The Inner Regions of Protoplanetary Disks
C.P. Dullemond & J.D. Monnier

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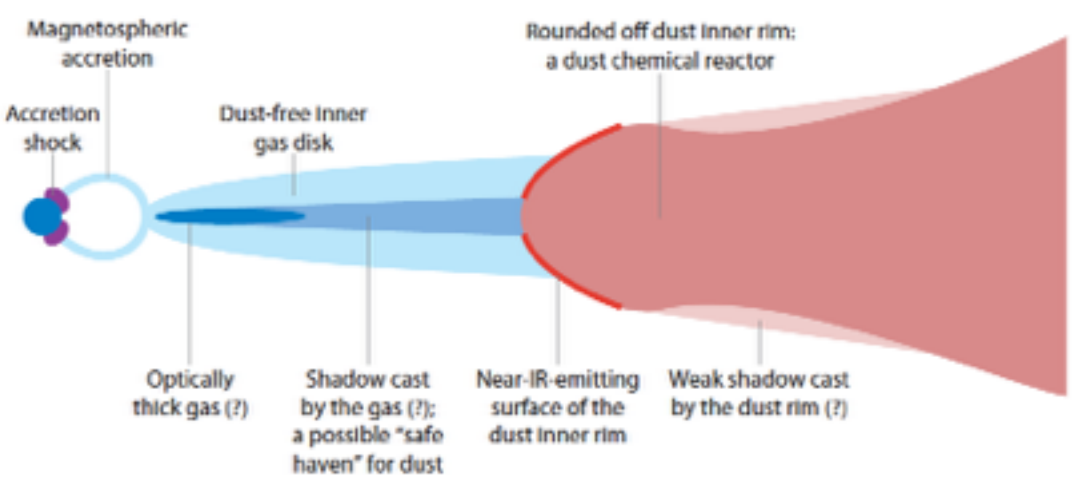


Section 4-5

Ábrahám Péter

Accretion processes, 2014. október 15.

GAS INWARD OF THE DUST RIM

The assumption of optically thin gas inward of the rim is rather crude. Muzerolle et al. (2004): for low accretion rates the gas is sufficiently transparent, but for higher rates (> $10^{-8}\, M_{sun}$/yr) the gas is optically thick.

First question to clarify: **gas opacities!**

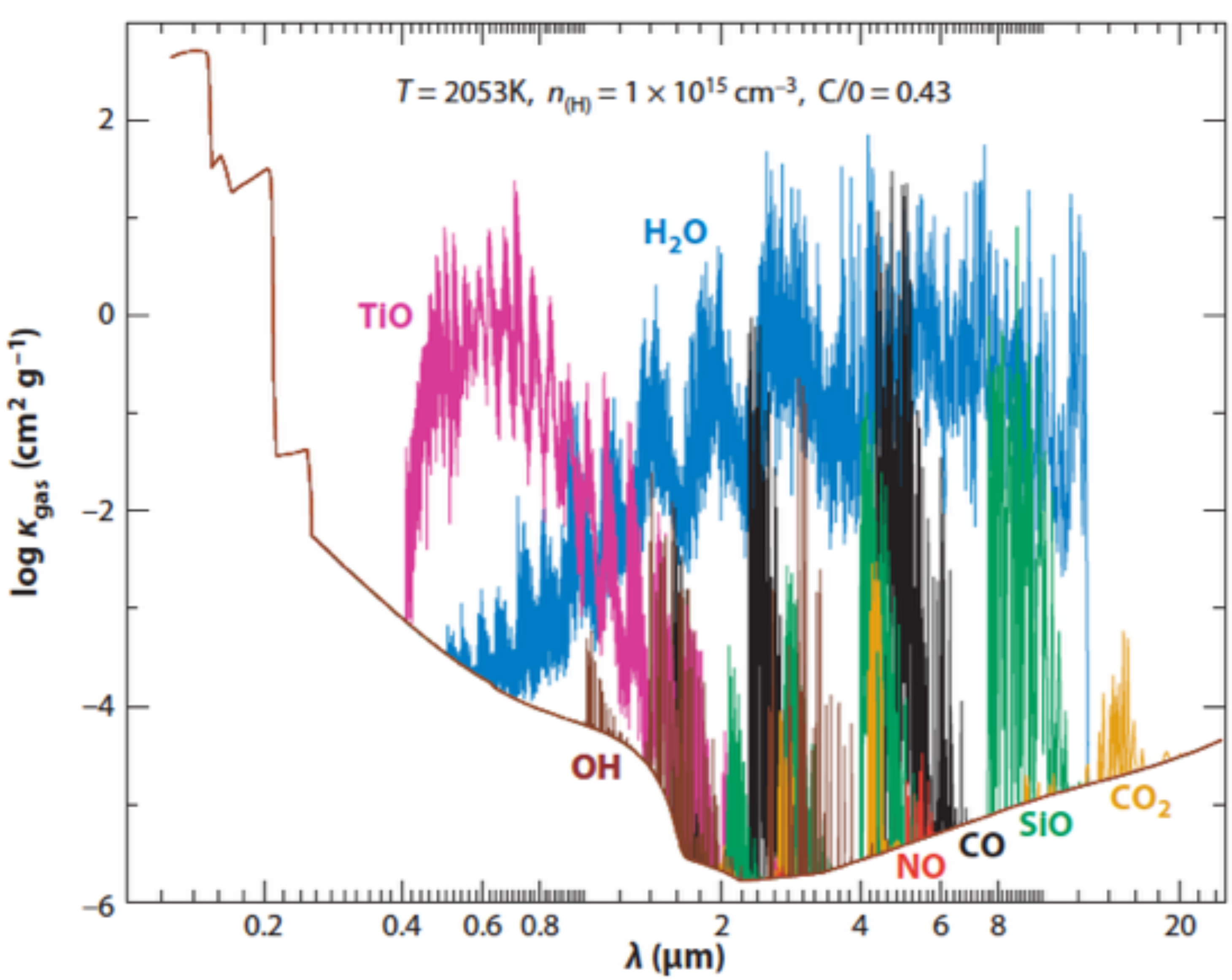
- $T_{rim} < T < T_{star}$
- appropriate densities
- Rosseland or Planck-mean gas opacities are valid only for optically thick medium (weighting factor: Planck function; or Rosseland: $u(\nu, T) = \partial B_\nu(T)/\partial T$)
- Within the rim gas is optically thin, externally illuminated

Frequency-dependent opacities

- gas temperature is too low for continuum opacity sources (like H^-) except for tenuous surface layers
- billions of molecular and atomic lines
- calculated for

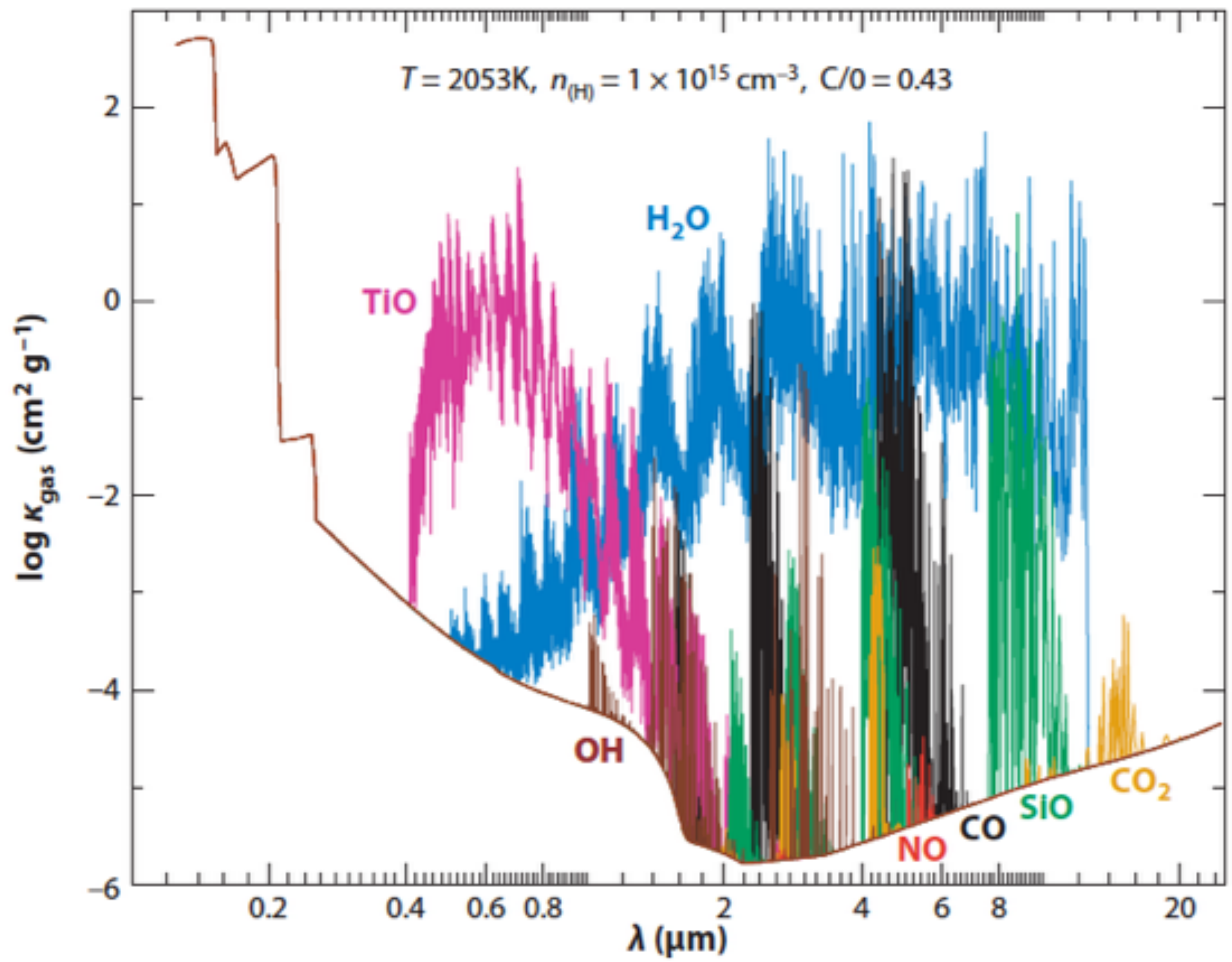
- T = 2000 K
- rho~4x10^{-9} g cm^{-3}

But molecules can be easily destroyed (collisions, UV)
It would reduce opacity



Frequency-dependent opacities

- how to handle the lines?
- opacity is high at line centers, but low between lines (+ weak continuum)
- 0.2 um - 0.4 um
- assuming LTE
- Muzerolle et al. (2004): treat the gap separately from the rest (mean opacity)



Structure of the Dust-Free Gas Inner Disk

- D'Alessio models, but dust opacities are replaced by appropriate gas mean opacities
- geometrically thin disk
- only half of the star…

- photons hit the disk at $\varphi(R) \simeq \frac{4}{3\pi}\frac{R_*}{R}$
- gas disk surface layer ~2000K; half of its NIR radiation is radiated down to the disk interior
- midplane temperature: $T_{\rm mid} = T_* \sqrt{\frac{R_*}{R}} \left(\frac{1}{4} f \varphi(R)\right)^{1/4} = \left(\frac{R_*^3 f}{3\pi}\right)^{1/4} T_* R^{-3/4}$

Structure of the Dust-Free Gas Inner Disk

- surface density: Shakura-Sunyaev accretion disk theory

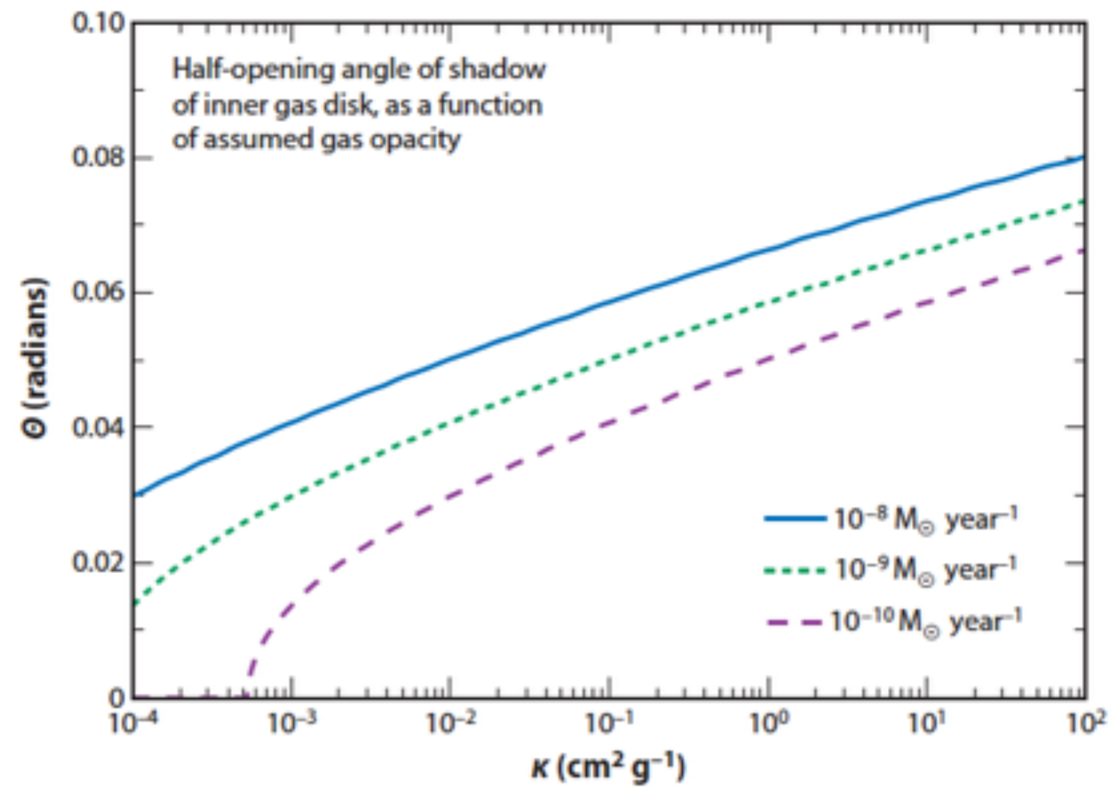
$$\dot{M} = 3\pi \Sigma_{\rm gas} \nu_t; \qquad \nu_t = \alpha k T_{\rm mid} / \mu_g \Omega_K$$

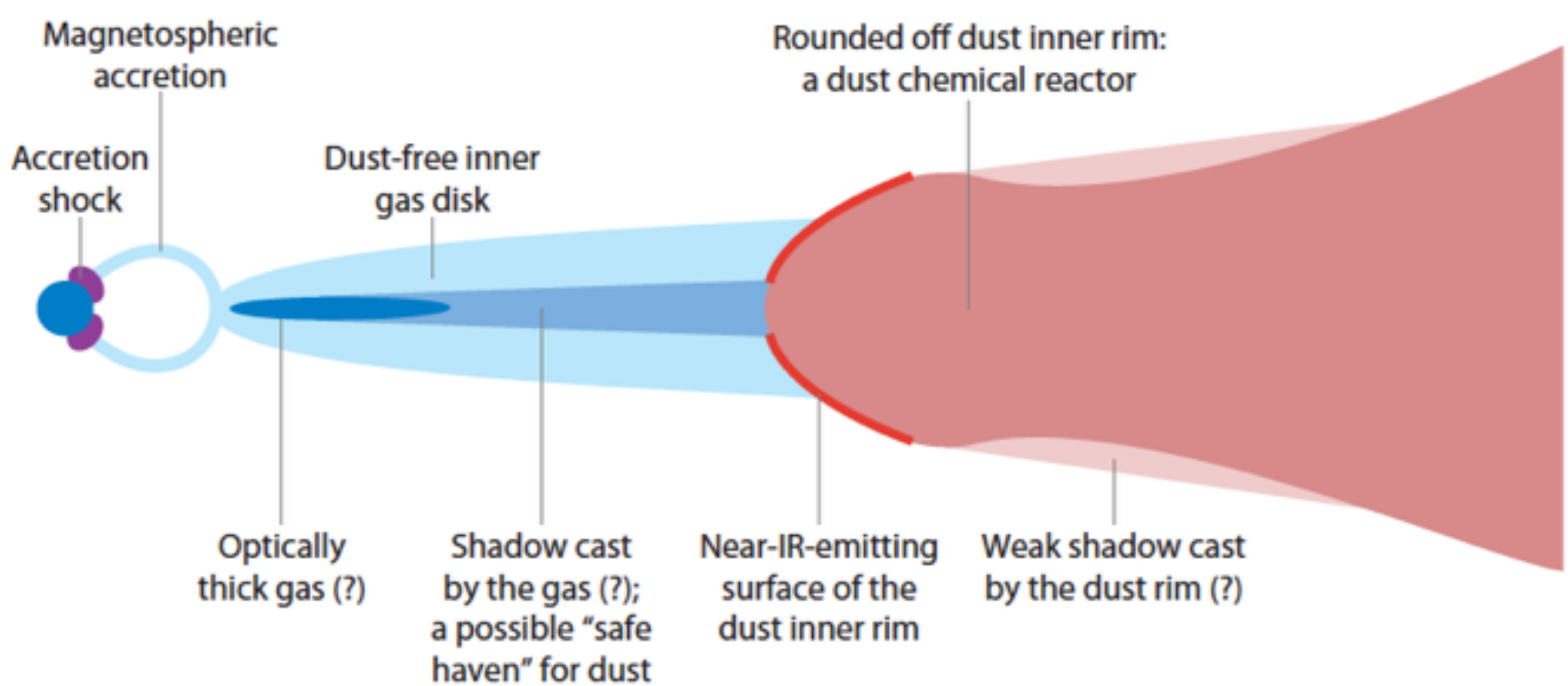
$$\Sigma_{\rm gas}(R) = C \dot{M} R^{-3/4}, \quad \text{with} \quad C \equiv \frac{\mu \sqrt{G M_*}}{(3\pi)^{3/4} R_*^{3/4} \alpha k T_* f^{1/4}}$$

- with the assumed opacities it shows that the inner gas disk is vertically optically thick for the surface layer's radiation
- Pressure scale height: $H_p / R = 0.0167 \, (R/\mathrm{AU})^{1/8}$
- at 0.5 AU H_p=0.6 R_{star}
- geometrically thin approximation fails!

Shadow on the dust rim

- radial integration of optical depth
- teta(rim)=0.2/1.5=0.133
- shadow in the mid plane
- cannot hide the rim, especially at 0.2-0.4um





PROBING THE INNER DUST-FREE DISK WITH GAS LINE OBSERVATIONS

- Search for Molecules in the Inner Dust-Free Disk
- Expectation: strong molecular emission
- Observation: deficit of molecules in the dust-free inner disk
- CO fundamental lines are commonly found (formed in the surface layer between 0.1 and 2 AU, Najita et al. 2007)
- CO overtone lines are rare, excited at >1000 K by collisions in the innermost part of the disk (0.05-0.3 AU)
- its lack may suggest that molecules are destroyed in the dust-free region
- or maybe density is too low

NIR spectrointerferometry

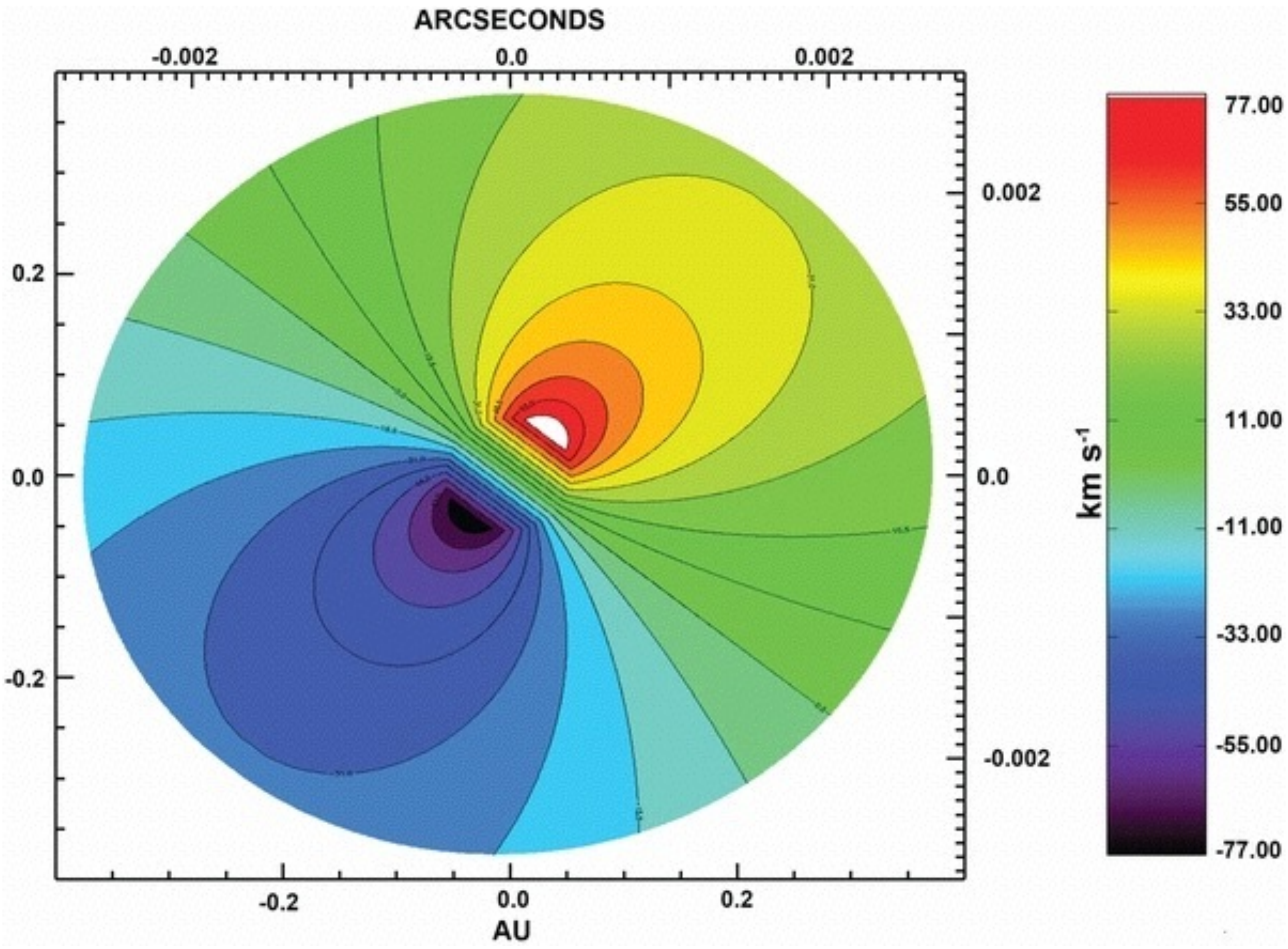
- Visibility as a function of wavelength
- Differences in continuum and line visibilities?
- Normal Herbig Ae star HD 104237 (Tatulli et al. 2007). Shocking result: Br gamma is coming from an extended region just inside the dust rim (and not the accretion shock)!
- Larger datasets (Kraus et al. 2008, Eisner et al. 2009) find a diversity of size scales for the Br-γ emission, from point-like to extended.
- Probably related to inner disk wind

Where are the molecules?

- Why YSO disks do not show stronger emission from molecules in the dust-free inner disk, given that the molecular emission is regularly seen in the surface layers of the disk in the dusty regions of these disks?
- there does seem to be evidence for molecules right within the dust rim, where dust may protect molecules

Probing the Dynamics of the Inner Gas Disk

- Spectroastrometry



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(Brown et al. 2013)

The accretion path: SINFONI observations

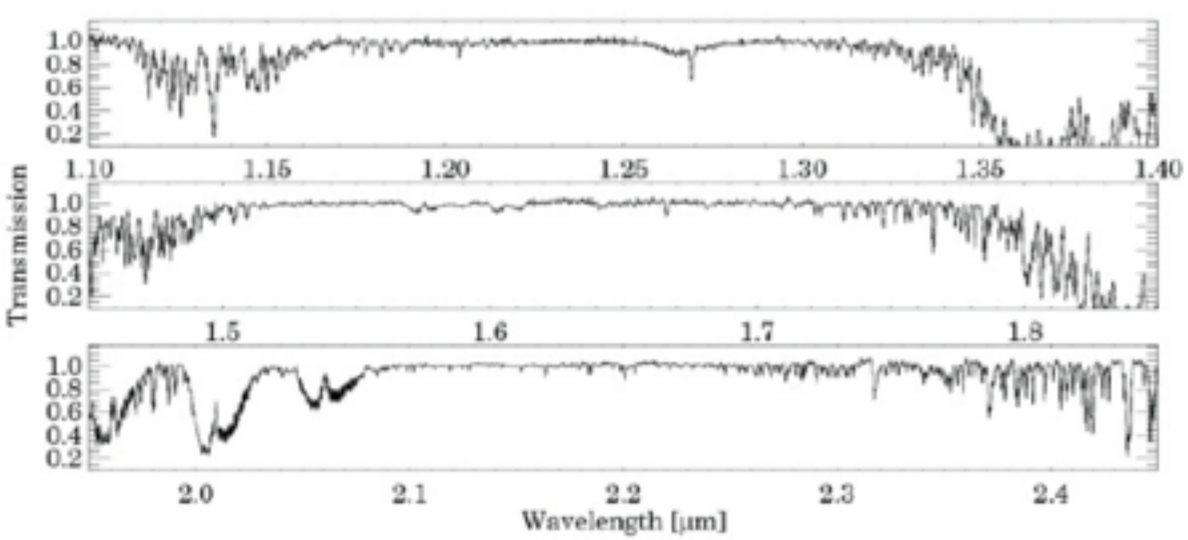
Kóspál et al. 2011, ApJ:

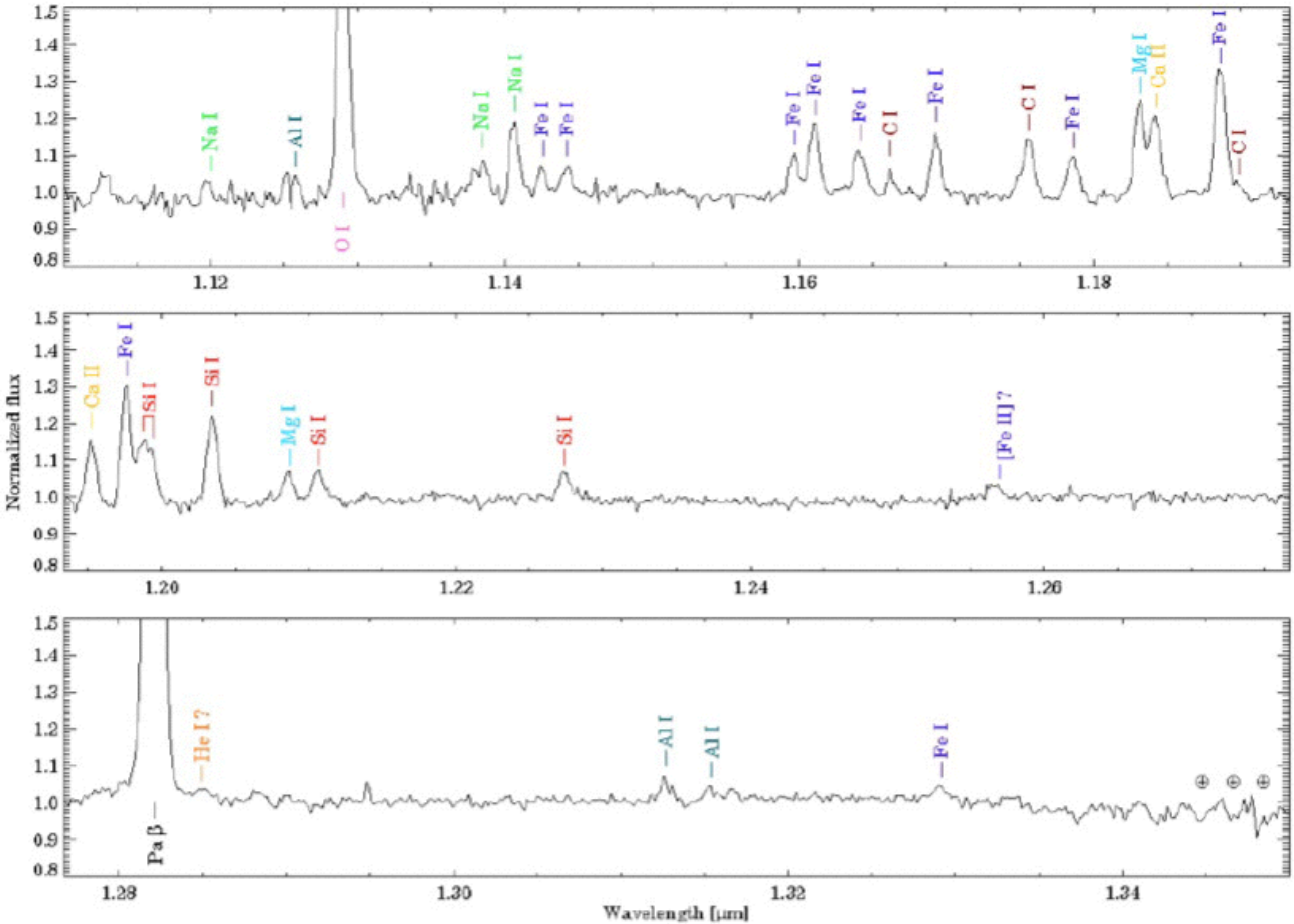
Three VLT/SINFONI observations in the JHK bands

SINFONI: AO-assisted integral field spectrograph on UT4

Medium resolution: R=2400 in J, 4100 in H, 4400 in K

Calibration with G-type stars and the solar spectrum





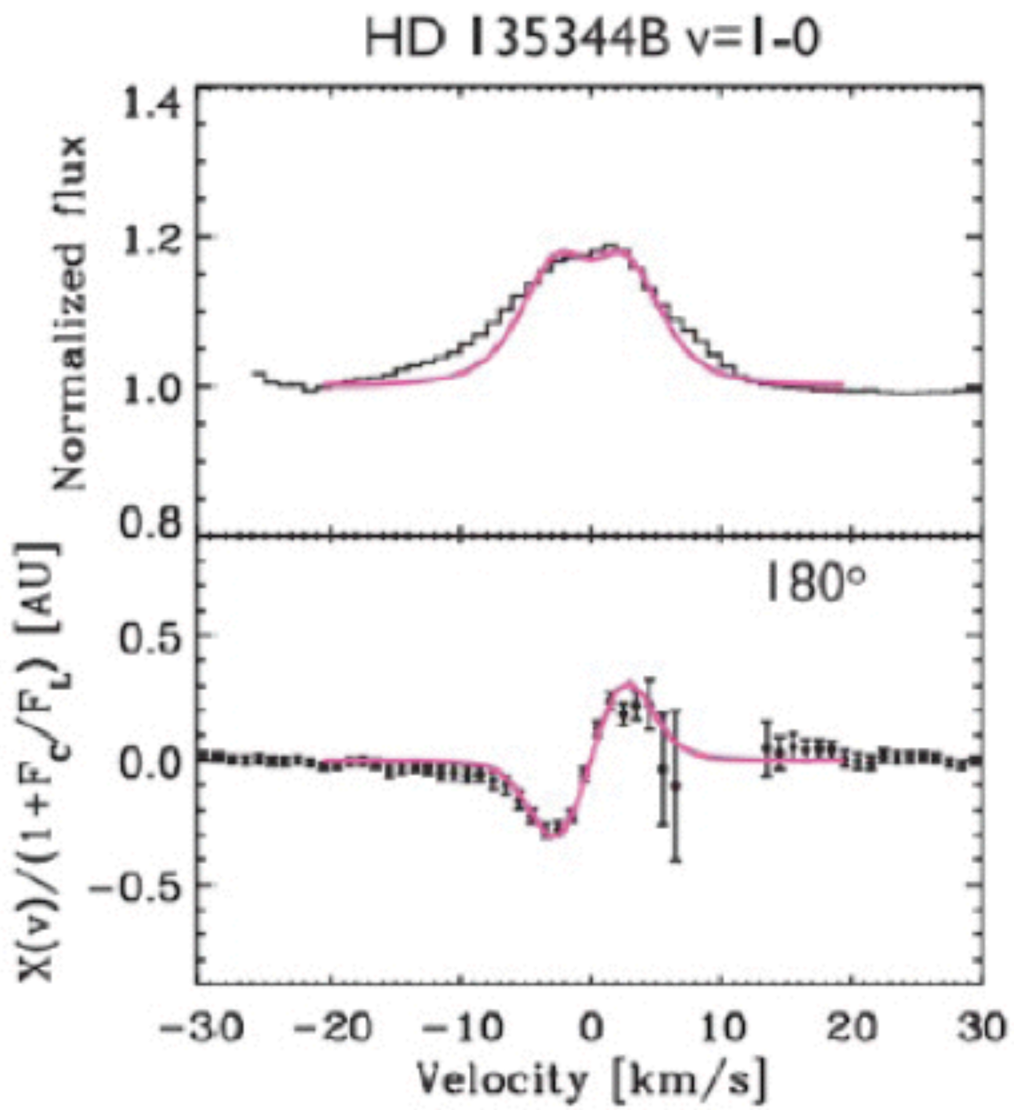
Na I
Al I
O I
Na I
Na I
Fe I
Fe I
Fe I
Fe I
Fe I
C I
Fe I
C I
Fe I
Mg I
Ca II
Fe I
C I
Ca II
Fe I
Si I
Si I
Mg I
Si I
Si I
[Fe II] ?
Pa β
He I ?
Al I
Al I
Fe I
Normalized flux
Wavelength [μm]

Spectro-astrometry with SINFONI

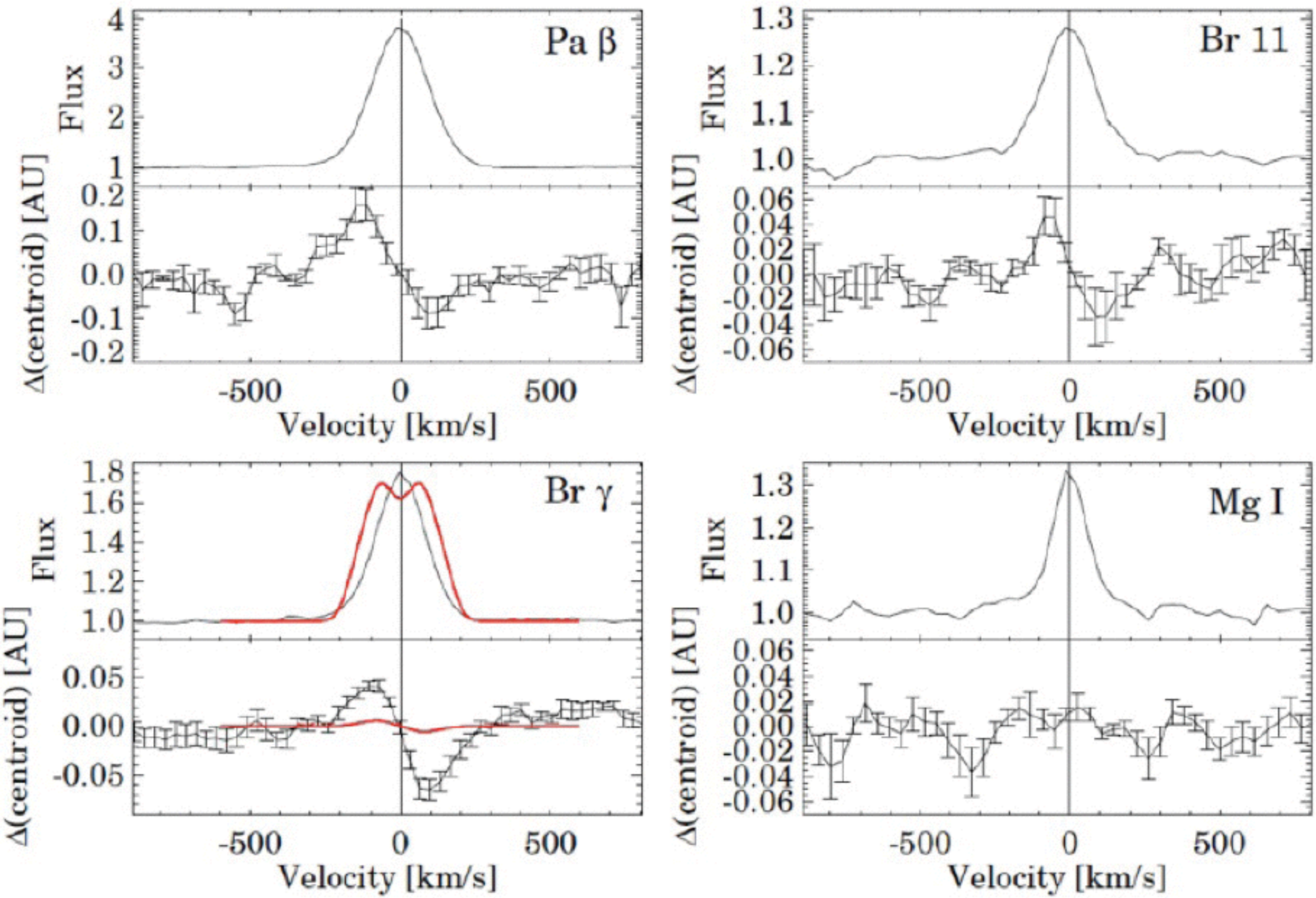
Measure the position of the source as the function of wavelength

Extended emission moving at different velocities: source position at different wavelengths will deviate from the source position in the continuum

Example: CO fundamental lines at 4.7 μm



Pontoppidan et al. 2008



Pa β
Br 11
Br γ
Mg I
Flux
Δ(centroid) [AU]
Velocity [km/s]

The origin of the hydrogen lines

Inner disk/boundary layer?

In the case of a Keplerian disk between the stellar surface and 0.04 AU the line profiles would be double peaked, but the spectro-astrometric signal would be much lower than observed

We detect high-velocity gas at larger distance from the star than predicted by a Keplerian disk model.