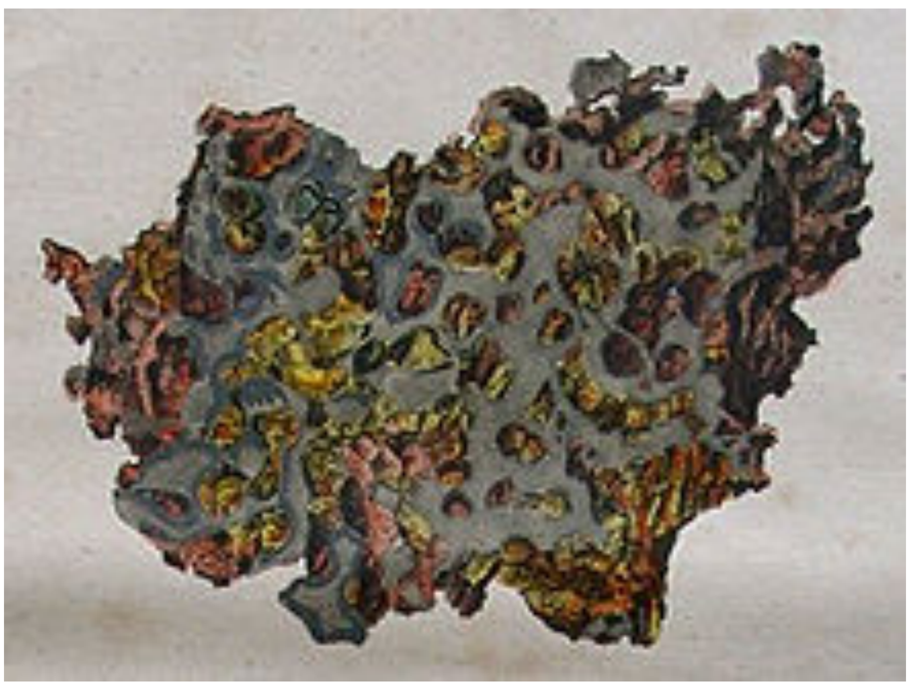
How Chondrules and CAIs Constrain Disk Processes and Planet Formation

Steve Desch
School of Earth and Space Exploration
Arizona State University

RESCEU/Planet Symposium
University of Tokyo
November 28, 2017

Iron Meteorites

Stony Achondrite
(angrite)



Pallasites

Carbonaceous Chondrites
(CI Orgueil)

Ordinary Chondrites
(L3-6 NWA 869)

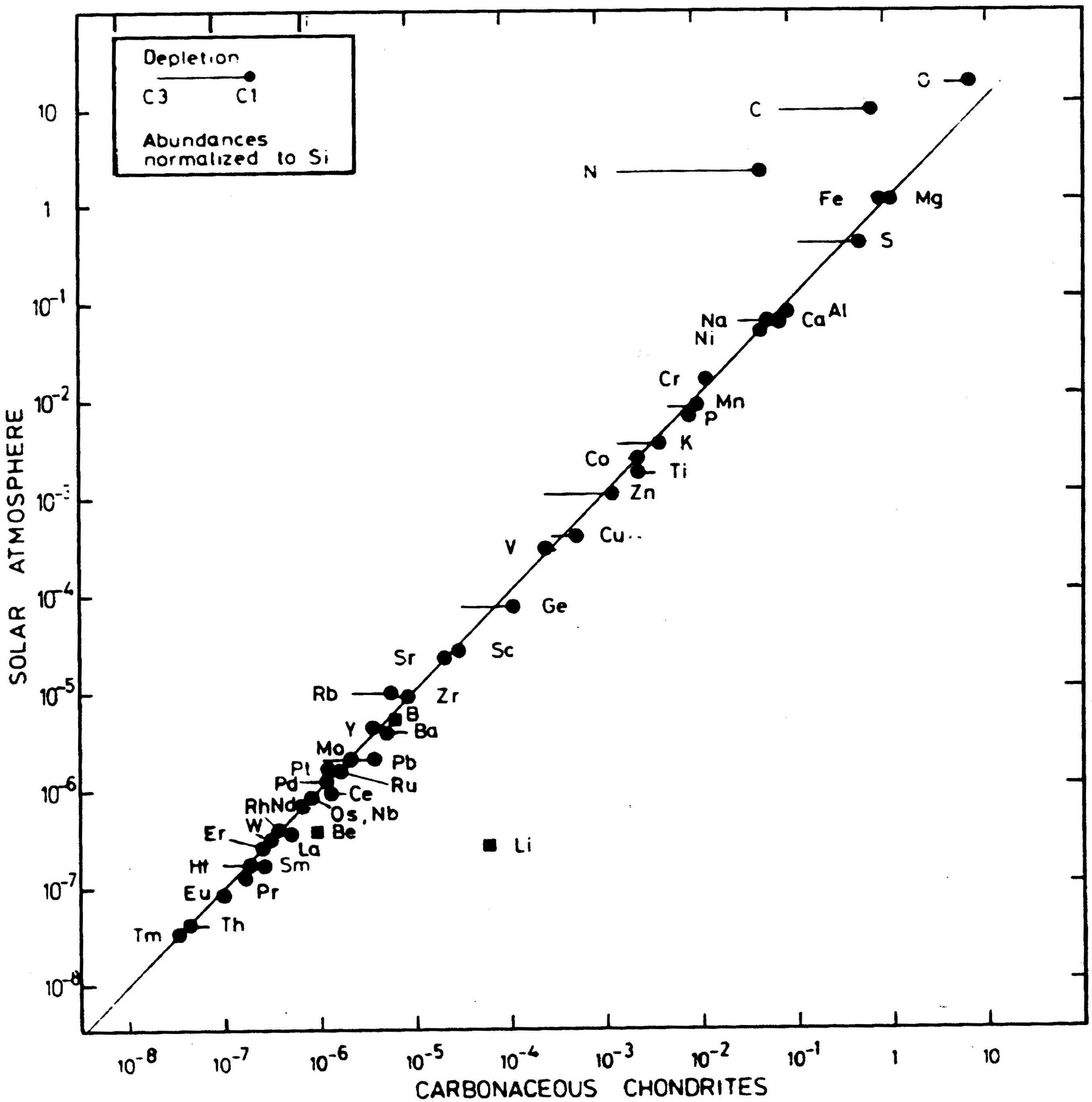
CM, CR, CI = water-rich,
CCs formed farther from Sun

OCs, ECs = water-poor,
formed closer to Sun

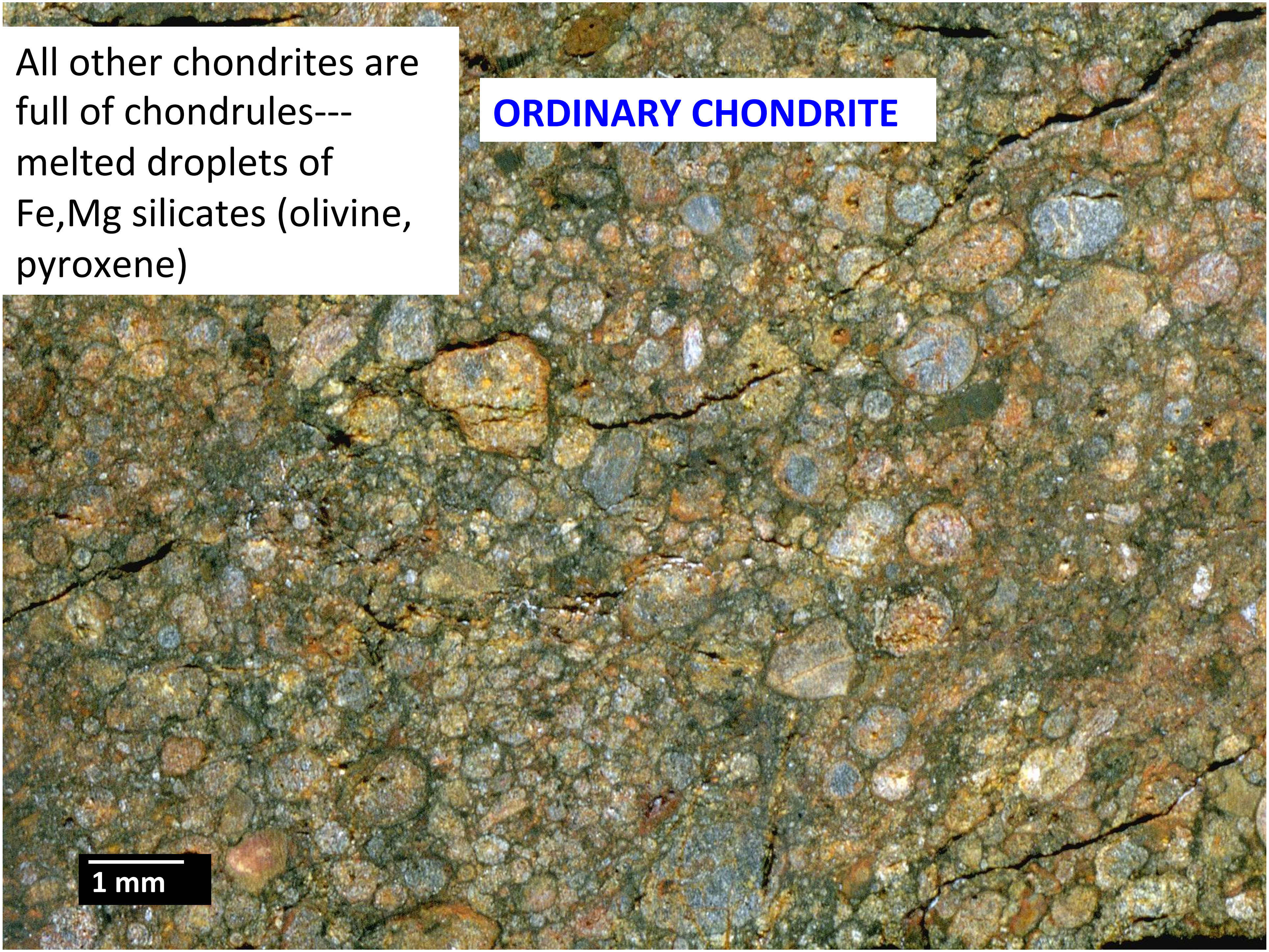
Enstatite Chondrites
(EH3 SAH97079)

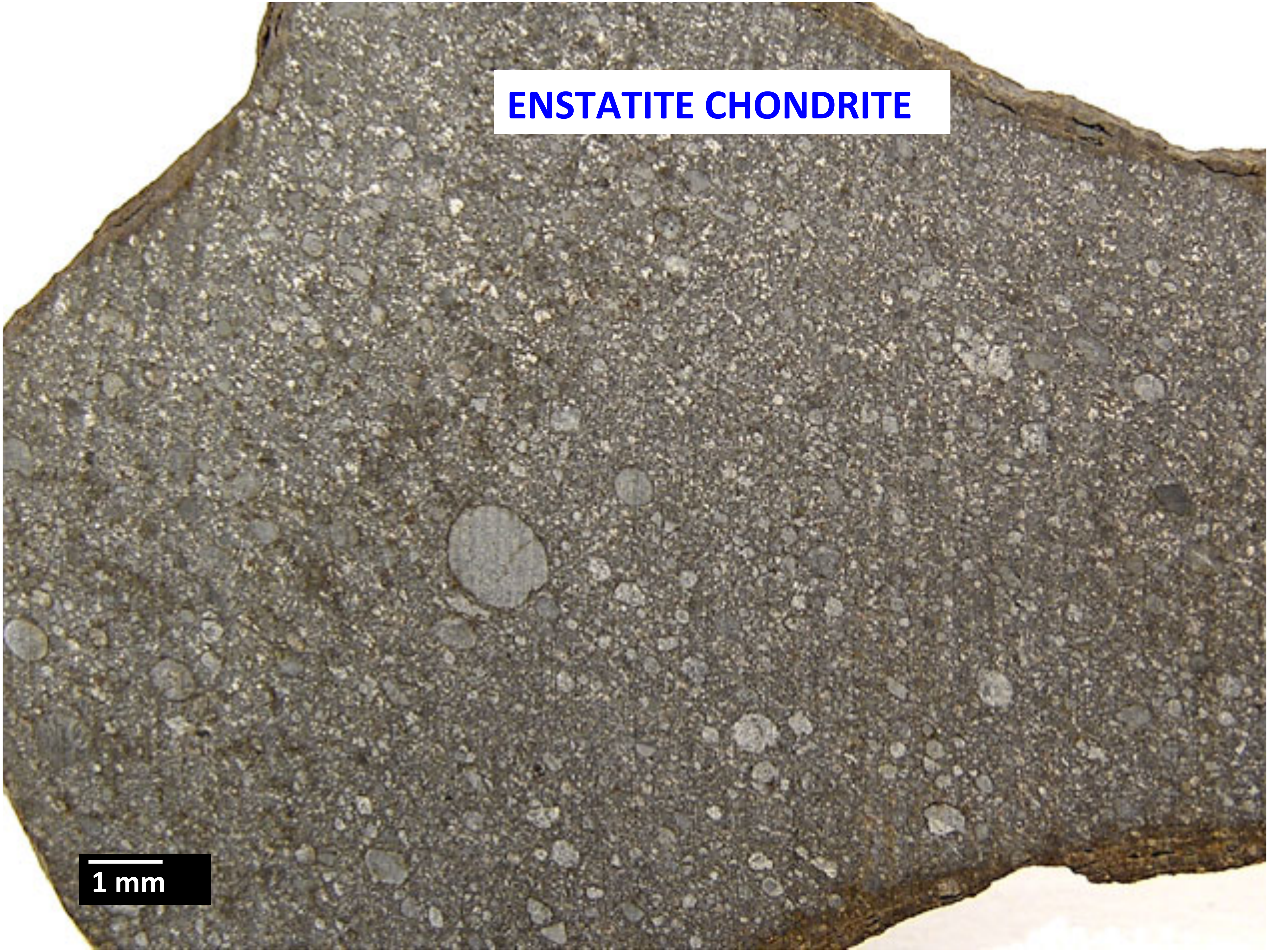
CI Chondrites are chemically identical to the Sun (< 10-25%).

They contain 'no' refractory inclusions.

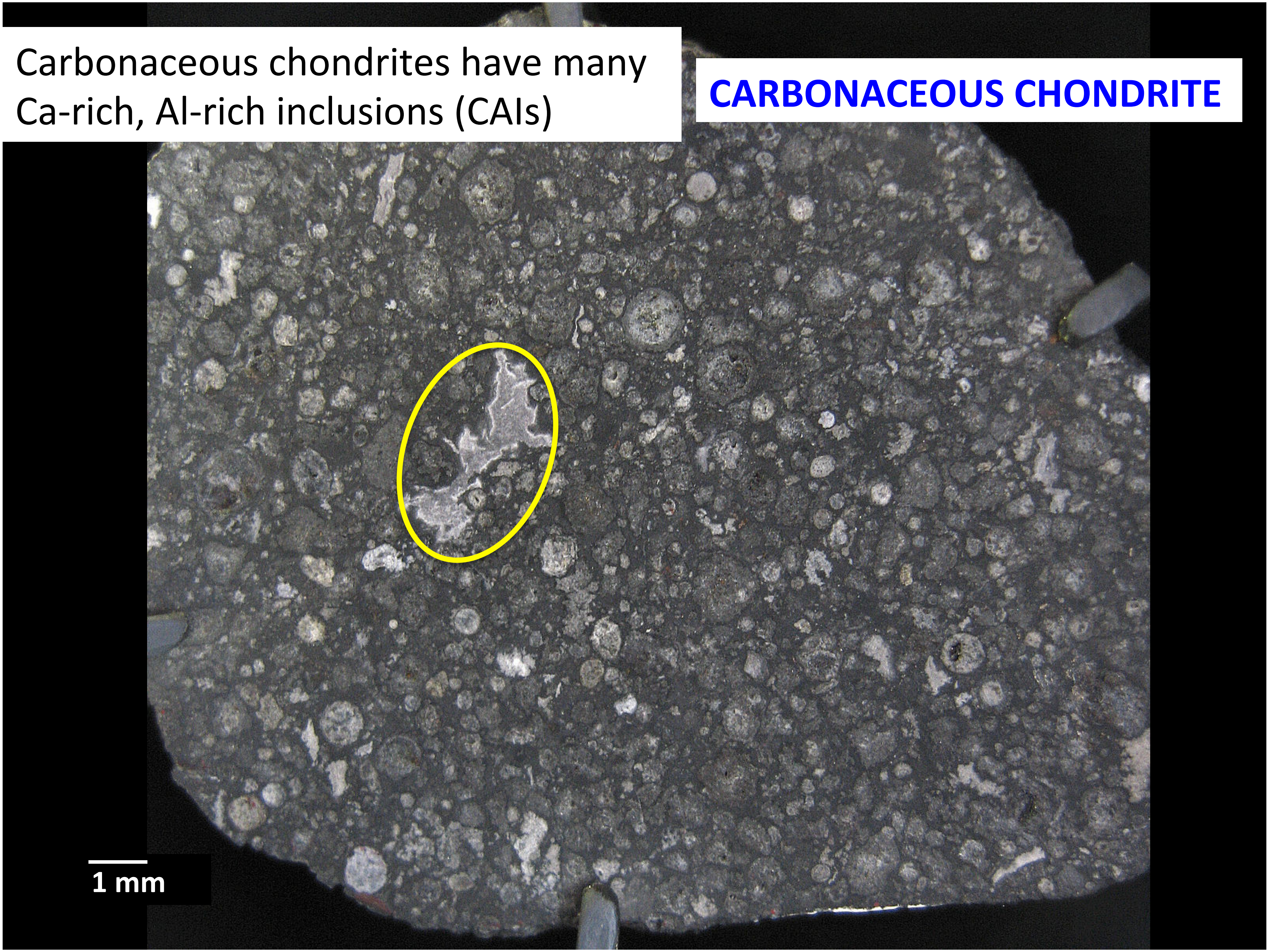


All other chondrites are full of chondrules---melted droplets of Fe,Mg silicates (olivine, pyroxene)



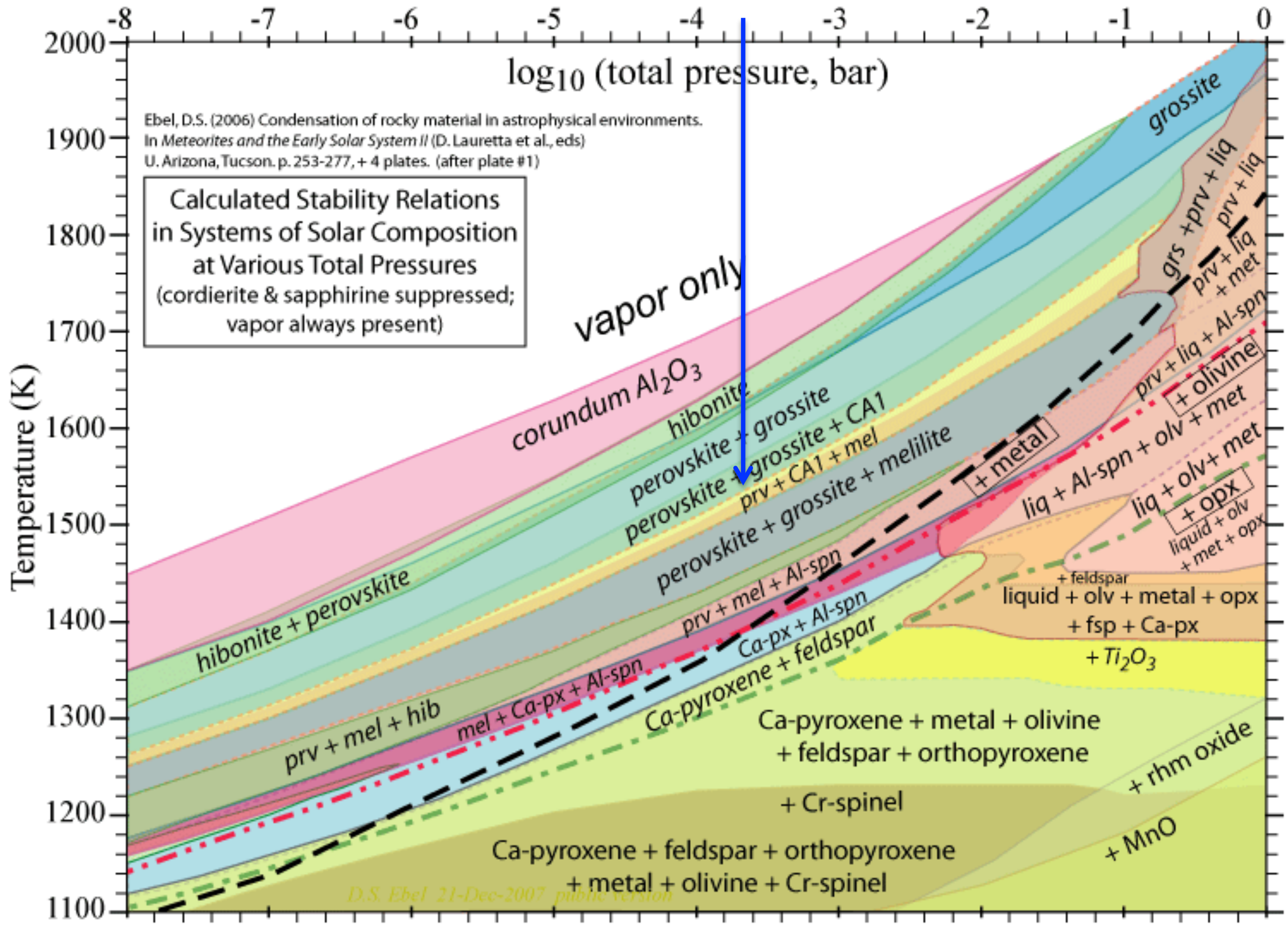

ENSTATITE CHONDRITE
1 mm

Carbonaceous chondrites have many Ca-rich, Al-rich inclusions (CAIs)



CAIs made of minerals that condense first from a cooling solar-composition gas.

Rich in refractory lithophiles (Ca, Al, Ti, Sc, Y, Hf, Zr, REEs)



CAIs condensed from gas at T > 1400 K (close to Sun)

Ebel (2006)

Table 1 of Desch, Kalyaan & Alexander, in revision (ApJ).

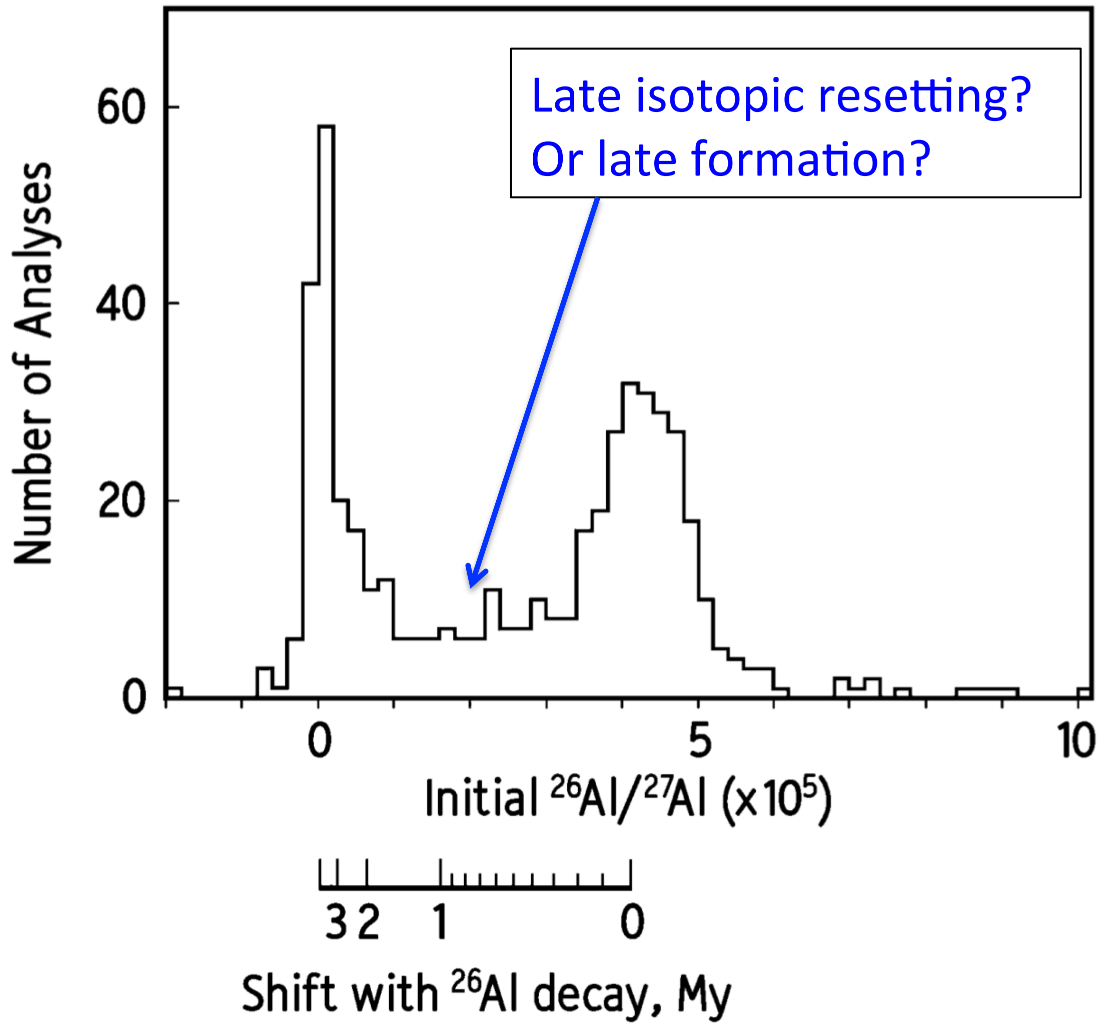
Why are Ordinary and Enstatite chondrites depleted in refractories and CAIs?
Why are Carbonaceous chondrites enriched?

Type	(X/Mg) / CI[a]	(X/Mg) / CI[b]	CAIs (vol%)[a]	CAIs (vol%)[b]	CAI (wt%)[c]	Adopted CAIs (wt%)
EH	0.87	**0.884**	< 0.1	0.01	0	**< 0.1**
EL	0.83	**0.871**	< 0.1	0.01	0	**< 0.1**
R	0.95	**0.974**	< 0.1	0.04	0	**< 0.1**
H	0.93	**0.899**	0.01 - 0.2	0.02	0	**< 0.2**
L	0.94	**0.904**	< 0.1	0.02	0	**< 0.1**
LL	0.90	**0.890**	< 0.1	0.02	0	**< 0.1**
CK	1.21	**1.24**	0.2	4	4	**< 4**
CV	1.35	**1.35**	3.0	3.0	6	**> 3**
CO	1.13	**1.11**	1.0	1.0	5	**> 1**
CM	1.15	**1.13**	1.2	1.2	2	**1-2**
CR	1.03	**1.02**	0.12	0.6	1	**0.5-1**
CI	$\equiv 1.00$	**1.00**	0.00	0.0	0	**0.0**

a) Scott & Krot (2014); b) Rubin (2011); c) estimate based on Trinquier et al. (2009)

CAIs define "time zero" of solar nebula

Most CAIs had live ^{26}Al. Consistent with uniform $^{26}Al/^{27}Al = 5.23 \times 10^{-5}$ in solar nebula at t=0, most CAIs forming in < 0.4 Myr or less.



MacPherson et al. (2012, 2017); Kita et al. (2013); Ushikubo et al. (2017).

Or < 0.02 Myr? (Thrane et al. 2006)

MacPherson et al. (1995)

Type	chondrule ages (Myr)	SF14 accretion time (Myr)[a]	Other	**Adopted Time of Accretion (Myr)**
angrites		0.5 ± 0.4	≤ 1.5[b]	**$\sim$ 0.5**
HEDs		0.8 ± 0.3	$\leq 2.2^{+1.1}_{-1.1}$[c],	**$\sim$ 0.8**
			$\leq 0.6^{+0.5}_{-0.4}$[d], < 1[e]	
acapulcoites-lodranites		1.3 ± 0.3	$1.5 - 2.0$[f]	**$\sim$ 1.5**
ureilites		1.0 ± 0.3	$< 1.9^{+2.2}_{-0.7}$[g], ~ 1.4[h],	**$\sim$ 0.6**
			~ 1.6[i], ~ 0.6[j]	
winonaites			~ 1.8[k]	**$\sim$ 1.8**
EH		1.8 ± 0.1	~ 2[l]	**1.7 - 1.9**
EL		1.8 ± 0.1		**1.7 - 1.9**
R		2.1 ± 0.1		**2.0 - 2.2**
H	1.7 ± 0.7[m]	2.1 ± 0.1	$1.8 - 2.7$[n], ~ 2[m,o]	**2.0 - 2.2**
L	$1.6 - 2.2$[p], $2.5 - 3.0$[q]	2.1 ± 0.1	$1.8 - 2.5$[r]	**2.0 - 2.5**
LL	$\sim 1.0 - 2.5$[s]	2.1 ± 0.1		**2.0 - 2.5**
	$\sim 0.7 - 2.4$[t]			
	$\sim 1.5 - 3.0$[u]			
	$\sim 2.0^{+0.5}_{-0.3}$[v]			
CK		2.6 ± 0.2		**2.4 - 2.8**
CV	$\sim 1.5 - 4$[w],	3.0 ± 0.2	$1.8 - 2.5$[r]	**$\sim$ 3.0**
	$2.0 - 2.5$[x]			
CO	$1.7 - 3.0$[y]	2.7 ± 0.2	$1.8 - 2.5$[r]	**$\sim$ 2.5 - 3.0**
CM		3.5 ± 0.5	3.0 - 4.0[z]	**3.0 - 4.0**
CR	2.5 ± 1.2[aa]	3.5 ± 0.5	$> 4.0^{+0.5}_{-0.3}$[ab]	**3.8 - 4.5**
	$3.5 - 3.8$[ab]			
CI		3.5 ± 0.5	3 - 4[z]	**3.0 - 4.0**

a. Sugiura & Fujiya (2014); b. Hf-W: Kleine et al. (2012); c. Mn-Cr: Trinquier et al. (2008); d. Al-Mg: Schiller et al. (2011); e. Al-Mg: Neumann et al. (2014); f. Hf-W: Touboul et al. (2009) g. Al-Mg: Baker et al. (2012); h. Hf-W: von Kooten et al. (2014); i. Hf-W: Budde et al. (2015); j. Wilson & Goodrich (2016); k. Hunt et al. (2017); l. Shukolyukov & Lugmair (2004); m. Kleine et al. (2008) n. Gail et al. (2014); o. Henke et al. (2013); p. Al-Mg: Rudraswami & Goswami (2007); q. U-Pb: Bollard et al. (2017); r. Mn-Cr: Doyle et al. (2015); s. Al-Mg: Rudraswami et al. (2008); t. Al-Mg: Mostefaoui et al. (2002); u. Al-Mg: Villeneuve et al. (2009); v. Kita et al. (2000); w. Al-Mg: Hutcheon et al. (2009); x. Al-Mg: Nagashima et al. (2015); y. Al-Mg: Kurahashi et al. (2008); z. Mn-Cr: Fujiya et al. (2013); aa. Pb-Pb: Amelin et al. (2002); ab. Al-Mg: Schrader et al. (2017).

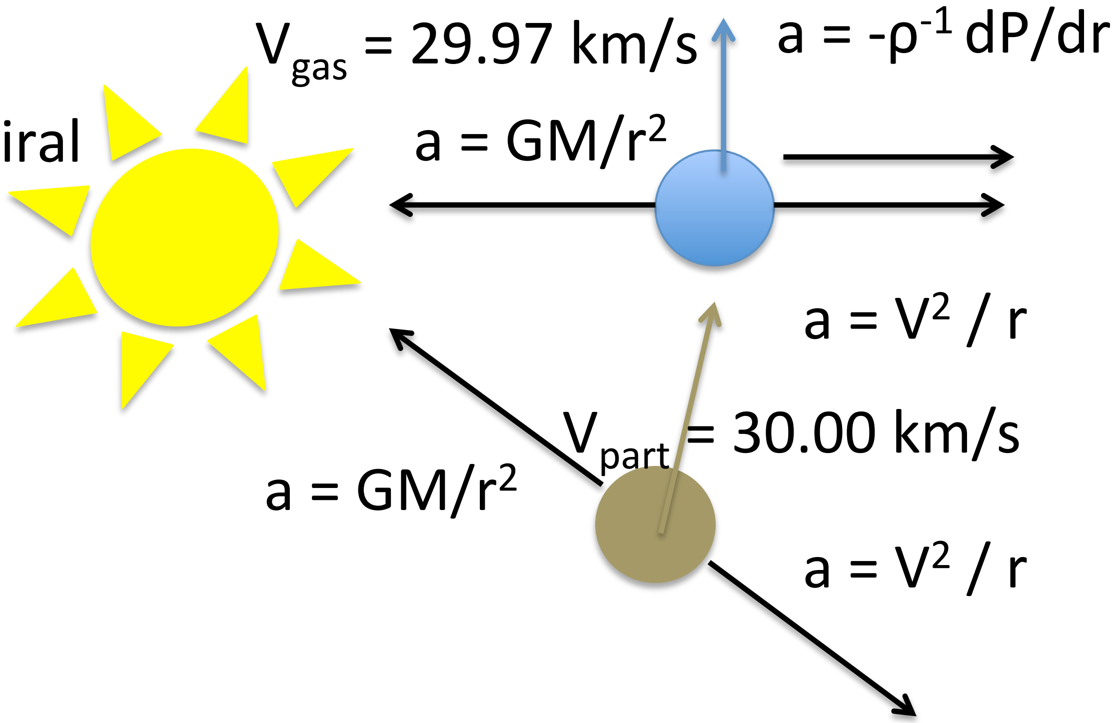
Table 2 of Desch, Kalyaan & Alexander, in revision (ApJ).

Chondrites formed 2-4 Myr after CAIs:

Chondrule ages and thermal modeling, esp. Sugiura & Fujiya (2014)

The “CAI Storage Problem”

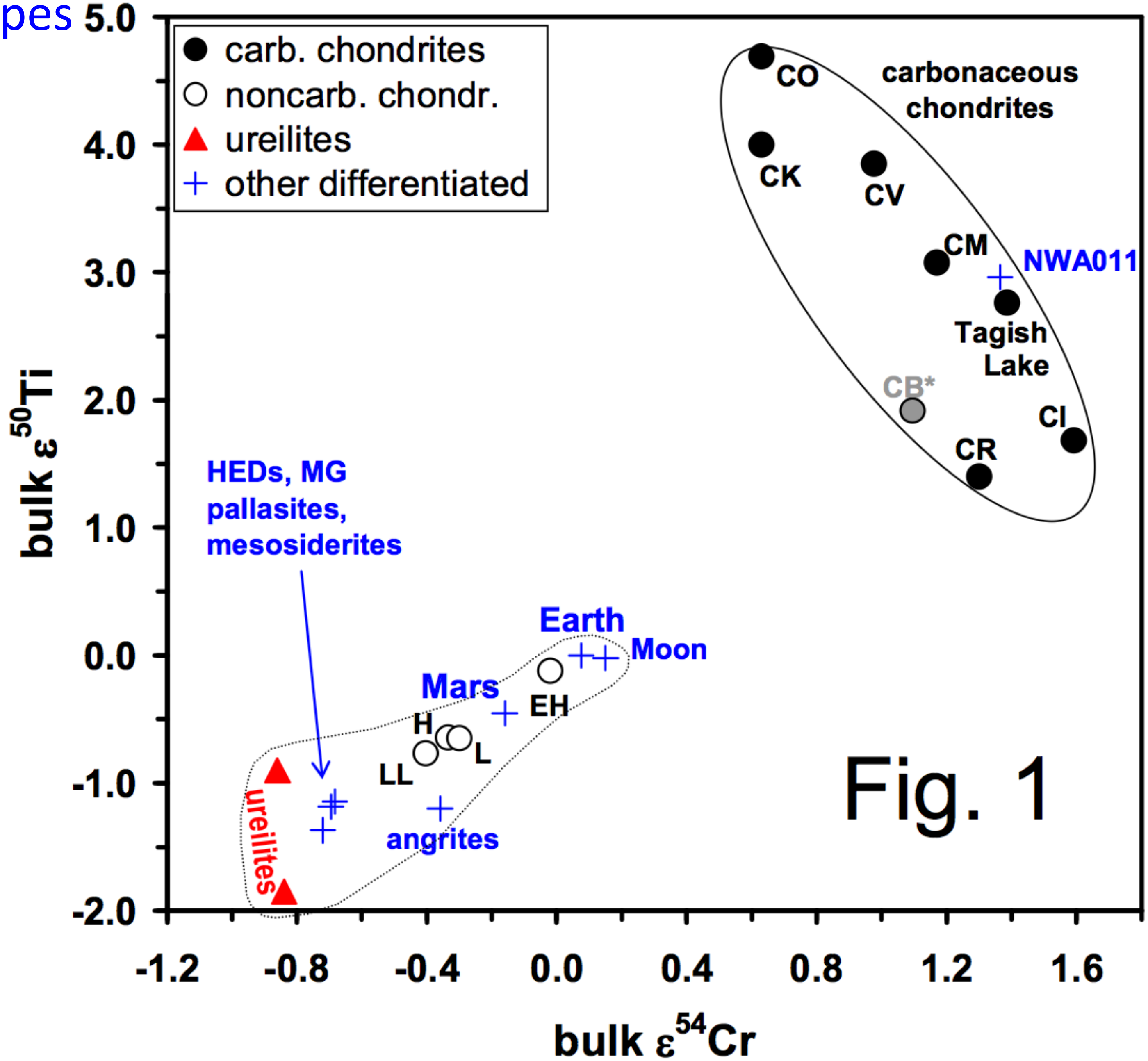
CAIs are big enough to spiral in to the Sun in < 1 Myr (Weidenschilling 1977)



How did they remain in nebula for > 3 Myr to accrete into chondrites?

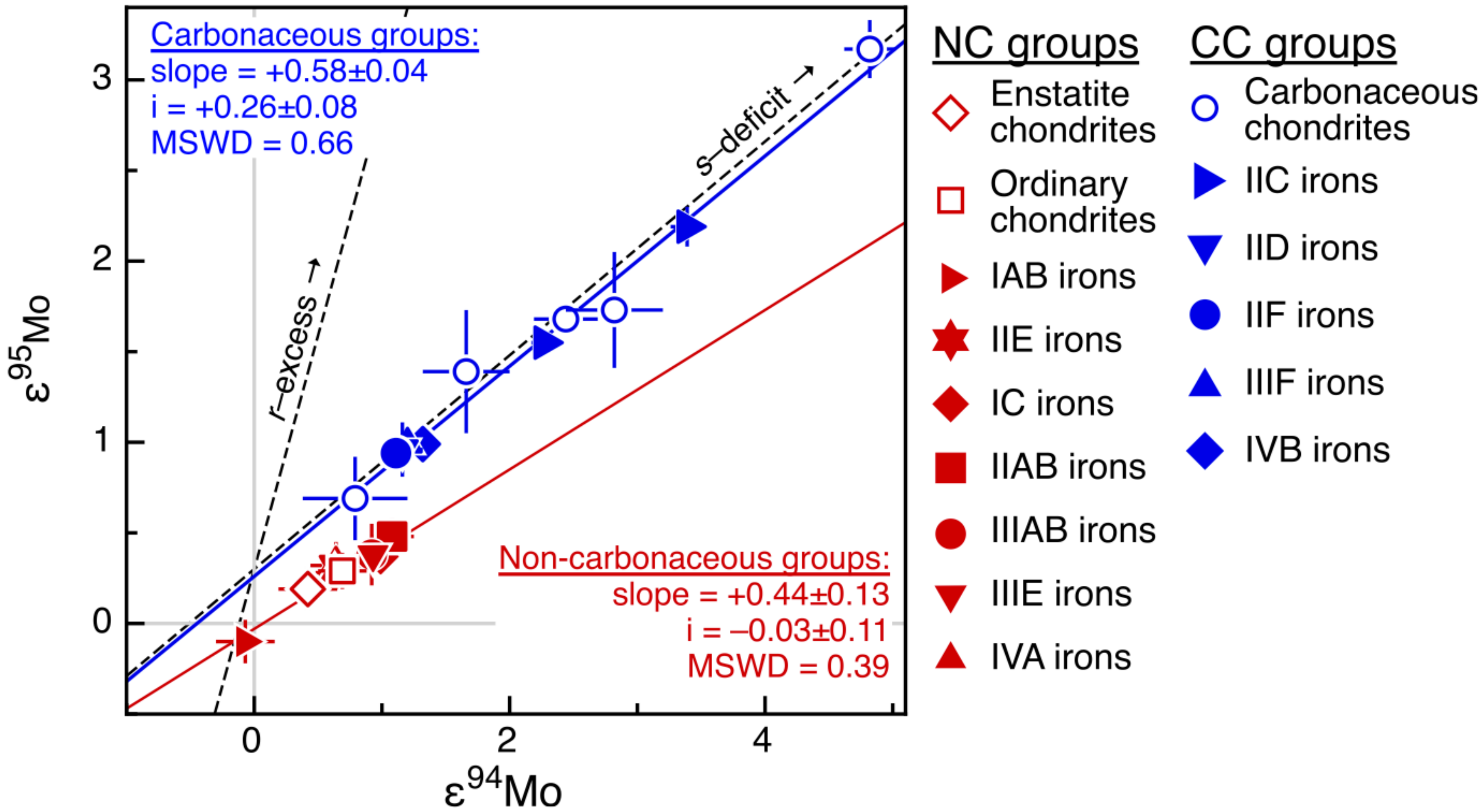
If they have to end up in any chondrite, why carbonaceous chondrites, which form farthest from the Sun? Why are they almost absent from ordinary and enstatite chondrites?

Hints from Isotopes



Warren 2011 Fig. 1

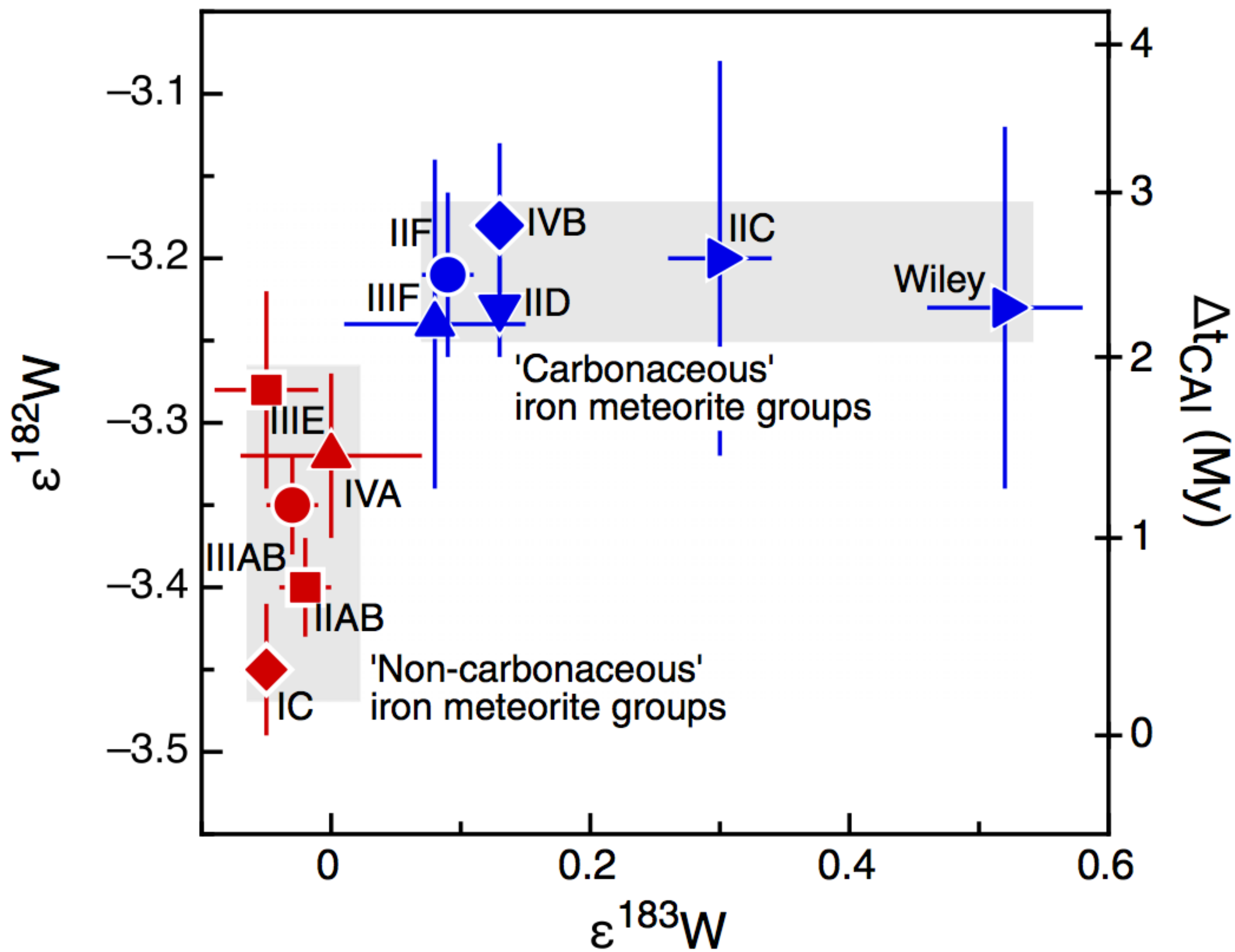
Hints from Isotopes



Kruijer et al. (2017)

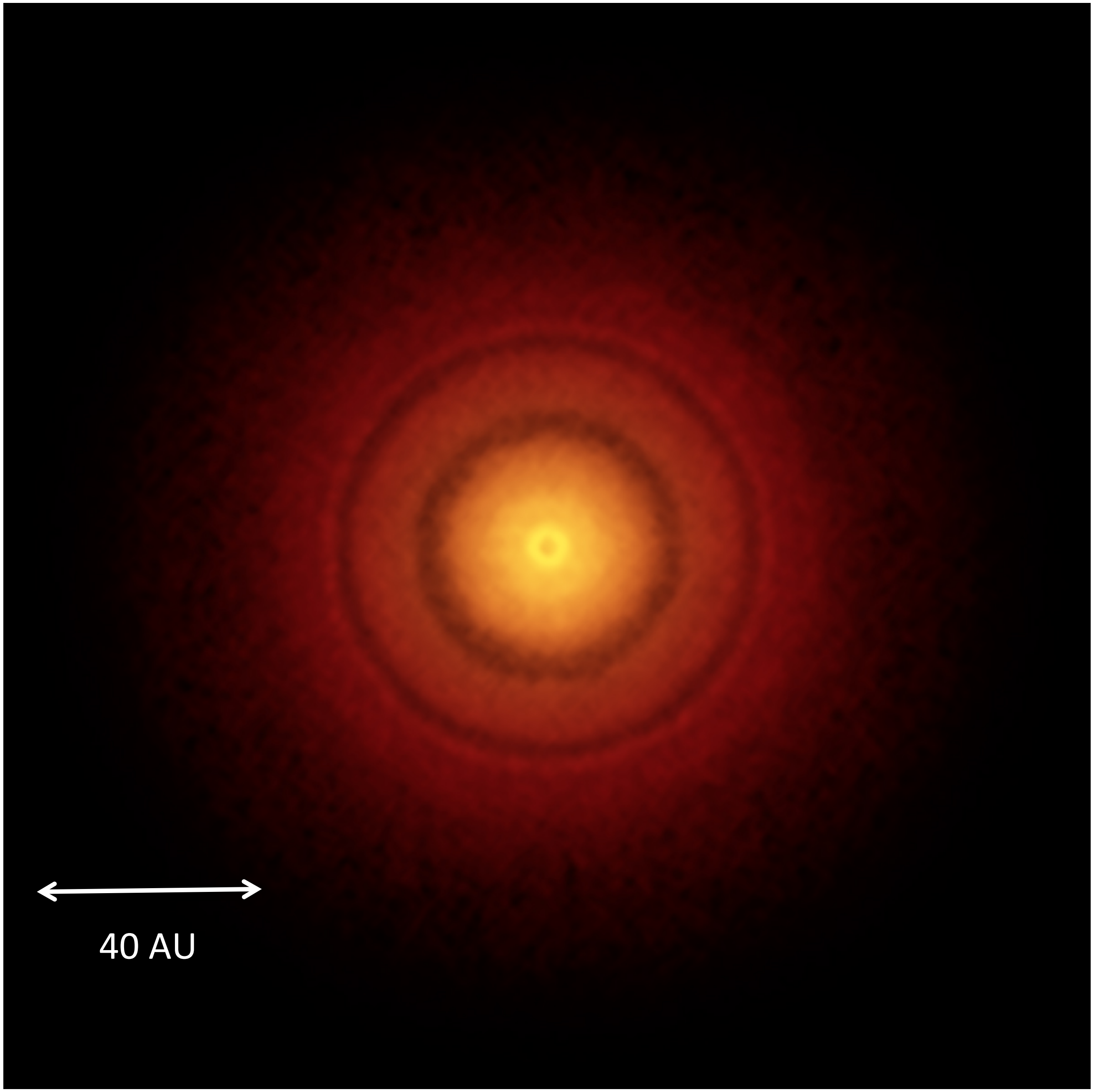
Hints from Isotopes

Solar nebula split into two reservoirs between 0.4 and 0.9 Myr



Kruijer et al. (2017)

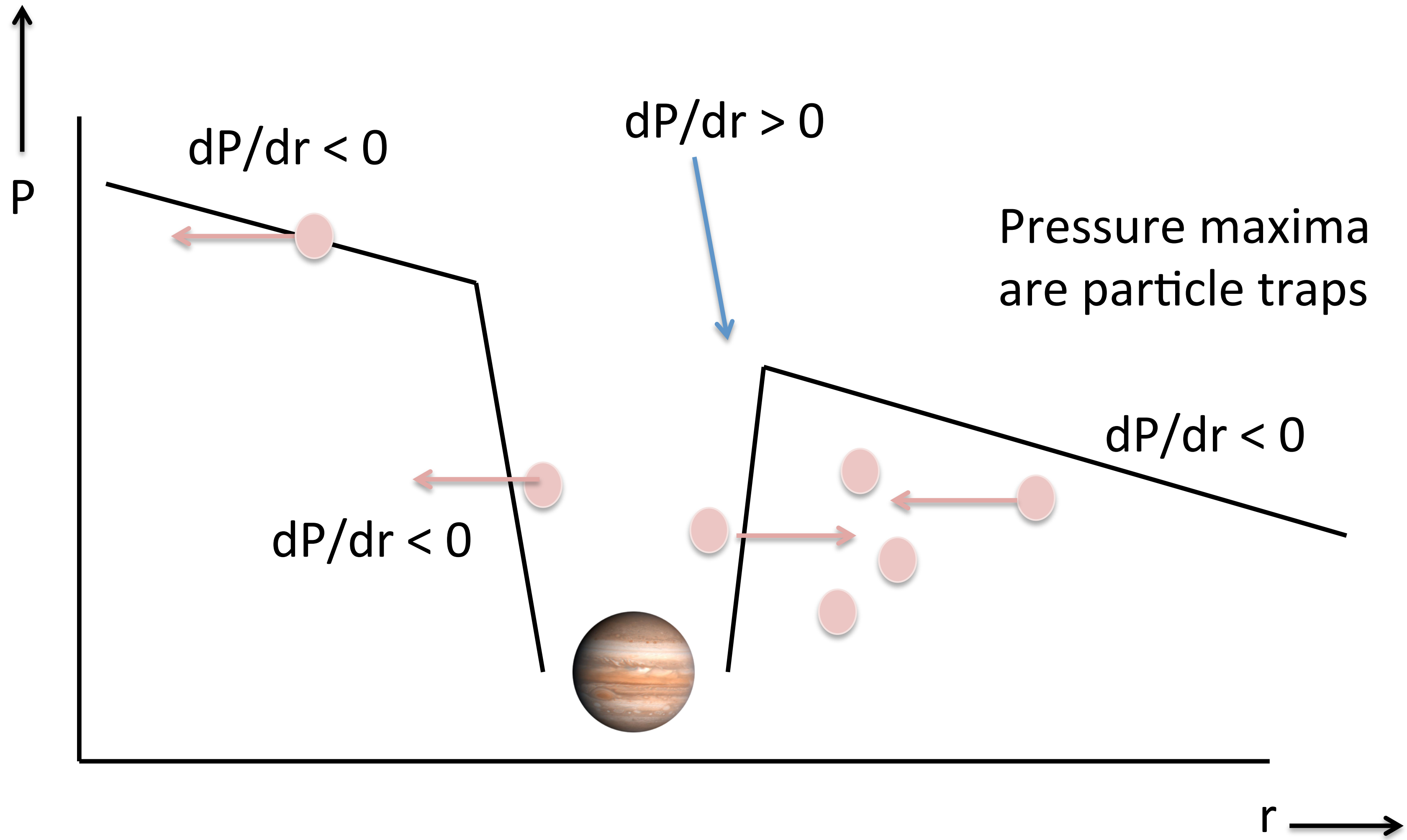
Hints from Astronomical Observations

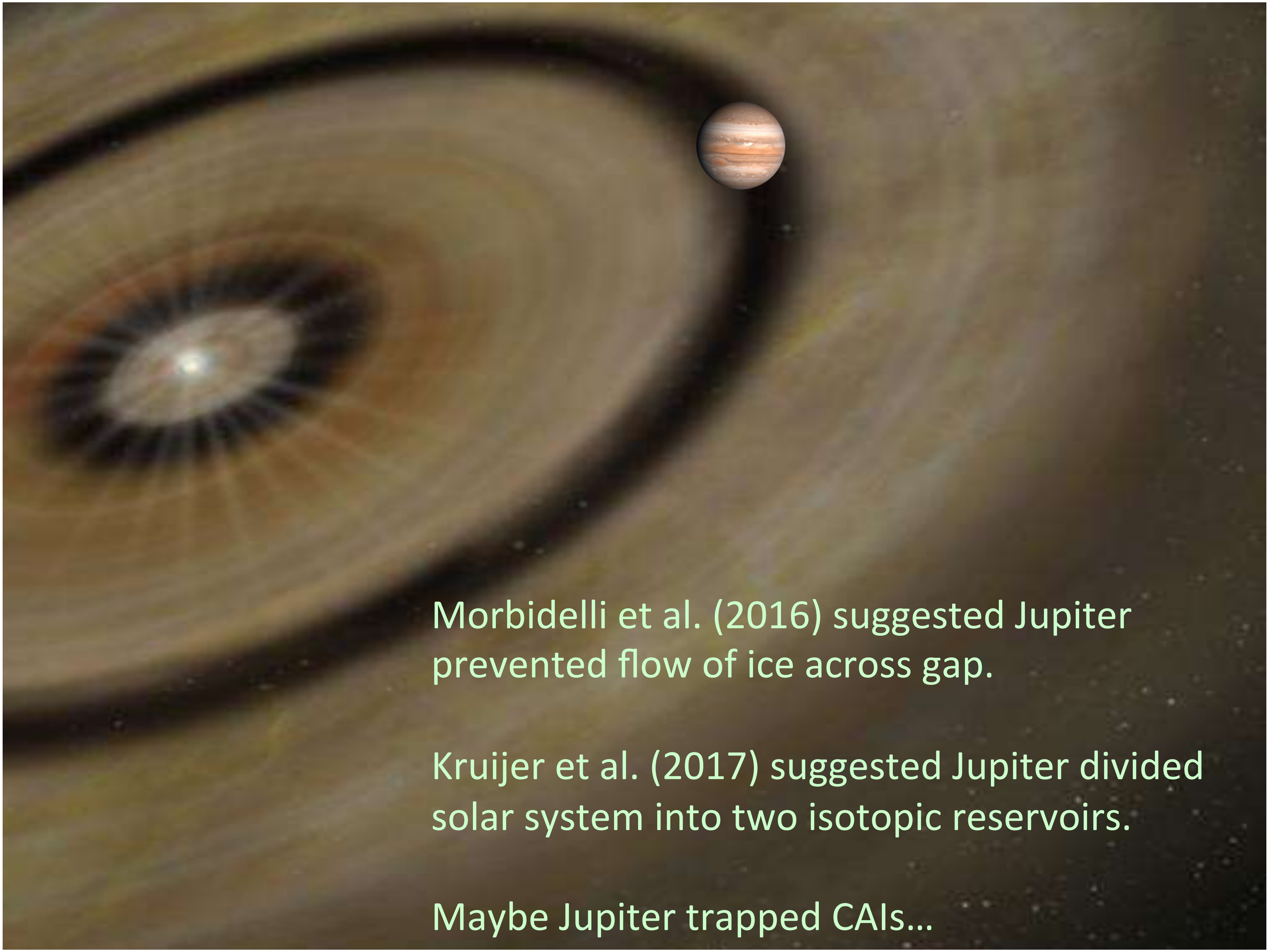


ALMA millimeter observations are revealing many protoplanetary disks have gaps and rings

Andrews et al. (2016)

Hints from Astronomical Observations




Morbidelli et al. (2016) suggested Jupiter prevented flow of ice across gap.
Kruijer et al. (2017) suggested Jupiter divided solar system into two isotopic reservoirs.
Maybe Jupiter trapped CAIs…

A Comprehensive Model

Similar to Yang & Ciesla (2012)

Standard 1-D alpha disk with accretional heating (Min et al. 2011) and opacities (Semenov et al. 2003), initialized with compact (R_1=1 AU) self-similar profile (Hartmann et al. 1998). T capped at 1400 K.

Jupiter forms at 3 AU at 0.6 Myr. Starts at 30 M_E, grows by accreting gas in Hill sphere.

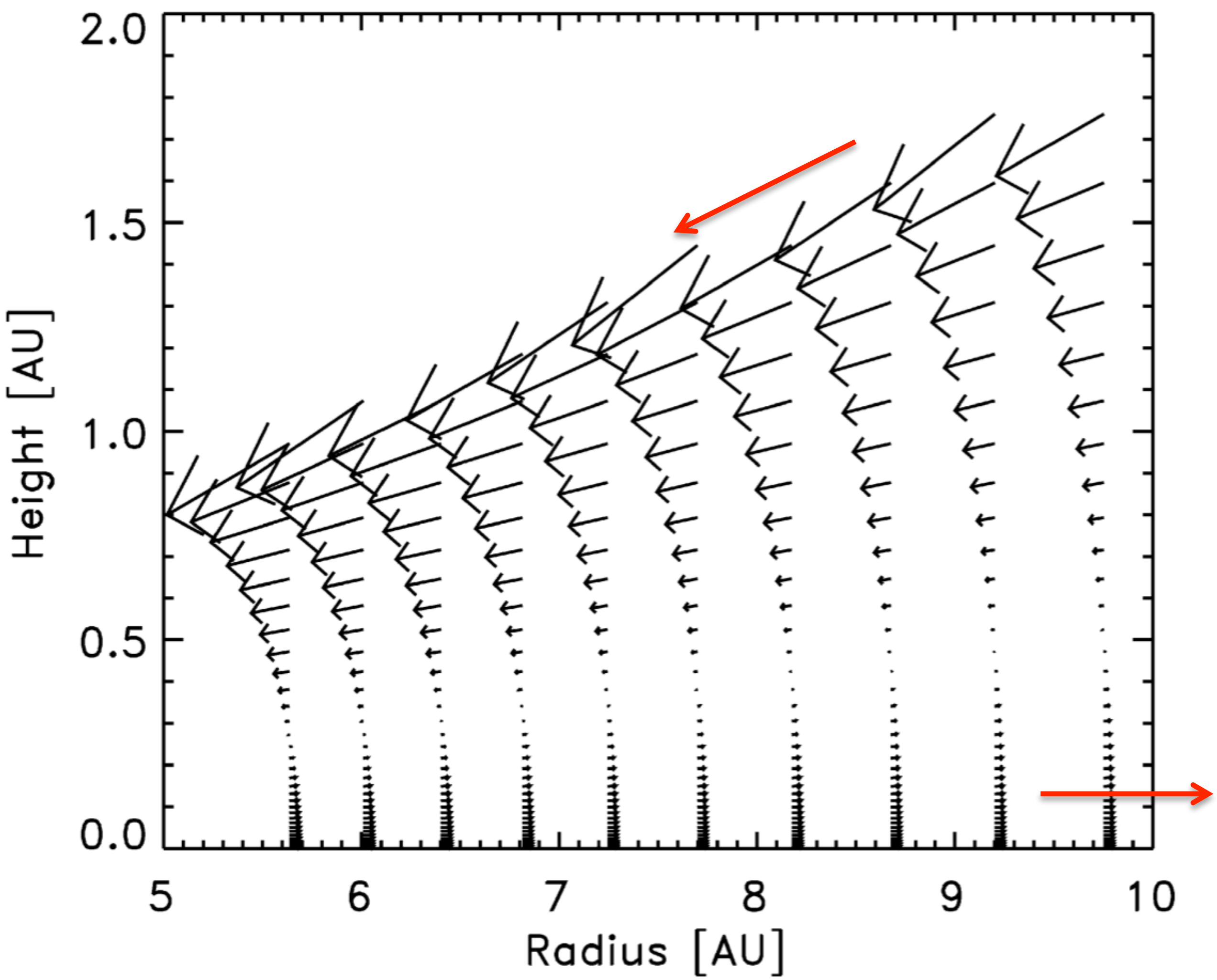
$\alpha = 1.25 \times 10^{-4}$ for $r < 1$ AU, transitioning to $\alpha = 1 \times 10^{-5}$ for $r > 10$ AU. $\alpha = 1 \times 10^{-2}$ in vicinity of Jupiter.

Starting composition like CI chondrites. If material ends up in region with T > 1400 K, 3.6% of rocky material converted into CAIs of various sizes (25% a=800 μm, 75% a=1600 μm).

Radial transport of volatiles and particles (Desch et al. 2017). Meridional transport included using Philippov & Rafikov (2017).

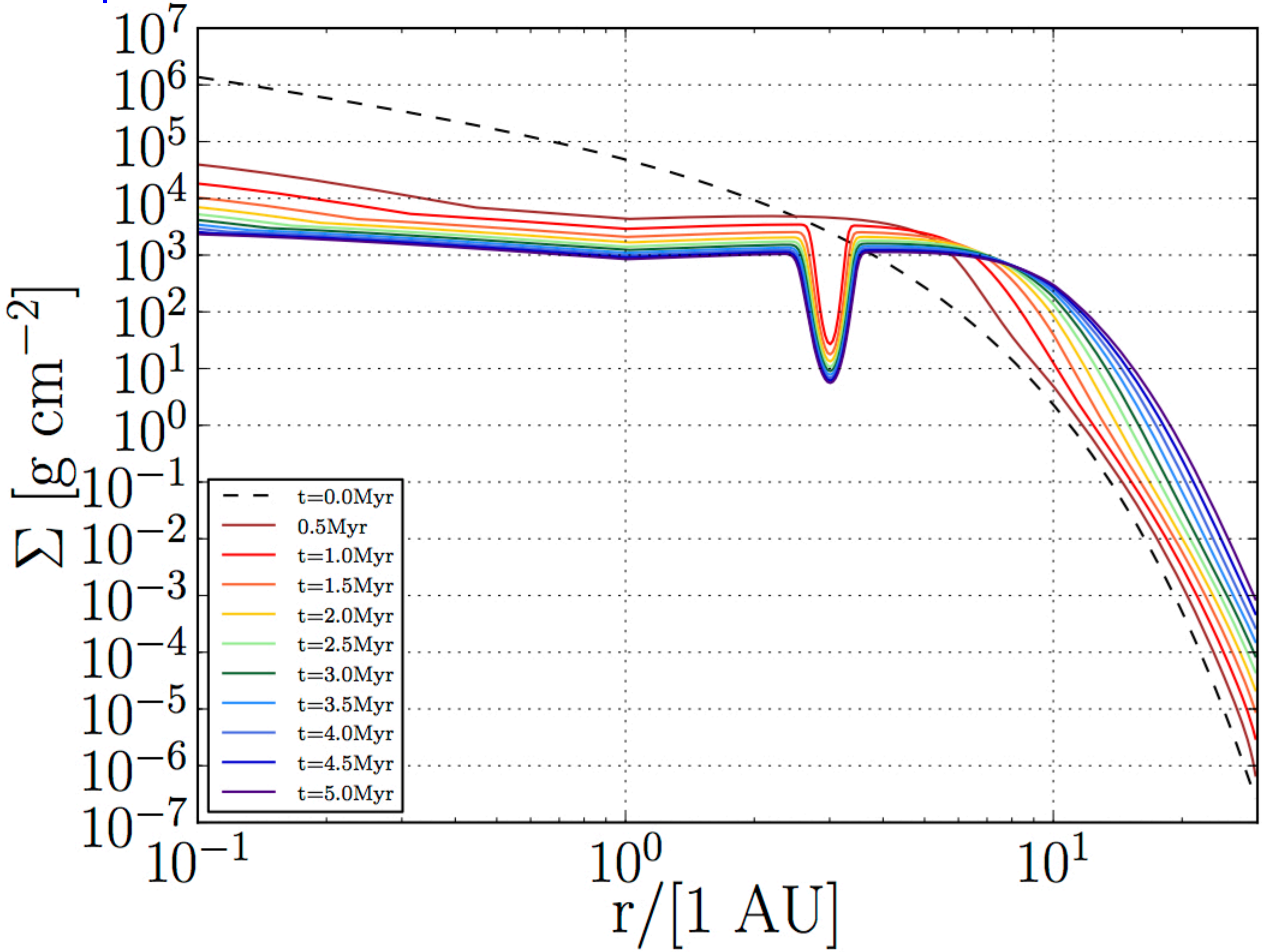
A Comprehensive Model

Particles participate in meridional flow if settled to midplane: requires $St = \Omega t_{stop} > 0.2 \alpha$, particles > 100 μm

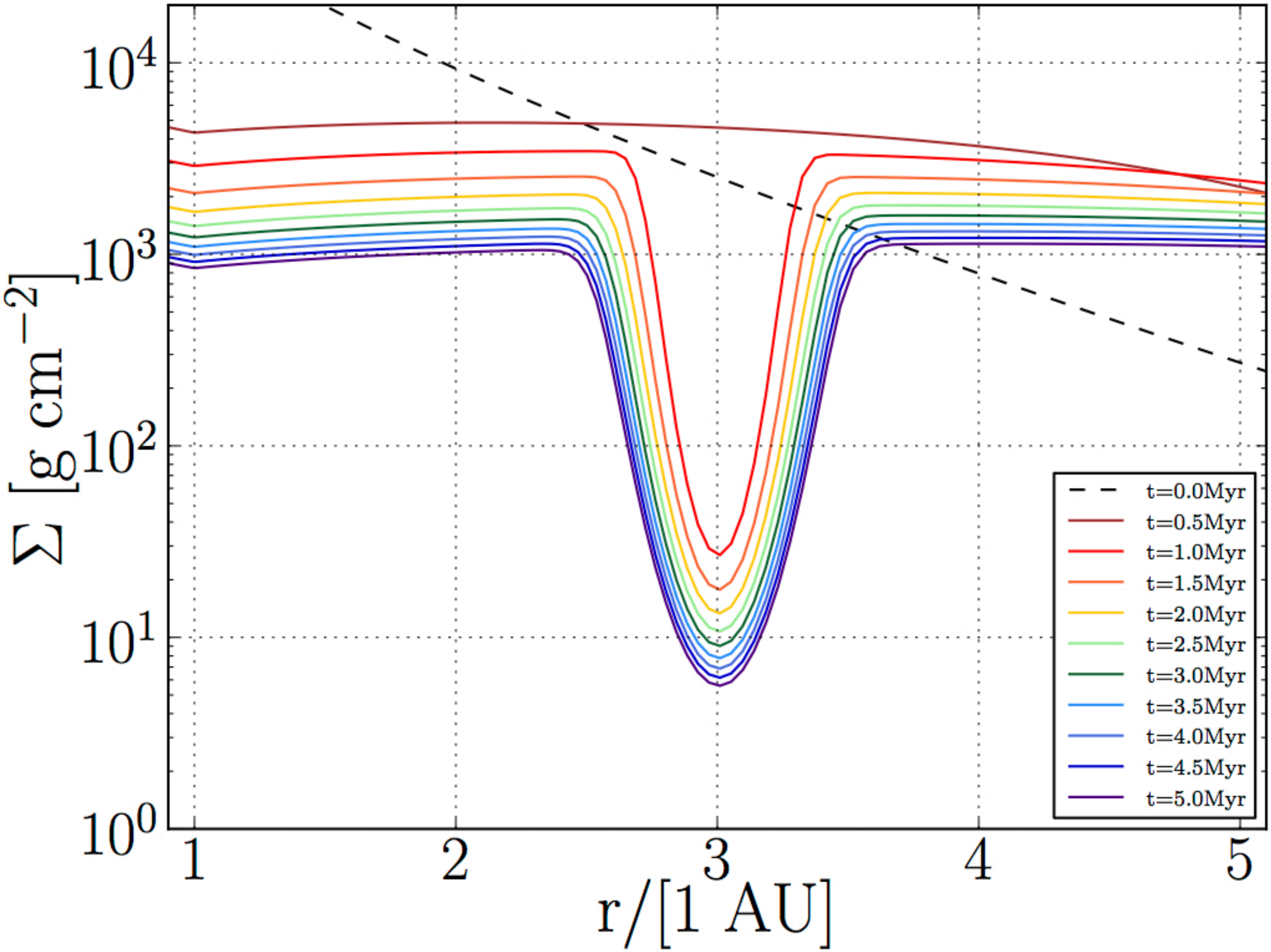


Ciesla (2009)

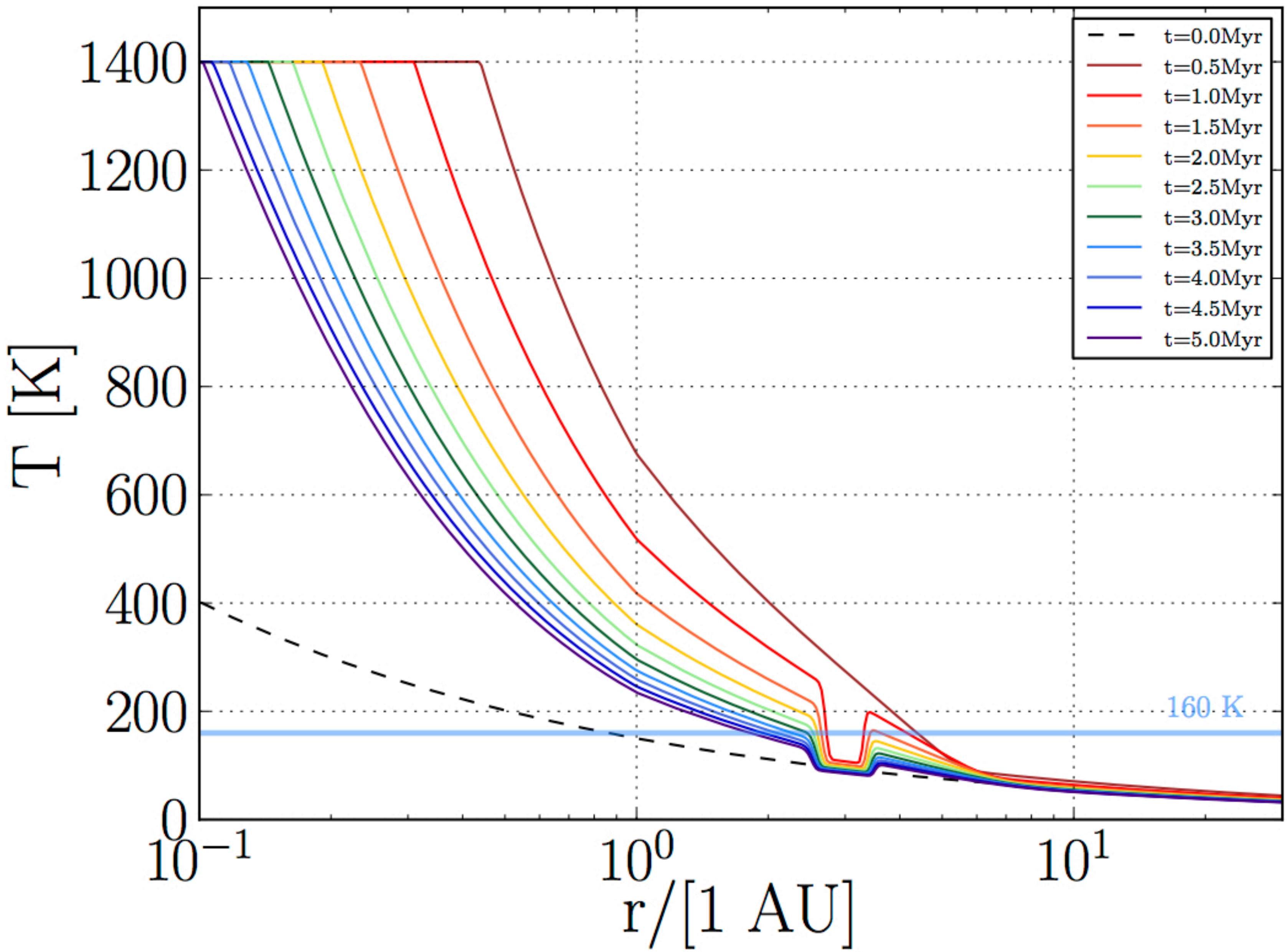
A Comprehensive Model



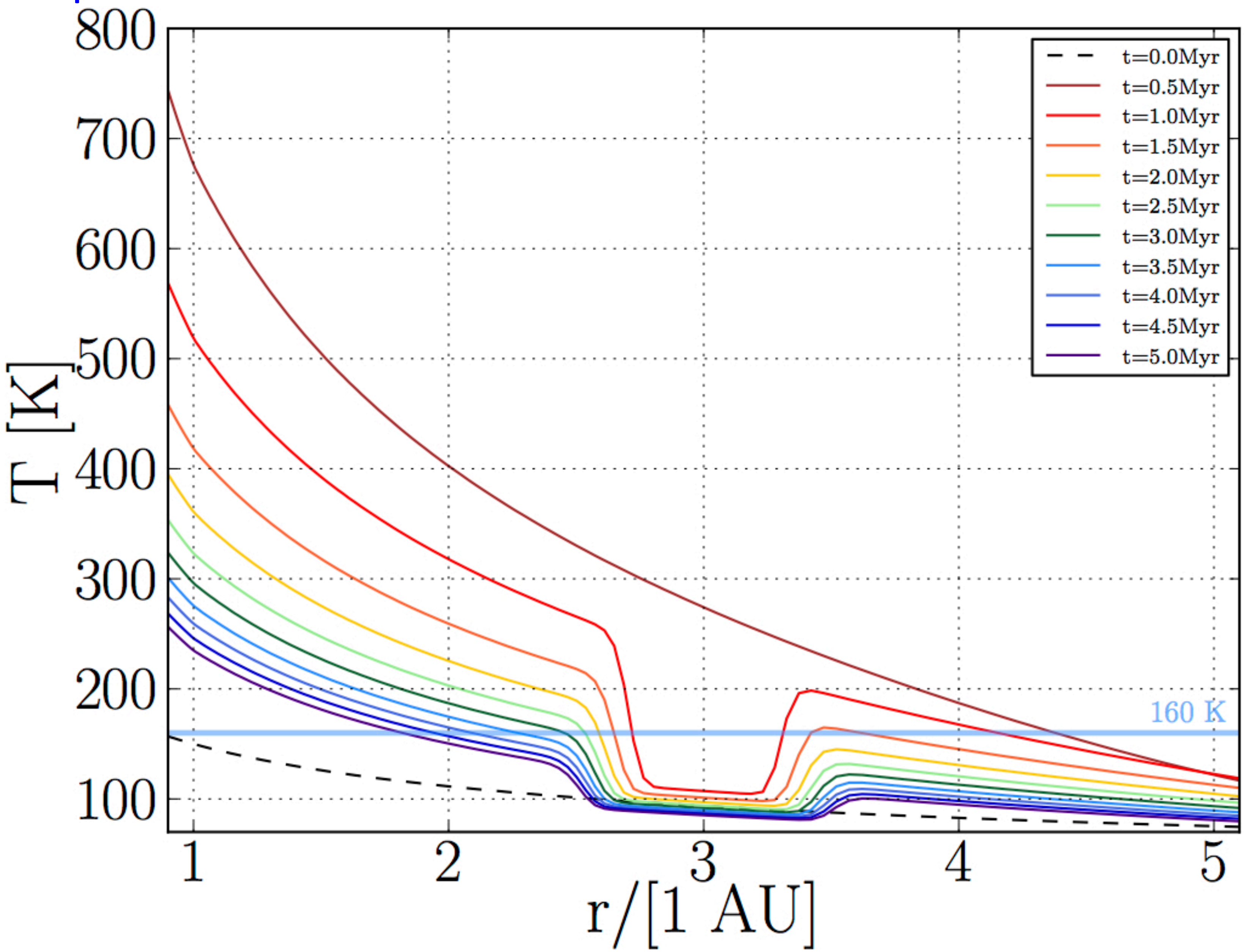
A Comprehensive Model



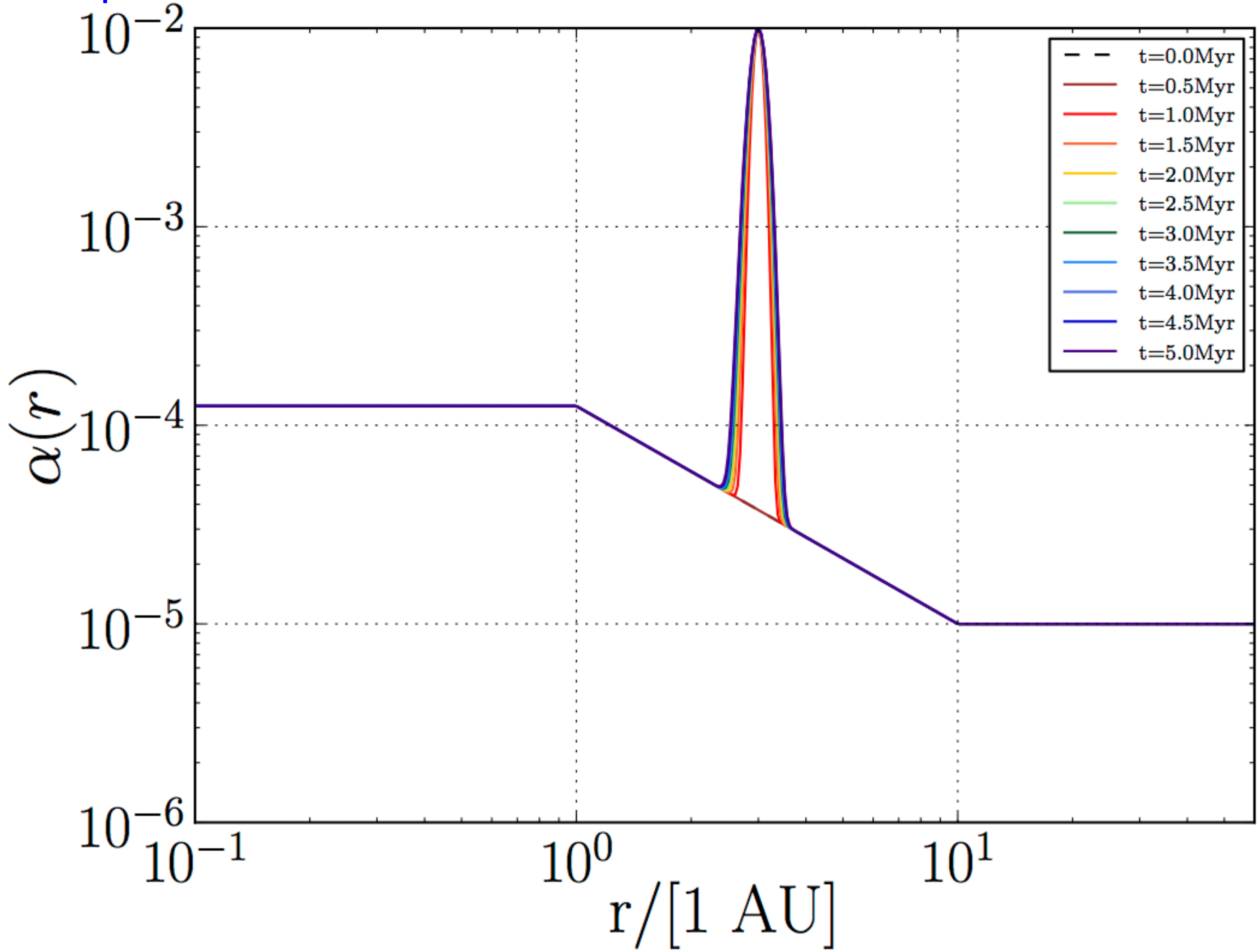
A Comprehensive Model

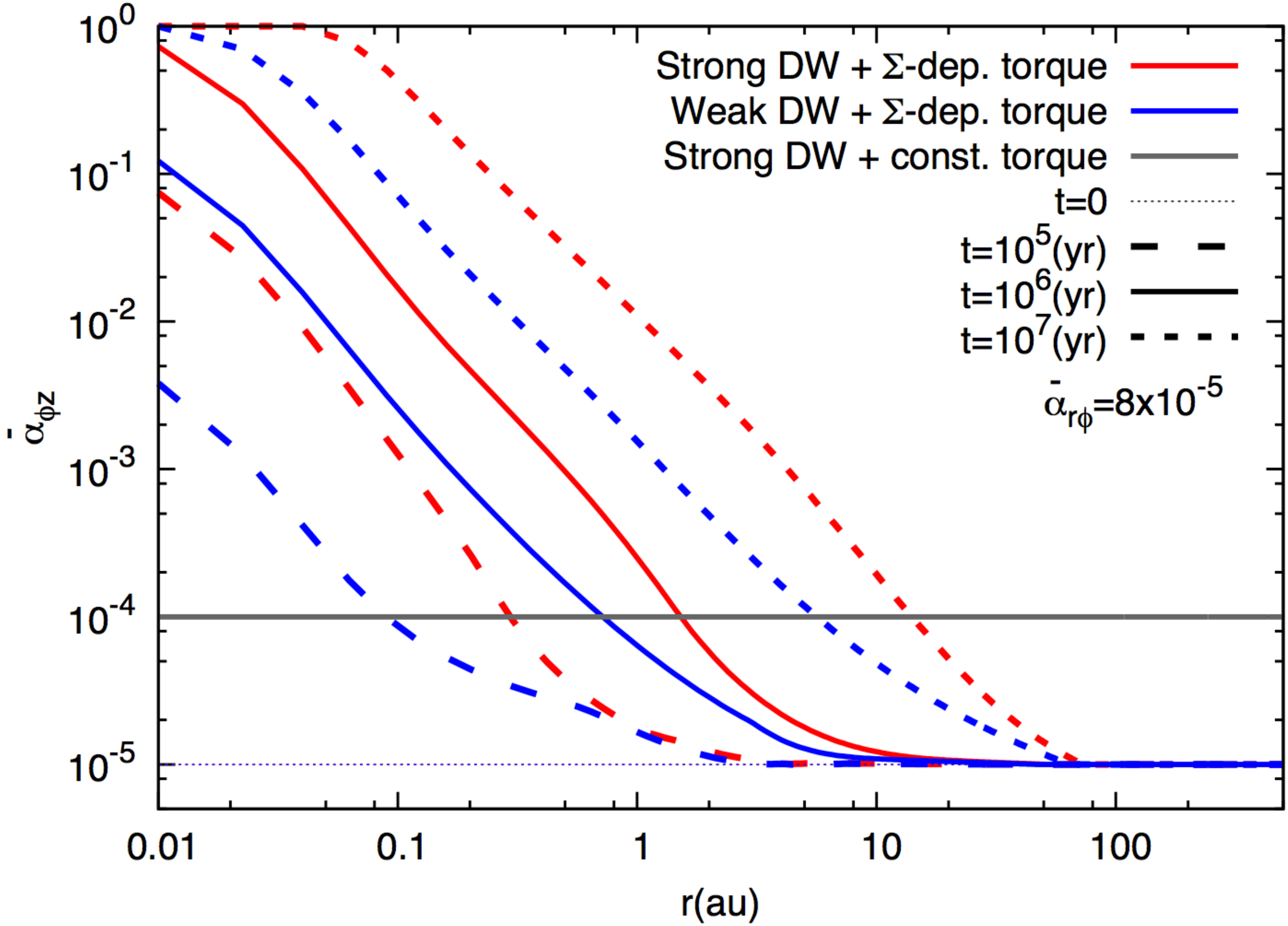


A Comprehensive Model



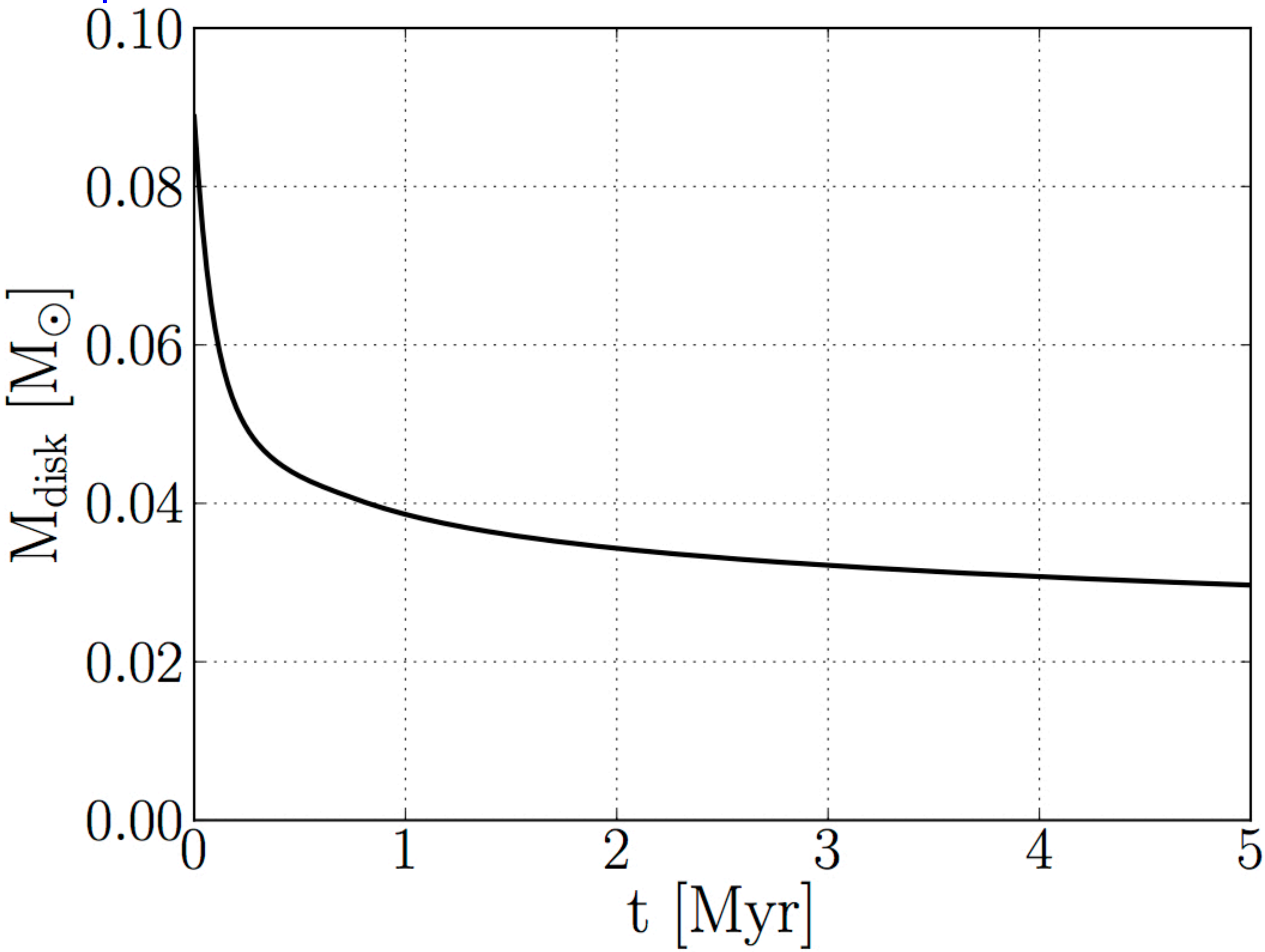
A Comprehensive Model



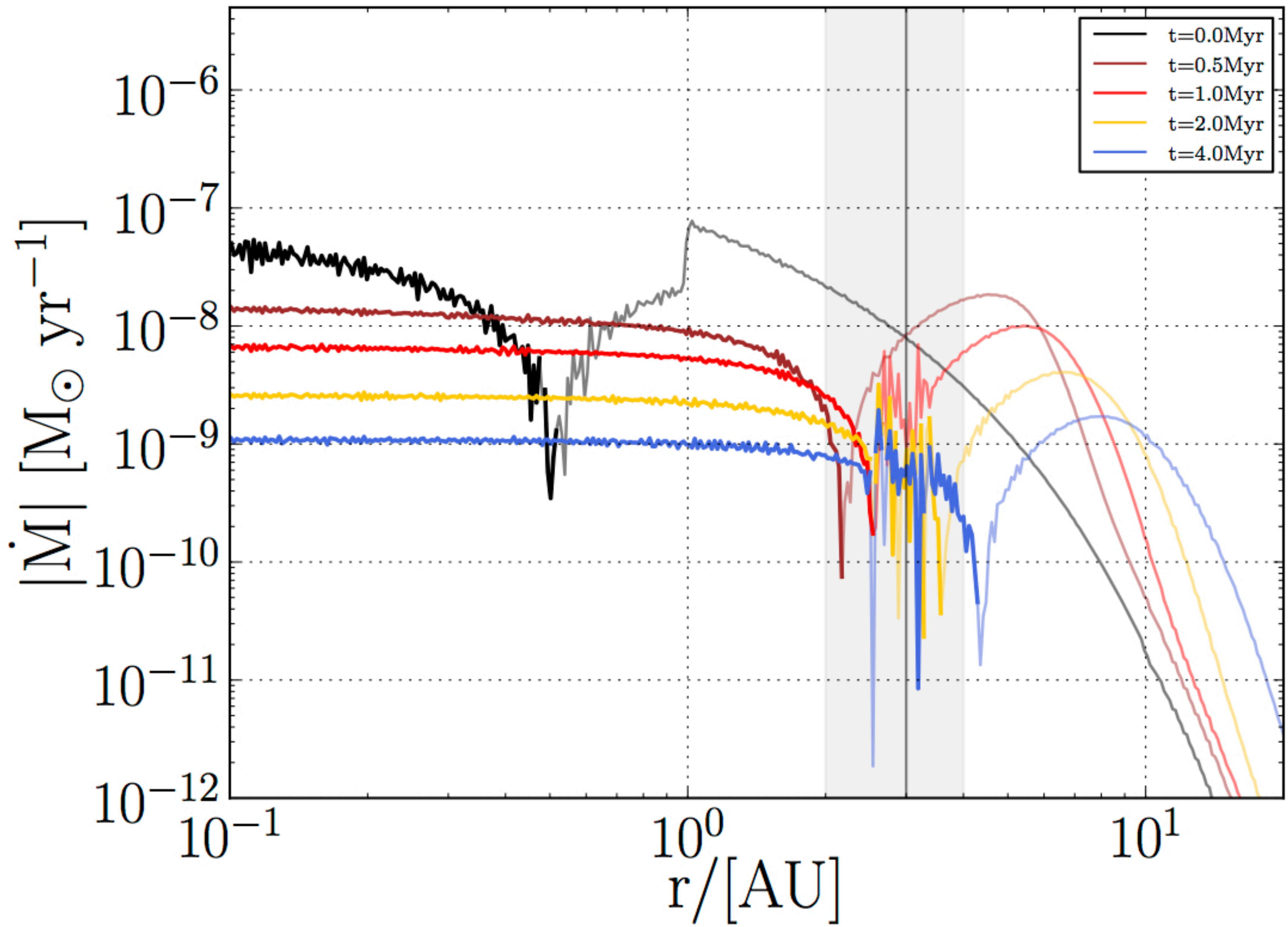


Strong DW + Σ-dep. torque
Weak DW + Σ-dep. torque
Strong DW + const. torque
t=0
t=10^5(yr)
t=10^6(yr)
t=10^7(yr)
$\bar{\alpha}_{r\phi}=8\times10^{-5}$
$\bar{\alpha}_{\phi z}$
r(au)

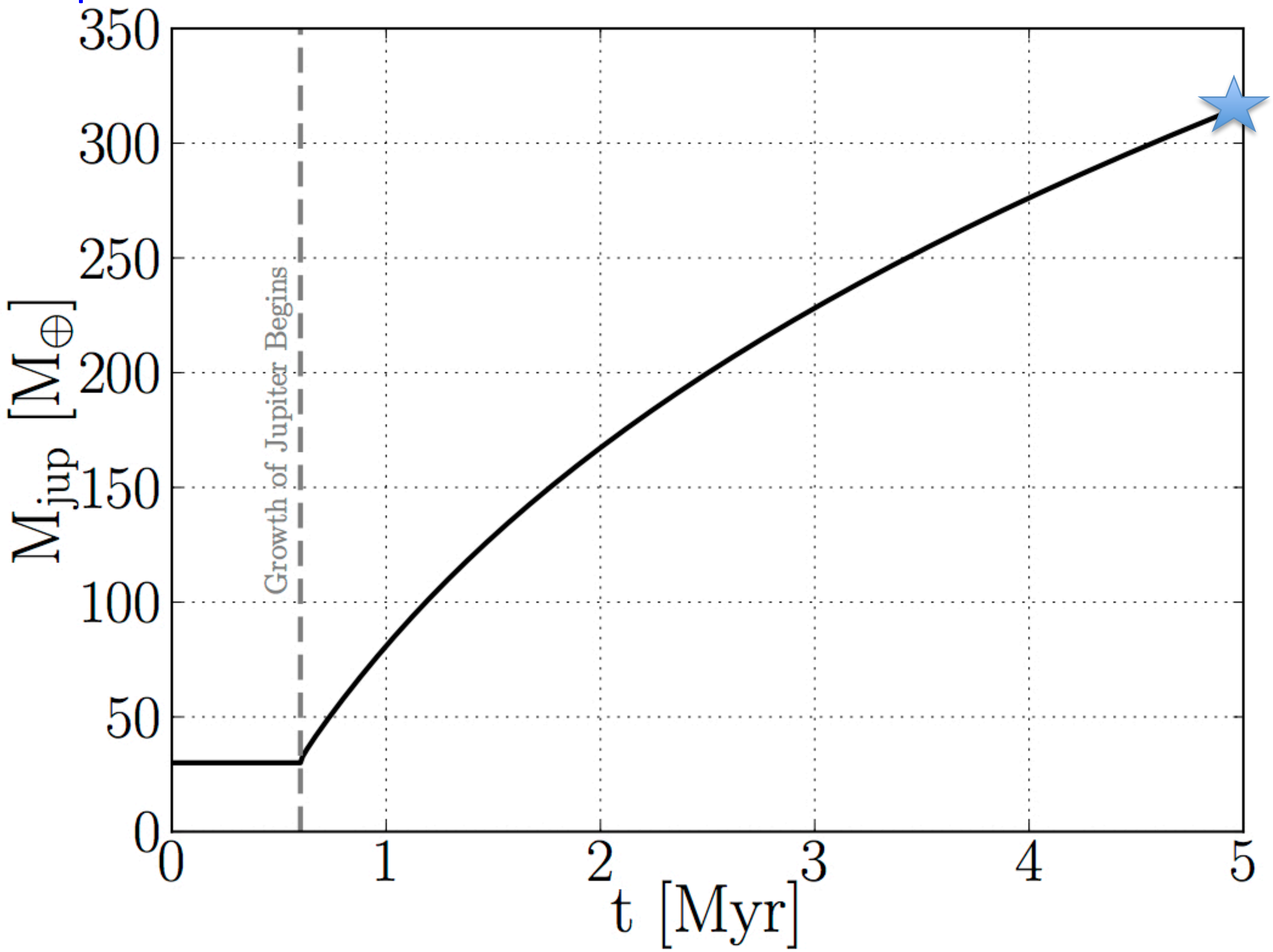
A Comprehensive Model



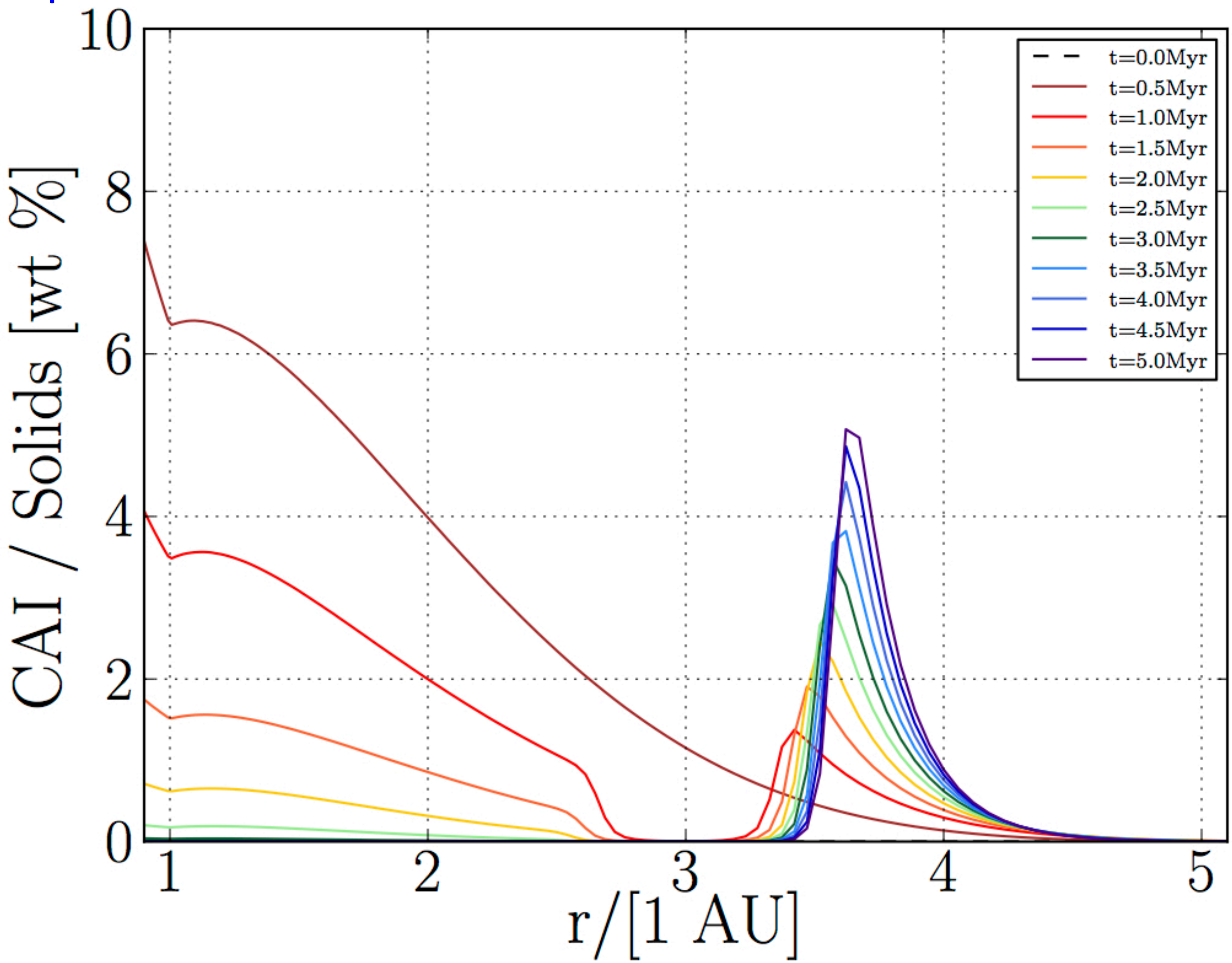
A Comprehensive Model



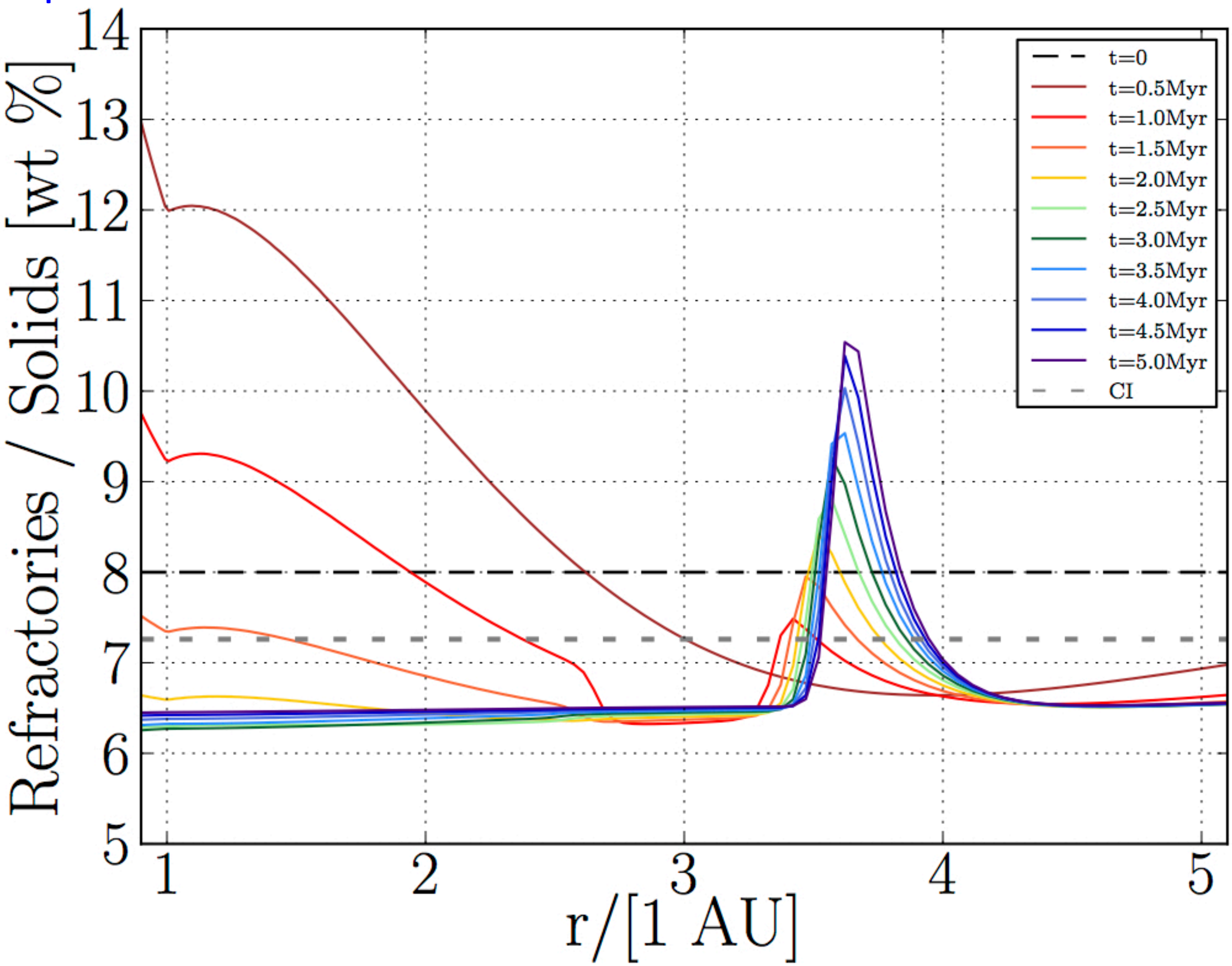
A Comprehensive Model



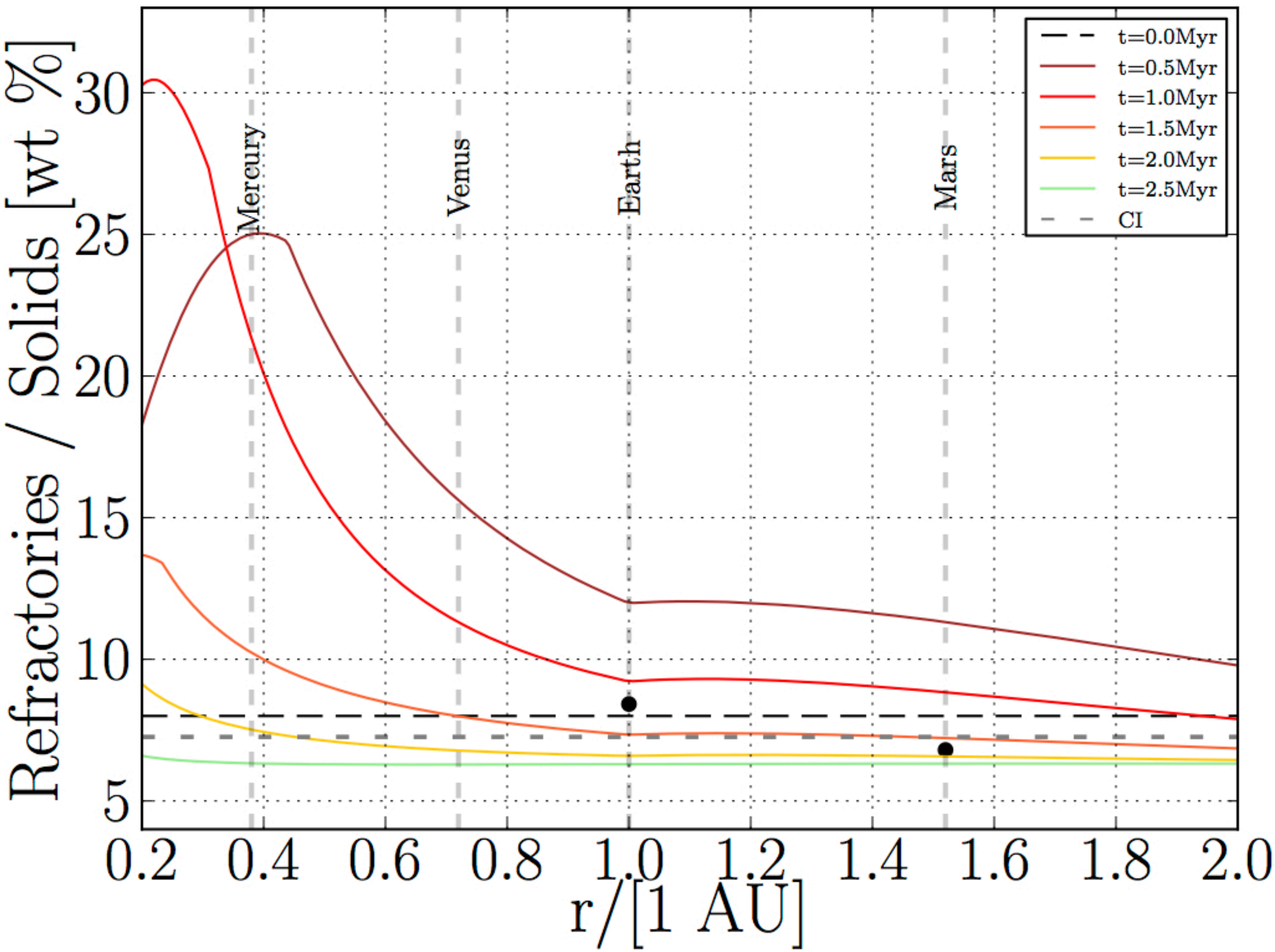
A Comprehensive Model



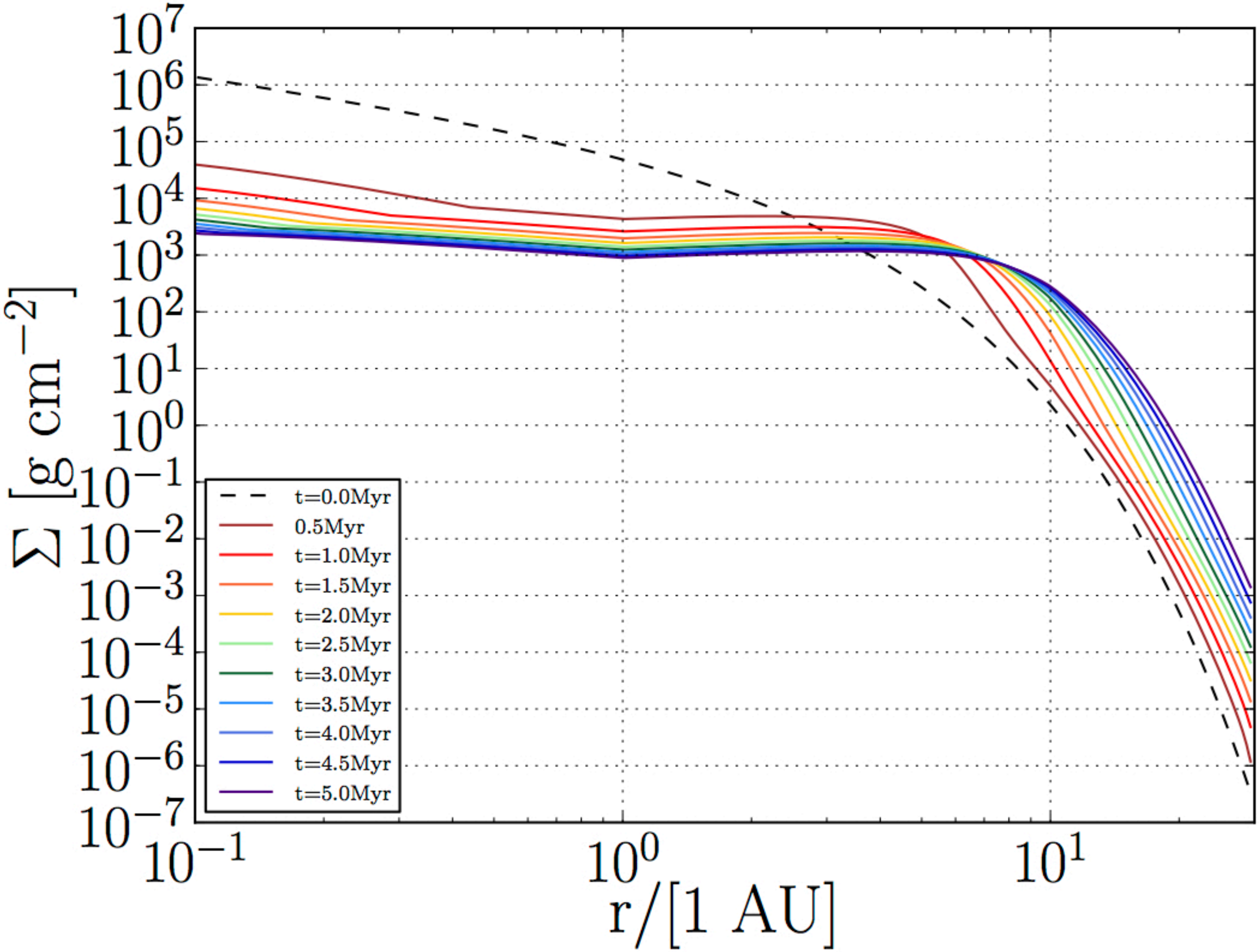
A Comprehensive Model



A Comprehensive Model

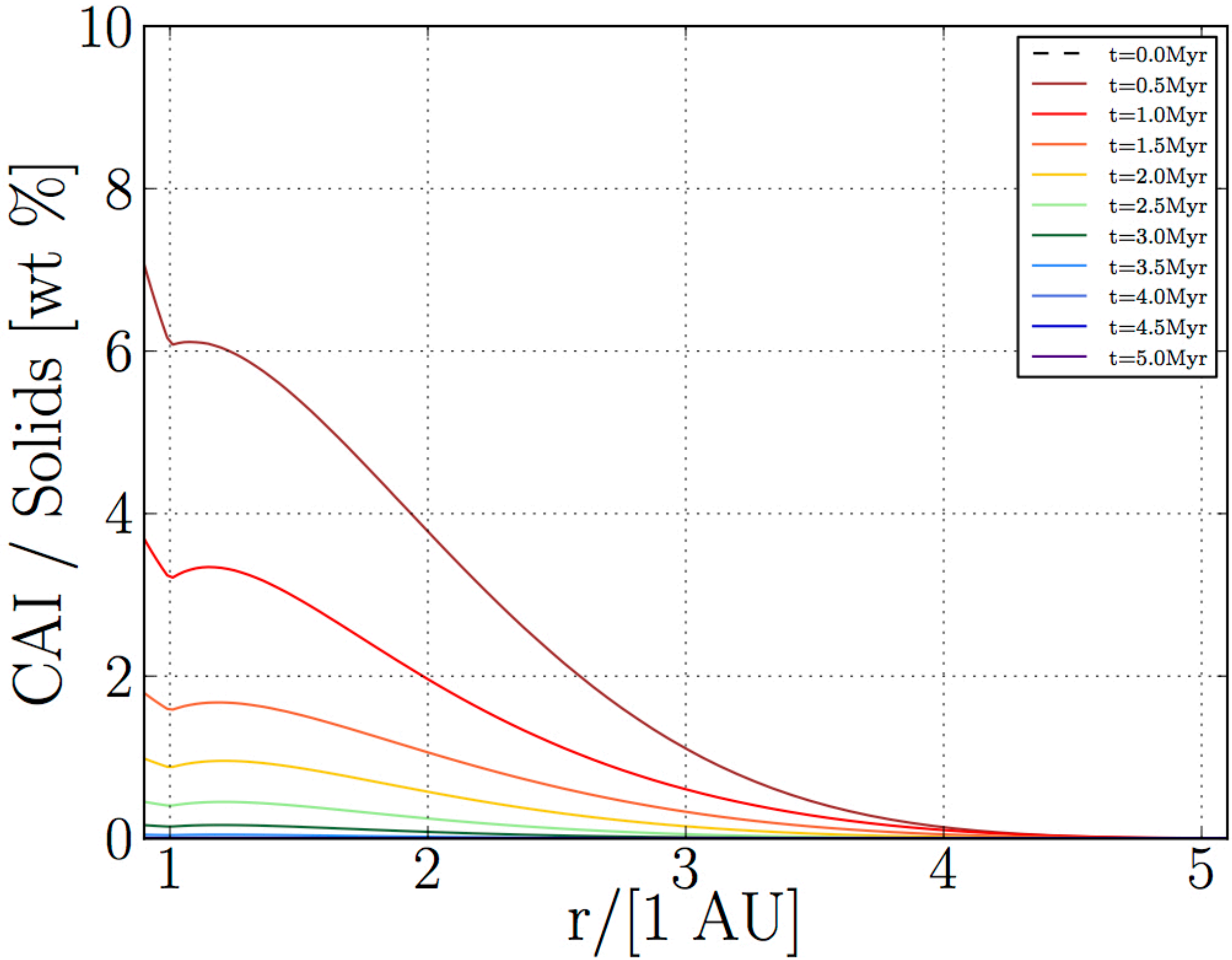


No Jupiter



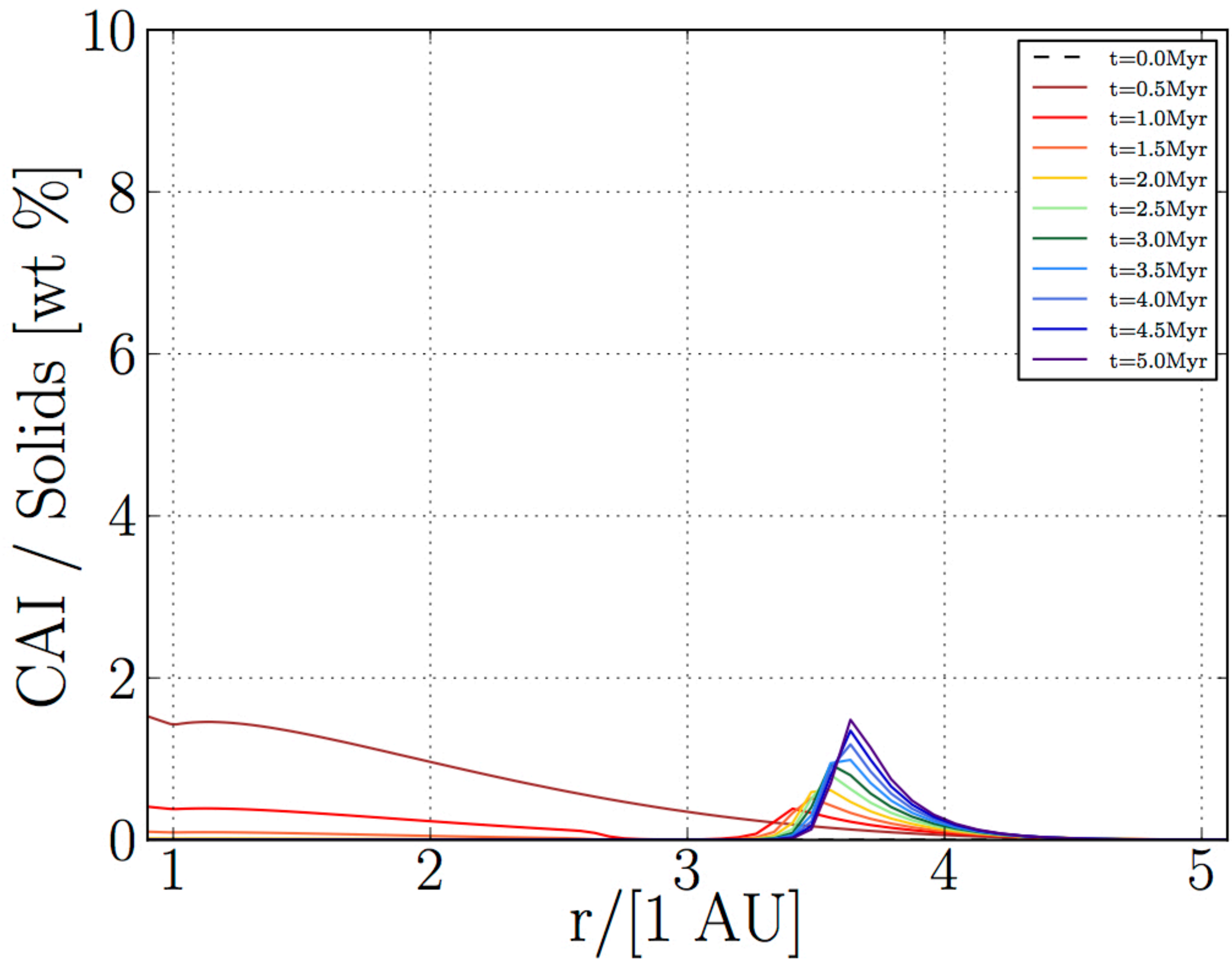
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Σ [g cm^{-2}]
10^{-1}
10^{0}
10^{1}
r/[1 AU]
t=0.0Myr
0.5Myr
t=1.0Myr
t=1.5Myr
t=2.0Myr
t=2.5Myr
t=3.0Myr
t=3.5Myr
t=4.0Myr
t=4.5Myr
t=5.0Myr

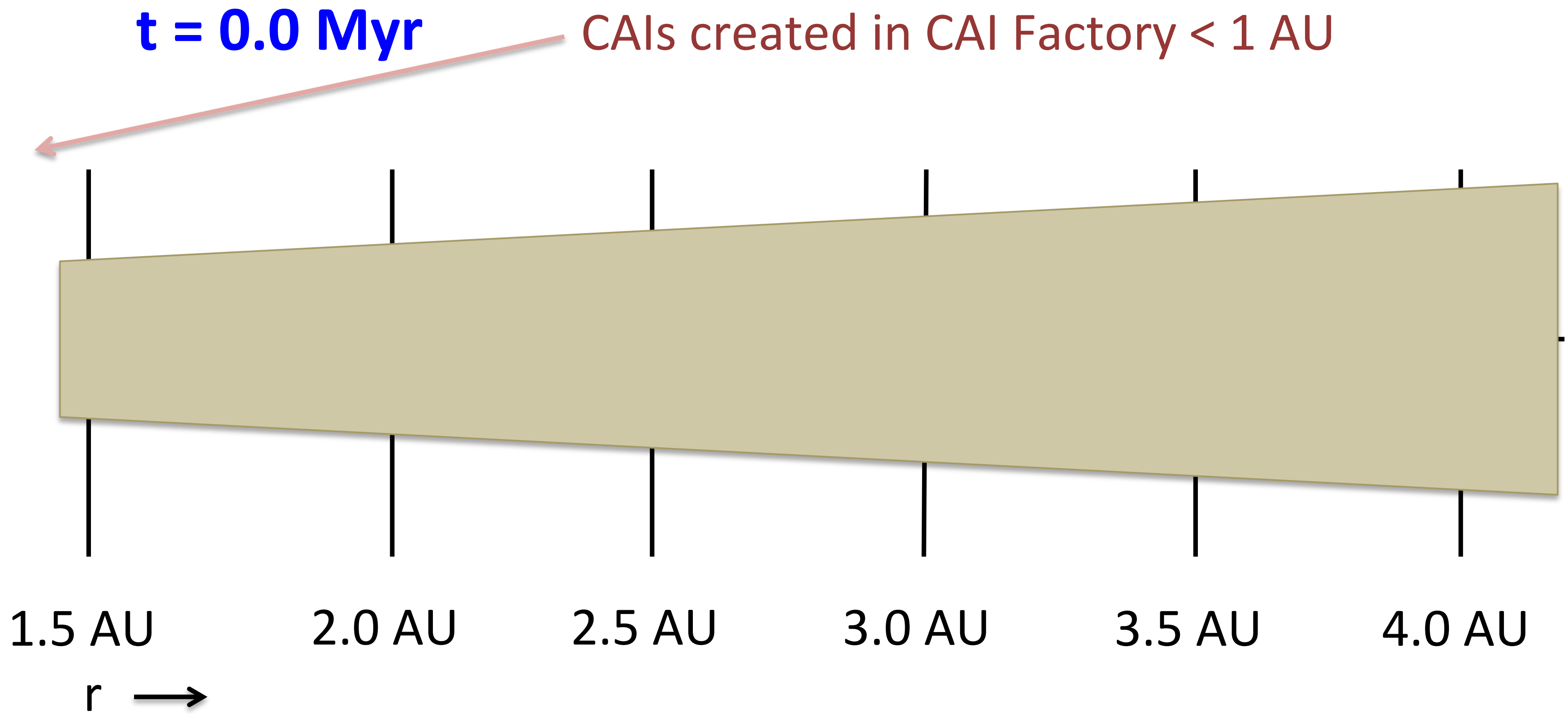
No Jupiter

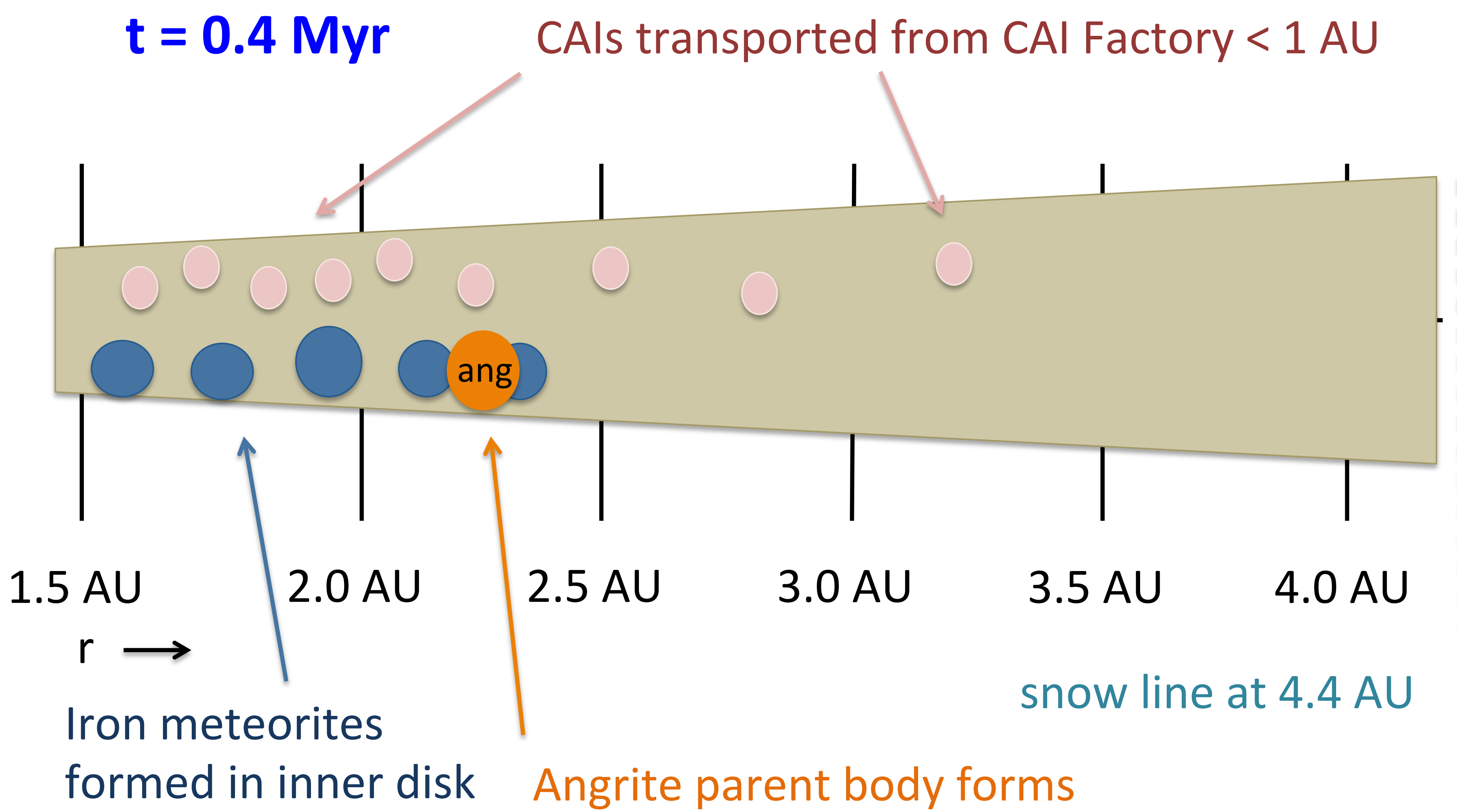


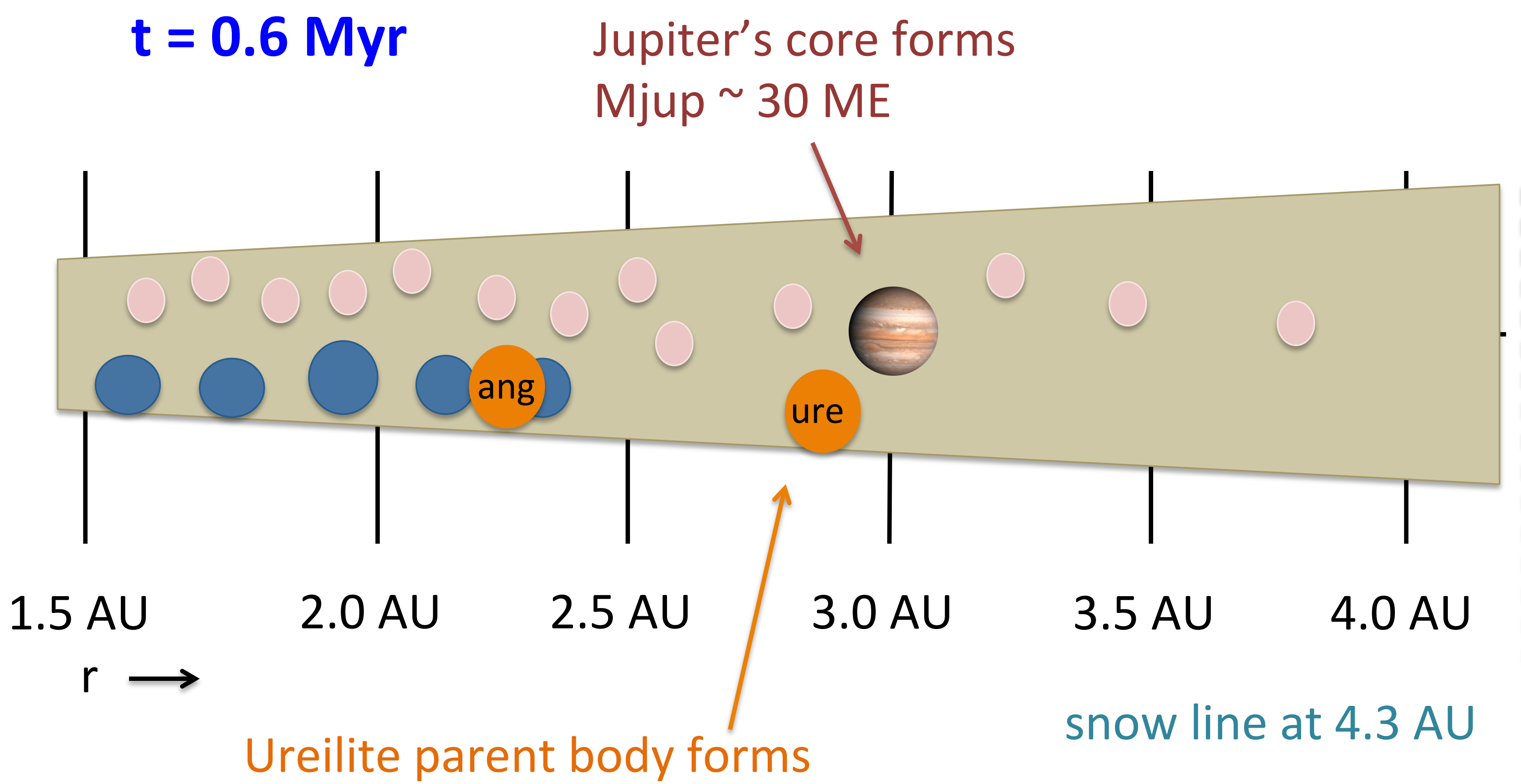
CAI / Solids [wt %]
0
2
4
6
8
10
1
2
3
4
5
r/[1 AU]
t=0.0Myr
t=0.5Myr
t=1.0Myr
t=1.5Myr
t=2.0Myr
t=2.5Myr
t=3.0Myr
t=3.5Myr
t=4.0Myr
t=4.5Myr
t=5.0Myr

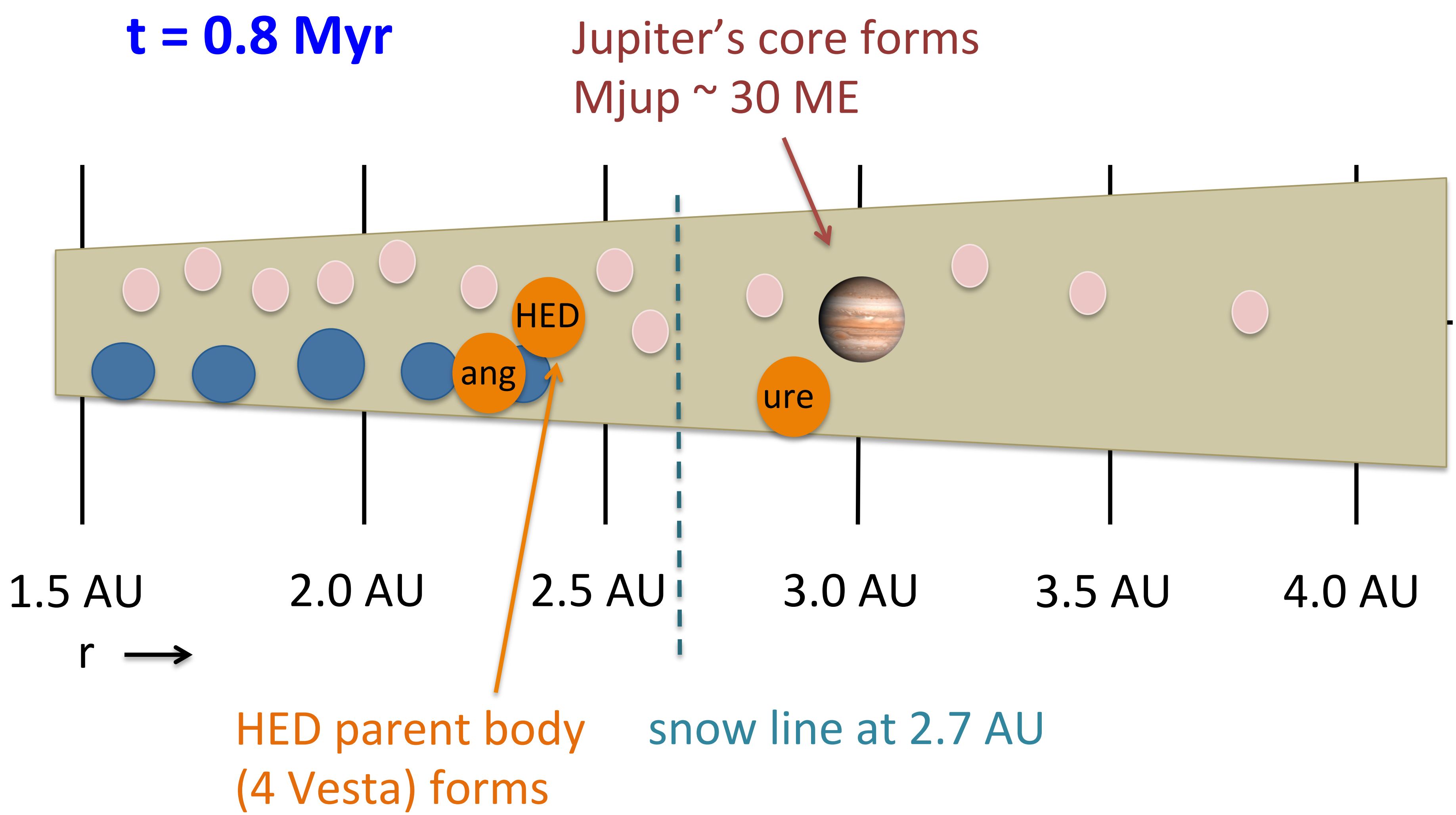
No Meridional Flow



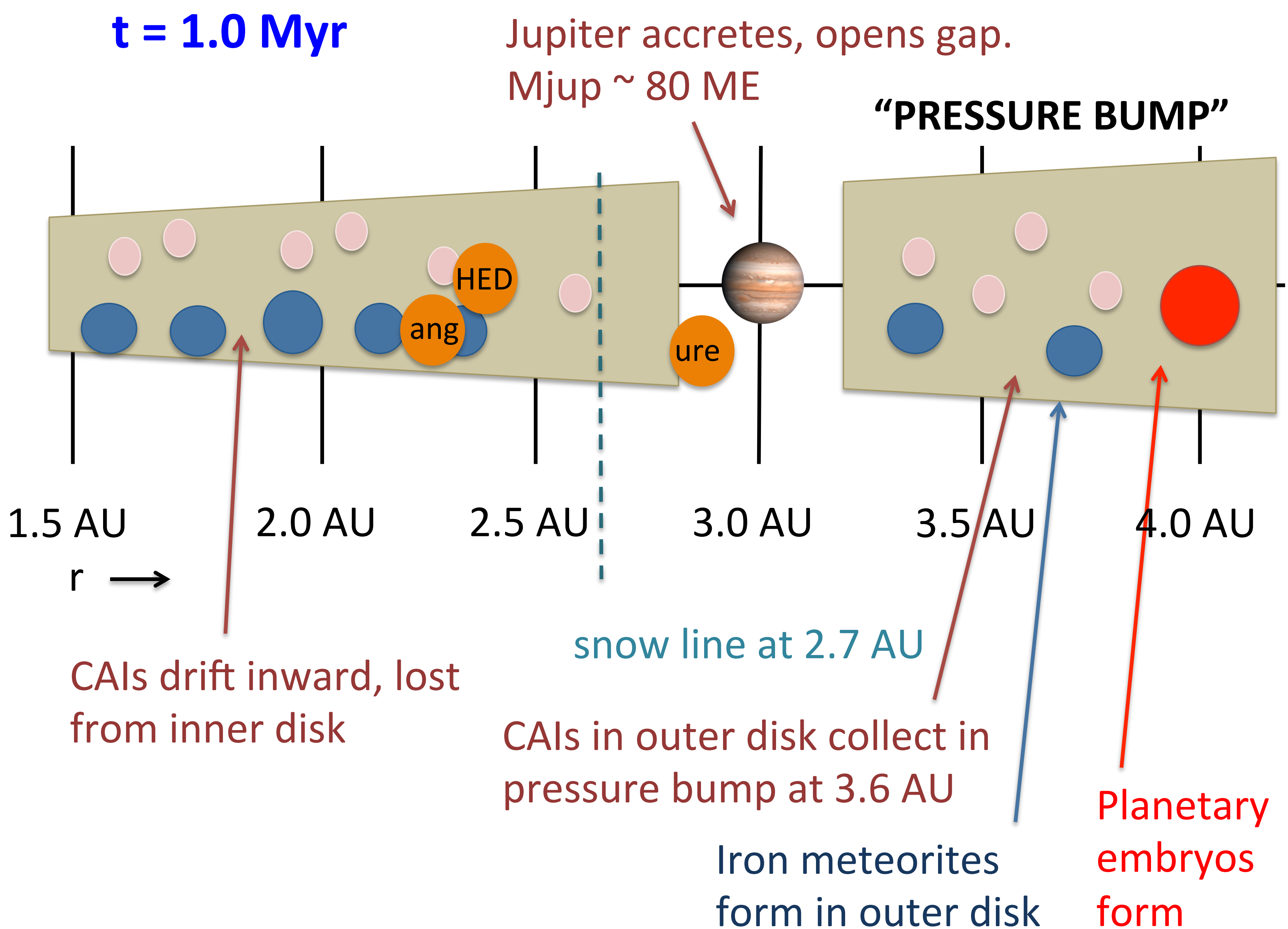

t = 0.0 Myr
CAIs created in CAI Factory < 1 AU
1.5 AU
2.0 AU
2.5 AU
3.0 AU
3.5 AU
4.0 AU
r


t = 0.4 Myr
CAIs transported from CAI Factory < 1 AU
ang
1.5 AU
2.0 AU
2.5 AU
3.0 AU
3.5 AU
4.0 AU
r
snow line at 4.4 AU
Iron meteorites
formed in inner disk
Angrite parent body forms

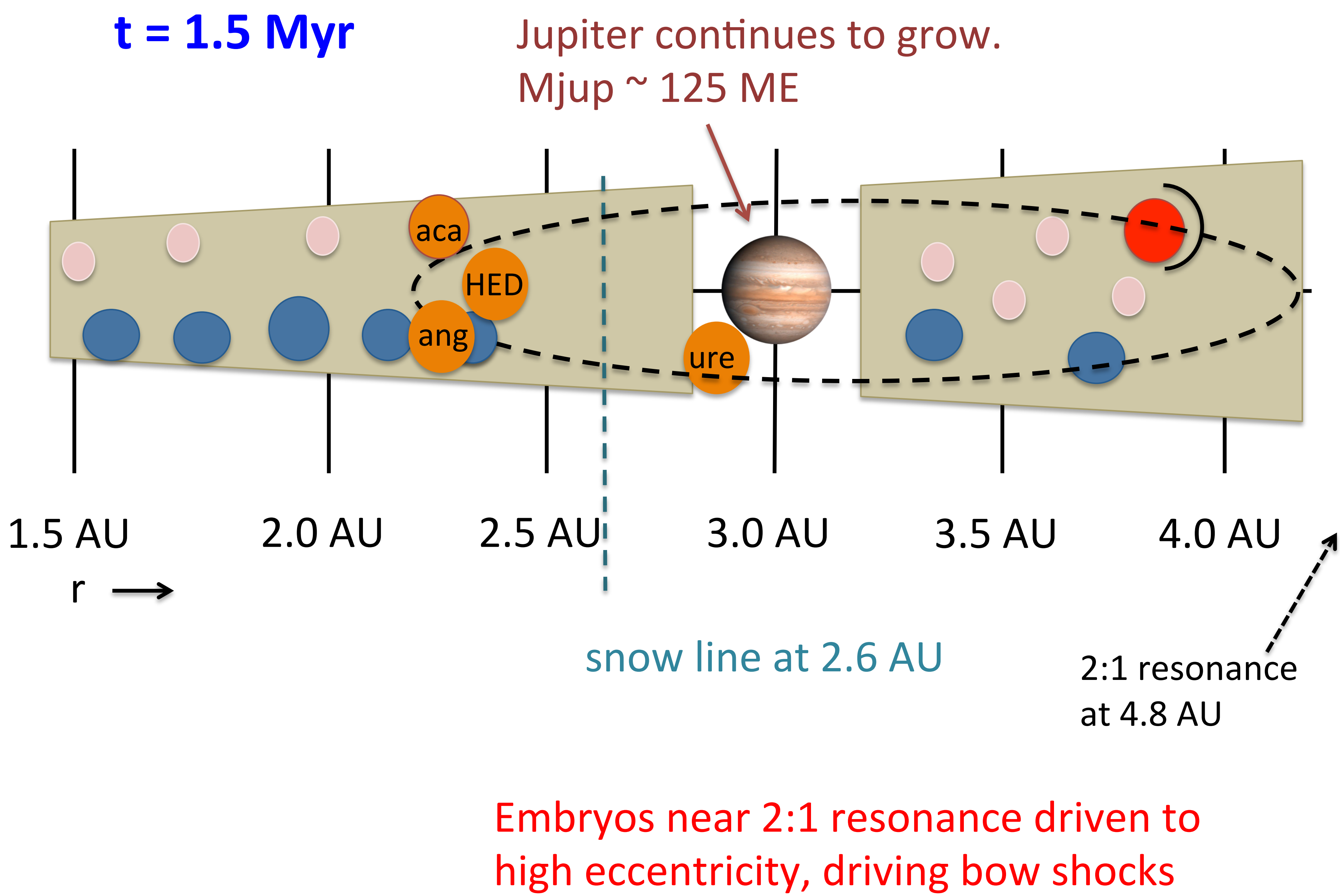

t = 0.6 Myr
Jupiter's core forms
Mjup ~ 30 ME
ang
ure
1.5 AU
2.0 AU
2.5 AU
3.0 AU
3.5 AU
4.0 AU
r
snow line at 4.3 AU
Ureilite parent body forms



t = 0.8 Myr
Jupiter's core forms
Mjup ~ 30 ME
HED
ang
ure
1.5 AU
2.0 AU
2.5 AU
3.0 AU
3.5 AU
4.0 AU
r →
HED parent body
(4 Vesta) forms
snow line at 2.7 AU



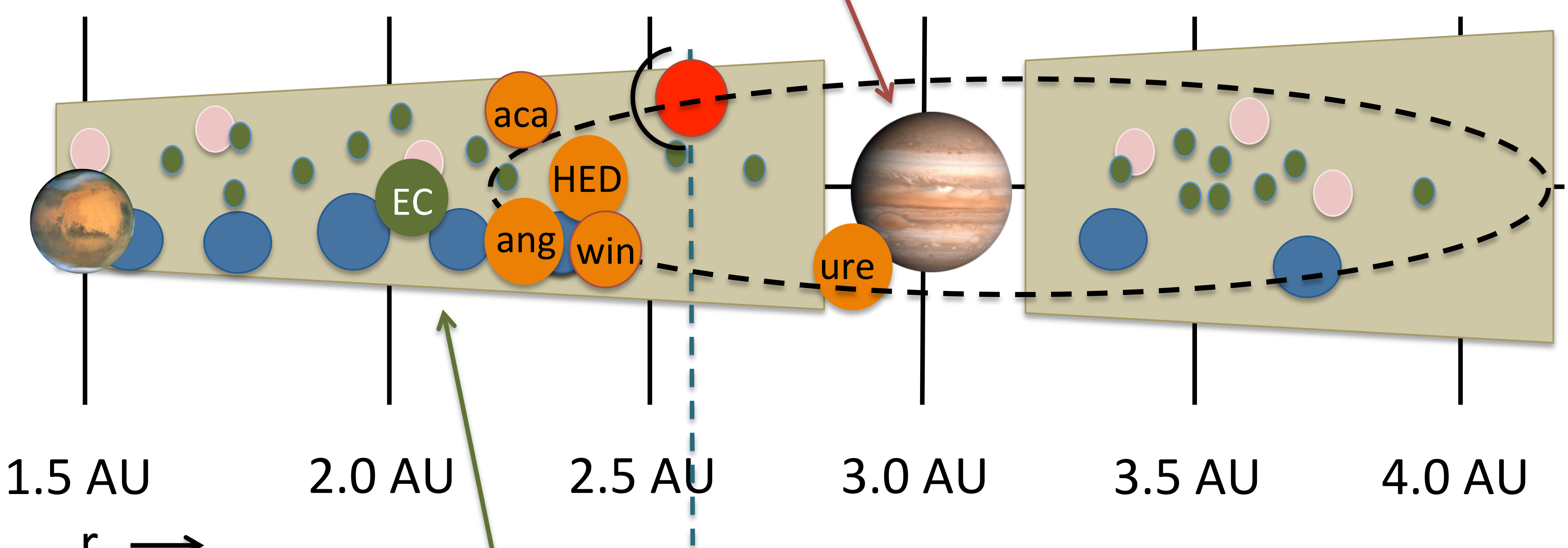
t = 1.0 Myr
Jupiter accretes, opens gap.
Mjup ~ 80 ME
"PRESSURE BUMP"
HED
ang
ure
1.5 AU
2.0 AU
2.5 AU
3.0 AU
3.5 AU
4.0 AU
r
snow line at 2.7 AU
CAIs drift inward, lost
from inner disk
CAIs in outer disk collect in
pressure bump at 3.6 AU
Iron meteorites
form in outer disk
Planetary
embryos
form



t = 1.5 Myr
Jupiter continues to grow.
Mjup ~ 125 ME
aca
HED
ang
ure
1.5 AU
2.0 AU
2.5 AU
3.0 AU
3.5 AU
4.0 AU
r
snow line at 2.6 AU
2:1 resonance
at 4.8 AU
Embryos near 2:1 resonance driven to
high eccentricity, driving bow shocks

t = 2.0 Myr

Jupiter continues to grow.
Mjup ~ 170 ME

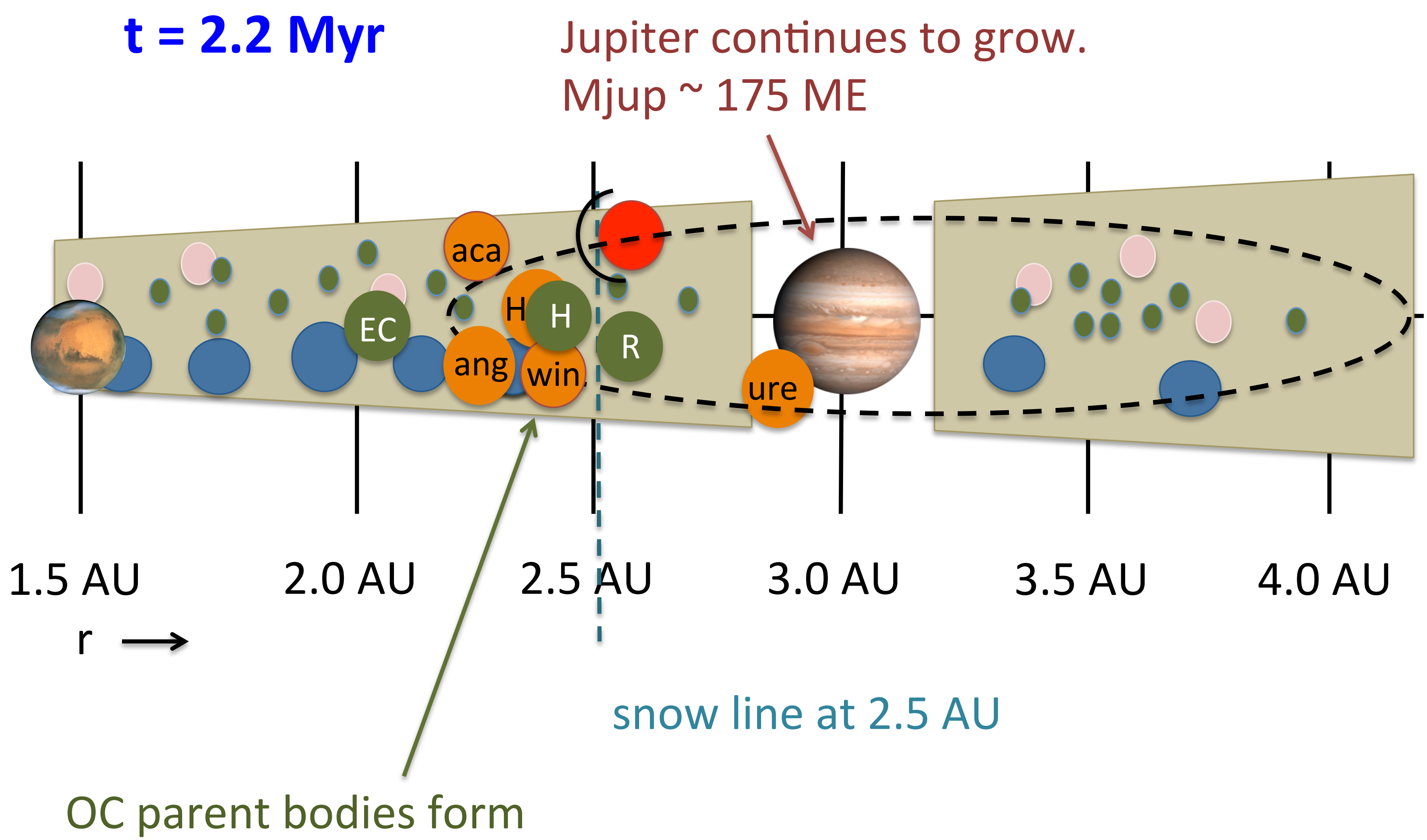


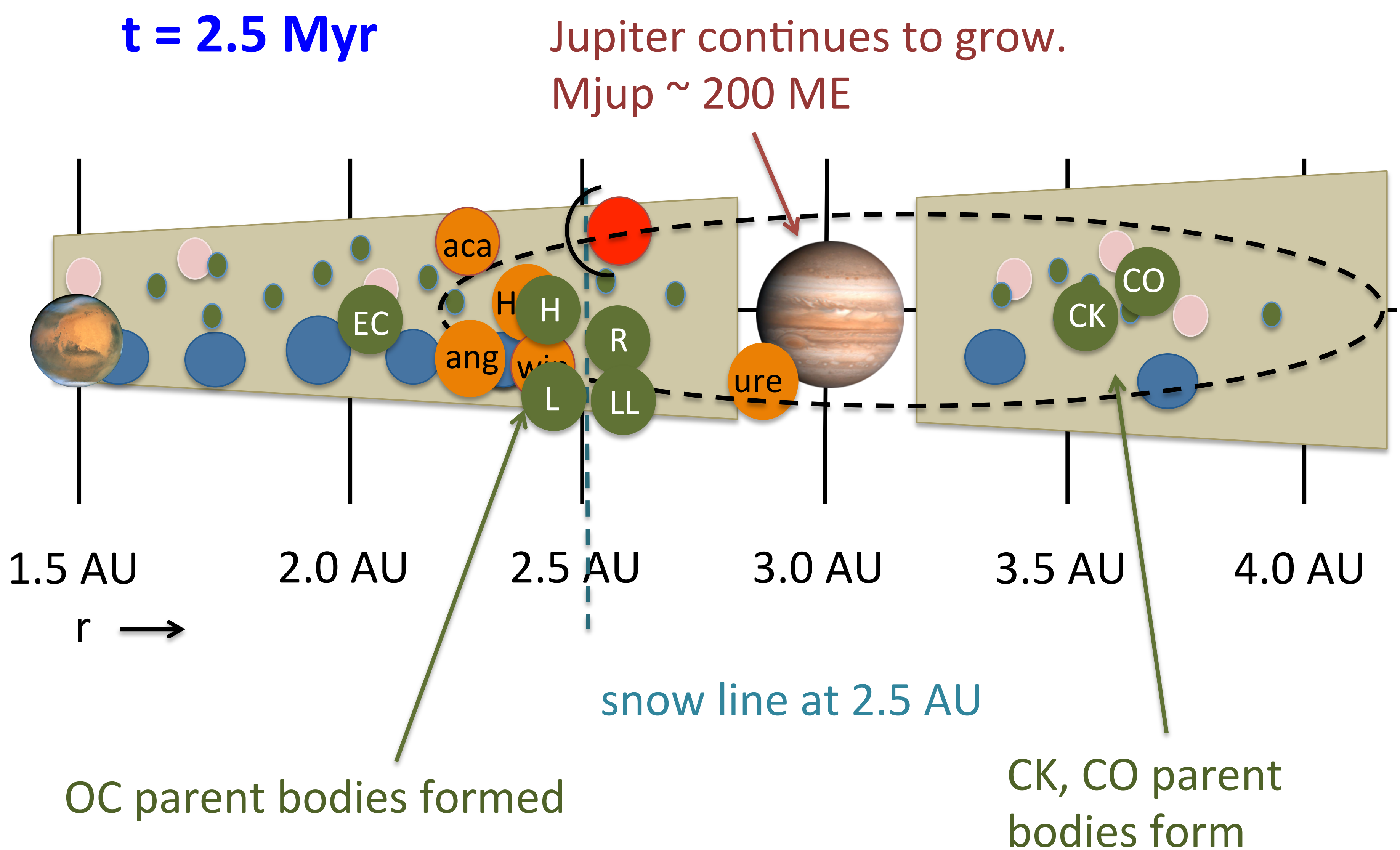
snow line at 2.6 AU

Mars
embryo
formed

EC parent bodies form

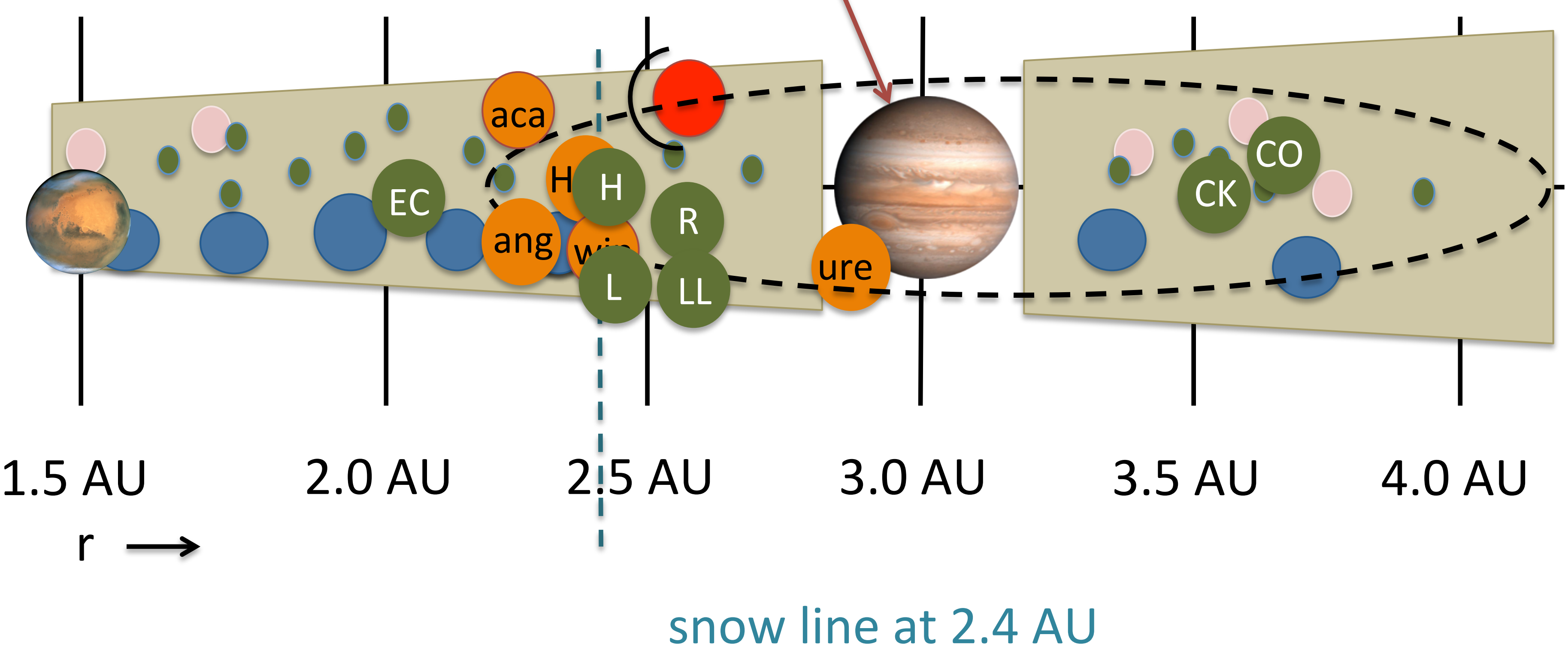
Planetary embryos on eccentric orbits create chondrules in both inner and outer disk

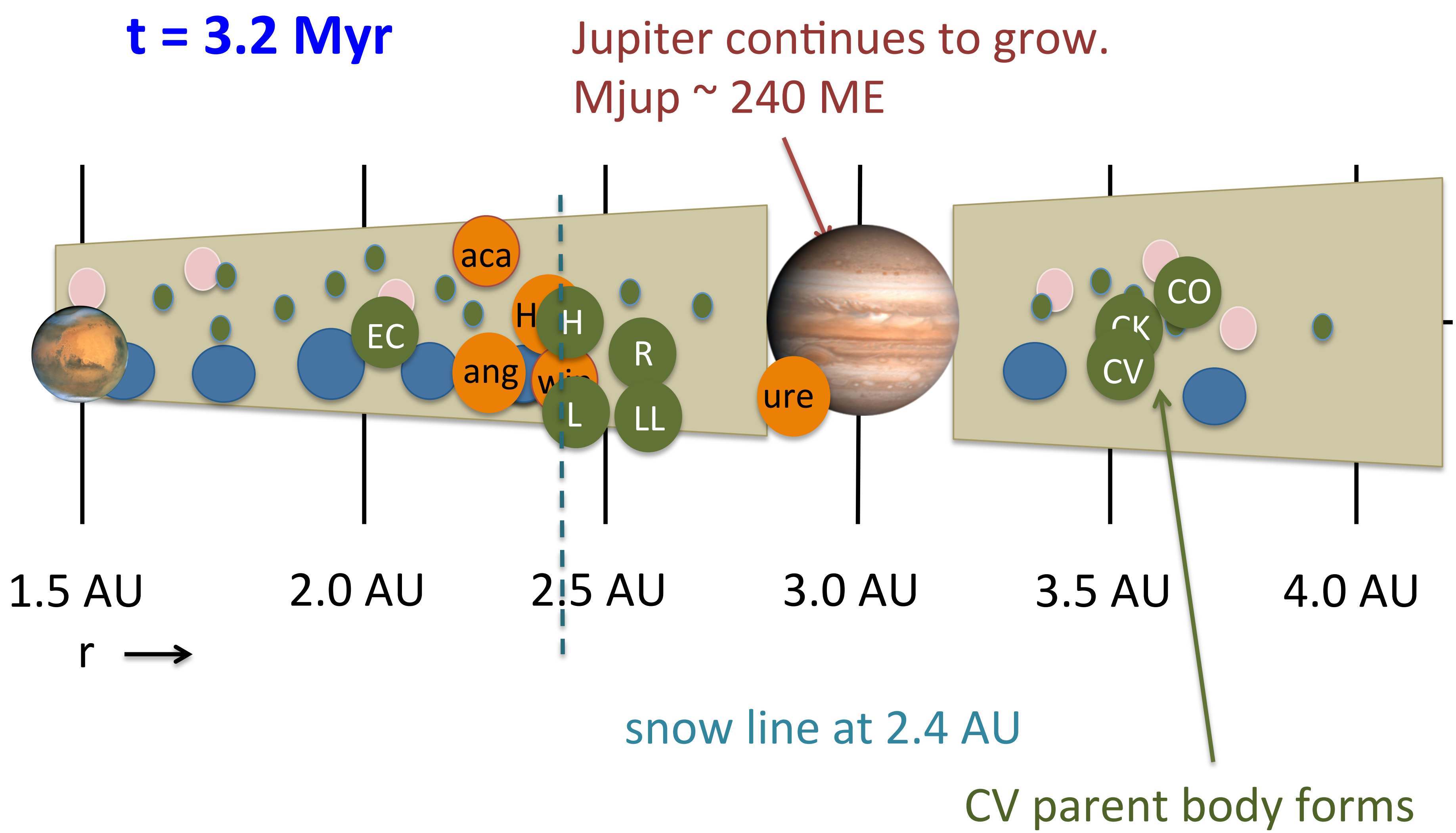

t = 2.2 Myr
Jupiter continues to grow.
Mjup ~ 175 ME
aca
H
H
EC
R
ang
win
ure
1.5 AU
2.0 AU
2.5 AU
3.0 AU
3.5 AU
4.0 AU
r
snow line at 2.5 AU
OC parent bodies form


t = 2.5 Myr
Jupiter continues to grow.
Mjup ~ 200 ME
aca
H
H
EC
ang
R
L
LL
ure
CO
CK
1.5 AU
2.0 AU
2.5 AU
3.0 AU
3.5 AU
4.0 AU
r →
snow line at 2.5 AU
OC parent bodies formed
CK, CO parent
bodies form

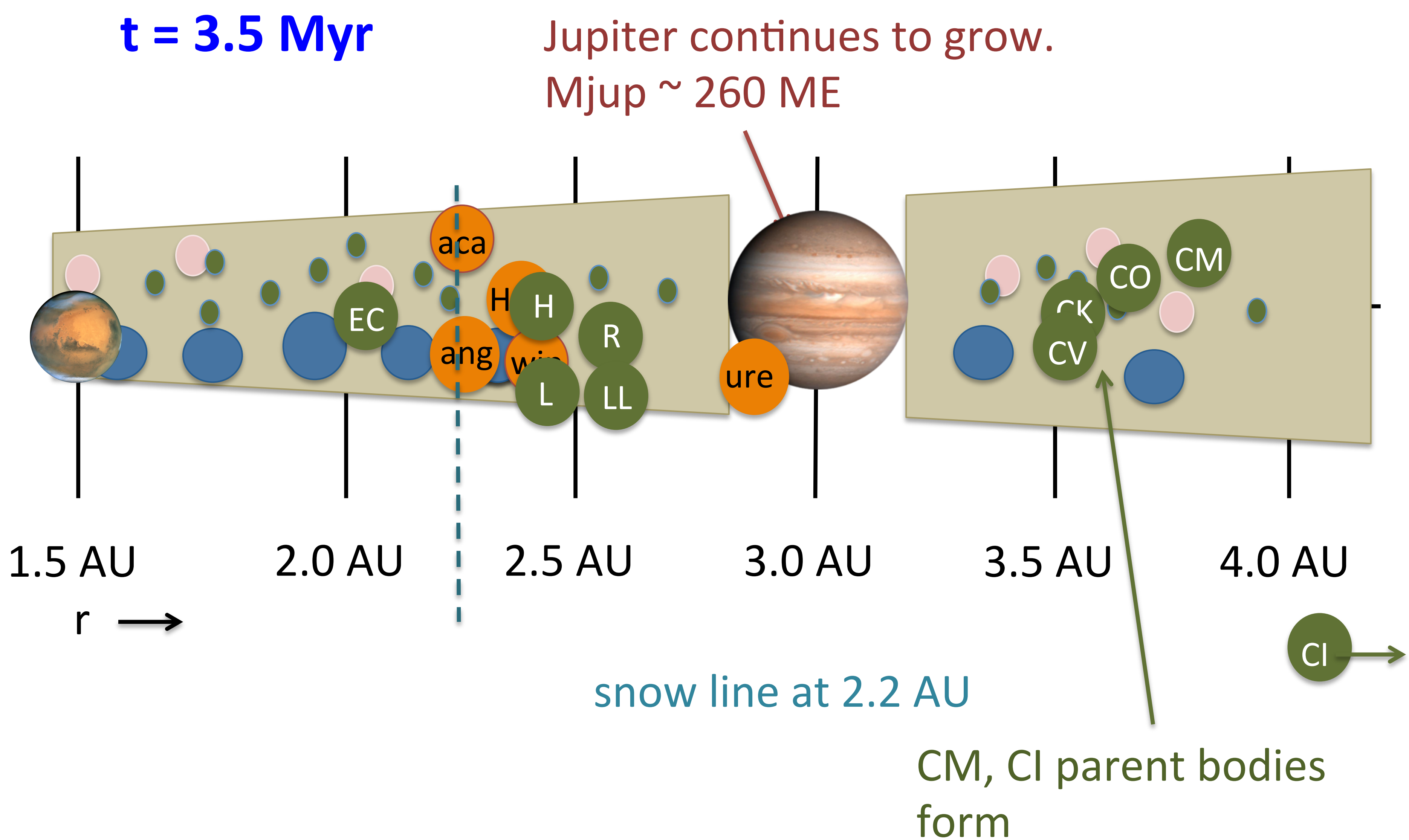
t = 3.0 Myr

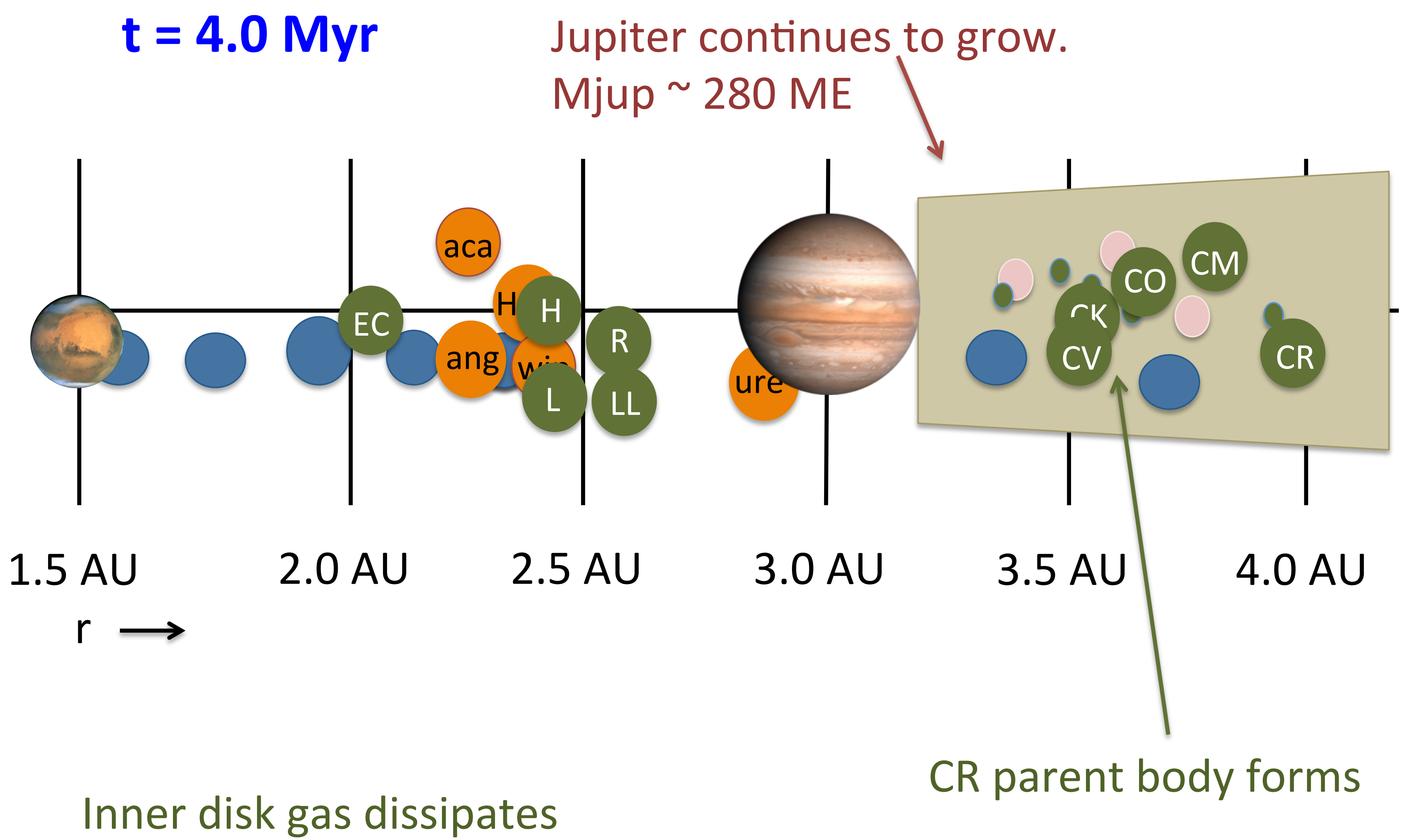
Jupiter continues to grow.
Mjup ~ 230 ME

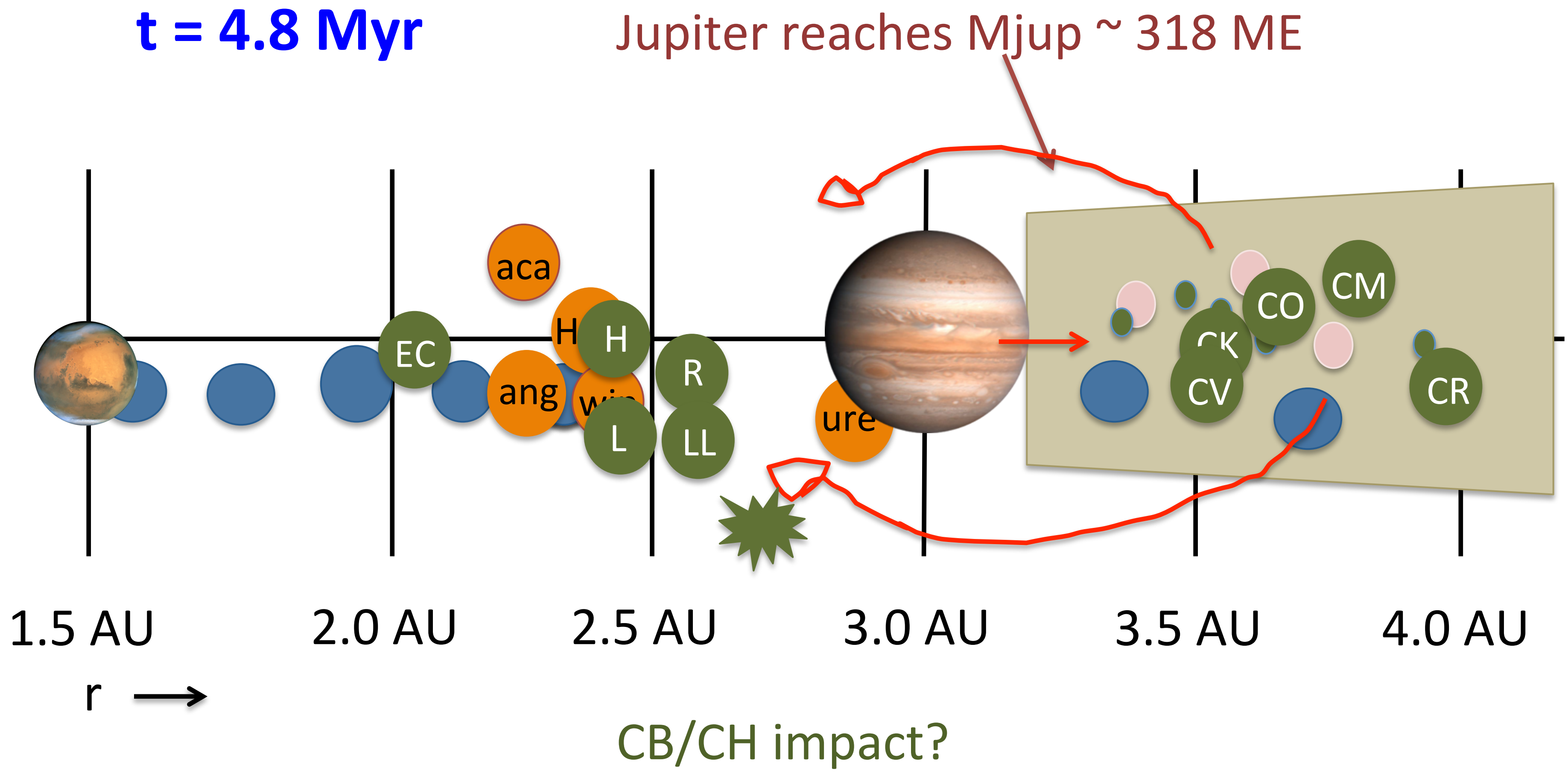




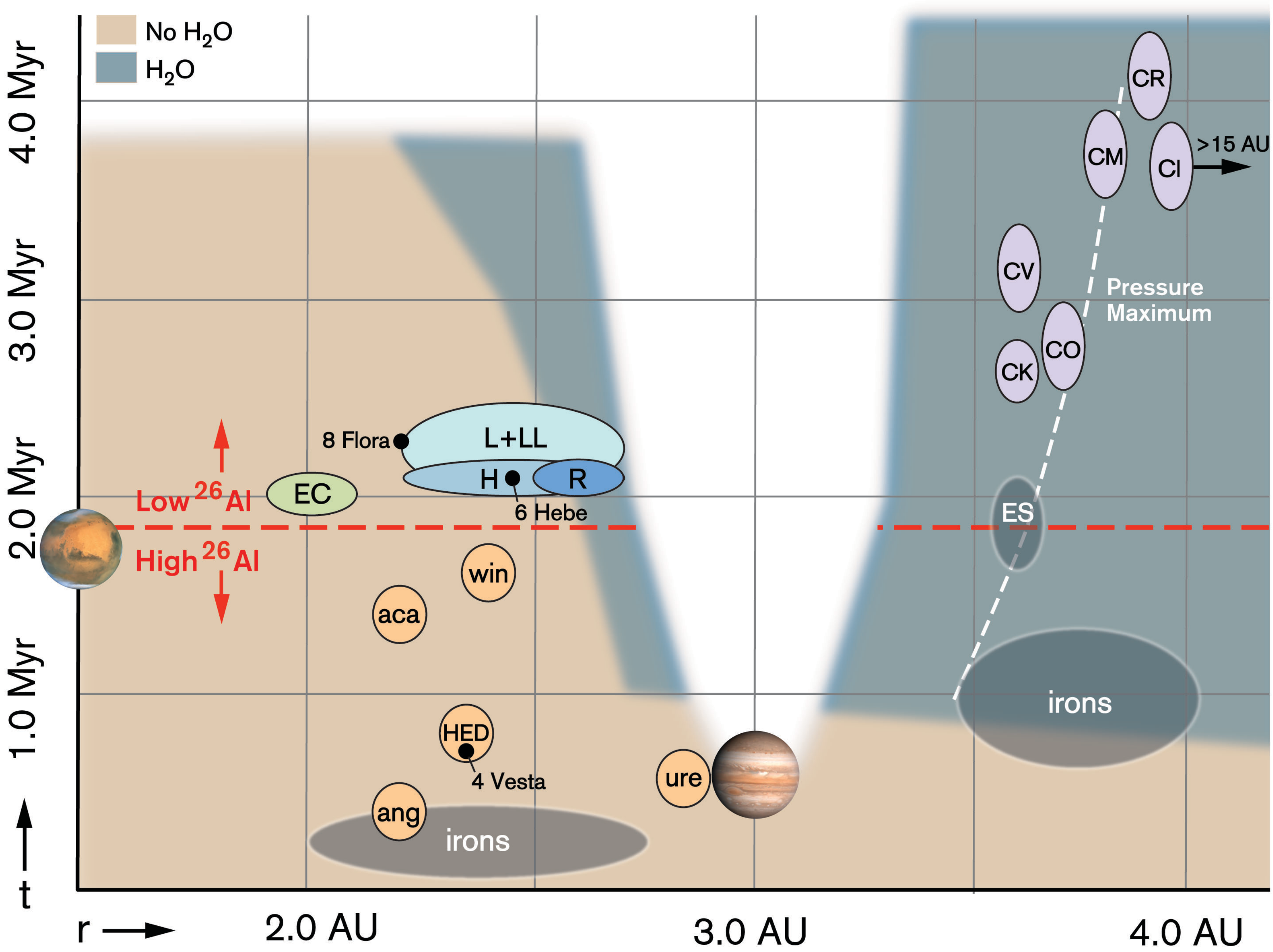
t = 3.2 Myr
Jupiter continues to grow.
Mjup ~ 240 ME
aca
H
H
EC
ang
R
L
LL
ure
CO
CK
CV
1.5 AU
2.0 AU
2.5 AU
3.0 AU
3.5 AU
4.0 AU
r →
snow line at 2.4 AU
CV parent body forms


t = 3.5 Myr
Jupiter continues to grow.
Mjup ~ 260 ME
aca
EC
H
H
R
ang
L
LL
ure
CO
CM
CV
1.5 AU
2.0 AU
2.5 AU
3.0 AU
3.5 AU
4.0 AU
r
CI
snow line at 2.2 AU
CM, CI parent bodies
form


t = 4.0 Myr
Jupiter continues to grow.
Mjup ~ 280 ME
aca
EC
H
H
ang
R
L
LL
ure
CO
CM
CV
CR
1.5 AU
2.0 AU
2.5 AU
3.0 AU
3.5 AU
4.0 AU
r →
CR parent body forms
Inner disk gas dissipates



Jupiter migrates outward,
scatters parent bodies



No H2O
H2O
4.0 Myr
3.0 Myr
2.0 Myr
1.0 Myr
t
r
2.0 AU
3.0 AU
4.0 AU
CR
CM
CI
>15 AU
CV
Pressure Maximum
CO
CK
8 Flora
L+LL
H
R
6 Hebe
EC
Low 26Al
High 26Al
ES
win
aca
irons
HED
4 Vesta
ure
ang
irons

A Comprehensive Model

Meteorite Type	Meteoritic Constraints: r (AU)	formation time (Myr)	(X/Mg) / CI	CAIs (vol%)	Model Predictions: r (AU)	formation time (Myr)	(X/Mg) / CI	CAIs (wt%)
angrites		~ 0.5	1.35		2.2	0.4	1.30	3.5
HEDs	2.36	~ 0.8	1.09		2.36	0.8	1.09	1.9
acapulcoite-lodranites		~ 1.5	0.90		2.2	1.4	0.90	0.8
ureilites	2.8	~ 0.6			2.8	0.6	1.03	1.4
winonaites		~ 1.8	0.90		2.4	1.8	0.90	0.3
ECs	1.9 - 2.1	1.7 - 1.9	0.87 - 0.88	< 0.1	< 2.1	2.0	0.90	0.27
R		2.0 - 2.2	0.97	< 0.1	2.6?	2.1	0.89	0.03
OCs	2 - 3	2.0 - 2.5	0.89 - 0.90	< 0.2	2.2 - 2.7	2.0 - 2.5	0.88 - 0.90	< 0.2
H	2.43?	2.0 - 2.2	0.90	0.01 - 0.2	2.43	2.1	0.90	0.11
L	2.20?	2.0 - 2.5	0.90	< 0.1	2.2 - 2.7	2.0 - 2.5	0.88 - 0.90	< 0.2
LL		2.0 - 2.5	0.89	< 0.1	2.2 - 2.7	2.0 - 2.5	0.88 - 0.90	< 0.2
CK	beyond	2.4 - 2.8	1.24	< 4	3.6	2.5	1.25	3.0
CV	Jupiter	~ 3.0	1.35	> 3	3.6	3.2	1.34	3.7
CO	"	~ 2.5	1.11	> 1	3.7	2.5	1.11	1.8
CM	"	3 - 4	1.13	1 - 2	3.8	3.5 - 4.0	1.13	2.0
CR	"	3.8 - 4.5	1.02	0.5 - 1	3.9	3.5 - 4.5	1.02	1.0
CI	"	3 - 4	1.00	0.0	> 15	4.0	≡ 1.00	0.0

Meteorite Type	r (AU)	Formation time (Myr)	Σ ($\mathrm{g\,cm^{-2}}$)	ρ ($10^{-10}\,\mathrm{g\,cm^{-3}}$)	T (K)
angrites	2.2	0.4	5600	12	410
HEDs	2.36	0.8	4100	8.6	309
acapulcoite-lodranites	2.2	1.4	2700	7.0	245
ureilites	2.8	0.6	4200	7.3	276
winonaites	2.4	1.8	2200	5.5	207
ECs	< 2.1	2.0	> 2000	> 6	> 217
R	2.6?	2.1?	1400	4	< 160
H	2.43	2.1	1980	5.1	190
L	2.2 - 2.7	2.0 - 2.5	< 2000	< 6	100 - 210
LL	2.2 - 2.7	2.0 - 2.5	< 2000	< 6	100 - 210
CK	3.6	2.5	1800	3.1	> 132
CV	3.6	3.2	1500	2.7	> 119
CO	3.7	2.5	1800	3.0	> 128
CM	3.8	3.5 - 4.0	1400	2.4	110
CR	3.9	3.5 - 4.5	1300	2.2	103
CI	~ 15	4.0	6.4	0.002	≈ 44

Conclusions

CAI Storage problem solved: CAIs that diffused past Jupiter trapped in pressure bump created by Jupiter forming at 3 AU at 0.6 Myr. CAIs in 2-3 AU region lost to Sun.

Refractory abundances and CAI abundances can be used to determine where and when different meteorite formed.

Chondrites do appear to be snapshots in time of solar nebula.

H chondrite parent body formed near 2.43 AU, where 6 Hebe orbits.
HEDs consistent with formation at 2.36 AU, where 4 Vesta orbits.
Many ordinary and enstatite chondrite parent bodies migrated little.
Carbonaceous chondrite parent bodies migrated ~ 1 AU.

Conclusions

Almost all carbonaceous chondrites formed in pressure bump beyond Jupiter, a good place to grow planetesimals!
Supports idea of common CK/CV/Eagle Station pallasite parent body (Elkins-Tanton et al. 2011).

CI Chondrites had to form beyond chondrule formation (> 7 AU), but where densities were not too low (< 10 AU), and late (3-4 Myr).
Pressure bump beyond Saturn??

Mixing inevitable. We predict CIs depleted in refractory lithophiles (Ca, Al, Ti, Sc, Y, Zr, Hf, REEs) and probably refractory siderophiles, relative to Sun, by about **9%** (0.04 dex).
Hints of this in data from Lodders et al. (2009)!

Conclusions

Planet formation was extremely rapid (Jupiter in < 1 Myr, embryos in ~ 1 Myr). Radial drift was extremely important.

$\alpha < 10^{-5}$ in disk beyond 10 AU suggests VSI or non-magnetic accretion. Higher $\alpha \sim 10^{-4}$ inside 10 AU suggests magnetic disk winds

Lots left to do: incorporate formation of disk (like Yang & Ciesla 2012), calculate water distribution, better assess chondrule formation, etc…

But careful consideration of constraints from CAIs and chondrules can provide unparalleled insights into disk processes and planet formation!

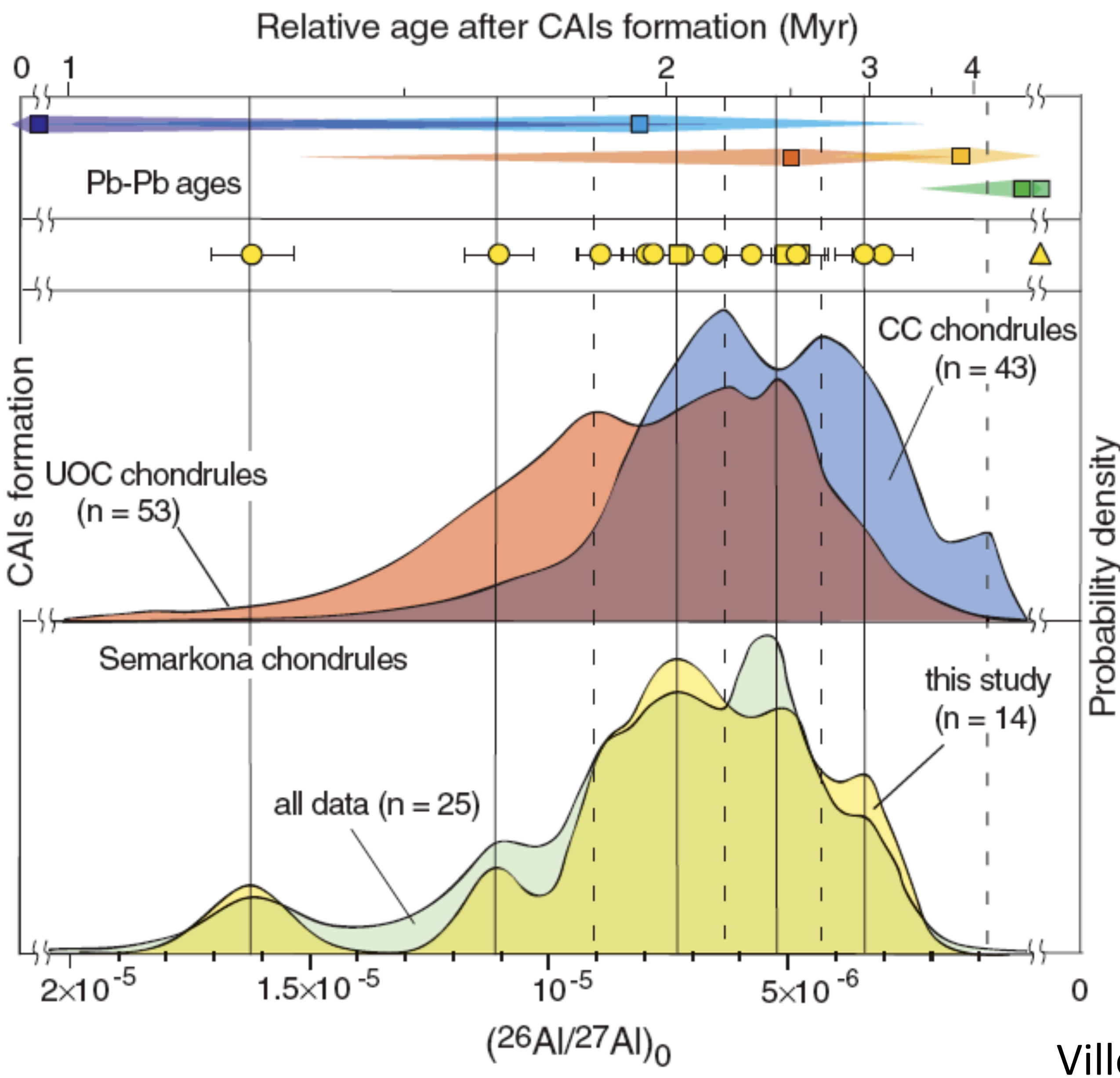
What melted chondrules?

As reviewed by Desch et al. (2012):

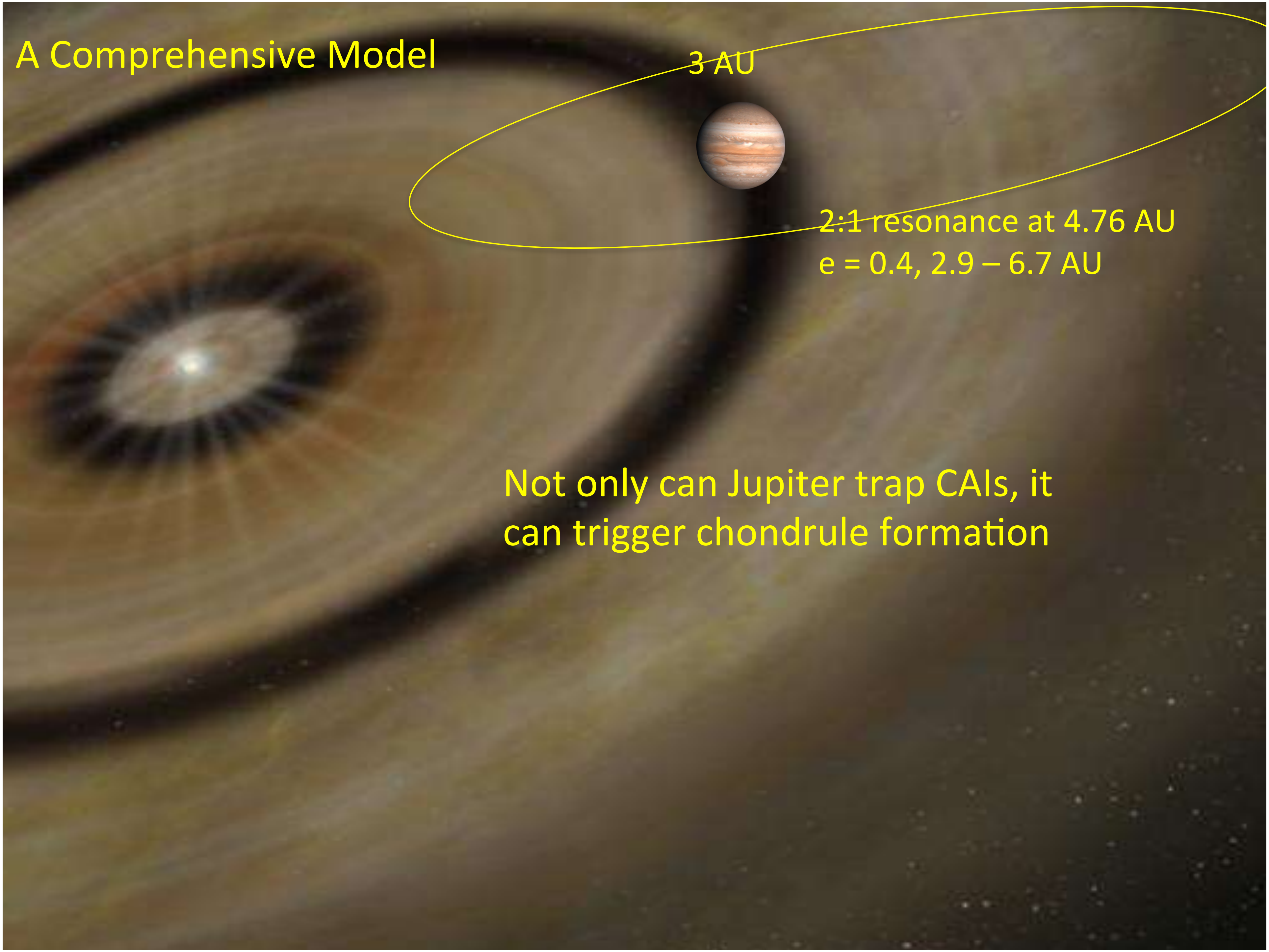
- Peak temperatures > 1800 K for minutes
- Cooling rates ~ 10 – 10^3 K/hr for hours.
- In the presence of gas, and cogenetic with matrix grains
- Densities of chondrules ~ 10 m^{-3} (suppression of evaporation, compound chondrule frequency)
- Repeatable process (relict chondrules)

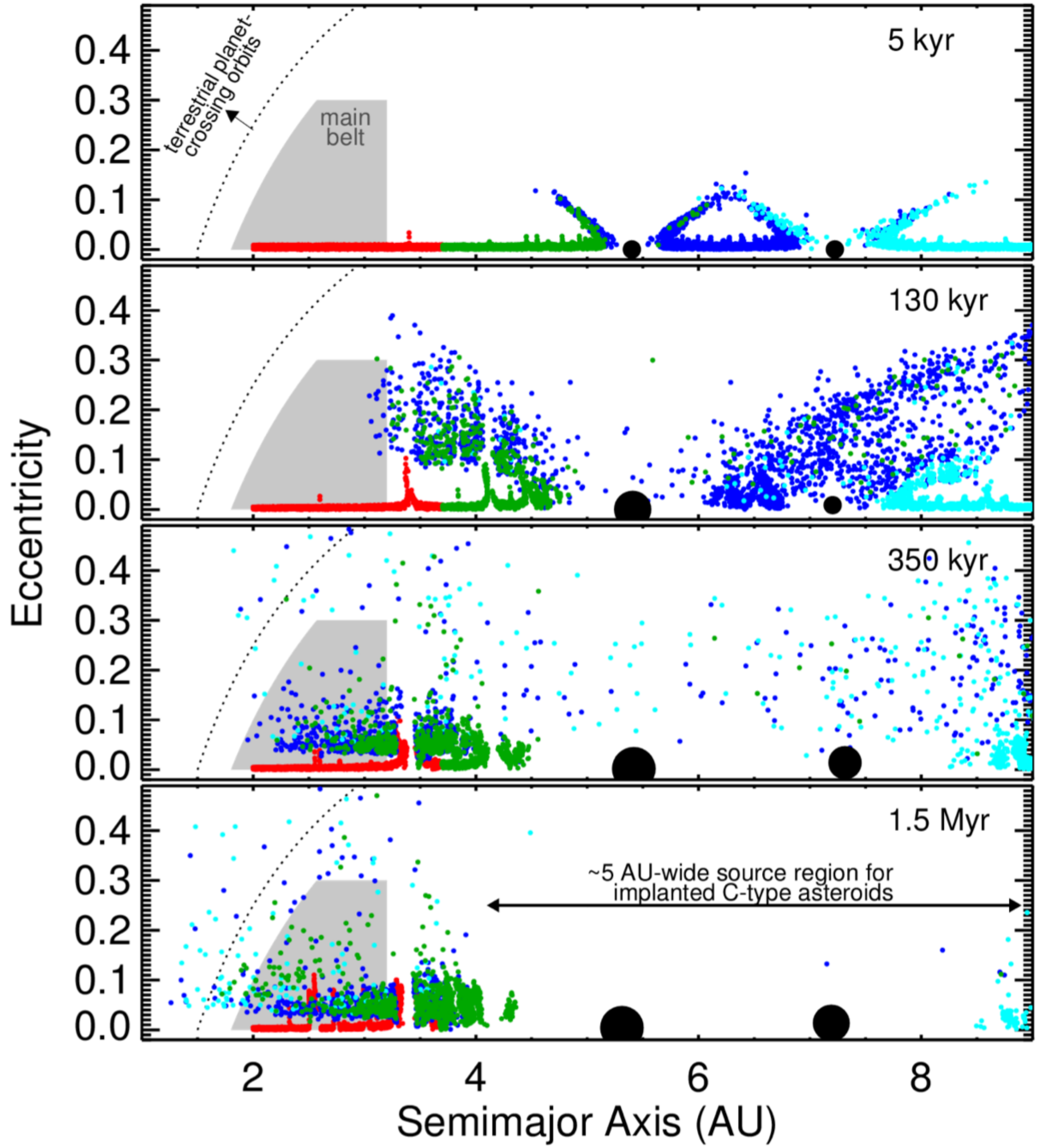
Large-scale nebular shocks (Desch & Connolly 2002; Ciesla et al. 2002)
Timing and sources?
Bow shocks around planetary embryos (Morris et al. 2012, Boley et al. 2013, Mann et al. 2016). Can cooling rates match?
Impact melt droplets (Johnson et al. 2015; Lichtenberg et al. 2017).
Geochemistry? Cooling rates? Efficiency?

Most chondrules formed ~ 1.5 – 3.0 Myr after CAIs



Villeneuve et al. (2009)

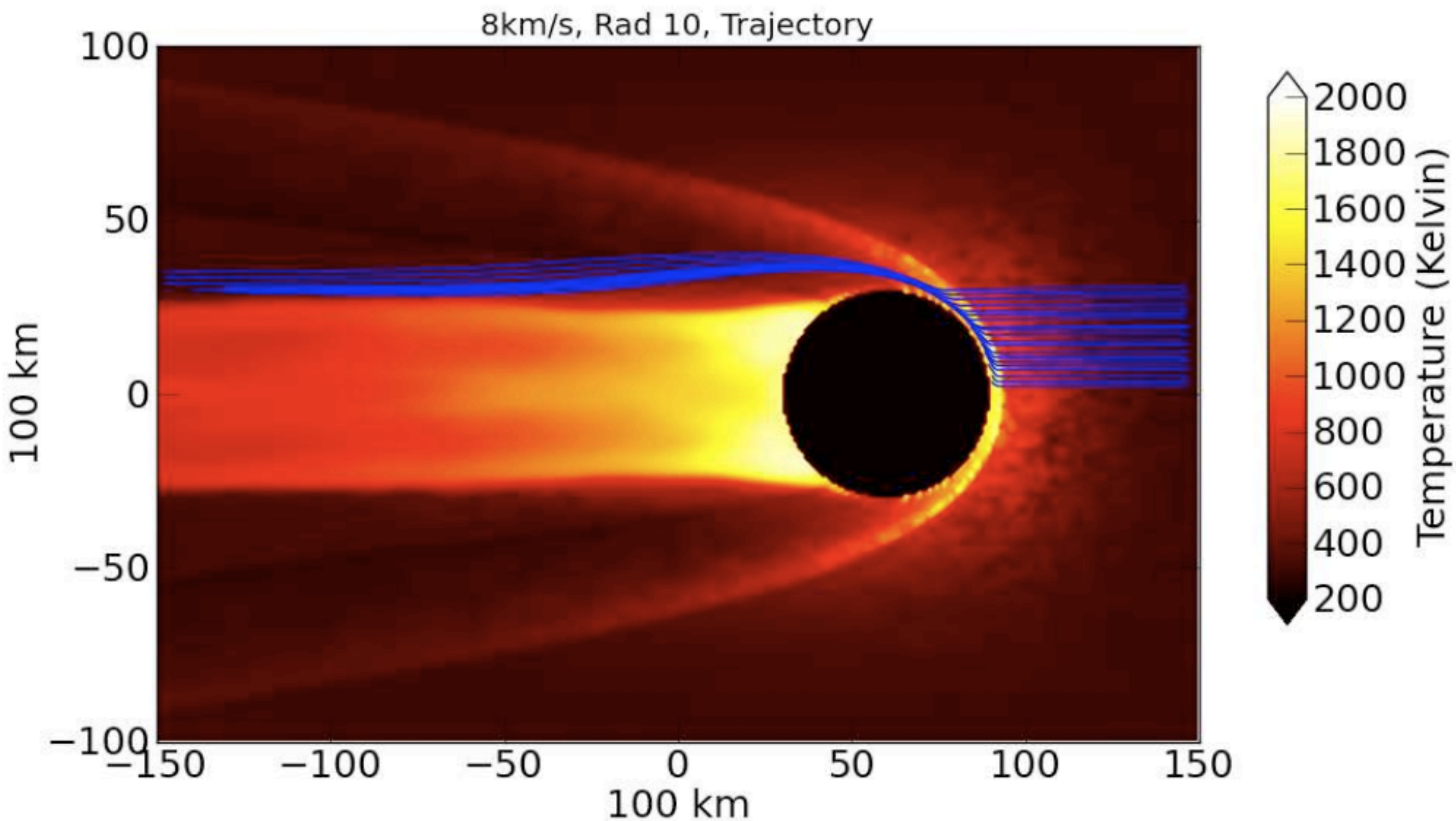

A Comprehensive Model
3 AU
2:1 resonance at 4.76 AU
e = 0.4, 2.9 – 6.7 AU
Not only can Jupiter trap CAIs, it can trigger chondrule formation

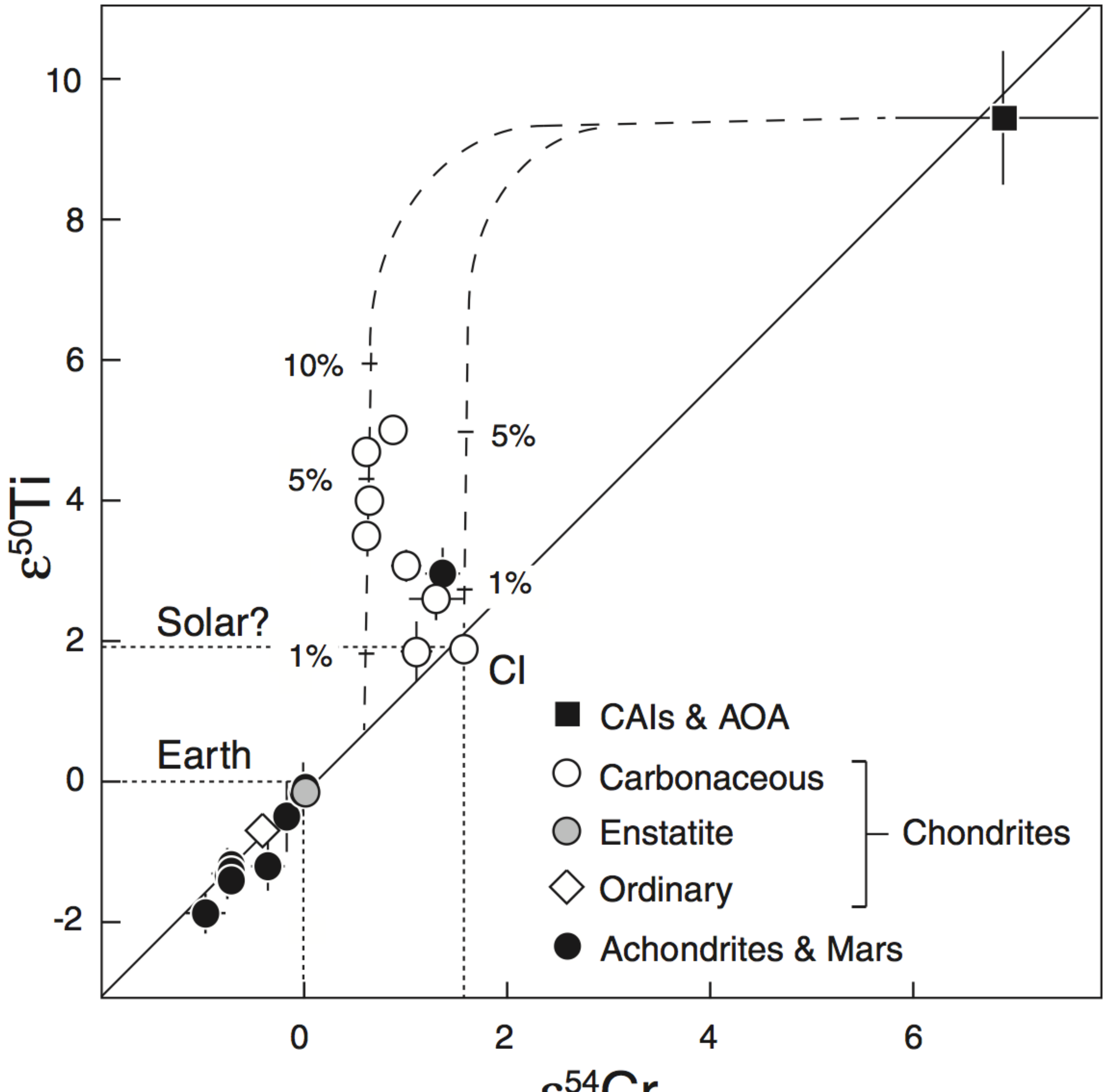


Raymond & Izidoro (2017)

What melted chondrules?

Requires e ~ 0.4 and $\rho \sim 10^{-9}$ g cm^{-3} (Boley et al. 2013).





10
8
6
4
2
0
-2
ε50Ti
0
2
4
6
ε54Cr
10%
5%
5%
1%
1%
Solar?
Earth
CI
CAIs & AOA
Carbonaceous
Enstatite
Ordinary
Achondrites & Mars
Chondrites