HERSCHEL/PACS observations of young (Class II) sources driving outflows

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and the GASPS team

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Outline:

Introduction: accretion/ejection process in YSO

role of stellar jets in the star formation process
theoretical models for jet launch
jets observational properties
Multi-λ studies: importance & problems

First results from GASPS/PACS data:

FIR maps of outflow from Class II sources (DG Tau B, DG Tau, RW Aur, T Tau, RY Tau, ...)

Extended, velocity-shifted emission in atomic and/or molecular lines

Estimate of mass flux rate > mass ejection/mass accretion

Open issues:

Desentangling jet/disk emission in the central spaxel

OI63-cont in jet and non-jet sources

Line ratios

HIFI observations > velocity resolved line profiles

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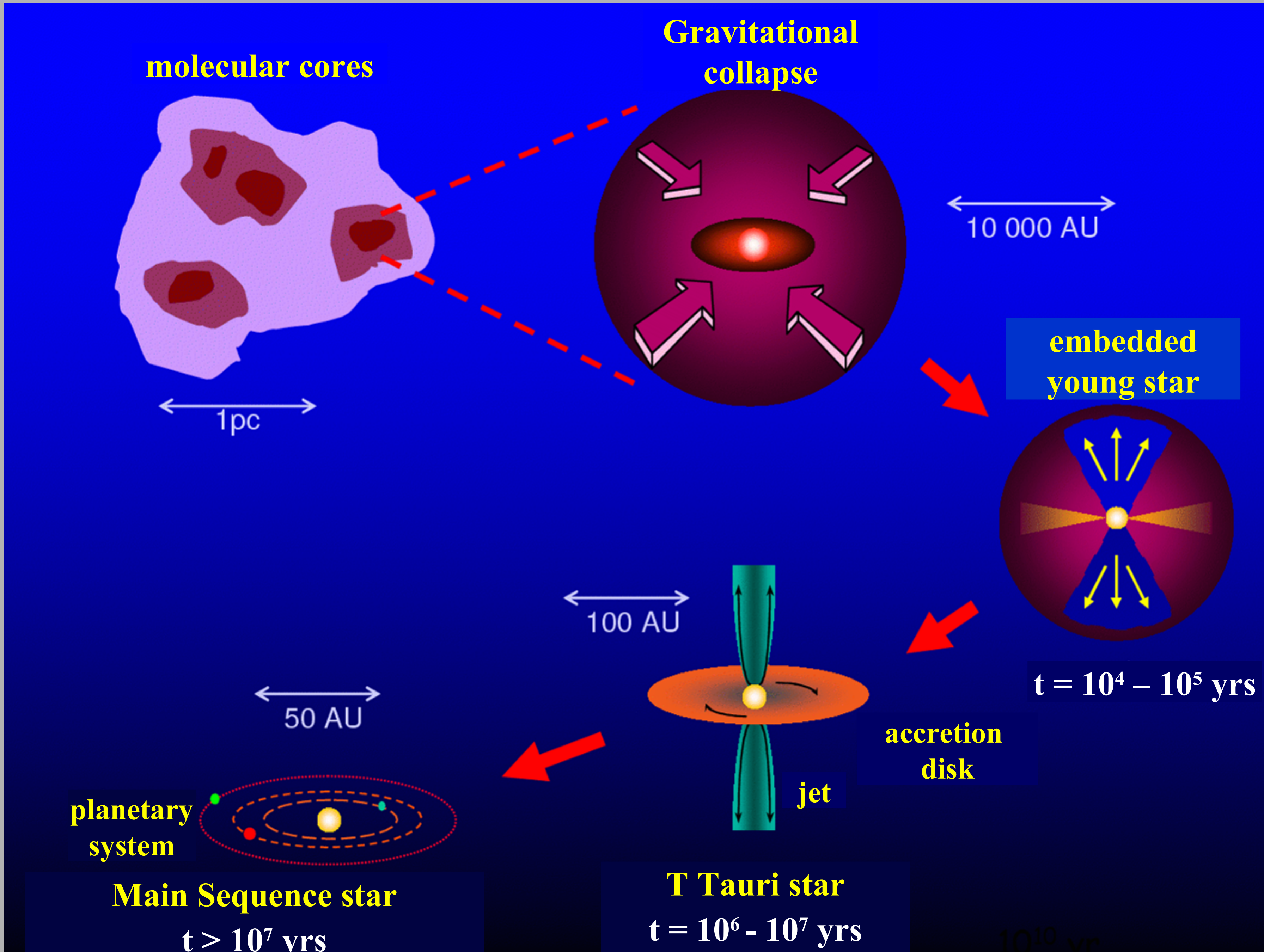
- HIFI observations > velocity resolved line profiles

Accretion/ejection in the star formation process



Why studying stellar jets ?

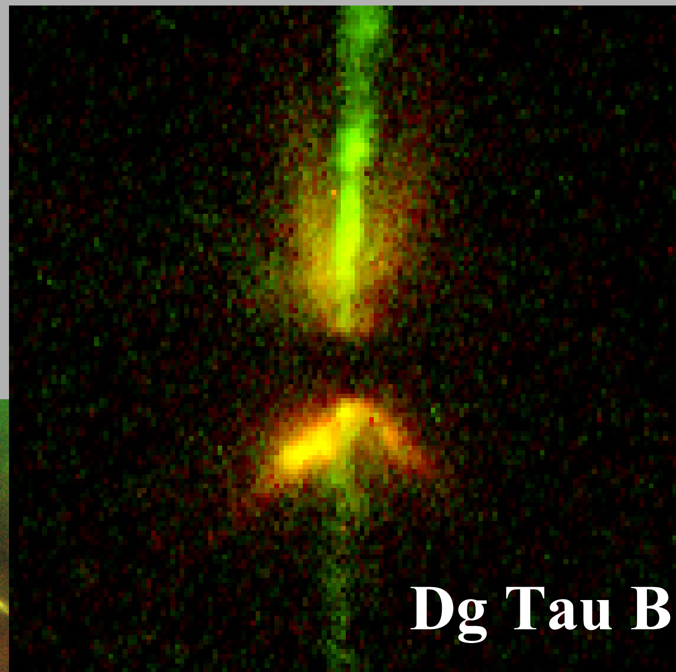
The existence of HH jets may help to justify:

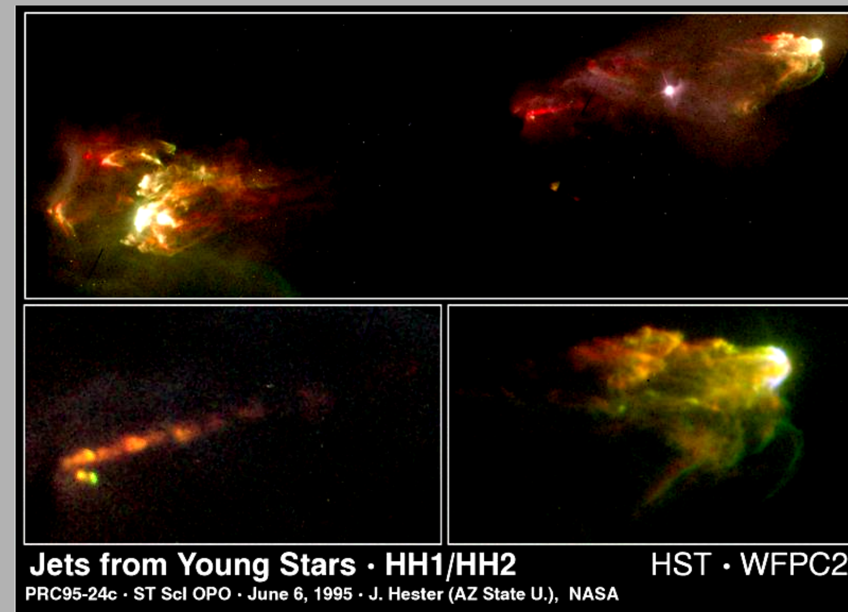
- *Removal of excess angular momentum*
- Dispersion of infalling envelope
- Injection of turbulence for cloud support ?

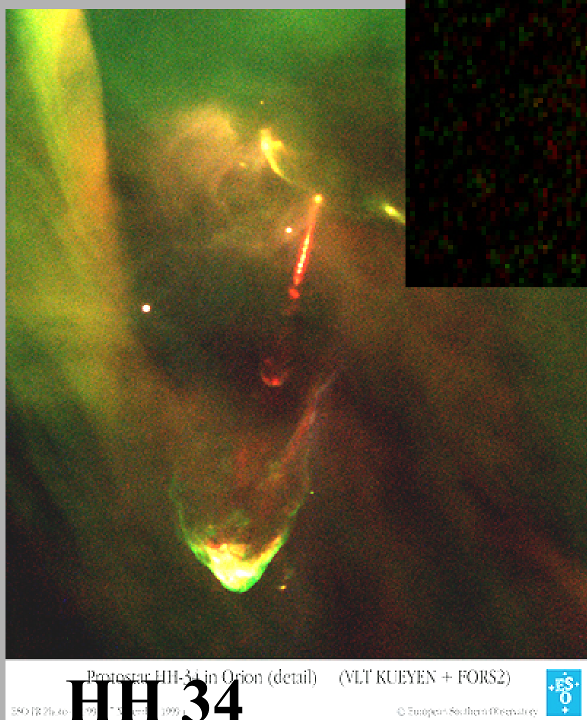
Other interesting issues:

- Jet structure traces past events in star/disk system
- Space laboratory for shock physics/chemistry
- Study of embedded sources
- Similarity with AGN jets

Properties of jets from young stars...







Association with accretion disk

Often bipolar, but asymmetric - perpendicular to disk plane - knotty

Observed Width: 10 - 200 AU

Observed Length : a few hundreds AU to a few pc

high speed: V_J = 100 - 400 km/s

highly supersonic: M= V_J/C_S~10-30, but mild shocks Vs ~30 – 70 km/s

Models for jet formation

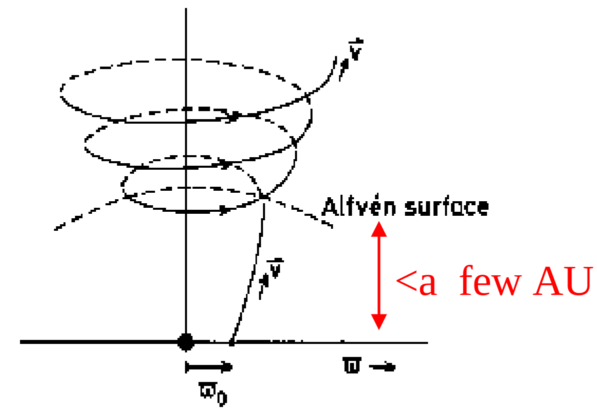


Figure 1.3: Development of the azimuthal field. With each rotation of the field line a loop of field is added to the flow at the Alfvén surface.

to produce a fast collimated jet one needs
an accretion disk + magnetic field

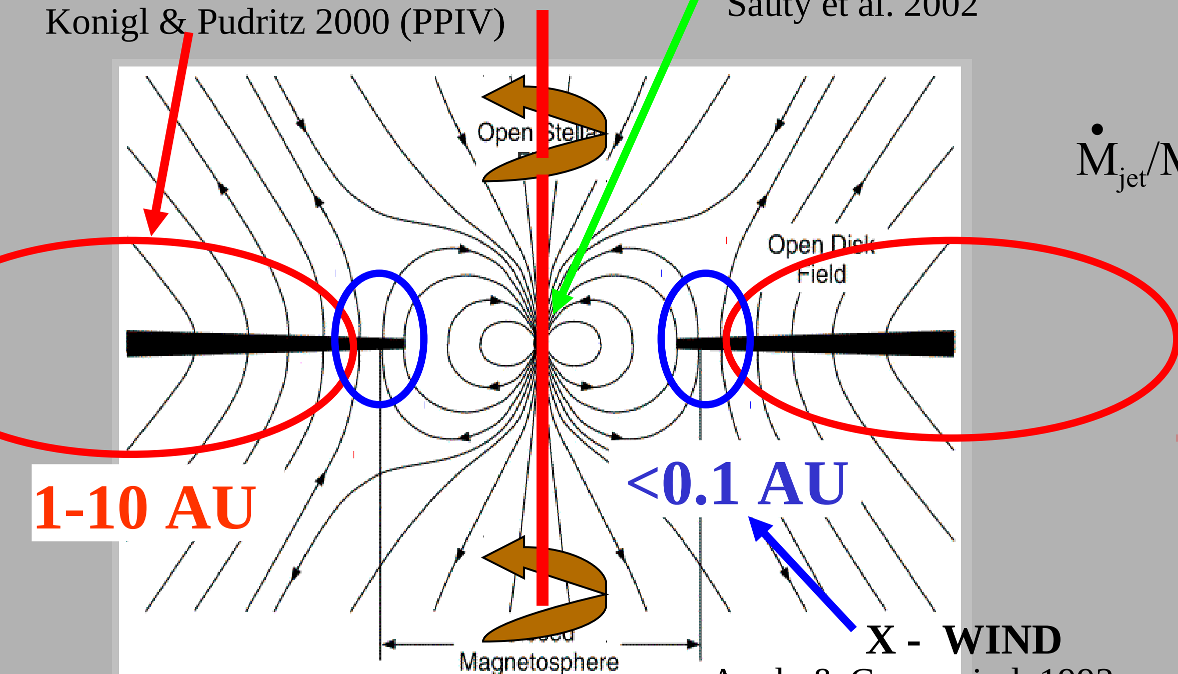
Magneto-centrifugal process

DISK WIND

Blandford & Payne 1982
Ferreira 1997
Konigl & Pudritz 2000 (PPIV)

STELLAR WIND

Sauty et al. 2002



X - WIND

Apple & Camenzind 1993
Shu et al. 1994, 1995, 1998, 2000 (PPIV)

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

MASS FLUX RATE = $\dot{M}_{jet}$
to understand
accretion/ejection interplay

Observational properties of jets & outflows

optical | **NIR** | **MIR** | **FIR** | **(sub-) mm**

0.3µm — 0.6 µm — 2.5µm

Hα, [SII], [OI], [NII], [CaII], [FeII], [OII], [CI], [SIII], [OIII]

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

H_2, [FeII], [SiII], [SI] ...

H_20, H_2, H_2S, high-J CO, OH, [CII] 158 um, [OI]63um, 145 um

CO, CS, SiO, SO

hot, partially ionized gas:
$T \sim 10^4$ K
Xe~0.01-0.6

warm gas:
T~100-5000 K

cold gas:
T~10-100 K

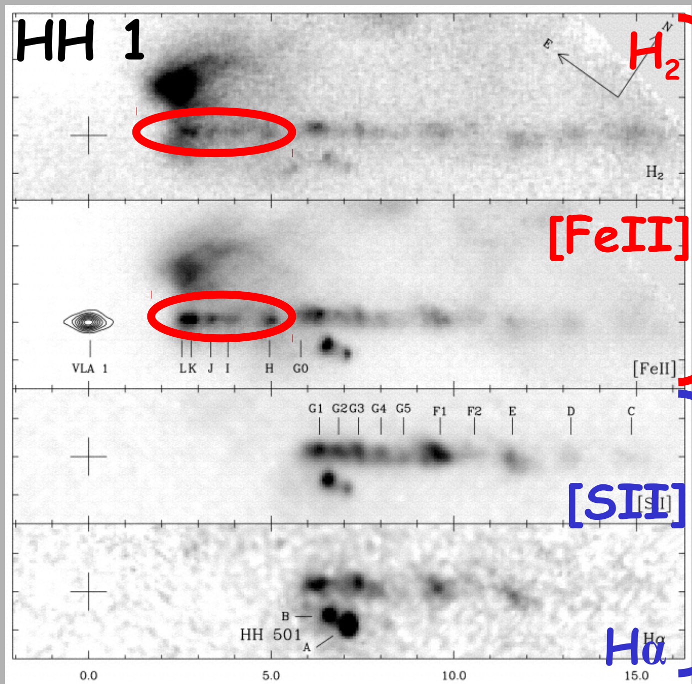
telescopes from ground (ESO, KECK)
telescopes from space (HST)
interferometer (VLTI/AMBER)

telescopes from space
SPITZER (MIR)
HERSCHEL (FIR)

mm telescopes,
interferometers
SMA
IRAM
ALMA

The importance of multi-wavelengths analysis

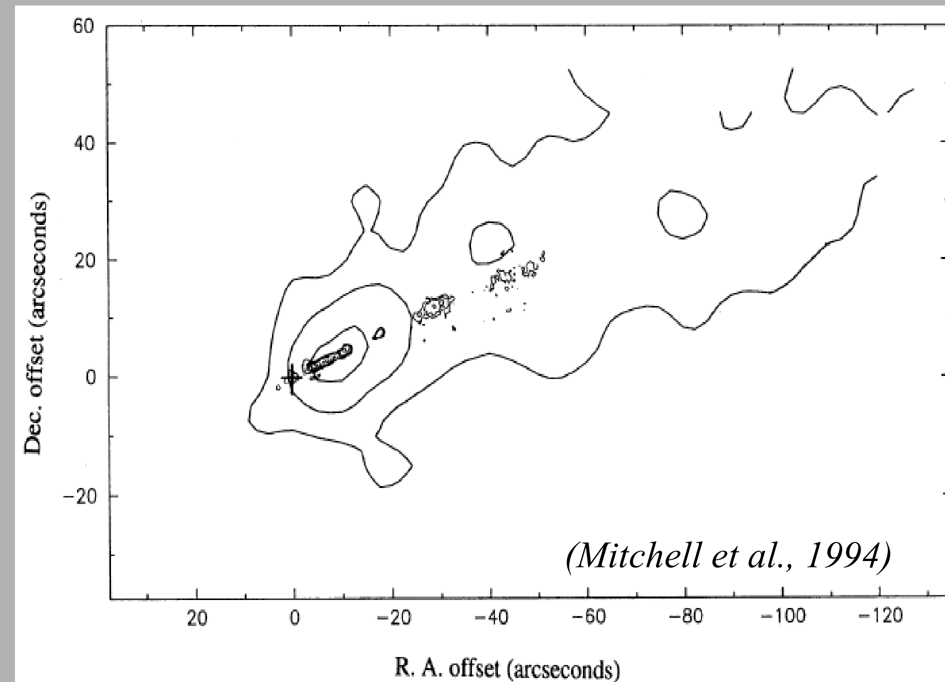
(Reipurth et al., 2000)



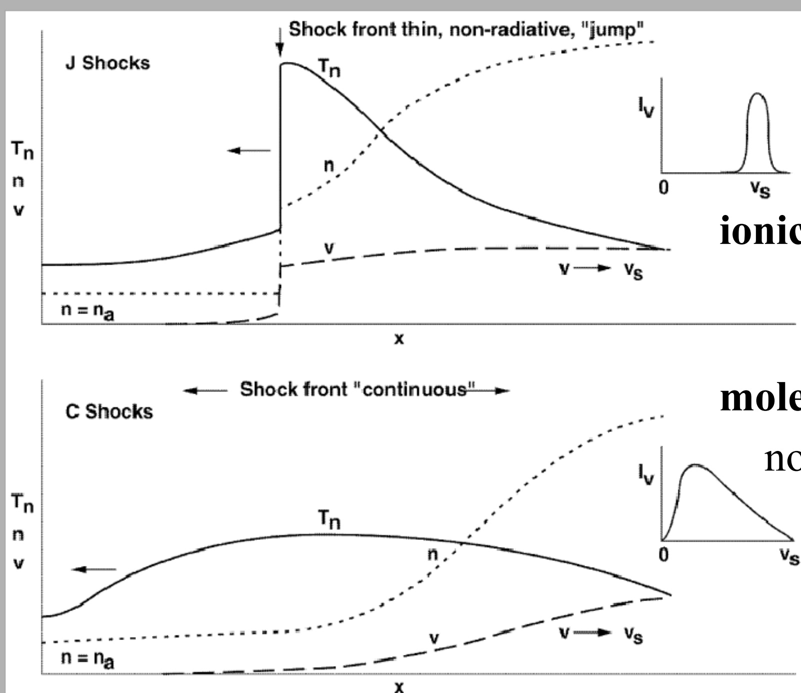
IR lines

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

optical lines



(Mitchell et al., 1994)



(Hollenbach et al., 1997)

ionic and atomic lines:

dissociative **J-shocks**

molecular H_2 emission

non-dissociative **C-shocks**

collimated optical jet

\+

molecular outflow

Comparison of observations taken at different lambda (e.g., optical/NIR and FIR obs) IS NOT EASY !

1. ANGULAR/SPECTRAL RESOLUTION PROBLEM

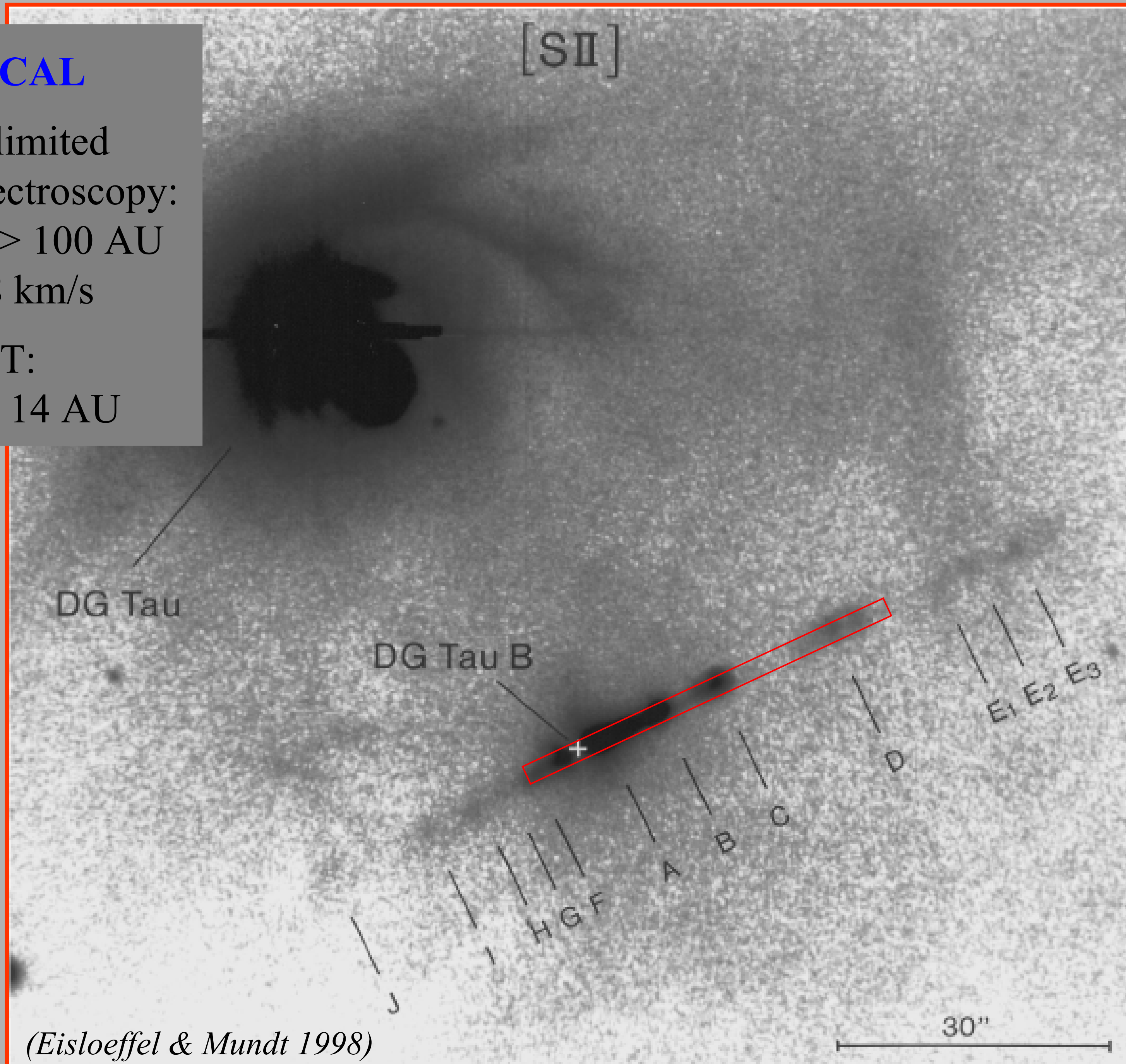
2. SENSITIVITY PROBLEM

1. ANGULAR/SPECTRAL RESOLUTION PROBLEM

OPTICAL

seeing-limited imaging/spectroscopy:
~ 0.6-0.8” > 100 AU
Dv ~ 8 km/s

HST:
~ 0.1” > 14 AU



(Eisloeffel & Mundt 1998)

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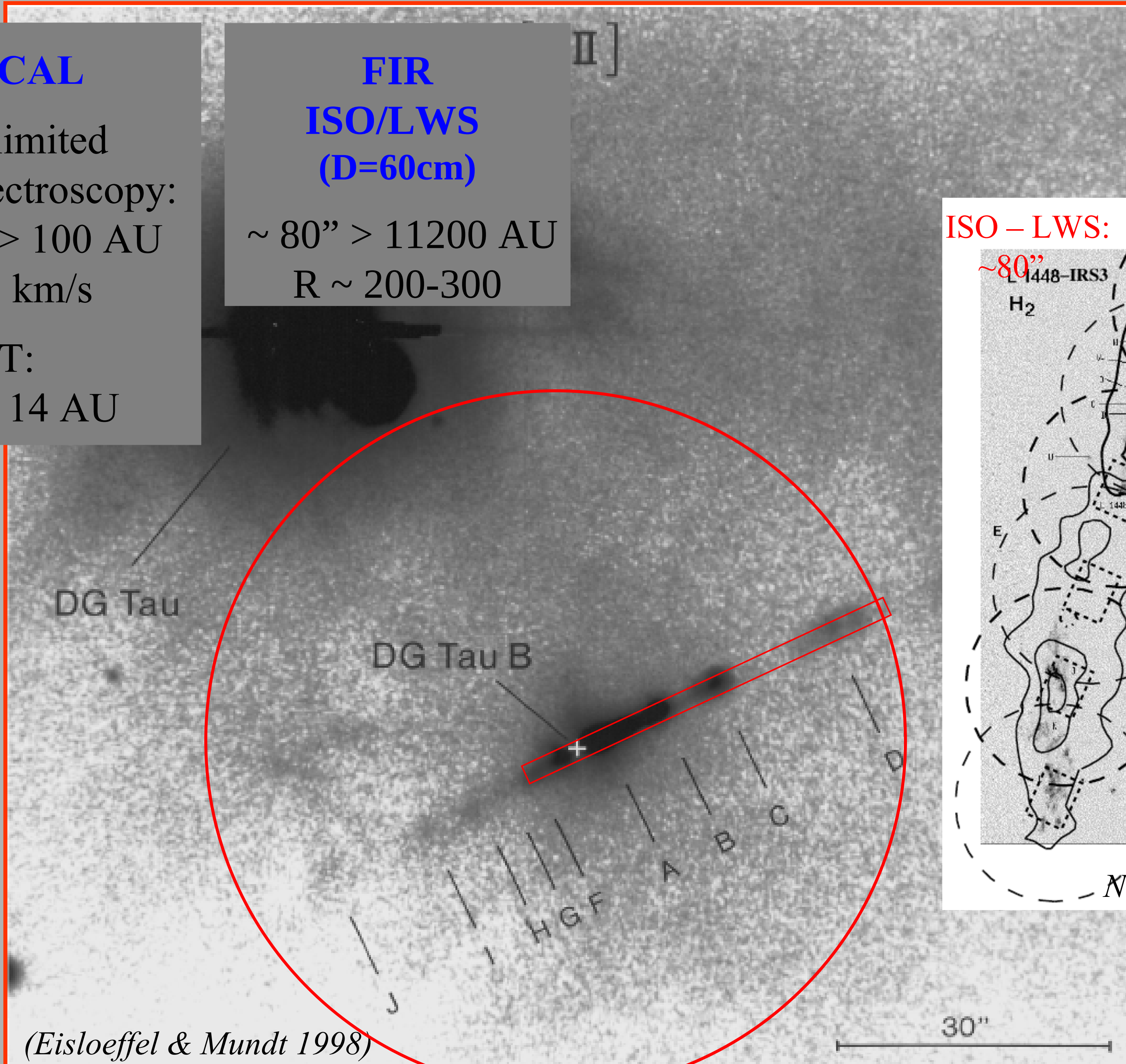
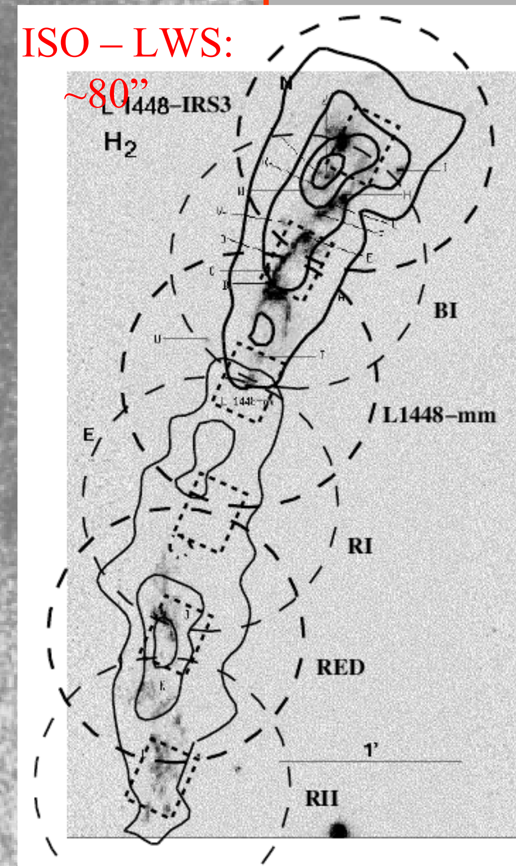
FIR
ISO/LWS
(D=60cm)

~ 80” > 11200 AU
R ~ 200-300



(Eisloeffel & Mundt 1998)



Nisini et al. 2000

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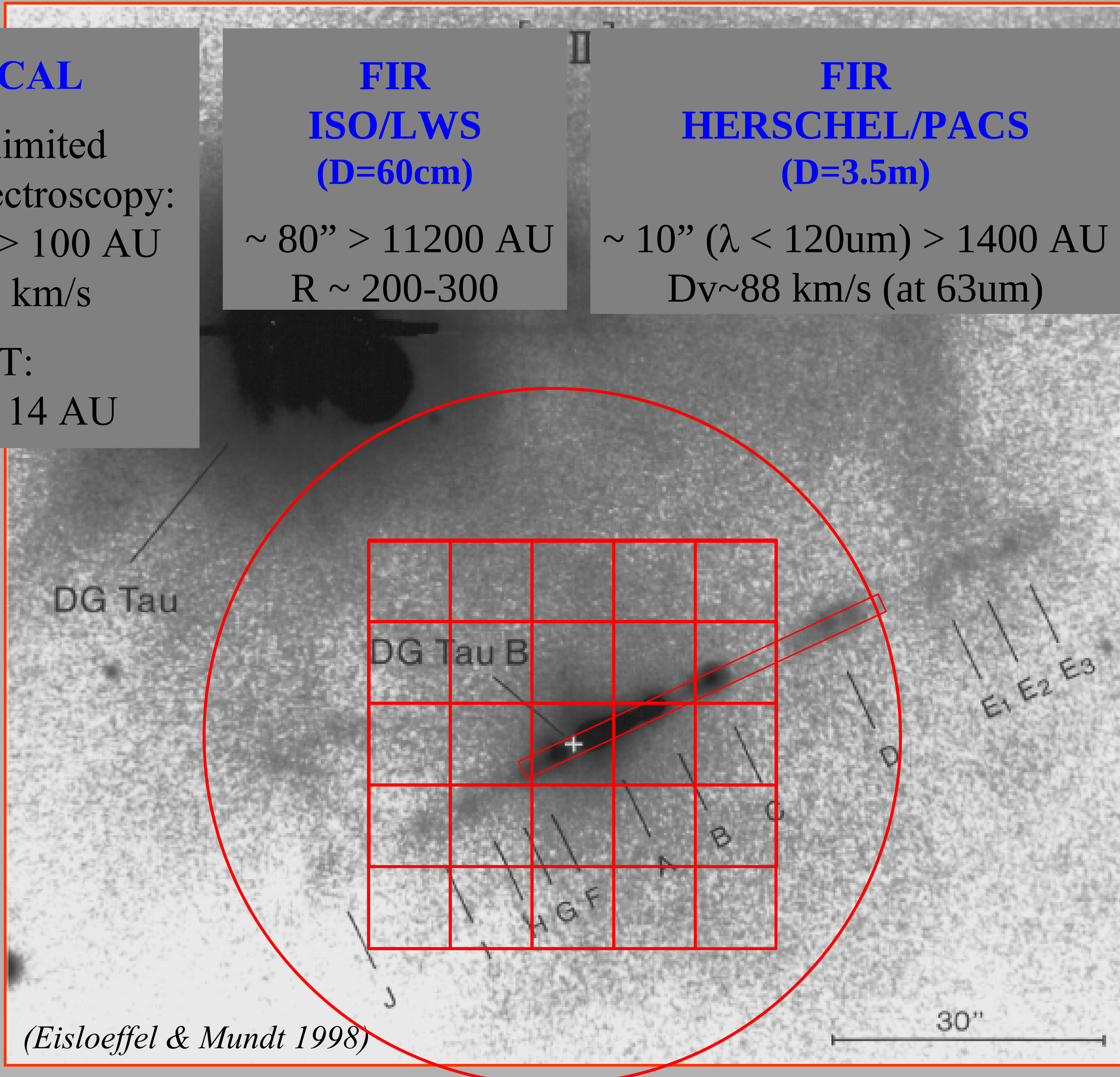
FIR
HERSCHEL/PACS
(D=3.5m)

~ 10" (λ < 120um) > 1400 AU
Dv~88 km/s (at 63um)



(Eisloeffel & Mundt 1998)

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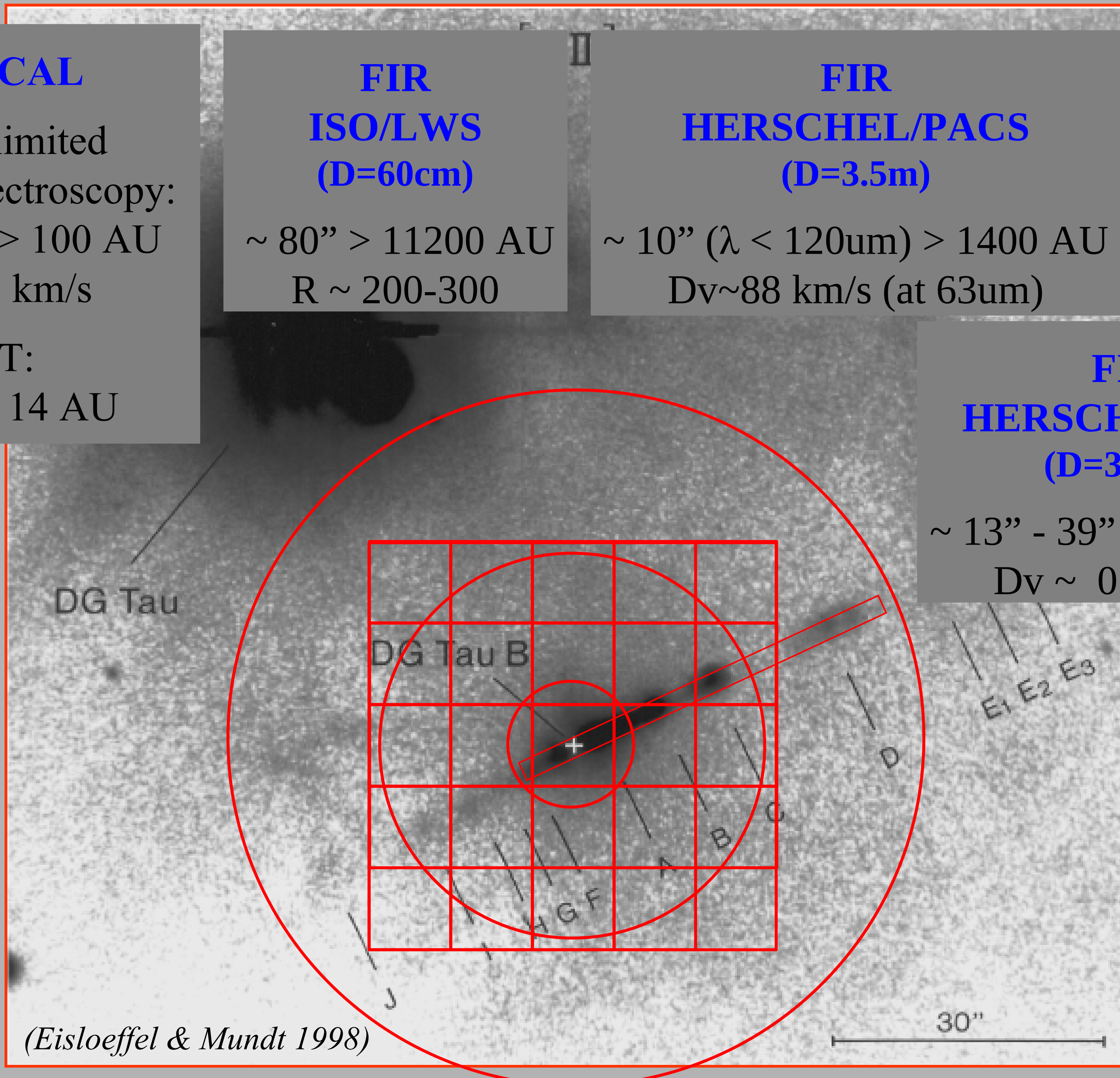
FIR
HERSCHEL/HIFI
(D=3.5cm)

~ 13” - 39” > 1-6e3 AU
Dv ~ 0.01 km/s

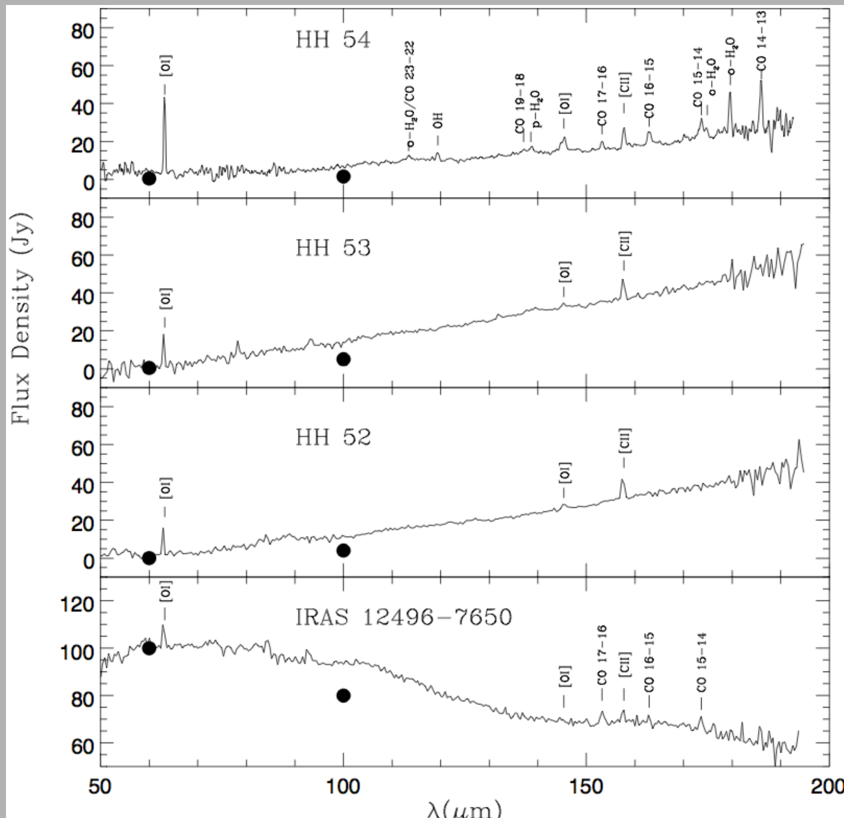


(Eisloeffel & Mundt 1998)

2. SENSITIVITY PROBLEM

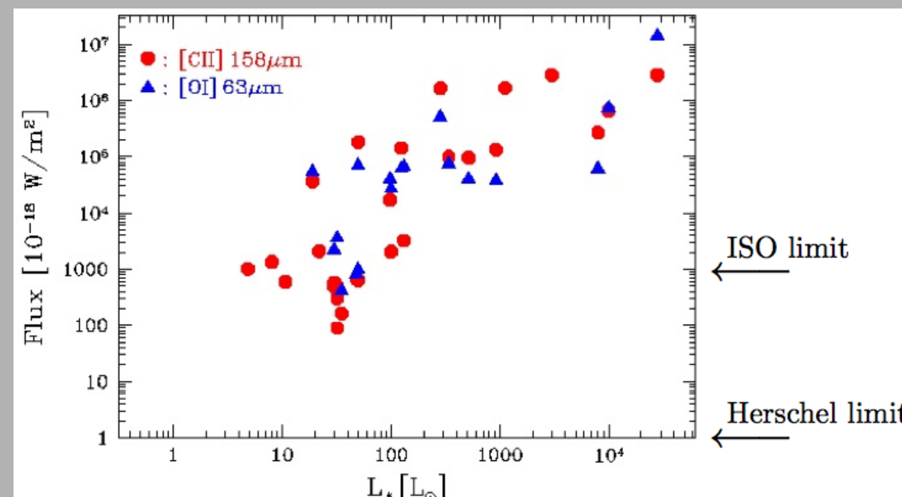
ISO/LWS (D=60cm): 1e-15 W/m^2 → ***jets from Class 0/I***

Class 0/I ISO spec (Nisini et al. 1996)



Nisini et al. 1996, 1999, 2000
Molinari et al. 2001
Ceccarelli et al. 1997
+ T Tau (Spinoglio et al. 2000)

Herbig Ae/Be, ISO fluxes (Lorenzetti et al. 2002)



HERSCHEL/PACS (D=3.5m): 1e-18 W/m^2 → ***jets from Class II***

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GASPS: GAS evolution in Protoplanetary System (PI: B. Dent)

Survey of atomic/molecular gas and dust in ~ 200 disks
wide range of ages: 1-30 Myr
disk masses: $10^{-2} – 10^{-5}$ Msol
not young/embedded sources: Class II/III
spectral types (A to M)
Nearby star-forming regions (Taurus, ηCha, βPic, Herbig Ae/Be, ...): d ~100-200 pc

Setting	Grating order	Species	Transition	Wavelength (μm)	E_{upper} (K)
A	3	**[OI]**	**3P1-3P2**	**63.184**	**228**
	1	DCO^+	J=22-21	189.570	874
B	2	**H_2O**	**o 4-23 - 3-12**	**78.741**	**432**
	2	OH	1/2 - 3/2 hfs	79.11/79.18	182
	2	CO	J=33-32	79.360	3092
	1	**[CII]**	**2P3/2 - 2P1/2**	**157.741**	**91**
	1	H_2O	p 3-31 - 4-04	158.309	410
C	2	H_2O	p 3-22 - 2-11	89.988	297
	2	CO	J=29-28	90.163	2400
	1	**H_2O**	**o 2-12 - 1-01**	**179.527**	**115**
	1	CH+	J=2-1	179.610	
	1	H_2O	o 2-21 - 2-12	180.488	194
D	2	CO	J=36-35	72.843	3700
	1	H_2O	p 4-13 - 3-22	144.518	396
	1	CO	J=18-17	144.784	945
	1	**[OI]**	**3P0 - 3P1**	**145.525**	**326**

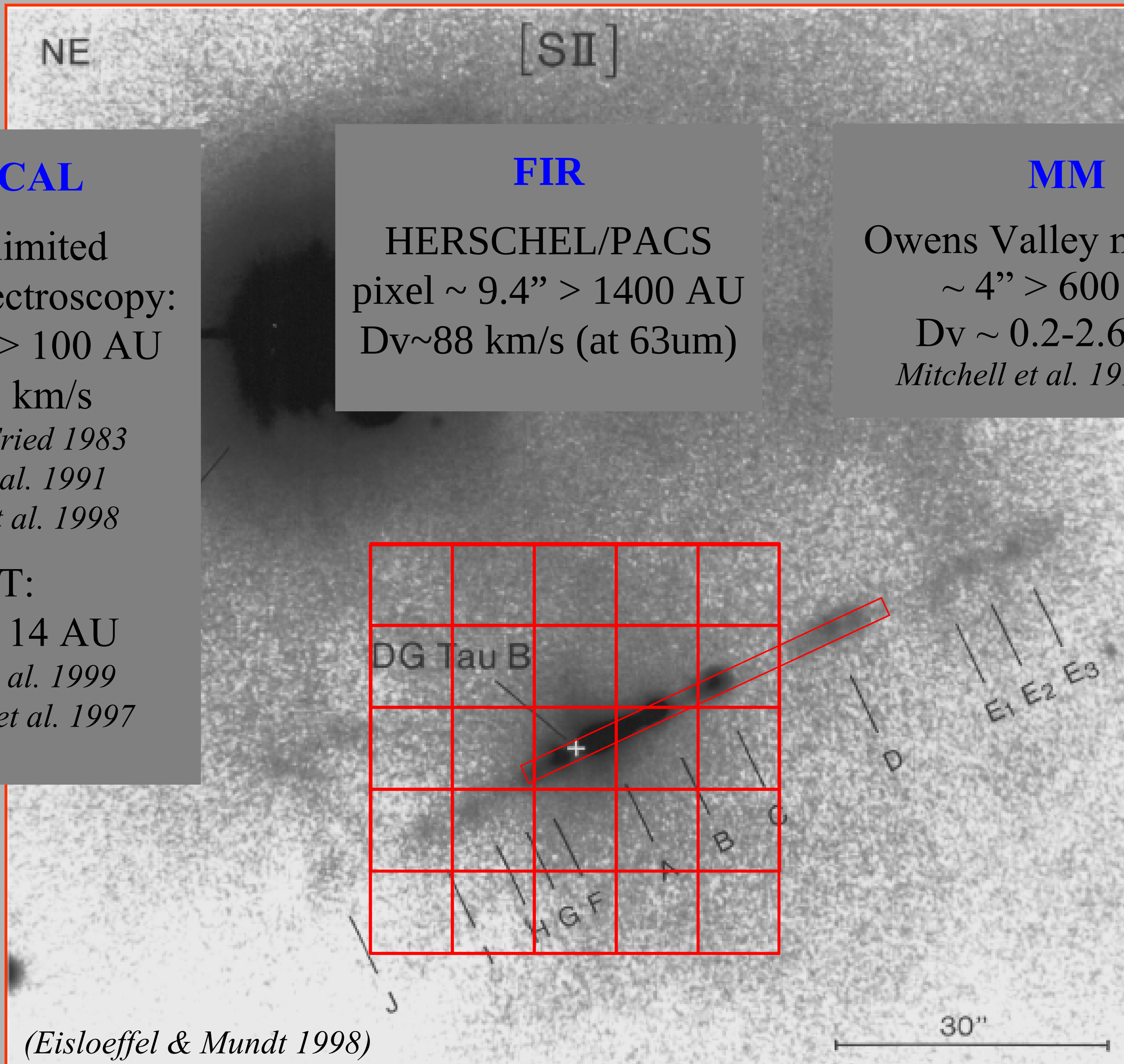
MOLECULAR LINES: H_2O, OH, high-J CO (J ≥ 18)

ATOMIC LINES: [OI] 63, 145 um, [CII] 158 um

- ***GAS in the JET***
- ***GAS in the DISK***

the GASPS survey includes
a number of well-known jet sources:
Taurus CTTSs (i.e., Class II)
associated to bright optical jets
which have never been studied at FIR wavelengths!

A multi-wavelength study of DG Tau B



(Eisloeffel & Mundt 1998)

OPTICAL

seeing-limited imaging/spectroscopy:
~ 0.6-0.8" > 100 AU
Dv ~ 8 km/s
Mundt & Fried 1983
Mundt et al. 1991
Eisloffel et al. 1998

HST:
~ 0.1" > 14 AU
Padgett et al. 1999
Stapelfeldt et al. 1997

FIR

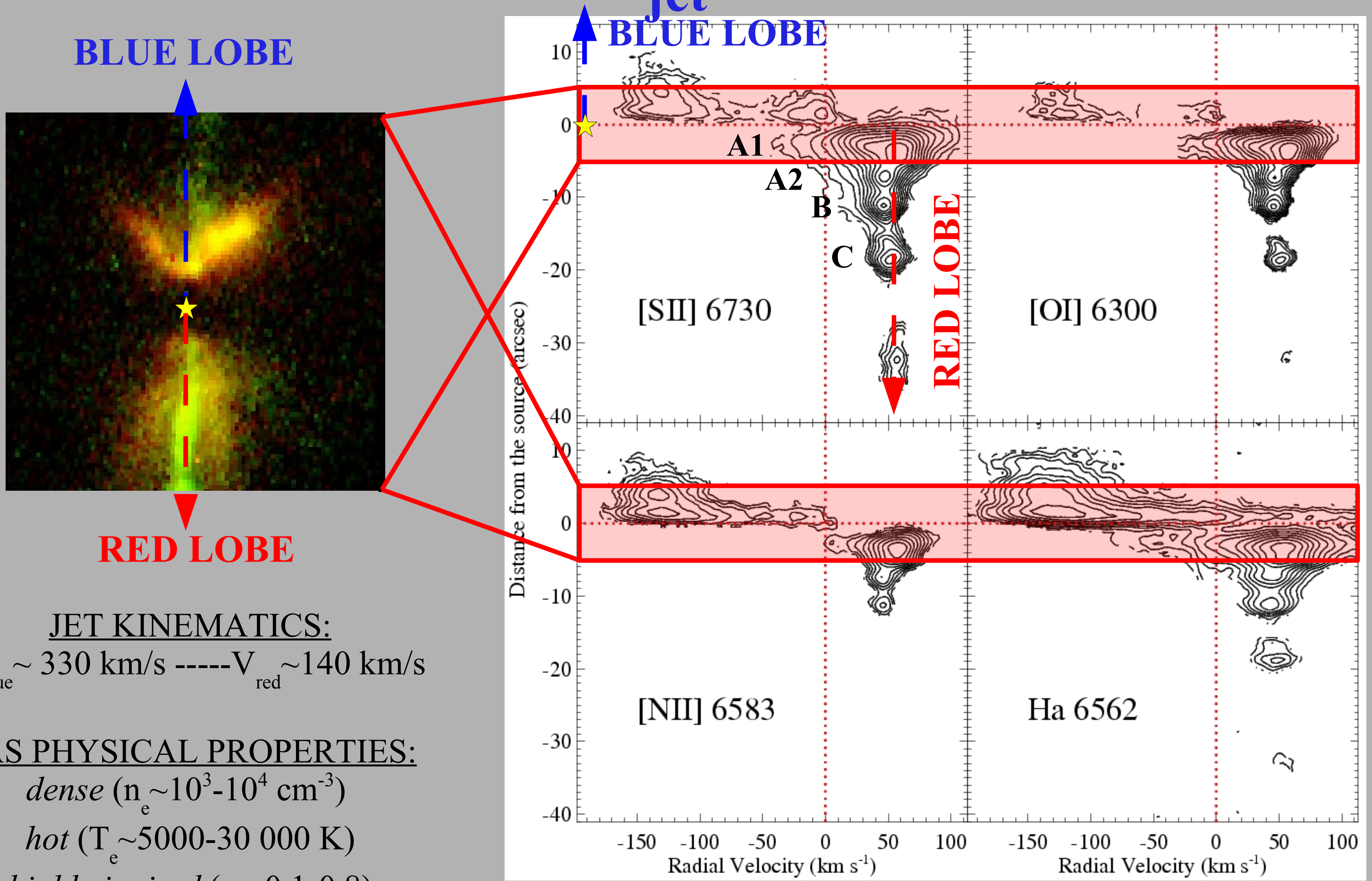
HERSCHEL/PACS
pixel ~ 9.4" > 1400 AU
Dv~88 km/s (at 63um)

MM

Owens Valley mm array
~ 4" > 600 AU
Dv ~ 0.2-2.6 km/s
Mitchell et al. 1994, 1997

OPTICAL observations > HOT, high-velocity, collimated atomic jet

HST IMAGING: WFPC2 + NICMOS (~0.1”):
(Stapelfeldt et al. 1997, Padgett et al. 1999)



KECK-HIRES SPEC STUDIES (~0.8”, Dv~8 km/s)
(Podio, Eisloffel et al., in prep)

<u>JET KINEMATICS:</u>

V_{blue} ~ 330 km/s -----V_{red} ~140 km/s

<u>GAS PHYSICAL PROPERTIES:</u>

dense (n_e~10^3-10^4 cm^{-3})

hot (T_e~5000-30 000 K)

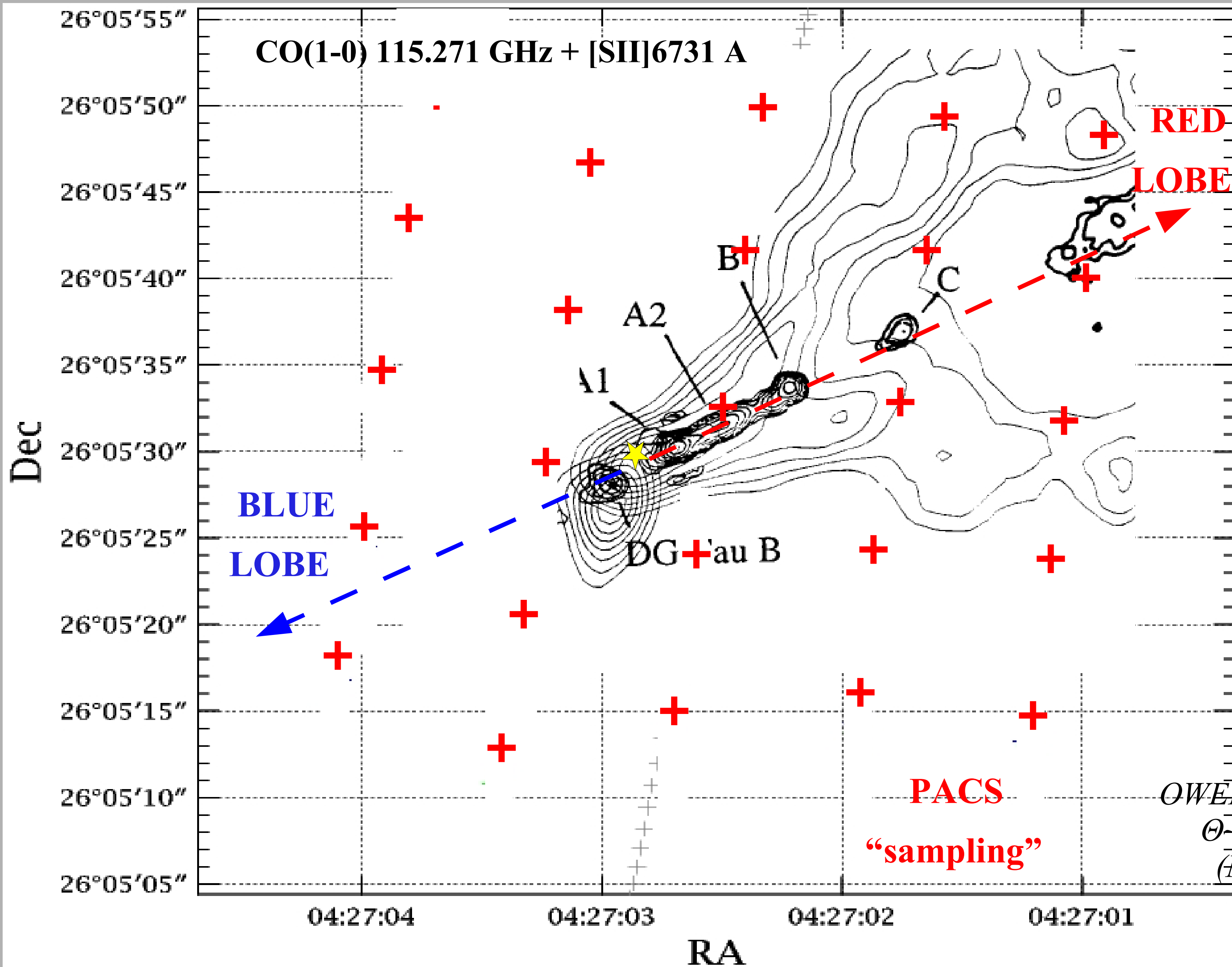
highly ionized (x_e~0.1-0.8)

<u>JET WIDTH (d < 5”):</u>

R_{blue} up to 100 AU ----- R_{red} ~ 50 AU

(Mundt et al. 1991, Stapelfeldt et al. 1999)

mm observations > COLD, molecular, wide-angle outflow



Strong correlation:
redshifted CO outflow
redshifted optical jet

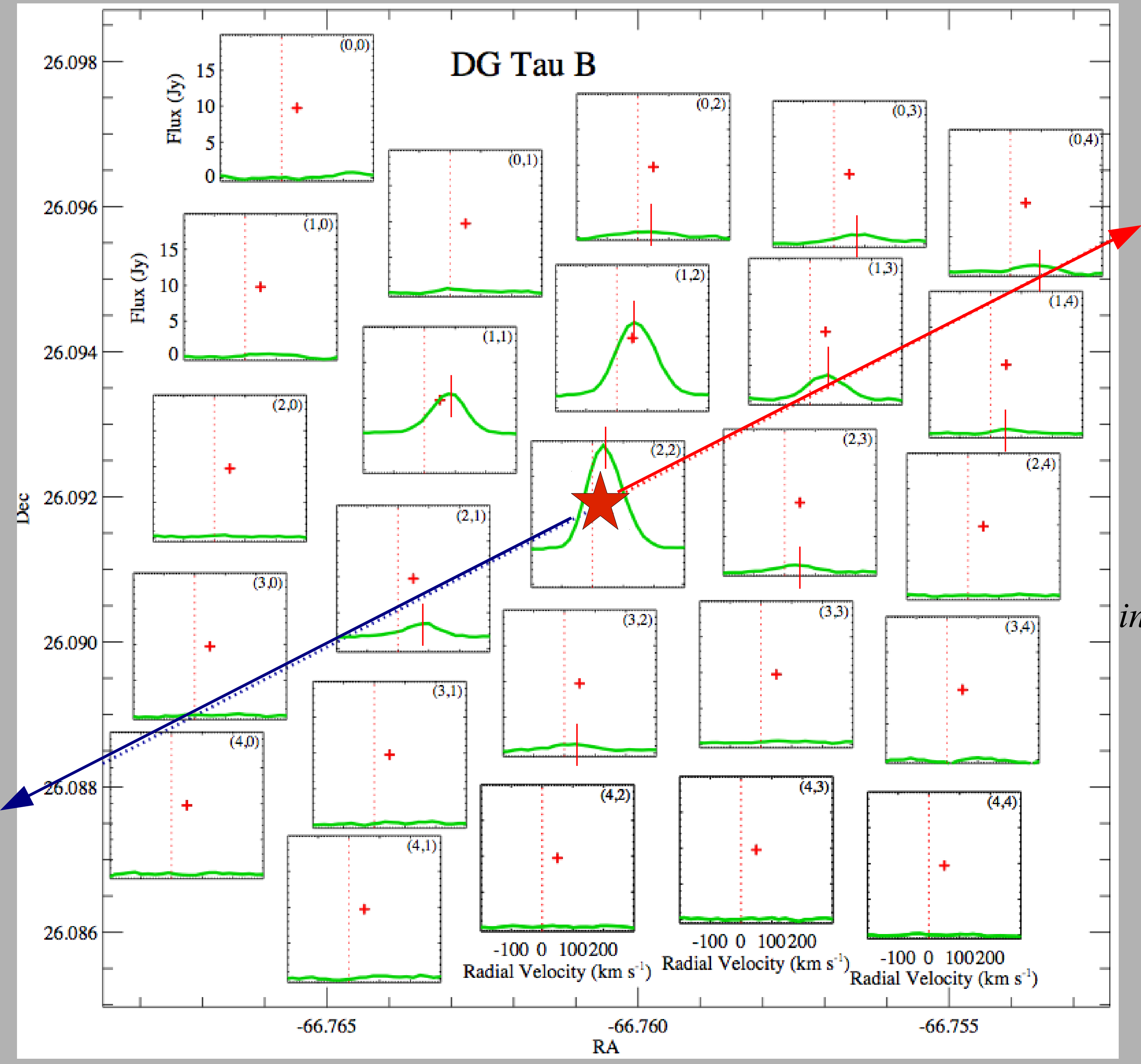
mm CO lines trace:
cold: T~50 K
slow: $V_{outflow}$~10 km/s

jet-driven outflow

momentum transported
by outflow
comparable to
jet momentum.
(P_{jet}~4 10^{-6} $M_{\odot}$ yr^{-1} km s^{-1})

OWENS VALLEY mm ARRAY
Θ~4", Dv~0.2-2.6 km/s
(Mitchell et al. 1997)

FIR observations > WARM component traced by [OI]63um



[OI]63um red-shifted emission well correlated to:

redshifed atomic jet (opt)

&

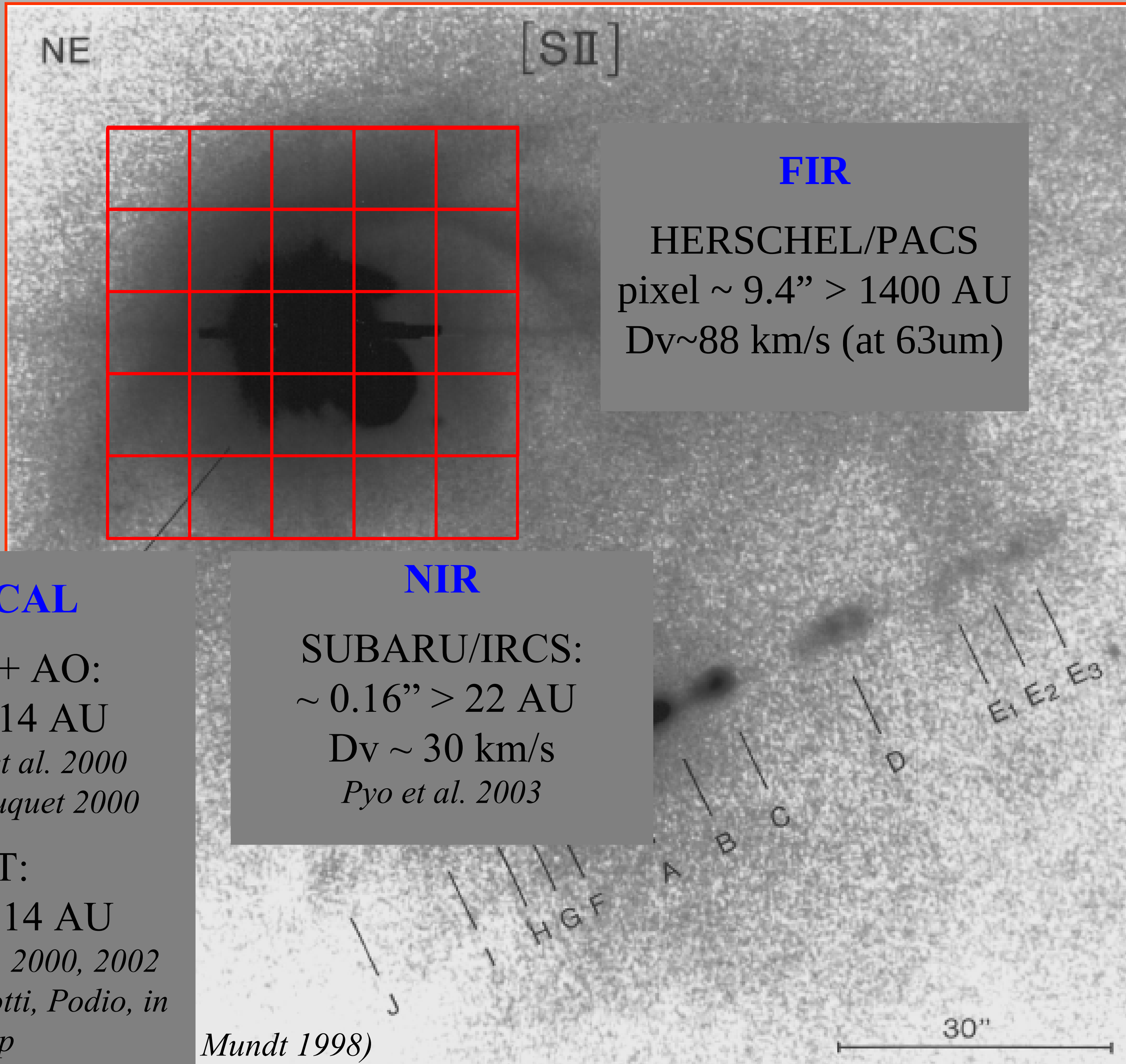
redshifted CO jet (mm)

[OI]63um line trace:

warm: T_{exc}~230 K

intermediate Vel: V~30-60 km/s

A multi-wavelength study of DG Tau



FIR

HERSCHEL/PACS
pixel ~ 9.4" > 1400 AU
Dv~88 km/s (at 63um)

OPTICAL

CFHW + AO:
~ 0.1" > 14 AU
Dougados et al. 2000
Lavalley-Fouquet 2000

HST:
~ 0.1" > 14 AU
Bacciotti et al. 2000, 2002
Maurri, Bacciotti, Podio, in prep

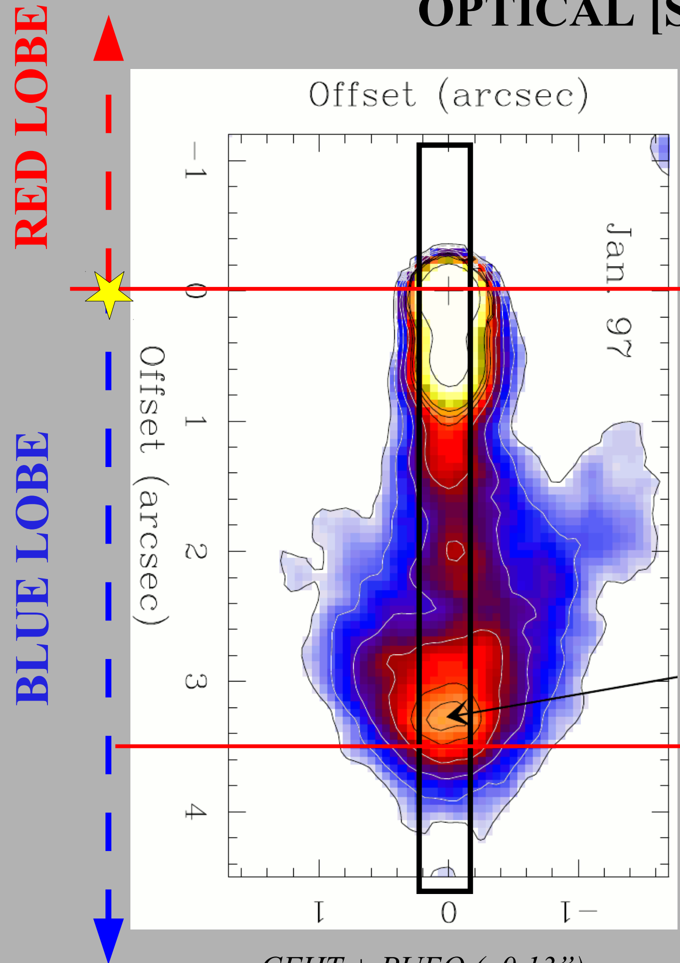
Mundt 1998)

NIR

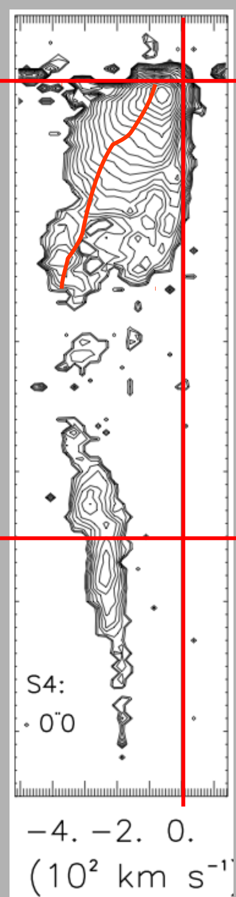
SUBARU/IRCS:
~ 0.16" > 22 AU
Dv ~ 30 km/s
Pyo et al. 2003

OPTICAL observations > HOT, high-velocity, collimated atomic jet

OPTICAL [SII]6731 A

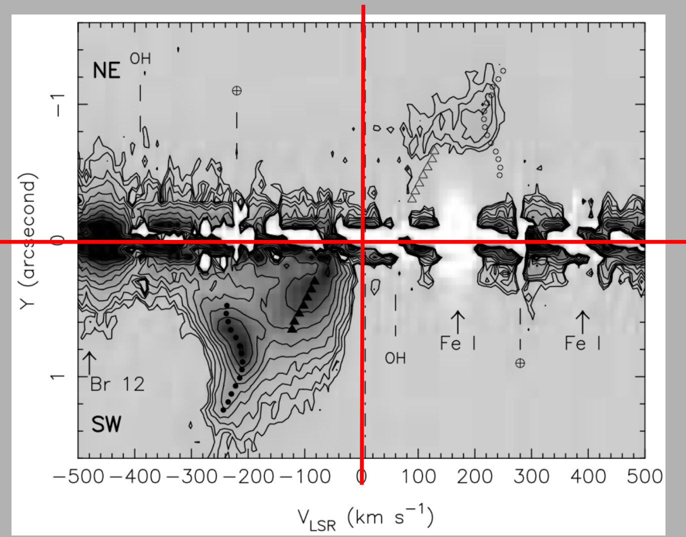


CFHT + PUEO (~0.13"):
(Dougados et al. 2000)



HST /STIS (~0.1", Dv~50 km/s):
(Maurri, Bacciotti, Podio, in prep)

NIR [FeII]1.64um



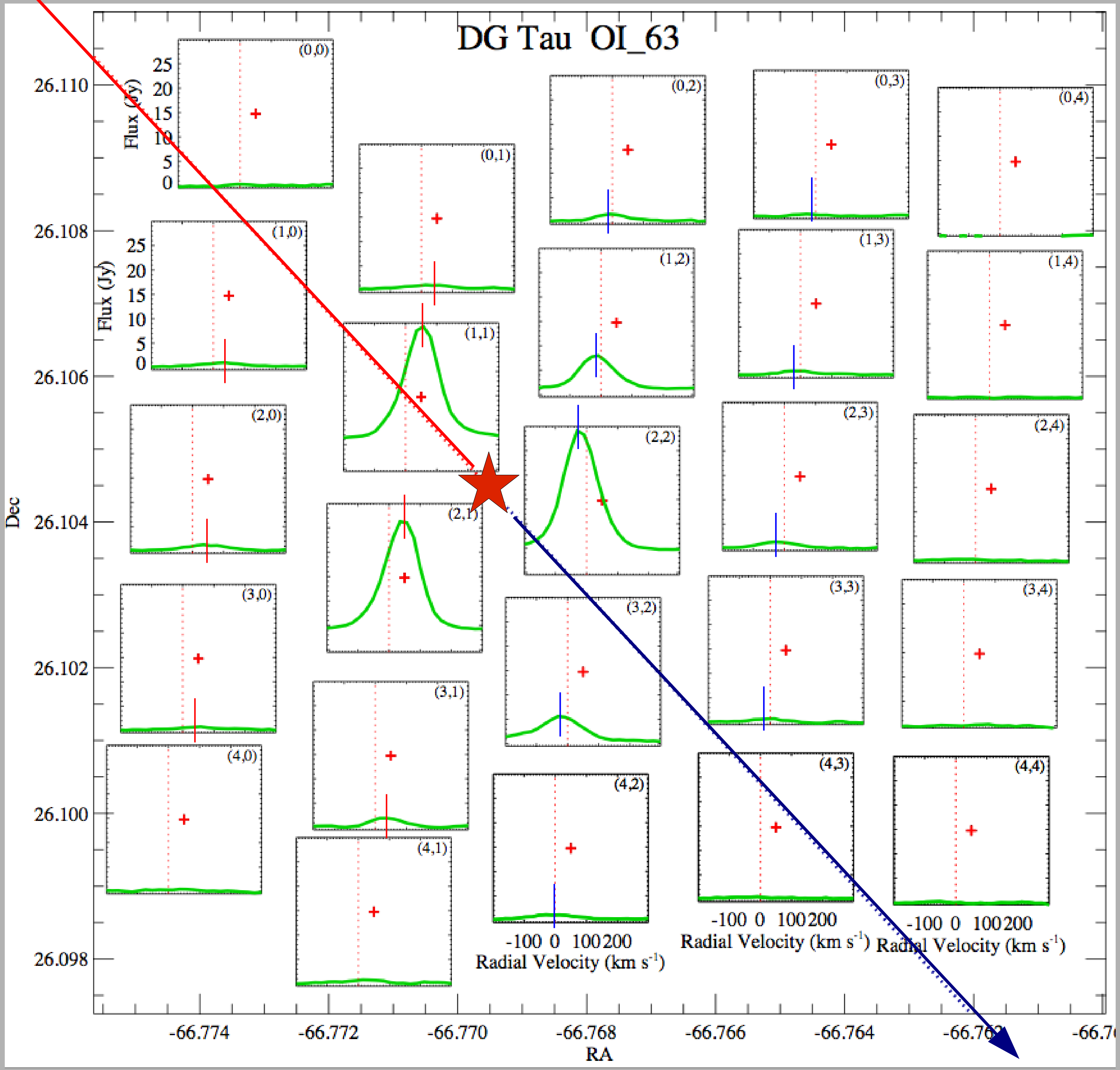
SUBARU/IRCS (~0.16"):
(Pyo et al. 2003)

JET WIDTH:
R_{blue} ~ 25 - 170 AU

JET KINEMATICS:
V_{blue} up to -400 km/s

GAS PHYSICAL PROPERTIES:
dense (n_e~10^3-10^4 cm^{-3})
hot (T_e~5000-30 000 K)
highly ionized (x_e~0.1-0.8)

PACS observation of DG Tau: the atomic component



extended emission
in ATOMIC lines !

[OI] 63um:
<u>extended</u>
<u>red and blue-shifted</u>
correlated with optical jet !
Also red lobe detected !

<u>VELOCITY AND RADIUS</u>

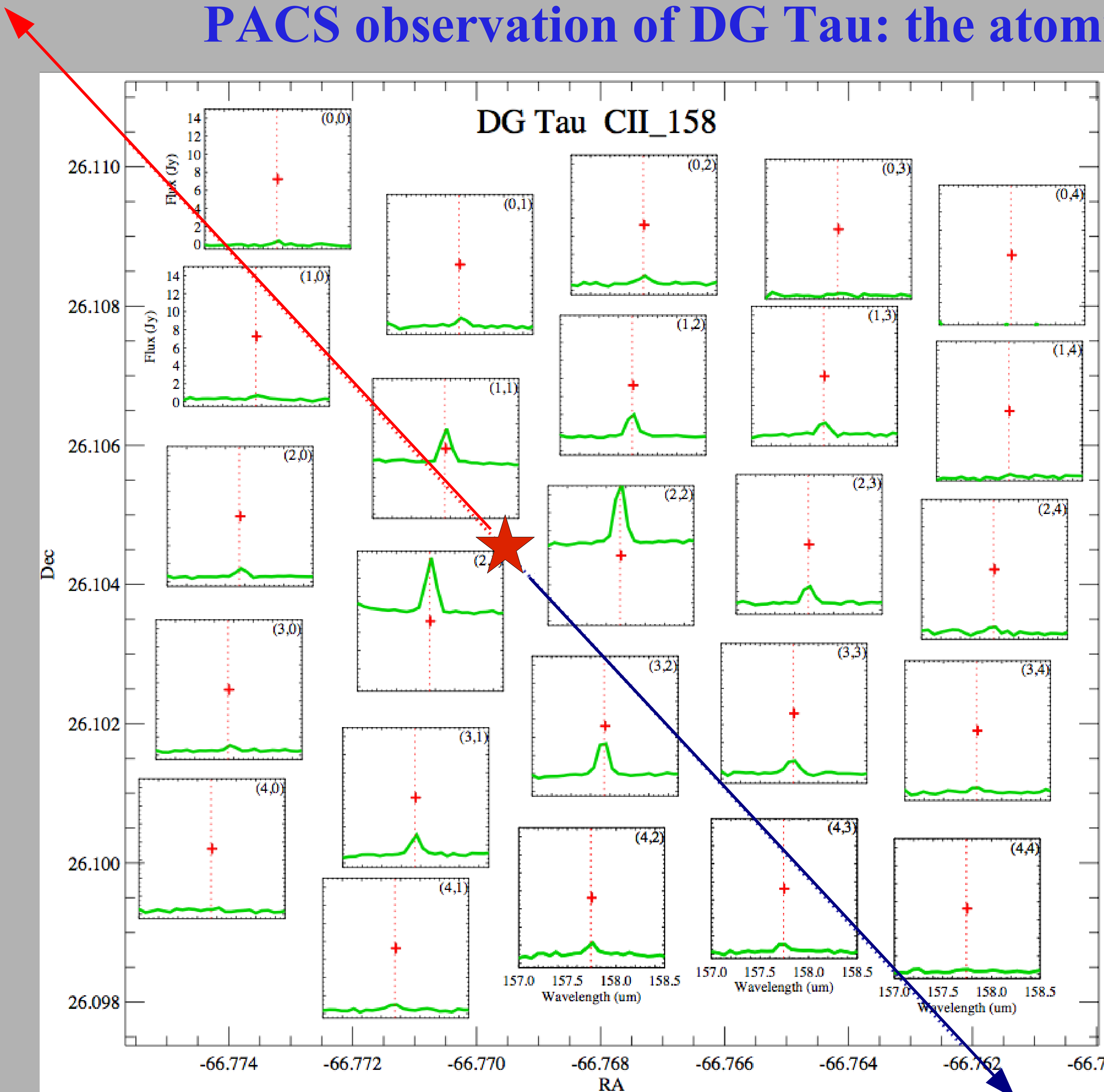
V[OI]63um (~30-50 km/s) <<
V[OI]6300 A (up to -400 km/s)

R[OI]63um >>
R[OI]6300 A (1.3", Dougados 2000)

FIR [OI]63um:
<u>wide-angle, slow and warm outflow !</u>

optical/NIR atomic lines
[OI]6300 ([SII], [NII], [FeII]):
<u>fast, collimated, hot jet !</u>

PACS observation of DG Tau: the atomic component



extended emission
in ATOMIC lines !

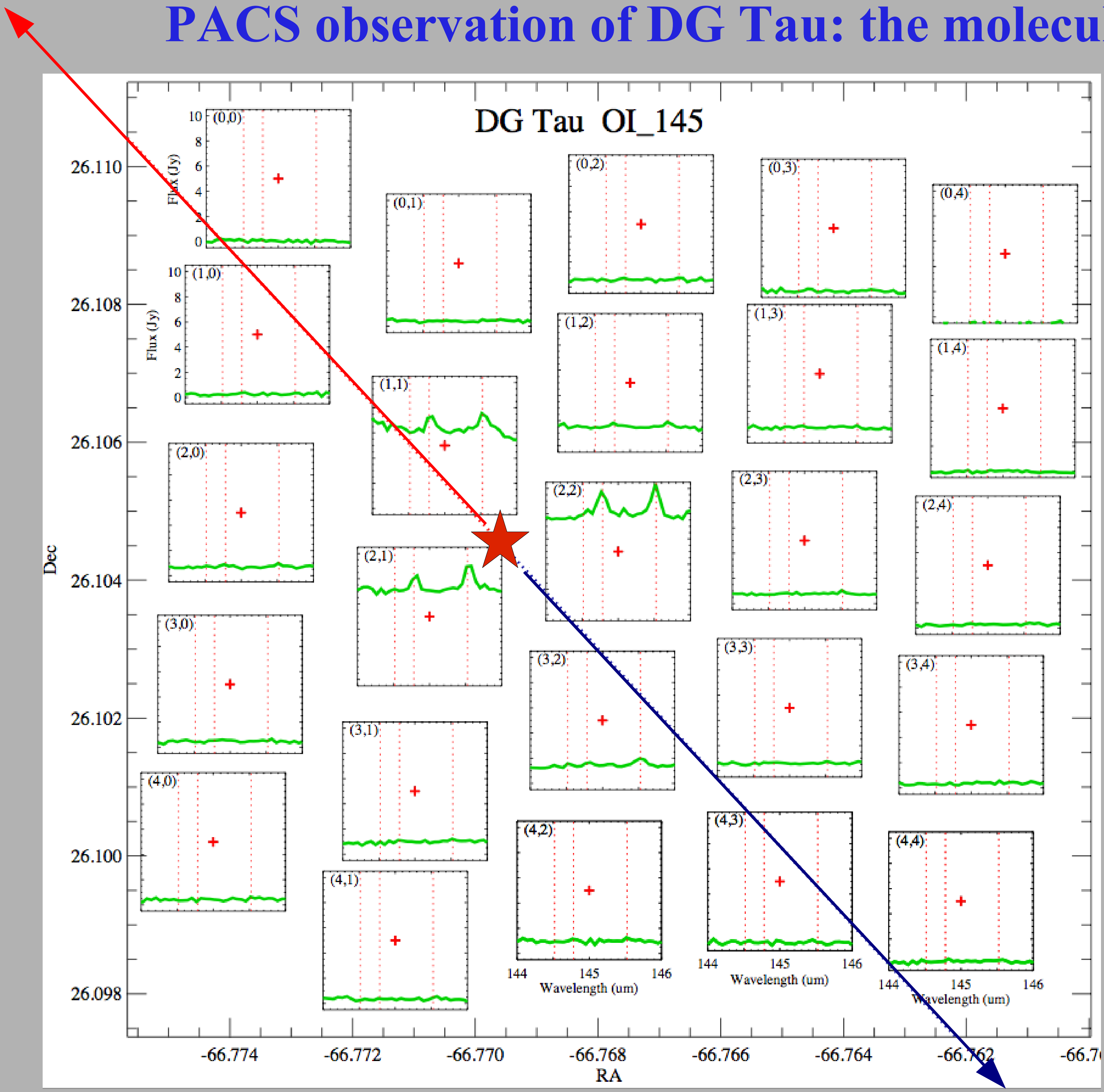
[CII] 158um:
<u>extended emission</u>
no velocity information
Also RED lobe detected !

$R_{[OI]63um}$ >>
$R_{[OI]6300\,A}$ (1.3", Dougados 2000)

FIR [CII]158um:
<u>Wide-angle, warm outflow !</u>

optical/NIR atomic lines
[OI]6300 ([SII], [NII], [FeII]):
<u>fast, collimated, hot jet !</u>

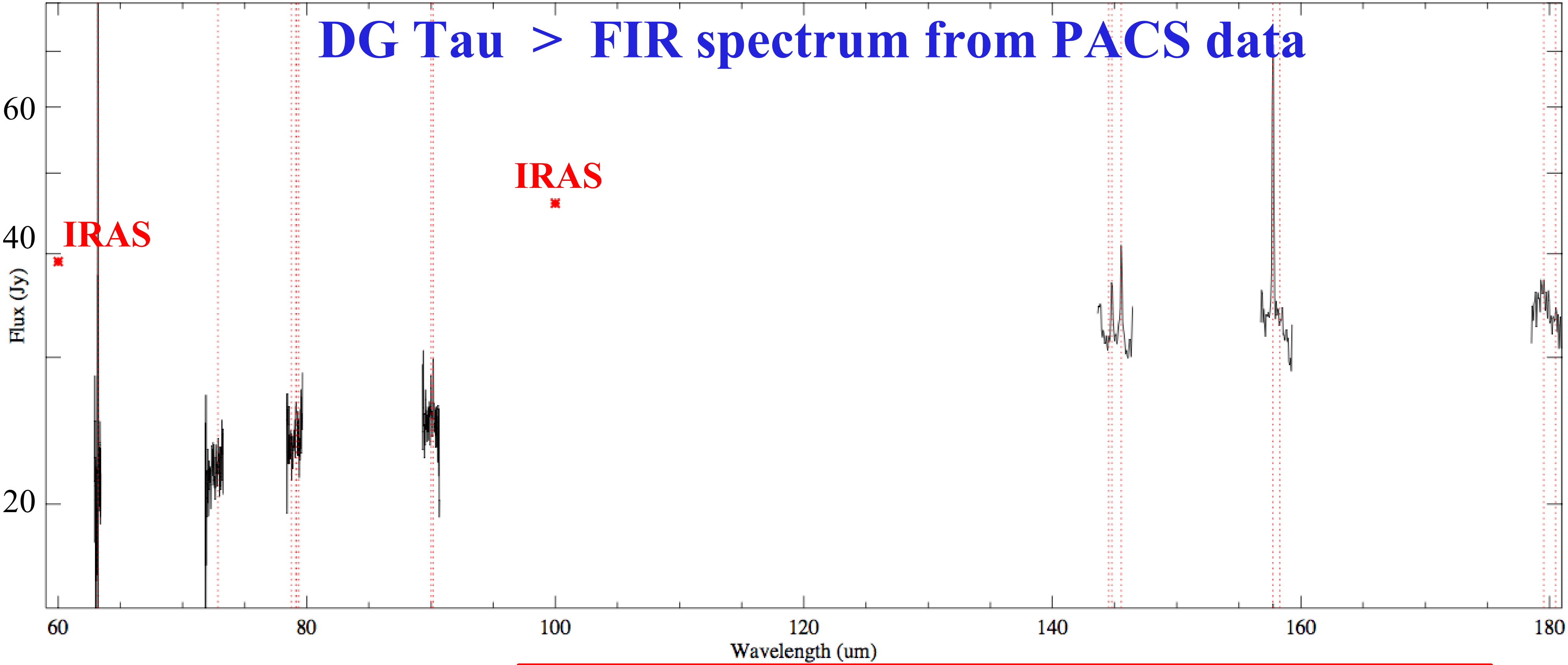
PACS observation of DG Tau: the molecular component



MOLECULAR emission
(high-J CO, H_2O, OH)
detected only
in the central spaxels,
in the circumstellar
unresolved region

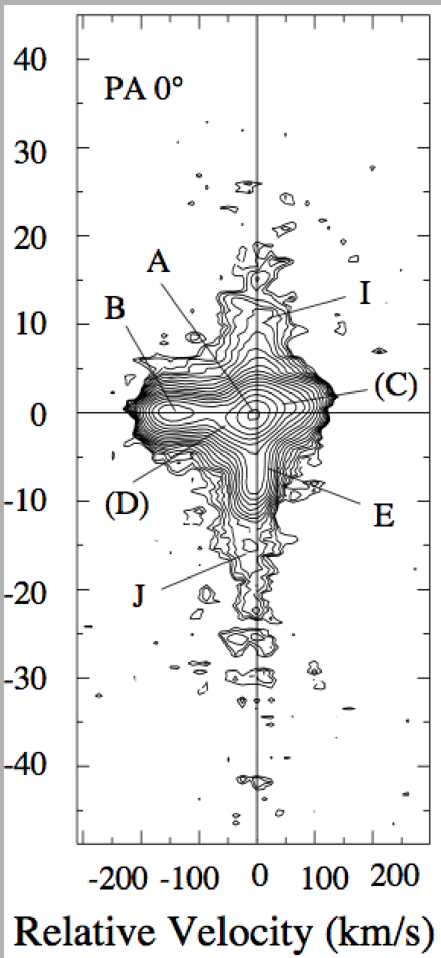
p-H_2O 144.5 um
CO(18-17) 144.784 um
[OI] 145um

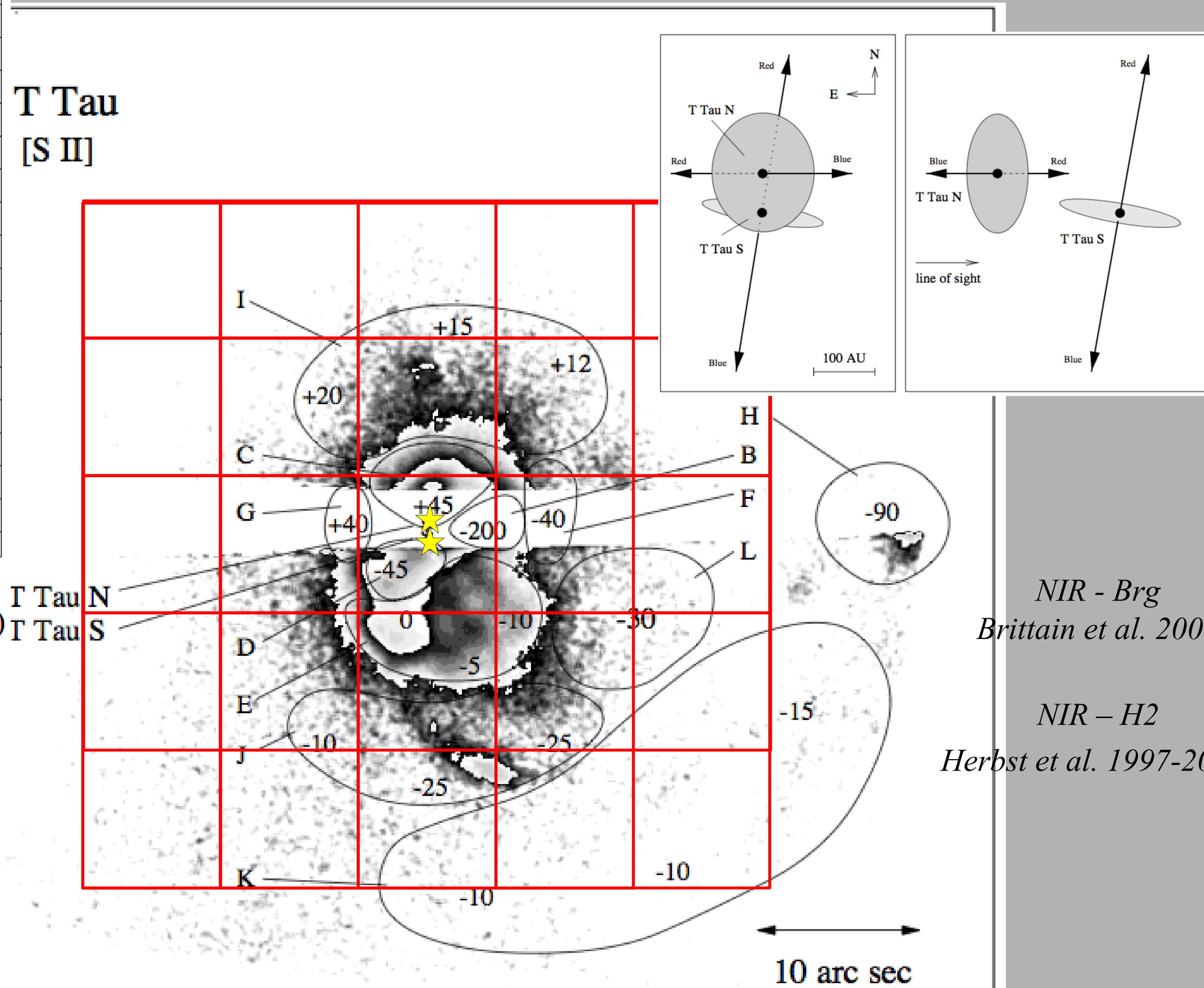
DG Tau > FIR spectrum from PACS data



Species	Transition	λ (μm)	E_{upper} (K)	cont ± err (Jy)	Flux ± err (W/m^2)
[OI]	3P1-3P2	63.184	228	5.51133 ± 0.05864	6.30e-16 ± 5.64e-18
OI]	3P0-3P1	145.525	326	8.08445 ± 0.13606	3.95e-17 ± 1.79e-18
[CII]	2P3/2-2P1/2	157.741	91	8.67586 ± 0.03127	1.06e-16 ± 2.29e-18
CO	J=36-35	72.843	3700	5.80398 ± 0.02868	-
CO	J=33-32	79.360	3092	6.20657 ± 0.06713	8.57e-18 ±
CO	J=29-28	90.163	2400	6.35590 ± 0.04193	1.00e-17 ±
CO	J=18-17	144.784	945	8.02271 ± 0.14646	3.55e-17 ± 1.98e-18
H_2O	p 3-22 - 2-11	89.988	297	6.35539 ± 0.03903	6.64e-18 ± 3.46e-18
H_2O	p 4-13 - 3-22	144.518	396	8.60150 ± 0.16805	-
H_2O	p 3-31 - 4-04	158.309	410	9.57034 ± 0.28915	-
H_2O	o 4-23 - 3-12	78.741	432	6.14538 ± 0.05279	7.91e-18 ± 4.65e-18
H_2O	o 2-12 - 1-01	179.527	115	9.02602 ± 0.04593	1.12e-17 ± 2.16e-18
H_2O	o 2-21 - 2-12	180.488	194	8.69165 ± 0.05328	7.01e-18 ± 2.52e-18

A multi-wavelength study of T Tau



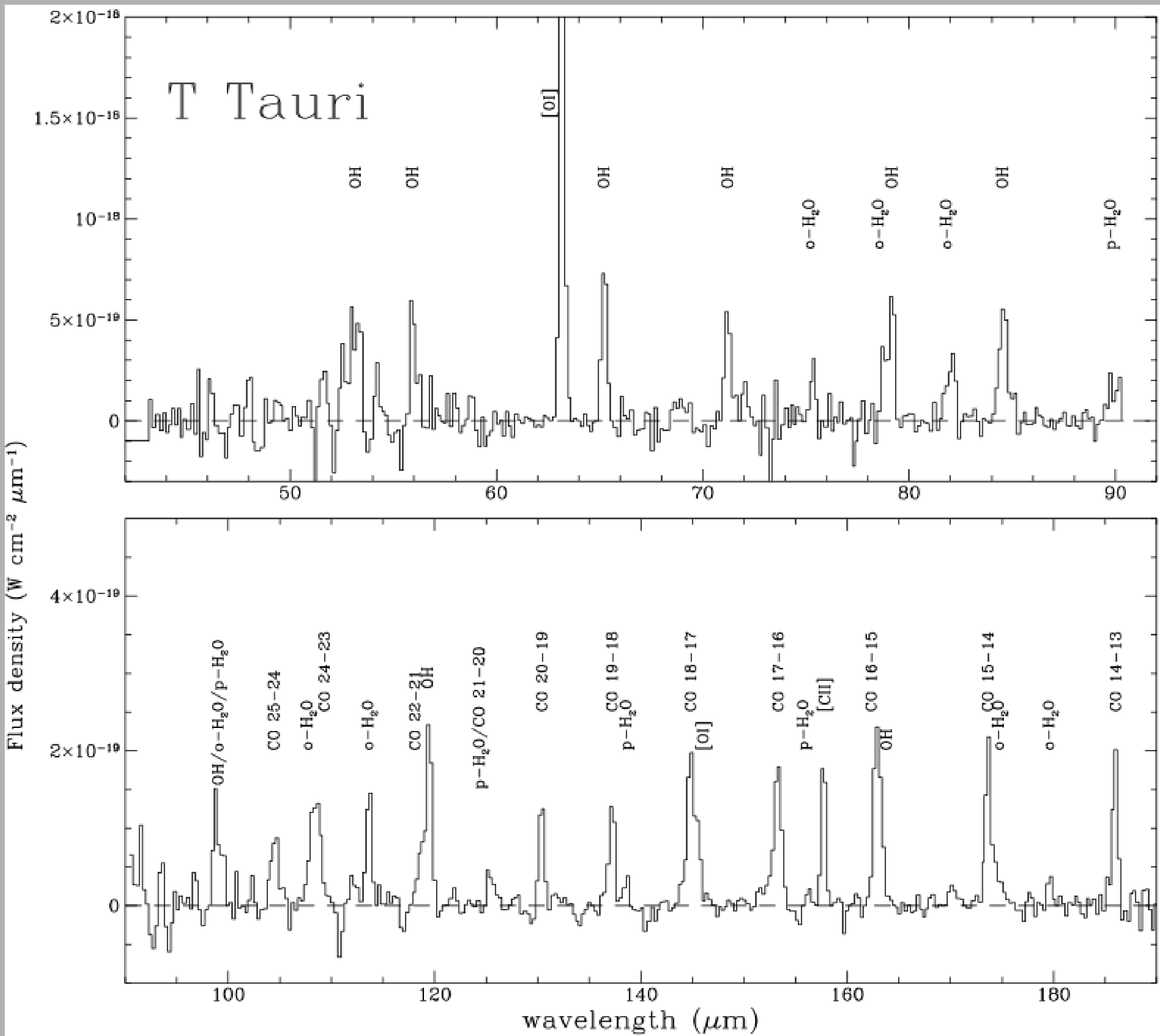


(Solf & Mundt 1999)

NIR - Brg
Brittain et al. 2007

NIR – H2
Herbst et al. 1997-2007

ISO observation of T Tau: atomic/molecular lines

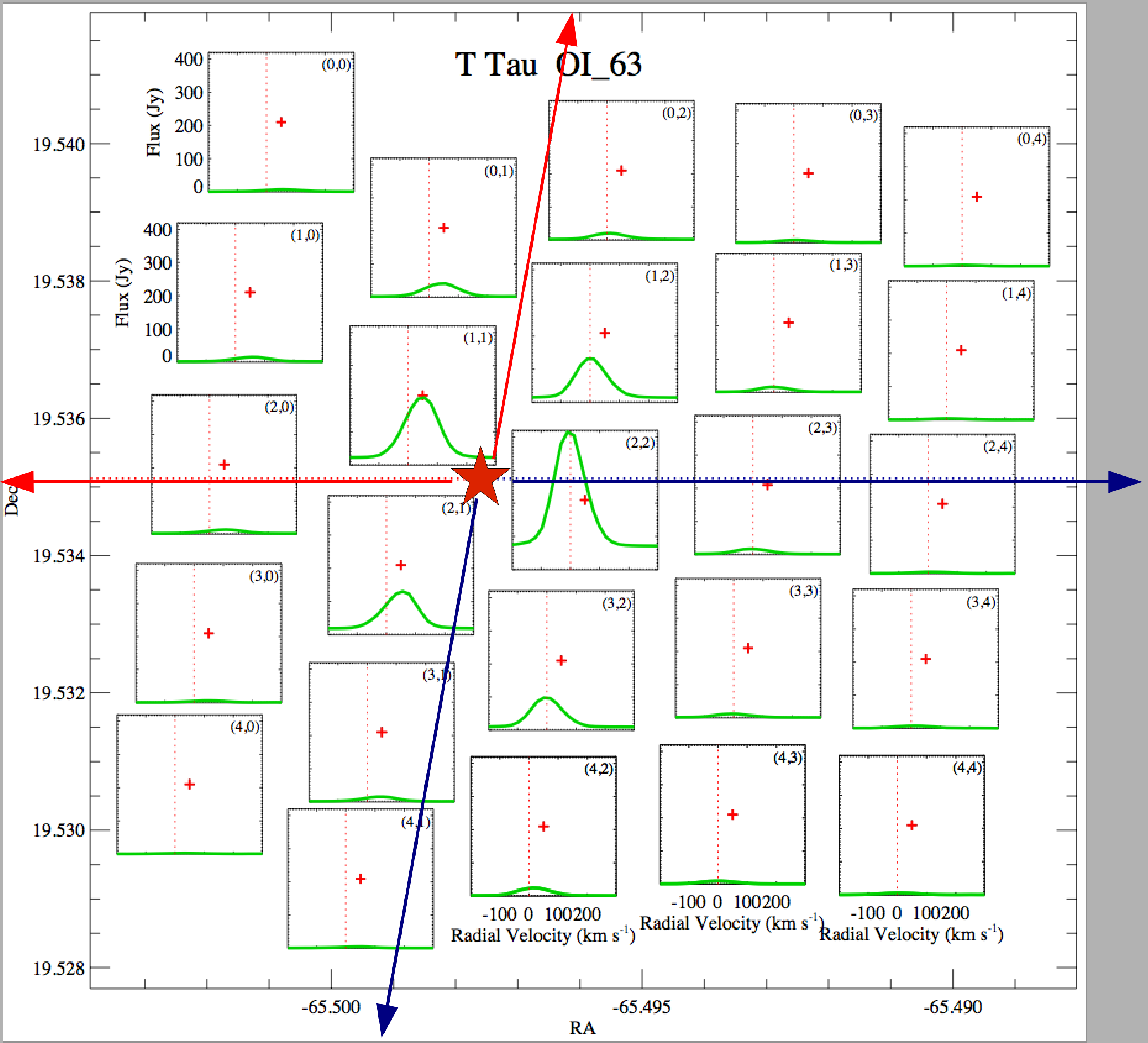


atomic/molecular lines !!!

no spatial information
no velocity info

Spinoglio et al. 2000

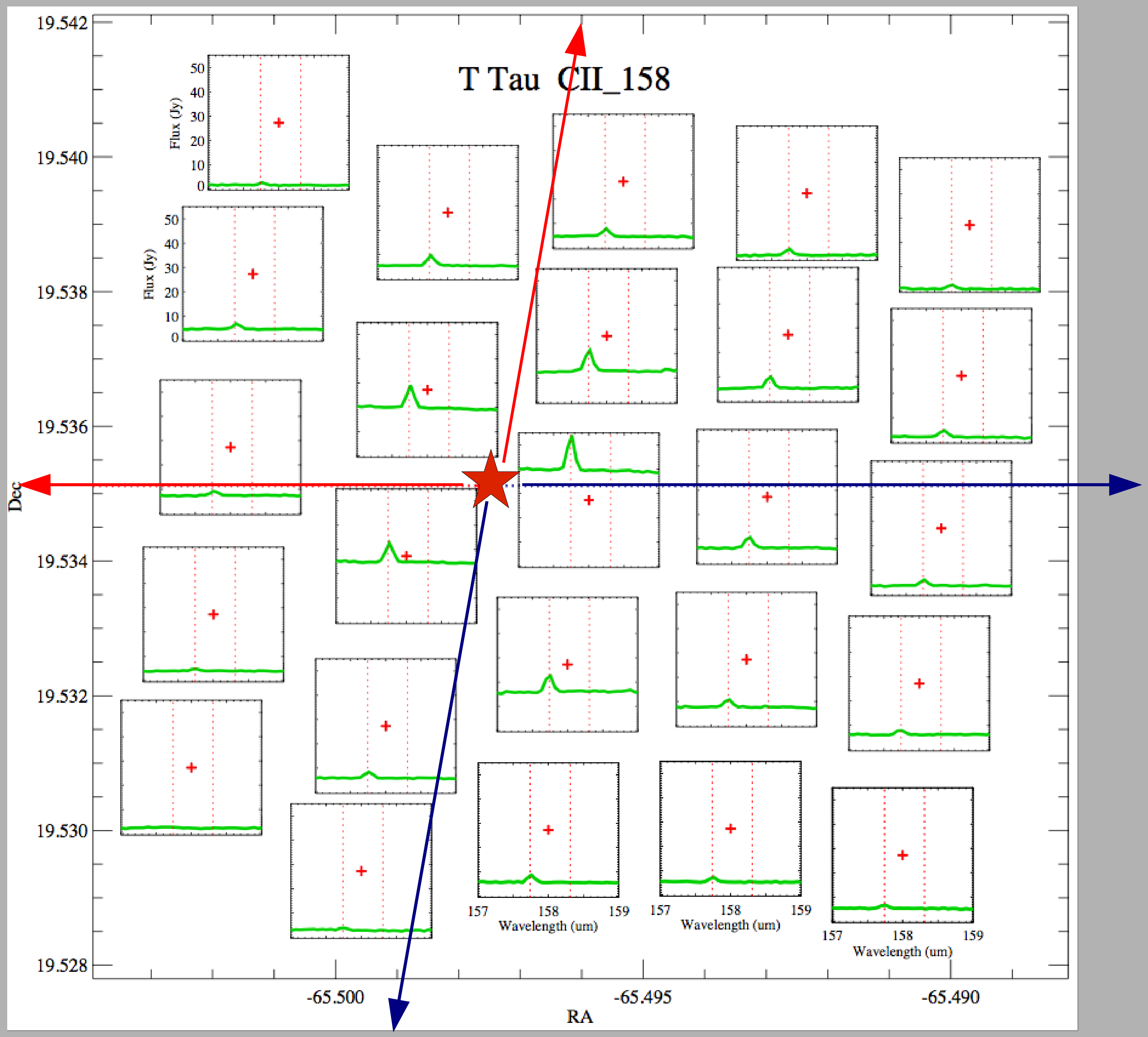
PACS observation of T Tau: the atomic component



extended emission
in ATOMIC lines

[OI] 63um:
extended
velocity shifted emission

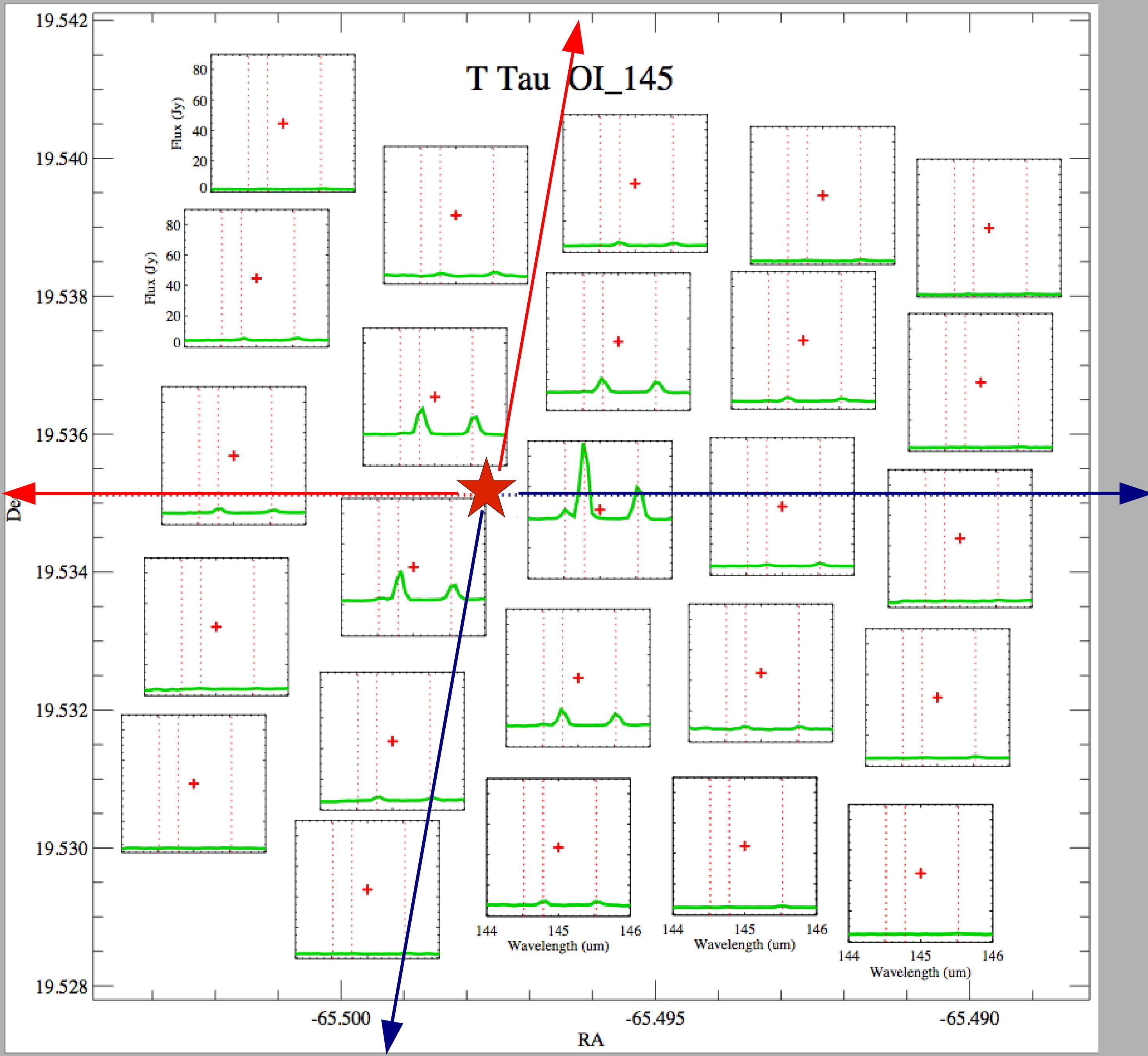
PACS observation of T Tau: the atomic component



extended emission
in ATOMIC lines

[CII] 158 um

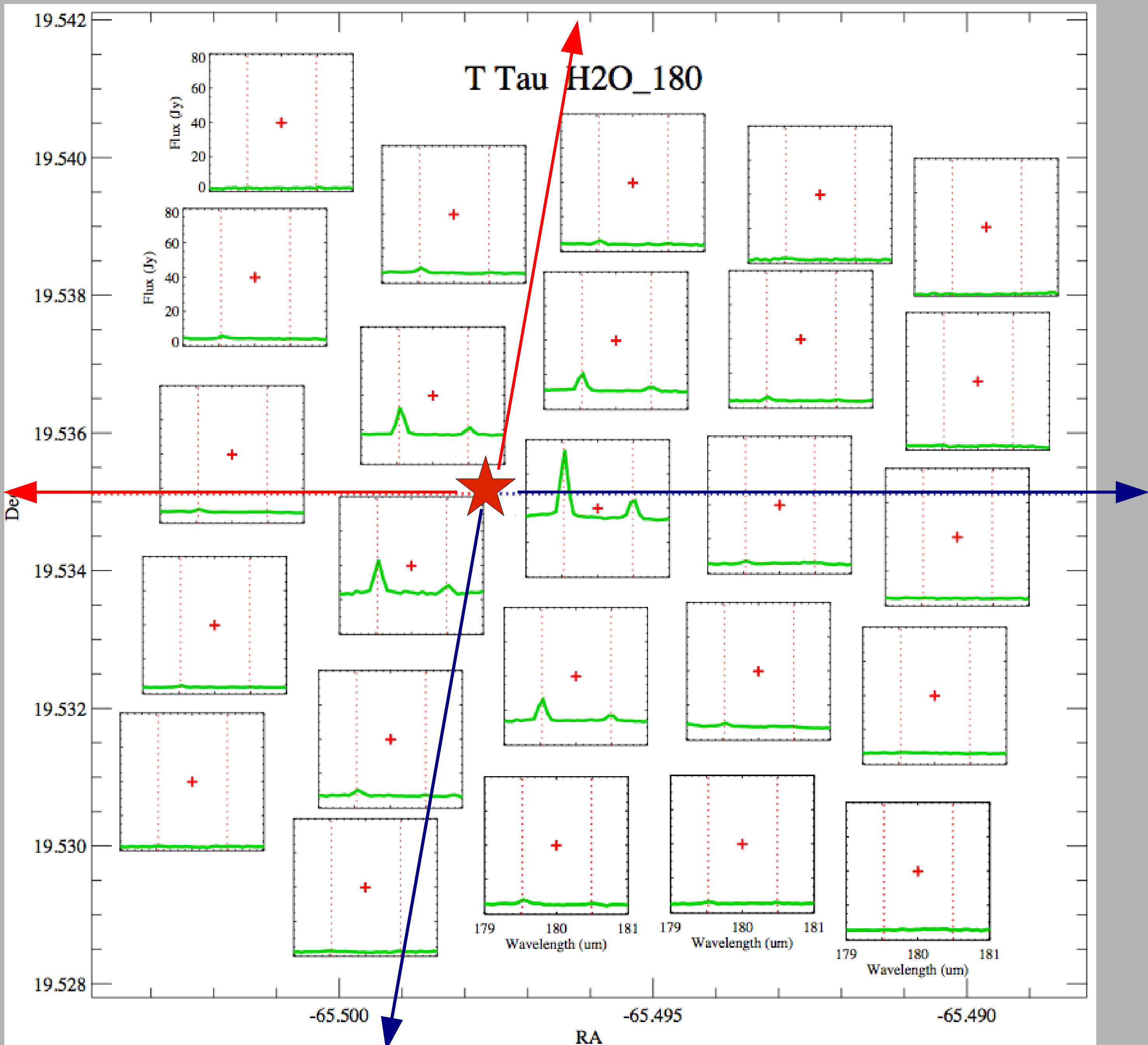
PACS observation of DG Tau: the molecular component



extended emission
in MOLECULAR lines

p-H_2O 144.518 um
CO(18-17) 144.784 um
[OI] 145.525 um

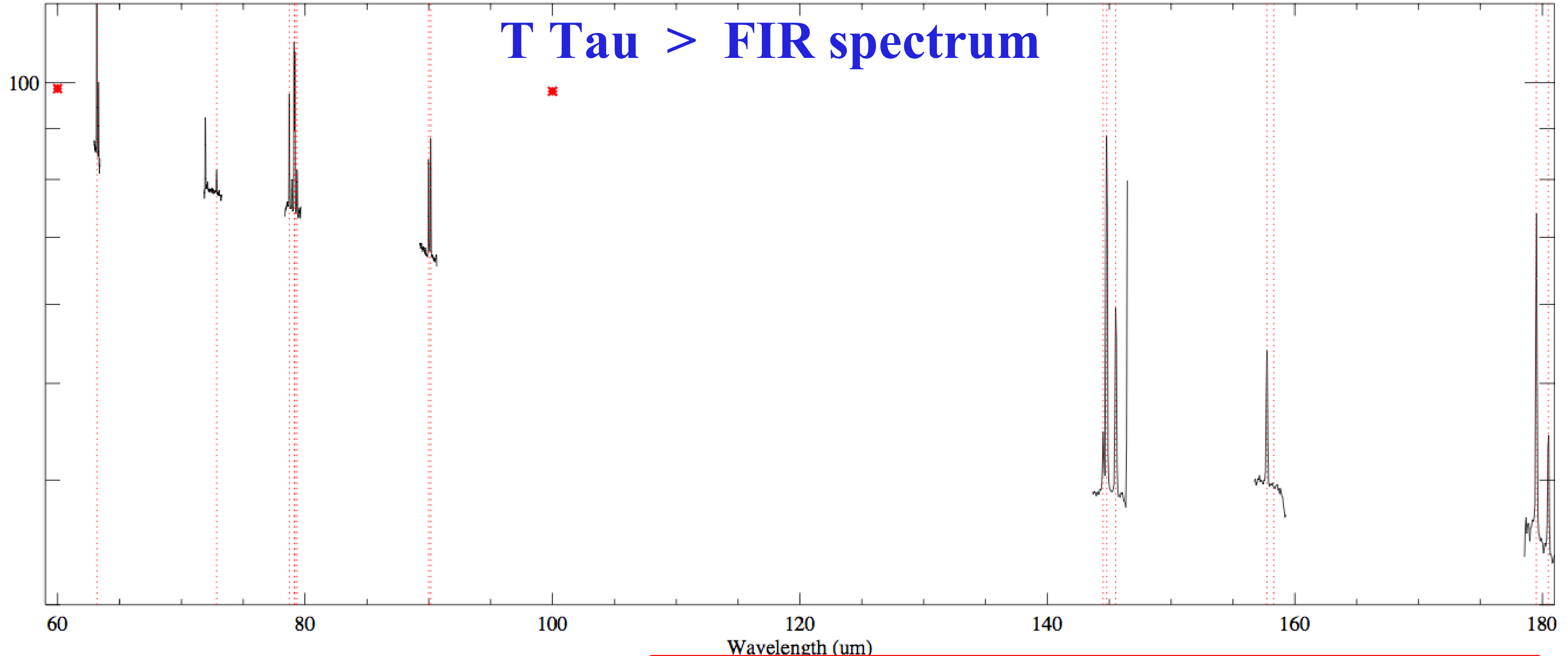
PACS observation of T Tau: the molecular component



extended emission
in MOLECULAR lines

o-H_2O 179.527 um
o-H_2O 180.488 um

T Tau > FIR spectrum



Species	Transition	λ (μm)	E_{upper} (K)	cont ± err (Jy)	Flux ± err (W/m^2)
[OI]	3P1-3P2	63.184	228	86.7 ± 0.6	8.15e-15 ± 3.14e-17
OI]	3P0-3P1	145.525	326	39.5 ± 2.3	4.00e-16 ± 3.98e-18
[CII]	2P3/2-2P1/2	157.741	91	39.7 ± 0.1	2.17e-16 ± 2.71e-18
CO	J=36-35	72.843	3700	77.6 ± 0.1	1.15e-16 ± 6.79e-18
CO	J=33-32	79.360	3092	76.5 ± 2.1	7.87e-17 ± 1.62e-17
CO	J=29-28	90.163	2400	68.0 ± 0.7	3.12e-16 ± 4.99e-18
CO	J=18-17	144.784	945	39.9 ± 0.9	8.95e-16 ± 5.57e-18
H_2O	p 3-22 - 2-11	89.988	297	68.4 ± 0.8	2.64e-16 ± 4.74e-18
H_2O	p 4-13 - 3-22	144.518	396	40.1 ± 1.6	6.77e-17 ± 2.11e-18
H_2O	p 3-31 - 4-04	158.309	410	40.1 ± 0.6	-
H_2O	o 4-23 - 3-12	78.741	432	75.9 ± 1.4	4.73e-16 ± 6.75e-18
H_2O	o 2-12 - 1-01	179.527	115	35.7 ± 0.5	4.34e-16 ± 3.29e-18
H_2O	o 2-21 - 2-12	180.488	194	34.4 ± 1.7	1.28e-16 ± 2.63e-18

[OI] 63 um: MASS LOSS tracer

In a dissociative J-shock
if [OI] emission is optically thin
($n_0 V_{shock} < 10^7$ km s^{-1} cm^{-3})

$$\dot{M}_* = 10^{-6} \left[\frac{L(\mathrm{O\,I\,63\,\mu m})}{10^{-2}\,\mathrm{L}_\odot} \right] \quad (\mathrm{M}_\odot\,\mathrm{yr}^{-1})$$

Hollenbach & McKee 1989

Source	$\dot{M}_{jet}$ ([OI]6300 A) $M_\odot$ yr^{-1}	$\dot{M}_{jet}$ ([OI]63 μm) $M_\odot$ yr^{-1}	$\dot{M}_{acc}$ $M_\odot$ yr^{-1}	$\dot{M}_{jet}/\dot{M}_{acc}$
DG Tau	3 10^{-7} [a]	1.5 10^{-7}	2 10^{-6} [a]	0.07 - 0.15
T Tau	-	5.0 10^{-7}	3-5 10^{-8} [b]	10

[a] from Hartigan et al. 1995
[b] from Calvet et al. 2004 for TTau N

Outflow Parameters Derived from CO and O I 63 μm

Source	t_d (yr)	v_{CO} (km s^{-1})	$\dot{M}_{CO}$ (10^{-6} $M_\odot$ yr^{-1})	$\dot{M}_{OI}$ (10^{-6} $M_\odot$ yr^{-1})	CO peak (arcsec)	O I peak (arcsec)
IRAS 16293−2422[a]	5000	15	7.5	1.9	45	45
VLA 1623	2000	50	2.2	1.9[b]	120	120
L1448-mm	3500	27	4.6	2.0	80	≤20
L1448–IRS 3	...	23	1.1	0.6	...	≤20
NGC 1333–IRAS 4A......	10000	20	1.4	1.8	120[c]	≤15

Ceccarelli et al. 1997

Outline:

Introduction: accretion/ejection process in YSO

role of stellar jets in the star formation process
theoretical models for jet launch
jets observational properties
Multi-λ studies: importance & problems

First results from GASPS/PACS data:

FIR maps of outflow from Class II sources (DG Tau B, DG Tau, RW Aur, T Tau, RY Tau, ...)

Extended, velocity-shifted emission in atomic and/or molecular lines

Estimate of mass flux rate > mass ejection/mass accretion

Open issues:

Desentangling jet/disk emission in the central spaxel

OI63-cont in jet and non-jet sources

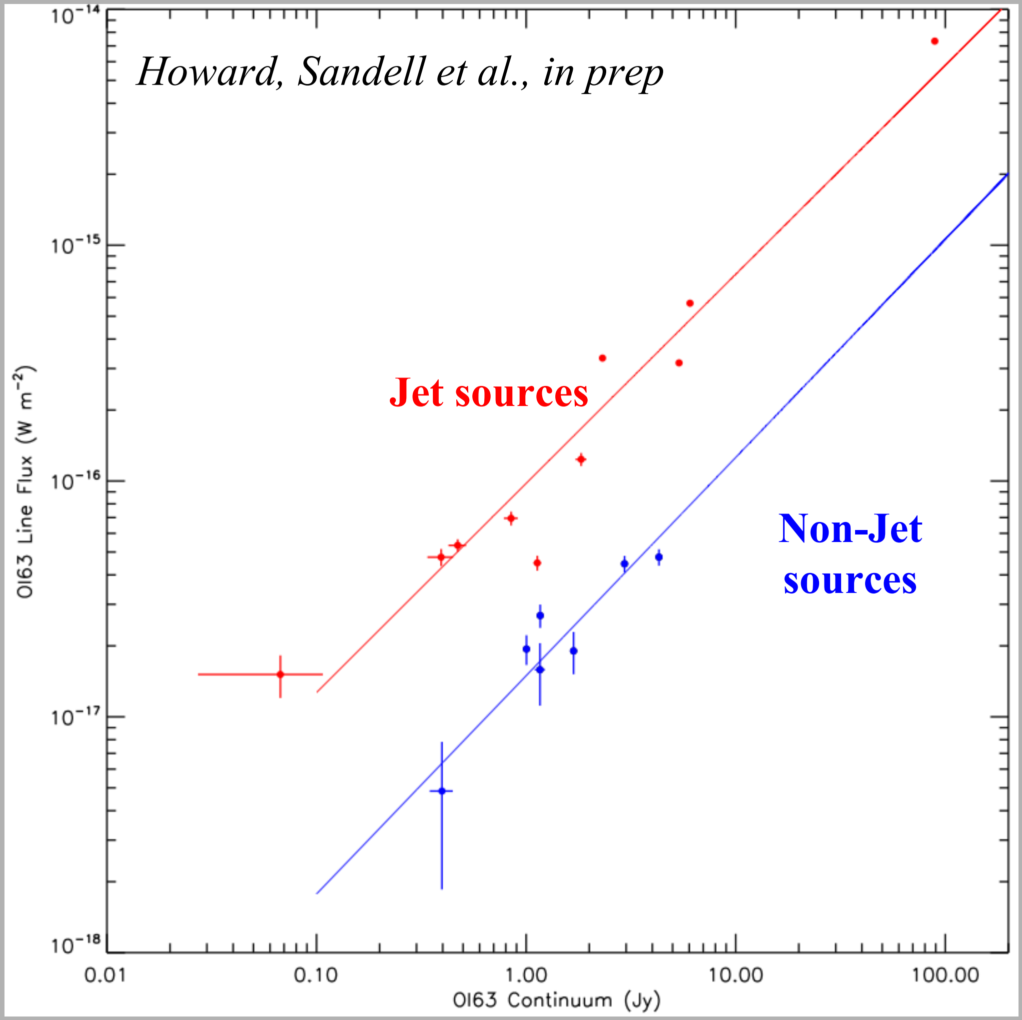
Line ratios

HIFI observations > velocity resolved line profiles

In the unresolved circumstellar region (central spaxel)
Can we distinguish between JET and DISK emission ???

- COMPARISON JET, NON-JET SOURCES
- LINE RATIOS
- HIGH SPECTRAL RESOLUTION HIFI FOLLOW-UP OBS

COMPARISON JET, NON-JET SOURCES

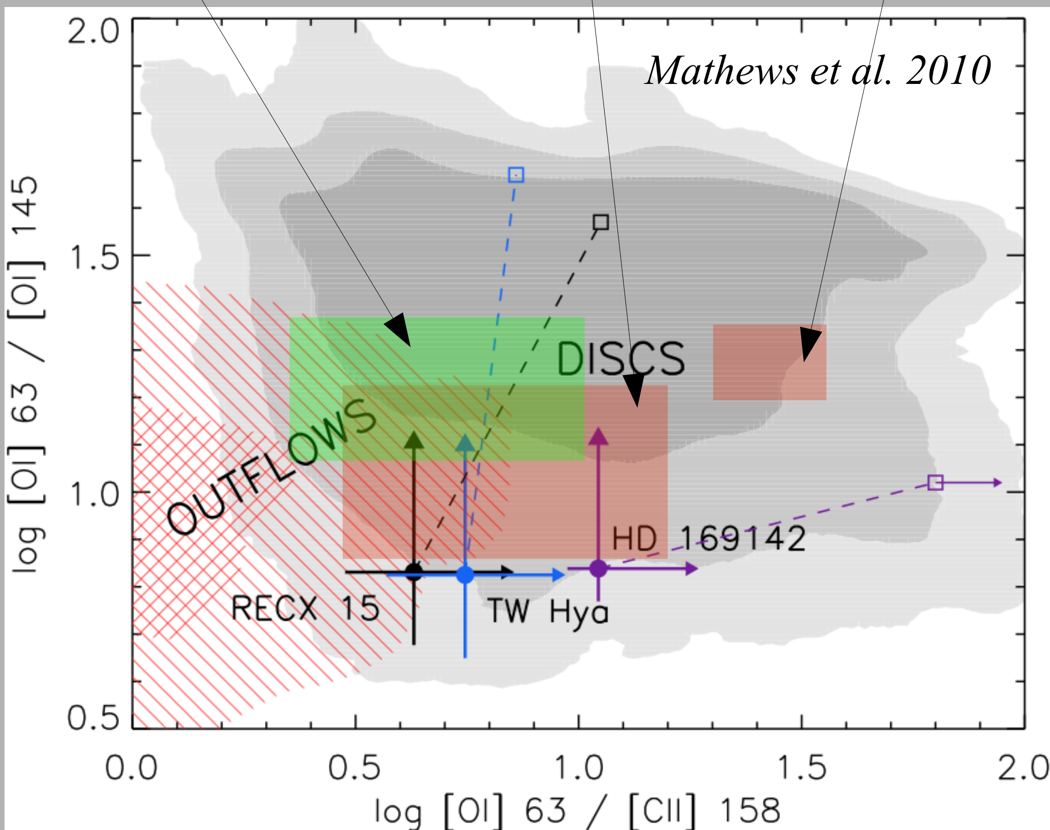


LINE RATIOS

DG Tau

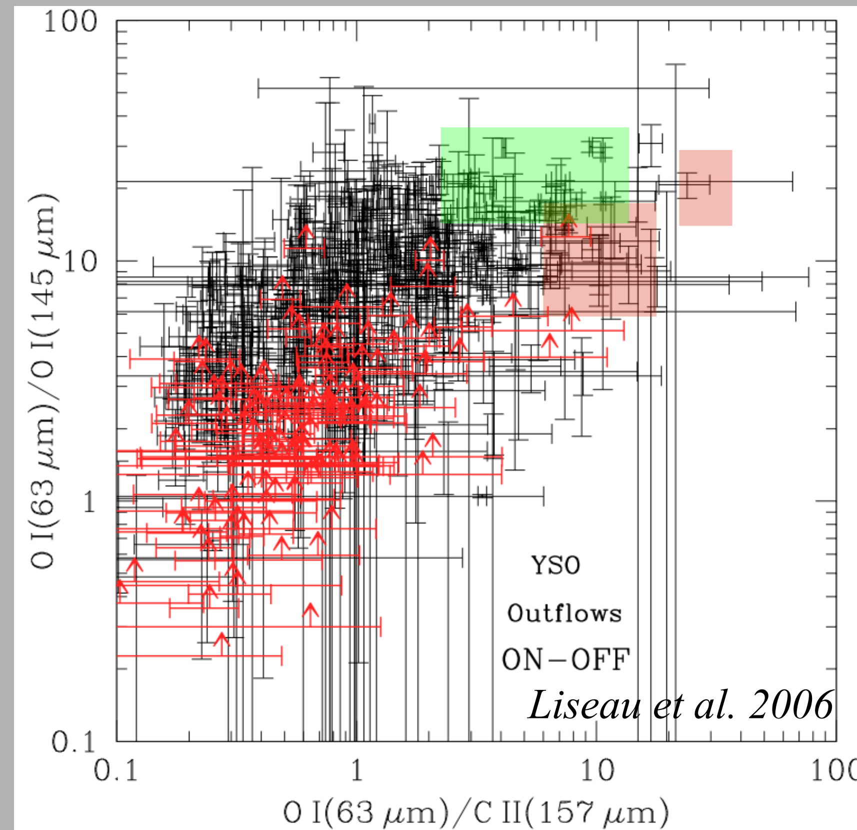
T Tau
outer spaxels

T Tau
central spaxels



Subset of the DENT grid of models (Woitke et al. 2009, Kamp et al. 2010, Pinte et al. 2010) which reproduce the observed [OI]63um fluxes (4-90 10^{-18} W/m^2)

Thi et al. 2010; RECX 15: Woitke et al. (in prep.). Outflow sources are shown in red (Liseau et al. 2006, lines indicate contour containing 90% of points, hash indicates 68% of points.). Gray regions indicate 99, 90, and 68% of DENT models with [OI] 63 flux consistent with our observations (4–90 × 10^{-18} W/m^2 at 140 pc).



From the analysis of 500 ISO observations of outflows from YSO:
1 < [OI]63/145 < 30
0.1 <[OI]63um/[CII]158 <20

HIFI OBSERVATION > LINE VELOCITY PROFILES

OT1 proposal for HIFI follow-up observations

Source	D(pc)	M_* ($M_\odot$)	PA_{jet}	mm	NIR	opt
DG Tau A	140	0.67	226°	-	Pyo et al. 2003	Bacciotti et al. 2000
DG Tau B	140	-	115°	Mitchell 1994	Padgett 1999	Eisloffel 1998
T Tau	140	2.2 / 0.6	0°, 90°	Edwards & Snell 1982	Herbst et al. 2007	Solf et al. 1999
HD 163296	122	2.3	223°	-	Benisty et al. 2010	Grady et al. 2000
AB Aur	144	2.4	-	-	-	Grady et al. 1999

Species	ν (GHz)	λ (μm)	trans	Obs Mode	beam (")	ΔV (km/s)
[CII]	1900.5	157.741	2P3/2-2P1/2	HMap DBS	13	0.2
CO	1152.0	260.2	J=10-9	HMap DBS	19	0.3
H_2O	556.9	538.3	ortho 1_{10}-1_{01}	HPoint DBS	39	0.6

Some data reduction issues...

- PSF: ~10" up to 120 um
  >10" for λ >120um

  POINT SOURCE: From reconstructed PSF at every λ
  > aperture correction to obtain correct flux

  EXTENDED SOURCE: flux in the outer pixel may be contaminated by emission on the central spaxel.
  If there is extended emission the flux in the outer spaxels is >> then PSF contribution

- VELOCITY SHIFTS may be caused by uneven slit illumination

- COMPUTATION OF LINE RATIOS on each spaxel

  May be an issue because the emission in every spaxel is contaminated by the emission on the surrounding spaxels
  DECONVOLUTION ?