Photochemistry in the Early Solar system: Summary of Observations and Explanations

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UCLA

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Les Houches

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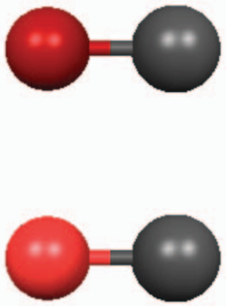
Isotope fractionation

$$\nu = \frac{1}{2\pi}\sqrt{\frac{K_f}{\mu}}$$

Reduced mass
controls frequency



$C^{16}O$

$C^{17}O$

Harold Urey

Jacob Bigeleisen

Maria Goeppert-Mayer

Harold Urey, *J. Chem. Soc. (London)* (1947)

J. Bigeleisen and M. G. Mayer, *J. Chem. Phys.* (1947)

Isotope fractionation

$$\nu = \frac{1}{2\pi}\sqrt{\frac{K_f}{\mu}}$$

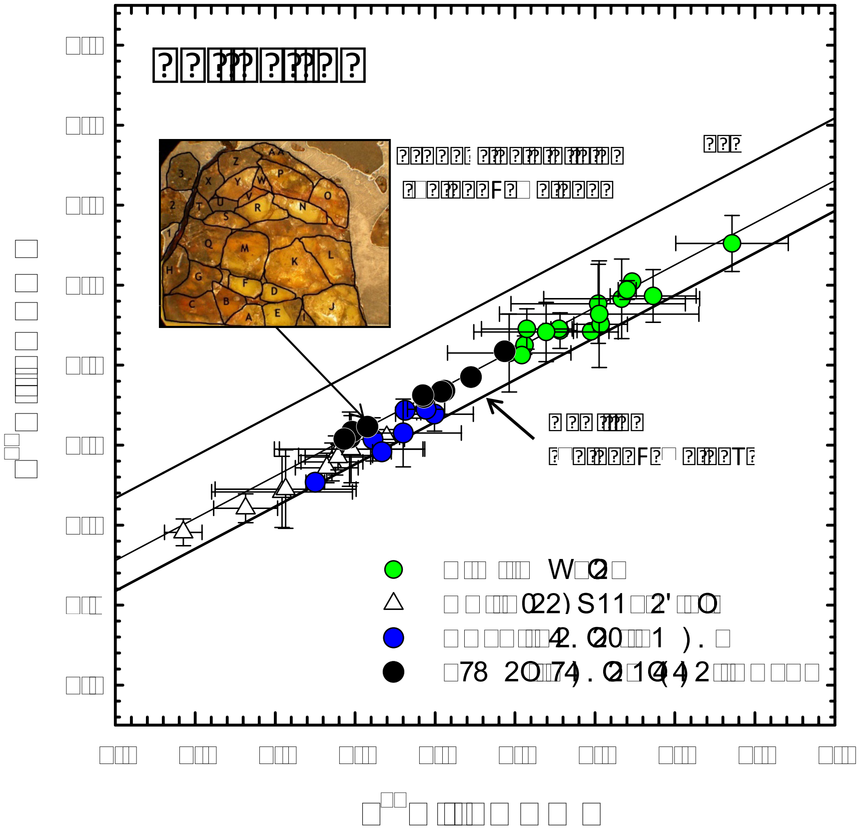
$$\delta^{17}\mathrm{O}_a - \delta^{17}\mathrm{O}_b \cong 10^3 \ln \alpha_{a-b}^{17/16} = \frac{10^3}{24}\left(\frac{h}{k_b T}\right)^2 \left(\frac{1}{m_{16}} - \frac{1}{m_{17}}\right)\left[\sum_{j=1}^{3N_a-3}\frac{K_{f,j,a}}{4\pi^2} - \sum_{j=1}^{3N_b-3}\frac{K_{f,j,b}}{4\pi^2}\right]$$

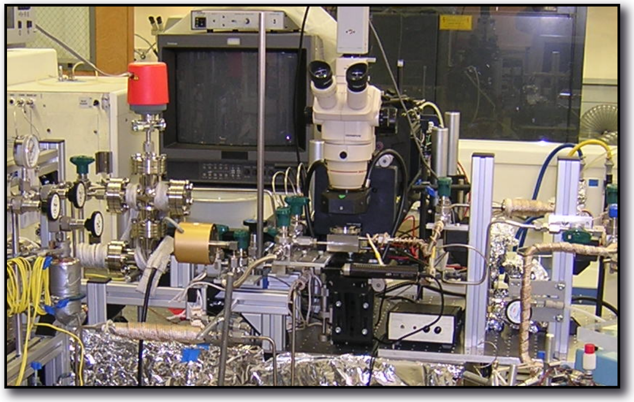
$$\delta^{18}\mathrm{O}_a - \delta^{18}\mathrm{O}_b \cong 10^3 \ln \alpha_{a-b}^{18/16} = \frac{10^3}{24}\left(\frac{h}{k_b T}\right)^2 \left(\frac{1}{m_{16}} - \frac{1}{m_{18}}\right)\left[\sum_{j=1}^{3N_a-3}\frac{K_{f,j,a}}{4\pi^2} - \sum_{j=1}^{3N_b-3}\frac{K_{f,j,b}}{4\pi^2}\right]$$

$$\frac{\delta^{17}\mathrm{O}_a - \delta^{17}\mathrm{O}_b}{\delta^{18}\mathrm{O}_a - \delta^{18}\mathrm{O}_b} = \frac{\left(\frac{1}{m_{16}} - \frac{1}{m_{17}}\right)}{\left(\frac{1}{m_{16}} - \frac{1}{m_{18}}\right)} = 0.531$$

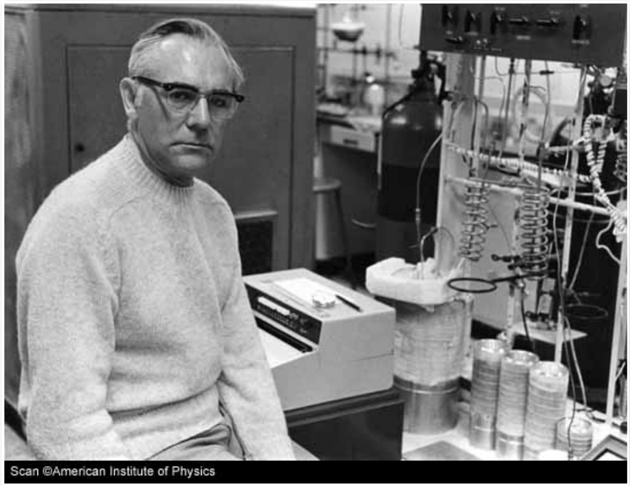
Mass-dependent fractionation

Isotope fractionation



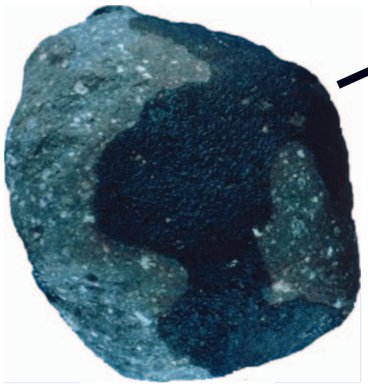


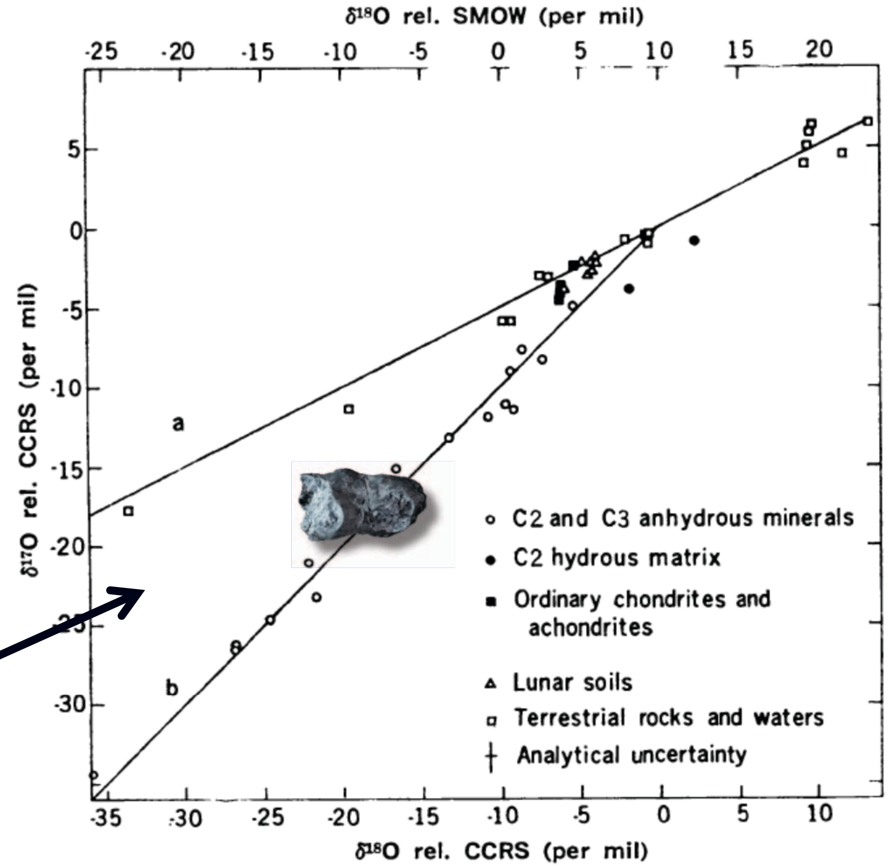
$$\delta^{17}\mathrm{O}/\delta^{18}\mathrm{O} = \frac{\left(\frac{1}{m_{16}} - \frac{1}{m_{17}}\right)}{\left(\frac{1}{m_{16}} - \frac{1}{m_{18}}\right)} = 0.531$$



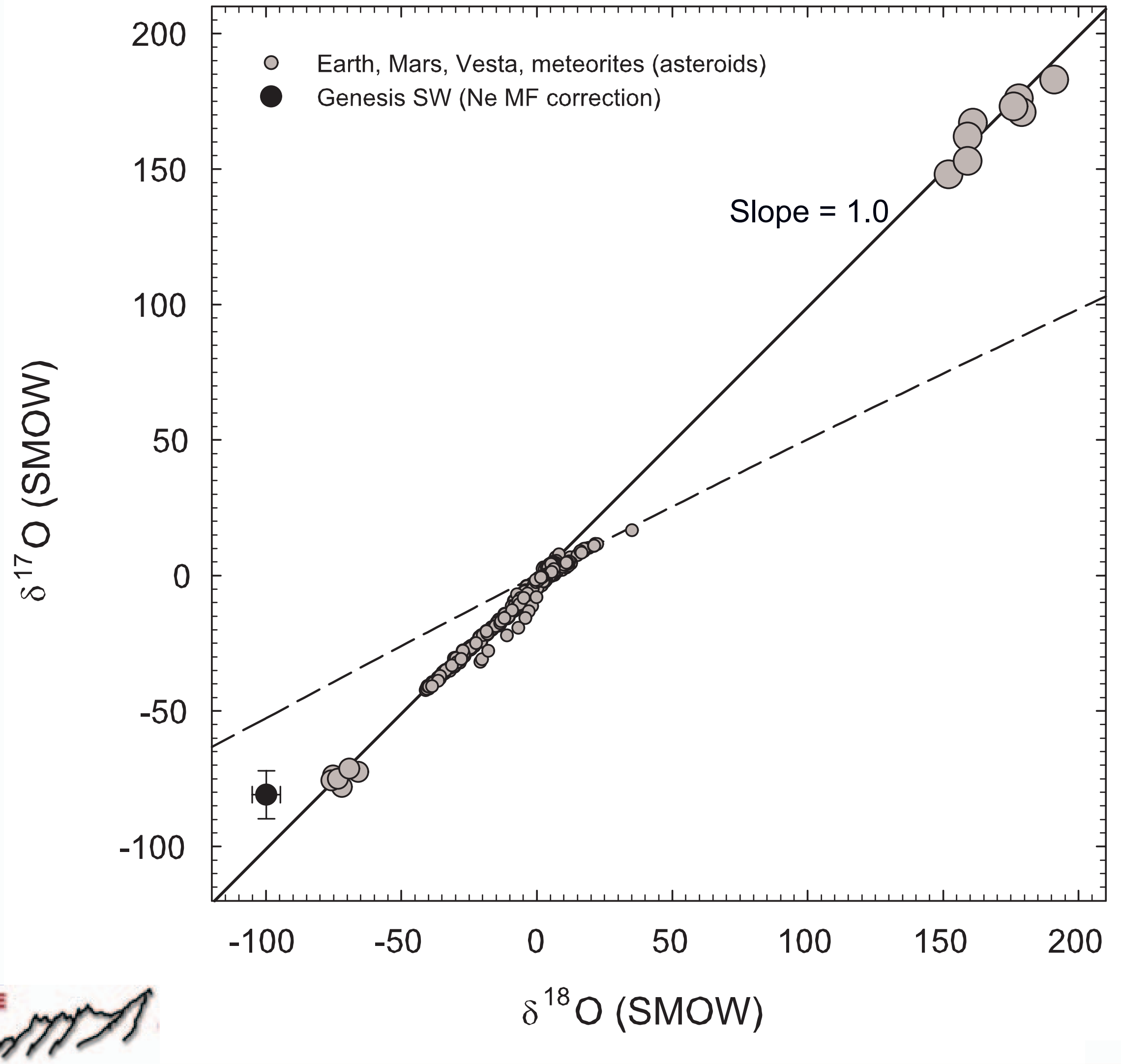
Scan ©American Institute of Physics

Robert N. Clayton





1973: oxygen isotope anomaly in meteorites (CAIs)



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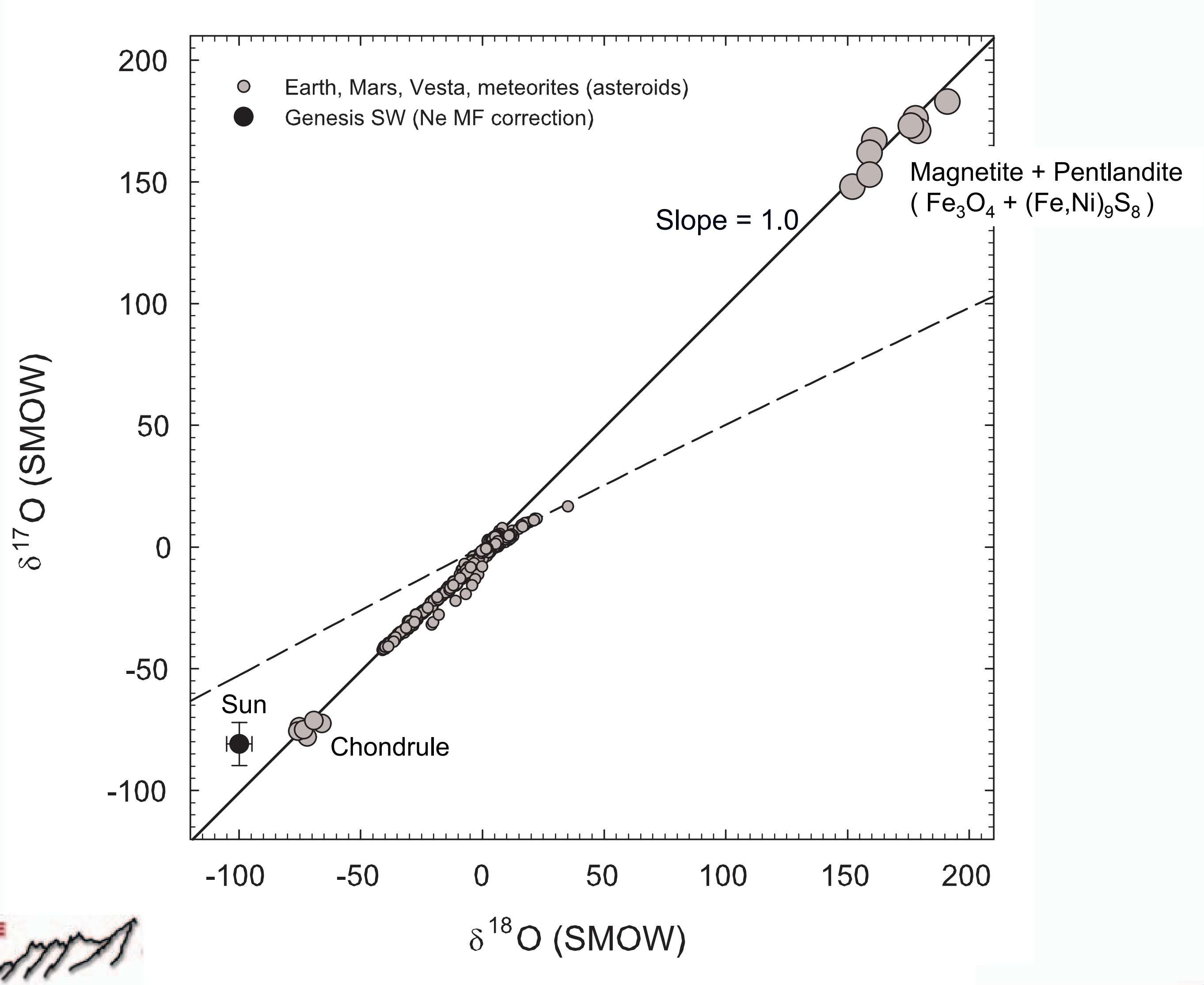
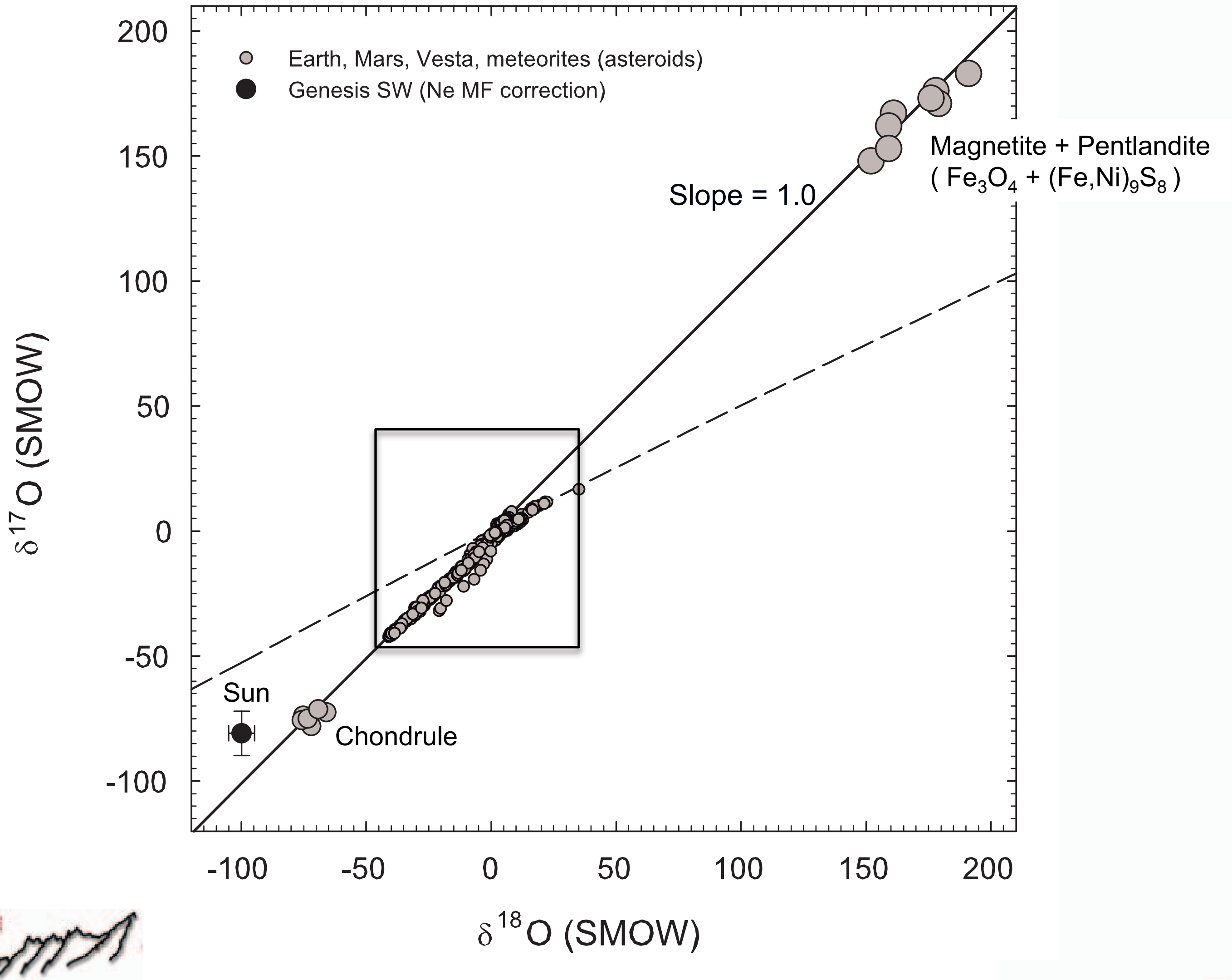


200
150
100
50
0
-50
-100
-100
-50
0
50
100
150
200
● Earth, Mars, Vesta, meteorites (asteroids)
● Genesis SW (Ne MF correction)
Slope = 1.0
Magnetite + Pentlandite
(Fe_3O_4 + $(Fe,Ni)_9S_8$)
Sun
Chondrule
$\delta^{17}O$ (SMOW)
$\delta^{18}O$ (SMOW)



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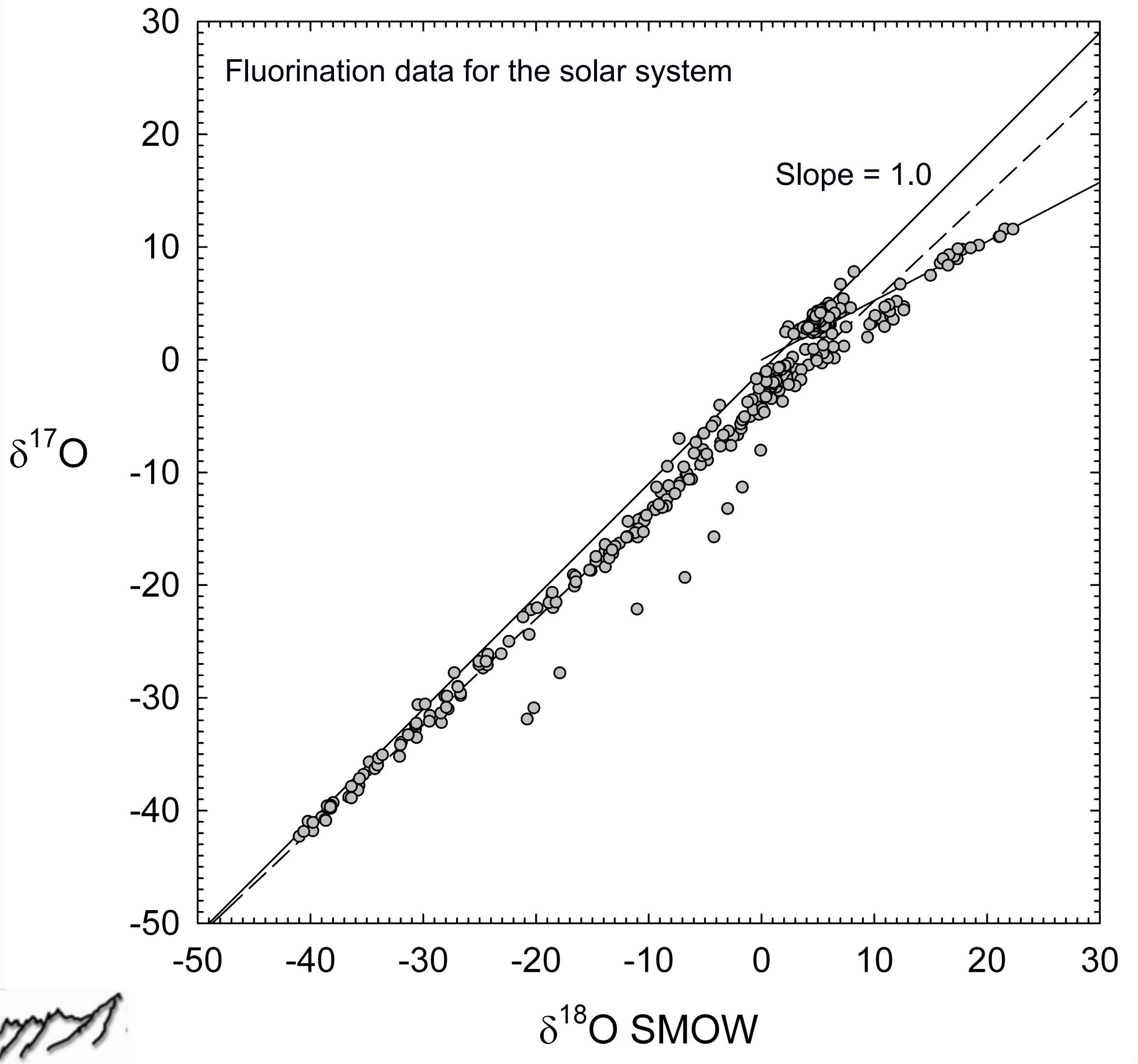

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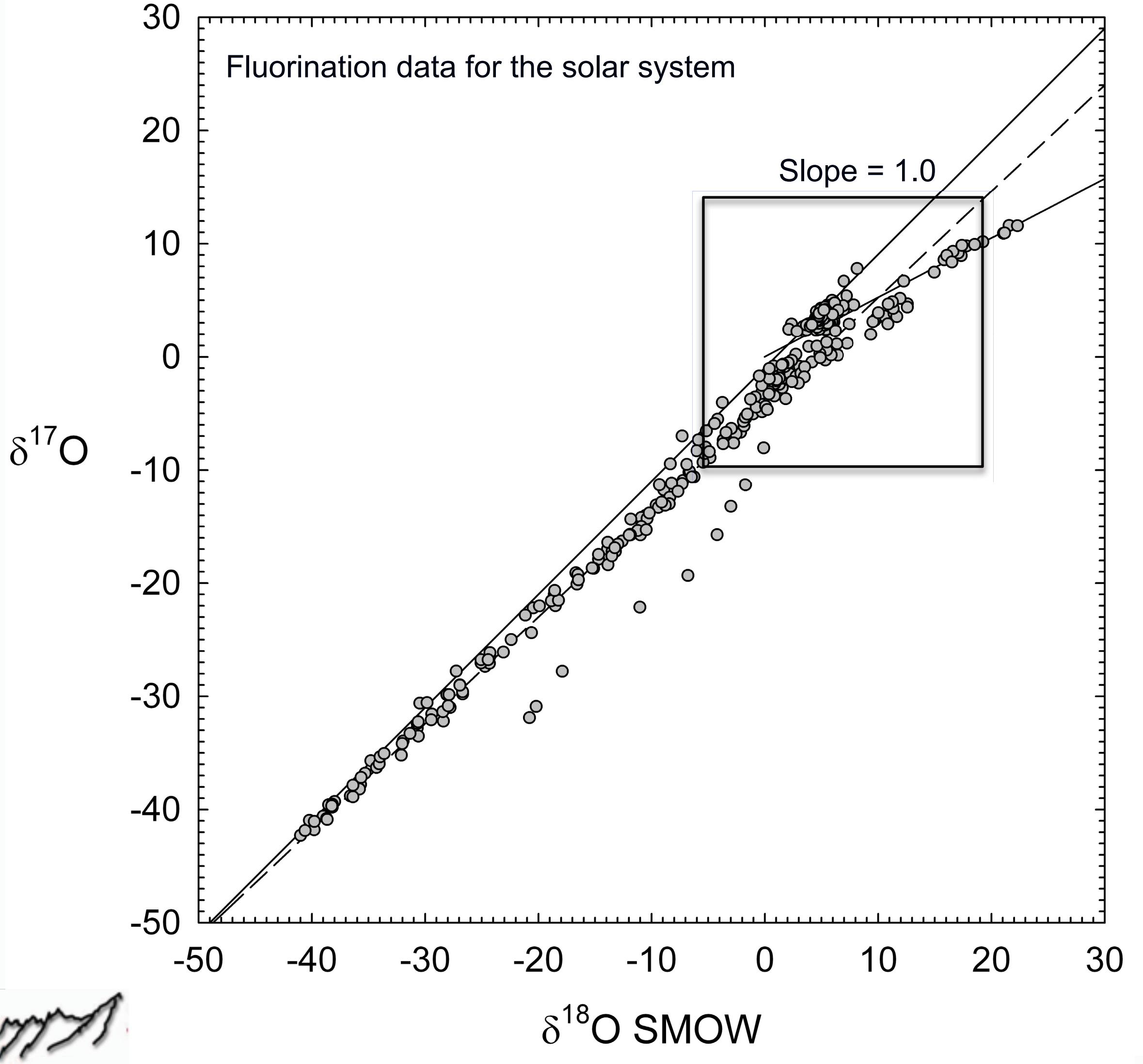
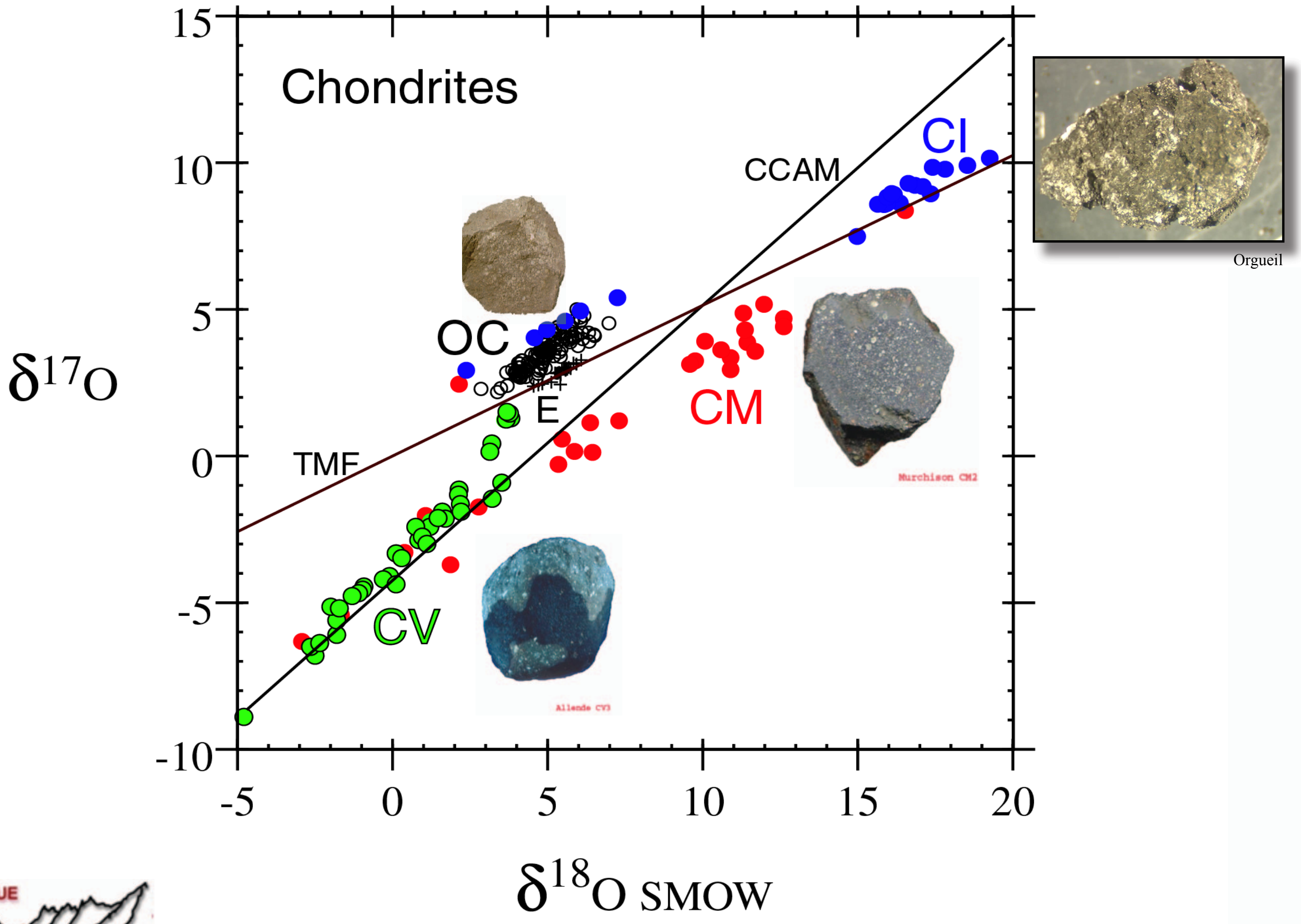


Fluorination data for the solar system
Slope = 1.0
δ17O
δ18O SMOW
30
20
10
0
-10
-20
-30
-40
-50
-50
-40
-30
-20
-10
0
10
20
30



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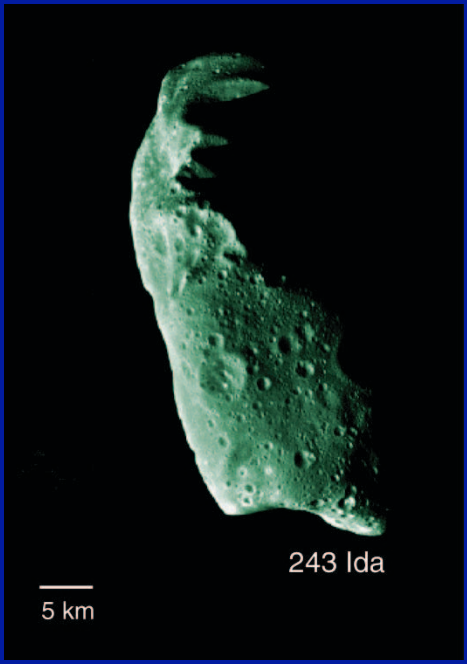
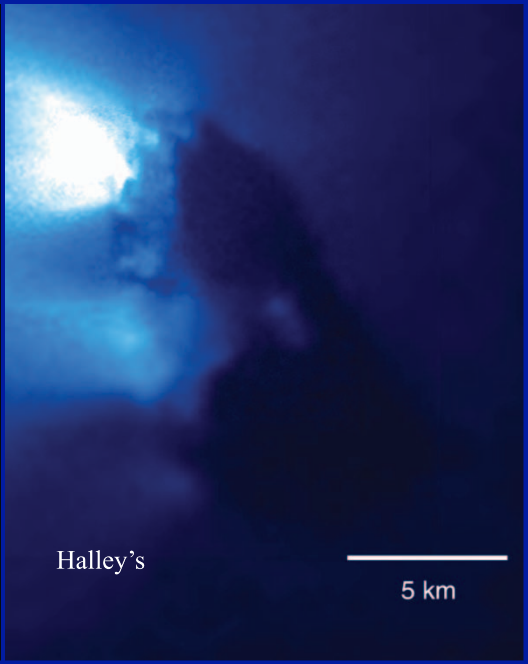
Planetesimal hydrology:

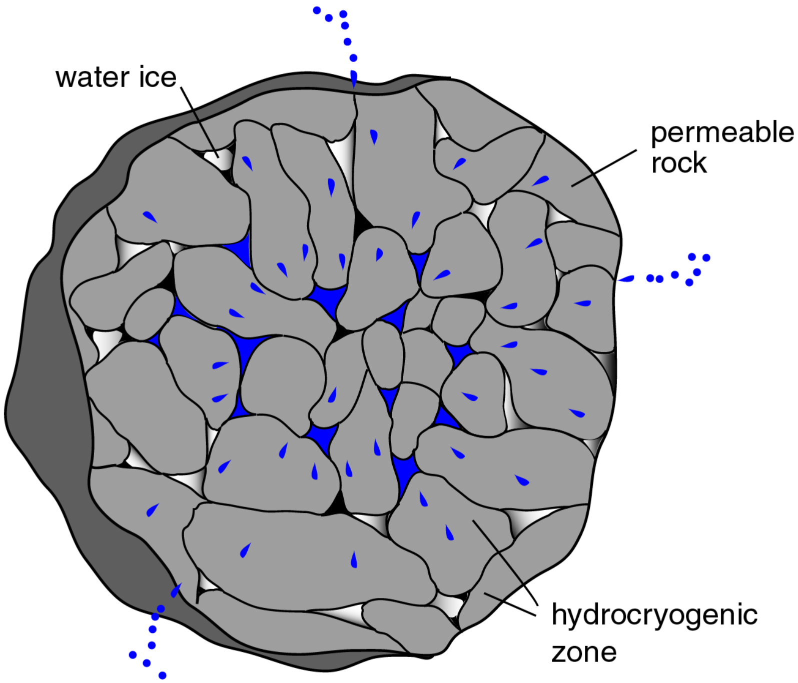


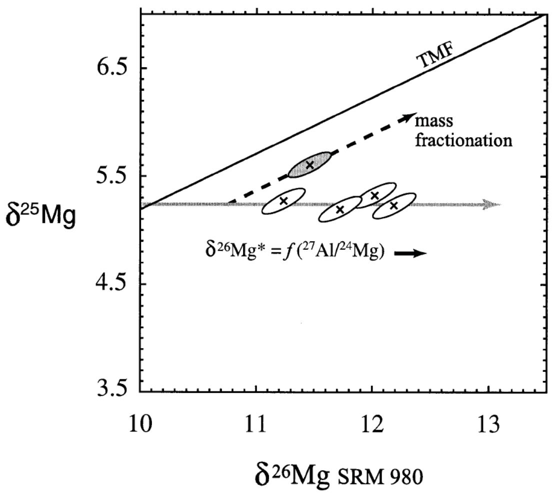


^{26}Al (half life = 0.7 Myr) = heat source in the early solar system

$$^{26}\mathrm{Al} \rightarrow {}^{26}\mathrm{Mg}^{*}$$

$$Q = 6 \times 10^{\square 3} \, (^{26}\mathrm{Al}/^{27}\mathrm{Al})_{\square} \exp(\square\lambda t) \quad \mathrm{W/kg}$$

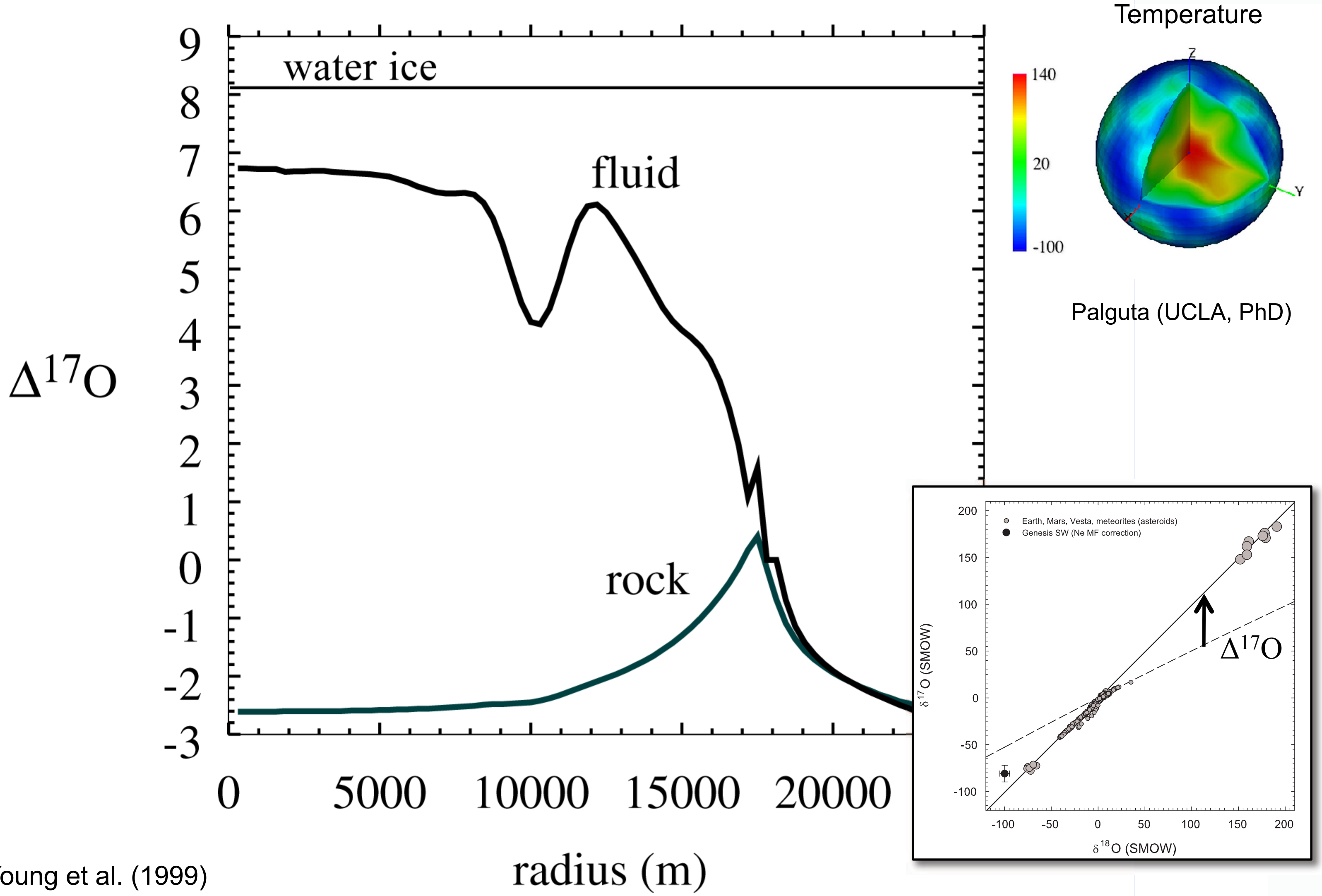




Water ice melts, water flows

Hydrology not unlike terrestrial water-rock systems

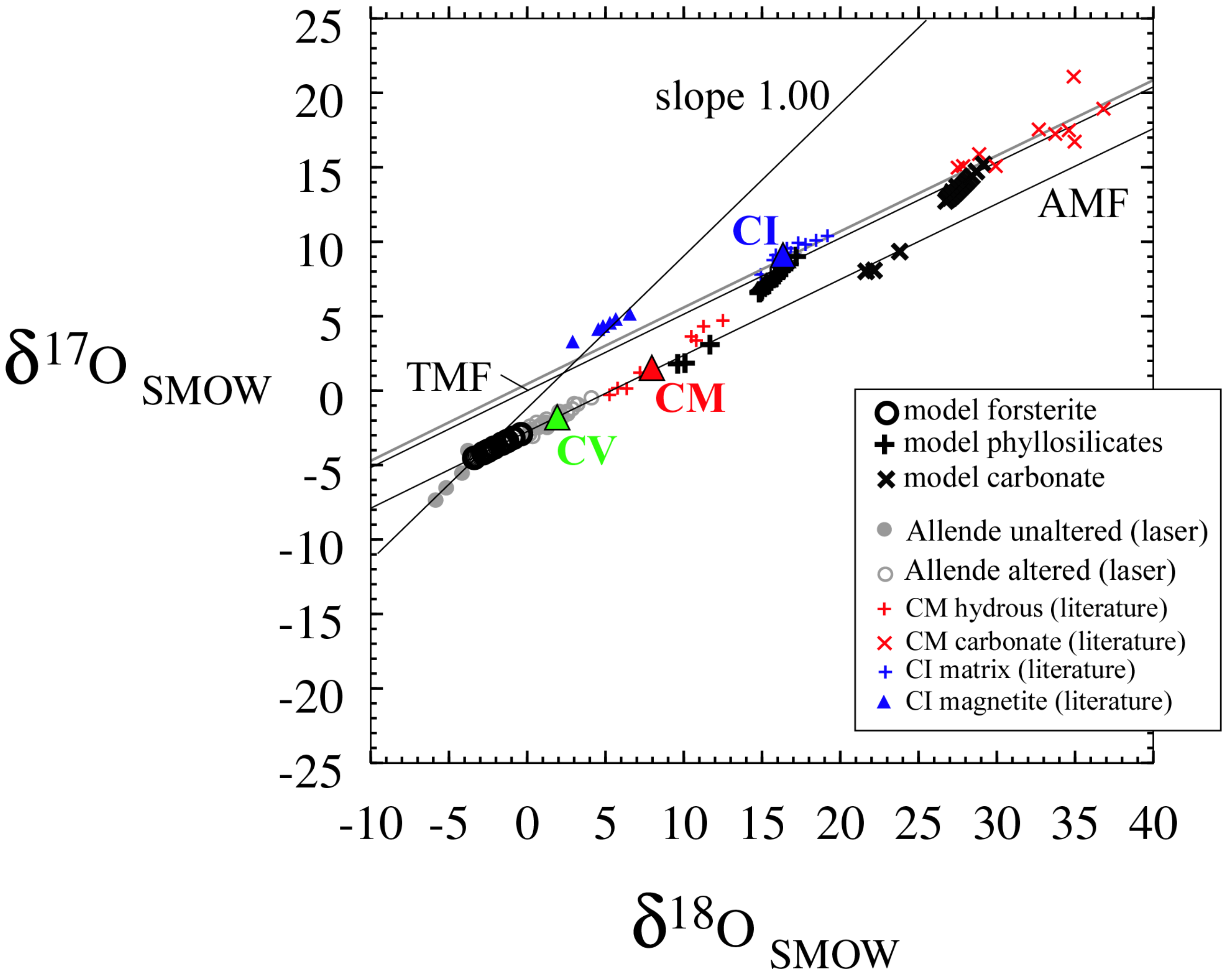
Kinetic models for fluid flow



Palguta (UCLA, PhD)

After Young et al. (1999)

Kinetic models for fluid flow



After Young et al. (1999)

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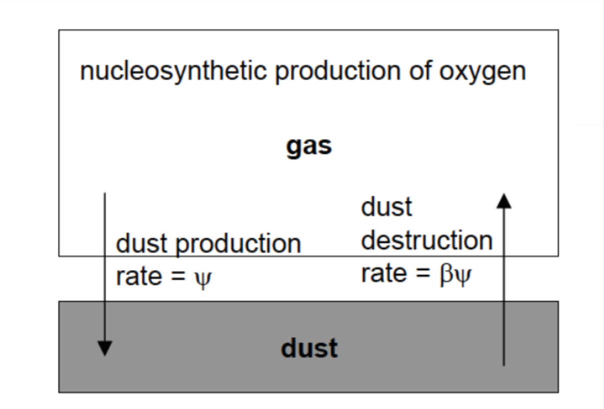
Explanations:

Galactic Chemical Evolution Preserved in Dust and Gas

(e.g., D.D. Clayton 1988; Jacobsen et al. 2007)



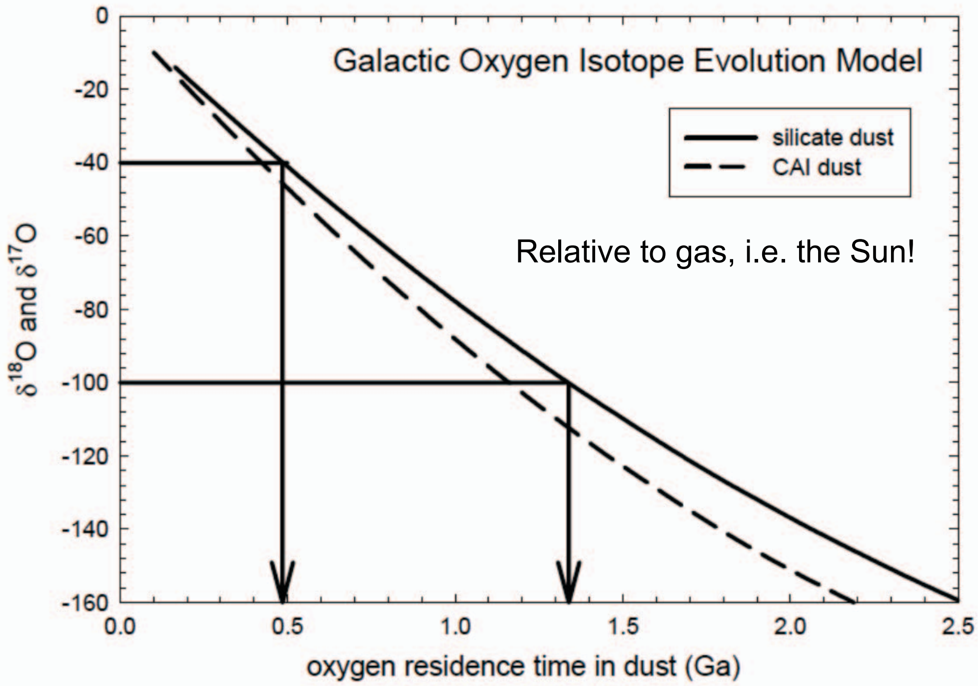
nucleosynthetic production of oxygen

gas

dust production rate = ψ

dust destruction rate = $\beta\psi$

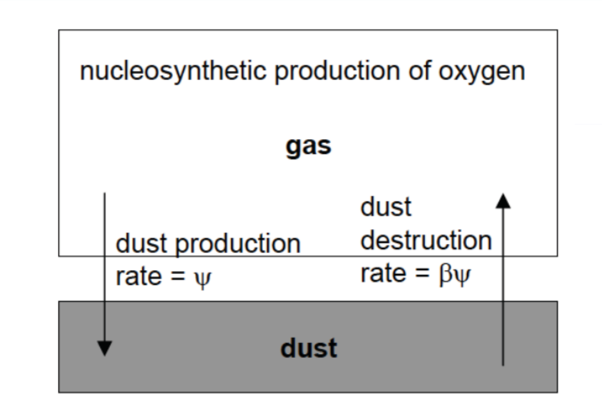
dust

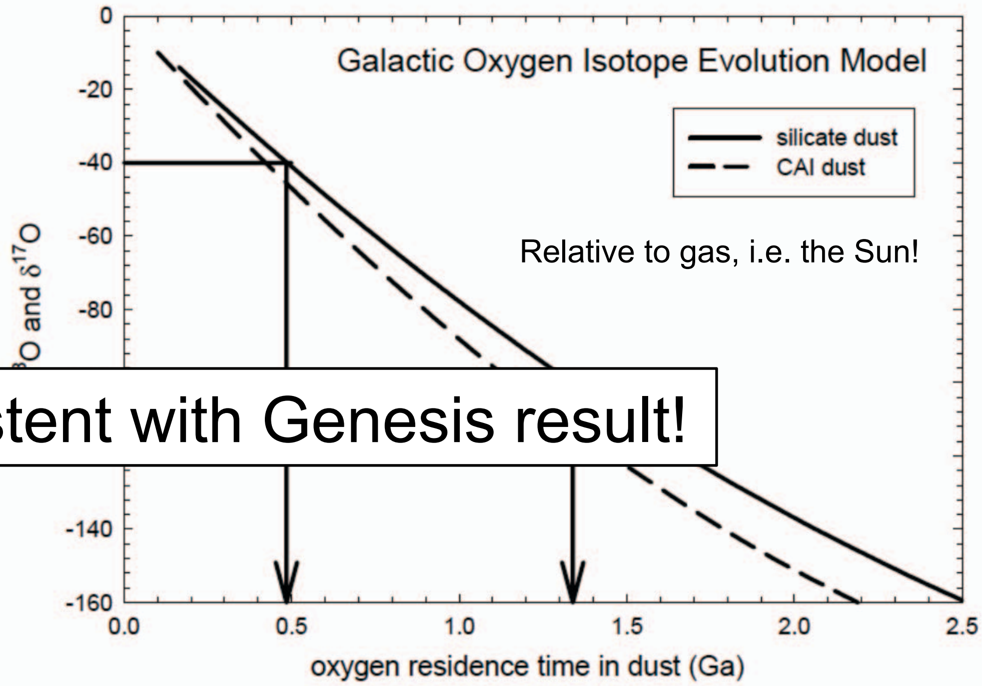


Relative to gas, i.e. the Sun!

Galactic Chemical Evolution Preserved in Dust and Gas

(e.g., D.D. Clayton 1988; Jacobsen et al. 2007)





Relative to gas, i.e. the Sun!

Inconsistent with Genesis result!

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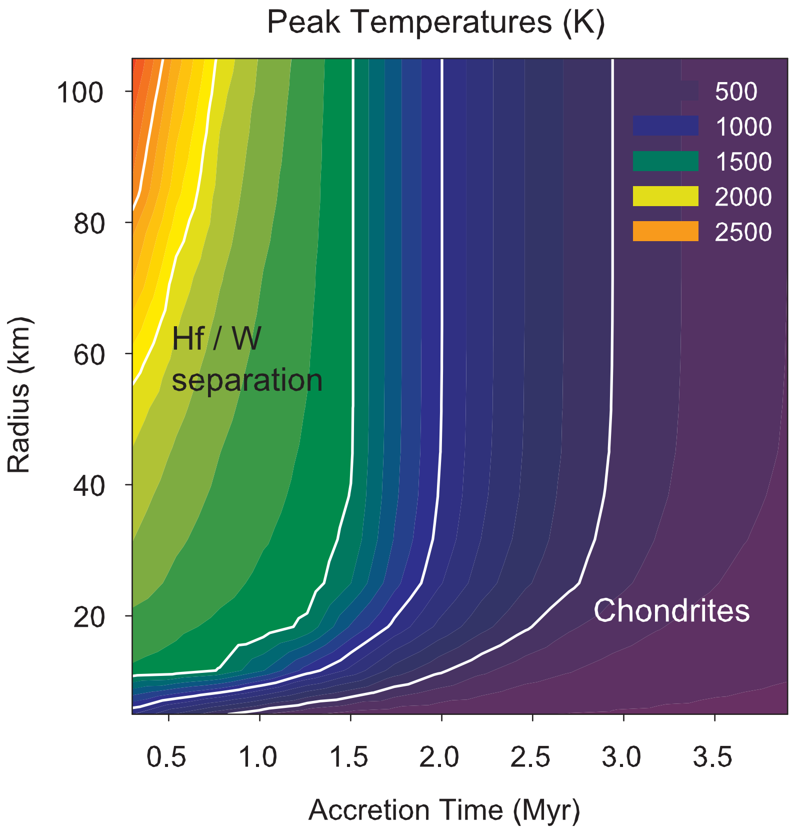
Galactic Chemical Evolution Preserved in Dust and Gas

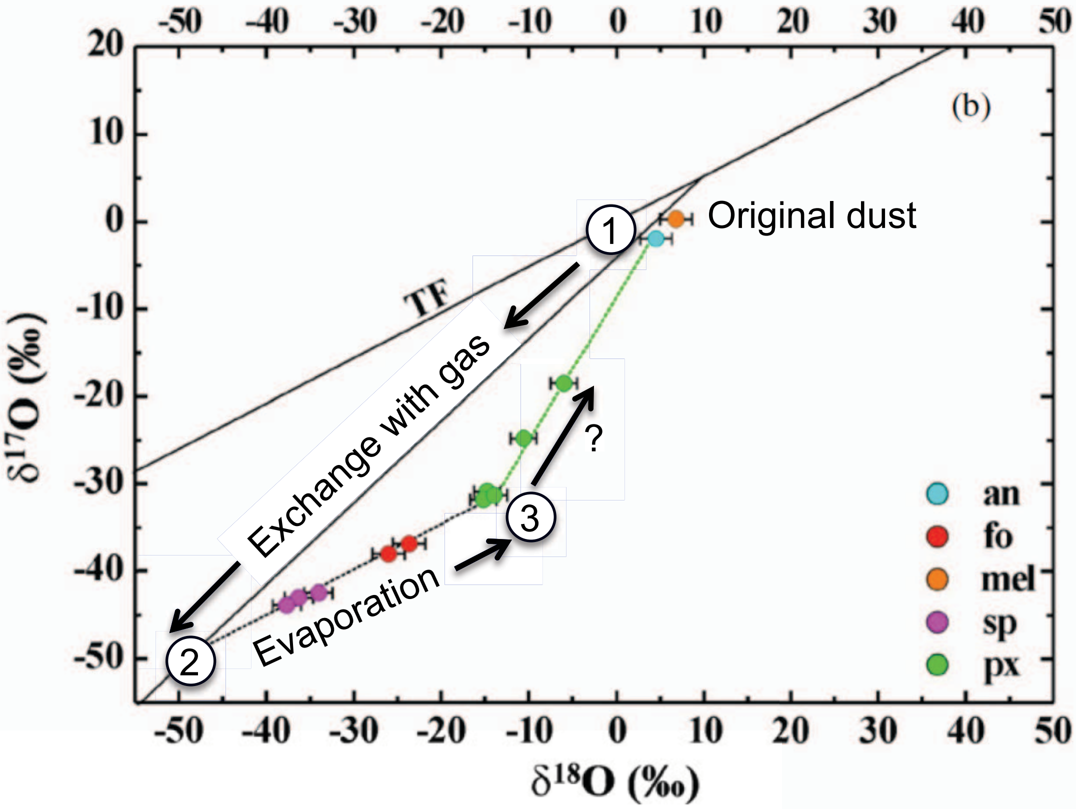
(Krot et al., 2010)

Differentiated asteroids formed early but are ^{16}O poor.

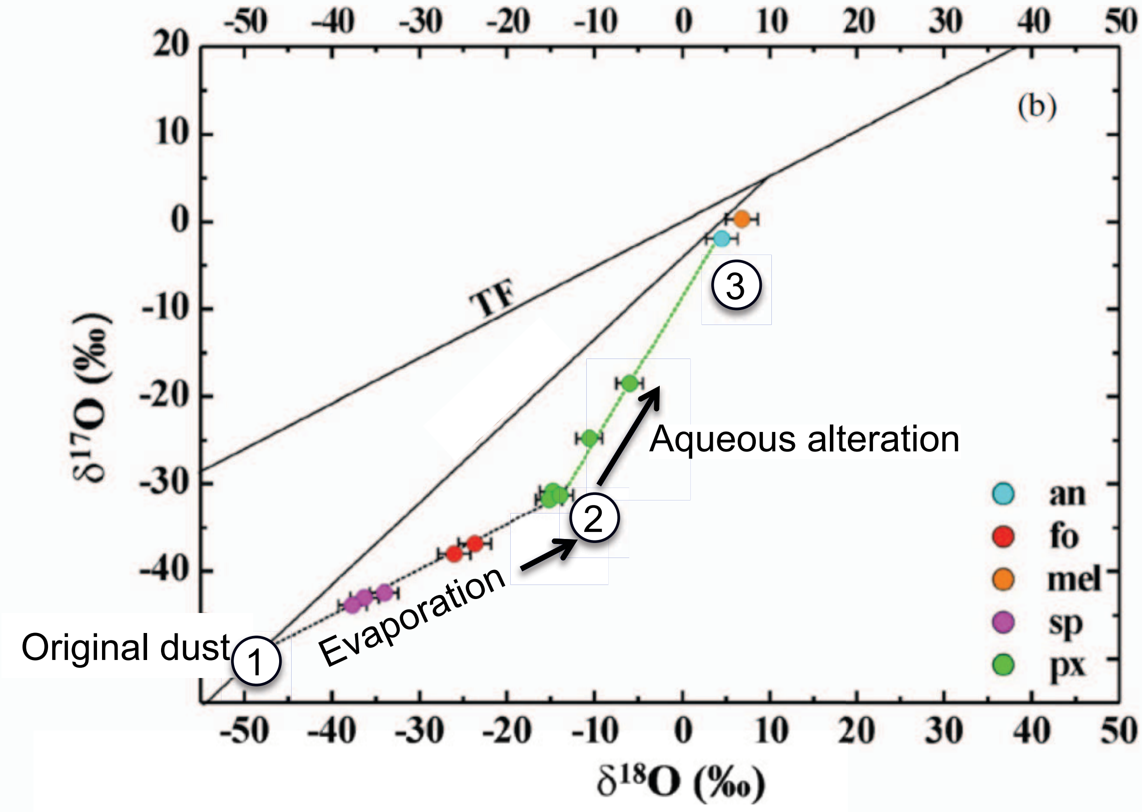


Young (2011, MetSoc)

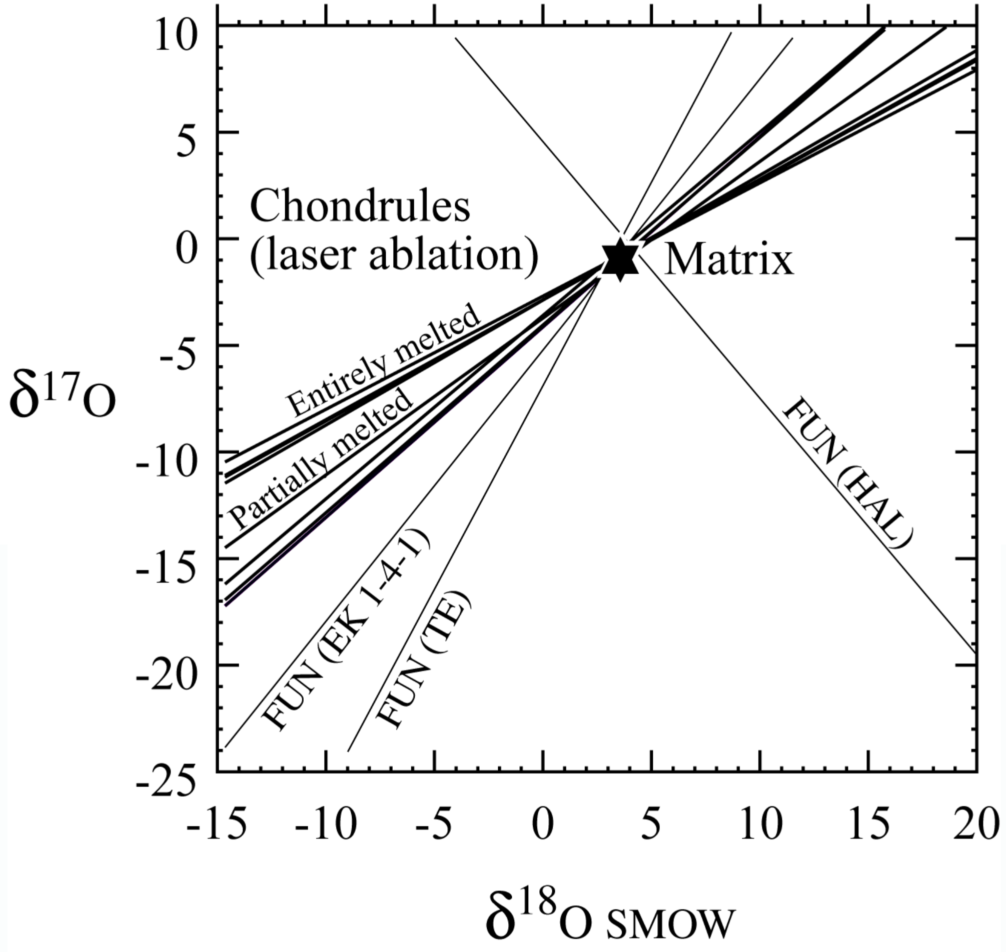
Galactic Chemical Evolution Preserved in Dust and Gas: Dust was ^{16}O poor? (Krot et al., 2010)



Two-stage alternative:



Galactic Chemical Evolution or Simply Aqueous Alteration?

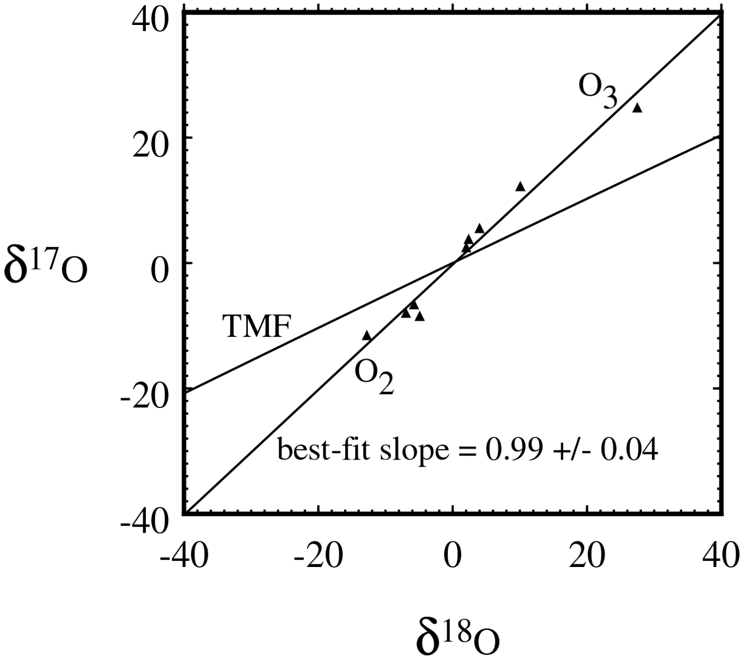


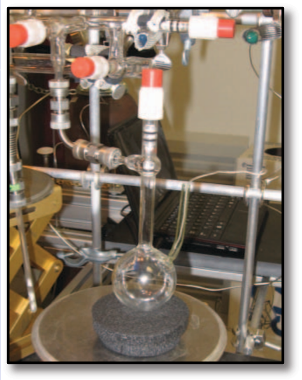
Intramolecular disequilibrium (Non-RRKM) effects

Mass-independent fractionation (MIF)

Thiemens and others, since 1983

$O + O_2 = O_3$ (electrical discharge)

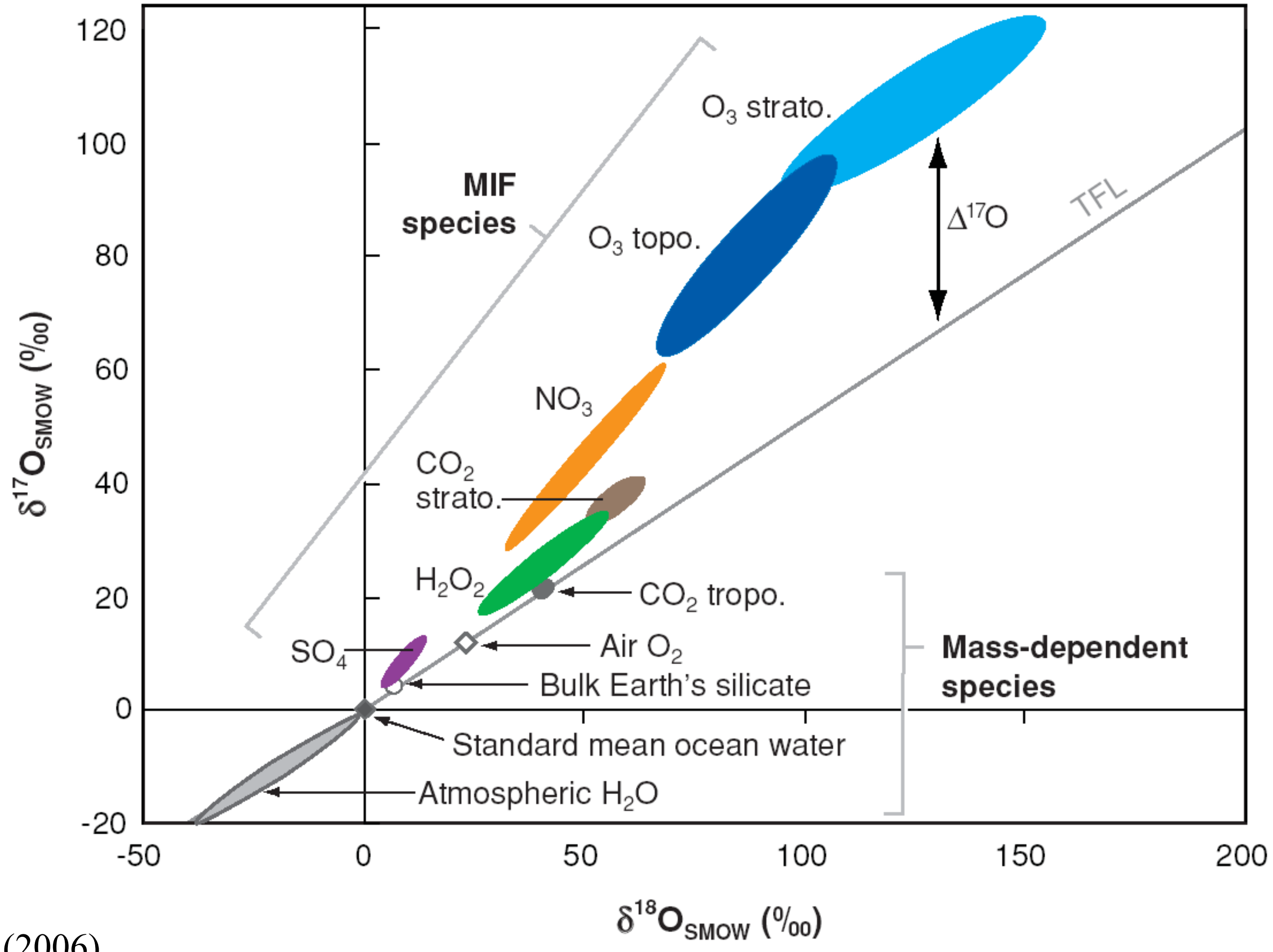




(Young and Hoering, unpub. data 1993)

P^O= 44-101 torr

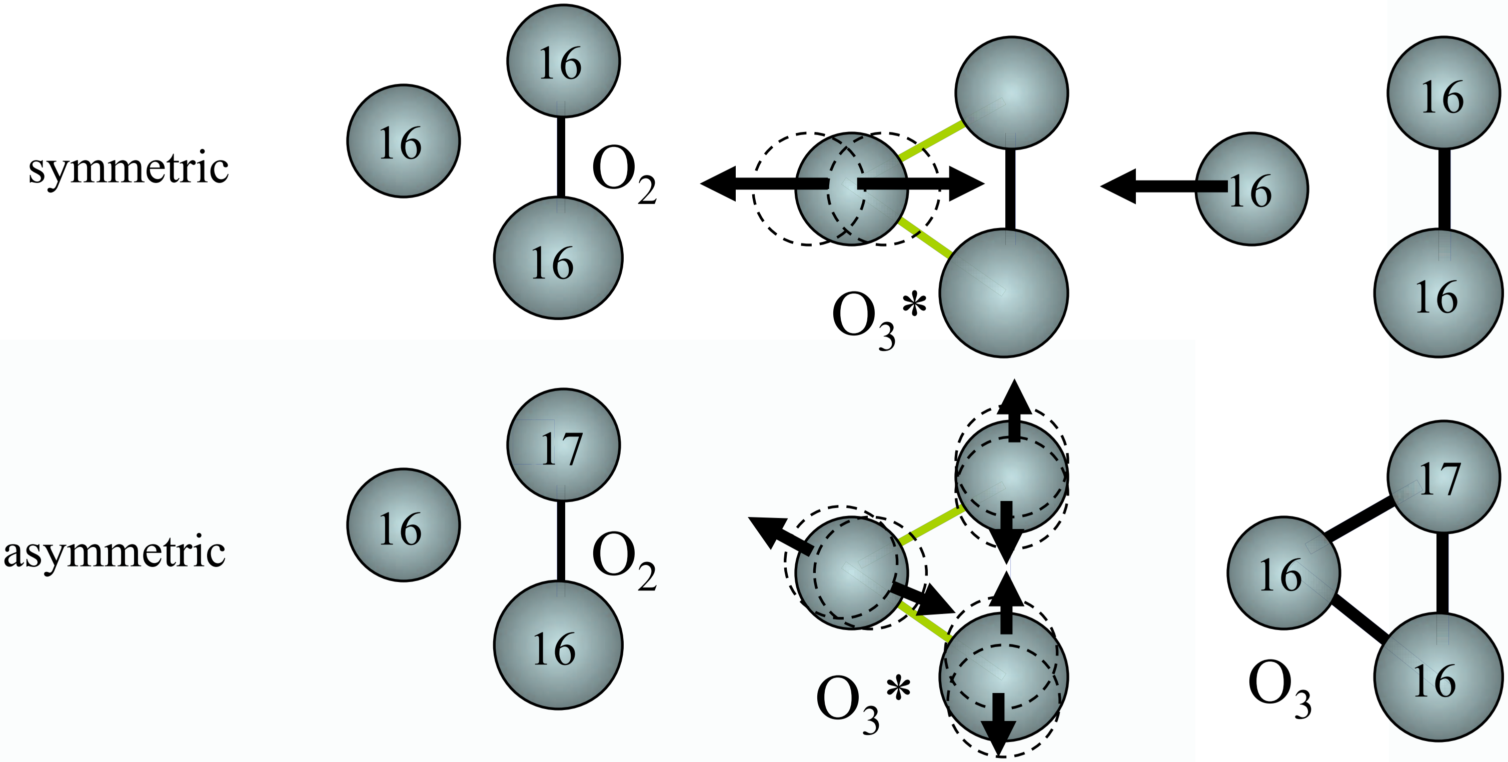
Intramolecular disequilibrium (Non-RRKM) effects



Thiemens (2006)

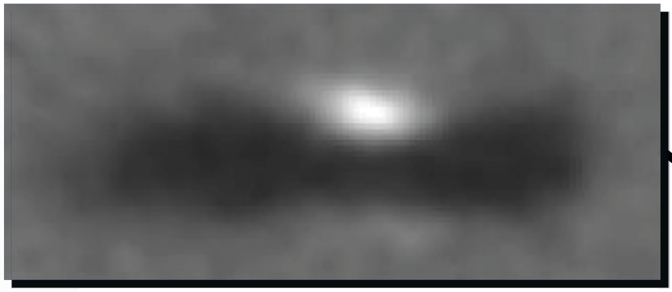
Intramolecular disequilibrium (Non-RRKM) effects

Rudolph A. Marcus proposes, with coworkers (1999 to 2004):
-A mechanism for the ozone mass independent fractionation (MIF) effect
-Departure from intramolecular equilibrium in the vibrationally excited state of the symmetrical isotopologue
-The so-called η effect…(non RRKM)

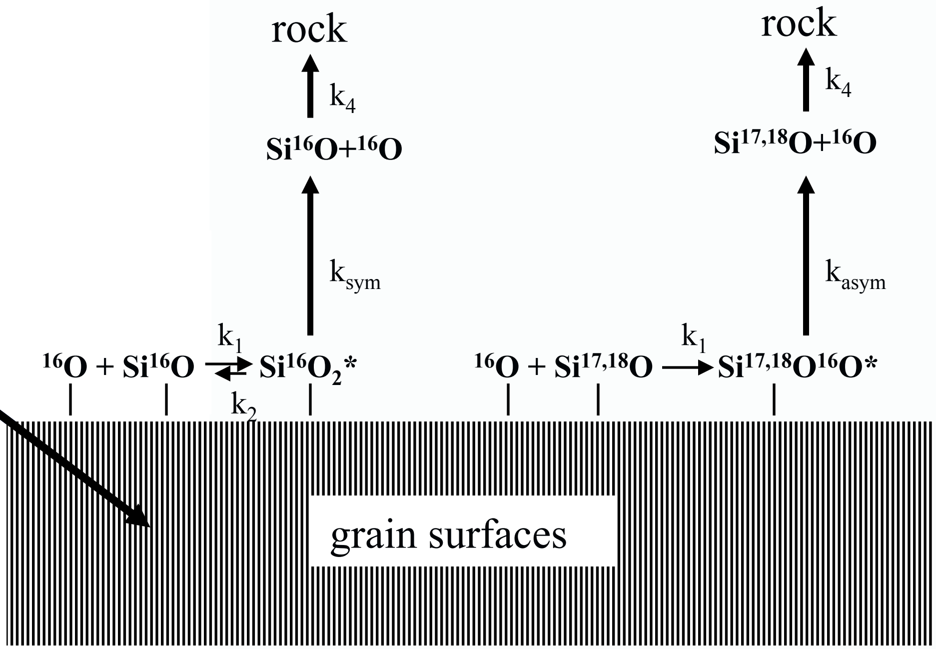


Intramolecular disequilibrium (Non-RRKM) effects

Marcus (2004) – analogous to ozone but mediated by grain surfaces…



Dusty disk environment



rock

$\uparrow k_4$

$Si^{16}O + {}^{16}O$

$\uparrow k_{sym}$

$^{16}O + Si^{16}O \underset{k_2}{\overset{k_1}{\rightleftarrows}} Si^{16}O_2^*$

rock

$\uparrow k_4$

$Si^{17,18}O + {}^{16}O$

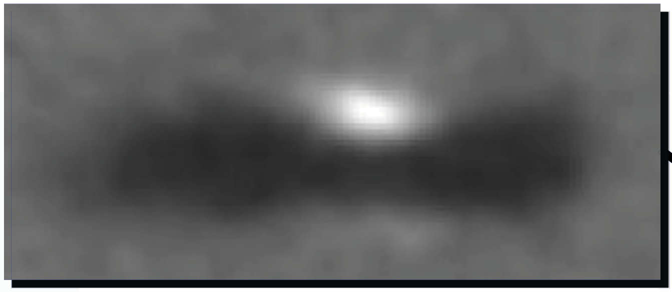
$\uparrow k_{asym}$

$^{16}O + Si^{17,18}O \xrightarrow{k_1} Si^{17,18}O^{16}O^*$

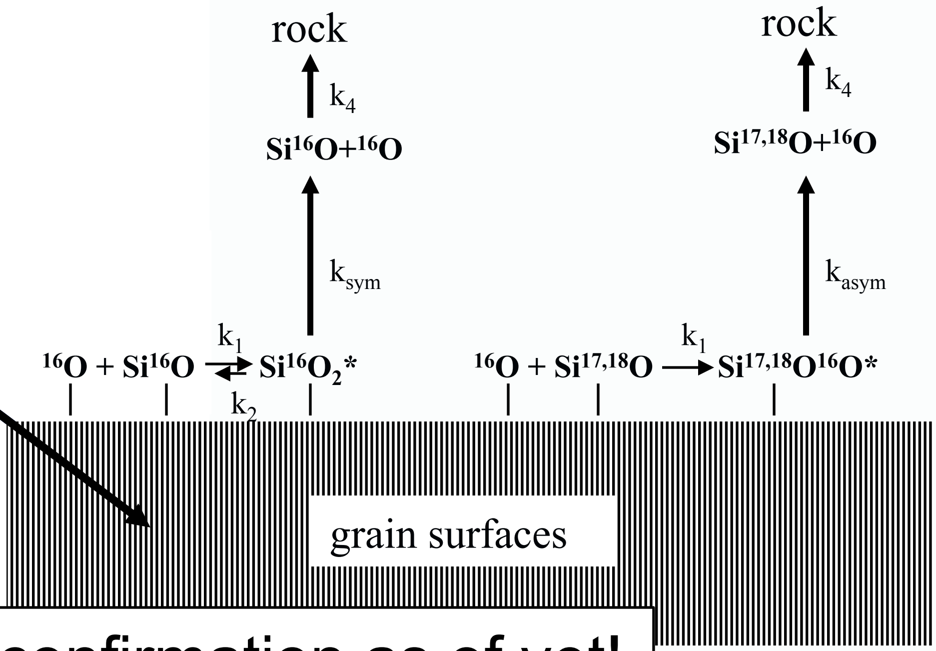
grain surfaces

Intramolecular disequilibrium (Non-RRKM) effects

Marcus (2004) – analogous to ozone but mediated by grain surfaces…



Dusty disk environment

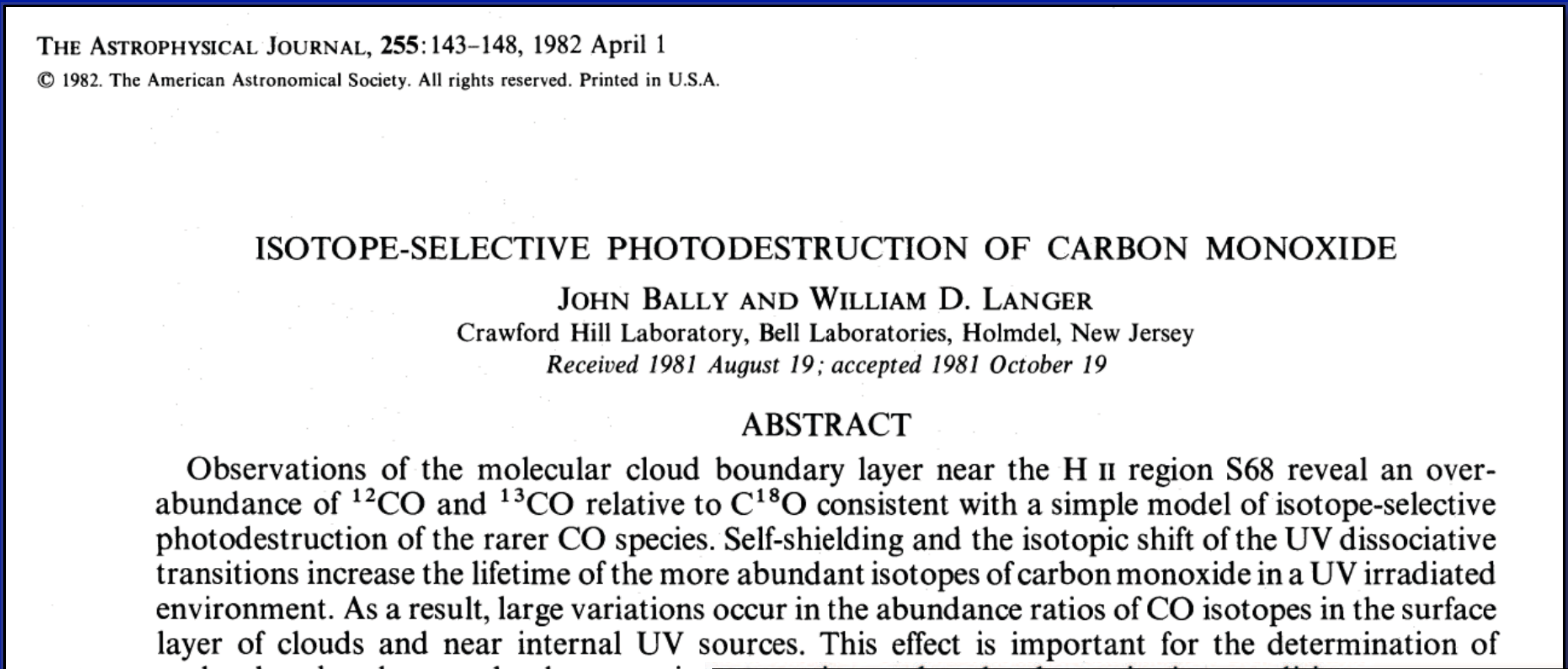


$^{16}O + Si^{16}O \underset{k_2}{\overset{k_1}{\rightleftarrows}} Si^{16}O_2^* \xrightarrow{k_{sym}} Si^{16}O + ^{16}O \xrightarrow{k_4} \text{rock}$

$^{16}O + Si^{17,18}O \xrightarrow{k_1} Si^{17,18}O^{16}O^* \xrightarrow{k_{asym}} Si^{17,18}O + ^{16}O \xrightarrow{k_4} \text{rock}$

grain surfaces

No experimental confirmation as of yet!



The Astrophysical Journal, **255**: 143–148, 1982 April 1

ISOTOPE-SELECTIVE PHOTODESTRUCTION OF CARBON MONOXIDE

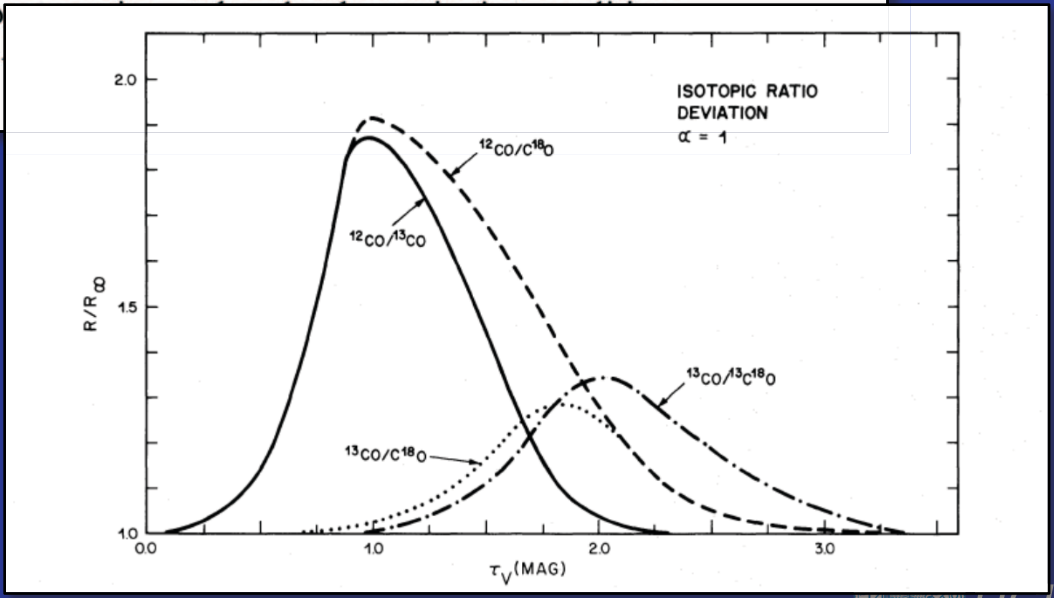
John Bally and William D. Langer
Crawford Hill Laboratory, Bell Laboratories, Holmdel, New Jersey

Received 1981 August 19; accepted 1981 October 19

ABSTRACT

Observations of the molecular cloud boundary layer near the H II region S68 reveal an over-abundance of ^{12}CO and ^{13}CO relative to C^{18}O consistent with a simple model of isotope-selective photodestruction of the rarer CO species. Self-shielding and the isotopic shift of the UV dissociative transitions increase the lifetime of the more abundant isotopes of carbon monoxide in a UV irradiated environment. As a result, large variations occur in the abundance ratios of CO isotopes in the surface layer of clouds and near internal UV sources. This effect is important for the determination of molecular abundances, cloud masses, iso

Subject headings: interstellar: molecules
nebulae: H II regions



$$N_i = \int_0^z n_i(Z)\,dz$$

$$\sigma_\nu = \phi_\nu \frac{\pi e^2}{m_e c} f_\nu$$

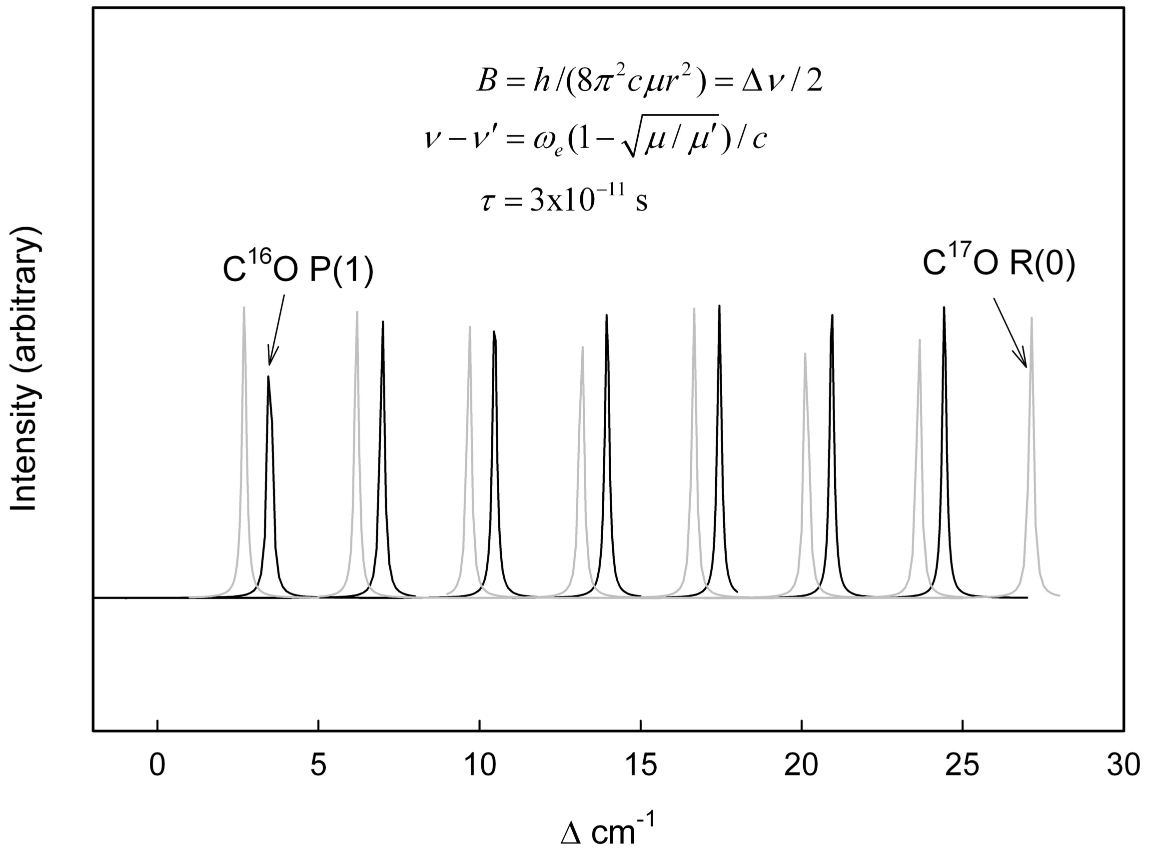
$$\frac{I_\lambda}{I_\lambda^o} = \prod_i \Theta_i(N_i)$$

$$= \prod_i \exp(-\tau_i)$$

$$= \prod_i \exp(-\sigma_i N_i)$$

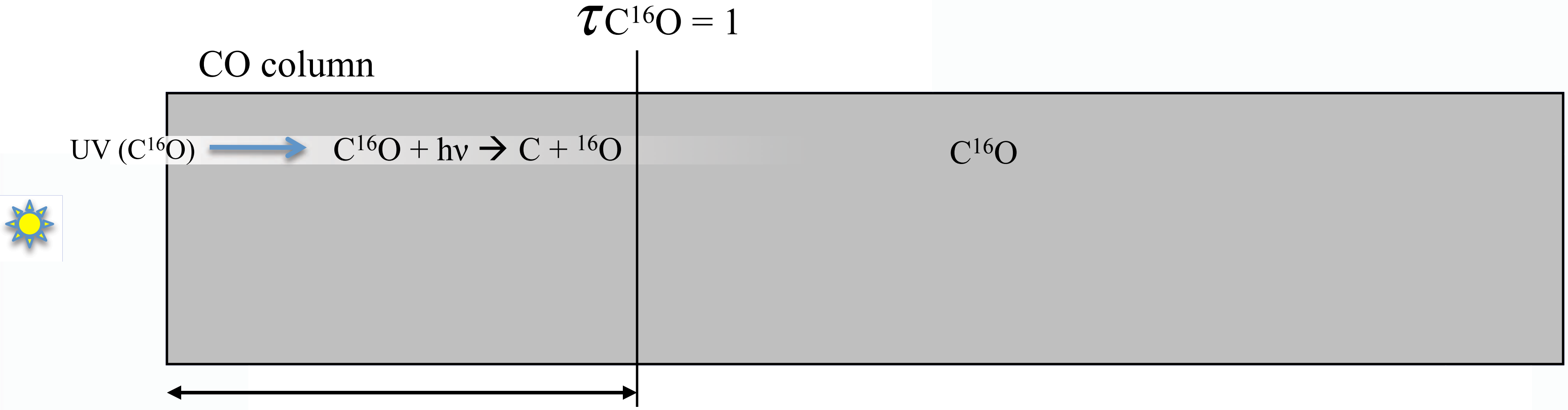
$$k = J^{\circ}\prod_i \exp(-\tau_i)$$

$$\alpha = \frac{k'}{k} = \frac{\prod_i \exp(-\sigma_i N_i')}{\prod_i \exp(-\sigma_i N_i')}$$


$B = h/(8\pi^2 c\mu r^2) = \Delta\nu/2$
$\nu - \nu' = \omega_e(1-\sqrt{\mu/\mu'})/c$
$\tau = 3\text{x}10^{-11}$ s
$C^{16}O$ P(1)
$C^{17}O$ R(0)
Intensity (arbitrary)
0
5
10
15
20
25
30
Δ cm^{-1}

CO photodissociation self shielding

$$I_\nu / I_\nu^o = e^{-\tau}$$



$\tau C^{16}O = 1$

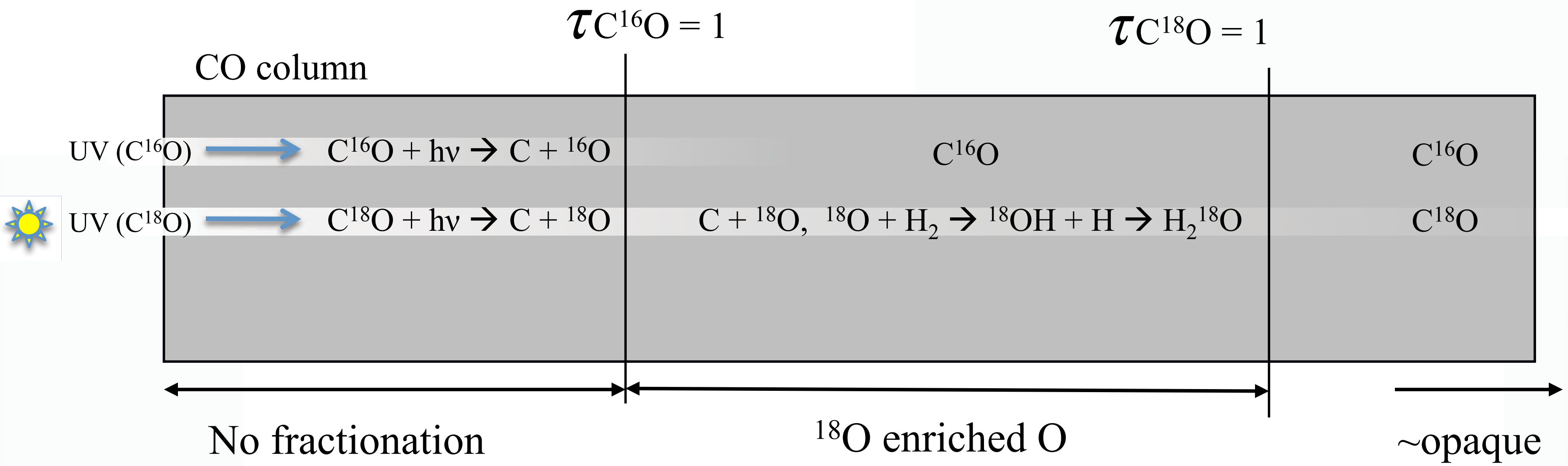
CO column

UV ($C^{16}O$) → $C^{16}O + h\nu \rightarrow C + {}^{16}O$

$C^{16}O$

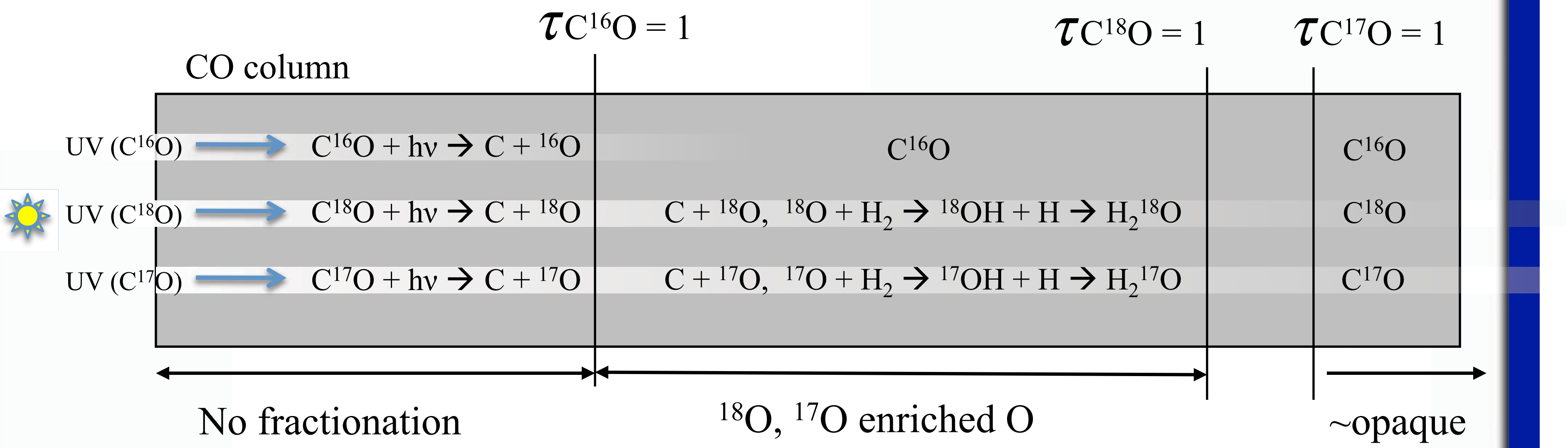
CO photodissociation self shielding

$$I_\nu / I_\nu^o = e^{-\tau}$$



CO photodissociation self shielding

$$I_\nu / I_\nu^o = e^{-\tau}$$



$\tau C^{16}O = 1$

$\tau C^{18}O = 1$

$\tau C^{17}O = 1$

CO column

UV ($C^{16}O$) → $C^{16}O + h\nu \rightarrow C + {}^{16}O$ | $C^{16}O$ | $C^{16}O$

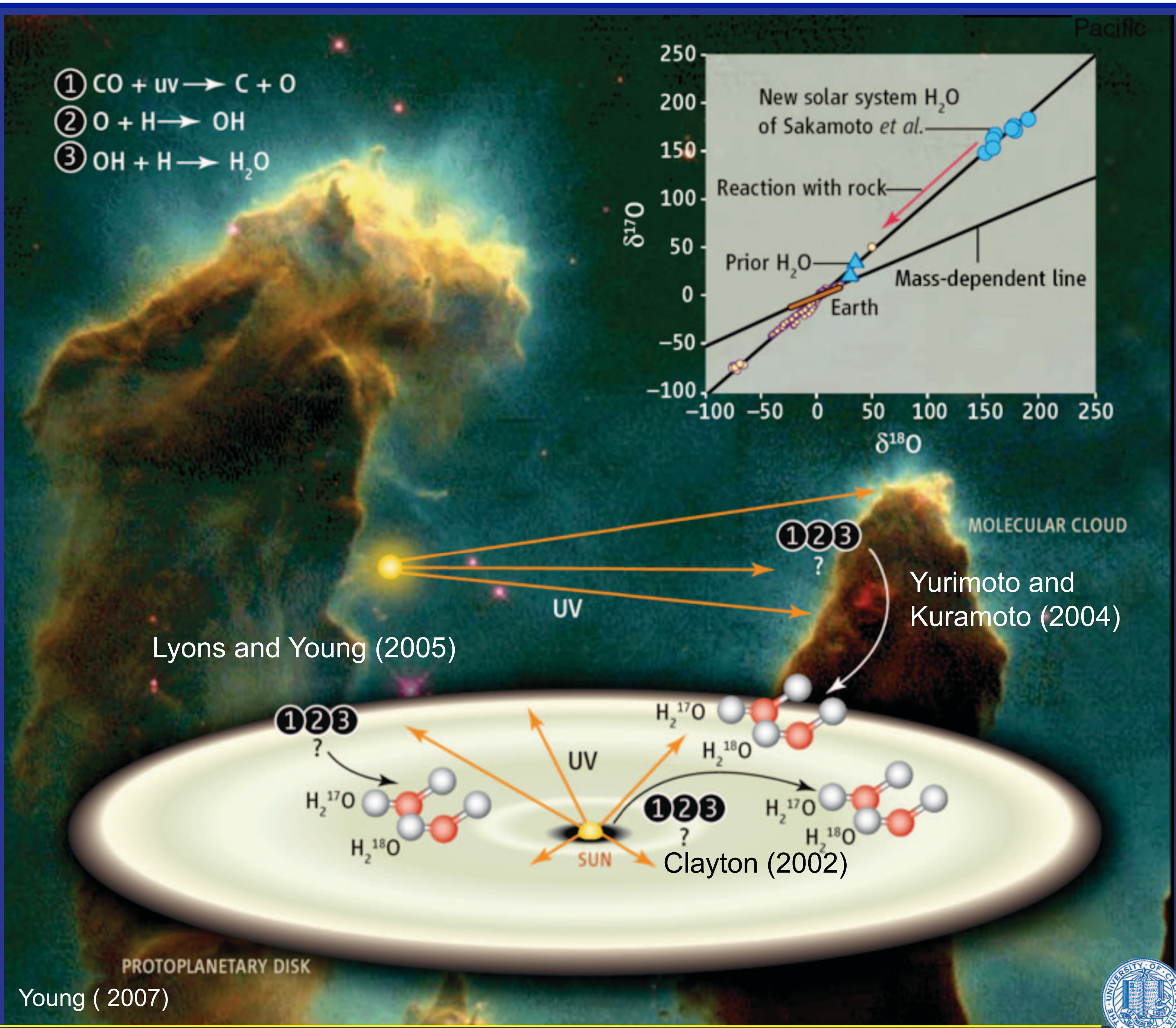
UV ($C^{18}O$) → $C^{18}O + h\nu \rightarrow C + {}^{18}O$ | $C + {}^{18}O,\ {}^{18}O + H_2 \rightarrow {}^{18}OH + H \rightarrow H_2{}^{18}O$ | $C^{18}O$

UV ($C^{17}O$) → $C^{17}O + h\nu \rightarrow C + {}^{17}O$ | $C + {}^{17}O,\ {}^{17}O + H_2 \rightarrow {}^{17}OH + H \rightarrow H_2{}^{17}O$ | $C^{17}O$

No fractionation

${}^{18}O$, ${}^{17}O$ enriched O

~opaque



① $CO + uv \rightarrow C + O$

② $O + H \rightarrow OH$

③ $OH + H \rightarrow H_2O$

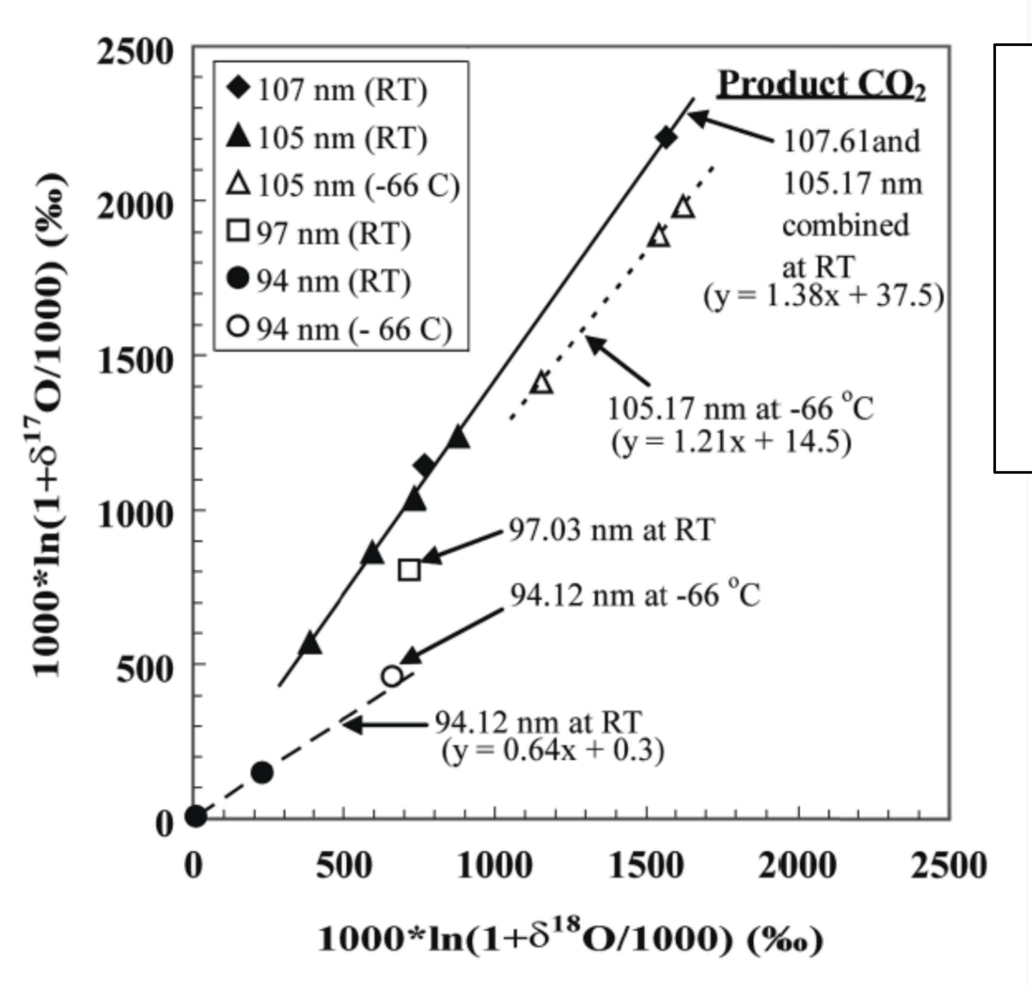
Lyons and Young (2005)

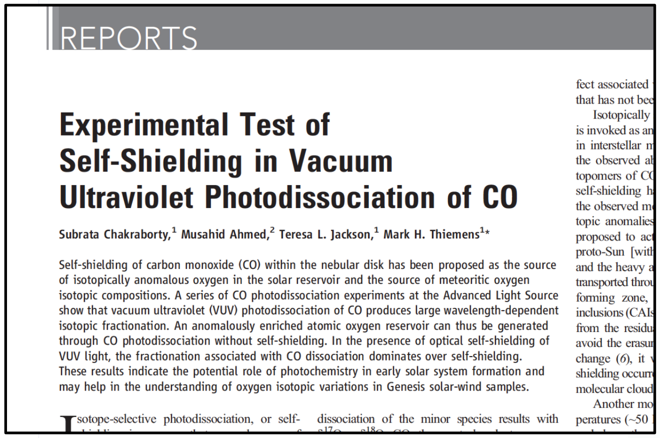
Yurimoto and Kuramoto (2004)

Clayton (2002)

Young (2007)

Chakraborty et al. (2009)




REPORTS

Experimental Test of Self-Shielding in Vacuum Ultraviolet Photodissociation of CO

Subrata Chakraborty,[1] Musahid Ahmed,[2] Teresa L. Jackson,[1] Mark H. Thiemens[1]*

Self-shielding of carbon monoxide (CO) within the nebular disk has been proposed as the source of isotopically anomalous oxygen in the solar reservoir and the source of meteoritic oxygen isotopic compositions. A series of CO photodissociation experiments at the Advanced Light Source show that vacuum ultraviolet (VUV) photodissociation of CO produces large wavelength-dependent isotopic fractionation. An anomalously enriched atomic oxygen reservoir can thus be generated through CO photodissociation without self-shielding. In the presence of optical self-shielding of VUV light, the fractionation associated with CO dissociation dominates over self-shielding. These results indicate the potential role of photochemistry in early solar system formation and may help in the understanding of oxygen isotopic variations in Genesis solar-wind samples.

Isotope-selective photodissociation, or self- dissociation of the minor species results with

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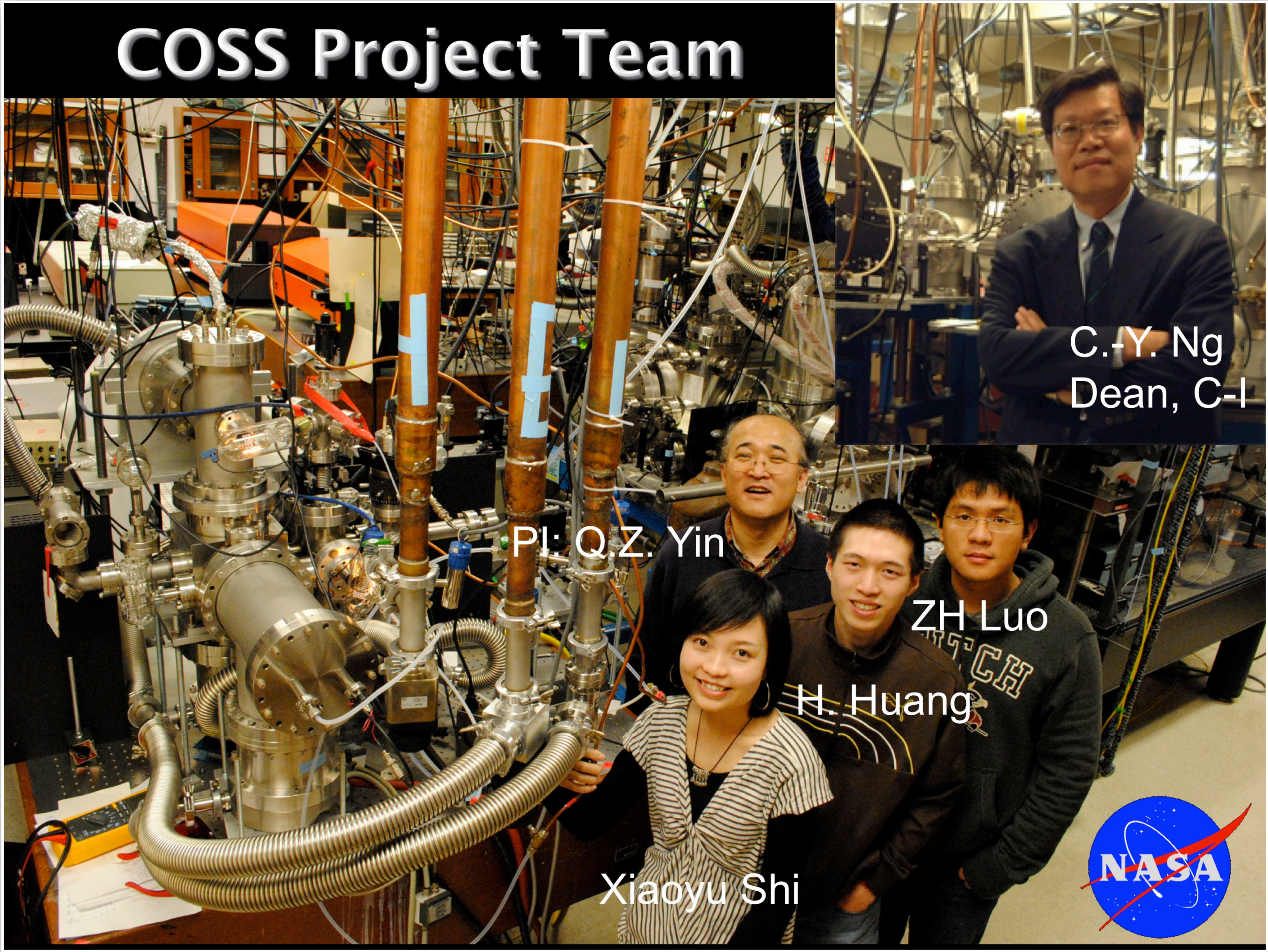
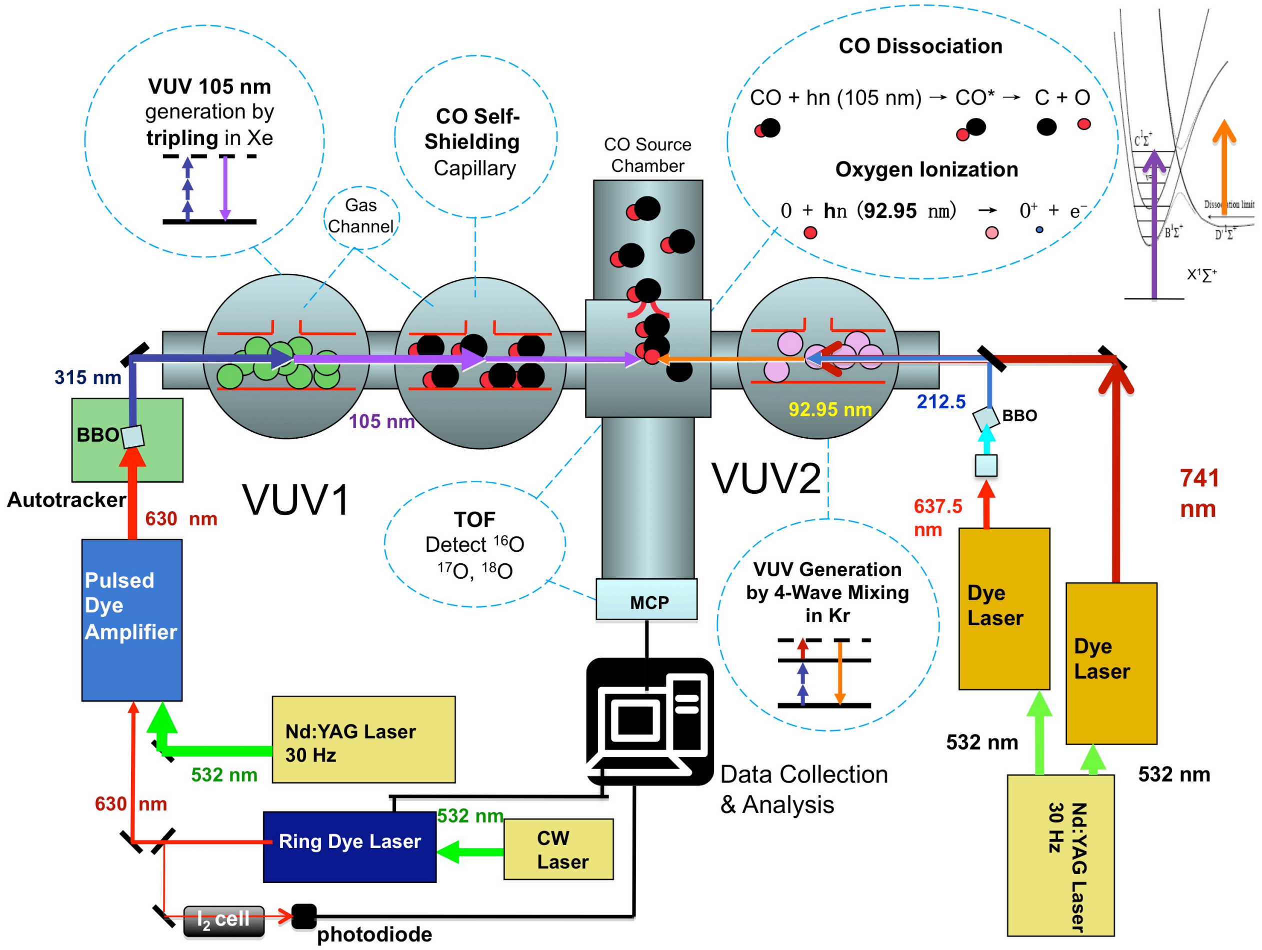
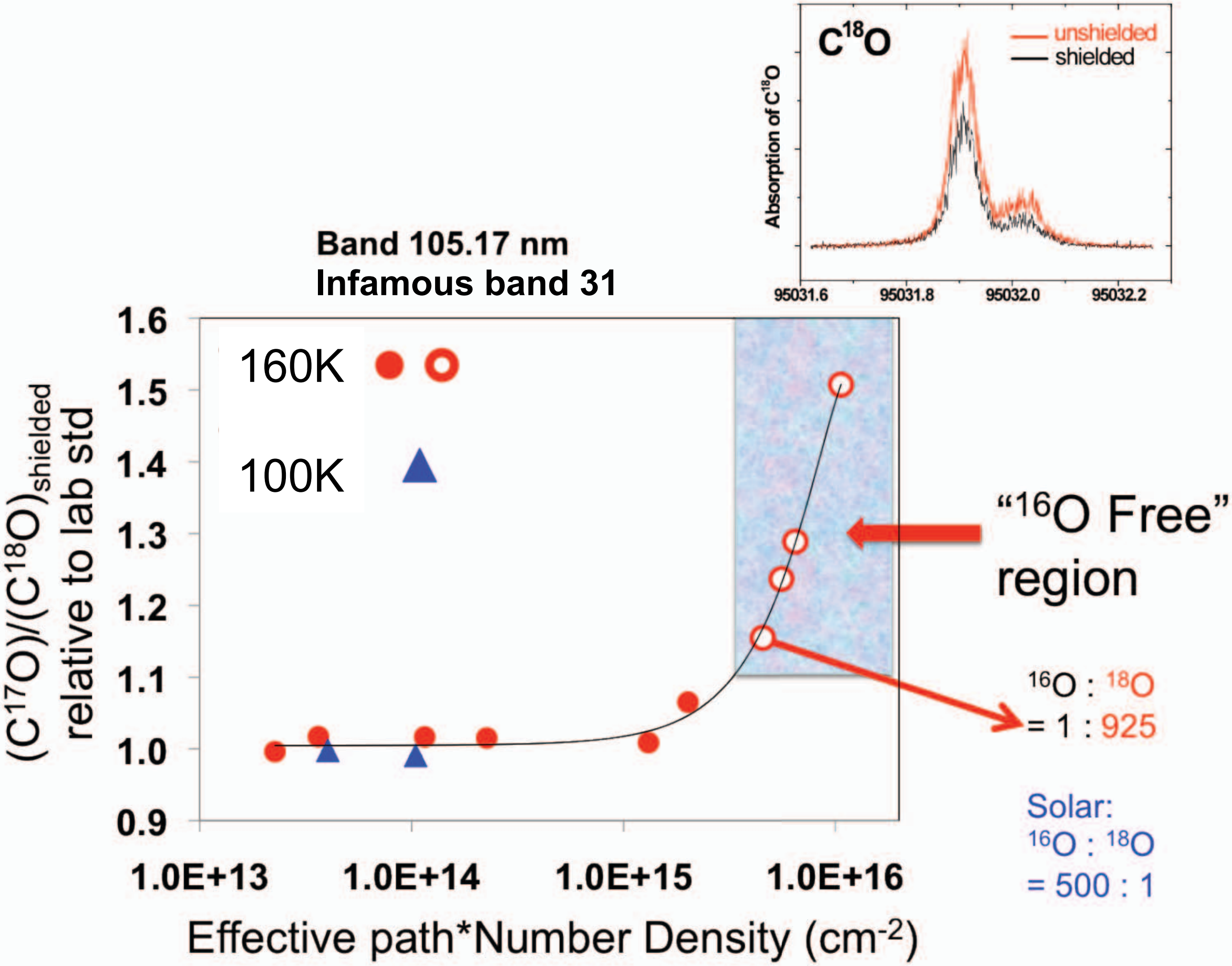
COSS Project Team




VUV 105 nm generation by tripling in Xe
Gas Channel
CO Self-Shielding Capillary
CO Source Chamber
CO Dissociation
CO + hn (105 nm) → CO* → C + O
Oxygen Ionization
0 + hn (92.95 nm) → 0^+ + e^-
$C^1\Sigma^+$
v=
$B^1\Sigma^+$
$D'^1\Sigma^+$
Dissociation limit
$X^1\Sigma^+$
315 nm
BBO
Autotracker
630 nm
105 nm
VUV1
VUV2
92.95 nm
212.5
BBO
637.5 nm
741 nm
Pulsed Dye Amplifier
TOF
Detect ^{16}O ^{17}O, ^{18}O
MCP
VUV Generation by 4-Wave Mixing in Kr
Dye Laser
Dye Laser
532 nm
532 nm
Nd:YAG Laser 30 Hz
Nd:YAG Laser 30 Hz
532 nm
630 nm
Ring Dye Laser
532 nm
CW Laser
Data Collection & Analysis
I_2 cell
photodiode



“^{16}O Free” region

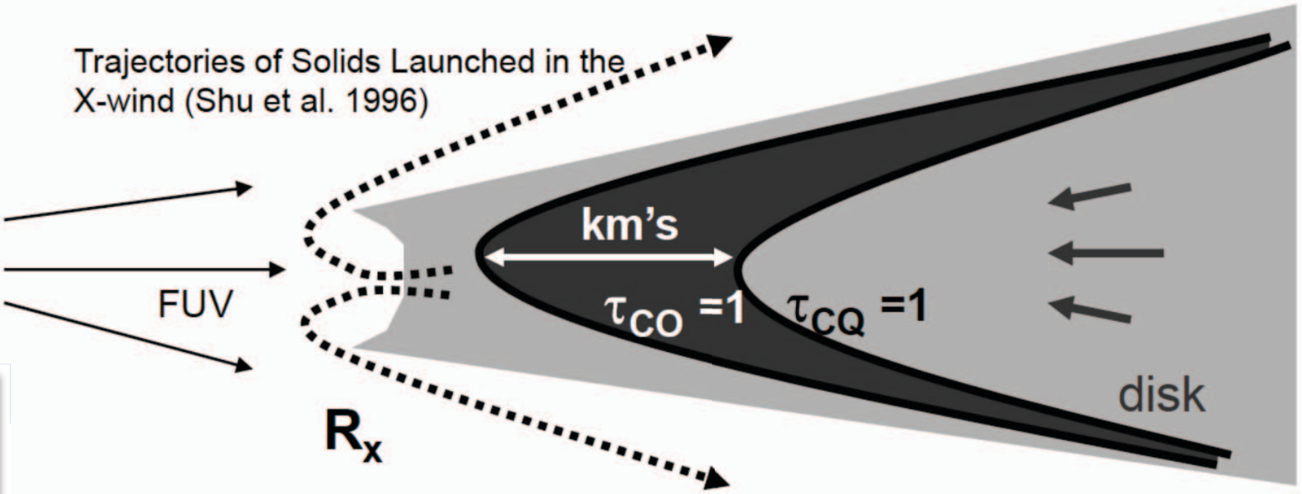
^{16}O : ^{18}O
= 1 : 925

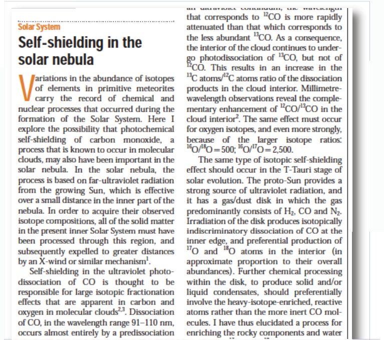
Solar:
^{16}O : ^{18}O
= 500 : 1

Inner Edge of Disk

Clayton (2002)

Self shielding by CO near R_x (high T)





Solar System

Self-shielding in the solar nebula

Variations in the abundance of isotopes of elements in primitive meteorites carry the record of chemical and nuclear processes that occurred during the formation of the Solar System. Here I explore the possibility that photochemical self-shielding of carbon monoxide, a process that is known to occur in molecular clouds, may also have been important in the solar nebula. In the solar nebula, the process is based on far-ultraviolet radiation from the growing Sun, which is effective over a small distance in the inner part of the nebula. In order to acquire their observed isotope compositions, all of the solid matter in the present inner Solar System must have been processed through this region, and subsequently expelled to greater distances by an X-wind or similar mechanism[1].

Self-shielding in the ultraviolet photodissociation of CO is thought to be responsible for large isotopic fractionation effects that are apparent in carbon and oxygen in molecular clouds[2,3]. Dissociation of CO, in the wavelength range 91–110 nm, occurs almost entirely by a predissociation

that corresponds to ^{12}CO is more rapidly attenuated than that which corresponds to the less abundant ^{13}CO. As a consequence, the interior of the cloud continues to undergo photodissociation of ^{13}CO, but not of ^{12}CO. This results in an increase in the ^{13}C atoms/^{12}C atoms ratio of the dissociation products in the cloud interior. Millimetre-wavelength observations reveal the complementary enhancement of $^{12}CO/^{13}CO$ in the cloud interior[2]. The same effect must occur for oxygen isotopes, and even more strongly, because of the larger isotope ratios: $^{16}O/^{18}O = 500$; $^{16}O/^{17}O = 2{,}500$.

The same type of isotopic self-shielding effect should occur in the T-Tauri stage of solar evolution. The proto-Sun provides a strong source of ultraviolet radiation, and it has a gas/dust disk in which the gas predominantly consists of H_2, CO and N_2. Irradiation of the disk produces isotopically indiscriminatory dissociation of CO at the inner edge, and preferential production of ^{17}O and ^{18}O atoms in the interior (in approximate proportion to their overall abundances). Further chemical processing within the disk, to produce solid and/or liquid condensates, should preferentially involve the heavy-isotope-enriched, reactive atoms rather than the more inert CO molecules. I have thus elucidated a process for enriching the rocky components and water

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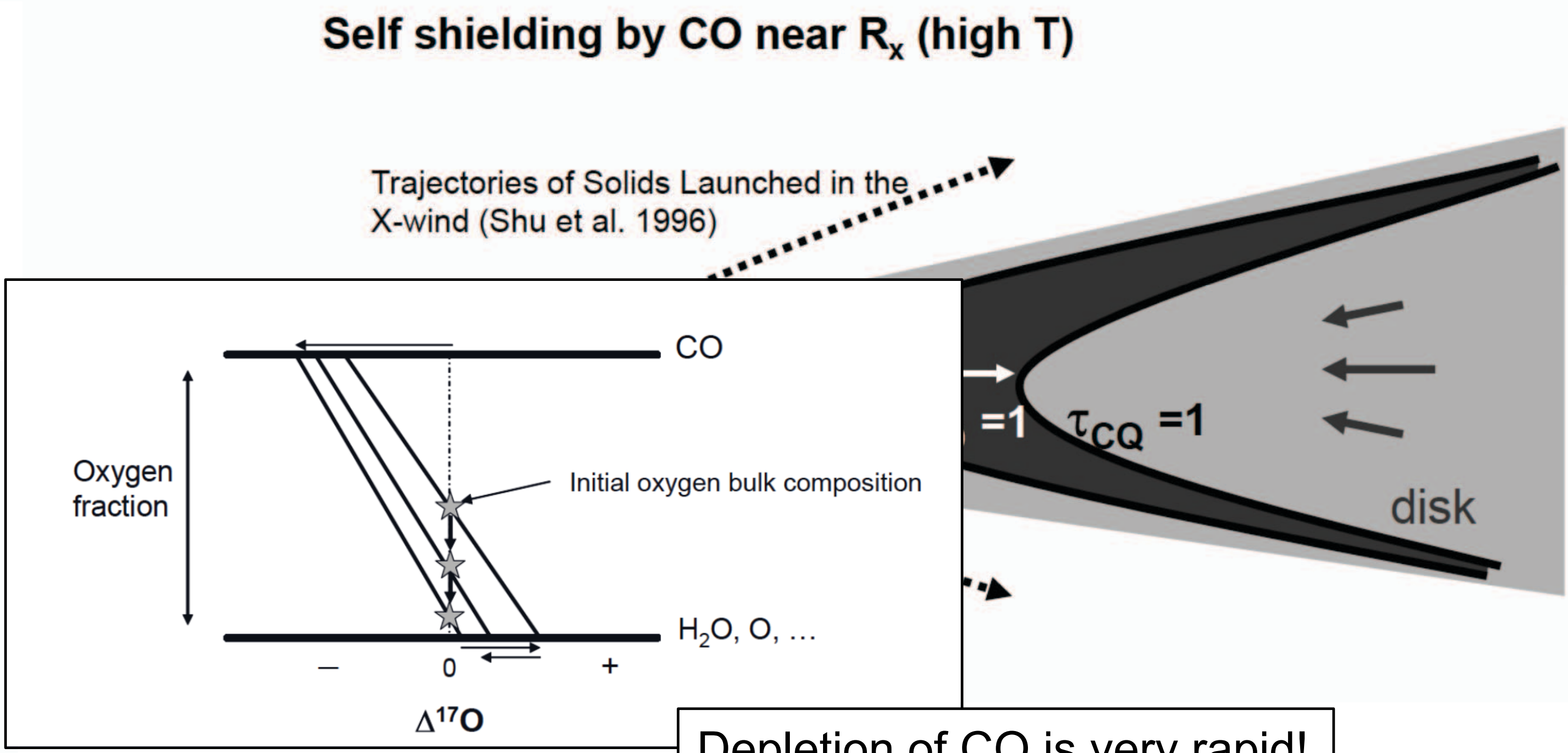
Inner Edge of Disk

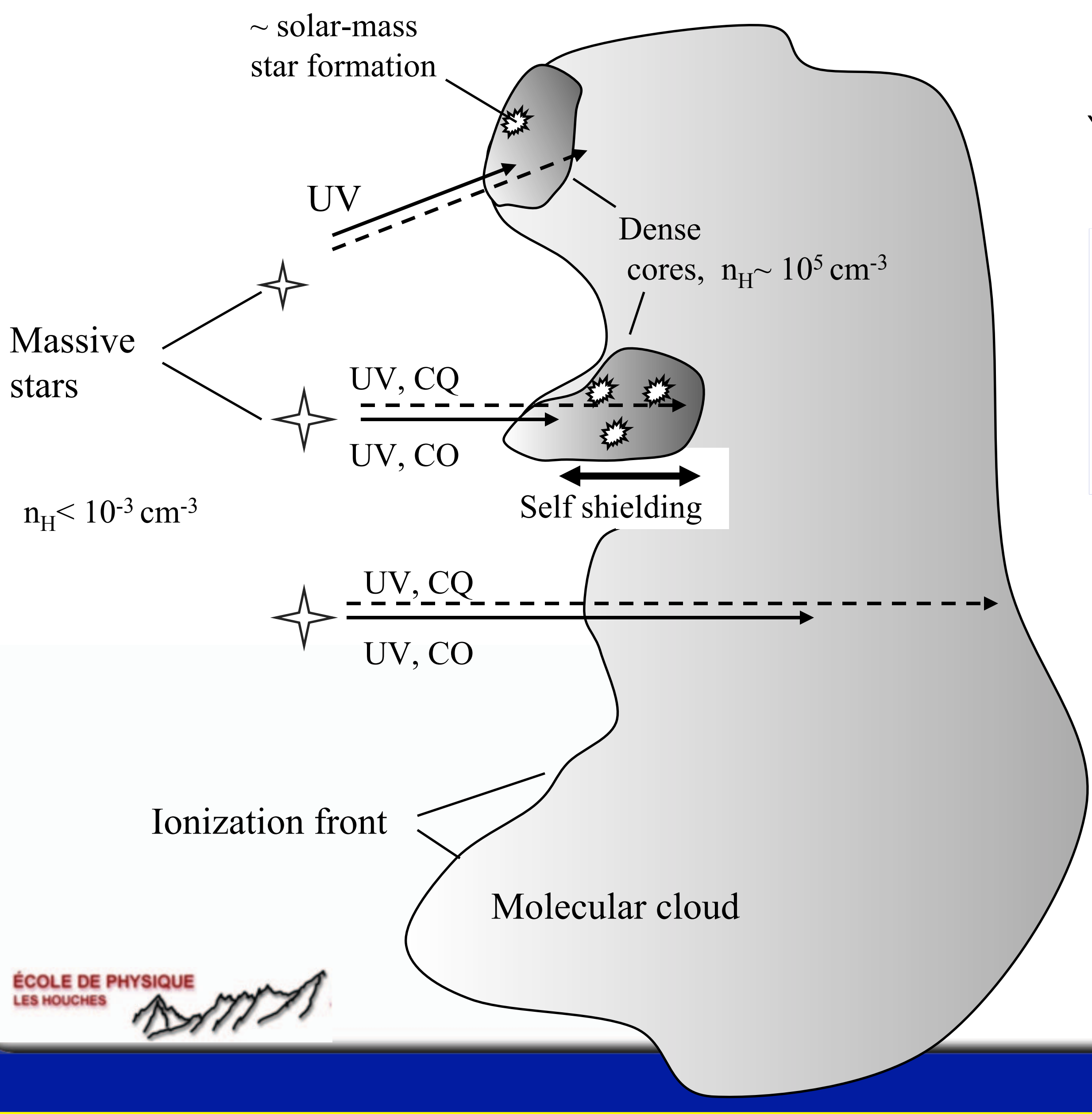
Clayton (2002)

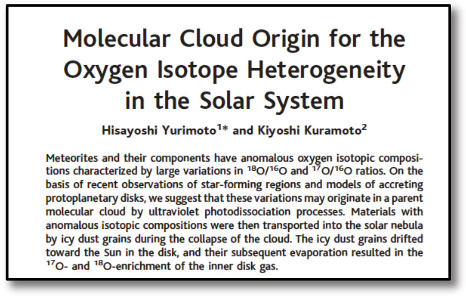


Depletion of CO is very rapid!

Molecular Cloud

Yurimoto and Kuramoto (2004)



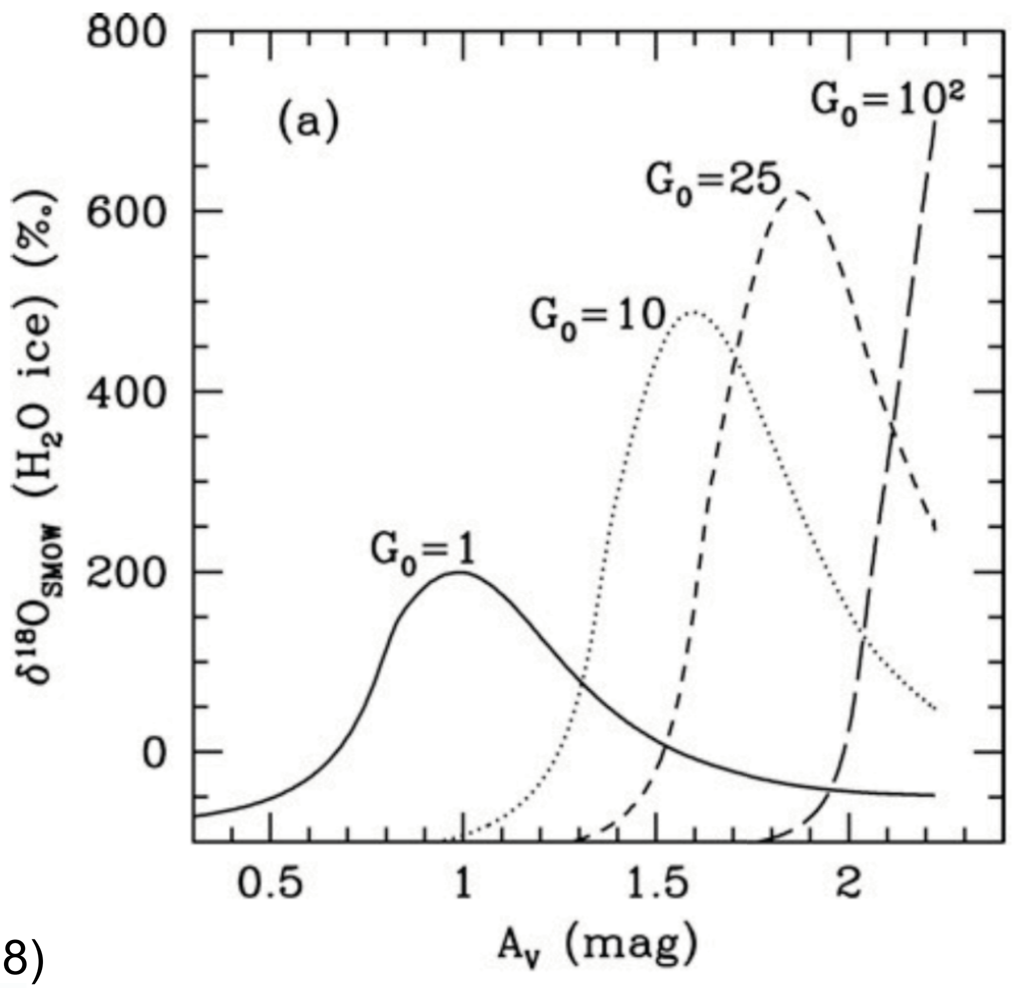


Molecular Cloud Origin for the Oxygen Isotope Heterogeneity in the Solar System

Hisayoshi Yurimoto[1*] and Kiyoshi Kuramoto[2]

Meteorites and their components have anomalous oxygen isotopic compositions characterized by large variations in $^{18}O/^{16}O$ and $^{17}O/^{16}O$ ratios. On the basis of recent observations of star-forming regions and models of accreting protoplanetary disks, we suggest that these variations may originate in a parent molecular cloud by ultraviolet photodissociation processes. Materials with anomalous isotopic compositions were then transported into the solar nebula by icy dust grains during the collapse of the cloud. The icy dust grains drifted toward the Sun in the disk, and their subsequent evaporation resulted in the ^{17}O- and ^{18}O-enrichment of the inner disk gas.

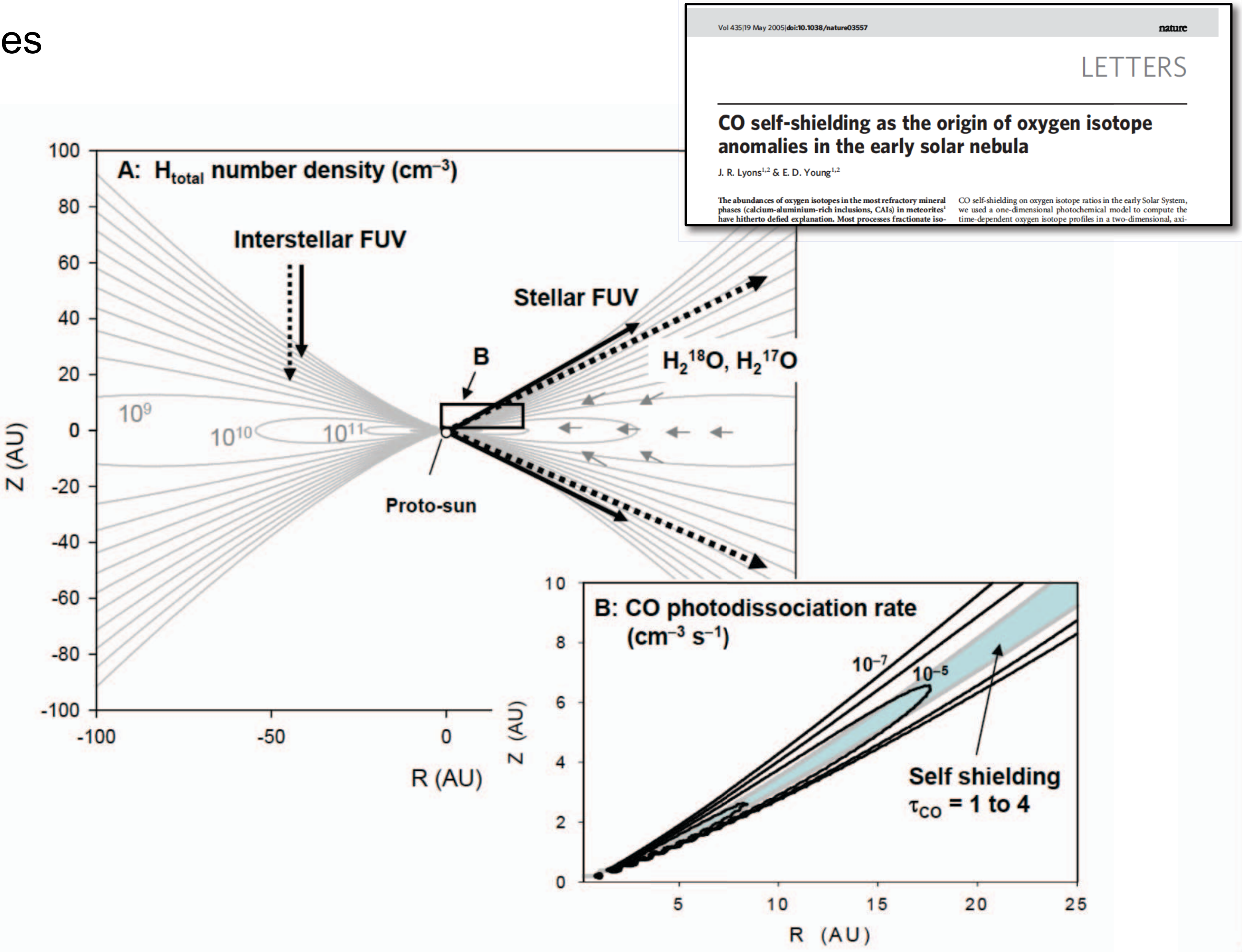
Molecular Cloud



Lee et al. (2008)

UCLA

Disk Surfaces



Vol 435|19 May 2005|**doi:10.1038/nature03557** **nature**

LETTERS

CO self-shielding as the origin of oxygen isotope anomalies in the early solar nebula

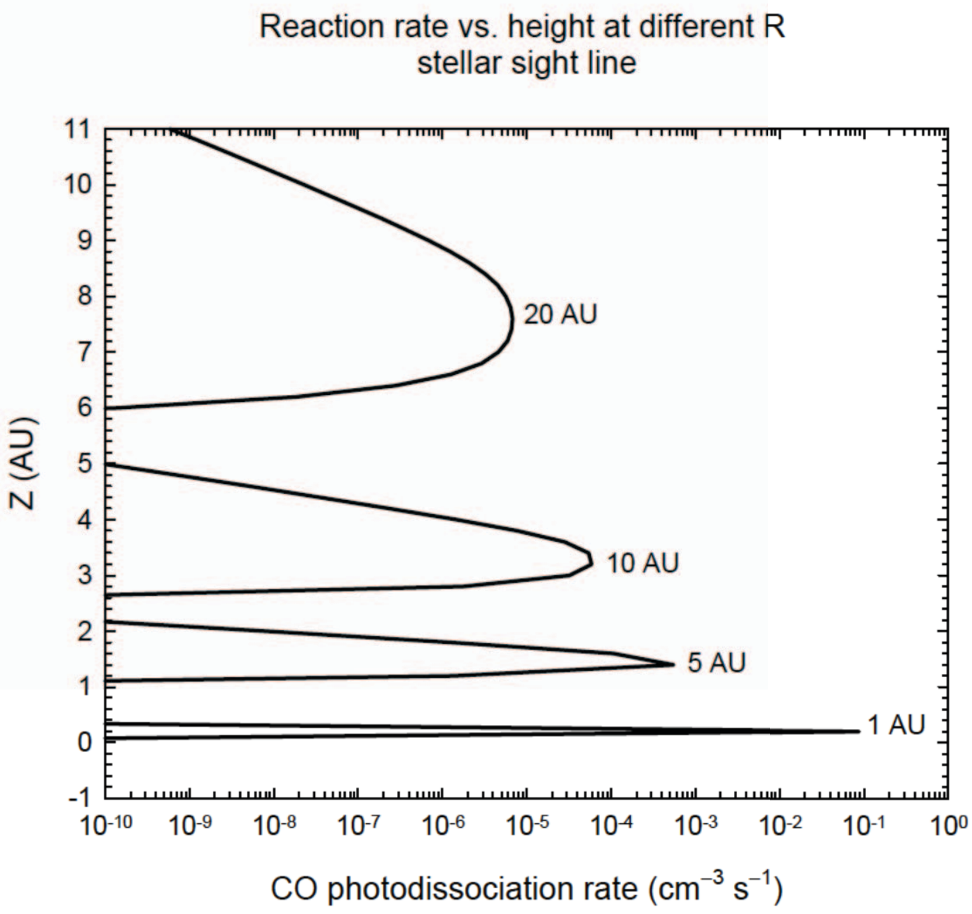
J. R. Lyons[1,2] & E. D. Young[1,2]

The abundances of oxygen isotopes in the most refractory mineral phases (calcium-aluminium-rich inclusions, CAIs) in meteorites[1] have hitherto defied explanation. Most processes fractionate iso-

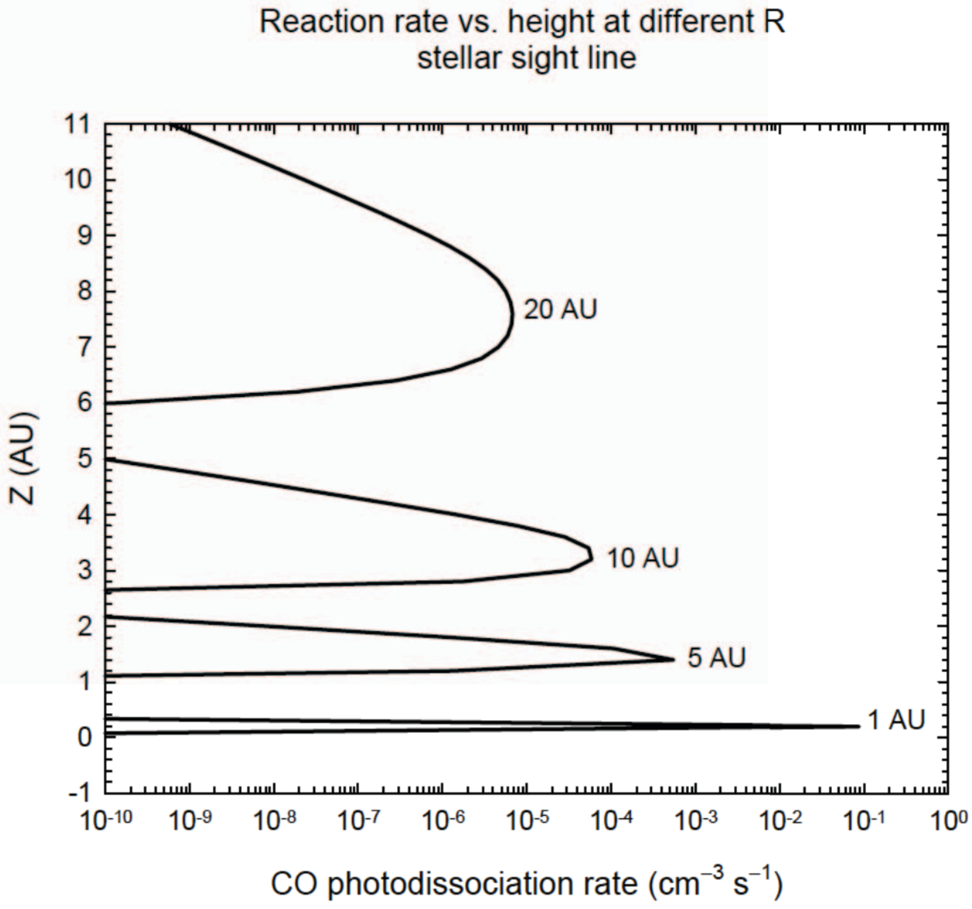
CO self-shielding on oxygen isotope ratios in the early Solar System, we used a one-dimensional photochemical model to compute the time-dependent oxygen isotope profiles in a two-dimensional, axi-

Young (2007)

Disk Surfaces

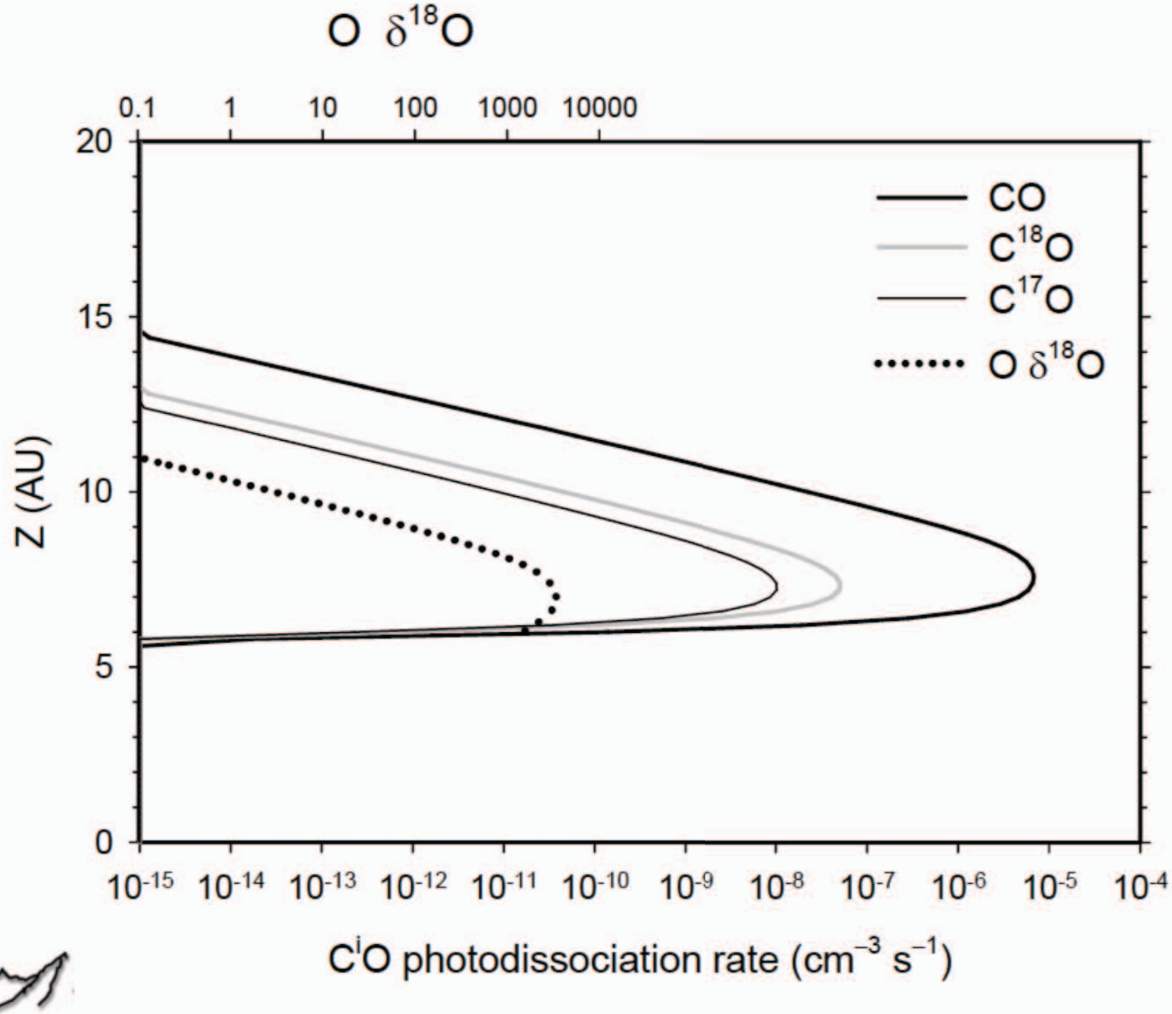


Disk Surfaces



Disk Surfaces

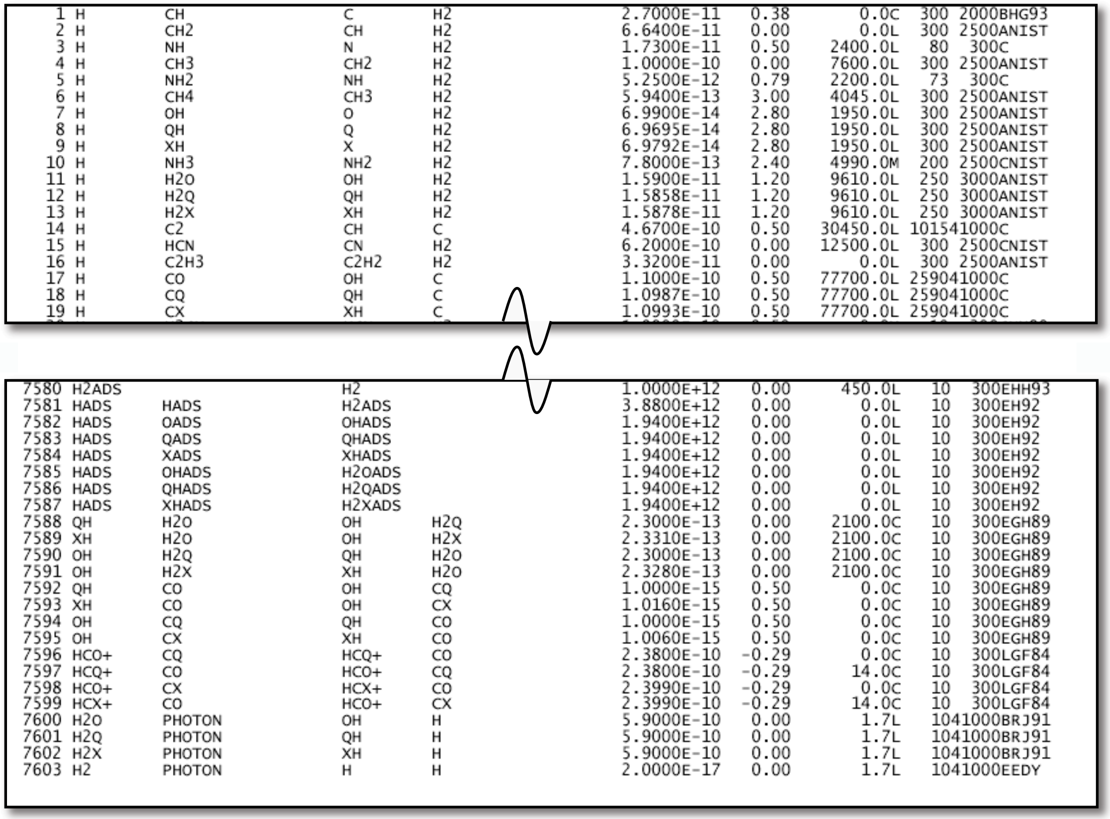
Young (2007)



Disk Surfaces

Reaction network – oxygen isotopologues

7603 reactions, 546 species, oxygen isotopologues, gas-grain reactions

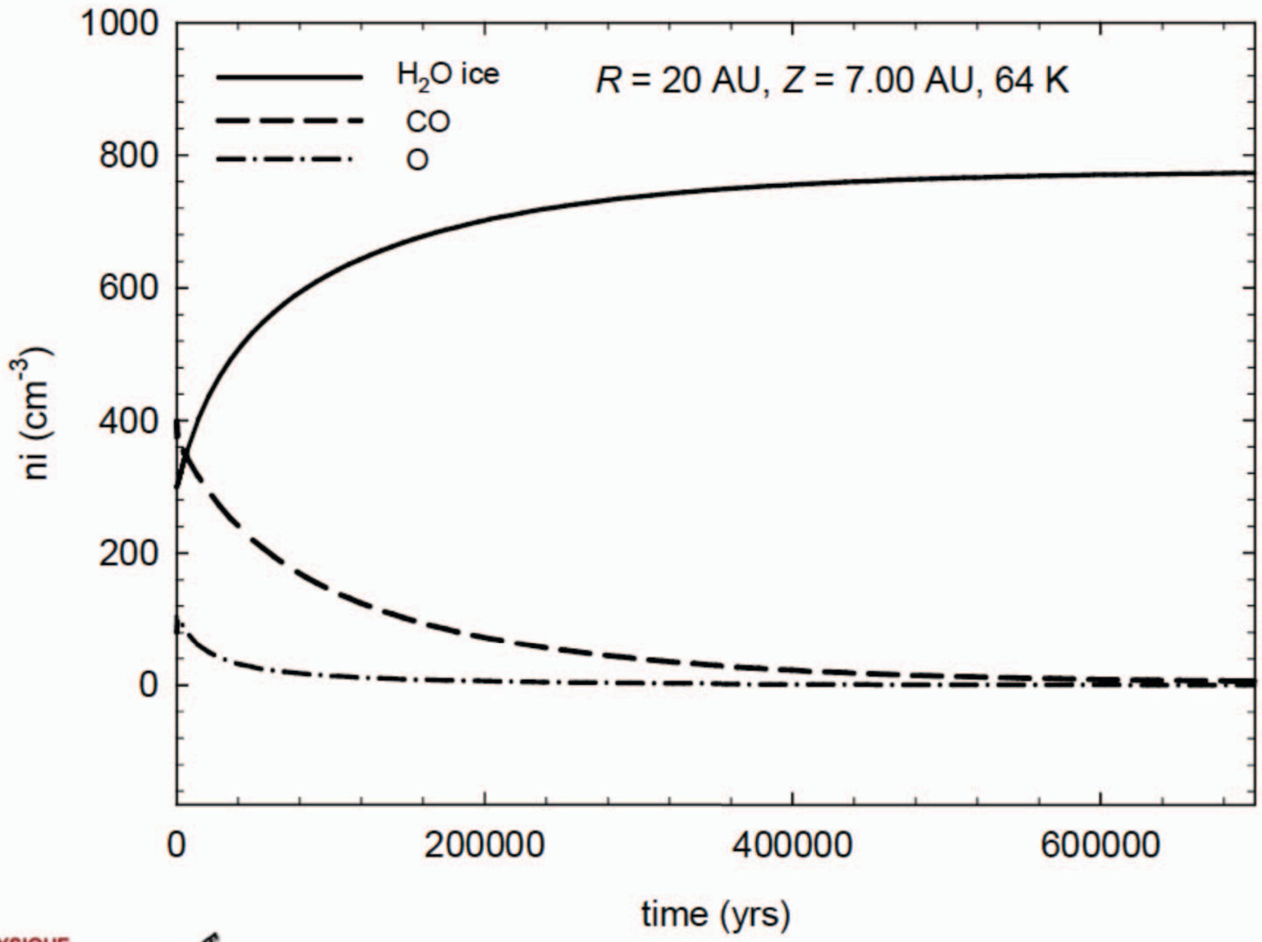


```
   1 H         CH             C        H2                   2.7000E-11  0.38        0.0C  300 2000BHG93
   2 H         CH2            CH       H2                   6.6400E-11  0.00        0.0L  300 2500ANIST
   3 H         NH             N        H2                   1.7300E-11  0.50     2400.0L   80  300C
   4 H         CH3            CH2      H2                   1.0000E-10  0.00     7600.0L  300 2500ANIST
   5 H         NH2            NH       H2                   5.2500E-12  0.79     2200.0L   73  300C
   6 H         CH4            CH3      H2                   5.9400E-13  3.00     4045.0L  300 2500ANIST
   7 H         OH             O        H2                   6.9900E-14  2.80     1950.0L  300 2500ANIST
   8 H         QH             Q        H2                   6.9695E-14  2.80     1950.0L  300 2500ANIST
   9 H         XH             X        H2                   6.9792E-14  2.80     1950.0L  300 2500ANIST
  10 H         NH3            NH2      H2                   7.8000E-13  2.40     4990.0M  200 2500CNIST
  11 H         H2O            OH       H2                   1.5900E-11  1.20     9610.0L  250 3000ANIST
  12 H         H2Q            QH       H2                   1.5858E-11  1.20     9610.0L  250 3000ANIST
  13 H         H2X            XH       H2                   1.5878E-11  1.20     9610.0L  250 3000ANIST
  14 H         C2             CH       C                    4.6700E-10  0.50    30450.0L 101541000C
  15 H         HCN            CN       H2                   6.2000E-10  0.00    12500.0L  300 2500CNIST
  16 H         C2H3           C2H2     H2                   3.3200E-11  0.00        0.0L  300 2500ANIST
  17 H         CO             OH       C                    1.1000E-10  0.50    77700.0L 259041000C
  18 H         CQ             QH       C                    1.0987E-10  0.50    77700.0L 259041000C
  19 H         CX             XH       C                    1.0993E-10  0.50    77700.0L 259041000C

7580 H2ADS                    H2                            1.0000E+12  0.00      450.0L   10   300EHH93
7581 HADS      HADS           H2ADS                         3.8800E+12  0.00        0.0L   10   300EH92
7582 HADS      OADS           OHADS                         1.9400E+12  0.00        0.0L   10   300EH92
7583 HADS      QADS           QHADS                         1.9400E+12  0.00        0.0L   10   300EH92
7584 HADS      XADS           XHADS                         1.9400E+12  0.00        0.0L   10   300EH92
7585 HADS      OHADS          H2OADS                        1.9400E+12  0.00        0.0L   10   300EH92
7586 HADS      QHADS          H2QADS                        1.9400E+12  0.00        0.0L   10   300EH92
7587 HADS      XHADS          H2XADS                        1.9400E+12  0.00        0.0L   10   300EH92
7588 QH        H2O            OH       H2Q                  2.3000E-13  0.00     2100.0C   10   300EGH89
7589 XH        H2O            OH       H2X                  2.3310E-13  0.00     2100.0C   10   300EGH89
7590 OH        H2Q            QH       H2O                  2.3000E-13  0.00     2100.0C   10   300EGH89
7591 OH        H2X            XH       H2O                  2.3280E-13  0.00     2100.0C   10   300EGH89
7592 QH        CO             OH       CQ                   1.0000E-15  0.50        0.0C   10   300EGH89
7593 XH        CO             OH       CX                   1.0160E-15  0.50        0.0C   10   300EGH89
7594 OH        CQ             QH       CO                   1.0000E-15  0.50        0.0C   10   300EGH89
7595 OH        CX             XH       CO                   1.0060E-15  0.50        0.0C   10   300EGH89
7596 HCO+      CQ             HCQ+     CO                   2.3800E-10 -0.29        0.0C   10   300LGF84
7597 HCQ+      CO             HCO+     CQ                   2.3800E-10 -0.29       14.0C   10   300LGF84
7598 HCO+      CX             HCX+     CO                   2.3990E-10 -0.29        0.0C   10   300LGF84
7599 HCX+      CO             HCO+     CX                   2.3990E-10 -0.29       14.0C   10   300LGF84
7600 H2O       PHOTON         OH       H                    5.9000E-10  0.00        1.7L   1041000BRJ91
7601 H2Q       PHOTON         QH       H                    5.9000E-10  0.00        1.7L   1041000BRJ91
7602 H2X       PHOTON         XH       H                    5.9000E-10  0.00        1.7L   1041000BRJ91
7603 H2        PHOTON         H        H                    2.0000E-17  0.00        1.7L   1041000EEDY
```

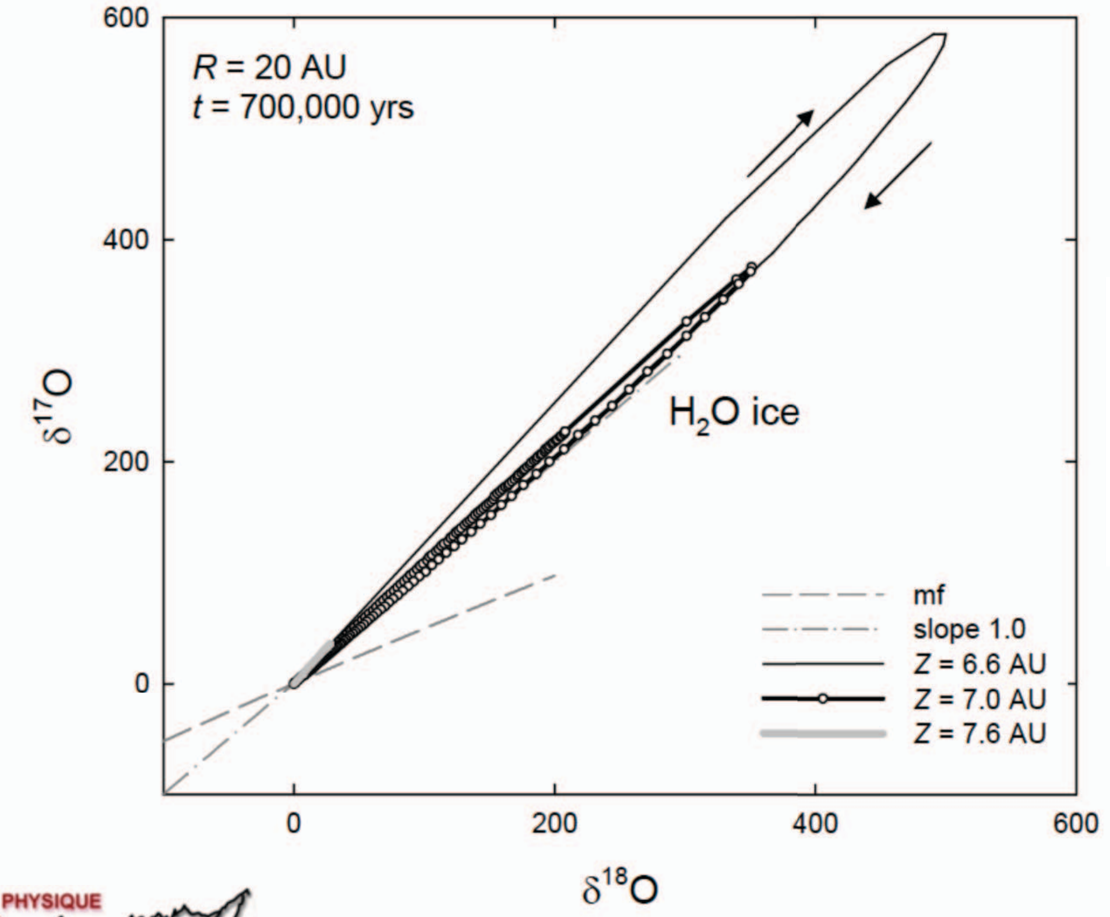
Disk Surfaces

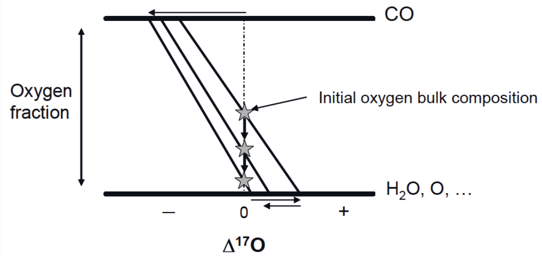
Young (2007)

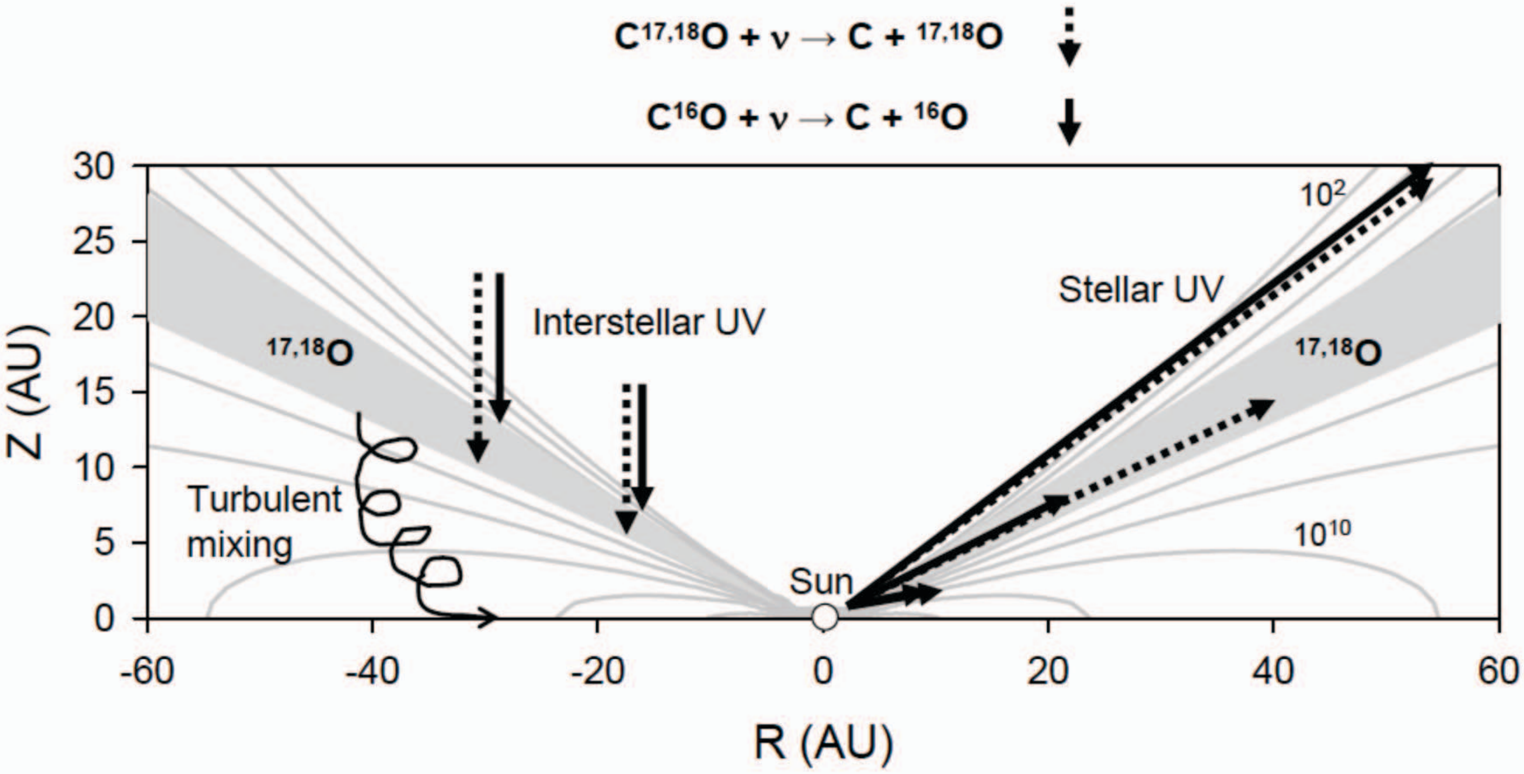


Calculated H_2O evolution in the early solar system

Young (2007)





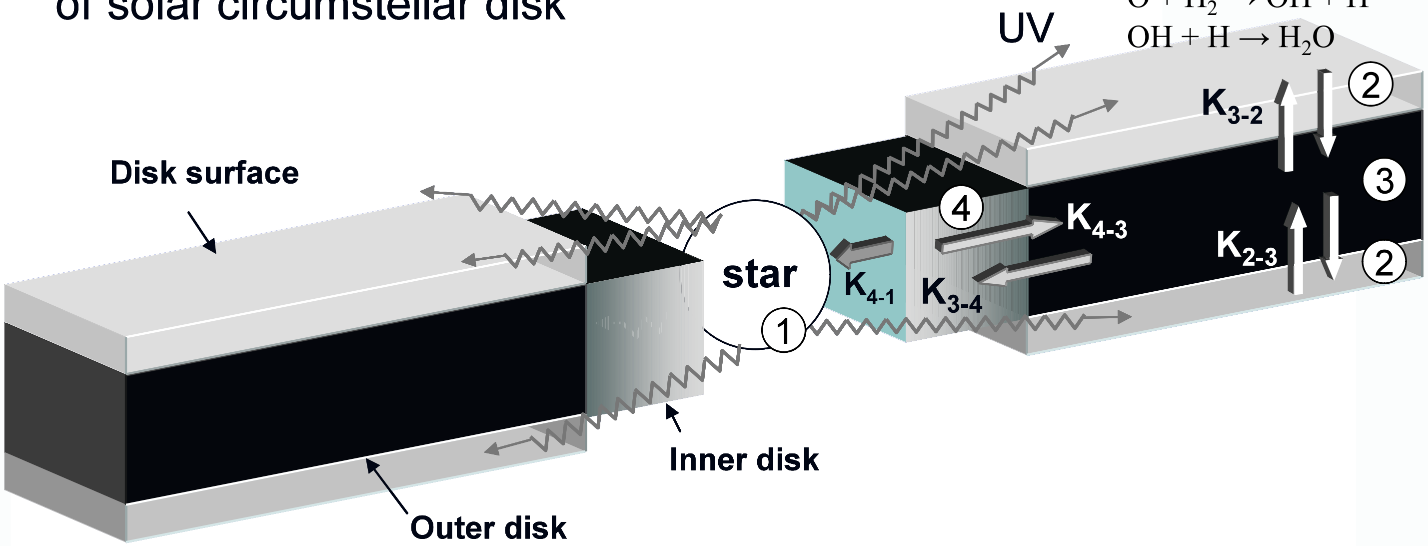

$C^{17,18}O + \nu \rightarrow C + {}^{17,18}O$
$C^{16}O + \nu \rightarrow C + {}^{16}O$
30
25
20
15
10
5
0
Z (AU)
-60
-40
-20
0
20
40
60
R (AU)
10^2
10^{10}
Interstellar UV
Stellar UV
$^{17,18}O$
$^{17,18}O$
Turbulent mixing
Sun

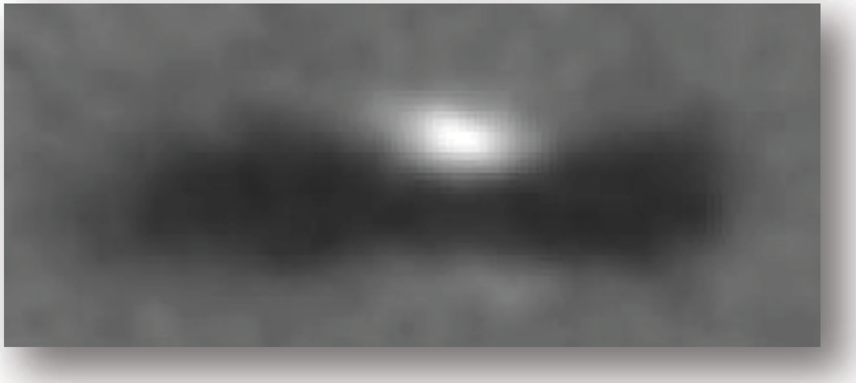
Box model
of solar circumstellar disk

$CO \rightarrow C + O$

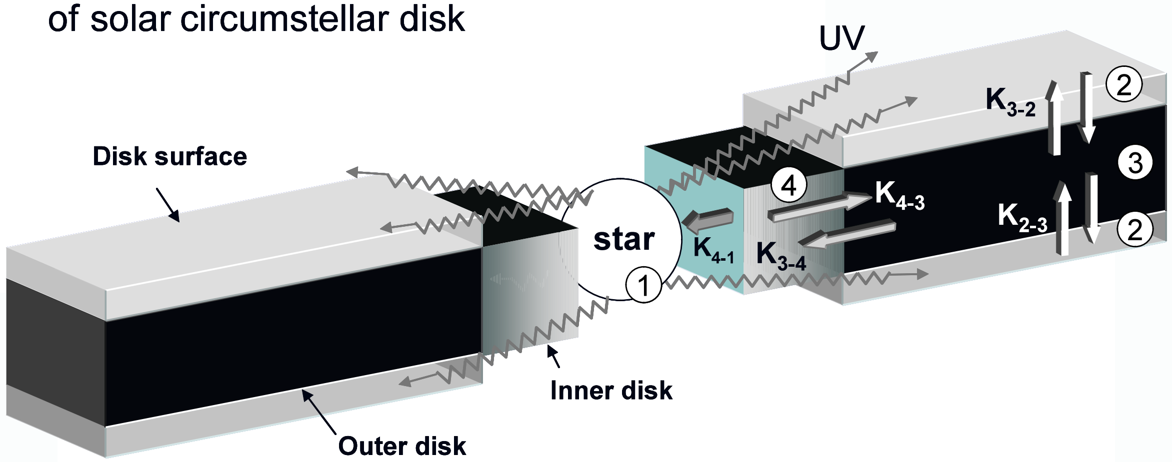
$O + H_2 \rightarrow OH + H$

$OH + H \rightarrow H_2O$





Box model
of solar circumstellar disk



$CO \rightarrow C + O$
$O + H_2 \rightarrow OH + H$
$OH + H \rightarrow H_2O$

Equations

$$\frac{dn_{l,j}}{dt} = \sum_i k_{ij} n_{l,i} - n_{l,j} \sum_i k_{ji}$$

$$\vdots$$

$$\frac{dn_{m,j}}{dt} = \sum_i k_{ij} n_{m,i} - n_{m,j} \sum_i k_{ji}$$

$$\vdots$$

$$\frac{dn_{m,p}}{dt} = \sum_i k_{ip} n_{m,i} - n_{m,p} \sum_i k_{pi}$$

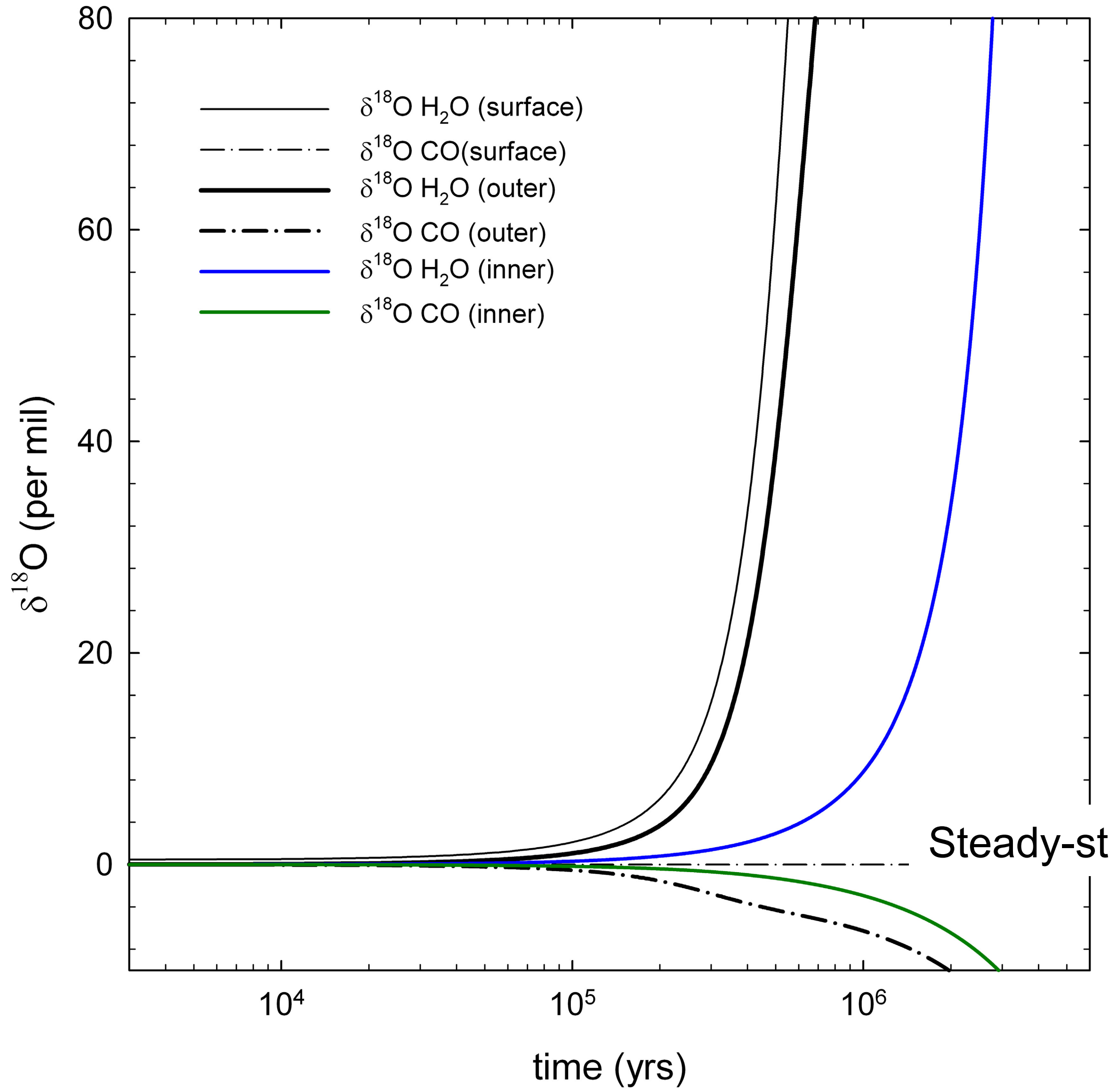
Input transport rate constants

$k_{4\text{-}1} = 10^{-7}\ \mathrm{yr}^{-1}$ ($10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$ OK, disk drains faster)

$k_{3\text{-}4} = 10^{-5}\ \mathrm{yr}^{-1}$ (R/100 AU) (Hartmann, 2000)
$k_{4\text{-}3} = k_{3\text{-}4}/10$ (radial mixing)
$k_{3\text{-}4(H2O)} > k_{3\text{-}4}$ (Cuzzi and Zahnle, 2004)

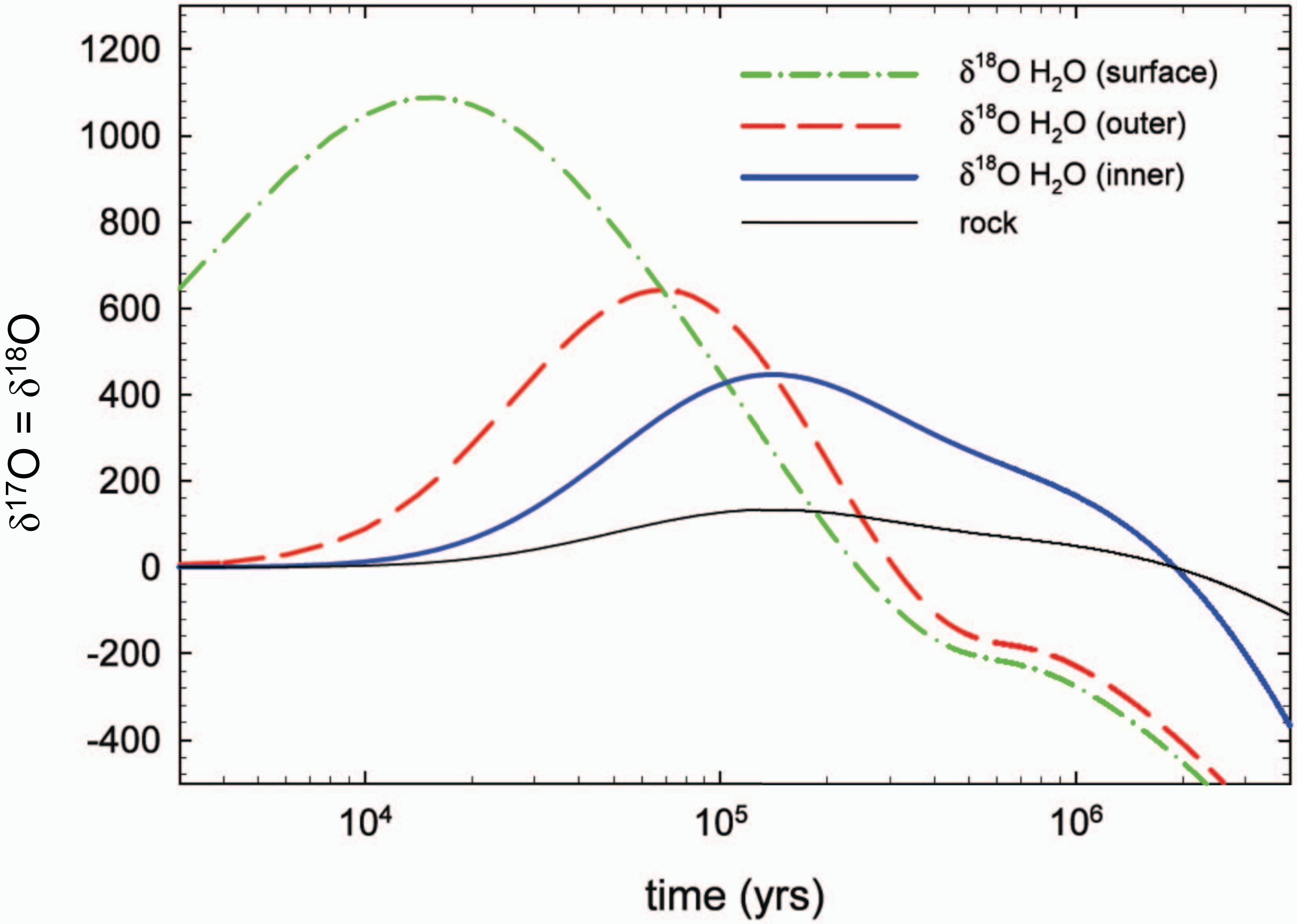
$k_{3\text{-}2} = k_{2\text{-}3} \sim 1/(\Omega\alpha)$ (Ω = angular velocity)

$R = 20$ AU, $\alpha = 10^{-2}$, $(\tau_v)^{-1} = 1\mathrm{x}10^{-4}\ \mathrm{yr}^{-1}$

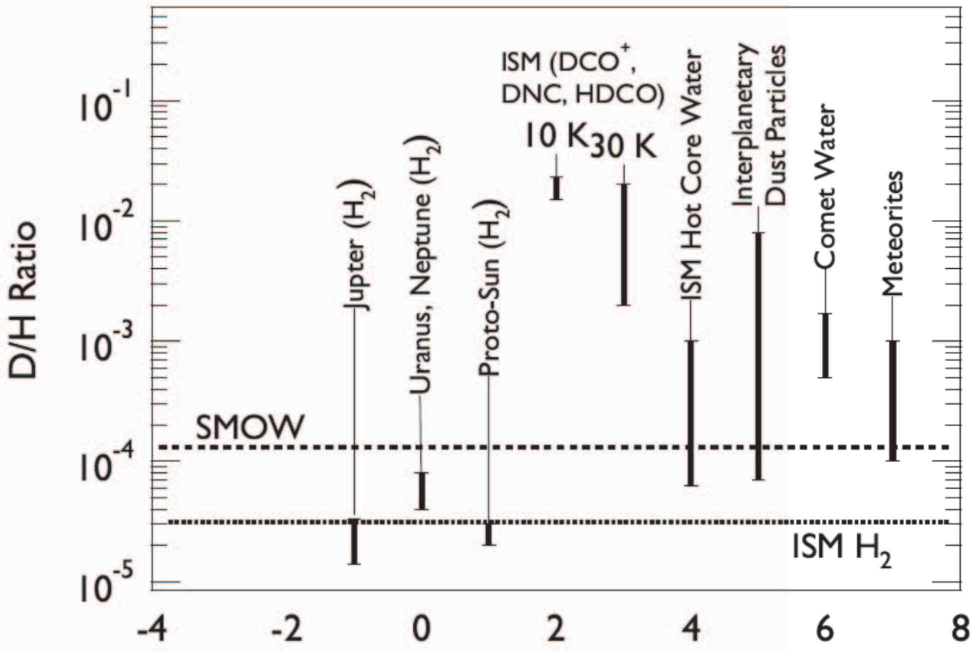


Steady-state surface layer

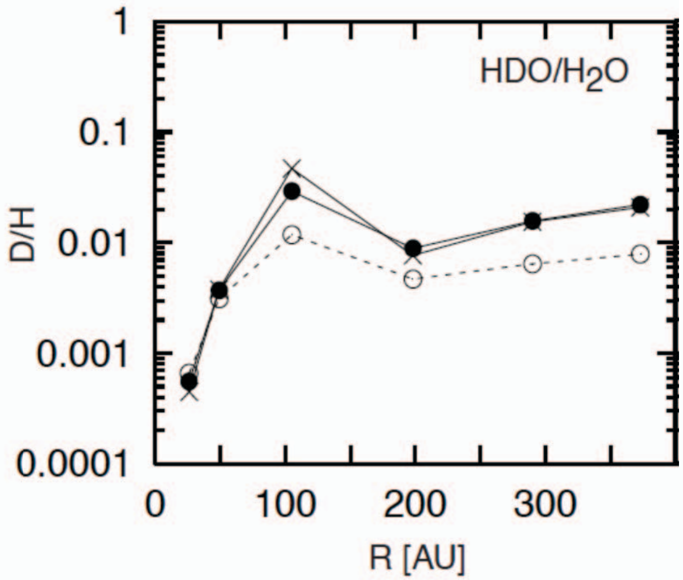
Young (2007)


$\delta^{18}O$ H_2O (surface)
$\delta^{18}O$ H_2O (outer)
$\delta^{18}O$ H_2O (inner)
rock
1200
1000
800
600
400
200
0
-200
-400
$\delta^{17}O = \delta^{18}O$
10^4
10^5
10^6
time (yrs)

Is there a D/H signature of inward H_2O migration?

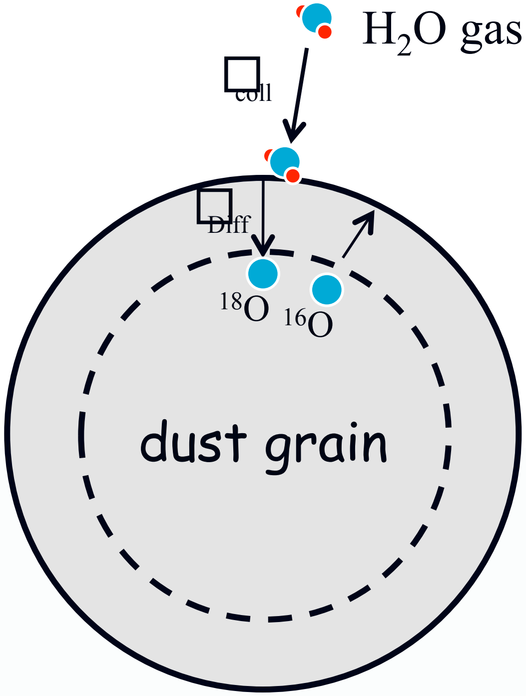


Bergin (2009)



Aikawa et al. (2002)

Timescale for oxygen isotopic equilibration of dust



H_2O gas – dust grain collision frequency

$$J_{i,\text{gas}} = \frac{\alpha n_{i,\text{gas}}}{4} \upsilon_{\text{gas}}$$

$$\upsilon_{gas} = \left(\frac{8kT}{\pi \mu_{\text{gas}}} \right)^{1/2}$$

$$\nu_{\text{coll}} = J_{i,\text{gas}} A_{\text{dust}}$$

$$\tau_{\text{coll}} = \frac{n_{i,\text{dust}} \left(\frac{4}{3} \pi r_{\text{dust}}^3 L / \hat{\text{V}}_{\text{dust}} \right)}{\nu_{\text{coll}}}$$

Self diffusion of O in dust grain

$$\frac{M_t}{M_\infty} = 1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-n\pi^2 \xi\right)$$

$$\xi = \frac{Dt}{r^2}$$

$$\tau_{\text{Diff}} = \frac{1.5 \xi r^2}{D(T)}$$

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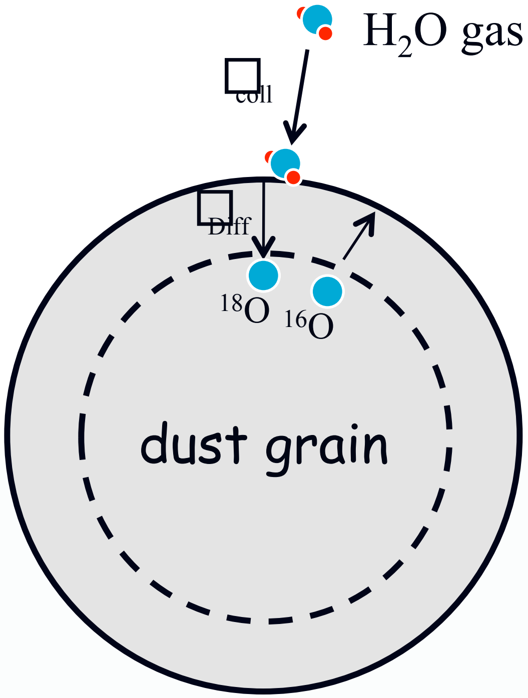
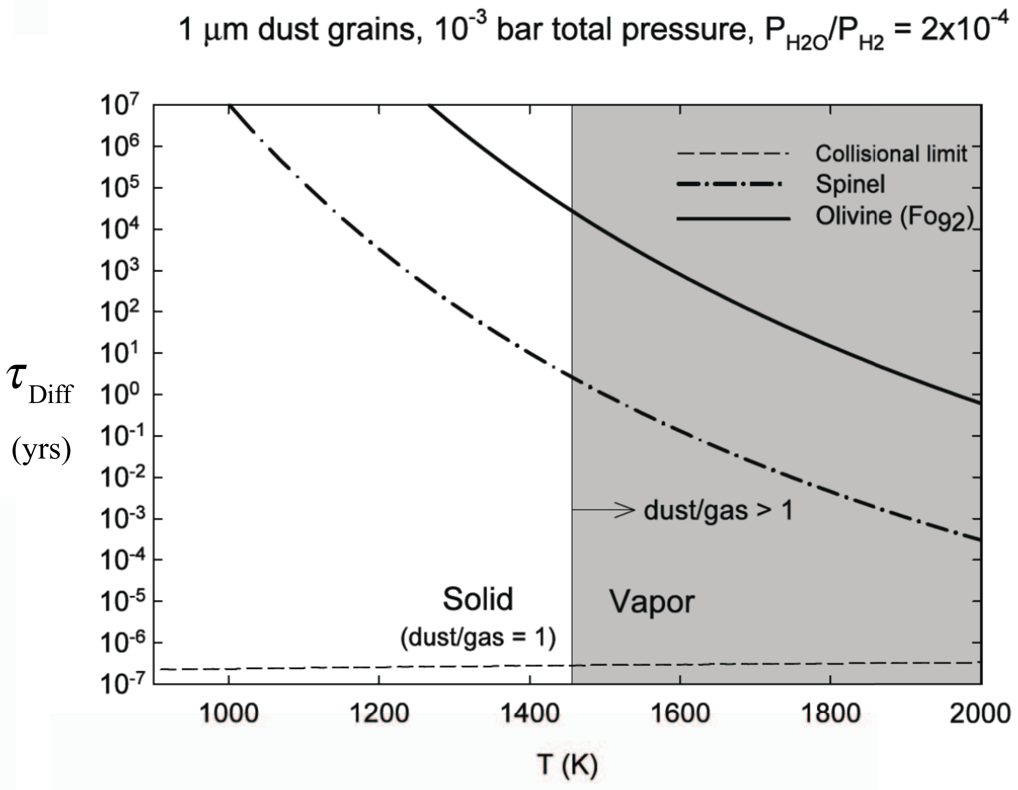
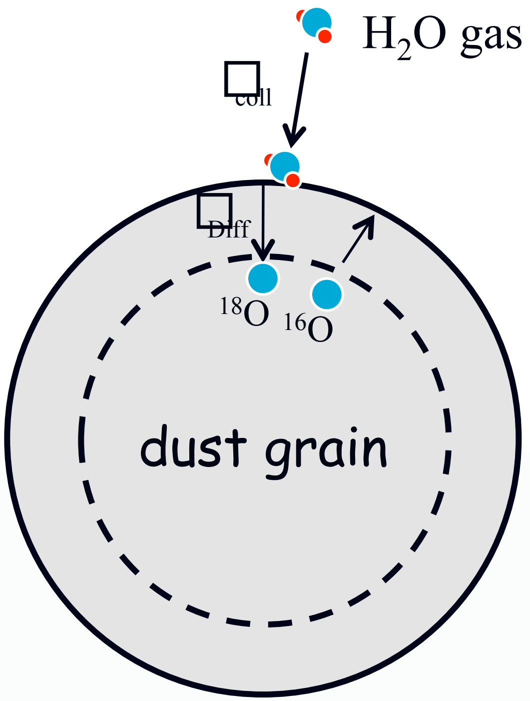
Timescale for oxygen isotopic equilibration of dust

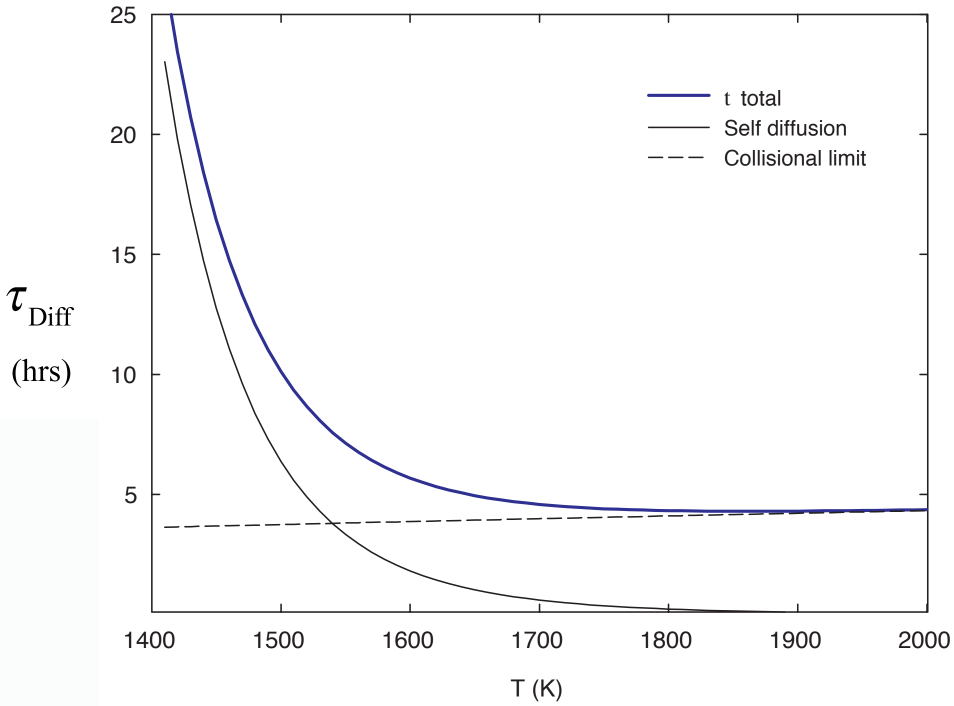


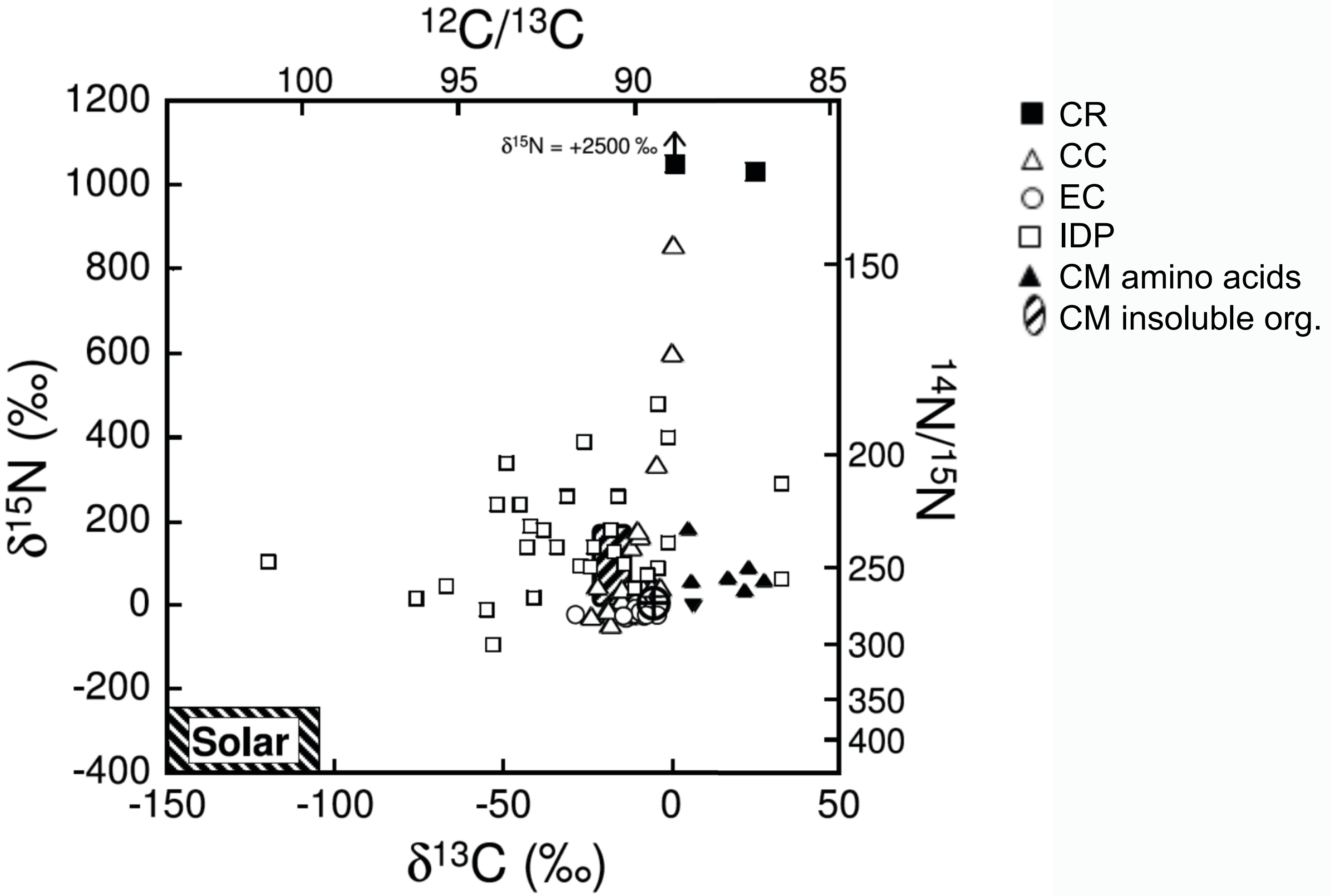


Timescale for oxygen isotopic equilibration of melt

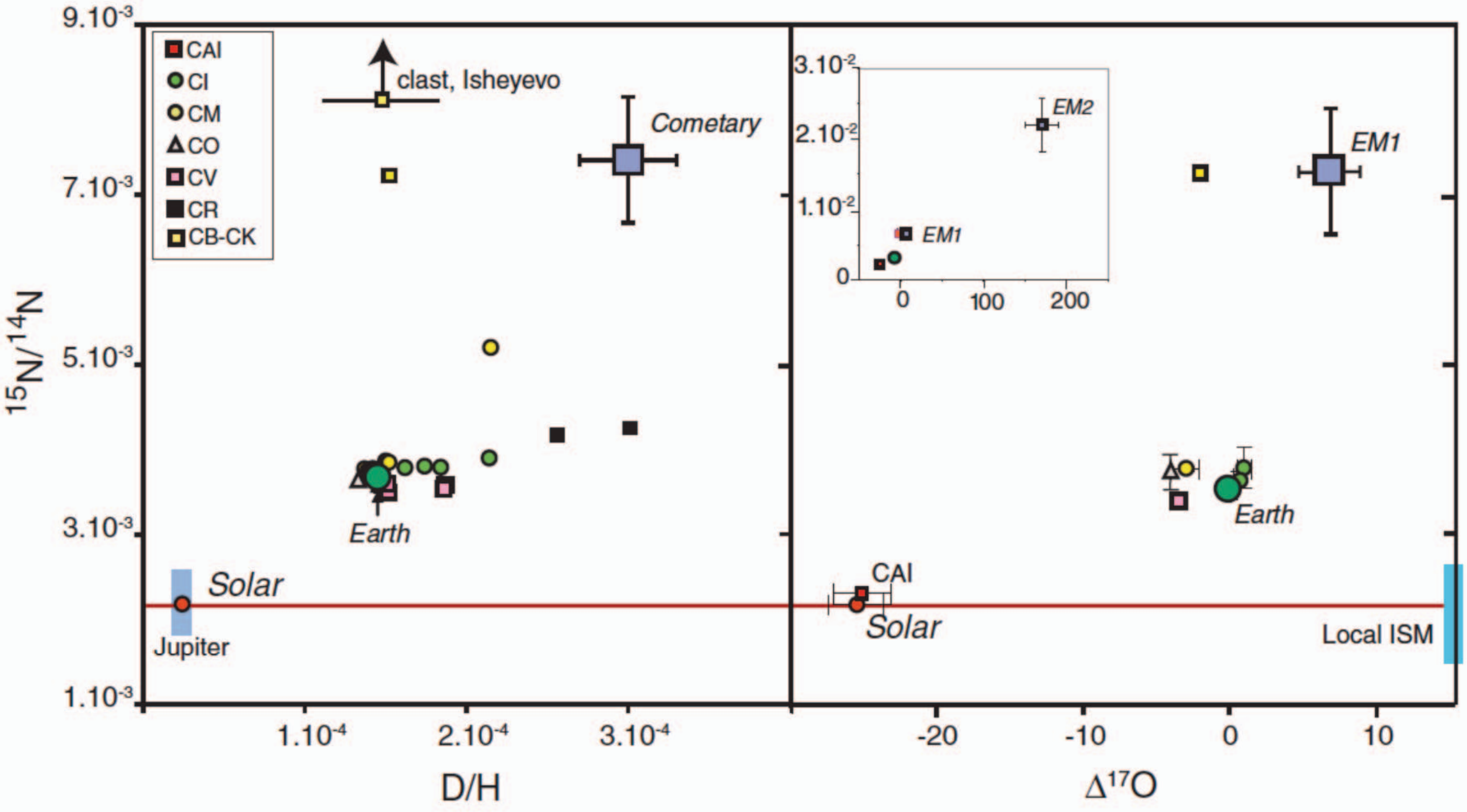


1 mm chondrule, 10^{-3} bar total pressure, $P_{H2O}/P_{H2} = 2x10^{-4}$

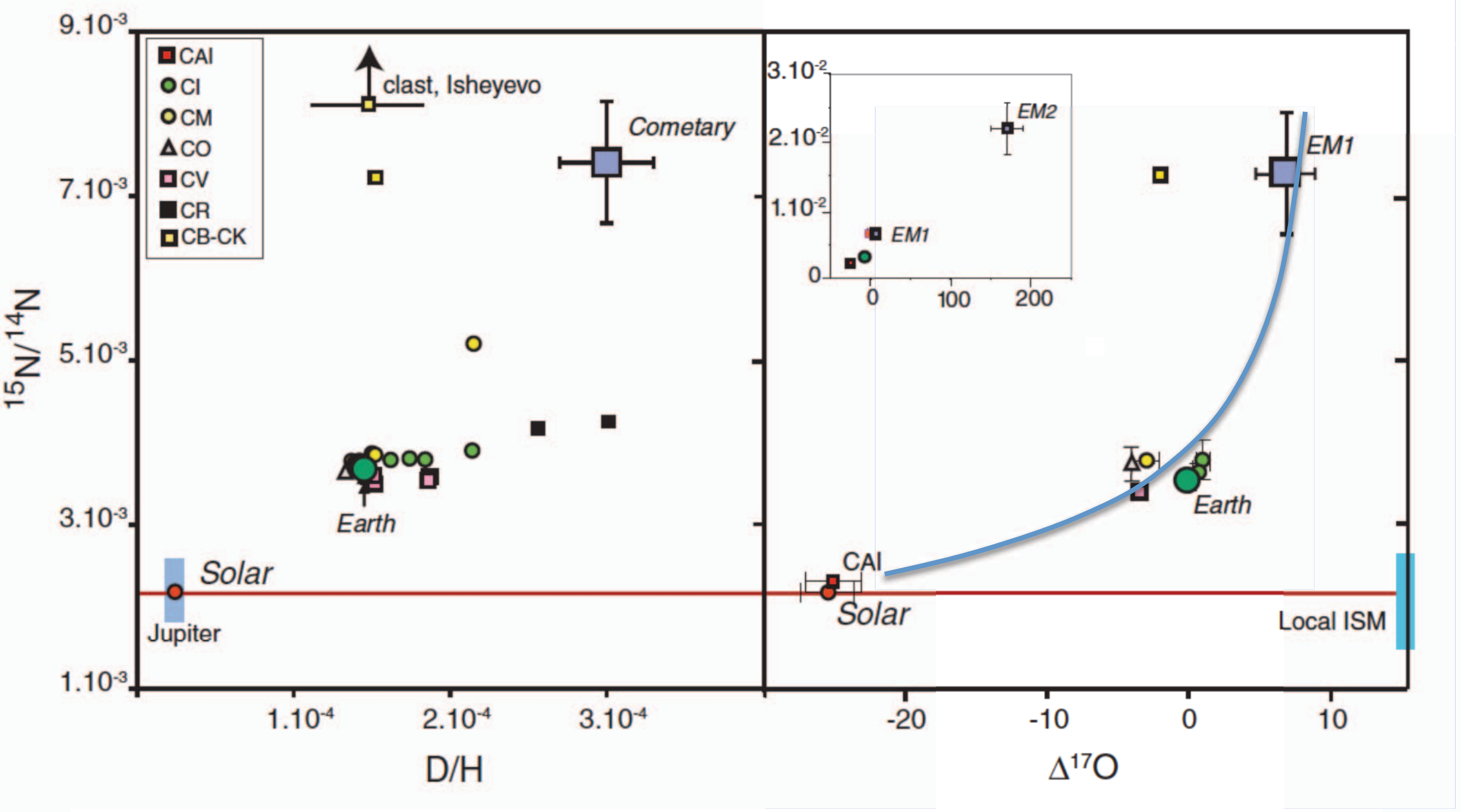




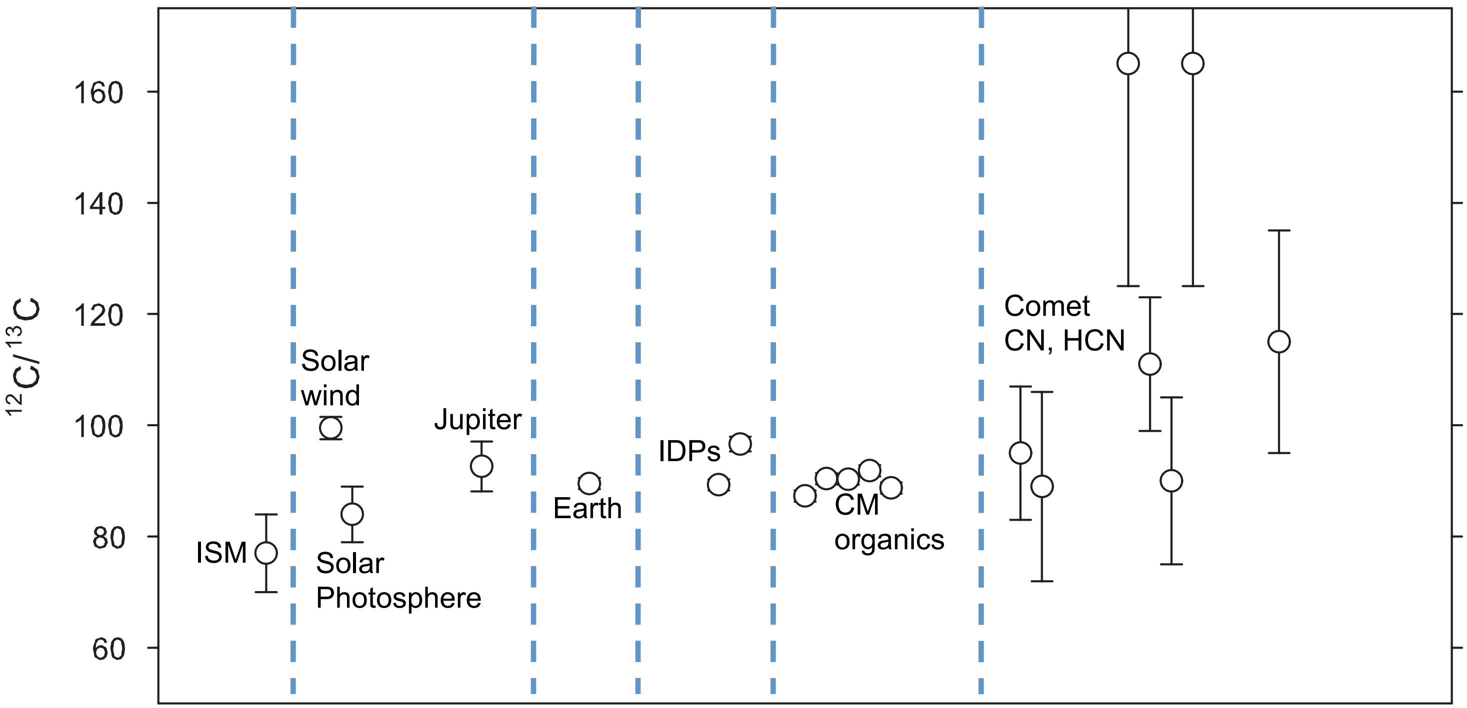
Hashizumet et al. (2004)



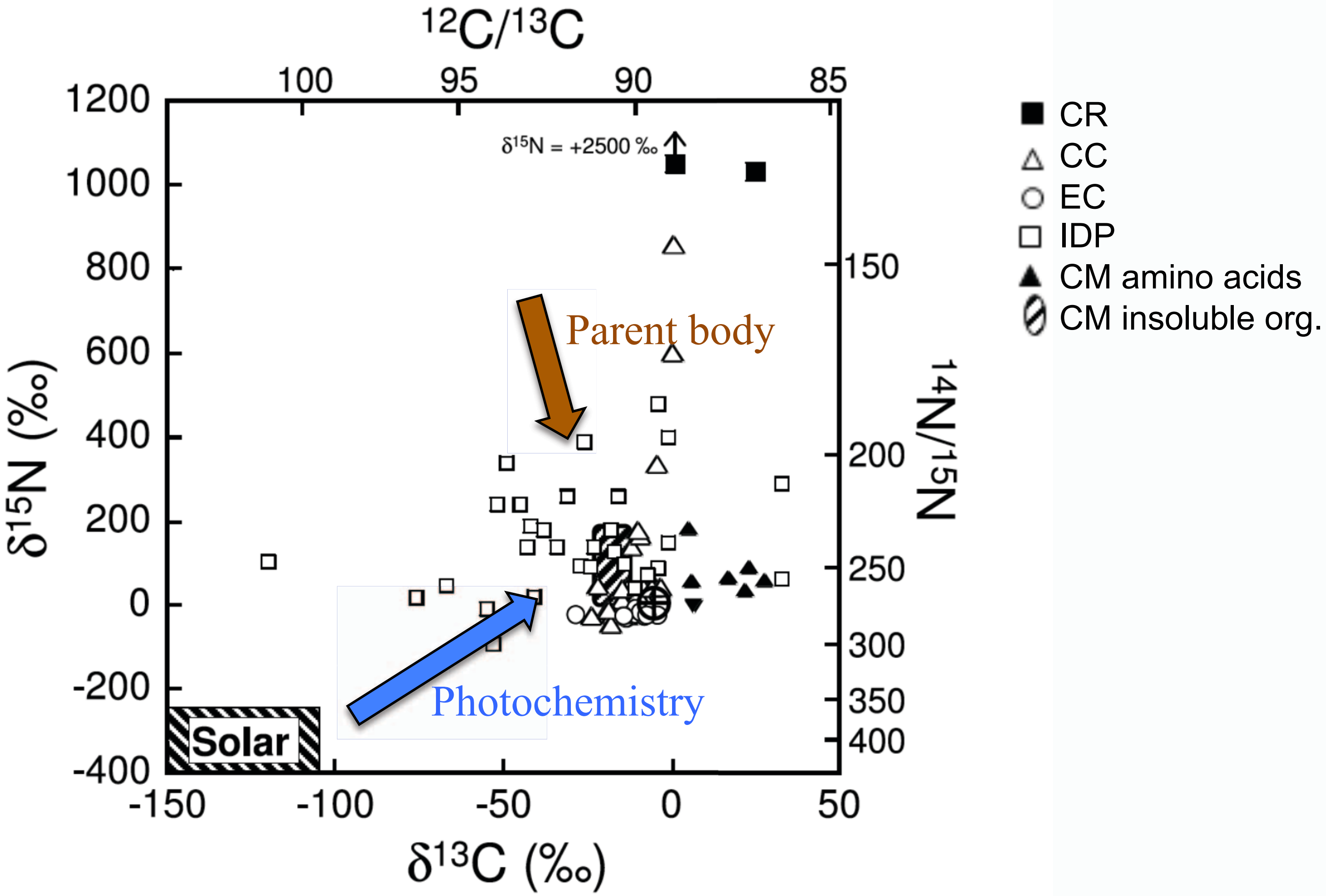
Marty et al. (2011)



Marty et al. (2011)



$^{12}C/^{13}C$
160
140
120
100
80
60
ISM
Solar wind
Solar Photosphere
Jupiter
Earth
IDPs
CM organics
Comet CN, HCN



Hashizumet et al. (2004)