

FORMATION AND EVOLUTION OF DISKS: THEORY AND MODELING

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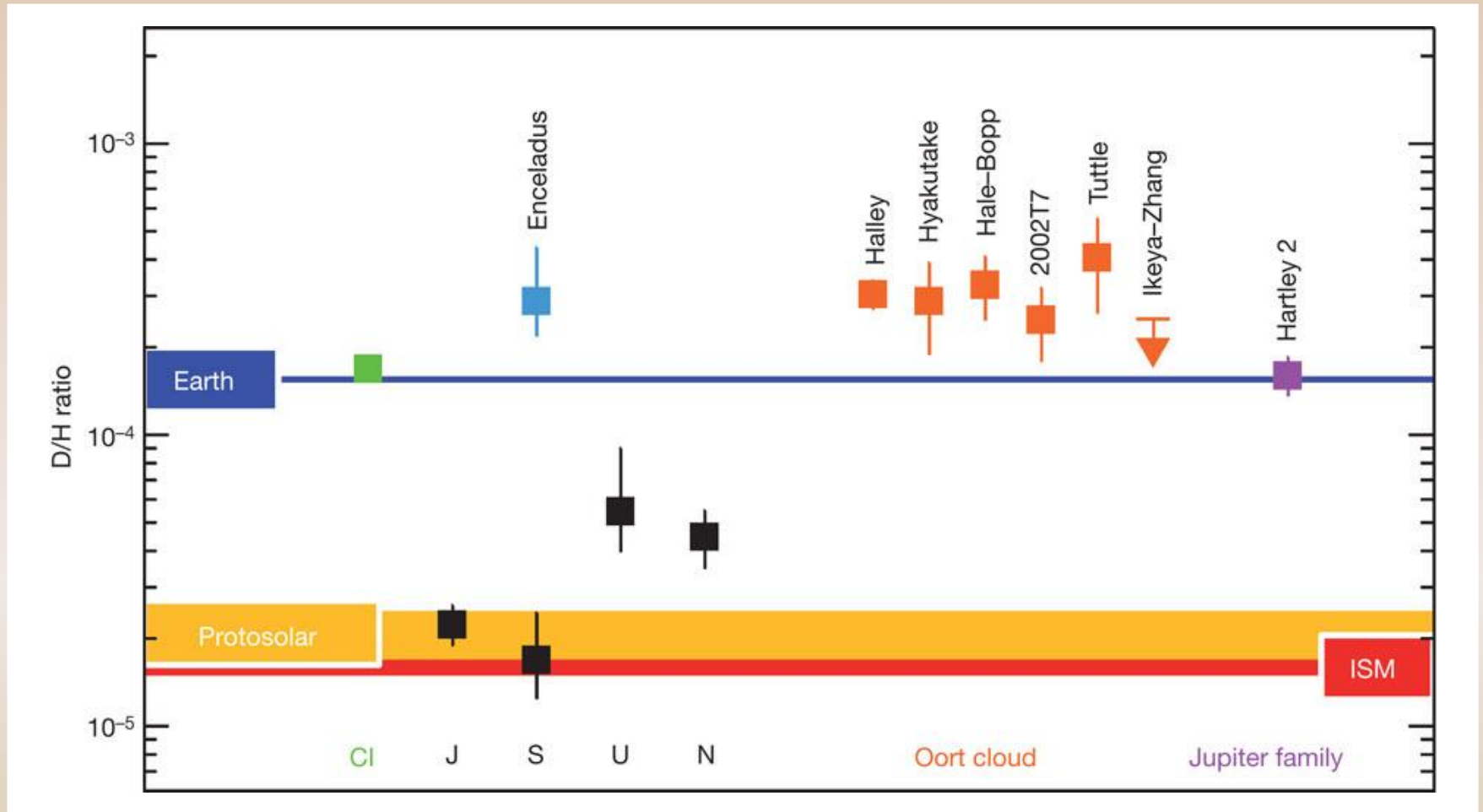
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INTRODUCTION

QUESTION 1: D/H RATIOS



How to explain the D/H trend in the solar system?

QUESTION 2: OXYGEN ISOTOPES IN METEORITES

- ✘ Stability at low temperature:



- ✘ Isotope enhancement (typically a few %):

$$\varepsilon(^y\text{O}) = \frac{([\text{O}]/[^{16}\text{O}])_{\text{silicate}}}{([\text{O}]/[^{16}\text{O}])_{\text{elemental}}} \quad (y = 17 \text{ or } 18)$$

- ✘ Expected in meteorites (Matsuhisa et al. 1978):

$$\varepsilon(^{17}\text{O}) = (0.52 \pm 0.01) \varepsilon(^{18}\text{O})$$

- ✘ Measured (Clayton et al. 1973):

$$\varepsilon(^{17}\text{O}) = (1.0 \pm 0.1) \varepsilon(^{18}\text{O})$$

How to explain the high $^{17}\text{O}/^{18}\text{O}$ ratio in meteorites?

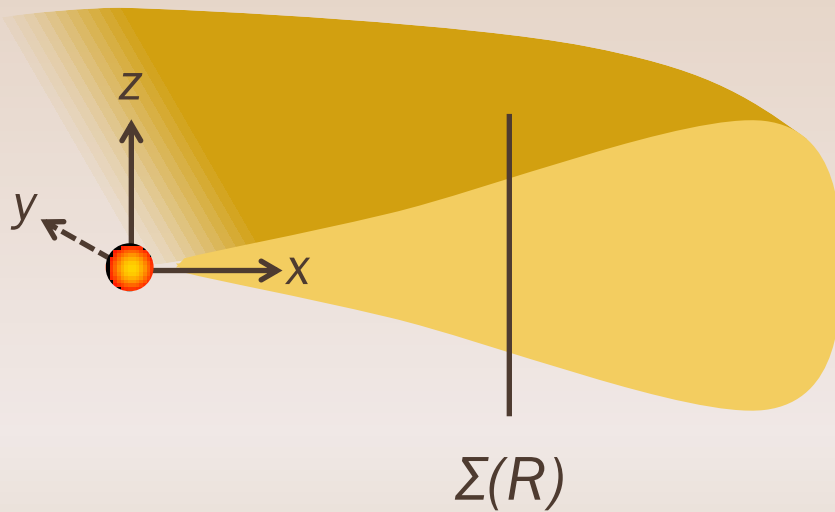


The answer: disks?

PART I: DISK PHYSICS

A. RADIAL AND VERTICAL STRUCTURE

RADIAL STRUCTURE: DEFINITION OF TERMS



- ✘ Assume axisymmetry

$$R = \sqrt{x^2 + y^2}$$

- ✘ Surface density:

$$\Sigma(R) = 2 \int_0^{\infty} \rho(R, z) dz$$

top and bottom half

mass density

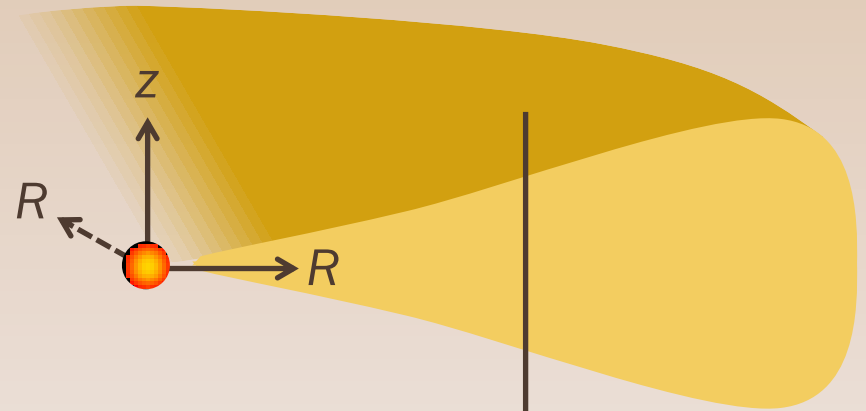
RADIAL STRUCTURE: ACCRETION AND SPREADING

Time evolution of surface density:

$$\frac{\partial \Sigma}{\partial t} = S(R, t) - \frac{1}{R} \frac{\partial R \Sigma v_R}{\partial R}$$

↑
accretion
from envelope

↑
advection/
diffusion



radial velocity

VERTICAL STRUCTURE

Hydrostatic equilibrium (no self-gravitation):

$$\frac{\partial P}{\partial z} = -\rho \Omega_K^2 z$$

Keplerian rotation rate

pressure

$$P = \rho c_s^2$$

VERTICAL STRUCTURE

Hydrostatic equilibrium (no self-gravitation):

$$\frac{\partial P}{\partial z} = -\rho \Omega_K^2 z$$

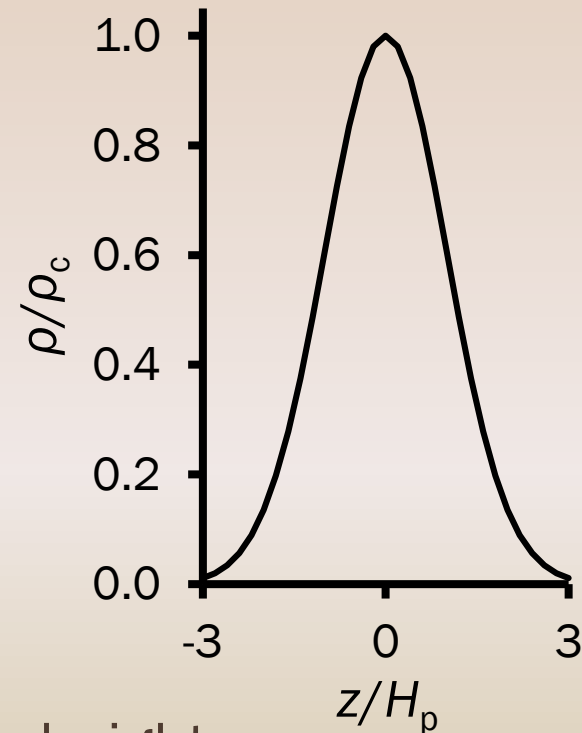
For a vertically isothermal disk:

$$\rho(R, z, t) = \frac{\Sigma}{\underbrace{H_p \sqrt{2\pi}}_{\text{mass density at midplane} \equiv \rho_c}} \exp\left(-\frac{z^2}{\underbrace{2H_p^2}_{\text{pressure scale height}}}\right)$$

mass density at midplane
 $\equiv \rho_c$

pressure scale height

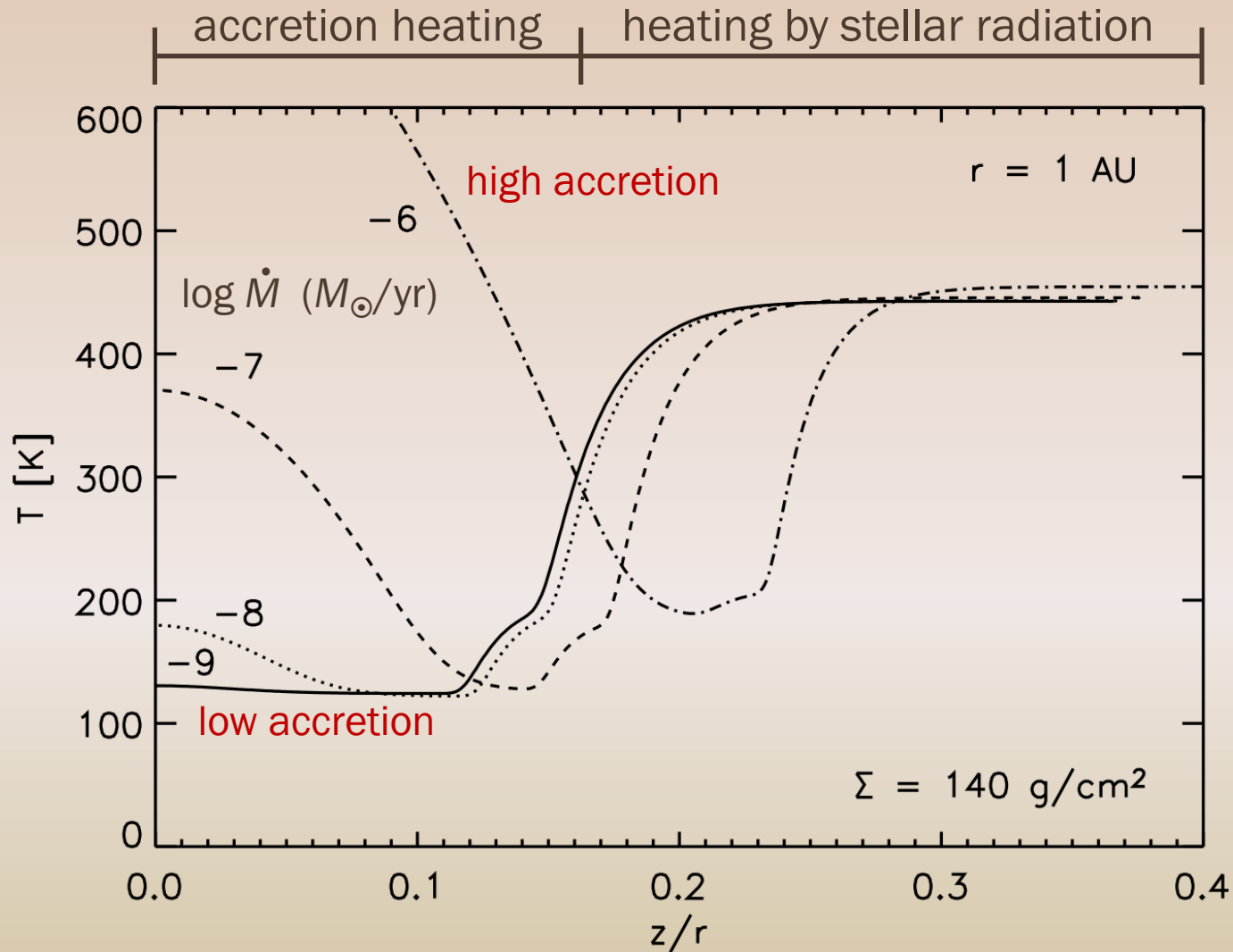
$$H_p = c_s / \Omega_K$$



DUST TEMPERATURE

- × Balance between heating and cooling
 - cooling: thermal emission
 - heating: stellar radiation
 - thermal radiation from other grains
 - viscous dissipation of gravitational energy due to accretion
- × Best solved with 2D/3D continuum radiative transfer code
- × Iterate with vertical structure
- × $T_{\text{gas}} \approx T_{\text{dust}}$ at midplane, but $T_{\text{gas}} \gg T_{\text{dust}}$ at surface

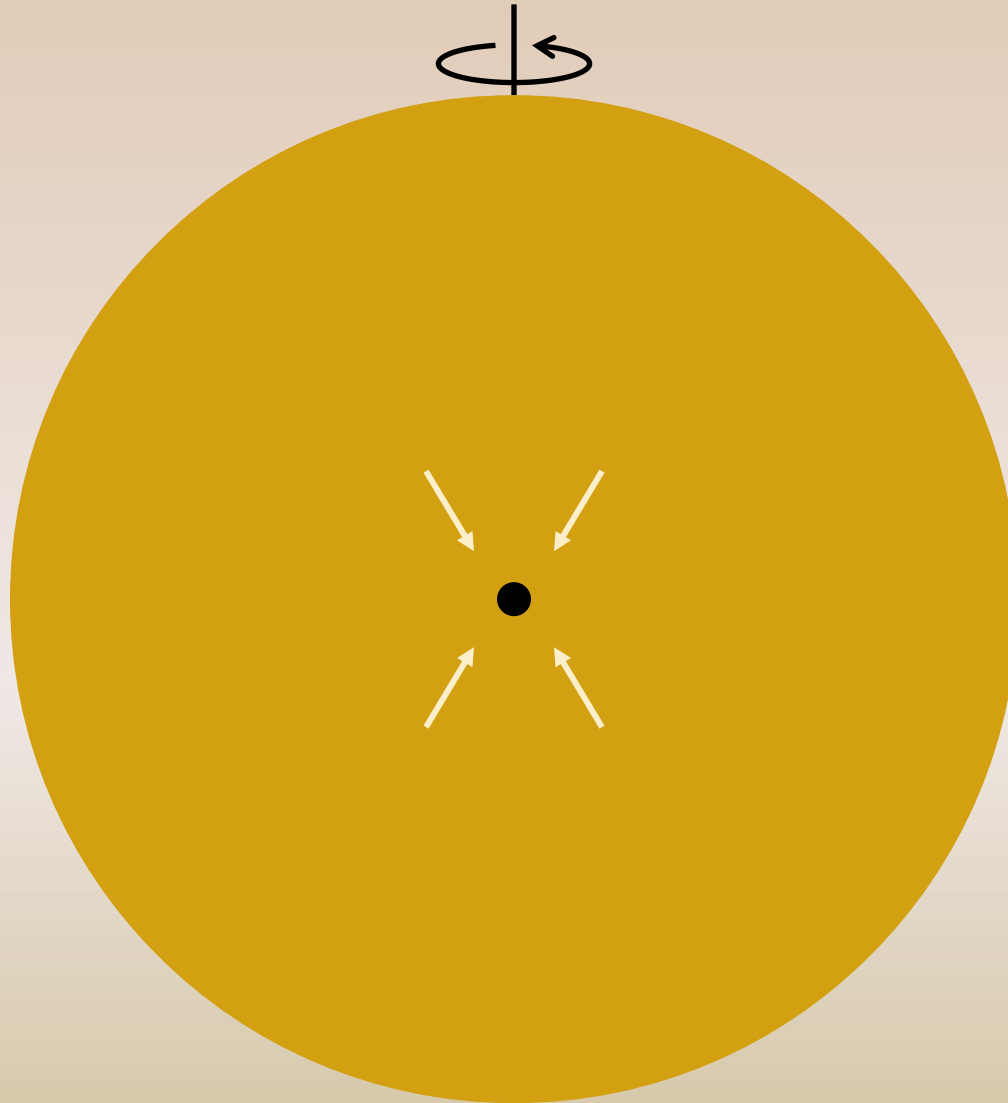
DUST TEMPERATURE



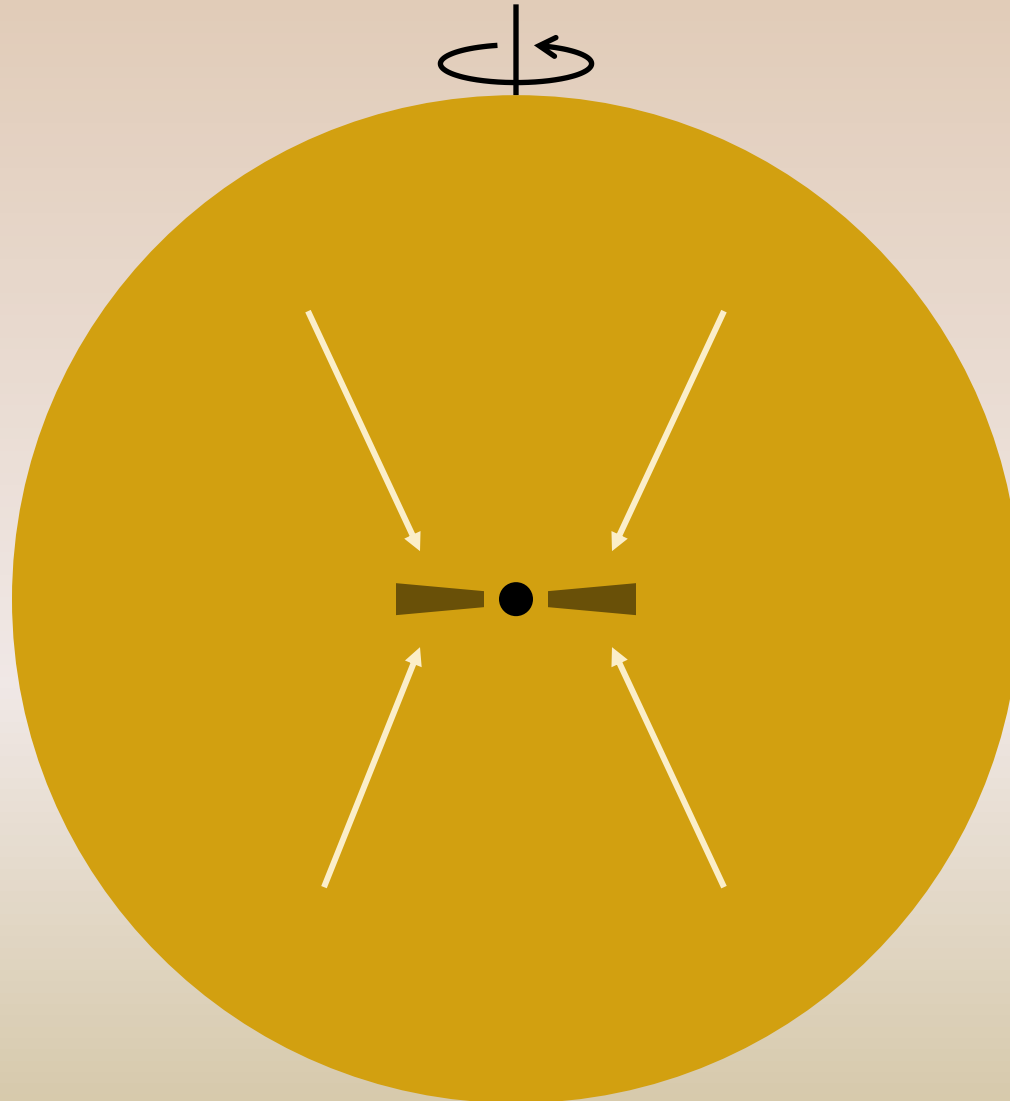
PART I: DISK PHYSICS

B. FORMATION AND EVOLUTION

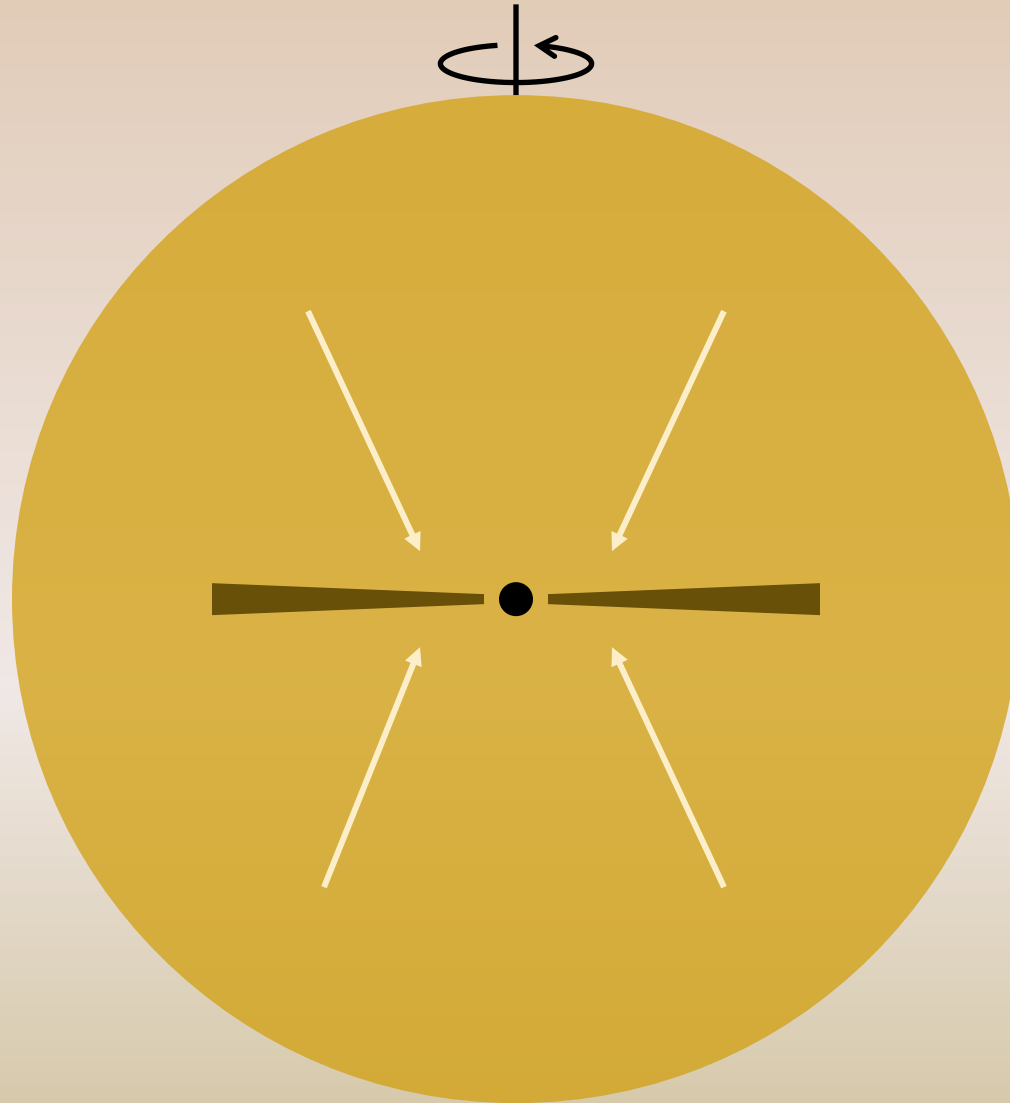
DISK FORMATION AND SPREADING



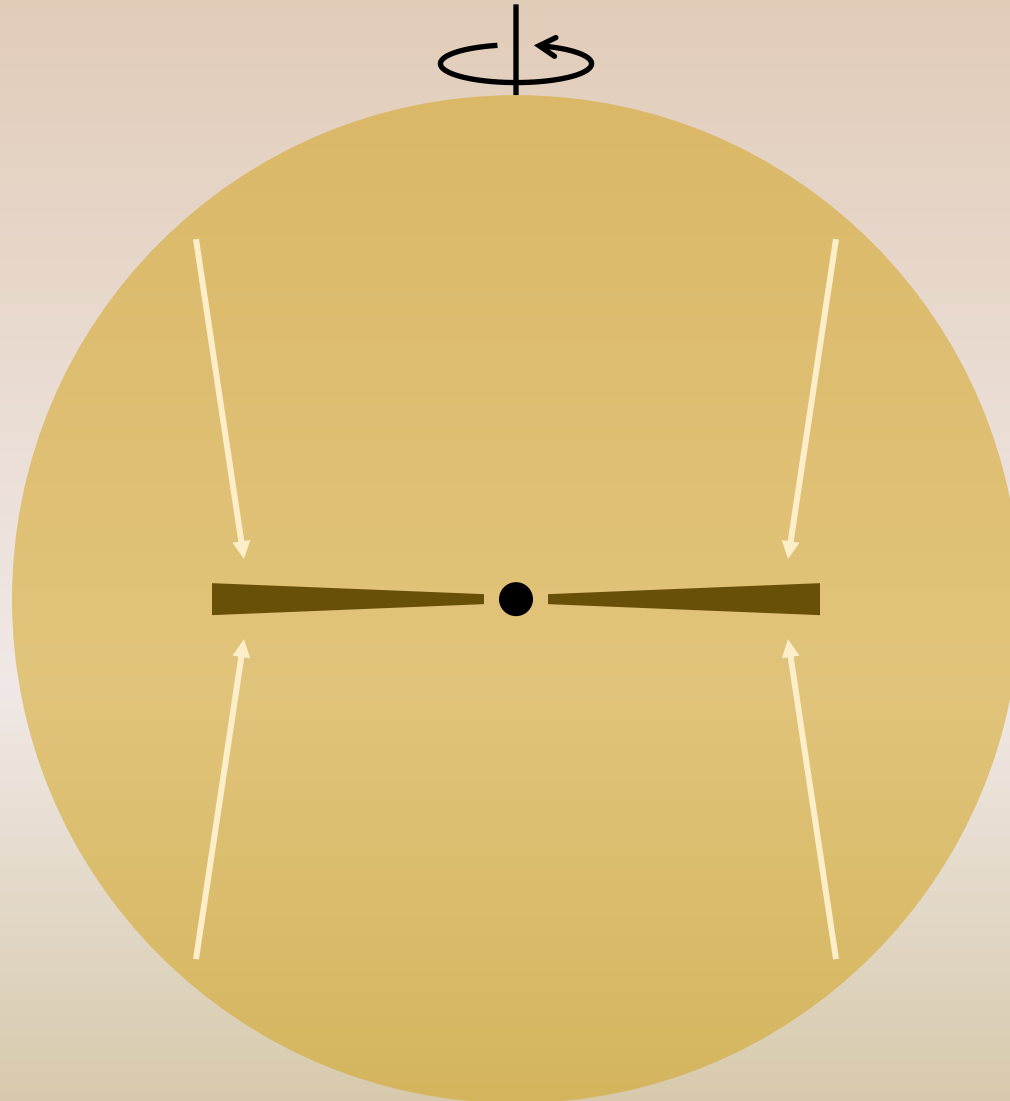
DISK FORMATION AND SPREADING



DISK FORMATION AND SPREADING



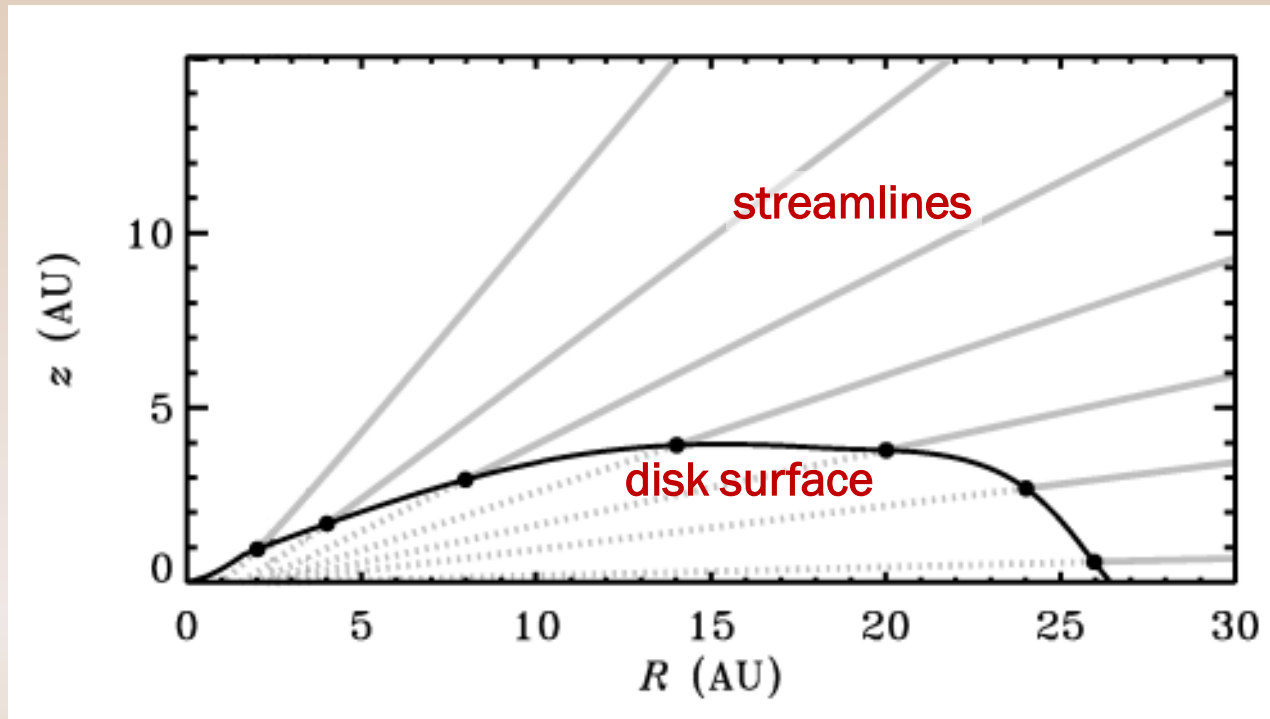
DISK FORMATION AND SPREADING



DISK FORMATION AND SPREADING

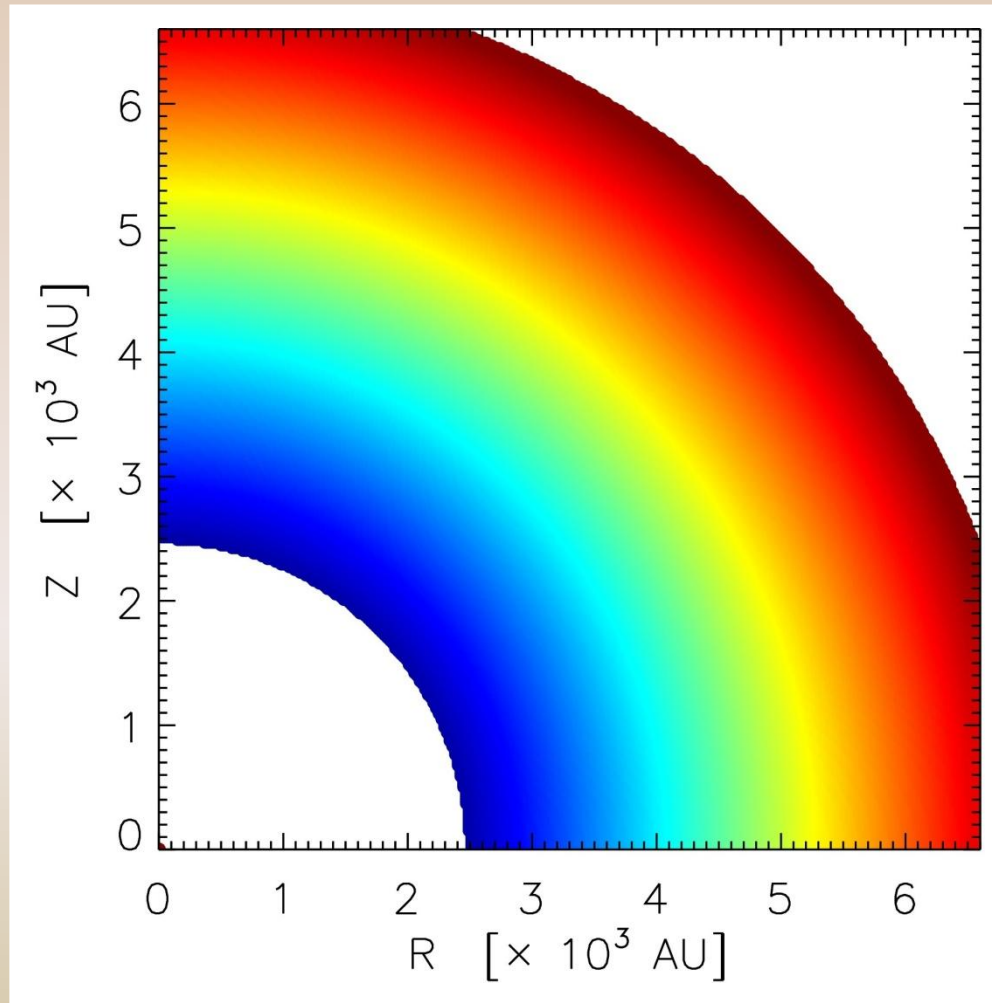


WHERE DOES MATERIAL ACCRETE ONTO THE DISK?



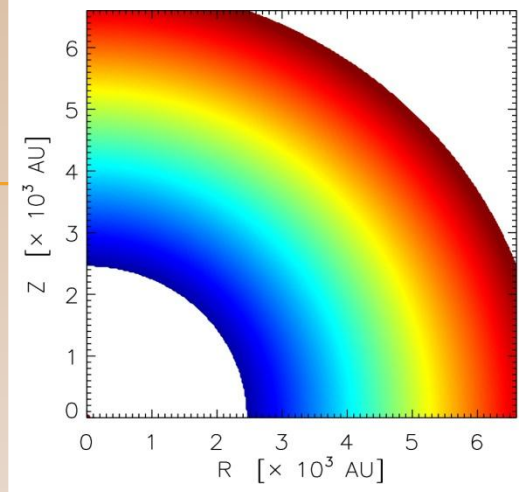
- ✗ Disks are not completely flat
- ✗ Include vertical structure: accretion occurs further out
- ✗ Accretion shock weaker than previously assumed

LAYERED ACCRETION



LAYERED ACCRETION

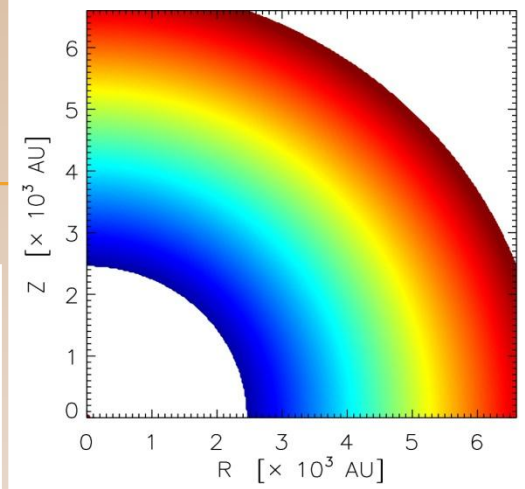
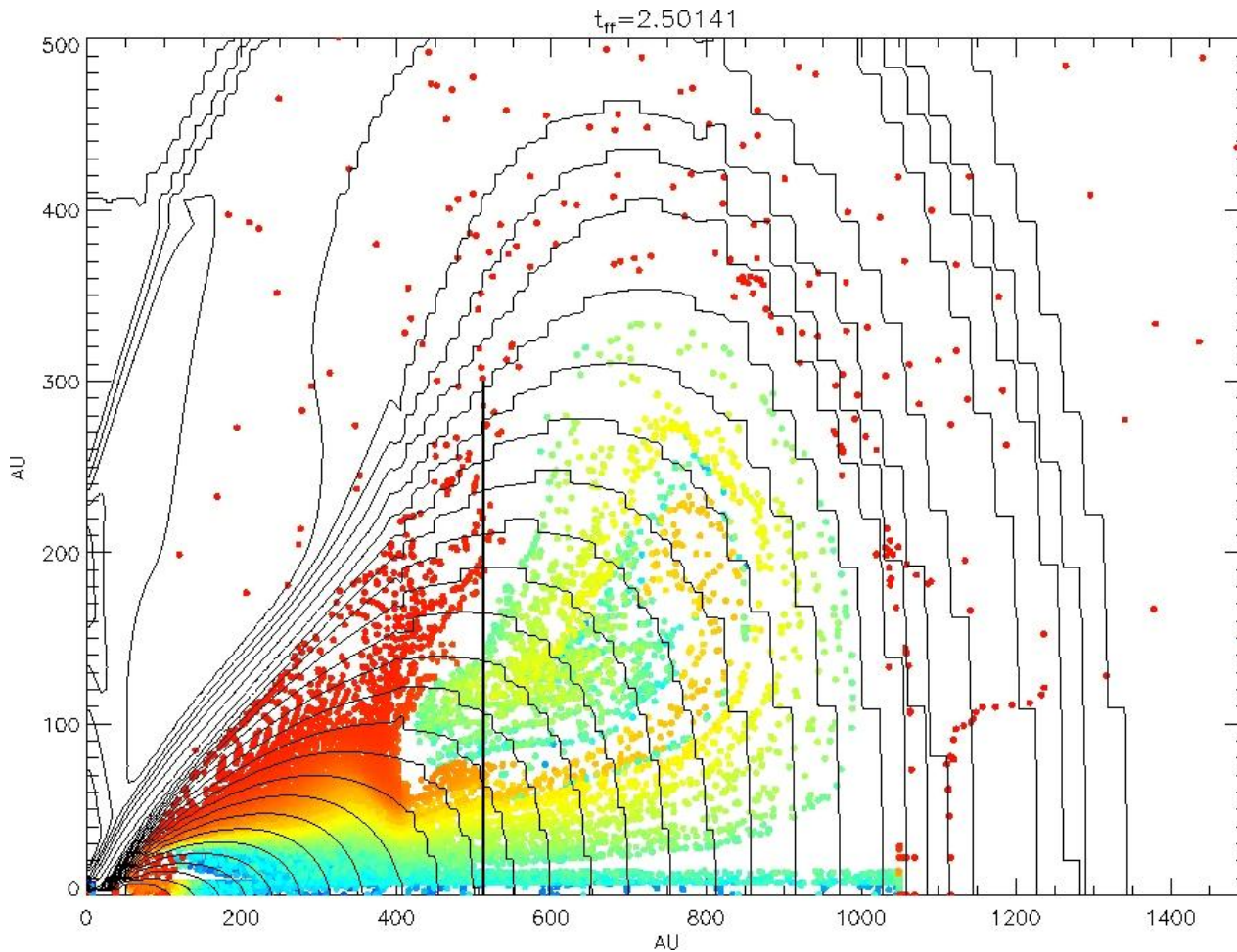
Infalling parcels in a collapsing core
by Reinout van Weeren



Note:

- Spreading of disk
- Accretion on top and at outer edge
- Inner envelope ends up at midplane
- Outer envelope ends up at surface

LAYERED ACCRETION



Note:

- Spreading of disk
- Accretion on top and at outer edge
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PART II: DISK CHEMISTRY

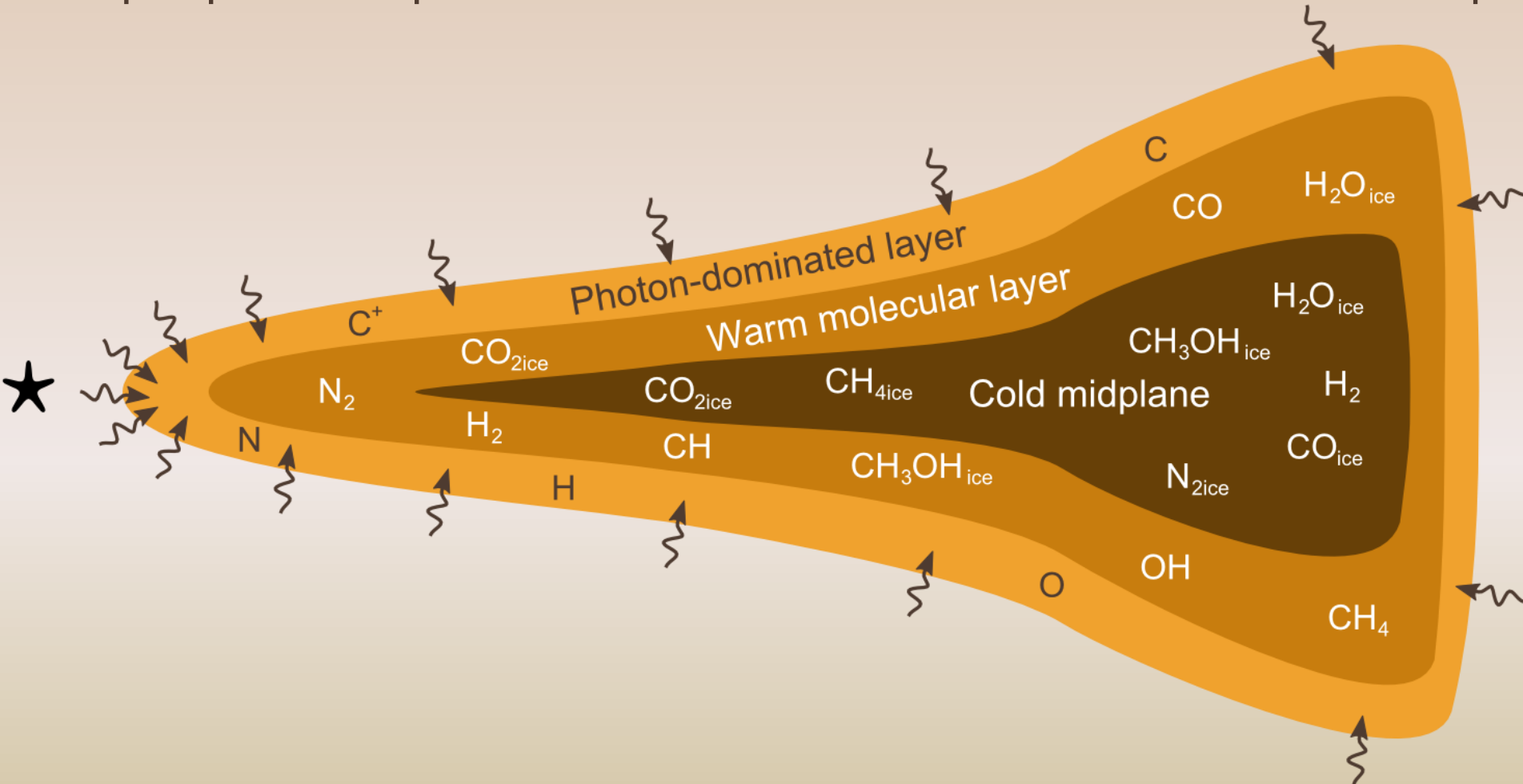
A. EVOLUTION FROM CORE TO DISK

CHEMICAL MODELS

- × 10s to 100s of species
- × 10s to 1000s of reactions
- × Gas phase: ion-molecule and neutral-neutral
- × Optional: photoprocesses
 - adsorption/desorption
 - grain-surface chemistry
 - isotopes
- × Equilibrium or time-dependent
- × Coupled with or uncoupled from physics

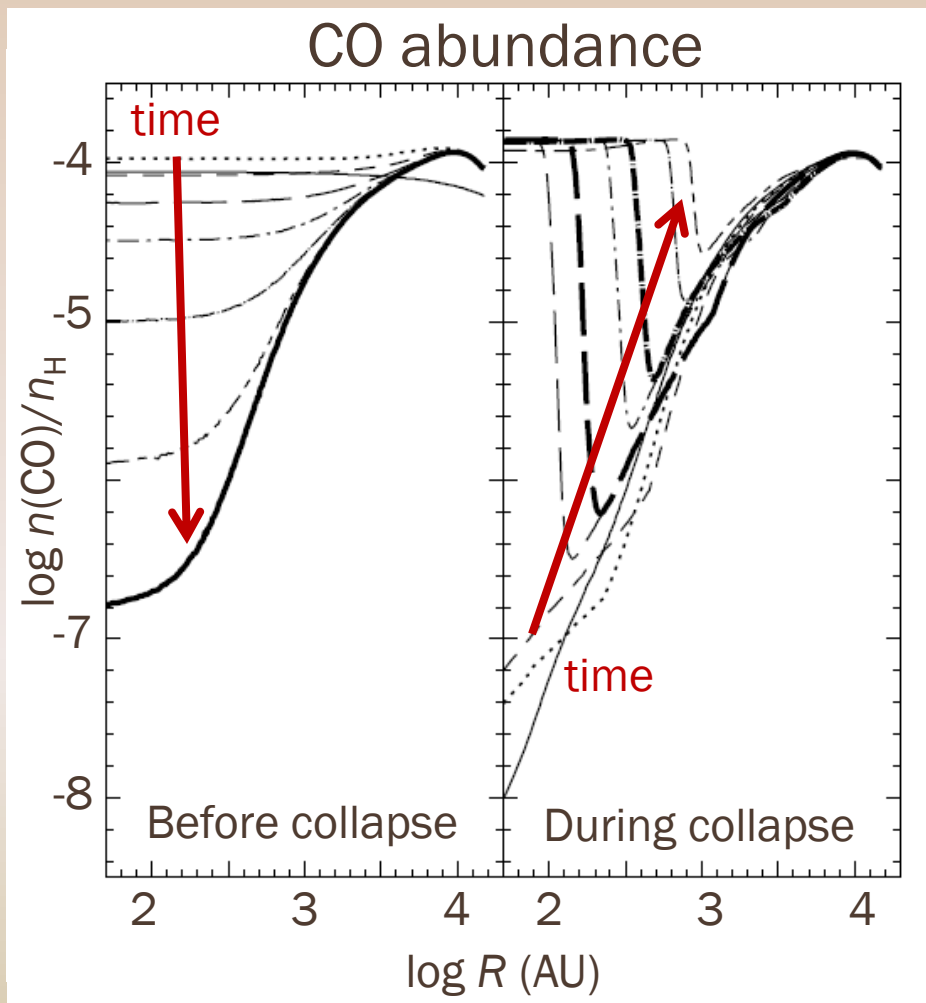
GLOBAL CHEMICAL COMPOSITION

0.1 1 5 R (AU) 100



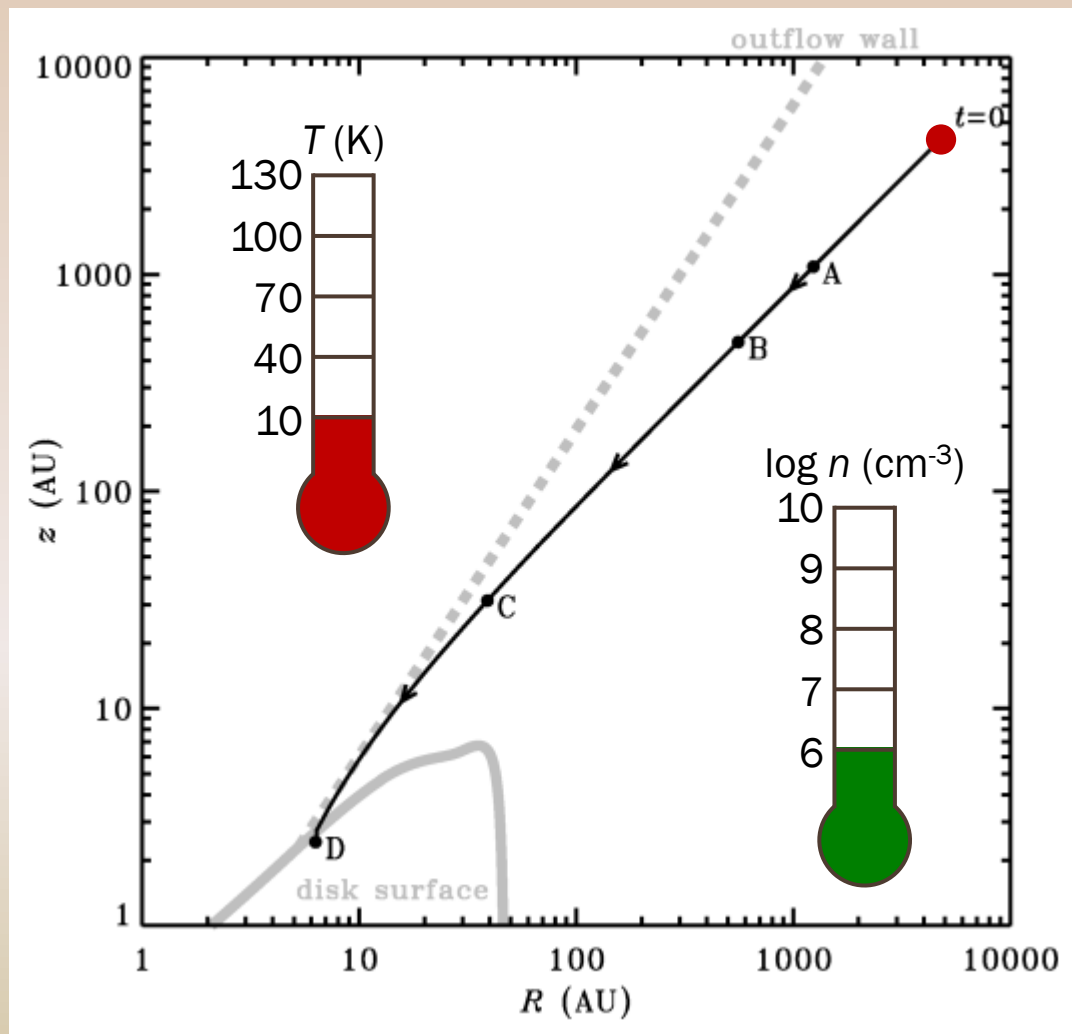
Aikawa & Herbst (1999), Bergin et al. (2007)

CHEMICAL EVOLUTION: PROTOSTAR (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

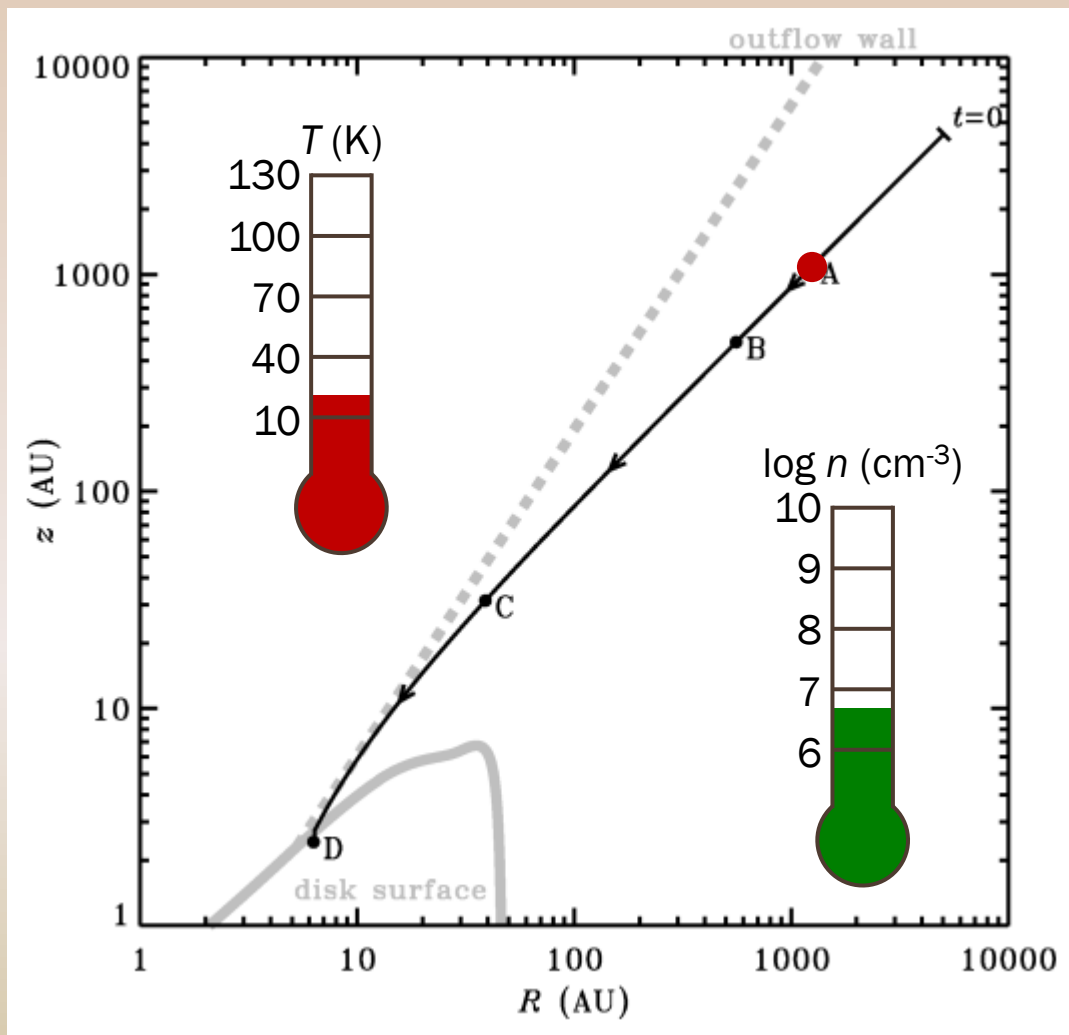
CHEMICAL EVOLUTION: PROTOSTAR + DISK (2D)



Point A:

- ✗ CO, N₂, O₂ evaporate
- ✗ HCO⁺, N₂H⁺ formed
- ✗ H₂O, CH₄, NH₃, NO remain frozen

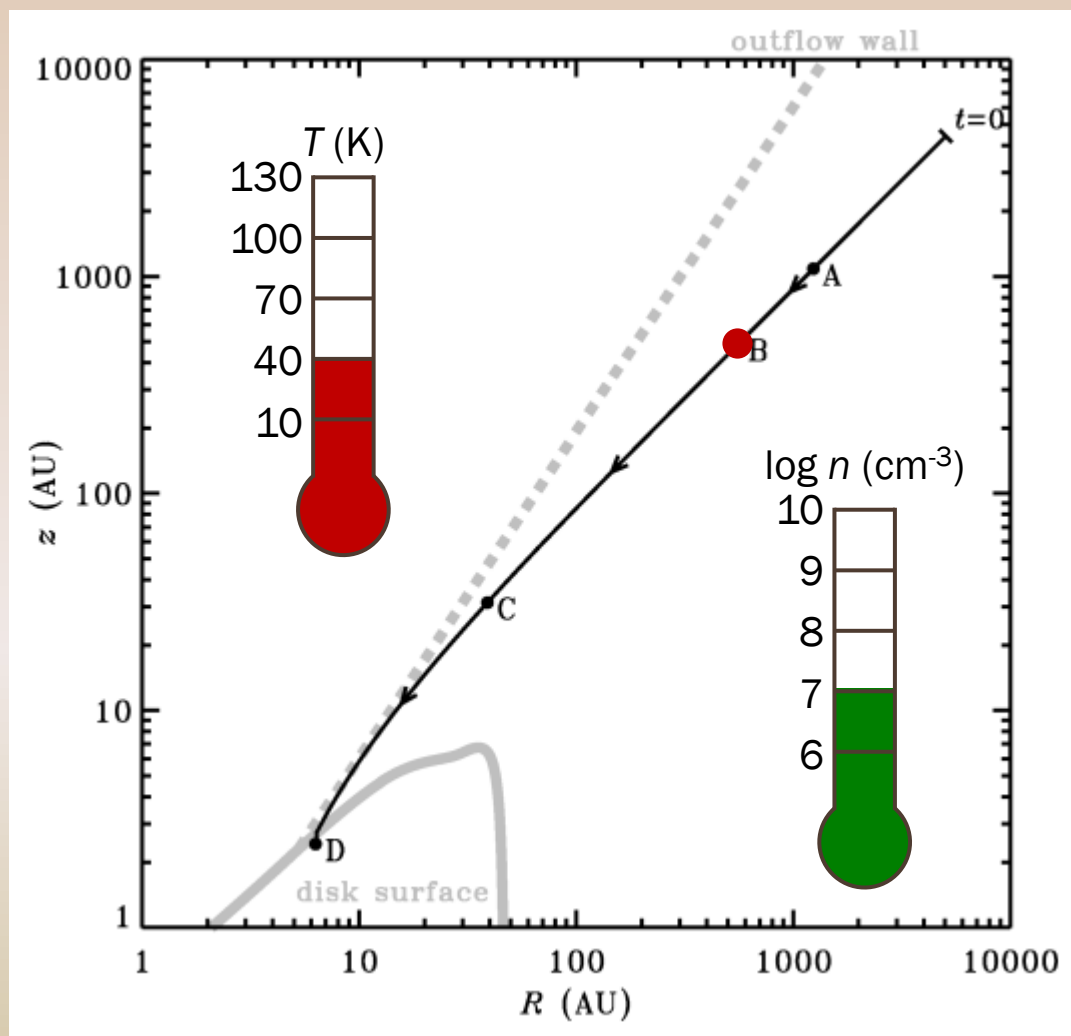
CHEMICAL EVOLUTION: PROTOSTAR + DISK (2D)



Point B:

- ✗ CH₄, NO evaporate
- ✗ CO, N₂, O₂ remain in gas
- ✗ H₂O, NH₃ remain frozen

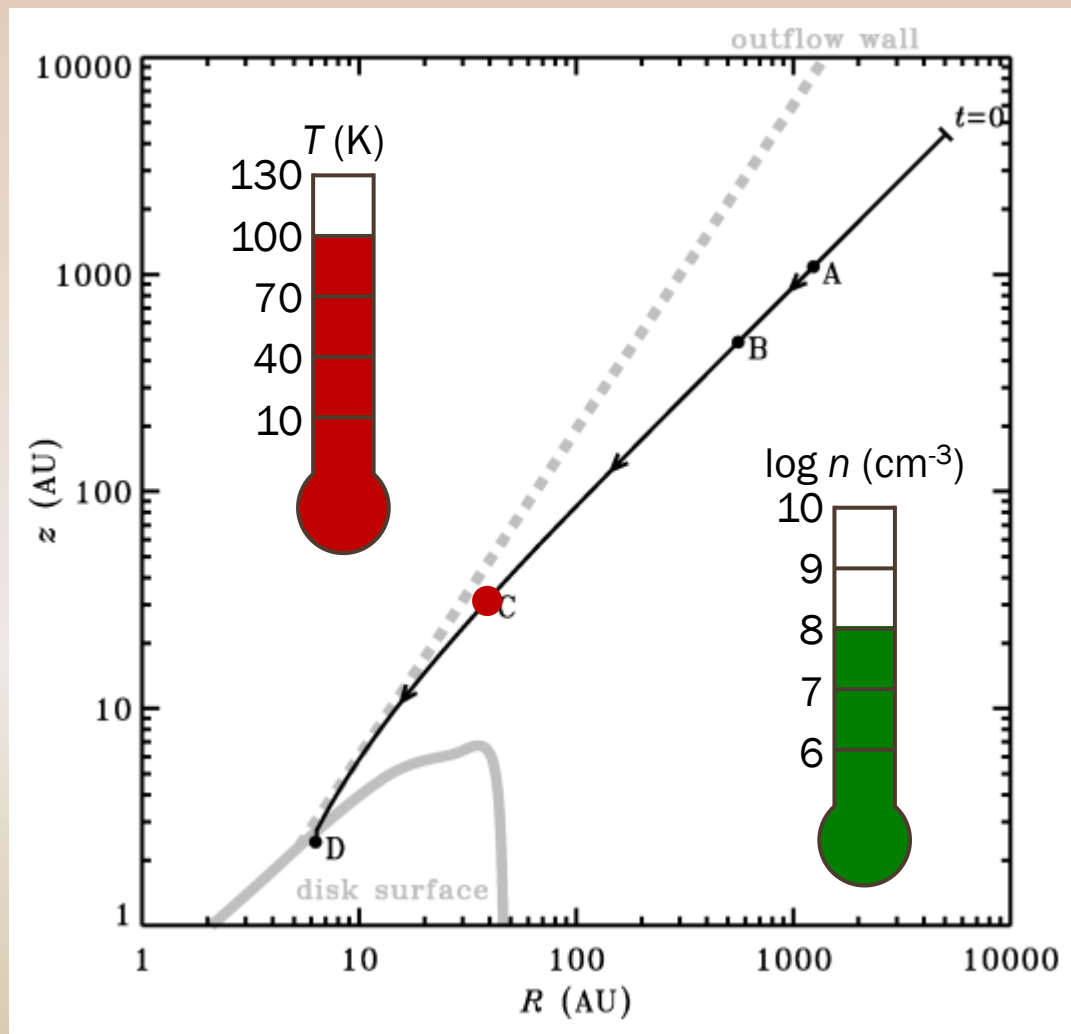
CHEMICAL EVOLUTION: PROTOSTAR + DISK (2D)



Point C:

- ✗ NH_3 , H_2O evaporate
- ✗ NH_3 , H_2O , O_2 , CH_4 photodissociated
- ✗ CO , N_2 may survive

CHEMICAL EVOLUTION: PROTOSTAR + DISK (2D)



Point D:

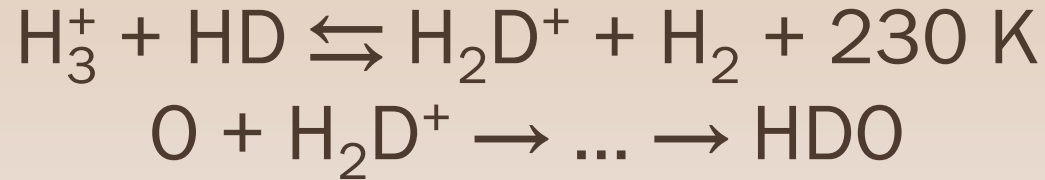
- ✘ Some NH_3 , H_2O , CH_4 reformed
- ✘ CO , N_2 most abundant

PART II: DISK CHEMISTRY

B. ISOTOPE EXCHANGE

DEUTERIUM FRACTIONATION

- × D enhancement at $T \lesssim 20$ K:



- × D/H re-equilibration at $T > 100$ K:

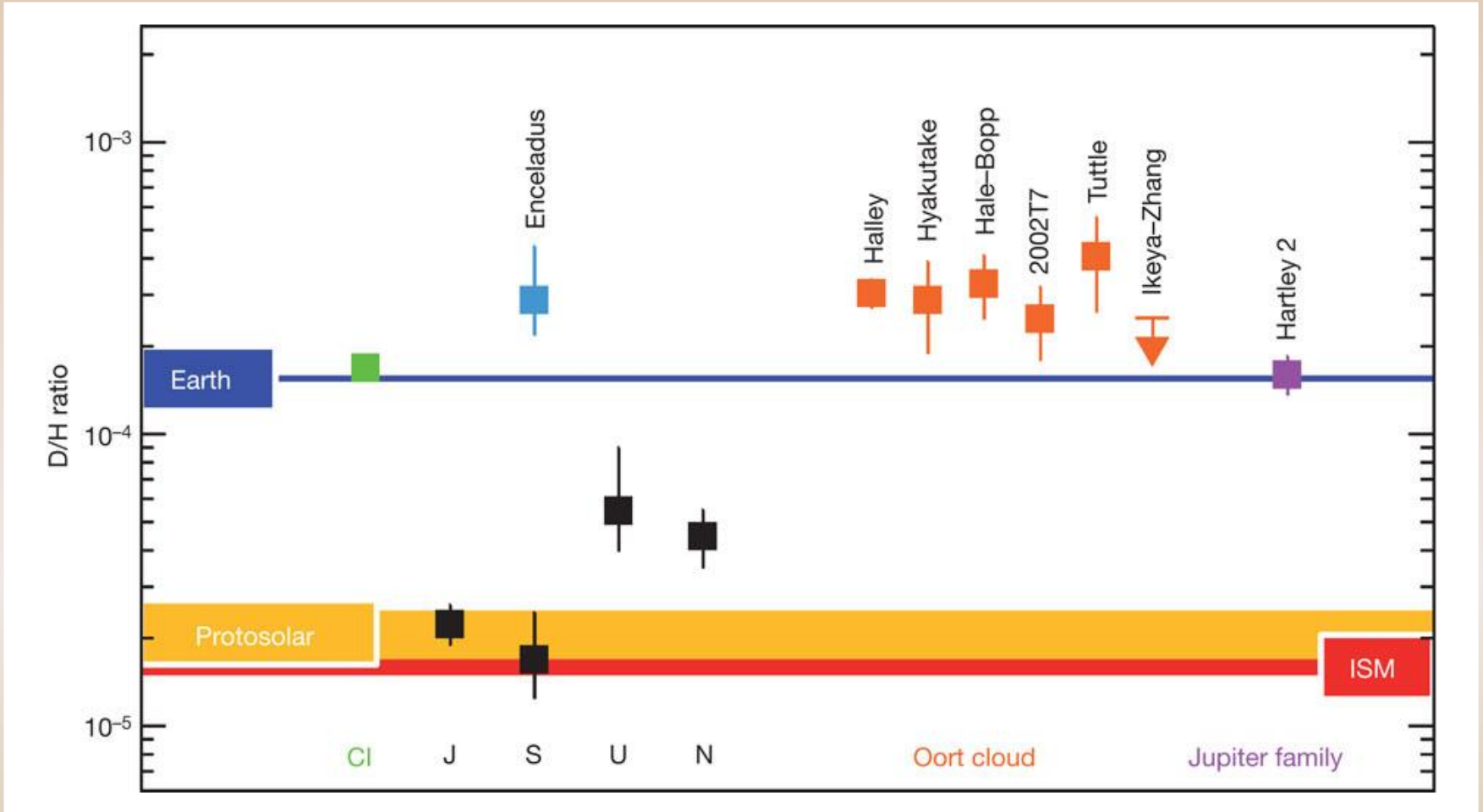


- × D enhancement at $T > 100$ K and low A_V ?



- × D fractionation on grain surfaces?

DEUTERIUM FRACTIONATION



No model can currently explain the D/H trend in the solar system

CARBON AND OXYGEN FRACTIONATION

× Isotope-selective photodissociation

× ^{13}CO enhancement at $T \lesssim 10$ K:



× No such reactions for oxygen (no O^+ available)

× Suprathermal chemistry?

- Alfvén waves can enhance ion-neutral rates

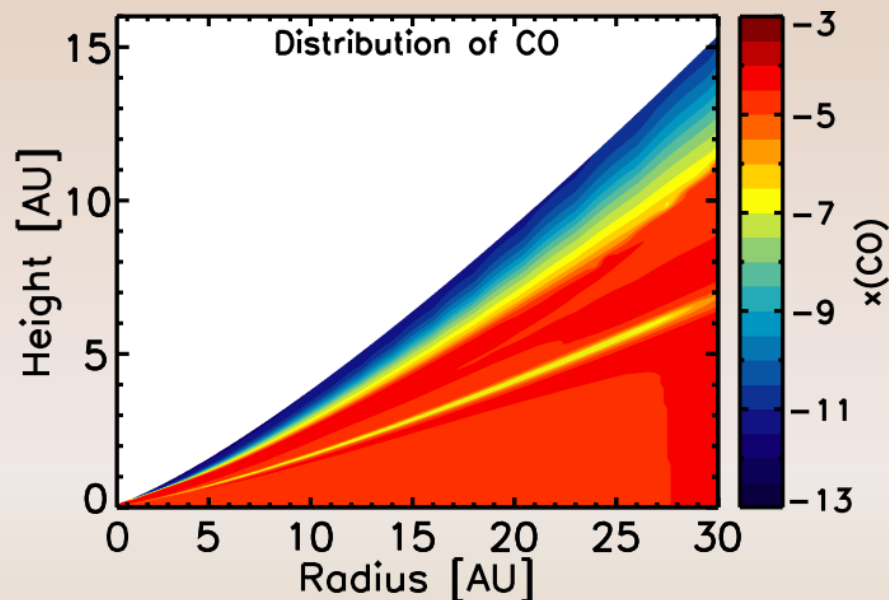
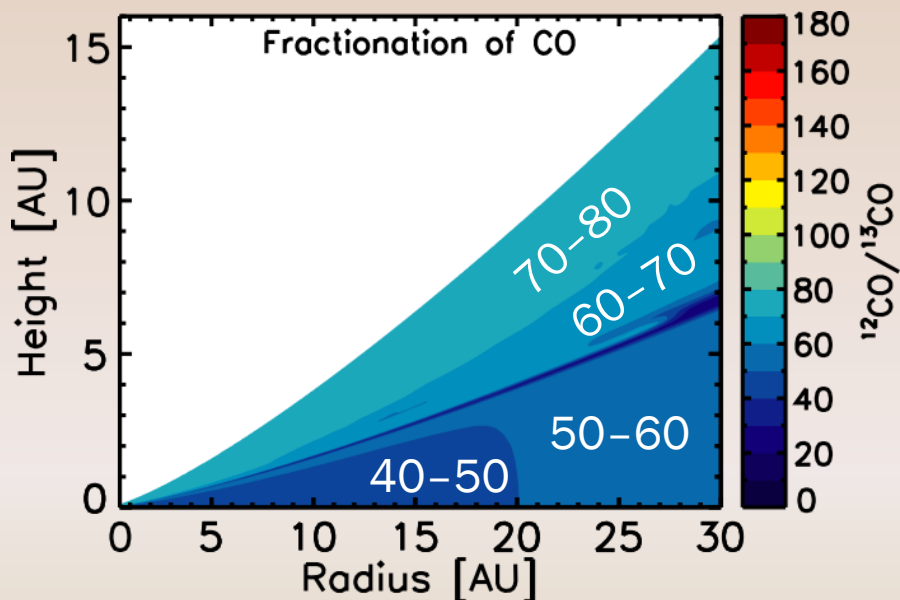
$$T_{\text{eff}} = T_{\text{gas}} + \frac{\mu v_{\text{A}}^2}{3k}$$

reduced mass \swarrow

\nwarrow Alfvén speed (few km s^{-1})

CARBON FRACTIONATION IN DISKS

✘ Model: $M_* = 0.7 M_\odot$, $M_d = 0.032 M_\odot$, $\dot{M} = 10^{-8} M_\odot \text{ yr}^{-1}$



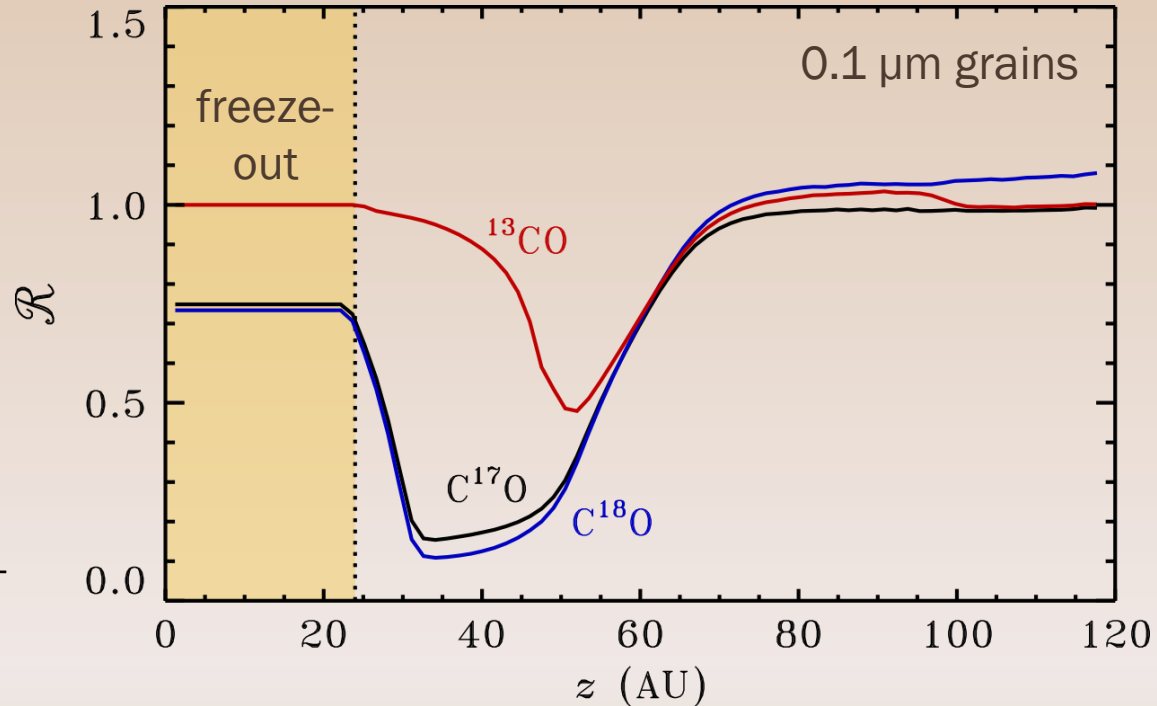
✘ Observed: 54 ± 15 (GV Tau, Gibb et al. 2007)

76 ± 9 (HL Tau, Brittain et al. 2005)

C AND O FRACTIONATION IN DISKS



$$\mathcal{R}(^{13}\text{CO}) = \frac{N(^{13}\text{CO})}{N(^{12}\text{CO})} \frac{[^{12}\text{C}]}{[^{13}\text{C}]}$$



- ✗ ^{13}CO , C^{17}O , C^{18}O all reduced relative to ^{12}CO
- ✗ Low- T chemistry replenishes some ^{13}CO
- ✗ $\varepsilon(^{18}\text{O}) = \varepsilon(^{17}\text{O})$, consistent with meteorites

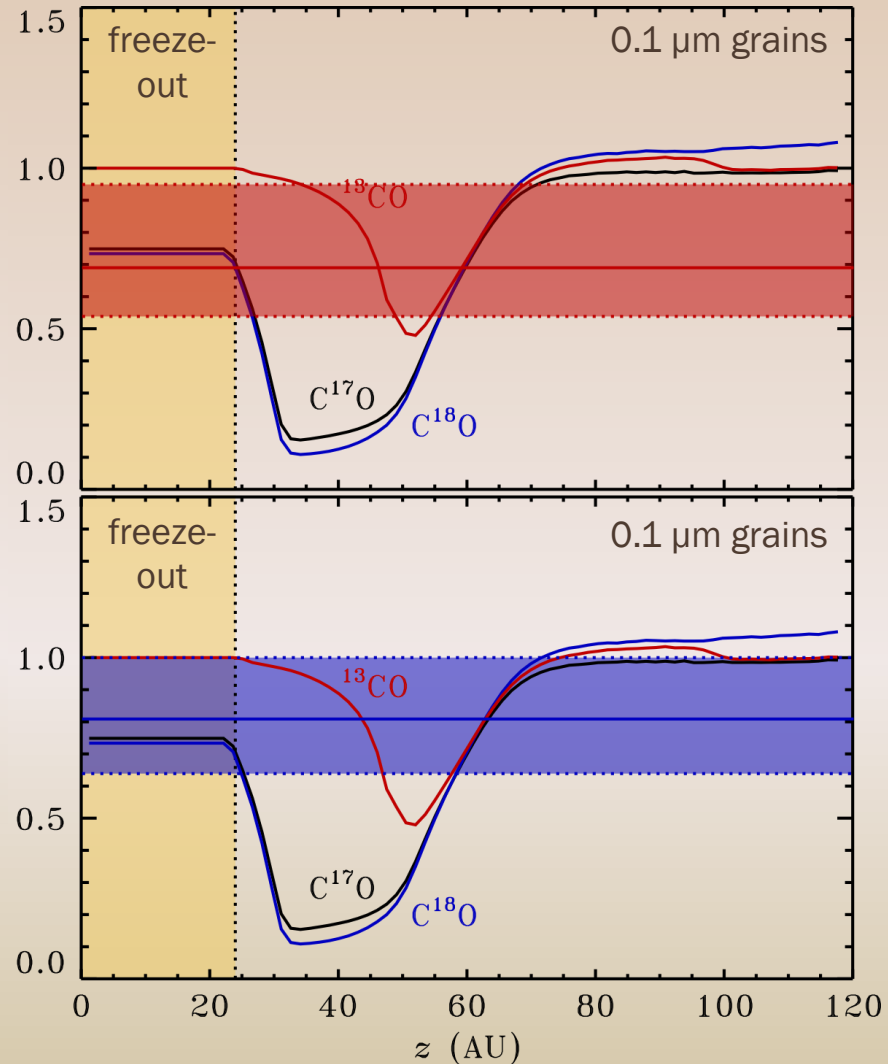
C AND O FRACTIONATION IN DISKS

^{13}CO in VV CrA
(Smith et al. 2009)

Note: $\mathcal{R} \approx 1$ in HL Tau
 $\mathcal{R} > 1$ in GV Tau

C^{17}O and C^{18}O in VV CrA

^{17}O , ^{18}O seem to be understood,
 ^{13}C not yet



NITROGEN FRACTIONATION

- ✘ N_2 also prone to self-shielding
- ✘ Experimental cross sections for $^{14}N_2$ available
(Sprengers et al. 2003–2006; Vieitiz et al. 2007–2008; Lewis et al. 2008)
- ✘ Xiaohu Li working on similar model as CO
- ✘ Need cross sections for $^{14}N^{15}N$ (and $^{15}N_2$)

CLOSING THOUGHTS

TOPICS FOR DISCUSSION

- ✘ Radial and vertical mixing
 - How to get $^{17}\text{O}/^{18}\text{O}$ into meteorites?
- ✘ Episodic accretion
 - Repeated cold/warm cycles could alter D/H
- ✘ Accretion shock
 - Is it really that weak?
- ✘ Suprathermal chemistry
 - Speed up $^{12}\text{CO} + ^{13}\text{C}^+$ to replenish ^{13}CO ?