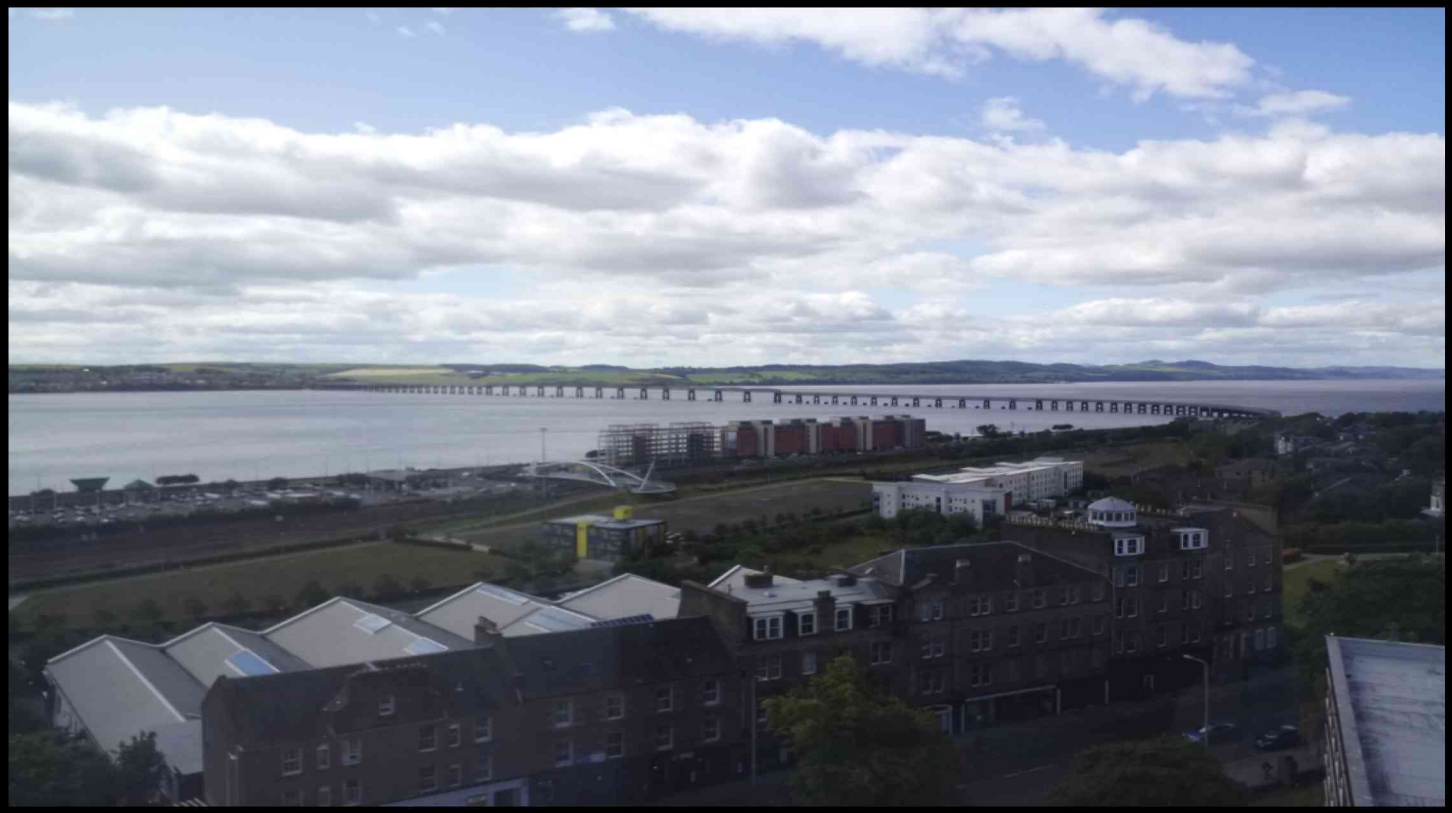
"Reading between the lines"

Adventures in spectroscopy of young and wild stars



Aurora Sicilia-Aguilar

J. Bouvier, M. Fang, V. Roccatagliata, P. Pinilla, C. Manara, M. Benisty,

T. Holoien, J. de Boer, Th. Henning, A. Kóspál, P. Ábrahám, et al.

SUPA

University of Dundee

Science & Technology Facilities Council

T Tauri Stars have a lot of emission lines*

Joy 1945: *"T Tauri variable stars"*

Eleven irregular variable stars have been observed whose physical characteristics seem much alike and yet are sufficiently different from other known classes of variables to warrant the recognition of a new type of variable stars whose prototype is T Tauri. The distinctive characteristics are: (1) irregular light-variations of about 3 mag, (2) spectral type F5–G5 with emission lines resembling the solar chromosphere, (3) low luminosity, and (4) association with dark or bright nebulosity. The stars included are RW Aur, UY Aur, R CrA, S CrA, RU Lup, R Mon, T Tau, RY Tau, UX Tau, UZ Tau, and XZ Tau. They are situated in or near the Milky Way dark clouds in the direction either of the center or of the anticenter of the galaxy.

Discussion of the spectra.—The spectral types of the T Tauri stars are estimated to be between F5 and G5, although for many of them the absorption lines generally used in classification are lacking. A small variation of type with phase was found for T Tau and RY Tau. Bright hydrogen has been found in all stars of the group, and bright *Ca* II (H and K) in all except R CrA. Most of the stars show an emission spectrum composed of many bright lines of low excitation. The strongest lines are those of *Ca* II, *H*, *Fe* II, *Ca* I, *Sr* II, *Fe* I, and *Ti* II. The identification and relative maximum intensities of 160 lines of the different stars are shown in Table 16. The intensity of the emission spectrum varies greatly from time to time in each star, the bright lines becoming more prominent at maximum light of the variable.

Absolute magnitudes and color indices.—Spectroscopic absolute magnitudes of three stars of the group, together with meager indirect evidence, indicate that the T Tauri stars are dwarfs of the main sequence. Color indices for five stars show some color excess, which is probably the result of selective absorption by surrounding nebulosity.

* by definition.

T Tauri Stars have a lot of emission lines*

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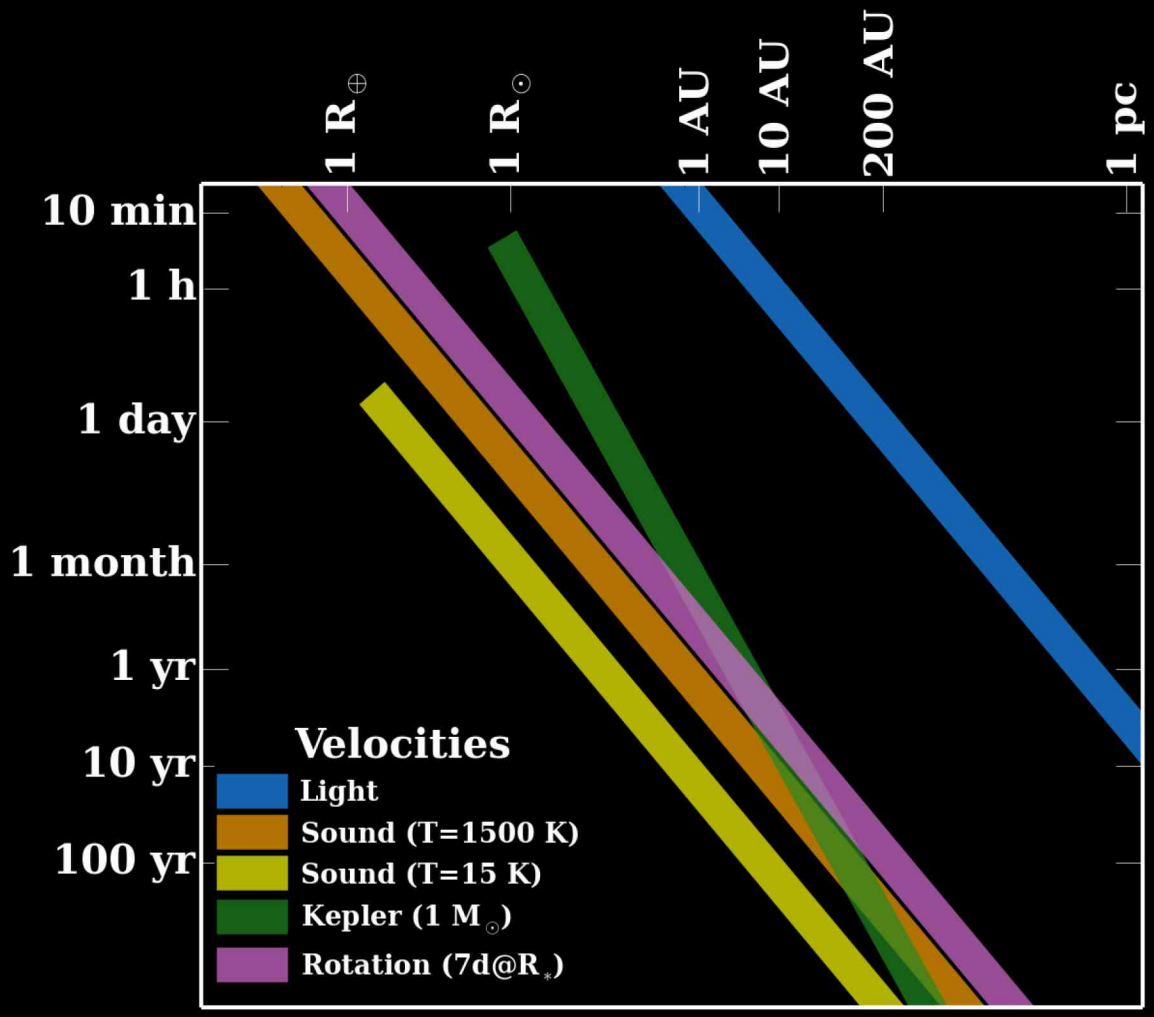
The lines and veiling are often an annoyance e.g. for spectral typing and search for companions or planets

* by definition.

Time, space, and velocities

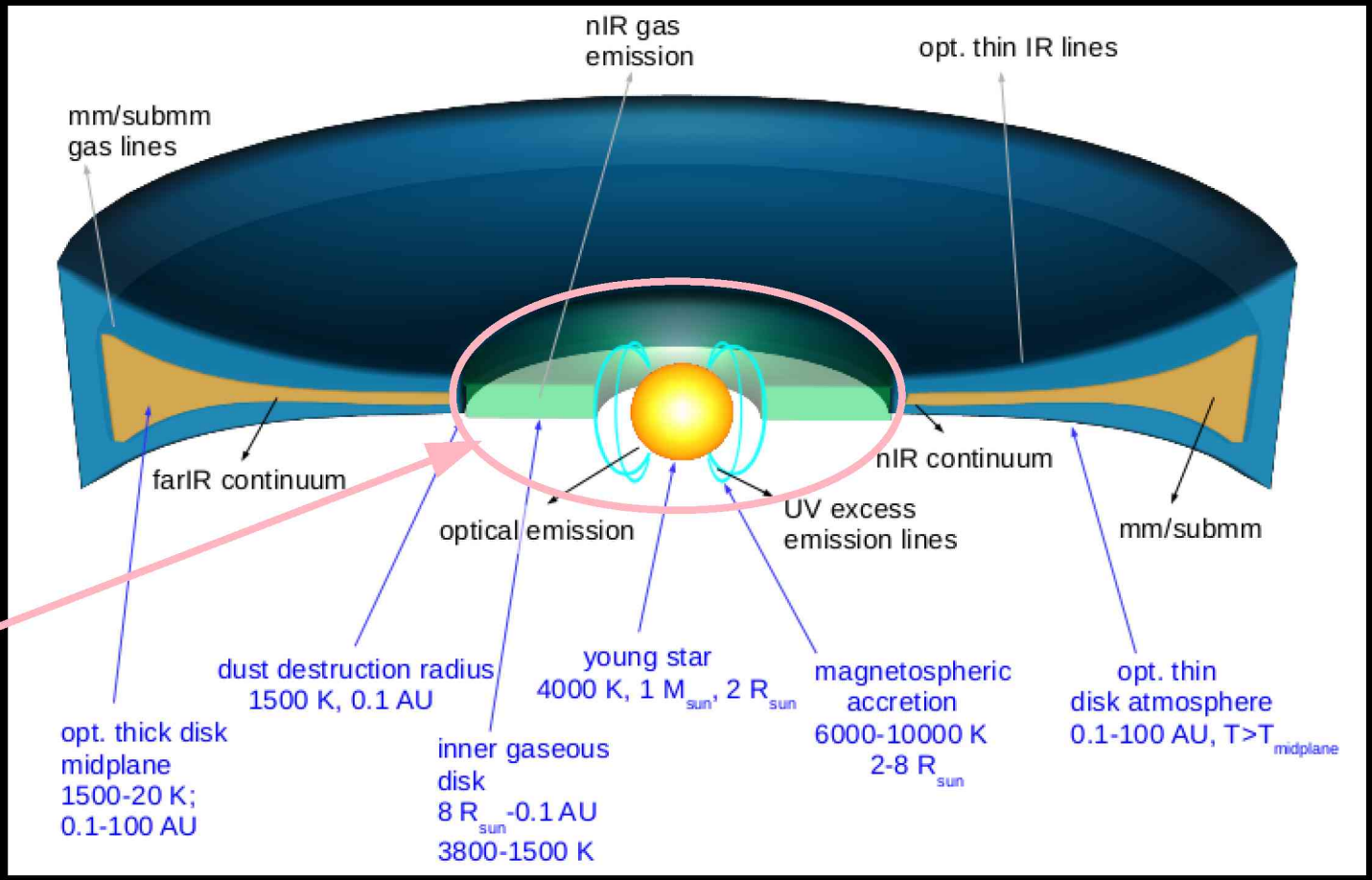
For every **time scale** there is a **spatial scale**...



… which can be much smaller than what we can directly resolve!

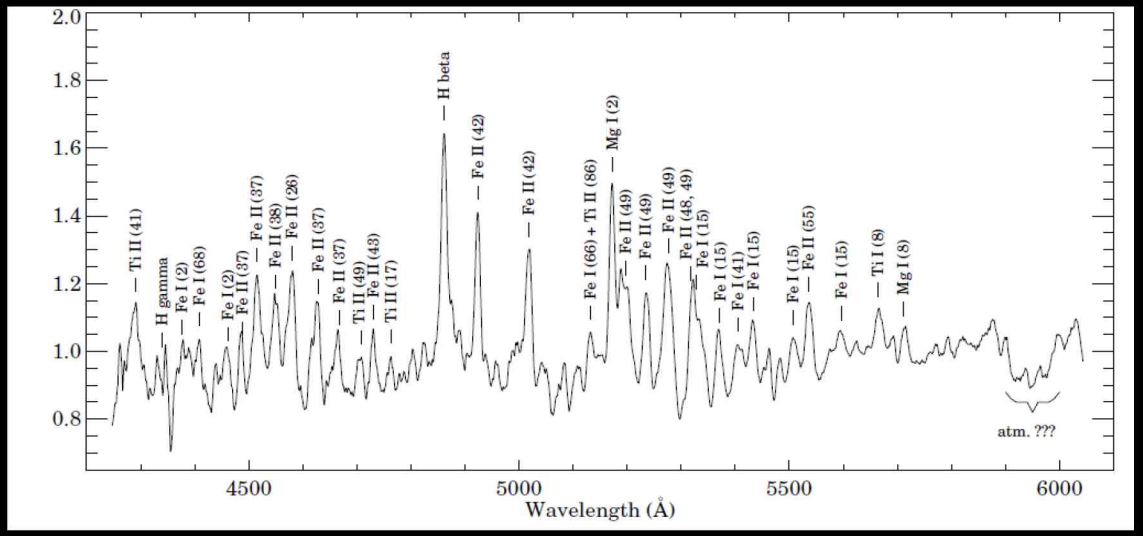
Time-resolved spectroscopy (and photometry)

you are here



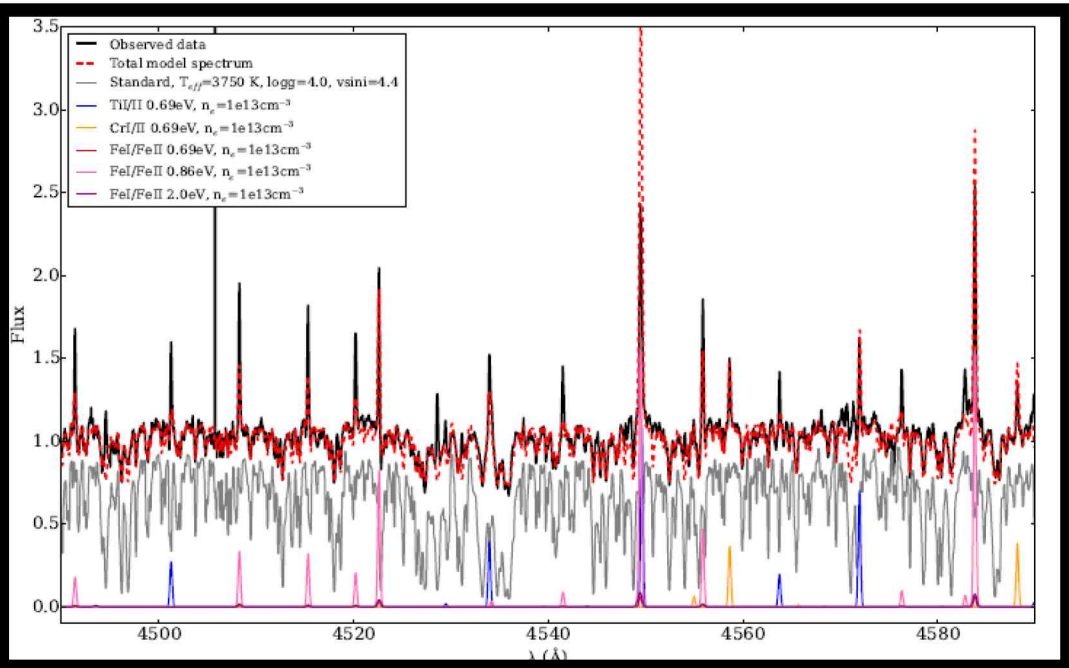
Time, space, and structure: How it works

EX Lupi: The prototype EXor has lots of lines with various energies and transition probabilities:



In outburst

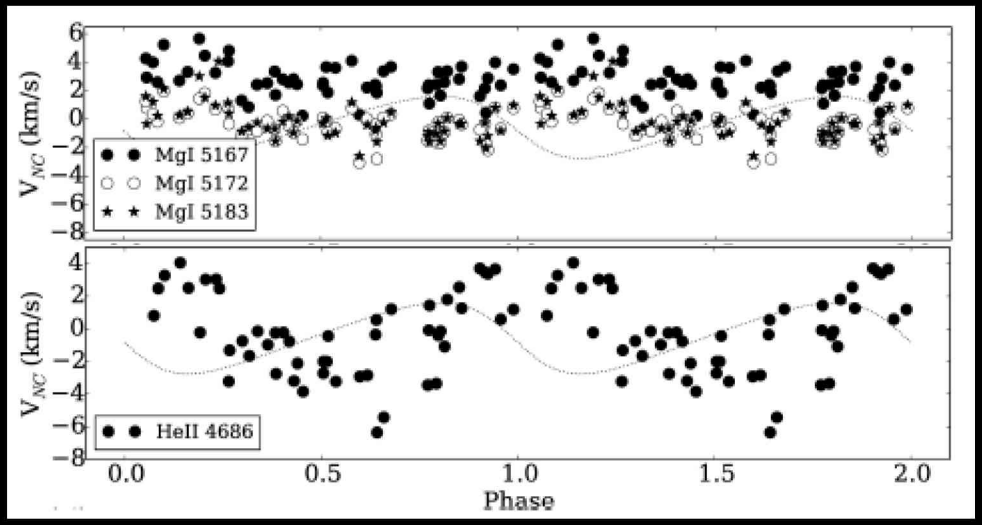
[Kóspál et al. 2008]



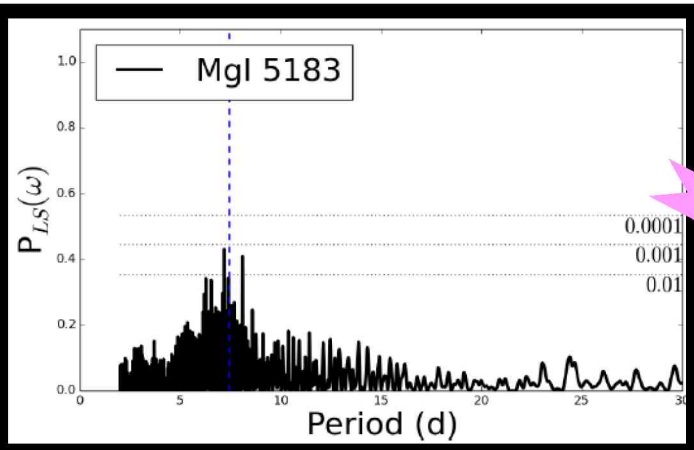
In quiescence

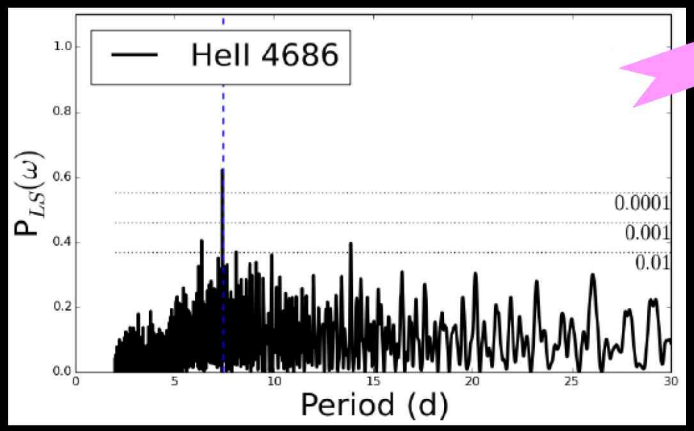
[Sicilia-Aguilar et al. 2015]

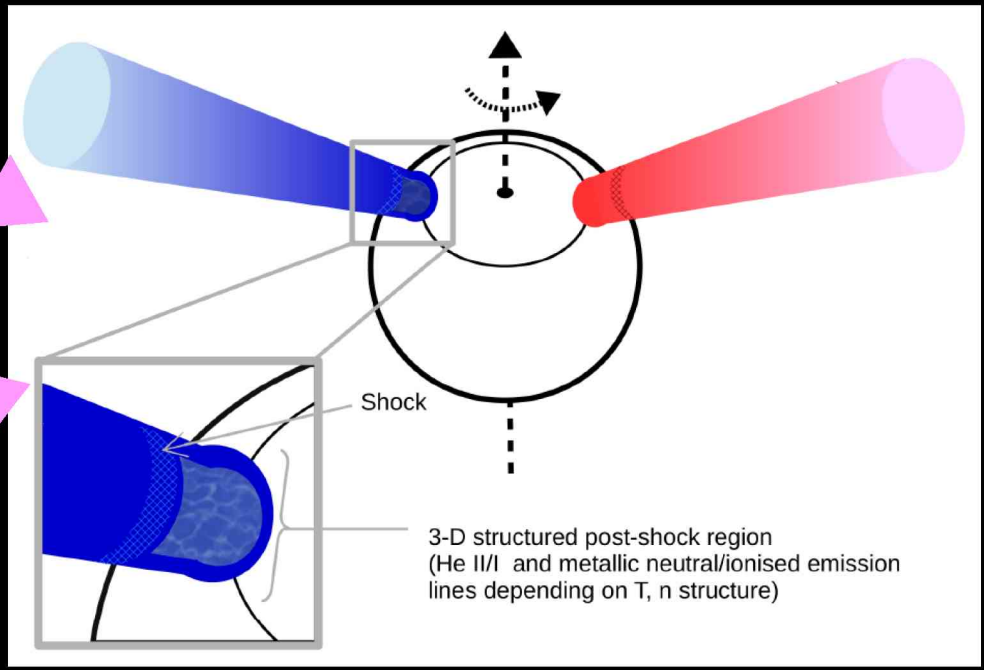
Time and velocity to track space



The rotational modulation of emission lines allows us to trace the physical structure of the accretion columns.

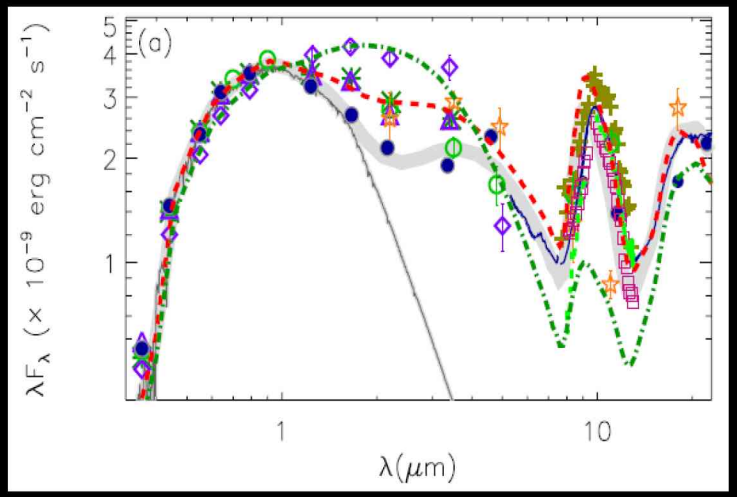


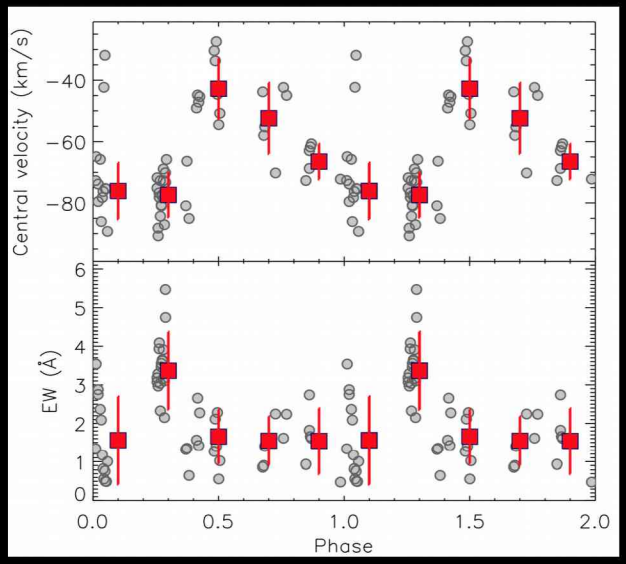




[Sicilia-Aguilar et al. 2015]

Reading *"between the lines"* of young stars

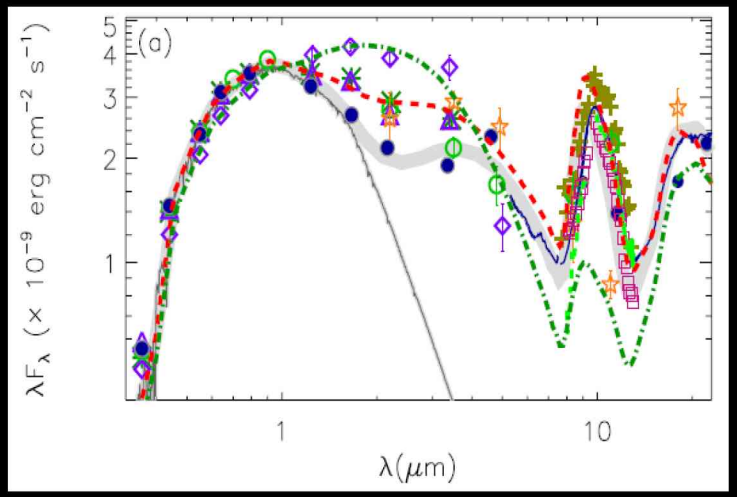


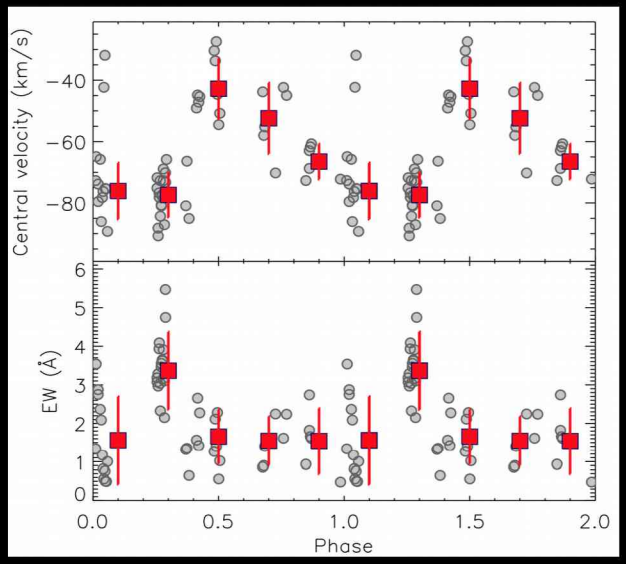


- **EX Lupi:** Stable accretion-related spot predicting a strong dipolar field.
- **GW Ori:** Use a binary to measure of the scale of the disk wind.
- **ASASSN-13db:** Identified a hot spot hovering over the surface.
- **ZCMa:** Asymmetric disk and asymmetric, multicomponent, variable wind.
- **J1604:** star with two ~perpendicular disks, shadows, and quasiperiodic eclipses.

[SA+ 2015, 2017; Fang+ 2014; Holoien+2014; Pinilla+ 2018; ongoing collab. with Bouvier, Ábrahám, Kóspal]

Reading *"between the lines"* of young stars





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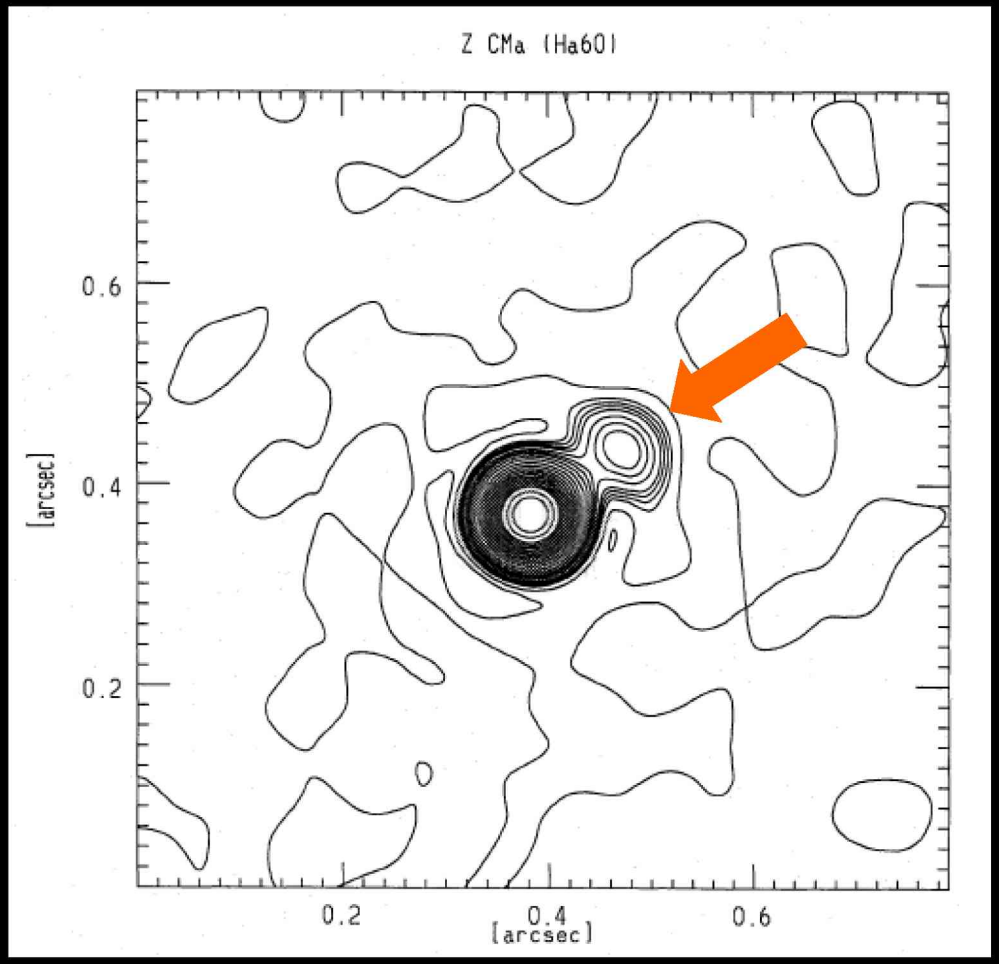
ZCMa: Not really a solar-type star

HBe star with accretion bursts and a FUor companion.

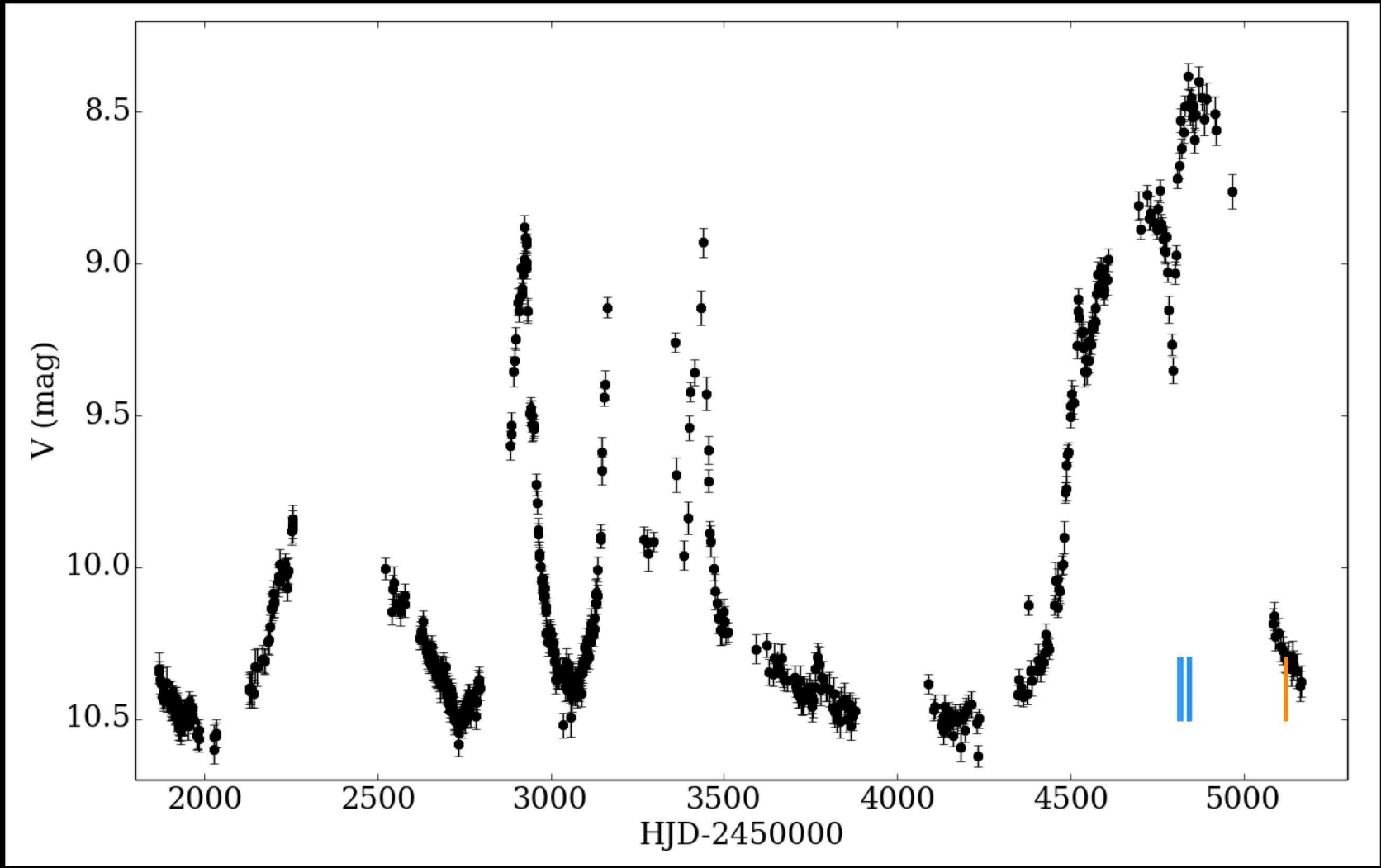


[Barth et al. 1994]

[see also Bonnefoy et al. 2017 for IR data and Lee Hartmann's talk yesterday]

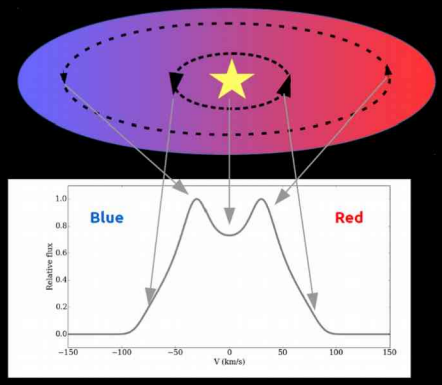
ZCMa Outburst

Strong accretion burst that lasted ~480 days and outshone the FUor.

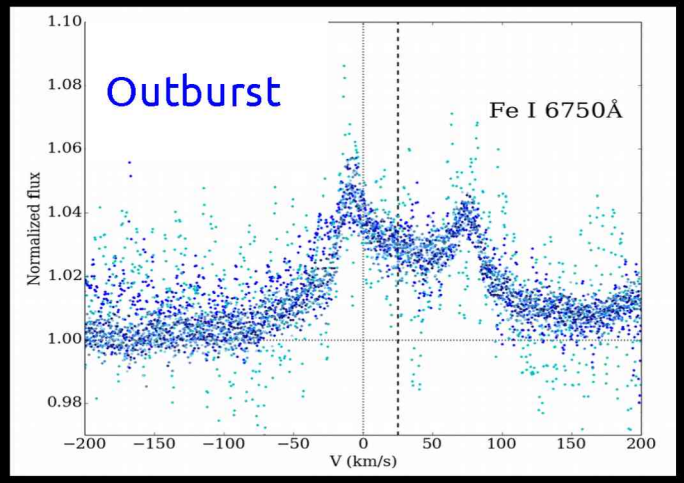


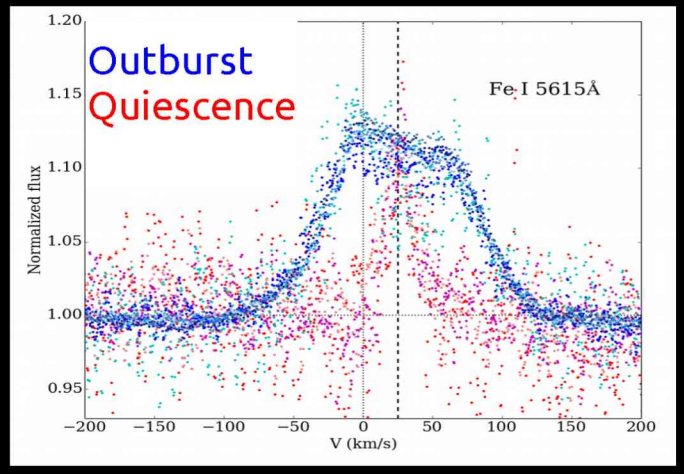
Photometry from the All Sky Automated Survey (ASAS)

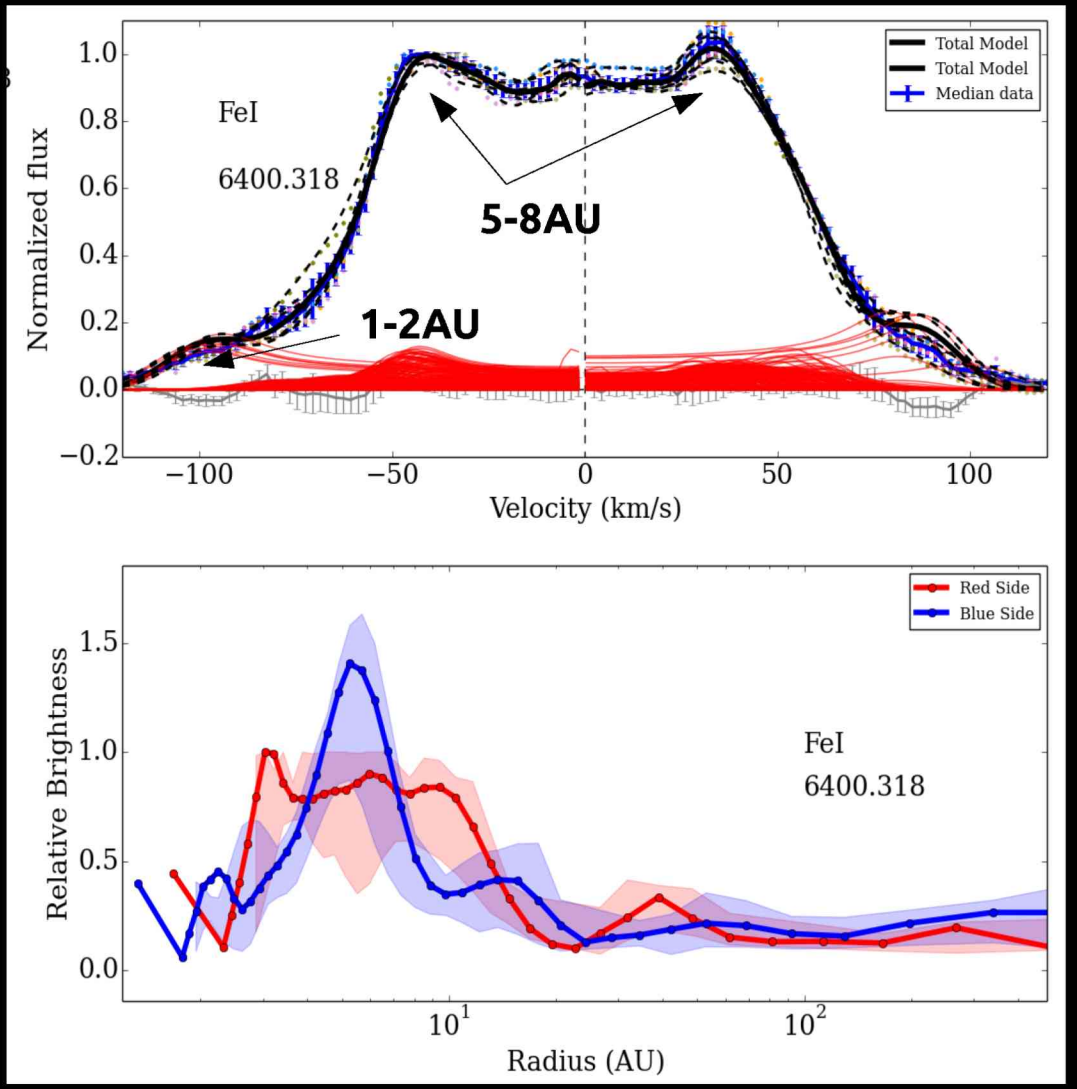
ZCMa: Disk emission



Fe I double-peaked lines trace material at 1-20 AU, revealing disk asymmetries as well as the vertical disk structure depending on line strength.

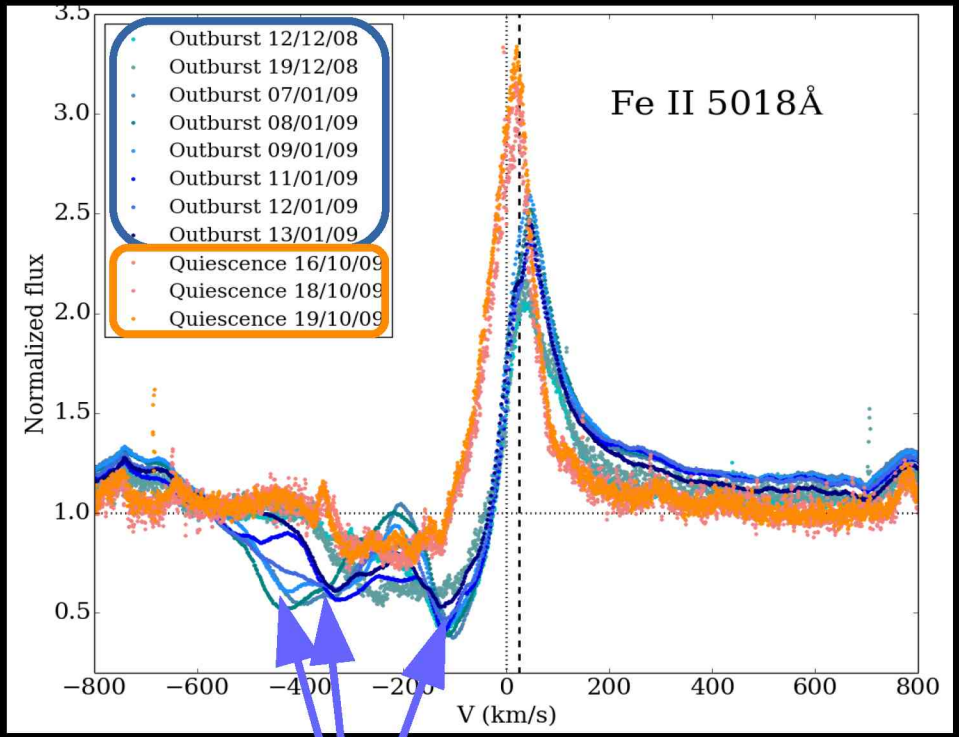




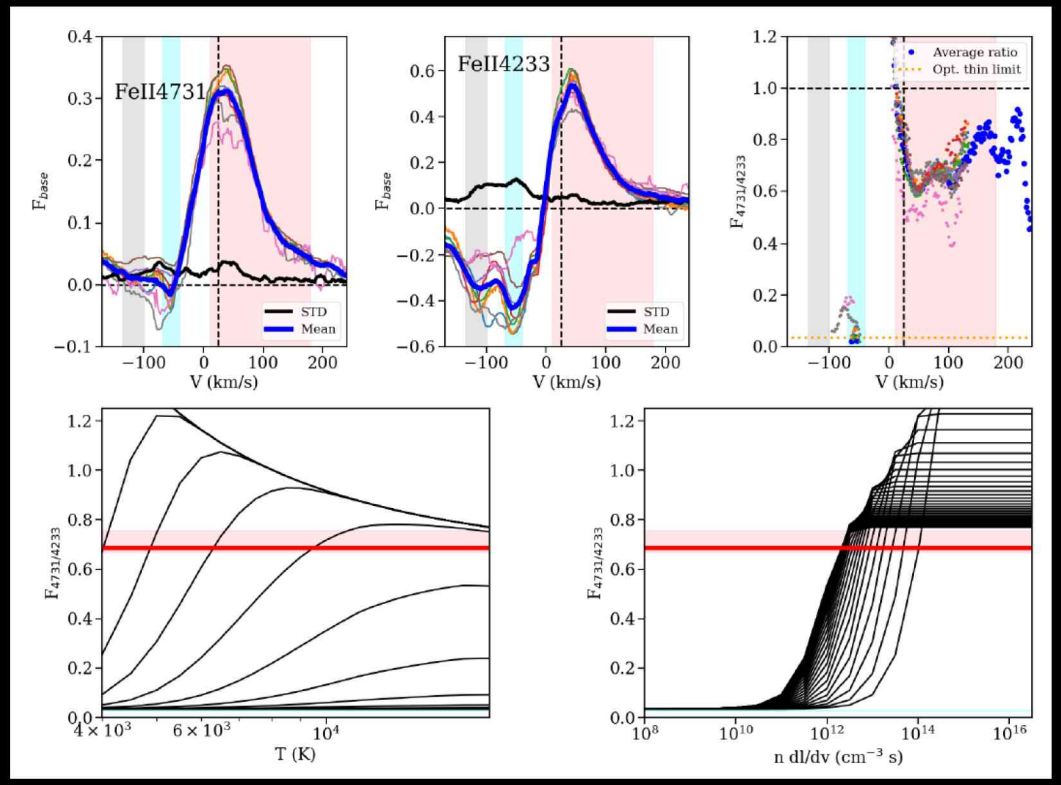


[Sicilia-Aguilar, Bouvier, et al. in prep]

ZCMa: Accretion and hot, complex, non-axisymmetric wind



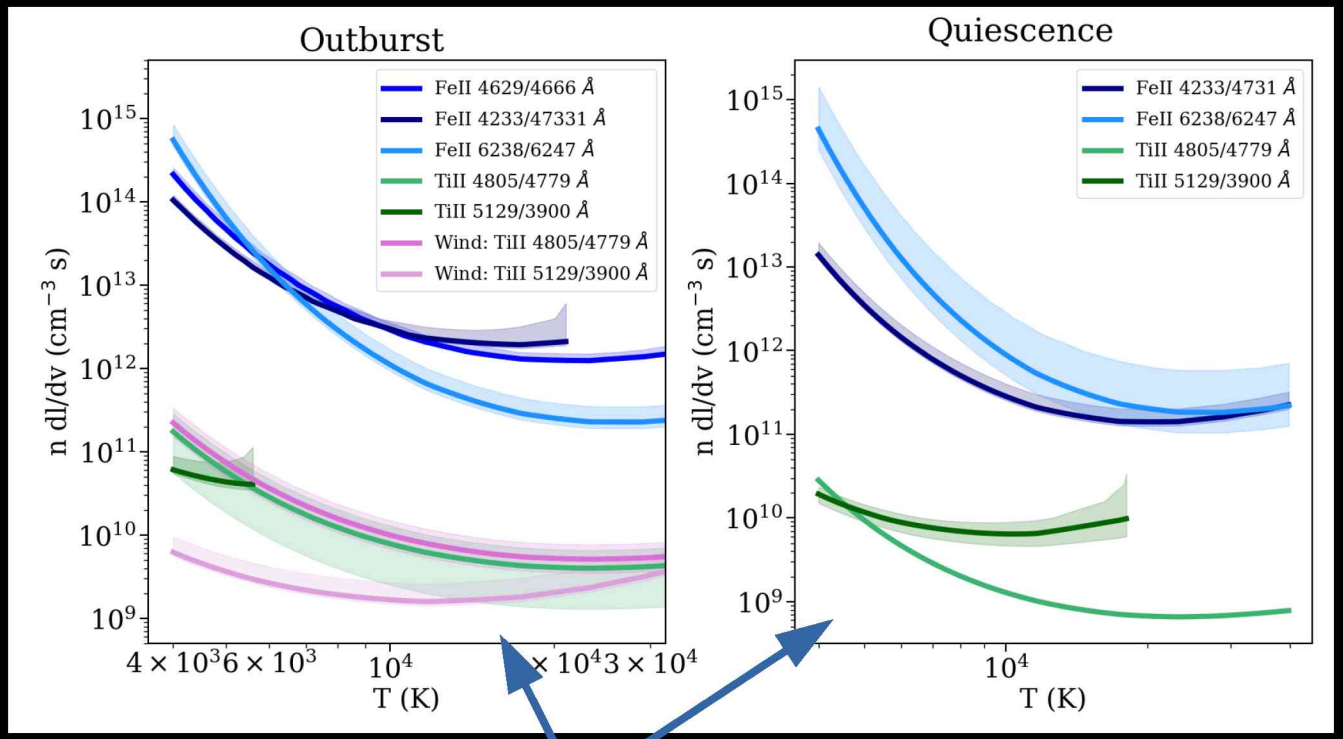
Fast, hot wind components developing during outburst *(as in ASASSN-13db!)*.

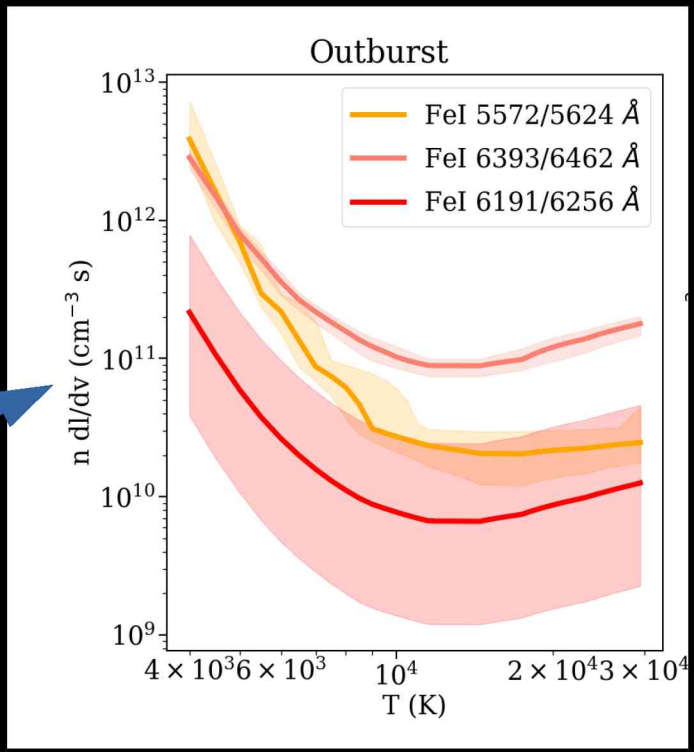


Ratios of lines from the same upper level constrain densities and temperatures [e.g. Beristain+1998].

[Sicilia-Aguilar, Bouvier, et al. in prep]

Putting this all together...



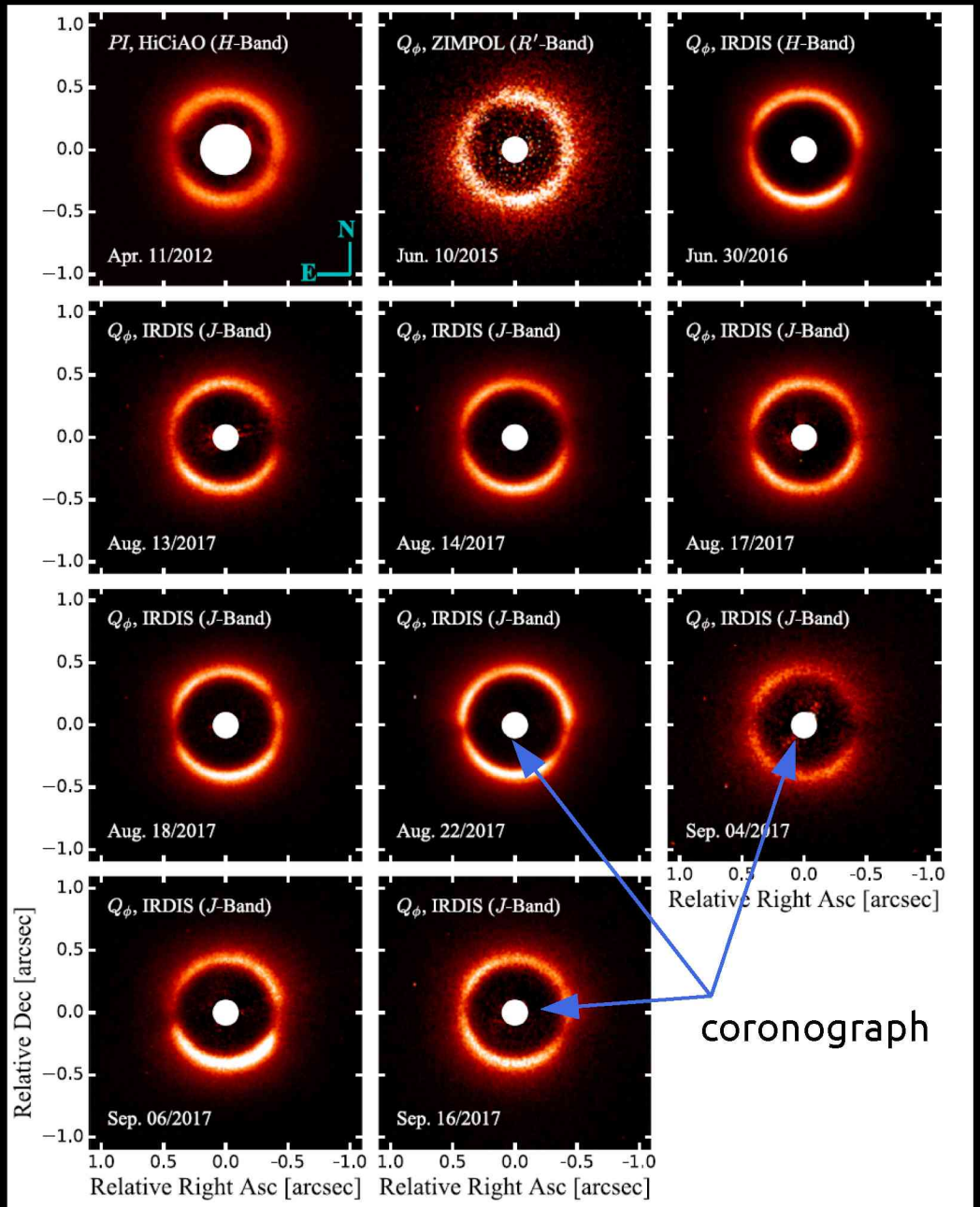


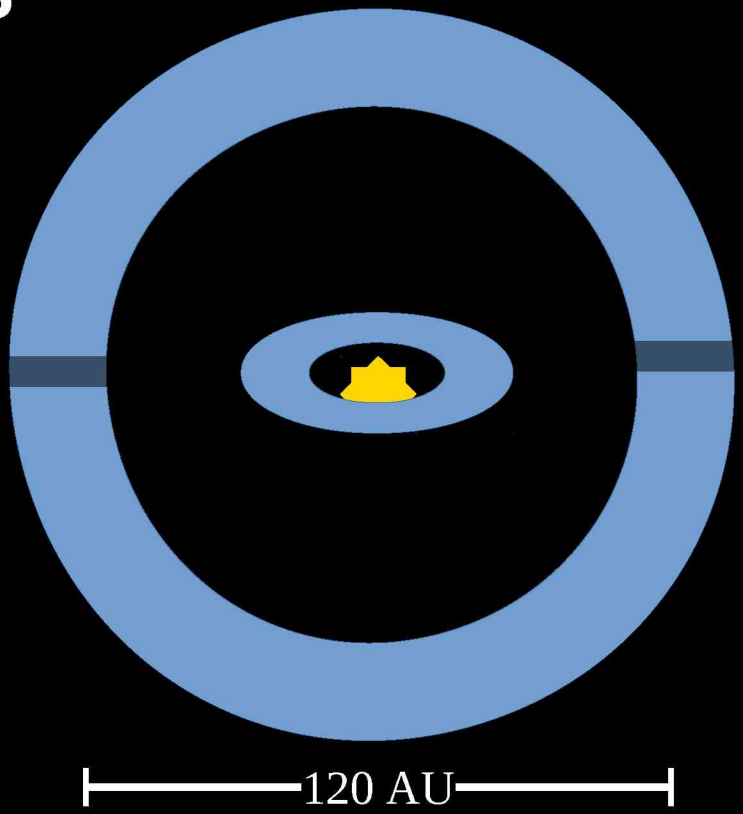
Signs of very hot wind and a complex density-temperature structure for the accretion part.

Density gradients and temperatures lower in the disk emission.

[Sicilia-Aguilar, Bouvier, et al. in prep]

J1604: A tale of two disks

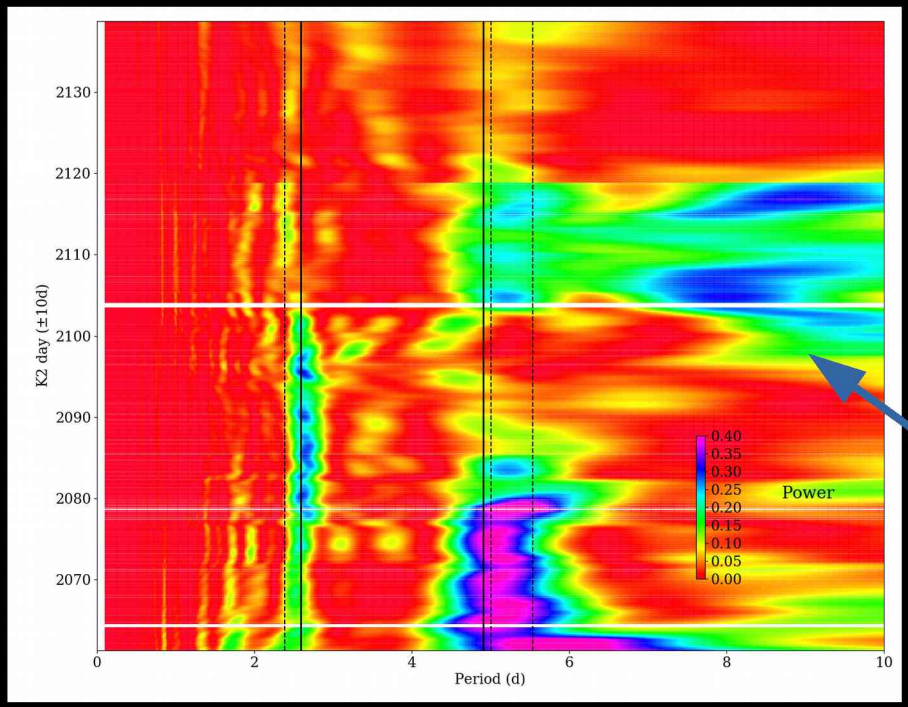




Shadows suggest two disks: one face-on, another very small, wobbly, and nearly perpendicular [Pinilla et al. 2018] .This is consistent with observed dipper behavior [Ansdell+ 2016, Rebull+2018].

It may be a binary [Köhler+2000].

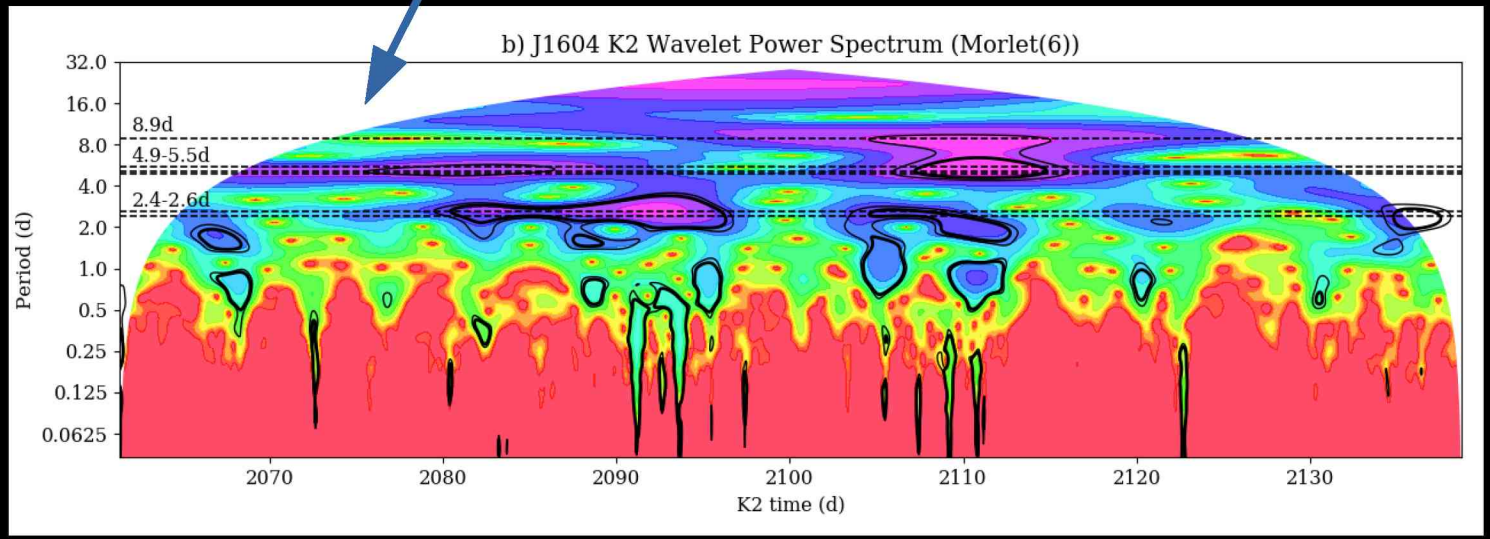
J1604: A tale of two disks



K2 and REM(ground) griz JHK

Quasiperiodicity:

- Stacked periodograms.
- Wavelet analysis.



[Sicilia-Aguilar et al. in prep]

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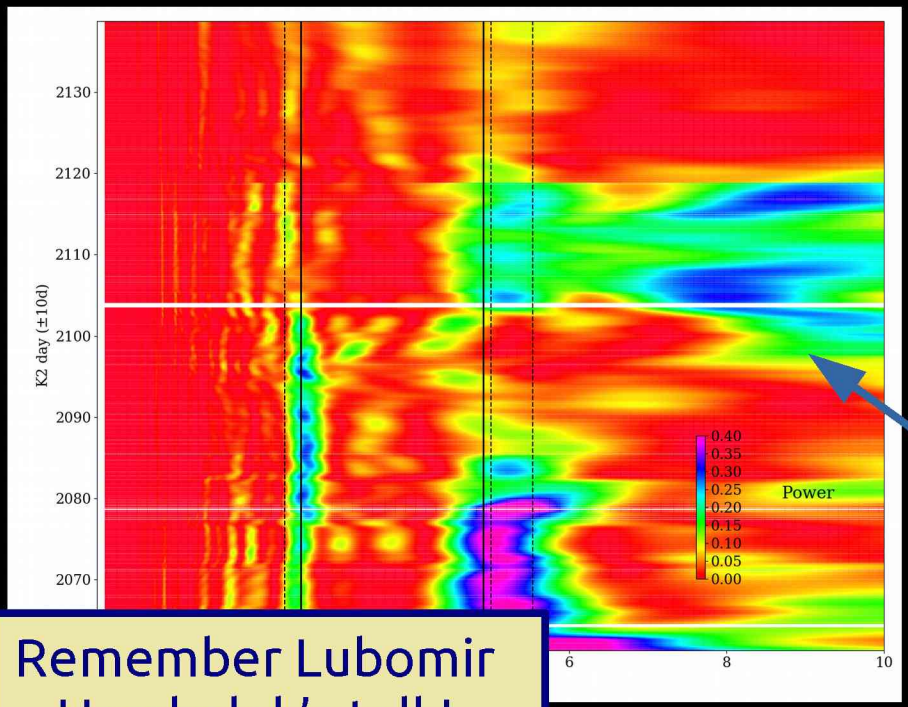

Remember Lubomir Hambalek's talk!

K2 and REM(ground) griz JHK

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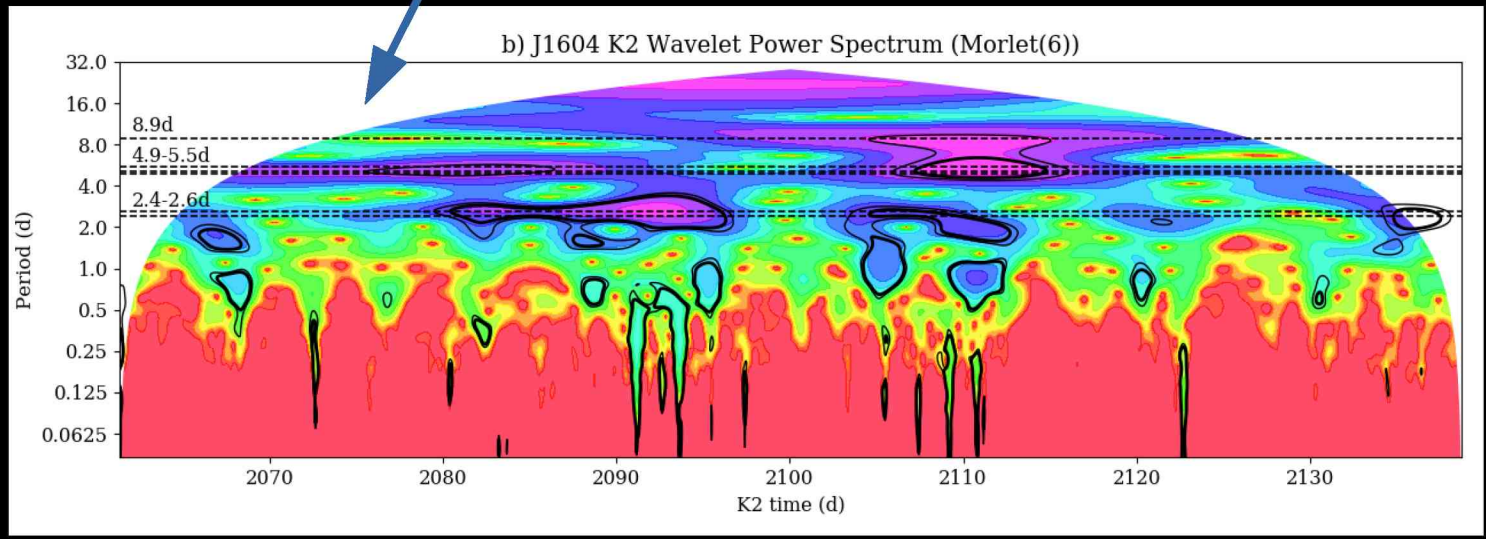
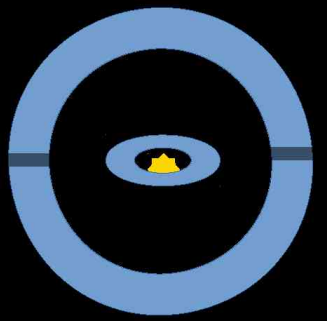
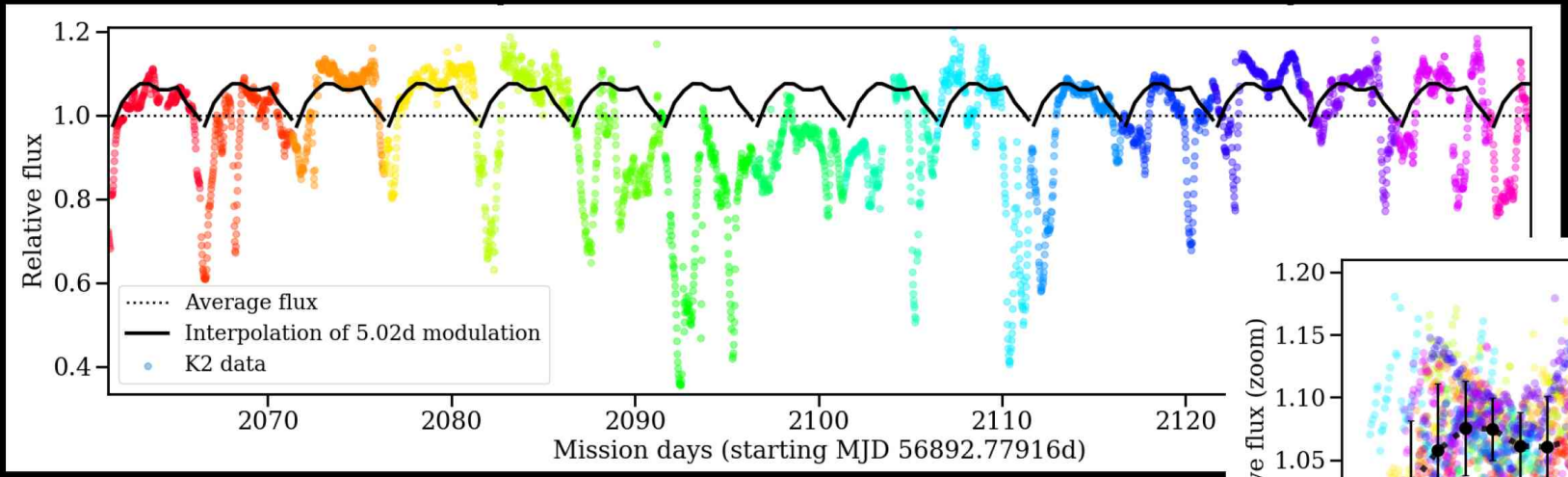


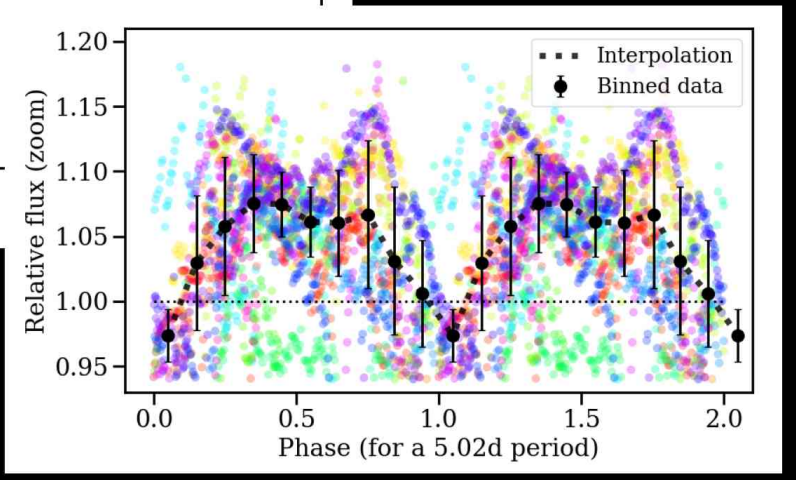
5d quasi-period: dust destruction radius (~1500 K, 0.06 AU).

[Sicilia-Aguilar et al. in prep]

J1604: A tale of two disks



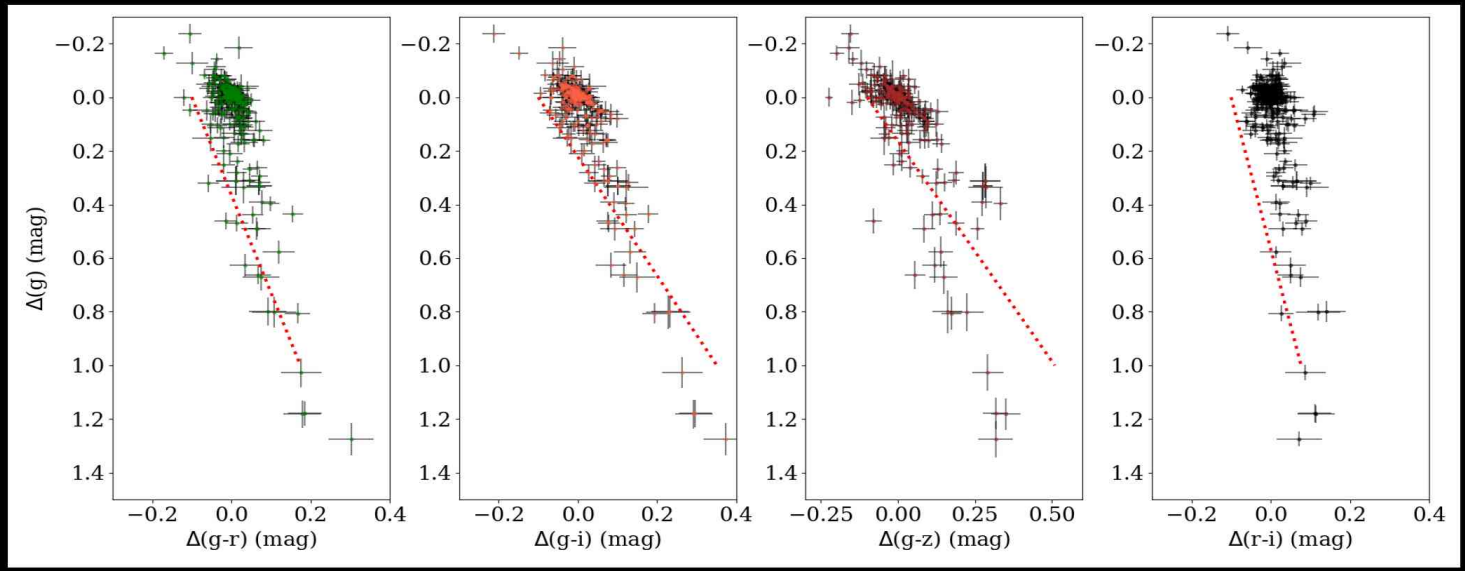




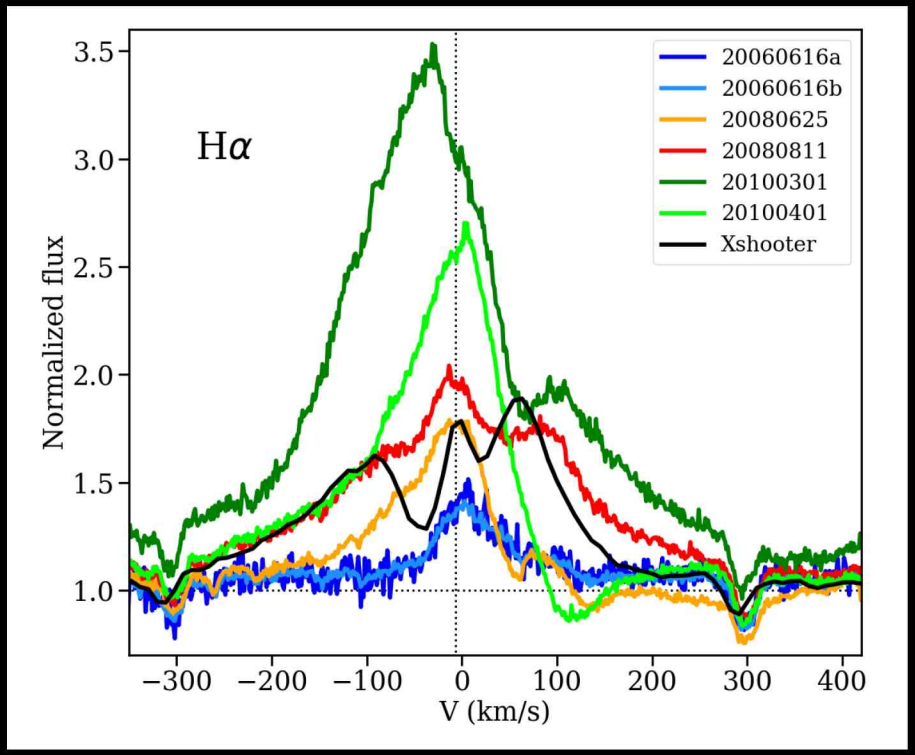
K2: Spots change rapidly: unstable accretion [Kurosawa & Romanova 2013]

REM: Dust extinction. Quasi-periodic eclipses (inner disk empties on ~10-20 days)

[Sicilia-Aguilar et al. in prep].



J1604: A tale of two disks

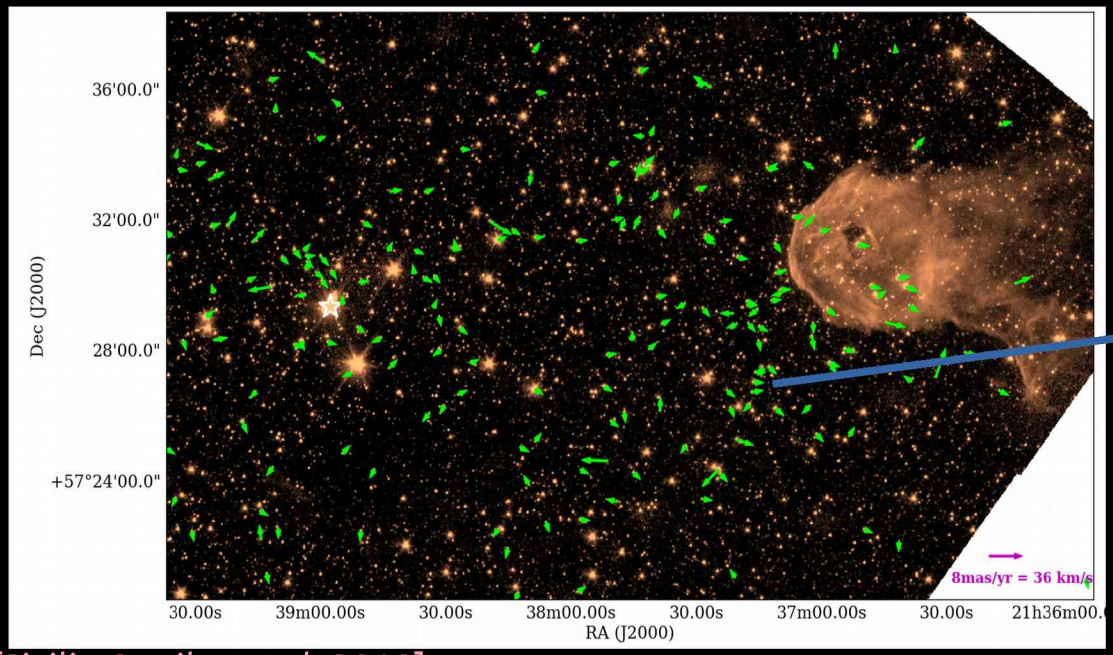


Spectroscopy reveals variable accretion (Hα above) and **fast rotation** (vsini~16 km/s [Dahm et al. 2012, Sicilia-Aguilar et al. in prep, Manara et al. in prep])
… so it is rather **aligned with the inner disk**, not the outer one!

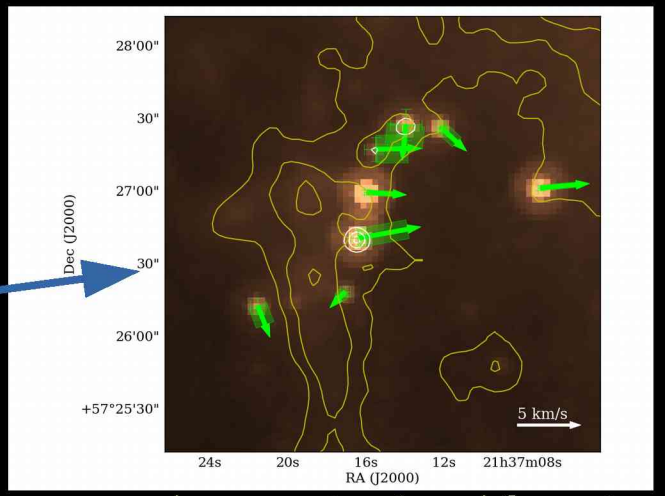
How do we reconcile this with the standard star-formation models?

[See also Davies et al. 2019]

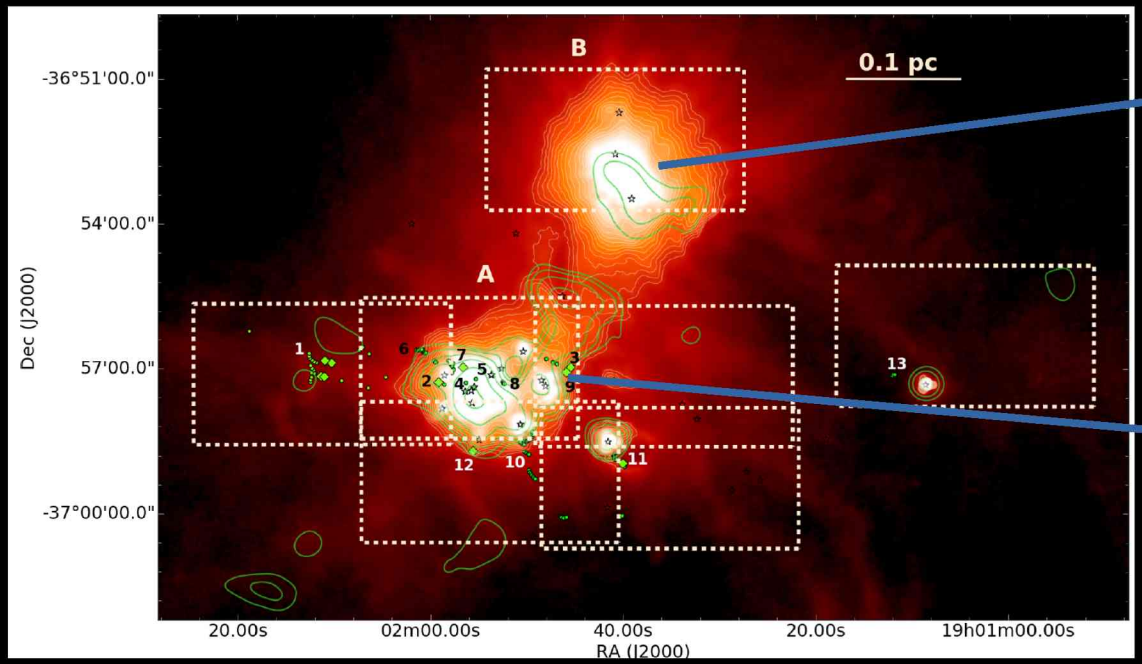
Is star formation more complex than expected?

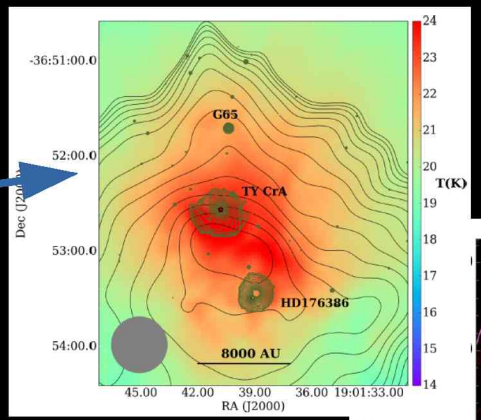


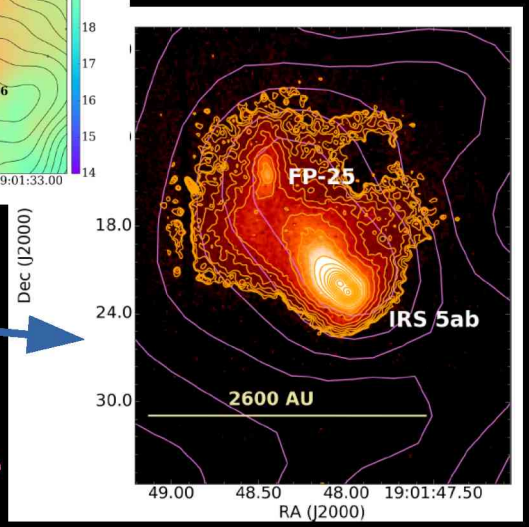
[Sicilia-Aguilar et al. 2019]



Remember gravitational focusing
[Burkert & Hartmann 2004]

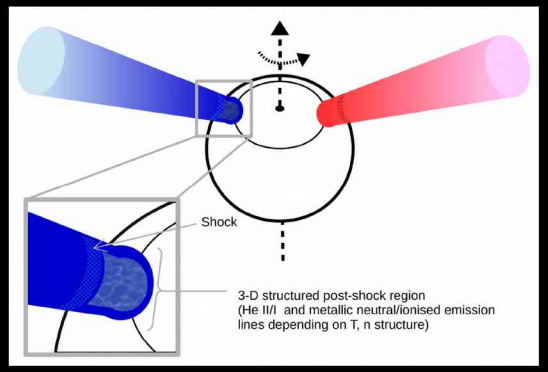


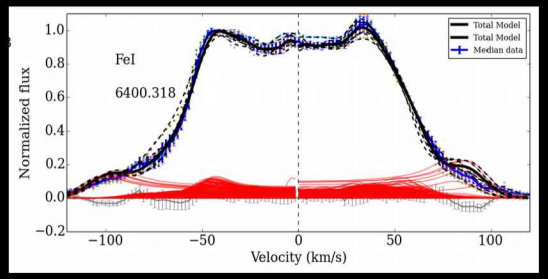


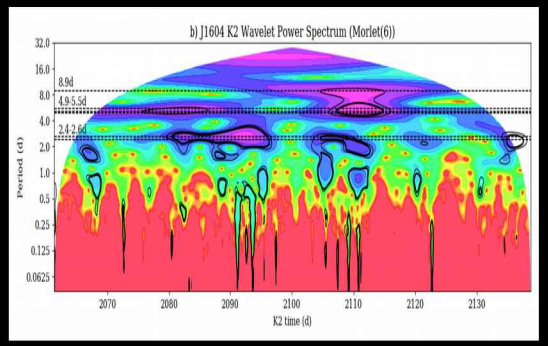


[Pelayo-Baldarrago et al. in prep]

Adventures in spectroscopy of young and wild stars







- ***"Reading between the (time-resolved) lines"*** to map accretion, inner disk structures and winds.
- **Emission lines** provide dynamical and physical (density, temperature) info on different regions.
- **Clusters and star formation:** gas kinematics and GAIA suggest that things may be more complex than expected...

Science & Technology Facilities Council
Line tomography: Accretion, winds, activity
PD: Justyn Campbell-White, CoI: Soko Matsumura