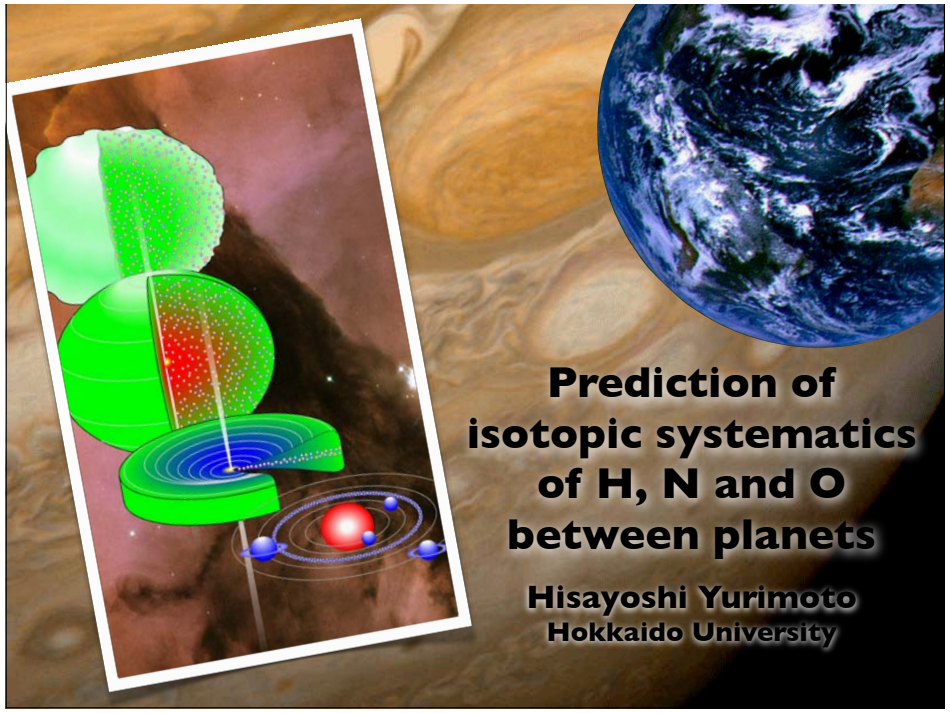
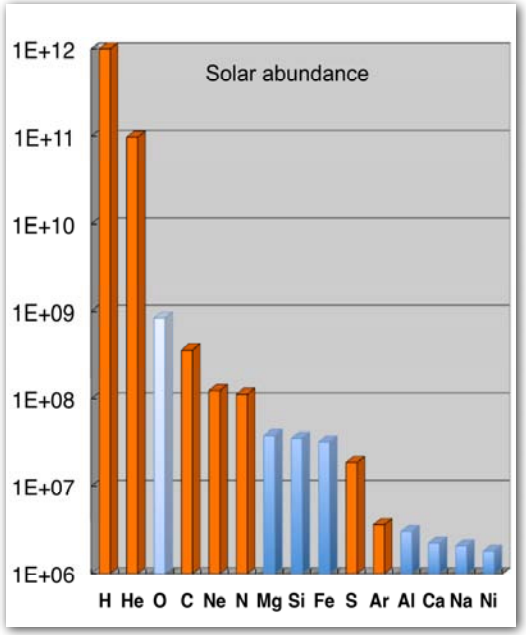


Science as method and methodology for problems on the Earth and life

- Watch carefully until understanding the problem.
- A natural sample
  - chemically disequilibrium
  - open system
  - unknown multiple processes (history)
  - one and only (synthesized by nature)
- Not difficult but exciting because you can create the method
- Find evidence from natural sample
- Write a paper what you understand

H, O, C, N

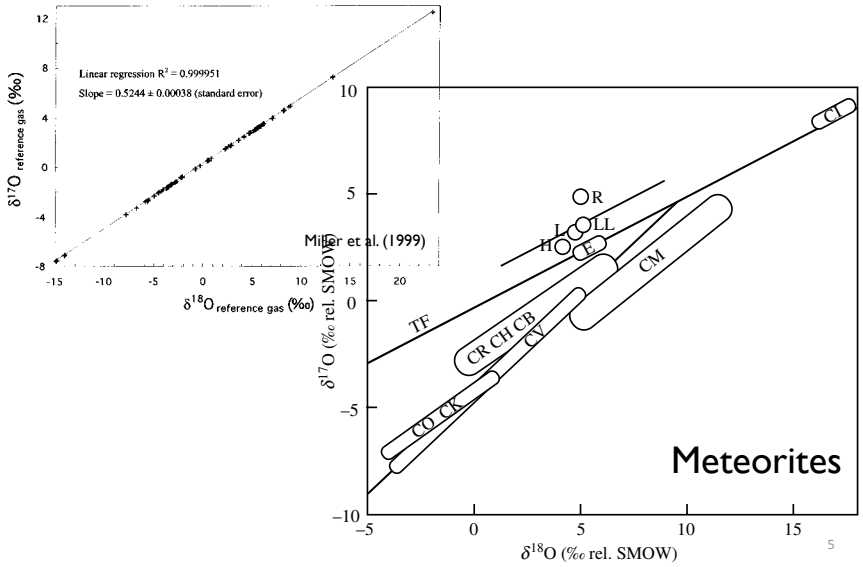
- Among the most abundant elements of the universe
- Large isotopic heterogeneities are observed in the universe.
- Their isotopic variations would be an important key to clarify how to form the solar system.



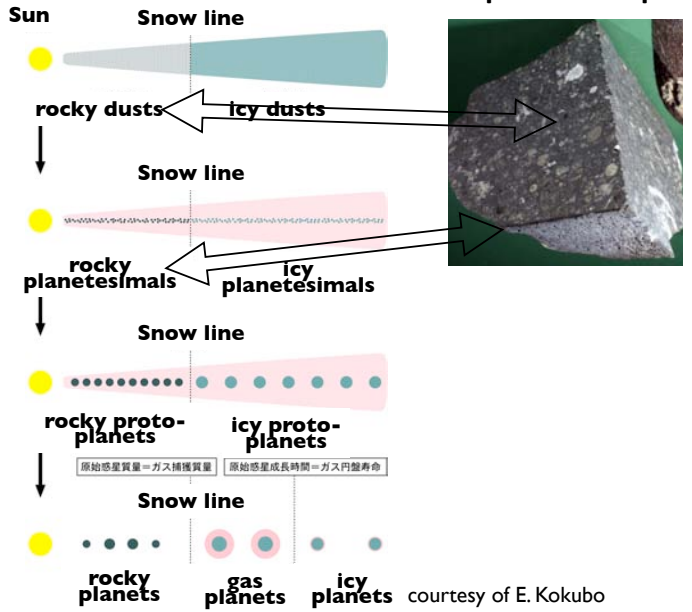
Outline

- Distribution of O isotopic composition in the proto-planetary disk
- Origin of O isotopic distribution in the proto-planetary disk
- Initial isotopic condition of proto-planetary disk
- Isotopic systematics of O, H and N between solar system planets
- Activity of violent proto-sun

Distribution of O isotopic composition

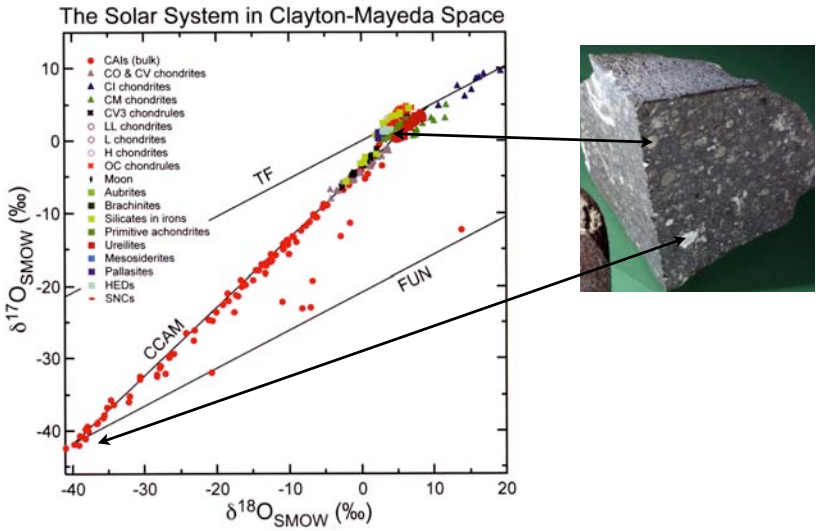


Distribution of O isotopic composition

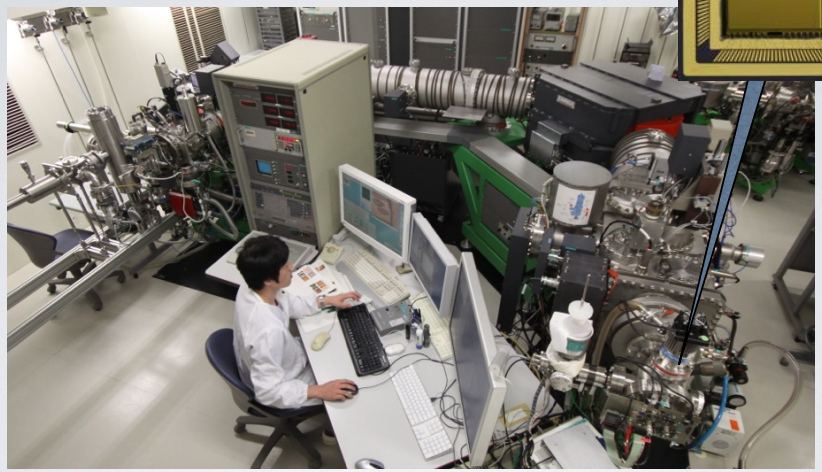


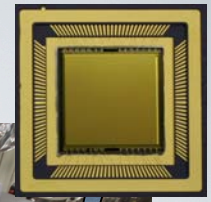
courtesy of E. Kokubo

Distribution of O isotopic composition



CAMECA IMS-1270 + SCAPS





ISOTOPE MICROSCOPE

CAMECA IMS-1270 + SCAPS

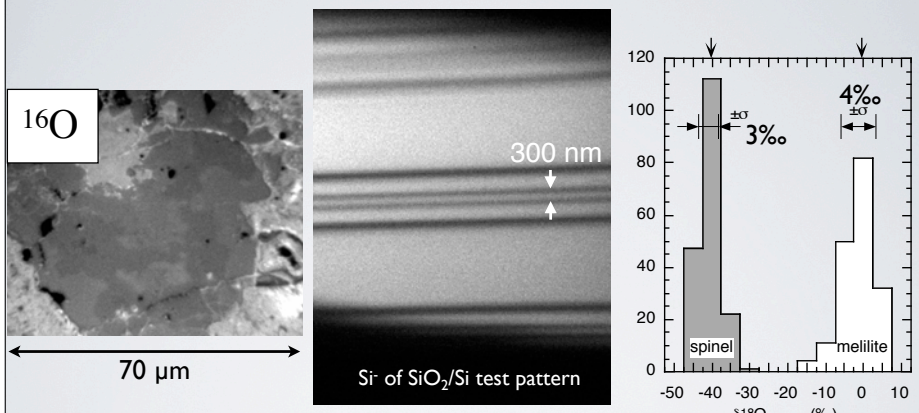
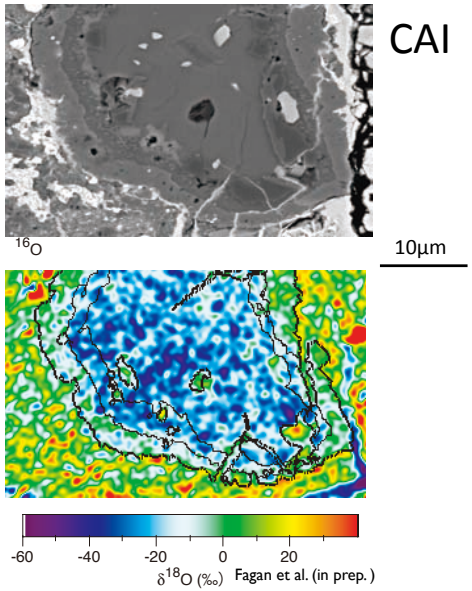


Image Field | Spatial resolution | Precision

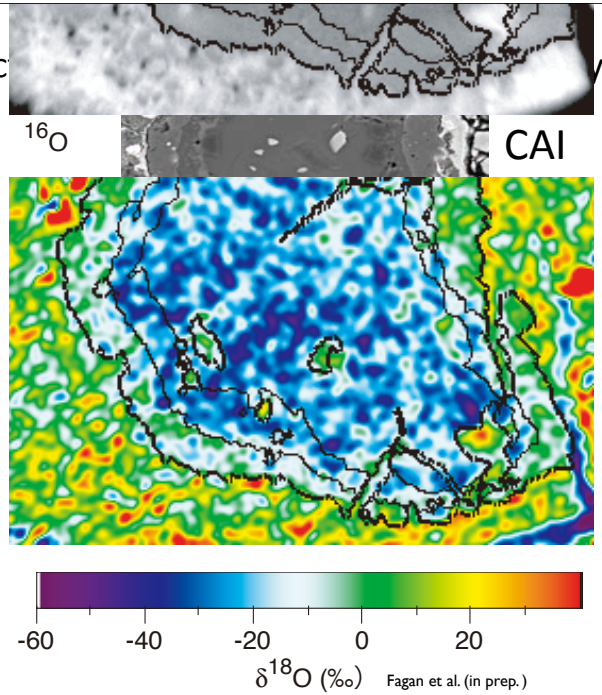
ISOTOPE MICROSCOPE

A direct solid condensate from protoplanetary disk gas



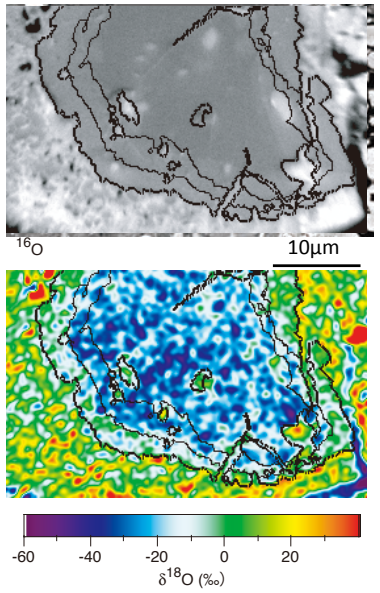
10

A direc [illegible] disk gas



11

A direct solid condensate from protoplanetary disk gas



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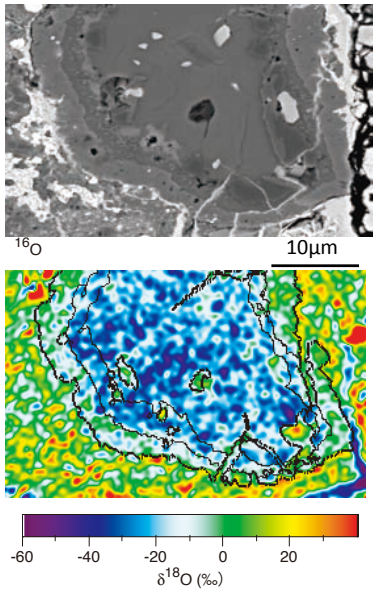
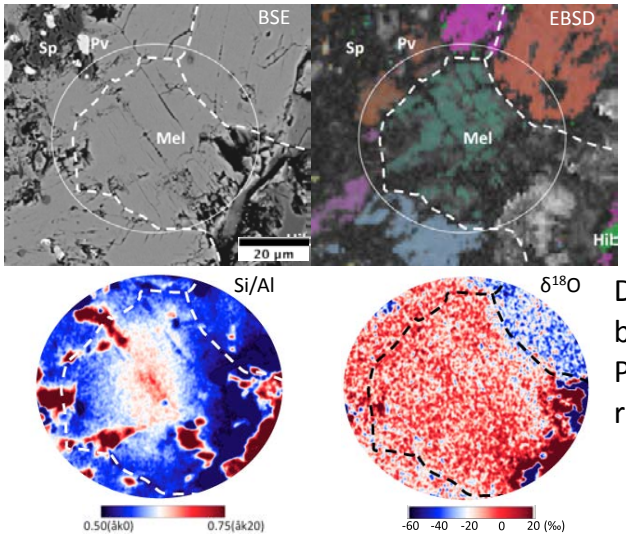
A direct solid condensate from protoplanetary disk gas



Fagan et al. (in prep.)

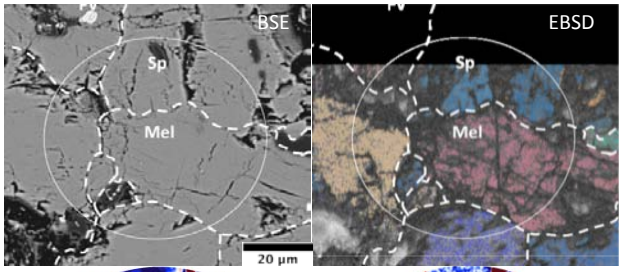
Crystal Growth in the Early Solar System

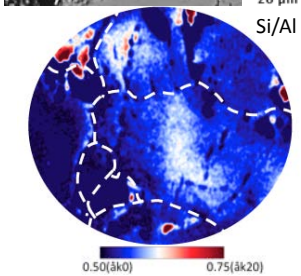


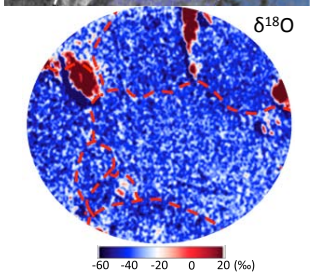
Direct adhesion between ^{16}O-Poor and ^{16}O-rich melilite

Choi et al. MAPS (2012)

Crystal Growth in the Early Solar System



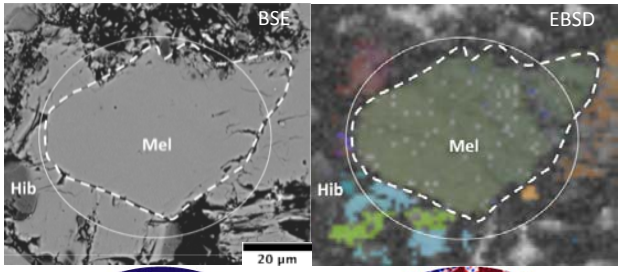


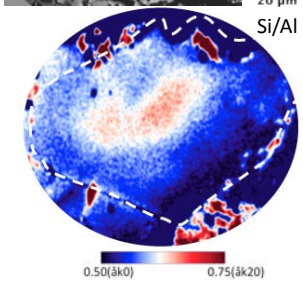


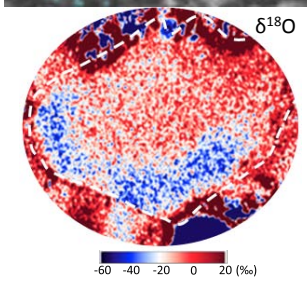
^{16}O-rich melilite

Choi et al. MAPS (2012)

Crystal Growth in the Early Solar System



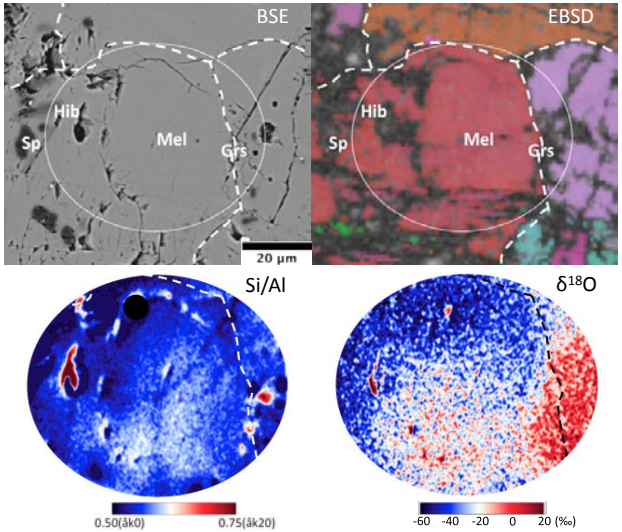




^{16}O-zoning in melilite

Choi et al. MAPS (2012)

Crystal Growth in the Early Solar System



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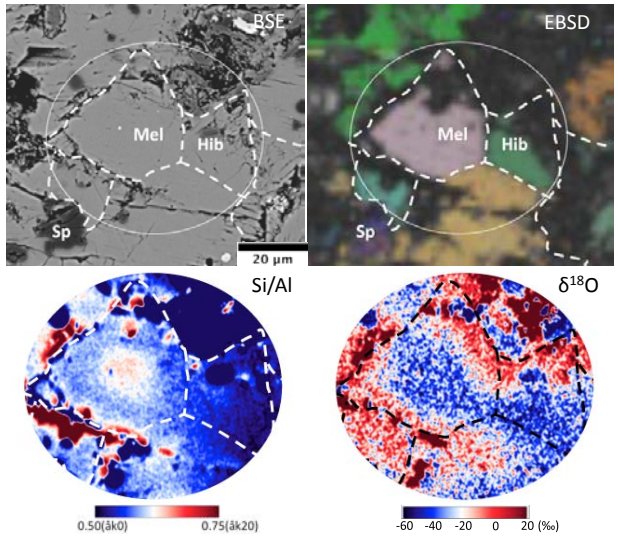
Choi et al. MAPS (2012)

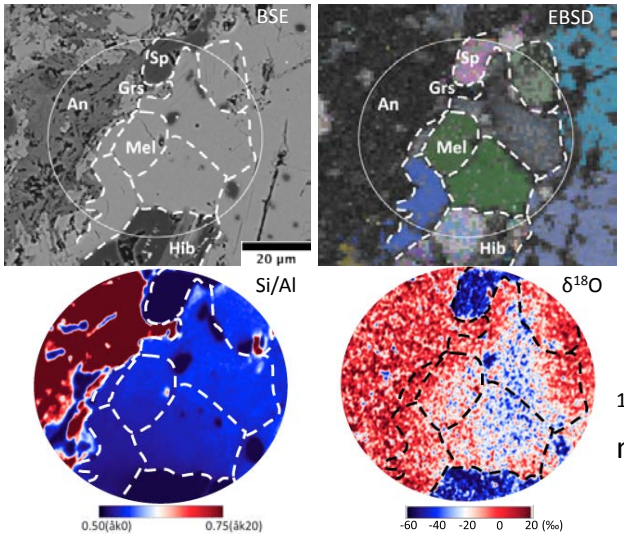
Crystal Growth in the Early Solar System



^{16}O-zoning in melilite

Choi et al. MAPS (2012)

Crystal Growth in the Early Solar System



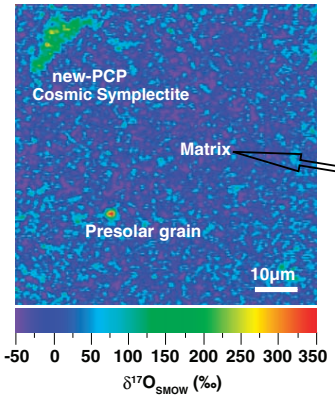
^{16}O-zoning in melilite

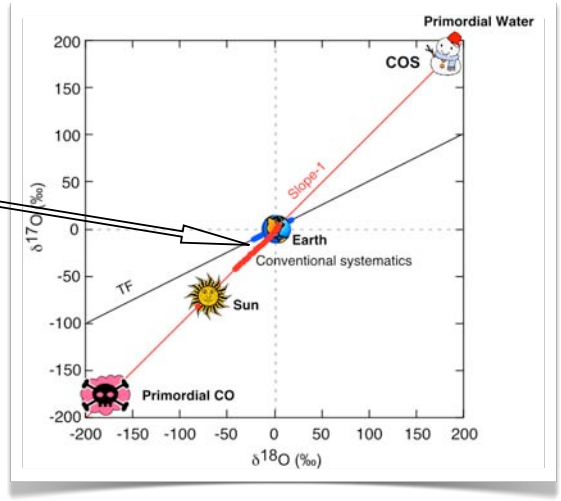
Choi et al. MAPS (2012)

O isotopes of proto-planetary disk

- Proto-planetary disk gas changed the O isotopic composition between ^{16}O-rich and ^{16}O-poor.

Wide Field Survey for Early Solar System Remnants

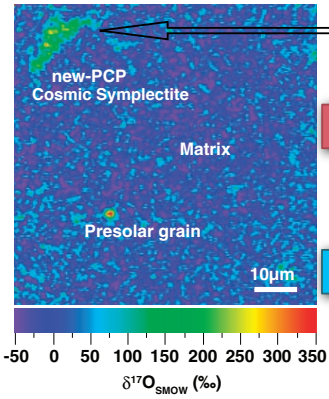


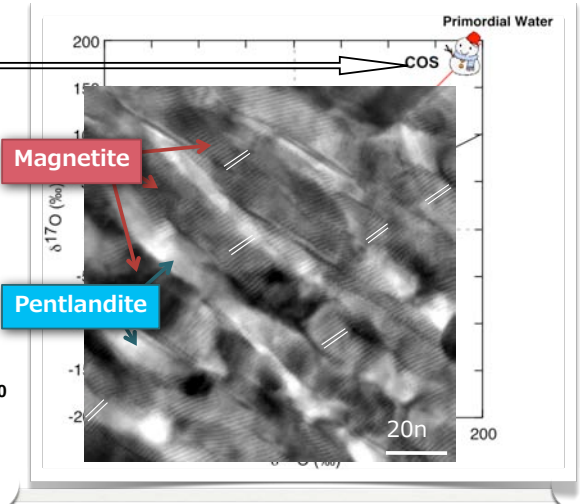


70μm field view
0.5μm resolution

Yurimoto & Kuramoto, *Science* (2004)
Sakamoto et al., *Science* (2007)

Wide Field Survey for Early Solar System Remnants





70μm field view
0.5μm resolution

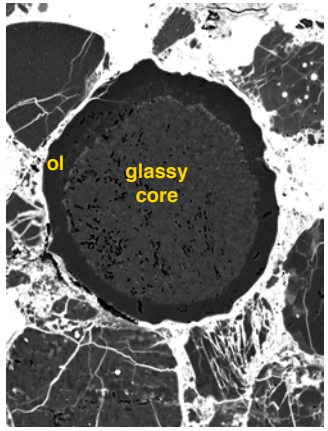
$$3FeS + 4H_2O = Fe_3O_4 + 3H_2S + H_2$$

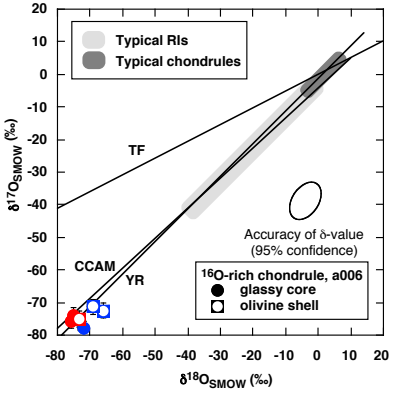
Sakamoto et al., *Science* (2007)

O isotopes of proto-planetary disk

- Proto-planetary disk gas changed the O isotopic composition between ^{16}O-rich and ^{16}O-poor.
- ^{16}O-poor disk gas is contributed by H_2O components.
-

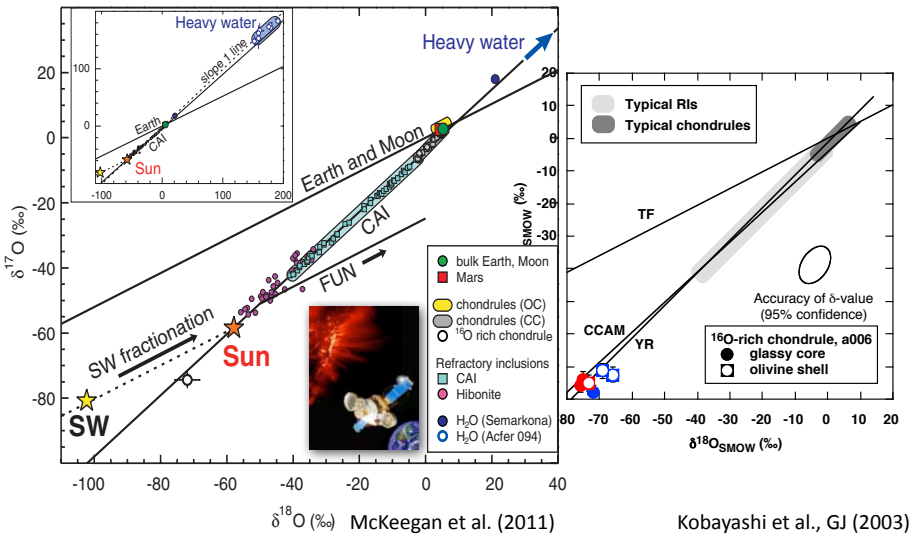
A ^{16}O-rich chondrule and the Sun





Kobayashi et al., GJ (2003)

A ^{16}O-rich chondrule and the Sun



McKeegan et al. (2011)

Kobayashi et al., GJ (2003)

O isotopes of protoplanetary disk

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- ^{16}O-poor disk gas is contributed by H_2O components.
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O isotopes of protoplanetary disk

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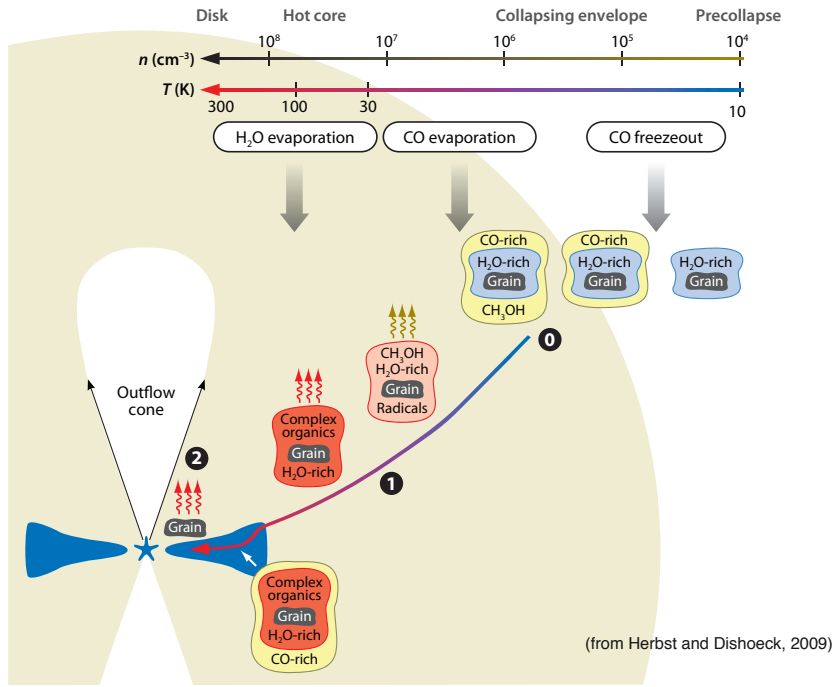
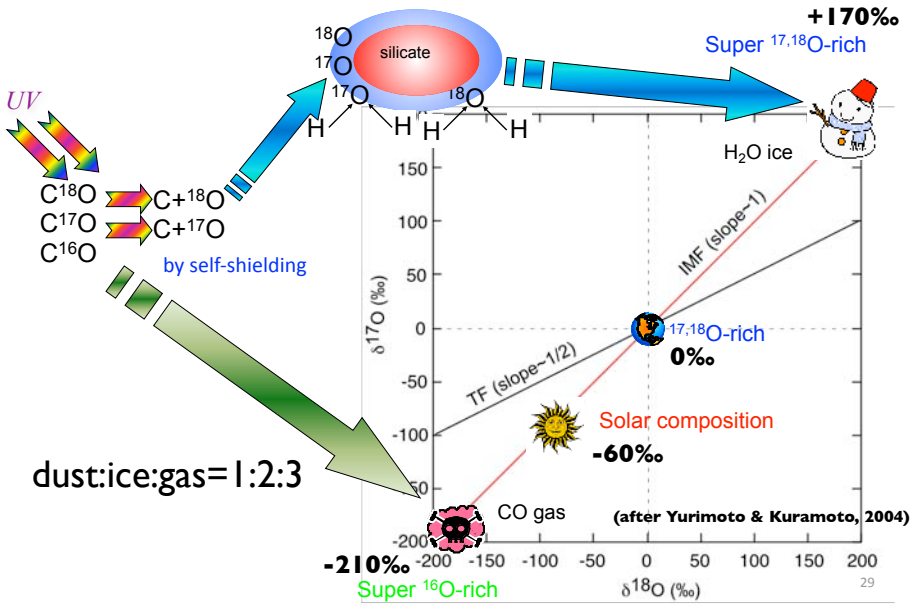
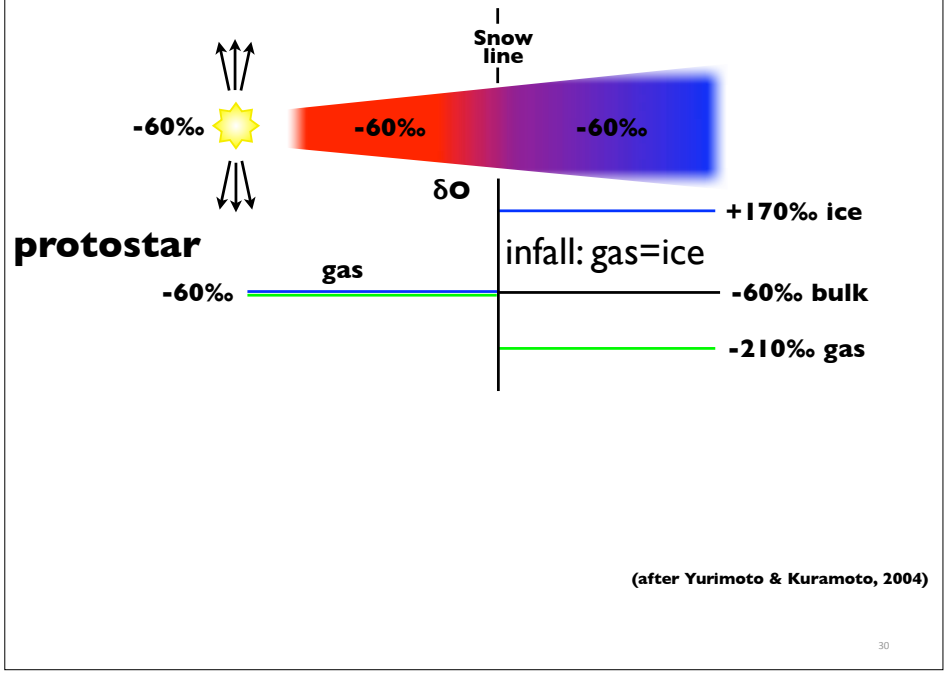
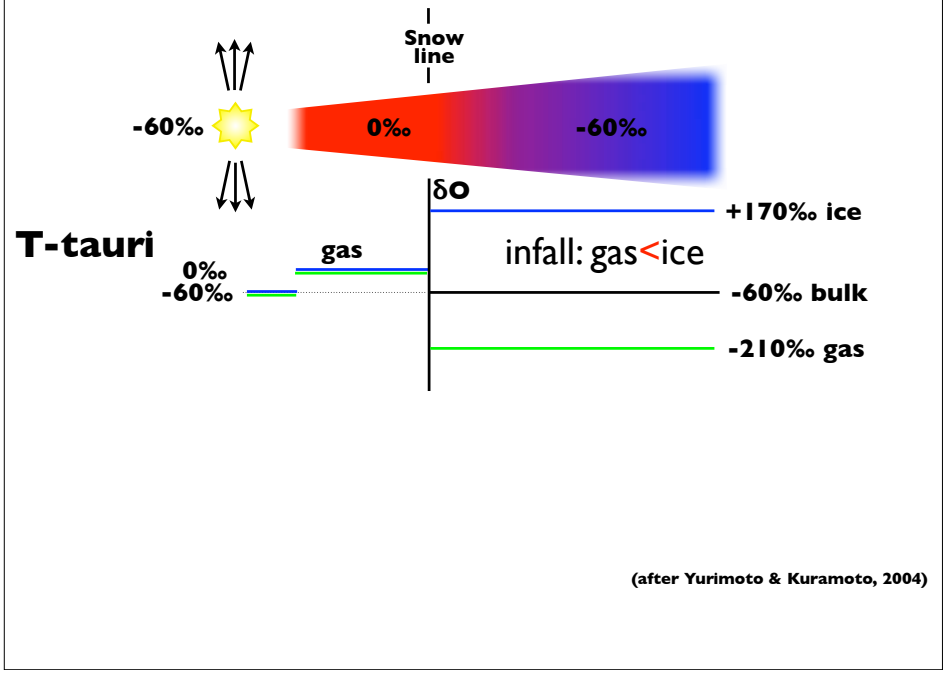
- ^{16}O-poor disk gas is contributed by H_2O components.
- ^{16}O-rich disk gas is contributed by the Solar component.
- These are the initial condition of the protoplanetary disk.
- Change of O isotopic composition of dusts is buffered by the disk gas because of High gas/dust of O.
- Change of O isotopic composition of disk gas in the early solar system is essential.

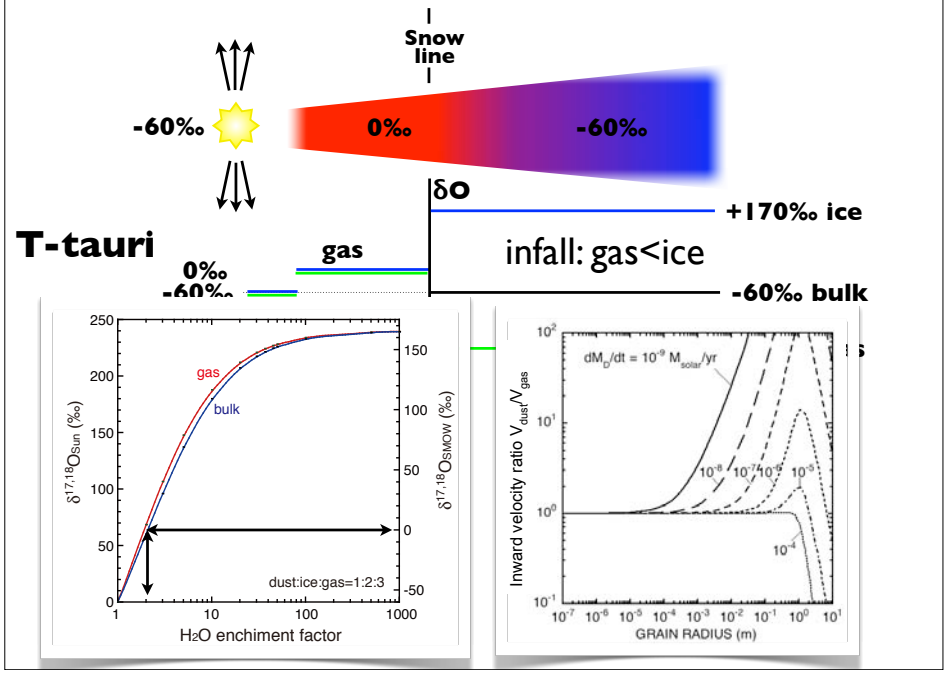


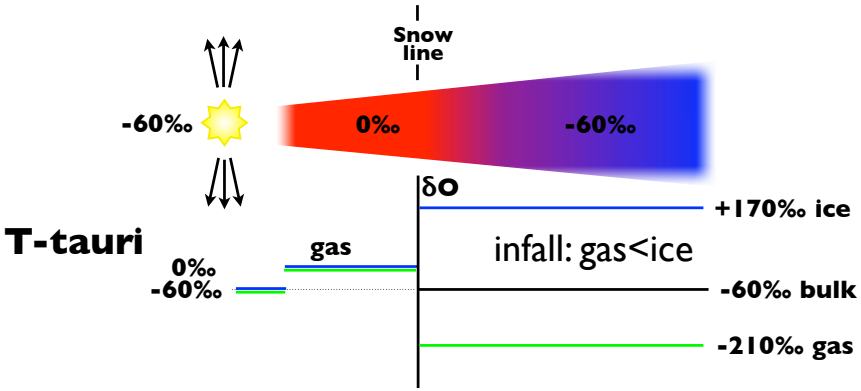
CO self-shielding and ice formation in MC



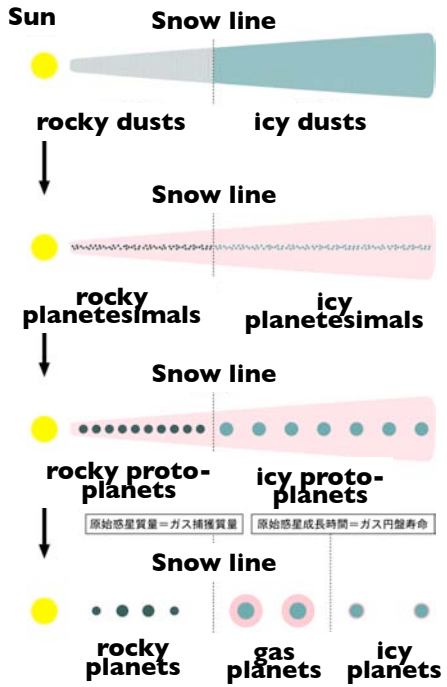








(after Yurimoto & Kuramoto, 2004)



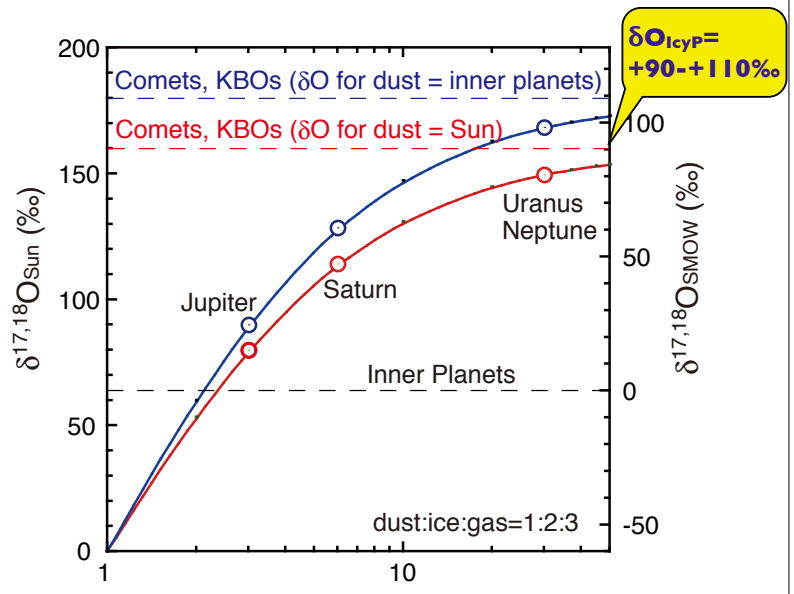
- Inner Planet (IP) =Rocky Planetesimals (RP)
- Outer Planet (OP) =Icy Planetesimals (IcyP) + Disk gas
- $\delta O_{IP} = \delta O_{RP} = \delta O_{inner\ gas}$
- $\delta O_{OP} = a_{IcyP}\delta O_{IcyP} + (1-a_{IcyP})\delta O_{gas} = f_{Ice}\delta O_{IcyP} + \delta O_{BSS}$

Yurimoto & Kuramoto (2004), Kuramoto & Yurimoto (2005)

courtesy of E. Kokubo

O isotopic compositions of outer planets

- Because icy planetesimals are a mixture of ice and dust of solar abundance ratio, Oxygen isotopic composition of icy planetesimals is expected to be +90 to +110 ‰ relative to Earth. (after Kuramoto and Yurimoto , 2004)
- Astronomical observations show that envelops of outer planets are enriched in heavy elements relative to solar composition (Atreya et al., 1999; Gautier and Owen, 1989)
- It is believed that the heavy element enrichments have been caused by excessive accretion of icy planetesimals.



$\delta O_{OP} = f_{Ice}\delta O_{IcyP} + \delta O_{ss}$ f: Ice component enrichment

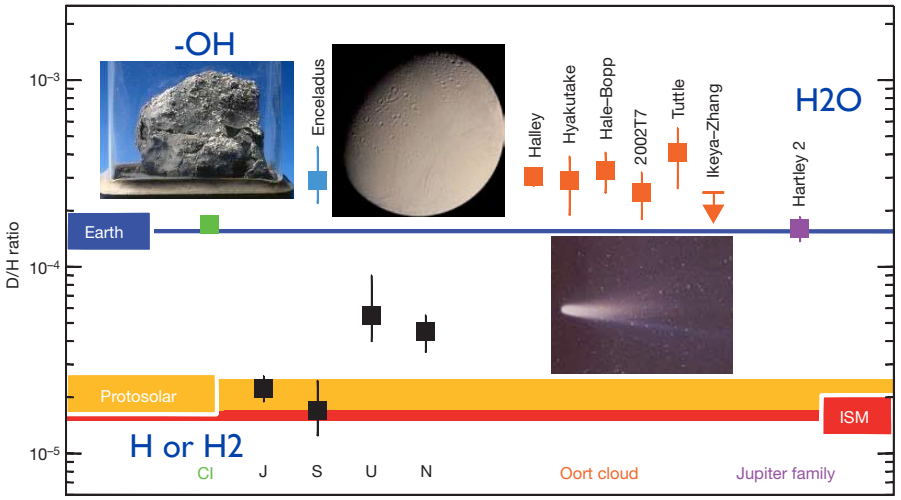
(after Kuramoto & Yurimoto, 2005)

H isotopic compositions of outer planets

H_2O ice consists of H and O. The same model for O isotopes can be applied to H isotopes.

- Protosolar Nebula H_2: D-poor, δD_{SMOW}=-850‰
  - by Solar ^{3}He abundance (Linsky et al, 2006)
- Cometary ice: D-rich, δD_{SMOW}
  - =+1400‰ by comets (e.g., Villanueva et al., 2009)
  - =+5450‰ by interstellar H_2O (e.g., Butner et al., 2007)
- Possible mechanisms for D enrichments
  - ion-molecule reaction in molecular cloud or outer disk
  - grain-surface reaction in molecular cloud or outer disk
  - self-shielding of H_2 in molecular cloud or outer disk
- dust/ice/gas ratios: 0/1/2000
  - by cosmic abundance

太陽系のH2OとH, H2の同位体比



Hartogh et al. (2011)

H isotopic compositions of outer planets

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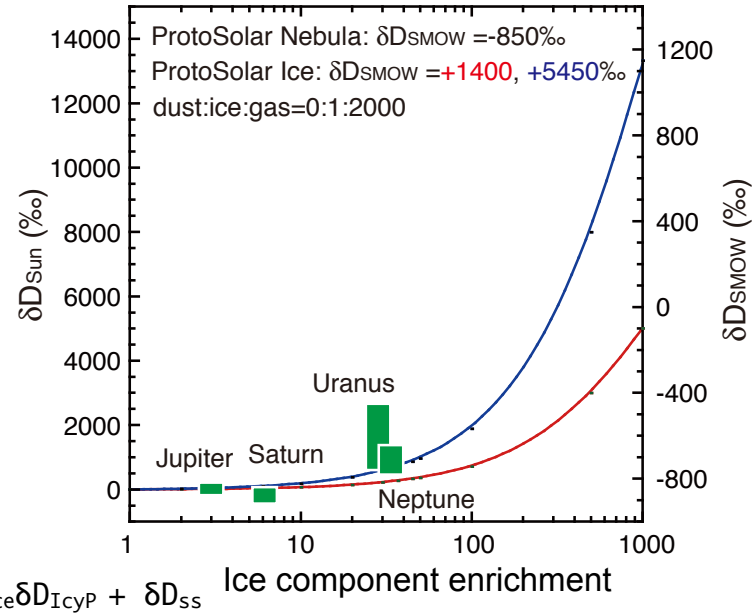
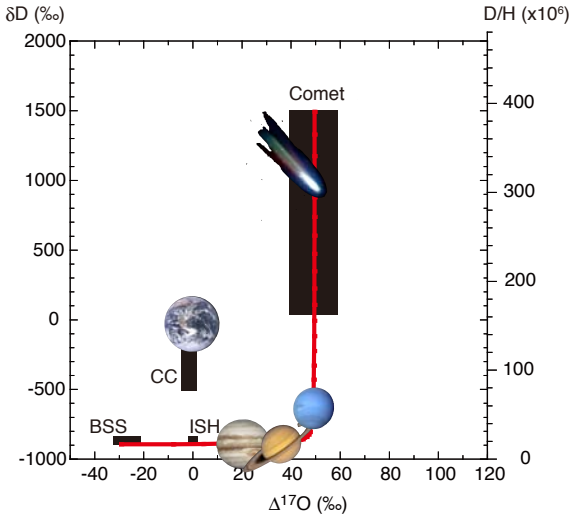


- $\delta D_{OP} = f_{Ice}\delta D_{IcyP} + \delta D_{ss}$

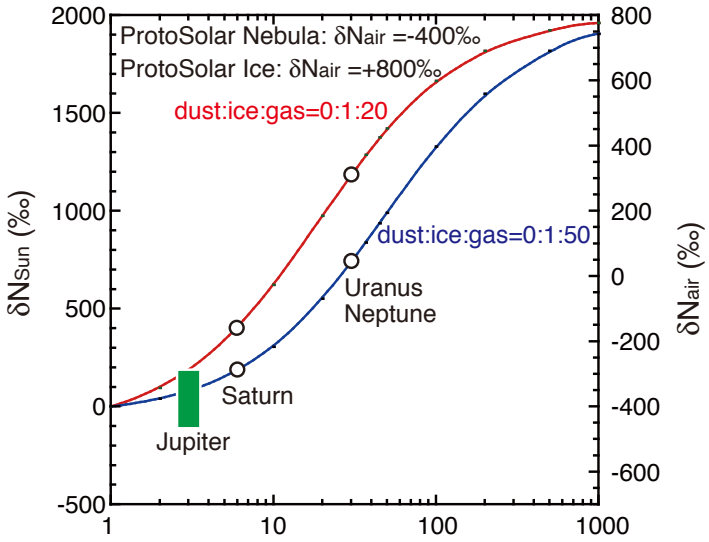
Isotopic Systematics between H and O of Outer Planets



N isotopic compositions of outer planets

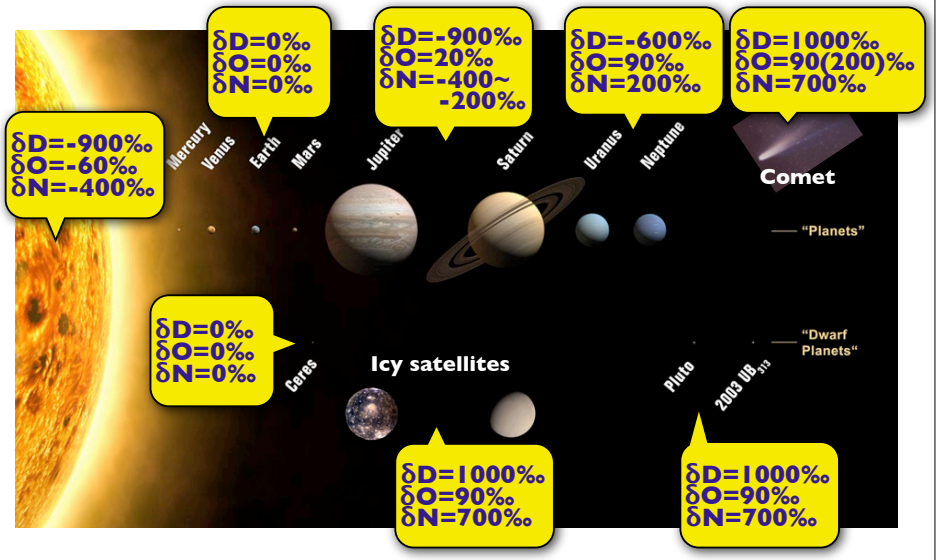
The same model for O isotopes can be applied to N isotopes. NH_3-bearing ice would be an ice in the solar nebula.

- Protosolar Nebula: ^{14}N-rich; $\delta^{15}N_{air}$=-400‰
  - by Solar wind (Marty et al., 2011)
- Cometary ice: ^{14}N-poor; $\delta^{15}N_{air}$=+800‰
  - by observations (e.g. Bockelée-Morvan et al., 2008).
- Possible mechanisms of ^{15}N enrichments
  - ion-molecule reaction in molecular cloud or outer disk
  - self-shielding of N_2 in molecular cloud or outer disk
- dust/ice(NH_3)/gas(N_2) ratios: 0/1/~10 (Owen and Niemann,2009)



- $\delta N_{OP} = f_{Ice}\delta N_{IcyP} + \delta N_{ss}$

Conclusions



Outline

- Distribution of O isotopic composition in the proto-planetary disk
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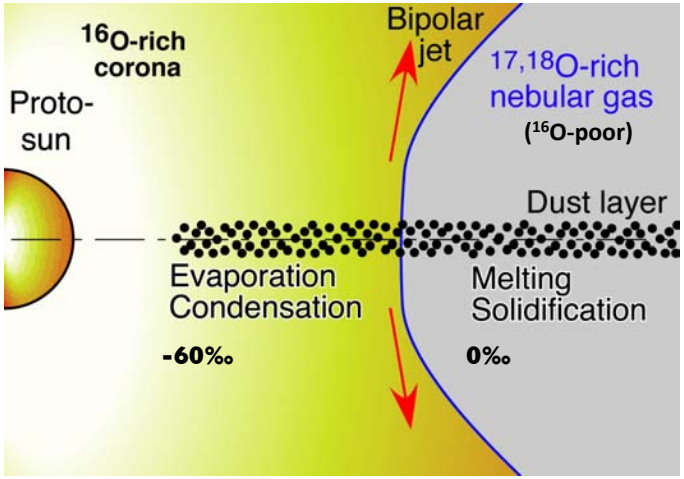
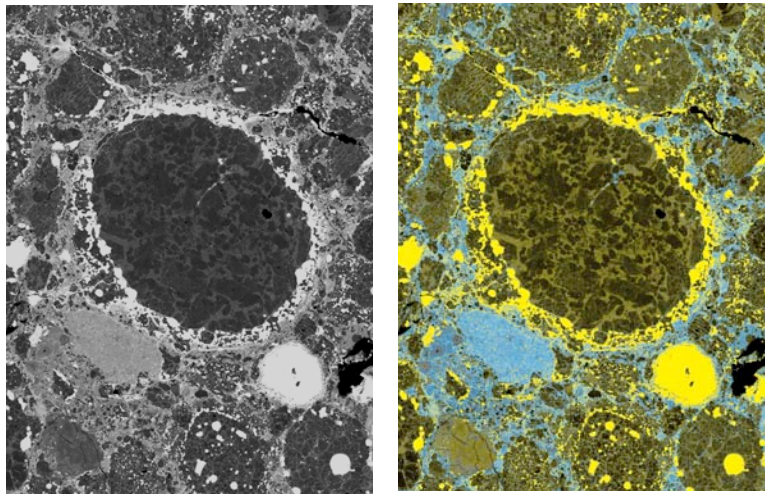
Inner edge region of protoplanetary disk



Itoh et al. (2003)
Yurimoto et al. (2008)

Solar wind-O isotopic composition of metal-



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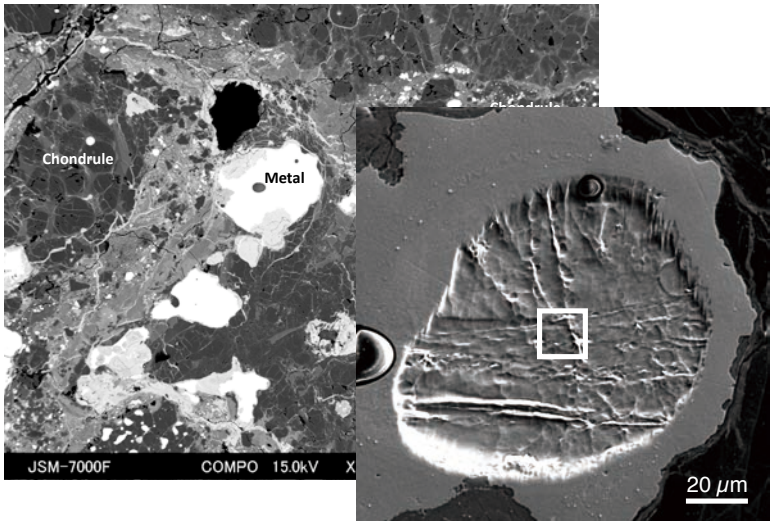
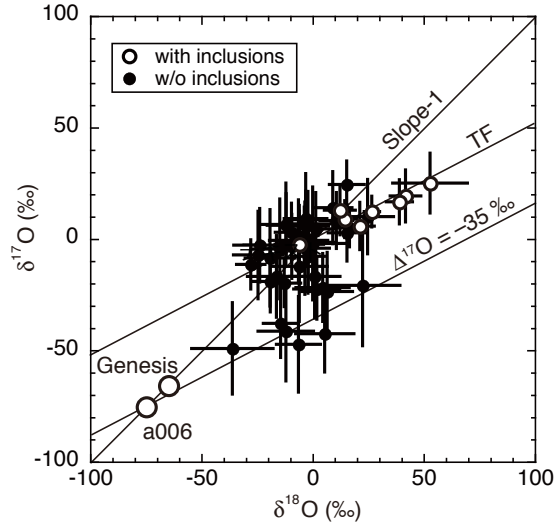
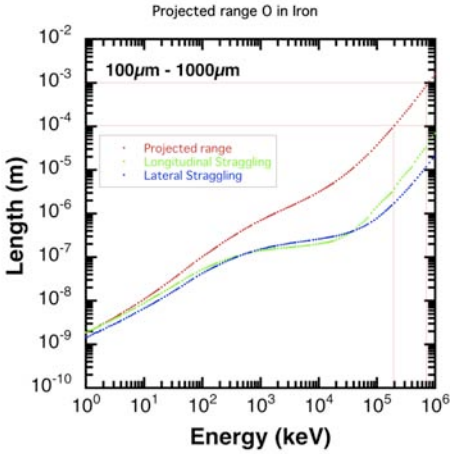


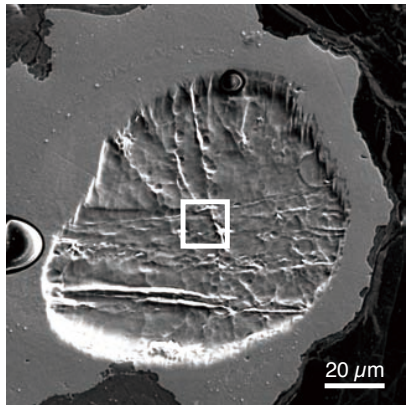
Oxygen isotope ratios of inclusion free area



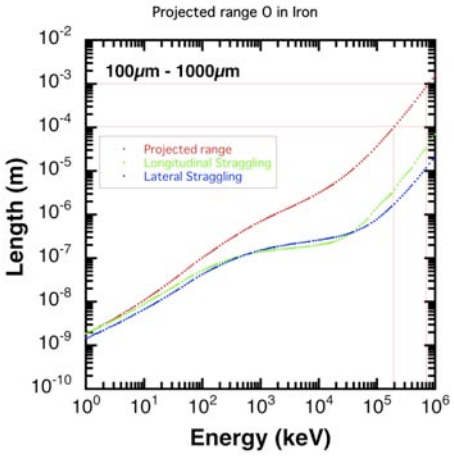
Fujimoto et al., GJ (2009)

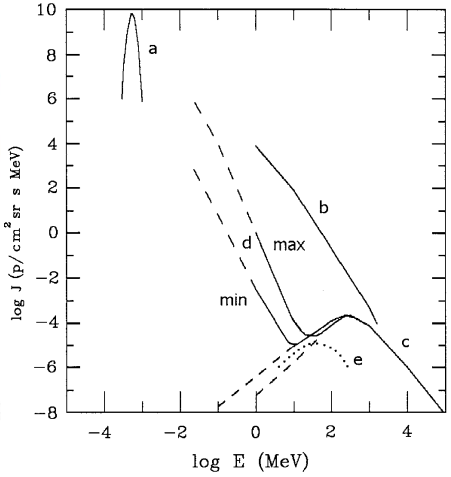
Solar wind-O isotopic composition of metal-



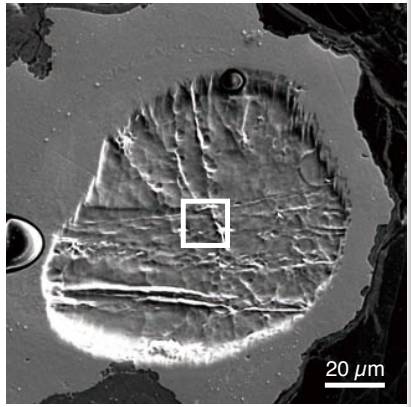


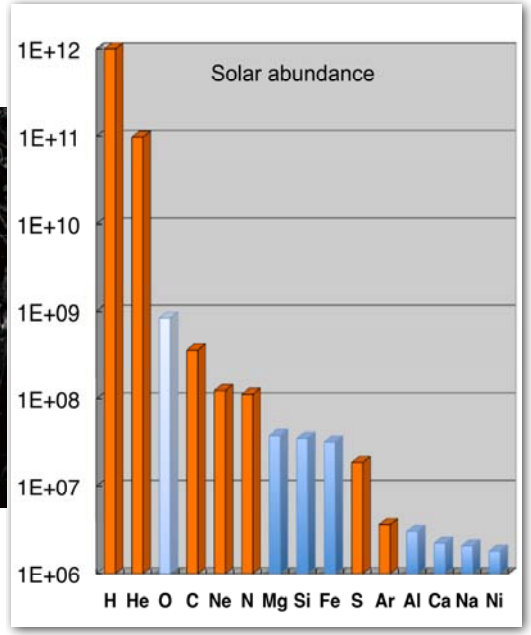
Solar wind-O isotopic composition of metal-





Logachev et al. (2002)

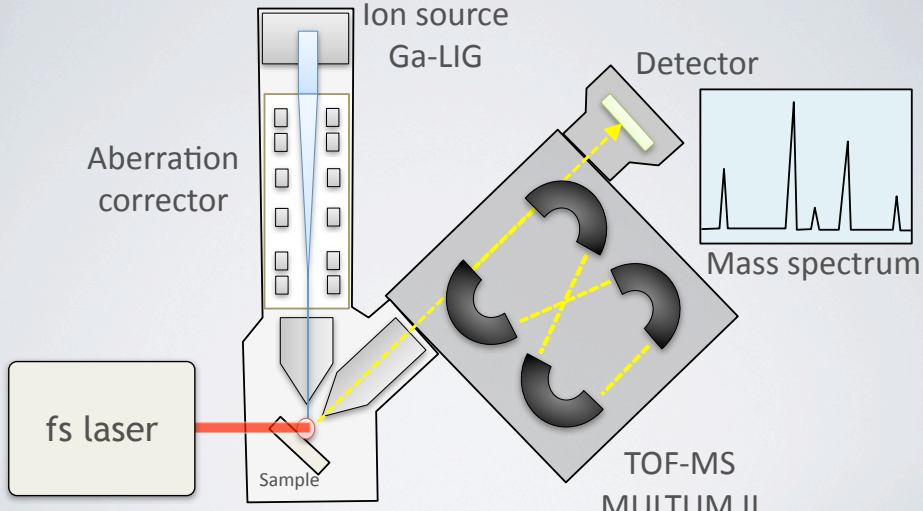




Laser Ionization Mass Nanoscope (LIMAS)

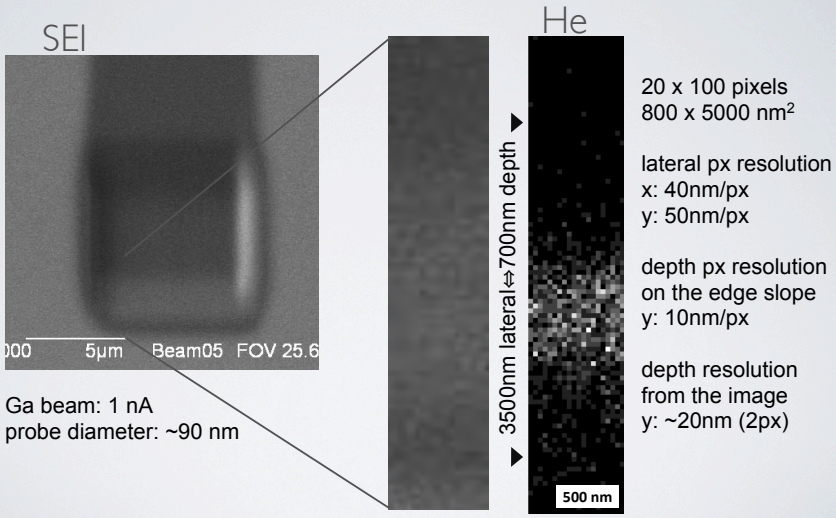
ISOTOPE NANOSCOPE

同位体ナノスコープ LIMAS



Surf. Int. Analys. (2011)

IMAGING OF CRATER EDGE



Ga beam: 1 nA
probe diameter: ~90 nm

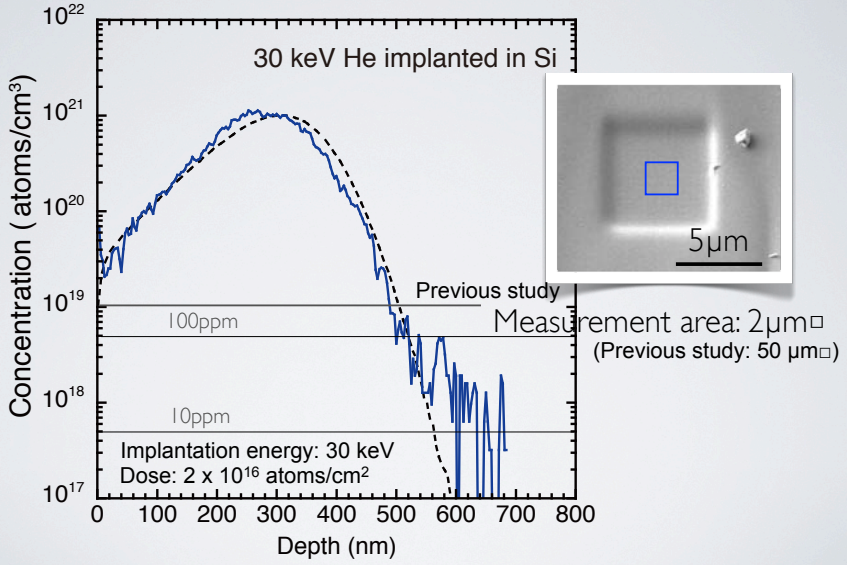
20 x 100 pixels
800 x 5000 nm^2

lateral px resolution
x: 40nm/px
y: 50nm/px

depth px resolution
on the edge slope
y: 10nm/px

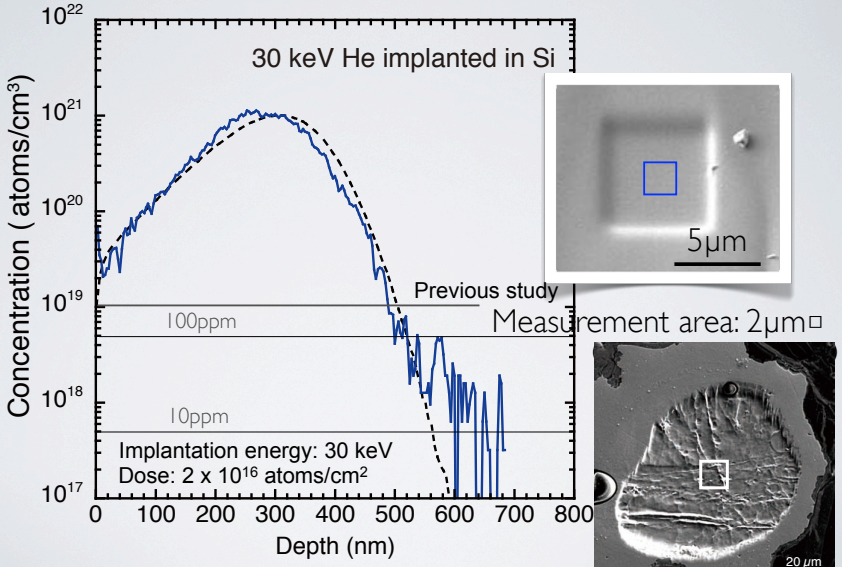
depth resolution
from the image
y: ~20nm (2px)

DEPTH PROFILING



Measurement area: 2μm□
(Previous study: 50 μm□)

DEPTH PROFILING



Science as method and methodology for problems on the Earth and life

- Watch carefully until understanding the problem.
- A natural sample
  - chemically disequilibrium
  - open system
  - unknown multiple processes (history)
  - one and only (synthesized by nature)
- Not difficult but exciting because you can create the method
- Find evidence from natural sample
- Write a paper what you understand