Structure and Evolution of Protoplanetary Disks

Review Talk

C.P. Dullemond
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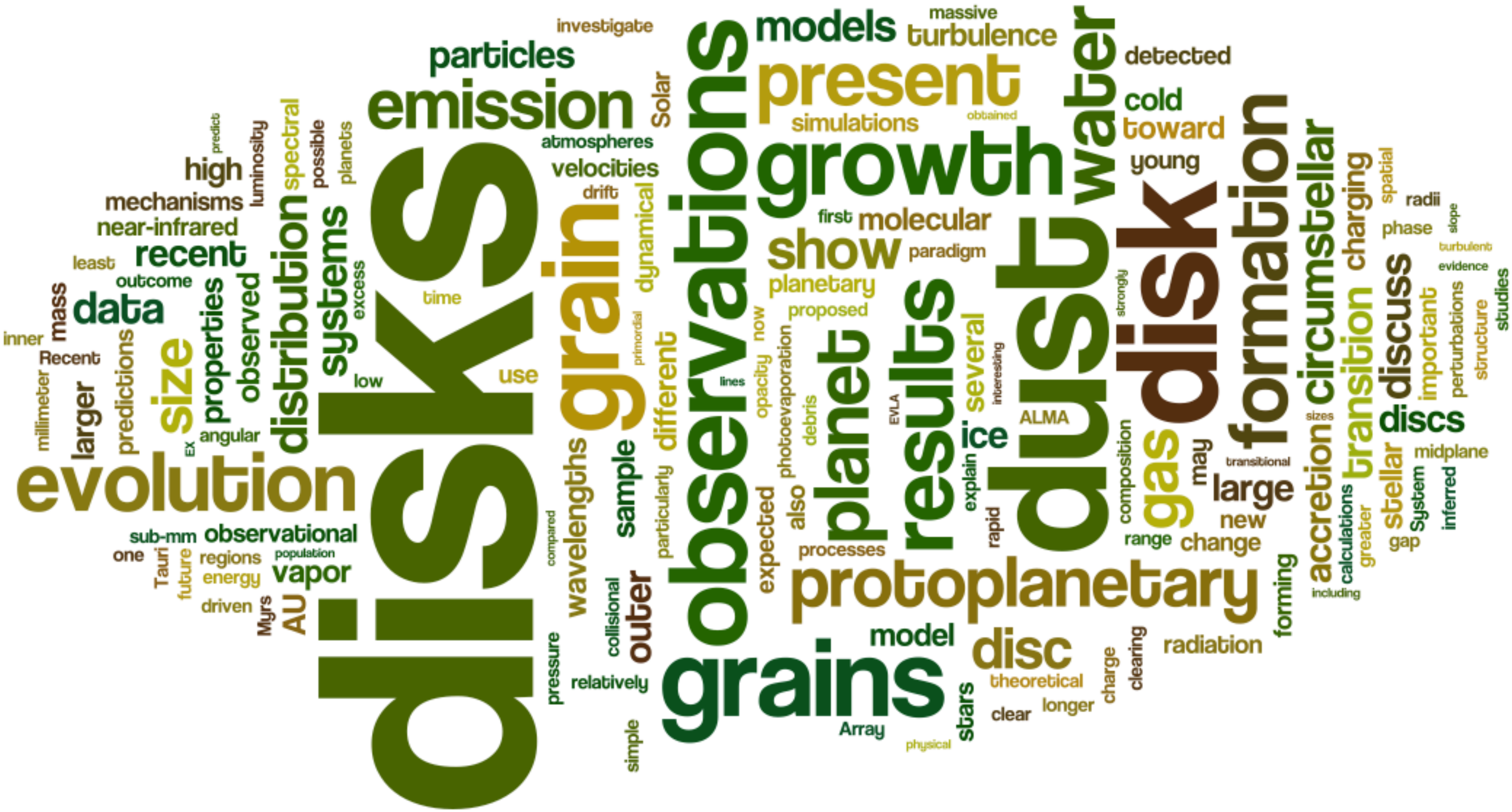
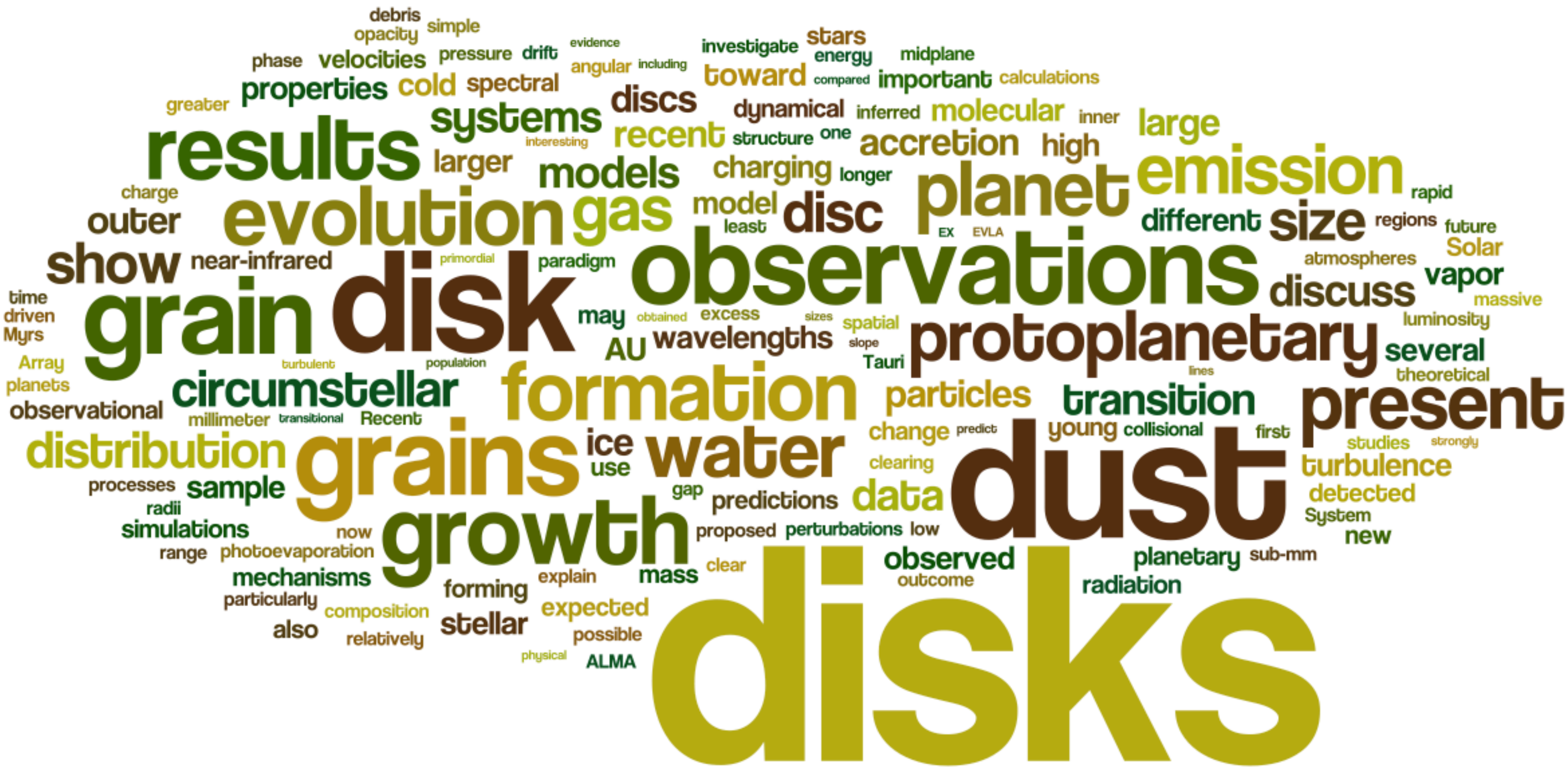
Heidelberg, Germany

This session as a word cloud:



Made with: www.wordle.net

This session as a word cloud:



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Main features of a protoplanetary disk

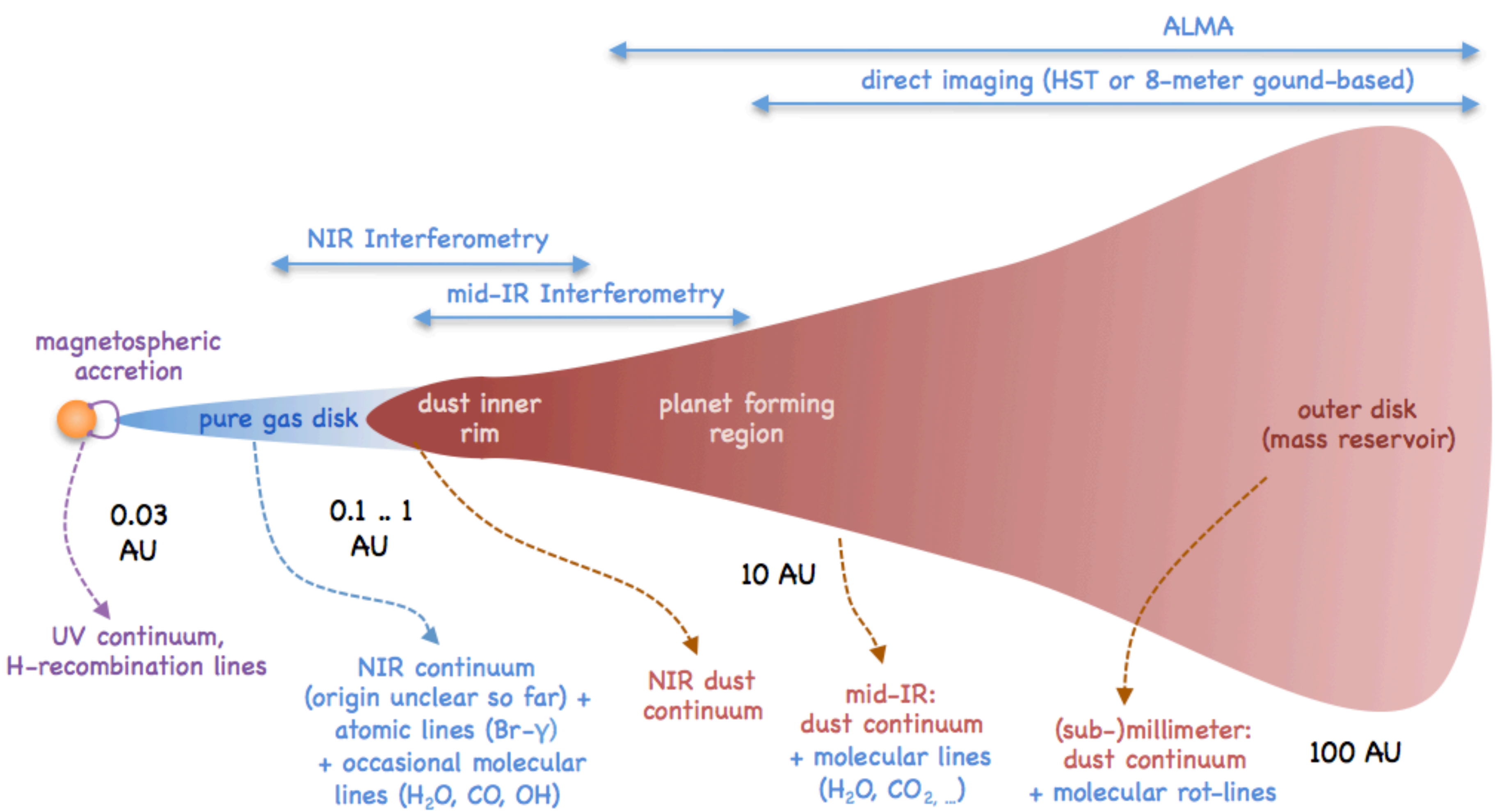
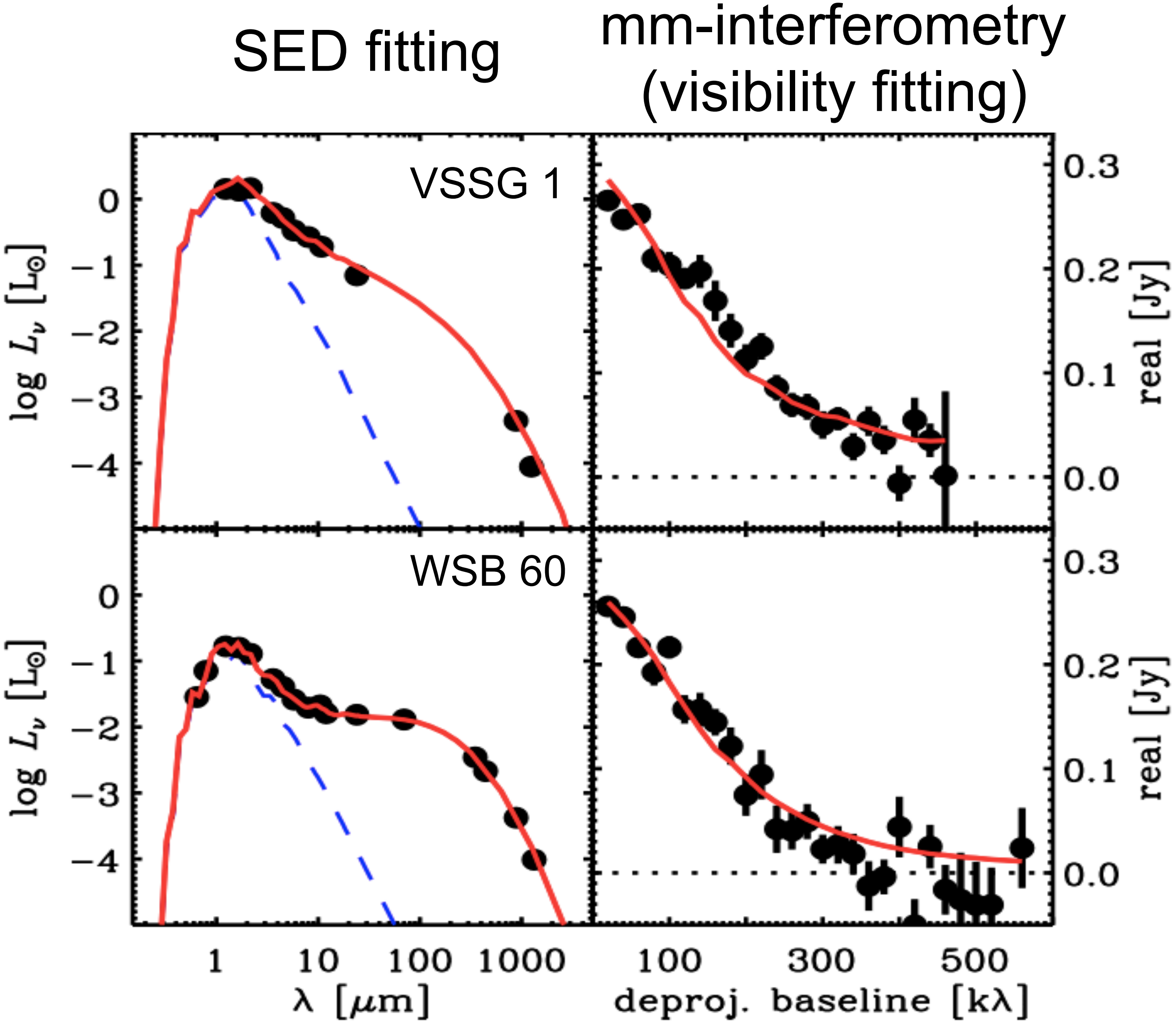


Figure from: Dullemond & Monnier (2010) Ann. Rev. A&A

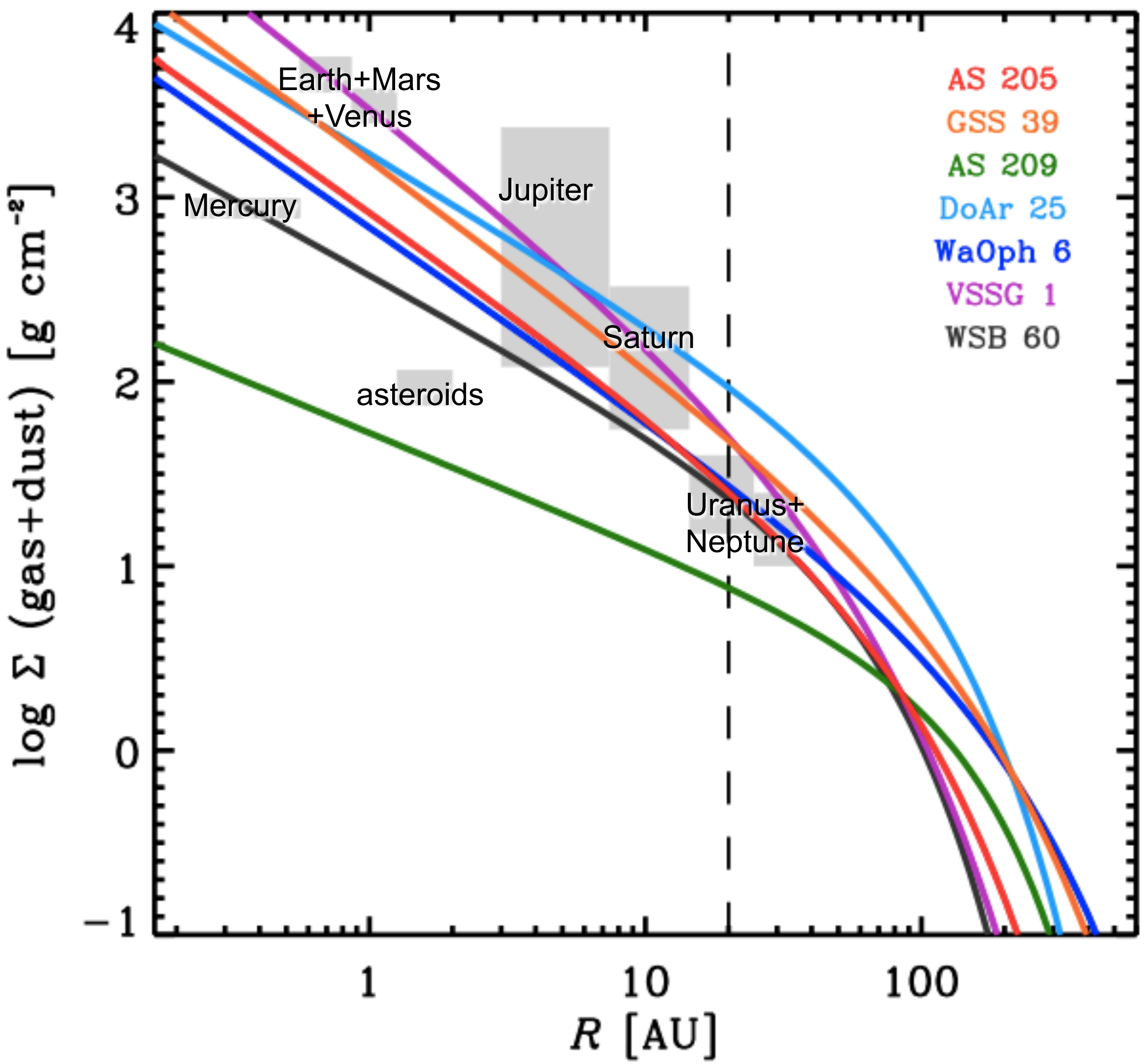
Radial distribution of matter



SED + millimeter resolved maps (=visibility values)

Andrews et al. (2009)

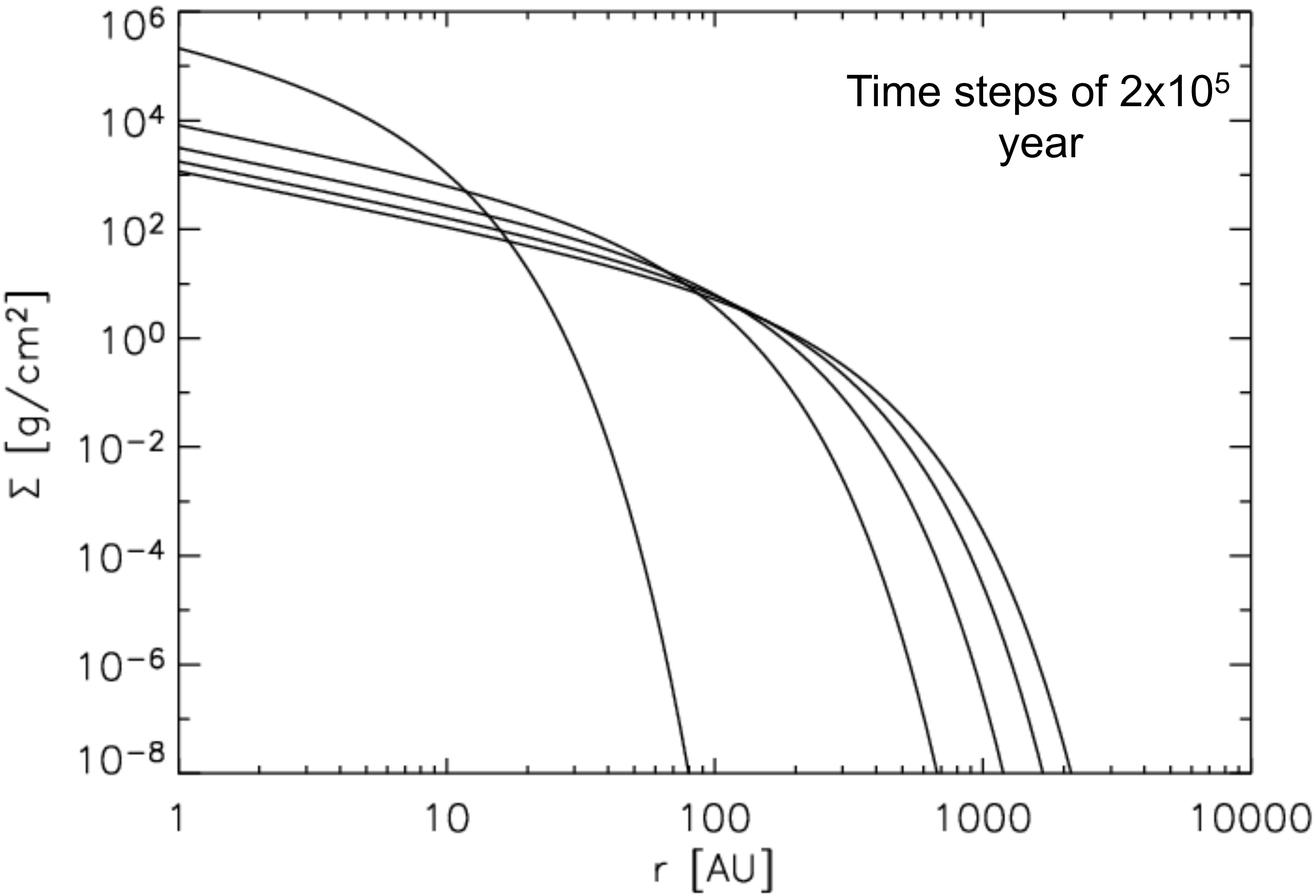
Radial distribution of matter



Andrews et al. (2009)

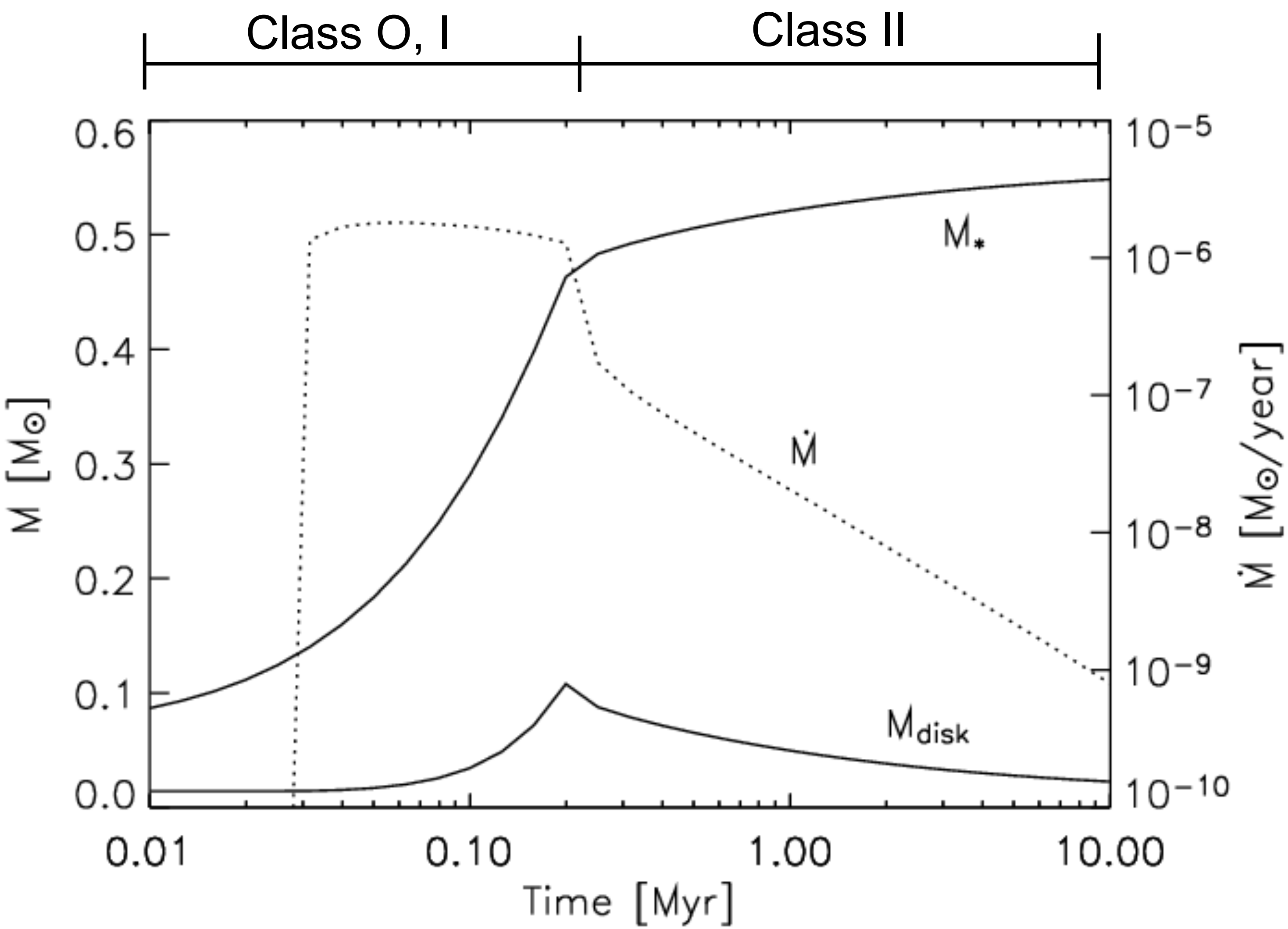
See also poster 78 Wright

Non-stationary (spreading) disks



Lynden-Bell & Pringle (1974), Hartmann et al. (1998)

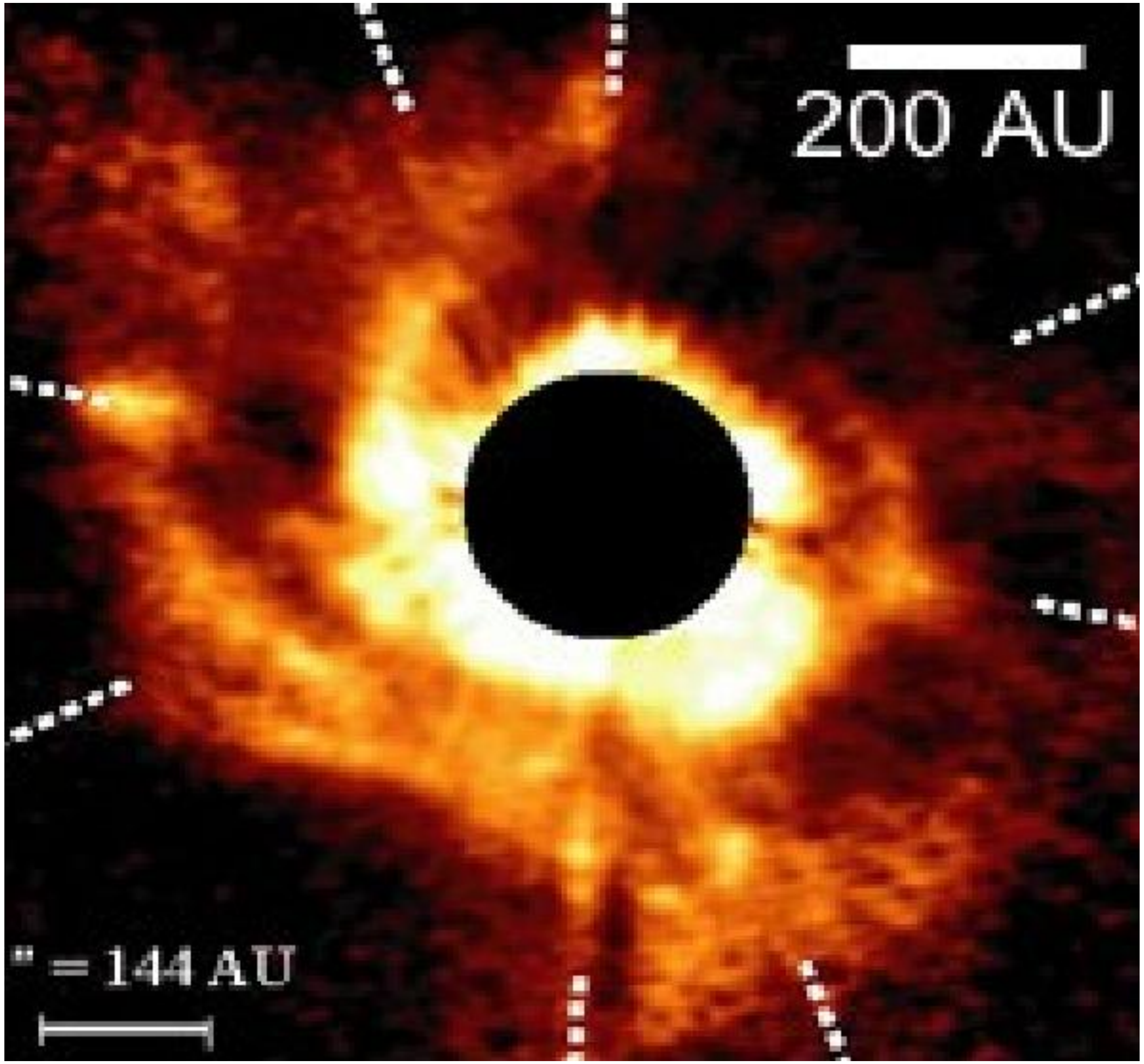
Evolution of disk parameters



See also poster 47 Manara and poster 63 Ratzka on disk evolution

(after Hueso & Guillot 2005)

However: disks are not axially symmetric...

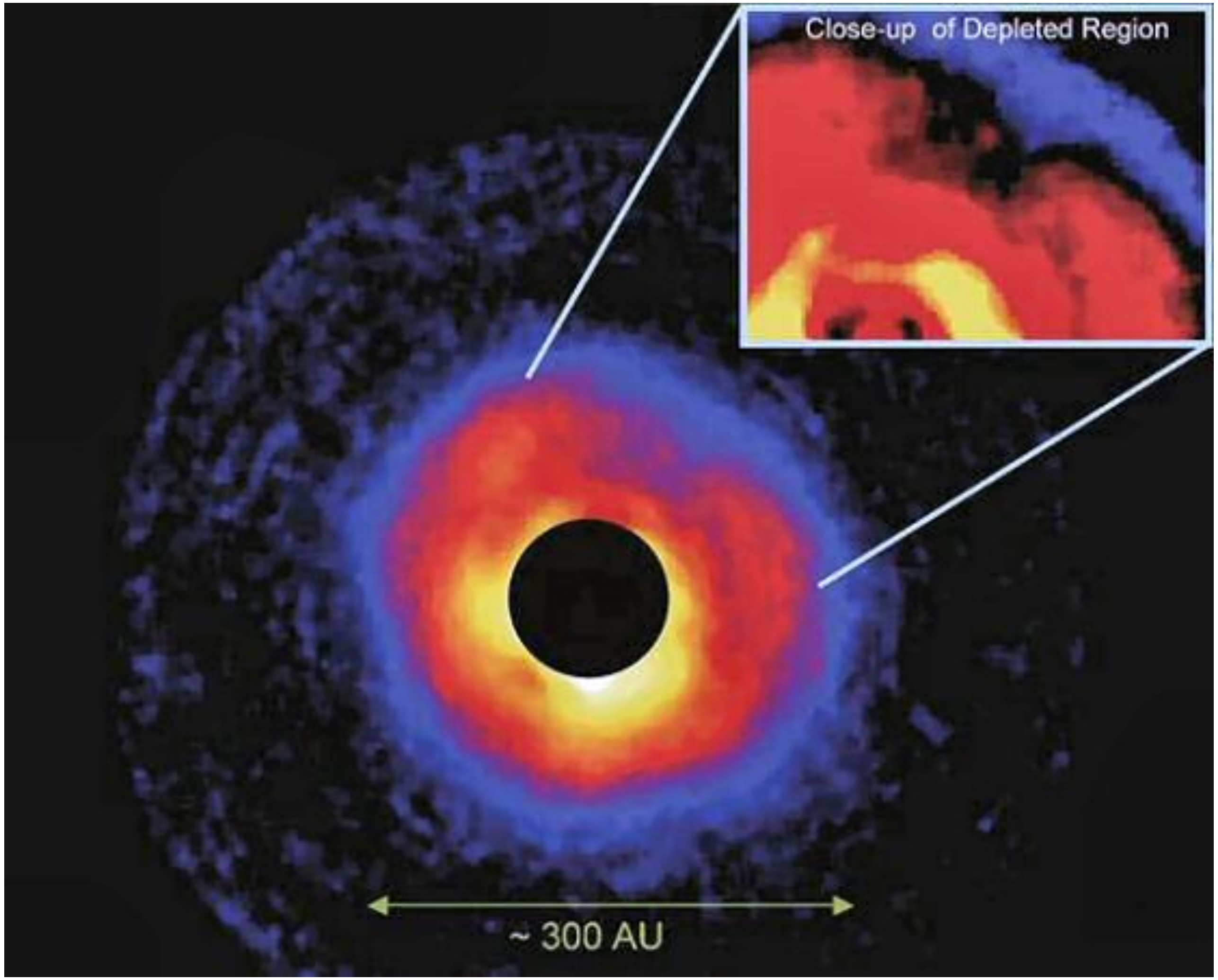


AB Aurigae

Scattered light

Fukagawa et al. 2004

However: disks are not axially symmetric...



Oppenheimer et al. 2008

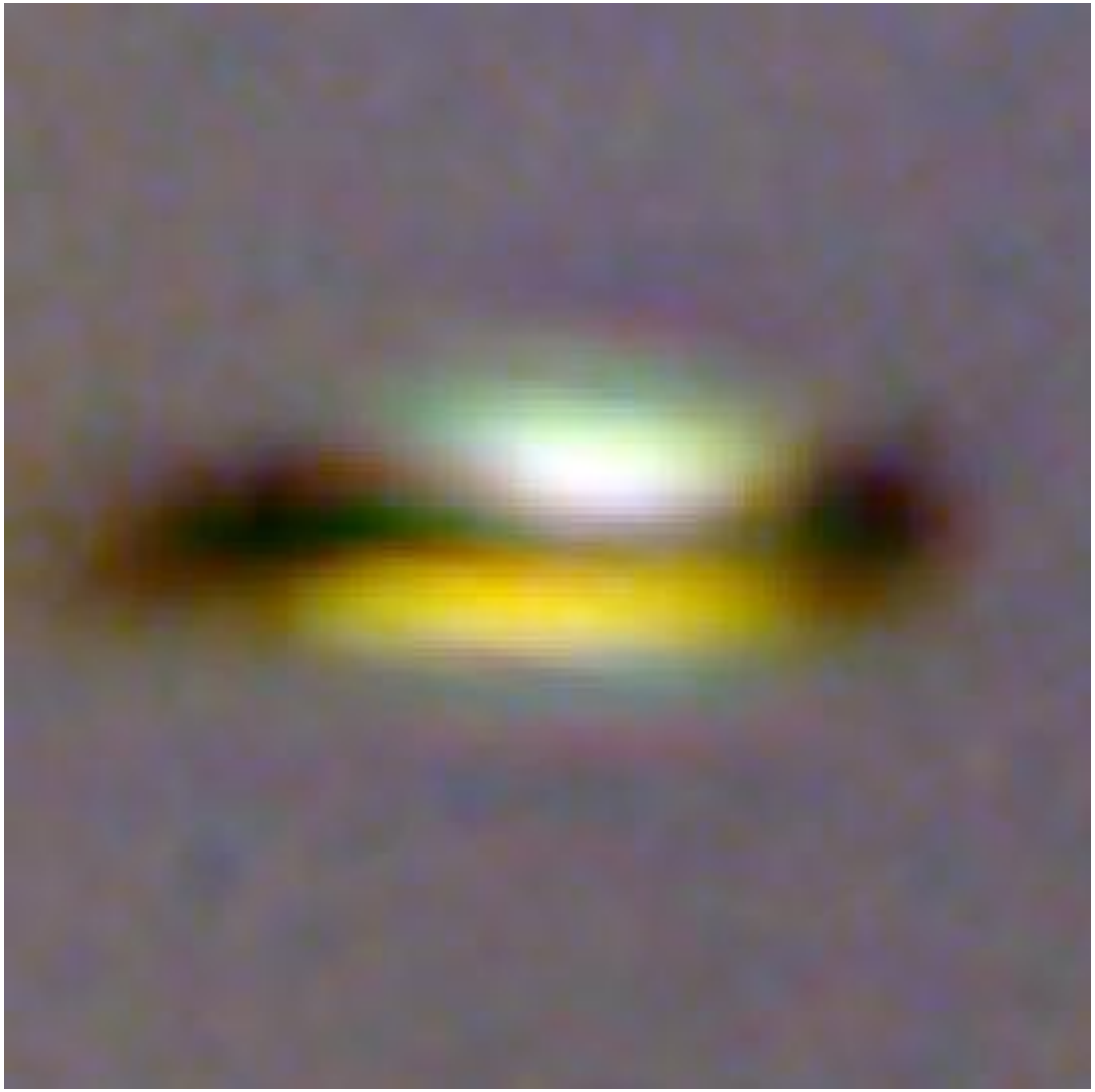
AB Aurigae

Scattered light, polarized component

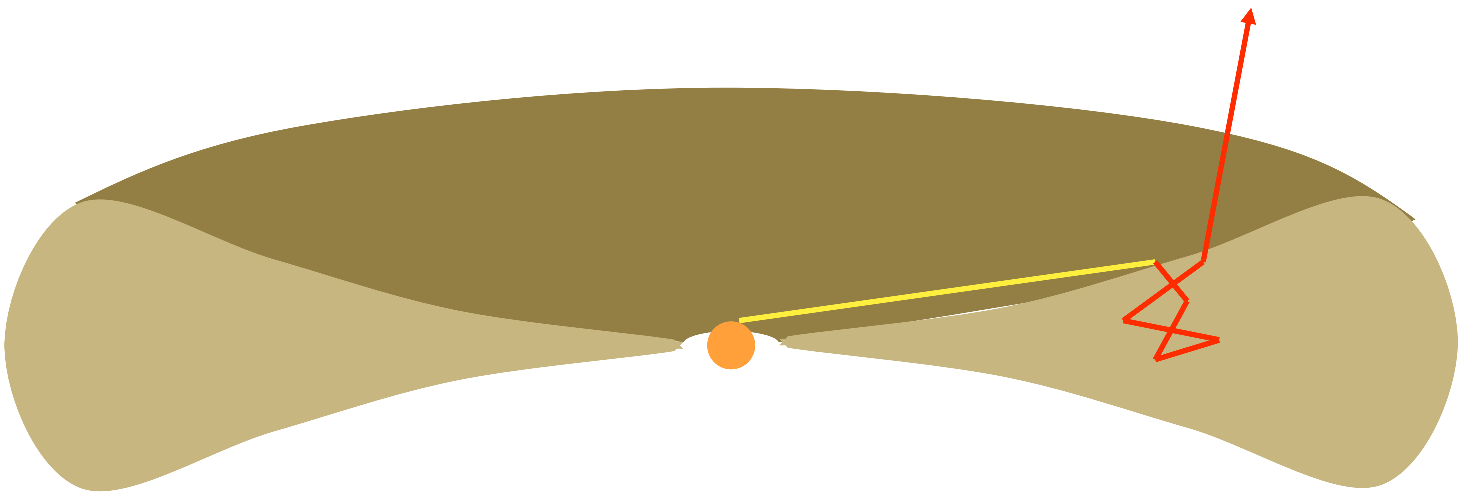
See also talk by Panic
See poster 13 Demidova, poster 33 Juhasz, poster 65 Rosenfeld, poster 66 Ruge (?)

Vertical structure of a protoplanetary disk

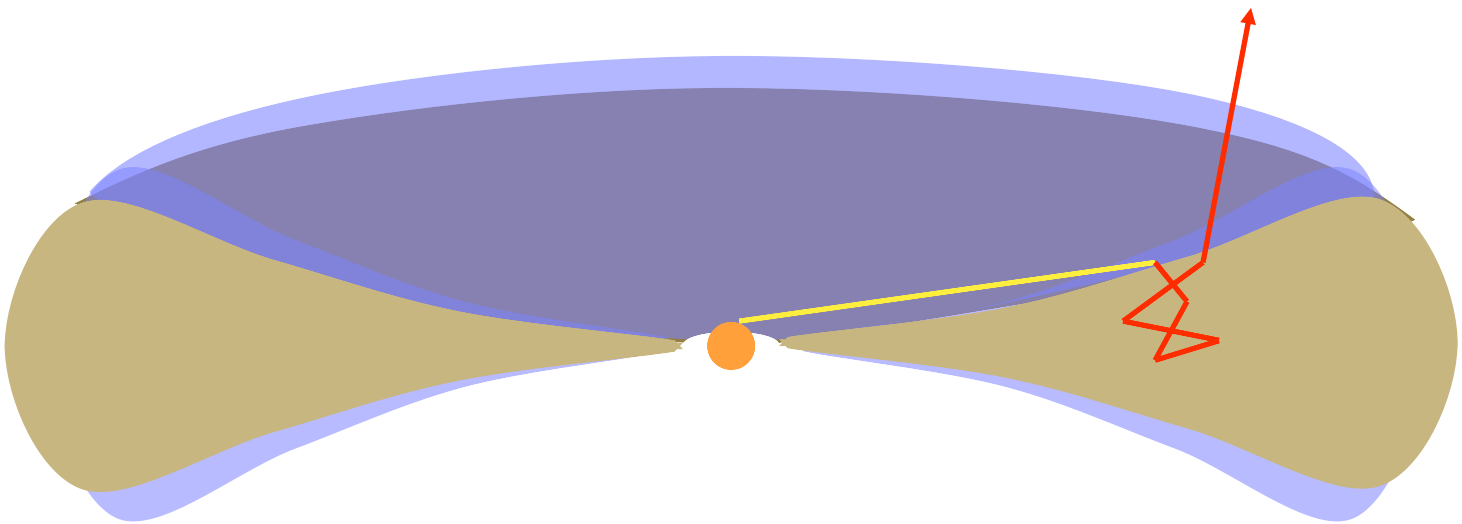
Still one of the nicest disk images:



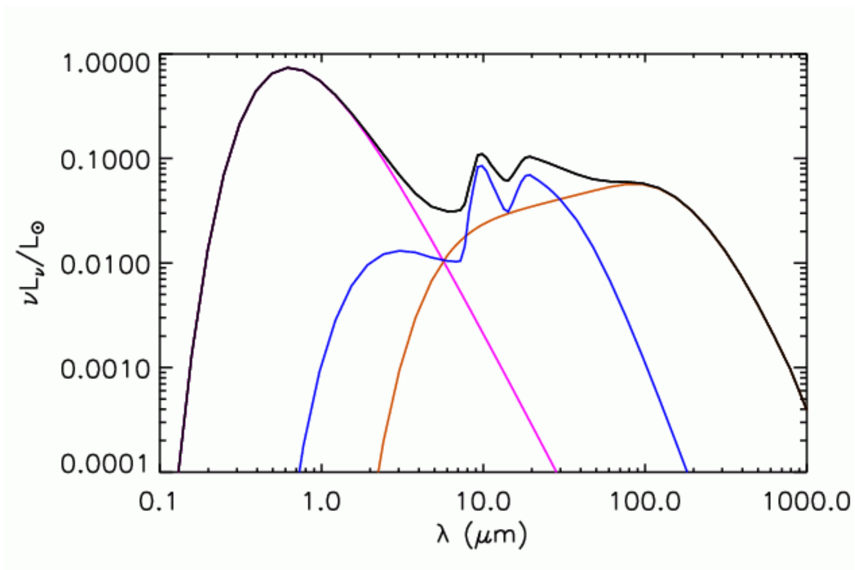
Flaring disk structure: irradiation



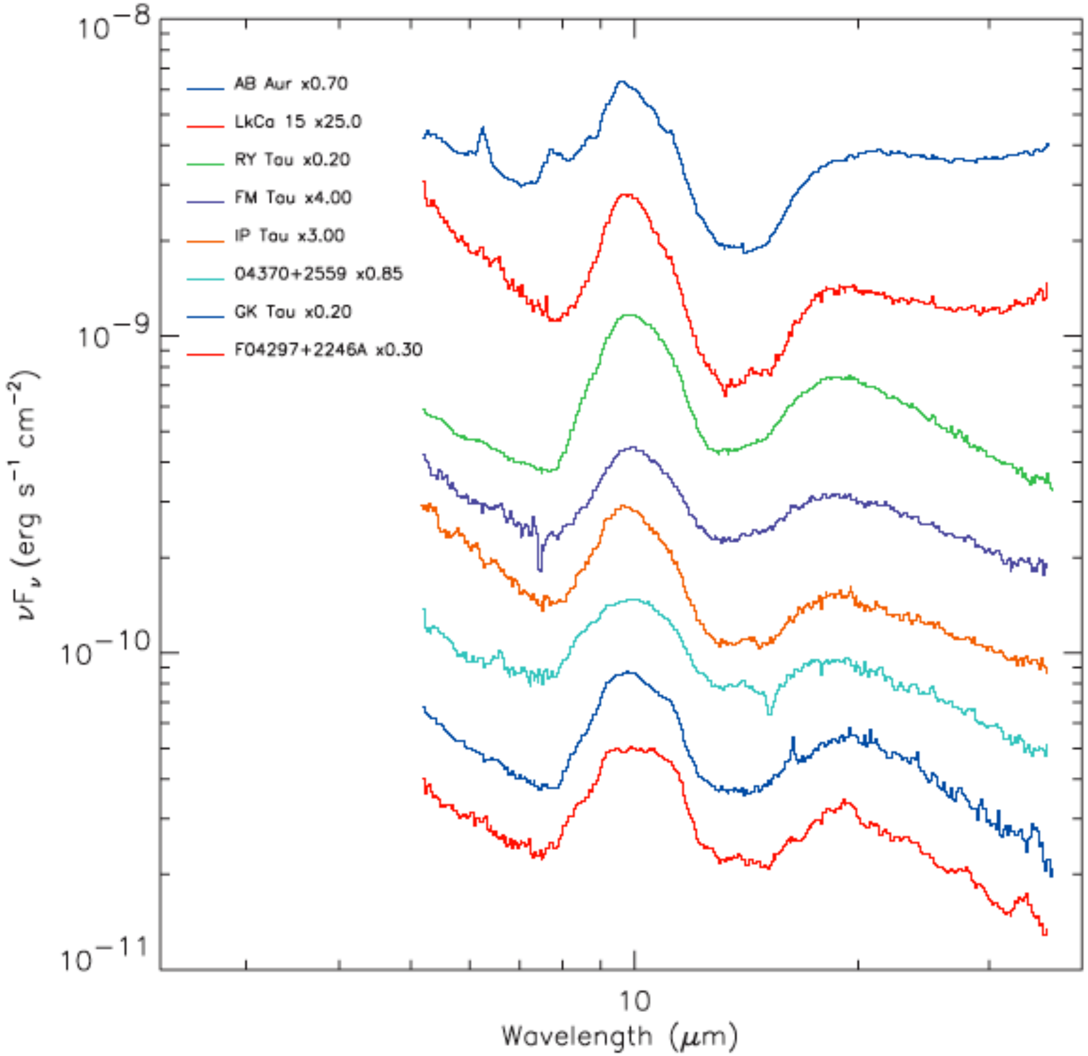
Creation of a warm surface layer



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



T Tauri Star SEDs:

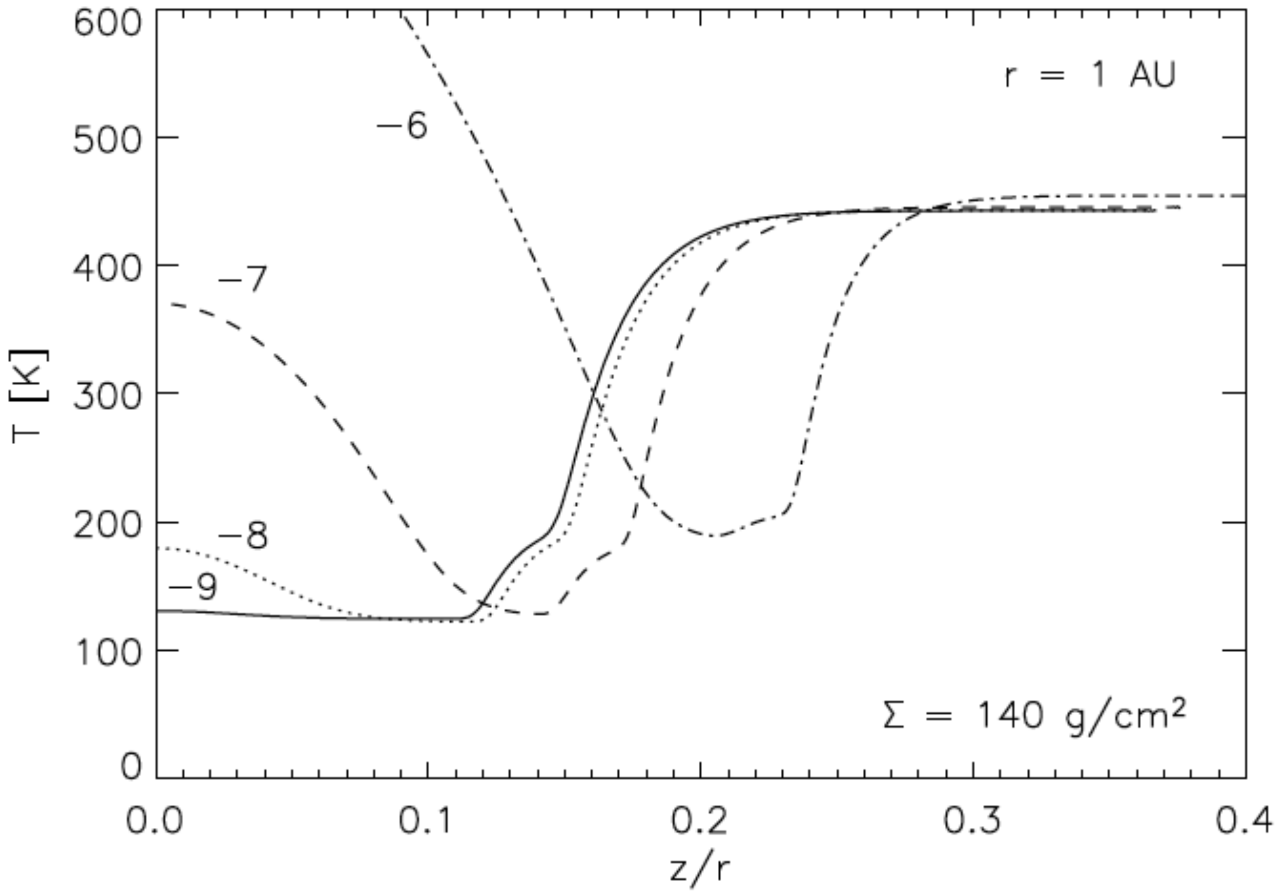


Furlan et al. 2006

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

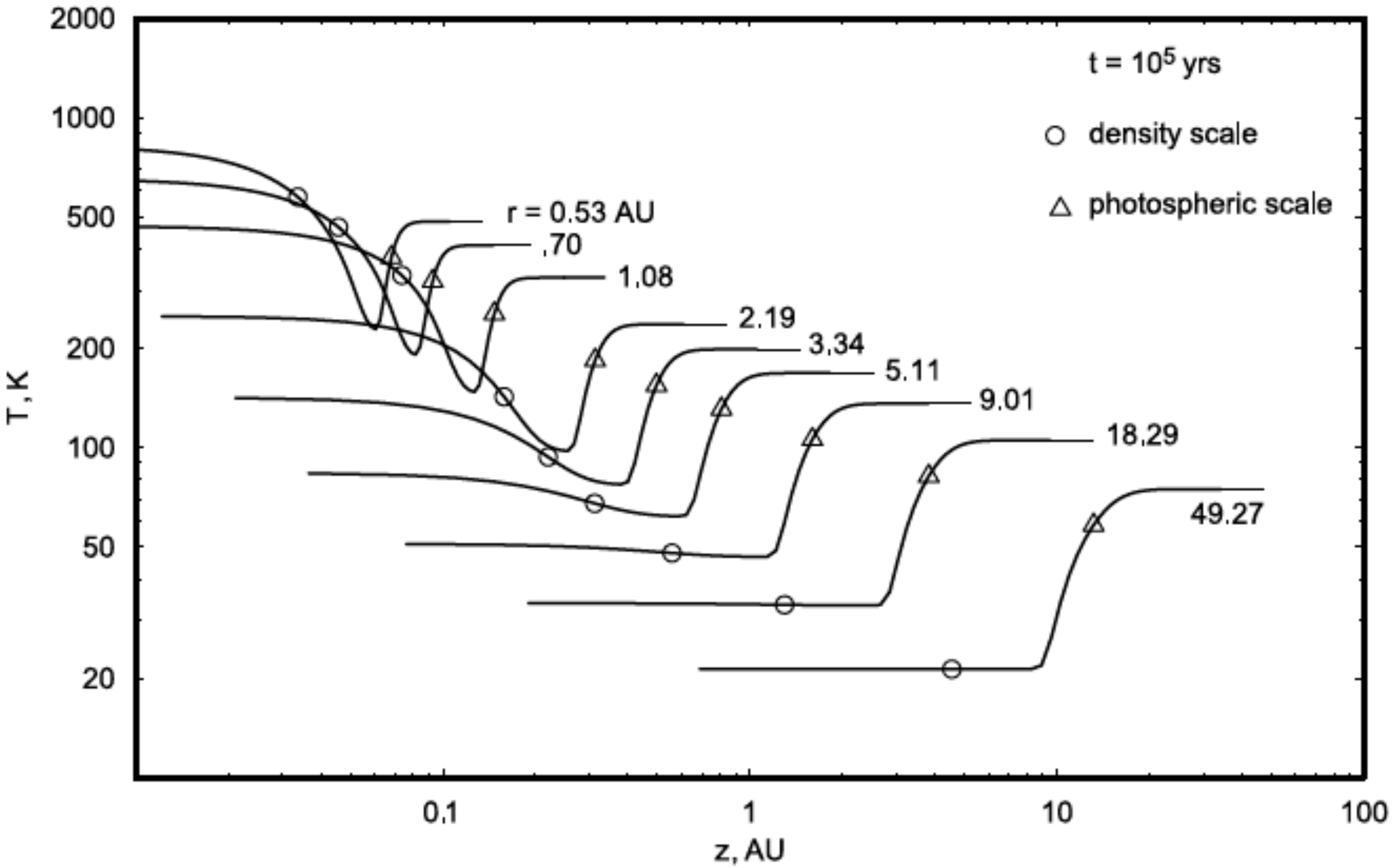


Model from Paola D'Alessio
(from: Dullemond, Hollenbach, Kamp & D'Alessio PPV review)

See poster
50 Mulders

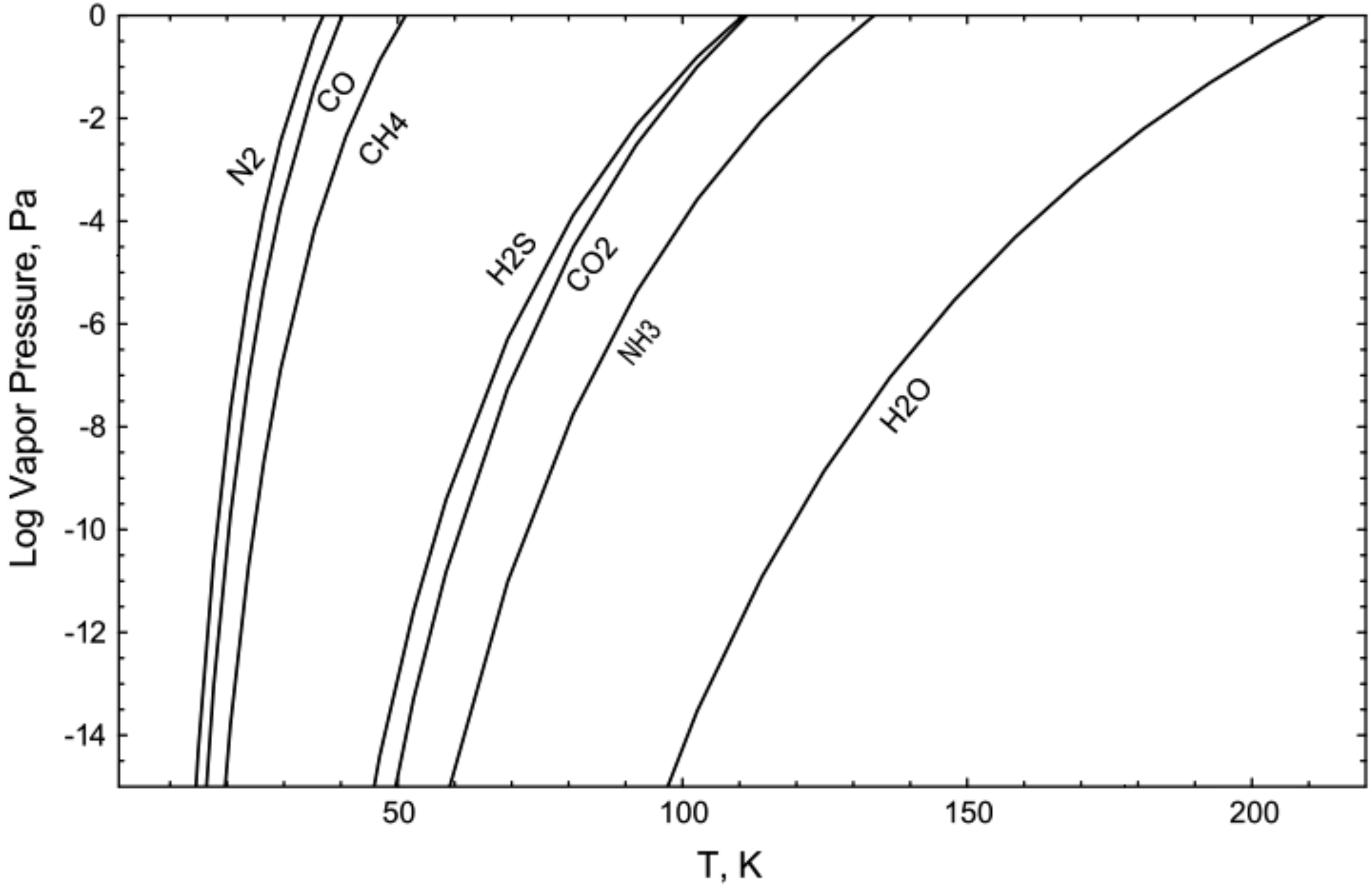
Cold midplane layers: Ice-coated dust? (i.e. where is the „snow line“?)

Where is the ‘snow line’?



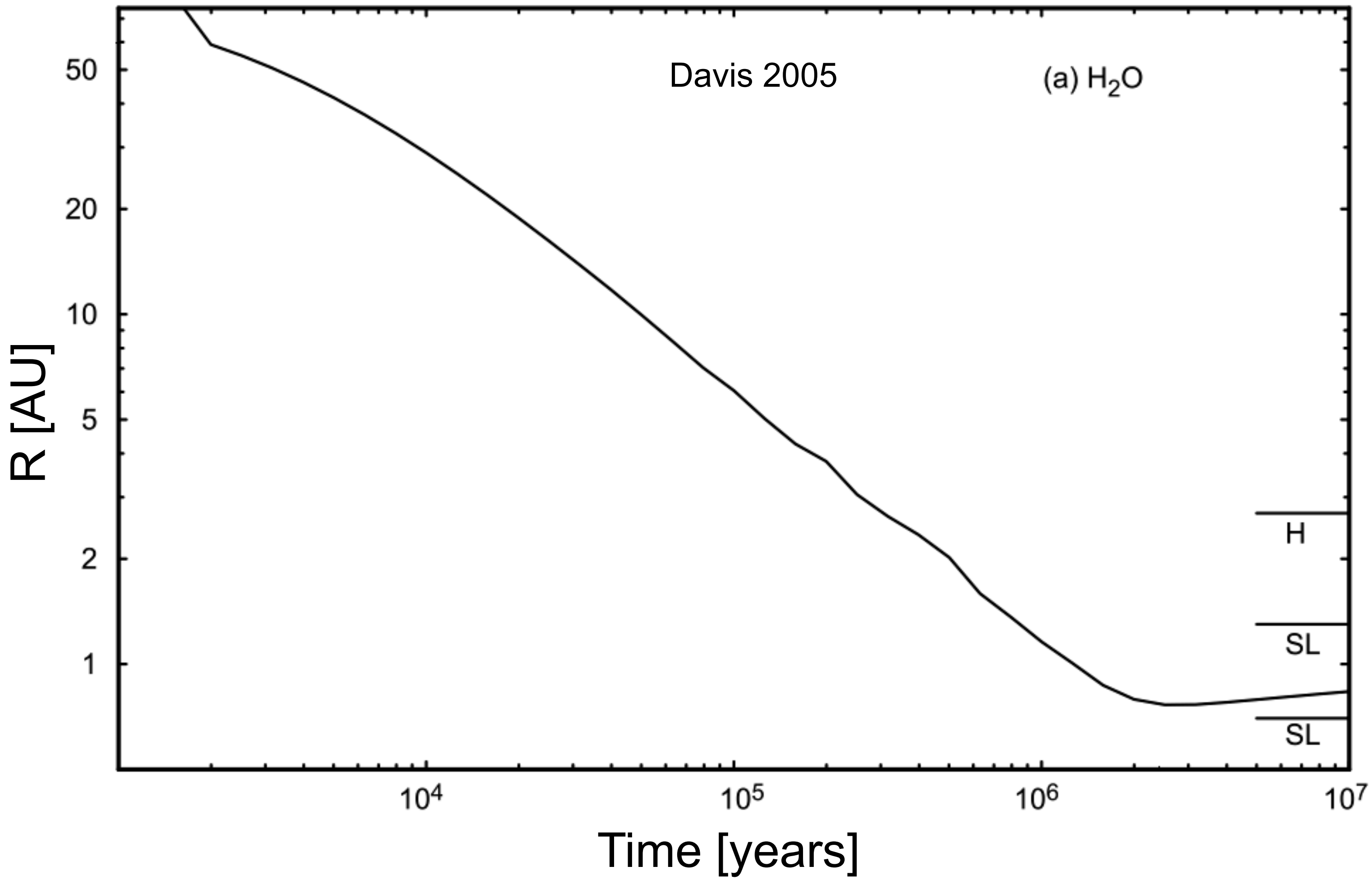
Davis (2005)

Where is the ‘snow line’?



Davis 2005
Lecar, Podolak, Sassalov & Chiang 2006

Where is the ‘snow line’?

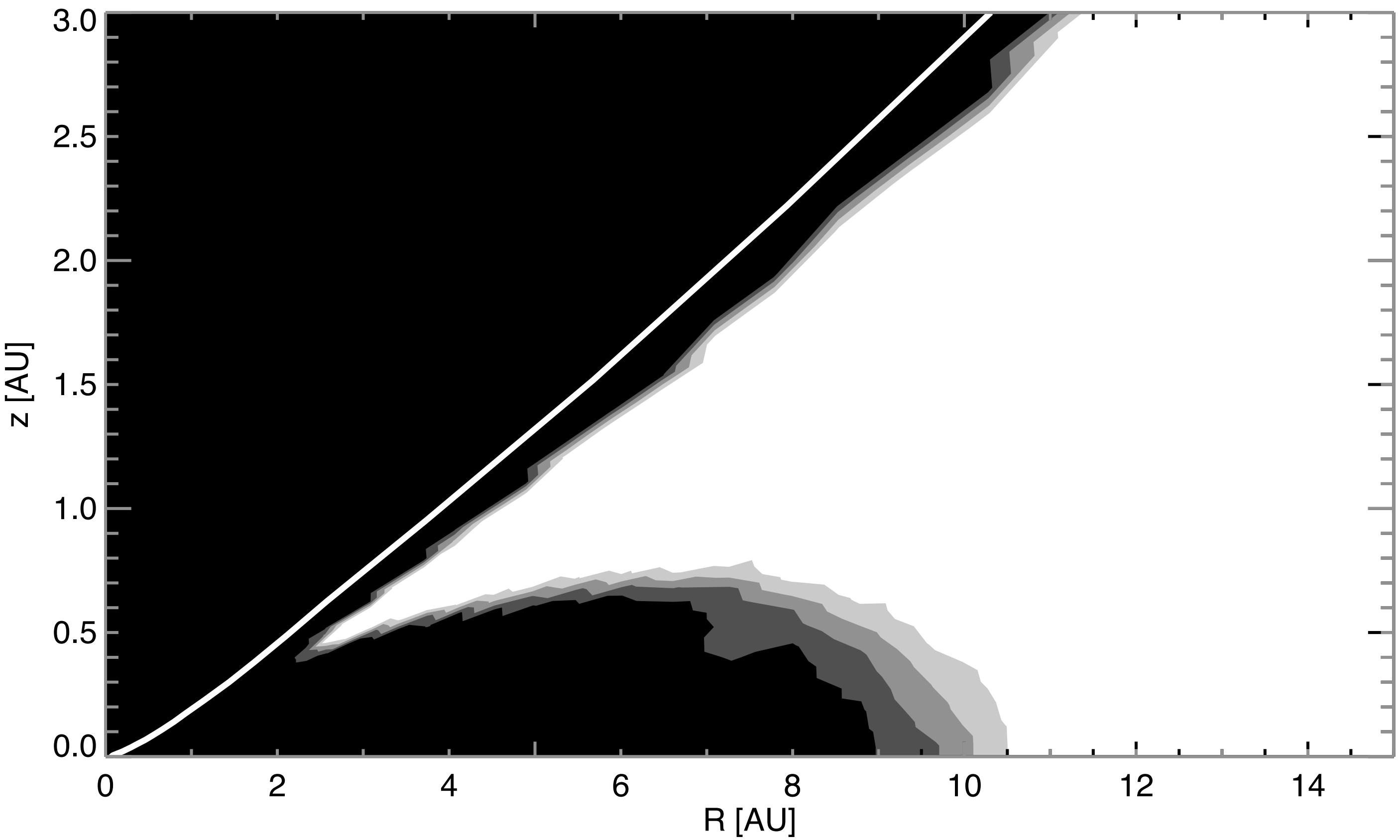


Davis 2005
Lecar, Podolak, Sassalov & Chiang 2006

Where is the ‘snow line’?

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

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

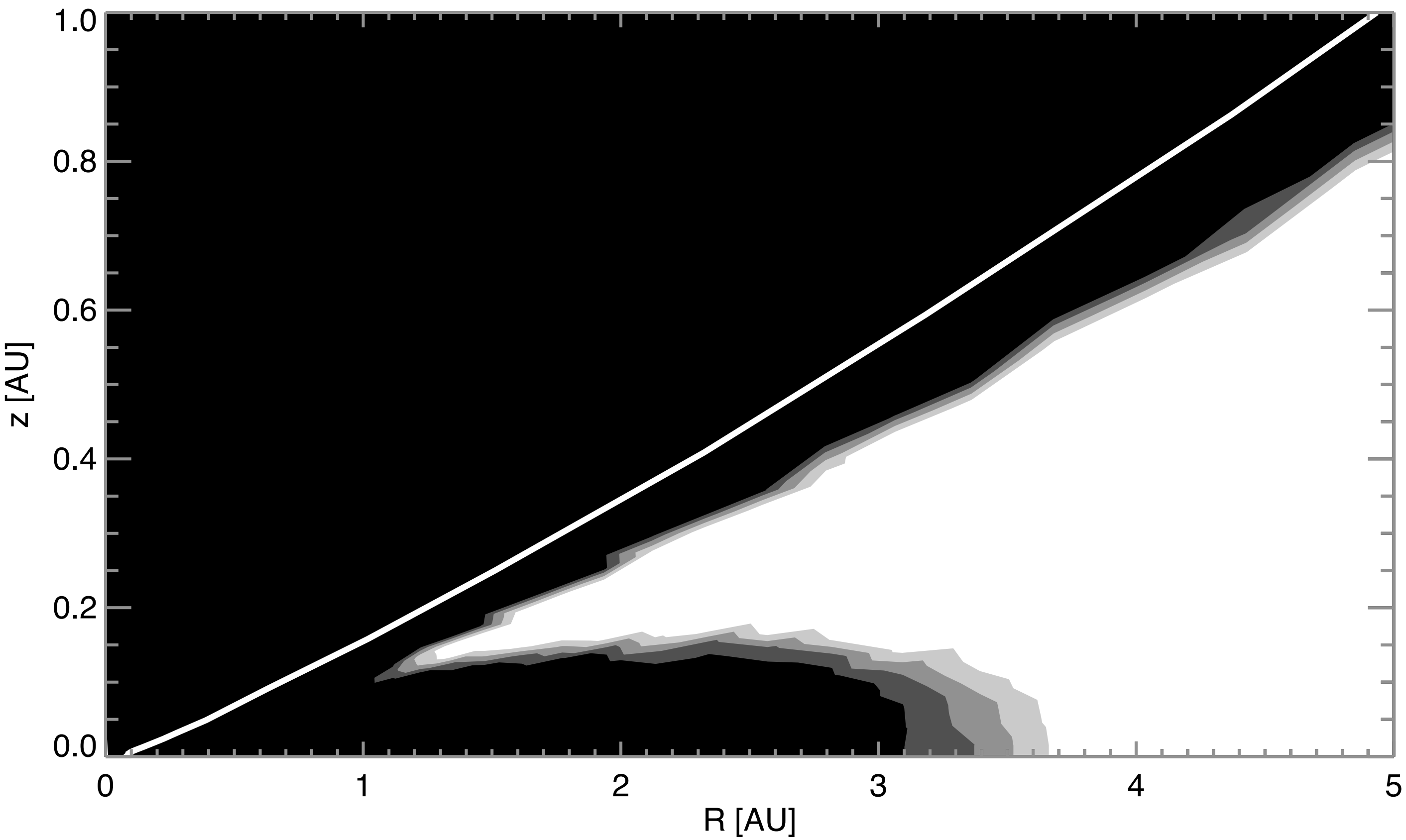


Min, Dullemond, Dominik & Kama 2011

Where is the ‘snow line’?

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

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

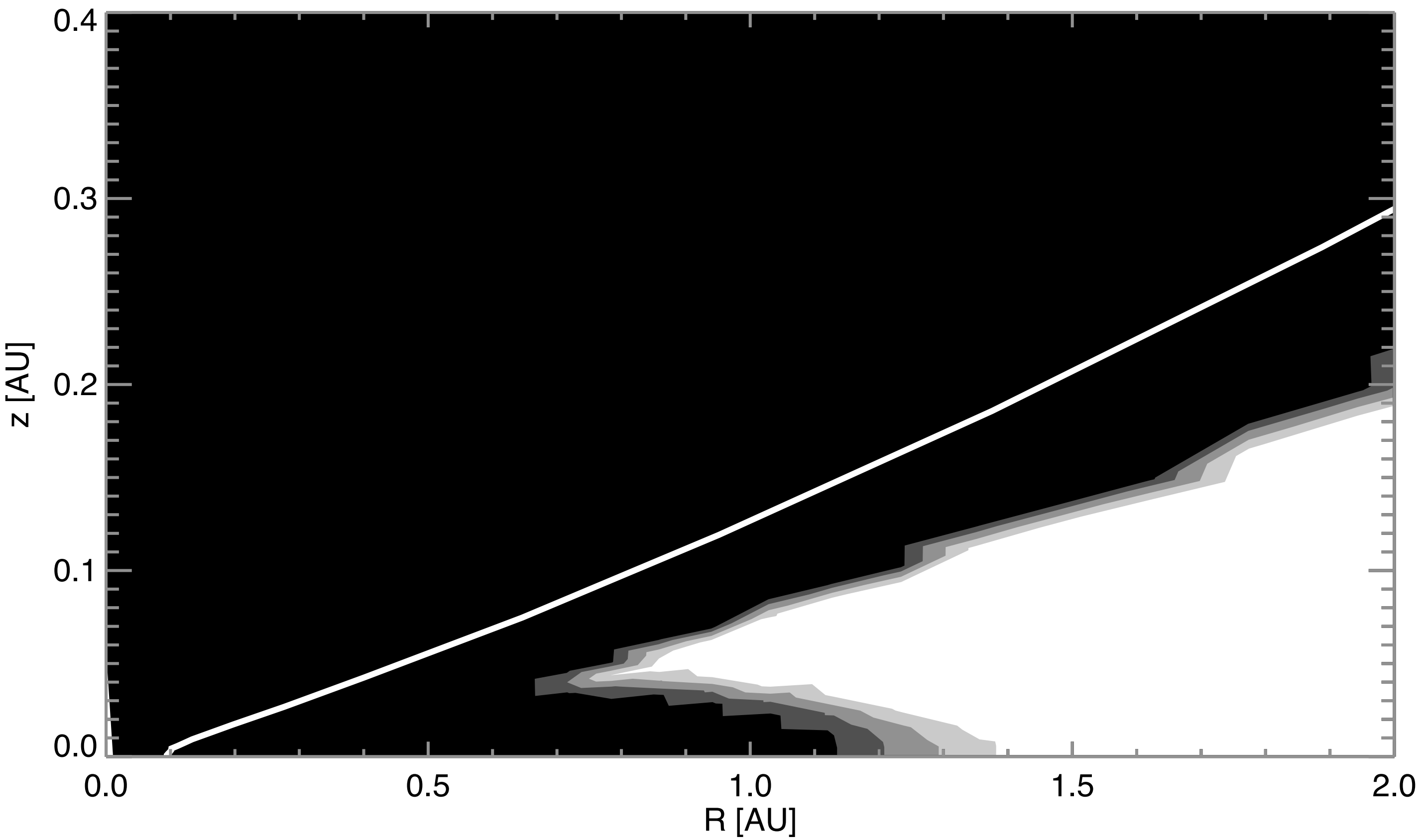


Min, Dullemond, Dominik & Kama 2011

Where is the ‘snow line’?

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

dM/dt = 10^{-9} $M_\odot$/yr, α=0.01

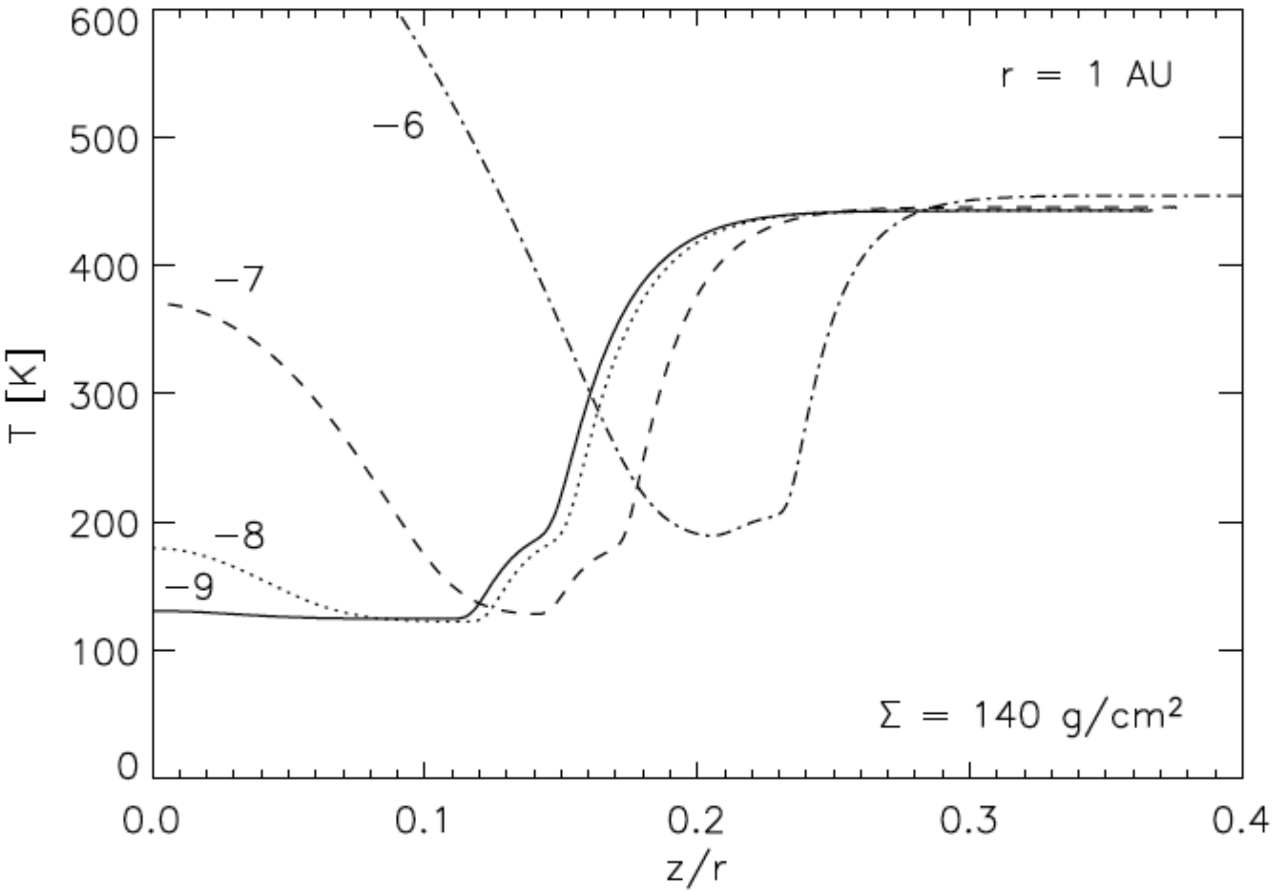


Min, Dullemond, Dominik & Kama 2011

See talk Dominik,
See poster 31 Honda
poster 73 Terada

Warm surface layers: rich in molecules?

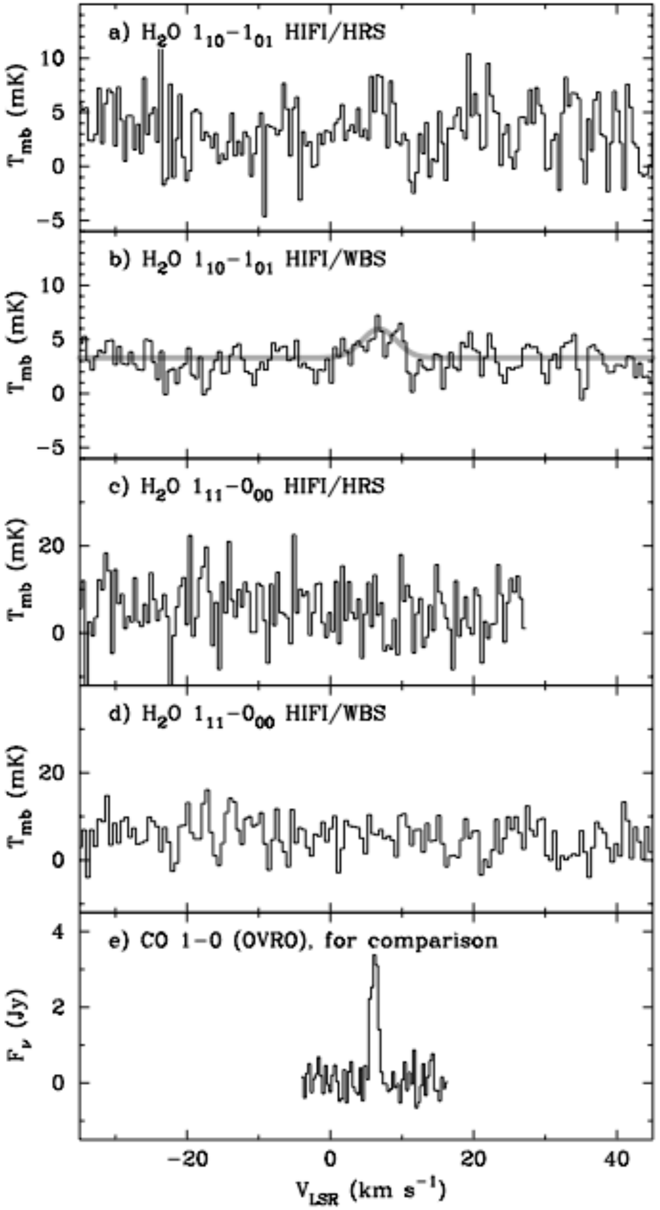
Warm surface layers: rich in molecules?



Model from Paola D'Alessio

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

The dryness of the surface layers



Several disks have much weaker H_2O vapor lines in their Herschel spectra than expected from models. Conclusion: Their outer disk surface layers appear to be „dry".

Bergin, Hogerheijde et al. 2010

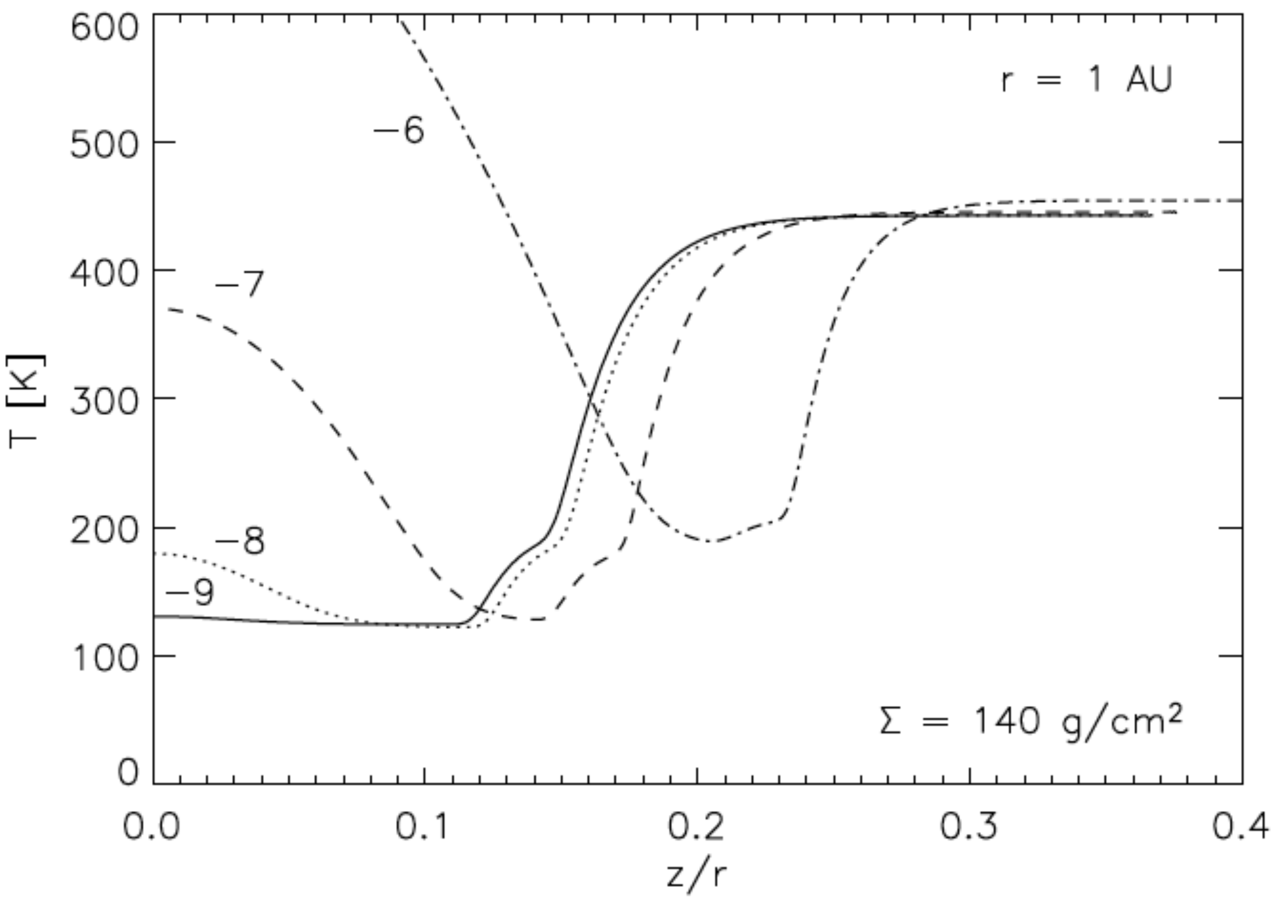
See talk Dominik about theoretical interpretation

See talk Hogerheijde about the latest on H_2O in disks

More on molecules in disks:
see talks by Mandell and by Banzatti,
see poster 43 Lahuis

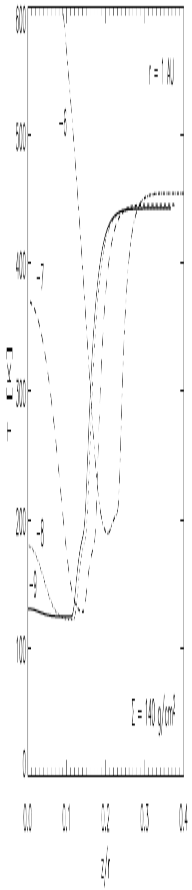
Vertical temperature structure

The *very* upper layers



Vertical temperature structure

The *very* upper layers



Vertical temperature structure

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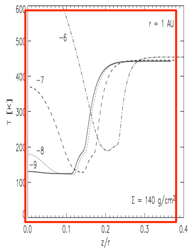
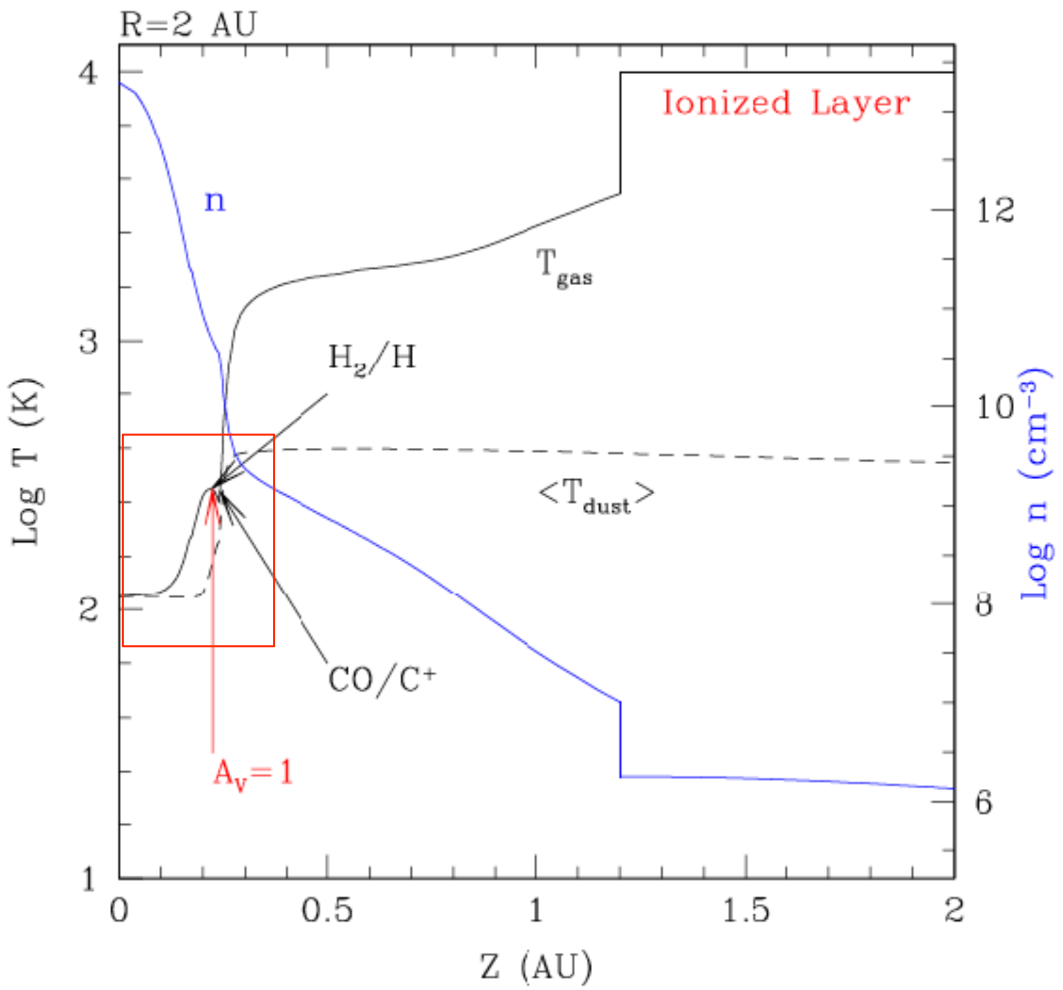


Vertical temperature structure

The *very* upper layers



Gorti & Hollenbach 2008

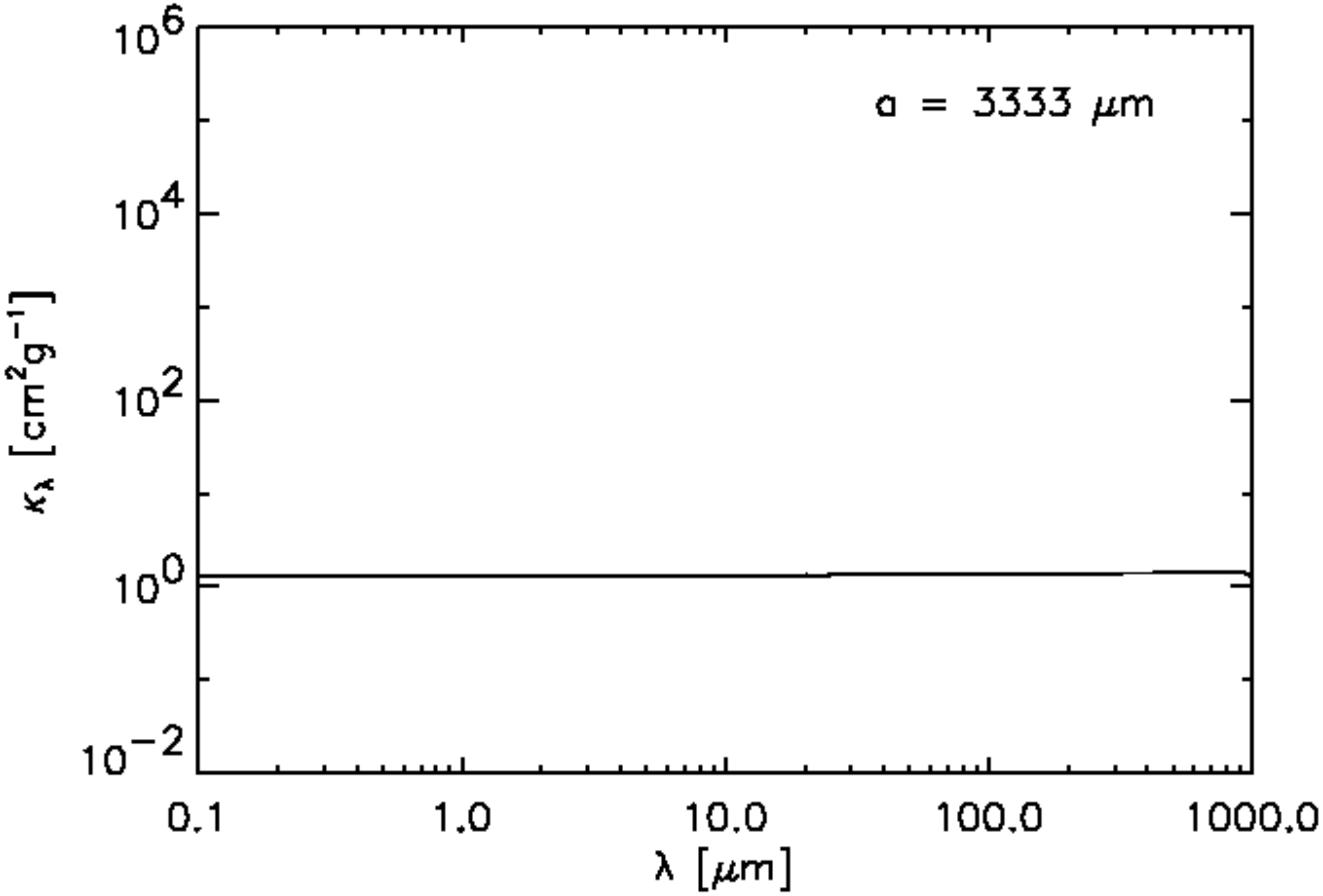
For thermally driven outflow (i.e. disk photoevaporation) see talks by Alexander and by Owen

For atomic line emission from these regions: Talks by Rigliaco and by Sacco

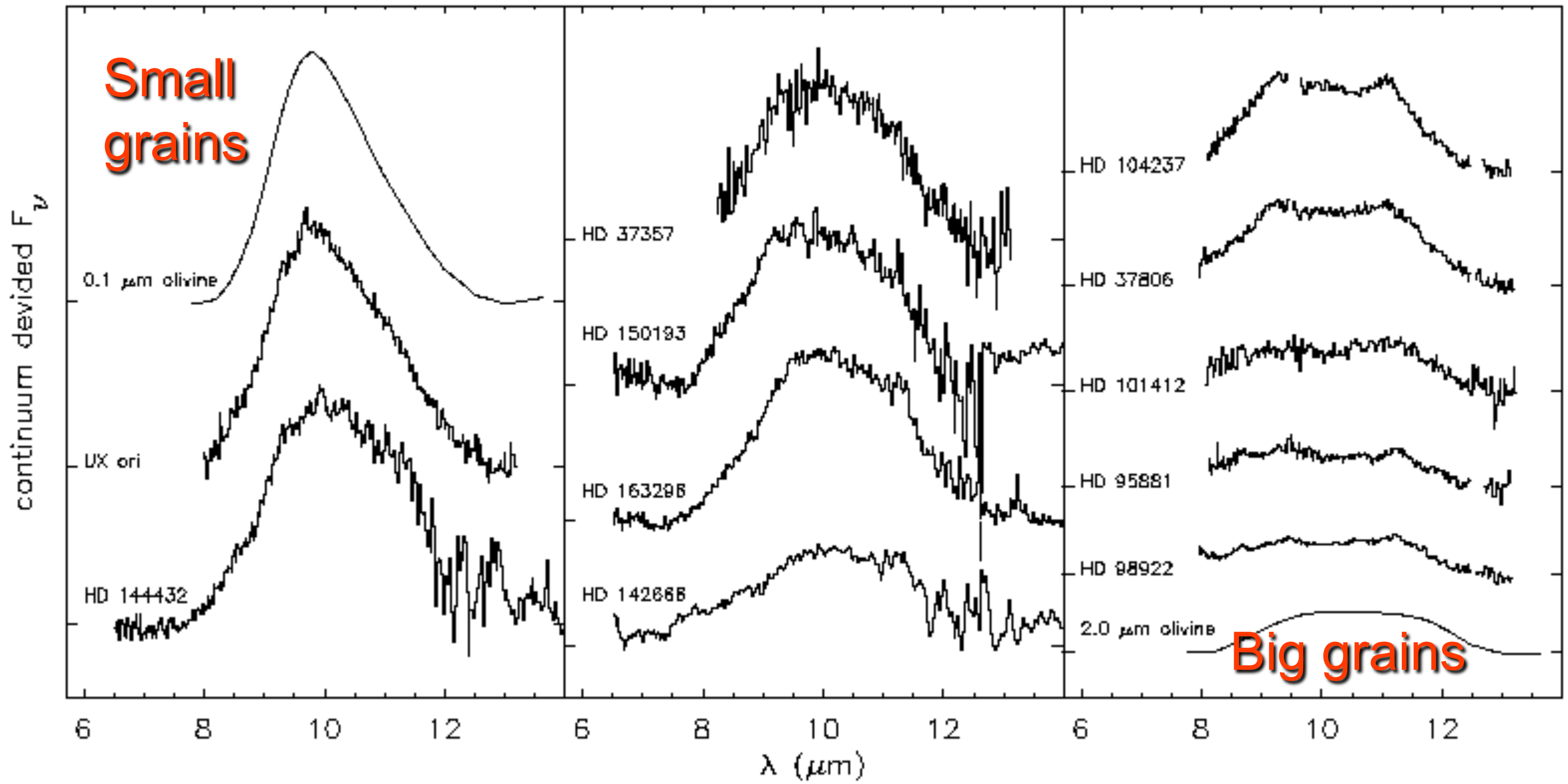
The evolution of the dust population

How is dust 'size' measured?

Example: Opacity of spherical silicate grain at various sizes

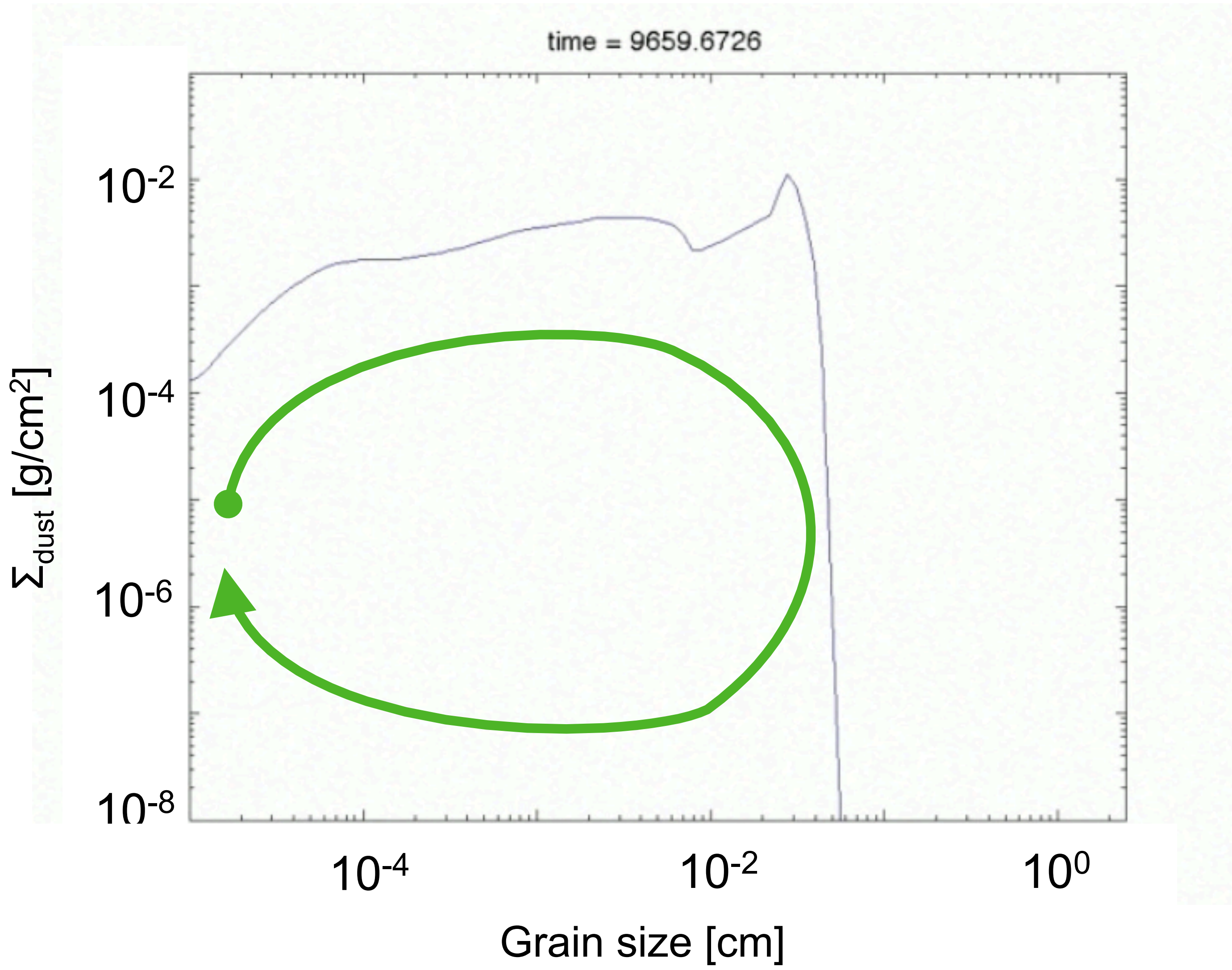


So... What is observed?



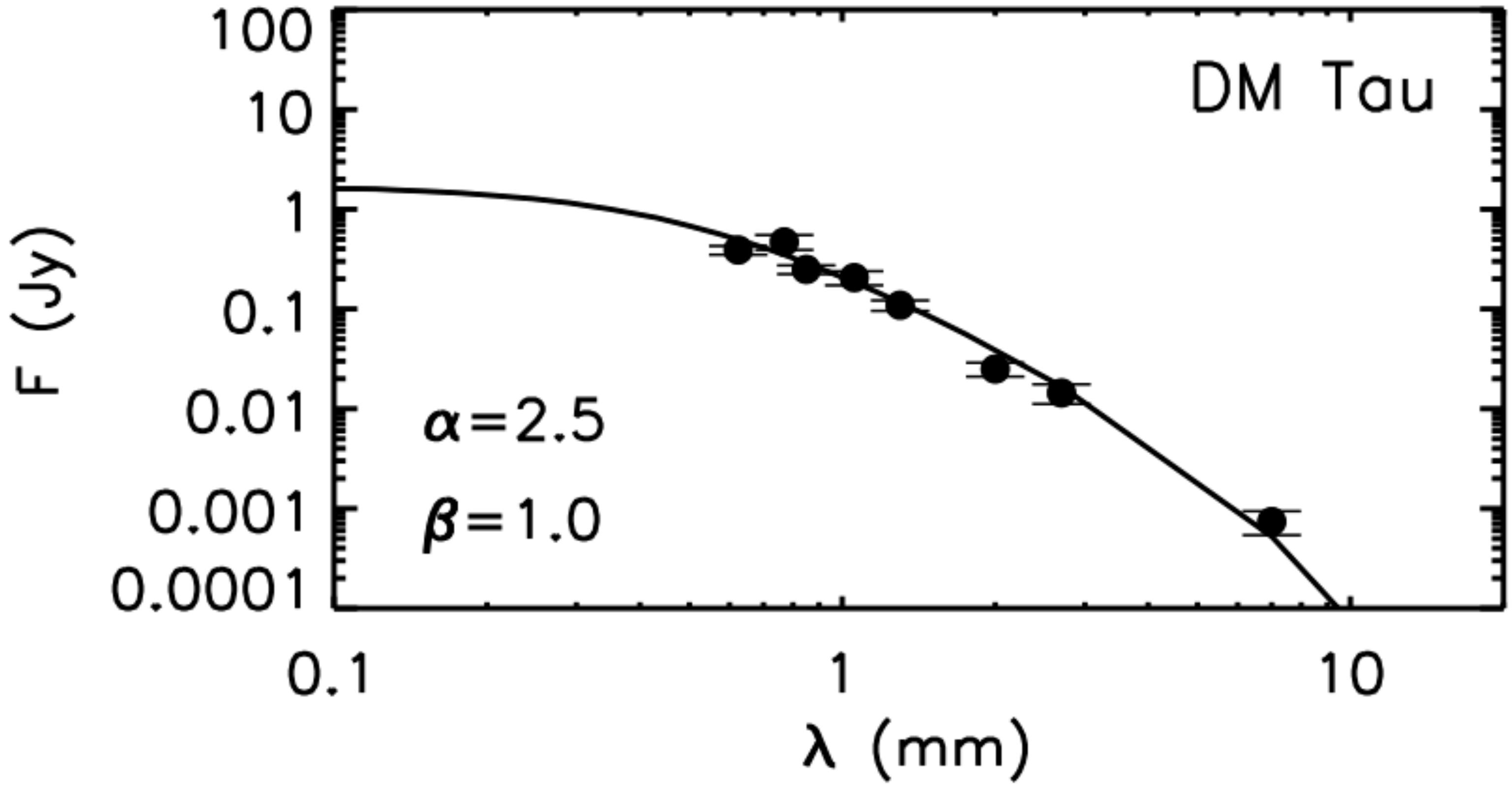
R. van Boekel et al. (2003), A&A 400L, 21

Dust coagulation model with fragmentation



Birnstiel, Dullemond & Ormel 2010

Measuring grain sizes from mm obs



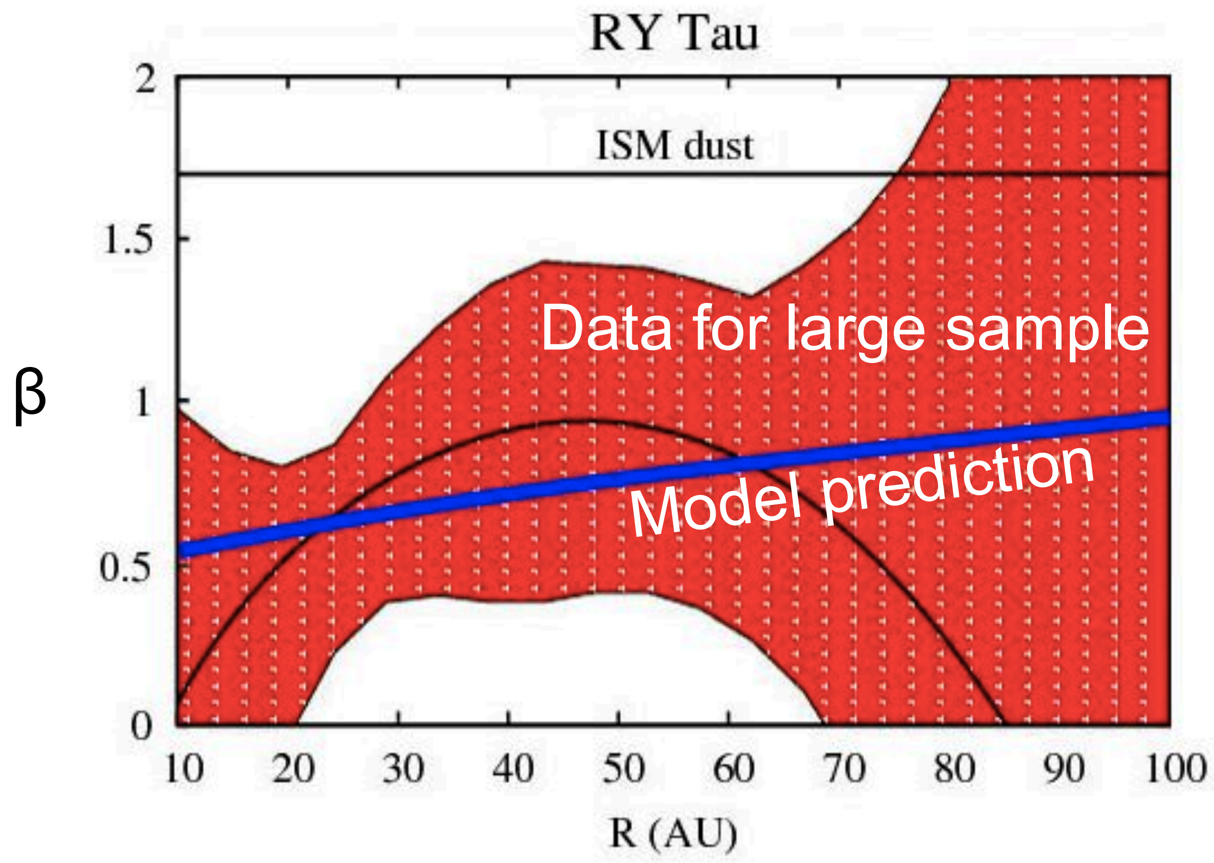
Ricci, Testi, Natta, Neri, Cabrit & Herczeg (2010)

See talks by Ricci, by Testi and by Carpenter
See poster 9 by Ubach Catarina

Comparing model to observation

Radial dependence in the disk?

larger
grains
in inner
disk



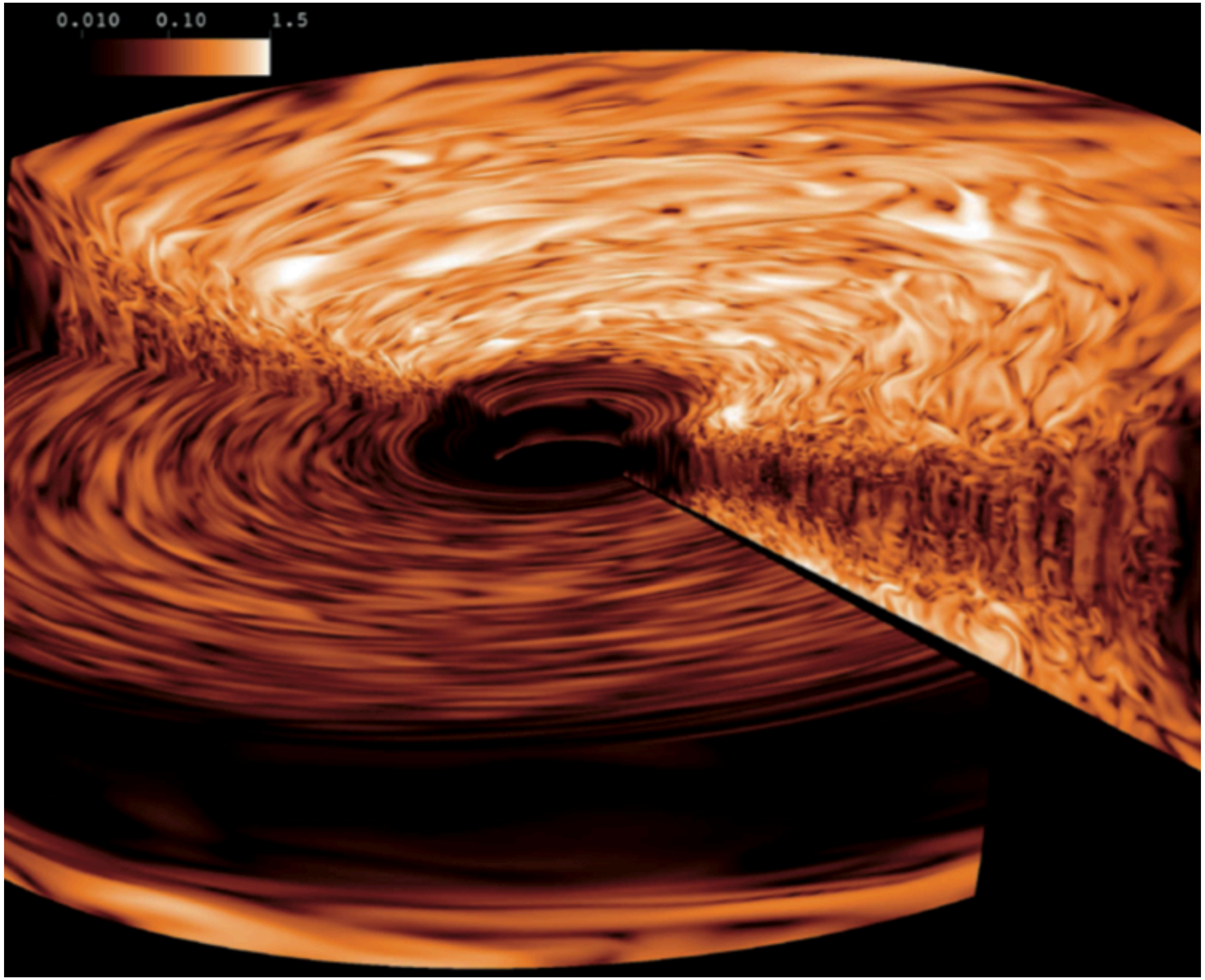
smaller
grains
in outer
disk

See talks by
Ricci and
by Birnstiel

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

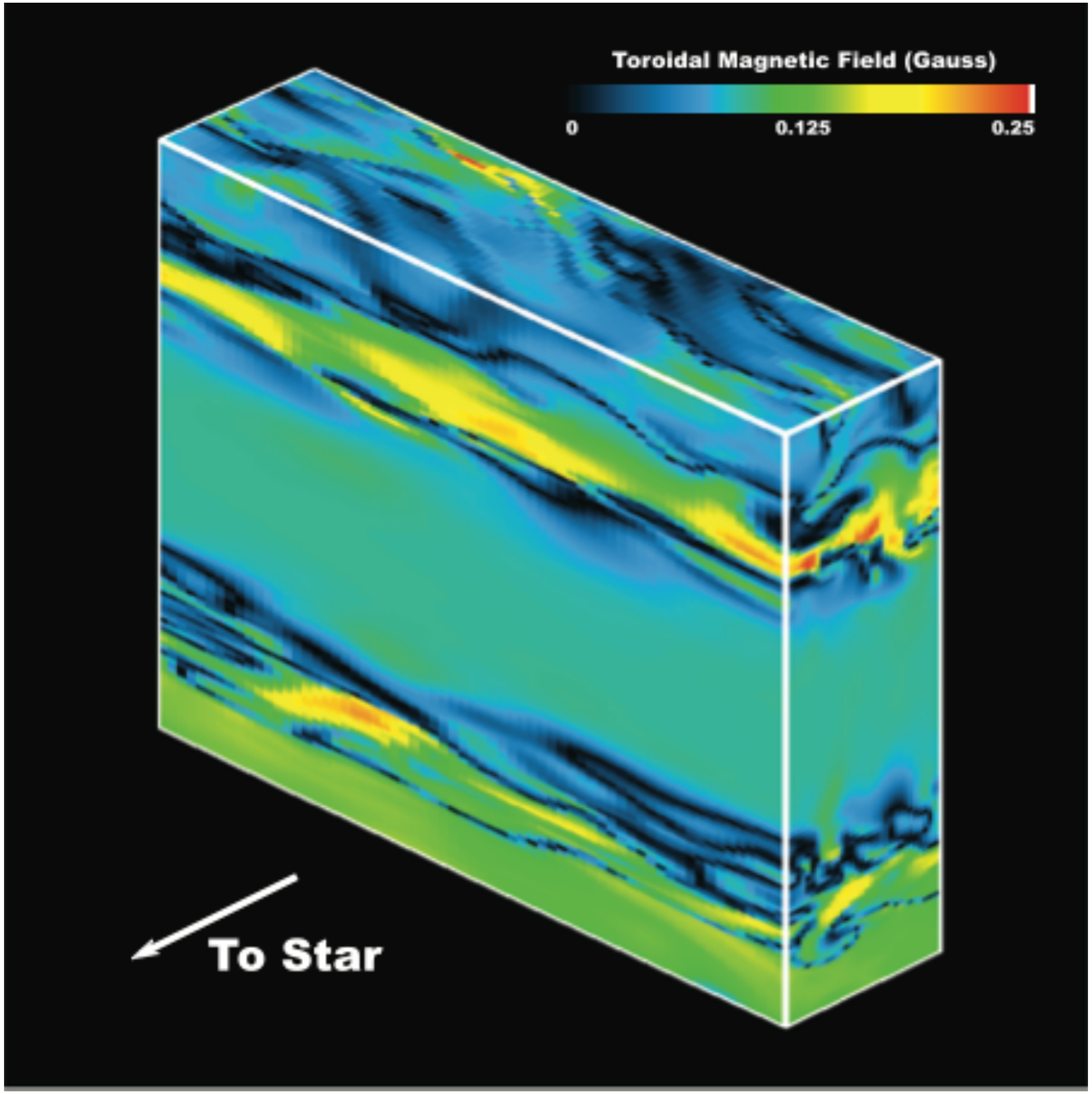
See poster Mario Flock

Observ. constraning turbulence: Talk by Simons

But: there is a „dead zone“

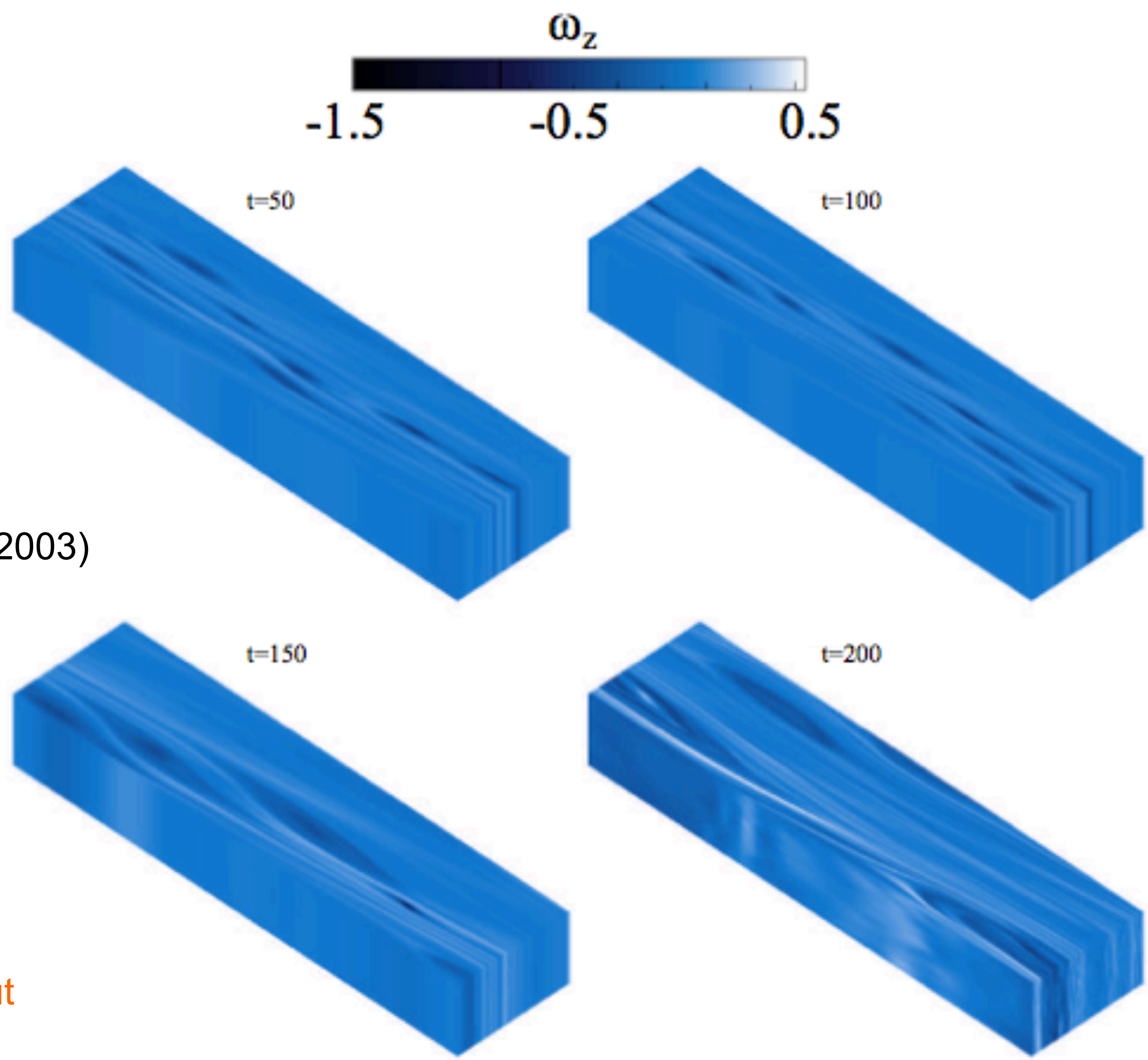
Gammie 1996

Here: Turner & Sano 2008



See talk by Ilgner on grains & electric charge, See poster 2 Ataiee, poster 16 Dzyurkevich, poster 18 Faure

Vortices in protoplanetary disks



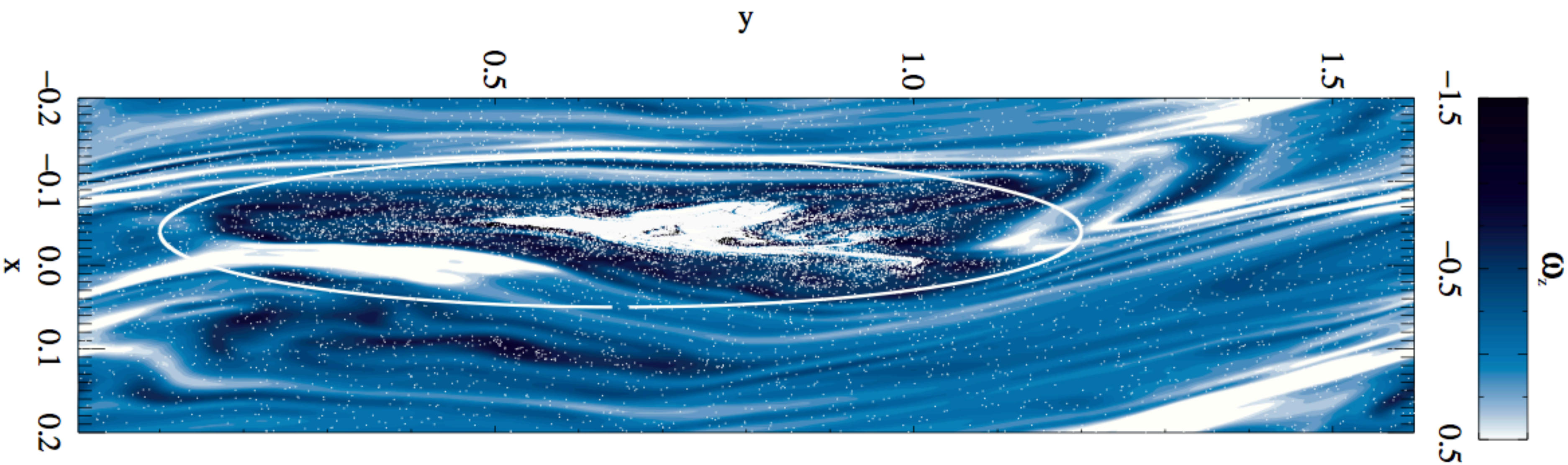
Vortex generation
by baroclinic instability

(Klahr & Bodenheimer 2003)

See poster 48 Meheut
on Rossby vortices

Raettig (PhD thesis 2012)

Vortices as particle traps



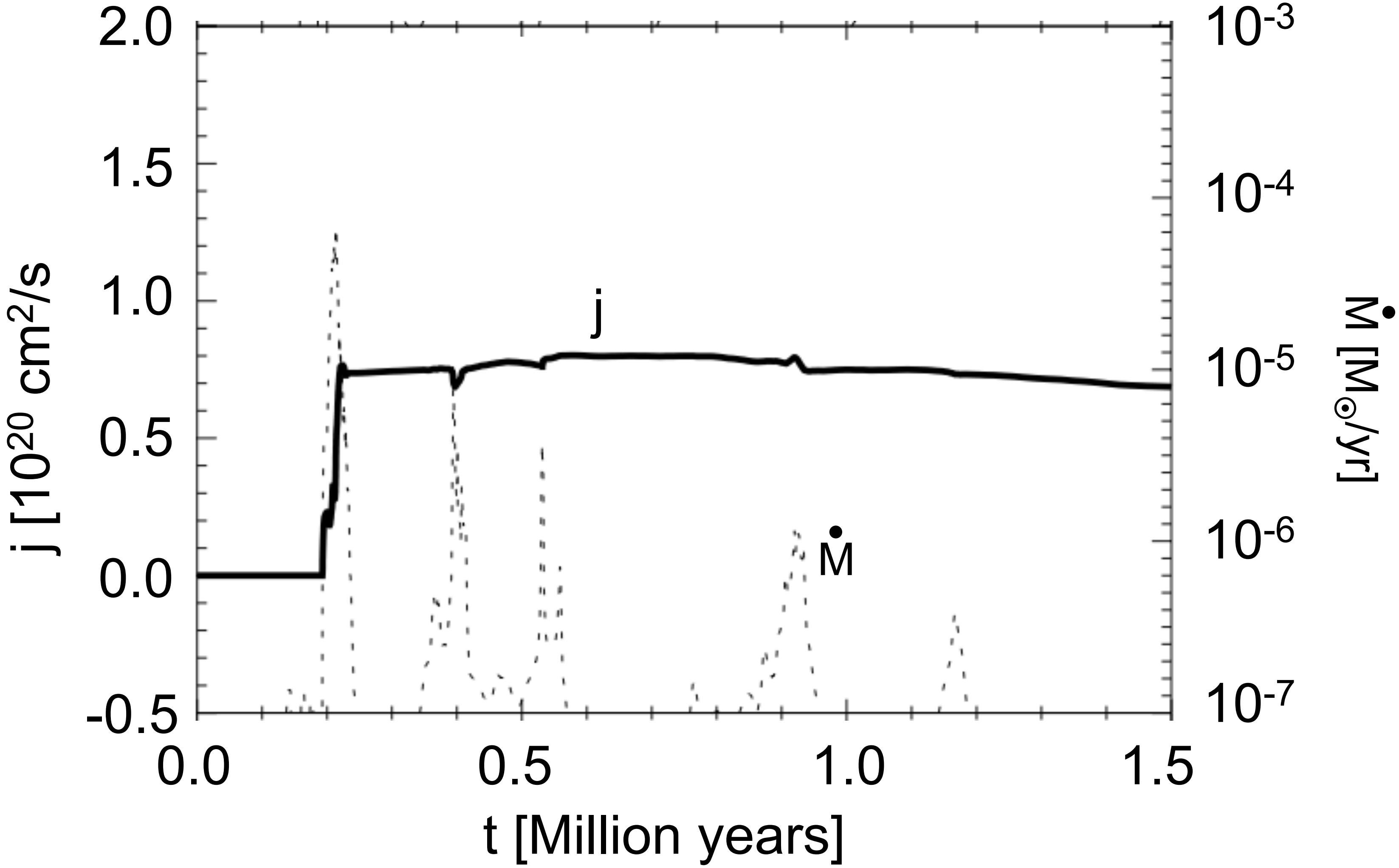
More on particle traps:
See talk Pinilla

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

Non-steady phenomena in protoplanetary disks

Episodic accretion of gas onto the disk

Result from model of turbulent star formation

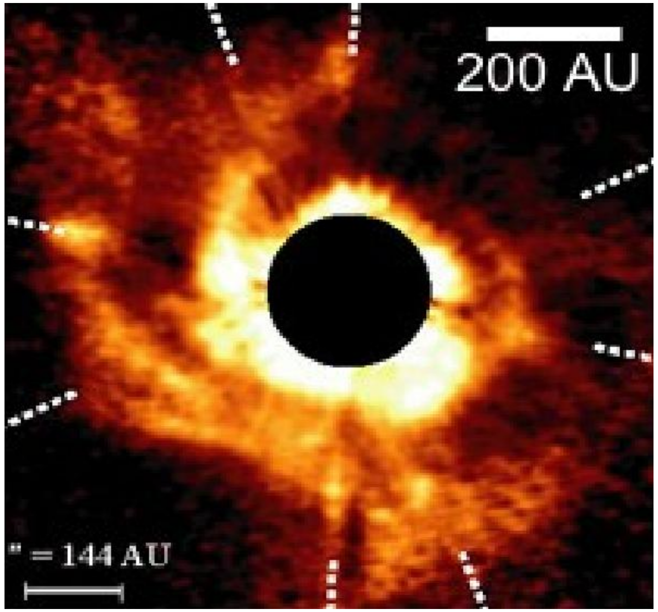


Jappsen & Klessen 2004

Episodic accretion of gas onto the disk

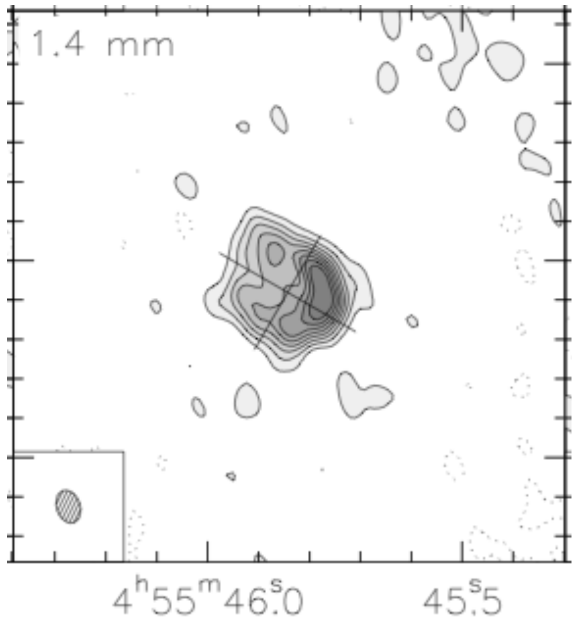
AB Aurigae: Perhaps an example of a recently acquired disk?

Spiral structures



Fukagawa et al. 2004

Off-center mm disk

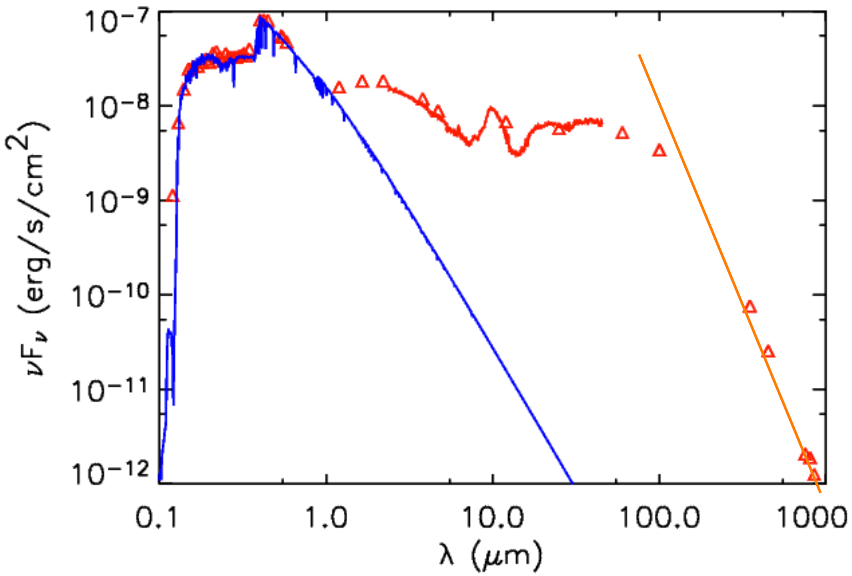


Pietu, Guilloteau & Dutrey 2005
See also Corder et al. 2005

Episodic accretion of gas onto the disk

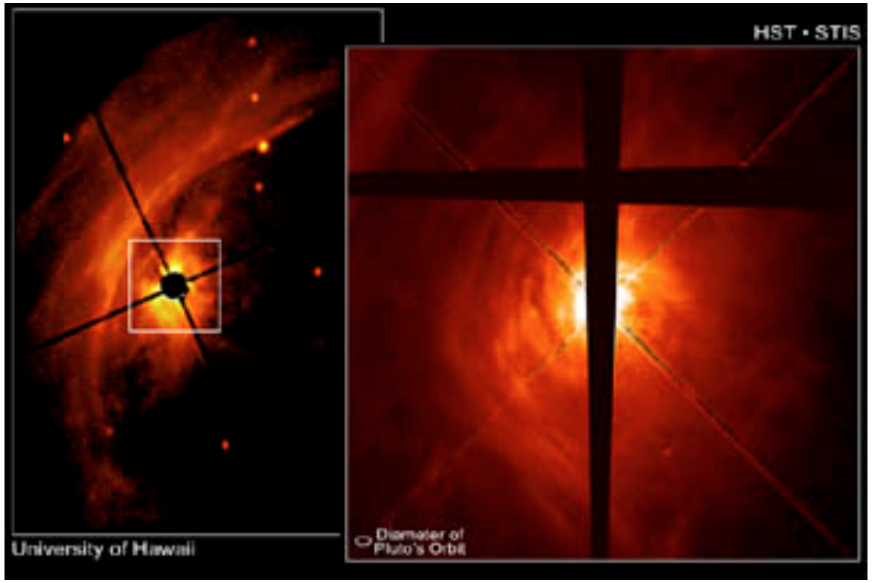
AB Aurigae: Perhaps an example of a recently acquired disk?

Evidence for small pristine dust from steep mm slope



See talk by I. Thies for models of episodically accreting disks

Evidence for Inflow of gas from large distances

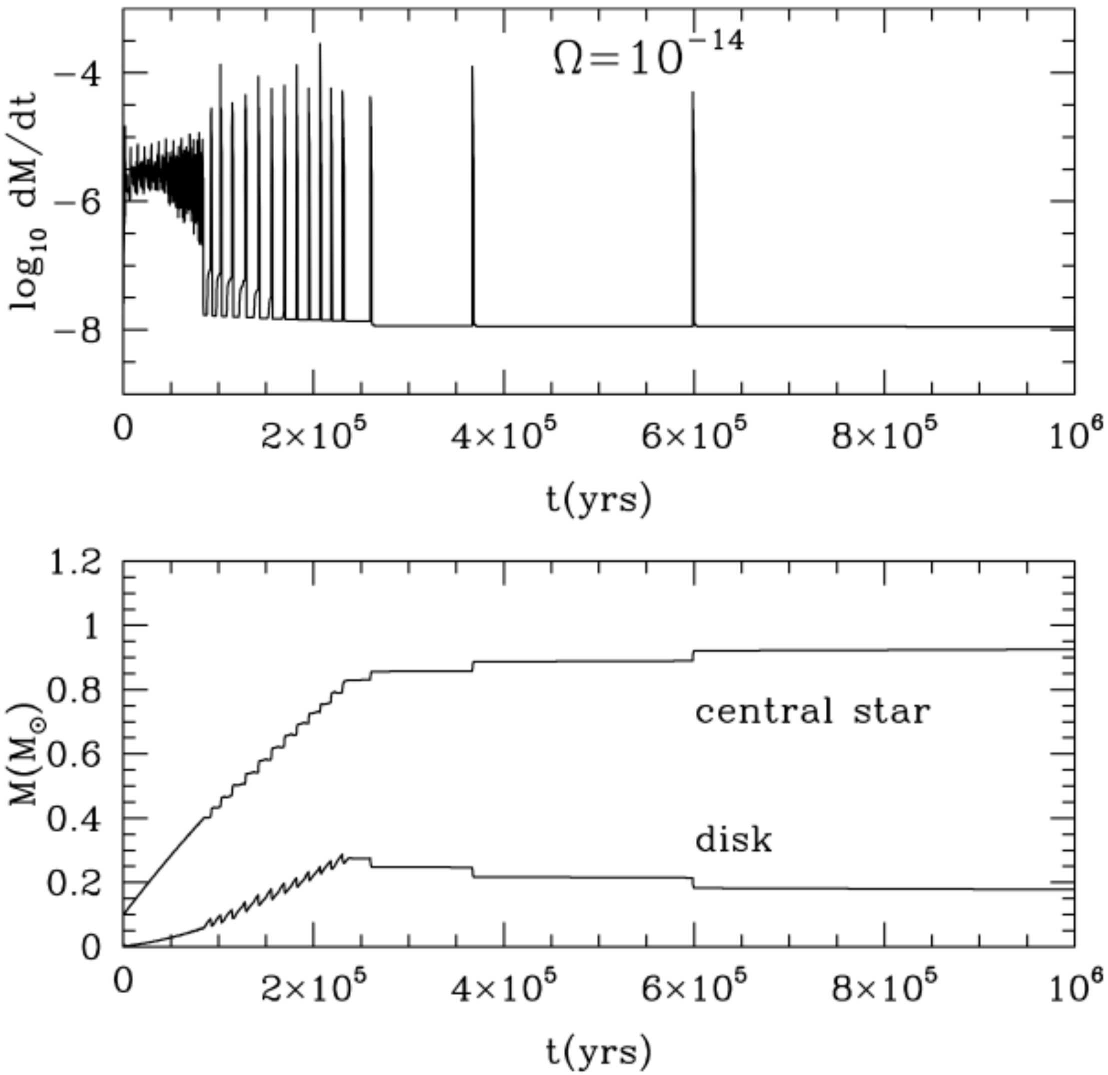


Grady et al.1999

Variable accretion in disks: FU Orionis stars

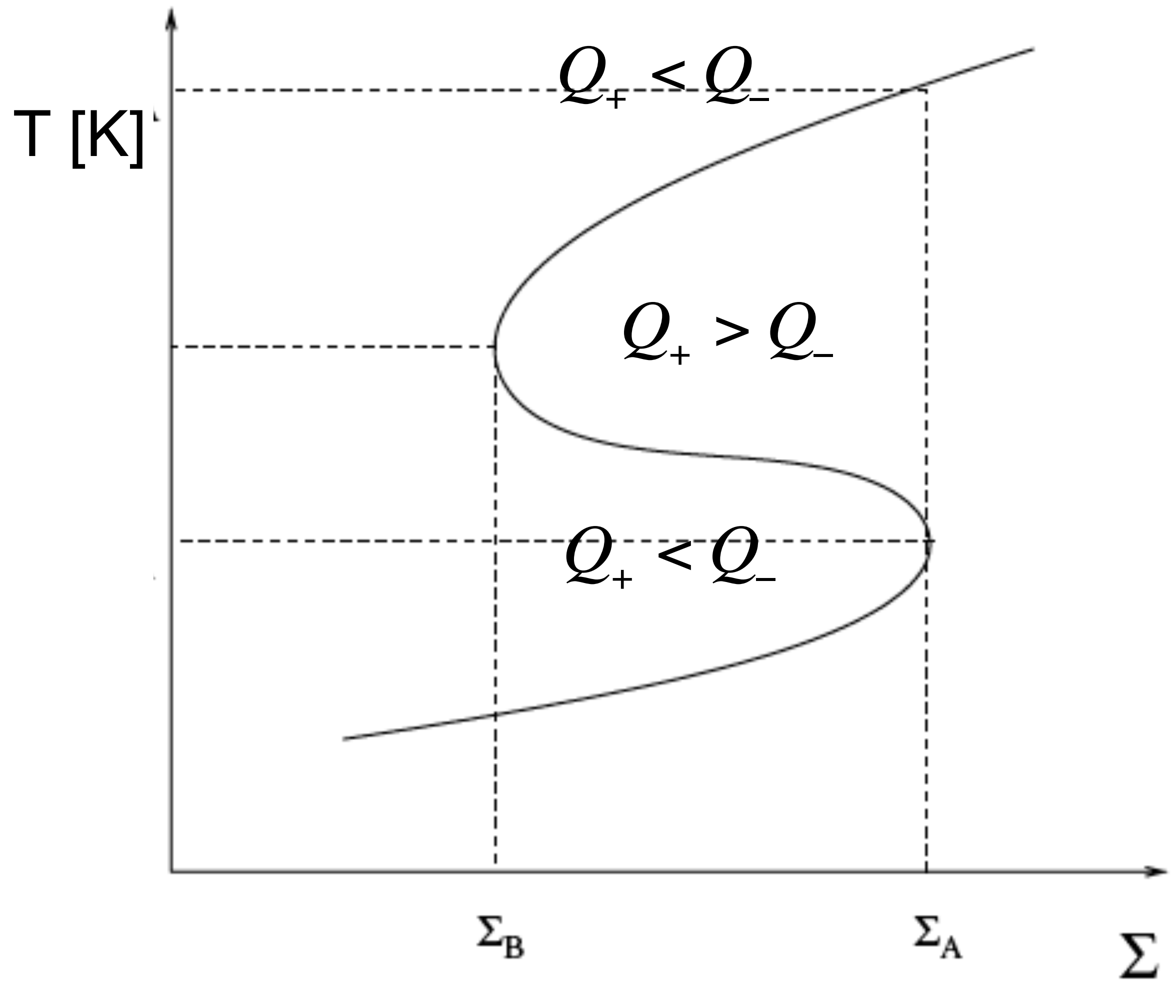
Variability time scale: $10^3..10^5$ yr

Possible origin:
- Instability of the dead zone (Armitage, Livio & Pringle 2001),
- possibly triggered by a massive planet (Lodato & Clarke 2004)
- Gravitational instability of continuously fed disk (Vorobyov & Basu 2004)



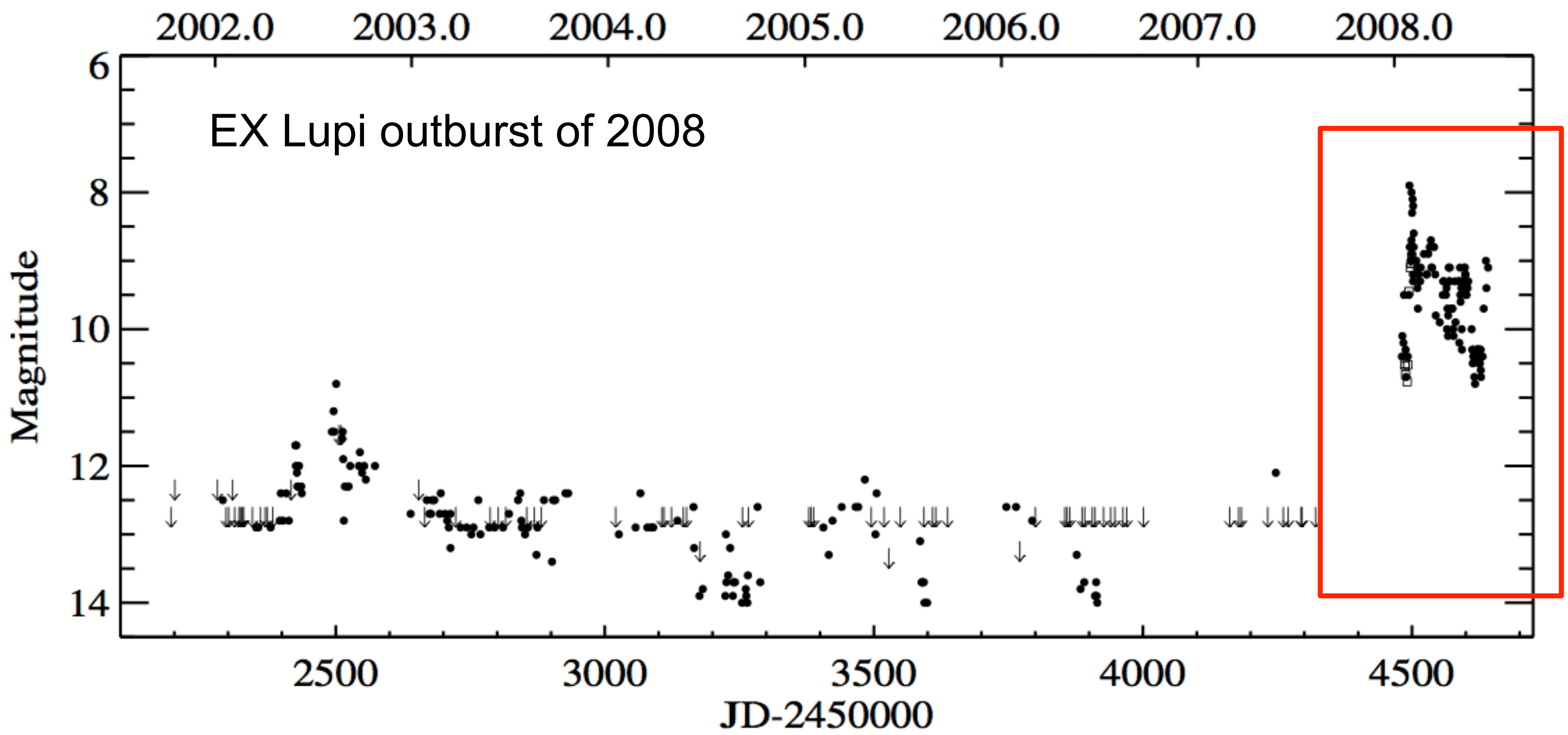
Model by Zhu et al. 2010

Thermal instability in the disk



See poster 34 Keisuke (?),
see poster 51 Müller on gravitational instability of irradiated disks

Variable accretion in disks: EX Lupi stars (EXOrs)

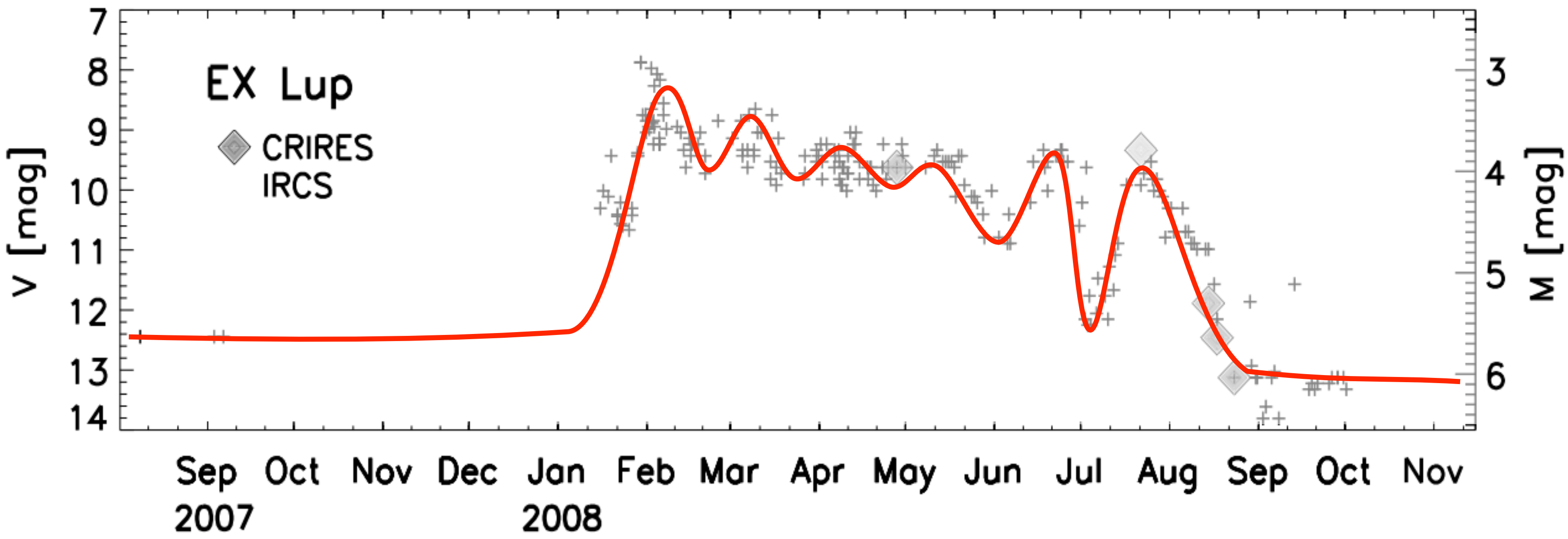


Variability time scale: 0.1 .. 100 yr

Possible origin:

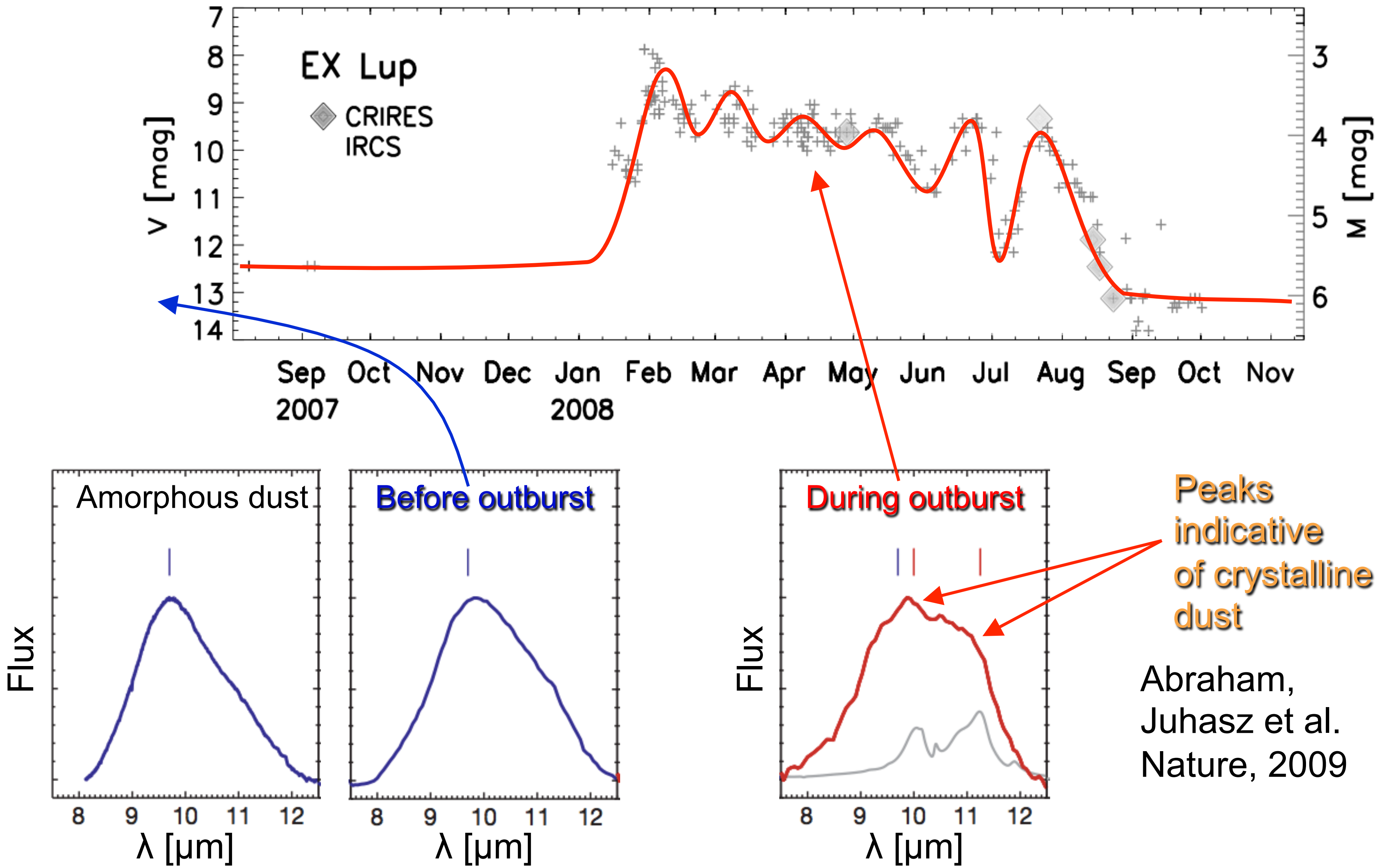
- Instability of the magnetic disk truncation point (D‘Angelo & Spruit 2010)
- ??

Variable accretion in disks: EX Lupi stars (EXOrs)



Abraham,
Juhasz et al.
Nature, 2009

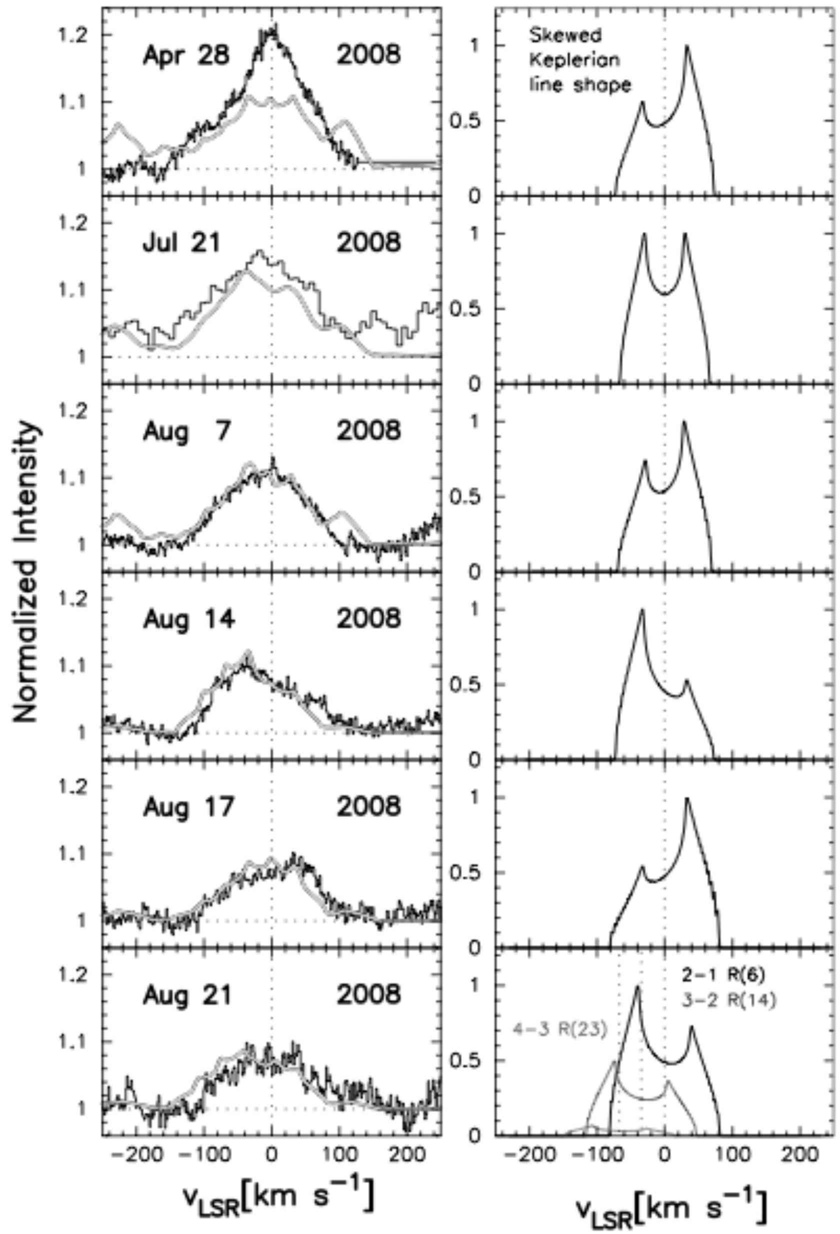
Variable accretion in disks: EX Lupi stars (EXOrs)



Abraham, Juhasz et al. Nature, 2009

Variable accretion in disks: EX Lupi stars (EXOrs)

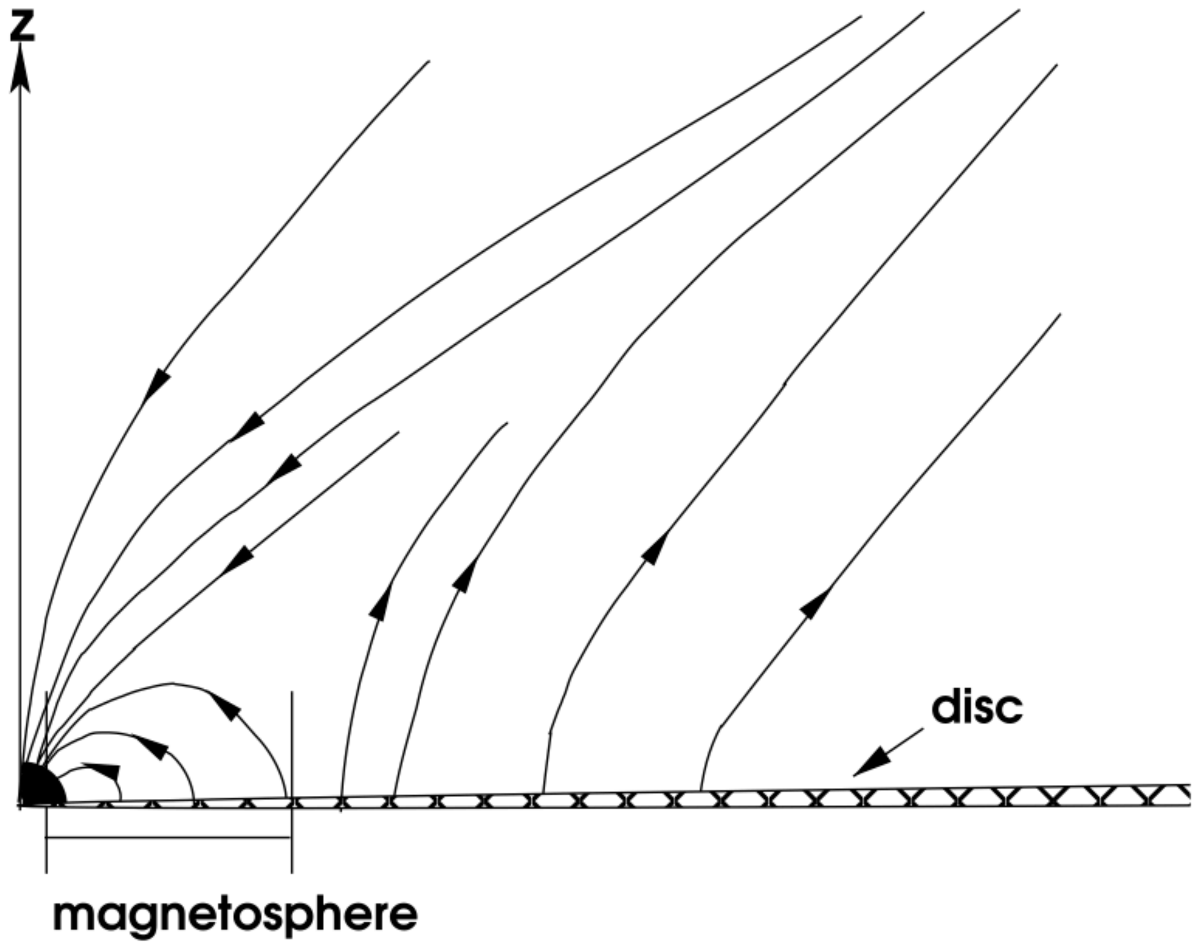
Wobbling inner disk of EX Lupi:



Goto, Regaly et al. 2011

Model for EXOr variability

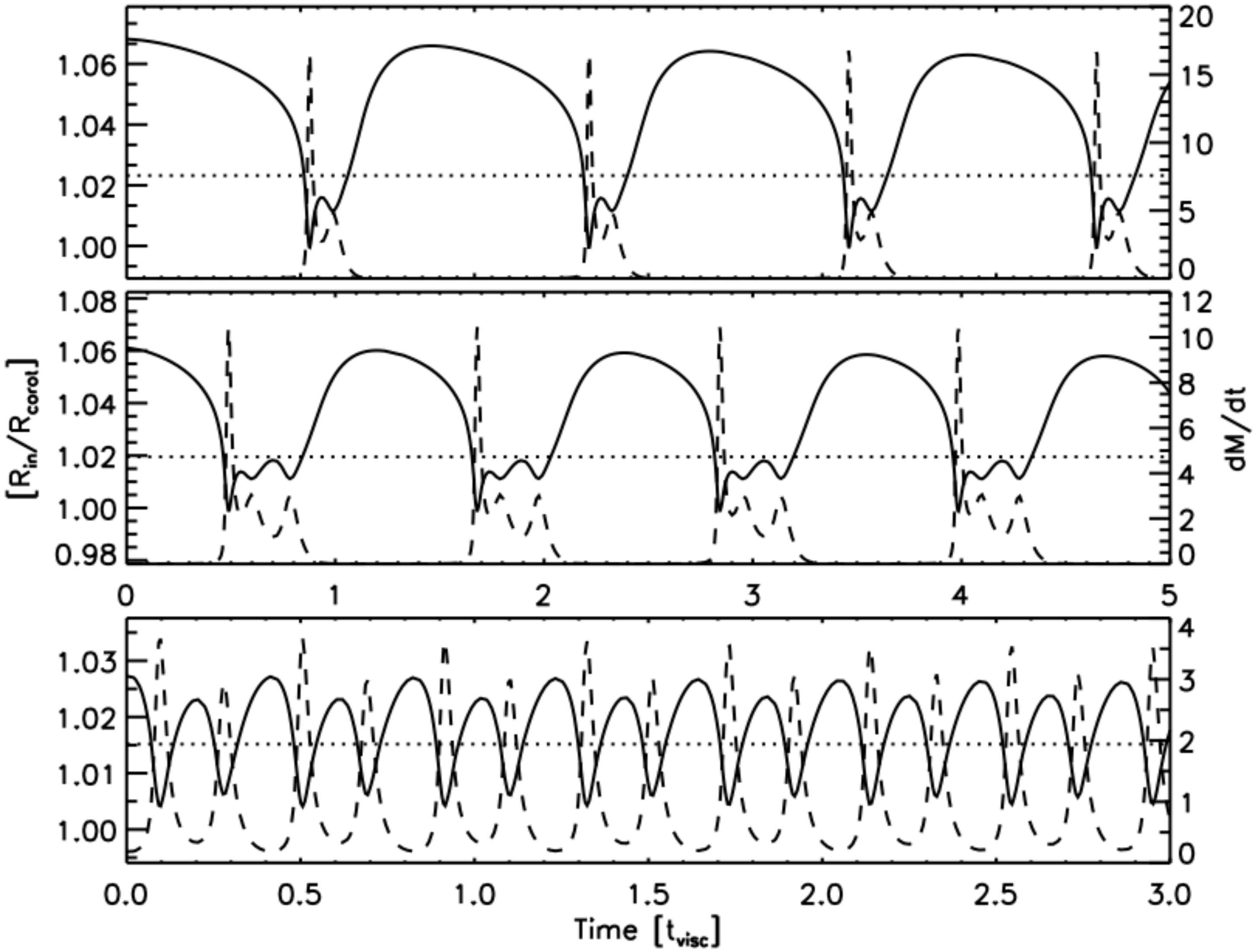
Unstable magnetic truncation point („X-point“)



D‘Angelo & Spruit 2010

Model for EXOr variability

Unstable magnetic truncation point („X-point“)



D‘Angelo & Spruit 2010

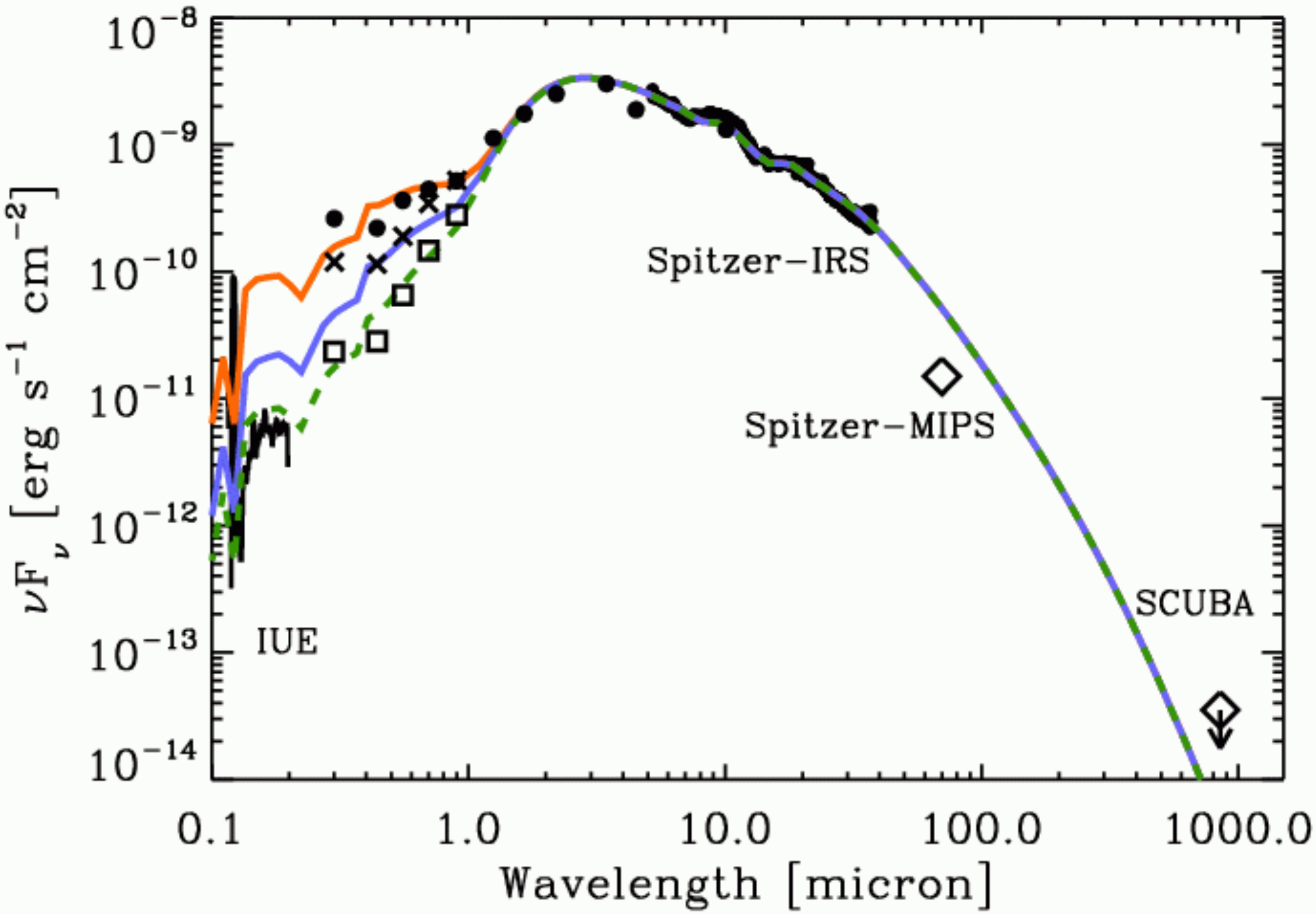
Variability of SEDs: UX Orionis stars (UXOrs)

Time scale: weeks

Probable origin:

- Dusty gas filaments passing through line of sight toward the star. Must be from very inner disk (time scale argument)

Example here: VV Serpens



Pontoppidan et al. 2007

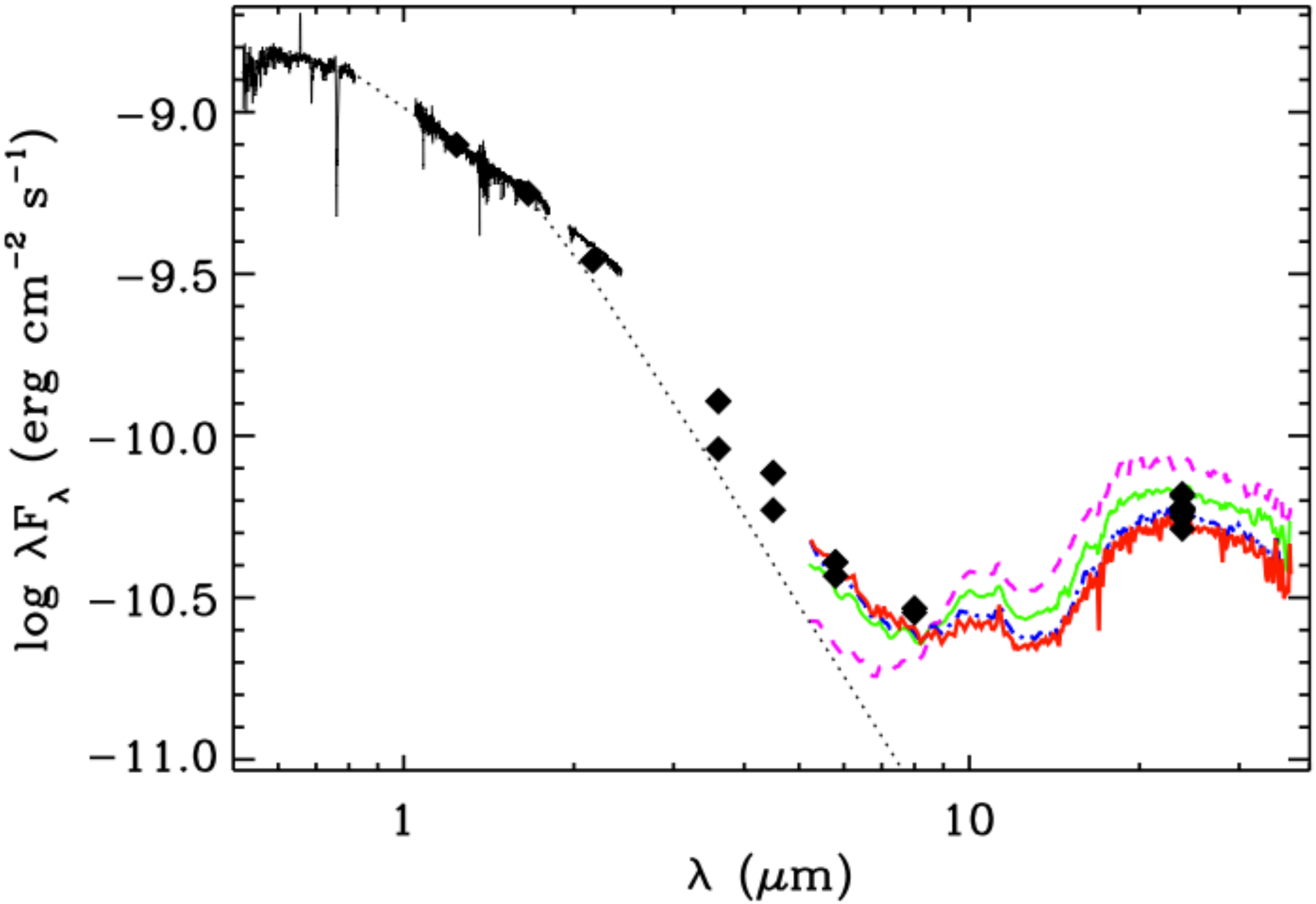
Variability of SEDs: Pivoting SEDs

Time scale: months/yrs

Probable origin:

- Varying height of the inner dust rim (for some reason see talk by Turner)
- Pivoting likely due to the corresponding variable shadowing

Example here: LRLL 31



Muzerolle et al. 2009

Variability of SEDs: UX Orionis stars (UXOrs)

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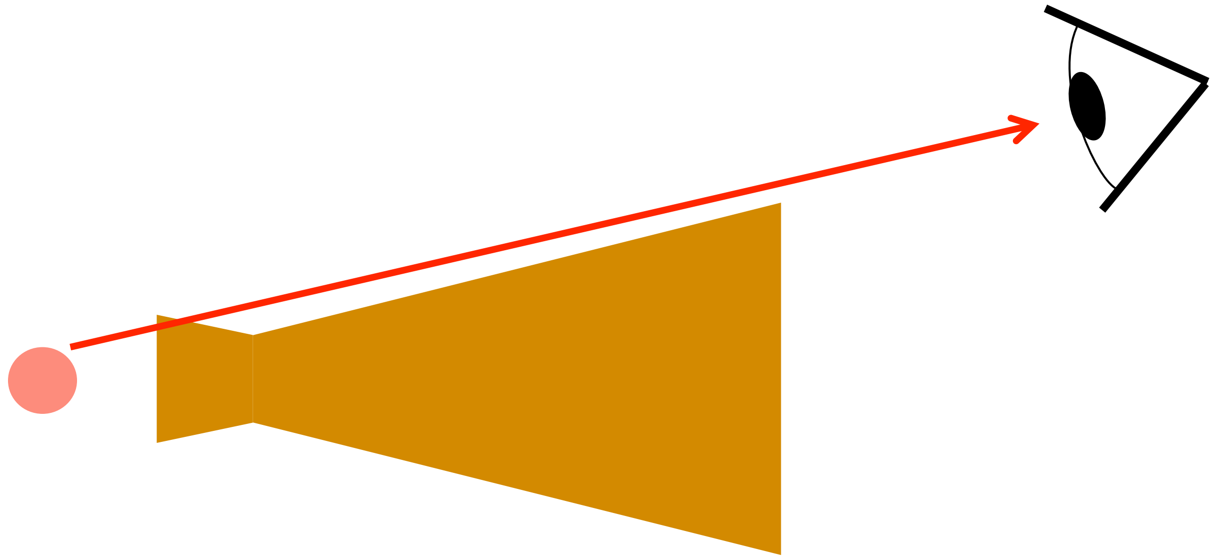


See talk by Neal Turner

So now we have arrived at the very inner disk regions

The inner disk regions

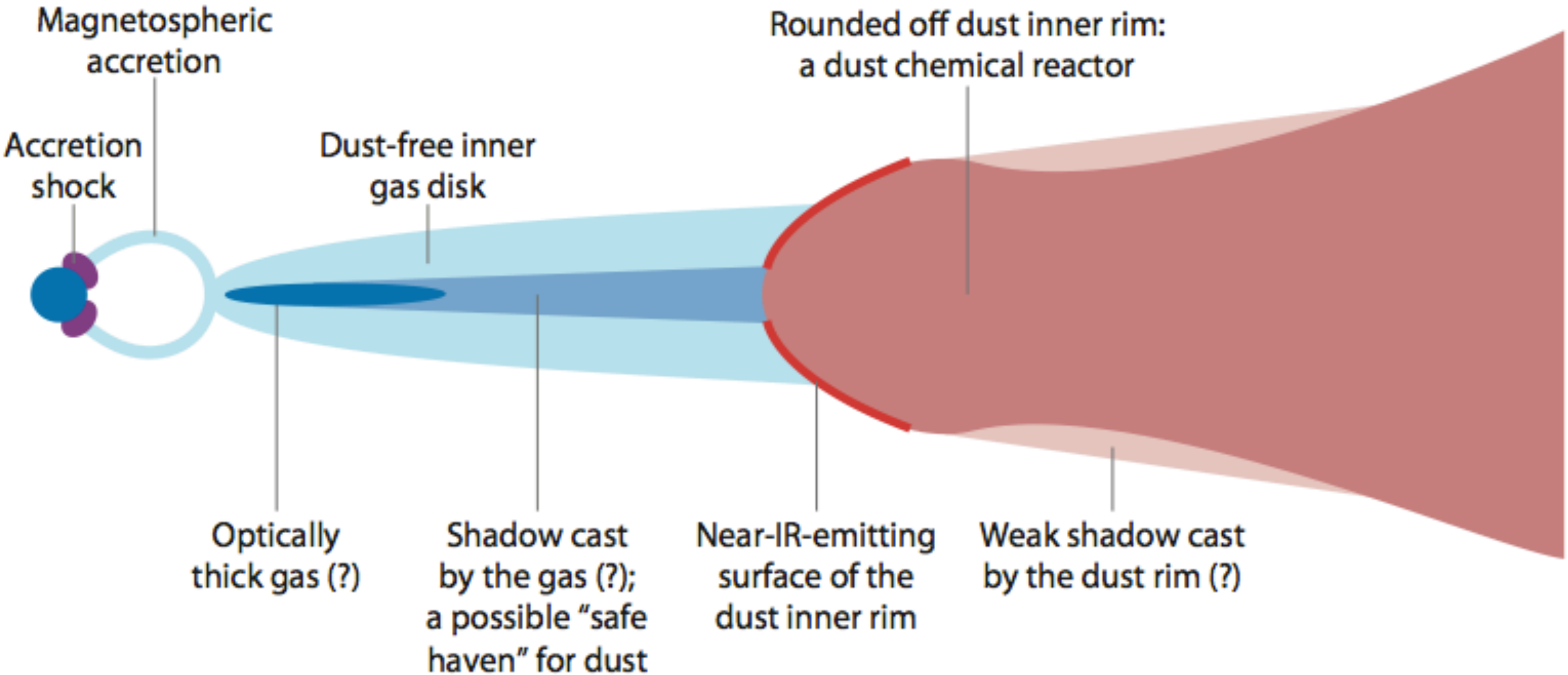
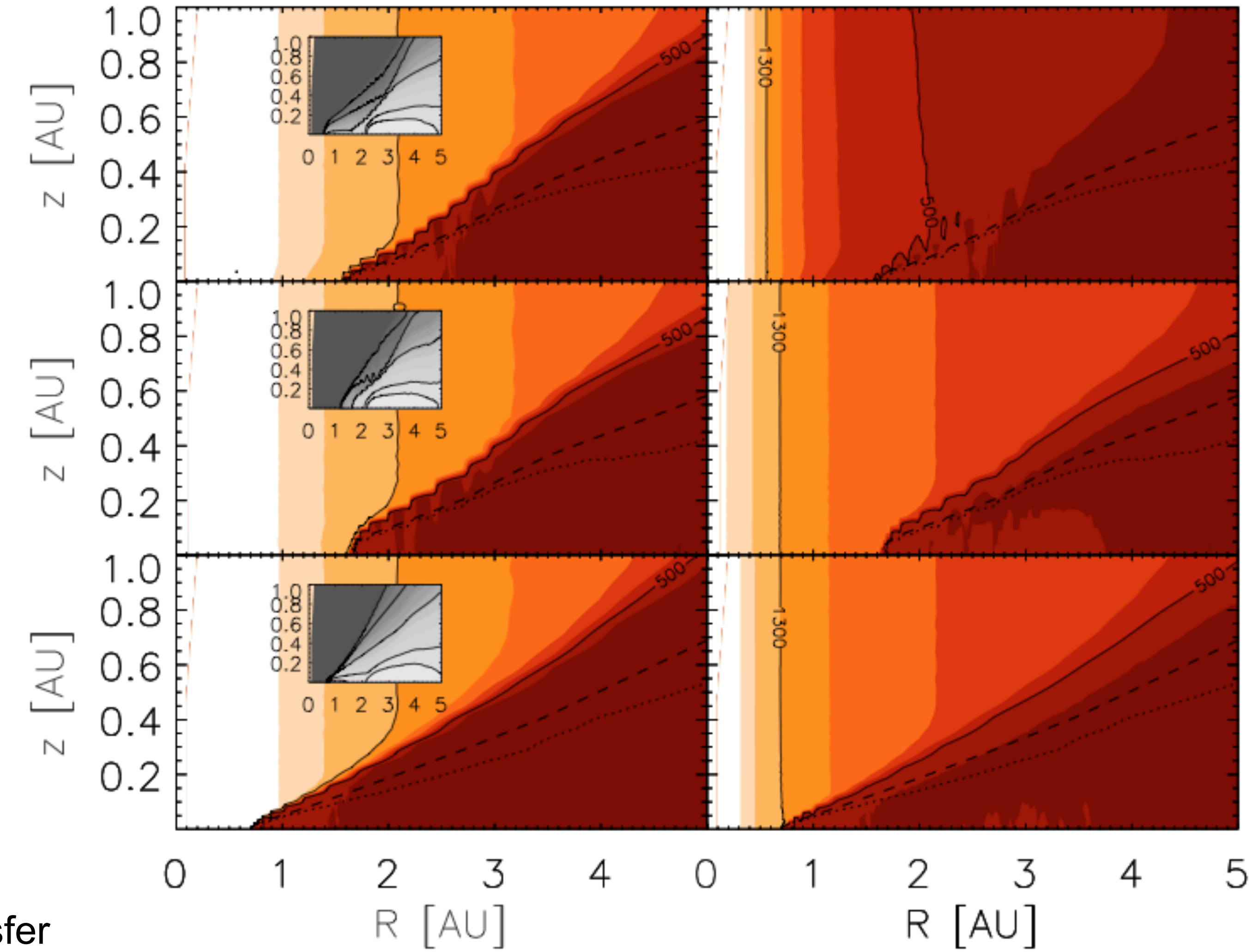


Figure from: Dullemond & Monnier (2010) Ann. Rev. A&A

Rounded shape of dust rim

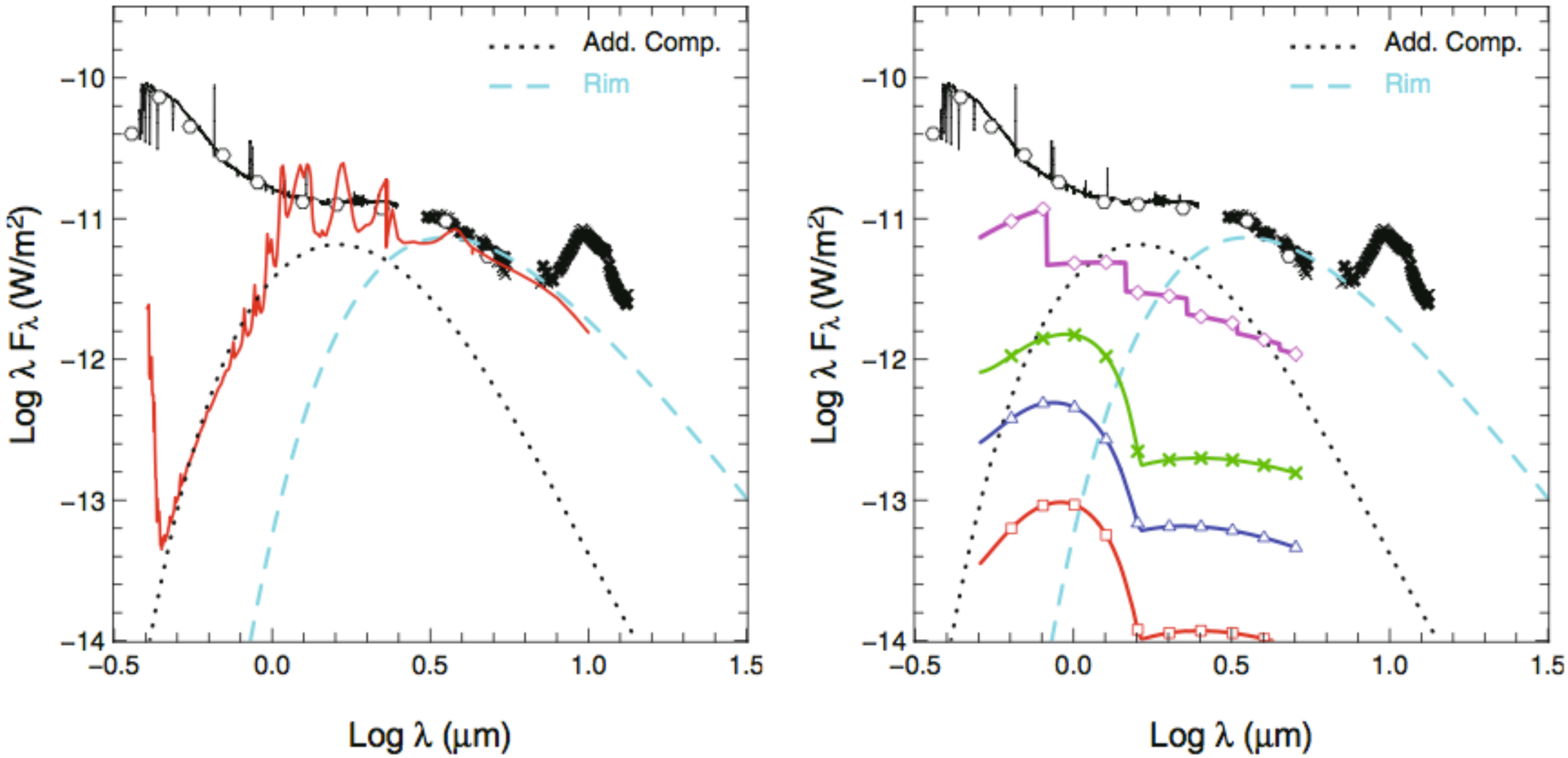
Originally shown by Isella & Natta 2005



Here: 2-D radiative transfer model by Kama et al. 2009
See also Tannirkulam et al. 2008

But the real mystery lies closer in...

The very inner disk appears to be inconsistent with molecular or even atomic gas! Is there still some dust surviving there?

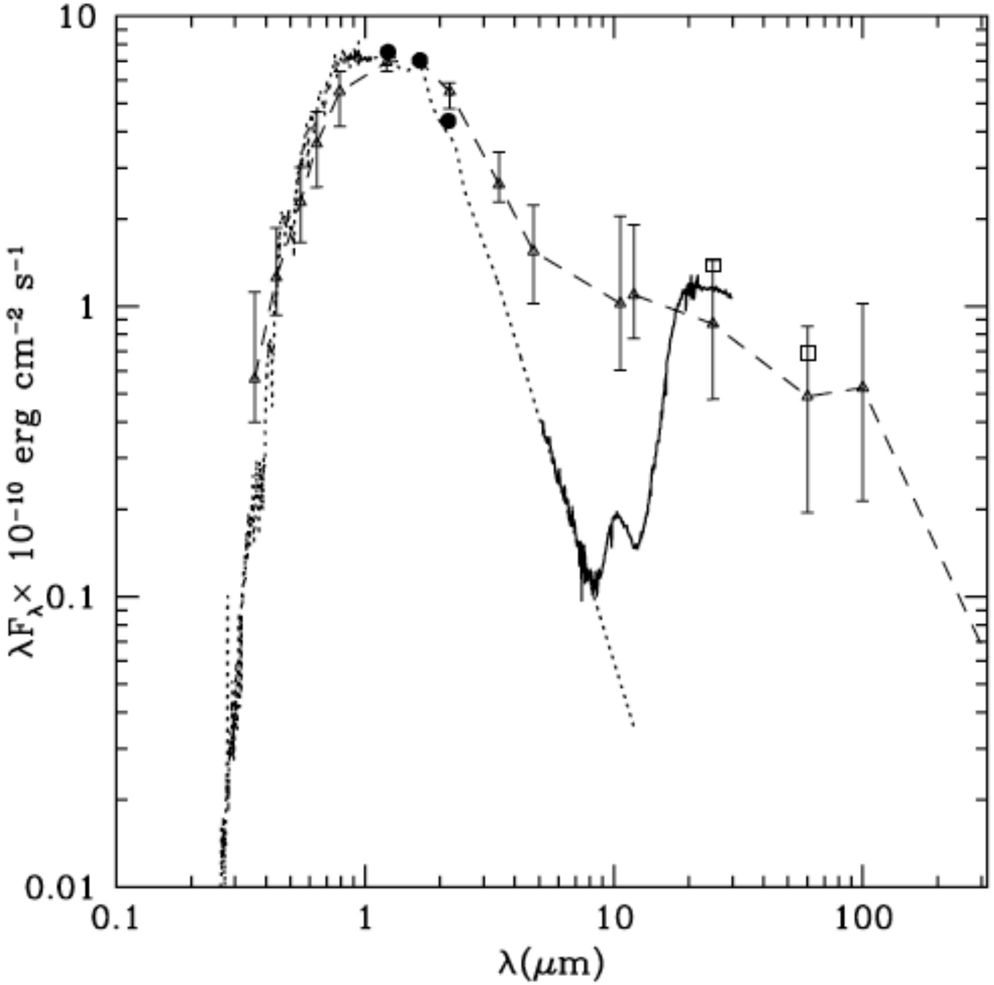


Benisty et al. 2010

Disks with huge holes
(„Transition disks“)

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

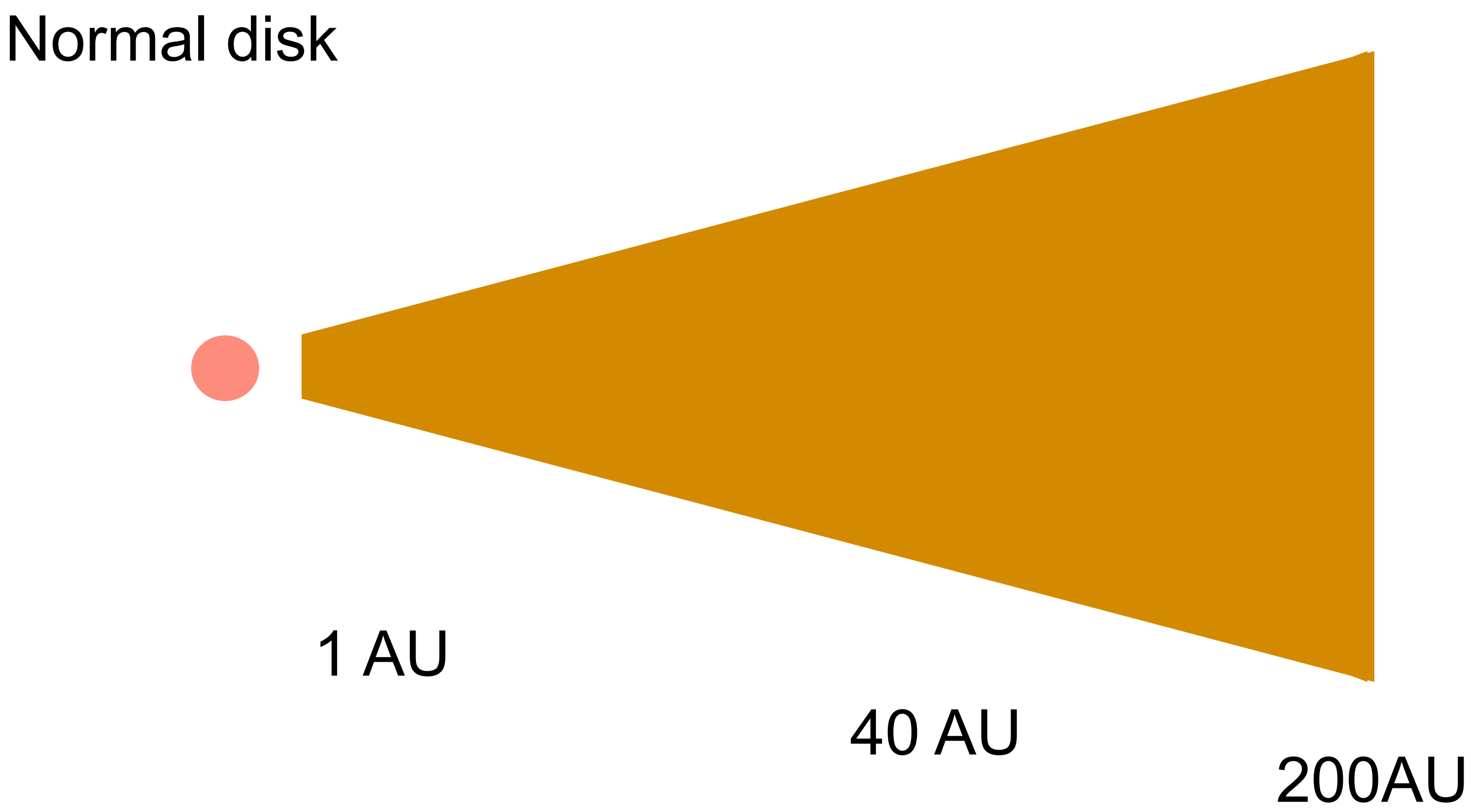
“Transition disks”: Huge inner holes



CoKu Tau 4

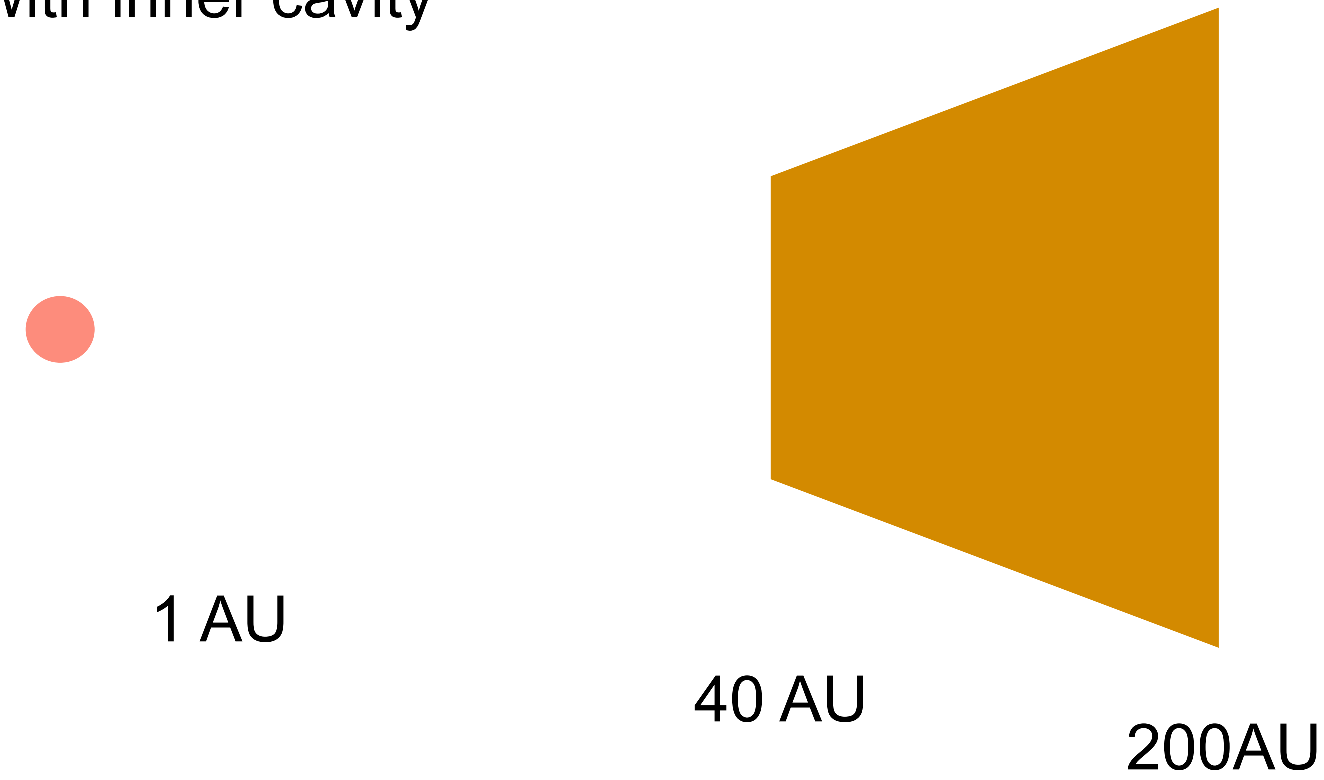
D’Alessio et al. 2005, Forrest et al. 2004

"Transition disks": Huge inner holes



“Transition disks”: Huge inner holes

Disk with inner cavity



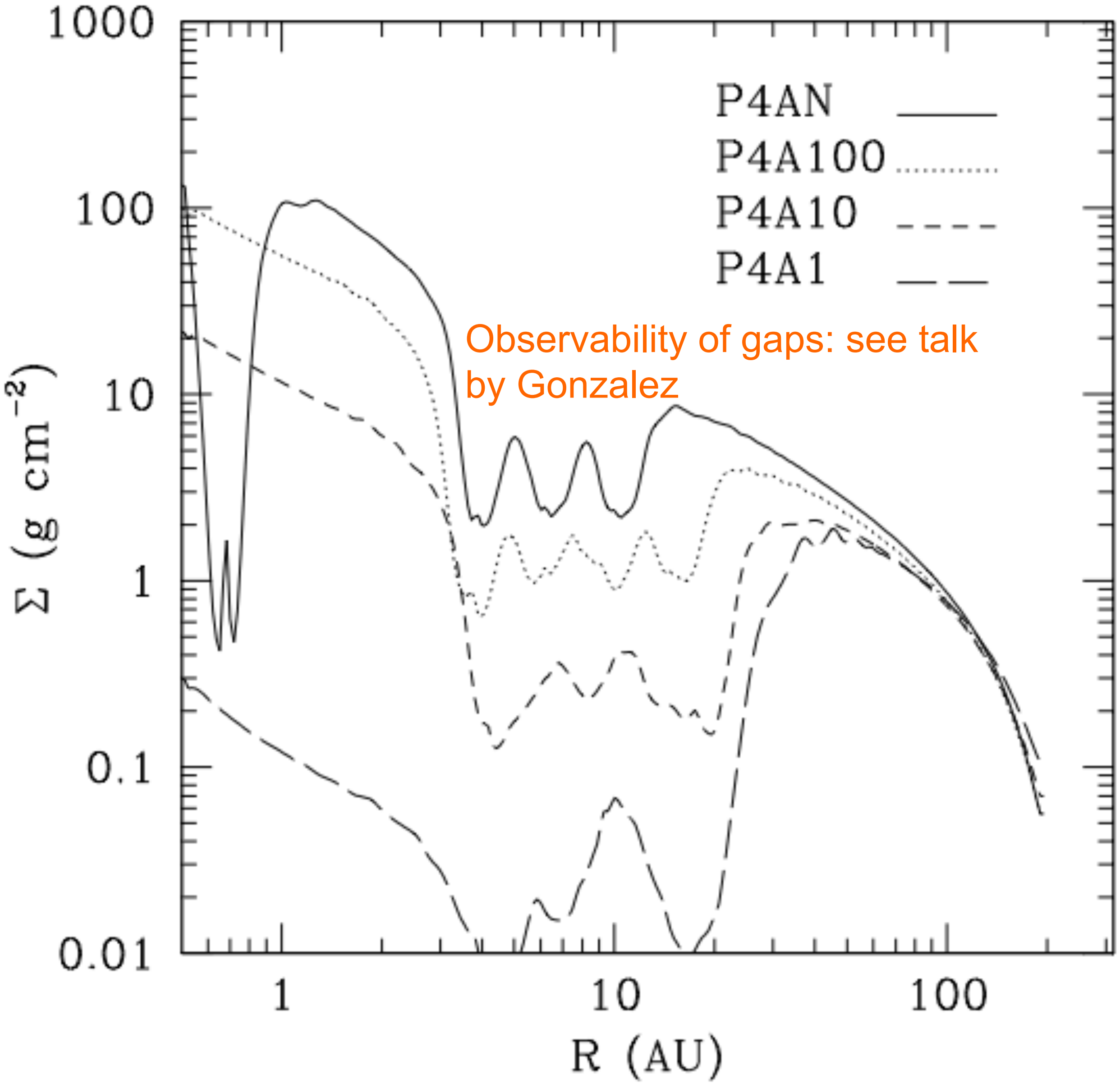
See talks by Alexander and by Owen
See poster 38 Koepferl
poster 49 Menu,
poster 69 Salinas,
poster 70 Sanz-Forcada

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.)

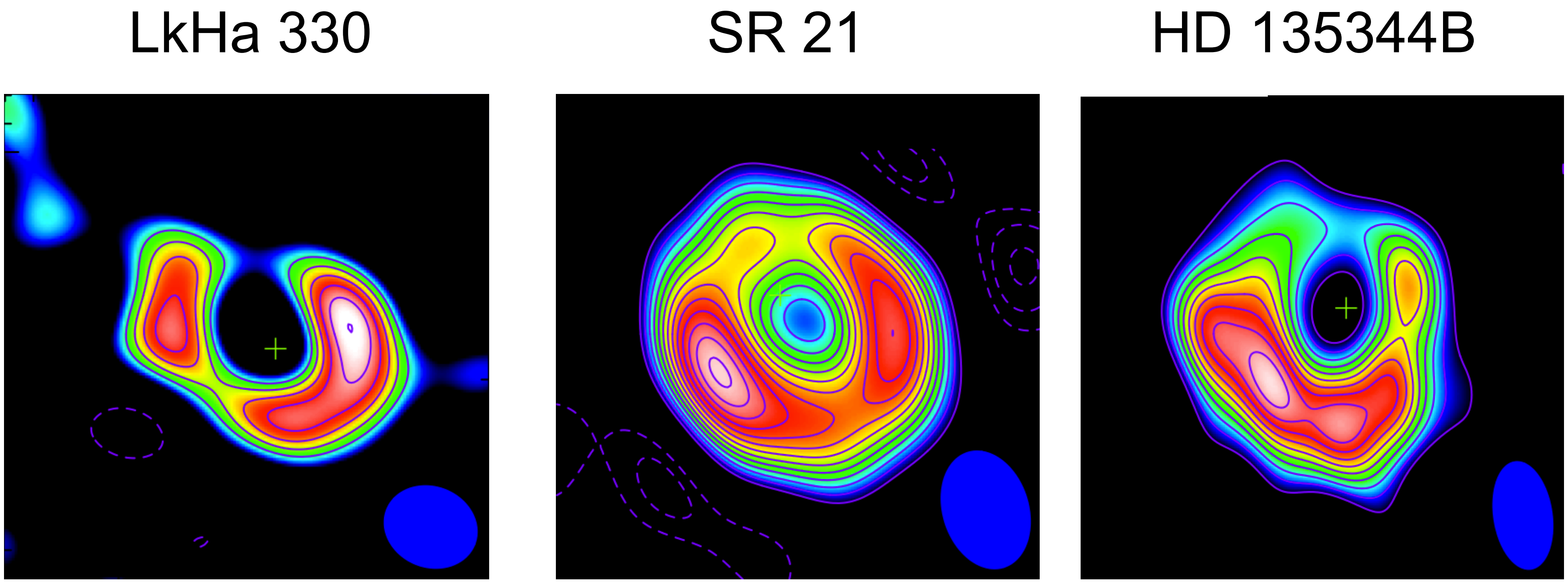
See talks by Andrews, by Birnstiel and by Pinilla



Observability of gaps: see talk by Gonzalez

Zhu et al. 2011

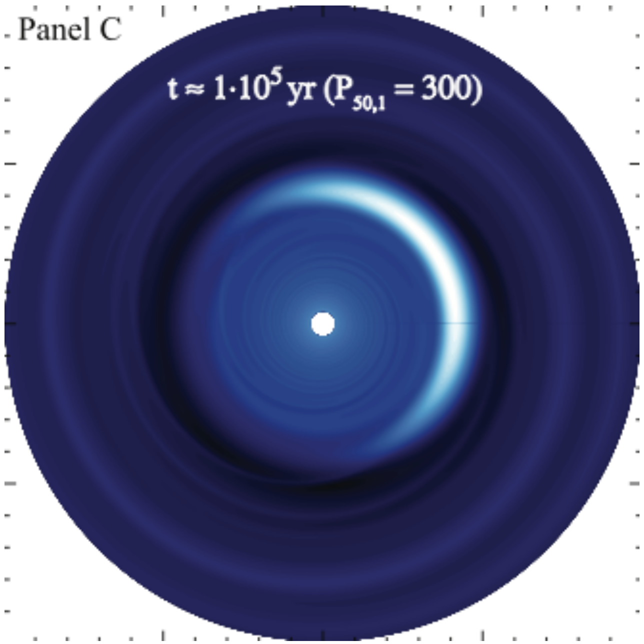
Transition disks: Ring-like structures



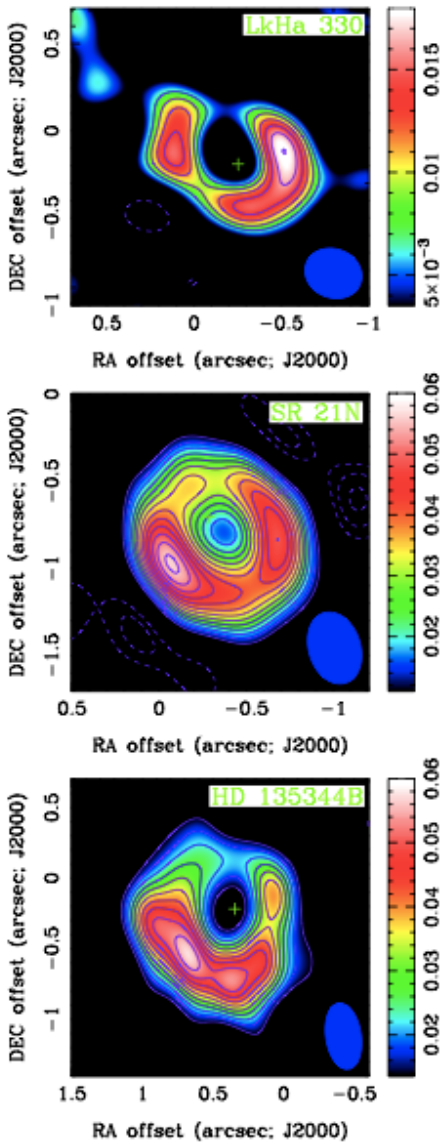
See also talks by
Schreiber and by Meru

Brown et al. 2009

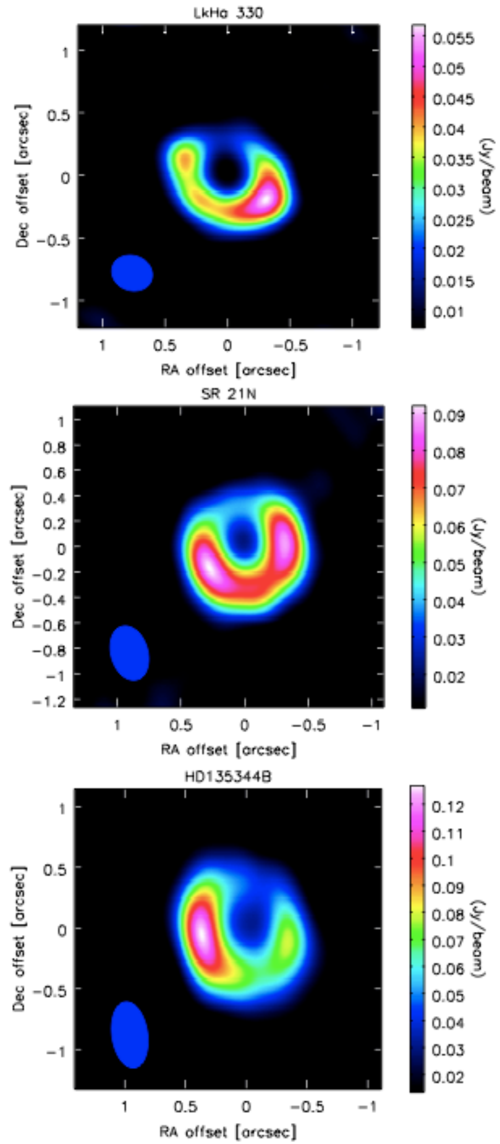
Asymmetries (if real): Dynamical origin?



Observations:



Model:



Regaly, Juhasz, Sandor et al. 2012

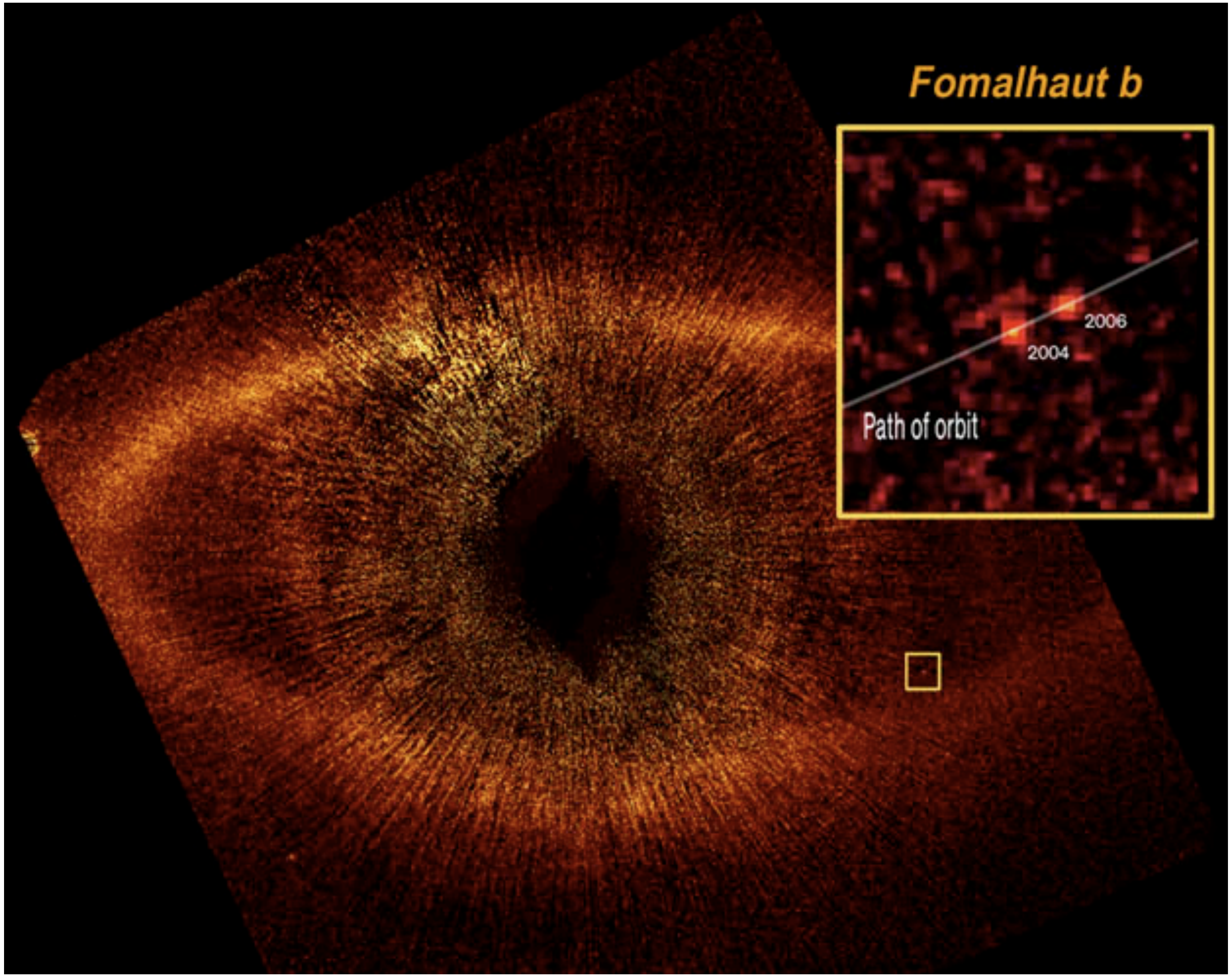
(Observations by Brown et al. 2009)

When the gas is gone:

From planet(esimals) back to dust...

„Debris disks“

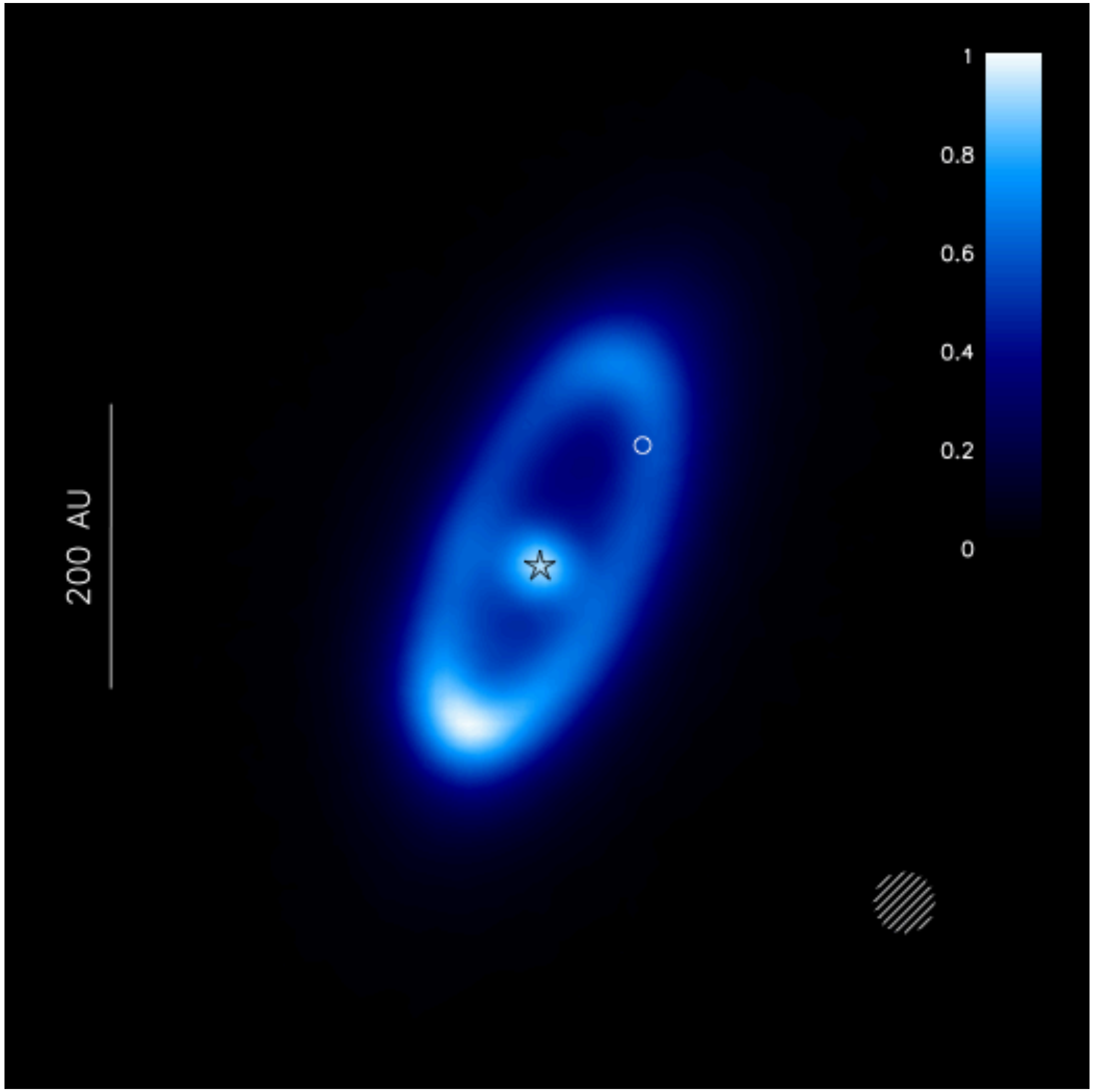
Fomalhaut: a nearby debris disk



Kalas NASA/ESA

Fomalhaut: a nearby debris disk

As seen by Herschel
PACS @ 70 microns



Acke, Min, Dominik et al. 2012

See talks by Krivov
and by Ertel
See poster 14 Donaldson,
poster 17 Faramaz,
poster 22 Fujiwara
poster 29 Harvey
poster 40 Kral
poster 45 van Lieshout
poster 46 Loehne

That‘s it for this overview...

Now let‘s hear what the speakers of this session have to say!