Is Mid-Infrared [Ne II] Emission a Tracer for X-Ray Ionized and Heated Gas in Protoplanetary Disks?

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Summary

Glassgold et al. (2007) proposed that the forbidden mid-infrared [Ne II] 12.81 micron transition is a tracer of X-ray irradiated and X-ray heated disk gas. [Ne II] observations may detect relatively small amounts of warm gas in the inner, planet-forming disk zone (R=10-20 AU), at the same time confirming the role stellar X-rays play in driving disk dynamics, accretion, photoevaporation, chemistry, and eventually the formation of planets. Theories of [Ne II] line formation in disks predict - for otherwise identical source and disk properties - a linear correlation between the [Ne II] luminosities, L(Ne II), and the X-ray luminosities, LX. However, further parameters may be relevant. We test such predictions using two approaches:

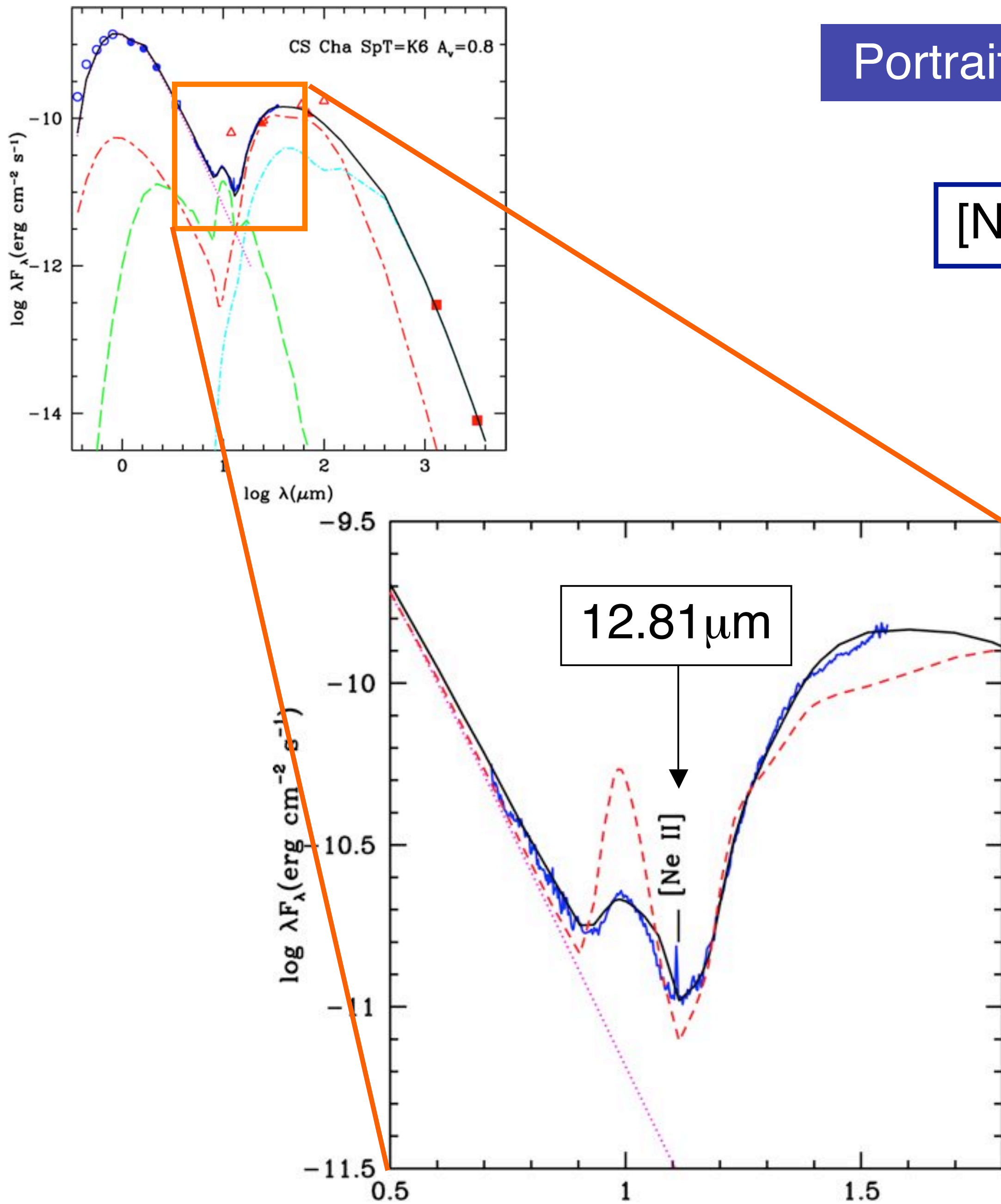
1) We use a sample of 86 classical T Tauri stars with [Ne II] 12.81 micron observations (of which 53 have [Ne II] detections and 54 have X-ray detections) to perform correlation studies, also with other stellar and disk parameters collected from the literature. Although we find a significant correlation between L(Ne II) and LX over 2-3 orders of magnitude, the correlation is dominated by systematic scatter. A tendency is also found for stronger accretors to be more luminous [Ne II] sources. However, stars driving "micro-jets" show systematically enhanced L(Ne II), and a tighter correlation is indeed found between L(Ne II) and the product of LX and L(O I), the latter defining the luminosity in the [O I] 6300A line, often taken to be an indicator for gas in micro-jets.

2) We present a detailed VLT/VISIR case study of [Ne II] emission in and around the T Tau triple. This system shows an extremely high L(Ne II) = 5E30 erg/s. The emission is concentrated at the embedded T Tau S binary, but widely dispersed components are found along structures that have previously been identified as outflow features. A high-velocity component (v = 126 km/s, blueshifted) is identified at the position of T Tau N.

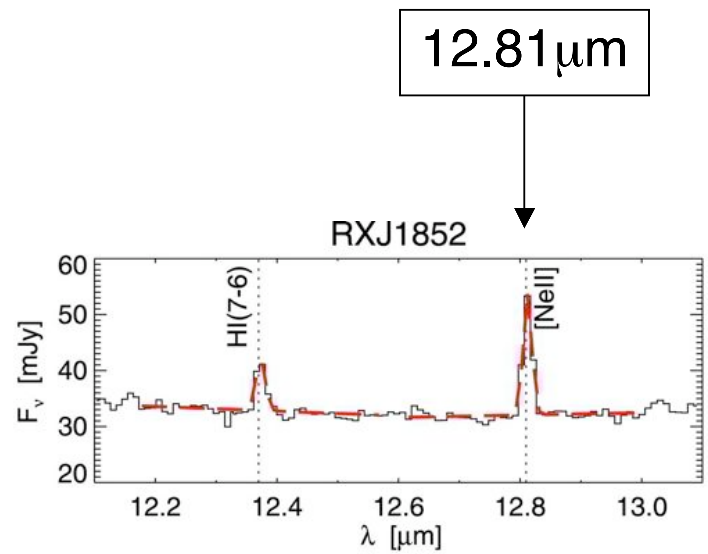
Both results suggest that the [Ne II] 12.81 micron flux is prominently formed in outflows and jets, probably as a result of irradiation with stellar X-rays. The line may therefore be an interesting tracer for X-ray irradiated jets/outflows. These findings do not exclude additional [Ne II] contributions from disk surfaces, photoevaporative flows, or accretion flows close to the star.

Portrait of the [Ne II] 12.81μm Line

[Ne II] $^2P_{3/2}$ - $^2P_{1/2}$ 12.81μm



(Espaillat et al. 2007, CS Cha)



(Pascucci et al. 2007)

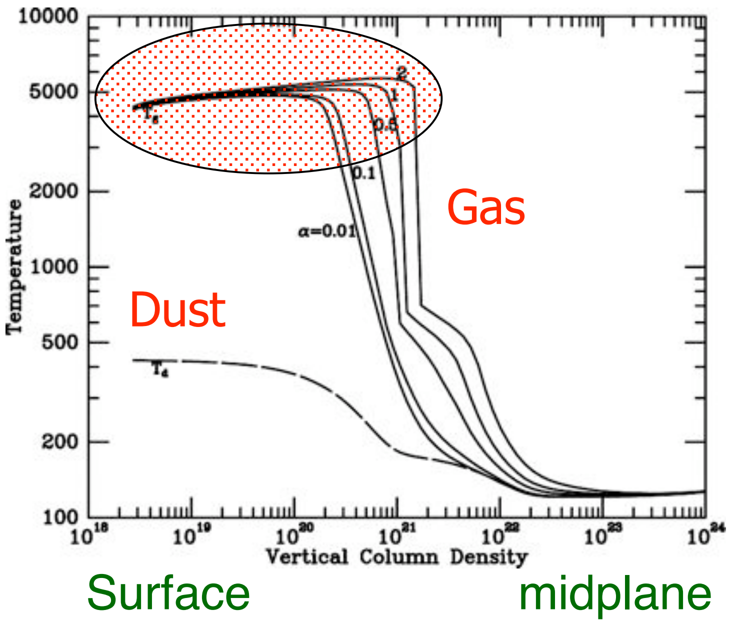
Why is the [Ne II] 12.81μm Transition Important?

Photoionization of Ne requires 21.56 eV (41.0 eV for Ne^{++}):

due to ***X-ray*** *or* ***EUV*** *photons from star?* *(Glassgold et al. 2007, Gorti & Hollenbach 2008 Ercolano et al 2008 - see also this conference)*

In that case, [Ne II] probes...

- small amounts of warm (> 1000 K) gas
- ...in the inner, spatially unresolved disk;
- i.e., at the origin of photoevaporative flows;
- tracer for magnetorotational instability?



(Glassgold et al. 1997, 2004)

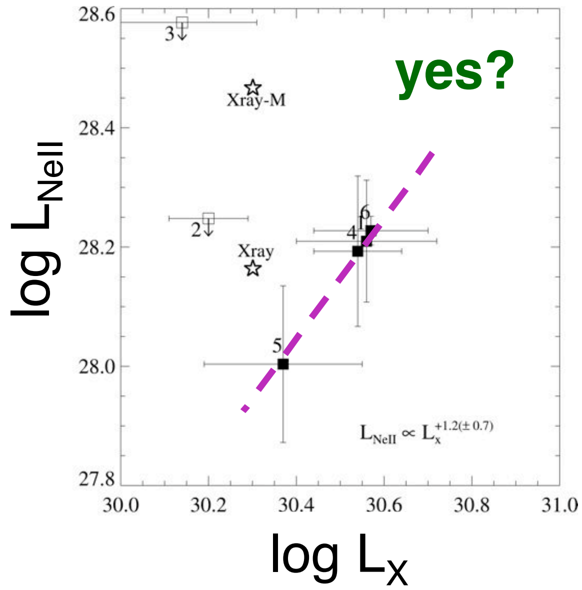
Alternative ionization sources include:

Cosmic rays*: but inner disk may be shielded by magnetized wind.*
Shocks *on disks (accretion shocks), in winds or jets.*

(Hollenbach & McKee 1989, Shang et al. 2002)

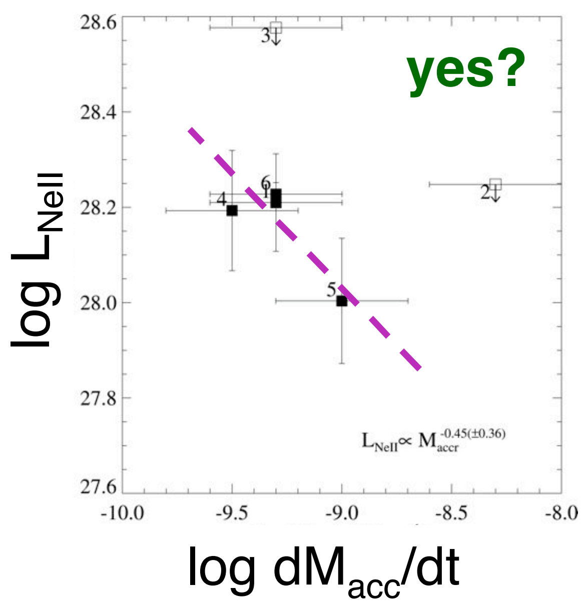
Does [Ne II] 12.81μm Flux Depend on X-Rays, or Accretion?

L_X:

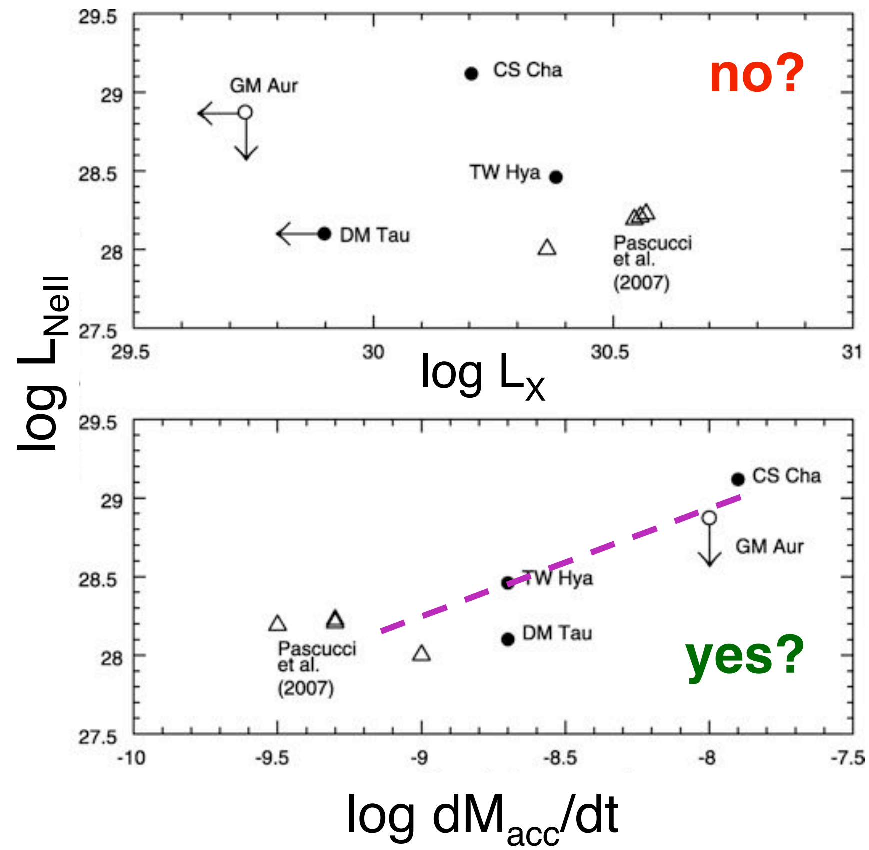


dM_{acc}/dt:

(EUV/UV heating & ionization?)



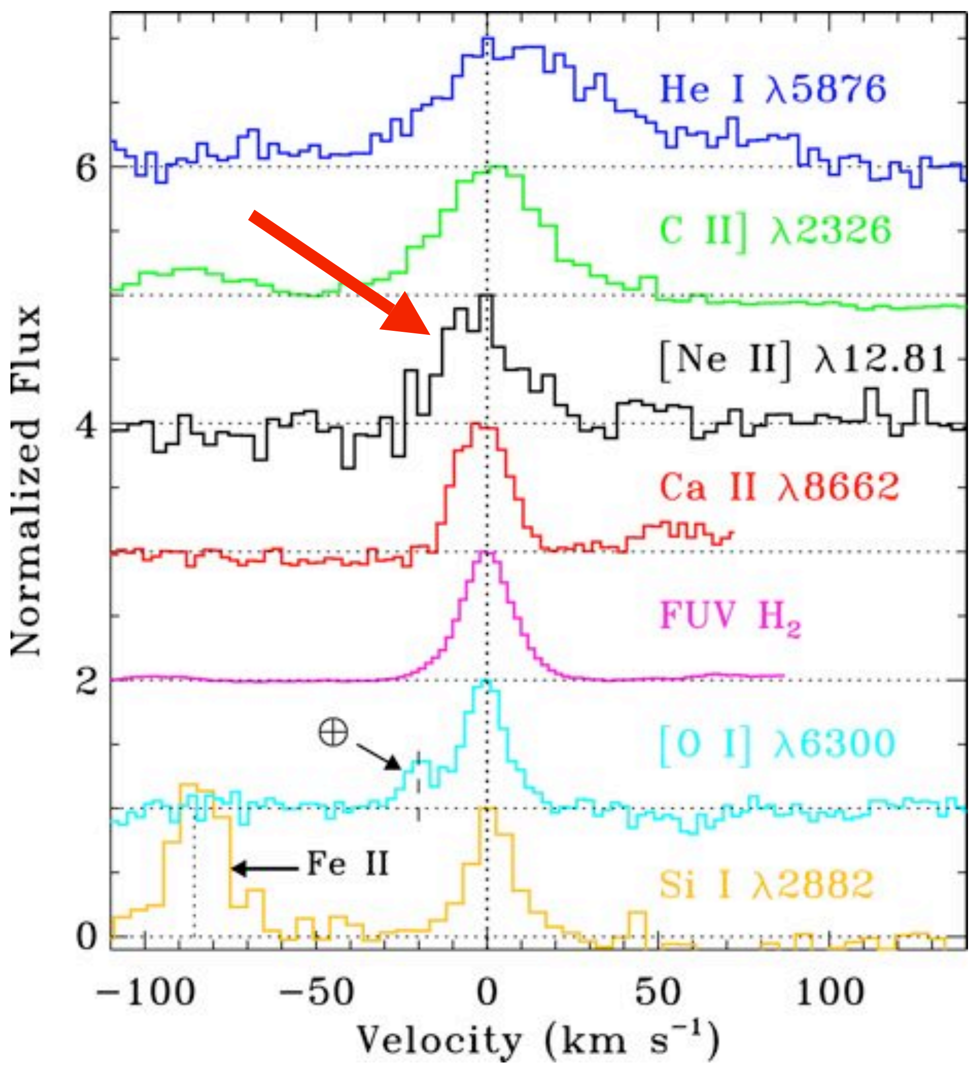
(Pascucci et al. 2007)



(Espaillat et al. 2007)

Important studies, but problem was small statistics then available.

Alternative Approach: Line Profile Analysis (TW Hya)



[Ne II] line is centered and narrow, with FWHM = 21 km s^{-1}

The line is compatible with emission from inner disk, or from photoevaporative flow.

(Herczeg et al. 2007)

Statistical Study: Characterization of [Ne II] Sample

New project discussed below:

[Ne II] fluxes from published literature and new observations:

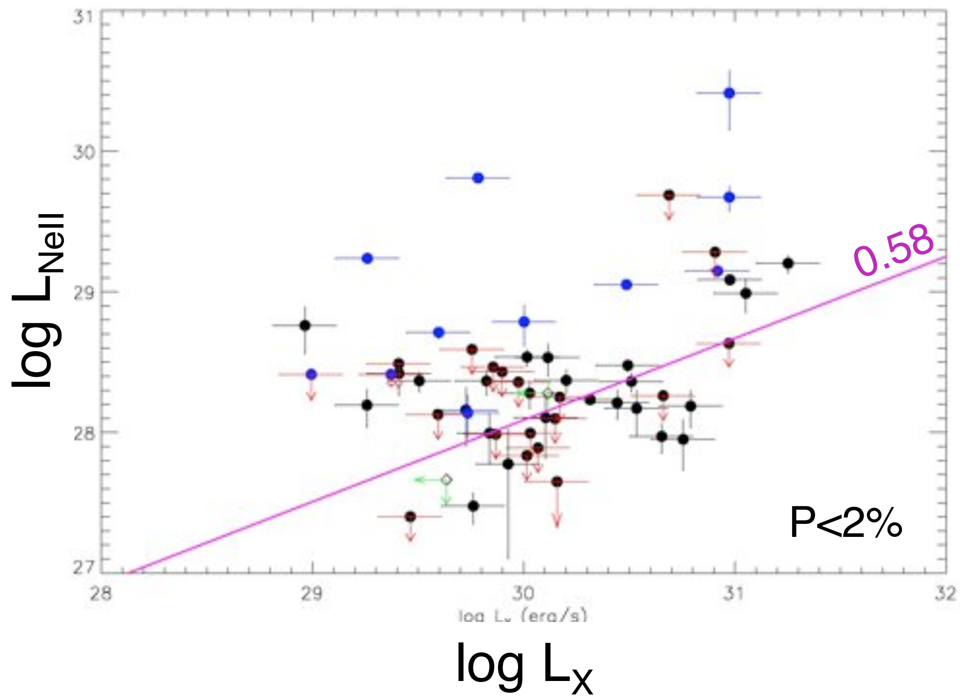
Lahuis et al. (2007) - 76 targets (CTTS+HAeBe), fully reanalyzed
Pascucci et al. (2007) - 6 targets
Espaillat et al. (2007) - 3 targets
Ratzka et al. (2007) - 1 target
J. Najita/J. Carr (GO) - 12 targets
Herczeg et al. (2007) - 3 targets
van Boekel et al. - 2 targets (T Tau)

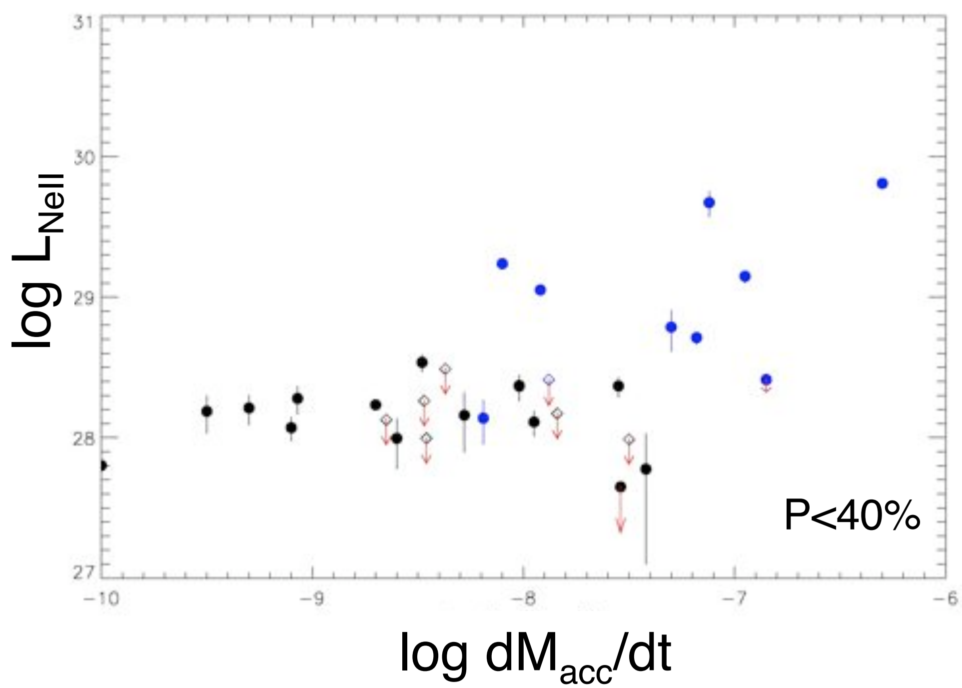
X-rays from our archival analysis of XMM-Newton & Chandra data:

all data were coherently reduced and analyzed, using same spectral-fit methods

Other data (dM_{acc}/dt, dM_w/dt, [O I]λ6300 data, etc) taken from literature

This results in sample of 86 CTTS: 53 [Ne II] detections, 33 UL
54 X-ray detections, 2 UL
33 [Ne II] & X-ray detections





Results

Systematics
between [Ne II] luminosity, X-ray luminosity, and mass accretion rate

1) both parameters show trends
2) but with large scatter
3) outflow/jet sources (in blue) show excess [NeII] emission

(P = probability for absence of correlation, based on three conventional tests)
(blue ● = objects with known jets)
(pink line: linear regression with slopes)

For [Ne II] formation, one needs: (1) gas, (2) radiation:

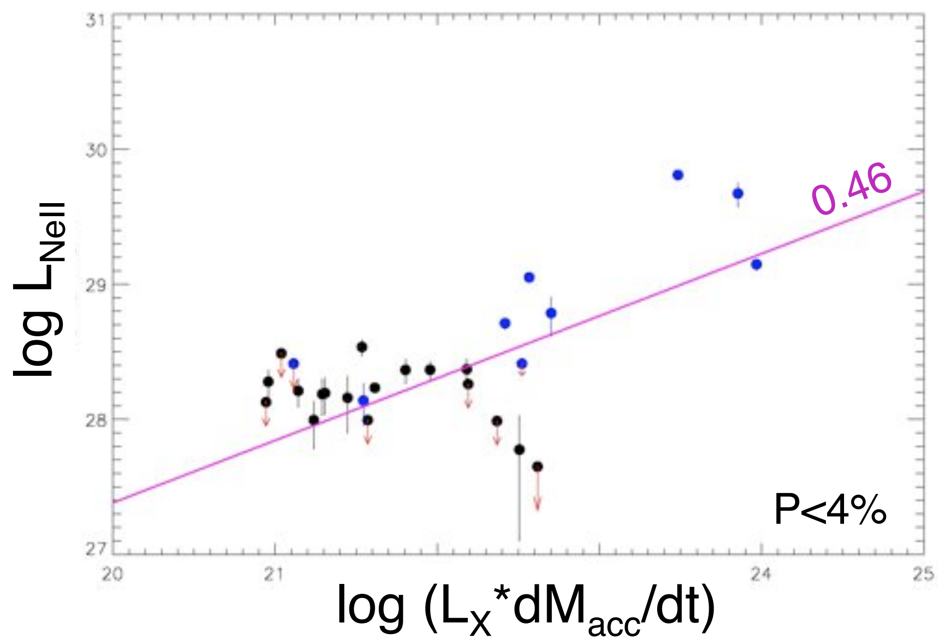
1. Use dM_{acc}/dt as a proxy for mass outflow rate ("gas")

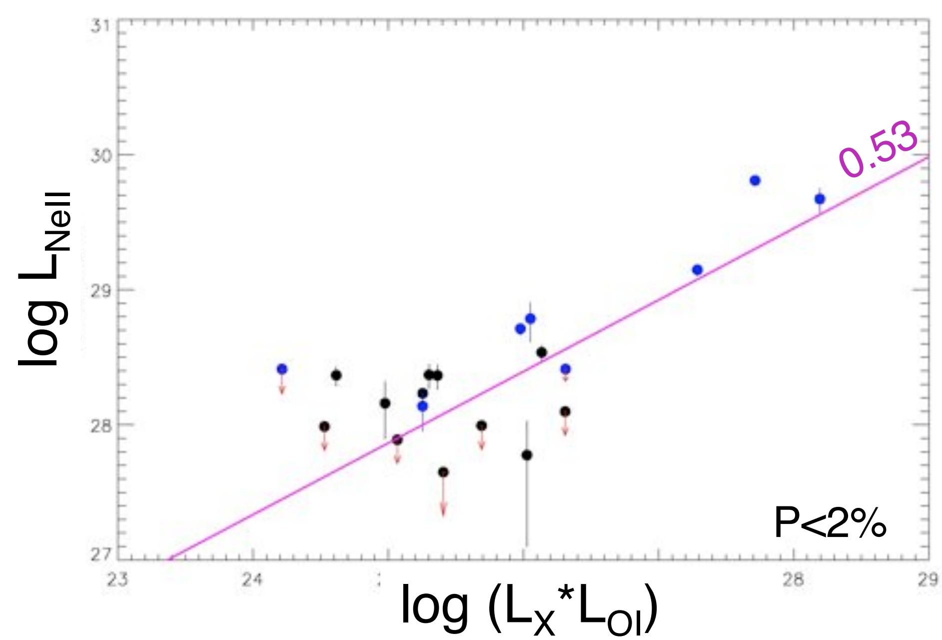
2. multiply by L_X ("radiation")

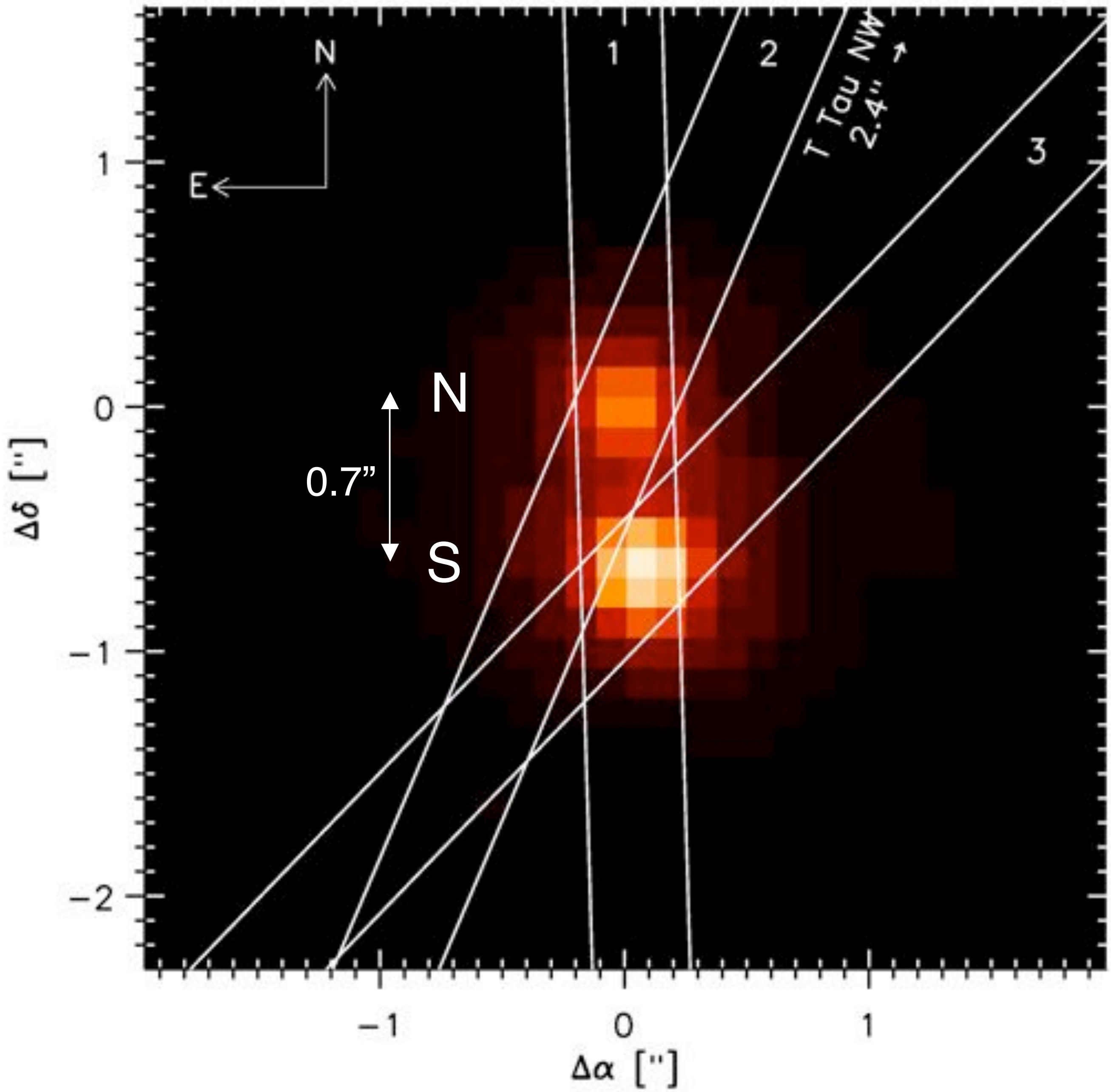
Even better: use [OI] λ6300 as an indicator for jet/outflow gas:

$L([OI]\lambda6300) * L_X$

cleanest correlation





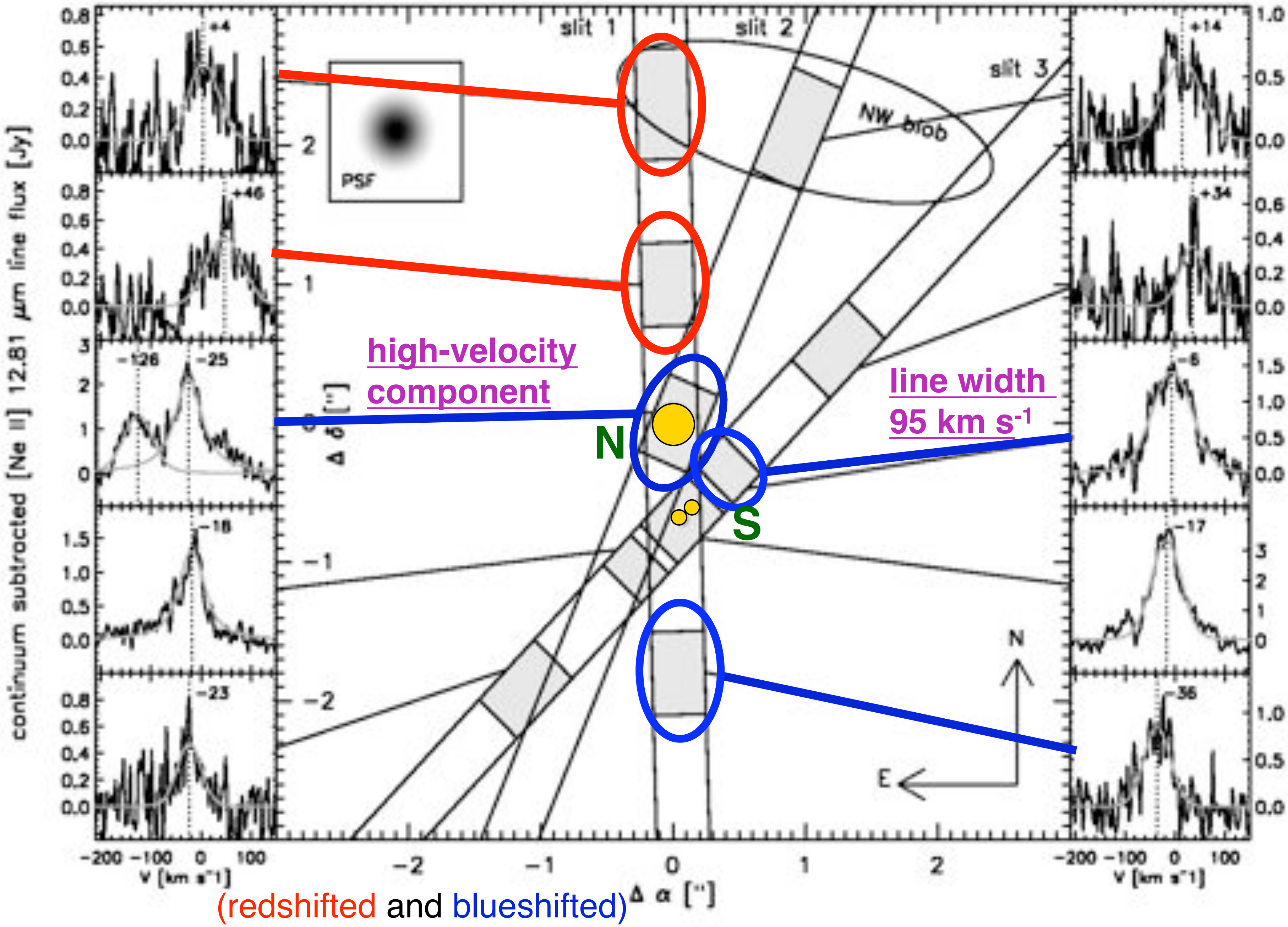


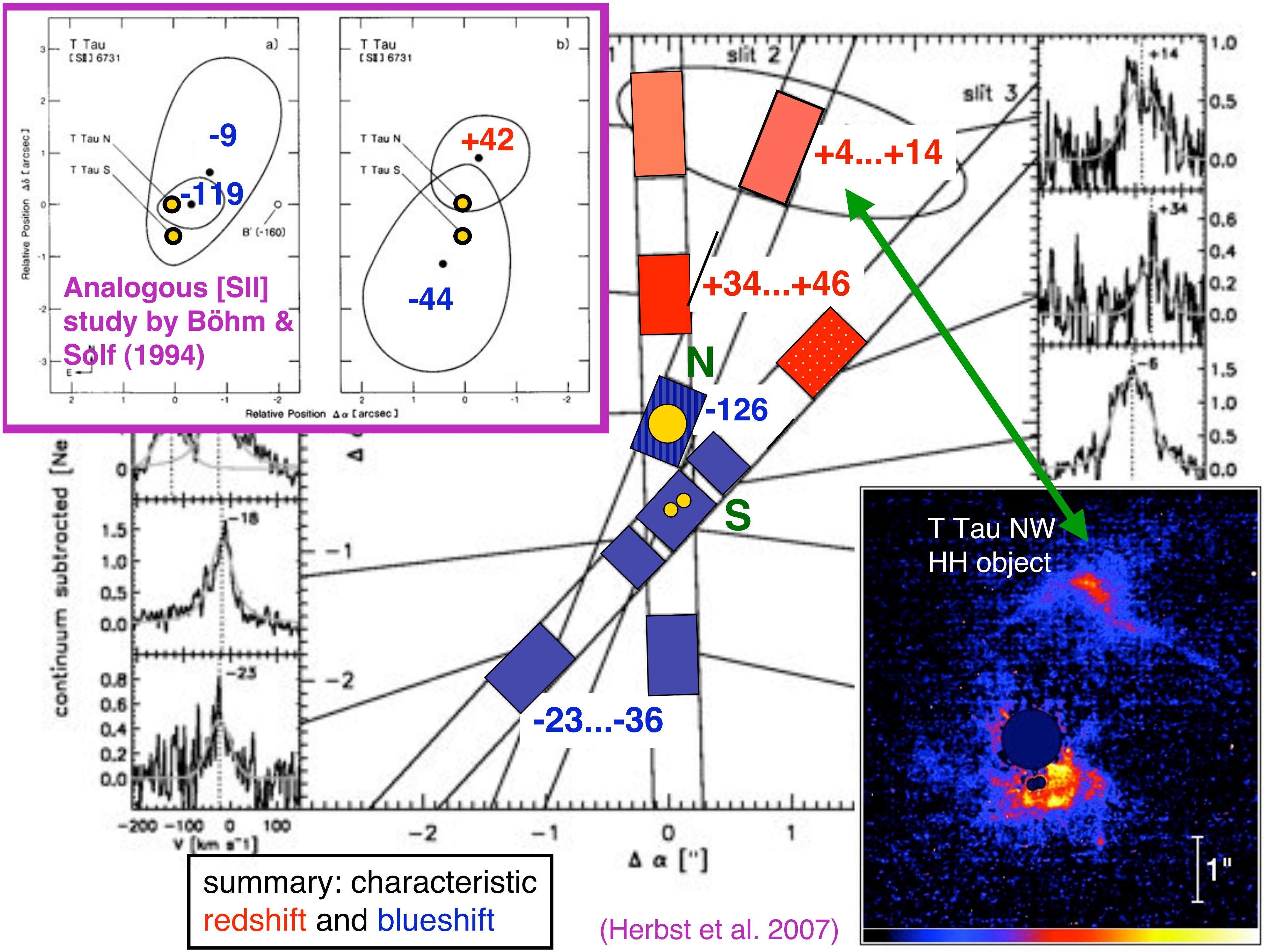
Case Study: T Tau observed with VLT VISIR

- resolving power R = 30,000
- used 3 slit orientations
- slit width 0.4"

(R. van Boekel, M. Guedel, Th. Henning, F. Lahuis 2008, submitted)

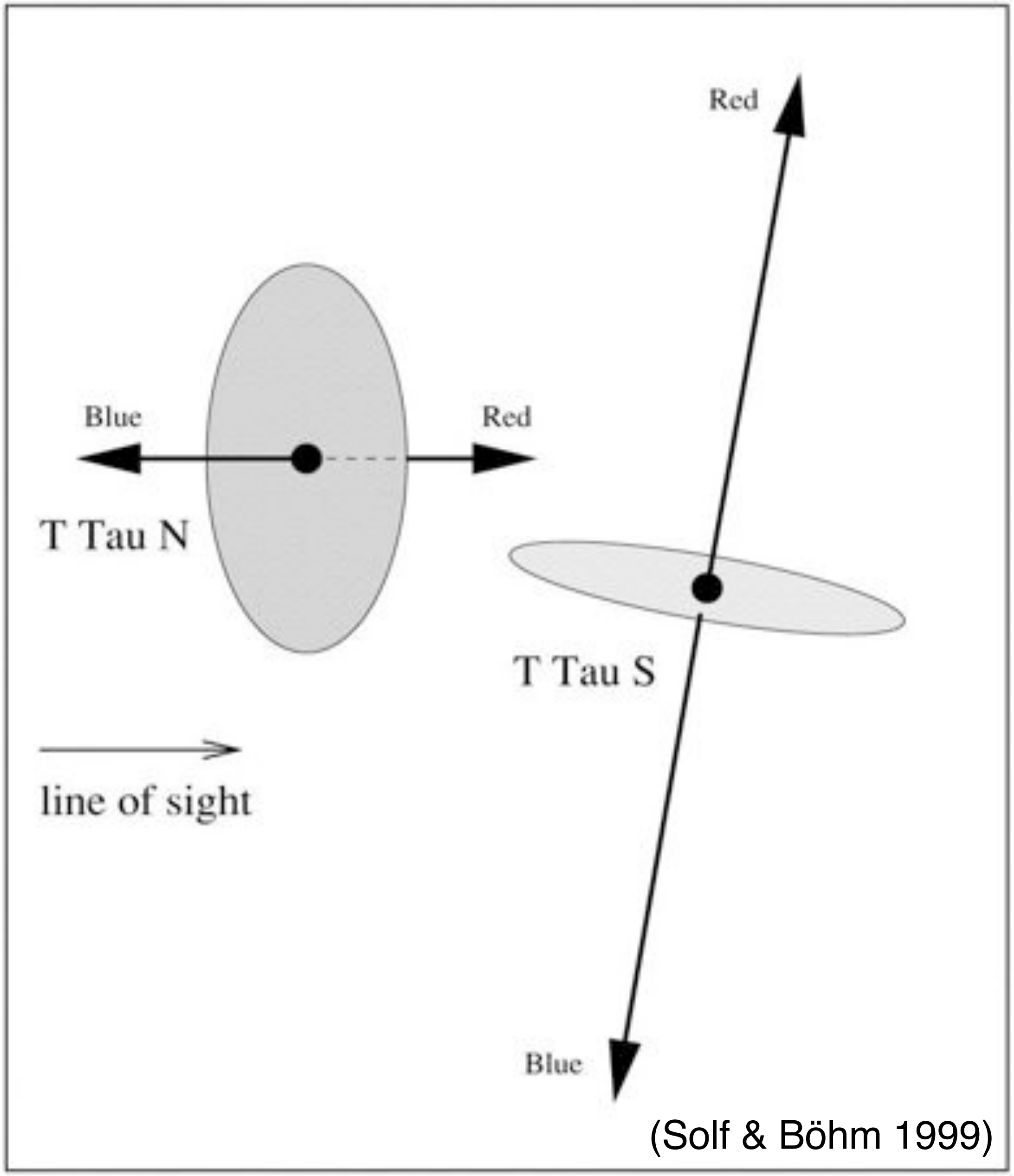
Example [Ne II] lines from different regions around T Tau





T Tau
[SII] 6731
a)
b)
T Tau N
T Tau S
-9
-119
B' (-160)
+42
-44
Relative Position Δδ [arcsec]
Relative Position Δα [arcsec]
Analogous [SII] study by Böhm & Solf (1994)
slit 2
slit 3
+4...+14
+34...+46
N
-126
S
-23...-36
T Tau NW
HH object
1"
continuum subtracted [Ne
V [km s⁻¹]
Δ α ["]
summary: characteristic
redshift and blueshift
(Herbst et al. 2007)

Possible Geometry of the T Tau Outflows



(Solf & Böhm 1999)

Simple Ionization and Emissivity Estimate (e.g. Glassgold et al. 2007)

1. Ionization rate

$$\zeta = \int_{E_0}^{\infty} F_{\rm X}(E)\sigma(E)\frac{E}{36\ {\rm eV}}dE$$

- $F_{\rm X}(E)$: spectral photon flux density
- $\sigma(E)$: ionization cross section
- $\frac{E}{36\ {\rm eV}}$: #photoelectrons per primary ionization

2. Ionization equilibrium

$$\zeta_0 x_0 + n_{\rm H}(\alpha_2 x_e + k_2) x_2 = \zeta_1 x_1 + n_{\rm H}(\alpha_1 x_e + k_1) x_1$$

formation of Ne^+:

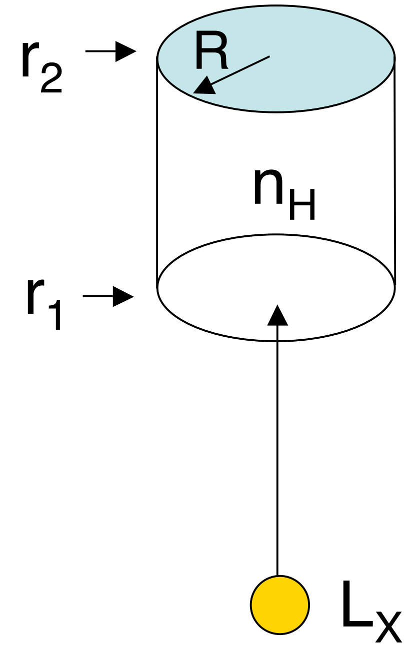
- $\zeta_0 x_0$: photoioniz. $Ne \rightarrow Ne^+$
- $\alpha_2 x_e$: recombination $Ne^{++} \rightarrow Ne^+$
- k_2: CX $Ne^{++} \rightarrow Ne^+$

destruction of Ne^+:

- $\zeta_1 x_1$: photoioniz. $Ne^+ \rightarrow Ne^{++}$
- $\alpha_1 x_e$: recombination $Ne^+ \rightarrow Ne$
- k_1: CX $Ne^+ \rightarrow Ne$

$x_{0,1,2}$ fractional abundance of Ne, Ne^+, Ne^{++} , and similar eq. for Ne^{++}

3. Define emission region and irradiating spectrum:
   Source distance from star $r = r_1 \ldots r_2$, radius R
   Source density n_H
   Stellar L_X and kT
   X-ray spectral range



4. Assume ambient <u>electron density</u>
   (from shocks etc, $x_e \approx 0.1$)

5. <u>Line flux</u> = emissivity of transition * V

<u>Examples</u>:

$L_X = 2\text{x}10^{30}$ erg s^{-1}	$1.5\text{x}10^{31}$ erg s^{-1}
r = 5-15 AU, R = 5.6 AU	300-400 AU, R = 150 AU
$n_H = 10^6$ cm^{-3}	$n_H = 10^5$ cm^{-3}
$L \approx 1.3\text{x}10^{28}$ erg s^{-1}	$L \approx 1.1\text{x}10^{29}$ erg s^{-1}

Alternative Models

Although we suggest here that jets and outflows produce [Ne II] emission, we do not exclude other contributions:

Alternative 1: Part of emission from disk surface layer

(*Glassgold et al. 2007, Ercolano et al. 2008)*

Alternative 2: from photoevaporative flow *(Alexander 2008),* but $v \approx 10$ km s^{-1}

Alternative 3: from shocks in jets: *but why is there a trend with X-rays?*

One needs high $v_{shock} \approx 100$ km s^{-1}

(Hollenbach & McKee 1989; D. Hollenbach, priv. comm)

Alternative 4: from ionization and excitation in strongly absorbing accretion flows close to the star.

(see Güdel et al. 2008, A&A, 478, 797)

Summary

[Ne II] 12.81μm luminosity is only moderately correlated with L_X or dM_{acc}/dt

Better correlation is found if jet/outflow parameters are involved

CTTS with jets show high [Ne II] 12.81μm fluxes

T Tau N+S: we find spatially resolved [Ne II] emission
[Ne II] line is shifted up to 126 km s^{-1},
line is broadened up to 90 km s^{-1}:
→ clear evidence for contribution by outflows/jets

Further contributions from disk surface layers, photoevaporative flows, or accretion flows are not excluded

Details in forthcoming papers (van Boekel et al. 2008, Güdel et al. 2008)