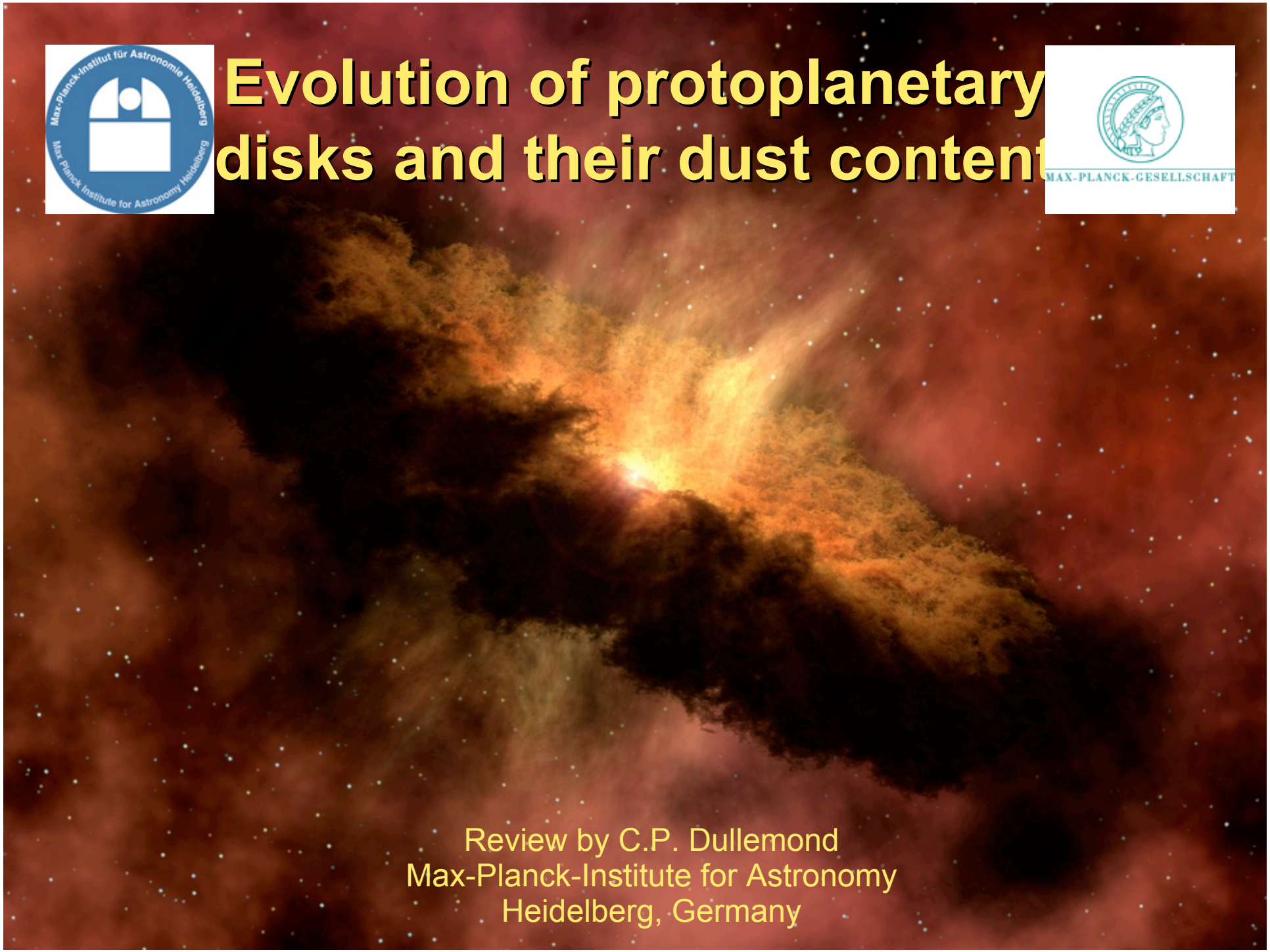
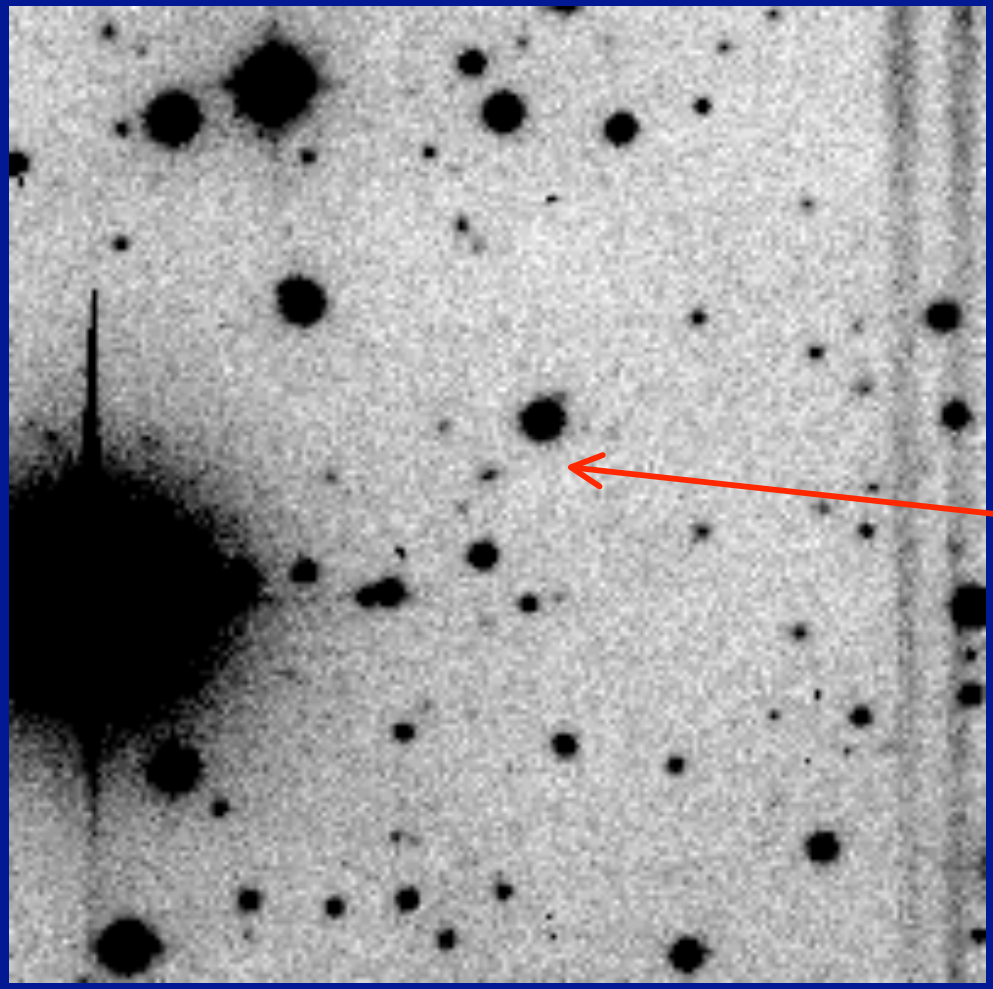

Evolution of protoplanetary disks and their dust content
Review by C.P. Dullemond
Max-Planck-Institute for Astronomy
Heidelberg, Germany

Tribute to Frithjof Brauer

(1980-2009)

Tribute to Frithjof Brauer

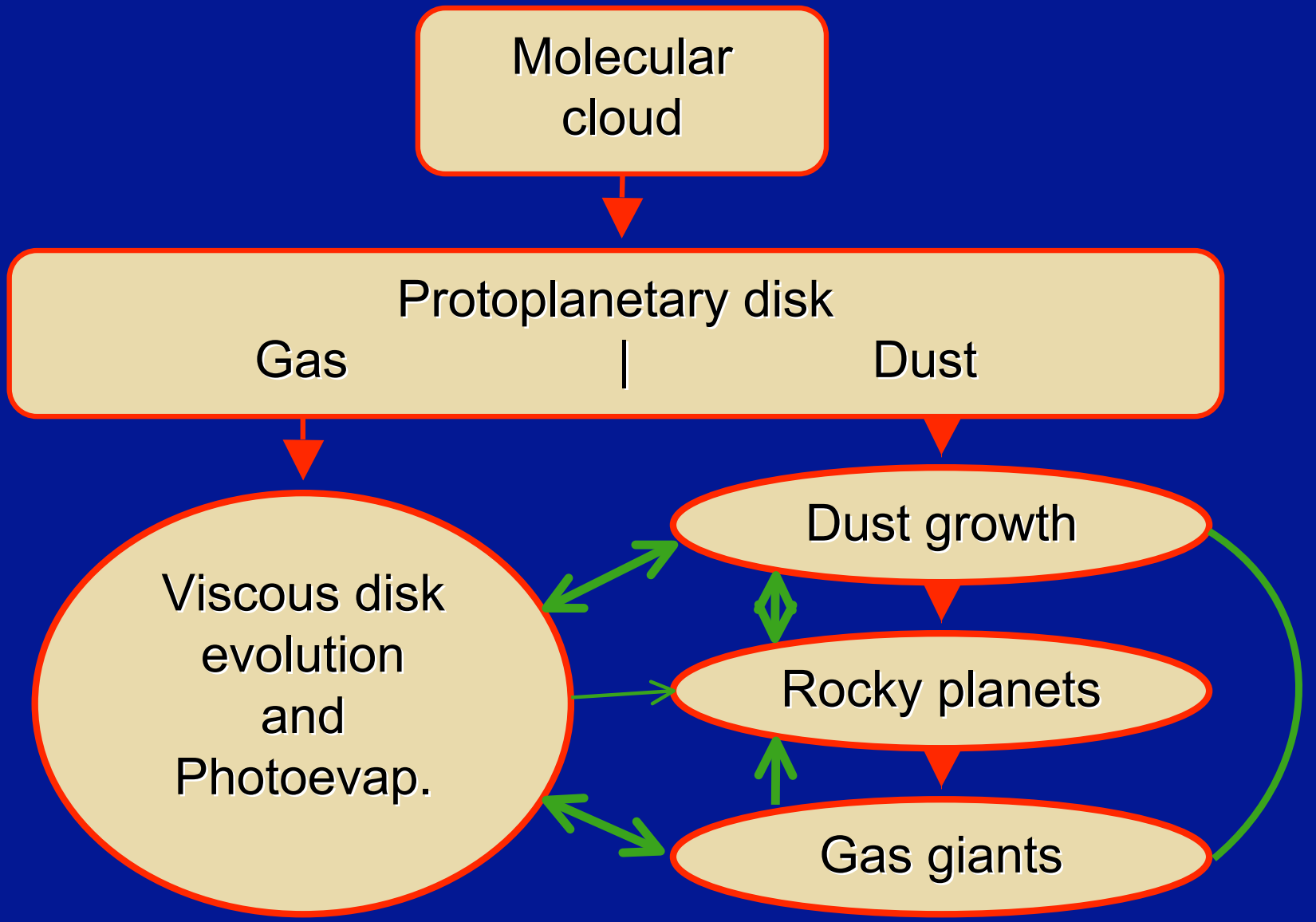
(1980-2009)



Asteroid “Frithjof”
Number 210444
Discovered by
Felix Hormuth (MPIA)
Dedication by
Juliet Datson (MPIA):

“Frithjof Brauer (b. 1980) developed in his Ph.D. thesis principles of dust coagulation and formation of planets beyond the meter size barrier. Apart from his contributions to science, he makes the life of his fellow human beings much brighter and bearable with wonderful piano improvisations and his open way with people.”

From molecular clouds to planets



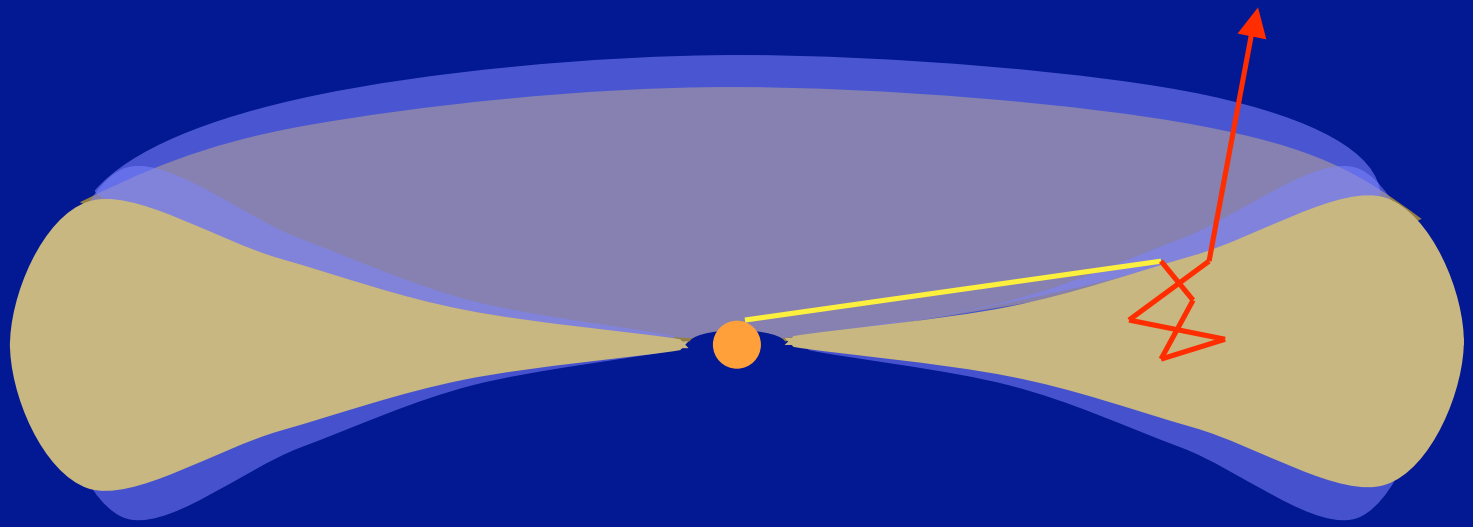
The birthplaces of planets: Basic structure

Still one of the clearest images...

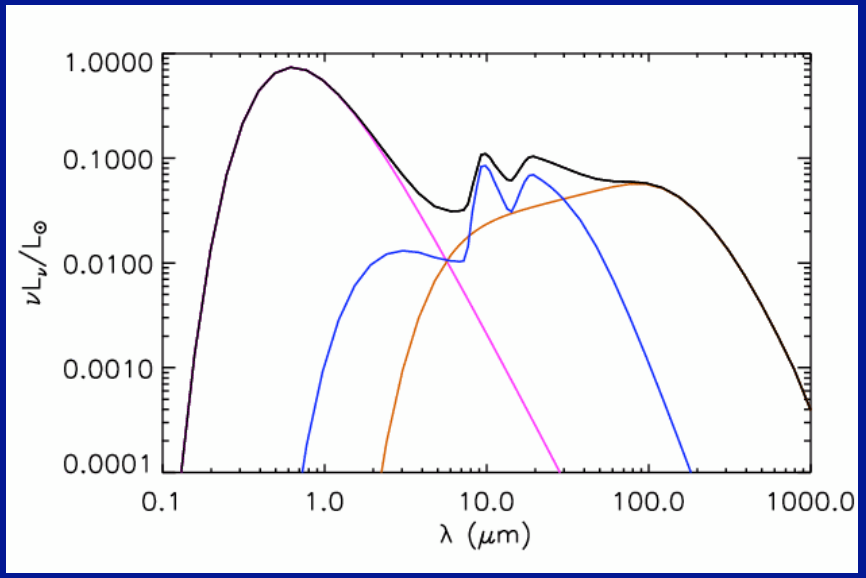
Image taken with the *Hubble Space Telescope*.

Location: in the Orion Nebula

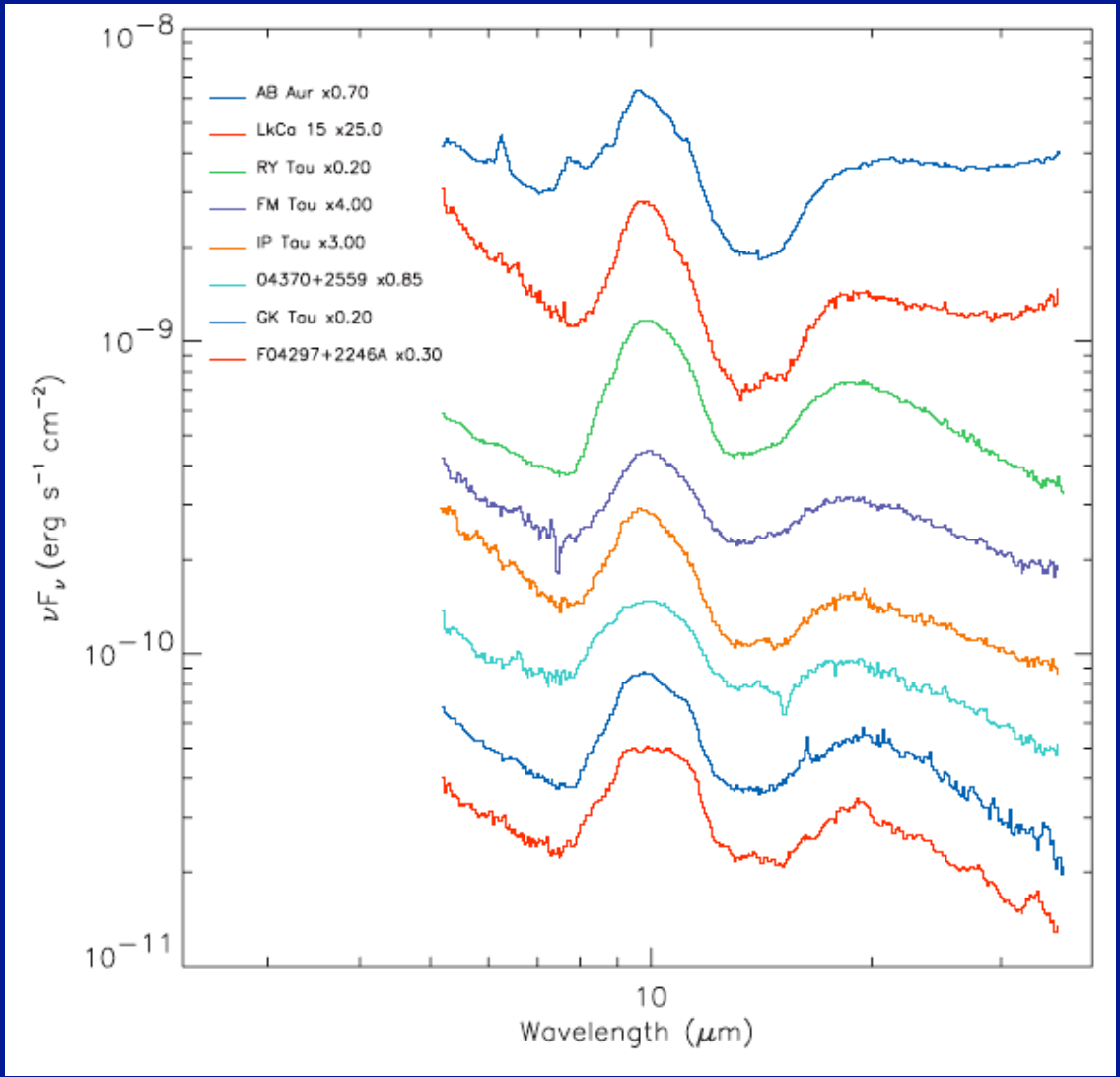
Creation of a warm surface layer



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



T Tauri Star SEDs:

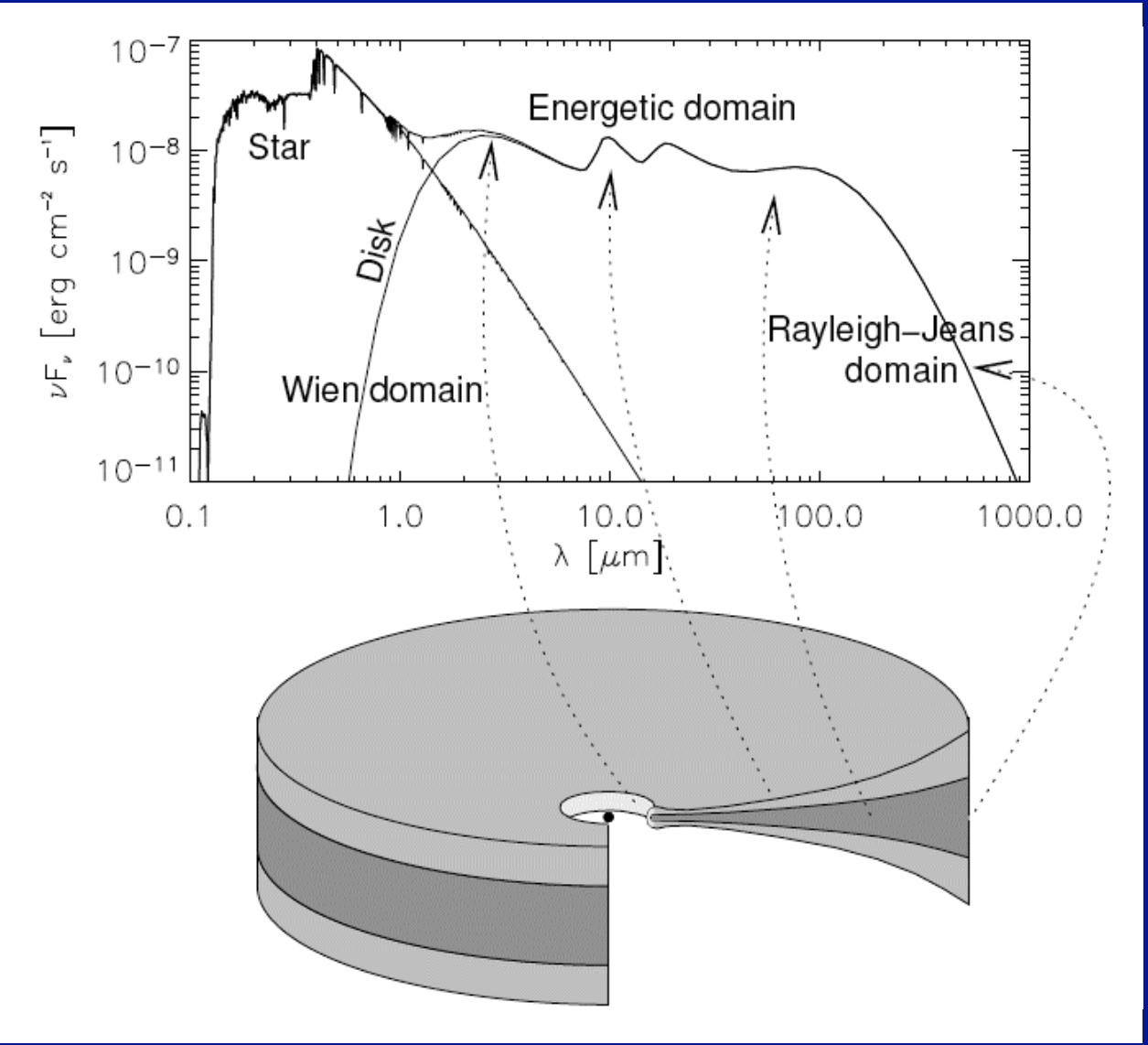


Furlan et al. 2006

Spitzer IRS spectra of large sample of class II sources. Furlan et al. 2006

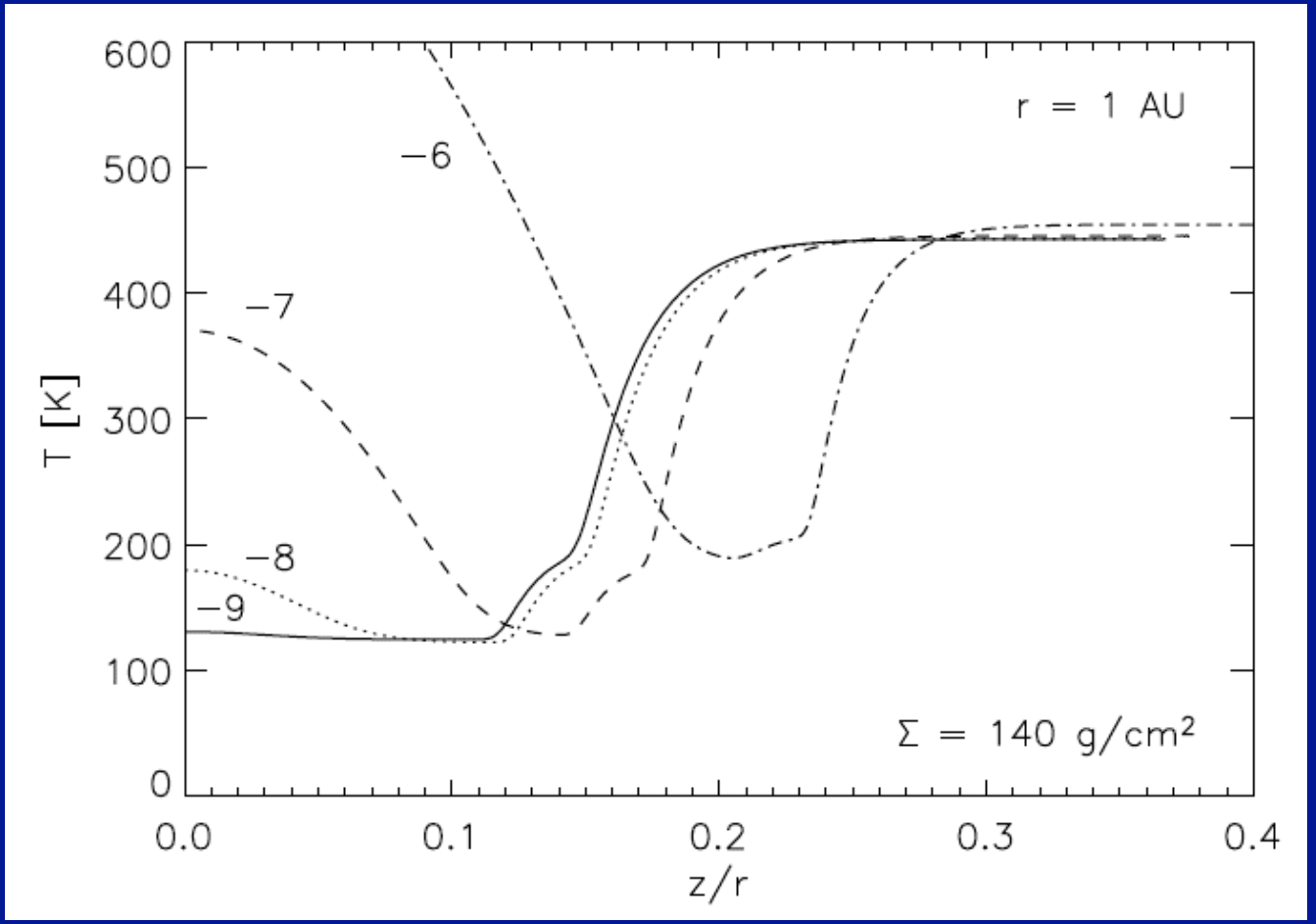
Shown here: the sources with the flattest SEDs, i.e. strongest disk flaring.

Where does the radiation come from?



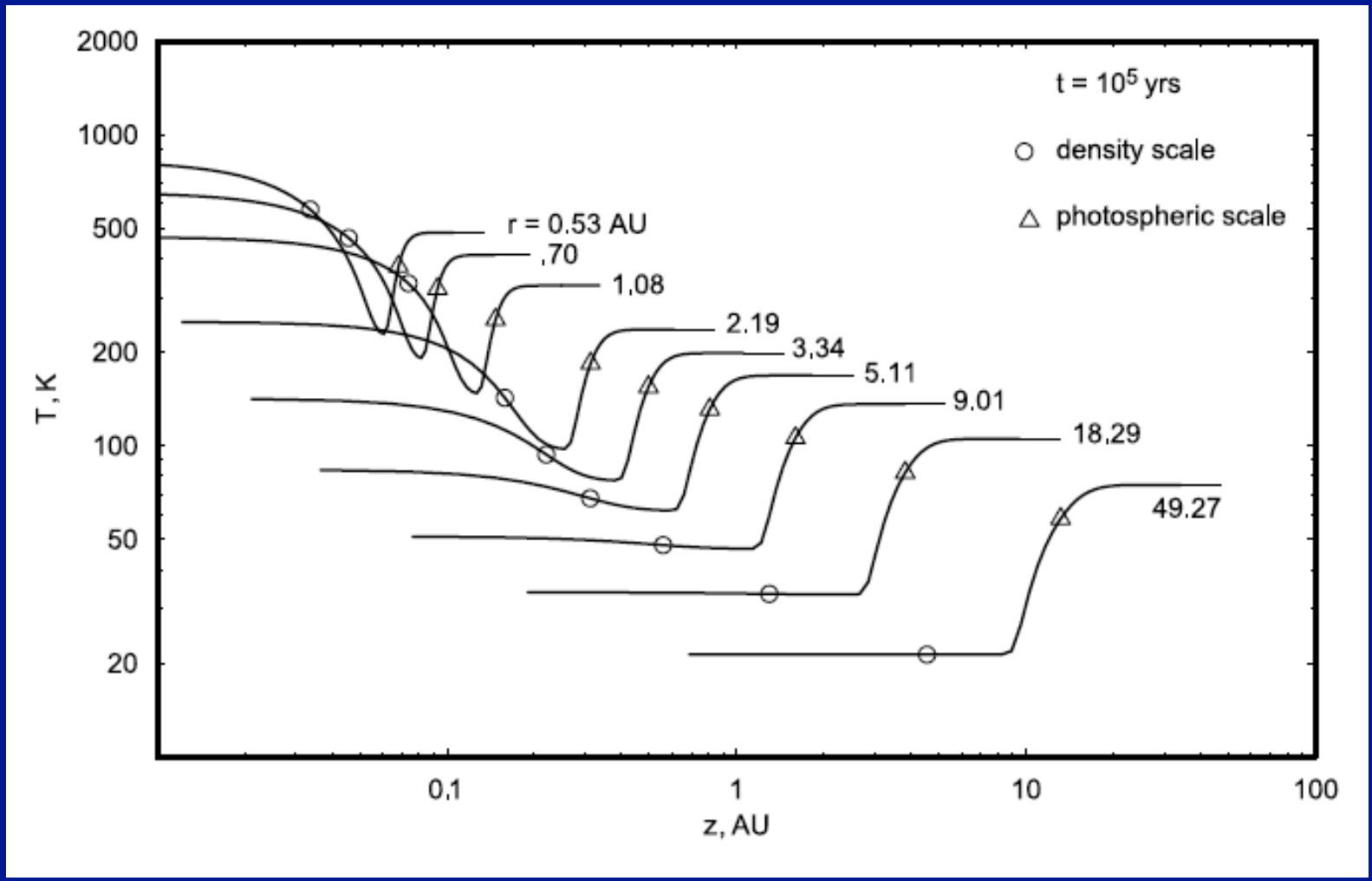
Dullemond, Hollenbach, Kamp & D'Alessio PPV review

Temperature structure of accreting disk



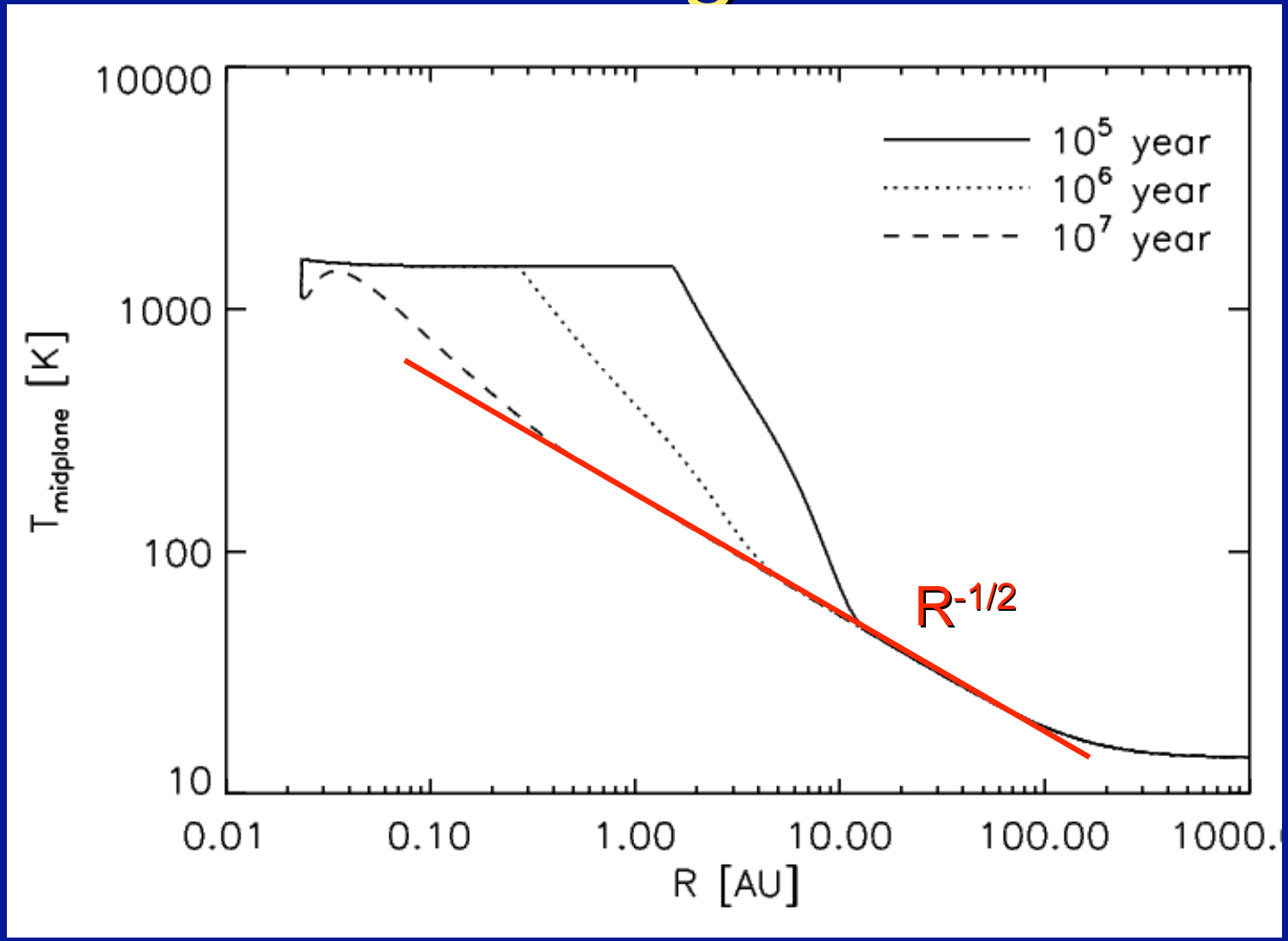
Vertical structure of a protoplanetary disk
(Model: P. D'Alessio)

Temperature structure of accreting disk



Davis (2005)

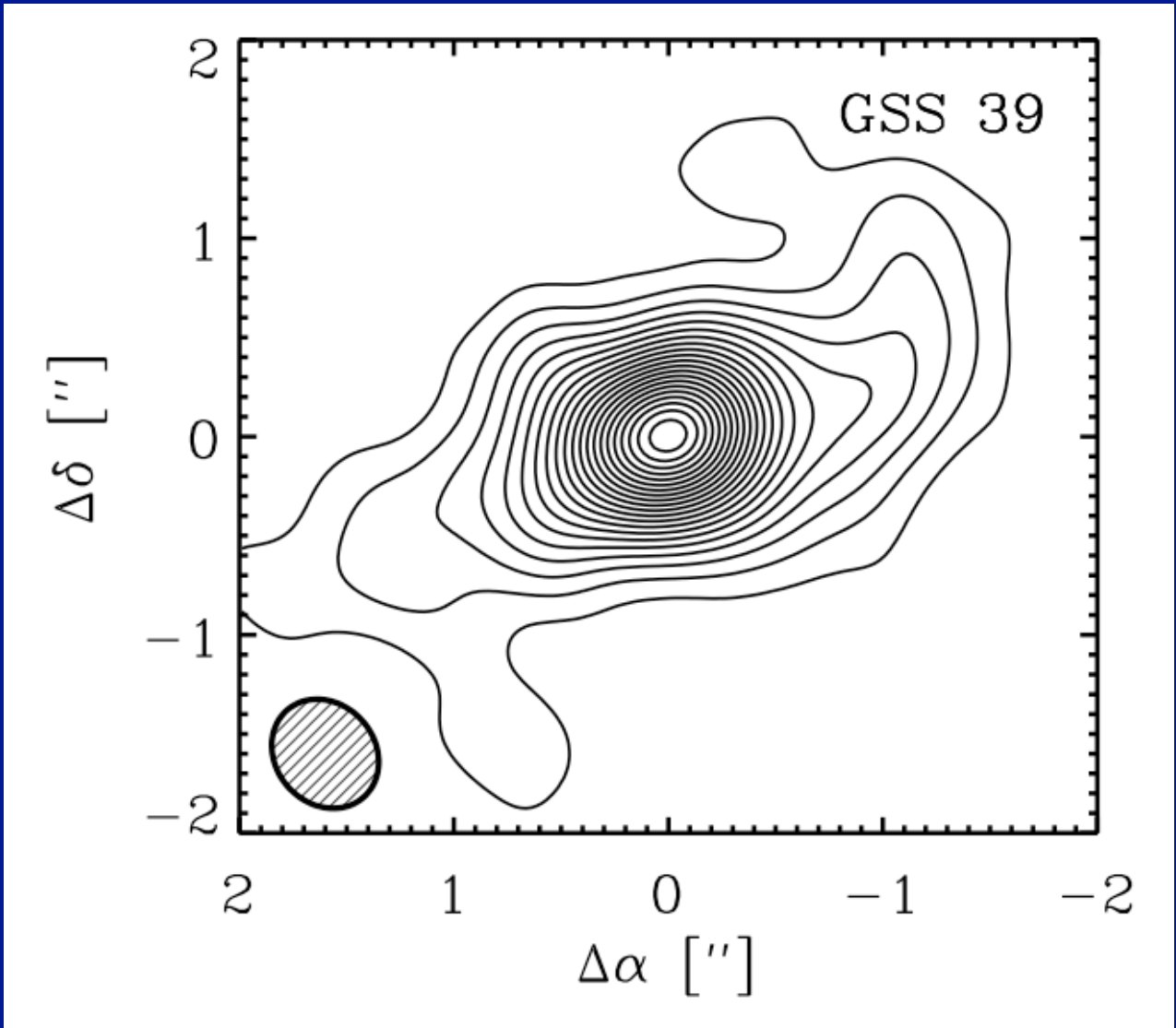
Temperature structure of accreting disk



Quick-n-dirty model: Dullemond

Are protoplanetary disks similar to the Minimum Mass Solar Nebula ?

Radial distribution of matter

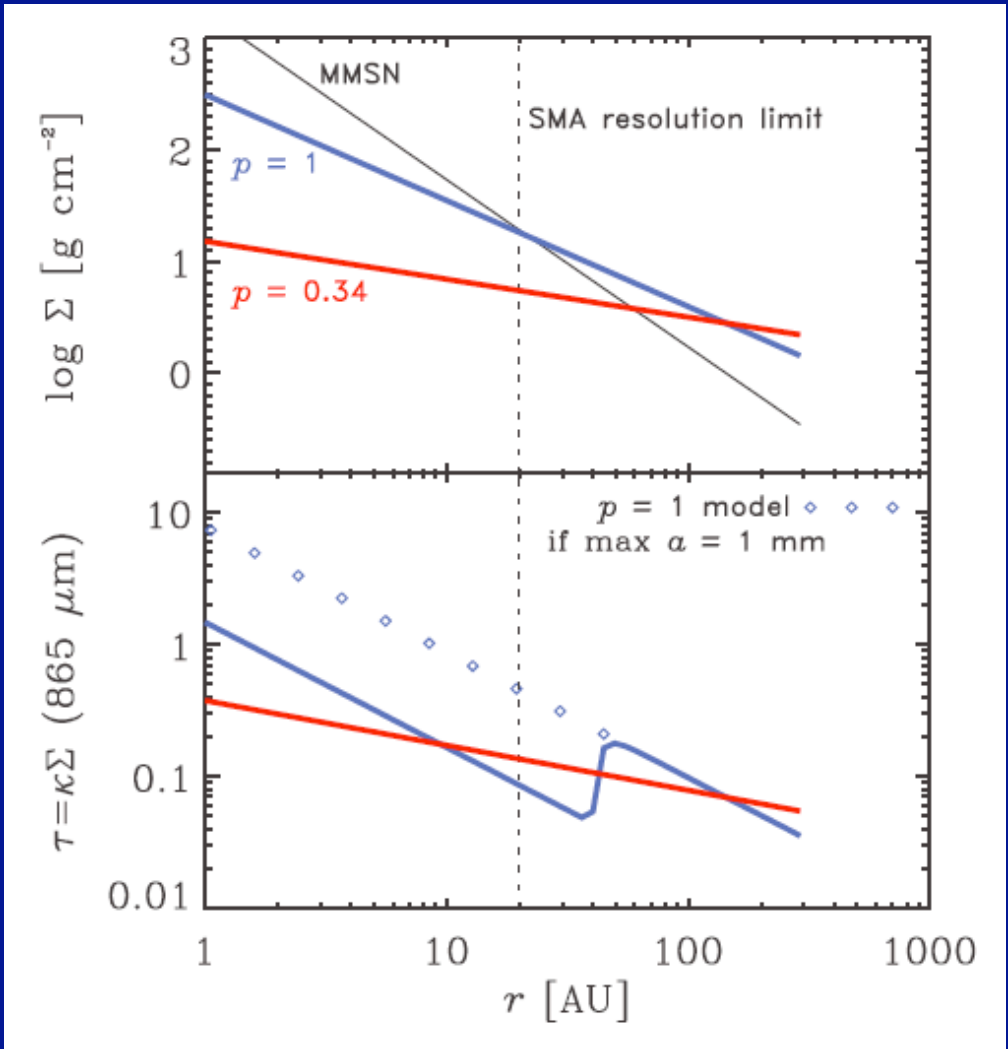


Millimeter interferometry map of bright disk in Ophiuchus with the SMA on Mauna Kea, Hawaii

Andrews et al. 2009

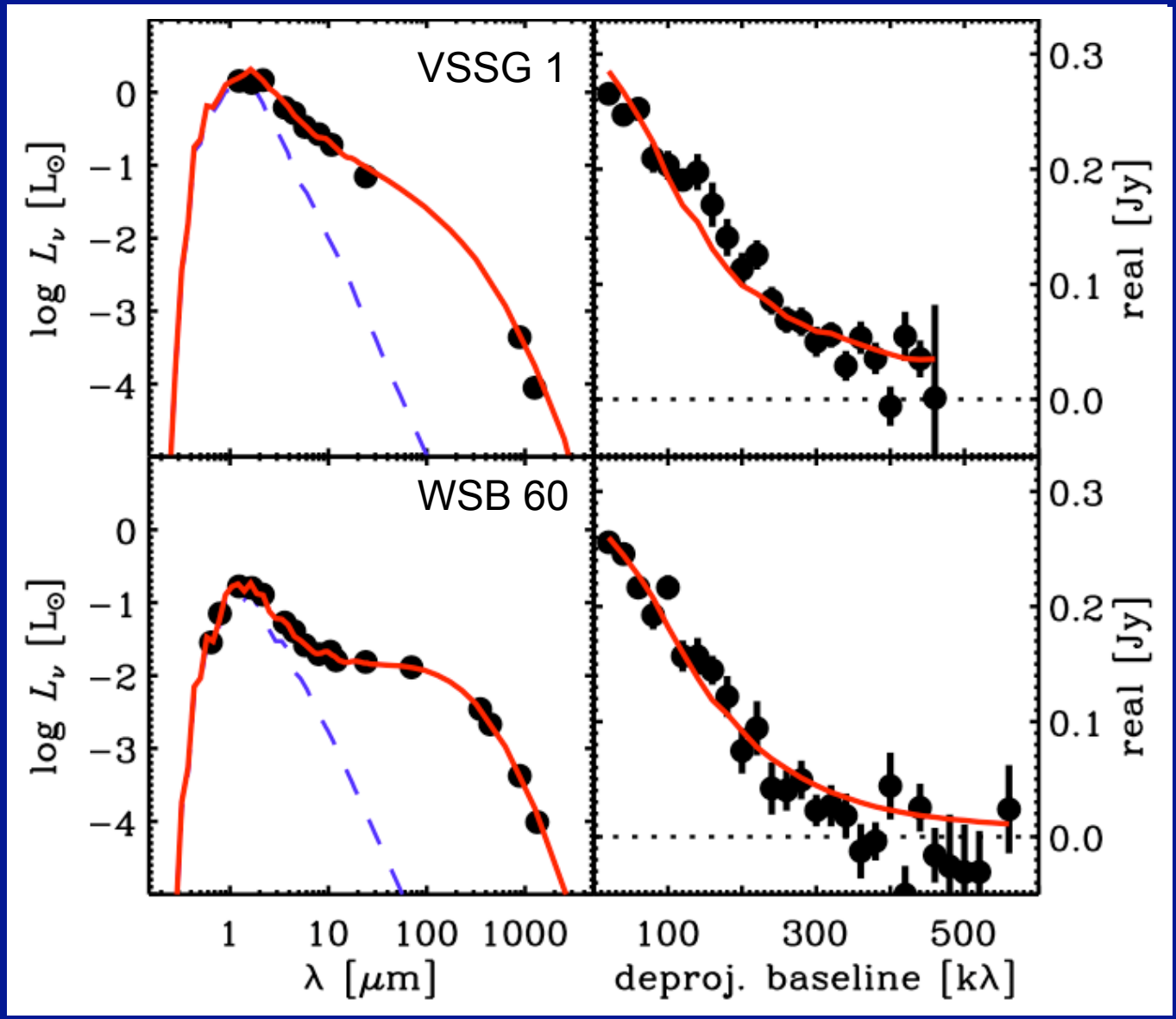
Radial distribution of matter

The case of DoAr 25



Andrews, Hughes, Wilner & Qi (2008)

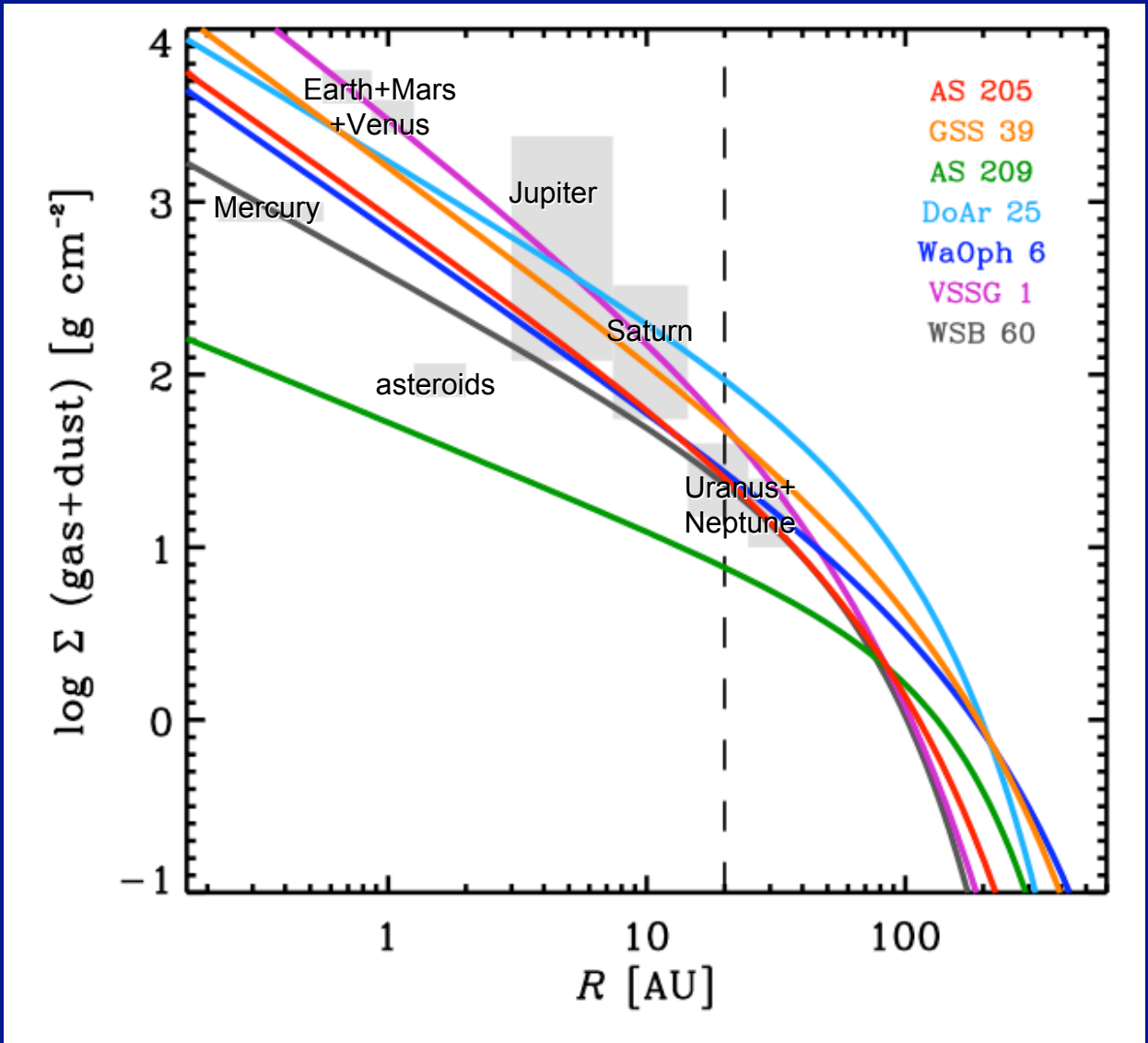
Radial distribution of matter



SED + millimeter resolved maps (=visibility values)

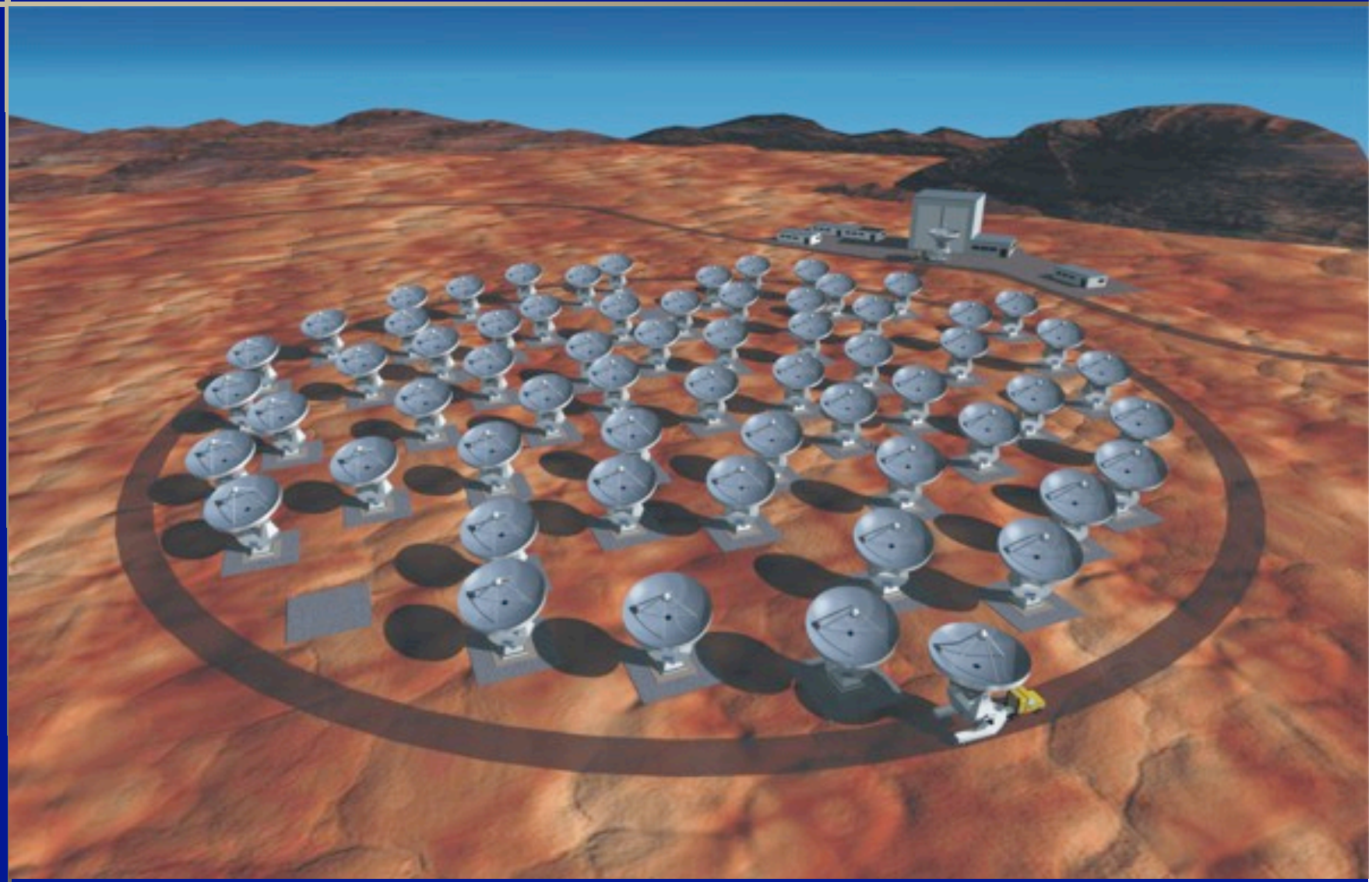
Andrews et al. (2009)

Radial distribution of matter



Andrews et al. (2009)

Looking forward to this toy:



Coming soon...

But...

- We measure the dust in the (sub-)mm continuum
- Dust evolves:
  - Grain growth first enhances, then reduces opacity
  - Radial drift reduces dust content
- So: Let us study the dust evolution

The evolution of the dust...

The evolution of the dust and the formation of planets!

From dust to planets

Need models that bridge the “gap”

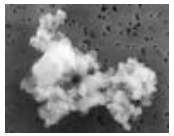
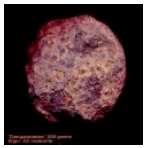
Directly observable through IR and mm observations

?

Exo-planets

Solar system constraints (but only 1 object! And 4.5 billion years ago!)

1μm 1mm 1m 1km 1000km

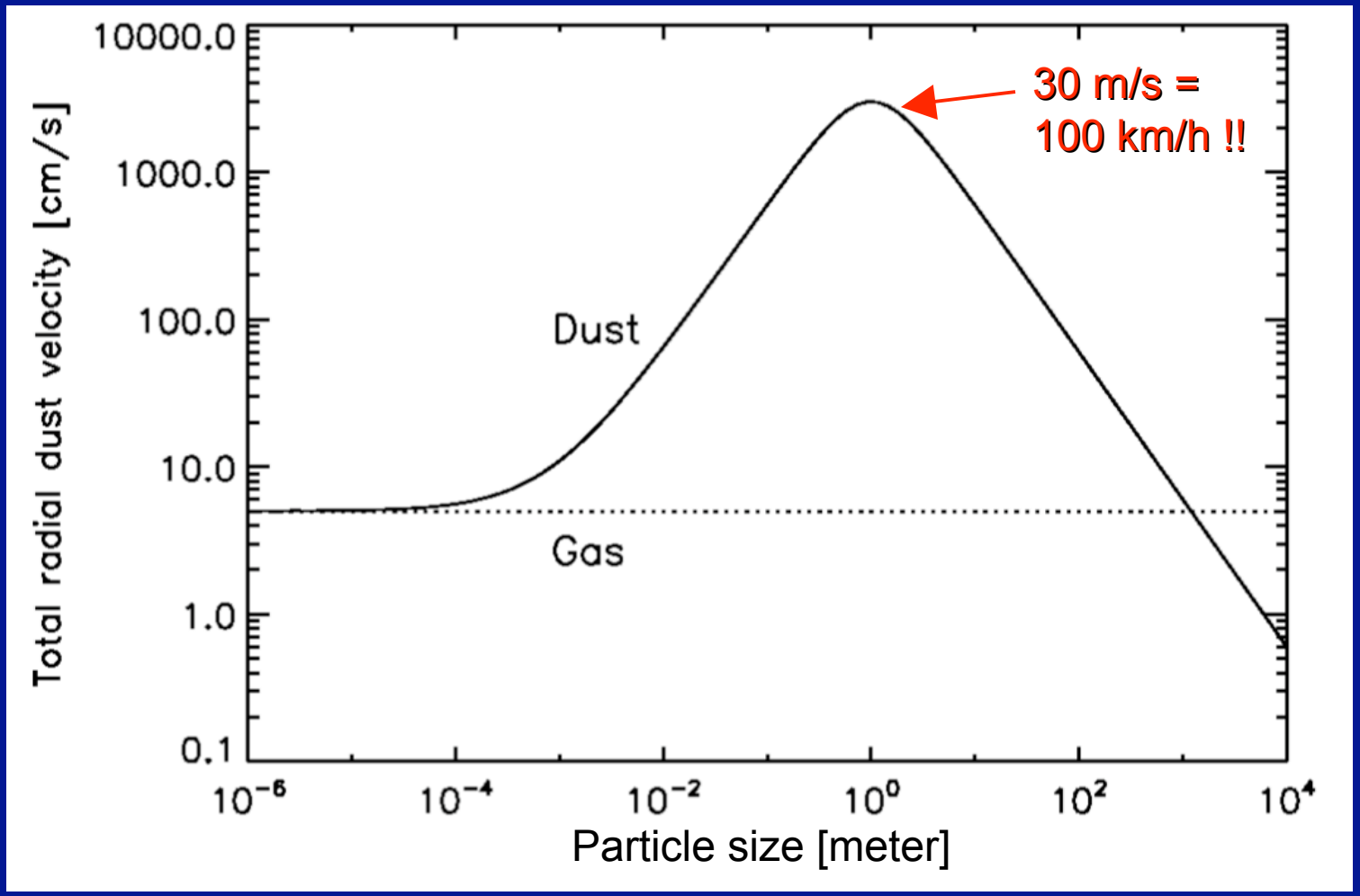
Radial drift

Particles drift toward pressure maximum

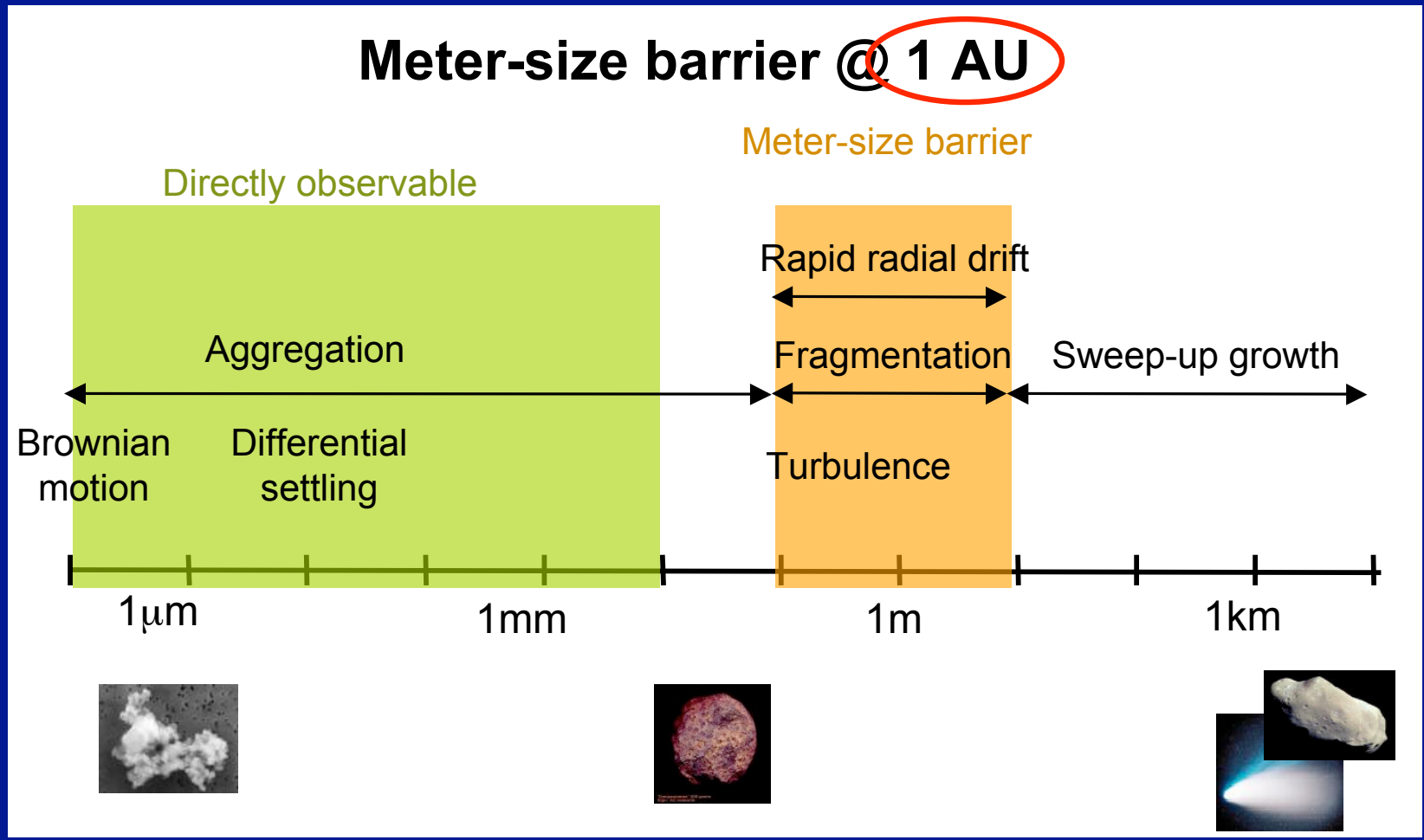
(DEMO)

This leads to inward drift of particles

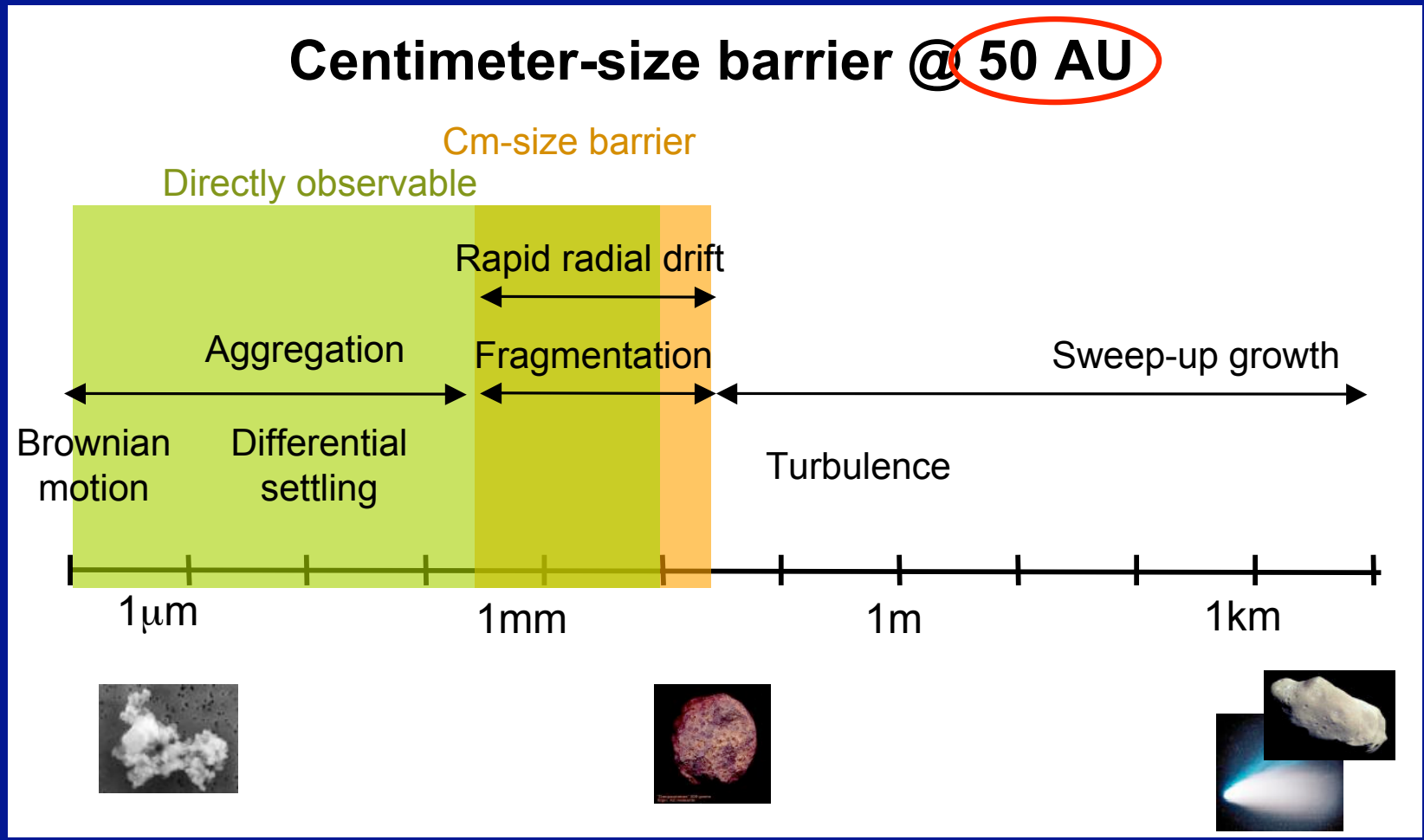
Main problem: high velocities



Main problem: high velocities



Main problem: high velocities

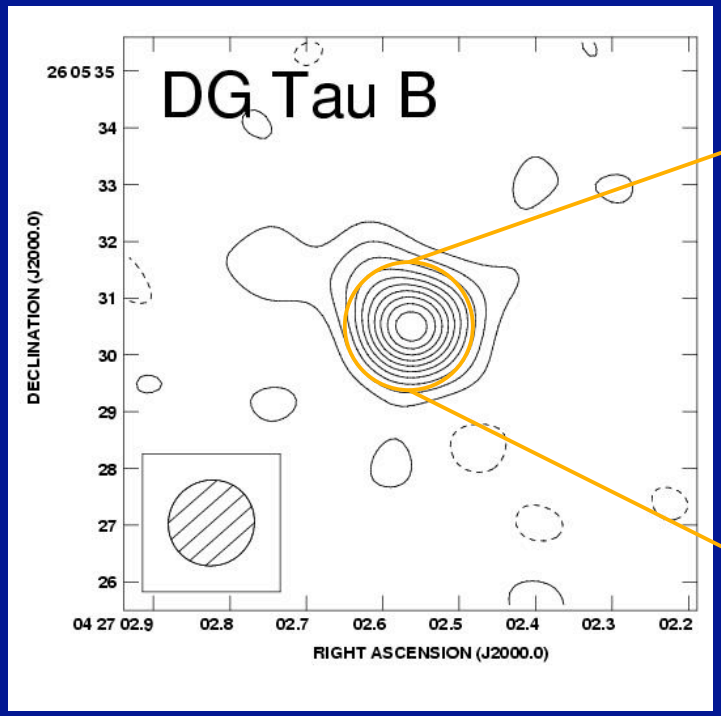


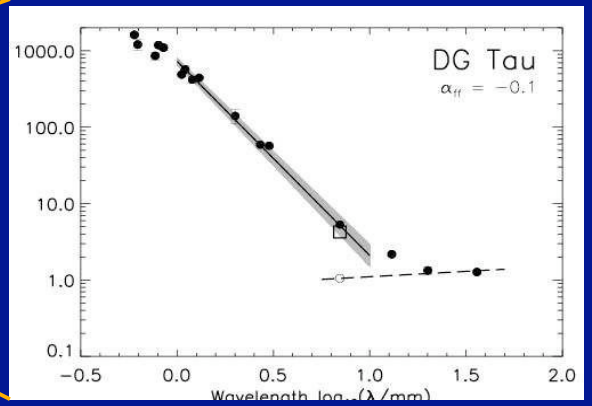
So... Two reasons to study 50 AU

1. Cm-size drift problem @ 50 AU is a proxy of the m-sizedrift problem @ 1 AU (=planet forming zone)

2. Cm-size drift problem @ 50 AU poses problem for disk mass estimates

Cm-size grains in outer disk

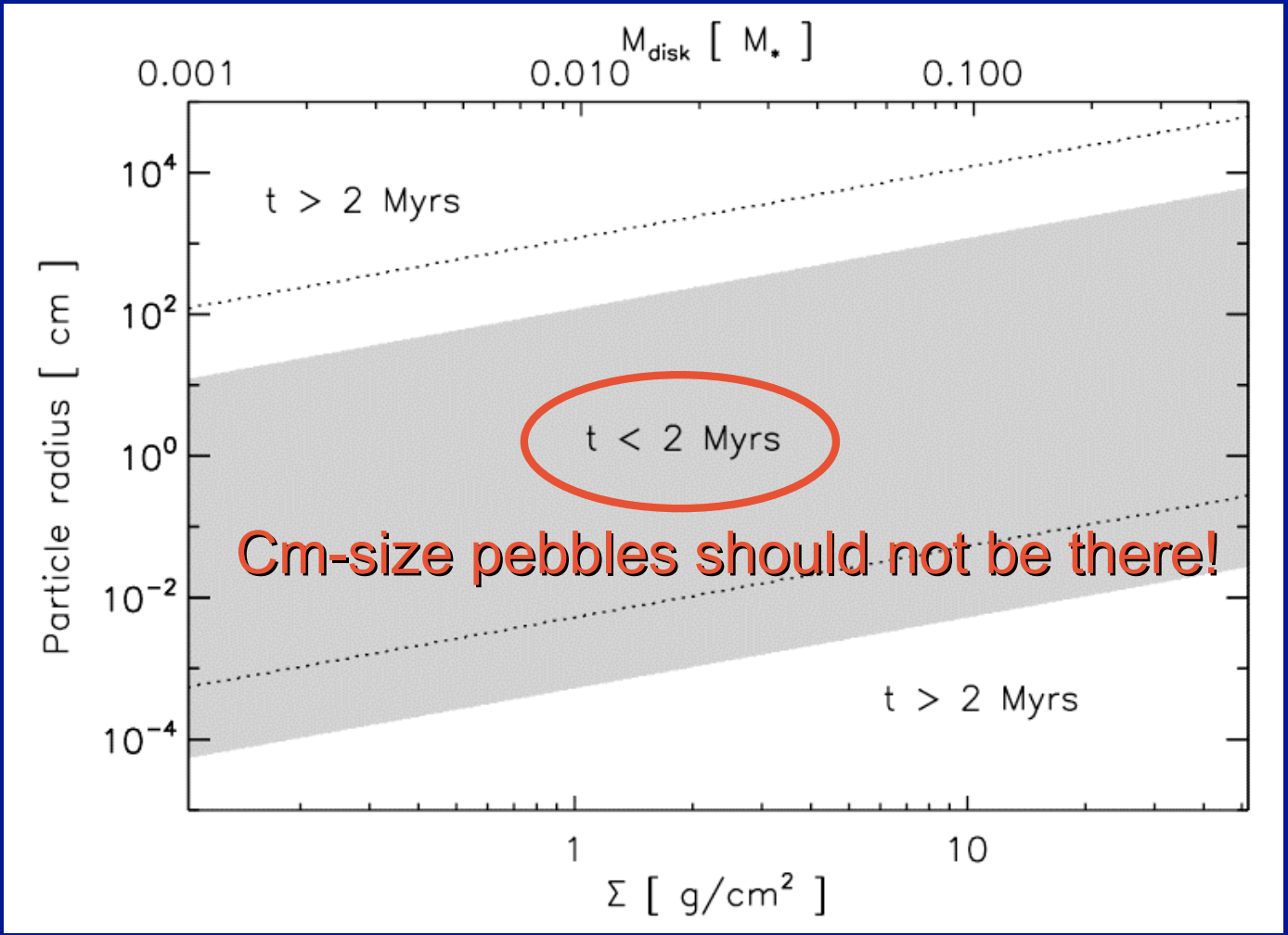




These grains must stay there for millions of years!

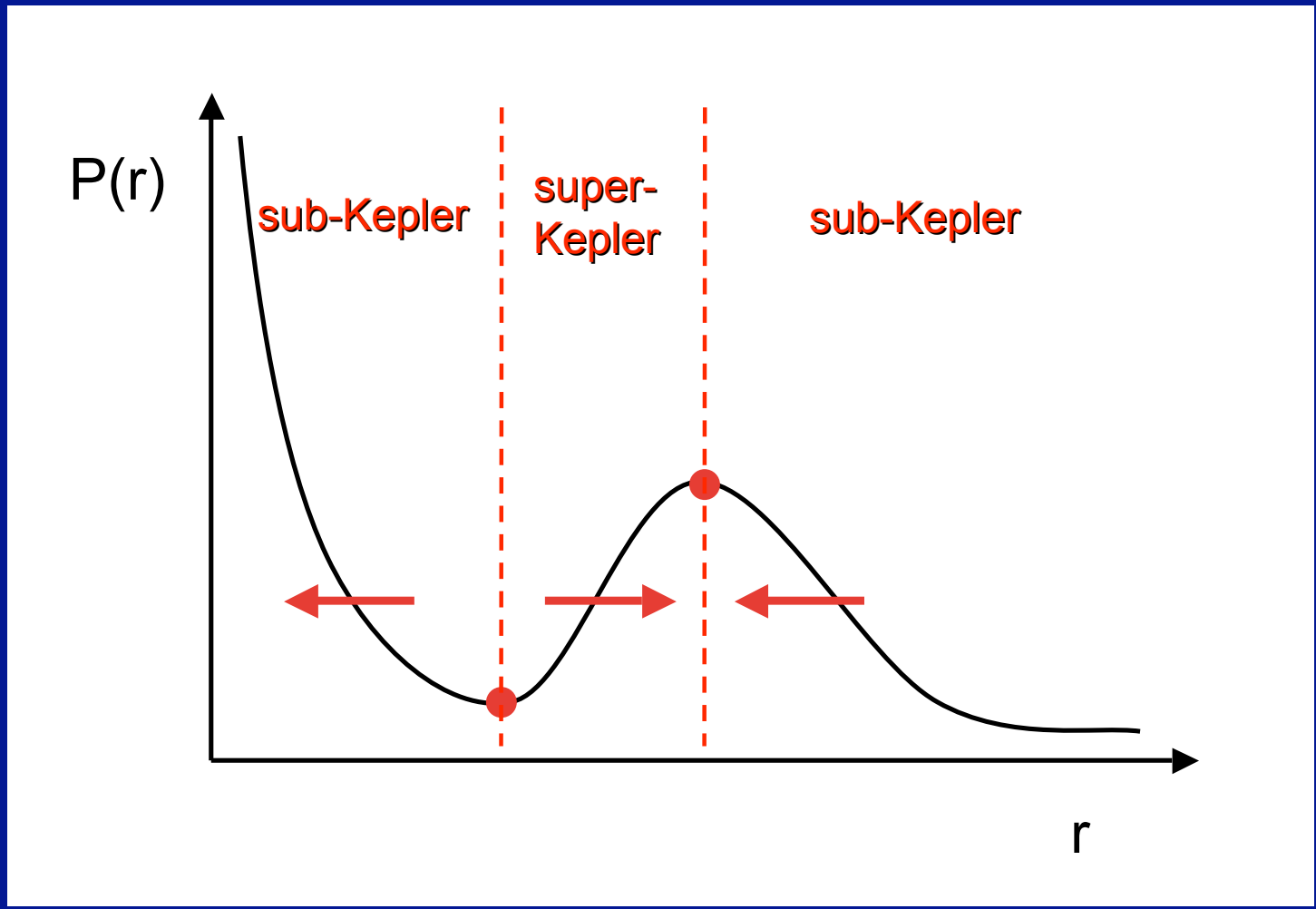
J. Rodmann, et al. 2005; Testi et al. 2003; Wilner et al. 2005

Radial drift time scales of cm-pebbles

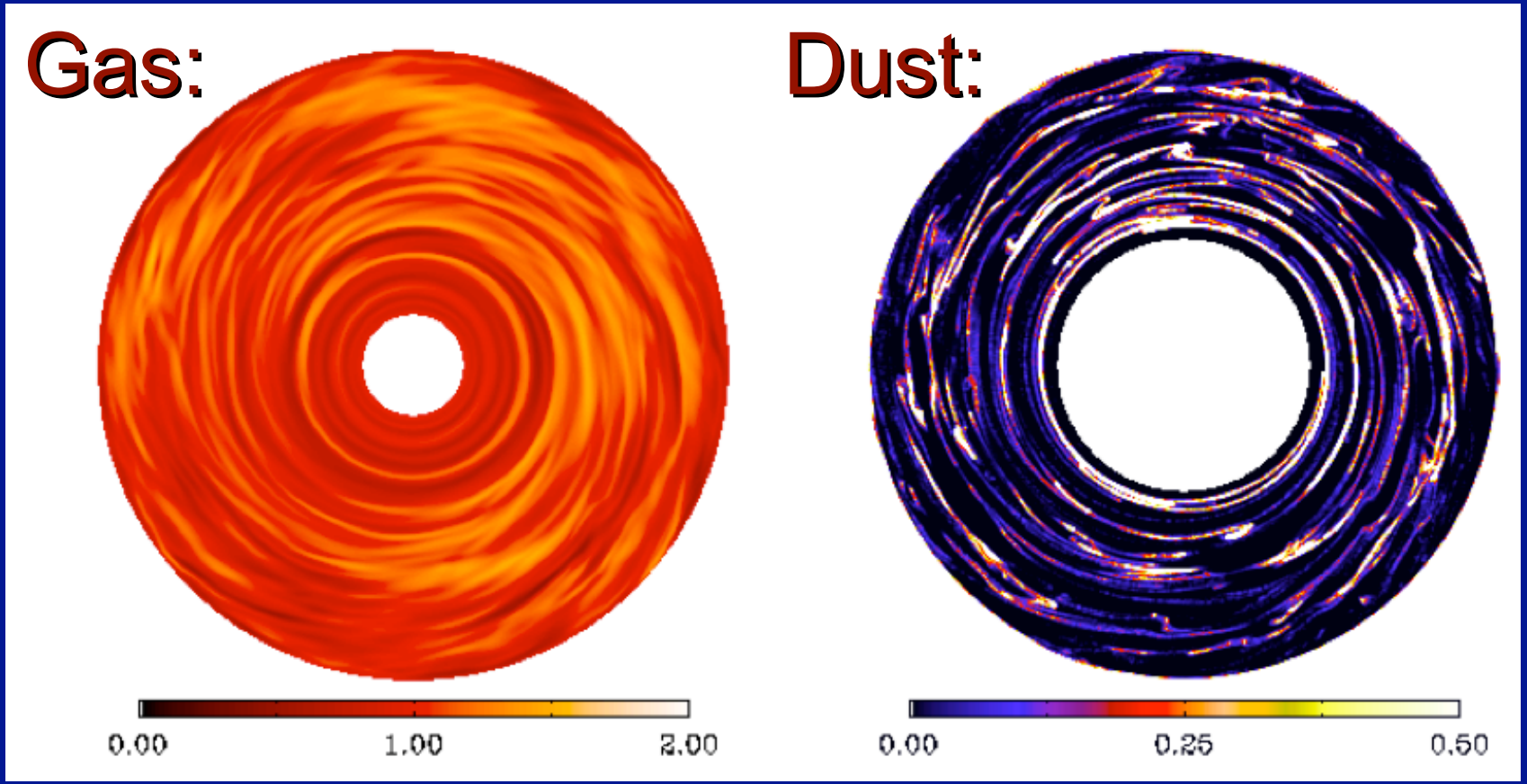


Brauer et al. 2007

Trapping dust in pressure maxima

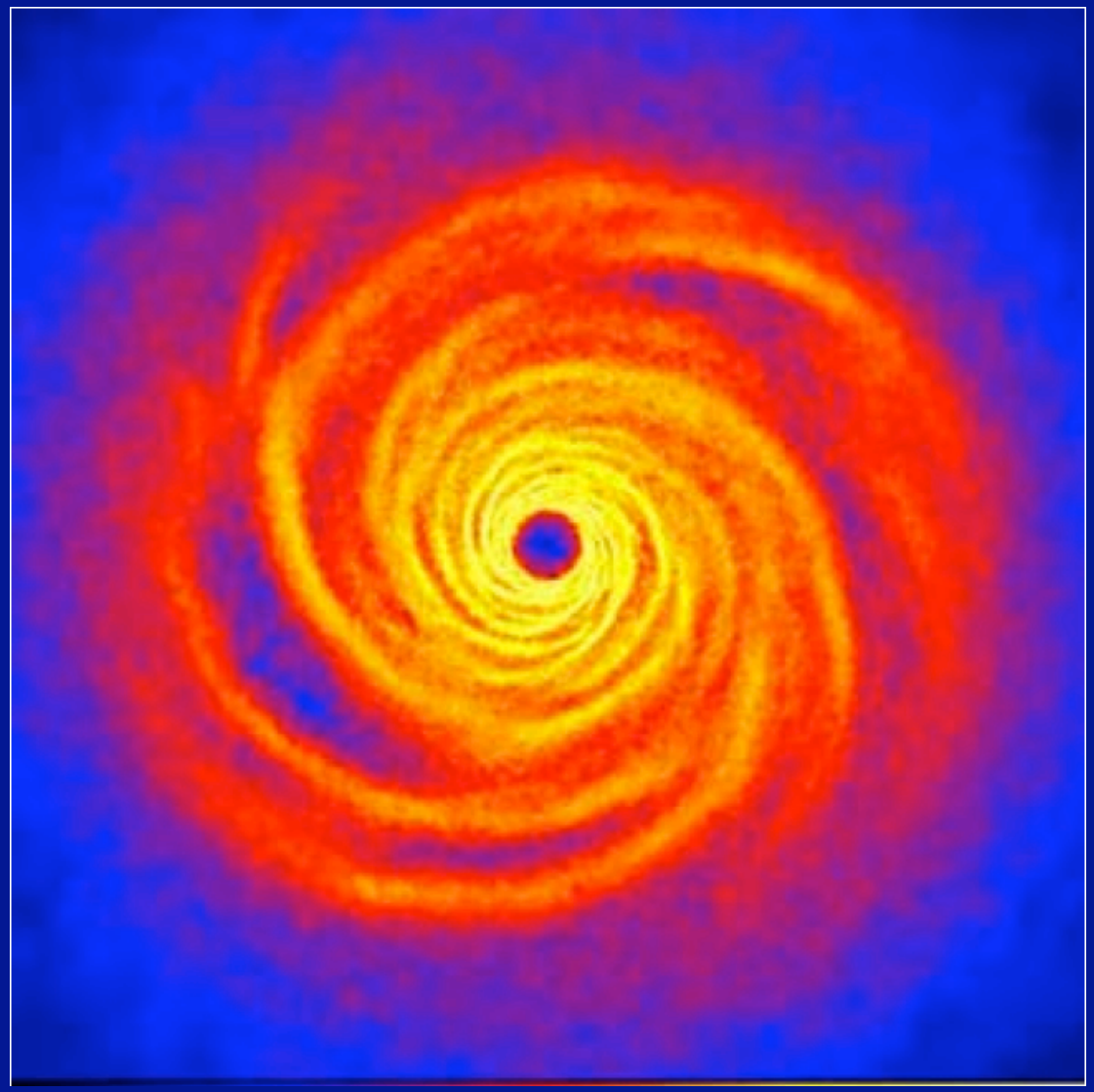


Trapping dust in pressure maxima



Lyra, Johansen et al. 2009

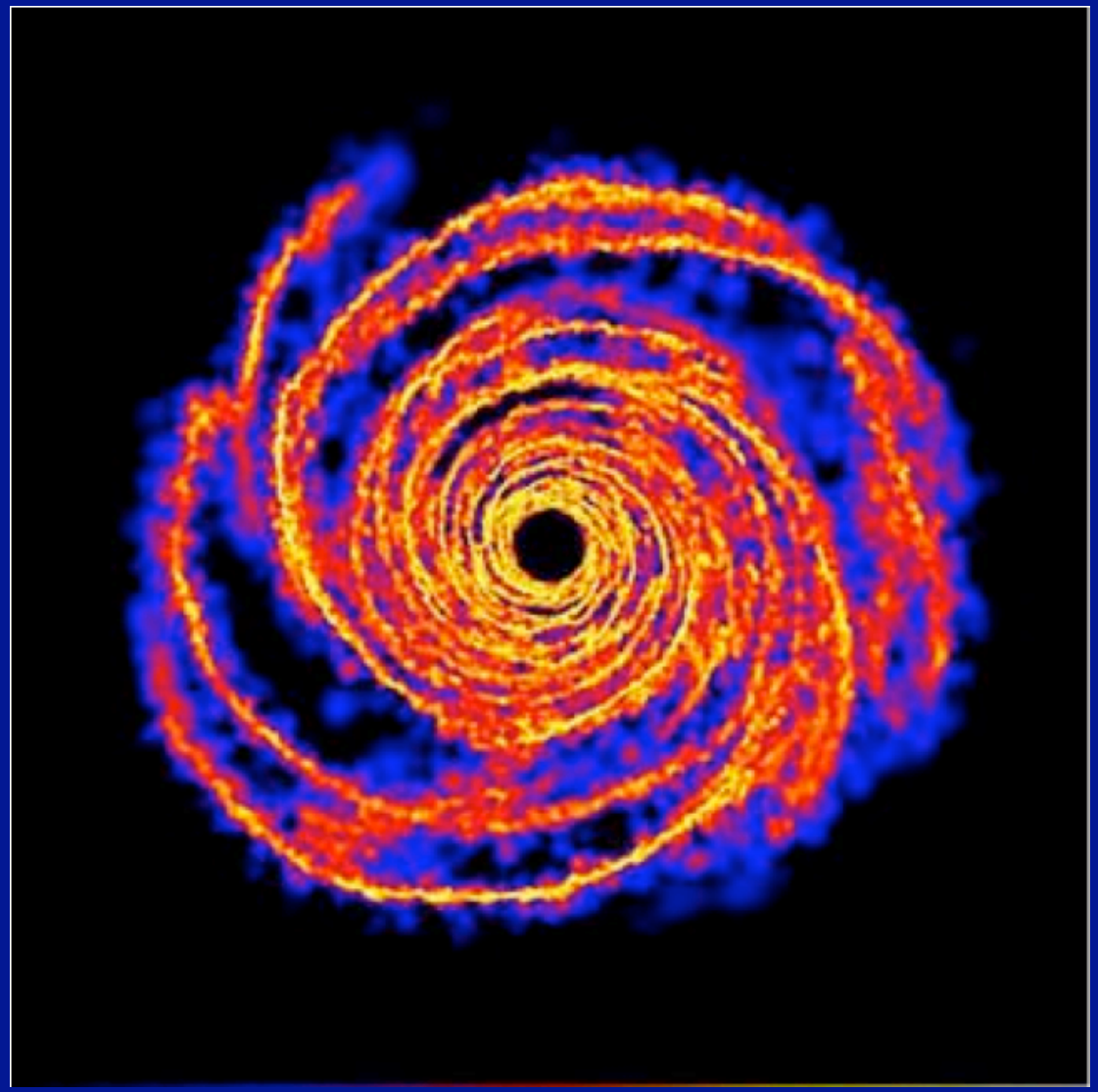
Trapping dust in pressure maxima



Gas structure

Rice, Lodato, Pringle, Armitage & Bonnell 2004

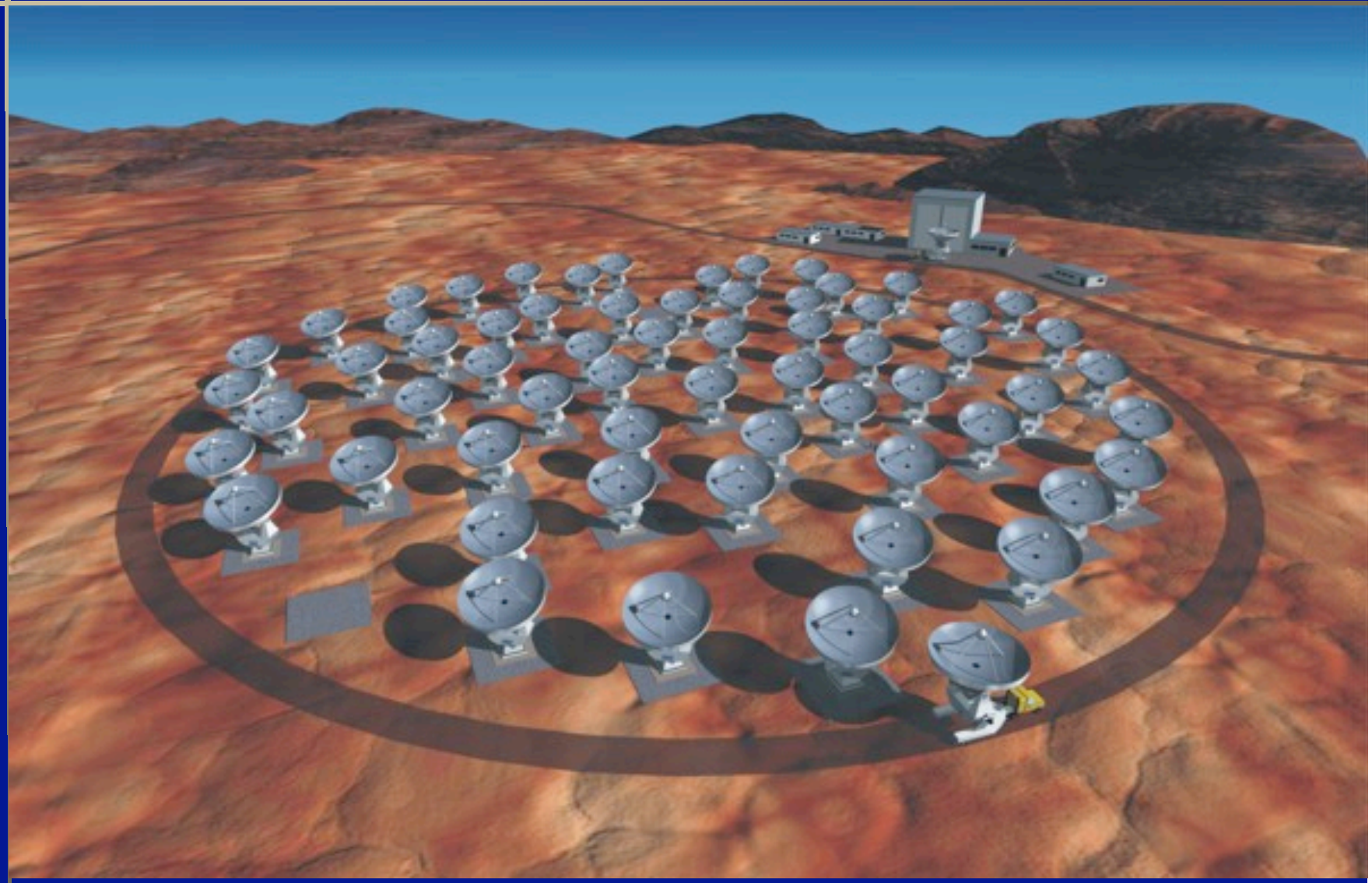
Trapping dust in pressure maxima



Dust trapping...

Rice, Lodato, Pringle, Armitage & Bonnell 2004

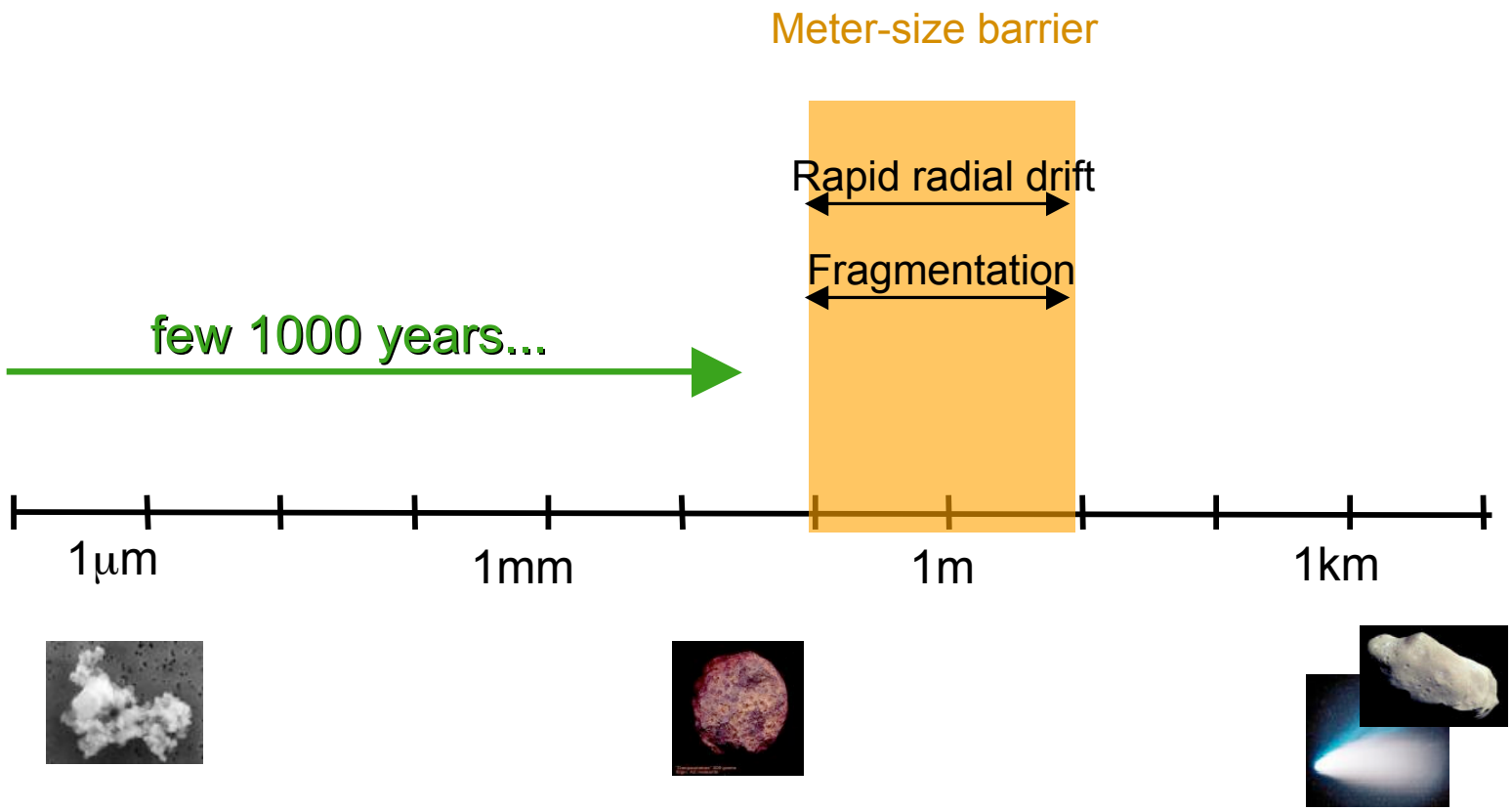
Again... Looking forward to this toy!



The growth and fragmentation of dust aggregates

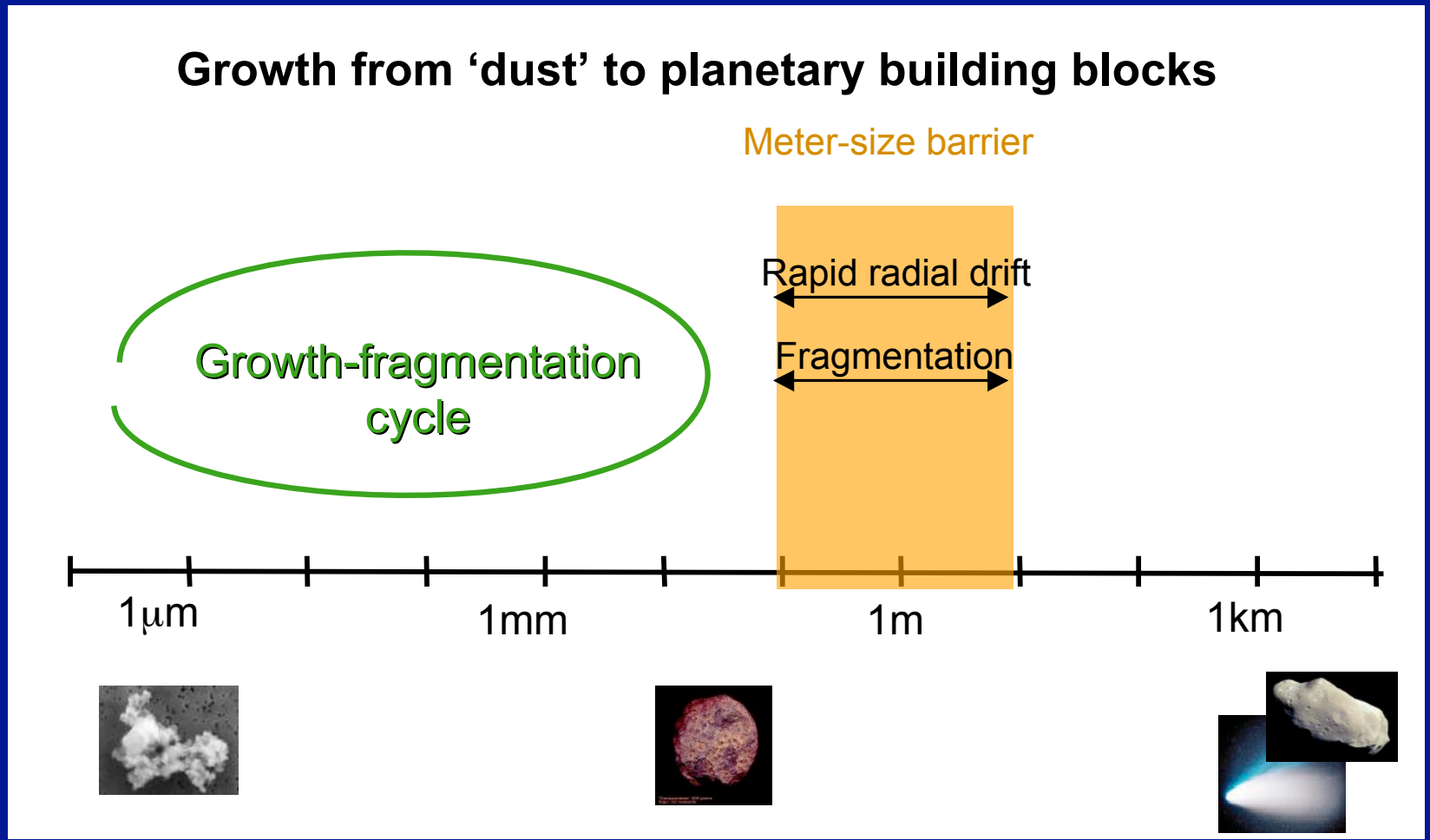
Grain growth is FAST

Growth from ‘dust’ to planetary building blocks



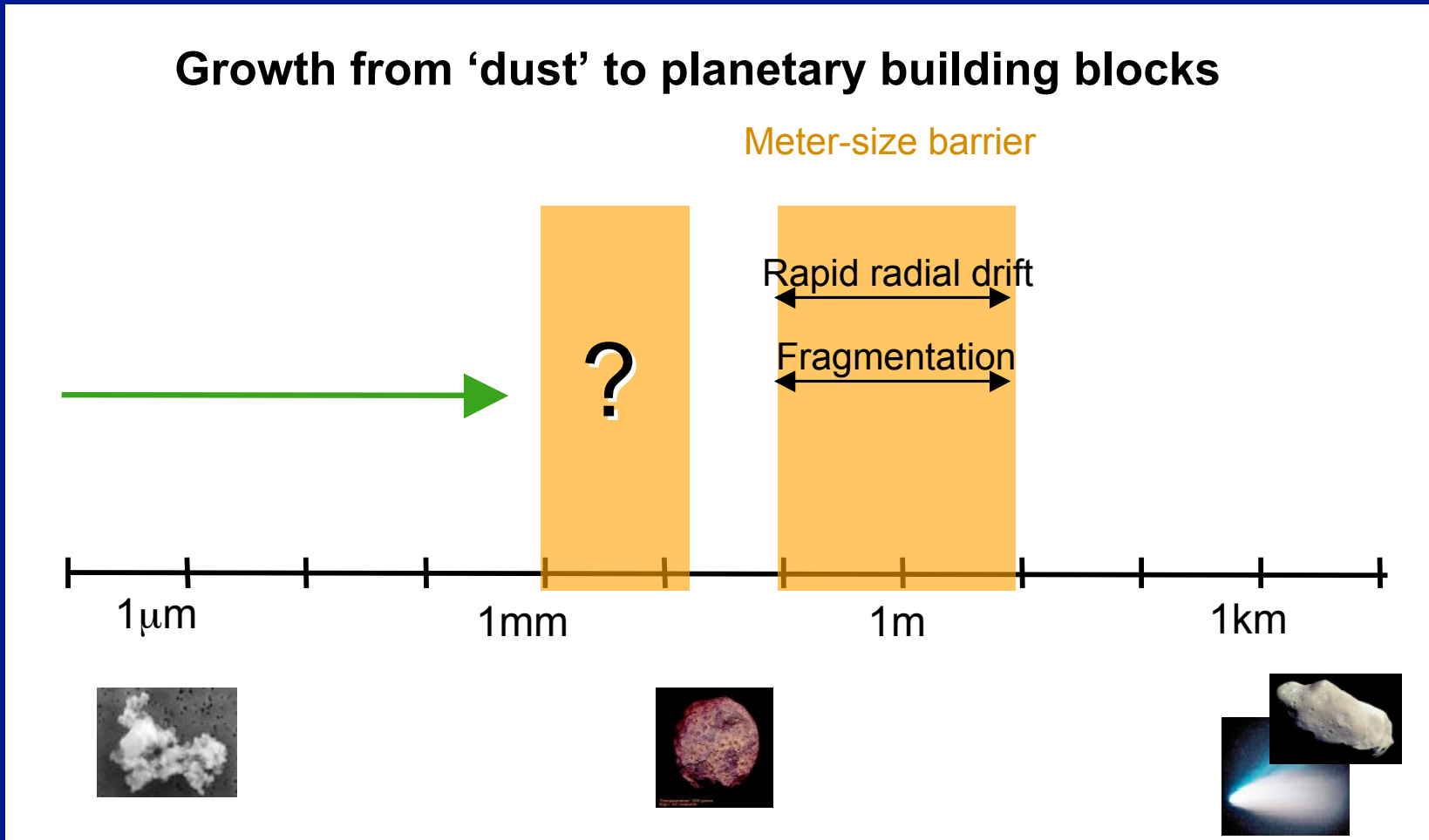
Grain growth is FAST

...and so is fragmentation...



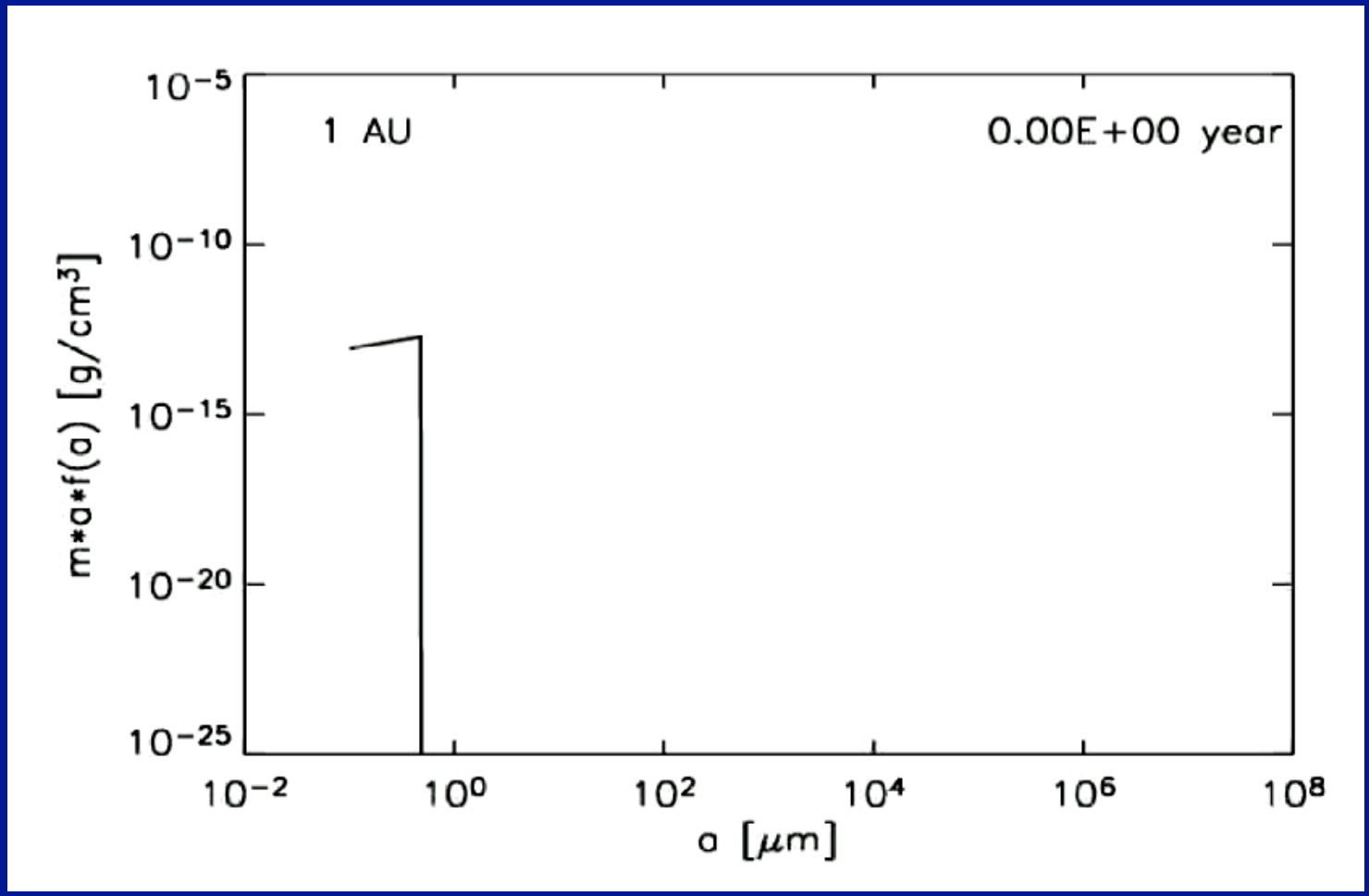
Grain growth is FAST

...and maybe even other physics
(see talk by Andras Zsom later)!



Aggregation models

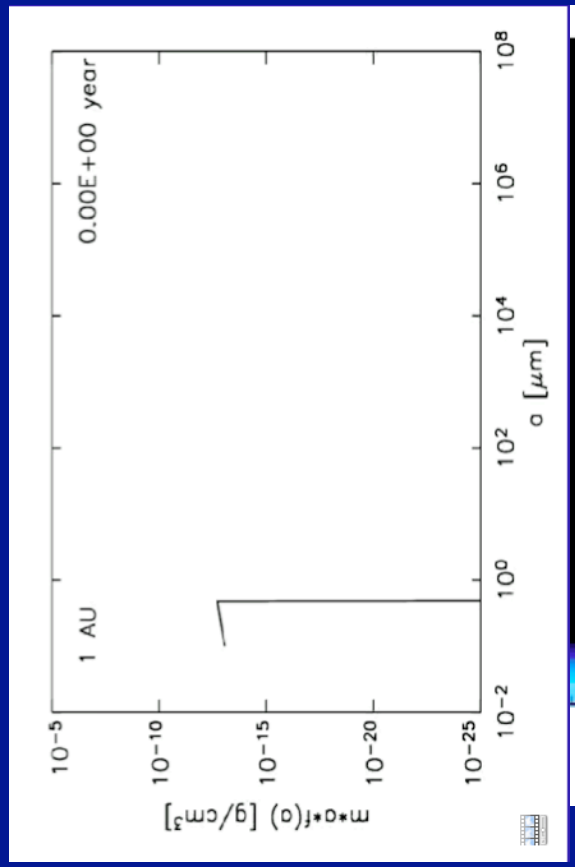
Example of growth without fragmentation

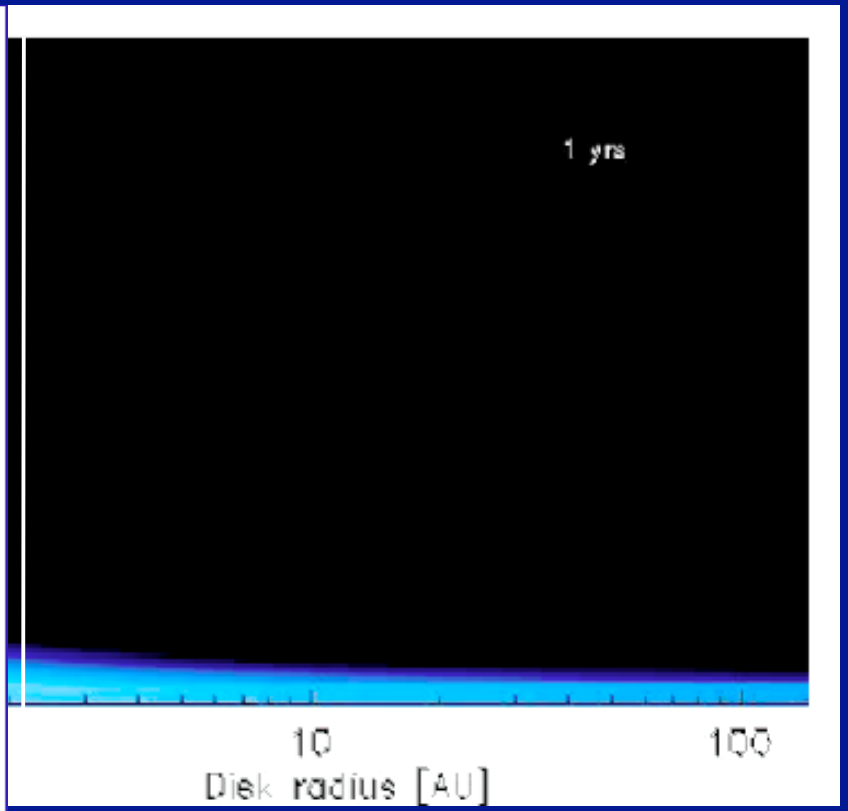


Dullemond & Dominik (2005)

Full 2-D dust evolution models

Includes: growth, fragmentation, drift and mixing





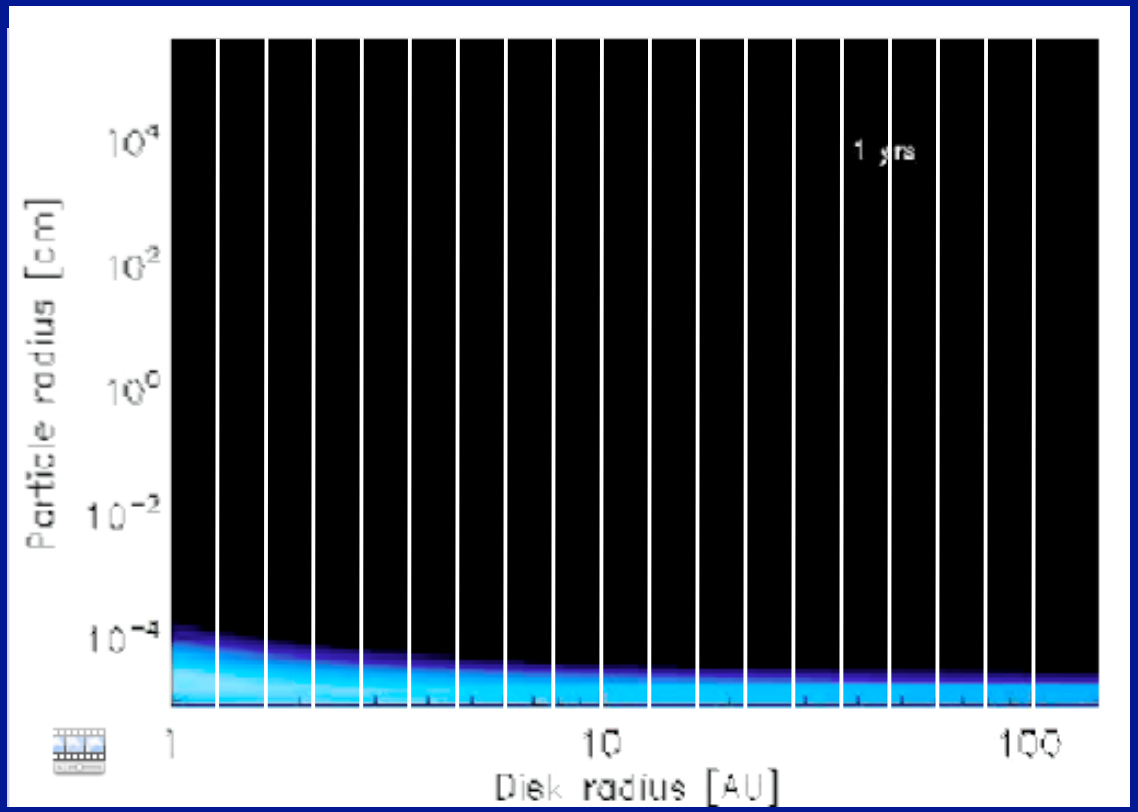
R

Brauer, Dullemond & Henning 2008

Full 2-D dust evolution models

Includes: growth, fragmentation, drift and mixing

Particle Size



R

Brauer, Dullemond & Henning 2008

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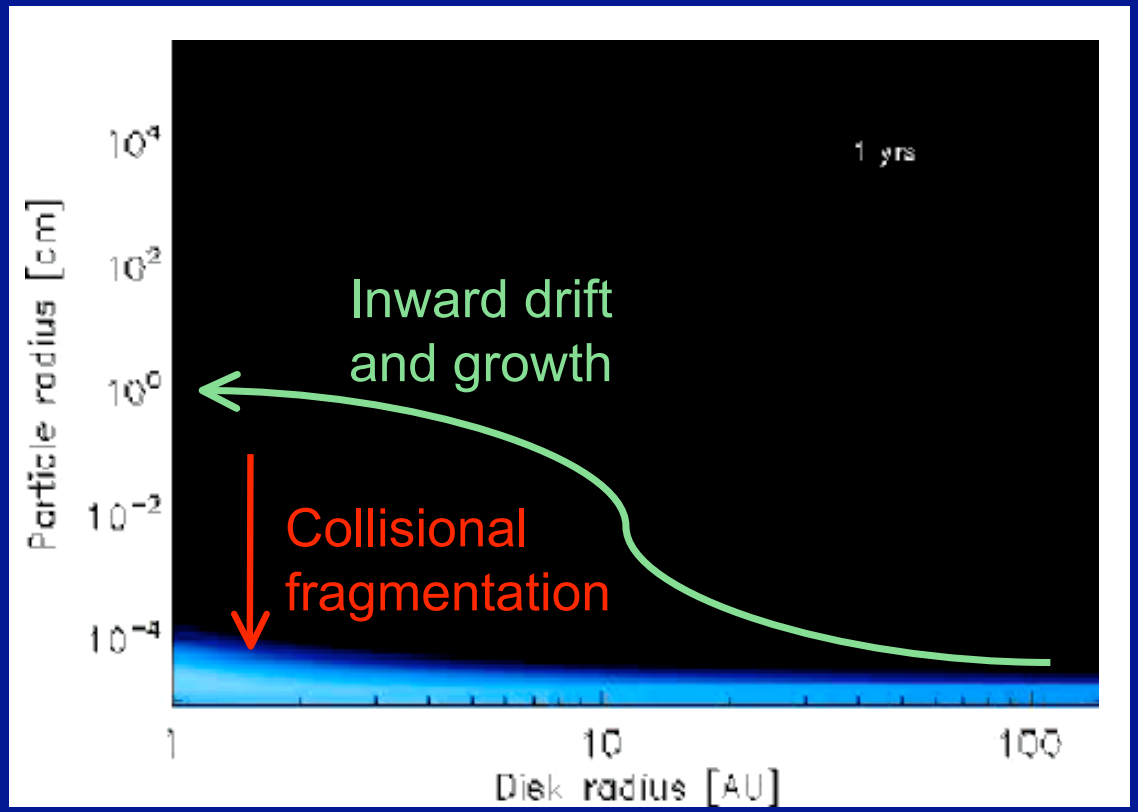


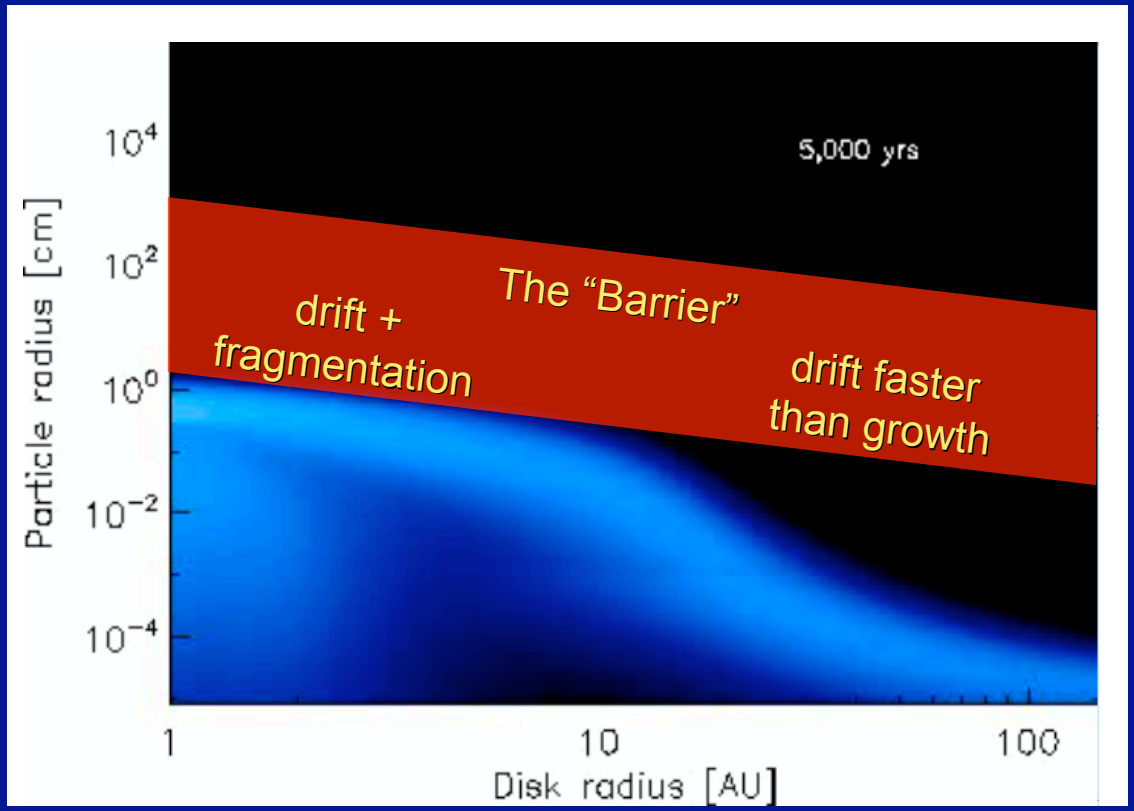
R

Brauer, Dullemond & Henning 2008

The nasty “meter size barrier”...

Includes: growth, fragmentation, drift and mixing

Particle Size



R

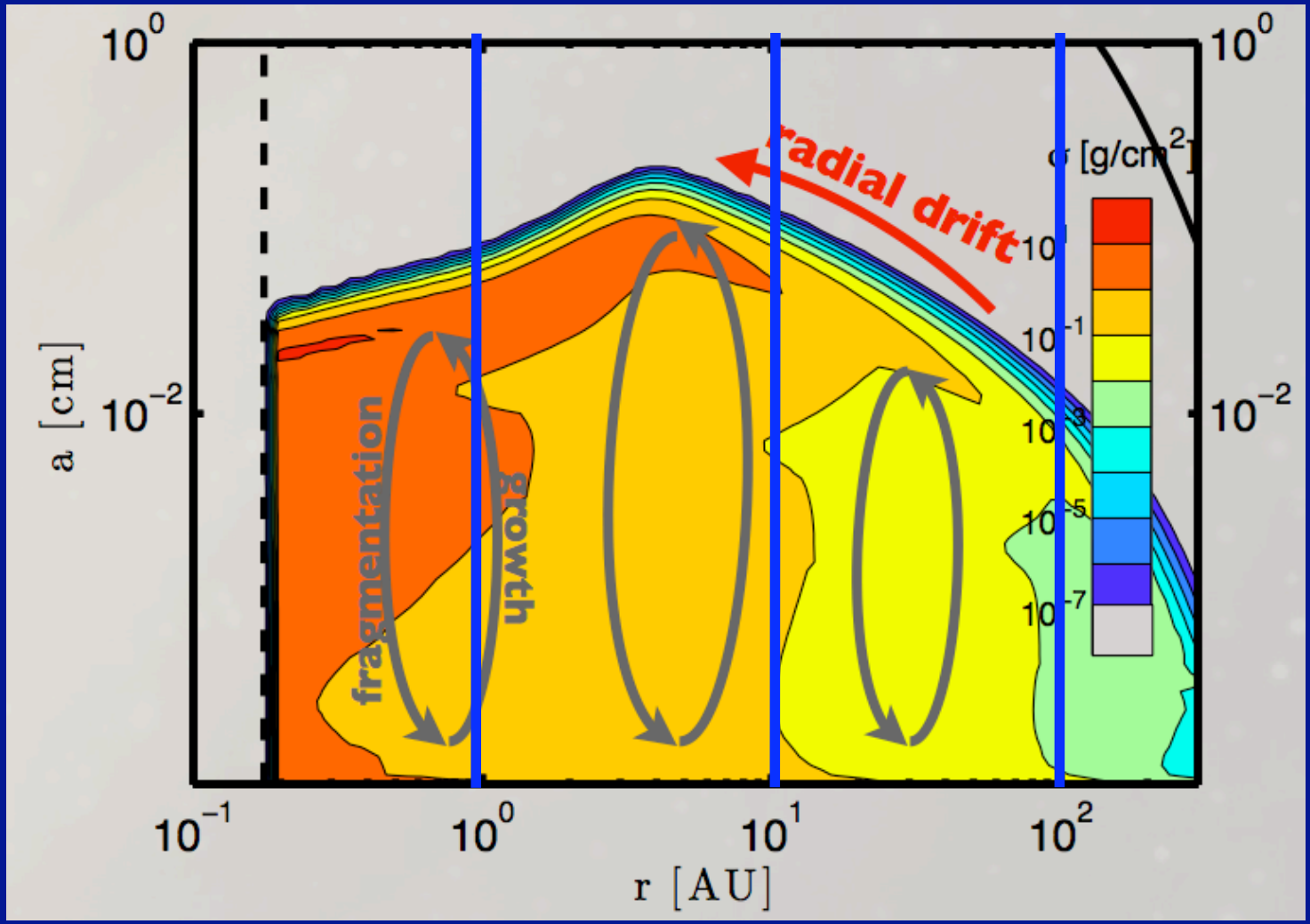
Brauer, Dullemond & Henning 2008

Global dust evolution models

+

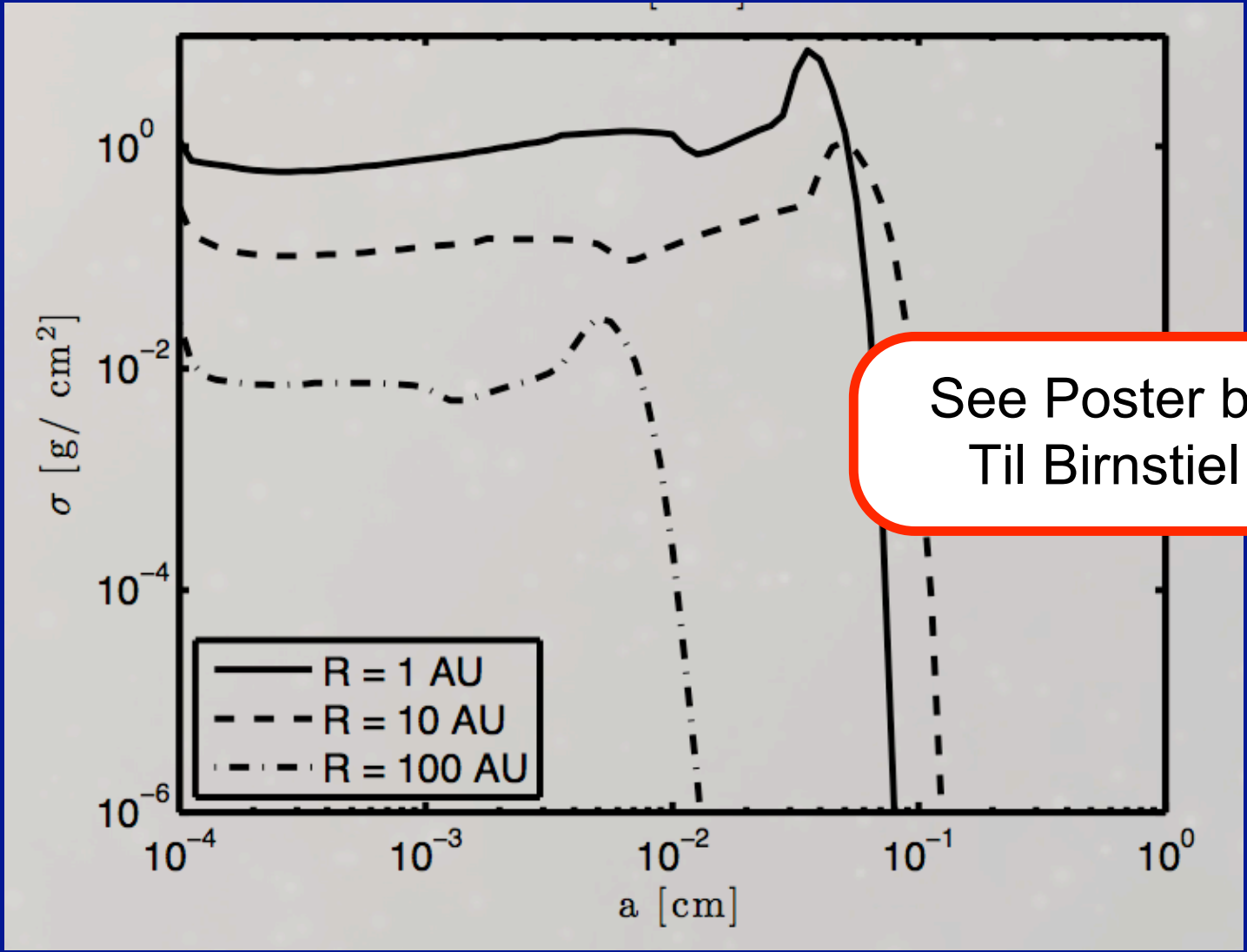
Disk evolution

Transport + coag + fragm



Birnstiel, Dullemond & Brauer 2010

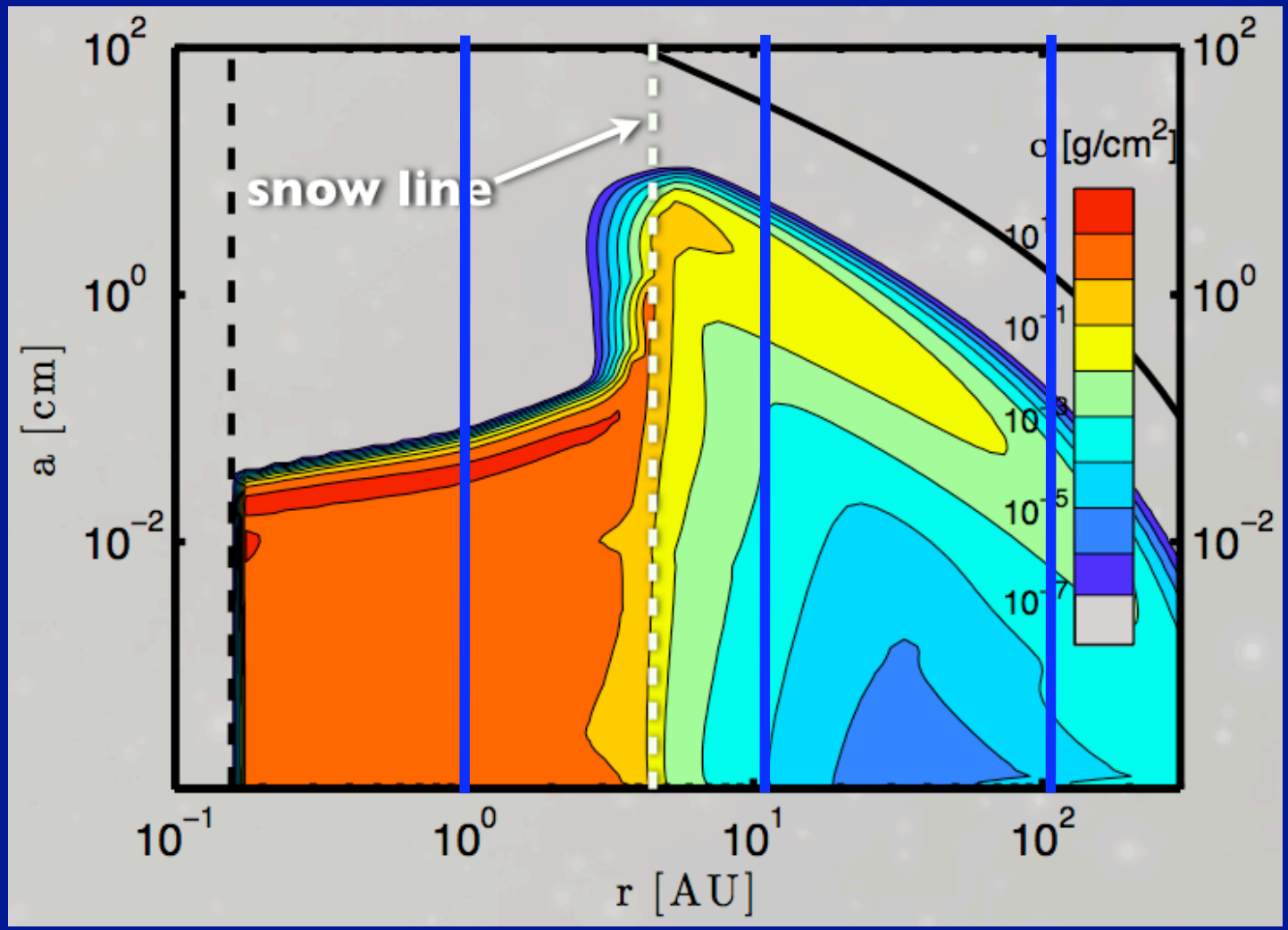
Transport + coag + fragm



See Poster by Til Birnstiel

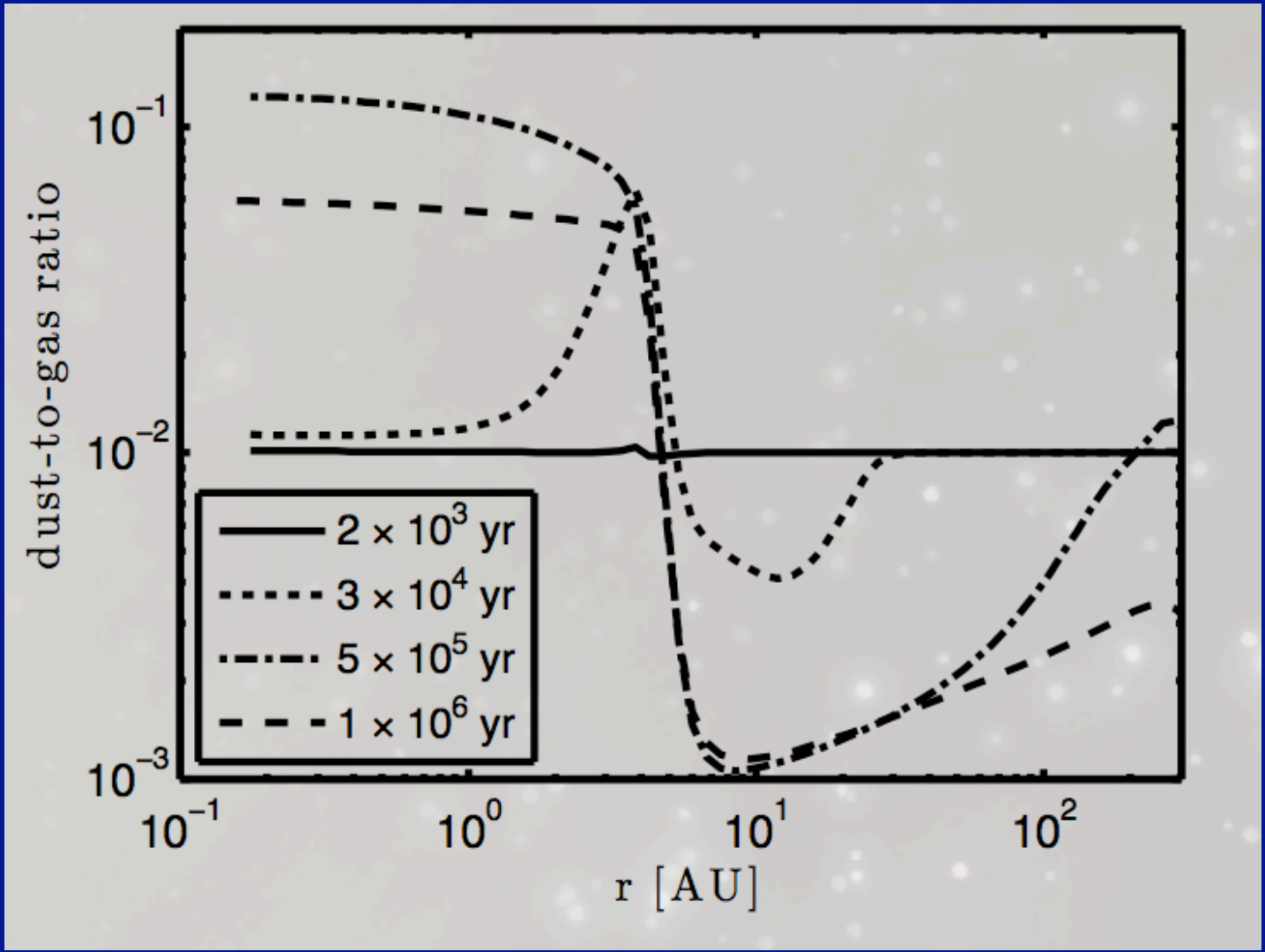
Birnstiel, Dullemond & Brauer 2010

Transport + coag + fragm



Birnstiel, Dullemond & Brauer 2010

Transport + coag + fragm

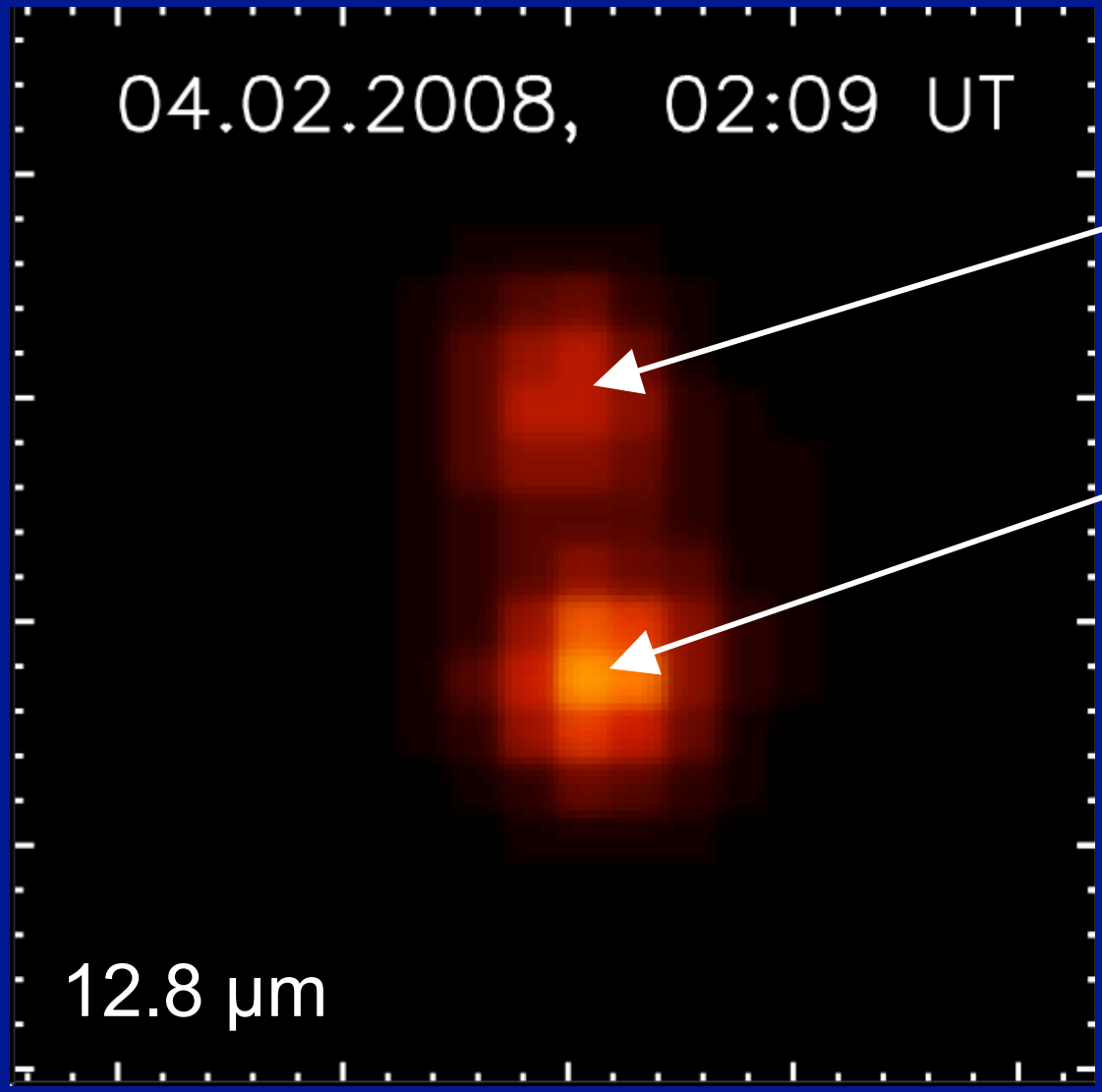


Birnstiel, Dullemond & Brauer 2010

But:

- Most stars form as binaries!
- Disks are not evolving smoothly: variability!

Cool example: T Tauri system

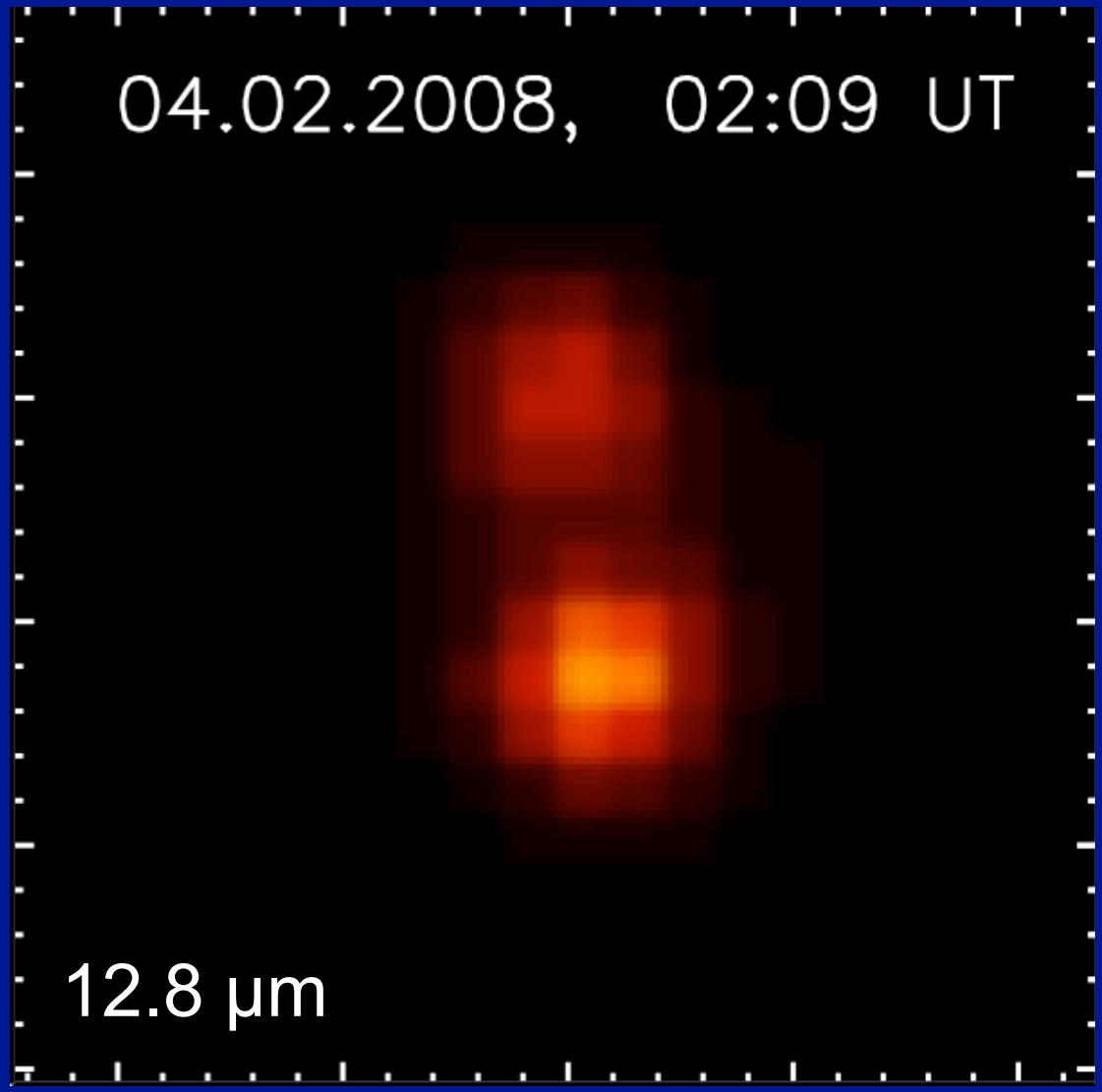


T Tau North

T Tau South a
and South b

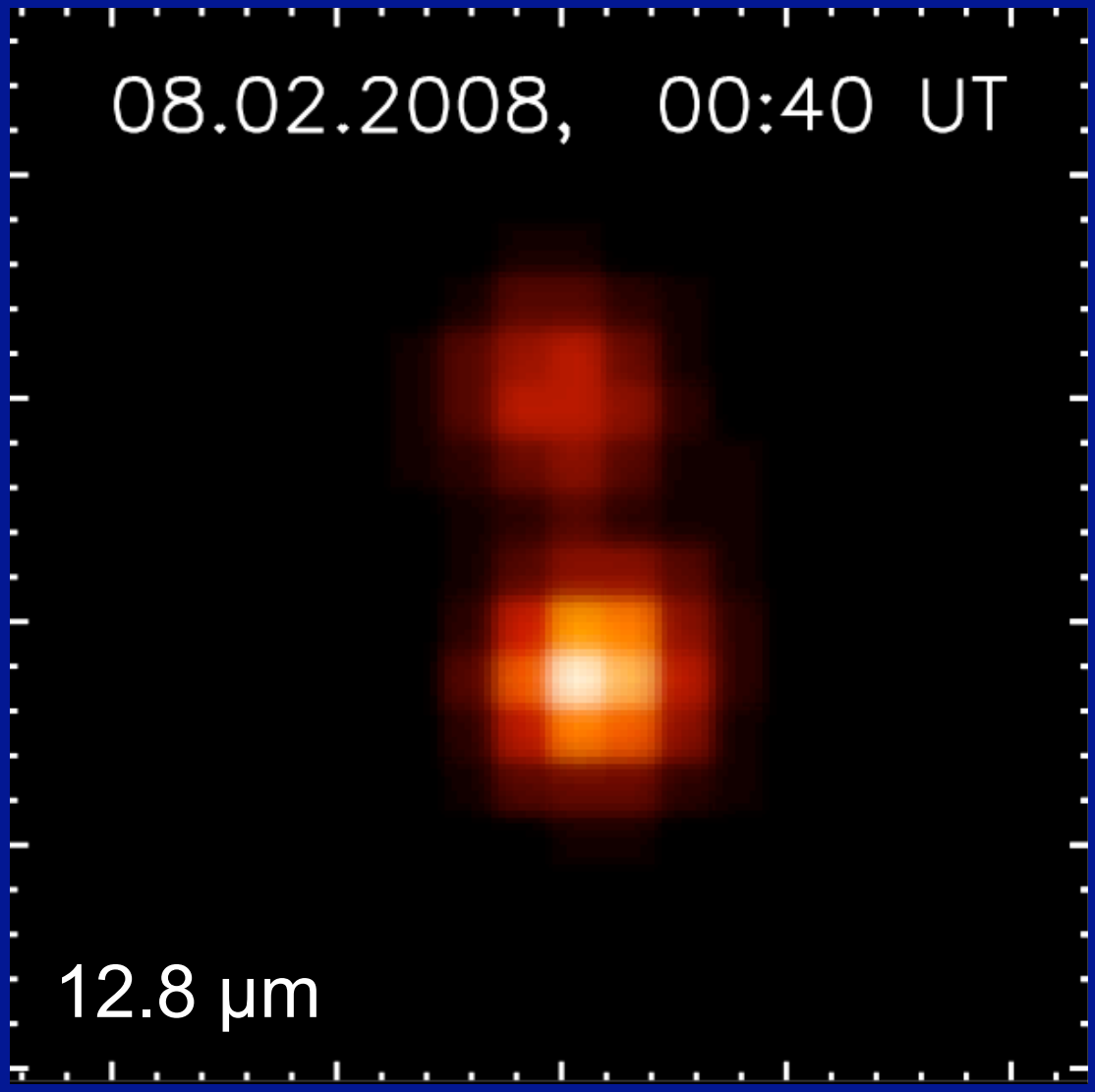
van Boekel et al.
A&A submitted

Cool example: T Tauri system



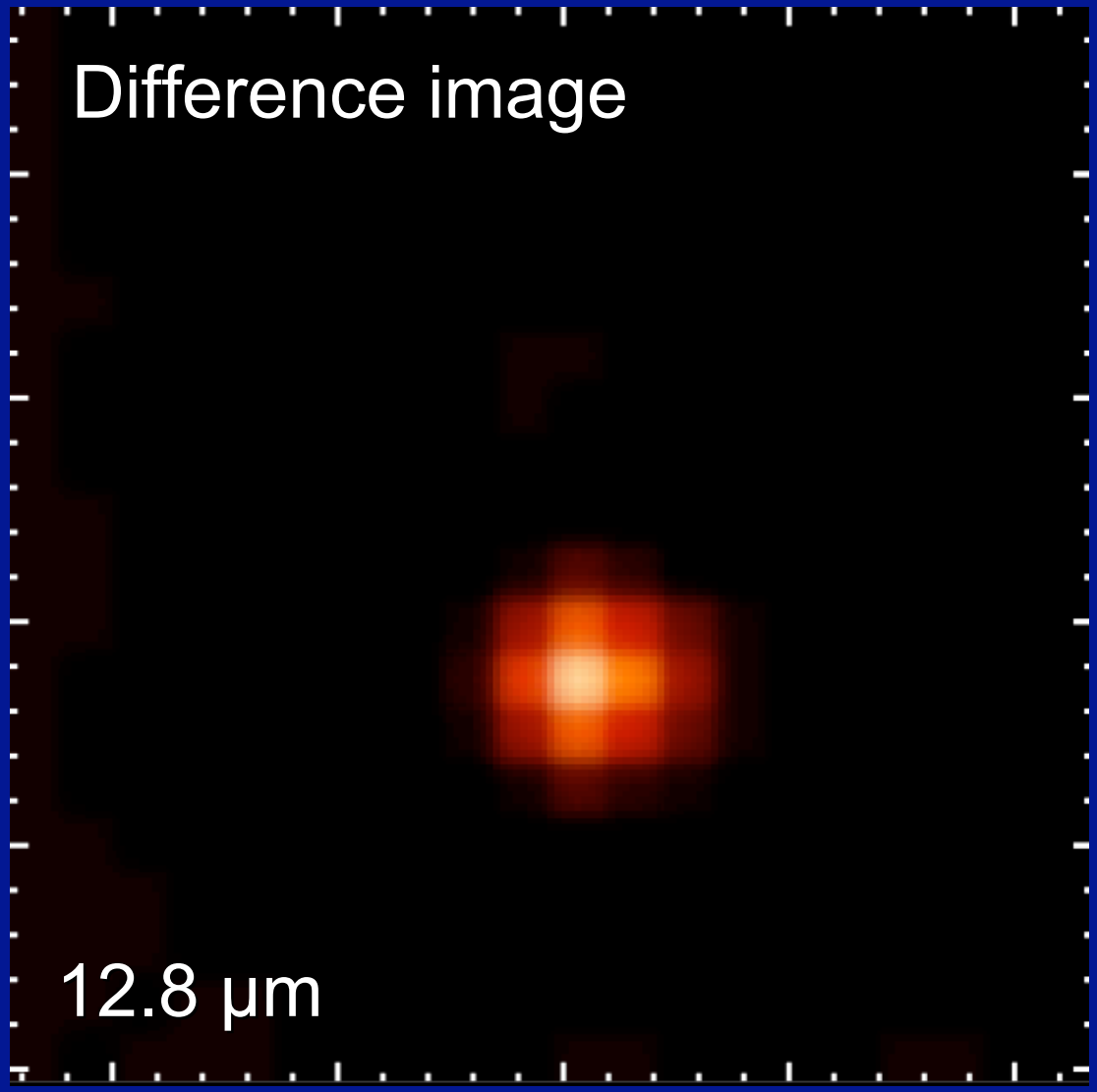
van Boekel et al.
A&A submitted

Cool example: T Tauri system



van Boekel et al.
A&A submitted

Cool example: T Tauri system



van Boekel et al.
A&A submitted

Take-home messages:

- Radial drift of dust is one of main unsolved problems
  - Maybe dust trapping is a solution?
  - Maybe ALMA may observe this!
- Dust evolution is not a linear one-direction growth process
  - Growth is very fast (10000 years)
  - Semi-equilibrium reached between growth – fragm
  - Long-time-scale evolution is change in this equilibrium

Conclusions

- We need to move toward a unified picture:
  - Disk formation (initial parameters)
  - Disk structure (temperature, snow line)
  - Disk evolution (where is the mass, when)
  - Dust evolution (how does the opacity change)
  - Planet formation
- But: please no Grand Unified Numerical Model
  - Step by step: understand each part separately AND in context

Thank you