Protoplanetary disks and their dust content

C.P. Dullemond
Institute for Theoretical Astrophysics (ITA/ZAH)
and Max-Planck-Institut für Astronomie (MPIA)
Heidelberg, Germany

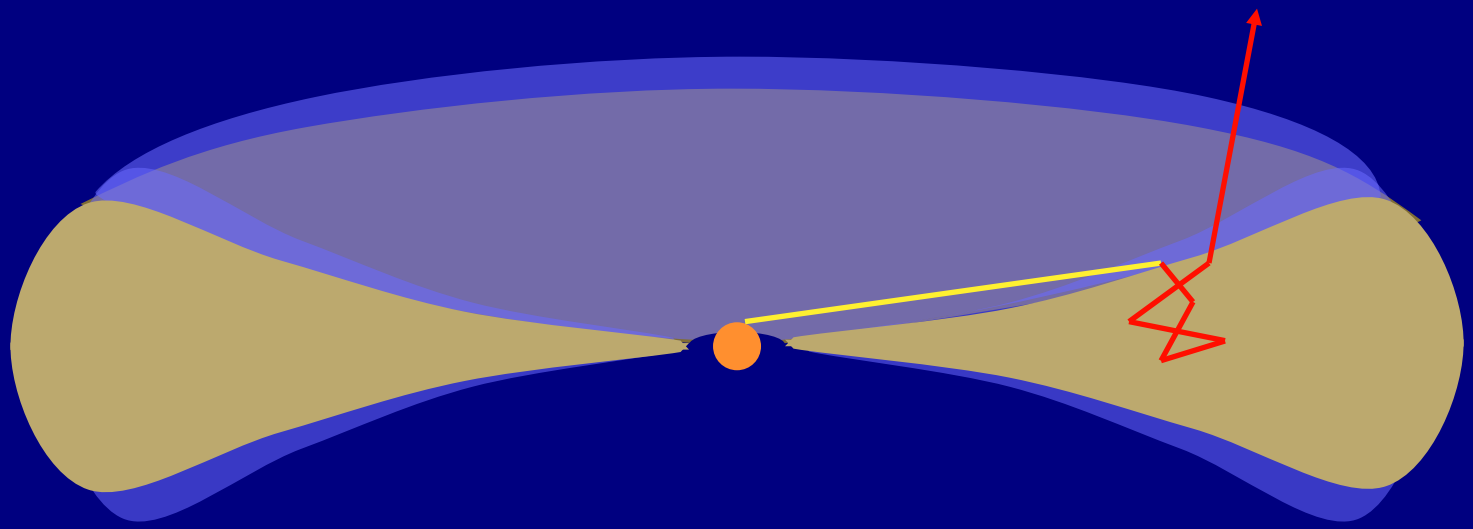
Introduction

Still among the best images of a PPD

Image taken with the *Hubble Space Telescope*.

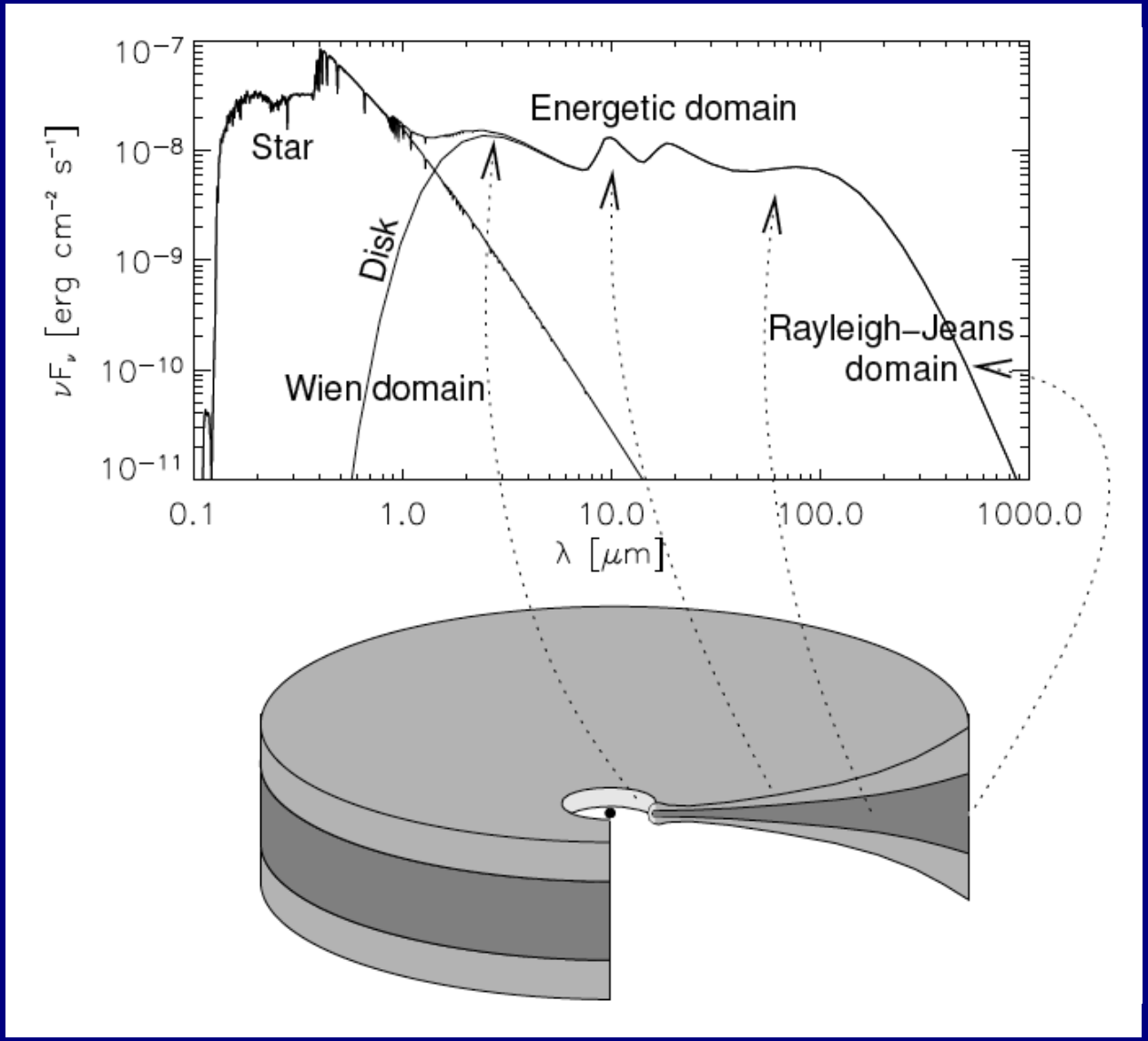
Location: in the Orion Nebula

Infrared spectrum of a disk: Diagnostics

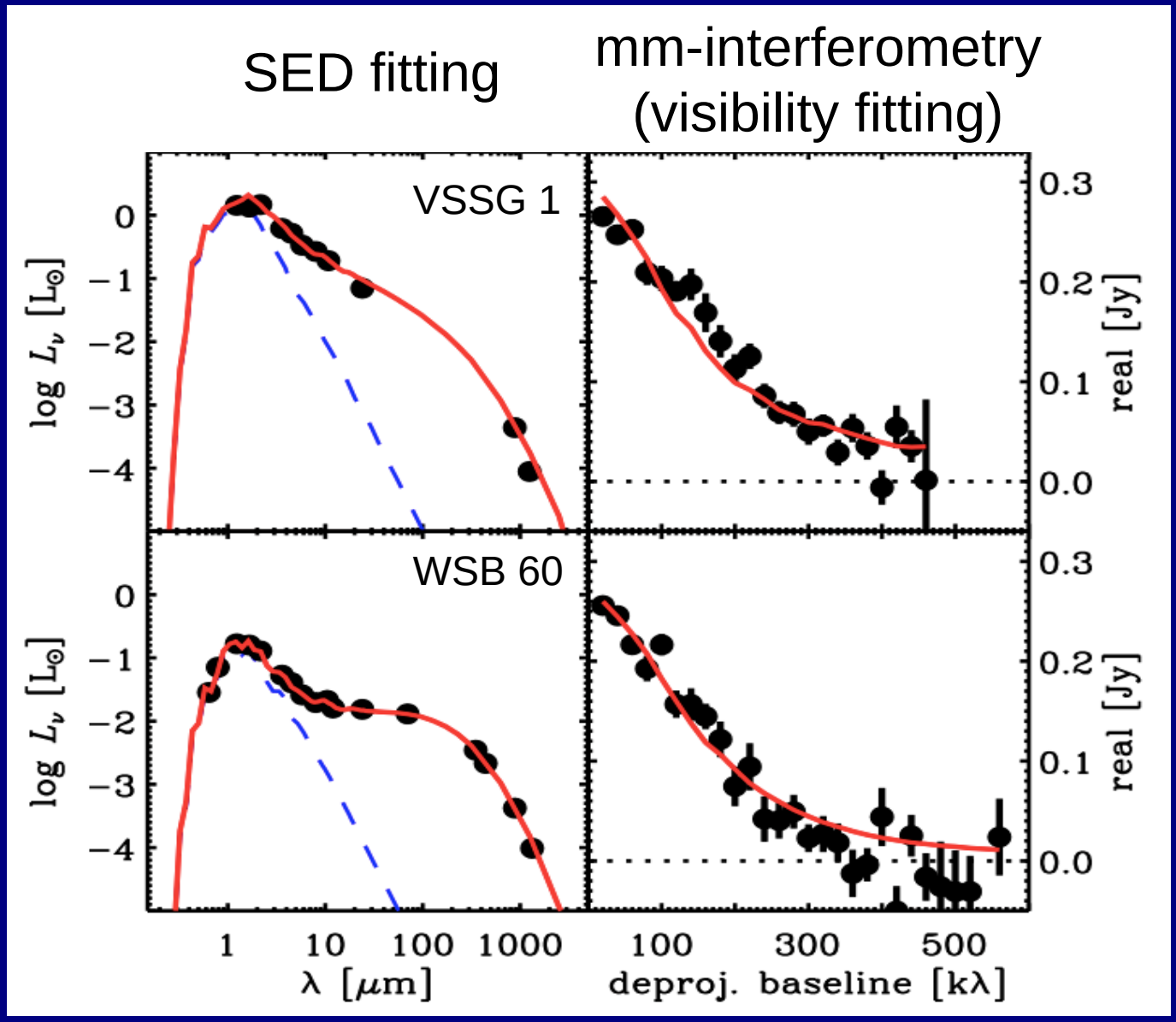


Calvet et al. 1991
Malbet & Bertout 1991
Chiang & Goldreich 1997

Probing different parts of the disk



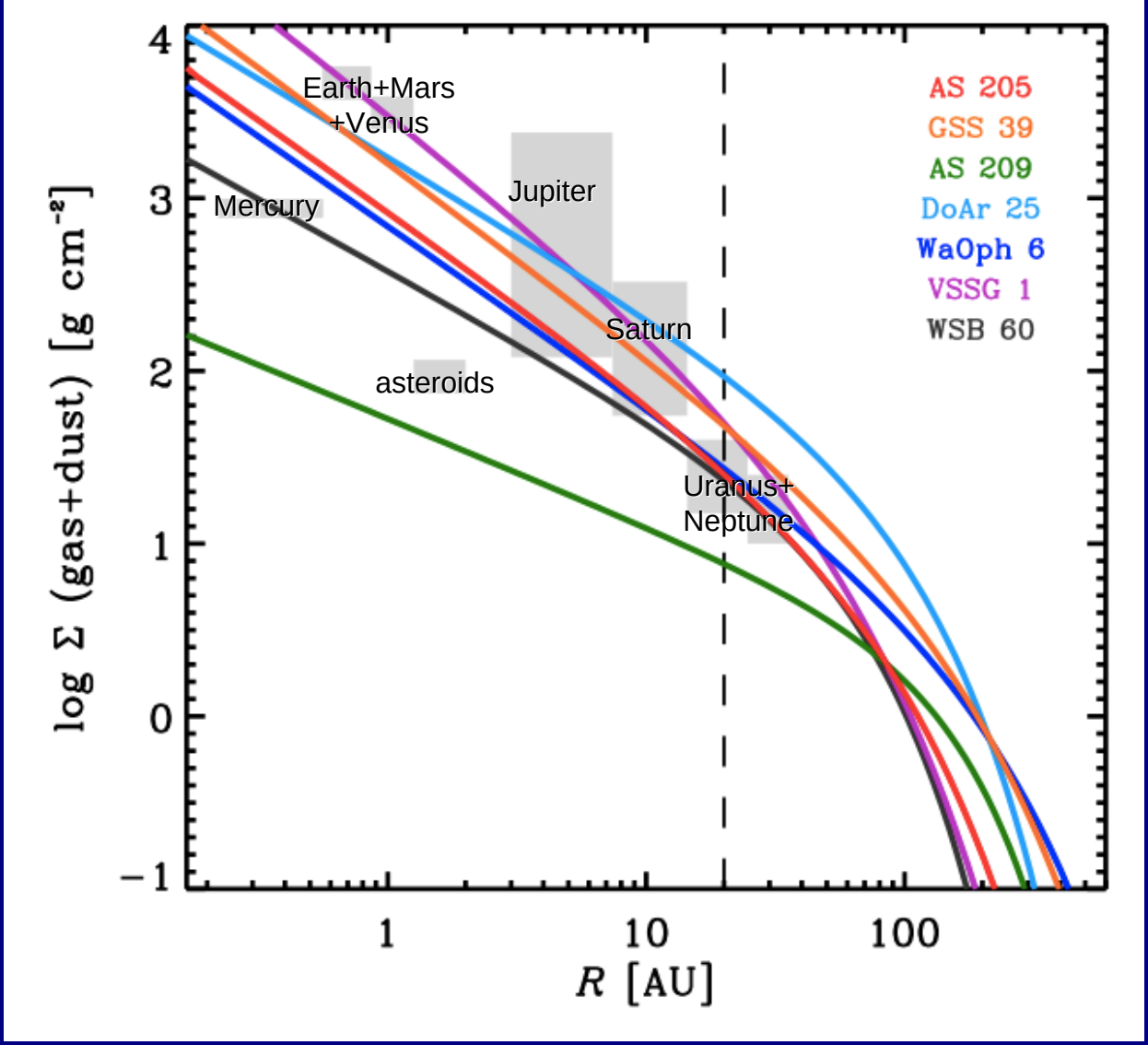
Radial distribution of matter



SED + millimeter resolved maps (=visibility values)

Andrews et al. (2009)

Radial distribution of matter



Andrews et al. (2009)

What about the gas?

- H_2 gas is notoriously difficult to detect
- CO gas is easy, but:
  - Photodissociation in the surface layers
  - Freeze-out in outer regions of the disk
- H_2O gas is doable, but:
  - Complex interplay between freeze-out, photodesorption, chemistry etc
- Other molecules have similar problems
- Atomic lines $[OI]_{63}$ $[CII]_{158}$ only from very tenuous hot surface layers

Dust as raw material of planets

Observational constraints:

Modeling effort

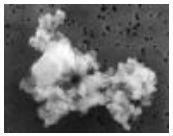
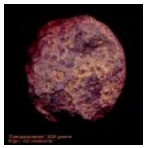
Directly observable through IR and mm observations

?

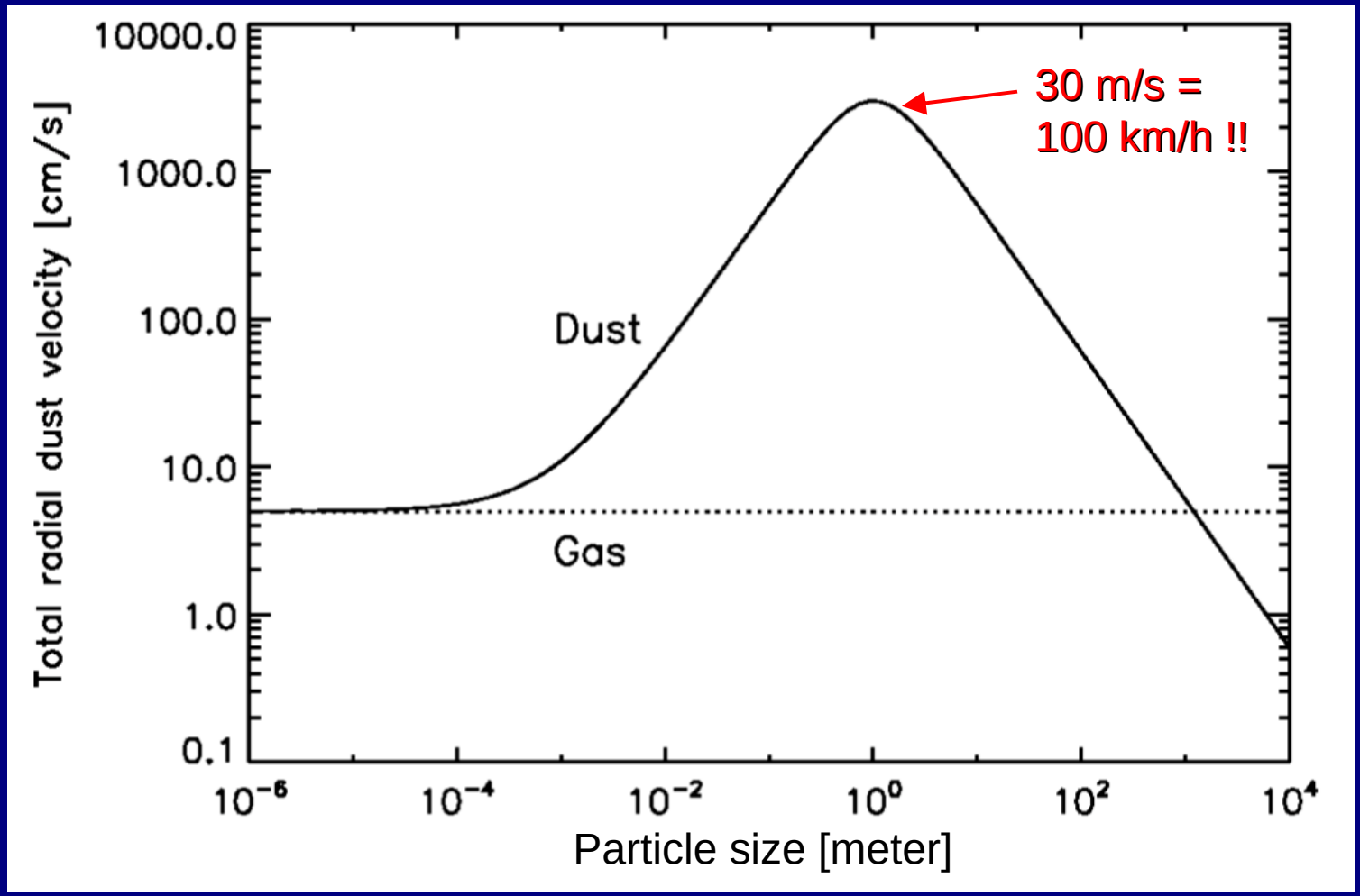
Exo-planets

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

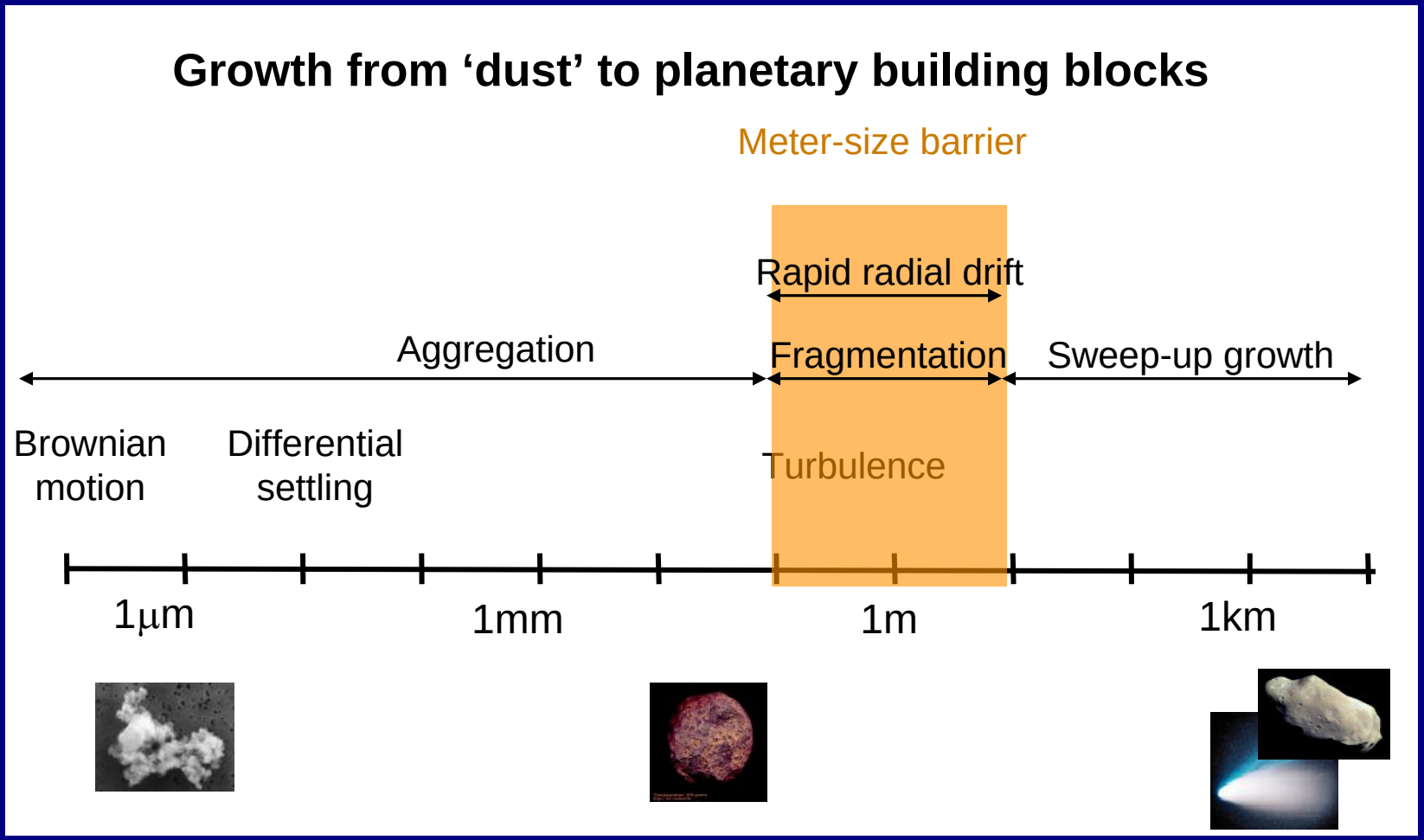
1μm 1mm 1m 1km 1000km

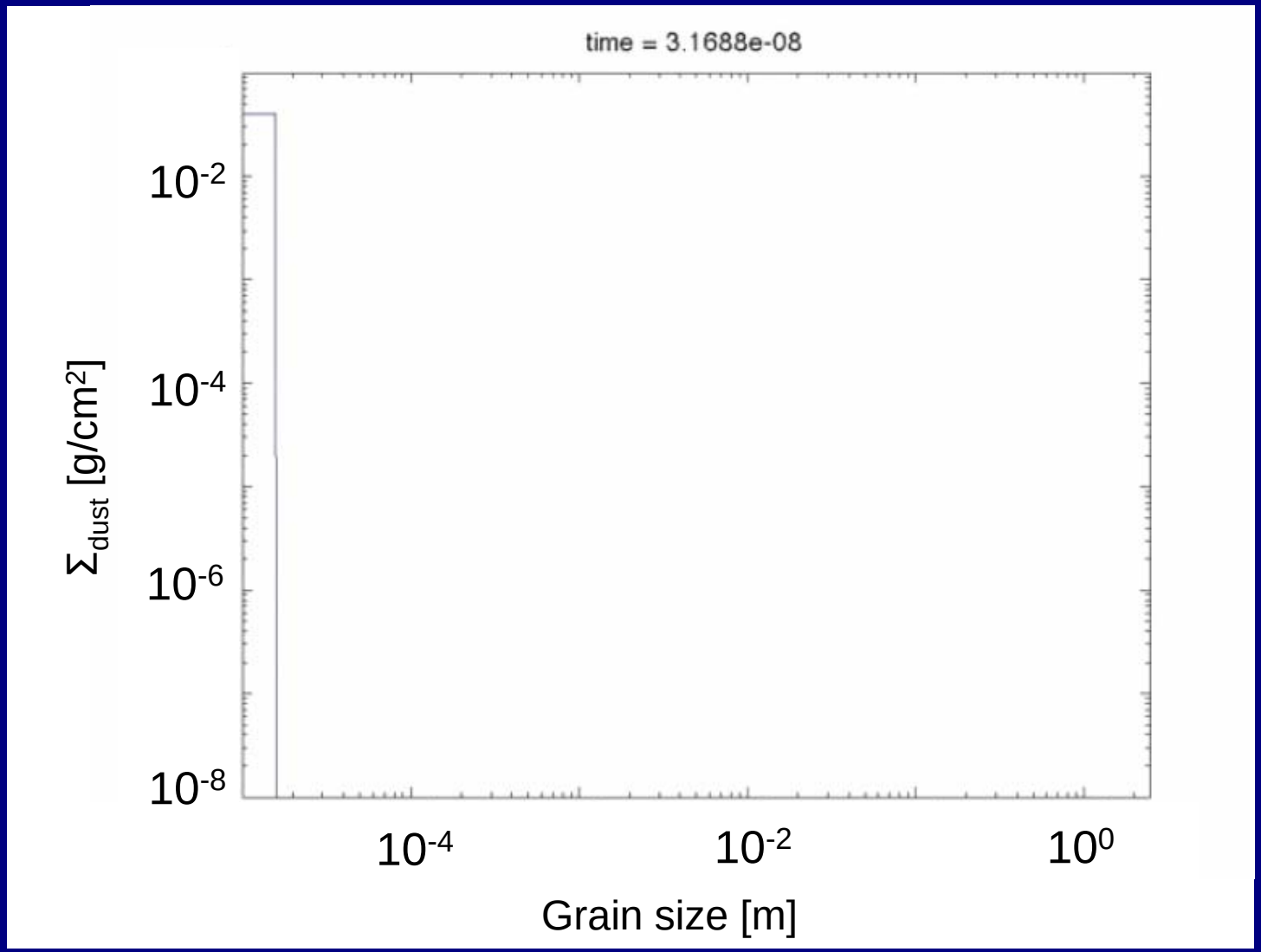
Main problem: high velocities



Meter-size barrier

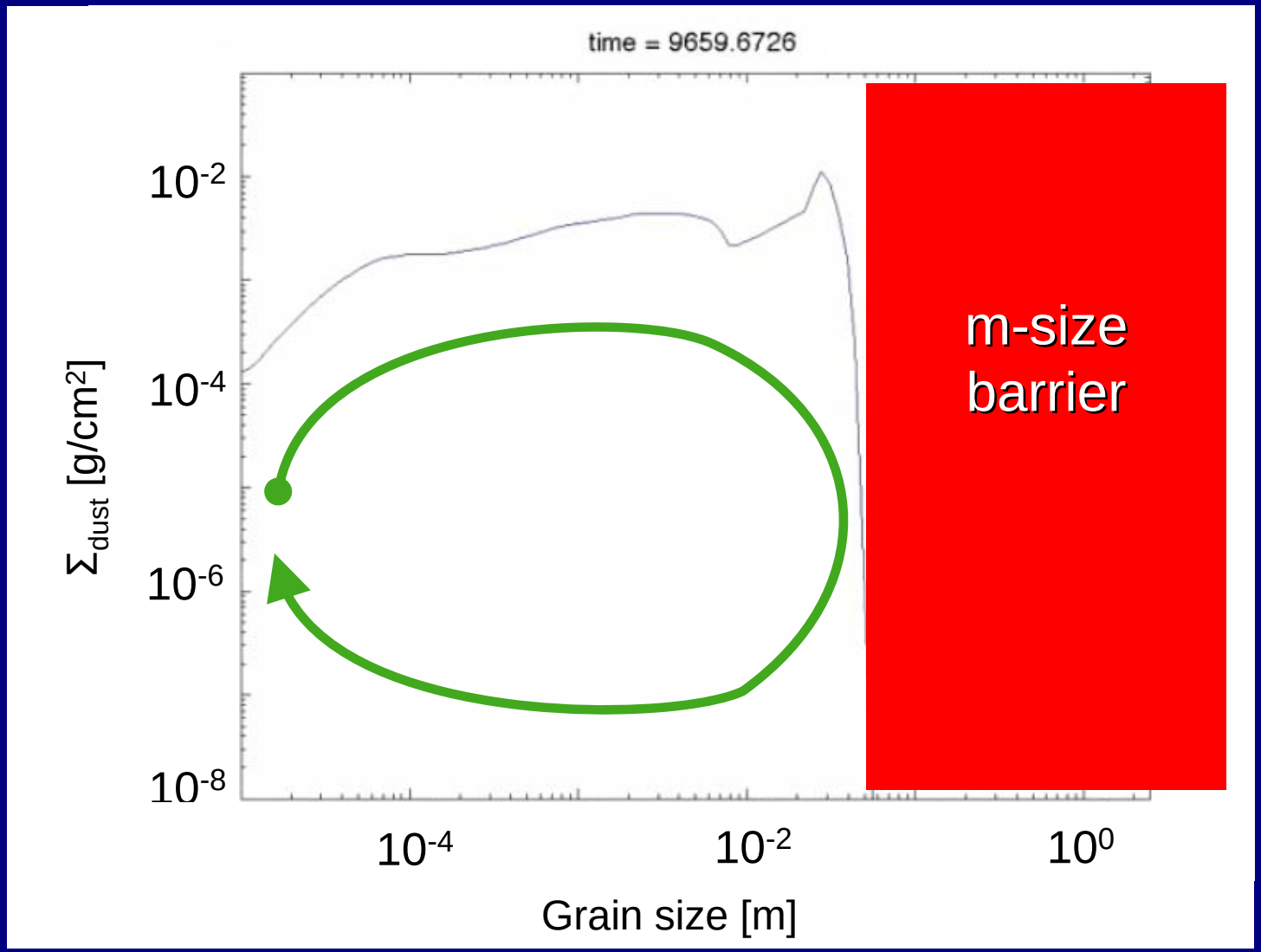


Dust coagulation+fragmentation model



Birnstiel et al. 2010

Dust coagulation+fragmentation model



Birnstiel et al. 2010, see also Zsom et al. 2010 for the “bouncing barrier”

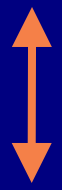
Opposing goals:

- Planet formation scientists: “Find a way to break through the barrier, and thus start planet formation for real!”
- Observational astronomers: “But not too efficiently, because we know that disks are ‘dusty’ for several million years!”

Key elements of a possible solution

- Snow line:

  May be a region of strong dust/ice density enhancement, and therefore preferential place for planet formation



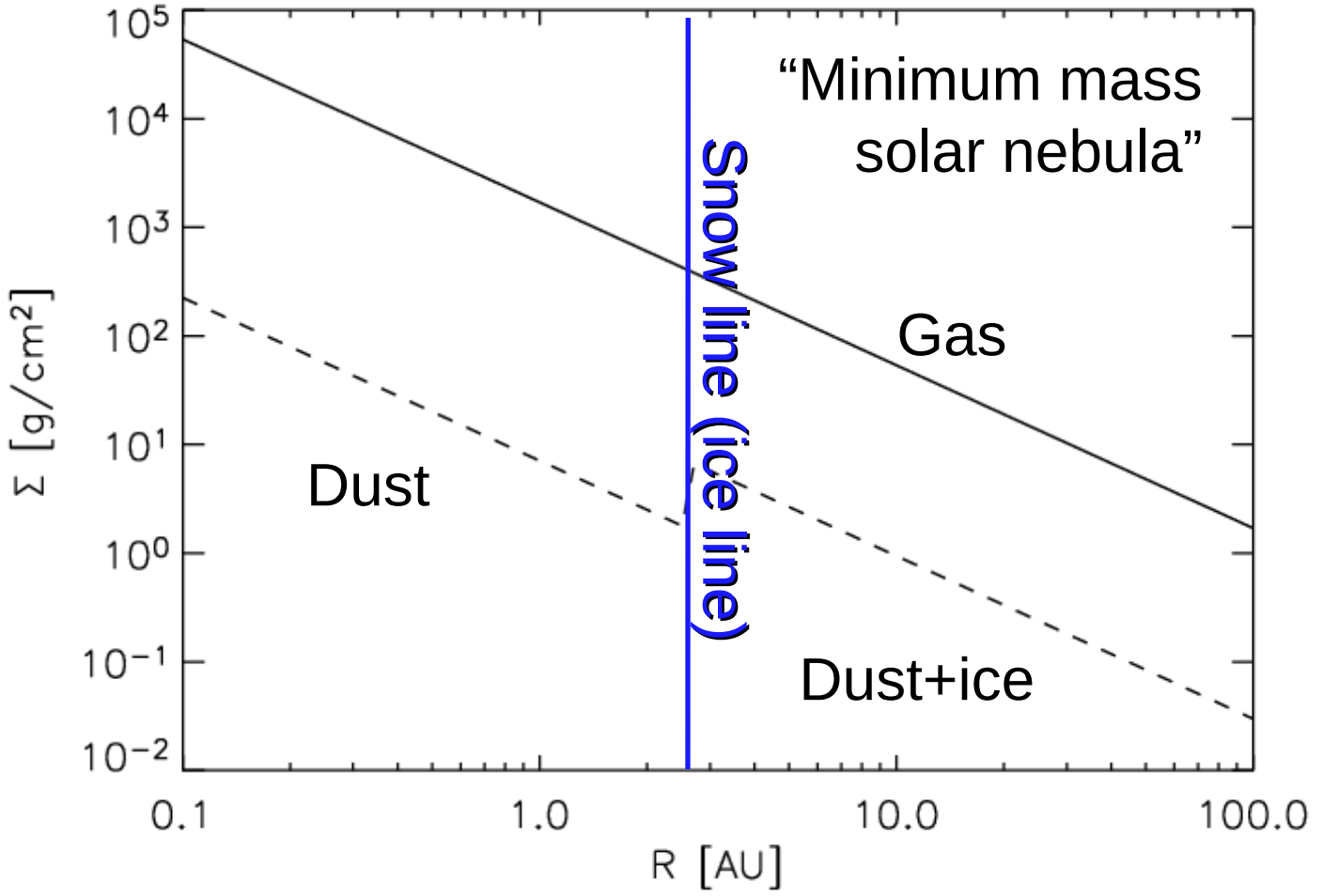
- Pressure bumps / vortices:

  Could trap dust, creating dust enhancements but also making “tranquil” environment for dust coagulation and preventing the radial drift catastrophe.

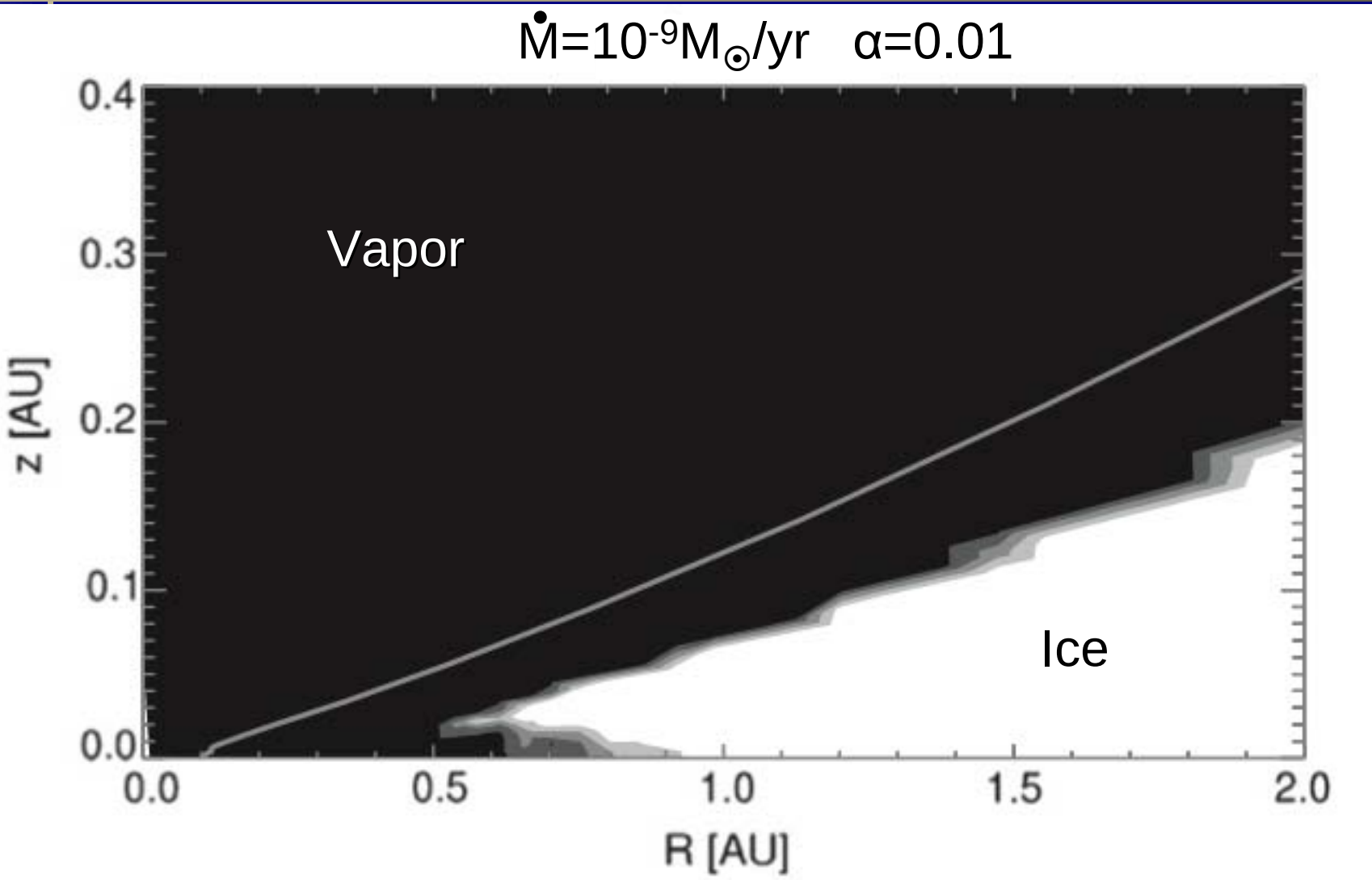
Snow line:

Theory
and
perhaps observations?

What *is* the snow line?

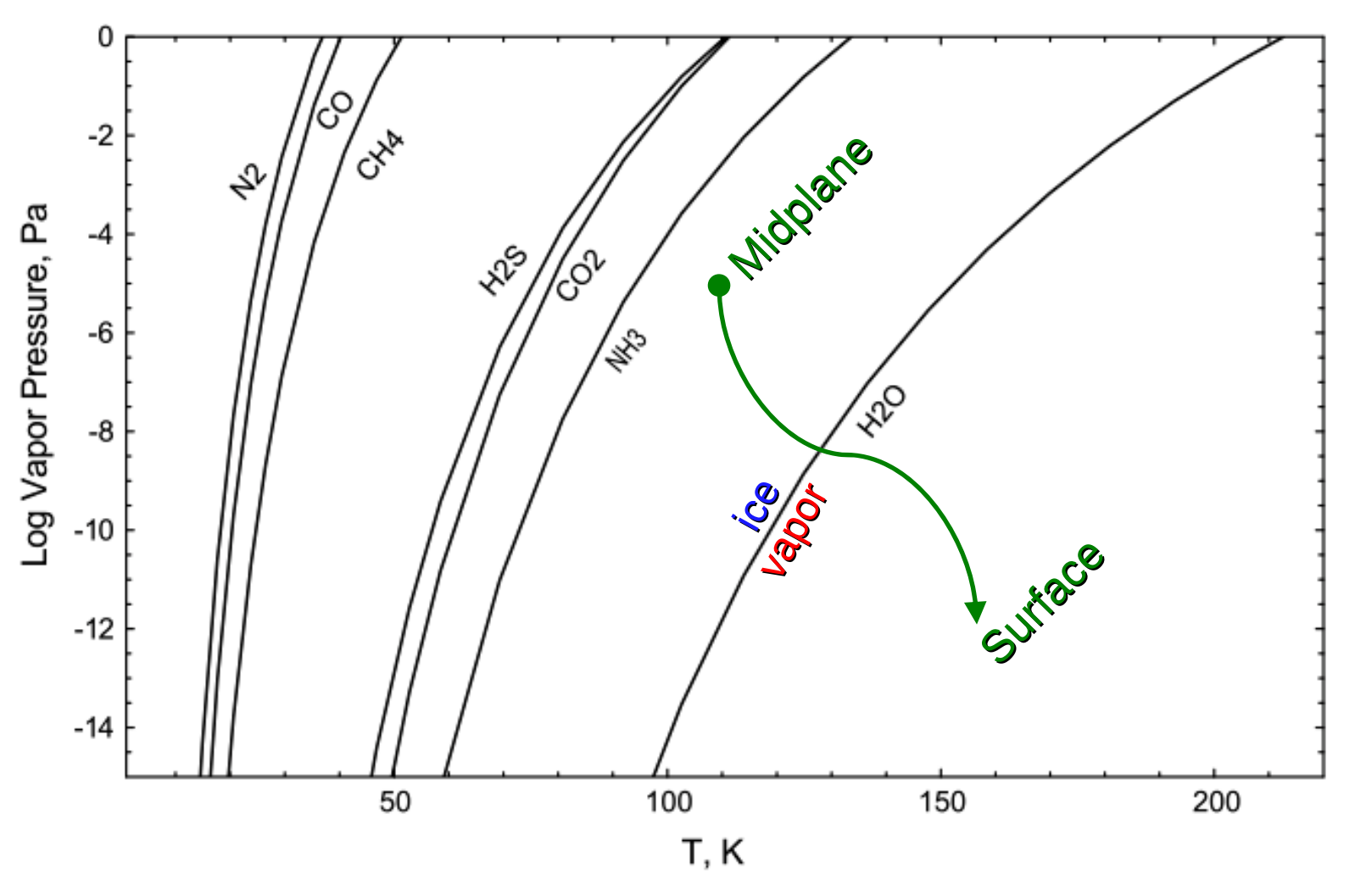


What *is* the snow line?



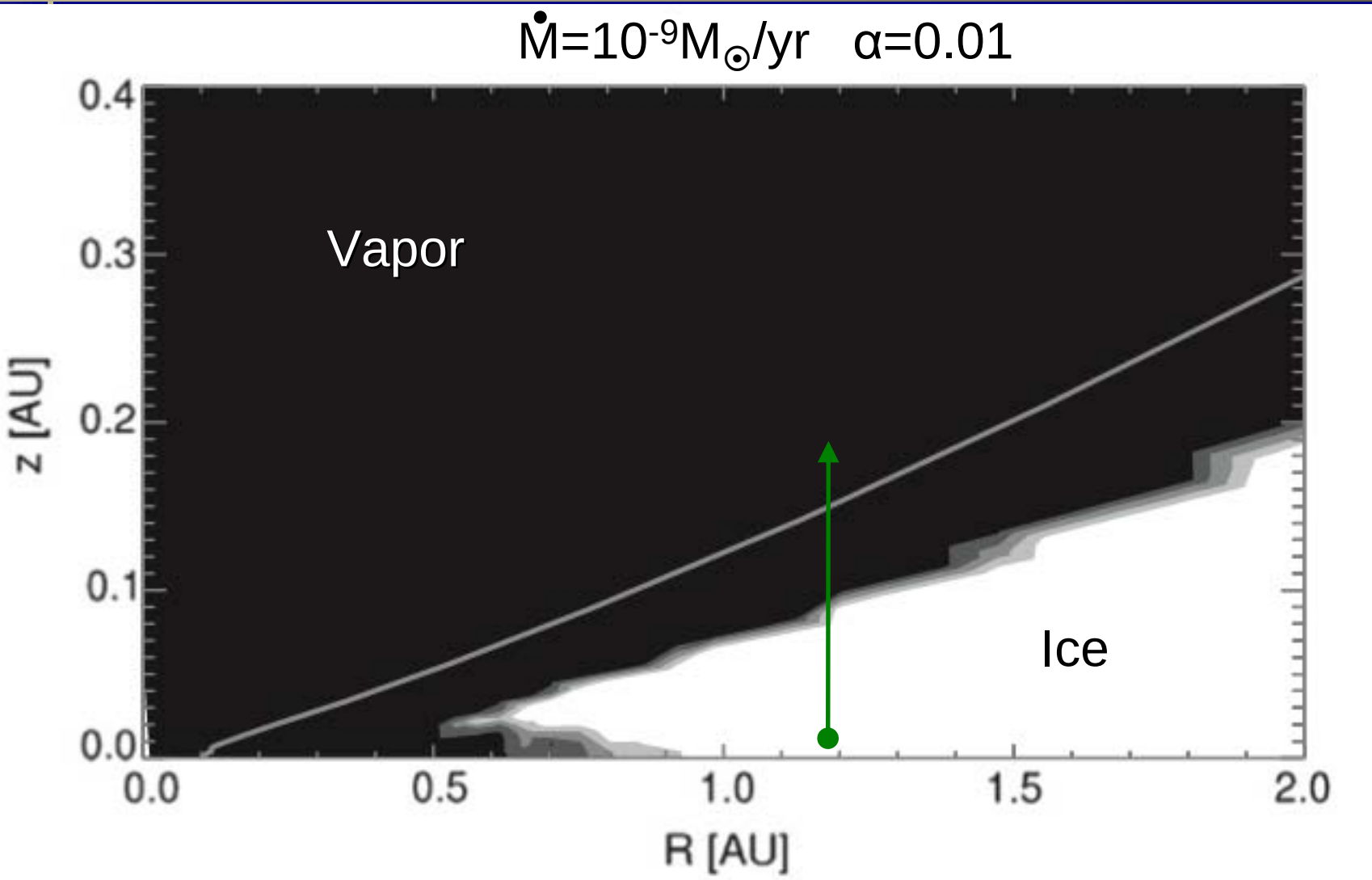
Min et al. 2011

Phase diagram of common volatiles



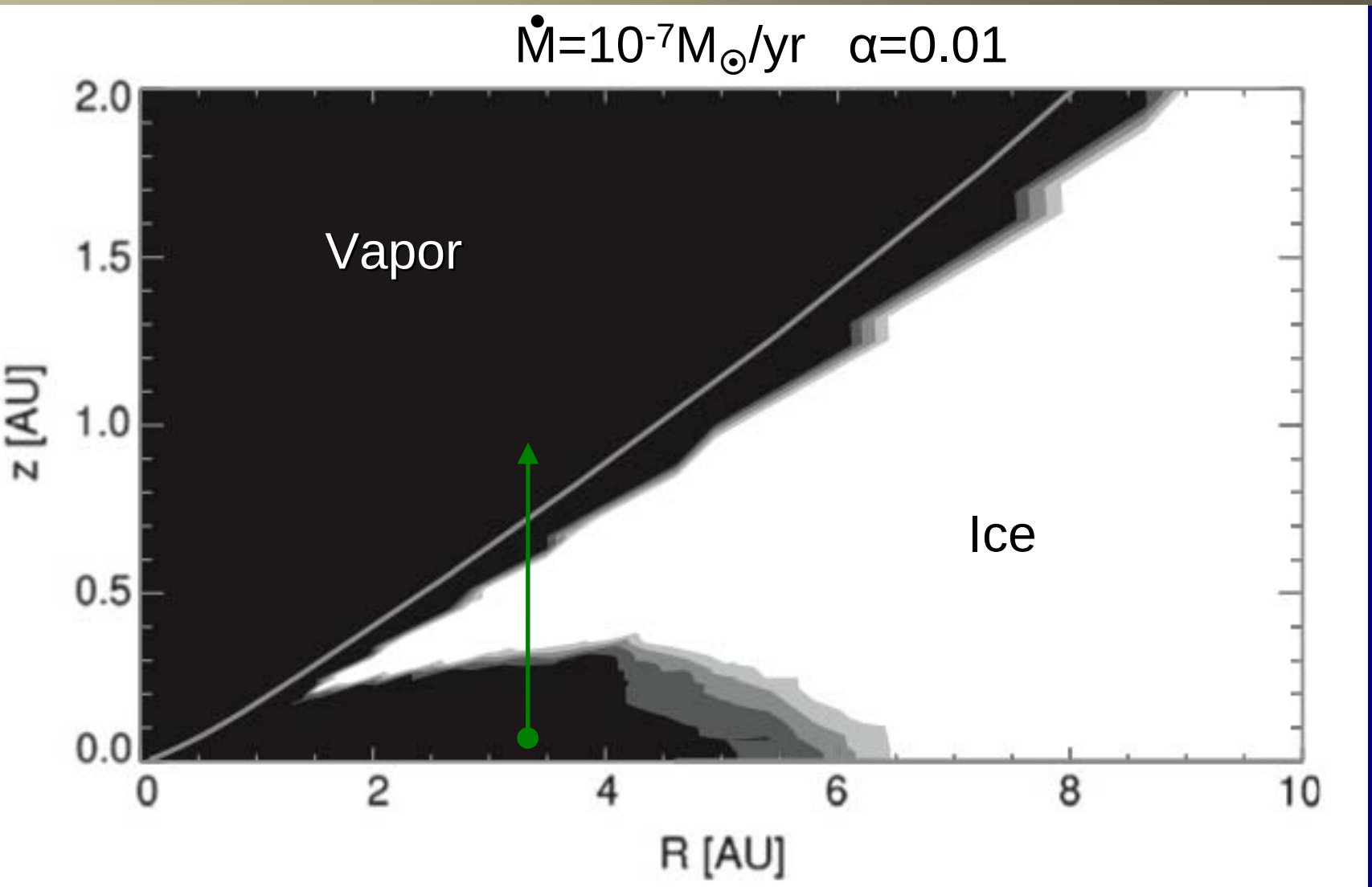
From: Davis 2005, formulae from Bauer et al. 1997; Colaprete; Lodders & Fegley 1998.

What *is* the snow line?



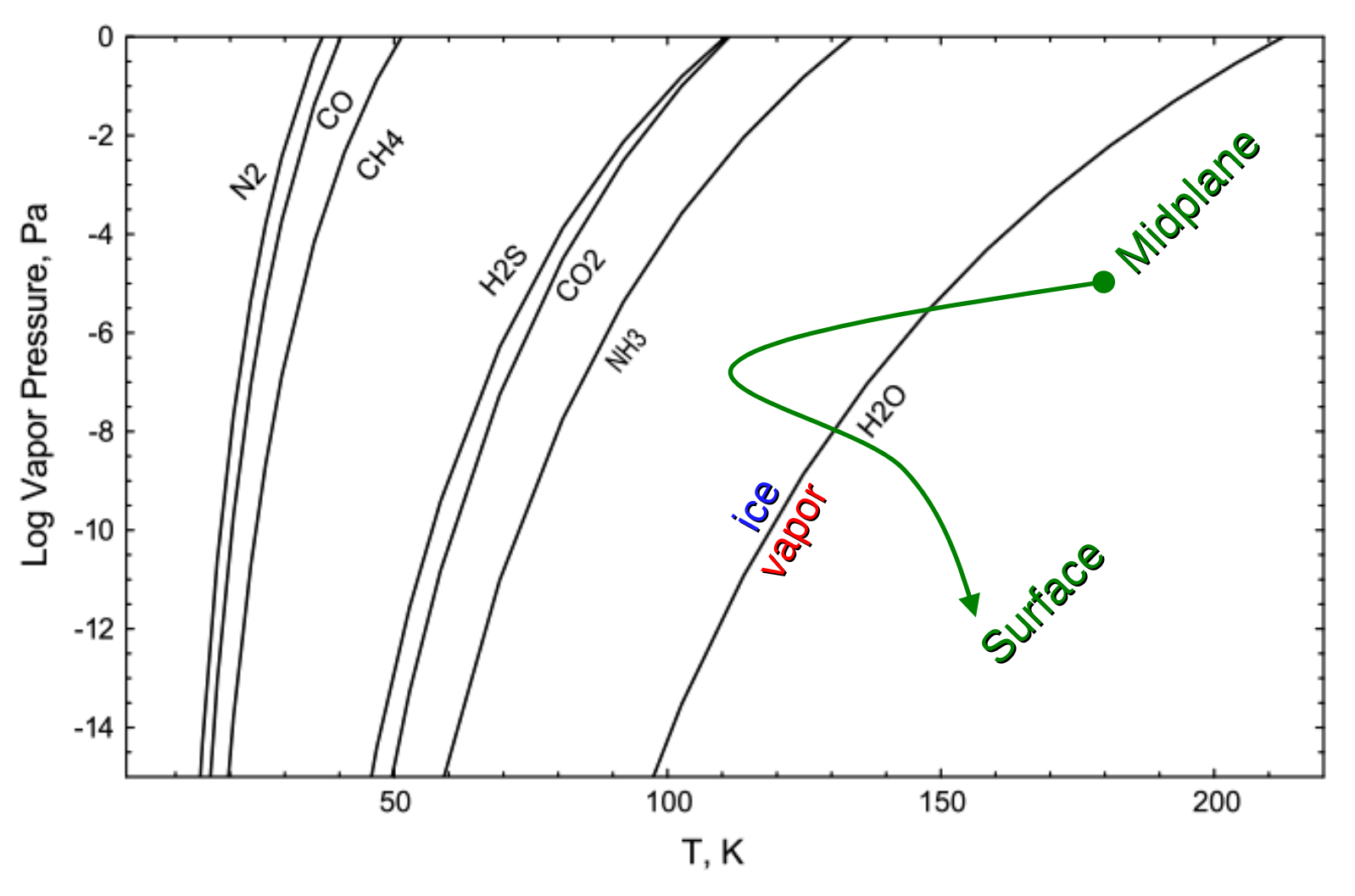
Min et al. 2011

What *is* the snow line?



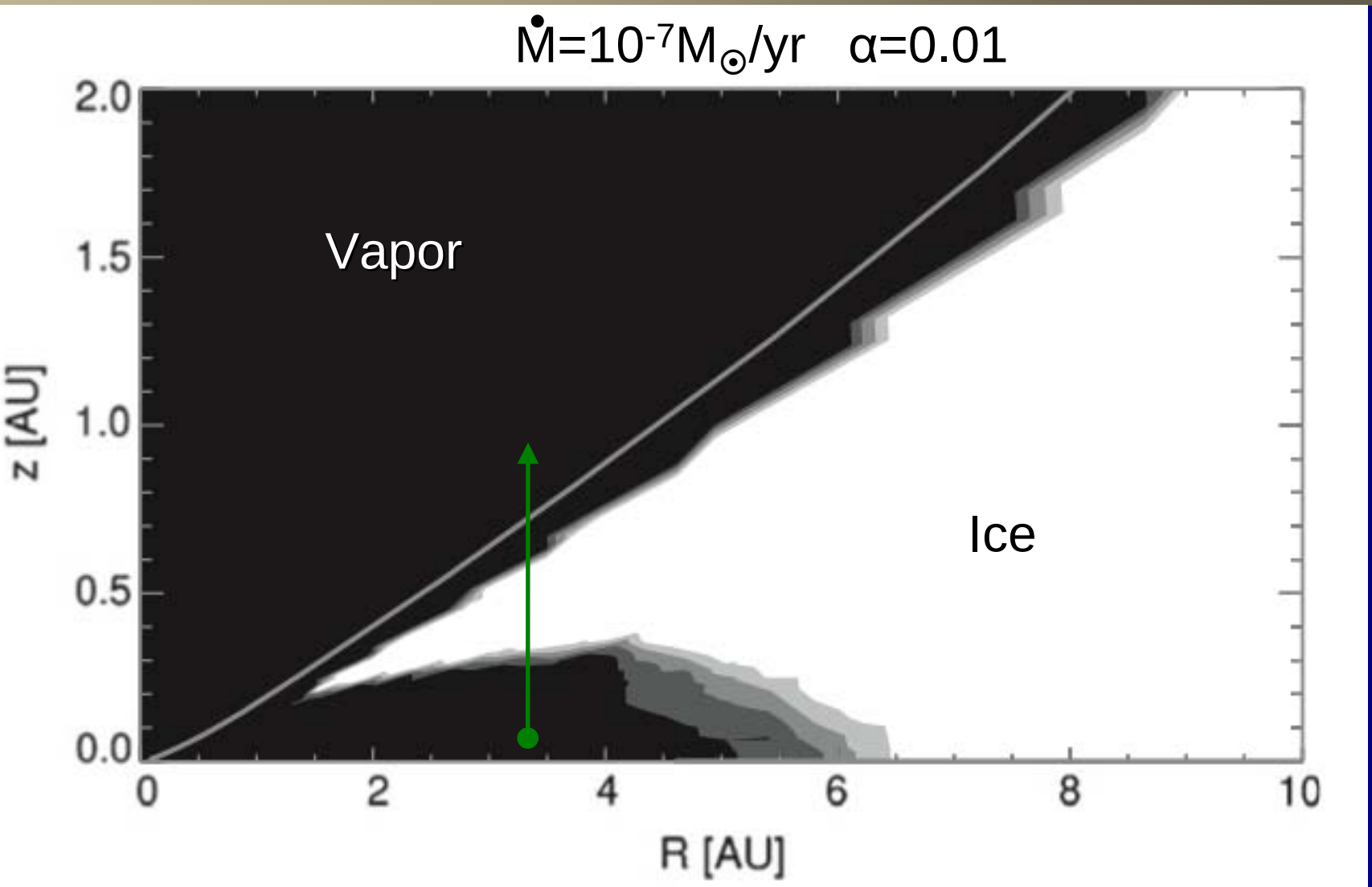
Min et al. 2011

Phase diagram of common volatiles



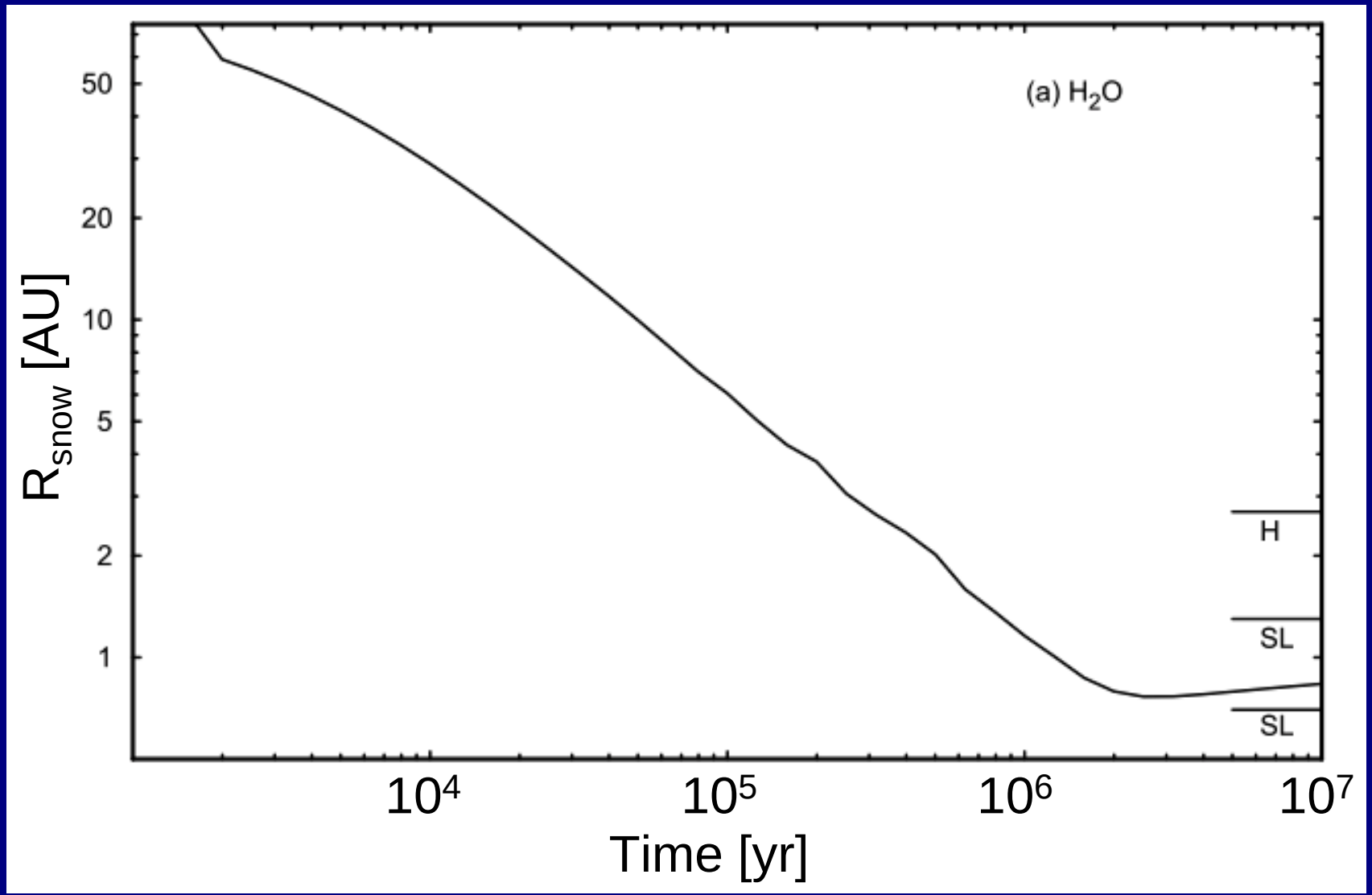
From: Davis 2005, formulae from Bauer et al. 1997; Colaprete; Lodders & Fegley 1998.

What *is* the snow line?



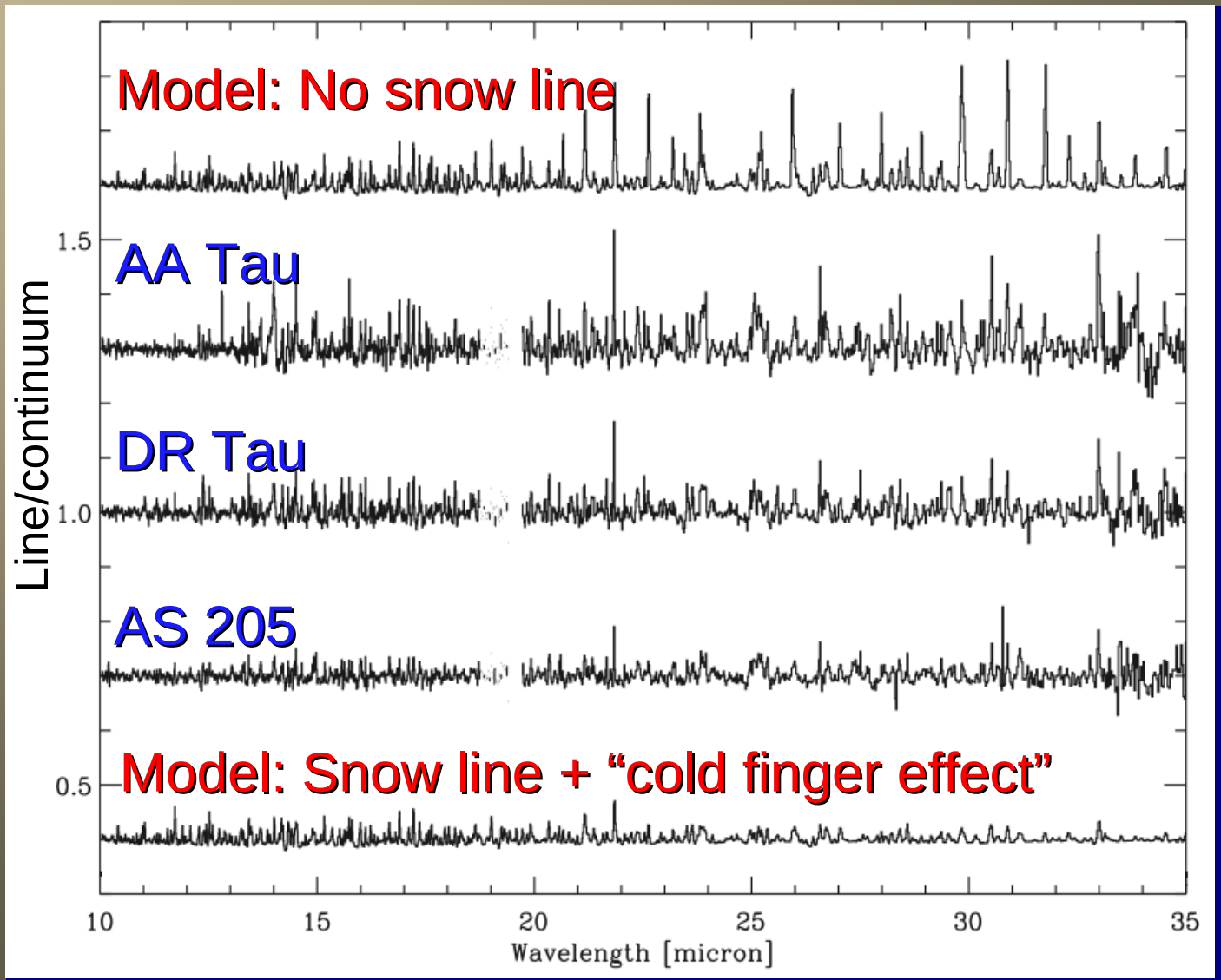
Min et al. 2011

Where is the snow line?



Davis 2005

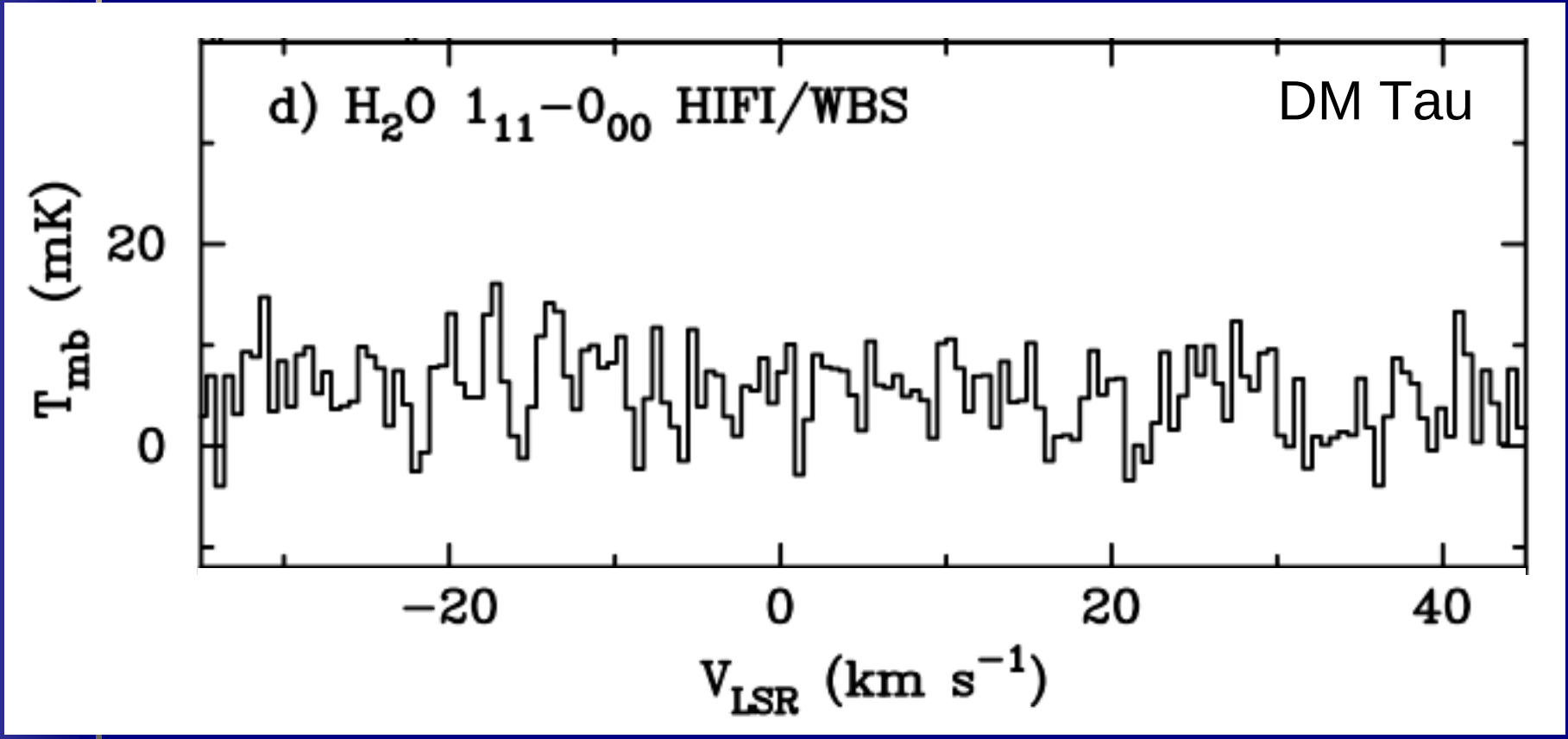
Gas-phase water in T Tauri disks



Requires strong jump in H_2O vapor density at ~ 1 AU

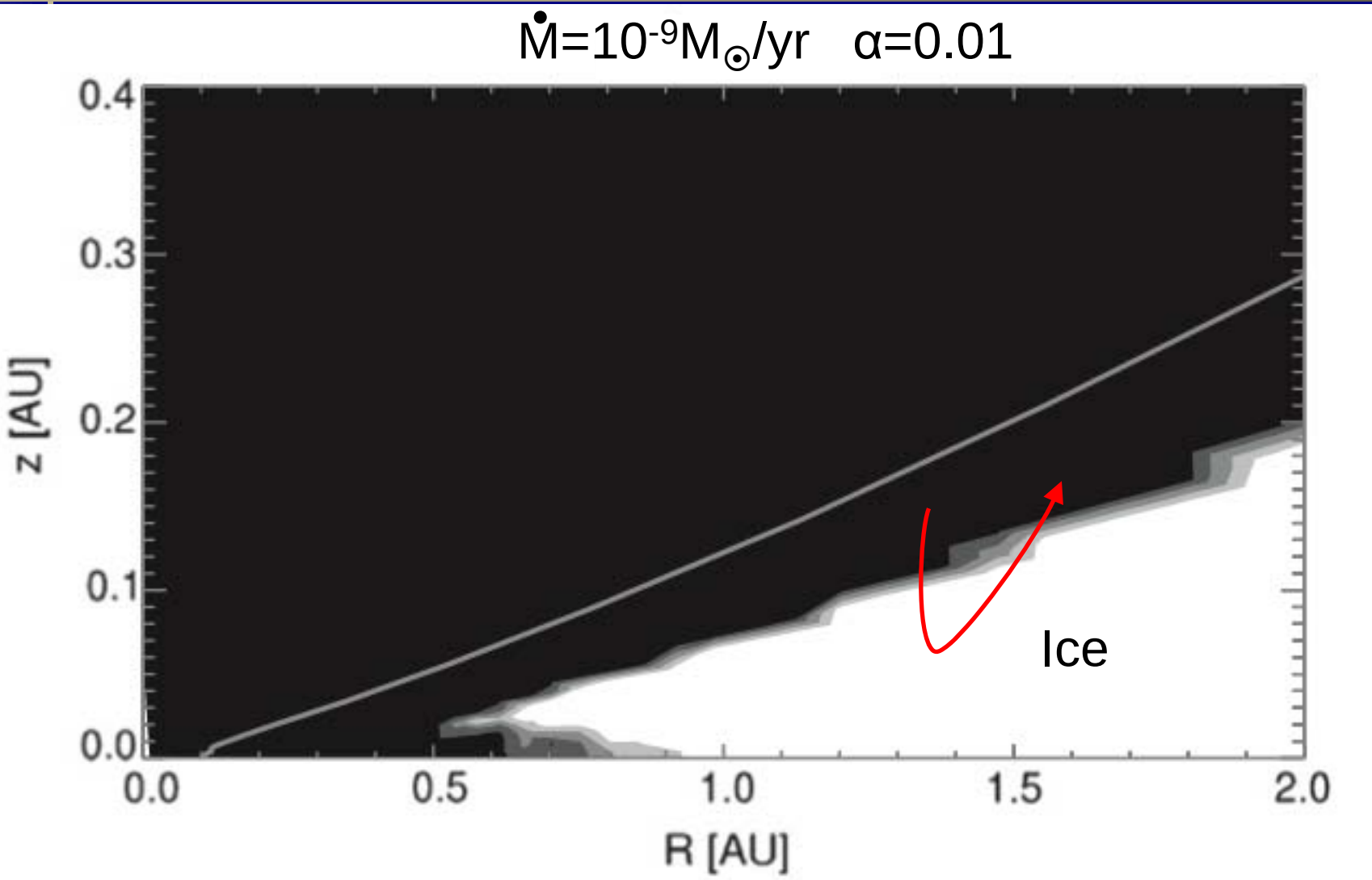
Meijerink et al. 2009

...and its absence in outer disk regions



Bergin, Hogerheijde et al. 2010

So, where is the vapor?

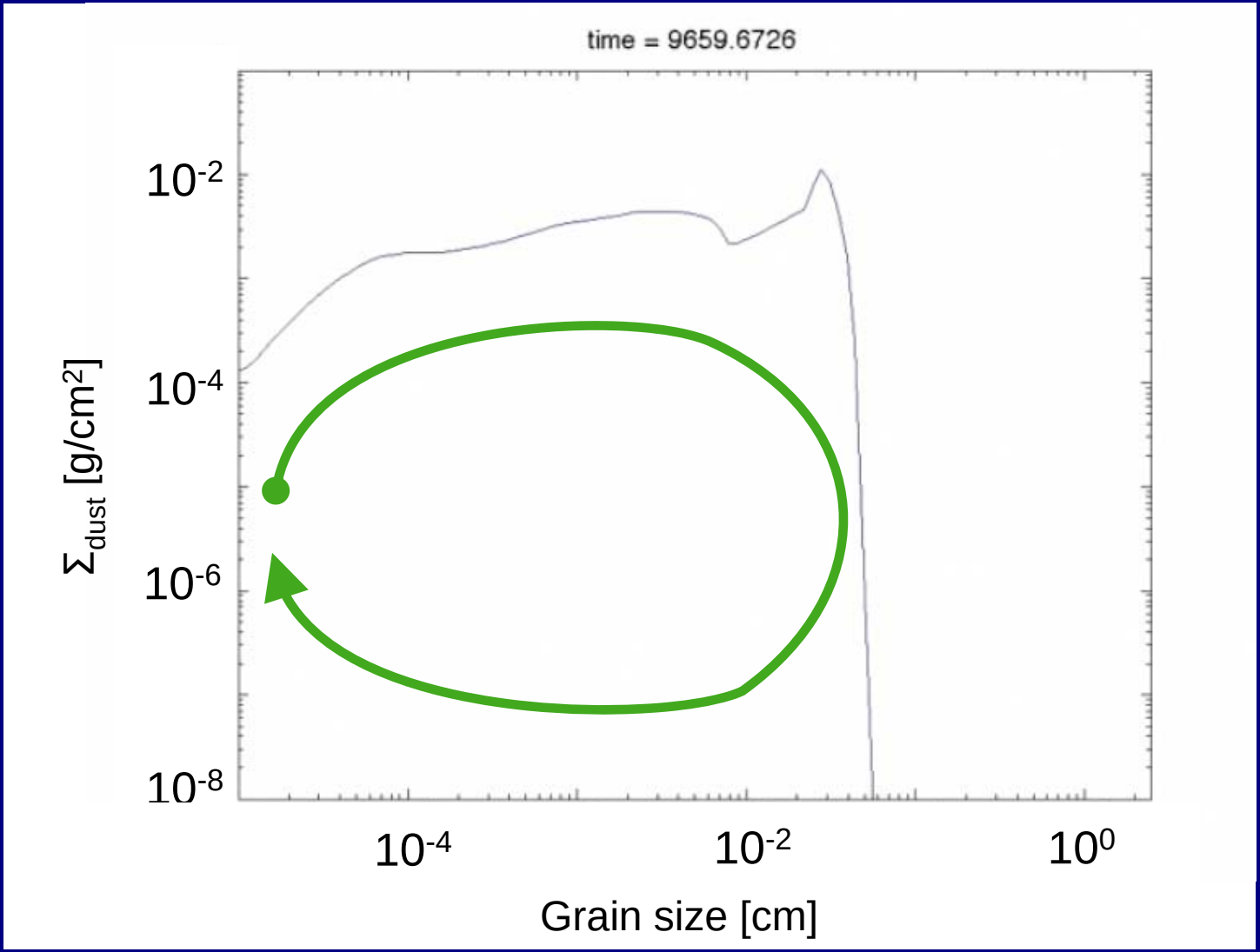


Idea: “vertical cold finger effect” (cf. Pontoppidan, Bergin)

Pressure bumps:

Preferred places of planet formation

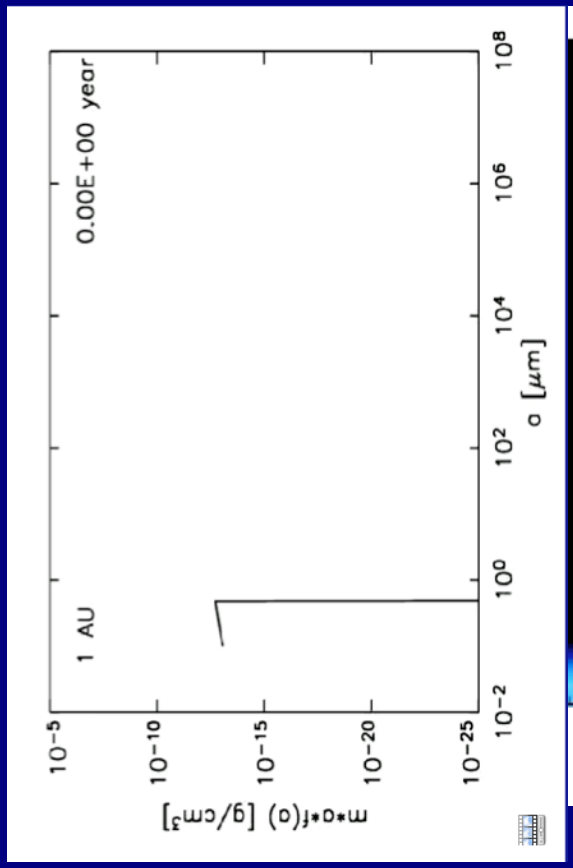
Remember the 1-zone dust growth model?

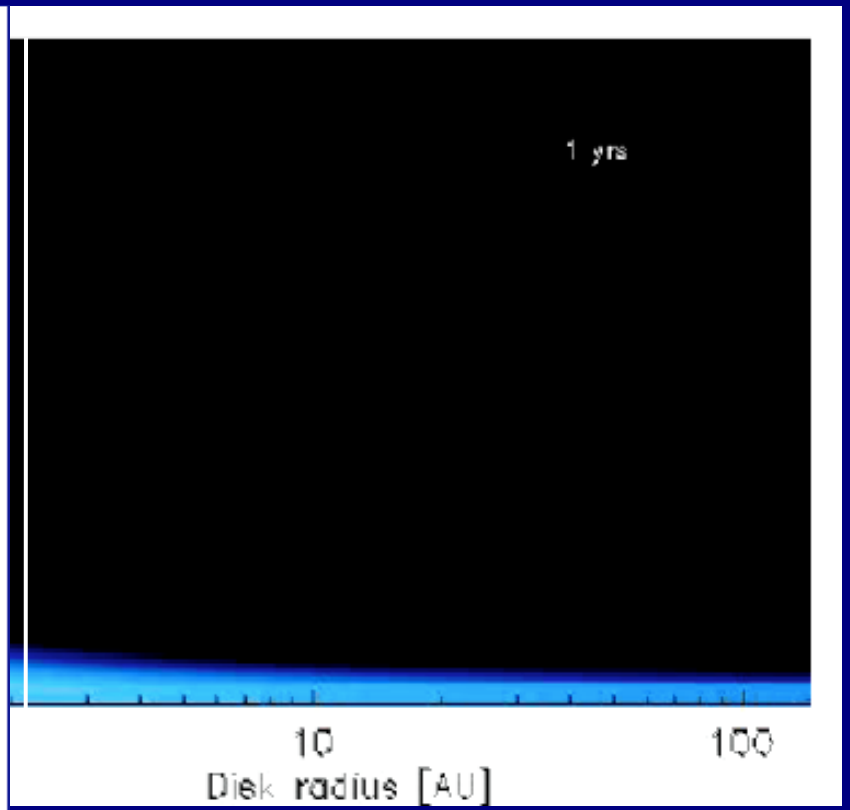


Birnstiel, Dullemond & Ormel 2010

Full 2-D dust evolution models

Includes: growth, fragmentation, drift and mixing





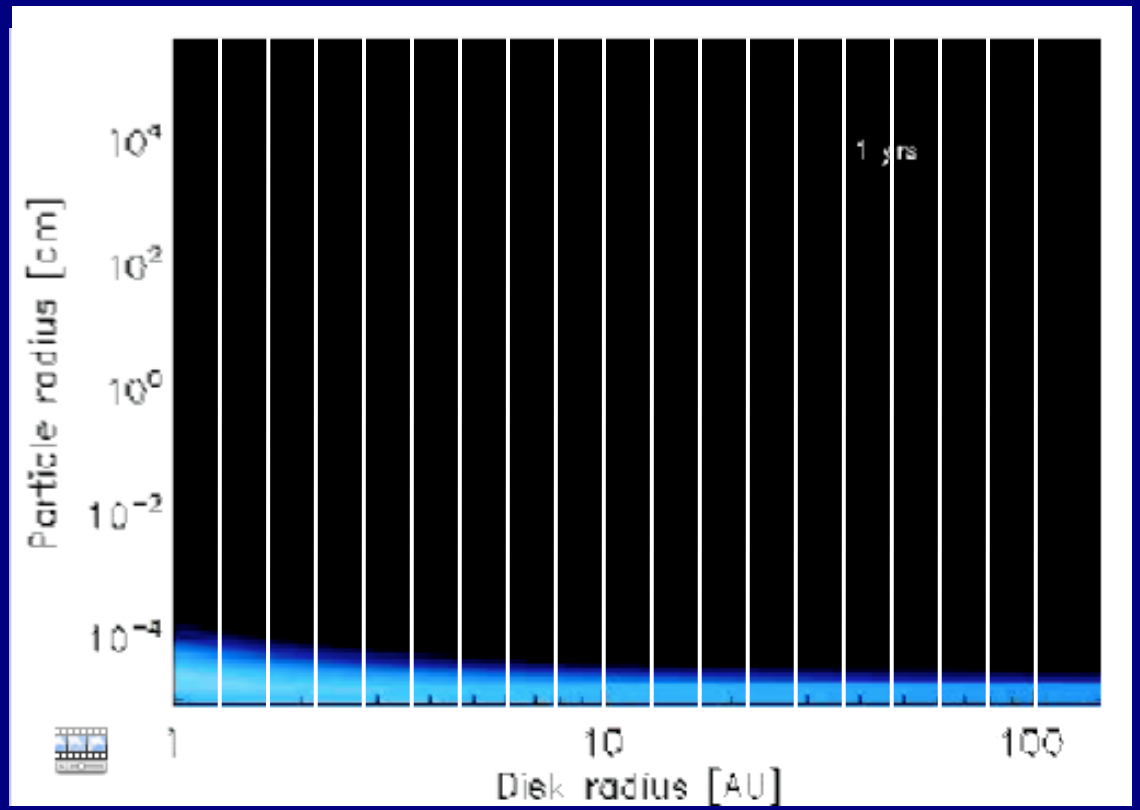
R

Brauer, Dullemond & Henning 2008

Full 2-D dust evolution models

Includes: growth, fragmentation, drift and mixing

Particle Size



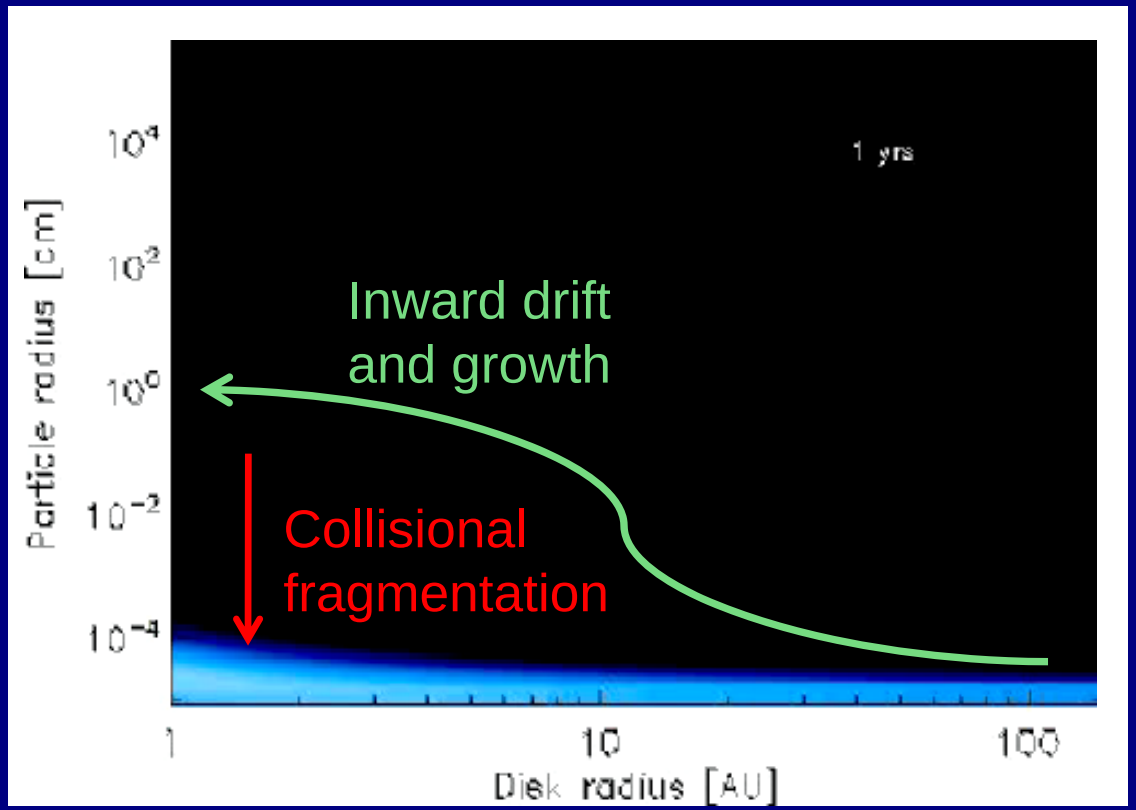
R

Brauer, Dullemond & Henning 2008

Full 2-D dust evolution models

Includes: growth, fragmentation, drift and mixing

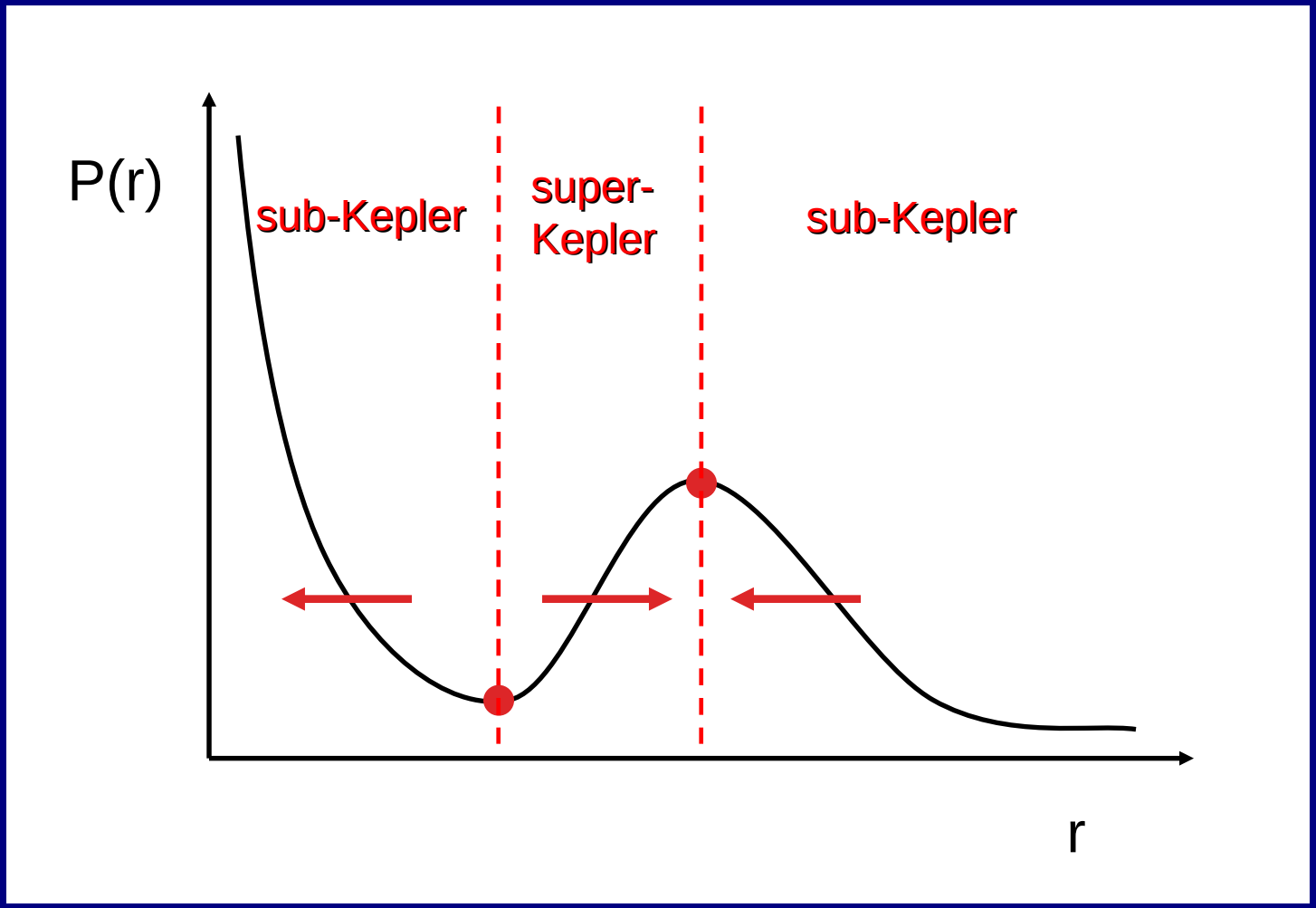
Particle Size



R

Brauer, Dullemond & Henning 2008

Particles move toward pressure peak



Particles move toward pressure peak

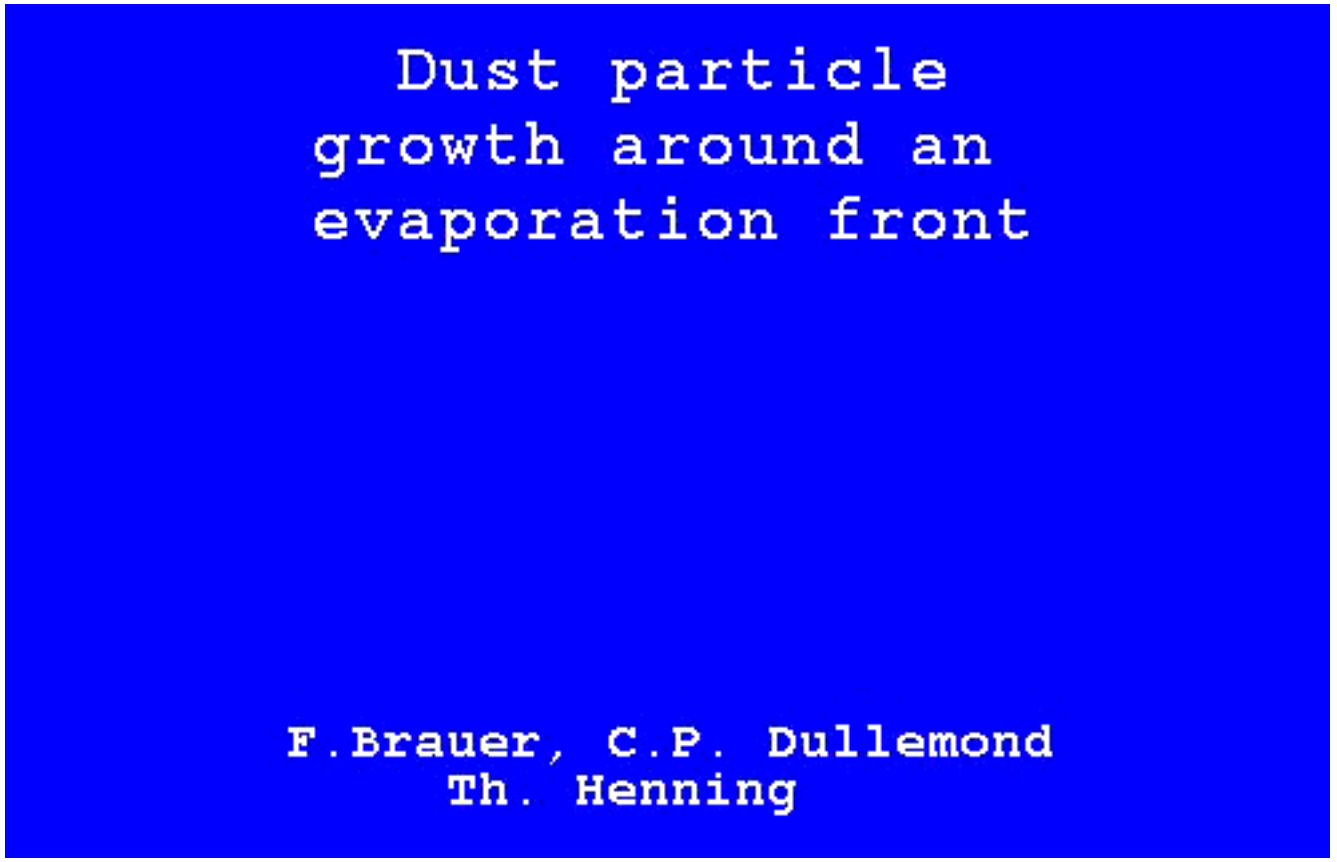
- In vortices: Klahr & Henning 1997
- Near ice line: Kretke & Lin 2008
- Dead zone edge: Dzyurkevich et al. 2010; Kato et al. 2010
- Zonal flows: Johansen et al. 2009

Particles move toward pressure peak

- In vortices: Klahr & Henning 1997
- Near ice line: Kretke & Lin 2008
- Dead zone edge: Dzyurkevich et al. 2010; Kato et al. 2010
- Zonal flows: Johansen et al. 2009

- Coagulation break through: Brauer et al. 2008
- Gravoturbulent PF: Johansen et al. 2007; Lyra et al. 2009

Breaking through the barrier



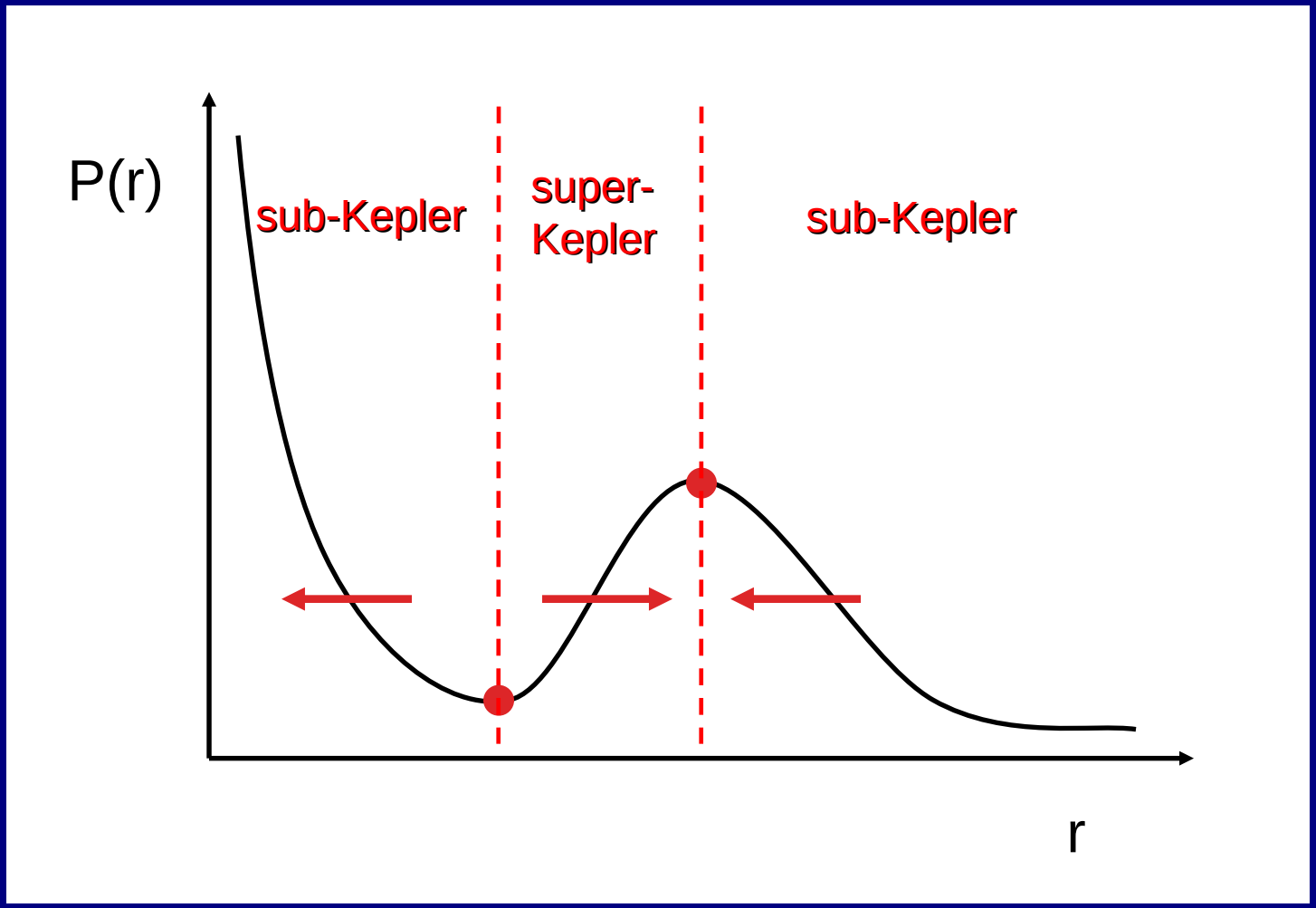
Brauer, Henning & Dullemond 2008

Trapping planets in a type-I migr. trap

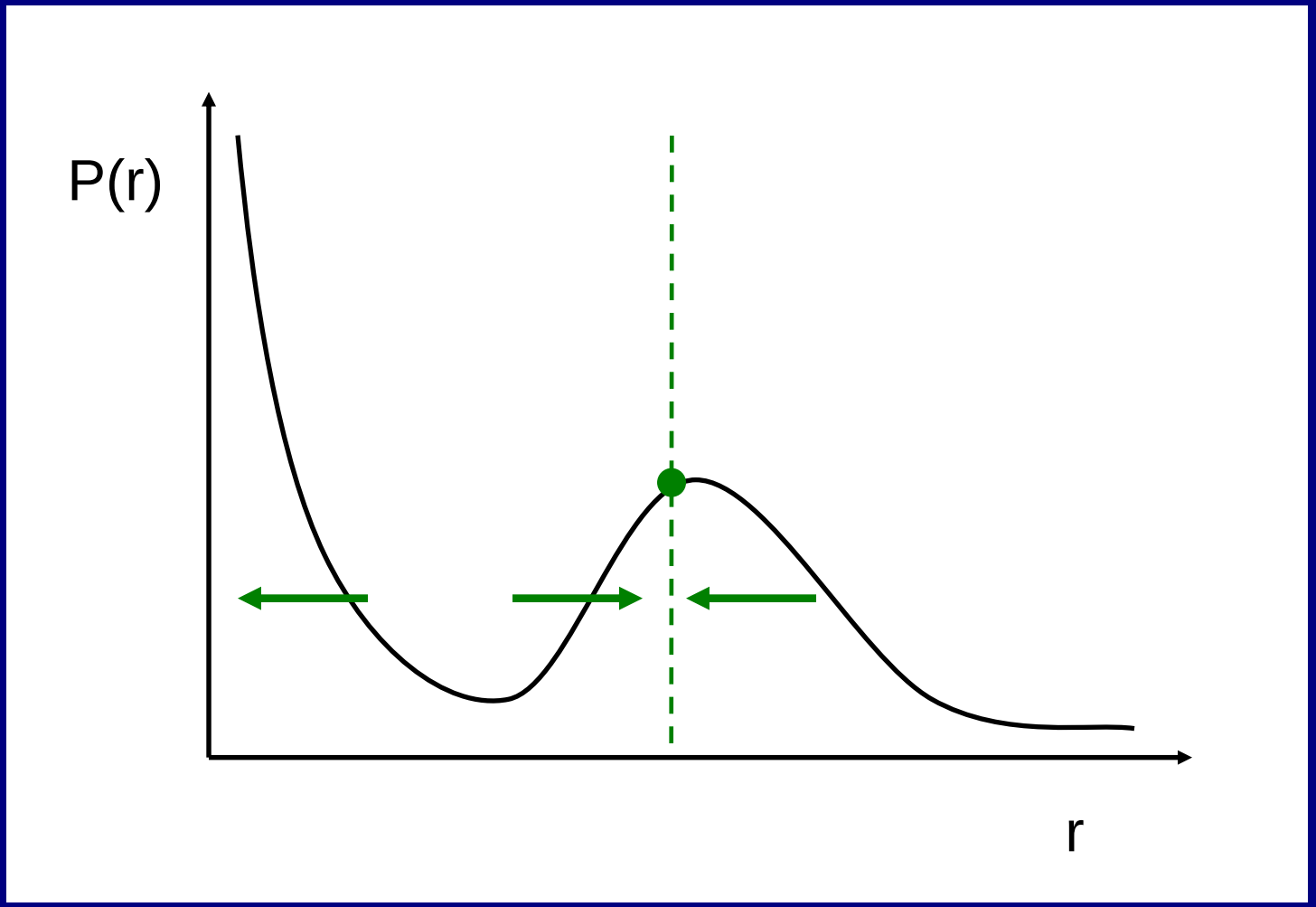
$$\Gamma \sim -0.85 + \frac{d\lg\Sigma}{d\lg r} + 0.9\frac{d\lg T}{d\lg r}$$

Paardekooper et al. 2010a+b; Lyra et al. 2010; Morbidelli et al. 2008

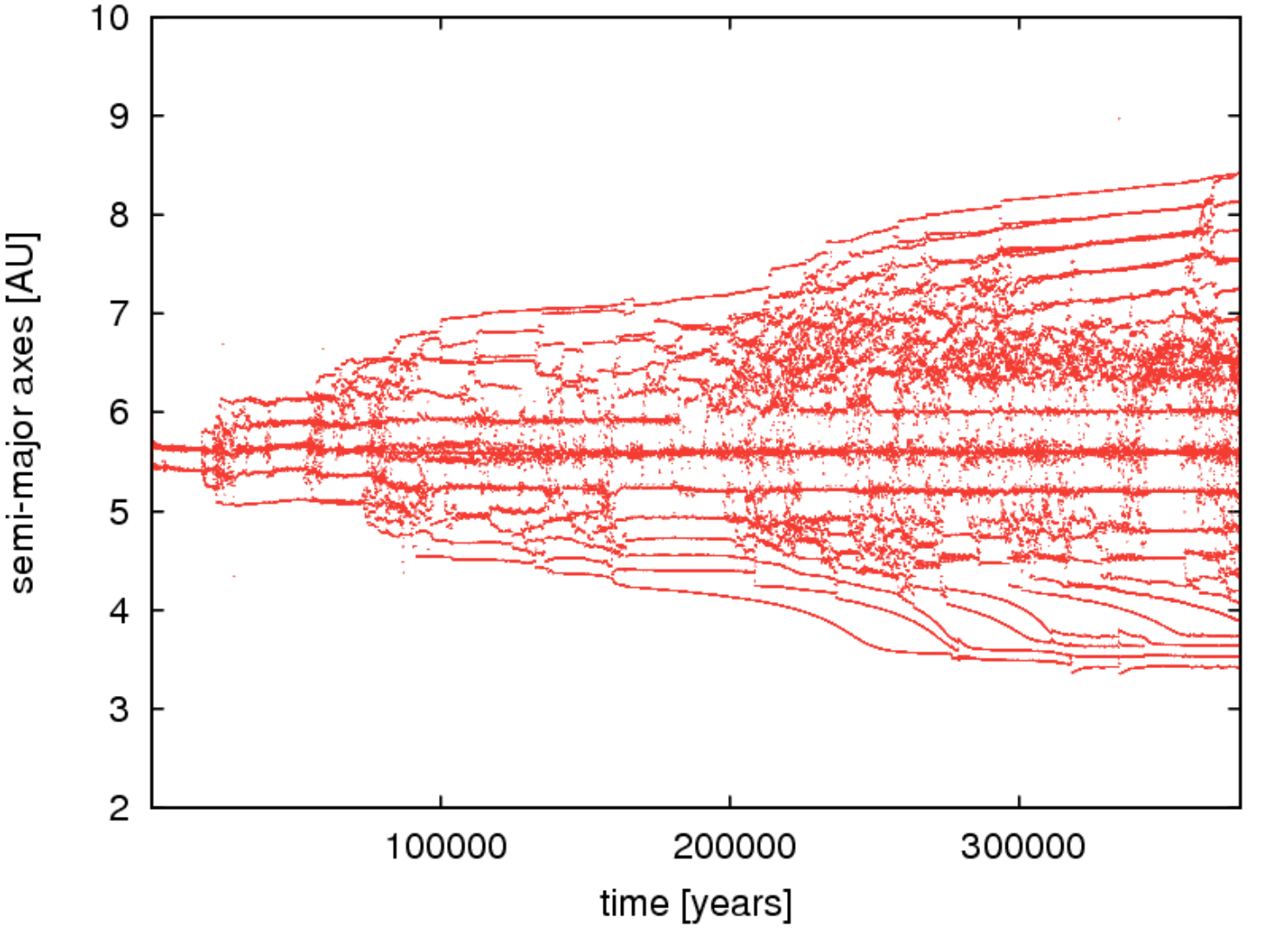
Remember:



Now for the migration:



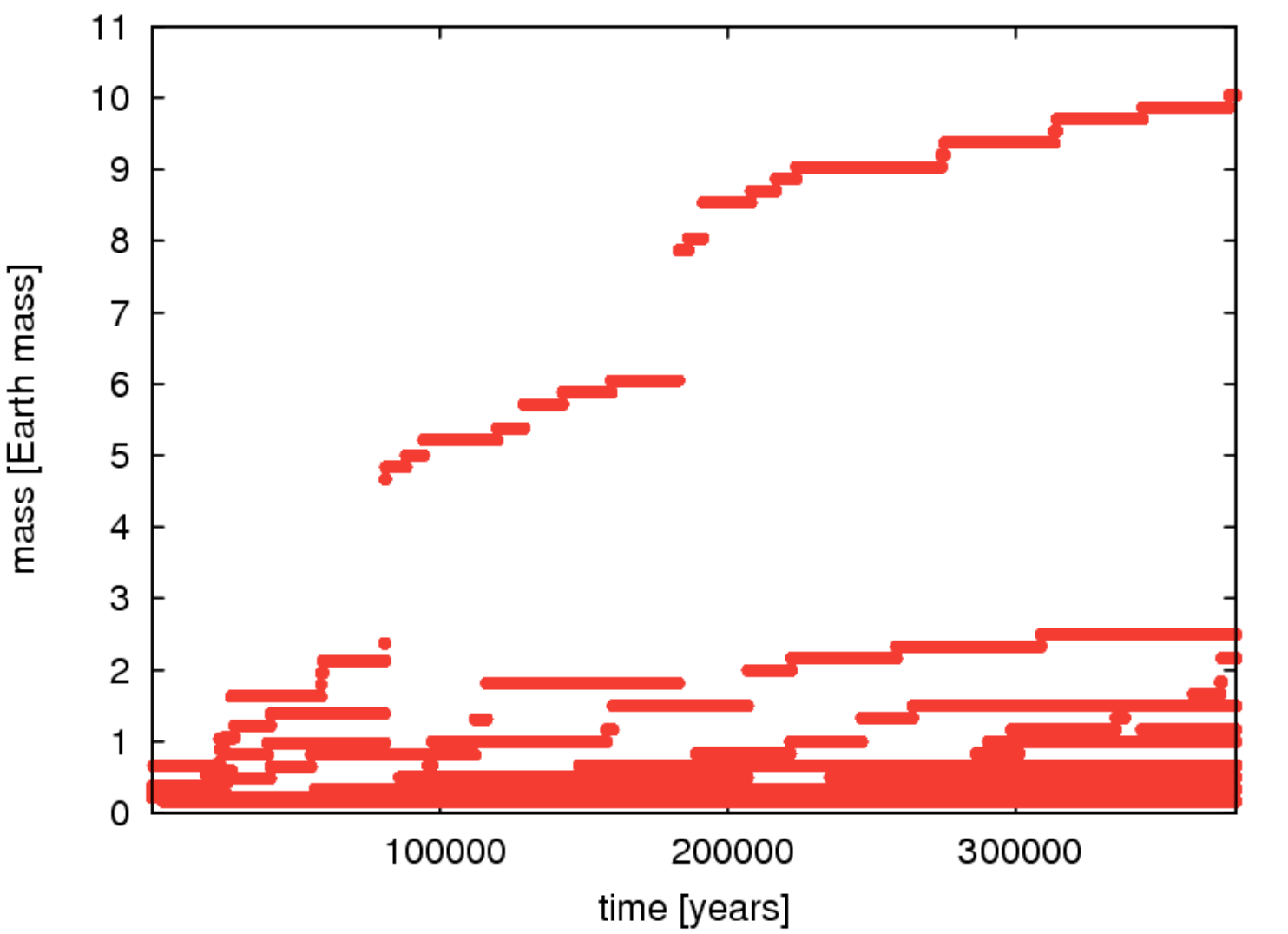
First results...



Sandor et al. (2011)

See also Morbidelli et al. (2008)

First results...

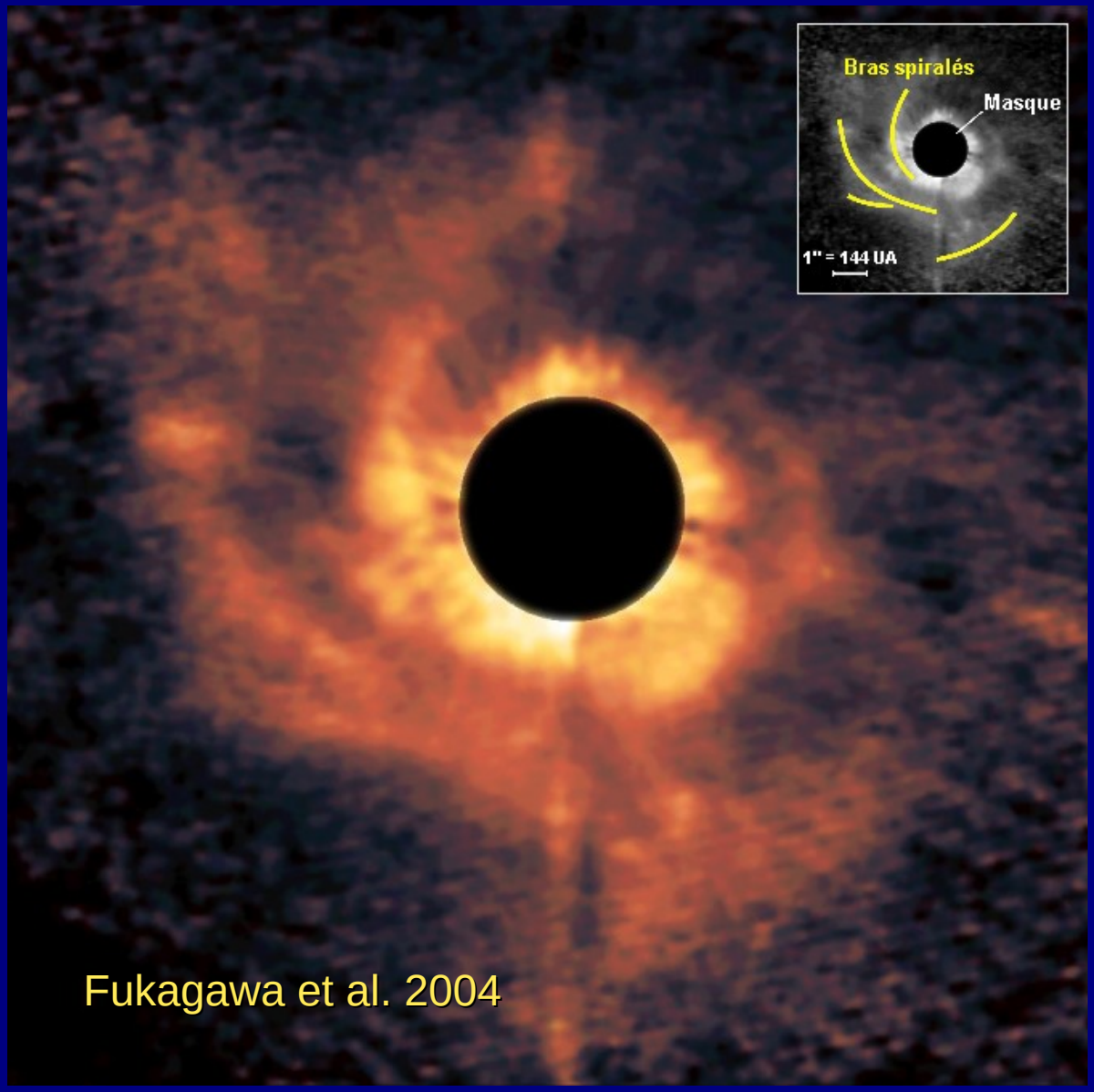


Sandor et al. (2011)

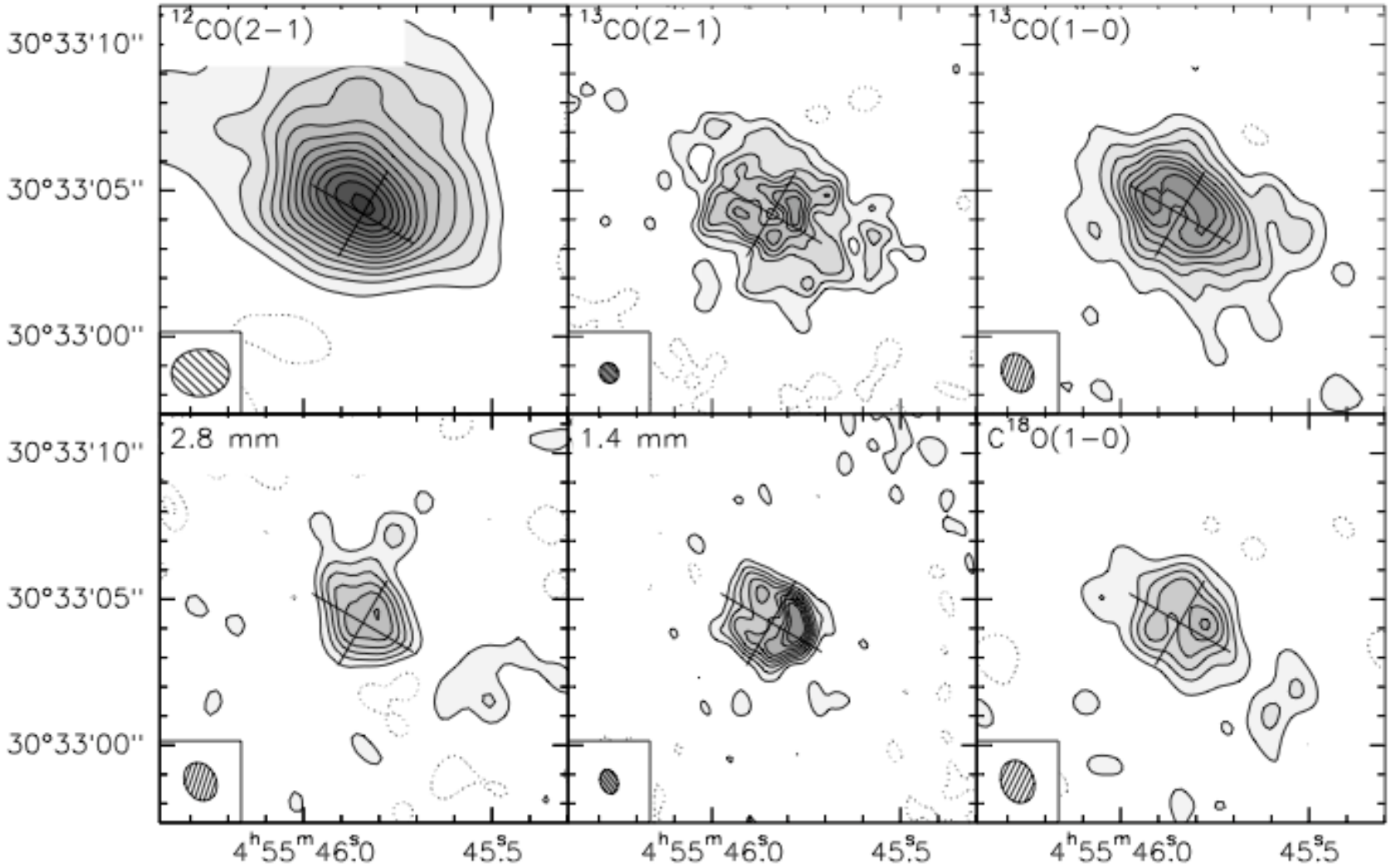
See also Morbidelli et al. (2008)

Is there evidence for the existence of such pressure bumps / vortices?

Mm view of AB Aurigae: a huge vortex?

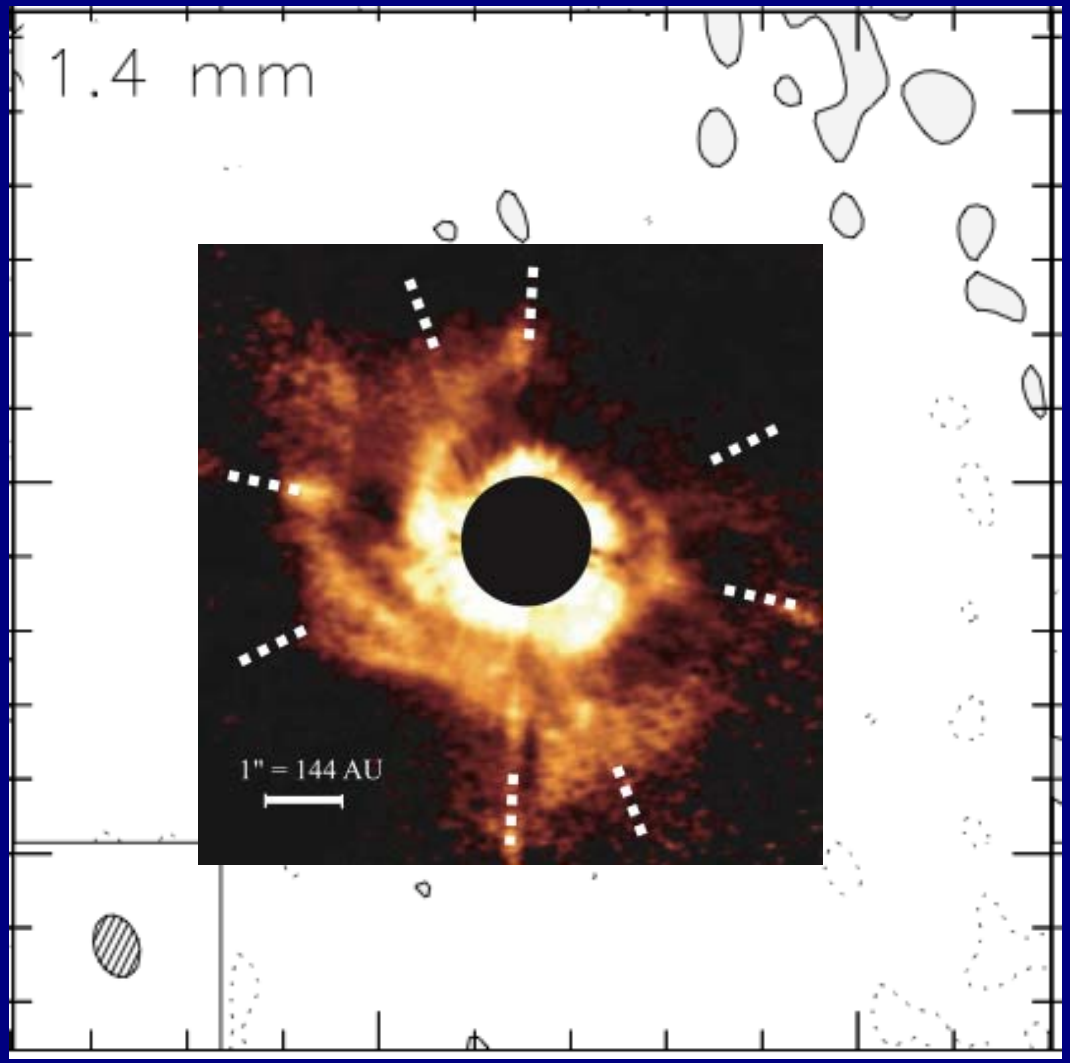


Mm view of AB Aurigae: a huge vortex?



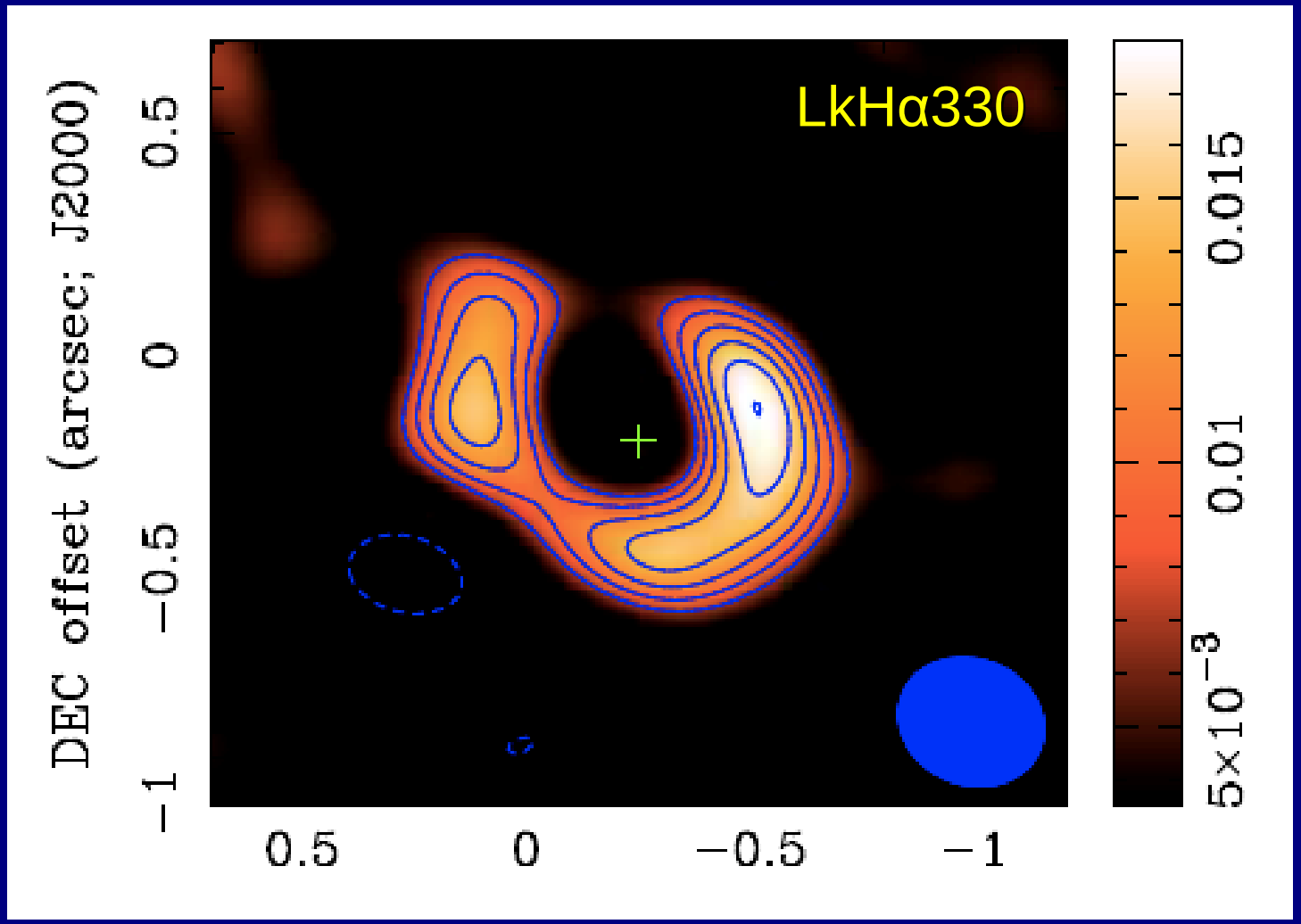
Pietu, Guilloteau & Dutrey 2005

Mm view of AB Aurigae: a huge vortex?



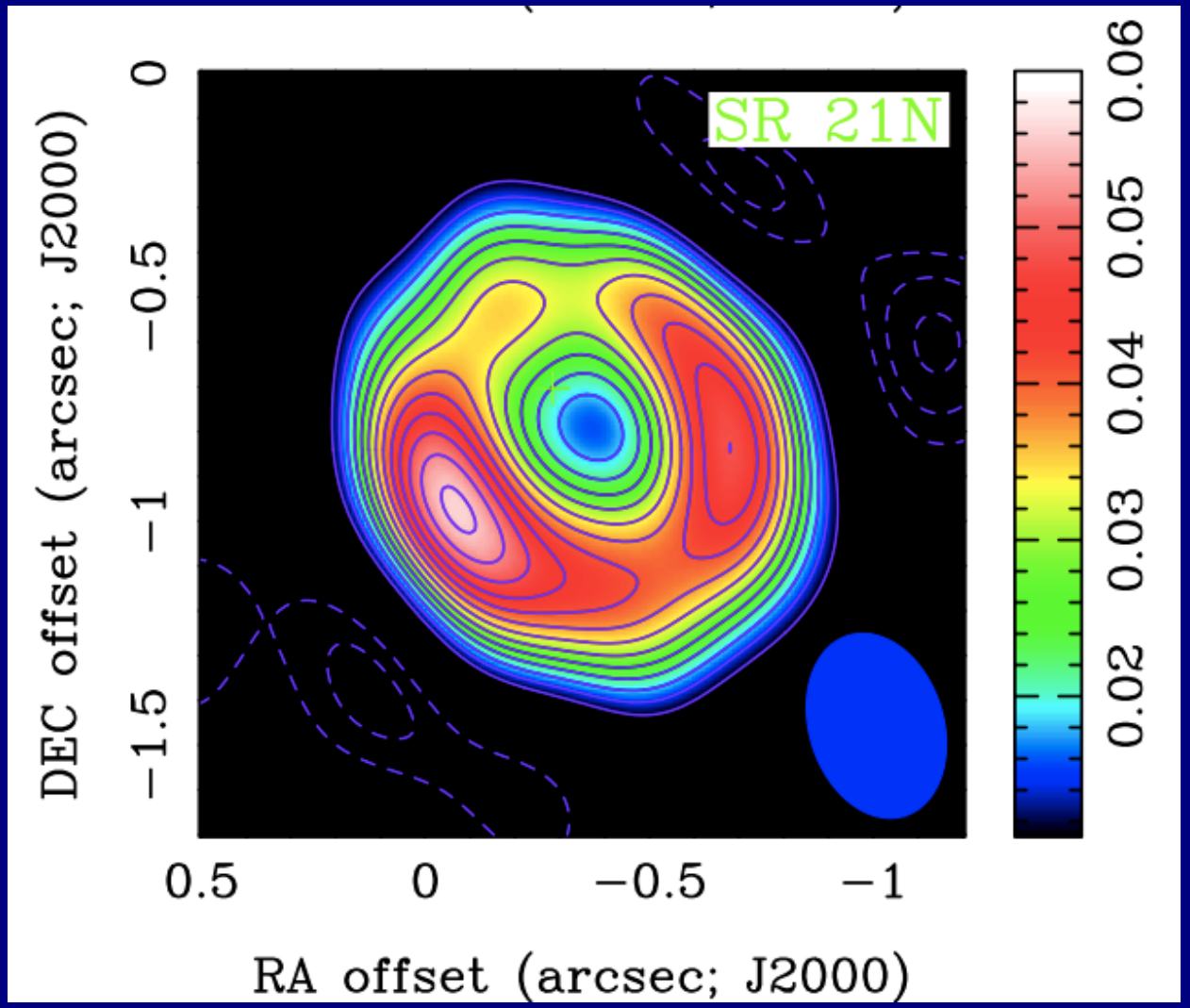
Pietu, Guilloteau & Dutrey 2005

Recently, many more are found...



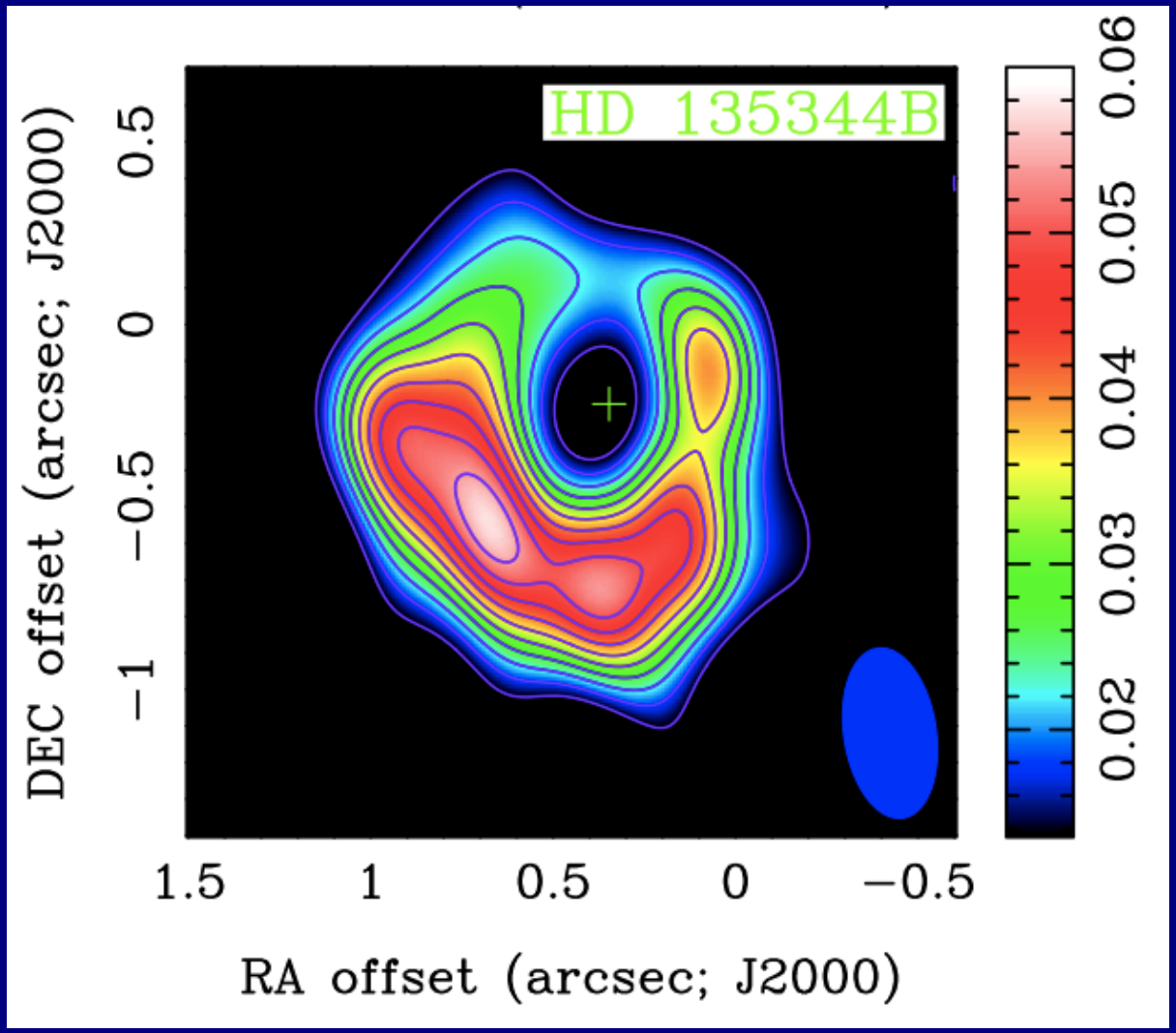
Brown et al. 2008

Recently, many more are found...



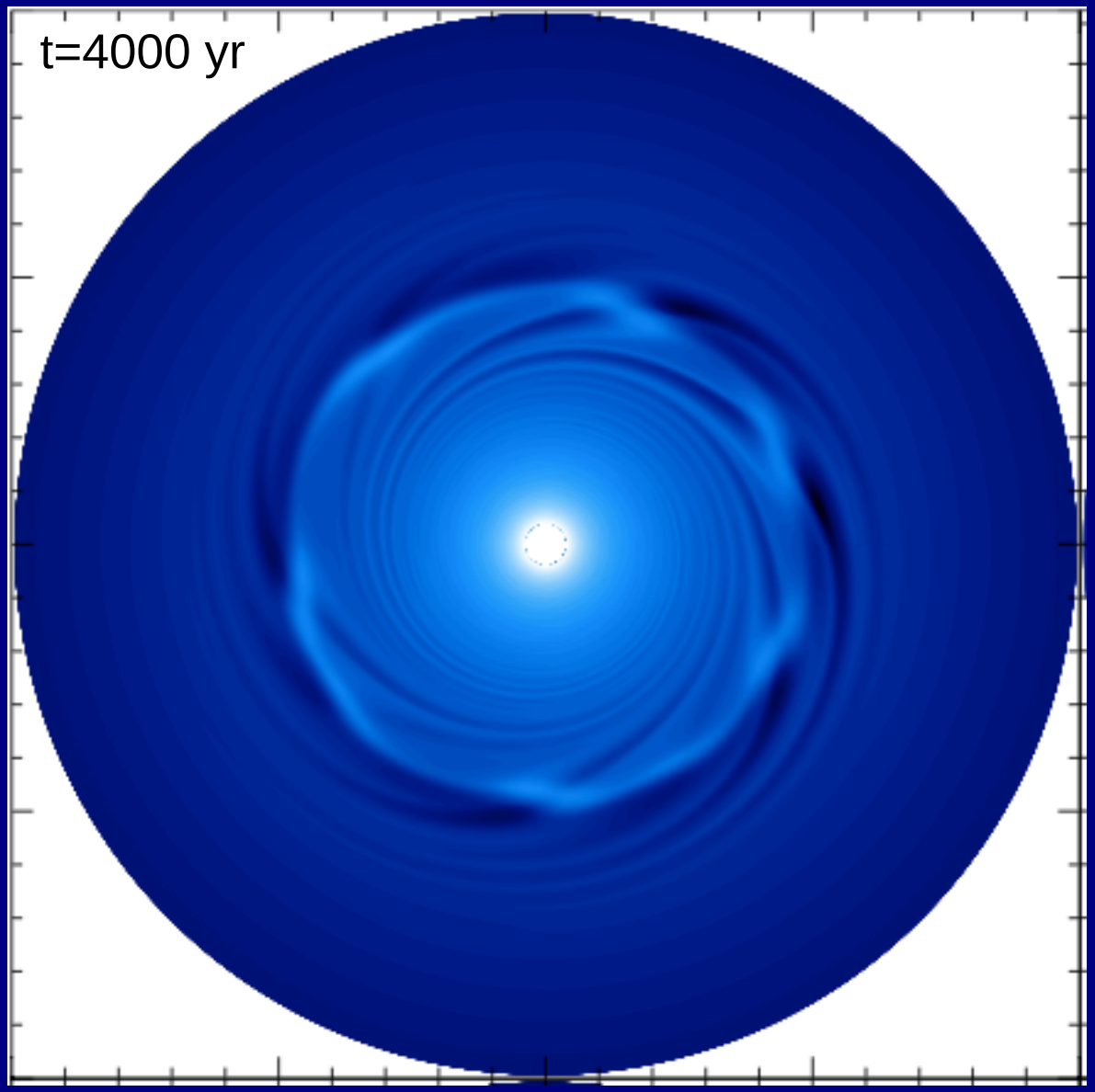
Brown et al. 2009

Recently, many more are found...



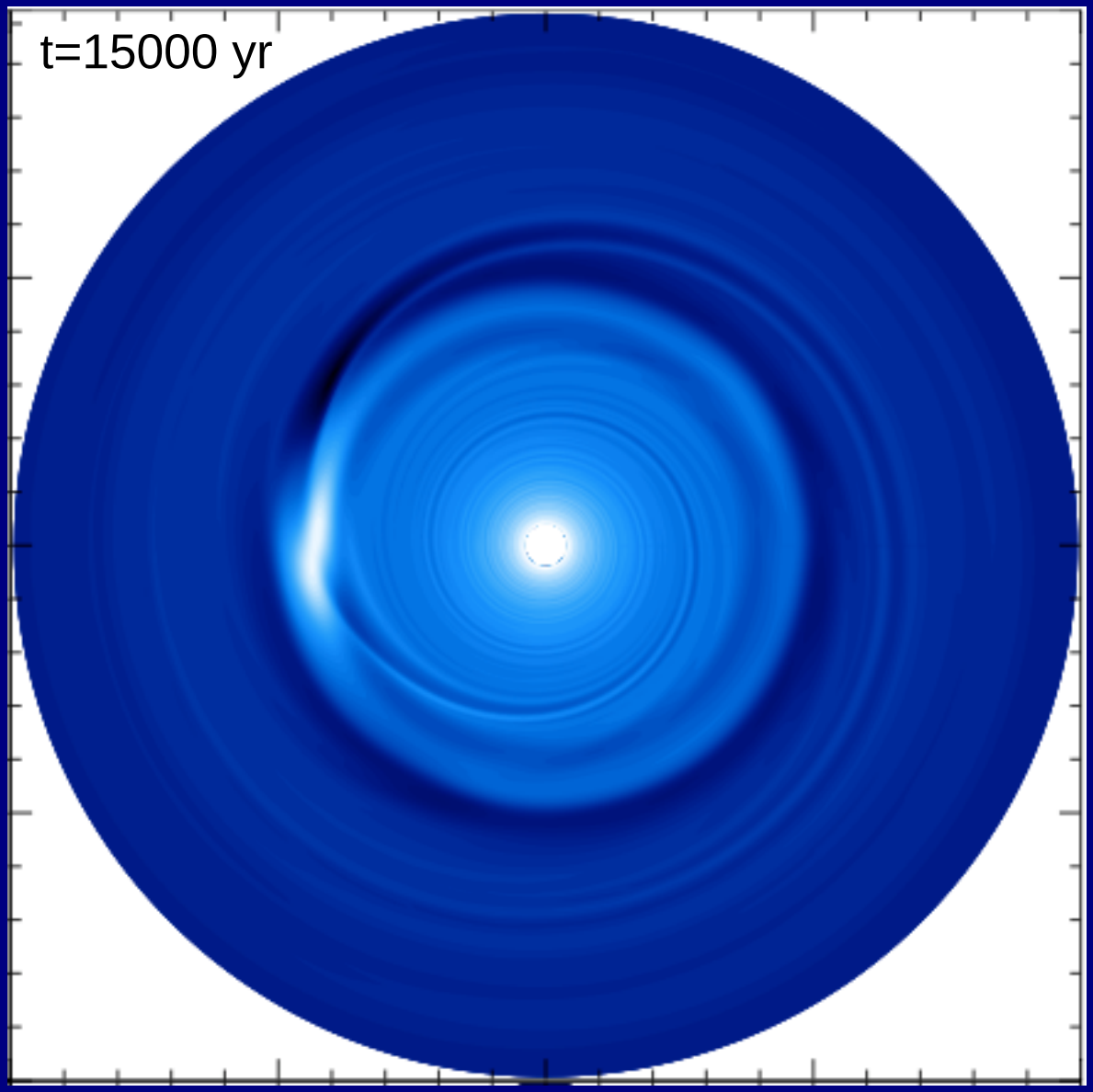
Brown et al. 2009

Vortex by Rossby wave instability?



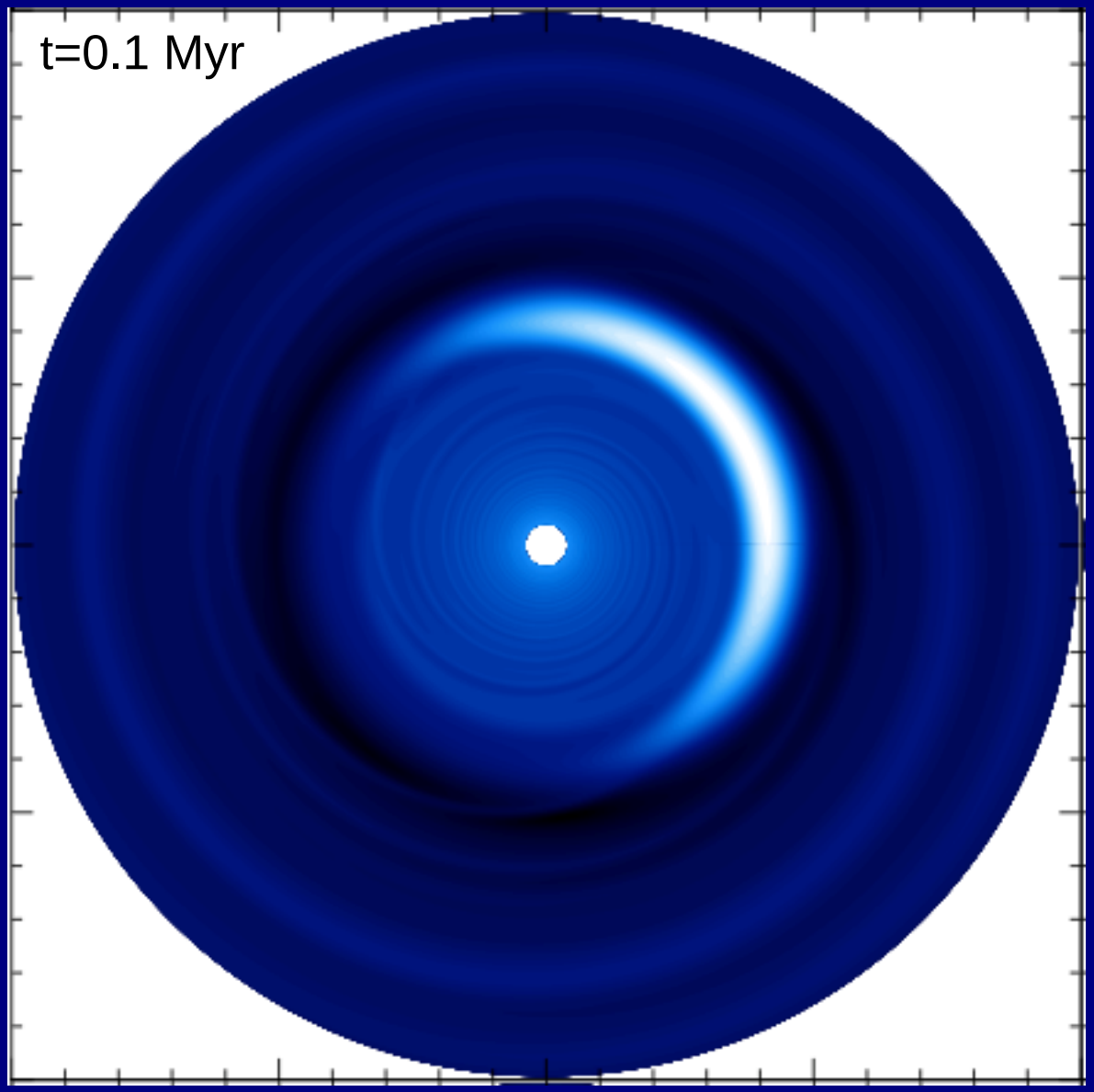
Regaly, Juhasz,
Sandor & CPD
A&A submitted

Vortex by Rossby wave instability?



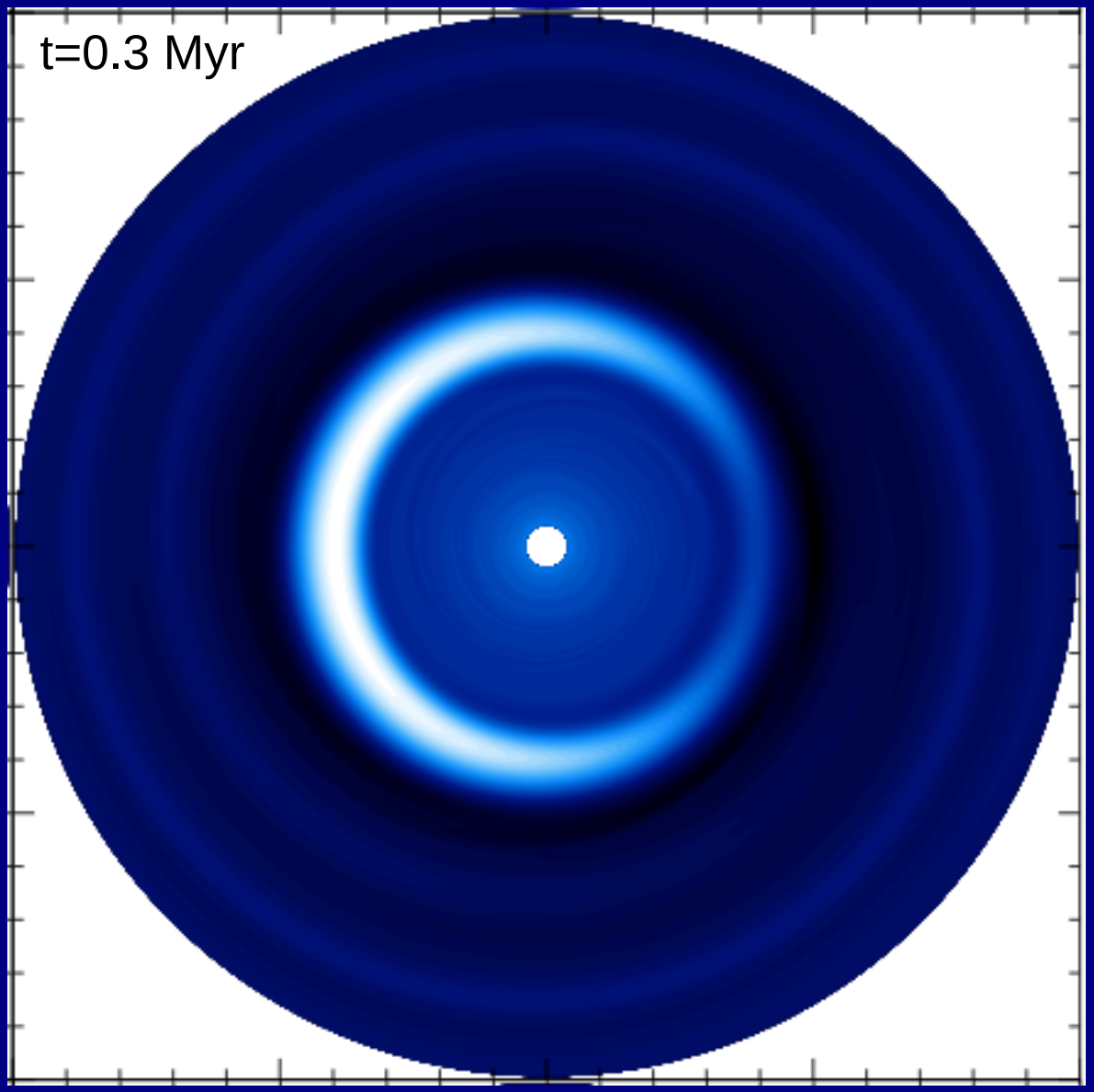
Regaly, Juhasz,
Sandor & CPD
A&A submitted

Vortex by Rossby wave instability?



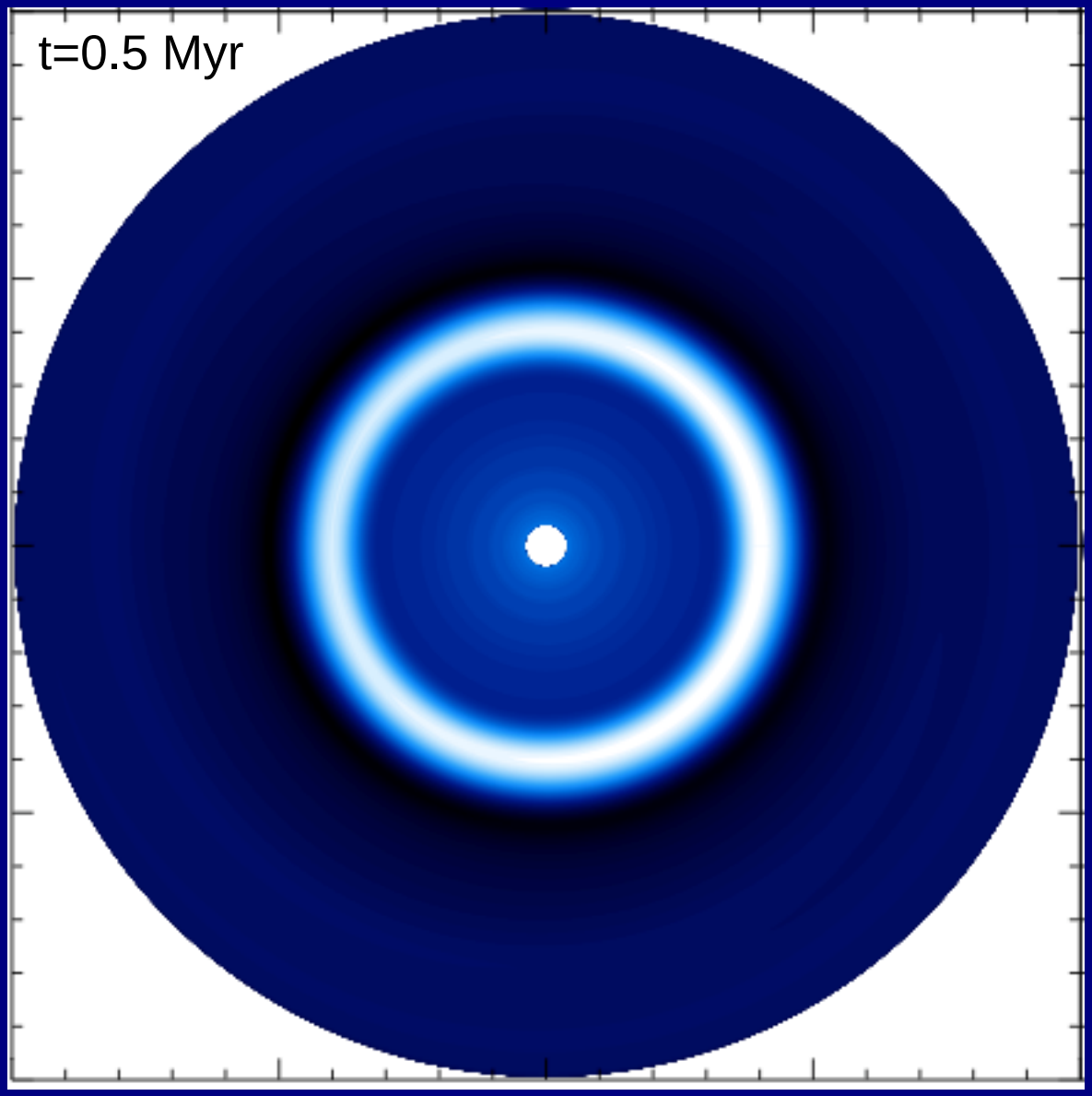
Regaly, Juhasz,
Sandor & CPD
A&A submitted

Vortex by Rossby wave instability?



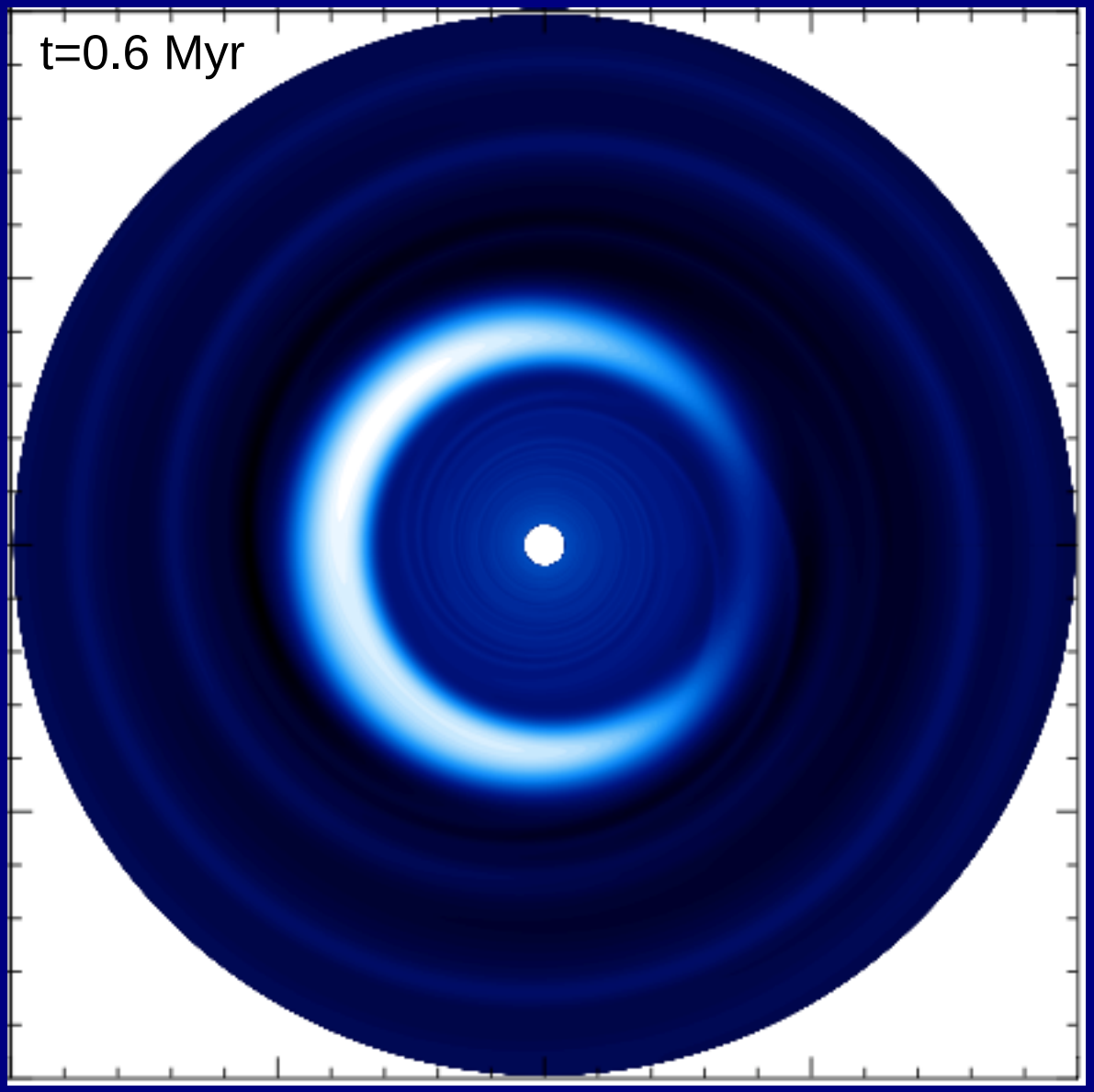
Regaly, Juhasz,
Sandor & CPD
A&A submitted

Vortex by Rossby wave instability?



Regaly, Juhasz,
Sandor & CPD
A&A submitted

Vortex by Rossby wave instability?



Regaly, Juhasz,
Sandor & CPD
A&A submitted

May explain large clumpy rings...

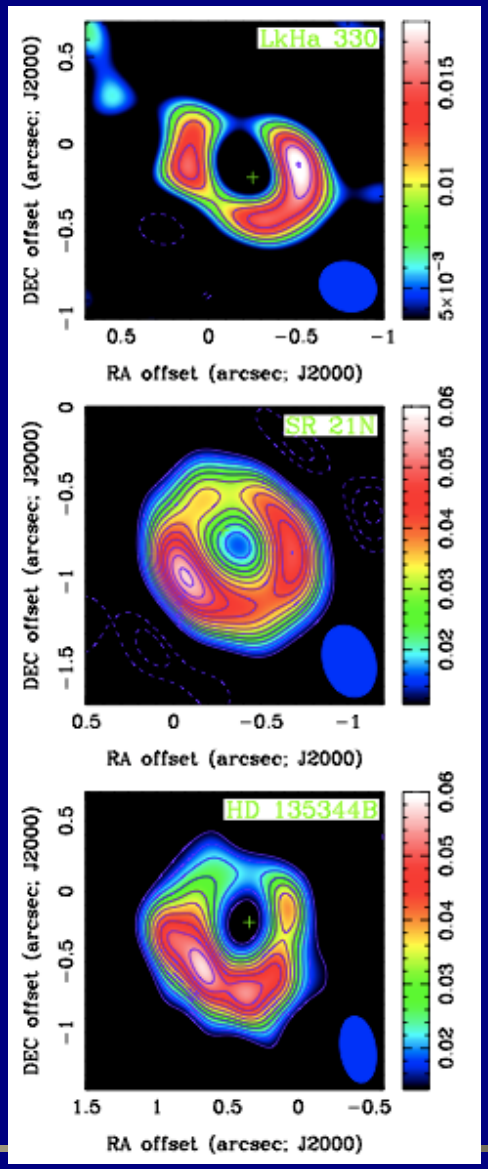
Observations:

Brown et al. 2009

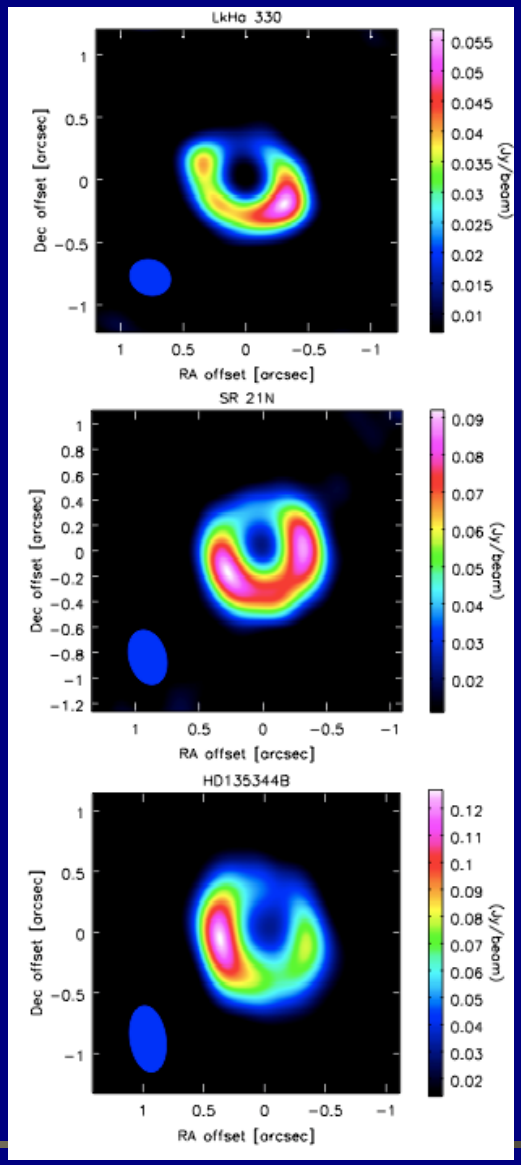
Model:

Regaly, Juhasz, Sandor & CPD A&A subm.

Observations:



Model:



Summary

- Slowly but surely the distribution of matter in disks is being observationally measured
  - ALMA will help a lot!
- Pressure bumps and/or snow line(s) may help to form planetesimals from dust
  - For planet formation people: you'd have preferred regions of planetesimal production!
- Maybe such regions area already observed:
  - Snow line: jump in water vapor density observed
  - Vortex: clumpy rings

So, do planet factories really exist?