The Role of Disk Volatile Chemistry and Dynamics in Shaping the Compositions of Nascent Planets

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Collaborators: Ruth Murray-Clay, Til Birnstiel, Ilse Cleeves
Thesis Advisory Committee: Matthew Holman, Sean Andrews, Dimitar Sasselov

TAC Meeting Presentation: April 29th, 2015

Outline

1. The disk-planet connection
2. Previous Research: Minimum Core Masses for Planet Formation
3. Protoplanetary disk compositions
4. Proposed Research
   - Radial drift of solids, snowline locations and C/O ratios
   - Chemical effects
4. Preliminary Results
5. Proposed Completion Timeline

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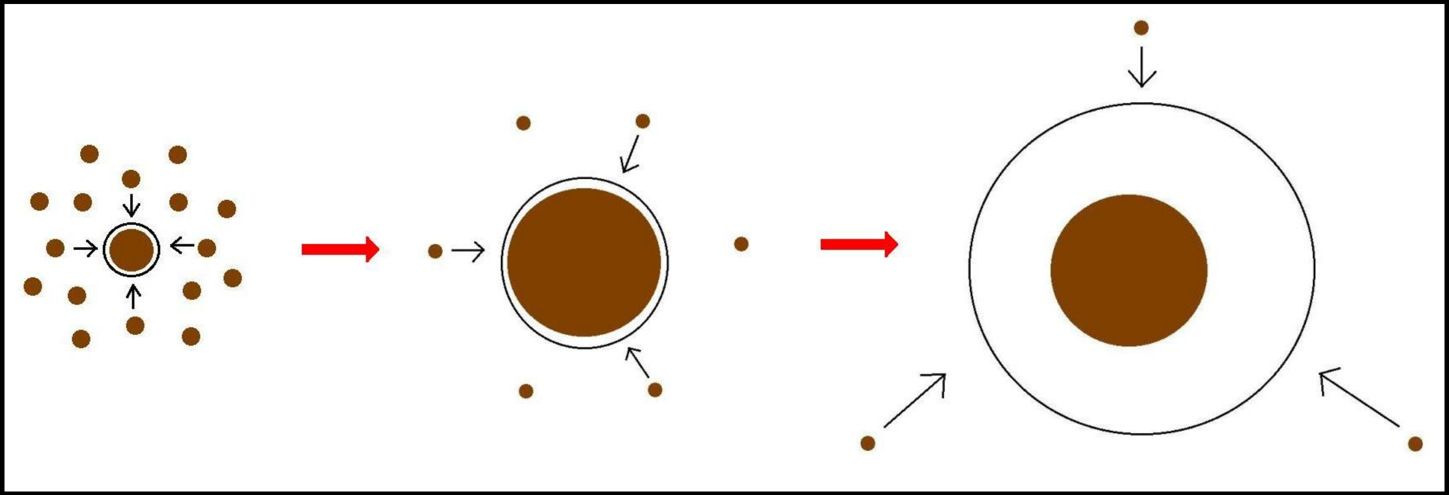
Core Accretion Model



The composition of planets is determined by and tightly linked to the disk composition

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Research Project: Minimum Core Masses for Giant Planet Formation

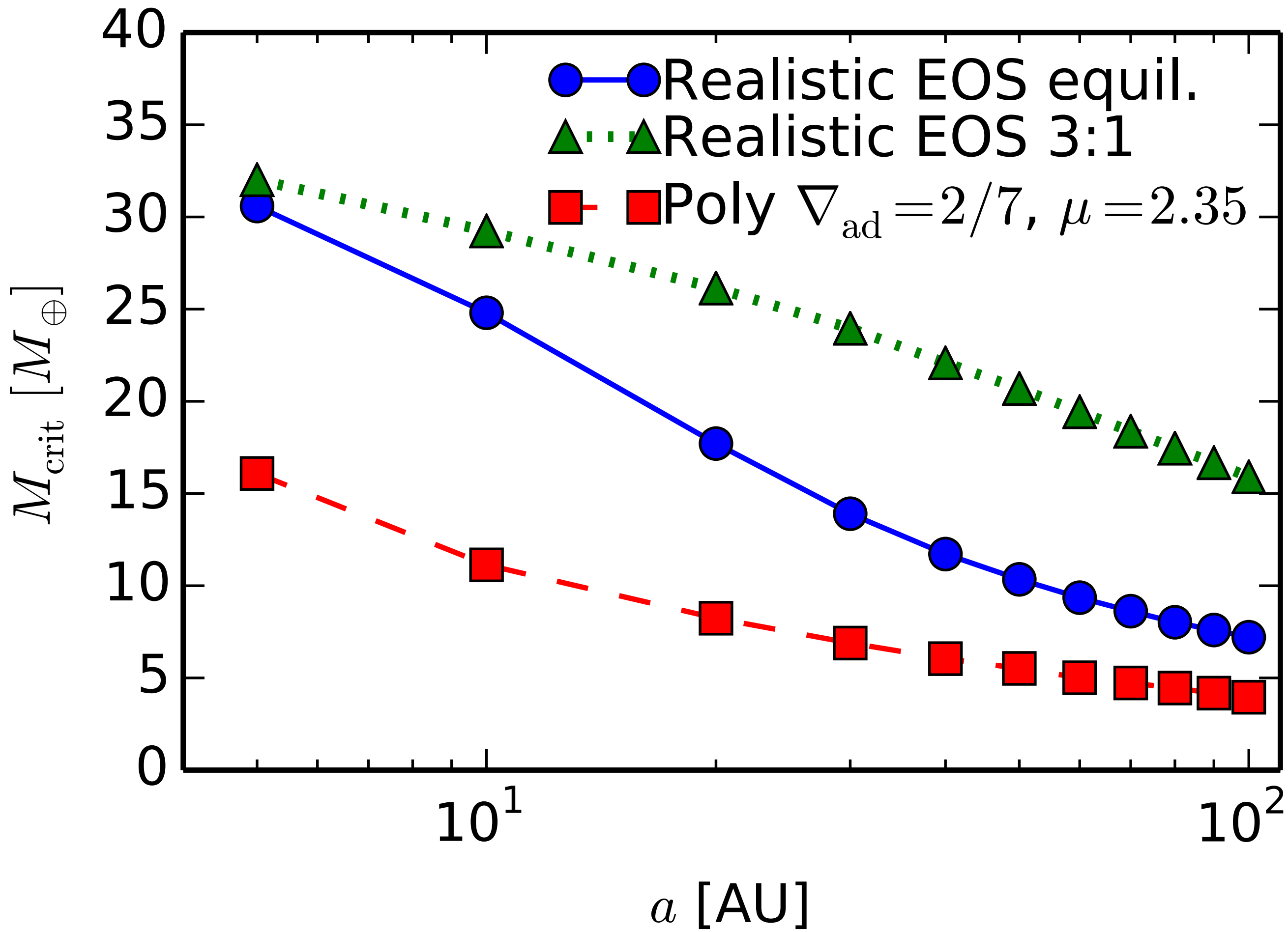
- Supervised by Dr. Andrew Youdin and Dr. Ruth Murray-Clay
- Has resulted in two first-author publications:
  - Ana-Maria A. Piso and Andrew N. Youdin, On the Minimum Core Mass for Giant Planet Formation at Wide Separations. ApJ, 2014, 786, 21
  - Ana-Maria A. Piso, Andrew N. Youdin, and Ruth A. Murray-Clay, Minimum Core Masses for Giant Planet Formation with Realistic Equations of State and Opacities. Apj, 2015, 800, 82

GOAL

Determine the minimum core mass, M_{crit}, to form a giant planet during the disk lifetime in the low planetesimal accretion regime when atmosphere dominated by KH contraction

Calculate M_{crit} with
REALISTIC EQUATION OF STATE (EOS)
REALISTIC DUST OPACITIES

Variations in ∇_{ad} due to non-ideal EOS effects INCREASE M_{crit}



t_disk ~ 3 Myr, ISM opacity

Piso, Youdin, & Murray-Clay (2015)

Grain growth opacity DECREASES M_{crit}

$dN/ds \sim s^{-p}$

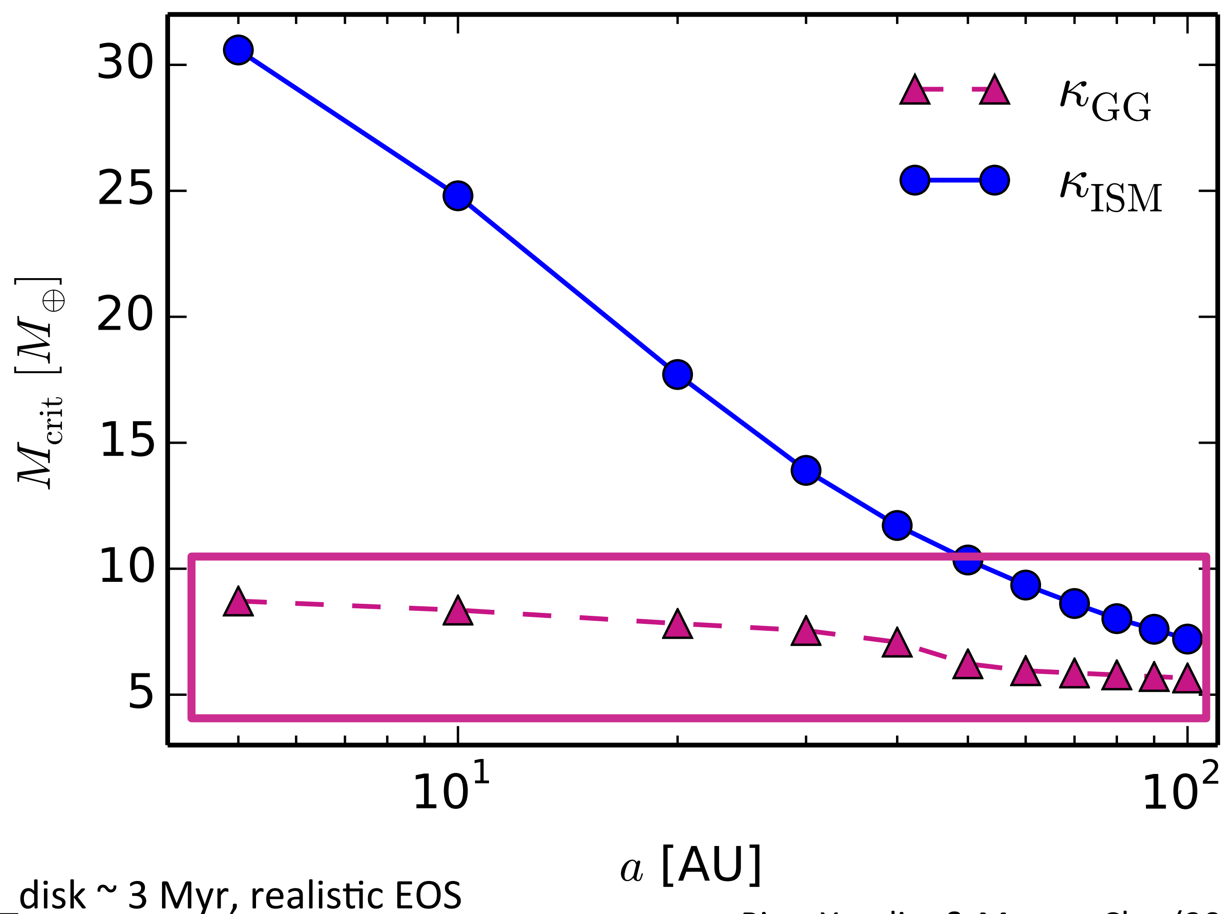
$p = 3.5$

$s_{max} = 1$ cm

M_{crit}:

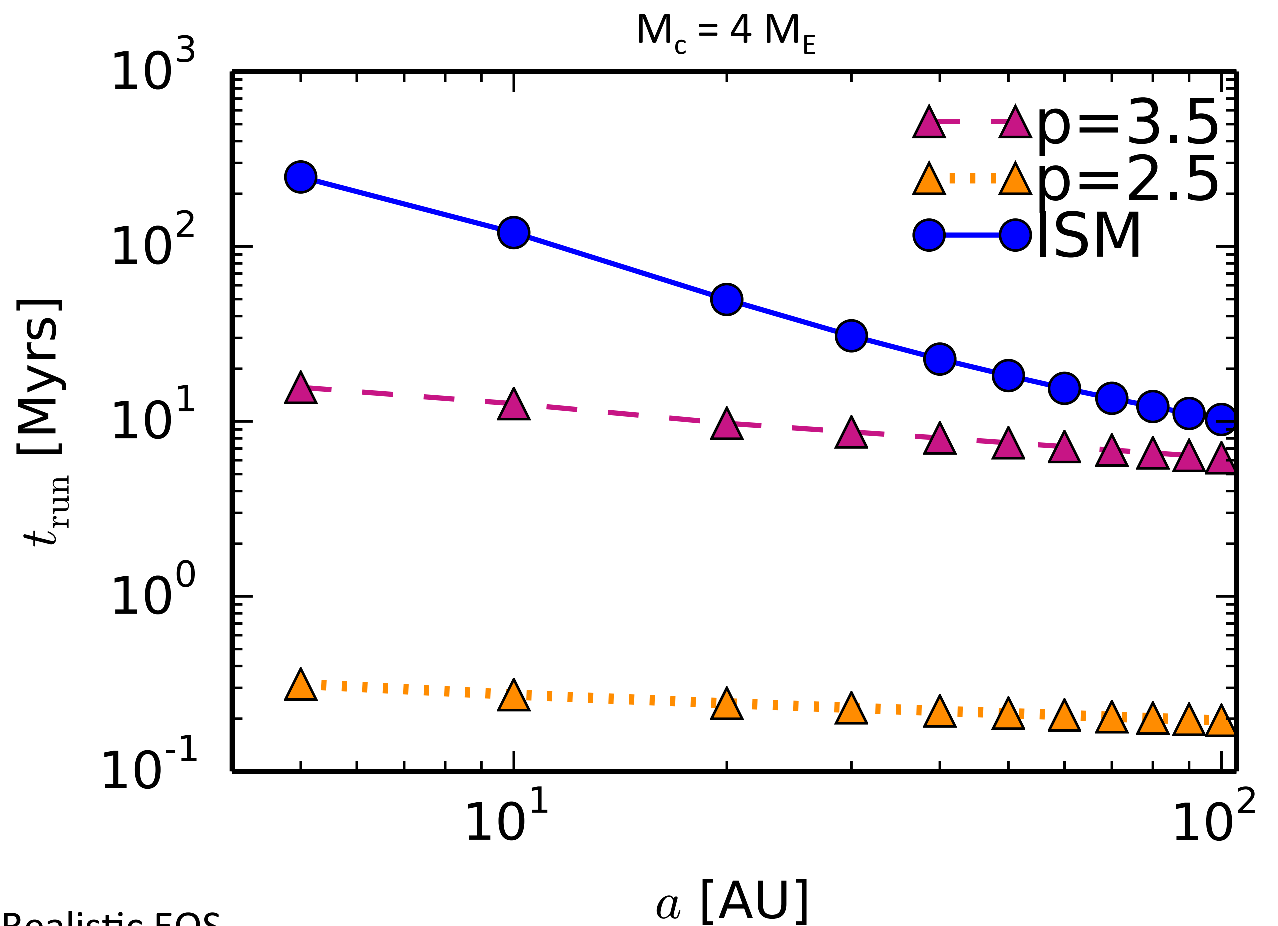
~8 M_E @ 5 AU

~5 M_E @ 100 AU



Piso, Youdin, & Murray-Clay (2015)

Coagulation *p=2.5* may decrease M_{crit} by up to one order of magnitude!



Realistic EOS

Piso, Youdin, & Murray-Clay (2015)

Summary

- H_2 dissociation and variable occupation of H_2 rotational states INCREASE M_{crit} when compared to an ideal gas polytrope
- Grain growth opacity DECREASES M_{crit} compared to ISM opacity
- M_{crit} ~ 8 M_E at 5 AU and ~ 5 M_E at 100 AU for a realistic EOS with H_2 spin isomers in thermal equilibrium and grain growth opacity with standard collisional cascade (*p=3.5*) and s_{max}=1 cm
- M_{crit} may decrease by up to one order of magnitude if coagulation is taken into account (*p=2.5*)

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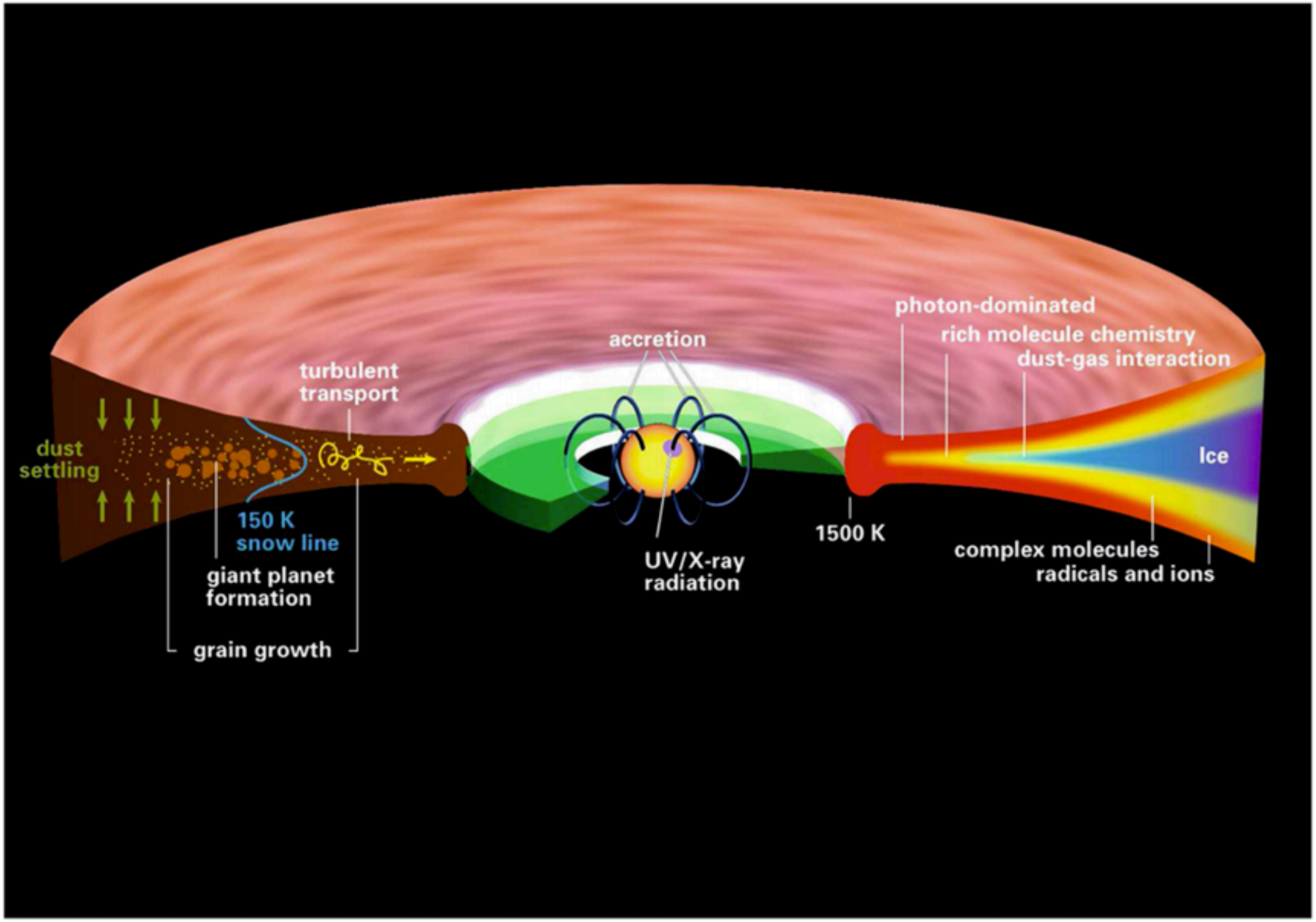
BASIC IDEA

The chemical composition of giant planet atmospheres can provide important constraints on the formation of these planets, as well as on their accretion and migration history

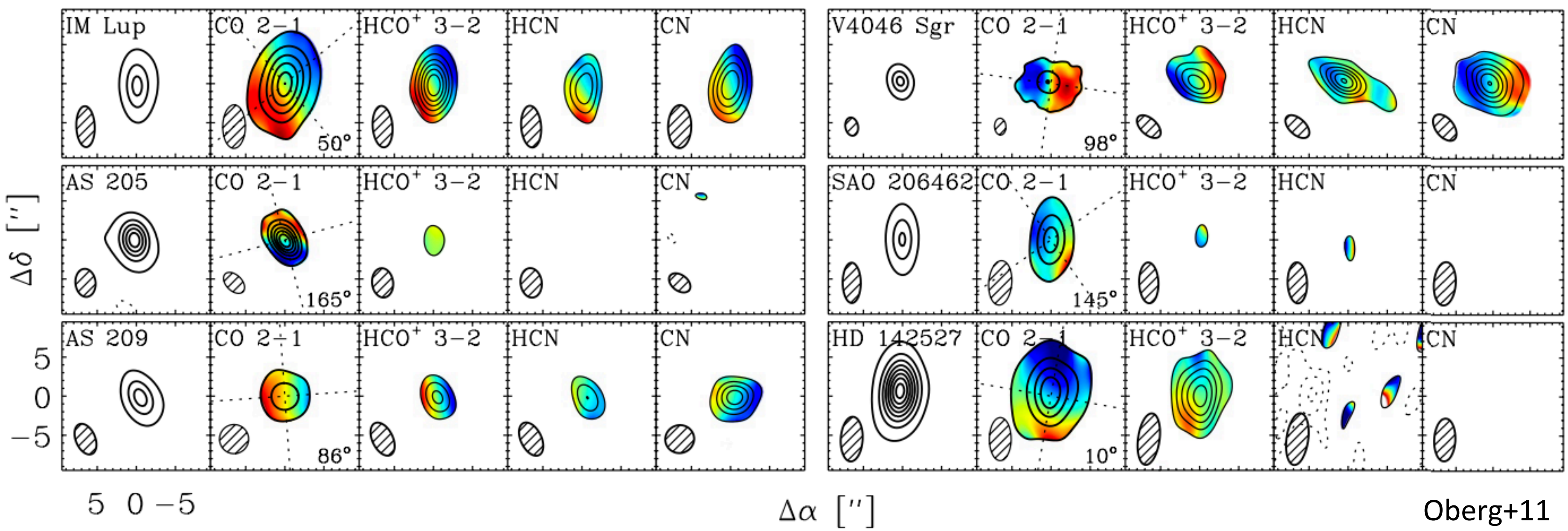
Understanding the composition of giant planet atmospheres can provide clues to the disk structure and chemistry itself

Disk structure is complex!



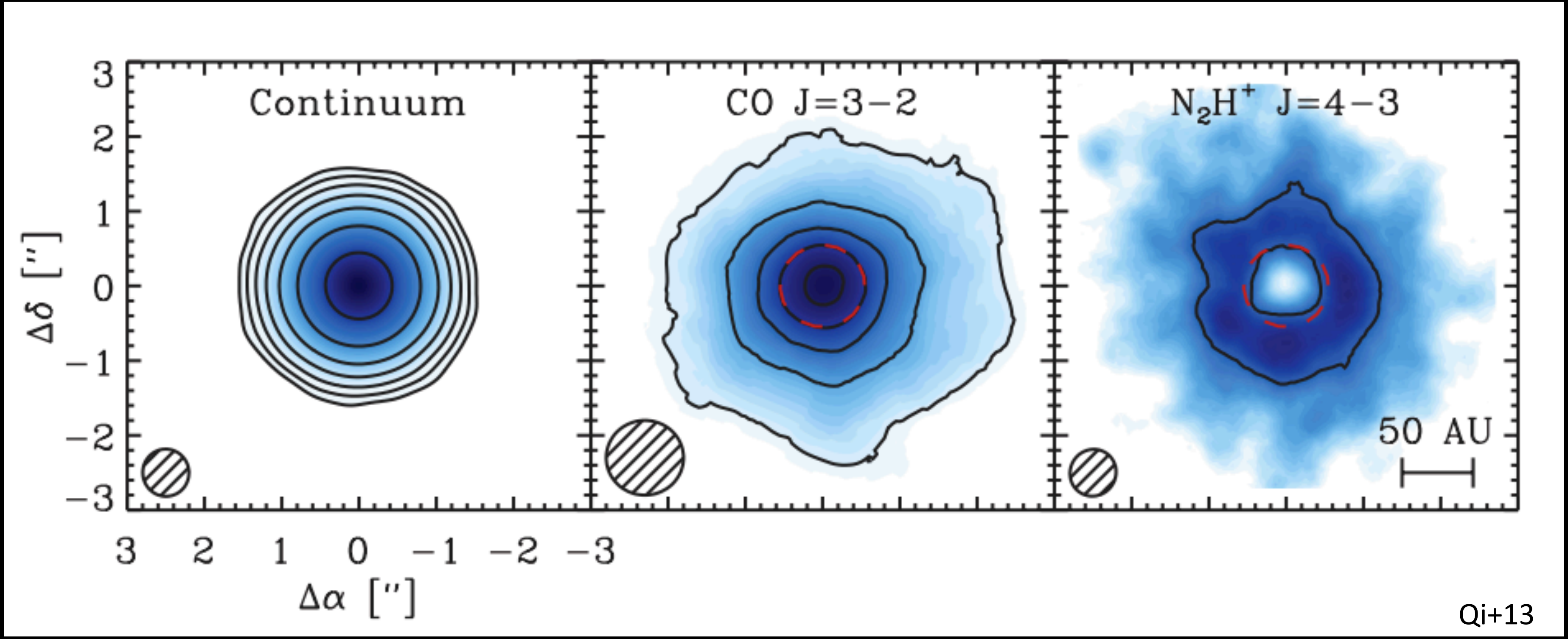
Henning&Semenov (2013)

Volatile compounds have been detected in the outer regions of protoplanetary disks



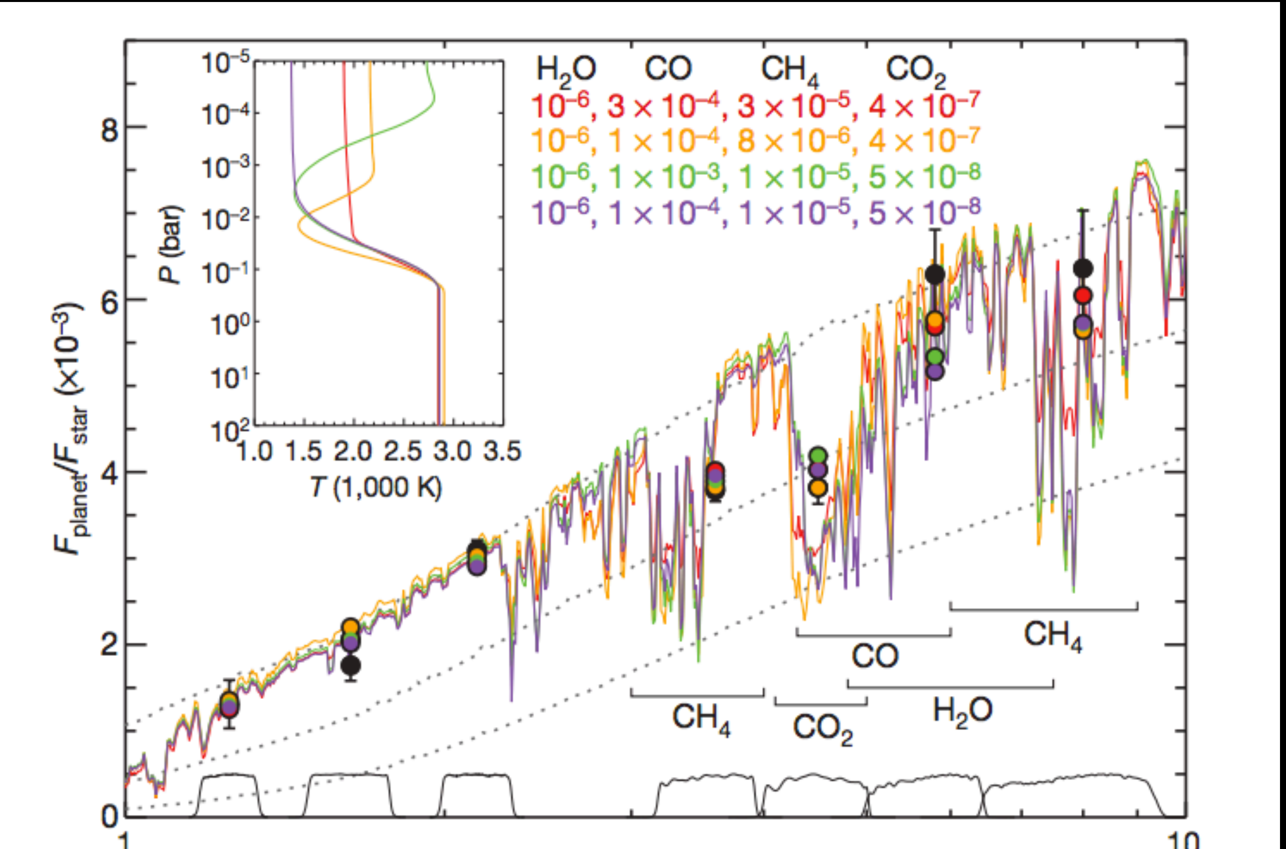
Oberg+11

Snowlines of volatile molecules have been detected in disks



C/O ratio is an important signature of atmospheric chemistry

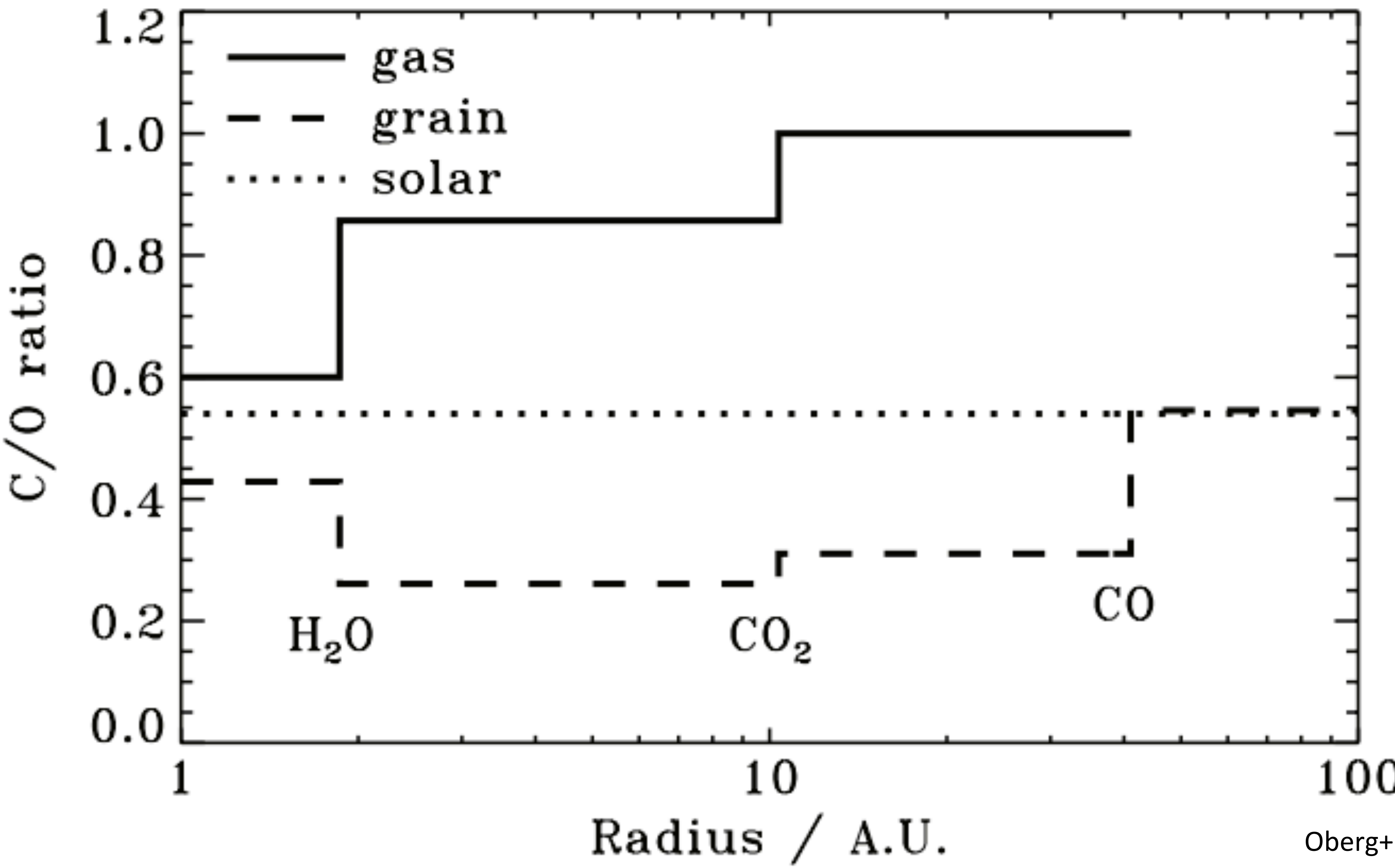
Some giant planets have C/O ratios different from the stellar value of 0.54



Madhusudhan+11

WHY?

Possible explanation: main carriers of C and O, i.e. H_2O, CO_2 and CO, have different condensation temperatures => variations in the abundances of C and O in solids and gas between the snow lines of these volatiles



gas
grain
solar
C/O ratio
1.2
1.0
0.8
0.6
0.4
0.2
0.0
H_2O
CO_2
CO
1
10
100
Radius / A.U.

Oberg+11

Additional chemical and dynamical processes affect C/O ratios in disks and disk chemistry

- The chemical composition and distribution of the main C and O carriers evolves with time (e.g., Vissser+09)
- Locations and shapes of snowlines evolve with time (e.g., Garaud & Lin 2007)
- Solids are redistributed throughout the protoplanetary disk due to radial drift (Chiang & Youdin 2010)
- Sun-like stars actively accrete gas from the disk (e.g., Hartmann+06)

GOAL

Explore and understand each of these processes, and their relative importance in shaping disk compositions throughout time

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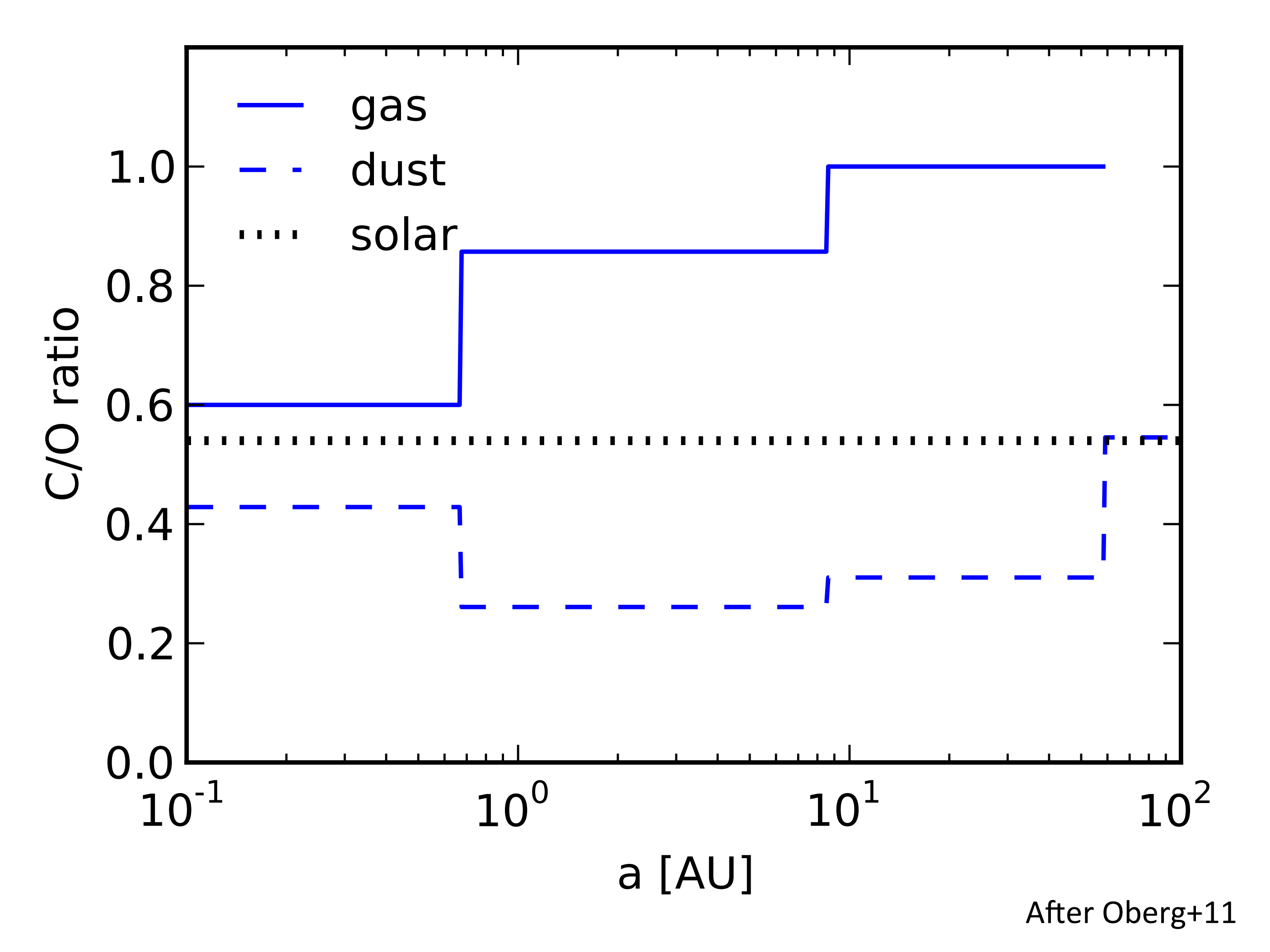
Observations show that C/O ratios in giant planet atmospheres are different from stellar



Radial drift of solids

- Gas moves at sub-Keplerian velocity:

  $v_{gas} \sim v_K \,(1 - c_s^2 \,/\, v_k^2)$

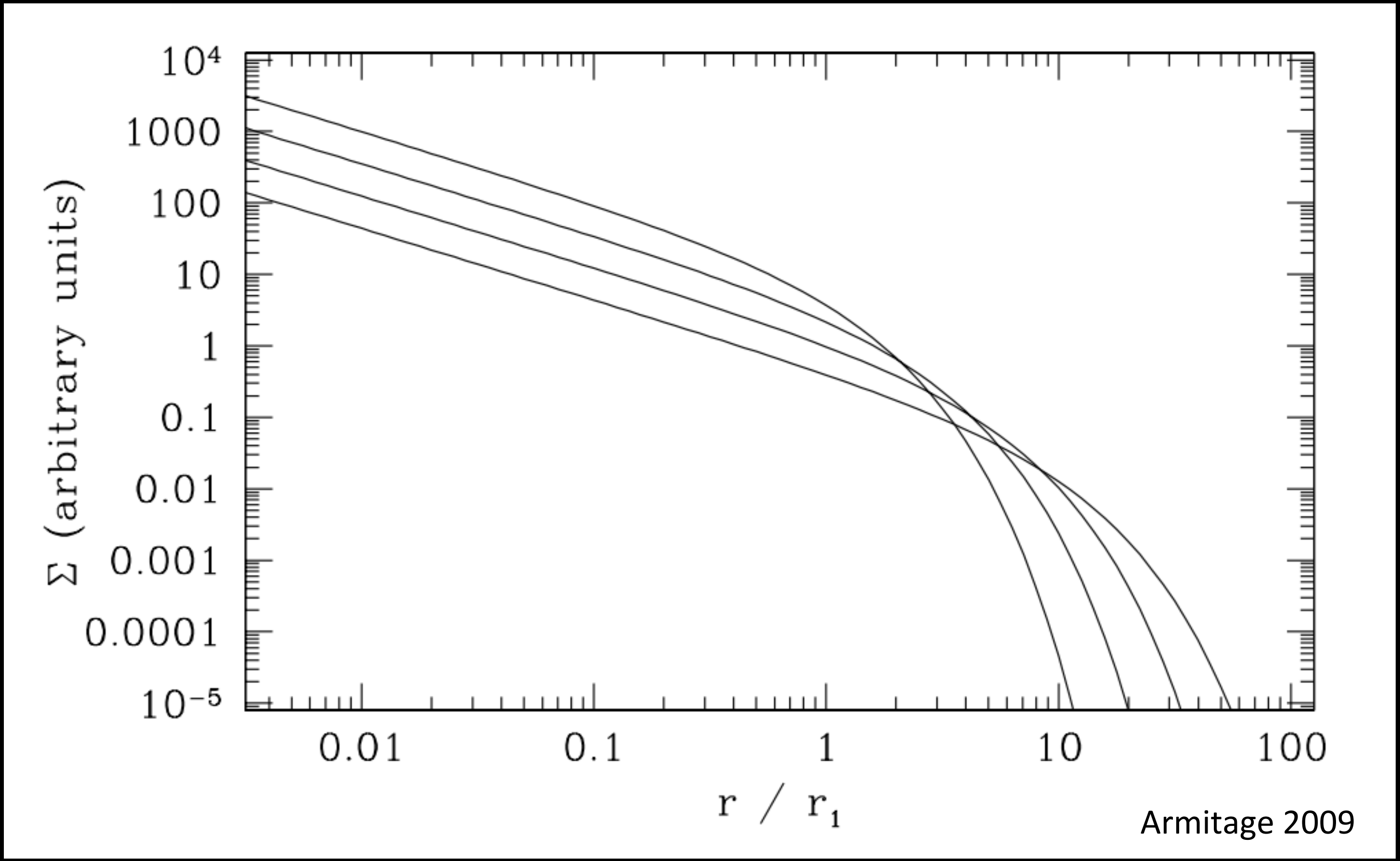
- Small particles (~micron size) move with the gas

- Large particles (~km size) are unaffected by gas drag

- "Intermediate sized" particles (~cm-m size) experience a headwind and drift towards the star

Gas disk accretes onto the central star

- alpha-disk prescription: $\nu = \alpha\, c_s\, H$



GOAL

Understand how radial drift and gas accretion affect snowline locations, and thus the C/O ratio in gas and dust throughout the disk

Add Nitrogen in the chemical and dynamical framework and explore its effects and the N/O ratio

Nitrogen Abundance

- Nitrogen is abundant in the Solar System and in disks, but its dominant form is largely unknown
- Primarily found as N_2, but ~10% of nitrogen abundance may be carried by NH_3 (e.g., Lahuis & van Dishoeck 2000)
- Can use abundance patterns both from the Solar System and from disk chemistry models (e.g., Schwarz & Bergin 2014) to define the range of abundance of different nitrogen carriers

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Gas-grain chemistry in disks is complex and evolves with time

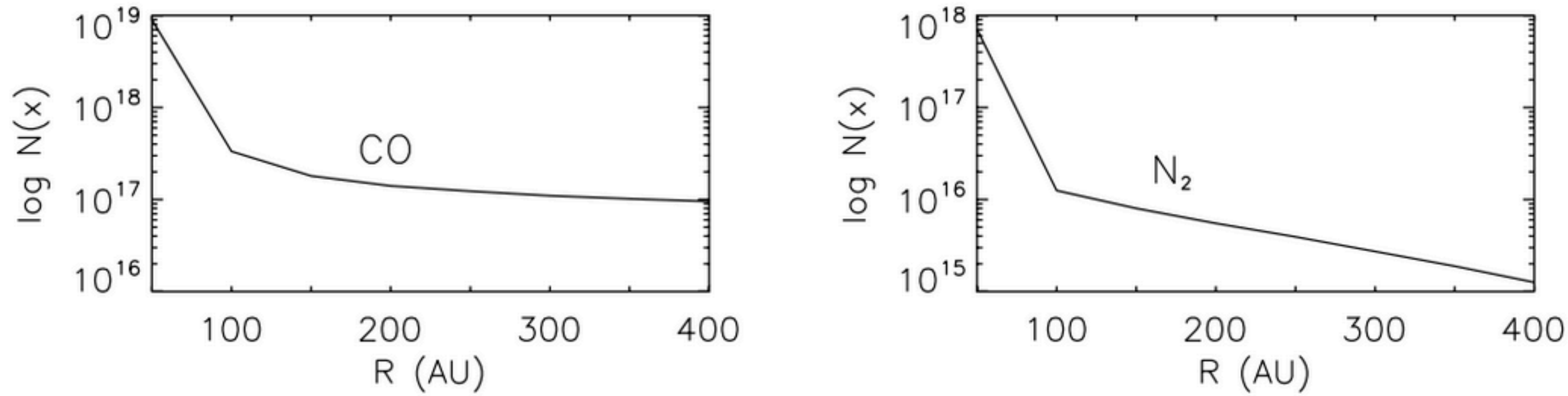
- Previous studies (e.g., Henning & Semenov 2013) have shown that disk chemistry is mostly regulated by disk temperature, density, stellar / interstellar radiation fields, and cosmic rays
- In the inner disk, chemistry approaches equilibrium due to intense sources of ionizing radiation (e.g., Ilgner+04)
- In the outer disk, high-energy radiation and cosmic rays are key drivers of the chemistry (e.g., van Dishoeck 2006) and chemistry is no longer in equilibrium
- Most chemical evolution models are decoupled from disk dynamics

GOAL

Parametrize the detailed, time-dependent chemical reaction network developed by Merchantz et al. (in prep.) and use it in the radial drift calculation

Parametrization of disk chemistry is possible

Willacy 2007



GOAL

Parametrize the detailed, time-dependent chemical reaction network developed by Merchantz et al. (in prep.) and use it in the radial drift calculation

Self-consistently evolve this chemical model and the disk dynamics

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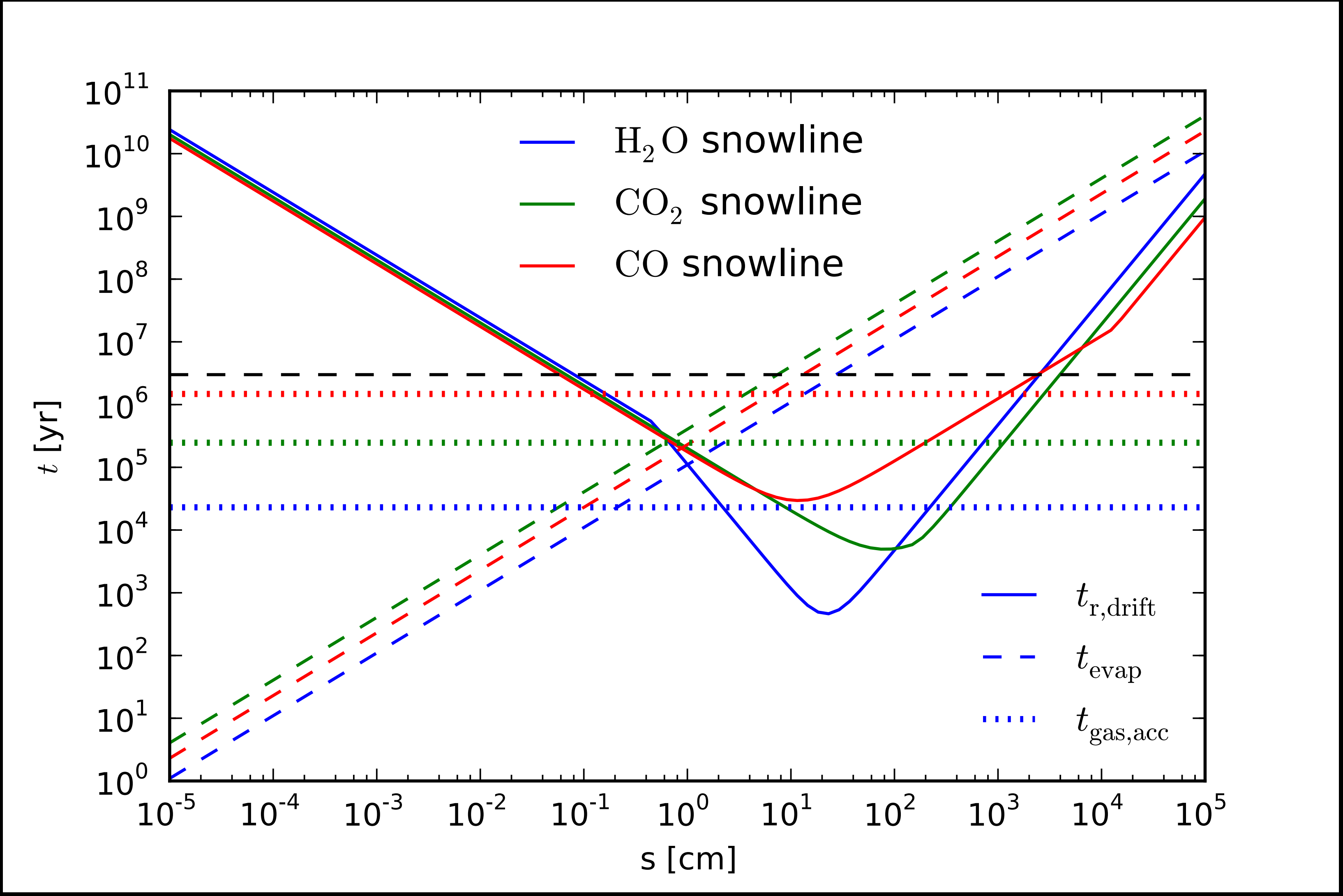
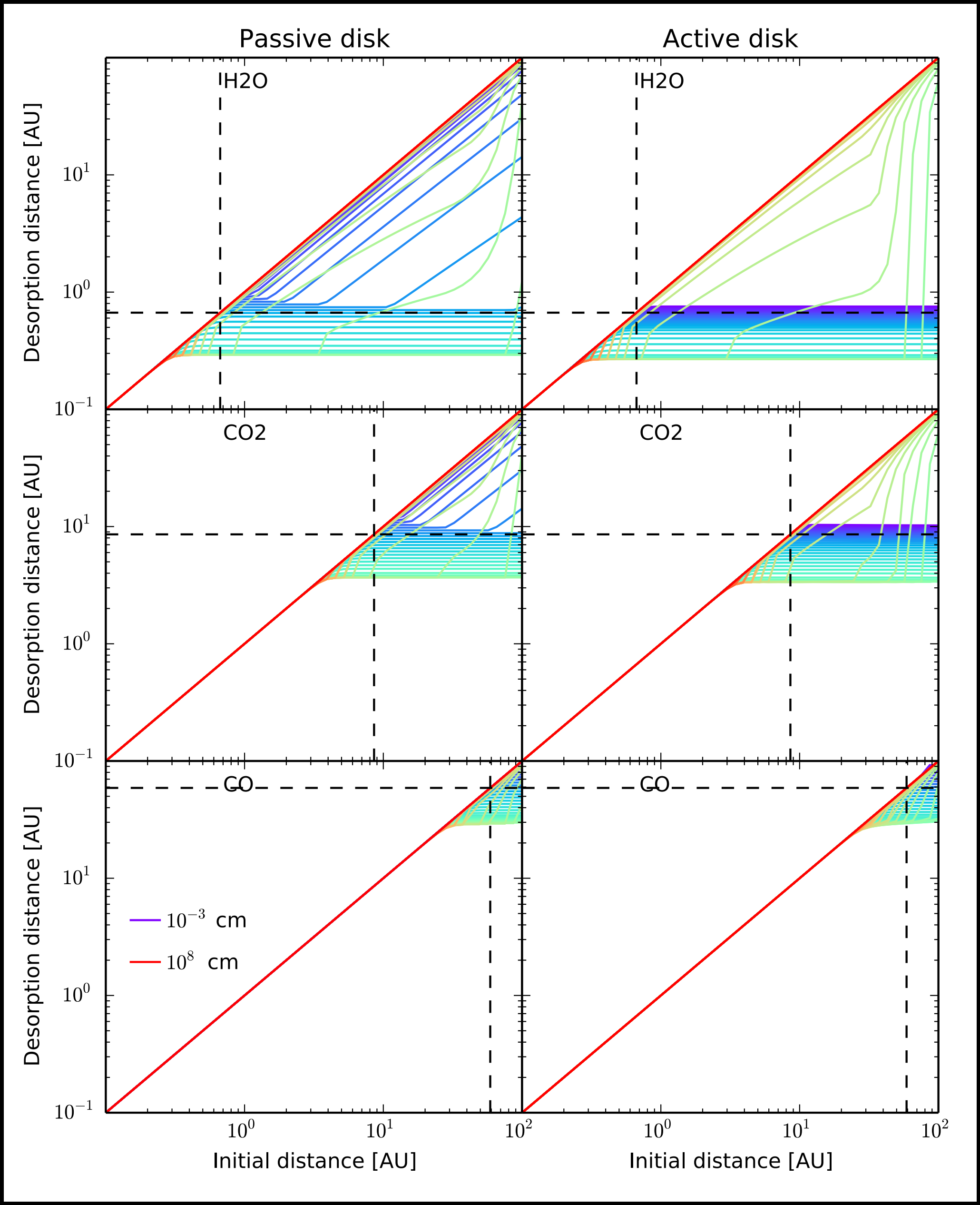
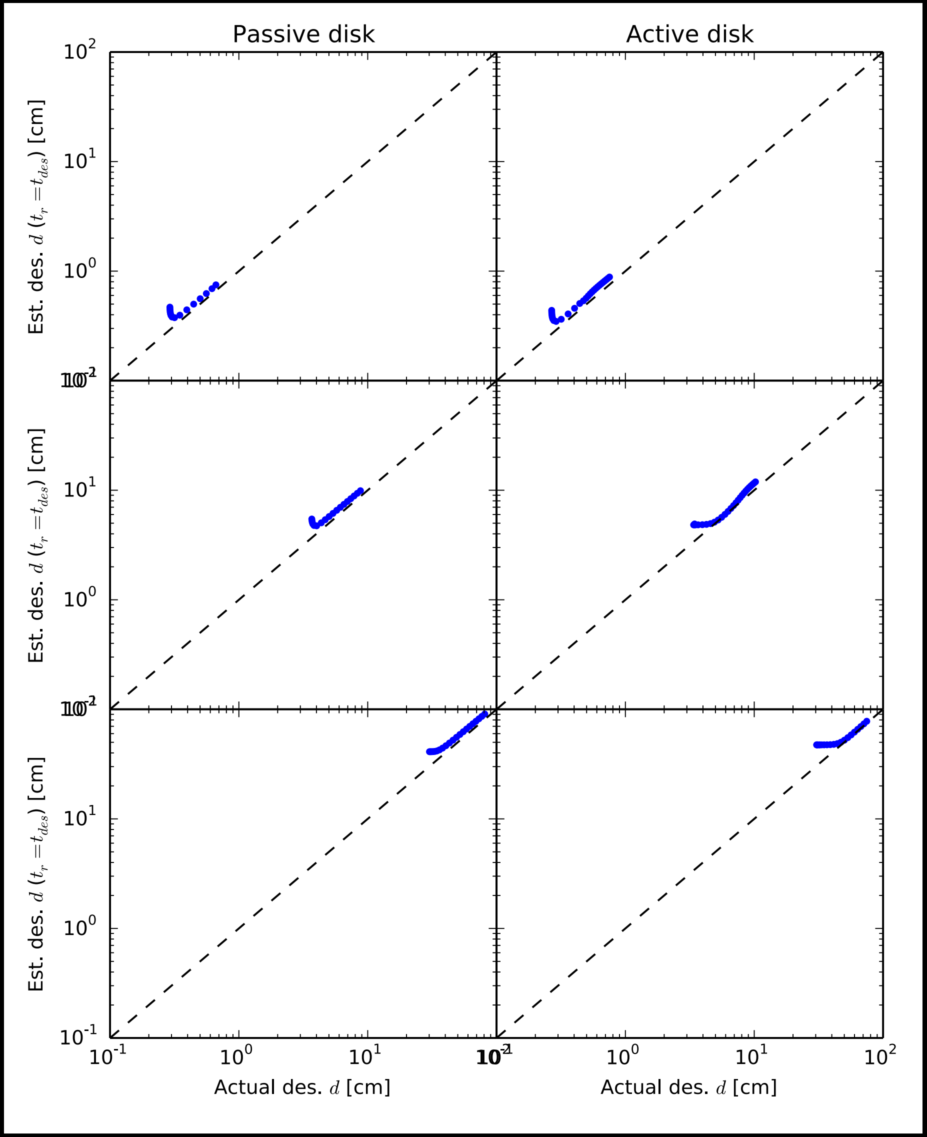
Timescales for desorption, radial drift and gas accretion ARE comparable



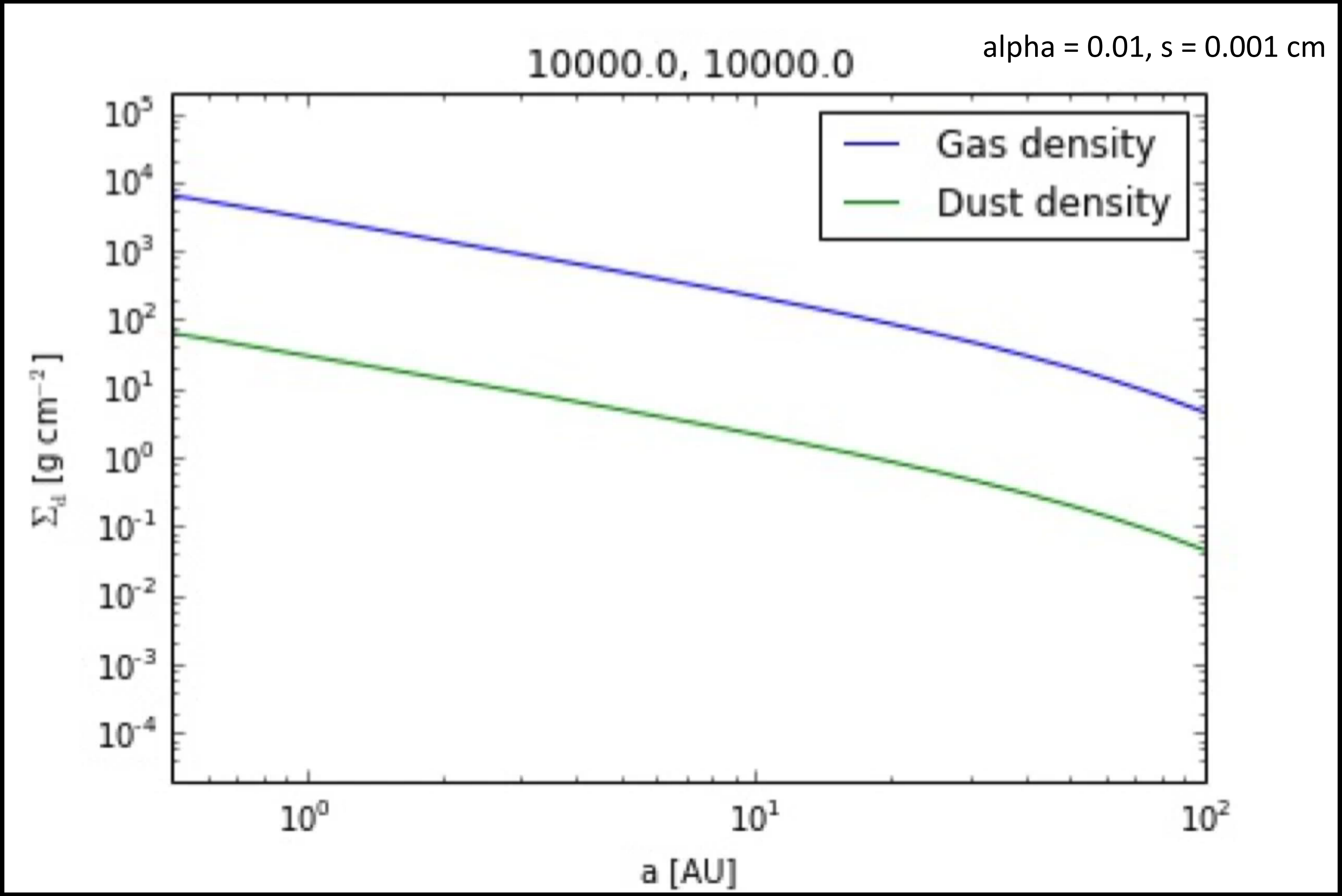
Radial drift affects snowline location



Analytic estimates and numerical results are in good agreement



Determined profiles for gas and dust surface densities



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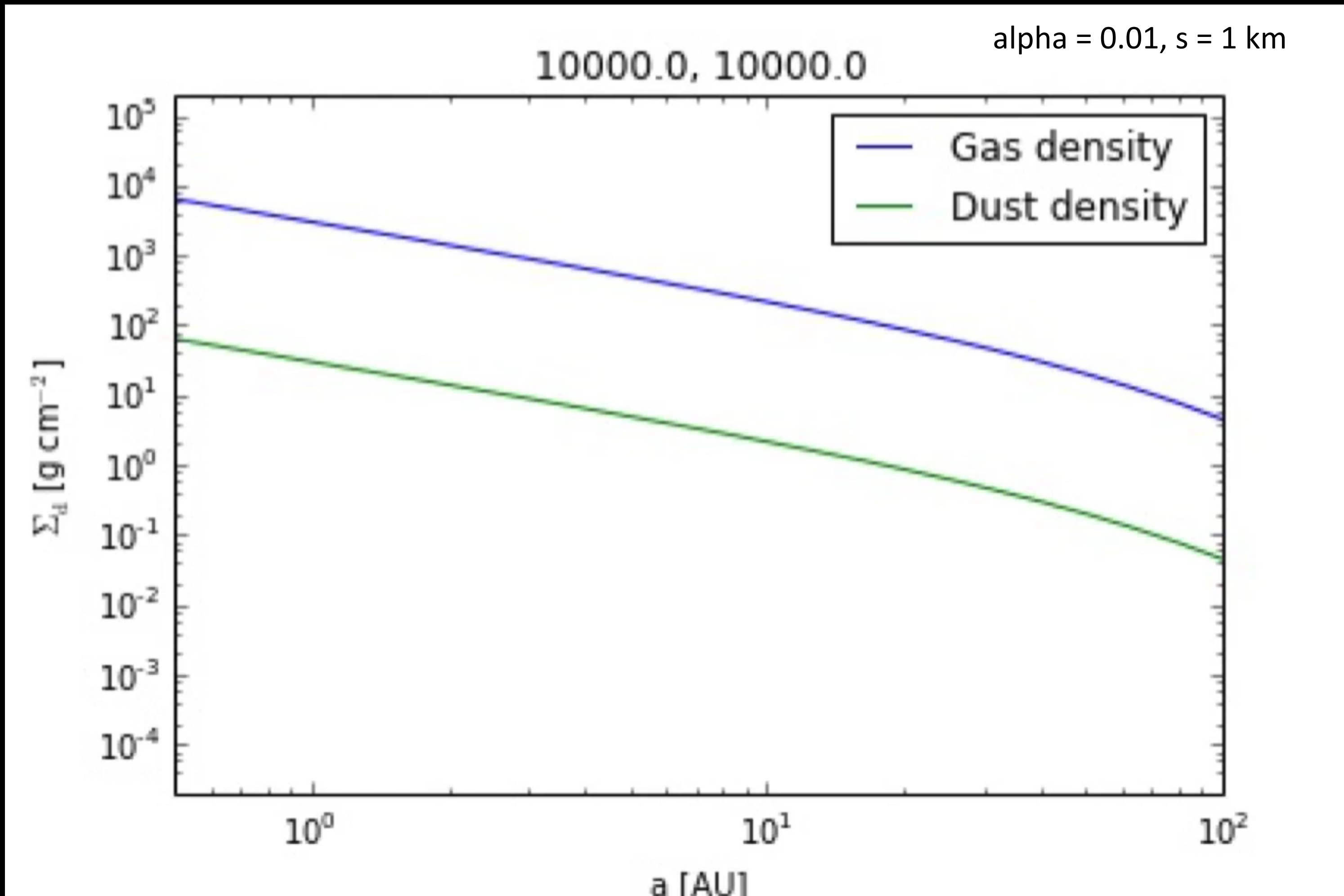

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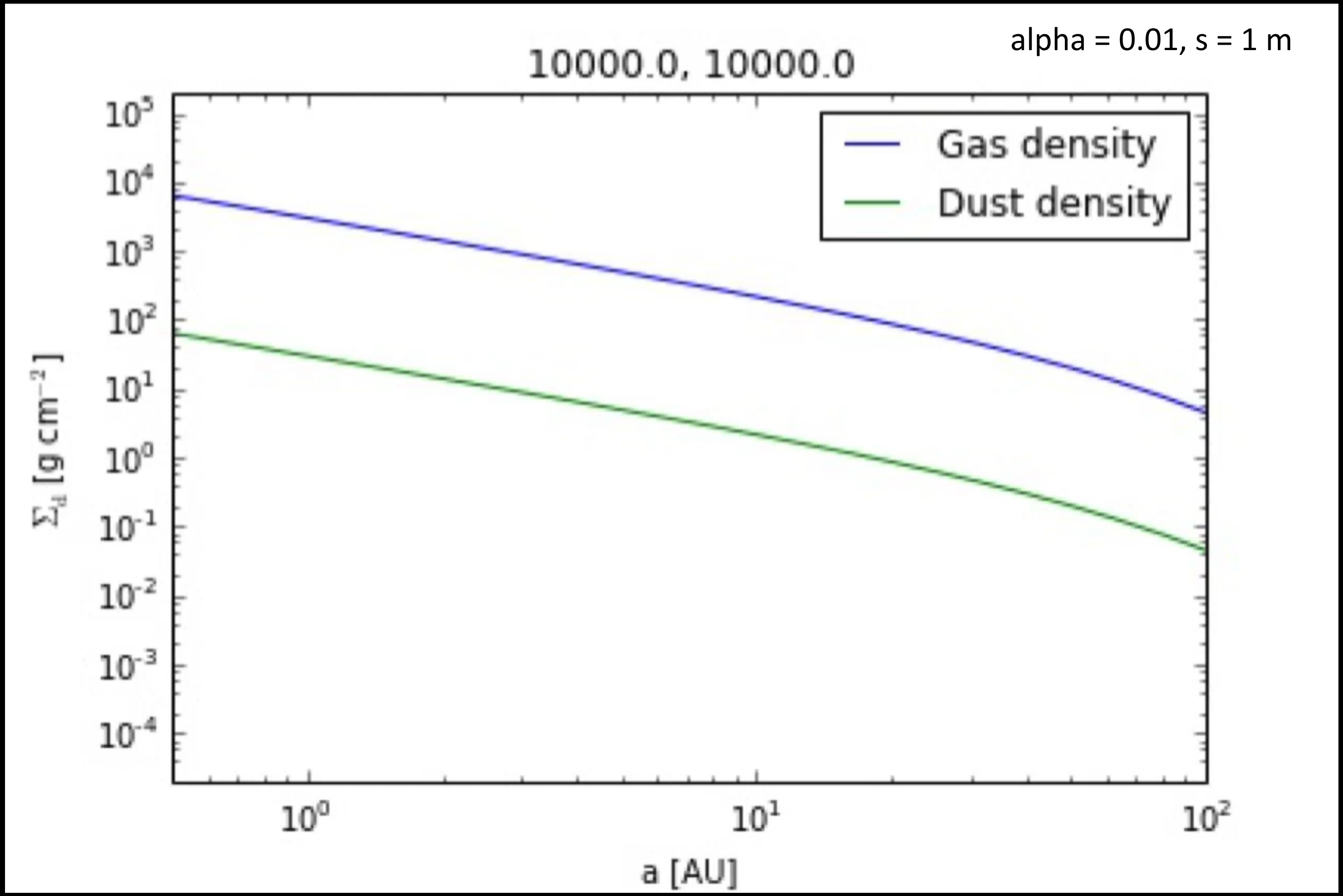

Next steps to completion

- Trace the abundance of H2O, CO2 and CO in gaseous and solid form as the disk evolves
  - Basic idea: treat each species in gaseous and solid form as two fluids that are interchanging and use advection-like equations to solve for their separate time-dependent abundance
  - Will collaborate closely with Til Birnstiel for the numerical solver
  - From these abundances, calculate C/O ratio throughout the disk as a function of time and particle size
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Thesis Timeline

- Paper I: "C/O IN PROTOPLANETARY DISKS: THE EFFECT OF RADIAL DRIFT AND VISCOUS ACCRETION". Estimated completion spring 2015
- Paper II: "N/O IN PROTOPLANETARY DISKS: THE EFFECT OF RADIAL DRIFT AND VISCOUS ACCRETION". Estimated completion summer 2015
- Paper III: Chemical evolution incorporated in radial drift model. Estimated completion fall 2015
- Paper IV: Self-consistently evolve chemical model from Paper III and disk dynamics. Estimated completion spring 2016
- Overall goal: complete thesis and graduate in spring 2016

Kelvin-Helmholtz contraction

M_{atm} is a function of time

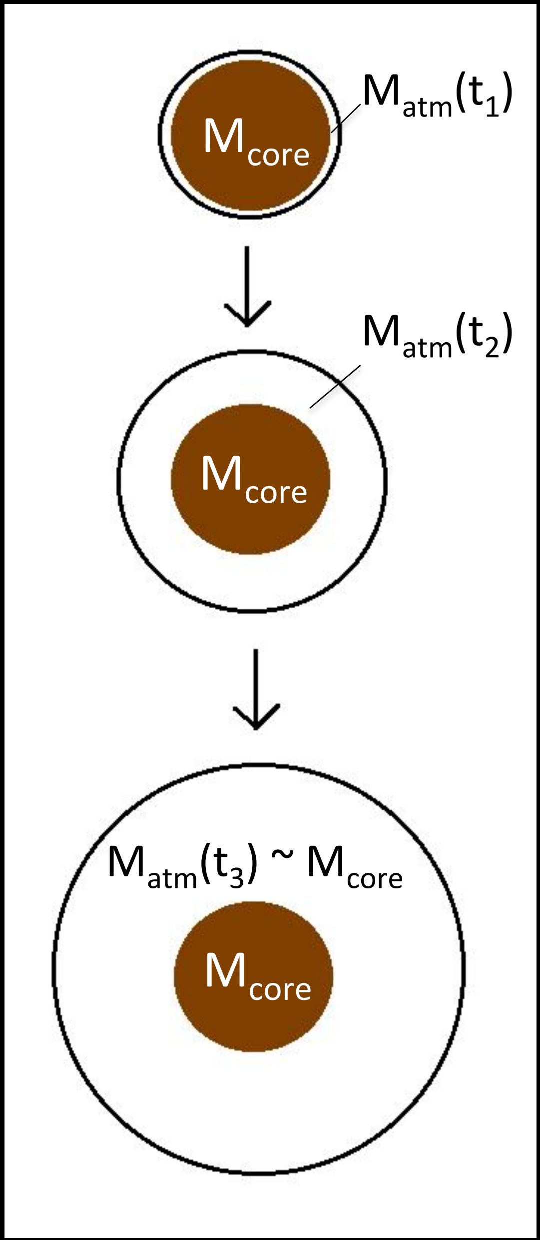
=> EVERY core can have

$$M_{atm} \sim M_{core}$$

$\Rightarrow$"critical core mass"

$M_{crit} = M_{core}$ for which

$M_{atm}(t_{disk}) \sim M_{core}$

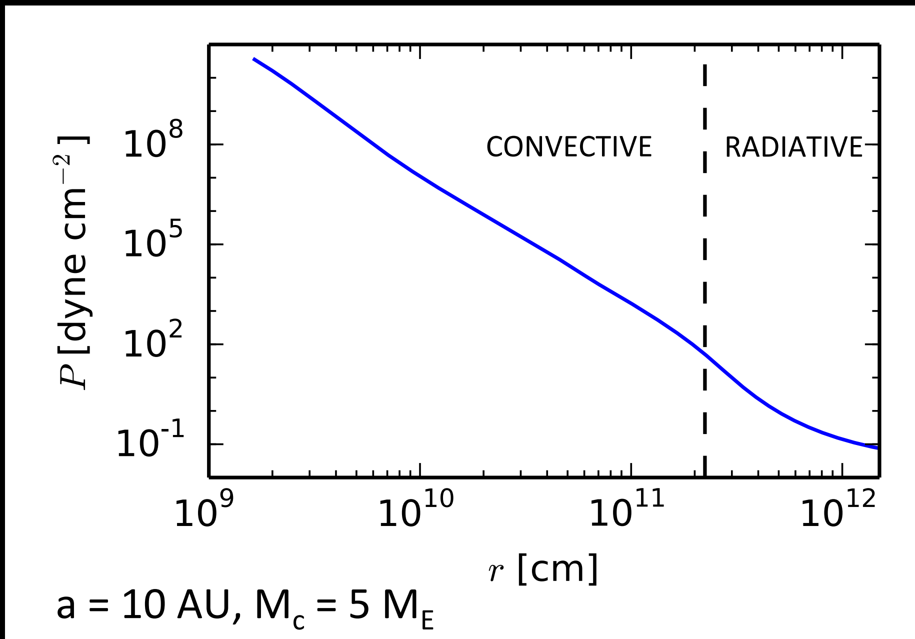


Model Assumptions

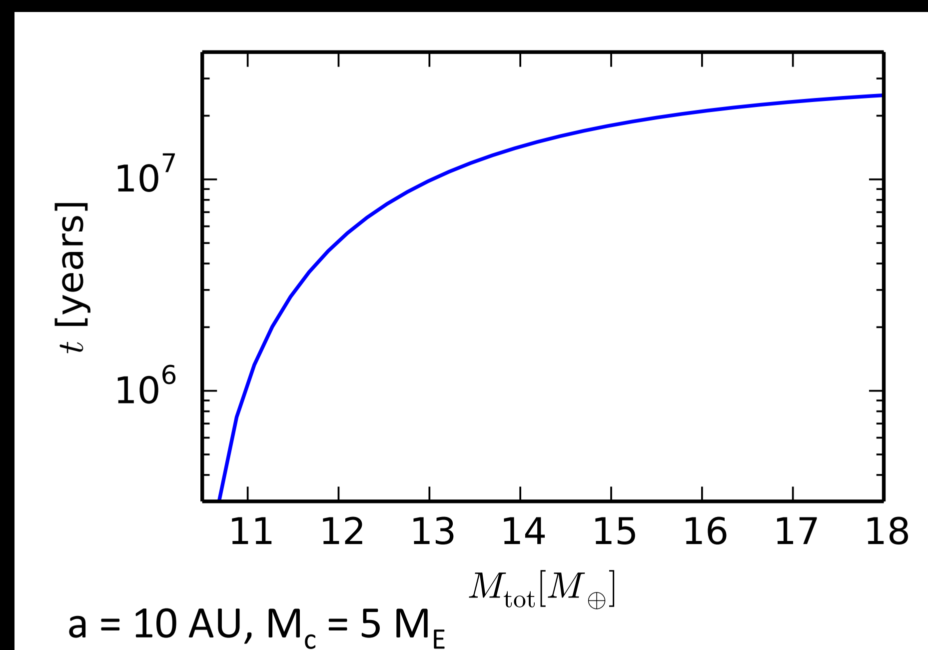
- Negligible planetesimal accretion => solid core of fixed mass M_c
- Atmosphere is embedded in the gas disk, spherically symmetric and in hydrostatic balance
- Two layer atmosphere: inner convective region and outer radiative region
- Constant luminosity throughout the radiative region

see Piso & Youdin (2014) for details

Static profiles connected by global cooling equation



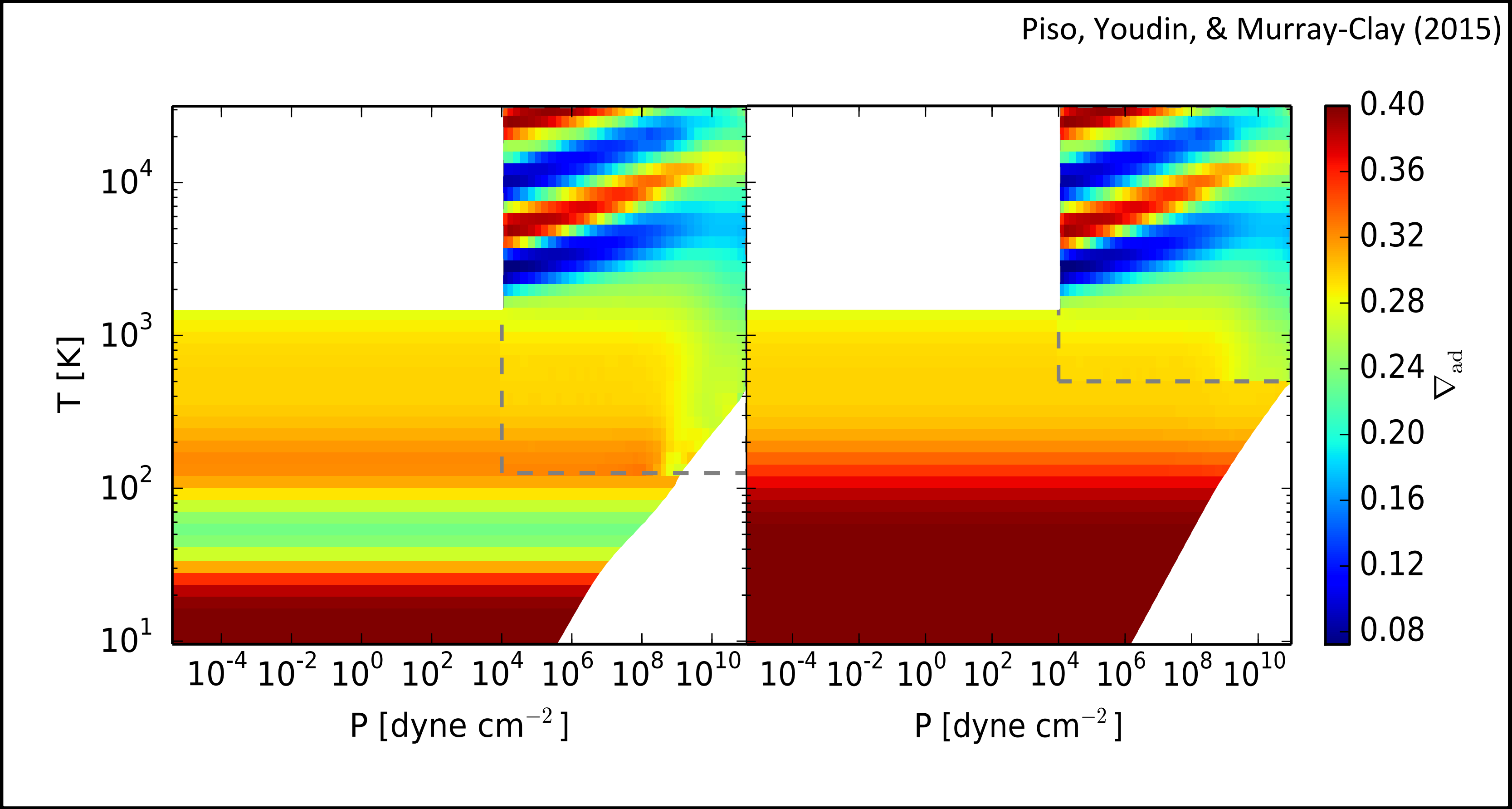
L ~ -dE/dt



$$\boxed{\nabla_{ad} = \left(\frac{d \ln T}{d \ln P} \right)_{ad}}$$

Adiabatic gradient relates *P*, *T*, *rho*
=> determines atmospheric profile and parametrizes EOS

Adiabatic gradient $\boxed{\nabla_{ad} = \left(\frac{d\ln T}{d\ln P}\right)_{ad}}$ is variable for realistic EOS



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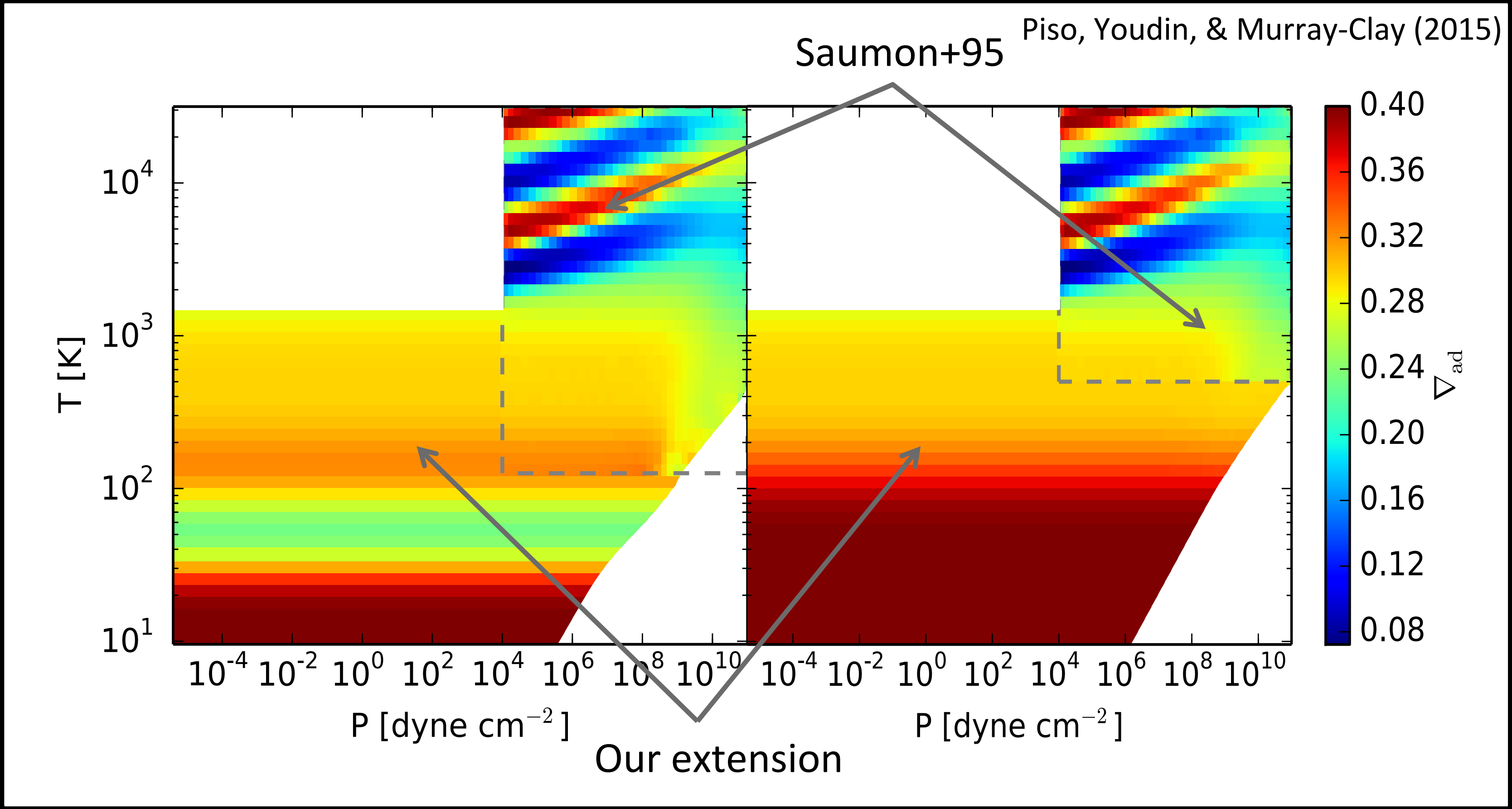

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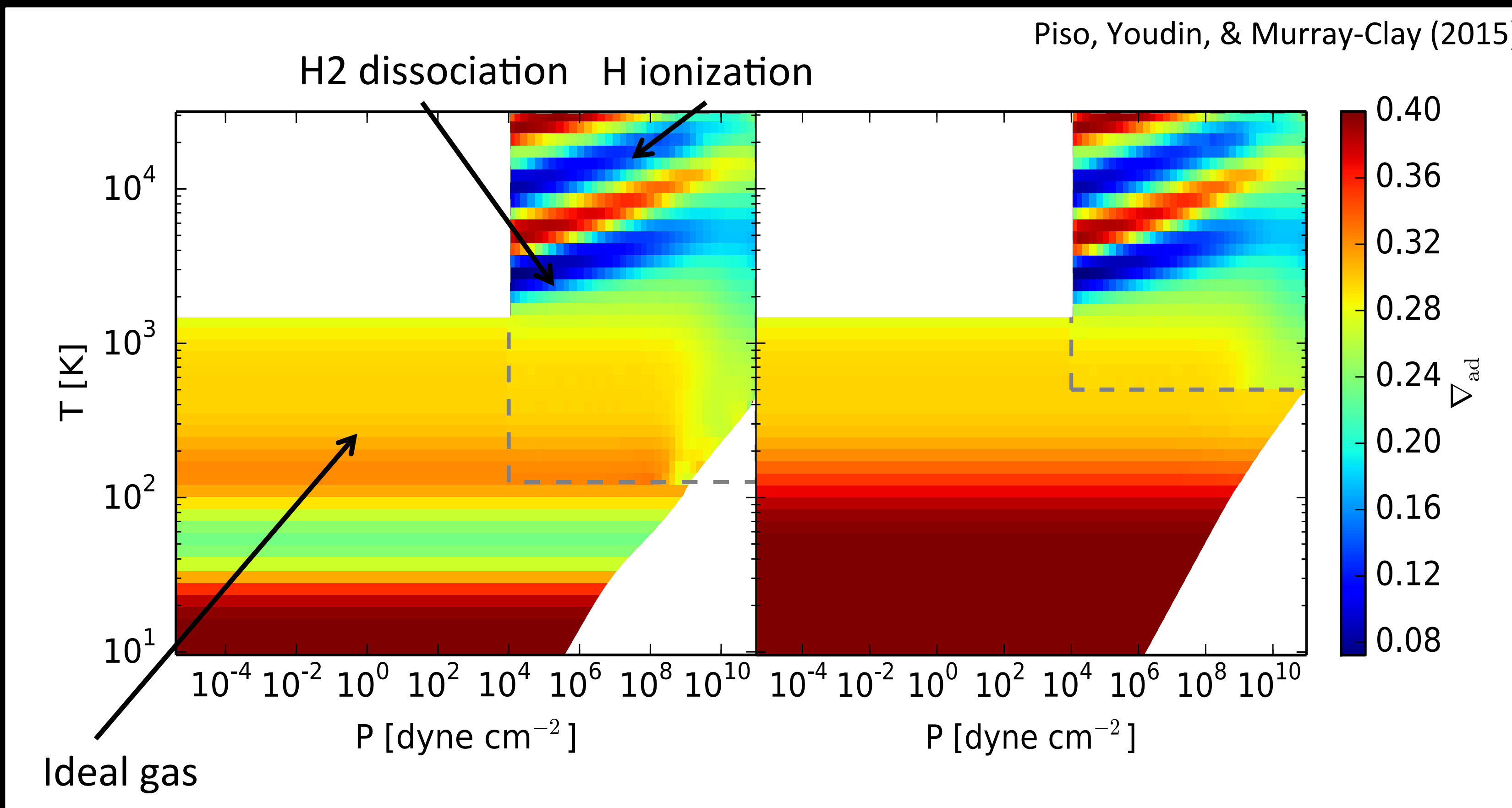

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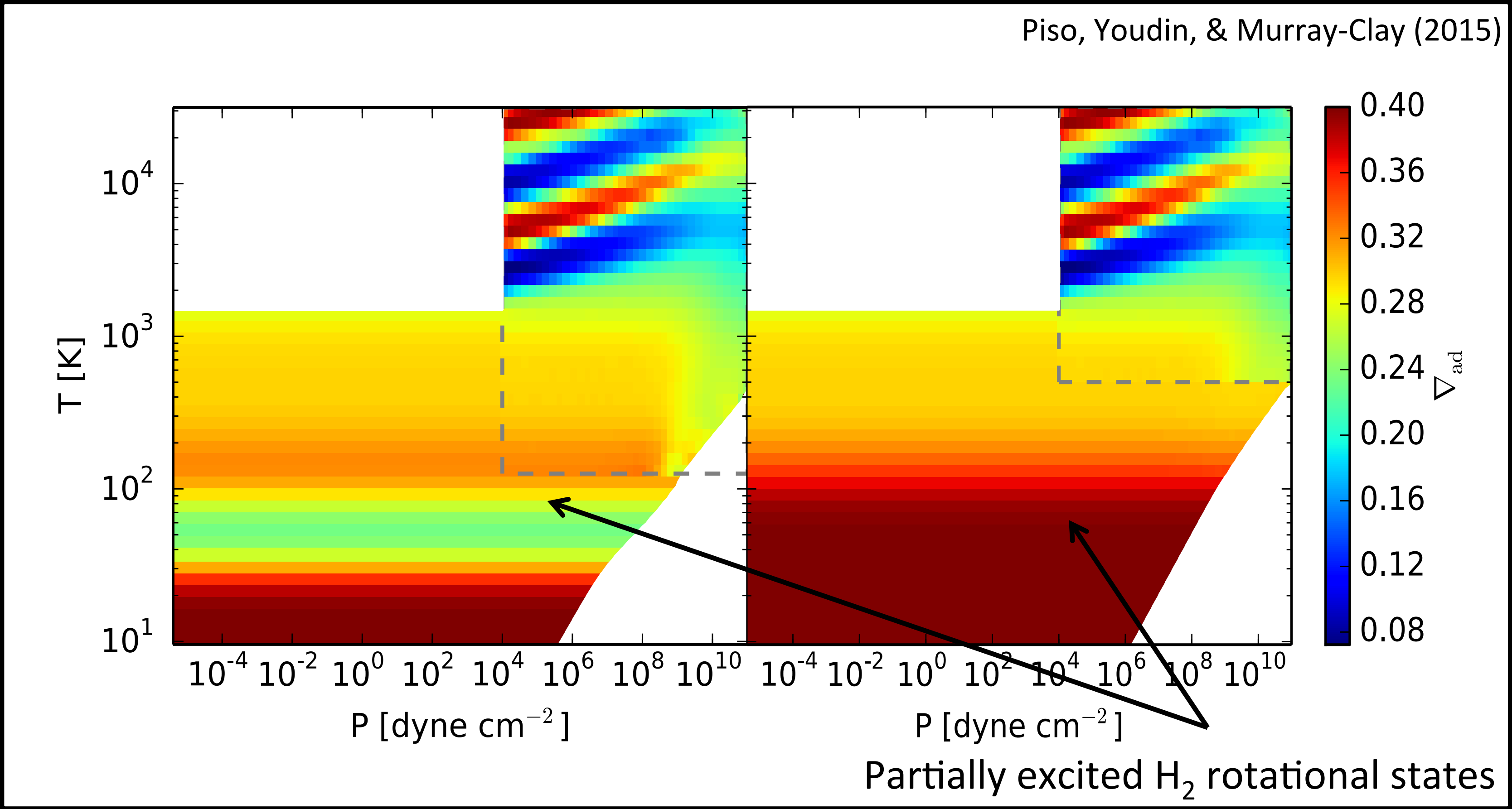

Adiabatic gradient $\nabla_{ad} = \left(\frac{d \ln T}{d \ln P}\right)_{ad}$ is variable for realistic EOS

H_2 spin isomers ↑↑ ORTHOHYDROGEN and ↑↓ PARAHYDROGEN can be in **thermal equilibrium** or **fixed ratio**