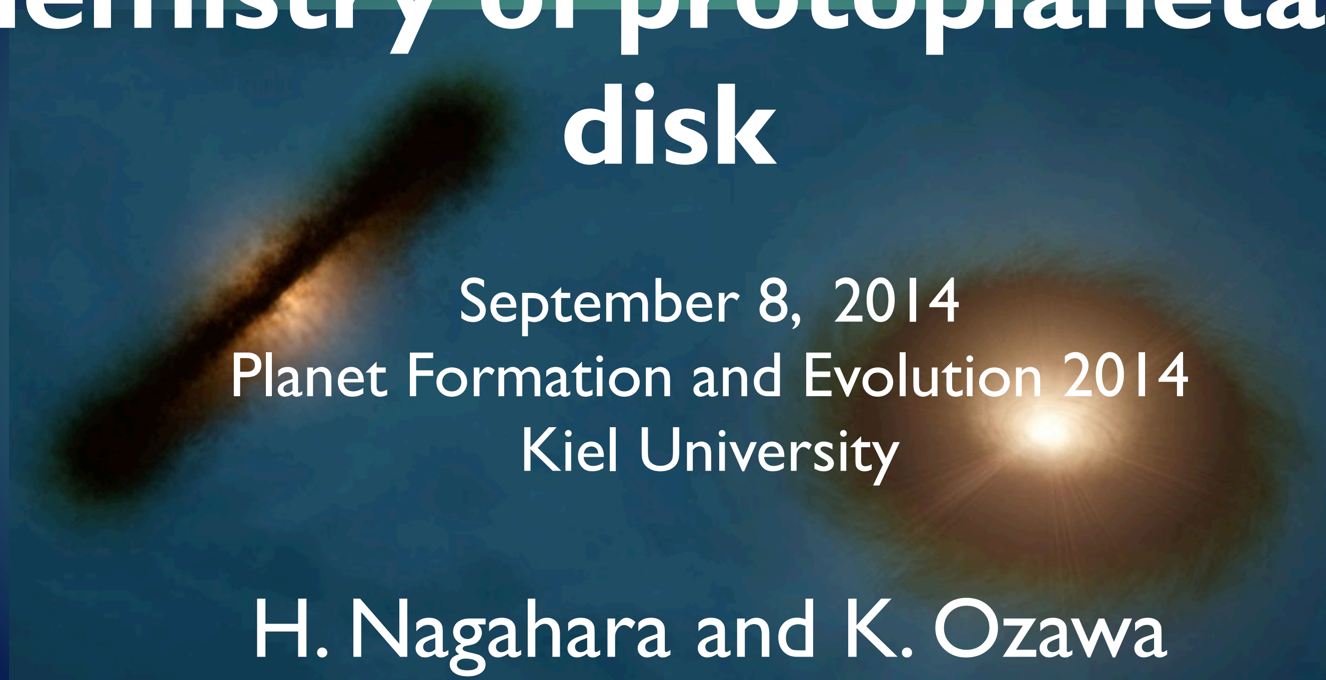
Co-evolution of physics and chemistry of protoplanetary disk



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Kiel University

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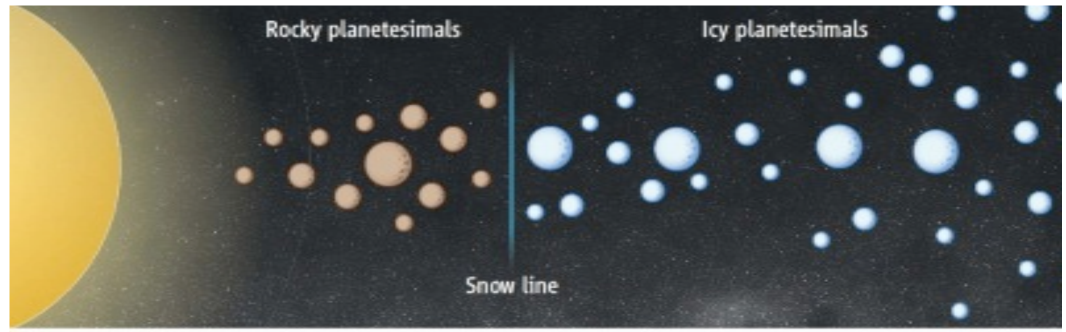
Evolution of the early stage of protoplanetary disks

- ✓ Extensive study on physics
- ✓ Few interests on chemistry



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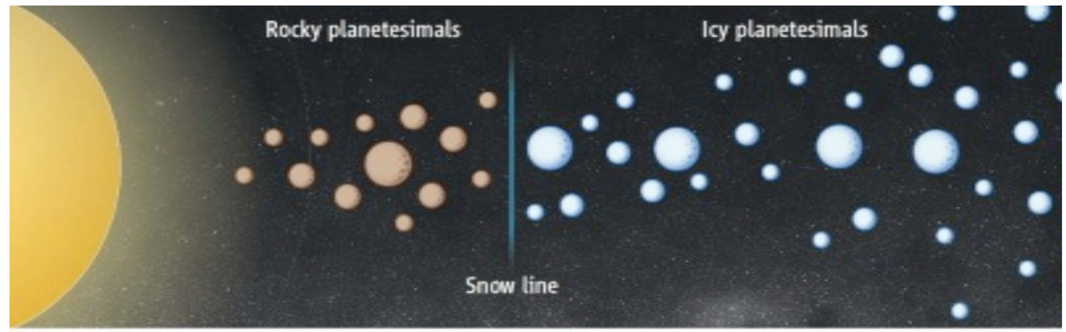
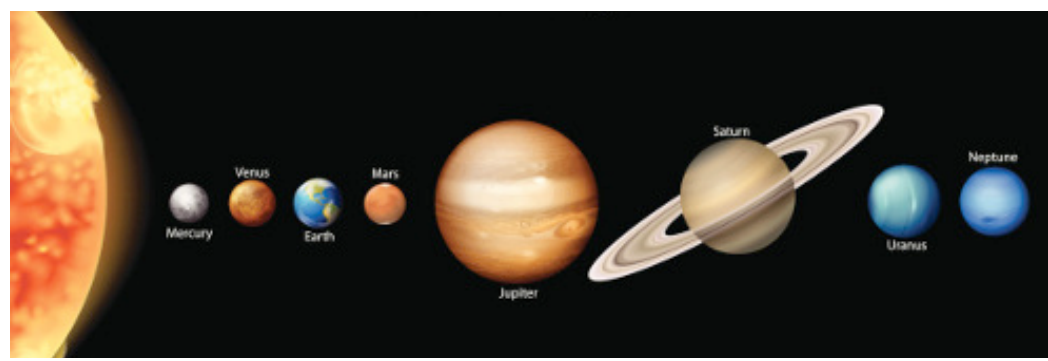


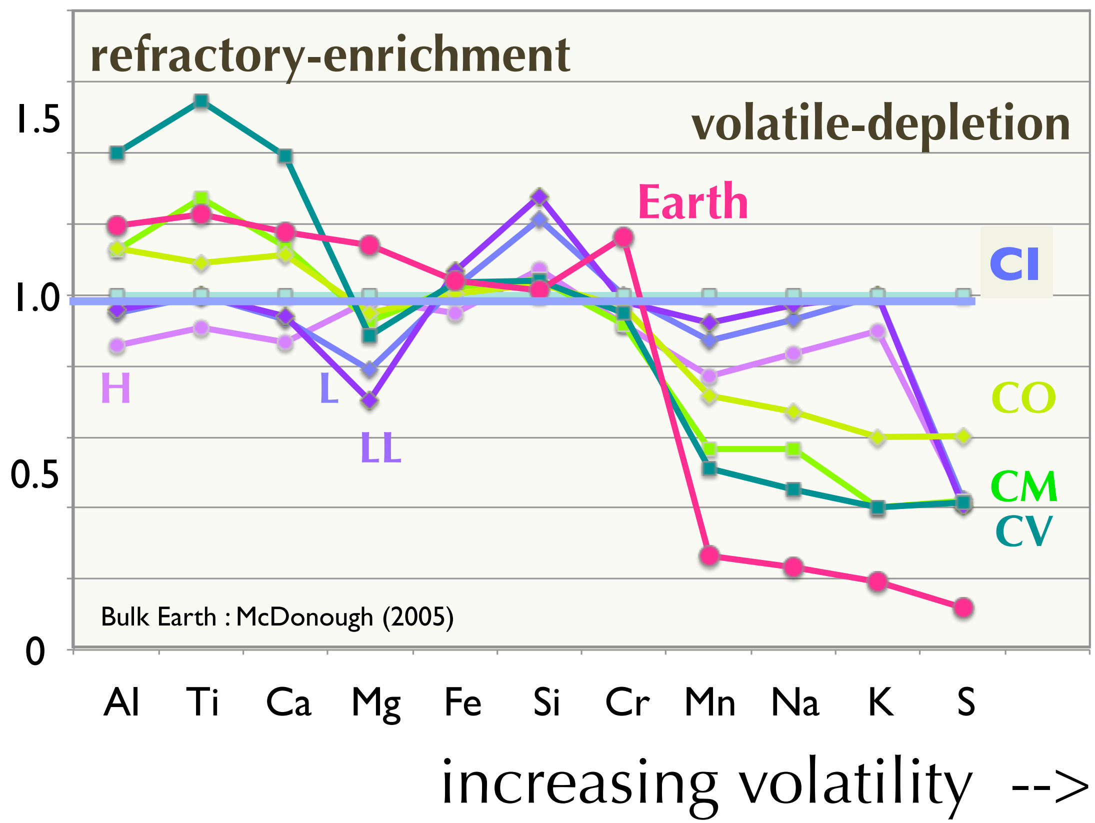
However,

- ✓ Our solar system is very variable
- ✓ Importance of chemistry



Evidence for imprtance of chemistry in protoplanetary disk : Chondrites

Elemental abundance [relative to the solar]



- ✓ Variable
- ✓ volatility-controlled
- ✓ volatile-depletion

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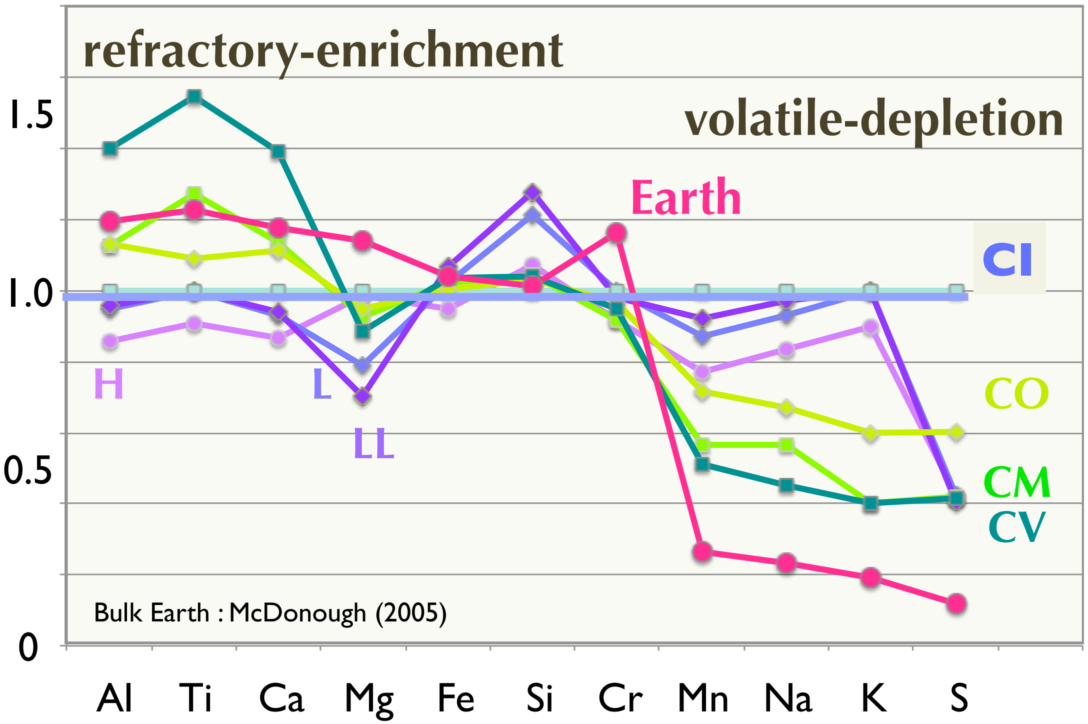


increasing volatility -->

- ✓ Variable
- ✓ volatility-controlled
- ✓ volatile-depletion

Importance of

- ✓ condensation / evaporation at high-temperature

Present Work

How the disk evolves chemically with physics ?

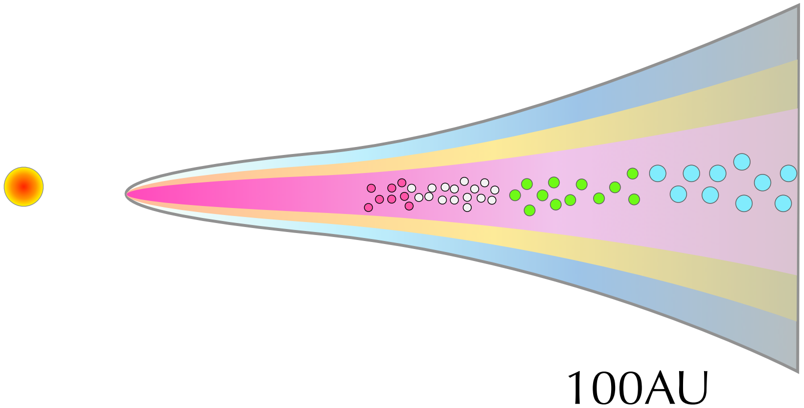
Method

- ✓ **physics (advection and diffusion) : particle tracking** model (trace the trajectory of individual grains) [Ciesla, 2010, 2011a, b]
- ✓ **chemistry** : **chemical equilibrium** calculation for dust grains

Key

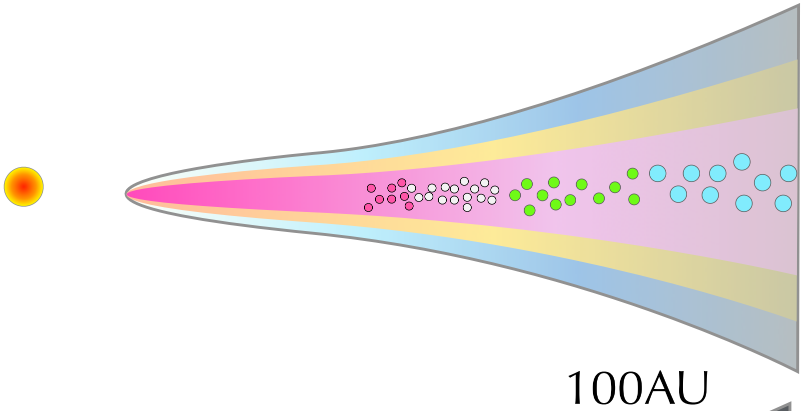
- ✓ disk conditions to reproduce chemical variations of chondrites at 2-4 AU within 10^6 years

Method



- disk mass
- $\Sigma(R, t)$ -> $T, P\ (R, t)$
- divide the disk into 13 bins
- put 10^5 grains in each bin
- chemical equilibrium calculation for individual bins

Method



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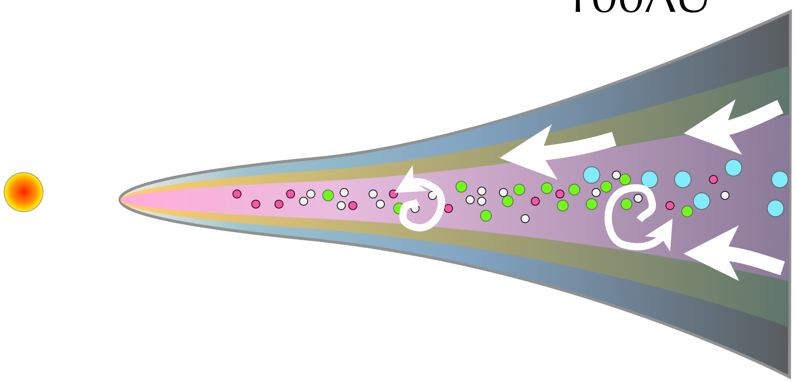

- dust transportation
- advection and diffusion (inward and outward)
- track all the grains for 10^6 yrs

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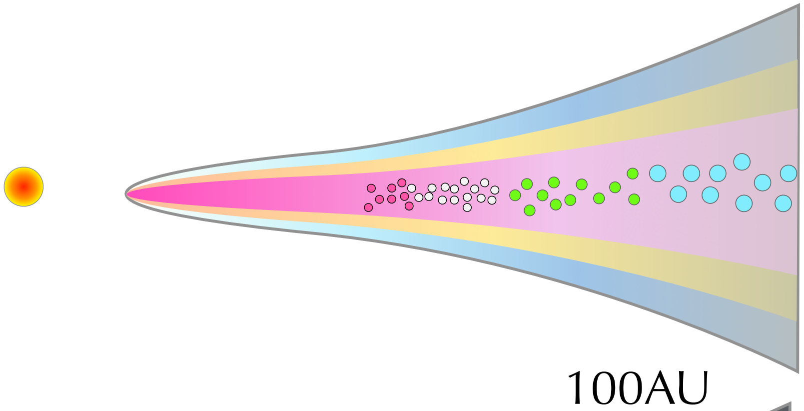

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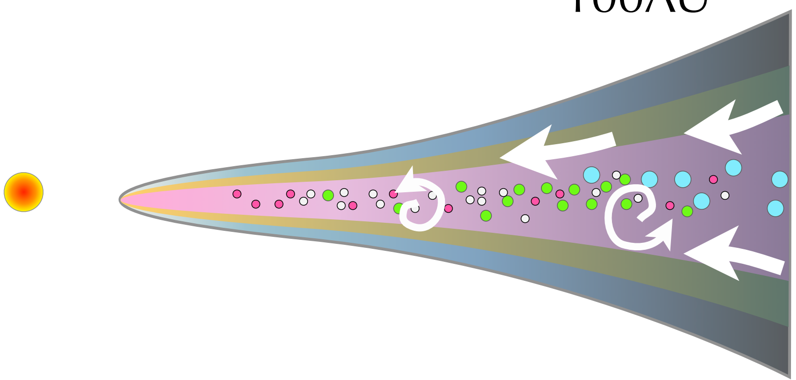

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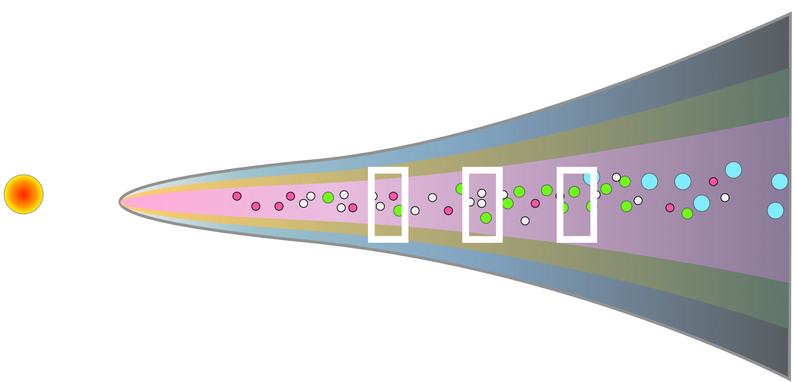
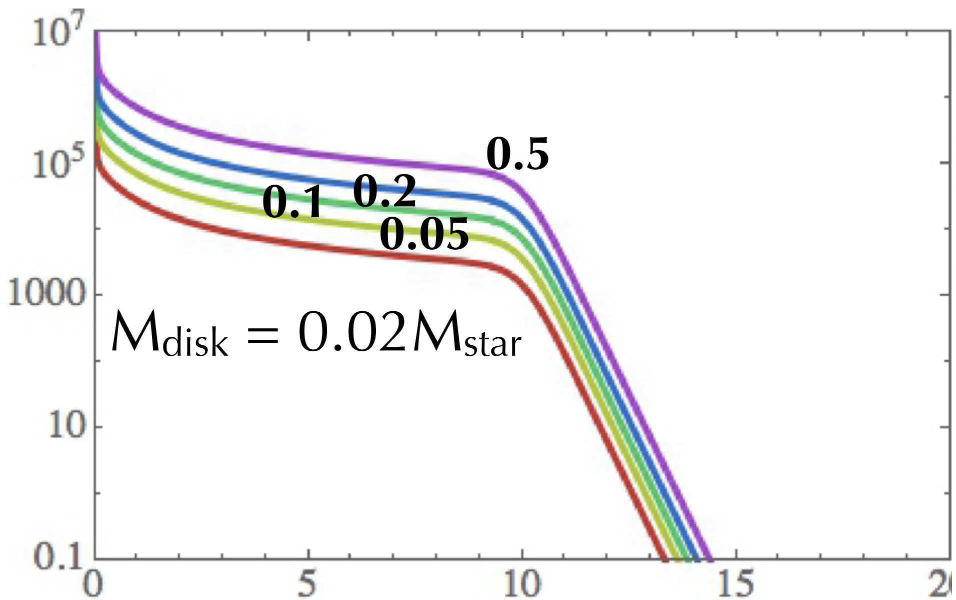


- Calculate chemical composition of a certain region of the disk at a certain time, $= \Sigma n_i C_i$

Disk initial conditions

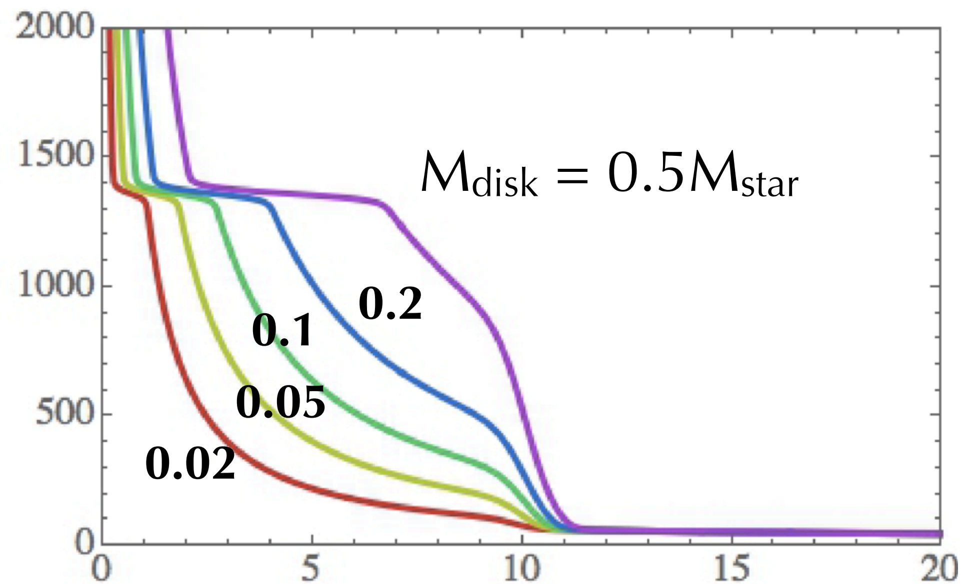
(after Ciesla, 2011)

Surface density [kg m^{-2}]



Radial distance [AU]

Temperature [K]



Radial distance [AU]

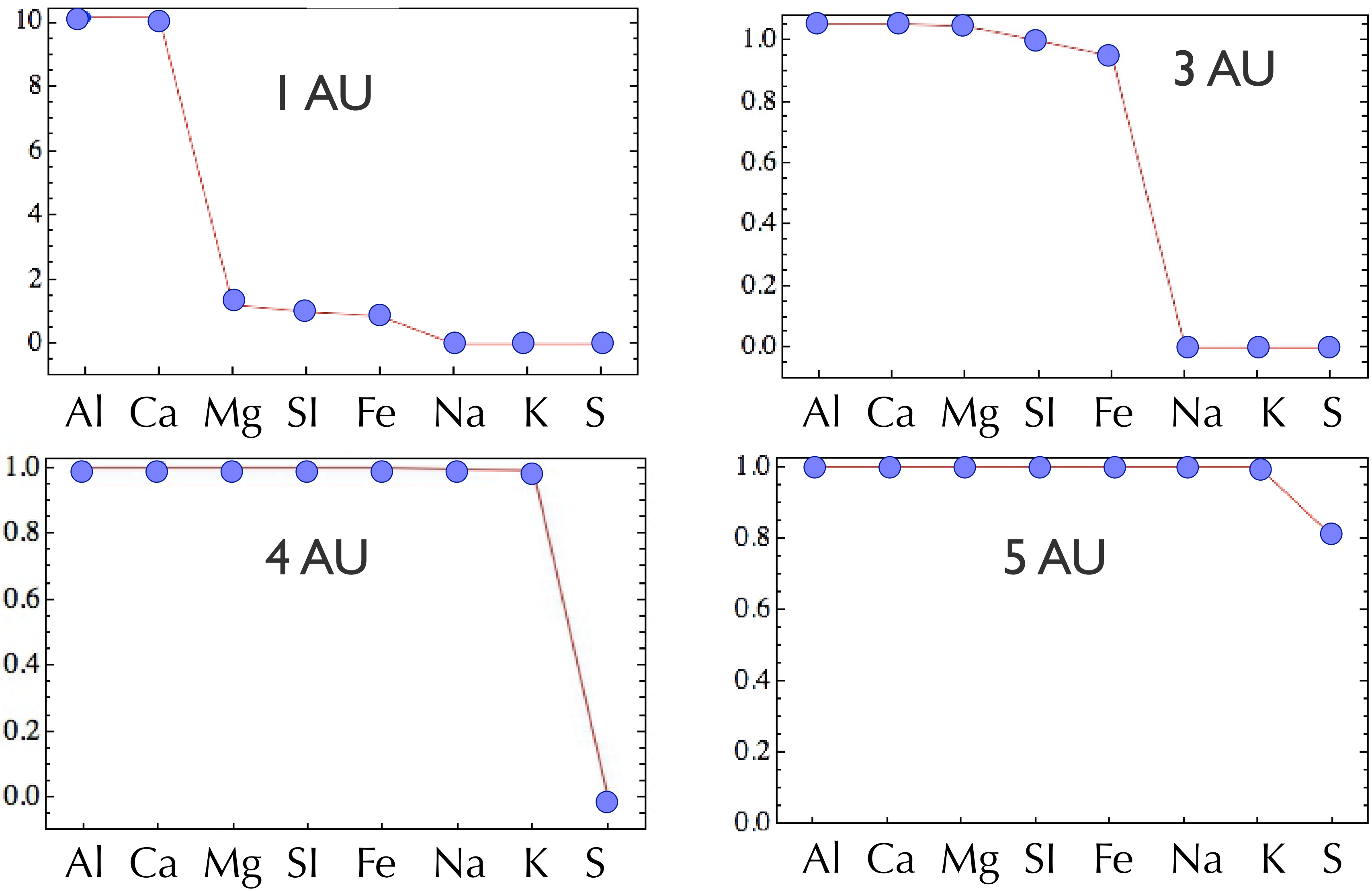
surface density *f*(M_{disk}, *r*)

T, P = f (surface density, r)

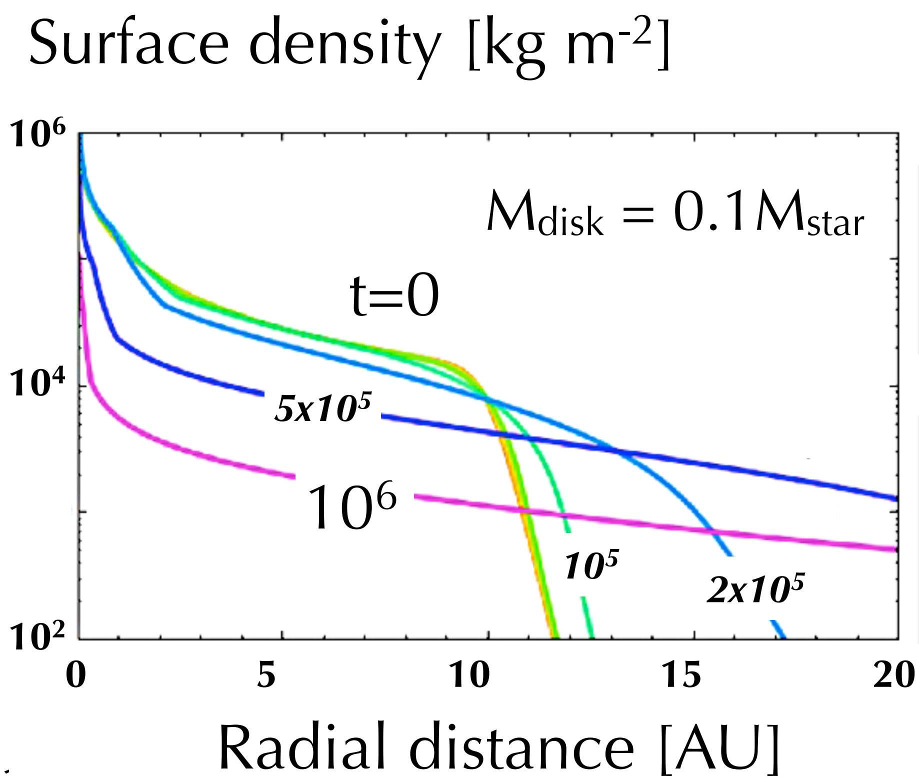
viscosity parameter $\alpha = 10^{-3}$

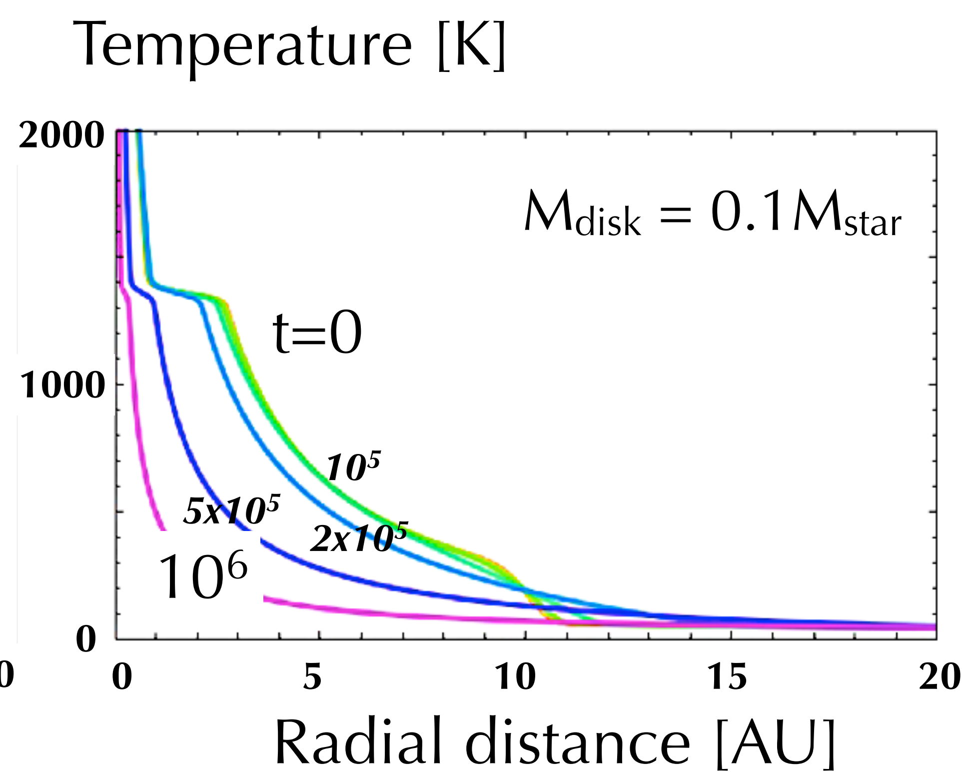
Initial Dust Composition

Elemental abundance [relative to the solar & Si] $M_{disk} = 0.1M_{star}$



Disk Evolution



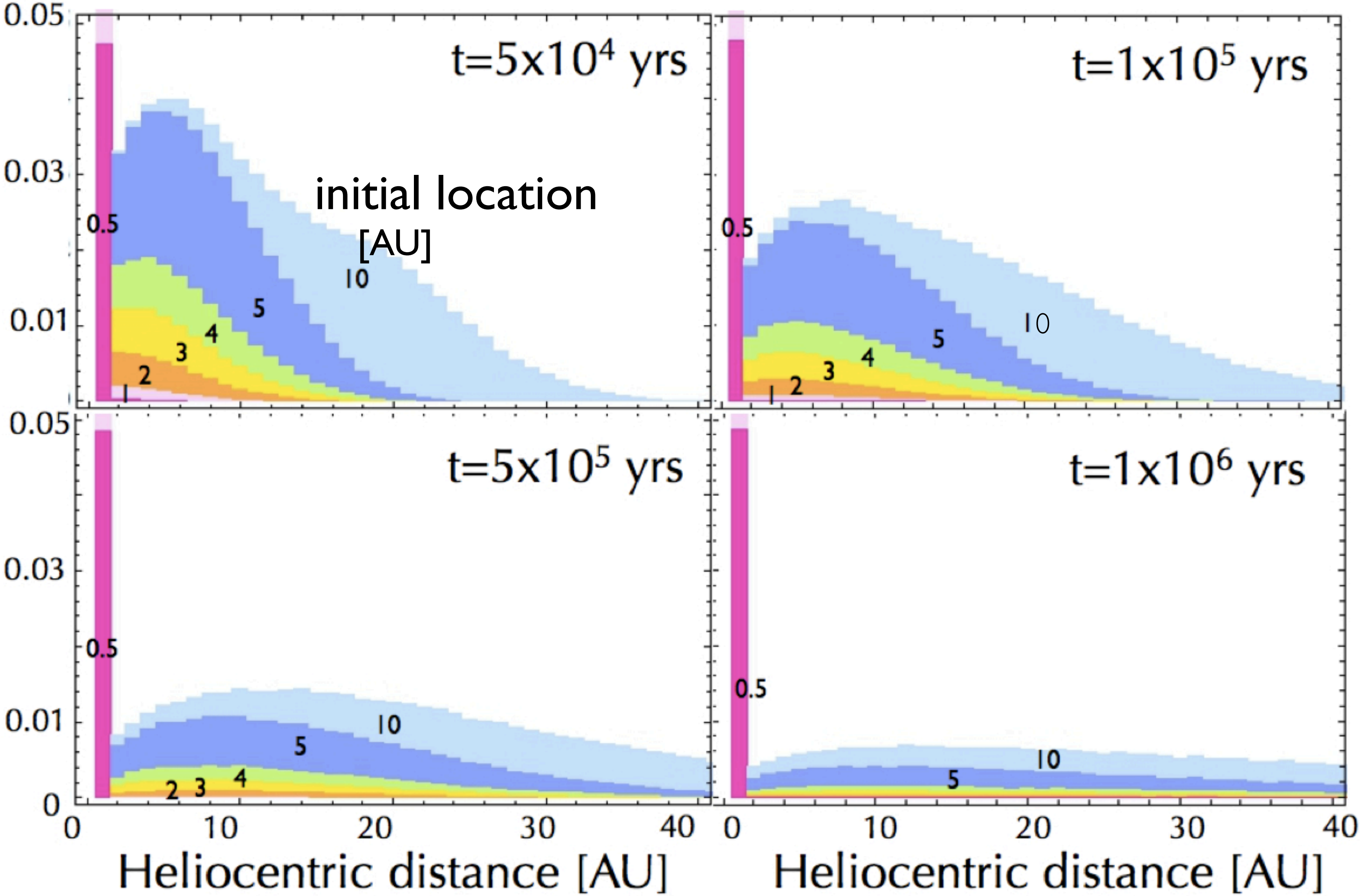


- surface density decreases
- disk extends outward
- temperature decreases

Dust Transportation

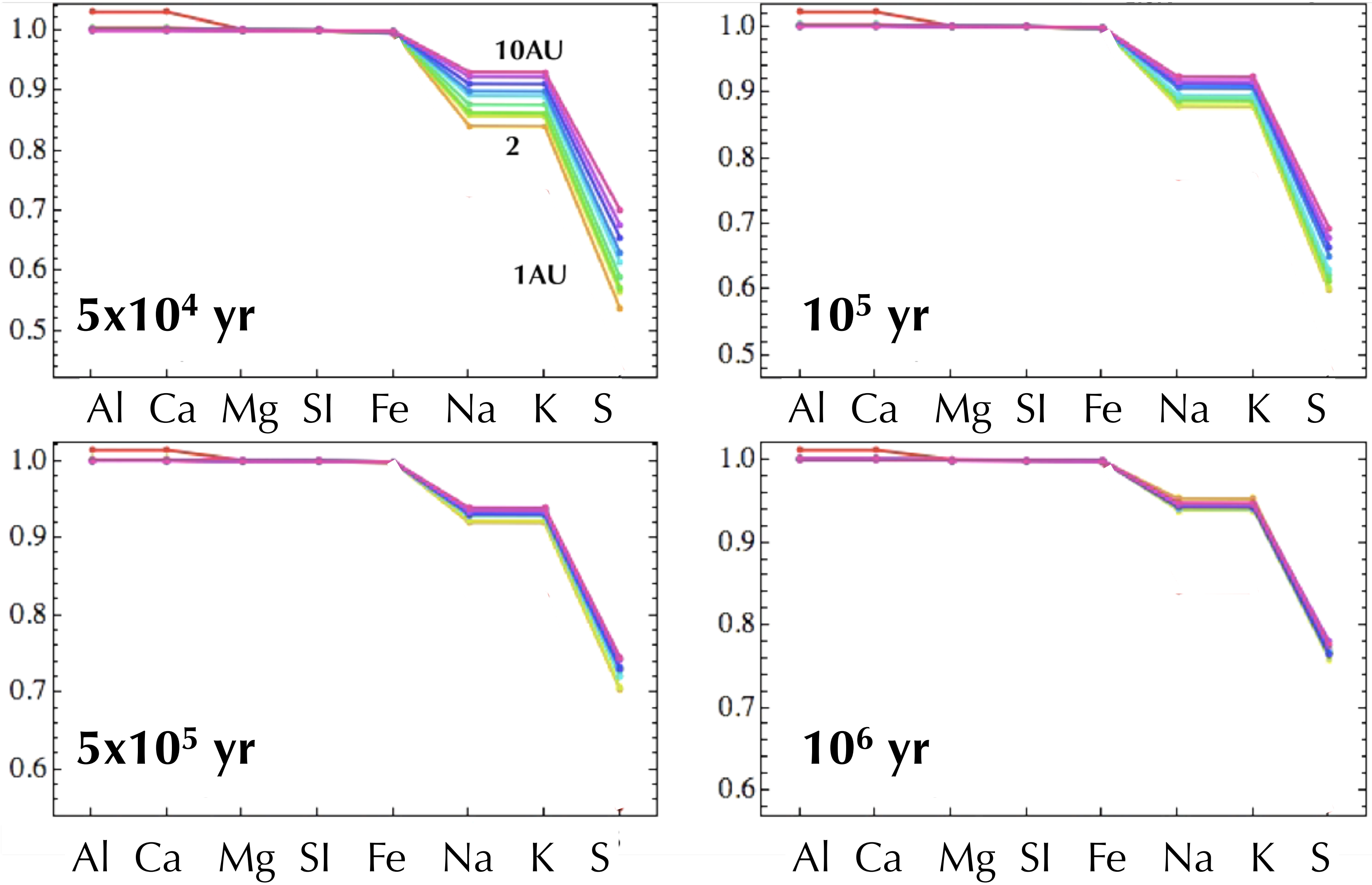
Fraction of dust remains in the disk

$M_{disk} = 0.1 M_{star}$



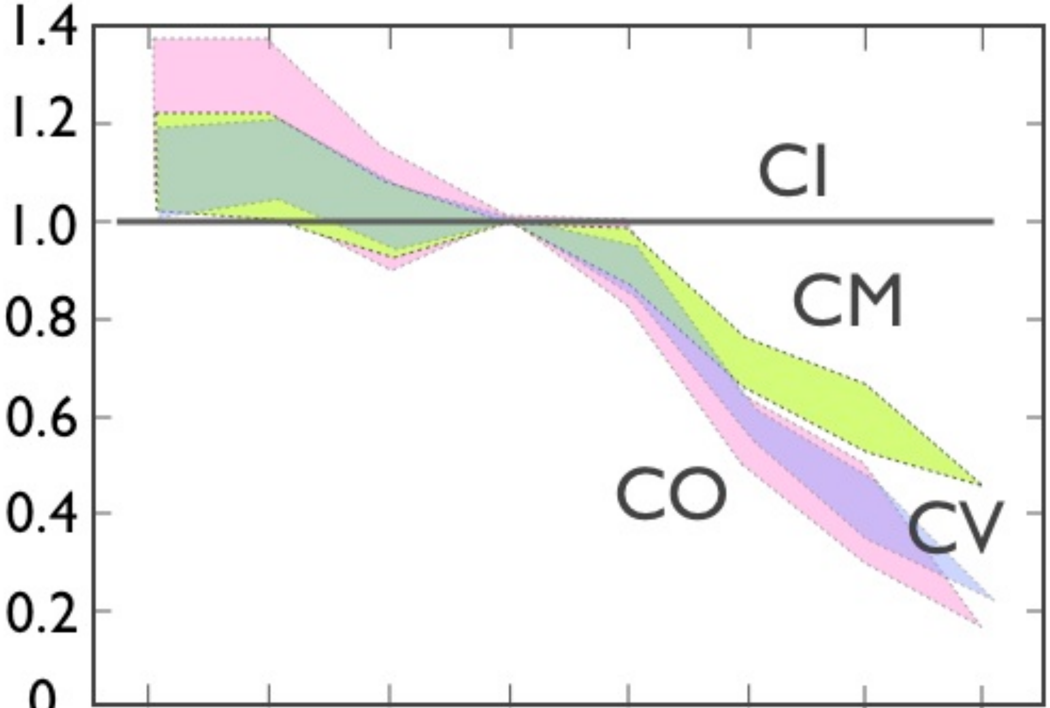
Disk Compositional Evolution

Elemental abundance [relative to the solar & Si] $M_{disk} = 0.1 M_{star}$



Comparison with Chondrite Compositions

Elemental abundance [relative to the solar & Si]

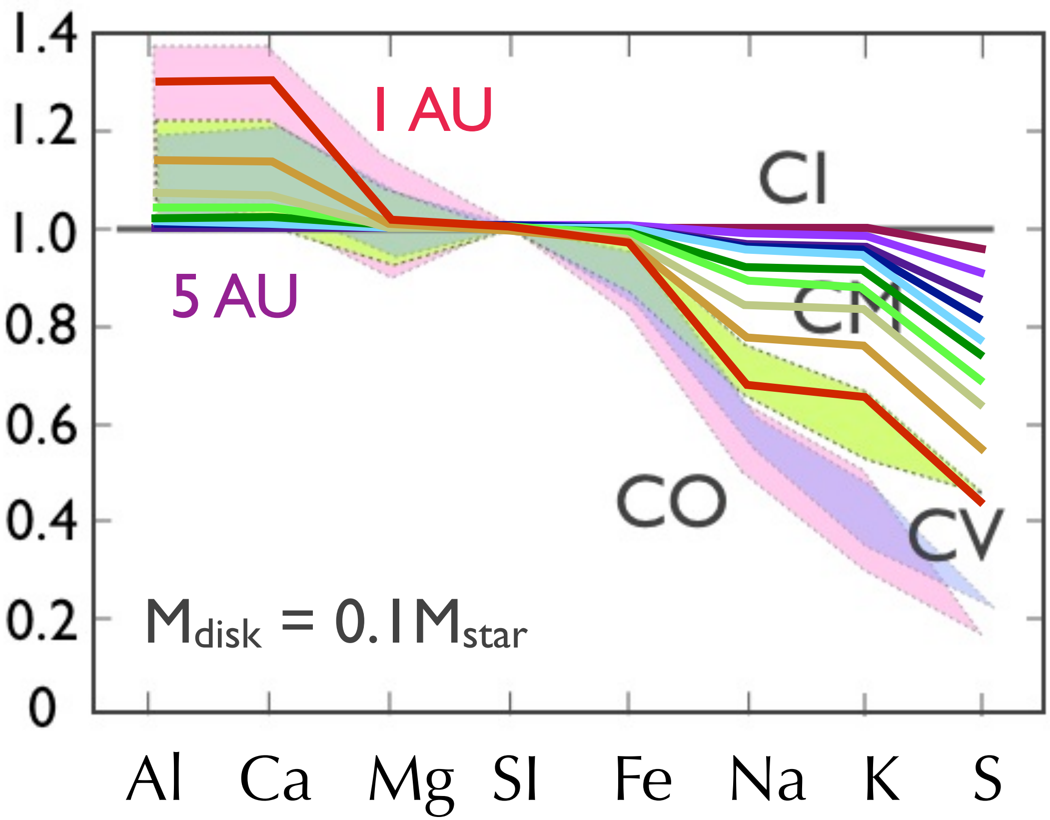


Elements [in order of volatility]

- compare model disk composition and chondrite compositions
- find plausible disk conditions

Comparison with Chondrite Compositions

Elemental abundance [relative to the solar & Si]



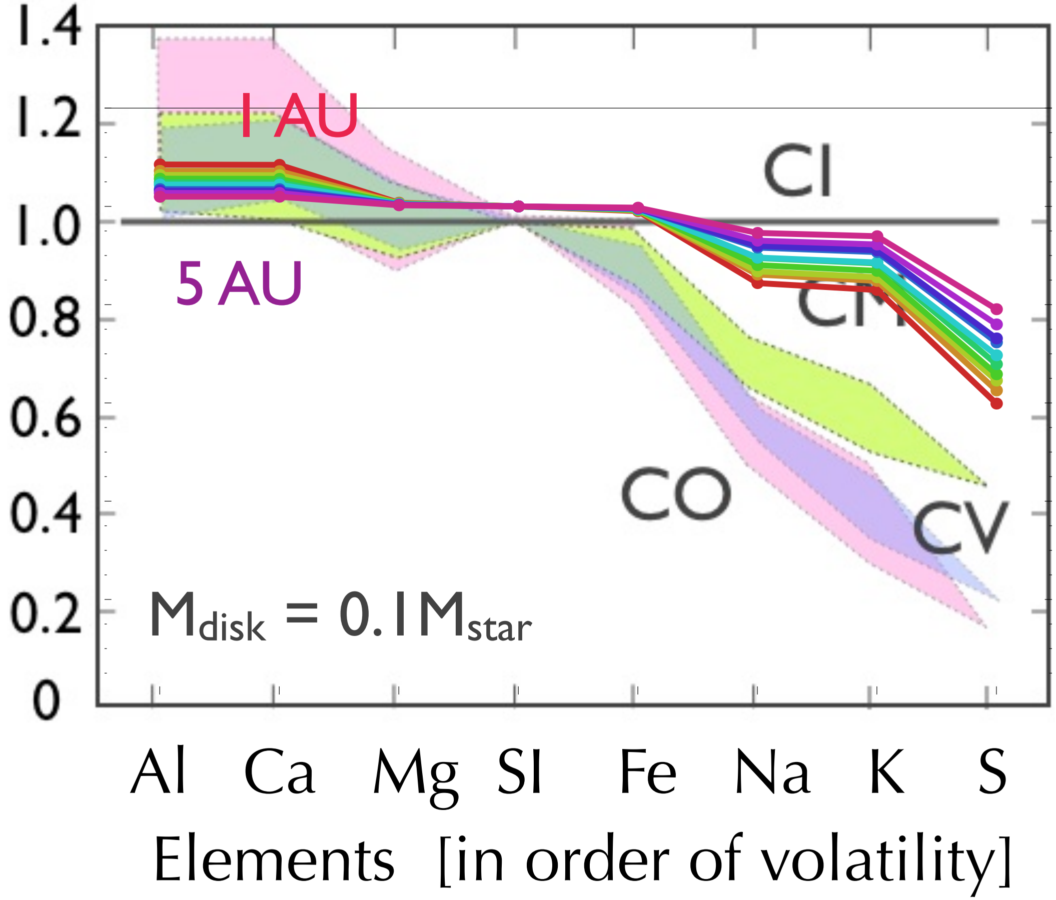
Elements [in order of volatility]

$M_{disk} = 0.1 M_{star}$

$t = 1 \times 10^4$ years

Comparison with Chondrite Compositions

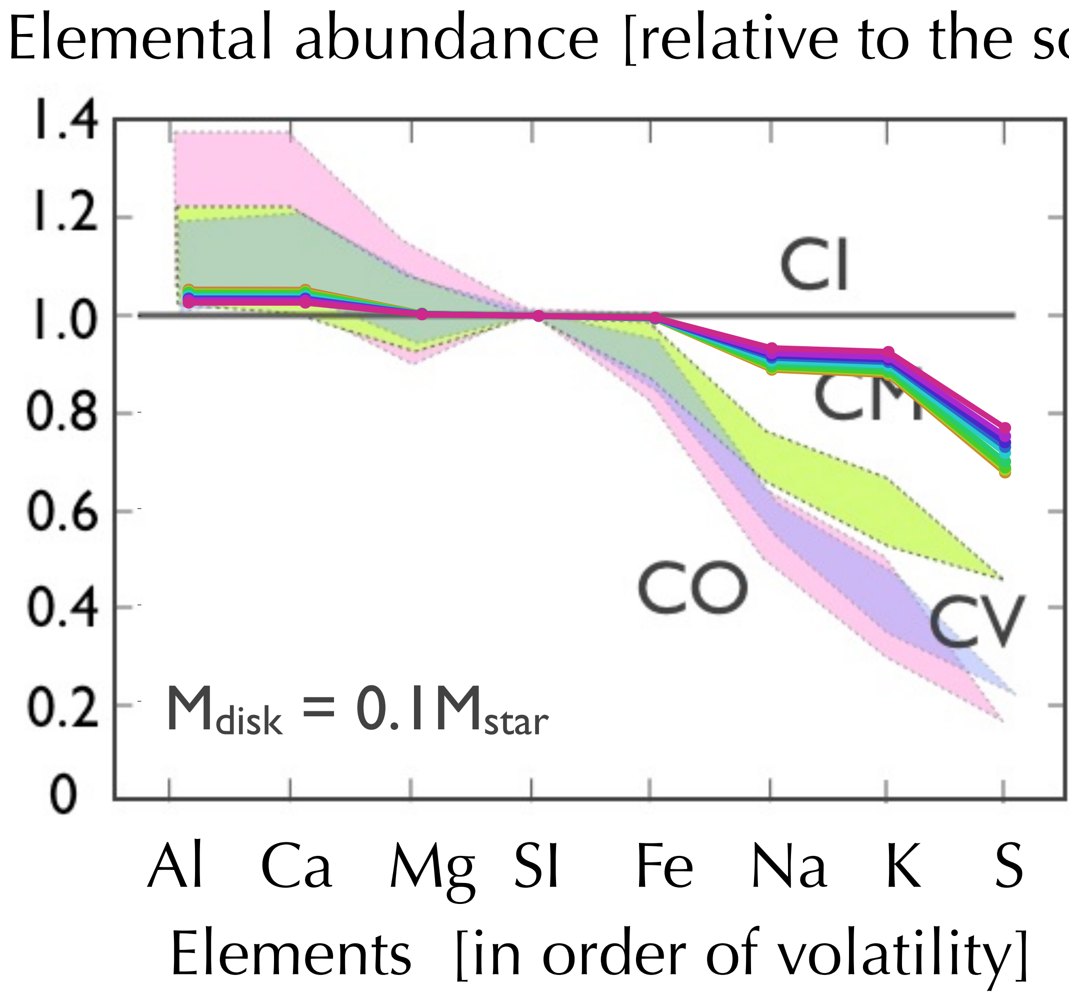
Elemental abundance [relative to the solar & Si]



$M_{disk} = 0.1M_{star}$

$t = 5 \times 10^4$ years

Comparison with Chondrite Compositions

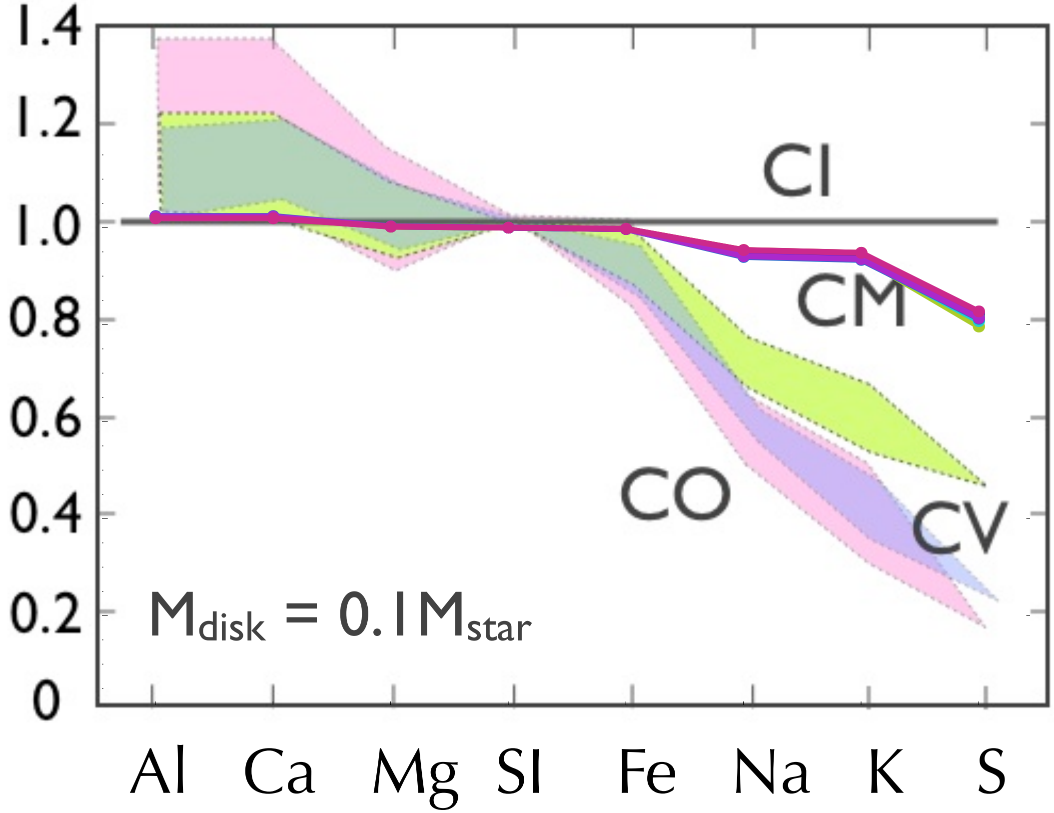


$M_{disk} = 0.1 M_{star}$

$t = 1 \times 10^5$ years

Comparison with Chondrite Compositions

Elemental abundance [relative to the solar & Si]



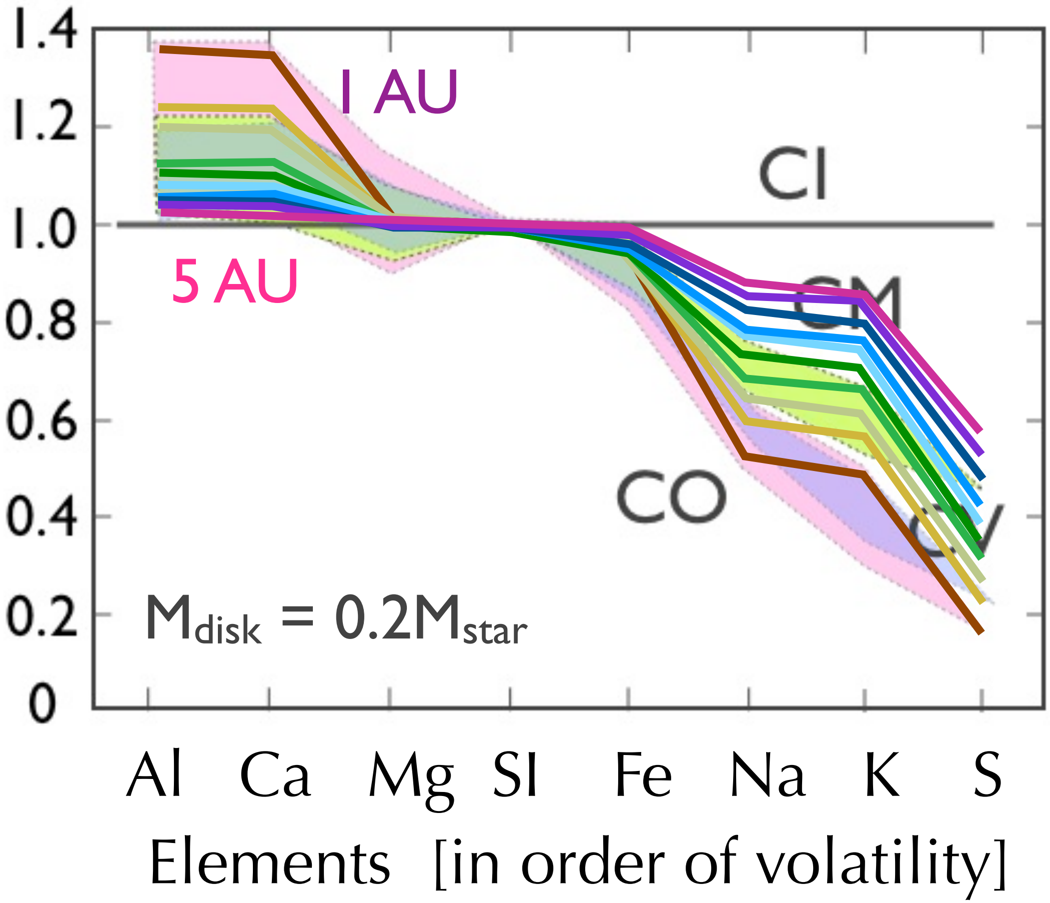
Elements [in order of volatility]

M_{disk} = 0.1M_{star}

t=1x10^6 years

Comparison with Chondrite Compositions

Elemental abundance [relative to the solar & Si]



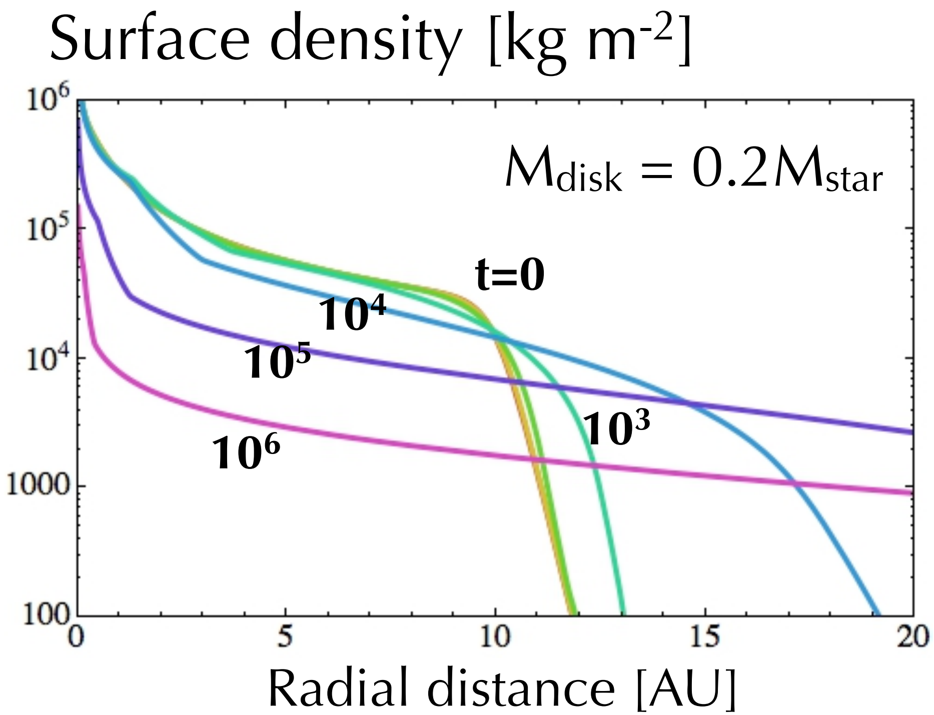
Best fit

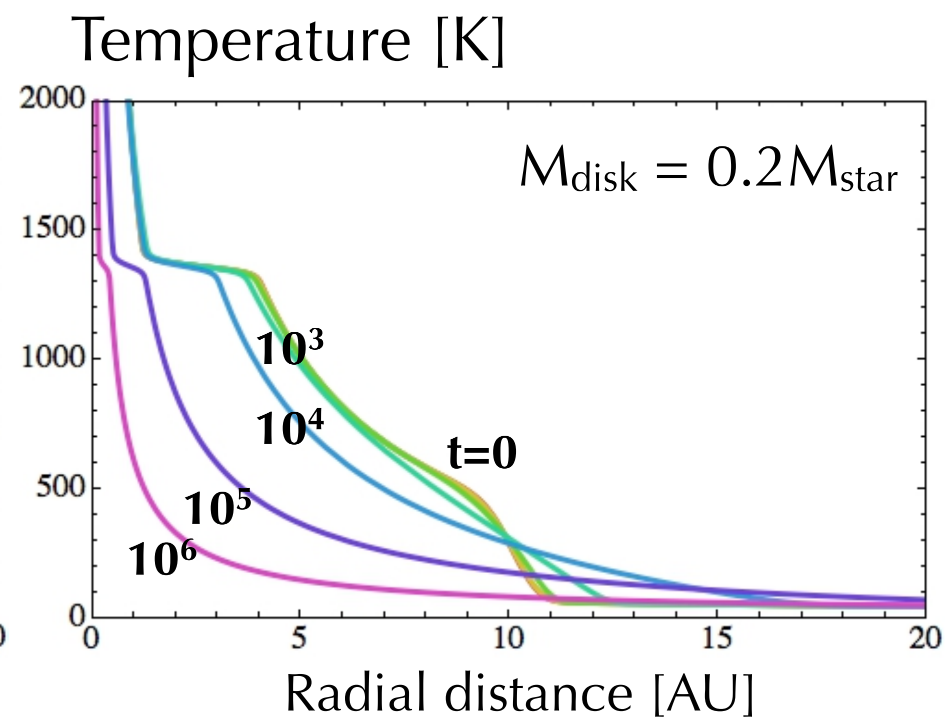
M_{disk} = 0.2xM_{star}

t=2x10^4 years

heavy and early !

Disk conditions for chemical fractionation and diversity of chondrites





- heavy disk
- initially hot (T>1300K) out to ~ 4AU

Conclusions

- ✓ Physical and chemical evolution of the protoplanetary disk by particle-tracking model and chemical equilibrium
- ✓ Disk was heterogeneous by diffusion at the early stage, but it evolves to be homogeneous
- ✓ Chemical fractionation pattern and diversity of chondrites require extension of high temperature region at the beginning, which further requires heavy disk
- ✓ Planetesimals were formed at the early stage