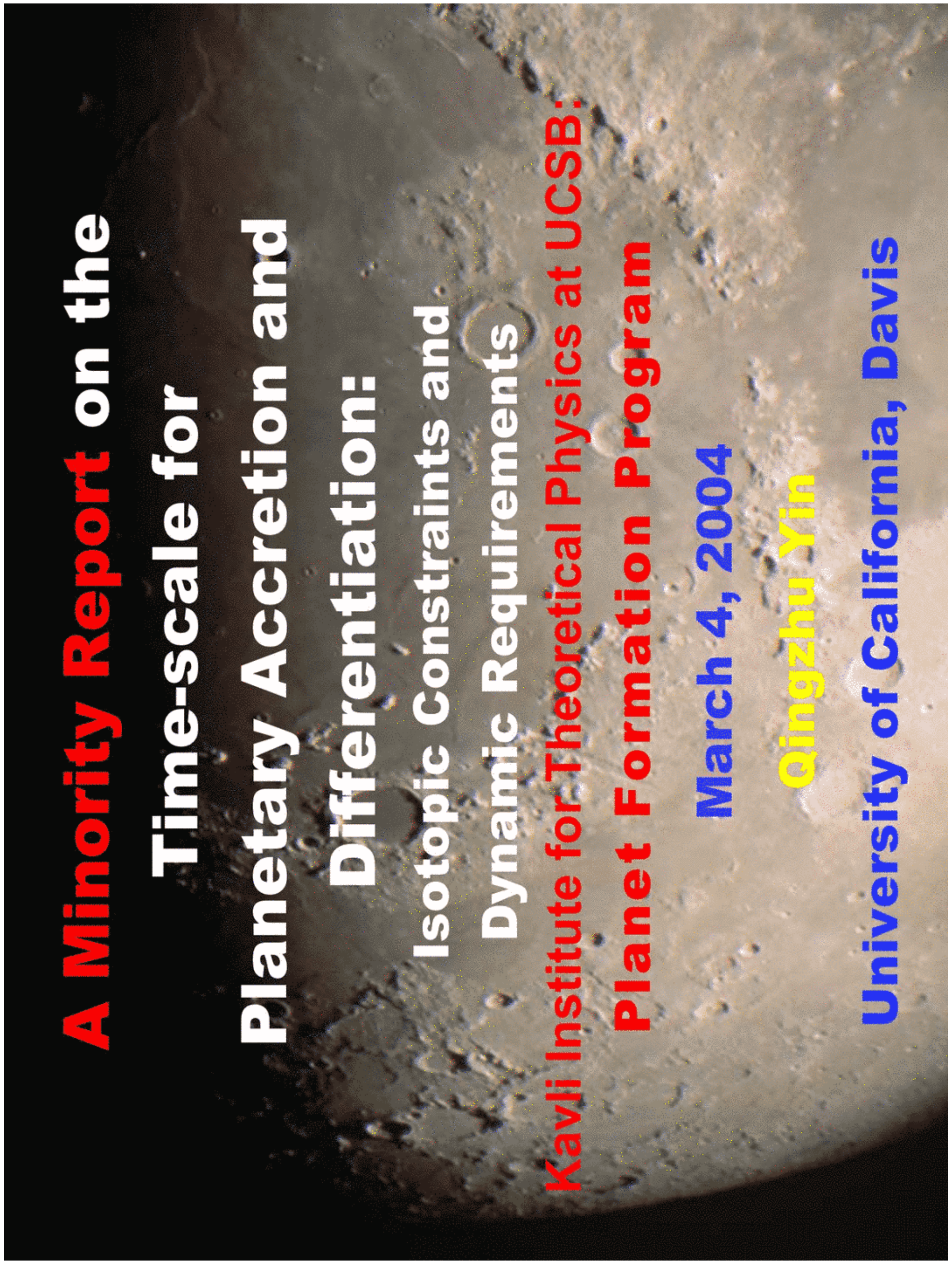
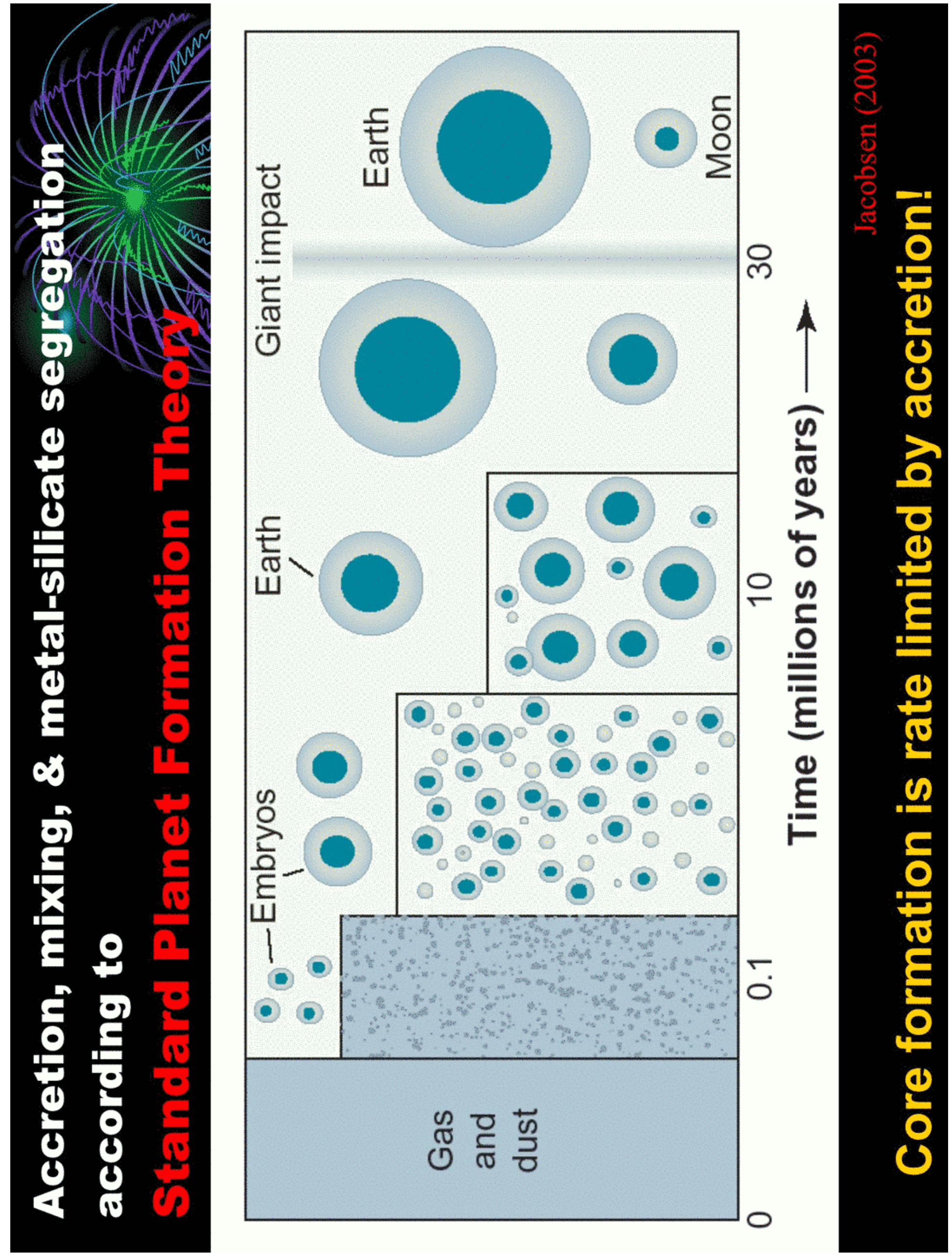
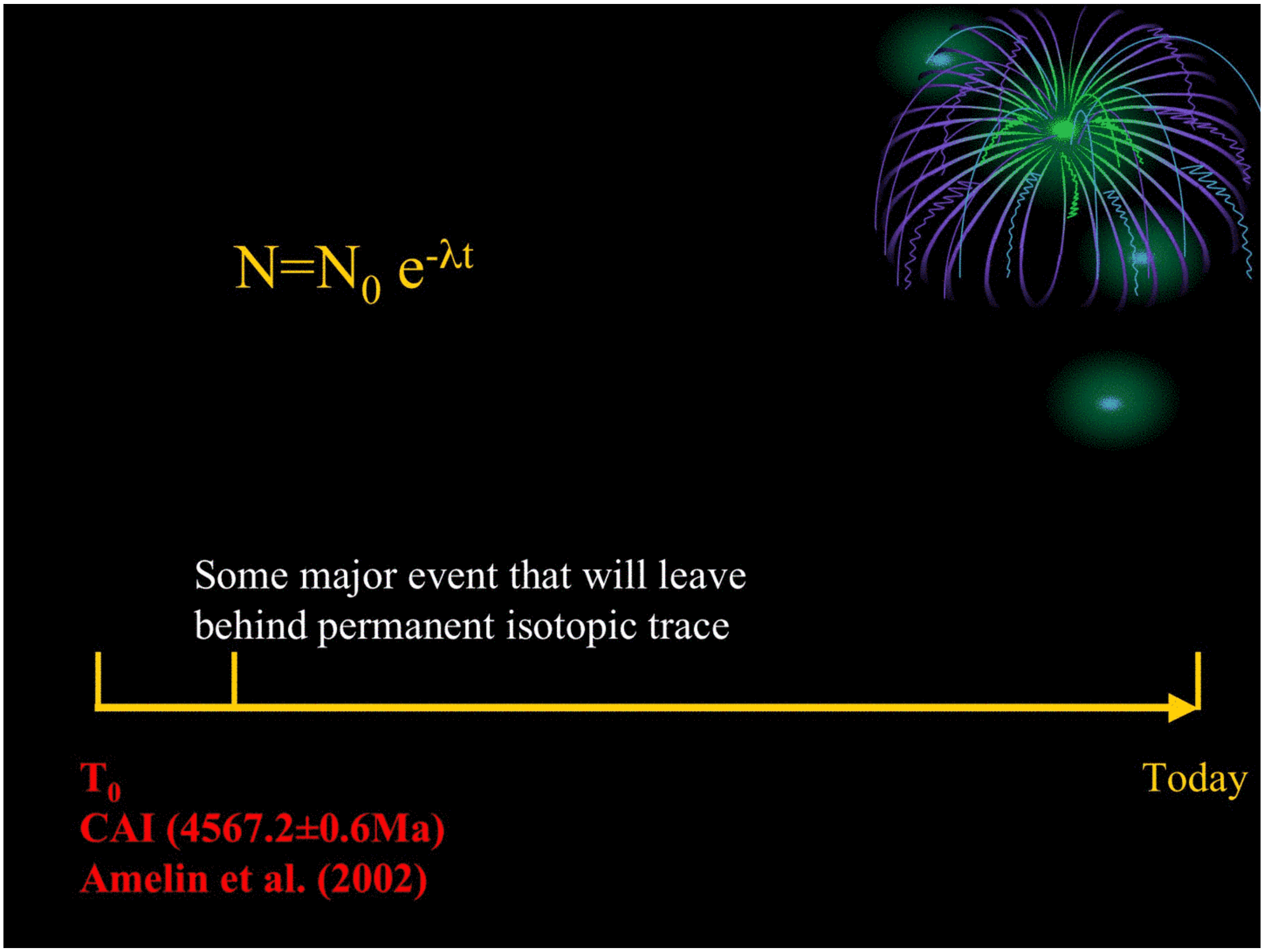

A Minority Report on the
Time-scale for
Planetary Accretion and
Differentiation:
Isotopic Constraints and
Dynamic Requirements
Kavli Institute for Theoretical Physics at UCSB:
Planet Formation Program
March 4, 2004
Qingzhu Yin
University of California, Davis


Accretion, mixing, & metal-silicate segregation
according to
Standard Planet Formation Theory
Gas
and
dust
Embryos
Earth
Giant impact
Earth
Moon
0
0.1
10
30
Time (millions of years)
Jacobsen (2003)
Core formation is rate limited by accretion!



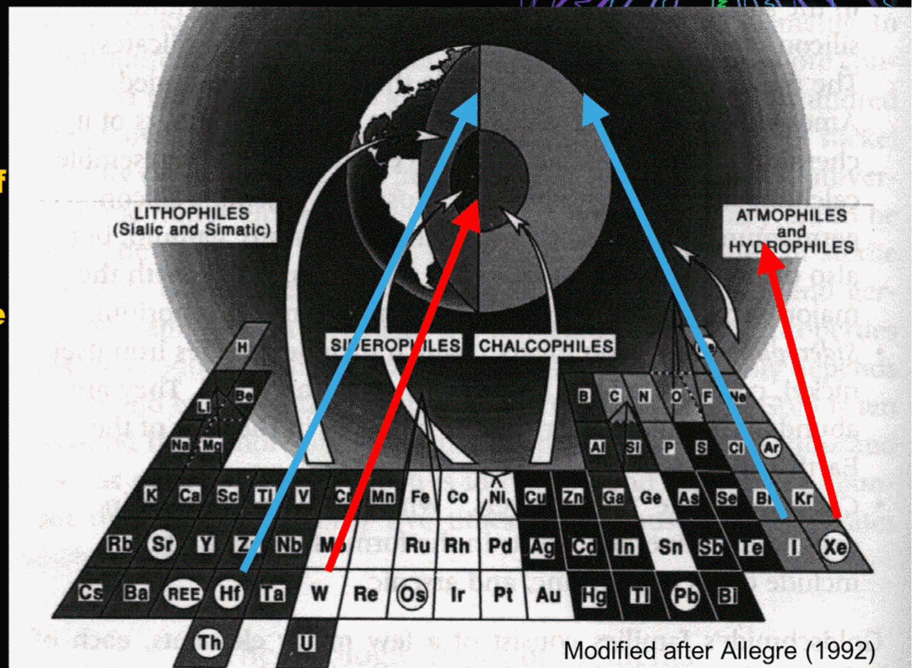
Radioactivities in the Early Solar System

Score	Parent	Daughter	Half-life (in Ma)	Score	Parent	Daughter	Half-life (in Ma)
?/+	^{7}Be	^{7}Li	53.28 days	+	^{107}Pd	^{107}Ag	6.5
+	^{10}Be	^{10}B	1.6	Active research	^{126}Sn	^{126}Te	0.2
+	^{26}Al	^{26}Mg	0.73	+	^{129}I	^{129}Xe	15.7
+	^{36}Cl	^{36}Ar	0.301	+	^{135}Cs	^{135}Ba	2.3
+	^{41}Ca	^{41}K	0.103		^{137}La	^{137}Ba	0.06
+	^{53}Mn	^{53}Cr	3.7	+	^{146}Sm	^{142}Nd	103
+	^{60}Fe	^{60}Ni	1.5		^{150}Gd	(^{146}Sm)	1.8
	^{59}Ni	^{59}Co	0.076	+	^{182}Hf	^{182}W	9
	^{79}Se	^{79}Br	0.065		^{202}Pb	^{202}Hg	0.053
	^{81}Kr	^{81}Br	0.21	Active research	^{205}Pb	^{205}Tl	15
?	^{93}Zr	^{93}Nb	1.5		^{239}Pu	a, SF	0.0241
+	^{92}Nb	^{92}Zr	36		^{242}Pu	a, SF	0.375
Active research	^{97}Tc	^{97}Mo	2.6	+	^{244}Pu	a, SF	80
Active research	^{98}Tc	^{98}Ru	4.2	Renewed search	^{247}Cm	(^{235}U)	15.6
Active research	^{99}Tc	^{99}Ru	0.213		^{248}Cm	(^{244}Pu)	0.348

Select appropriate "ruler or clock" for different purposes!!

Geochemistry of Hf-W, I-Pu-Xe

- **Hf-I-Pu is highly *lithophile*, retain in the silicate portion of the Earth.**
- **W is *moderately siderophile*, some enters core, some retains in the silicate mantle.**
- **Xe is atmophile (gas)**



Modified after Allegre (1992)

Chronometers for Planet Formation

- Both Hf-W and I-Pu-Xe clocks are uniquely affected by large-scale processes; core-mantle segregation in a Hf-W clock and atmosphere-solid Earth segregation in I-Pu-Xe system.
- "Ruler" sizes are just right: ^{182}Hf (9Ma); ^{129}I (15.6 Ma); ^{244}Pu (80 Ma)

$^{182}W^*$ Evolution due to ^{182}Hf Decay

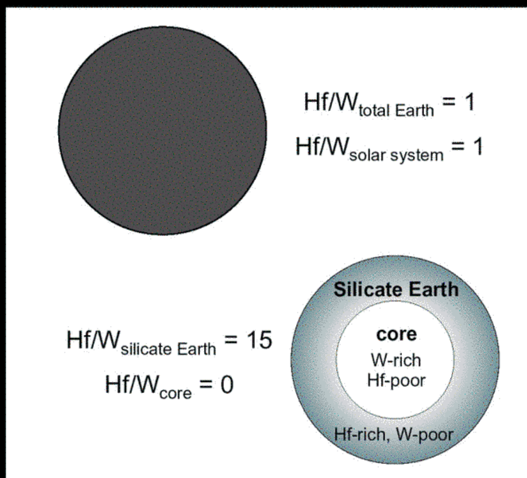
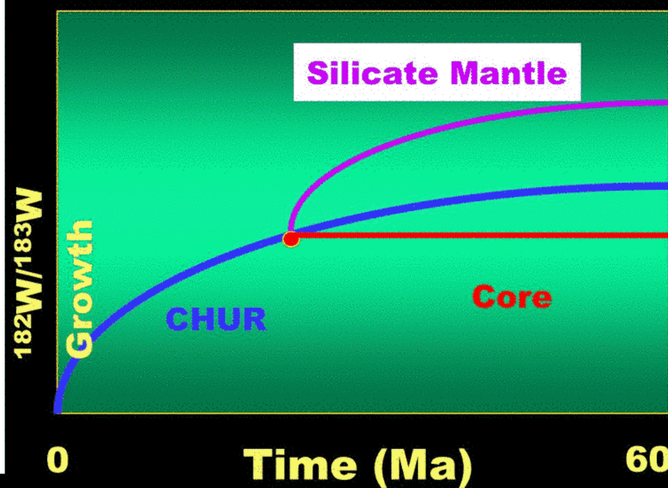


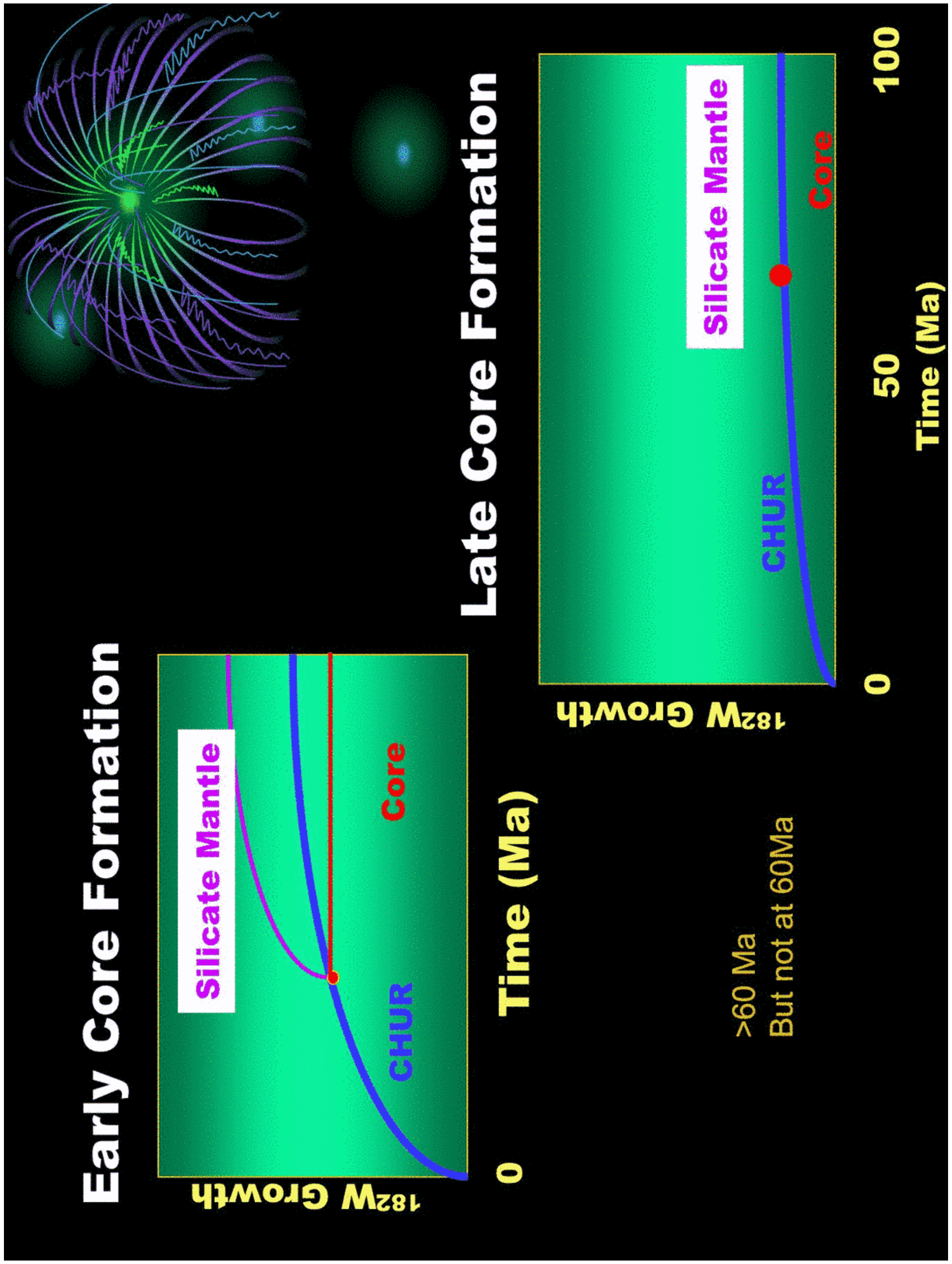
Fig. 2. Schematic showing the fractionation of Hf from W in the early solar system.

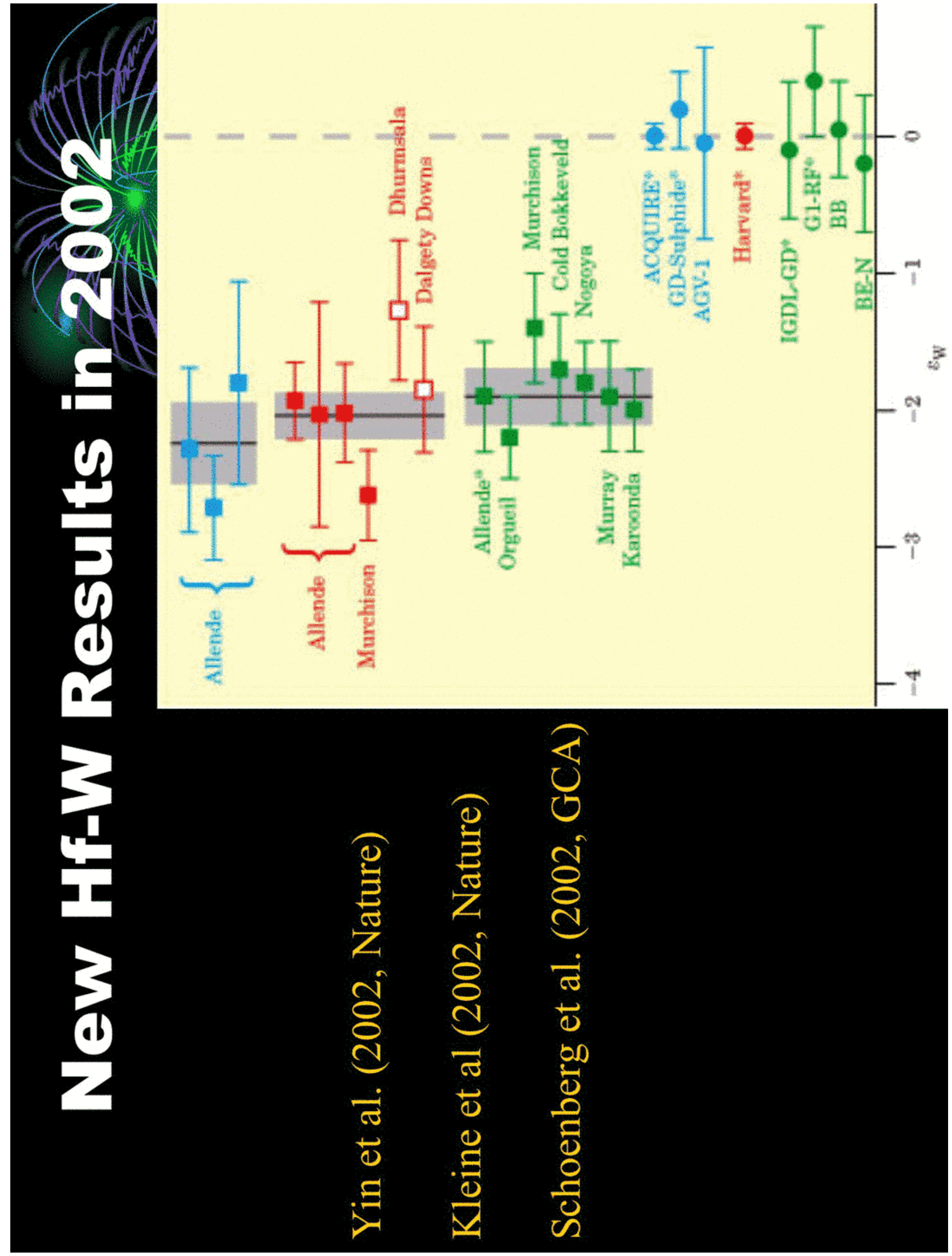
After Halliday et al. (2000)

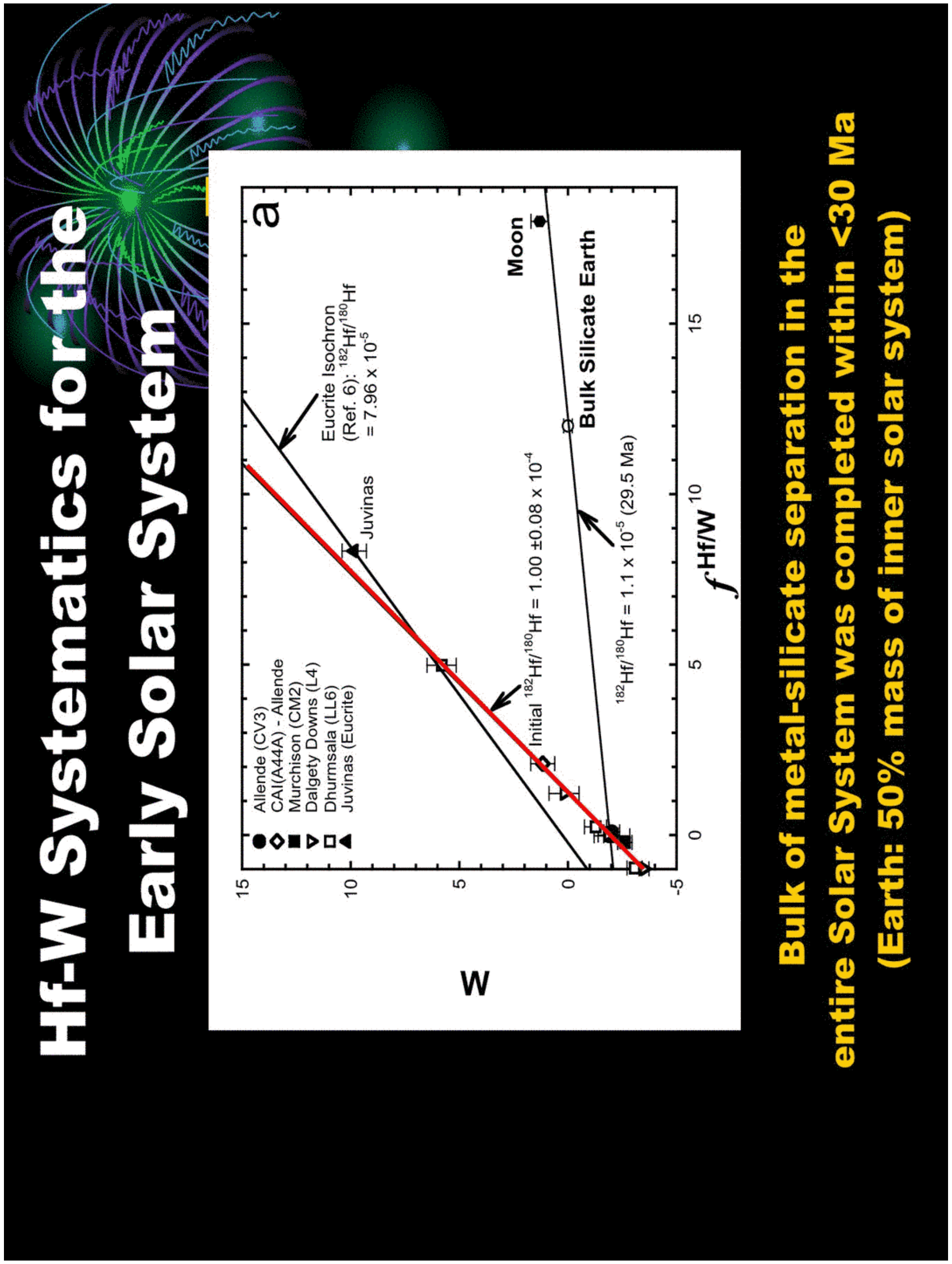


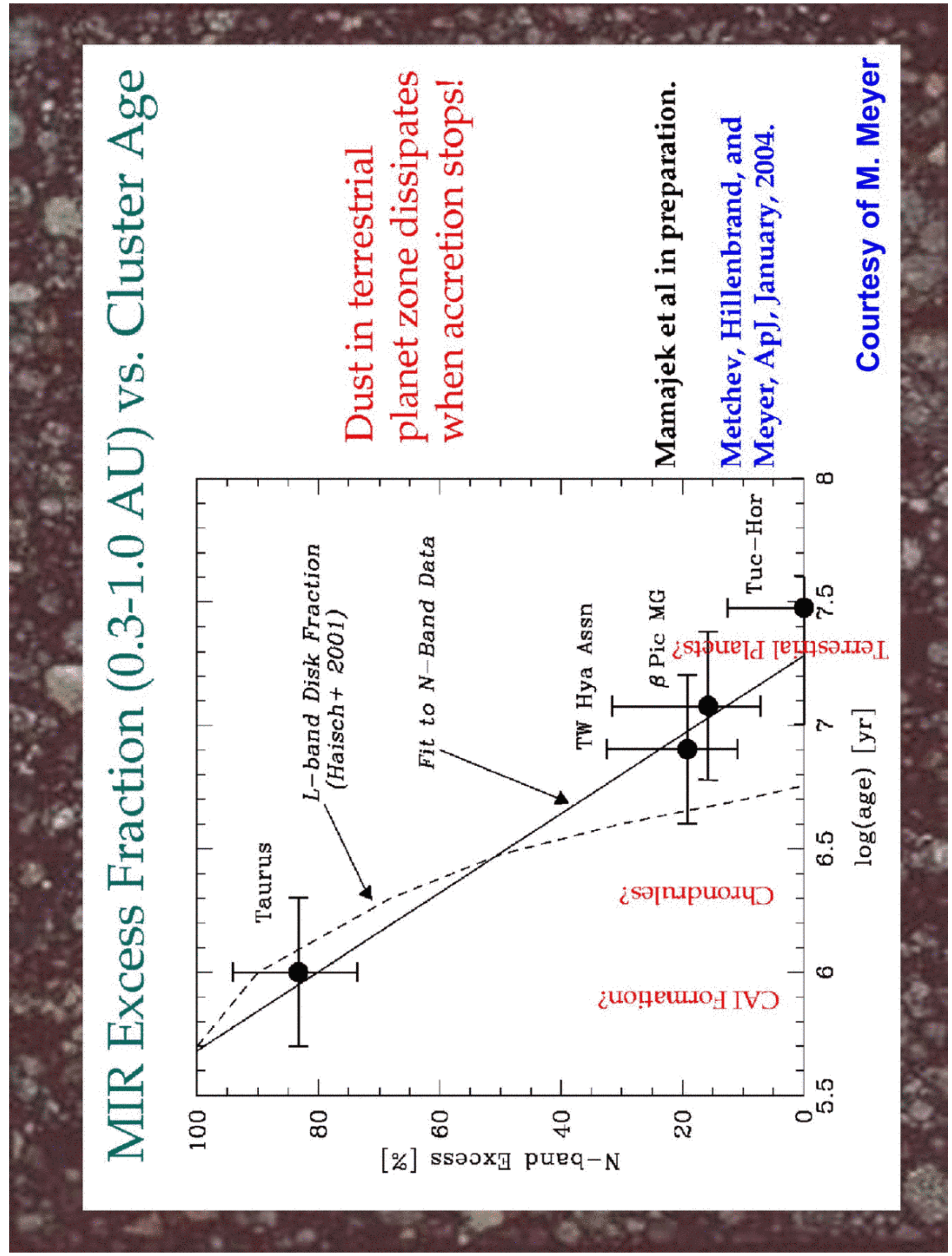
W isotope data that have been widely cited and dominated our thinking between 1995-2002

- Lee and Halliday (1995, 1996 and many later papers)
- Sample — $\varepsilon^{182}W$ (part per 10^4)
- Allende-1 — $-0.10\pm0.56\varepsilon$
- Allende-2 — $-0.50\pm0.50\varepsilon$
- Murchison — $-0.05\pm0.50\varepsilon$
- Mean — $-0.17\pm0.29\varepsilon$

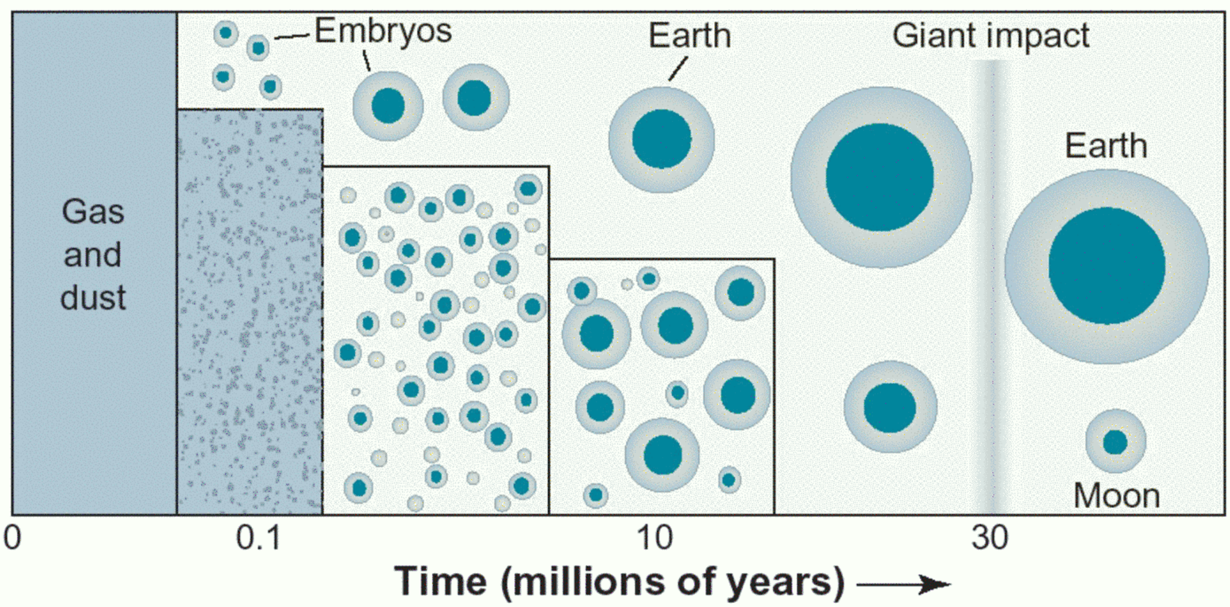

Early Core Formation
182W Growth
Silicate Mantle
Core
CHUR
0
Time (Ma)
>60 Ma
But not at 60Ma
Late Core Formation
182W Growth
Silicate Mantle
Core
CHUR
0
50
100
Time (Ma)


New Hf-W Results in 2002
Allende
Allende
Murchison
Dhurmsala
Dalgety Downs
Allende*
Orgueil
Murray
Karoonda
Murchison
Cold Bokkeveld
Nogoya
ACQUIRE*
GD-Sulphide*
AGV-1
Harvard*
IGDL-GD*
G1-RF*
BB
BE-N
−4
−3
−2
−1
0
εW
Yin et al. (2002, Nature)
Kleine et al (2002, Nature)
Schoenberg et al. (2002, GCA)


Hf-W Systematics for the
Early Solar System
a
Allende (CV3)
CAI(A44A) - Allende
Murchison (CM2)
Dalgety Downs (L4)
Dhurmsala (LL6)
Juvinas (Eucrite)
Eucrite Isochron
(Ref. 6): 182Hf/180Hf
= 7.96 x 10-5
Juvinas
Initial 182Hf/180Hf = 1.00 ±0.08 x 10-4
182Hf/180Hf = 1.1 x 10-5 (29.5 Ma)
Bulk Silicate Earth
Moon
W
fHf/W
Bulk of metal-silicate separation in the
entire Solar System was completed within <30 Ma
(Earth: 50% mass of inner solar system)


MIR Excess Fraction (0.3-1.0 AU) vs. Cluster Age
Dust in terrestrial
planet zone dissipates
when accretion stops!
Mamajek et al in preparation.
Metchev, Hillenbrand, and
Meyer, ApJ, January, 2004.
Courtesy of M. Meyer
Taurus
L-band Disk Fraction
(Haisch+ 2001)
Fit to N-Band Data
TW Hya Assn
β Pic MG
Tuc-Hor
CAI Formation?
Chondrules?
Terrestrial Planets?
N-band Excess [%]
log(age) [yr]

Accretion, mixing, & metal-silicate segregation according to **Standard Planet Formation Theory**

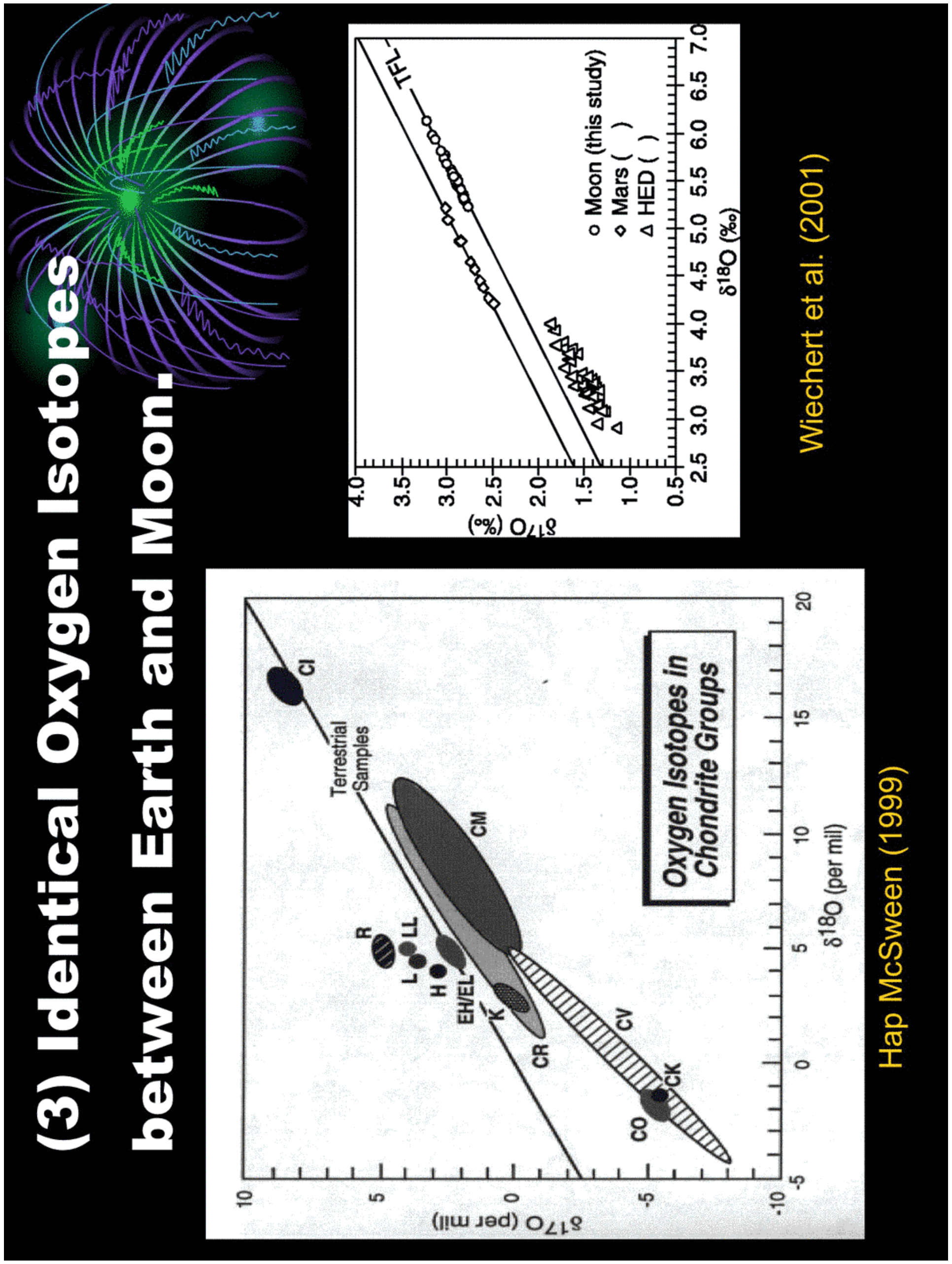


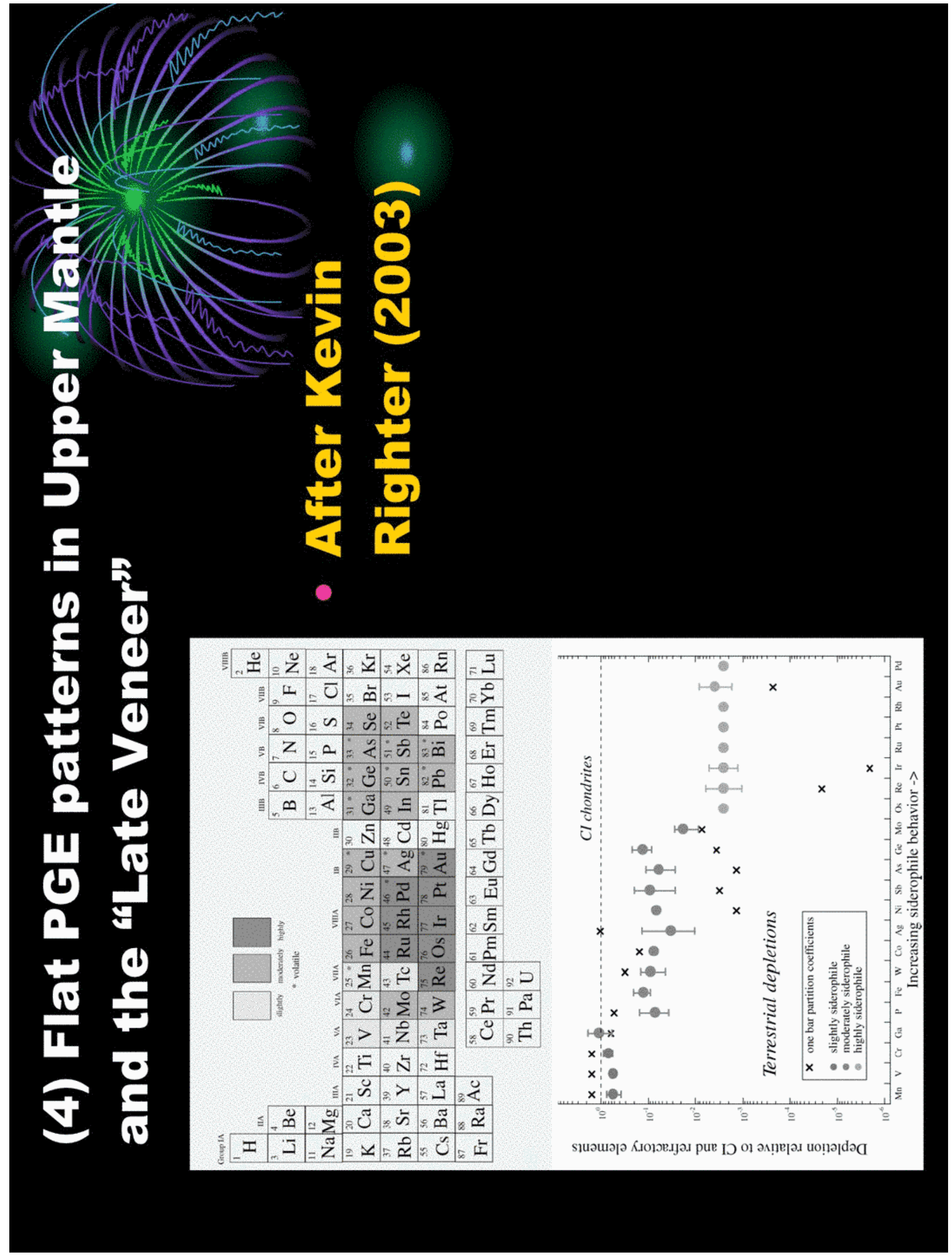
Jacobsen (2003)

Core formation is rate limited by accretion!

Evidences for Chemical Equilibrium during Planet Building Processes

- **(1). Vesta (0.6 to 3 Ma), Mars (3-12 Ma), Earth (10-30 Ma) (Yin et al., 2002; Kleine et al., 2002; Schoenberg et al., 2002).**
- **(2) Testable Predictions: If there was NO chemical equilibrium during the planet formation, W isotope anomalies (with large + and - epsilons) should be found on Earth.**


(3) Identical Oxygen Isotopes between Earth and Moon.
Oxygen Isotopes in Chondrite Groups
Terrestrial Samples
CI
CM
CV
CR
CO
CK
R
LL
L
H
EH/EL
K
δ18O (per mil)
δ17O (per mil)
Hap McSween (1999)
TFL
o Moon (this study)
◇ Mars ( )
Δ HED ( )
δ18O (‰)
δ17O (‰)
Wiechert et al. (2001)


(4) Flat PGE patterns in Upper Mantle and the "Late Veneer"
• After Kevin Righter (2003)
CI chondrites
Terrestrial depletions
one bar partition coefficients
slightly siderophile
moderately siderophile
highly siderophile
Depletion relative to CI and refractory elements
Increasing siderophile behavior ->

Accretion Energy

- Simple physics for faint-hearted, point-and-click geochemist:

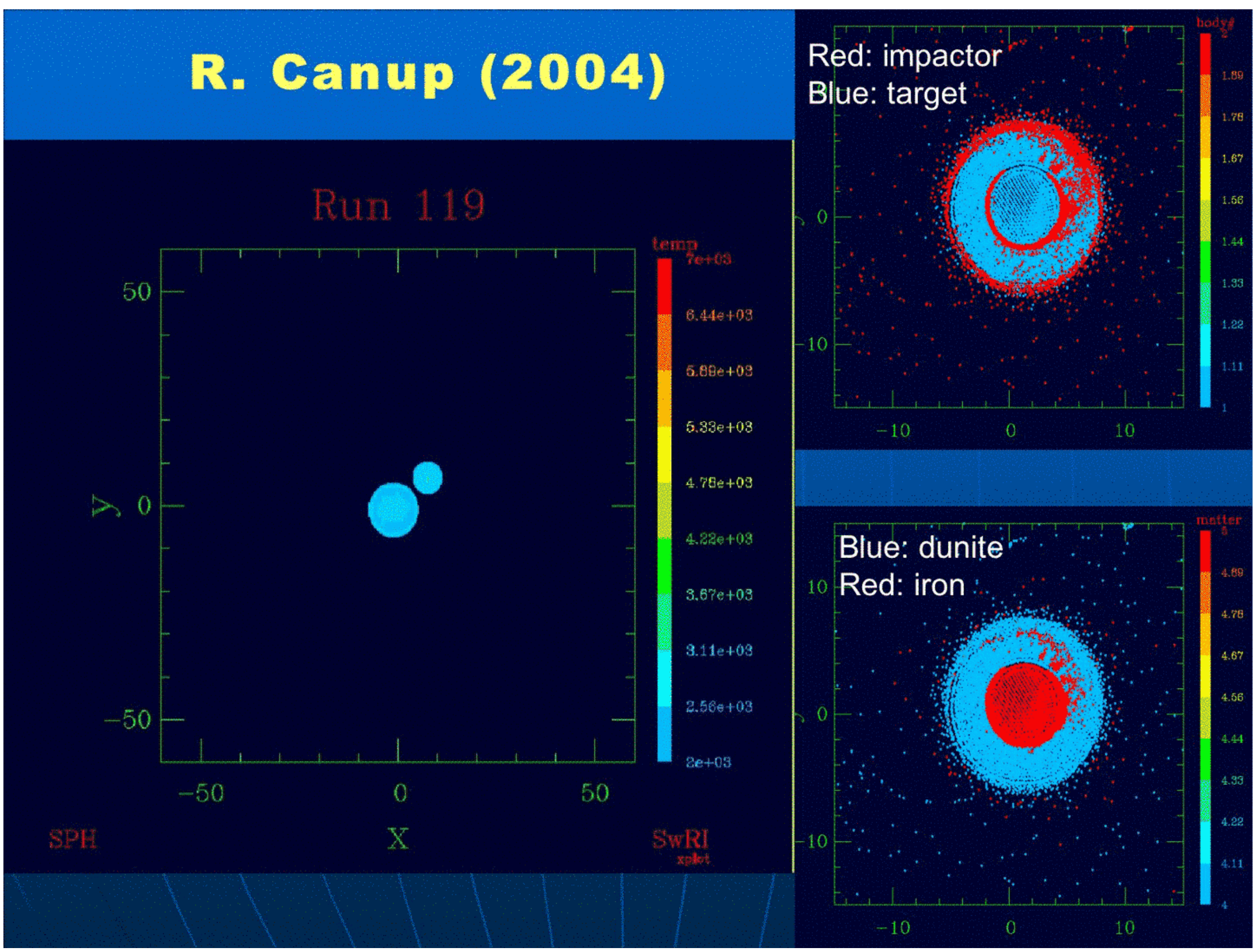
$$\frac{GM^2}{r_p} = MC_p\Delta T$$

$$\Delta T = \frac{1}{C_p}\frac{GM}{r_p} \quad \propto r_p^{\,2}$$

G : gravity constant
M : mass of the planet
r_p : planetary radius
C_p : specific heat
ΔT : temperature increase

ΔT~5E3 to 1E4 K for terrestrial planets

- Enough energy to warrant chemical equilibrium!
- If you think this is too simple and naïve?



Chandrasekhar (1961); Rubie et al. (2003) Stevenson (1990)

Think about pouring down a bucket of water from a balcony of a high rise building : by the time it reach the ground……..

- When dense liquid (metal) falls through a less dense liquid (silicates).
- Rayleigh-Taylor instabilities (density contrast) cause "pancake flattening" of infalling denser materials.
- This instabilities will initiate a cascade of disruption into smaller droplet size.
- Initial core (size<magma ocean depth) break up to the rain of cm-size droplets by the time it reaches magma ocean depth.
- Rubie et al. (2003) showed full chemical equilibration is achieved in 400 second, as soon as it reach cm-sized droplets.
- Stevenson (1990) the largest iron droplets are ~1cm following the rapid (~hours) emulsifcation event of a large impact"

Sasaki and Abe (2003)

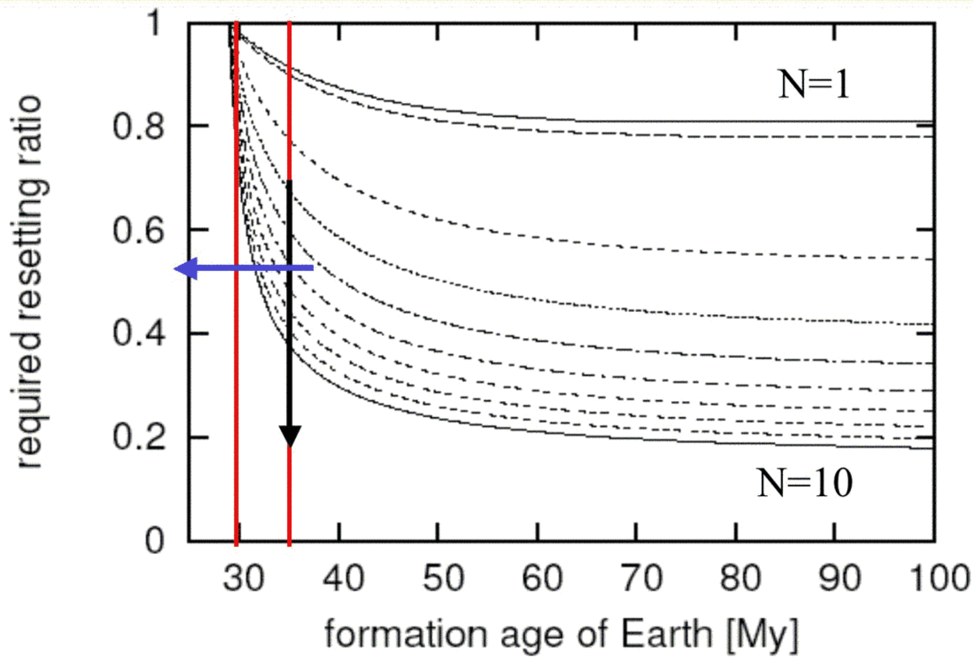


Fig. 4.— Required resetting ratio for observed value of Earth's samples as a function of Earth formation age. The number of giant impacts is 1 to 10 from top to bottom. Initial state is $\epsilon = 8$ and $t = 10$. Total time for perfect resetting (resetting ratio = 1) is about 30 Myr, corresponds to previous study (Yin et al. 2002).

Summary

- Give or take, fully grown Earth is (4567-30)= 4537 ±1Ma old. Equivalent to a 45 year old man with a memory from his infancy (first 100 days) to within 3.5 days
- Hf-W age (accretion and core formation age) and I-Pu-Xe closure age (accretion and atmospheric formation age) are consistent at 30 Ma.

Summary (cont.)

- **30 Ma timescale is consistent with disk observation in young stellar objects.**
- **There are many evidences to support that equilibrium is achieved. The 30 Ma timescale could be accommodated in dis-equilibrium case. Halliday's 50Ma is not unique solution.**
- **Debates 100 years ago:**