Minimum Core Masses for Giant Planet Formation

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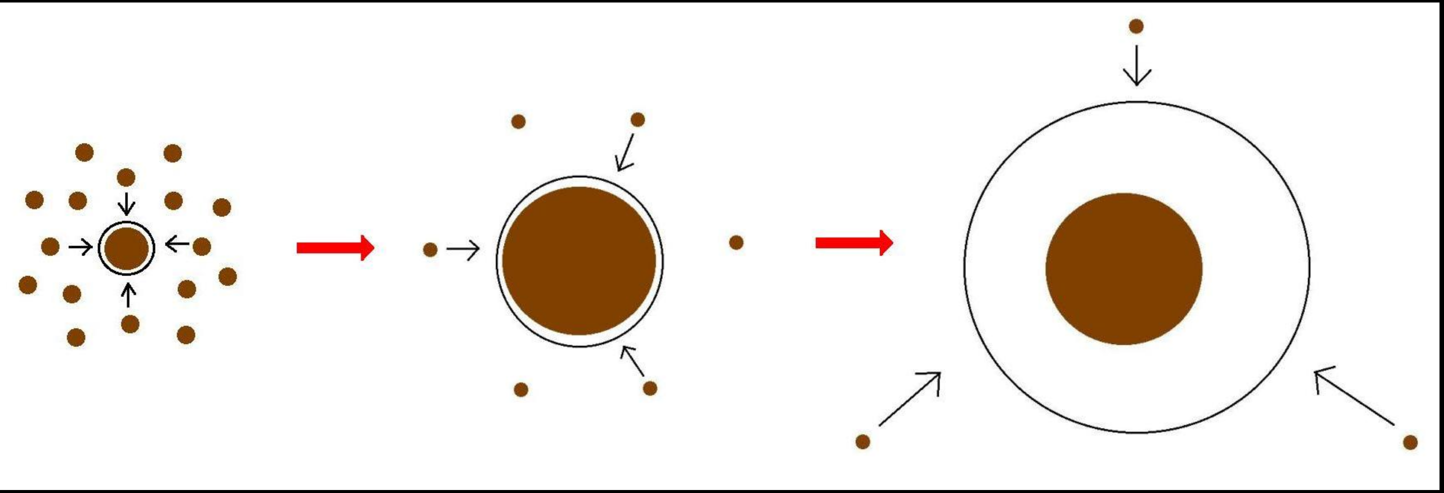

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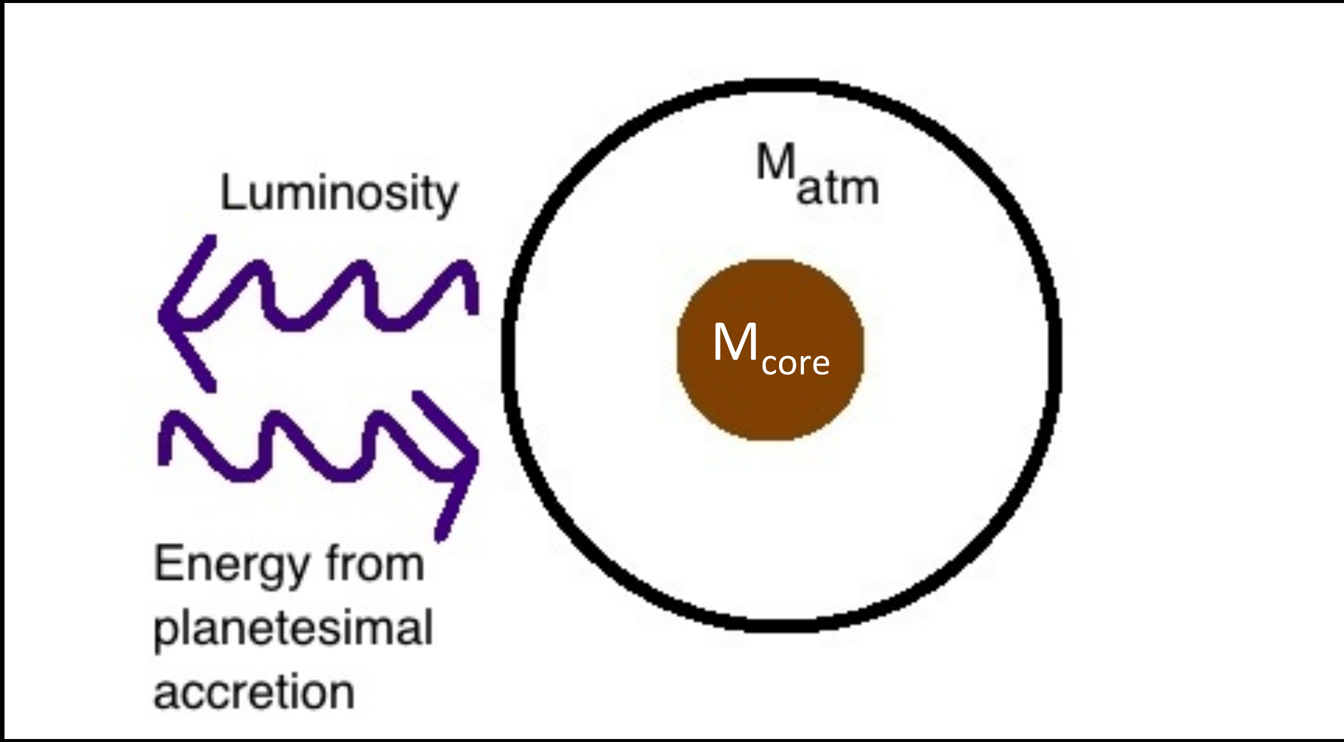
Core Accretion at high planetesimal accretion rates yields steady state

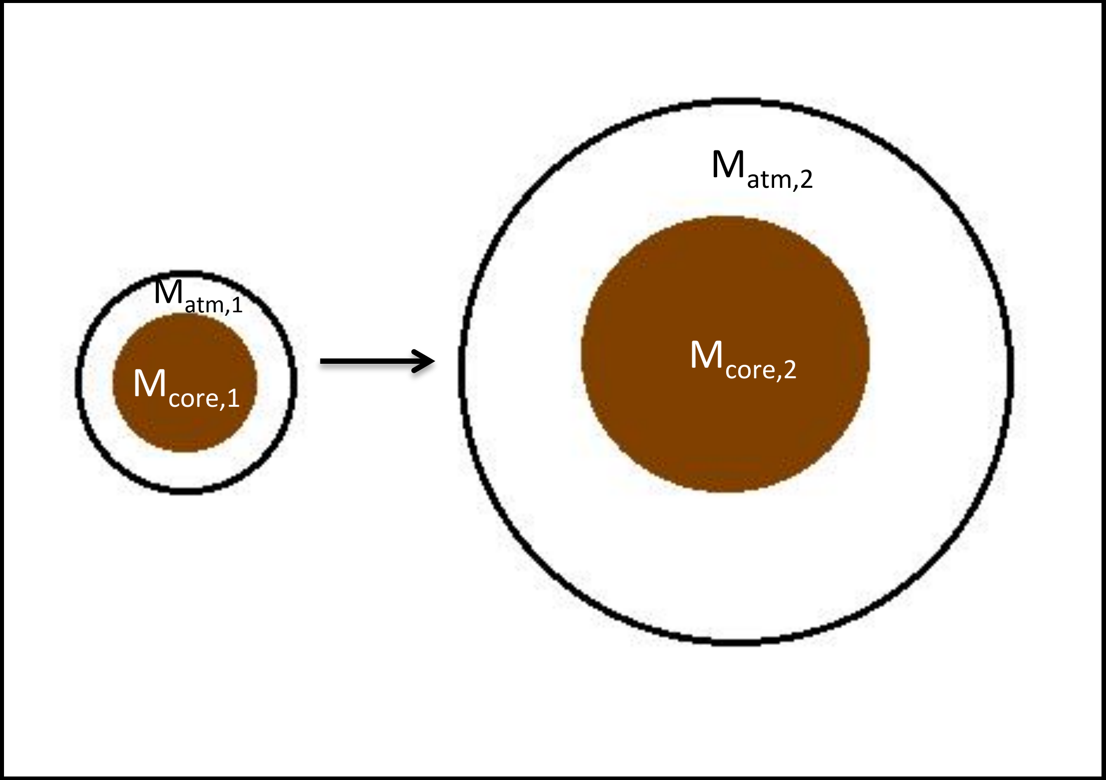
=> M_{atm} is a function of M_{core}



Planetesimal accretion

ONE M_{atm} for each M_{core}

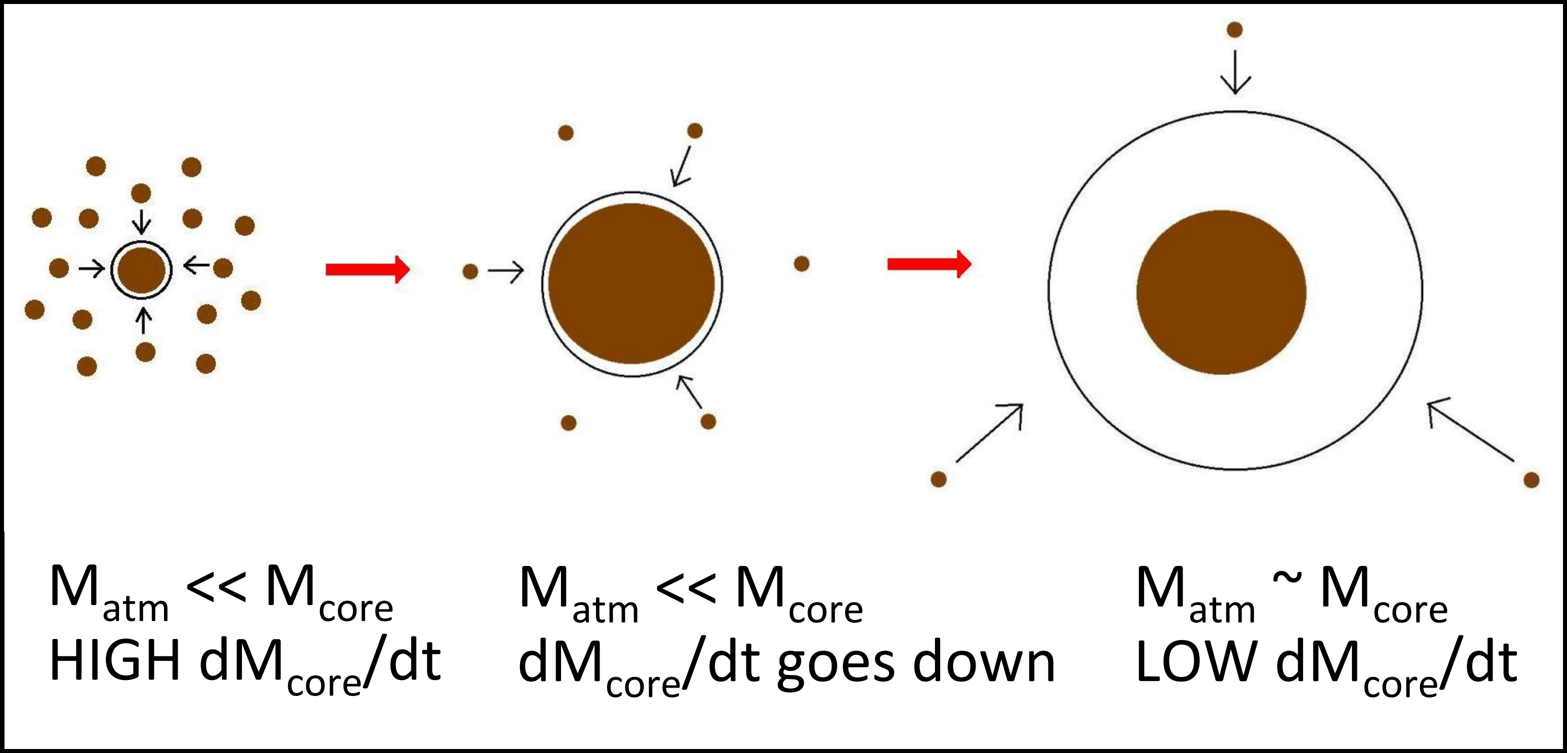
=> ONE core mass for which $M_{atm} \sim M_{core}$ = "critical core mass"



larger cores hold fractionally larger atmospheres

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

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



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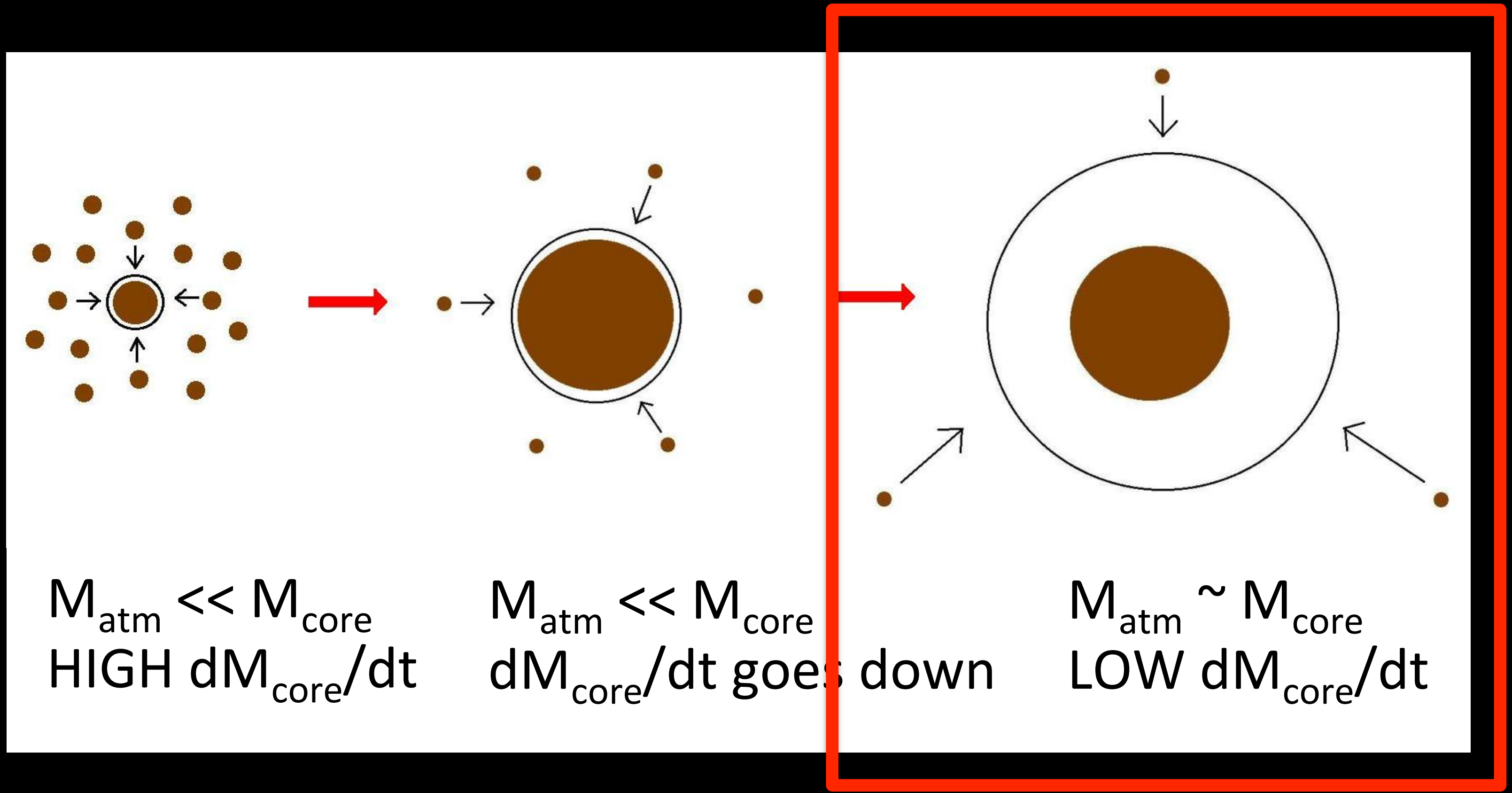
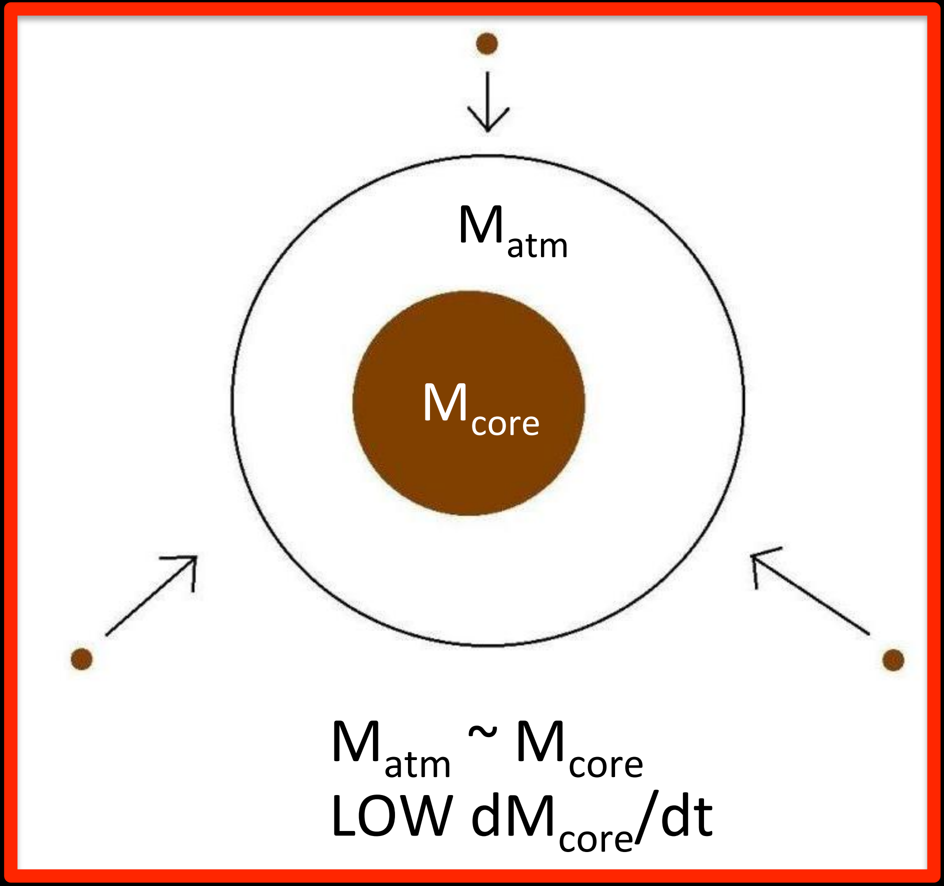


Low planetesimal accretion regime

⇒Atmospheric evolution dominated by

Kelvin-Helmholtz contraction



Kelvin-Helmholtz contraction

M_{atm} is a function of time

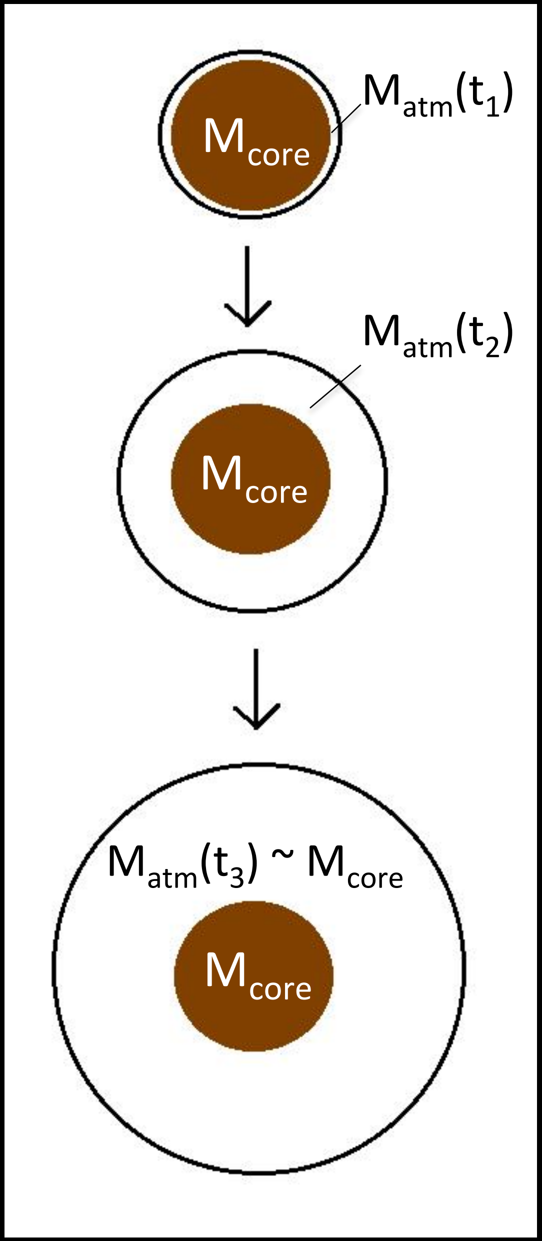
=> EVERY core can have

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

$\Rightarrow$ "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
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
- Static profiles connected by global cooling equation,

  $L \sim -dE/dt$

Atmospheric evolution and M_{crit} are highly dependent on

EQUATION OF STATE

DUST OPACITY

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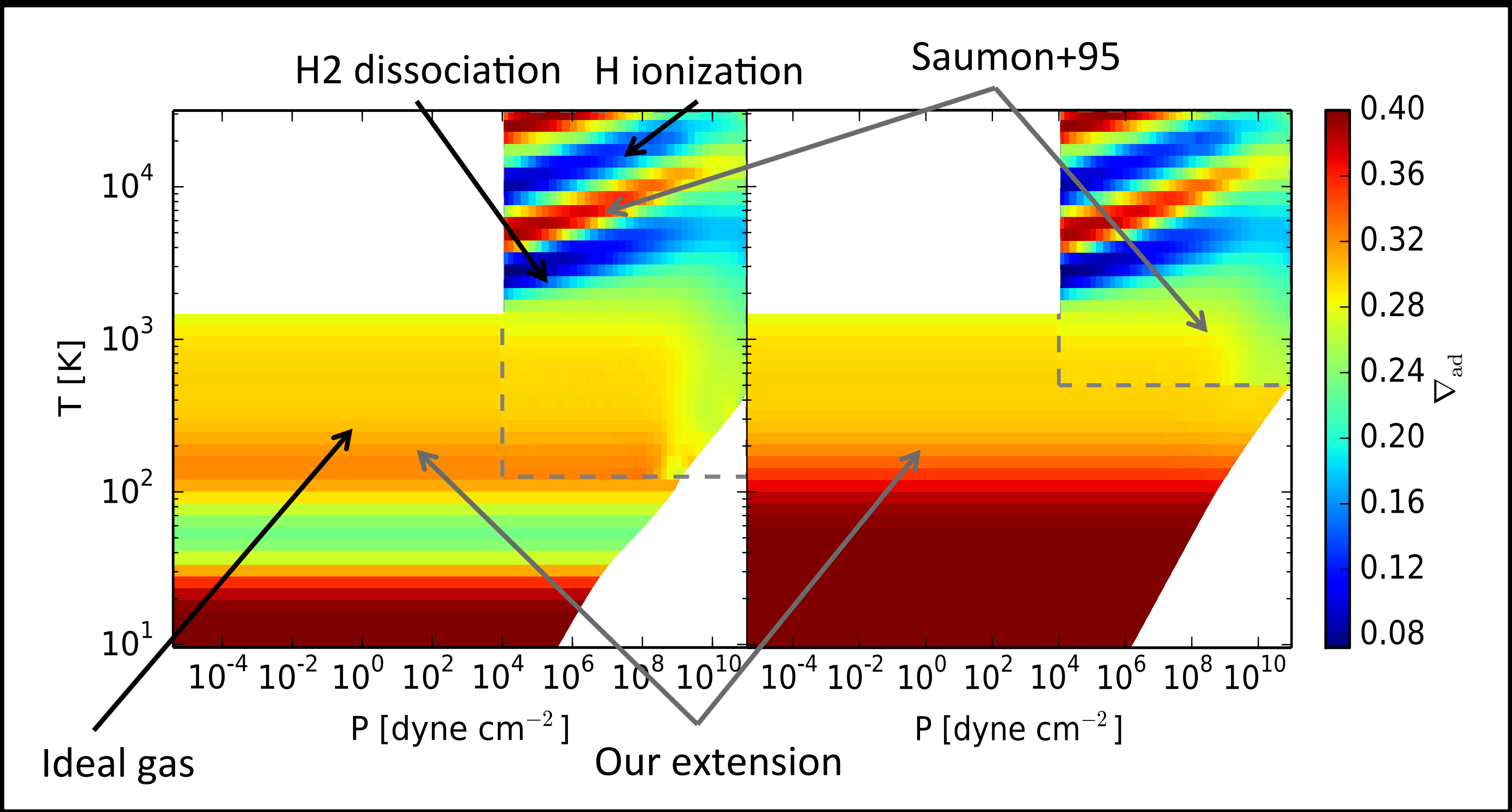
Adiabatic gradient $\boxed{\nabla_{ad} = \left(\frac{d\ln T}{d\ln P}\right)_{ad}}$ is variable for realistic EOS



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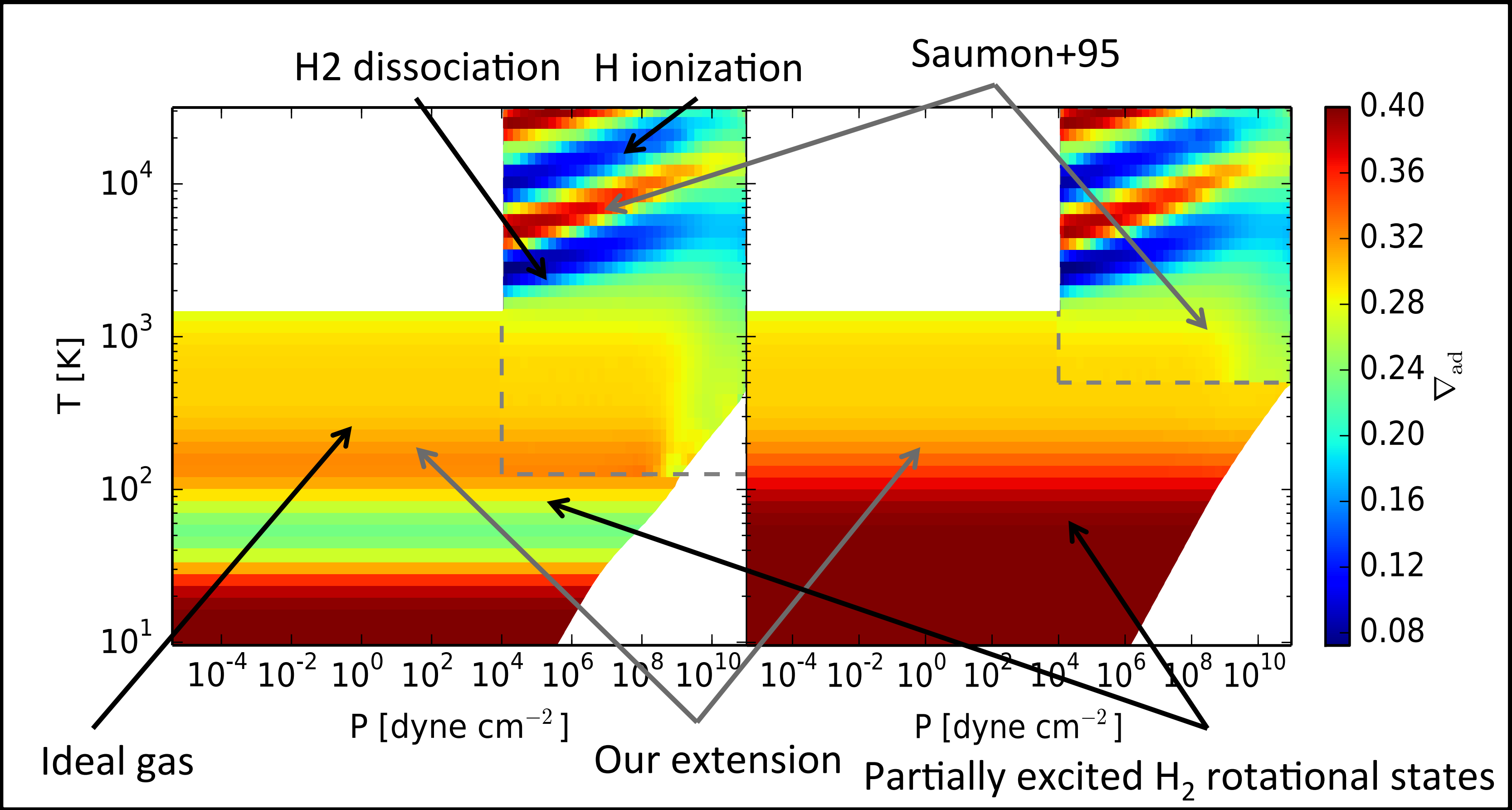
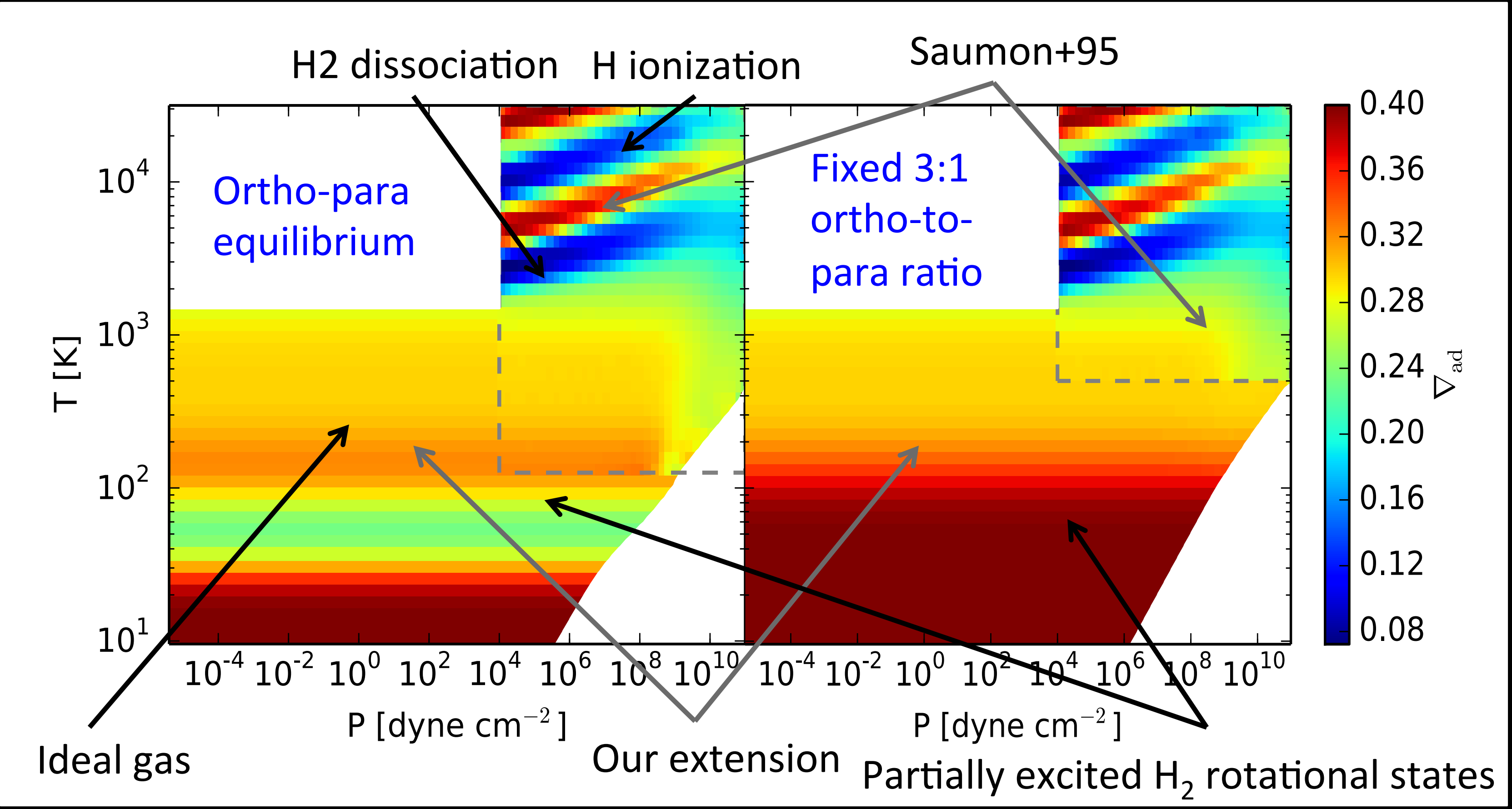
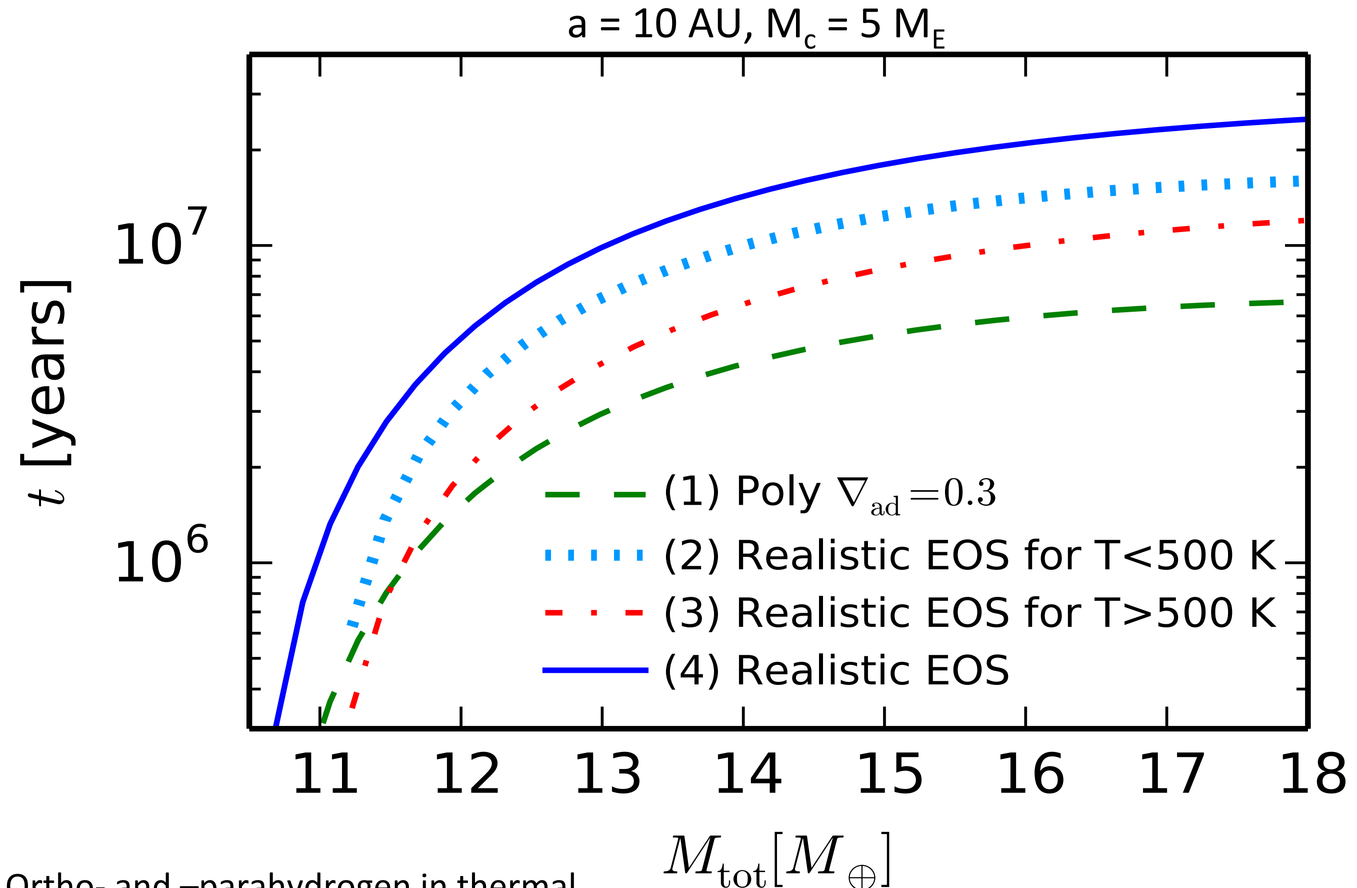


Adiabatic gradient $\nabla_{ad} = \left(\frac{d \ln T}{d \ln P}\right)_{ad}$ is variable for realistic EOS

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



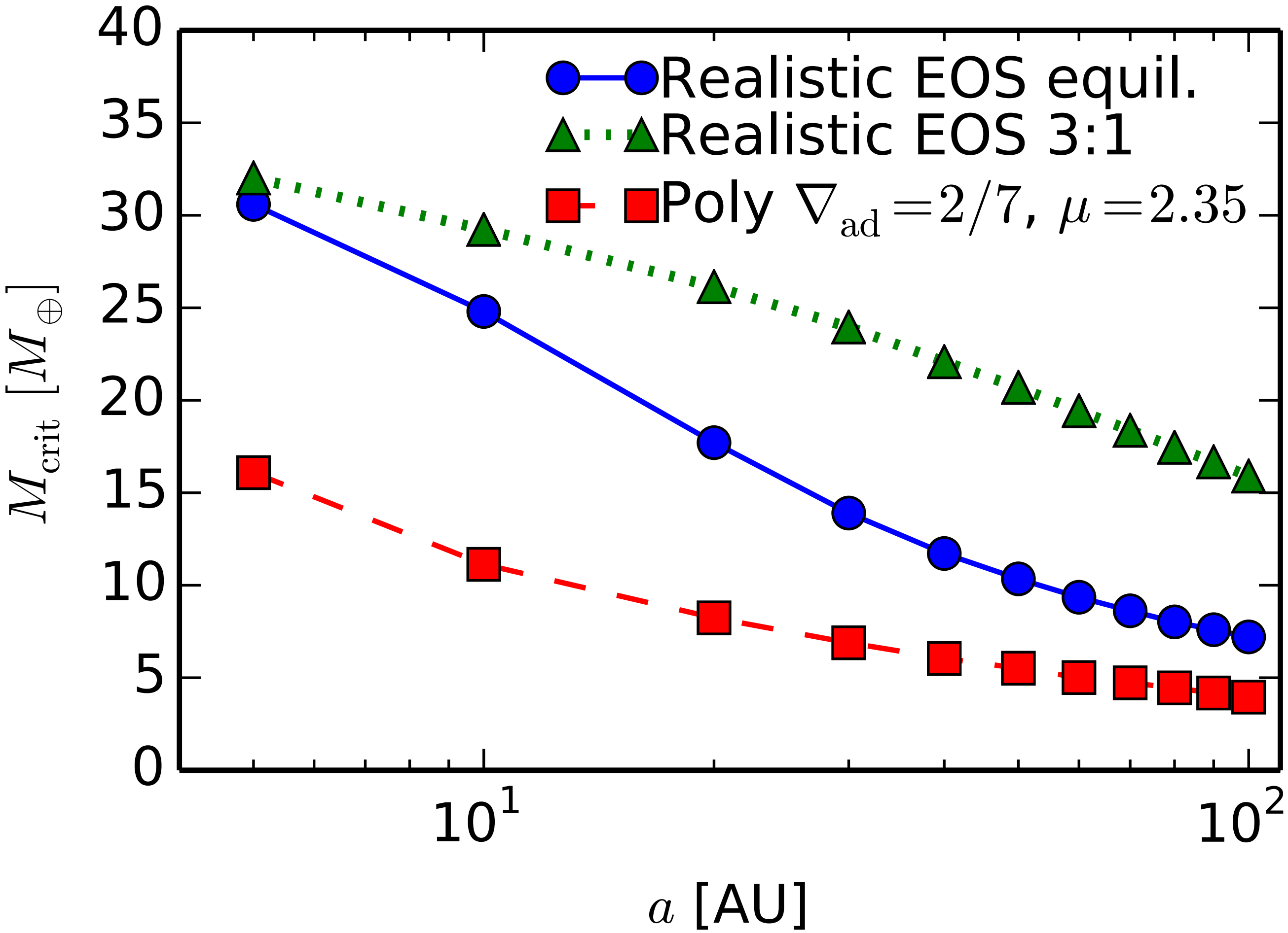
Variations in ∇_{ad} due to non-ideal EOS effects INCREASE the atmospheric evolutionary time



Ortho- and –parahydrogen in thermal equilibrium, ISM opacity

Piso, Youdin, & Murray-Clay (2015)

Critical Core Mass



t_disk ~ 3 Myr, ISM opacity

Piso, Youdin, & Murray-Clay (2015)

Atmospheric evolution and M_{crit} are highly dependent on

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Atmospheric evolution and M_{crit} are highly dependent on

EQUATION OF STATE

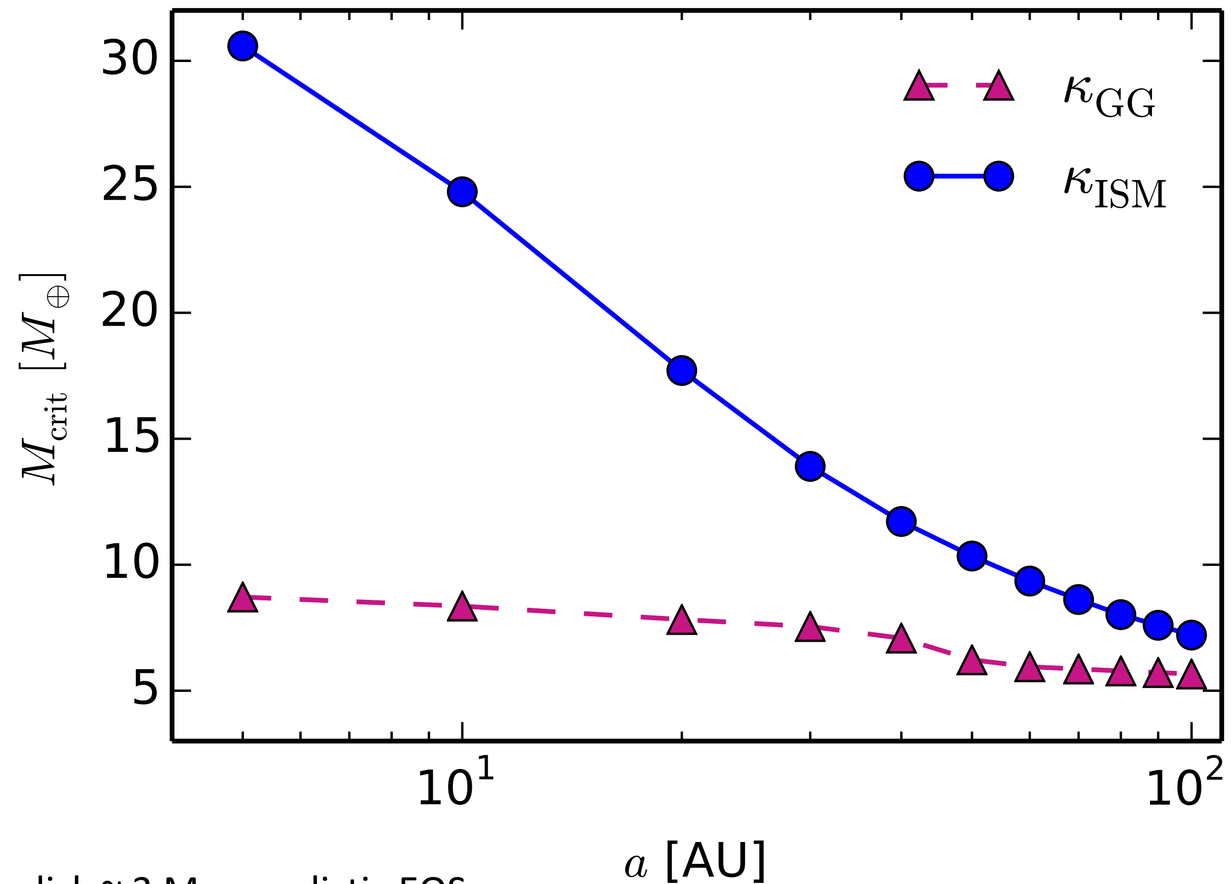
$\boxed{\text{DUST OPACITY}}$

Grain growth opacity DECREASES M_{crit}

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

$p = 3.5$

s_{max} = 1 cm



t_disk ~ 3 Myr, realistic EOS

Piso, Youdin, & Murray-Clay (2015)

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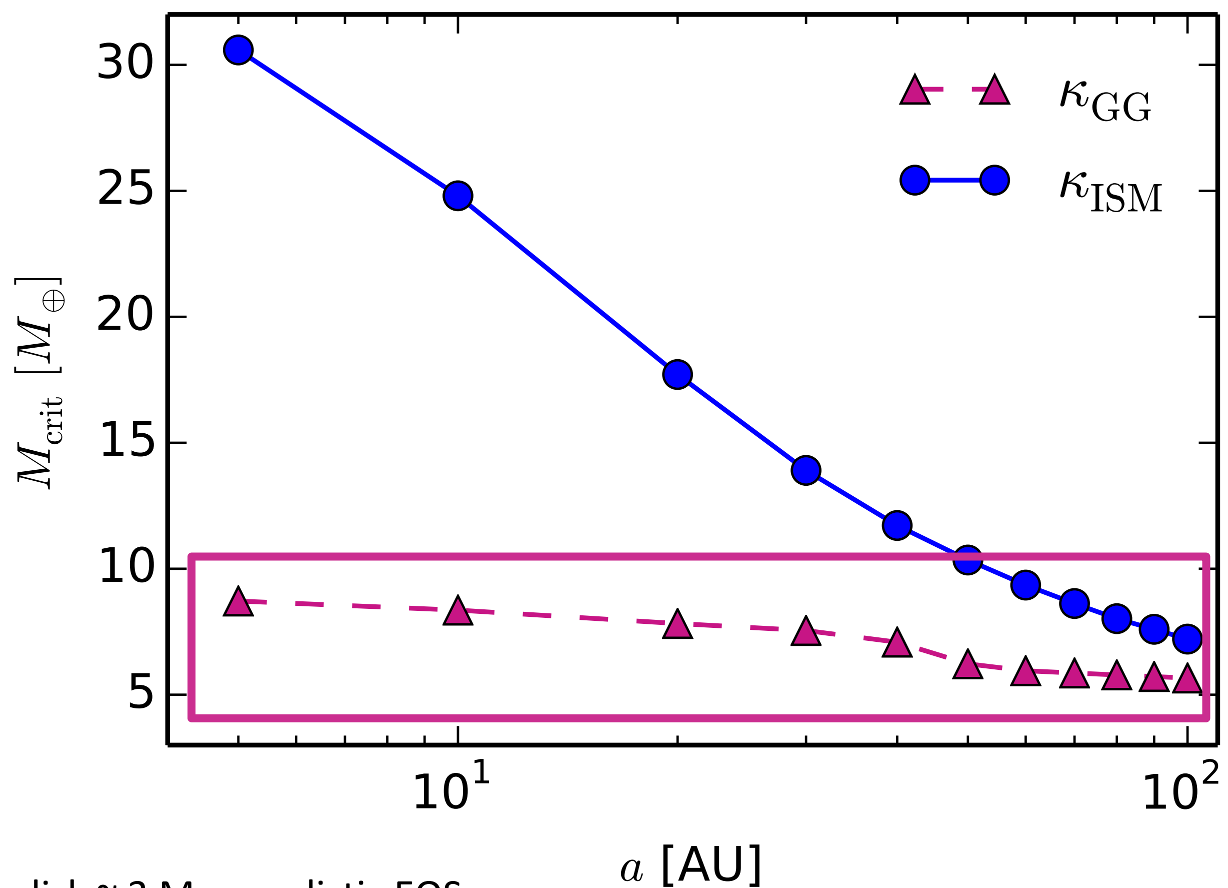
M_{crit}:

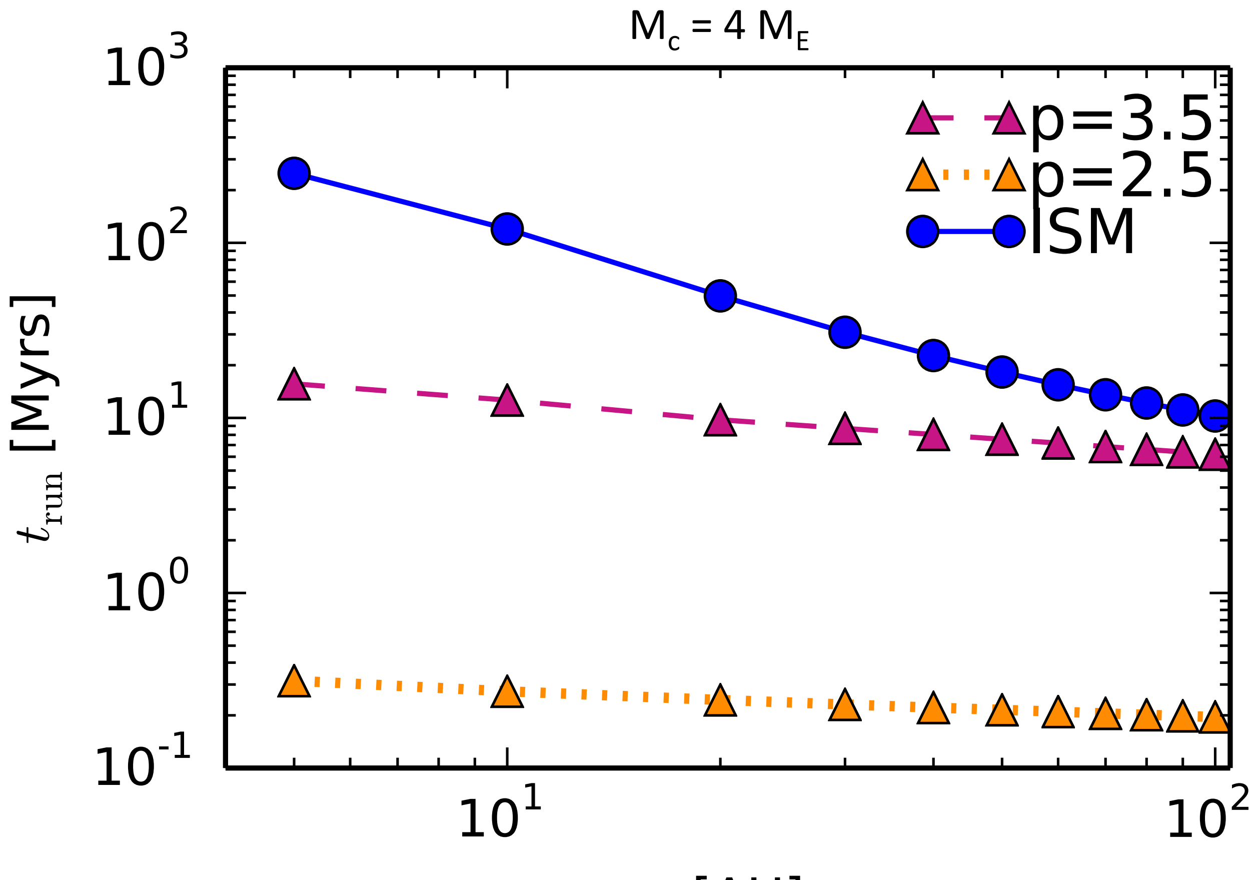
~8 M_E @ 5 AU
~5 M_E @ 100 AU



t_disk ~ 3 Myr, realistic EOS

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*)