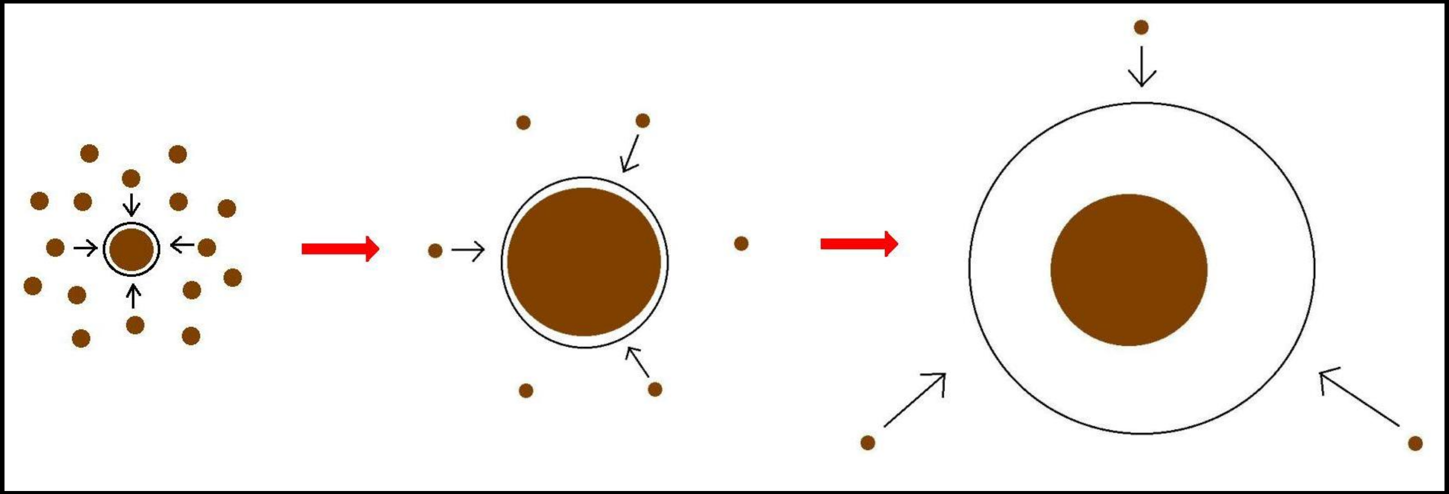
# Minimum Core Masses for Giant Planet Formation


Ana-Maria Piso[1]

Andrew Youdin[2], Ruth Murray-Clay[1,3]

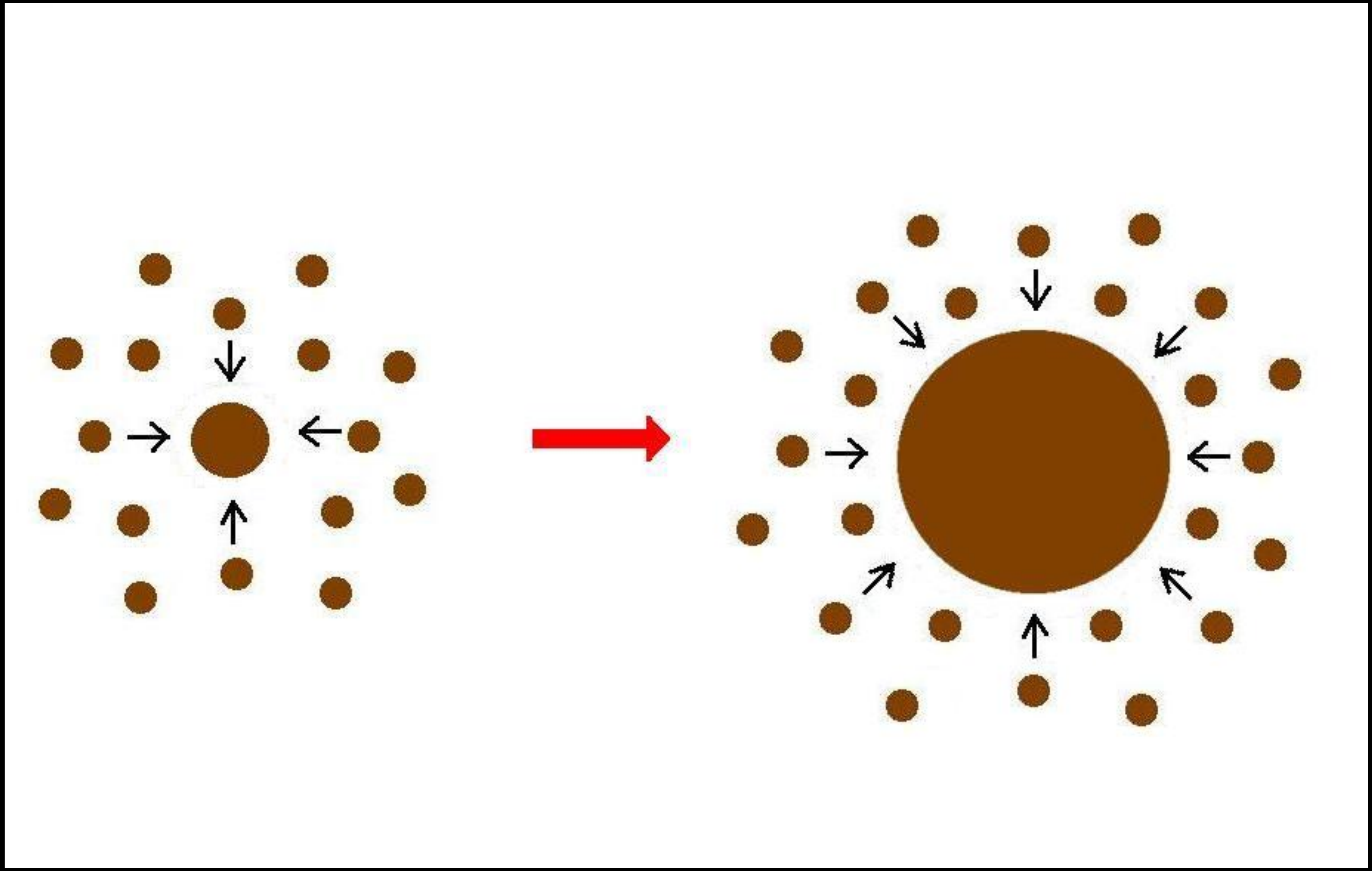



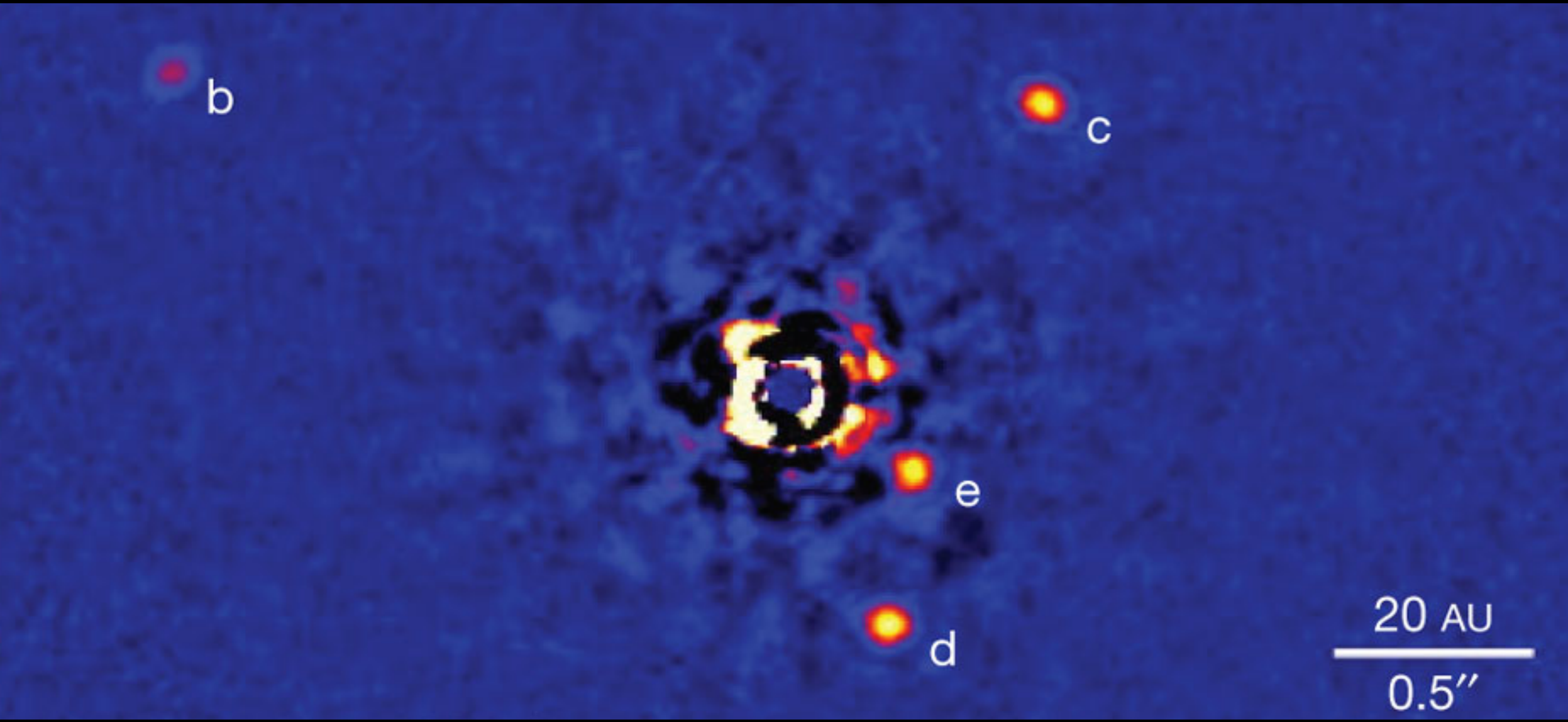

[1]Harvard-Smithsonian Center for Astrophysics

[2]Steward Observatory, University of Arizona

[3]University of California Santa Barbara

# Giant planet formation requires fast core growth

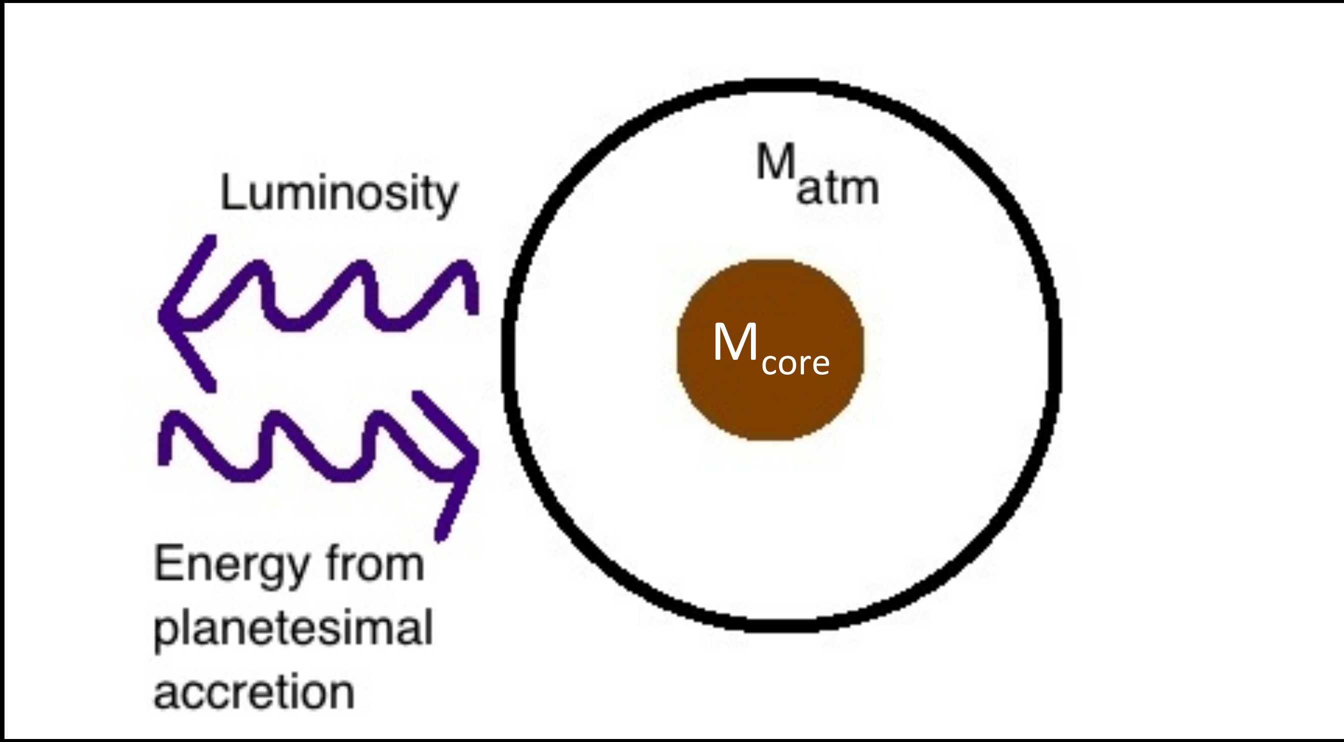





Marois+2010

# Core Accretion at high planetesimal accretion rates yields steady state

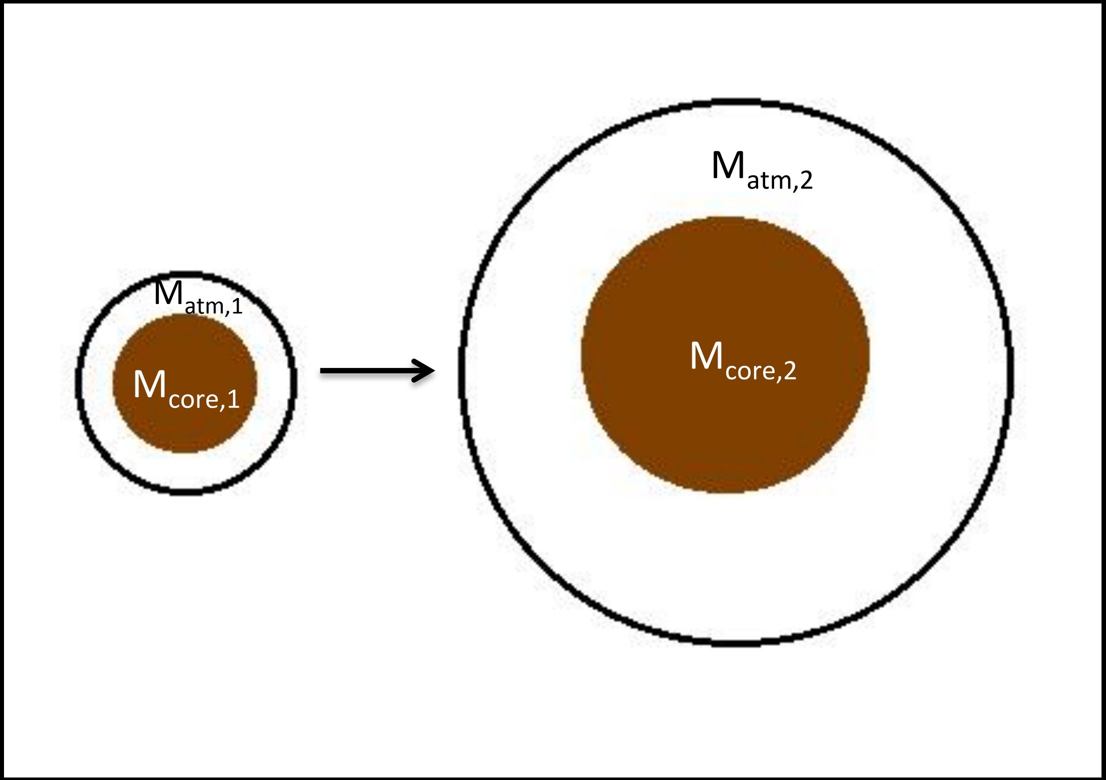
=> $M_{atm}$ is a function of $M_{core}$



# High planetesimal accretion

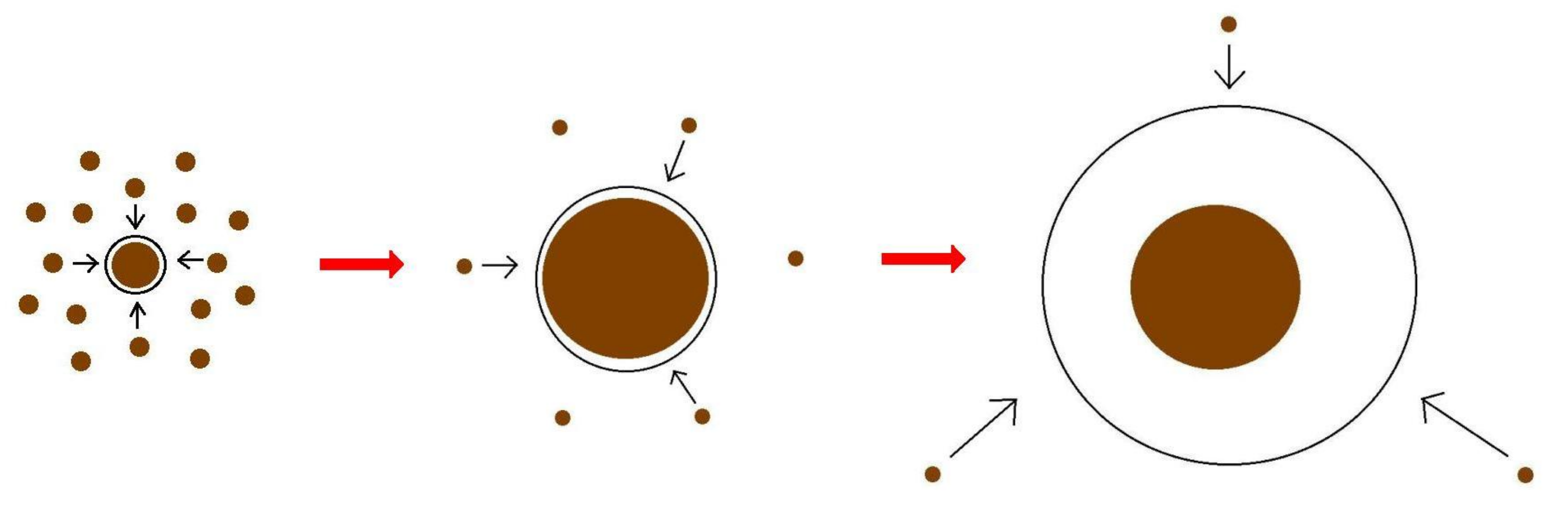
ONE $M_{atm}$ for each $M_{core}$

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



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

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



$M_{atm} << M_{core}$
HIGH $dM_{core}/dt$

$M_{atm} << M_{core}$
$dM_{core}/dt$ goes down

$M_{atm} \leq M_{core}$
LOW $dM_{core}/dt$

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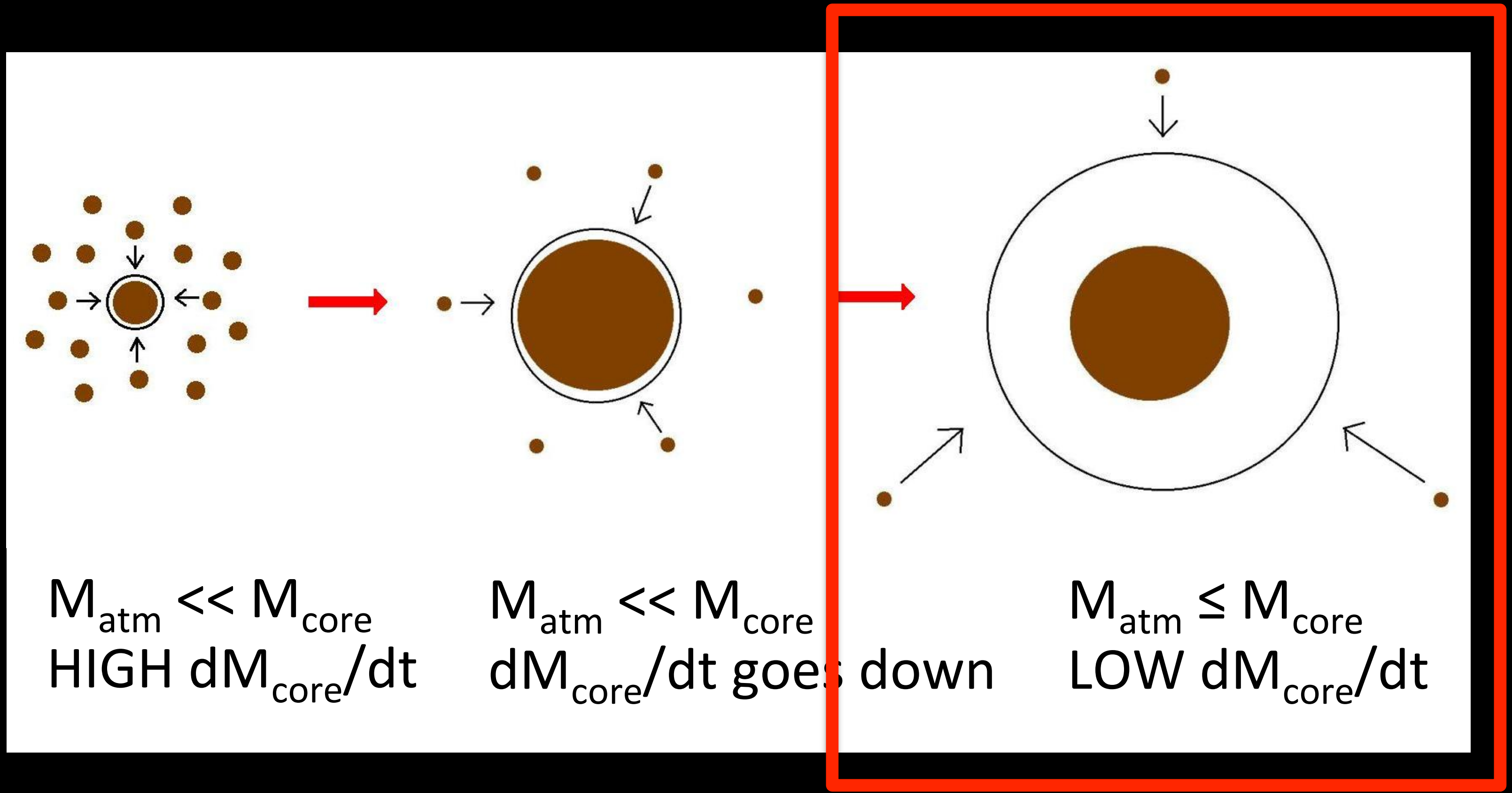
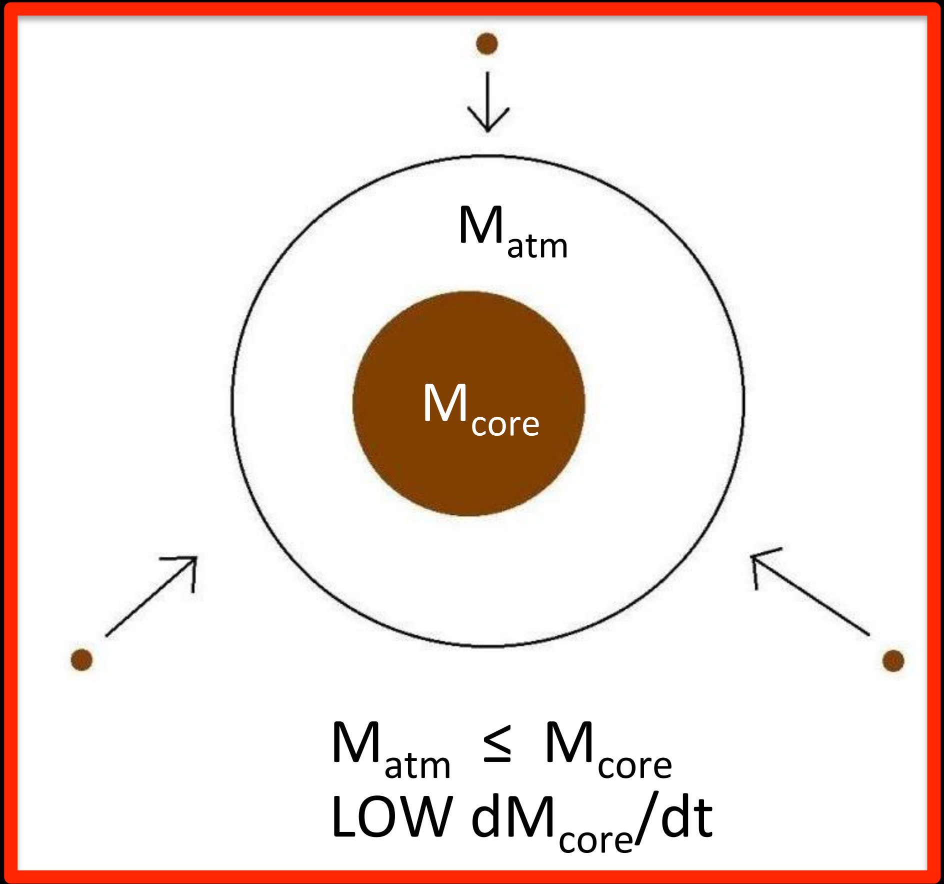


# Low planetesimal accretion regime

$\Longrightarrow$Atmospheric evolution dominated by Kelvin-Helmholtz contraction



# Kelvin-Helmholtz contraction

$M_{atm}$ is a function of time

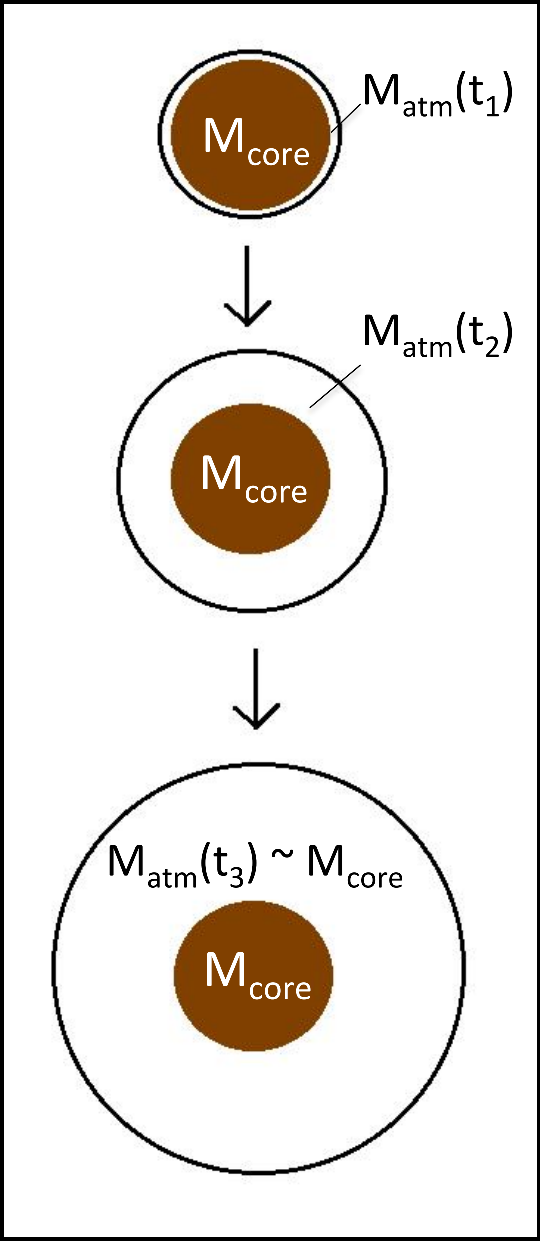
=> EVERY core can have

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

$\Rightarrow$ "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)

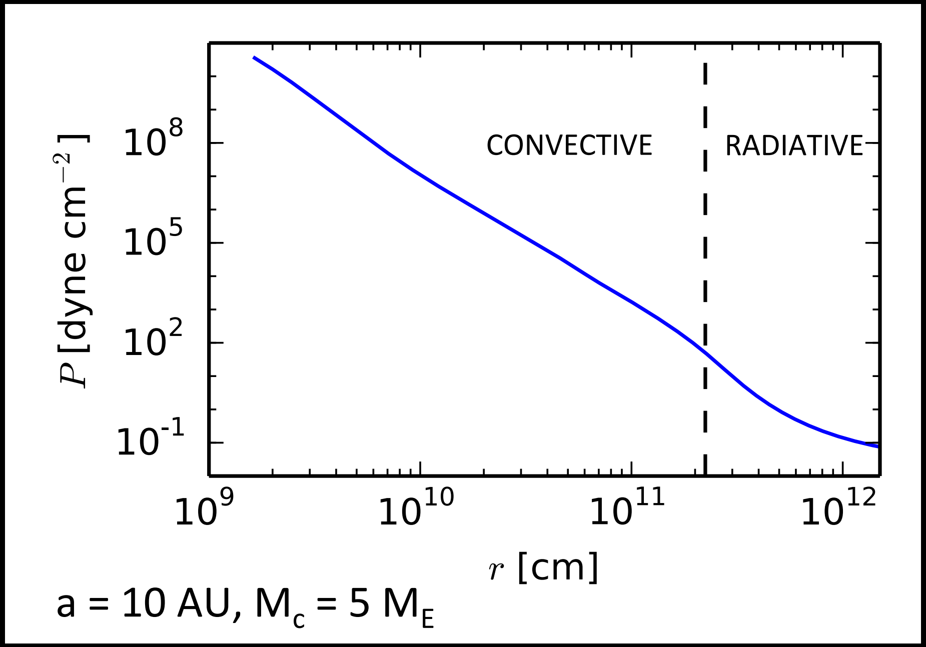
REALISTIC DUST OPACITIES

# 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

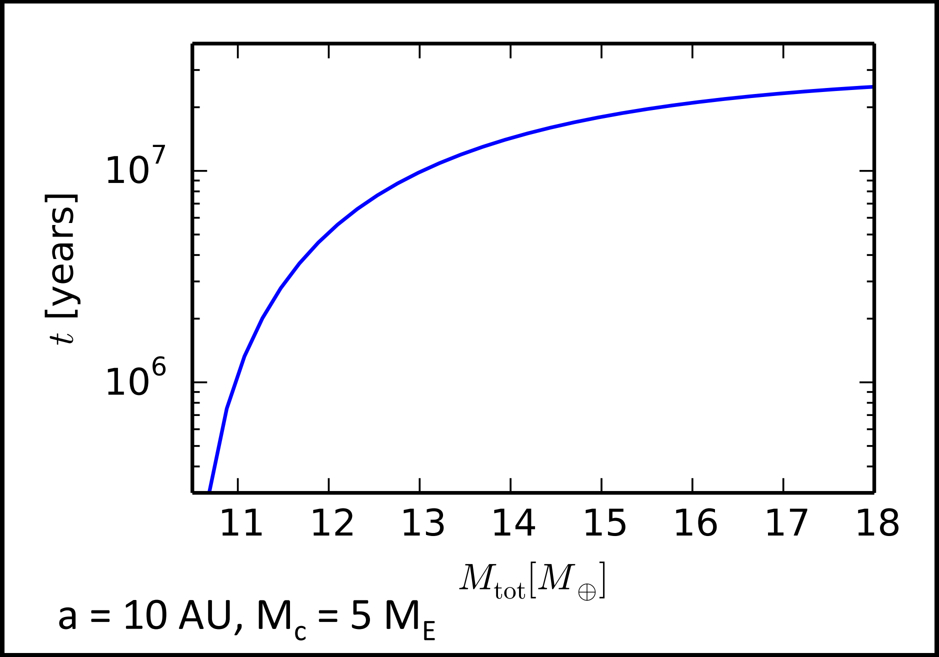
see Piso & Youdin (2014) for details

# 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

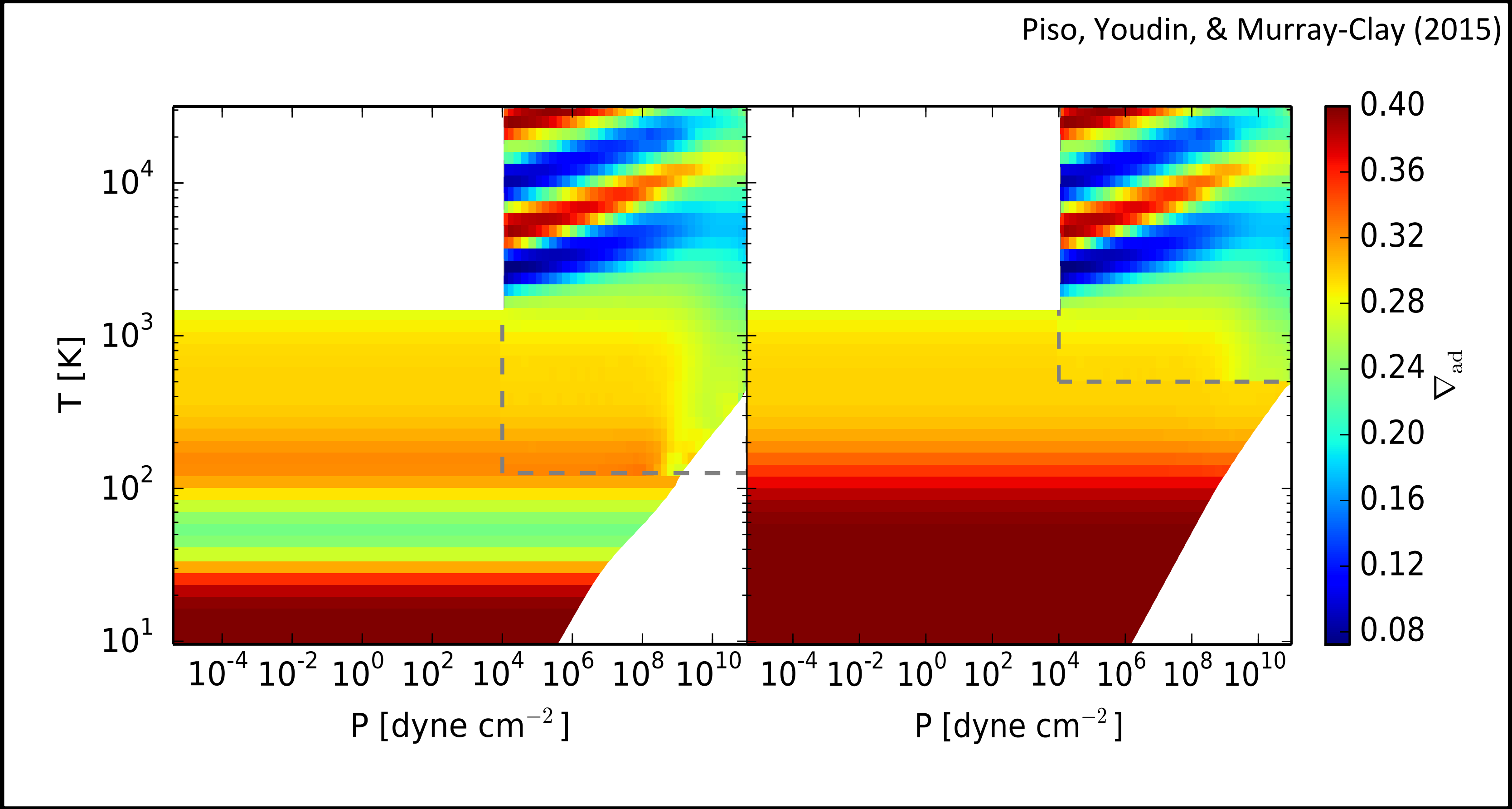
DUST OPACITY

Atmospheric evolution and $M_{crit}$ are highly dependent on

$\boxed{\text{EQUATION OF STATE}}$

DUST OPACITY

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



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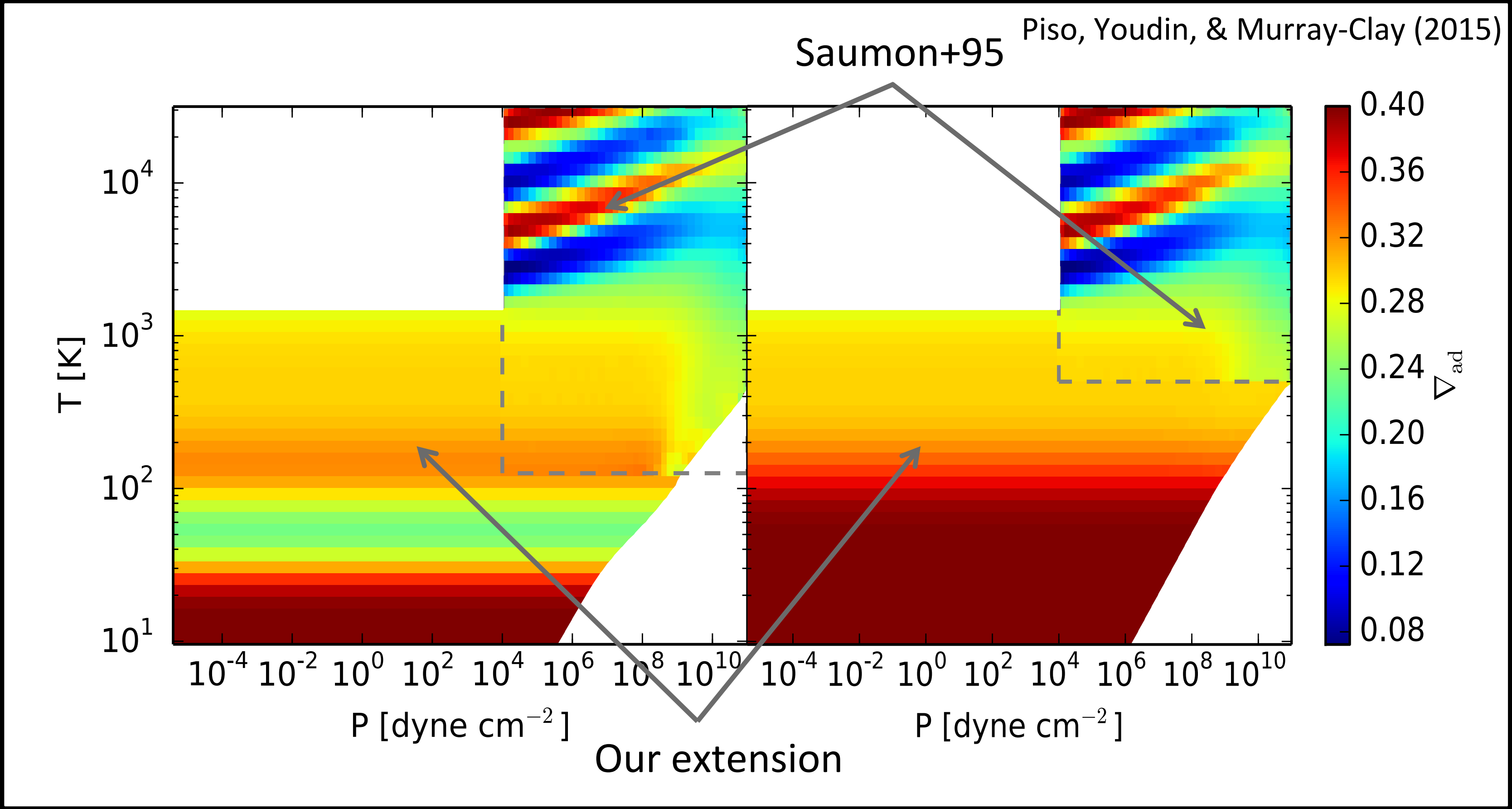

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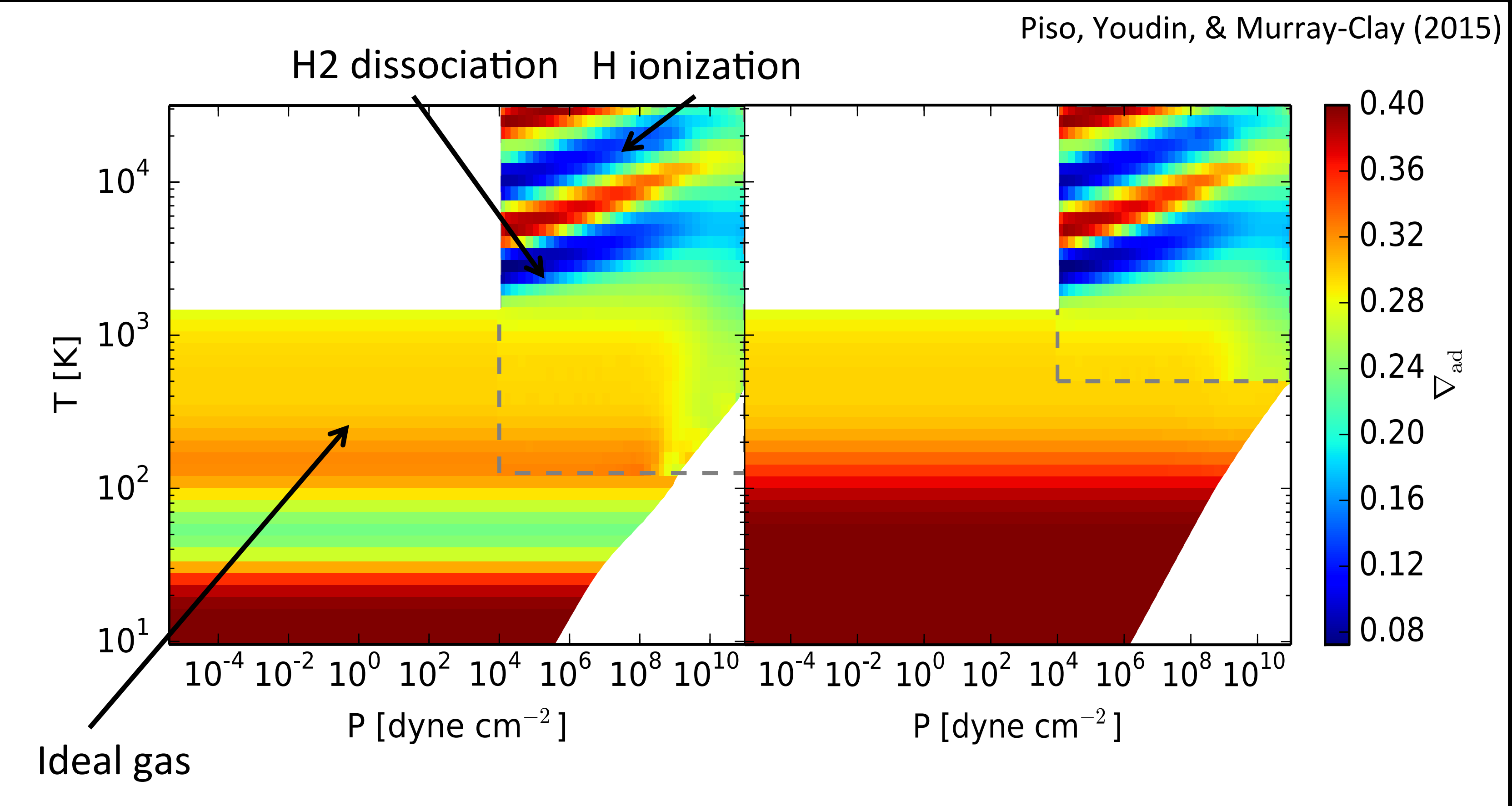

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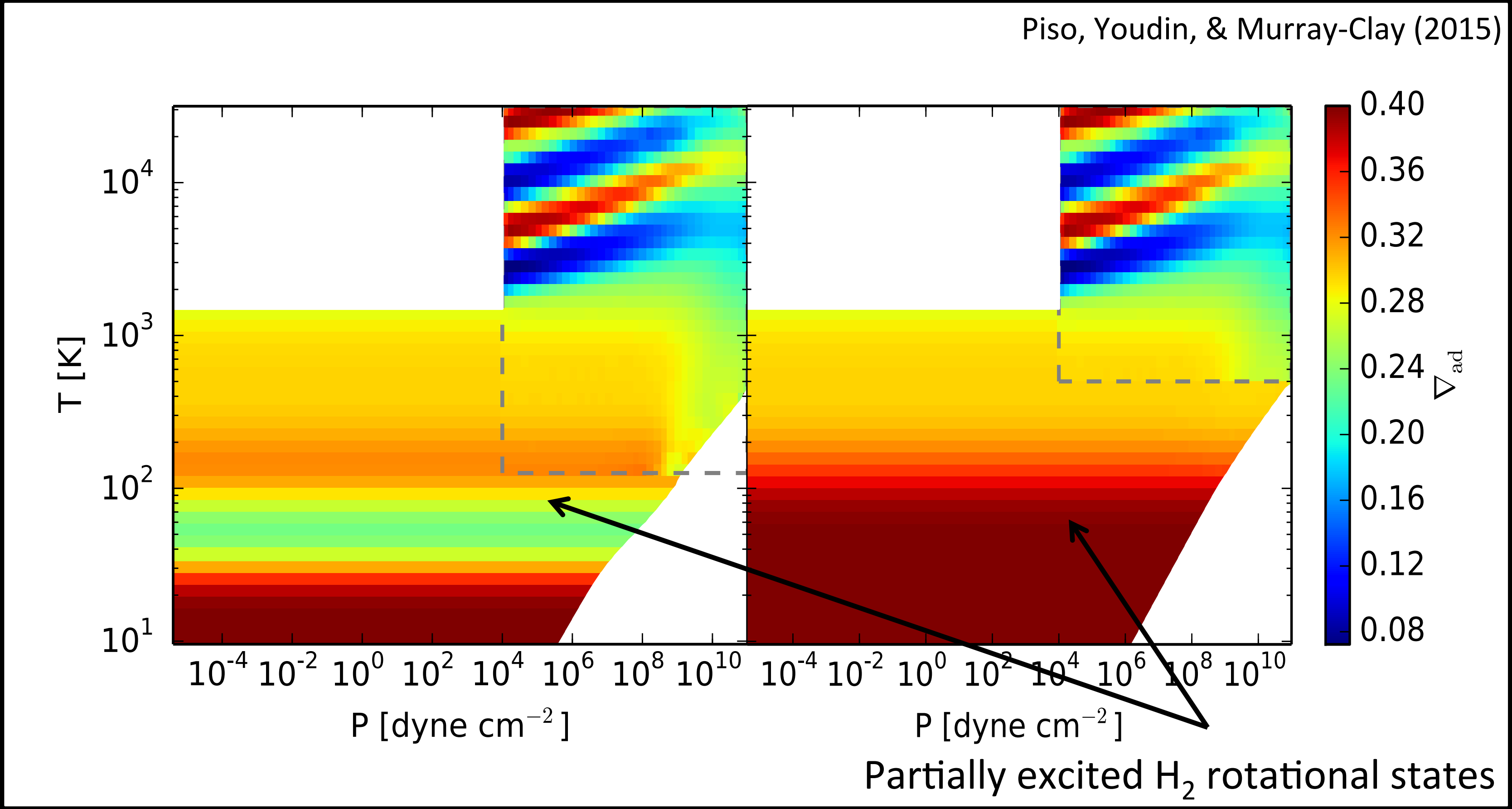
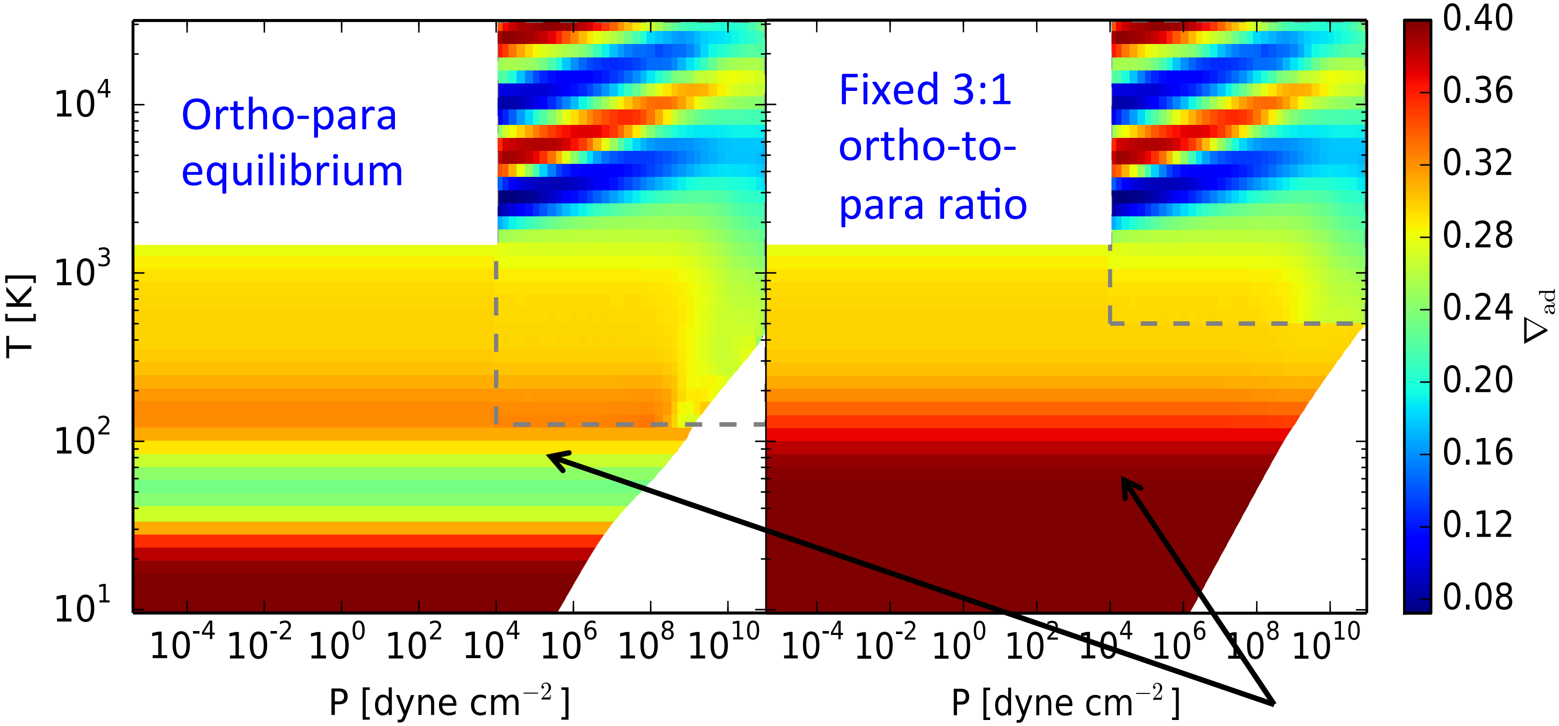


# Adiabatic gradient $\boxed{\nabla_{ad} = \left(\frac{d\ln T}{d\ln P}\right)_{ad}}$ is variable for realistic EOS

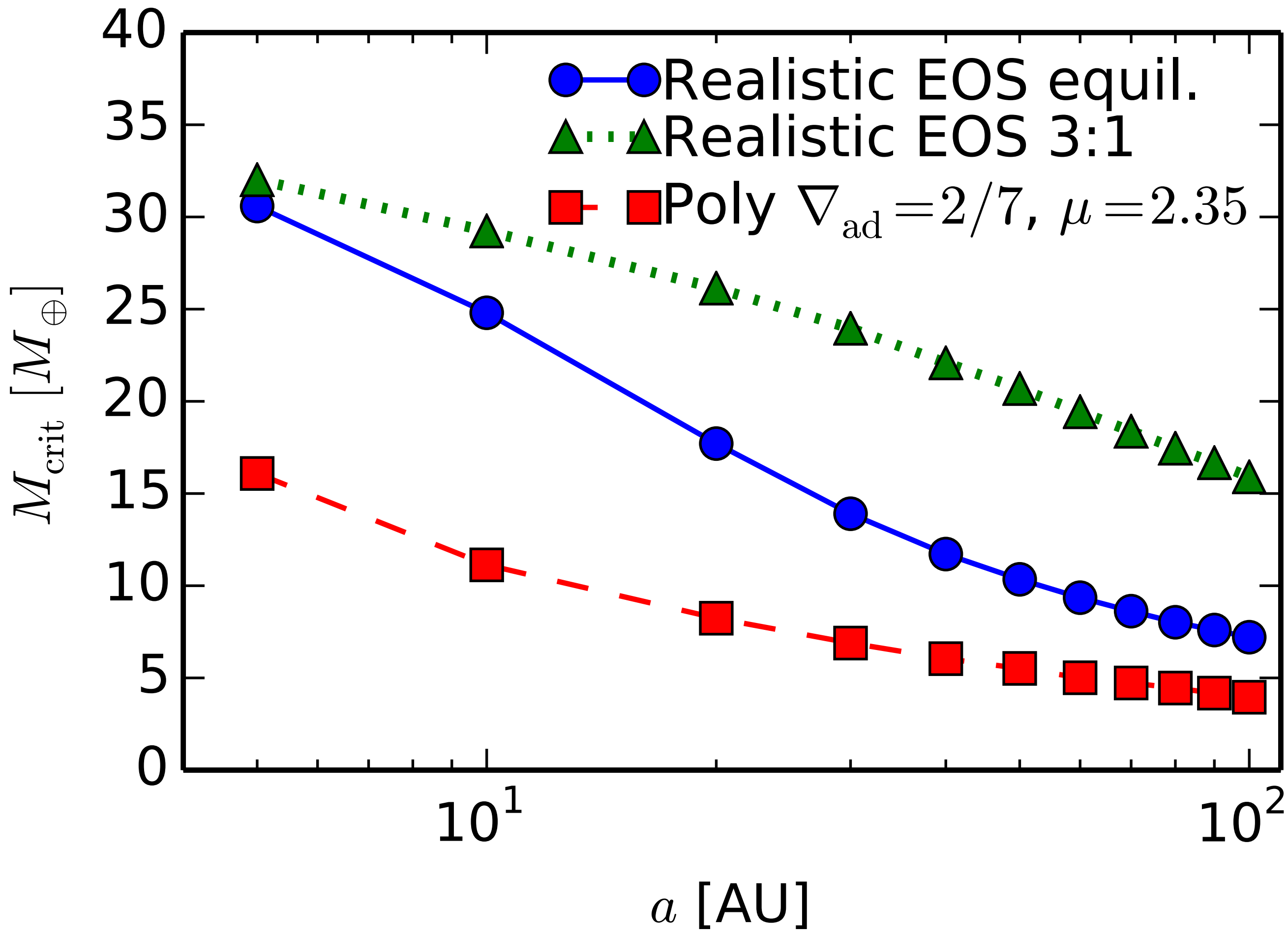
$H_2$ spin isomers ↑↑ORTHOHYDROGEN and ↑↓ PARAHYDROGEN can be in **thermal equilibrium** or **fixed ratio**

Piso, Youdin, & Murray-Clay (2015)




Partially excited $H_2$ rotational states

# Variations in $\nabla_{ad}$ due to non-ideal EOS effects INCREASE $M_{crit}$




t_disk ~ 3 Myr, ISM opacity

Piso, Youdin, & Murray-Clay (2015)

# Atmospheric evolution and $M_{crit}$ are highly dependent on

EQUATION OF STATE

DUST OPACITY

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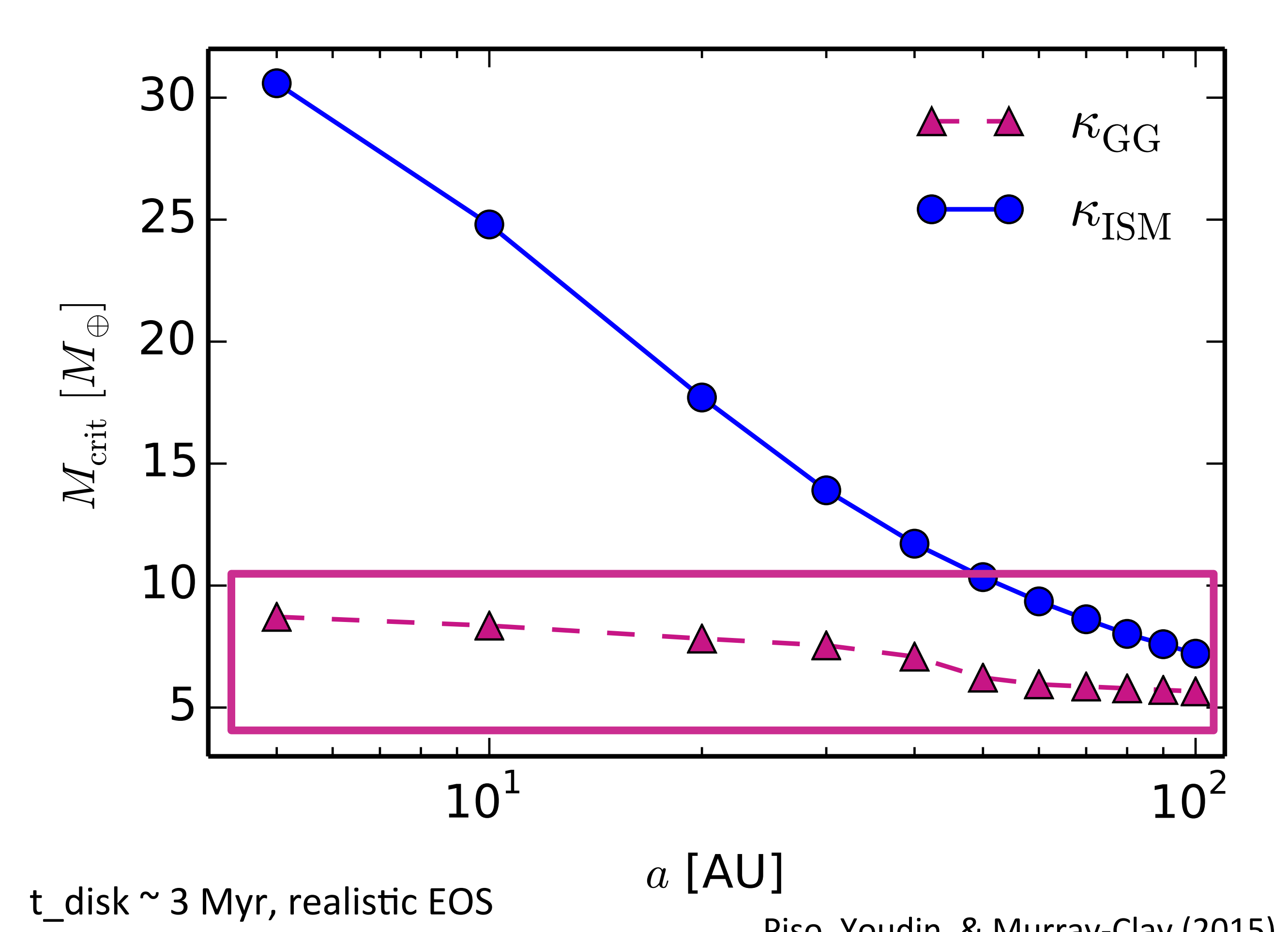
# Grain growth opacity DECREASES $M_{crit}$

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

$p = 3.5$

$s_{max} = 1$ cm




Piso, Youdin, & Murray-Clay (2015)

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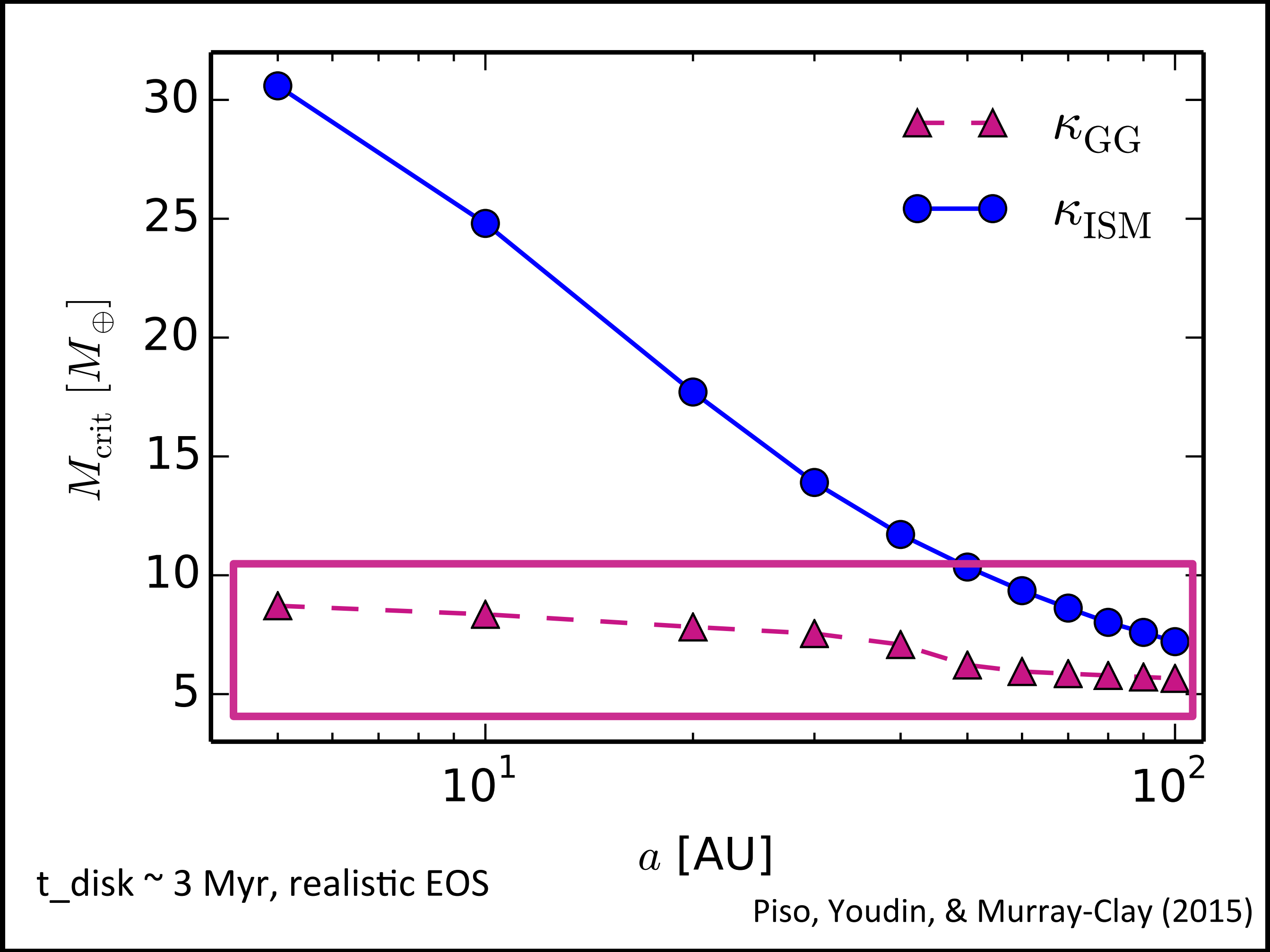
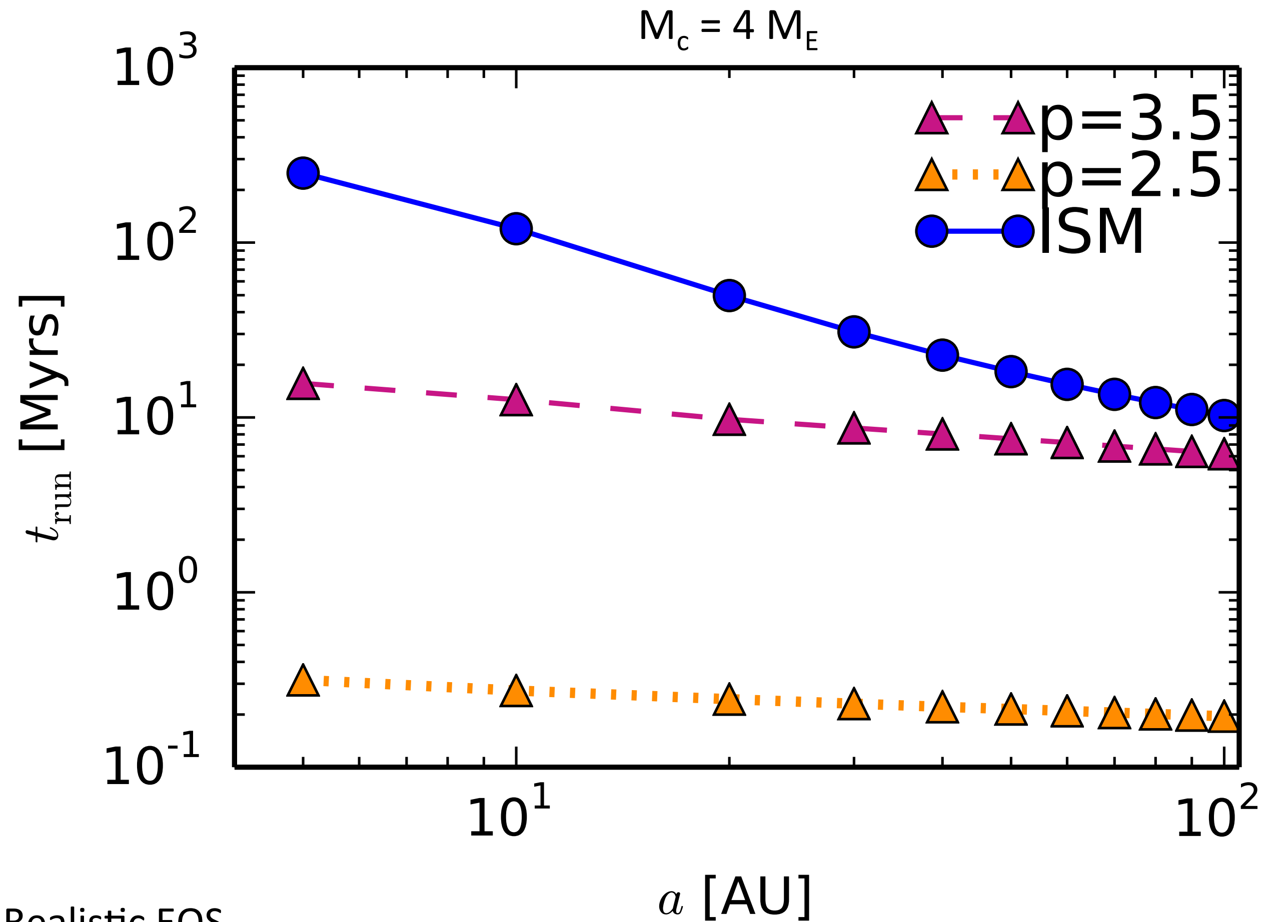



$M_{crit}$:

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

# 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*)