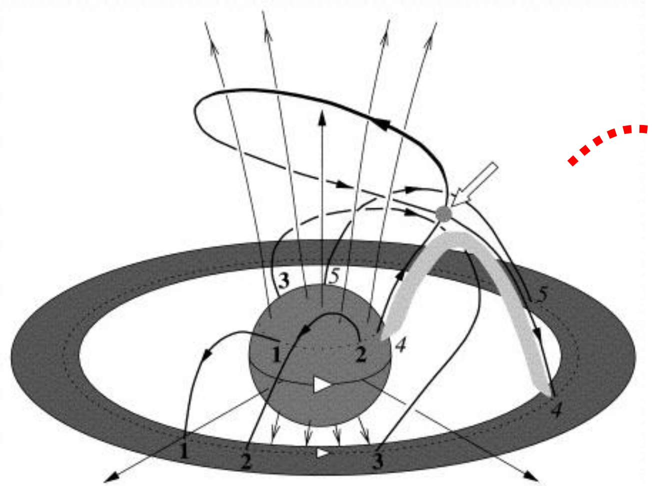


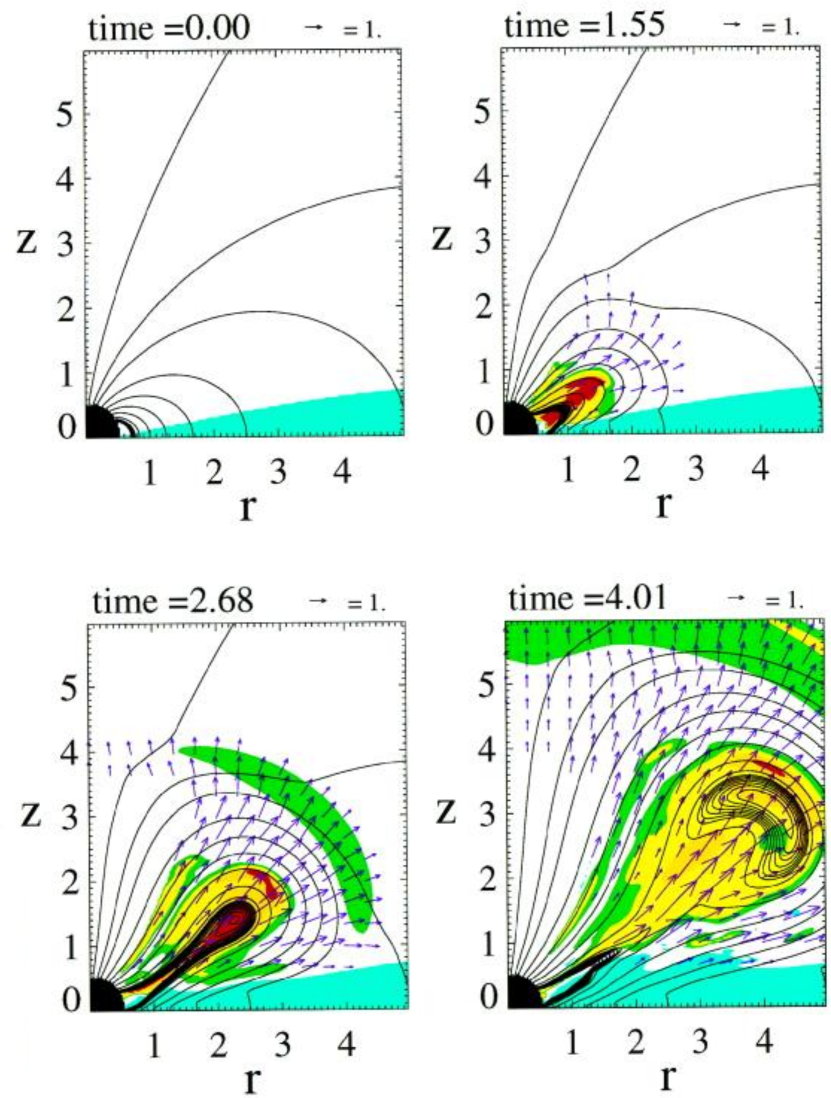


Diamond shock at nozzle, 1500 km $s^{-1} \rightarrow$ 8 MK (Bonito et al. 2011 for L1551 IRS5)

Reconnection

(Montmerle et al. 2000):





Winding up star-disk fields

→ Antiparallel fields
→ Heating and Reconnection
→ <u>Ejection of hot plasmoids</u>
→ Further shock heating
→ Jets?

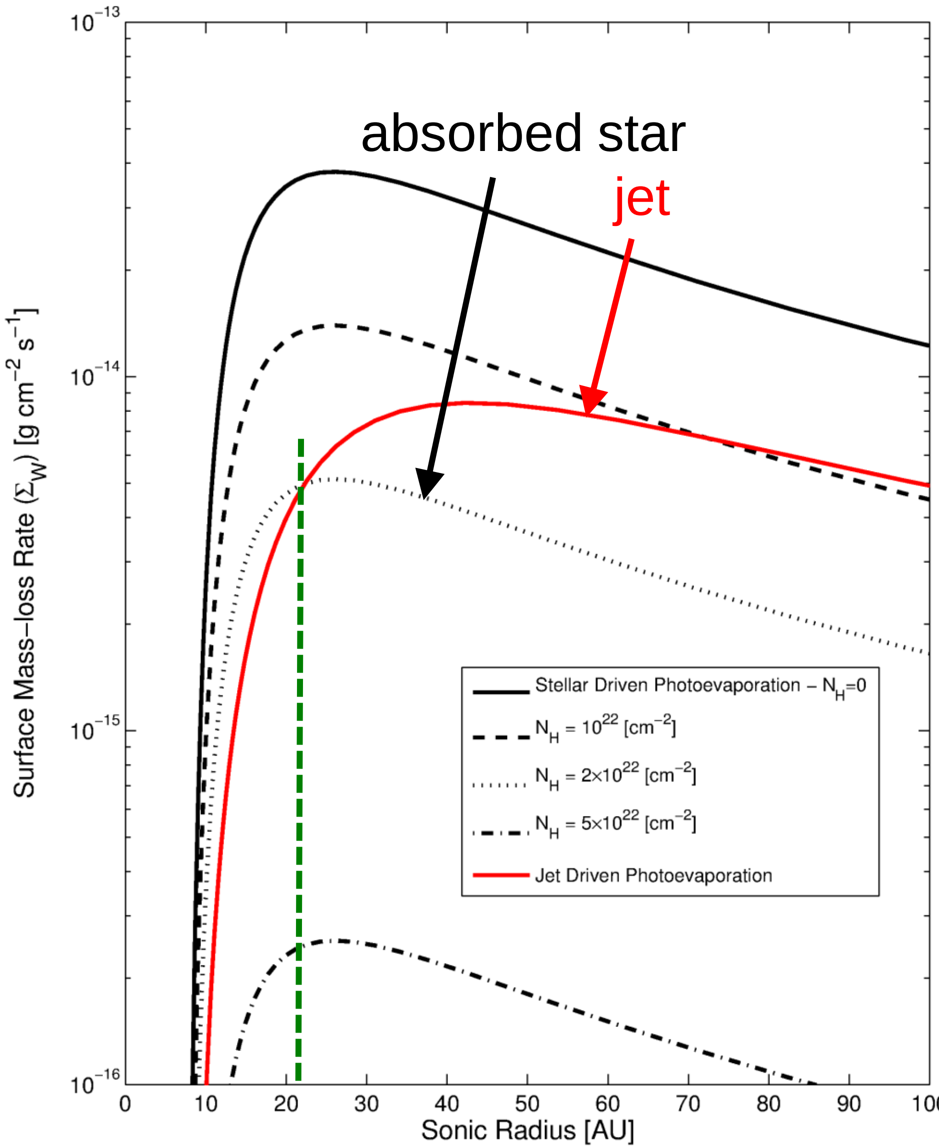
(Hayashi et al. 1996)

Photoevaporation by X-Ray Jets?

Mass loss rate from DG Tau disk dominated by jet irradiation at

r > 22 AU

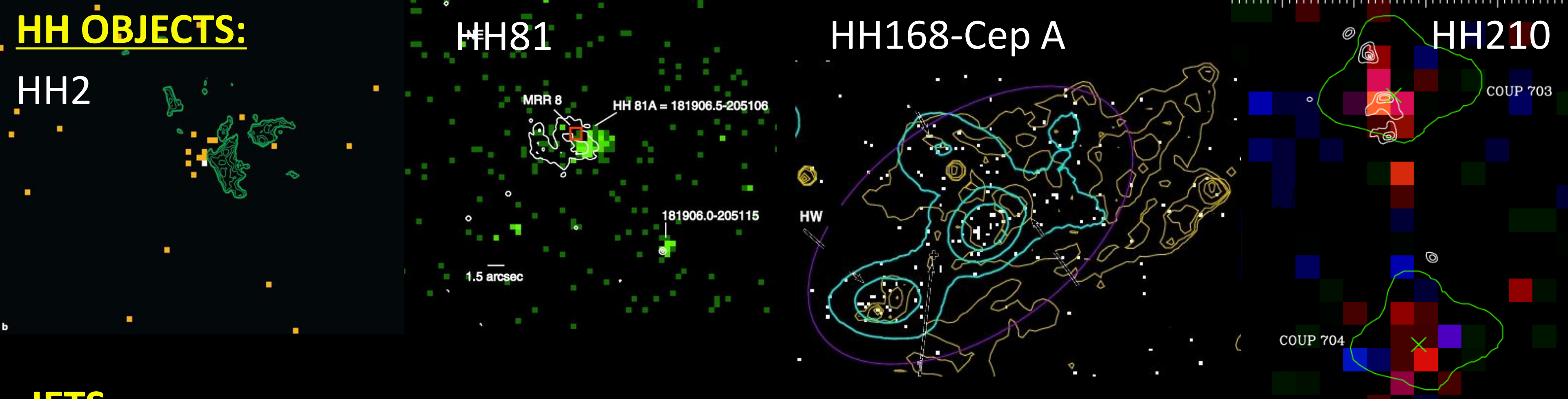
(Owen et al. in prep.)



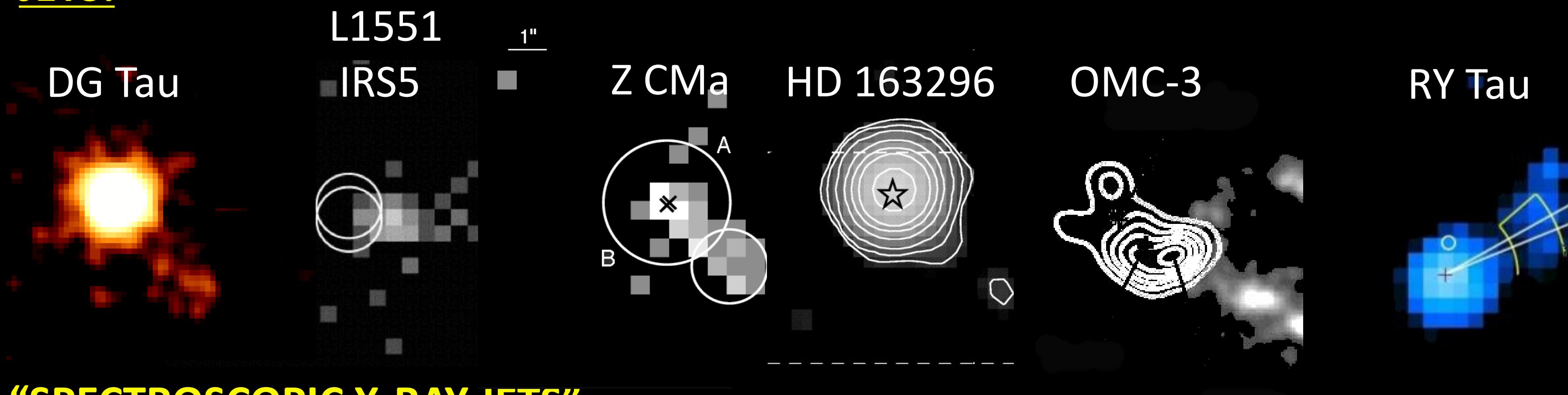
…although this wind does not compete with accretion:

star: $dM/dt \approx 3\times10^{-10}\, M_\odot\, yr^{-1}$
jet: $dM/dt \approx 7\times10^{-10}\, M_\odot\, yr^{-1}$

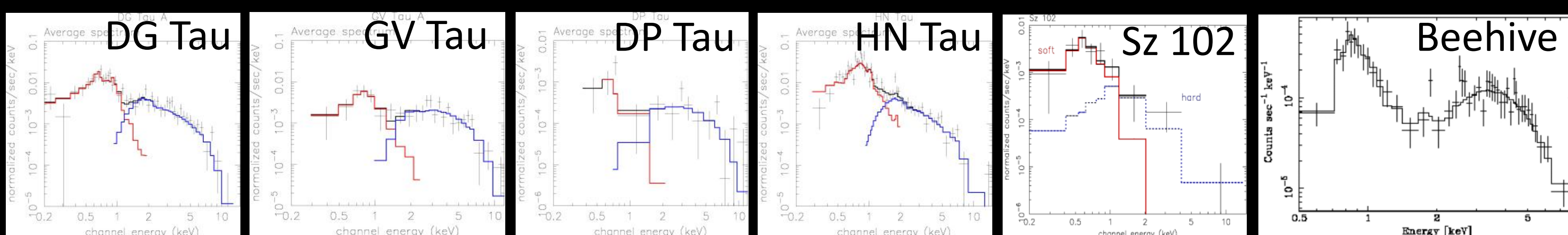
HH OBJECTS:



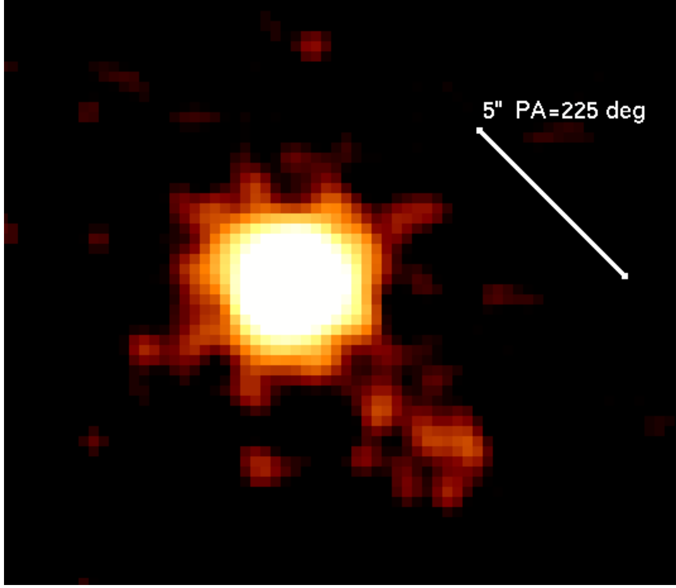
JETS:



“SPECTROSCOPIC X-RAY JETS”:



Conclusions



- X-rays found in protostellar and T Tauri jets from the base (collimation region?) to distant Herbig-Haro objects

- Plasma close to stars: high densities in standing structure

- Heating: shocks or magnetic?

- Important influence on protoplanetary disks: heating, ionisation, chemistry, photoevaporation

END