Origins of Gas Giant Compositions: The Role of Disk Location and Dynamics

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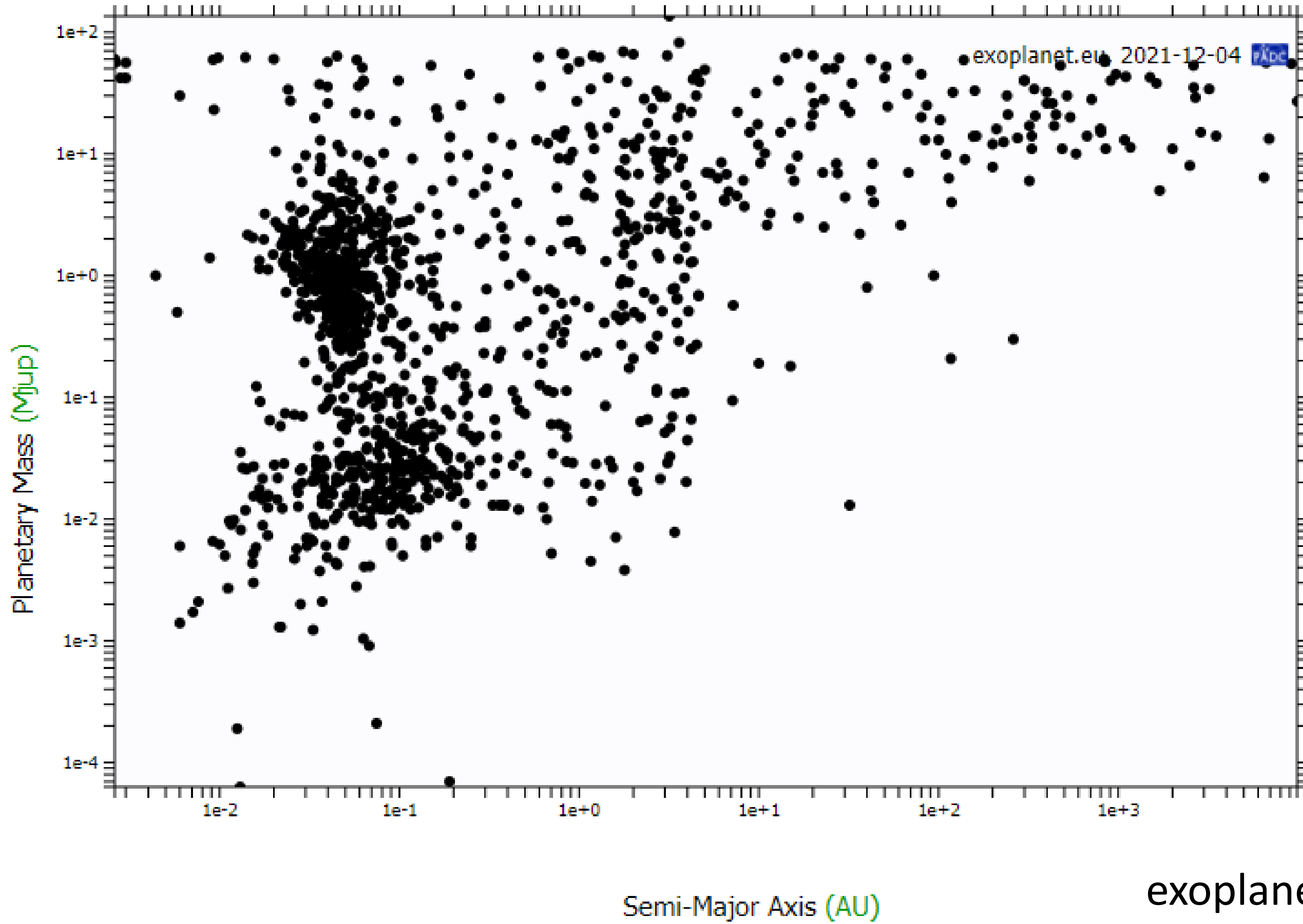
GMV

AIRA Scientific Seminar: December 8th, 2021

Fundamental Questions

1. Where in the disk can giant planets form?

2. What compositions will the formed giant planets have obtained?



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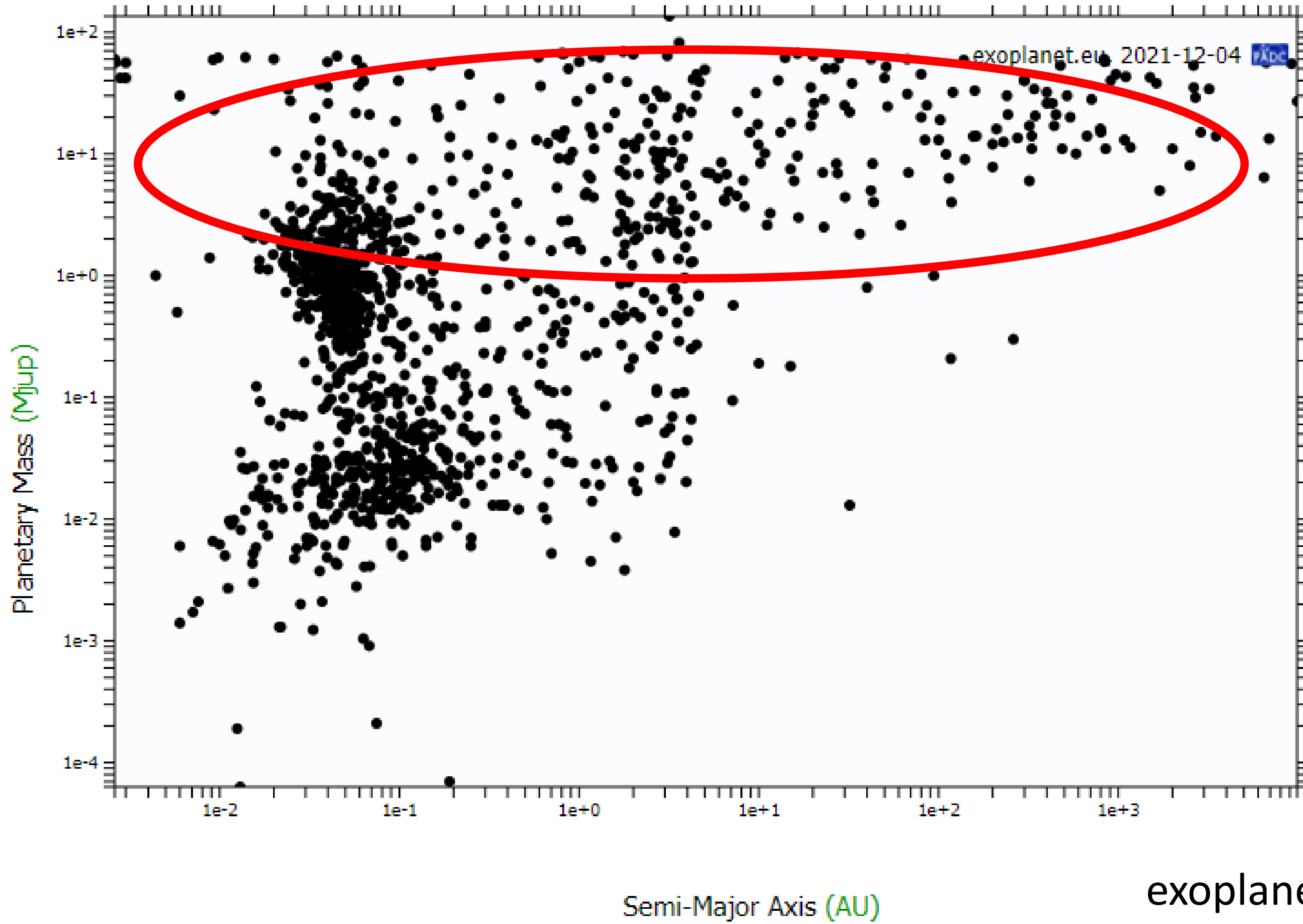

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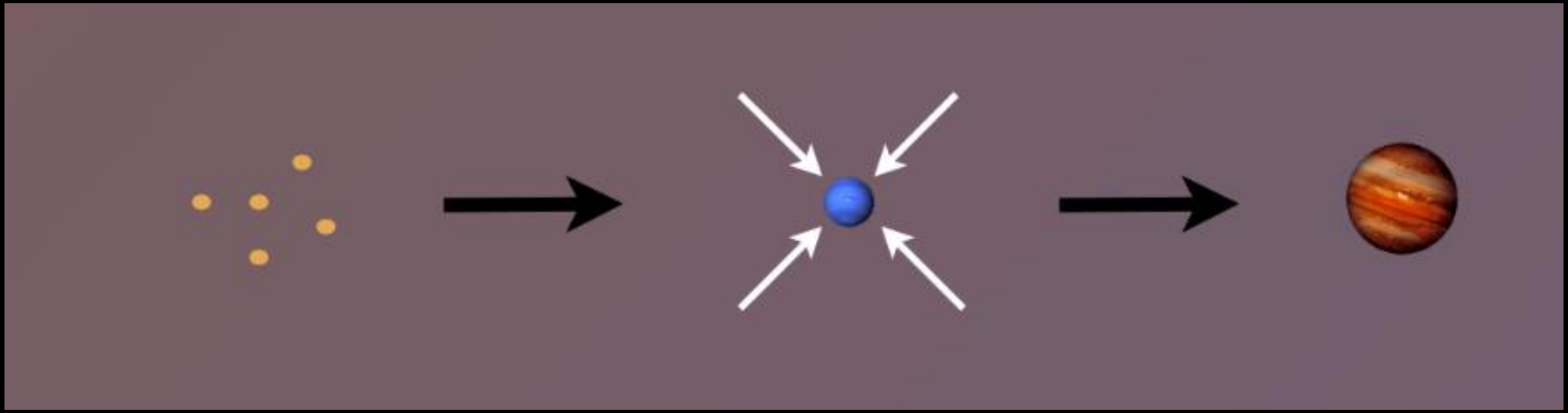
Gas Giants

Disk-Planet Connection



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

Talk Structure

1. The role of disk location in the formation of wide separation gas giants (Piso et al. 2014, 2015a)

2. The effect of disk structure and composition at different radii on the eventual composition of giant planets (Piso et al. 2015b, Piso et al. 2016)

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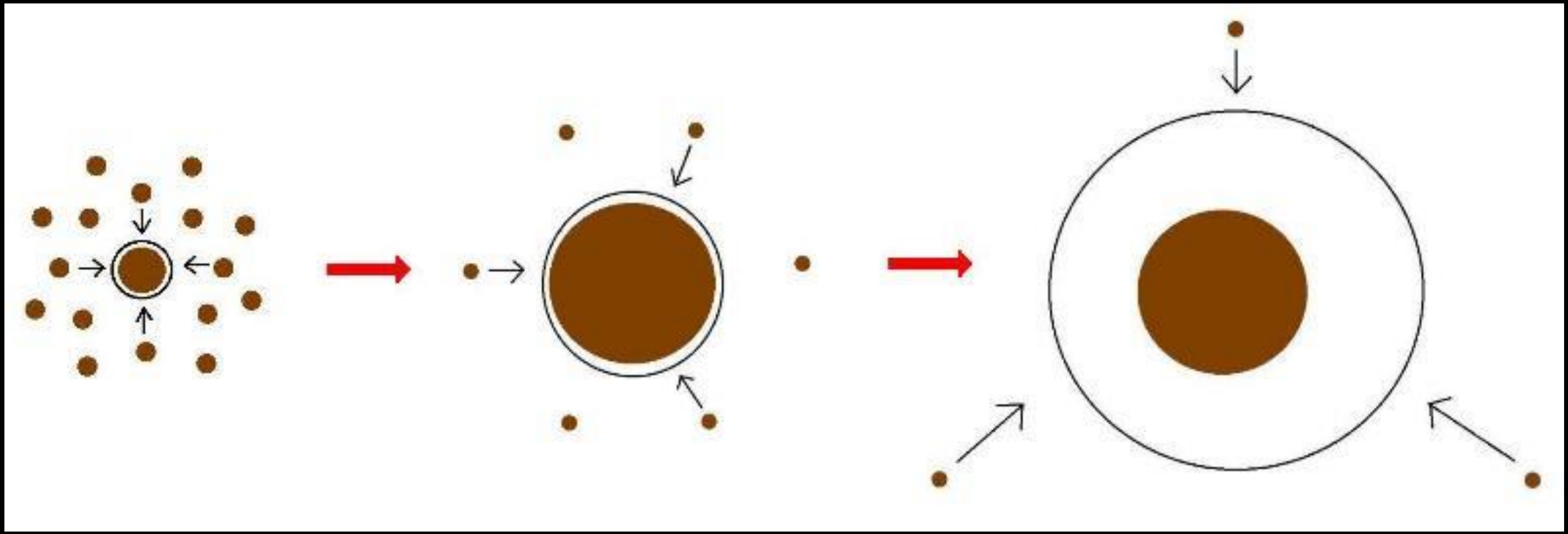
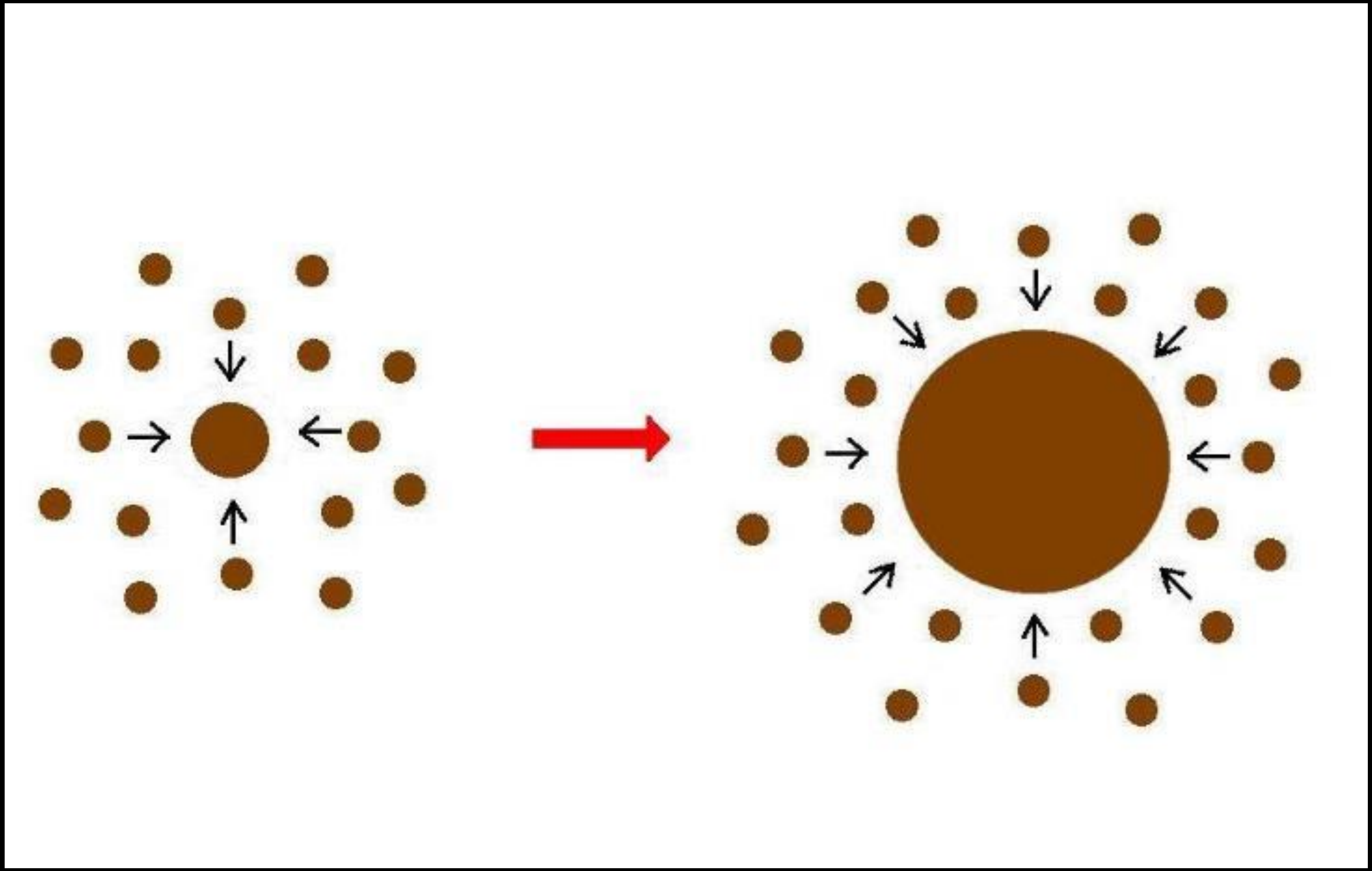
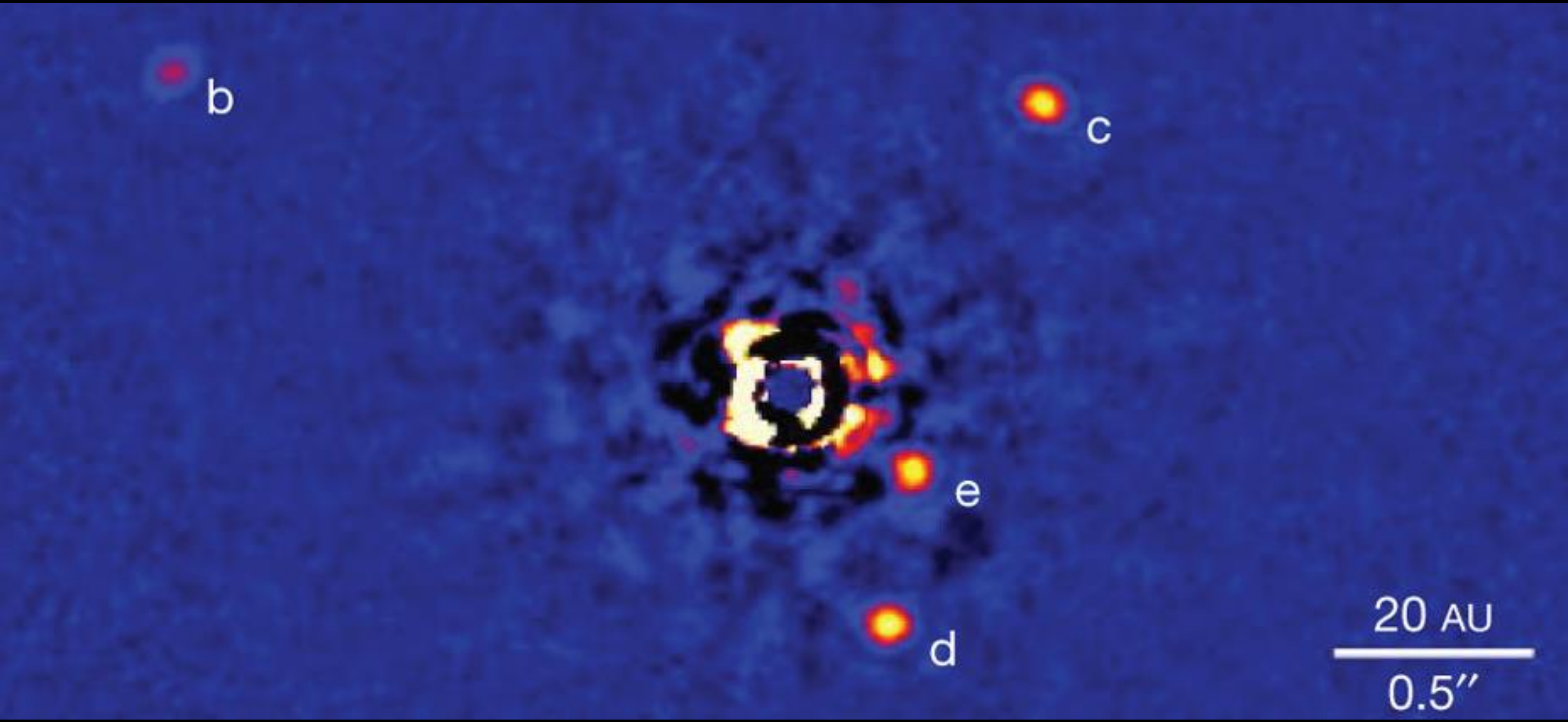
Minimum Core Masses for Giant Planet Formation



Giant planet formation requires fast core growth

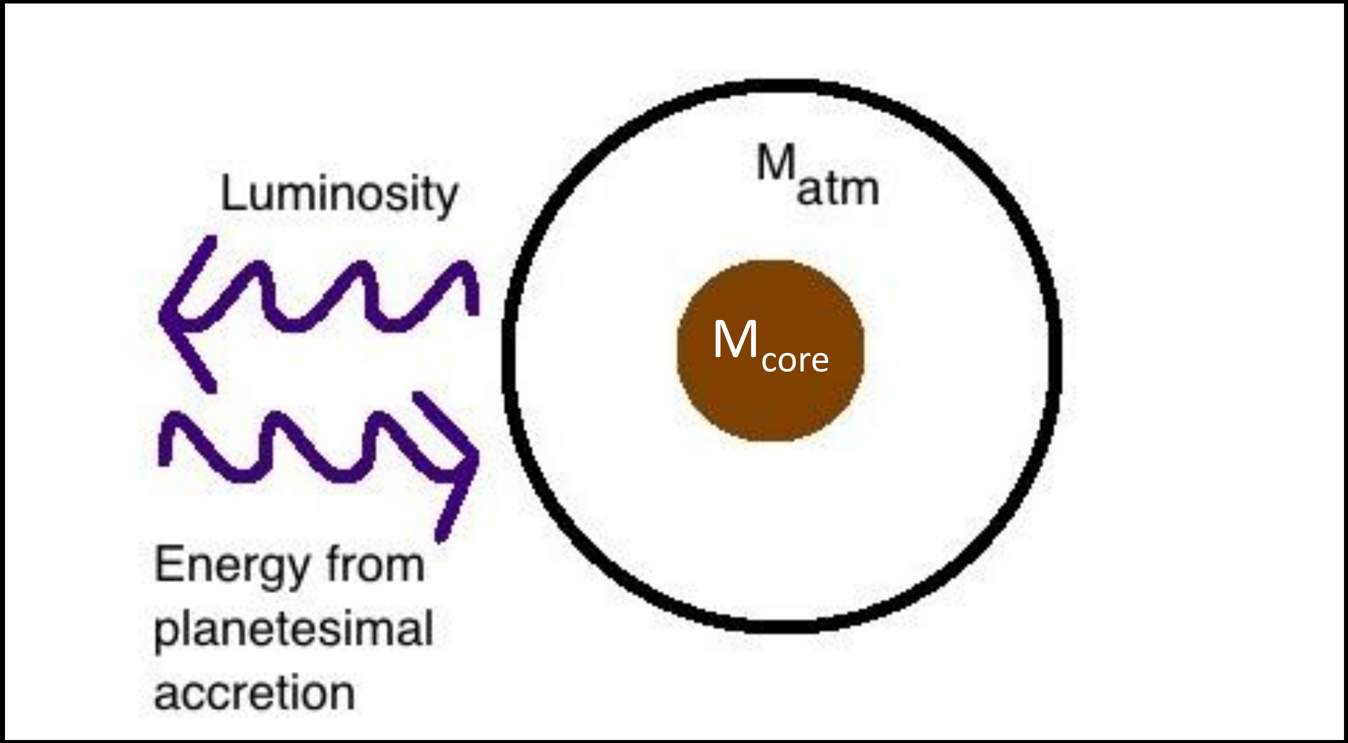




Marois+2010

Core Accretion at high planetesimal accretion rates yields steady state

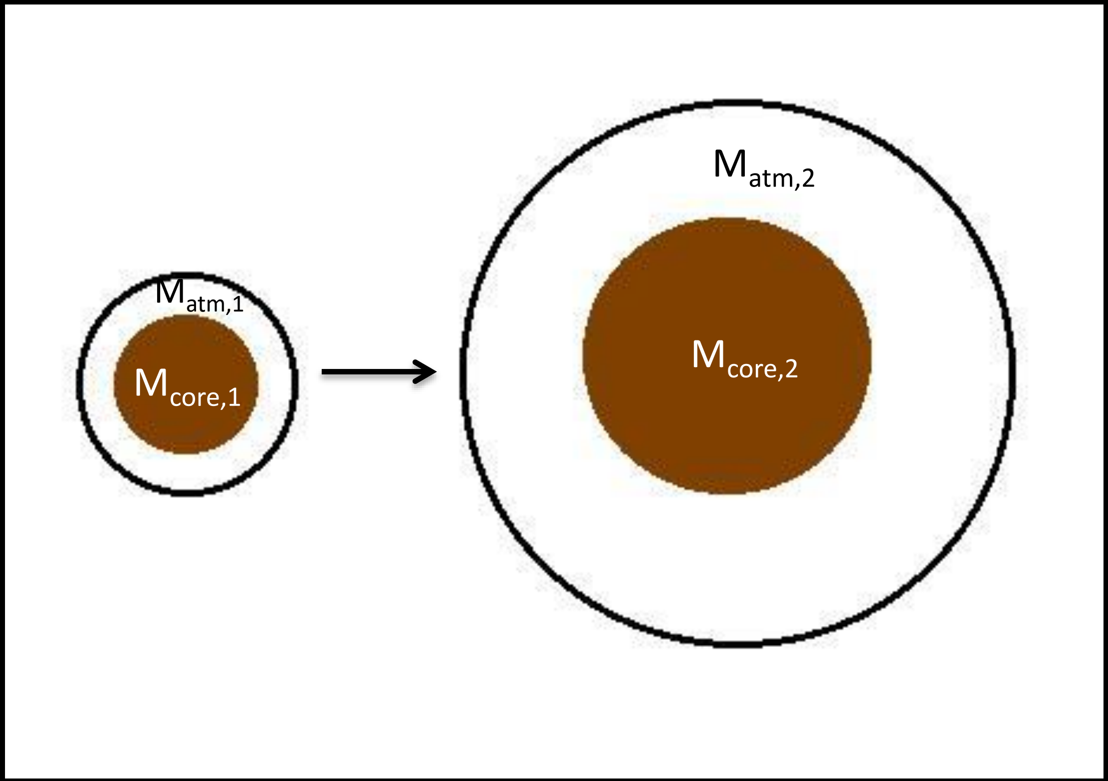
=> M_{atm} is a function of M_{core}



High planetesimal accretion

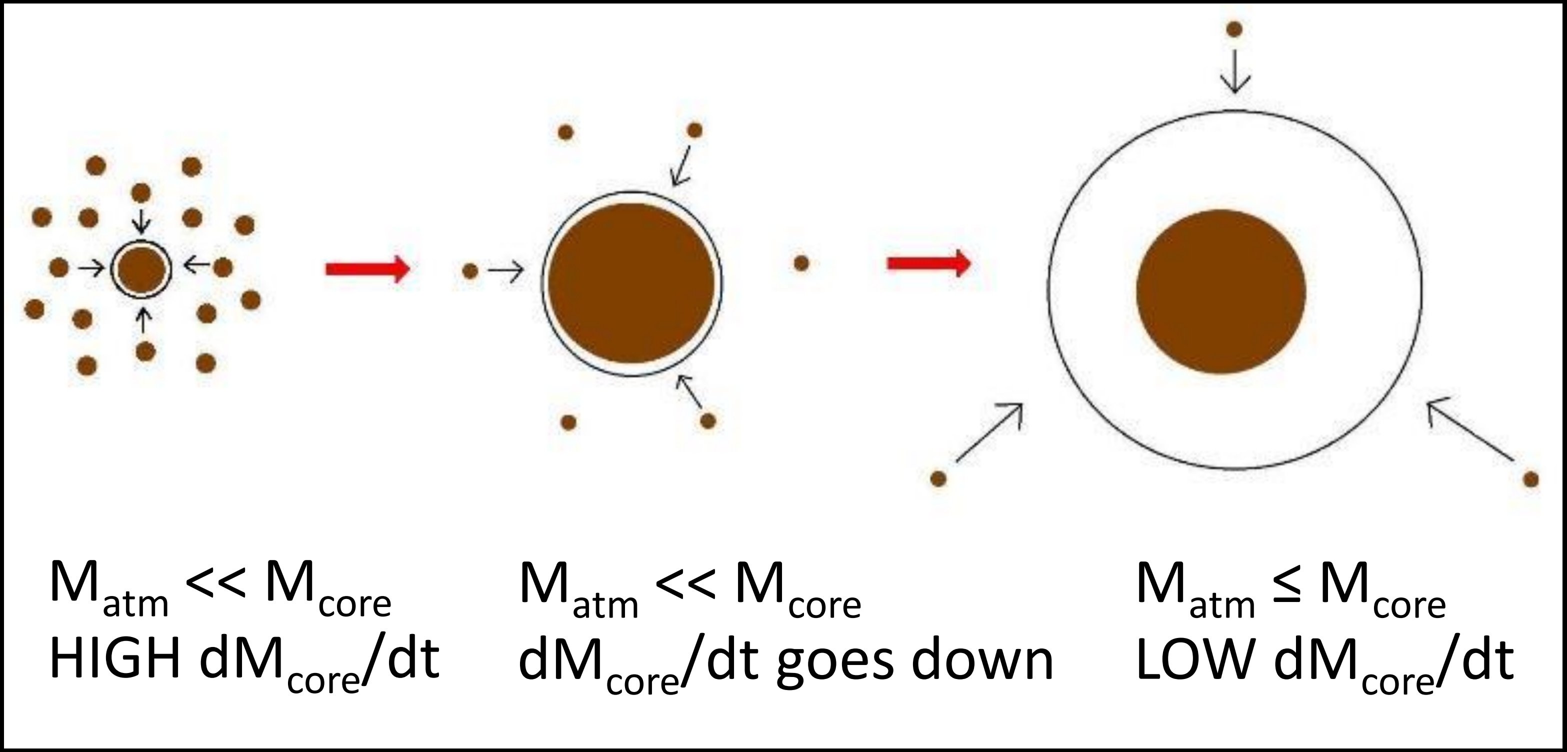
ONE M_{atm} for each M_{core}

=> ONE core mass for which M_{atm} ~ M_{core} = "critical core mass"



Planetesimal accretion is not constant at a given location throughout disk life

- e.g., Pollack+96, Ikoma+00



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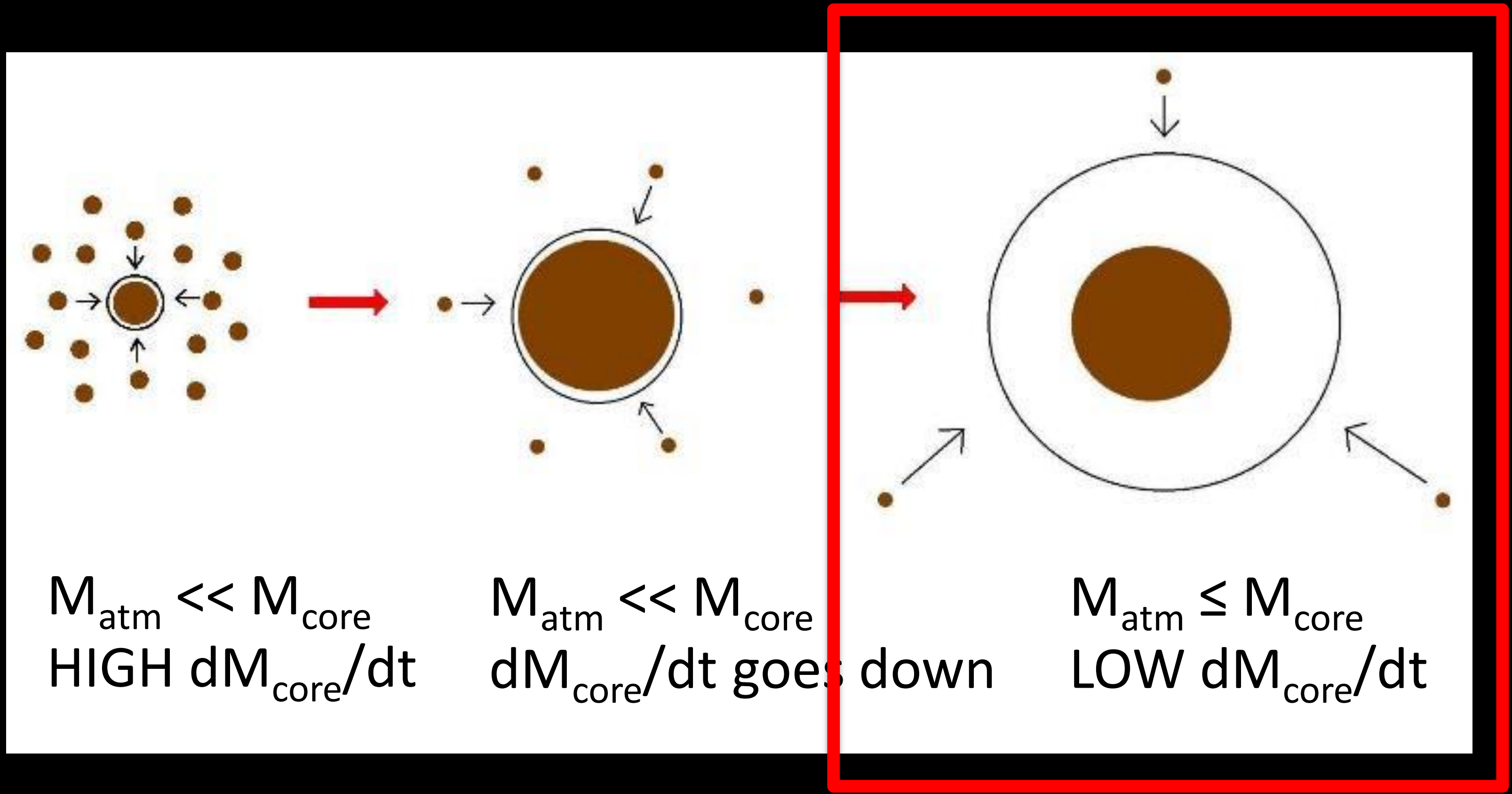
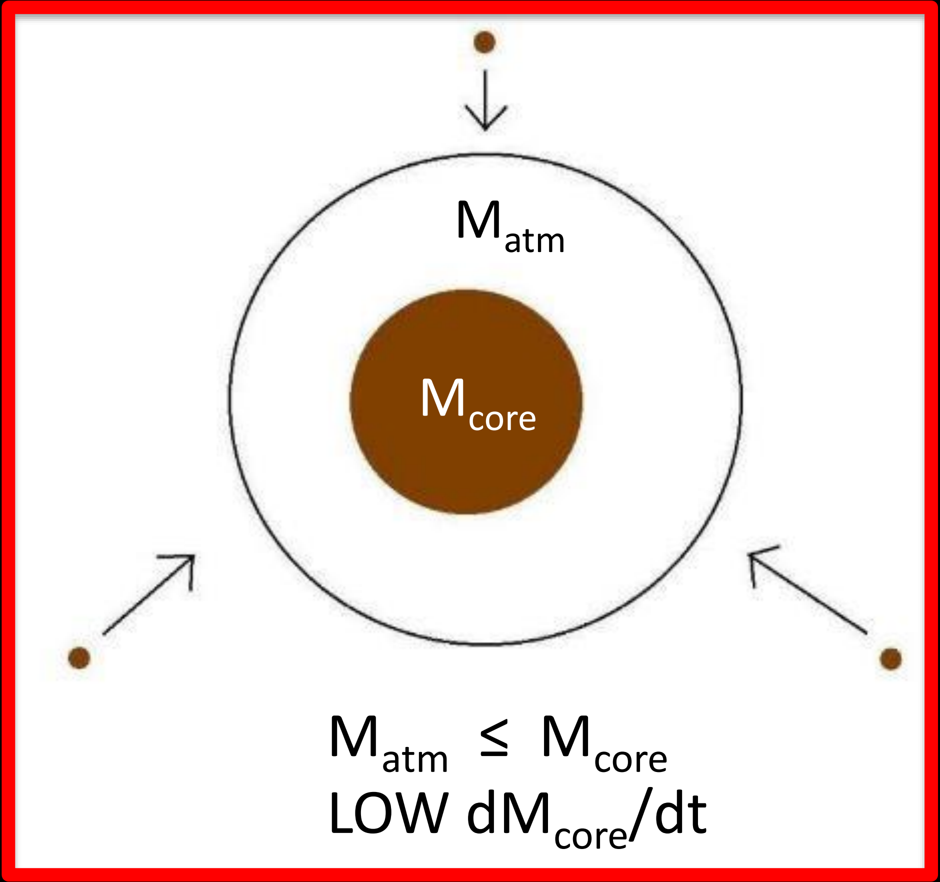


Low planetesimal accretion regime

⇒Atmospheric evolution dominated by Kelvin-Helmholtz contraction



Kelvin-Helmholtz contraction

M_{atm} is a function of time

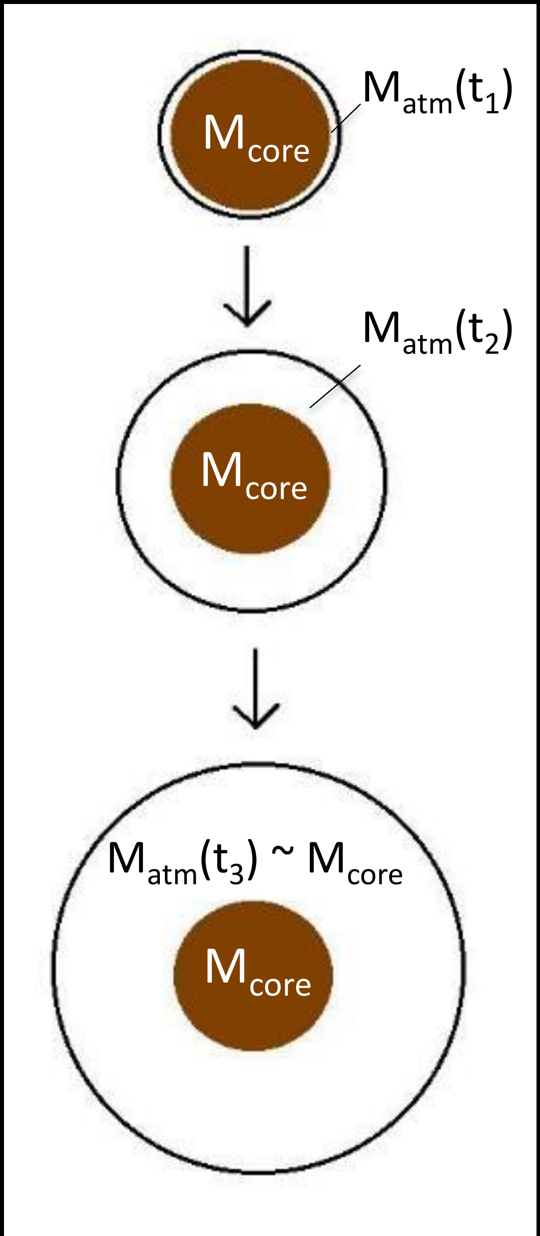
=> EVERY core can have

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

$\Rightarrow$ "critical core mass"

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

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



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

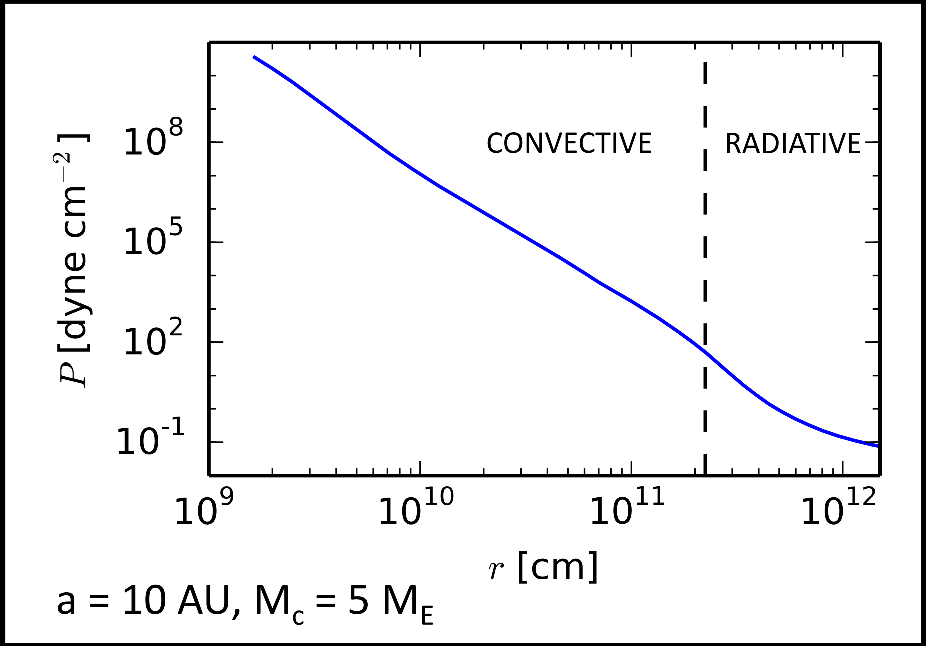
Calculate M_{crit} with
REALISTIC EQUATION OF STATE (EOS)
REALISTIC DUST OPACITIES

Model Assumptions

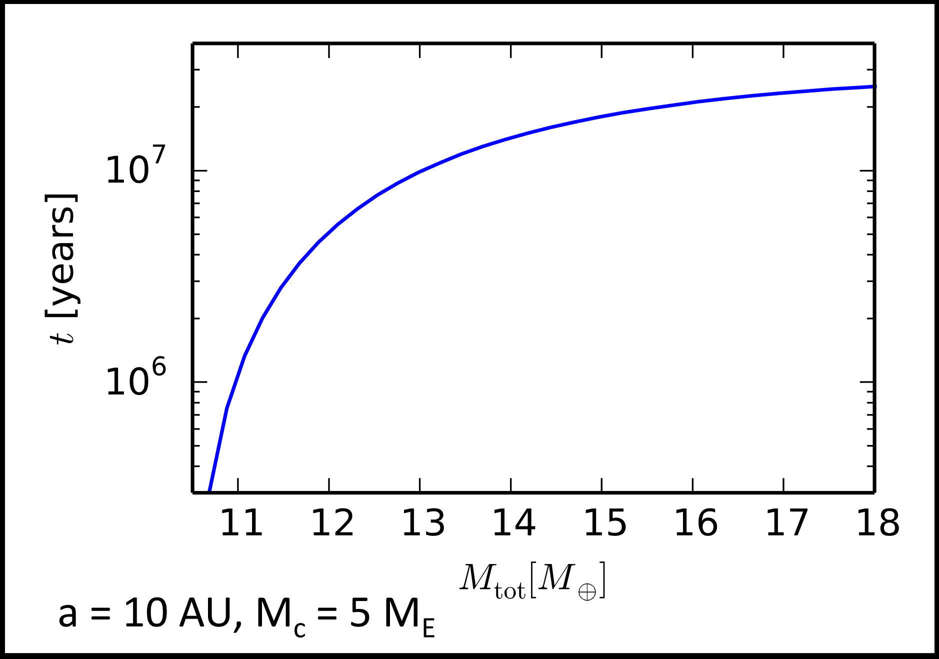
- Negligible planetesimal accretion => solid core of fixed mass M_c
- Atmosphere is embedded in the gas disk, spherically symmetric and in hydrostatic balance
- Two layer atmosphere: inner convective region and outer radiative region
- Constant luminosity throughout the radiative region

see Piso & Youdin (2014) for details

Static profiles connected by global cooling equation



L ~ -dE/dt



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

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

Atmospheric evolution and M_{crit} are highly dependent on

EQUATION OF STATE

DUST OPACITY

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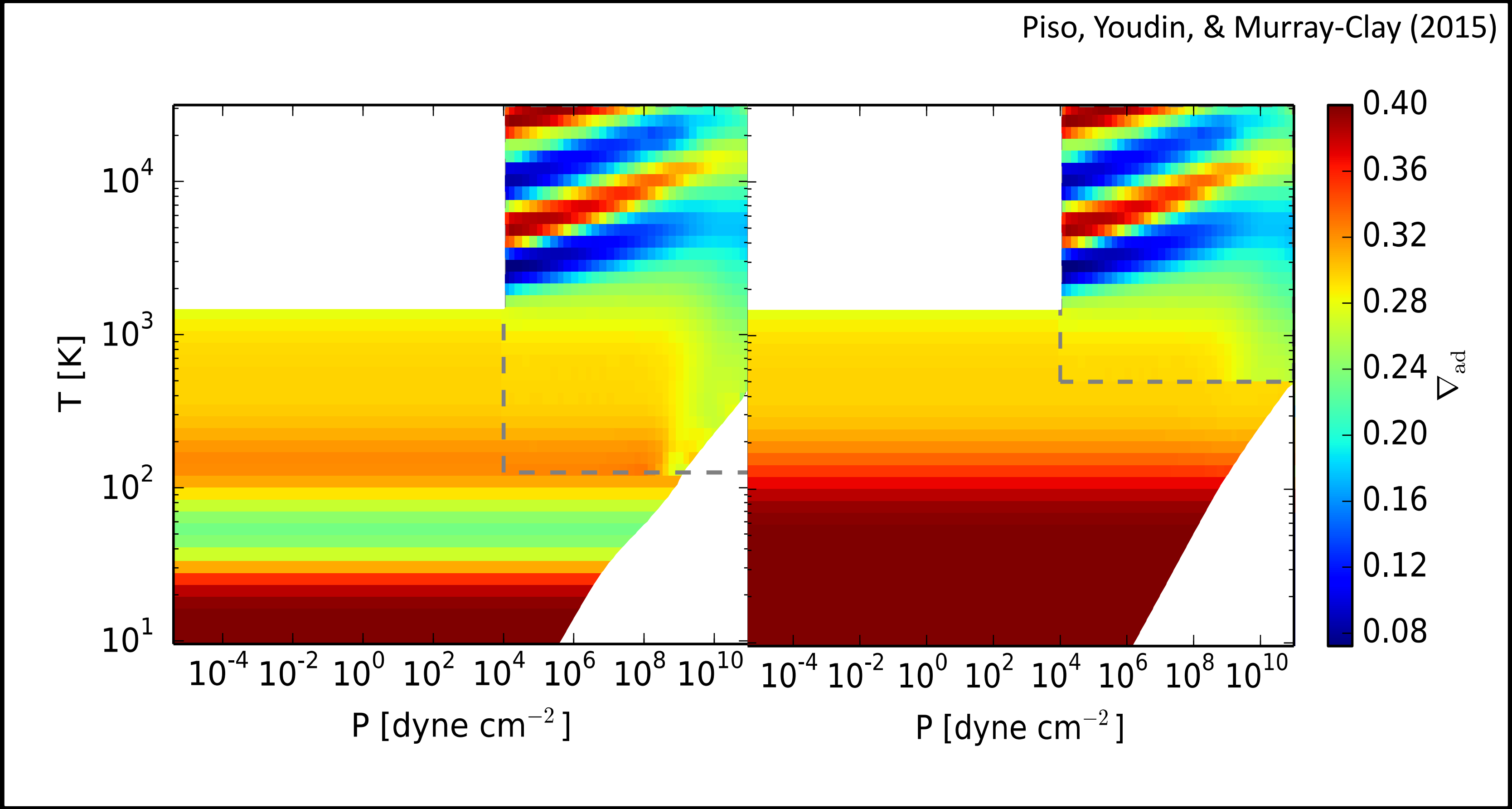
Adiabatic gradient $\nabla_{ad} = \left(\frac{d \ln T}{d \ln P}\right)_{ad}$ is variable for realistic EOS



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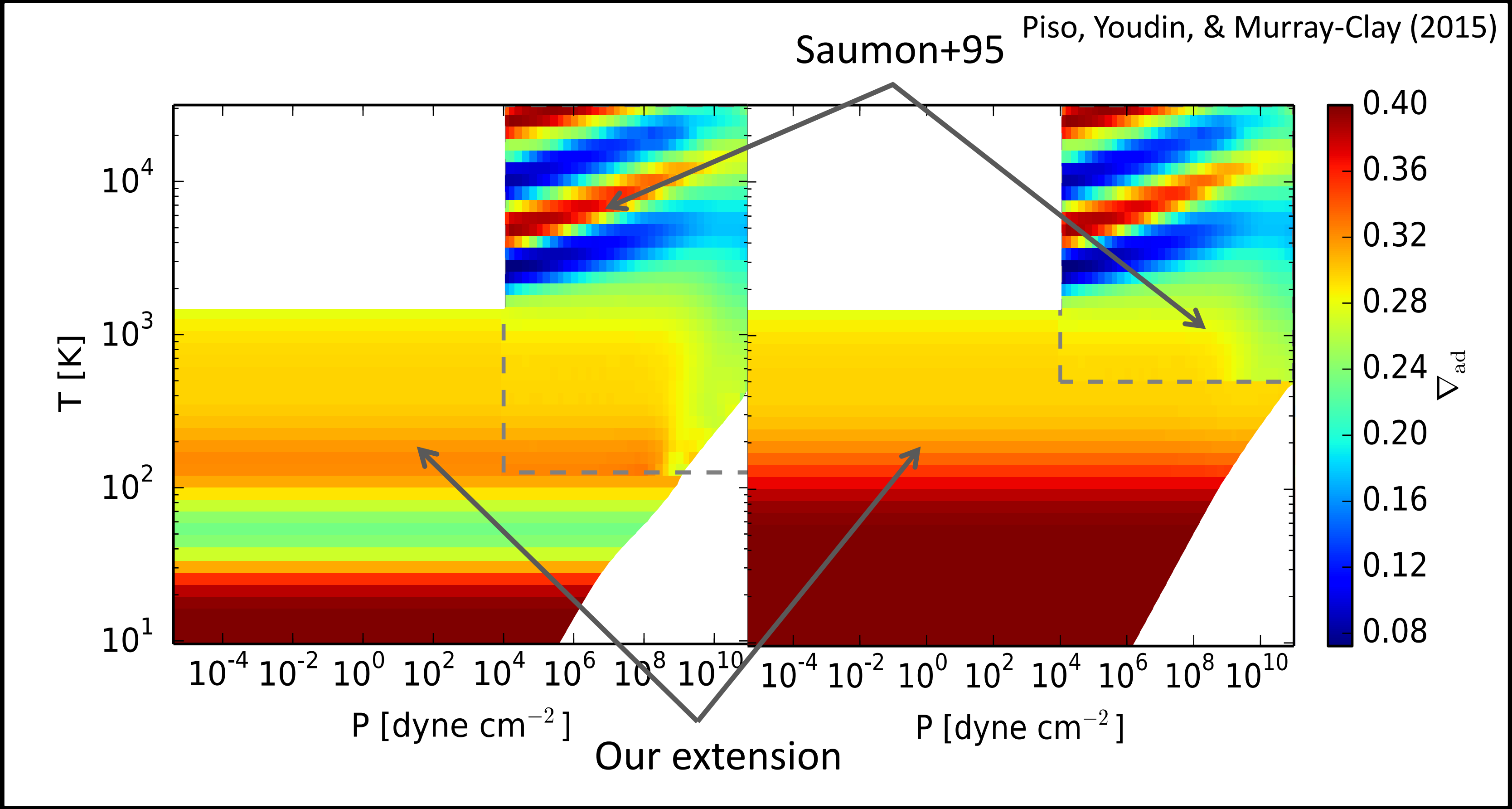

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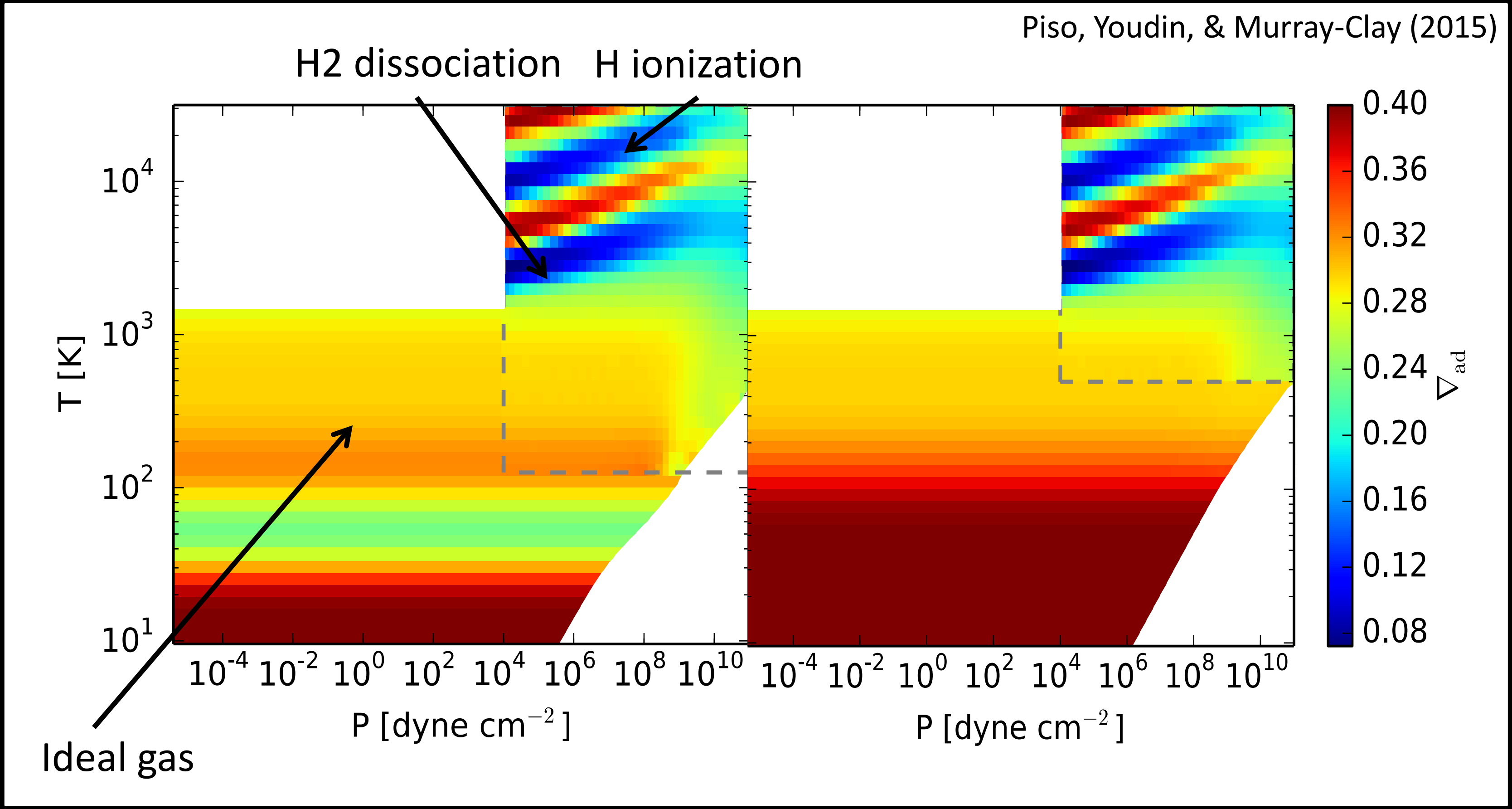

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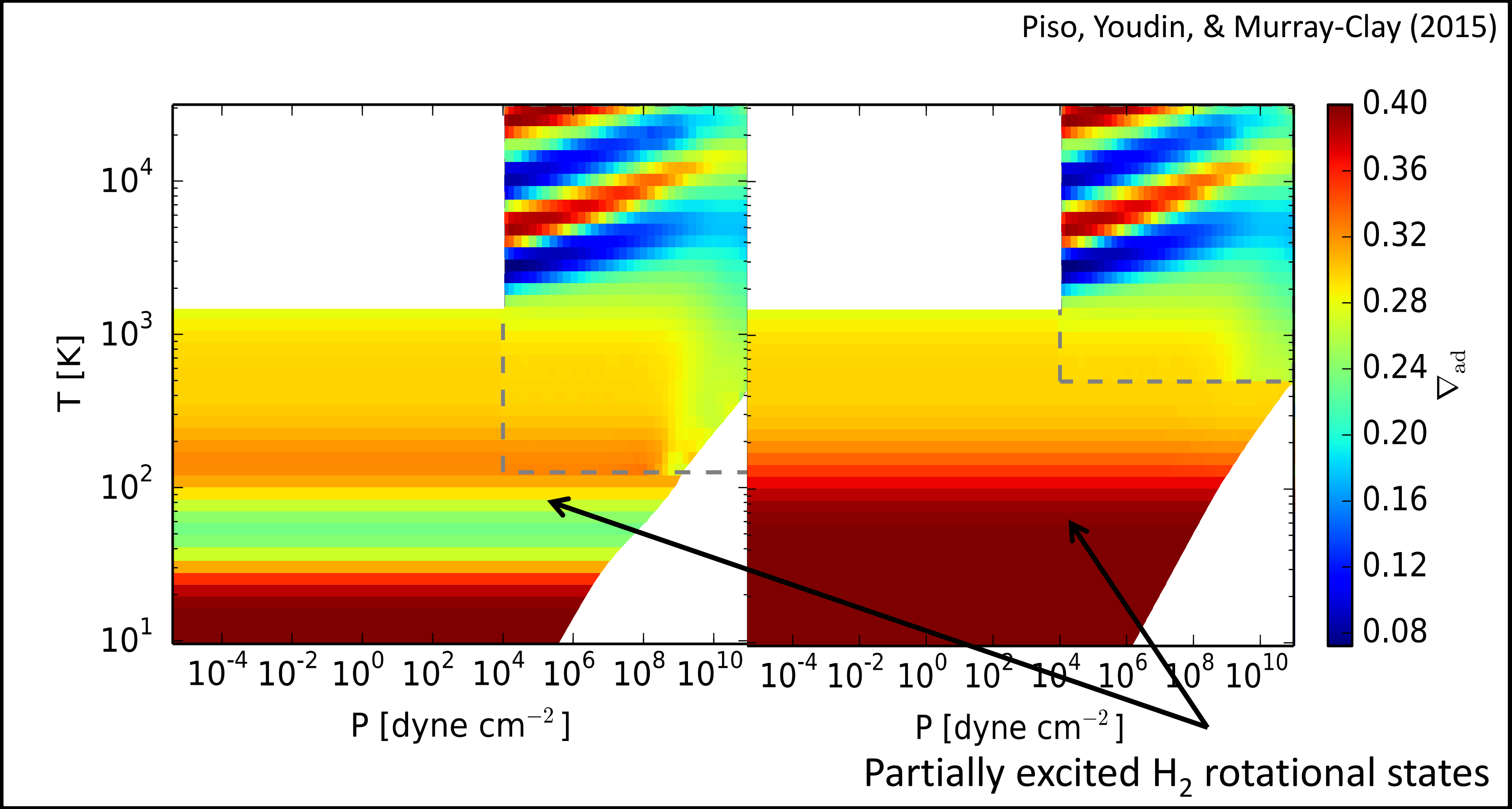
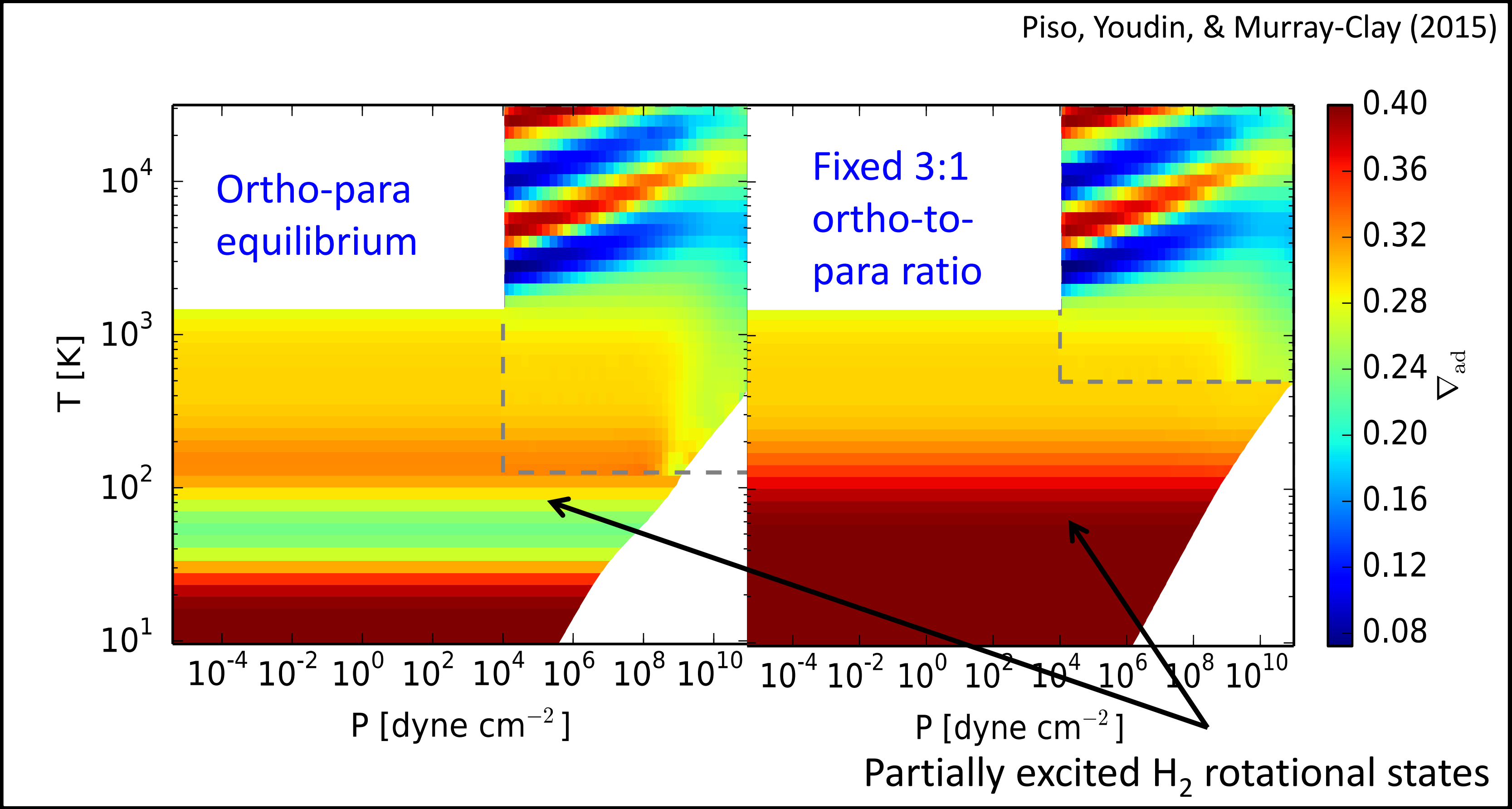
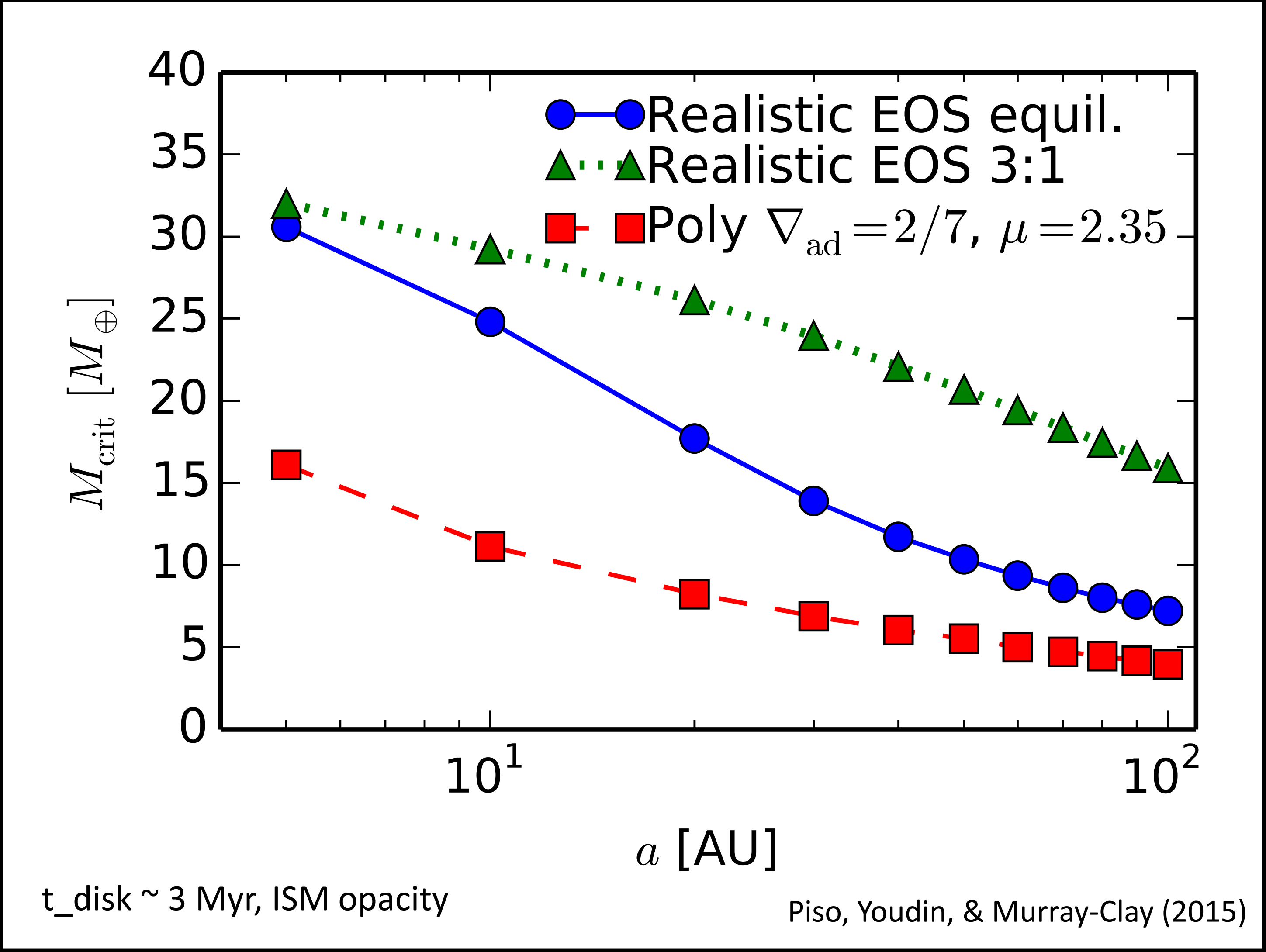


Adiabatic gradient $\nabla_{ad} = \left(\frac{d\ln T}{d\ln P}\right)_{ad}$ is variable for realistic EOS

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



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



Atmospheric evolution and M_{crit} are highly dependent on

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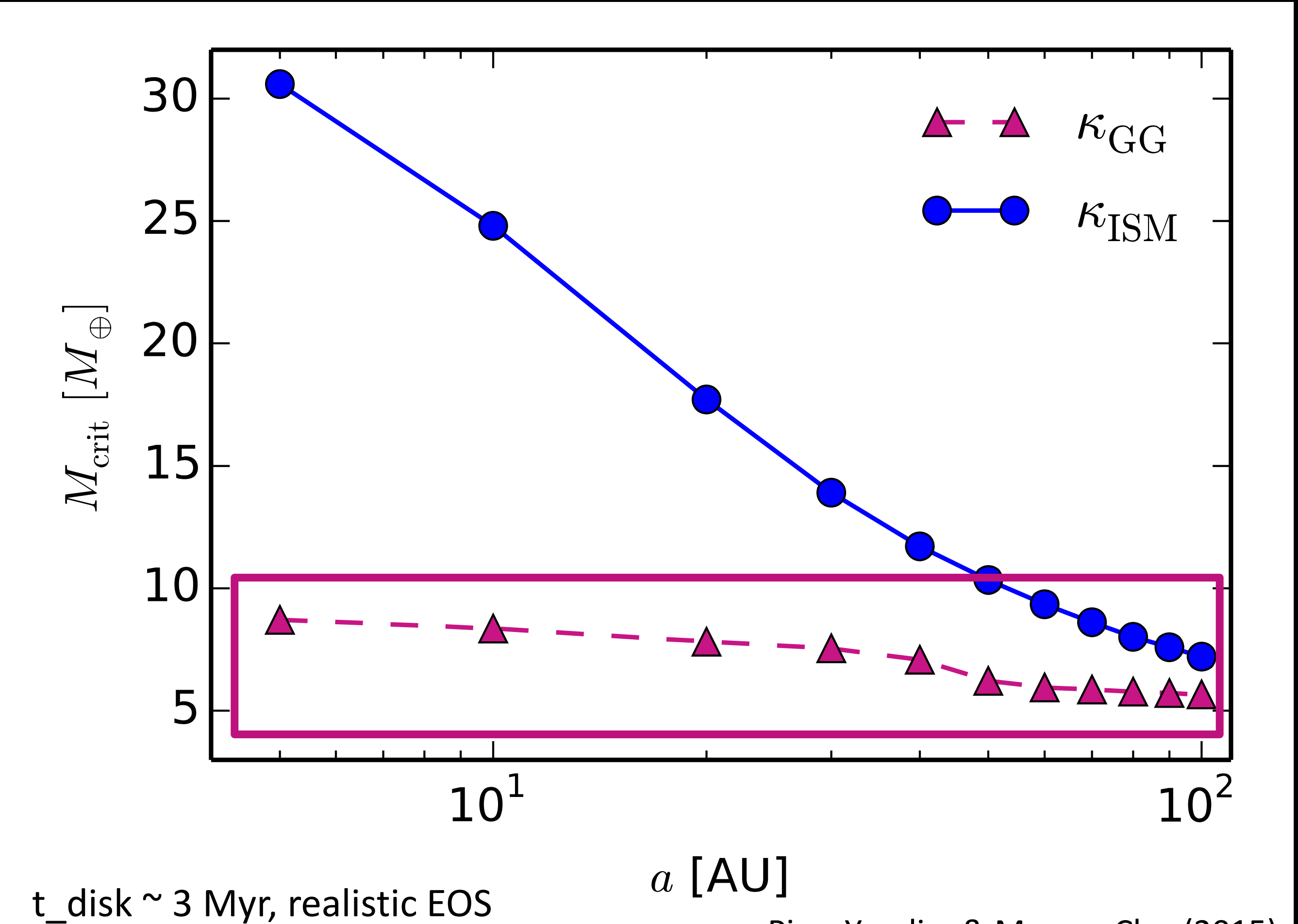
Grain growth opacity DECREASES M_{crit}

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

$p = 3.5$

s_{max} = 1 cm



Piso, Youdin, & Murray-Clay (2015)

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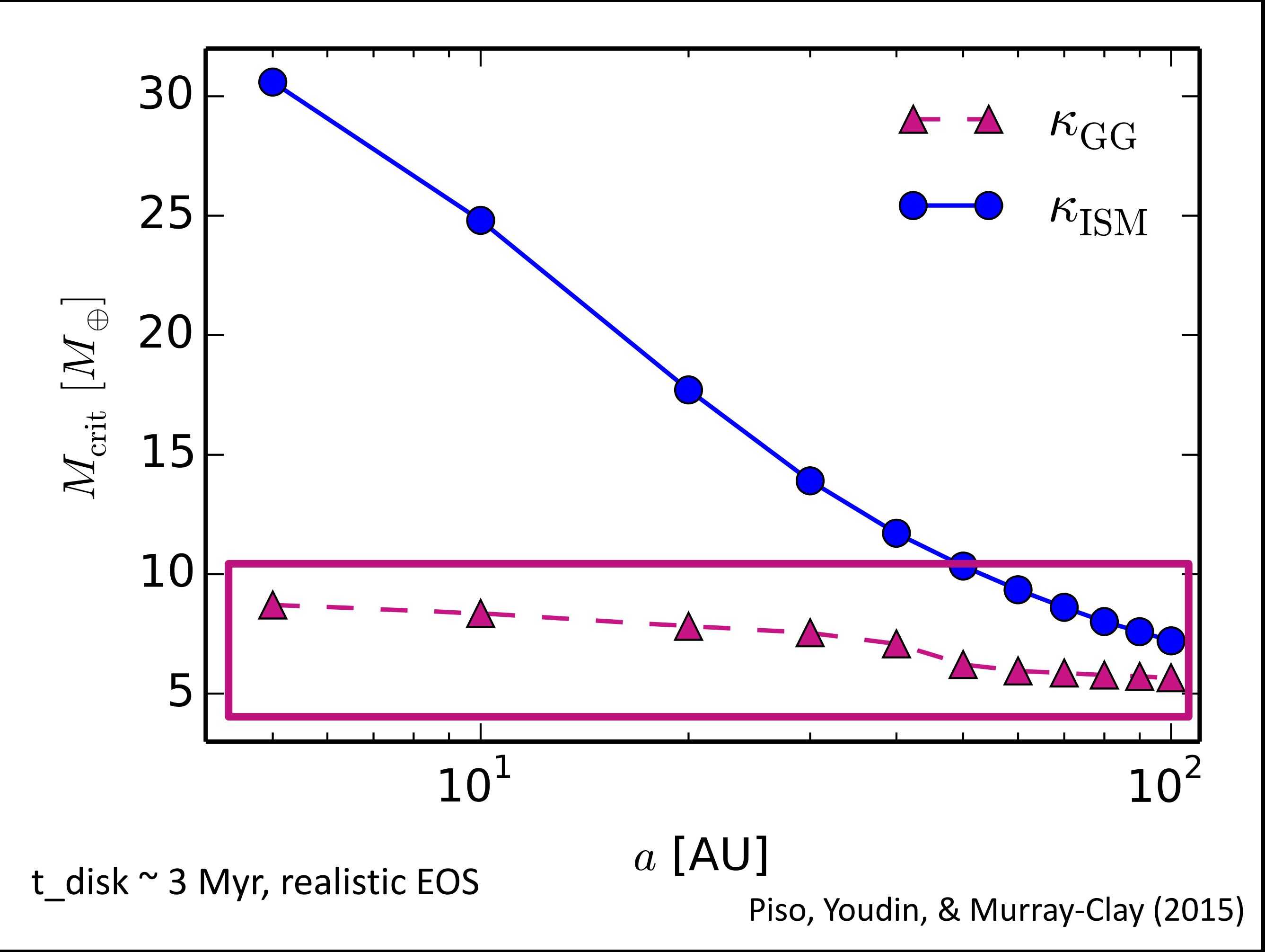

M_{crit}:

~8 M_E @ 5 AU

~5 M_E @ 100 AU

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dN/ds ~ s^{-p}

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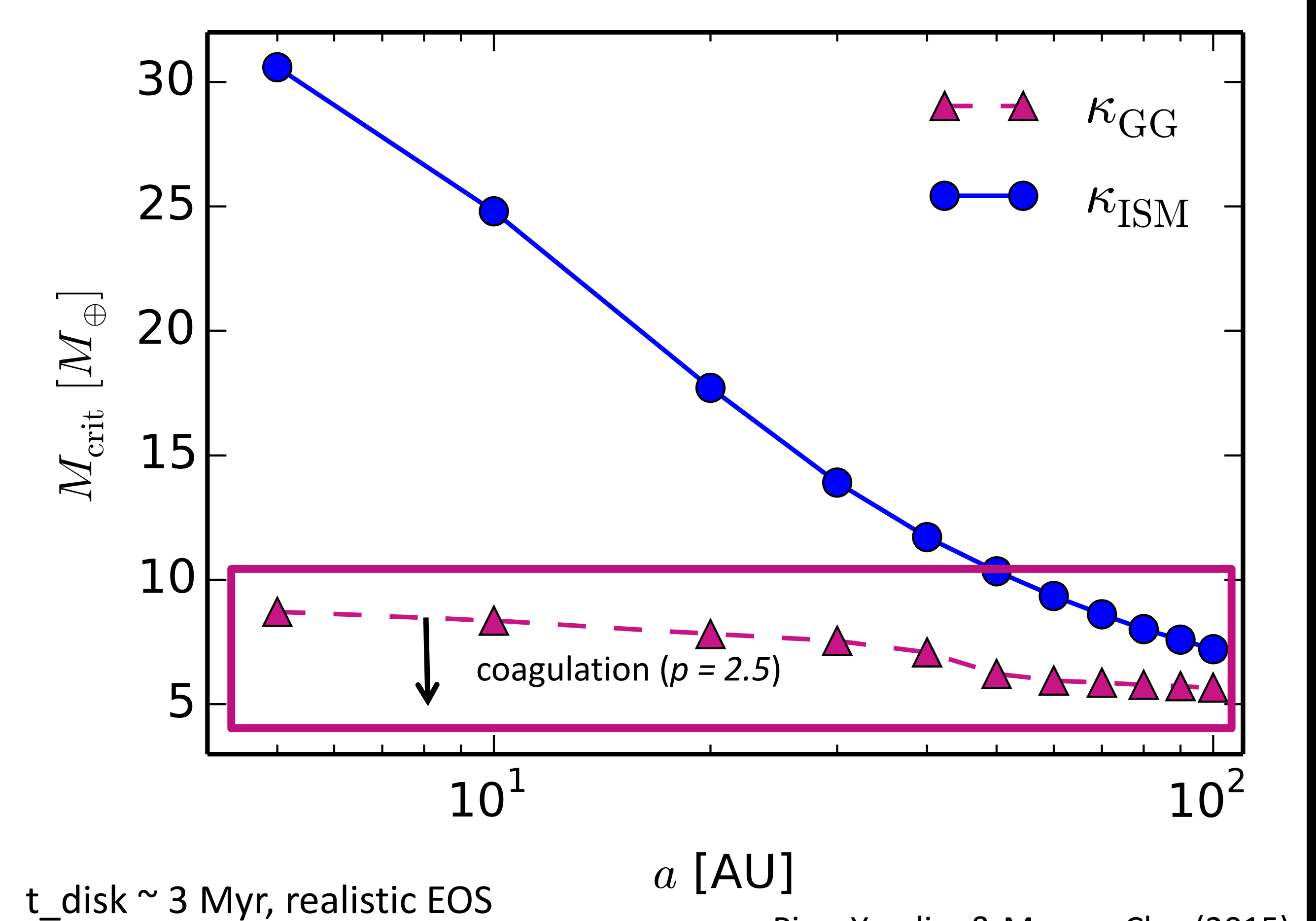
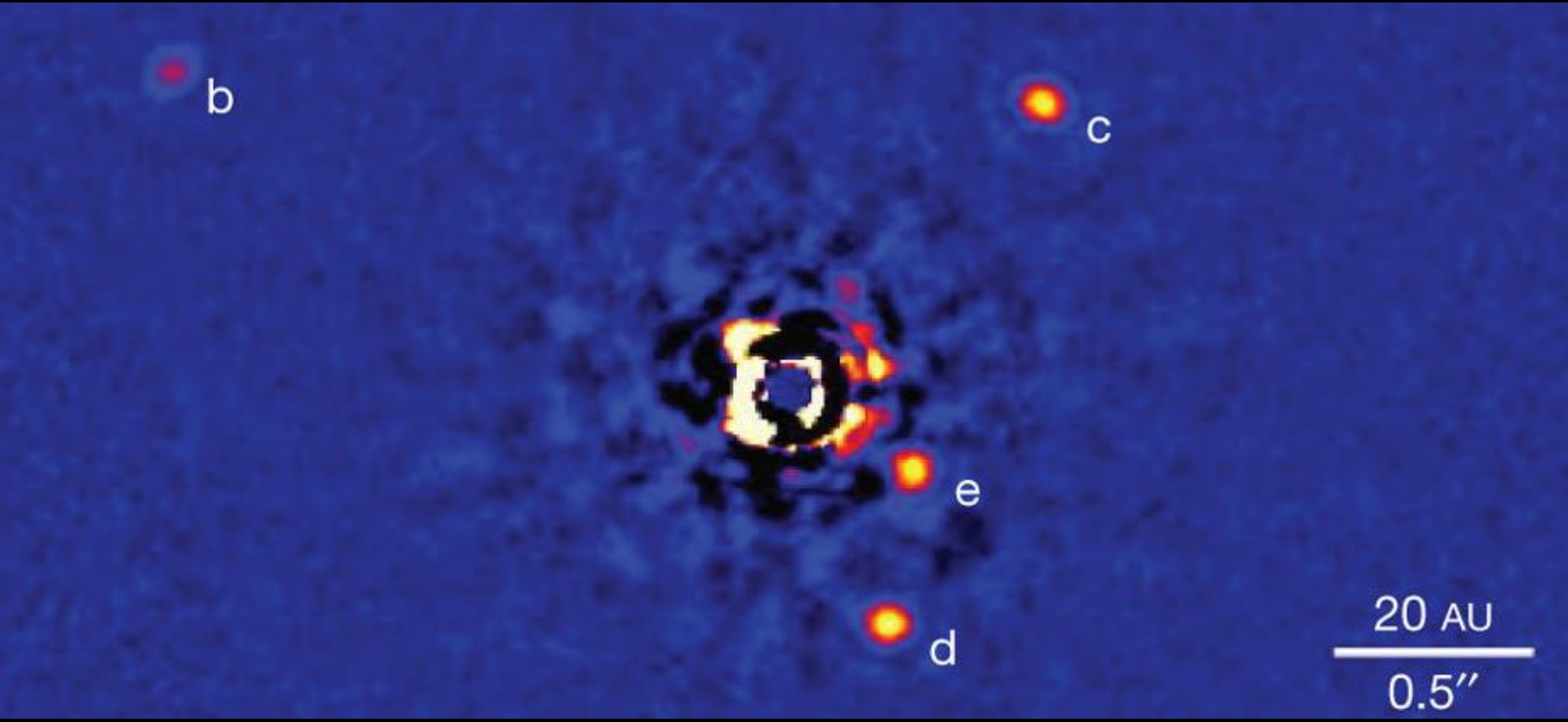


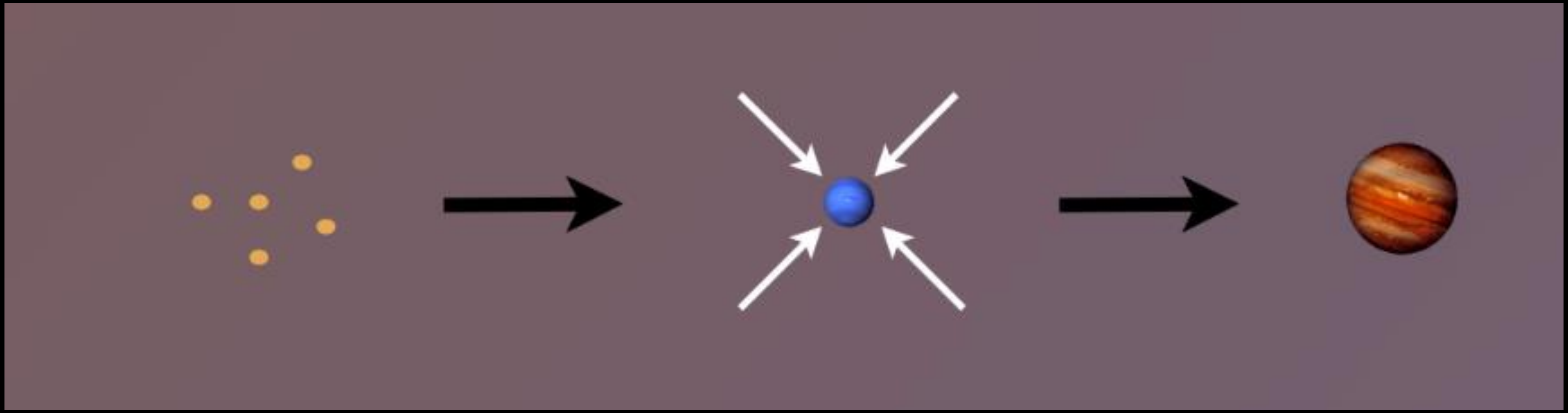
Piso, Youdin, & Murray-Clay (2015)

Takeaway point 1: M_{crit} is highly dependent on disk location and properties, and may be as low as 1 M_E



Marois+2010

Disk Compositions Regulate Planet Compositions



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

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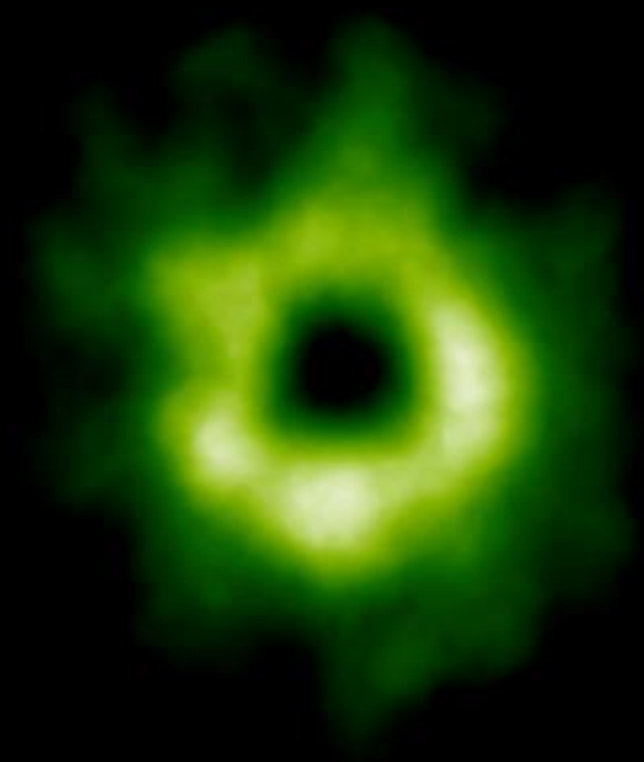
Snowline Locations in Protoplanetary Disks and C/N/O ratios

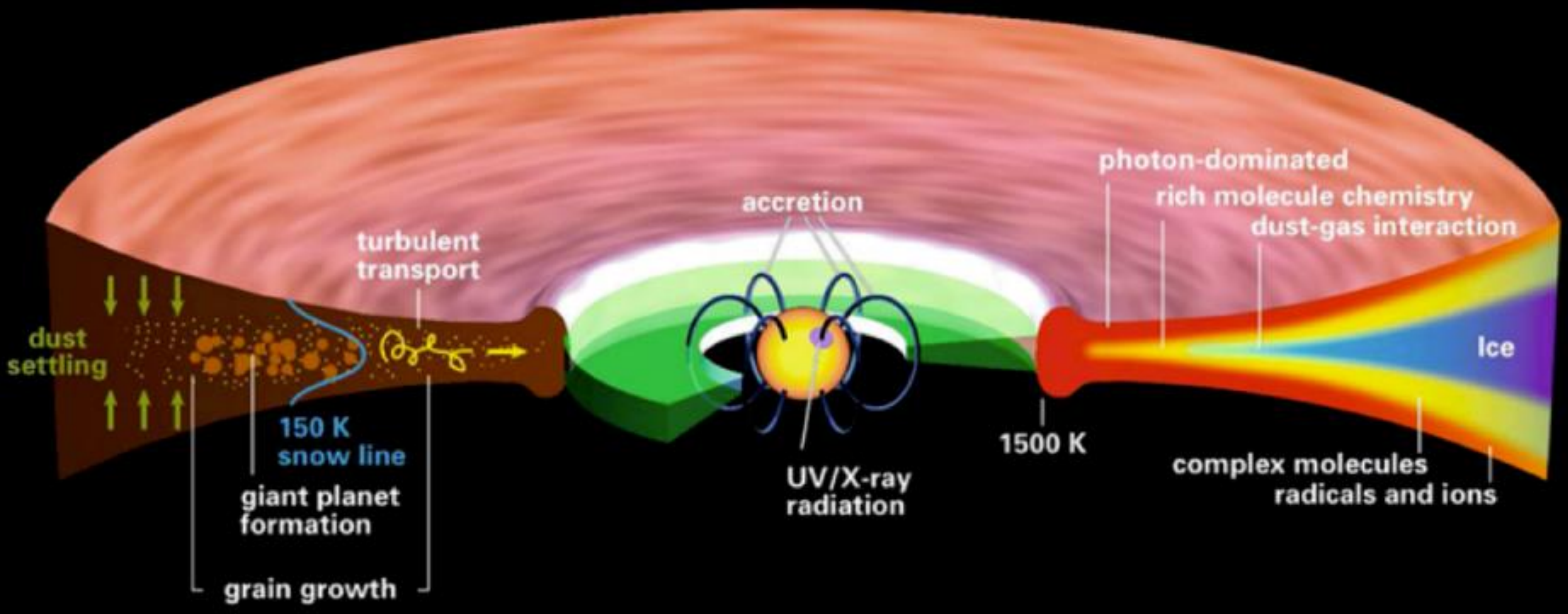


BASIC IDEA

Understand the disk well enough to:

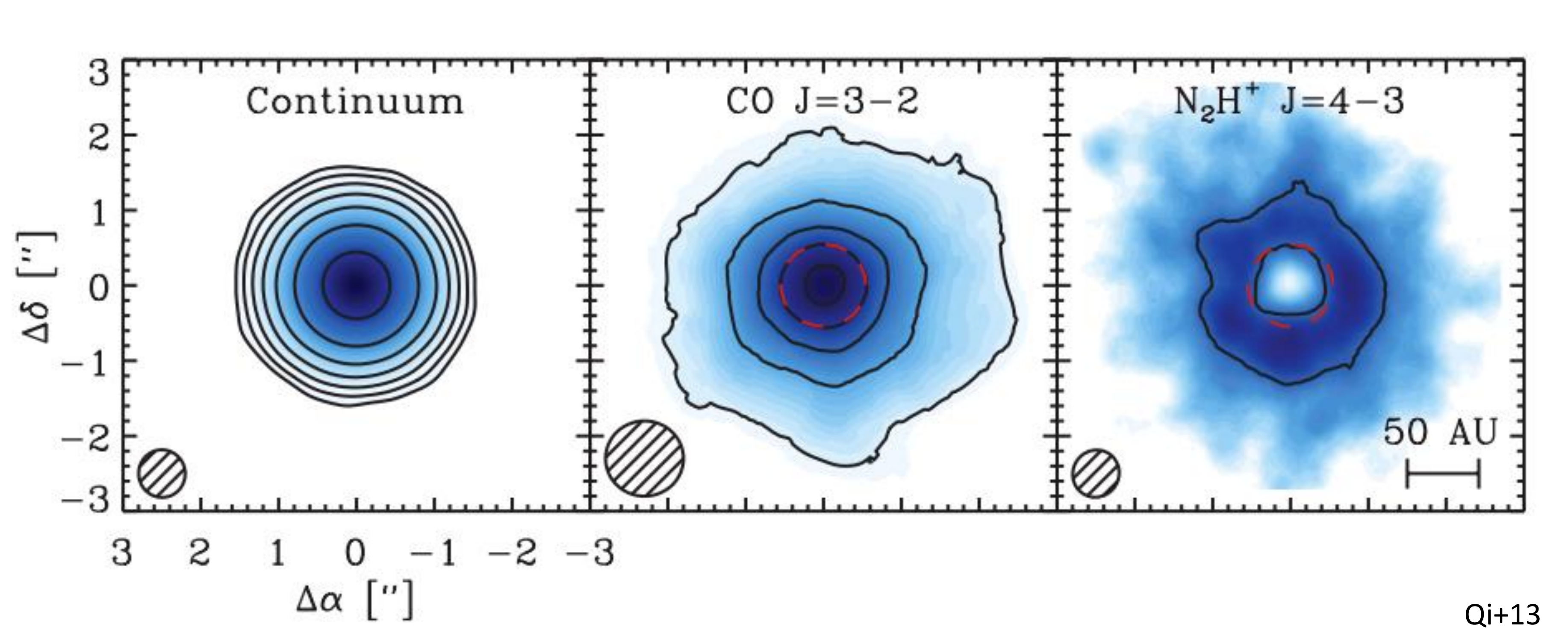
1. Predict what kind of planet compositions result from planet formation in different parts of the disk
2. Back-track the planet formation location based on the planet composition

Disk structure is complex!



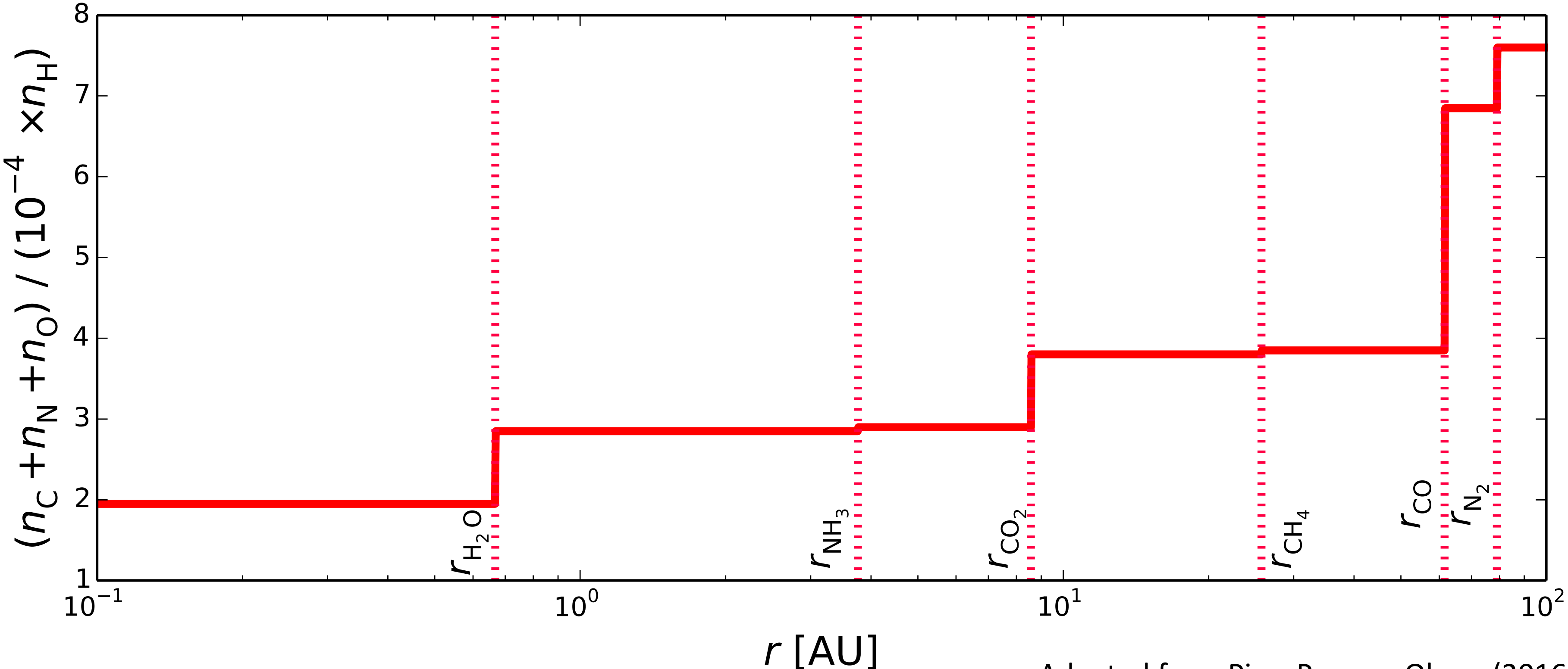
Henning&Semenov (2013)

Snowlines of volatile molecules have been detected in disks



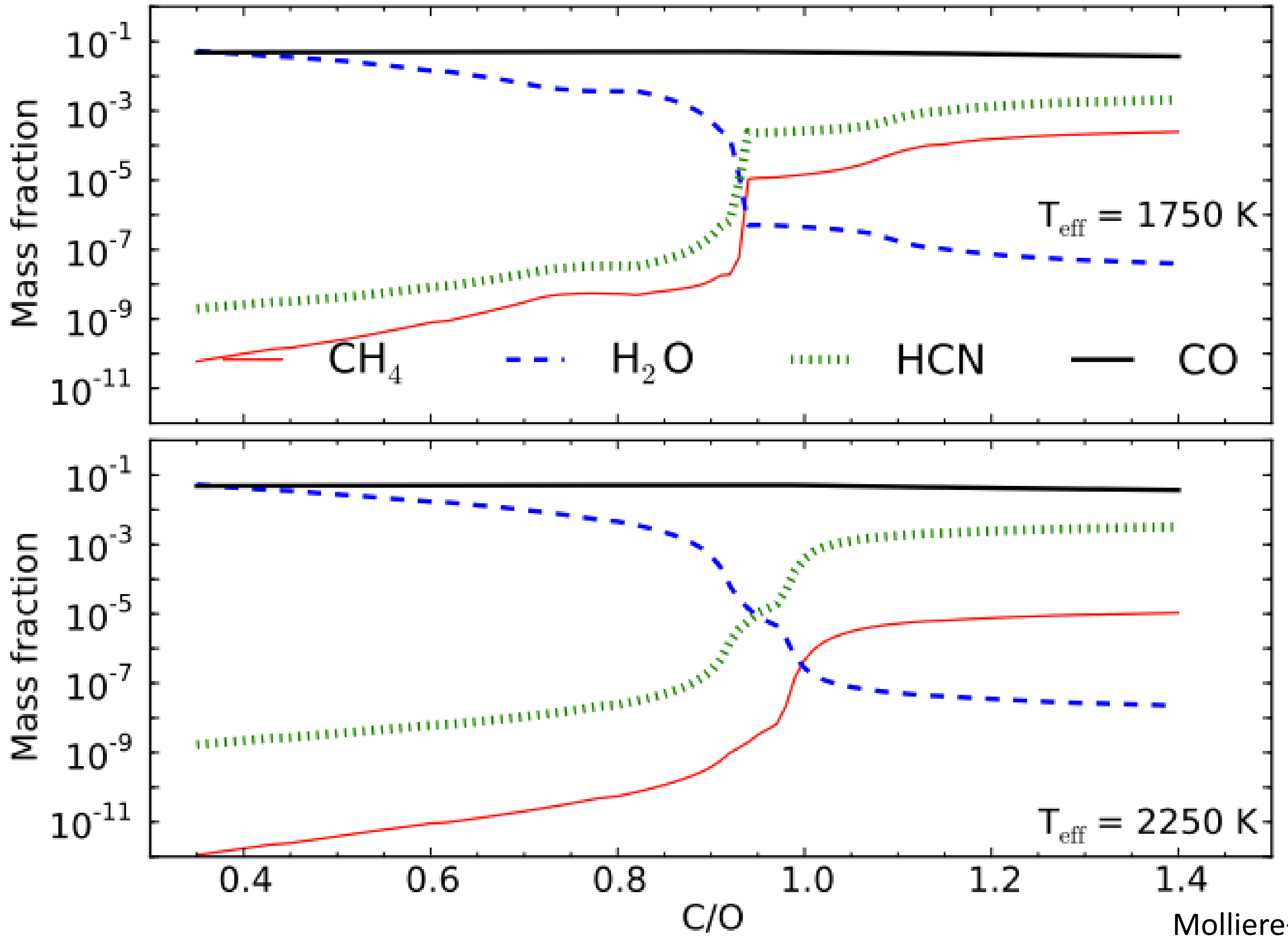
Qi+13

More volatile snowlines in disks



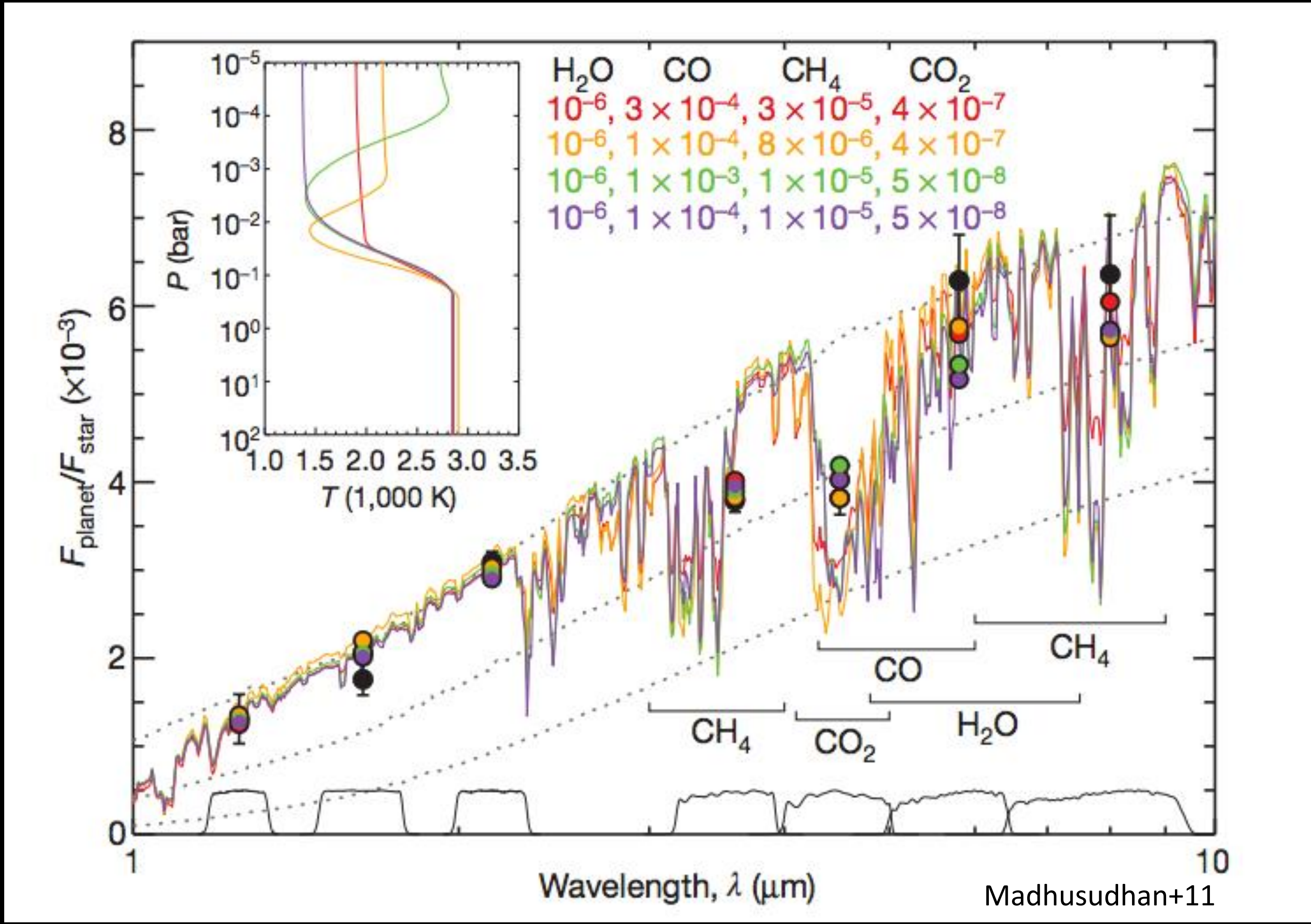
Adapted from Piso, Pegues, Oberg (2016)

C/O ratio is an important signature of atmospheric chemistry

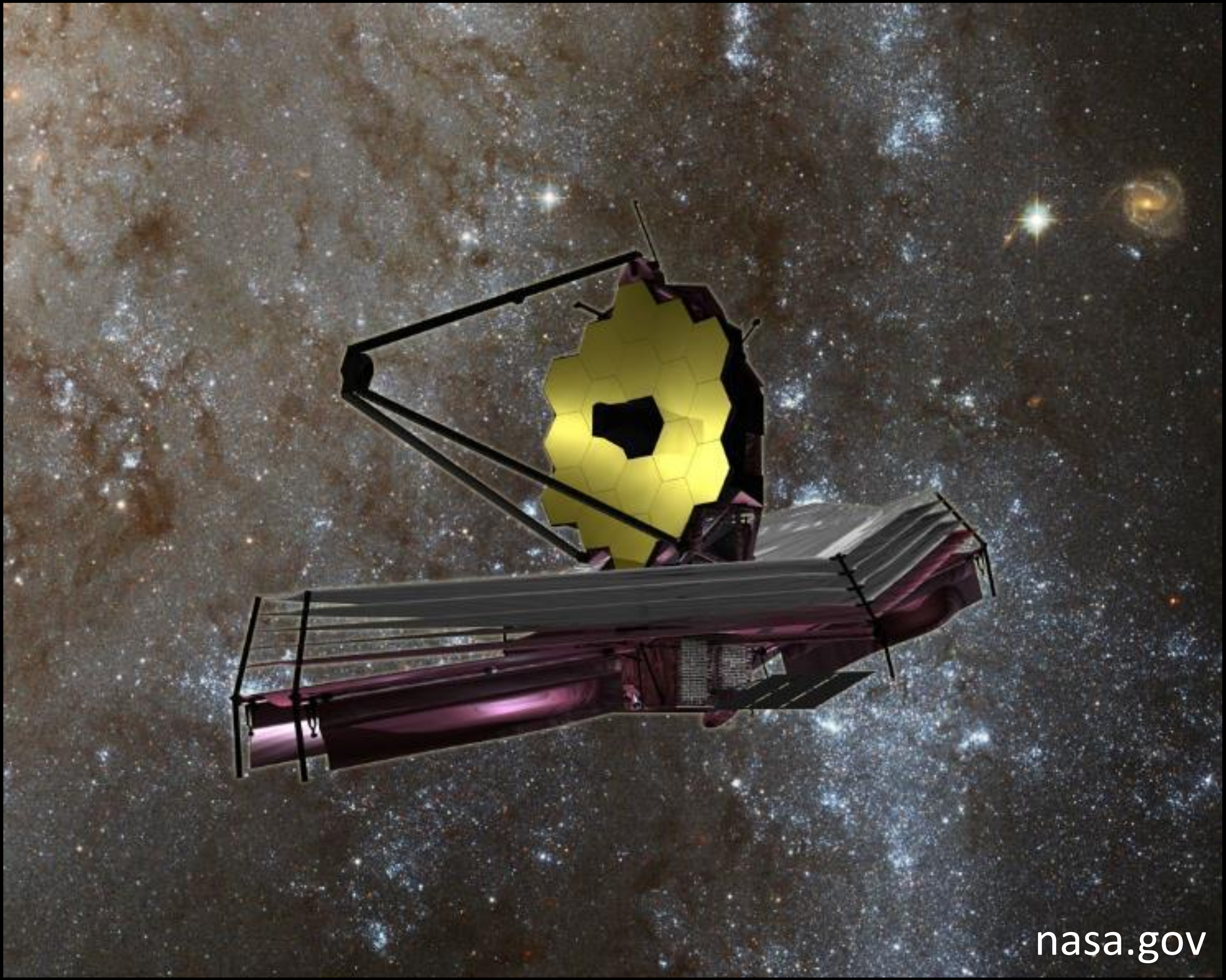


Molliere+15

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

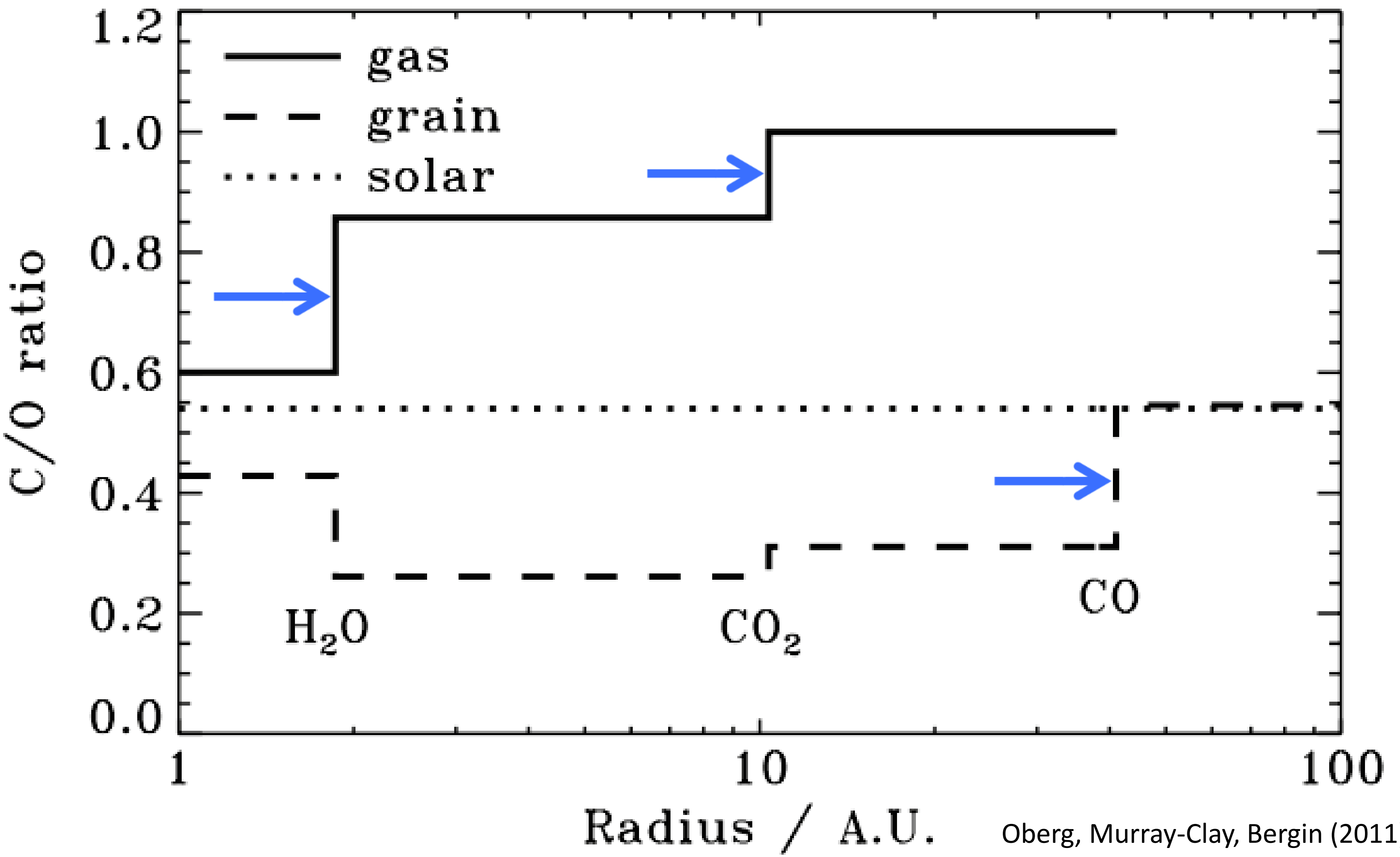


Madhusudhan+11


nasa.gov

WHY Different C/O Ratios?

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



Oberg, Murray-Clay, Bergin (2011)

GOAL

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

Radial drift of solids

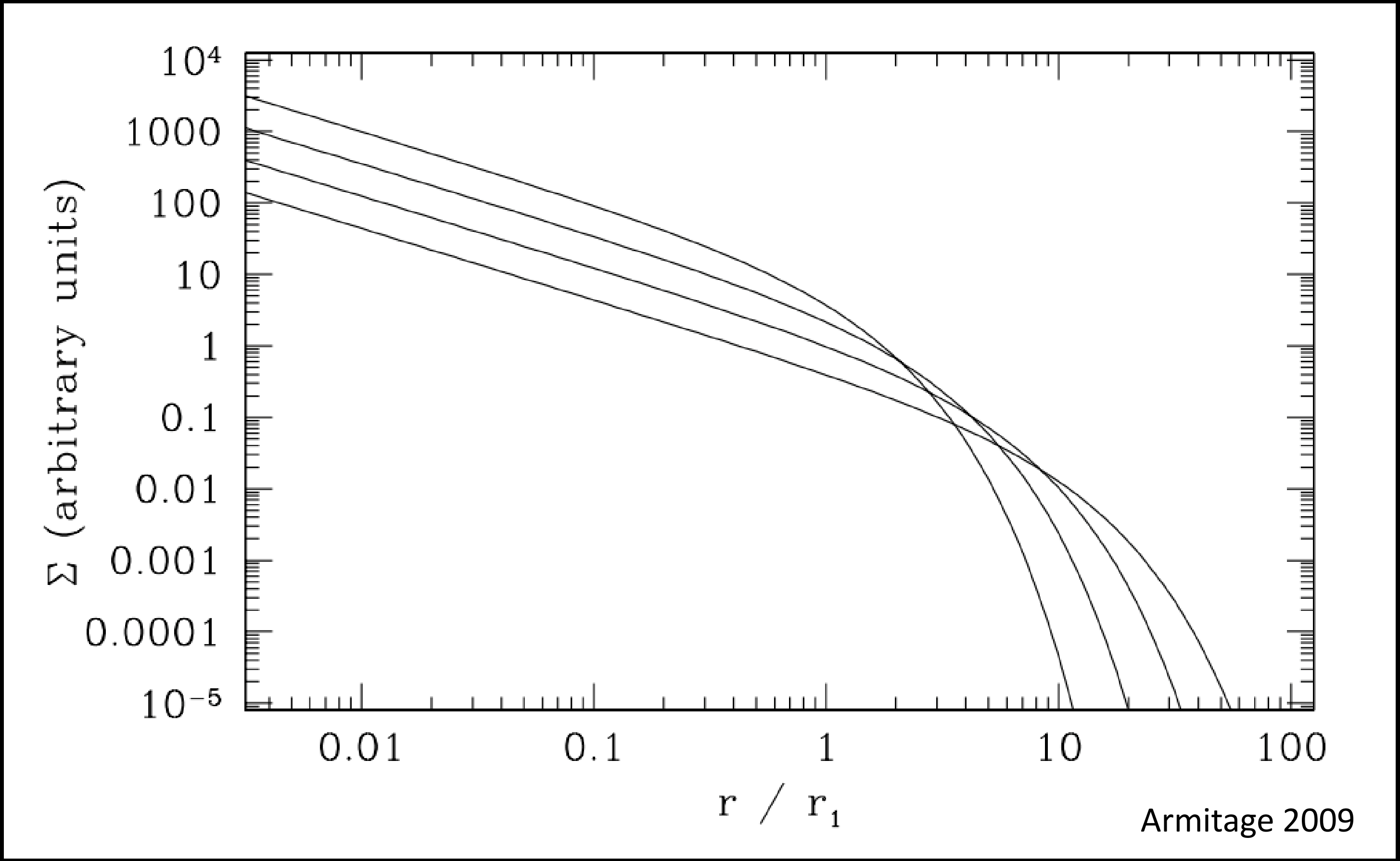
- Gas moves at sub-Keplerian velocity:

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

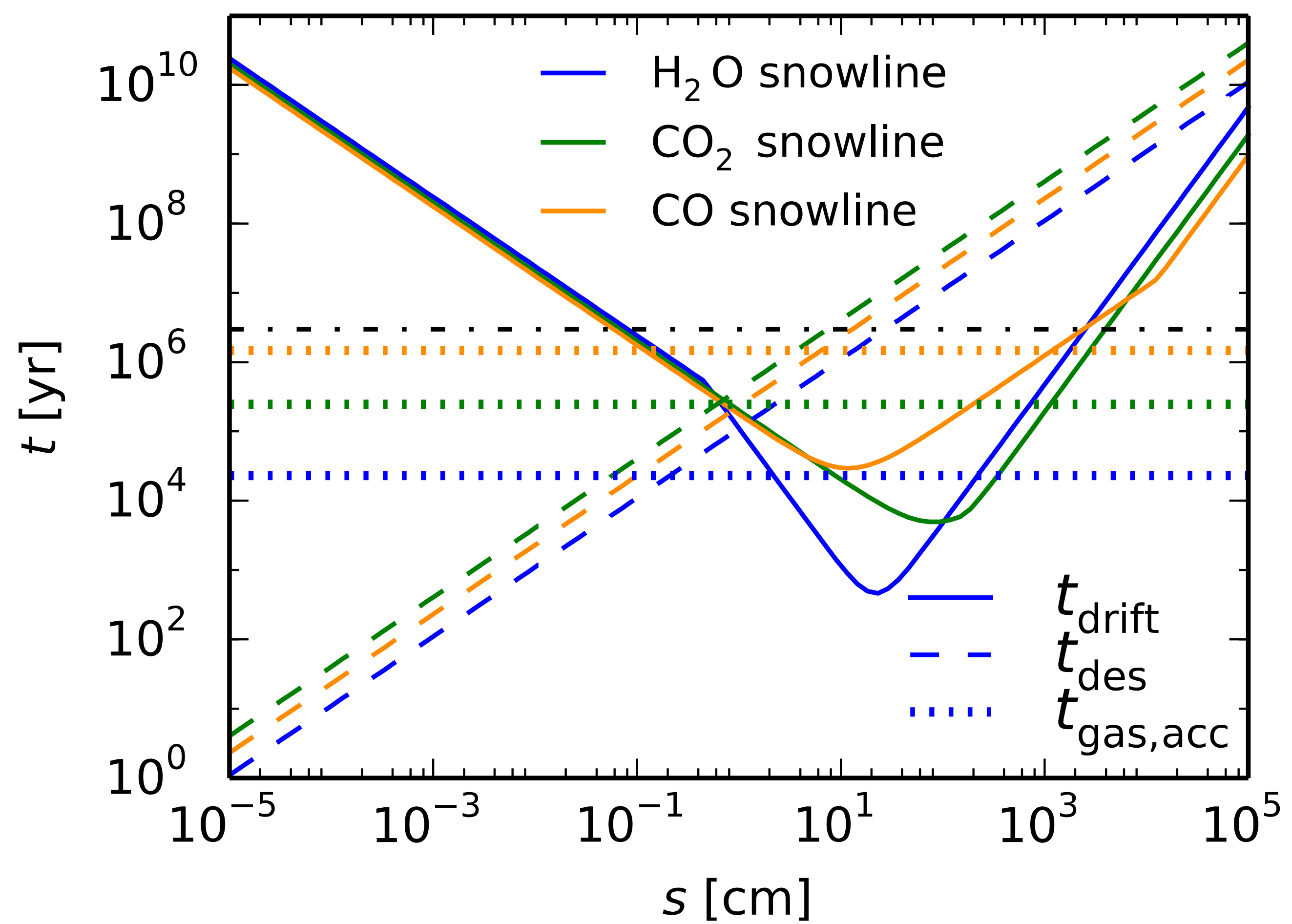
- Small particles (~micron size) move with the gas
- Large particles (~km size) are unaffected by gas drag
- "Intermediate sized" particles (~cm-m size) experience a headwind and drift towards the star

Gas disk accretes onto the central star

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

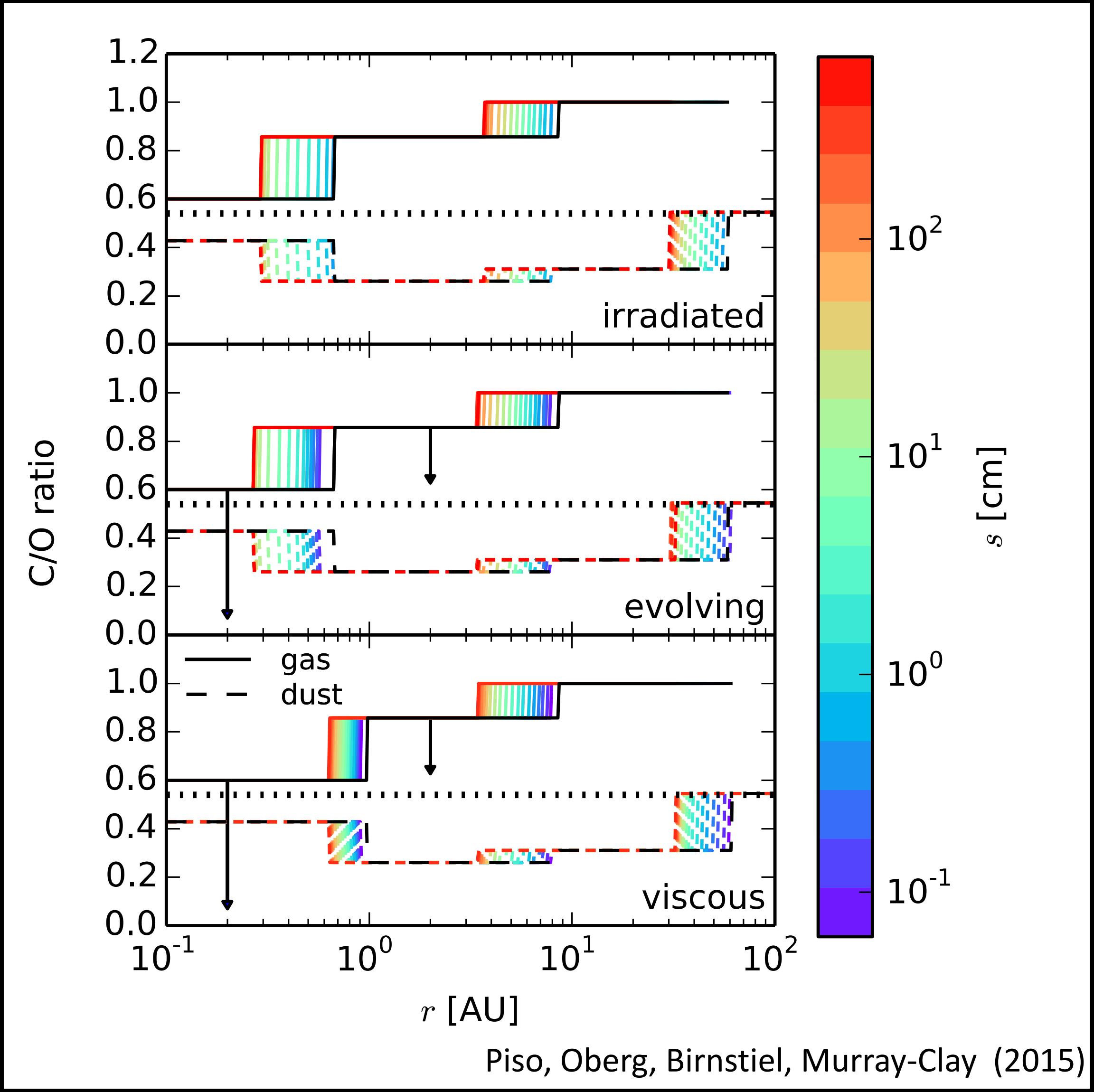


Timescales for desorption, radial drift and gas accretion ARE comparable



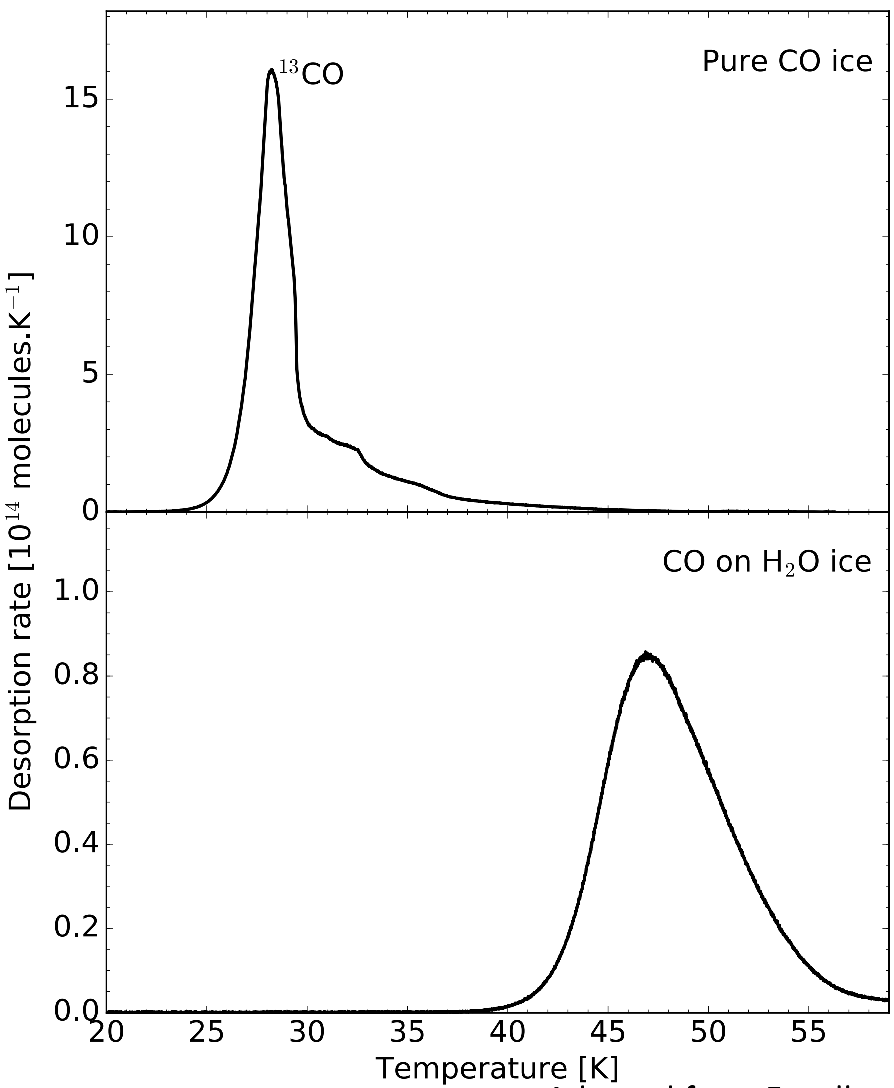
Piso, Oberg, Birnstiel, Murray-Clay (2015)

We determined upper limits for the C/O ratio across the disk



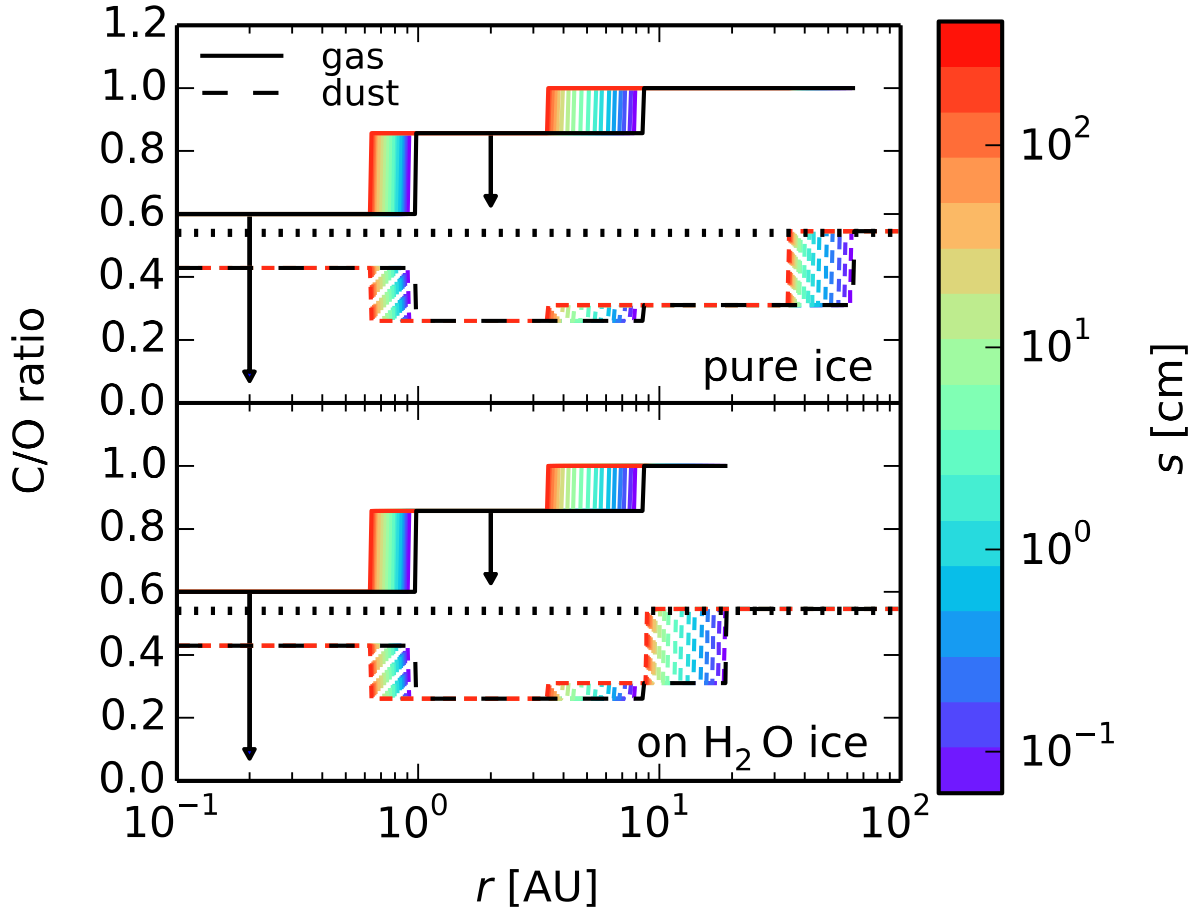
Ice Morphology

The binding energies of CO varies by a factor of ~1.7 depending on whether CO is pure or water dominated ice



Adapted from Fayolle+16

Disk dynamics and ice morphology may change the CO snowline location by a factor of 7!



Piso, Pegues, Oberg (2016)

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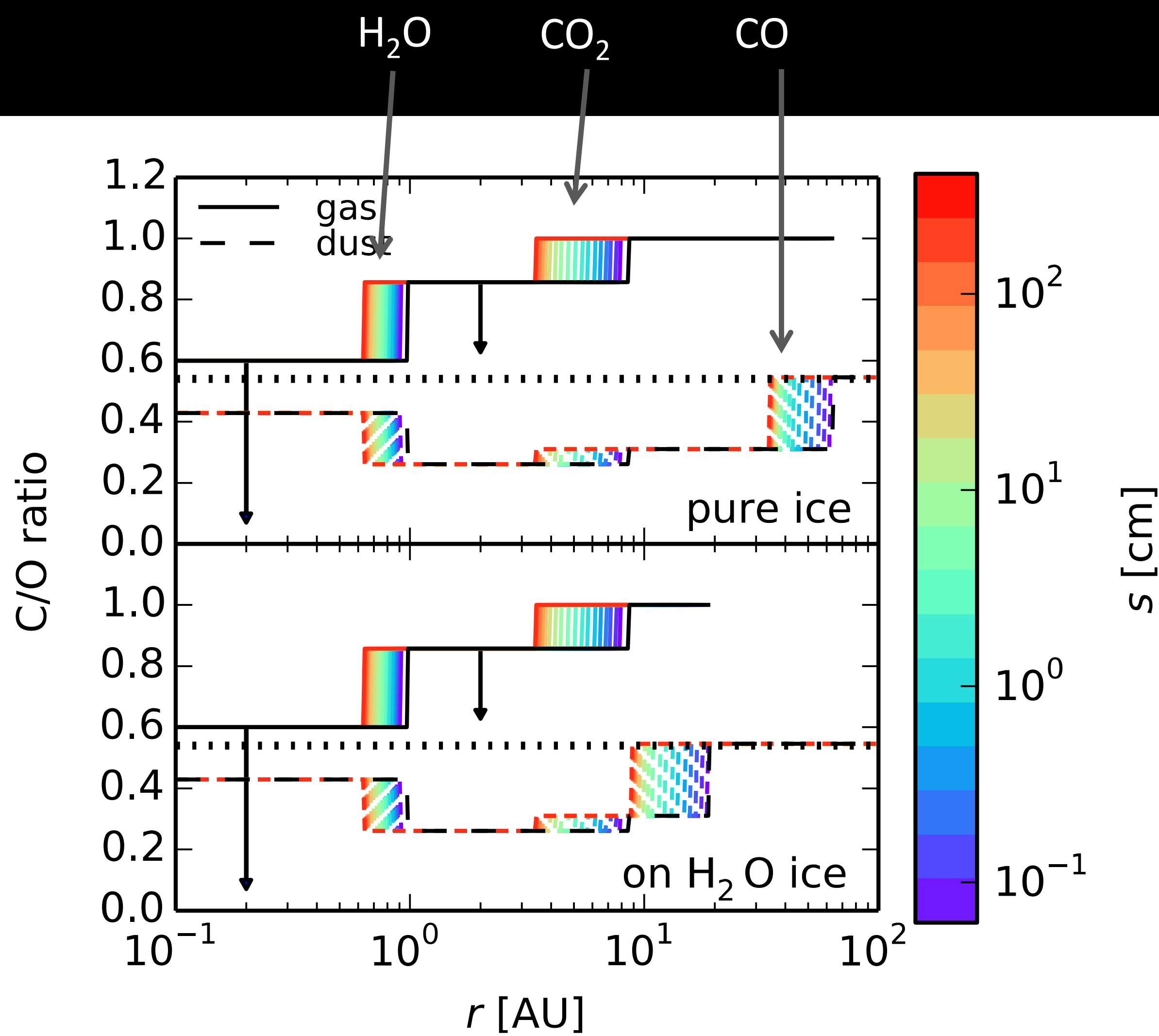

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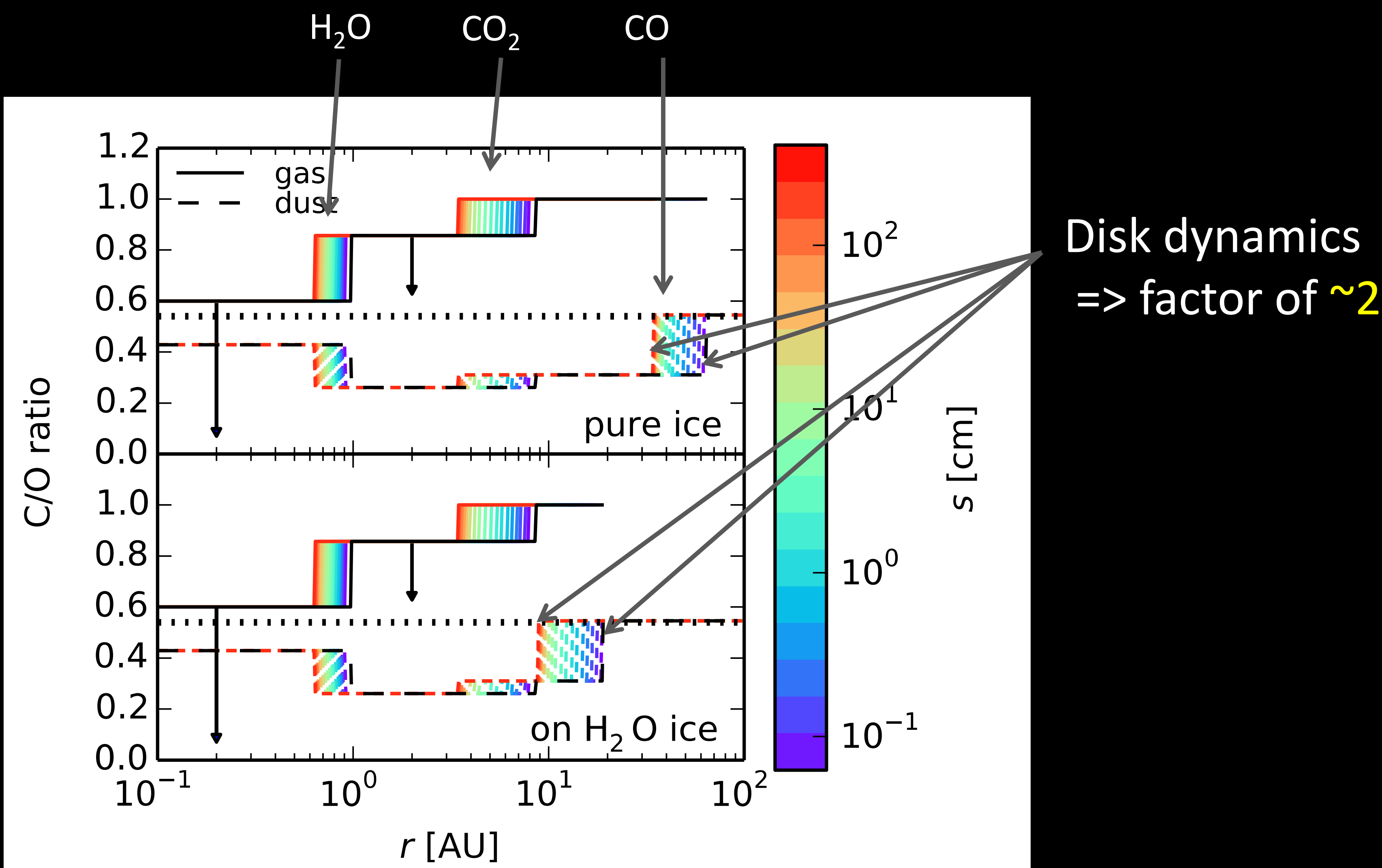

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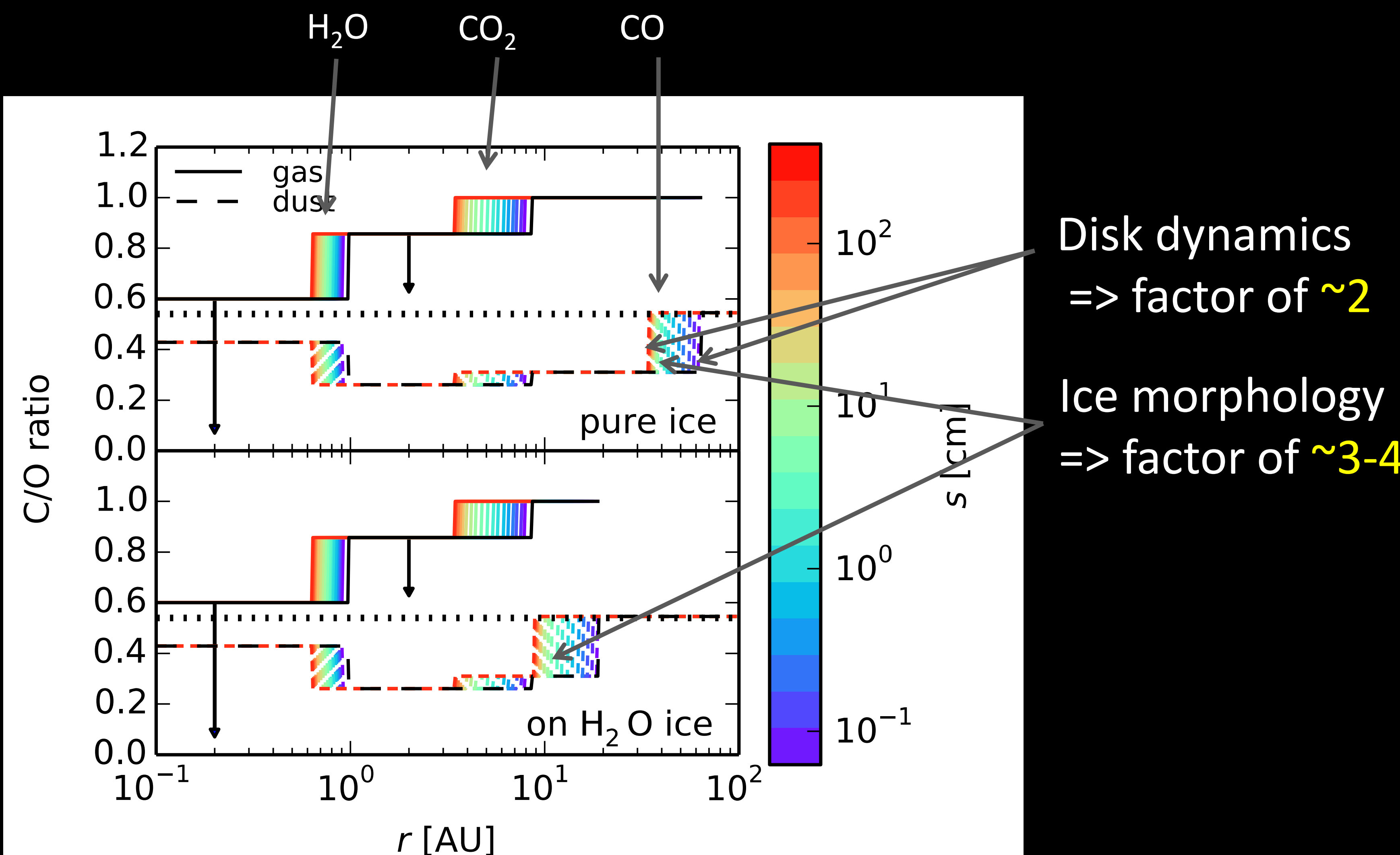

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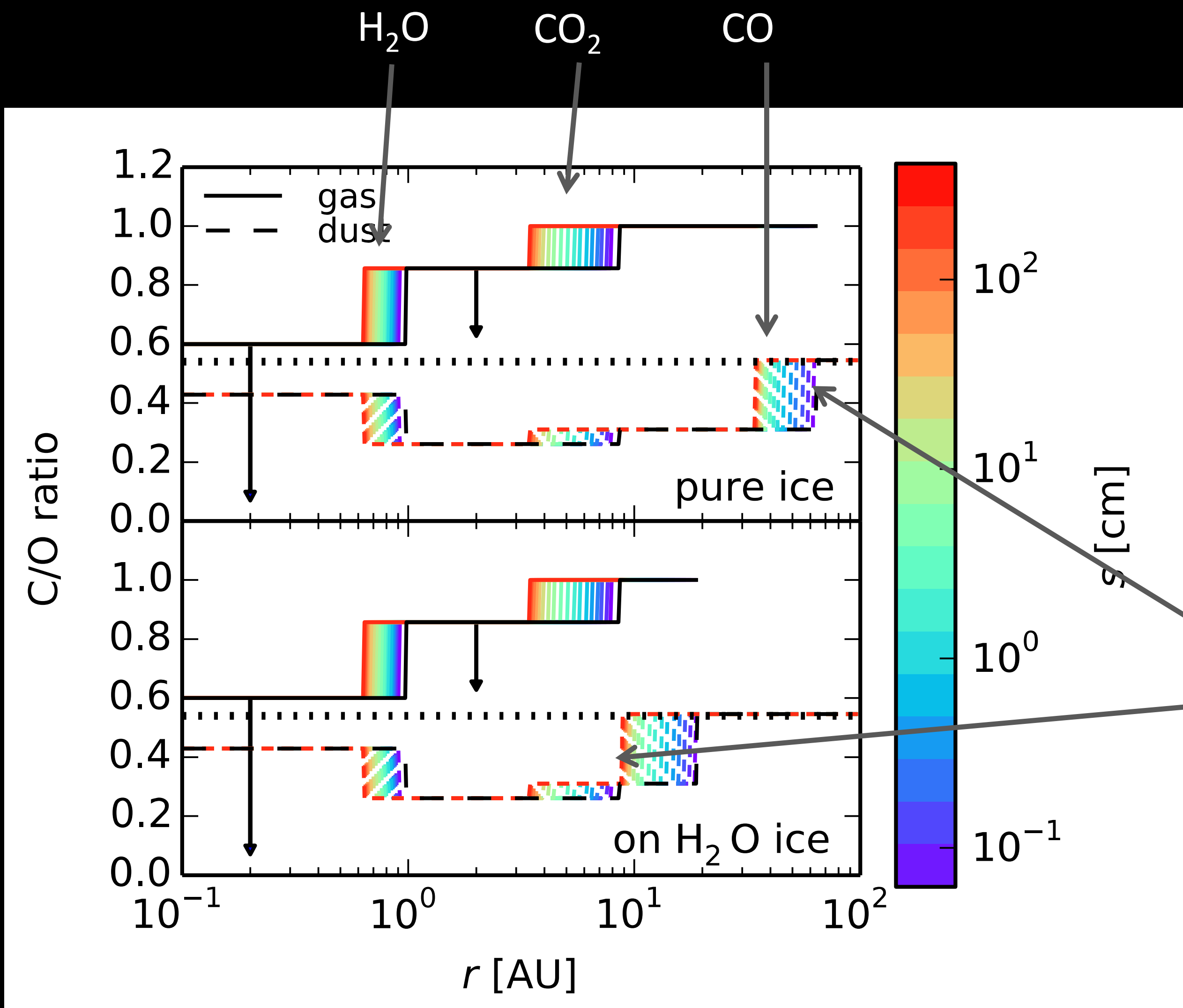


Piso, Pegues, Oberg (2016)

Disk dynamics
=> factor of ~2

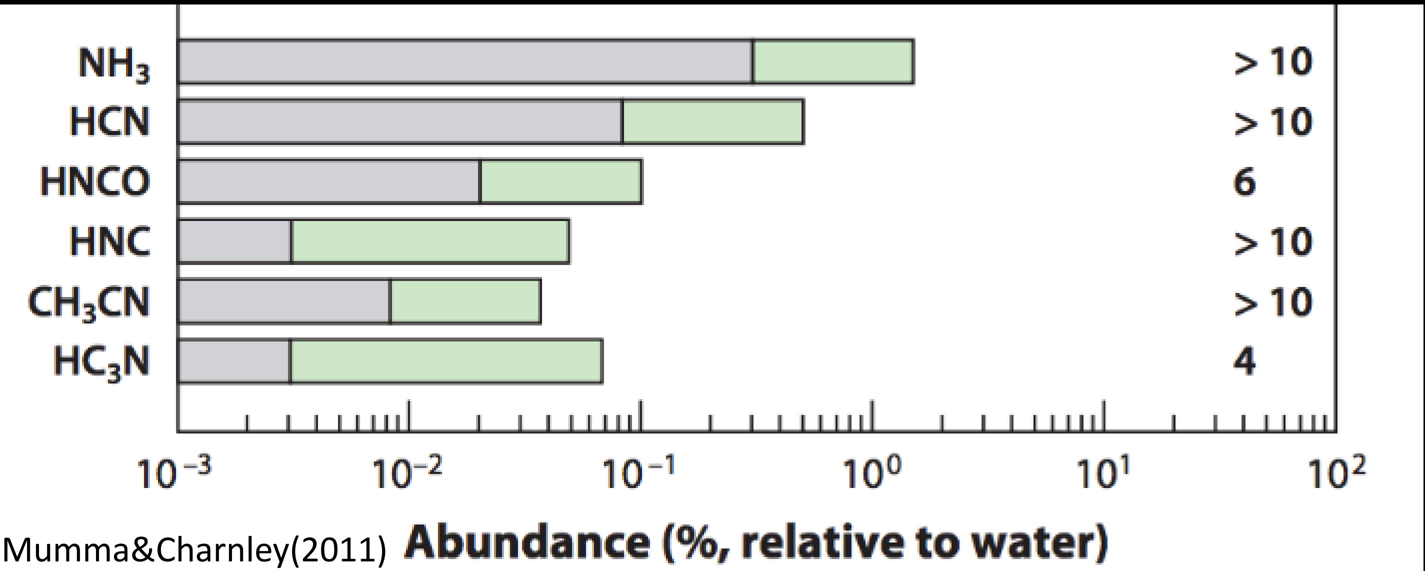
Ice morphology
=> factor of ~3-4

CO snowlines span 9-61 AU!

Nitrogen is important!

- Add nitrogen-bearing molecules – nitrogen highly abundant in the Solar System and in disks and primarily found as N_2
- Some N present in the form of NH_3

  => Use the median and maximum NH_3 abundances observed in protostellar cores from *Spitzer* c2d Legacy ice survey (Oberg et al. 2008, Oberg et al. 2011, etc.)



Mumma&Charnley(2011)

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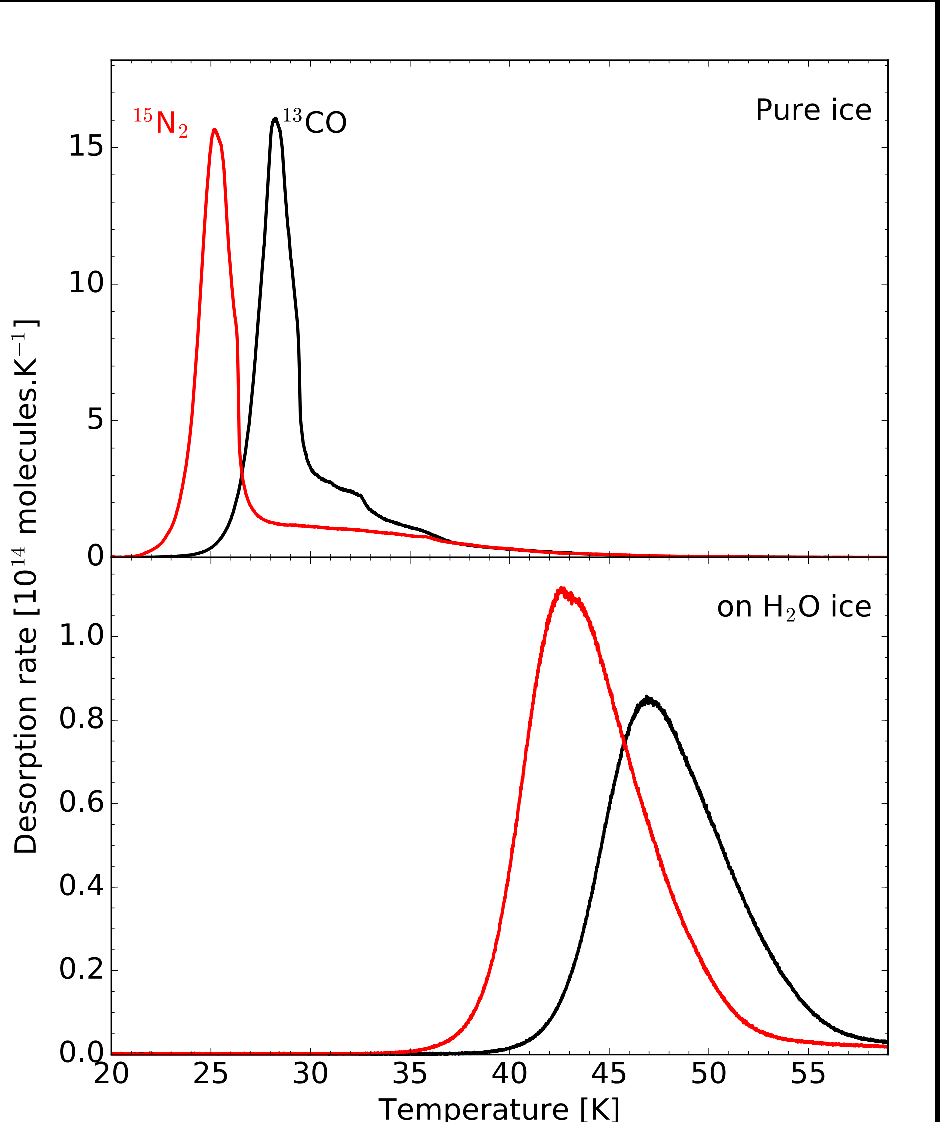
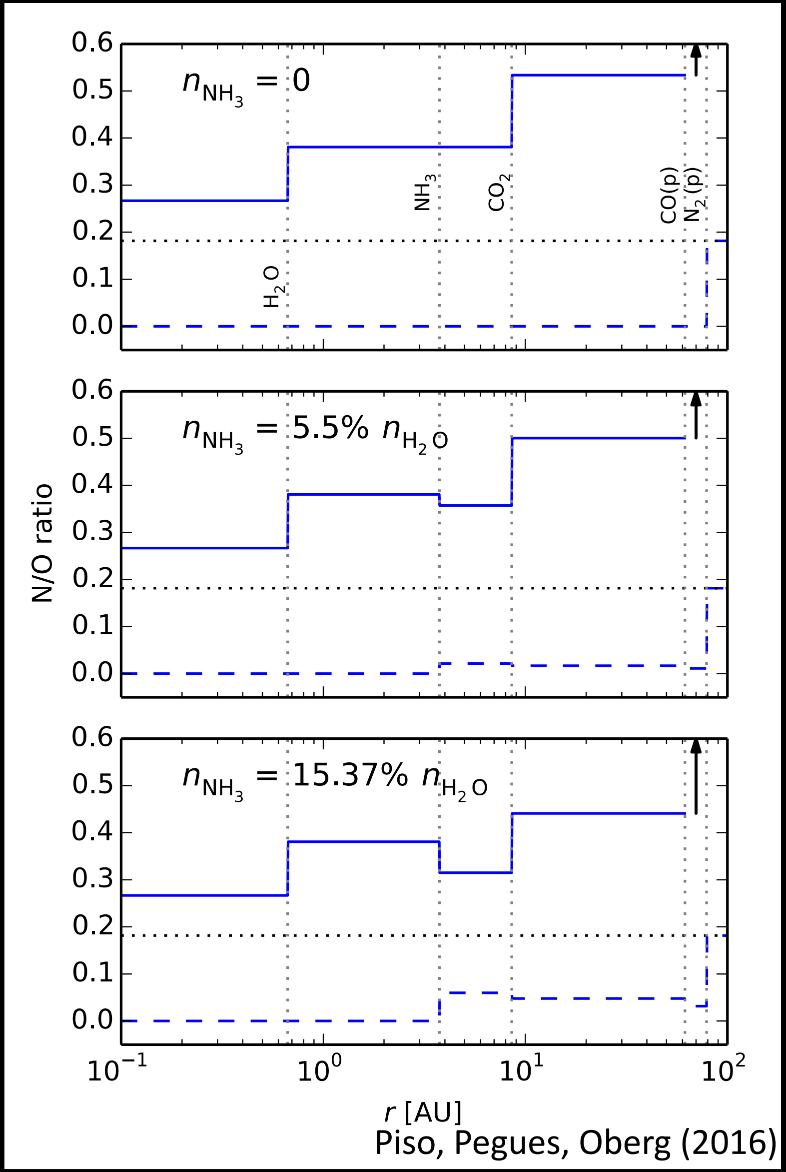
The binding energies of N_2 varies by a factor of ~1.7 depending on whether N2 is pure or water dominated ice

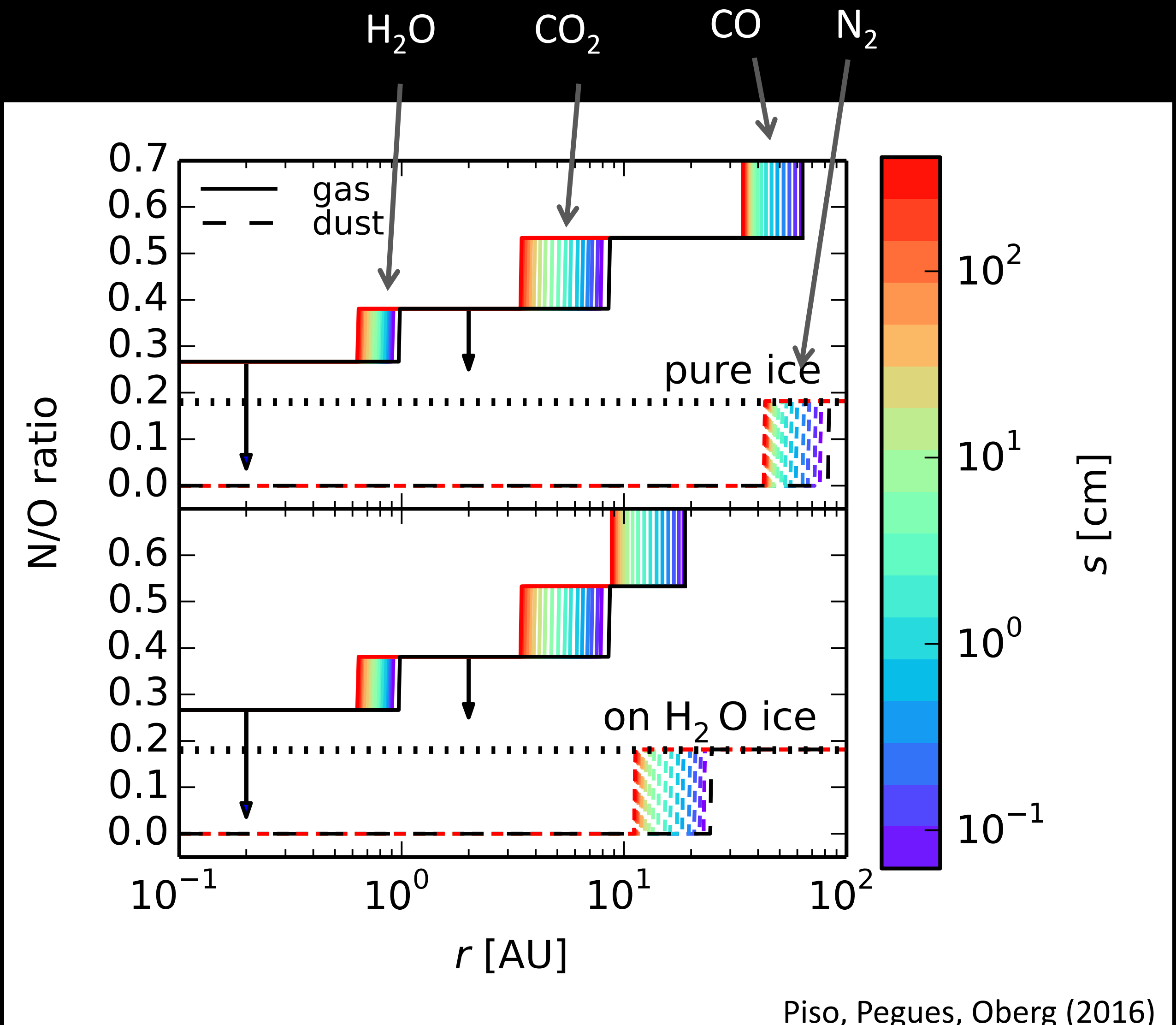


Adapted from Fayolle+16

N/O ratios in static disks: highly enhanced gas N/O compared to the average value



Disk dynamics and ice morphology may change the N_2 snowline locations by a factor of 7!

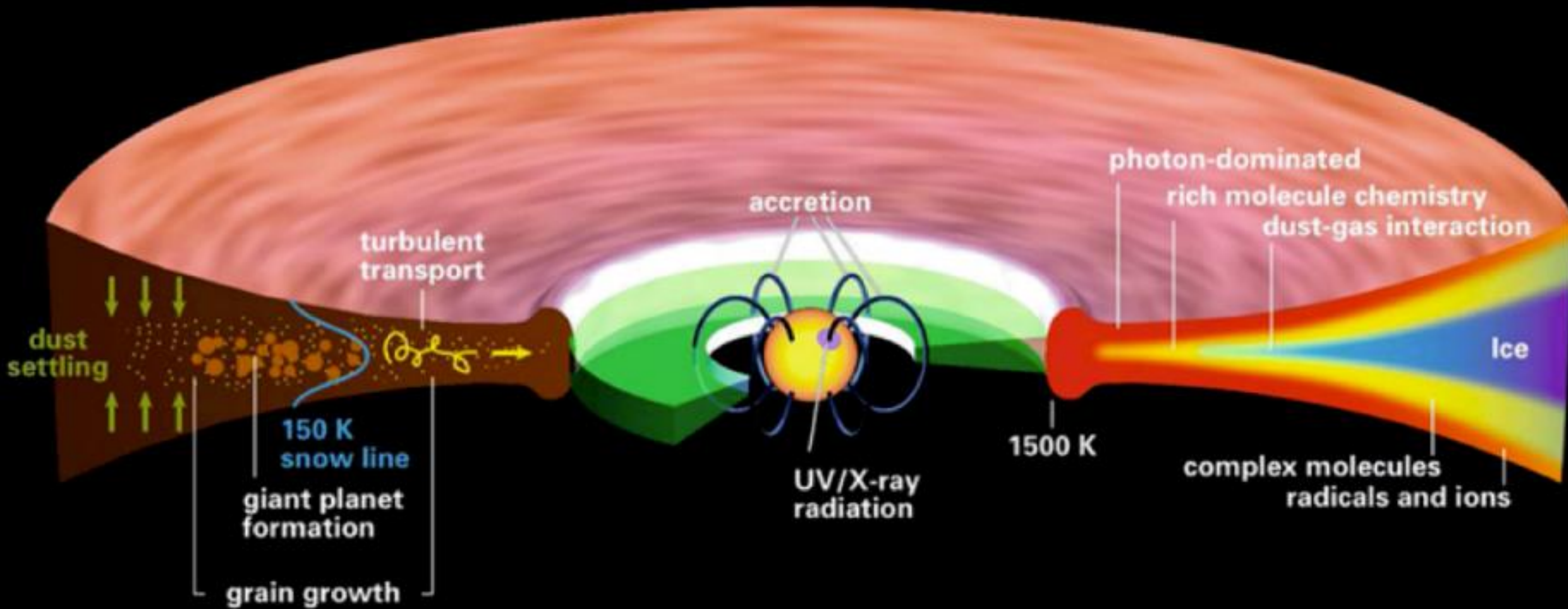


N_2 snowlines span 11-79 AU!

Takeaway point 2: Gas phase N/O ratios are highly enhanced throughout most of the disk compared to the average value, and more enhanced than the C/O ratio

Takeaway point 3: The locations of the CO and N_2 snowlines are highly uncertain and can span several tens of AU due to disk dynamics and ice morphology => observations are KEY

NEXT STEPS



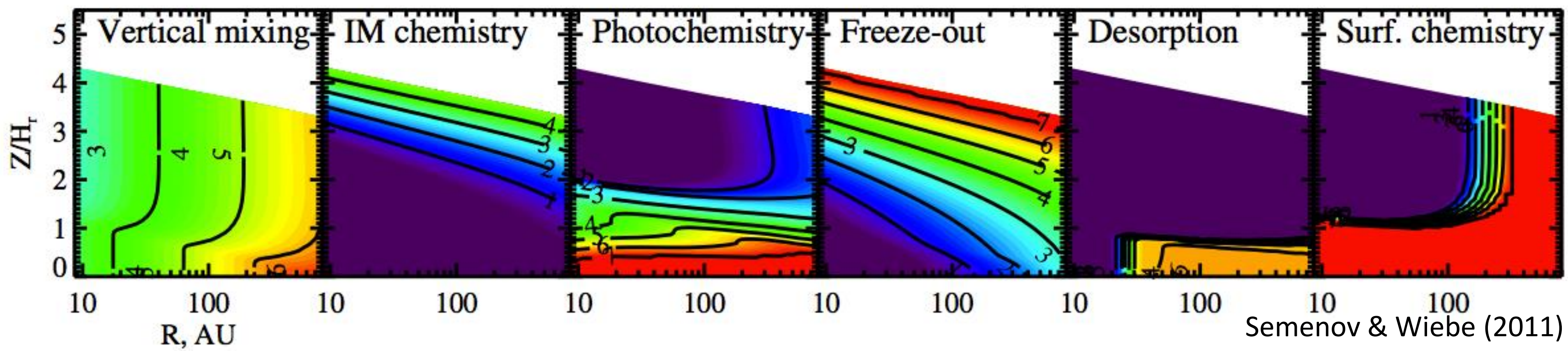
Henning&Semenov (2013)

Additional chemical and dynamical processes to be explored

Process	Effect
Radial drift	$\leftarrow$
Gas accretion	$\leftarrow$
Particle growth	$\rightarrow \leftarrow$
Turbulent diffusion	$\rightarrow \leftarrow$
Particle fragmentation	$\rightarrow \leftarrow$
Grain morphology	$\rightarrow$
Particle composition	$\rightarrow \leftarrow$
Disk gaps and holes	$\rightarrow$
Accretion rate evolution	$\rightarrow \leftarrow$
Stellar luminosity evolution	$\leftarrow$
Non-static chemistry	$\rightarrow \leftarrow$

Piso, Oberg, Birnstiel, Murray-Clay (2015)

Chemistry and Dynamics need to be coupled



Semenov & Wiebe (2011)

Fundamental Questions

1. Where in the disk can giant planets form?

    Piso & Youdin (2014)

    Piso, Youdin, & Murray-Clay (2015)

2. What compositions will the formed giant planets have obtained?

    Piso, Öberg, Birnstiel, & Murray-Clay (2015)

    Piso, Pegues, & Öberg (2016)