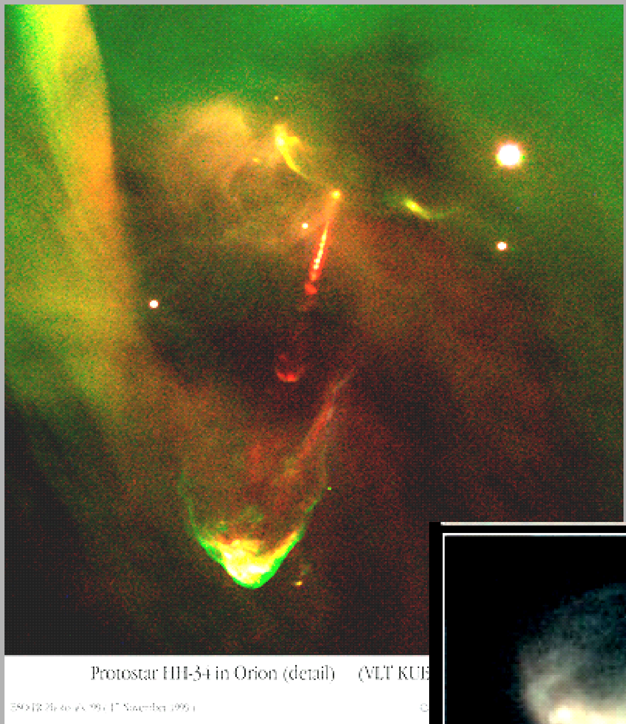
JETS TOMOGRAPHY IN VELOCITY SPACE



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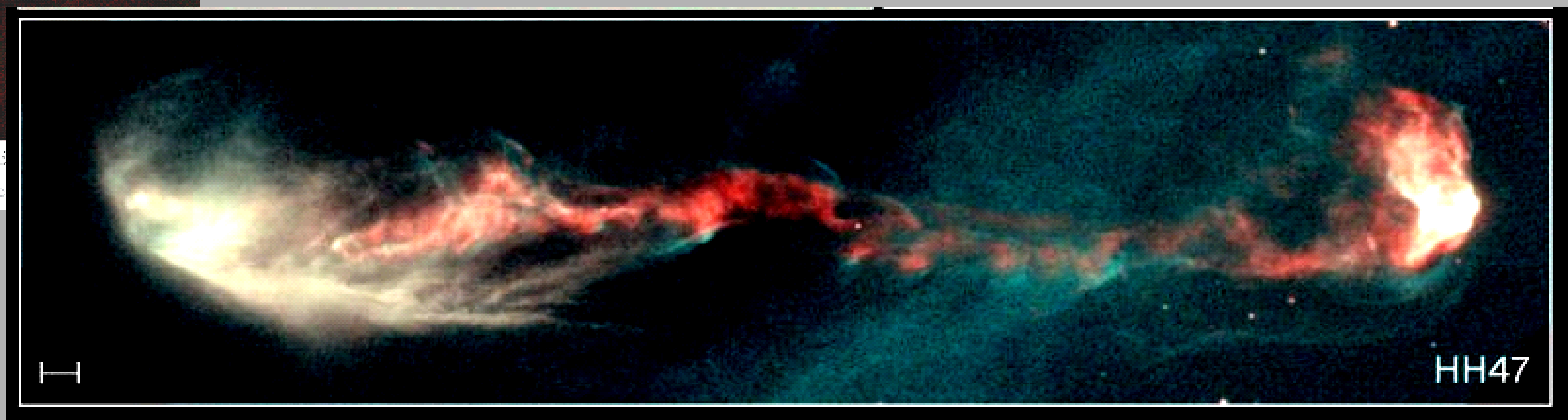


Outline

Observation of stellar jets

- observational properties
- physics of shocks – spectral tracers – diagnostic techniques

Large scale physical/dynamical jet structure

- results from optical/NIR spectral diagnostics
- results from a jet tomography in velocity space

Observational properties of stellar jets

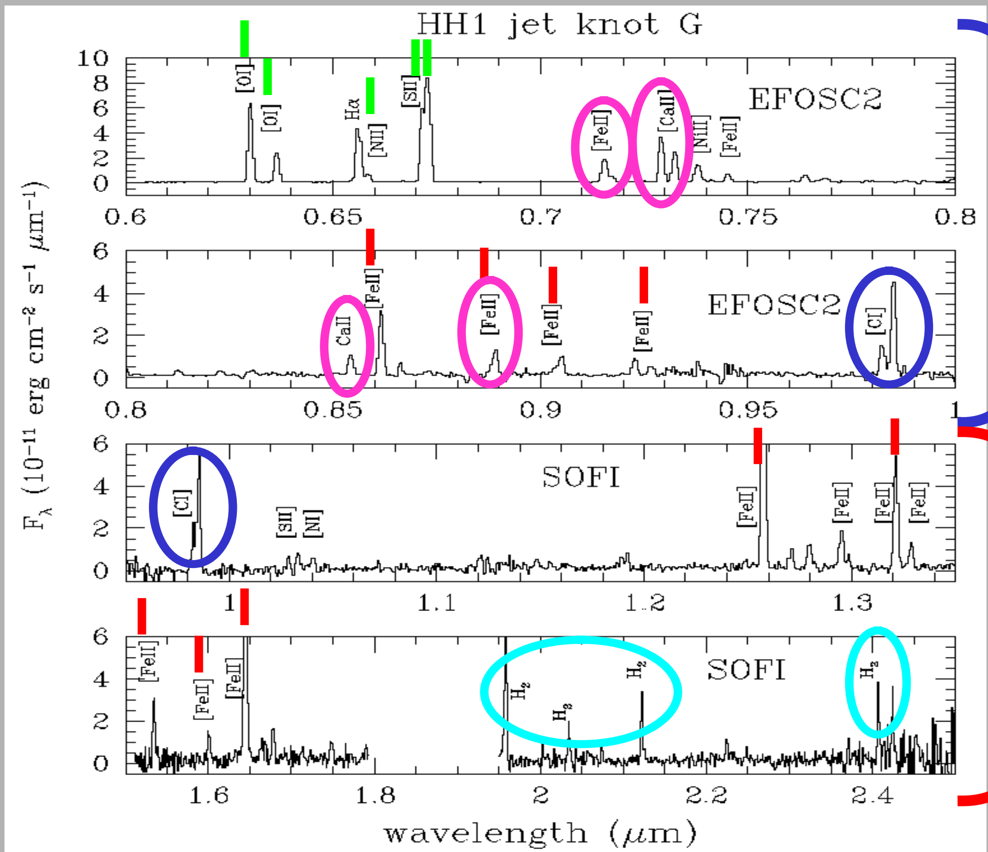
0.6 μm **optical** 1 μm **NIR** **FIR**

Ha, [SII], [OI], [NII], [CaII], [FeII], [OII],....

[CI], [SIII], [FeII] ..

H2, [Fe II], H, [N I], [S II], [SIII] ...

H_20, H_2, H_2S, ... [CII] 158 μm, [OI]63μm,



OPTICAL spectrum

NIR spectrum

(Nisini et al. 2005)

spectral diagnostics:

Hartigan et al. 1994
Bacciotti & Eisloffel 1999
Bacciotti et al. 1999
Bacciotti et al. 2000
Lavalley-Fouquet 2000
Hartigan et al. 2007
Coffey et al. 2008

Giannini et al. 2001
Nisini et al. 2001
Pesenti et al. 2003
Garcia Lopez et al. 2008

A_V, n_e, T_e, x_e, n_H, $\dot{M}_{jet}$, $\dot{P}_{jet}$, $\dot{L}_{jet}$

Physical structure of jets derived from observations

SHOCK cooling region: NOT resolved in observations!

To "resolve" shock cooling regions -> use of different tracers!!

Nisini et al. 2005, Podio et al. 2006

IONIZATION FRACTION Xe:

Hartigan 1994 -> grid of shock models
BE99 -> model independent

Physical parameters ALONG the jet:

Bacciotti & Eisloffel 1999, Bacciotti et al. 1999, Nisini et al. 2001, Nisini et al. 2005, Podio et al. 2006

Physical parameters ACROSS the jet:

Jet width 100-200 AU -> NOT resolved in obs from the ground!

Bacciotti 2000 -> HST data of DG Tau, 7 slits along the jet covering 0.5"
Hartigan 2007 -> HST slitless obs of HH 30 (2" slit – jet width<0.5")
Coffey 2008 -> HST obs with slit perp to the jet axis (0.1" x 52")

Physical parameters vs VELOCITY:

Lavalley-Fouquet 2000 -> OASIS obs of DG Tau (0.5"=70 AU, 90 km/s)
Garcia-Lopez 2008 -> VLT/ISAAC obs of HH1, HH34 (0.3" x 120" slit)
Coffey 2008 -> HST obs with slit perp to the jet axis (0.1" x 52")

LOW SPECTRAL/SPATIAL RESOLUTION

+

forbidden lines diagnostics

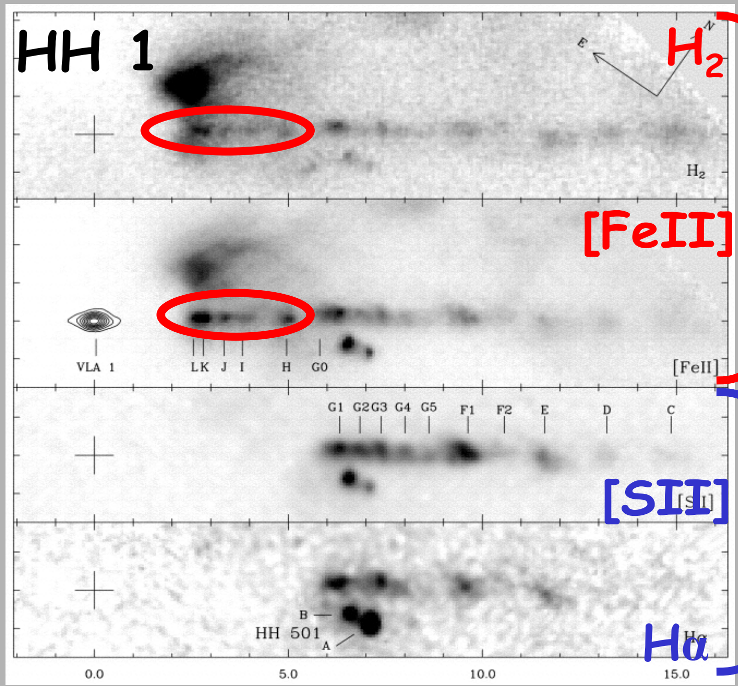
Physical structure of jets

along the jet

in each cooling region by using different tracers

The importance of using different tracers

(Reipurth et al., 2000)

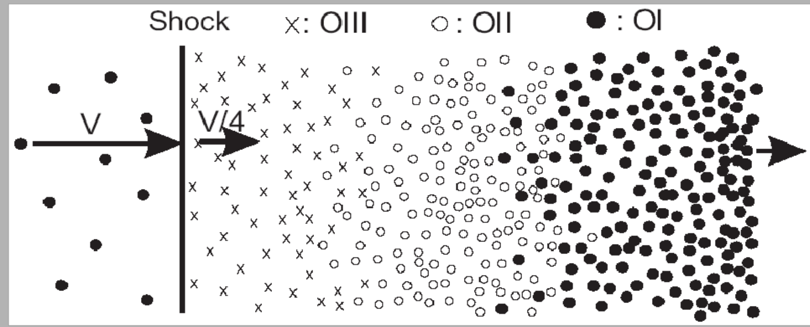


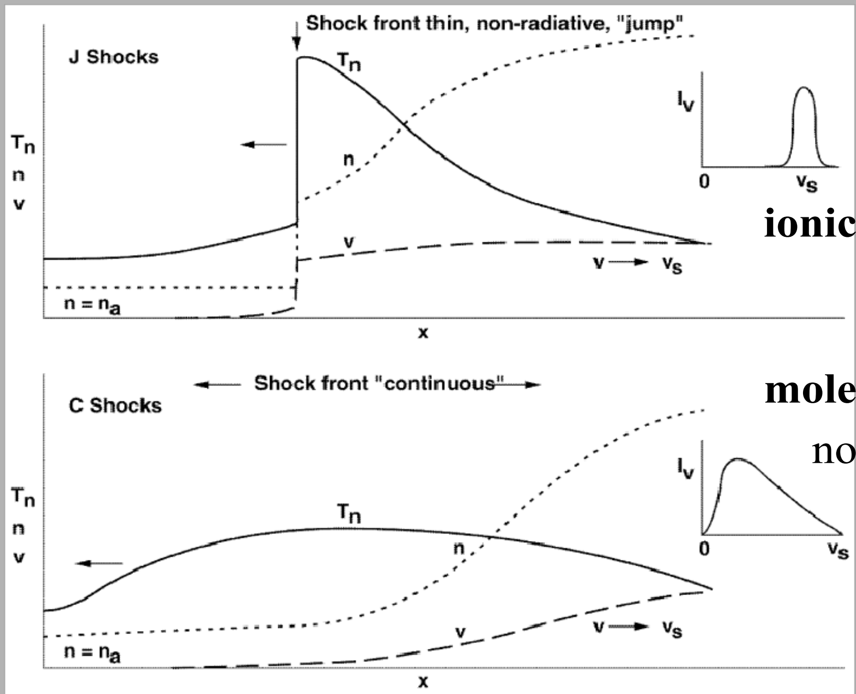
IR lines

to observe the **embedded** part of the jet

optical lines

to "resolve" the **shock cooling regions**

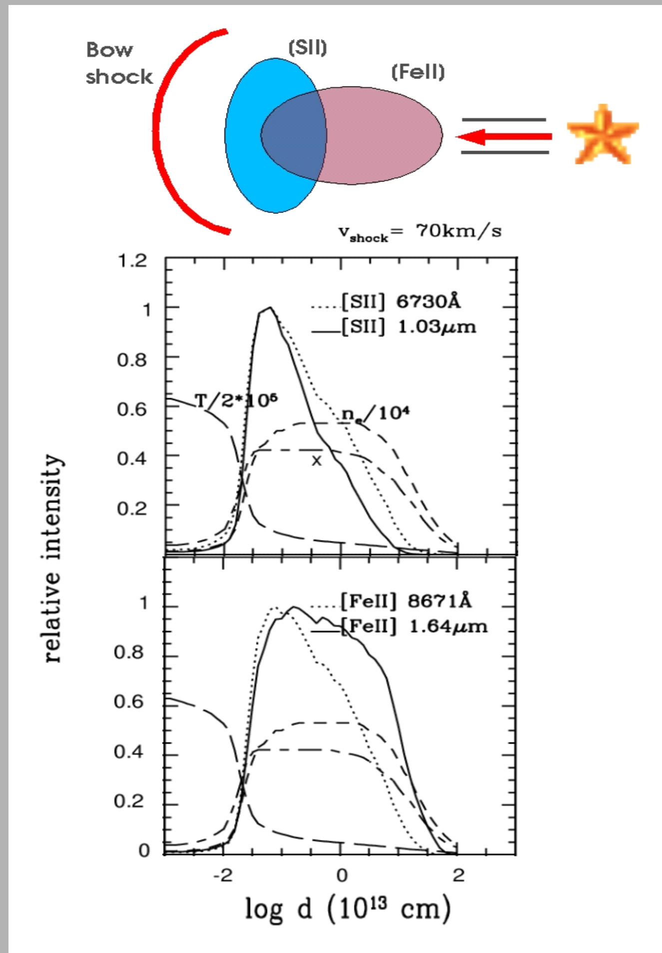




(Hollenbach et al., 1997)

ionic and atomic lines:
dissociative **J-shocks**

molecular H_2 emission
non-dissociative **C-shocks**

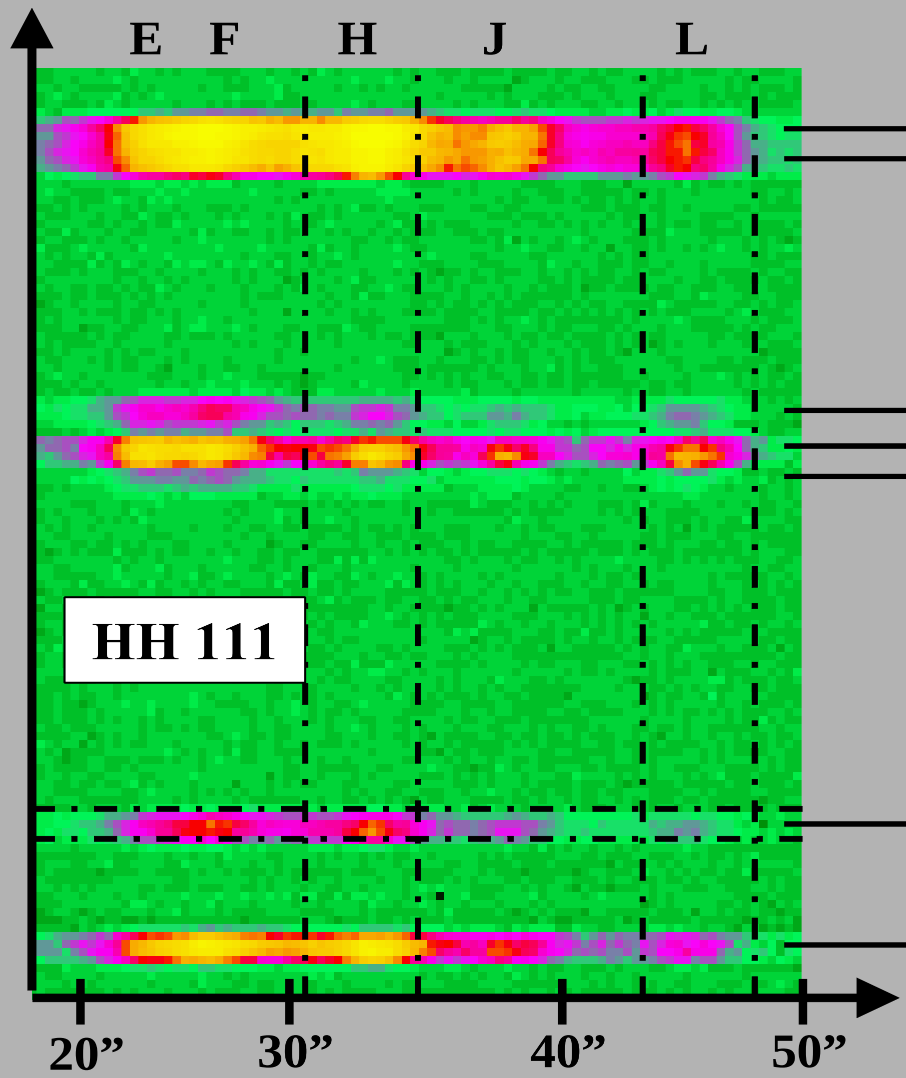


ESO-3.6m / EFOSC2 LR + ESO-NTT / SofI spectra

- sample: HH 111, HH 34, HH 73, HH 83, HH 24 C/E
- spectral range: 6015 Å – 2.5 μm
- slit: 1”× 290” → R ~ 600

Δv ~ 500 Km/s

BE TECHNIQUE



OBS FLUXES

INPUT

[SII]λ 6716, 6731
[NII]λ 6548, 6583
[OI]λ 6300, 6363

↓

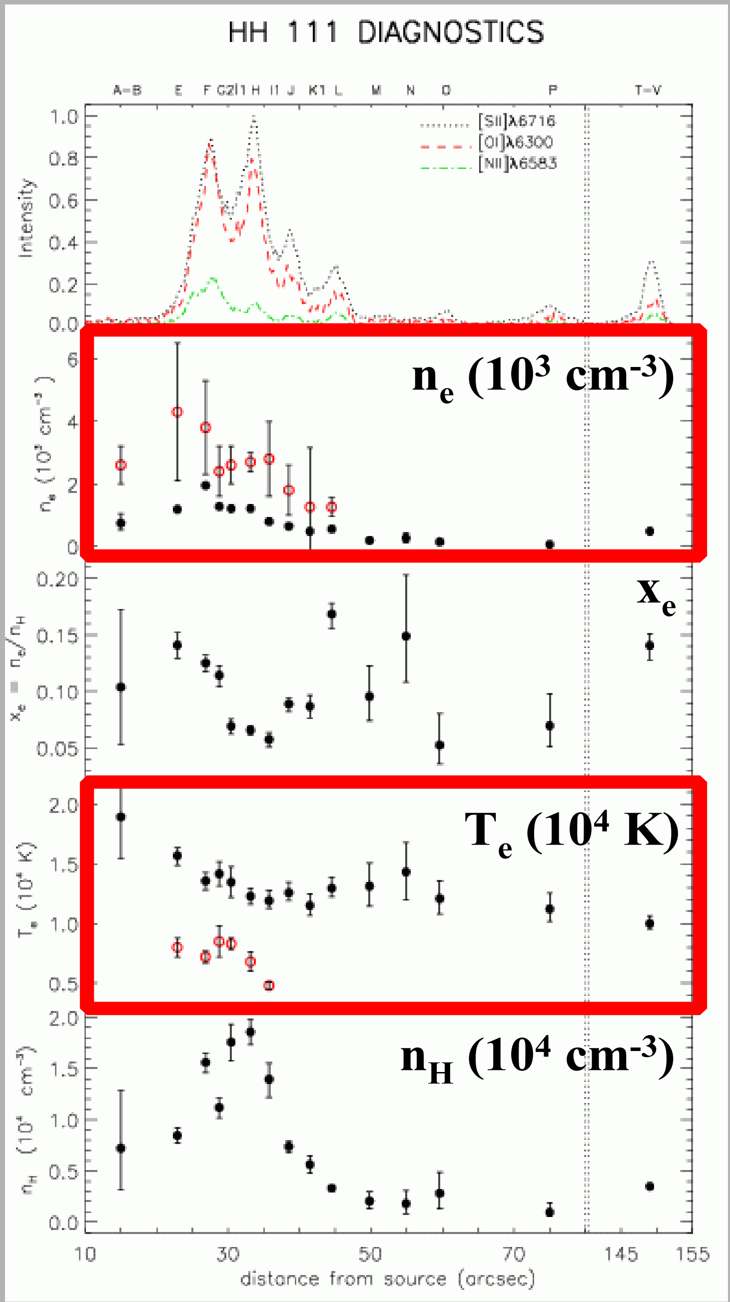
n_e (from S^+ lines)
[SII]/[OI] = f (x_e, T_e)
[OI]/[NII] = f (x_e, T_e)

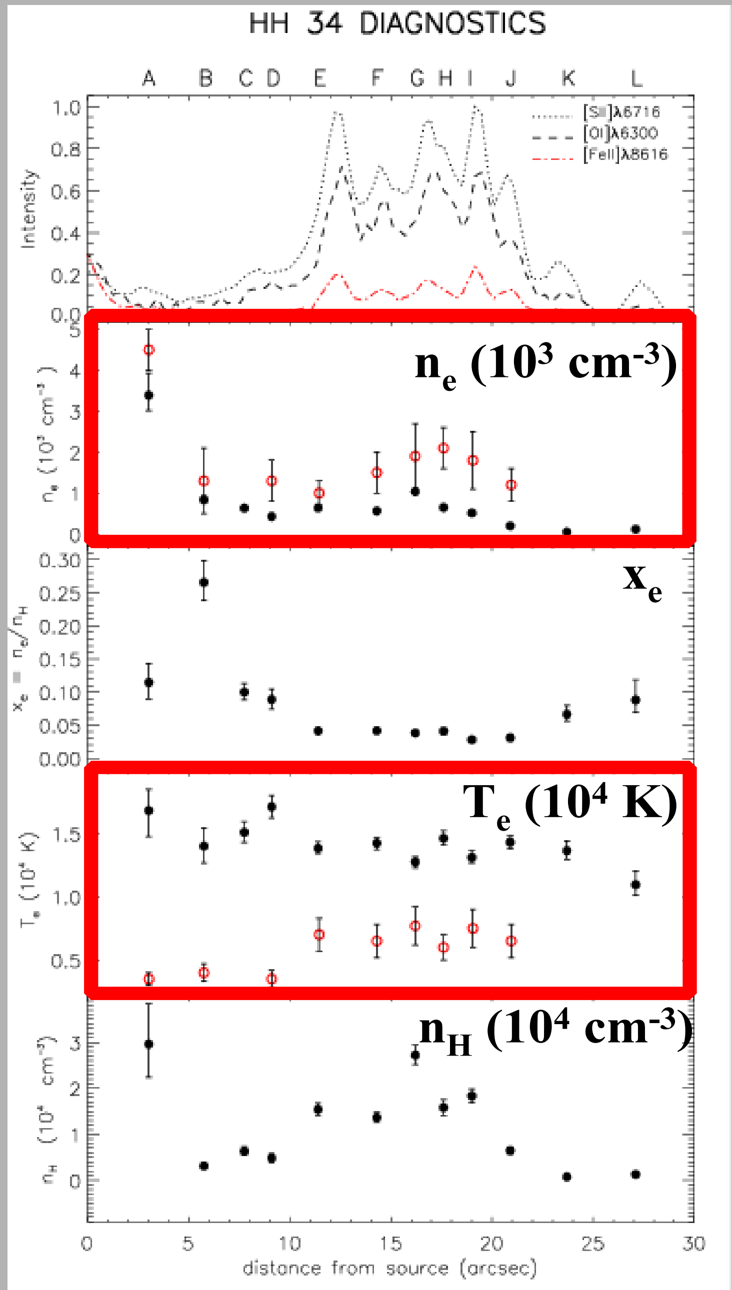
↓

OUTPUT

n_e
T_e (from [SII]/[OI])
x_e (from [OI]/[NII])
n_H = n_e/x_e

Opt/NIR diagn: physical structure of HH 111, HH 34





n_e (opt) ~ 10^2 - 3.4 10^3 cm^{-3}

n_e (Fe) ~ 1 - 5 10^3 cm^{-3}

x_e ~ 0.03 – 0.3

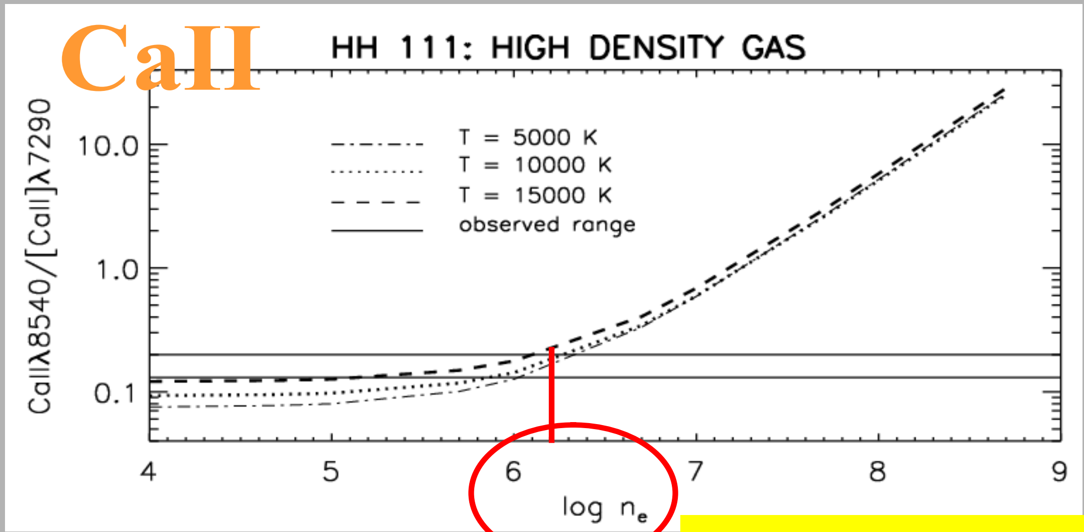
T_e (opt) ~ 1 - 2 10^4 K

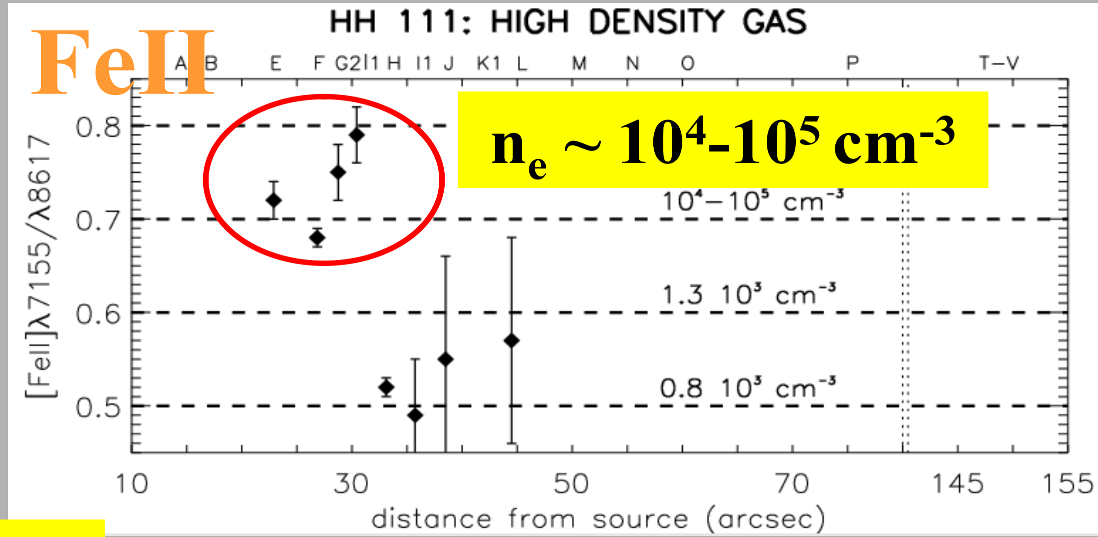
T_e (Fe) < 10^4 K

n_H ~ 0.3 - 3 10^4 cm^{-3}

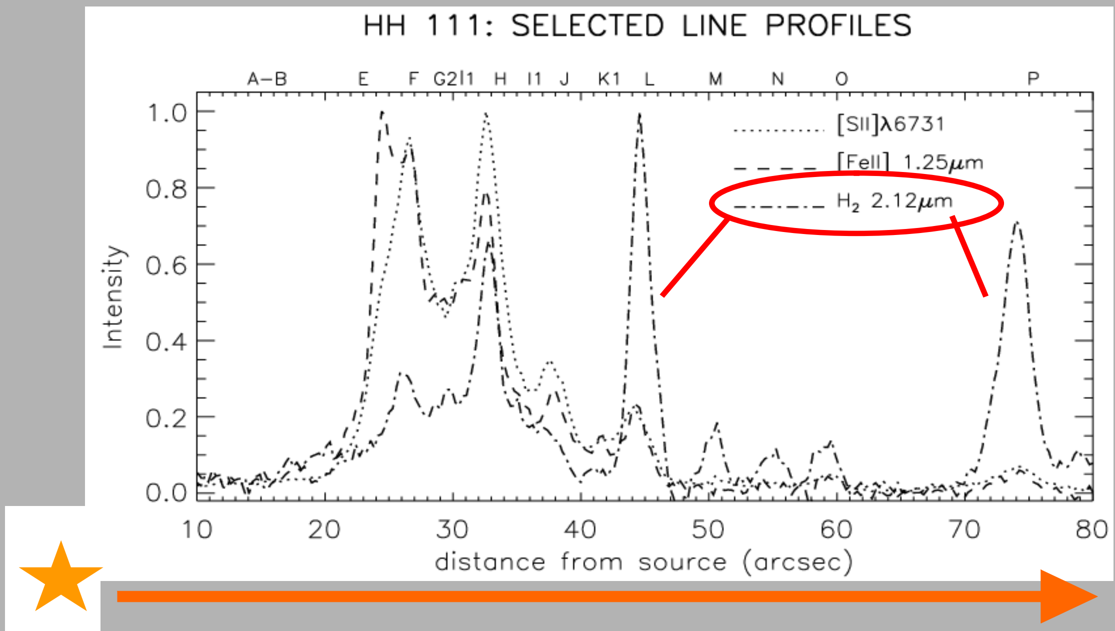
(Nisini et al. 2005, Podio et al. 2006)

n_e stratification in the knots along HH 111, HH 34





n_e up to 10^6 cm^{-3}



Spatial distribution of

H_2 emission vs atomic lines (S^+, Fe^+)
C-shocks vs J-shocks

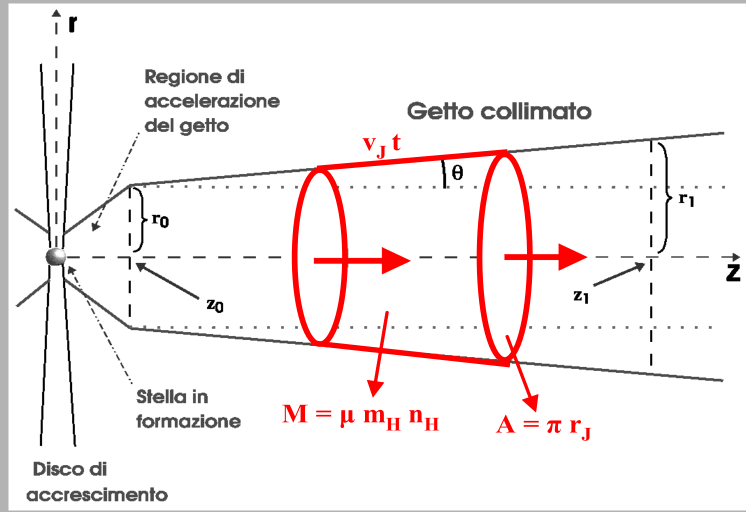
H_2 excited in the bow wings

Prevalence of C-shocks in the outer bows

(Nisini et al. 2005, Podio et al. 2006)

MASS FLUX RATE = $\dot{M}_{jet}$ regulates the jet DYNAMICS !

$$\dot{M} = dM/dt = (\pi\ r^2\ v_J\ t) \cdot (\mu\ m_H\ n_H)\ /\ t$$



$\dot{M}_{jet}/\dot{M}_{acc} \sim 0.01 - 0.1$ in the **MHD WIND MODELS**

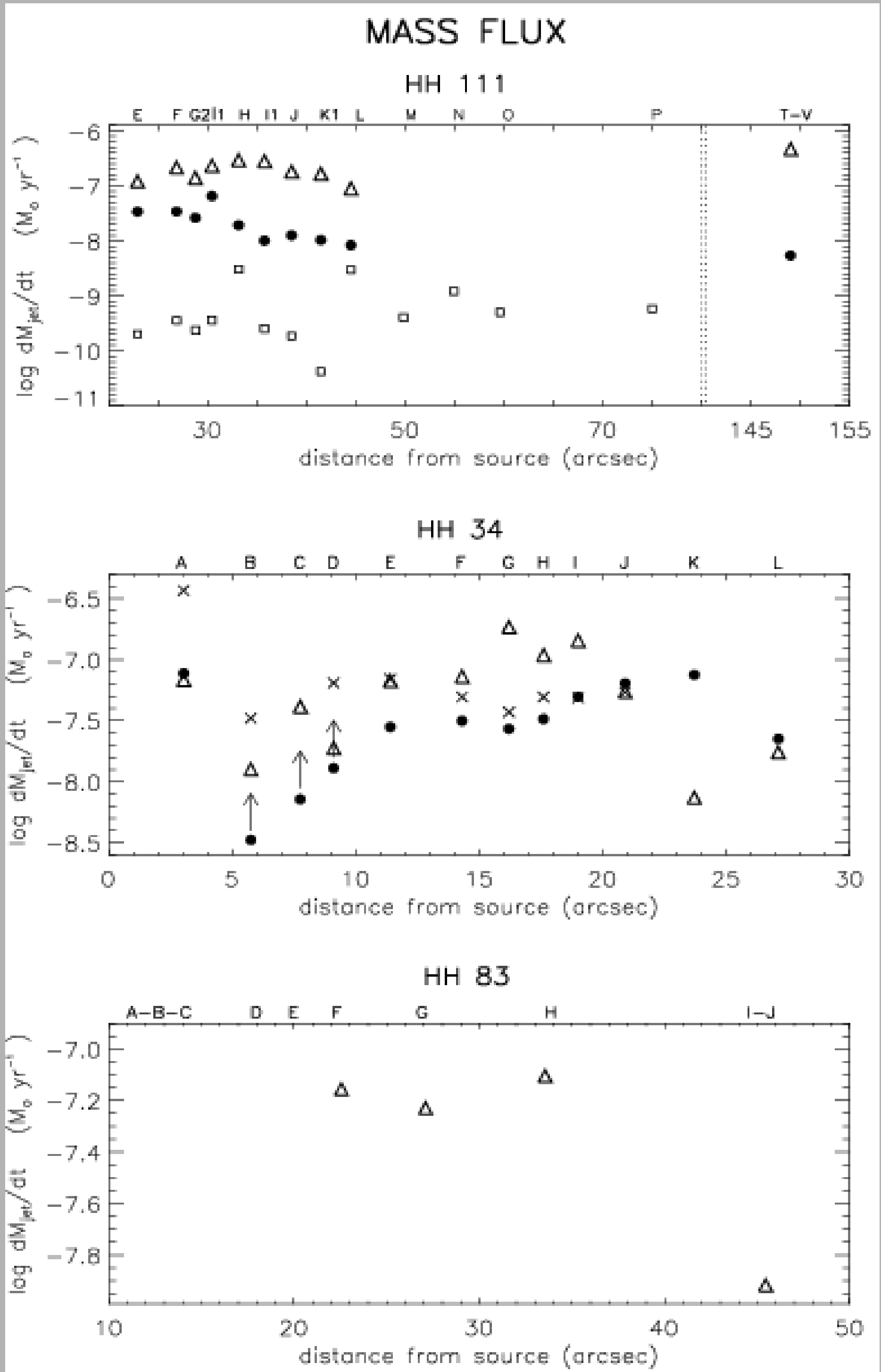
ANGULAR MOMENTUM $\dot{L}_J = \dot{M}_J \cdot r\ v_\varphi$

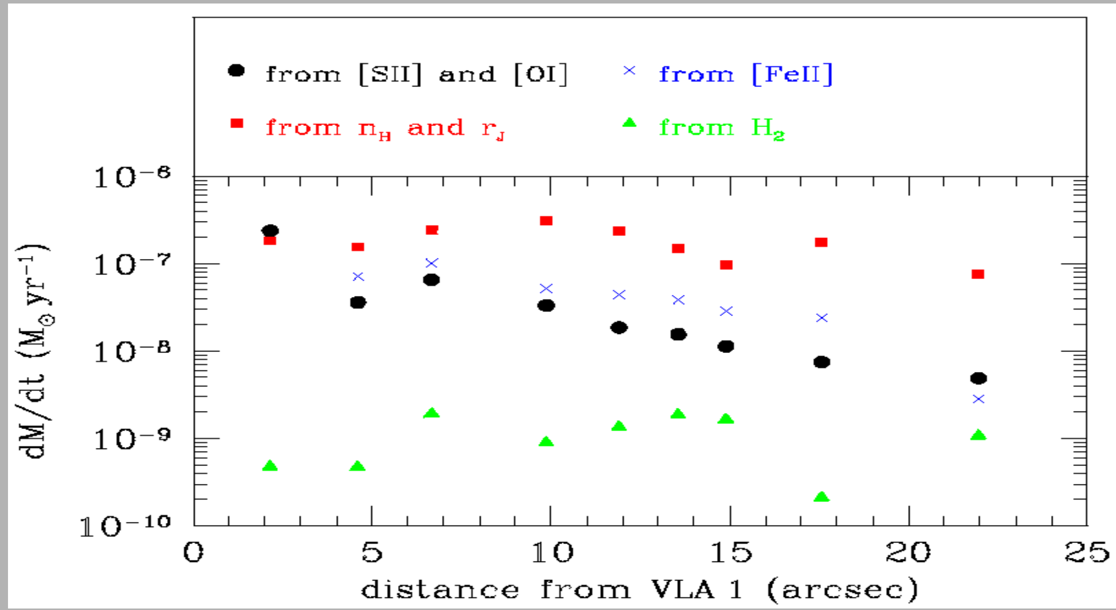
Jet "thrust" = **LINEAR MOMENTUM** $\dot{P}_J = \dot{M}_J \cdot v_J$

to accelerate molecular outflows
to inject turbolence in the cloud

class	Jet	v_{jet}[a] ($km\ s^{-1}$)	r_{jet}[b] ($''$)	n_H[c] ($10^3\ cm^{-3}$)	ff[d]	$\dot{M}_{jet}$ (A)[e] ($M_\odot\ yr^{-1}$)	$\dot{M}_{jet}$ (B)[f] ($M_\odot\ yr^{-1}$)	$\dot{P}_{jet}$ (A)[g] ($M_\odot\ yr^{-1}\ km\ s^{-1}$)	$\dot{P}_{jet}$ (B)[h] ($M_\odot\ yr^{-1}\ km\ s^{-1}$)	$\dot{P}_{outflow}$[i] ($M_\odot\ yr^{-1}\ km\ s^{-1}$)
0	HH 1	297	0.1 - 0.5	30.0	0.2	$2.4\ 10^{-7}$	$4.0\ 10^{-8}$	$7.1\ 10^{-5}$	$1.2\ 10^{-5}$	$3.0\ 10^{-5}$
I	HH 111	268	0.25 - 1.0	11.3	0.2	$2.2\ 10^{-7}$	$5.0\ 10^{-8}$	$5.9\ 10^{-5}$	$1.3\ 10^{-5}$	$1.8\ 10^{-5}$
	HH 34	211	0.15 - 0.35	16.2	0.4	$1.1\ 10^{-7}$	$3.9\ 10^{-8}$	$2.3\ 10^{-5}$	$0.8\ 10^{-5}$	$1.2\ 10^{-6}$
II	HH 83	213	0.8	0.9	-	$6.9\ 10^{-8}$	-	$1.5\ 10^{-5}$	-	-
	HH 24 C	425	0.6	1.3	-	$9.9\ 10^{-8}$	-	$4.2\ 10^{-5}$	-	-

n_H, $\dot{M}_{jet}$, $\dot{P}_{jet}$ decreases with evolutionary state





	$\dot{M}_{jet}$ ($M_{\odot}$ yr^{-1})	$\dot{P}_{jet}$ ($M_{\odot}$ yr^{-1} km s^{-1})
HH 111	**5.0 10^{-8}**	**1.3 10^{-5}**
HH 34	**3.9 10^{-8}**	**0.8 10^{-5}**
HH 1	**9.0 10^{-8}**	**2.8 10^{-5}**
HH 83	**6.9 10^{-8}**	**1.5 10^{-5}**
HH 24 C	**9.9 10^{-8}**	**4.2 10^{-5}**

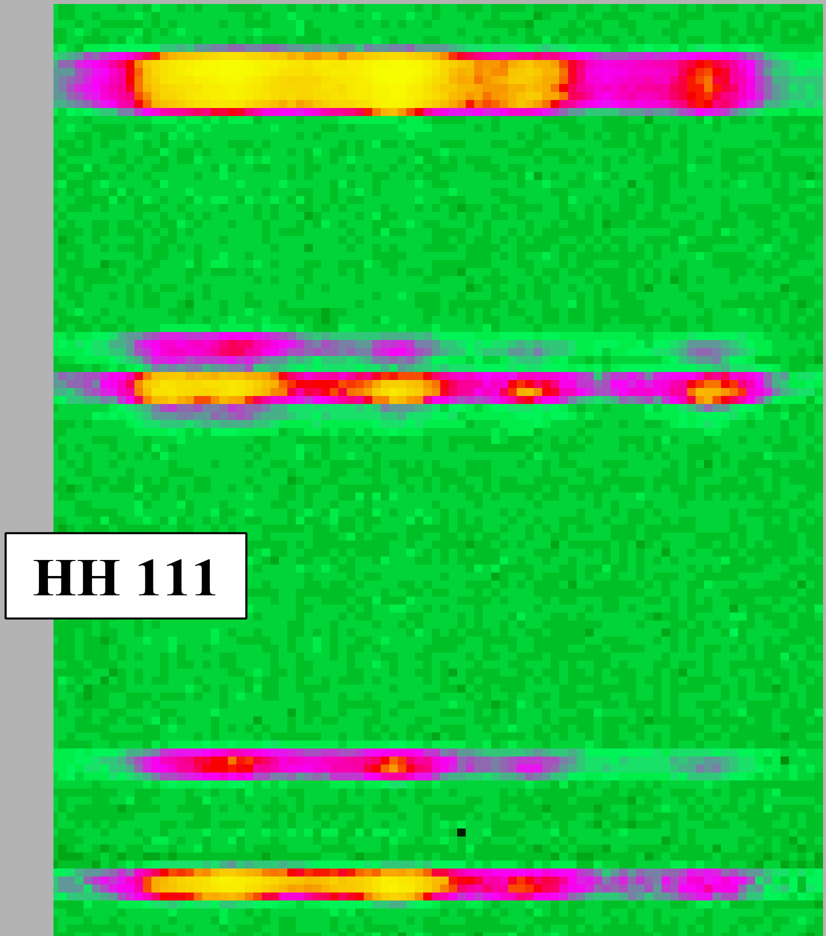
HIGH SPECTRAL RESOLUTION
+
forbidden lines diagnostics

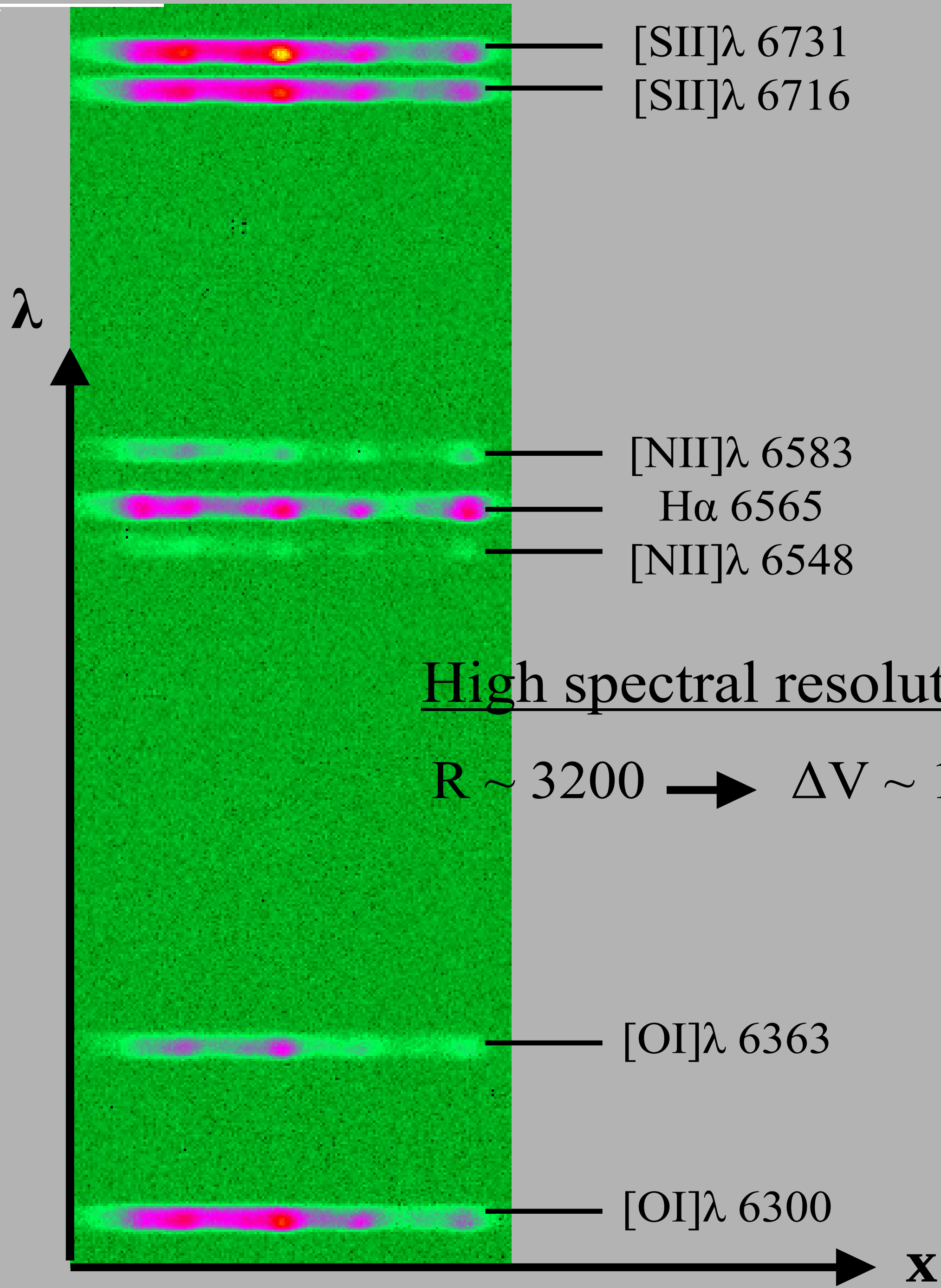
Physical structure of jets

along the jet

in different velocity bins

ESO-3.6m / EFOSC2 HR spectra





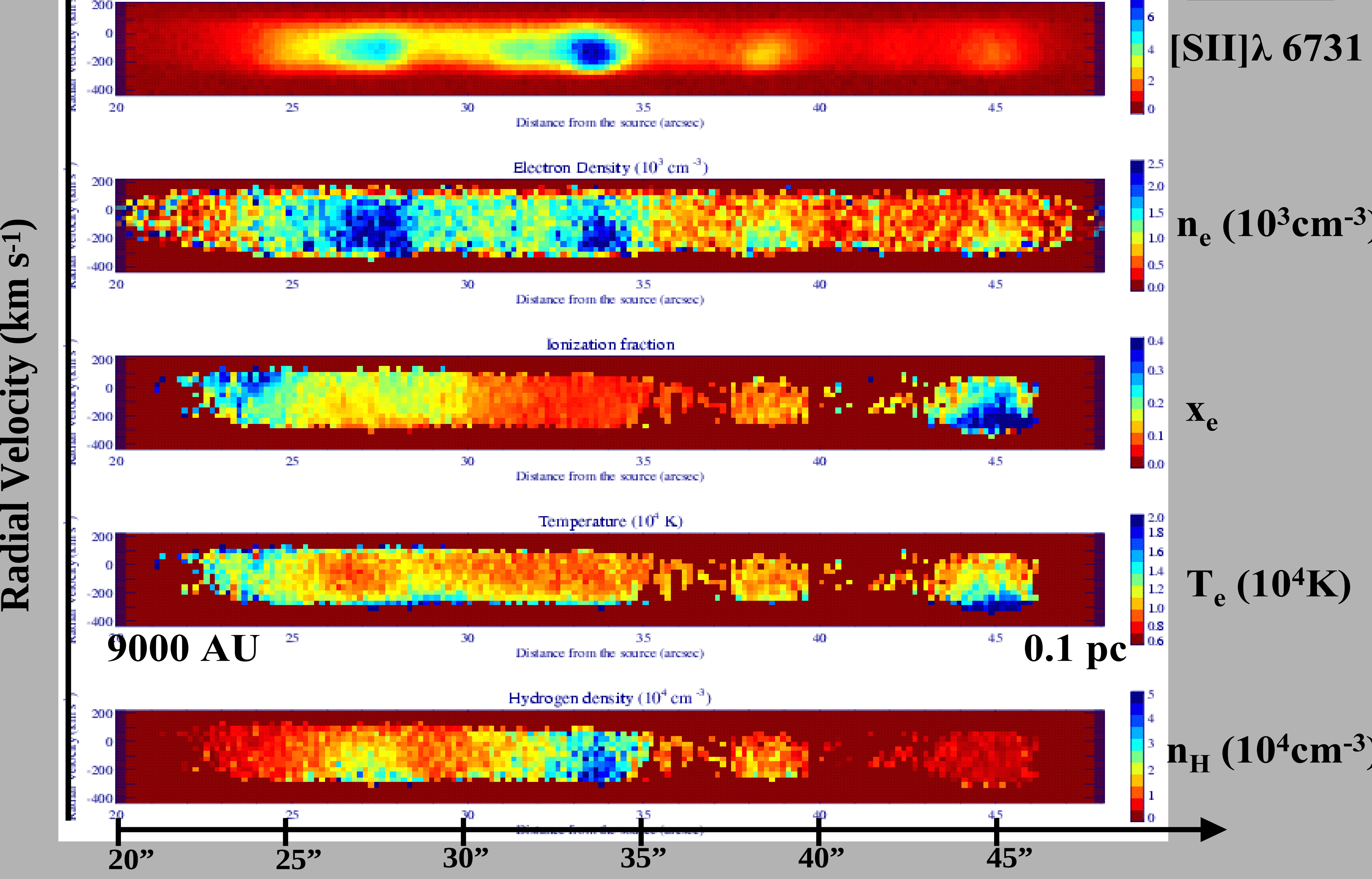
High spectral resolution data:

R ~ 3200 → ΔV ~ 100 Km/s

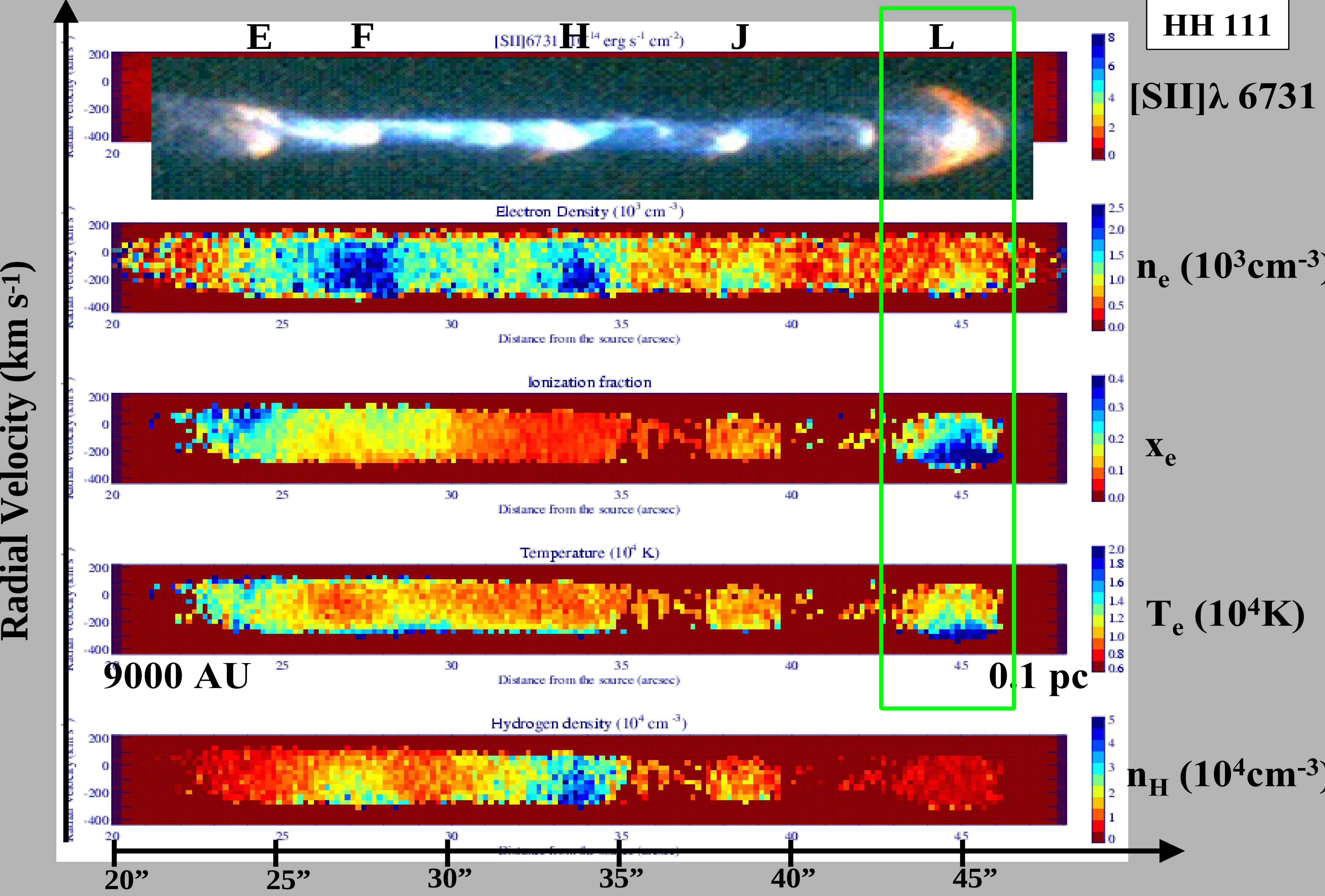
Low spectral resolution data:

R ~ 600 → ΔV ~ 500 Km/s

HH 111



E
F
H
J
L
[SII]6731 (10^-14 erg s^-1 cm^-2)
[SII]λ 6731
Electron Density (10^3 cm^-3)
n_e (10^3cm^-3)
Ionization fraction
x_e
Temperature (10^4 K)
T_e (10^4K)
Hydrogen density (10^4 cm^-3)
n_H (10^4cm^-3)
Distance from the source (arcsec)
Radial Velocity (km s^-1)
9000 AU
0.1 pc
20”
25”
30”
35”
40”
45”


HH 111
E
F
H
J
L
[SII]6731 (10-14 erg s-1 cm-2)
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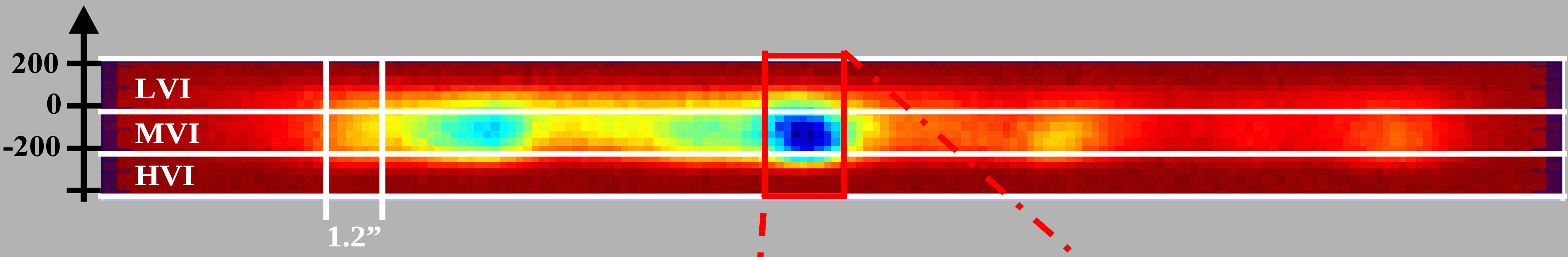
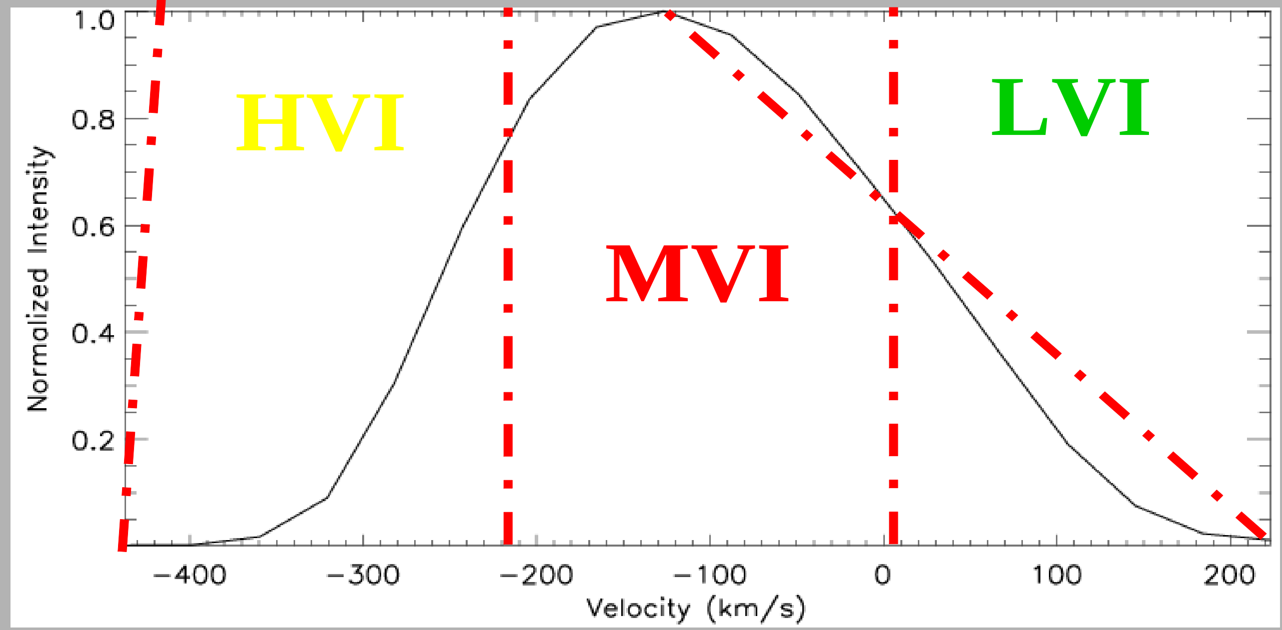
Electron Density (10^3 cm-3)
n_e (10^3cm-3)
Distance from the source (arcsec)
Ionization fraction
x_e
Temperature (10^4 K)
T_e (10^4K)
9000 AU
0.1 pc
Hydrogen density (10^4 cm-3)
n_H (10^4cm-3)
Radial Velocity (km s-1)
20”
25”
30”
35”
40”
45”

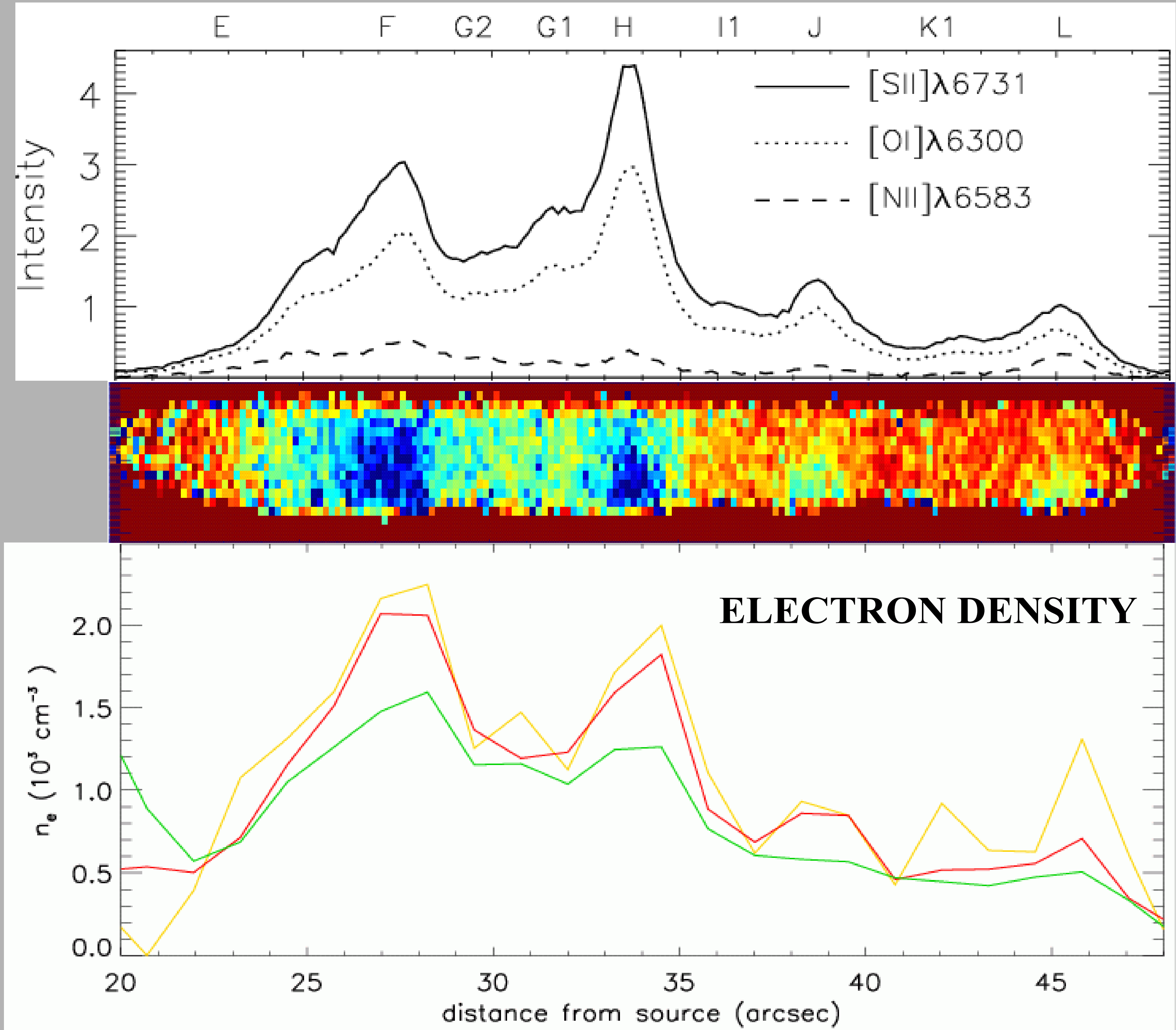
spatial scale: 0.157''/pix --- spatial resolution: ~1.2" ~ 500 AU
spectral scale: ~40 km s^{-1}/pix --- spectral resolution: ~100 km s^{-1}



Velocity bins: ~200 km/s

Spatial bins: $FWHM_{seeing}$= 1.2"





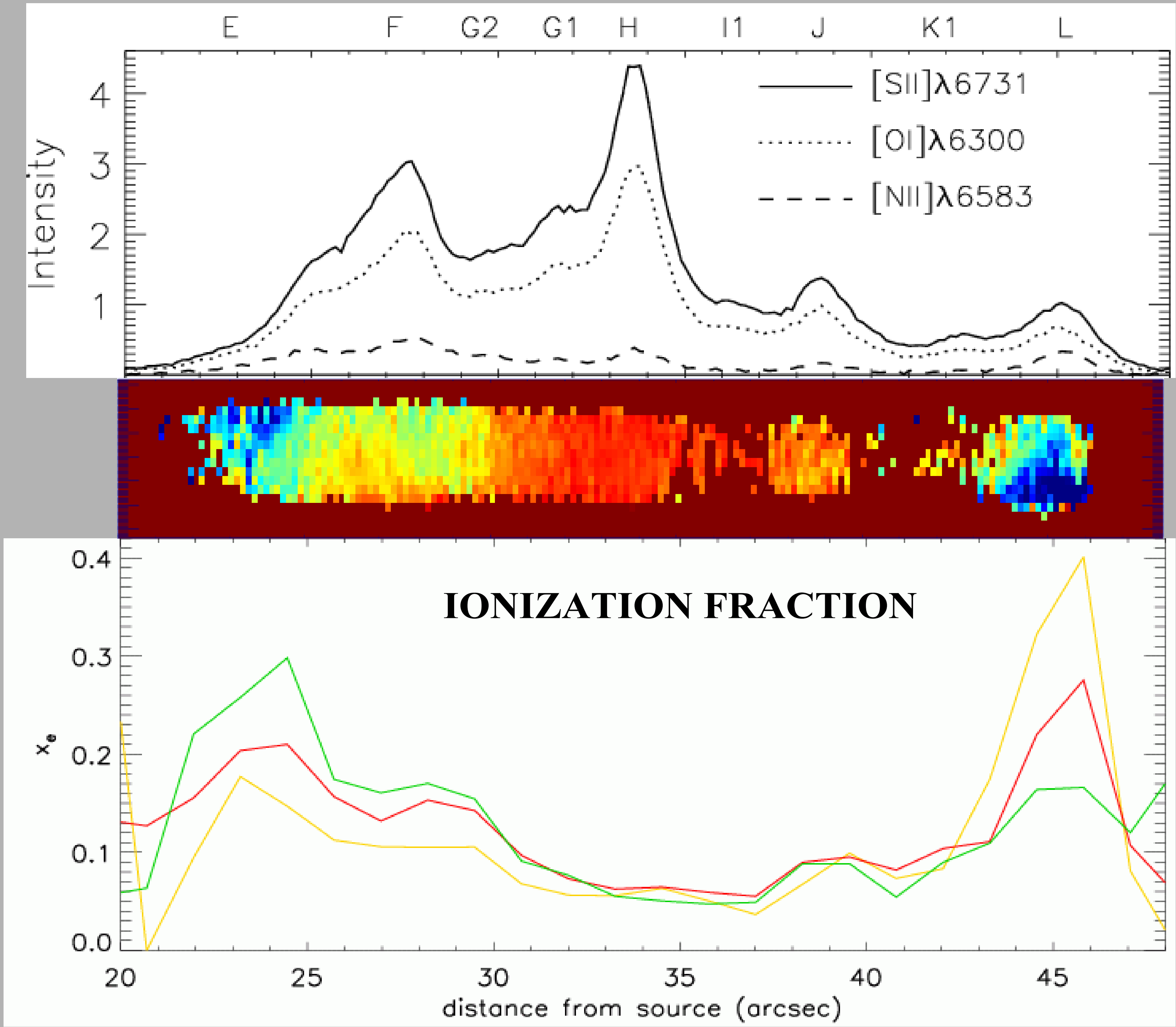
$n_e \sim 50 - 2.3\ 10^3\ cm^{-3}$

n_e increases with velocity

HVI: n_e up to $2.3\ 10^3\ cm^{-3}$

MVI: n_e up to $2.0\ 10^3\ cm^{-3}$

LVI: n_e up to $1.6\ 10^3\ cm^{-3}$



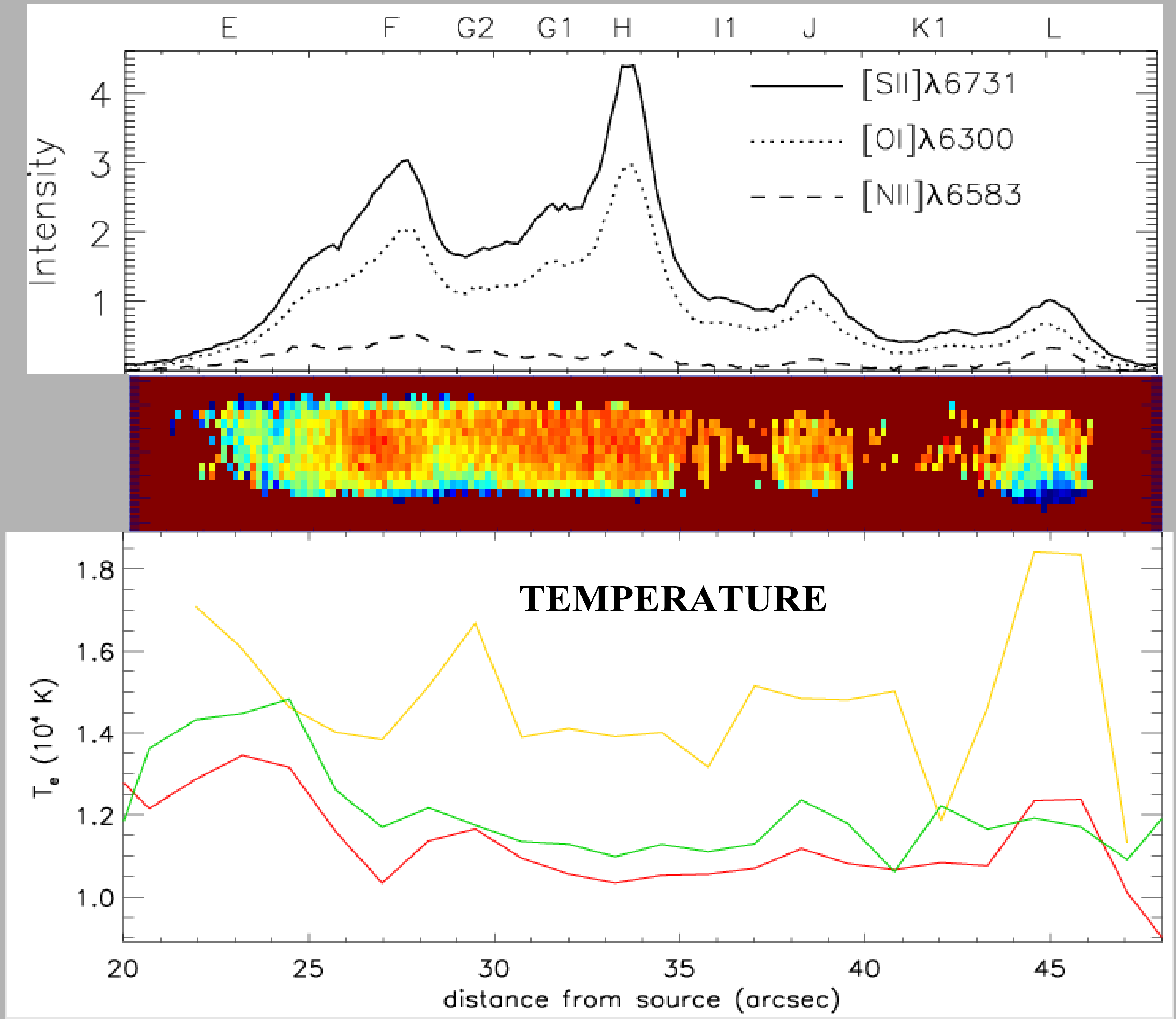
$x_e \sim 0.05 - 0.4$

x_e increases with velocity only in knot L !

HVI: x_e up to 0.4

MVI: x_e up to 0.28

LVI: x_e up to 0.3



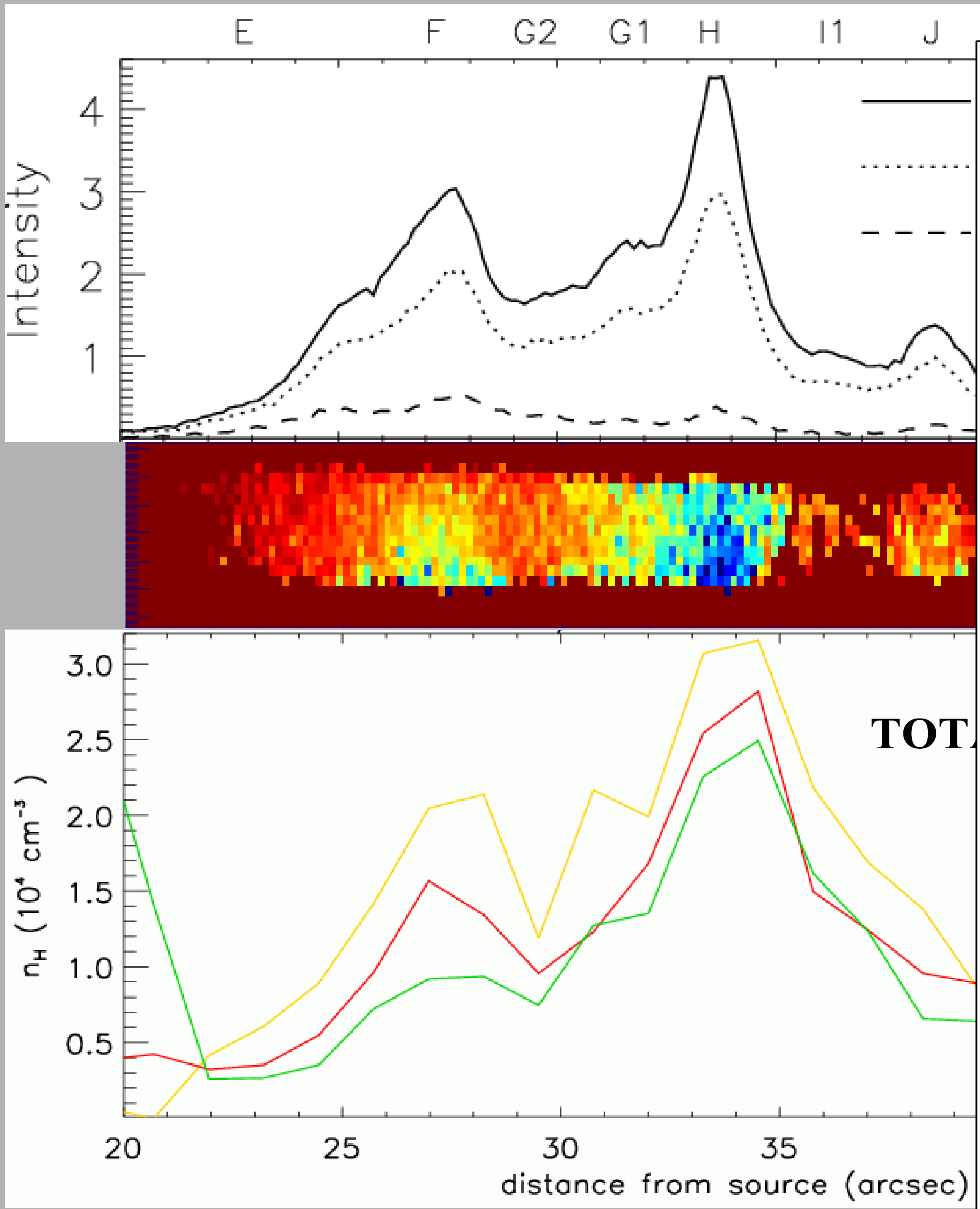
$T_e \sim 1.0–1.9\ 10^4$ K

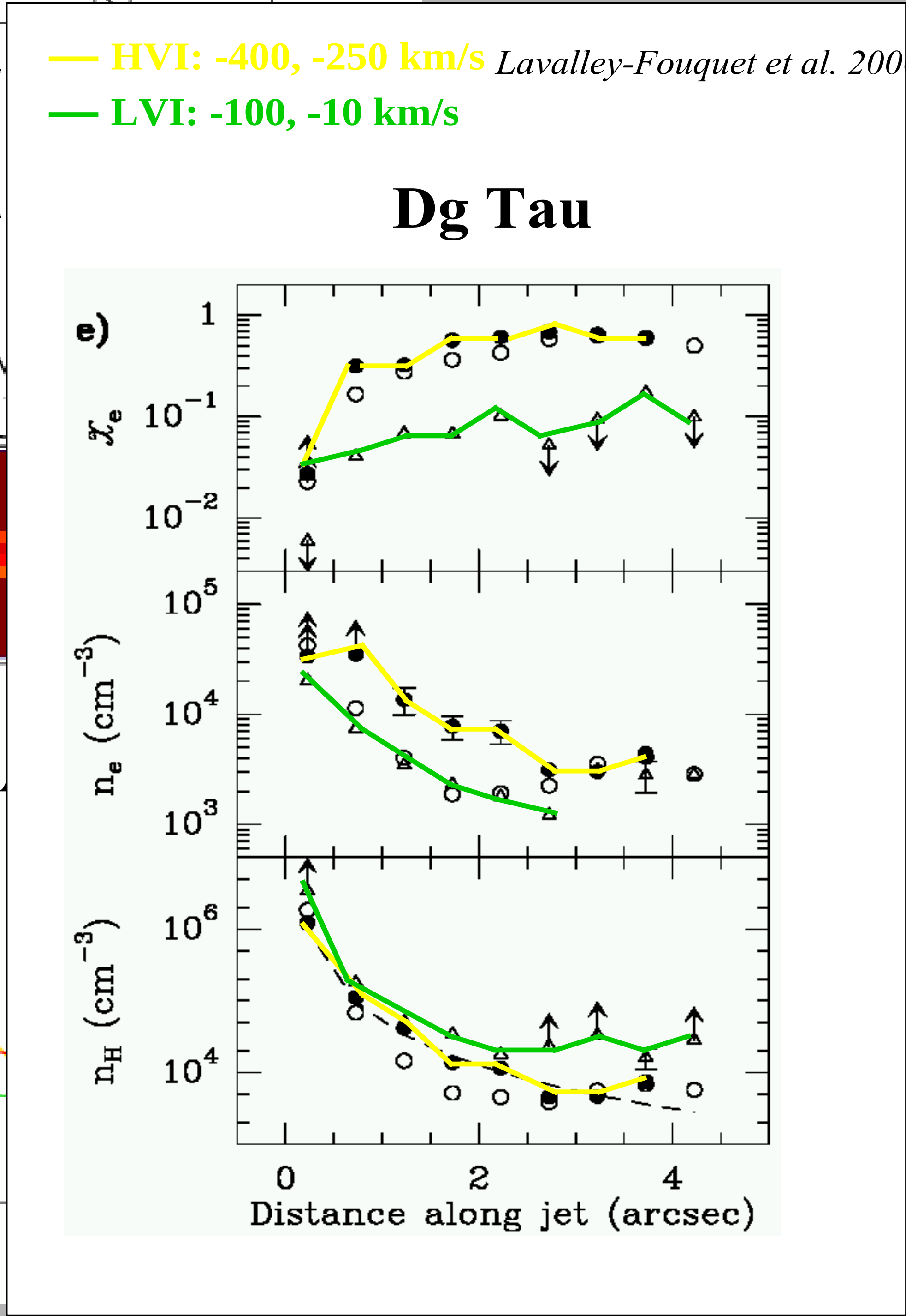
T_e increases with velocity

HVI:
T_e up to 1.9 10^4 K

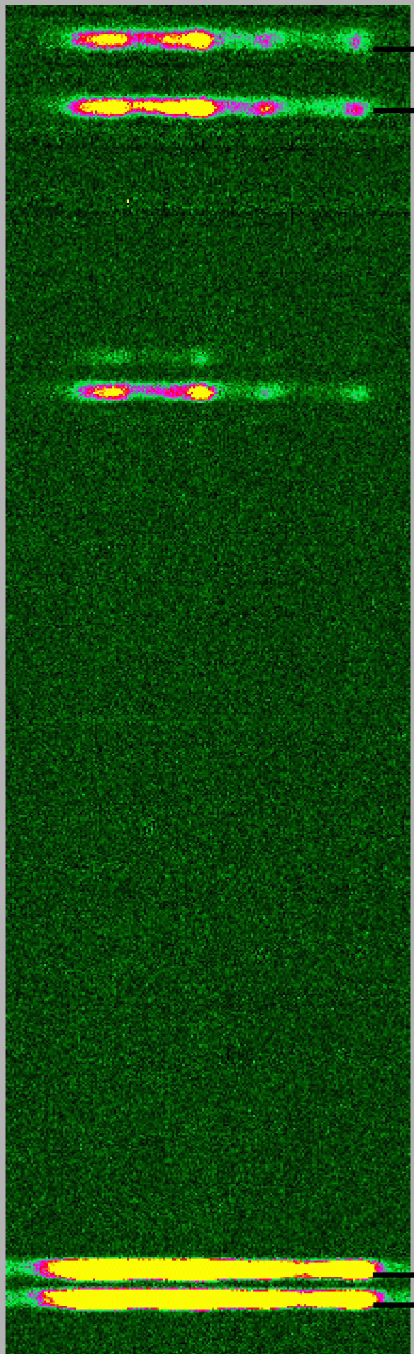
MVI:
T_e up to 1.5 10^4 K

LVI:
T_e up to 1.3 10^4 K


E
F
G2
G1
H
I1
J
K1
Intensity
TOT
n_H (10^4 cm^{-3})
distance from source (arcsec)


HVI: -400, -250 km/s
Lavalley-Fouquet et al. 2000
LVI: -100, -10 km/s
Dg Tau
e)
χ_e
n_e (cm^{-3})
n_H (cm^{-3})
Distance along jet (arcsec)

The Calcium lines: content of DUST GRAINS in the jet



Refractory species (Ca, Fe) are expected to be largely depleted in neutral or molecular ISM, because their atoms are locked on dust grains

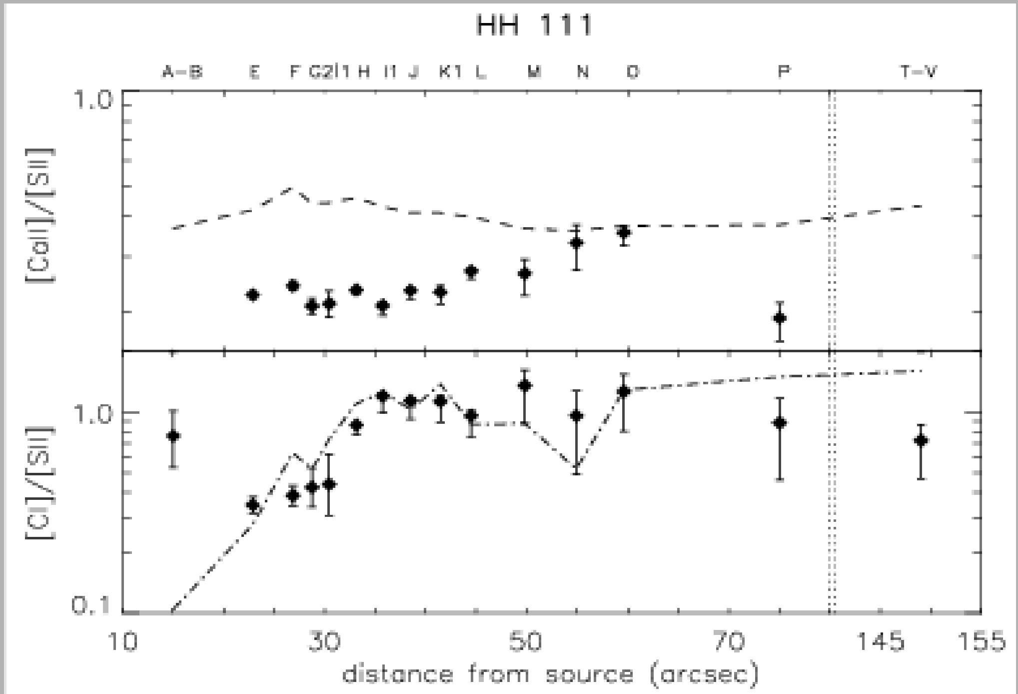
BUT:

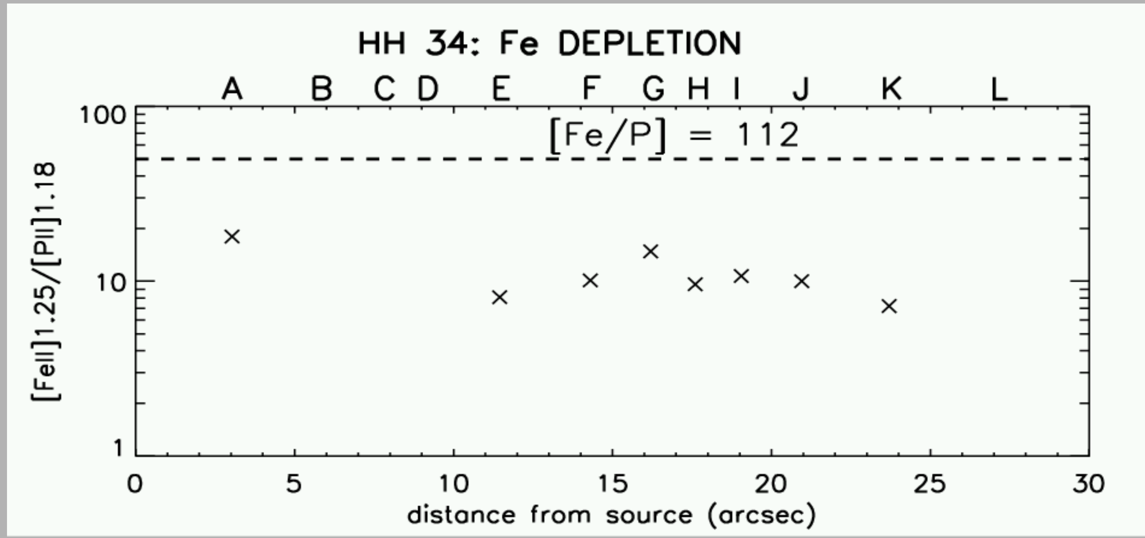
dust grains should be destroyed by jet shocks
and release the atoms of Ca and Fe.

observed vs predicted ratios

between refractory and non-refractory species

From LR spectra: presence of DUST GRAINS in the jet



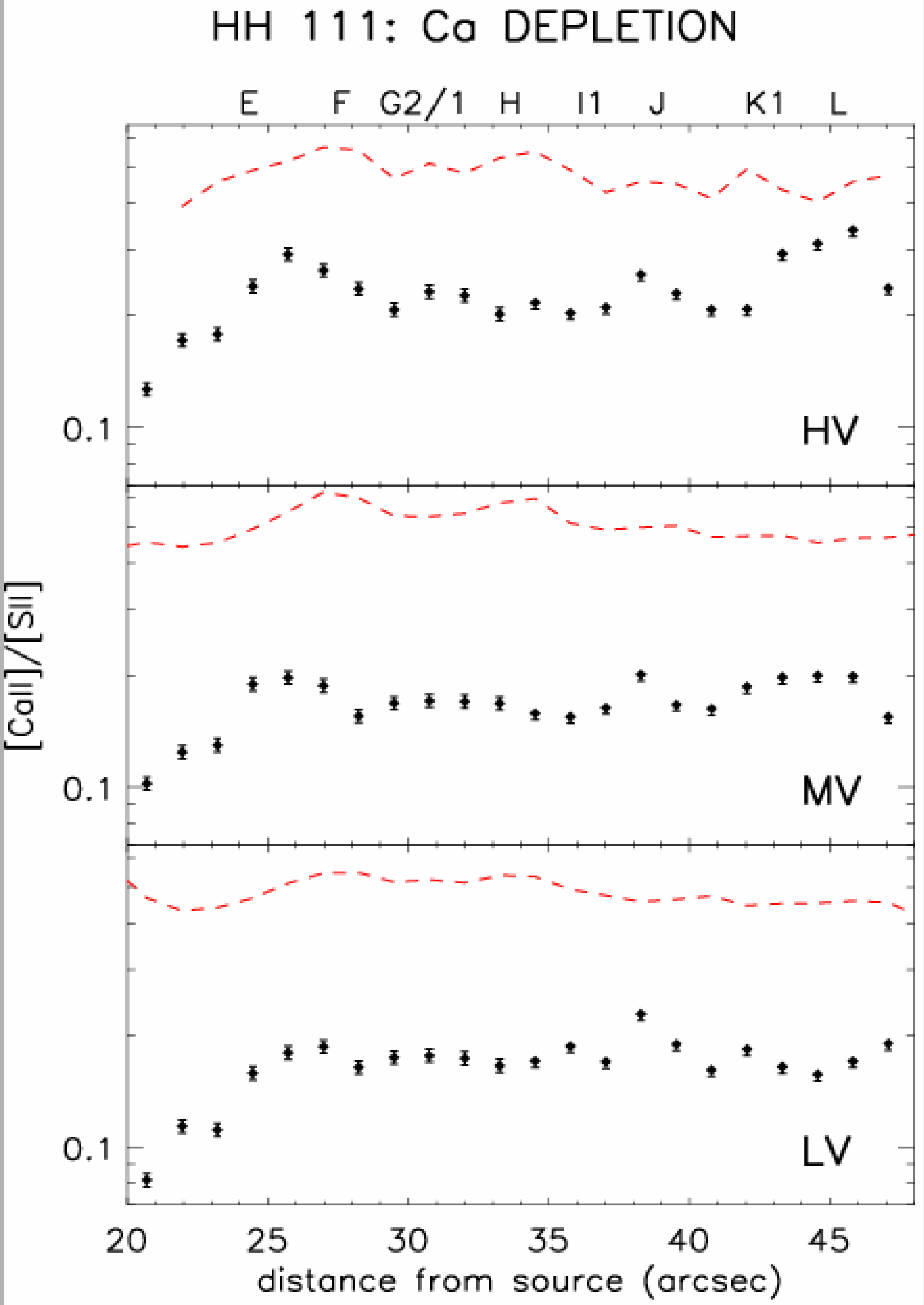


Ca and **Fe** are still locked on grains ...

complete dust grain destruction
is expected only in shocks with $v_s > 100$ km/s
(Jones 2000; Draine 2003)

Species	$[X]_{gas}/[X]_{solar}$			Abundances: (X/H)	
	HH 111	HH 34	Orion Cloud	Orion Abundances[a]	Solar Abundances[b]
Ca	0.5–1	0.3–1	0.01	2×10^{-8}	2.04×10^{-6}
C	∼1	∼1	1.07	2.63×10^{-4}	2.45×10^{-4}
Fe	–	0.13	0.05	1.29×10^{-6}	2.82×10^{-5}

[a] from Esteban et al. (2004), except for the Ca abundance which was determined by Baldwin et al. (1991); [b] from Asplund et al. (2005).

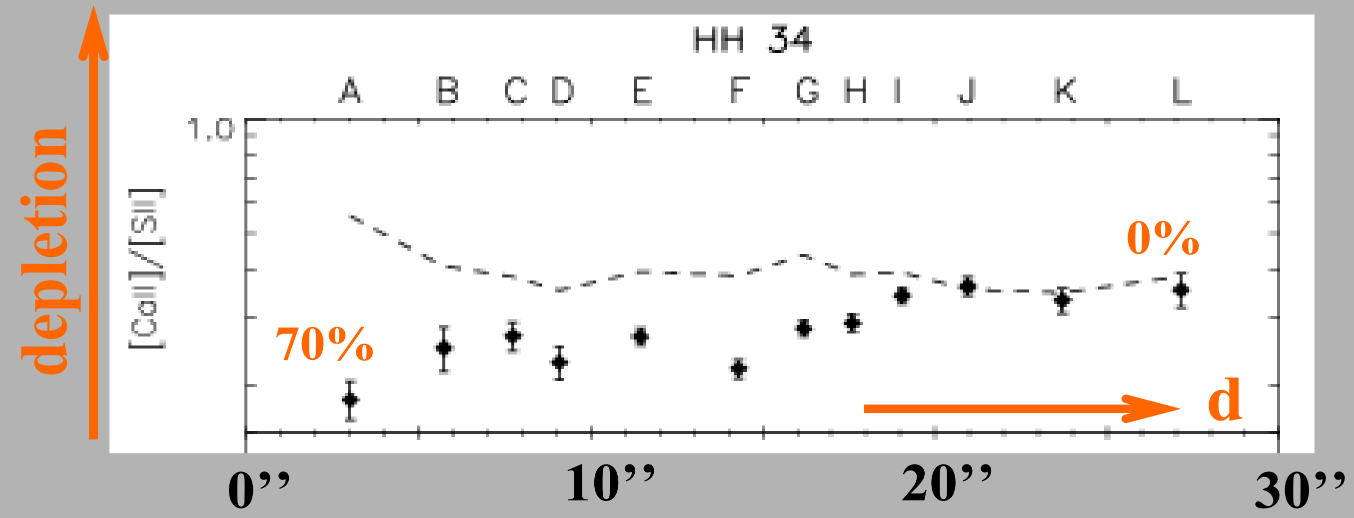


DUST GRAINS content vs gas velocity

Ca depletion decreases with velocity

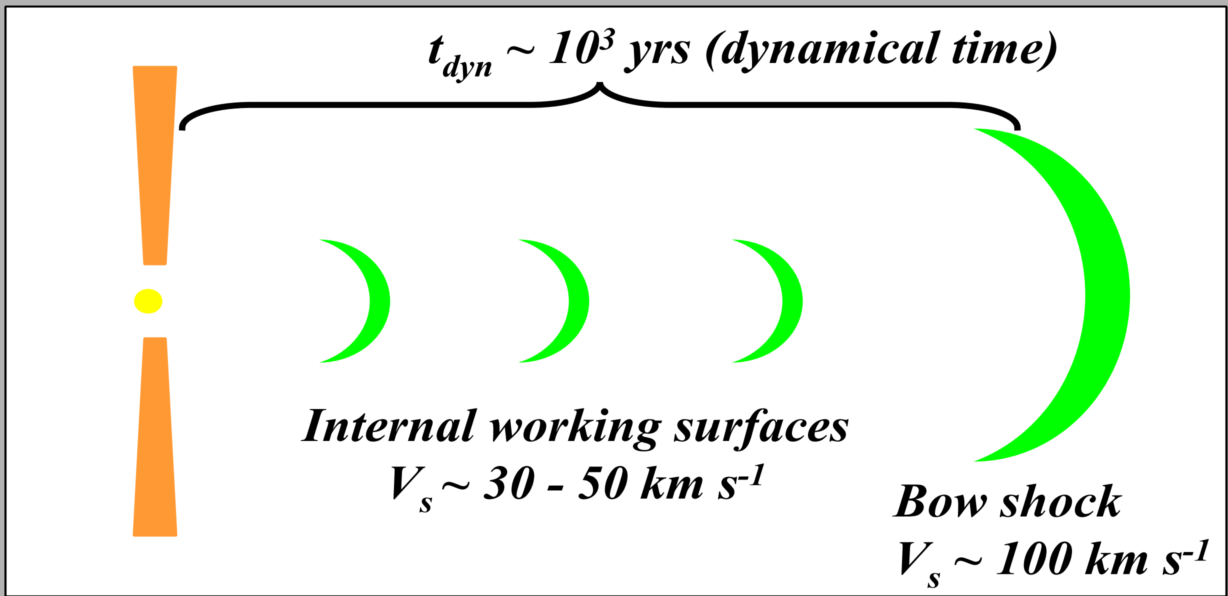
there is more dust in the LV and MV components

DUST GRAINS: in the jet or in the ISM ?



Along HH 111 and HH 34:

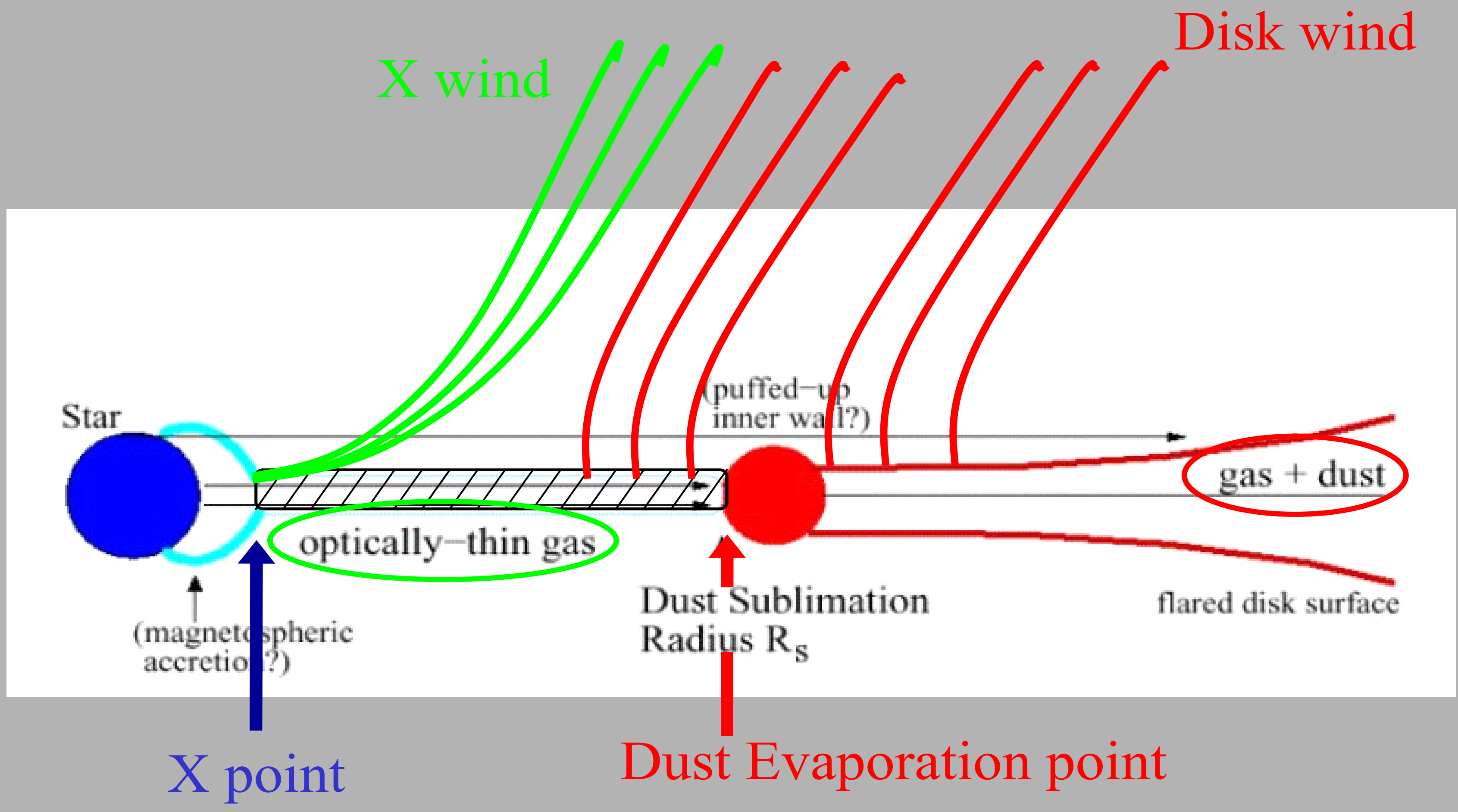
- Complete grains destruction at the bow shock ($V_s \sim 100$ km s-1);
- Dust grains survive in the internal working surfaces (Vs ~ 30-50 km s-1)



Dust reformation timescale :
$t_{dust} \sim 10^6$ yr

$t_{dust} \gg t_{dyn}$

dust is coming from the DISK !



The position of R_{evp} with respect to R_x can put constraints on the size of the launching region!

$$R_X(AU) = R_* \alpha_X \left(\frac{B_*^4 R_*^5}{G M_* \dot{M}_{acc}{}^2} \right)^{\frac{1}{7}}$$

~ 0.03 AU (CTTS)

Shu et al. 1994

$$R_{evp}(AU) = 0.034 \left(\frac{1500}{T_{evp}} \right)^2 \sqrt{\frac{L_*}{L_\odot} \left(2 + \frac{1}{\epsilon} \right)}$$

$\sim 0.03 - 0.08$ AU (CTTS)

$\sim 0.08 - 0.2$ AU (CTTS, from interferometric obs)

(Akeson et al. 2005)

Isella & Natta 2005

Conclusion and future perspectives

from spectral diagnostics → **large scale physical/dynamical structure of jets**

from optical/NIR diagnostics → **ne, Te stratification** in the shock cooling region

from tomography in velocity space → velocity shock structure → **HVC: higher excitation**

follow-up

- parsec-scale jets from **more evolved CTTS** or **intermediate-mass** sources
  see poster by Mc Groarty, Podio et al.
- more diagnostic **across the jet** (HST data)
- **jet tomography at higher spectral res** (Keck data)

from depletion of refractory species → **dust grains in the jets**
possible constrains for the models ?

follow-up

- dust content in jets from **CTTS** and **Herbig Ae/Be** stars
- Ca, Fe depletion in the **jet basis** (is the dust really coming from the disk?)

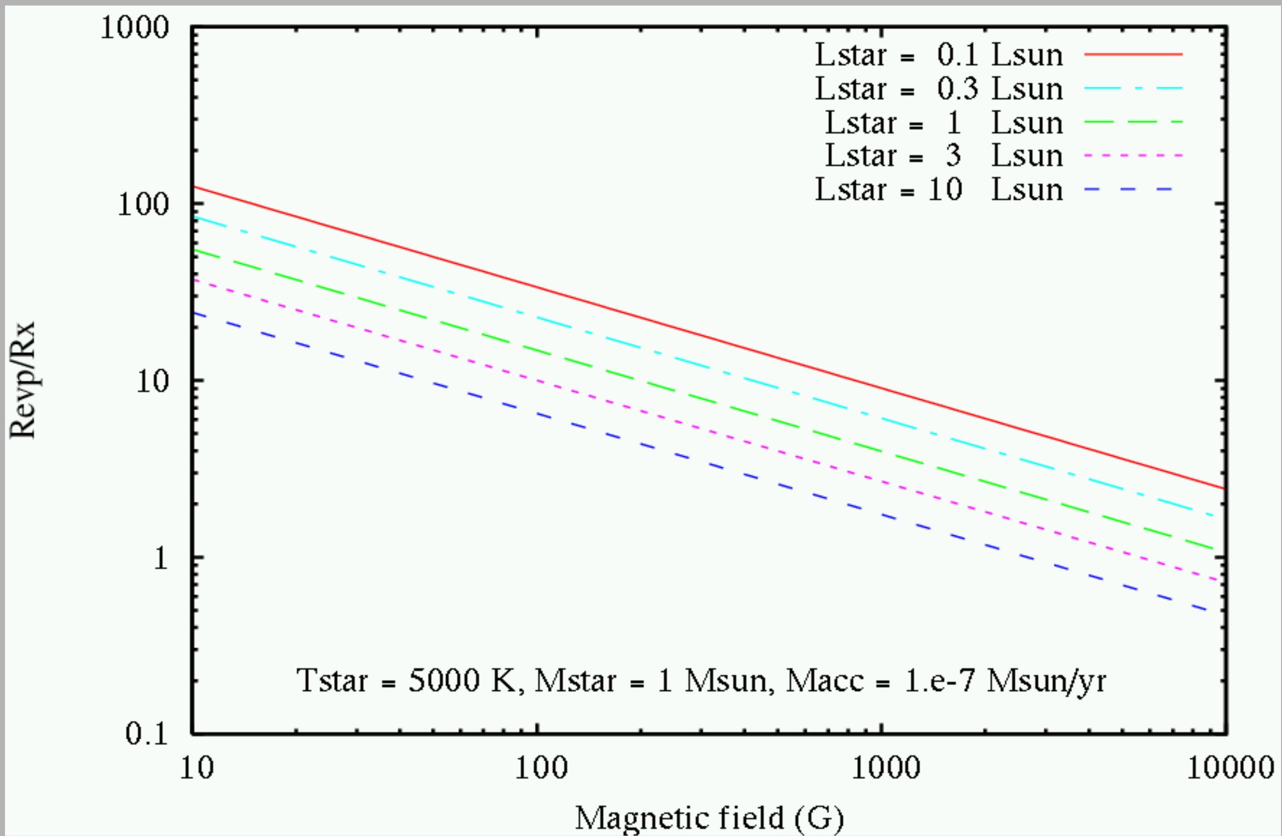
Constraining the launching region...

Accurate estimate of R_{evp}/R_x (L_*, B_*)

Inner rim model (Isella & Natta 2005) is valid for $\dot{M}_{acc} < 10^{-7}\ M_\odot/yr$

$$R_{evp}(AU) = 0.034 \left(\frac{1500}{T_{evp}}\right)^2 \sqrt{\frac{L_*}{L_\odot}\left(2 + \frac{1}{\epsilon}\right)}$$

HH 111: $\dot{M}_{jet} \sim 5\ 10^{-8}\ M_\odot/yr$



CTTS:

$M_{acc} \sim 10^{-8} - 10^{-7}\ M_\odot/yr$

$B \sim$ KG

$R_{evp}/R_x \sim 1$

Class 0, I:

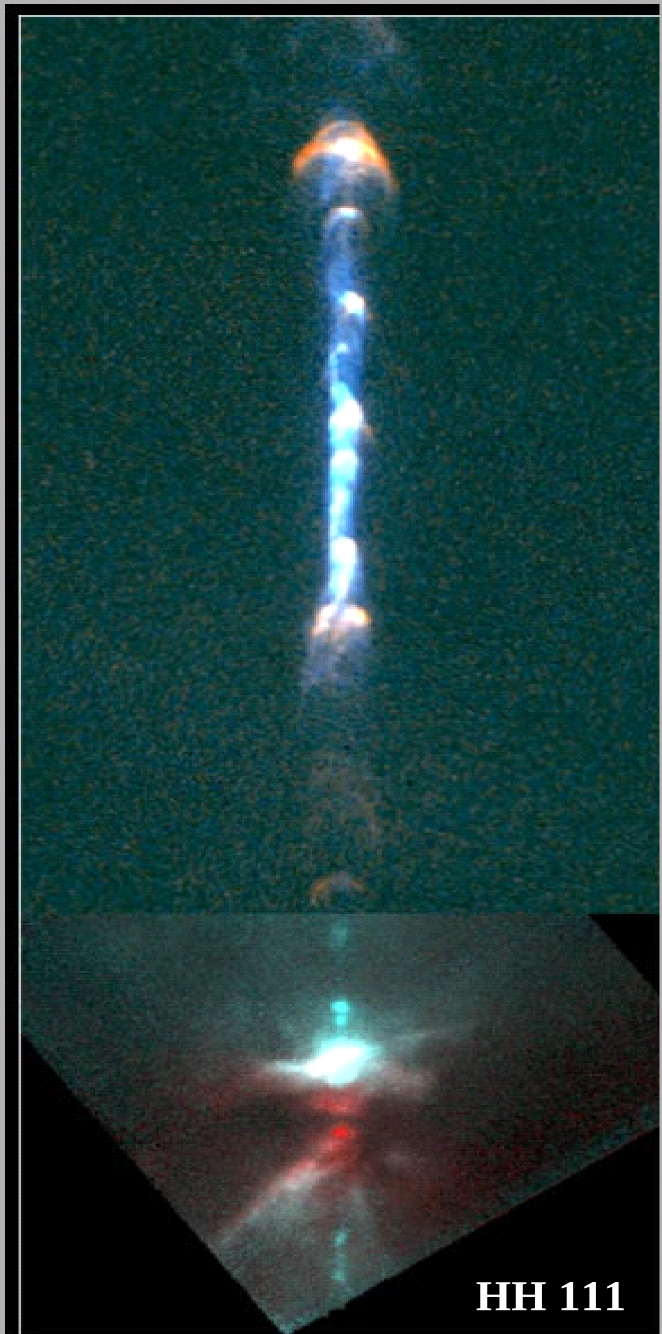
$M_{acc} > 10^{-7}\ M_\odot/yr$

$B <$ KG

$R_{evp}/R_x > 1$

To calculate R_{evp} consider:

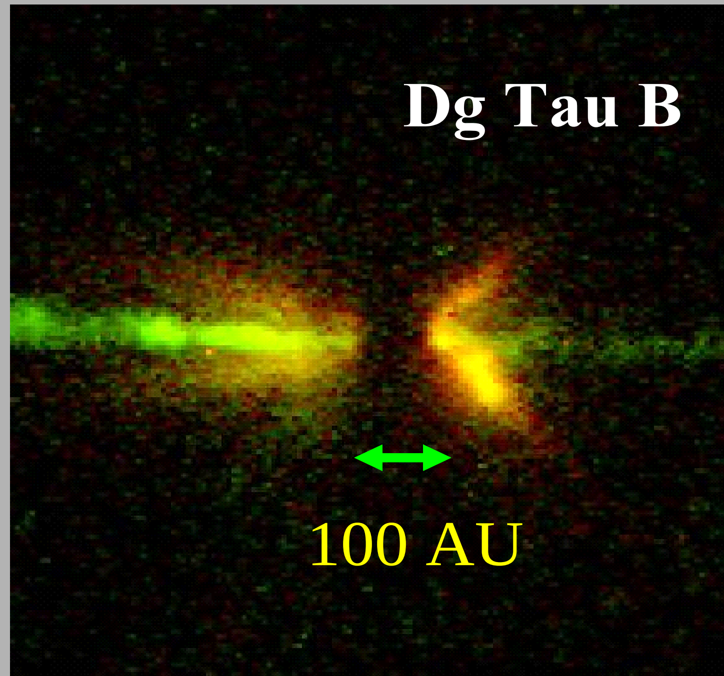
- flat disk heated by viscous dissipation
- stellar radiation, accretion luminosity



400 AU - 0.4 pc

Large scales

observations from the ground
angular resolution limited by the seeing: 1”
(for sources in Orion, D=450 pc, 1”=450 AU)



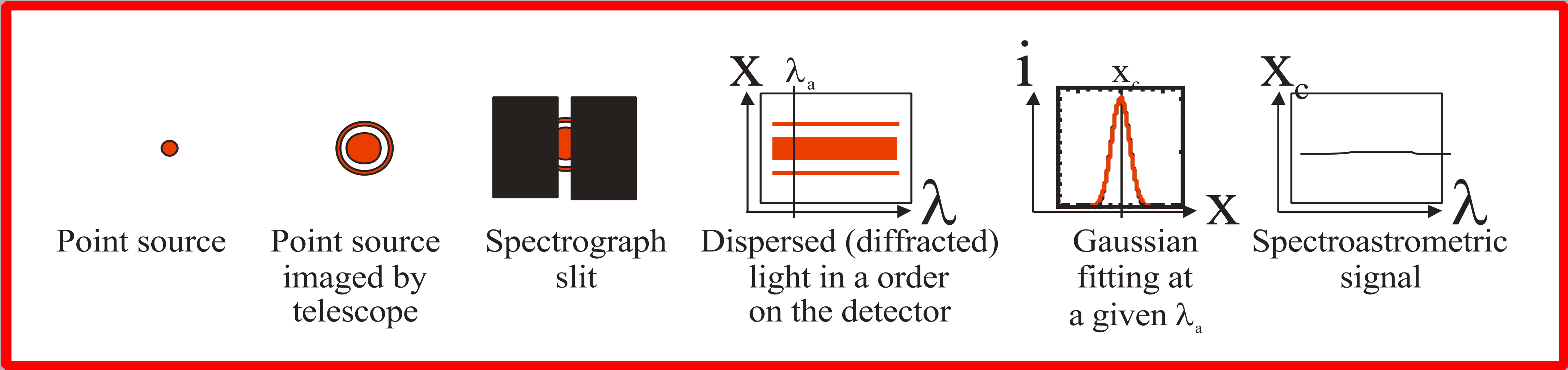
small scales

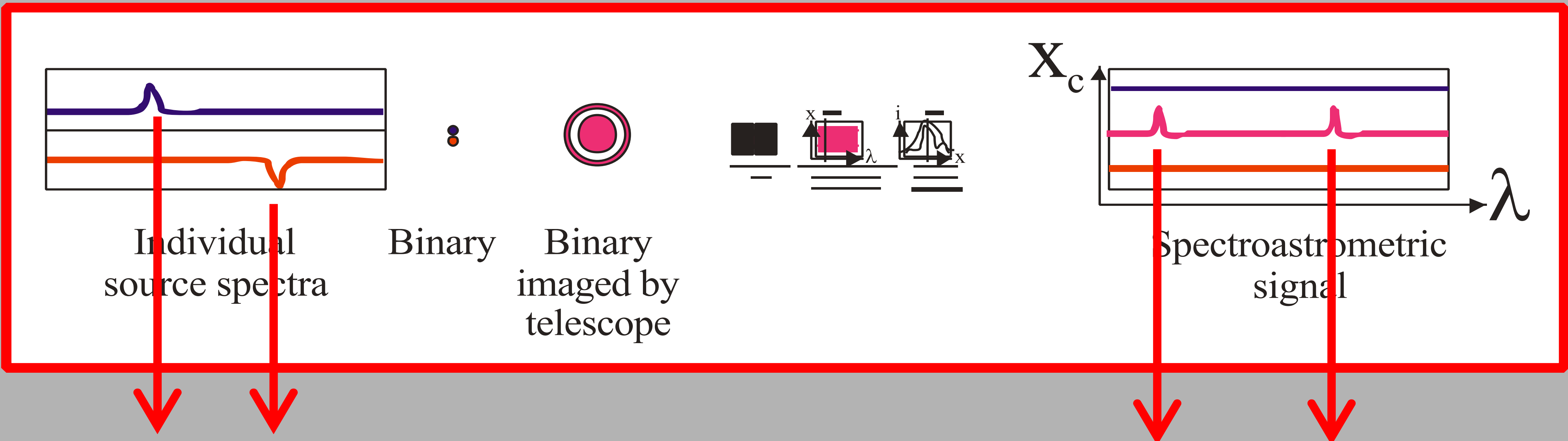
High angular resolution!
AO, HST: 0.1”
(for near source, D=140 AU, 0.1”=14 AU)

Spectro-astrometry: positional information on mas scales !!

...hat is spectro-astrometry ?

(Hirth et al. 1994, 1997, Bailey et al. 1998, Takami et al. 2001, 2003, Whelan et al. 2004)



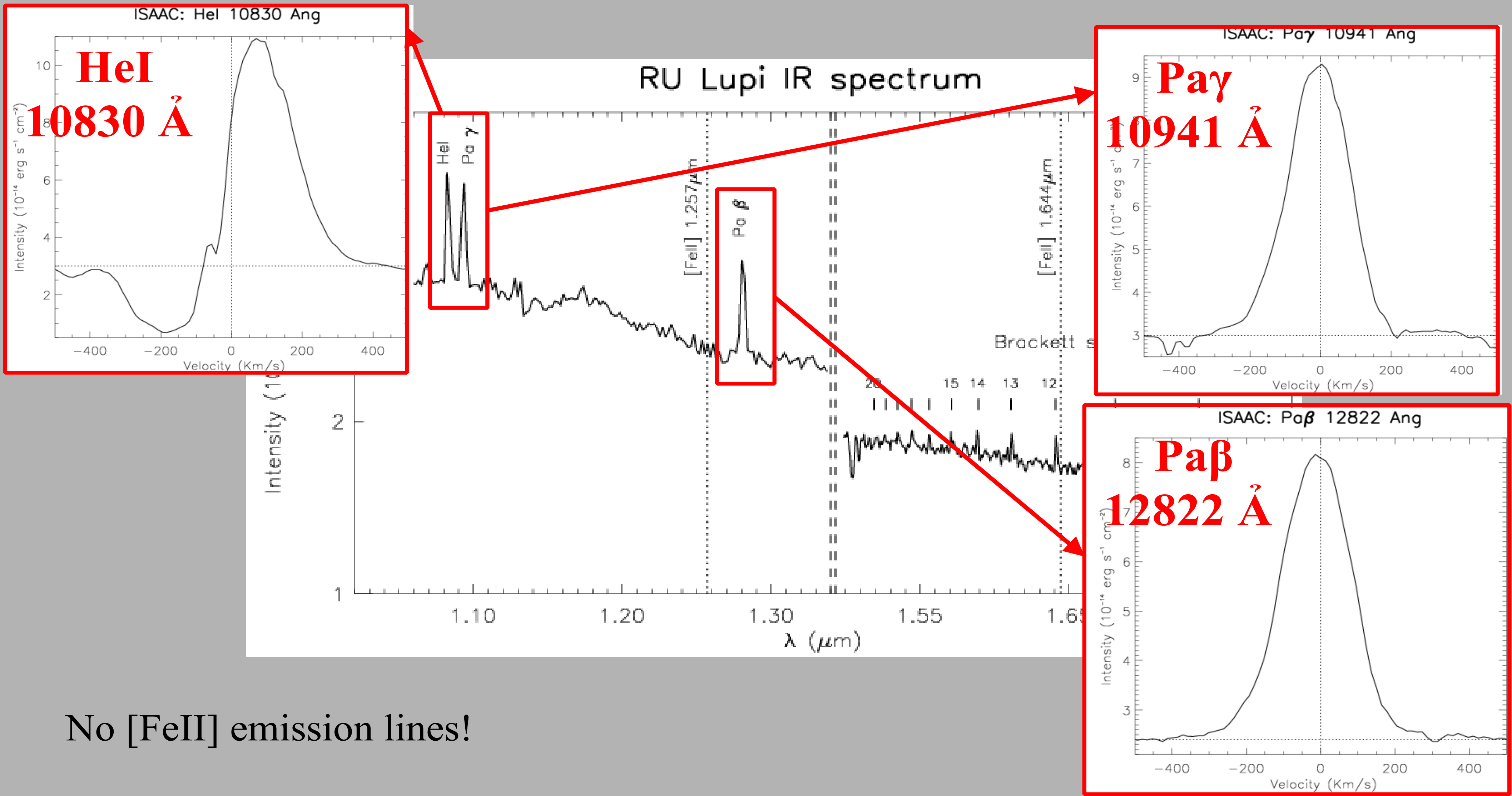


<u>UNRESOLVED</u> binary star or outflow
<u>with dinstinctive features</u> in their spectra

<u>Centroid position shifted at $\lambda_{features}$</u>

with respect to the continuum emission

NACO + ISAAC spectra of RU Lupi



No [FeII] emission lines!

HeI P-Cygni profile: spherical inner wind

HI lines: wind or accretion ?

ACCRETION vs WIND:

HI lines: clear manifestation of circumstellar activity
is difficult to define their origin (easily excited)

Historically:

- Excited in circumstellar ionized winds
(on the basis of the often observed P-Cygni Hα profile)

Hartmann et al. 1990,
Calvet et al. 1992

- Magnetospheric accretion models

Calvet & Hartmann 1992, Hartmann 1994,
Muzerolle et al. 1998, 2001

Supported by the observed relation
L(Hα, Paβ, Brγ) - L_{acc}

Muzerolle et al. 1998, Natta et al. 2002

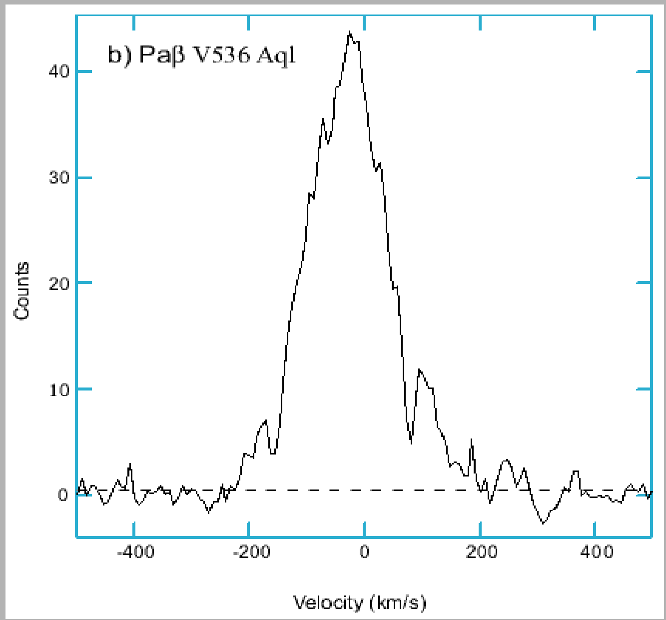
- Accretion + wind contribution

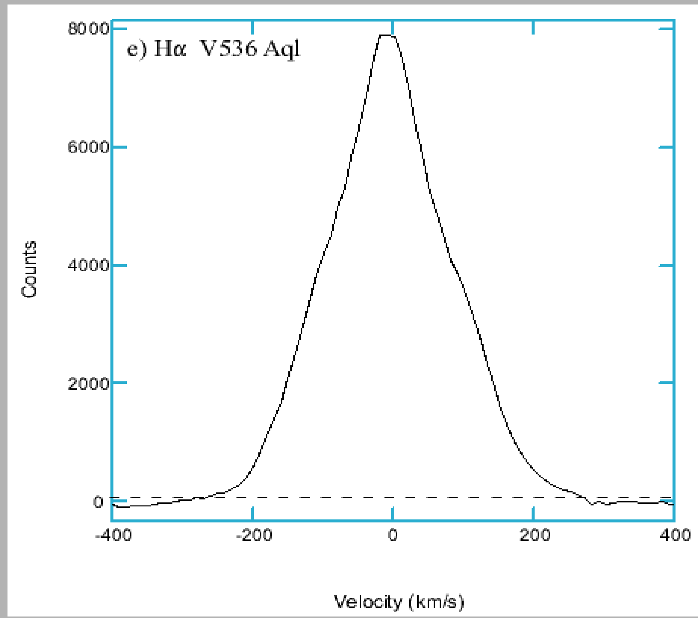
The observed profiles and ratios can not be fully reproduced by accretion models

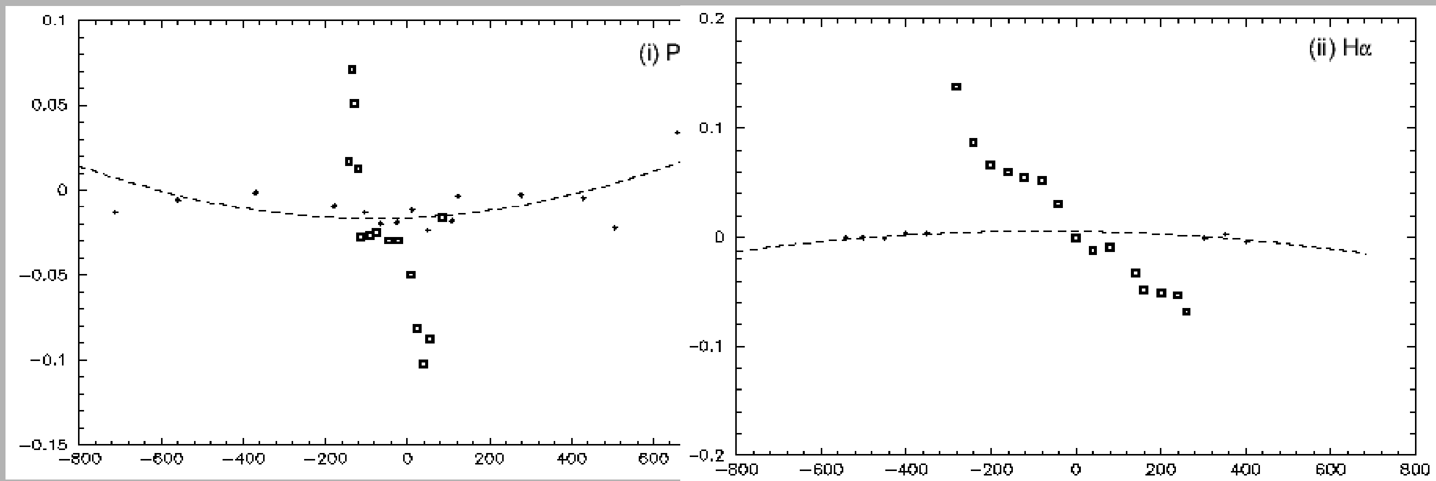
Folha et al. 2001
Edwards et al. 2006
Nisini et al. 2004

Extended emission
- *Spectro-astrometry* — *Takami et al. 2001, Whelan et al. 2004, 2006*
- *Interferometry* — *Tatulli et al. 2006*

Can spectro-astrometry disentangle the accretion & the wind contributions in the permitted lines profile ?

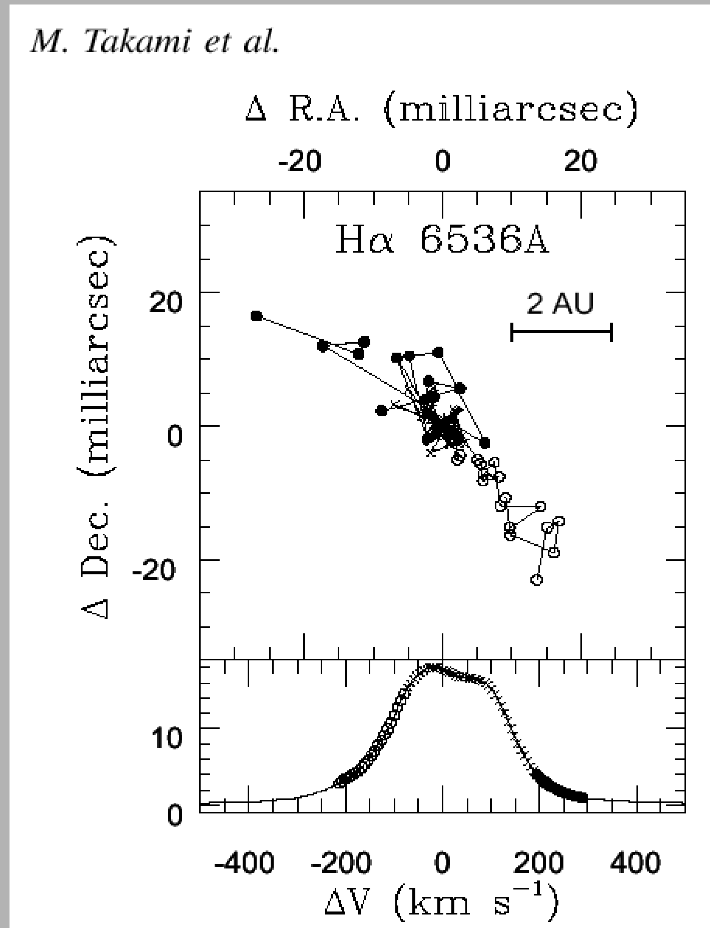






Extended emission in the Paβ, Hα line wings in T Tauri sources

(Whelan et al. 2004)



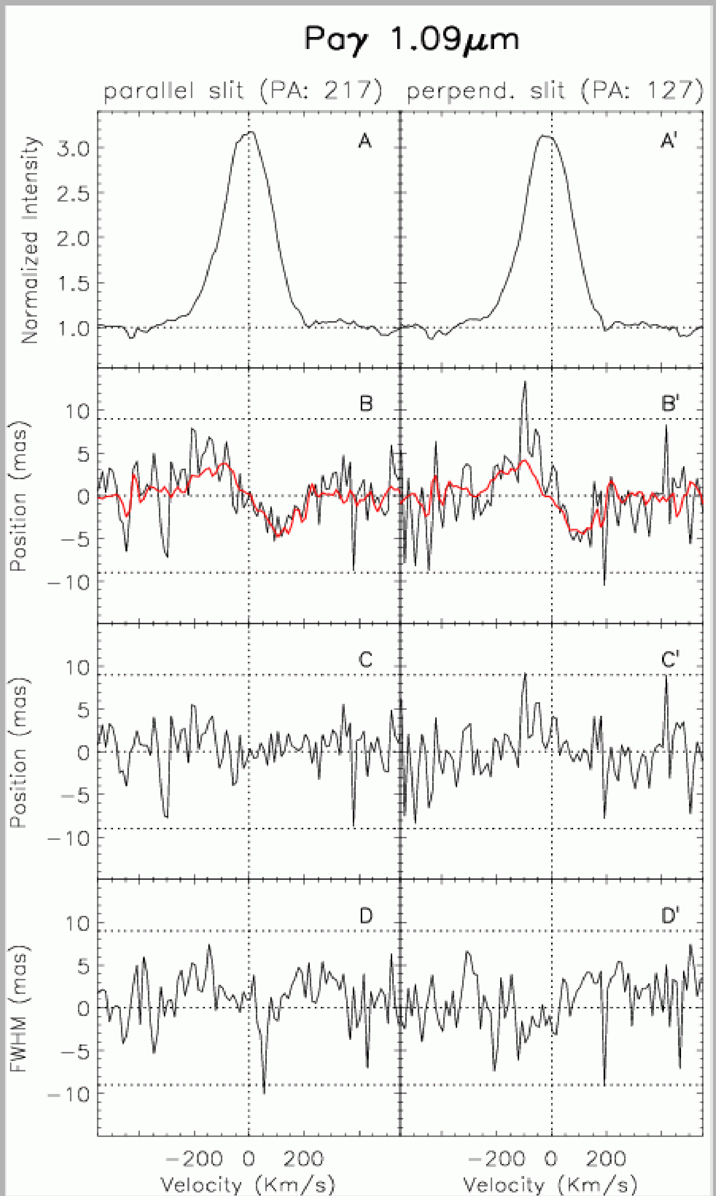
Extended emission

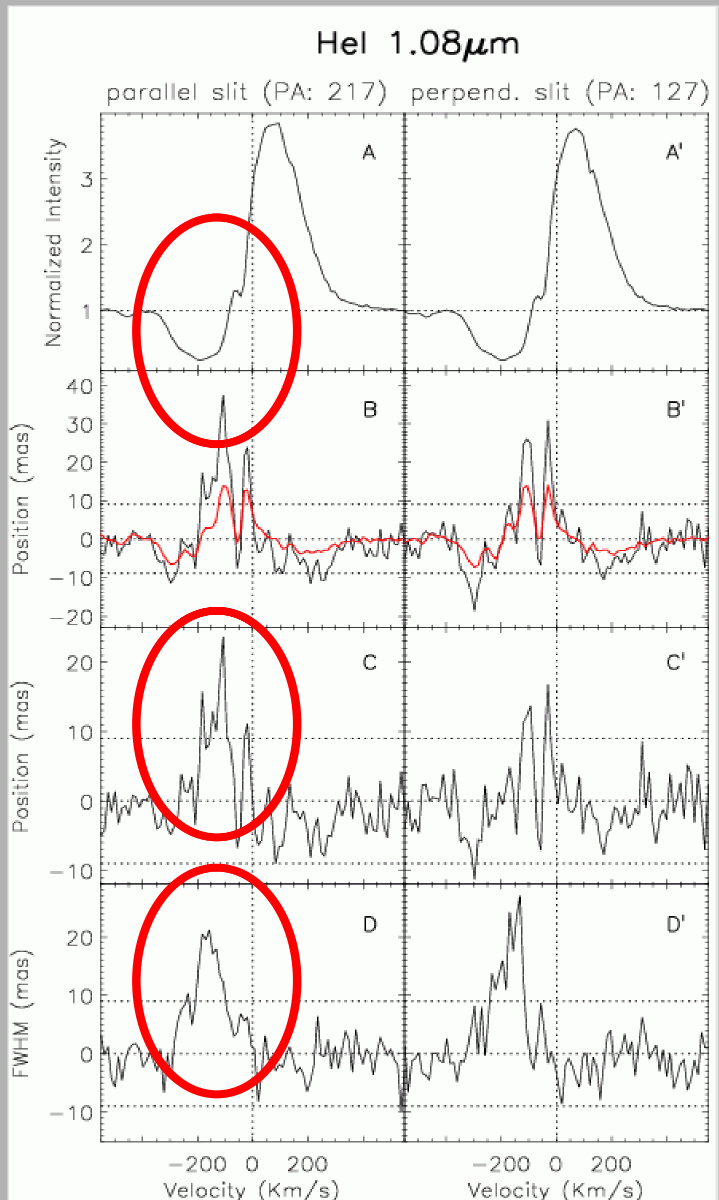
in the wings of the Hα line

(Takami et al. 2001)

spectro-astrometry on RU Lupi

(Podio et al. 2008)





Simulation of biases following Brannigan et al. 2006

<u>He I line</u>

<u>EXTENDED COLLIMATED WIND</u>

(up to 3 AU from the source)

In the line profile:

accretion

inner spherical wind

collimated wind

(see also Takami et al. 2002)

<u>HI lines</u>

The emission is compact (R < 1 AU) and/or symmetric

The problem is still open...

Conclusion and future perspectives

from spectral diagnostics → **large scale physical/dynamical structure of jets**
(jets from Class 0/I/II low-mass sources) (**A_V, n_e, T_e, x_e, n_H, mass and momentum flux**)

from optical/NIR diagnostics → **ne, Te stratification** in the shock cooling region

from tomography in velocity space → velocity shock structure -> **HVC: higher excitation**

follow-up
- parsec-scale jets from **more evolved CTTS** or **intermediate-mass** sources (data, *Mc Groarty, Podio et al., in prep., see poster*)
- more diagnostic **across the jet** (HST data: Coffey, Bacciotti, Podio, submitted)
- **in velocity bins** (NIR: *Garcia Lopez et al. 2008*; optical: Keck data of HH 30)

from depletion of refractory species → **dust grains in the jets**
possible constrains for the models ?

follow-up
- dust content in jets from **CTTS** and **Herbig Ae/Be** stars
- Ca, Fe depletion in the **jet basis** (is the dust really coming from the disk?)

from spectro-astrometric analysis of He, H NIR lines on RU Lupi
→ both **wind and accretion contributions to the HeI line**

follow-up
- analysis of He, H lines on a larger sample of CTTS (VLT/ISAAC data just acquired)
- analysis of Class 0/I sources (VLT/ISAAC data, *see Garcia Lopez talk*)

Outline

Observation of stellar jets

observational properties

physics of shocks – spectral tracers – diagnostic techniques

Large scale physical/dynamical jet structure

results from optical/NIR spectral diagnostics

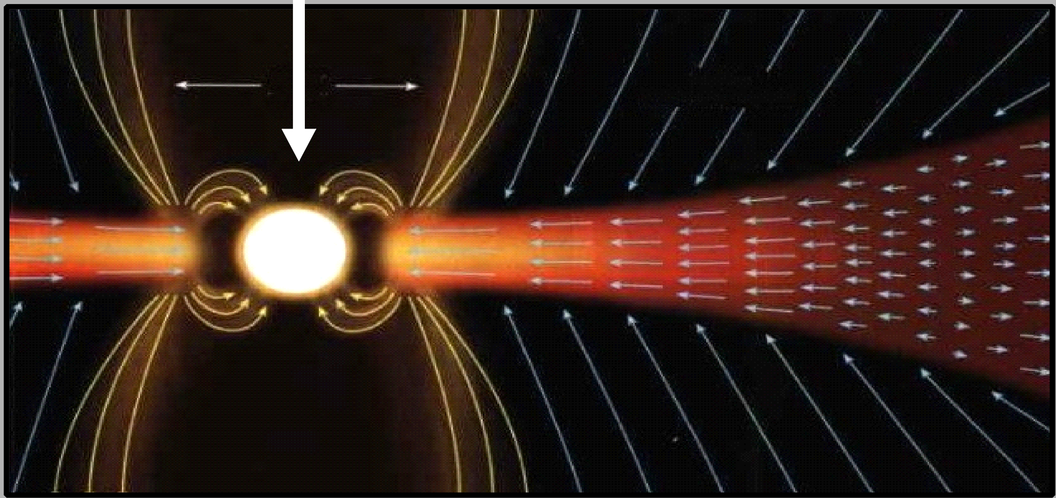
results from a jet tomography in velocity space

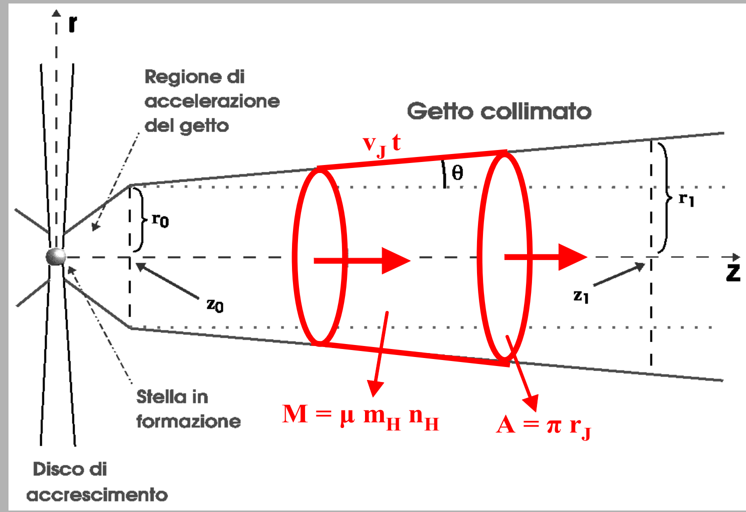
Small scale: accretion/ejection mechanism

results from a spectro-astrometric analysis of permitted H and He NIR lines

MASS FLUX RATE = $\dot{M}_{jet}$ regulates the jet DYNAMICS !

$$\dot{M} = dM/dt = (\pi\, r^2\, v_J\, t) \cdot (\mu\, m_H\, n_H)\ /\ t$$





$$\frac{\text{mass ejection rate}}{\text{mass accretion rate}}$$ is fixed the **MHD WIND MODELS**

ANGULAR MOMENTUM transported by the jet

$$\dot{L}_J = \dot{M}_J \cdot r\, v_\varphi$$

Jet “thrust” = **LINEAR MOMENTUM**

$$\dot{P}_J = \dot{M}_J \cdot v_J$$

to accelerate molecular outflows
to inject turbolence in the cloud