Sources of Volatiles to Earth

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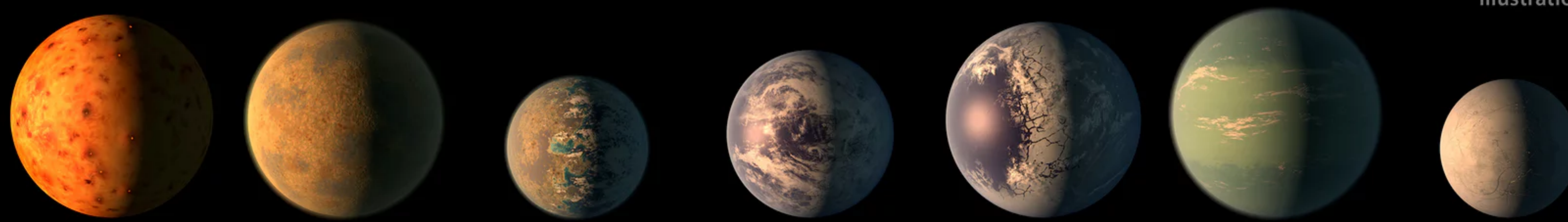
Exoplanet discovery

In a press release on February 22, 2017, NASA announced the discovery of the most Earth-sized planets found in the habitable zone of a single star, called TRAPPIST-1. This system of seven rocky worlds–all of them with the potential for water on their surface–is an exciting discovery in the search for life on other worlds. There is the possibility that future study of this unique planetary system could reveal conditions suitable for life.

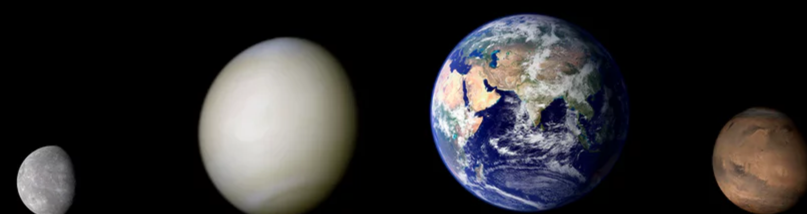
In February 2018, closer study of the seven planets suggested that some could harbor far more water than the oceans of Earth, in the form of atmospheric water vapor for the planets closest to their star, liquid water for others, and ice for those farthest away. The new study pinned down the density of each planet more precisely, making TRAPPIST-1 the most thoroughly known planetary system apart from our own.

Trappist-1 system

Illustrations



TRAPPIST-1 System	b	c	d	e	f	g	h
Orbital Period *days*	1.51 *days*	2.42 *days*	4.05 *days*	6.10 *days*	9.21 *days*	12.35 *days*	~20 *days*
Distance to Star *Astronomical Units (AU)*	0.011 *AU*	0.015 *AU*	0.021 *AU*	0.028 *AU*	0.037 *AU*	0.045 *AU*	~0.06 *AU*
Planet Radius *relative to Earth*	1.09 R_{earth}	1.06 R_{earth}	0.77 R_{earth}	0.92 R_{earth}	1.04 R_{earth}	1.13 R_{earth}	0.76 R_{earth}
Planet Mass *relative to Earth*	0.85 M_{earth}	1.38 M_{earth}	0.41 M_{earth}	0.62 M_{earth}	0.68 M_{earth}	1.34 $_{earth}$	–

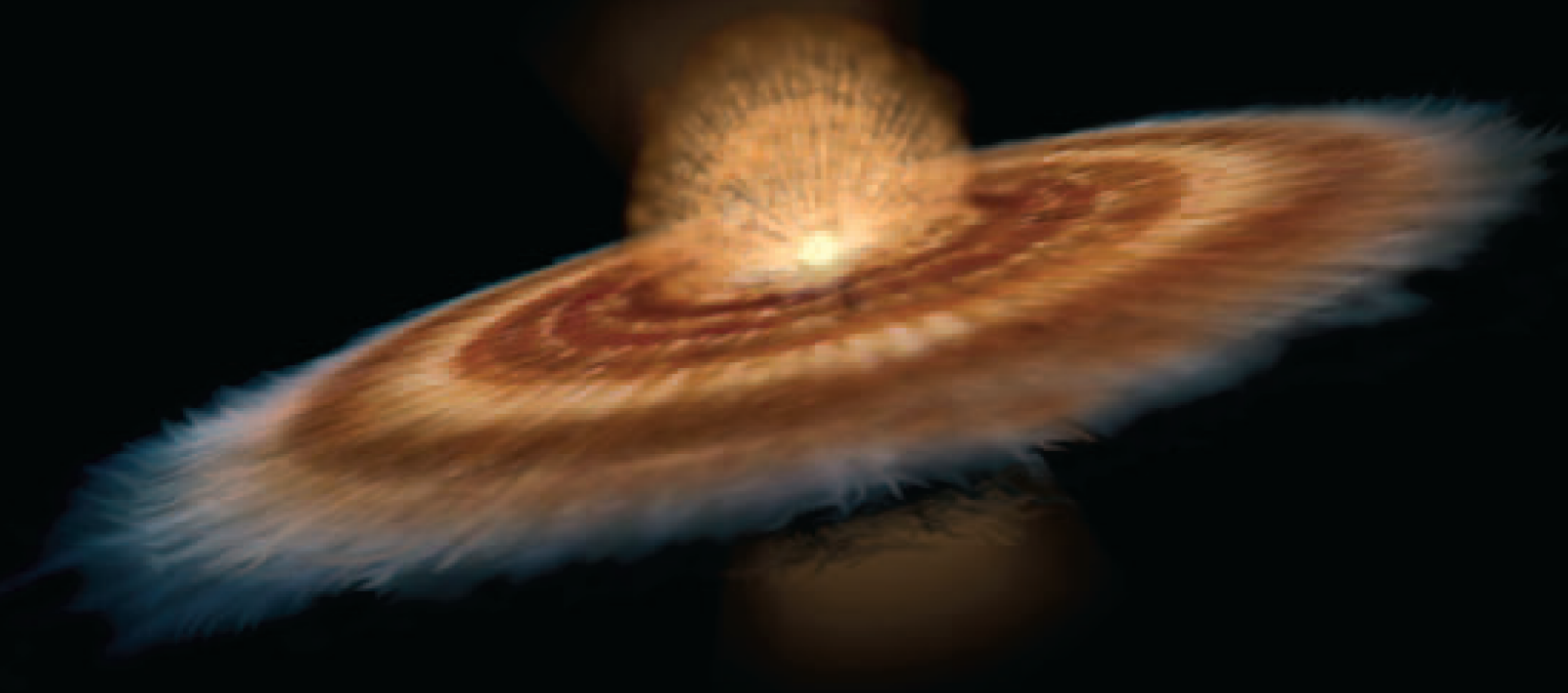


Solar System *Rocky Planets*	Mercury	Venus	Earth	Mars
Orbital Period *days*	87.97 *days*	224.70 *days*	365.26 *days*	686.98 *days*
Distance to Star *Astronomical Units (AU)*	0.387 *AU*	0.723 *AU*	1.000 *AU*	1.524 *AU*
Planet Radius *relative to Earth*	0.38 R_{earth}	0.95 R_{earth}	1.00 R_{earth}	0.53 R_{earth}
Planet Mass *relative to Earth*	0.06 M_{earth}	0.82 M_{earth}	1.00 M_{earth}	0.11 M_{earth}

How to make a planet

molecular cloud Cepheus B – stellar nursery

Collapse of molecular cloud –
settling of gas at midplane
Temperatures rises to ~2000 K



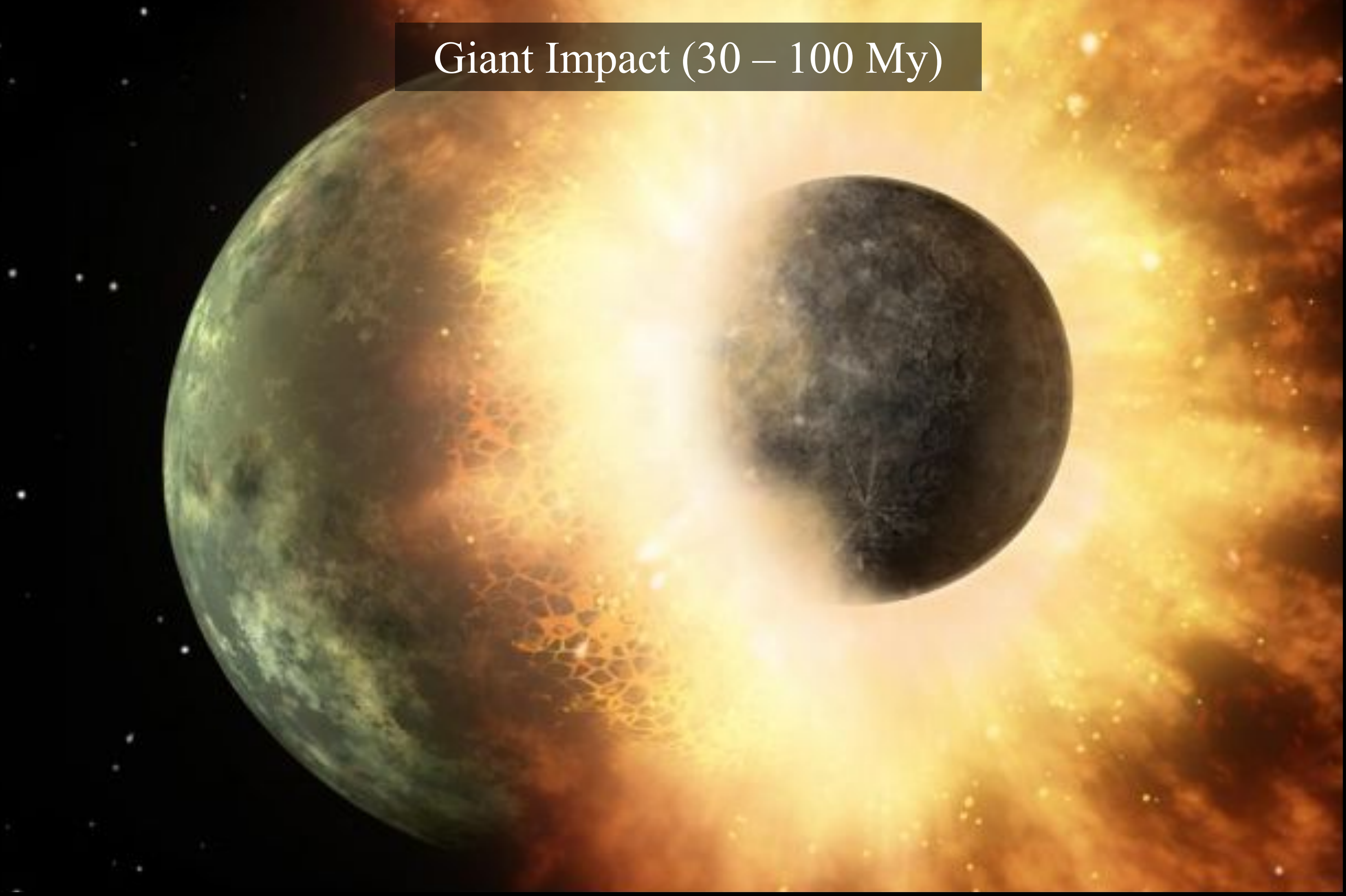
Don Dixon

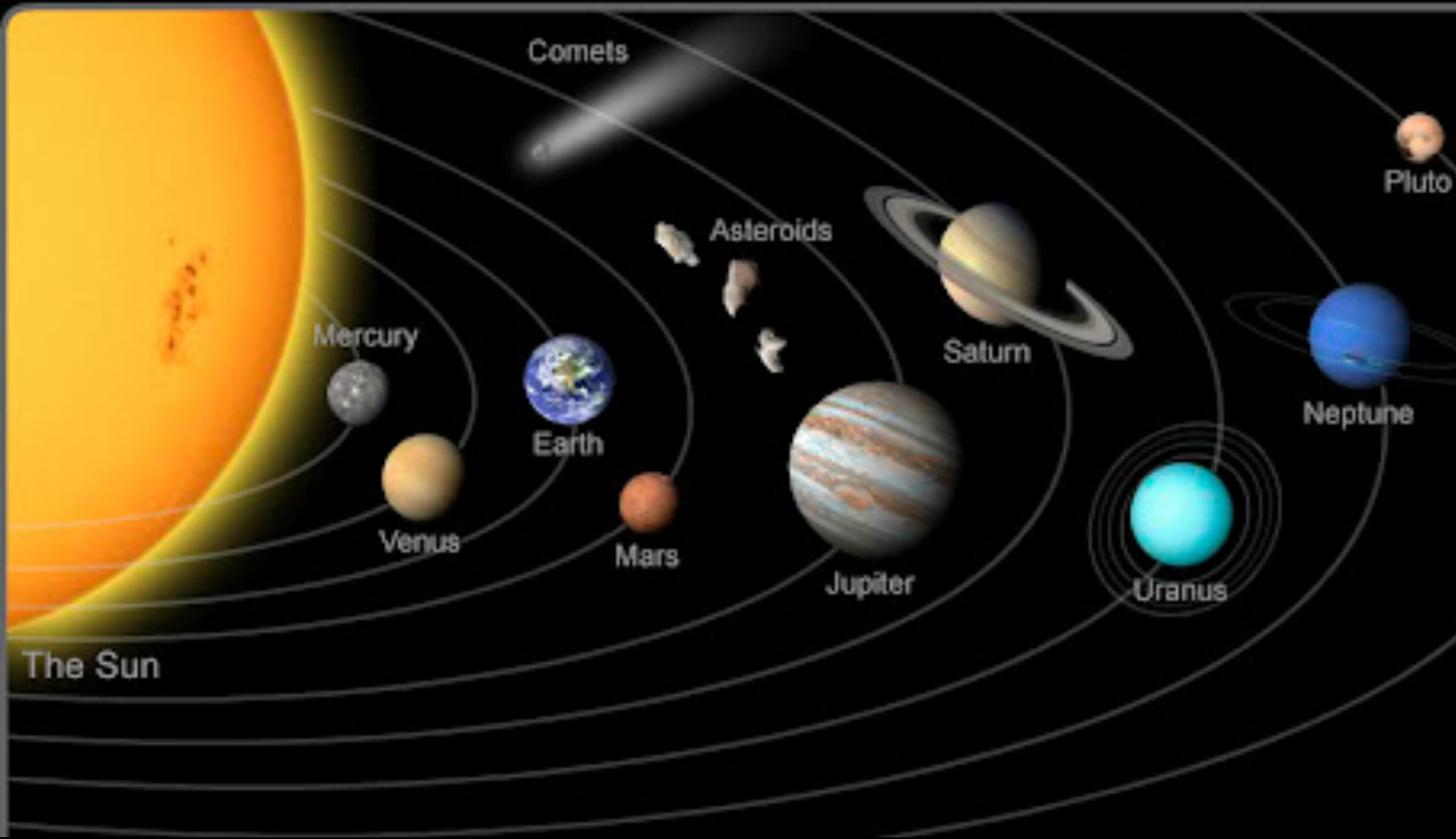
Coalescence of dust grains

Growth of planetesimals (km size) 10^5 years

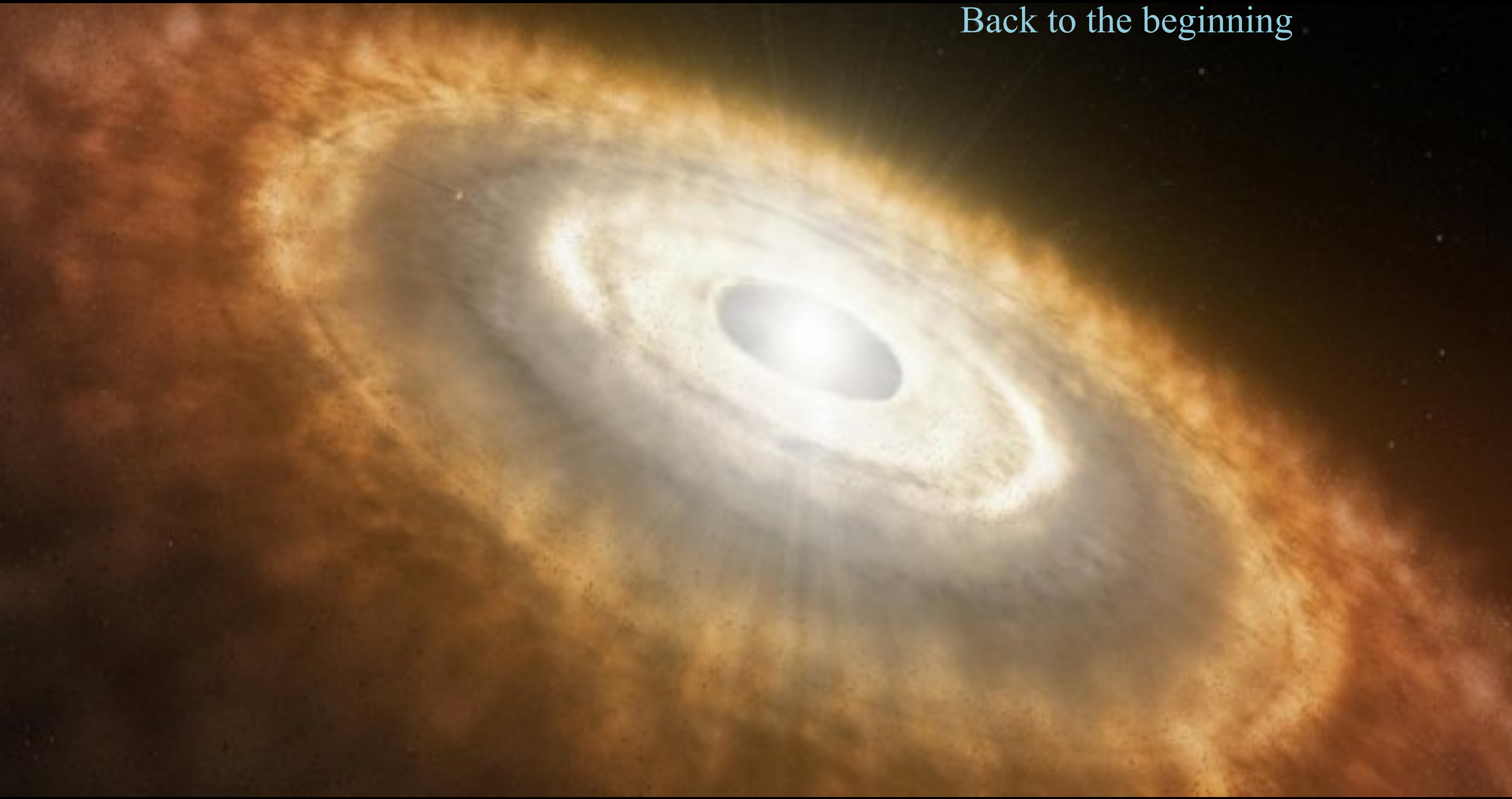
Growth of planetary embryos (100 - >1000 km) – >10^6 years

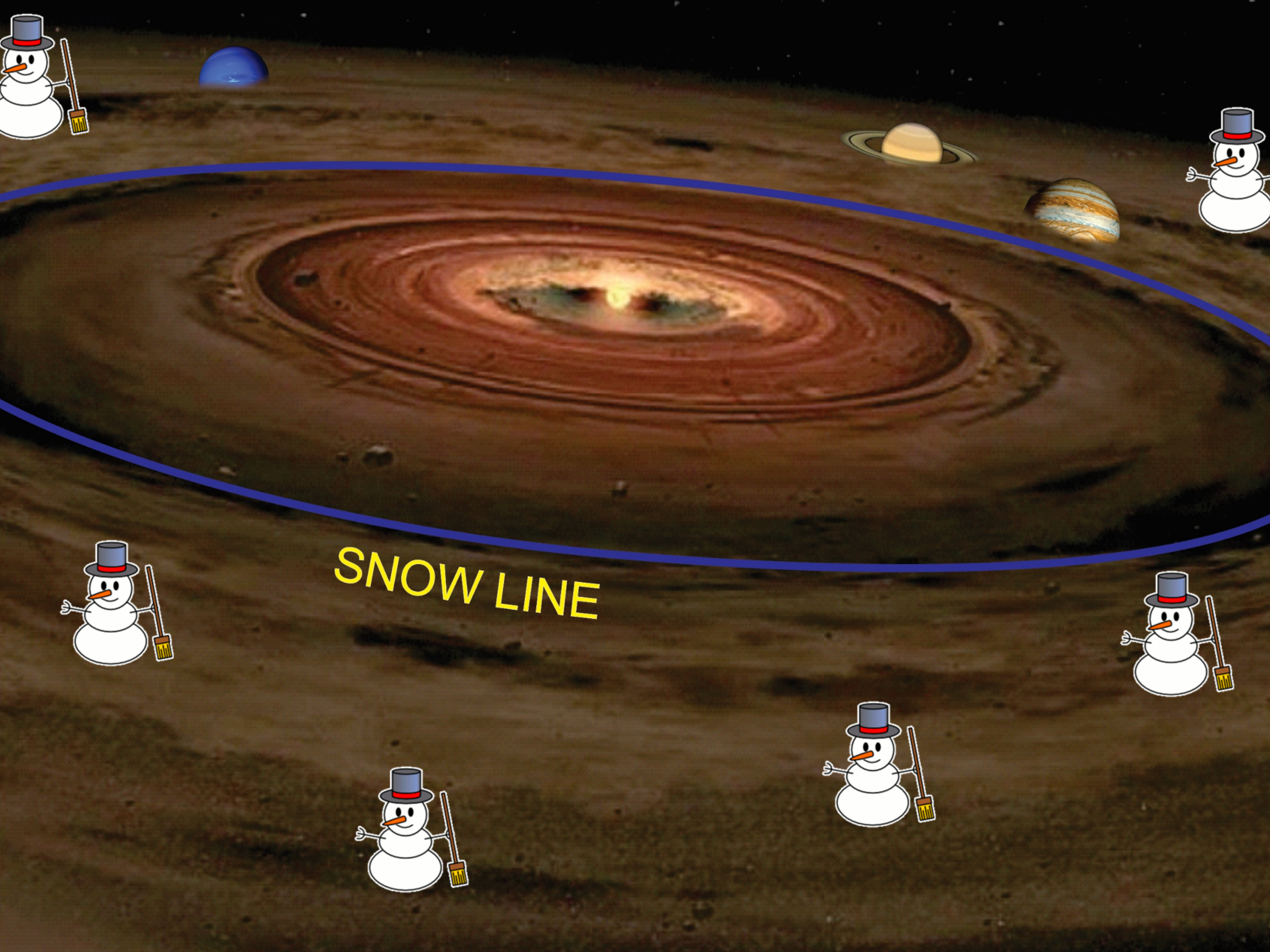
Giant Impact (30 – 100 My)

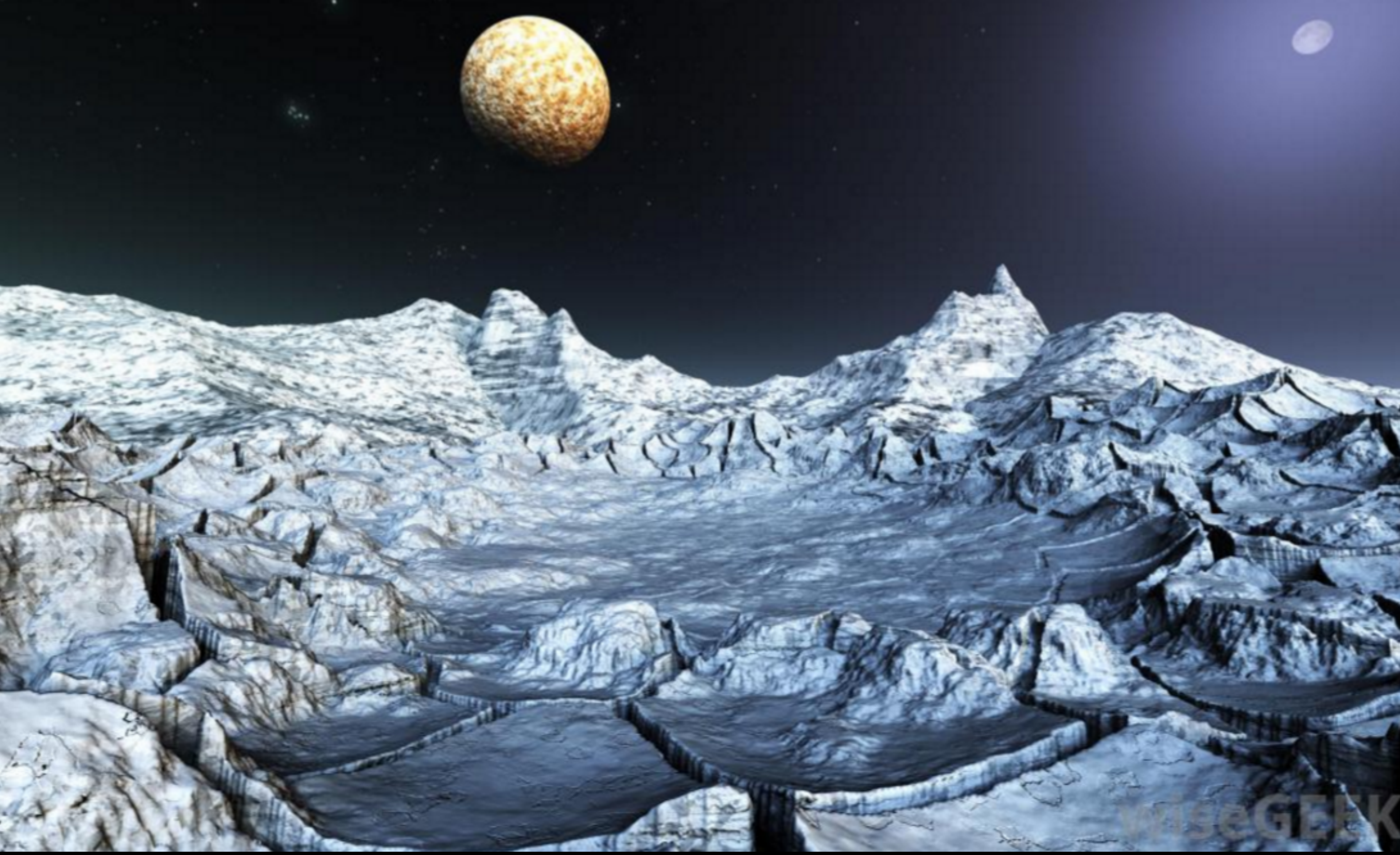



Comets
Pluto
Asteroids
Saturn
Mercury
Earth
Neptune
Venus
Mars
Jupiter
Uranus
The Sun

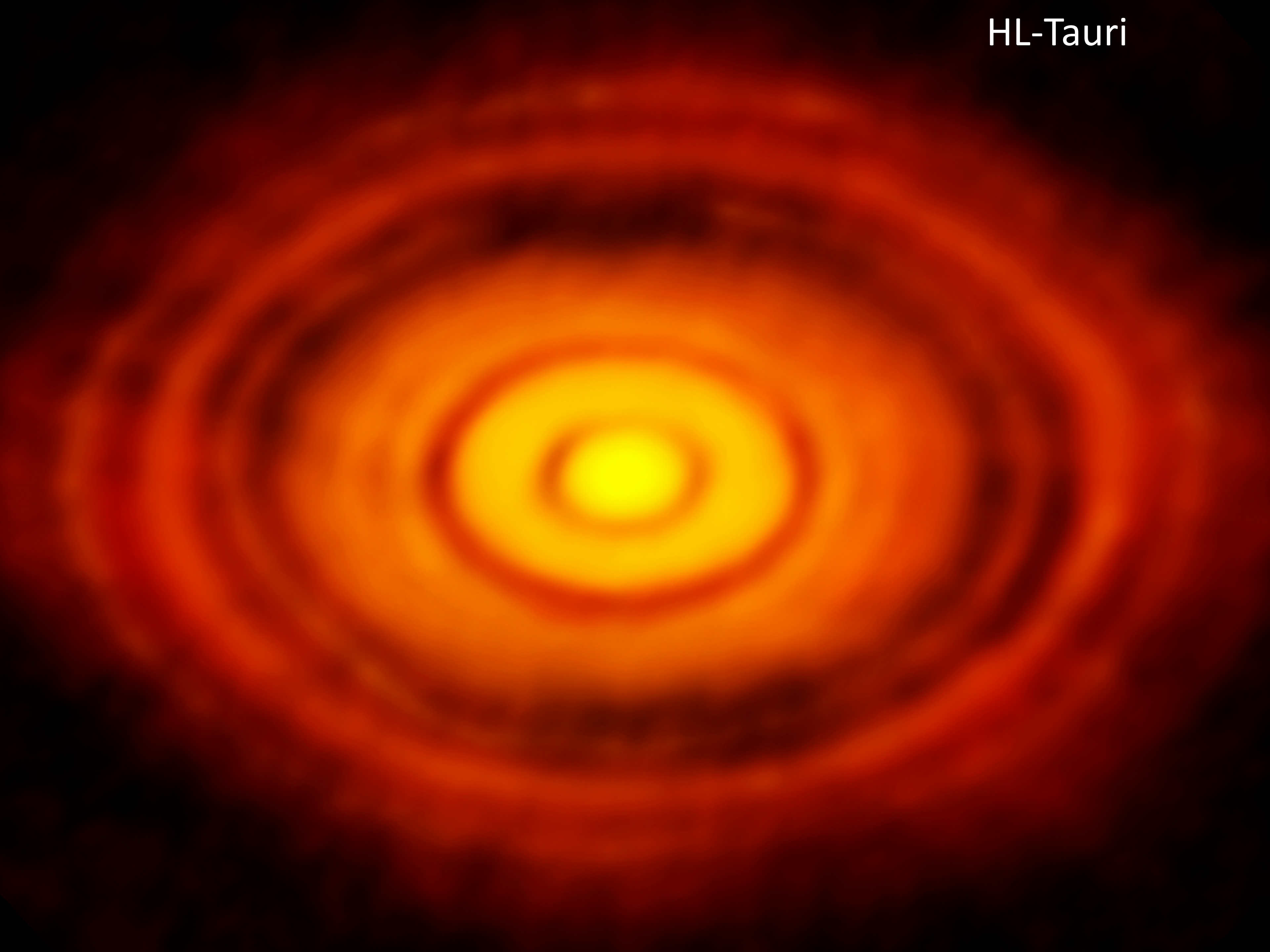
Back to the beginning

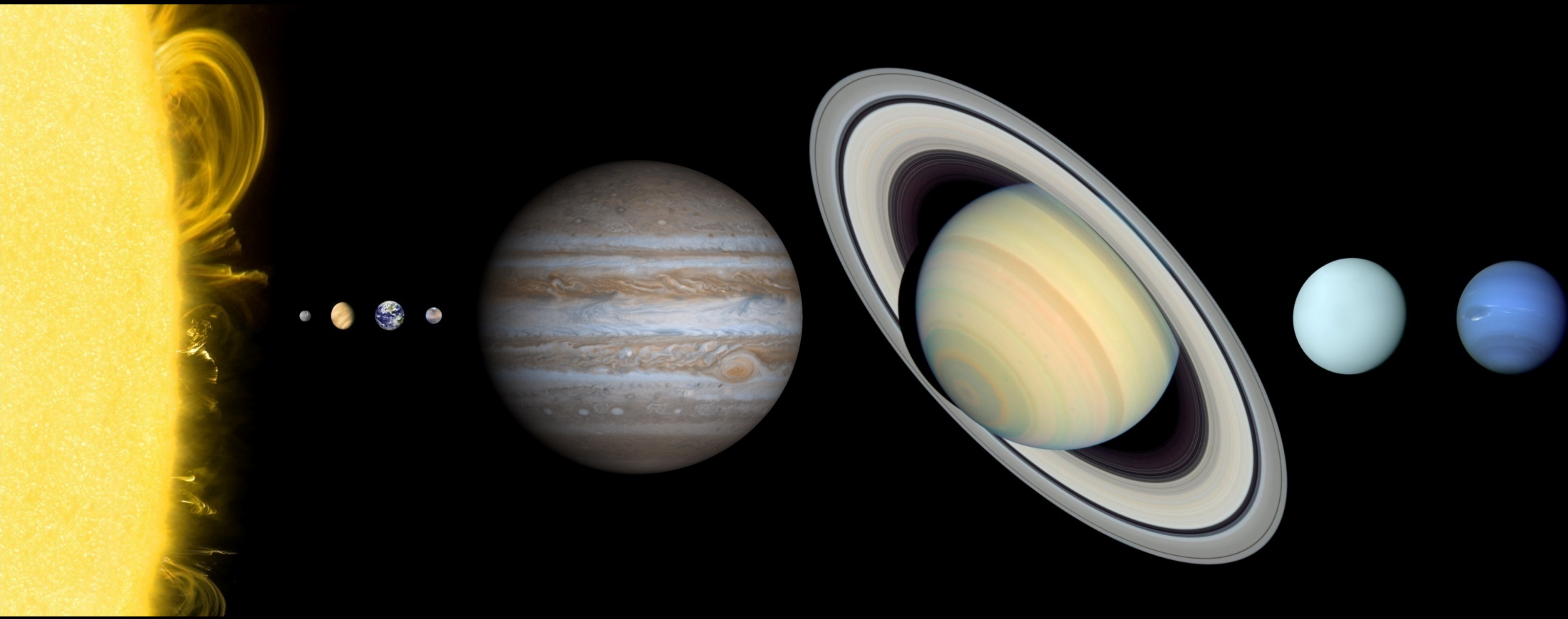



SNOW LINE

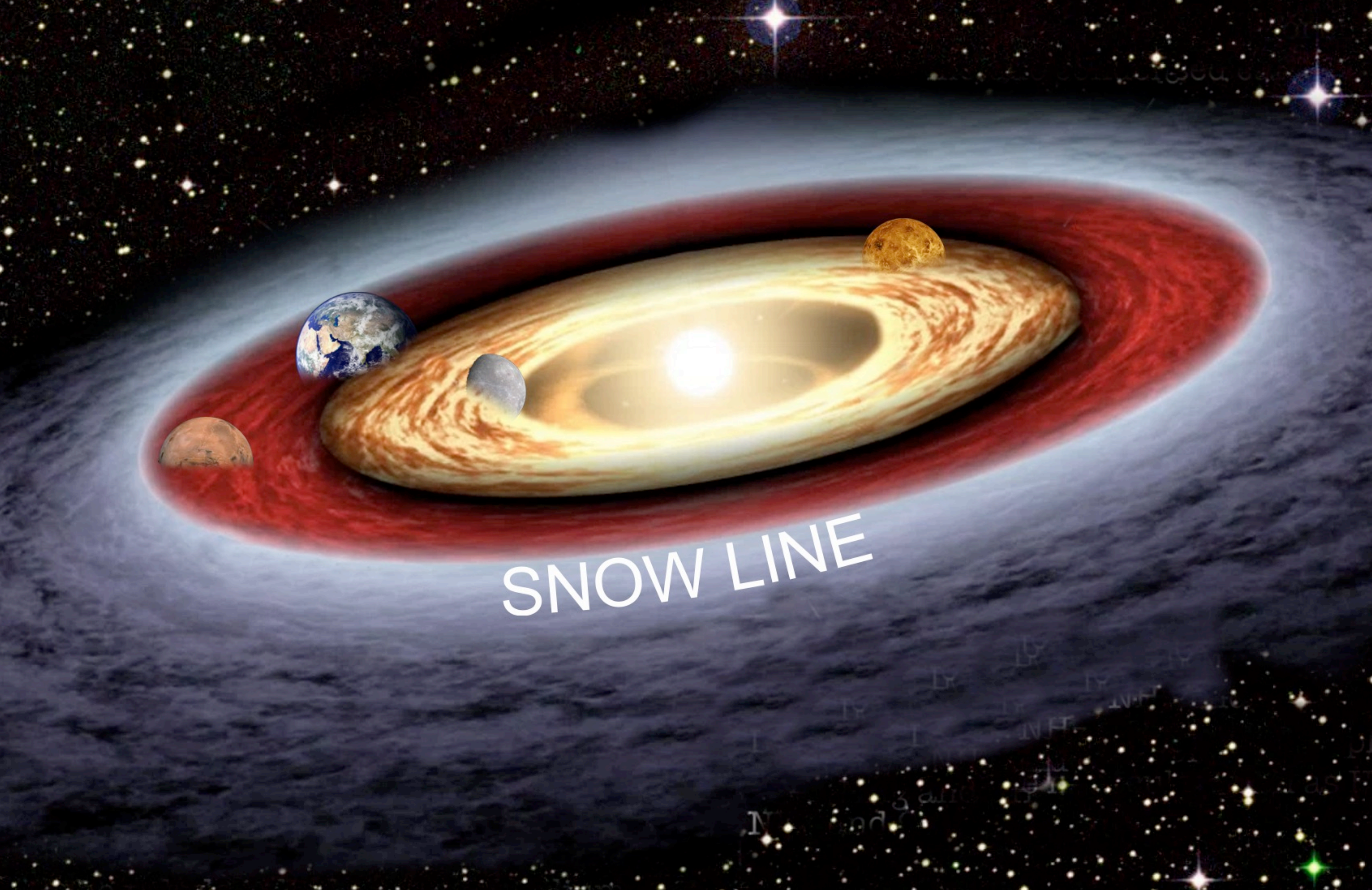


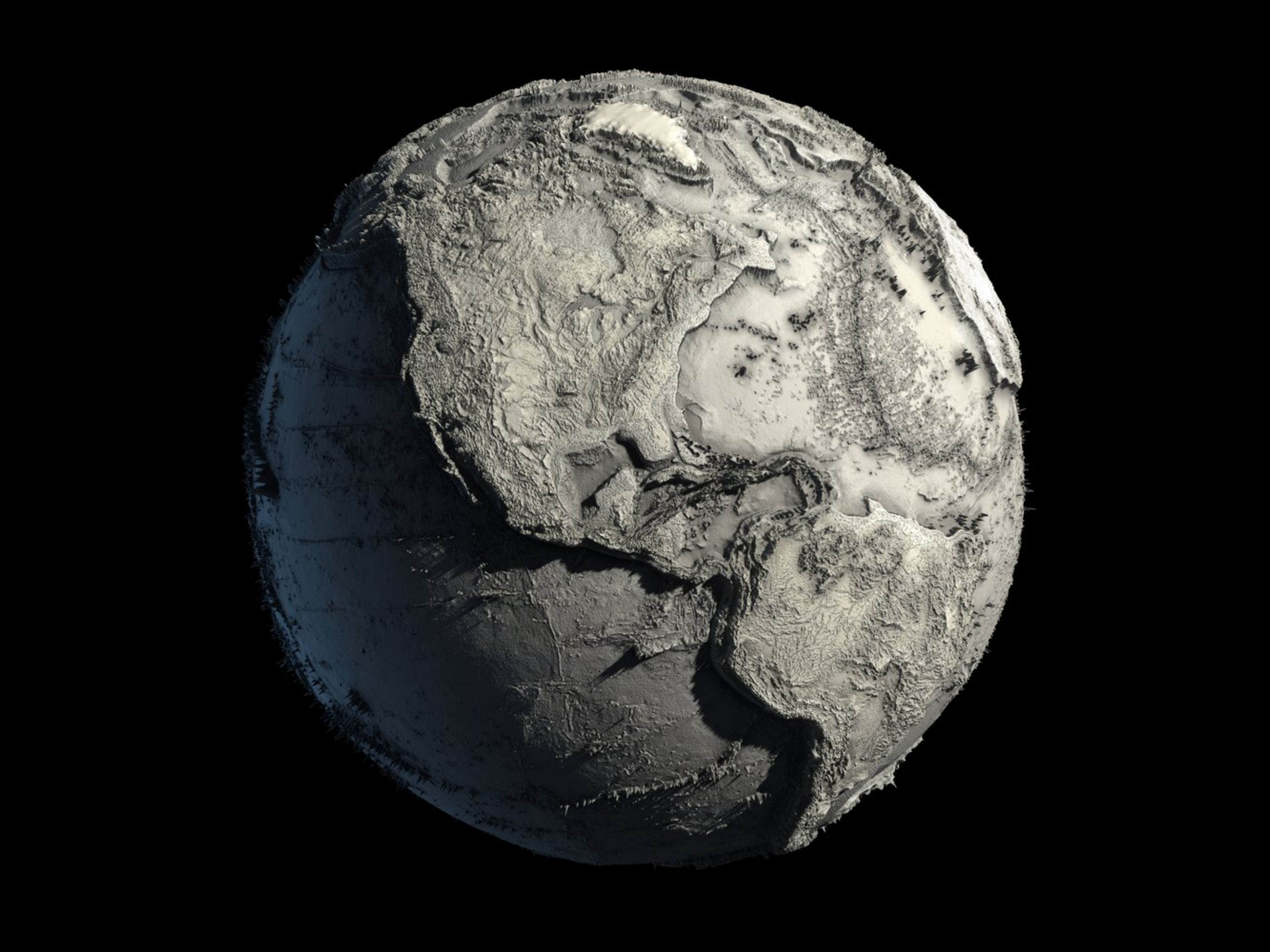
Ice can be incorporated beyond the snow line


HL-Tauri

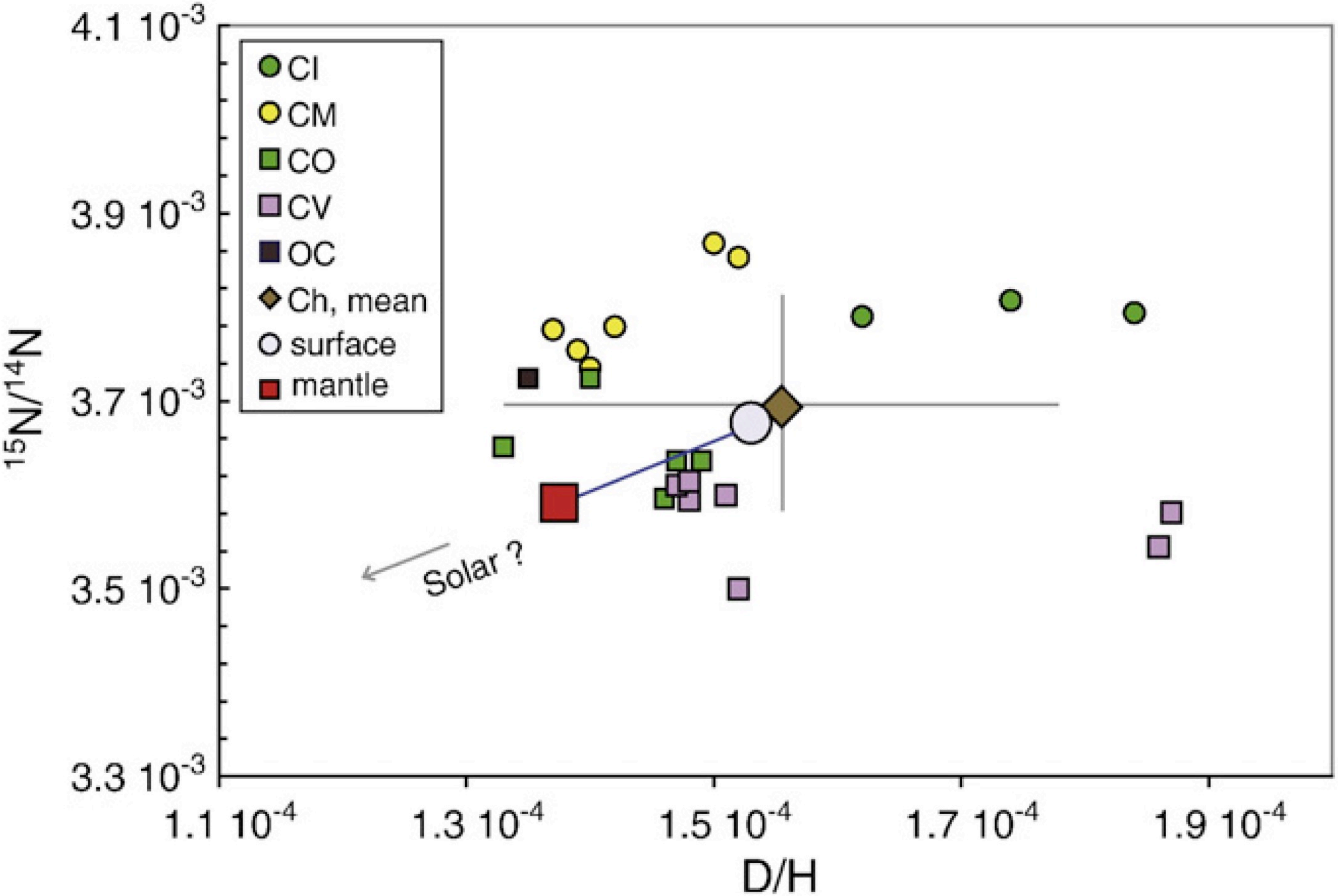


No volatiles (water) expected inside the snow line

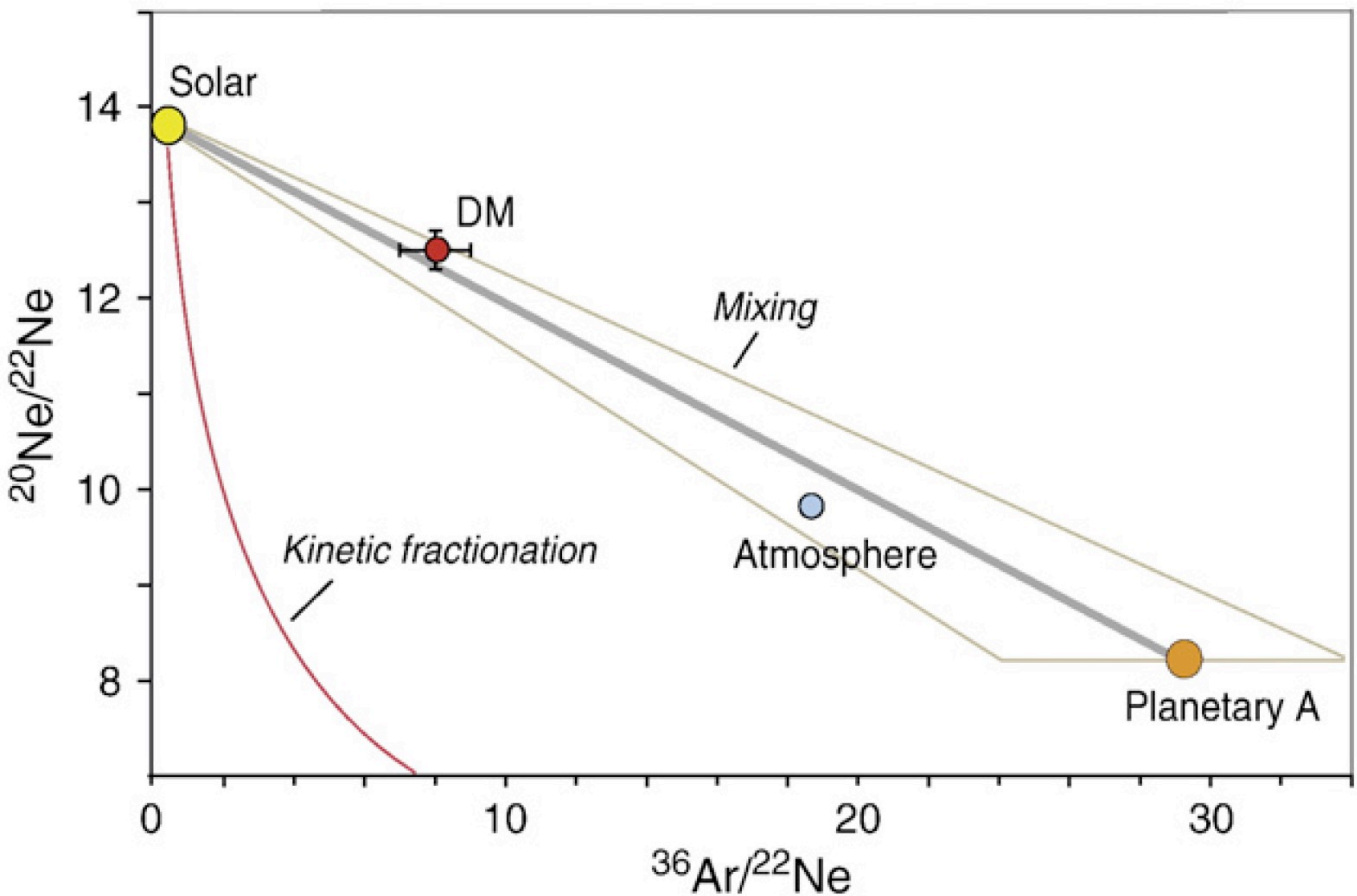




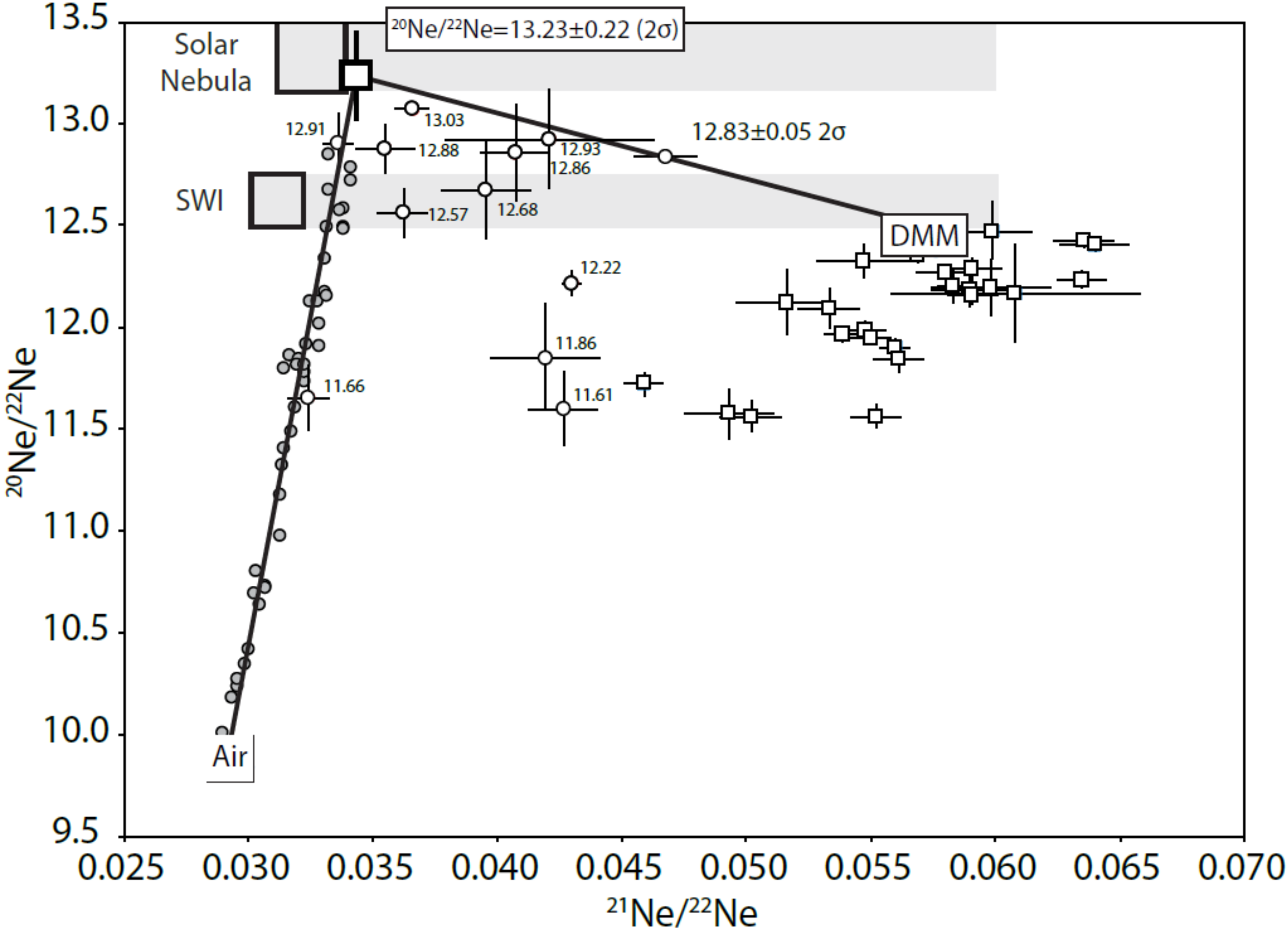
What is the source of volatiles to Earth?



Marty et al., 2012 EPSL

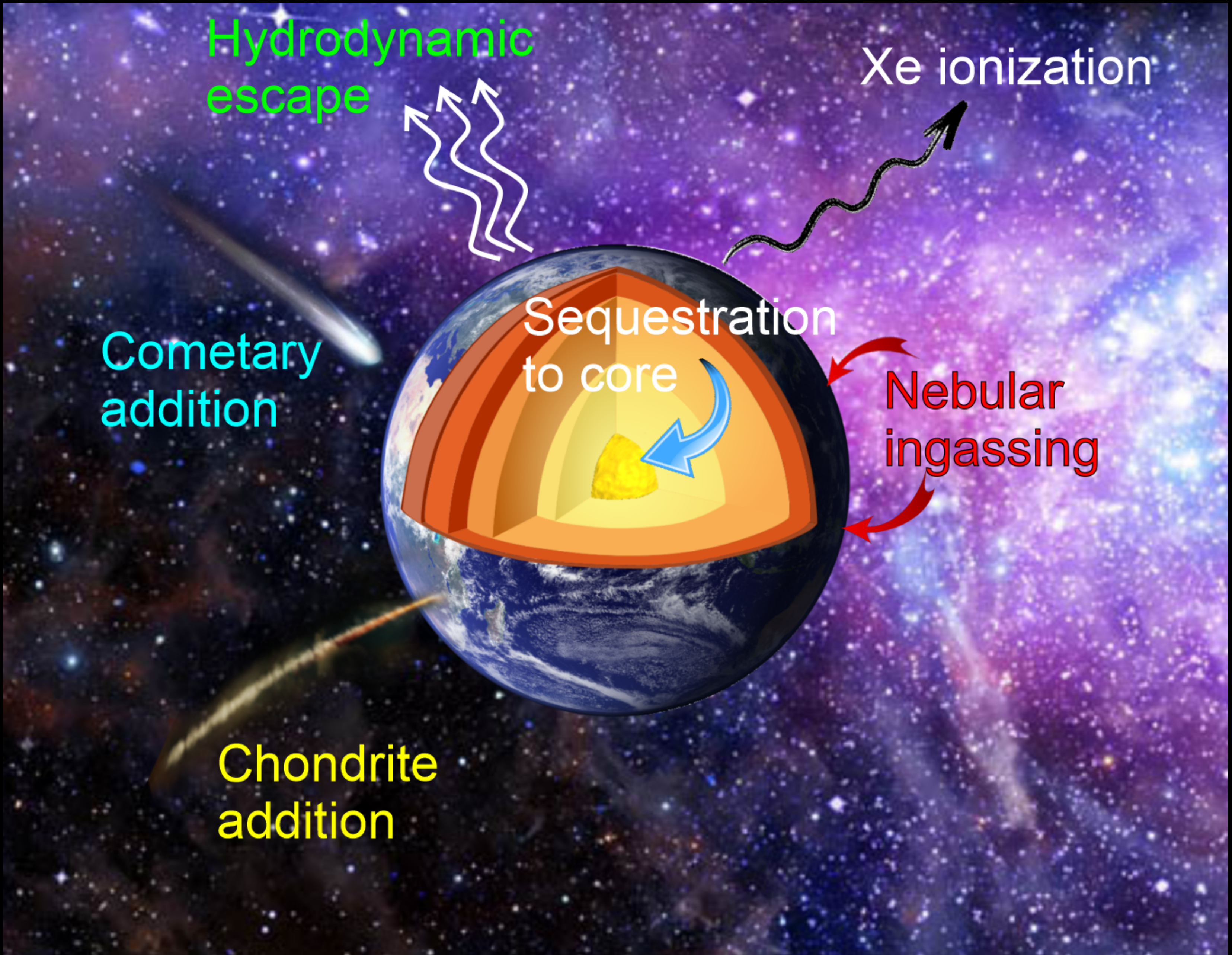


Marty et al., 2012 EPSL



Williams and Mukhopadhyay, Science, 2018

Sources and sinks considered



What is the source of volatiles for bodies within the ‘snow line’?

- Late accretion

Late Veneer (Accretion) – addition of chondritic material (80-130 Ma)

Late Accretion

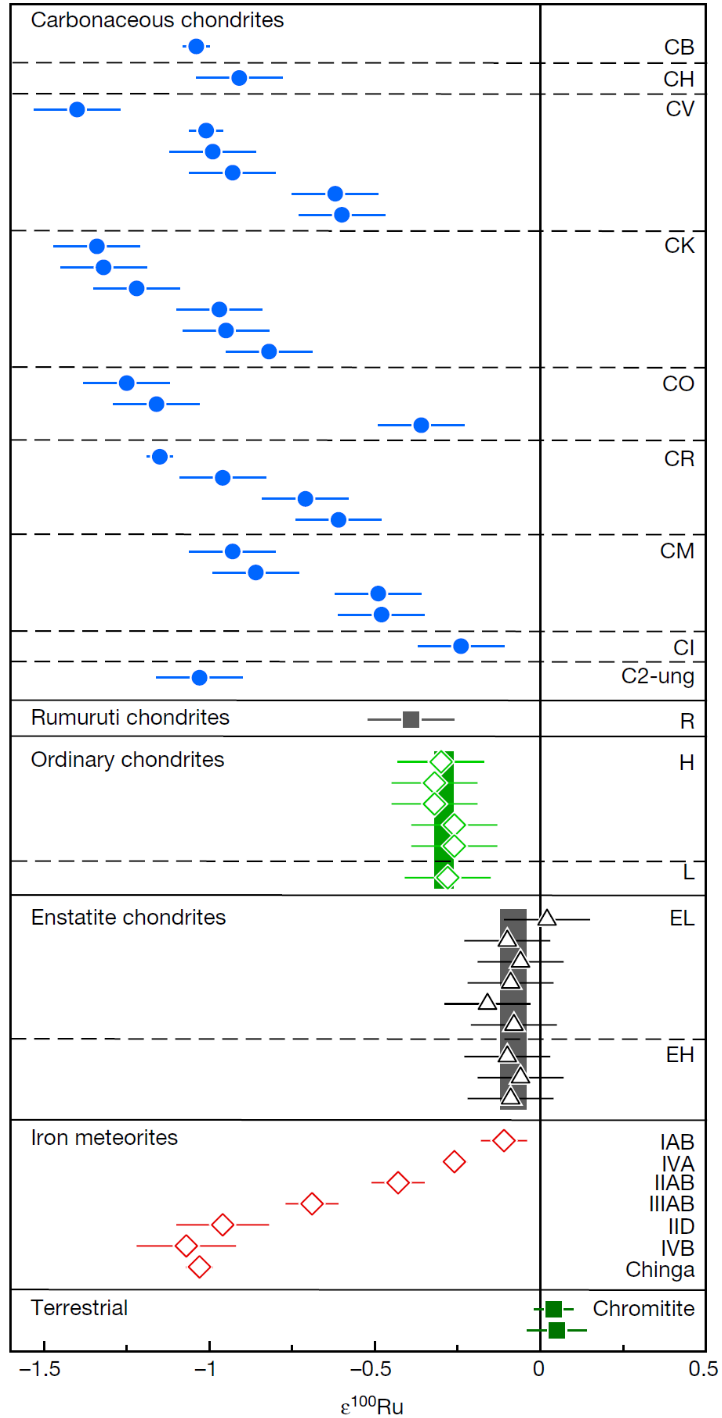
Pros

- Source of HSE (*Os, Ir, Ru, Rh, Pt, Pd, Re, Au*) (0.5-1.0%)
- 1-2 % of carbonaceous chondrites needed for water
- D/H ratio of Earth and CM chondrites overlap

Cons

- $^{187}Os/^{188}Os$ of Earth matches enstatite and ordinary chondrites, but not CM chondrites (Walker et al., 2002)
- Ru isotope ratios ($\varepsilon^{100}Ru$) of carbonaceous chondrites and Earth do not match (Fischer-Gödde et al. 2017)
- Xe/Kr ratios of Earth are very different from C chondrites
- Nitrogen isotopes do not match C chondrites

Ruthenium Isotopes

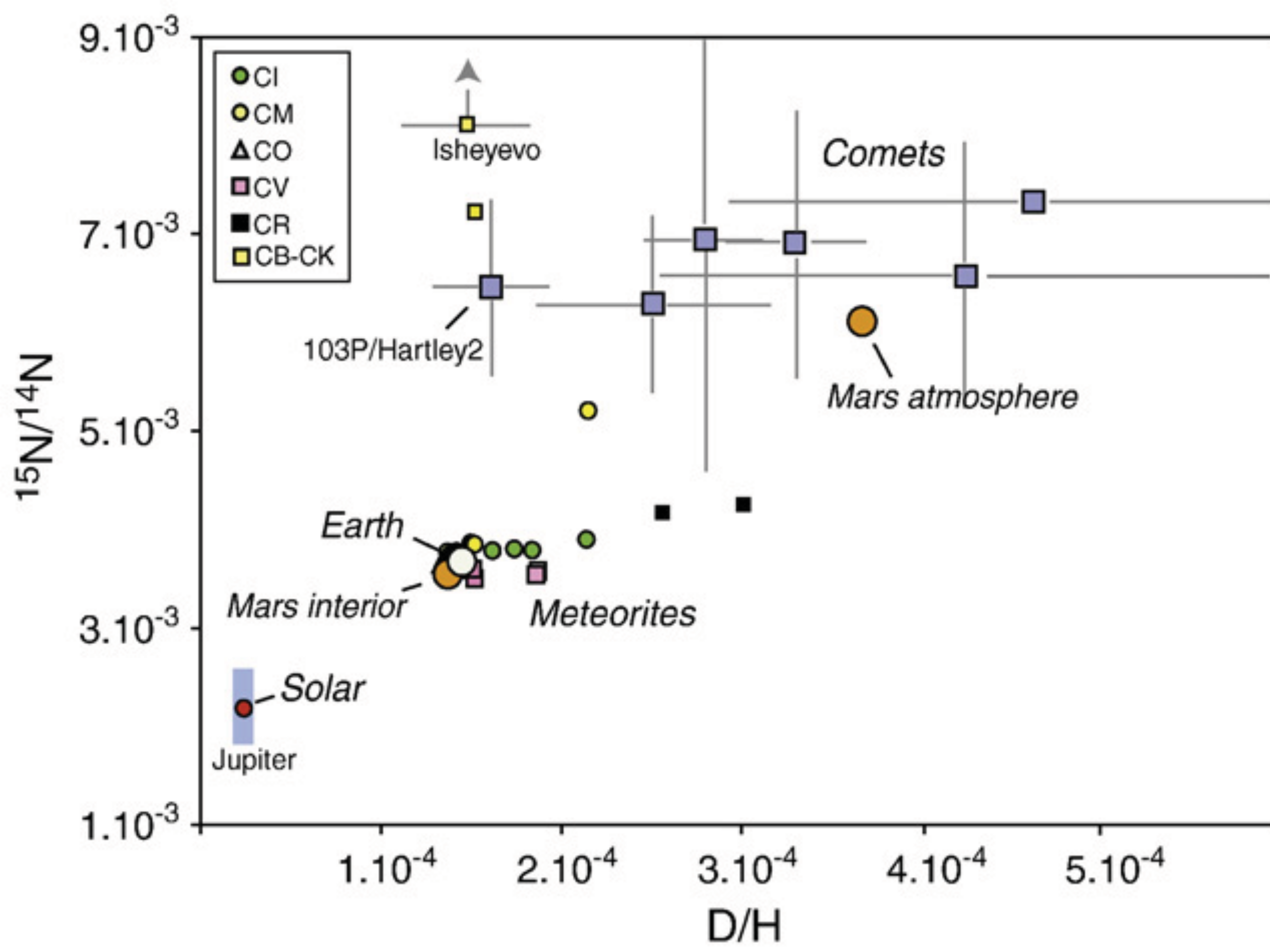


Fischer Gödde & Kleine (2017)

What is the source of water for bodies within the ‘snow line’?

- Late accretion?
- Comets?

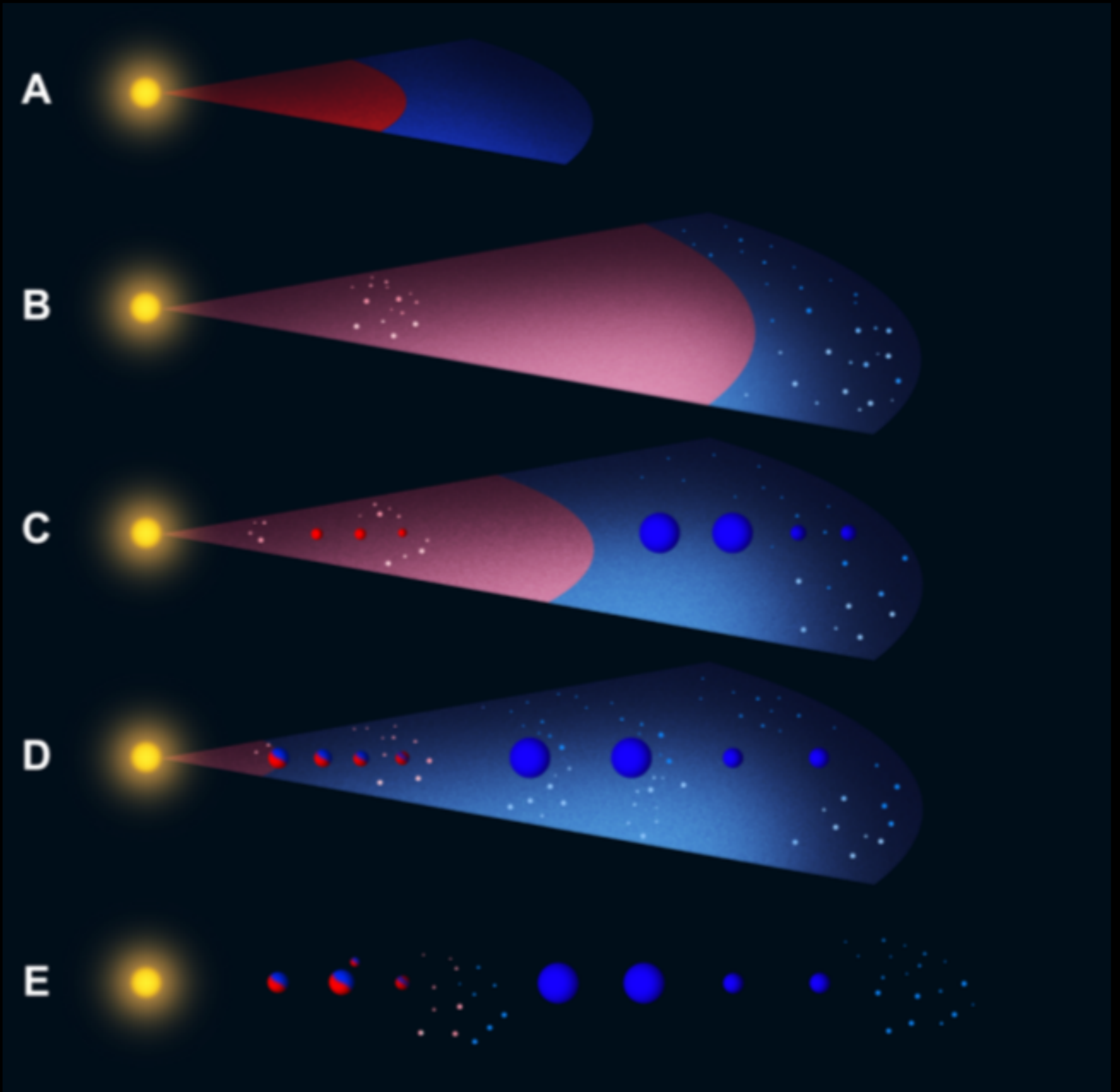
Comets – rich in volatiles



CI
CM
CO
CV
CR
CB-CK
Isheyevo
Comets
103P/Hartley2
Mars atmosphere
Earth
Mars interior
Meteorites
Solar
Jupiter
9.10-3
7.10-3
5.10-3
3.10-3
1.10-3
1.10-4
2.10-4
3.10-4
4.10-4
5.10-4
15N/14N
D/H

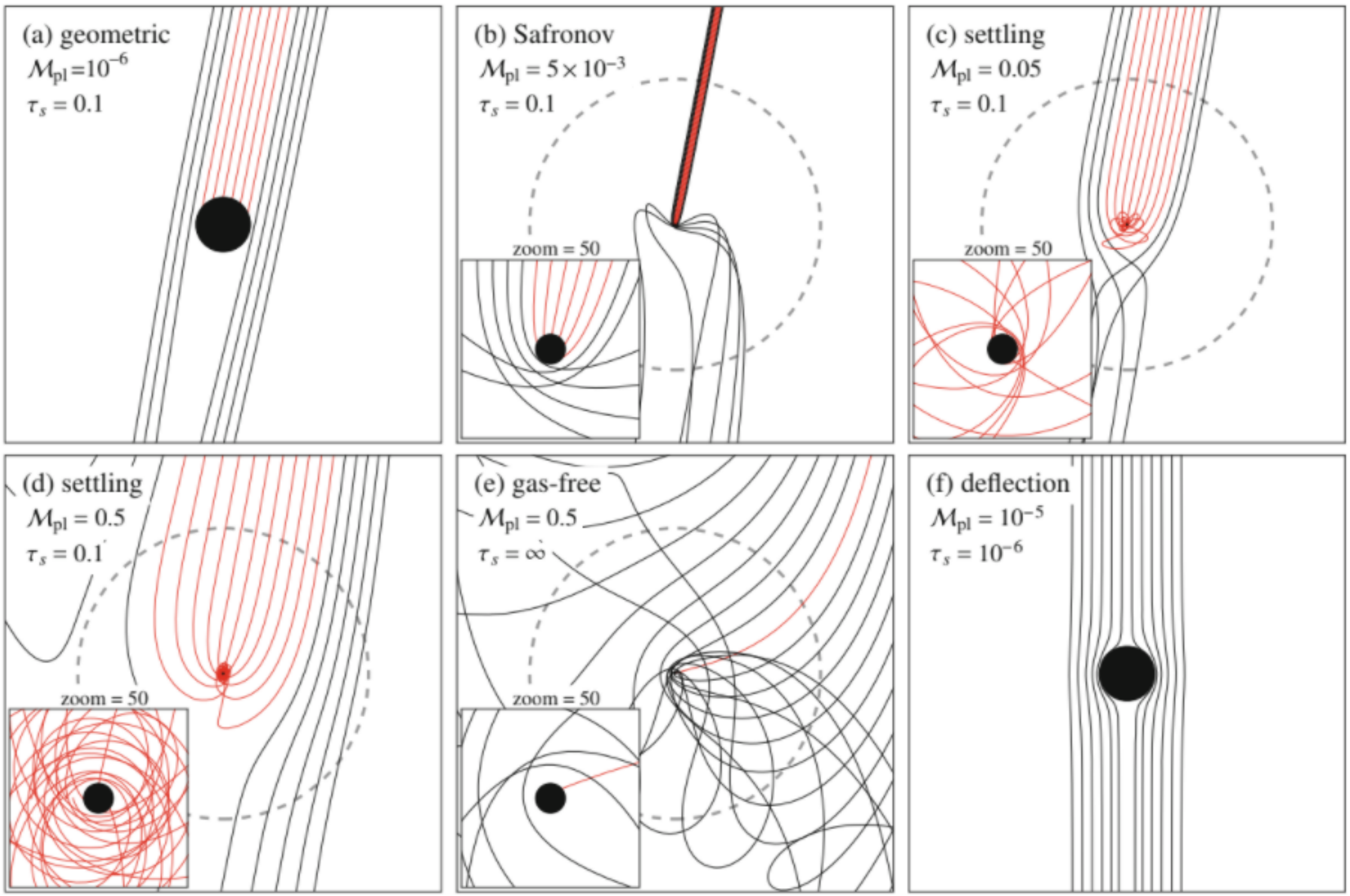
What is the source of water for bodies within the 'snow line'?

- Late veneer?
- Comets?
- Pebble accretion: 'Pebbles' sourced in the outer solar system were dragged into growing planetesimals during inward radial drift.
  - Brings in volatile rich material
  - Rapid planet formation
  - Requires nebula to be present



Johansen et al., 2021 (Sci. Adv.)

Pebble accretion trajectories



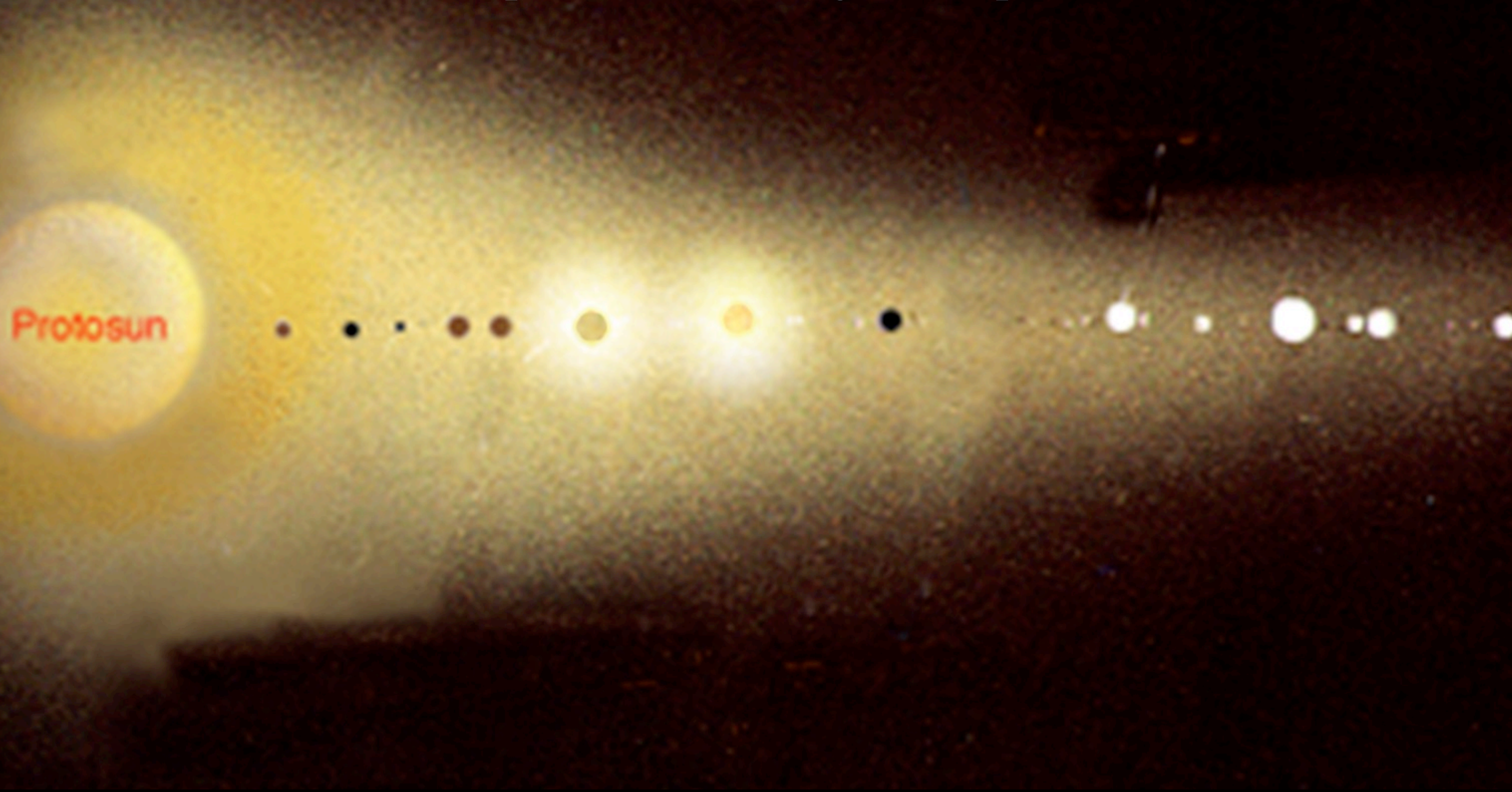
Reprinted from C.W. Ormel, 2017

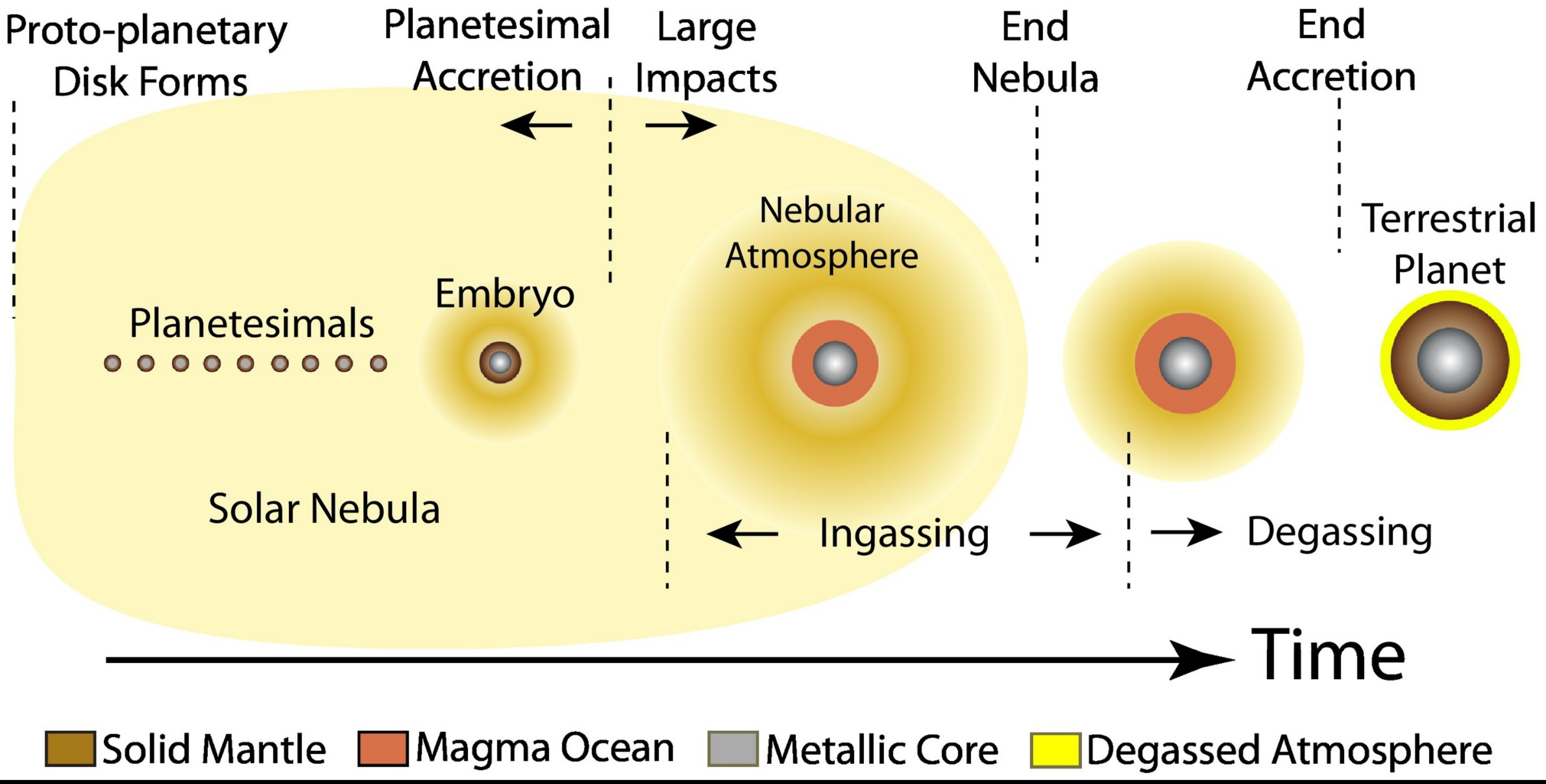
What is the source of water for bodies within the ‘snow line’?

- Late veneer?
- Comets?
- Wet accretion: ‘Pebbles’ dragged into growing planetesimals during inward radial drift.
- Nebular Ingassing. Dissolution of solar nebula into a magma ocean?

Nebular ingassing:

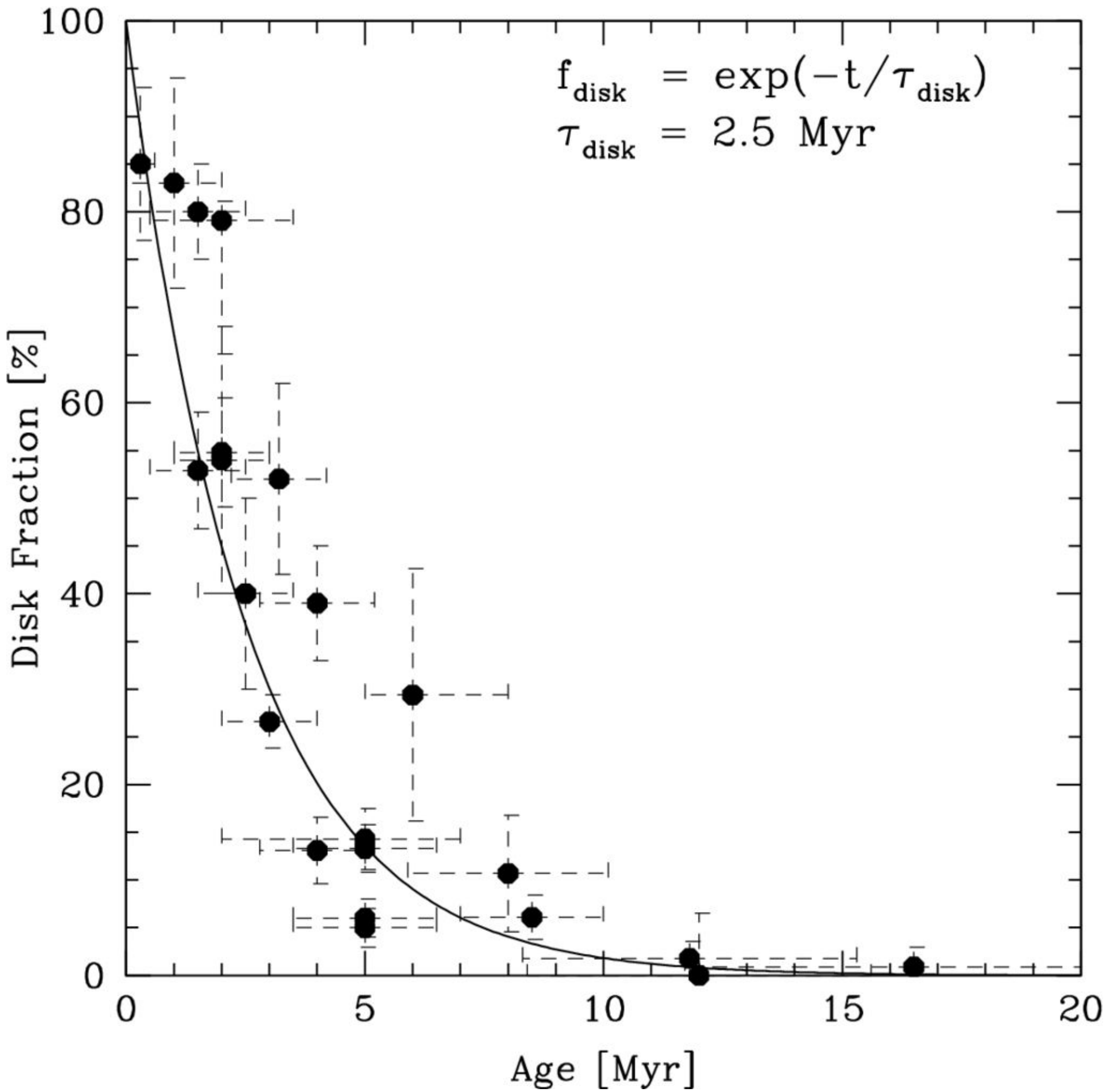
Early in Solar System history, an H_2, He-rich nebular atmosphere would engulf the planets





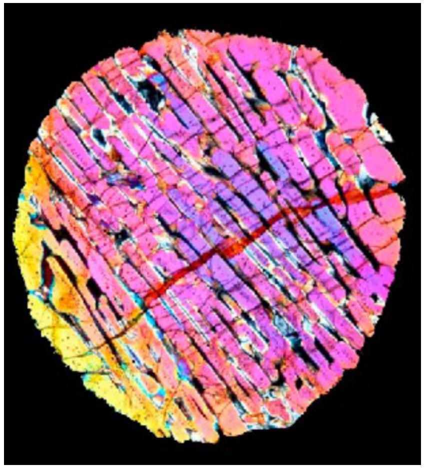
Proto-planetary
Disk Forms
Planetesimal
Accretion
Large
Impacts
End
Nebula
End
Accretion
Nebular
Atmosphere
Terrestrial
Planet
Embryo
Planetesimals
Solar Nebula
Ingassing
Degassing
Time
Solid Mantle
Magma Ocean
Metallic Core
Degassed Atmosphere

Ages of extant nebular disks

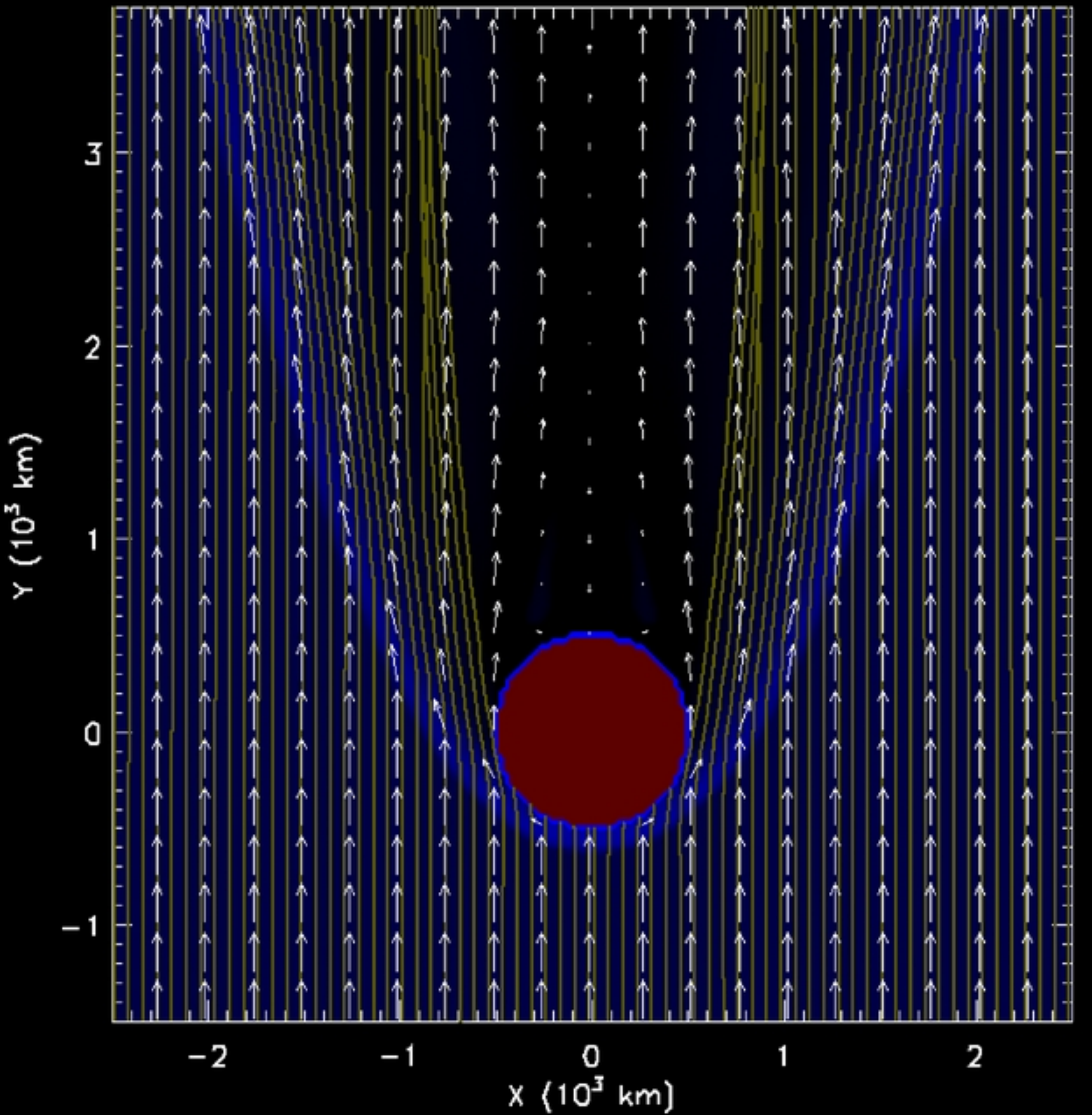


Mamajek_ApJ_09

Chondrules

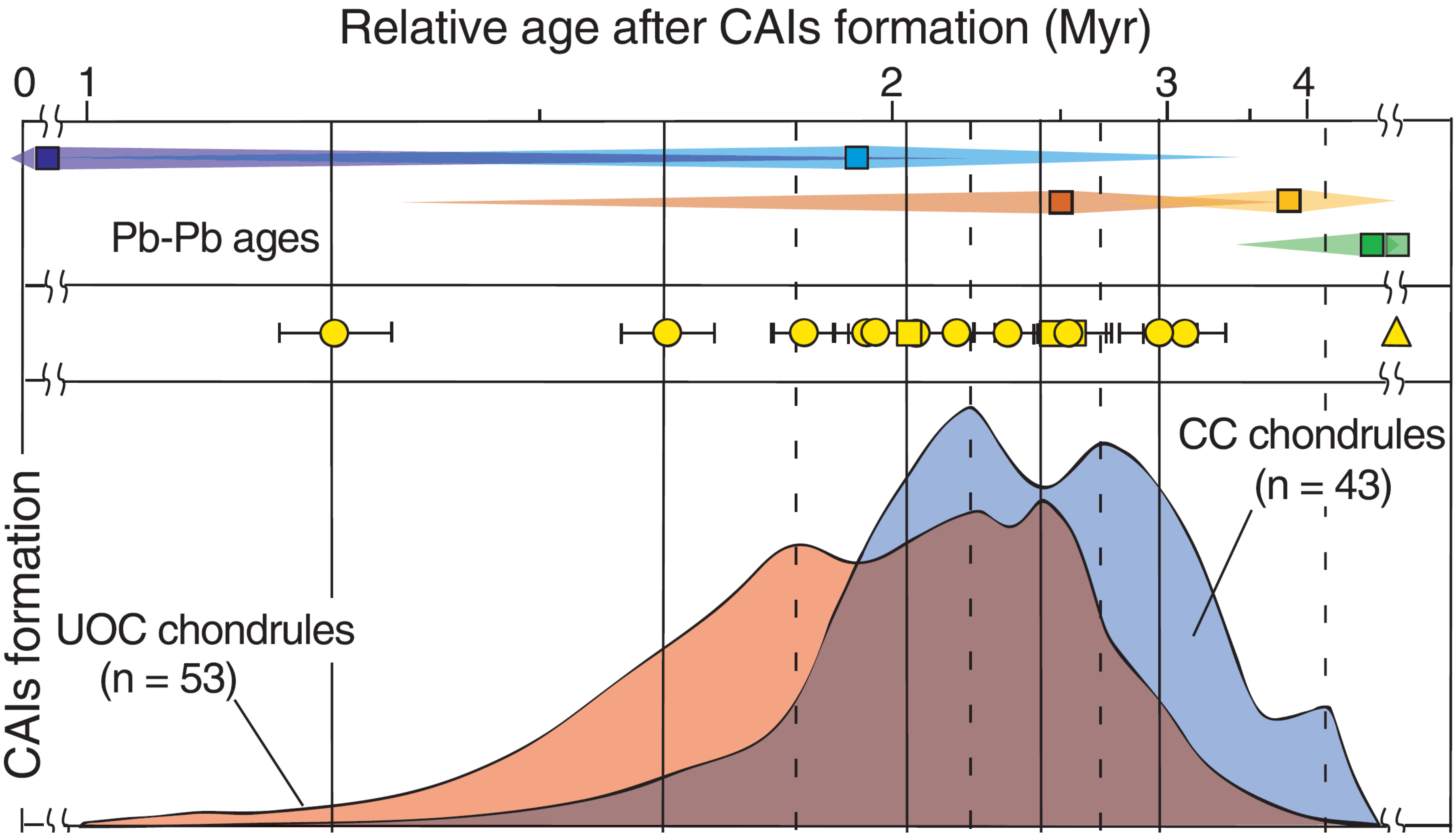


Semarkona, ordinary chondrite



Y (10^3 km)
X (10^3 km)
−2
−1
0
1
2
3

Ages of chondrules
(form in presence of nebula)



Dating based on ^{26}Al decay -- $\lambda_{½} = 0.717$ My

Villeneuve *et al.* (2009)

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Nebular atmosphere to magma ocean: A model for volatile capture during Earth accretion

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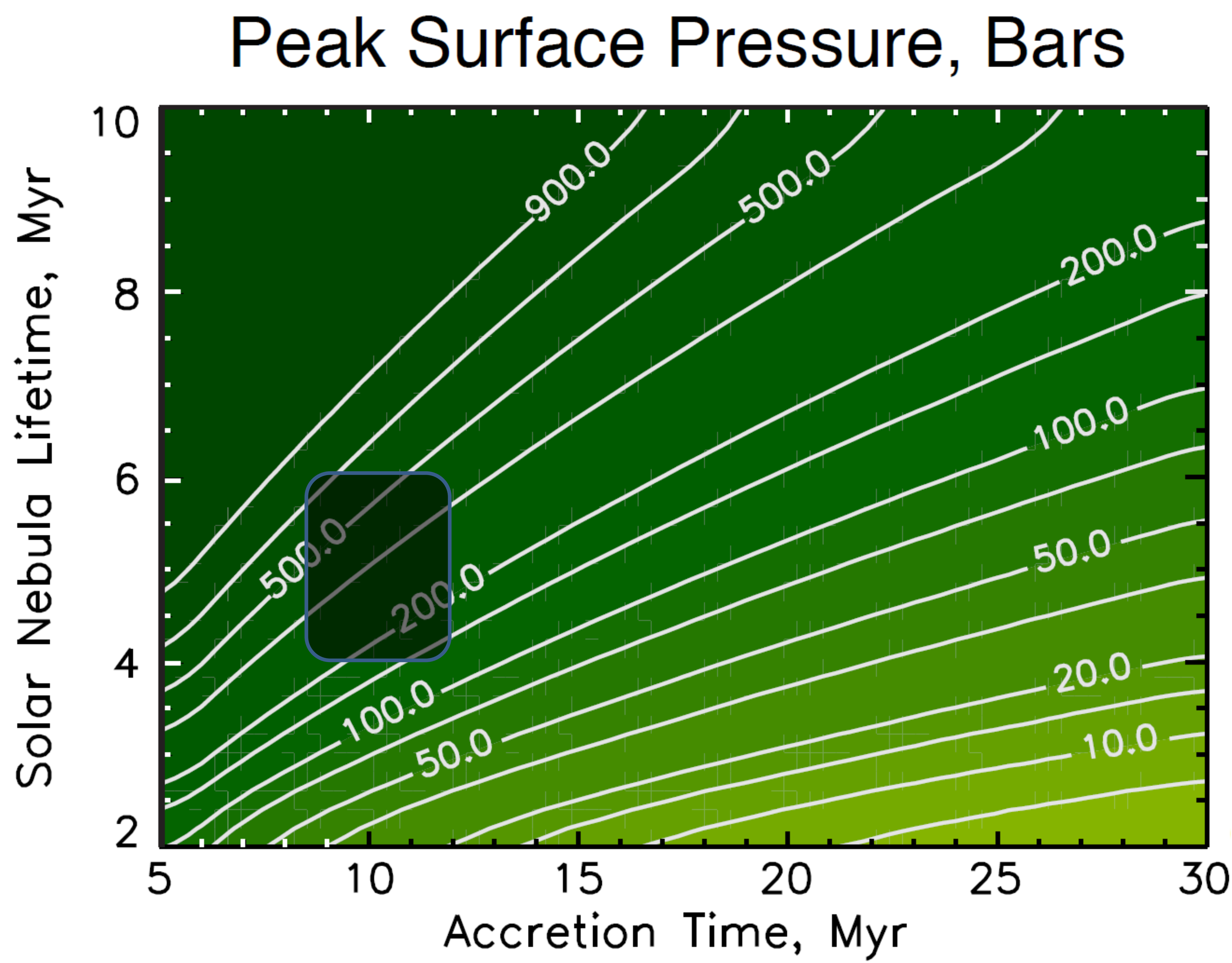
A R T I C L E I N F O

Keywords:
Volatile ingassing
Earth's accretion
Magma ocean
Nebular atmosphere
Hadean dynamo

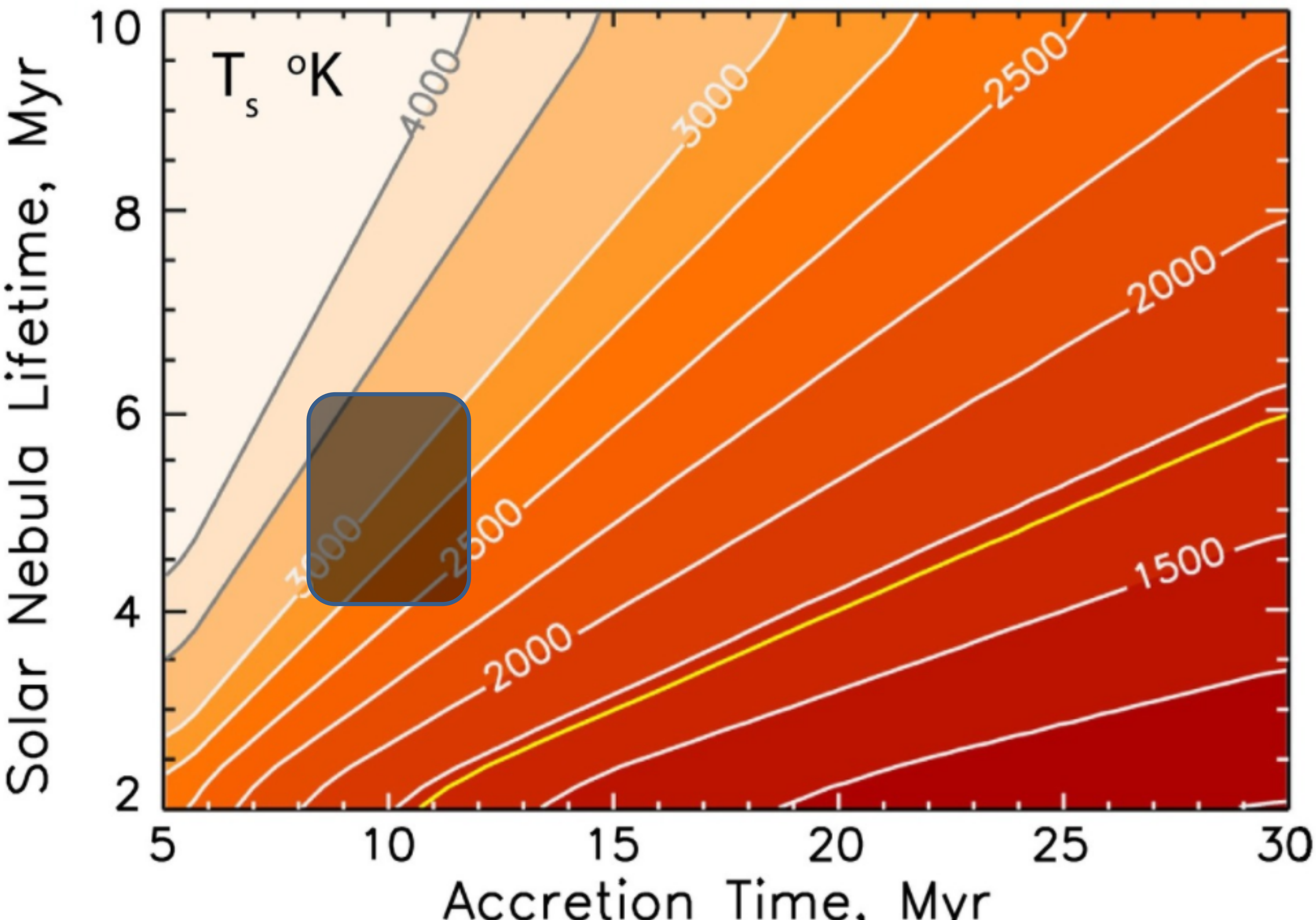
A B S T R A C T

The origin and abundance of mantle volatiles present major questions for Earth's evolution. Here we quantify volatile capture from an atmosphere derived from the solar nebula during accretion, using a boundary layer model of magma ocean dynamics coupled to a nebular atmosphere model adapted to Earth formation. Key elements include (i) nebular atmosphere winds based on scaling laws for deep rotating fluids; (ii) water production at the magma surface; and (iii) gas transfer between magma and atmosphere based on the systematics of air-sea gas exchange by wind and diffusion. Provided the Earth accreted to 30% or more of its final mass in the presence of the solar nebula, the mantle is expected to have ingassed several ocean mass equivalents of water plus hydrogen, along with hundreds of petagrams of helium-3 and other light noble gases. In contrast to light gases, nebular ingassing does not provide the mantle with enough heavy noble gases to account for their present-day atmosphere abundances. Our model also predicts that thermal insulation by the nebular atmosphere led to very hot conditions in Earth's interior during accretion, with peak temperatures above 6000 K at the core-mantle boundary and possible dynamo conditions in the Early Hadean.



Peak Surface Pressure, Bars
900.0
500.0
200.0
100.0
50.0
20.0
10.0
500.0
200.0
100.0
50.0
Solar Nebula Lifetime, Myr
Accretion Time, Myr
10
8
6
4
2
5
10
15
20
25
30

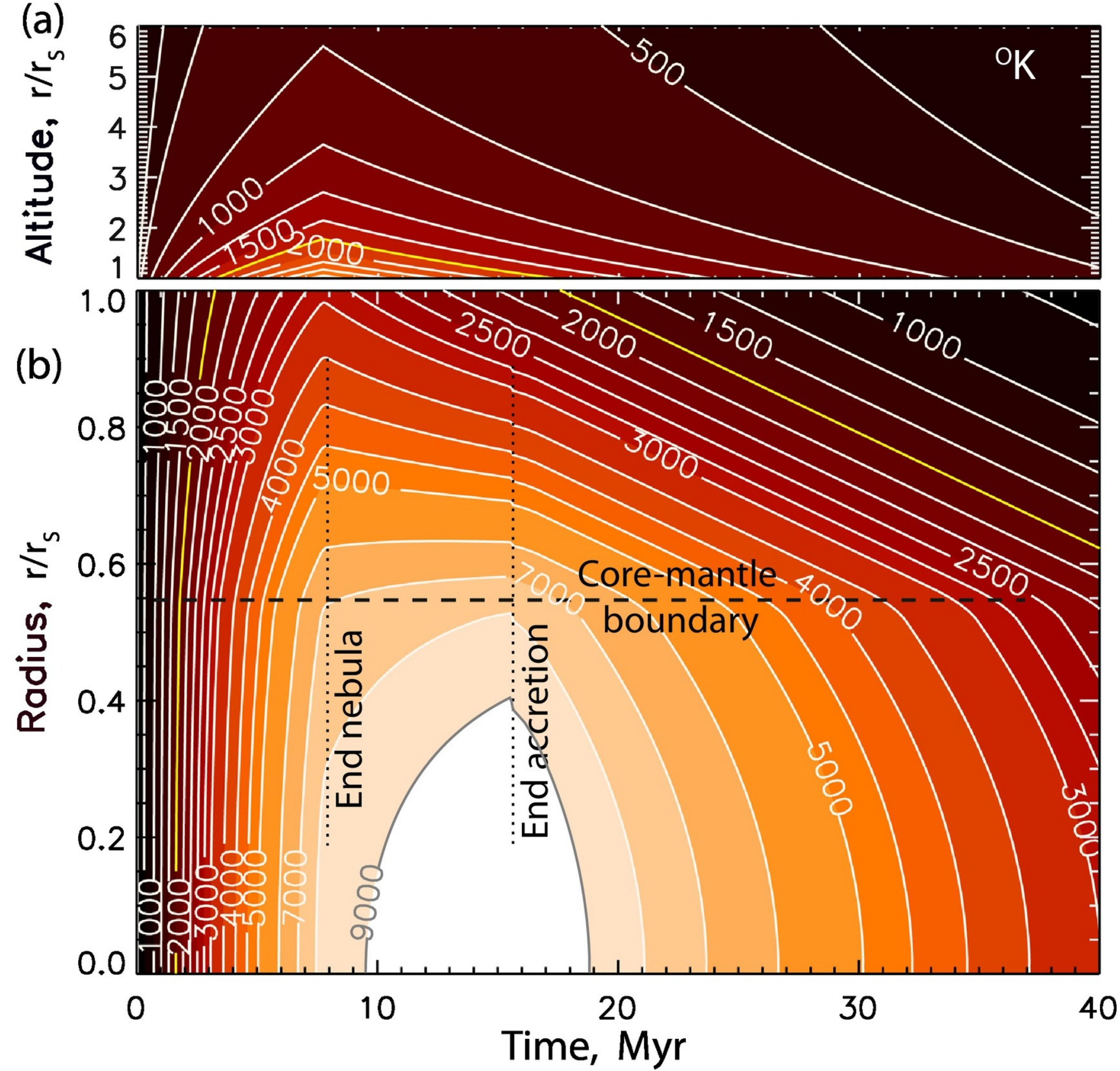
Peak Surface Temperature (K)



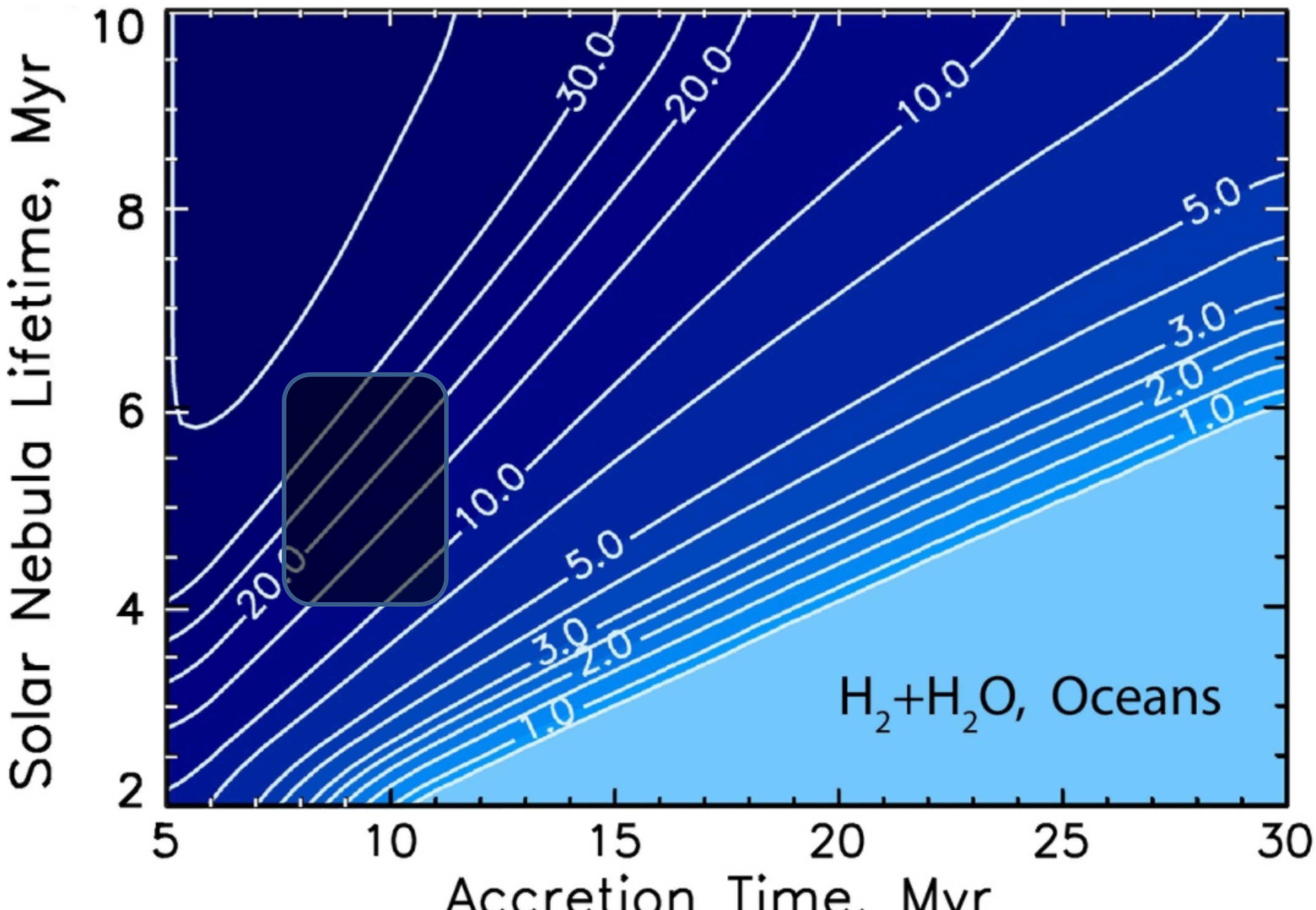
Temperature profile

Atmosphere

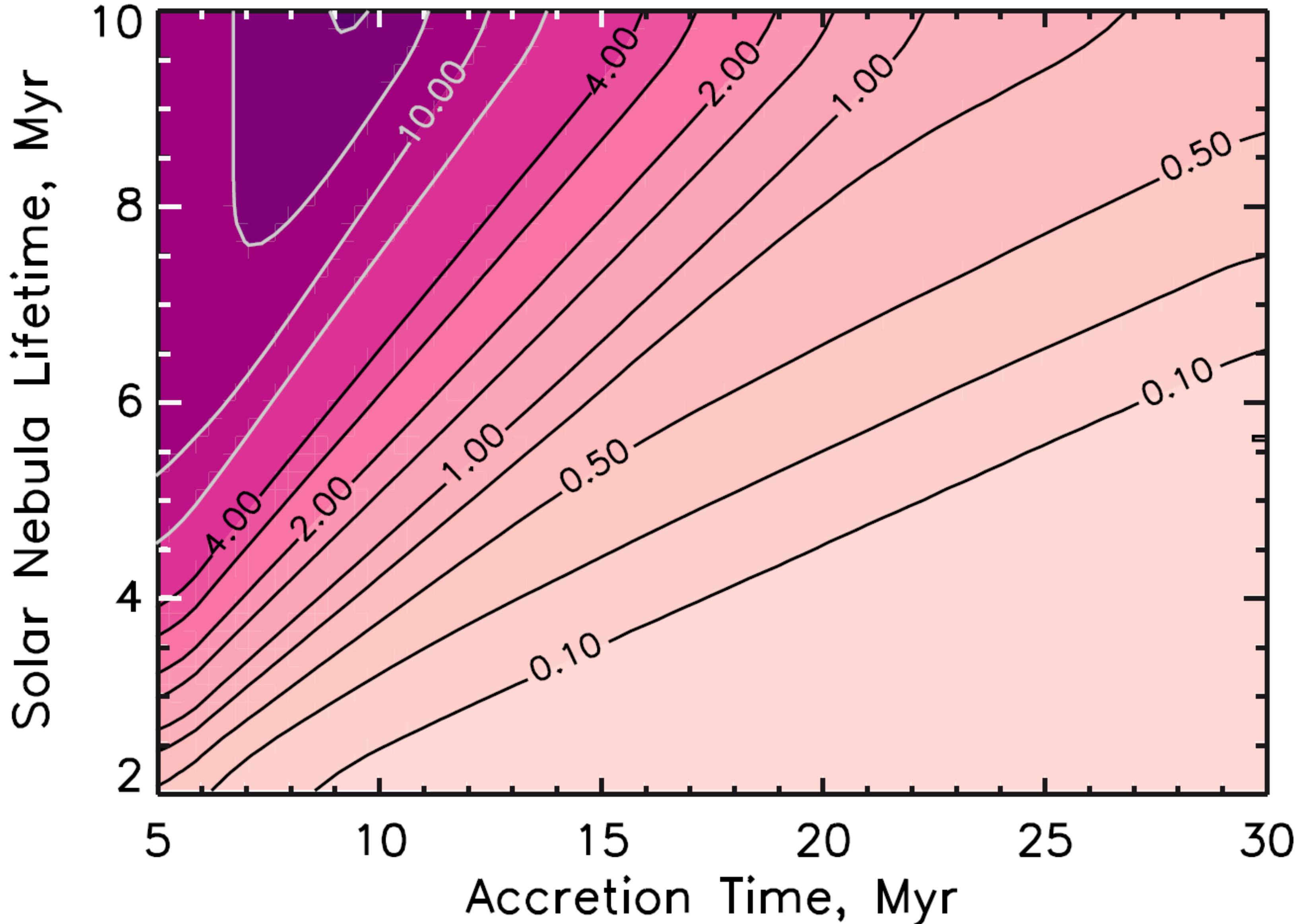
Depth in planet



Ingassed H_2 & H_2O
-- ocean equivalents



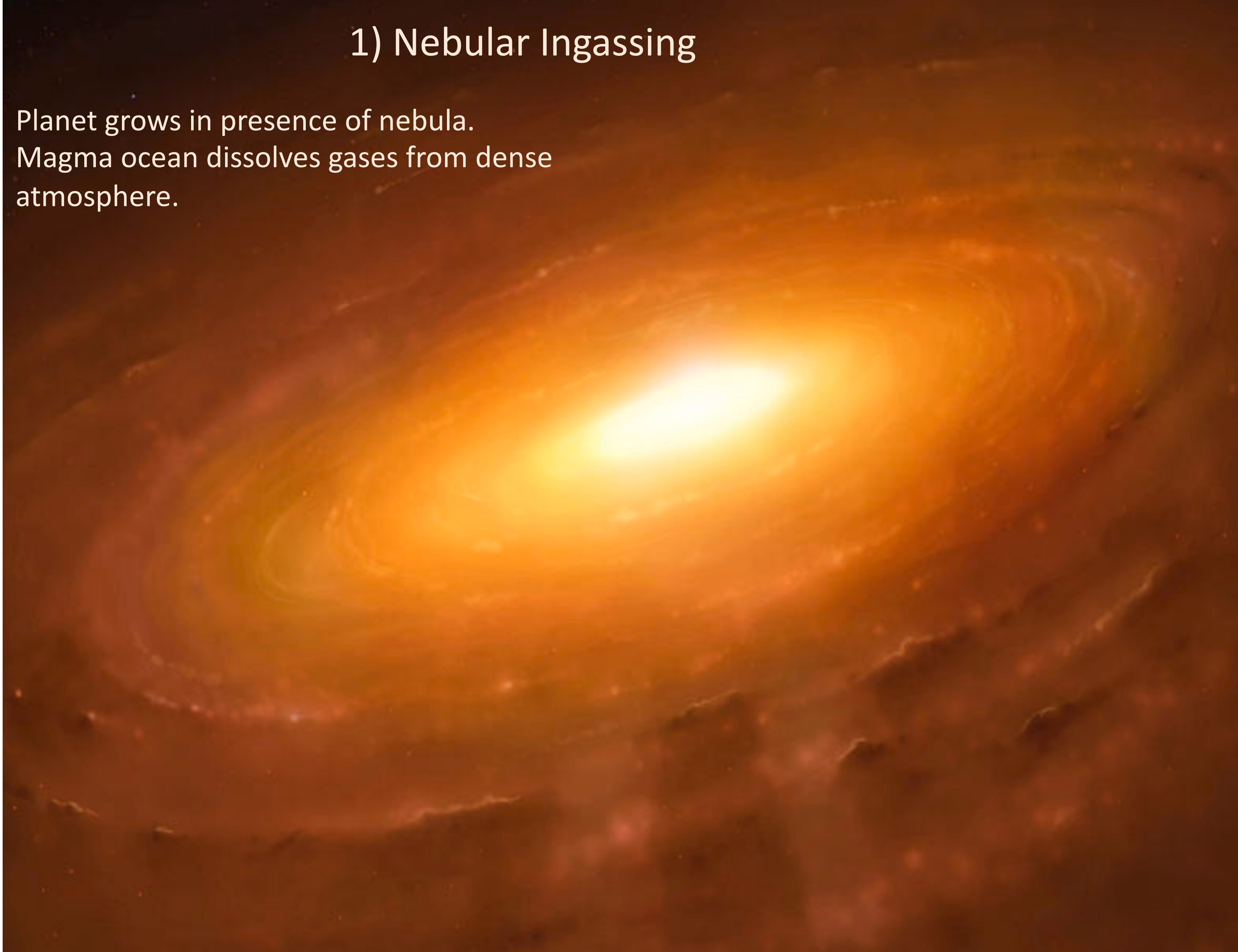
Ingassed ^{3}He
--exagrams (10^{18} g)




Our model for
volatiles to Earth

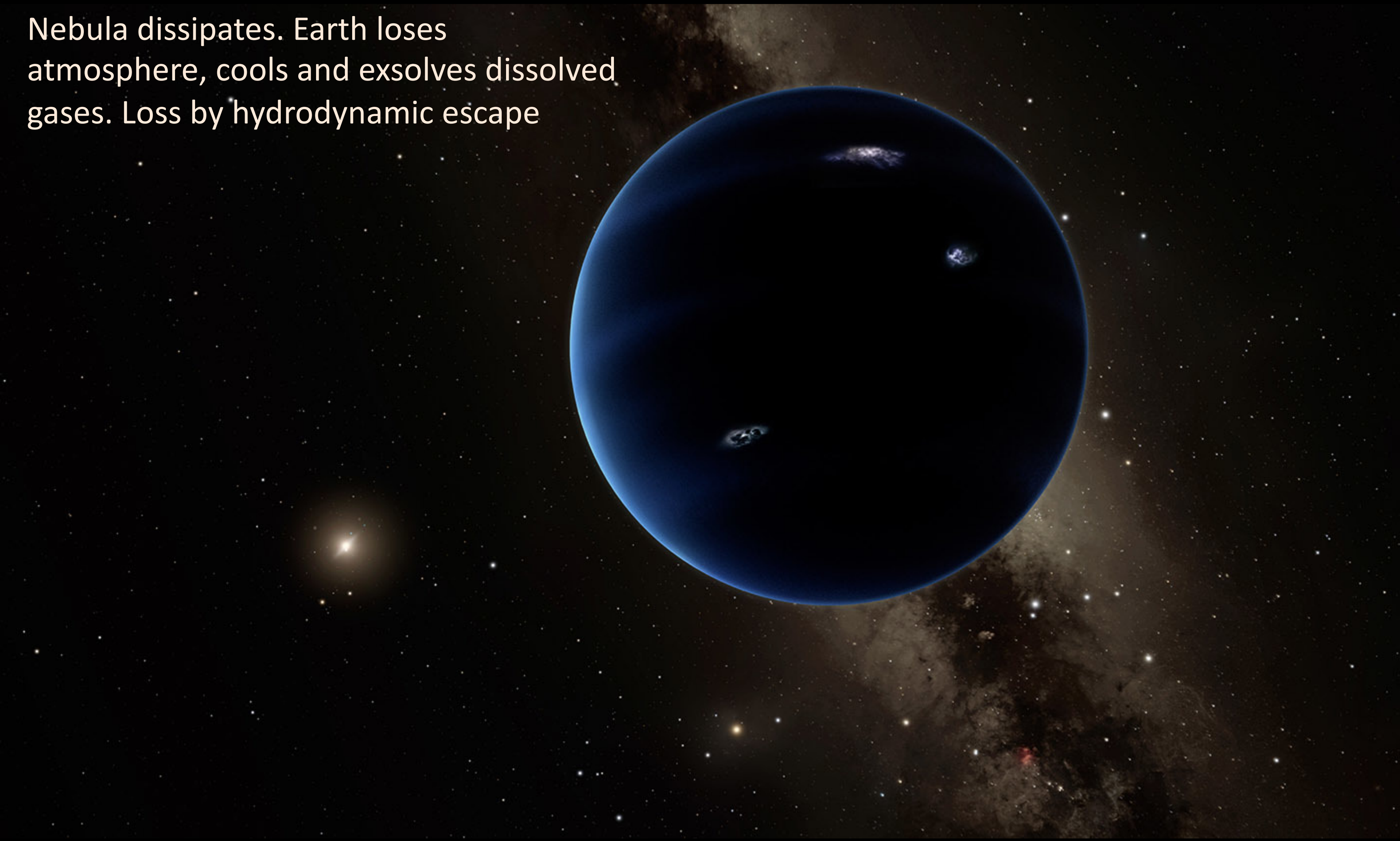
1) Nebular Ingassing

Planet grows in presence of nebula.
Magma ocean dissolves gases from dense atmosphere.



2) Loss by hydrodynamic escape

Nebula dissipates. Earth loses atmosphere, cools and exsolves dissolved gases. Loss by hydrodynamic escape



3) Late addition

Cometary and chondritic material is added following planetary differentiation and Moon forming event

4. Loss of Xe

Ionization of Xe in atmosphere leads to loss over Earth history

Simulation protocol

He, N, Ne, Ar, Kr, Xe

Nebular ingassing

- Composition is fixed
- ***Vary amount by 0.01, 0.1, 1x***

Hydrodynamic escape

- Loss follows log loss vs. atomic mass
- Best fit to modern values

Late addition (comets and chondrites)

- Fit to Kr/Xe ratios

Variables: ***1) comet composition***
2) chondrite composition (C vs E)
3) Xe loss

Balance for Kr/Xe ratio of Earth:

Inputs: Ingassing, comets, chondrites

Loss: Xe ionization

$$X_{Xe\text{-}ing} + x_{chon} C_{Xe\text{-}chon} + x_{com} C_{Xe\text{-}com} - X_{Xe\text{-}loss} = X_{Xe\text{-}Earth}$$

$$X_{Kr\text{-}ing} + x_{chon} C_{Kr\text{-}chon} + x_{com} C_{Kr\text{-}com} = X_{Kr\text{-}Earth}$$

The solution!?

$$X_{\mathbf{He}\text{-}ing} - X_{\mathbf{He}\text{-}hydrodynamic\ escape} + x_{chon} C_{\mathbf{He}\text{-}chon} + x_{com} C_{\mathbf{He}\text{-}com} = X_{\mathbf{He}\text{-}Earth}$$

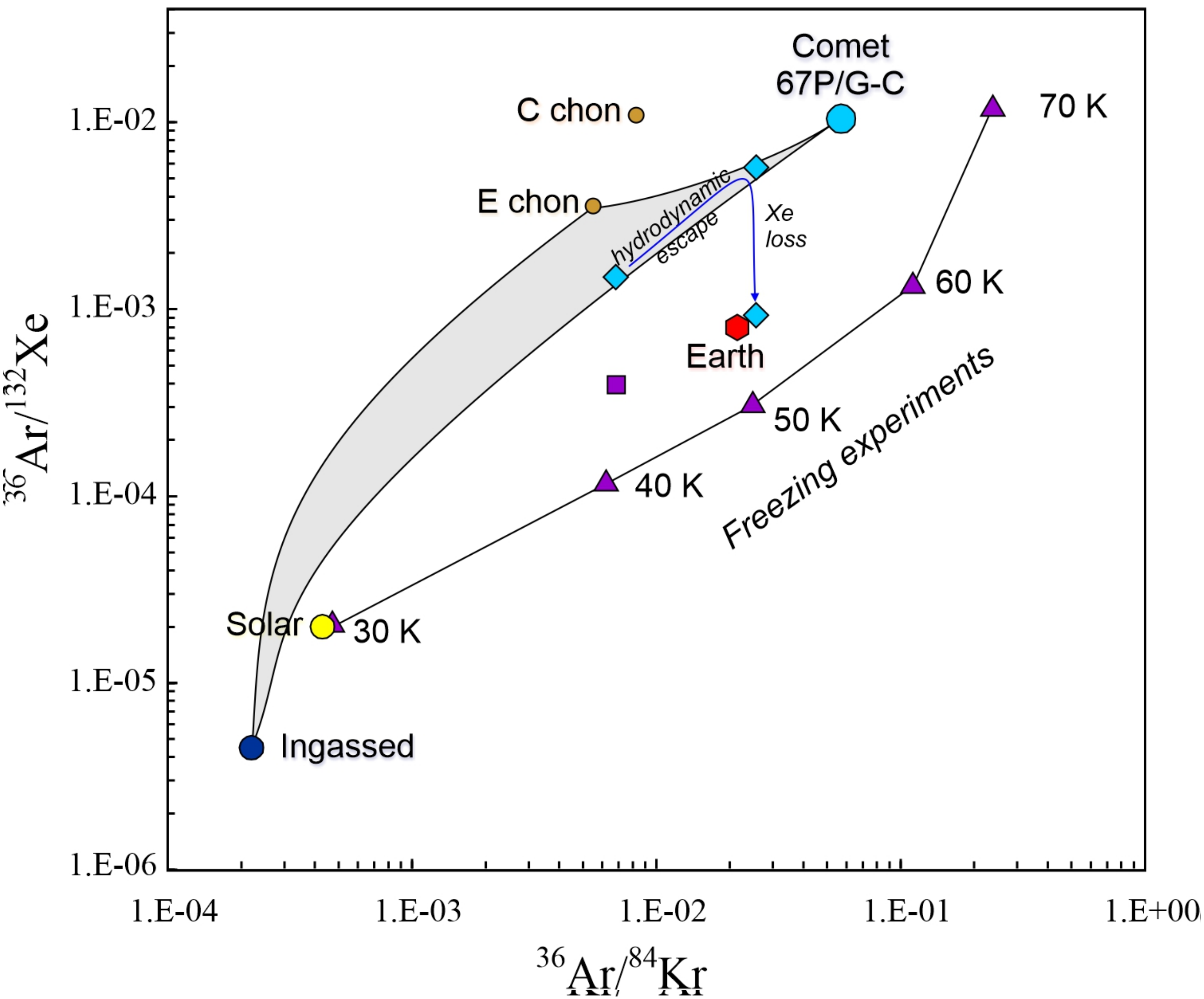
$$X_{\mathbf{N_2}\text{-}ing} - X_{\mathbf{N_2}\text{-}hydrodynamic\ escape} + x_{chon} C_{\mathbf{N_2}\text{-}chon} + x_{com} C_{\mathbf{N_2}\text{-}com} = X_{\mathbf{N_2}\text{-}Earth}$$

$$X_{\mathbf{Ne}\text{-}ing} - X_{\mathbf{Ne}\text{-}hydrodynamic\ escape} + x_{chon} C_{\mathbf{Ne}\text{-}chon} + x_{com} C_{\mathbf{Ne}\text{-}com} = X_{\mathbf{Ne}\text{-}Earth}$$

$$X_{\mathbf{Ar}\text{-}ing} - X_{\mathbf{Ar}\text{-}hydrodynamic\ escape} + x_{chon} C_{\mathbf{Ar}\text{-}chon} + x_{com} C_{\mathbf{Ar}\text{-}com} = X_{\mathbf{Ar}\text{-}Earth}$$

$$X_{\mathbf{Kr}\text{-}ing} - X_{\mathbf{Kr}\text{-}hydrodynamic\ escape} + x_{chon} C_{\mathbf{Kr}\text{-}chon} + x_{com} C_{\mathbf{Kr}\text{-}com} = X_{\mathbf{Kr}\text{-}Earth}$$

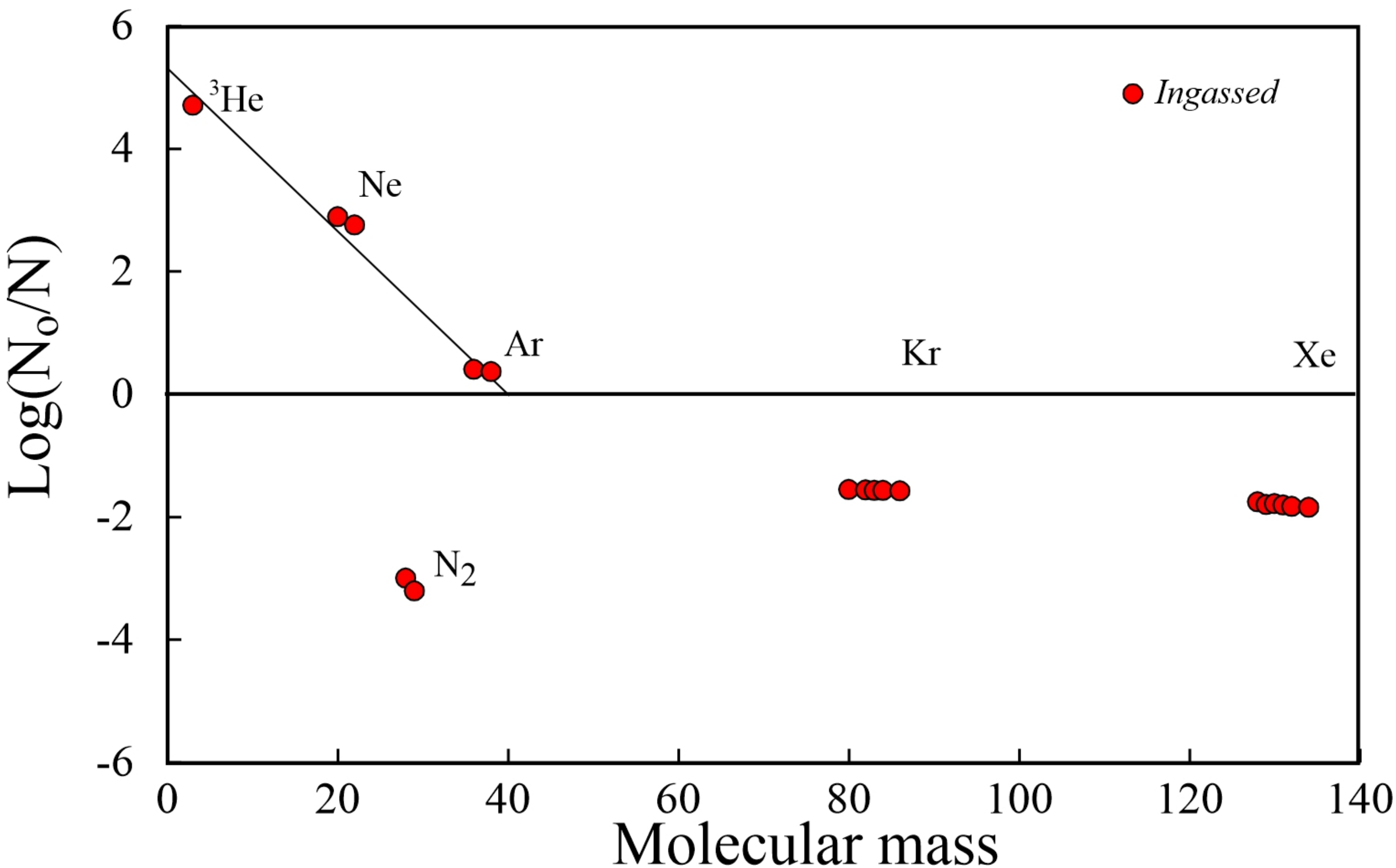
$$X_{\mathbf{Xe}\text{-}ing} - X_{\mathbf{Xe}\text{-}hydrodynamic\ escape} + x_{chon} C_{\mathbf{Xe}\text{-}chon} + x_{com} C_{\mathbf{Xe}\text{-}com} - X_{\mathbf{Xe}\text{-}ionized} = X_{\mathbf{Ar}\text{-}Earth}$$



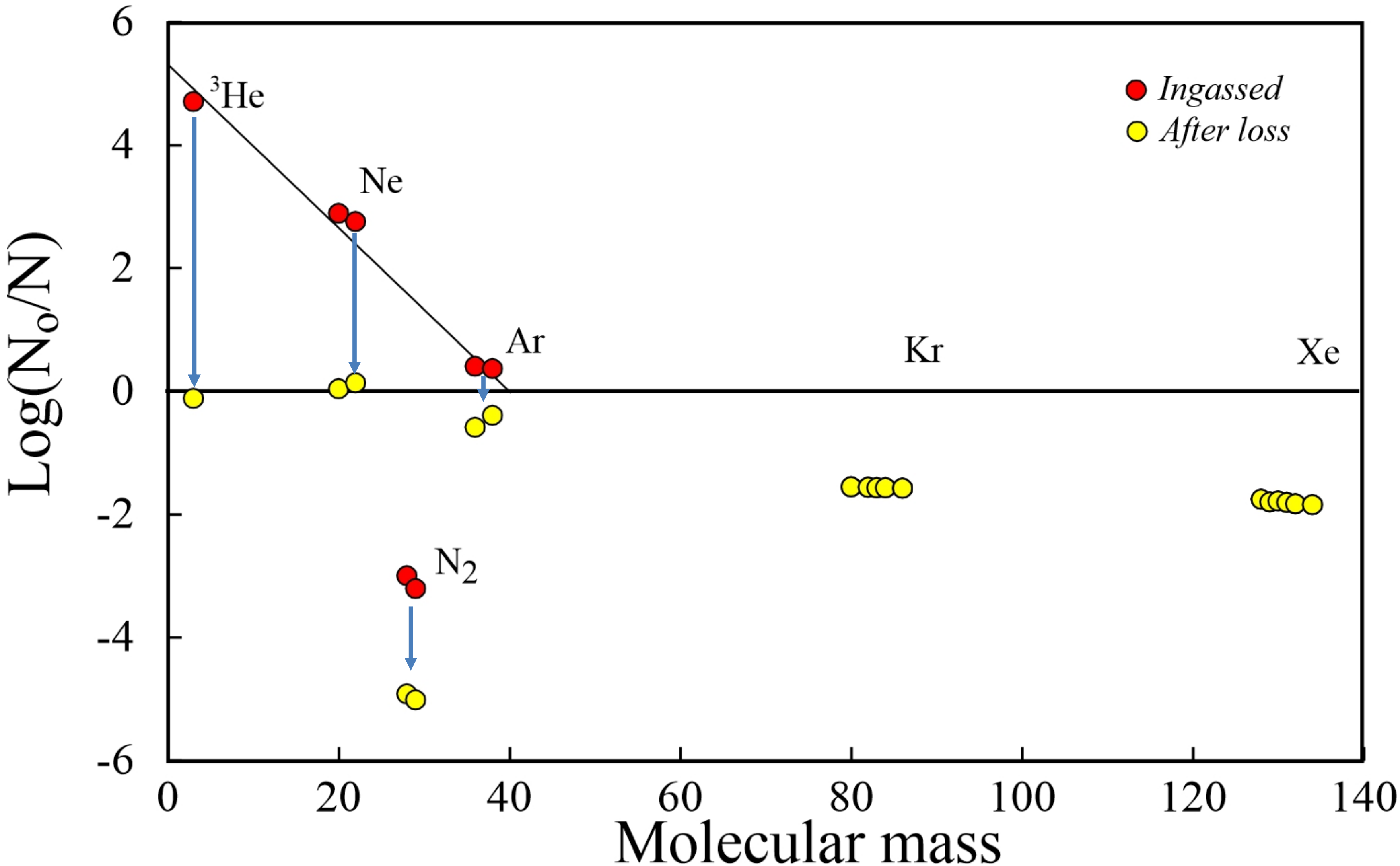
Comet
67P/G-C
C chon
E chon
hydrodynamic
escape
Xe
loss
70 K
60 K
50 K
40 K
30 K
Earth
Freezing experiments
Solar
Ingassed
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-04
1.E-03
1.E-02
1.E-01
1.E+00
$^{36}Ar/^{132}Xe$
$^{36}Ar/^{84}Kr$

Volatile species (ingassing)

10% C, 90% E chondrite, 100% ingas, 5x10^{11} g Xe lost

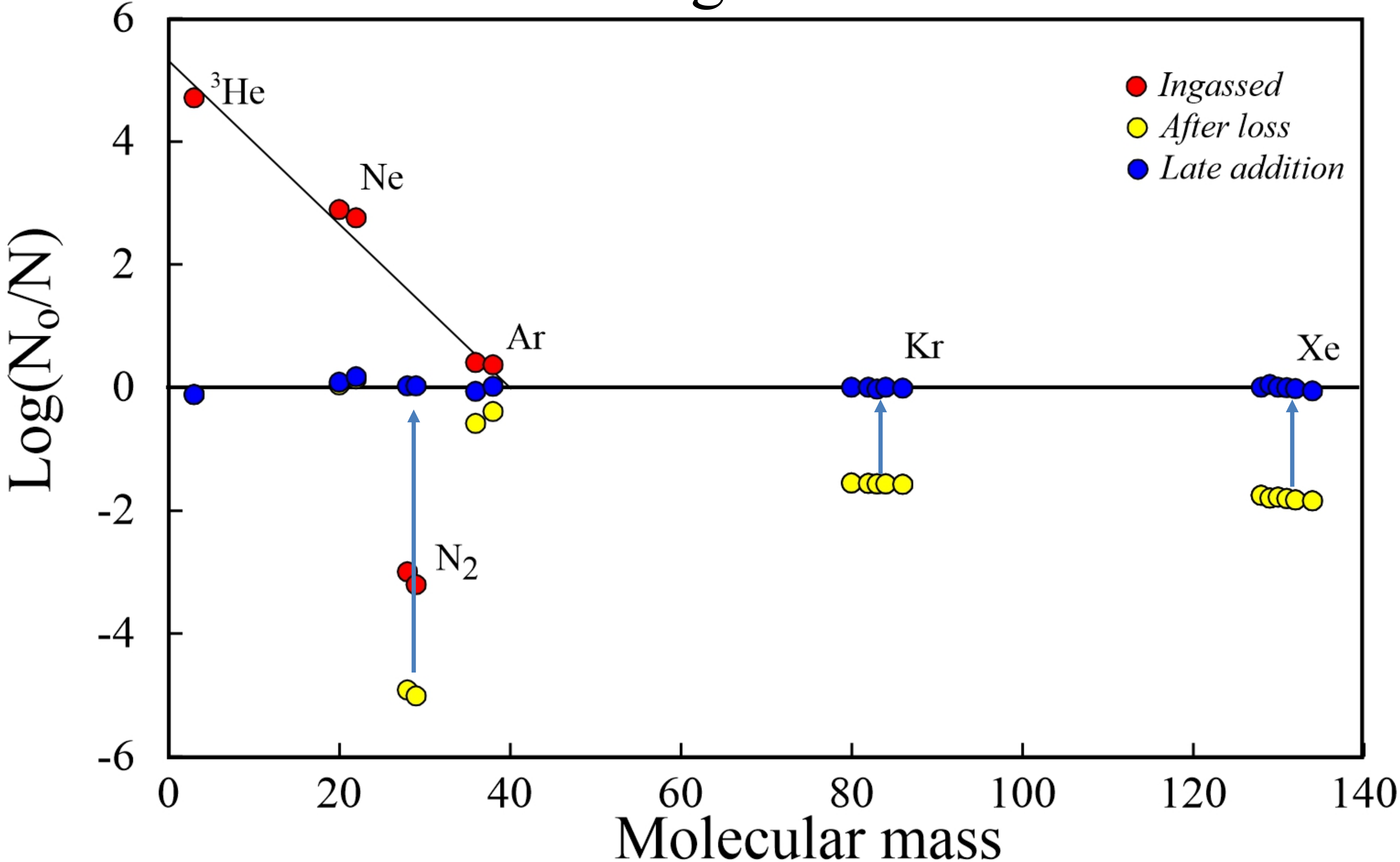


After hydrodynamic escape



With late addition

2.9×10^{21} g comet
3.63×10^{25} g chondrite



Results

Chon	Meas/Exp	loss	ingassing												9.78	5.3			
				S.E.	3	14	15	28	29	20	22	36	38	$\delta^{15}N$	20Ne/22N	36Ar/38Ar	Com	C chon	E chon
0.9 E 0.1 C	Exp	5.0E+11	1	0.09	-0.24	0.04	0.05	0.04	0.05	0.20	0.48	-0.15	0.04	1.01	7.919599	4.357301	2.82258E+21	3.61248E+24	3.25123E+25
0.9 E 0.1 C	Exp	5.0E+11	0.1	0.09	-0.23	0.05	0.05	0.05	0.05	0.19	0.46	-0.14	-0.12	1.20	7.937472	5.17343	2.89563E+21	3.62916E+24	3.26624E+25
C	Exp	1.0E+12	1	0.10	-0.27	0.09	0.11	0.09	0.11	0.24	0.54	-0.15	0.01	25.70	7.897913	4.439231	2.82241E+21	1.12101E+25	0
E	Exp	5.0E+11	0.1	0.09	-0.17	0.37	0.35	0.37	0.35	0.10	0.34	-0.12	0.01	-13.86	8.057423	4.615753	2.83752E+21	0	6.44057E+25
0.9 E 0.1 C	Measured	4.0E+12	1	0.10	-0.26	0.12	0.13	0.12	0.13	0.22	0.54	-0.17	0.04	9.35	7.770571	4.224157	9.14108E+21	3.82102E+24	3.43892E+25
0.9 E 0.1 C	Measured	4.0E+12	0.1	0.11	-0.26	0.00	0.01	0.00	0.01	0.23	0.55	-0.22	-0.20	12.17	7.756389	5.189223	9.44682E+21	3.39688E+24	3.05719E+25
E	Exp	5.0E+11	1	0.09	-0.18	0.37	0.35	0.37	0.35	0.12	0.36	-0.13	0.06	-14.01	8.033549	4.363272	2.76473E+21	0	6.41097E+25
C	Exp	1.0E+12	0.1	0.11	-0.27	0.09	0.12	0.09	0.12	0.24	0.53	-0.18	-0.21	25.90	7.913589	5.488139	2.89573E+21	1.1244E+25	0
C	Measured	4.5E+12	1	0.11	-0.29	0.13	0.17	0.13	0.17	0.27	0.60	-0.18	0.01	33.88	7.753524	4.300016	9.15348E+21	1.1597E+25	0
0.9 E 0.1 C	Exp	5.0E+11	0.01	0.11	-0.23	0.05	0.05	0.05	0.05	0.19	0.46	-0.37	-0.33	1.22	7.939287	5.008645	2.90294E+21	3.63083E+24	3.26775E+25
E	Measured	4.0E+12	0.1	0.11	-0.21	0.43	0.42	0.43	0.42	0.14	0.42	-0.15	-0.05	-7.06	7.876137	4.737367	9.19479E+21	0	6.67323E+25
E	Exp	5.0E+11	0.01	0.11	-0.17	0.37	0.35	0.37	0.35	0.10	0.34	-0.28	-0.20	-13.84	8.059867	4.754894	2.8448E+21	0	6.44354E+25
C	Exp	5.0E+11	1	0.13	-0.28	-0.29	-0.26	-0.29	-0.26	0.26	0.58	-0.17	0.01	30.58	7.833861	4.349304	2.88211E+21	7.32955E+24	0
C	Measured	4.5E+12	0.1	0.13	-0.29	0.06	0.10	0.06	0.10	0.27	0.60	-0.26	-0.28	35.63	7.75	5.50	9.43262E+21	1.08E+25	0.00E+00
E	Exp	0.0E+00	1	0.12	-0.26	-0.35	-0.35	-0.35	-0.35	0.22	0.52	-0.17	0.03	-5.40	7.843948	4.269673	2.88658E+21	0	3.01671E+25
0.9 E 0.1 C	Measured	4.0E+12	0.01	0.14	-0.26	-0.02	0.00	-0.02	0.00	0.23	0.55	-0.45	-0.41	12.50	7.754987	4.986894	9.47739E+21	3.35447E+24	3.01902E+25
0.9 E 0.1 C	Exp	1.0E+12	0.1	0.12	-0.18	0.60	0.59	0.60	0.59	0.12	0.35	-0.11	-0.01	-2.30	8.083448	4.735116	2.80442E+21	5.54177E+24	4.98759E+25
C	Measured	4.0E+12	1	0.14	-0.29	-0.30	-0.27	-0.30	-0.27	0.29	0.64	-0.20	0.01	45.16	7.683244	4.189412	9.38076E+21	7.05152E+24	0
E	Exp	0.0E+00	0.1	0.12	-0.25	-0.34	-0.35	-0.34	-0.35	0.21	0.51	-0.19	-0.17	-5.17	7.86045	5.204111	2.95936E+21	0	3.04632E+25
0.9 E 0.1 C	Exp	1.0E+12	1	0.12	-0.19	0.59	0.59	0.59	0.59	0.13	0.37	-0.12	0.05	-2.44	8.060501	4.444769	2.73137E+21	5.52508E+24	4.97258E+25
C	Exp	1.0E+12	0.01	0.14	-0.26	0.09	0.12	0.09	0.12	0.24	0.53	-0.41	-0.42	25.92	7.915177	5.386714	2.90307E+21	1.12474E+25	0
E	Measured	4.0E+12	1	0.12	-0.19	0.61	0.59	0.61	0.59	0.12	0.38	-0.14	0.07	-9.06	7.914449	4.259566	8.85758E+21	0	7.50645E+25
C	Exp	5.0E+11	0.1	0.13	-0.27	-0.28	-0.26	-0.28	-0.26	0.26	0.57	-0.23	-0.25	30.86	7.848378	5.500724	2.95543E+21	7.3634E+24	0
E	Measured	4.0E+12	0.01	0.13	-0.21	0.42	0.41	0.42	0.41	0.14	0.42	-0.35	-0.26	-6.83	7.872505	4.68695	9.22851E+21	0	6.5899E+25
C	Measured	4.5E+12	0.01	0.15	-0.28	0.05	0.09	0.05	0.09	0.27	0.60	-0.48	-0.49	35.82	7.749813	5.386223	9.46053E+21	1.0736E+25	0
0.9 E 0.1 C	Exp	0.0E+00	1	0.15	-0.27	-0.50	-0.50	-0.50	-0.50	0.25	0.57	-0.18	0.02	12.03	7.80722	4.264483	2.9138E+21	1.69987E+24	1.52988E+25
0.9 E 0.1 C	Exp	1.0E+12	0.01	0.14	-0.18	0.60	0.59	0.60	0.59	0.12	0.35	-0.28	-0.22	-2.29	8.085792	4.882441	2.81172E+21	5.54344E+24	4.98909E+25
	Measured	5.0E+12	1	0.14	-0.28	0.57	0.61	0.57	0.61	0.25	0.56	-0.16	0.01	28.86	7.828492	4.409385	8.92621E+21	1.61424E+25	0
E	Exp	0.0E+00	0.01	0.14	-0.25	-0.34	-0.35	-0.34	-0.35	0.21	0.51	-0.41	-0.38	-5.14	7.862124	5.013262	2.96664E+21	0	3.04928E+25
E	Exp	1.0E+12	1	0.20	0.06	1.08	1.05	1.08	1.05	-0.08	0.07	-0.10	0.07	-16.70	8.41634	4.454847	2.64289E+21	0	9.80522E+25
0.9 E 0.1 C	Exp	0.0E+00	0.1	0.15	-0.27	-0.50	-0.49	-0.50	-0.49	0.25	0.56	-0.23	-0.23	12.34	7.822098	5.344764	2.98685E+21	1.71655E+24	1.5449E+25

Chon	Meas/Exp	loss	ingassing						
				S.E.	3	14	15	28	29
0.9 E 0.1 C	Exp	5.0E+11	1	0.09	-0.24	0.04	0.05	0.04	0.05
0.9 E 0.1 C	Exp	5.0E+11	0.1	0.09	-0.23	0.05	0.05	0.05	0.05
C	Exp	1.0E+12	1	0.10	-0.27	0.09	0.11	0.09	0.11
E	Exp	5.0E+11	0.1	0.09	-0.17	0.37	0.35	0.37	0.35
0.9 E 0.1 C	Measured	4.0E+12	1	0.10	-0.26	0.12	0.13	0.12	0.13
0.9 E 0.1 C	Measured	4.0E+12	0.1	0.11	-0.26	0.00	0.01	0.00	0.01
E	Exp	5.0E+11	1	0.09	-0.18	0.37	0.35	0.37	0.35
C	Exp	1.0E+12	0.1	0.11	-0.27	0.09	0.12	0.09	0.12
C	Measured	4.5E+12	1	0.11	-0.29	0.13	0.17	0.13	0.17
0.9 E 0.1 C	Exp	5.0E+11	0.01	0.11	-0.23	0.05	0.05	0.05	0.05
E	Measured	4.0E+12	0.1	0.11	-0.21	0.43	0.42	0.43	0.42
E	Exp	5.0E+11	0.01	0.11	-0.17	0.37	0.35	0.37	0.35
C	Exp	5.0E+11	1	0.13	-0.28	-0.29	-0.26	-0.29	-0.26
C	Measured	4.5E+12	0.1	0.13	-0.29	0.06	0.10	0.06	0.10
E	Exp	0.0E+00	1	0.12	-0.26	-0.35	-0.35	-0.35	-0.35
0.9 E 0.1 C	Measured	4.0E+12	0.01	0.14	-0.26	-0.02	0.00	-0.02	0.00
0.9 E 0.1 C	Exp	1.0E+12	0.1	0.12	-0.18	0.60	0.59	0.60	0.59
C	Measured	4.0E+12	1	0.14	-0.29	-0.30	-0.27	-0.30	-0.27
E	Exp	0.0E+00	0.1	0.12	-0.25	-0.34	-0.35	-0.34	-0.35
0.9 E 0.1 C	Exp	1.0E+12	1	0.12	-0.19	0.59	0.59	0.59	0.59
C	Exp	1.0E+12	0.01	0.14	-0.26	0.09	0.12	0.09	0.12
E	Measured	4.0E+12	1	0.12	-0.19	0.61	0.59	0.61	0.59
C	Exp	5.0E+11	0.1	0.13	-0.27	-0.28	-0.26	-0.28	-0.26

COSMOCHEMISTRY

Xenon isotopes in 67P/Churyumov-Gerasimenko show that comets contributed to Earth's atmosphere

B. Marty,[1*] K. Altwegg,[2,3] H. Balsiger,[2] A. Bar-Nun,[4†] D. V. Bekaert,[1] J.-J. Berthelier,[5] A. Bieler,[2,6] C. Briois,[7] U. Calmonte,[2] M. Combi,[6] J. De Keyser,[8] B. Fiethe,[9] S. A. Fuselier,[10] S. Gasc,[2] T. I. Gombosi,[6] K. C. Hansen,[6] M. Hässig,[2,10] A. Jäckel,[2] E. Kopp,[2] A. Korth,[11] L. Le Roy,[2] U. Mall,[11] O. Mousis,[12] T. Owen,[13†] H. Rème,[14] M. Rubin,[2] T. Sémon,[2] C.-Y. Tzou,[2] J. H. Waite,[10] P. Wurz[2]

The origin of cometary matter and the potential contribution of comets to inner-planet atmospheres are long-standing problems. During a series of dedicated low-altitude orbits, the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) on the Rosetta spacecraft analyzed the isotopes of xenon in the coma of comet 67P/Churyumov-Gerasimenko. The xenon isotopic composition shows deficits in heavy xenon isotopes and matches that of a primordial atmospheric component. The present-day Earth atmosphere contains 22 ± 5% cometary xenon, in addition to chondritic (or solar) xenon.

were measured
Spectrometer (D
trometer for Ion
instrument sui
DFMS is a high-
divided by cha
height at a ma
measured gases
Gerasimenko (6
mation of ice (
carried out durin
orbits, between
ter of mass, fron
of the high resol
of 129, 131, 132,
free of interfer
confirmed by t
interference pre
at mass/charge
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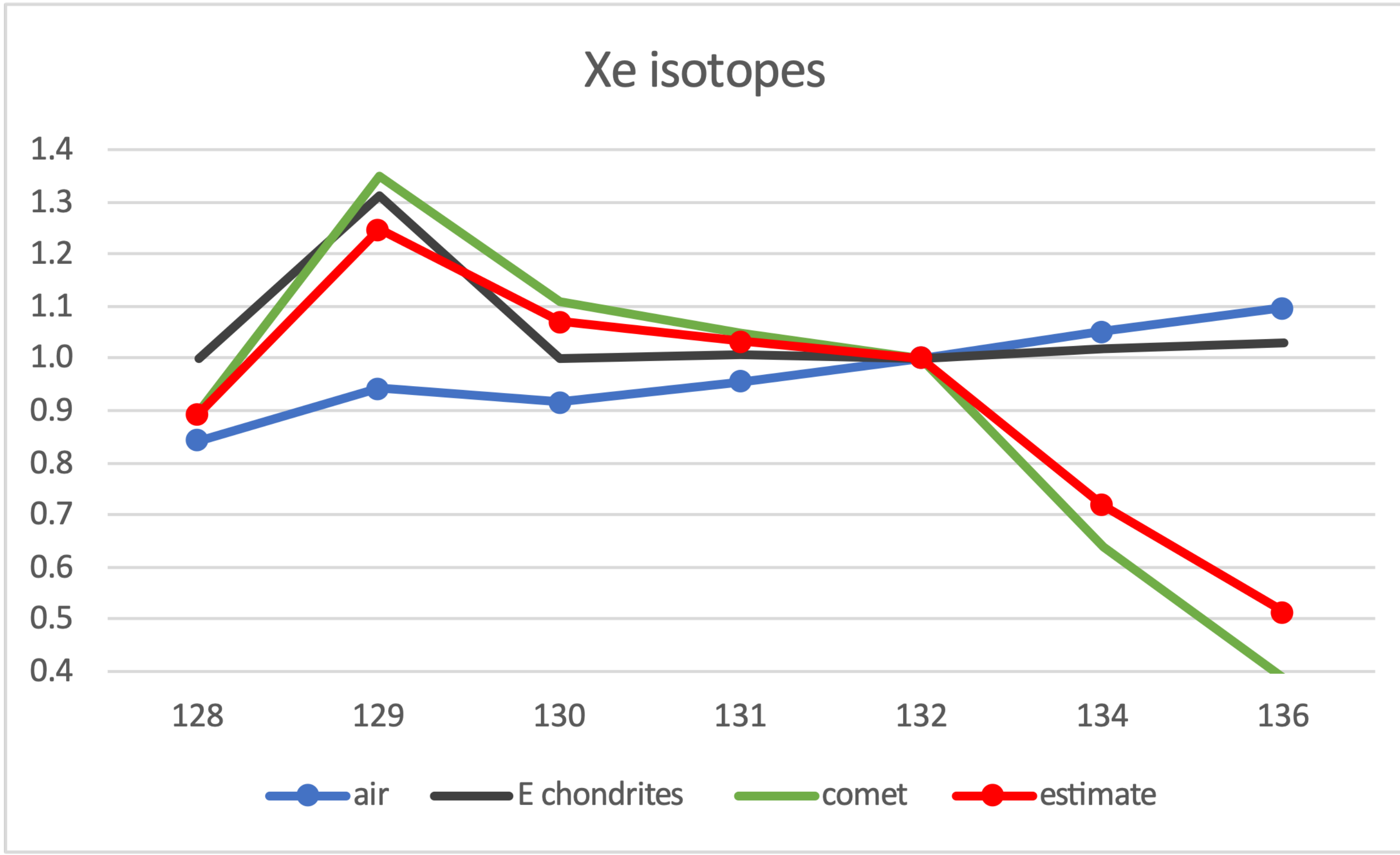
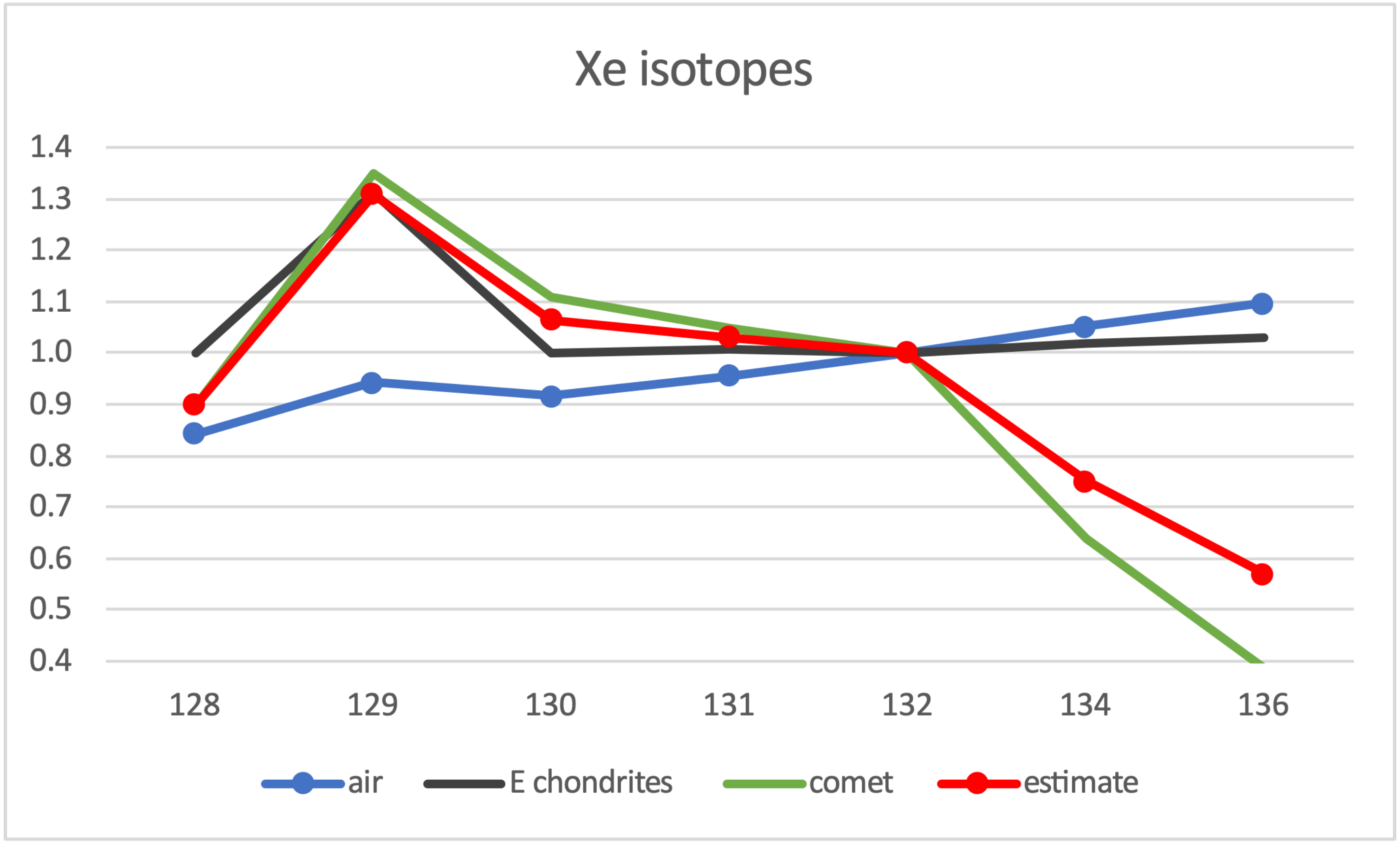
a few percent a
S_4^+-containing
erage Xe isoto
database, with
1 standard devia

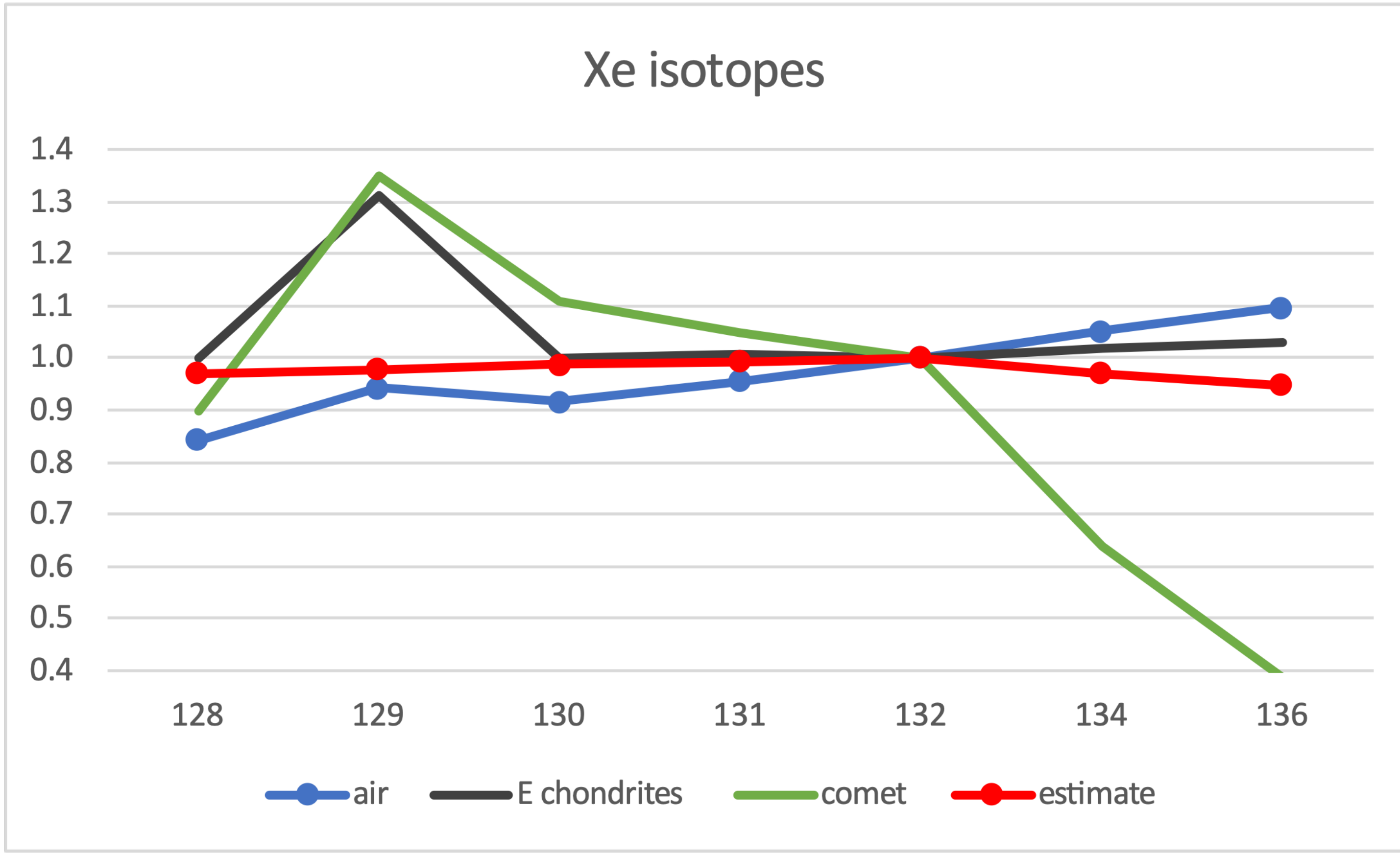
Measured cometary abundances and isotope ratios, C chondrite



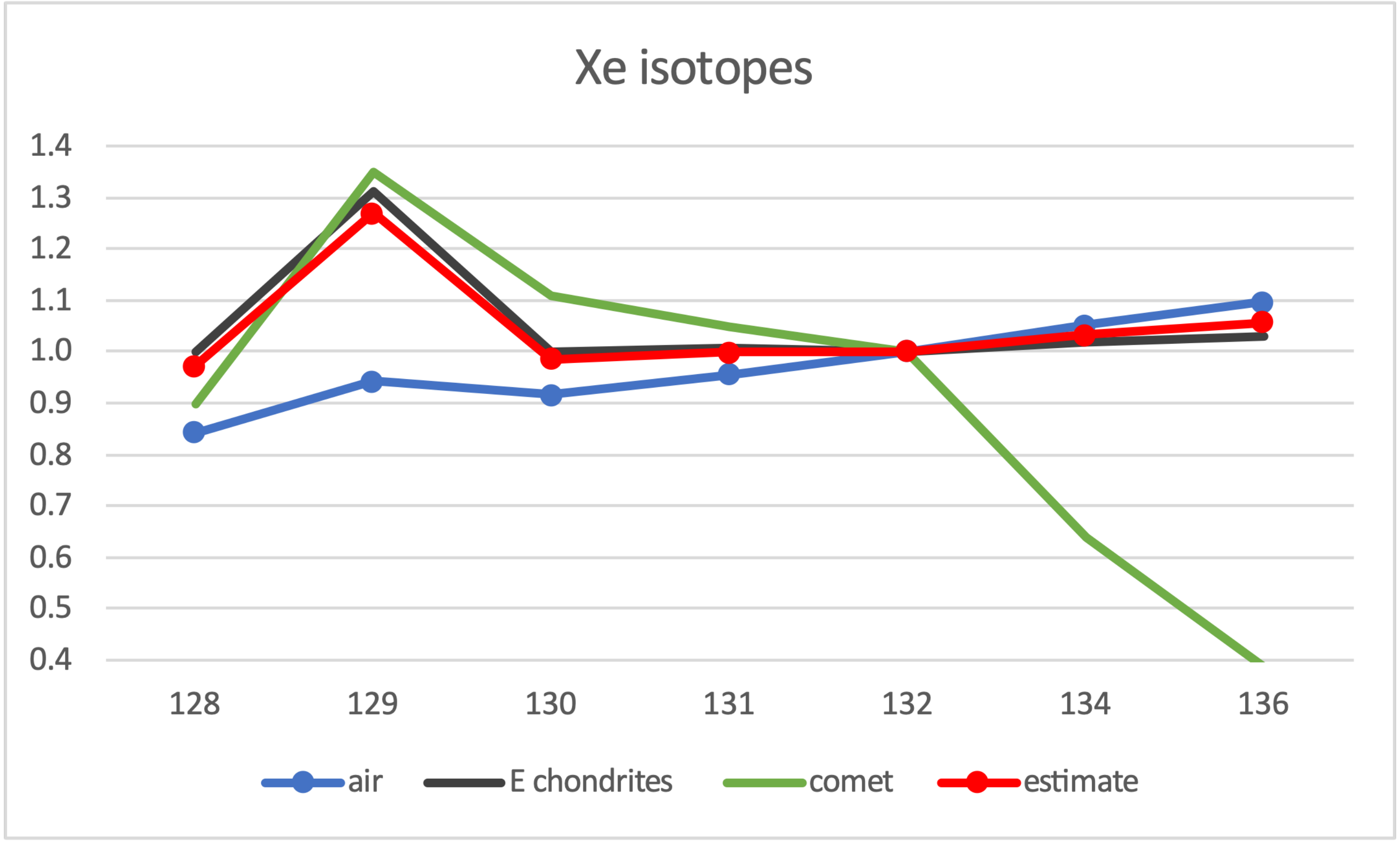
Measured cometary abundances and isotope ratios, E chondrite



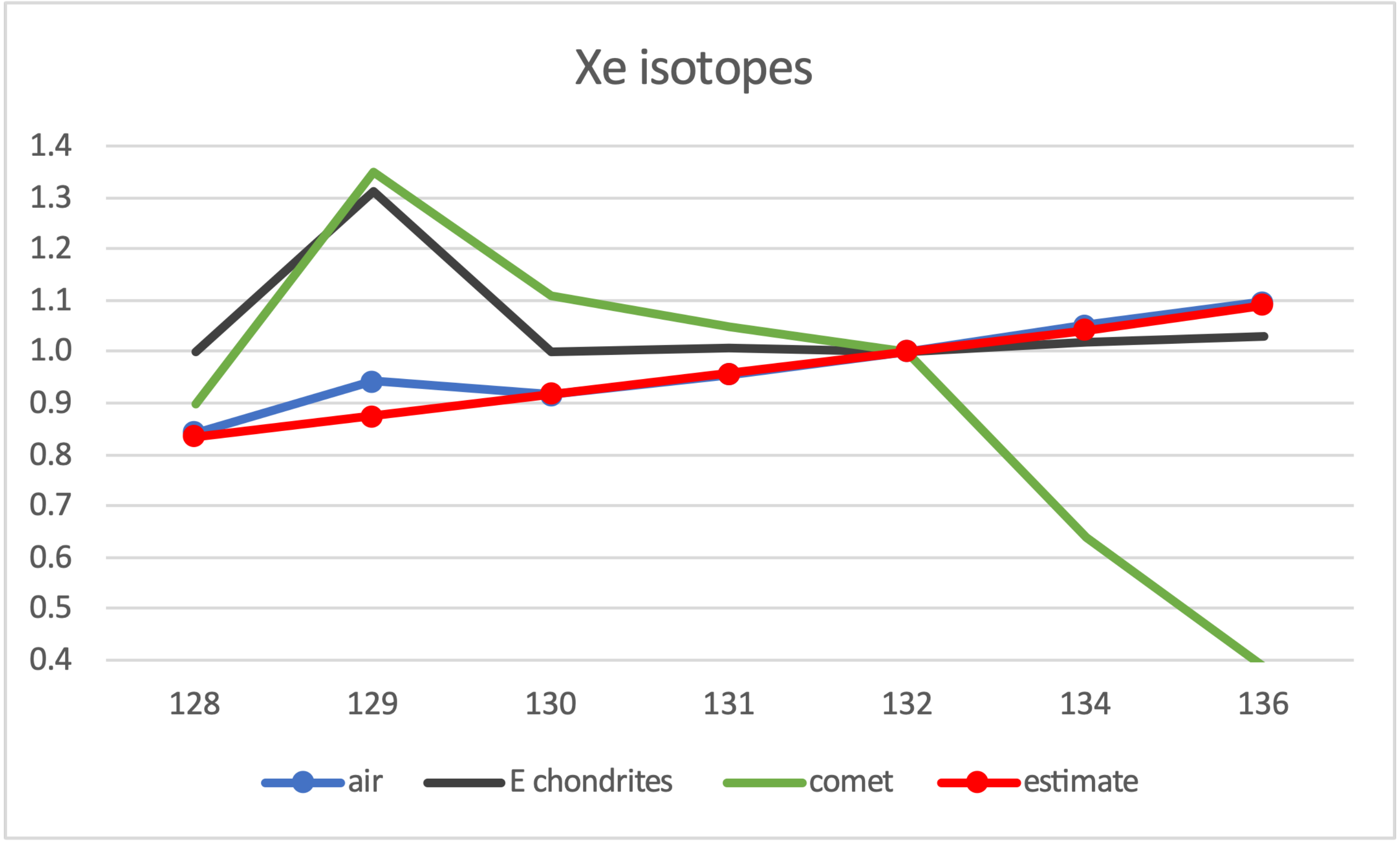
Experimental cometary abundances and solar isotope ratios, C chondrite



Experimental cometary abundances and solar isotope ratios, E chondrite



Experimental cometary abundances and solar isotope ratios, C chondrite, Extreme mass dependent isotope fractionation



Ready for Krypton?

SCIENCE ADVANCES | RESEARCH ARTICLE

PLANETARY SCIENCE

Krypton isotopes and noble gas abundances in the coma of comet 67P/Churyumov-Gerasimenko

Martin Rubin[1*], Kathrin Altwegg[1,2], Hans Balsiger[1], Akiva Bar-Nun[3†], Jean-Jacques Berthelier[4], Christelle Briois[5], Ursina Calmonte[1], Michael Combi[6], Johan De Keyser[7], Björn Fiethe[8], Stephen A. Fuselier[9,10], Sebastien Gasc[1], Tamas I. Gombosi[6], Kenneth C. Hansen[6], Ernest Kopp[1], Axel Korth[11], Diana Laufer[3], Léna Le Roy[1], Urs Mall[11], Bernard Marty[12], Olivier Mousis[13], Tobias Owen[14†], Henri Rème[15,16], Thierry Sémon[1], Chia-Yu Tzou[1], Jack H. Waite[8], Peter Wurz[1,2]

The Rosetta Orbiter Spectrometer for Ion and Neutral Analysis mass spectrometer Double Focusing Mass Spectrometer on board the European Space Agency's Rosetta spacecraft detected the major isotopes of the noble gases argon, krypton, and xenon in the coma of comet 67P/Churyumov-Gerasimenko. Earlier, it was found that xenon exhibits an isotopic composition distinct from anywhere else in the solar system. However, argon isotopes, within error, were shown to be consistent with solar isotope abundances. This discrepancy suggested an additional exotic component of xenon in comet 67P/Churyumov-Gerasimenko. We show that krypton also exhibits an isotopic composition close to solar. Furthermore, we found the argon to krypton and the krypton to xenon ratios in the comet to be lower than solar, which is a necessity to postulate an addition of exotic xenon in the comet.

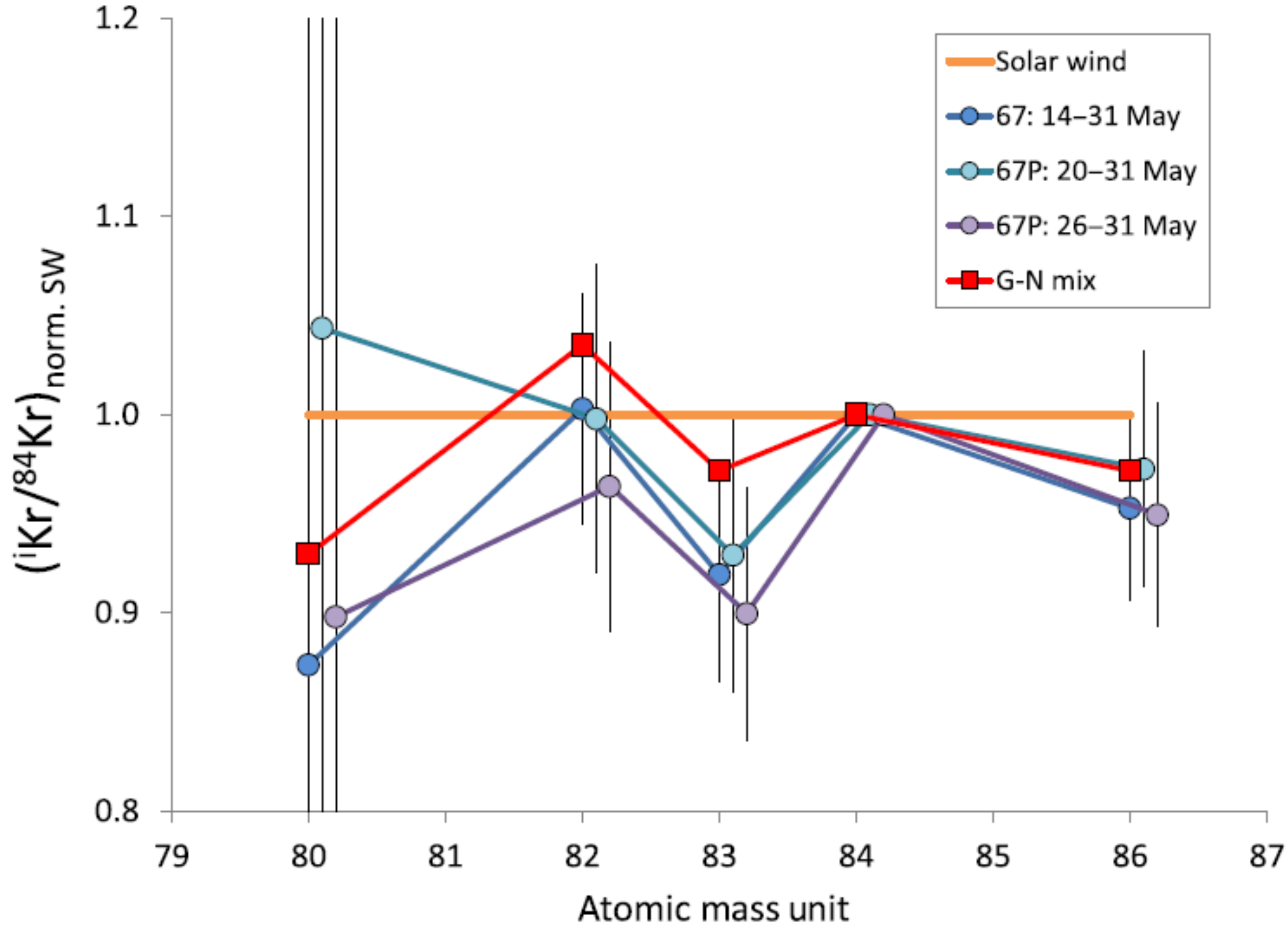
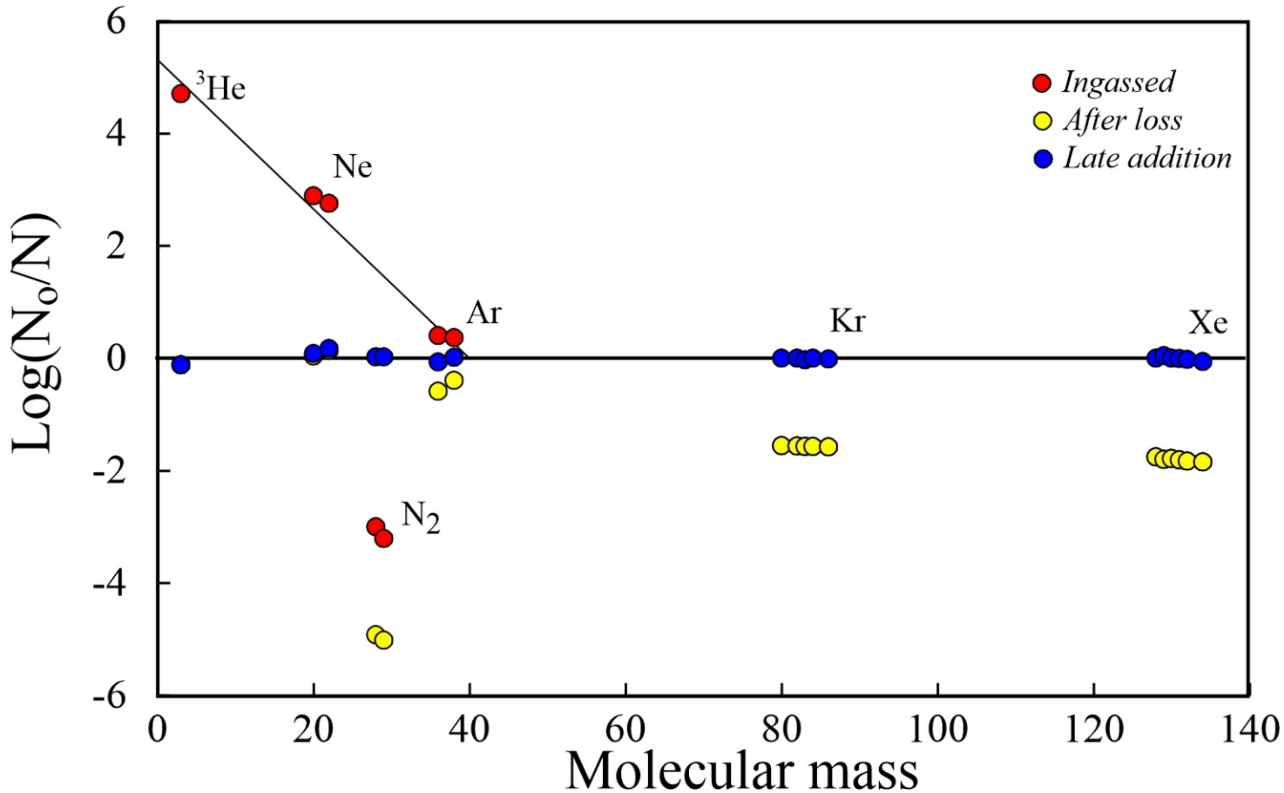


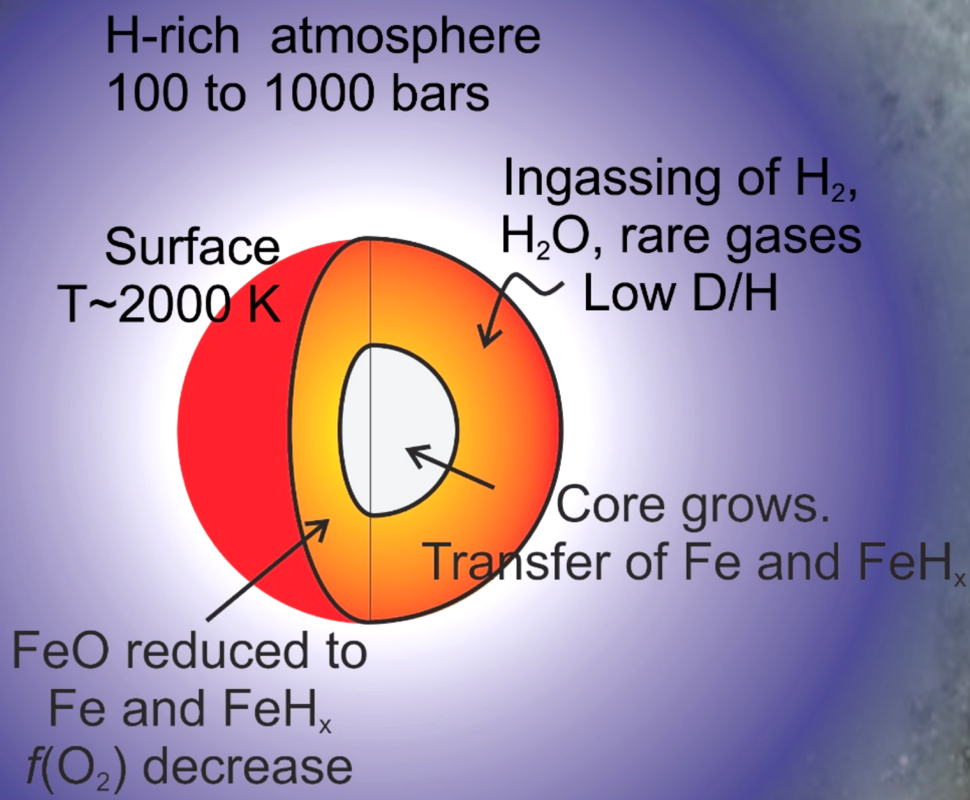
Fig. 1. Isotopic composition of 67P/C-G krypton, normalized to ^{84}Kr and the SW composition [from (*18*)]. 67P/C-G errors reflect 1-σ SEM and calibration uncertainties for the corresponding averaging periods. In this format, SW-Kr is represented by the horizontal orange line. ^{83}Kr appears to be slightly depleted relative to solar. The red line represents a mix of different nucleosynthetic components [the so-called G-Kr and N-Kr components; (*11*, *20*)]. For the G-Kr composition, we consider the weak s-process composition having low ^{86}Kr/^{84}Kr ratios (*20*). The best fit was obtained for a proportion of 5% G-Kr in cometary krypton.

Results

1. The vast majority of He, Ne and Ar were supplied by nebular ingassing.
2. 3×10^{21} g of comet and 4×10^{25} g (90% NC, 10% CC) chondrite were supplied to Earth
3. Kr was almost entirely supplied by comets
4. 98% of N_2 and >80% of Xe was supplied by chondrites.
5. Nitrogen isotope ratios balance, but nitrogen isotope compositions require a predominantly E chondrite source.
   (This is supported by isotope systems: $^{187}Os/^{188}Os$, $\varepsilon^{100}Ru$, $\varepsilon^{50}Ti$, $\varepsilon^{54}Cr$).
6. Xe and Kr isotopes do not work if measured comet values are used.



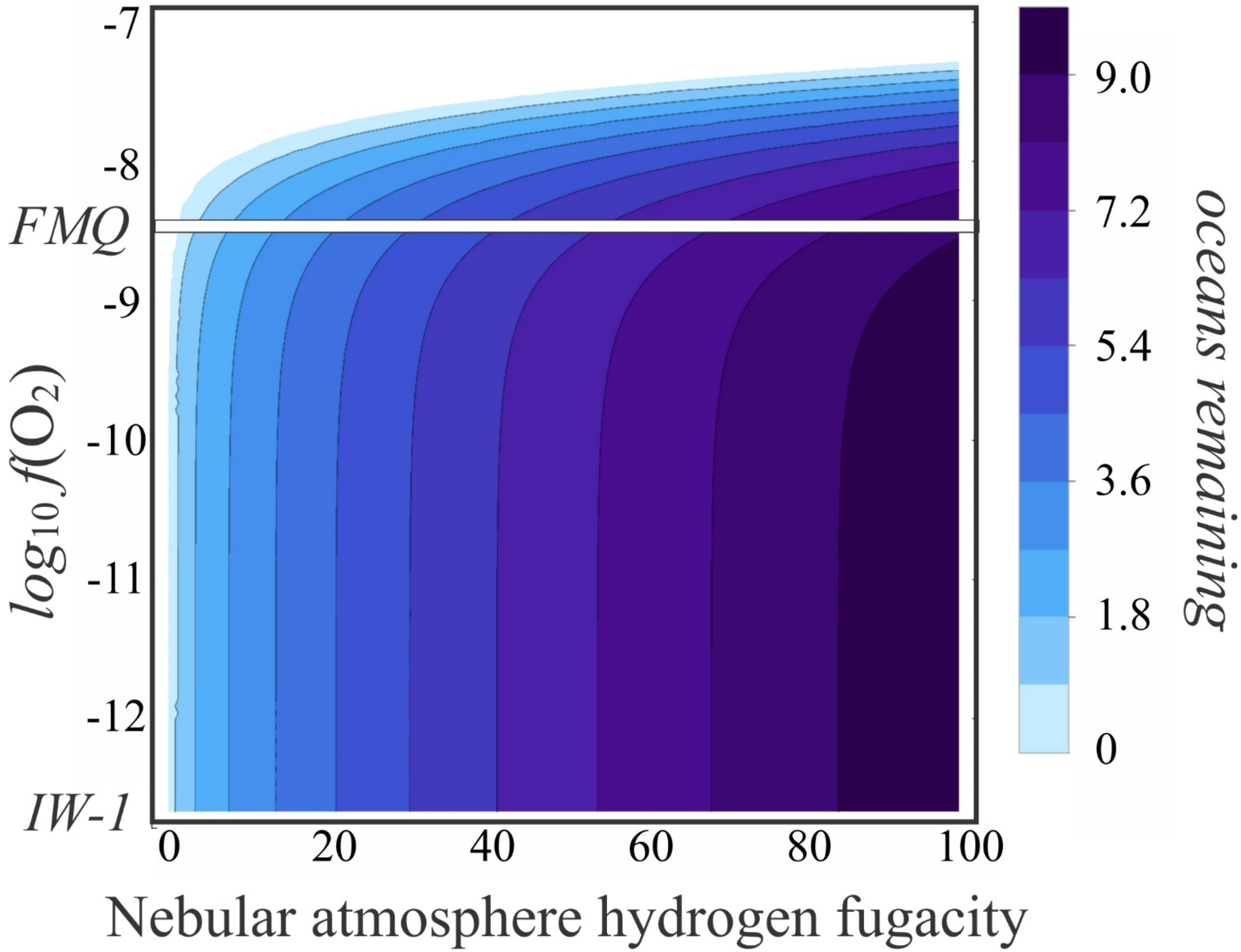
0-10 My: Early H-rich atmosphere in presence of solar nebula



Planet is not yet full-size. Core grows due to FeO reduction

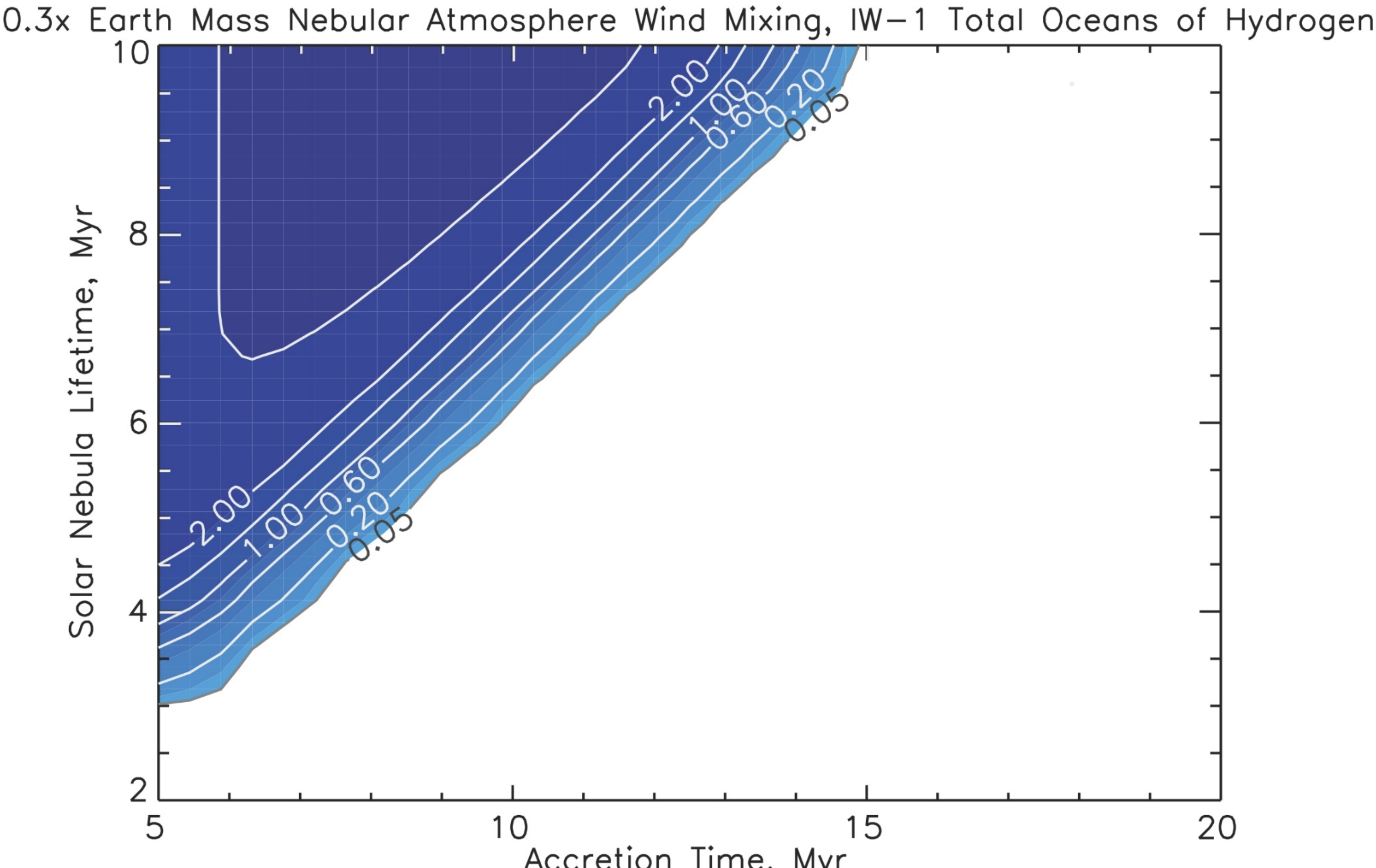
Loss of H_2 raises $f(O_2)$ from IW-1 to FMQ.

- The reaction $H_2O \to H_2 + ½\ O_2$ (H_2O/H_2 increases)
- $Fe^{2+}O + ½O_2 = Fe^{3+}O_{1.5}$
- Oxidation of Fe^{2+} to Fe^{3+} (Fe^{3+}/Fe^{2+} increases)

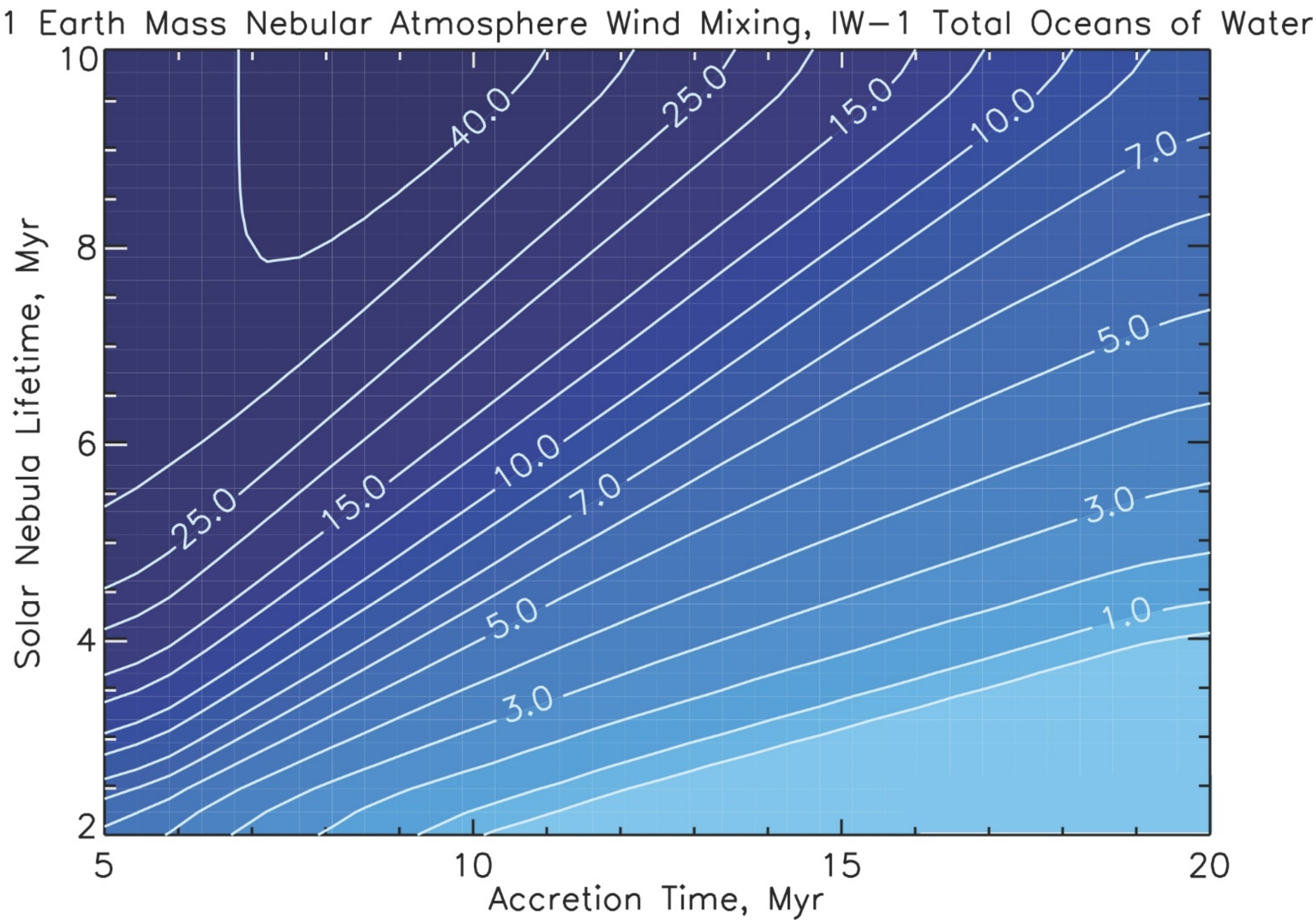


Loss of 1 ocean's worth of hydrogen raises the $f(O_2)$ from IW-1 to FMQ

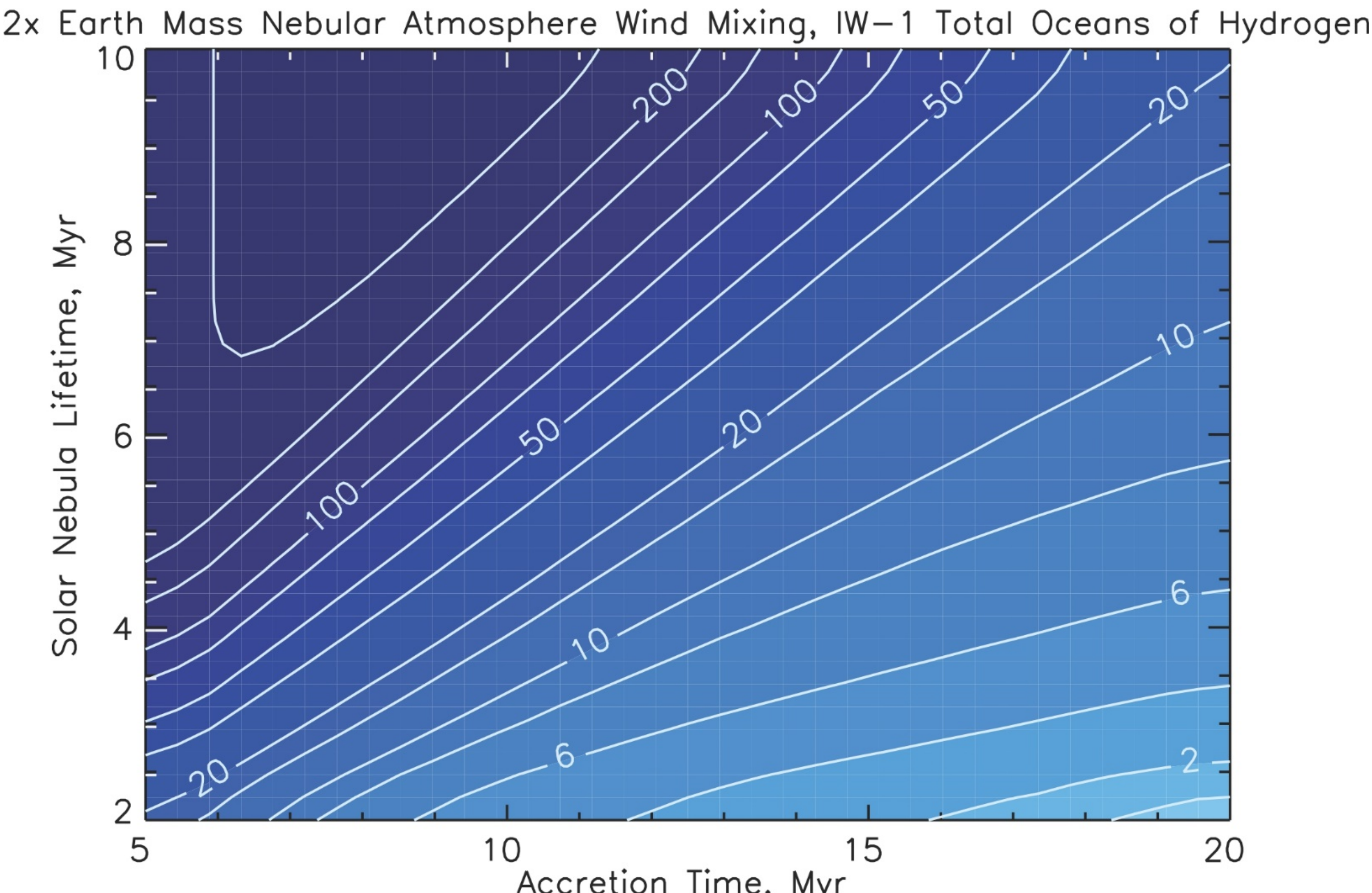
Mars Magma Ocean H_2 Ingassing;
Ocean mass equivalents



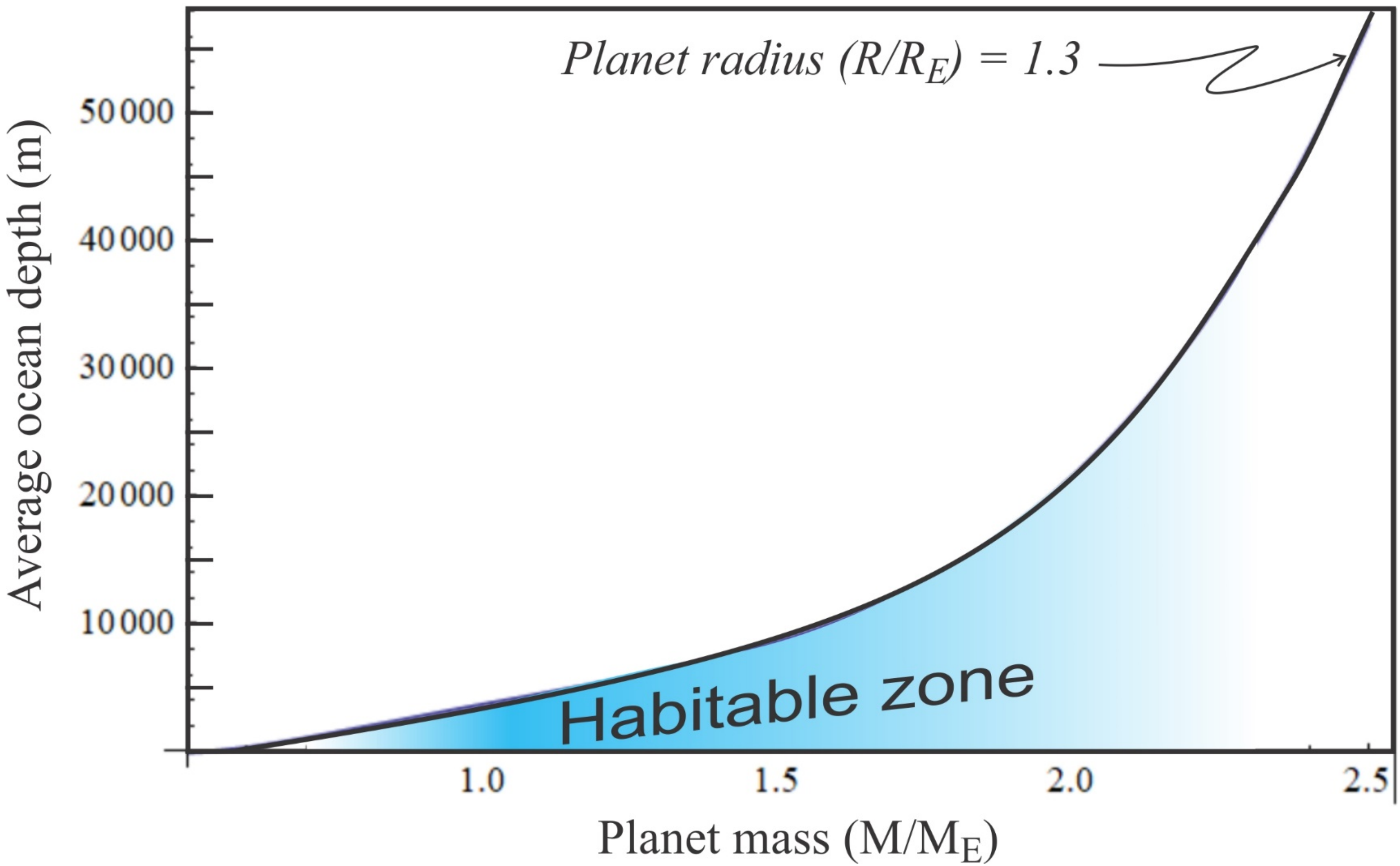
Earth Magma Ocean H_2 Ingassing;
Ocean mass equivalents



Super-Earth ($2M_E$) Magma Ocean H_2 Ingassing; Ocean mass equivalents



Ocean depth vs. mass



Summary of events

Stage1: Protoplanetary Disk

- Planetary embryos form in the protoplanetary disk in $<$10 My
- High P-T atmosphere forms. Surface melts – magma ocean.
- Multiple oceans worth of hydrogen ingas
- Large amounts of ^{3}He ingassed.
- Insufficient heavy noble gases are ingassed

Stage 2: Protoplanetary disk dispersal

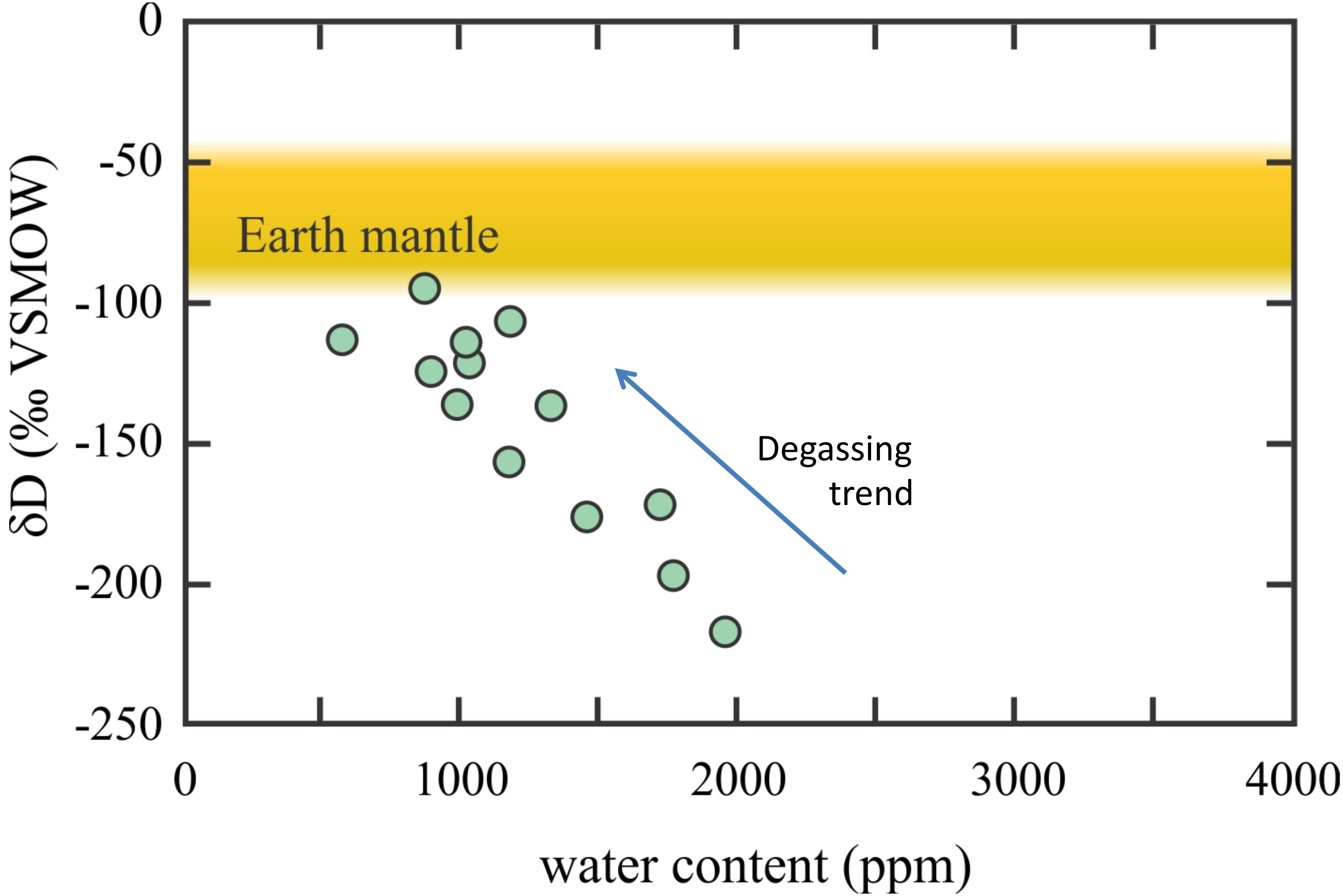
- Pressure release. Degassing of H_2
- Raises $f(O_2)$ from IW-1 (iron stable) to present value of FMQ (water stable)
- Loss of light noble gases by hydrodynamic escape
- Addition of ~1 % chondrites explains heavy noble gas deficit

Conclusion

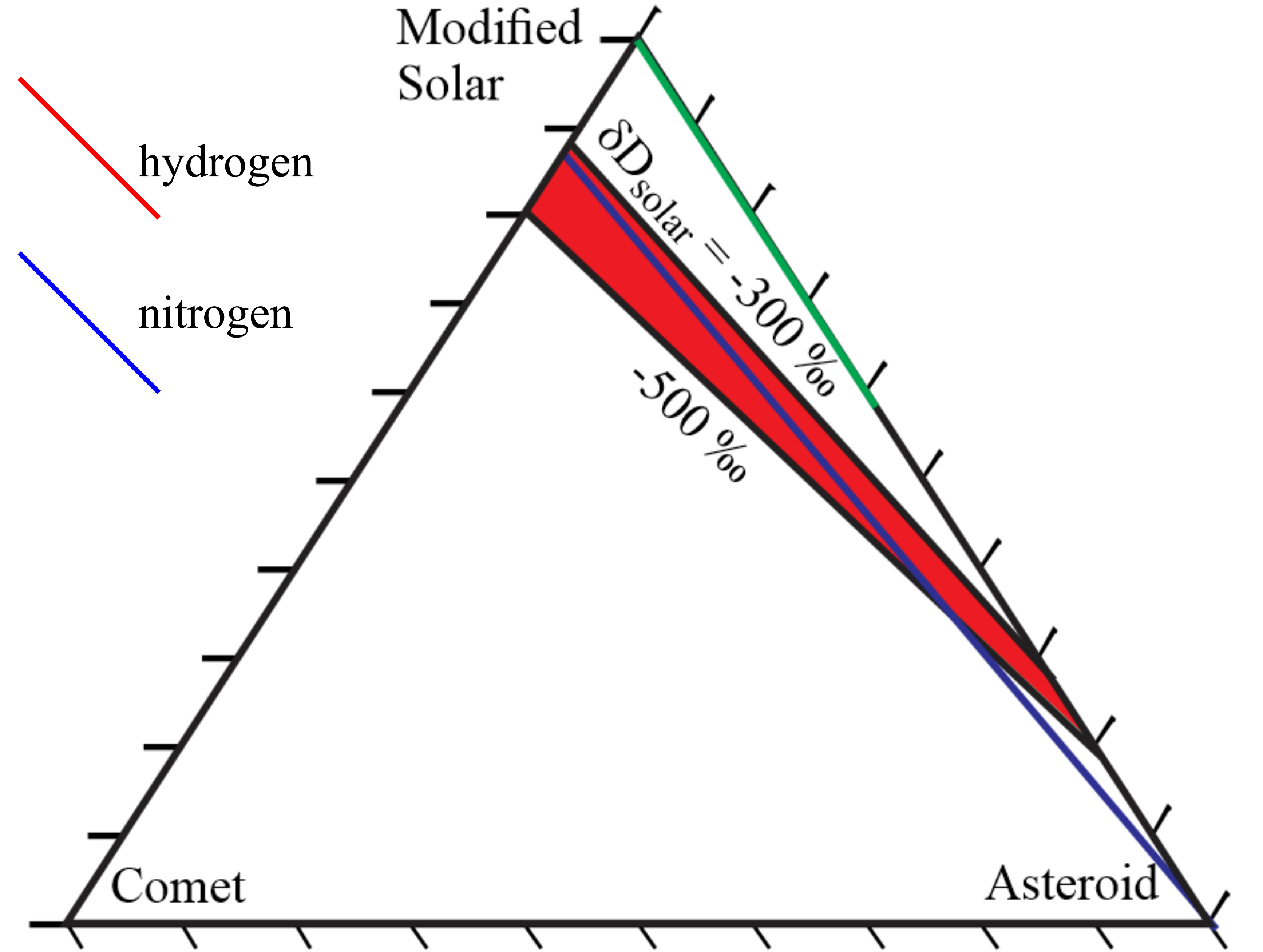
- Nebular ingassing of H_2 may be an important mix to Earth's water inventory.
- Eliminates radiogenic isotope 'mismatch' between Earth and chondrites.
- Explains source of ^3He to Earth, but still requires chondritic addition (heavy noble gases)
- Explains Earth's highly oxidized upper mantle
- Suggests that an Earth-sized body is the 'Goldilocks' size for advanced life.

Do we have evidence for the solar component in the terrestrial planets?

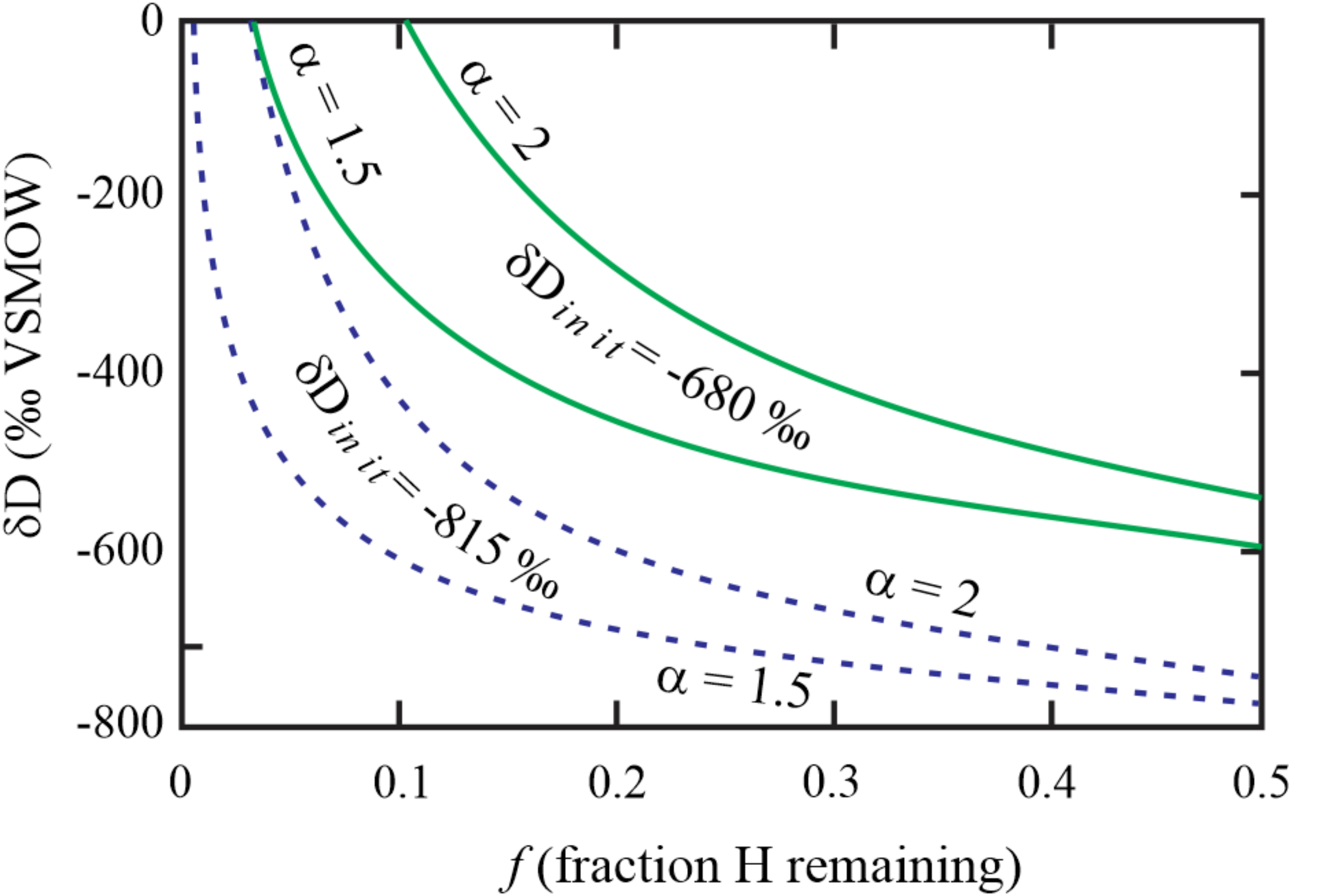
Baffin Islands



Hallis *et al.* Science, 2015



Modified Solar
hydrogen
nitrogen
δD$_{solar}$ = -300 ‰
-500 ‰
Comet
Asteroid



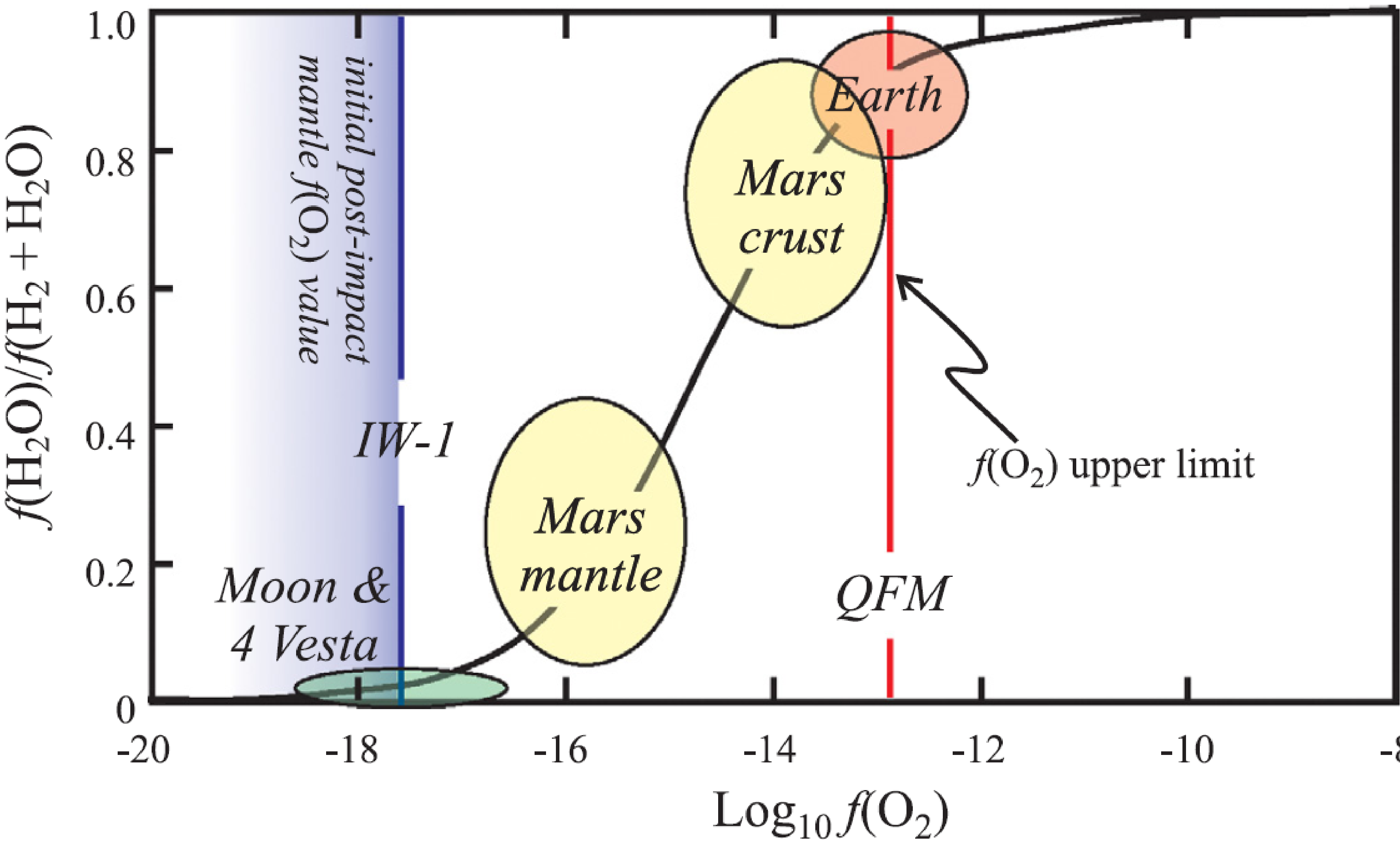
δD (‰ VSMOW)
0
-200
-400
-600
-800
0
0.1
0.2
0.3
0.4
0.5
f (fraction H remaining)
α = 1.5
α = 2
δD init = -680 ‰
δD init = -815 ‰
α = 2
α = 1.5

Ingassing Model Assumptions

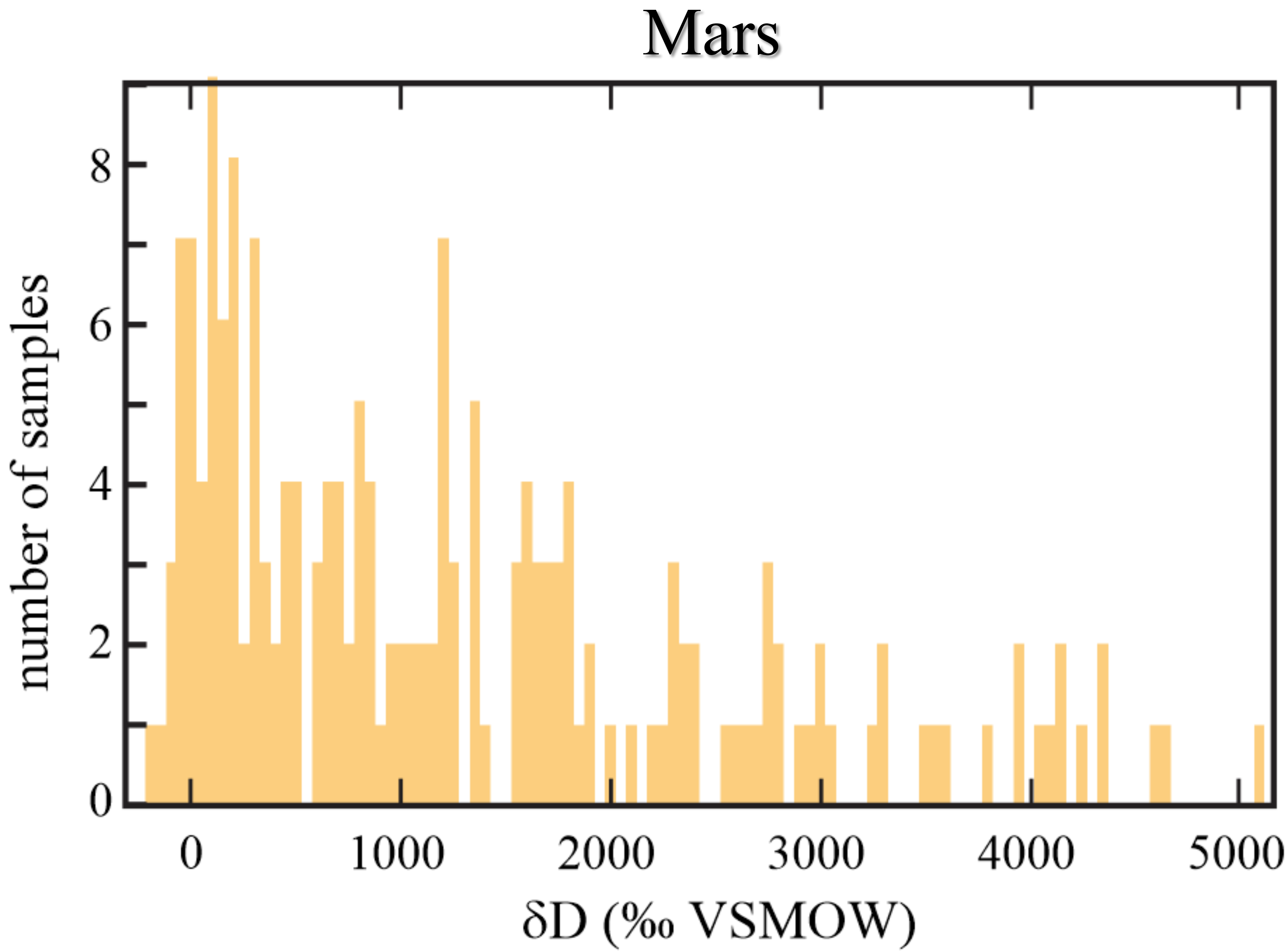
- Nebular atmosphere: 85% H_2, 15% He; 3He/4He=1.67e-4
- Nebular atmosphere lasts through accretion
- Accretion times: Earth=1-20Myr; Mars=1-5Myr
- Uniform accretion rate, dM/dt=constant
- Power law dependence of atm pressure on planet mass
- Global magma ocean
- Linear dependence of surface gas concentration C_s on partial pressure
- Gas flux depends on surface age: $\bar{f} = 2\rho_m \Delta C (\kappa/\pi\Delta\tau)^{1/2}$
- H & He diffusivity in magma: 5e-9 m^2/s
- H_2 solubility 4e-4 @ 1kb; He solubility 1.3e-5 @ 1kb

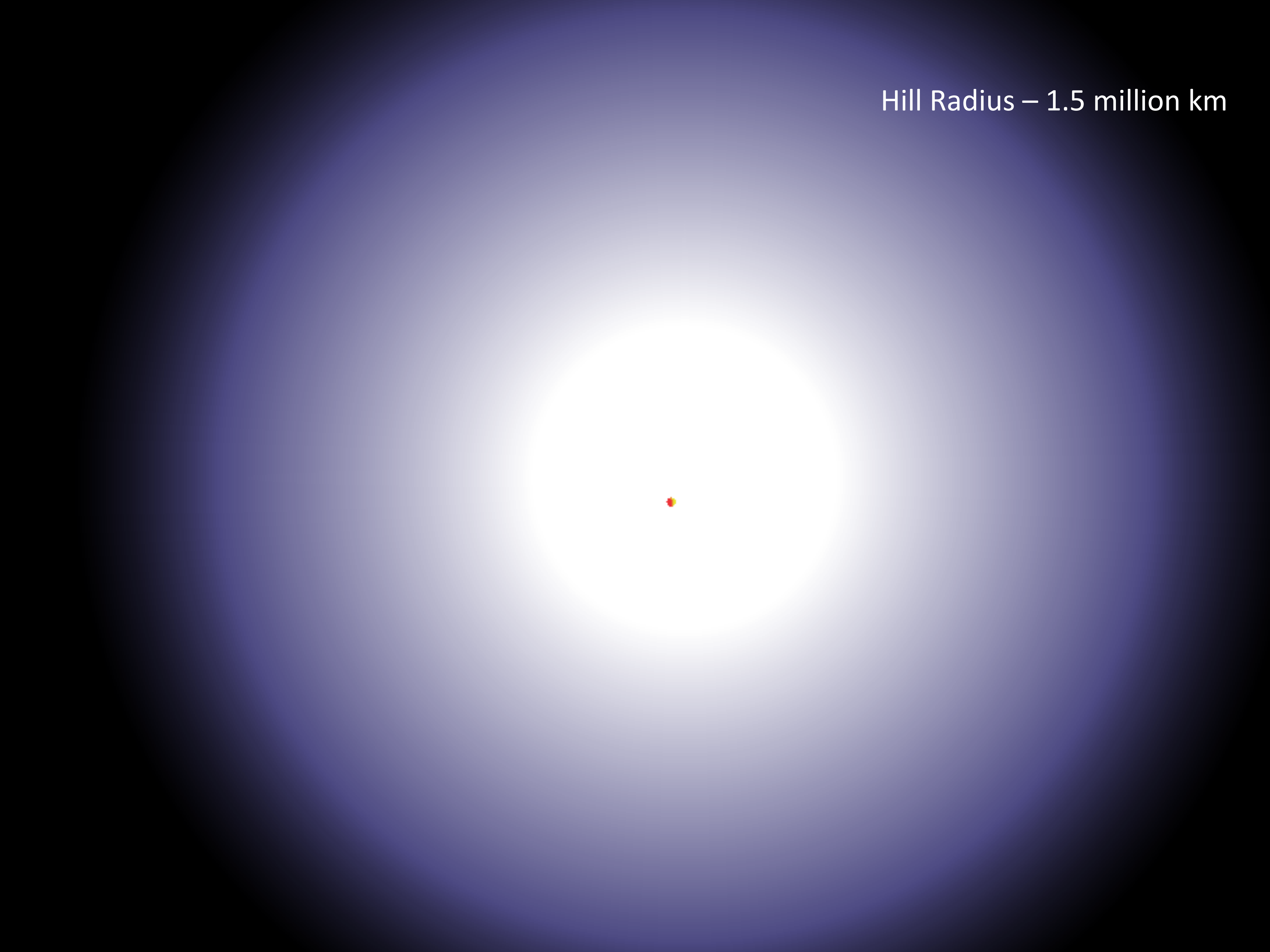
Does the timeline work?

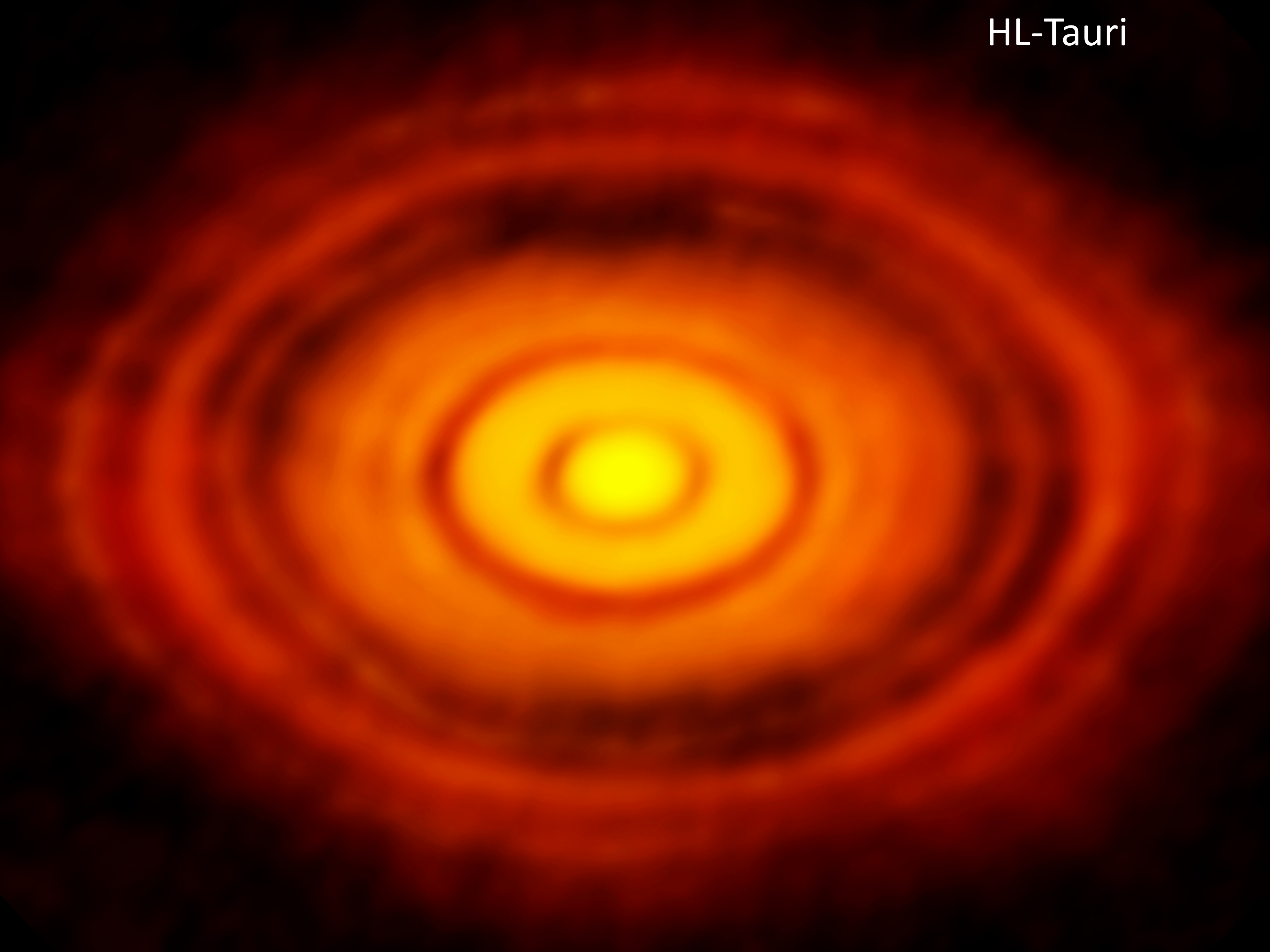
- Planetary embryo formation (Mars-sized or greater) – 1 – 5 My
- Age of the nebula (2-6 My) and up to 10 My (TW Hydrae – a T-Tauri star 80% the size of the Sun – 10 My).



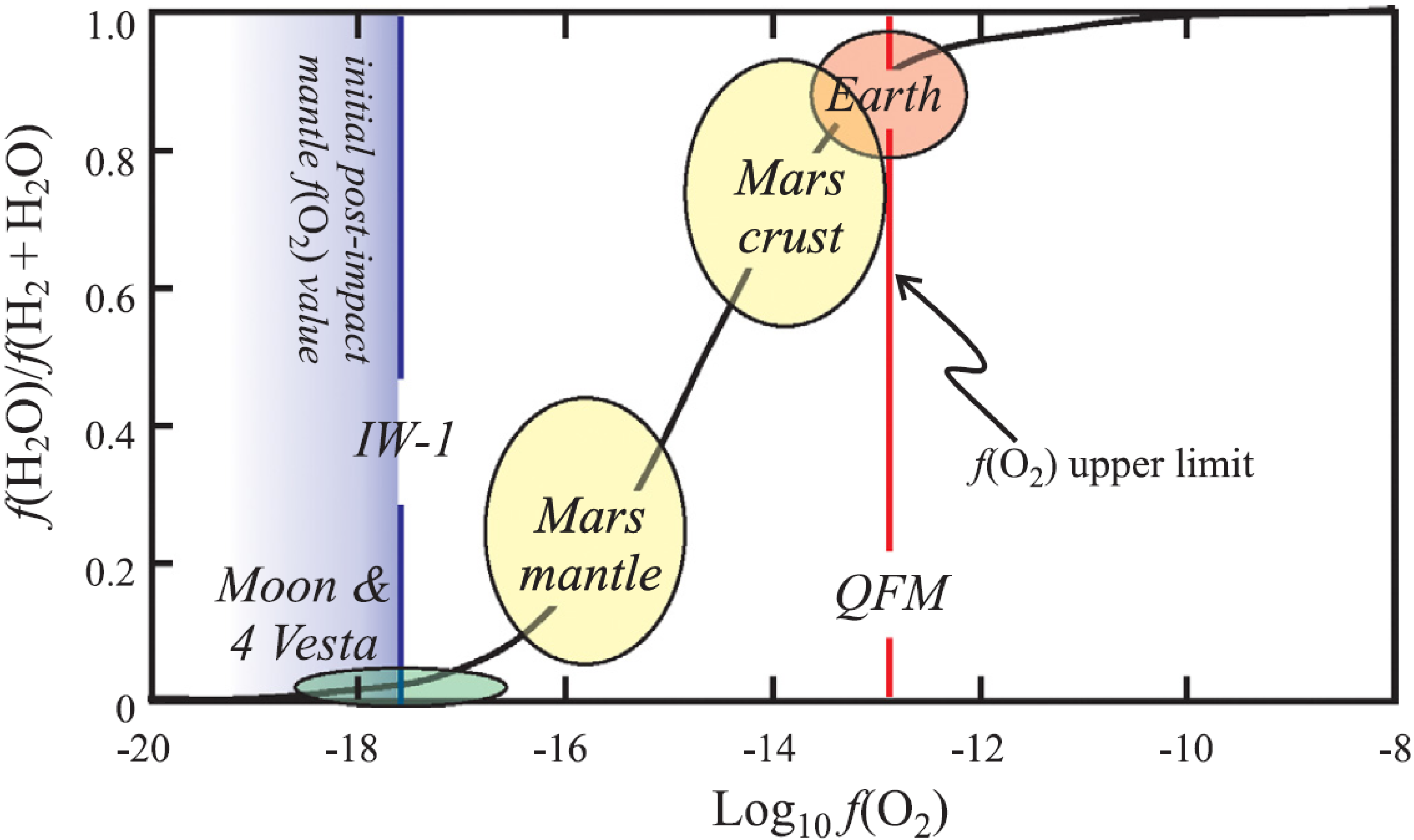
1.0
0.8
0.6
0.4
0.2
0
-20
-18
-16
-14
-12
-10
-8
$f(H_2O)/f(H_2 + H_2O)$
$Log_{10} f(O_2)$
initial post-impact mantle $f(O_2)$ value
IW-1
Moon & 4 Vesta
Mars mantle
Mars crust
Earth
QFM
$f(O_2)$ upper limit


Mars
number of samples
0
2
4
6
8
0
1000
2000
3000
4000
5000
δD (‰ VSMOW)


Hill Radius – 1.5 million km


HL-Tauri


SNOW LINE



Sharp et al., EPSL, 2013

Free parameters in our model

- Ingassing: Amount ingassed: We consider 0.01, 0.1 and 1.0 times our best estimate.

- Hydrodynamic escape: Loss is determined in order to best fit the equation

$$Log\left(\frac{N}{N_o}\right) = m\left(Mass\right) + b$$

where N_o is ingassed amount, N is present day amount, m is related to H flux

- Late addition: C chondrites, E chondrites, or some combination are considered. Comet compositional data are either measured from comet 67P/G-C or from ice formation experiments.

- Xe loss: The amount of ionized Xe lost is treated as a free parameter. Mass dependent Xe isotope fractionation factor (α) is treated as a free variable.

The solution!?

$$X_{\mathbf{He}\text{-}ing} - X_{\mathbf{He}\text{-}hydrodynamic\ escape} + x_{chon}C_{\mathbf{He}\text{-}chon} + x_{com}C_{\mathbf{He}\text{-}com} = X_{\mathbf{He}\text{-}Earth}$$

$$X_{\mathbf{N_2}\text{-}ing} - X_{\mathbf{N_2}\text{-}hydrodynamic\ escape} + x_{chon}C_{\mathbf{N_2}\text{-}chon} + x_{com}C_{\mathbf{N_2}\text{-}com} = X_{\mathbf{N_2}\text{-}Earth}$$

$$X_{\mathbf{Ne}\text{-}ing} - X_{\mathbf{Ne}\text{-}hydrodynamic\ escape} + x_{chon}C_{\mathbf{Ne}\text{-}chon} + x_{com}C_{\mathbf{Ne}\text{-}com} = X_{\mathbf{Ne}\text{-}Earth}$$

$$X_{\mathbf{Ar}\text{-}ing} - X_{\mathbf{Ar}\text{-}hydrodynamic\ escape} + x_{chon}C_{\mathbf{Ar}\text{-}chon} + x_{com}C_{\mathbf{Ar}\text{-}com} = X_{\mathbf{Ar}\text{-}Earth}$$

$$X_{\mathbf{Kr}\text{-}ing} - X_{\mathbf{Kr}\text{-}hydrodynamic\ escape} + x_{chon}C_{\mathbf{Kr}\text{-}chon} + x_{com}C_{\mathbf{Kr}\text{-}com} = X_{\mathbf{Kr}\text{-}Earth}$$

$$X_{\mathbf{Xe}\text{-}ing} - X_{\mathbf{Xe}\text{-}hydrodynamic\ escape} + x_{chon}C_{\mathbf{Xe}\text{-}chon} + x_{com}C_{\mathbf{Xe}\text{-}com} - X_{\mathbf{Xe}\text{-}ionized} = X_{\mathbf{Ar}\text{-}Earth}$$