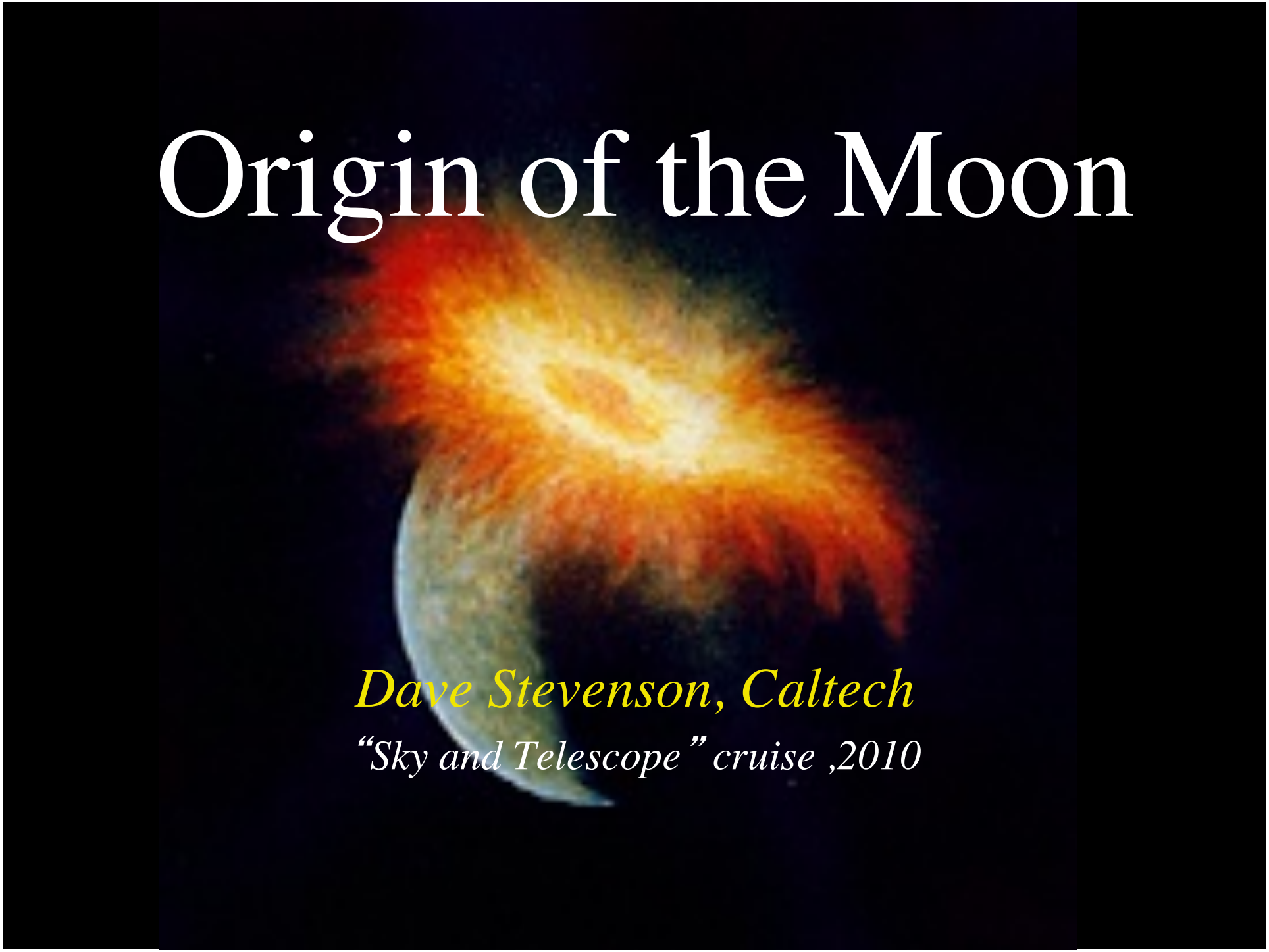
Origin of the Moon



Dave Stevenson, Caltech

"Sky and Telescope" cruise ,2010

Our Neighbor, the Moon

Why should we Care?

- Moon might tell us something important about how we (the Earth) came to be
- Moon might tell us something important about how planets form
- The moon affects us
  - Tides
  - Stability of rotation axis (affects how life evolved)

  Some people even think the moon may be a resource (but I'm skeptical)

What is the Moon made of?

- "The moon is made of green* cheese" John Heywood *Proverbs* 1546

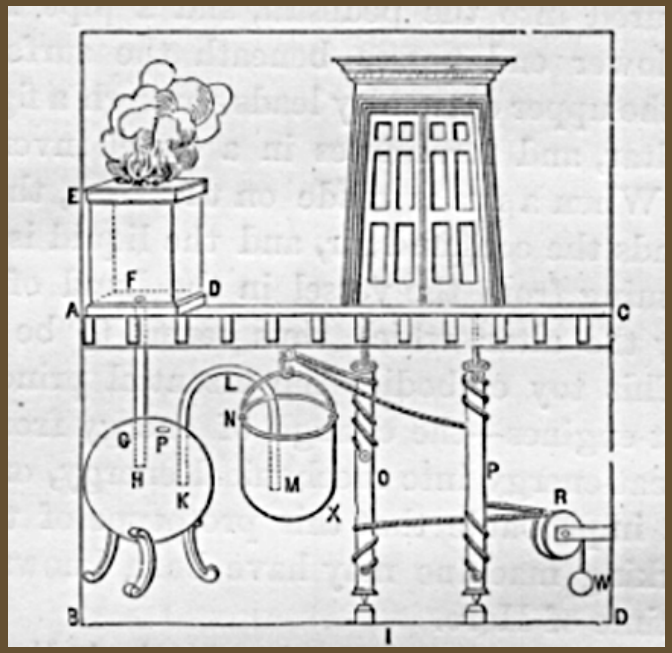
  * Green means not aged
- The moon is actually made of rocks that are similar to the outer part of Earth
- The Moon has remarkable isotopic similarity to Earth (especially oxygen)
- There is only a very small iron core
- Moon is volatile depleted; very little water for example
- Testament to a high temperature origin

What does the Orbit of the Moon tell Us?

- Moon is moving away from Earth at ~10 cm/year.
- Extrapolated back in time this means that the moon was once much closer to Earth (e.g., 4.5 billion years ago)
- Capture of the moon would have been very difficult (though not impossible)
- Angular momentum of the Moon and Earth are insufficient to allow for the fission model proposed by George Darwin.
- Angular momentum not readily explained by building Earth and Moon together from small bodies.
- Angular momentum is explained by a giant impact

How to think about Planets?

- Could discuss provenance- the properties of an apple depend on the environment in which the tree grows
- Or could discuss it as a machine (cf. Hero[n], 1st century AD)
- ***Need to do both***



Earth

1. Most of the core is liquid and predominantly Fe.
2. Identity of other elements not known, but Si is suspected and requires high T.
3. Presence of the inner core explained if central T for Earth is 5000 to 6000K.
4. Increasing evidence of modest mantle layering- possibly primordial

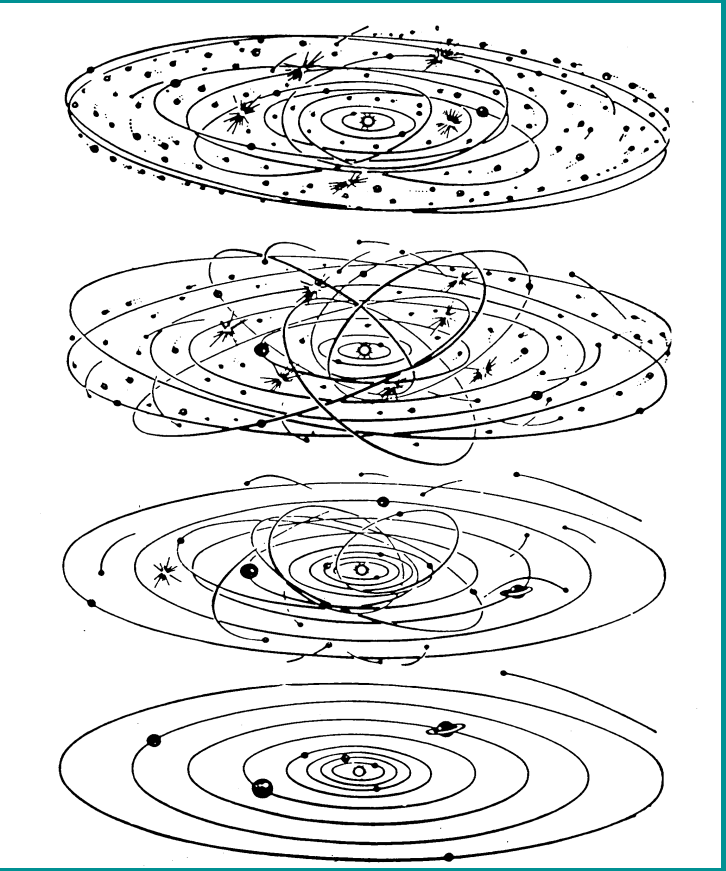
Interstellar medium contains gas & dust that undergoes gravitational collapse

A “solar nebula” forms: A disk of gas and dust from which solid material can aggregate

What should you Believe about Planet formation?

- Rapid collapse from ISM; recondensation of dust; high energy processing
- Small (km) bodies form quickly ($<10^6$yr)

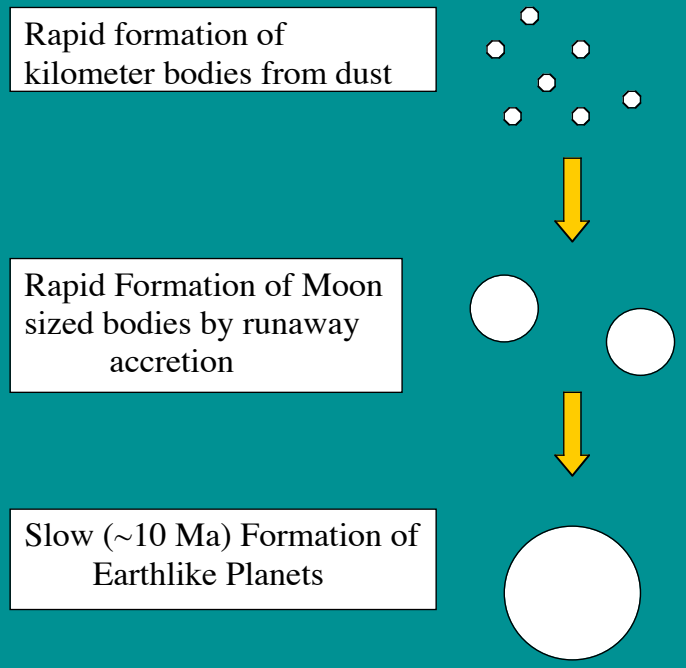
  [observation]. Some of these bodies differentiate (^{26}Al heating)
- Moon & Mars sized bodies *may* also form as quickly[theory] - will also therefore differentiate (perhaps imperfectly)



Only a cartoon!

Terrestrial Planet formation

- Early stages are fast but may nonetheless involve quite large bodies
- Orbit crossing limits growth of big bodies: Time ~ 10^7- 10^8 yr.
- Last stages in *absence* of solar nebula [astronomical obs.]
- Mixing across ~1AU likely (chemical disequilibrium?)



Some Important Numbers

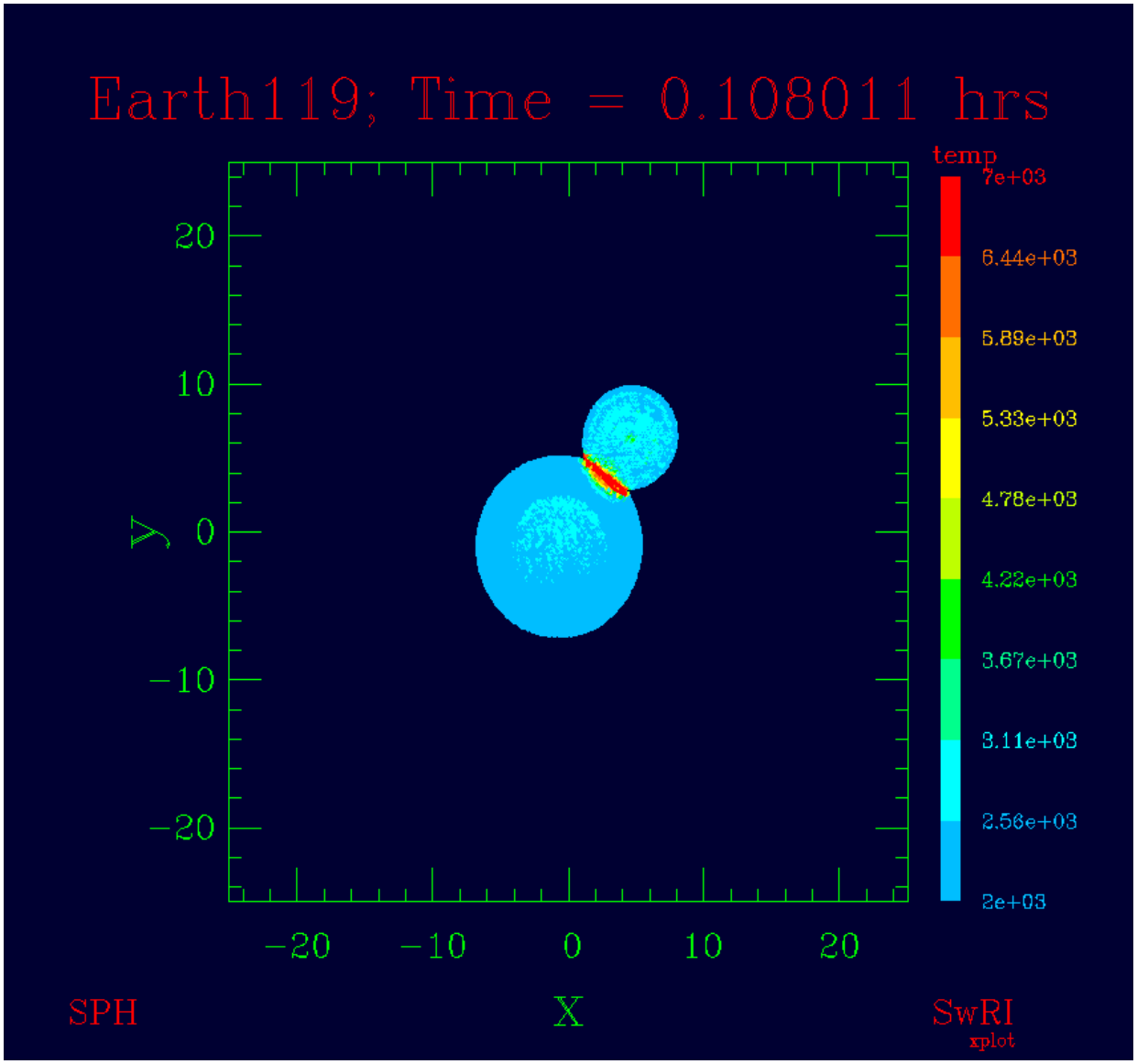
- $GM/RC_p \sim 4 \times 10^4 K$ *where M is Earth mass, R is Earth radius, C_p is specific heat*
- $GM/RL \sim 1$ *where L is the latent heat of vaporization of rock*
- Equilibrium temp. to eliminate accretional heat ~400K *(but misleading because of infrequent large impacts and steam atmosphere)*
- $E_{grav} \sim 10\ E_{radio}$ *where E_{grav} is the energy released by Earth formation and E_{radio} is the total radioactive heat release over geologic time*

The Importance of Giant Impacts

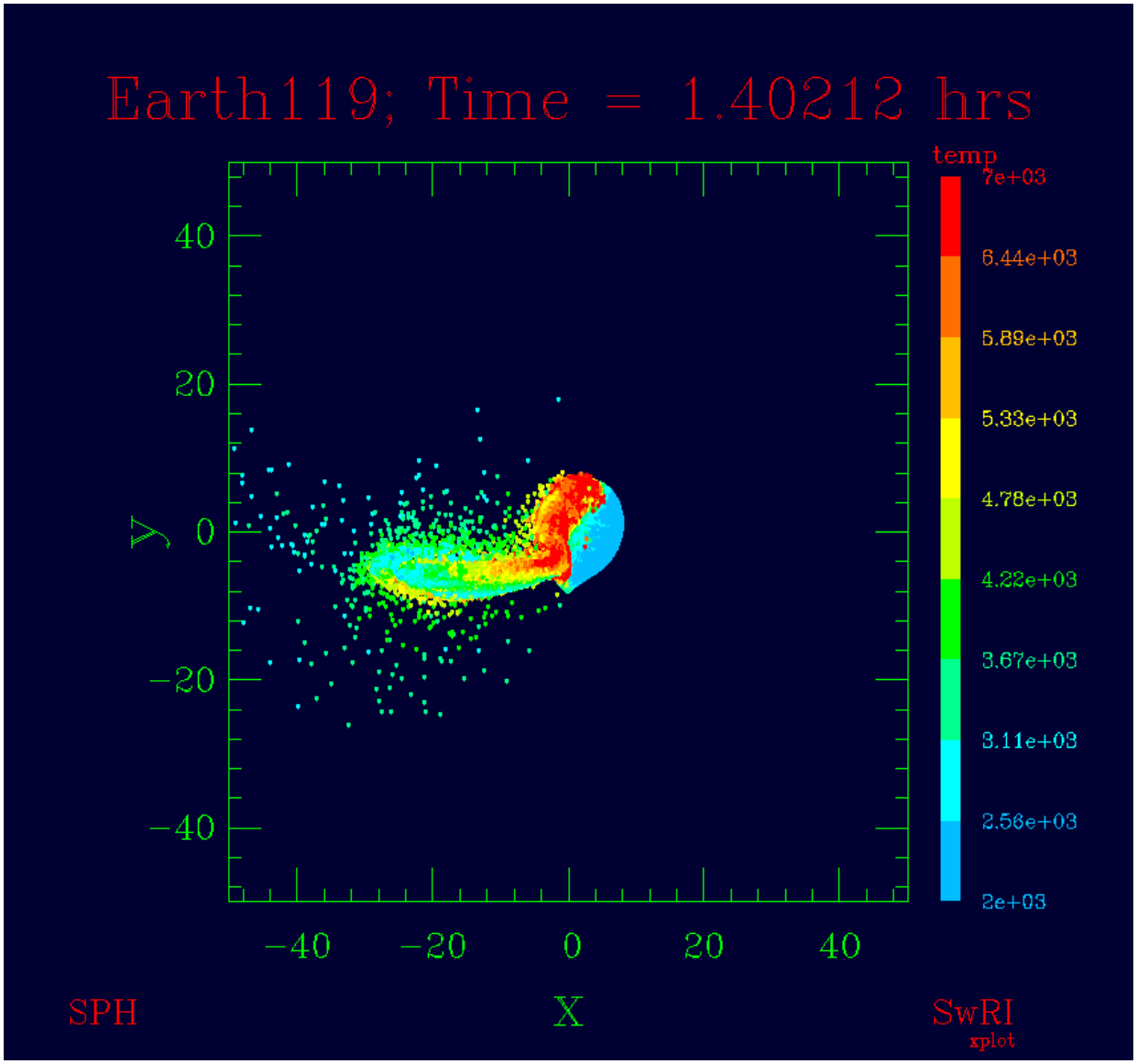
- Simulations indicate that Mars-sized bodies probably impacted Earth during it's accumulation.
- These events are extraordinary… for a thousand years after one, Earth will radiate like a low-mass star!

Formation of the Moon

- Impact "splashes" material into Earth orbit
- The Moon forms from a disk in perhaps ~100 years
- One Moon, nearly equatorial orbit, near Roche limit- tidally evolves outward



All these snapshots are from Canup, *Icarus*, 2004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3.67e+03
3.11e+03
2.56e+03
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40
X
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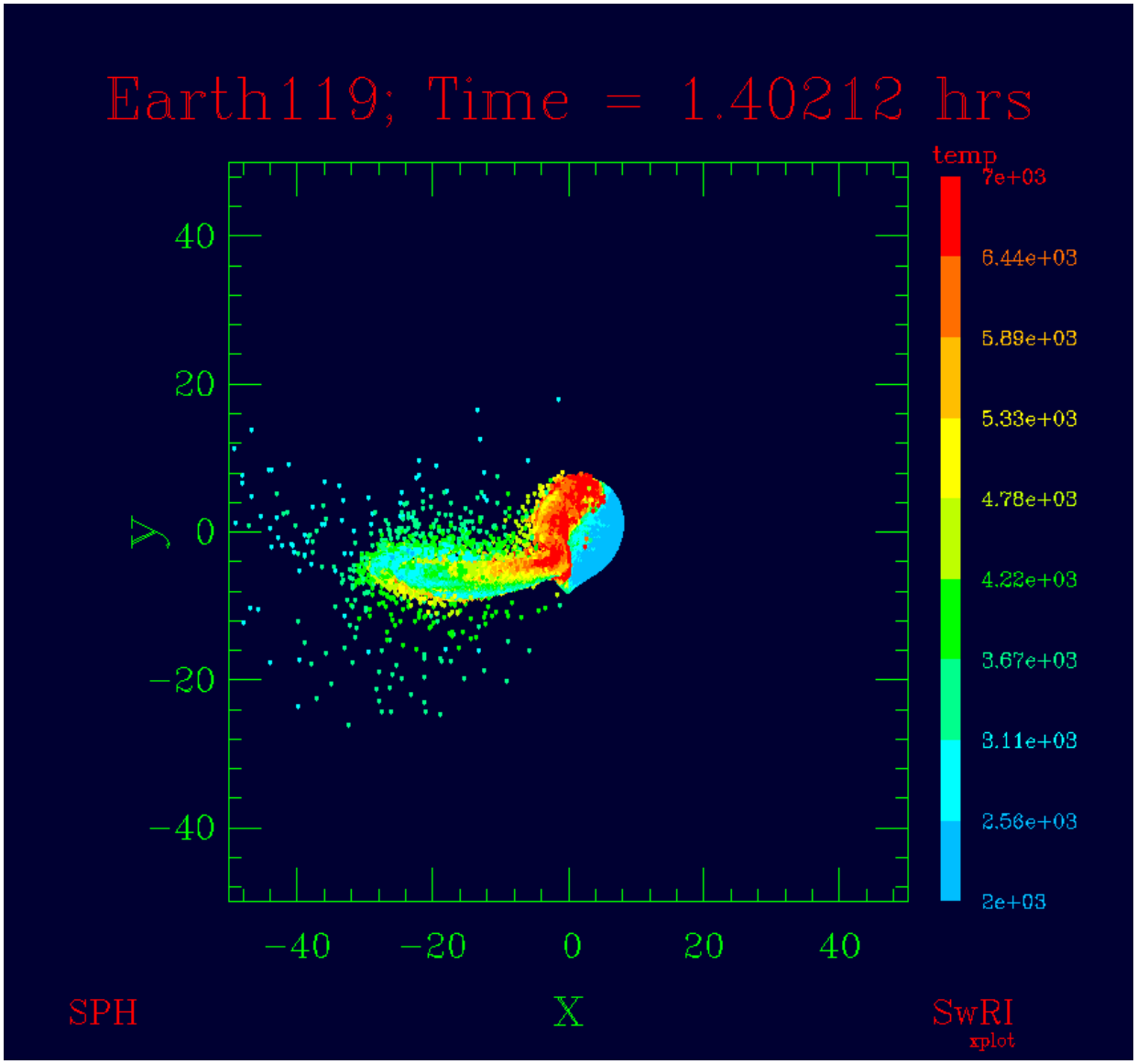
SwRI
xplot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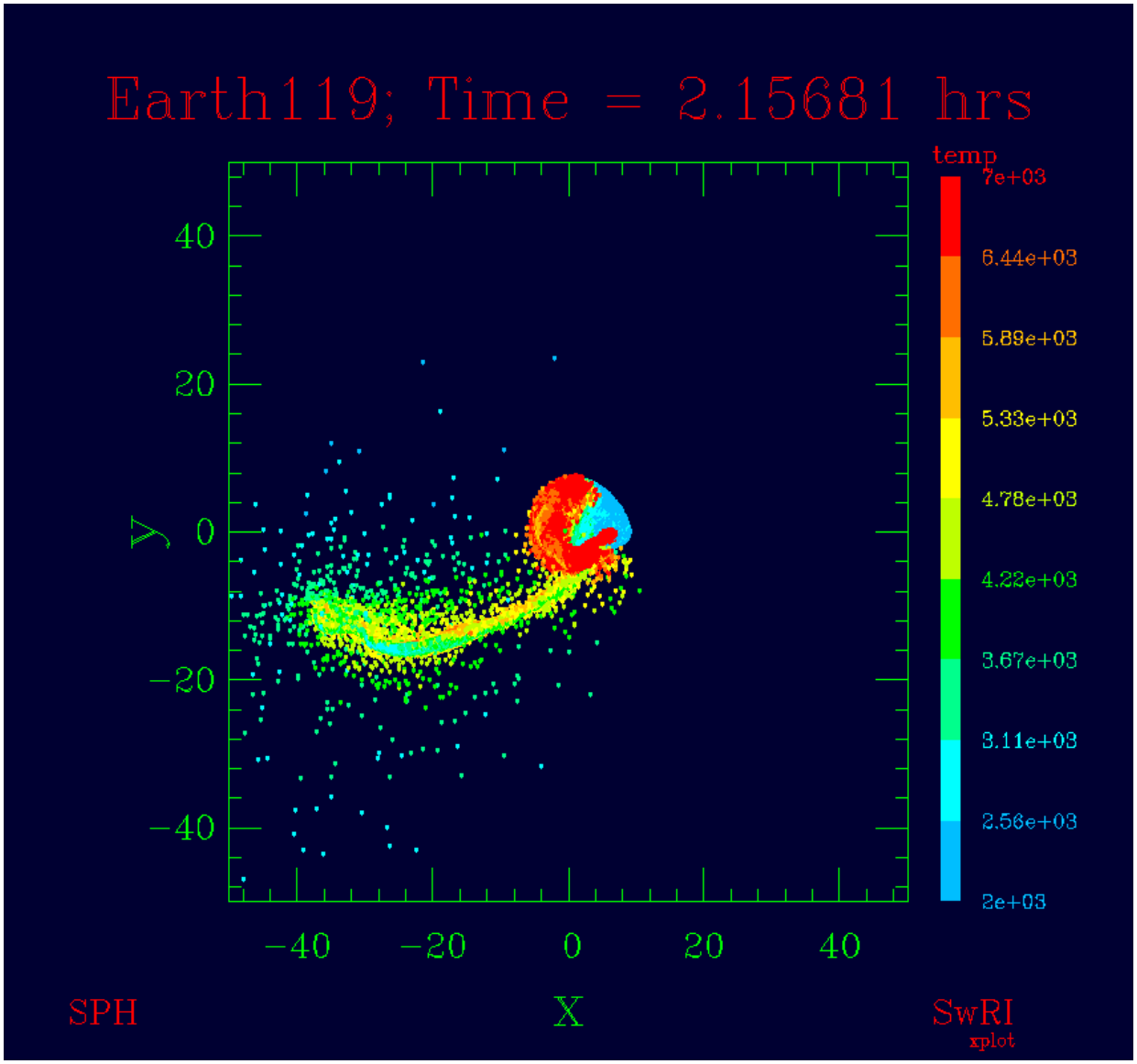
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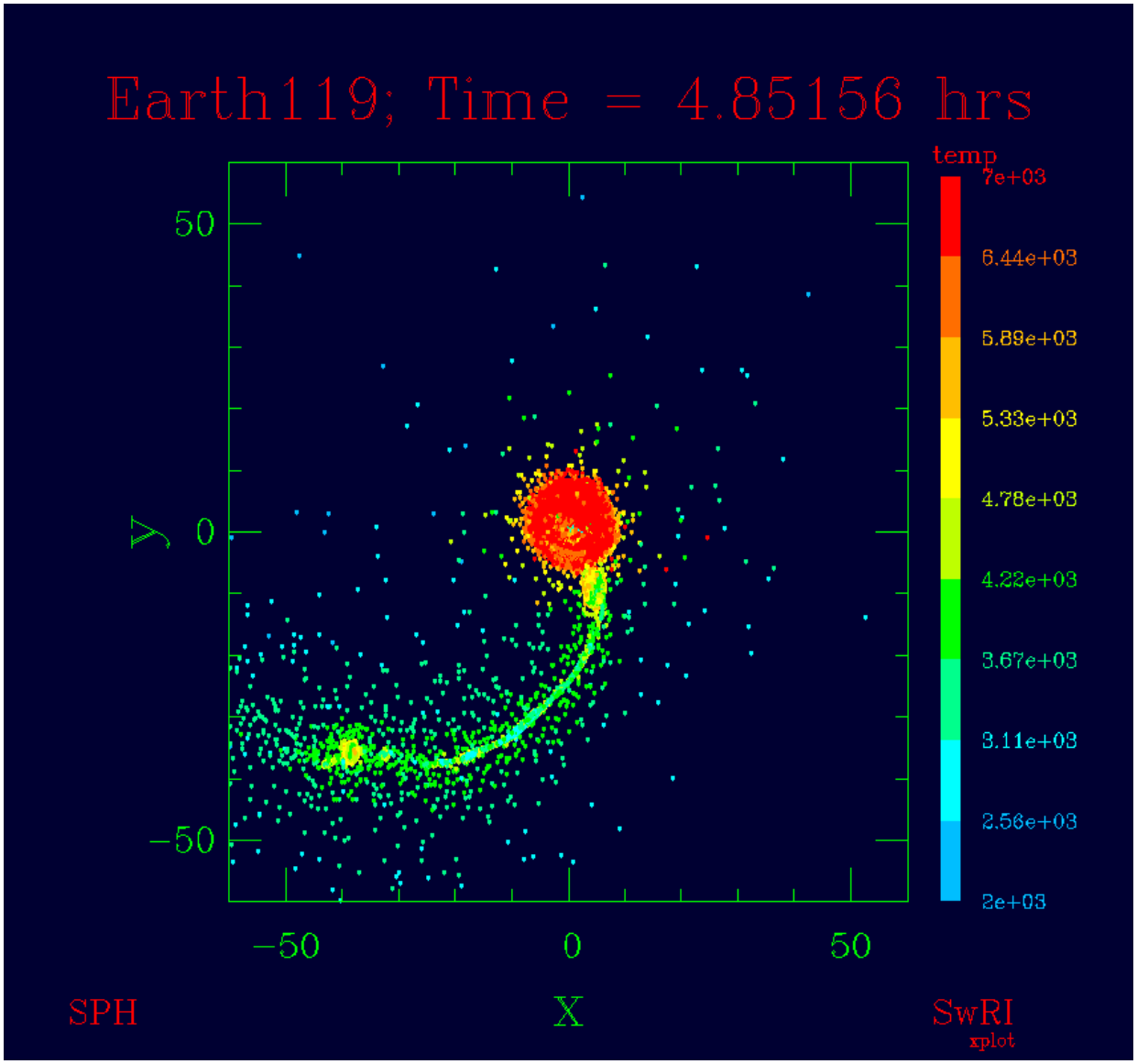
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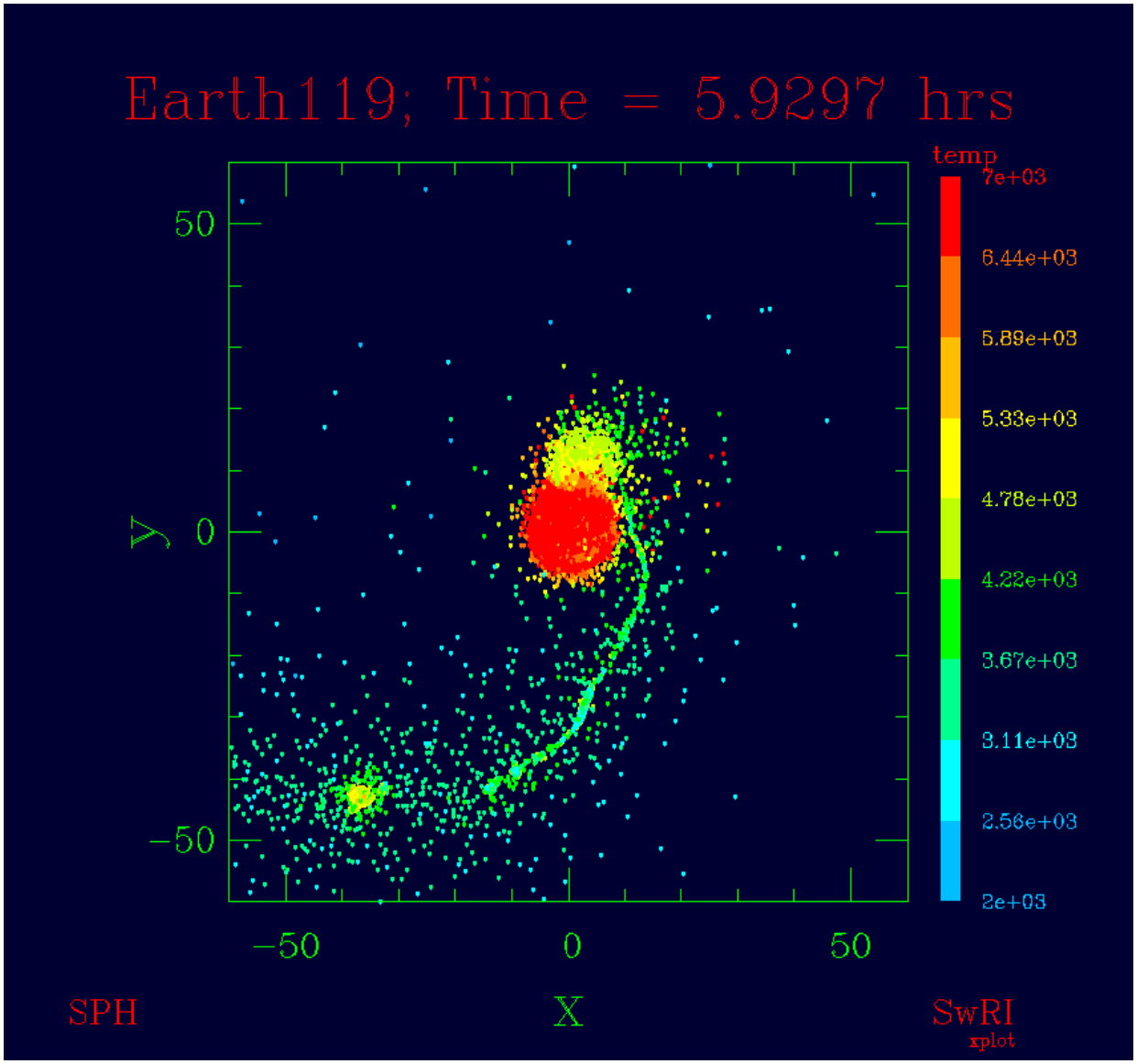
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X
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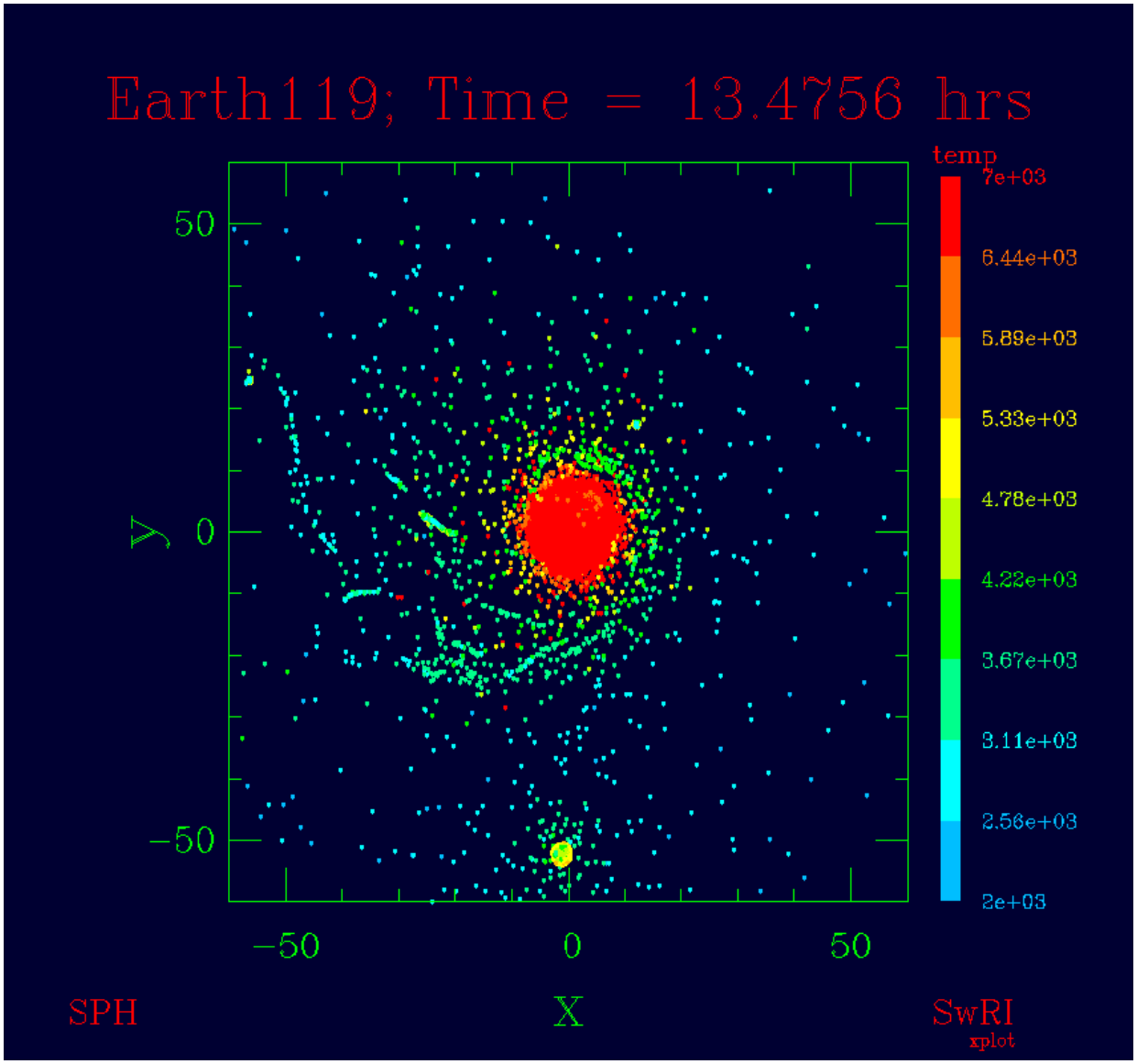
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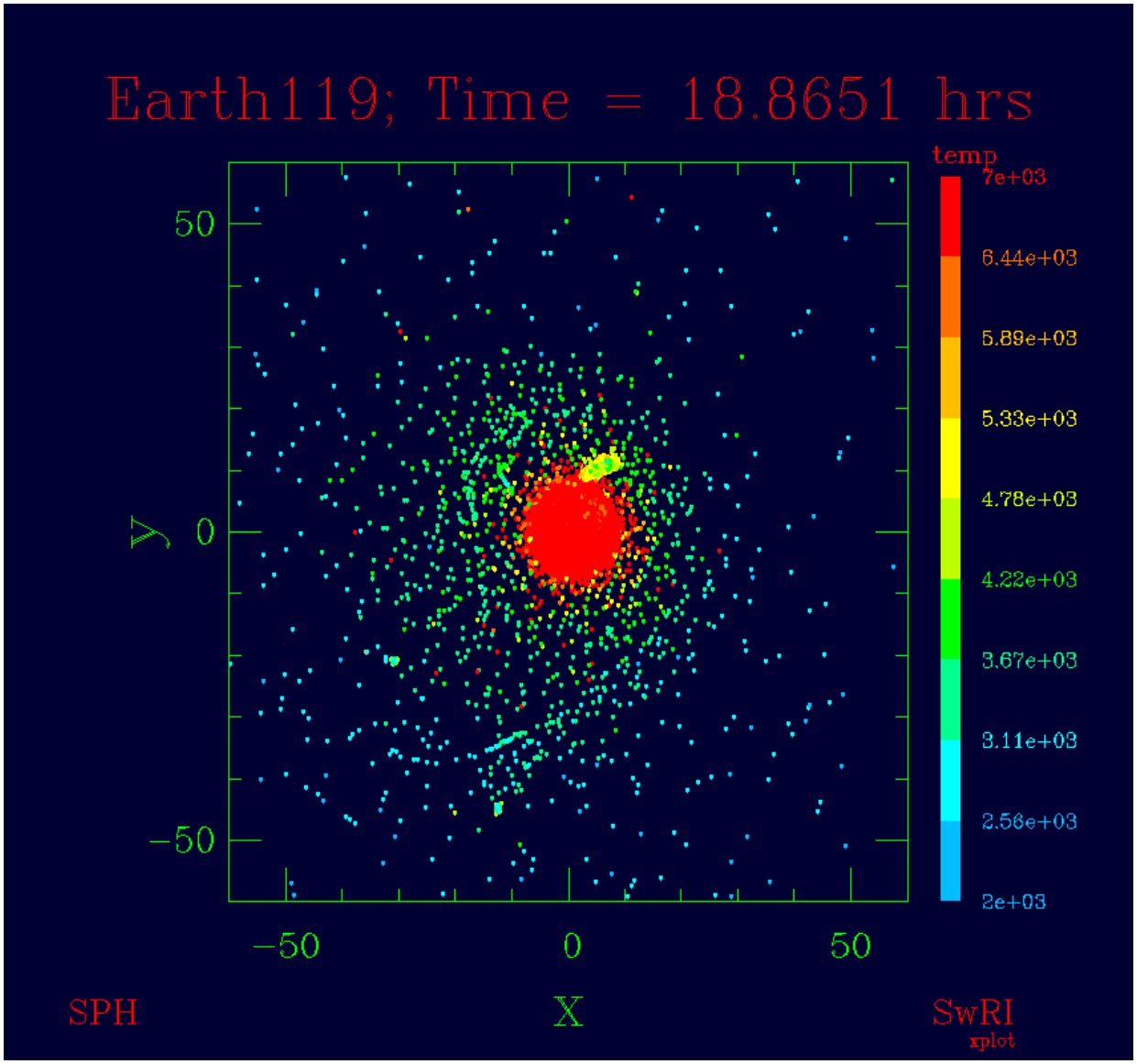
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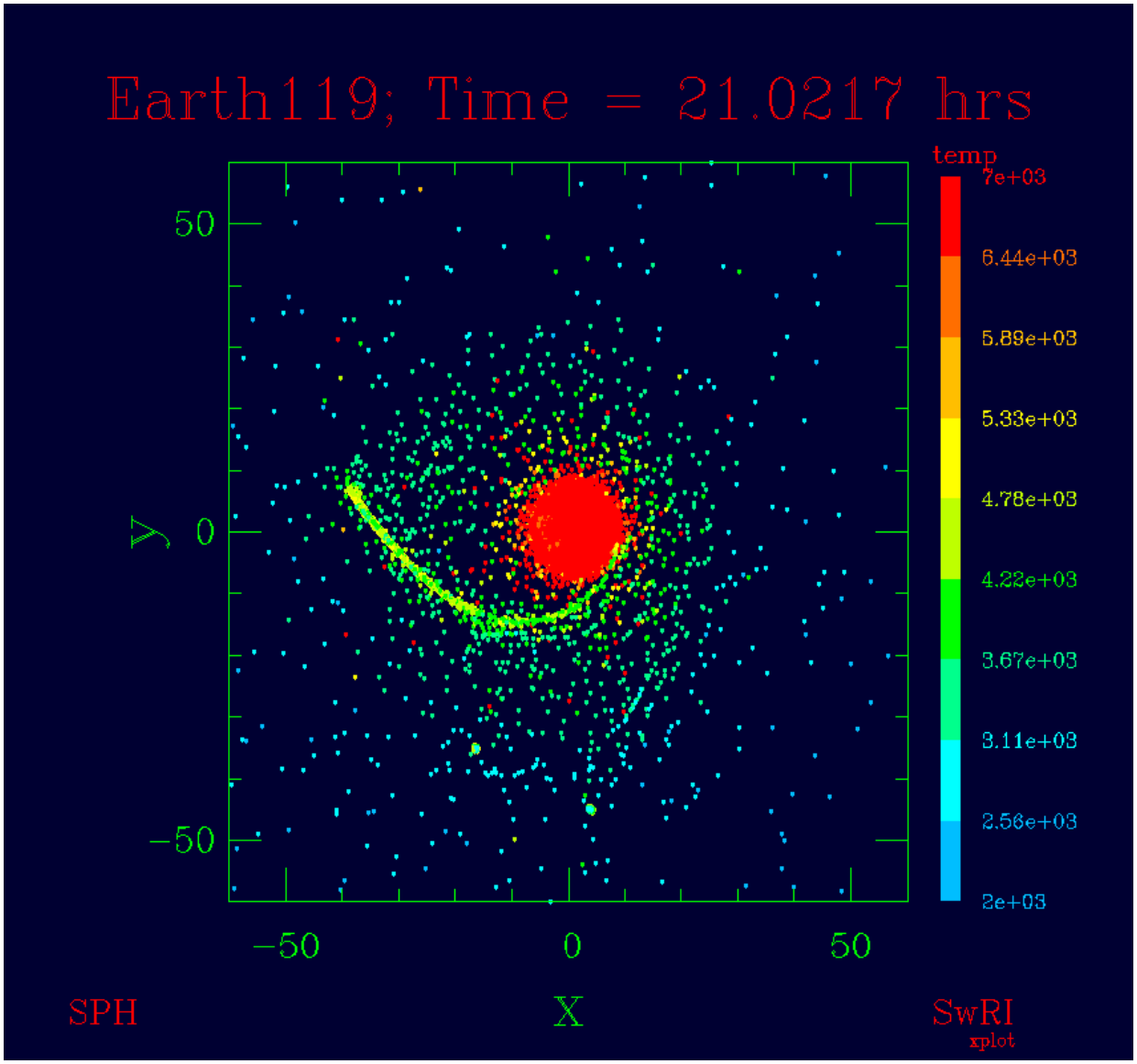
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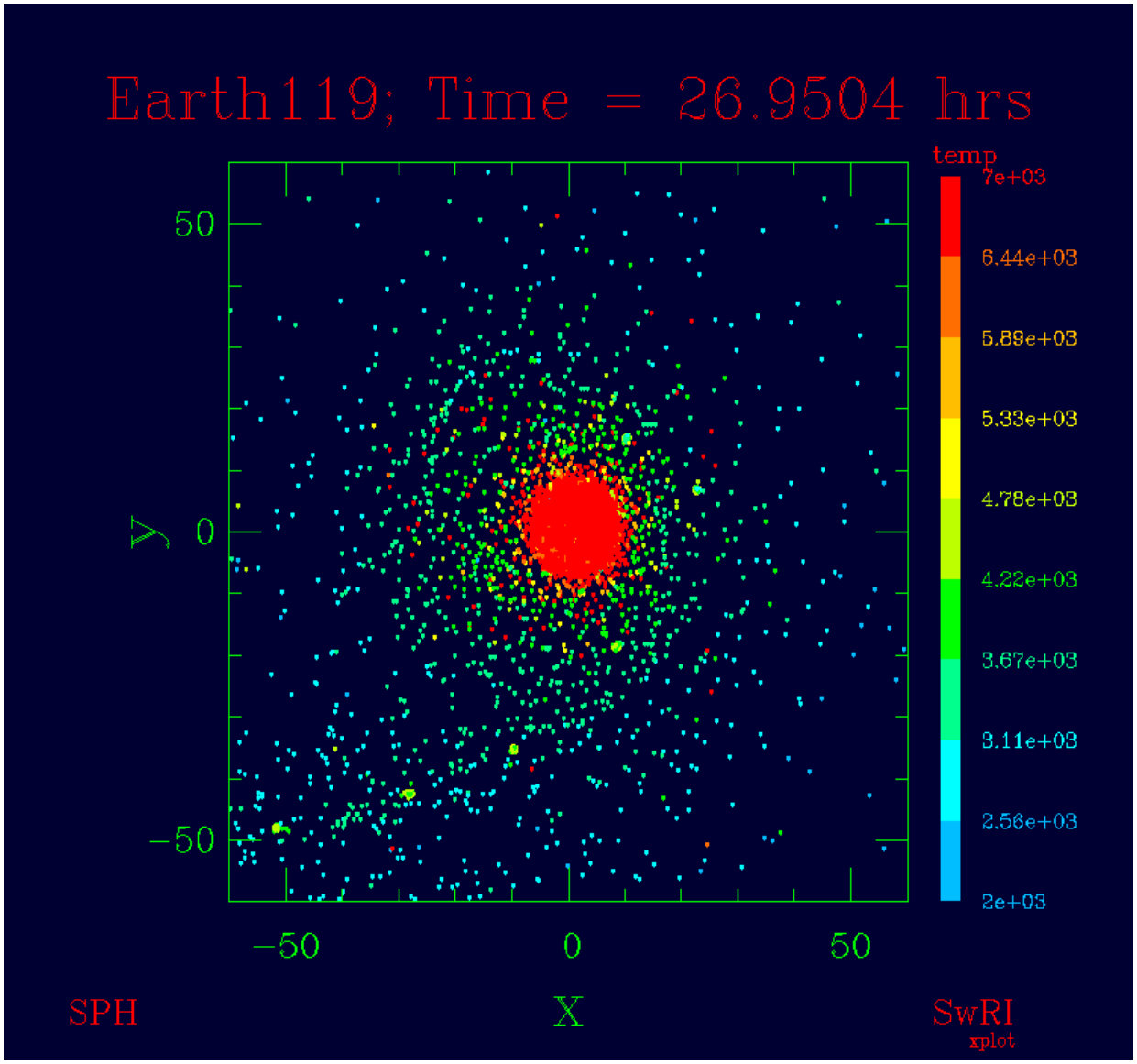
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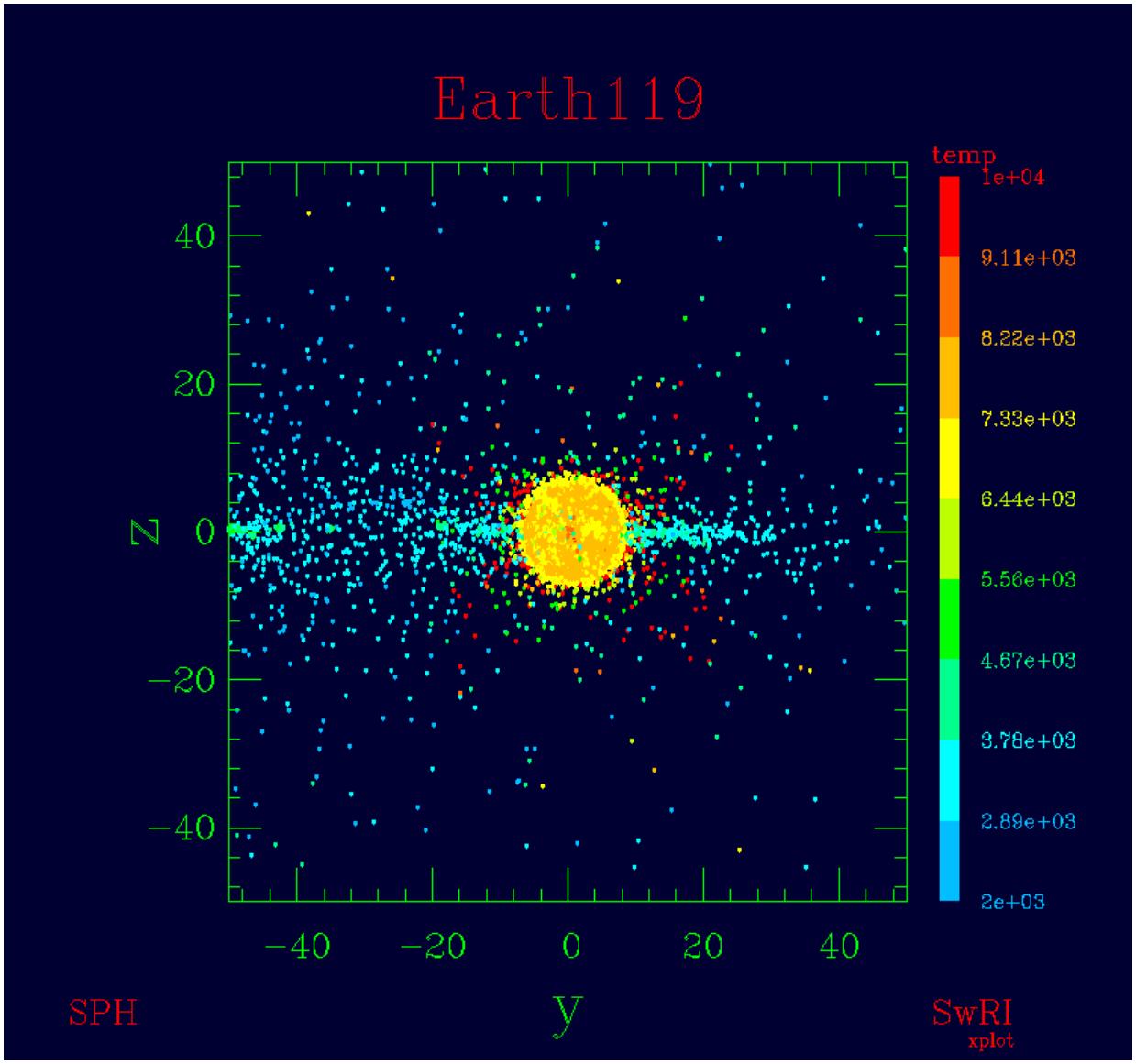
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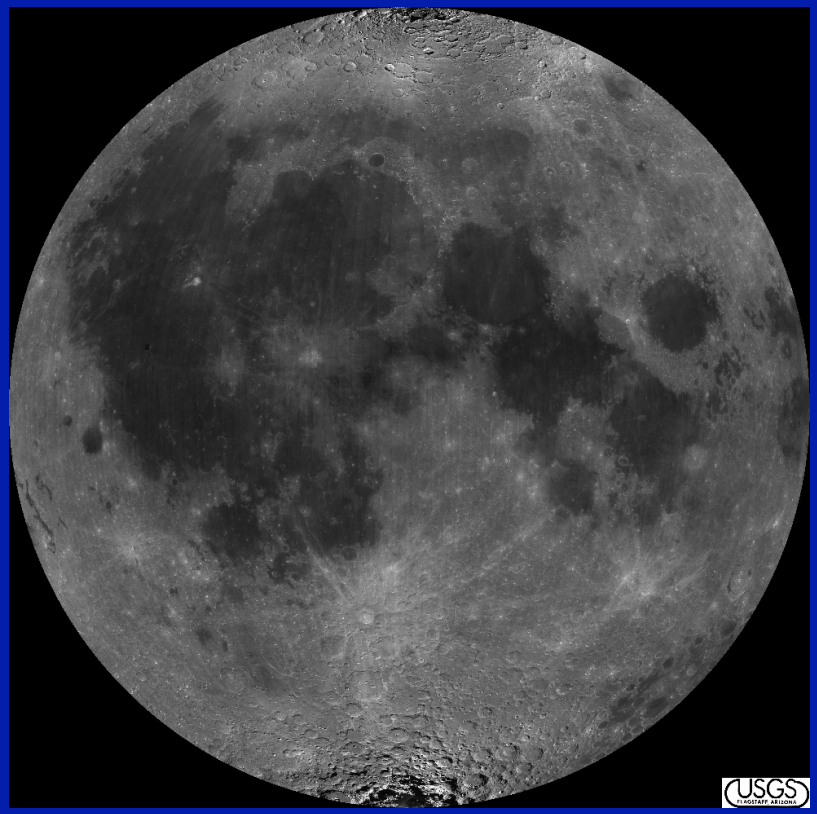
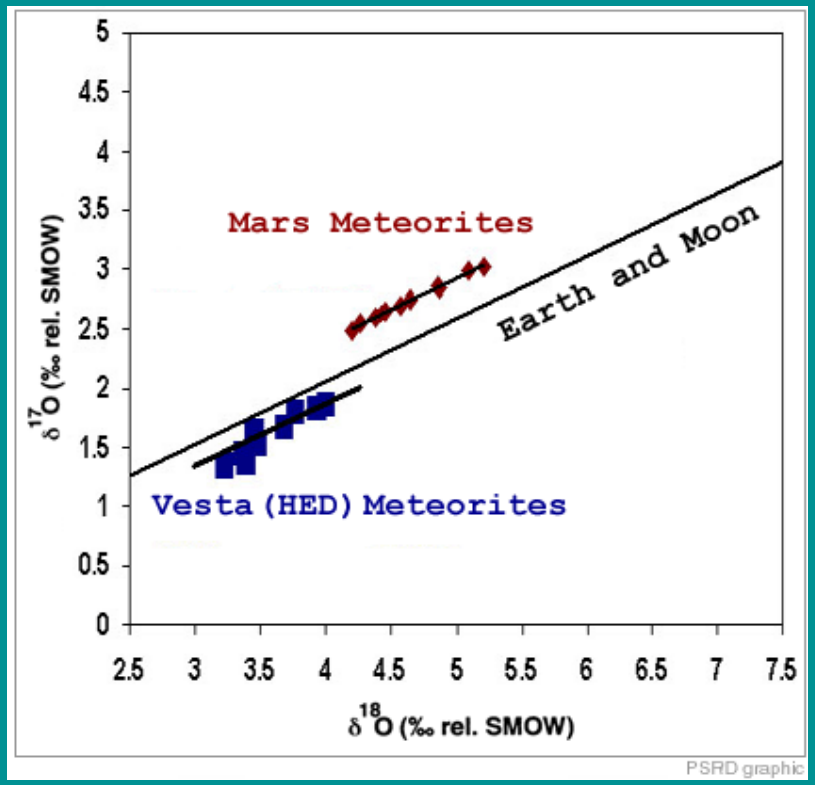
Conclusions for the Moon



- Alternatives to giant impact hypothesis have major dynamical problems
- Giant impact naturally explains high early temperatures
- Giant impact may not make clear predictions about chemistry - a shortcoming (but we're working on it!)

Oxygen Isotopes

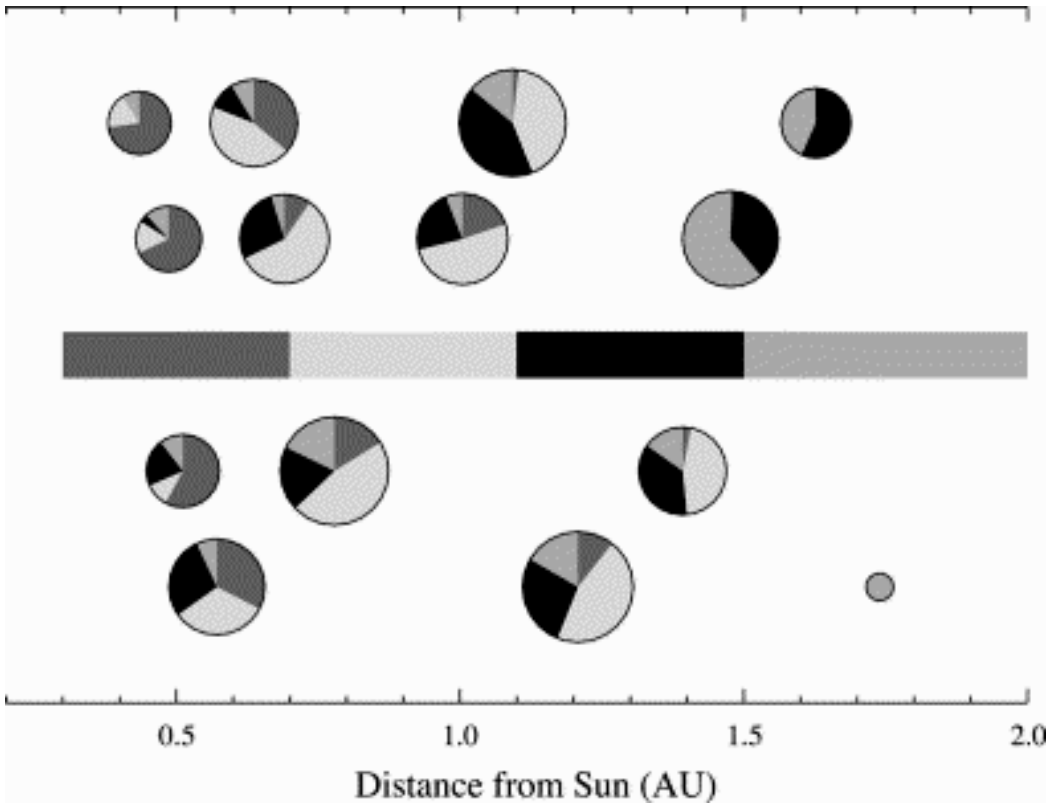
- Fundamental origin of the differences between Earth, Mars and meteorites is ***not understood***
- Still, the "identity" of Earth & Moon is often taken to imply same "source"



Possible Explanations for the Earth-Moon Strong Similarity in Oxygen Isotopes

- Mars is special (i.e., Earth & Venus will turn out to be the same)
- Fortuitous similarity of projectile and target
- Errors in current models of accretion or impact physics
- Post-impact equilibration of lunar forming disk and Earth

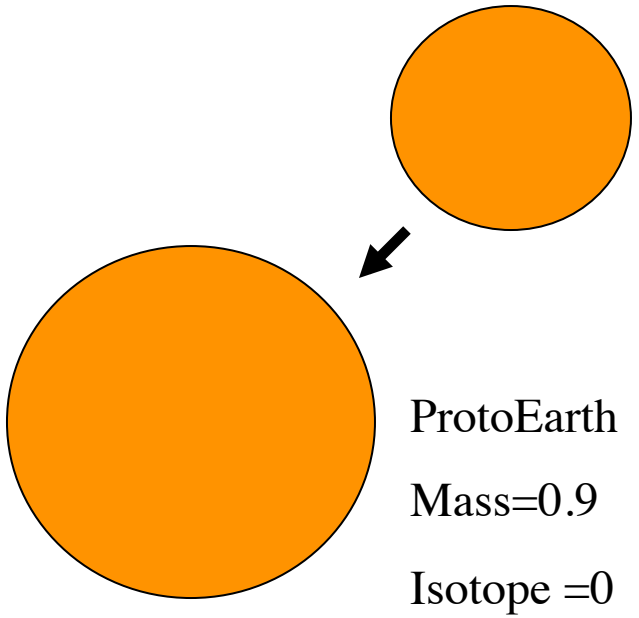
In current terrestrial accretion models, the material that goes into making Earth comes from many different regions…it is **very unlikely** that the Moon-forming projectile would have the same isotopic composition as protoEarth.



Results from Chambers, 2003 (Similar results from Morbidelli)

Possible Explanations for the Earth-Moon Strong Similarity in Oxygen Isotopes

- Mars is special (i.e., Earth & Venus will turn out to be the same)
- Fortuitous similarity of projectile and target
- Errors in current models of accretion or impact physics
- Post-impact equilibration of lunar forming disk and Earth Work reported here is with Kaveh Pahlevan (now a pstodoc at Yale)



Impactor

Mass=0.11

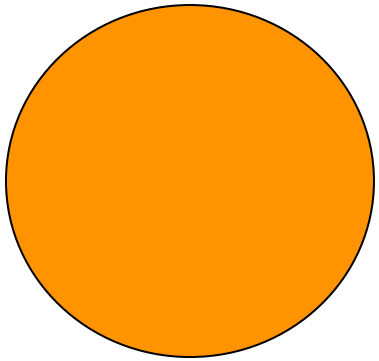
Isotope =ε

ProtoEarth

Mass=0.9

Isotope =0

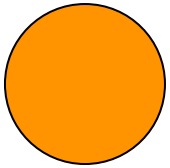
BEFORE



Final Earth

Mass=1.0

Isotope =0.1 ε

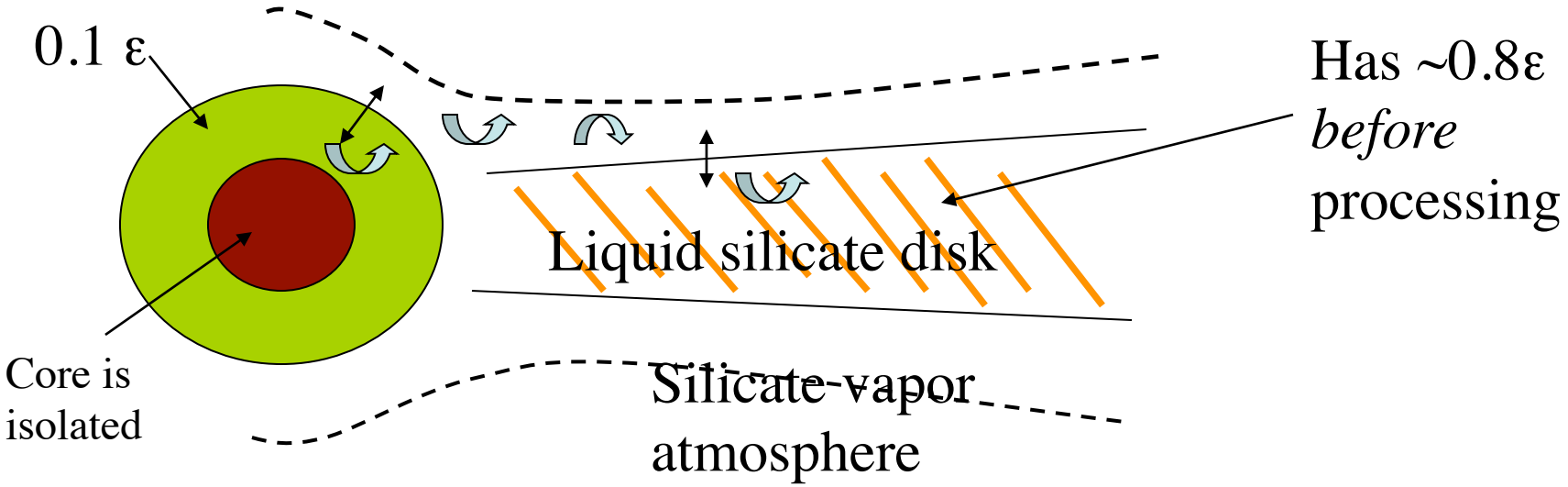


Moon

Mass=0.01

Isotope =0.1 to 0.15 ε

AFTER



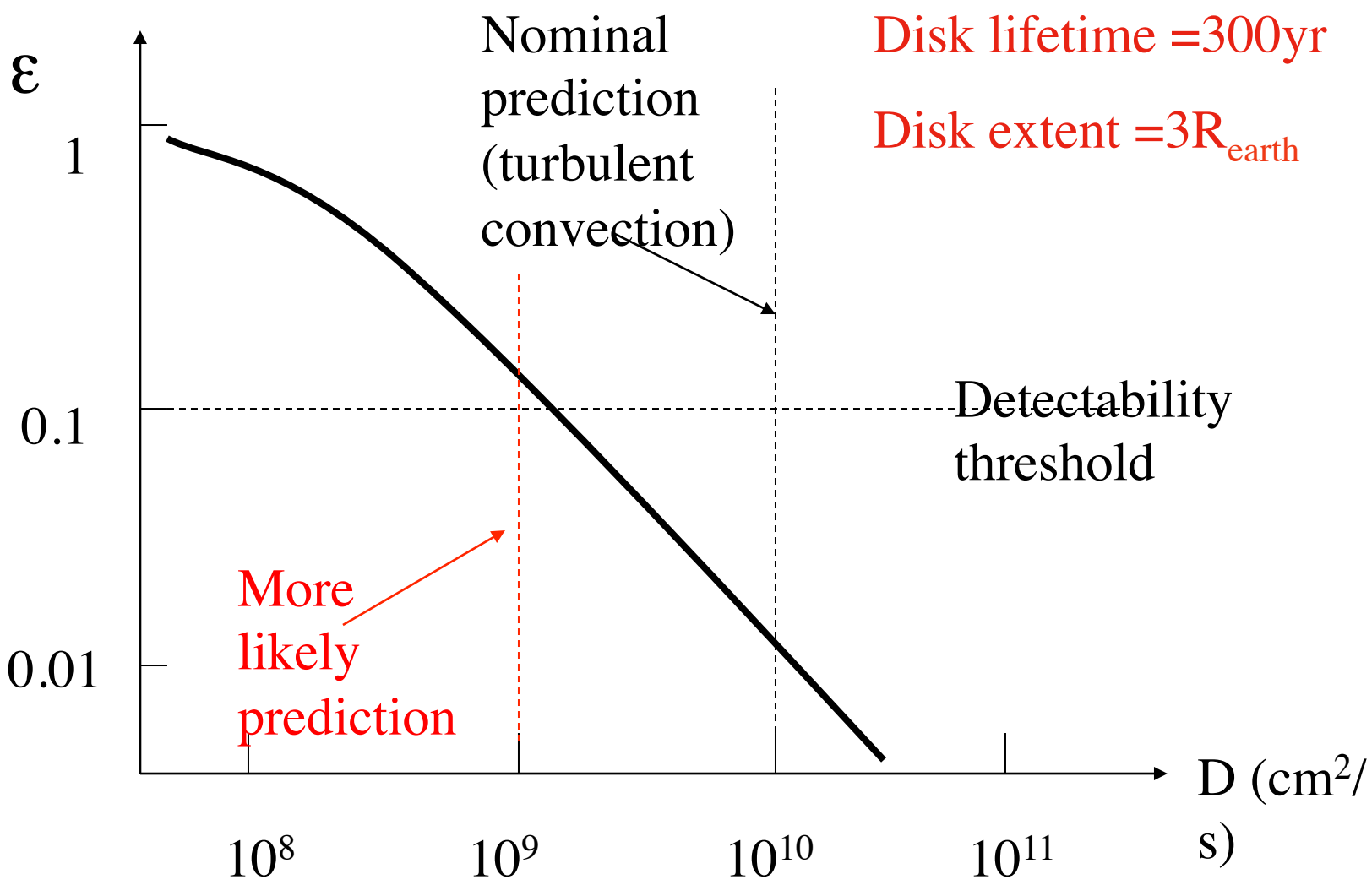
IN BETWEEN

A disk exists for 10^2 10^3 years. Radiates at ~2500K. Vapor pressure ~10 to 100 bars.

Timescale for exchange between vapor & atmosphere ~$10c/(G\sigma)$ ~ week. Aided by "foam".

Convective timescale in disk or Earth mantle ~week

Convective timescale in atmosphere ~days

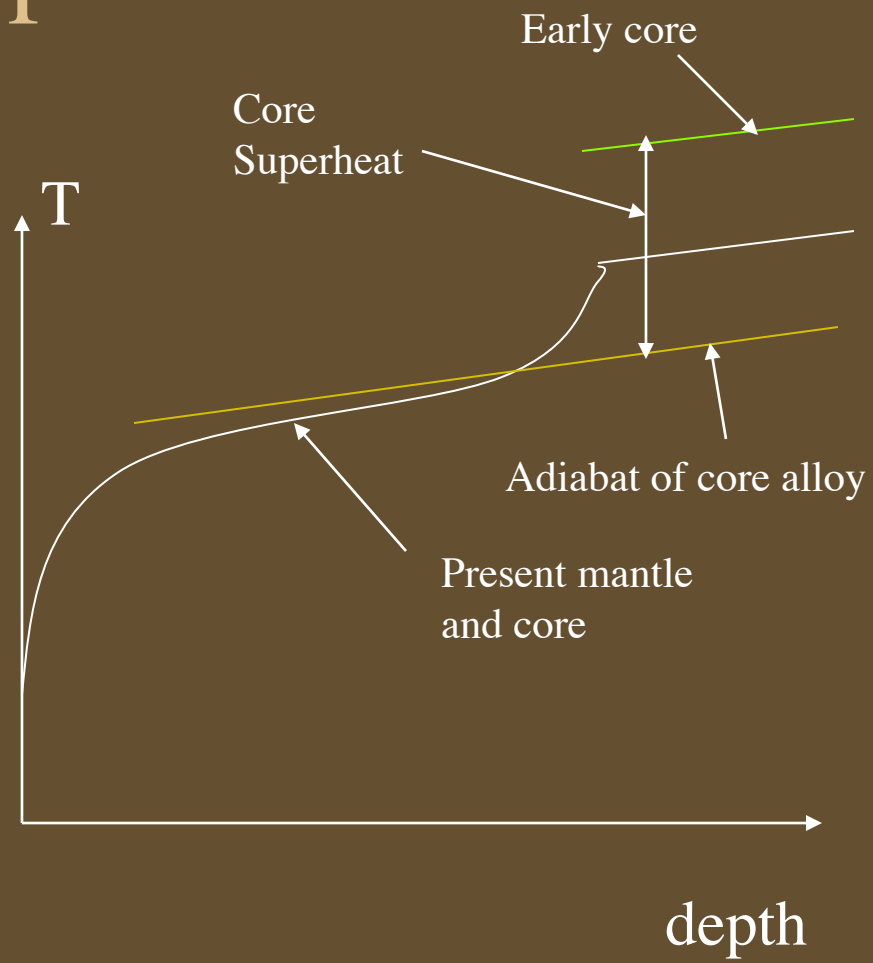

ε
1
0.1
0.01
Nominal prediction (turbulent convection)
Disk lifetime =300yr
Disk extent =3R_earth
Detectability threshold
More likely prediction
D (cm²/s)
10⁸
10⁹
10¹⁰
10¹¹

Conclusion for Oxygen Isotopes

- Mixing (dilution of Earth-Moon difference) is a possible explanation of Earth-Moon similarity.
- Small (measurable?) Earth-Moon difference predicted.
- Real test lies in the interpretation of other similarities & differences (e..g water loss, Fe behavior, Fe isotopes….)

Core Superheat

- This is the excess entropy of the core relative to the entropy of the same liquid material at melting point & and 1 bar.
- Corresponds to about 1000K for present Earth, may have been as much as 2000K for early Earth.
- *It is diagnostic of core formation process*...it argues against percolation and small diapirs.



Other Consequences of Large Impacts

- Delivery of volatiles- perhaps from Jupiter zone (our water did not come primarily from comets)
- Impact frustration of the origin of life? Or seeding the origin of life? Maybe both!

Conclusions

- Last great event in Earth formation was the formation of the Moon. Happened at around 50 to 100Ma following formation of the solar system.
- Oxygen isotopic similarity of Earth & Moon may be the legacy of post-giant impact mixing
- High energy origin of Earth ⇒extensive melting and magma ocean. Likewise for Moon
- Legacy expressed in core superheat & composition (siderophiles in the mantle, light elements in the core) and in the Moon-*but not yet understood*. Maybe also in primordial mantle differentiation.

- Should we go back?…yes!