Lecture notes:

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

The Inner Regions of Protoplanetary Disks

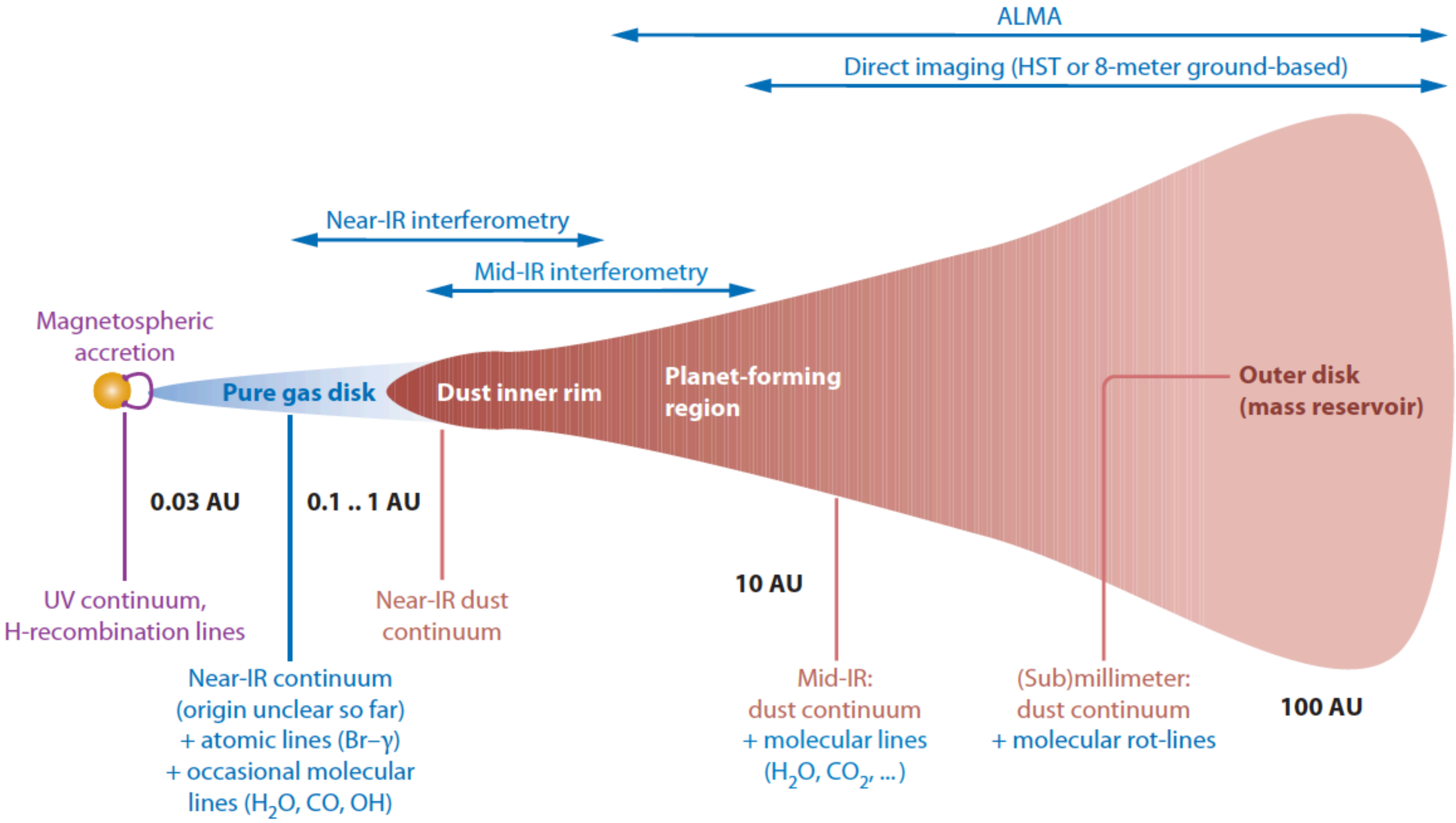
C.P. Dullemond & J.D. Monnier

Annu. Rev. Astron. Astrophys. 2011, 48:205−39

Inner 1 au – a puzzle

- Difficult to spatially resolve
- Physics is poorly understood (hot → dust evaporates)
- Numerical modeling is challenging

Rich structure



Large dynamic range

- Spatial scale:
  inner disk ↔ outer disk
  few stellar radii ↔ 100 − 1000 au
- Dynamical/orbital timescale:
  factor of 10^6 difference between inner and outer disk
- Temperature:
  inner disk ↔ outer disk
  >1000 K ↔ 10 − 30 K
- Density

Inner disk

- Roughly < 1 au
- T 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

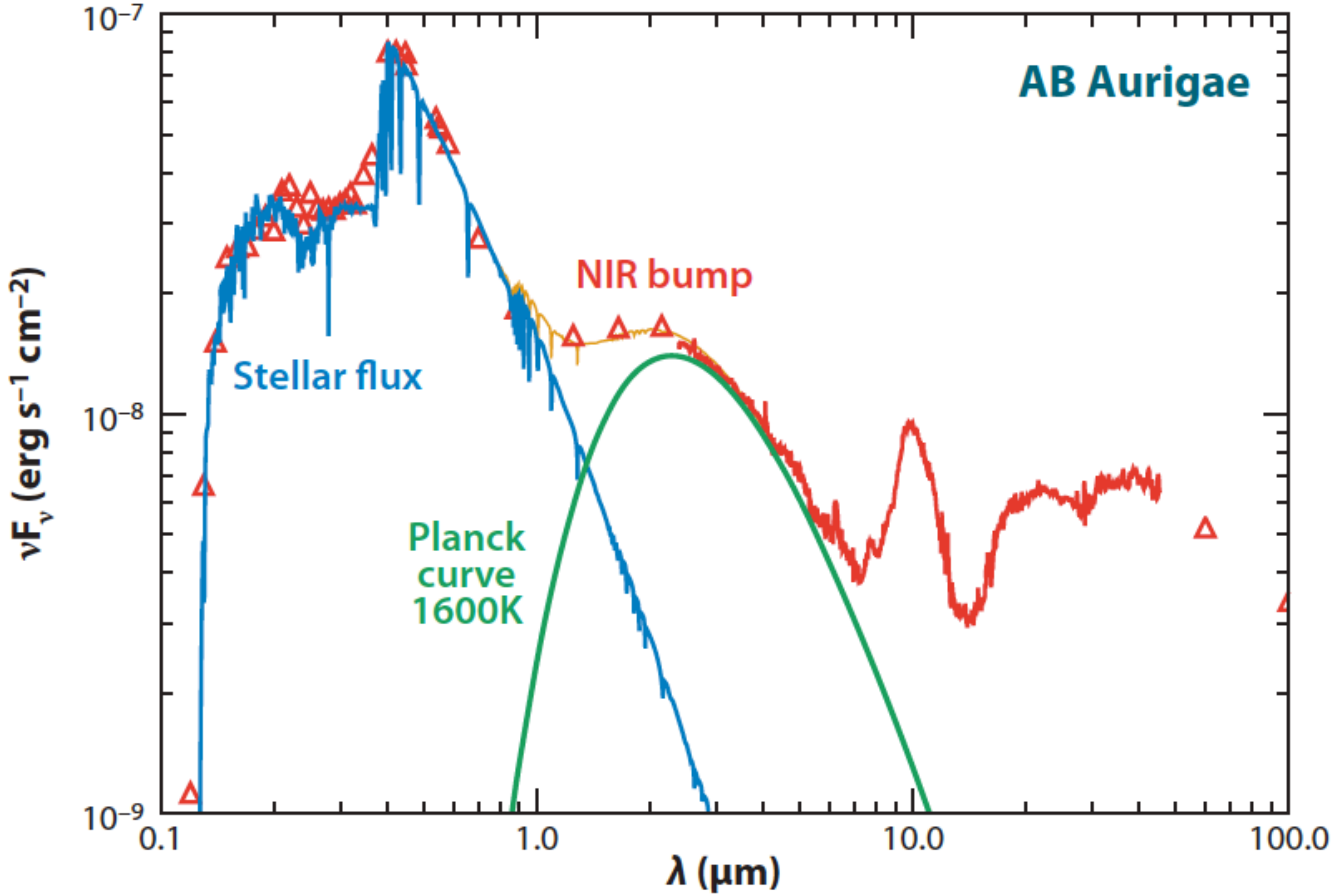
Inner disk

1. Intro
2. NIR bump – what is it?
3. Models of the inner dust rim
4. Physics of gas inward of the dust rim
5. Gas line observations

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

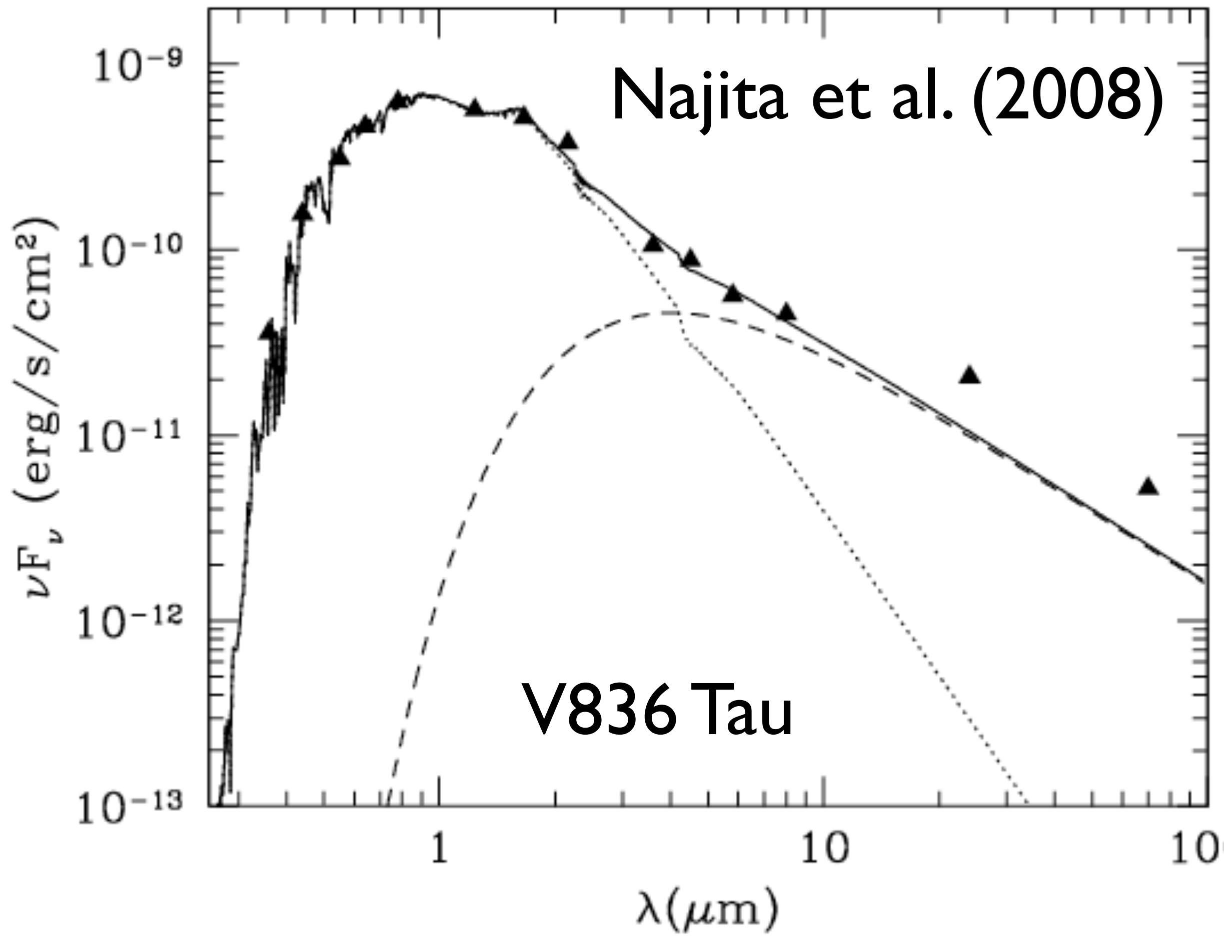
NIR bump

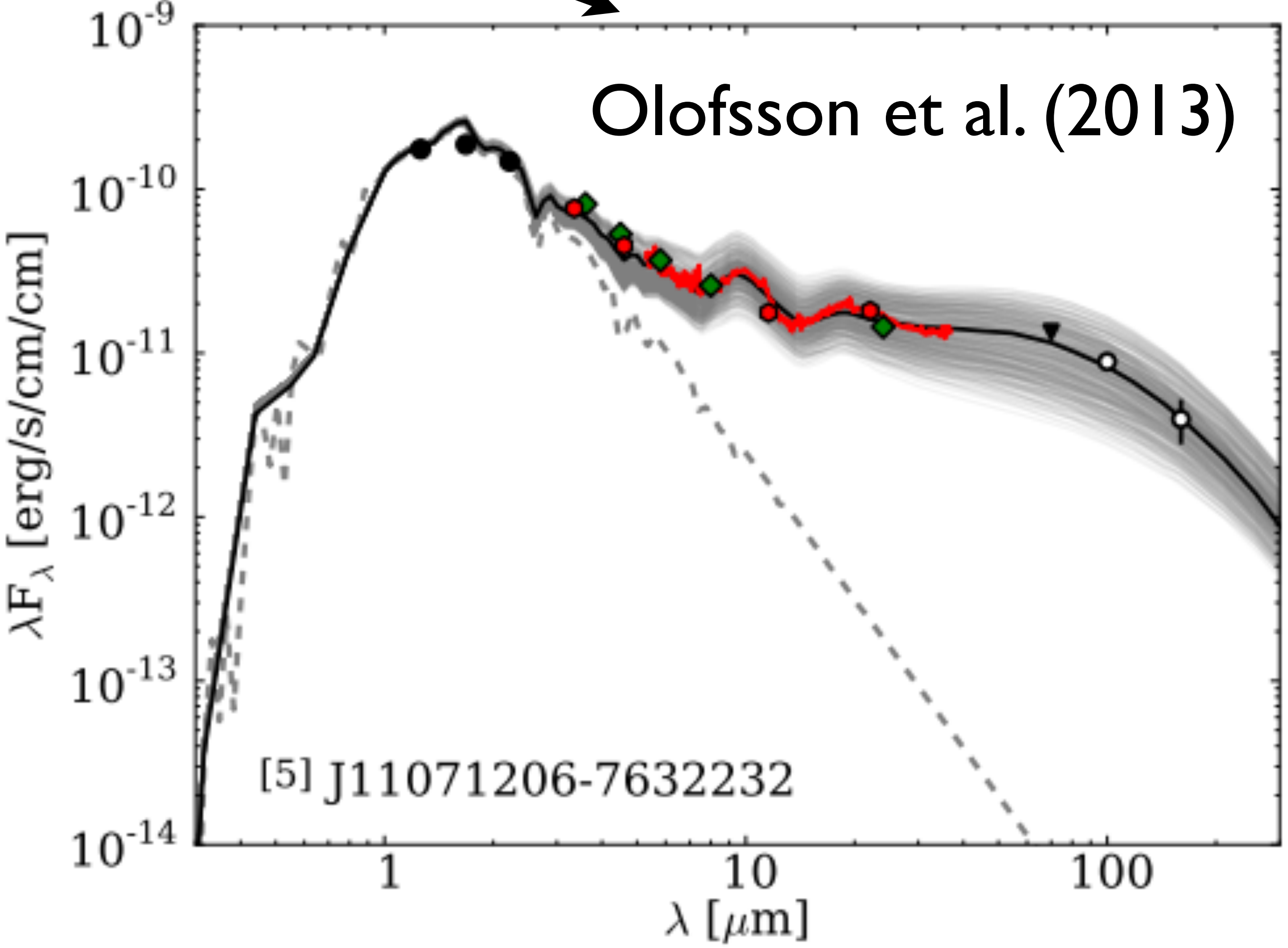


AB Aurigae
NIR bump
Stellar flux
Planck curve 1600K
νF_ν (erg s^{-1} cm^{-2})
10^{-7}
10^{-8}
10^{-9}
0.1
1.0
10.0
100.0
λ (μm)

NIR bump

- Herbig Ae/Be stars often show a NIR bump
- JHKL line up to form a ~1500 K blackbody
- Unexpected for a flat or flared disk SED


Najita et al. (2008)


Olofsson et al. (2013)

NIR bump

- Not a small feature: can contain half the IR flux of the system
- Systematic study of the NIR bump: Hillenbrand et al. (1992); their interpretation: hot emission from an accretion disk
- Problems:
    - inner radius had to be ~ 0.1 au (large inner hole inward of which there is no emission at all)
    - large accretion rate (10^{-5} $M_\odot$/yr)
    - where does the material go after is passes through the inner edge?

Accretion disk interpretation

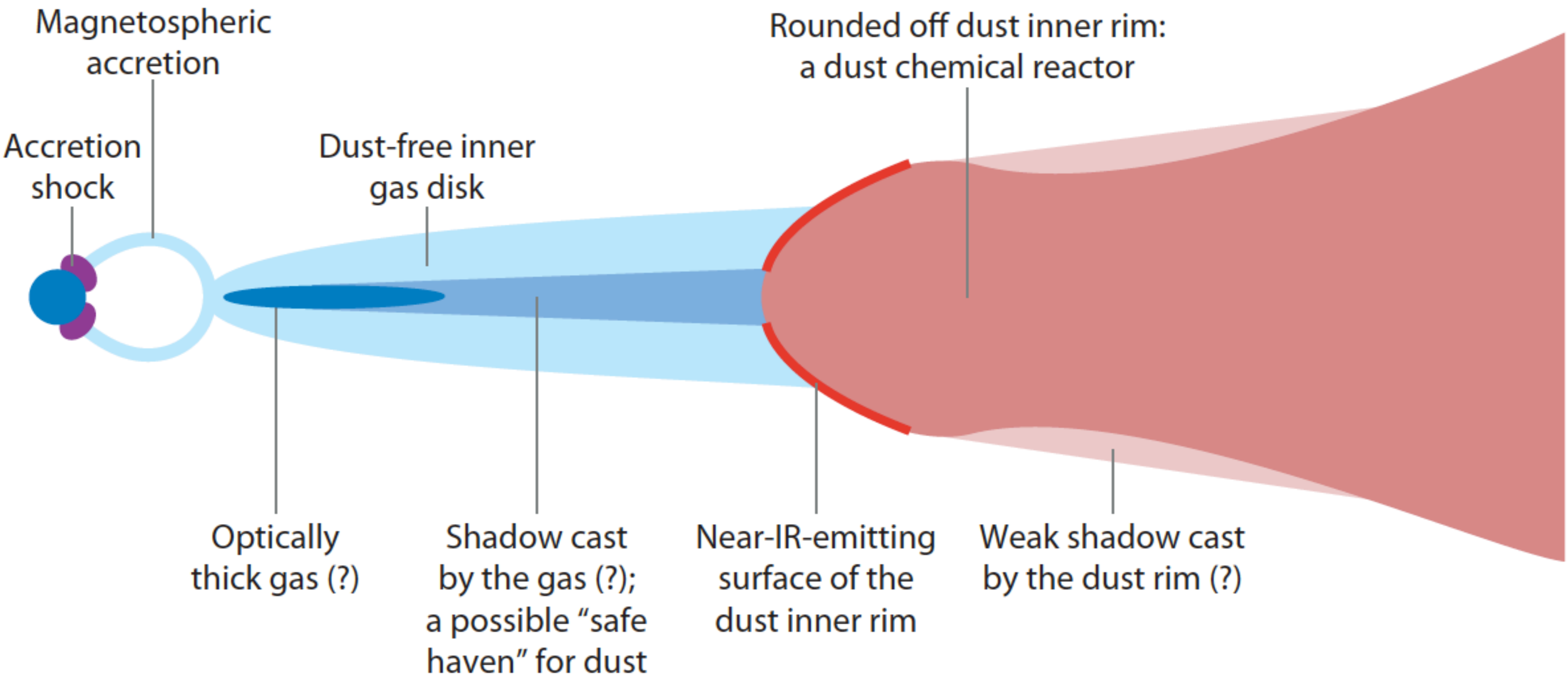
- If the material continues inward, release of energy would create hotter emission → no NIR bump
- If magnetospheric accretion: material that crashes into the star would create strong UV excess → not observed
- We can rule out the accretion disk as the only explanation for the NIR bump

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):

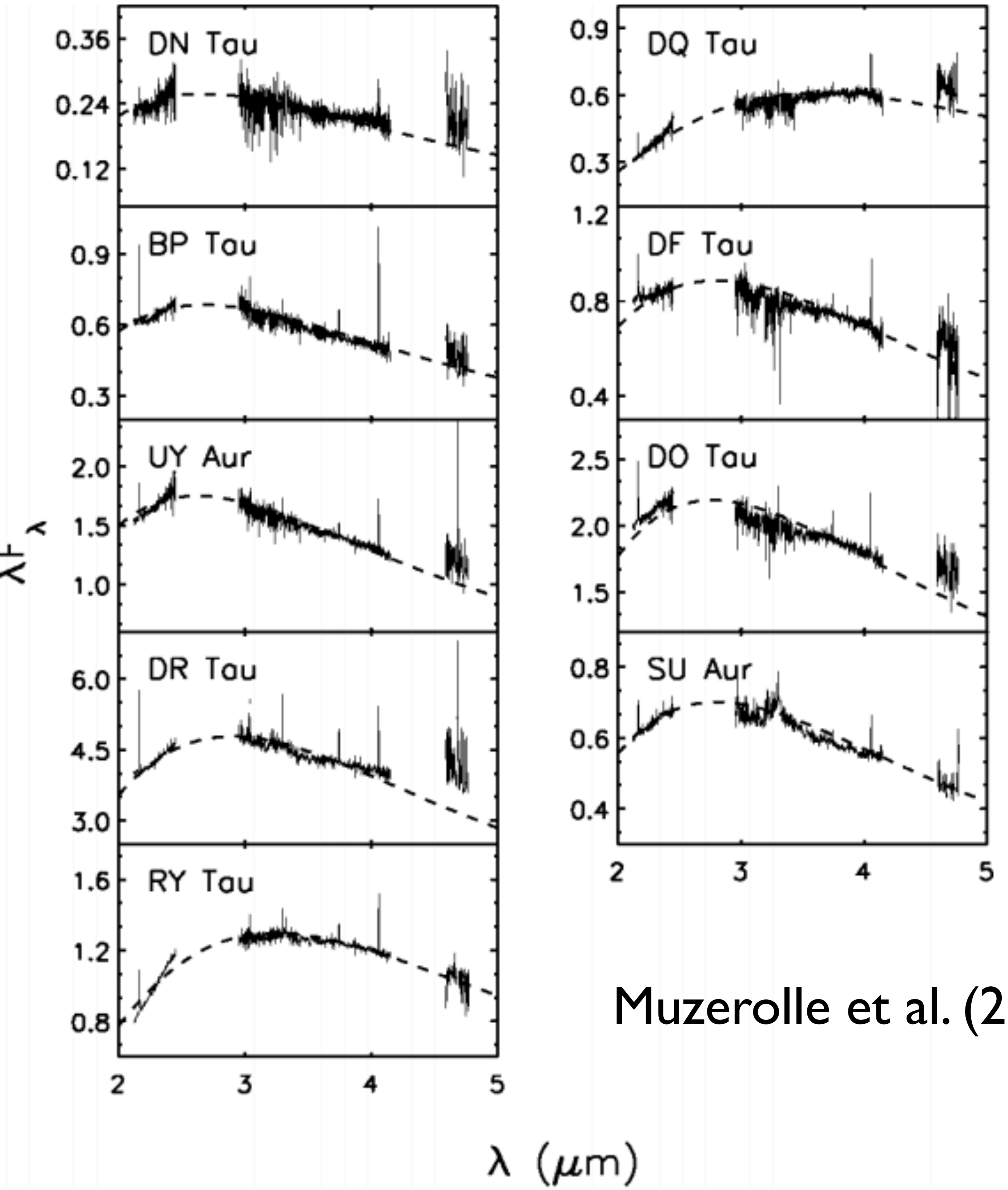


Inner dust wall naturally explains the NIR bump

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 Tauris

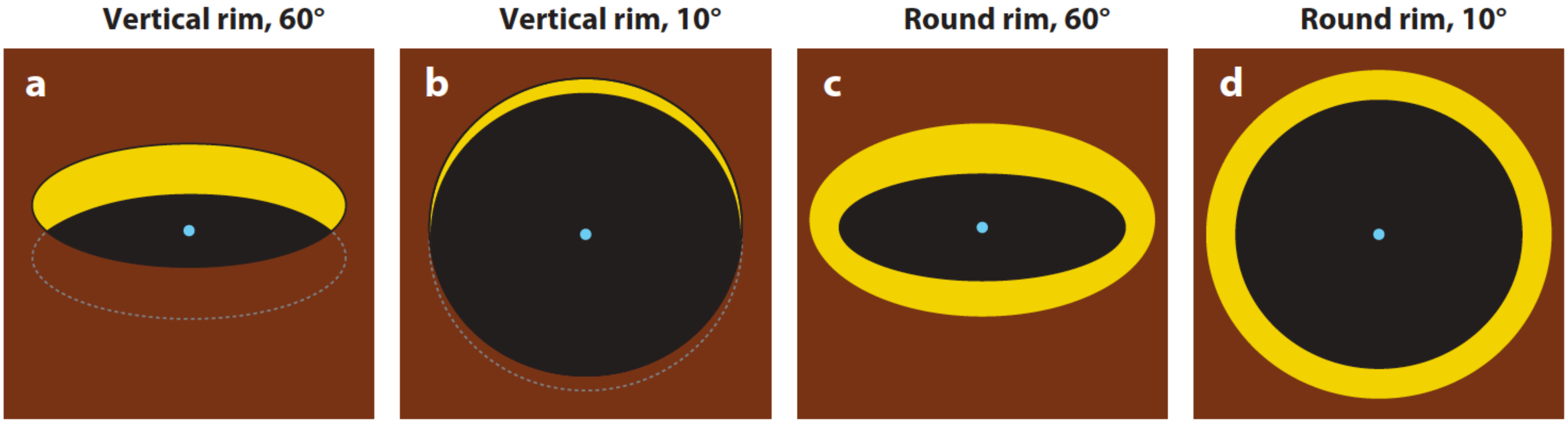


Stellar photosphere-subtracted SEDs

Muzerolle et al. (2003)

Dust rim: unique solution?

- Only a few NIR photometric points are not enough
- Spherically symmetric envelope models, with no dust within the dust evaporation radius can also reproduce the NIR bump
- No clear correlation between the NIR flux and the disk inclination also supports the envelope model

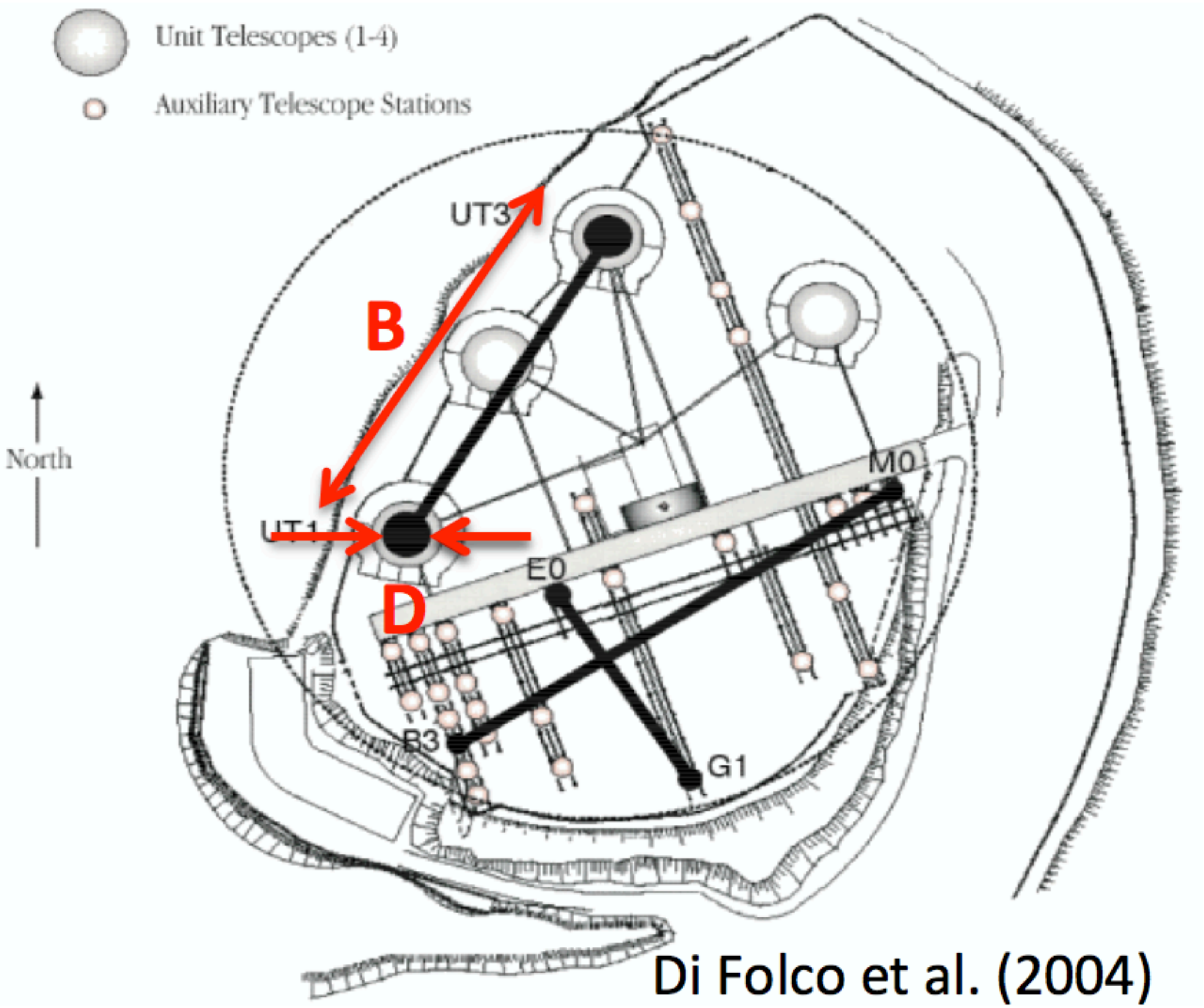


Dust rim: unique solution?

- Clearest counter-example: AB Aur: almost face-on, but has a huge NIR bump
- Solution: spatially resolve the NIR emission
- Difficult: 1 au ↔ 7 mas (at the distance of Taurus)
- Needs NIR interferometry

NIR interferometry

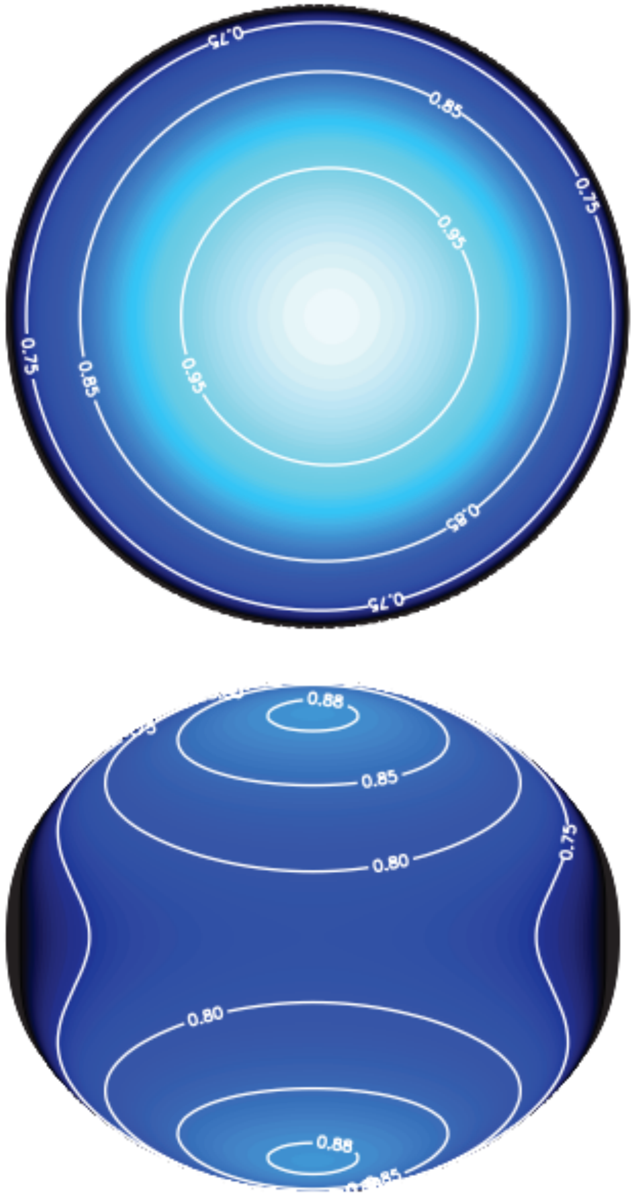
- Resolving power: λ/B (radian)
- λ: observing wavelength
- B: projected baseline
- E.g. λ = 2 μm, B = 100 m ⟹ resolution: 2×10^{-8} rad = 4 mas ⟺ 0.6 au (@ 150 pc)



Di Folco et al. (2004)

NIR interferometry

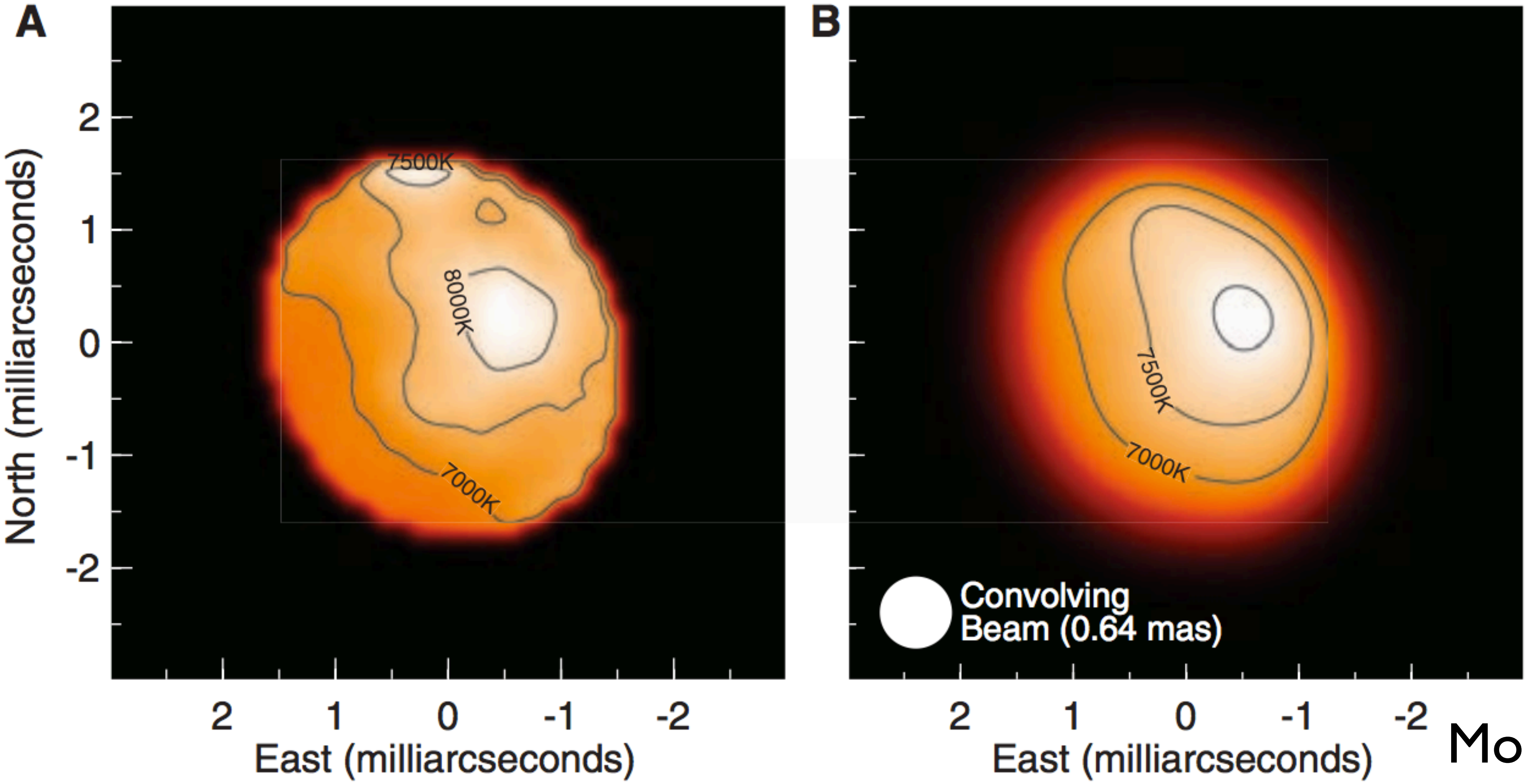
- Challenging: so far only 2 telescope (one baseline) or 3 telescopes (three baselines) could be joined
- Past NIR interferometers: Palomar Testbed Interferometer (PTI), Keck Interferometer; Infrared Optical Telescope Array (IOTA); Infrared Spatial Interferometer (ISI); Cambridge Optical Aperture Synthesis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



Vega (Aufdenberg et al. 2006)

NIR interferometry

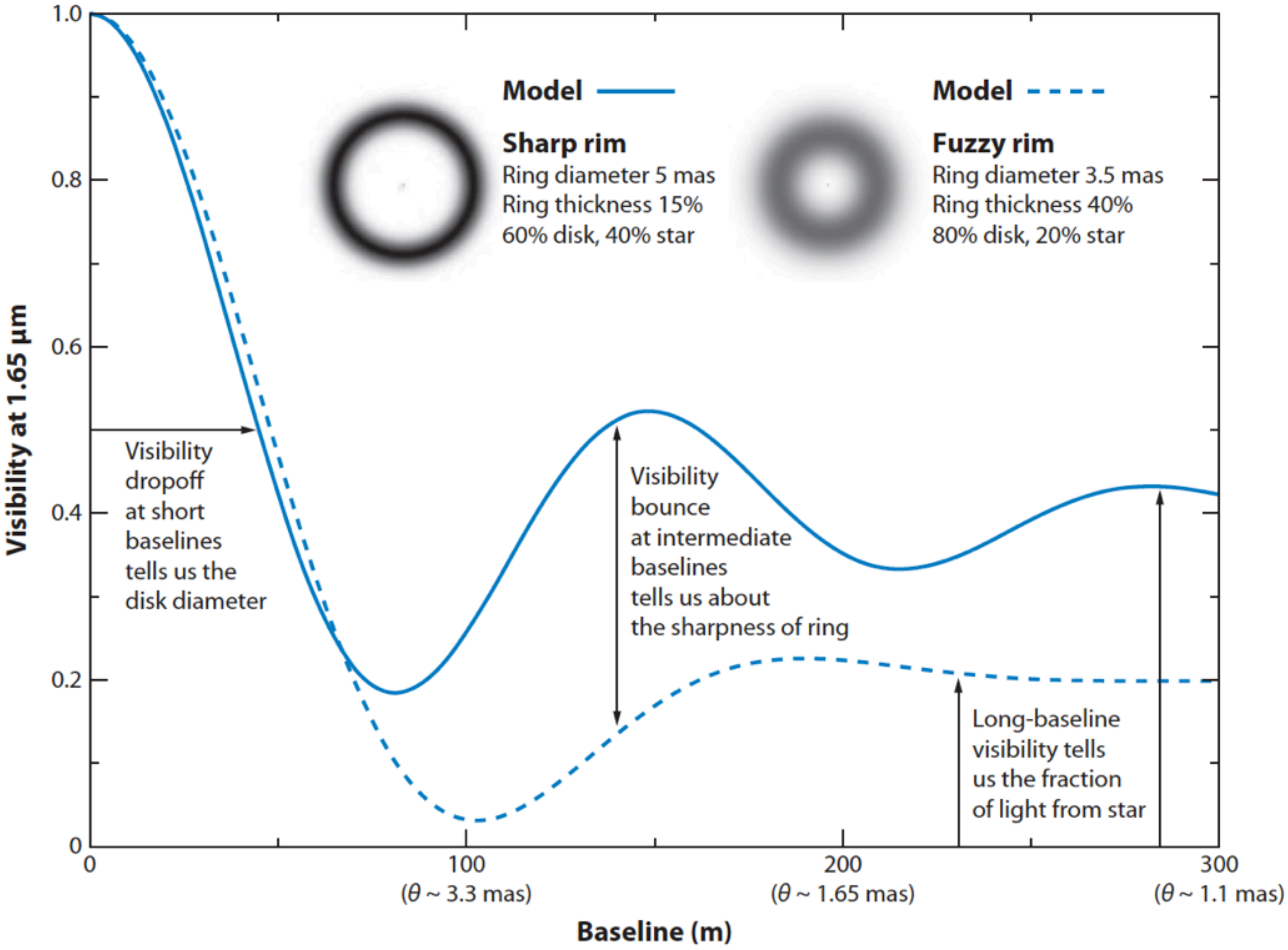
- In most cases NIR interferometry does not provide images, model fitting is required to interpret the visibilities
- Few exceptions: Vega, Altair (bright stellar disks)



Monnier et al. (2007)

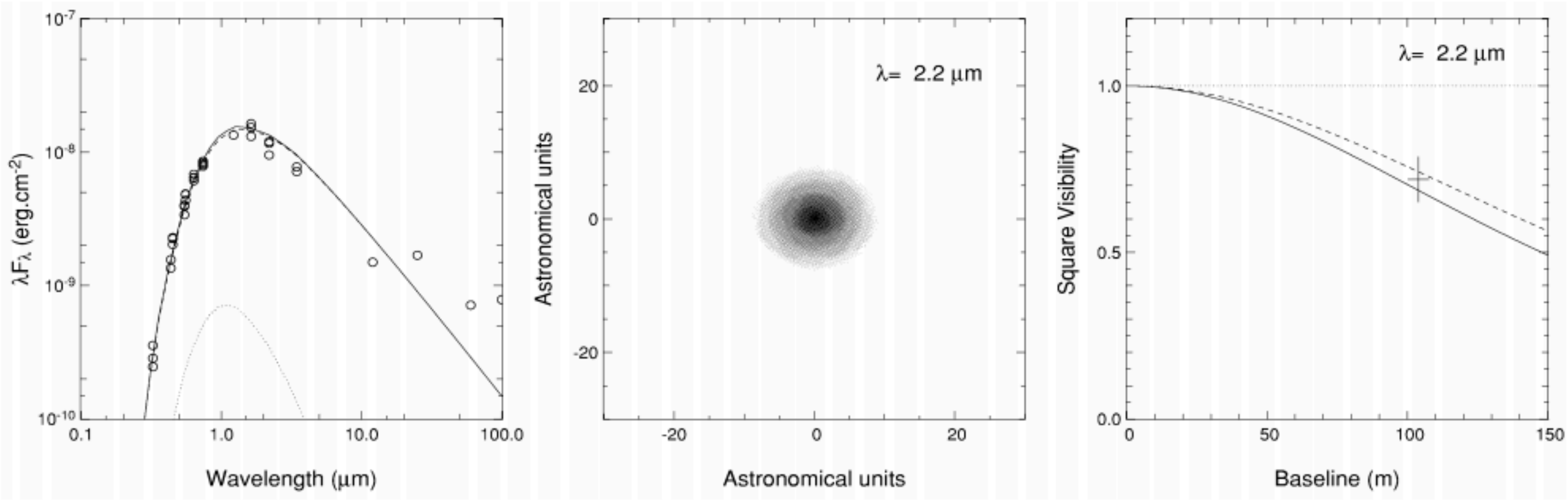
NIR interferometry

Interpretation of interferometric observations:



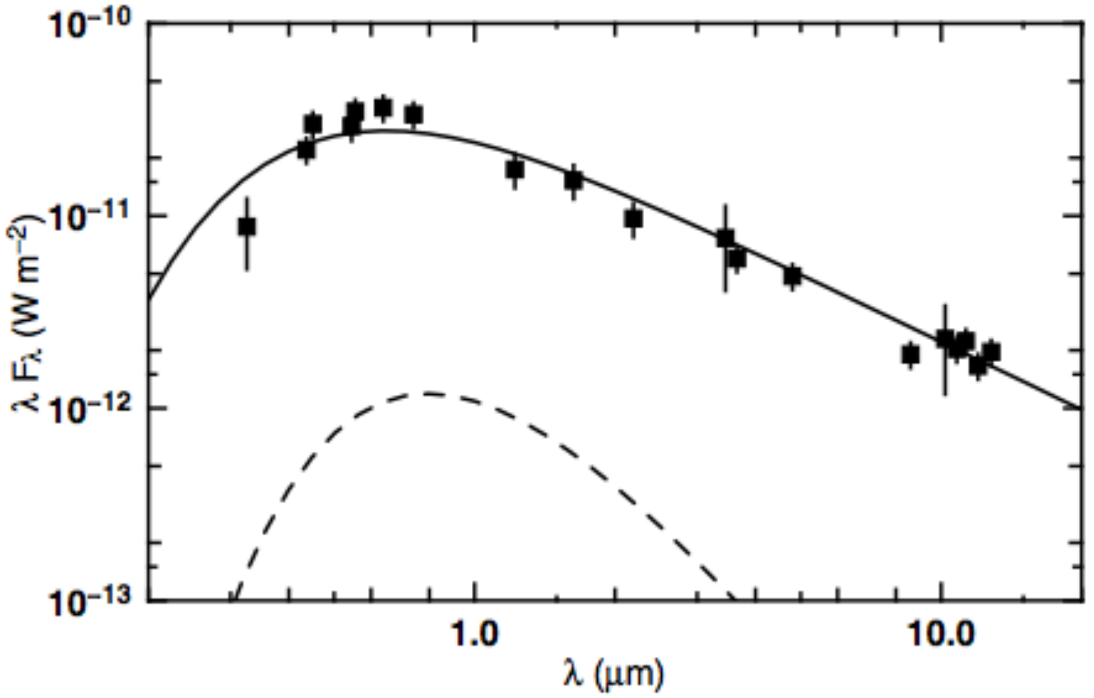
First young star targeted

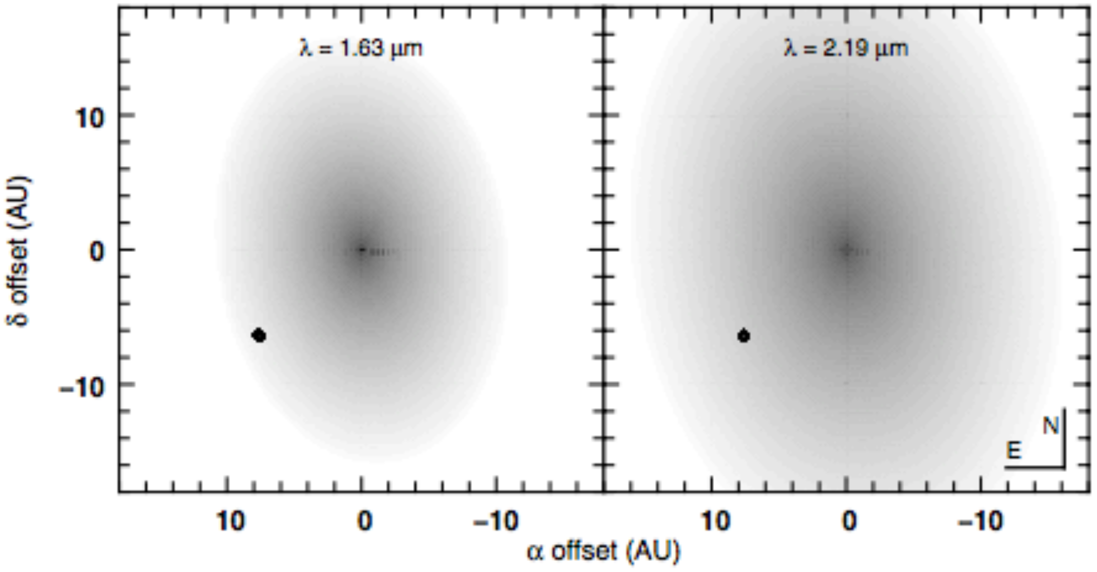
- FU Orionis (PTI, Malbet et al. 1998)
- Accretion rate: $10^{-4}\ M_\odot/\mathrm{yr}$ → very bright disk

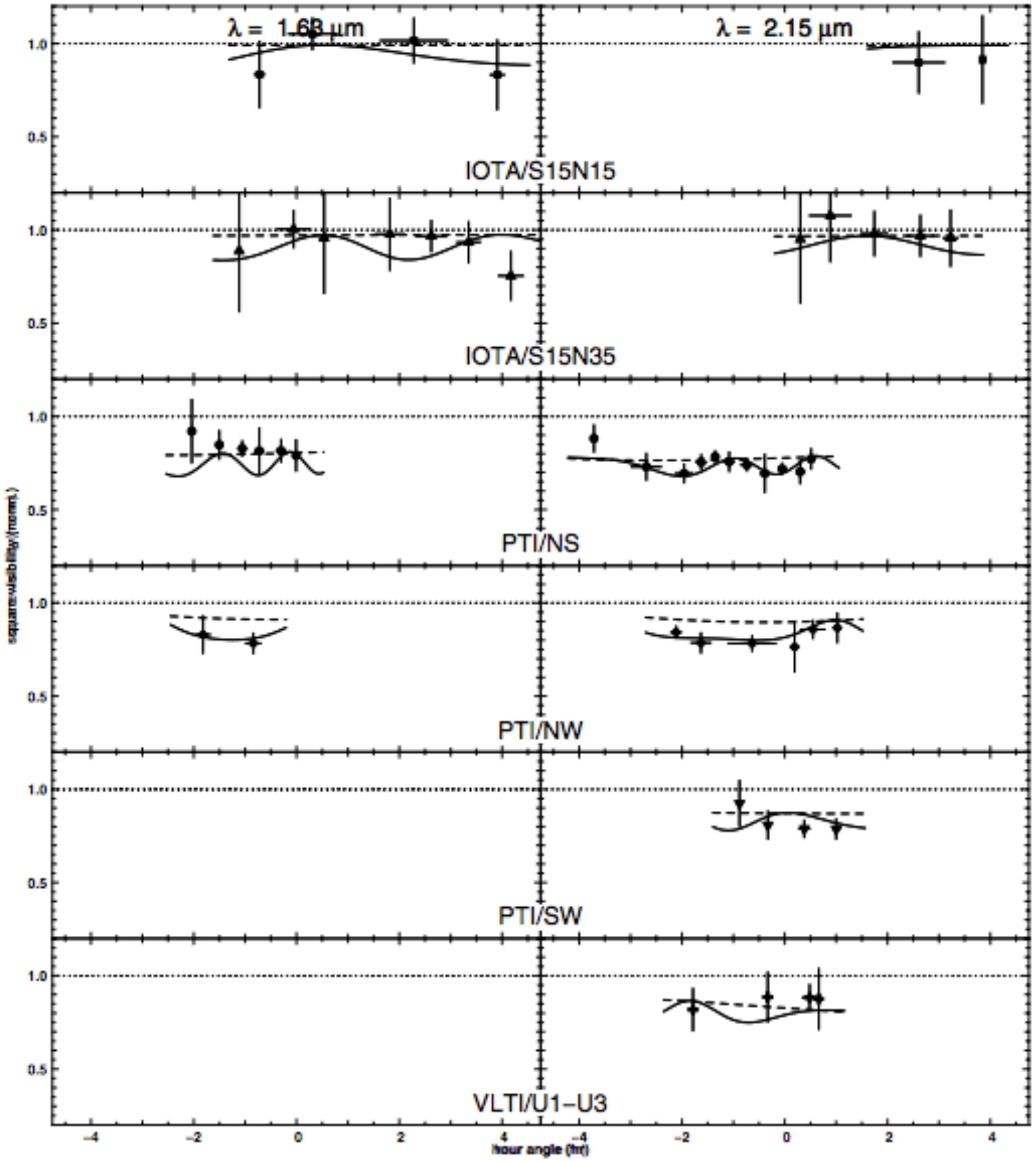


First young star targeted

- FU Orionis (Malbet et al. 2005)

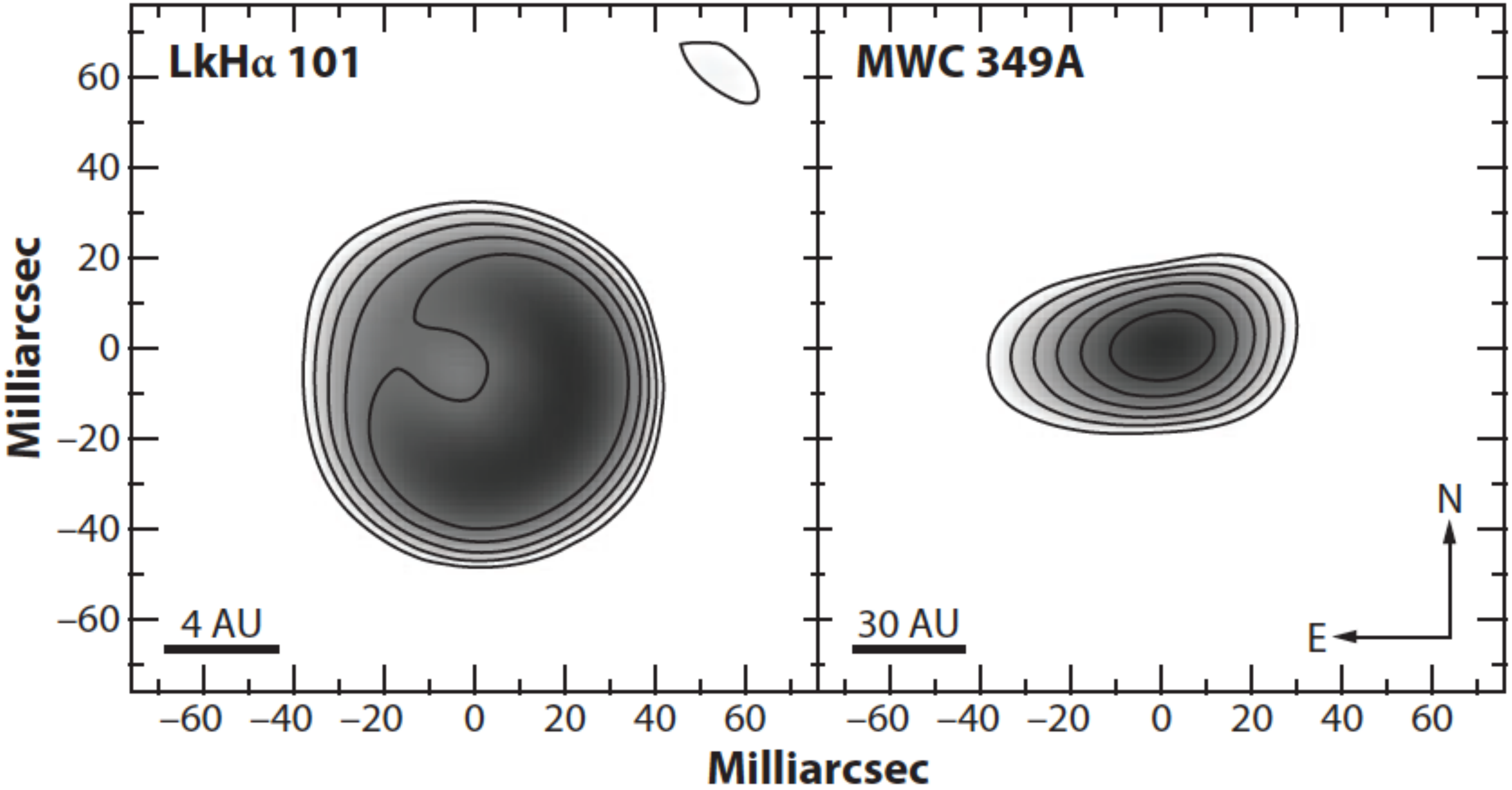






Herbig disks

- Aperture masking interferometry



Contours (% of peak): 1.6, 3.1, 6.2, 12.5, 25, 50

Tuthill, Monnier & Danchi (2001)   Danchi, Tuthill & Monnier (2001)

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
- $R_{rim} \sim L_*^{1/2}$

Size-luminosity diagram