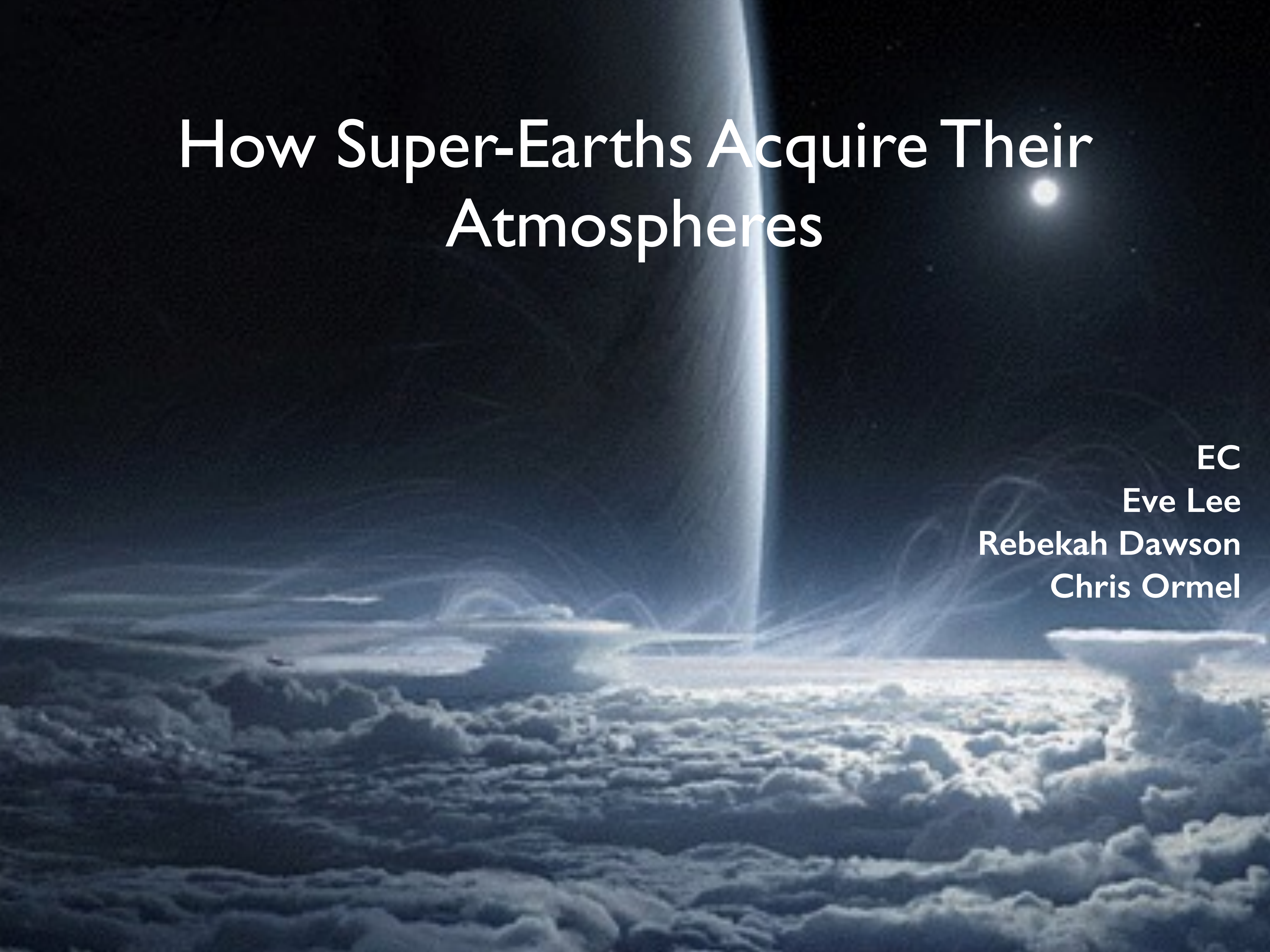
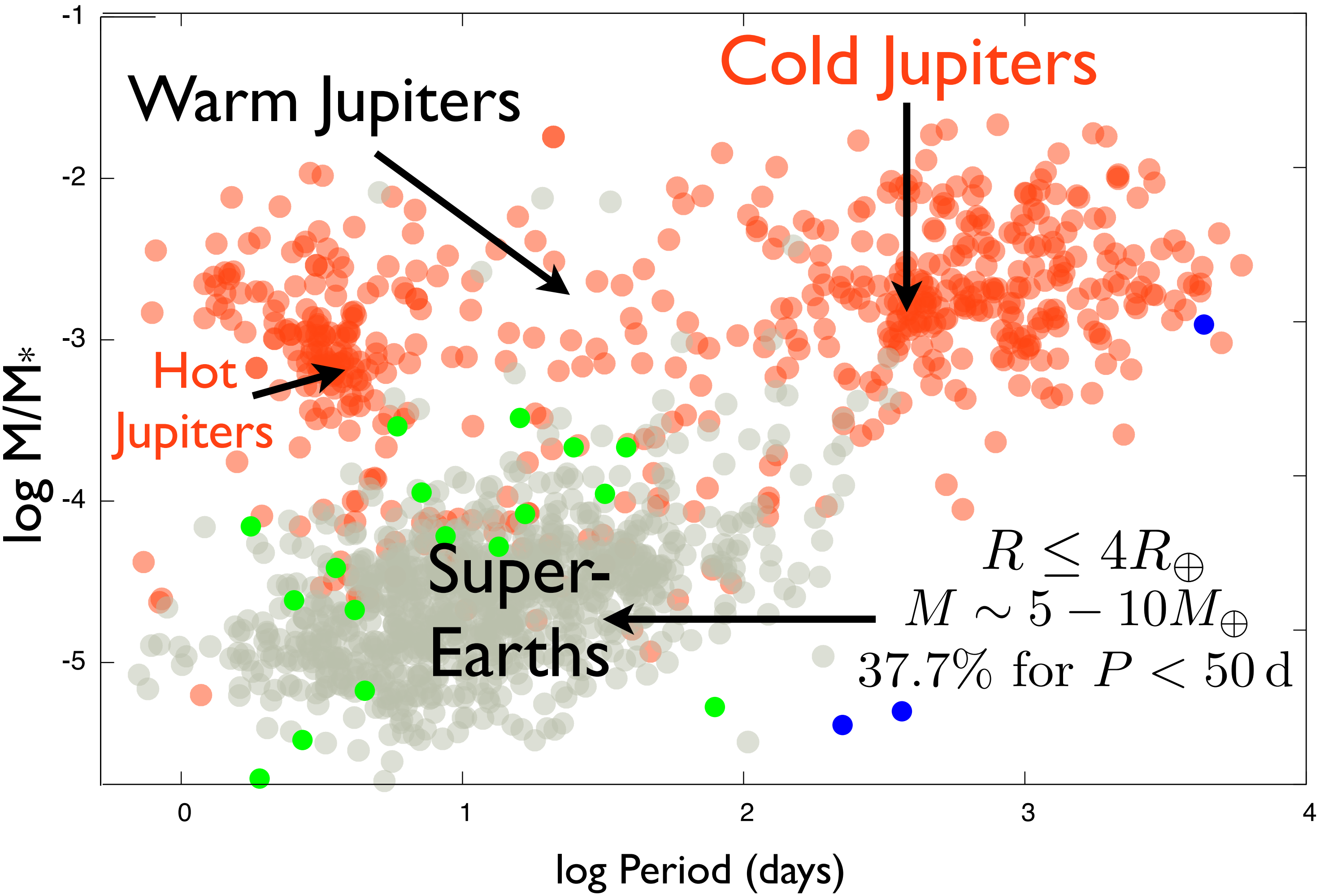


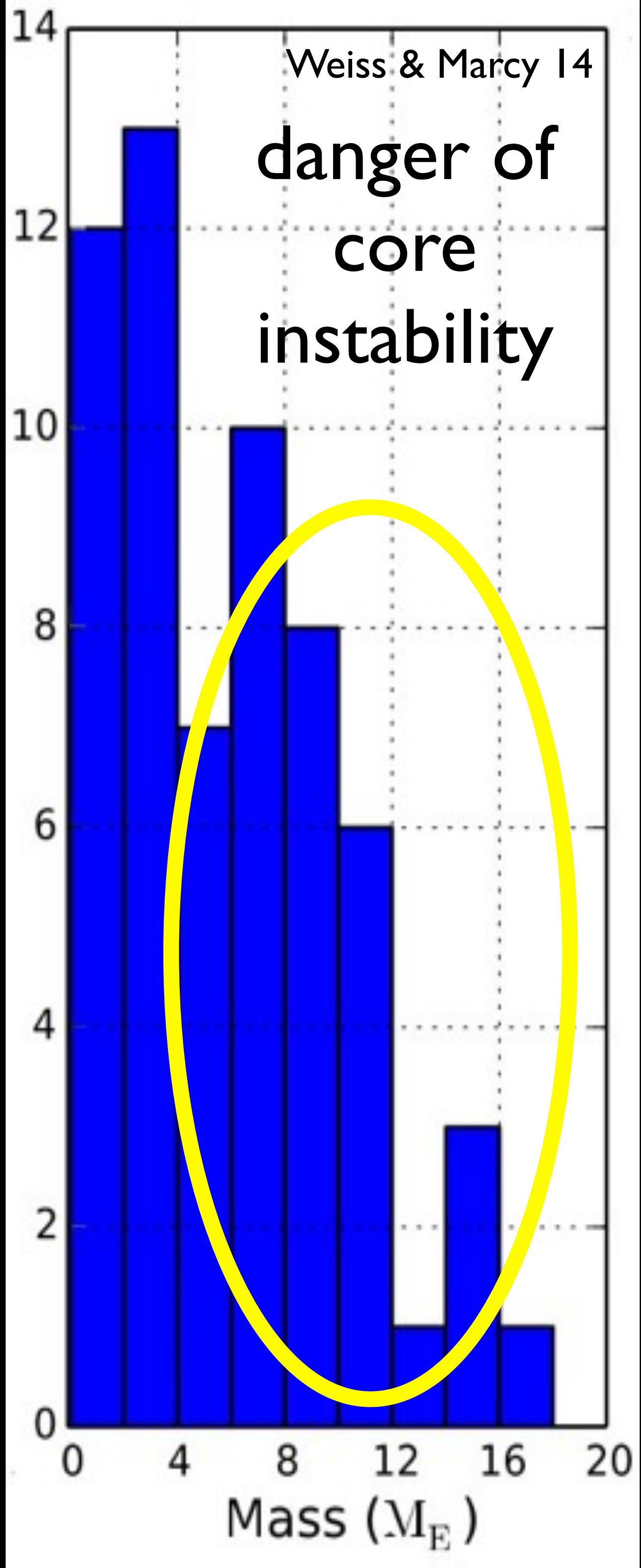
How Super-Earths Acquire Their Atmospheres

EC
Eve Lee
Rebekah Dawson
Chris Ormel

How do super-Earths avoid becoming Jupiters?



$R \leq 4R_\oplus$
$M \sim 5-10M_\oplus$
37.7% for $P < 50\,\mathrm{d}$

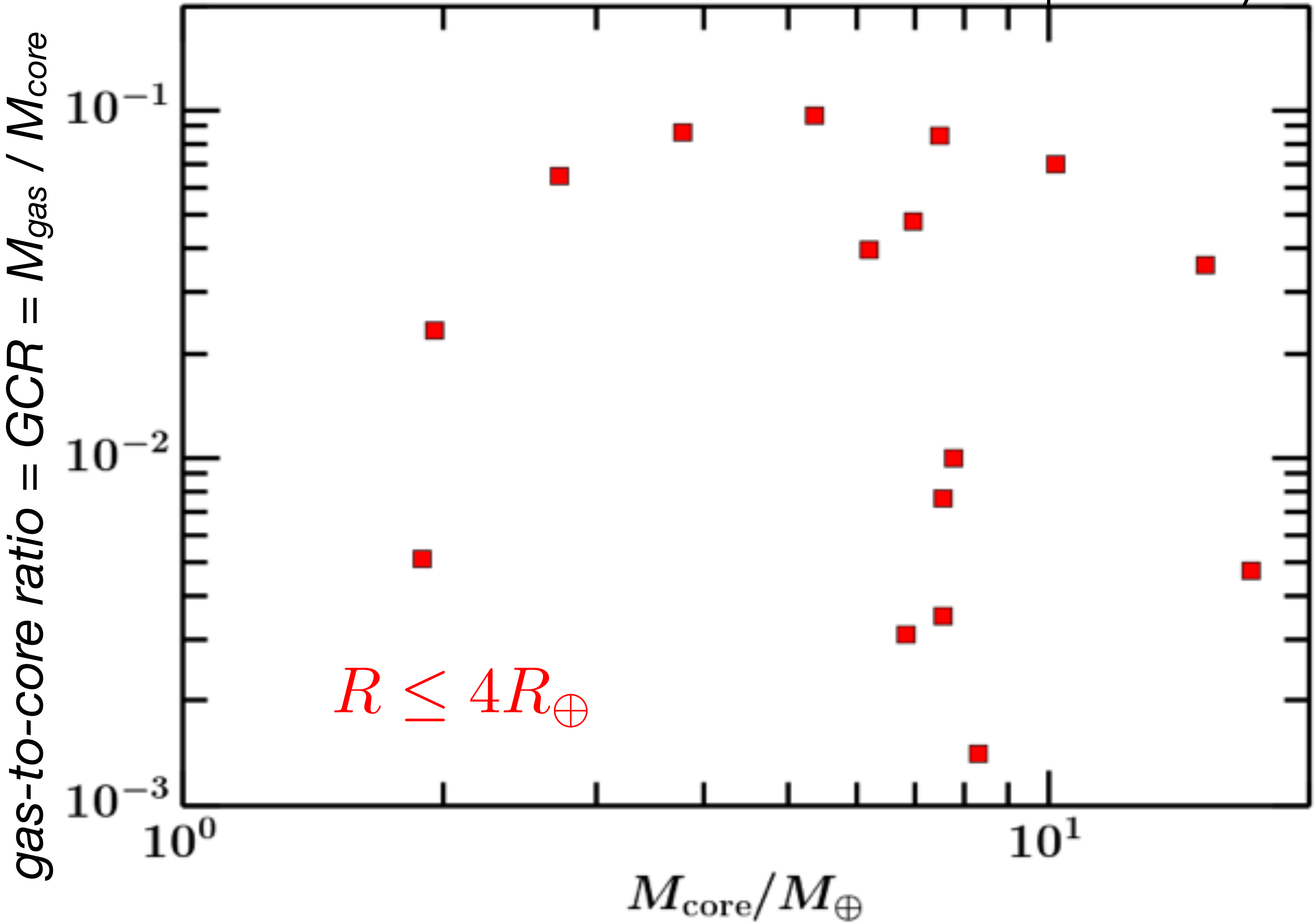


Weiss & Marcy 14

danger of core instability

Super-Earth Atmospheres

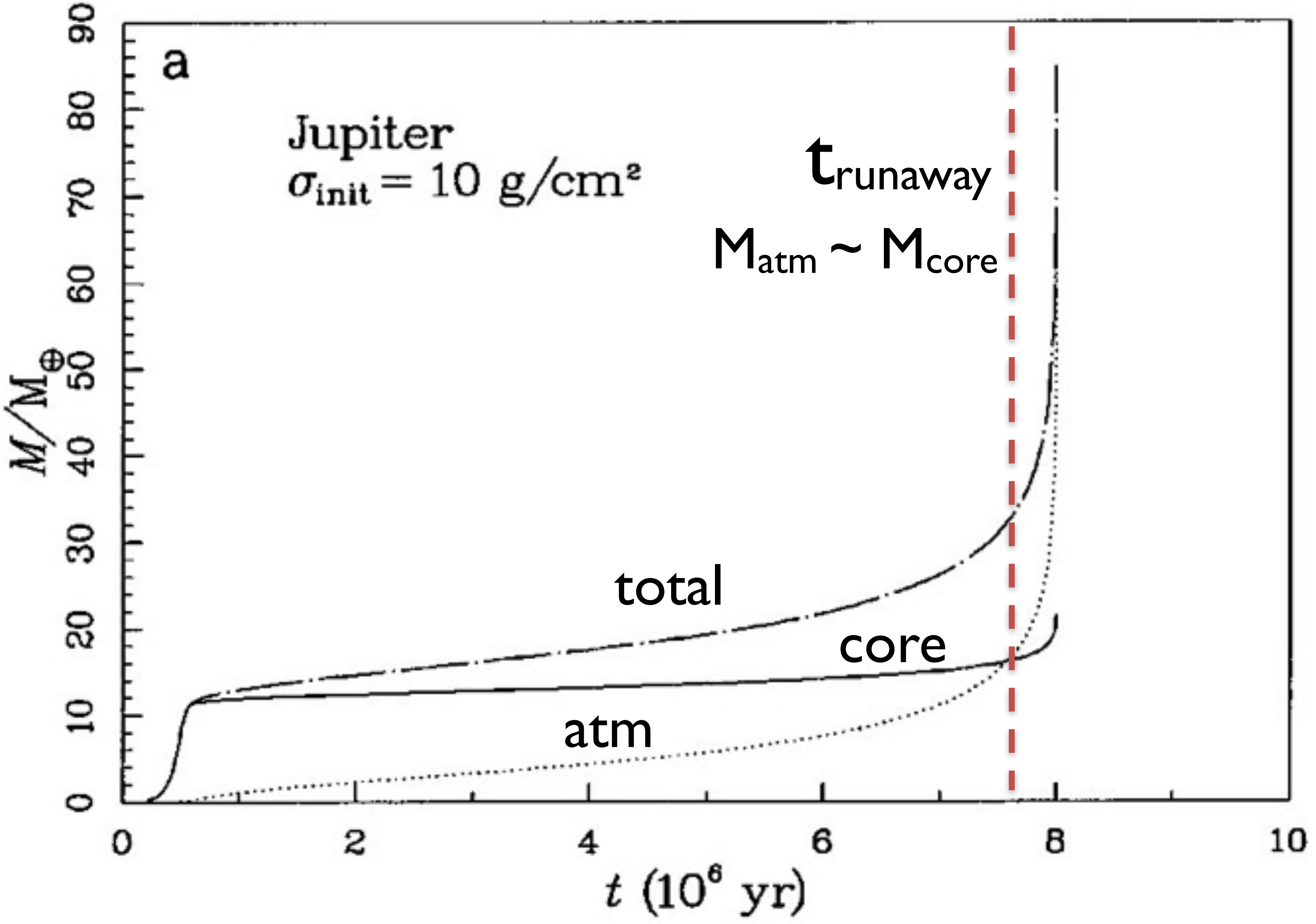
~0.1-10% “H/He” by mass.
Up to 50x solar metallicity (Z ~ 0.5)



Lopez & Fortney 14

Gas giant formation by runaway gas accretion

$t_{runaway}$ vs. t_{disk}



Pollack+ 1996

Gas giant formation by runaway gas accretion

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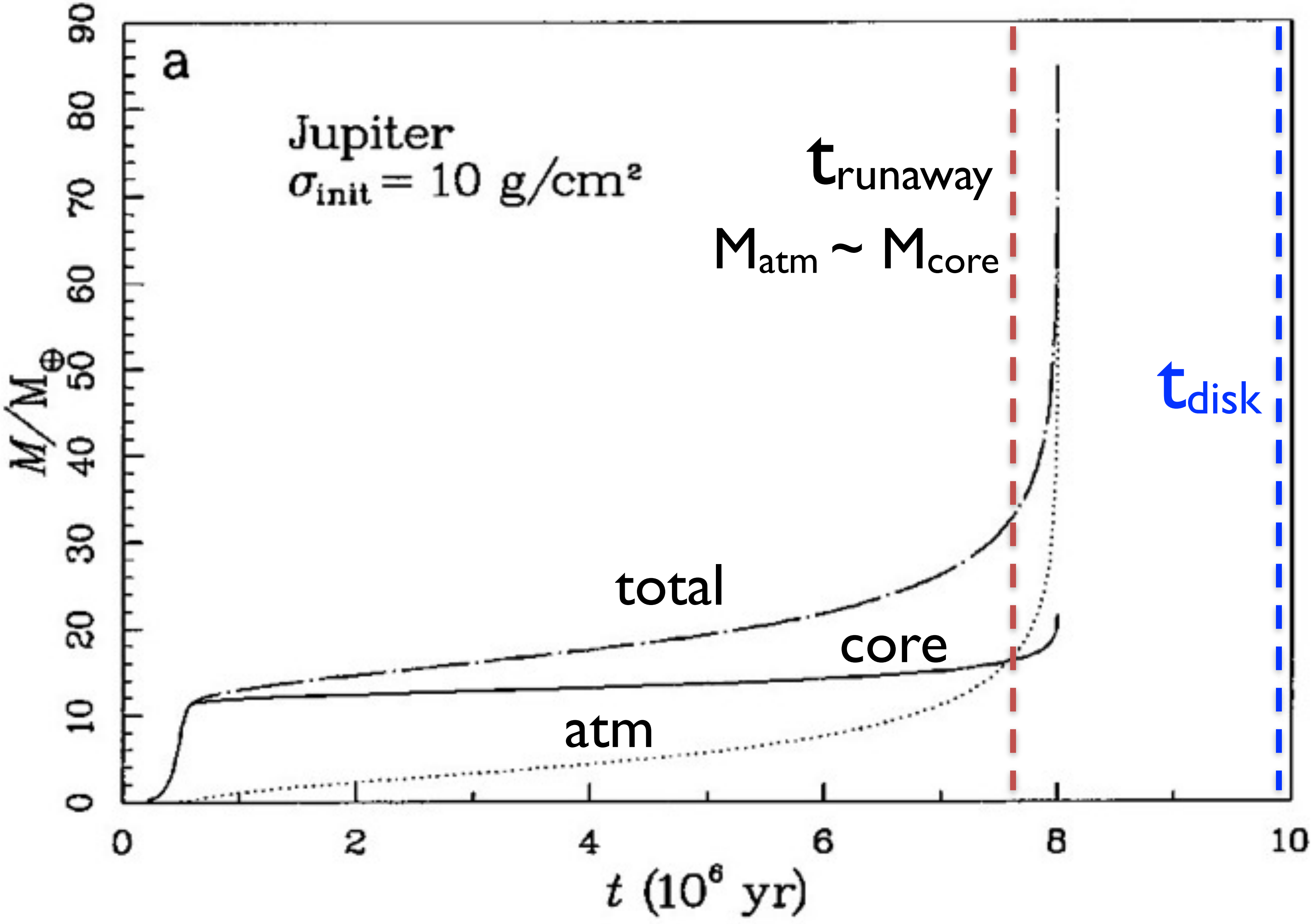

Pollack+ 1996

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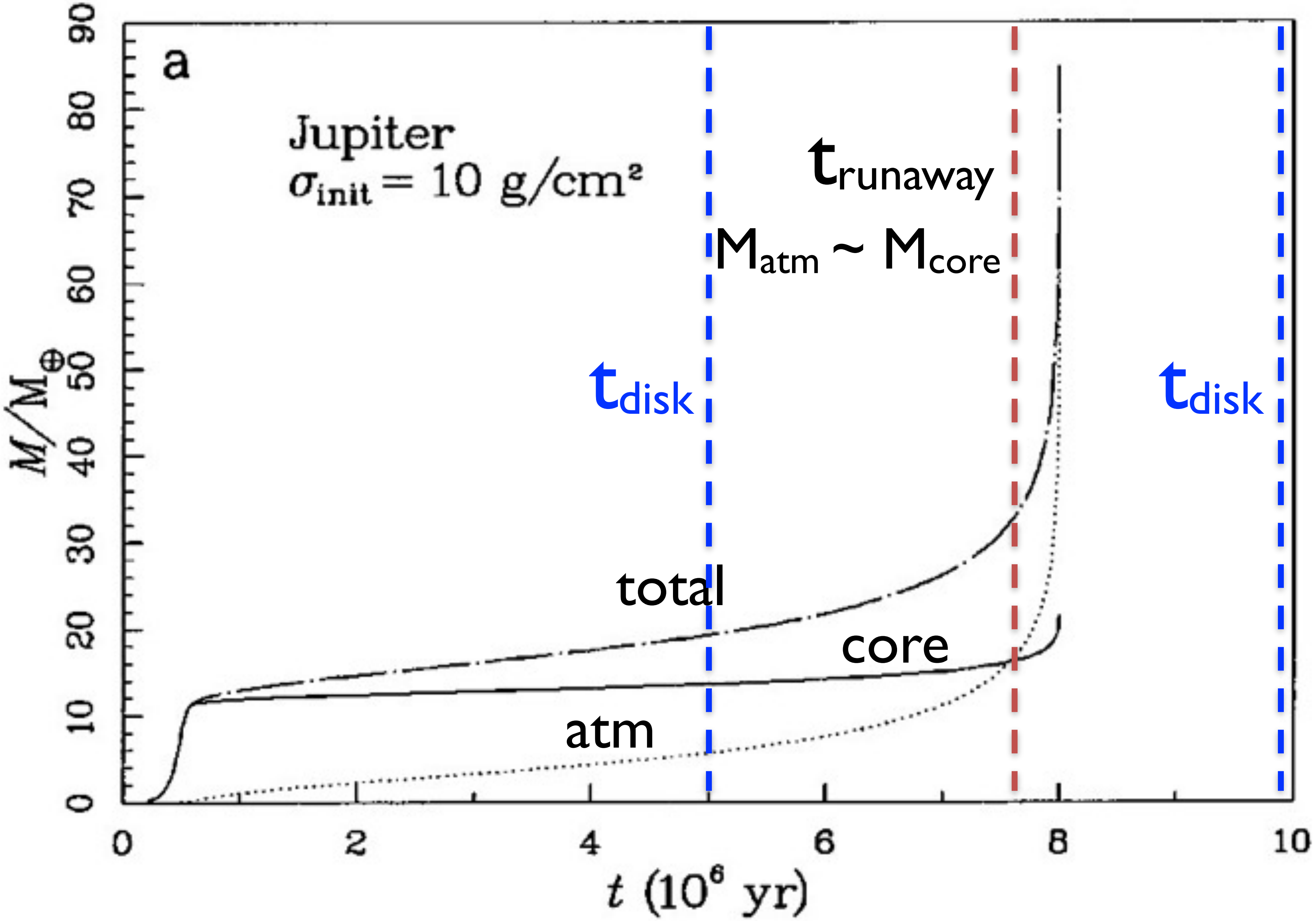
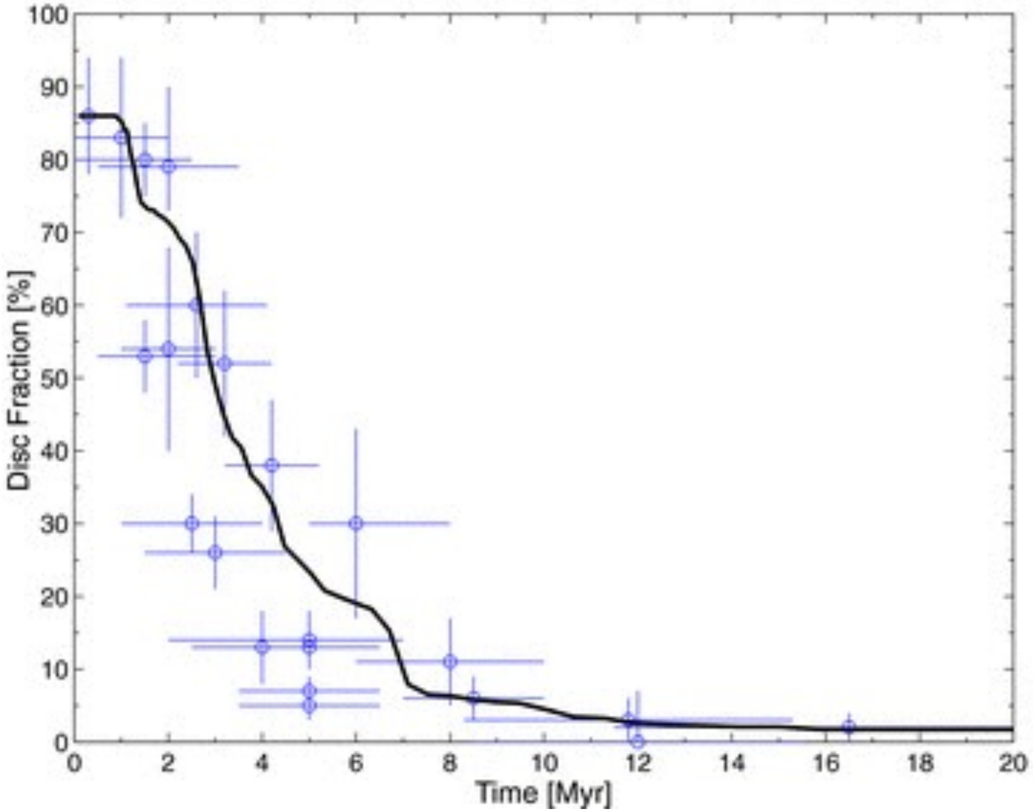
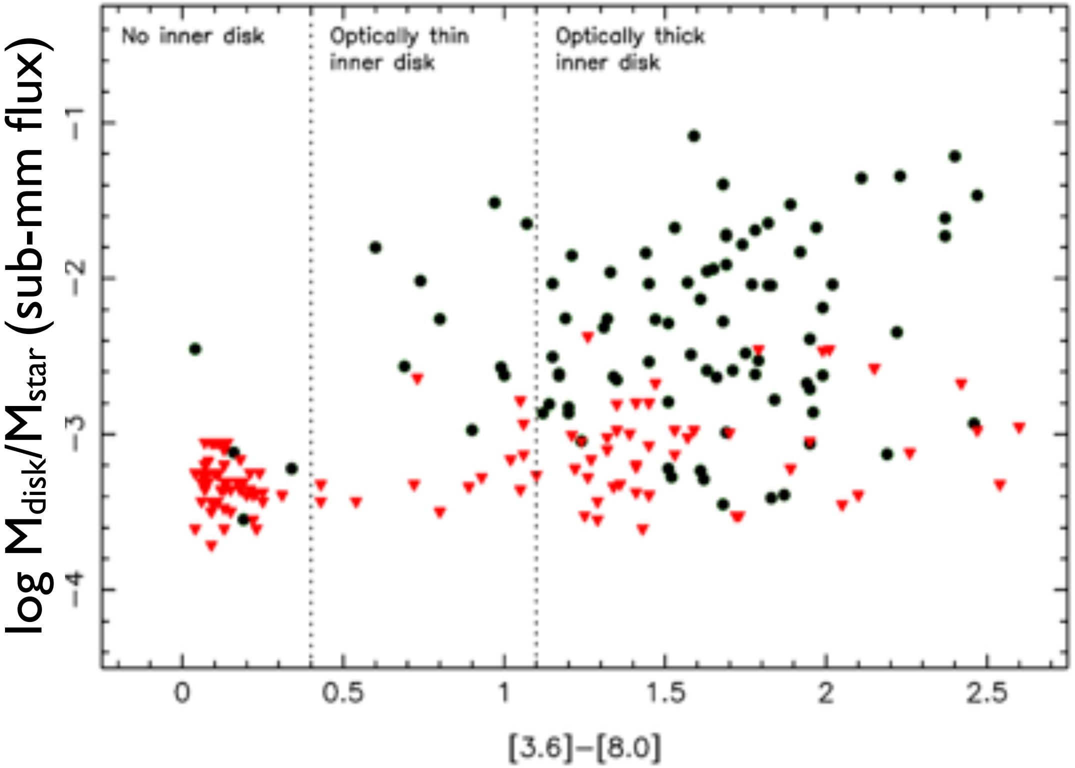


Pollack+ 1996

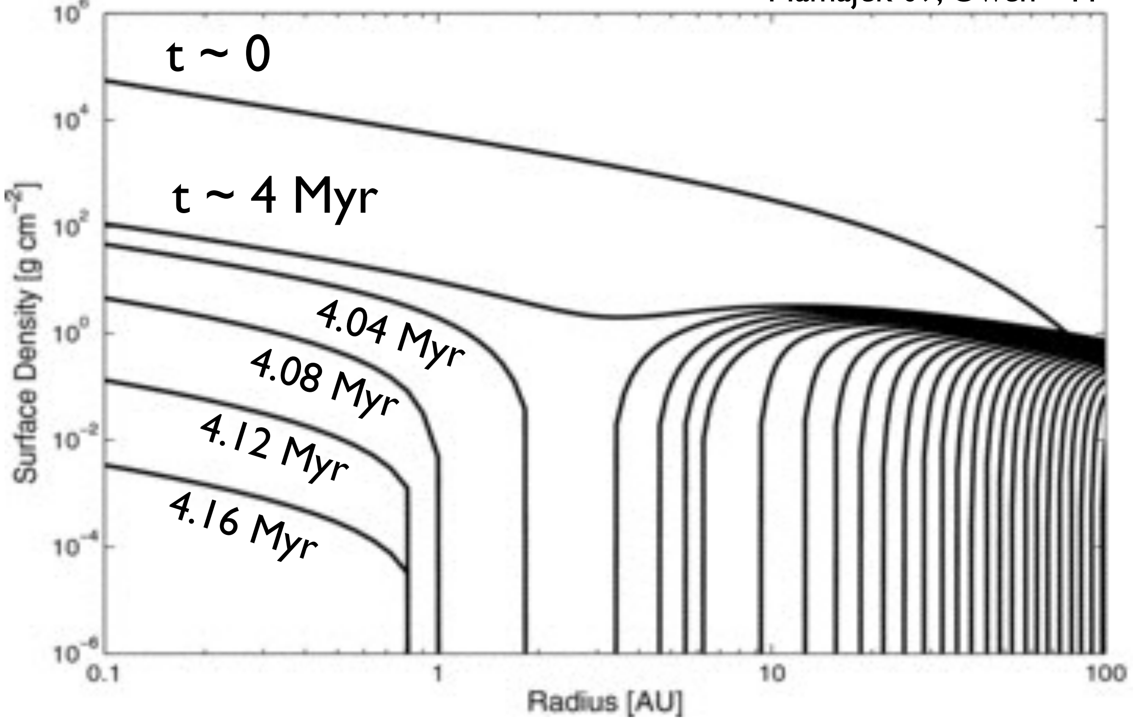




inner disk tracer

Alexander+ 13

Mamajek 09, Owen+ 11

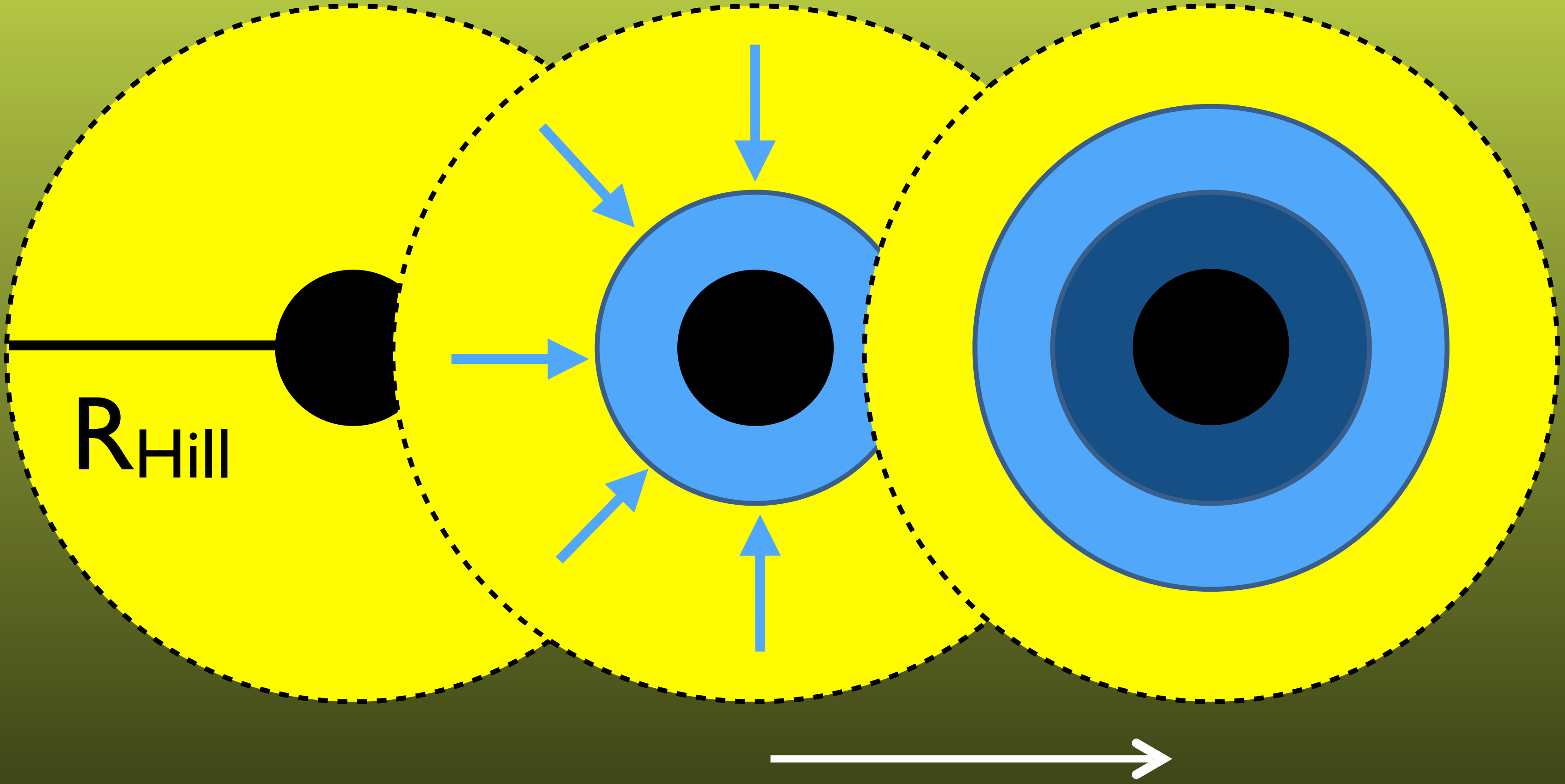


Gas disks persist for $t_{disk,slow}$ ~ 5-10 Myr

then disperse over $t_{disk,fast}$ ~ 0.5-1 Myr

Piso & Youdin 14

To cool is to accrete



$$\Delta M/\dot{M} \sim \Delta t_{\rm cool} \sim |\Delta E|/L$$

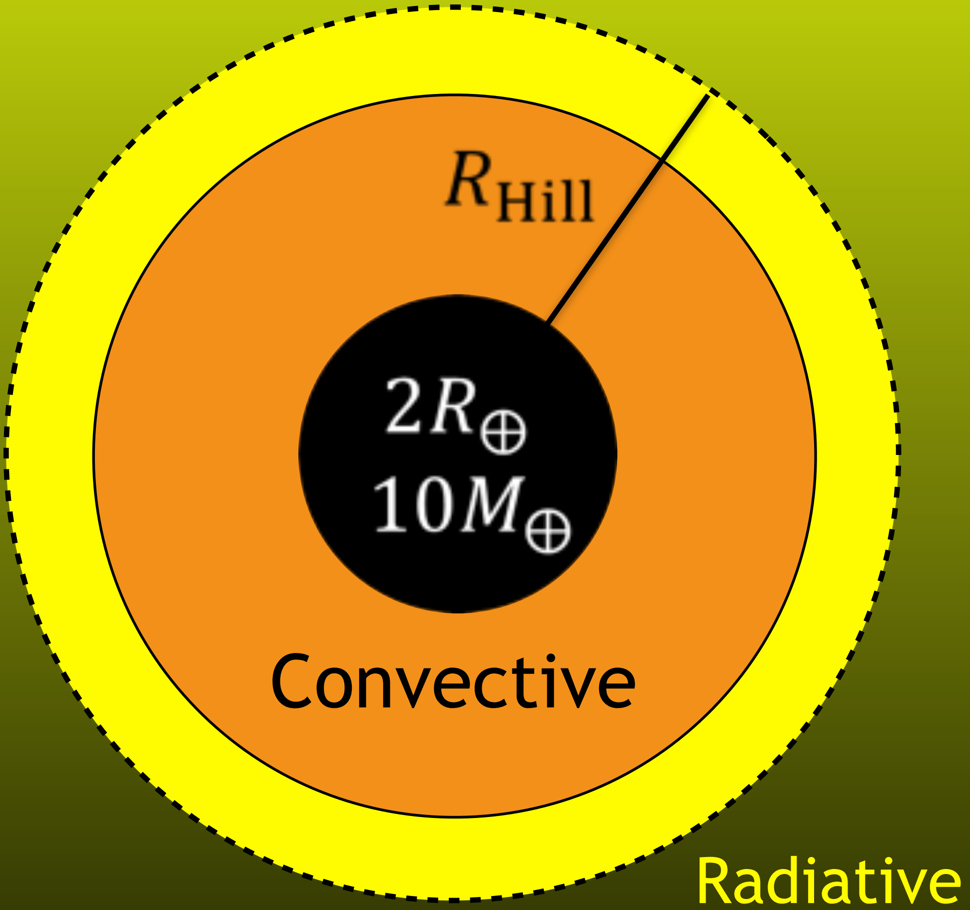
$$\Delta t_{\rm cool} \sim {\rm Myr} \gg \Delta t_{\rm hydrostatic} \sim {\rm day}$$

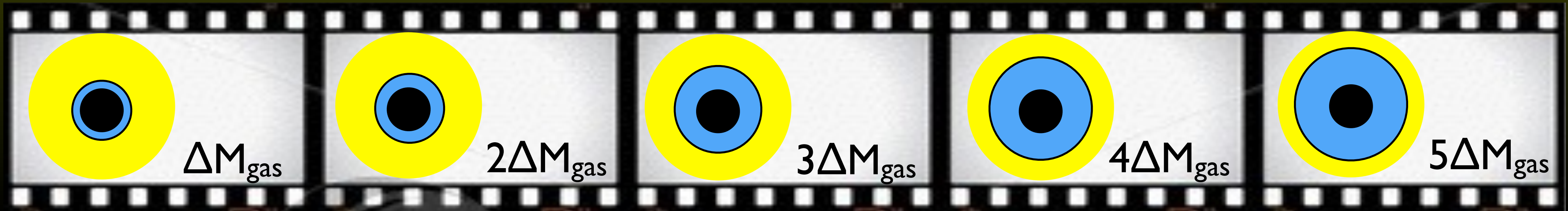
Hydrostatic snapshots

Lee, EC & Ormel 14

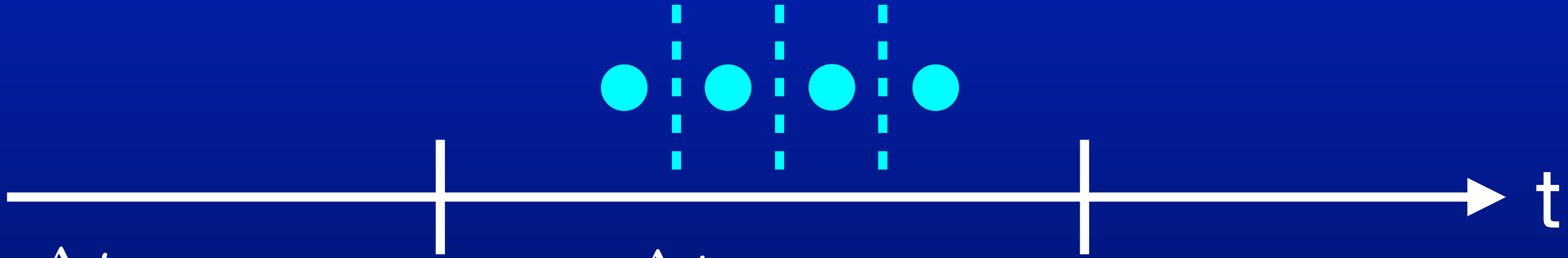
For given M_{gas}, solve for L

- Ideal gas with variable ∇_{ad}
  H_2, HI, HII
- Scaled to “MMEN”
  $\rho_{out} \sim 10^{-6}$ g/cc, $T_{out} \sim 10^3$ K
- Ferguson+ 05 opacities
  with and without dust
- Purely passive cooling
  $L_{accretion} = 0$ and $L_{core} = 0$





Two scenarios:

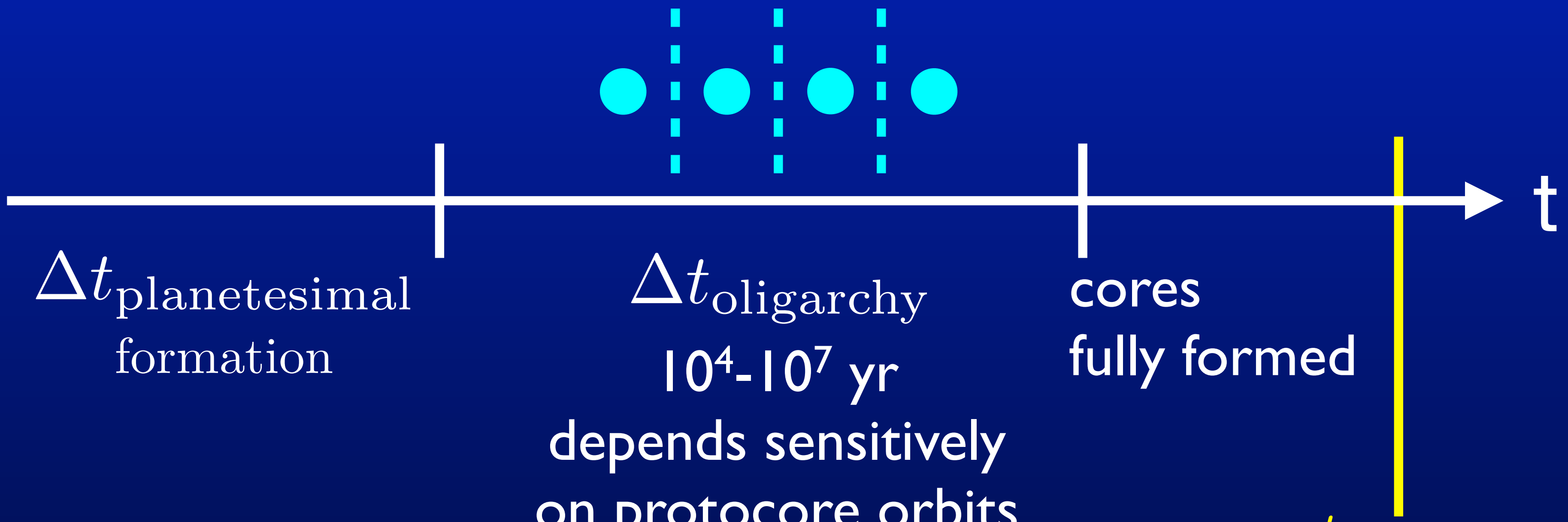


$\Delta t_{\text{planetesimal}}$
formation

$\Delta t_{\text{oligarchy}}$
10^4-10^7 yr
depends sensitively
on protocore orbits

cores
fully formed

Two scenarios:



$\Delta t_{\text{planetesimal}}$
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10^4-10^7 yr
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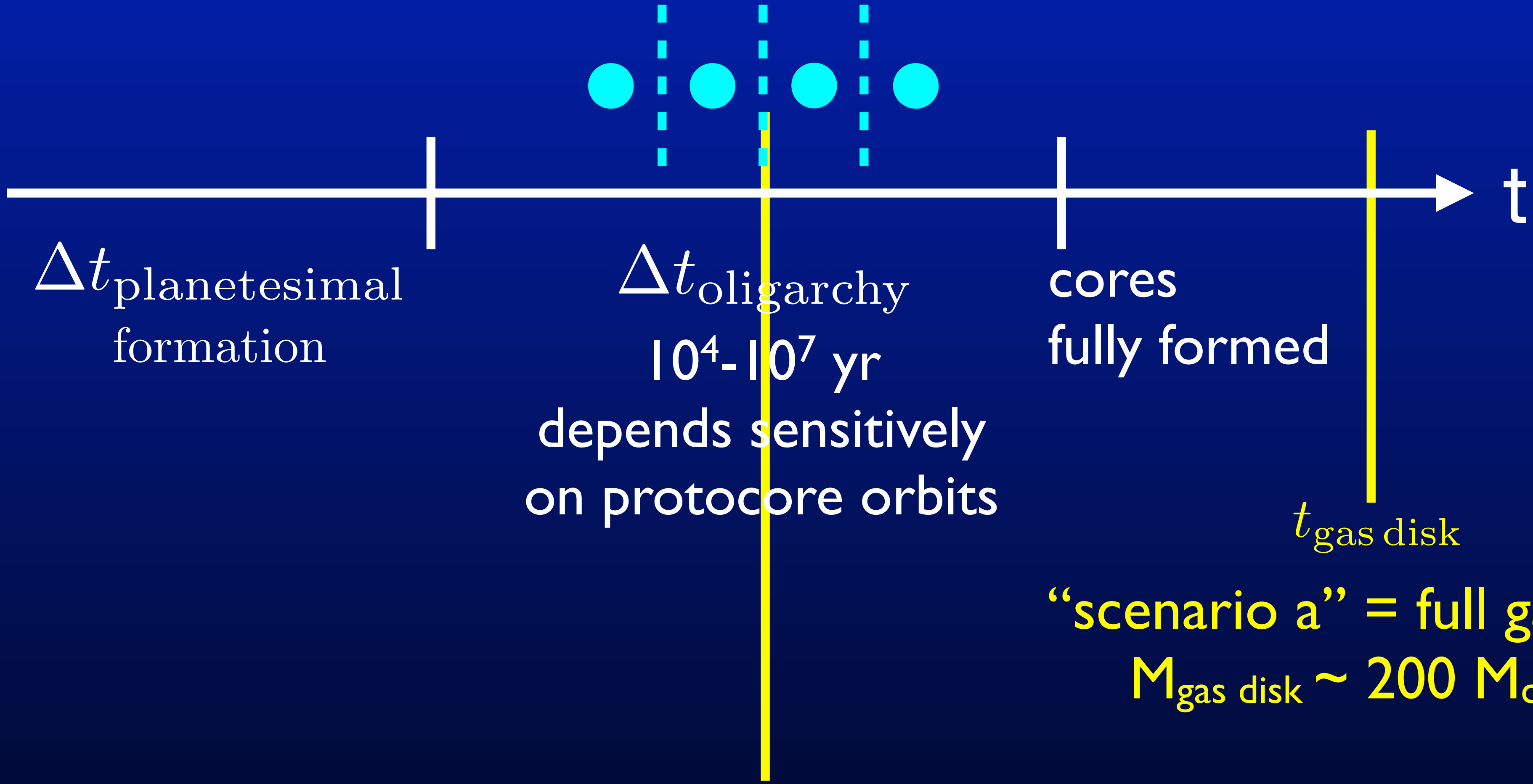
$t_{\text{gas disk}}$

“scenario a” = full gas disk
$M_{\text{gas disk}} \sim 200\ M_{\text{cores}}$

Two scenarios:



$\Delta t_{\text{planetesimal}}$ formation

$\Delta t_{\text{oligarchy}}$

10^4-10^7 yr

depends sensitively on protocore orbits

cores fully formed

$t_{\text{gas disk}}$

"scenario a" = full gas disk

$M_{\text{gas disk}} \sim 200\ M_{\text{cores}}$

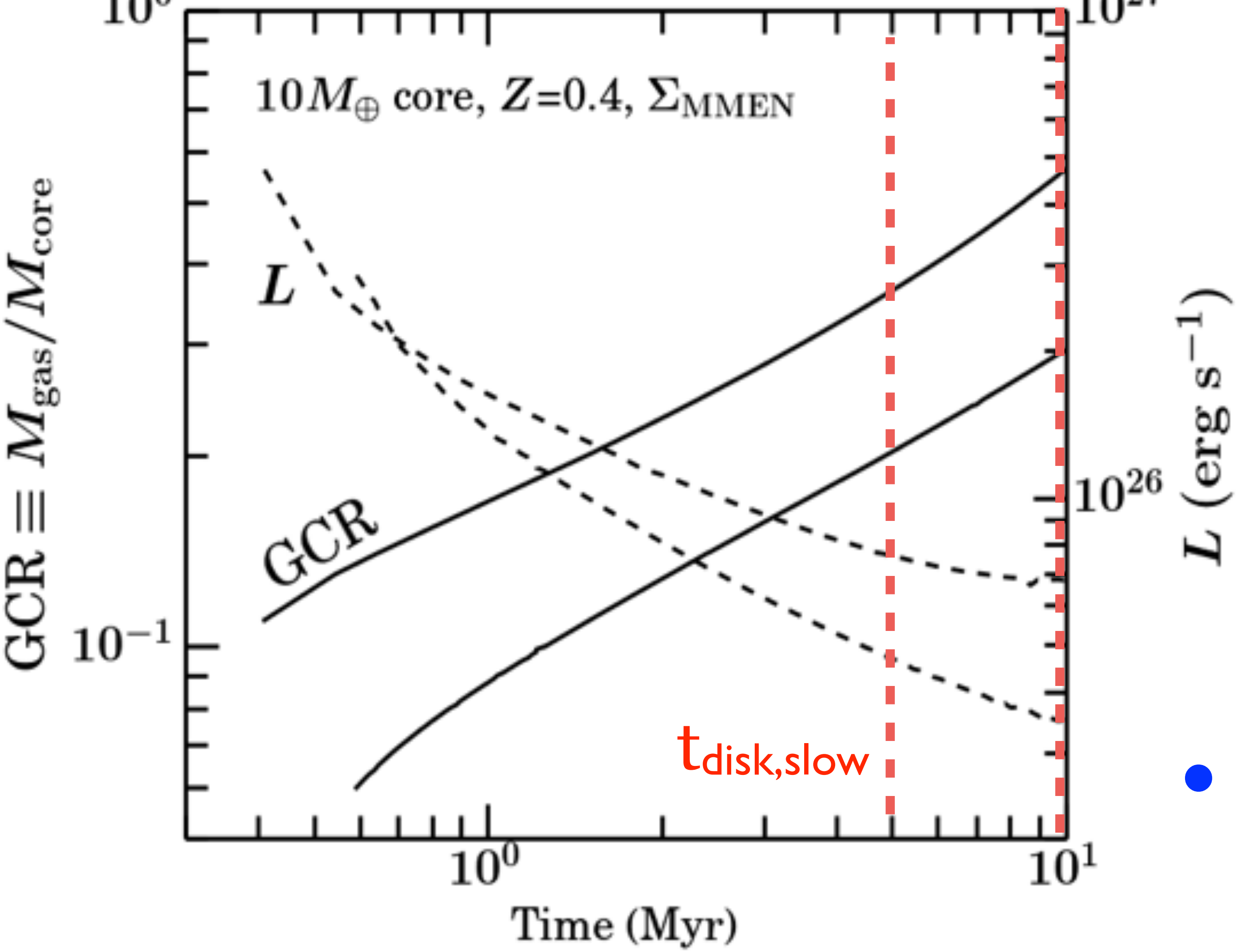
$t_{\text{gas disk}}$

"scenario b" = cores form in depleted gas disk

$M_{\text{gas disk}} < M_{\text{cores}}$

gas dynamical friction weakens to allow for mergers

Scenario “a” model (10 $M_\oplus$ @ 0.1 AU, $Z=20Z_\odot$)



“Full” nebula

- Avoid runaway if atmosphere is dusty and $Z \gg Z_\odot$

  At H_2-H front, H- opacity $\kappa \propto Z$
  $L \propto 1/\kappa \propto 1/Z$

- $t_{\rm cool} \sim t$
  $\Rightarrow \mathrm{GCR} \propto t^{1/2}$

- Lower GCR by:
  (i) photoevaporation
  (ii) $L_{\rm core} > 0$

Lee, EC & Ormel 14

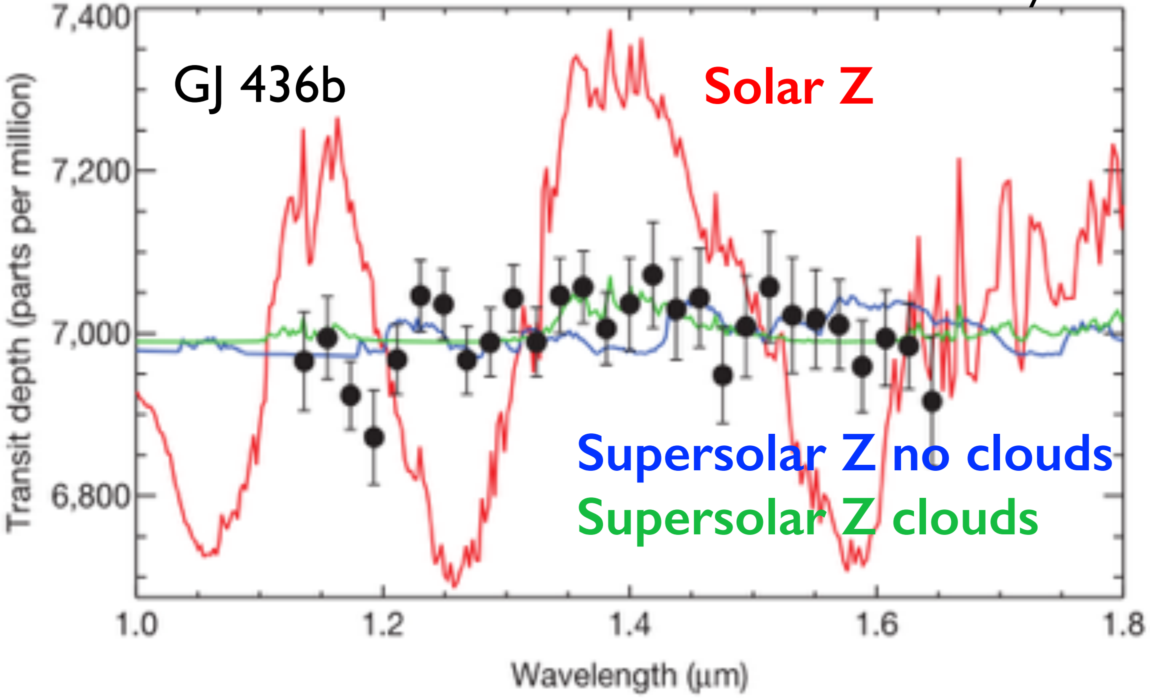
Scenario “a” (full nebula) pros

- Disk metallicity gradient by aerodynamic drift of solids
  $Z = 0.4$ @ 0.1 AU
  $Z = 0.04$ @ 5 AU

Youdin & EC 04

- Super-Earth atmospheres are supersolar

Knutson+ 14
Kriedberg+ 14
Morley+ 13



Scenario “a” cons

- Too large Z ⇒ runaway (μ catastrophe)
- Dust-free atmospheres ⇒ runaway (κ catastrophe)
- Loss of planets to orbital migration in full gas disk

Hori & Ikoma 11
Ormel 14
Inamdar & Schlichting 15

Scenario “a” cons

- Too large Z ⇒ runaway
  (μ catastrophe)
- Dust-free atmospheres
  ⇒ runaway
  (κ catastrophe)
- Loss of planets to orbital migration in full gas disk

Hori & Ikoma 11
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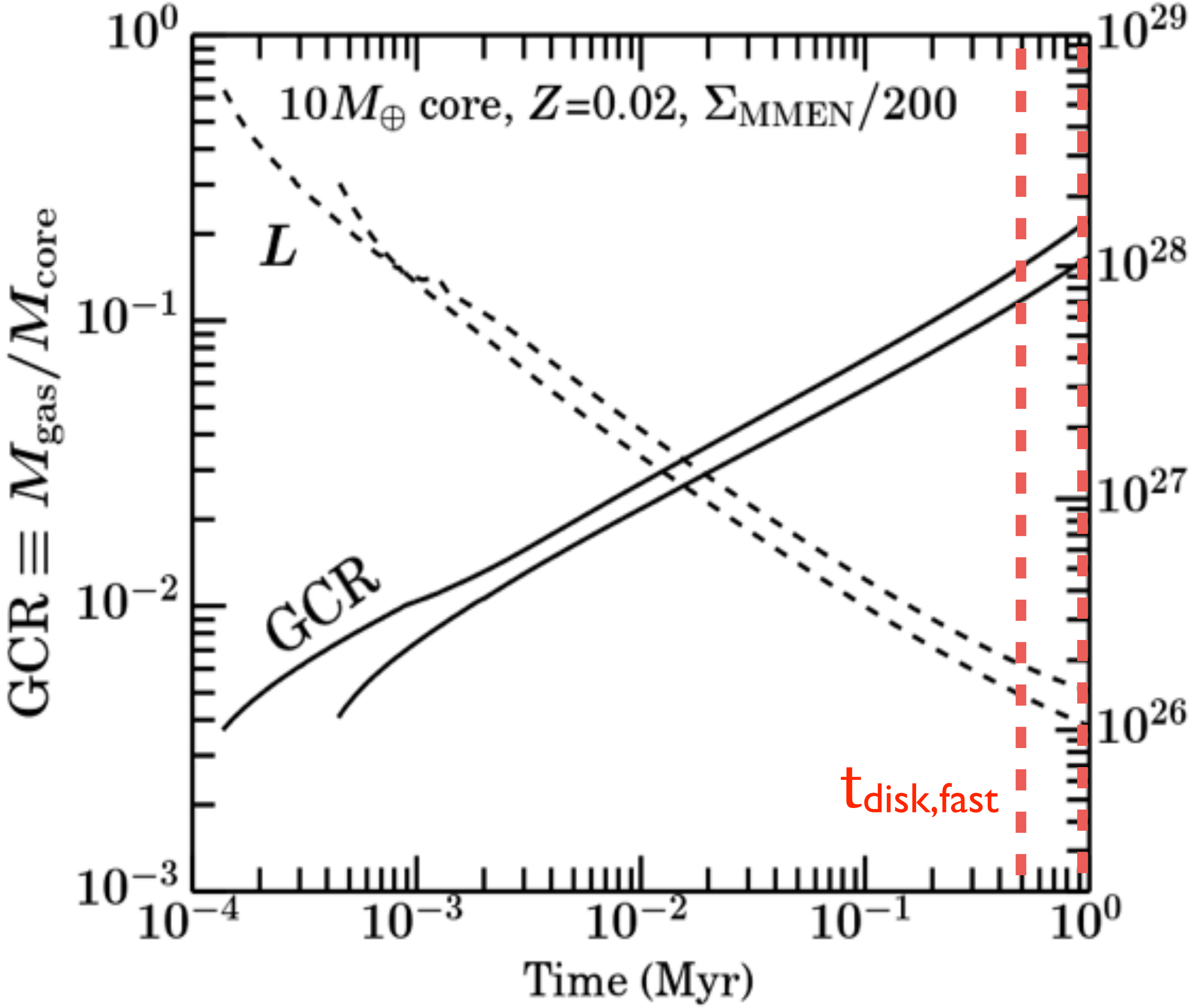
Inamdar & Schlichting 15

Scenario “b” pros
Cores form in gas-poor disk
$M_{\text{gas disk}} < M_{\text{cores}}$

- No runaway
  regardless of Z, μ, or κ
- No orbital migration since disk lacks angular momentum
- Need gas disk to deplete to allow protocores to merge

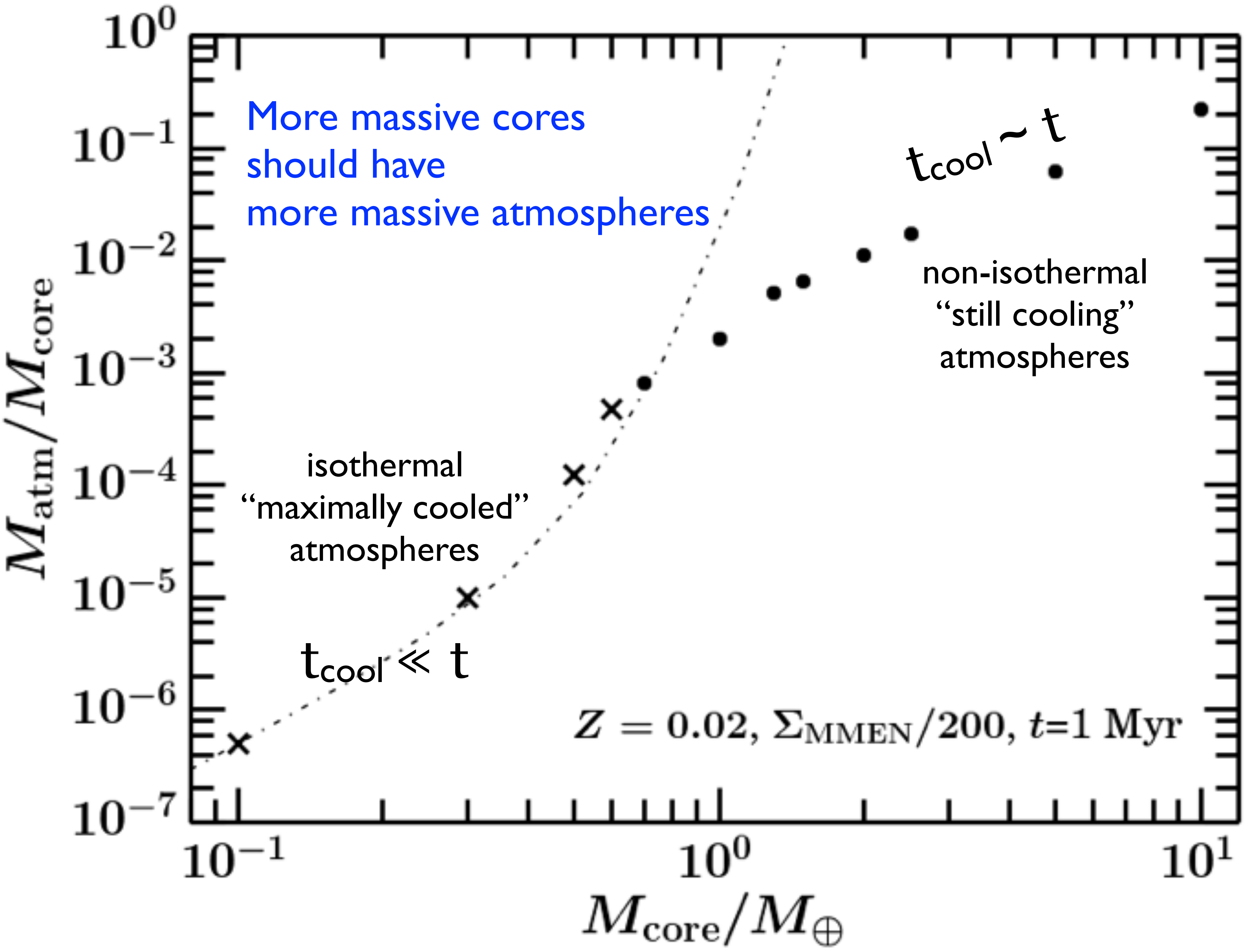
Solution for scenario "b" (depleted nebula): Accrete whatever is left



Lower GCR by:
(i) photoevaporation
(ii) $L_{\rm core} > 0$
(iii) more disk depletion

Similar to scenario "a" because cooling history is insensitive to external environment

Lee, EC & Ormel 14



More massive cores
should have
more massive atmospheres

$t_{\rm cool} \sim t$

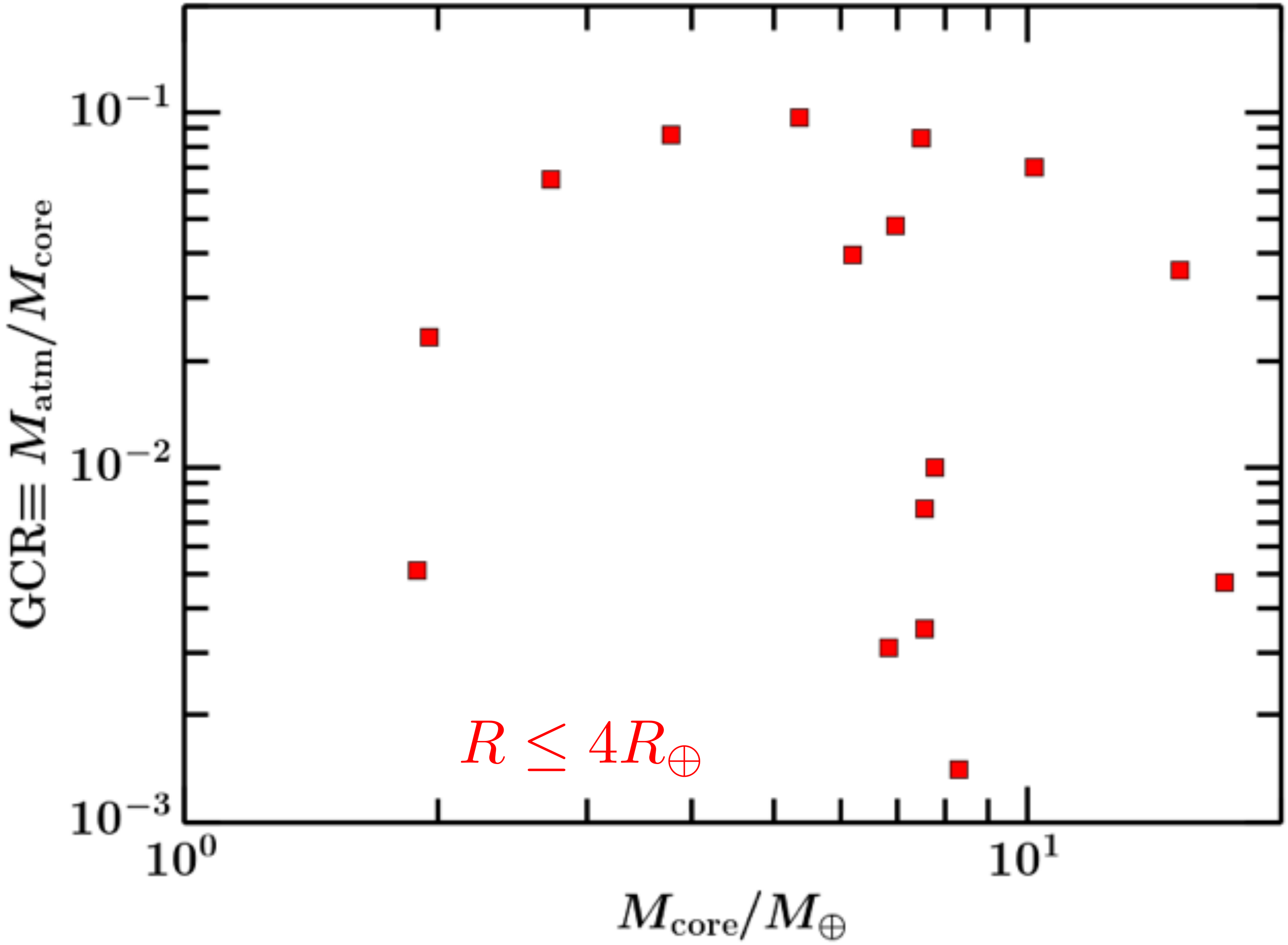
non-isothermal
“still cooling”
atmospheres

isothermal
“maximally cooled”
atmospheres

$t_{\rm cool} \ll t$

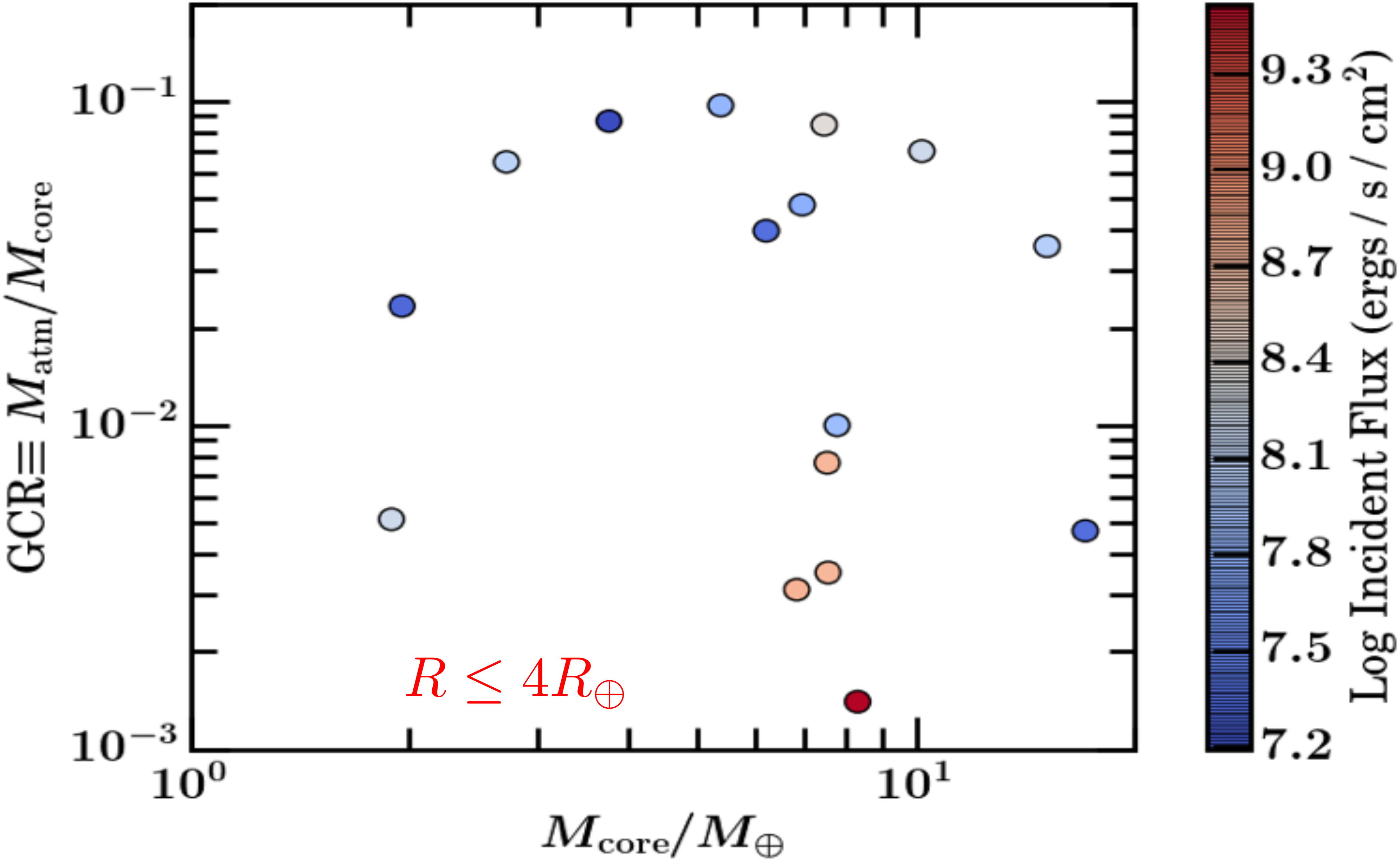
Correlation or no correlation?

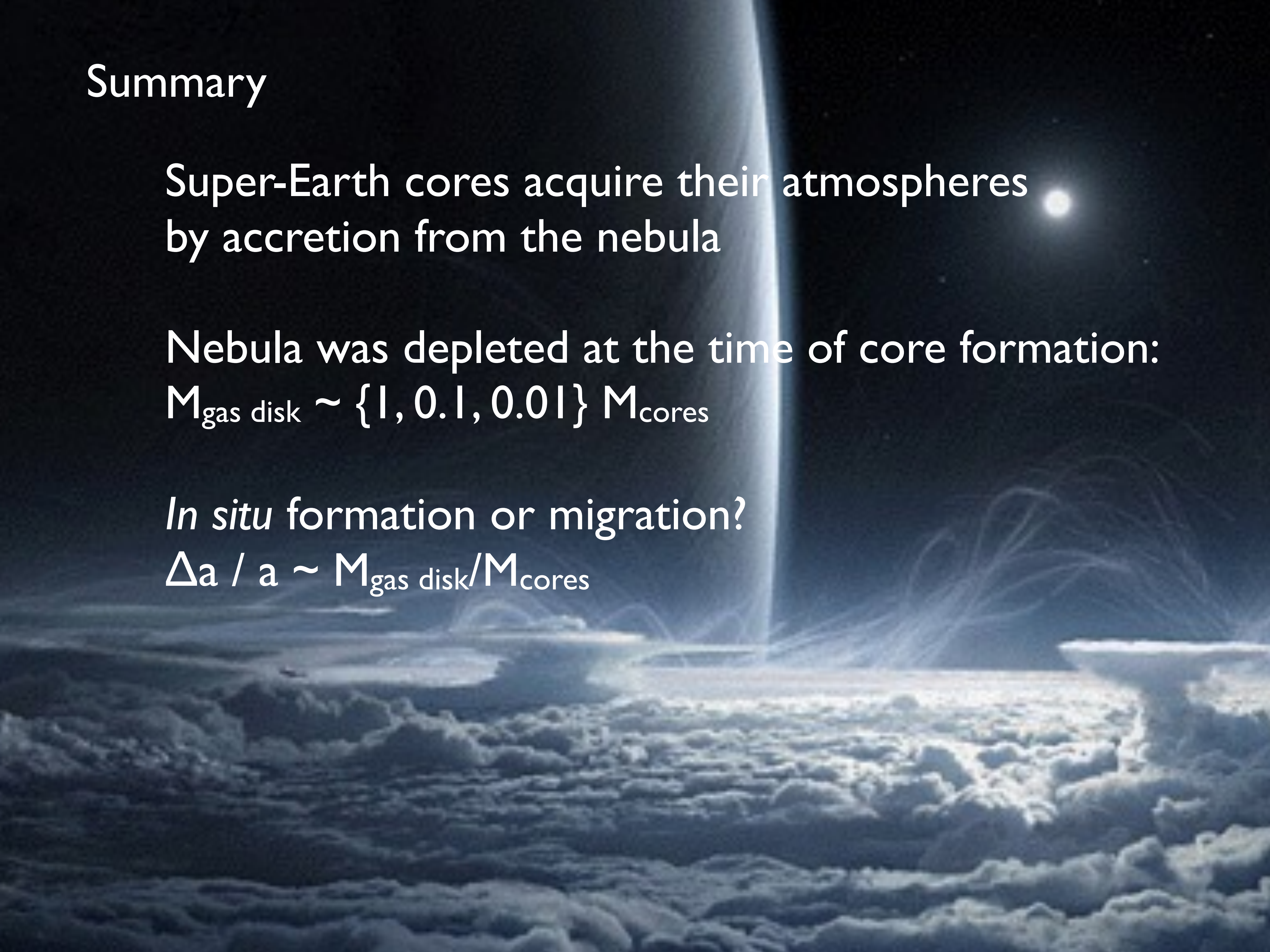
Lopez & Fortney 14



Correlation or no correlation?

Lopez & Fortney 14





Summary

Super-Earth cores acquire their atmospheres by accretion from the nebula

Nebula was depleted at the time of core formation:
$M_{\text{gas disk}} \sim \{1, 0.1, 0.01\}\, M_{\text{cores}}$

In situ formation or migration?
$\Delta a \,/\, a \sim M_{\text{gas disk}}/M_{\text{cores}}$