Inner disk structure and accretion

Ágnes Kóspál
Konkoly Observatory

http://konkoly.hu/staff/kospal/teaching.html

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Main literature

C. P. Dullemond & J. D. Monnier
Annu. Rev. Astron. Astrophys. 2010, 48:205−239

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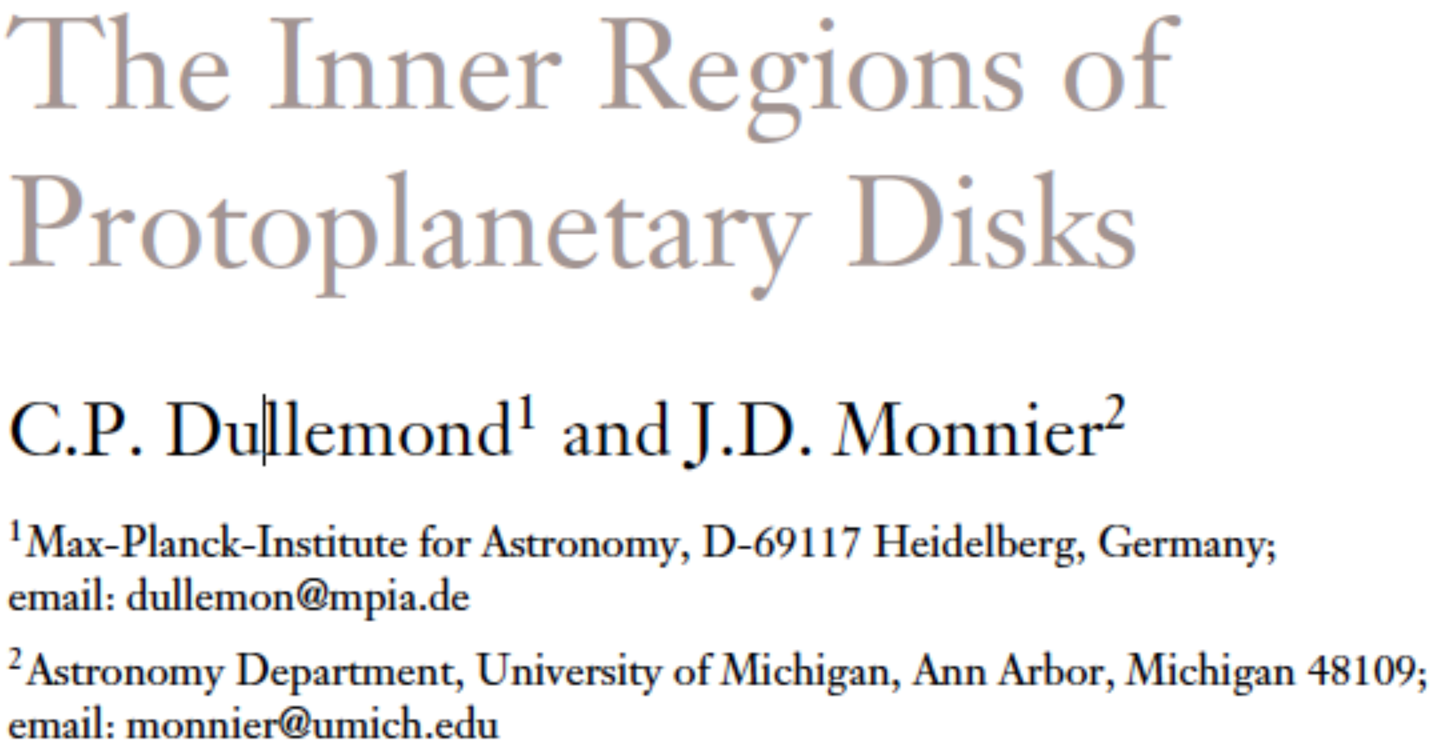


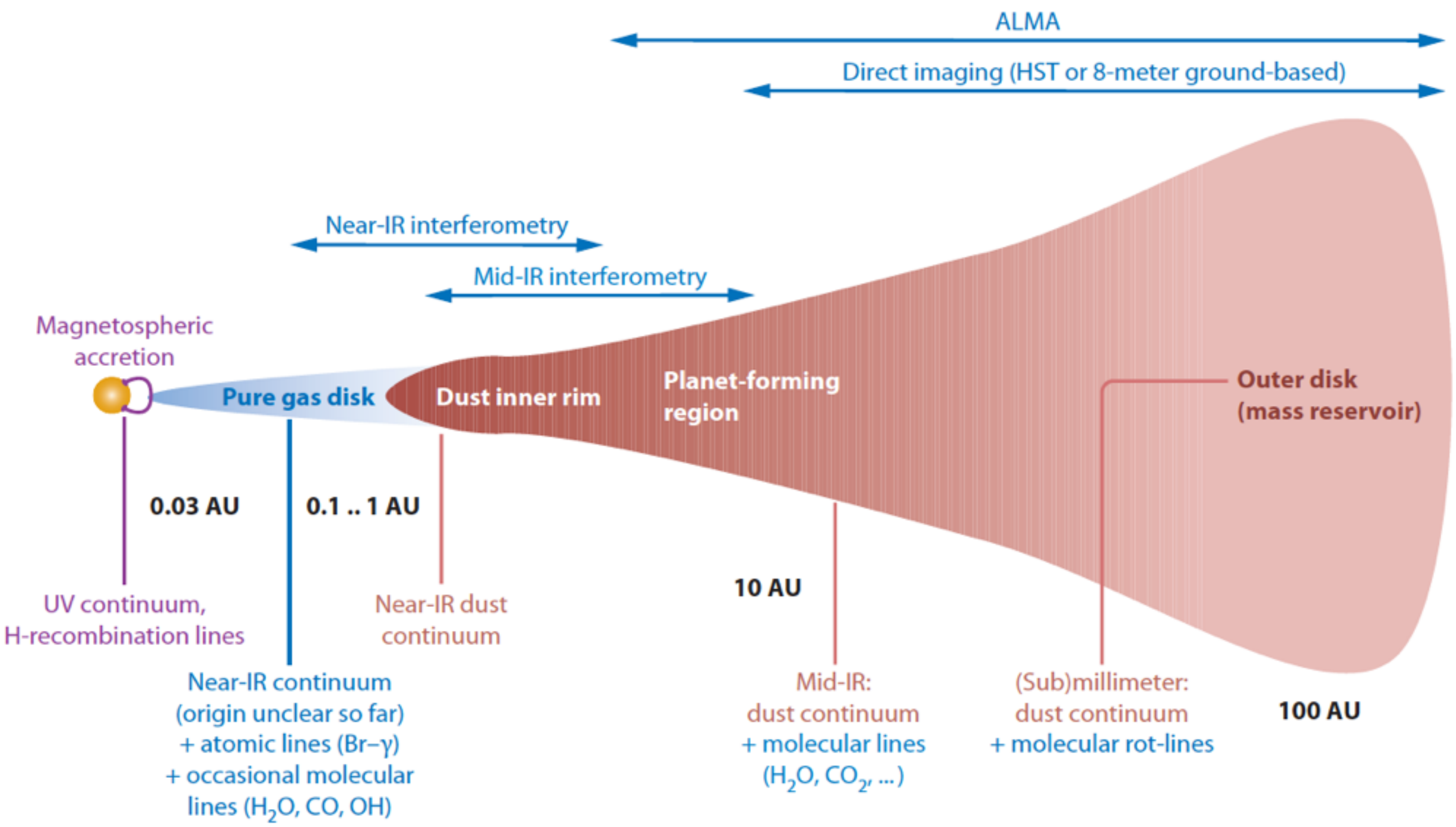
The Inner Regions of Protoplanetary Disks

C.P. Dullemond[1] and J.D. Monnier[2]

[1]Max-Planck-Institute for Astronomy, D-69117 Heidelberg, Germany;
email: dullemon@mpia.de

[2]Astronomy Department, University of Michigan, Ann Arbor, Michigan 48109;
email: monnier@umich.edu

The Inner Regions of Protoplanetary Disks

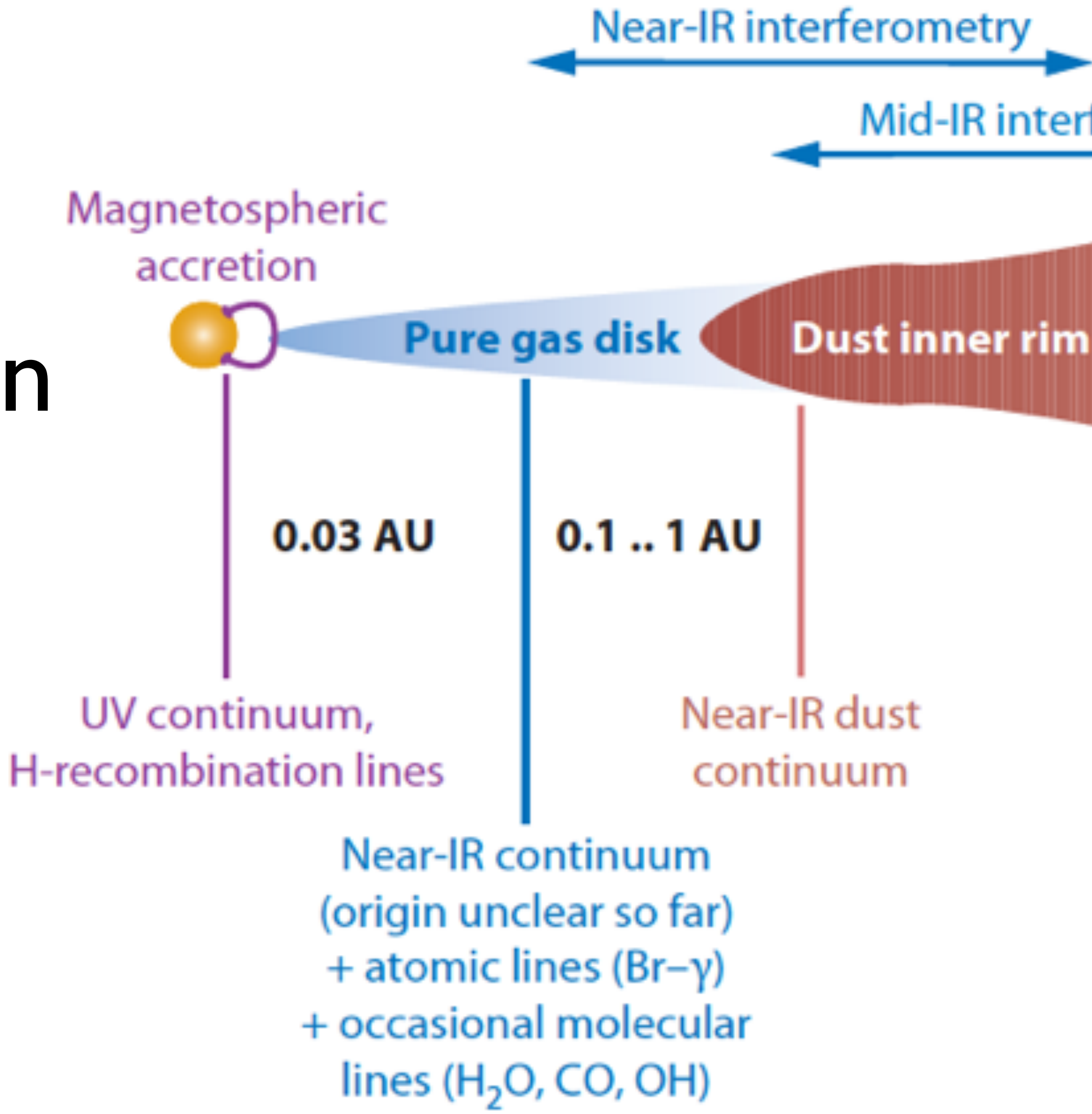


Rich structure

- Large dynamic range
  - spatial scale: few stellar radii ↔ 100 − 1000 au
  - orbital timescale: factor of 10^6 difference between inner and outer disk
  - temperature: >1000 K ↔ 10 − 30 K
- Inner 1 au is a puzzle because:
  - Difficult to spatially resolve
  - Physics is poorly understood (hot → dust evaporates)
  - Numerical modeling is challenging

Inner disk

- Roughly < 1 au
- Temperature is high enough to evaporate dust grains
- Energy is radiated in the UV, visible, and NIR
- Until recently, unresolved region (1 au at 150 pc is 7 mas)
- Spectroscopy gave hints about complex structure and interesting physics
- Now: IR interferometry



Near-IR interferometry

Mid-IR inter

Magnetospheric accretion

Pure gas disk

Dust inner rim

0.03 AU

0.1 .. 1 AU

UV continuum, H-recombination lines

Near-IR dust continuum

Near-IR continuum (origin unclear so far) + atomic lines (Br–γ) + occasional molecular lines (H_2O, CO, OH)

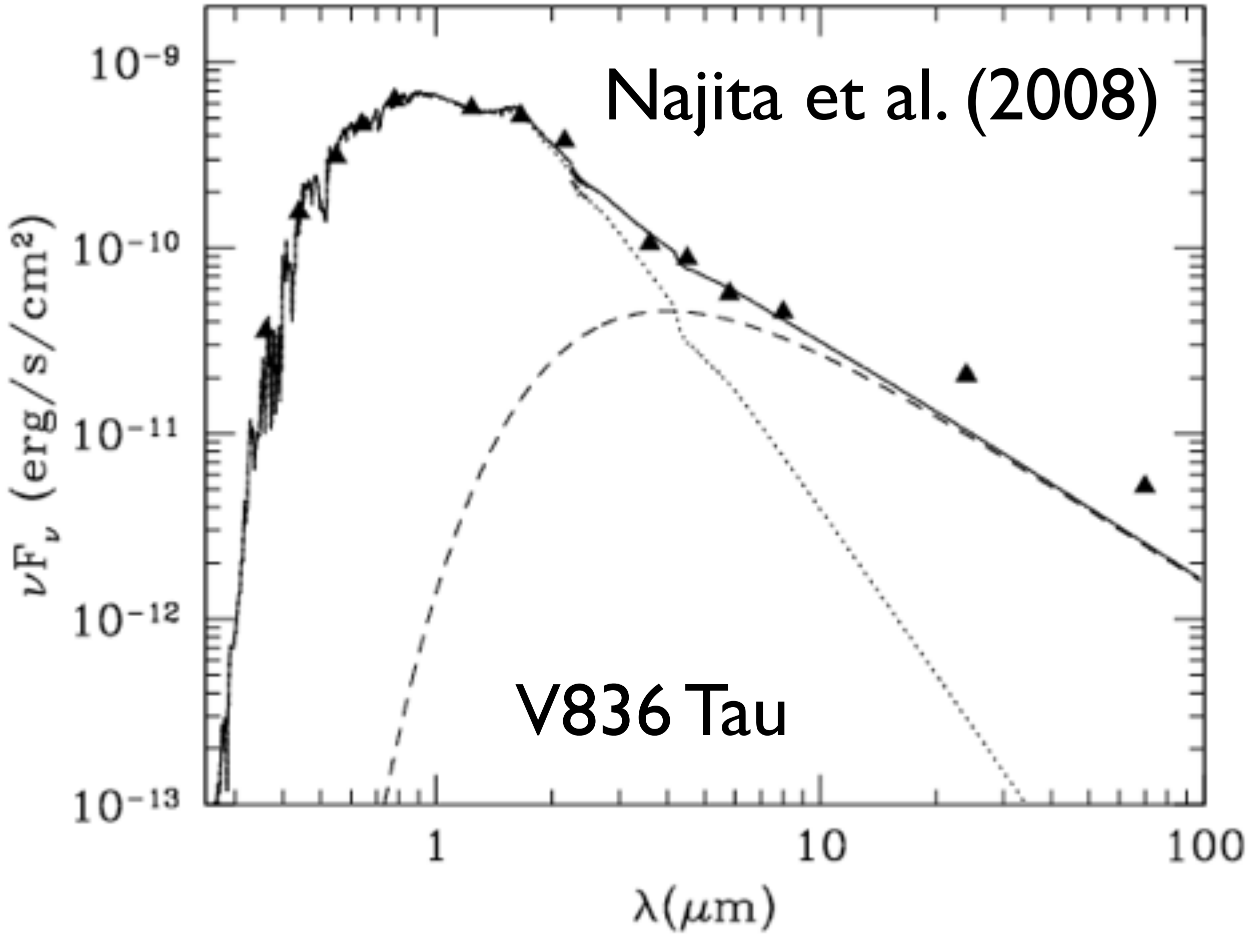
Existence of disks?

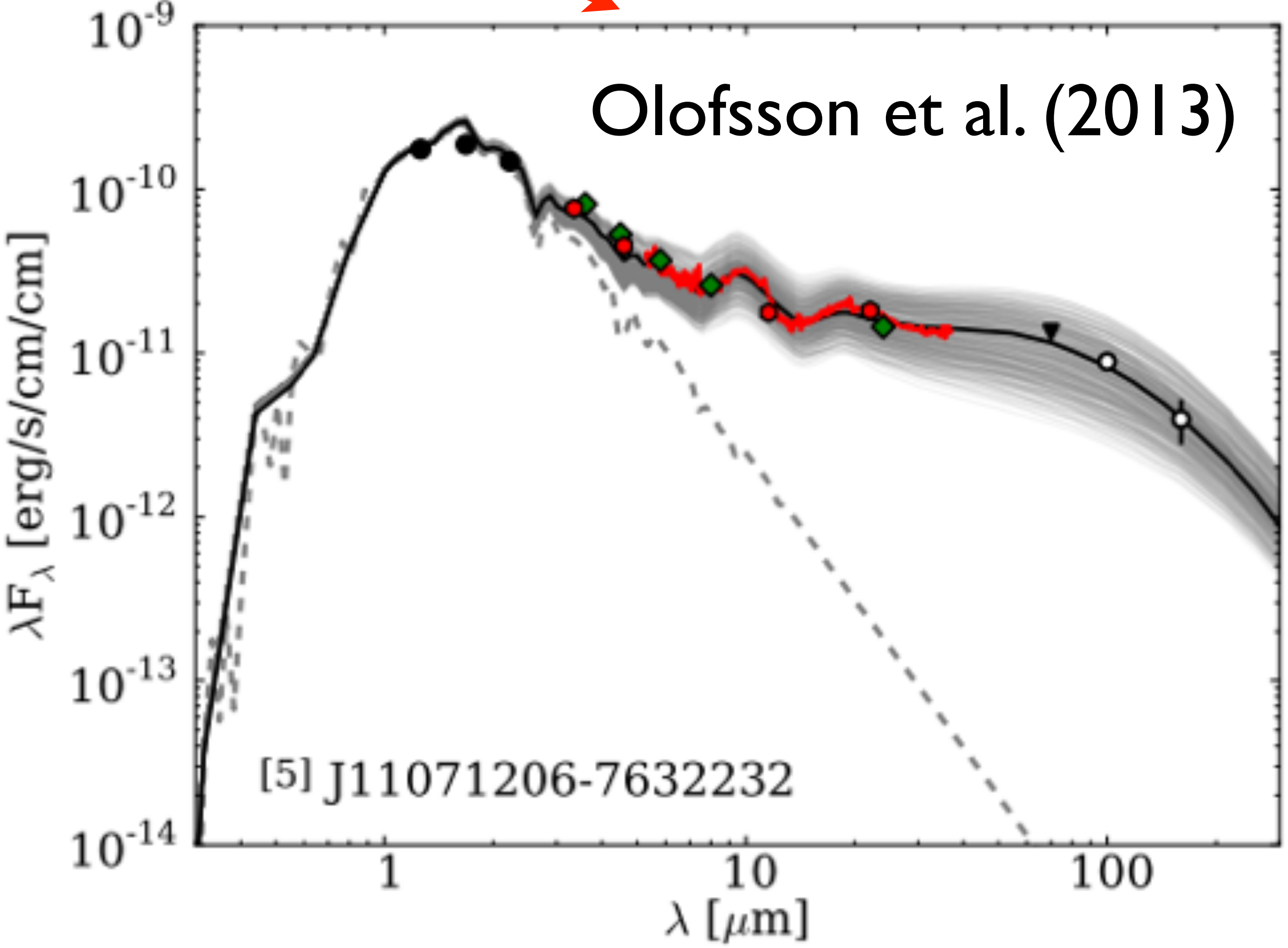
- Presence of disks: for low- and intermediate mass stars, it's now well established
- Indicator for circumstellar material: IR excess
- Outer part of the circumstellar material is disk-like (direct imaging)

- What about the inner (unresolved) part?
- Can it be spherical? No, there is no correlation between NIR excess and A_V

T Tauri and BD disks

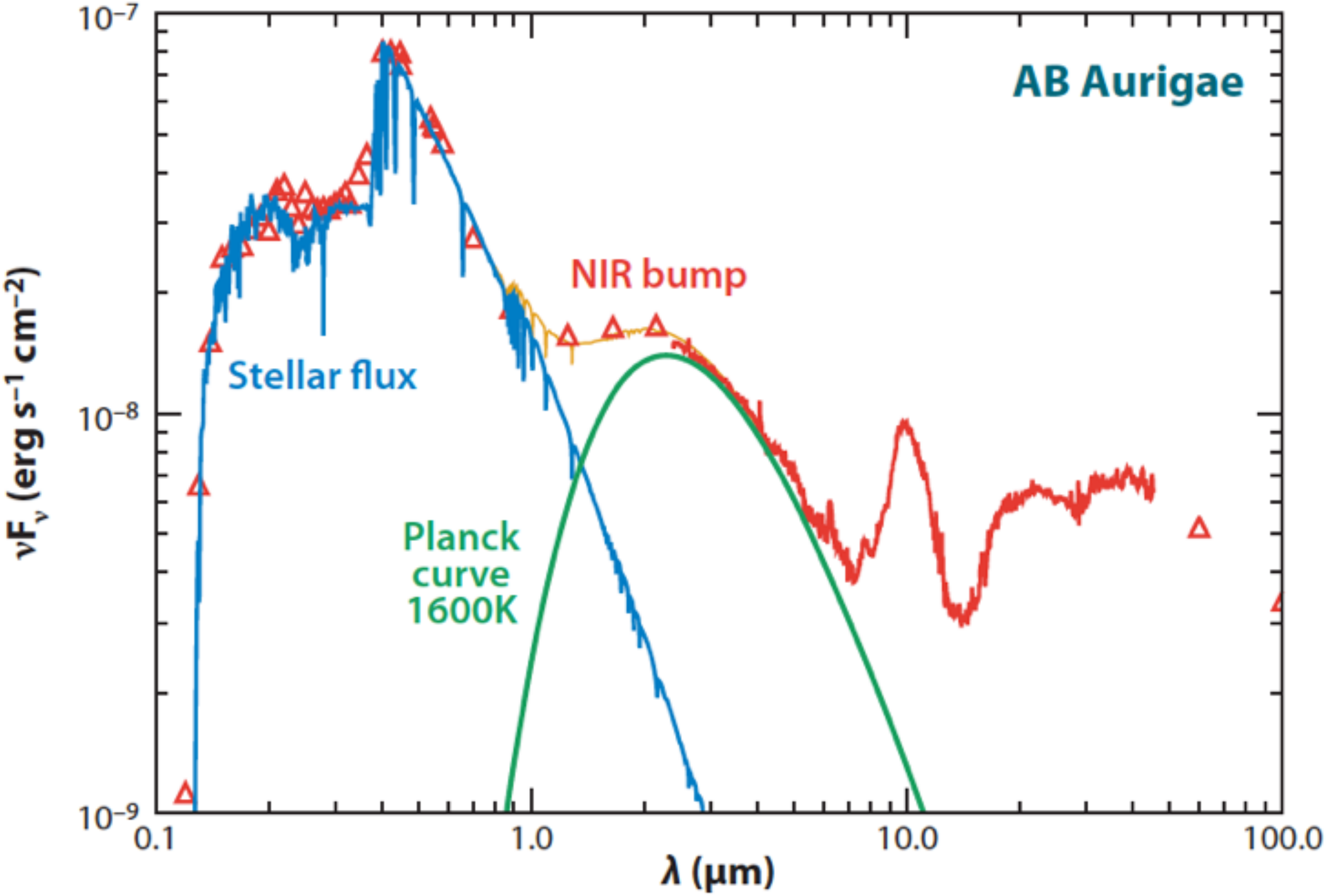
- SED shape of T Tauri stars and BDs consistent with flat or flared disk geometry


Najita et al. (2008)


Olofsson et al. (2013)

NIR bump

- Herbig Ae/Be stars often show a NIR bump
- JHKL line up to form a ~1500 K blackbody

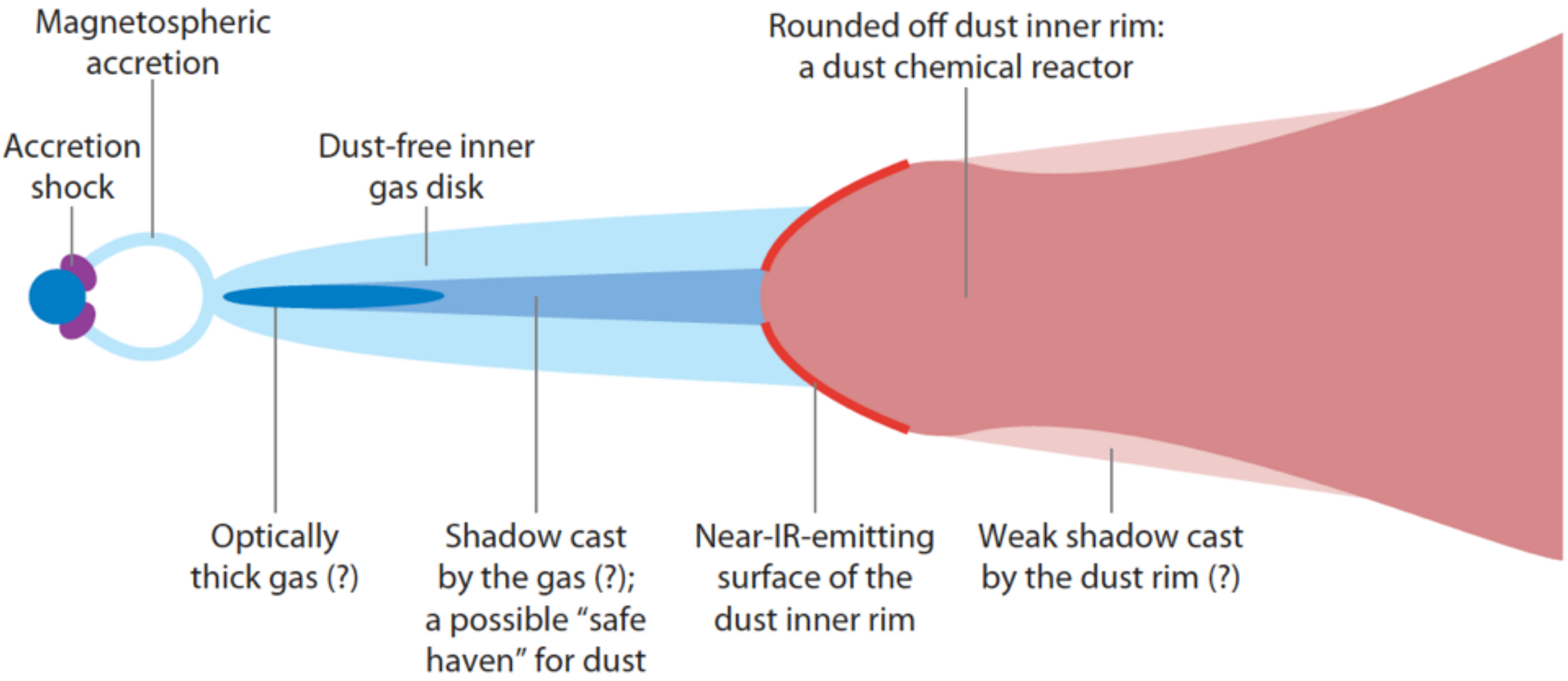


1500 K ↔ dust sublimation

- Most species of interstellar dust can survive until 1500 K
- Reasonable assumption: NIR bump is due to emission from dust grains on the brink of evaporation
- Dust dominates the opacity; gas is much less optically thick (may even be optically thin / transparent)
- Consequence: the dust rim looks like an optically thick "wall" seen from the inside

Inner disk structure

Proposal of Natta et al. (2001) and
Tuthill, Monnier & Danchi (2001):

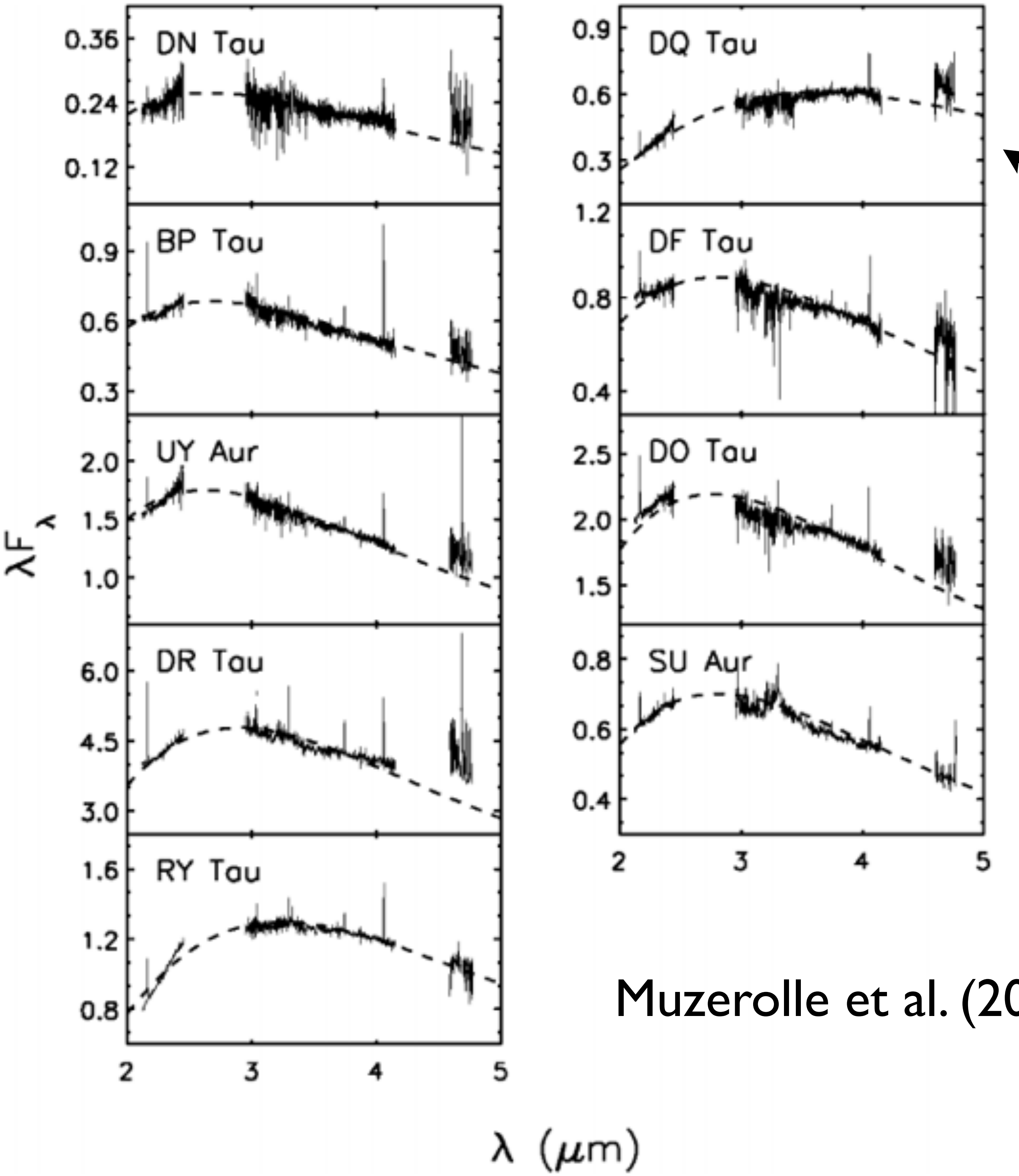


Inner dust wall naturally explains the NIR bump

Puffed-up inner rim

- Dust wall is puffed-up, because it is hotter → vertical scale height is higher
- Dullemond, Duminik & Natta (2001): complete description of Herbig Ae/Be star SEDs in terms of a simple irradiated disk model
- Why do only Herbig stars show this feature?
- Lower luminosity, lower temperature → stellar emission is at longer wavelengths, bump is relatively weaker than in Herbig stars, but it is there.

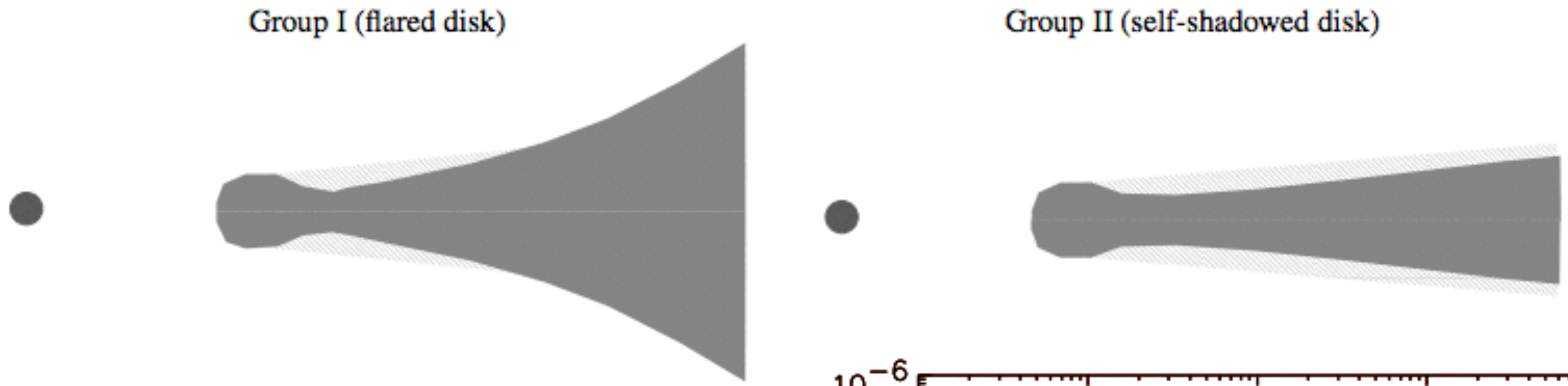
NIR bump in T Tauri stars



Stellar photosphere-subtracted SEDs

Muzerolle et al. (2003)

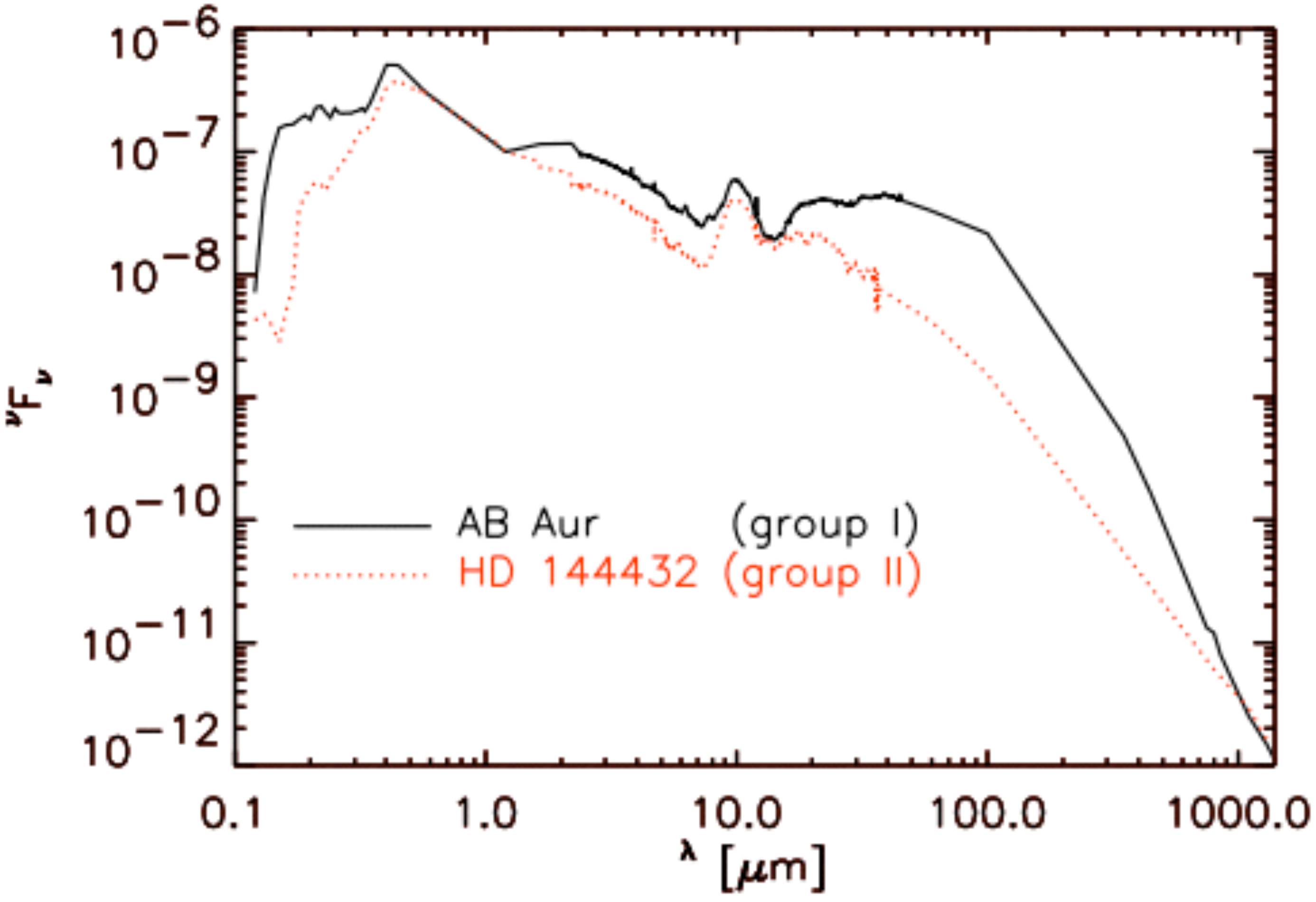
Shadowing by puffed-up rim in Herbig stars



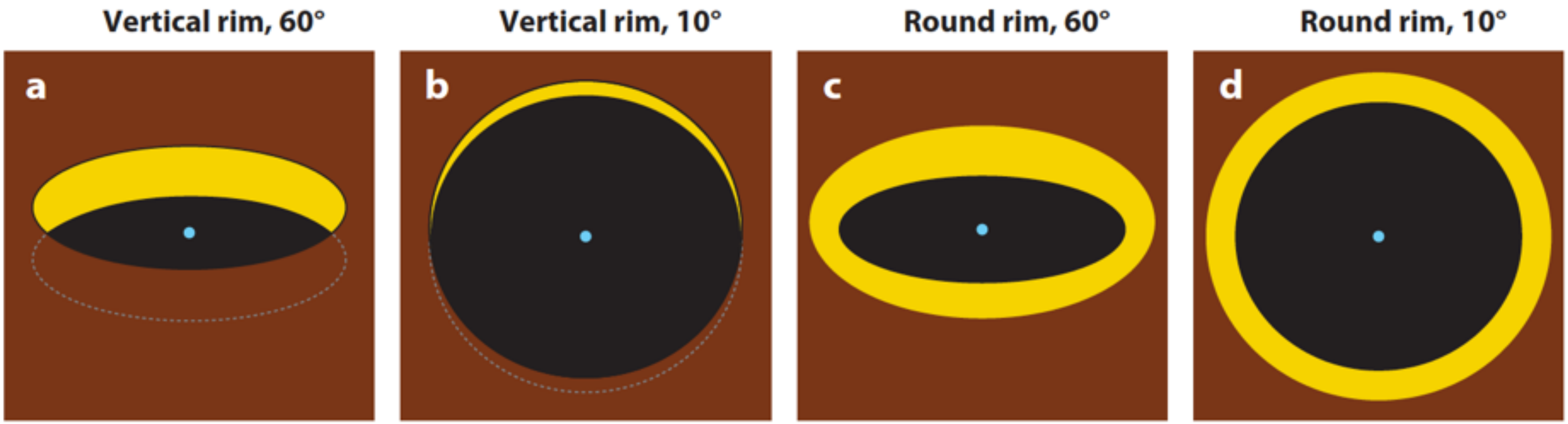
- Radiative diffusion is important
- Disk will never collapse completely

Meeus et al. (2001)

Dullemond & Dominik (2004)



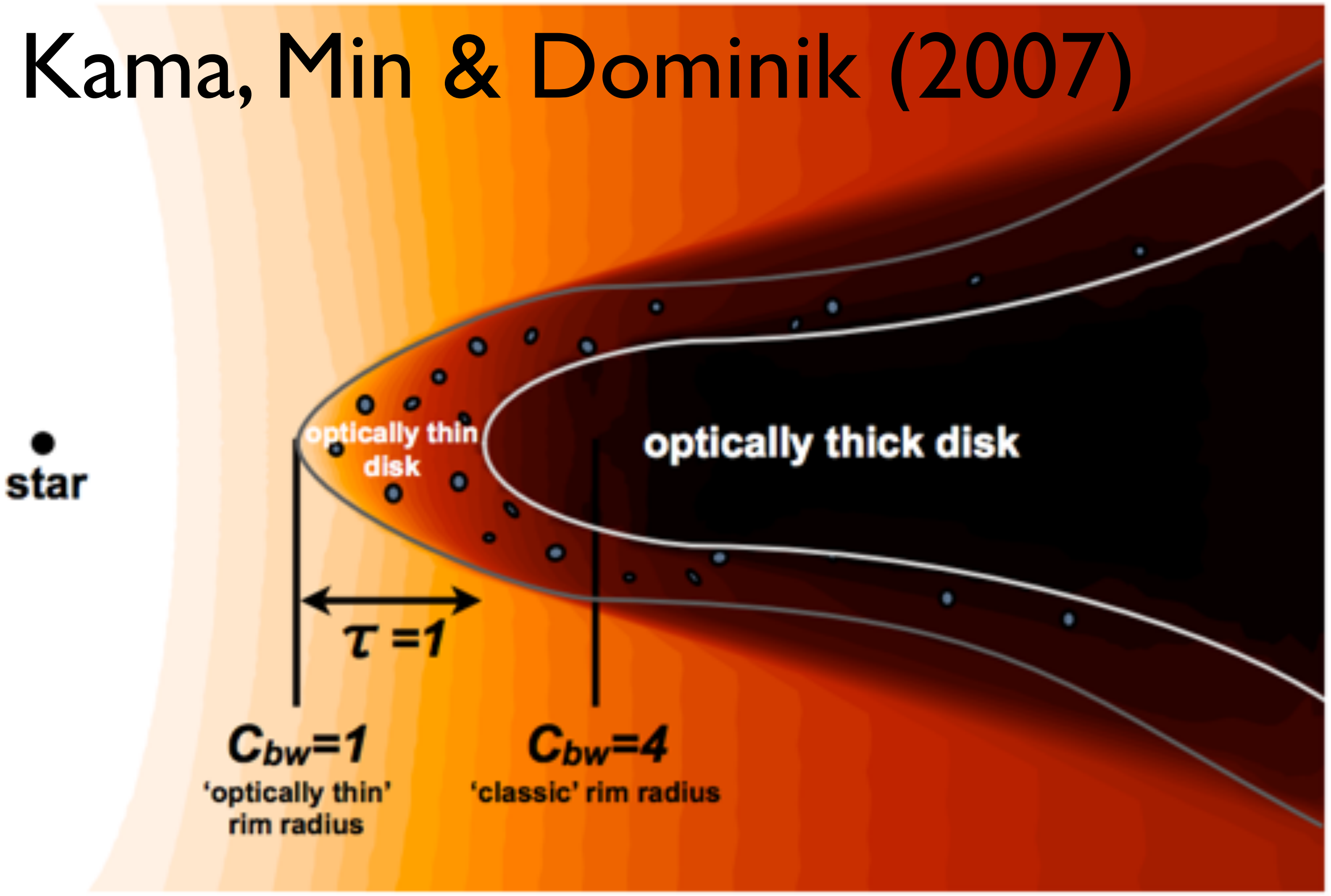
Dust rim: not vertical!



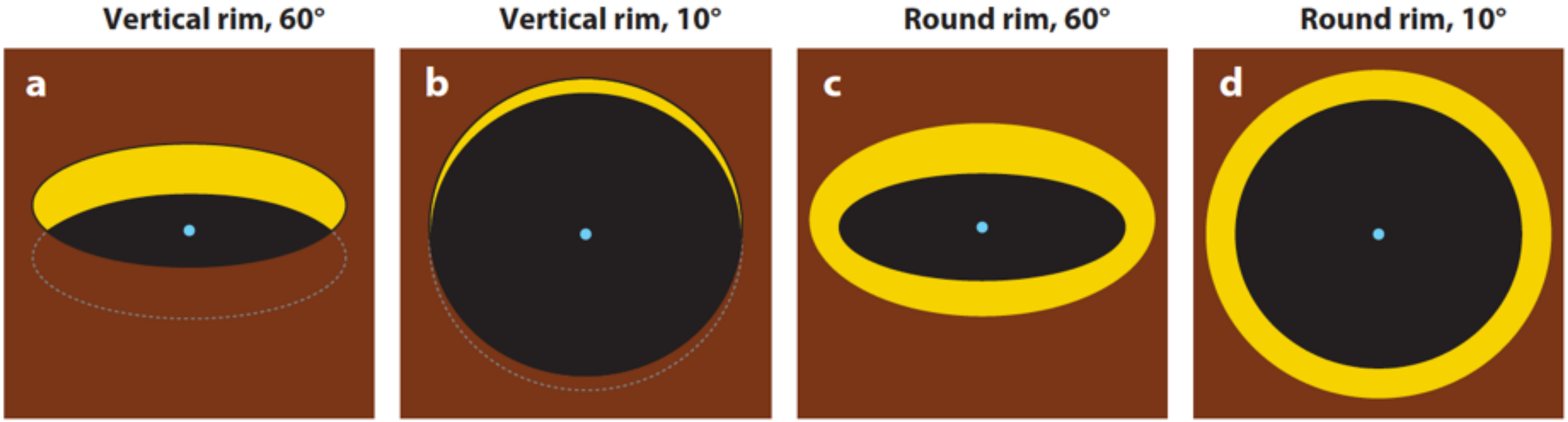
- No clear correlation between the NIR flux and the disk inclination
- AB Aur: almost face-on, but has a huge NIR bump
- Solution: rounded rim

Evaporation/condensation

- Complex process, depends not only on T
- Depends also on the abundance of condensable atoms in the gas phase (partial pressure)
- For a given gas density, there is a critical T_{evap}:
  - Above T_{evap}, dust evaporates
  - Below T_{evap}, dust condensates
- Rounded-off rim model of Isella & Natta (2005)


Kama, Min & Dominik (2007)

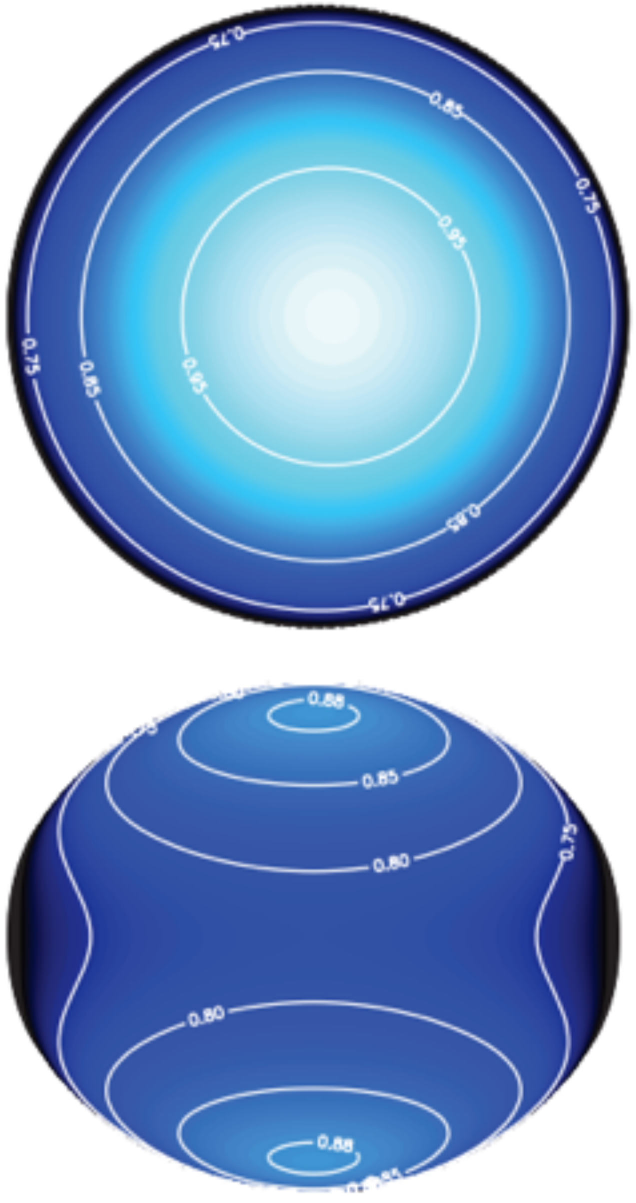
Dust rim: not vertical!



- Spatially resolve the NIR emission from the rim?
- Difficult: 1 au ↔ 7 mas (at the distance of Taurus)
- Needs NIR interferometry
- Image reconstruction is now possible yet, model fitting is needed

IR interferometry

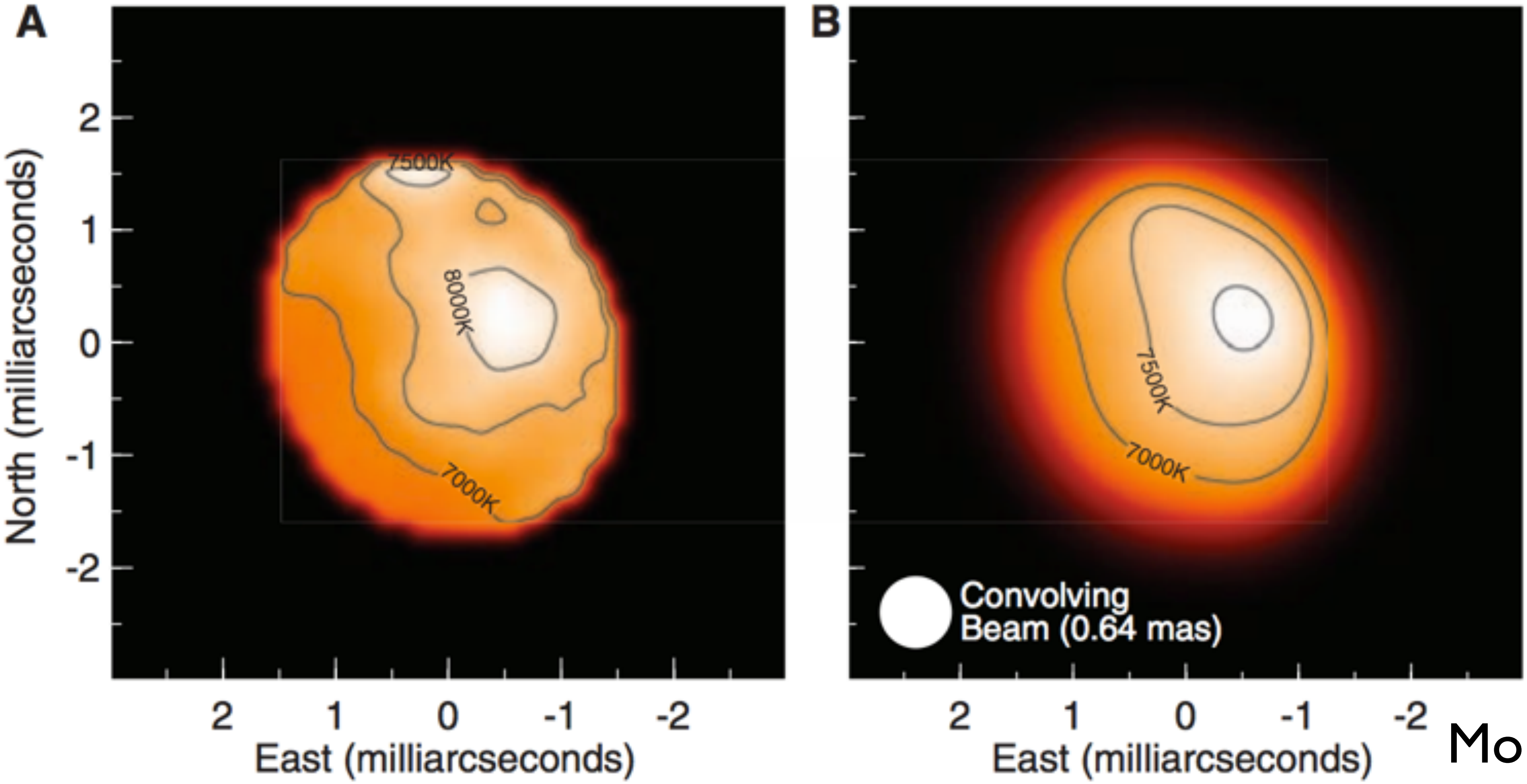
- Challenging: so far only 2 telescope (one baseline) or 3 telescopes (three baselines) could be joined
- Past IR interferometers: Palomar Testbed Interferometer (PTI), Keck Interferometer; Infrared Optical Telescope Array (IOTA); Infrared Spatial Interferometer (ISI); Cambridge Optical Aperture Synthesis Telescope (COAST)
- Current NIR interferometers: CHARA array, VLTI



Vega (Aufdenberg et al. 2006)

IR interferometry

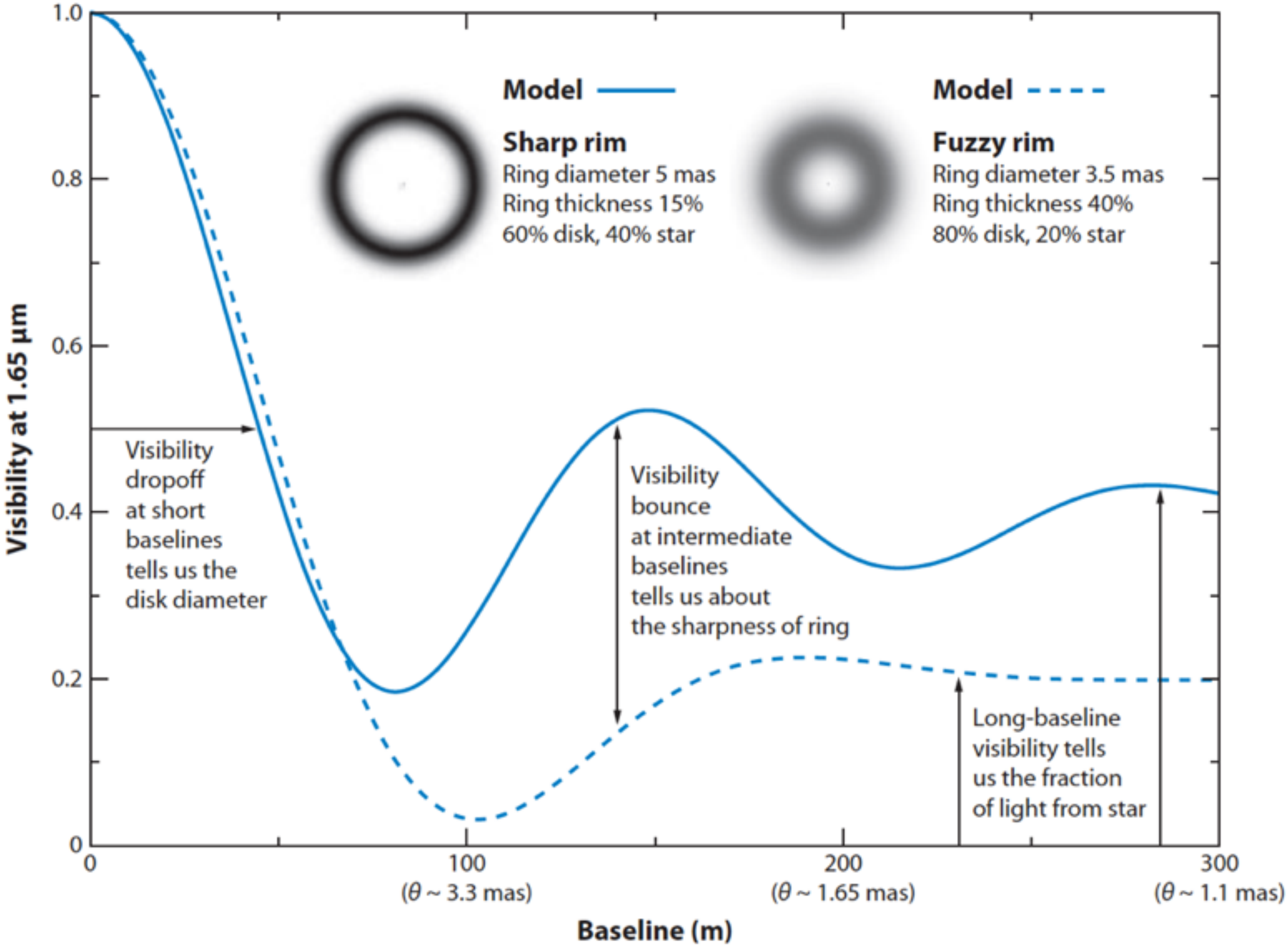
- In most cases IR interferometry does not provide images, model fitting is required to interpret the visibilities
- Few exceptions: Vega, Altair (bright stellar disks)



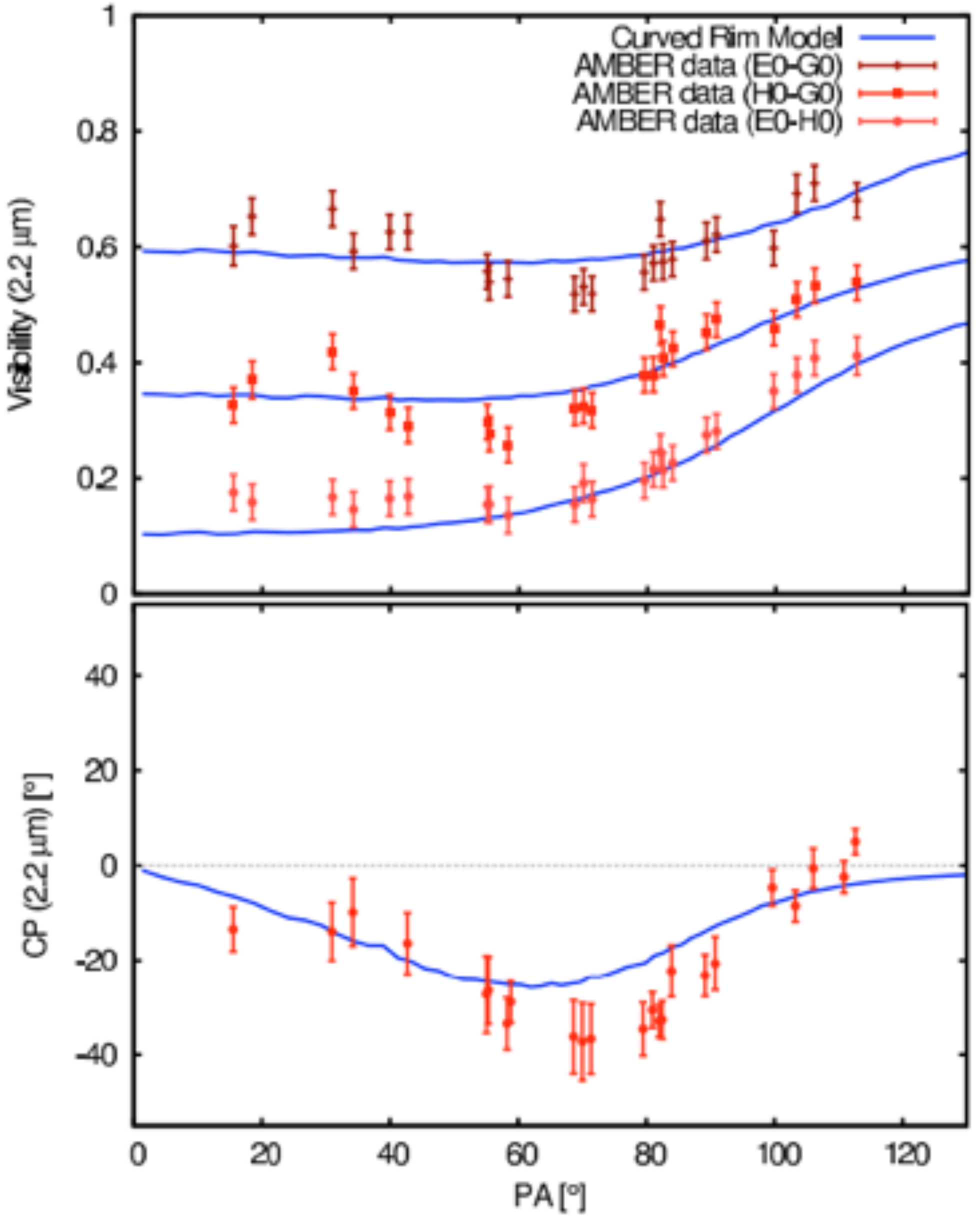
Monnier et al. (2007)

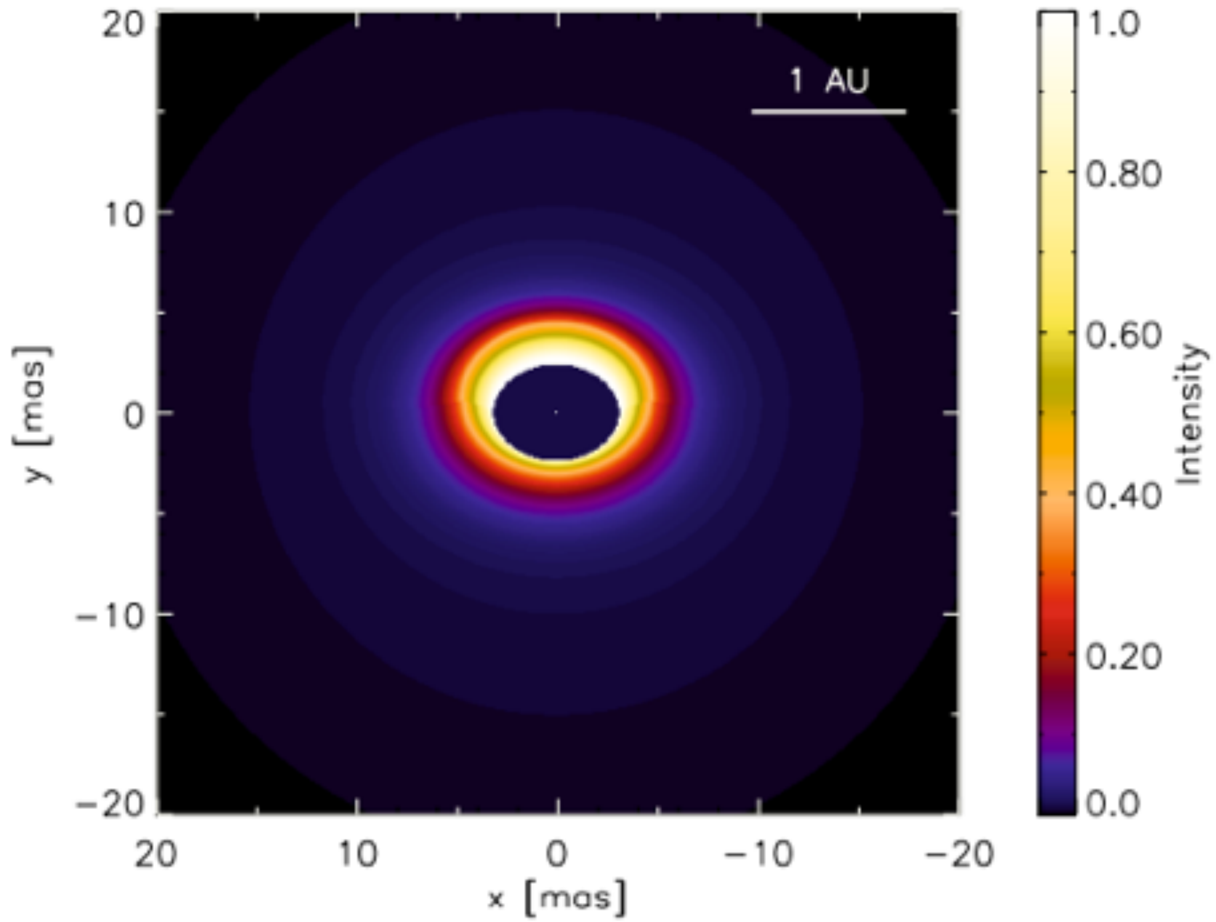
IR interferometry

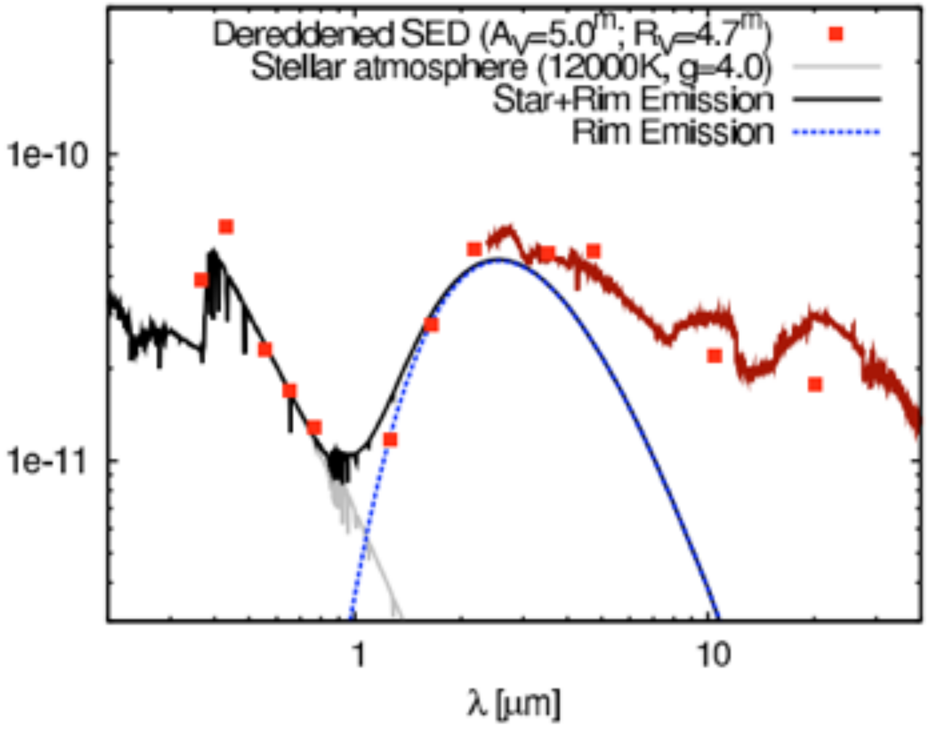
Interpretation of interferometric observations:

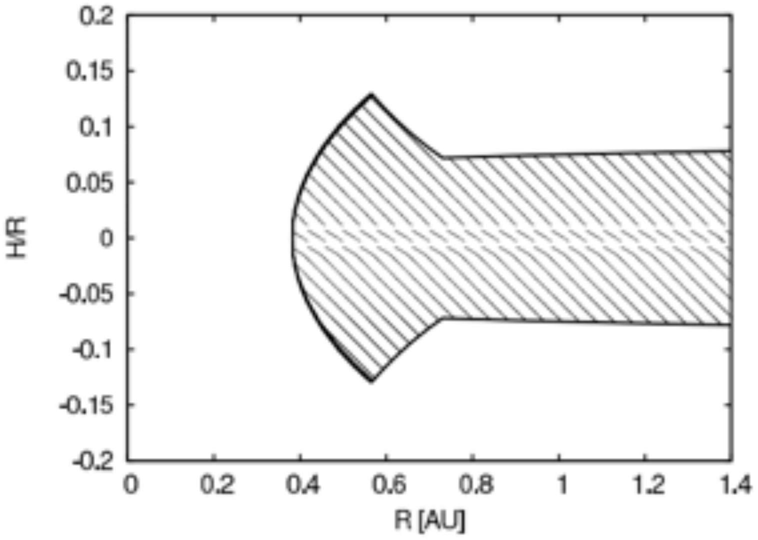


IR interferometry





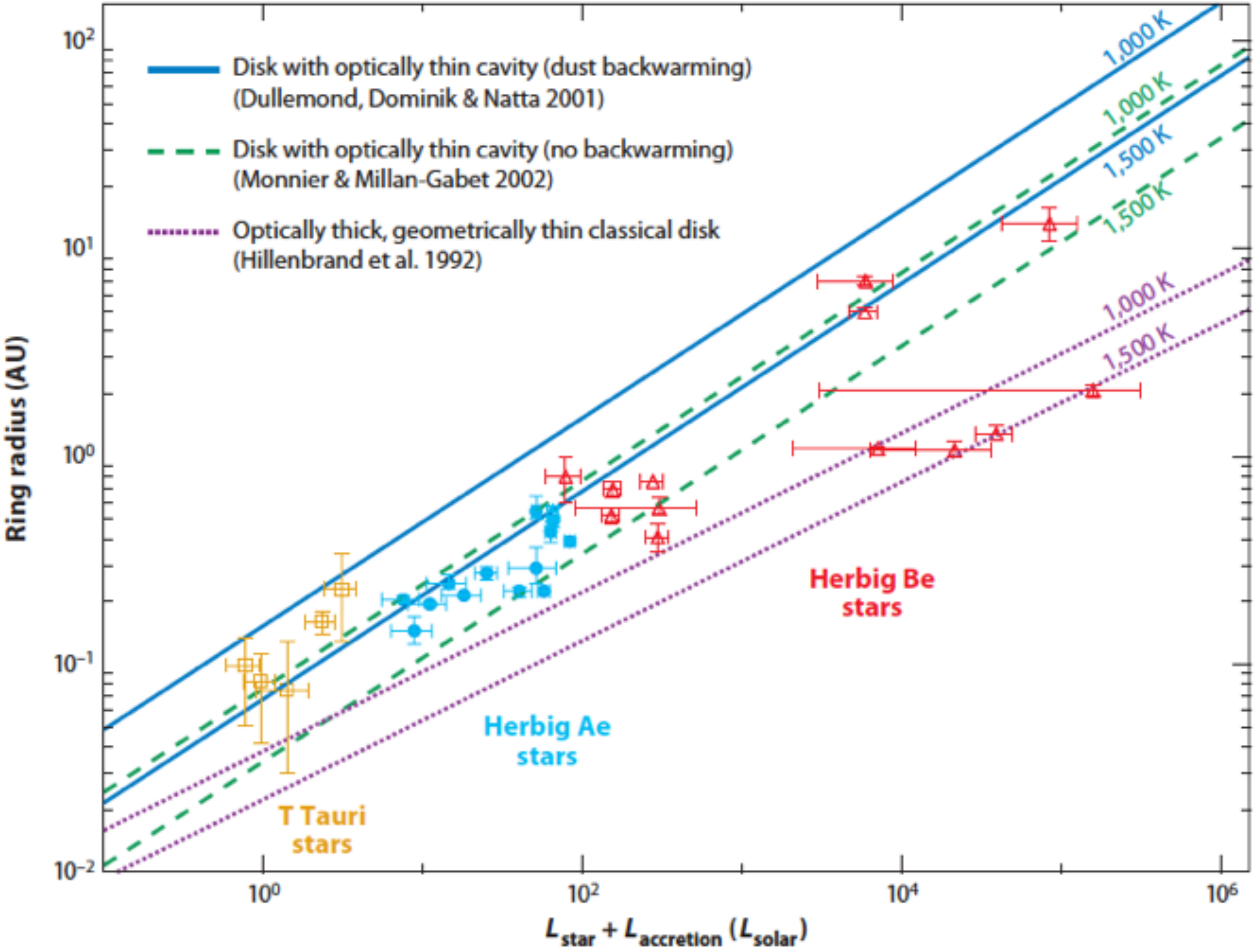




Herbig Ae star: R CrA
(Kraus et al. 2009)

Size-luminosity diagram

- Let's fit the visibilities with a simple ring model
- This gives the radius of the inner rim for each system
- Let's compare it with the stellar luminosity
- Expected result: $R_{rim} \sim L_*^{1/2}$

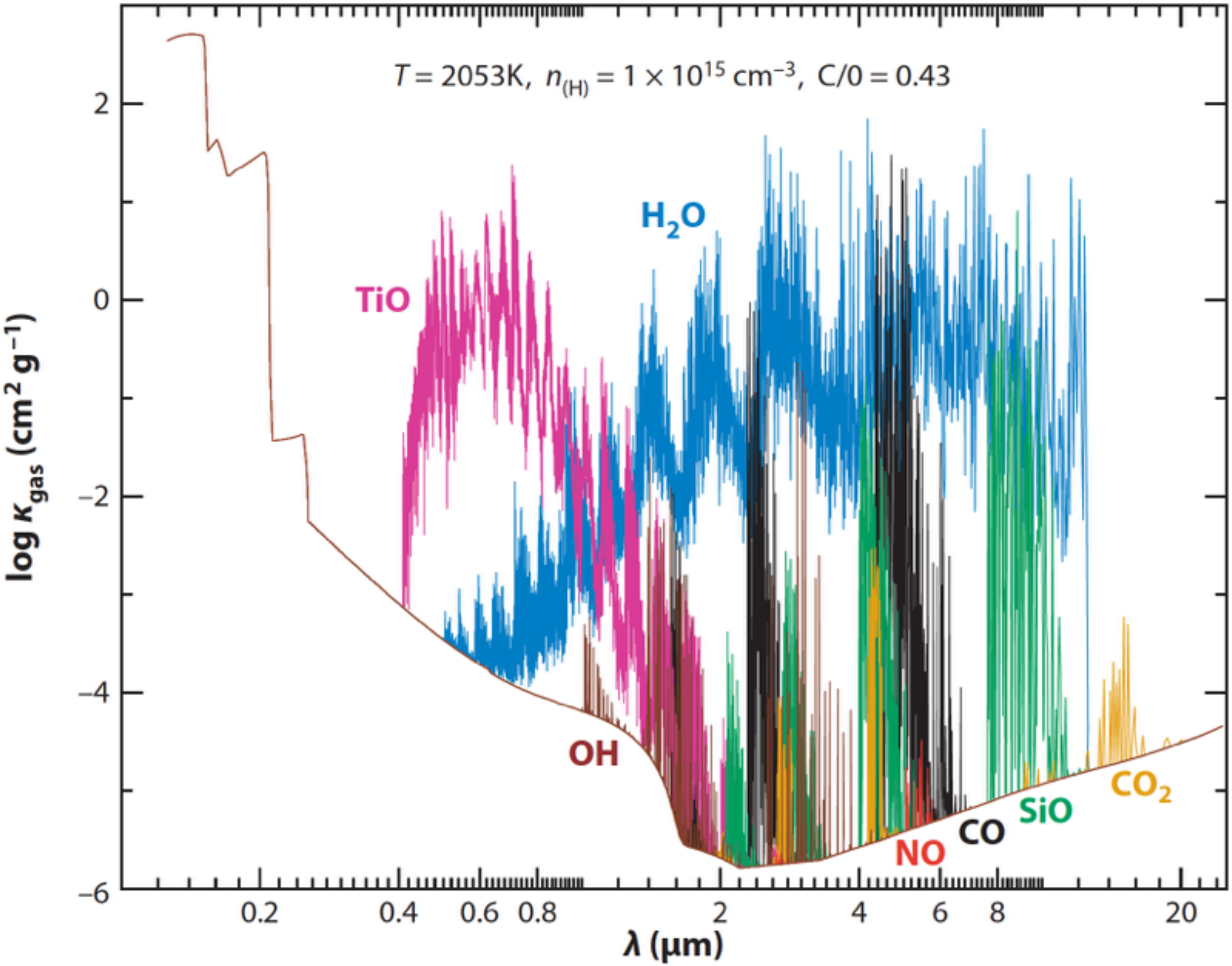


Gas inward of the dust rim

- 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
- $T_{rim} < T < T_{star}$

- Temperature is too low for continuum opacity sources (like H^-) except for tenuous surface layers
- Billions of atomic and molecular lines!

Gas inward of the dust rim



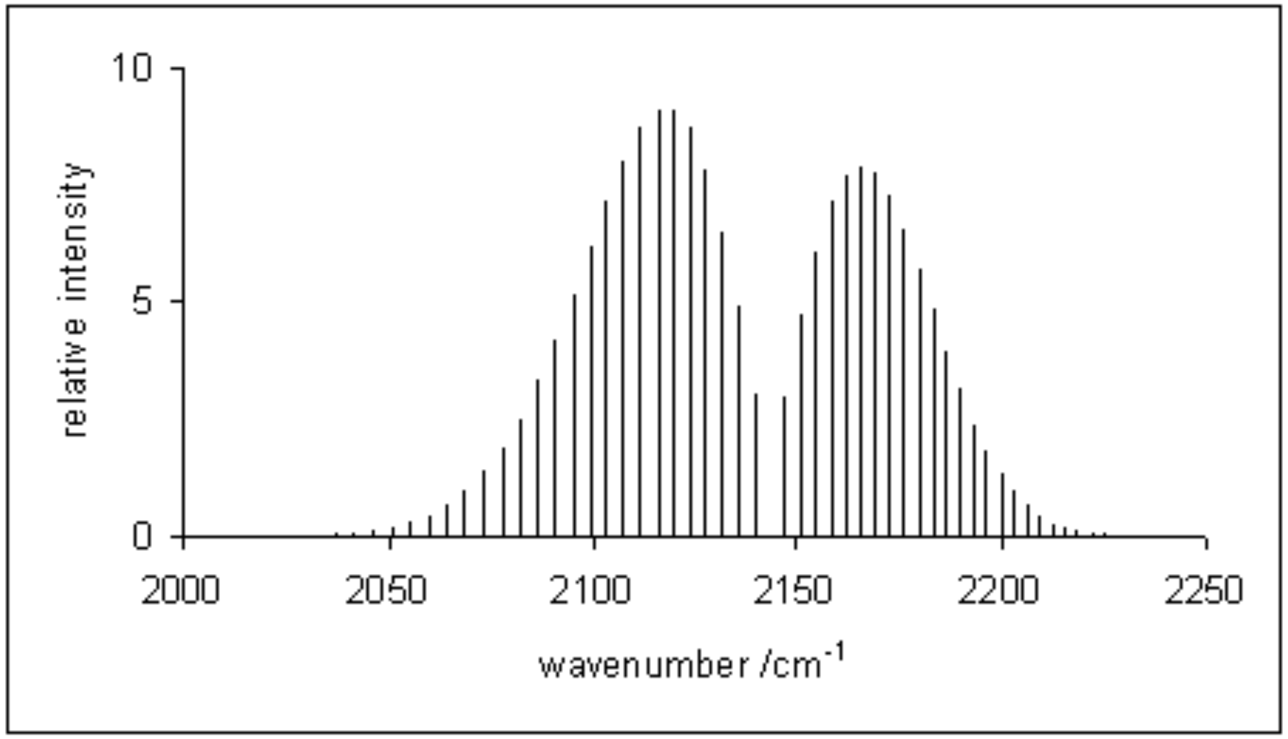
Gas inward of the dust rim

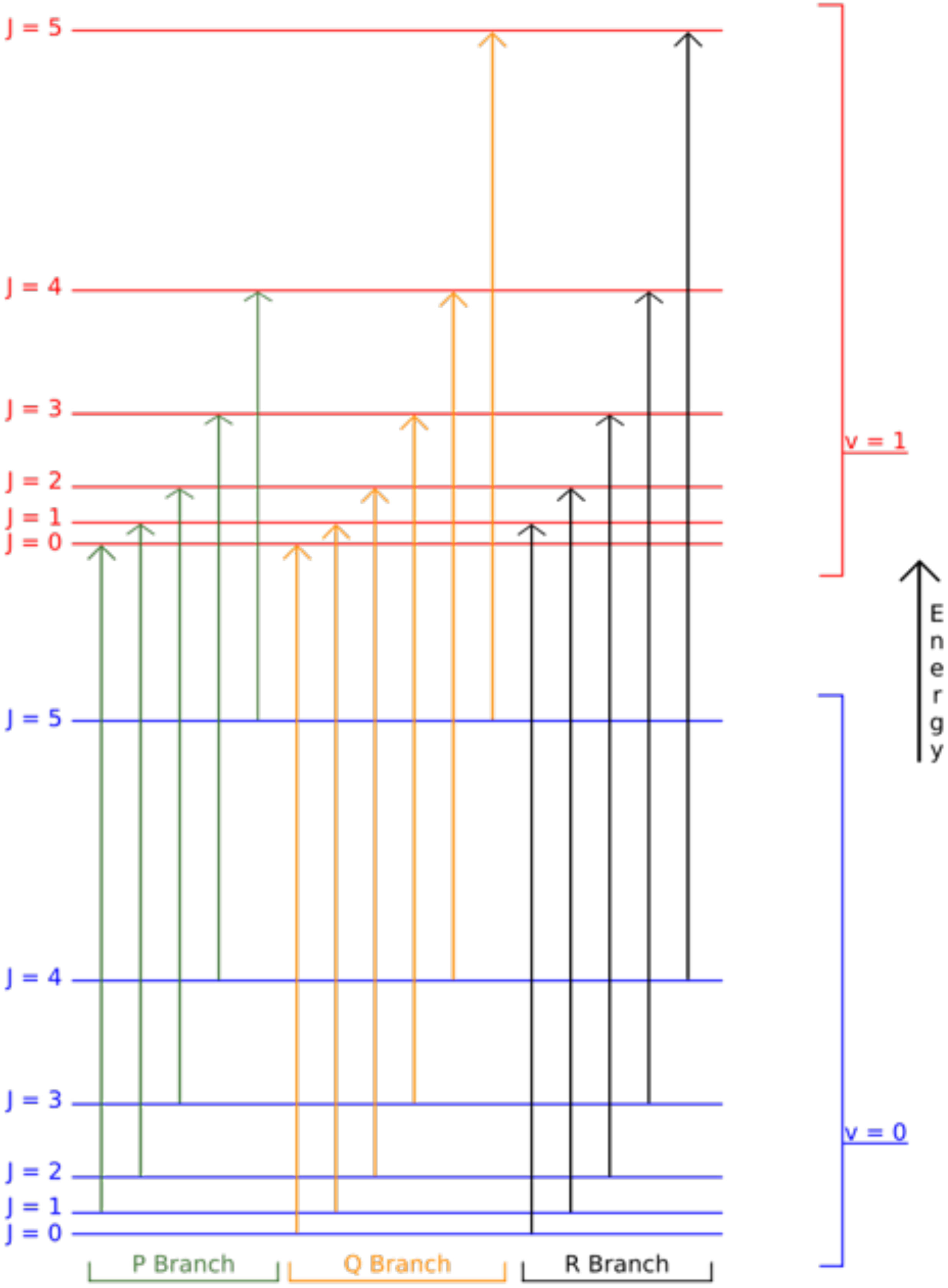
- Complex problem
- Opacity is high at line center, low between the lines
- Opacity is low between 0.2−0.4 μm
- Molecules are easily destroyed (collisions, UV photons)
- Usually, we assume local thermodynamic equilibrium (LTE), i.e. $T_{kin} = T_{ex} = T_{rad}$

Probing the inner dust-free disk with gas line observations

- Expectation: strong molecular emission
- Observation: deficit of molecules
- CO fundamental ($\Delta v=1$) lines are commonly found (formed in the surface layer between 0.1 and 2 au, Najita et al. 2007)
- CO overtone ($\Delta v=2$) lines are rarer, excited at >1000 K in the innermost part of the disk (0.05−0.3 au)

CO fundamental lines





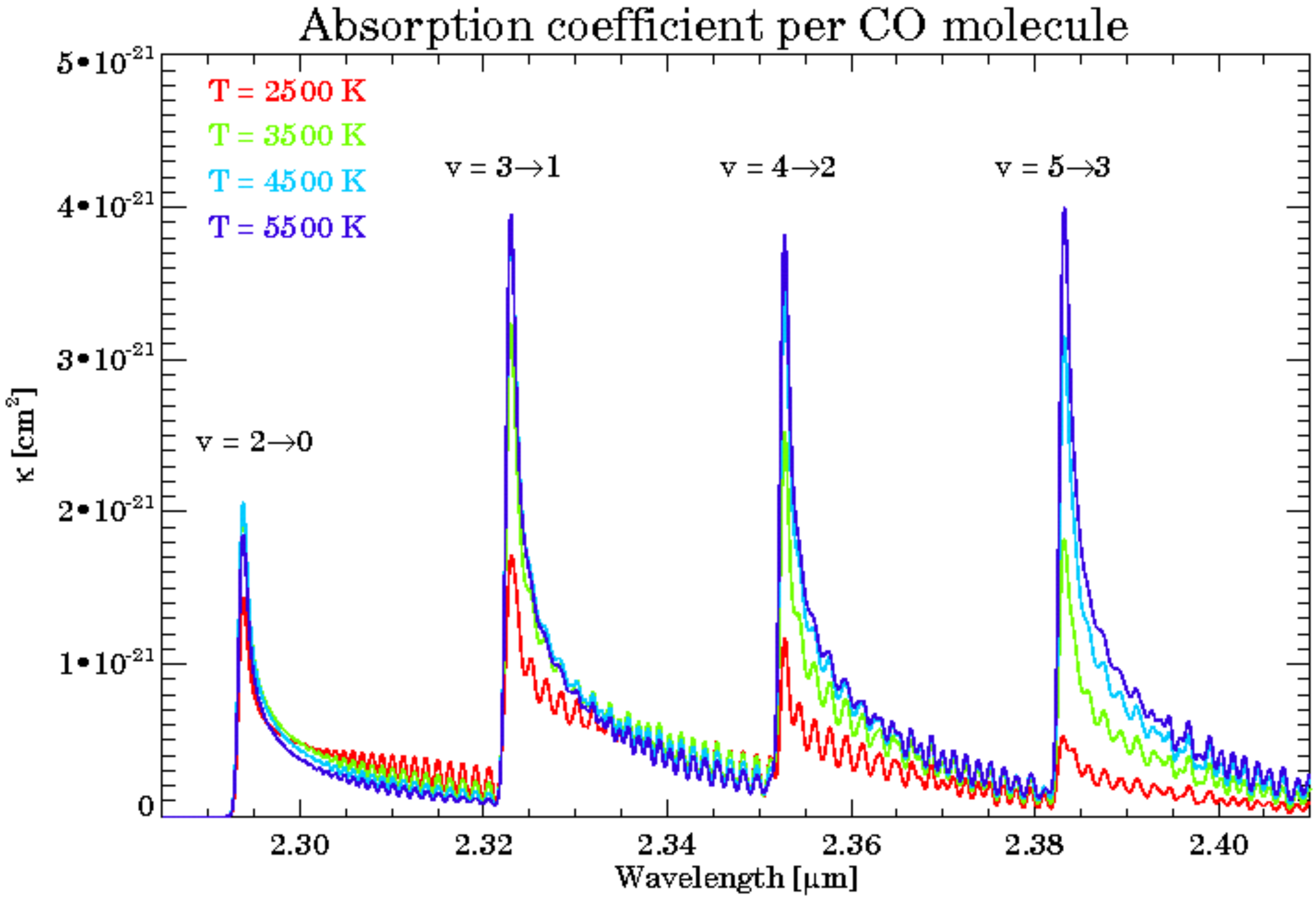
Mid-infrared (4−5 μm)

$\Delta v=1$

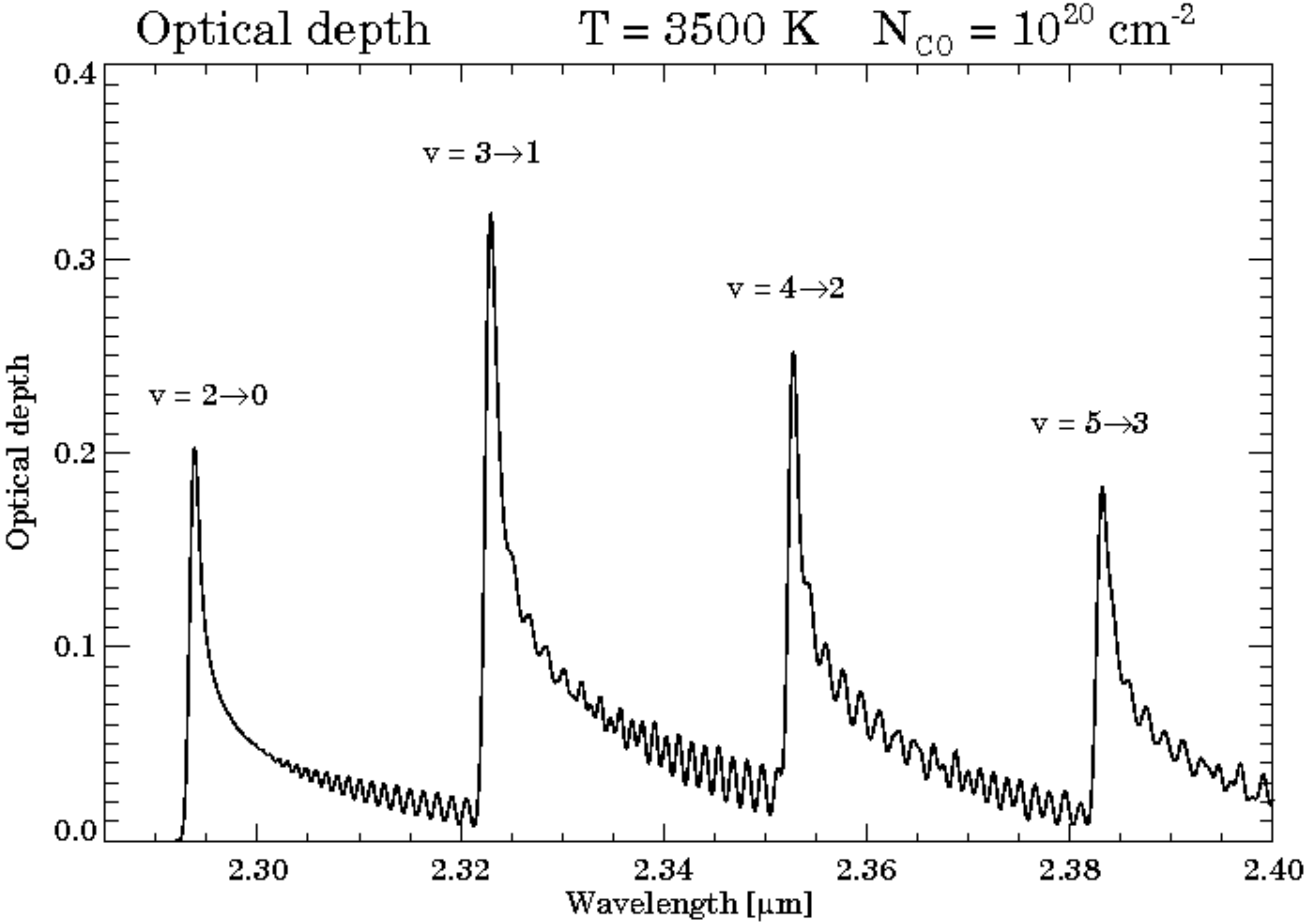
http://en.wikipedia.org/wiki/
Rotational-vibrational_spectroscopy

CO overtone lines

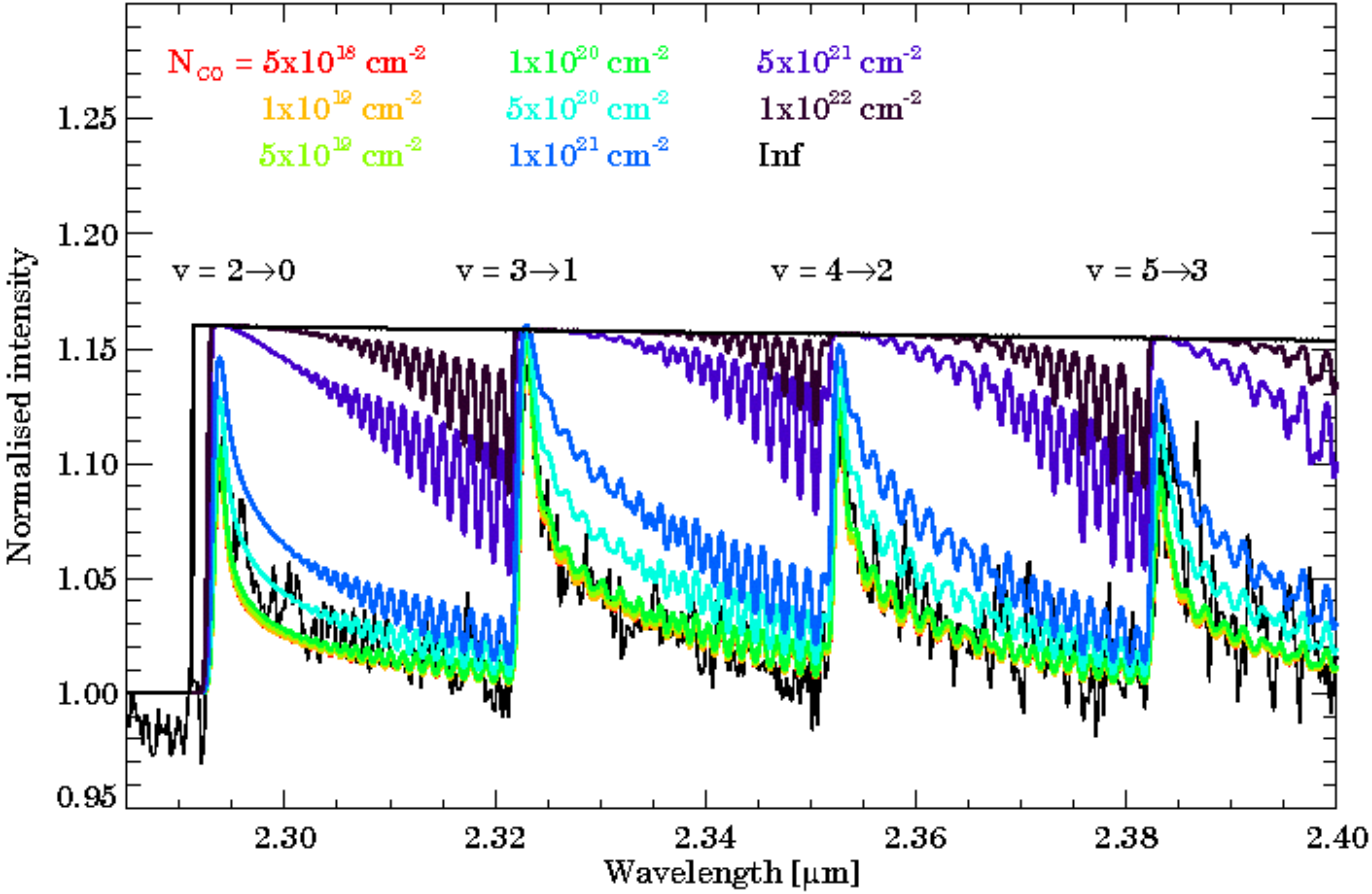
Near-infrared (2.3−2.4 μm) $\Delta v=2$



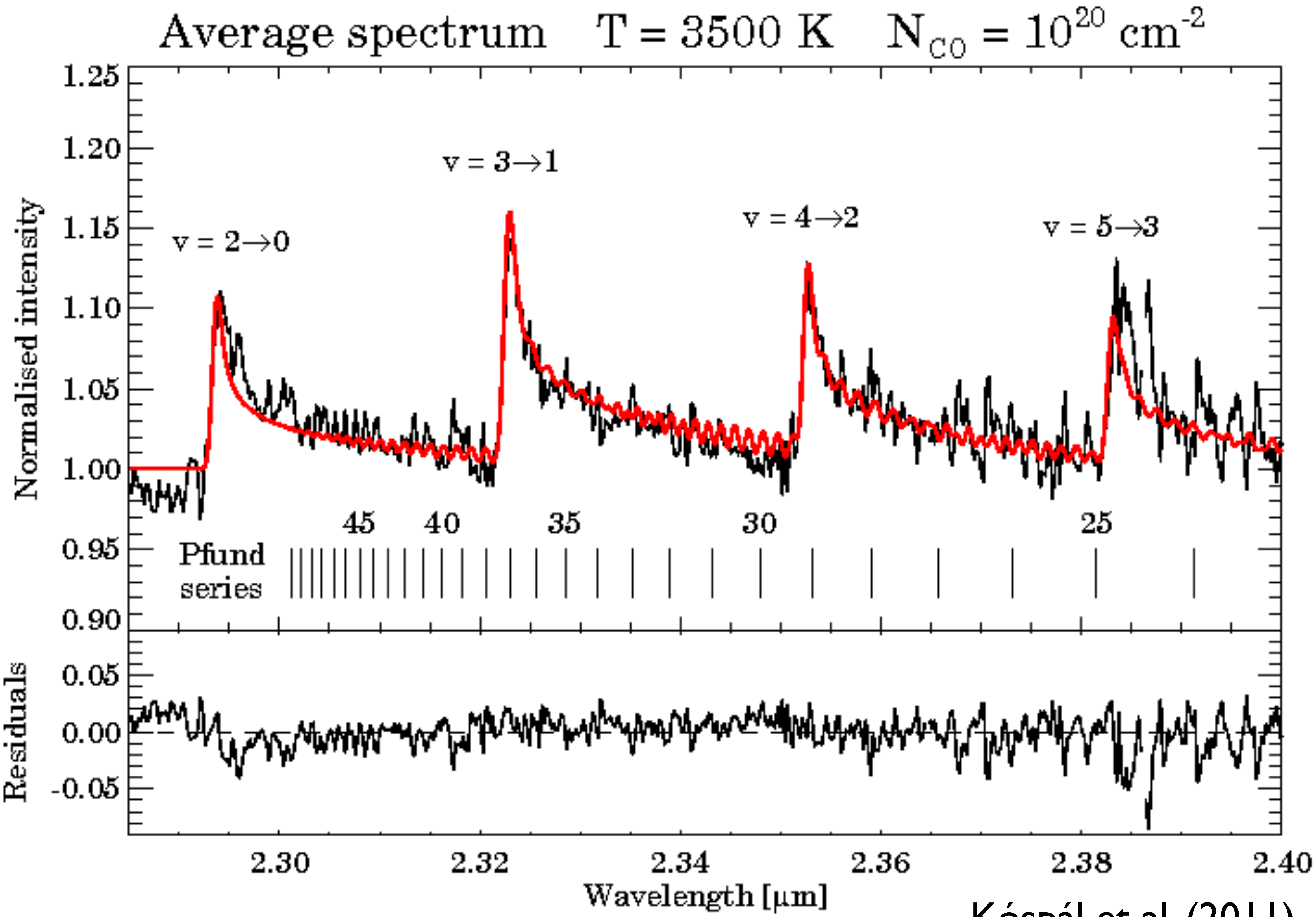
CO overtone lines



CO overtone lines

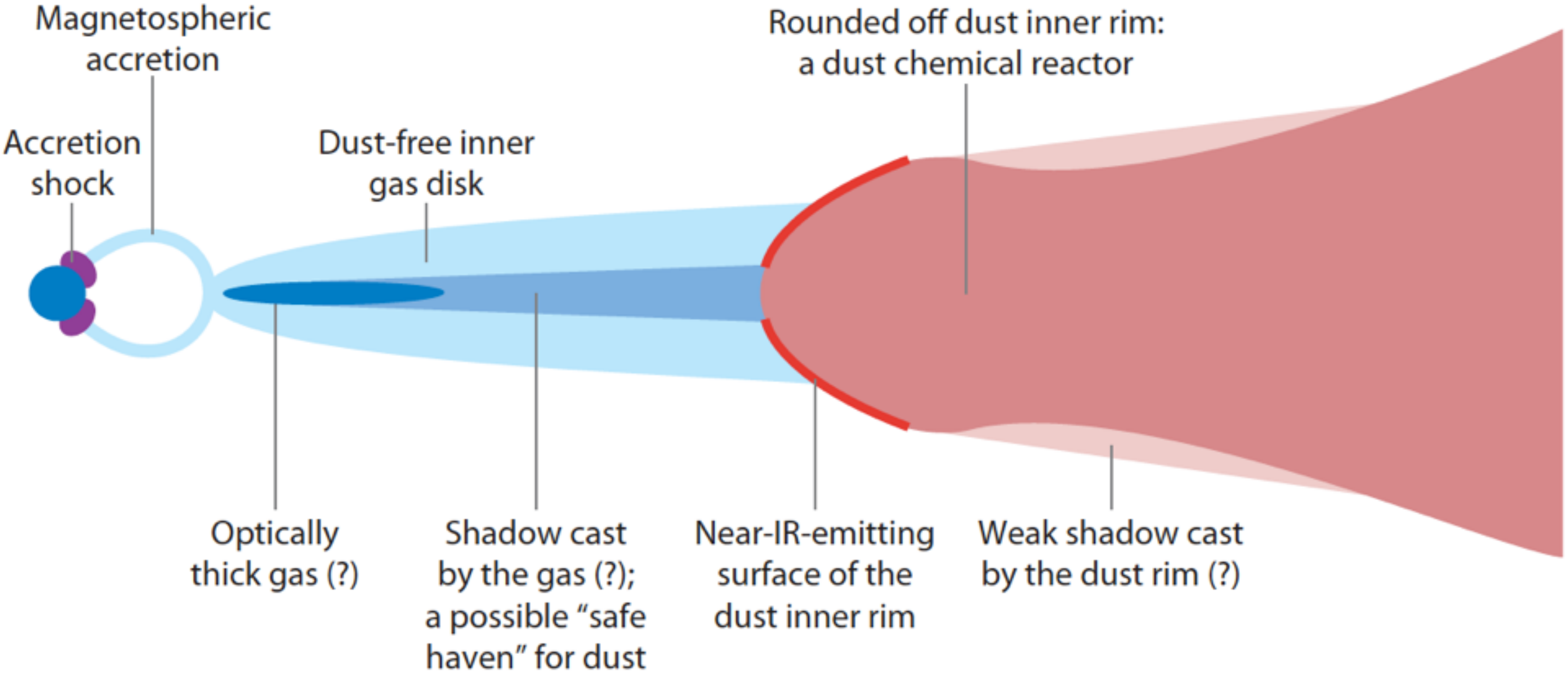


CO overtone lines

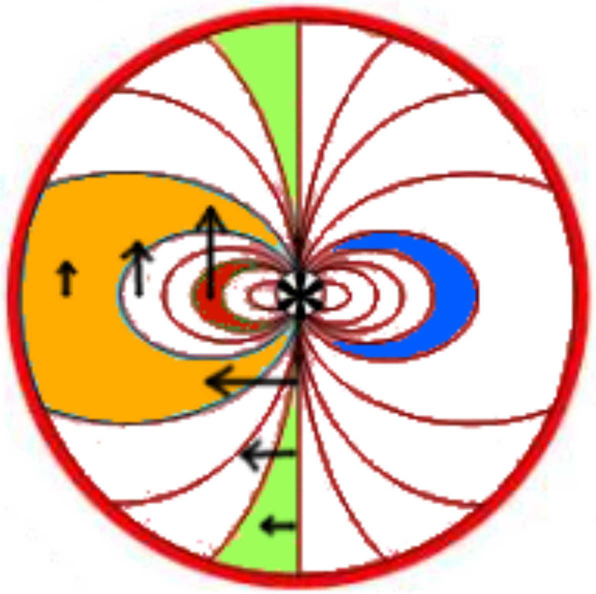


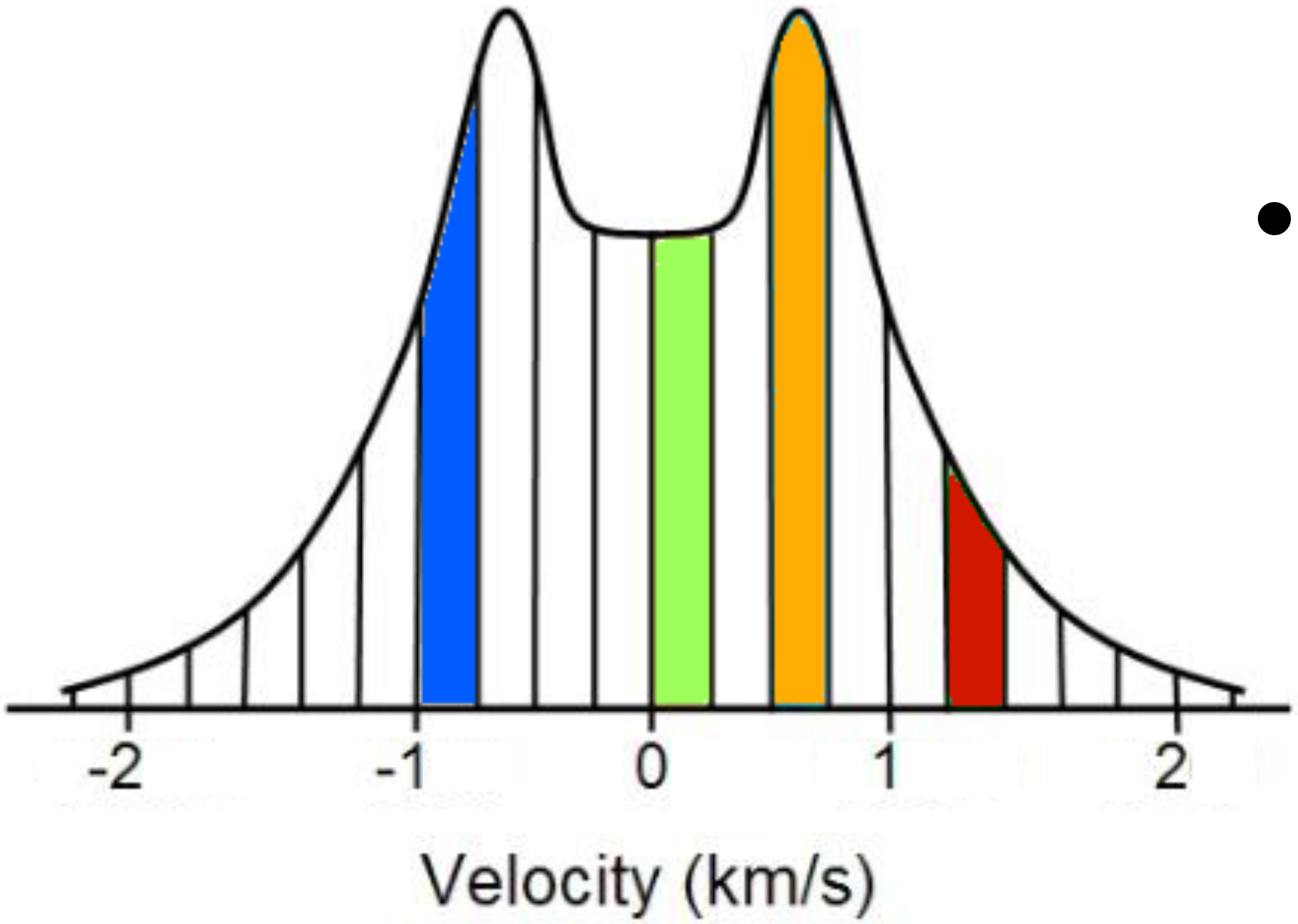
Kóspál et al. (2011)

Gas inward of the dust rim



Dynamics of the inner gas disk

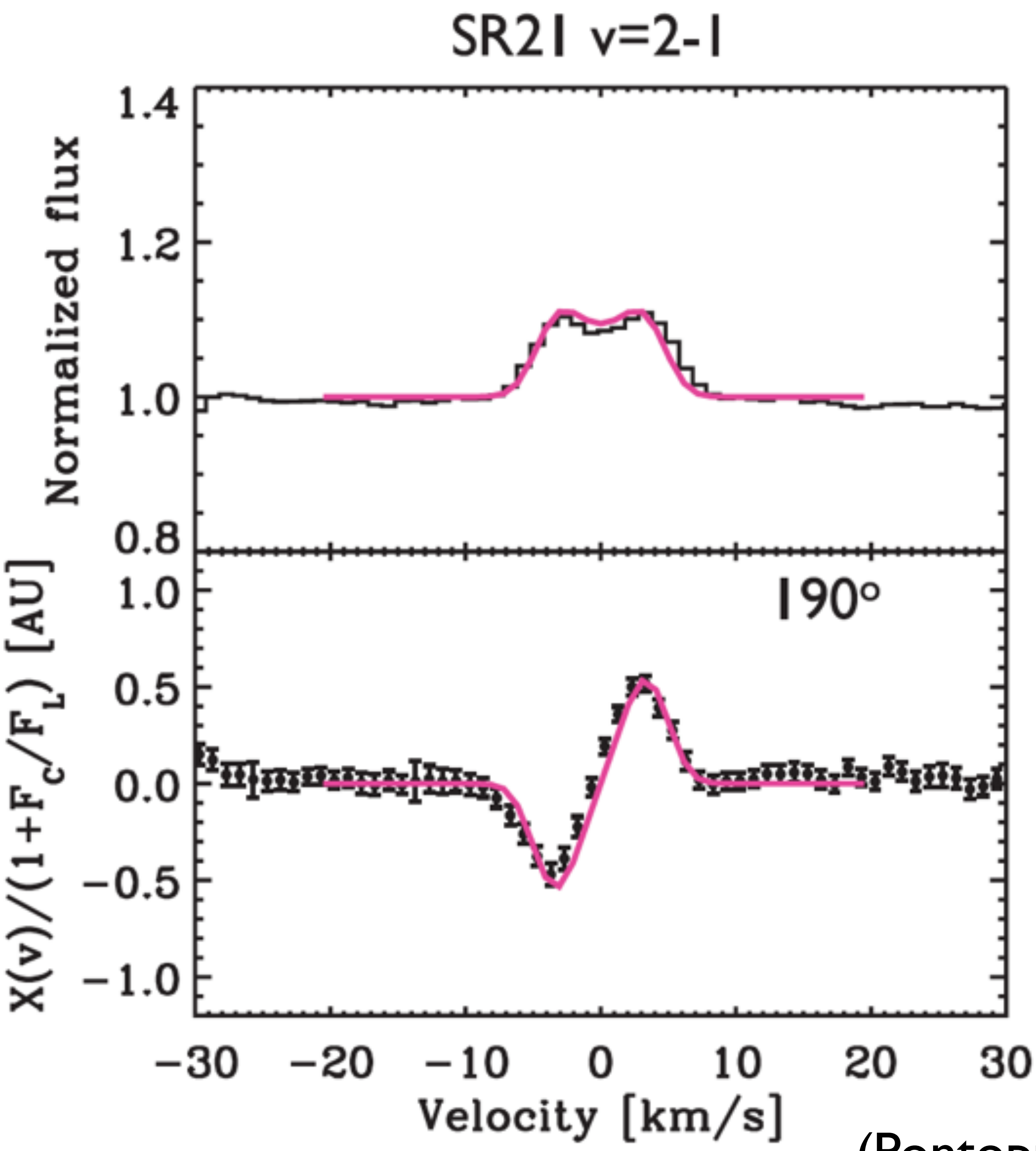




Spectro-astrometry:

- Measure the centroid of the image as a function of wavelength/velocity
- If S/N is good enough, tiny sub-pixel shifts can be observed

Dynamics of the inner gas disk

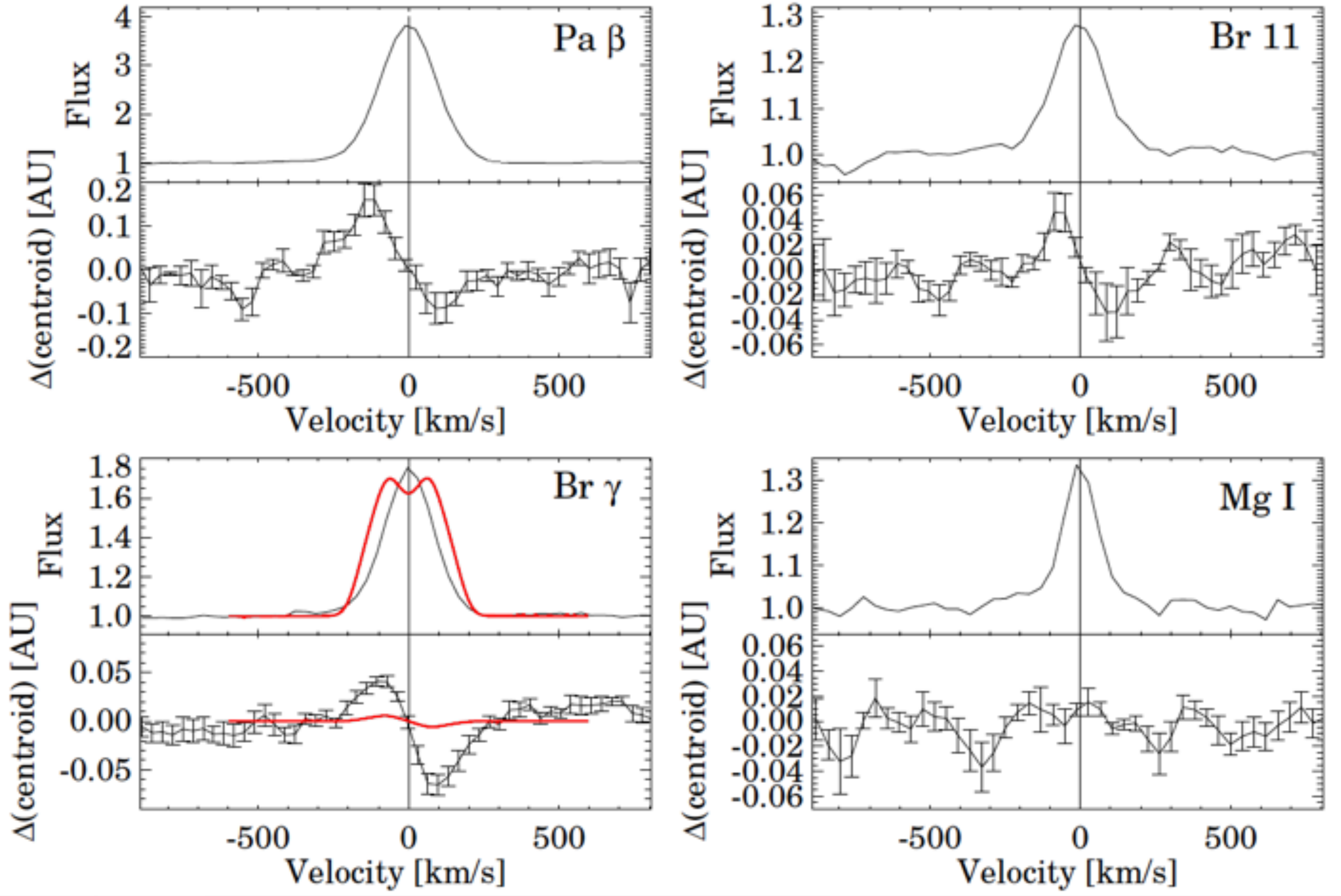


Evidence for CO emission from a disk in Keplerian rotation

(Pontoppidan et al. 2008)

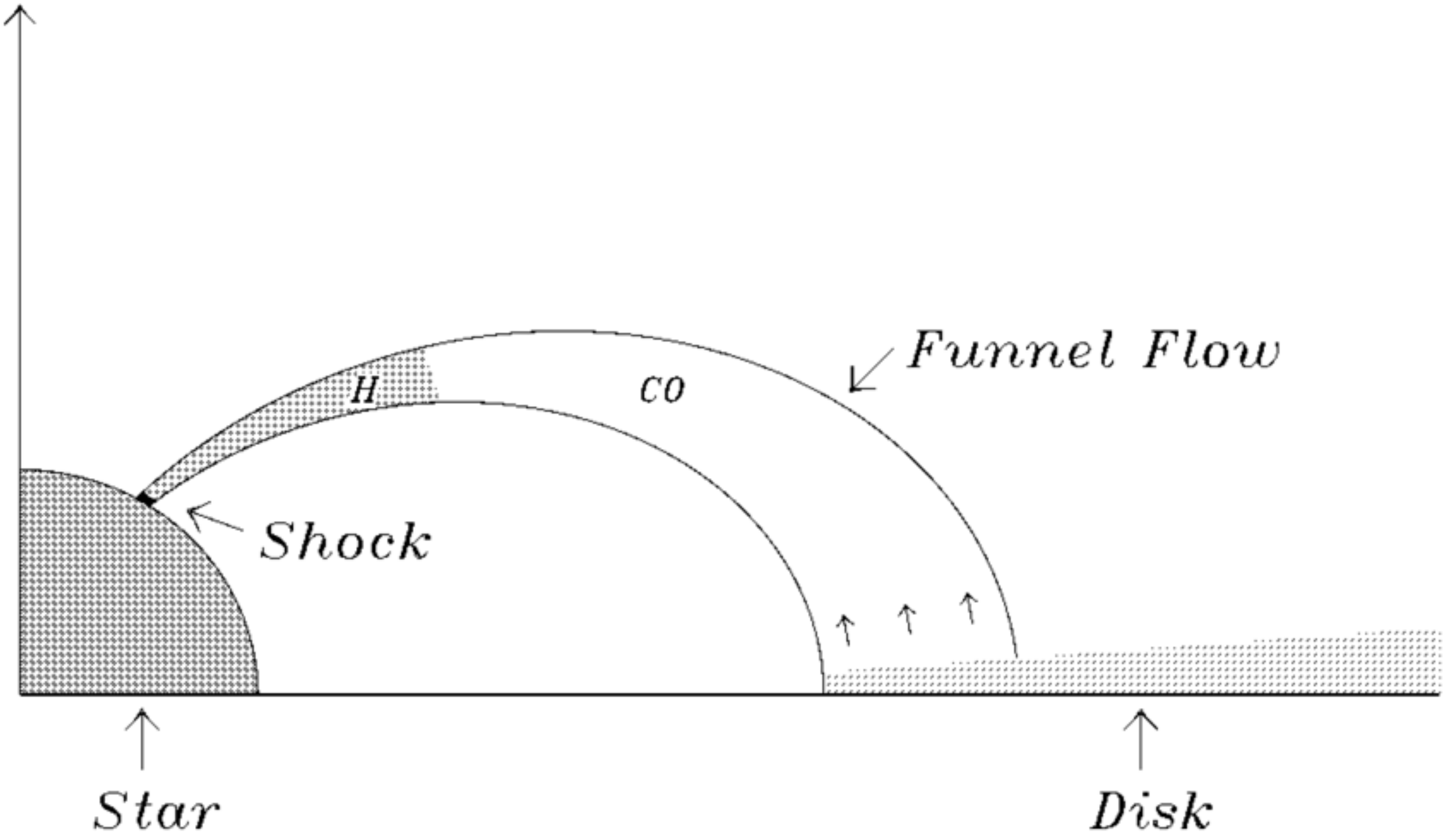
Dynamics of the inner gas disk

- Where does the hydrogen emission come from?
- Evidence for high-velocity gas farther from the star than predicted by a Keplerian model



(Kóspál et al. 2011)

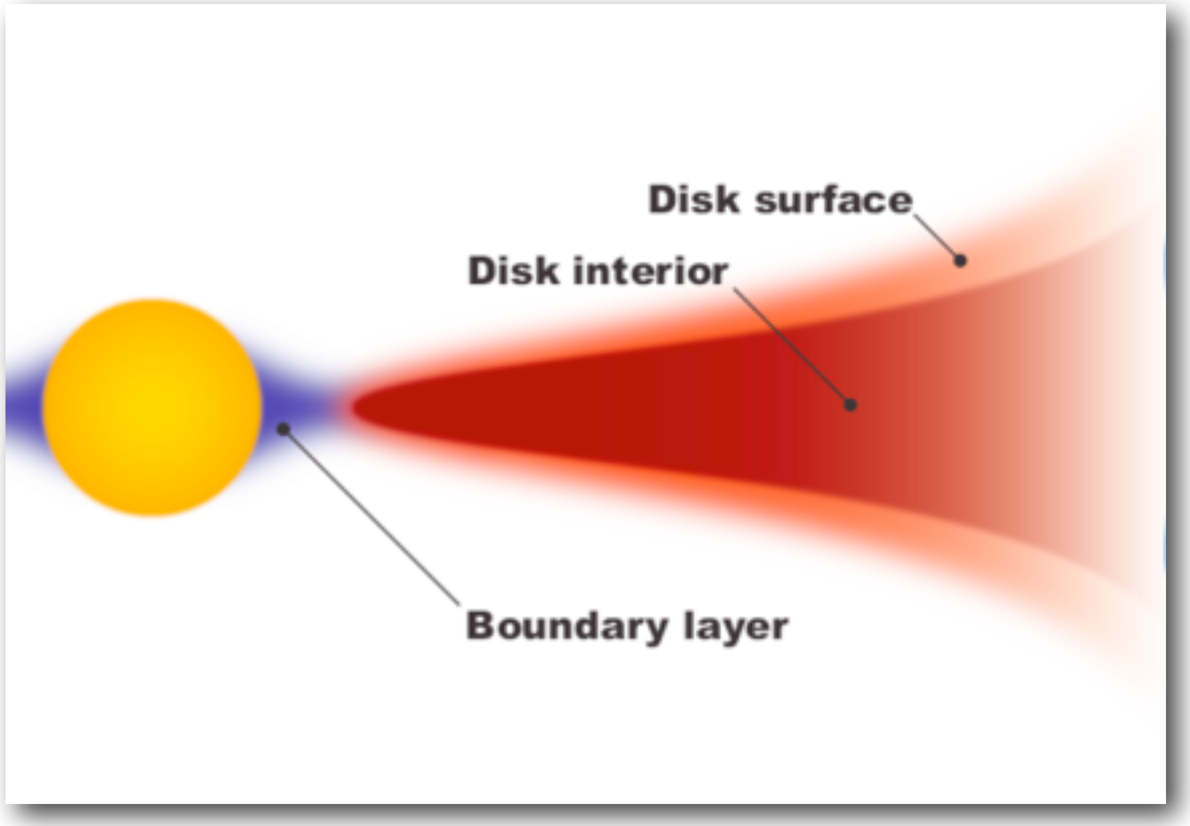
Dynamics of the inner gas disk

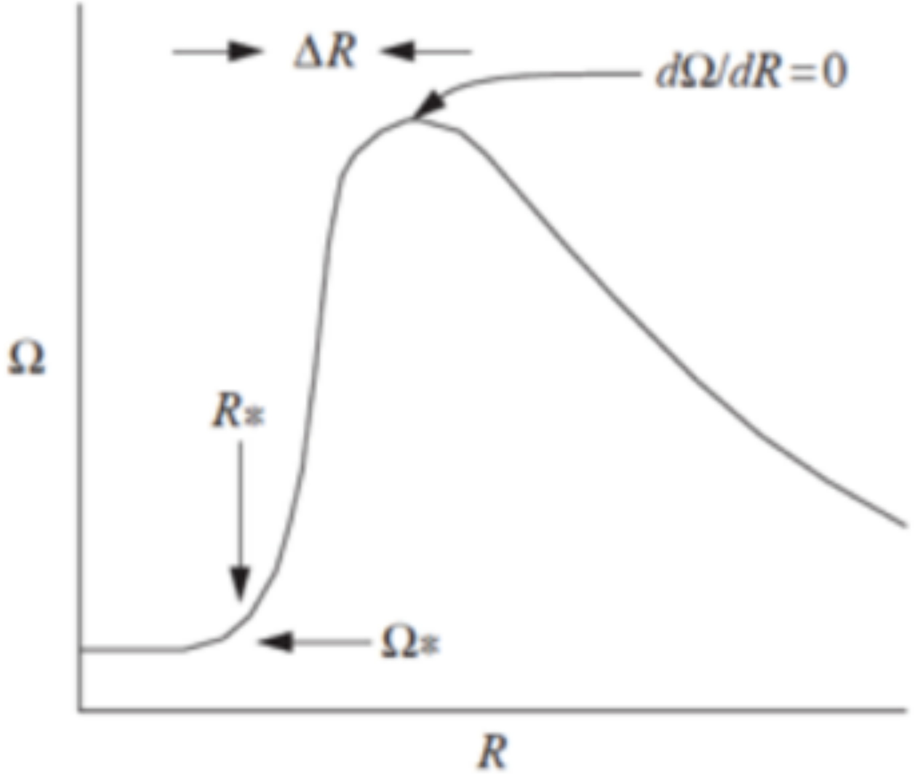


(Martin 1997)

Early models for accretion

Boundary layer



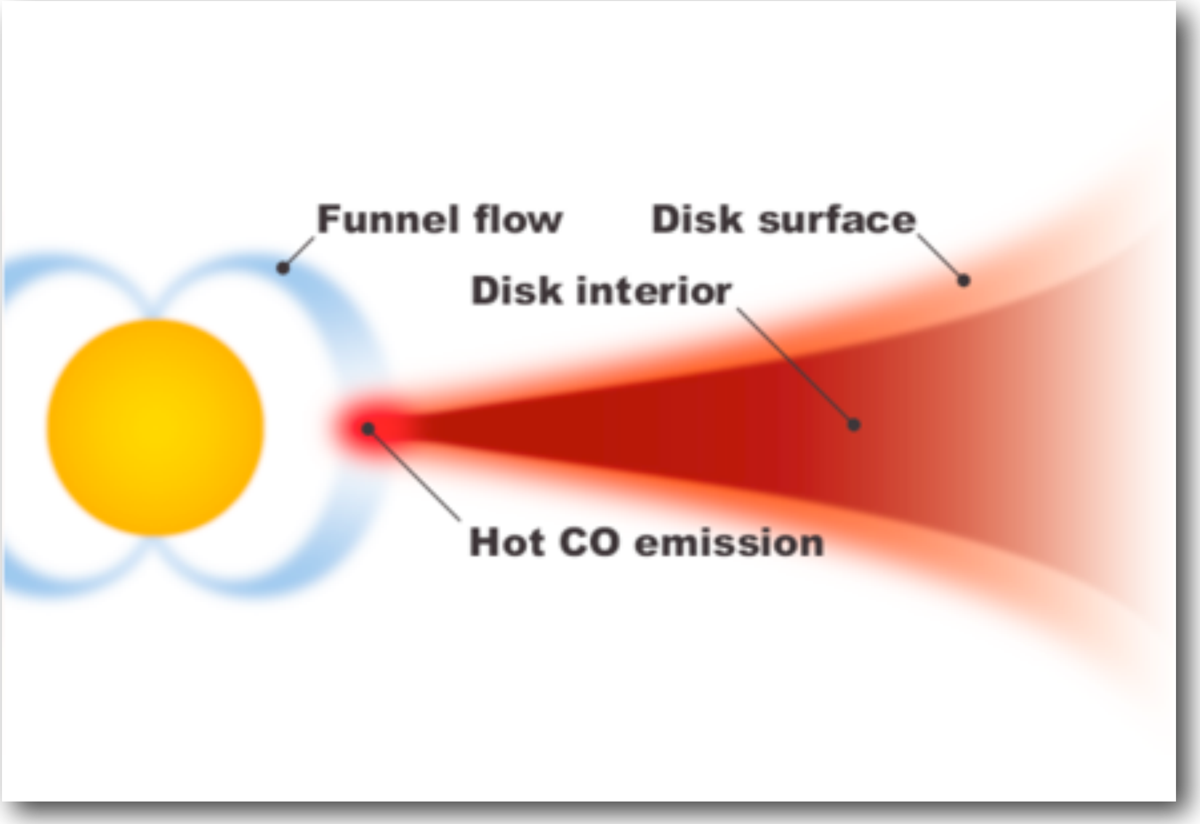


Lynden-Bell & Pringle (1974)

- Material must slow down, radiate away the energy

Early models for accretion

Magnetospheric accretion

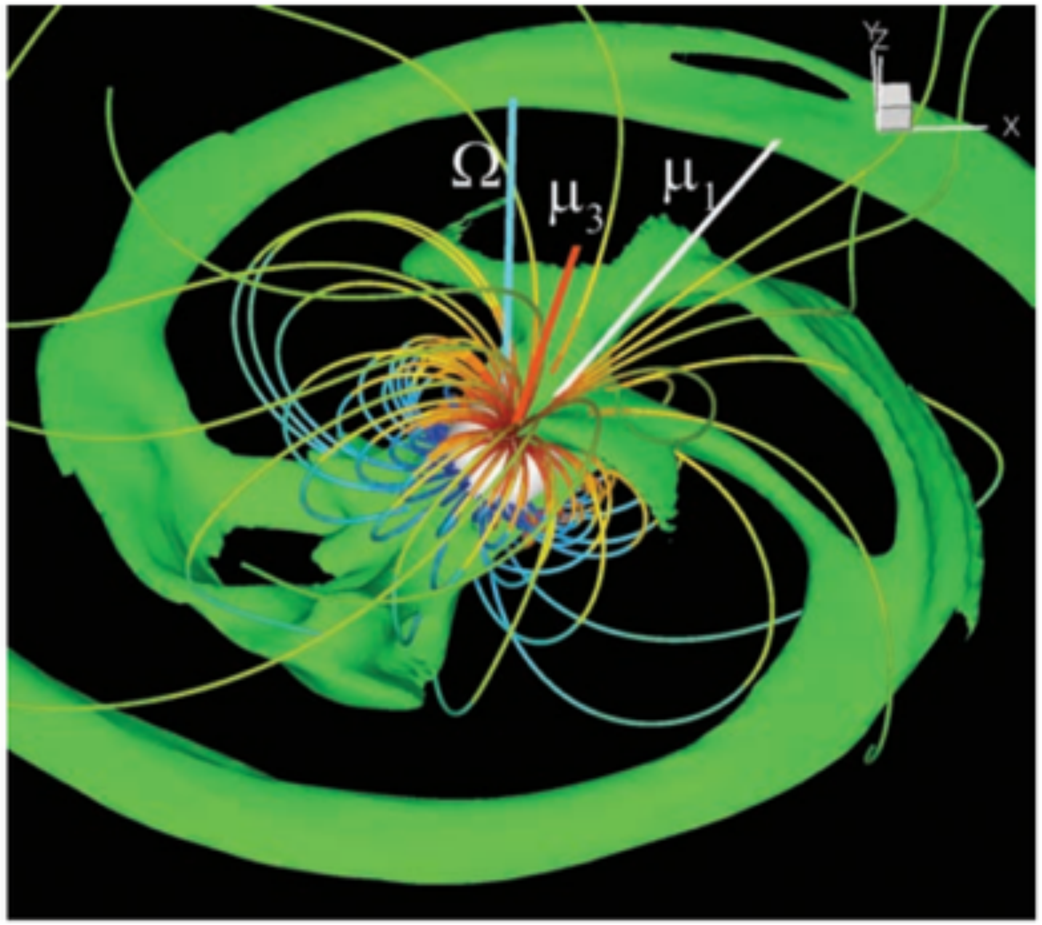


Kamenzind (1990)
Königl (1991)

- Stellar magnetic field truncates the disk
- Gas infall along magnetic lines at free-fall velocities

Magnetospheric accretion

- High latitude accretion shocks
- X-ray/EUV radiation immediately absorbed, producing UV-optical excess, consistent with observations
- If accretion occurs in magnetic “columns”, or if the magnetic axis is misaligned with the rotation axis, photometric changes appear



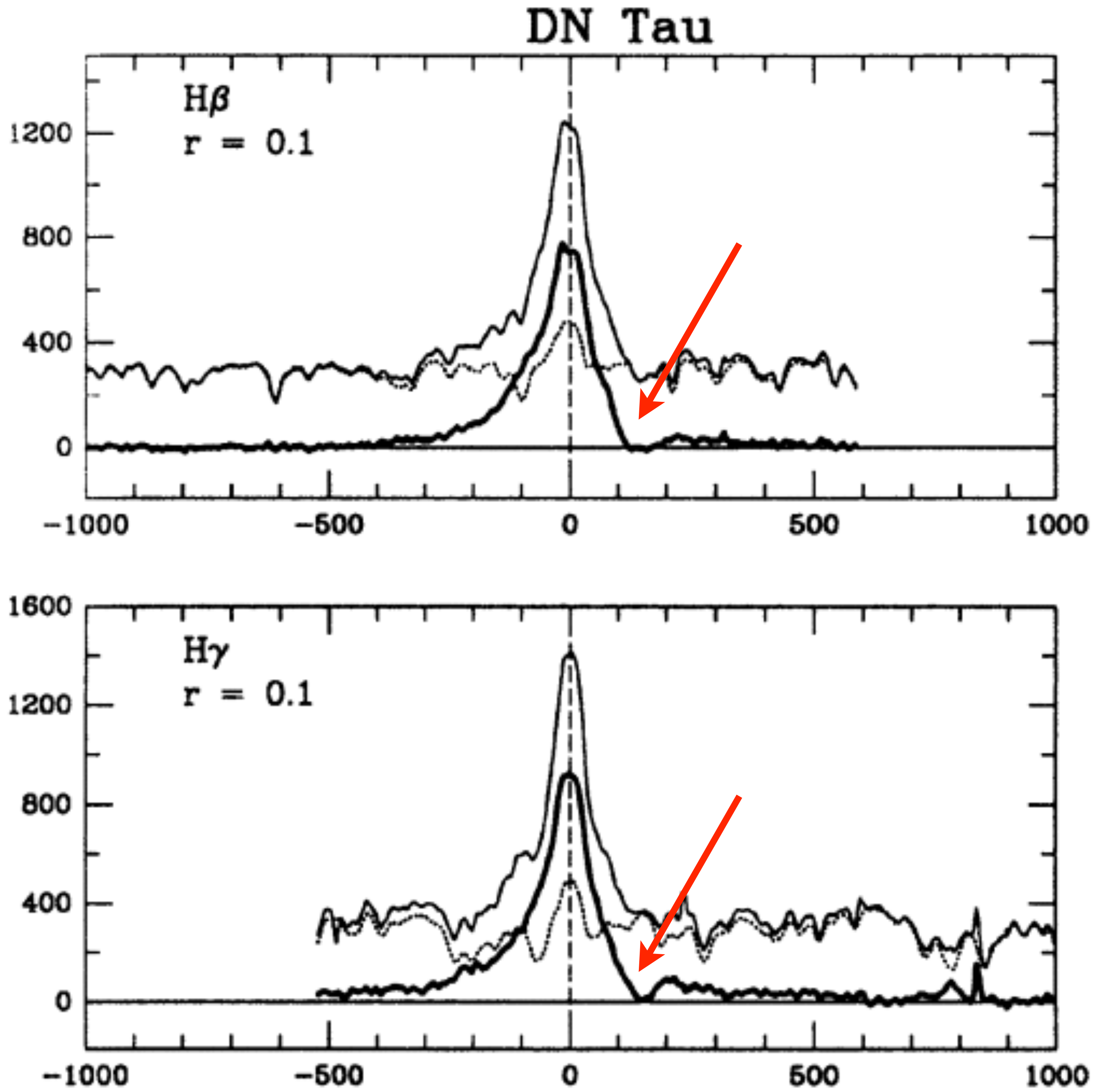
(Romanova et al. 2011)

Magnetospheric accretion

Pros: it explains

- hot spots rotating with the star
- absence of emission from boundary layer)
- slower rotation of stars with inner disks (due to the disk torque communicated to the star by the magnetic field)
- emission line profiles of permitted lines (inverse P Cygni redshifted absorption features)

Redshifted absorption

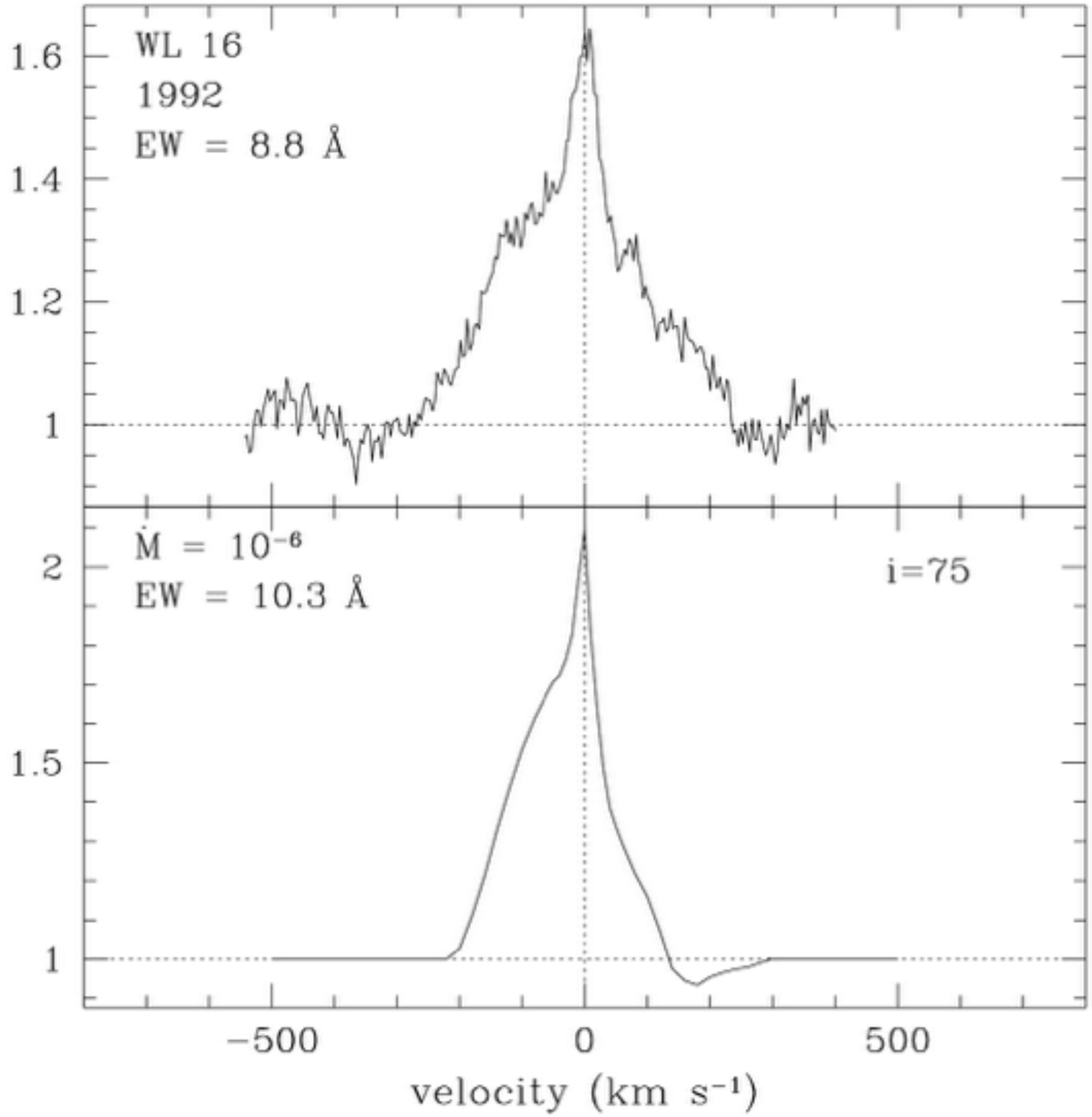


Indicates mass infall at high velocities (free-falling gas along the magnetic field lines)

Edwards et al (1994)

Observations vs. model

Line radiative transfer of magnetospheric infall can reproduce hydrogen line profiles and line fluxes



(Muzerolle et al. 1998)

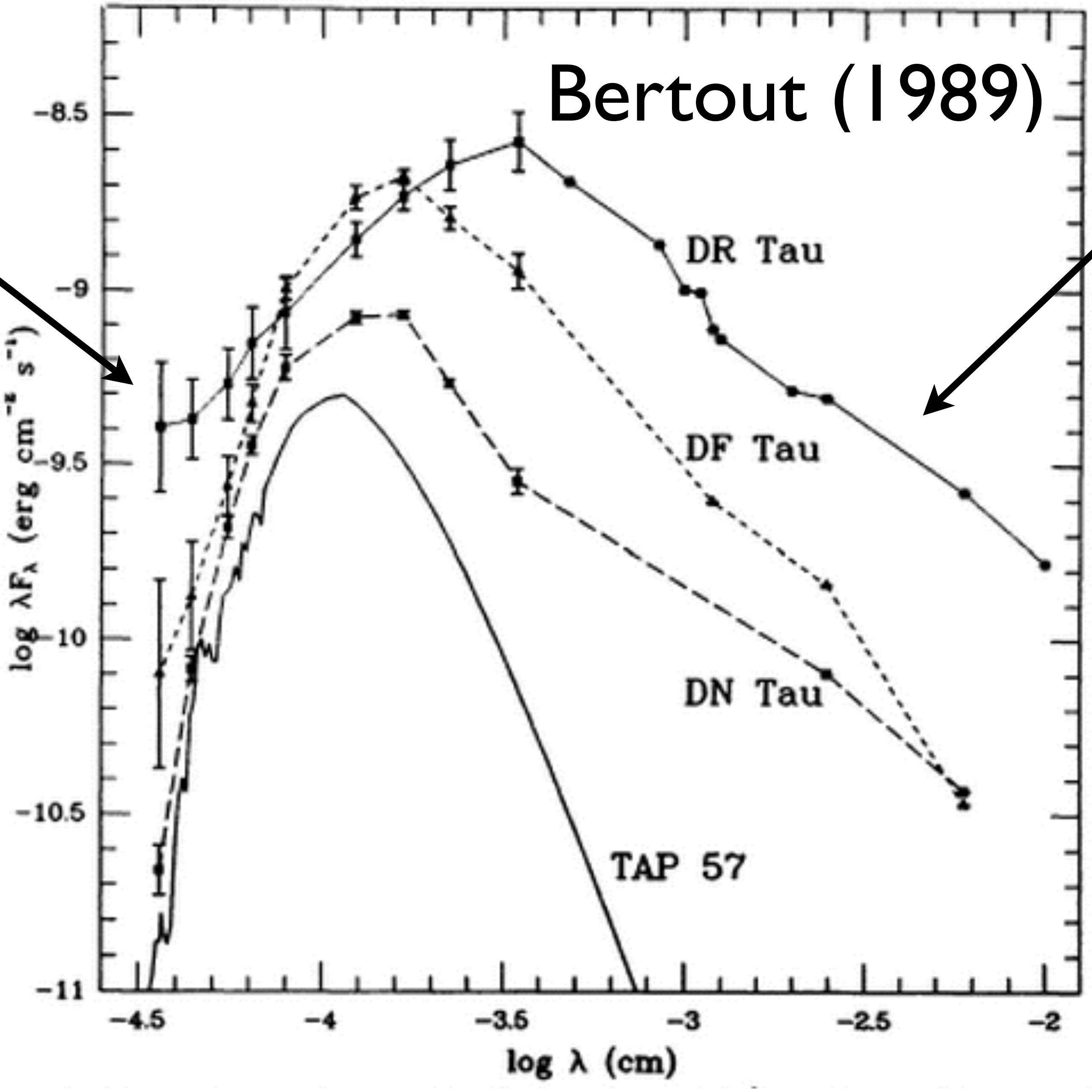
Accretion rate from lines?

- Ultimate goal: use emission lines to measure accretion rate
- Complications:
    - temperature and size of magnetosphere are important factors
    - Balmer lines and Br gamma are optically thick (no dependence on gas density!)
    - chromospheric activity also causes emission lines

Accretion rate from continuum?

UV continuum excess

produced by disk material landing on the stellar surface



Bertout (1989)

IR continuum excess

produced by viscous dissipation in the disk

+

re-processed starlight

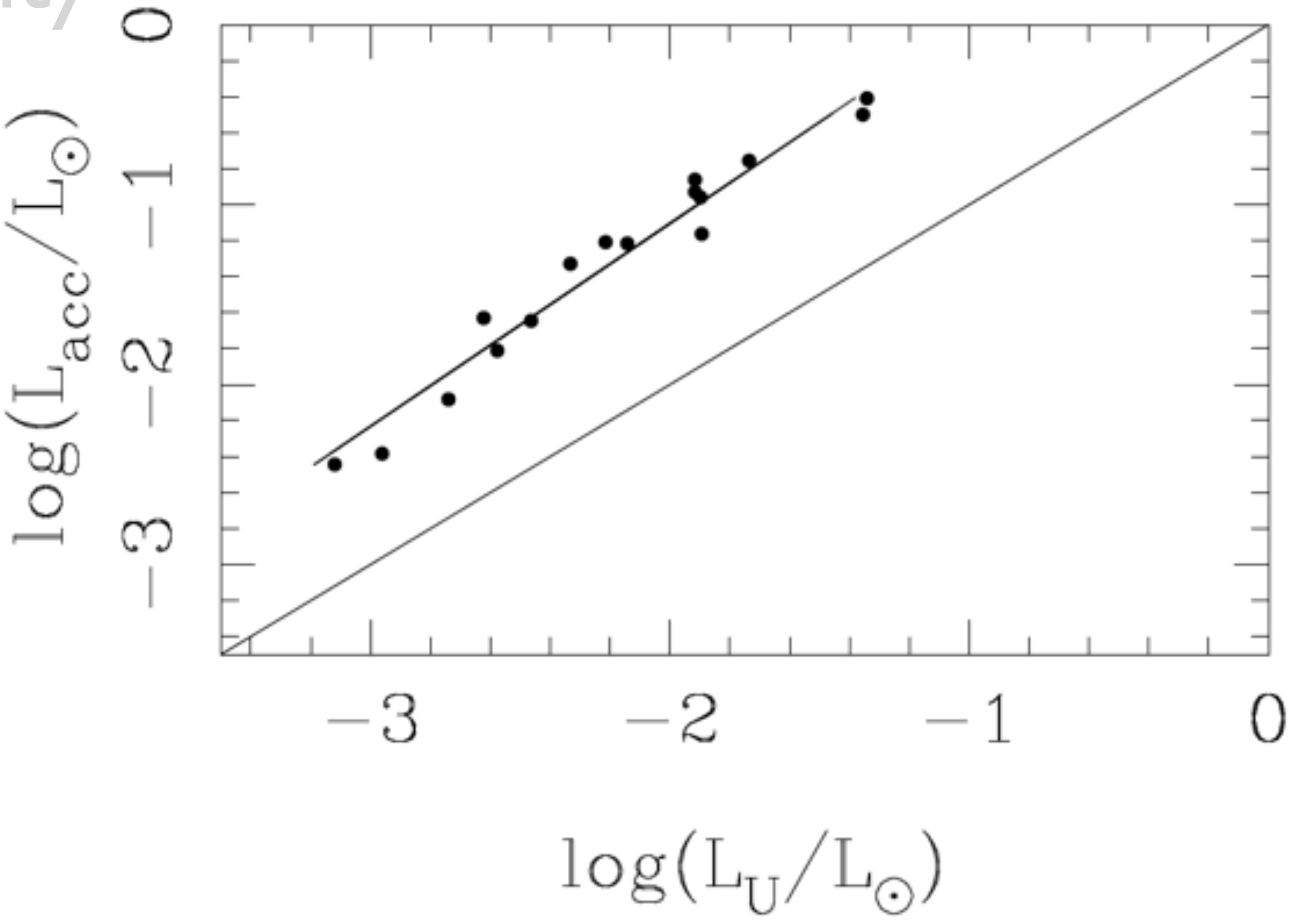
Good accretion rate tracers

- U-band photometry
- Hα line luminosity
- [OI]6300 line luminosity
- Brγ line luminosity
- Hα 10% width

Good accretion rate tracers

- U-band photometry
- Hα line luminosity
- [OI]6300 line luminosity
- Brγ line luminosity
- Hα 10% width

(Gullbring et al. 1998)

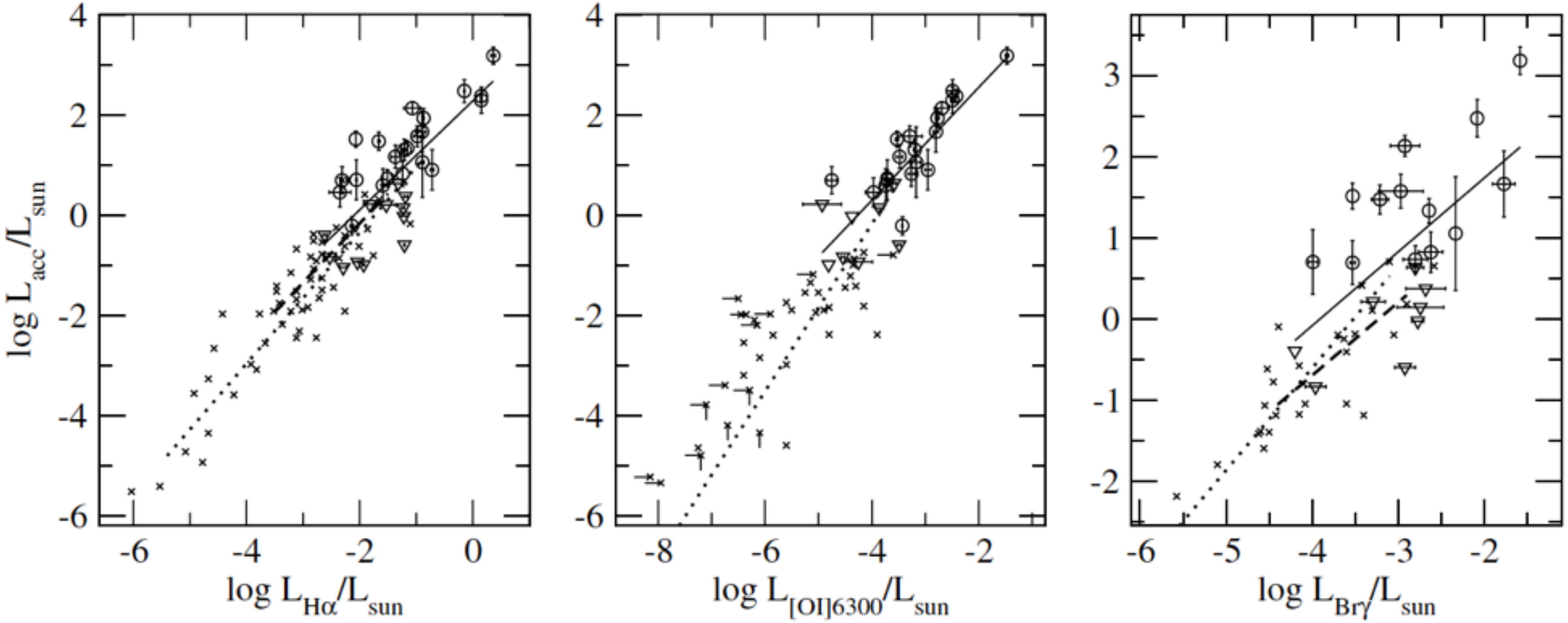


$$\log\,(L_{\mathrm{acc}}/L_\odot) = 1.09^{+0.04}_{-0.18}\,\log\,(L_U/L_\odot) + 0.98^{+0.02}_{-0.07}$$

Good accretion rate tracers

- U-band photometry
- Hα line luminosity
- [OI]6300 line luminosity
- Brγ line luminosity

(Mendigutía et al. 2011)



Good accretion rate tracers

- U-band photometry
- Hα line luminosity
- [OI]6300 line luminosity
- Brγ line luminosity
- Hα 10% width

$$L_{\rm acc} \simeq \frac{GM_* \dot{M}}{R_*}\left(1 - \frac{R_*}{R_{\rm in}}\right)$$

where M_* is the stellar mass

R_* is the stellar radius

$R_{\rm in}$ is the inner disk radius

Herbig stars

$$\log\left(\frac{L_{\rm acc}}{L_\odot}\right) = 2.28(\pm 0.25) + 1.09(\pm 0.16) \times \log\left(\frac{L_{\rm H\alpha}}{L_\odot}\right)$$

$$\log\left(\frac{L_{\rm acc}}{L_\odot}\right) = 4.80(\pm 0.50) + 1.13(\pm 0.14) \times \log\left(\frac{L_{\rm [OI]6300}}{L_\odot}\right)$$

$$\log\left(\frac{L_{\rm acc}}{L_\odot}\right) = 3.55(\pm 0.80) + 0.91(\pm 0.27) \times \log\left(\frac{L_{\rm Br\gamma}}{L_\odot}\right).$$

T Tauri stars

$$\log\left(\frac{L_{\rm acc}}{L_\odot}\right) = 2.27(\pm 0.70) + 1.31(\pm 0.16) \times \log\left(\frac{L_{\rm H\alpha}}{L_\odot}\right)$$

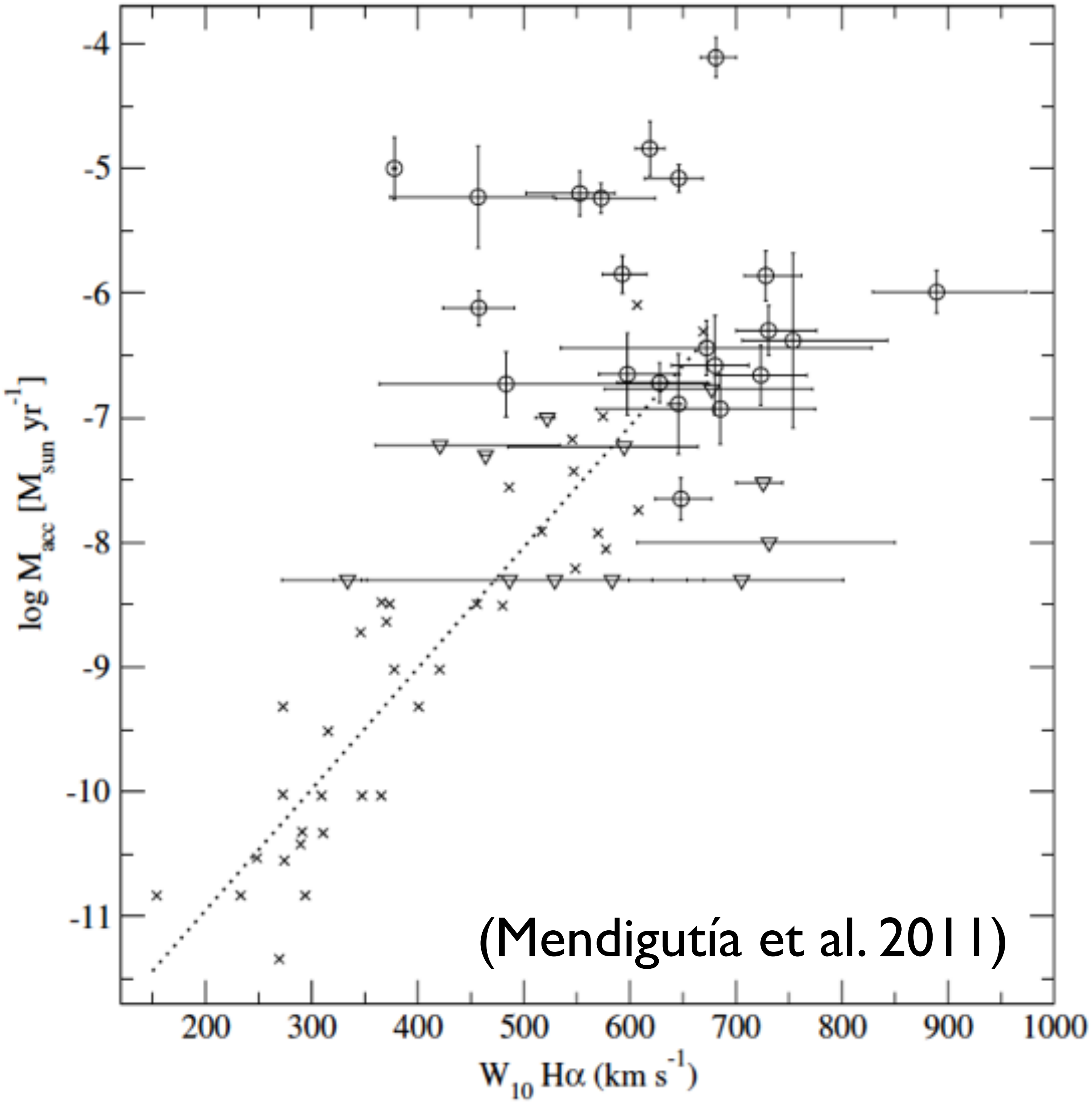
$$\log\left(\frac{L_{\rm acc}}{L_\odot}\right) = 6.50(\pm 2.18) + 1.67(\pm 0.28) \times \log\left(\frac{L_{\rm [OI]6300}}{L_\odot}\right)$$

$$\log\left(\frac{L_{\rm acc}}{L_\odot}\right) = 4.43(\pm 0.79) + 1.26(\pm 0.19) \times \log\left(\frac{L_{\rm Br\gamma}}{L_\odot}\right).$$

Good accretion rate tracers

- U-band photometry
- Hα line luminosity
- [OI]6300 line luminos
- Brγ line luminosity
- Hα 10% width

Good empirical correlation, but only works for T Tauri stars



(Mendigutía et al. 2011)

Variability of accretion in Herbig stars

Mendigutía et al. (2011):

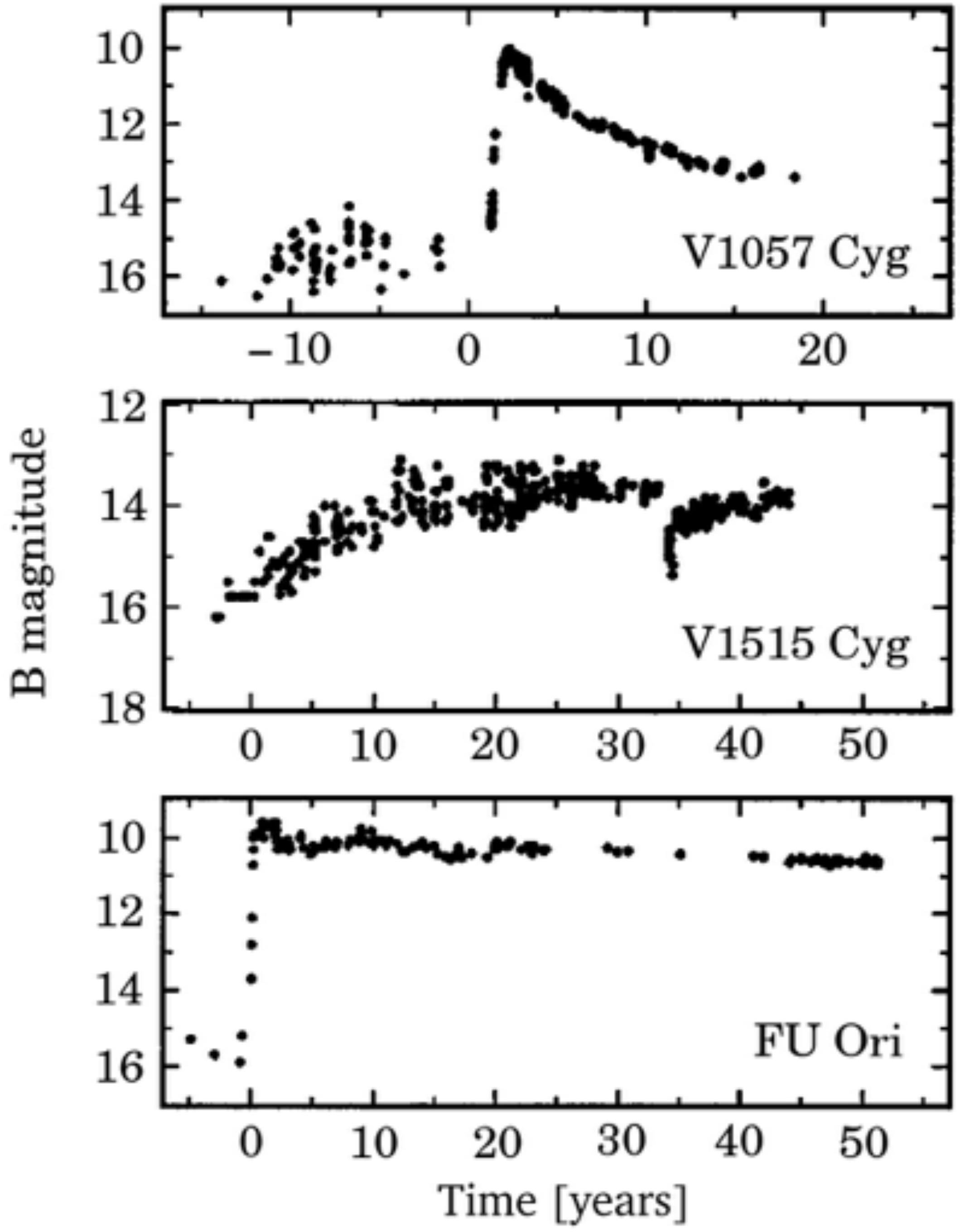
- Multi-epoch Balmer excesses
- Multi-epoch Hα and [OI]6300 luminosities
- Most stars show constant Balmer excess (within the uncertainties); variation < 0.2 mag → factor of < 5 in $\dot{M}_{acc}$
- Two most extreme cases:
V1686 Cyg: Balmer excess changed from 0.04 mag to 0.18 mag → implies an accretion rate change of a factor < 5
WW Vul: Balmer excess changed from 0.14 mag to 0.04 mag → implies a accretion rate change of a factor < 4

Variability of accretion in T Tauri stars

Eruptive phenomenon:

5 mag optical outburst due to several orders of magnitude increase in the accretion rate

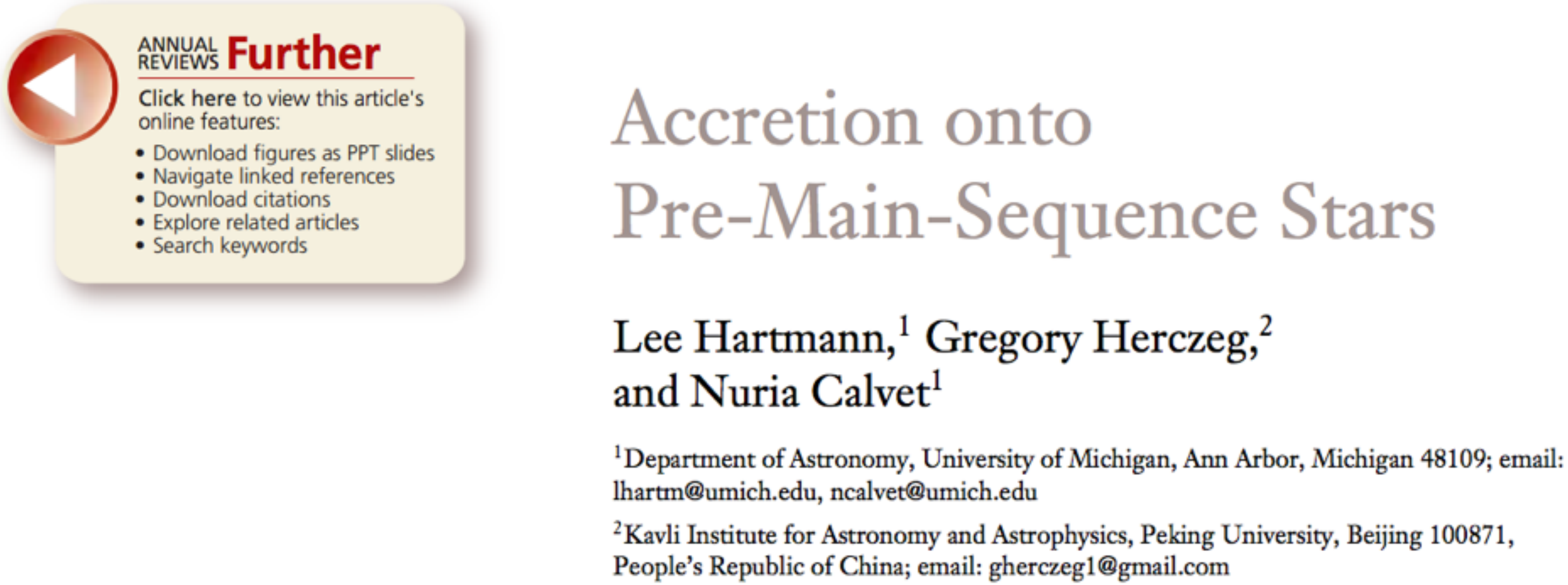
To be continued…



(Hartmann & Kenyon 1996)

Further reading

L. Hartmann, G. Herczeg, N. Calvet
Annu. Rev. Astron. Astrophys. 2016, 54:135−180



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Accretion onto Pre-Main-Sequence Stars

Lee Hartmann,[1] Gregory Herczeg,[2] and Nuria Calvet[1]

[1]Department of Astronomy, University of Michigan, Ann Arbor, Michigan 48109; email: lhartm@umich.edu, ncalvet@umich.edu

[2]Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, People's Republic of China; email: gherczeg1@gmail.com