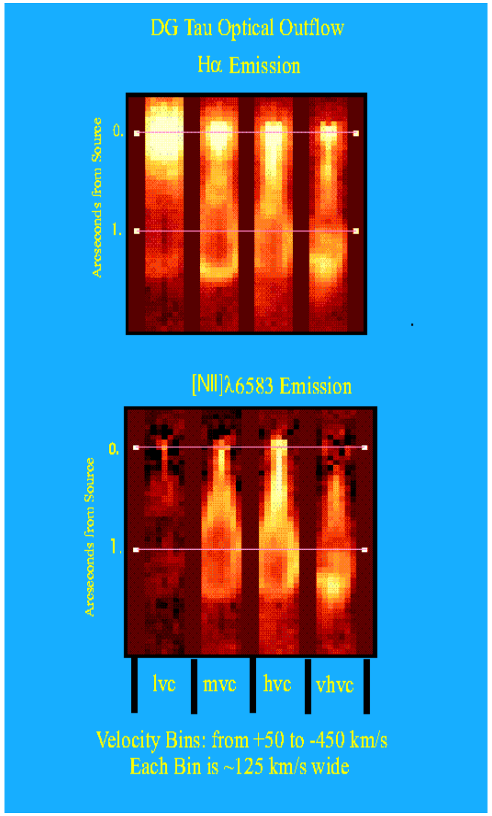
RESOLVED INNER JETS FROM T TAURI STARS



Francesca Bacciotti

INAF – Osservatorio Astrofisico di Arcetri

Tom Ray
Jochen Eisloeffel
Reinhard Mundt
Deirdre Coffey
Jens Woitas
Stanislav Melnikov

www.jetsets.org

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OUTLINE:

- Motivation
- Results from the ground
- Results from space
- Derivation of physical parameters
- Implications for theory

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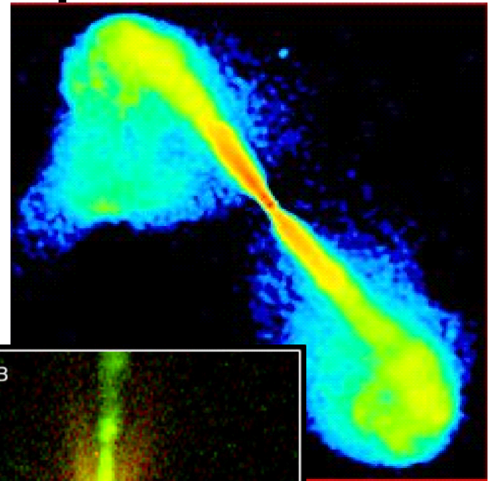
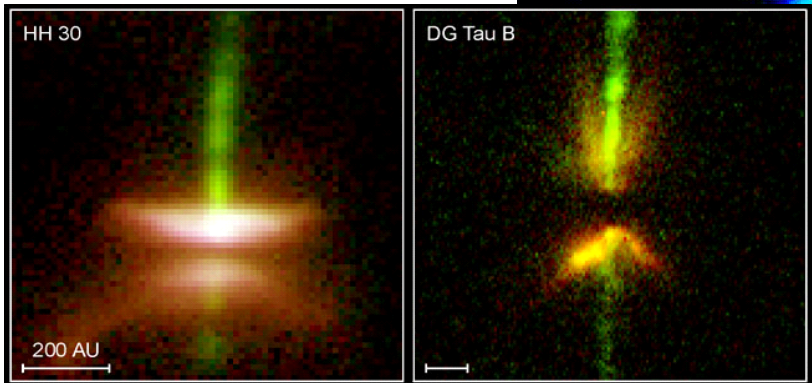
MARIE CURIE ACTIONS

- **Jets and Accretion disks appear to be ubiquitos and present at many different scales in the universe.**
- **ROBUST MECHANISM !!**



Open Issues :

- How does mass accretion proceeds ?
- Extraction of excess angular momentum ?
- Accretion/ejection relationship ?
- Jet generation mechanism ?
- Is the process similar at all masses ?



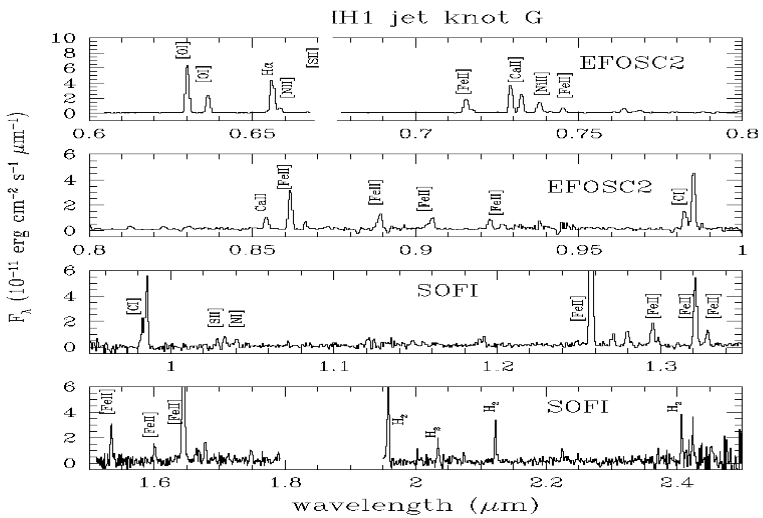
Obs Advantages of YSO vs AGN jets:.

-closeness

-properties of source well known

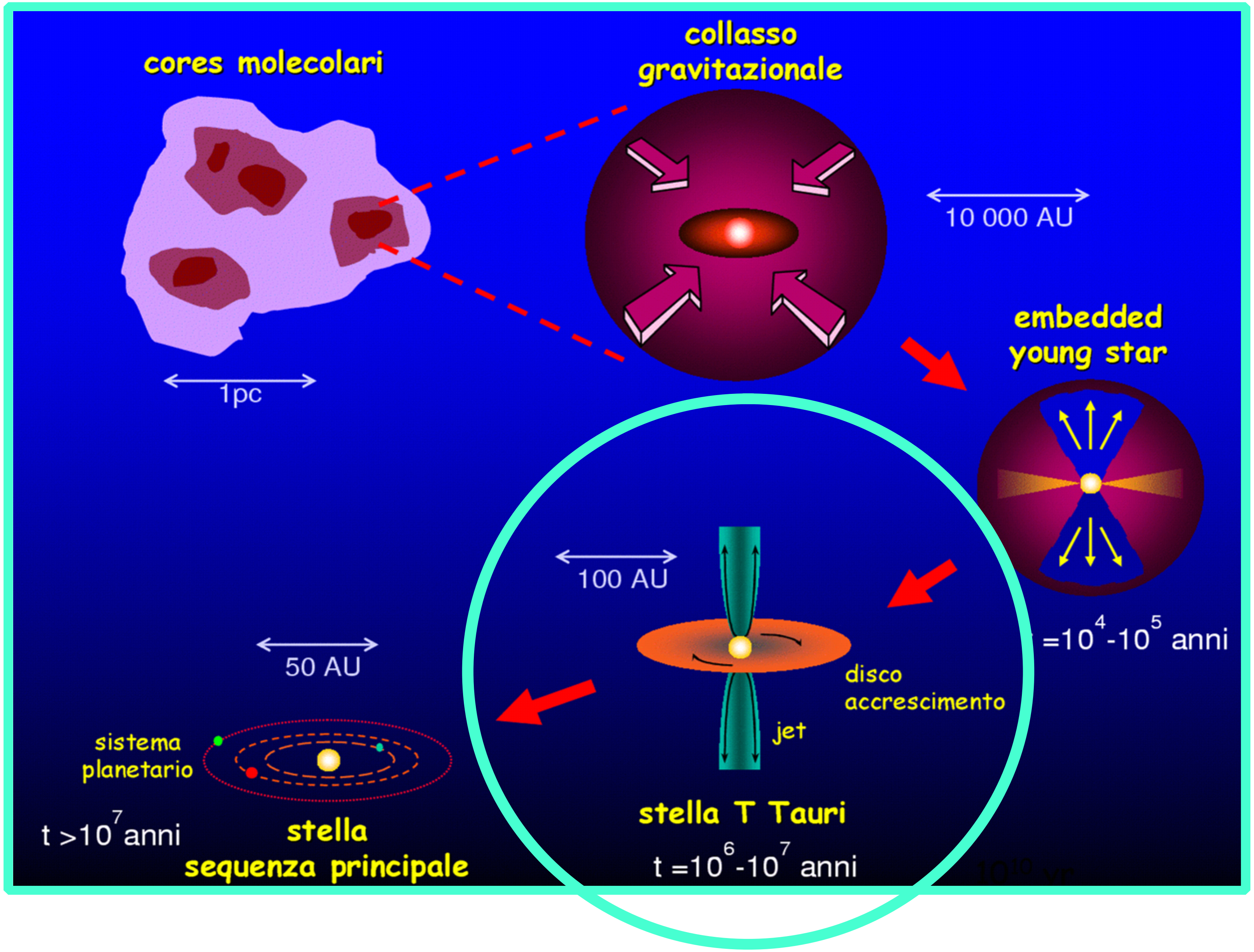
- EMISSION LINES !!!!

→ a lot of diagnostics !!

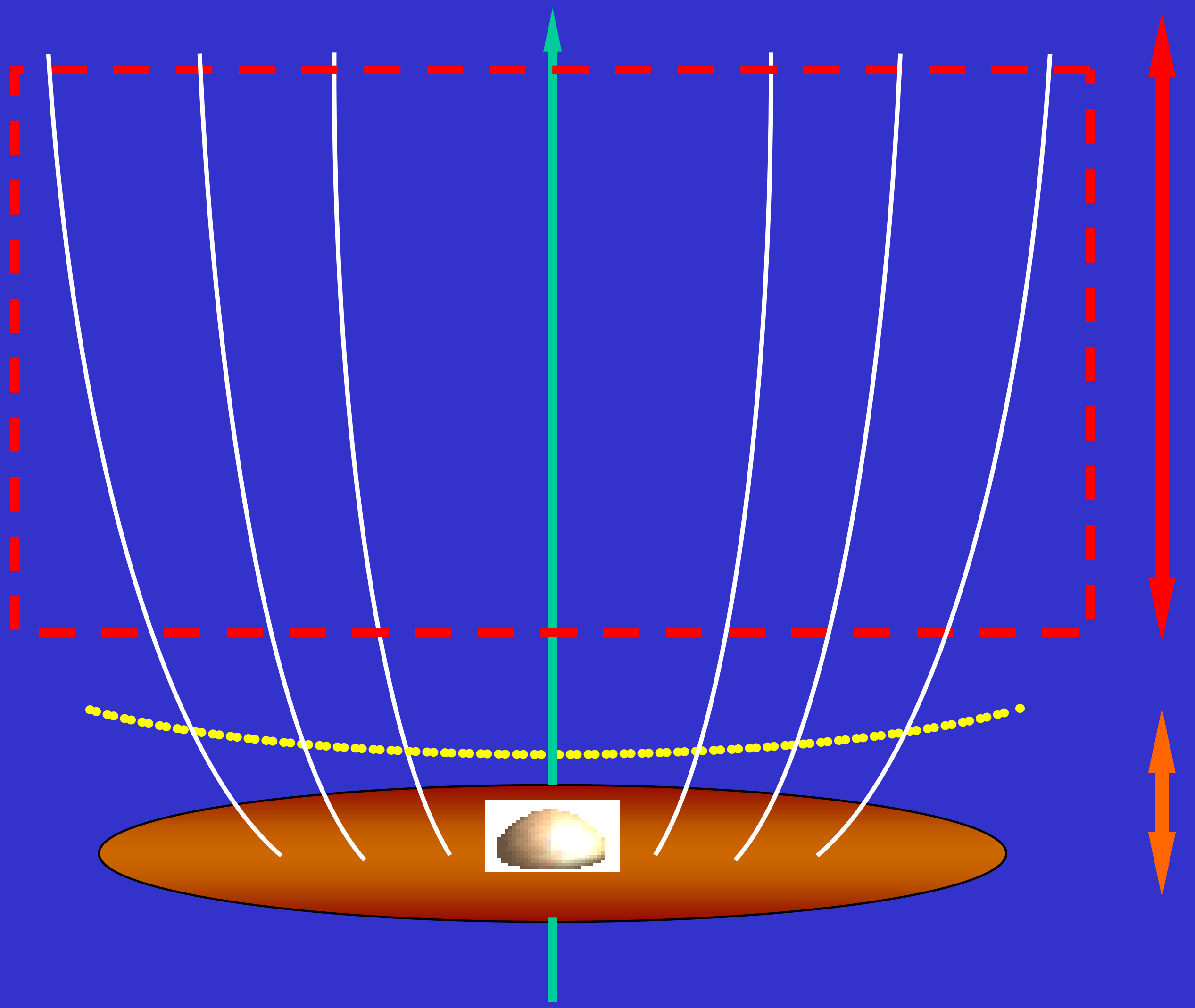


Motivation

Why T Tauri jets



Need for high ang. resolution



Magnetic/ flow surfaces

Alfvén surface

collimation region: 15 – 200 AU from source

the „engine“: < 5 AU

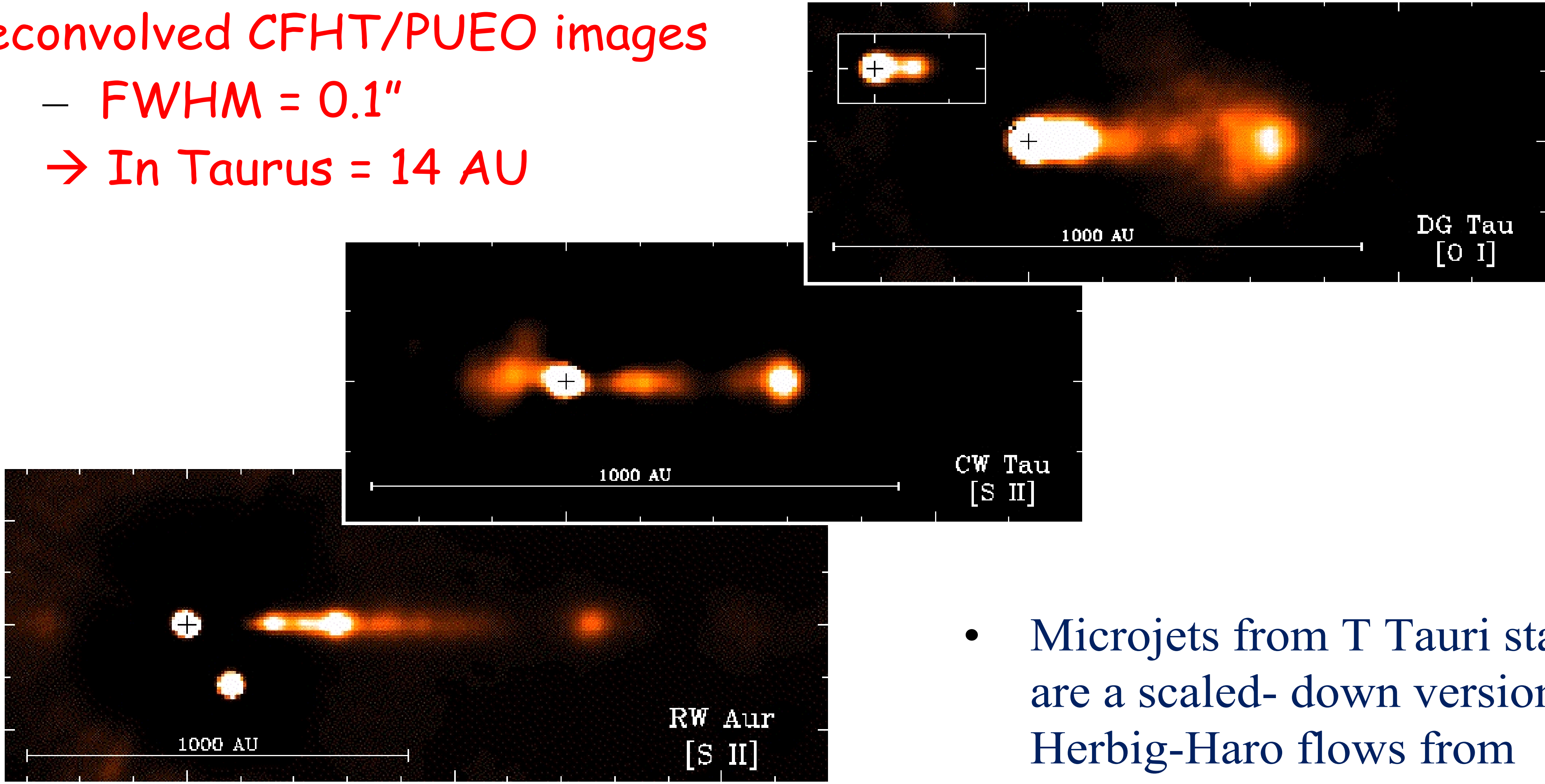
nearest star forming regions: 0."1 ~ 15 AU

T Tauri jets
with Adaptive Optics

Optical AO imaging

deconvolved CFHT/PUEO images

- FWHM = 0.1"
- → In Taurus = 14 AU

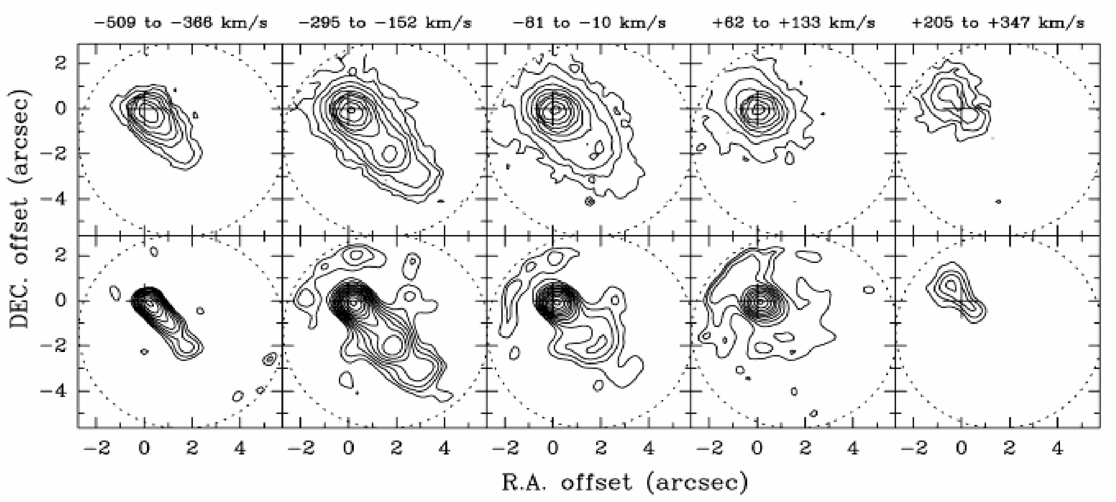


Dougados et al 2000

- Microjets from T Tauri stars are a scaled- down version of Herbig-Haro flows from younger sources

Early AO studies

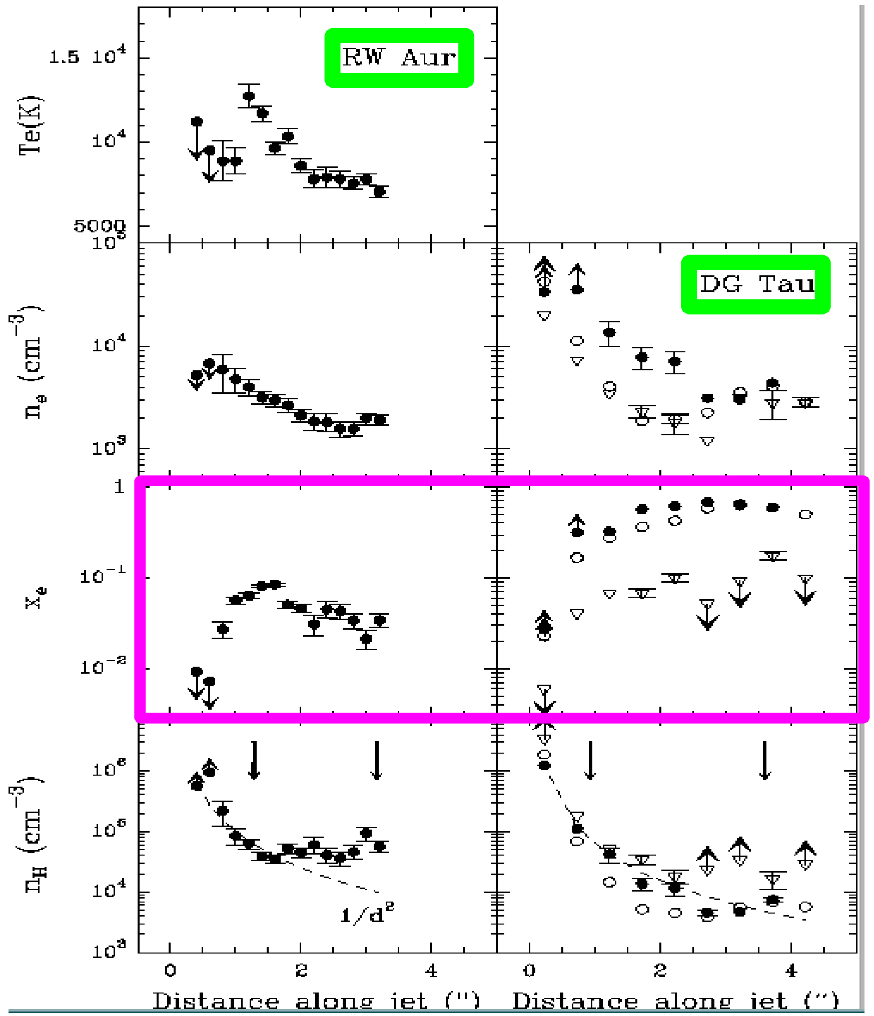
Velocity channel maps
DG Tau jet



Velocity

Lavalley et al. 1997

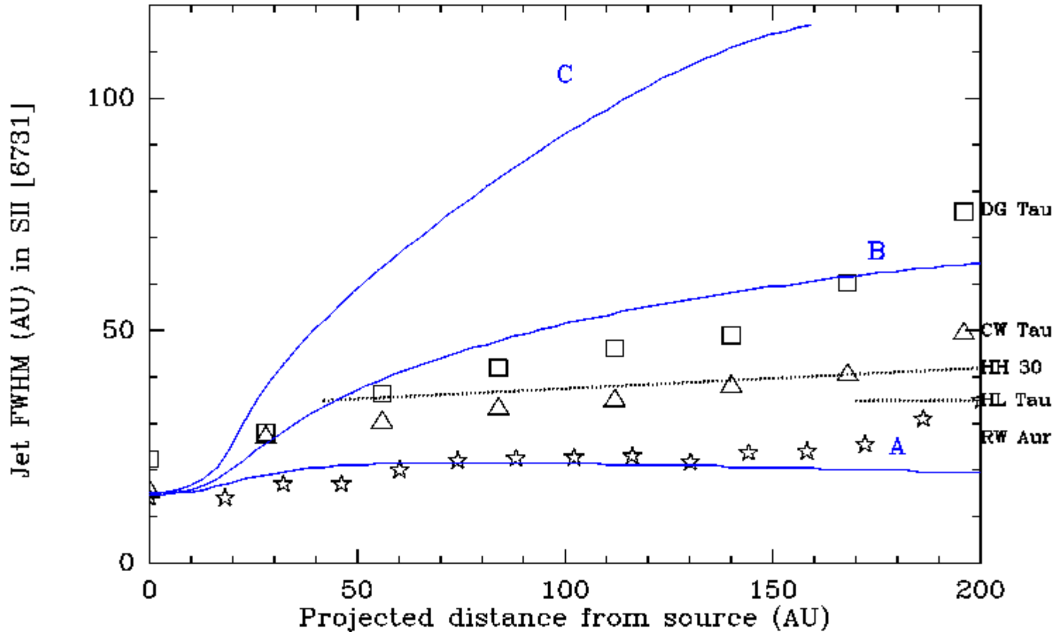
Spectral diagnostics with BE technique



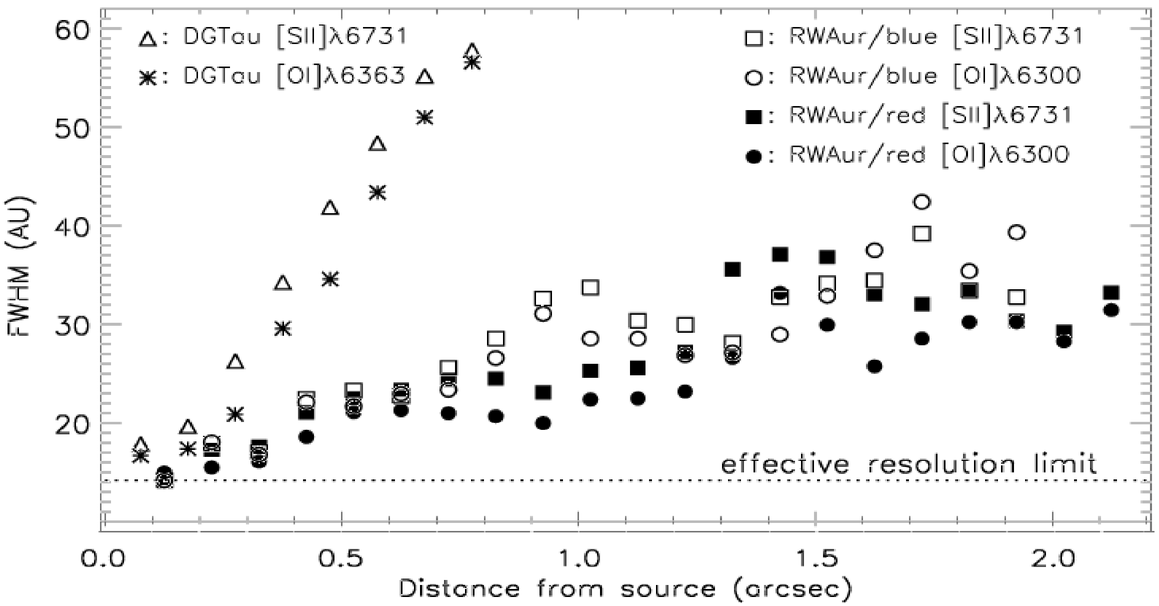
Dougados, Lavalley, Cabrit 2000, 2001

Jets resolved transversely !

width and collimation scales



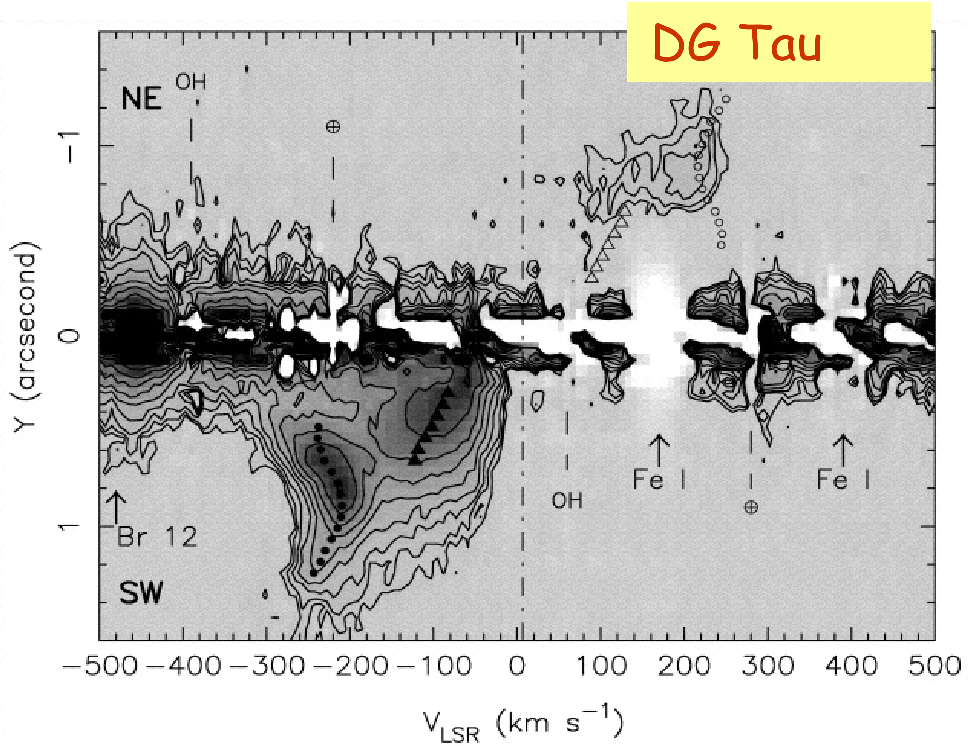
Garcia et al. 2001a,b



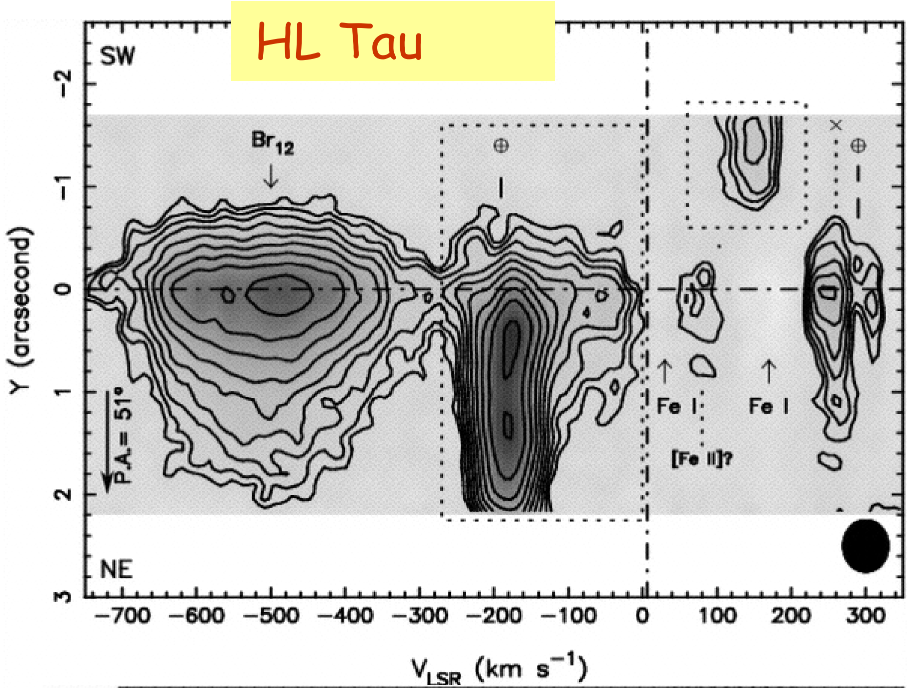
Woitas et al. 2002
(HST)

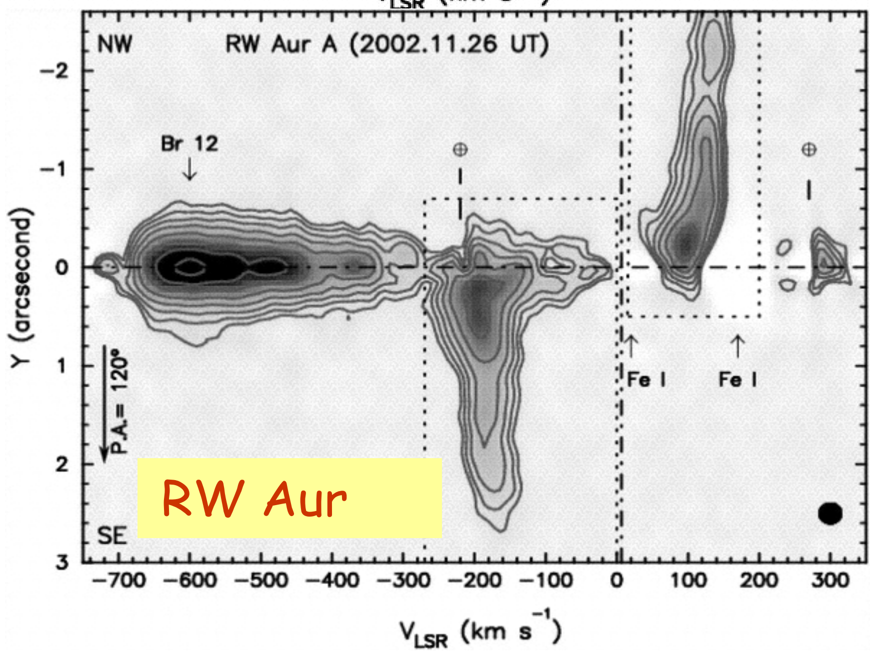
NIR AO spectra

Position-Velocity diagrams in [Fe II] 1.64mm
Obtained with SUBARU + AO
(0."2 - 0."5 resolution)



Pyo et al., 2003, 2006



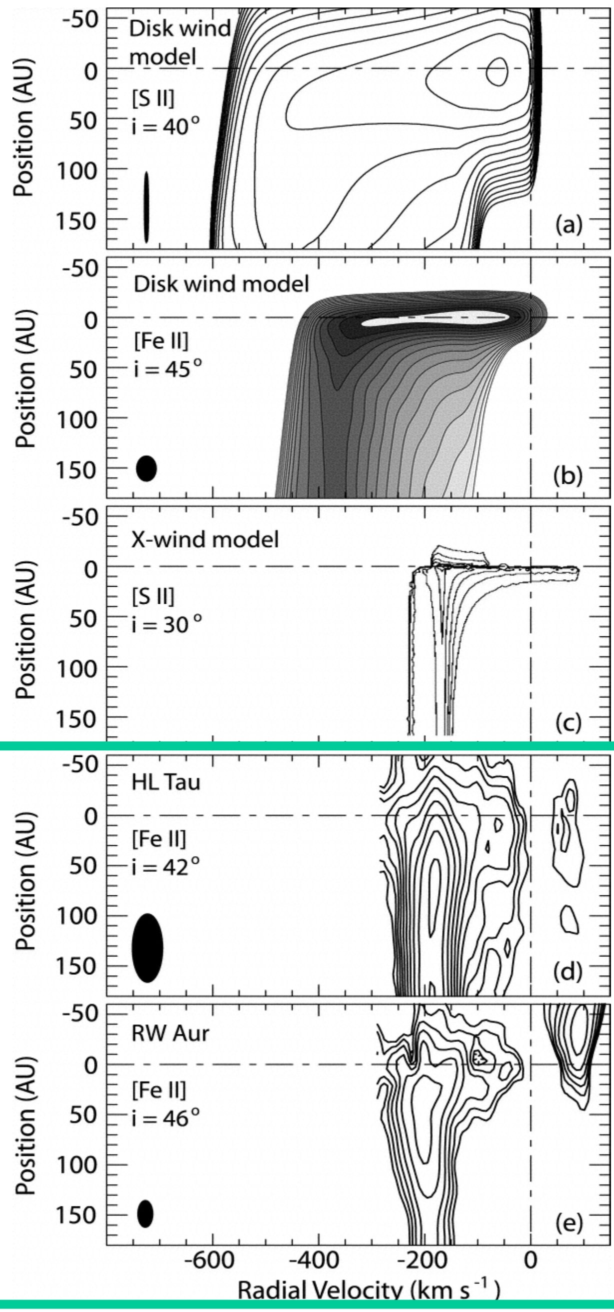


Comparison with

synthetic PVs from

launch models

Pyo et al., 2006

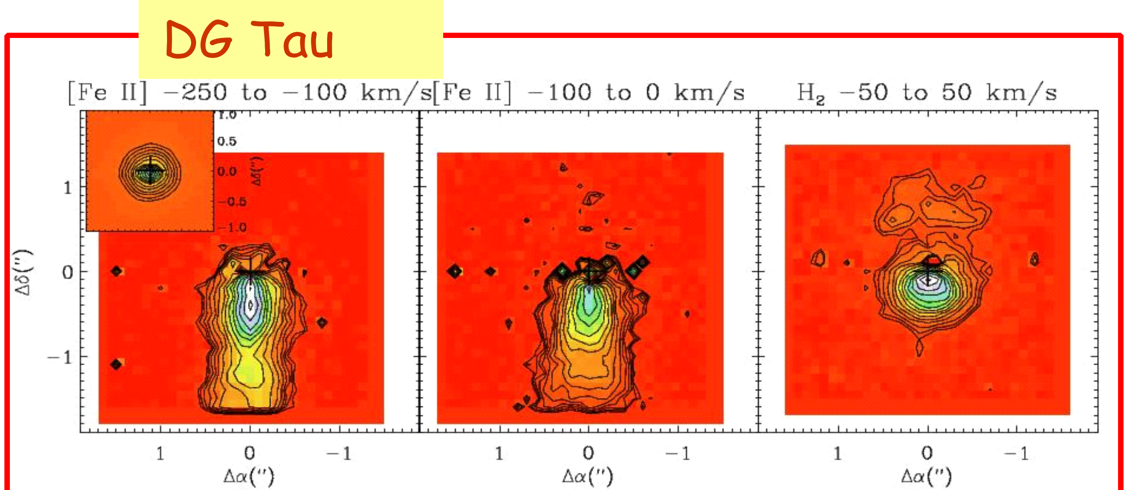


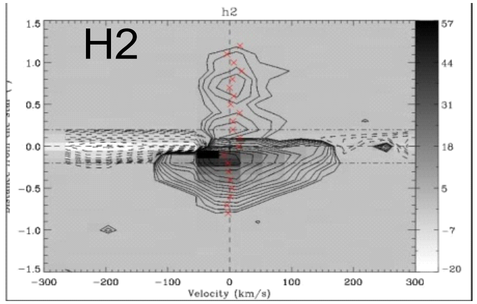
observed

Spectro-imaging with AO.

Morphology of DG Tau jet with VLT/SINFONI + AO
Ang. Resol. 0.”15, R=3000

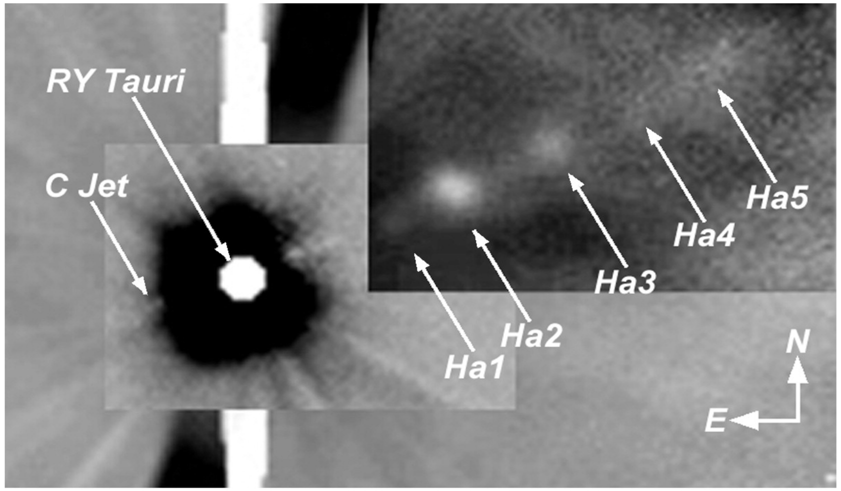
- atomic FeII + molecular H2





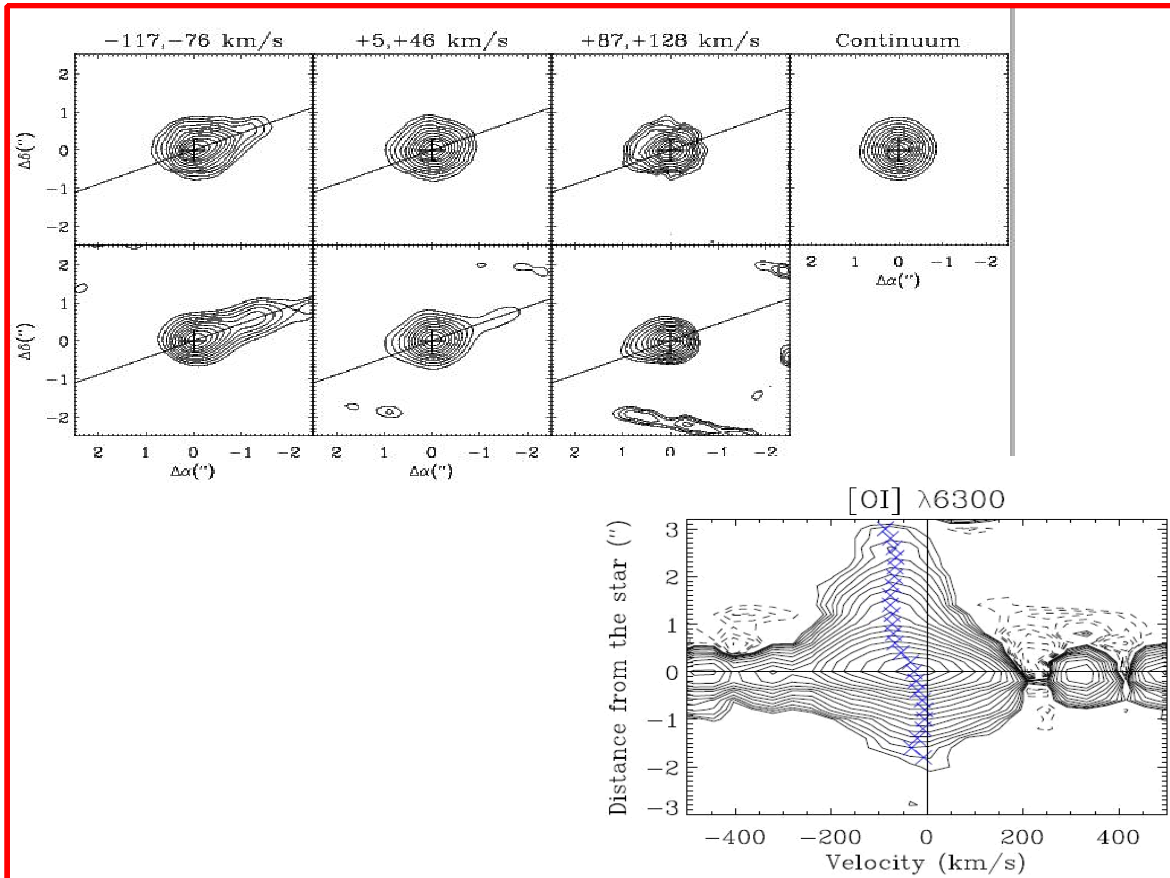
Agra-Amboage et al.,2008 subm

RY Tau bipolar jet



Ha image,
Gemini / GMOS

St.Onge & Bastien 2008



Detection of microjet in OI from RY Tau with OASIS/CFHT + AO

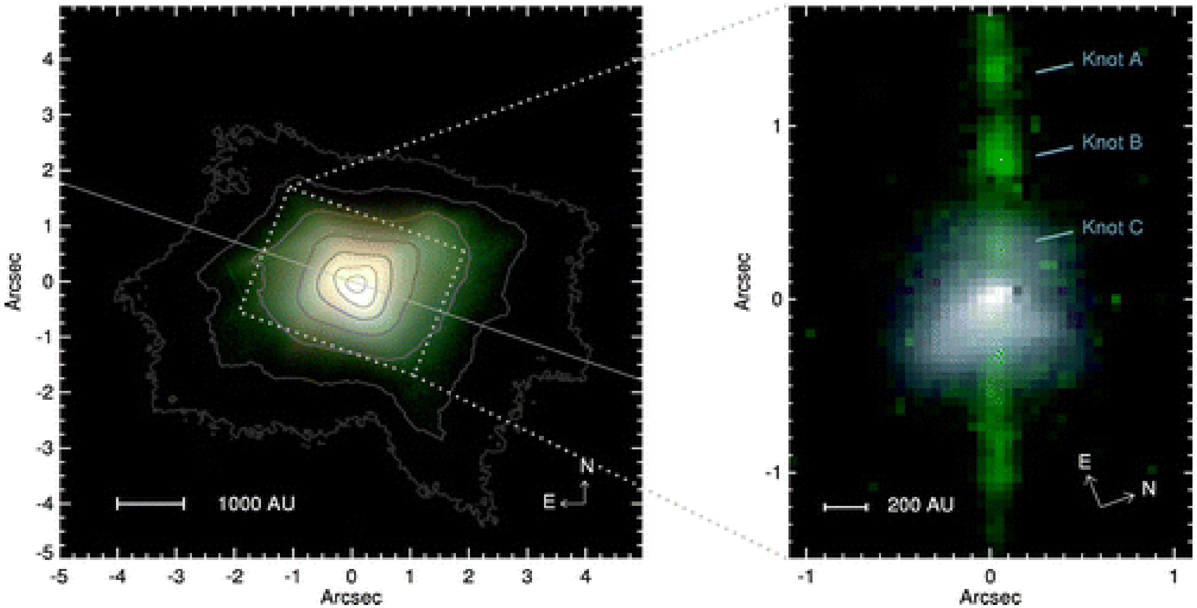
Agra-Amboage et al., submitted

Herbig AeBE jets with AO

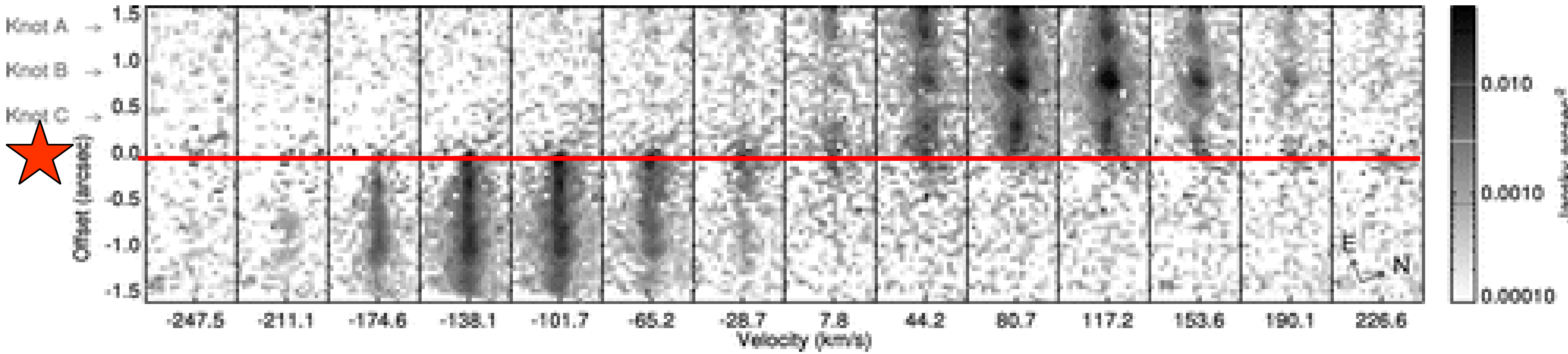
LkHα 233 jet in FeII lines

Perrin & Graham, 2007

KECK - OSIRIS IFU + AO +
Laser Guide Star !!



Velocity channel maps



AO Obs. vs Space Obs..

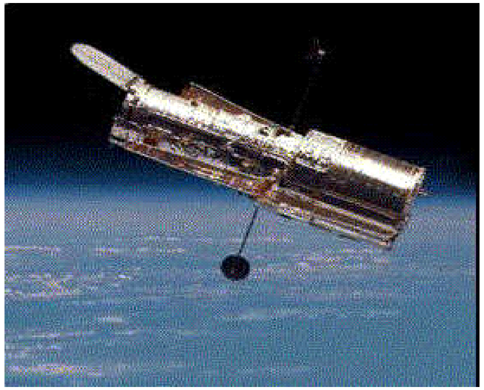
Pros

- AO obs easy to plan/execute
- Large telescopes = more sensitivity
- more and more facilities equipped with AO
- can have high Strehl ratio on small field of view
- ground based instruments repaired more easily !!

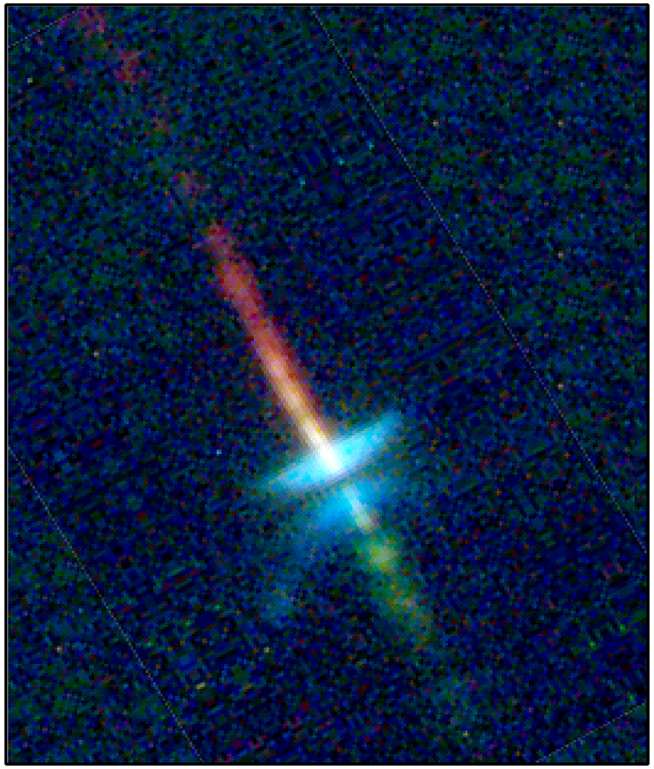
Cons

- low spectral resolution (except a few cases eaten by exoplaneters)
- limited wavelength range
- require close bright star or laser guide star
- problems with position of targets in the sky (big airmass)
- obtained AO correction depends on seeing after all

Good old HST not beaten yet !

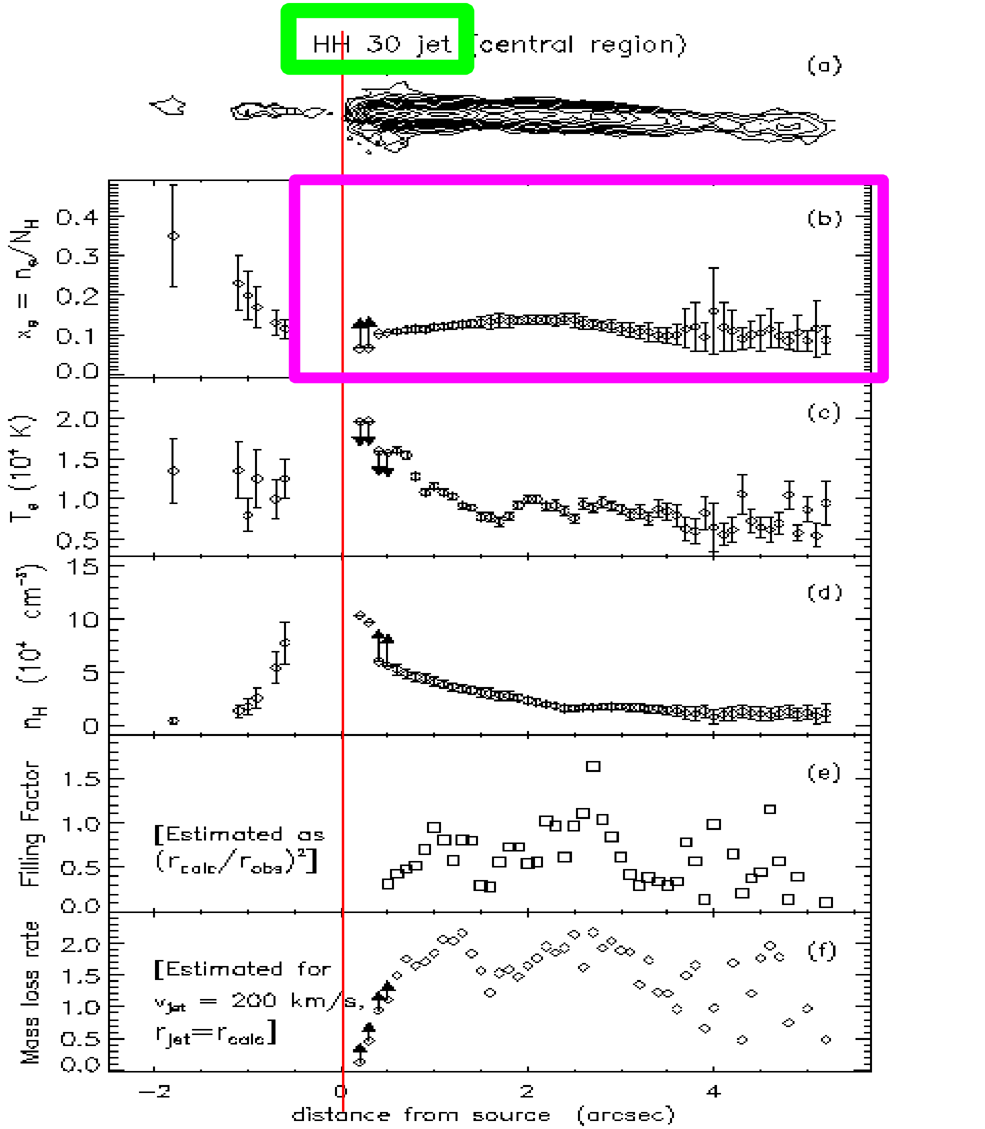


HST/WFPC2 imaging



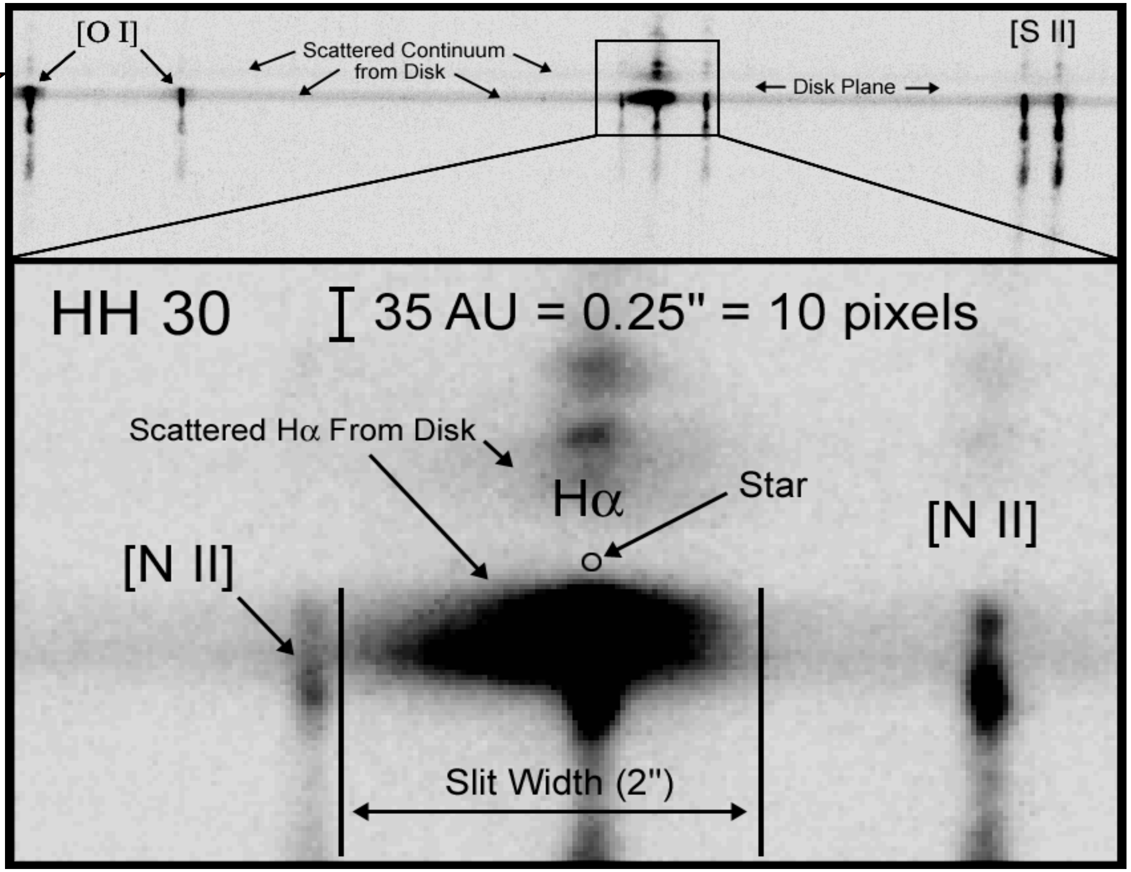
Ray et al. et al., 1996

HST/WFPC2 filtered images: diagnostics



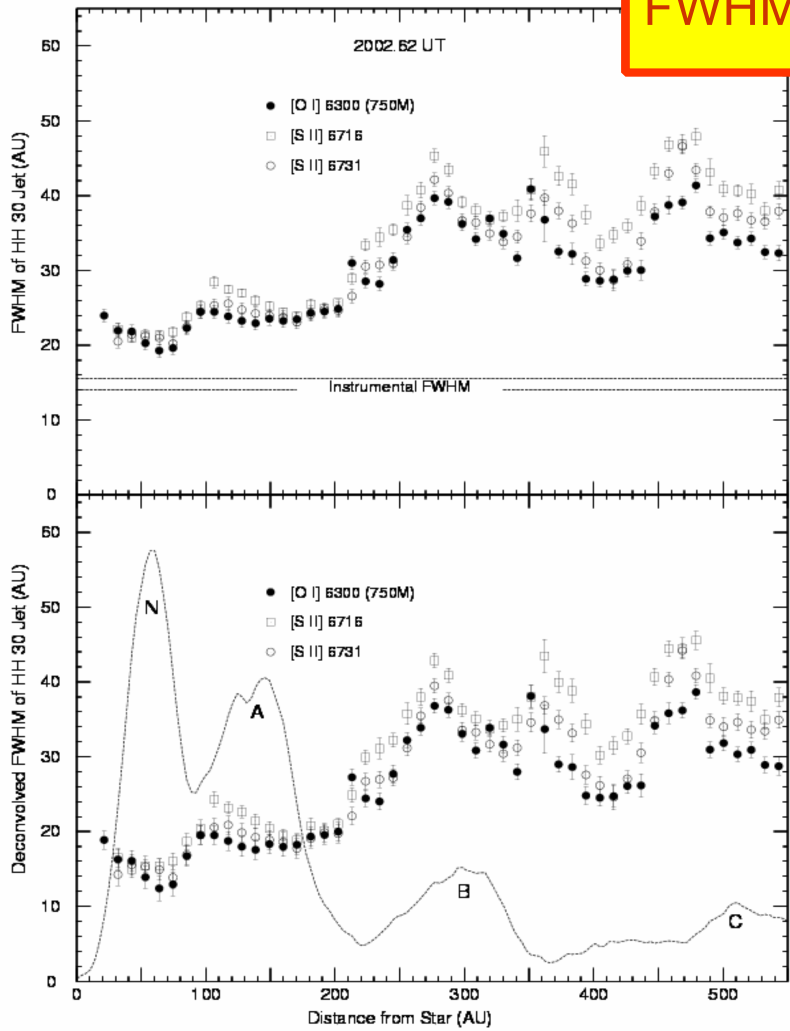
Bacciotti, Eisloeffel & Ray 1999

HST/STIS
slitless spectroscopy : images in all lines in one go
(not resolved in v)



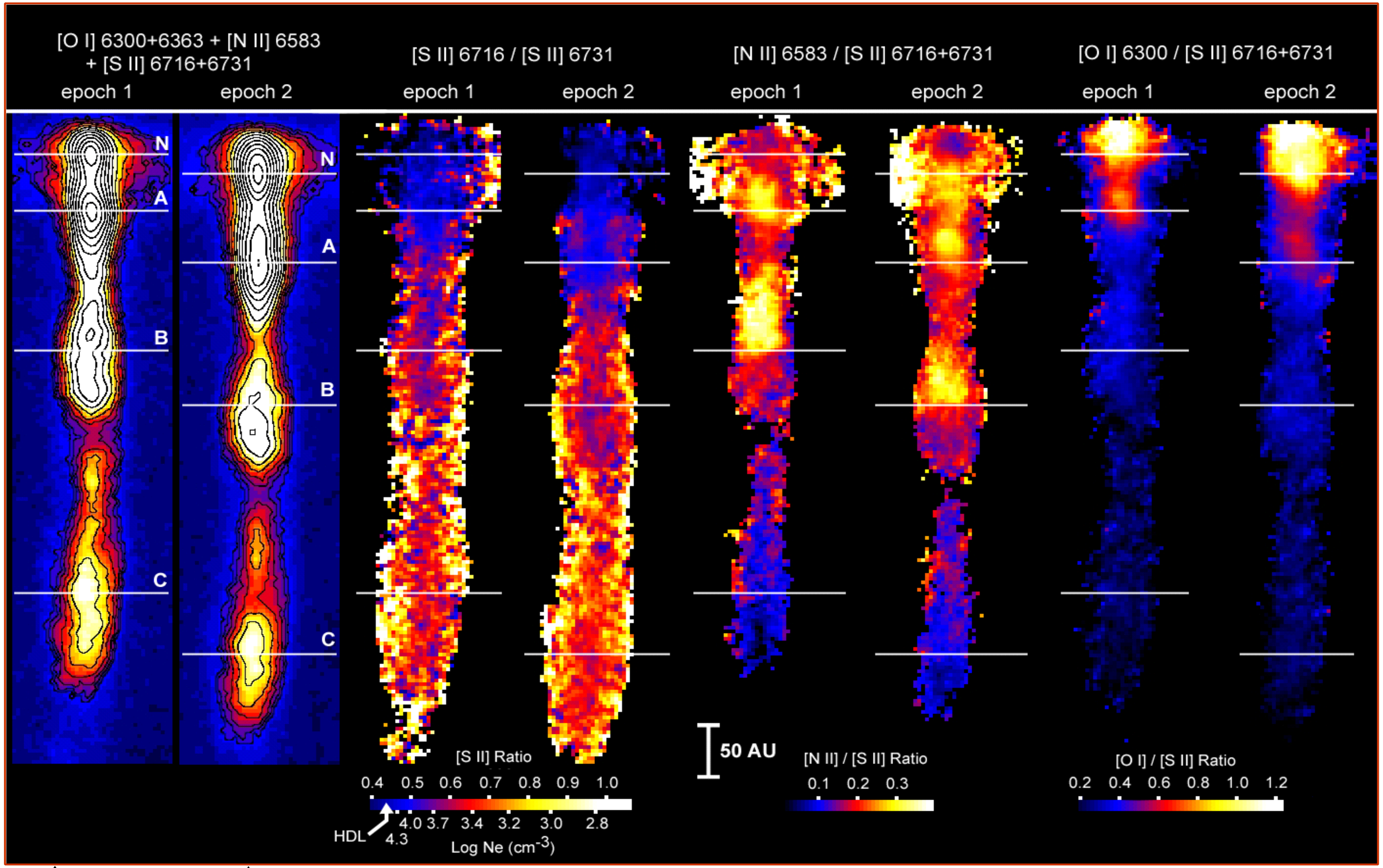
Hartigan & Morse 2007

FWHM



HST/STIS
slitless spectroscopy : line ratios

Jet direction

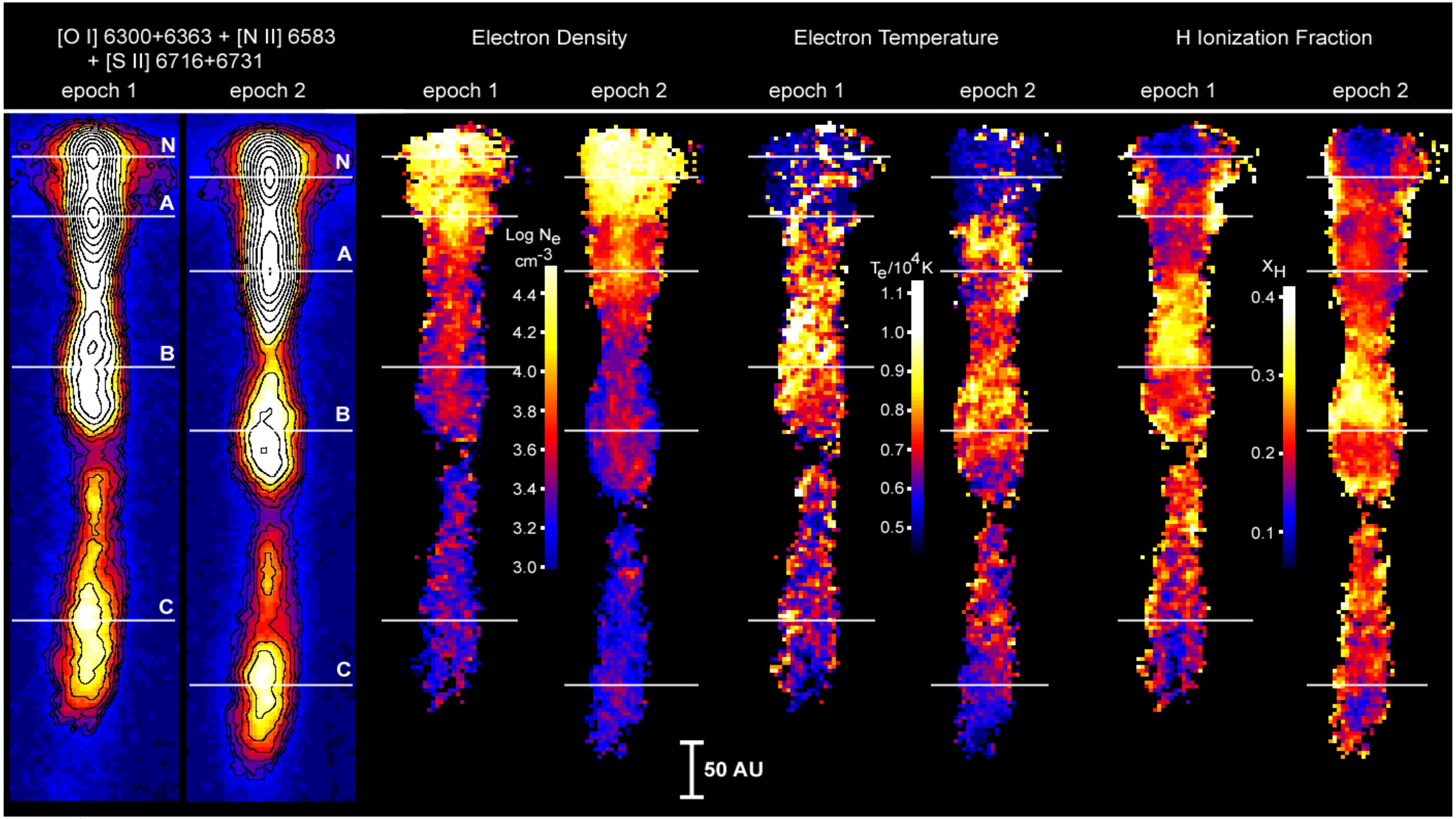


1.5 years

Hartigan & Morse 2007

derived from spectral diagnostics : excitation conditions

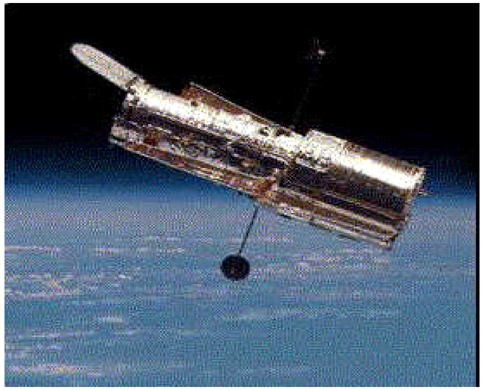
Jet direction

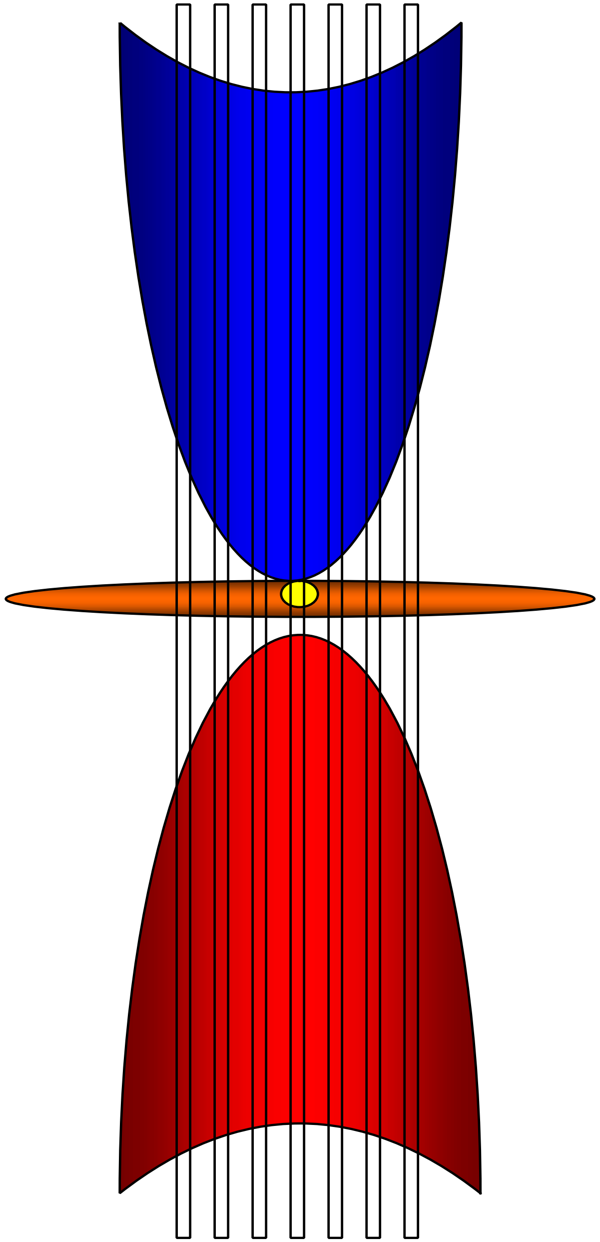


1.5 years

Hartigan & Morse 2007

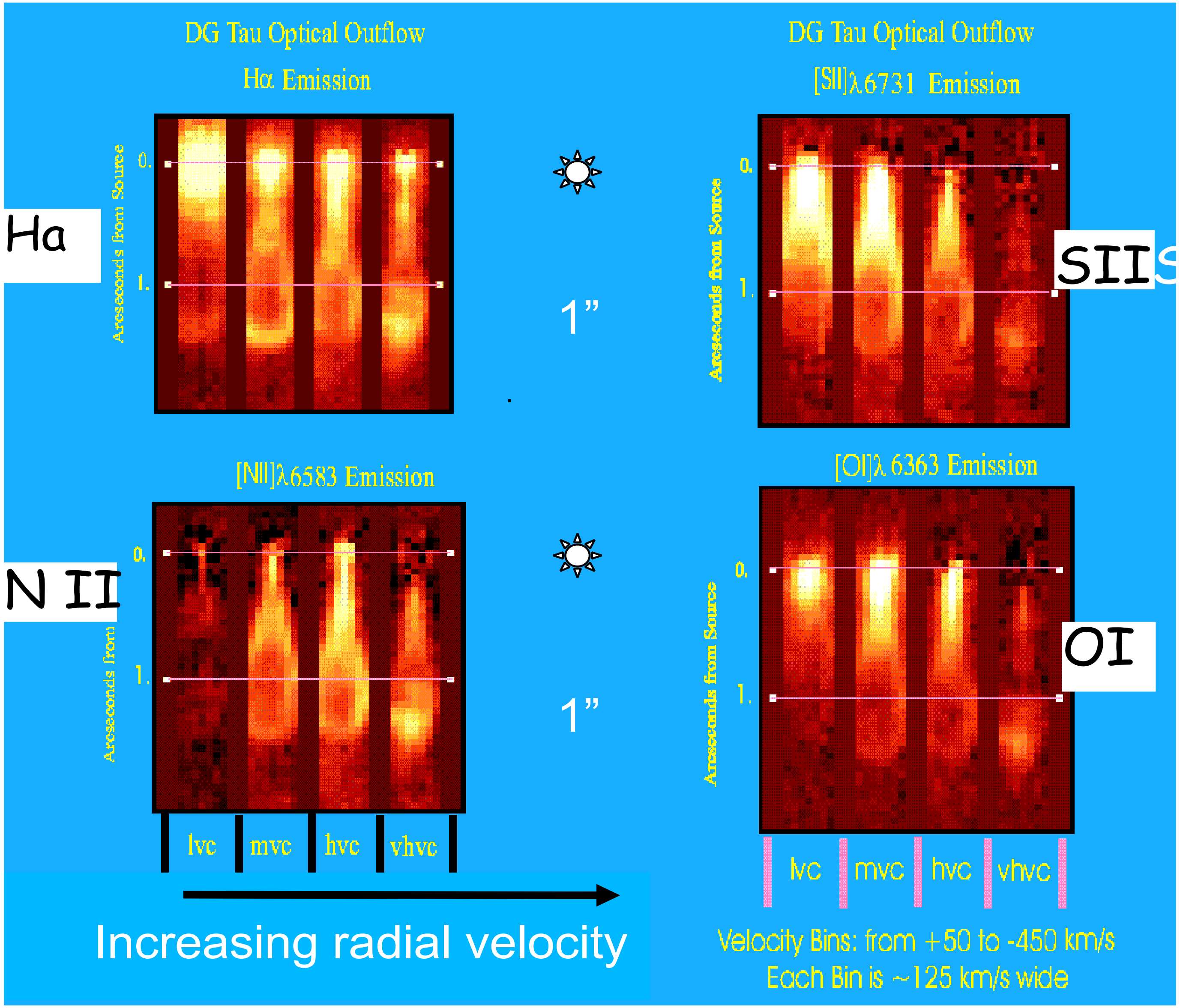
HST velocity resolved observations



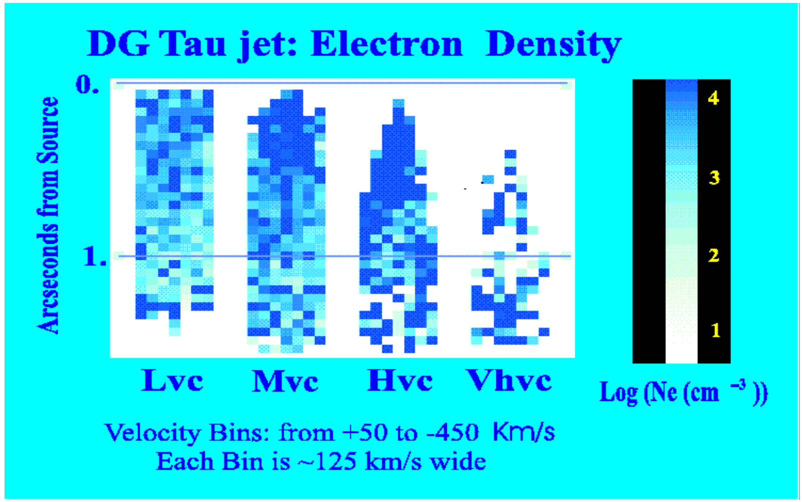


0 "5

DG Tau: channel maps from STIS datacube



JET Diagnostics
In 3D (x,y,velocity)



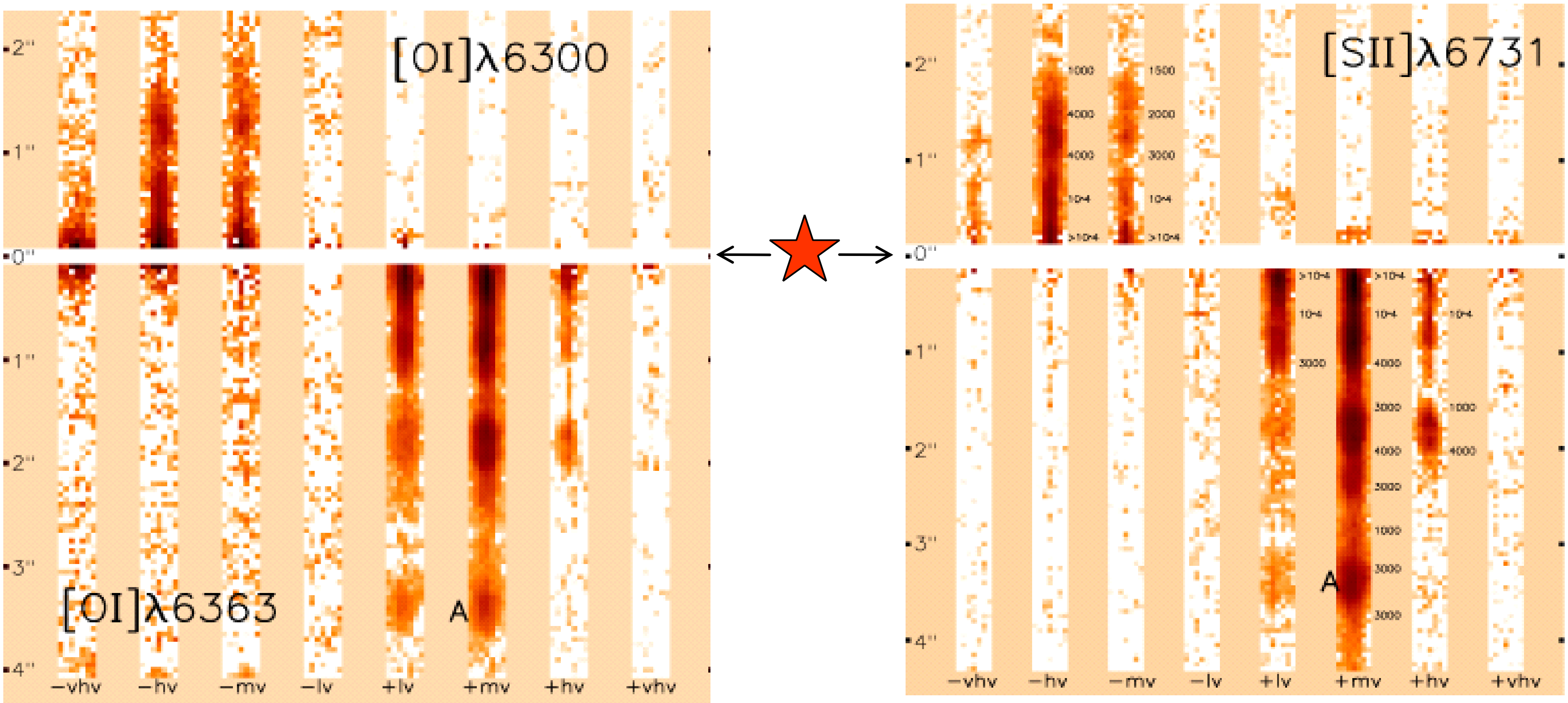
Bacciotti 2003,

Increasing radial velocity

Ne increases with velocity, collimation and proximity to the axis.

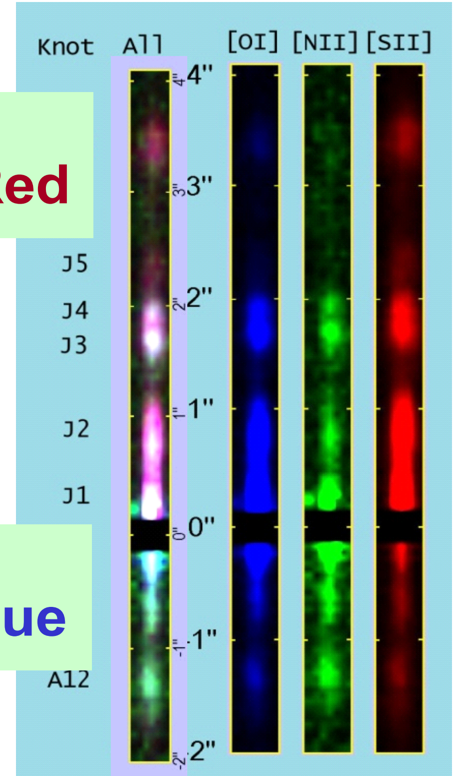
HST spectro-imaging

RW Aur: channel maps from HST/STIS cube



RW Aur bipolar jet

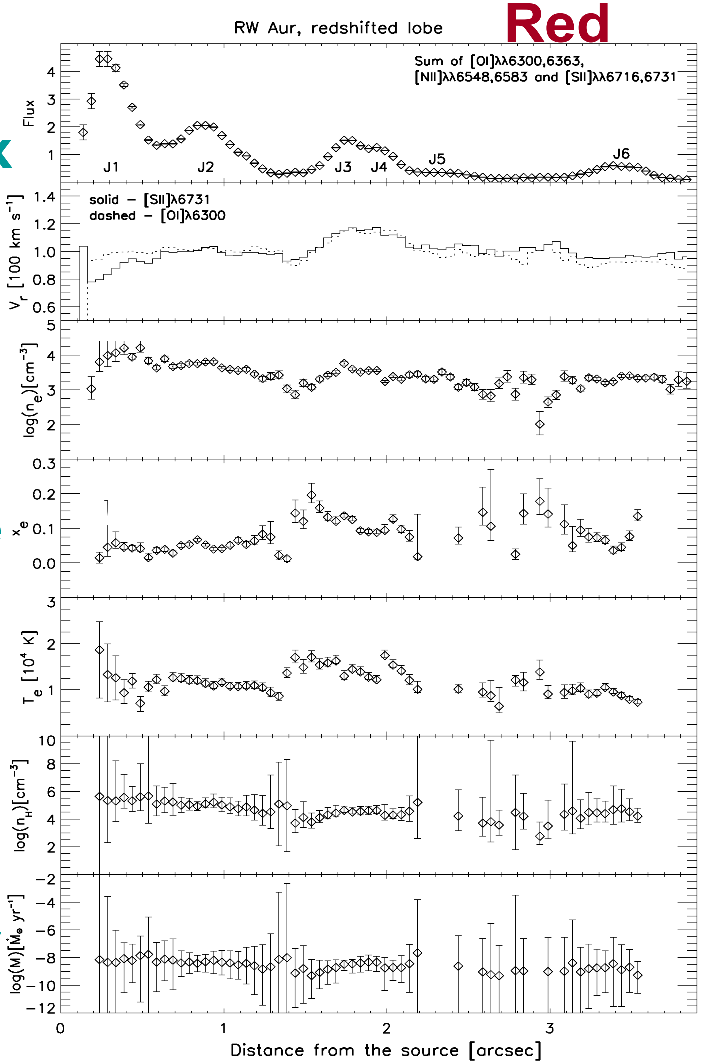
HST/STIS spectra + BE Technique



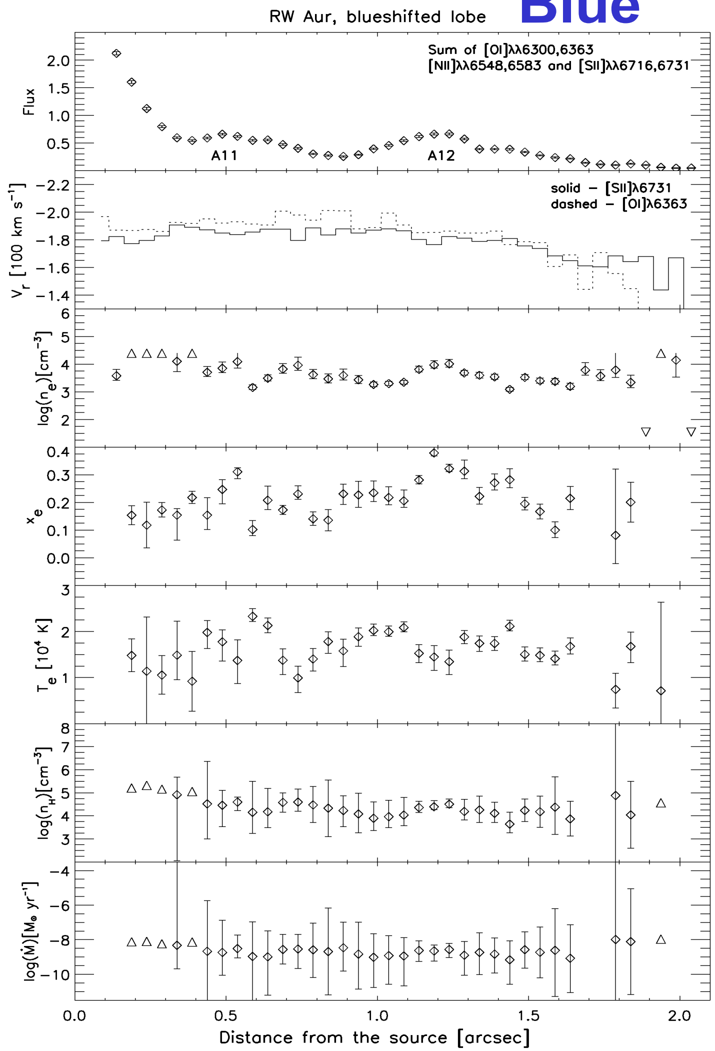
Reconstructed images

Flux
Vr
ne
Xe
Te
nH
Ṁw

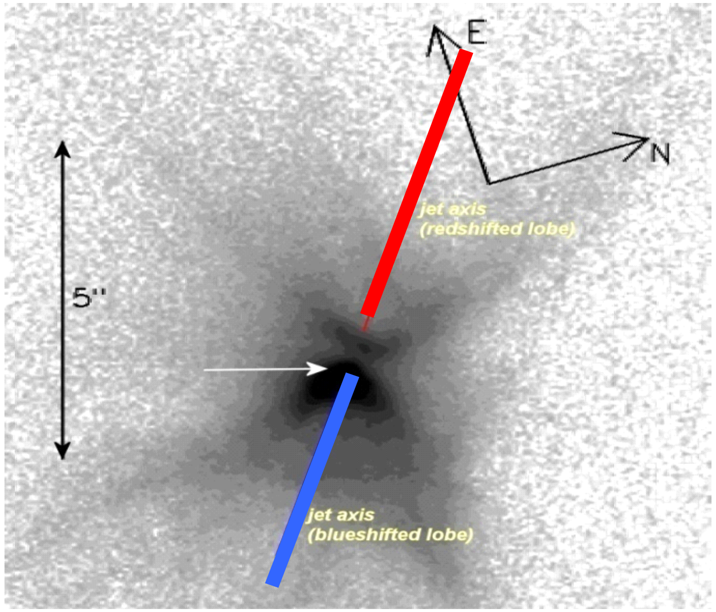
Red



Blue



Melnikov, Eisloeffel et al., 2008 in prep
(see POSTER)

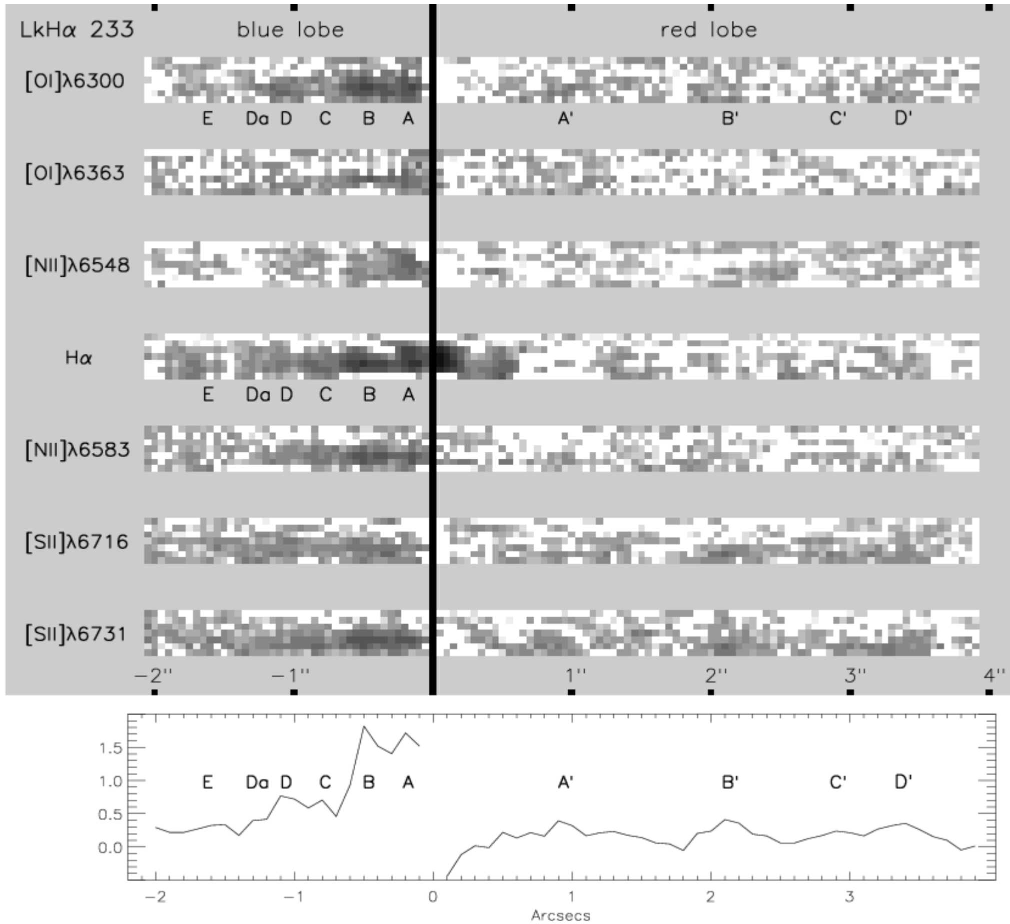


HST / WFPC2 image
W814 filter (7900 angstroms)

LkHα 233 jet

Melnikov et al., 2008

Spectroimaging with
HST / STIS, G750M



HerbigAeBe jets with HST

Flux

Vr

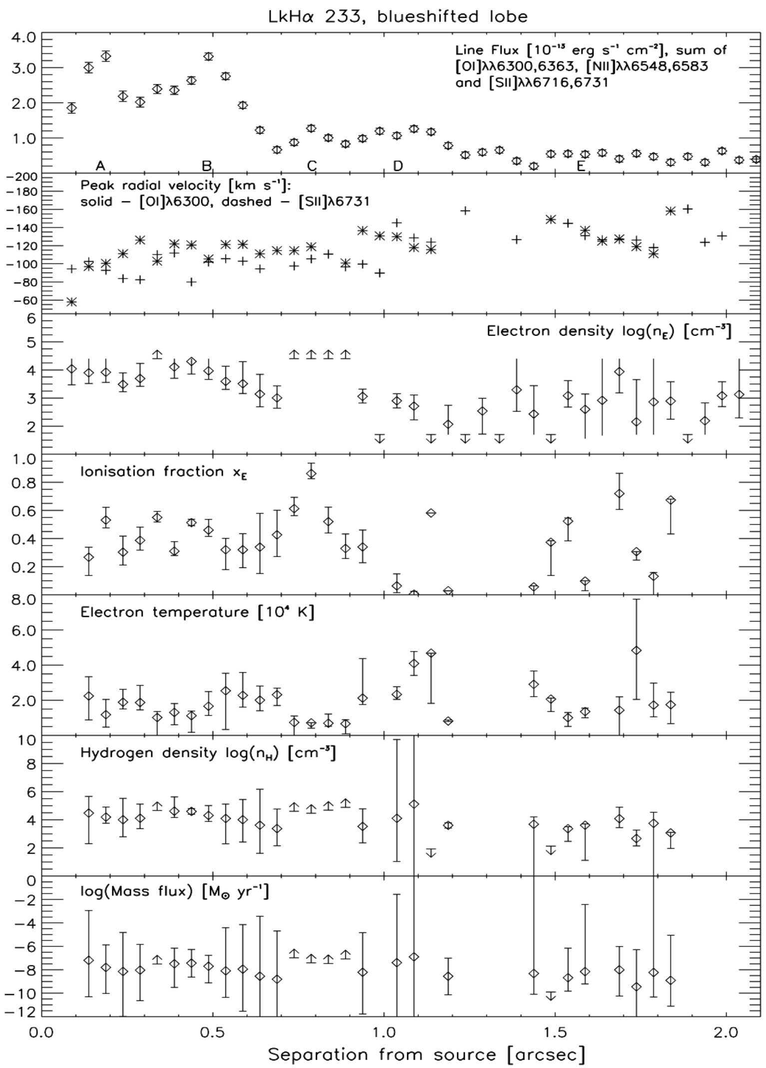
ne

Xe

Te

nH

Mw

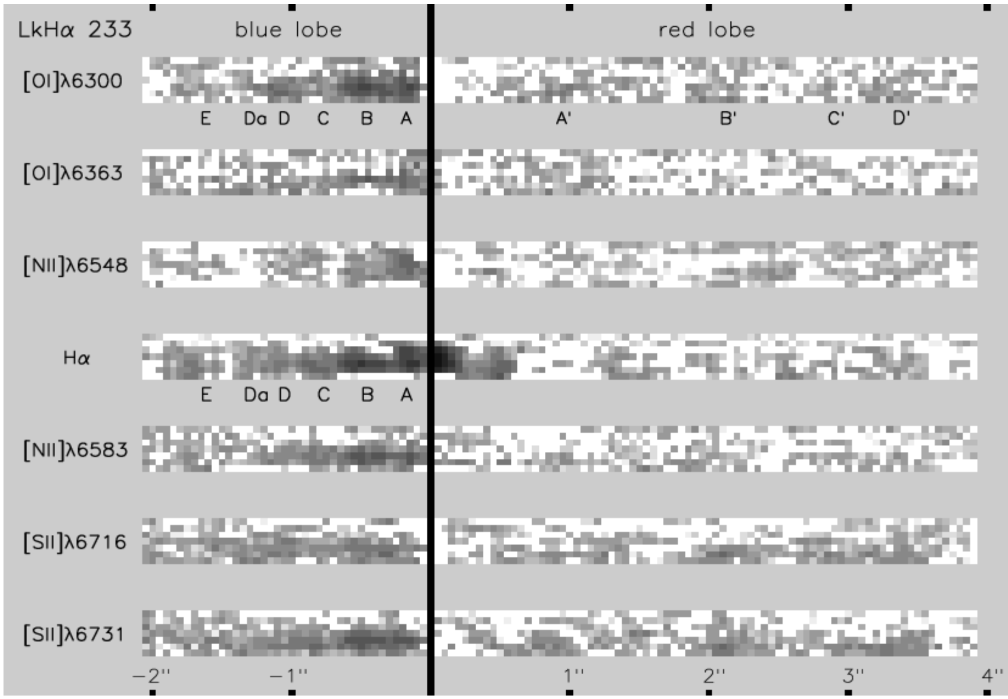


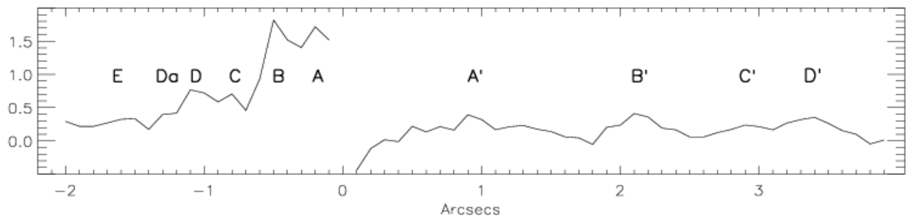
Spectral diagnostics with BE technique

LkHα 233 jet

Melnikov et al., 2008

Spectroimaging with HST / STIS, G750M

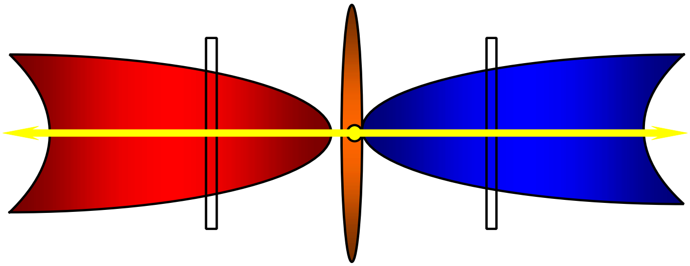




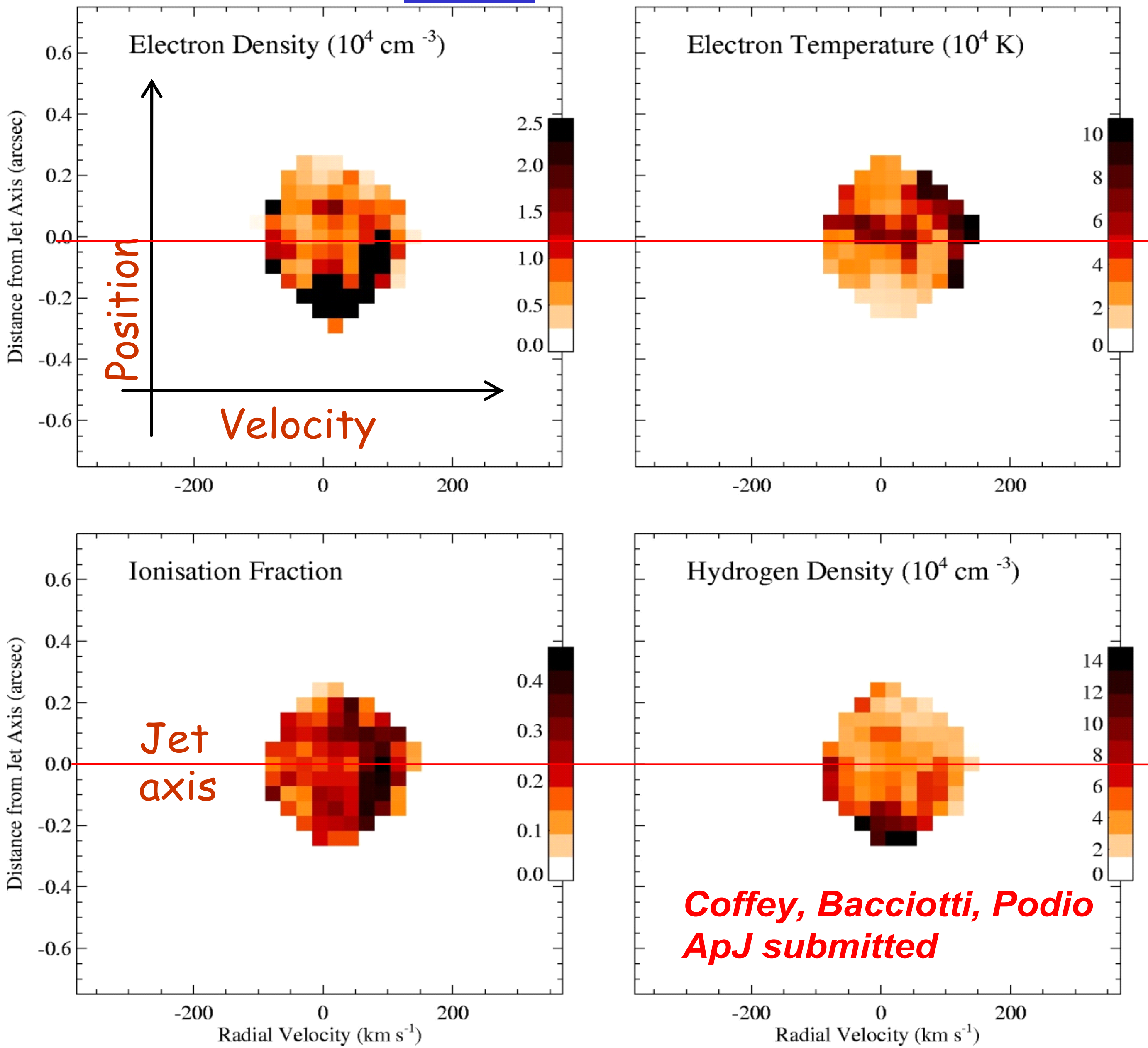
Jet transverse structure

T TAURI JET PHYSICS RESOLVED NEAR LAUNCH REGION
At 100 AU from star

Renewed BE technique applied to optical HST/STIS spectra
gas conditions as function of velocity and distance from the jet axis



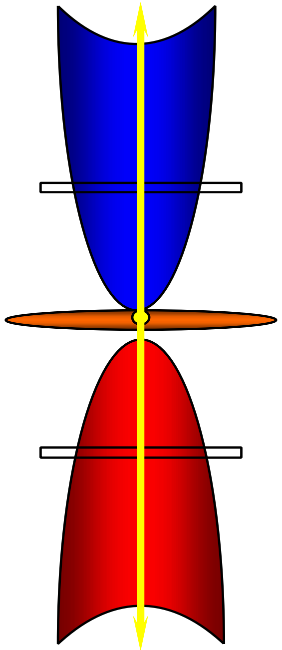
th28 Receding Jet

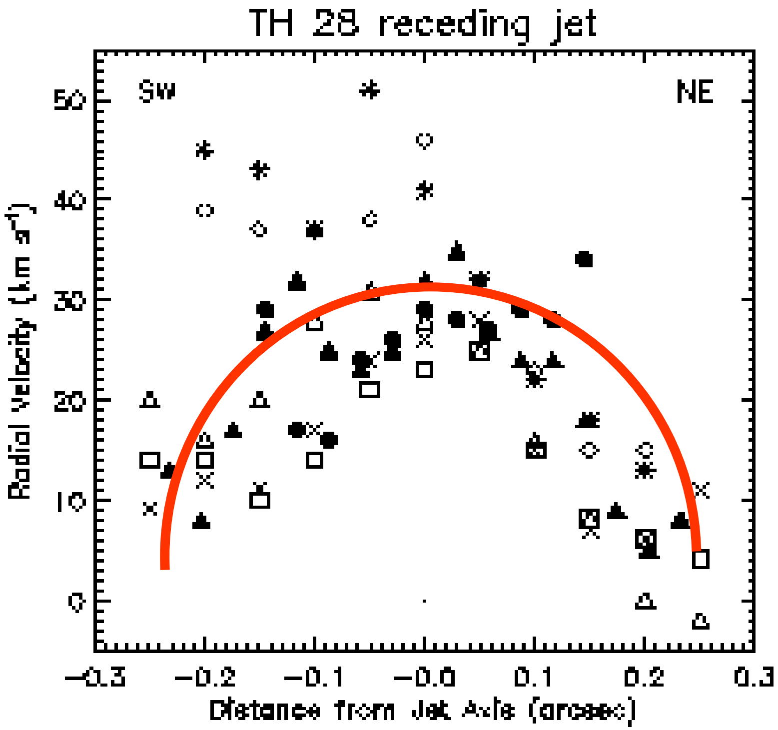


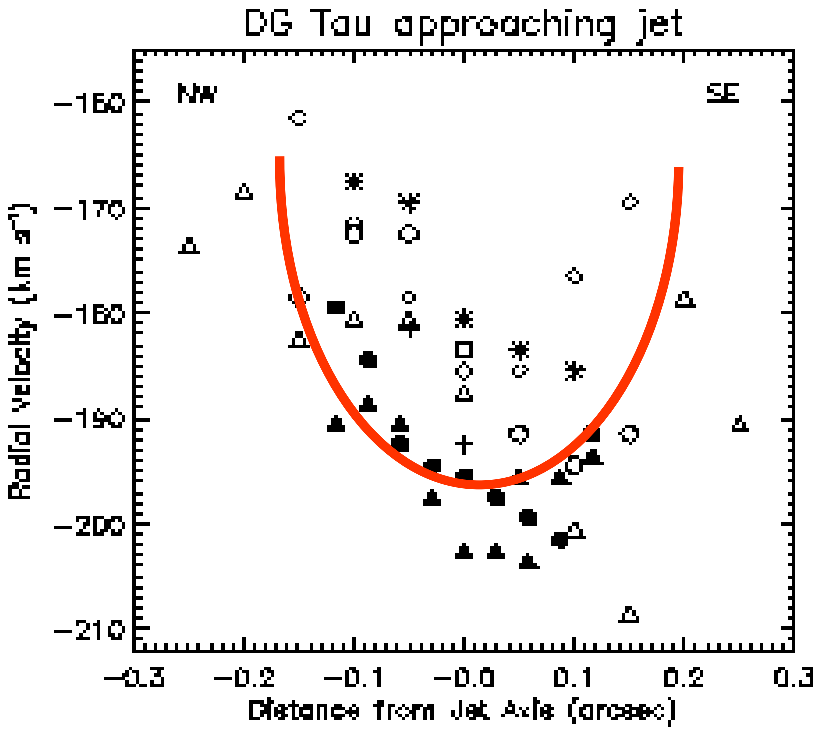
Coffey, Bacciotti, Podio ApJ submitted

Results: high ne and Te, while ionisation level varies.
Asymmetries
Mass and Angular momentum fluxes
resolved in space and velocity
HVC close to axis plays dominant role

Radial velocity profile *across* the jet @ 50 AU from source







Coffey et al. 2007

From HST/STIS spectra,

empty symbols :optical lines filled symbols: MgII 2796 , 2803

Within the first 100 AU :

- early collimation
- Onion-like structure
- electron density > 10^3 cm^-3, higher in axial region
- Partial ionisation X: 0.02 – 0.6
- T: 0.8 – 3 10^4 K
- $\dot{M}$_jet / $\dot{M}$_acc 0.05 -0.1
- poloidal velocity decreasing toward jet borders
- Asymmetries jet/counter-jet
- Herbig AeBe jets scaled to T Tauri jets

JET ROTATION

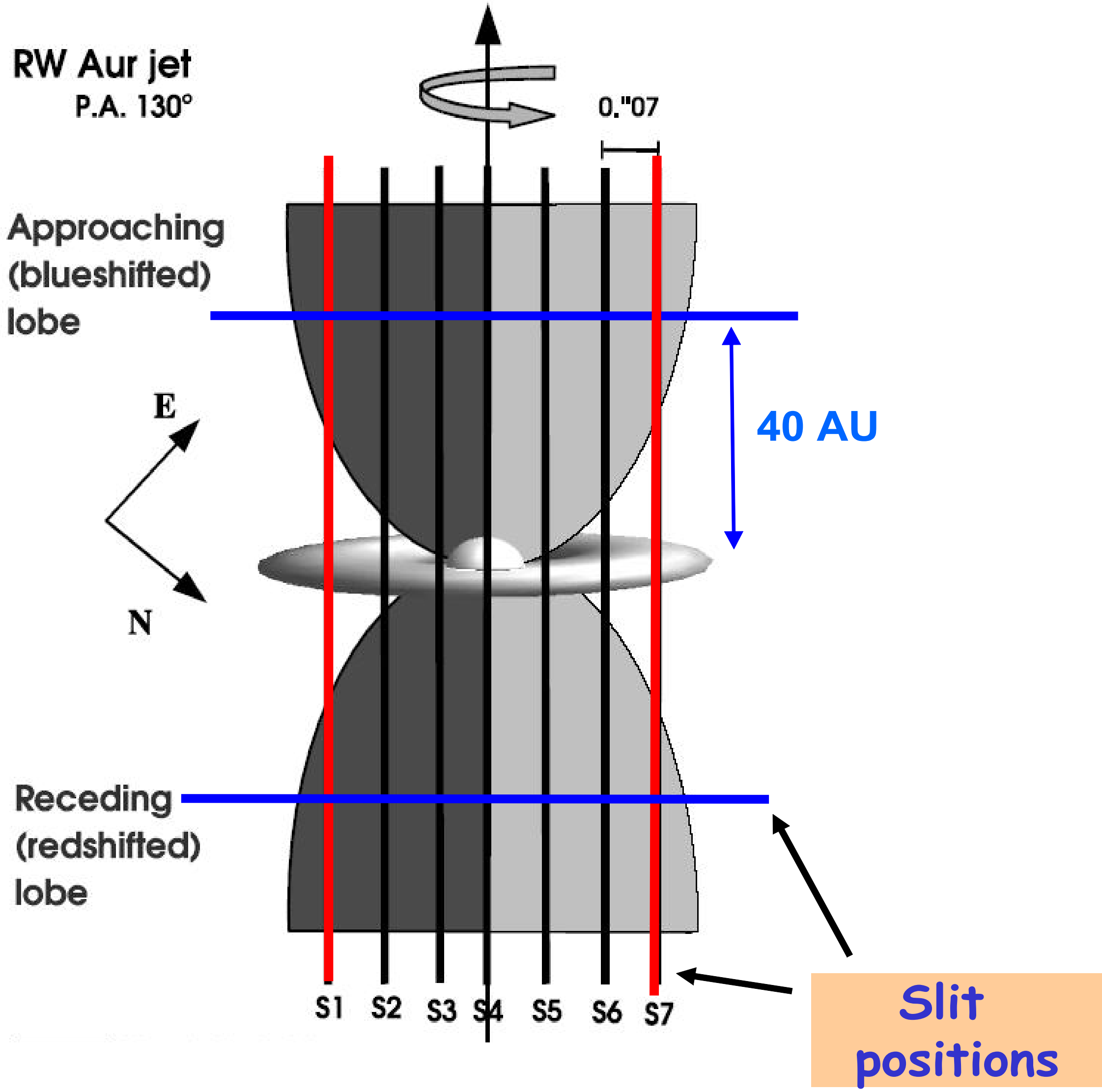
Observing strategy

Since ROTATION is
transferred to the JET
from the disk

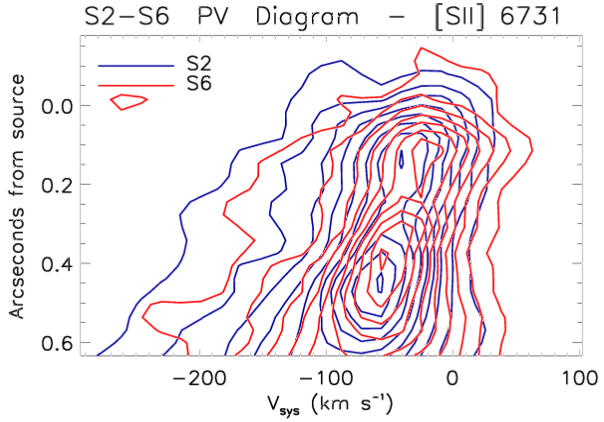
-> We should be able
to observe it
as velocity differences
at the jet borders
close to the star

High angular resolution needed
to resolve jet borders
and collimation region
(< 0.5"–0.7" in closest systems)

Good spectral resolution needed
to resolve expected
radial velocity differences
of 5 -20 km/s

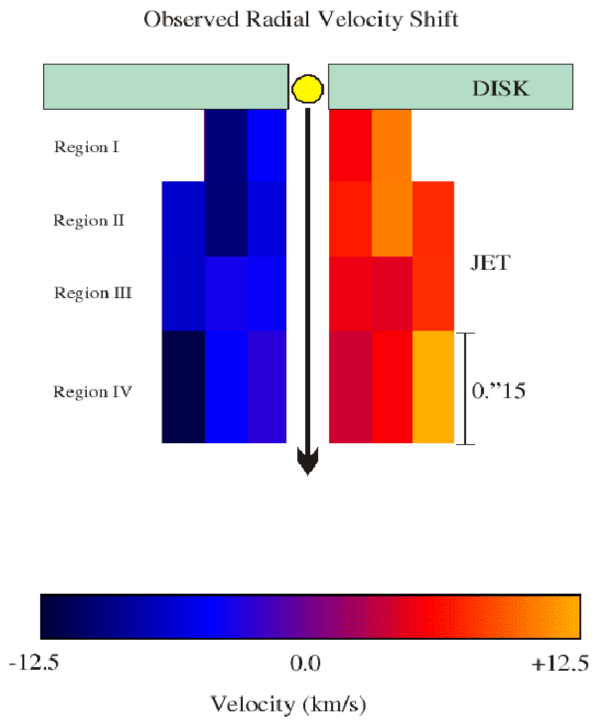


Results : velocity asymmetries

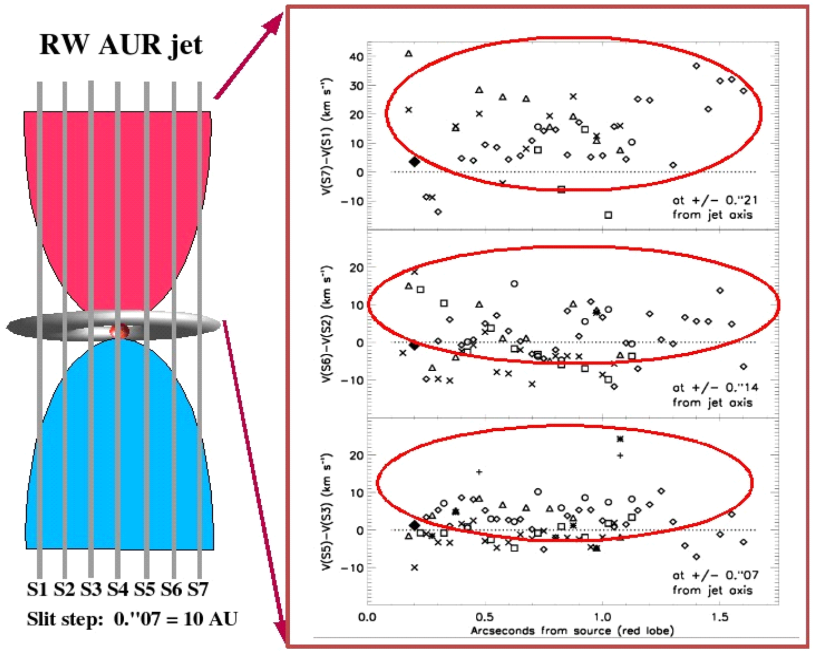


DG TAU

Bacciotti et al. 2002



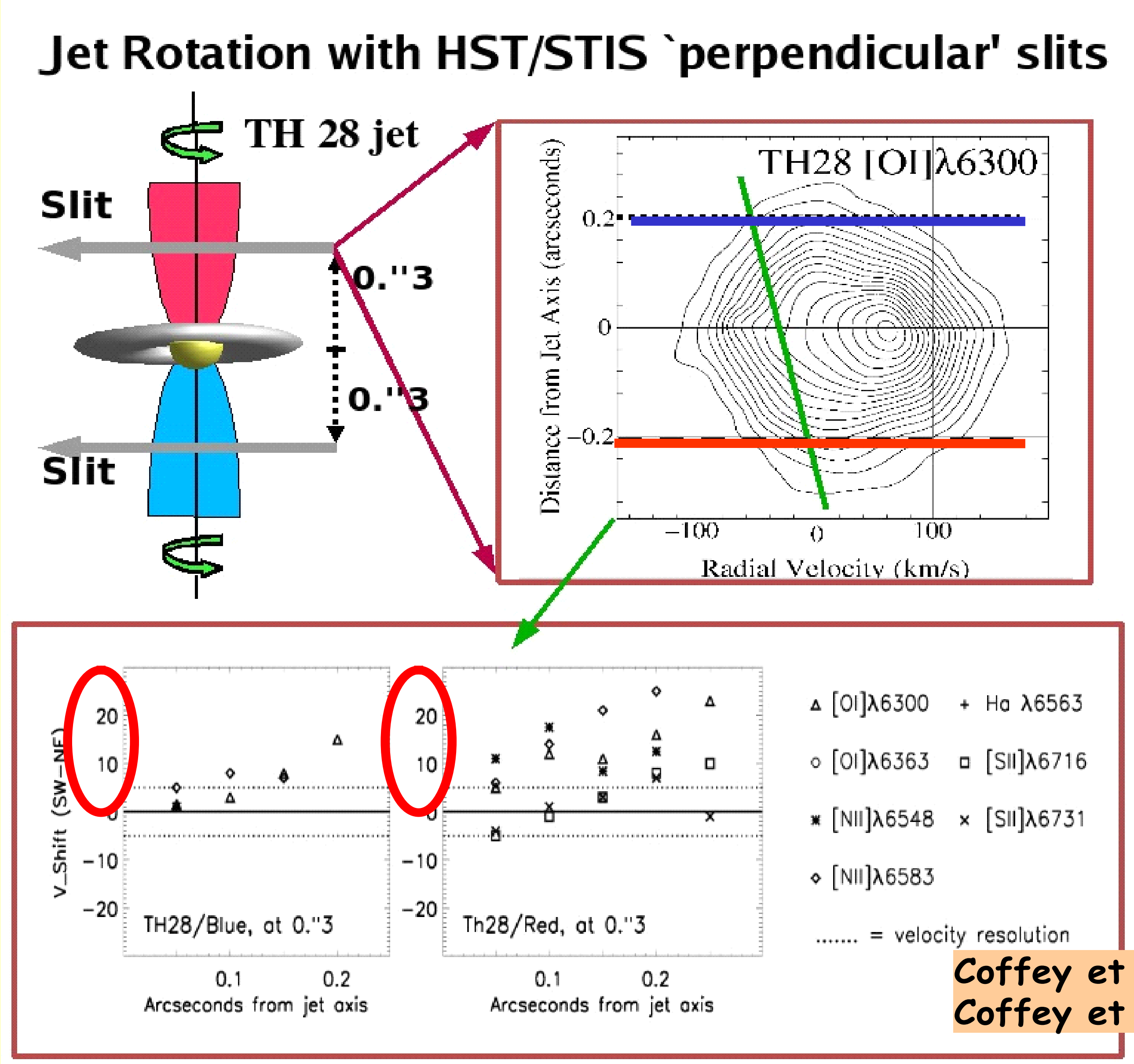
Jet Rotation with HST/STIS `parallel' slits

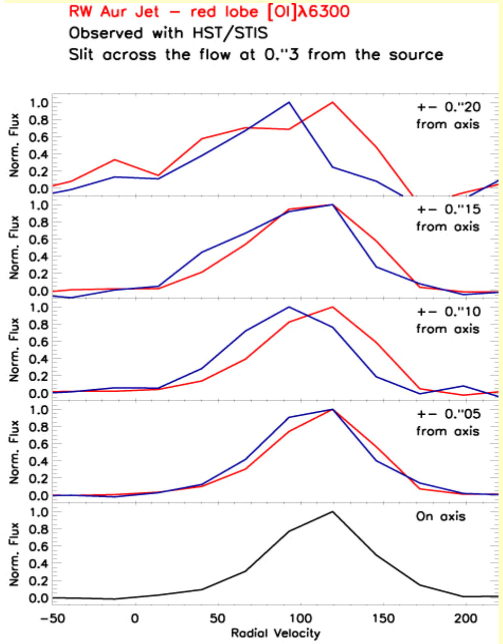


Woitas et al. 2002

RW AUR

Results : velocity asymmetries





Projected velocity shift

Coffey et al. 2004, Optical
Coffey et al. 2007, NUV

Velocity (km/s)

Implications for the jet launch

FROM MEASURED VELOCITY SHIFTS :

(Bacciotti et al. 2002
Anderson et al. 2003
Coffey et al. 2004, 2007
Pesenti et al. 2004
Woitas et al. 2005)

1. JETS DO EXTRACT EXCESS ANGULAR MOMENTUM !!!
AT LEAST FOR 60 – 70 %
→ role of disk viscosity in the inner disk ?

2. EXTENDED LAUNCHING REGION:
JET FOOTPOINTS: TO 0.5-4 AU FROM STAR
→ disk winds ..
but X-winds may be inside

3. MAGNETIC FIELD CAN COLLIMATE THE JET
$B_\phi/B_p \sim 4 - 8$
Toroidal field dominant →
hoop stress pushes jet toward the axis

Implications for the jet launch

FROM MEASURED VELOCITY SHIFTS :

(Bacciotti et al. 2002
Anderson et al. 2003
Coffey et al. 2004, 2007
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Woitas et al. 2005)

1. JETS DO EXTRACT EXCESS ANGULAR MOMENTUM !!!
AT LEAST FOR 60 – 70 %
→ minor role of disk viscosity in the inner disk

2. EXTENDED LAUNCHING REGION:
JET FOOTPOINTS UP TO 0.5-4 AU FROM STAR
→ disk winds favoured
but X-winds may be inside

3. MAGNETIC FIELD CAN COLLIMATE THE JET
$B\phi/Bp \sim 4 - 8$
Toroidal field dominant →
hoop stress pushes jet toward the axis

Implications for the jet launch

FROM MEASURED VELOCITY SHIFTS :

(Bacciotti et al. 2002
Anderson et al. 2003
)7

Is this the long awaited-for

observational validation of

Magneto-centrifugal
jet acceleration ?

Questioning jet rotation

Is the rotation interpretation correct ?

- Alternative interpretation proposed:
  asymmetric bow shocks, jet precession (Cerqueira et 2006)
-At least one disk rotating in the opposite sense (Cabrit et al. 2006)
- Instruments pushed to the limits

More statistics needed…

test rotation in: more targets,

bipolar lobes,

associated disks,

different telescopes

different wavelenght ranges

next talk by Deirdre Coffey !!

Conclusions

- Impressive wealth of information from high angular resolution
- Observations apparently validate magneto-centrifugal launch
- Jet properties similar for different masses of central object
- Need to Increase number of targets observed with HAR
- model comparisons needed (Synthetic maps)
- Future: Space Missions (post-SM4 HST, JWST, Herschel ..)

  Interferometry (if sensistivity problems solved)

  ALMA