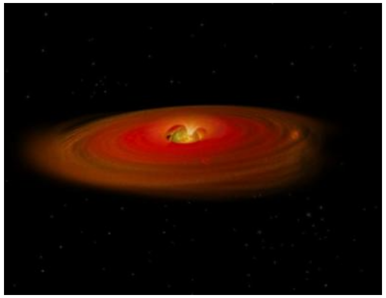
Chemical evolution from cores to disks



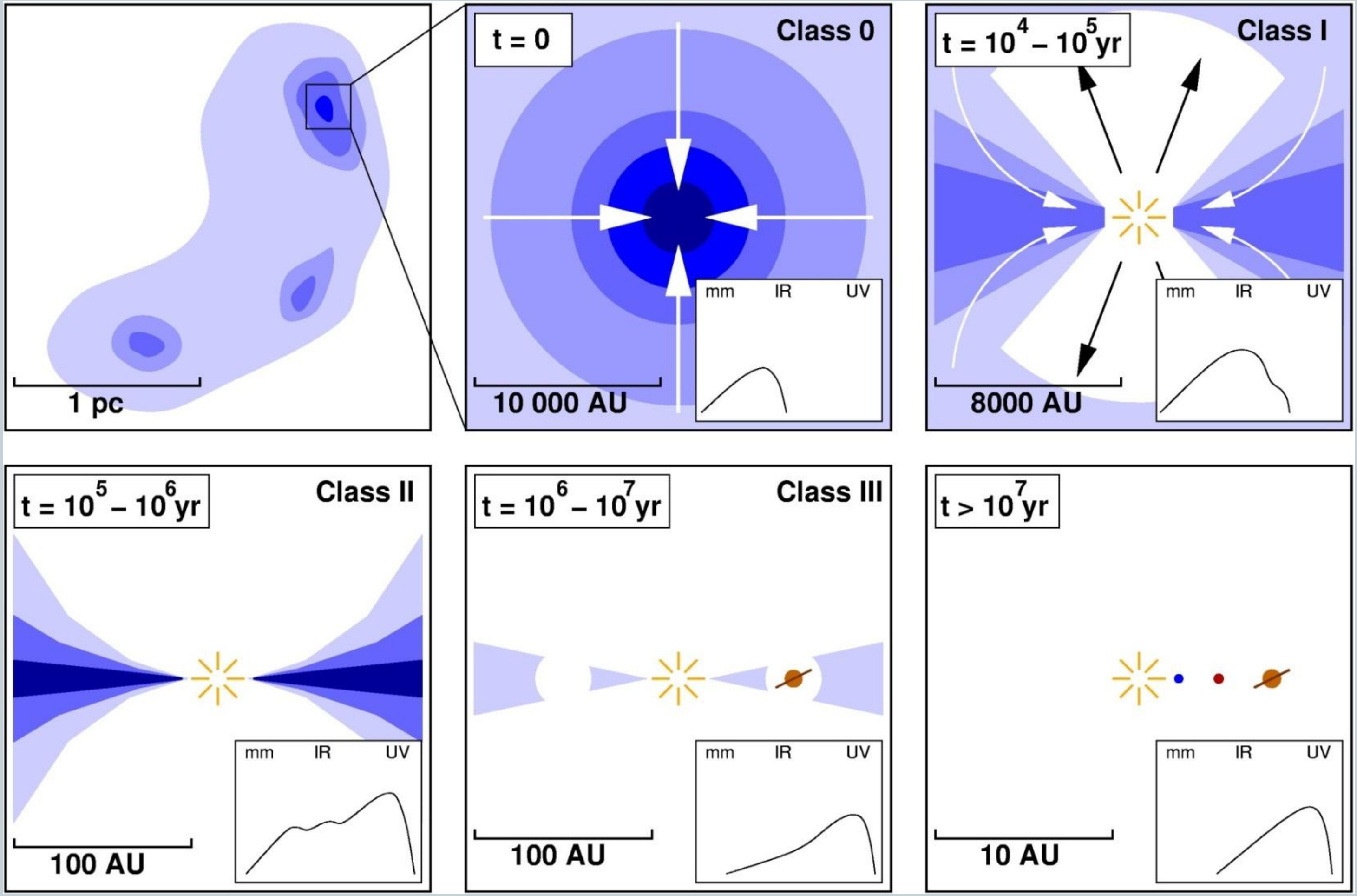
Ruud Visser
Leiden Observatory

Ewine van Dishoeck, Steve Doty, Kees Dullemond , Jes Jørgensen, Christian Brinch, Michiel Hogerheijde, John Black

November 16, 2009

Sterrewacht Leiden

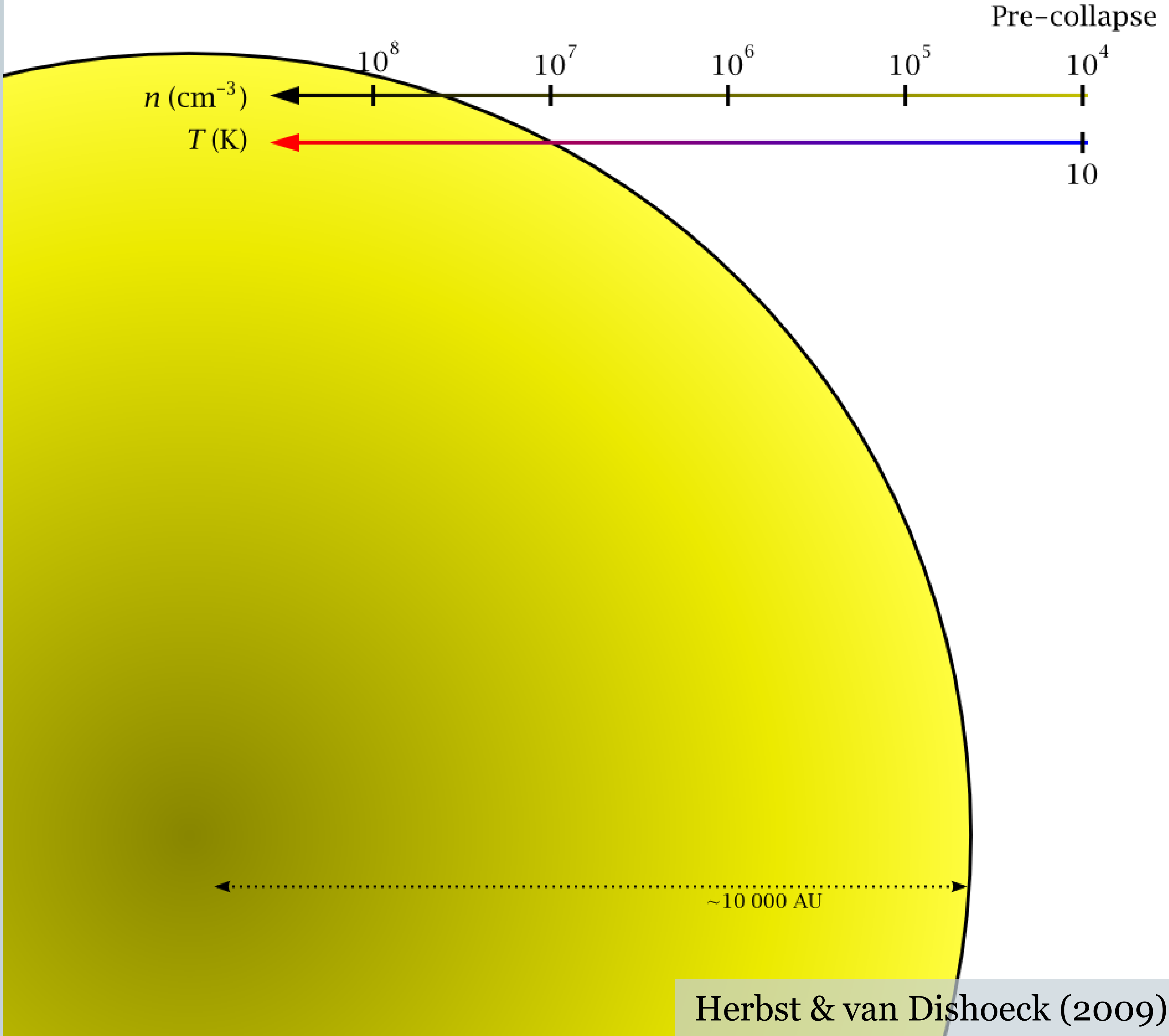
Low-mass star formation



Jonkheid et al. 2006

Low-mass star formation

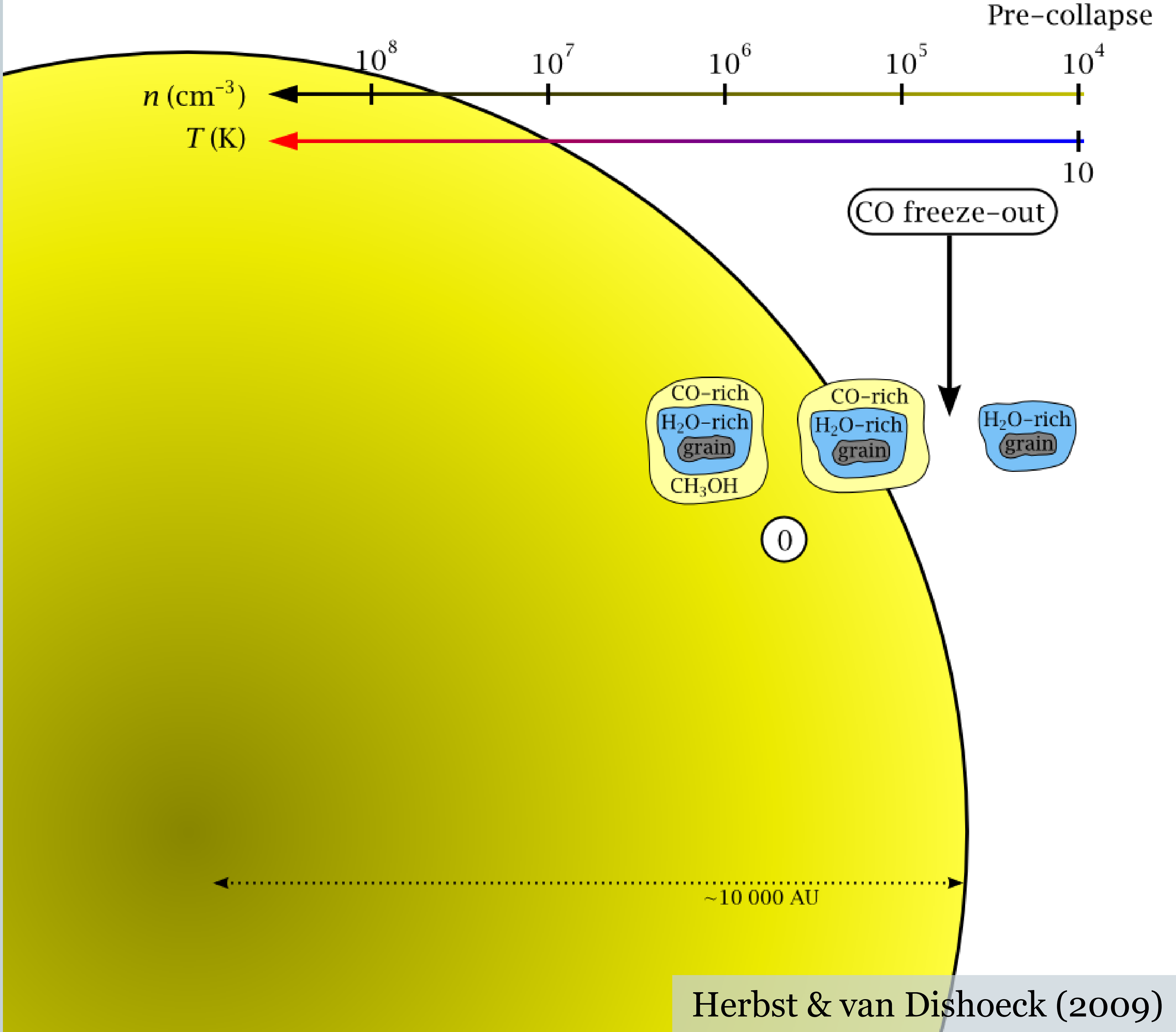
Evolution of gas and dust



Herbst & van Dishoeck (2009)

Low-mass star formation

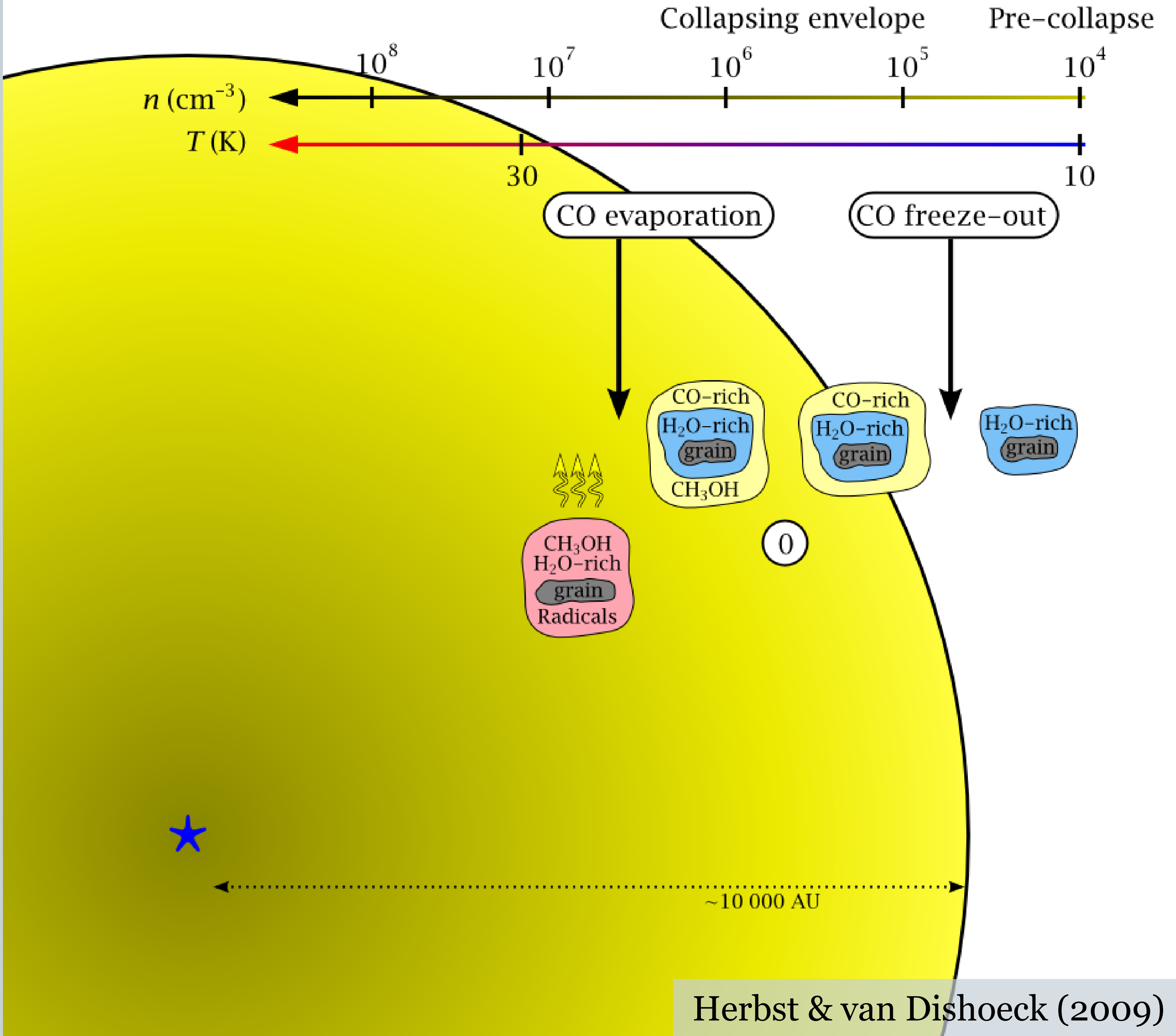
Evolution of gas and dust



Herbst & van Dishoeck (2009)

Low-mass star formation

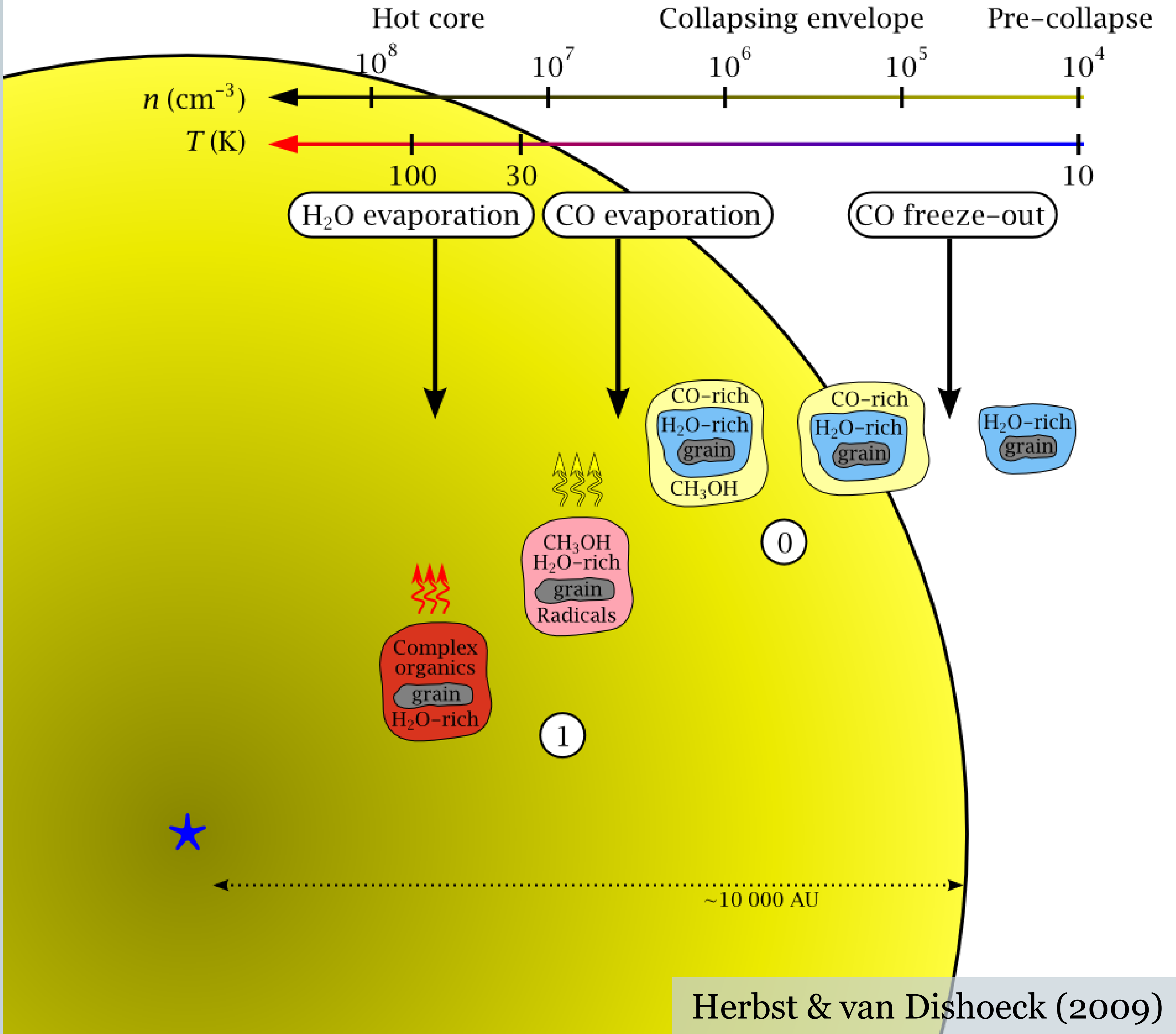
Evolution of gas and dust



Herbst & van Dishoeck (2009)

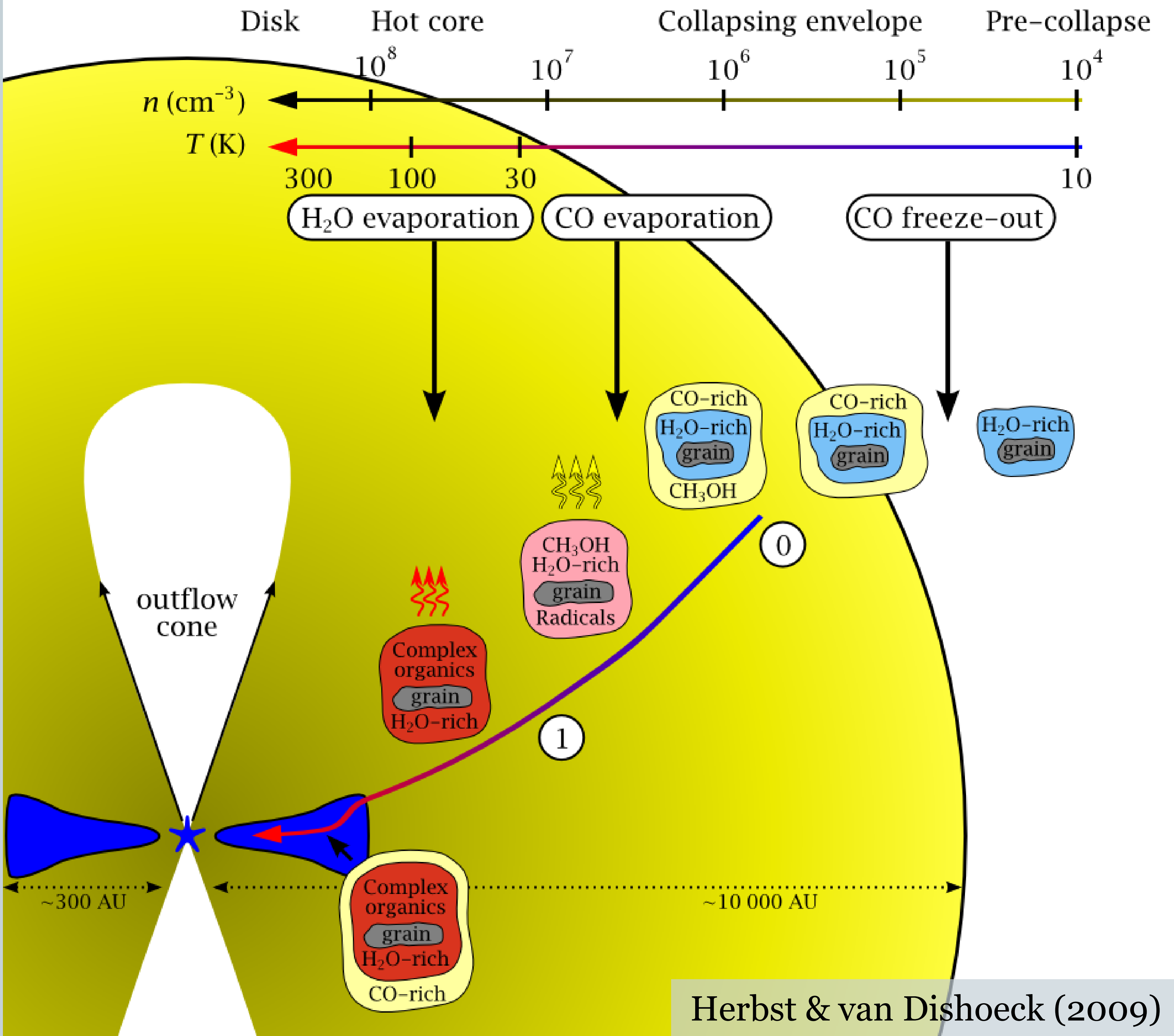
Low-mass star formation

Evolution of gas and dust



Herbst & van Dishoeck (2009)

Low-mass star formation

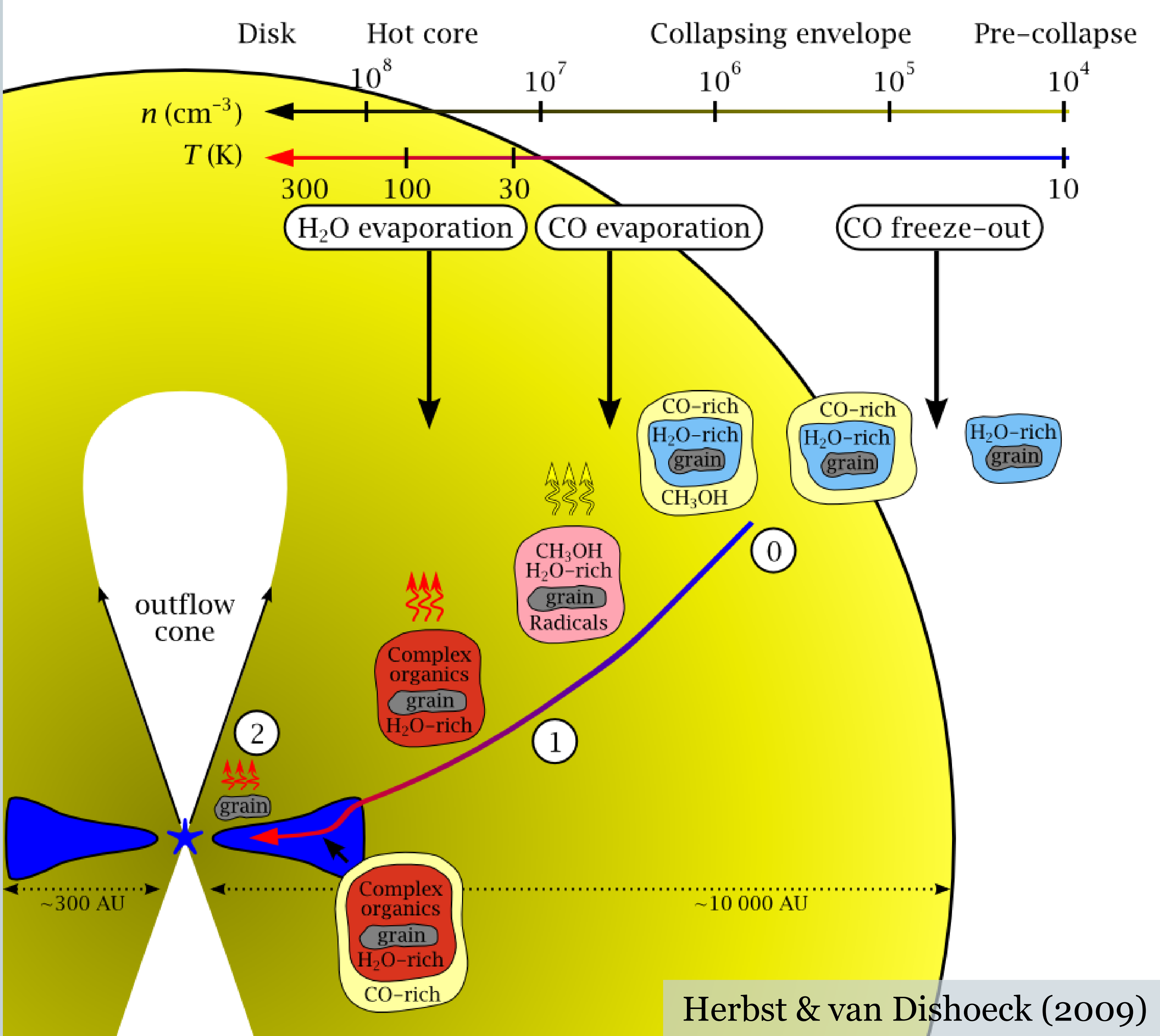


Herbst & van Dishoeck (2009)

Evolution of gas and dust

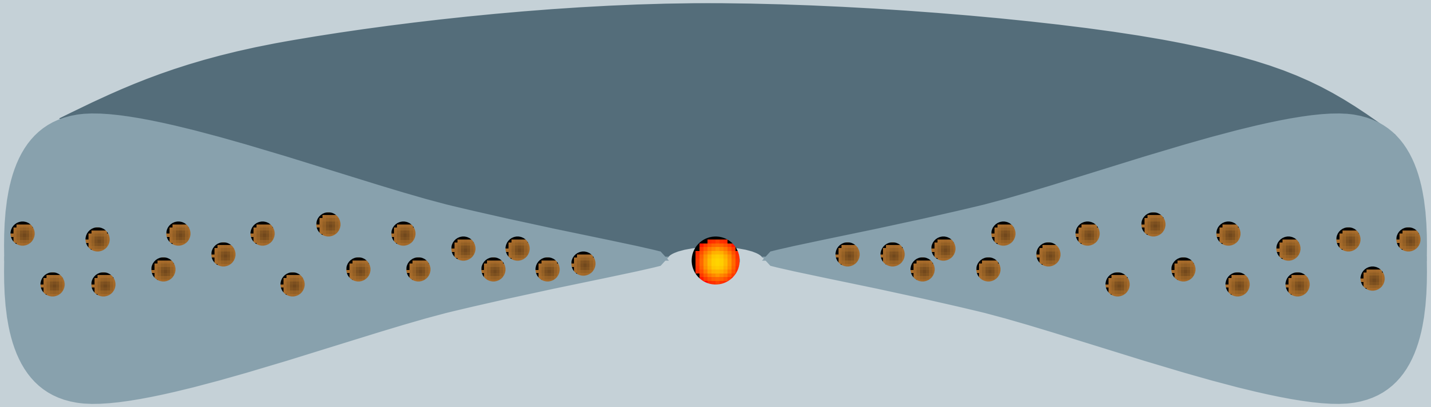
Low-mass star formation

Evolution of gas and dust



Herbst & van Dishoeck (2009)

T Tauri star and disk



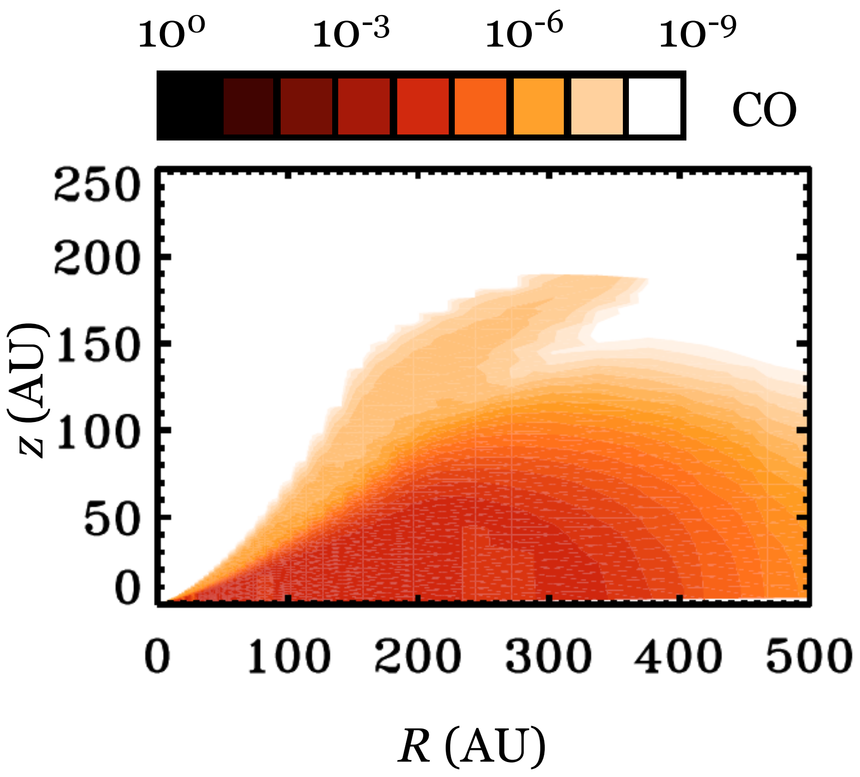
Star

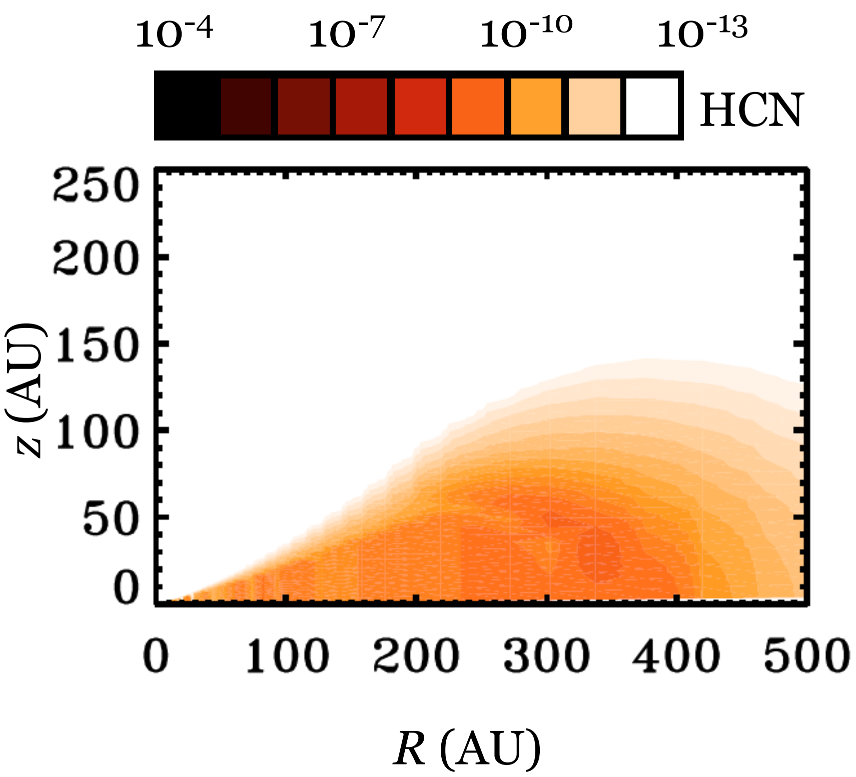
- Low-mass: $< 2\ M_\odot$
- Age: few Myr

Disk

- Lifetime: ~10 Myr
- Size: few 100 AU
- Mass: ~0.001–0.1 $M_\odot$
- Grain growth

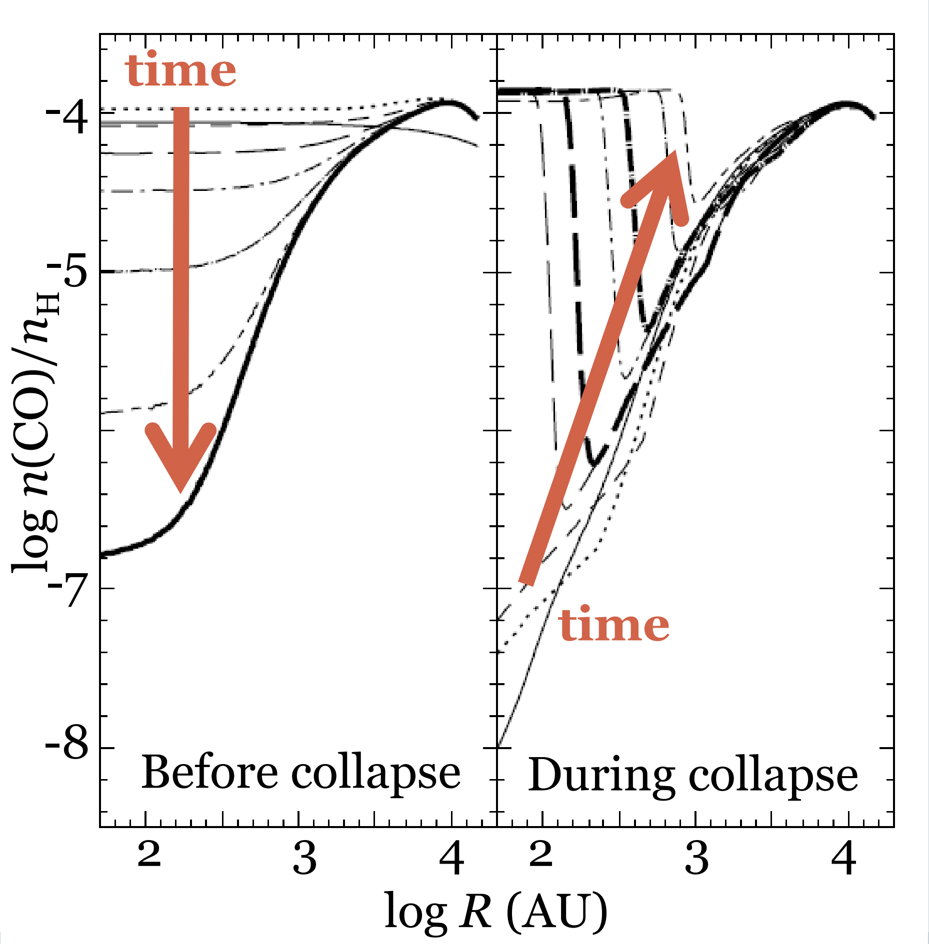
Chemistry in static disk models





Jonkheid et al. (2007)

Chemical evolution in 1D



- Freeze-out towards center before onset of collapse
- Warm-up during collapse leads to evaporation
- Abundances of many molecules controlled by CO gas abundance

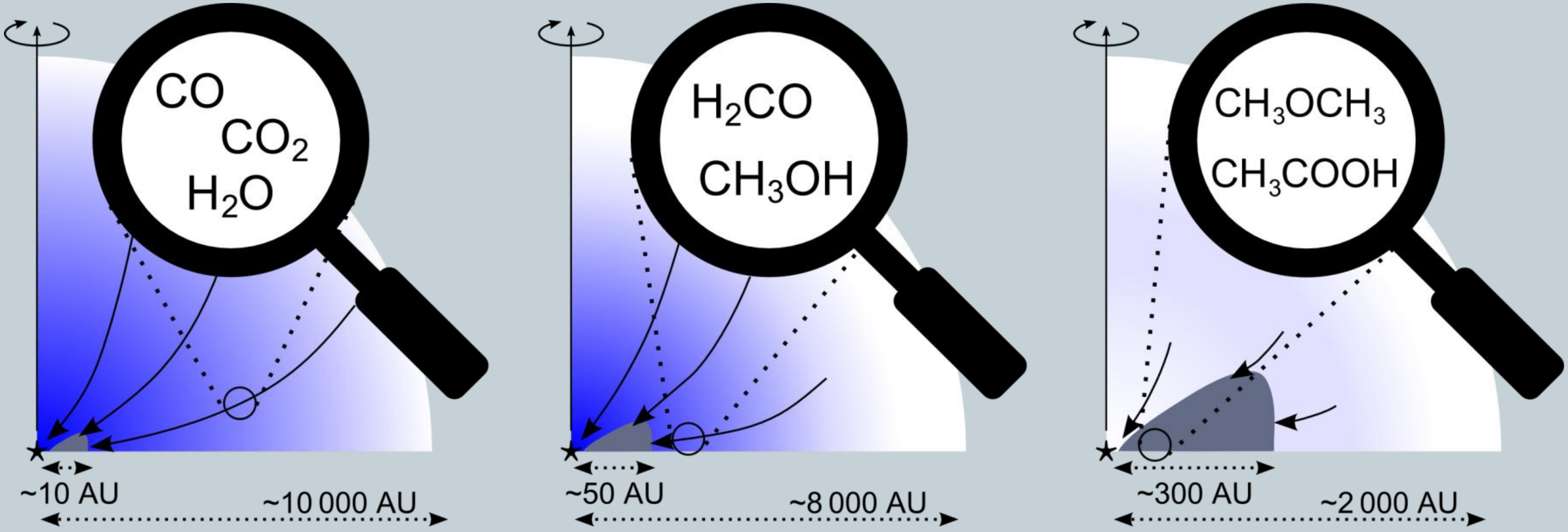
Lee, Bergin & Evans (2004)

Open questions

- When is the disk first formed?
- How do its size and mass evolve?
- How does material flow onto it from the envelope?
    - Onto hot inner parts or cold outer parts?
- How does the gas evolve?
    - Temperature, chemical composition, …
- How does the dust evolve?
    - Size, amorphous or crystalline, ice mantle, …
- What fraction of cometary ices is truly pristine?

Main features of this study

- One model from pre-stellar core to circumstellar disk
- Two-dimensional, axisymmetric
- Study chemical evolution
    - Composition of cometary and planetary building blocks
    - Chemistry affects physics: temperature, MRI, GI, …
    - Diagnostic tool



Analytical star formation model in 2D

- Fast to run, high resolution,
  easy to change initial conditions

  Cloud mass (M_o), rotation rate (Ω_o), sound speed (c_s), …
- Density & velocity: inside-out collapse

  Shu (1977), Terebey, Shu & Cassen (1984)
- Dust temperature (important!) from full radiative transfer

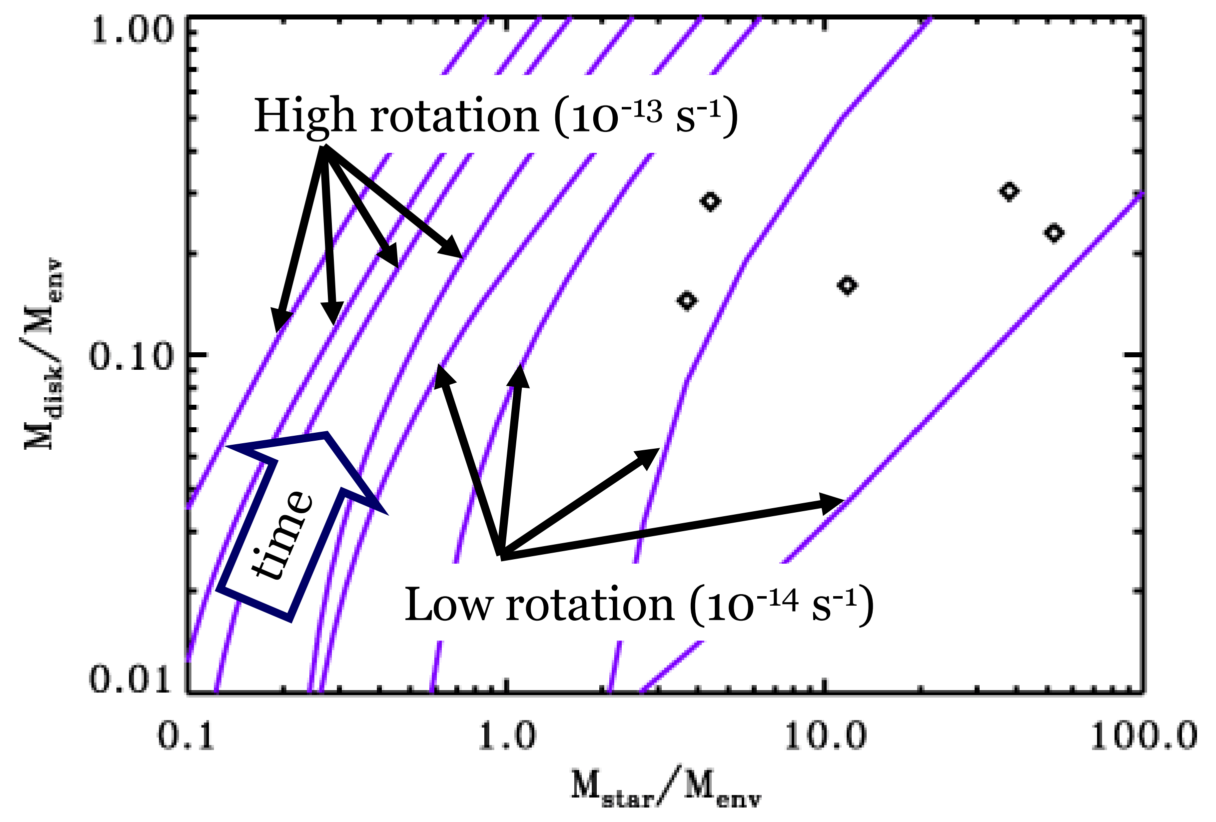
  RADMC: Dullemond & Dominik 2004
- Physics compare well with hydrodynamical models

  Yorke & Bodenheimer 1999, Brinch et al. 2008a,b
- Density profiles compare well with observations

  Jørgensen et al. 2009

Visser et al. (2009), Visser & Dullemond (subm.), Visser et al. (in prep.)

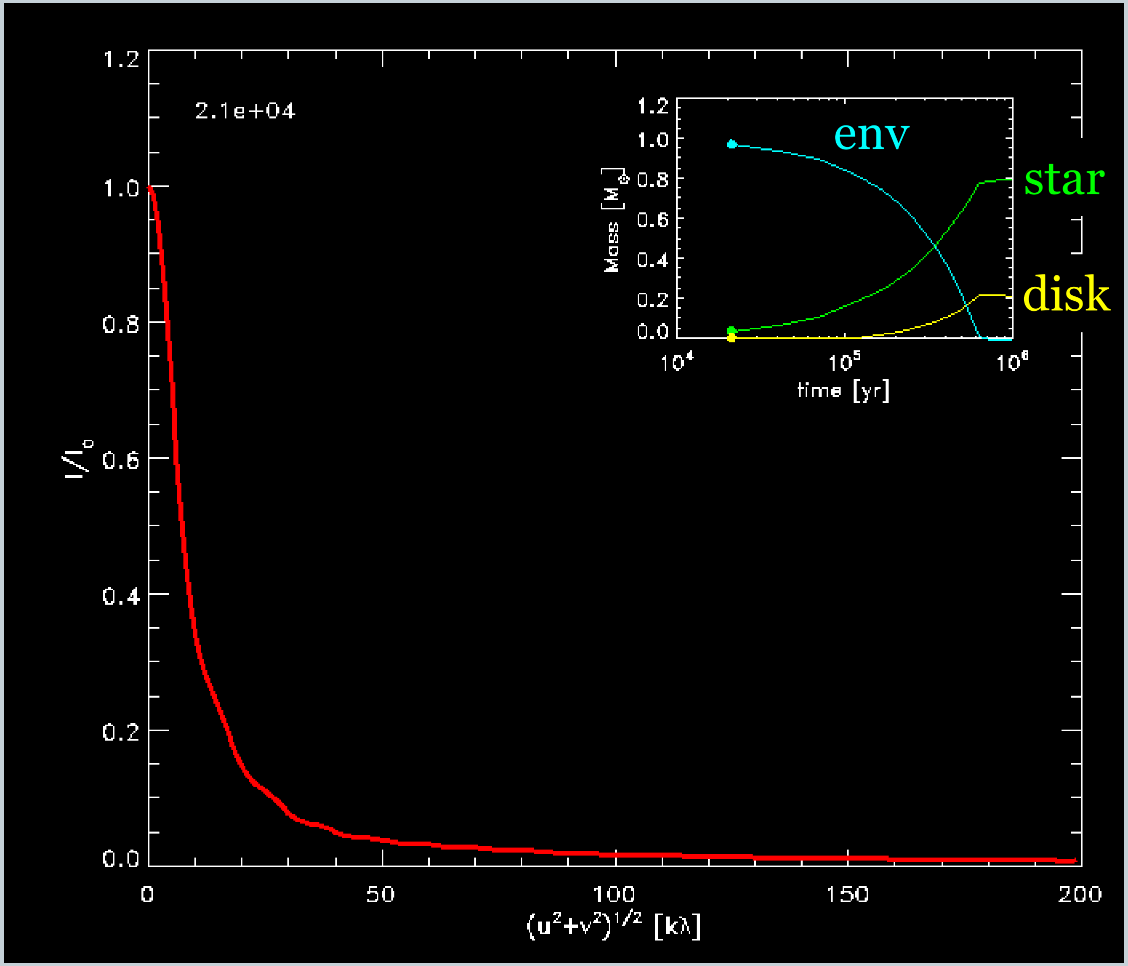
Model vs. observations: masses



- Lines: model with different initial conditions
- Points: SMA observations
- Model over-predicts disk mass

Jørgensen et al. 2009

Sub-mm model visibilities



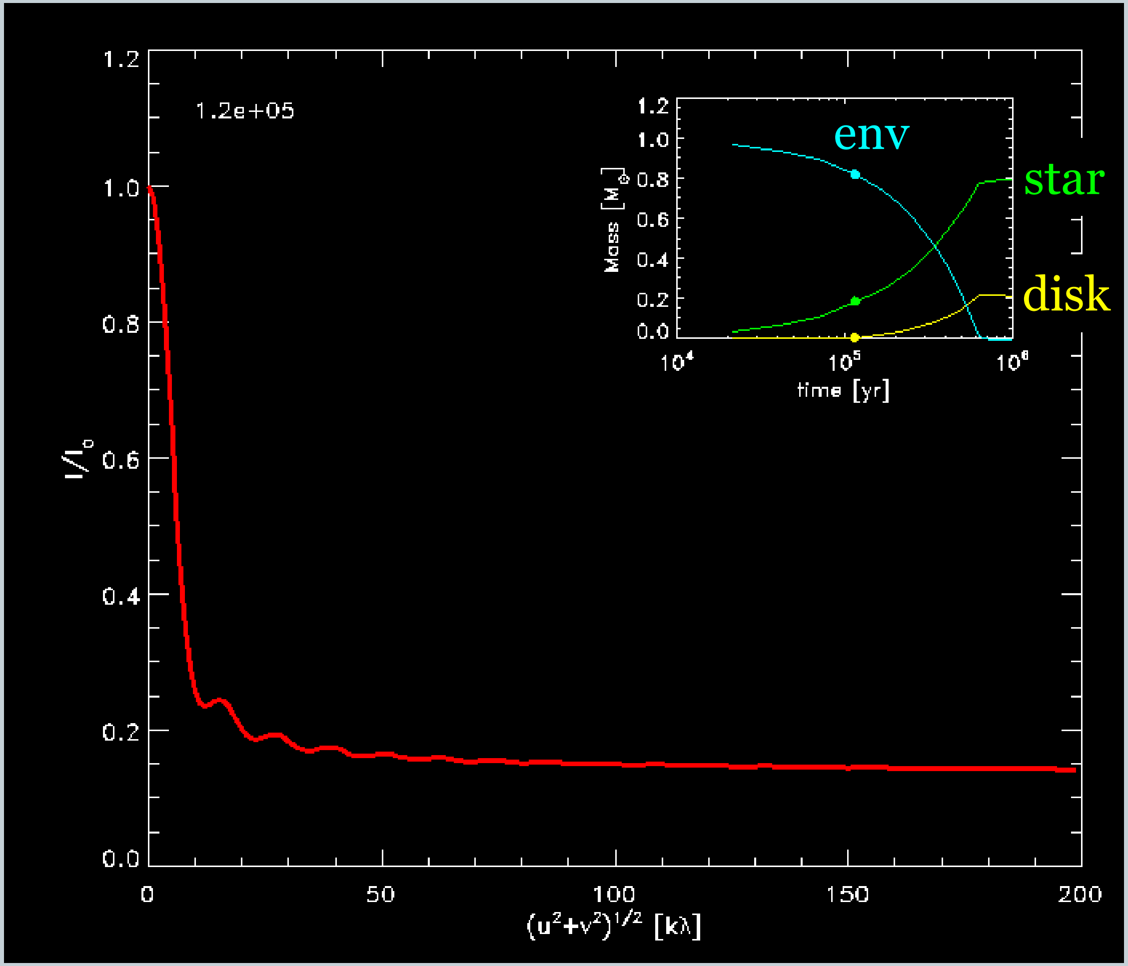
short baselines

=

large spatial scales

Jørgensen et al. 2009

Sub-mm model visibilities



short baselines

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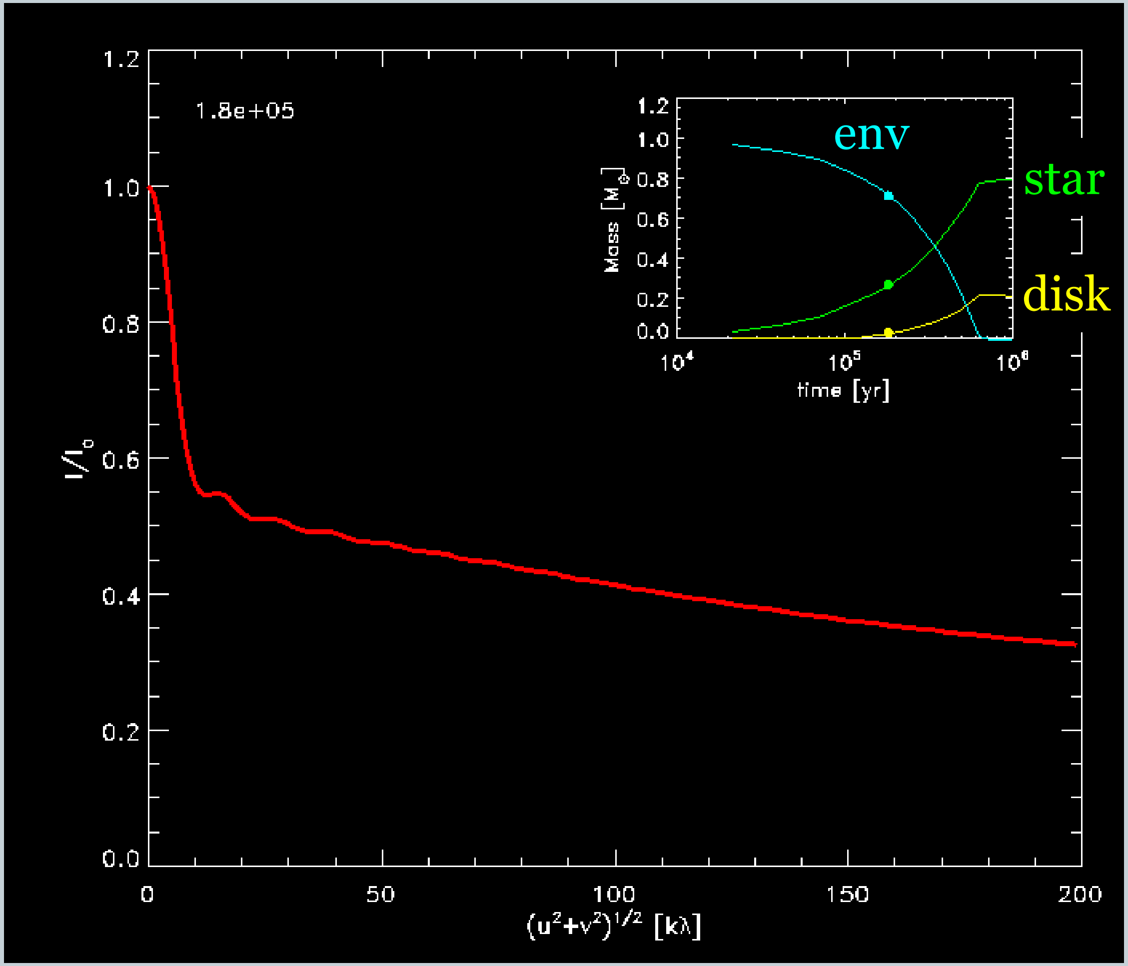
large spatial scales

Jørgensen et al. 2009

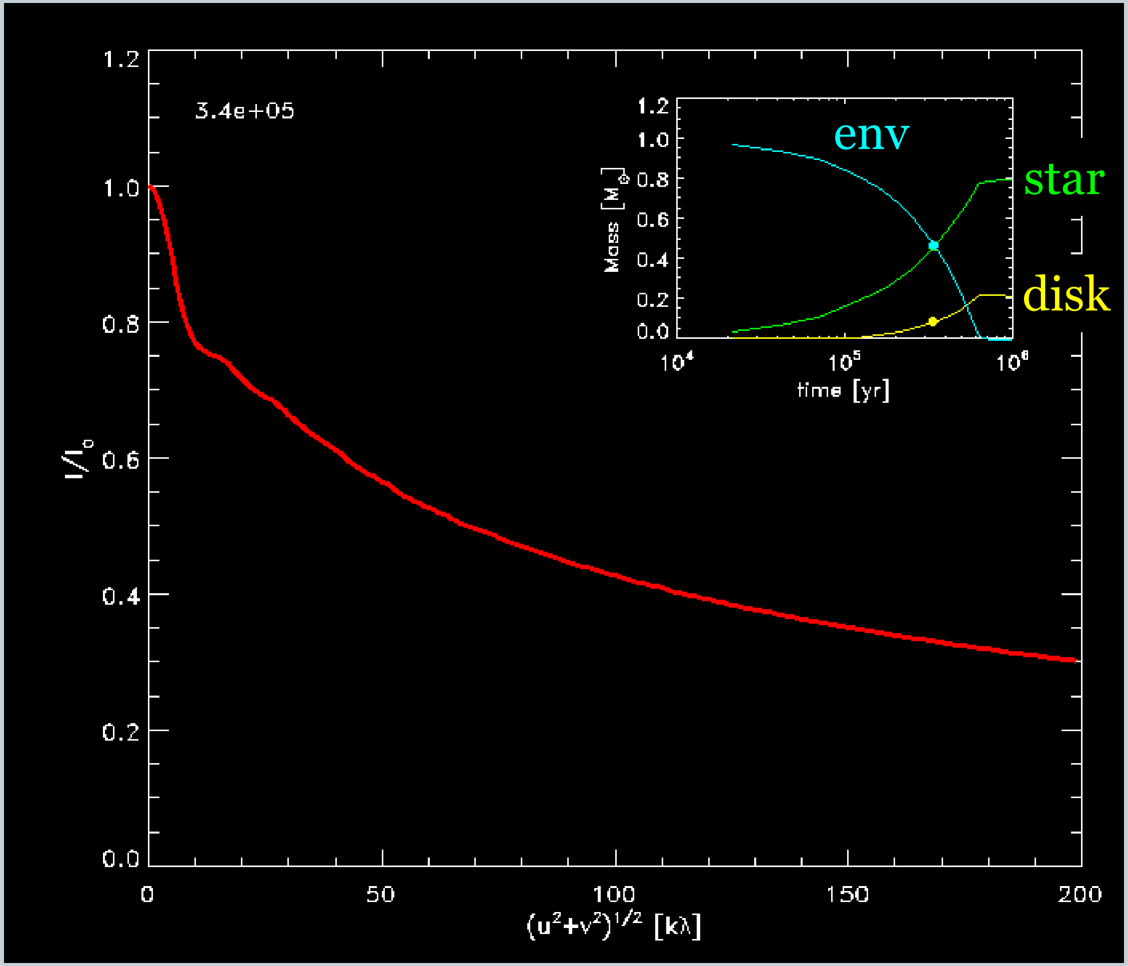
Sub-mm model visibilities



short baselines
=
large spatial
scales

Jørgensen et al. 2009

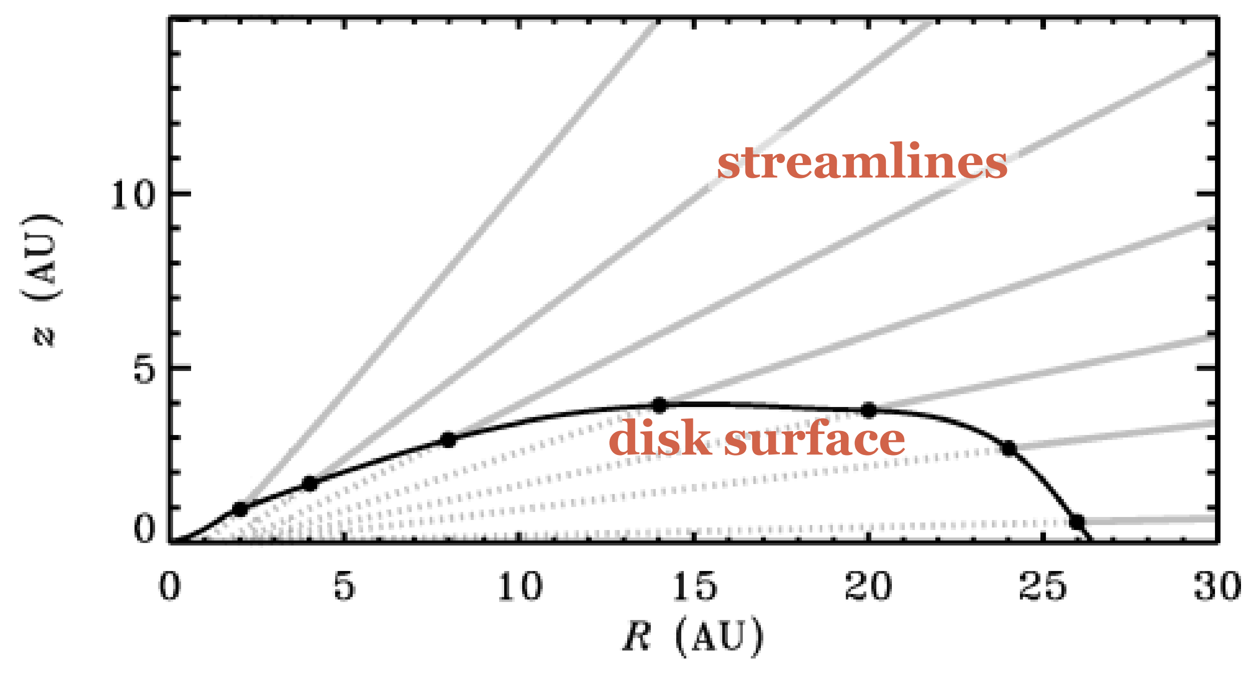
Sub-mm model visibilities



short baselines
=
large spatial
scales

Jørgensen et al. 2009

From one to two dimensions

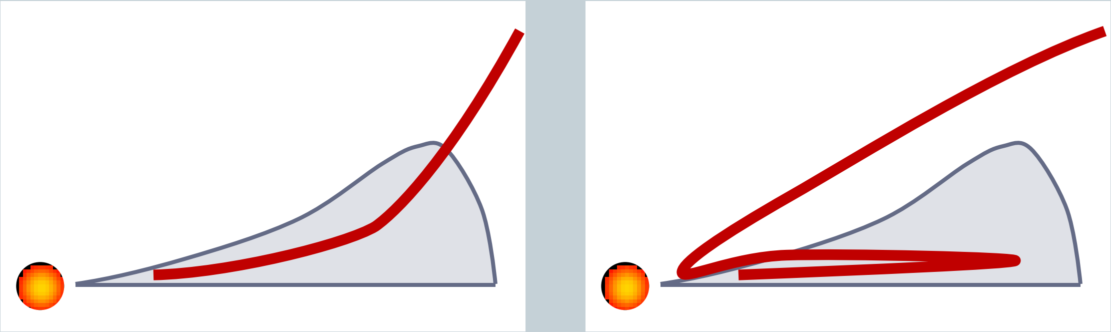


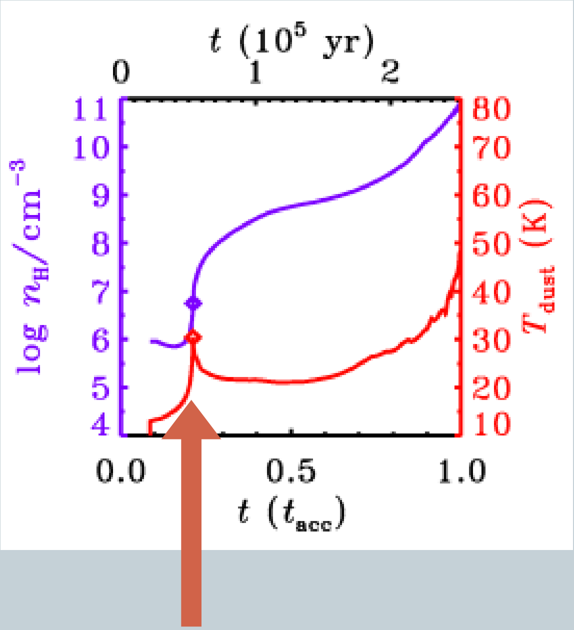
- Previous collapse models treated disk as completely flat
- Include vertical structure: accretion occurs further out
- Accretion shock is weak, except in very inner part

Visser & Dullemond (subm.)

Infall trajectories

- Need to solve chemistry dynamically: compute *n*, *T* along many trajectories





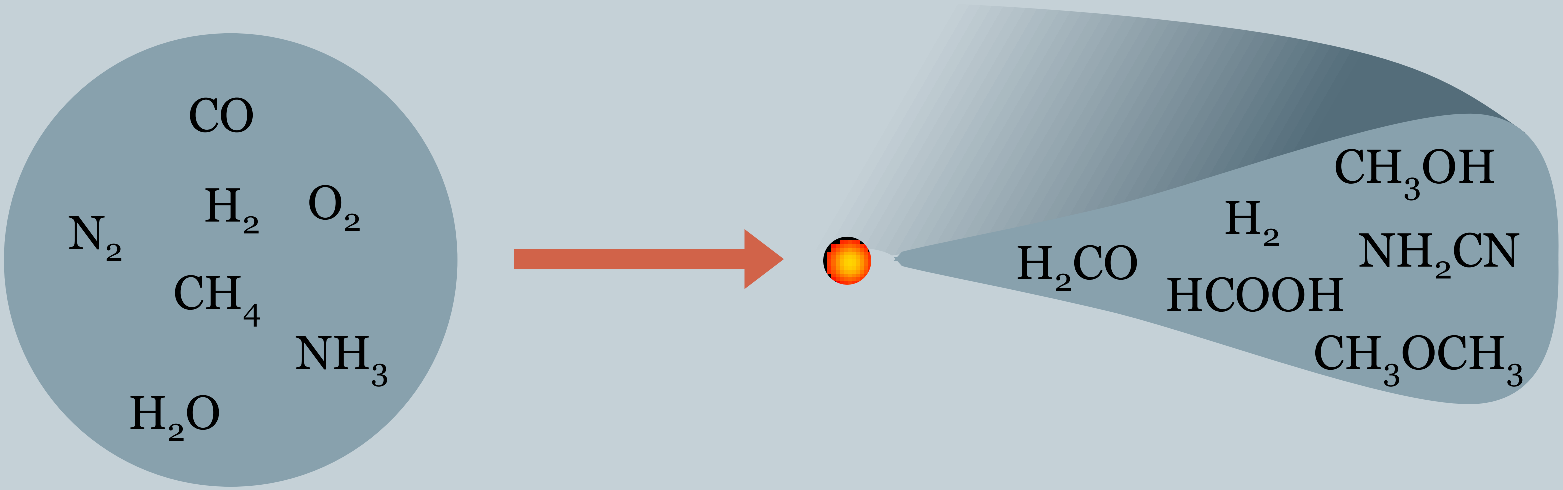
entering disk

- Different trajectory shapes
- Jump in *n*, *T* upon entering disk

Visser et al. (2009) , Visser et al. (in prep.)

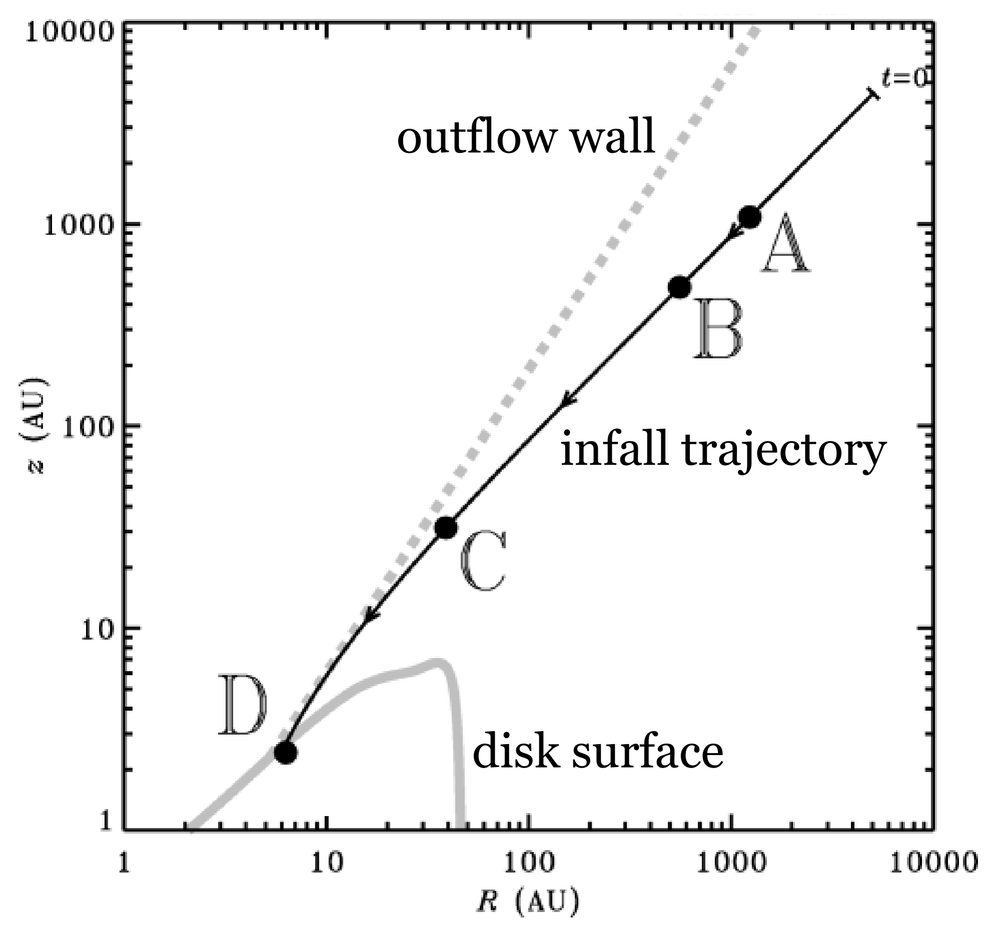
Full chemical model

- ~450 molecules connected by ~4500 reactions
- Reaction rates depend on n_H, T, F_{UV}, A_V
- Start with simple composition
- Follow abundances along infall trajectories



Visser et al. (in prep.)

Chemical evolution along one trajectory



A: volatiles evaporate (e.g. CO, N_2)

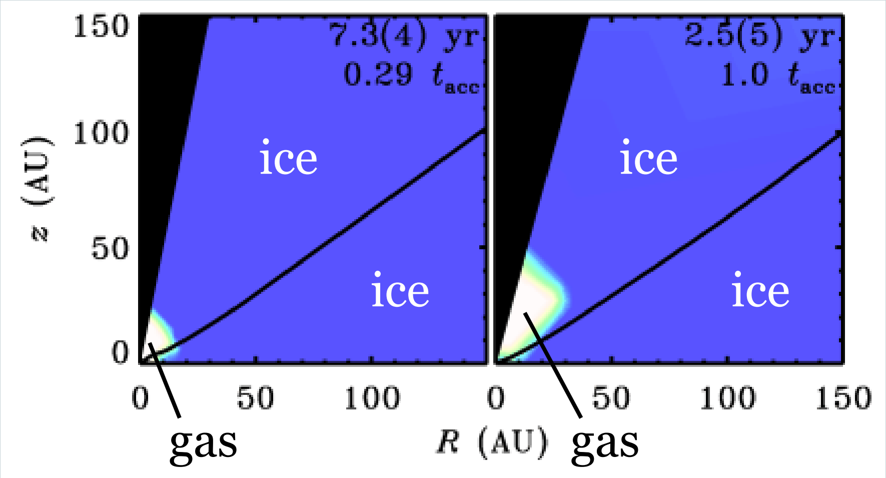
B: intermediates evaporate (e.g. CH_4, NO)

C: other ices evaporate (e.g. H_2O, NH_3, CH_3OH) photodissociation of many species

D: some species reformed

Visser et al. (in prep.)

Gas and ice: H_2O



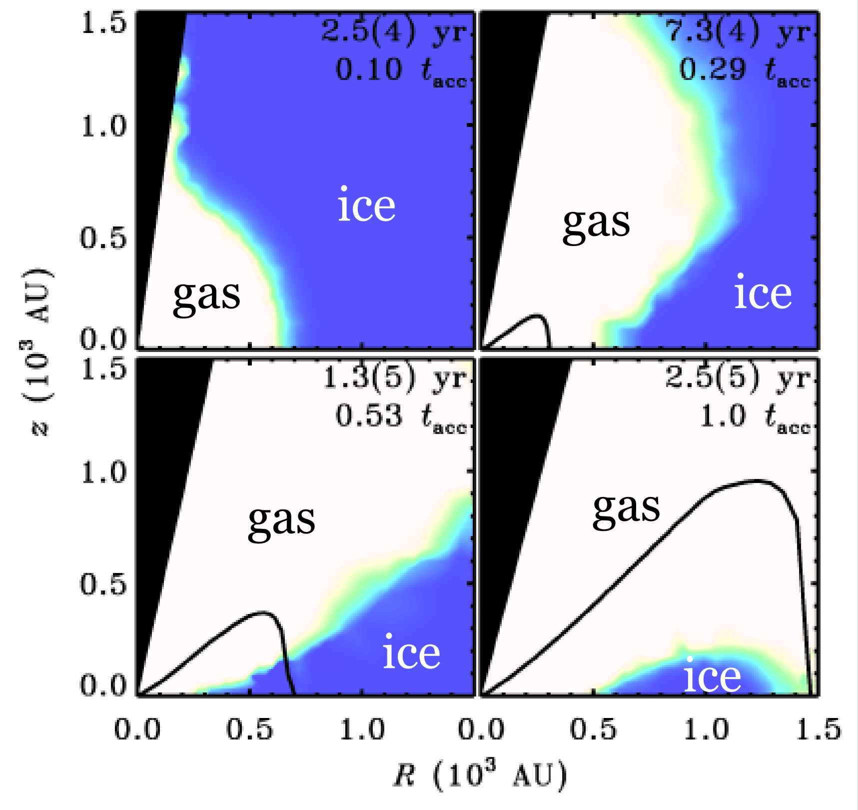
blue: all ice
white: all gas
black: outflow
black curve: disk surface

M_0 = 1.0 M_{sun}
Ω_0 = 10^{-13} s^{-1}
c_s = 0.26 km s^{-1}

- H_2O remains solid except inner ~5 AU
- H_2O in comet-forming zone, depending on parameters:
  - *either* unprocessed
  - *or* evaporated and re-frozen

Visser et al. (2009)

Gas and ice: CO



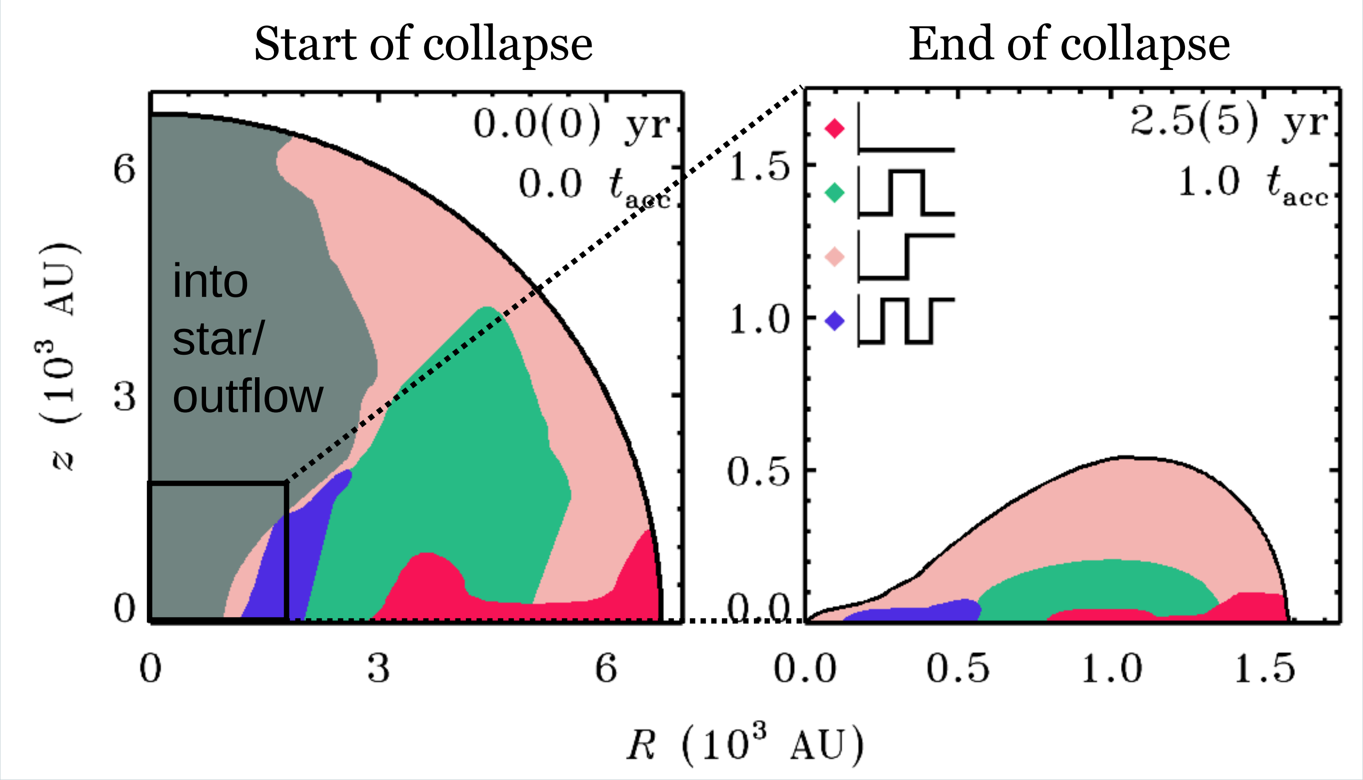
blue: all ice
white: all gas
black: outflow
black curve: disk surface

$M_0 = 1.0\ M_{sun}$
$\Omega_0 = 10^{-13}\ s^{-1}$
$c_s = 0.26\ km\ s^{-1}$

CO desorbs during infall, re-adsorbs in disk below 18 K

Visser et al. (2009)

Chemical zones: CO gas/ice



M_0 = 1.0 M_{sun}
Ω_0 = 10^{-13} s^{-1}
c_s = 0.26 km s^{-1}

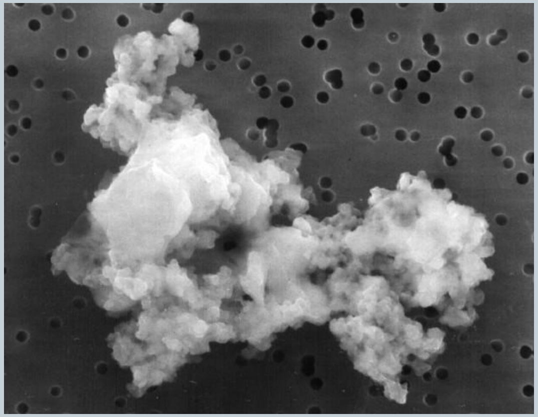
Red: CO remains adsorbed (pristine!)
Green: CO desorbs and re-adsorbs

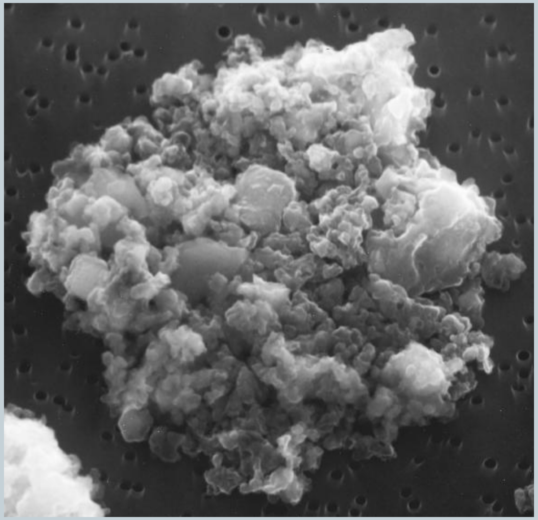
Pink: CO desorbs and remains desorbed
Blue: multiple desorption/adsorption

Visser et al. (2009)

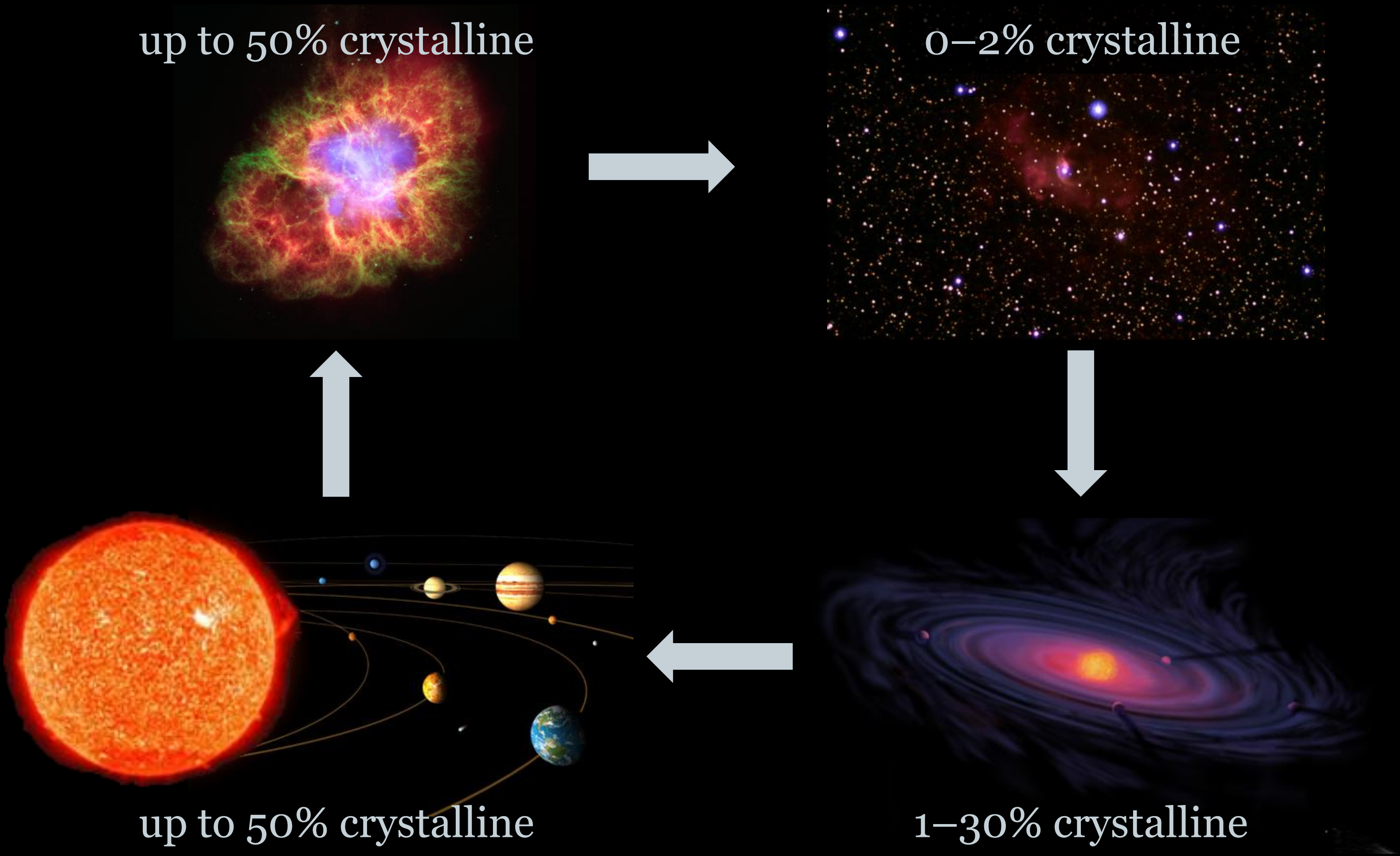
Another application of our model: dust

- Carbonaceous material
    - Graphite (small-scale limit: PAHs)
    - Hydrogenated amorphous carbon
    - Diamonds
- Silicates
    - Amorphous (olivine, pyroxene, …)
    - Crystalline (forsterite, enstatite, …)
- Ices
    - H_2O, CO, CO_2, CH_3OH, NH_3, …





From crystalline to amorphous and back



up to 50% crystalline

0–2% crystalline

1–30% crystalline

up to 50% crystalline

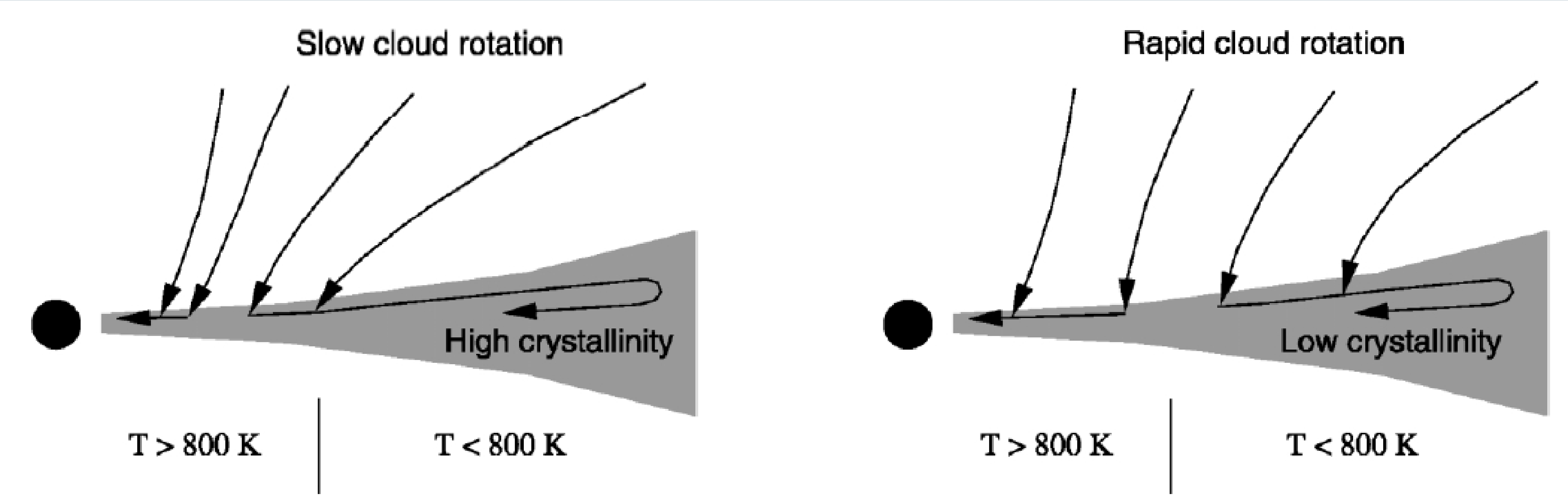
Origin of crystalline silicates in disks

- Crystallization by thermal annealing requires 800 K
- Crystalline silicates observed down to 150 K
- Bouwman et al. (2008): enstatite/forsterite ratio depends on radius

- Transport from hot inner parts to cold outer parts?
  - Nuth 1999, Bockelée-Morvan et al. 2002, Keller & Gail 2004
- Local heating by shocks?
  - Harker & Desch 2002, Desch et al. 2005

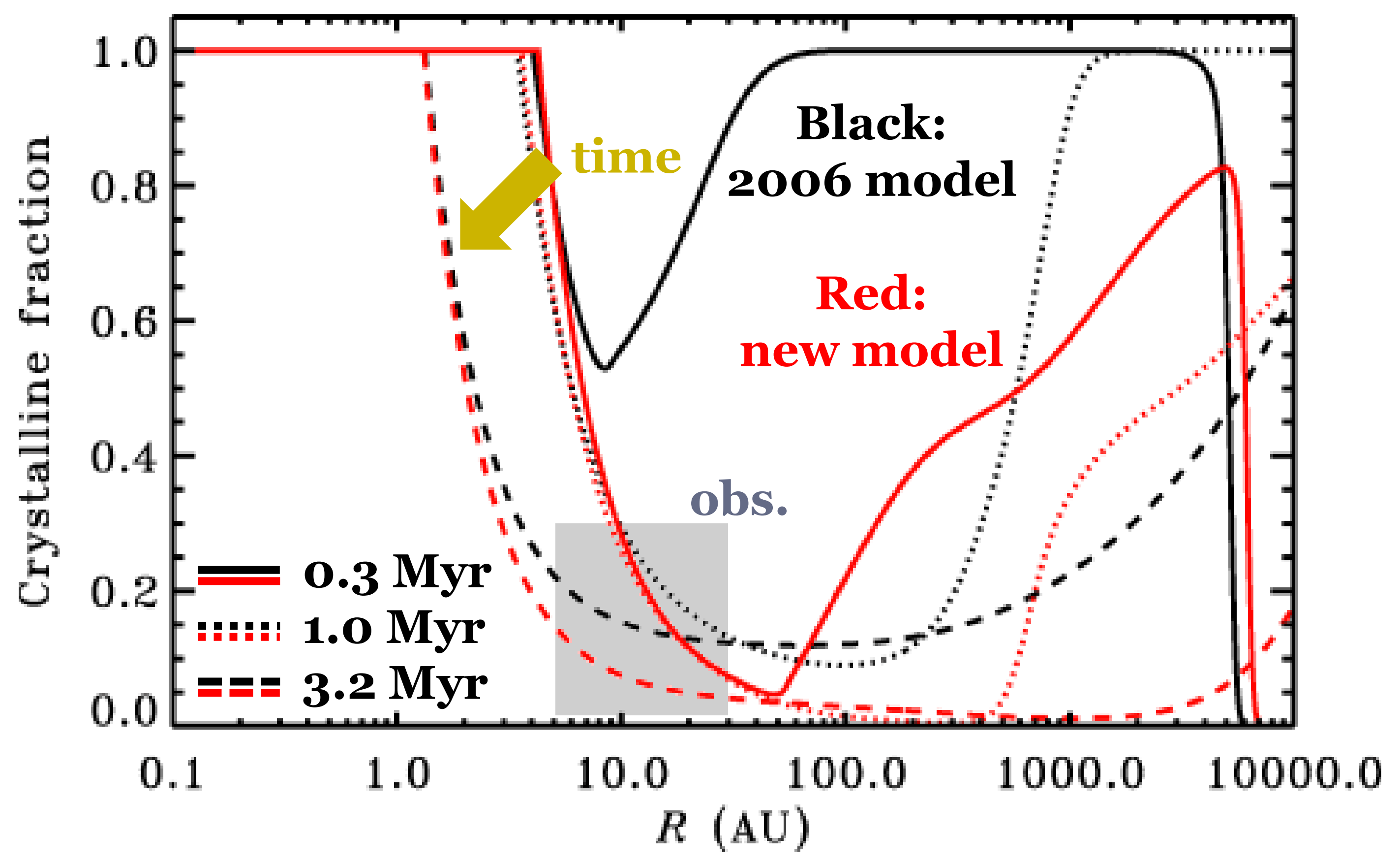
Disk evolution model

- 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), Visser & Dullemond (subm.)

Crystalline fractions



Model results in good agreement with observed range!

Visser & Dullemond (subm.)

Implications for comets

Observations

- Silicate dust
  - Partially crystalline
  - Partially amorphous
- Chemical composition
  - Generally similar to ISM
  - Individual differences

Model

- Silicate dust
  - Partially crystalline
  - Partially amorphous
- Chemical composition
  - Outer disk unprocessed
  - Inner disk processed

Cometary material is of mixed origins

Caveats

- Gas temperature
  - Gas-phase production of water
  - Increase inner-disk scale height
- Shape of stellar spectrum
  - Allow photodissociation of H_2, CO, N_2
- Trapping of volatiles in water ice
  - Increase ice abundances of CO, N_2, …
- Mixing
  - Chemical zones in disk more diffuse

Conclusions

- First model to follow chemistry from pre-stellar cores to circumstellar disks in 2D
- Masses and densities compares well with hydro simulations and SMA observations
- Great tool for chemical evolution
- Disk is divided into zones with different chemical histories
    - Outer part pristine, inner part processed
- Thermal annealing followed by radial transport is responsible for at least part of observed silicates

Future work

- Compute line profiles
  - Compare with observations by SMA, JCMT, IRAM 30m, …
  - Analyse water data from Herschel (WISH key program)
  - Make predictions for ALMA
- Add grain-surface chemistry
  - Formation of complex organics
- Add isotope-selective CO photodissociation
  - New model: Visser, van Dishoeck & Black (2009)
- Quantify effects of mixing on chemistry
  - Better match with cometary abundances?