Observational appearance of Protoplanetary Disks

Review Talk

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Main features of a protoplanetary disk

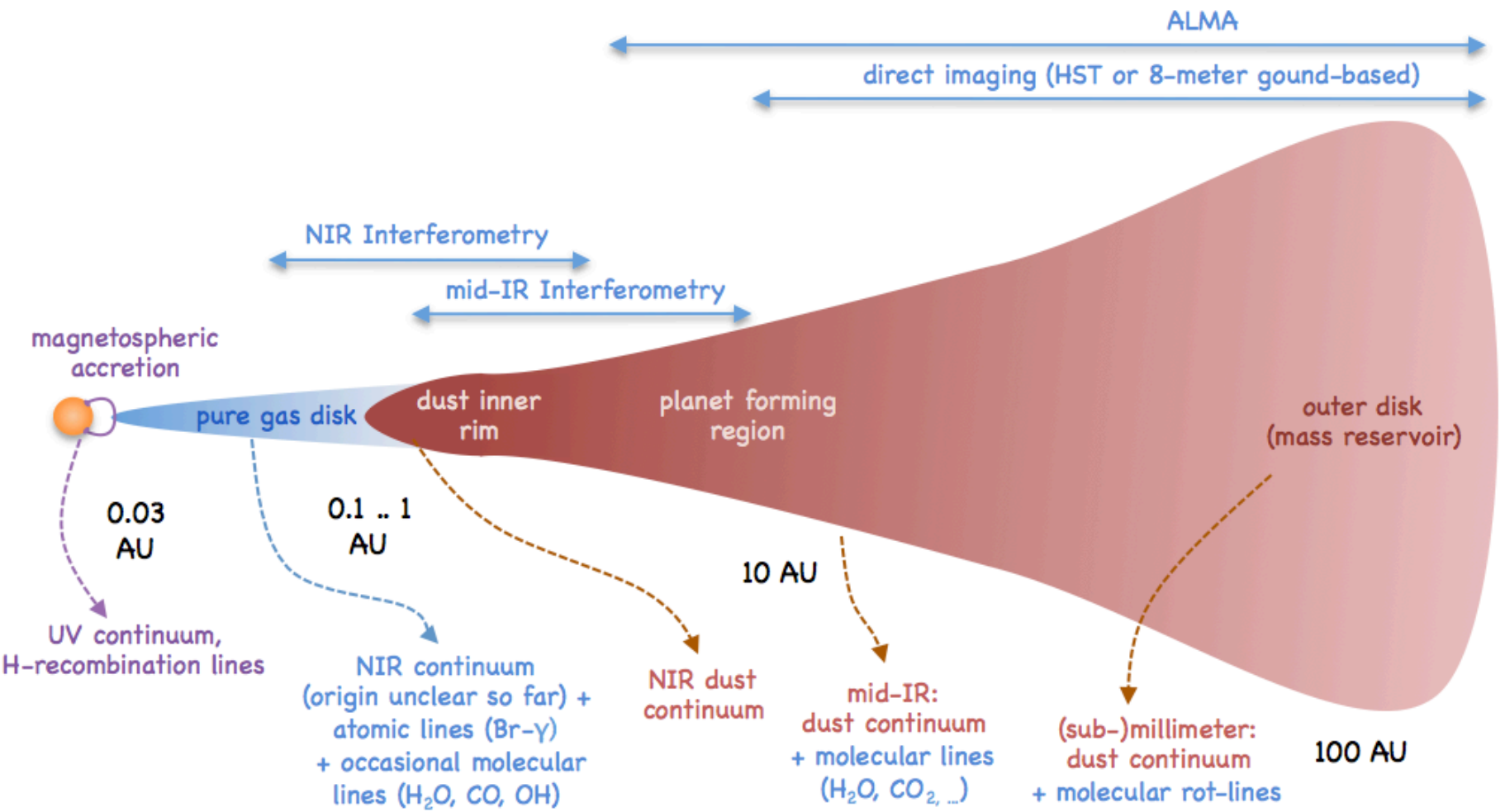
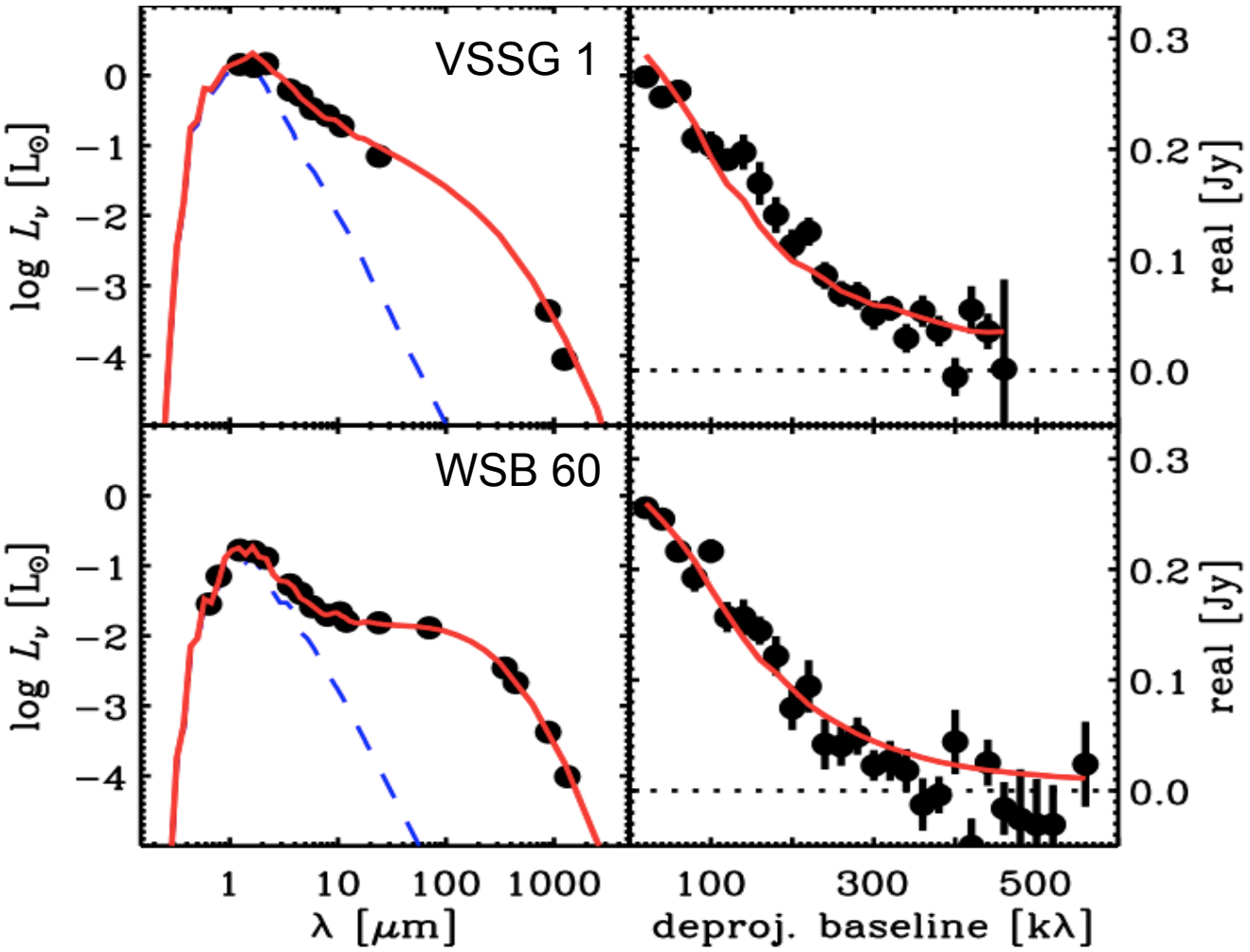


Figure from: Dullemond & Monnier (2010) Ann. Rev. A&A

Radial distribution of matter

SED fitting

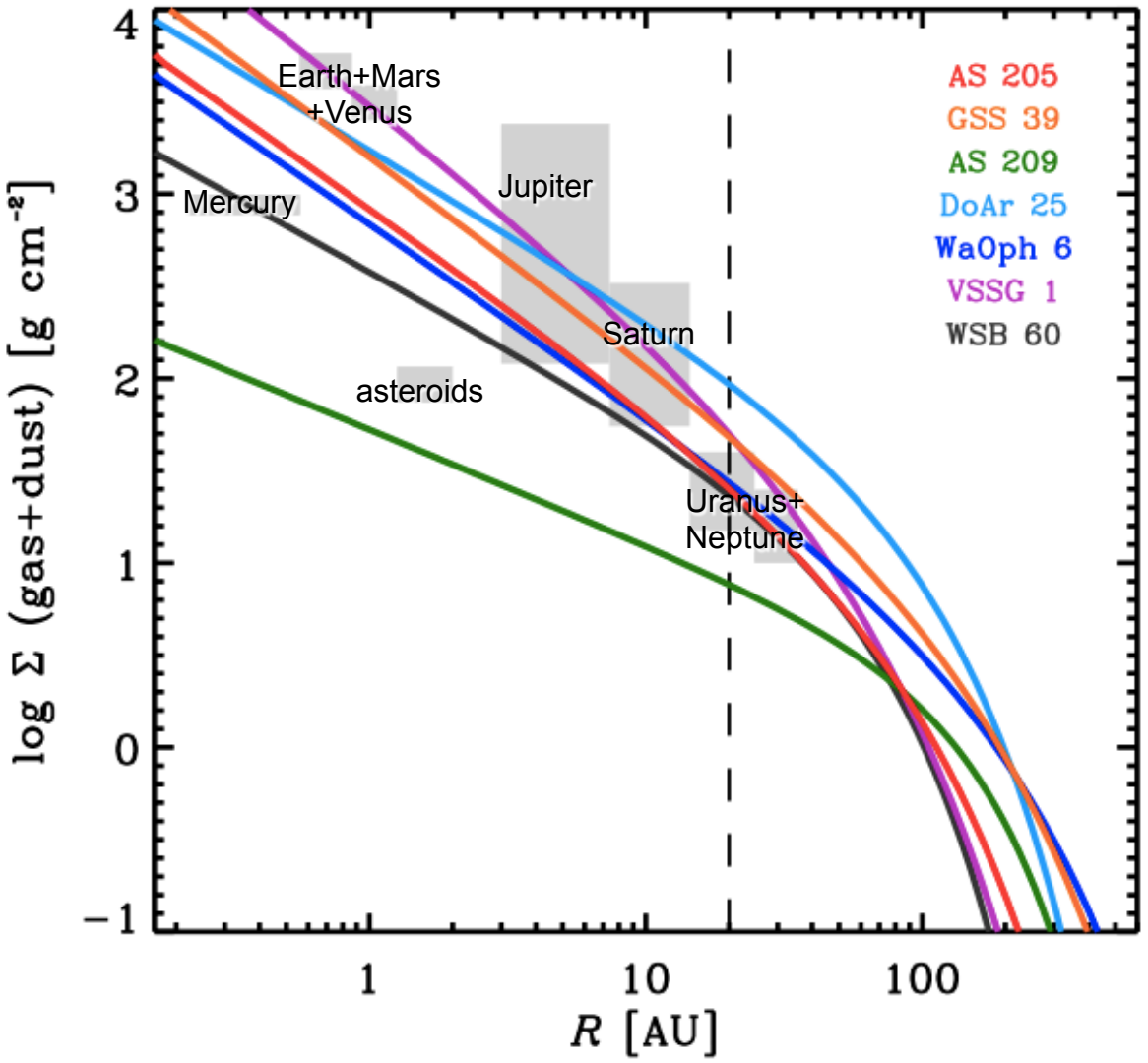
mm-interferometry (visibility fitting)



SED + millimeter resolved maps (=visibility values)

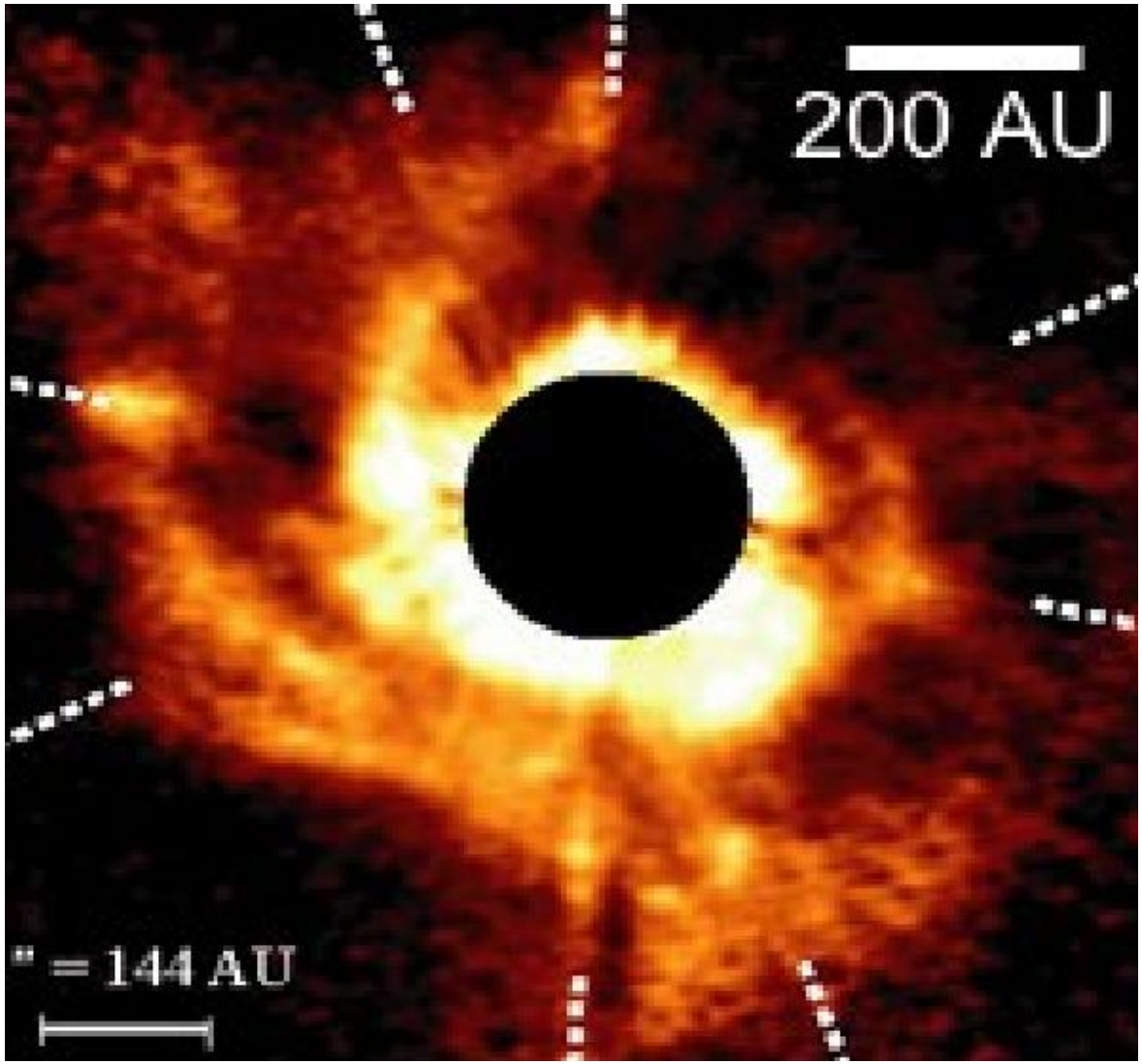
Andrews et al. (2009)

Radial distribution of matter



Andrews et al. (2009)

However: disks are not axially symmetric...

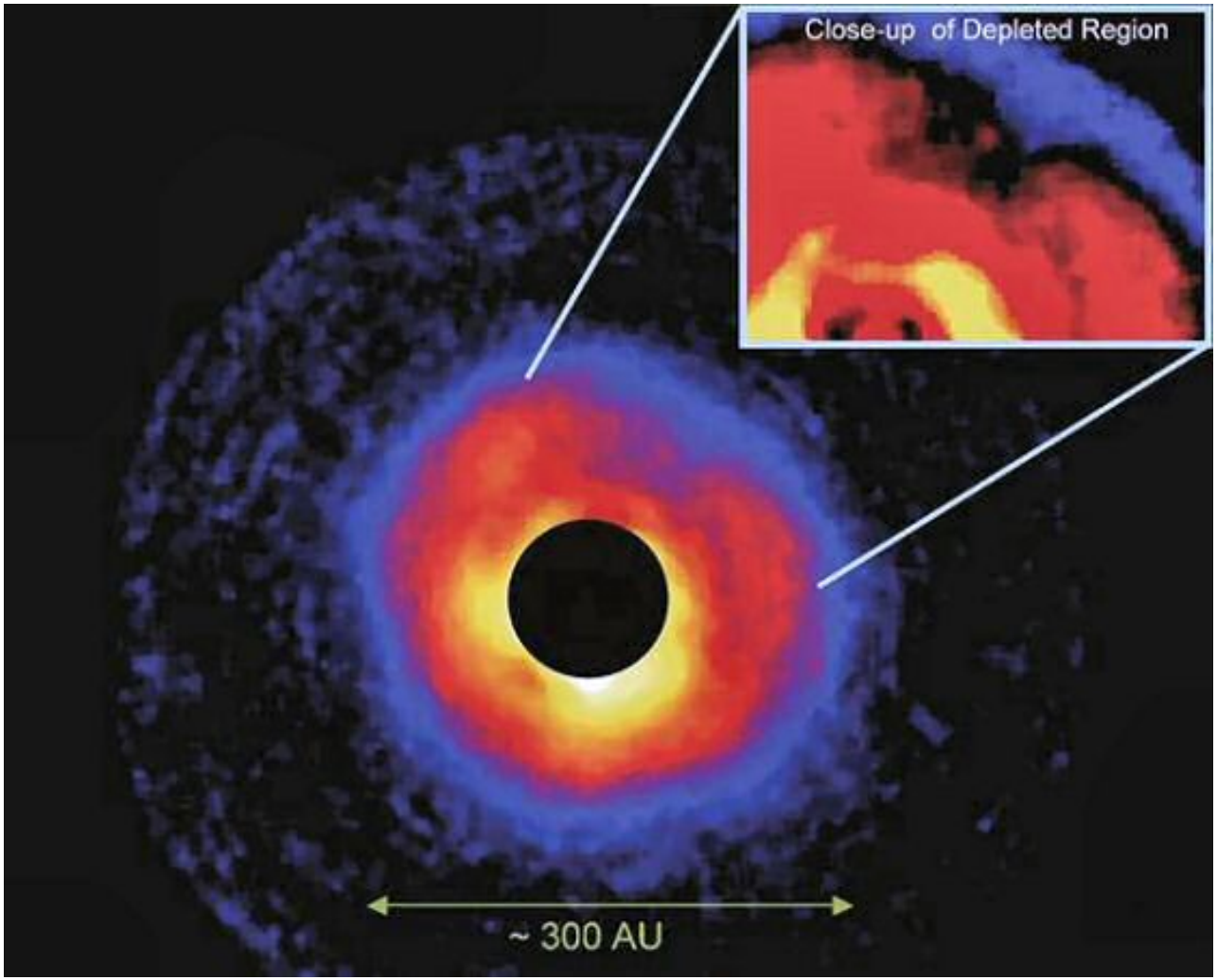


AB Aurigae

Scattered light

Fukagawa et al. 2004

However: disks are not axially symmetric...



AB Aurigae

Scattered light, polarized component

Oppenheimer et al. 2008

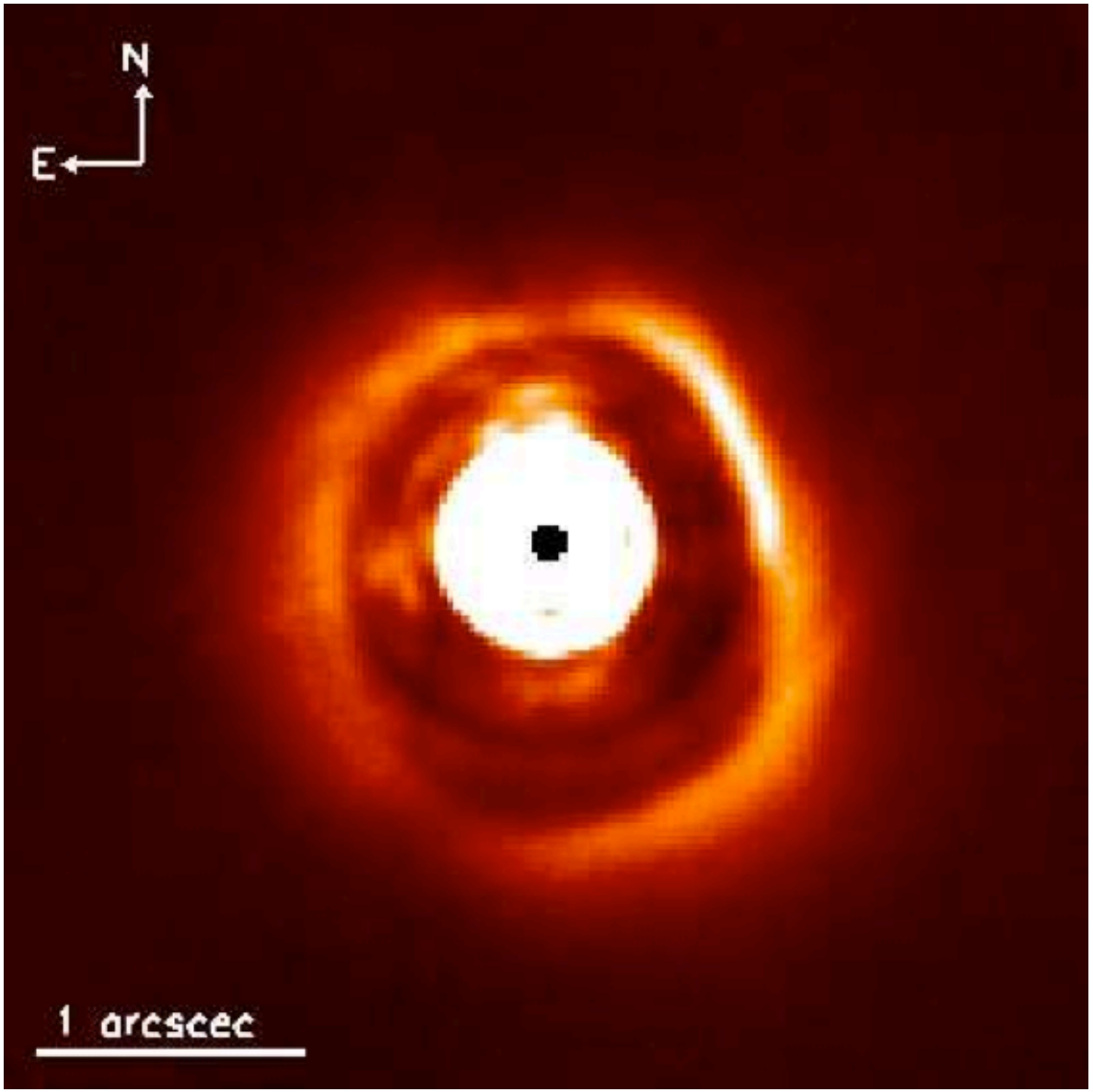
However: disks are not axially symmetric...

HD 142527

A transition disk
with a huge ring.

Here seen in
scattered light
with the VLT/NACO

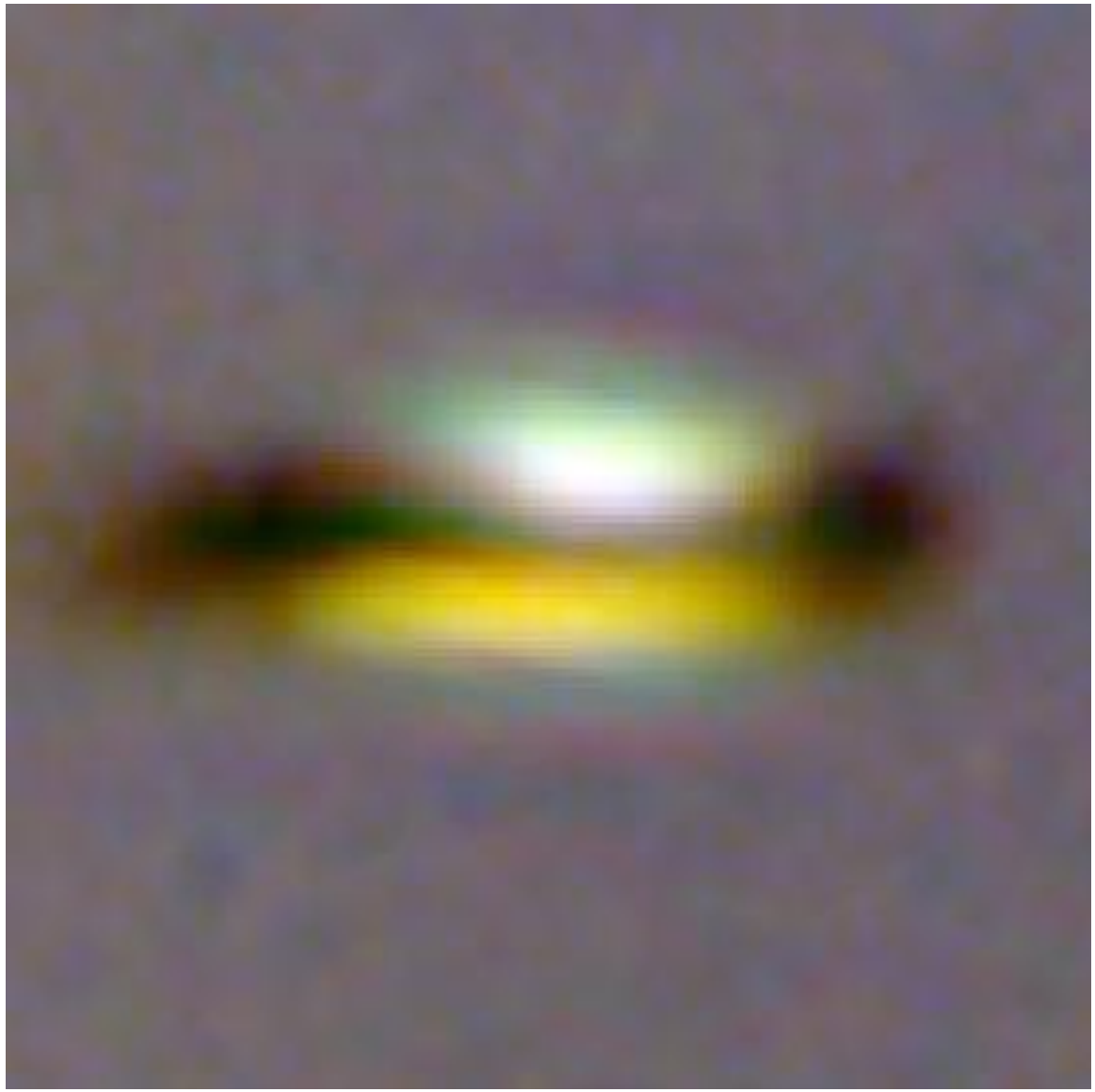
Keep an eye open for
the ALMA image to be
published soon!



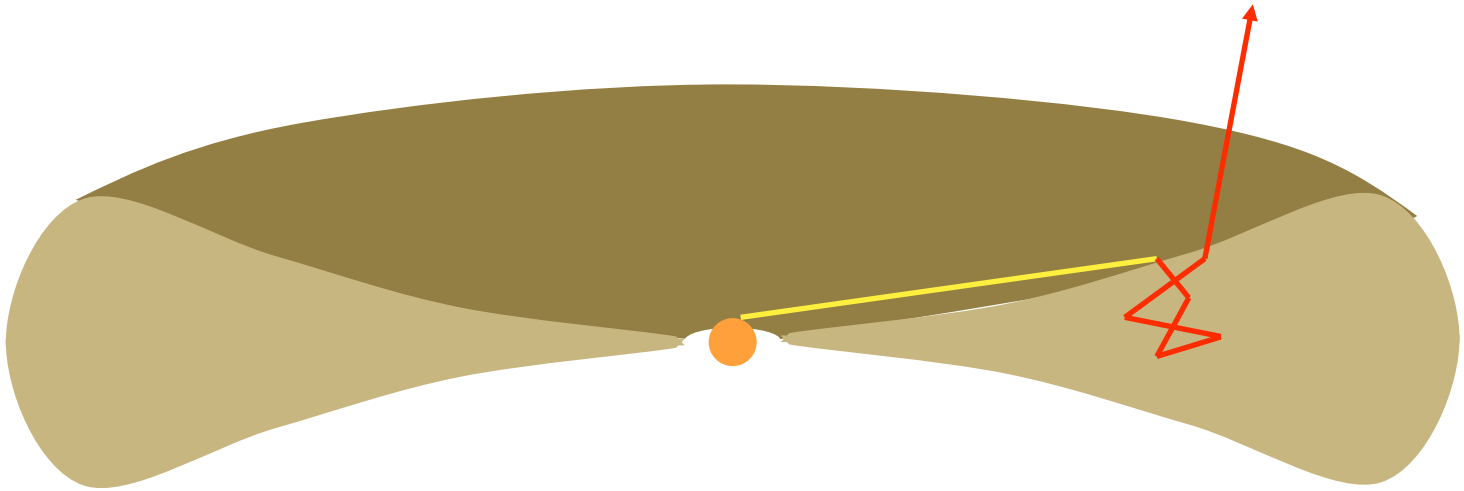
Rameau et al. 2012

Vertical structure of a protoplanetary disk

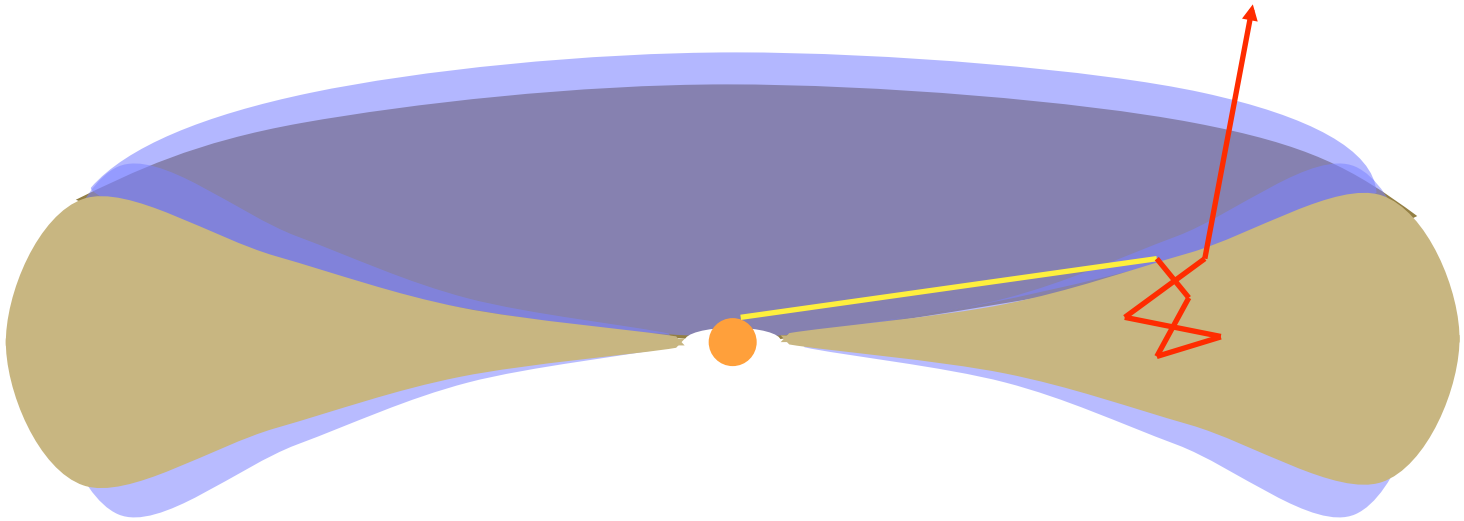
Still one of the nicest disk images:



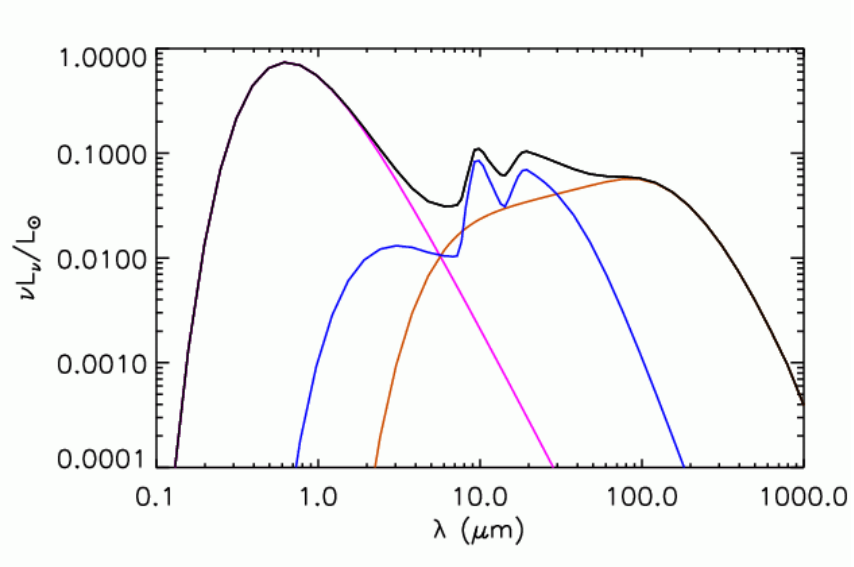
Flaring disk structure: irradiation



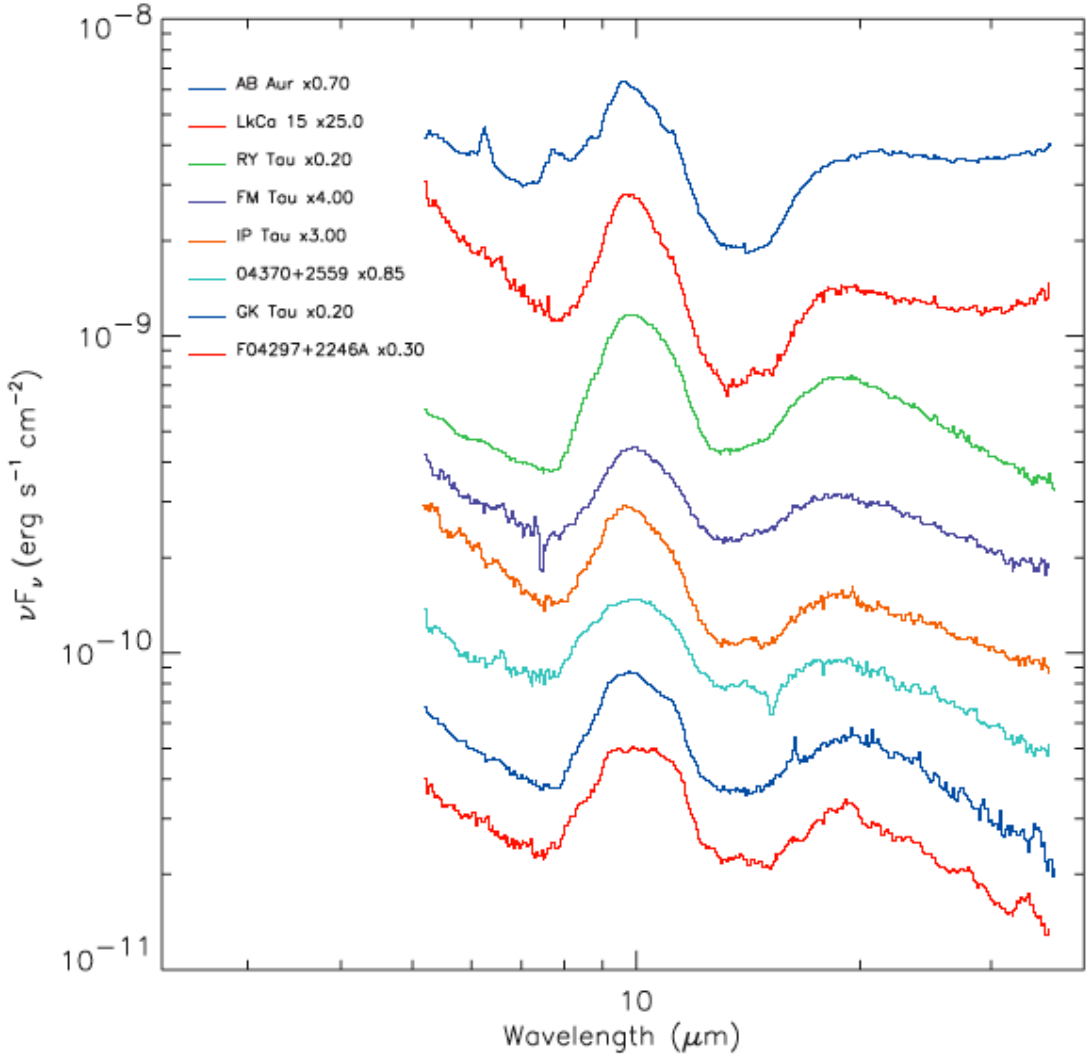
Creation of a warm surface layer



Calvet et al. 1991
Malbet & Bertout 1991
Chiang & Goldreich 1997



T Tauri Star SEDs:

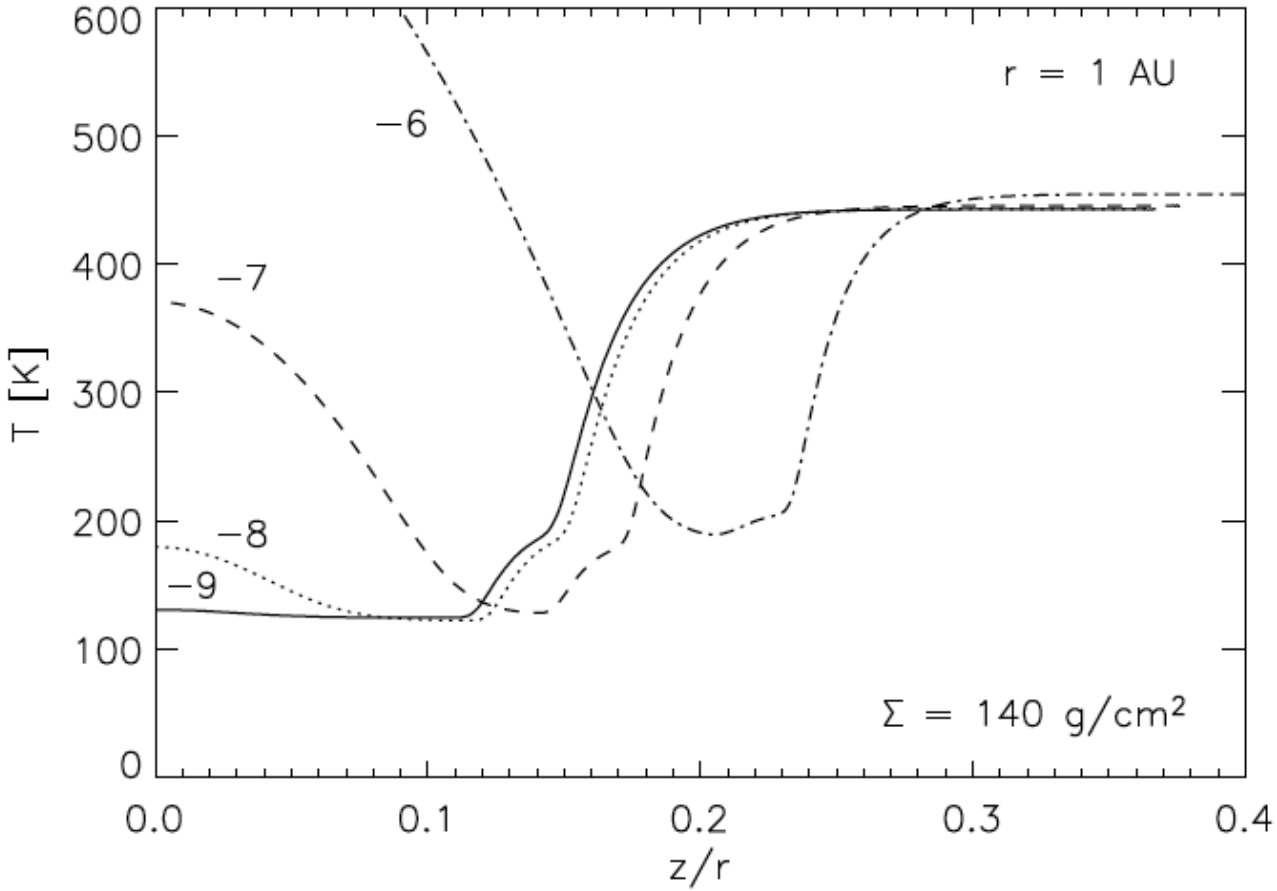


Furlan et al. 2006

Spitzer IRS spectra of large sample of class II sources.

Shown here: the sources with the flattest SEDs, i.e. strongest disk flaring.

Vertical temperature structure

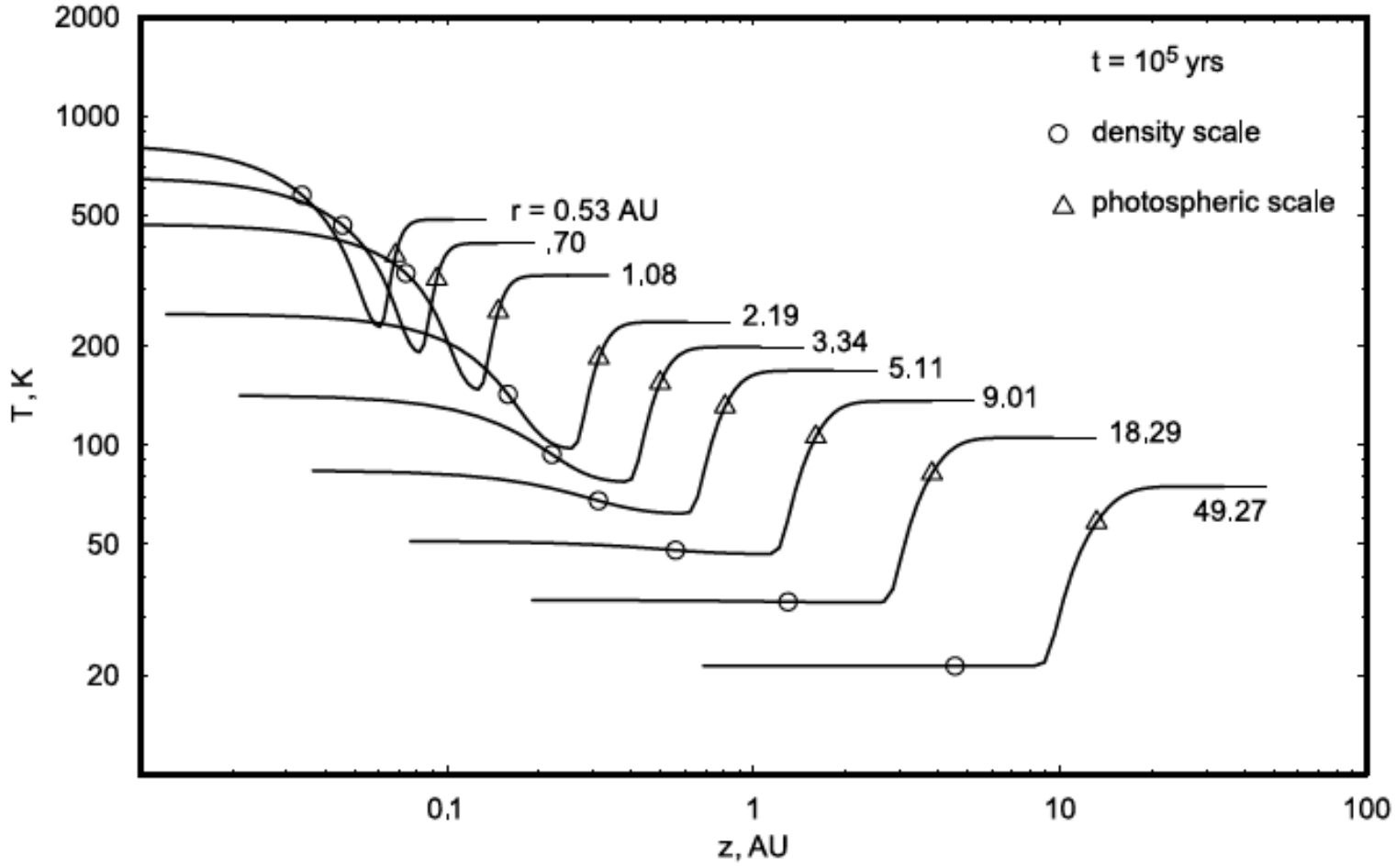


Model from Paola D'Alessio

(from: Dullemond, Hollenbach, Kamp & D'Alessio PPV review)

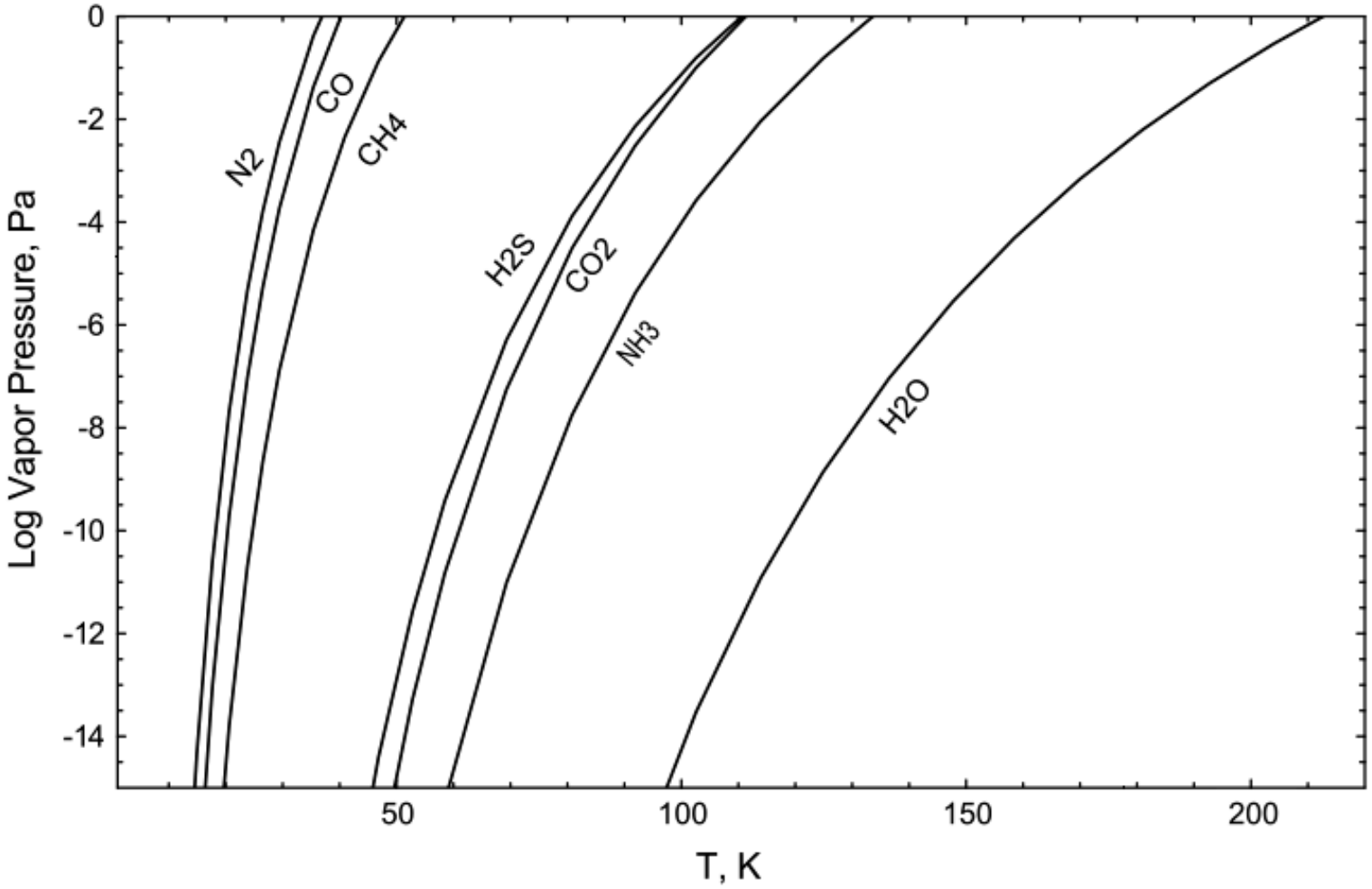
Cold midplane layers:
Ice-coated dust?
(i.e. where is the „snow line“?)

Where is the ‘snow line’?



Davis (2005)

Where is the ‘snow line’?



Davis 2005
Lecar, Podolak, Sassalov & Chiang 2006

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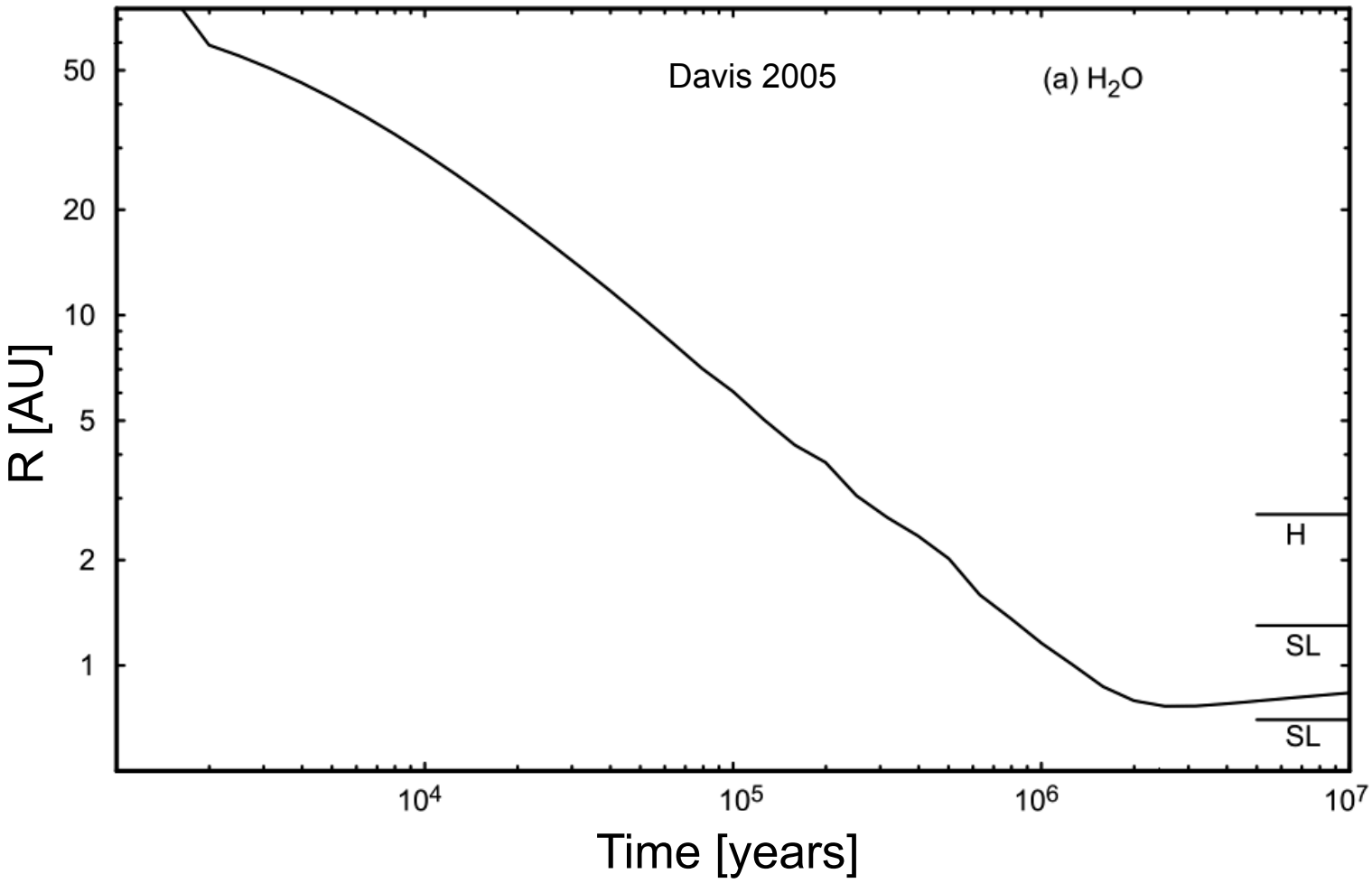
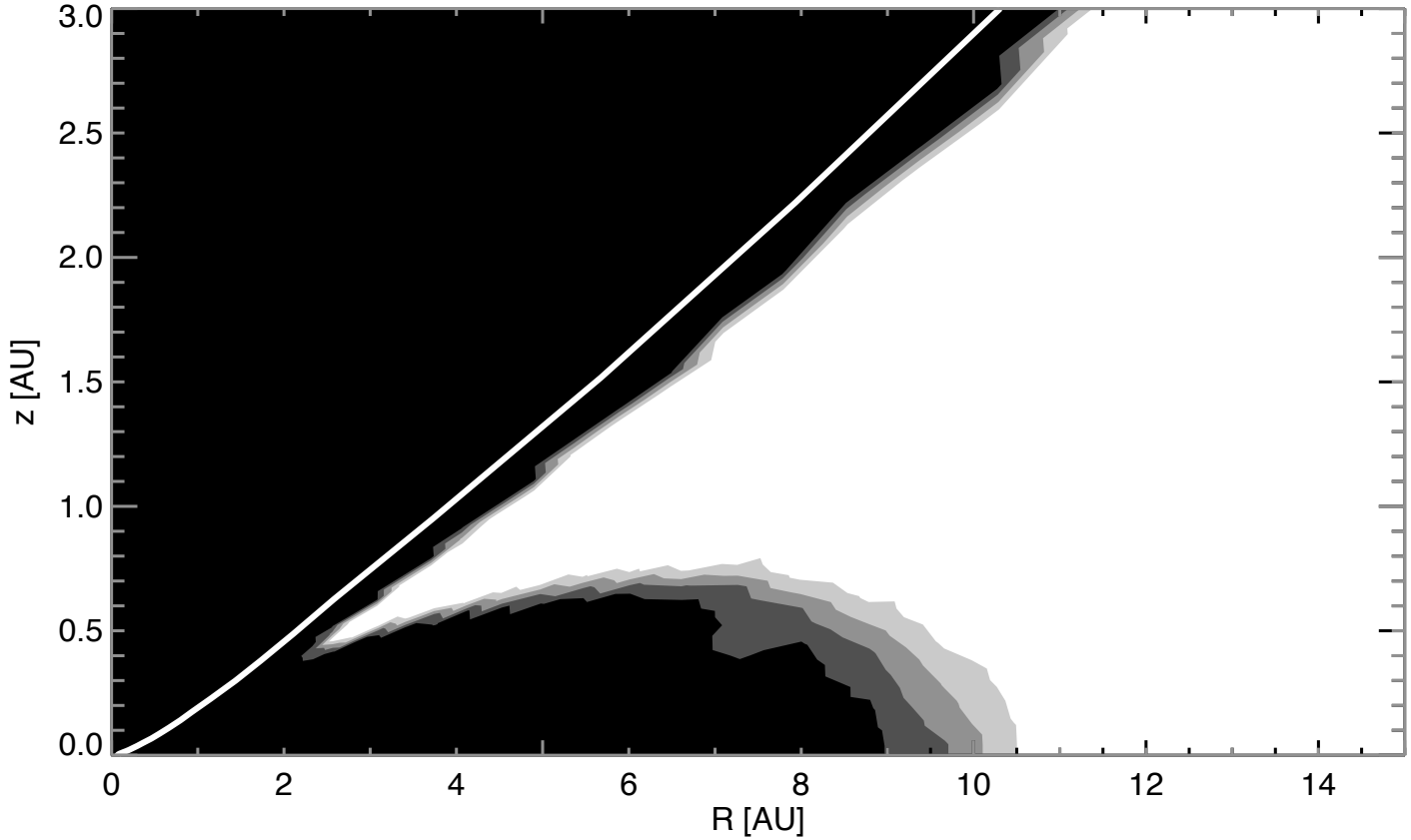


Davis 2005
Lecar, Podolak, Sassalov & Chiang 2006

Where is the ‘snow line’?

First fully 2-D/3-D radiative transfer model of snow line

$dM/dt = 10^{-7}\ M_{\odot}/yr, \qquad \alpha=0.01$

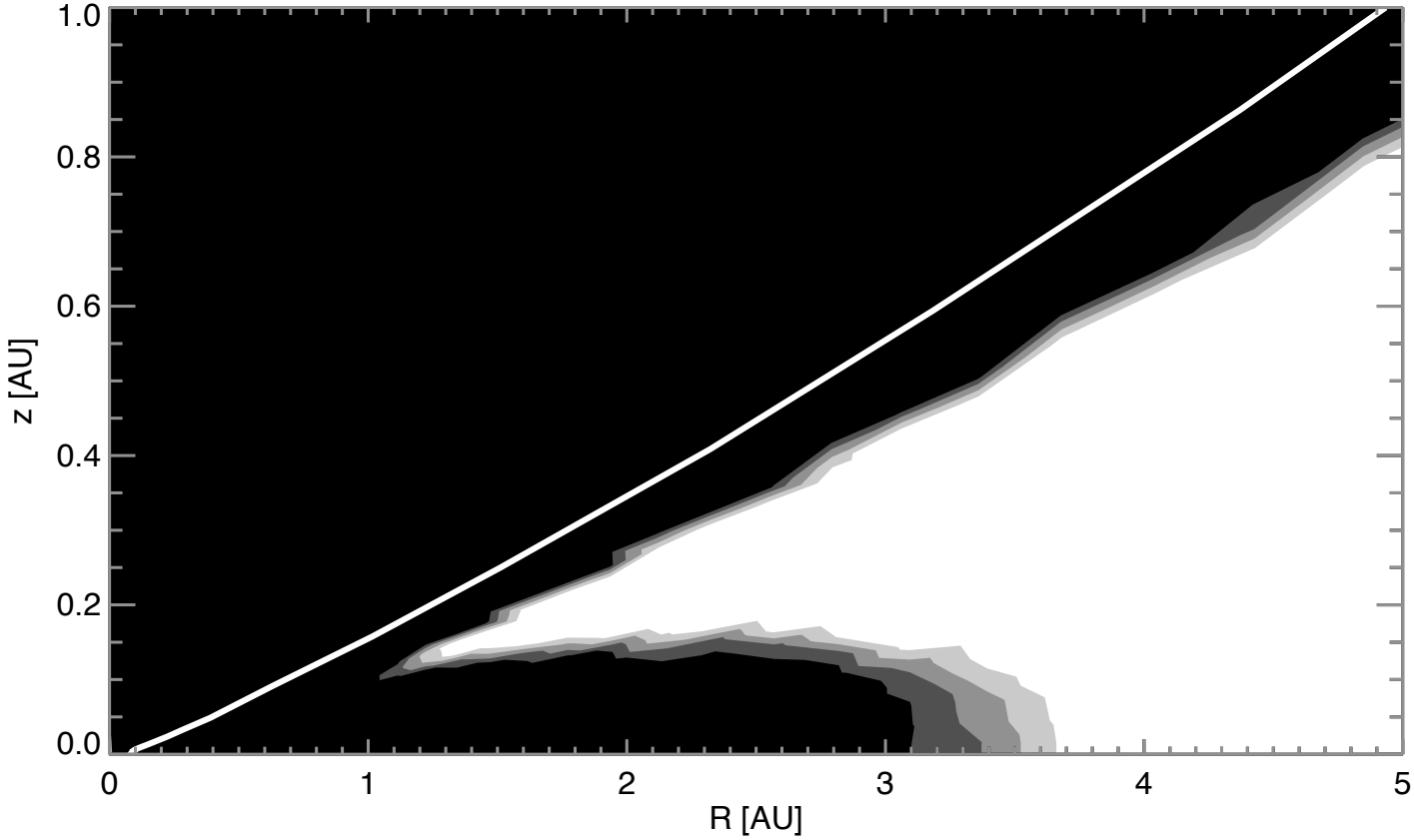


Min, Dullemond, Dominik & Kama 2011

Where is the ‘snow line’?

First fully 2-D/3-D radiative transfer model of snow line

$dM/dt = 10^{-8}\ M_{\odot}/yr, \qquad \alpha=0.01$

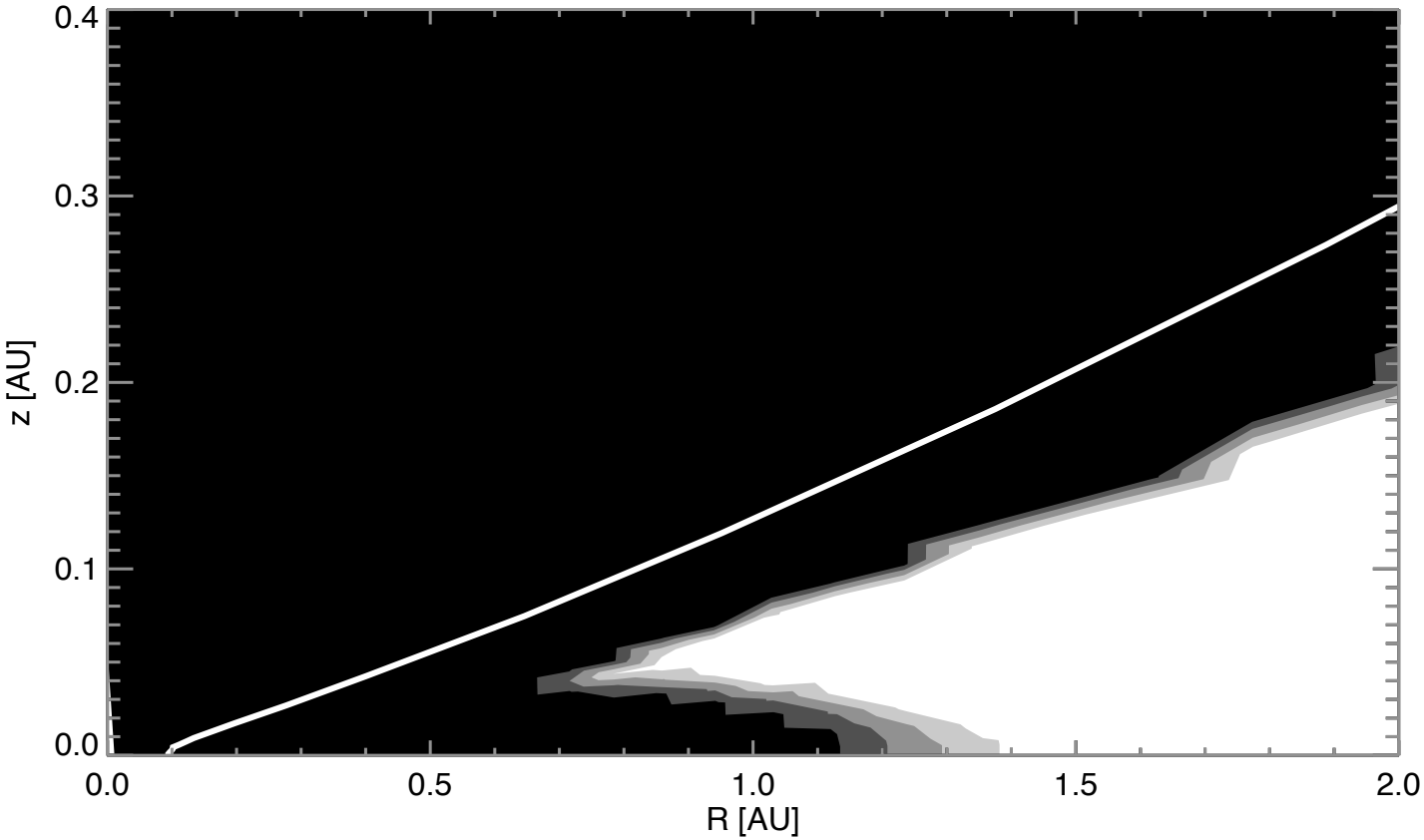


Min, Dullemond, Dominik & Kama 2011

Where is the ‘snow line’?

First fully 2-D/3-D radiative transfer model of snow line

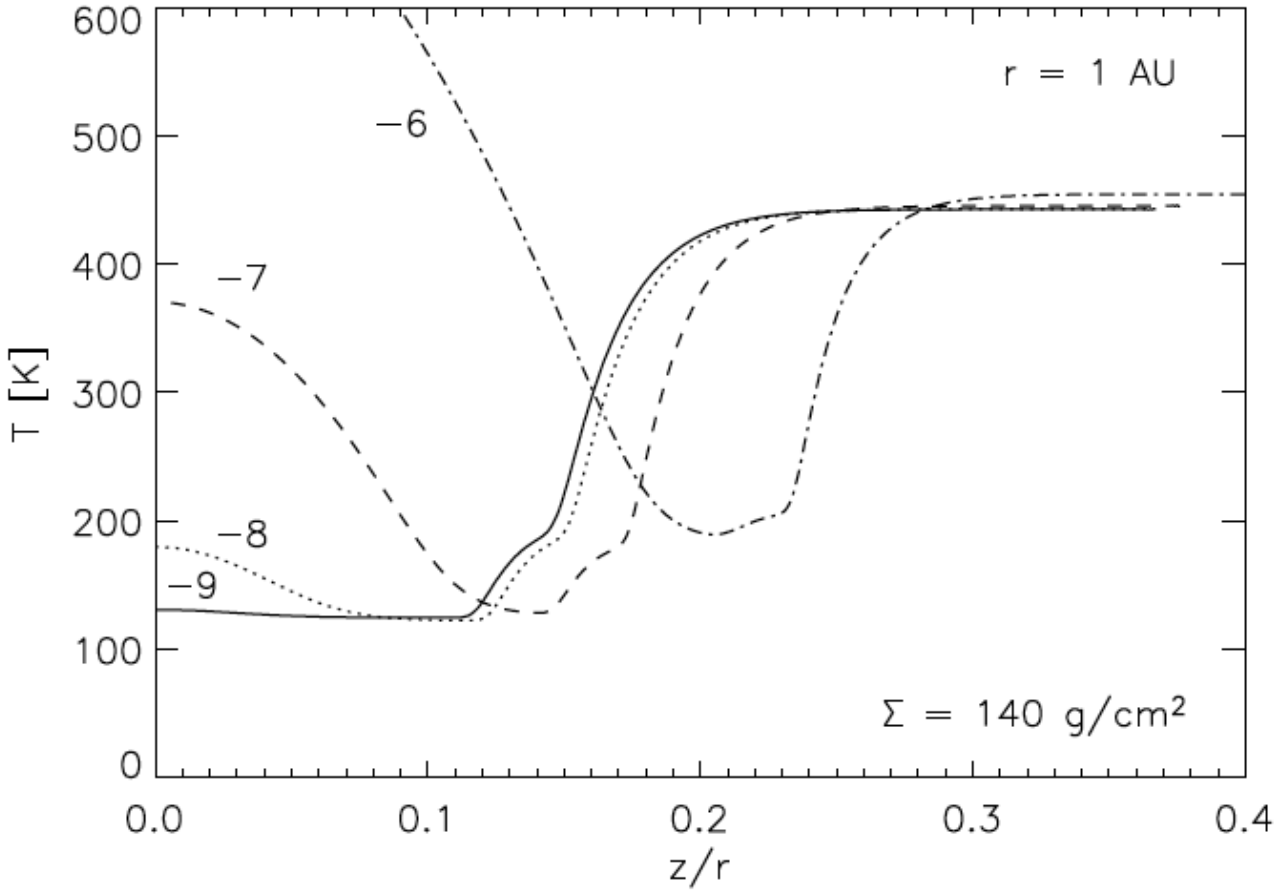
$dM/dt = 10^{-9}\ M_{\odot}/yr, \qquad \alpha=0.01$



Min, Dullemond, Dominik & Kama 2011

Warm surface layers:
rich in molecules?

Warm surface layers: rich in molecules?

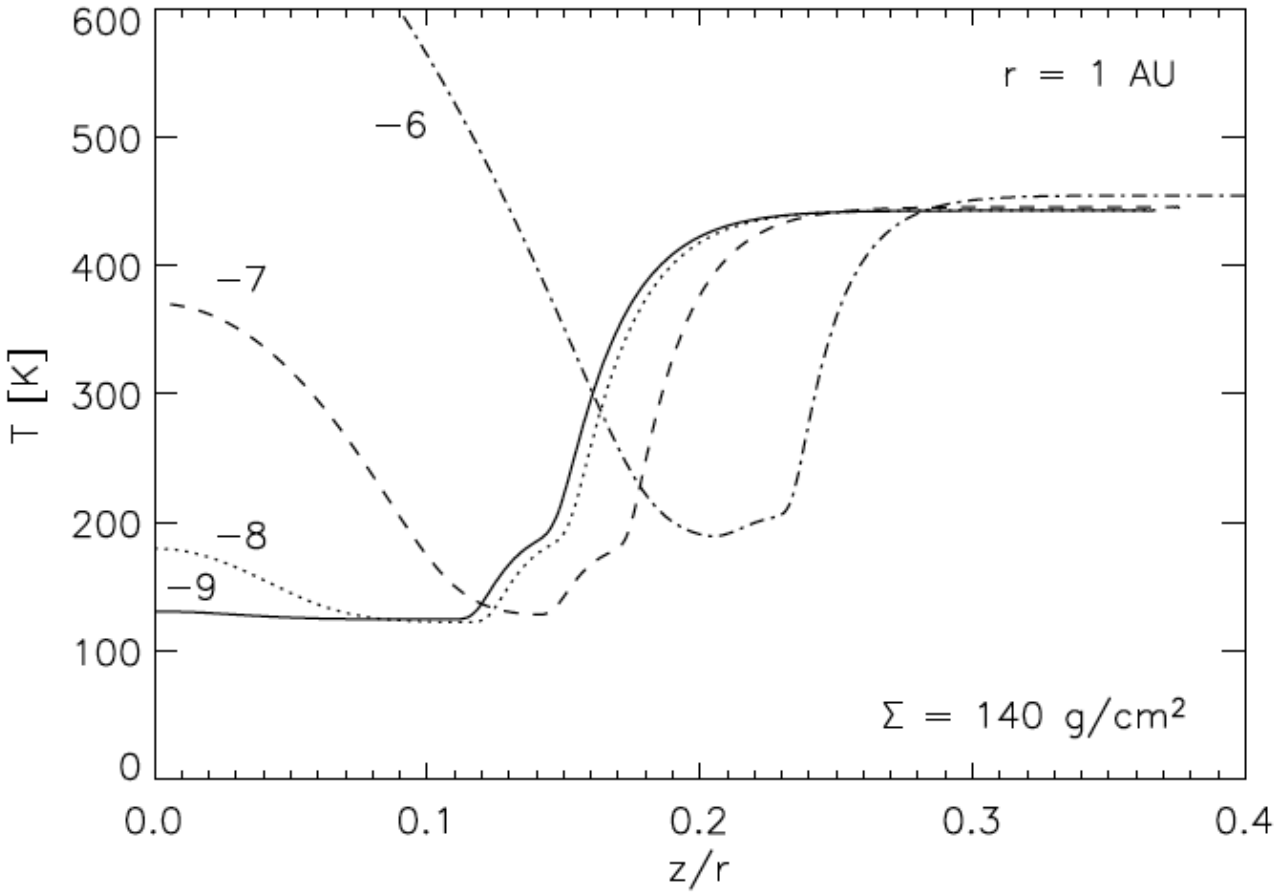


Model from Paola D'Alessio

(from: Dullemond, Hollenbach, Kamp & D'Alessio PPV review)

Vertical temperature structure

The *very* upper layers



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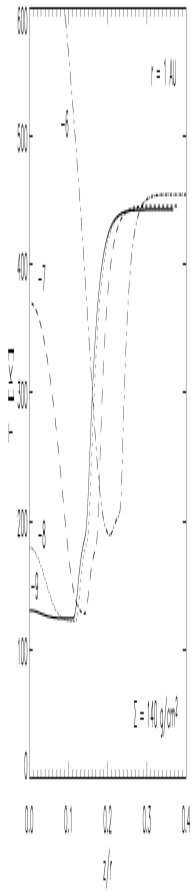

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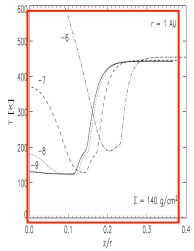

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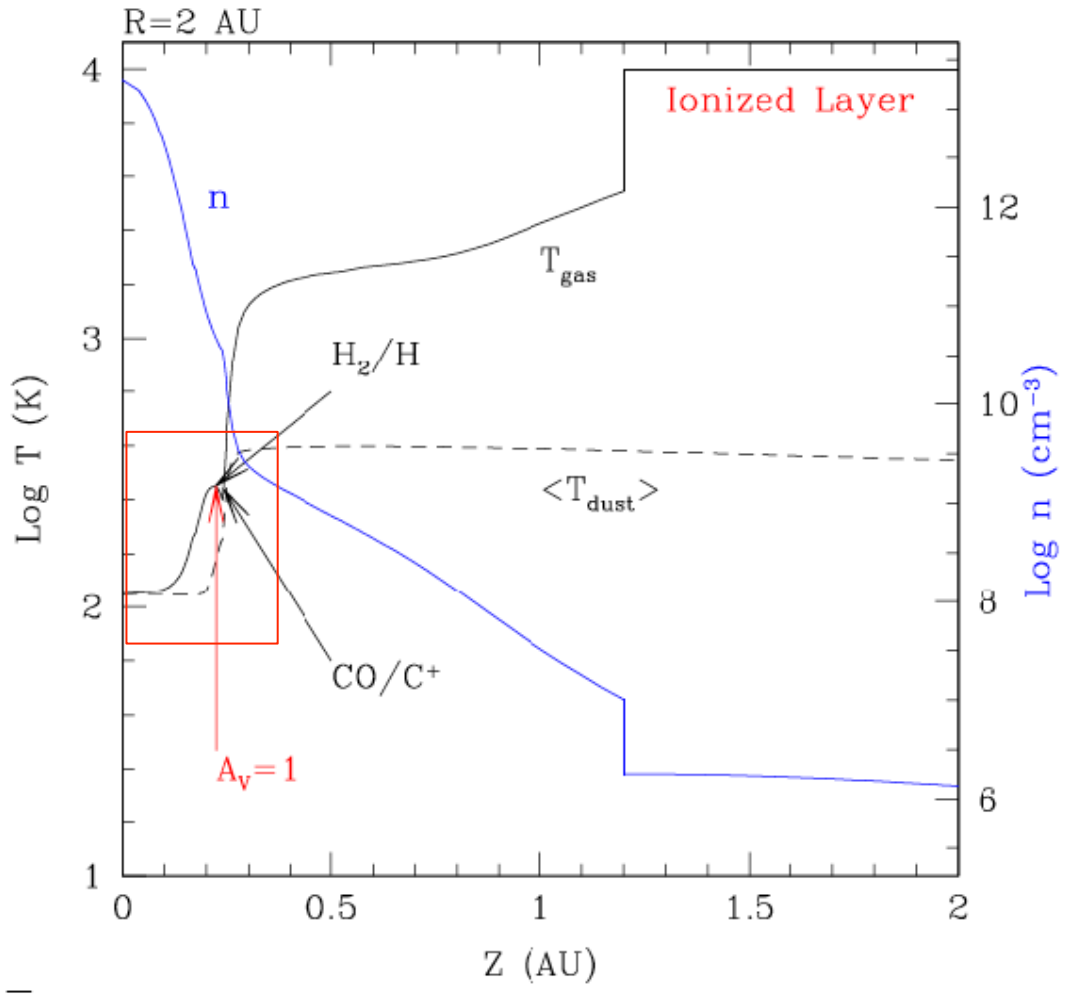
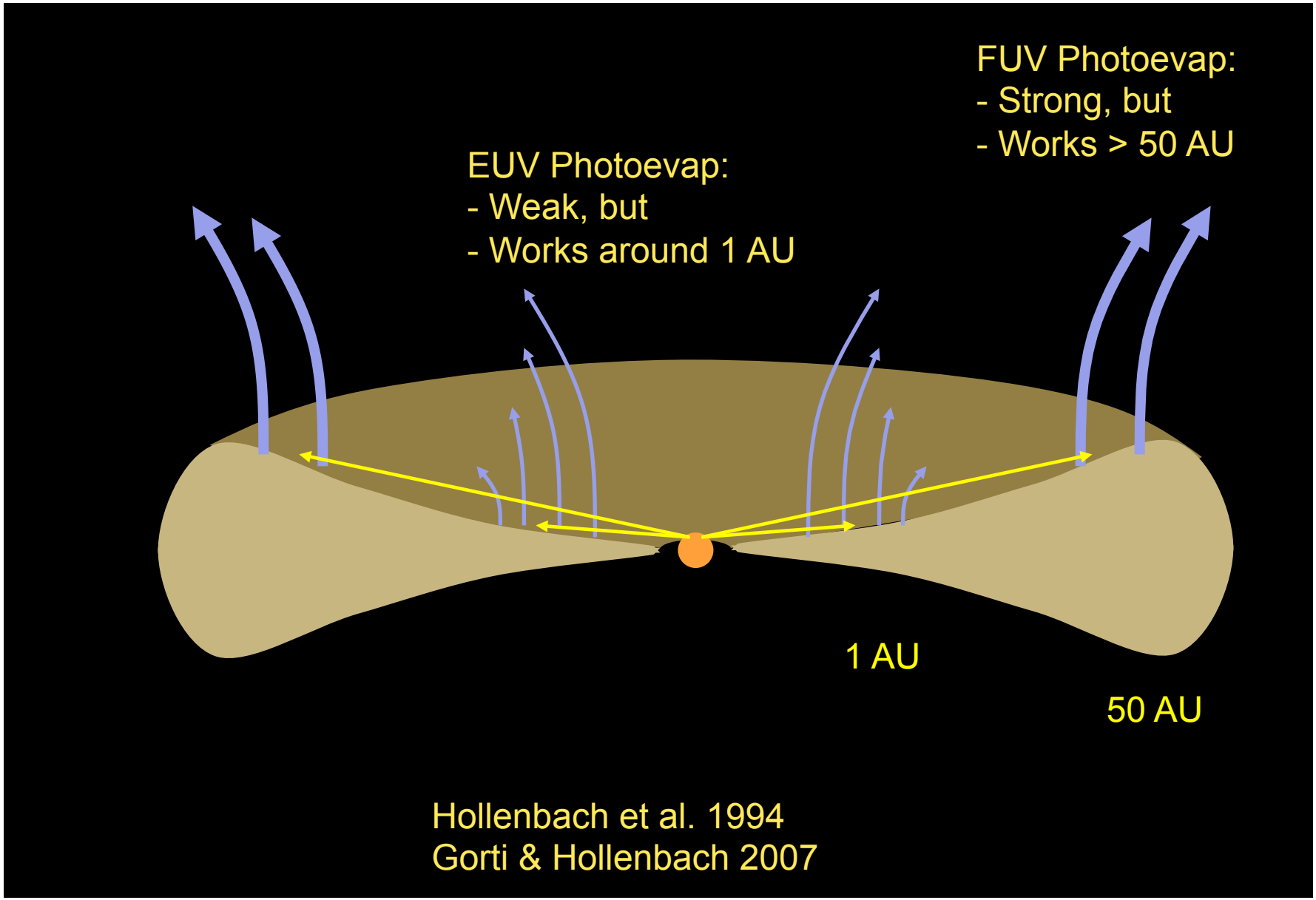


Gorti & Hollenbach 2008

Very hot surface layers may become unbound → disk photoevaporation (Hollenbach et al. 1994; Clarke, Gendrin, Sotomayor 2001; Alexander et al. 2006a/b; Gorti et al. 2009a/b; Owen et al. 2010; Ercolano et al. 2009)

EUV-driven Photoevaporation → Holes in disks



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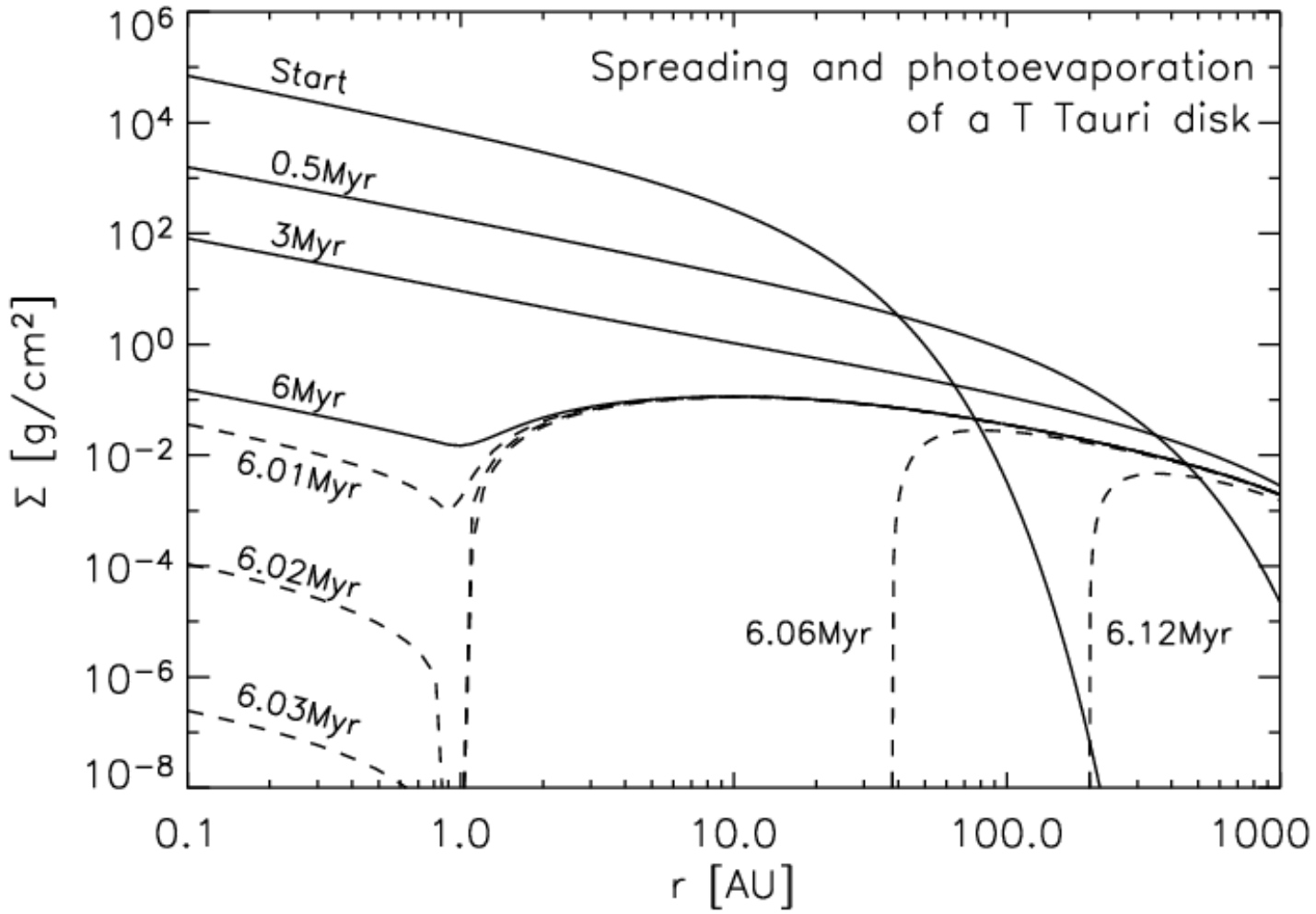
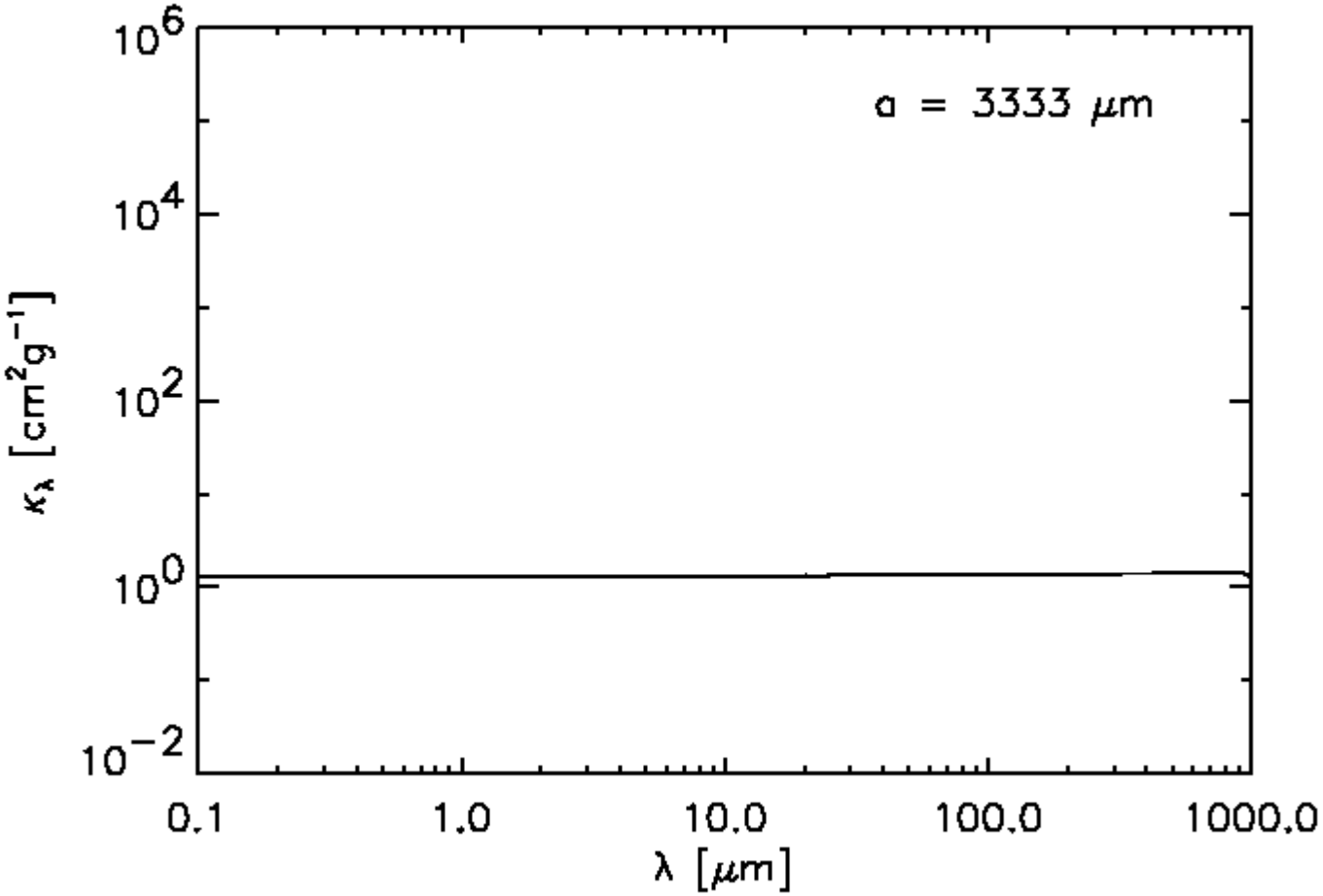


Hollenbach 1994; Clarke et al. 2001
Alexander, Clarke & Pringle 2006

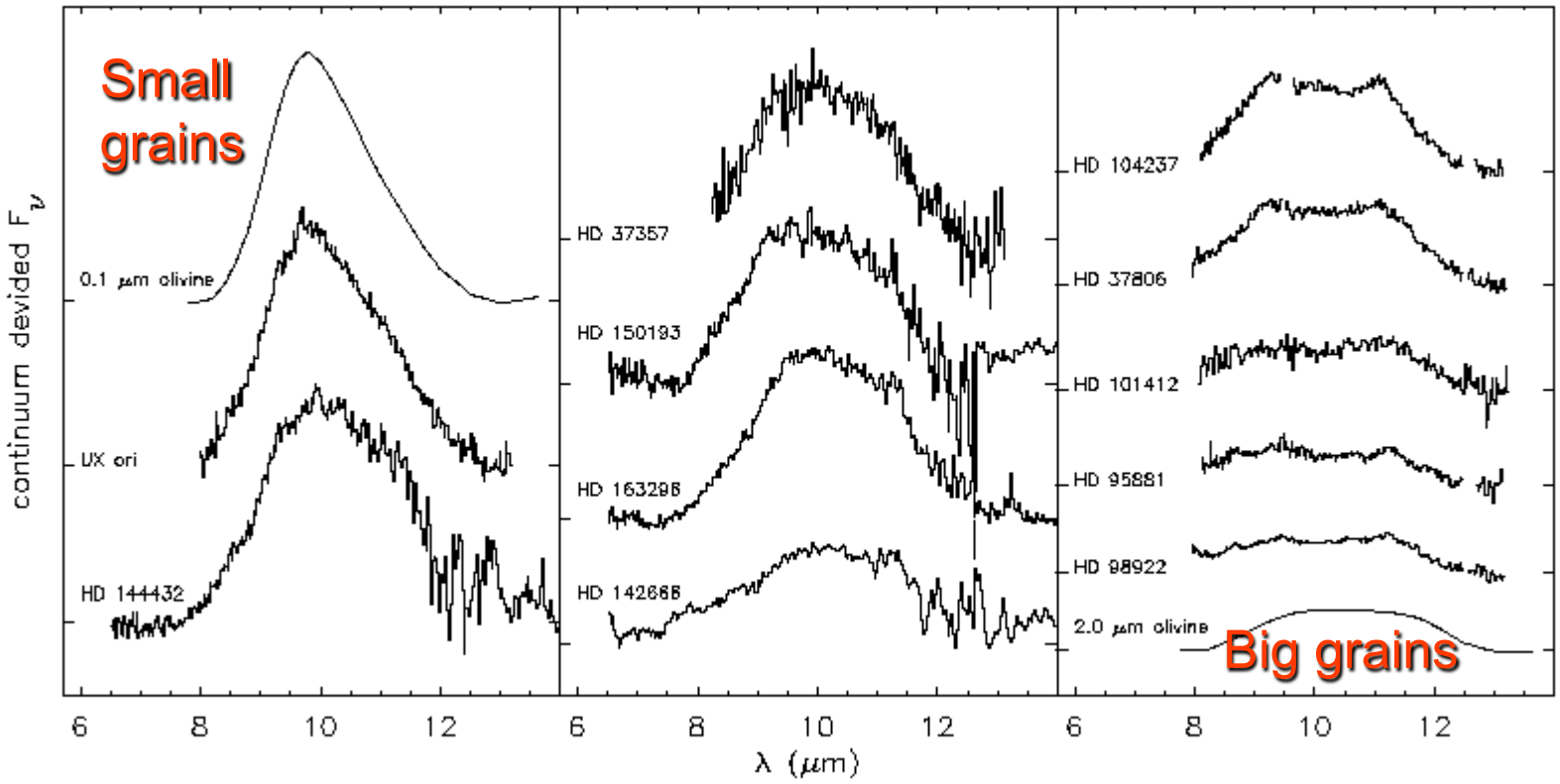
The evolution of the dust population

How is dust ‘size’ measured?

Example: Opacity of spherical silicate grain at various sizes

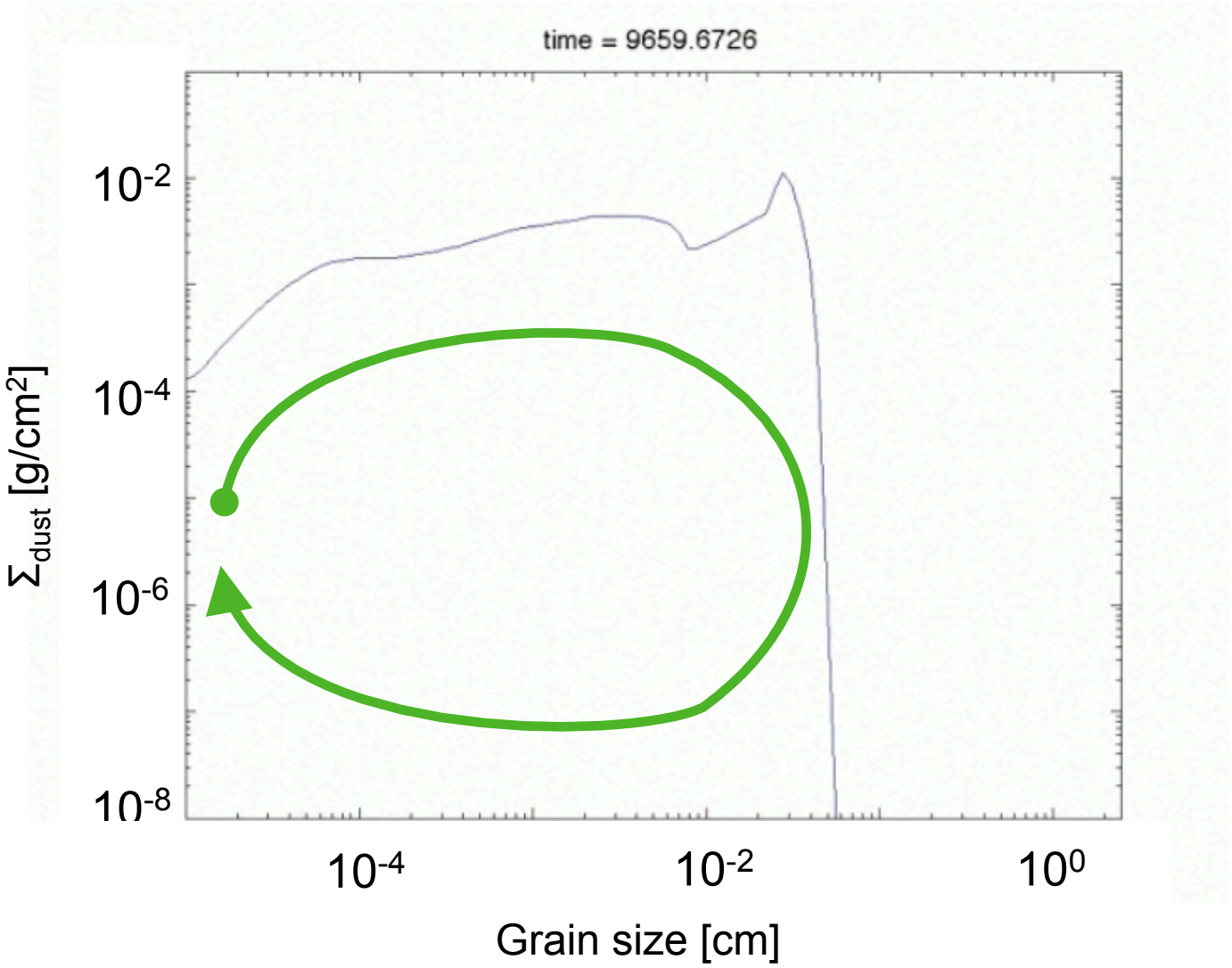


So... What is observed?



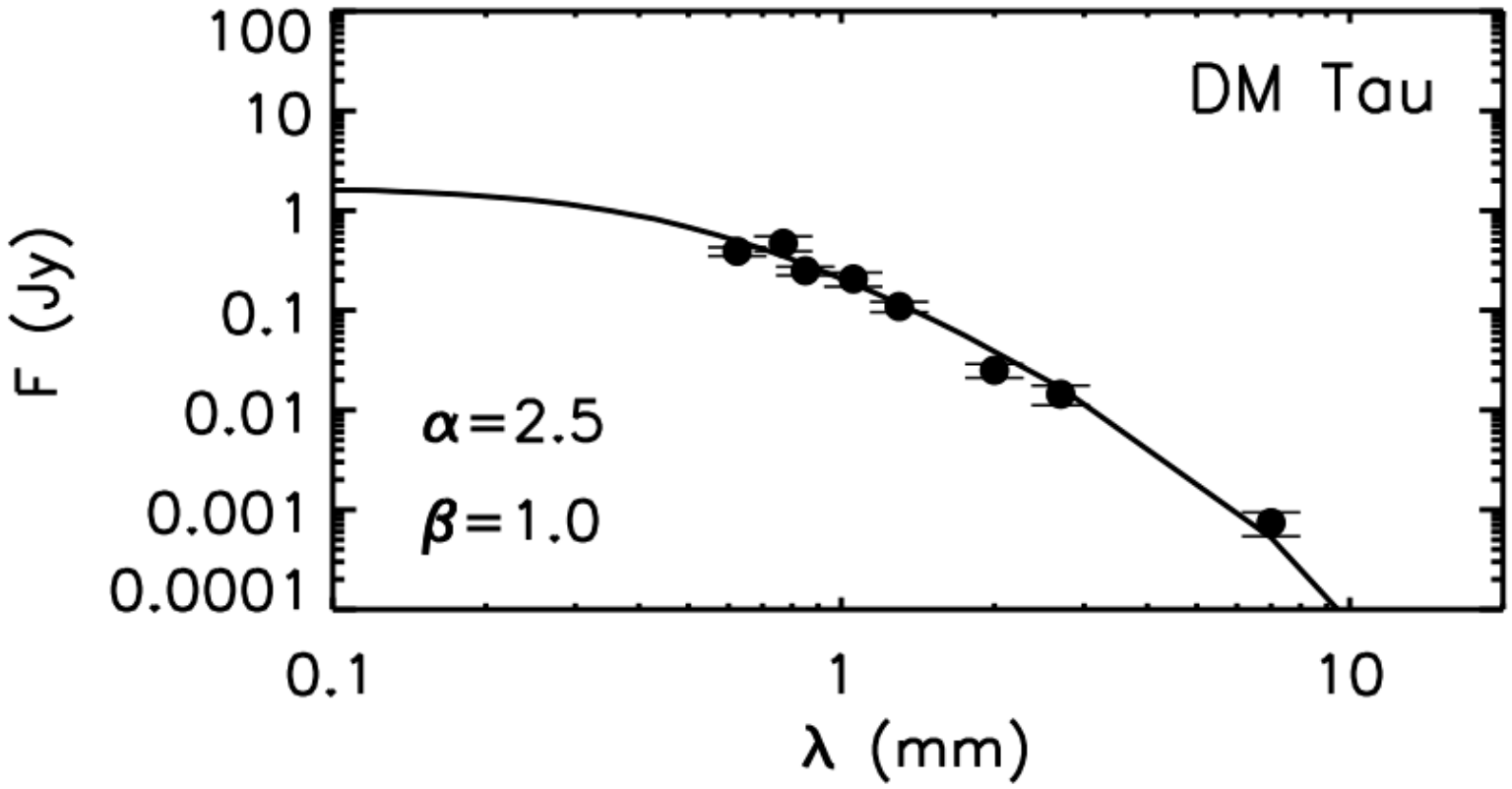
R. van Boekel et al. (2003), A&A 400L, 21

Dust coagulation model with fragmentation



Birnstiel, Dullemond & Ormel 2010

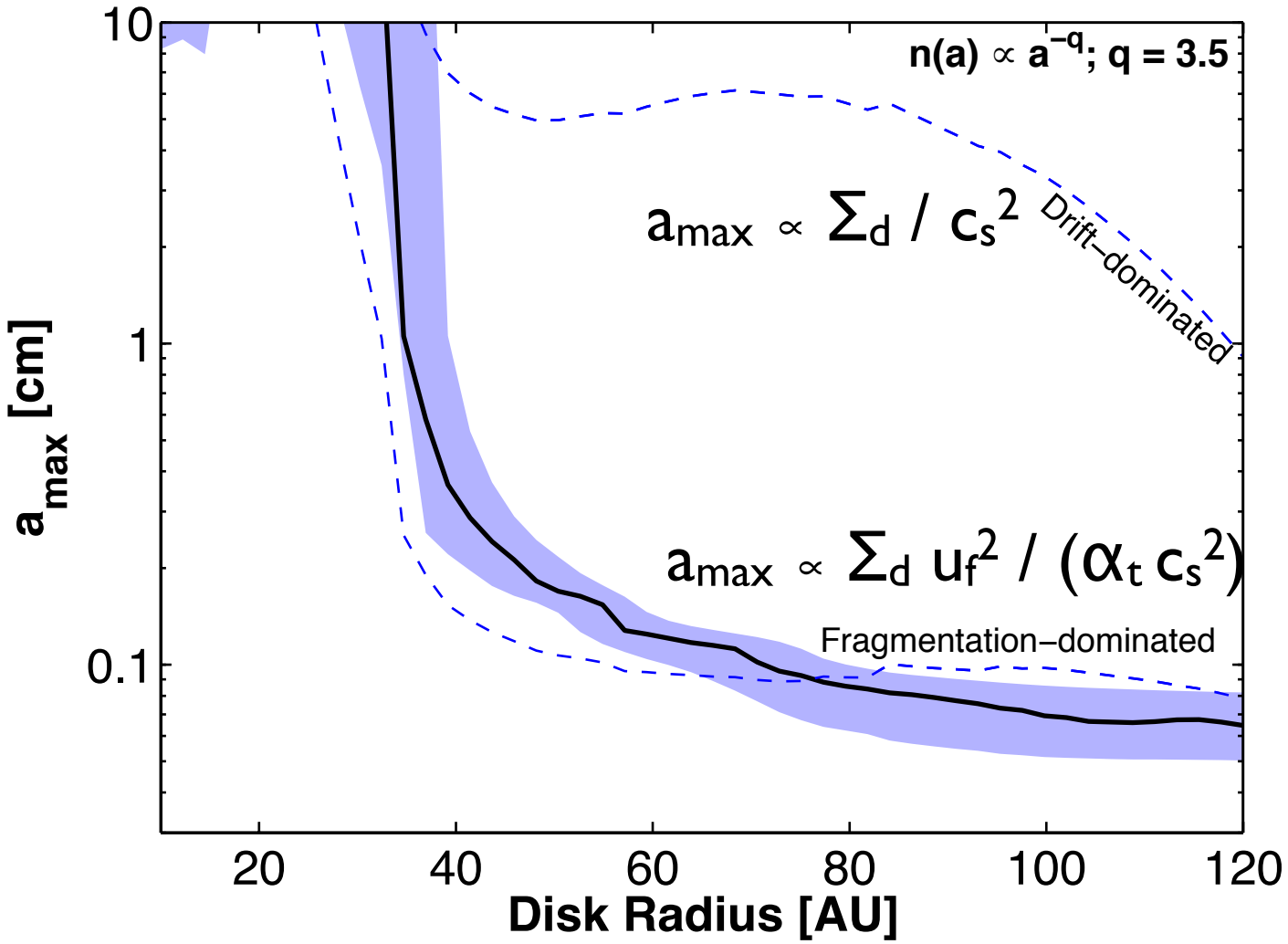
Measuring grain sizes from mm obs



Ricci, Testi, Natta, Neri, Cabrit & Herczeg (2010)

Comparing model to observation

Radial dependence in the disk?



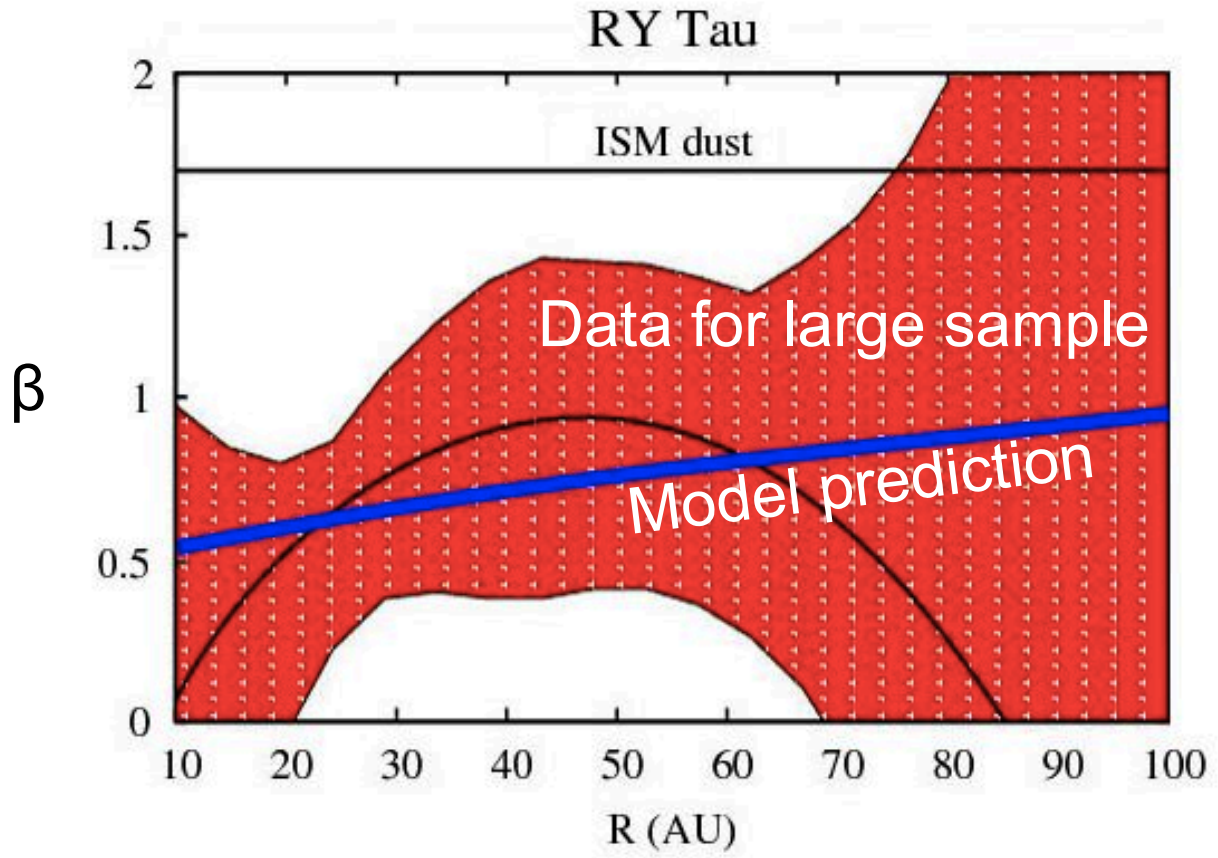
Data: Perez et al. submitted 2012

Model: Birnstiel, Ricci, Trotti et al. 2010

Comparing model to observation

Radial dependence in the disk?

larger grains in inner disk

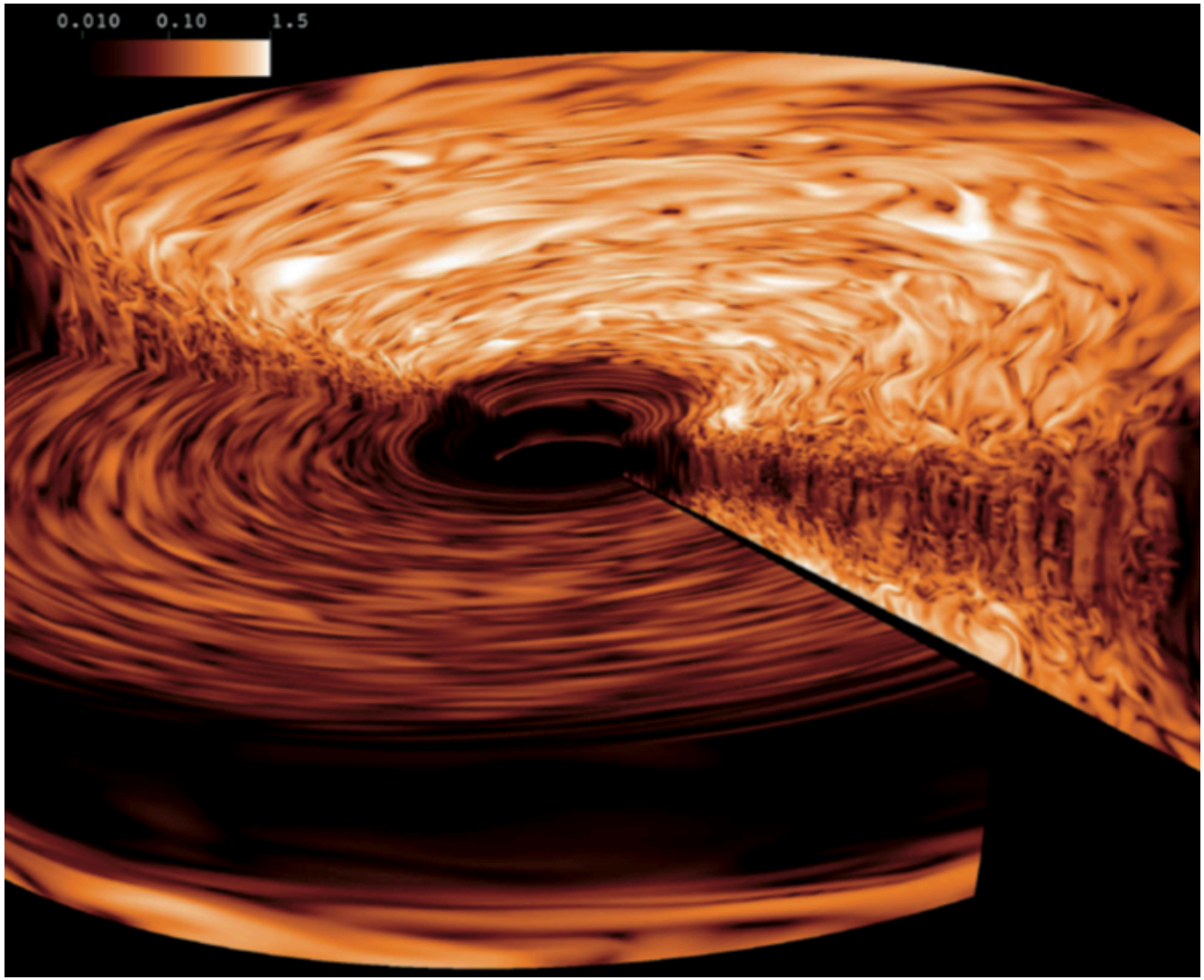


smaller grains in outer disk

Data: Isella et al. 2010
Model: Birnstiel, Ricci, Trotti et al. 2010

Essential for dust growth: Turbulence and vortices

Standard model for turbulence: MRI

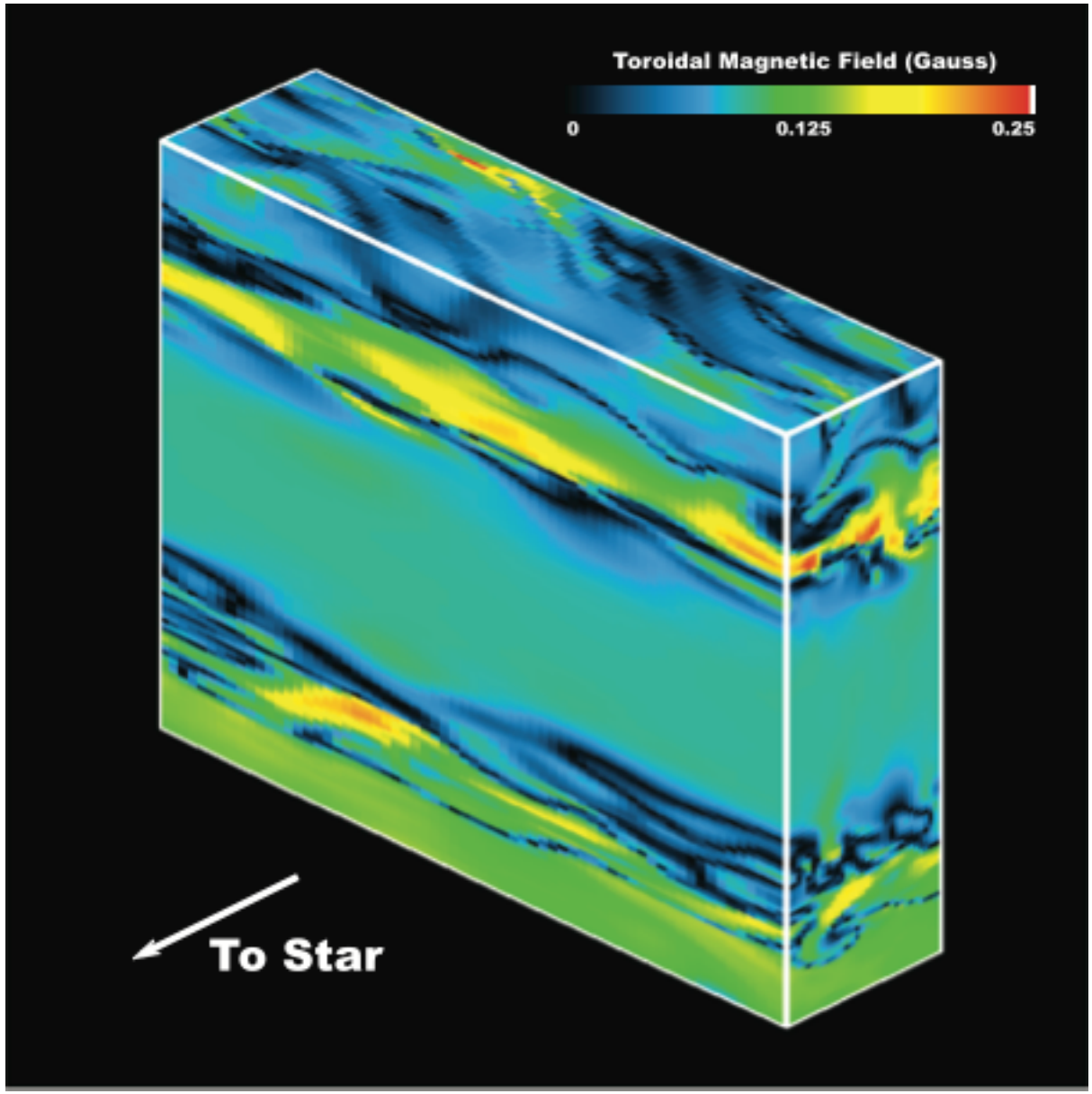


Flock et al. 2011; Dzyurkevich et al. 2010 for global MRI models

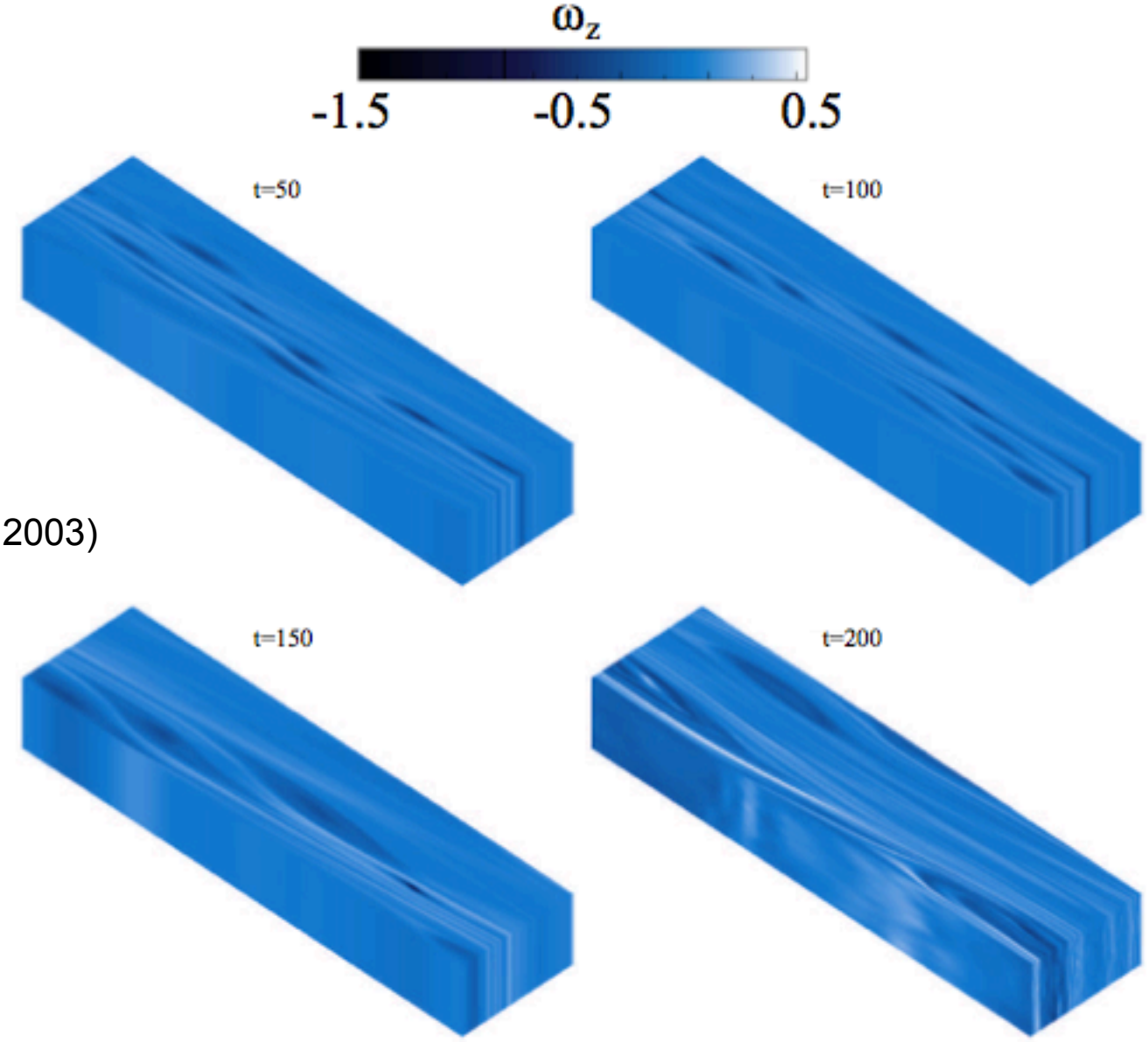
But: there is a „dead zone“

Gammie 1996

Here: Turner & Sano 2008



Vortices in protoplanetary disks

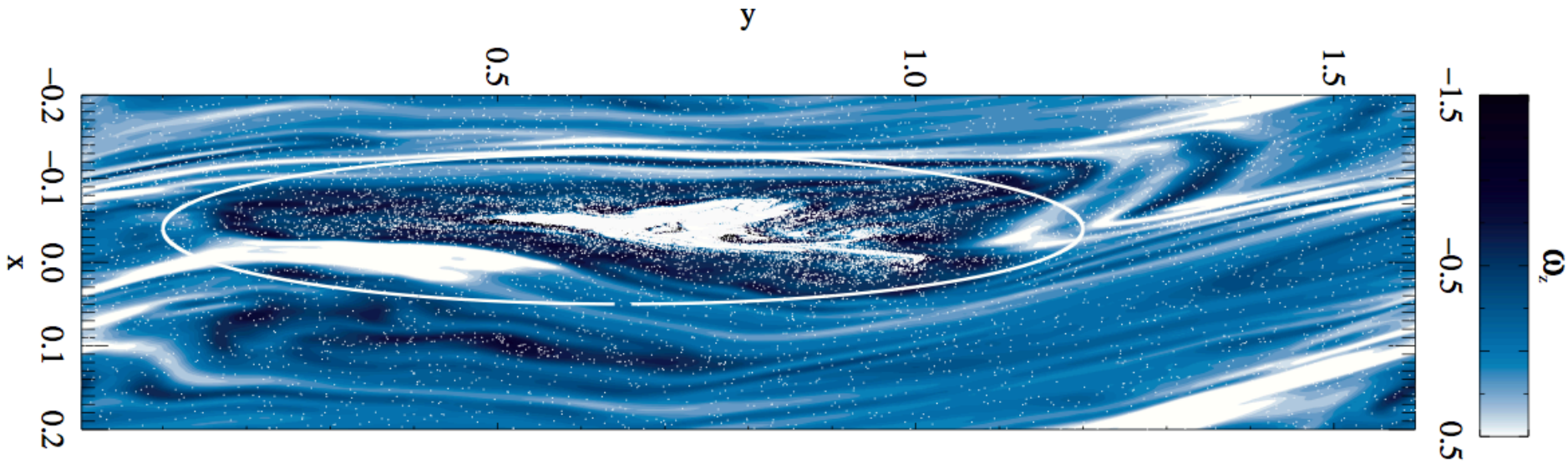


Vortex generation
by baroclinic instability

(Klahr & Bodenheimer 2003)

Raettig (PhD thesis 2012)

Vortices as particle traps



Barge & Sommeria 1995; Klahr & Henning 1997
Here from: Raettig (PhD thesis 2012)

Observing vortices in protoplanetary disks

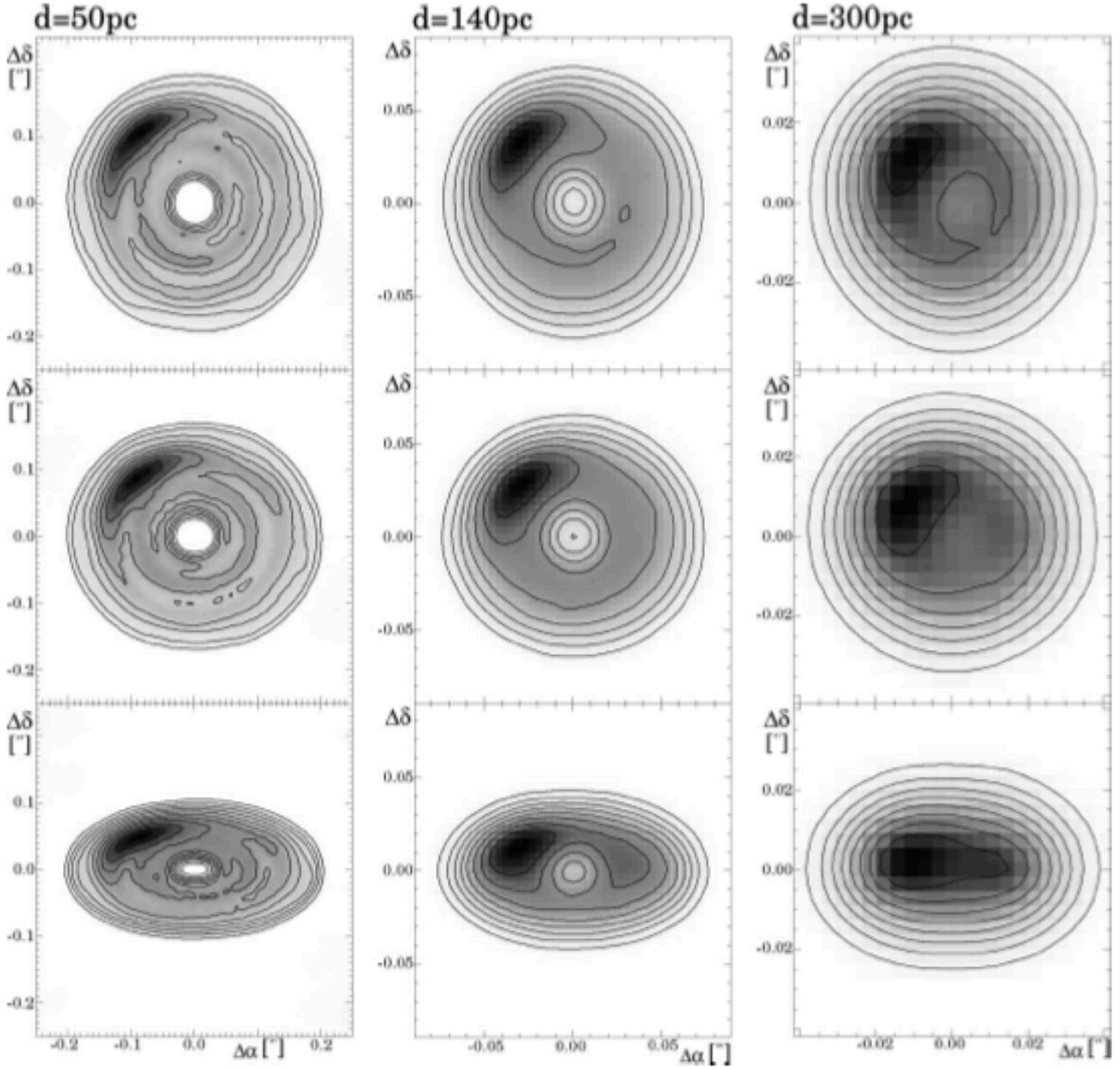
Early model predictions

Hydrodynamic model of a large-scale vortex at about 5 AU from the star.

Model predictions for ALMA.

NOTE: These are valid only for the *full configuration* (largest baselines). Currently not yet available!

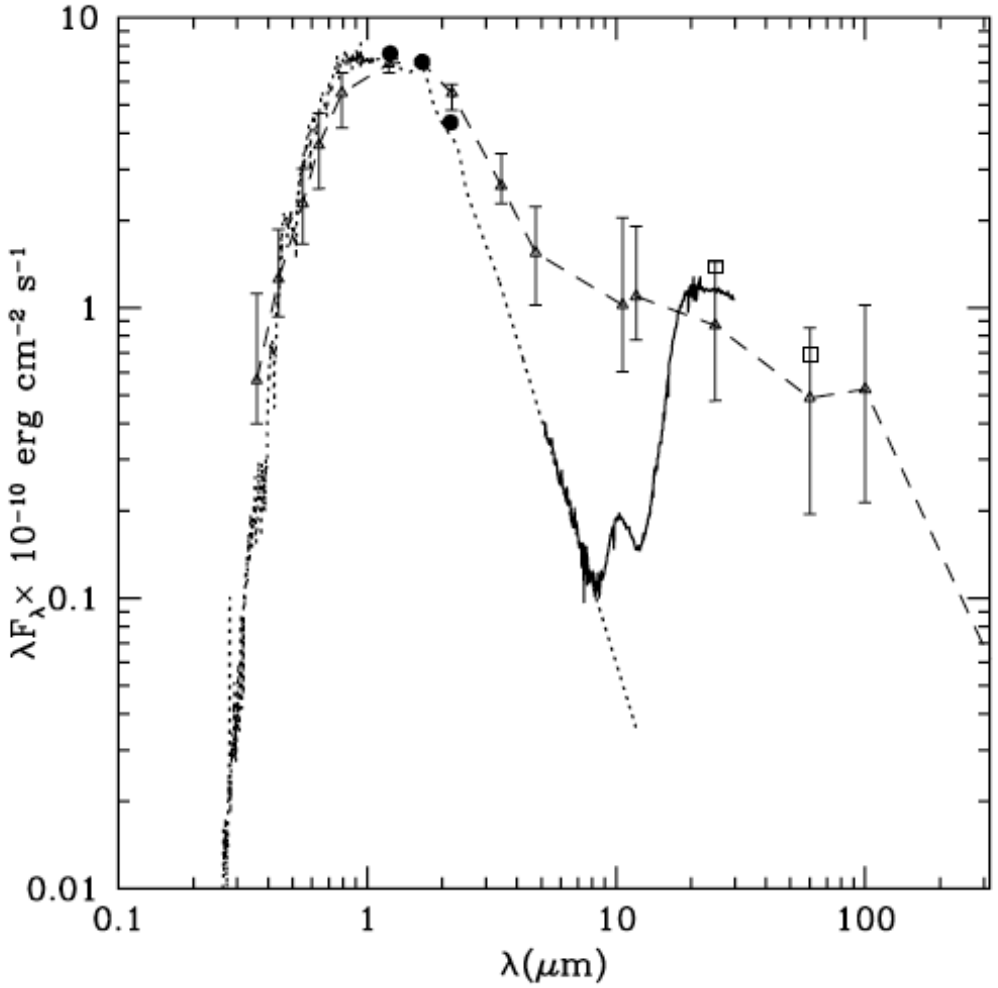
Wolf & Klahr 2002



Disks with huge holes
(„Transition disks“)

Death of a disk
and/or
birth of a planetary system

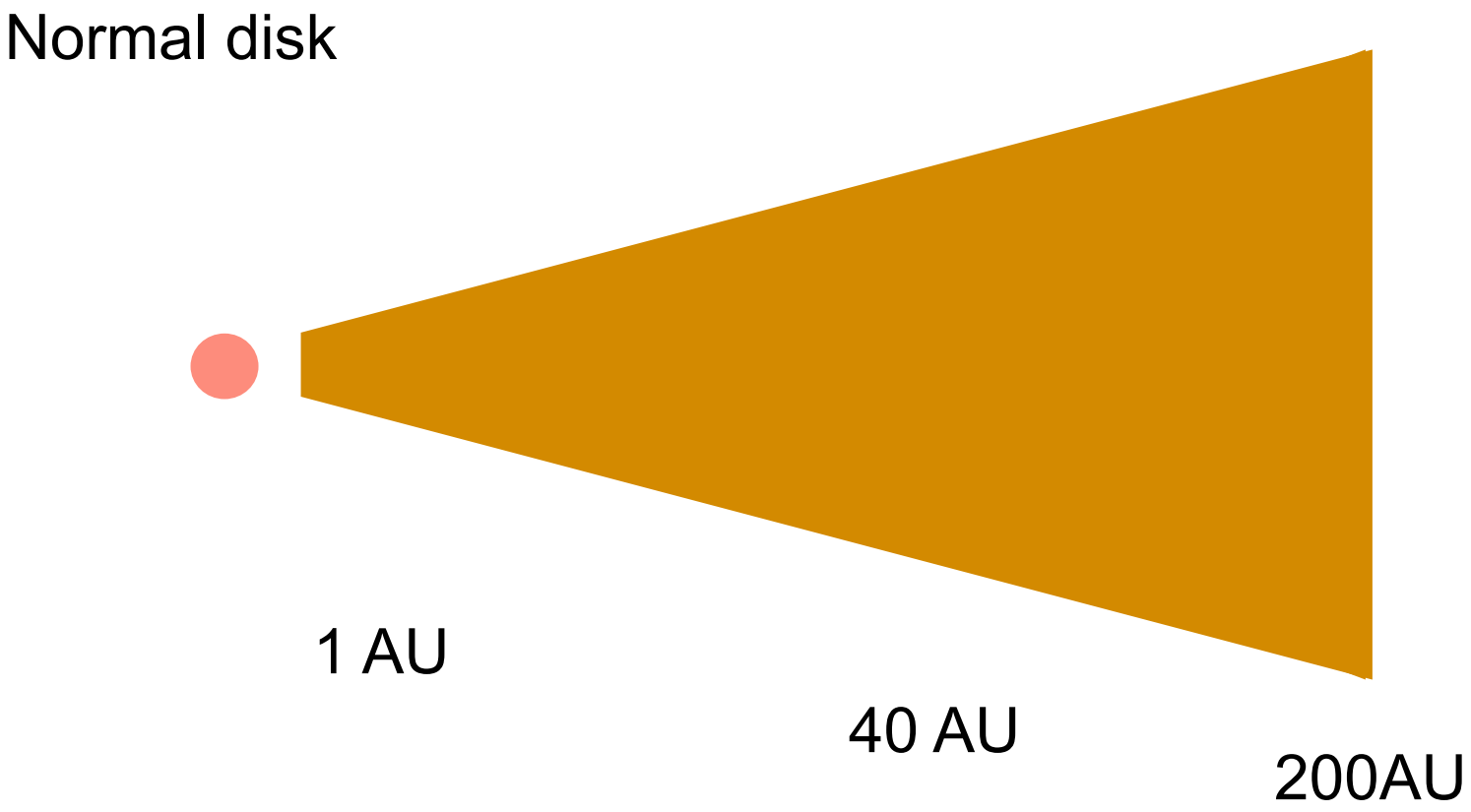
“Transition disks”: Huge inner holes



CoKu Tau 4

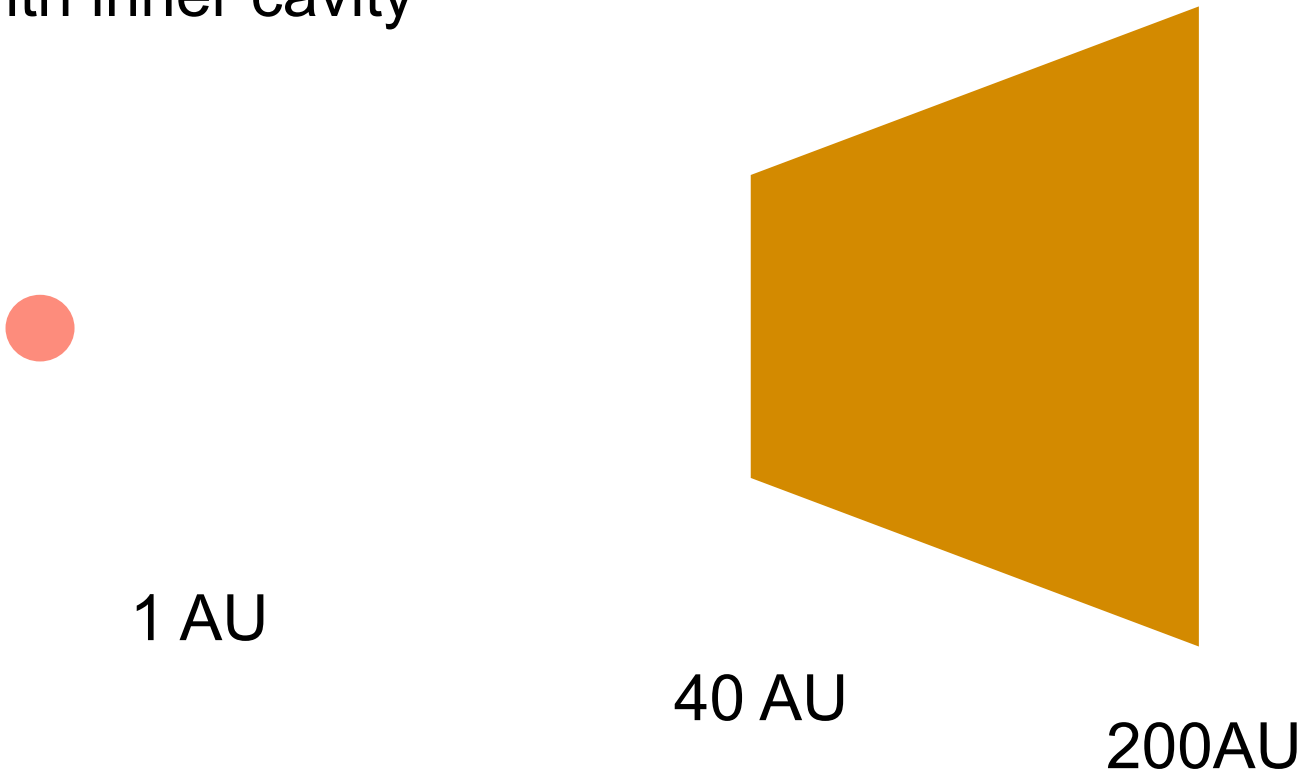
D’Alessio et al. 2005, Forrest et al. 2004

“Transition disks”: Huge inner holes



“Transition disks”: Huge inner holes

Disk with inner cavity



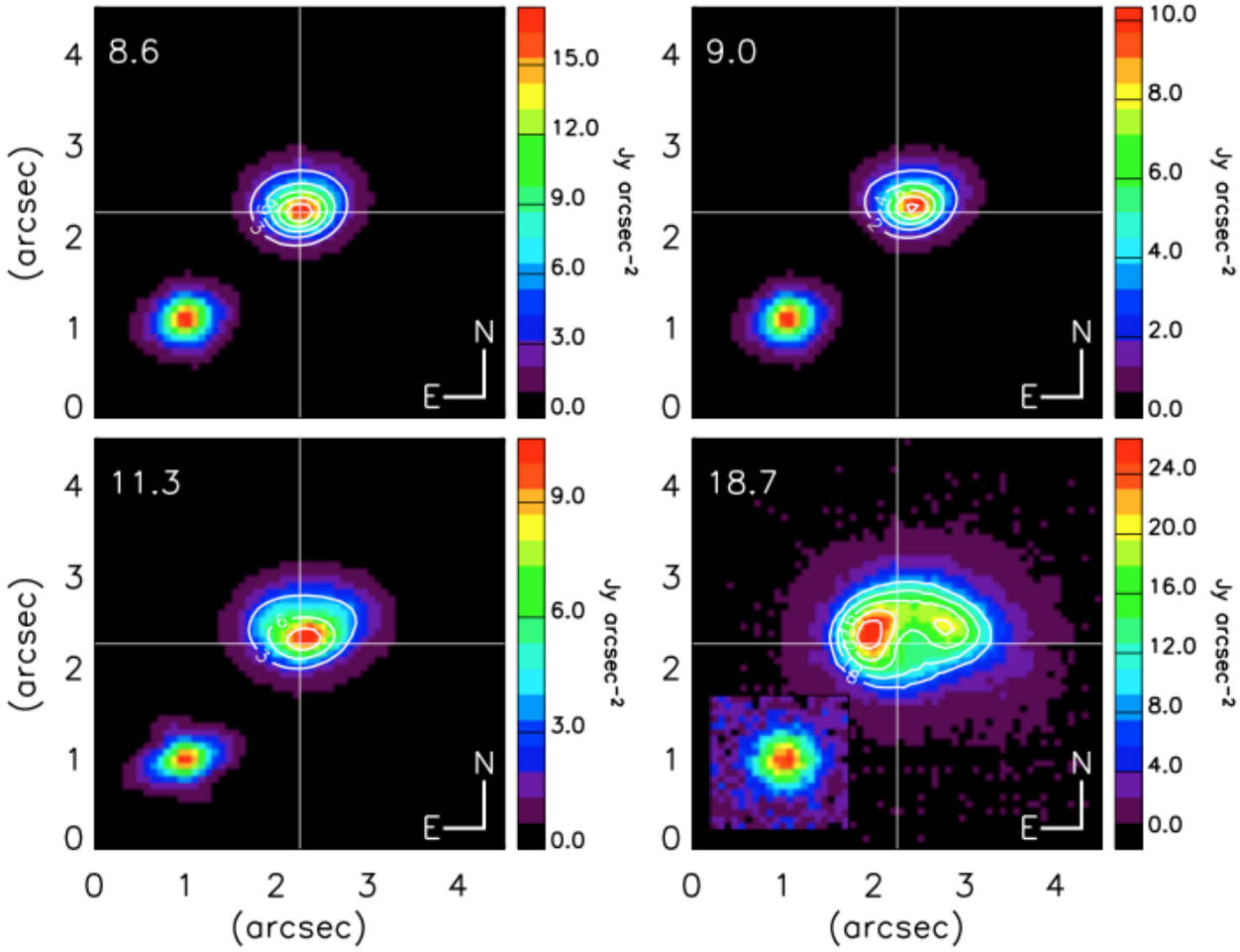
Not all transition disk holes are completely empty...

IRS 48

A transition disk with a huge ring as seen in 18.7 continuum.

But: the inner hole is not empty: there appears to be PAH emission inside!

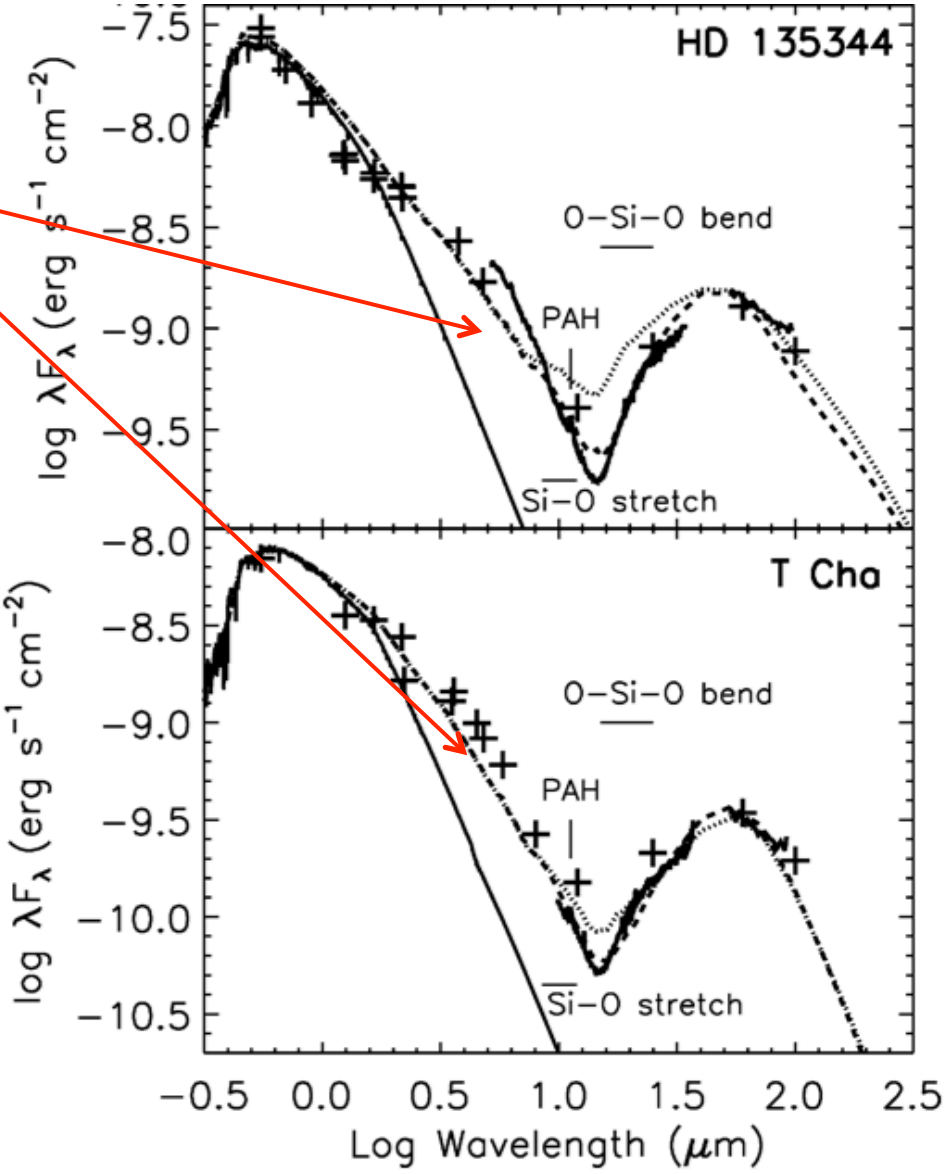
Seems to exclude EUV-photoevaporation



Geers et al. 2007

Not all transition disk holes are completely empty...

Clearly there is SOME hot dust, i.e. dust at < AU.

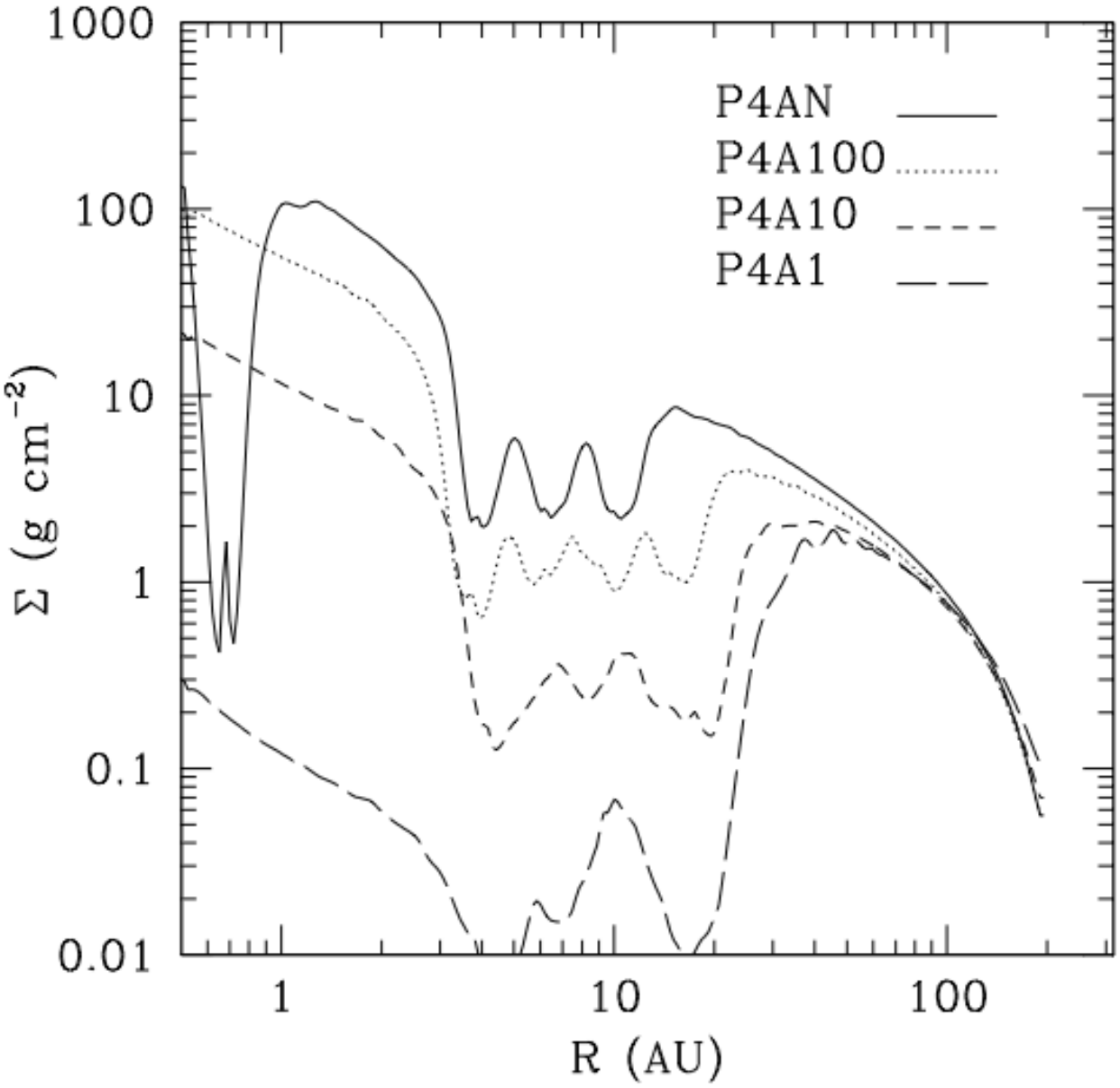


Brown et al. 2007

Can the birth of a „solar system“ be the cause?

Just the existence of planets does not seem to cause a strong enough „inner hole“

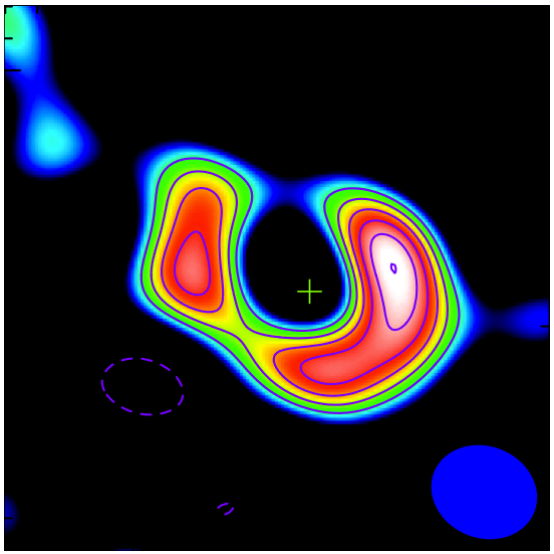
Need dust dynamics and growth (e.g. Rice et al.)



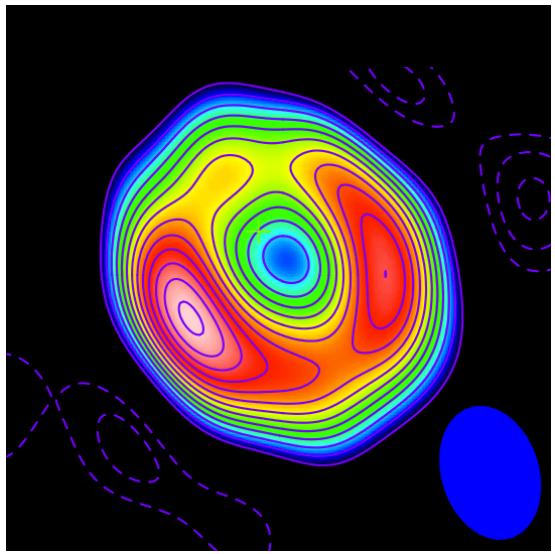
Zhu et al. 2011

Transition disks: Ring-like structures

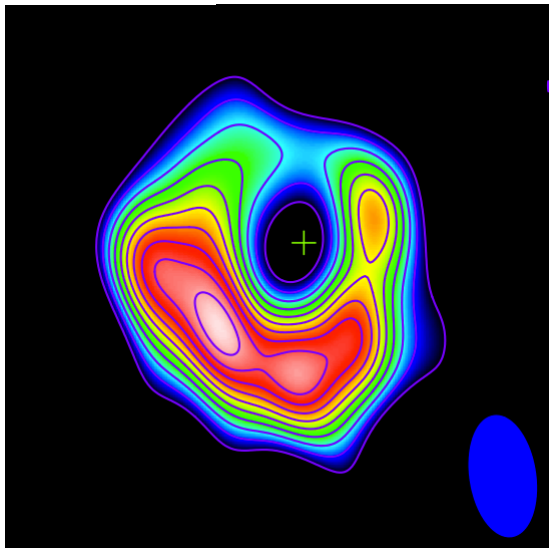
LkHa 330



SR 21



HD 135344B

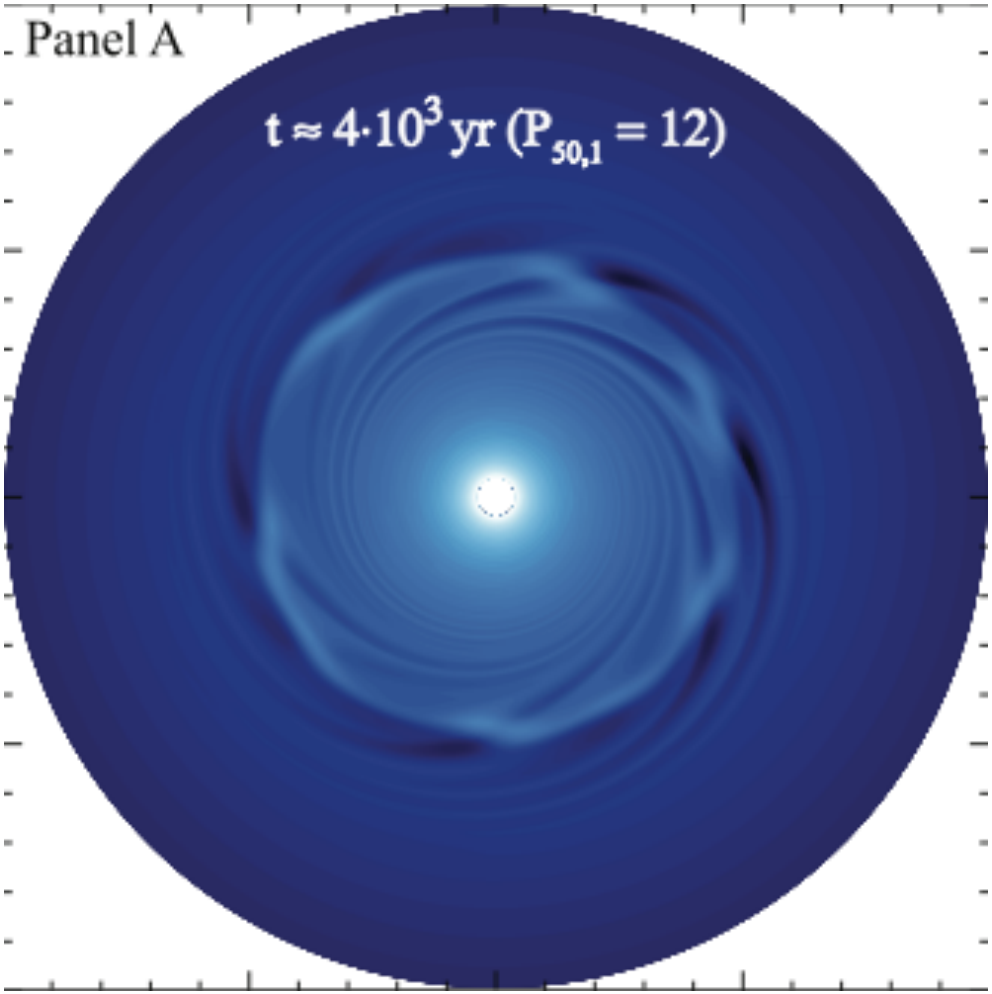


NOTE: These structures are at 5-50 AU

Brown et al. 2009

Hydrodynamics of a pressure bump

If the bump is too strong, hydrodynamic instabilities will occur:
e.g. Rossby wave instability
Vortices will form!



Regaly, Juhasz et al. 2011

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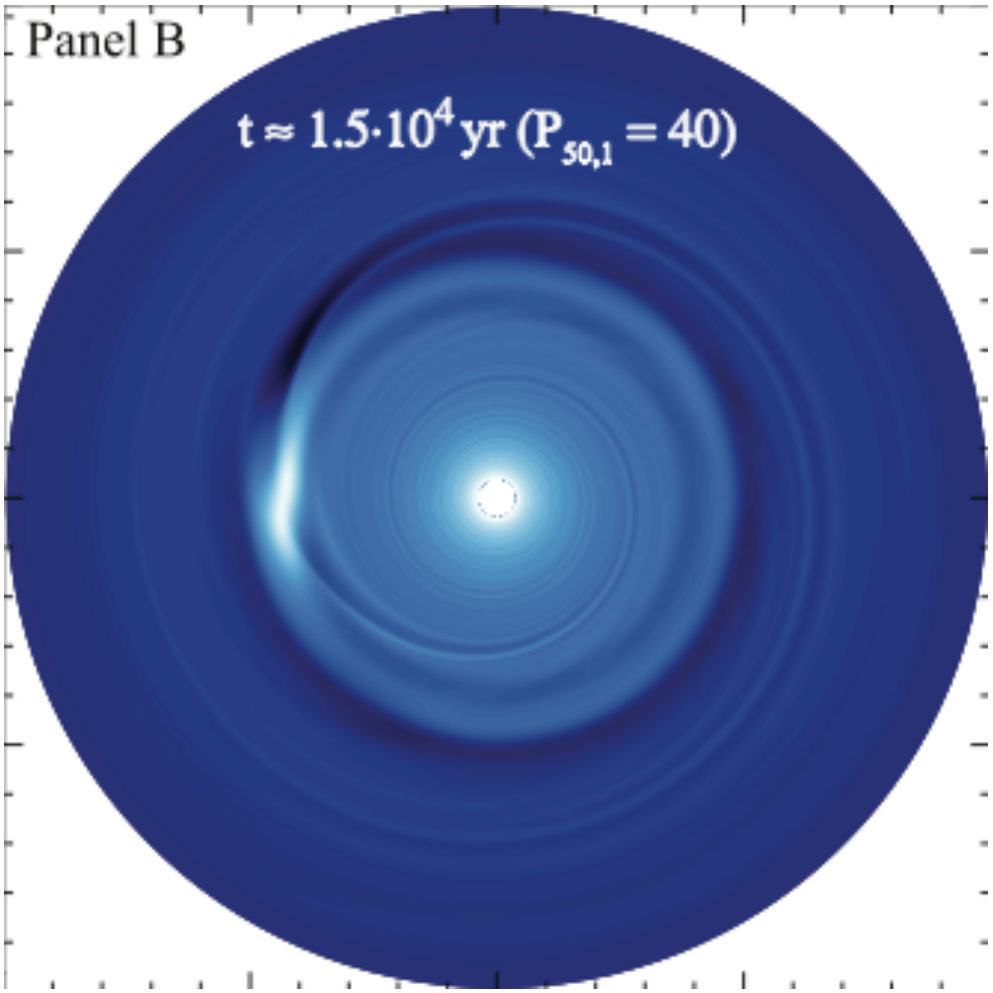

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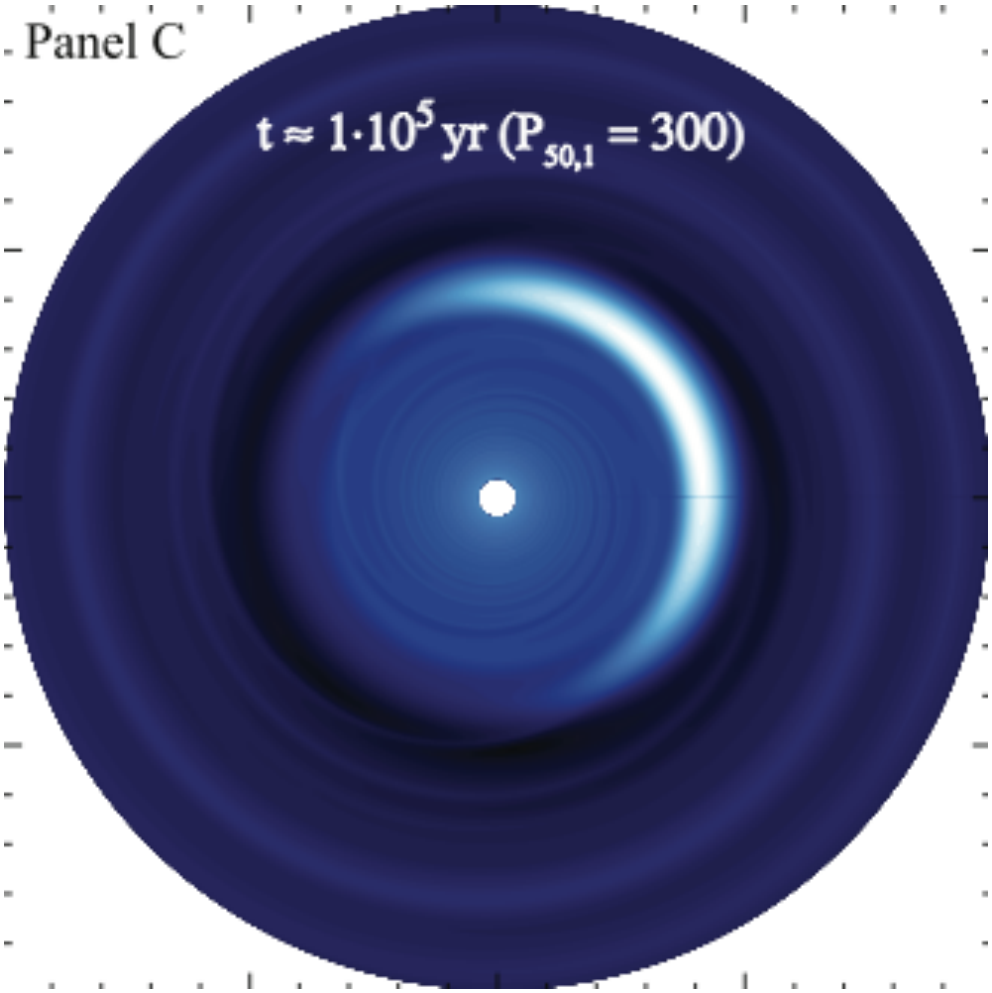

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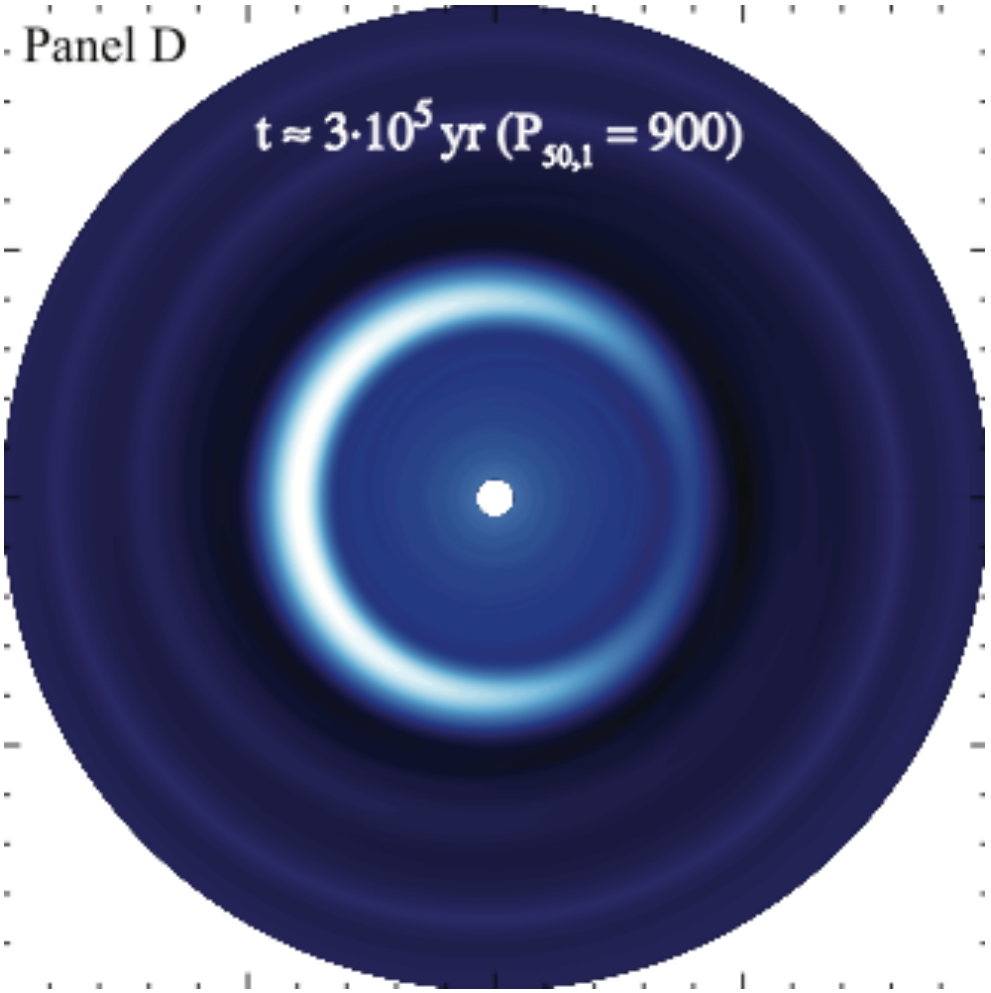

Regaly, Juhasz et al. 2011

Hydrodynamics of a pressure bump

If the bump is too strong, hydrodynamic instabilities will occur:
e.g. Rossby wave instability
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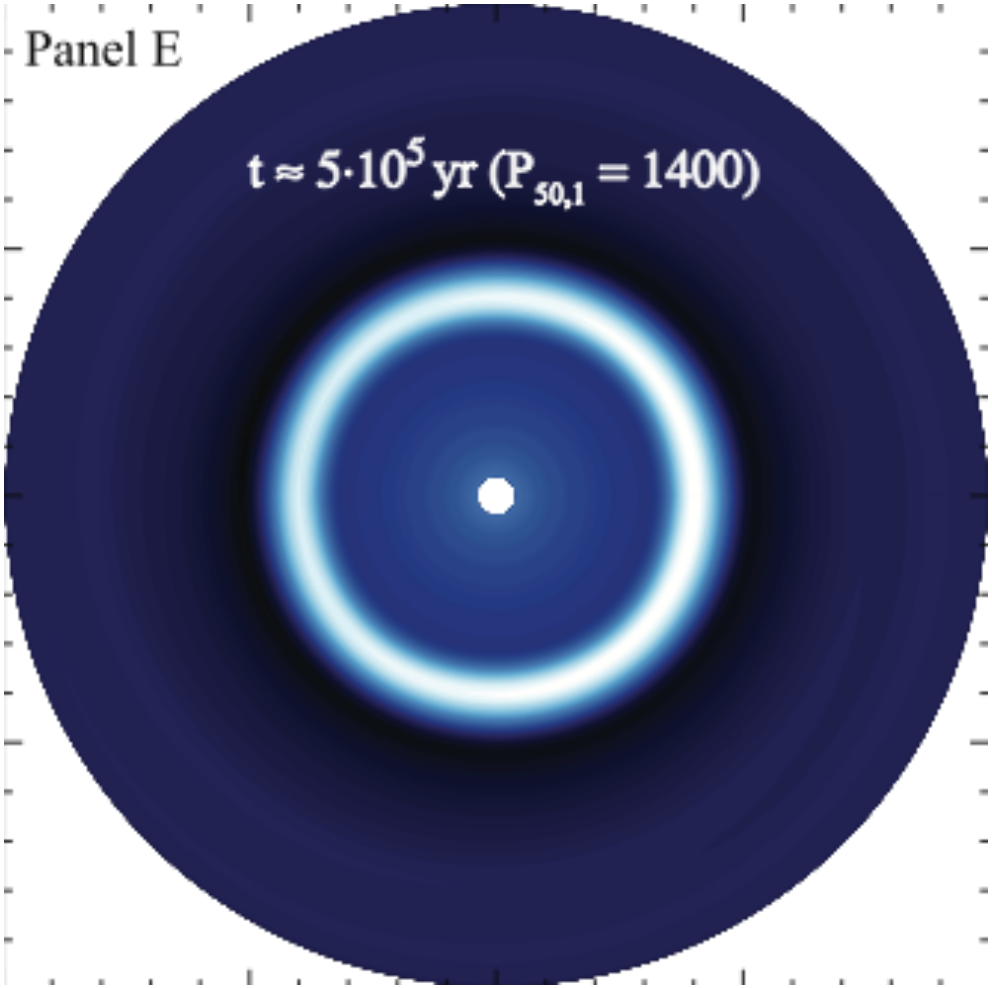

Regaly, Juhasz et al. 2011

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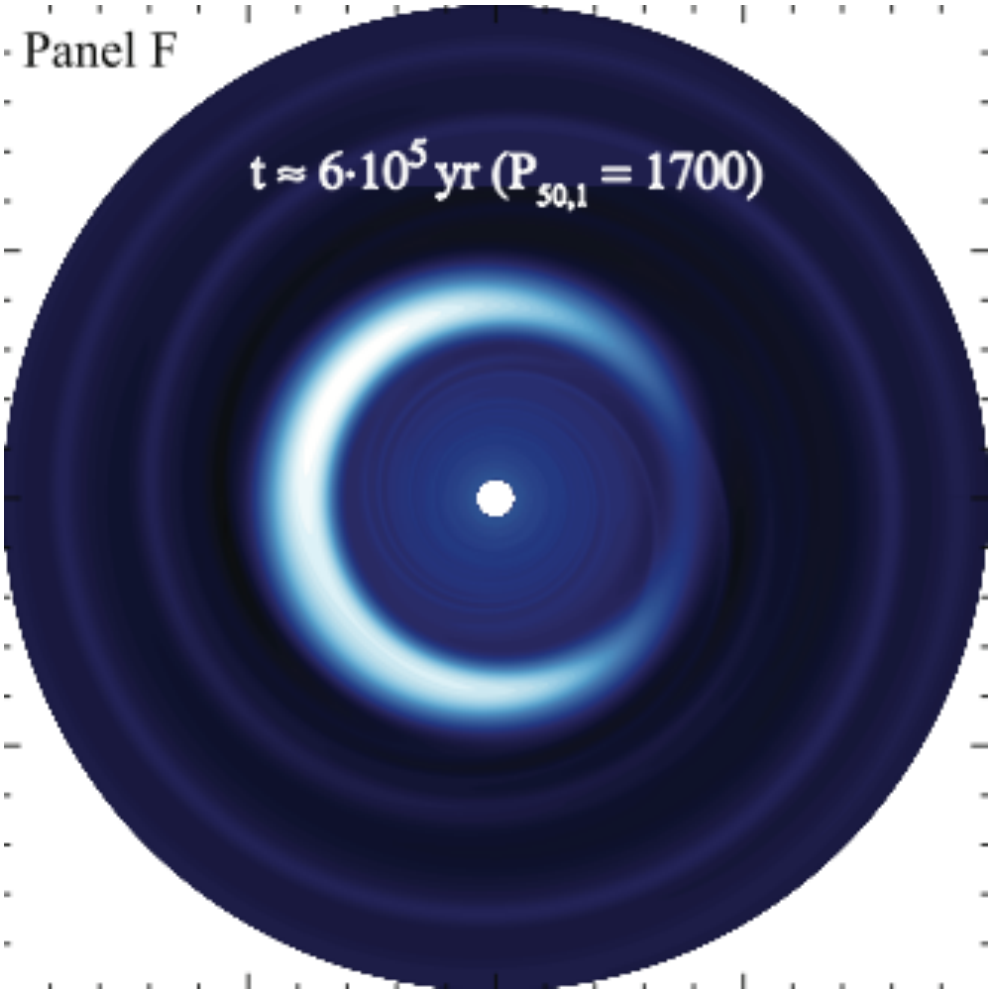
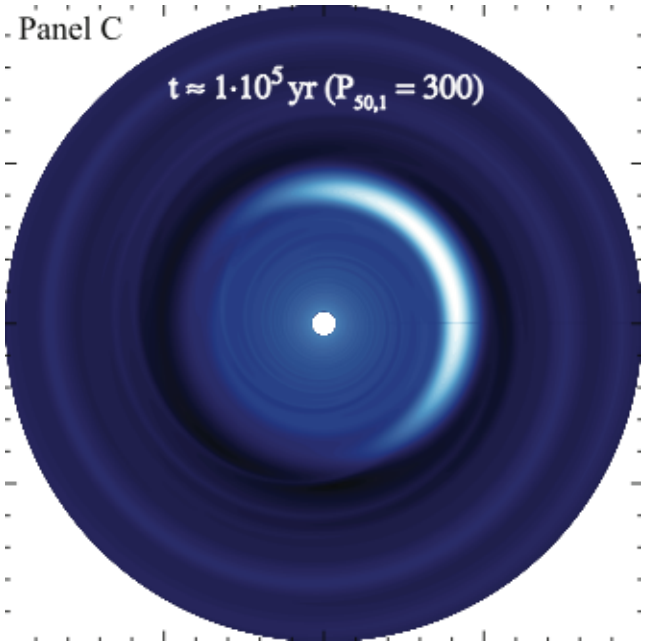
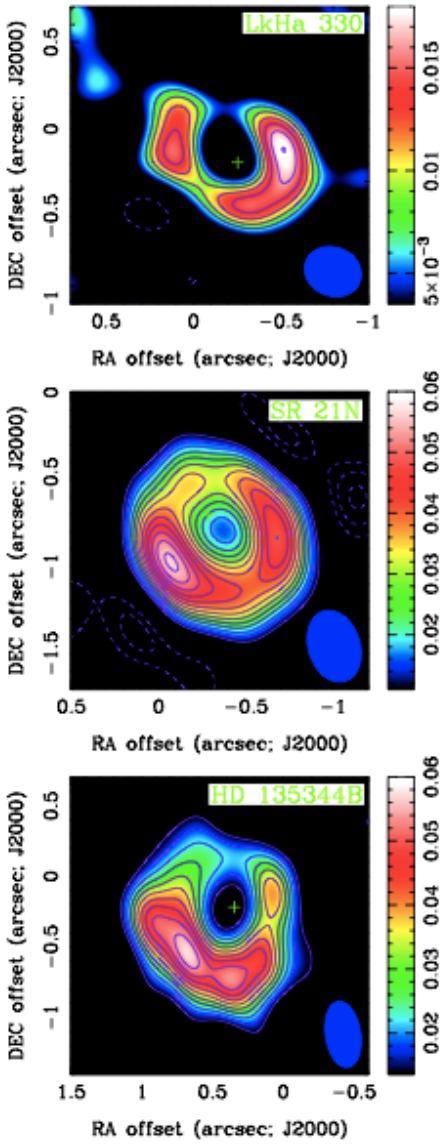


Regaly, Juhasz et al. 2011

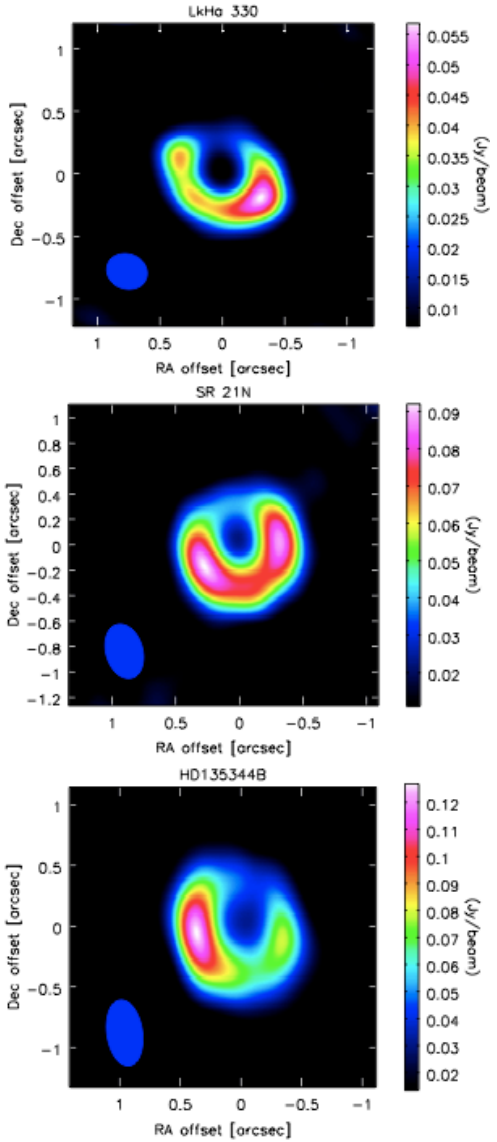
Asymmetries (if real): Dynamical origin?



Observations:



Model:



Regaly, Juhasz, Sandor et al. 2012

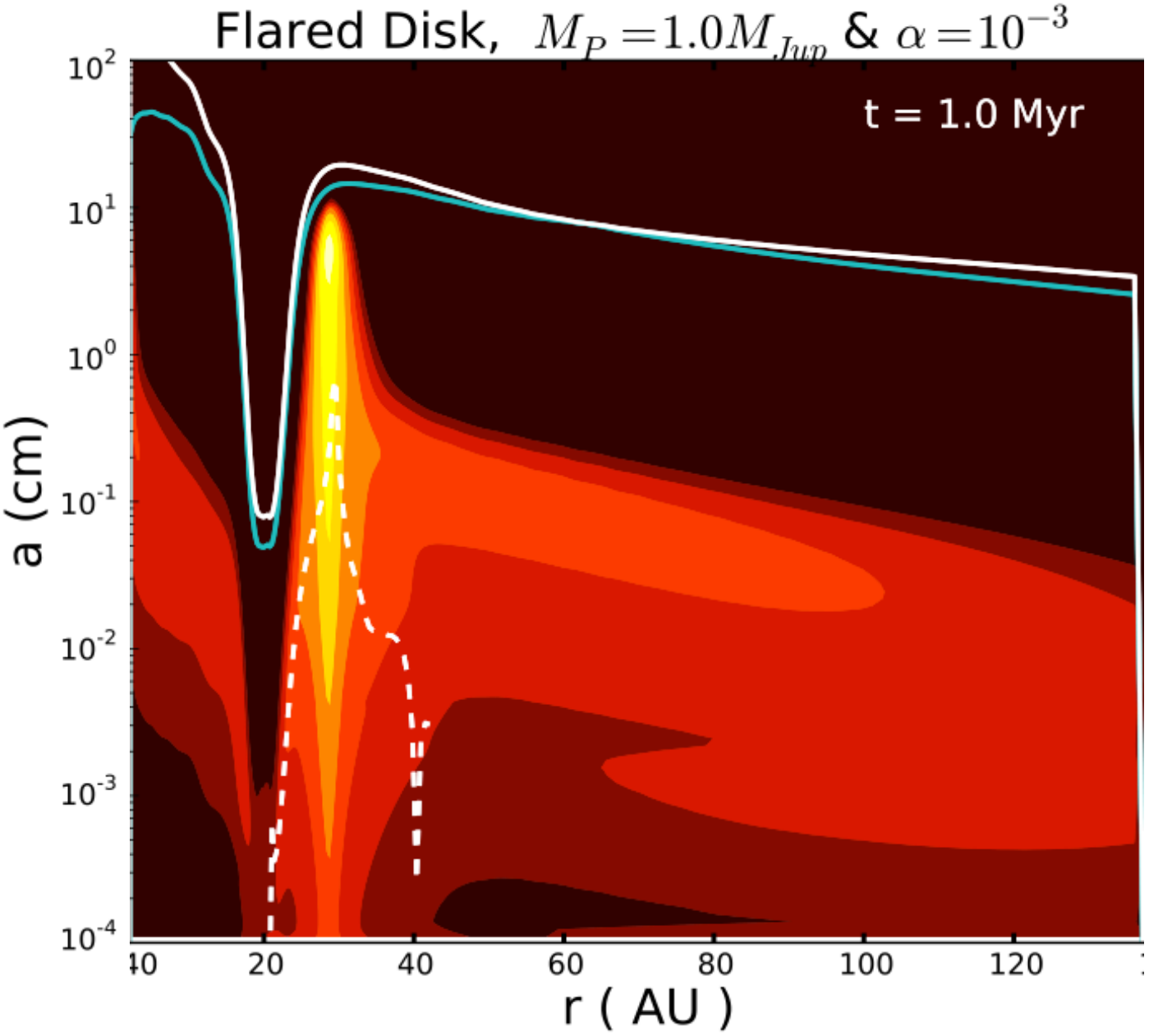
(Observations by Brown et al. 2009)

Conjecture:

The asymmetric rings seen in many transition disks are in fact huge vortices and thus huge dust traps

Regaly, Juhasz, Sandor & CPD 2012
Pinilla, Benisty & Birnstiel 2012

Dust evolution in transition disks



Pinilla, Benisty & Birnstiel 2012

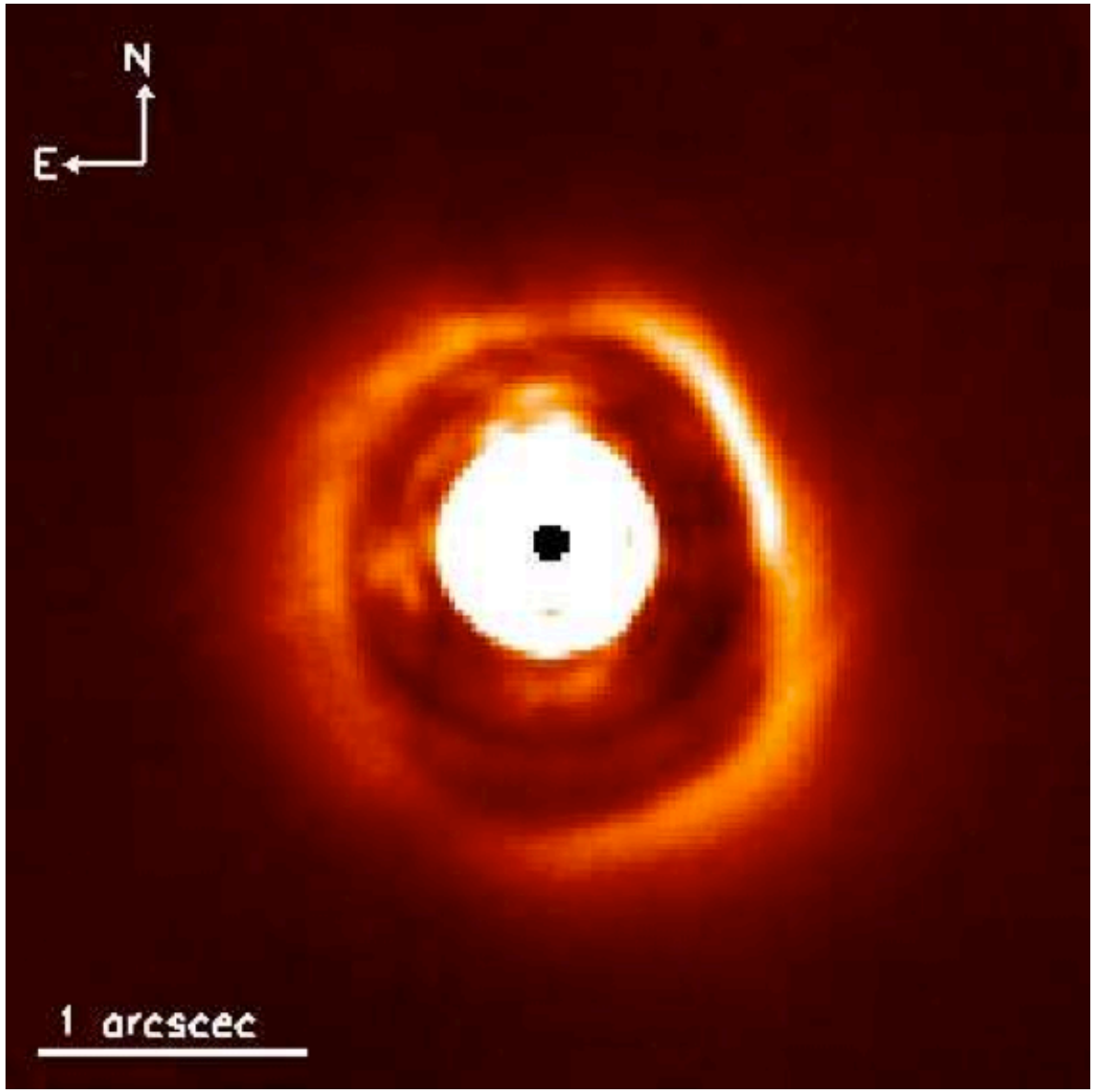
Are we seeing dust trapping here?

HD 142527

A transition disk
with a huge ring.

Here seen in
scattered light
with the VLT/NACO

Keep an eye open for
the ALMA image to be
published soon!



Rameau et al. 2012

Conclusion

- There are quite a number of transition disks:
  - They usually have a large dust ring in their mm-continuum images
  - There is evidence (and presumably more to come) that many of these rings have asymmetries
- Maybe interpretation in terms of vortices:
  - Numerical hydrodynamic modeling (Klahr et al.; Regaly et al.) show that huge vortices can form under certain conditions.
  - They appear similar to the observed ones
  - Dust trapping can enhance this
  - Conjecture: the asymmetric rings are such vortices