The early development of the Earth, Moon and Mars

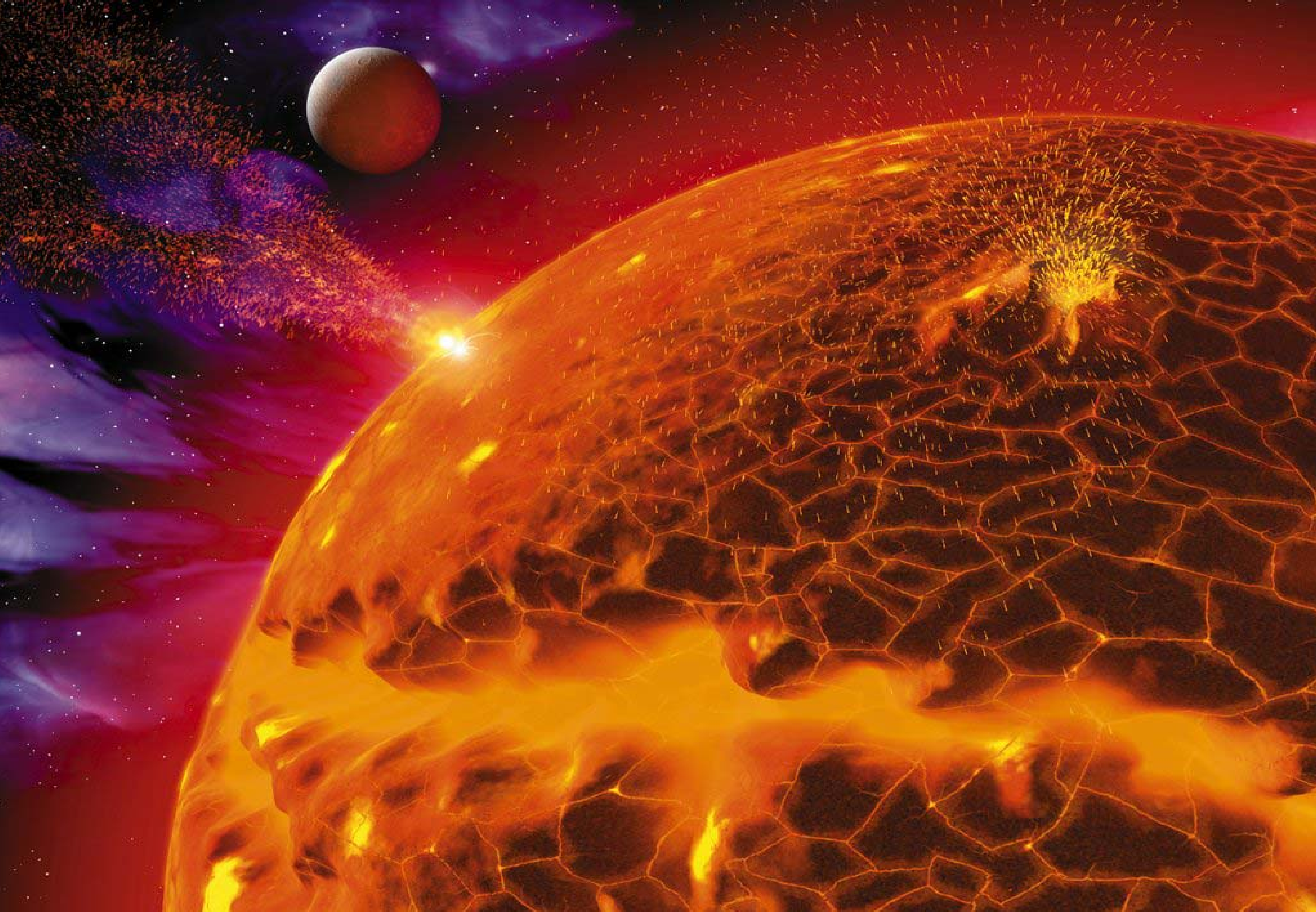
GIFT 2005
The History of the Earth

EGU, Vienna
26-27th April 2005

Issues

- How are Earth-like planets built?
- How did silicate and metal reservoirs form?
- How did Earth acquire its volatile elements?

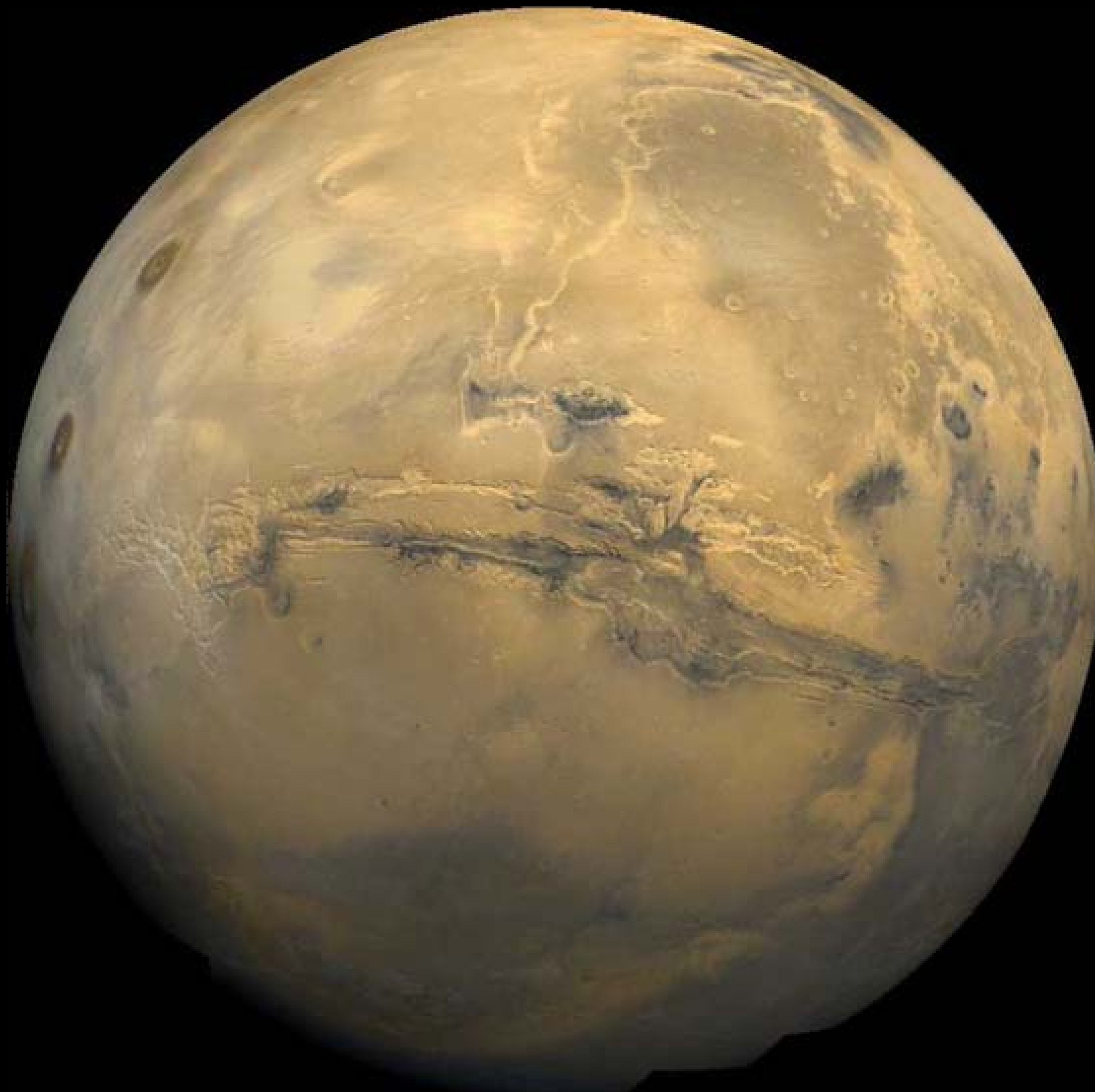
Why isotope geochemistry ?



Why isotope geochemistry ?

Three main kinds of information:

- Rates and timing
- Tracing
- Past and present conditions

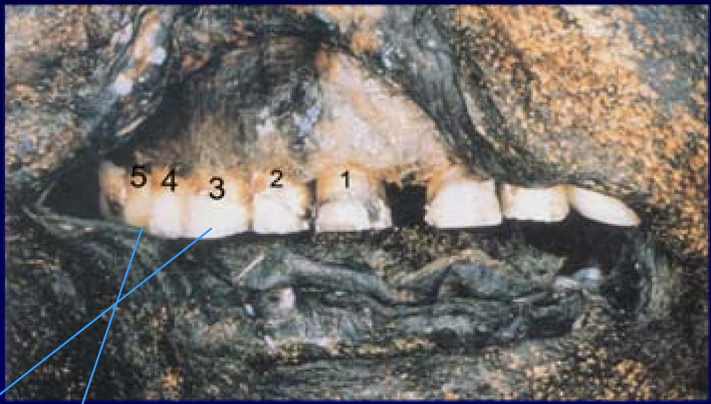


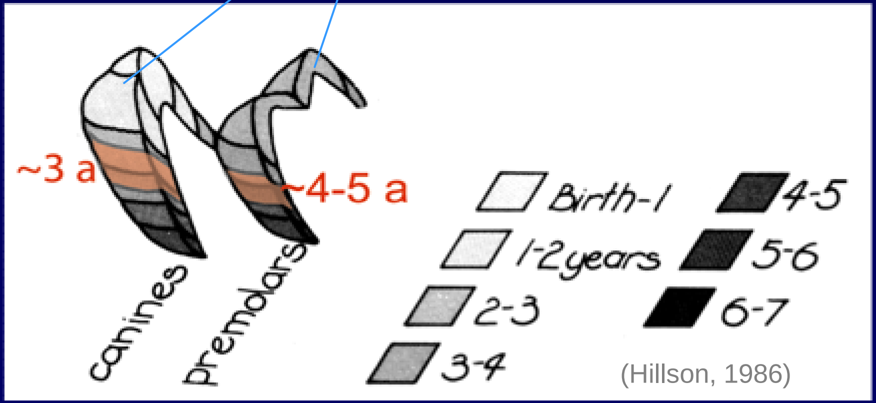
Rates and timing

Some significant radio-nuclides in the early solar system

Nuclide	Half-life (Myrs)	Daughter
^{41}Ca	0.1	^{41}K
^{26}Al	0.73	^{26}Mg
^{60}Fe	1.5	^{60}Ni
^{53}Mn	3.7	^{53}Cr
^{107}Pd	6.5	^{107}Ag
^{182}Hf	8.9	^{182}W
^{247}Cm	12	^{235}U
^{205}Pb	15	^{205}Tl
^{129}I	16	^{129}Xe
^{92}Nb	36	^{92}Zr
^{244}Pu	80	^{136}Xe
^{146}Sm	103	^{142}Nd
^{235}U	704	^{207}Pb
^{238}U	4468	^{206}Pb
^{87}Rb	48800	^{87}Sr

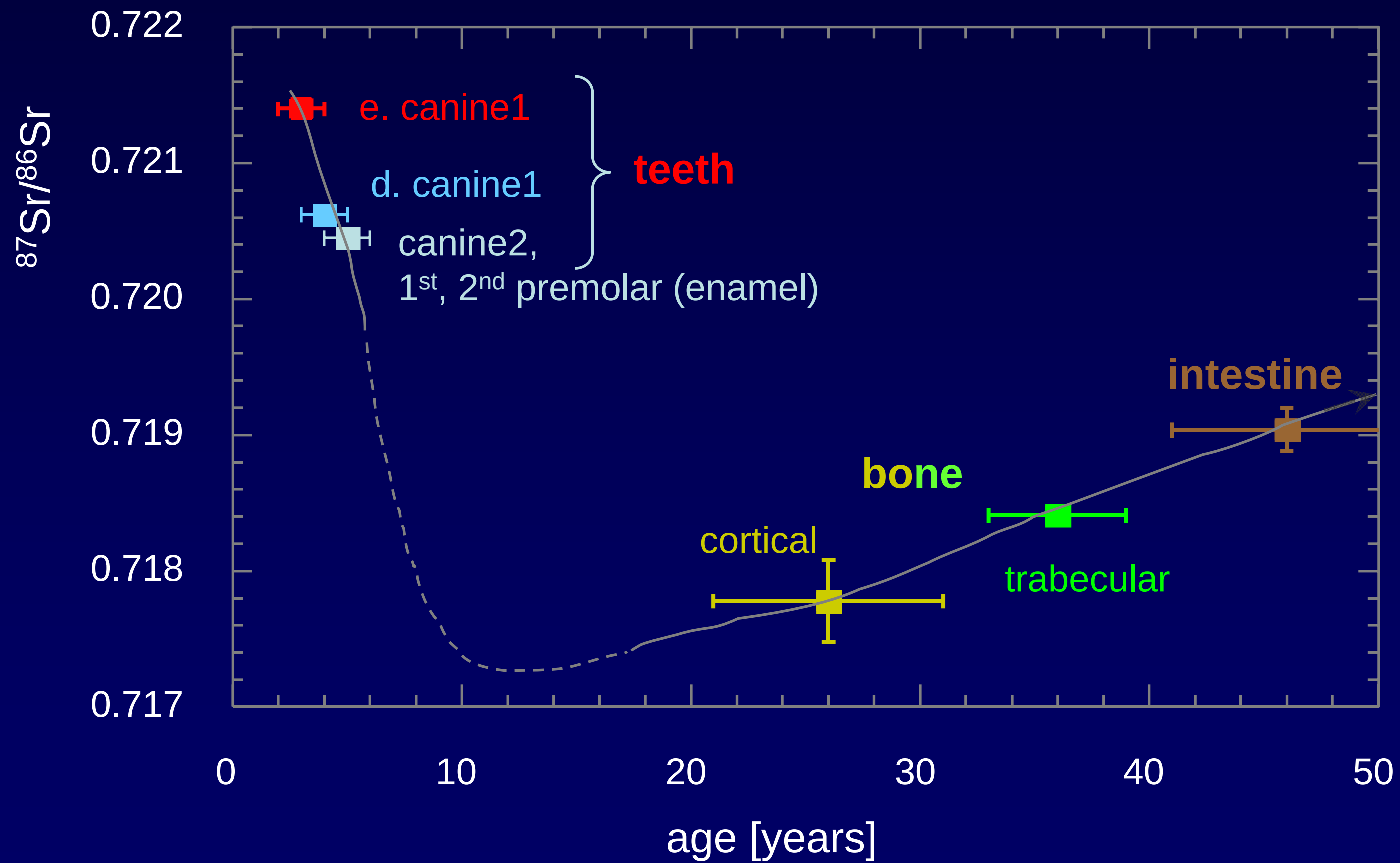
Tracing



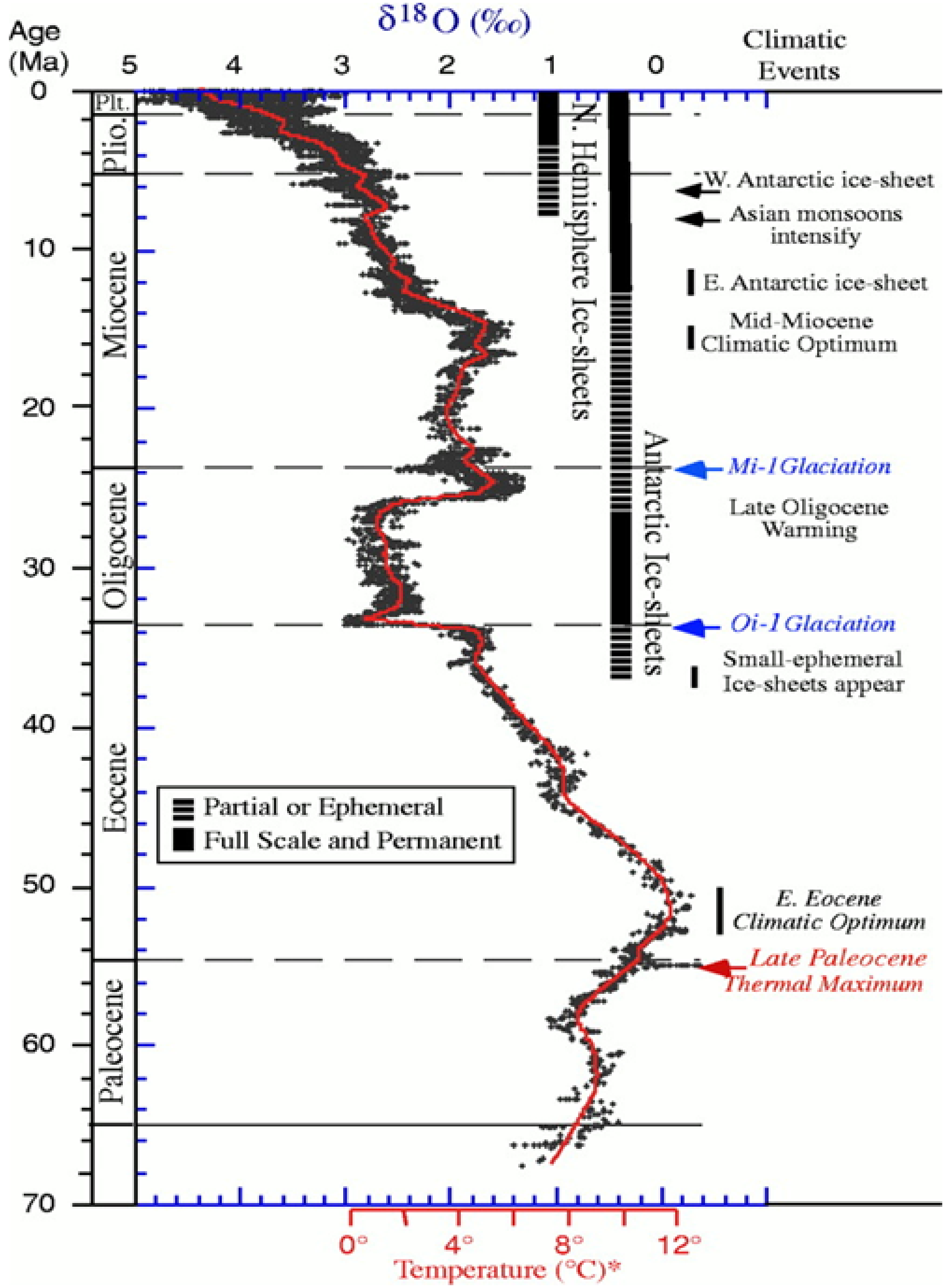


(Hillson, 1986)

Tracing



0.722
0.721
0.720
0.719
0.718
0.717
$^{87}Sr/^{86}Sr$
e. canine1
d. canine1
canine2,
1st, 2nd premolar (enamel)
teeth
intestine
bone
cortical
trabecular
0
10
20
30
40
50
age [years]



Past and present conditions

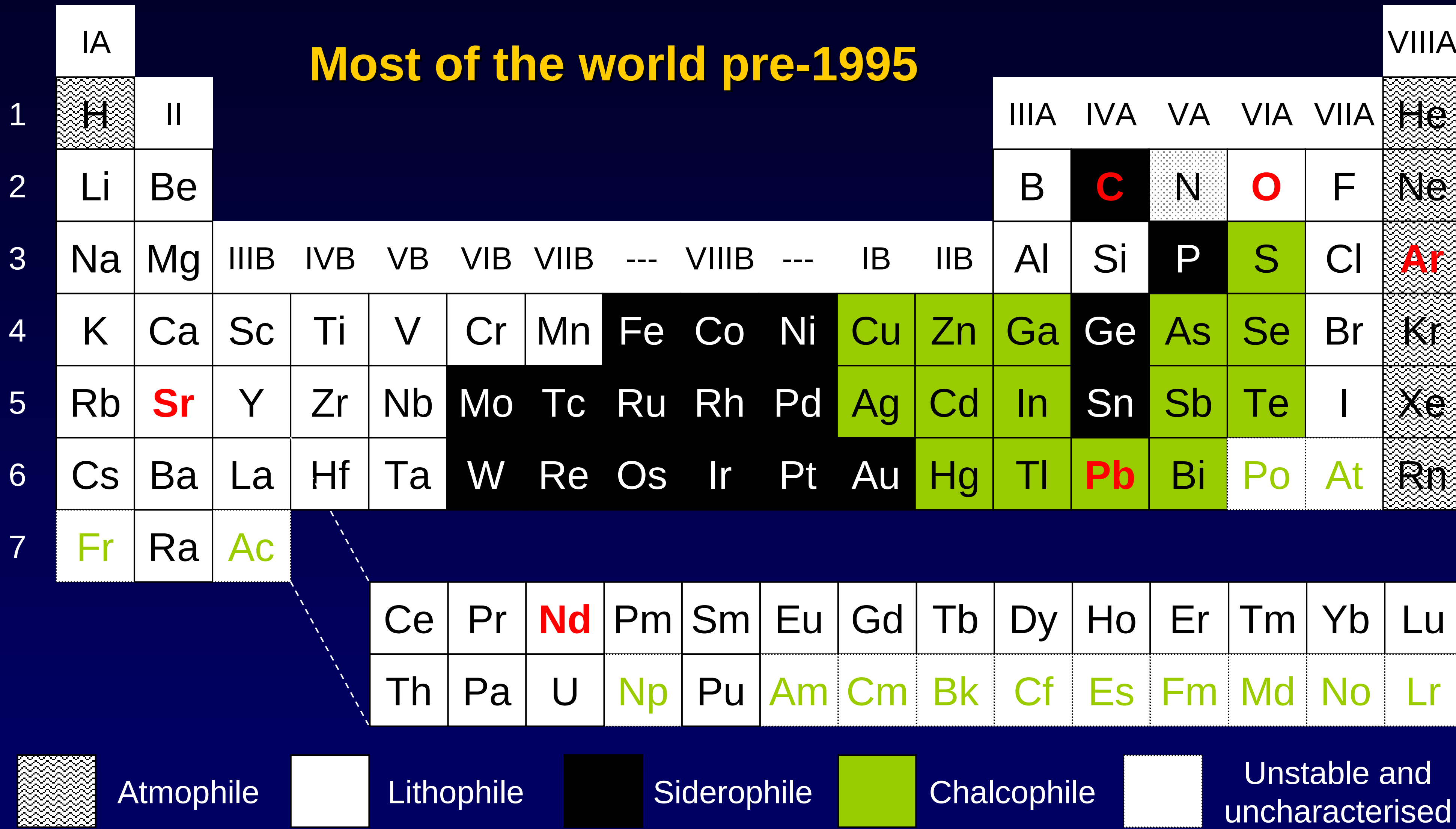
Stable isotopes

$$\delta^{18}O = \frac{\frac{^{18}O}{^{16}O} sample - \frac{^{18}O}{^{16}O} std.}{\frac{^{18}O}{^{16}O} std.} x1000$$

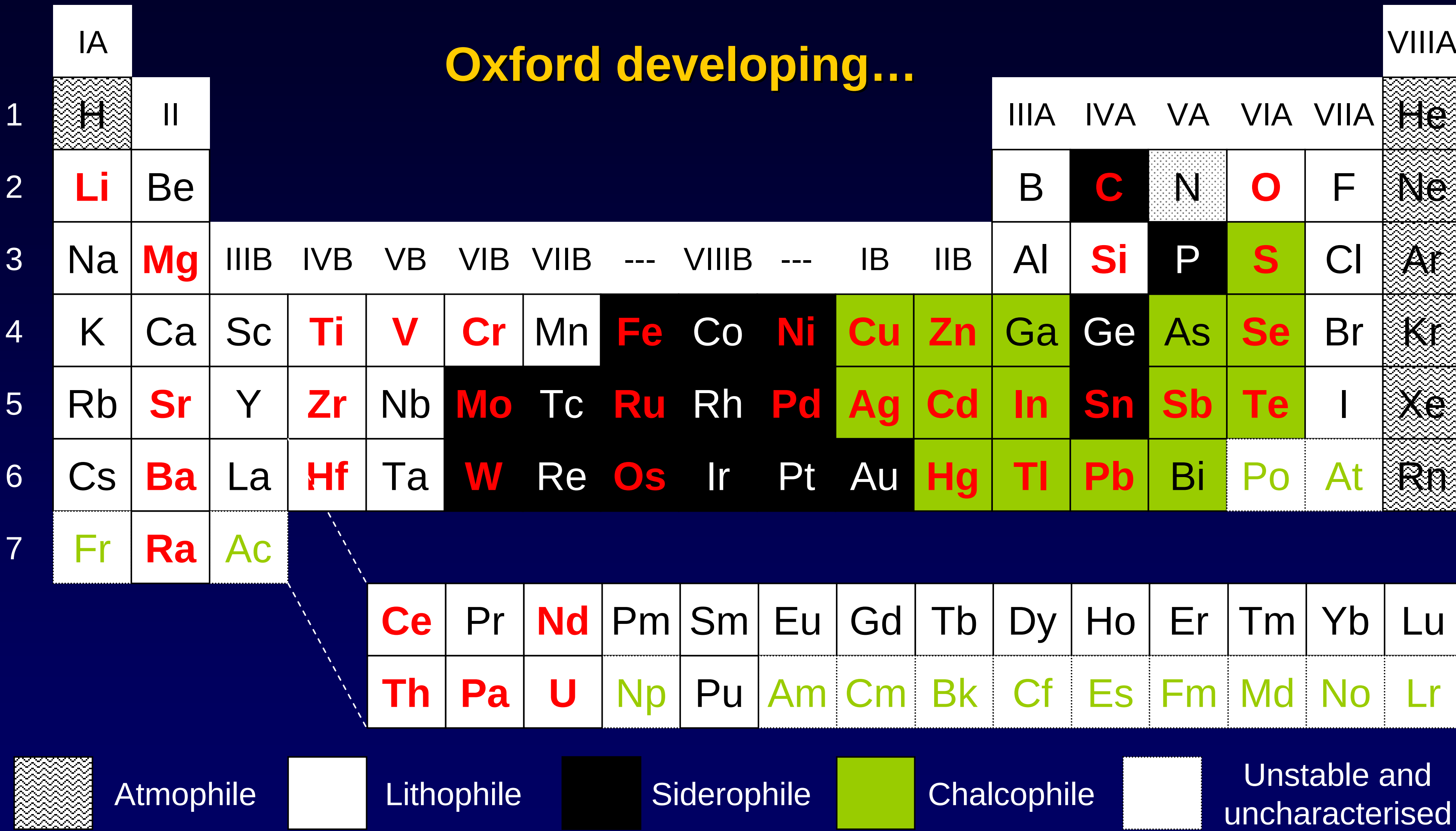
Multiple collector inductively coupled plasma source mass spectrometry

Opens the periodic table for isotopic research

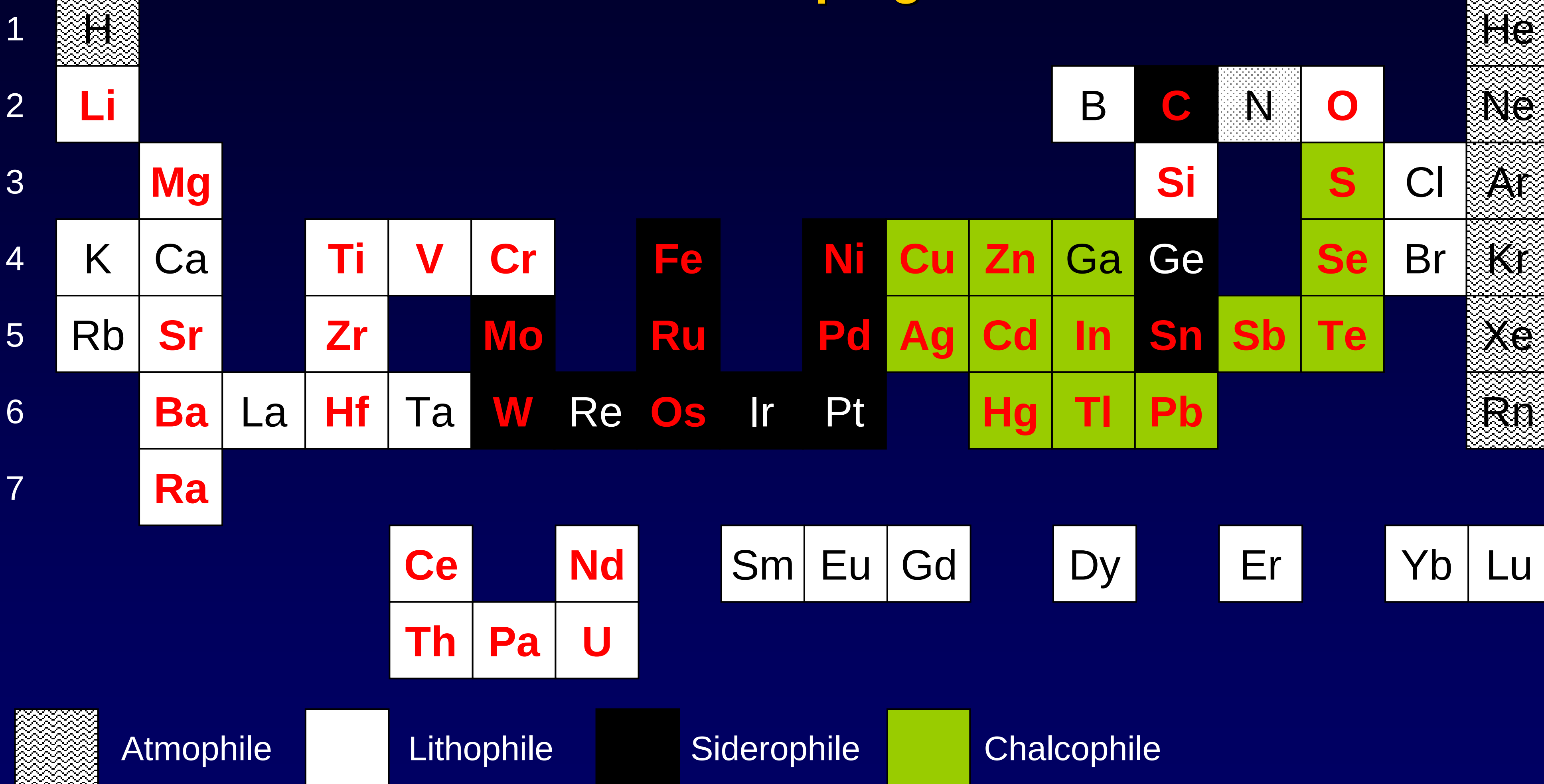
Most of the world pre-1995



Oxford developing…



Oxford developing…




To take advantage of
MC-ICPMS you need
Physicists who can design
and build new kinds
of MC-ICPMS instruments

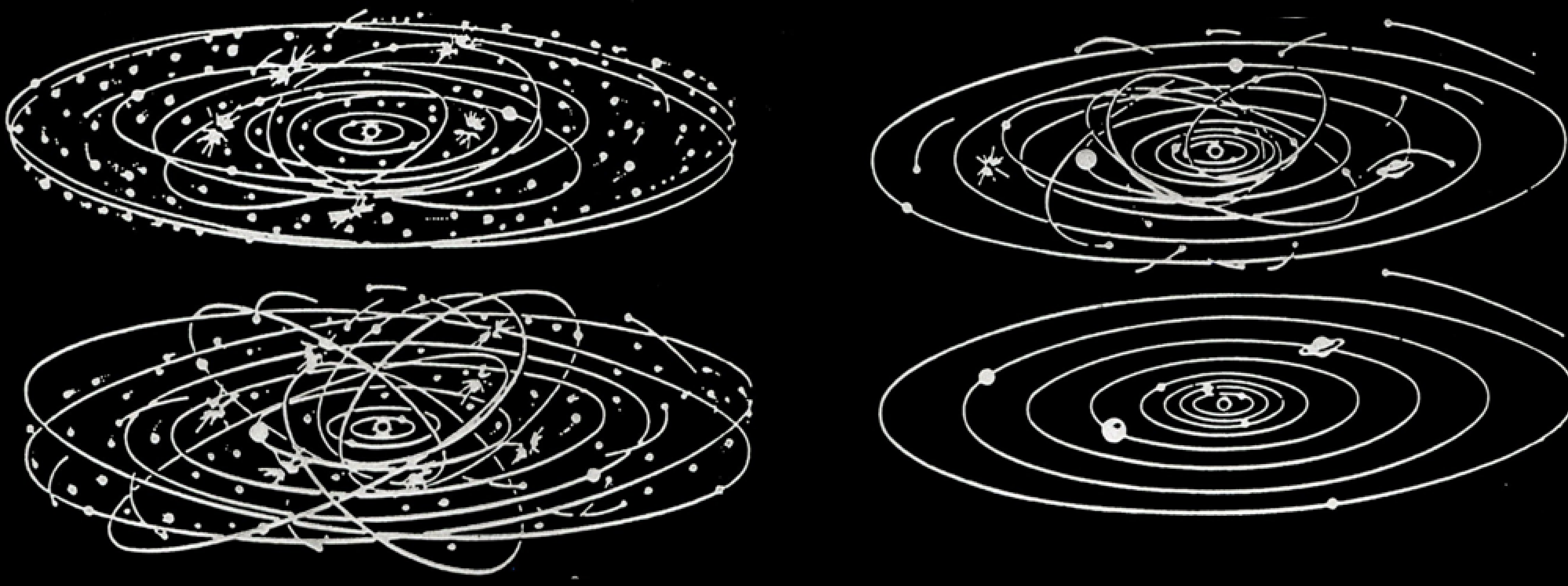

To take advantage of
MC-ICPMS you need
Experts in laser technology
LAMBDA PHYSIK
HAL 100

Issues

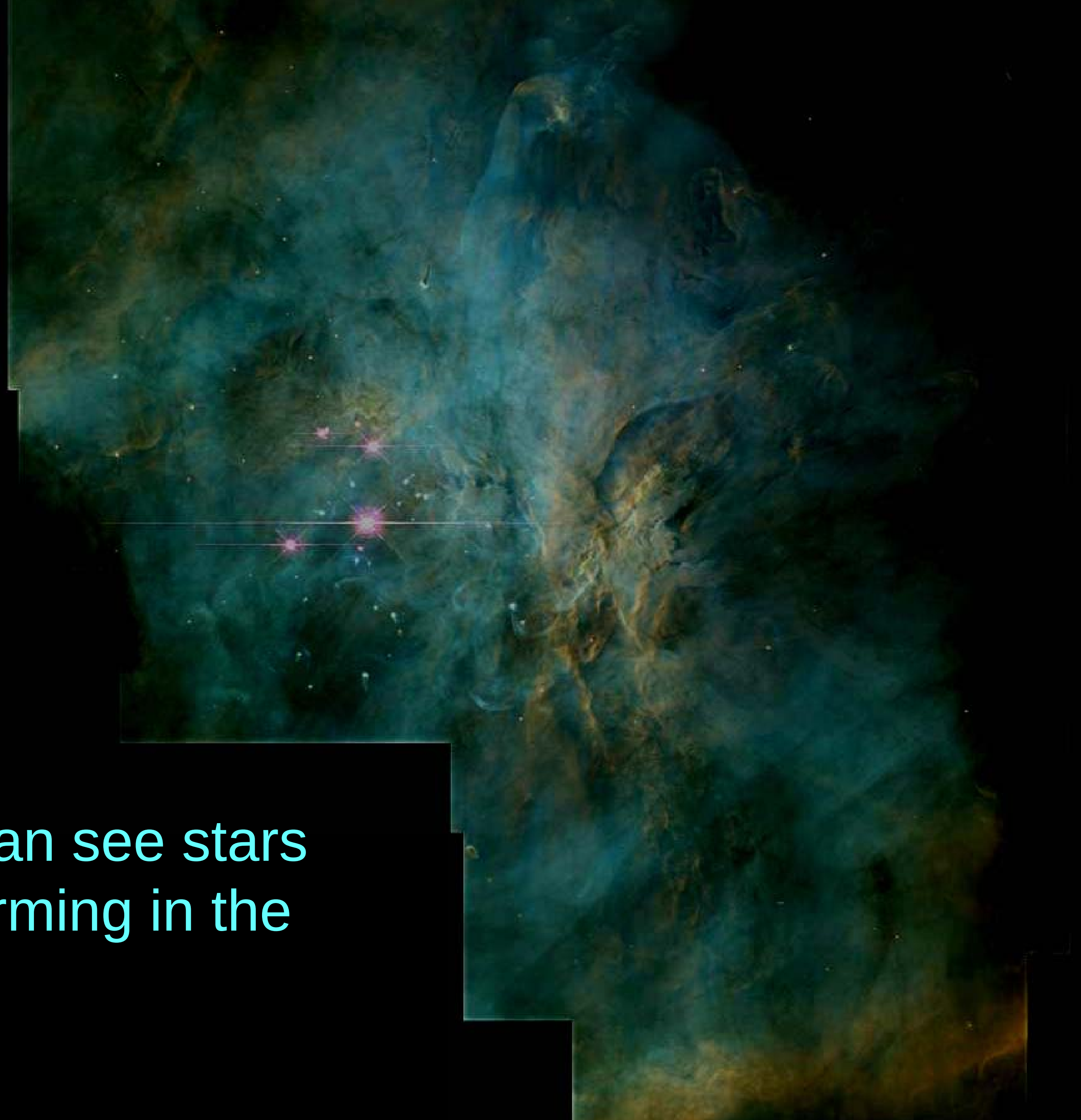
- How are Earth-like planets built?
- How did silicate and metal reservoirs form?
- How did Earth acquire its volatile elements?

Planet formation

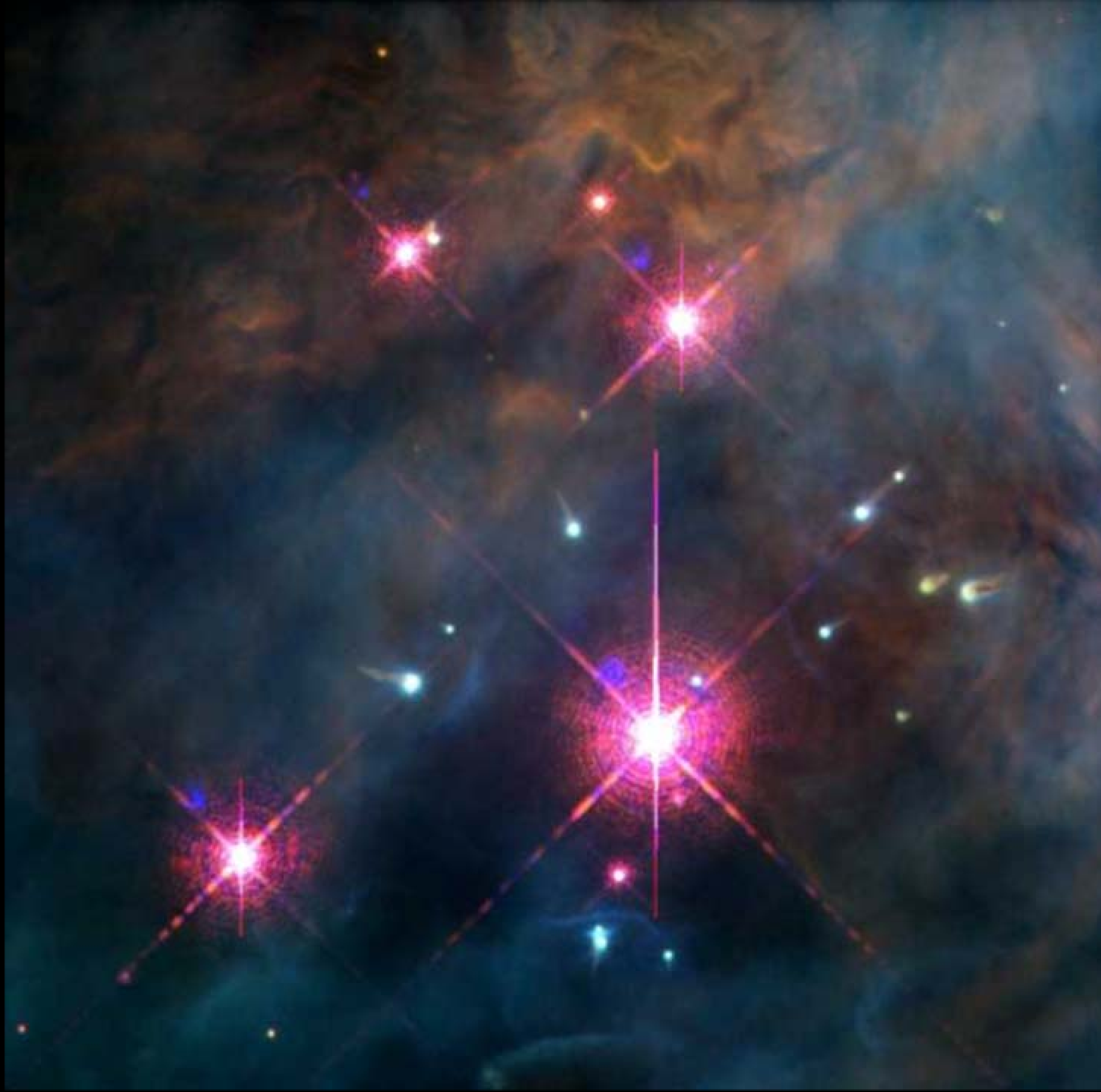
Disk theory



Star formation

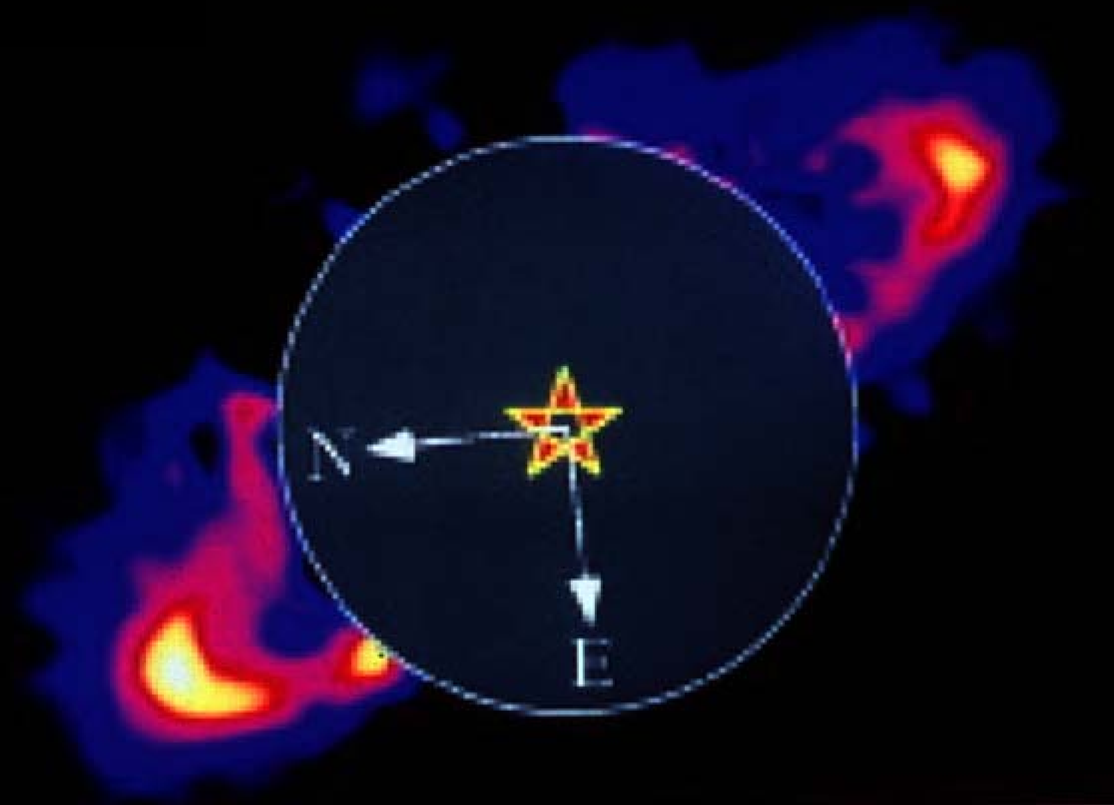


Astronomers can see stars like our Sun forming in the Orion Nebula



Many of the new stars are embedded in a disk of dust and gas

Dusty disks can also be detected around slightly older stars with interferometry.



HR4796A is ~ 8 million years old

Time-scales

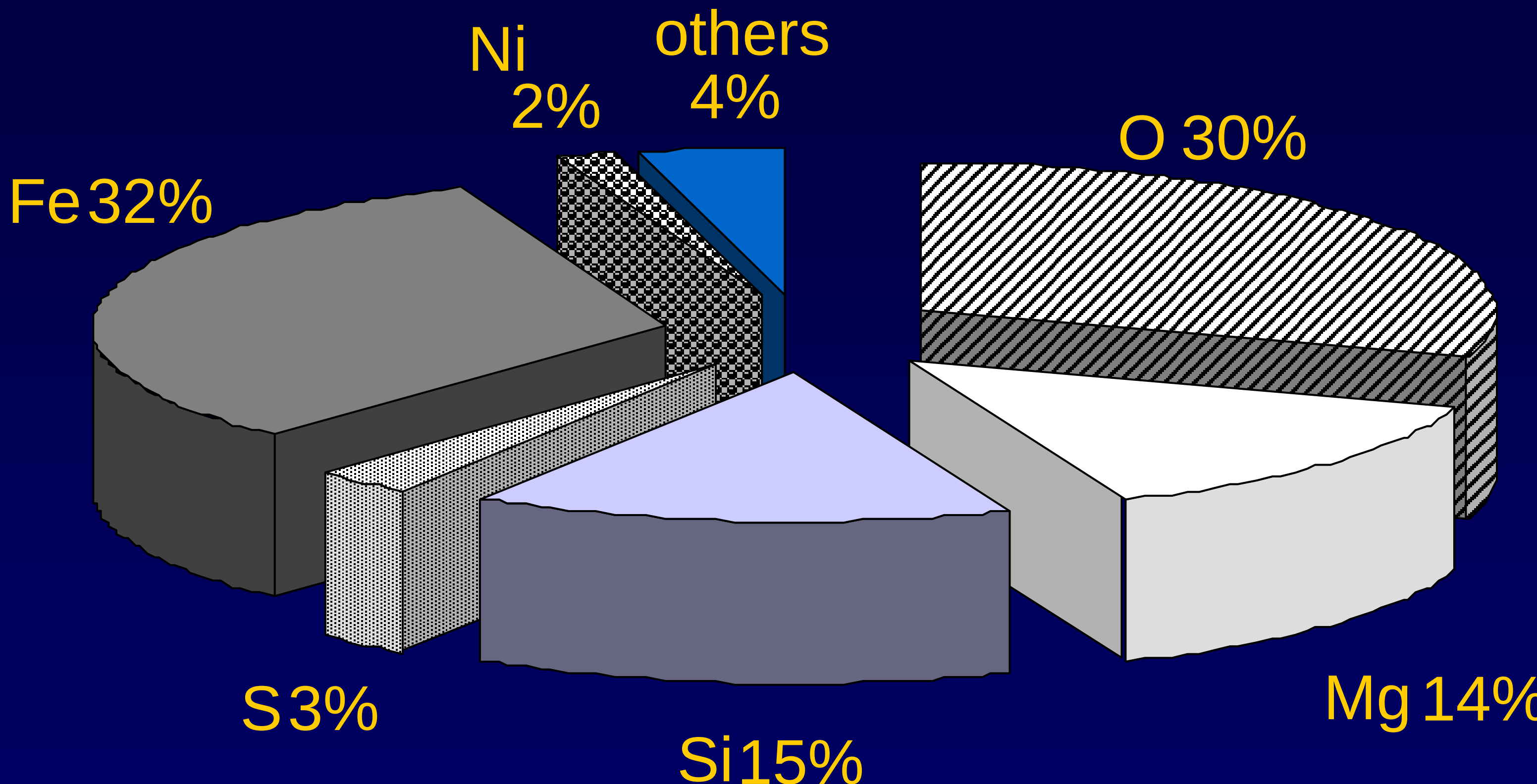
Saturn

About 100 times bigger than the Earth

Must have formed fast to trap nebular gases

How did the Earth and Moon form?

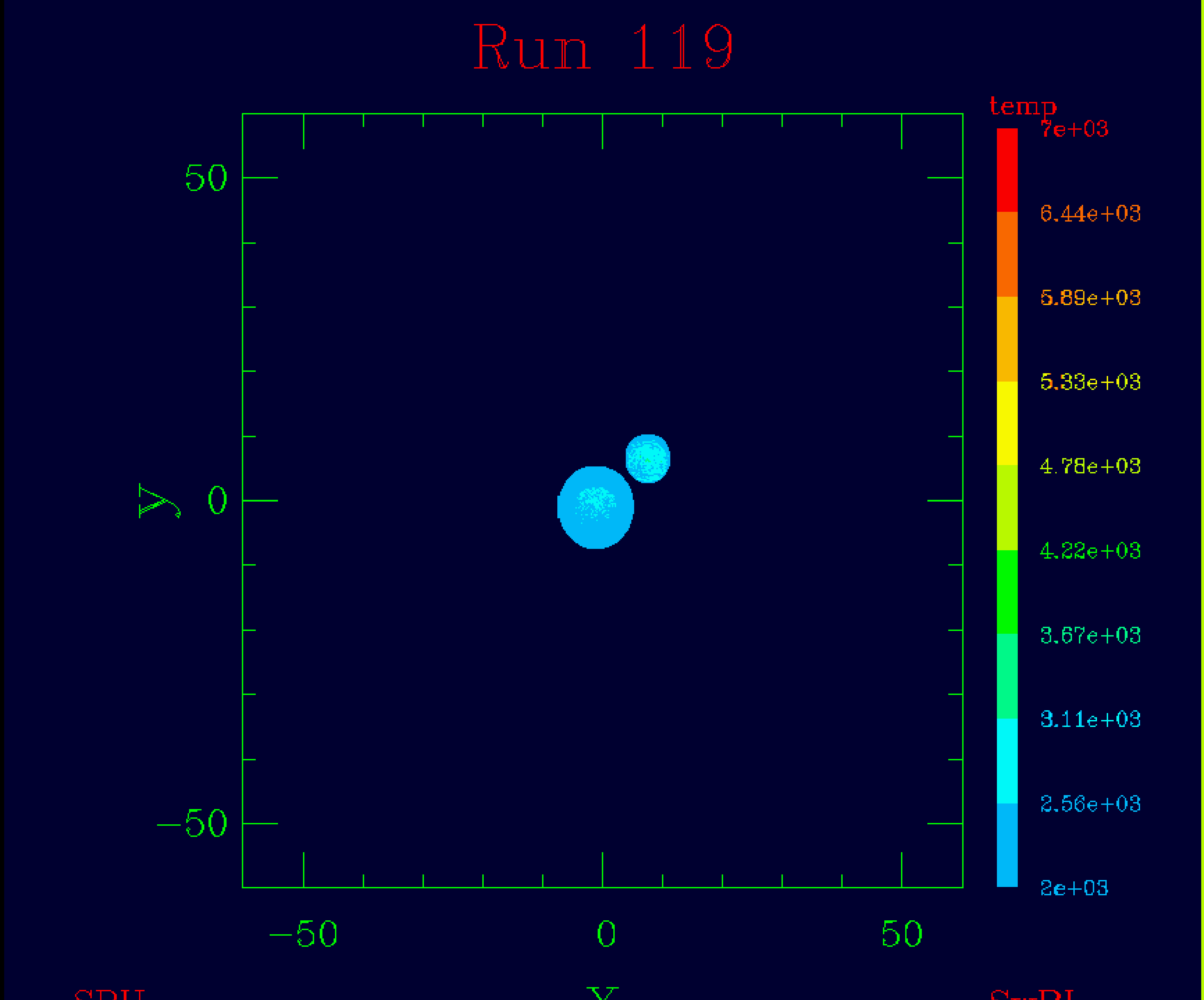
“Earth Pie”



Models for accreting the Earth

- Solar mass nebula
  (Cameron 1978)
- Minimum mass solar nebula
  (e.g. Hayashi 1978)
- Late stage collisions with no nebula
  (e.g. Wetherill 1986)

The Moon probably formed from debris produced in a giant impact between the proto-Earth (~90% Earth mass) and another planet called "Theia" (~10% Earth mass).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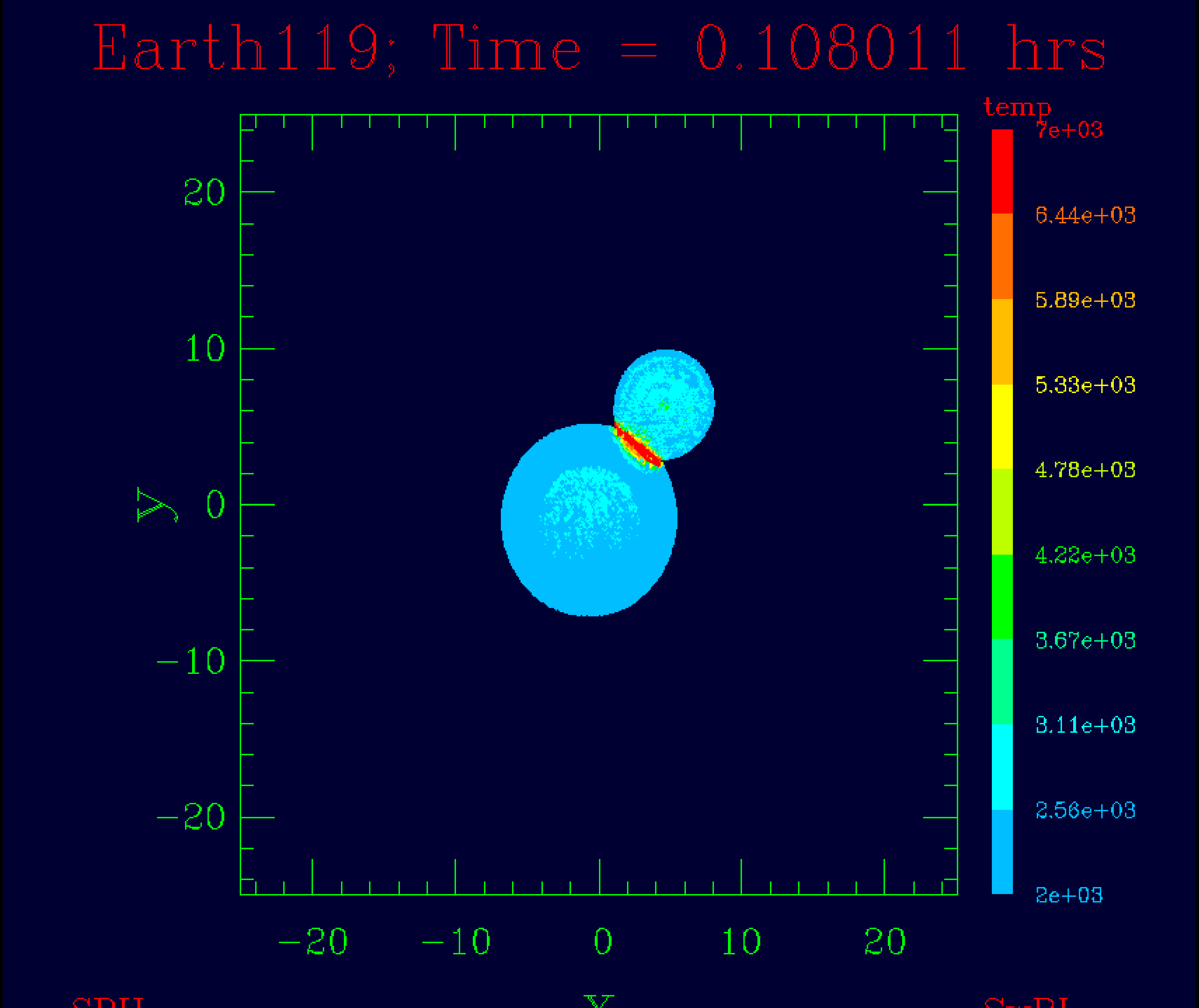
6.44e+03
5.89e+03
5.33e+03
4.78e+03
4.22e+03
3.67e+03
3.11e+03
2.56e+03
2e+03
50
y 0
−50
−50
0
50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3.67e+03
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2.56e+03
2e+03
y
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10
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−10
−20
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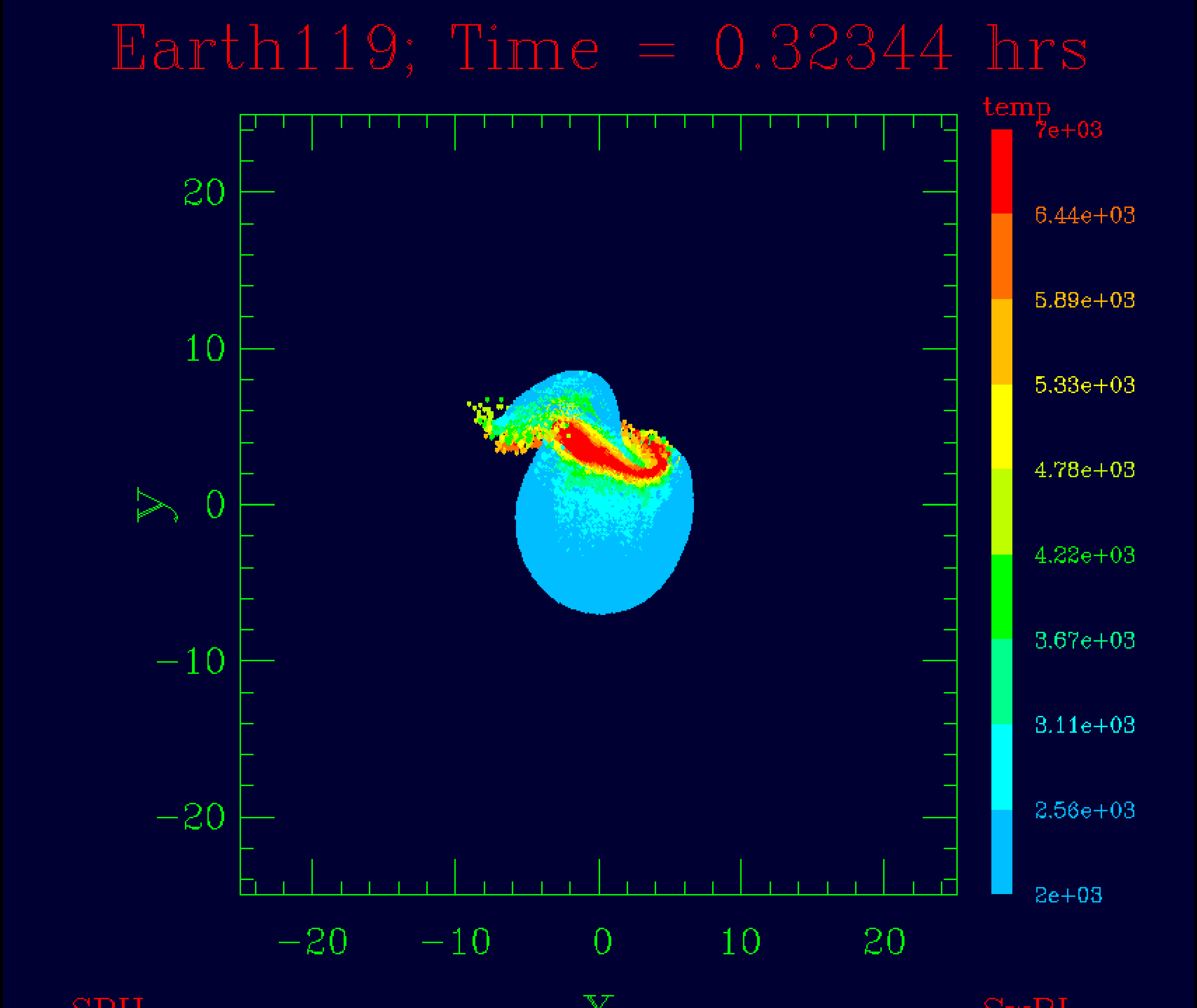
−10
0
10
20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3.67e+03
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y
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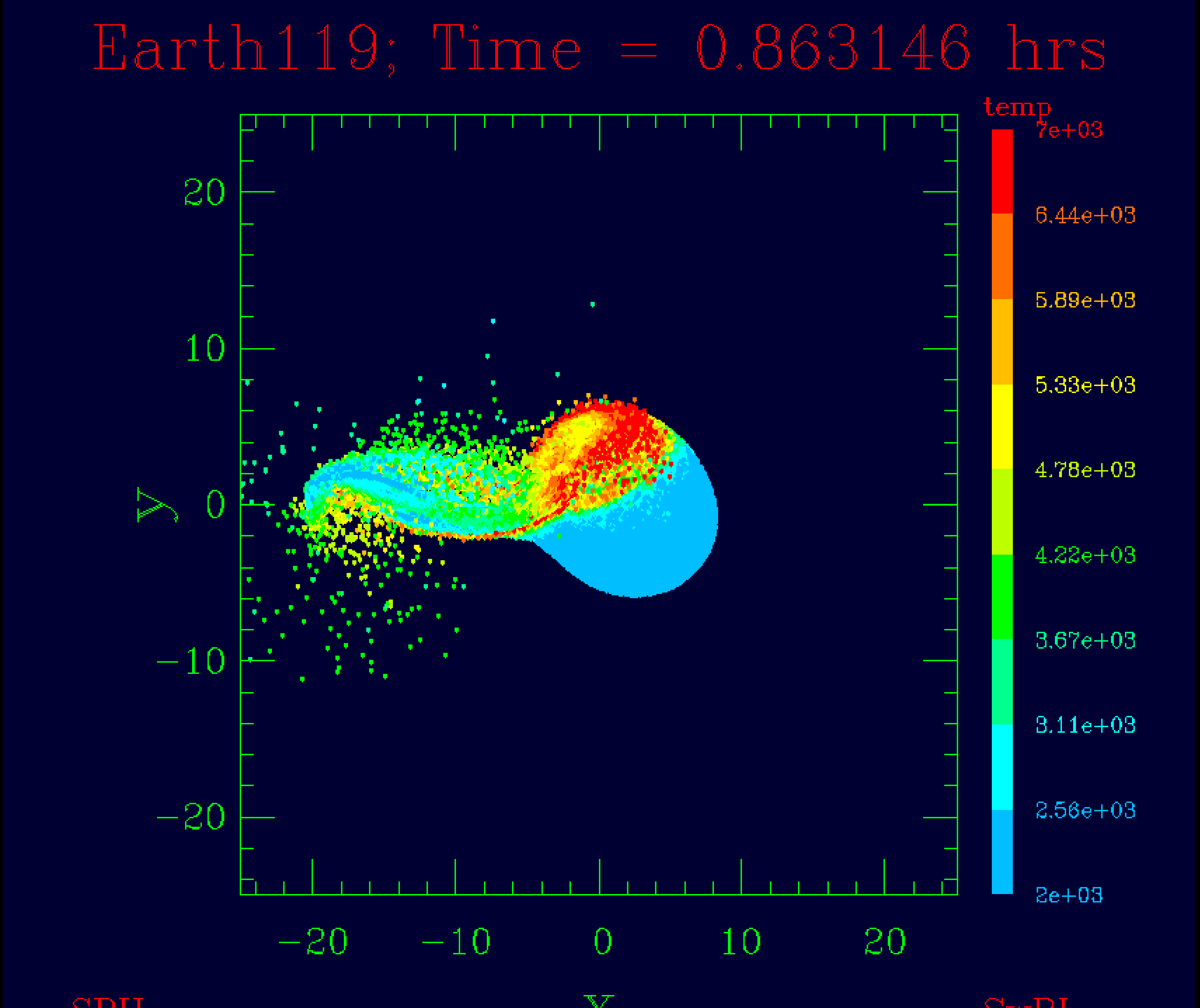
0
10
20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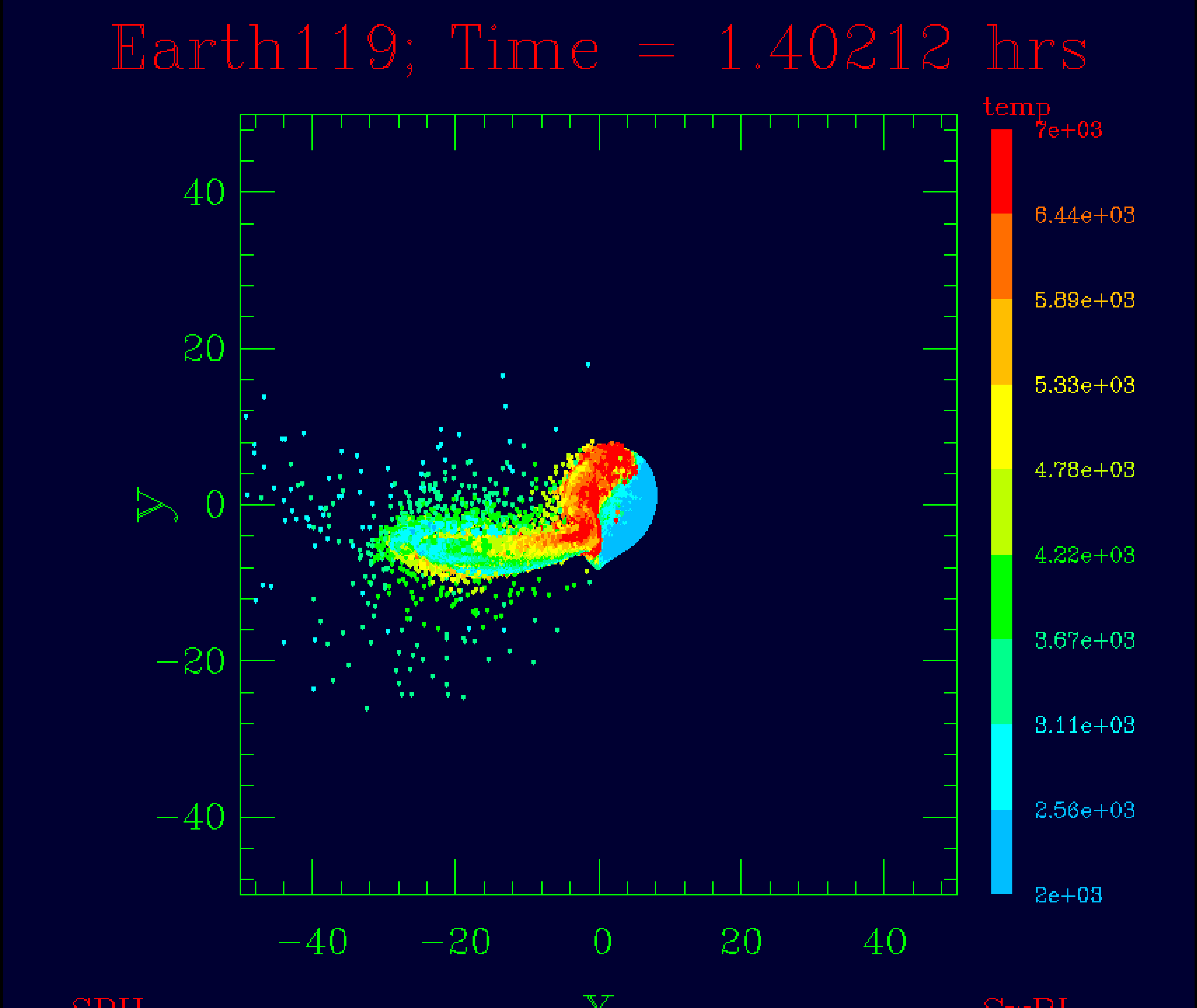
−10
0
10
20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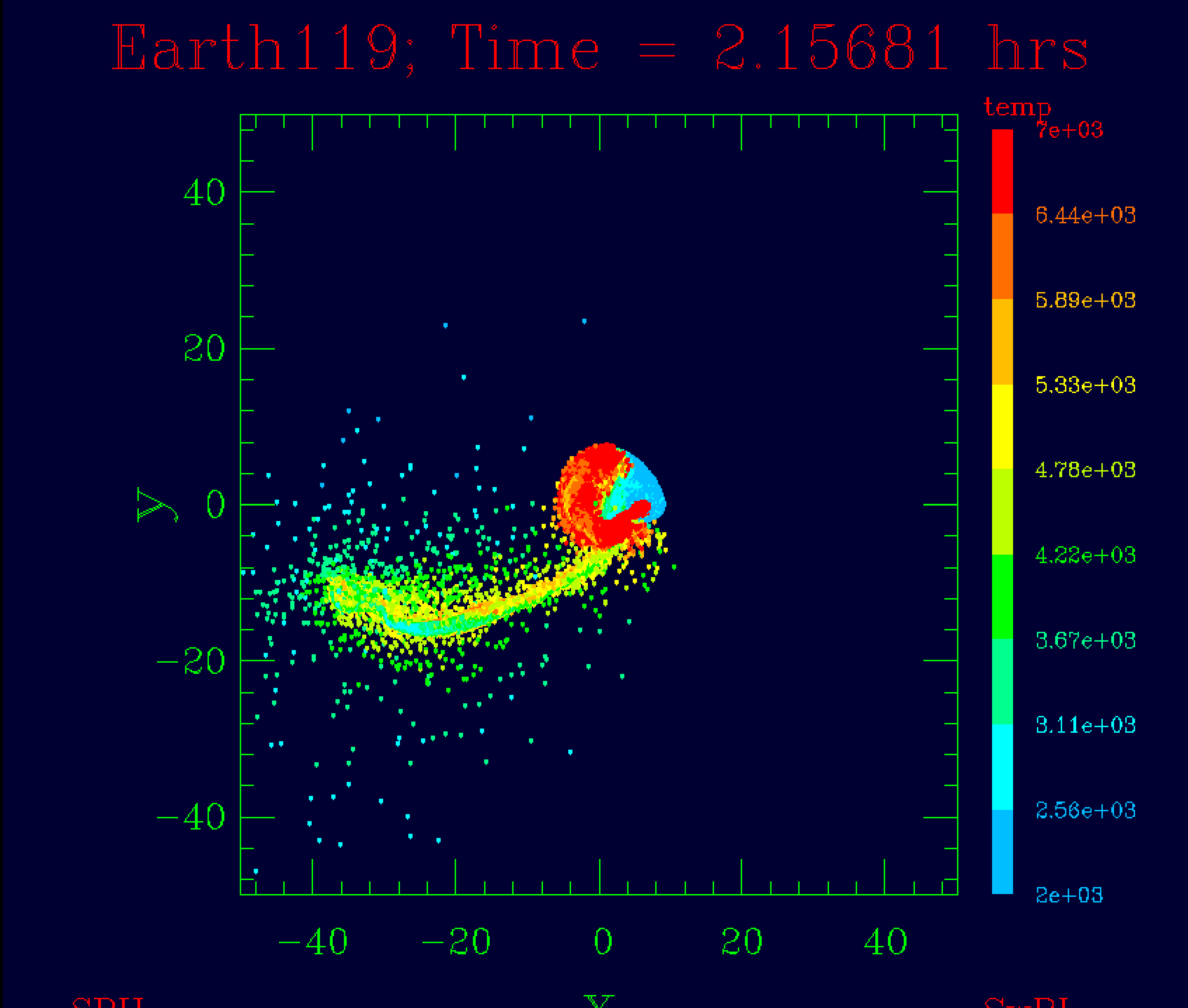
3.11e+03
2.56e+03
2e+03
40
20
0
−20
−40
y
x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4.78e+03
4.22e+03
3.67e+03
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2e+03
y
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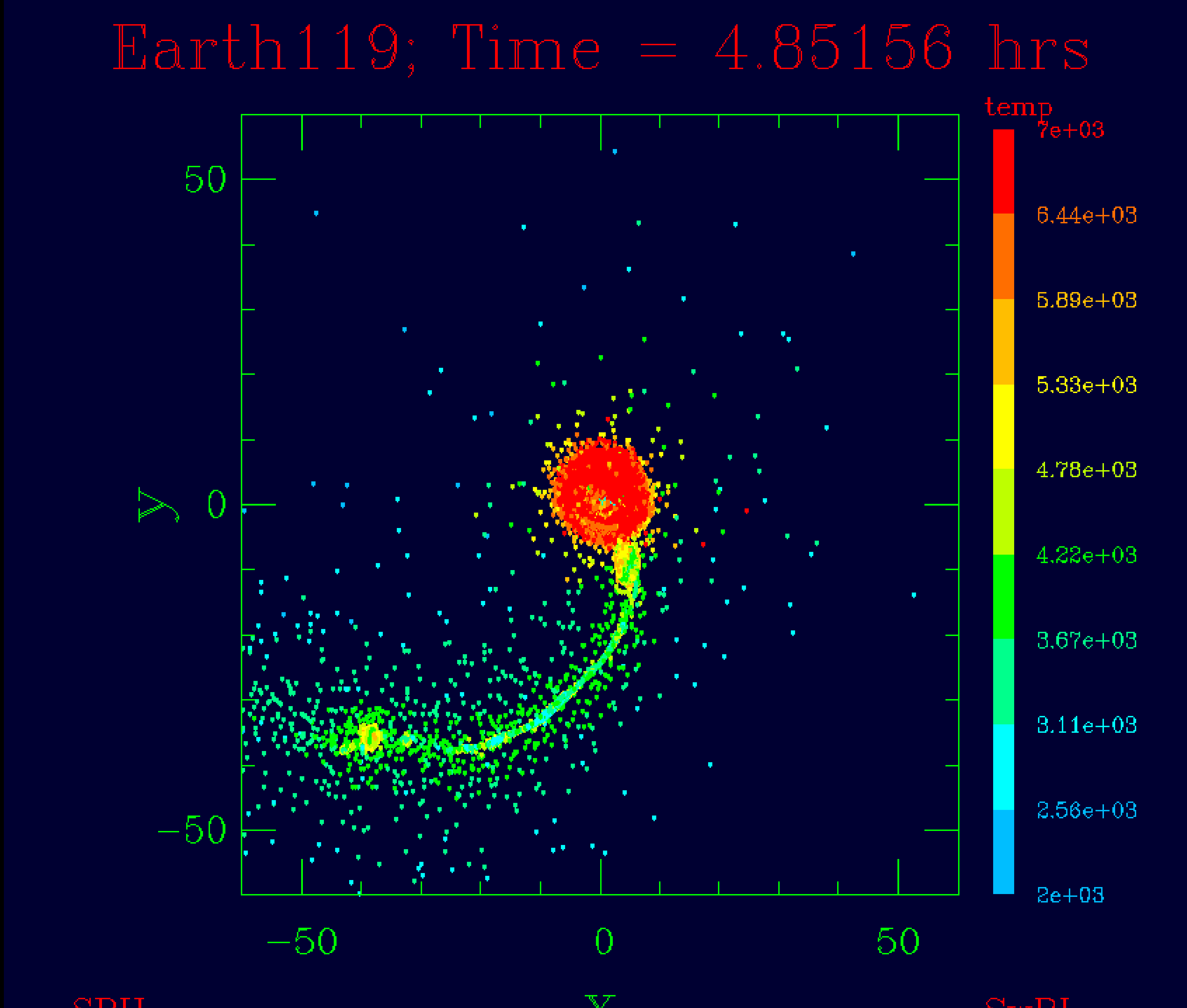
20
0
−20
−40
−40
−20
0
20
40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2e+03
y
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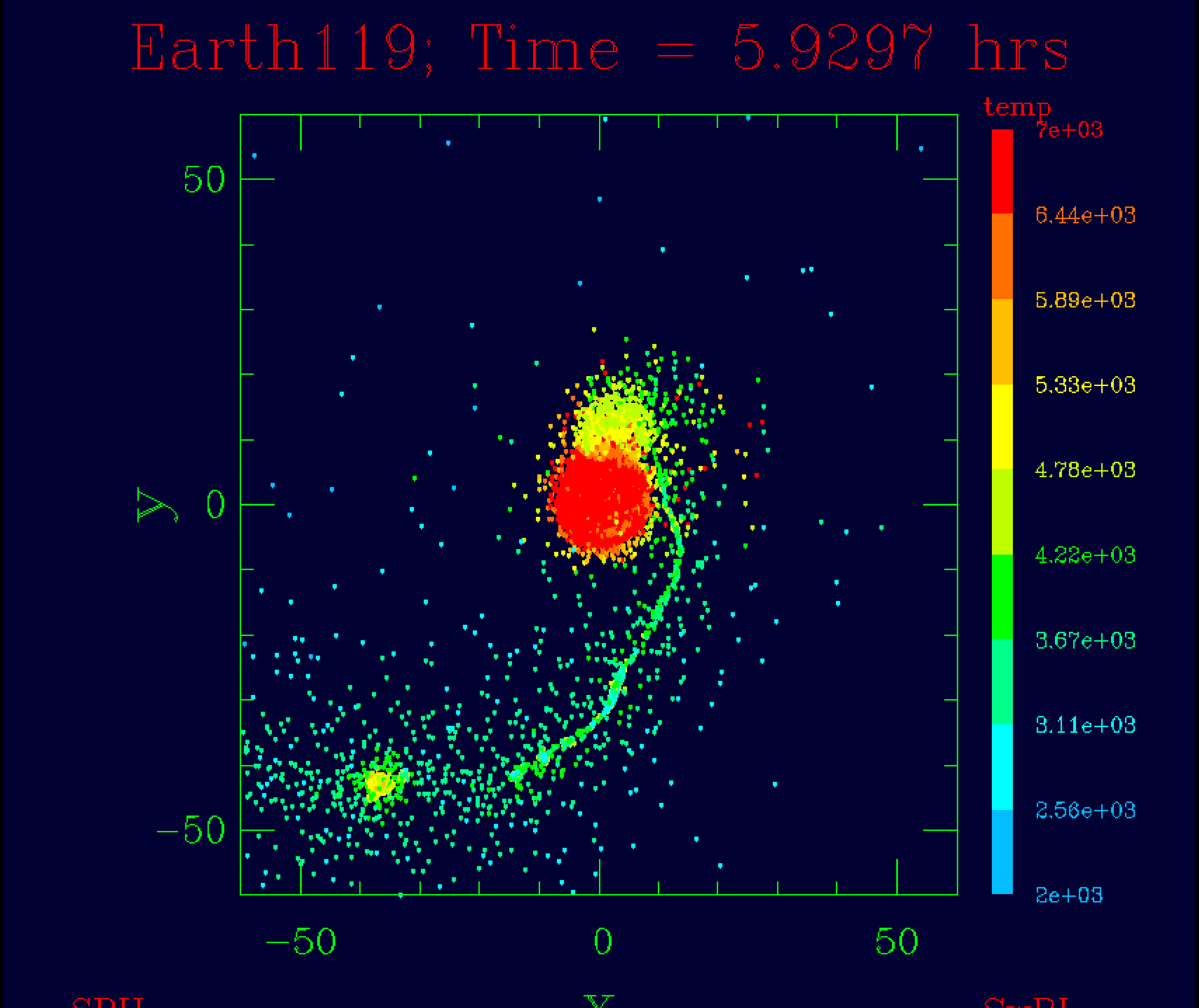
0
−50
−50
0
50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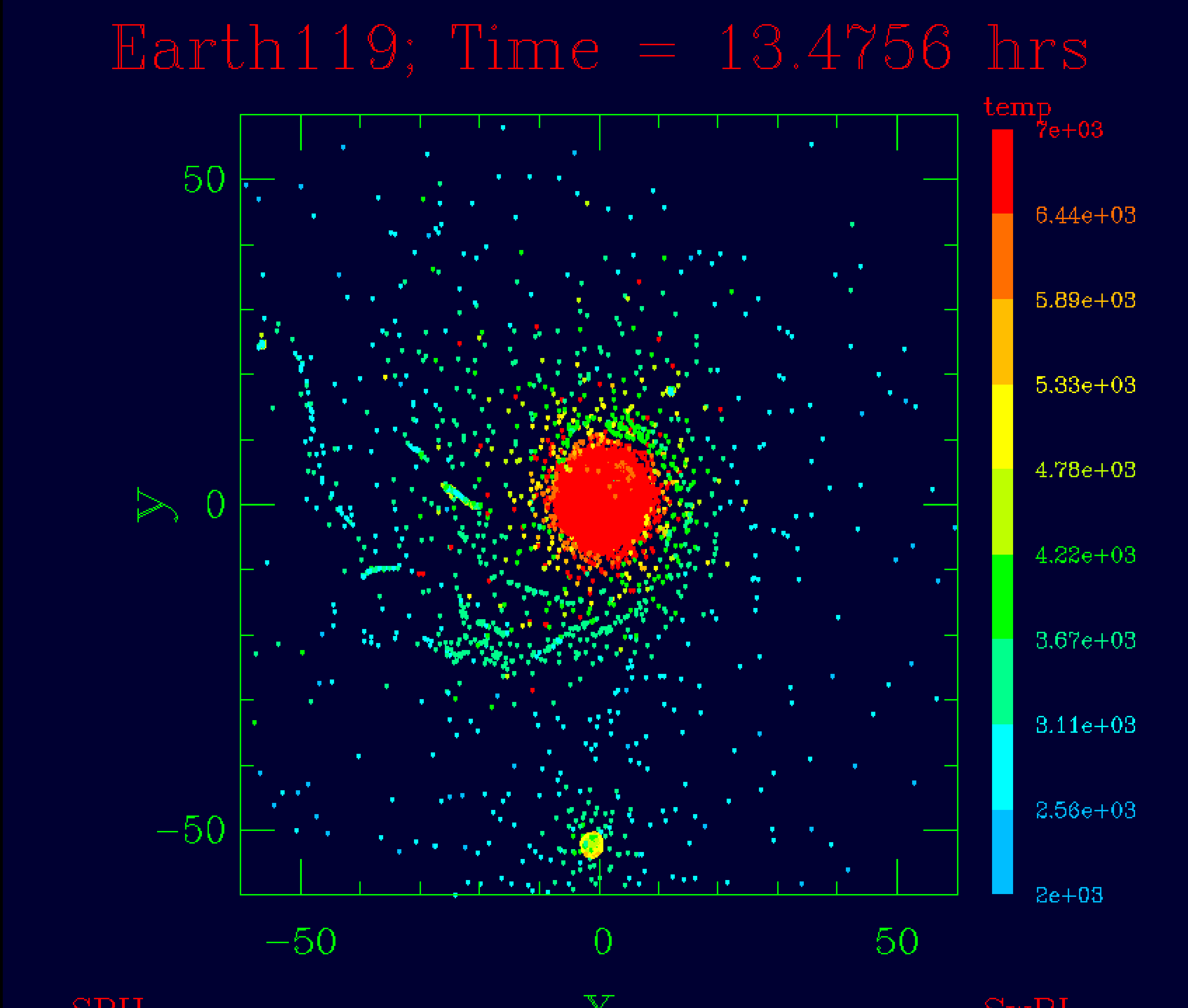
2e+03
y
50
0
−50
−50
0
50


Earth119; Time = 13.4756 hrs
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2e+03
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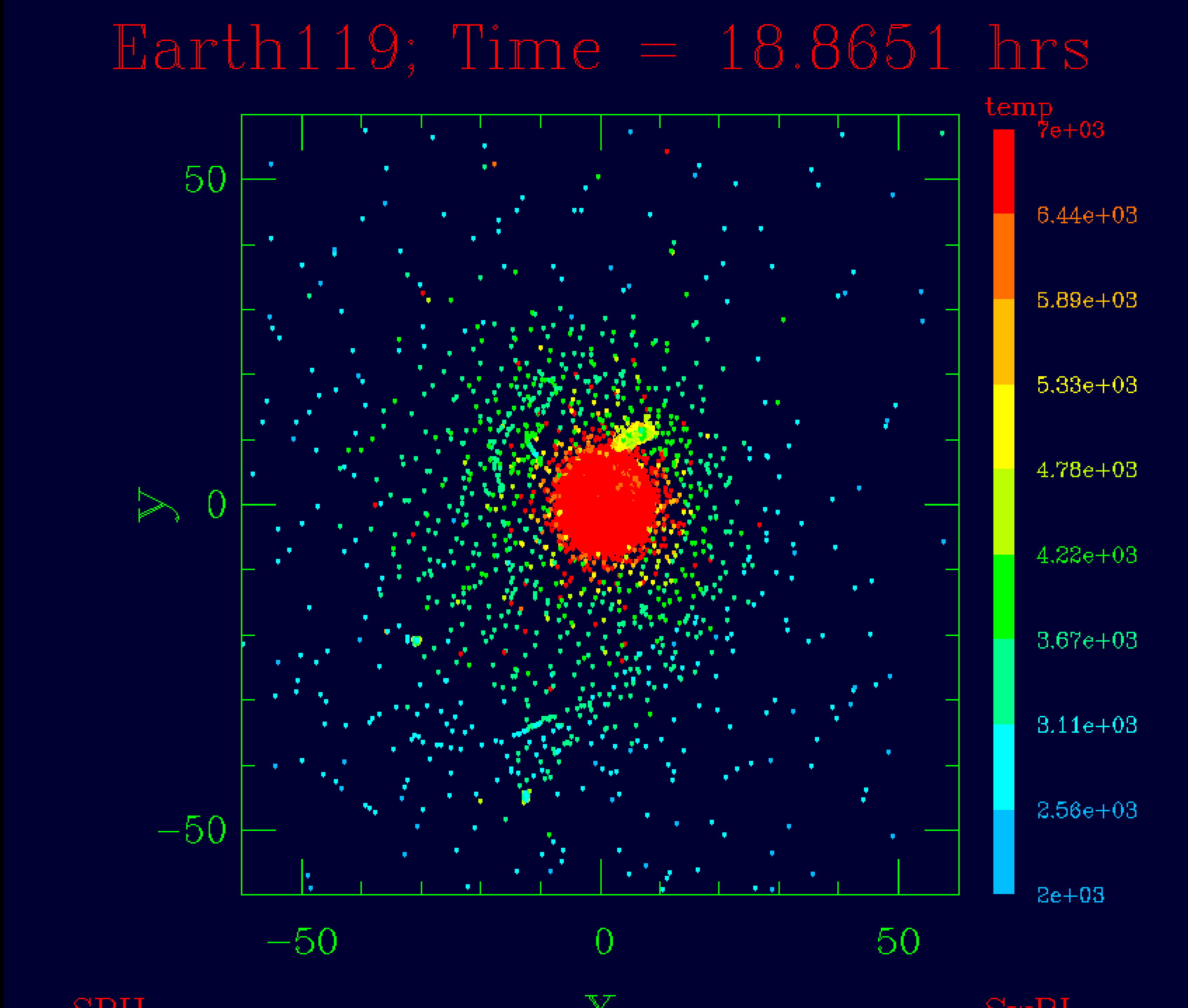
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2e+03
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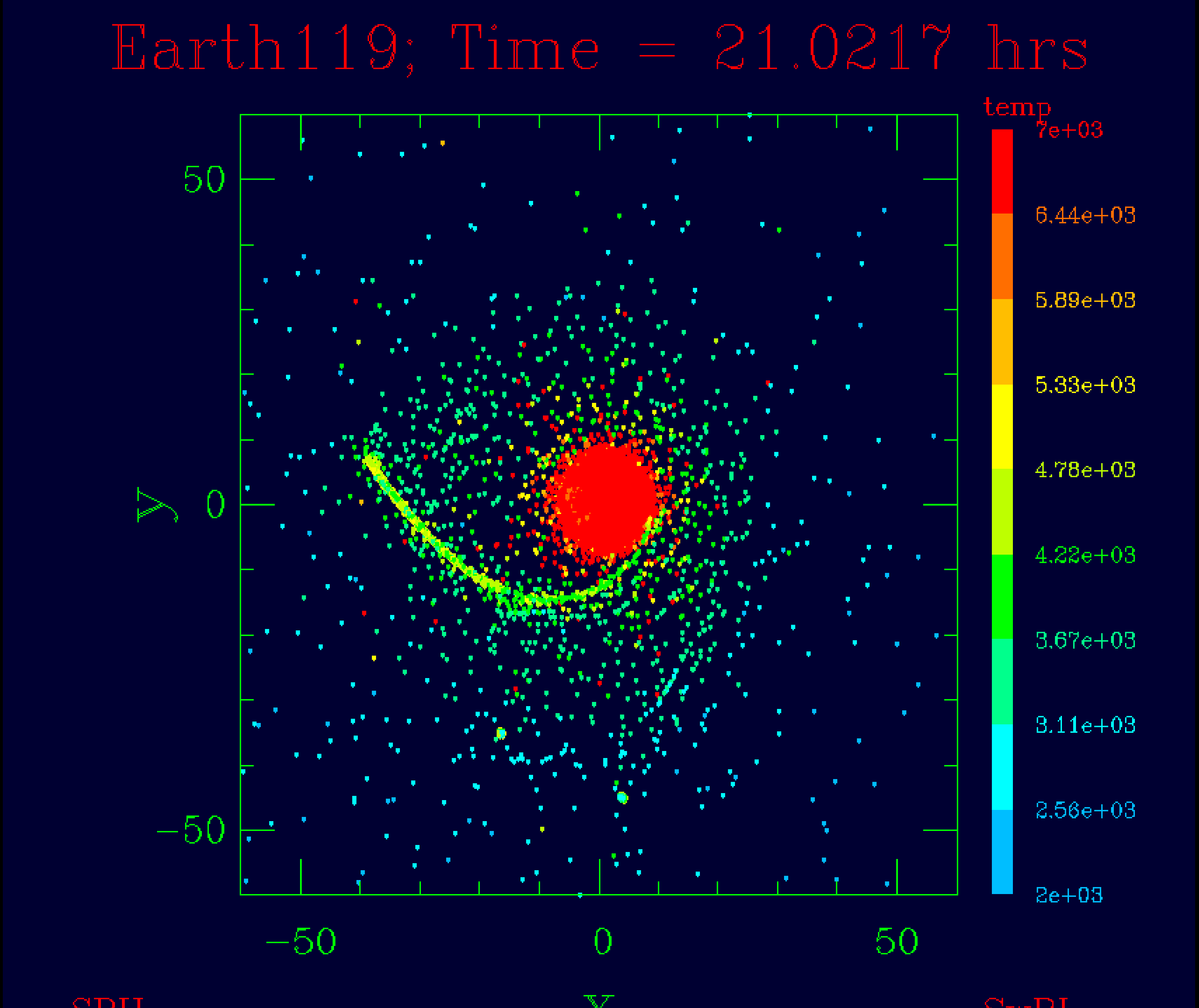

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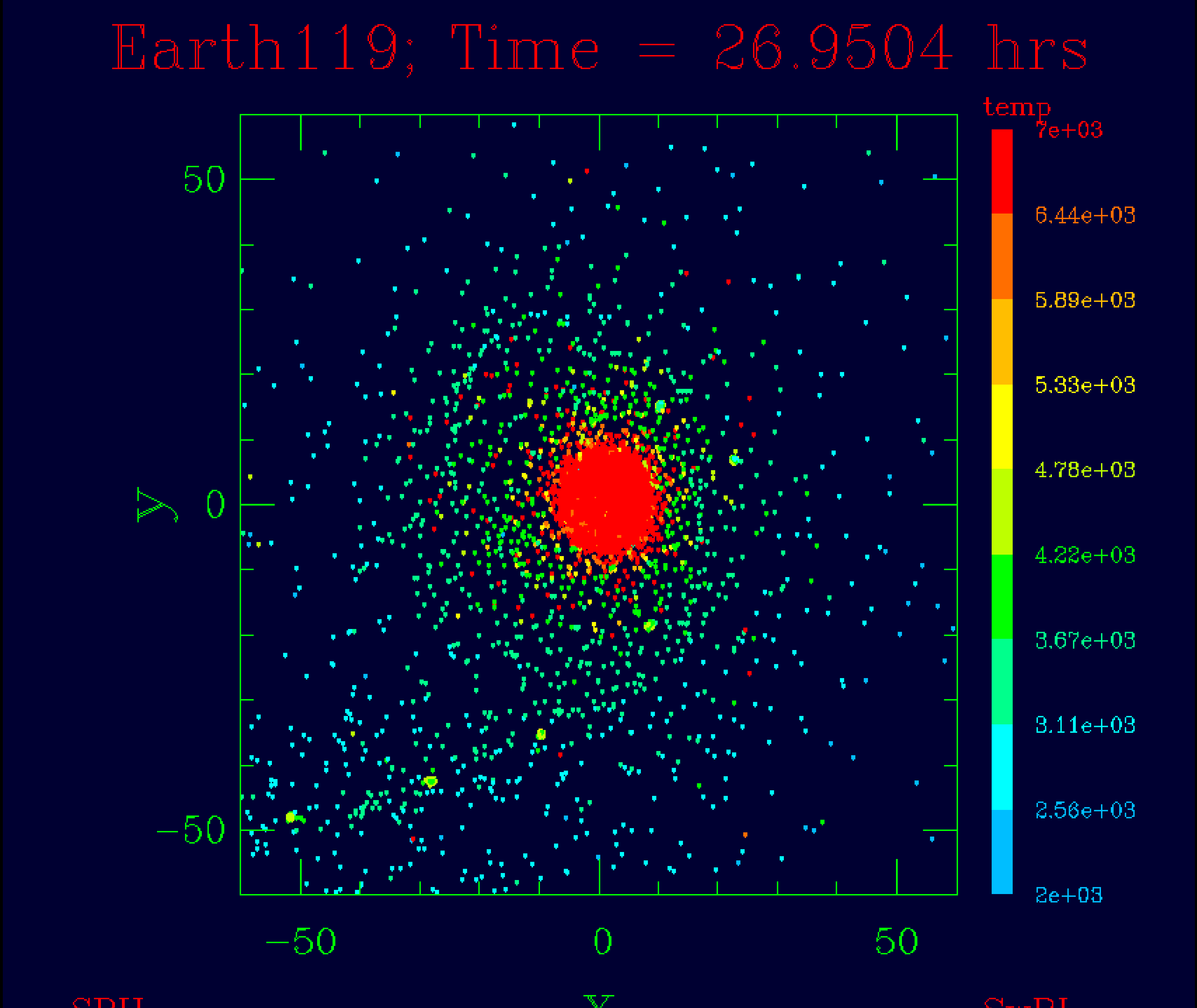
0
−50
y
x



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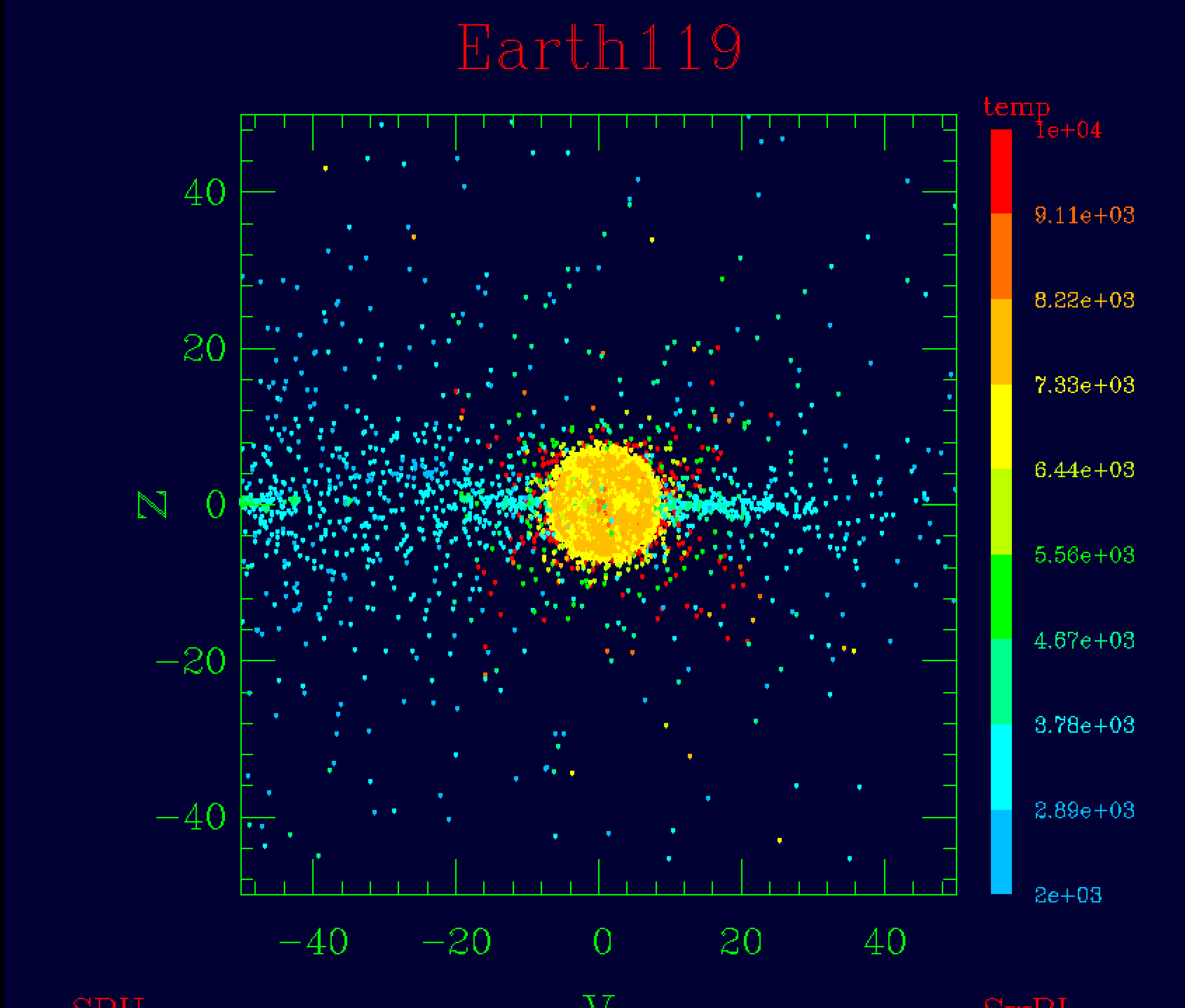
0
−50
y
−50
0
50


Earth119
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4.67e+03
3.78e+03
2.89e+03
2e+03
Z
40
20
0
−20
−40
−40
−20
0
20
40

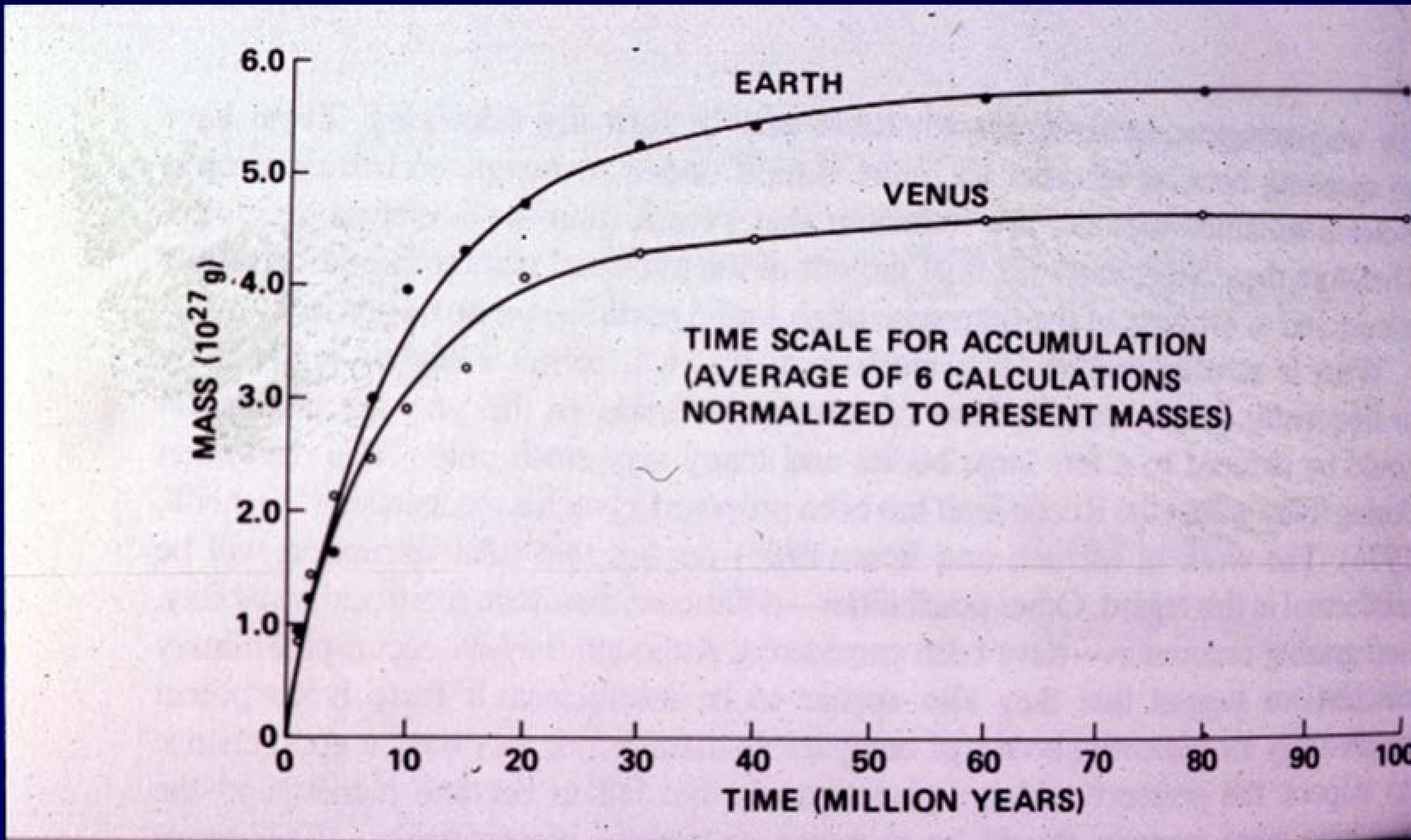

dust and rock debris...


clumped together...

...and formed the Moon

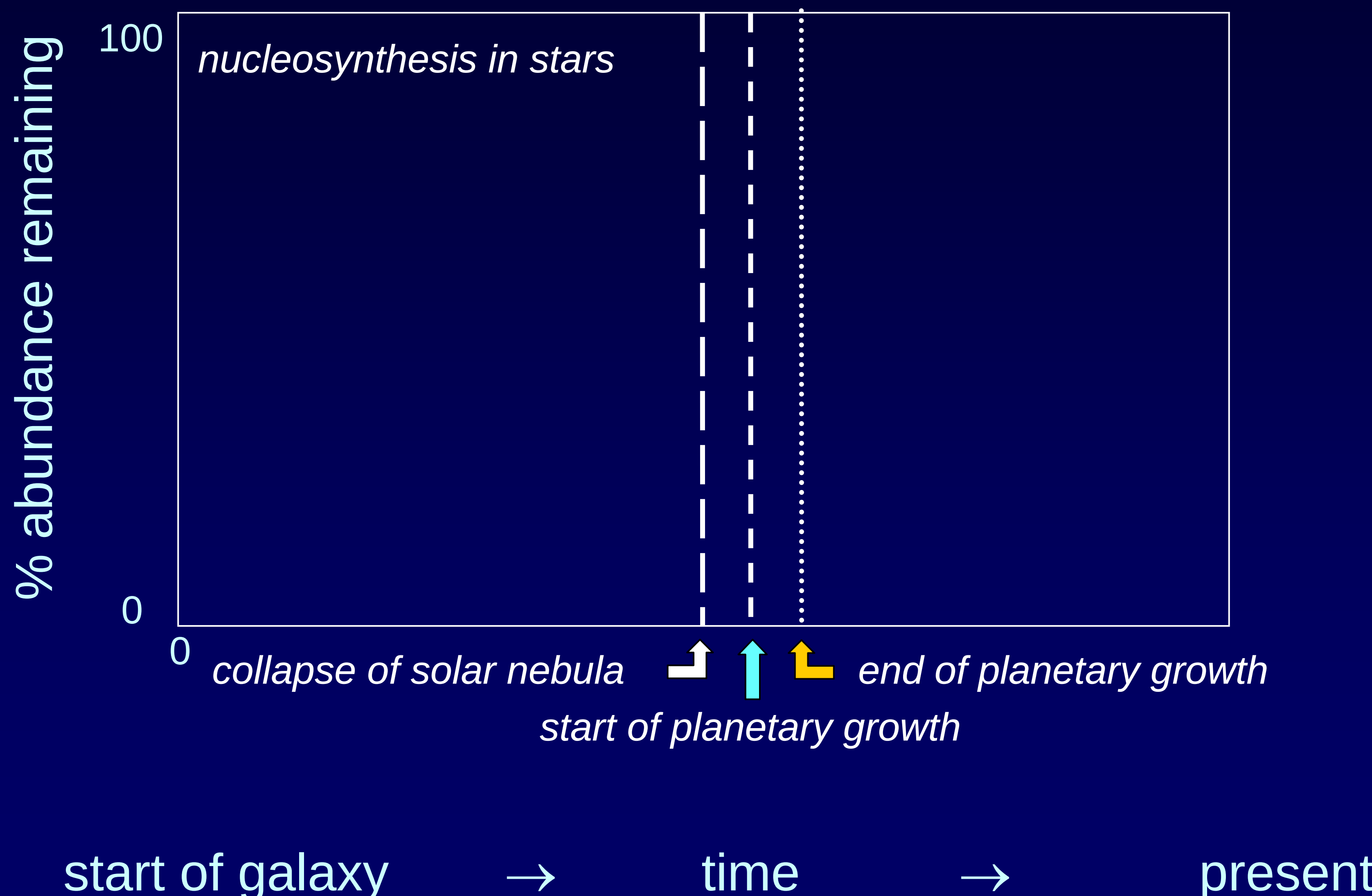
Model Time-scales for Accreting the Earth (>95%)

- Solar mass nebula
  $< 10^6$ yrs (Cameron 1978)
- Minimum mass solar nebula
  $\sim 5 \times 10^6$ yrs (e.g. Hayashi 1978)
- Late stage collisions with no nebula
  $10^7 - 10^8$ yrs (e.g. Wetherill 1986)

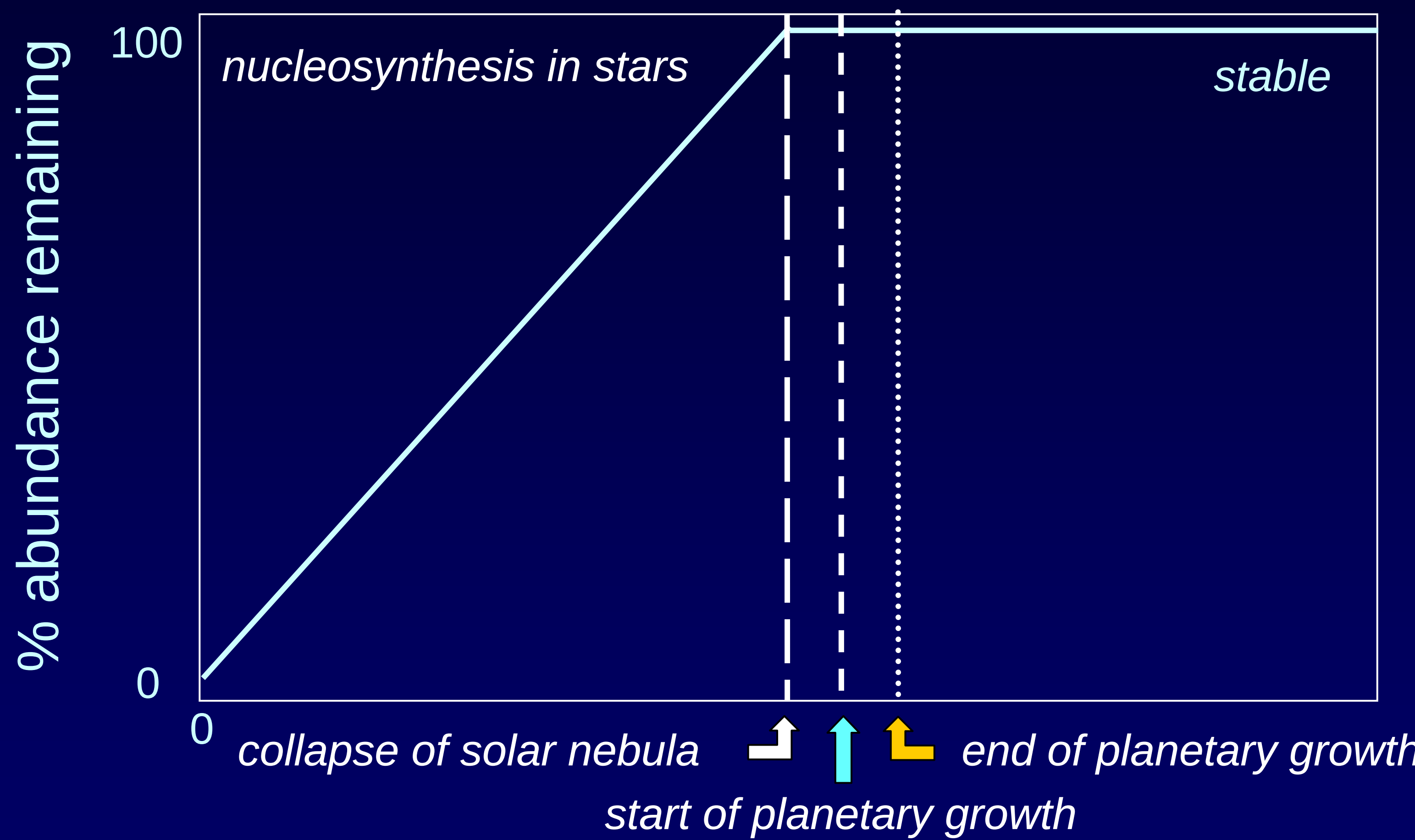


George Wetherill, 1986

Isotopes and time-scales

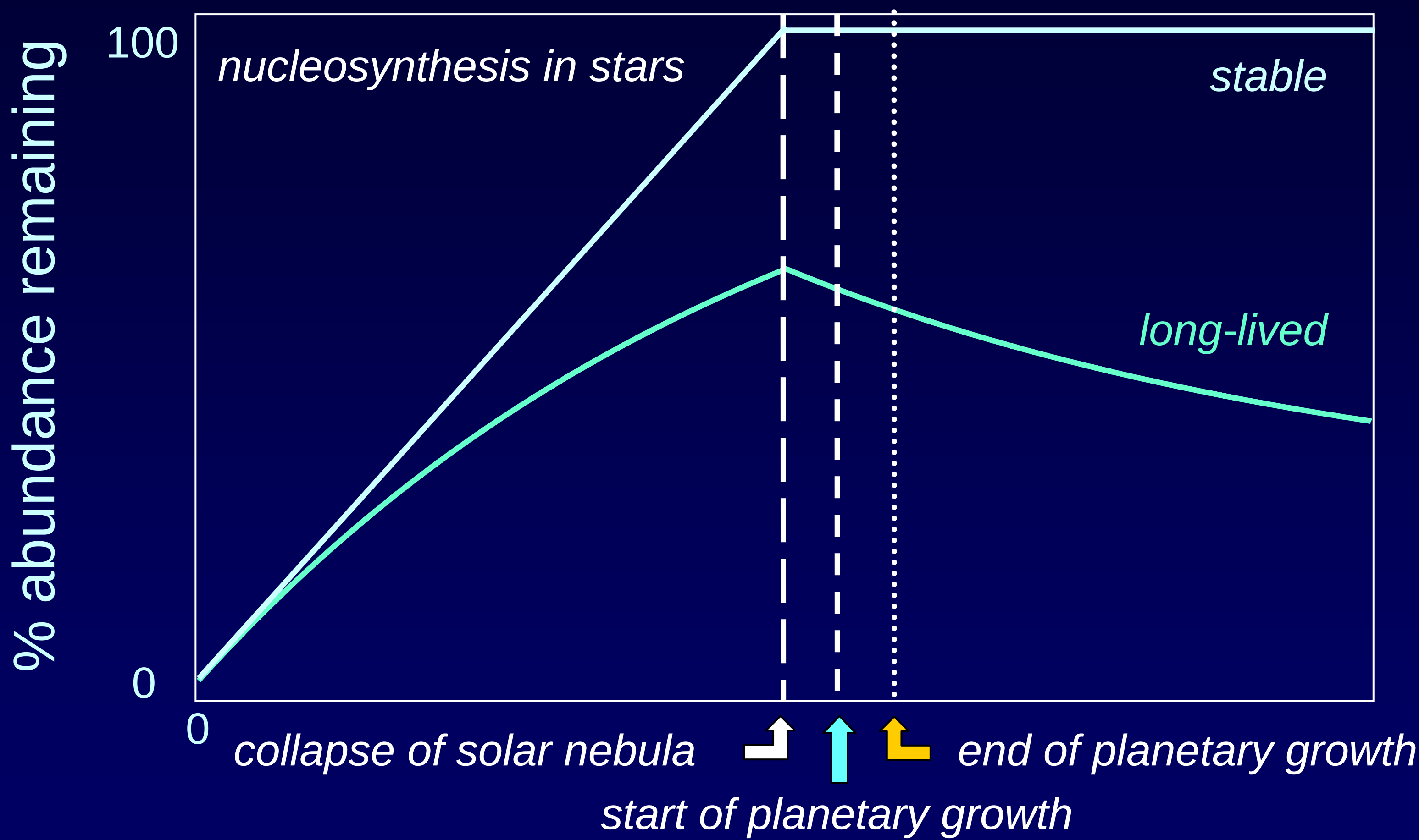


Isotopes and time-scales



start of galaxy → time → present

Isotopes and time-scales

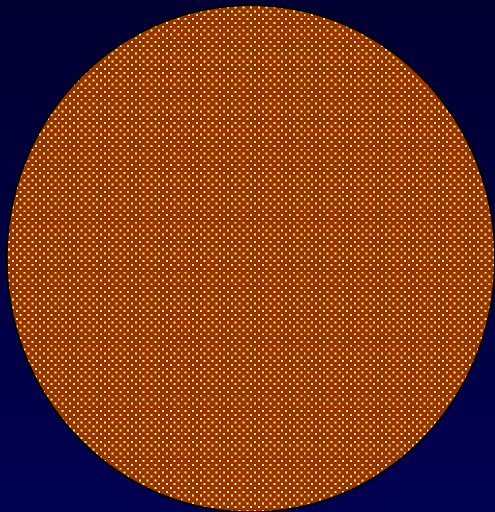


start of galaxy → time → present

Some significant radio-nuclides in the early solar system

Nuclide	Half-life (Myrs)	Daughter
^{41}Ca	0.1	^{41}K
^{26}Al	0.73	^{26}Mg
^{60}Fe	1.5	^{60}Ni
^{53}Mn	3.7	^{53}Cr
^{107}Pd	6.5	^{107}Ag
^{182}Hf	8.9	^{182}W
^{247}Cm	12	^{235}U
^{205}Pb	15	^{205}Tl
^{129}I	16	^{129}Xe
^{92}Nb	36	^{92}Zr
^{244}Pu	80	^{136}Xe
^{146}Sm	103	^{142}Nd
^{235}U	704	^{207}Pb
^{238}U	4468	^{206}Pb
^{87}Rb	48800	^{87}Sr

$^{238}U/^{204}Pb$ in the earth

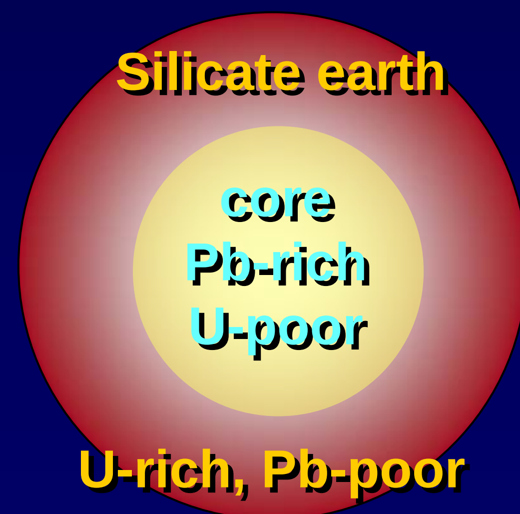


$^{238}U/^{204}Pb_{\text{total earth}} = 5 \times {}^{238}U/^{204}Pb_{\text{solar system}}$

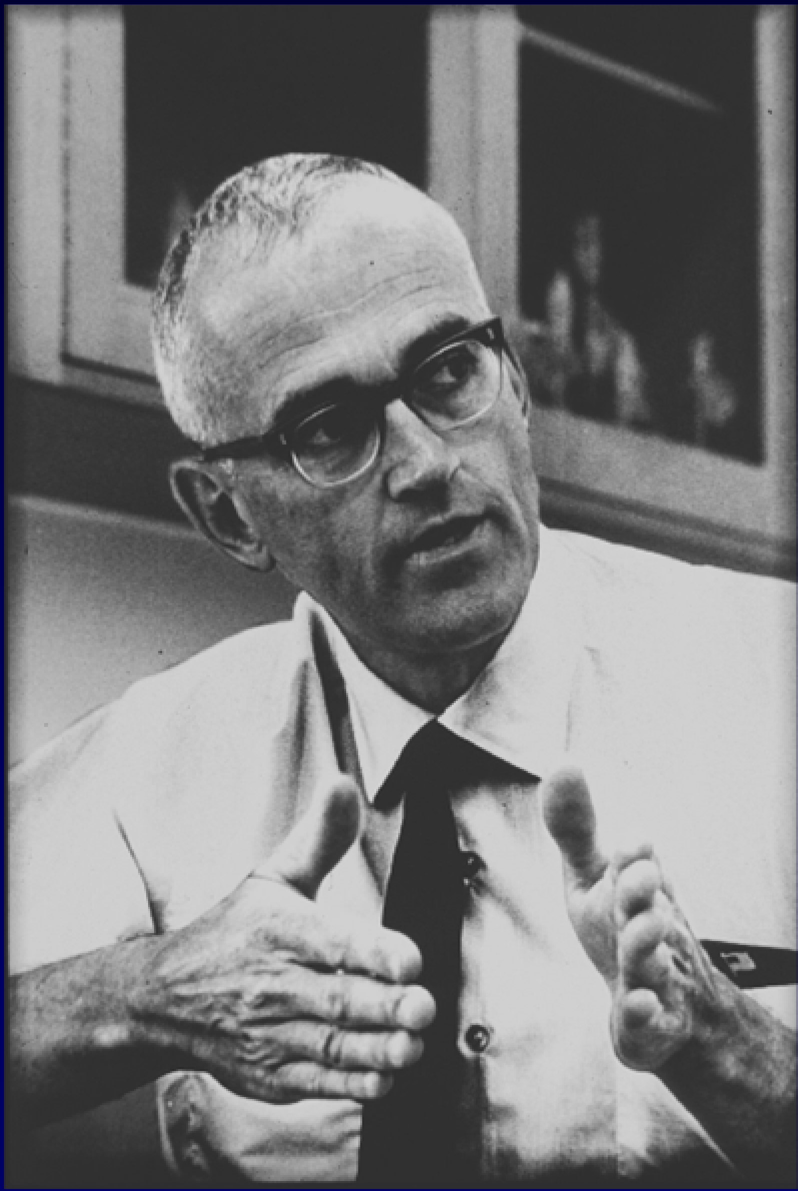
$^{238}U/^{204}Pb_{\text{total earth}} = 0.7$

$^{238}U/^{204}Pb_{\text{silicate earth}} \sim 8$

$^{238}U/^{204}Pb_{\text{core}} = 0$



Clair Patterson 1956



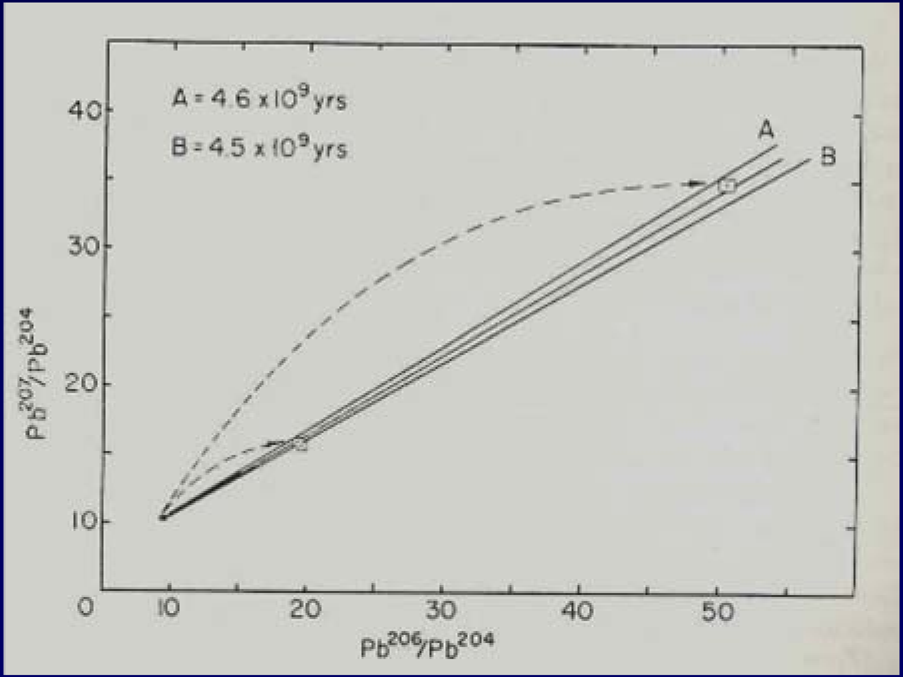
Geochimica et Cosmochimica Acta, 1956, Vol. 10, pp. 230 to 237. Pergamon Press Ltd., London

Age of meteorites and the earth

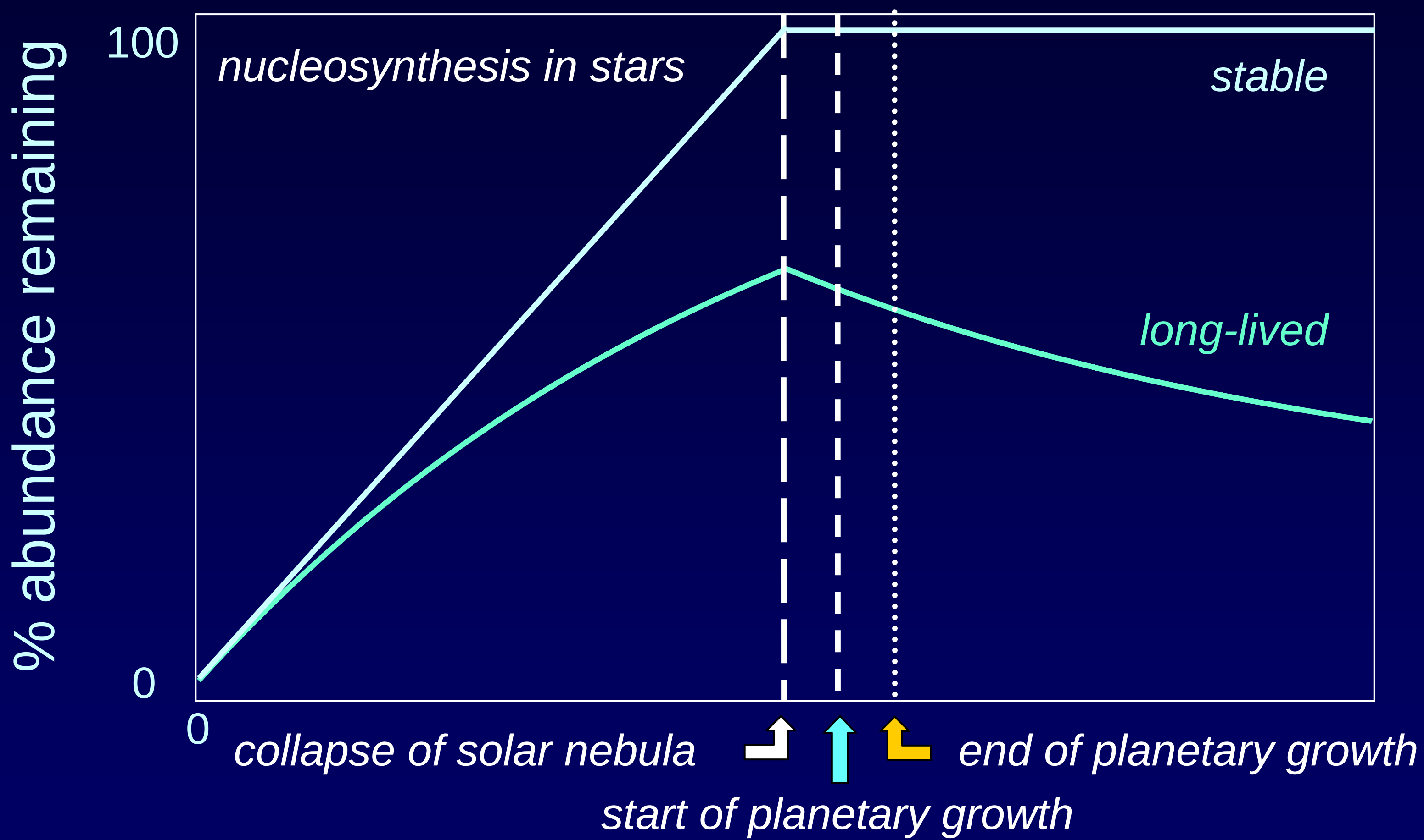
CLAIRE PATTERSON
Division of Geological Sciences
California Institute of Technology, Pasadena, California

(*Received* 23 *January* 1956)

Abstract—Within experimental error, meteorites have one age as determined by three independent radiometric methods. The most accurate method (Pb^{207}/Pb^{206}) gives an age of 4·55 ± 0·07 × 10^9 yr. Using certain assumptions which are apparently justified, one can define the isotopic evolution of lead for any meteoritic body. It is found that earth lead meets the requirements of this definition. It is therefore believed that the age for the earth is the same as for meteorites. This is the time since the earth attained its present mass.

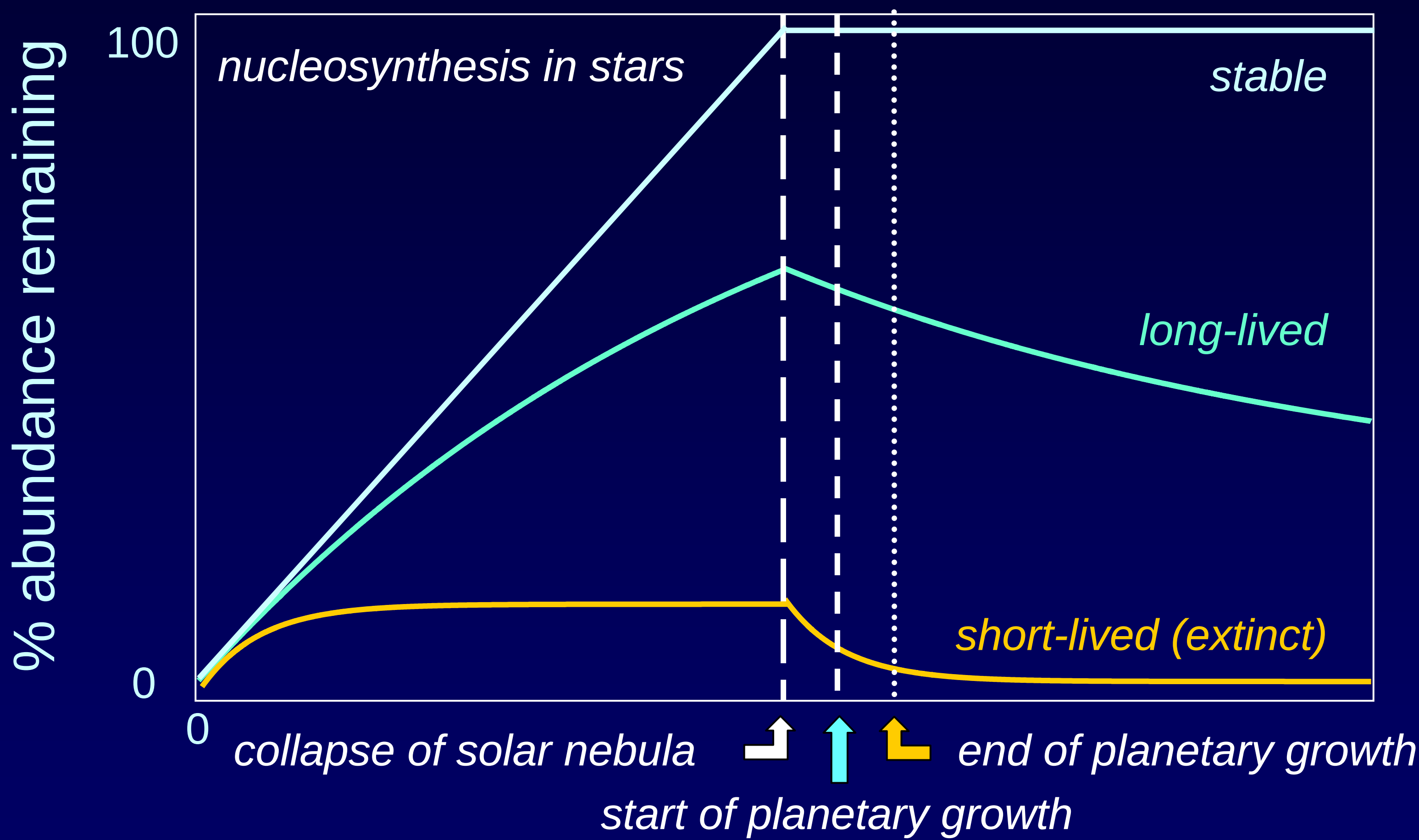


Isotopes and time-scales



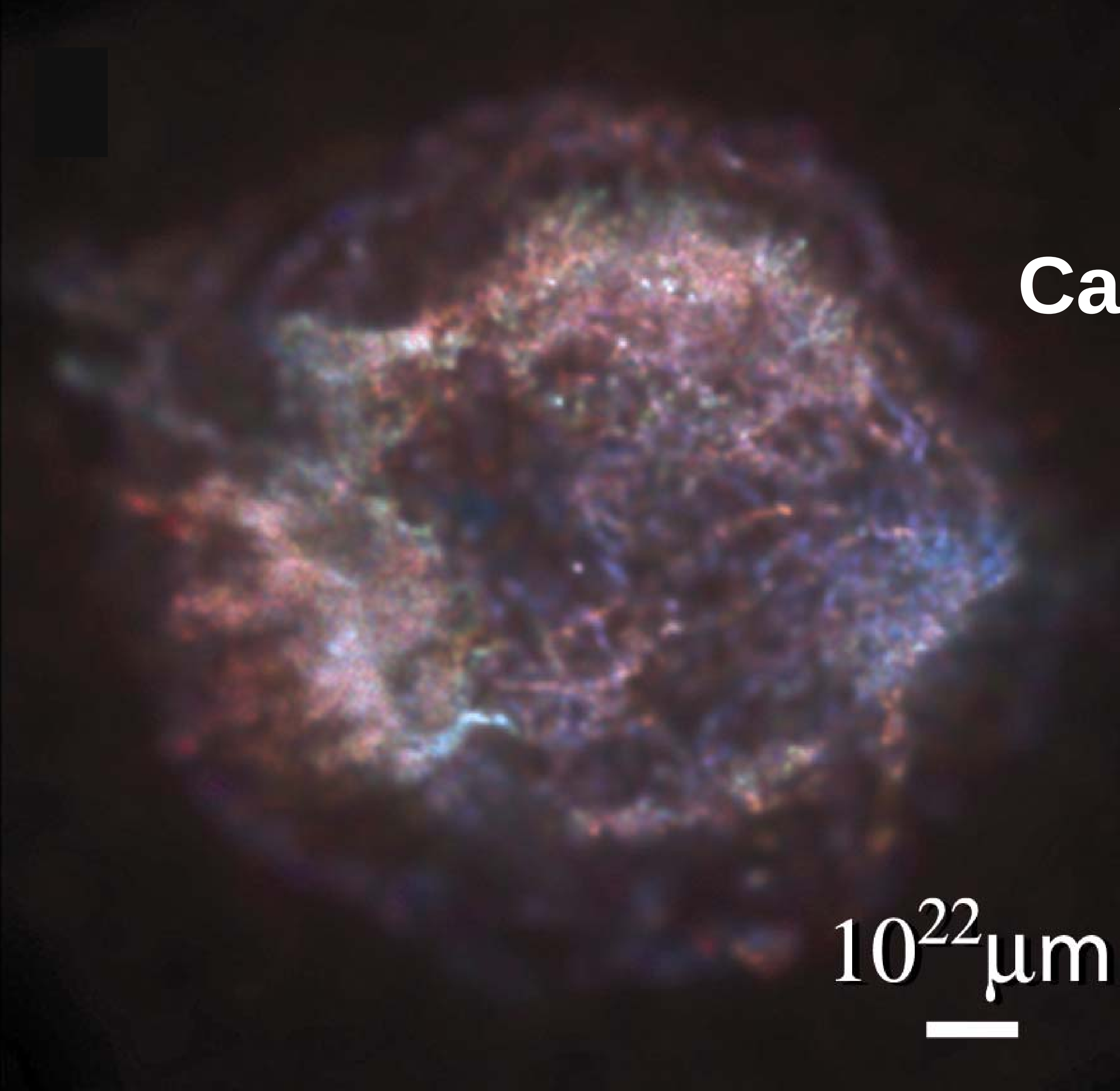
start of galaxy → time → present

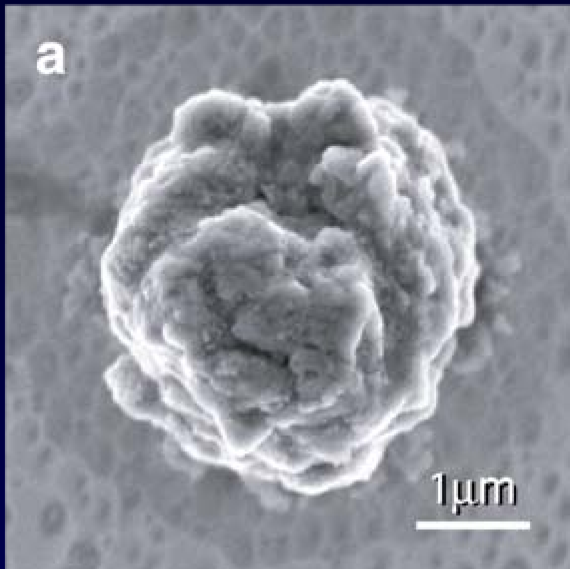
Isotopes and time-scales

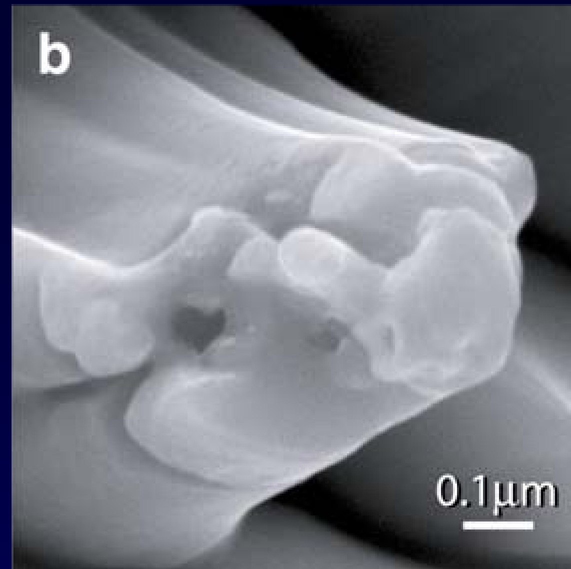


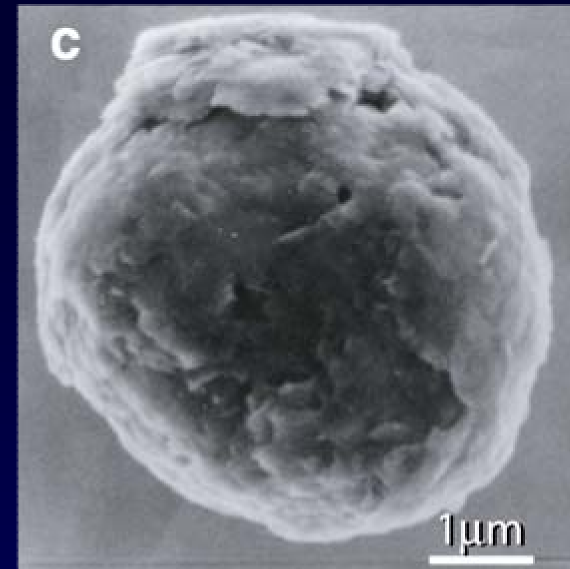
start of galaxy → time → present

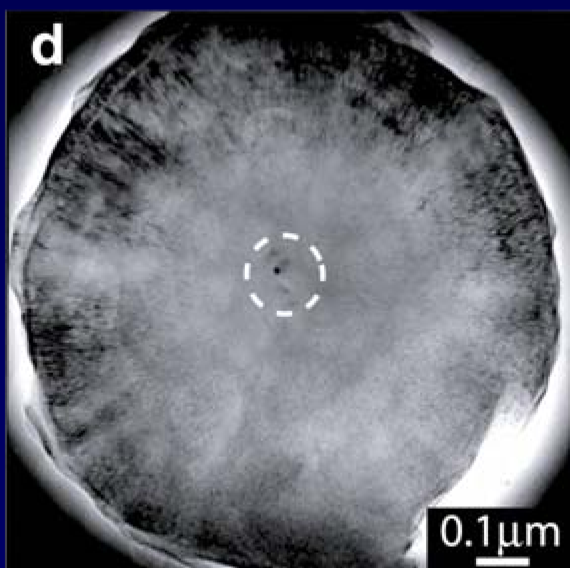
supernova remnant Cassiopeia A











real stardust

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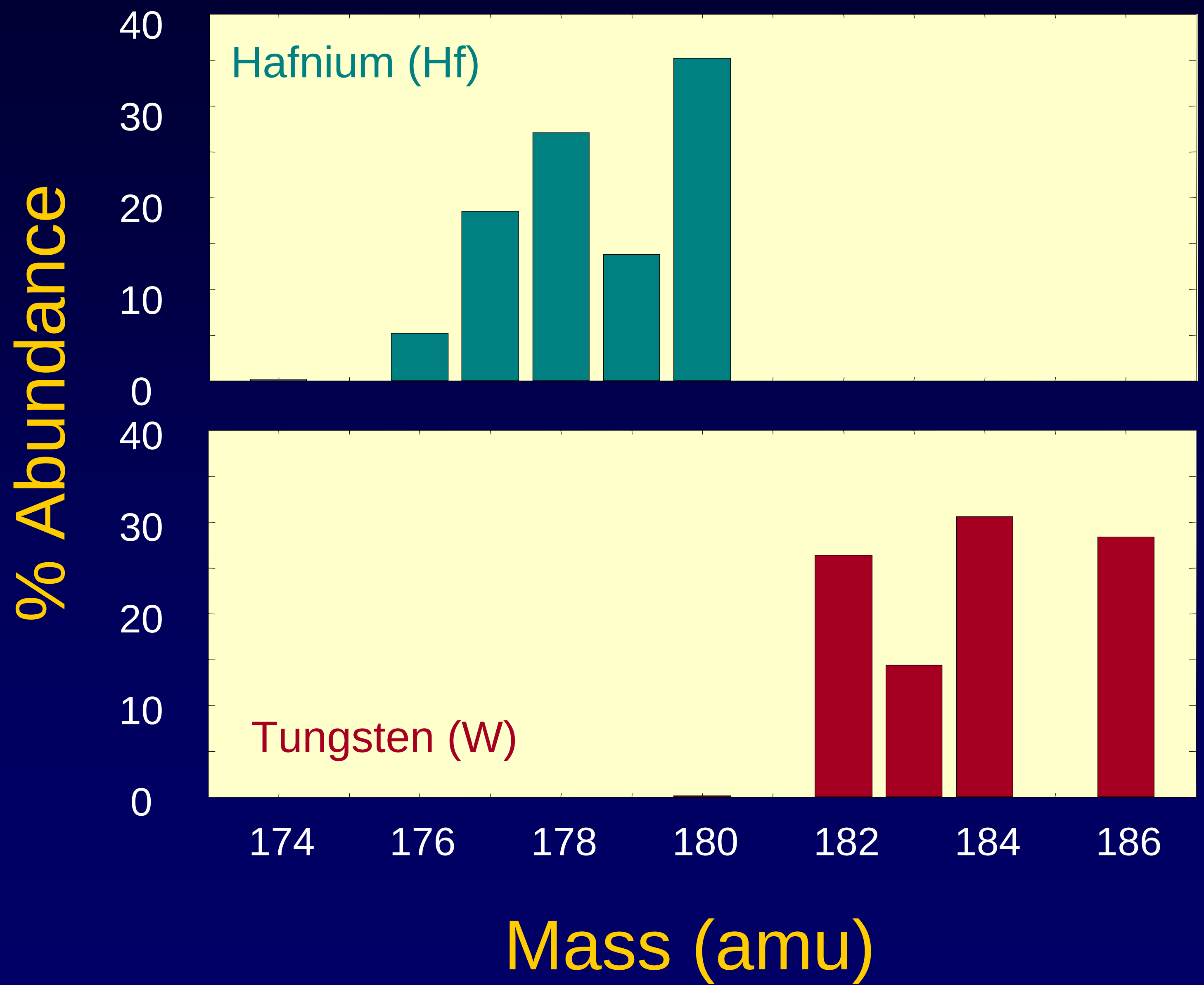
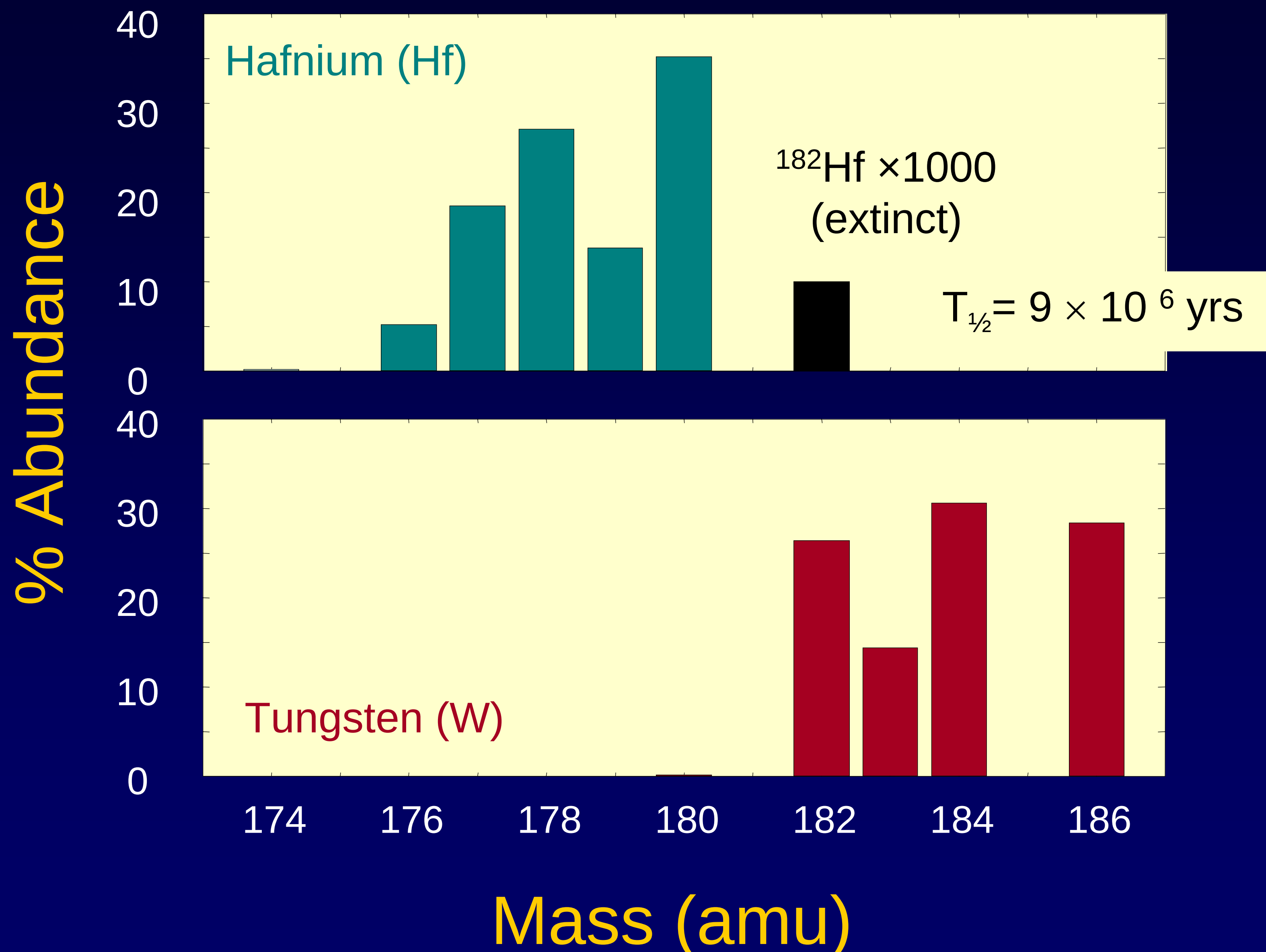
^{244}Pu	80	^{136}Xe
^{146}Sm	103	^{142}Nd
^{235}U	704	^{207}Pb
^{238}U	4468	^{206}Pb
^{87}Rb	48800	^{87}Sr

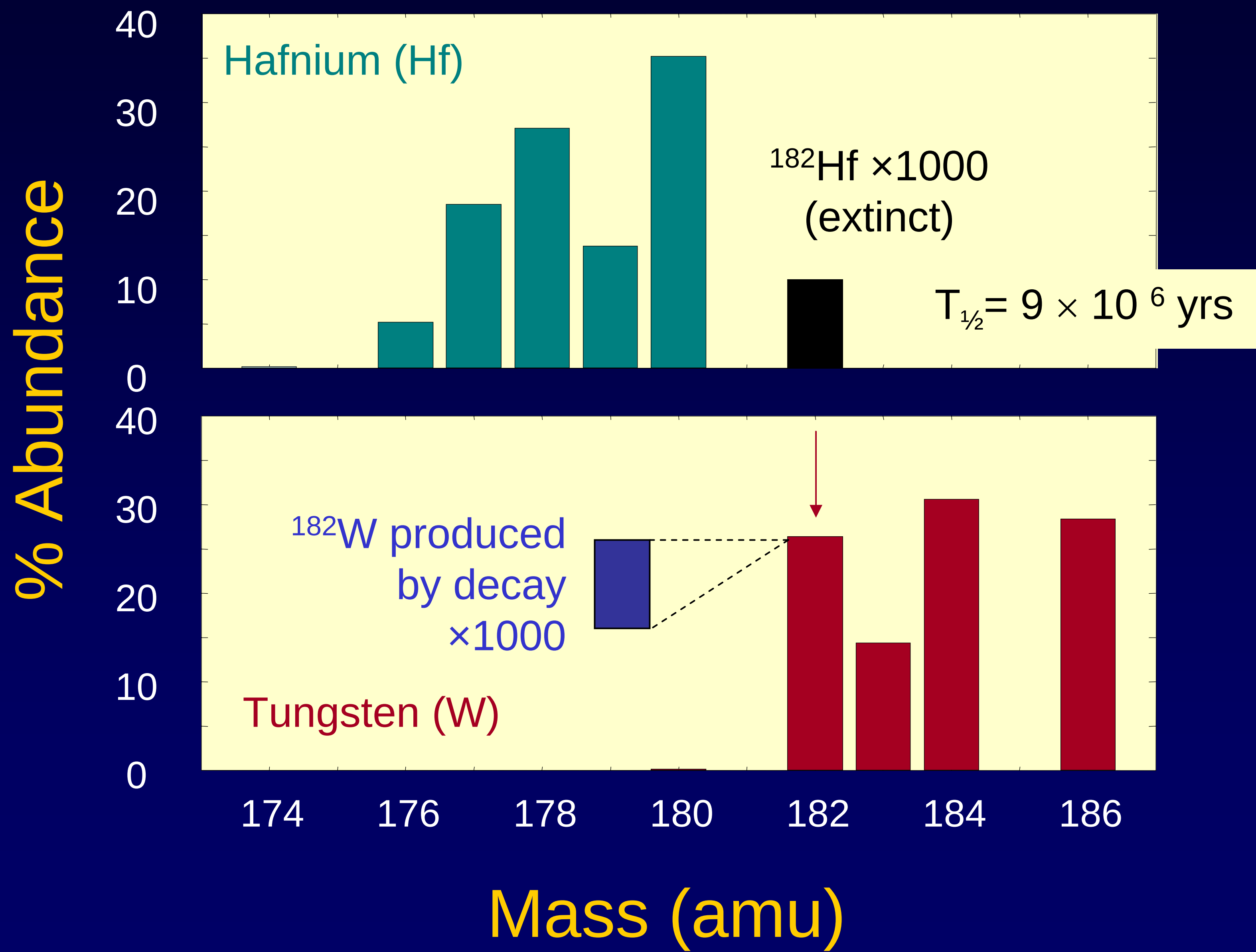
Isotopes of hafnium and tungsten



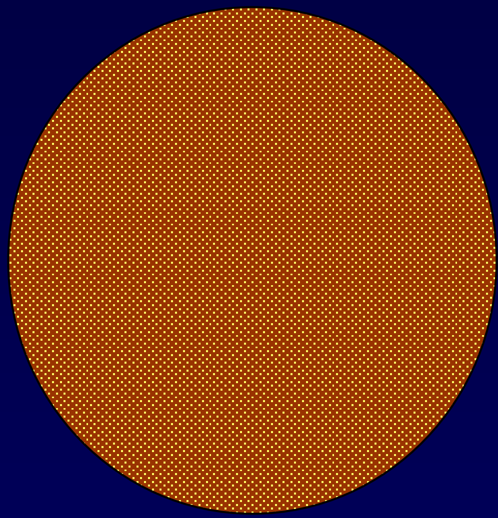
Isotopes of hafnium and tungsten



Isotopes of hafnium and tungsten



Hf/W in the Earth



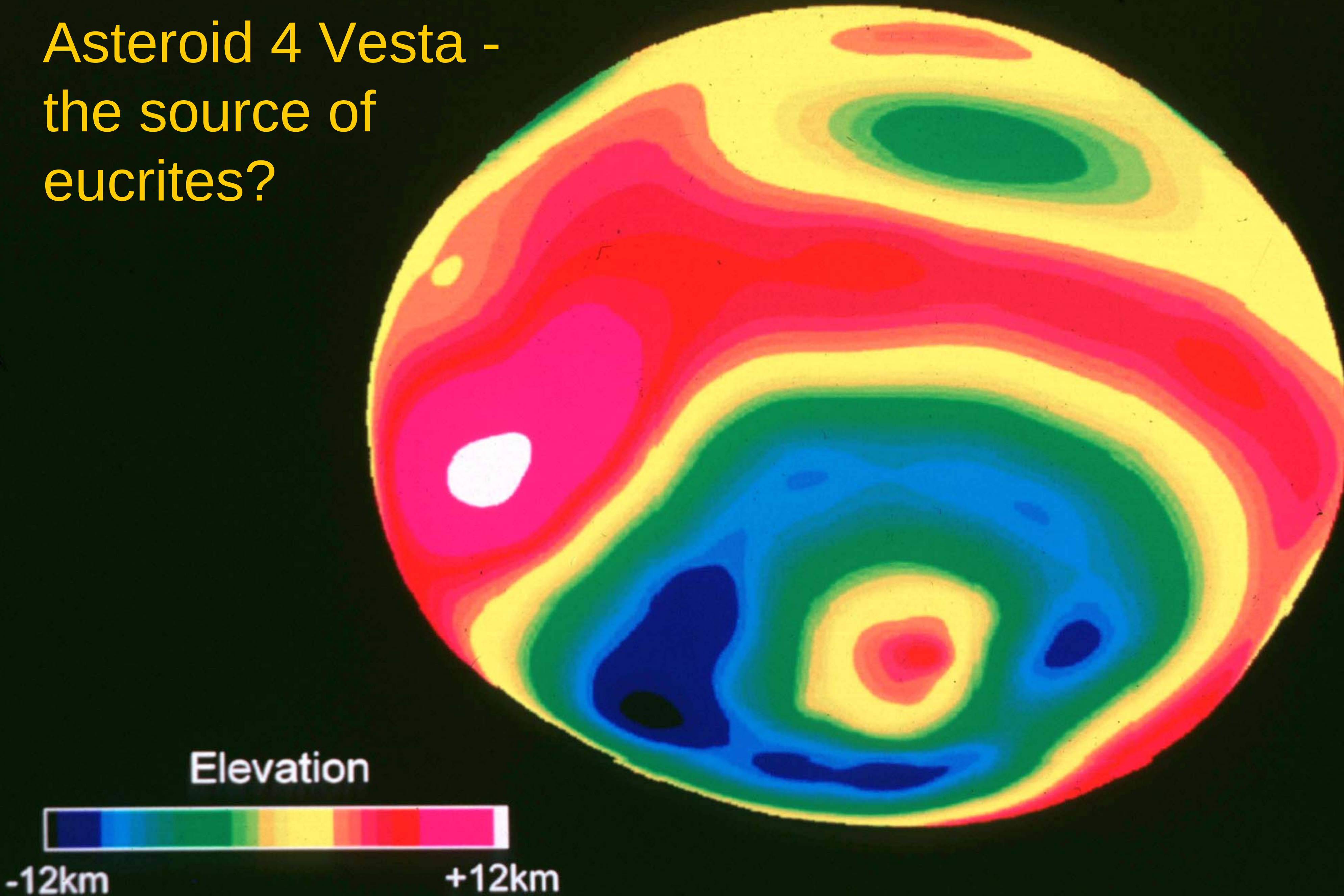
$$Hf/W_{\text{total Earth}} = Hf/W_{\text{solar system}} = 1$$

$$Hf/W_{\text{silicate Earth}} = 15$$

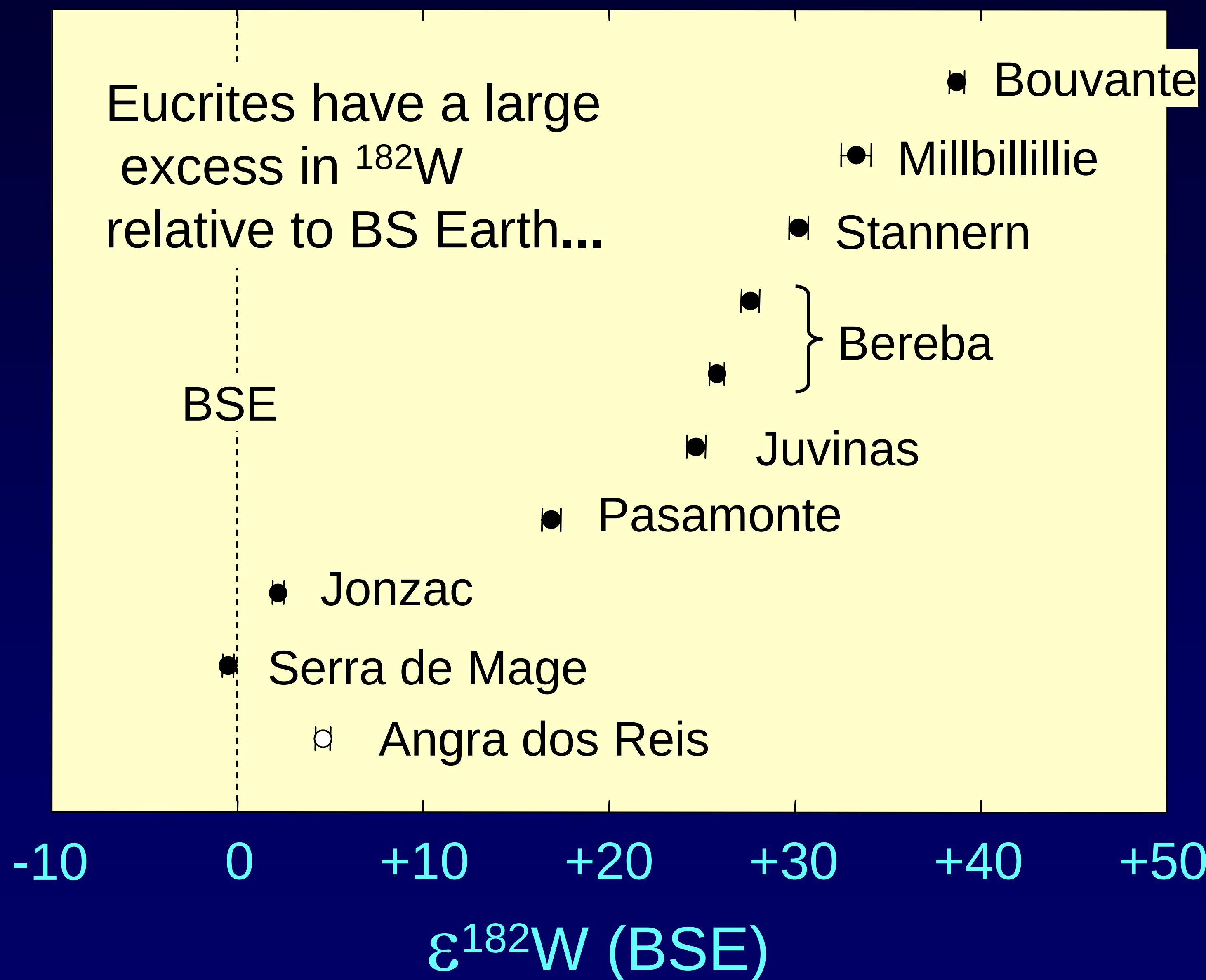
$$Hf/W_{\text{core}} = 0$$

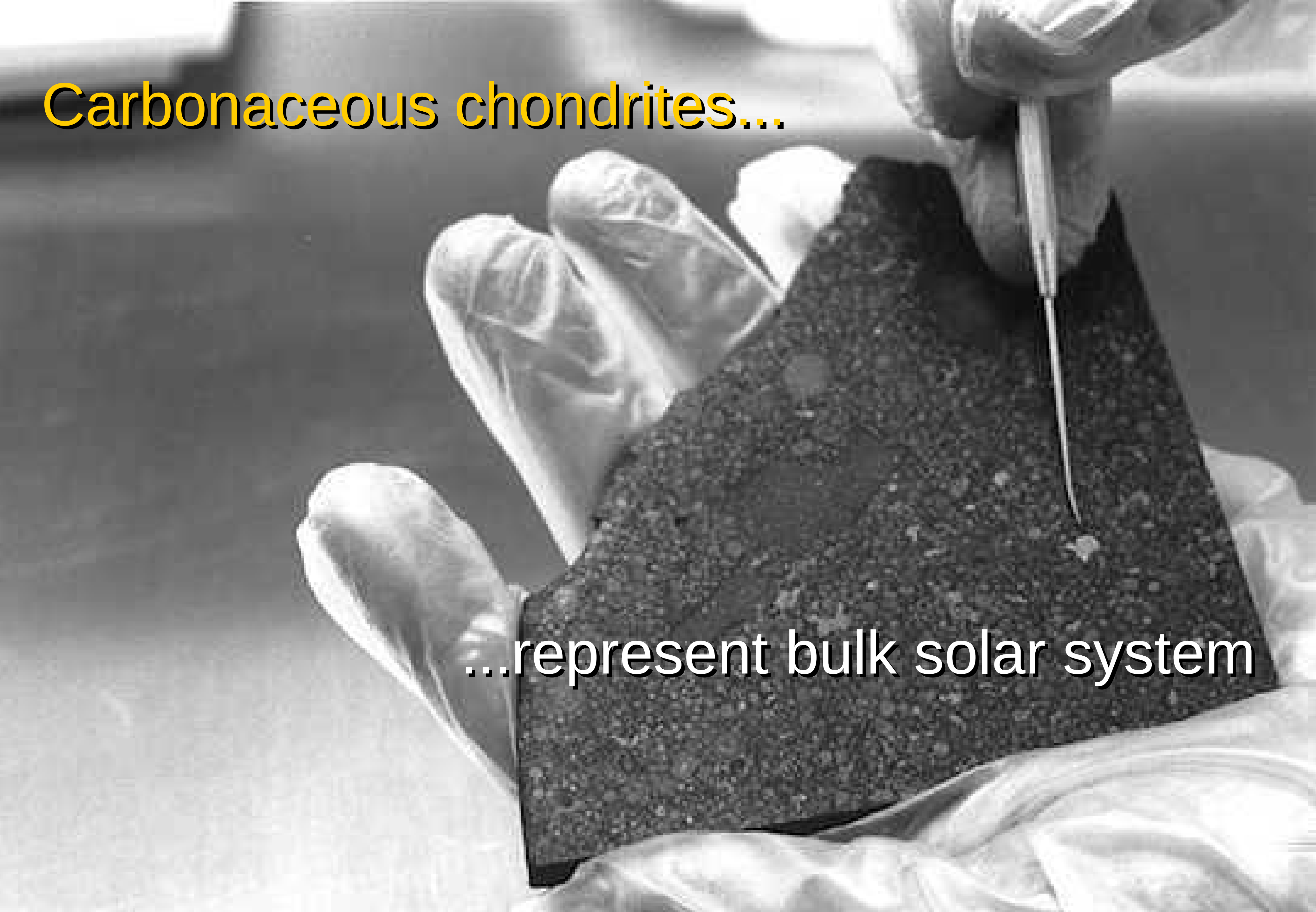
NB Silicate Earth = Earth's Primitive Mantle

Asteroid 4 Vesta - the source of eucrites?

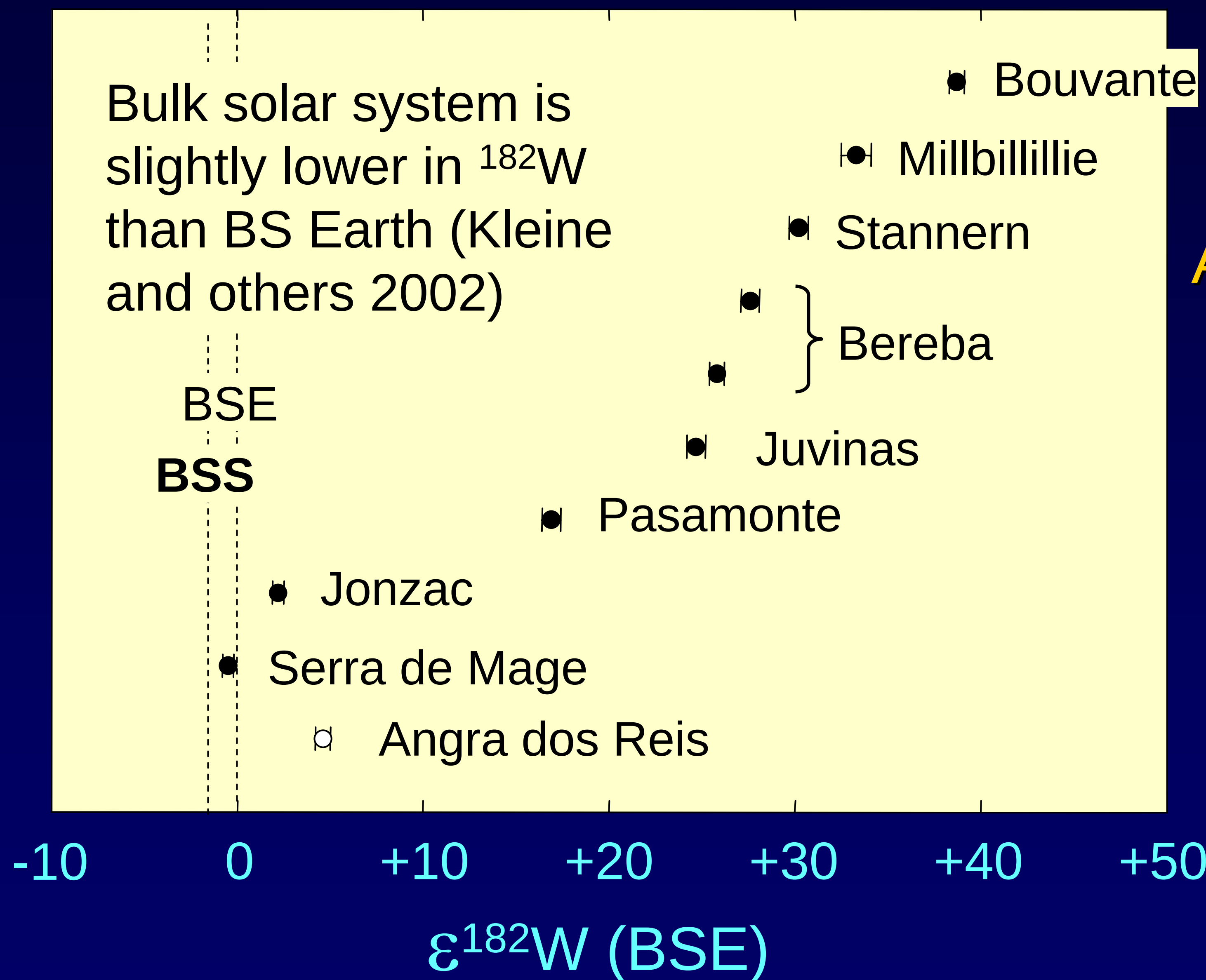


Eucrites relative to bulk silicate Earth

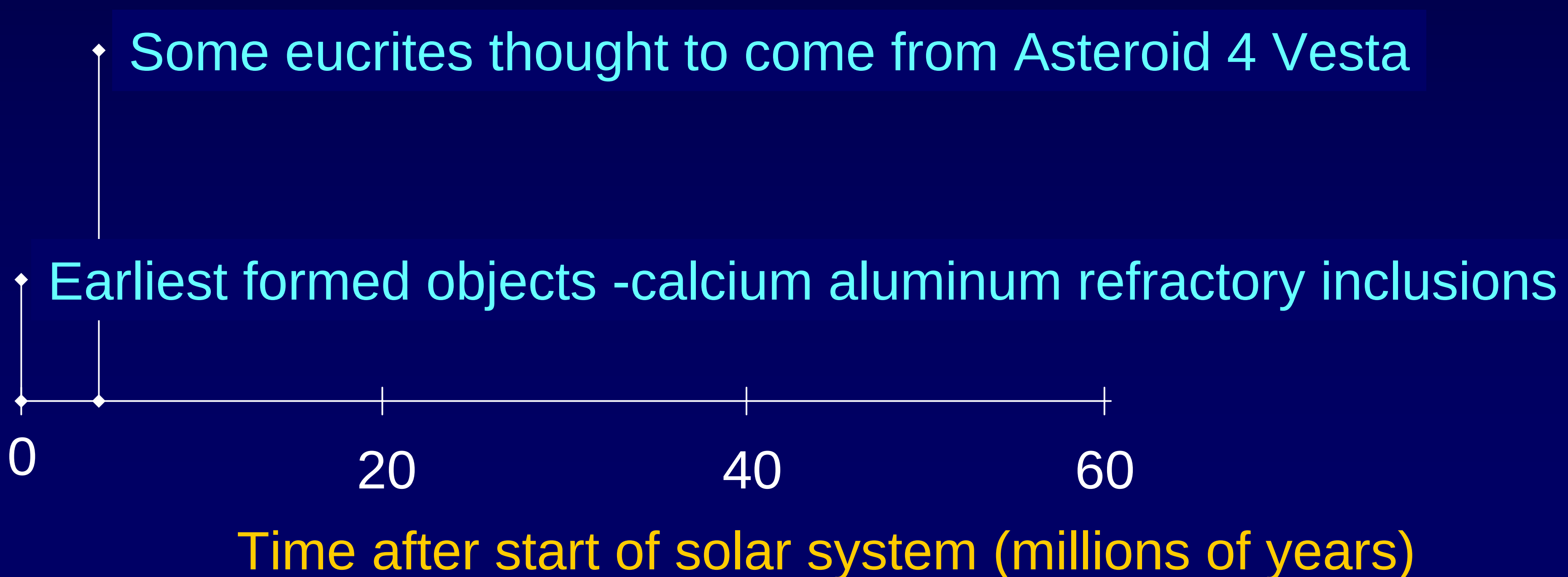



Carbonaceous chondrites...
...represent bulk solar system

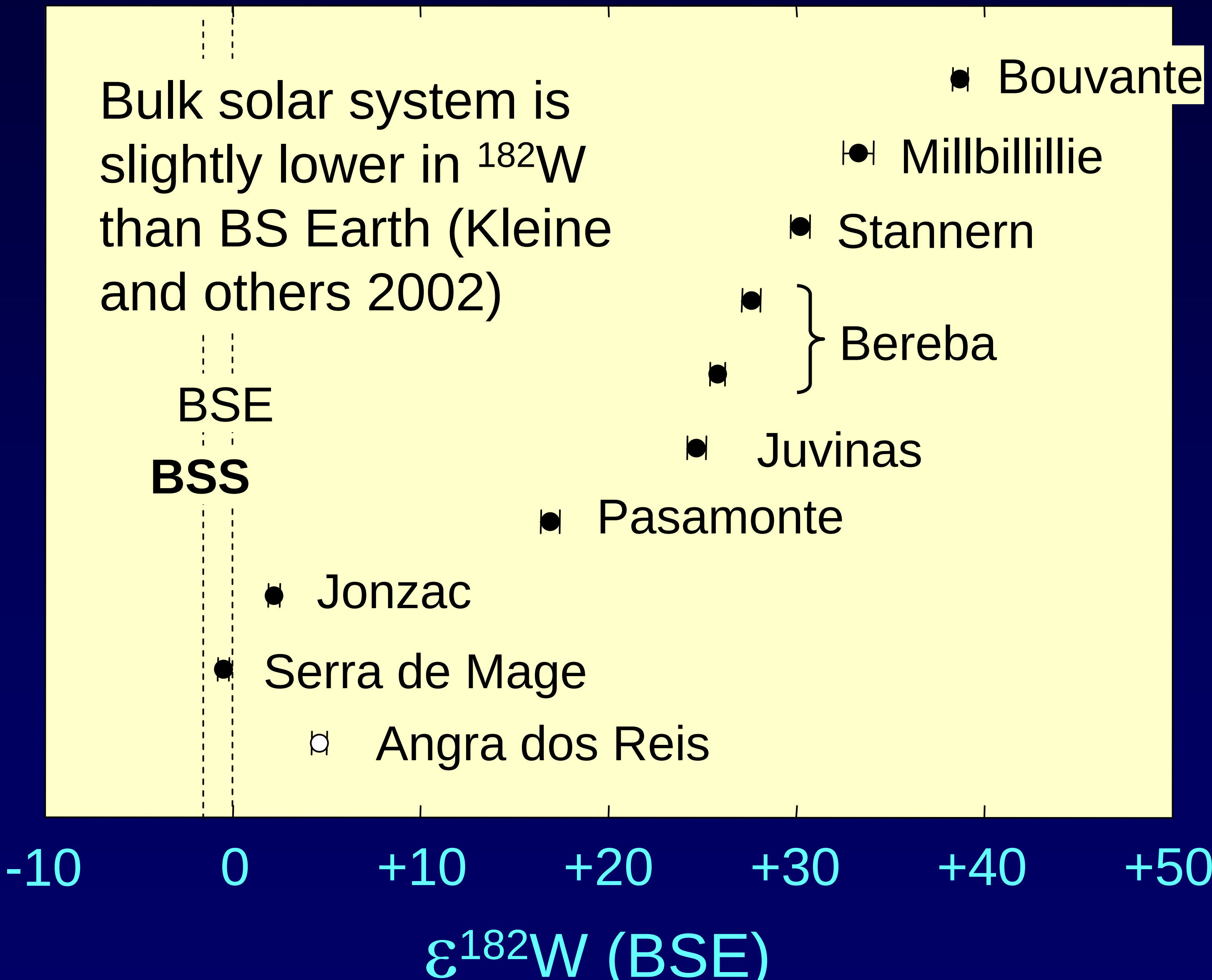
Eucrites relative to bulk solar system



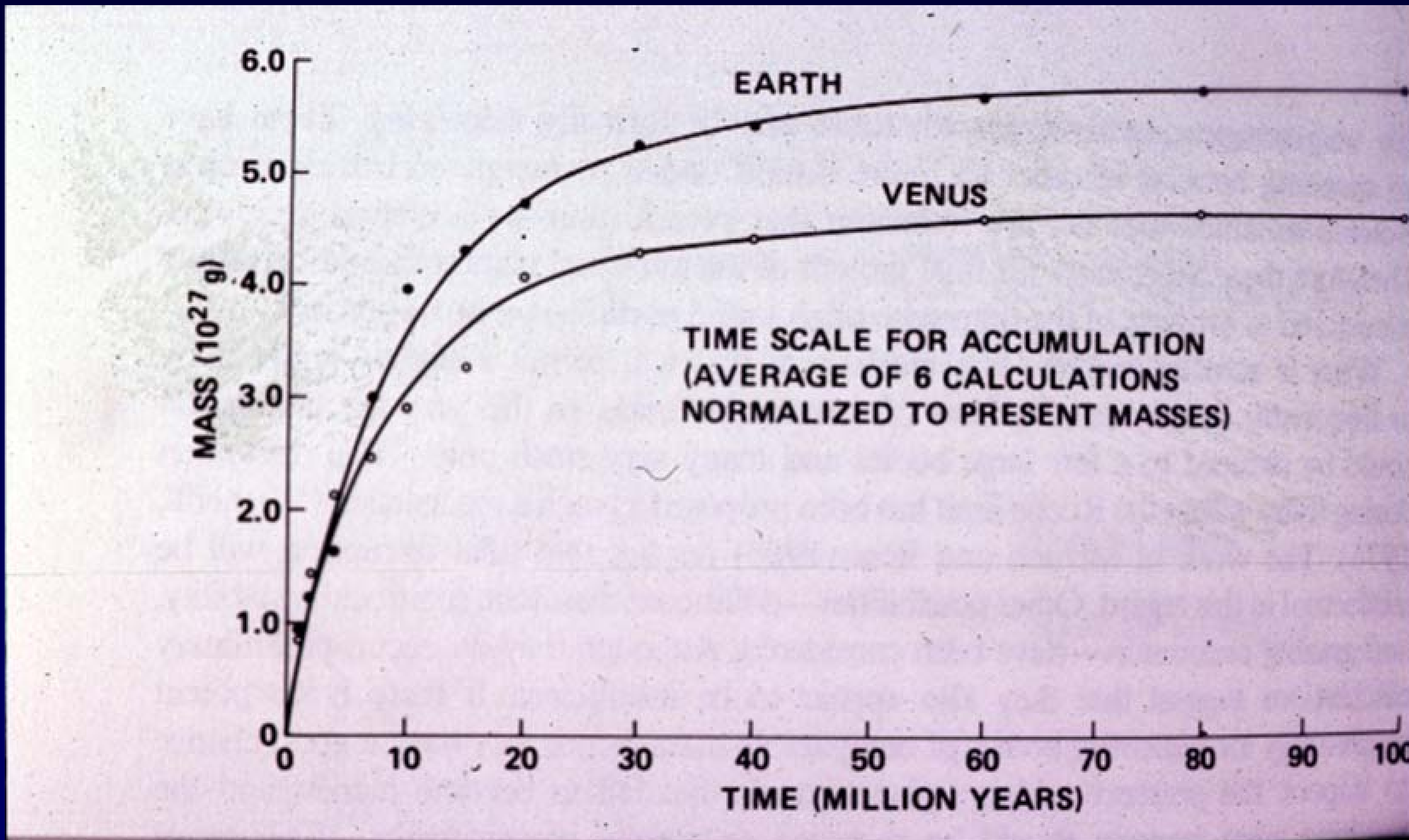
...therefore Asteroid 4 Vesta accreted and differentiated over a shorter time frame than Earth


Some eucrites thought to come from Asteroid 4 Vesta
Earliest formed objects -calcium aluminum refractory inclusions
0
20
40
60
Time after start of solar system (millions of years)

Eucrites relative to bulk solar system

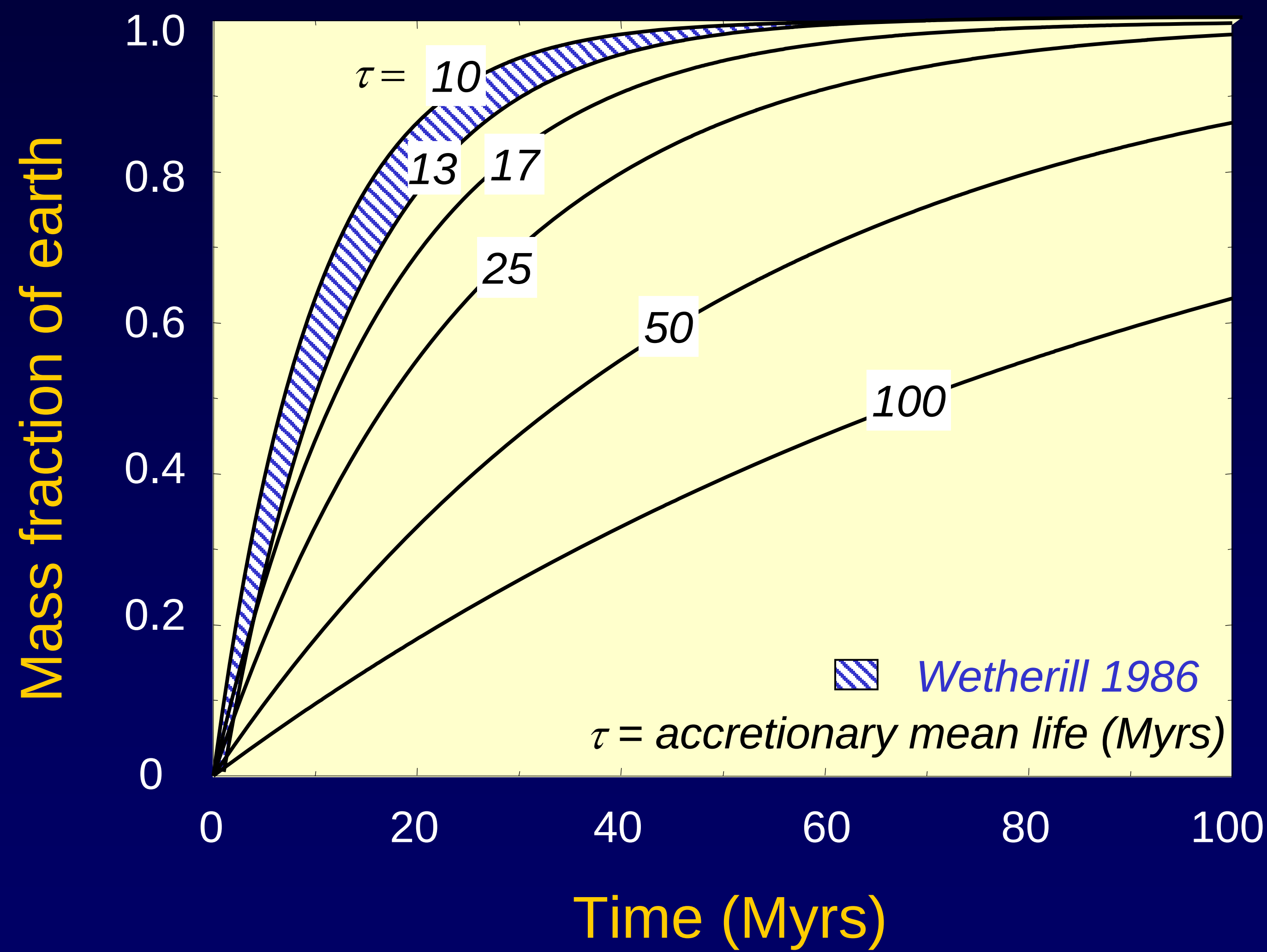


…what does this mean for the time-scale of Earth accretion?

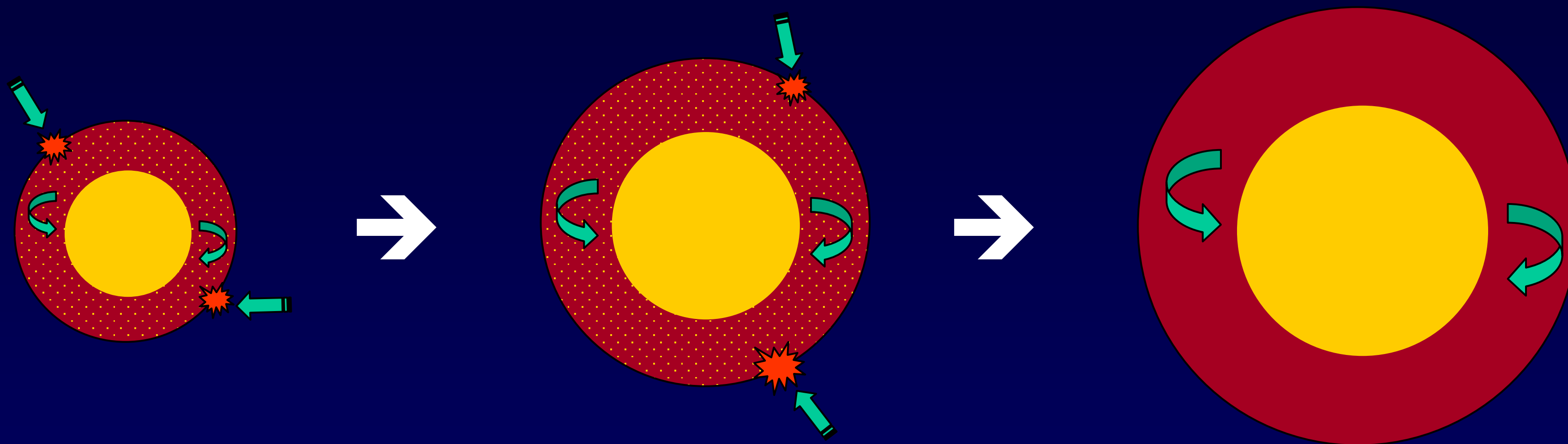


George Wetherill, 1986

Accretion of the Earth

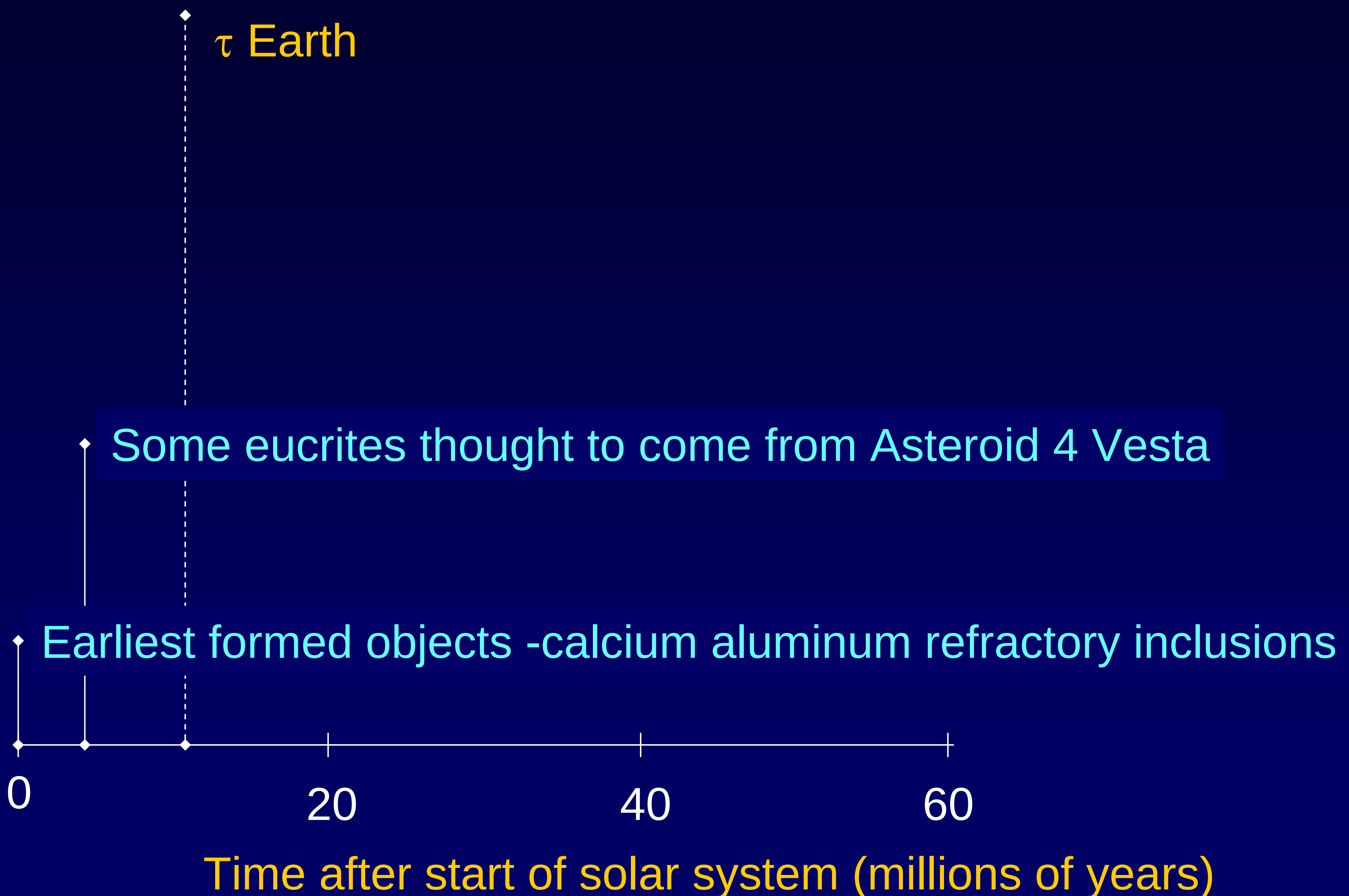


Continuous core formation



Gradual accretion, mixing, isotopic equilibration and metal segregation

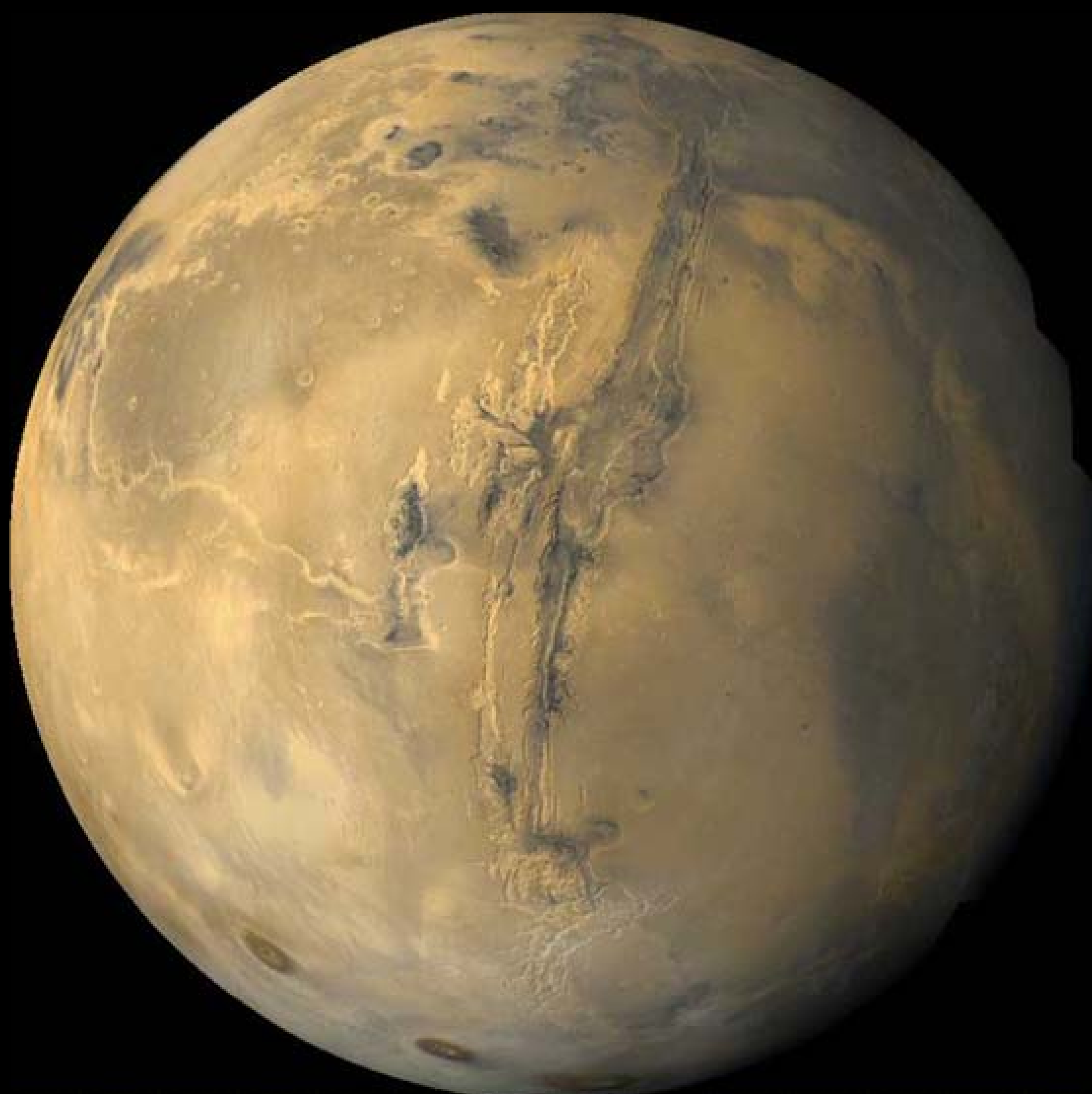
The ~ 2 ε_W excess of the silicate Earth relative to average solar system is consistent with ~63% accretion in 11 Myrs


τ Earth
Some eucrites thought to come from Asteroid 4 Vesta
Earliest formed objects -calcium aluminum refractory inclusions
0
20
40
60
Time after start of solar system (millions of years)

Model Time-scales for Accreting the Earth (>95%)

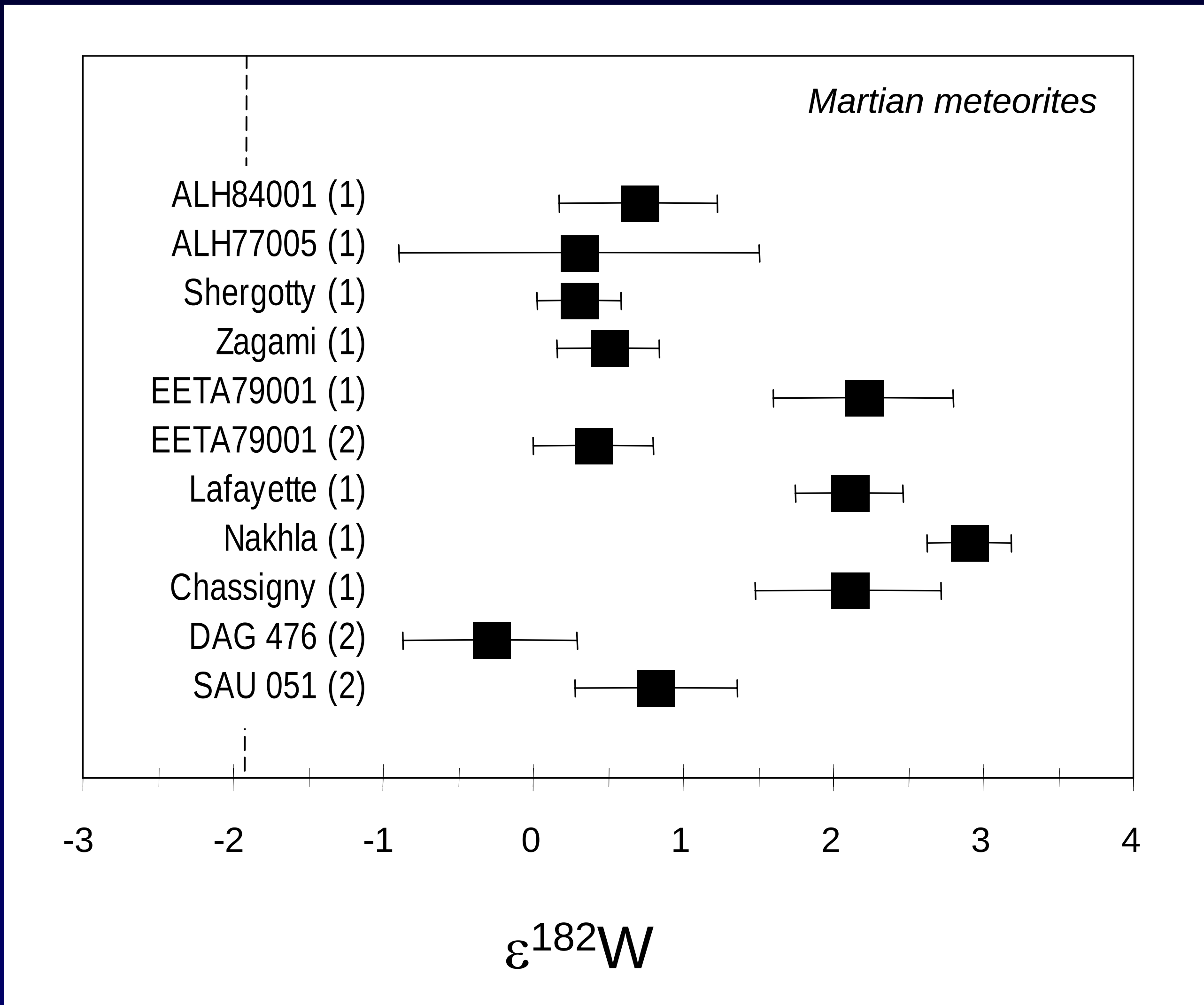
- Solar mass nebula
  $< 10^6$ yrs (Cameron 1978)
- Minimum mass solar nebula
  $\sim 5 \times 10^6$ yrs (e.g. Hayashi 1978)
- Late stage collisions with no nebula
  $10^7 - 10^8$ yrs (e.g. Wetherill 1986) ✓

Mars - rates and timing



Martian meteorites

Martian meteorites

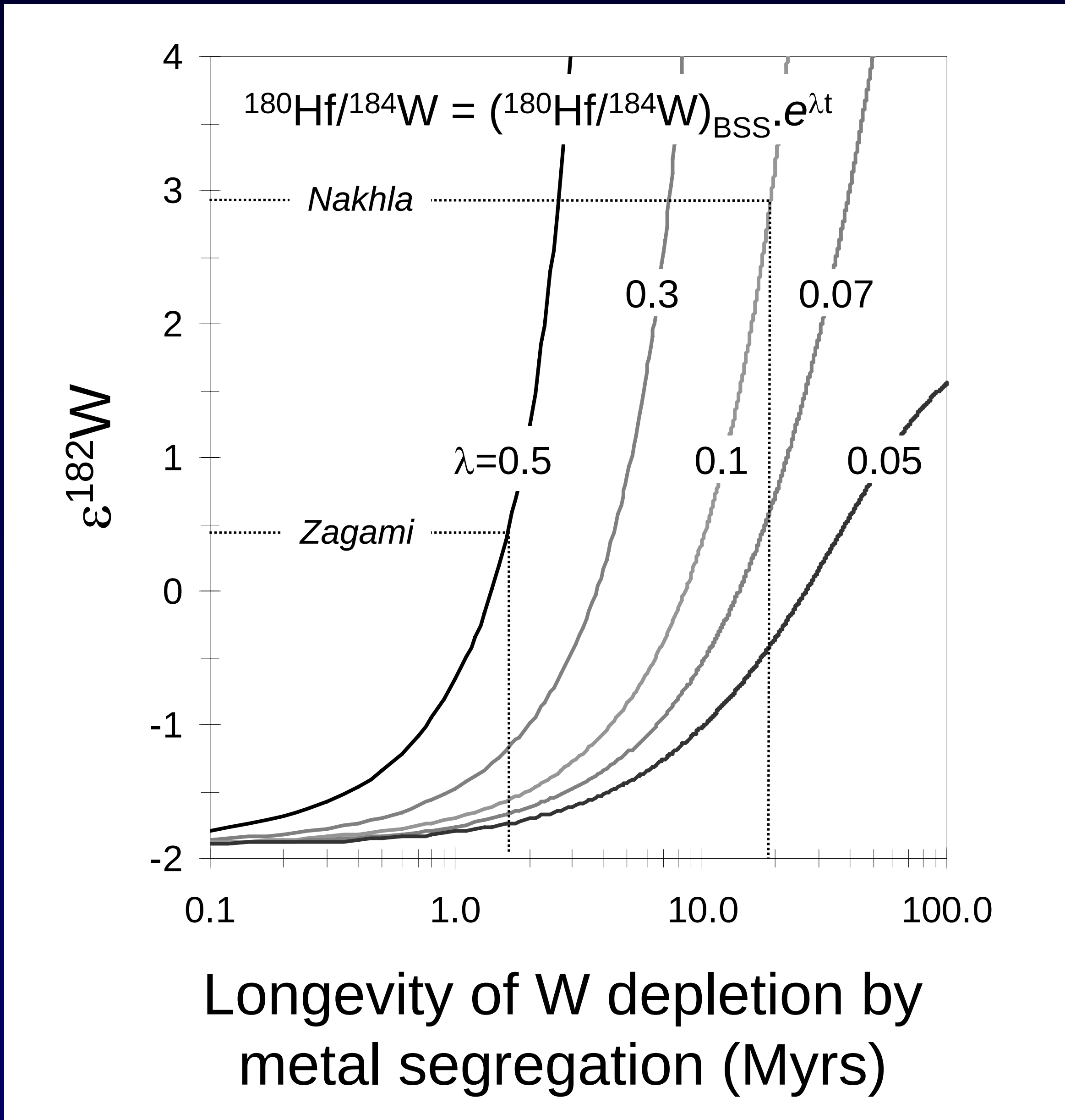


Martian meteorites

Have high $\varepsilon^{182}W$ but low Hf/W in martian mantle

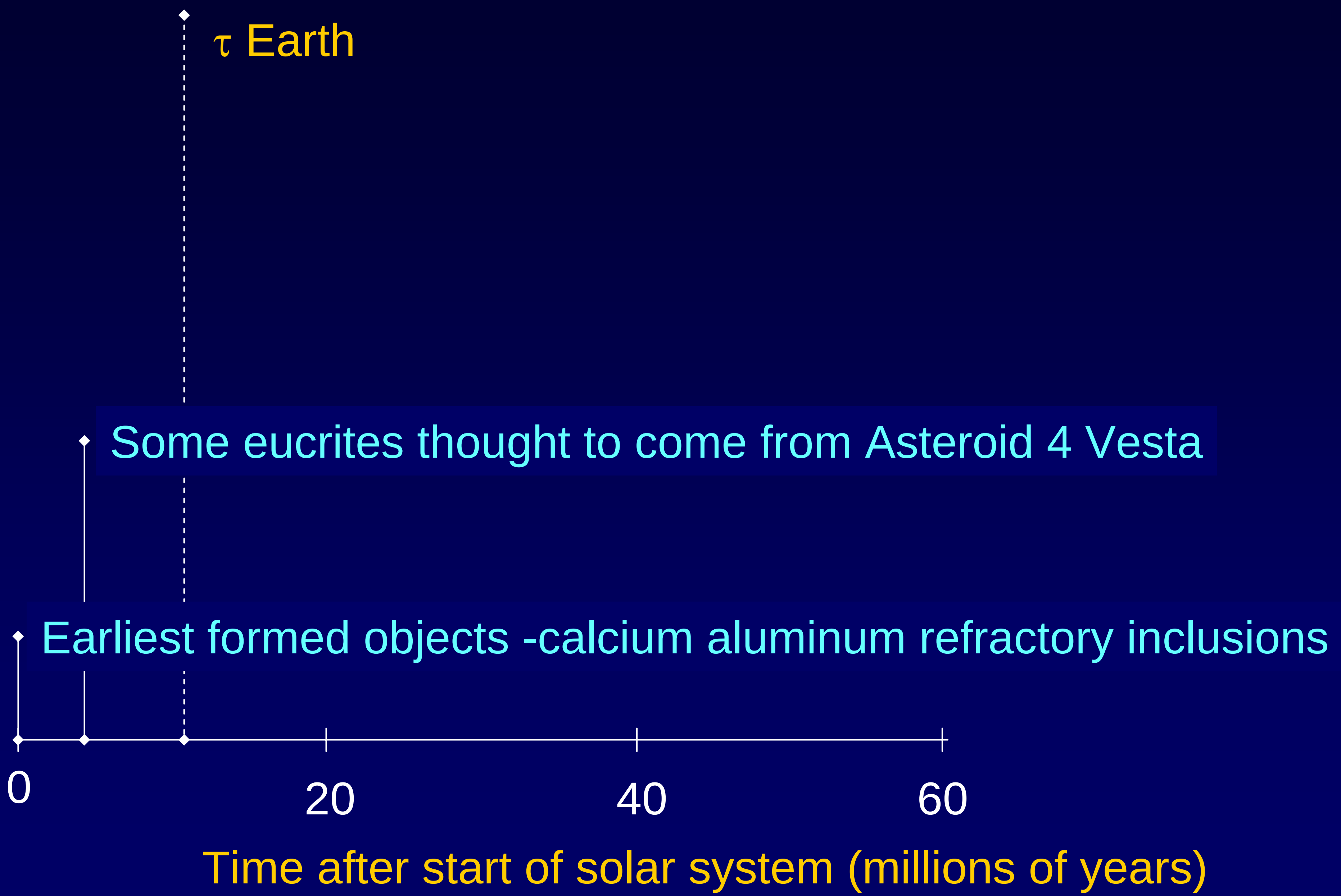
(Lee and Halliday 1997, Kleine et al. 2004)

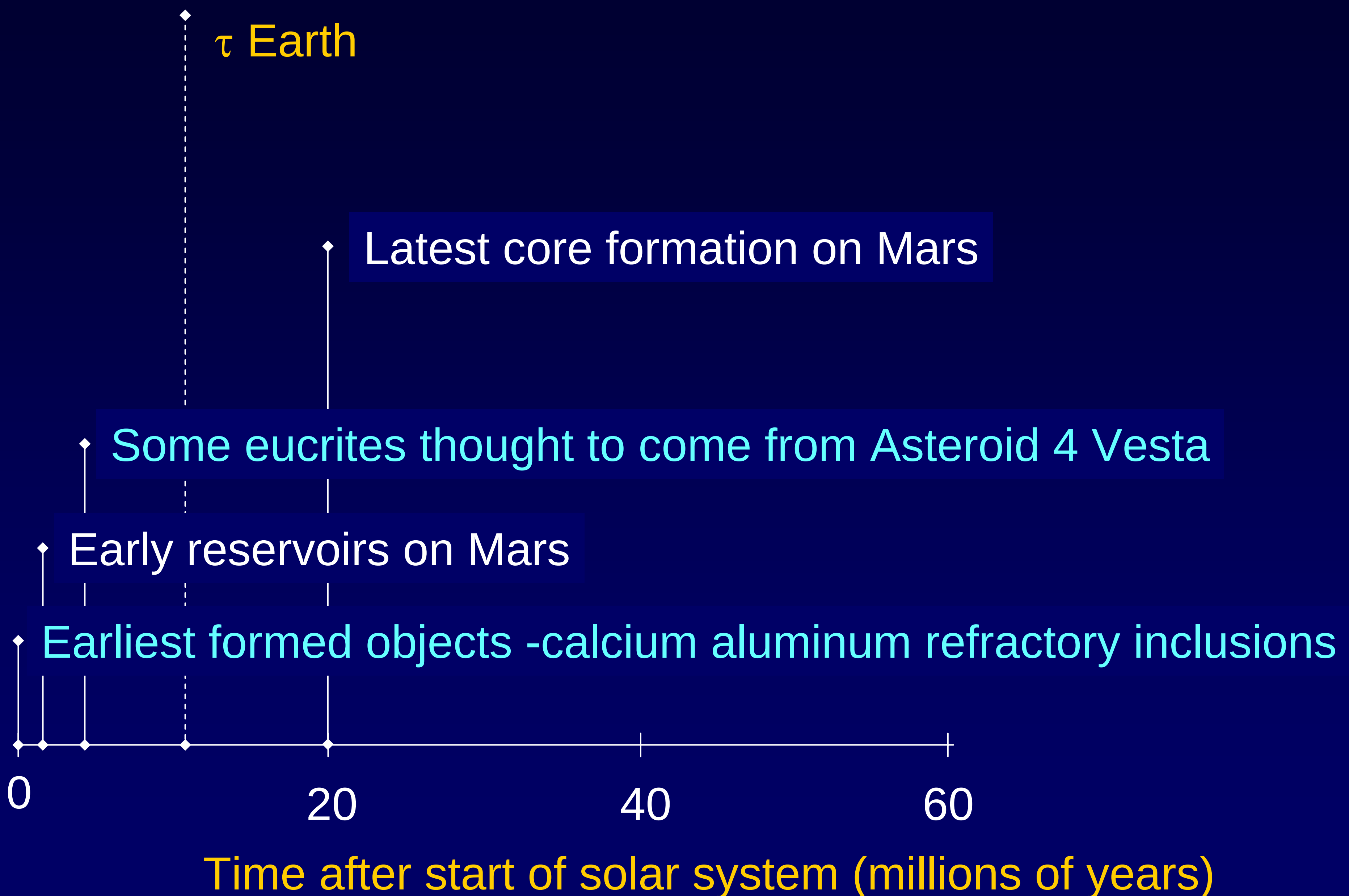
Martian meteorites



Tungsten data calibrated with a model of exponential core formation

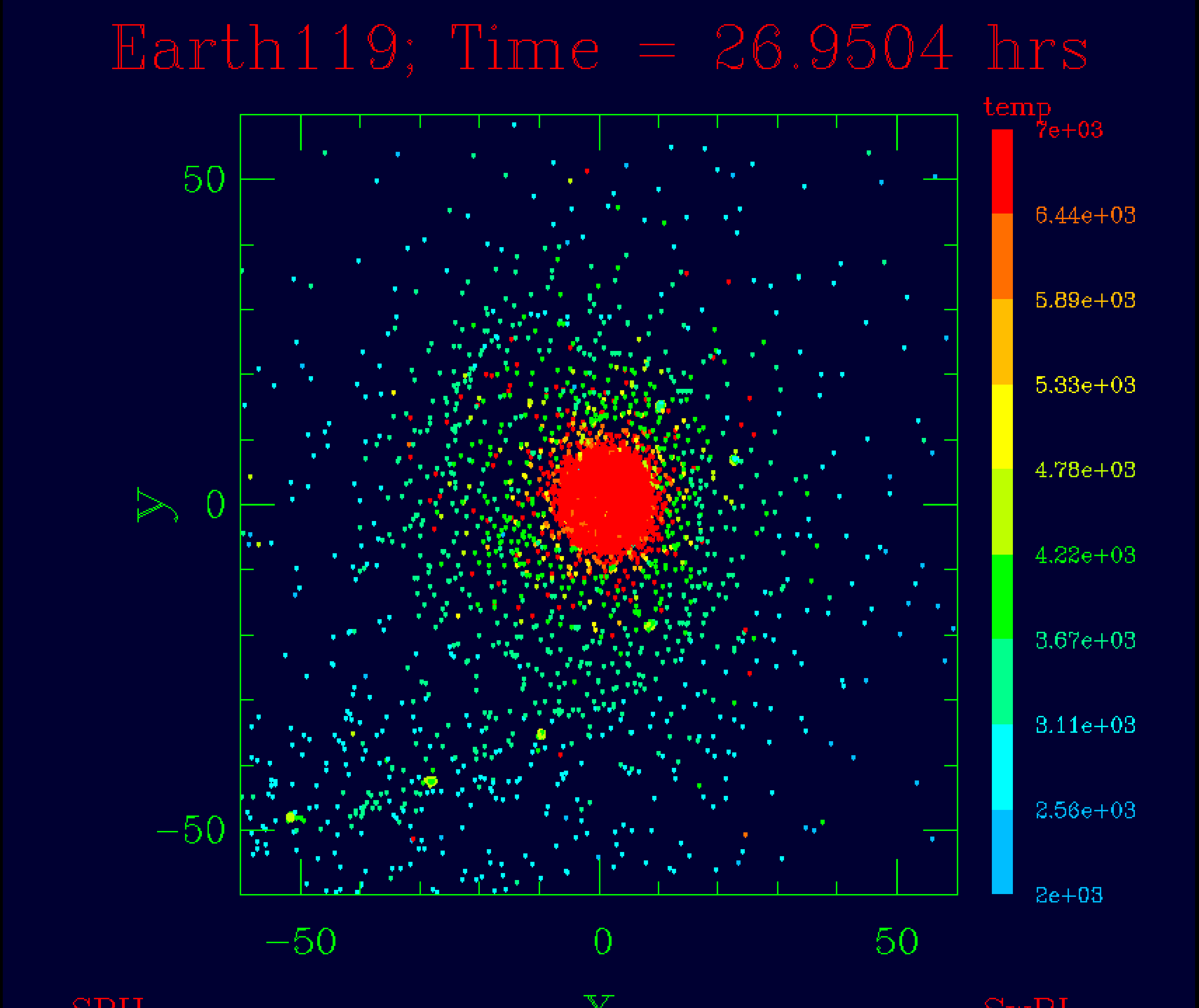
Some sources developed within about 1 million years


τ Earth
Some eucrites thought to come from Asteroid 4 Vesta
Earliest formed objects -calcium aluminum refractory inclusions
0
20
40
60
Time after start of solar system (millions of years)

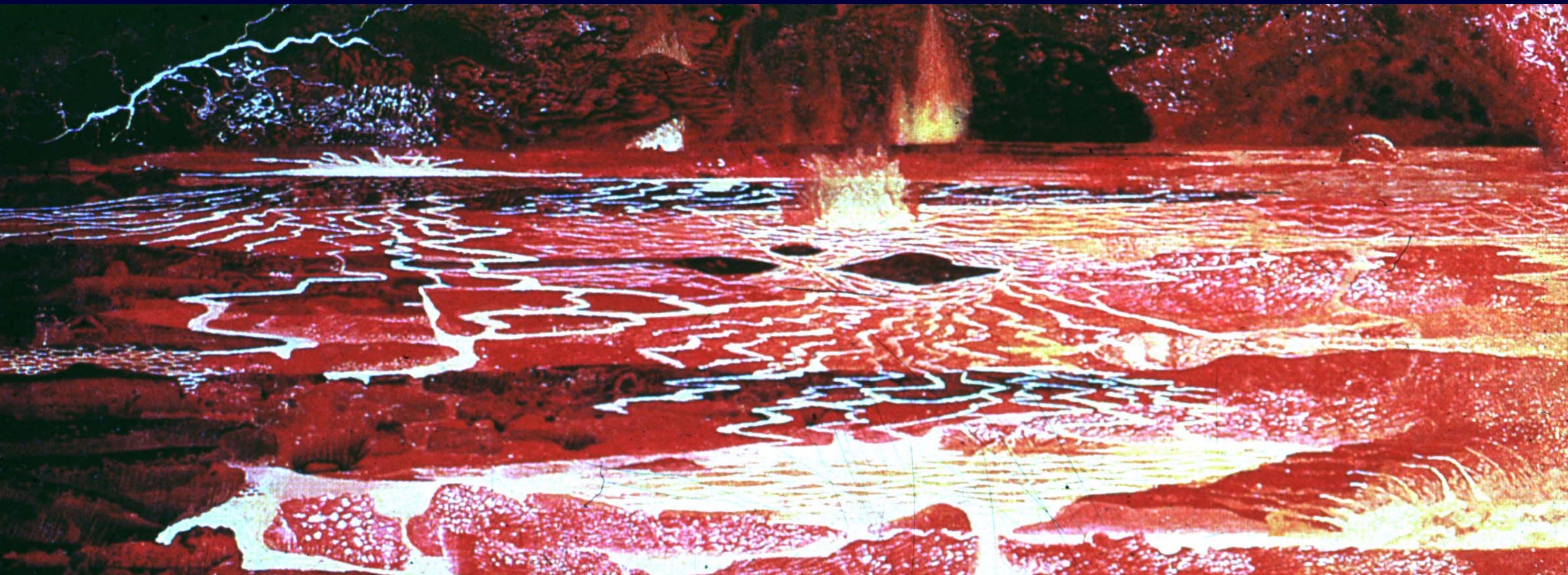

τ Earth
Latest core formation on Mars
Some eucrites thought to come from Asteroid 4 Vesta
Early reservoirs on Mars
Earliest formed objects -calcium aluminum refractory inclusions
0
20
40
60
Time after start of solar system (millions of years)

Issues

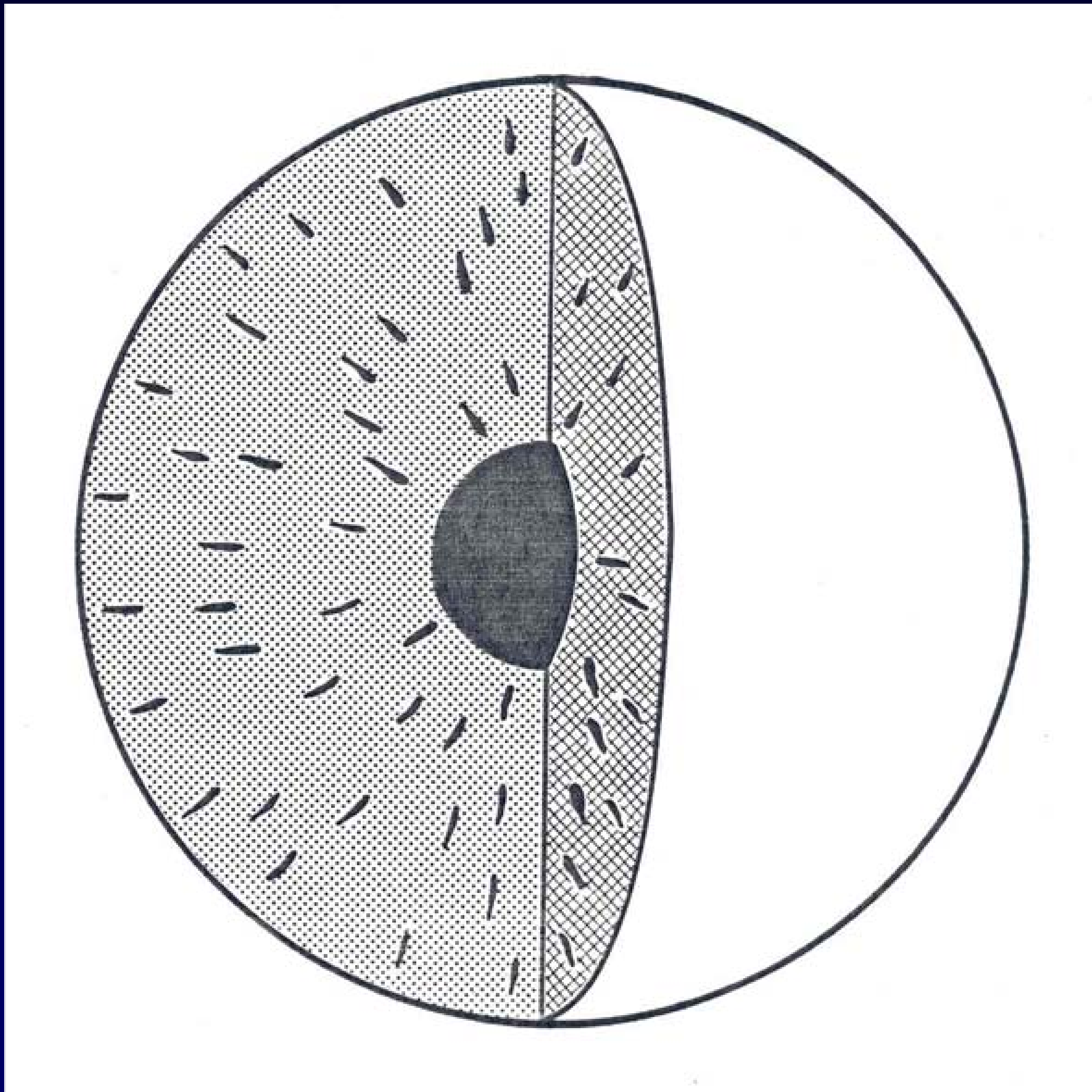
- How are Earth-like planets built?
- How did silicate and metal reservoirs form?
- How did Earth acquire its volatile elements?


Earth119; Time = 26.9504 hrs
temp
7e+03
6.44e+03
5.89e+03
5.33e+03
4.78e+03
4.22e+03
3.67e+03
3.11e+03
2.56e+03
2e+03
y
50
0
−50
−50
0
50

Accretion would have left the Earth really HOT...



...with oceans of MOLTEN ROCK

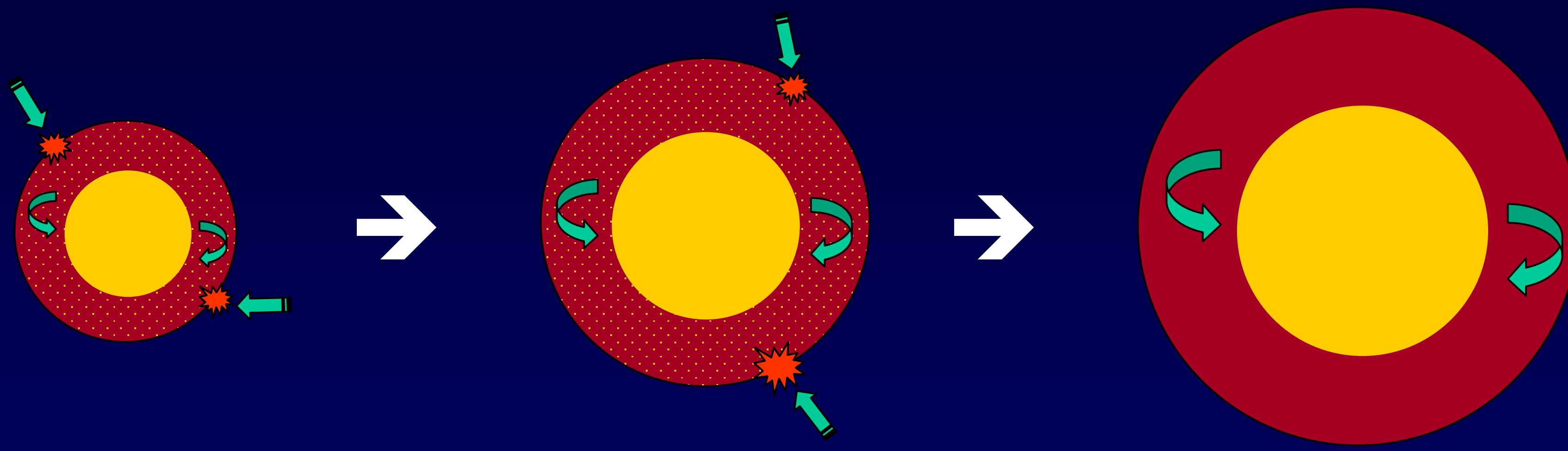


Core formation

The standard model

Dense metallic iron liquids descend through the silicate Earth

Continuous core formation



Gradual accretion, mixing, isotopic equilibration and metal segregation

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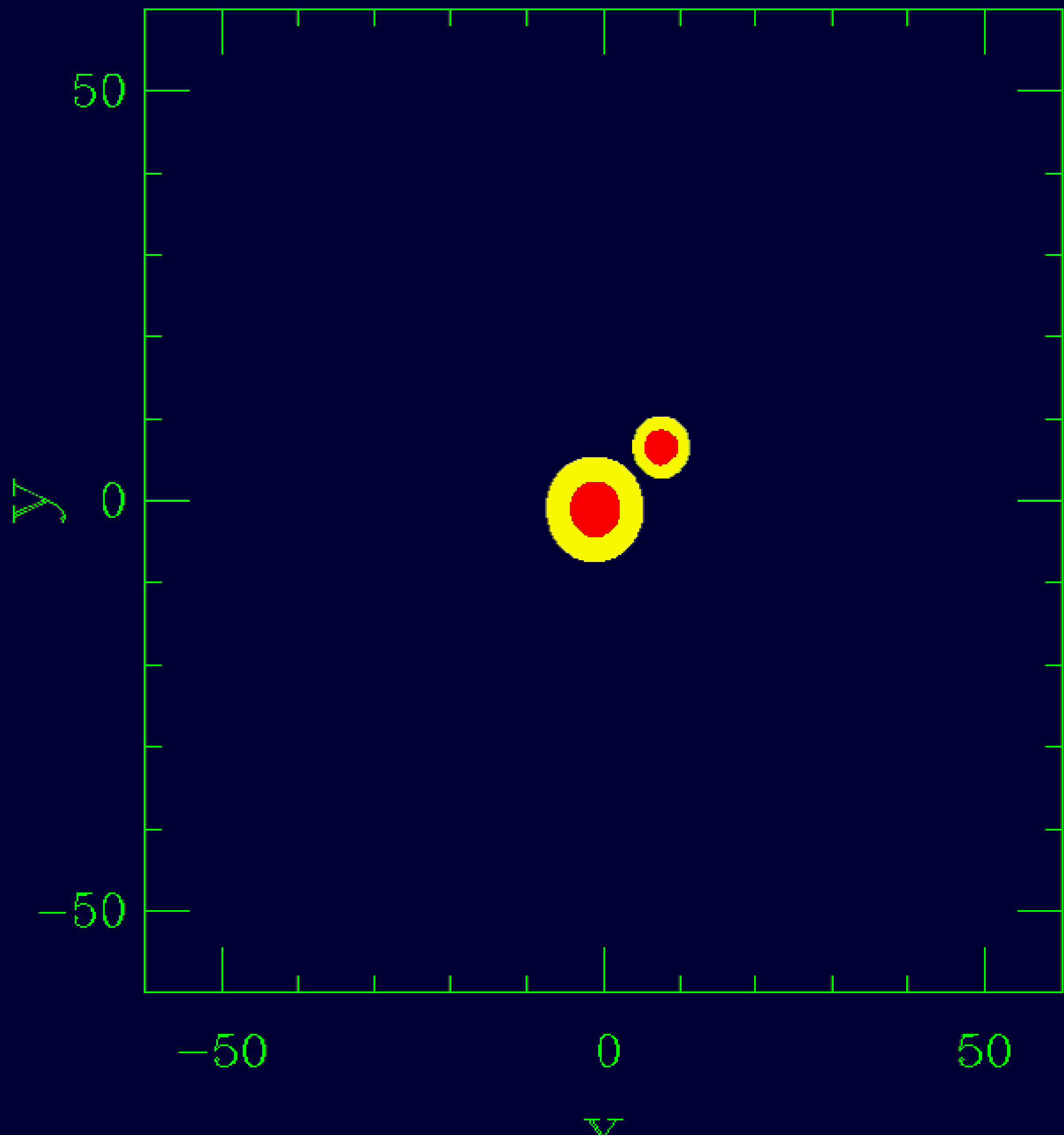
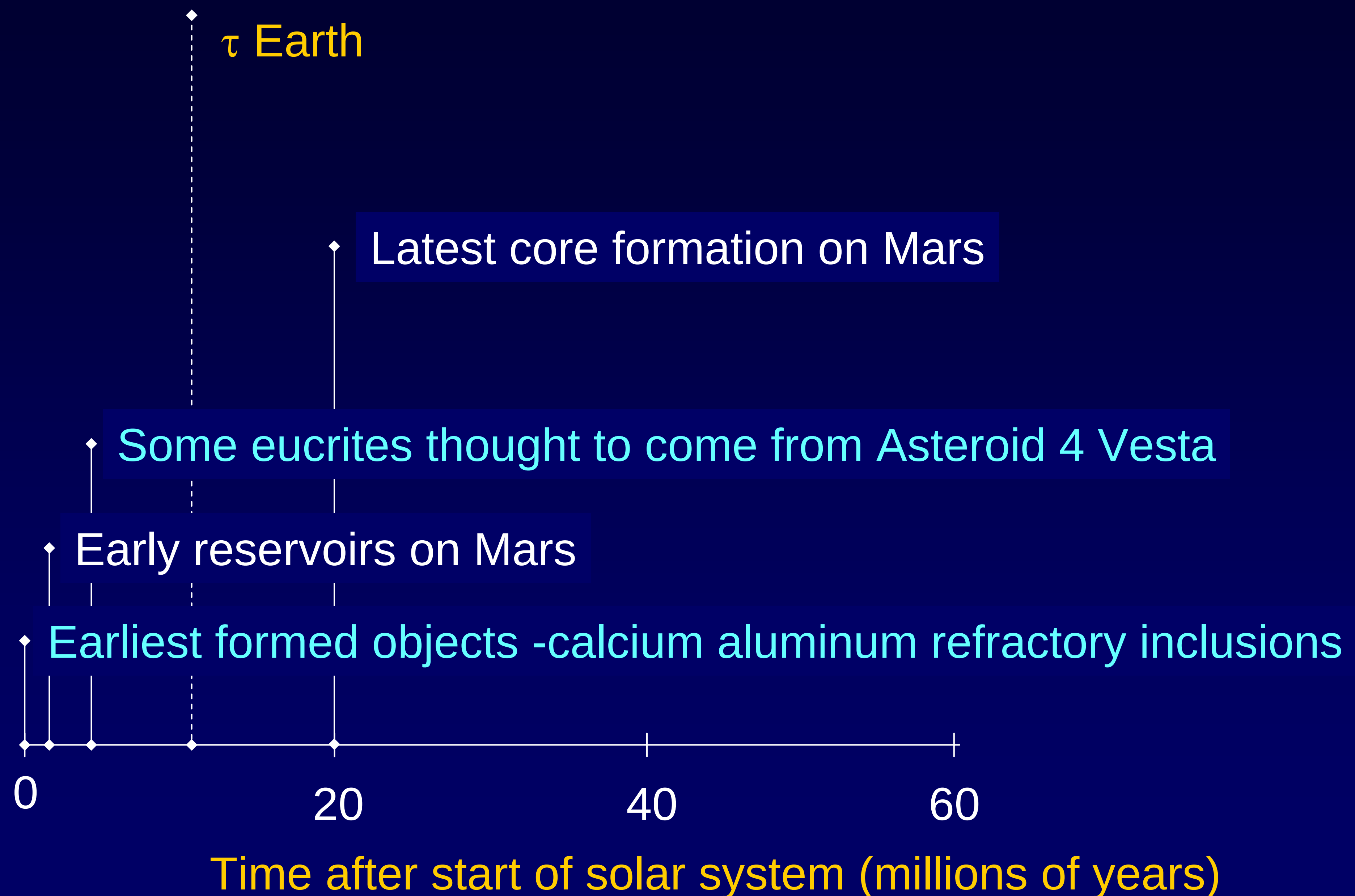
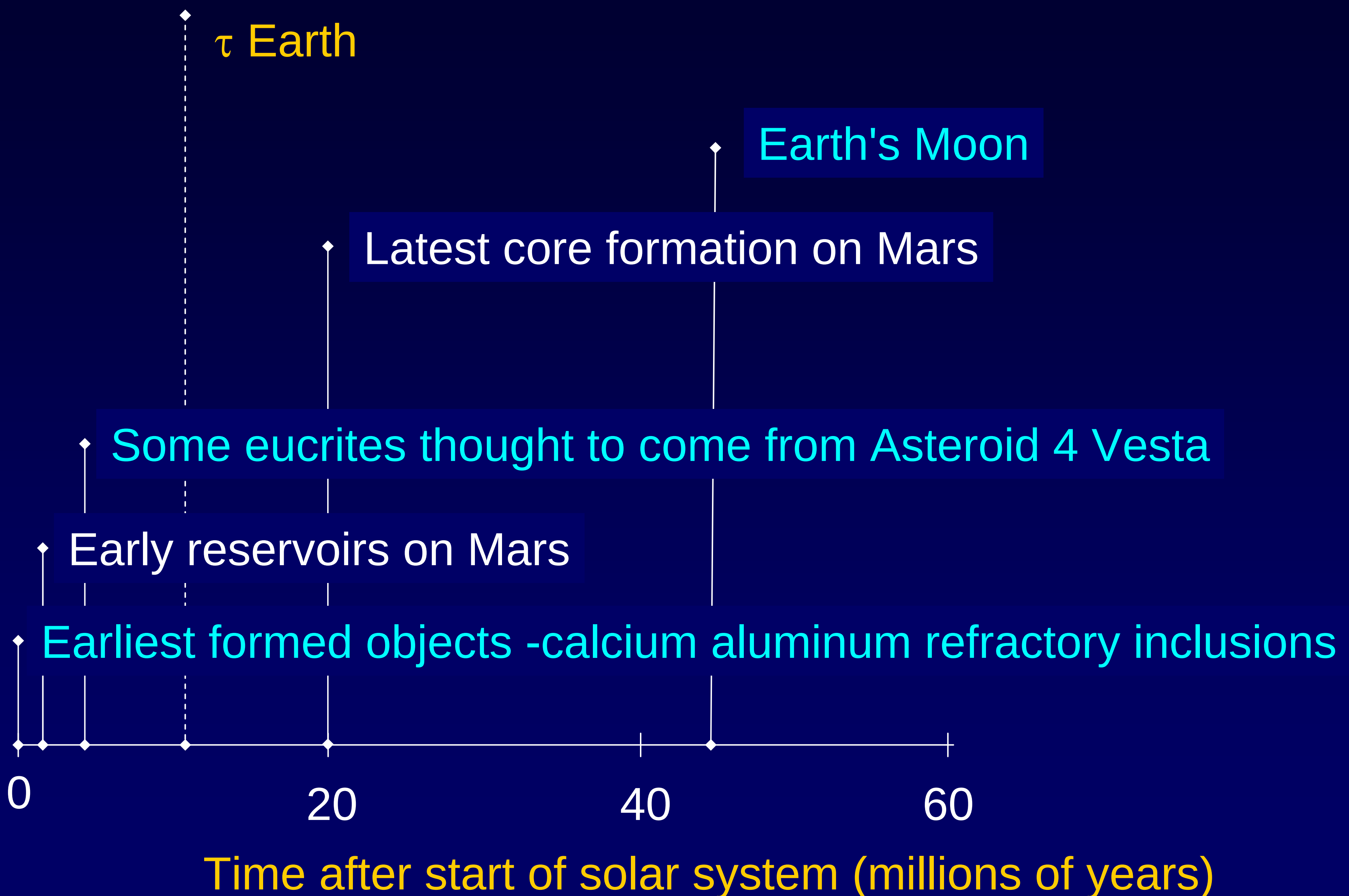
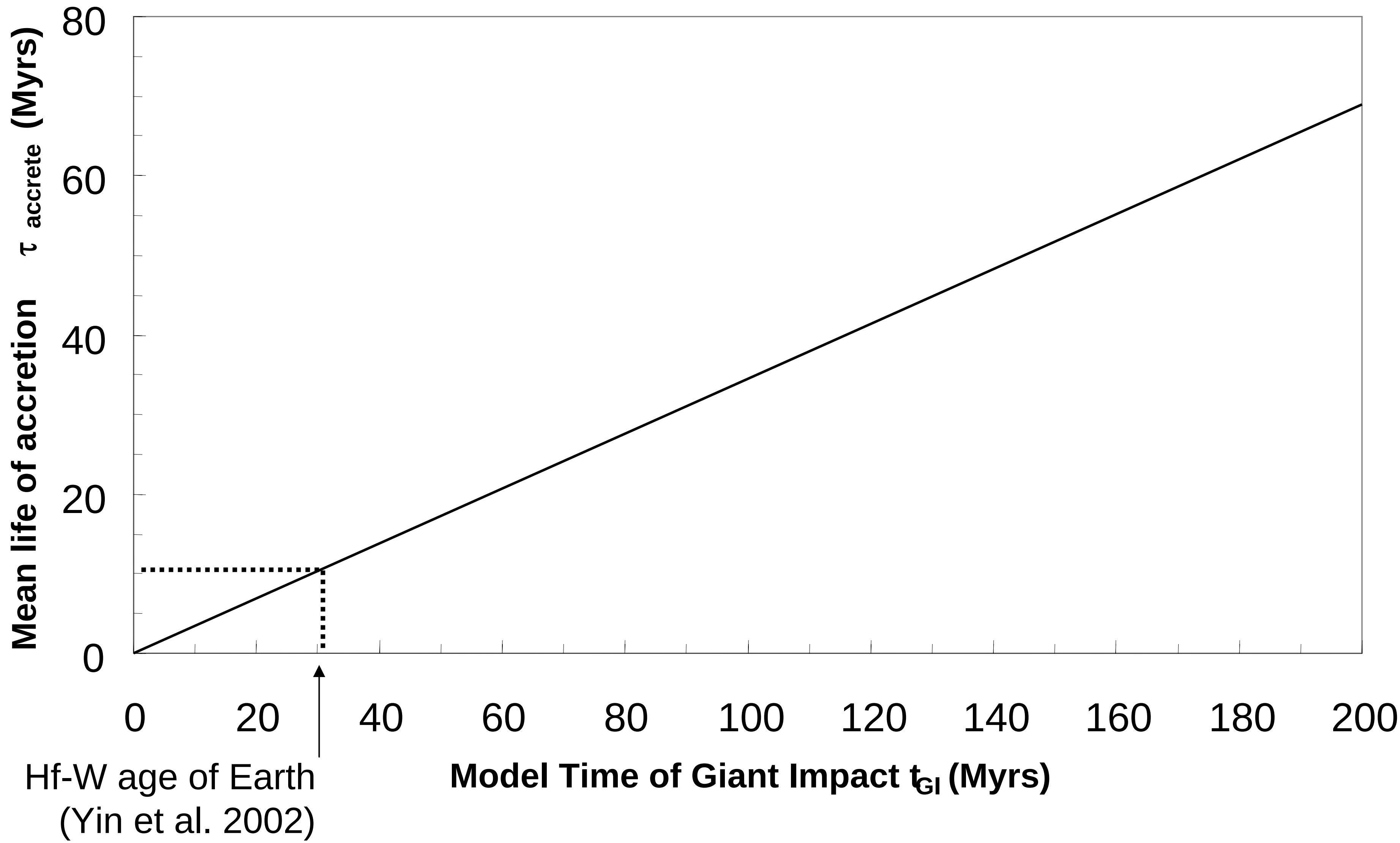
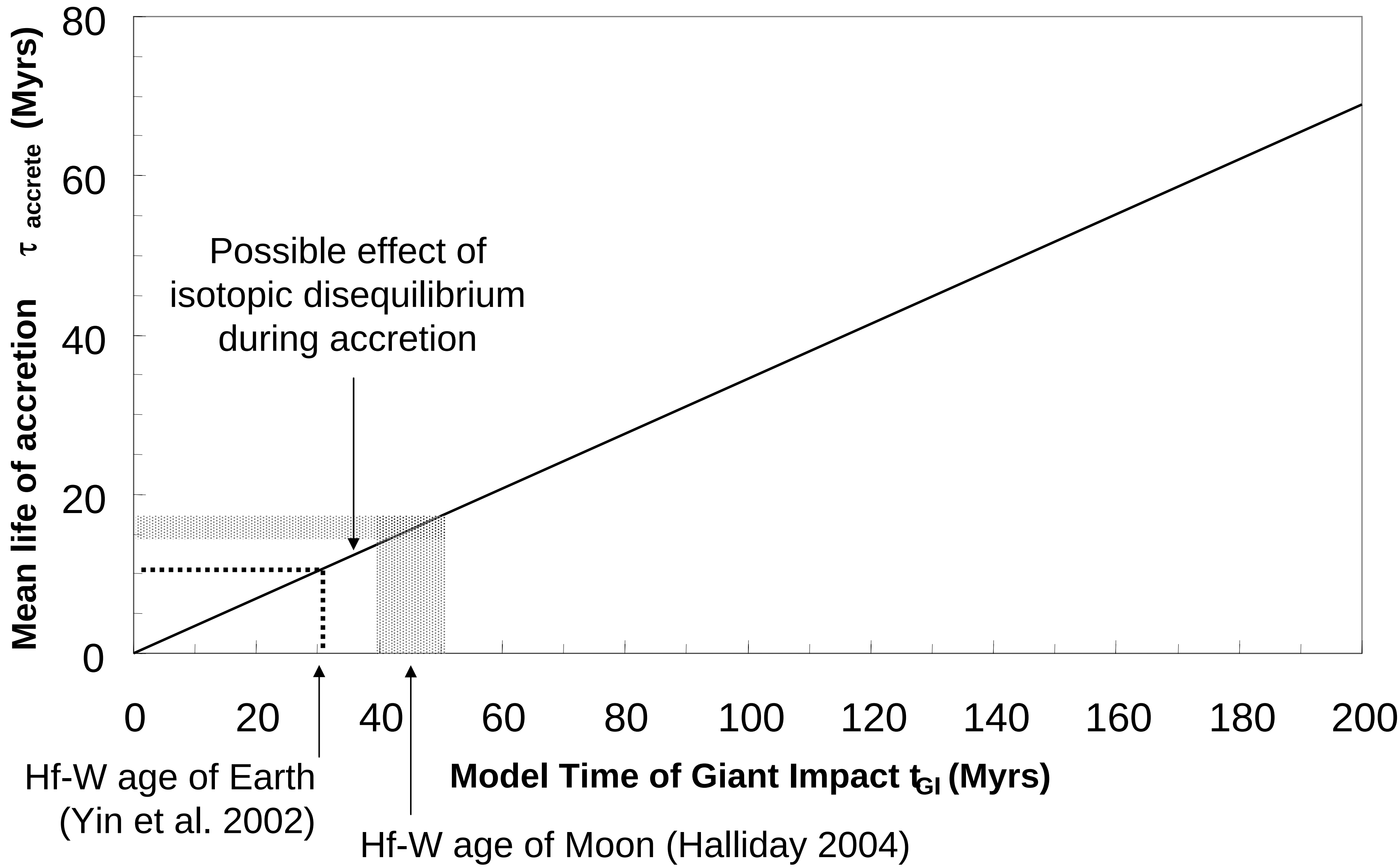

50
0
−50
y
−50
0
50
x


τ Earth
Latest core formation on Mars
Some eucrites thought to come from Asteroid 4 Vesta
Early reservoirs on Mars
Earliest formed objects -calcium aluminum refractory inclusions
0
20
40
60
Time after start of solar system (millions of years)

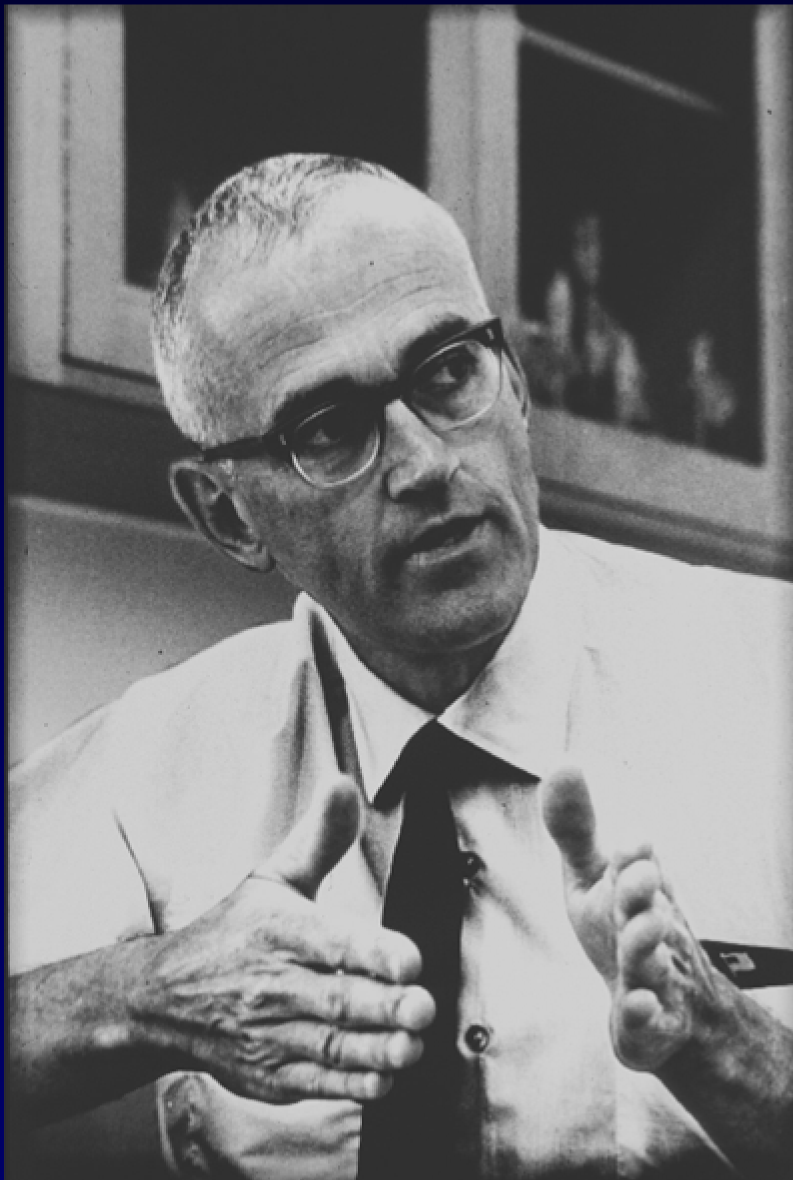

τ Earth
Earth's Moon
Latest core formation on Mars
Some eucrites thought to come from Asteroid 4 Vesta
Early reservoirs on Mars
Earliest formed objects -calcium aluminum refractory inclusions
0
20
40
60
Time after start of solar system (millions of years)

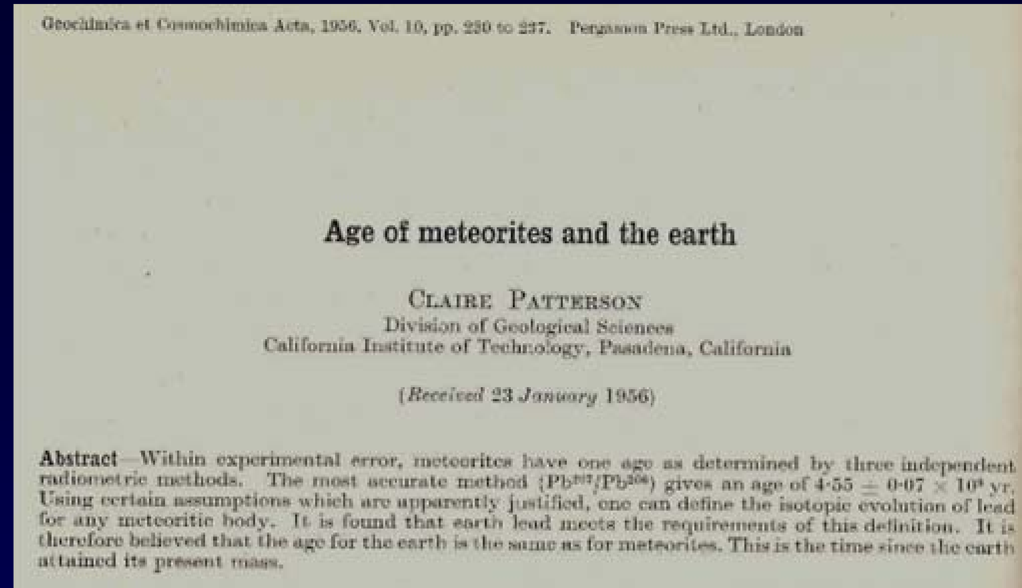

Mean life of accretion τ accrete (Myrs)
0
20
40
60
80
0
20
40
60
80
100
120
140
160
180
200
Hf-W age of Earth
(Yin et al. 2002)
Model Time of Giant Impact t GI (Myrs)



80
60
40
20
0
Mean life of accretion τ accrete (Myrs)
Possible effect of
isotopic disequilibrium
during accretion
0
20
40
60
80
100
120
140
160
180
200
Model Time of Giant Impact tGI (Myrs)
Hf-W age of Earth
(Yin et al. 2002)
Hf-W age of Moon (Halliday 2004)

Clair Patterson 1956





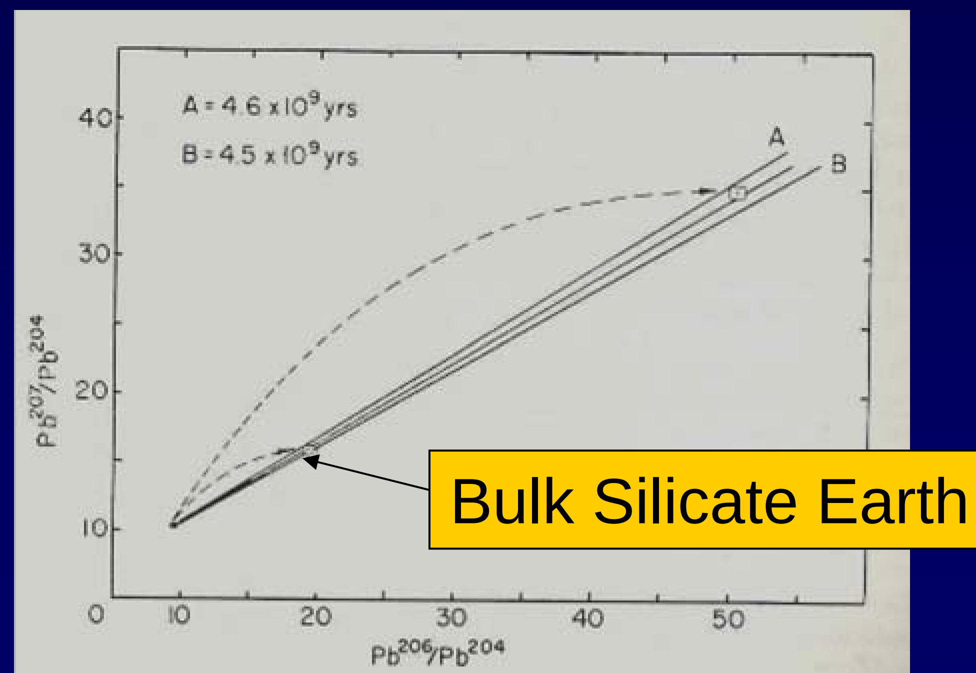
Geochimica et Cosmochimica Acta, 1956, Vol. 10, pp. 230 to 237. Pergamon Press Ltd., London

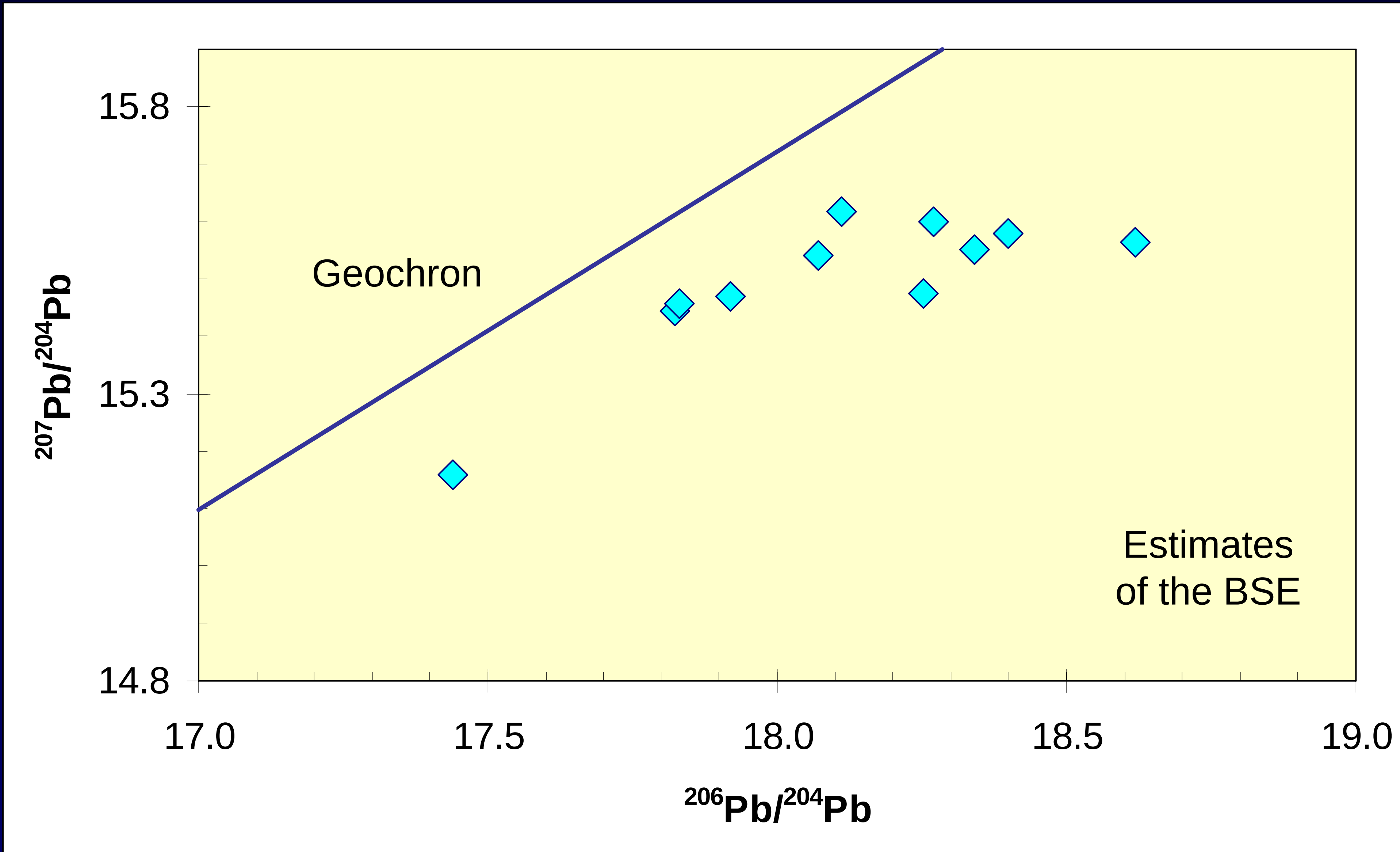
Age of meteorites and the earth

CLAIRE PATTERSON
Division of Geological Sciences
California Institute of Technology, Pasadena, California

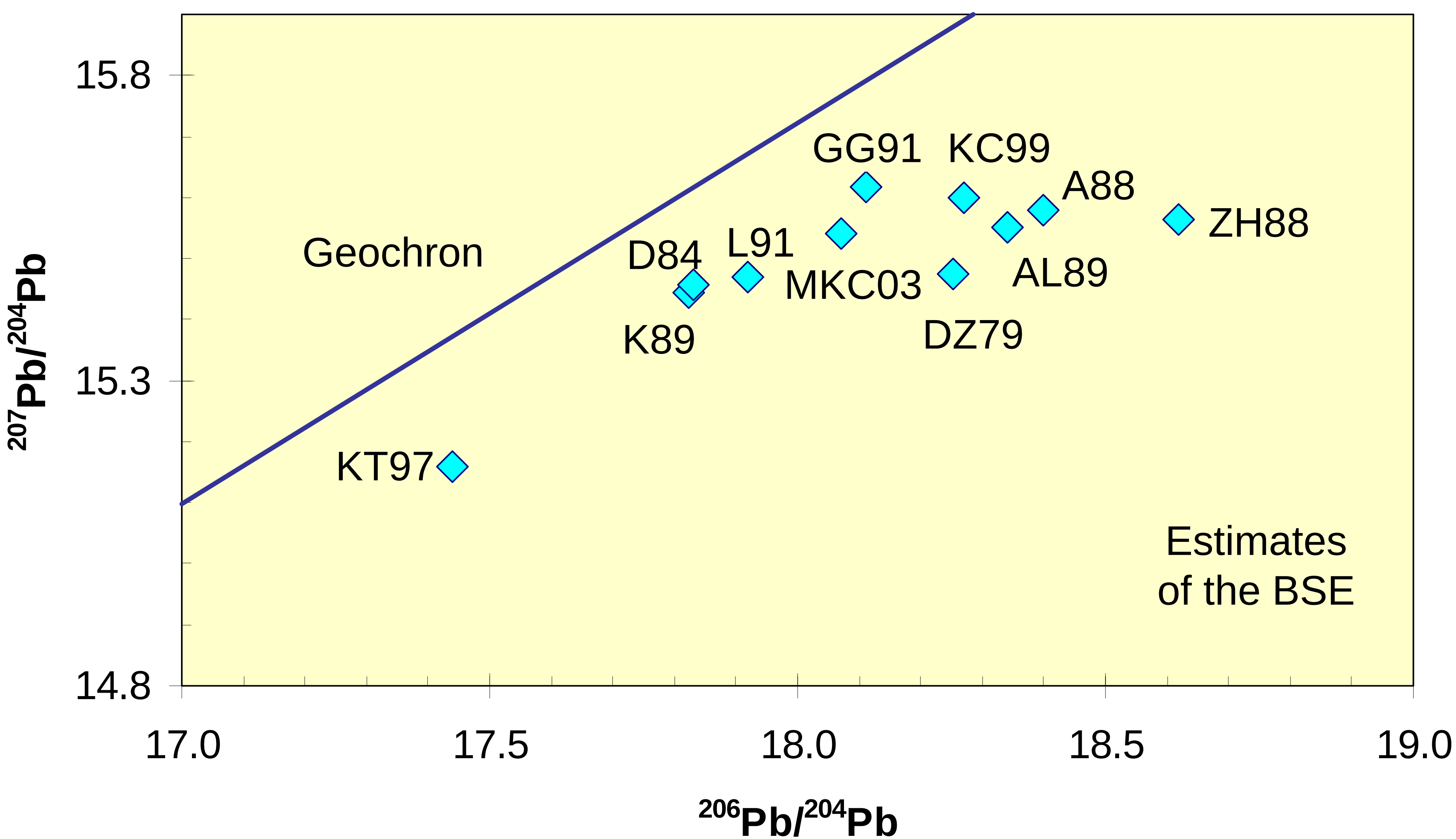
(*Received* 23 *January* 1956)

Abstract—Within experimental error, meteorites have one age as determined by three independent radiometric methods. The most accurate method (Pb^{207}/Pb^{206}) gives an age of 4·55 ± 0·07 × 10^9 yr. Using certain assumptions which are apparently justified, one can define the isotopic evolution of lead for any meteoritic body. It is found that earth lead meets the requirements of this definition. It is therefore believed that the age for the earth is the same as for meteorites. This is the time since the earth attained its present mass.

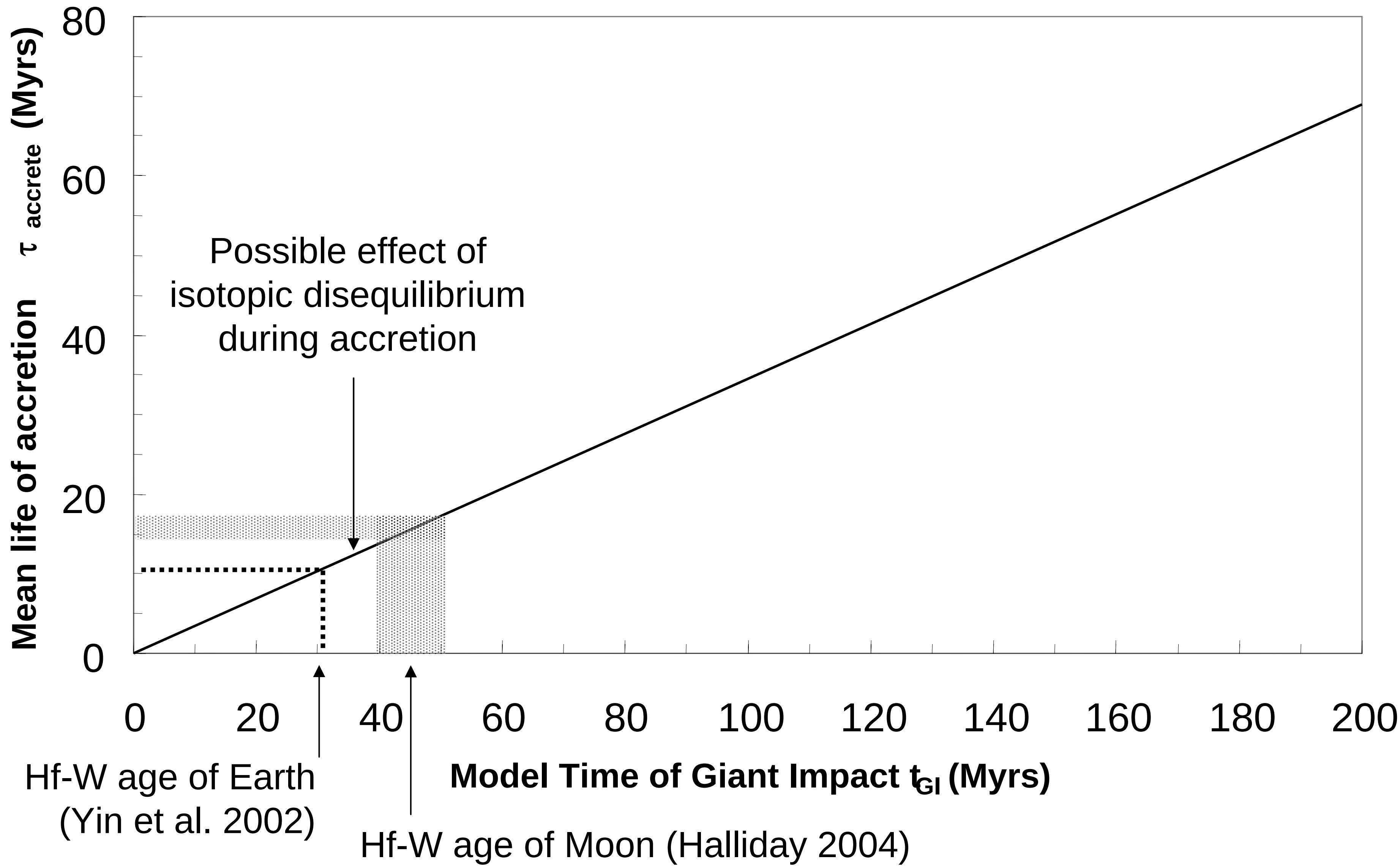


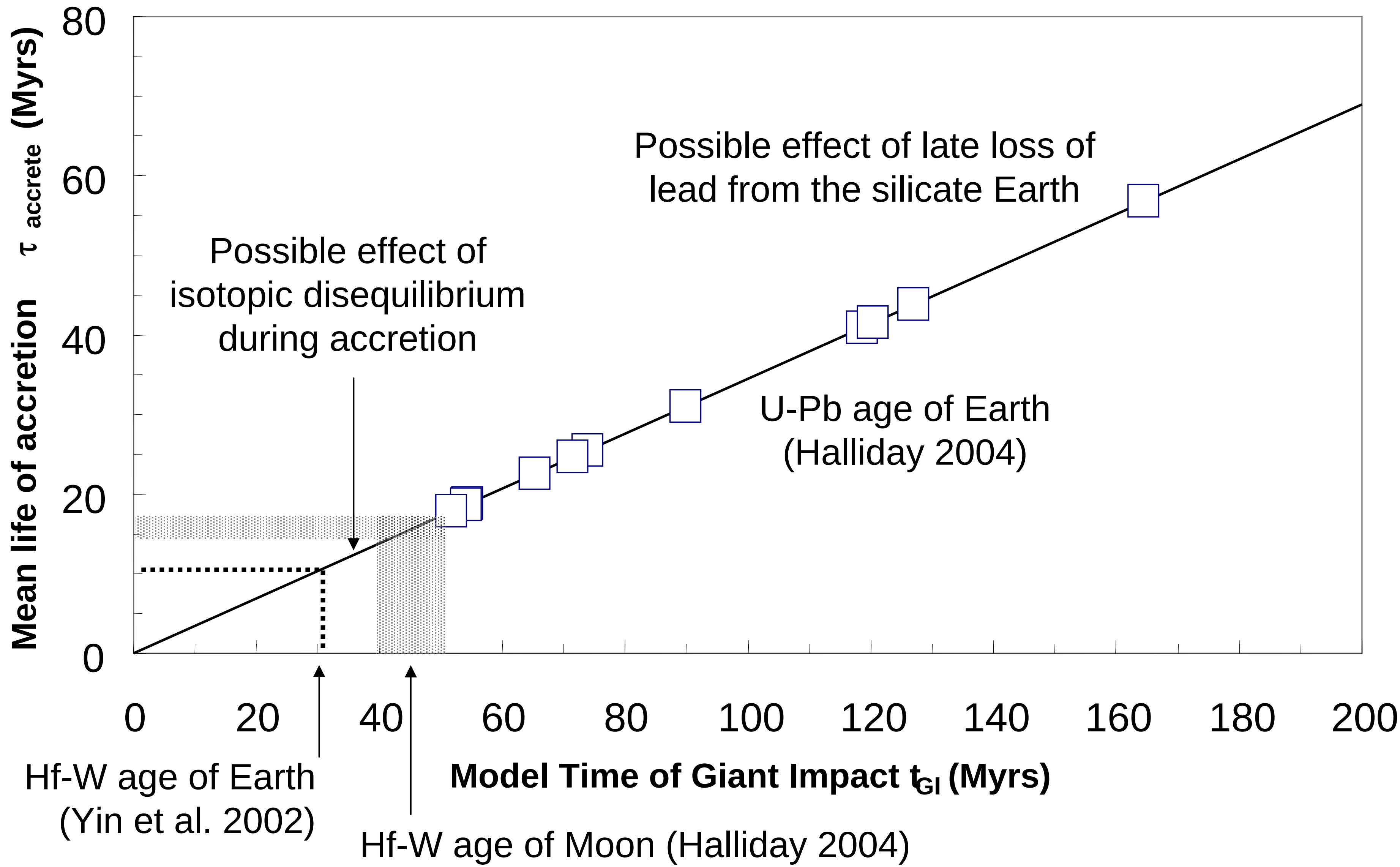


15.8
15.3
14.8
17.0
17.5
18.0
18.5
19.0
$^{207}Pb/^{204}Pb$
$^{206}Pb/^{204}Pb$
Geochron
Estimates
of the BSE



15.8
15.3
14.8
17.0
17.5
18.0
18.5
19.0
$^{207}Pb/^{204}Pb$
$^{206}Pb/^{204}Pb$
Geochron
GG91
KC99
A88
ZH88
L91
D84
MKC03
AL89
K89
DZ79
KT97
Estimates
of the BSE

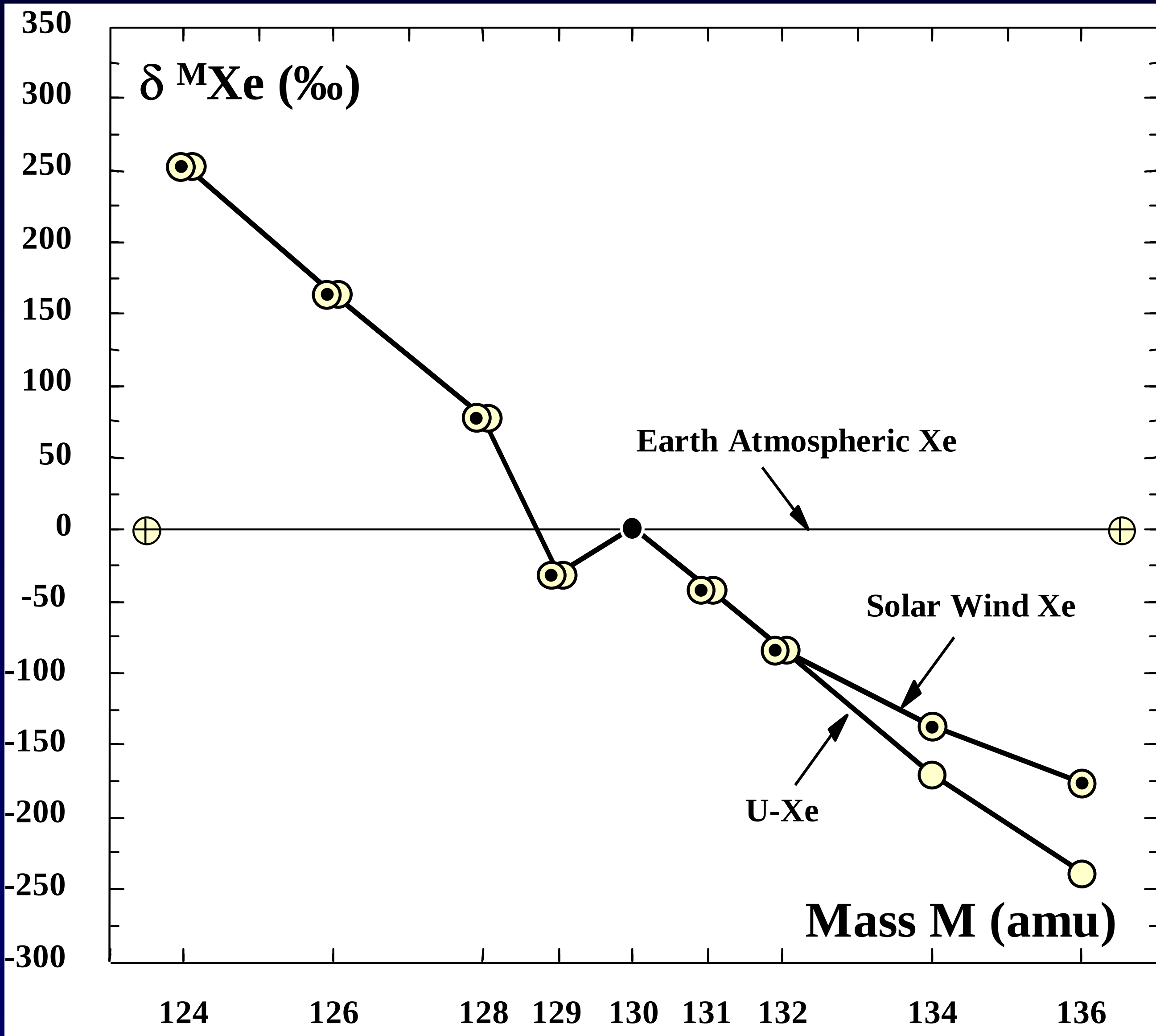

80
60
40
20
0
Mean life of accretion τ accrete (Myrs)
Possible effect of
isotopic disequilibrium
during accretion
0
20
40
60
80
100
120
140
160
180
200
Hf-W age of Earth
(Yin et al. 2002)
Model Time of Giant Impact t_{GI} (Myrs)
Hf-W age of Moon (Halliday 2004)



Mean life of accretion τ accrete (Myrs)
80
60
40
20
0
0
20
40
60
80
100
120
140
160
180
200
Model Time of Giant Impact t_{GI} (Myrs)
Possible effect of late loss of lead from the silicate Earth
Possible effect of isotopic disequilibrium during accretion
U-Pb age of Earth (Halliday 2004)
Hf-W age of Earth (Yin et al. 2002)
Hf-W age of Moon (Halliday 2004)

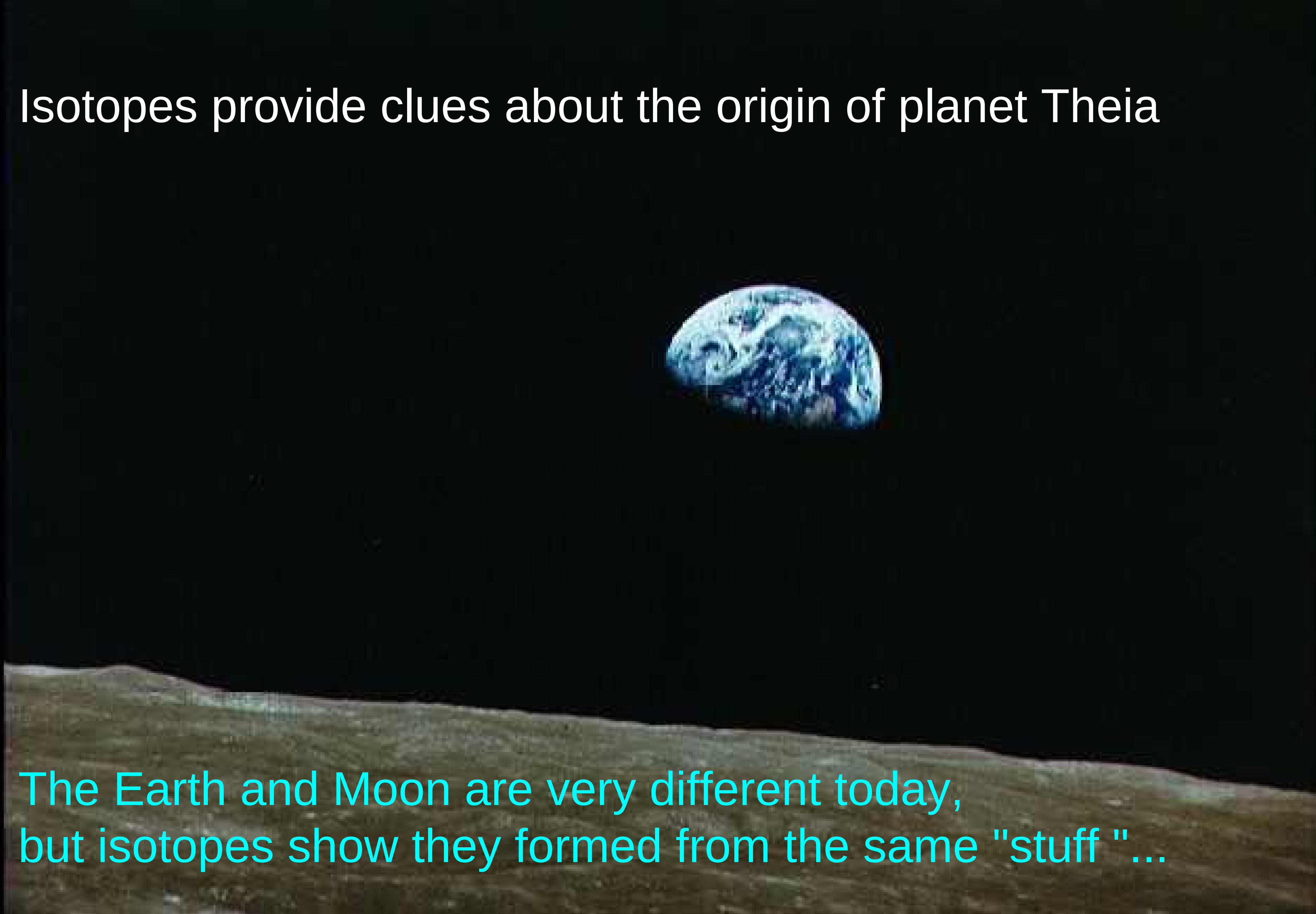
Issues

- How are Earth-like planets built?
- How did silicate and metal reservoirs form?
- How did Earth acquire its volatile elements?



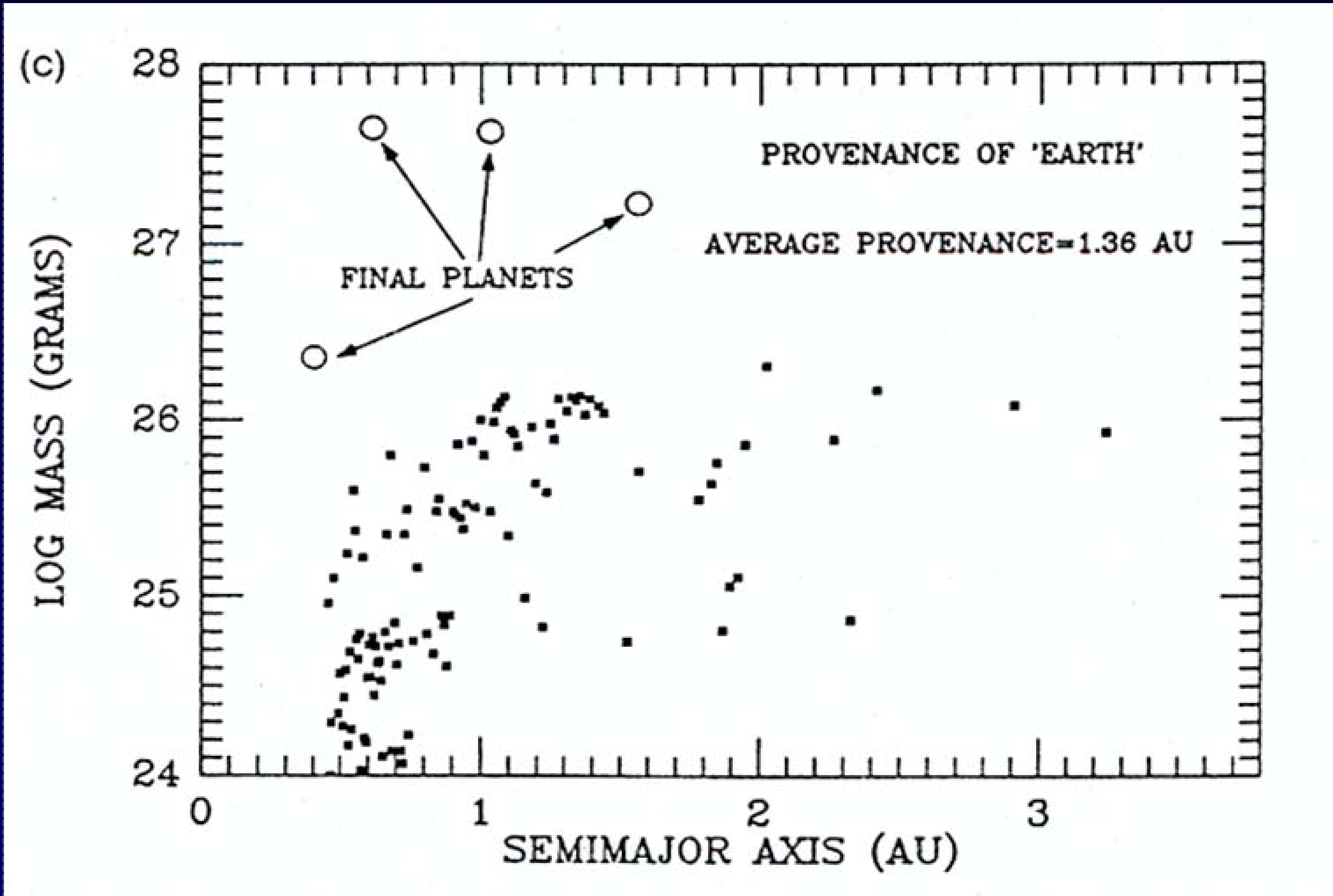
The Earth's atmosphere is fractionated relative to the solar wind or U-Xe

Isotopes provide clues about the origin of planet Theia



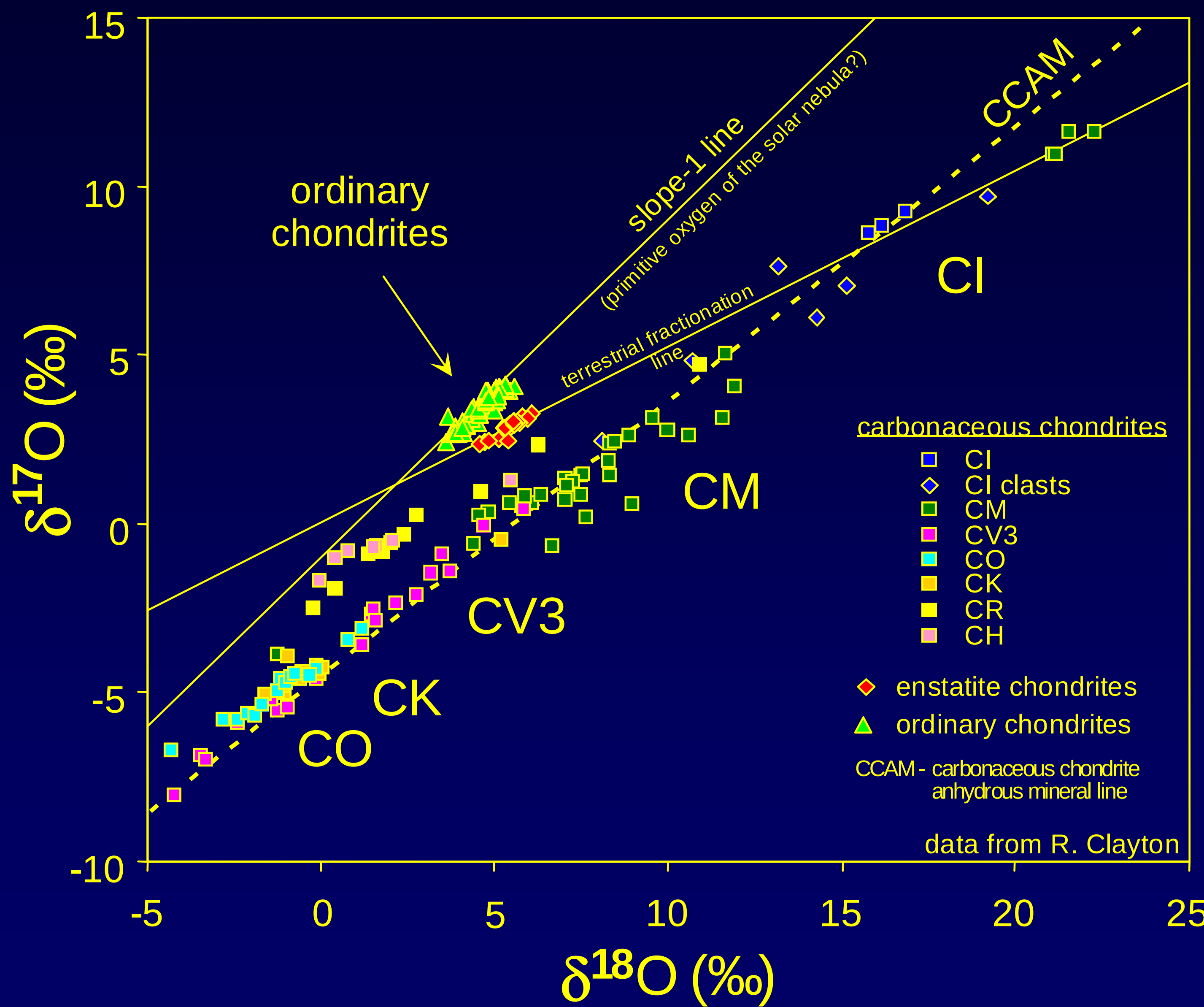
The Earth and Moon are very different today,
but isotopes show they formed from the same "stuff "...

Oxygen isotope tests of provenance

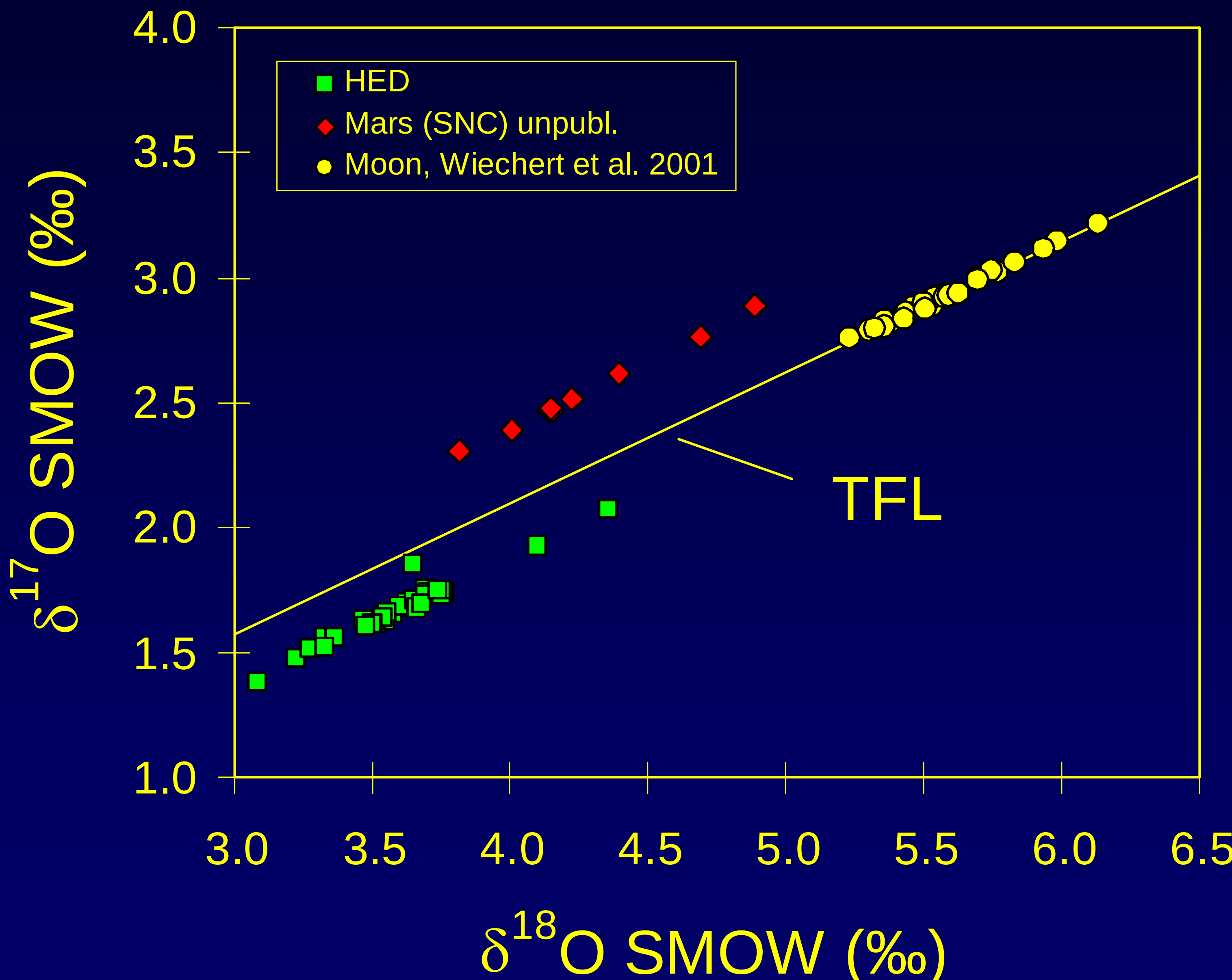


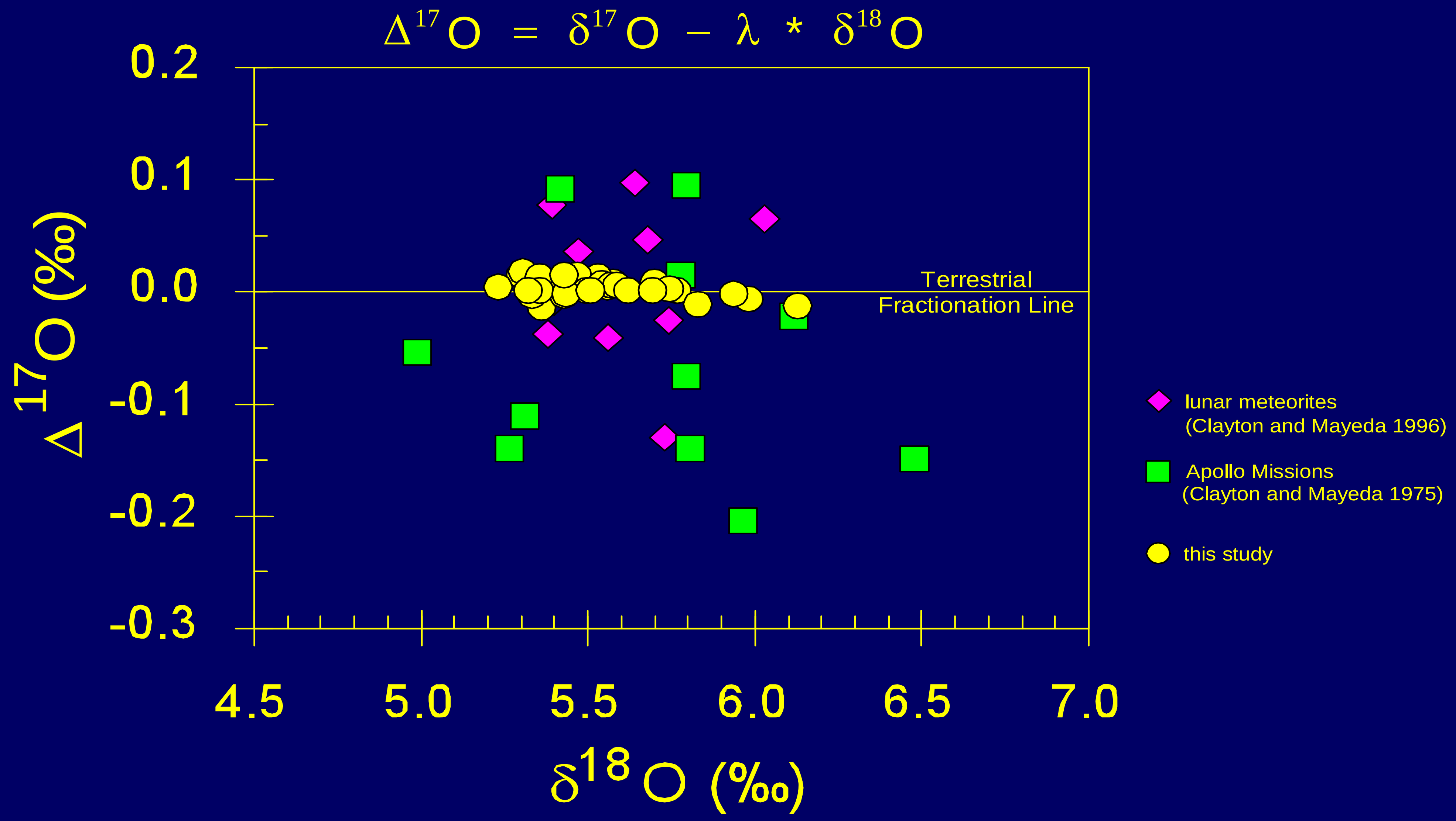
from Wetherill (1994)

Oxygen Isotopes in Primitive Meteorites



Oxygen isotopes for the Moon, Mars and Vesta

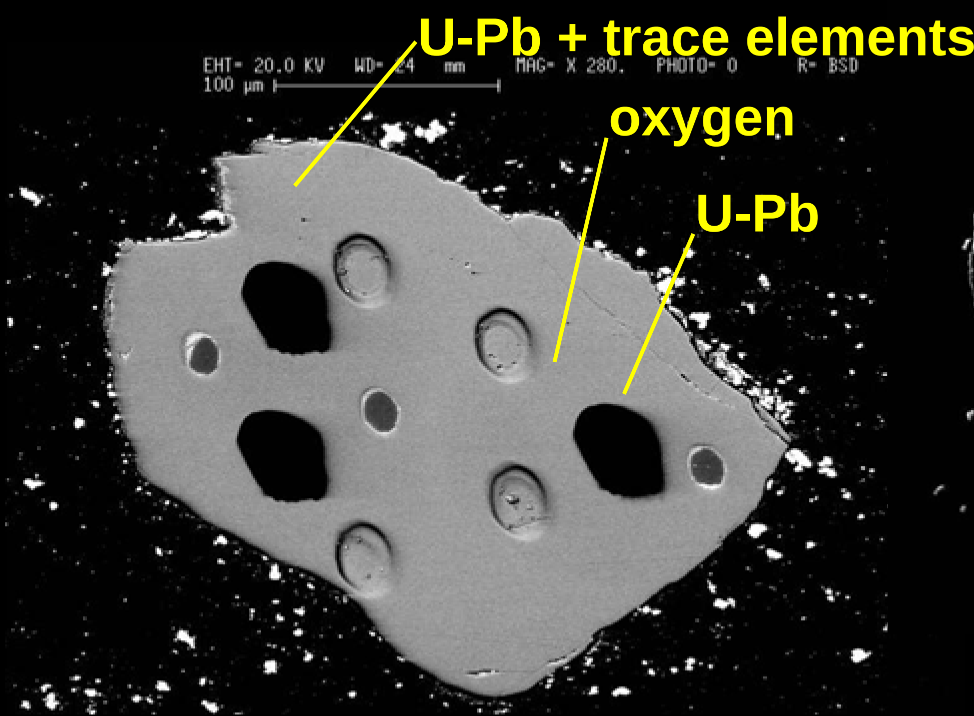


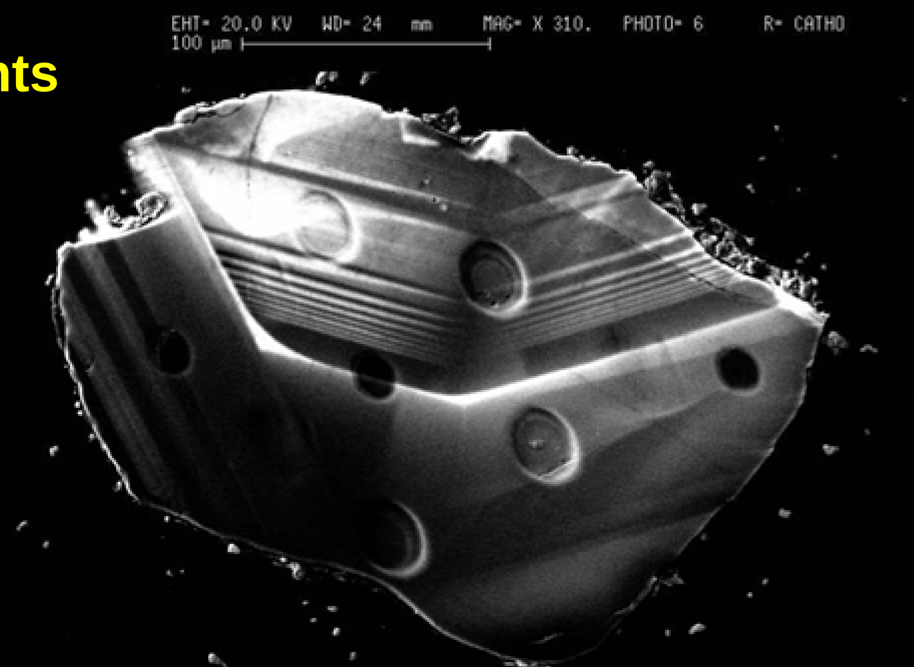


$\Delta^{17}O = \delta^{17}O - \lambda * \delta^{18}O$
0.2
0.1
0.0
-0.1
-0.2
-0.3
$\Delta^{17}O$ (‰)
Terrestrial Fractionation Line
4.5
5.0
5.5
6.0
6.5
7.0
$\delta^{18}O$ (‰)
lunar meteorites (Clayton and Mayeda 1996)
Apollo Missions (Clayton and Mayeda 1975)
this study

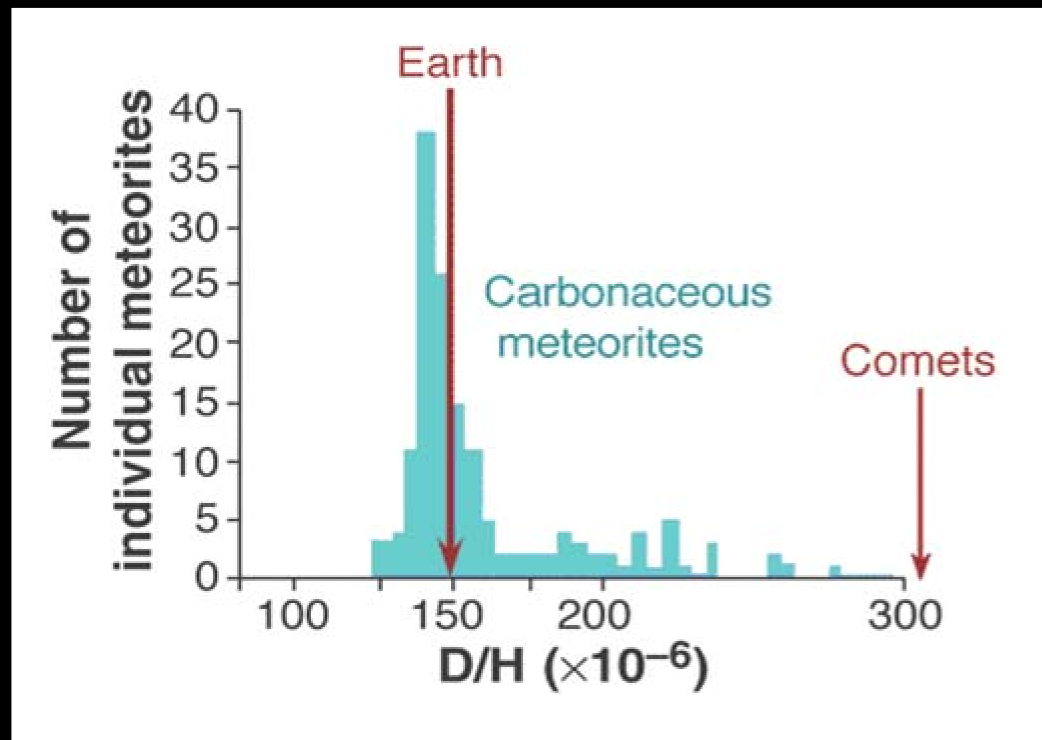
Origin of Earth’s water ?

Isotopic analysis of oxygen in zircons with an ion probe provides evidence of the existence of low temperature water since 4.3 billion years ago



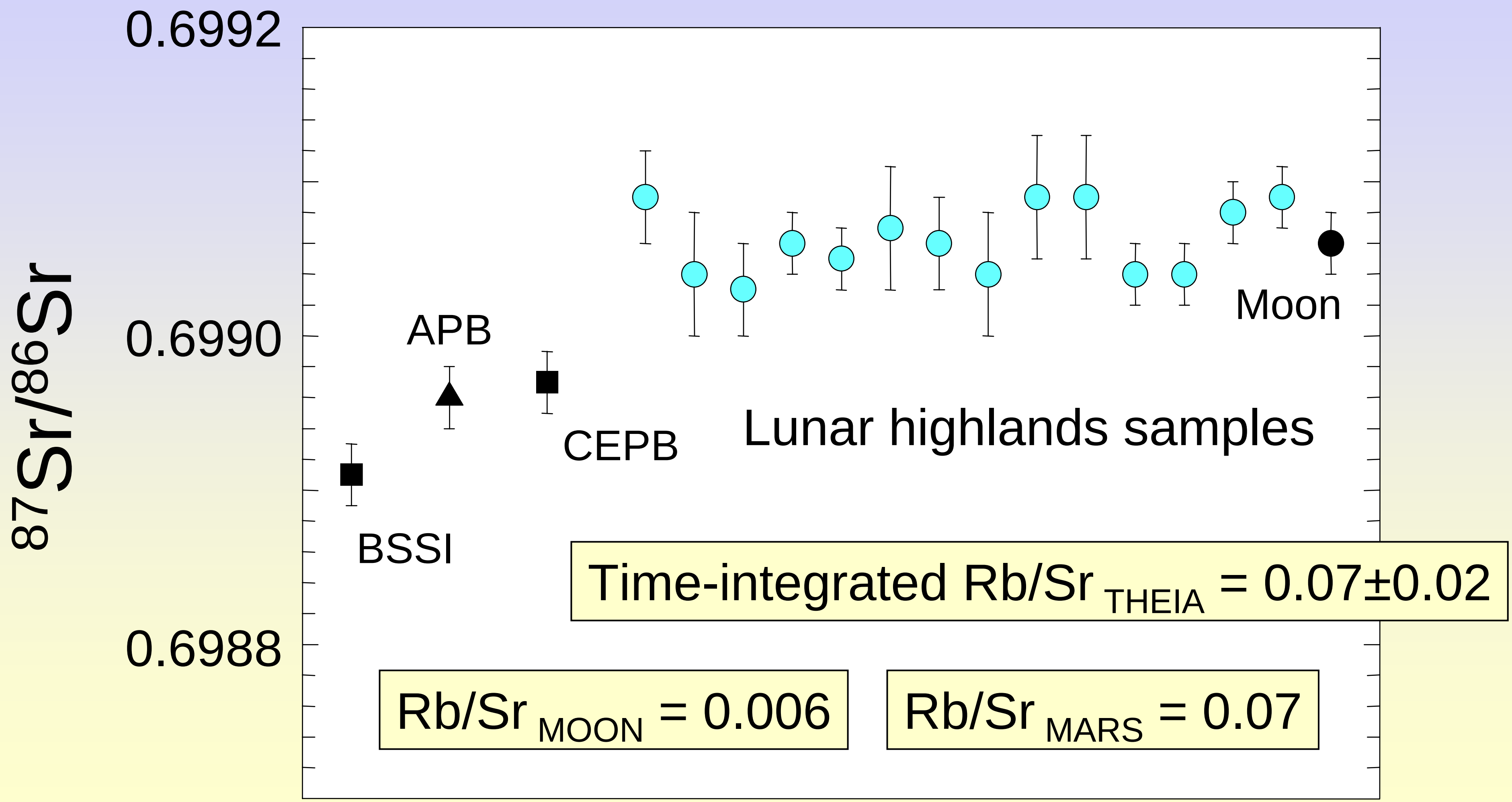


The major portion of Earth's water may come from water-rich planetesimals



Comets have a different D/H

The Sr isotopic composition of the Moon provides time-integrated Rb/Sr for Theia



The inner solar system may have been dominated by volatile-rich Mars-like proto-planets

Lark and deGoursac [2001]

- The Earth accreted with a mean life of >15 Myrs and over time-scales of 10^7 to 10^8 yr
- This is consistent with accretion with little nebular gas
- The Moon-forming Giant Impact occurred at ~ 45 Myrs
- Discrepant time-scales are consistent with incomplete mixing of metal and silicate during accretion
- There was also late of loss of volatiles from the Earth
- Theia had a chemistry similar to that of Mars but formed at a heliocentric distance similar to Earth
- The inner solar system may have been dominated by Mars-like objects
- Water was added by 4.3 Ga