The inner regions of protoplanetary disks

Review by C.P. Dullemond

Probing the inner disk regions...

Herbig Ae/Be

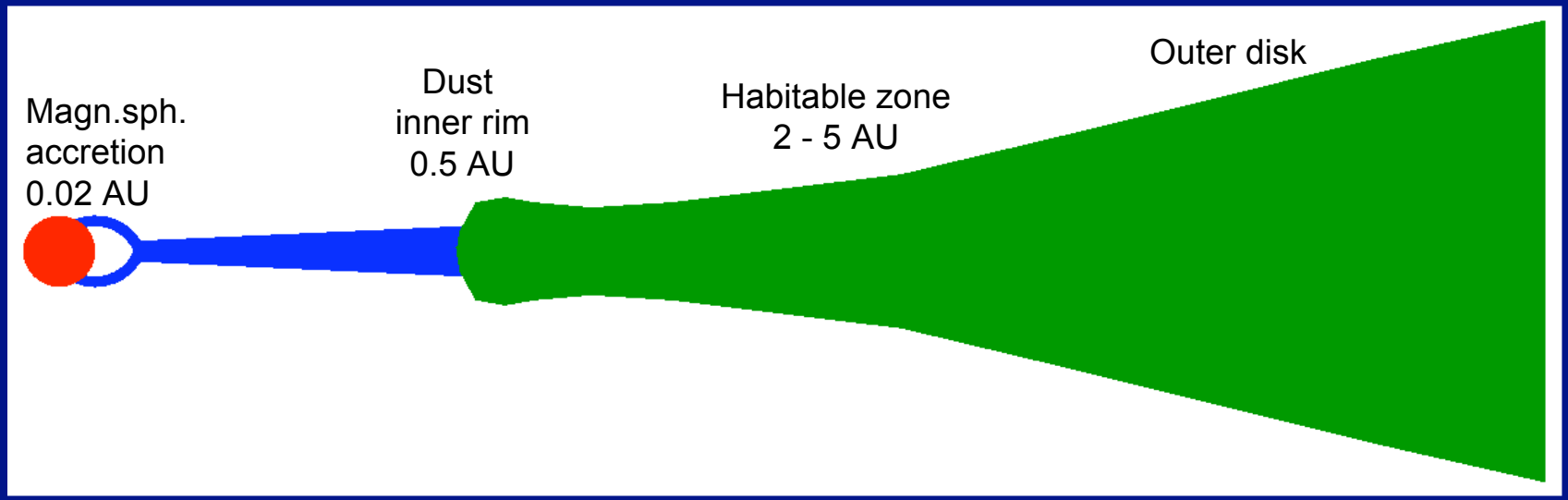
Near-IR interferometry

(sub-)mm interferometry

Mid-IR interferometry

8-10 meter Telescope

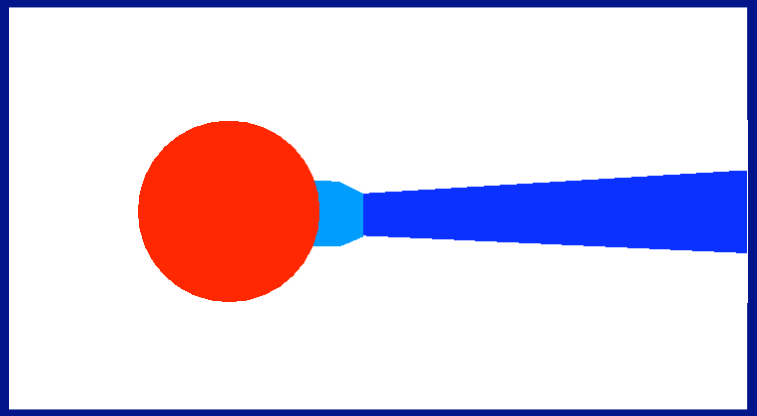
Hubble Space Telescope



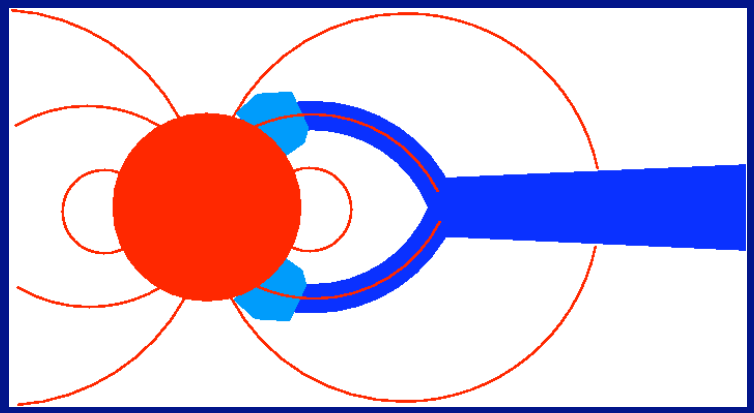
Magnetospheric accretion

Accretion onto stellar surface

Two modes:



Boundary layer



Magnetospheric accretion

Evidence for magnetosph. accr.

- Broad emission lines with red-shifted absorption

  Calvet & Hartmann (1992), Hartmann et al. (1994), Muzerolle et al. (1998)

- Evidence for B-field

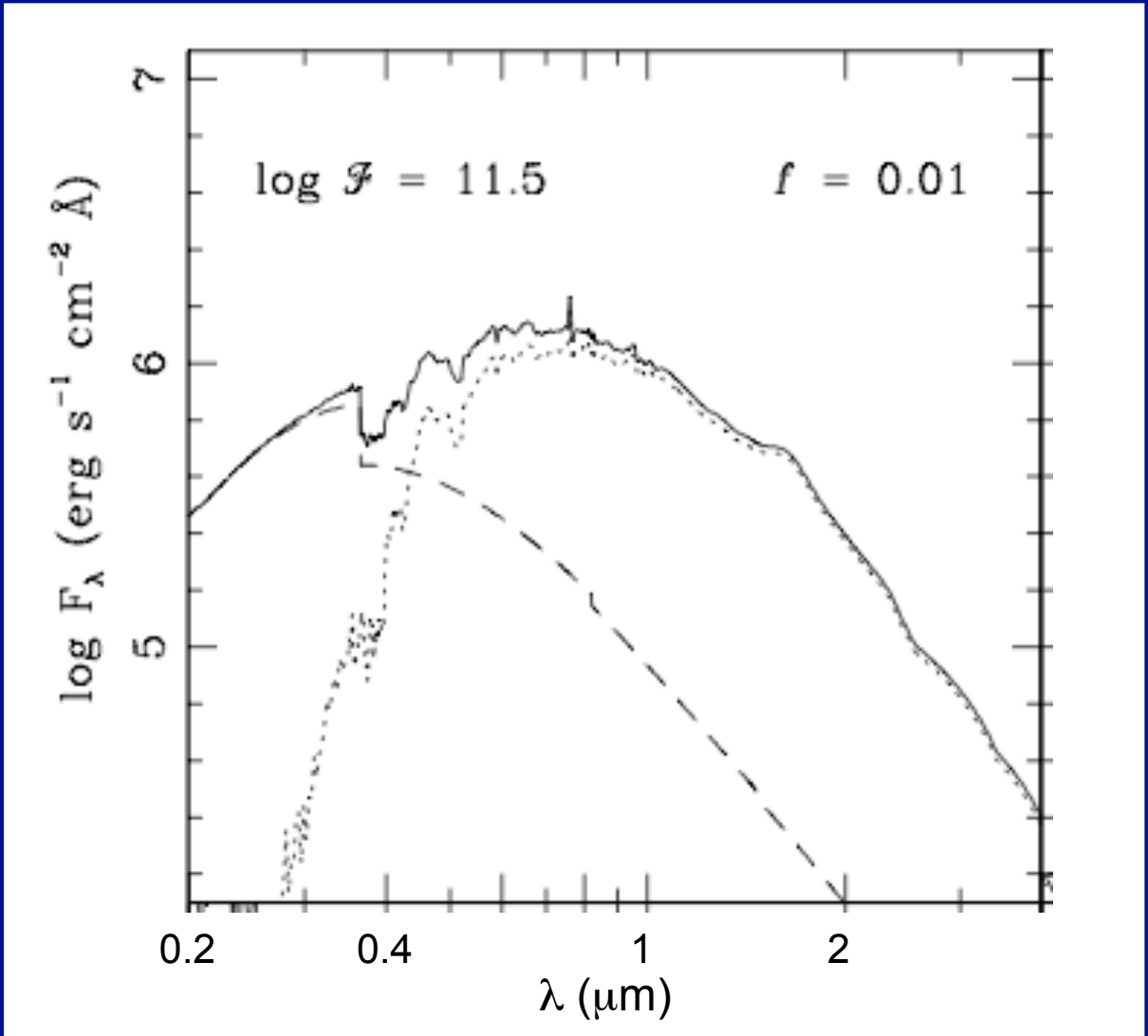
  Johns-Krull et al. (1999), Hubrig et al. (2004, poster #77)

Magnetospheric accretion models

- Magnetic disruption of disk and gas flow along fields:
  - Ghosh & Lamb (1979)
  - Camenzind (1990)
  - Königl (1991)
  - Romanova et al. (2004)
  - Jardine et al. (poster #80 this conference)

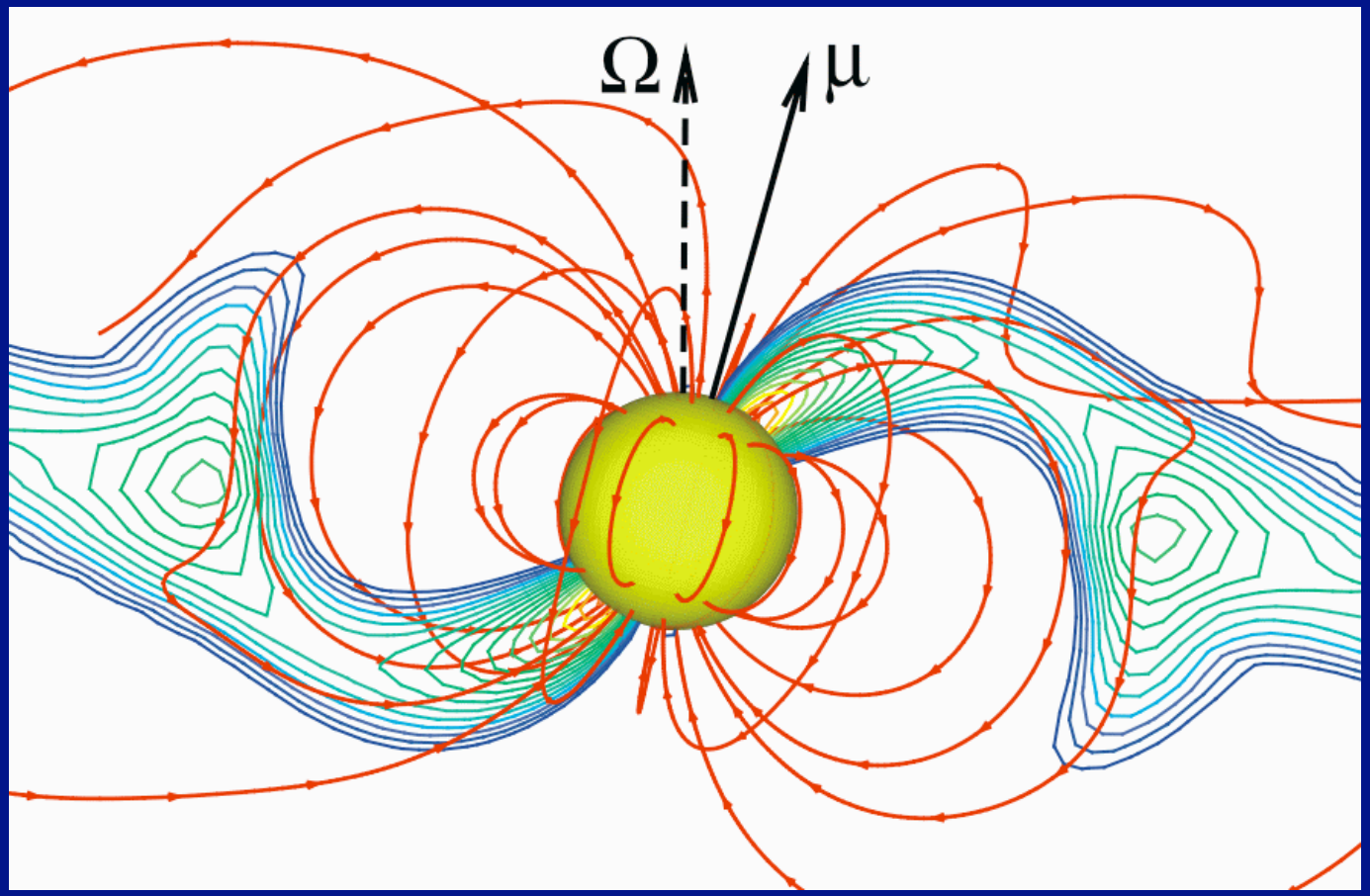
- Accretion shock near stellar surface:
  - Stahler, Shu & Taam (1980)
  - Calvet & Gullbring (1998)
  - Muzerolle, D'Alessio, Calvet & Hartmann (2004)

Veiling: accretion continuum



Calvet & Gullbring (1998)

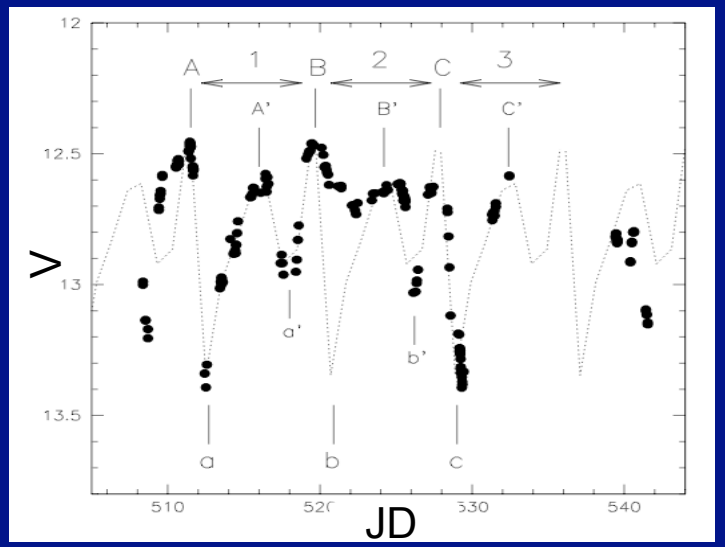
Inclined dipole

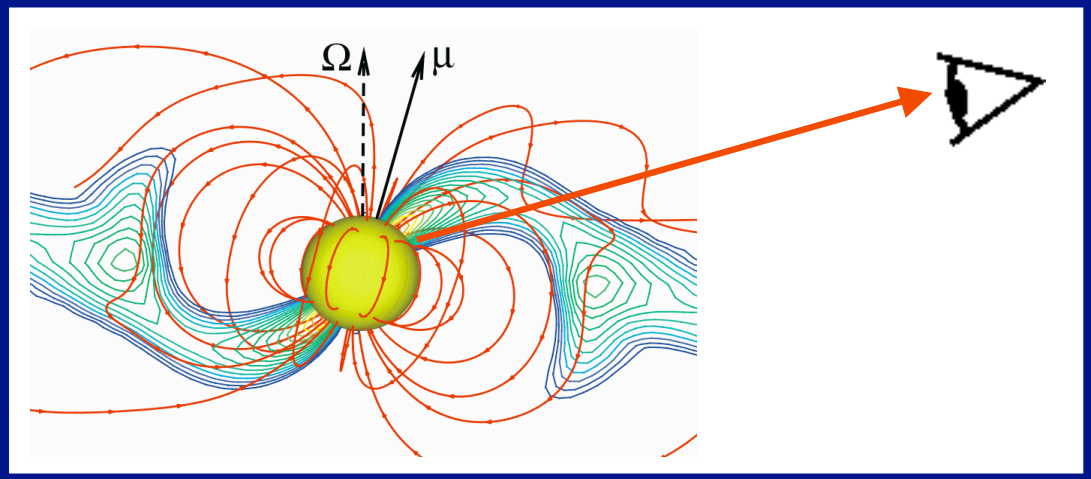


Romanova, Ustyugova, Koldoba & Lovelace (2004)

AA Tau: an inclined dipole?

- Periodic extinction events
  - $\Delta A_V \approx 1$
  - P=8.2 days
- Variations in veiling: two hotspots on star: polar caps

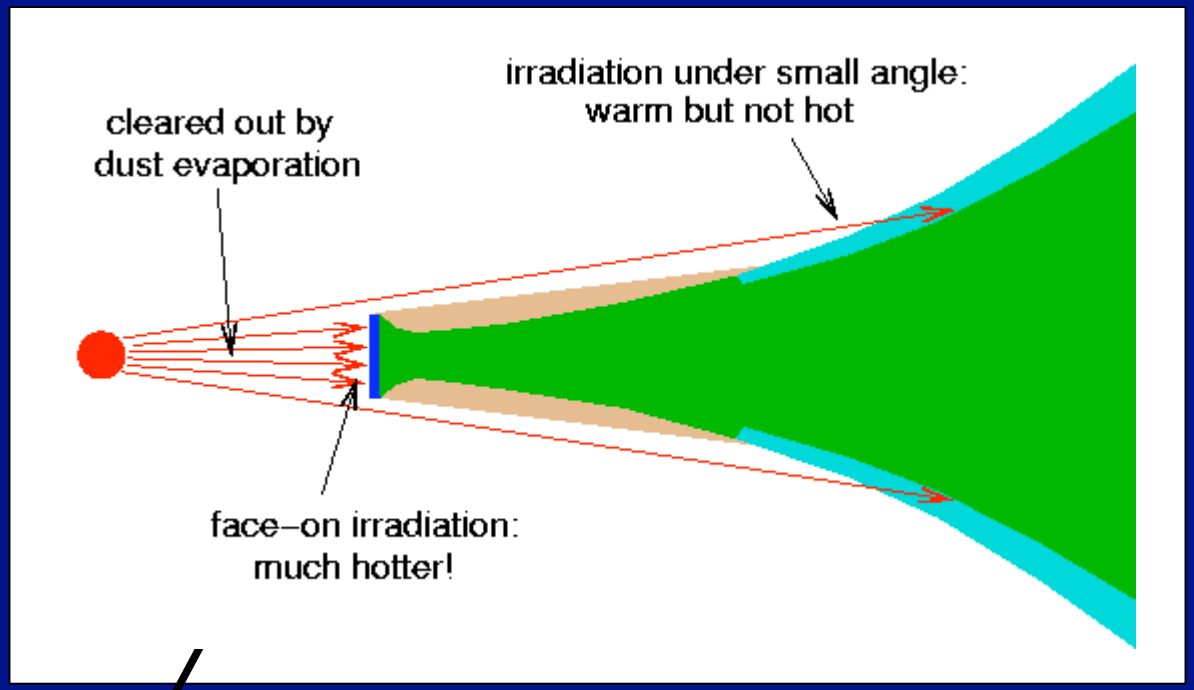


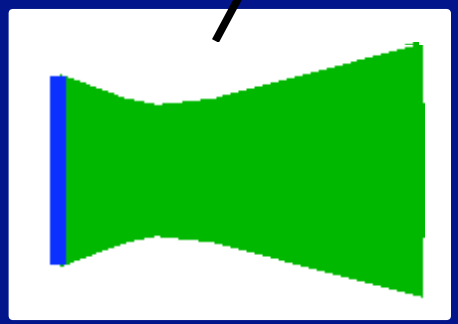


Bouvier et al. 1999, 2003, Terquem & Papaloizou 2000
Menard et al. 2003, O'Sullivan et al. 2005

The inner rim of the dust disk

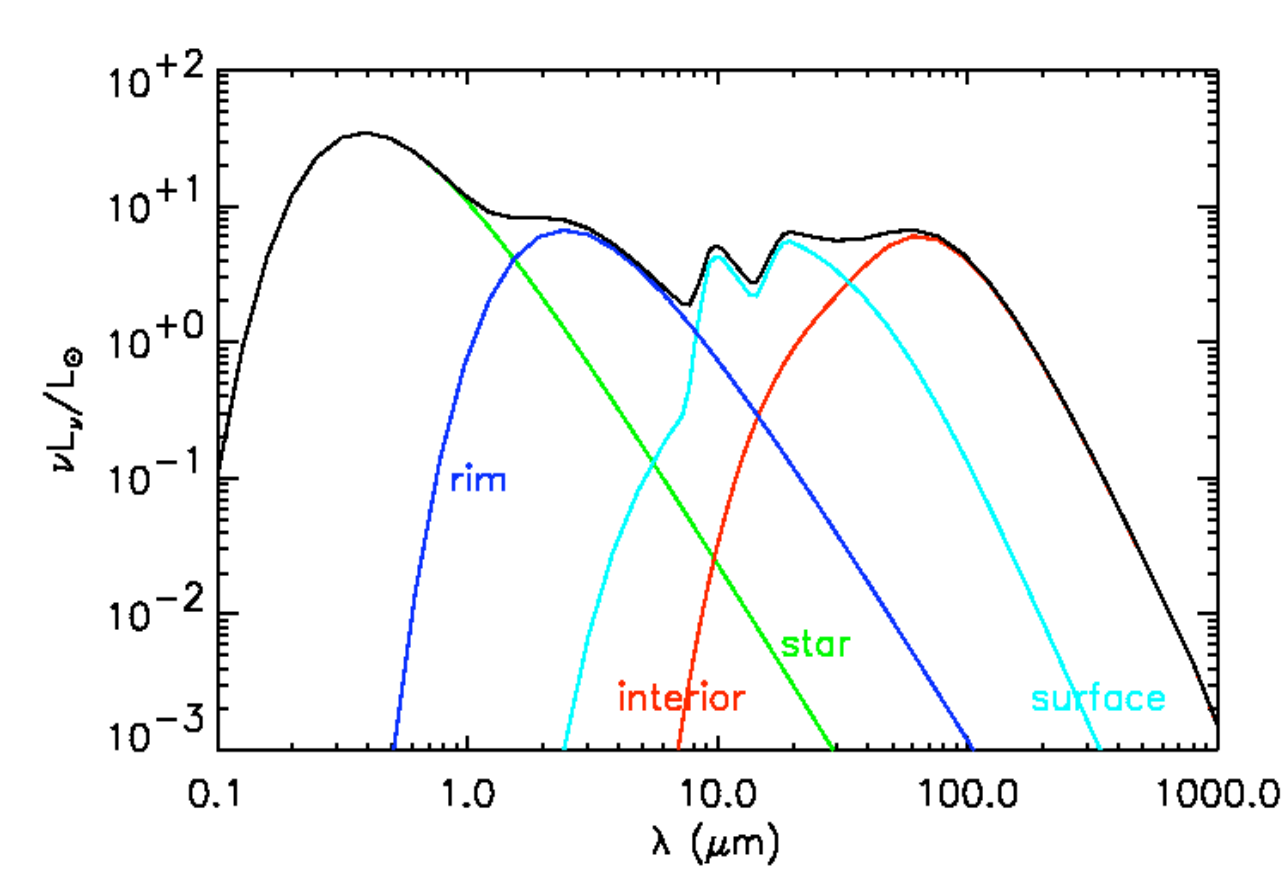
Disk with puffed-up dusty inner rim



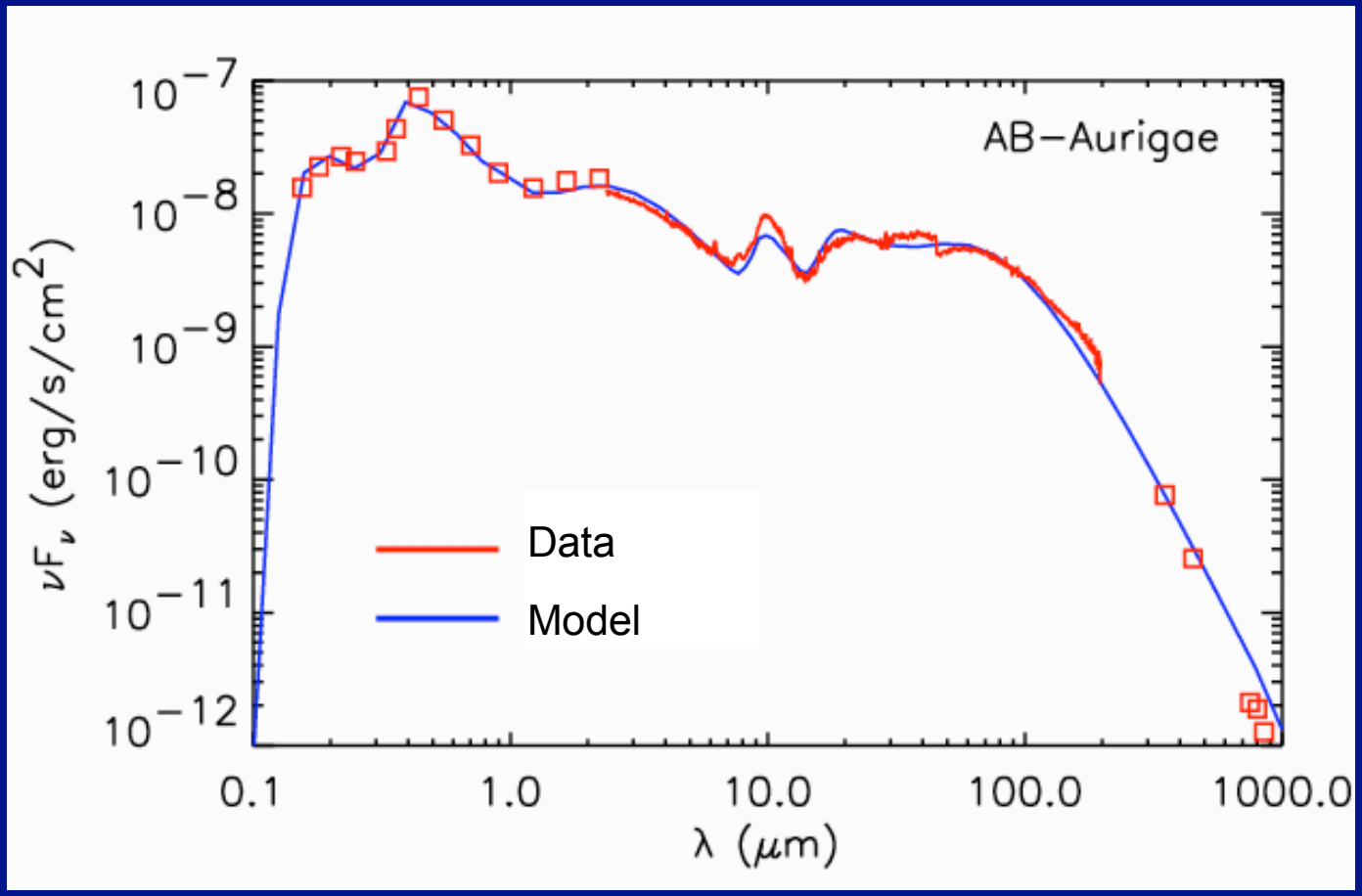


Natta et al. 2001
Dullemond, Dominik & Natta 2001

Inner rim: 3-micron bump in SED



Inner rim: 3-micron bump in SED

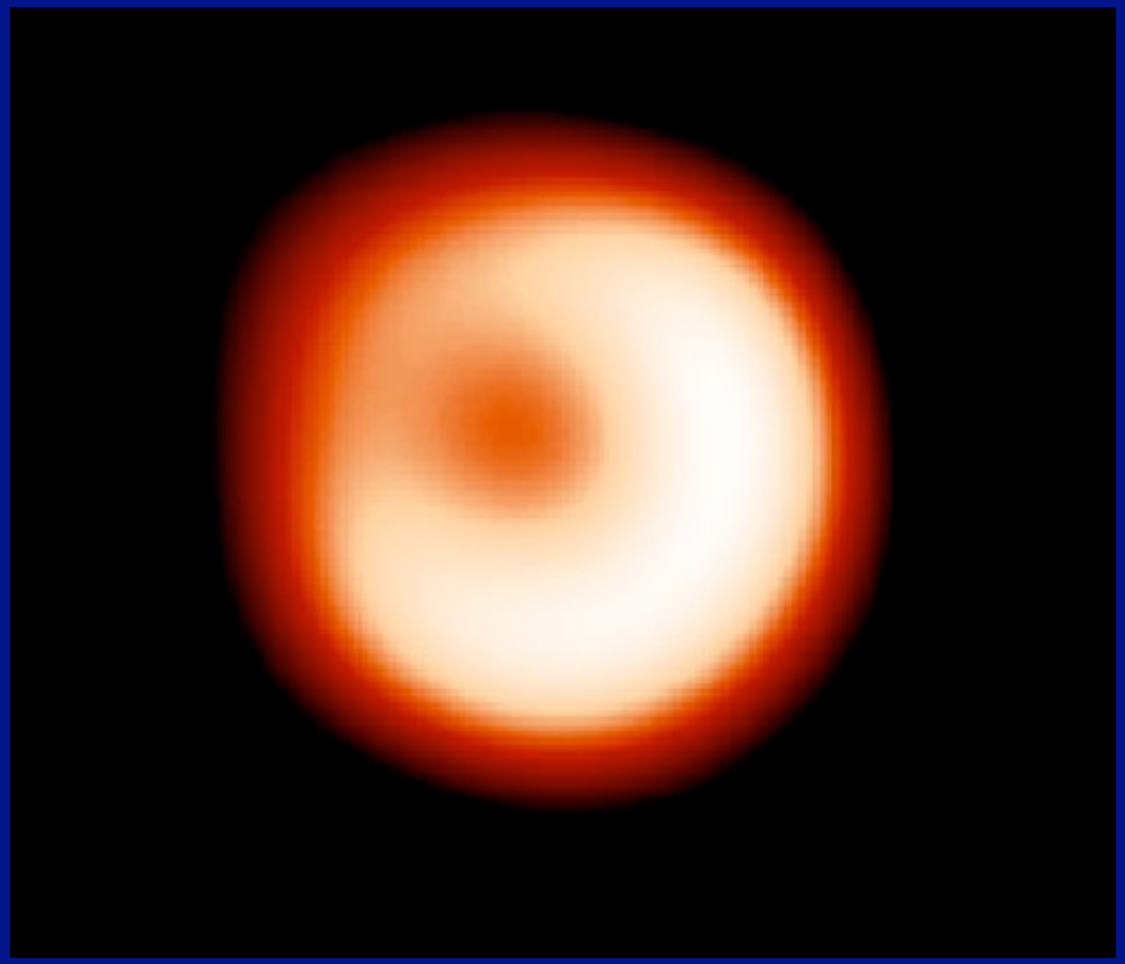


Resolving the inner rim

Near-infrared interferometry

- Tuthill et al. (2001)
- Millan-Gabet et al. (1999,2001)
- Monnier et al. (2002)
- Akeson et al. (2005)
- Eisner et al. (2003,2004,2005)
- Colavita et al. (2003)

First ‘image’ of dust rim (HBe star)



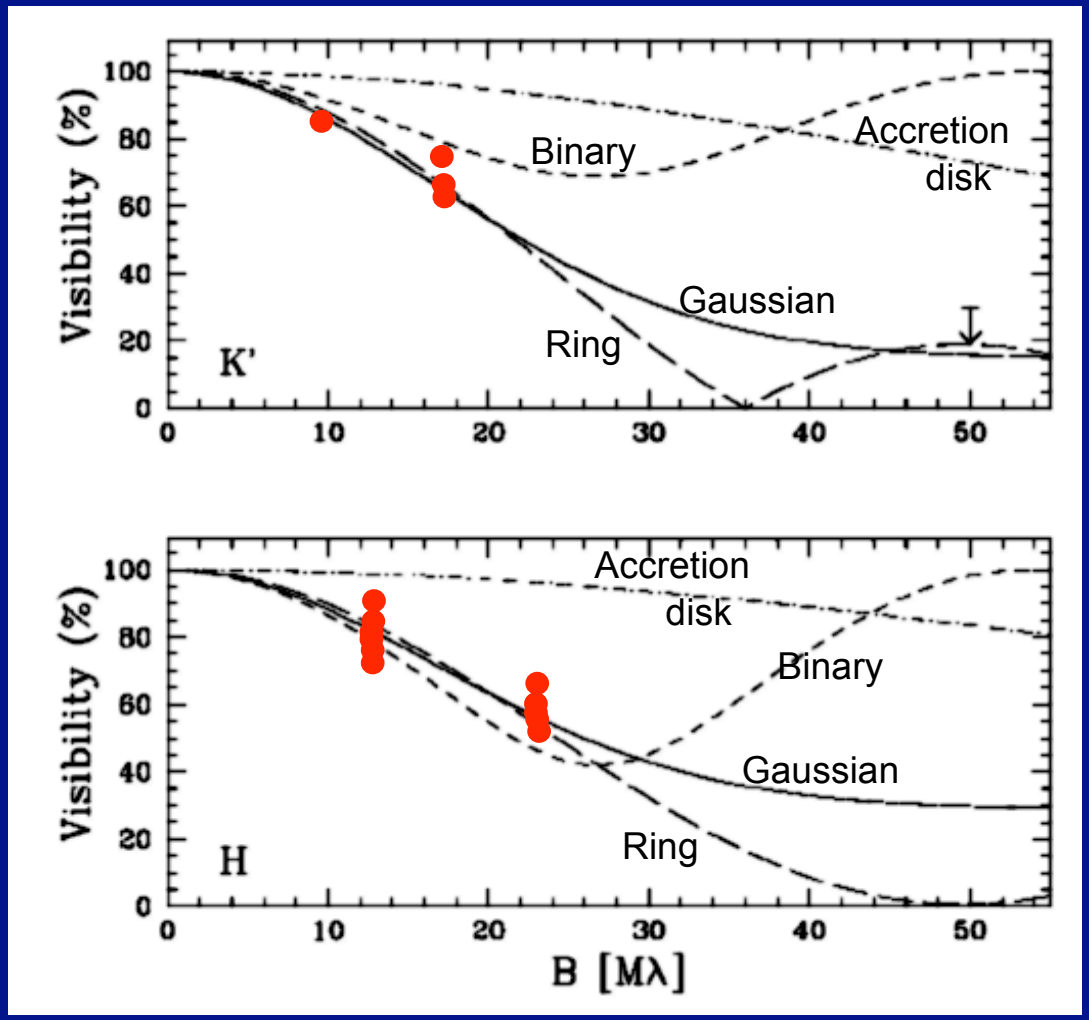
LkHa101: Inner rim imaged in NIR

Tuthill, Monnier, Danchi, Hale & Townes 2002
Tuthill, Monnier, Danchi 2001

For less bright stars: ‘visibilities’

Millan-Gabet, Schloerb,Traub et al 1999/2001

AB Aurigae, observed with near-IR interferometry



Rim or accretion disk?

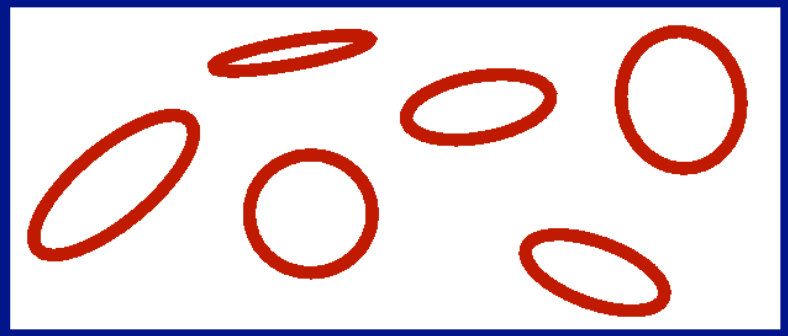
- Eisner et al. 2003 find:
  - *Early type stars (Herbig Be):*

    Accretion disk model fits best
  - *Later type stars (Herbig Ae):*

    Inner rim model fits best
  - Inner rim radius consistent with Tevap=2000 K (i.e. somewhat smaller than DDN01)

Rim or spherical shell?

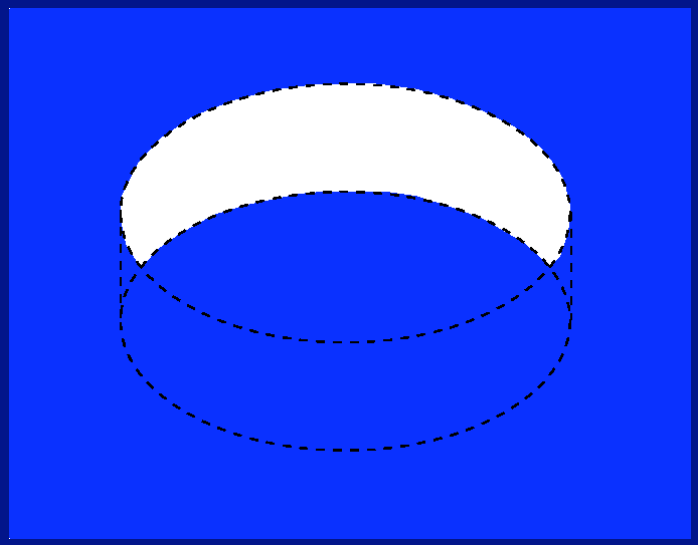
For rims you expect:



- Early measurements yielded isotropy
  (Millan-Gabet et al. 2001)
- Might be evidence for spherical halo?
  (see Vinkovic et al. 2003 and talk Vinkovic this conference)
- New measurements reveal an-isotropy
  (Eisner et al. 2003)

The shape of the inner rim

Inner rim face-on: a problem...



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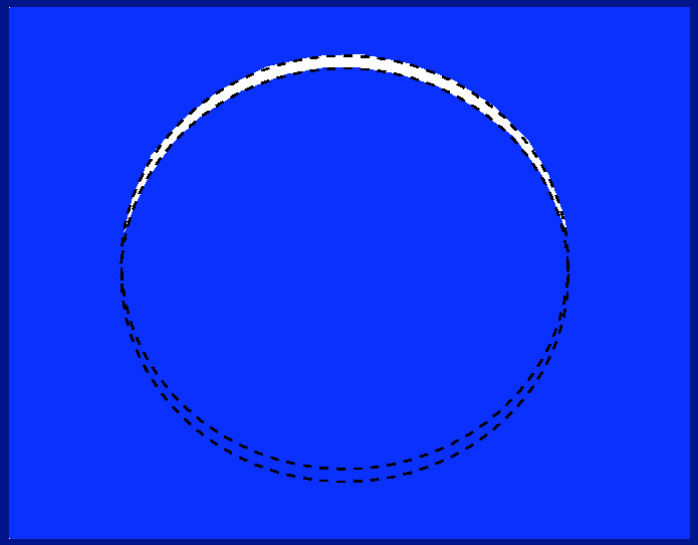


i=5

An explanation for rounded rims…

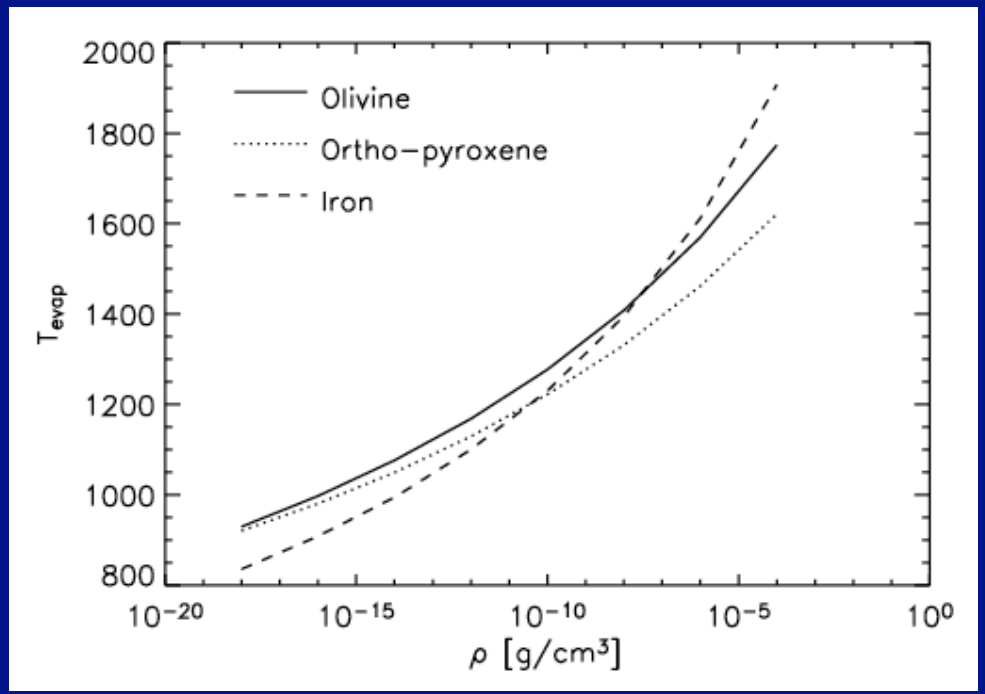
Evaporation temperature depends on gas density:

$$T_{\rm evap} = 2000\ \rho_{\rm gas}^{0.0195}$$

(Fit to Pollack et al 1994 Table 2)

$$R_{\rm rim} = \frac{1}{2} R_* \left(2\mu + \frac{1}{\epsilon}\right)^{\frac{1}{2}} \left(\frac{T_*}{T_{\rm evap}}\right)^2$$

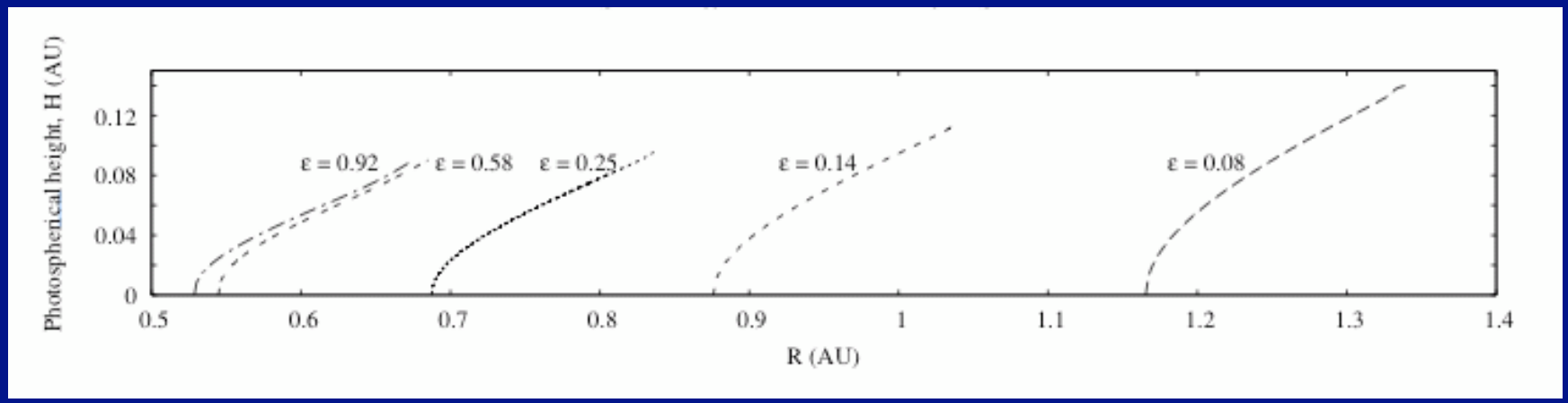
(Optically thin limit)



Pollack et al. (1994)

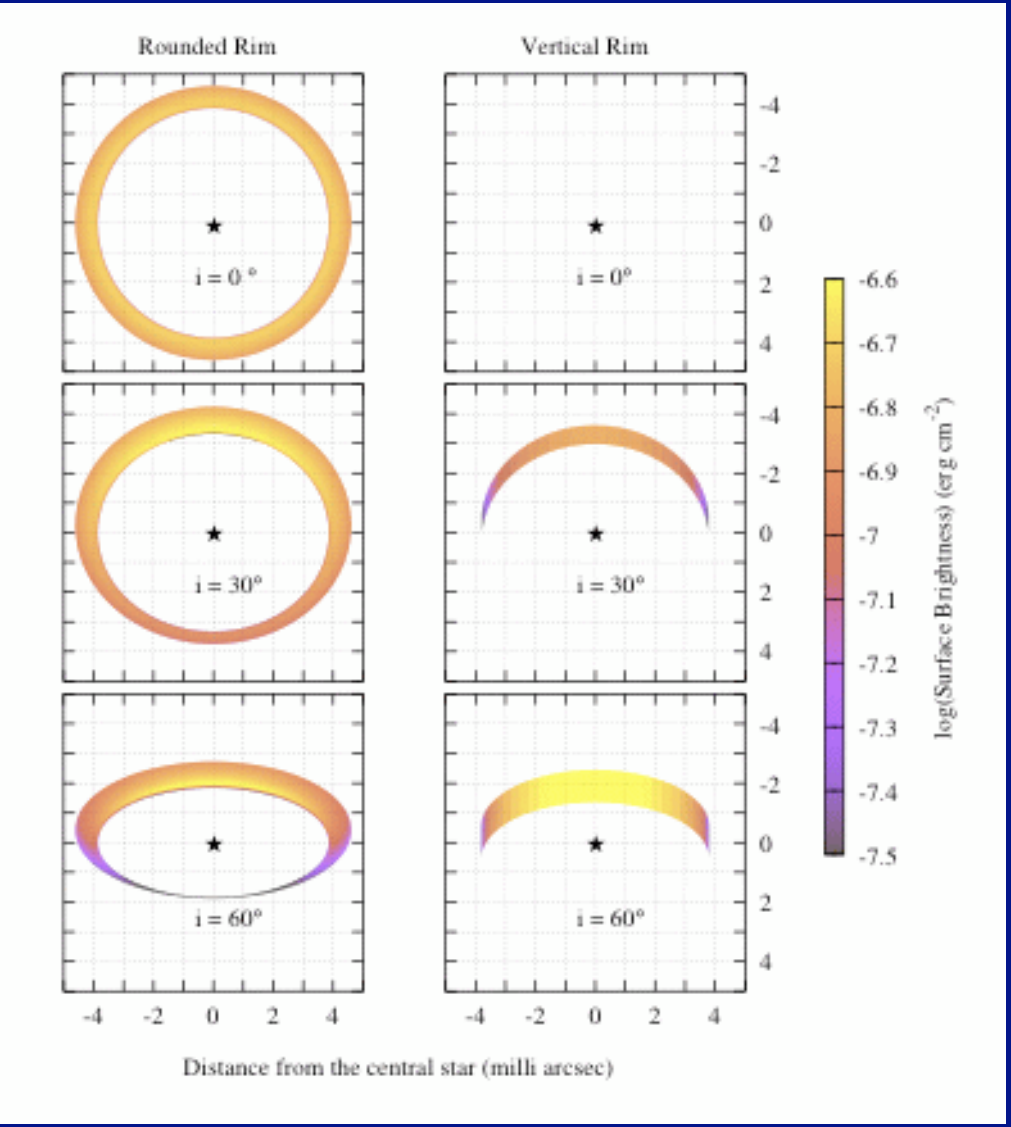
Isella & Natta (A&A in press, poster #78)

An explanation for rounded rims…



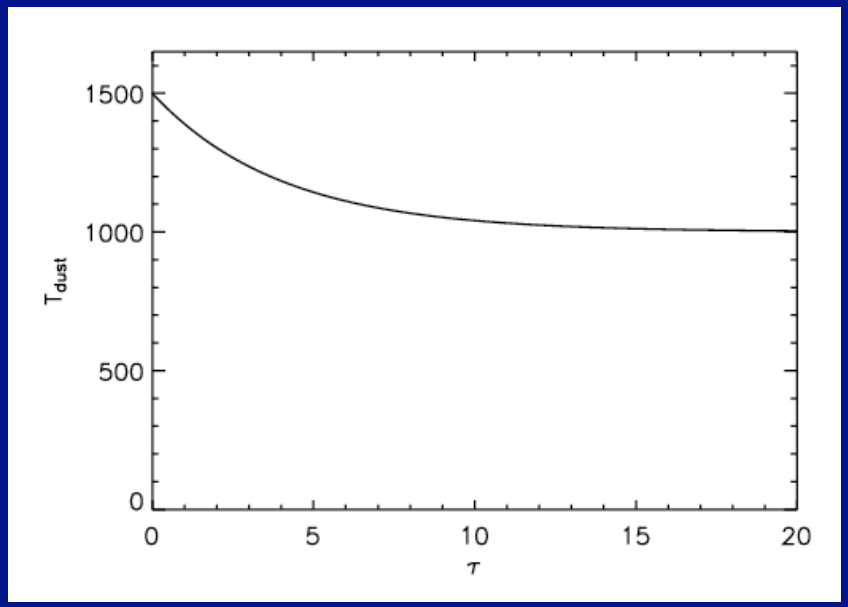
Isella & Natta (A&A in press, poster #78)

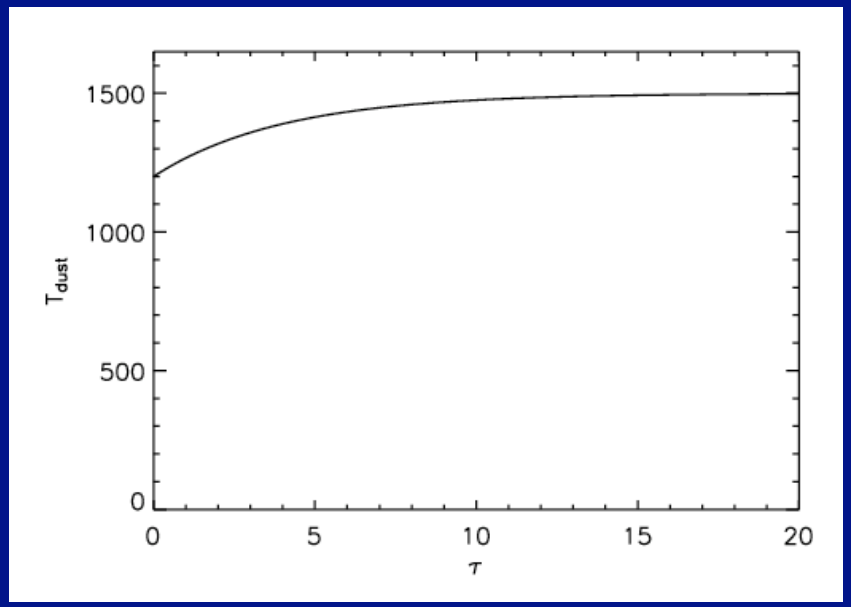
An explanation for rounded rims…



Isella & Natta (A&A in press, poster #78)

Sharp and fuzzy rims...





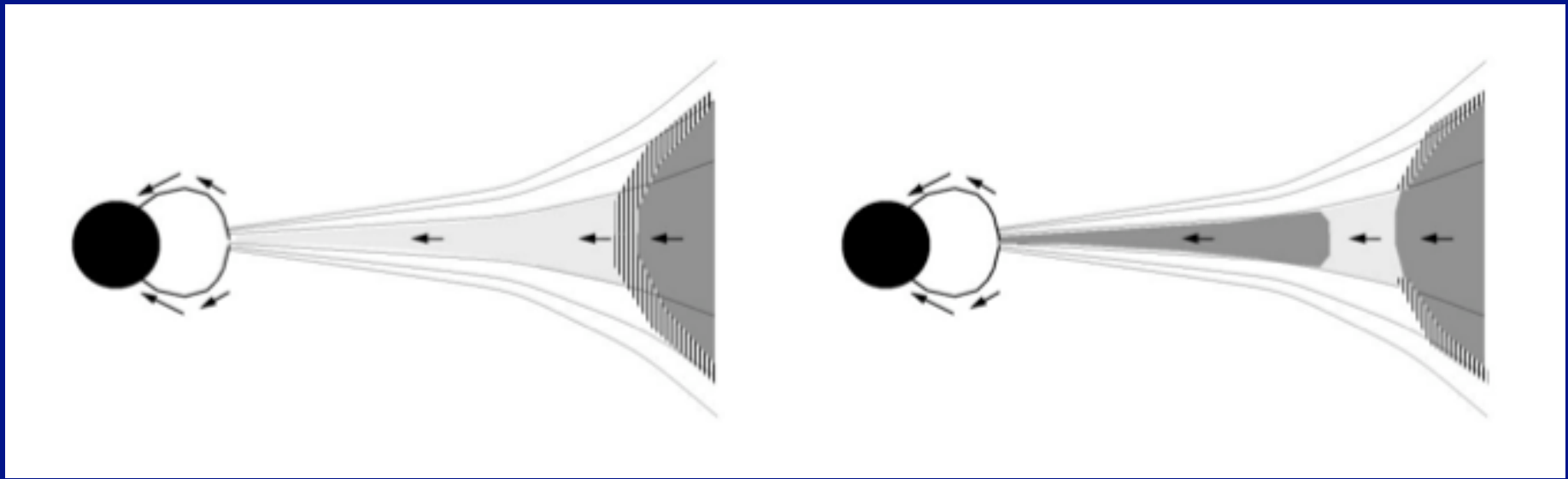
Sharp rim

Fuzzy rim

Isella & Natta (A&A in press, poster #78)

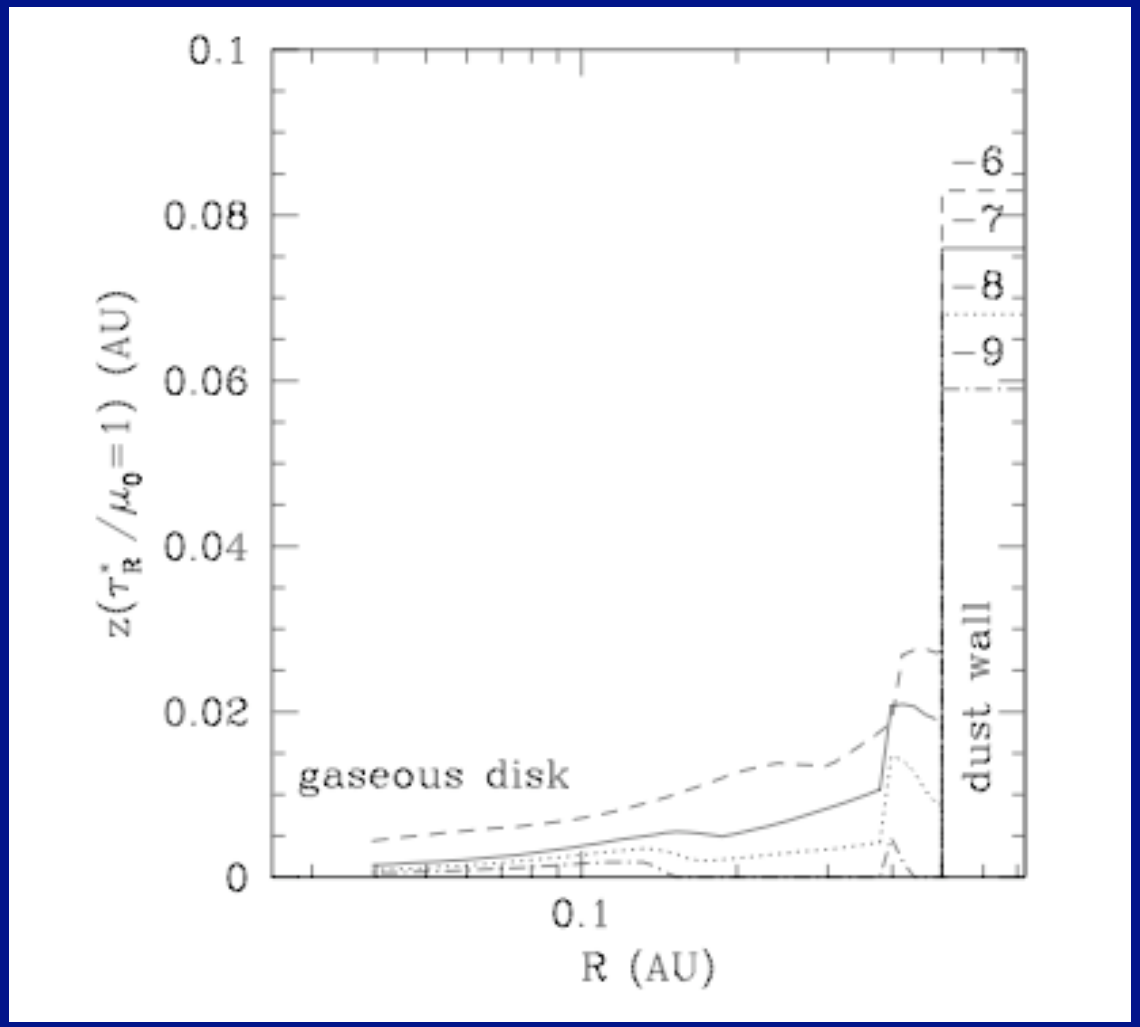
The gas inward of the inner dust rim

The gas inward of the rim



Muzerolle, D'Alessio, Calvet and Hartmann (2004)

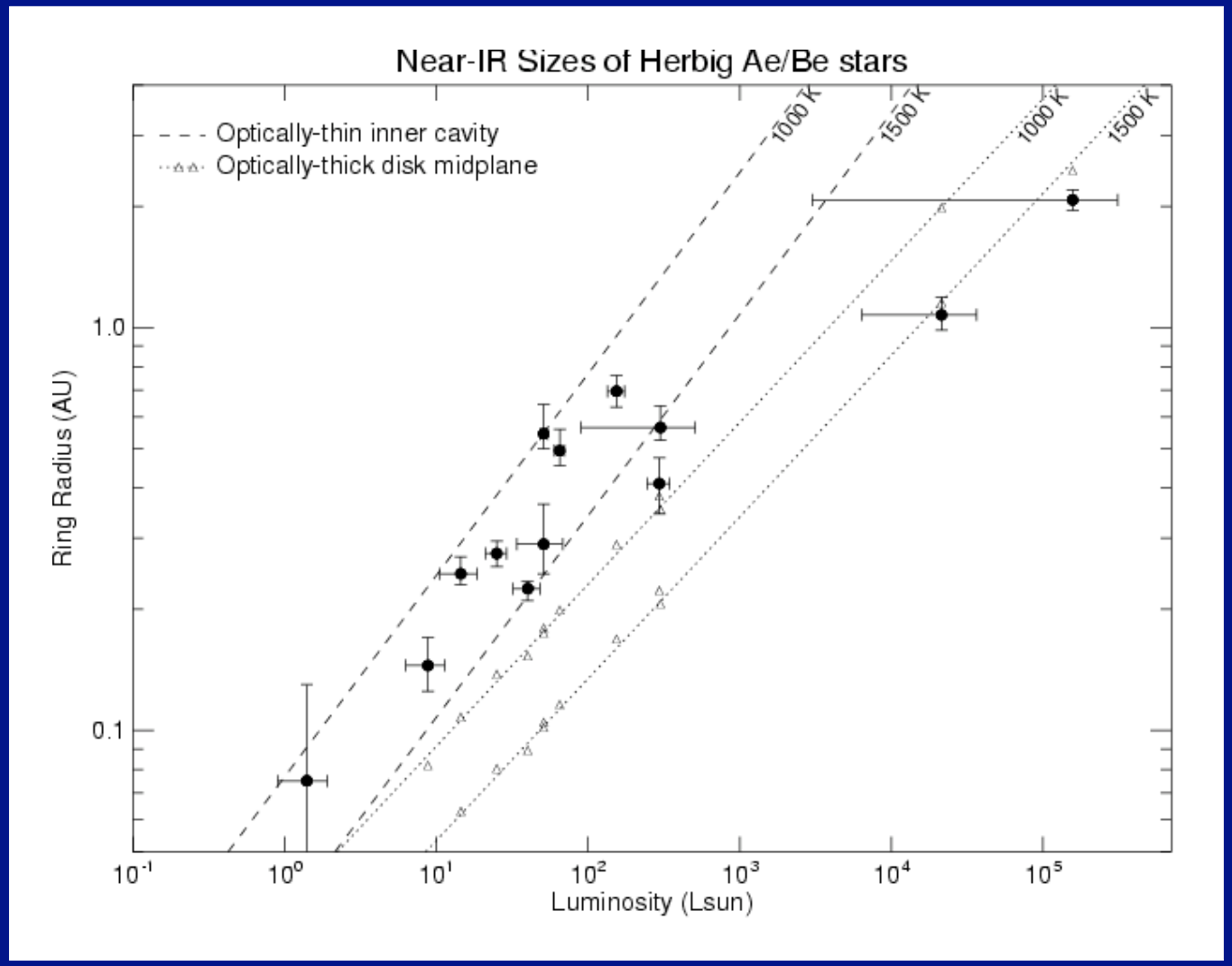
The gas inward of the rim



Muzerolle, D'Alessio, Calvet and Hartmann (2004)

Radius of the inner rim

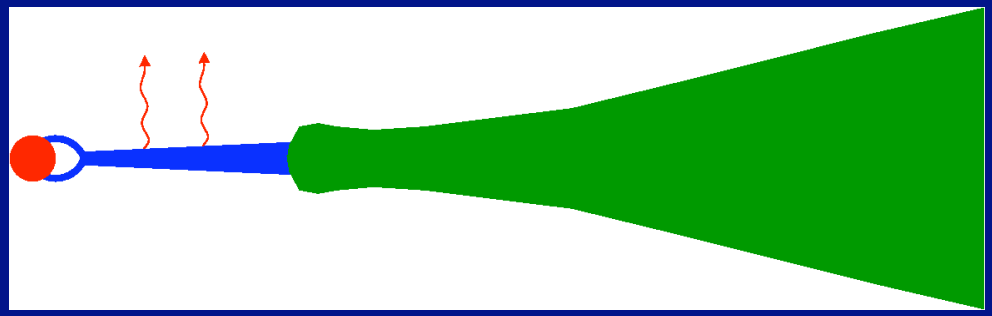
Size-luminosity relation



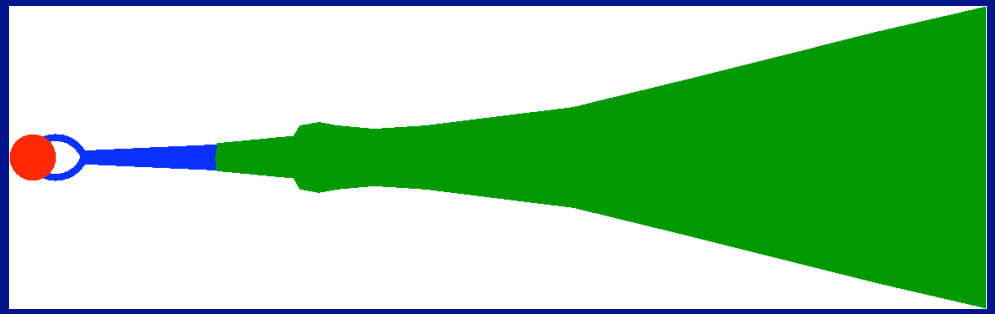
Monnier, Millan-Gabet et al. 2005

How to make the ‘rim’ smaller

- Emission from gas accretion inward of the rim (Akeson, Walker, Wood et al. ApJ 2005)



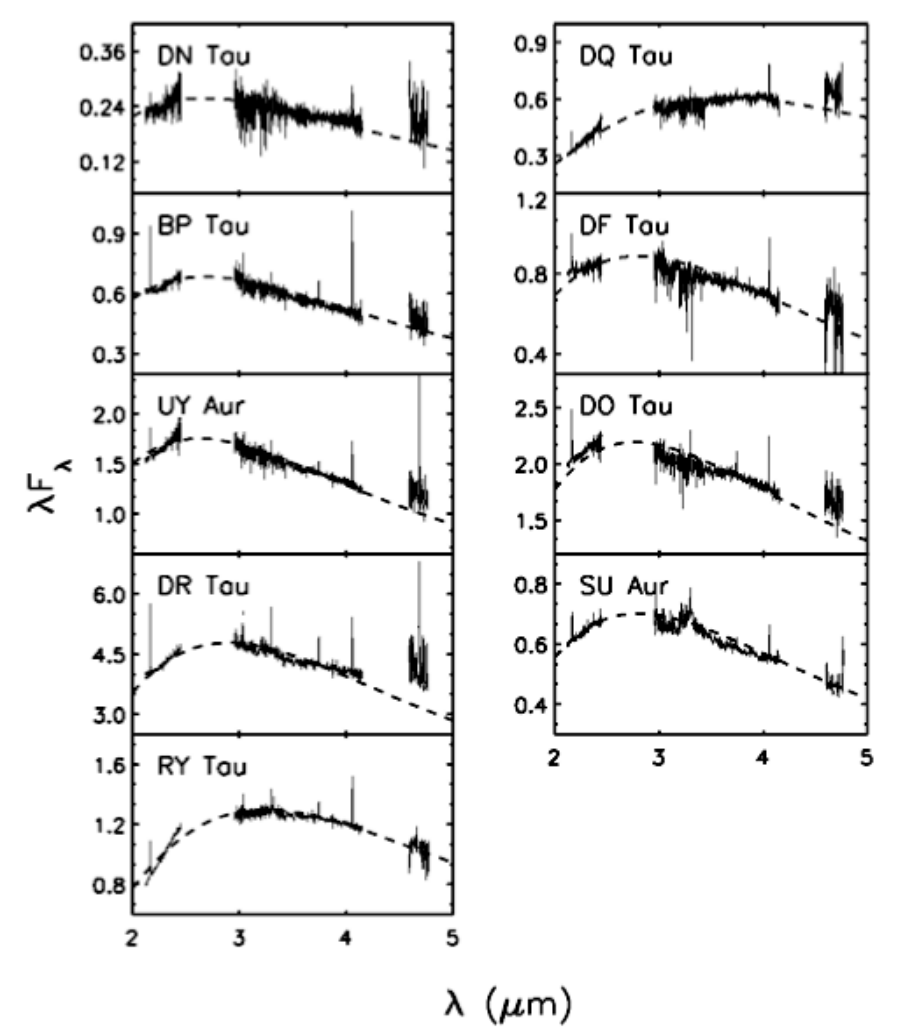
- Gas opacity protecting the dust: moving the rim inward (Monnier, Millan-Gabet et al. 2005)



(Typical for high-Luminosity systems)

Inner rim in T Tauri star disks

Rim of T Tauri star disks



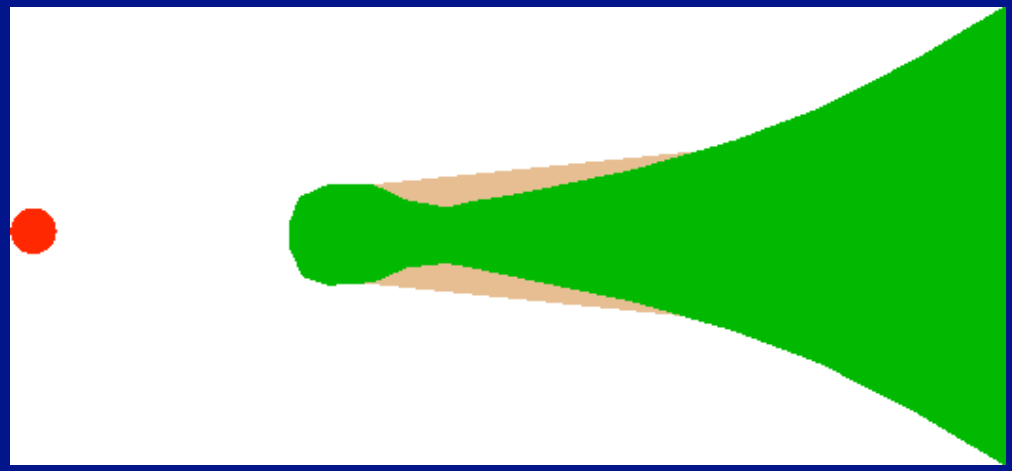
Accretion luminosity turns out to be important for the rim radius and for powering the rim emission

Muzerolle, Calvet, Hartmann & D'Alessio 2003
Cieza et al. in prep.

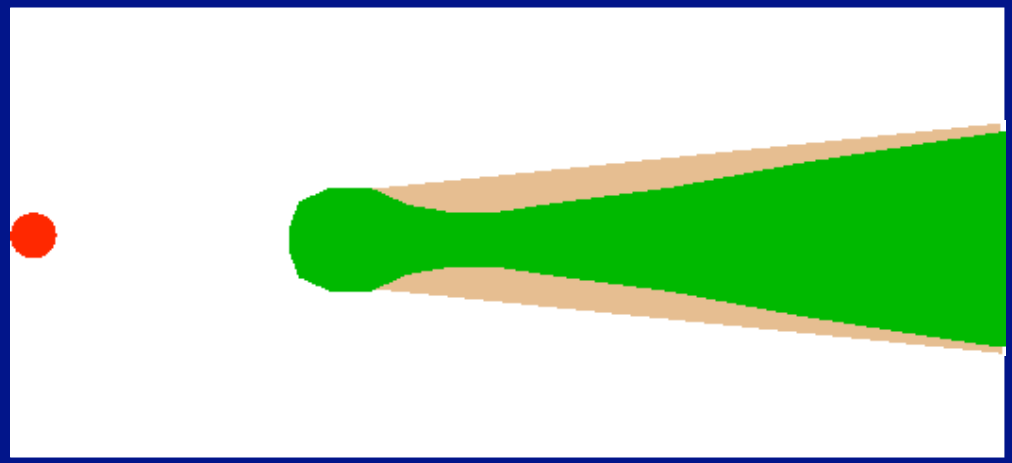
Effect of the inner rim on the outer disk

Rim shadow

Flaring disk

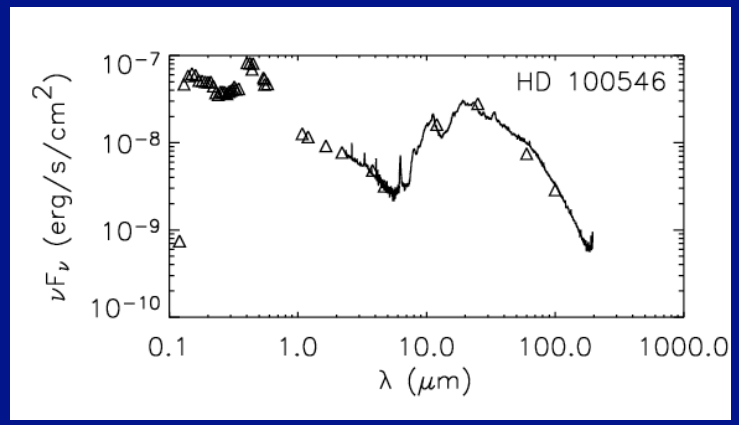


Self-shadowed disk



Dullemond 2002, Dullemond & Dominik 2004

Rim shadow



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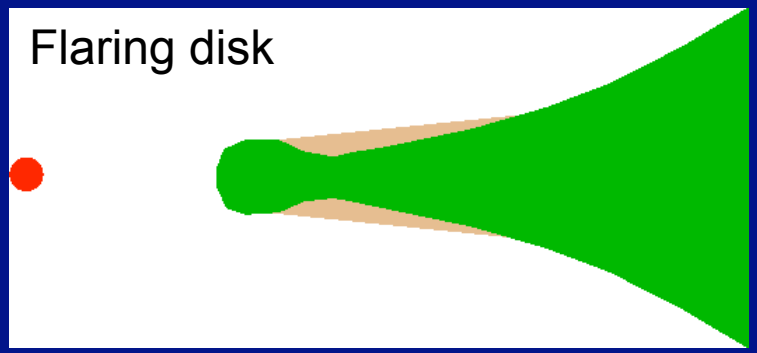

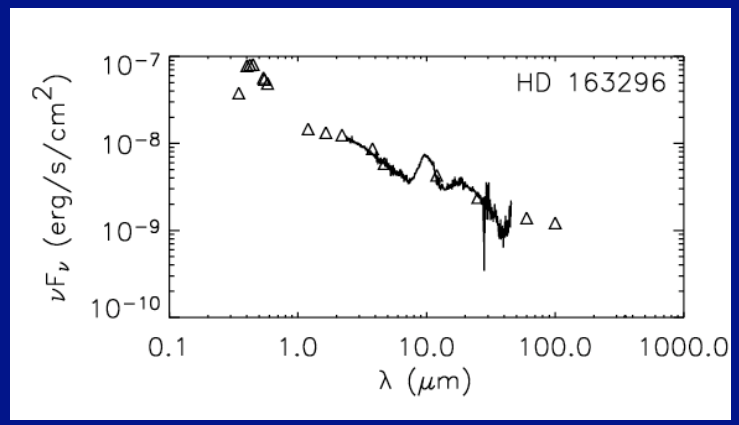

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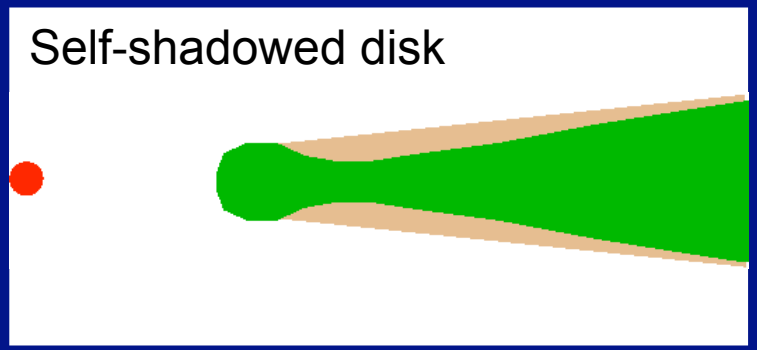


Meeus et al. (2001)

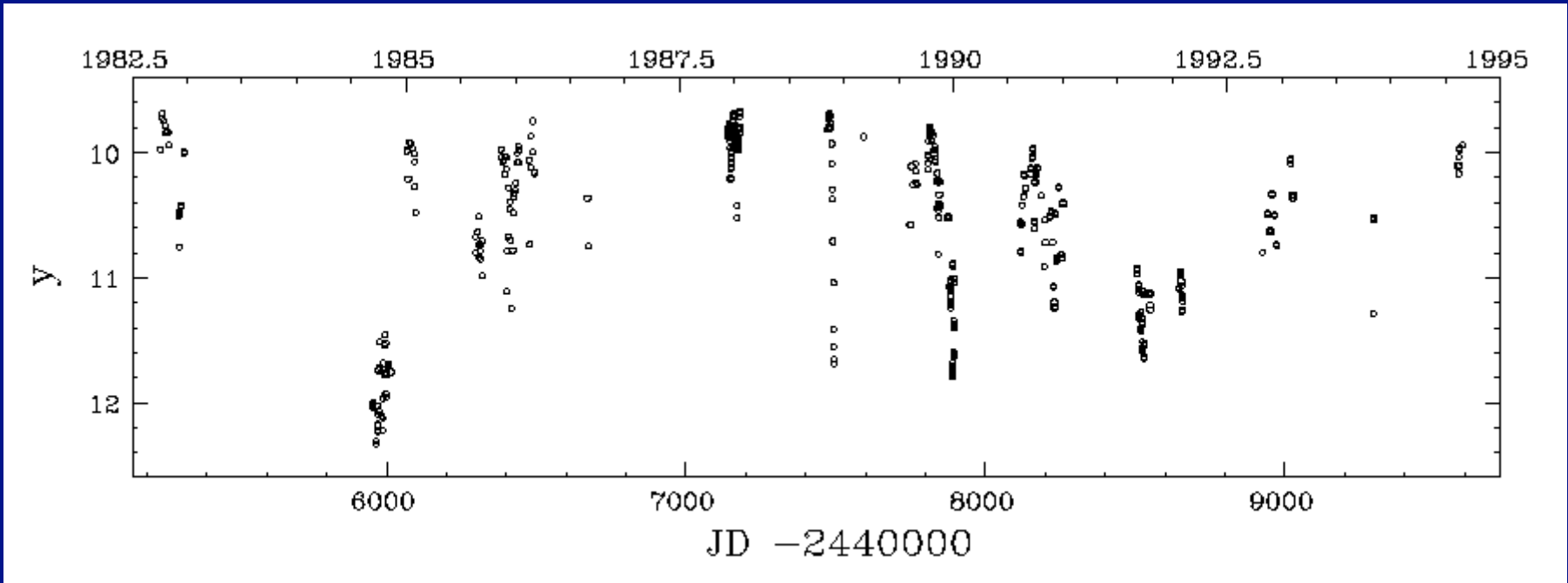
Dullemond 2002, Dullemond & Dominik 2004

(see also critical note Kenneth Wood ; tests e.g.: Misato Fukagawa)

Near-edge-on disks: Extinction events caused by the inner rim

UX Orionis extinction events...

Example light curve:

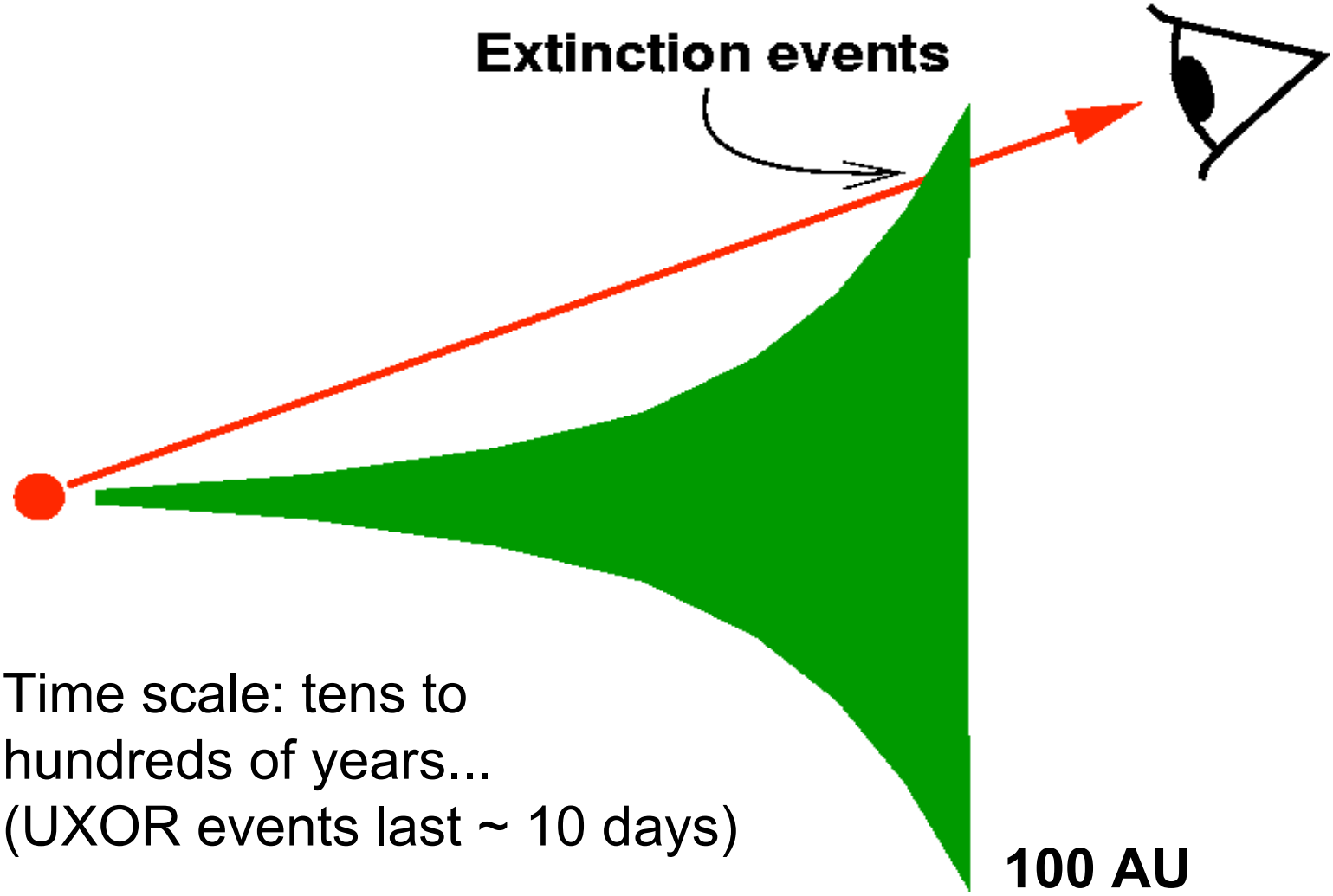


(UX Orionis)

Various theories of UXOR events

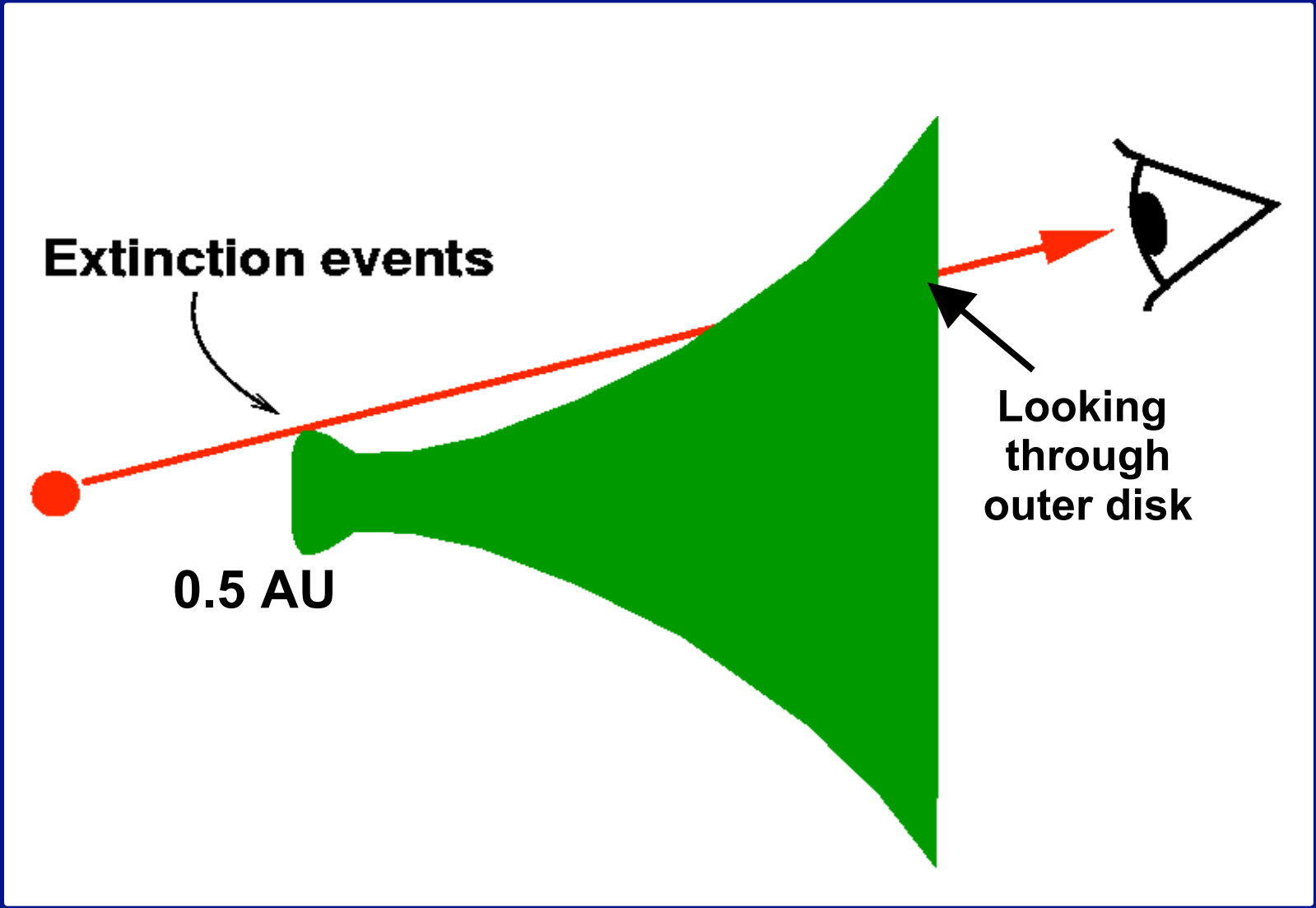
- Infalling / orbiting cometary objects
  - For Beta-Pic: Ferlet et al. (1987), Lagrange-Henri (1988), de Winter et al. 1999, Grady et al. 1996
  - Grinin et al. (1988,1994,1995)
  - Grady (2000)
- Fluctuations in near-edge-on disks
  - Bertout (2000)
  - Natta & Whitney (2000)
  - Dullemond et al. (2003)

UX Orionis extinction events...

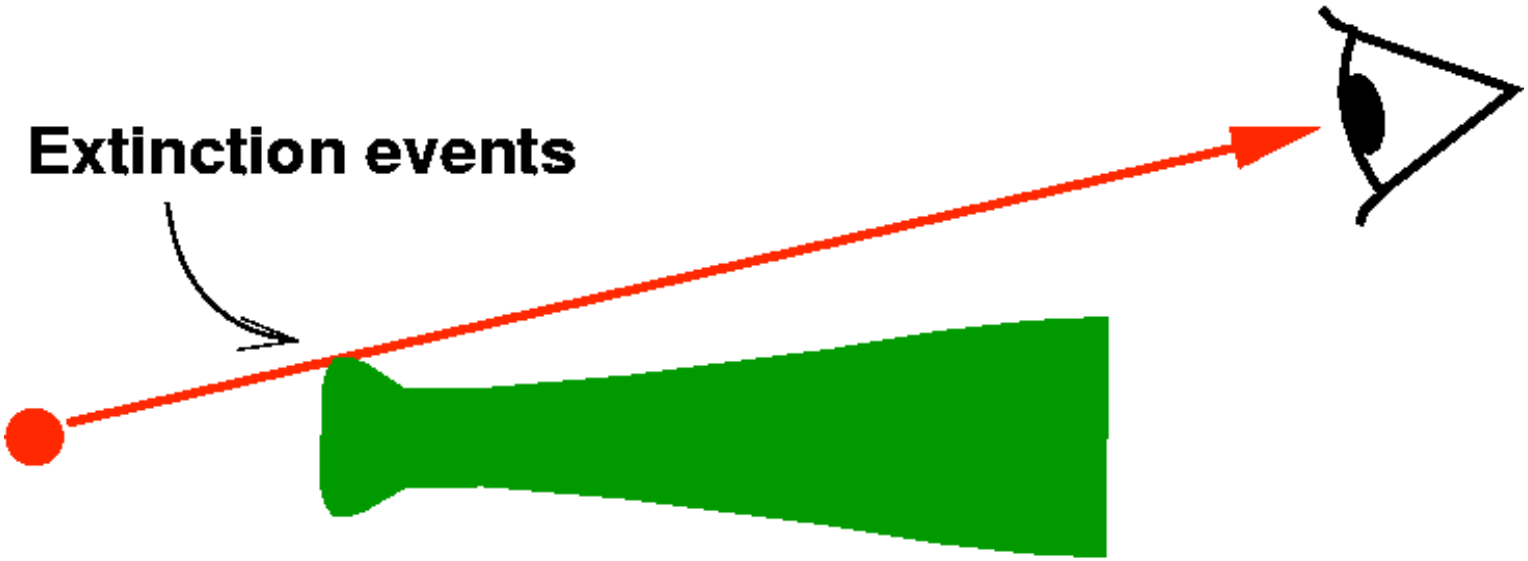


Time scale: tens to hundreds of years...
(UXOR events last ~ 10 days)

UX Orionis extinction events...



UX Orionis extinction events...

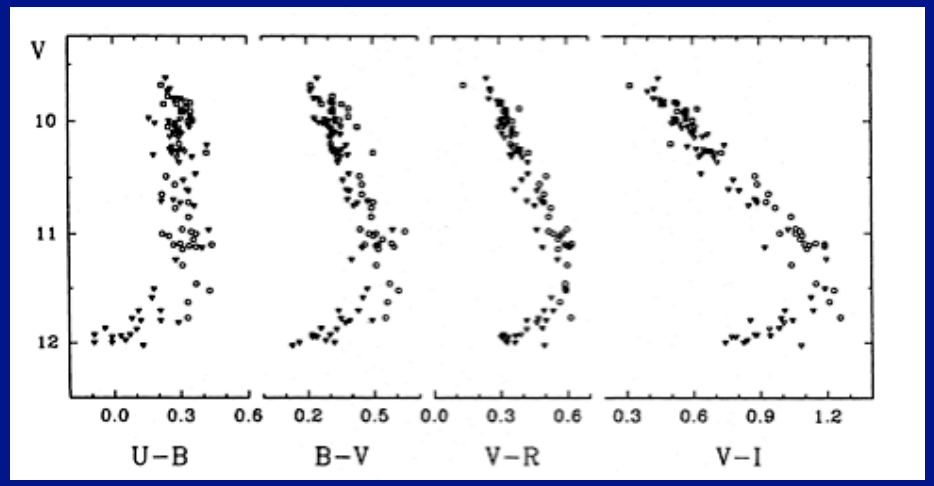


This scenario works!
So UXORs must be self-shadowed
or only very mildly flaring...

Dullemond, van den Ancker, Acke & van Boekel (2003)

UX-Ori events as a probe of the rim

- Determine grain sizes and mineralogy of inner rim from color-magnitude diagrams of UXOR events



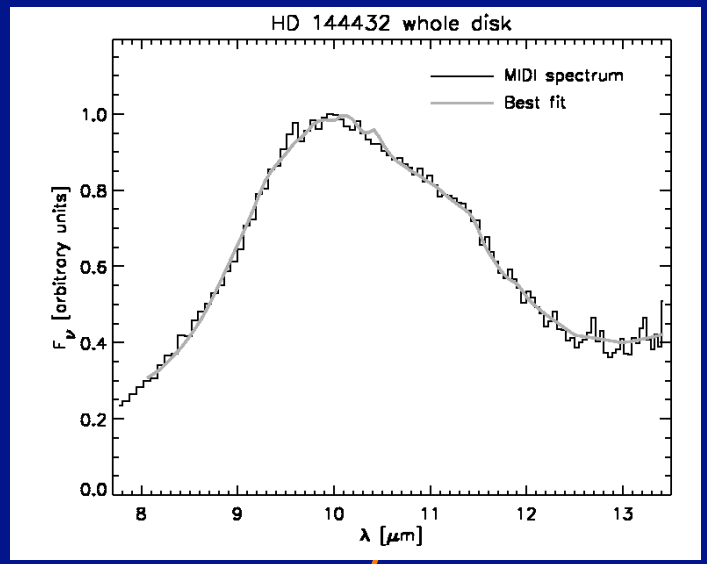
UX Orionis
Grinin et al. (1994)

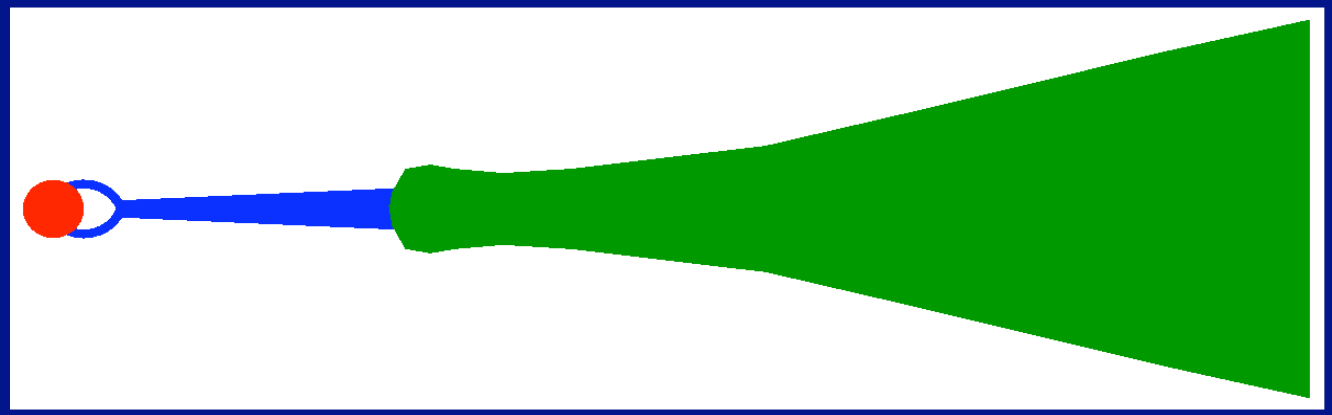
- Determine dynamics (size of eddies/clumps) of inner rim from light-curves of UXOR events

- Determine optical depth of the inner rim from typical reddening/depth of UXOR events

Mid-infrared interferometry: resolving the habitable zone

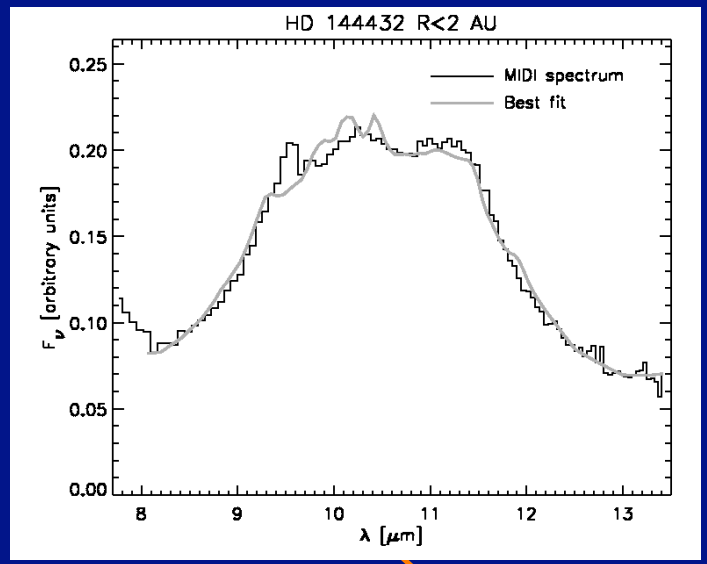
10 μm spectra from inner disk

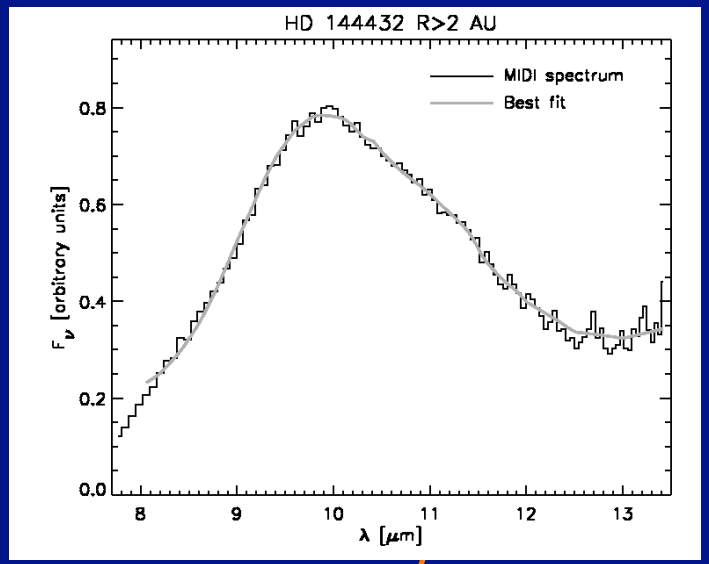


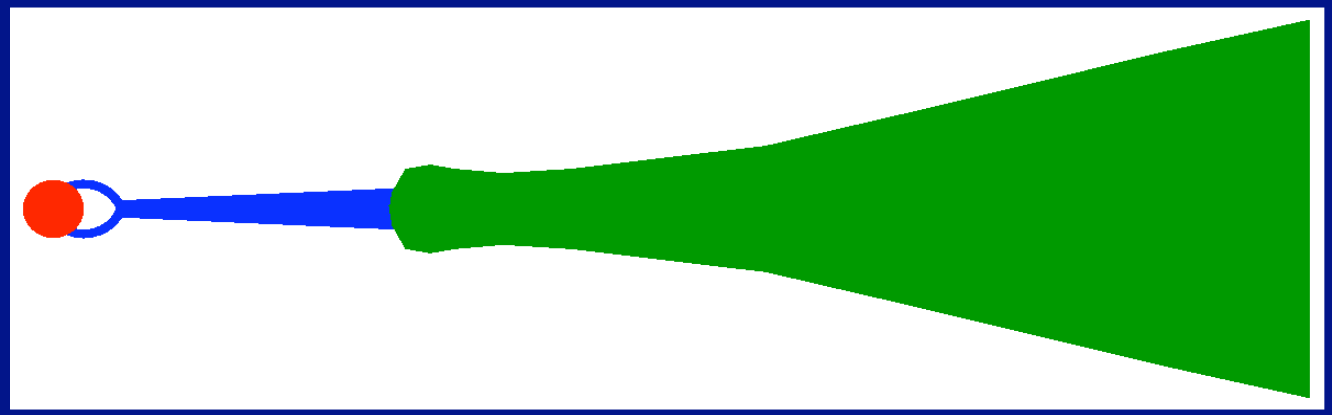


van Boekel et al. 2005, see talk by Waters/van Boekel, poster #90 of Meijer et al.

10 μm spectra from inner disk







van Boekel et al. 2005, see talk by Waters/van Boekel, poster #90 of Meijer et al.

Many other important topics...

- PAHs from inner disks (3.3 μm feature)
  Habart et al. (2005)
- CO Ro-vibrational lines from inner disk region
  Brittain et al. (2003, talk later today), Najita et al. (1996), Carr, Mathieu & Najita (2001), Blake & Boogert (2004)
- UV observations of H2
  Bergin et al. (2004), Martin et al. (poster # 86 this conference)
- Spectropolarimetry
  e.g. Vink et al. 2002...2005 (talk this conference)
- Clearing-out of inner disk (large inner holes)
  Forrest et al. 2004, Bouwman et al. 2003, Calvet et al. 2002
- Internal physics of inner disks (coagulation/chemistry)

Concluding remarks

- Near-infrared interferometry is maturing
  - PTI, IOTA, Keck...
  - Phase closure is now becoming possible
  - VLT-AMBER soon available
- Mid-infrared interferometry is now possible!
  - Radius-dependent mineralogy
- Adaptive optics
- Spitzer!

Exciting times for the study of the inner regions of disks!