Planet-Forming Disks
A workshop to honor Antonella Natta

Low-velocity Winds: what we know and what they are telling us on disk dispersal

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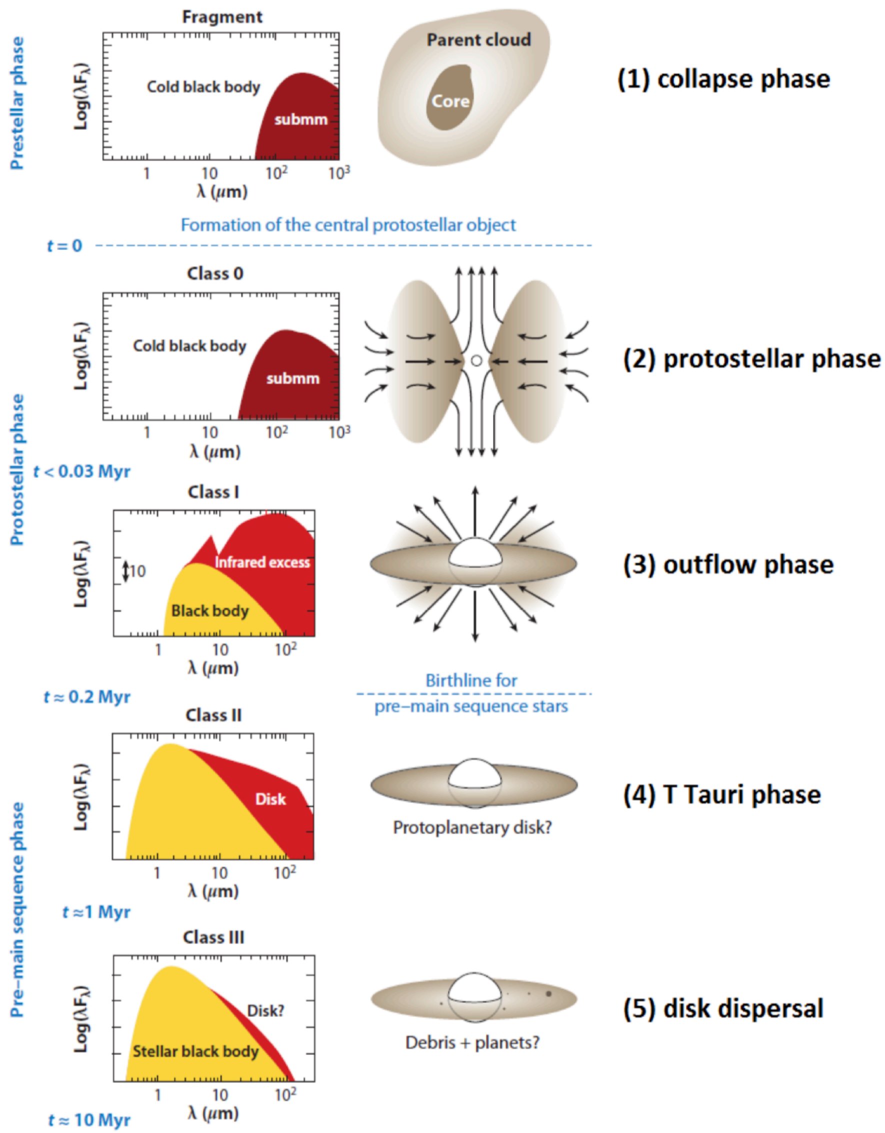
Disk Evolution



Disk formation

Disk dissipation

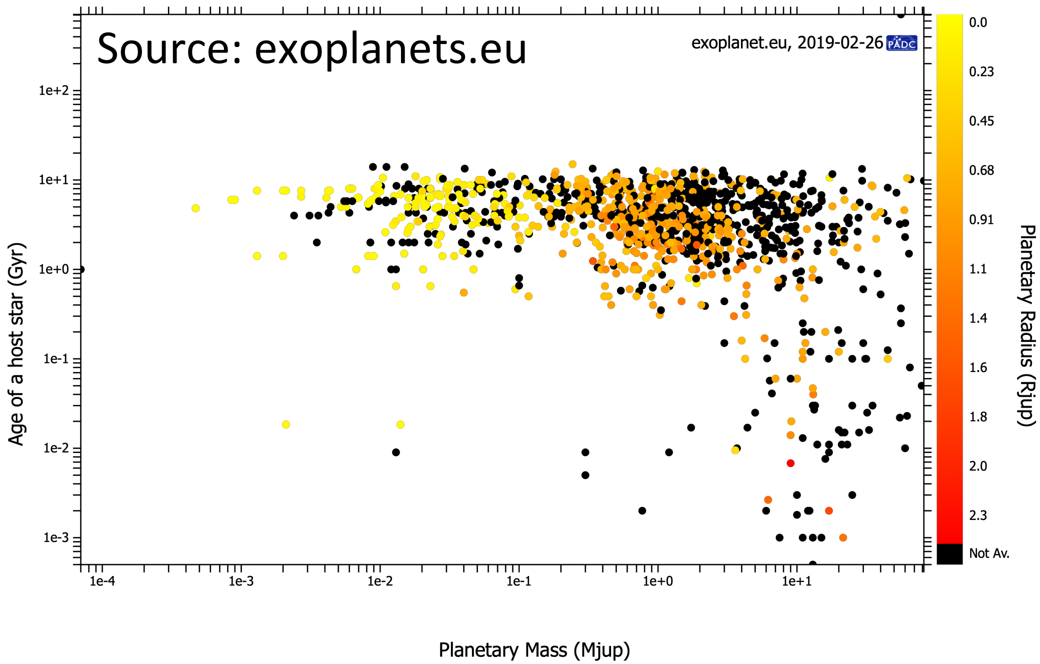
The final stage of disk evolution is the disk dispersal

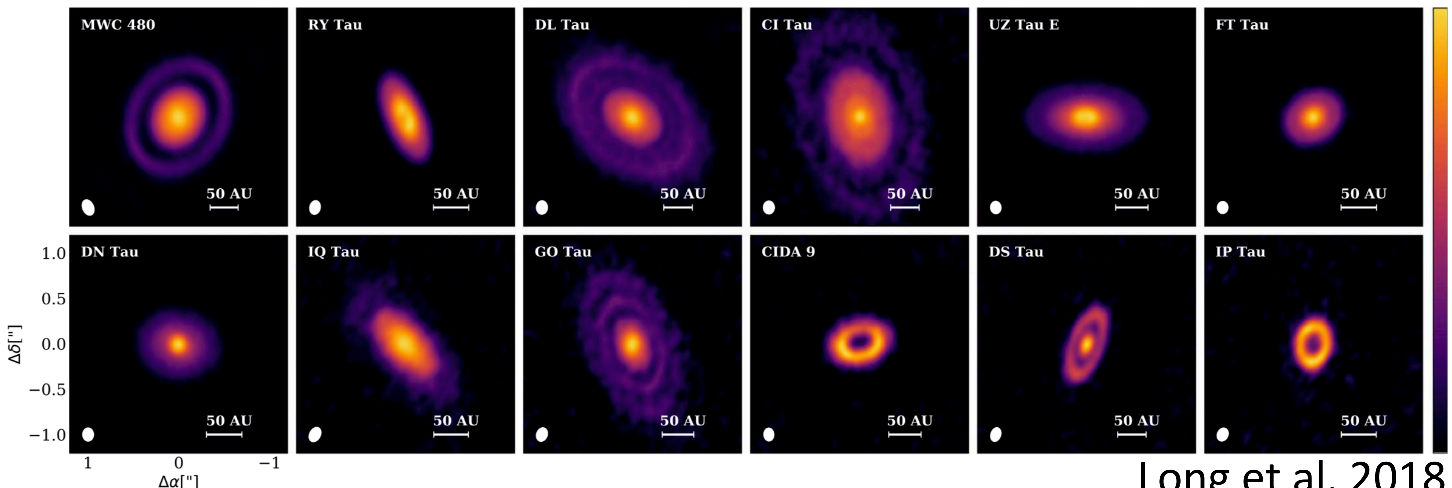
We need to Disperse the Disk!

Why?

Planets (byproducts of disks) are observed around adult stars

Disks (natal environment of planets) are observed around young stars



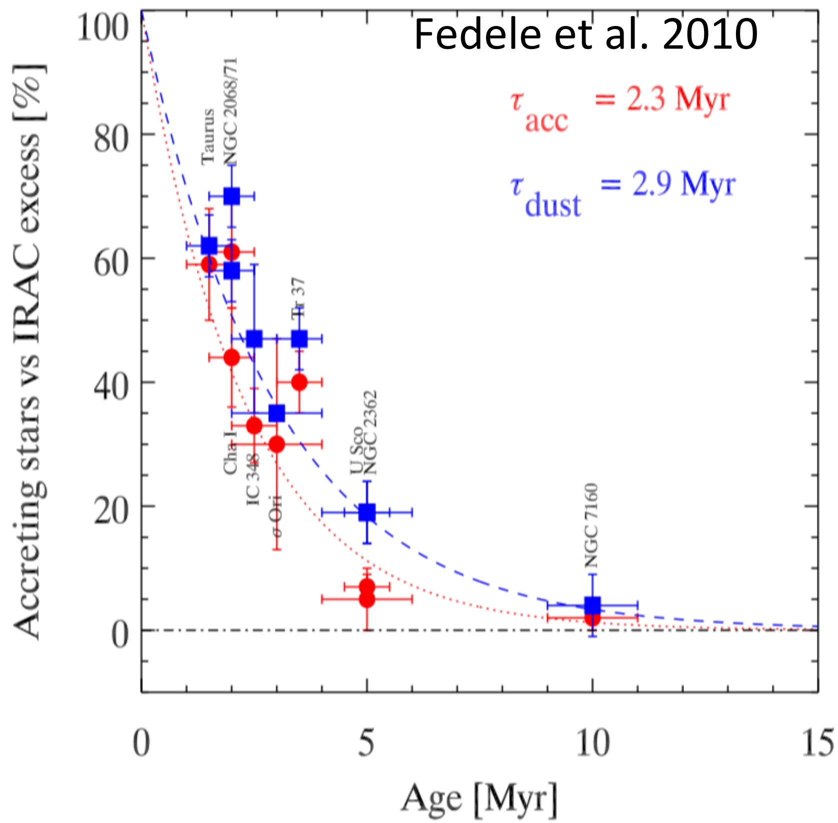


Long et al. 2018

We need to Disperse the Disk!

When?

Within approx. 10 Myrs the fraction of accreting stars is as low as a few %



We need to Disperse the Disk!

How?

Different processes

Inward dispersal → Accretion

Reprocessing of material → Planet formation

Outward dispersal → Outflows/Winds

Different mechanisms

Jets

Photoevaporation

Magnetically driven disk winds

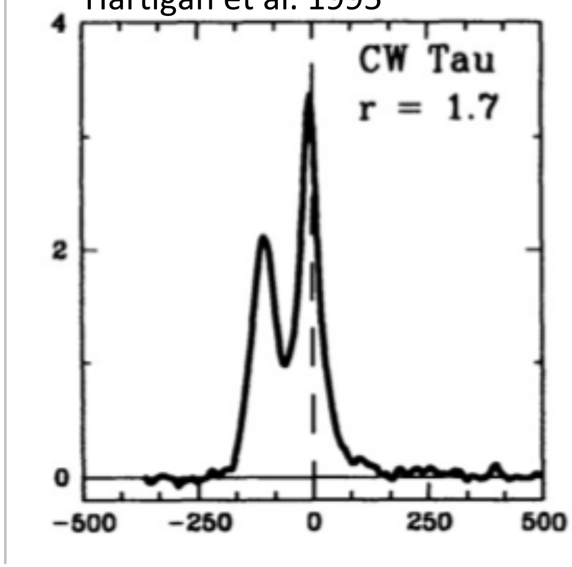
How Do we investigate Outflows/Winds?

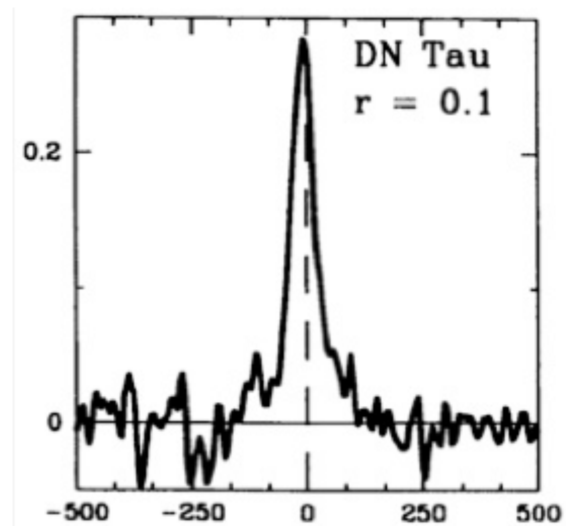
In poorly embedded young stars → optical atomic forbidden lines

HVC: comes from the warm and dense shocked gas along the jet stream

LVC: ubiquitous in high- and low-accretors, comes from denser gas

Hartigan et al. 1995

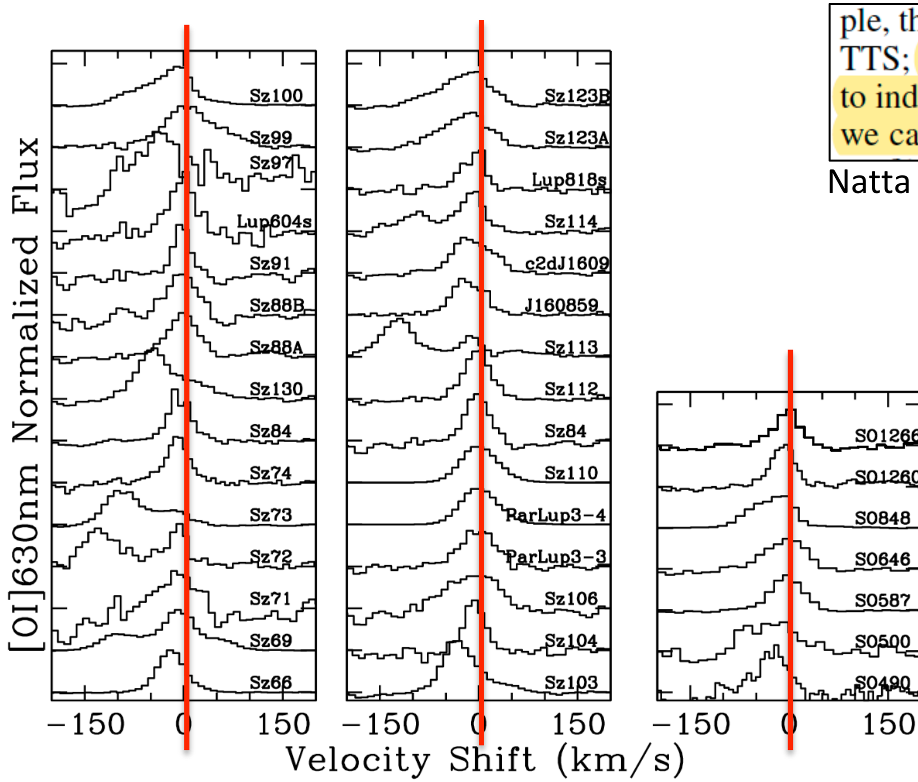




High-accretion rate: $\dot{M}_{acc} \sim 10^{-6}\ M_{\odot}/yr$

Low-accretion rate: $\dot{M}_{acc} \sim 10^{-9}\ M_{\odot}/yr$

Slow-Winds traced by the LVC



ple, the properties of the LVC previously observed in solar-mass TTS; the small blue shift of the line peaks, in particular, seem to indicate their origin in outflowing, low velocity matter, which we call *slow wind*. We do not find any correlation between line

Natta et al. 2014

Slow winds driven by:

Photoevaporation

Magnetohydrodynamical effects

Slow-Winds traced by the LVC

1983

BLUESHIFTED FORBIDDEN LINES IN T TAURI STARS*

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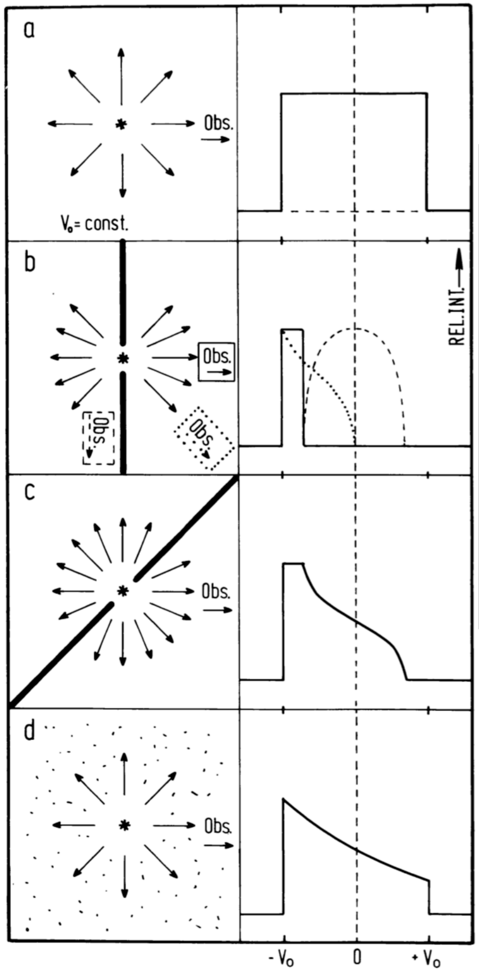
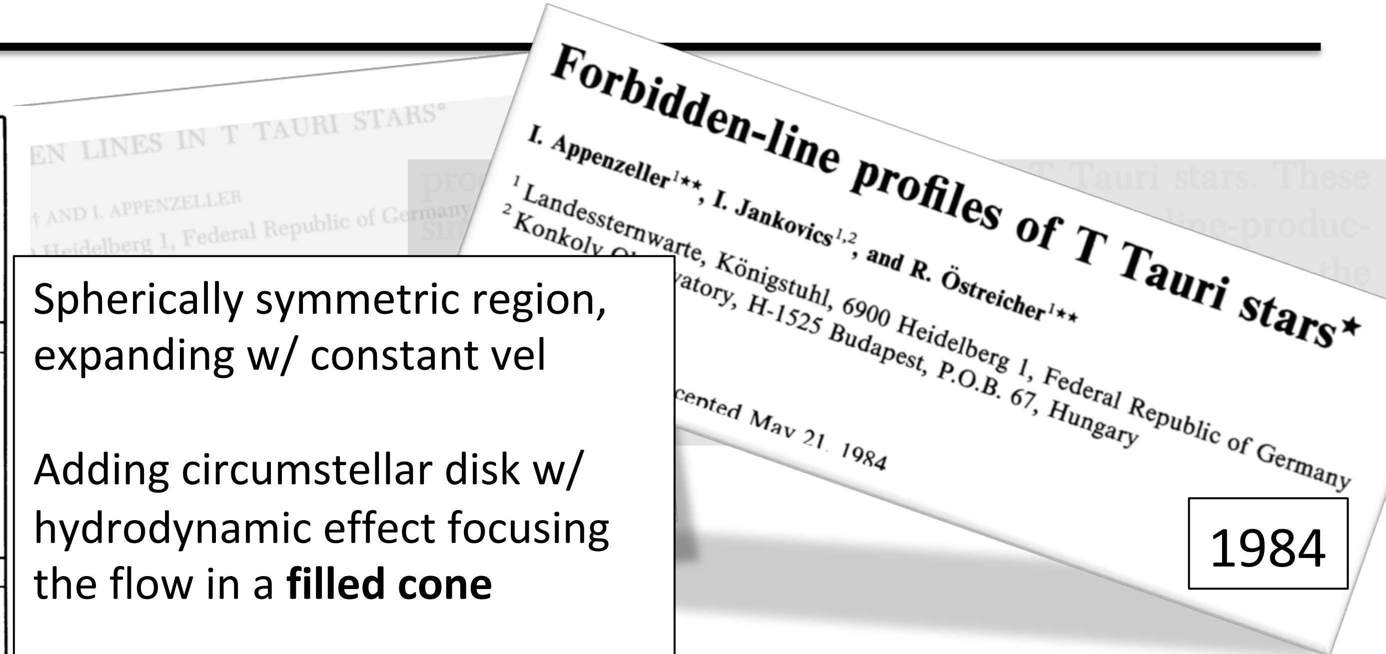
Received 1983 June 20

We report observational evidence for a predominance of blueshifts among the radial velocities of the forbidden lines in the spectra of T Tauri stars. The similarities of the velocity distributions and spectra suggests a related physical nature of

producing gaseous envelopes of the T Tauri stars. These similarities may indicate that the forbidden-line-producing circumstellar regions of the T Tauri stars are, like the H-H objects, a phenomenon of the nonisotropic mass outflow from T Tauri stars, only occurring much closer to the star than in the case of the resolved H-H objects.

Slow-Winds traced by the LVC




Forbidden-line profiles of T Tauri stars*

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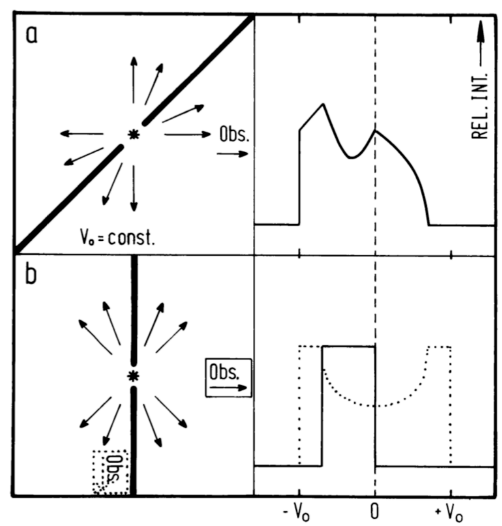
...cepted May 21, 1984

1984

Spherically symmetric region, expanding w/ constant vel

Adding circumstellar disk w/ hydrodynamic effect focusing the flow in a **filled cone**

All profiles are single-peaked…



… **hollow cone** geometry: "flows or emission patterns where the line emission is restricted to the volume outside the surfaces of the cones"

More line profiles (observations and models) in, e.g., Edwards et al. 1987

Slow-Winds traced by the LVC

1988

JETS FROM T TAURI STARS: SPECTROSCOPIC EVIDENCE AND COLLIMATION MECHANISM

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Received 1988 April 1; accepted 1988 June 7

ABSTRACT

We argue, based upon analysis of observed [O I] λ6300 line profiles, that two separate gas components contribute to the forbidden line emission from T Tauri stars. There is a high-speed component due to a wind from the star, and a low-speed component due to a wind from the circumstellar disk and/or a warm disk corona. Further, most of the high-speed gas particles have velocity vectors nearly parallel to one another, indicating a well-collimated flow. We ascribe the collimation of an initially radially expanding wind to the effect of the magnetic field produced by currents in the circumstellar disk. Assuming that this magnetic field is roughly parallel to the stellar rotation axis, the stellar wind will be collimated into bipolar jets. We estimate that the disk radius R_D is ~ 100 AU, the disk magnetic field B_D is ~ 0.1 G, and the stellar mass-loss rate $\dot{M}$ is $\sim 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$. The orientation of the disk can be deduced from the velocity displacement of the jet emission from the stellar rest velocity.

... Thus, whereas they attempt to model the whole ... by a stellar wind, we believe the profile is made up of emissions from *two* separate components, namely, a high-speed component due to a stellar wind and a low-speed component due to a wind from the circumstellar disk (the escape velocity from which is less than ~ 10 km s^{-1} as opposed to that of greater than ~ 200 km s^{-1} from the stellar object) and/or a warm disk corona. To us it is the low-speed component that produces the emission peak at v_*, so *the line profile from the* ... *single-peaked*. This is the blue peak in the ... velocity structure. Its narrow width ...

DISK ACCRETION AND MASS LOSS FROM YOUNG STARS

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Received 1995 January 9; accepted 1995 May 2

1995

Slow-Winds traced by the LVC

The interpretation of the SLOW WINDS traced via the LVC has been reached following different paths:

- Increasing the resolution

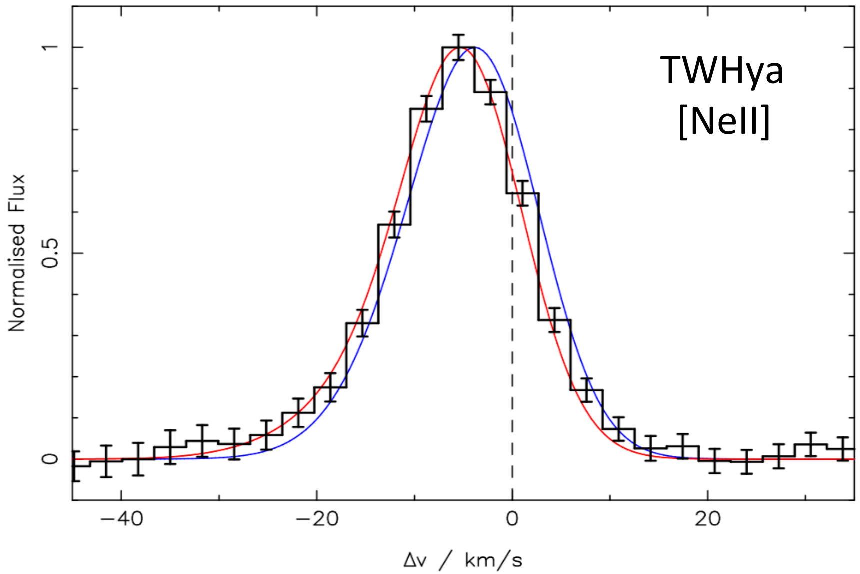
- Enlarging the sample

- Comparing observational results to always more sophisticated theoretical model

Observational Wind Diagnostics

Slow Winds can be either thermally or magnetically driven

Thermally driven *photoevaporative wind*



Vpeak ≈ -5.5 km/s → slow wind

e.g., Gorti et al 2015
Alexander et al. 2013,
Pascucci et al. 2011
Ercolano & Owen 2010
Pascucci & Sterzik 2009
Alexander et al. 2008

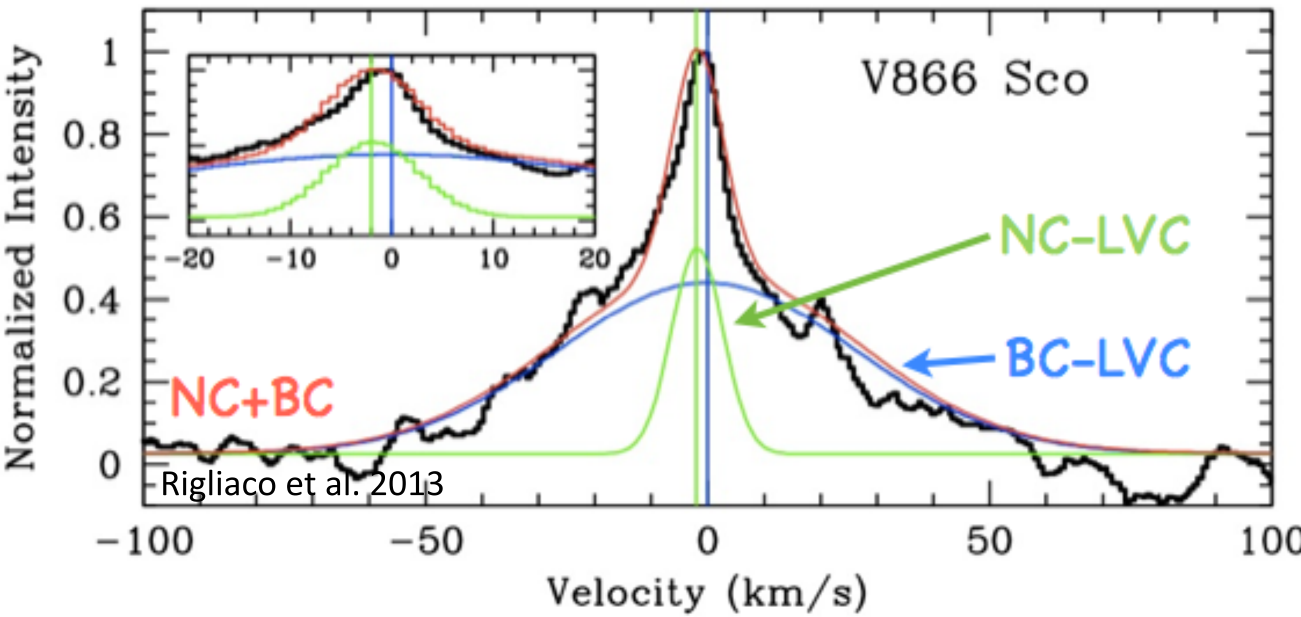
Good news I:
[NeII] most promising indicator of photoevaporative wind;

Good news II:
Theoretical models predict line luminosities and profiles;

Problem:
Both X-rays and EUV models reproduce quite well the line profile, but the predicted mass loss rate is 2 OoM different.

Observational Wind Diagnostics

UVES/VLT observations (resolution in the VIS ~3.5 km/s):



Broad Component (BC) centrally peaked and broad → bound gas

Narrow Component (NC) blueshifted and narrow → unbound gas

Good news:
NC of the ubiquitous LVC might be a (ubiquitous) photoevaporative wind tracer;

Problem:
Results TBC enlarging the sample

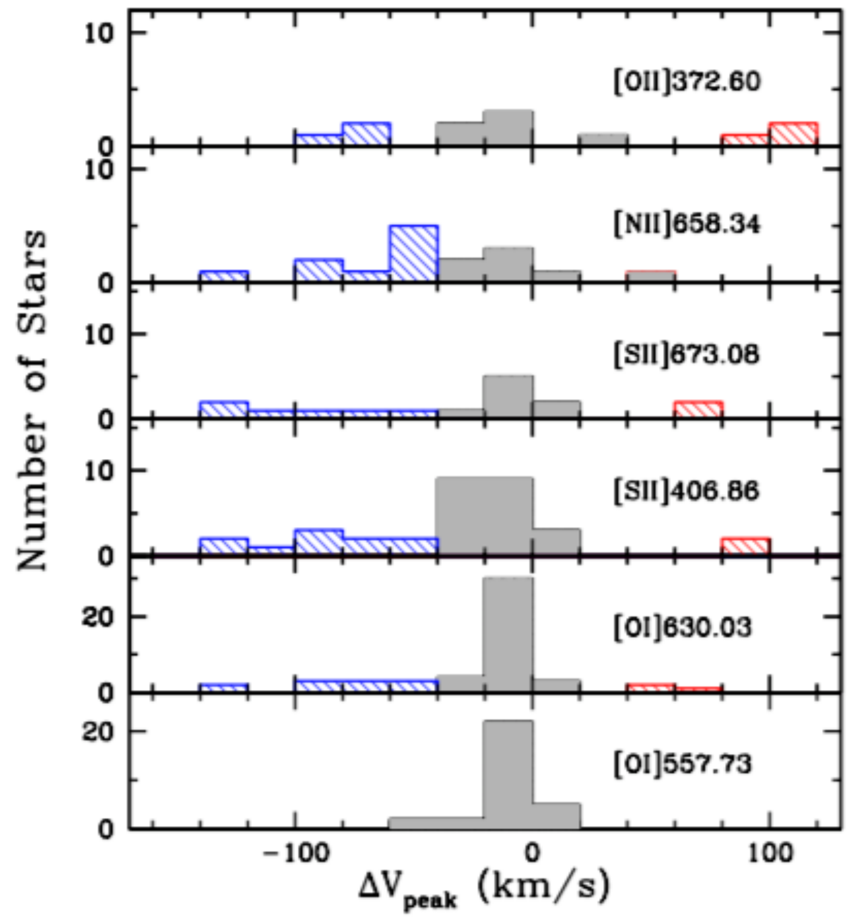
Observational Wind Diagnostics

X-Shooter observations (resolution in the VIS ~35 km/s):

Analysis of forbidden lines ([OII], [OI], [NII], [SII]) in a sample of 44 YSOs, focusing on the LVC ([OI6300Å] line detected in 86% of the sample)

Pros: relatively large sample
Cons: “low” spectral resolution

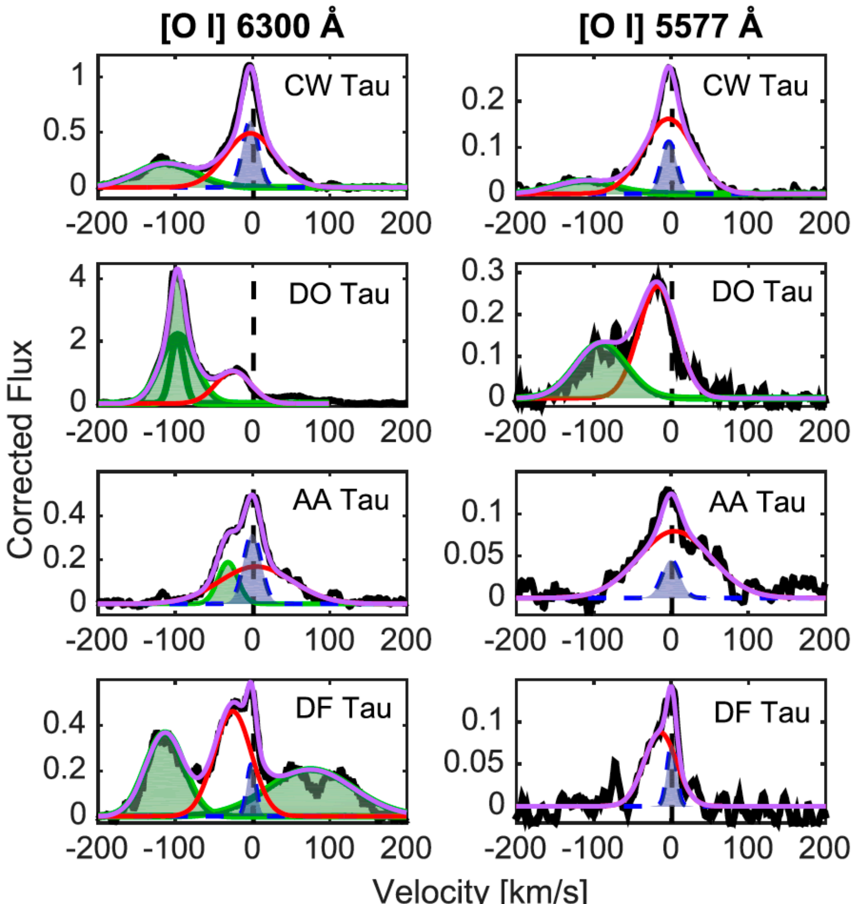
Problem:
“The comparison with the prediction of outflow models is difficult, and so far the origin of the slow TTS winds remain elusive”



Natta et al. 2014

Observational Wind Diagnostics

Keck/HIRES observations (resolution in the VIS ~7 km/s):



Simon et al. 2016

Analysis of forbidden lines in a sample of 30 YSOs, focusing on the kinematic analysis of multiple components (broad and narrow) in the LVC

We confirm that the deconvolution of the LVC in NC and BC is a consolidated result

NC+BC in 13/30
BC only in 12/30
NC only in 5/30

Observational Wind Diagnostics

Keck/HIRES observations (resolution in the VIS ~7 km/s):

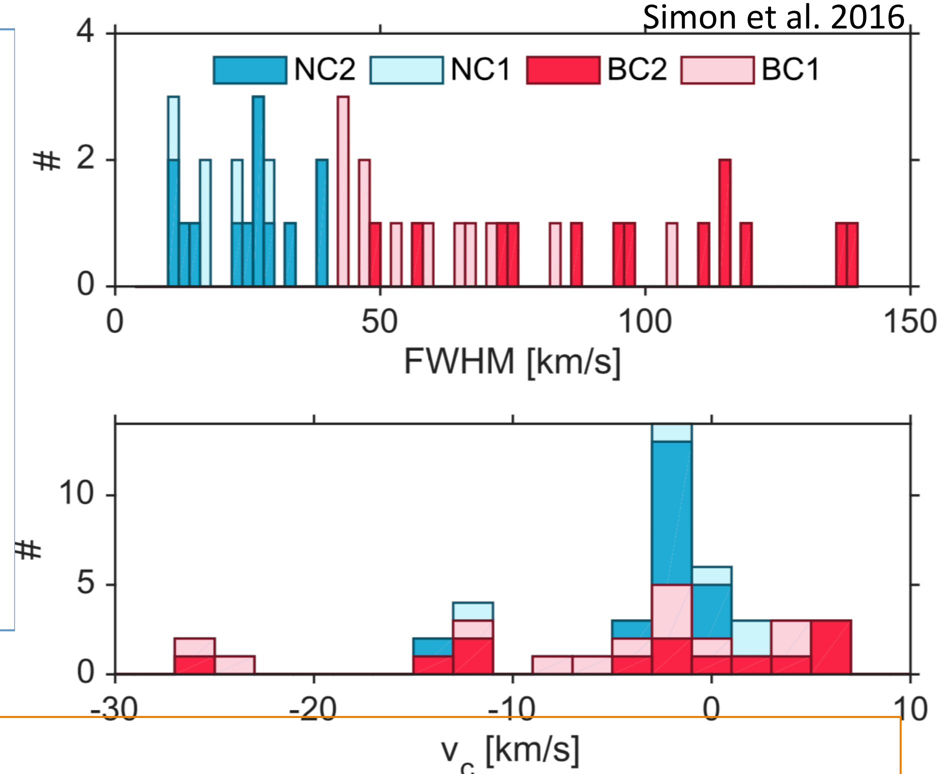
Differences in the behavior of V_{peak} in the 2 components:

- NO redshifted velocity in NC
- Average peak vel:

  $V_{peak\ NC} \sim -2.5$ km/s

  $V_{peak\ BC} \sim -3.7$ km/s
- Stars with higher Lacc are more likely to have blueshifted vel in the BC (no correlation seen in NC)

Simon et al. 2016



Good news:

NC and BC have two different kinematic properties (as found by Rigliaco+2013);

Problem:

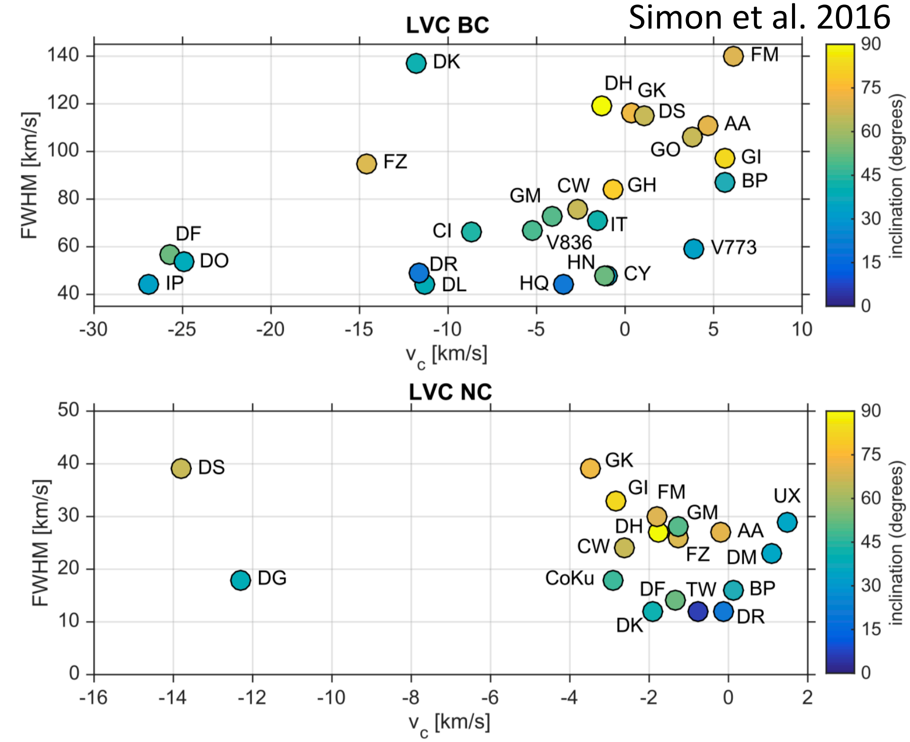
Cannot assess whether NC and BC both arise from the same phenomenon from different radial ranges in the disk, or in different formation scenarios.

Observational Wind Diagnostics

BC:
Larger FWHM - larger inclination
Decreasing v_{peak} – increasing inclination

Scenario:
BC comes from gas at the base of MHD disk wind broadened by Keplerian rotation inside 0.5 AU (emitting region inside gravitational radius → photoevaporation cannot occur)

Simon et al. 2016



NC:
Larger FWHM - larger inclination
No correlation v_{peak} - inclination

Scenario:
NC might come from gas broadened between 0.5-5 AU → photoevaporation can occur.

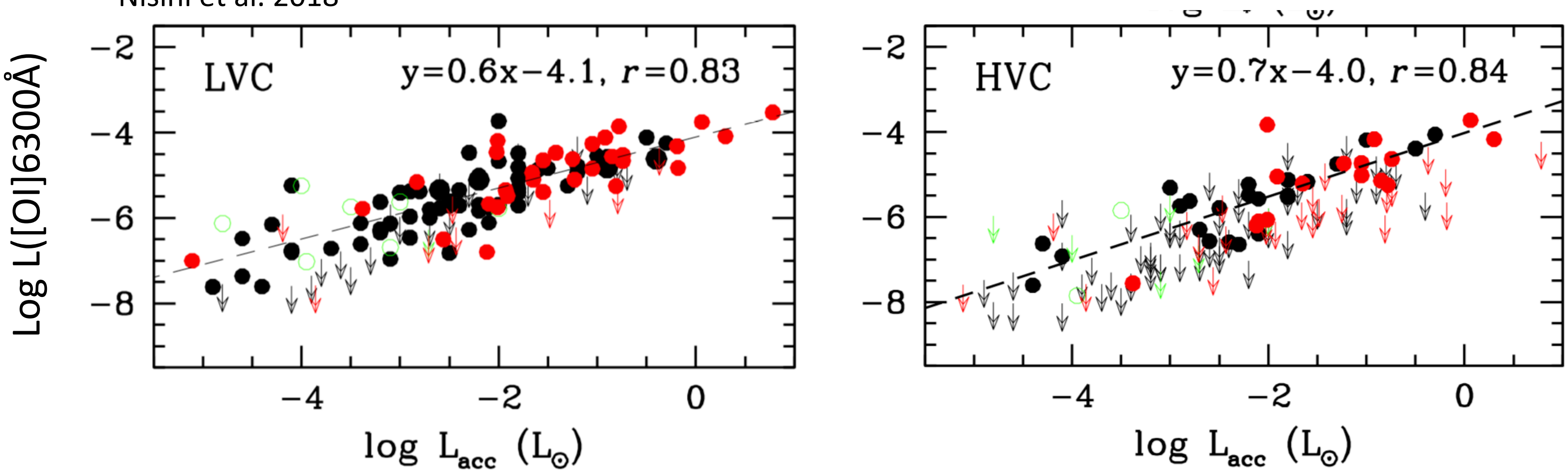
Observational Wind Diagnostics

X-Shooter observations (resolution in the VIS ~35 km/s):

Analysis of forbidden lines in a sample of 131 YSOs, focusing on the HVC ([OI]λ6300Å-HVC line detected in 30% of the sample, LVC in 77%)

Common mechanism for the formation of HVC and LVC:
magnetically driven disk-winds

Nisini et al. 2018

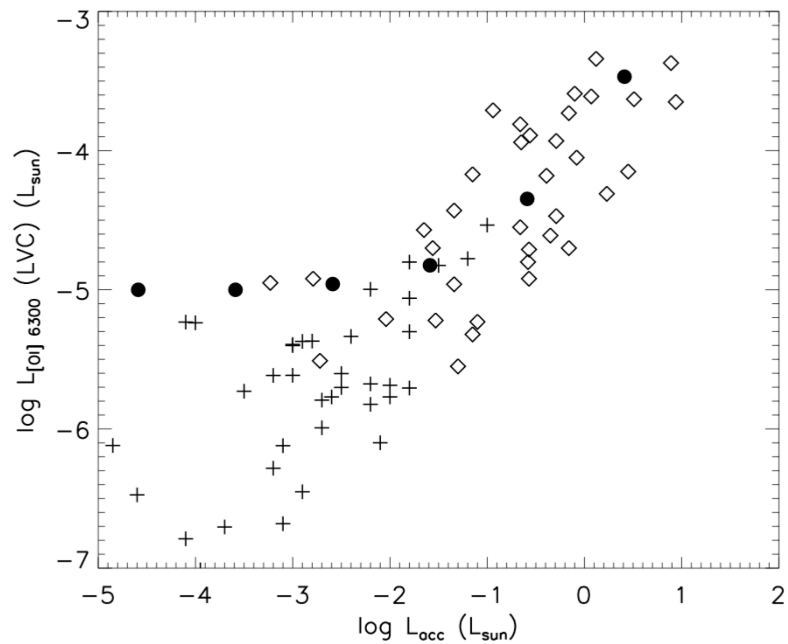


Observational Wind Diagnostics

HVC: $L_{[OI]\text{-}HVC} - L_{acc}$ is related to the accretion-driven jet-formation model.

LVC: correlation explained by the underlying correlation between line excitation and EUV flux reaching the disk (Ercolano & Owen 16)

Ercolano & Owen 2016



HVC and LVC should not follow the same correlation as they arise from distinct mechanisms.

HVC and LVC from common mechanism: *magnetically driven disk-winds*

HVC from collimated high-velocity jets

LVC from un-collimated slow-winds originating from the outer streamlines

Observational Wind Diagnostics

FLAMES observations (resolution in the VIS ~11 km/s):

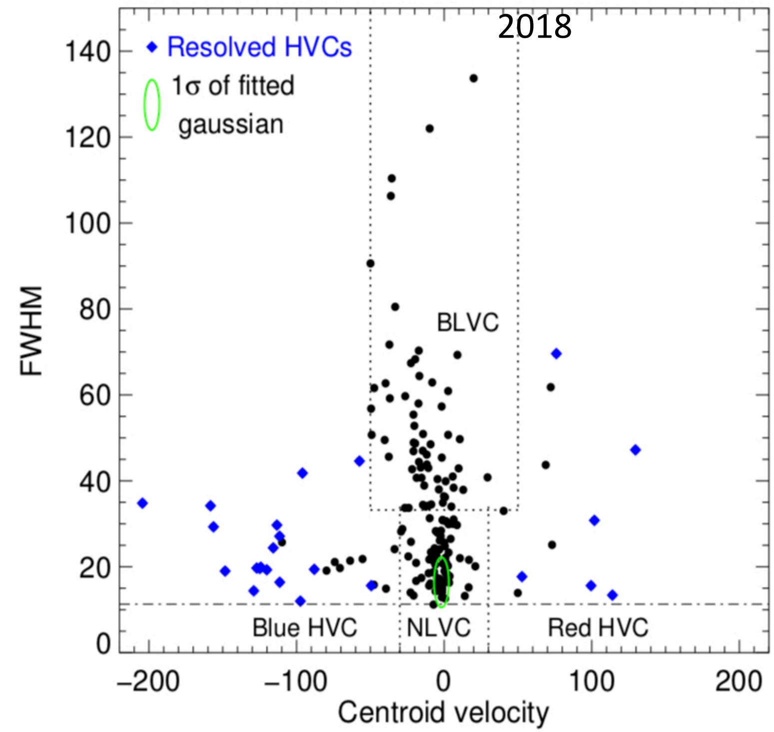
Analysis of the [OI]λ6300Å line in the NCG2264 open cluster. Detection of the line in 108 CTTSs (out of the 184 observed − 64%) (HVC line detected in 28% of the sample)

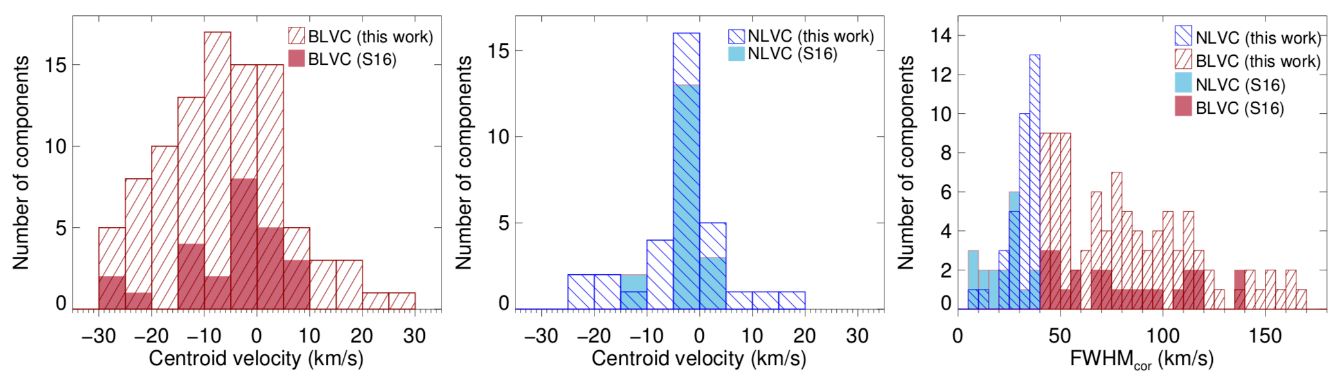
Narrow-LVC from photoevaporative disk wind − but no conclusive evidence

Broad-LVC represents the base of the jet traced by the HVC

HVC from jets

McGinnis et al. 2018





Observational Wind Diagnostics Summary and What Next

- The presence of 2 kinematic components in the LVC (Narrow and Broad) is a consolidated results;
- There is still NO consensus on the origin of the 2 different components: MHD disk winds, photoevaporation, or a combination of both;
- the analysis of one optical forbidden lines alone is not the enough to pin down the origin of the winds traced via the LVC (more forbidden lines needed)
- Winds MATTER! (not only accretion)… the way we disperse the disk has strong impact on the planets we are forming in the disk itself (next talks)

How Do we investigate winds…what Next

Acquisition of spectra at the best resolution (UVES)

PI Rigliaco: extending the sample to CTTSs → aimed at resolving the LVC gas kinematic components

PI Manara: extending the sample TD → aimed at determining where the forbidden lines are emitted within the disk

PI Nisini: extending the sample to accretors with and without jets → aimed at resolving their kinematic components

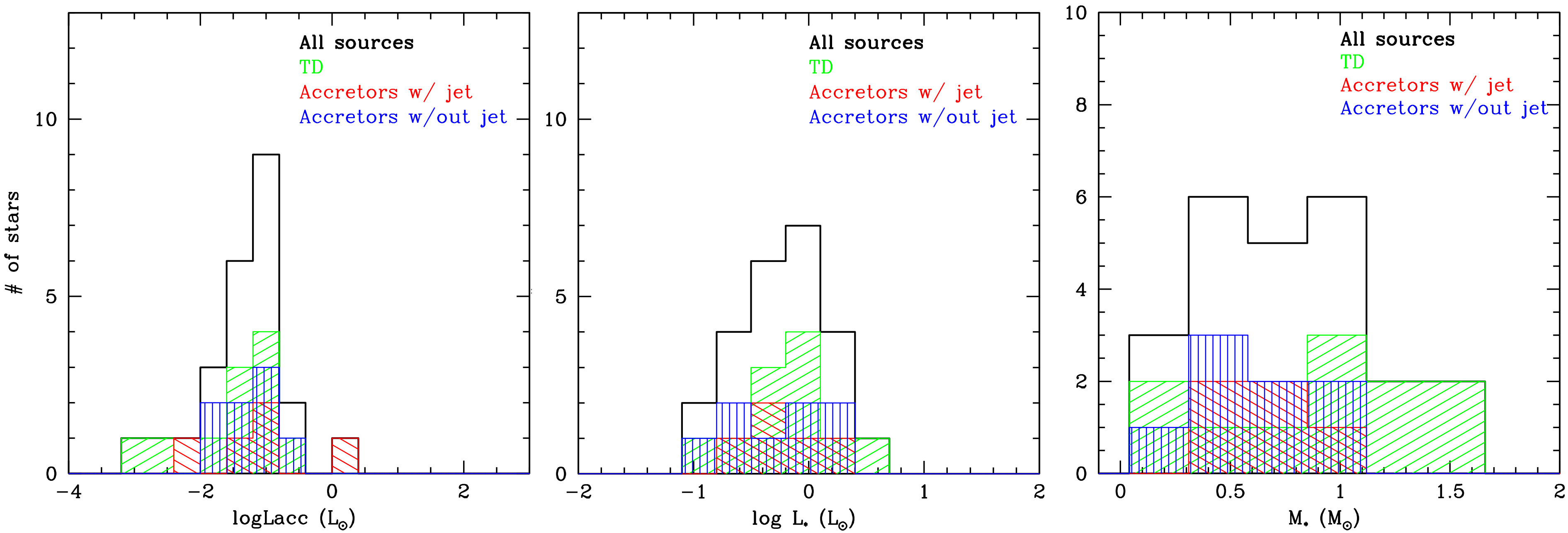
TOTAL of 24 stars

Spectral Type range: K0 – M5.5
SFRs: Taurus, Chameleon, Lupus
Evolutionary stages: Class II with jet, Class II without jet, TD

The Sample

7 Accretors with jet
7 Accretors without jet
10 Transitional Disks

LVC detected in all object: 14 stars → only NC
2 stars → NC + BC
3 stars → NC + HVC
5 stars → NC + BC + HVC

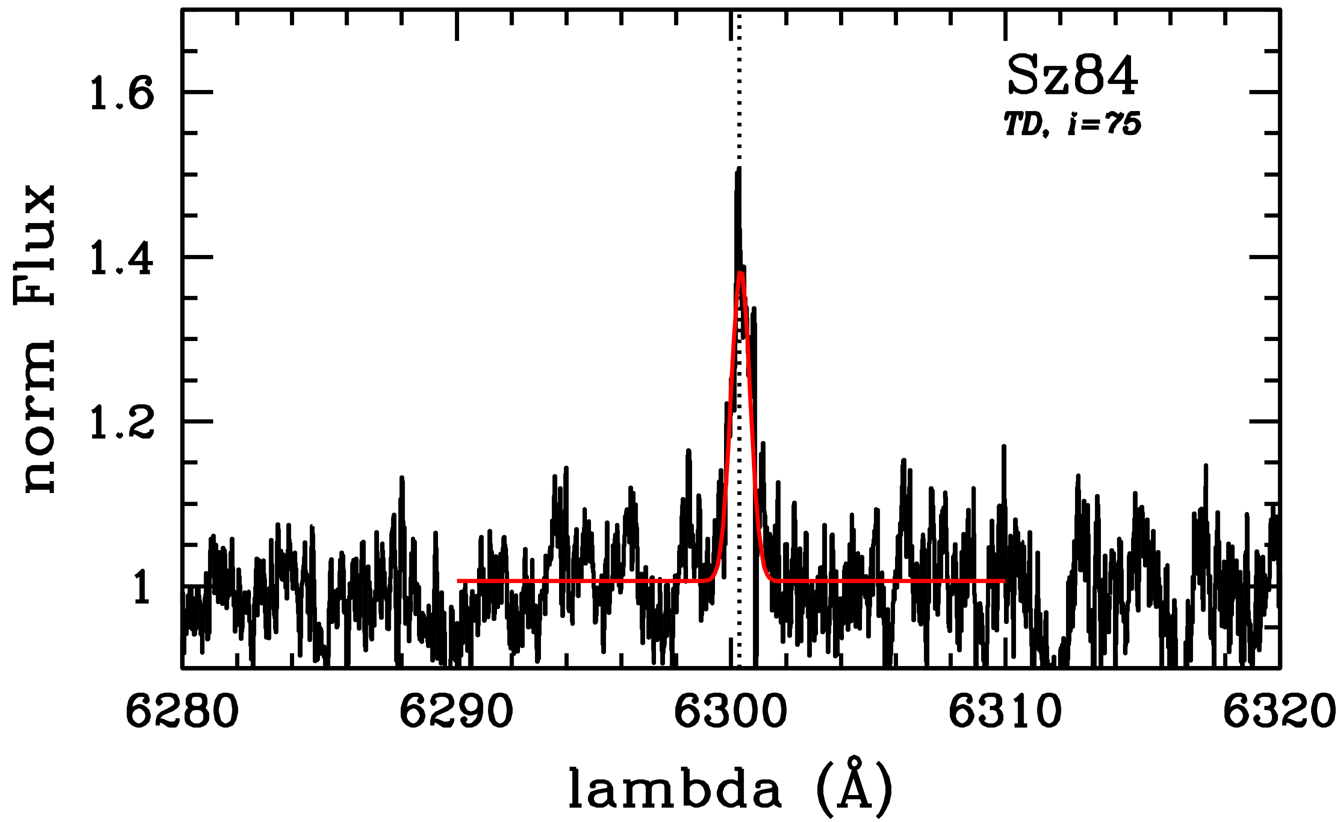


Accretors with or without jets, and stars surrounded by transitional disks do not show any clear segregation in L_{acc}, L_* and M_*

THE SAMPLE

LVC detected in all object: 14 stars → only NC
2 stars → NC + BC
3 stars → NC + HVC
5 stars → NC + BC + HVC

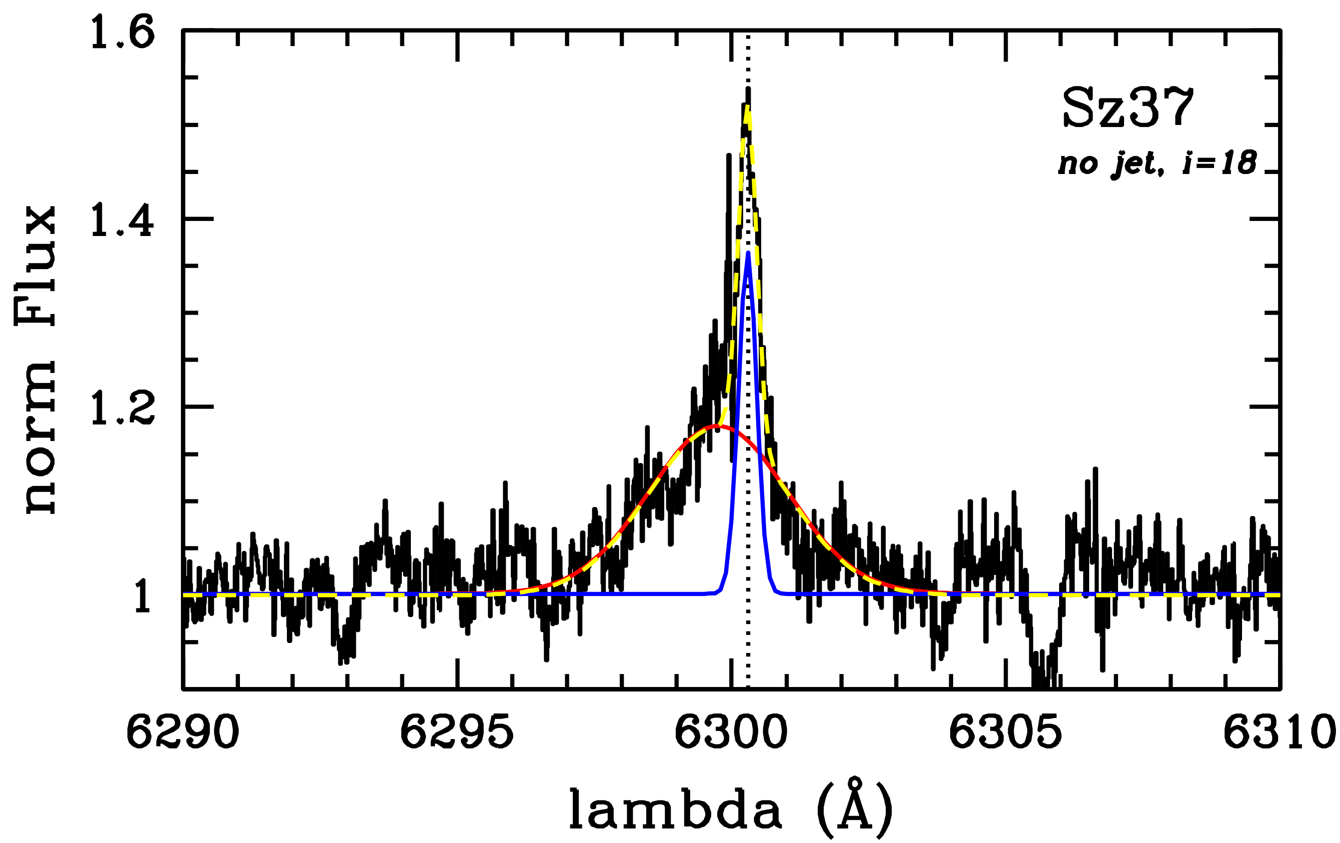
V_{peak} = 1.9 km/s



The Sample

LVC detected in all object: 14 stars → only NC
2 stars → NC + BC
3 stars → NC + HVC
5 stars → NC + BC + HVC

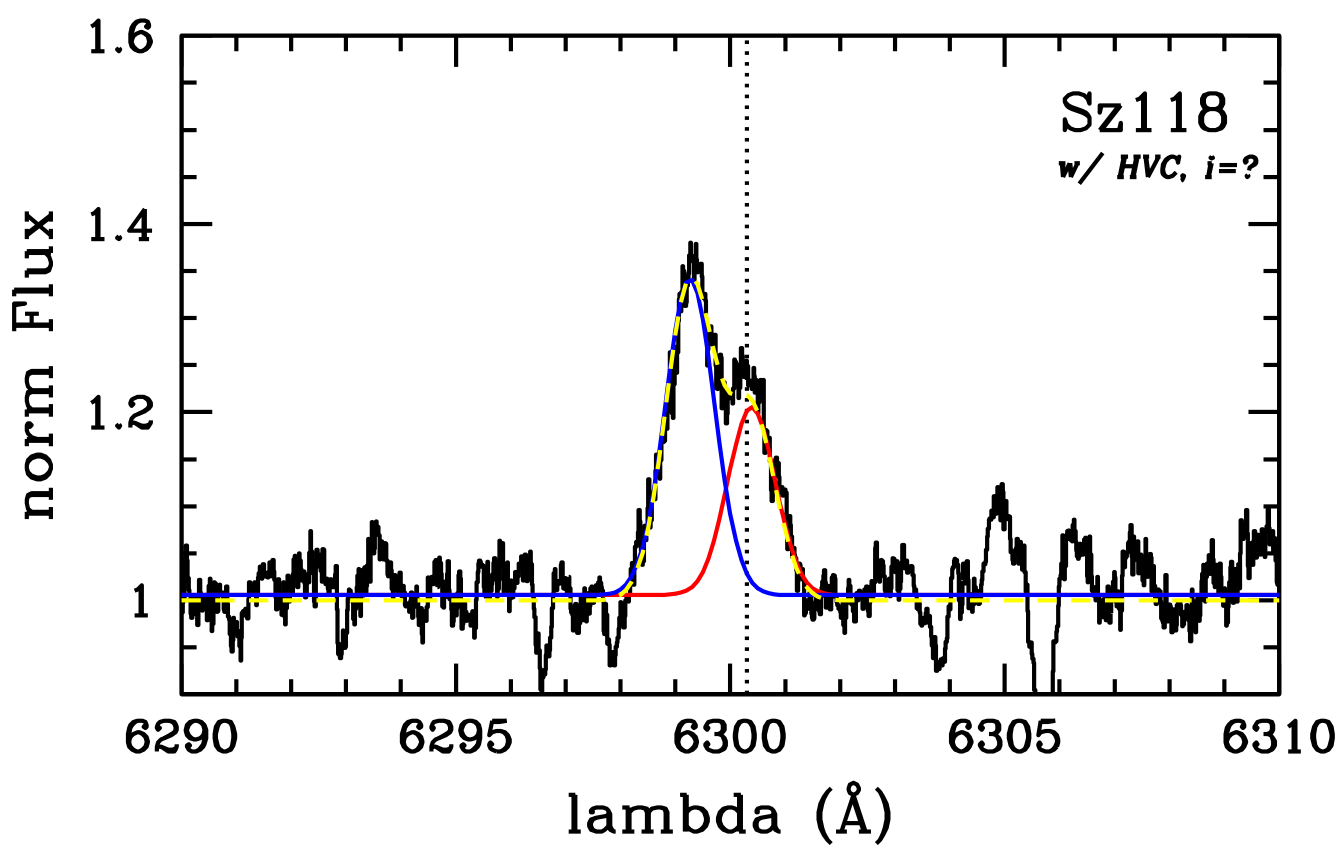
$V_{peak, C1}$ = -0.6 km/s
$V_{peak, C2}$ = -26.2 km/s



The Sample

LVC detected in all object: 14 stars → only NC
2 stars → NC + BC
3 stars → NC + HVC
5 stars → NC + BC + HVC

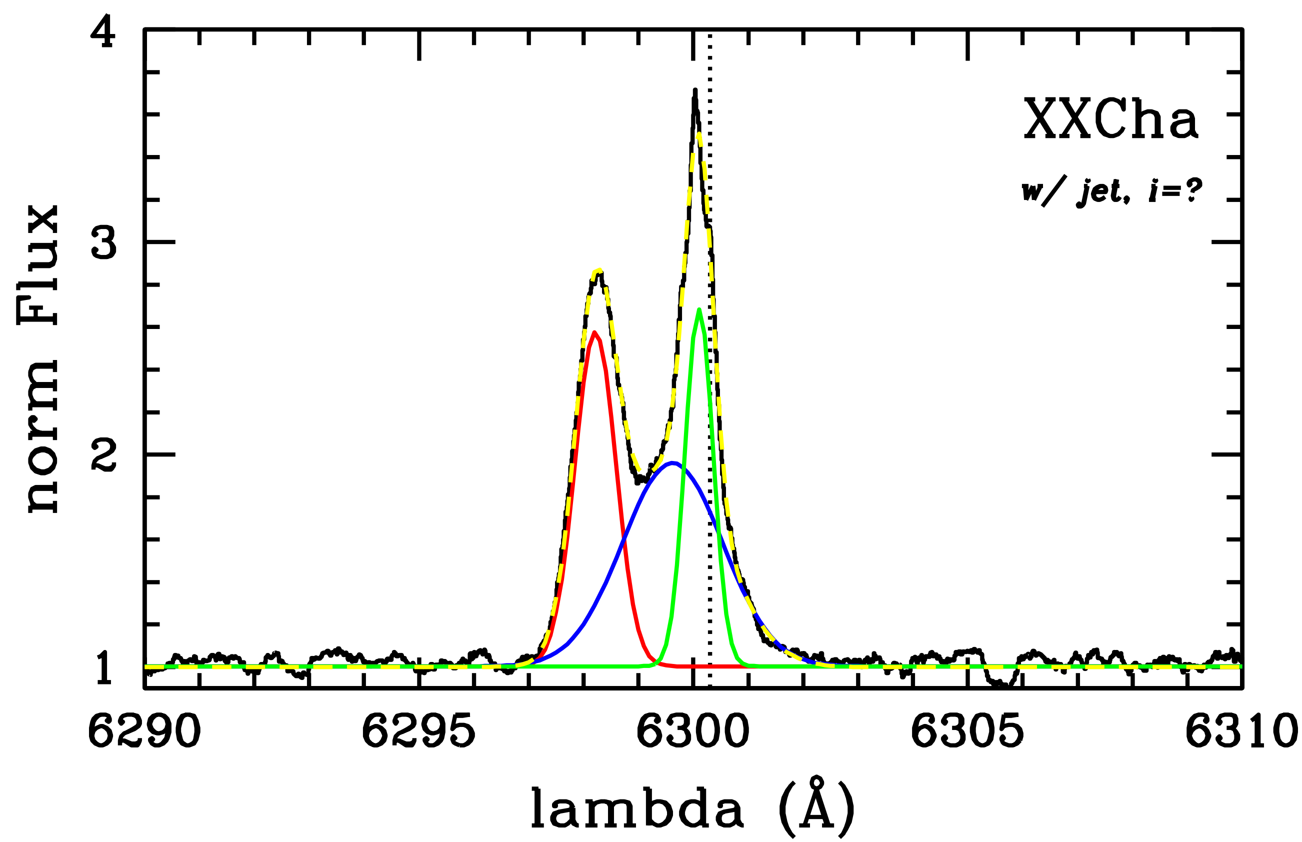
$V_{peak,\,C1}$ = 3.9 km/s
$V_{peak,\,C2}$ = -49.4 km/s



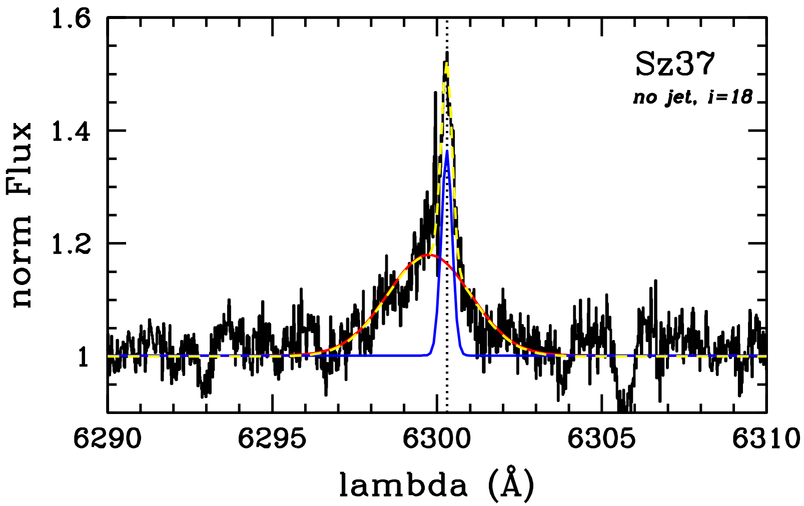
The Sample

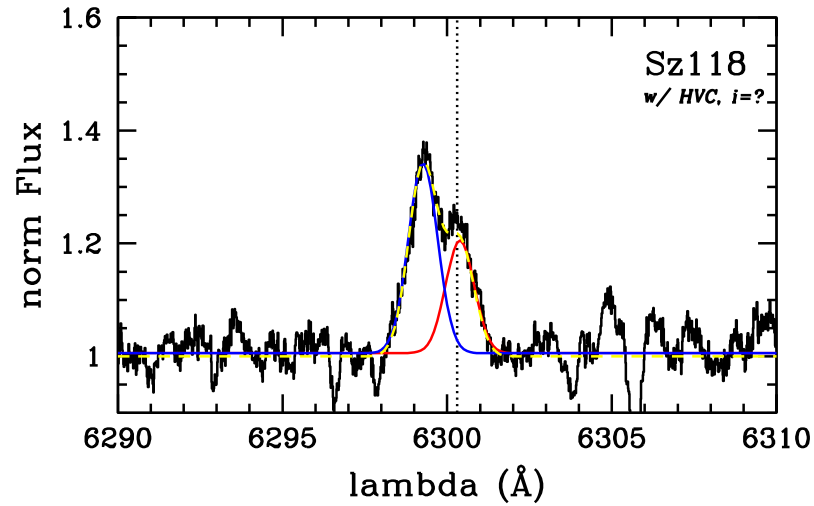
LVC detected in all object: 14 stars → only NC
2 stars → NC + BC
3 stars → NC + HVC
5 stars → NC + BC + HVC

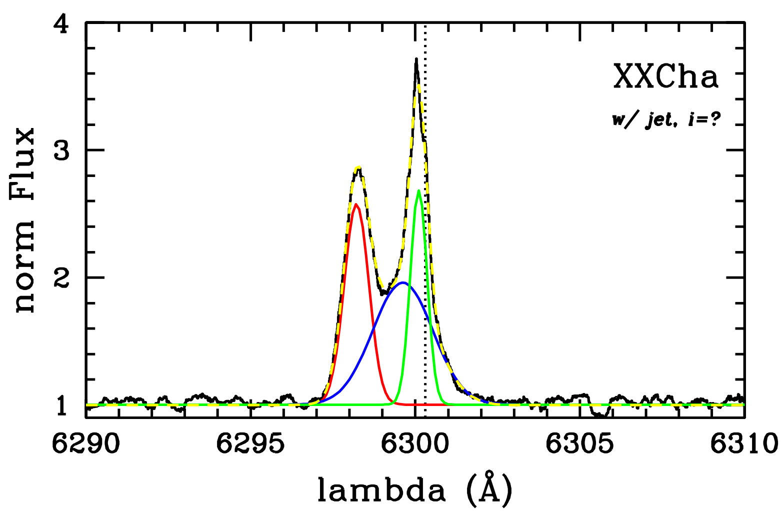
$V_{peak, C1}$ = -9.6 km/s
$V_{peak, C2}$ = -32.6 km/s
$V_{peak, C2}$ = -99.5 km/s



Preliminary Results





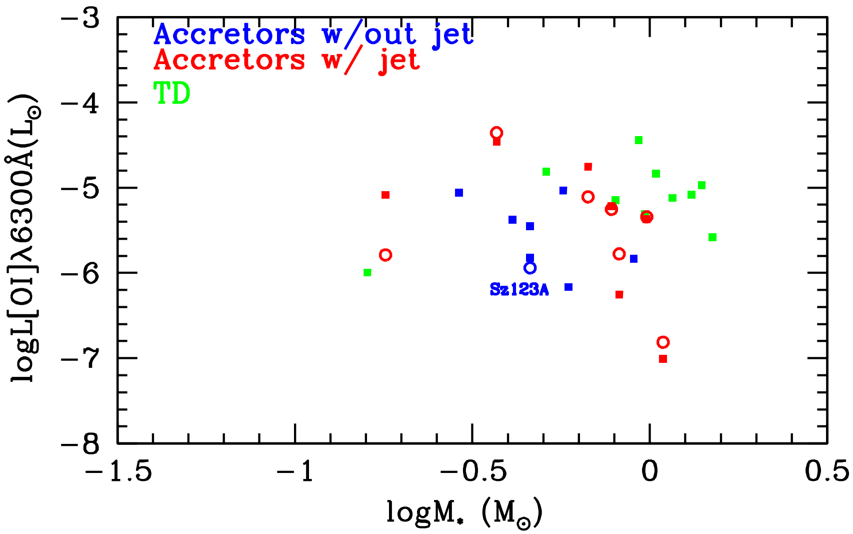


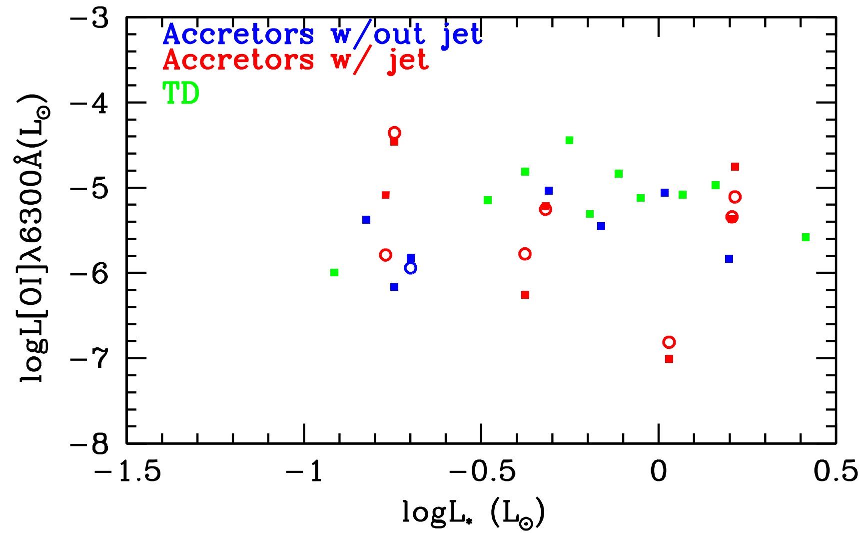
The NC of the LVC is always detected

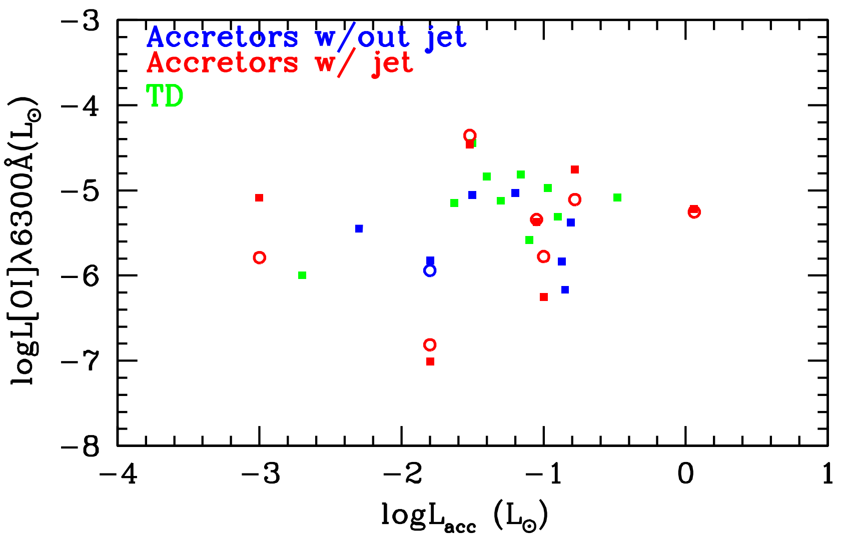
The shift of the NC and BC of the LVC varies among the different stars, we cannot identify any common path

It appears accretors w/ jets have the 2 components of the LVC more blueshifted than accretors w/out jet.

Preliminary Results







We cannot identify any trend between the luminosity of the [OI] line and the stellar properties (sample too small?)

Accretors with and without jets do not show any difference in the luminosity of the [OI]