From amorphous to crystalline silicates in disks: a crystal clear picture?

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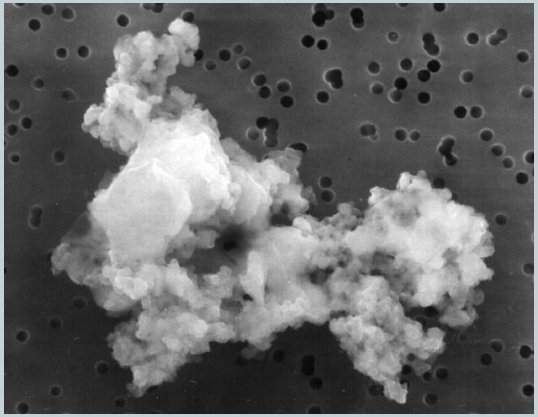
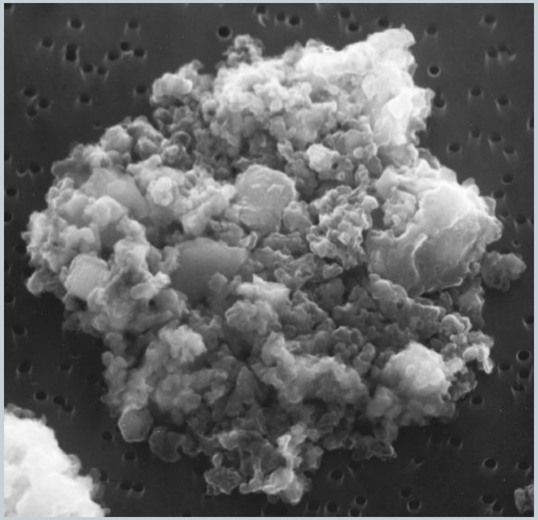
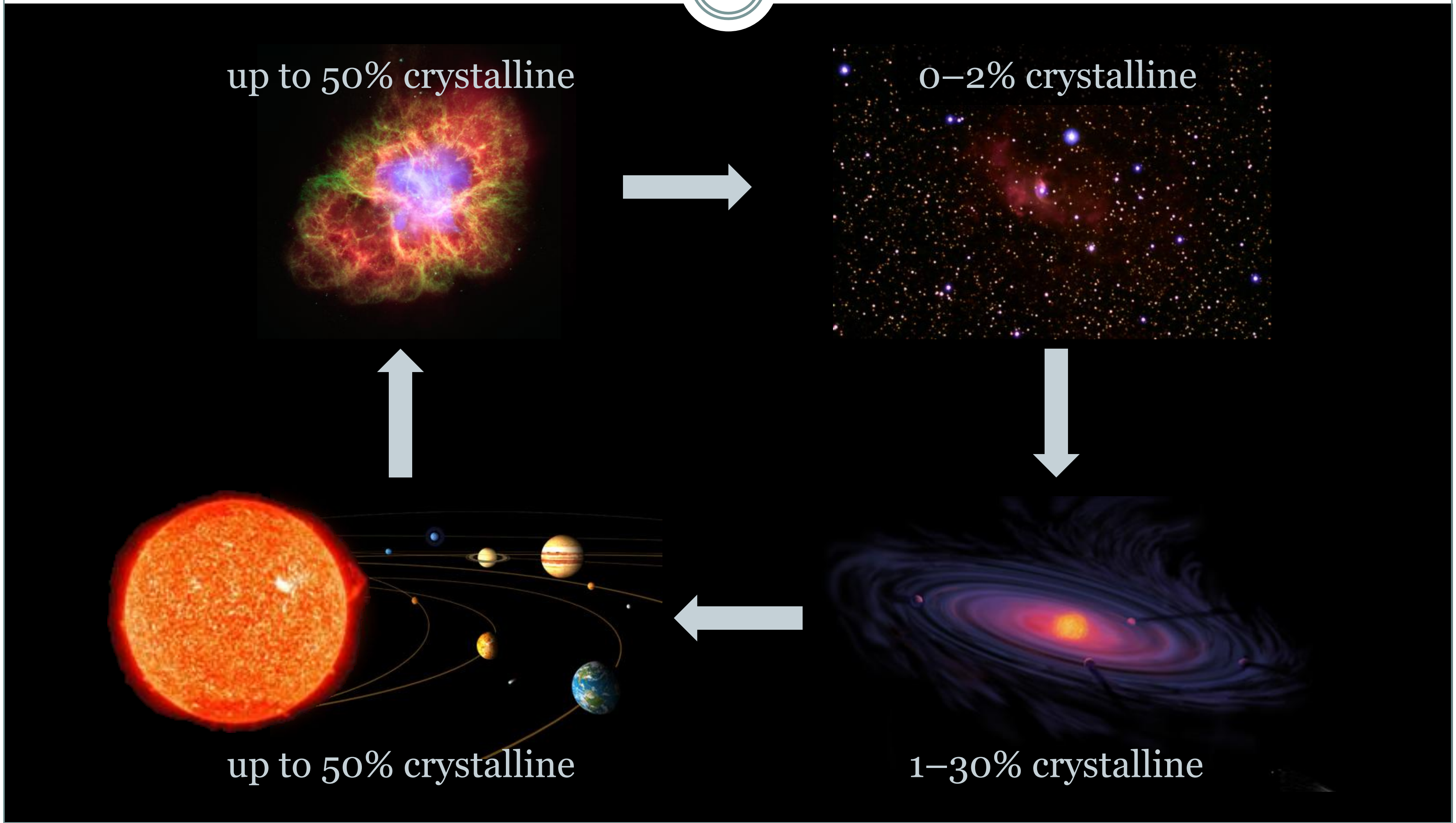
Composition of interstellar dust

- Carbonaceous material
  - Graphite (small-scale limit: PAHs)
  - Hydrogenated amorphous carbon
  - Diamonds
- Silicates
  - Amorphous (olivine, pyroxene, ...)
  - Crystalline (forsterite, enstatite, ...)
- Ices
  - Water, CO, CO_2, CH_3OH, NH_3, ...

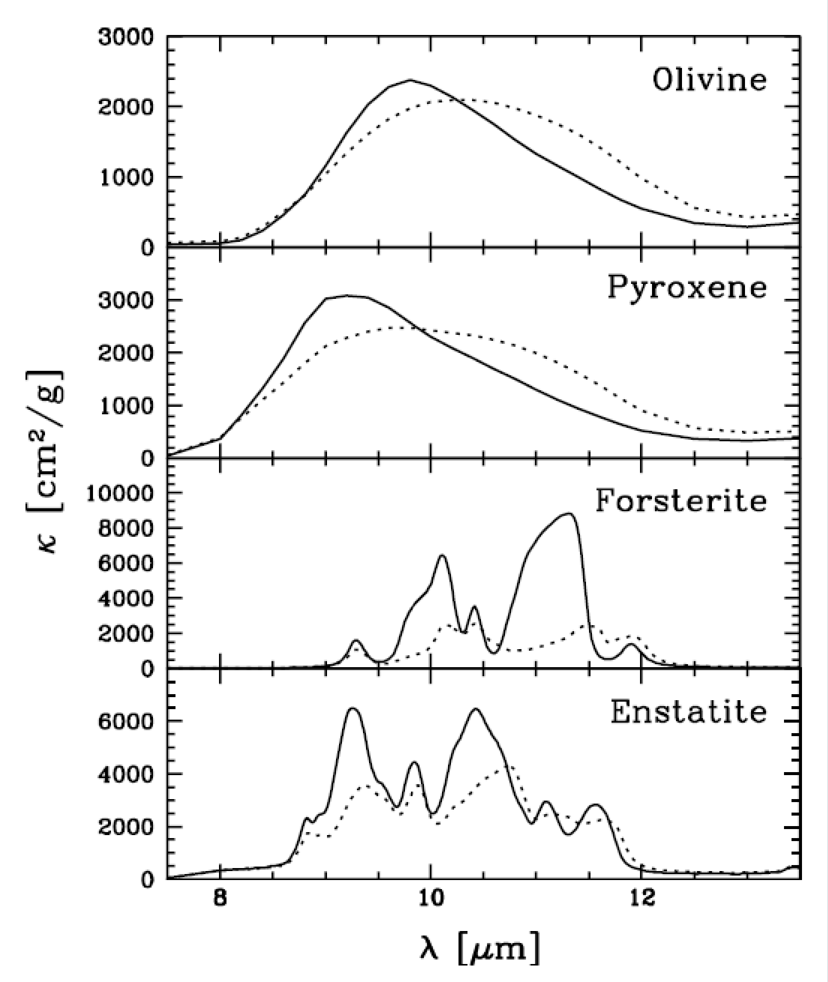




Lifecycle of interstellar dust



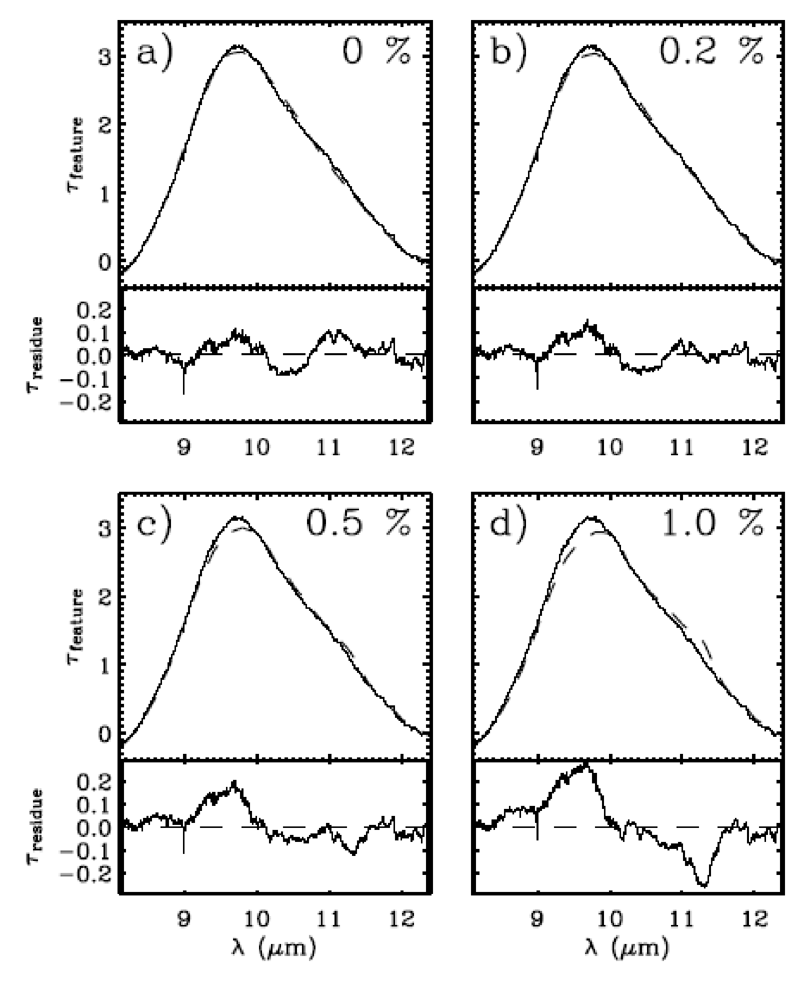
Silicate spectra



- Top two panels: amorphous
- Bottom two panels: crystalline
- Solid line: 0.1 μm grains
- Dotted line: 1.5 μm grains

van Boekel et al. (2005)

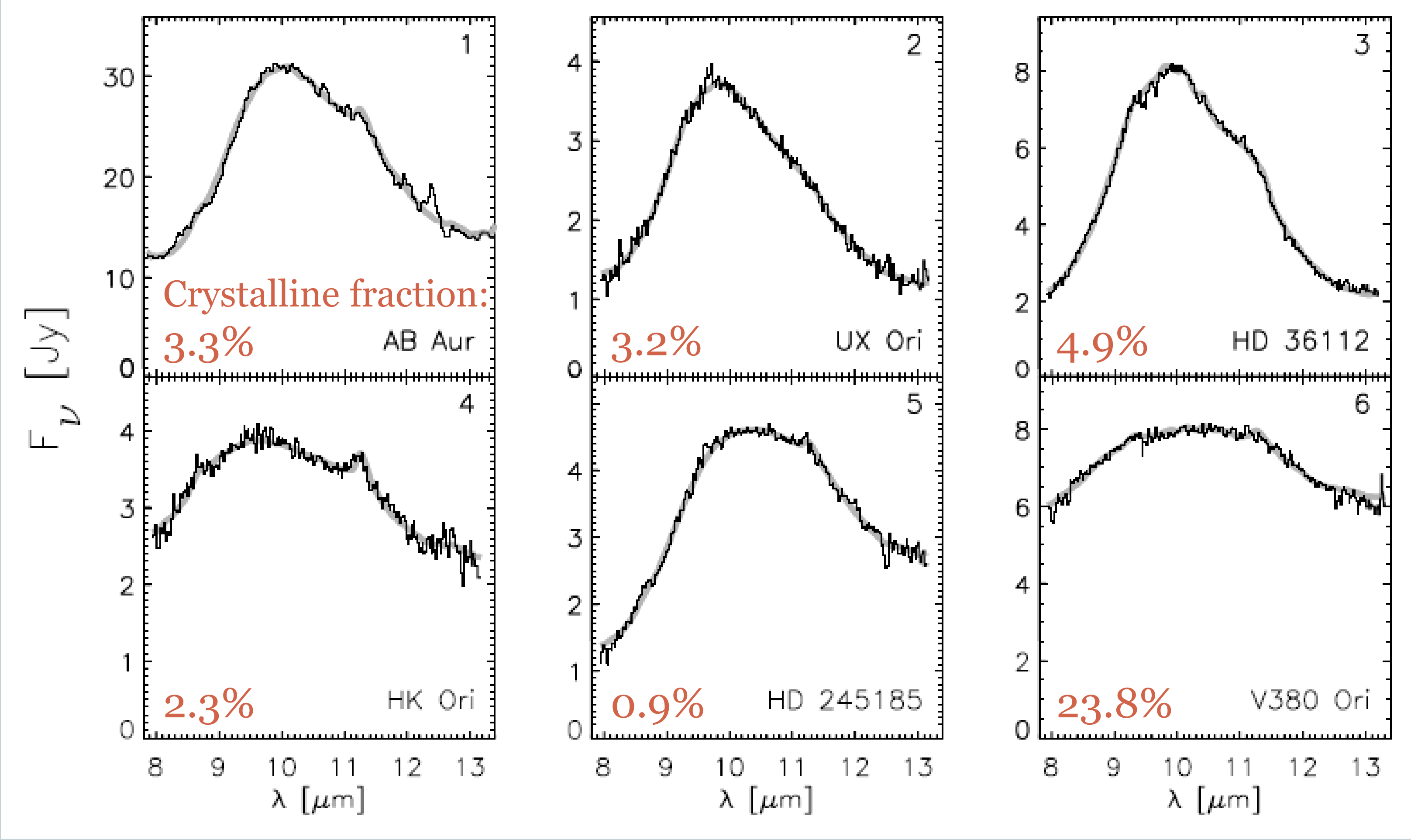
Silicate dust in the ISM



- ISO 10 μm spectra toward Sgr A* (galactic center)
- Model fits: amorphous silicates with small crystalline fraction
- Best fit: 0.2% crystalline (later revised to 1.0%)

Kemper, Vriend & Tielens (2004, 2005)

Silicate dust in circumstellar disks



van Boekel et al. (2005)

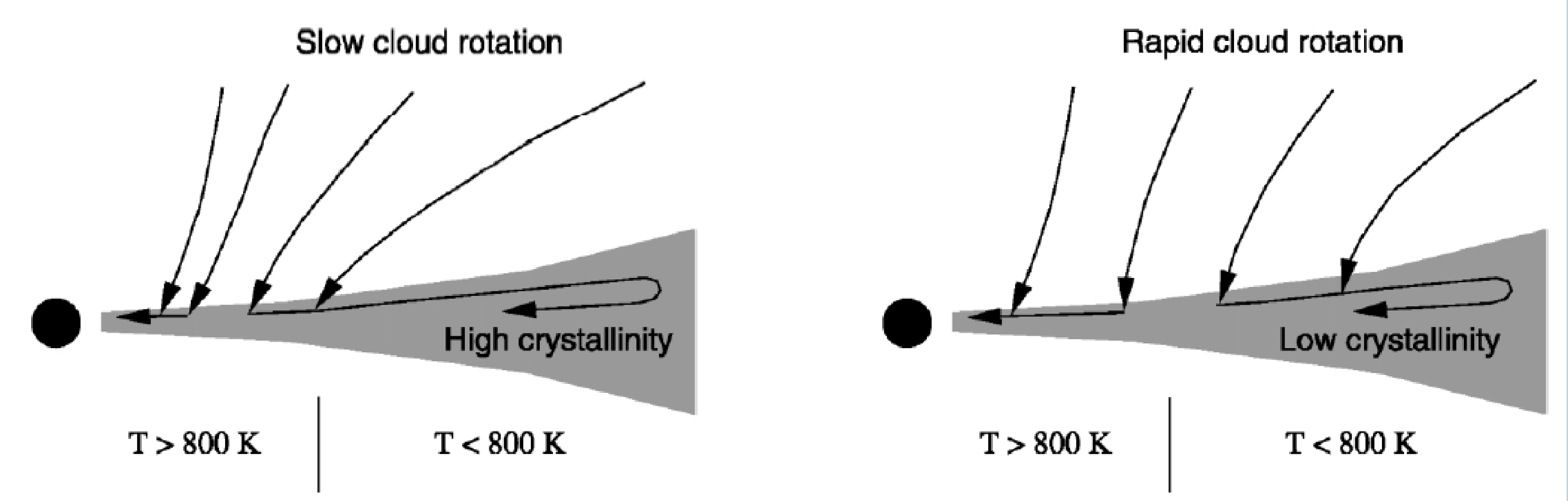
The Big Question

- ISM: 1% crystalline; disks: 1–30% crystalline
- Crystallization by thermal annealing requires 800 K
  - Works for material accreting close to the star
- Crystalline silicates observed down to 150 K and in comets formed in 100–200 K regions

- How can we explain these cold crystalline silicates?

Disk evolution model (DAW06)

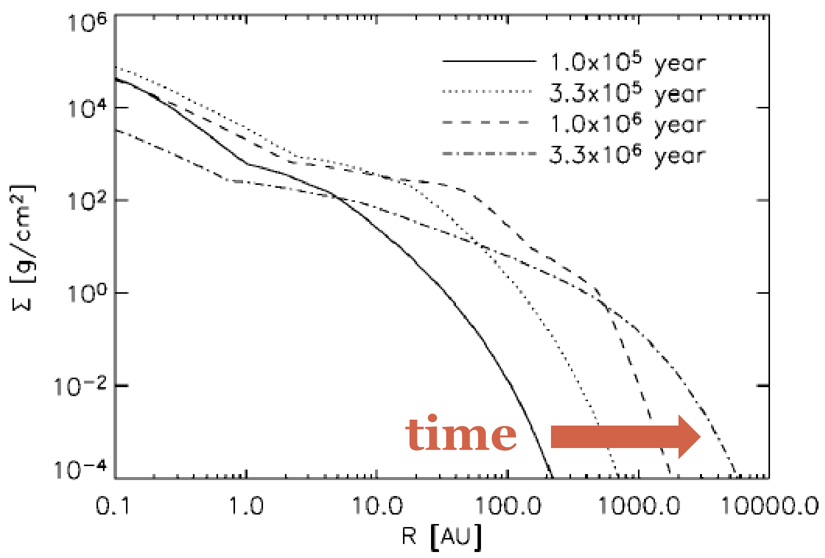
- Inside-out collapse with rotation
- Dust accreting in hot inner region is crystallized
- Disk spreads out to conserve angular momentum
- Crystalline material transported to colder areas

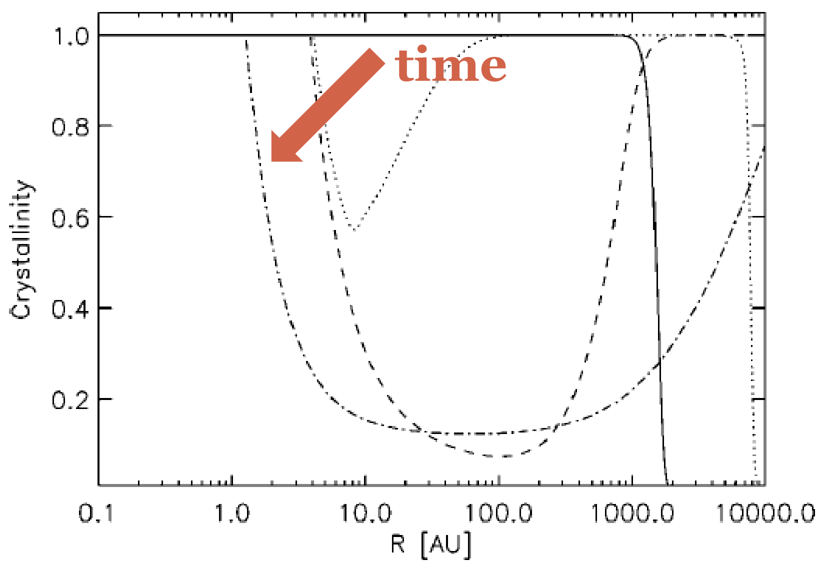


Dullemond, Apai & Walch (2006)

Crystallinity as function of time

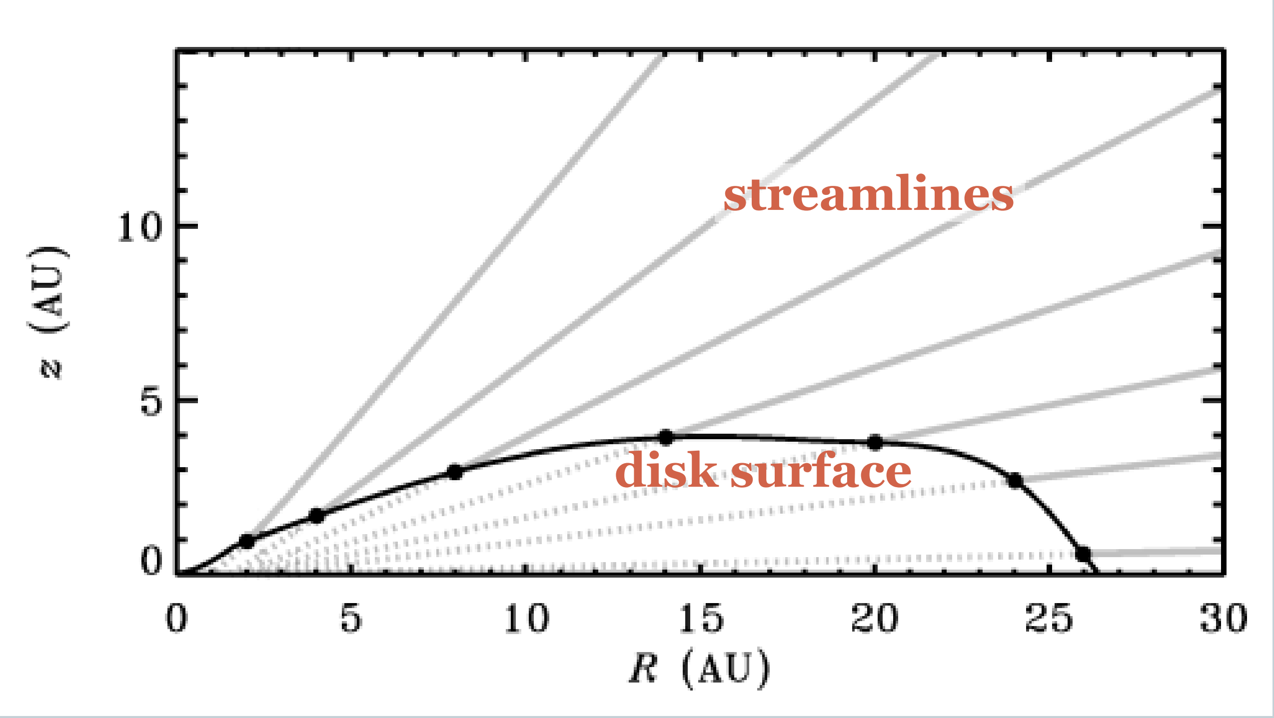
- Crystalline fraction decreases with time
  - Tentative age-crystallinity anti-correlation observed by van Boekel et al. (2005) and Apai et al. (2005)





- Problem: model overpredicts crystalline fractions

From one to two dimensions

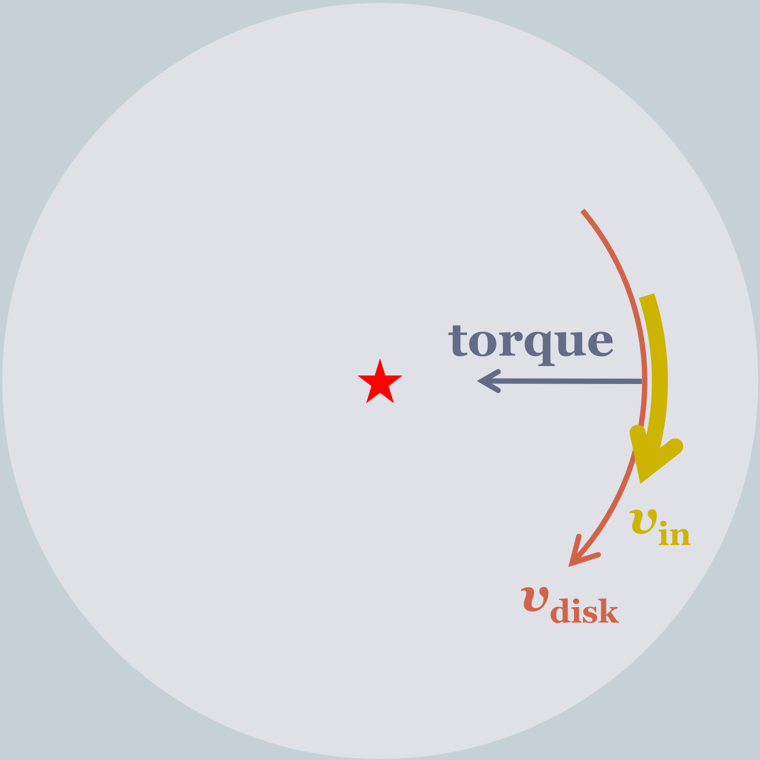


- DAW06 treated disk as completely flat
- Include vertical structure: accretion occurs further out

Visser & Dullemond (in prep.)

A problem: sub-Keplerian infall

- Disk rotates with Keplerian velocity
- Infalling material has sub-Keplerian velocity
- Velocity difference results in inward torque
- Hueso & Guillot (2005): place infalling material at Keplerian radius
- We: adjust radial velocity of the disk



$v_{in} < v_{disk} = v_{Kep}$

Two radial velocity corrections

Visser et al. (2009):

$$-\eta_r\sqrt{(GM_*/R)}$$

- Ad-hoc method
- Computationally easy
- Angular momentum not conserved
- Biggest effect at small *R*

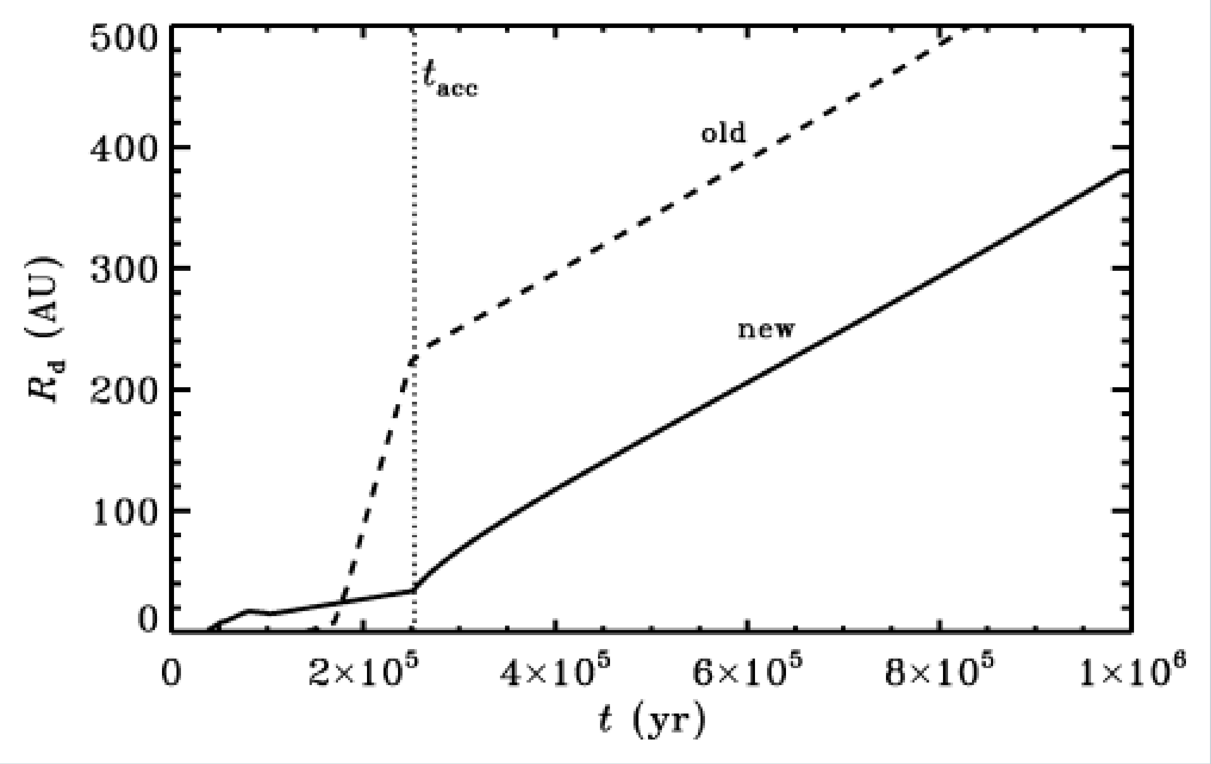
New method:

$$-2RS(1-\acute{\omega})/\Sigma$$

$$\acute{\omega} = \Omega_{\rm in}/\Omega_{\rm K}$$

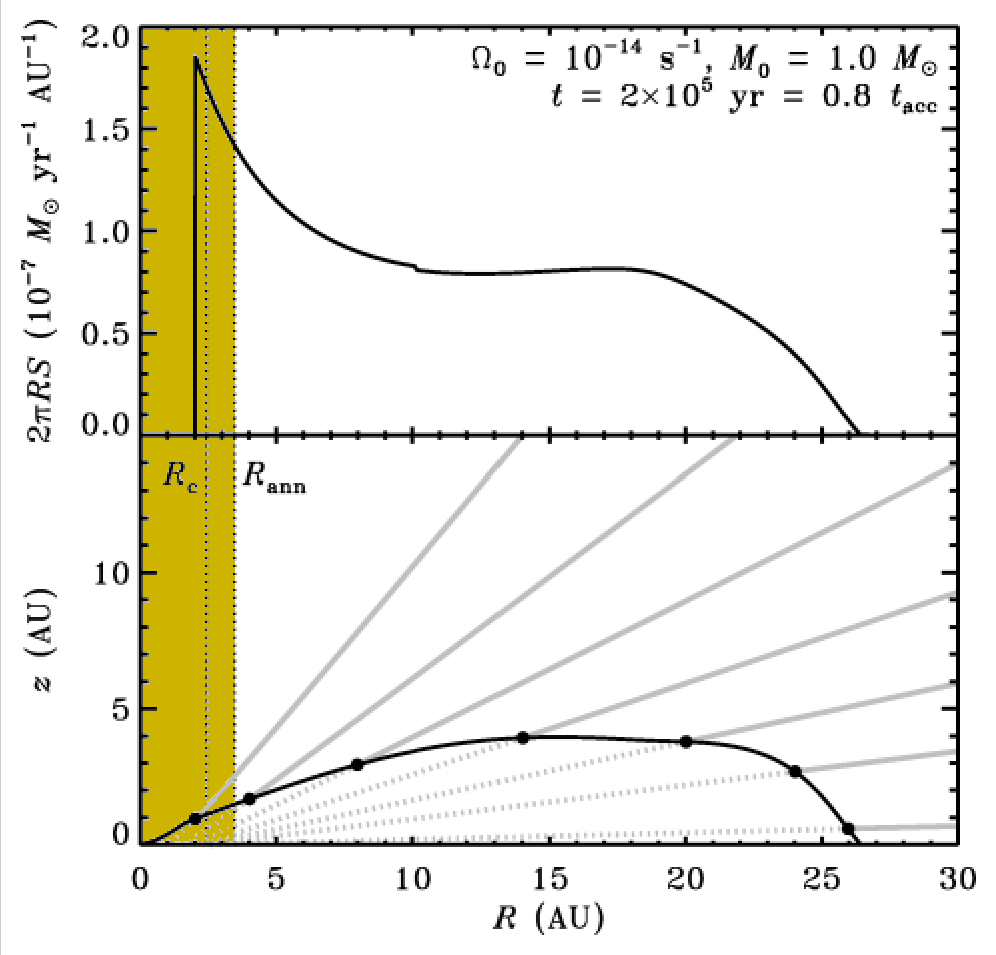
- Exact solution
- Hard to get stable results
- Angular momentum is conserved
- Biggest effect at large *R*

Disk mass and size



- Mass nearly equal between old and new method
- Outer radius smaller with new method

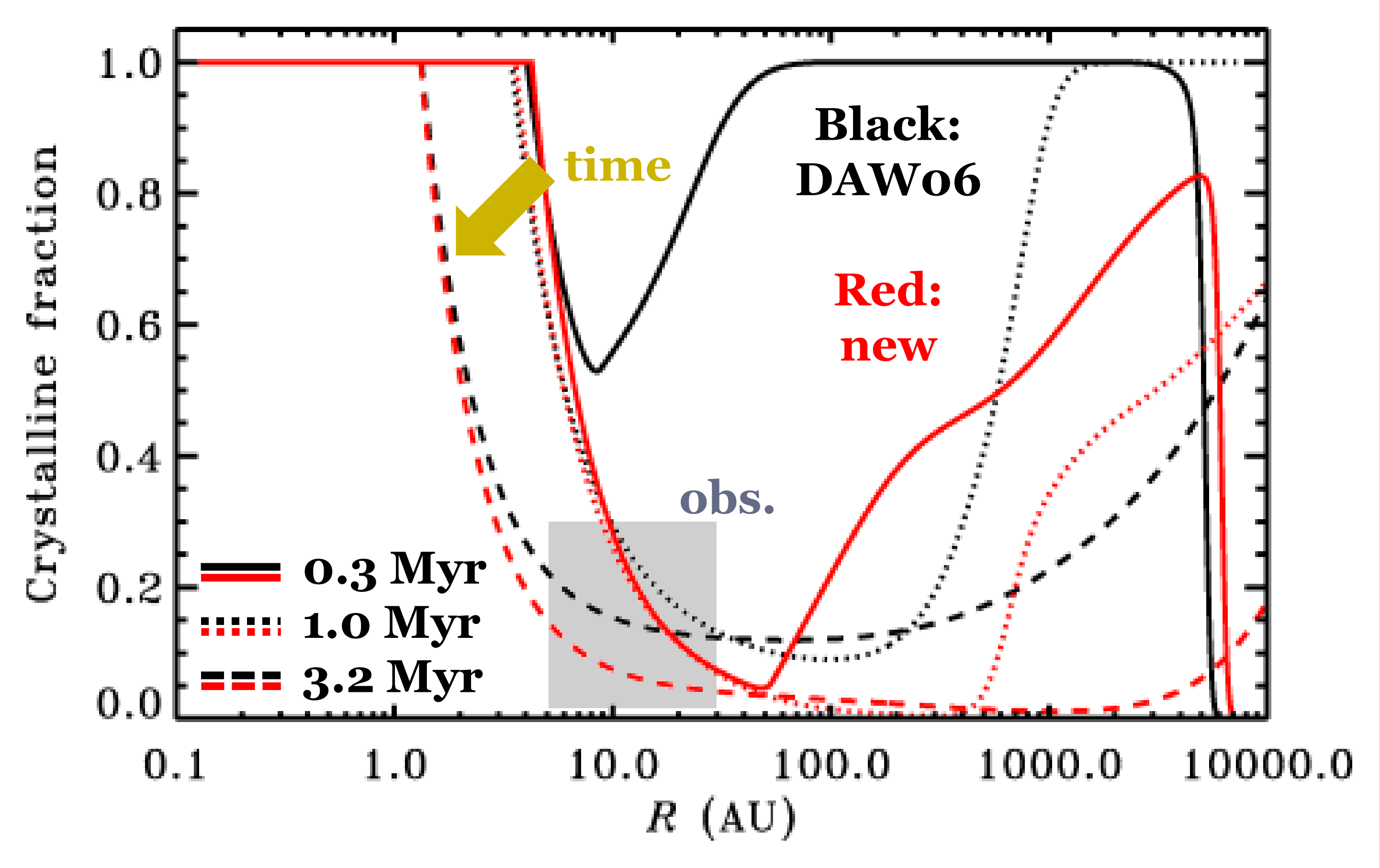
Streamlines revisited



- Crystallization occurs inside of R_{ann}
- Fraction of infalling material crystallized at t = 2 Myr:
  - DAW06: 100%
  - New method: 12%

Visser & Dullemond (in prep.)

New crystallinity results



New results in better agreement with observed range!

Visser & Dullemond (in prep.)

Caveats

- Infalling material interacts first with disk surface
  - Radial velocity not independent of height
  - Correction on radial velocity probably overestimated
  - Disk radius probably underestimated
  - Hydrodynamical simulations confirm far-out accretion
- Grain size distribution
  - Grain growth lowers disk temperature
- Accretion shock
  - Not strong enough to make a difference

Conclusions

- Vertical structure of the disk is essential to properly understand accretion from the envelope
- Our model quantitatively reproduces the range of observed crystalline silicate fractions