Percival Lowell

"the maximum speed [a molecule] may attain Clerk-Maxwell deduced from the doctrine of chances to be seven-fold the average. What may happen to one, must eventually happen to all."

Evidence of Ancient Escape

Earth

- Xe isotopic fractionation, scarcity of radiogenic ^{129}Xe, ^{136}Xe
- O_2 atmosphere (speculative, this)

Venus

- dessication, high D/H ratio in rump water

Mars

- Xe fractionation, extreme scarcity of radiogenic ^{129}Xe, ^{136}Xe
- heavy D/H, $^{15}N/^{14}N$, $^{36}Ar/^{38}Ar$ ratios
- heavy C, O
- general absence of atmophiles

Io

- **Sulfur? follow the water?**

Thermal Escape

“Jeans escape” = escape one hot atom or molecule at a time

escape is from an “exobase”

defined as scale height = mean free path

rule of thumb: scale height < Planet Radius/6

its relatively slow, but not necessarily unimportant

examples include modern H on Earth, Mars, Titan

it is extremely mass fractionating

it is not usually discussed for Io

“Jeans” Escape (what’s in a name)

1846 - Waterston suggested thermal escape from atmospheres. Paper rejected.

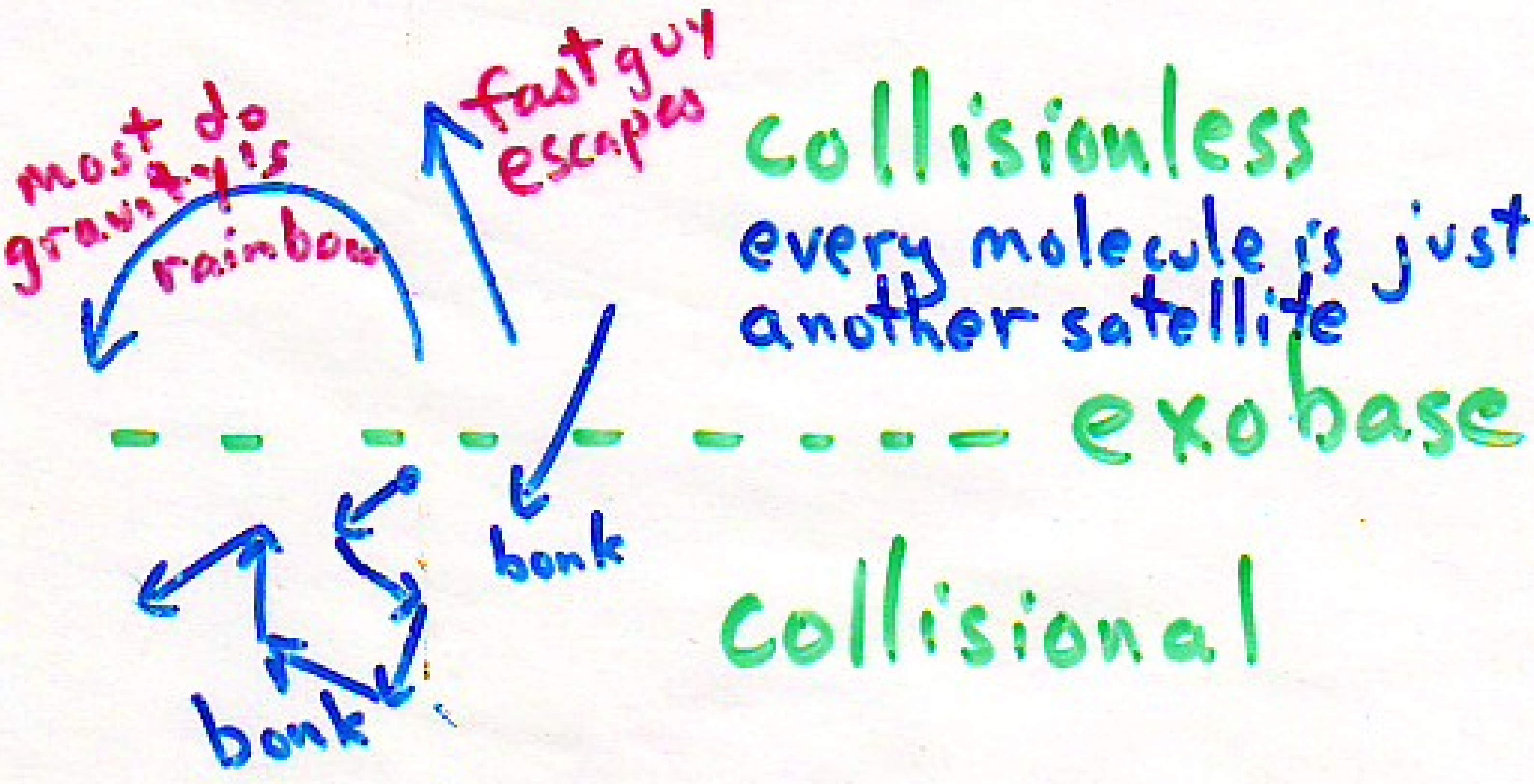
1868, 1898 - Stoney introduced concept of “exosphere,” rediscovered thermal escape.

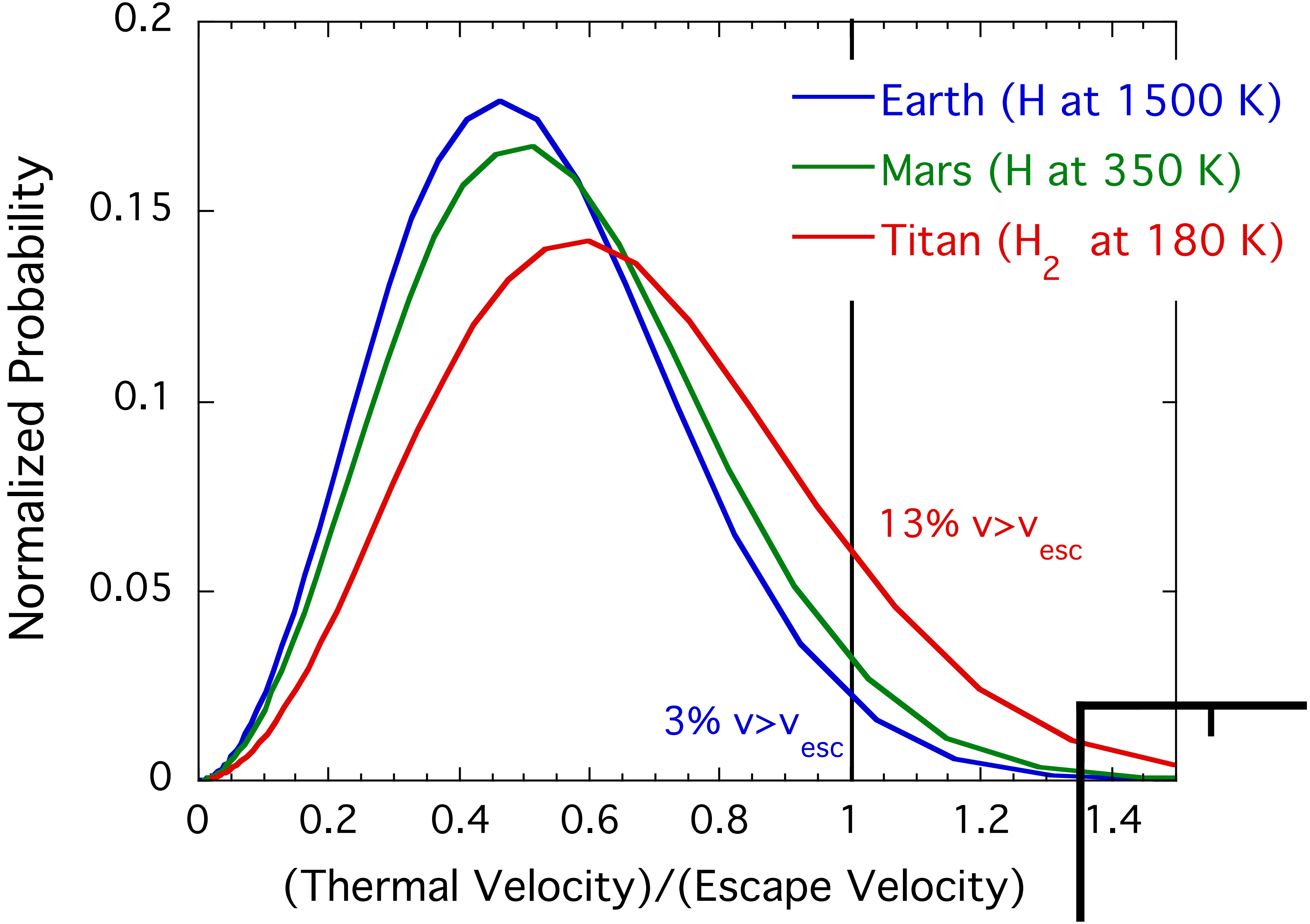
1904 - Jeans reinvents exosphere and thermal escape. He ignores all previous work. Thermal escape becomes known as “Jeans escape.” IAU-approved.

Jeans escape describes the loss of atoms or molecules from an exobase that is treated like a surface

Exobase (aka "critical level")

what goes up, may come down





Earth (H at 1500 K)
Mars (H at 350 K)
Titan (H2 at 180 K)
13% v>vesc
3% v>vesc
Normalized Probability
(Thermal Velocity)/(Escape Velocity)
0.2
0.15
0.1
0.05
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4

Thermal Escape continued

"hydrodynamic escape" = pressure-driven fluid flow

There is no exobase

its usually faster. Probably the only way to lose a Ganymede of H_2O

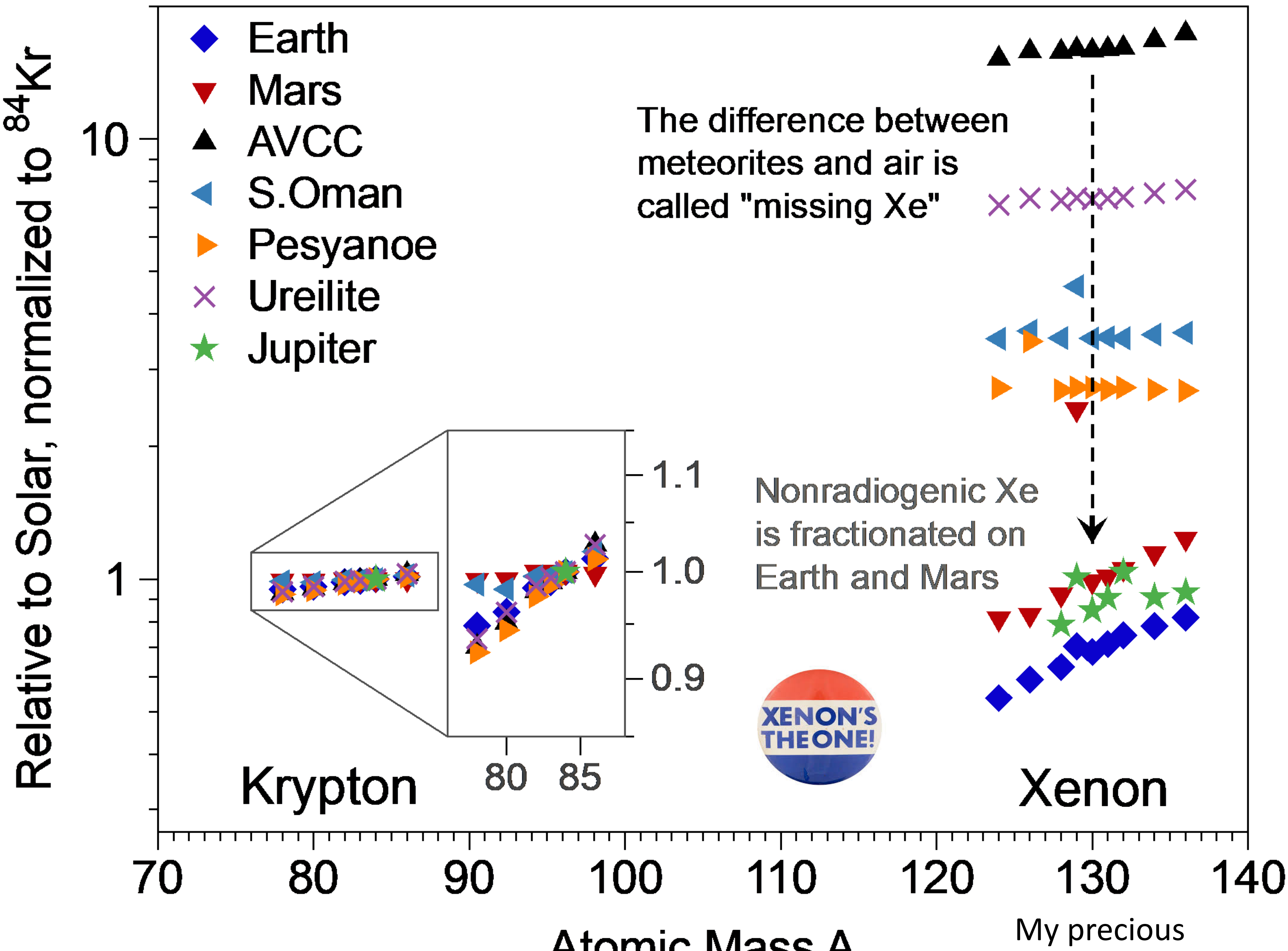
- solar wind; ancient Earth and Mars; possibly current Pluto
- doubtless ancient Venus

the canonical escape flux from Io is only 3-10 X smaller than would require a hydrodynamic description

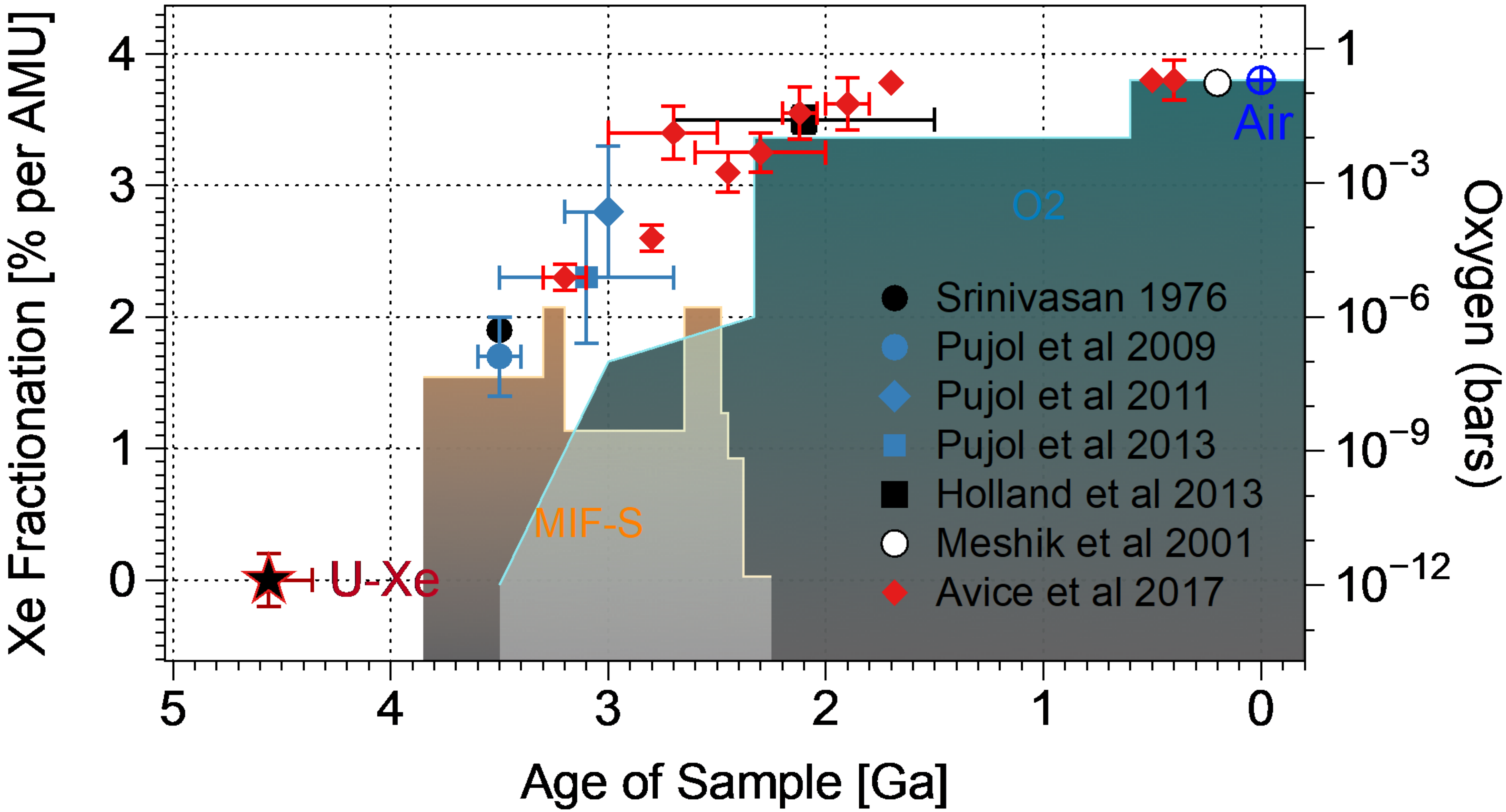
Fractionation in hydrodynamic escape occurs when the carrier gas drags heavier species into space. My favorite e.g. is Xenon.

Fractionation depends on the flux of the carrier gas

- if the flux much exceeds what is required to drag off the heavy gas, fractionation is modest
- if the flux is just barely sufficent to carry off the heavy gas, fractionations can be large with very little actual escape

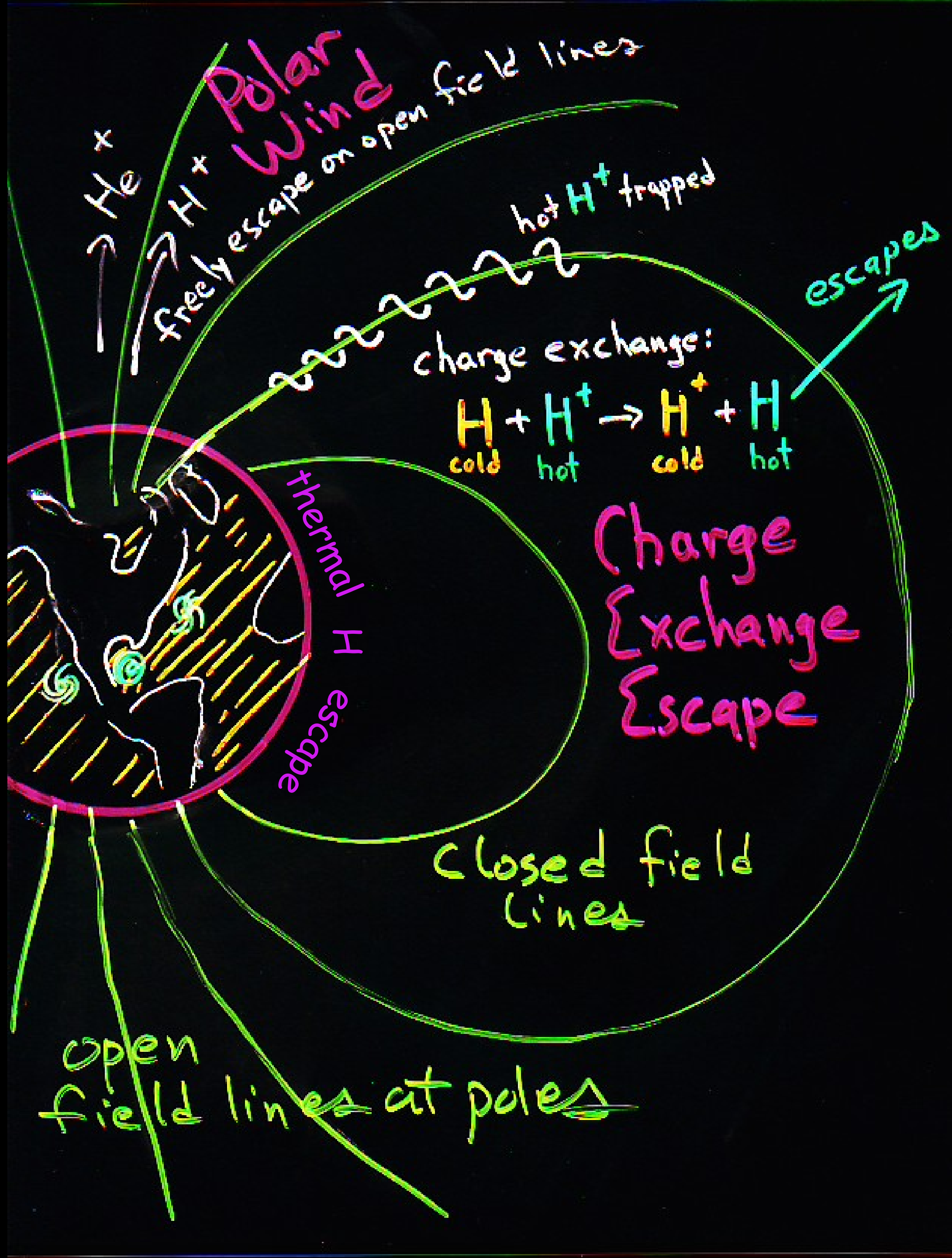

Earth
Mars
AVCC
S.Oman
Pesyanoe
Ureilite
Jupiter
The difference between meteorites and air is called "missing Xe"
Nonradiogenic Xe is fractionated on Earth and Mars
XENON'S THE ONE!
Krypton
Xenon
1.1
1.0
0.9
80
85
10
1
70
80
90
100
110
120
130
140
Relative to Solar, normalized to ^{84}Kr
Atomic Mass A
My precious

Adapted from Guillaume Avice et al 2017



Nonthermal Escape (many many mechanisms)

- most but not all are one atom at a time, and therefore most are slow
- charge exchange (fast X^+ + slow X > fast X + slow X^+)
  - H and O on Earth, Venus, Mars.
  - **Na, O, S, Cl on Io**
- dissociative recombination ($XY^+ + e^-$ > fast X + fast Y)
  - N, O, C on Mars [Titan?]; **NaCl, SO, S2, O2 at Io**
- solar wind sweeping, sputtering, ion pickup etc
  - Ar, N on Mars
  - **S, O, Na, Cl on Io**
- polar wind (electric field acceleration)
  - this is a kind of nonthermal hydrodynamic escape; possibly fast
  - He^+ on Earth, H+ on Venus; H^+, O^+, N^+, Xe^+ on ancient Earth, Mars
  - **probably something like this with ions and Io (the big current)**
- fractionating power varies



He^+
H^+
Polar Wind
freely escape on open field lines
hot H^+ trapped
escapes
charge exchange:
$H + H^+ \rightarrow H^+ + H$
cold hot cold hot
thermal H escape
Charge Exchange Escape
Closed field lines
open field lines at poles

Diffusion limited escape – applies generally

limits how quickly one gas can diffuse through another*

$$\phi_{\mathrm{DL}} = b_{ij}\left(\frac{1}{H_i} - \frac{1}{H_j}\right) f(\mathrm{H})$$

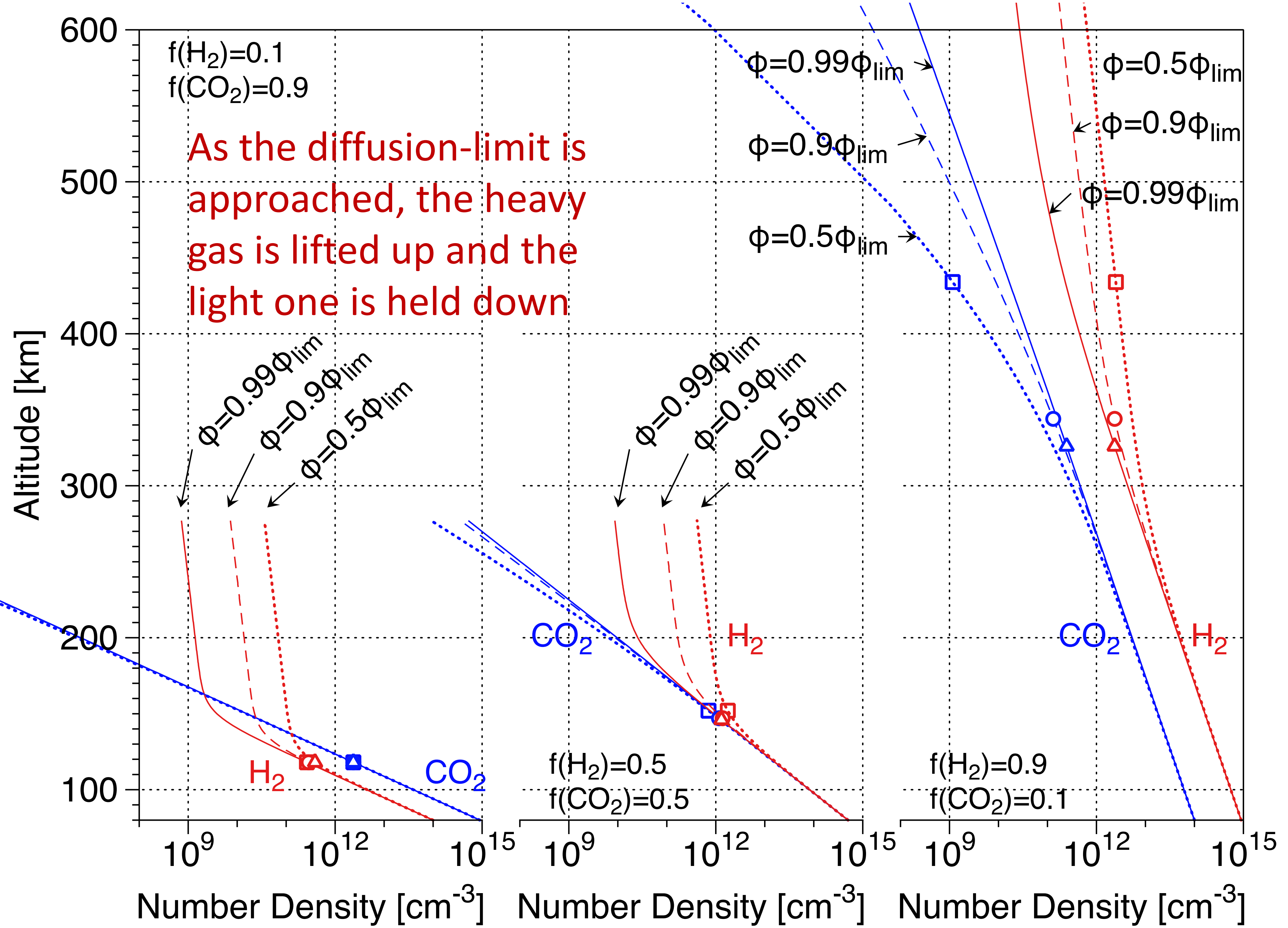
$f(\mathrm{H})$ is the total hydrogen mixing ratio

and b_{ij} is the binary diffusion coefficient [$\mathrm{cm}^{-1}\mathrm{s}^{-1}$]

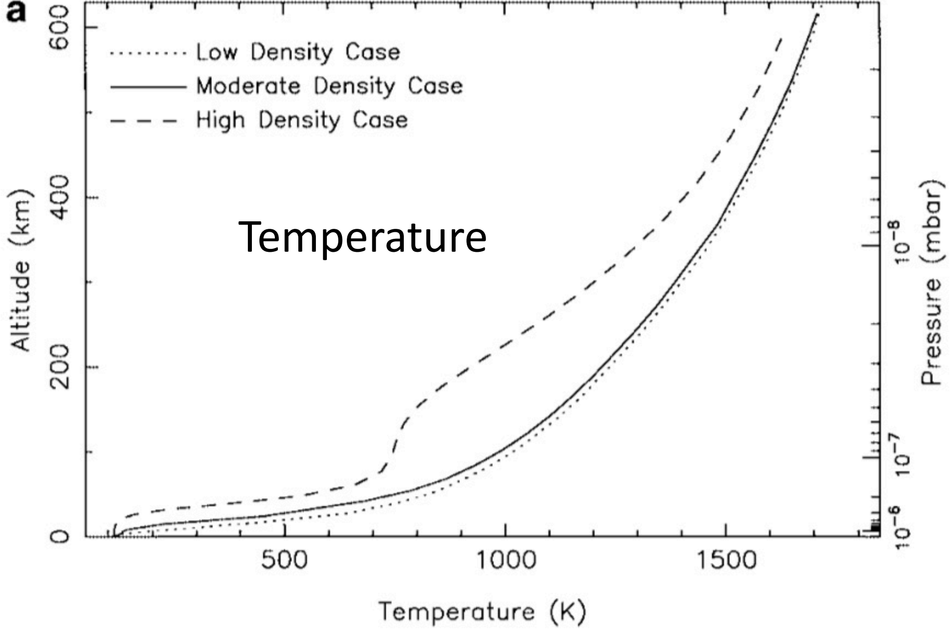
b_{ij} is the thermal velocity divided the collision cross section

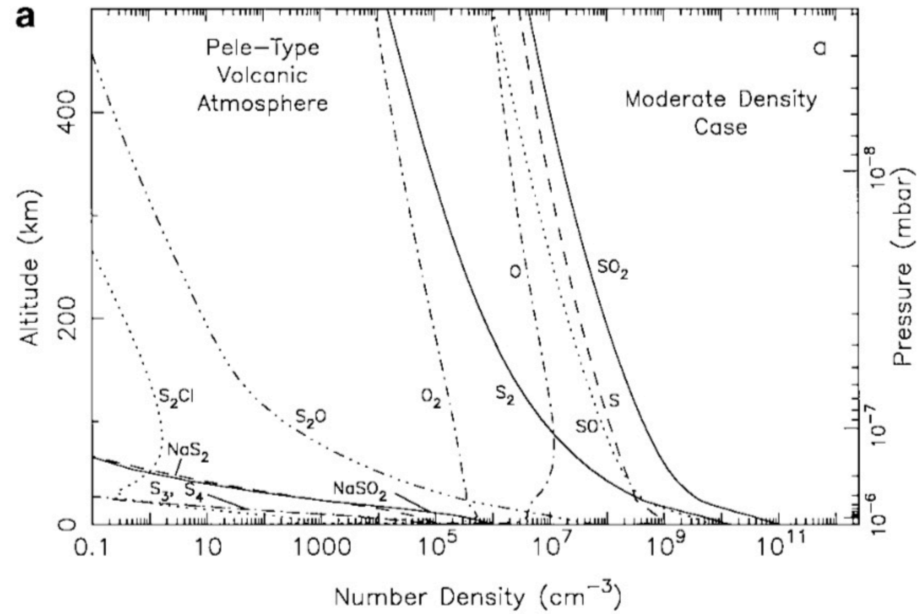
Moses et al 2002 estimate diffusion limits for Na, Cl, S, O with respect to SO2 for Io

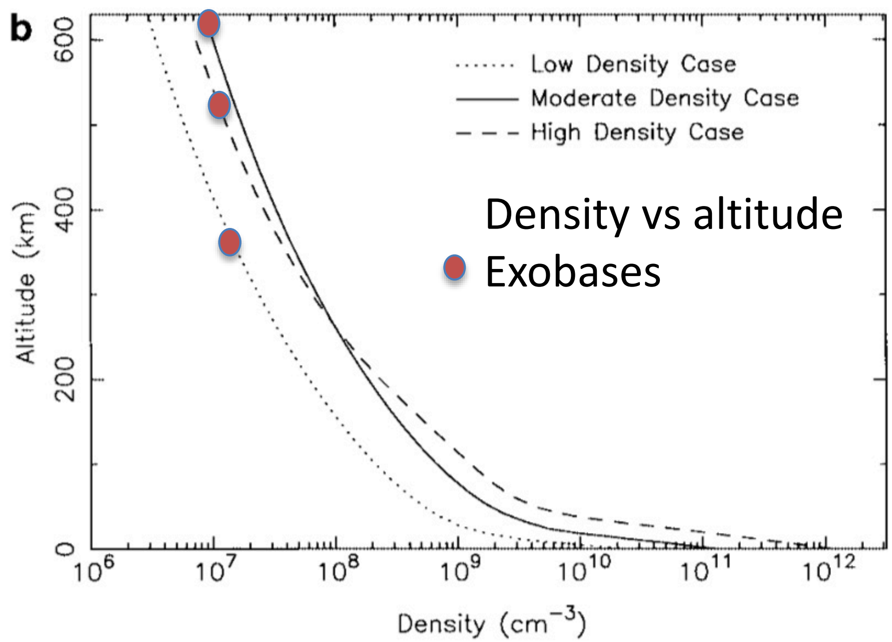
*To do better requires phases separating – e.g., solids precipitating

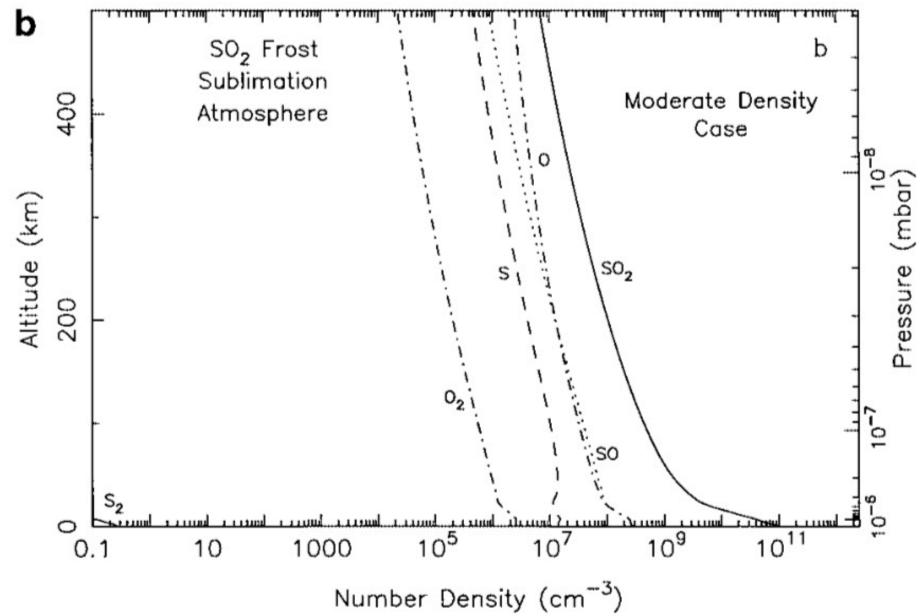


f(H2)=0.1
f(CO2)=0.9
As the diffusion-limit is approached, the heavy gas is lifted up and the light one is held down
Altitude [km]
Number Density [cm-3]
ϕ=0.99ϕlim
ϕ=0.9ϕlim
ϕ=0.5ϕlim
H2
CO2
f(H2)=0.5
f(CO2)=0.5
f(H2)=0.9
f(CO2)=0.1









MOSES, ZOLOTOV, AND FEGLEY 2002

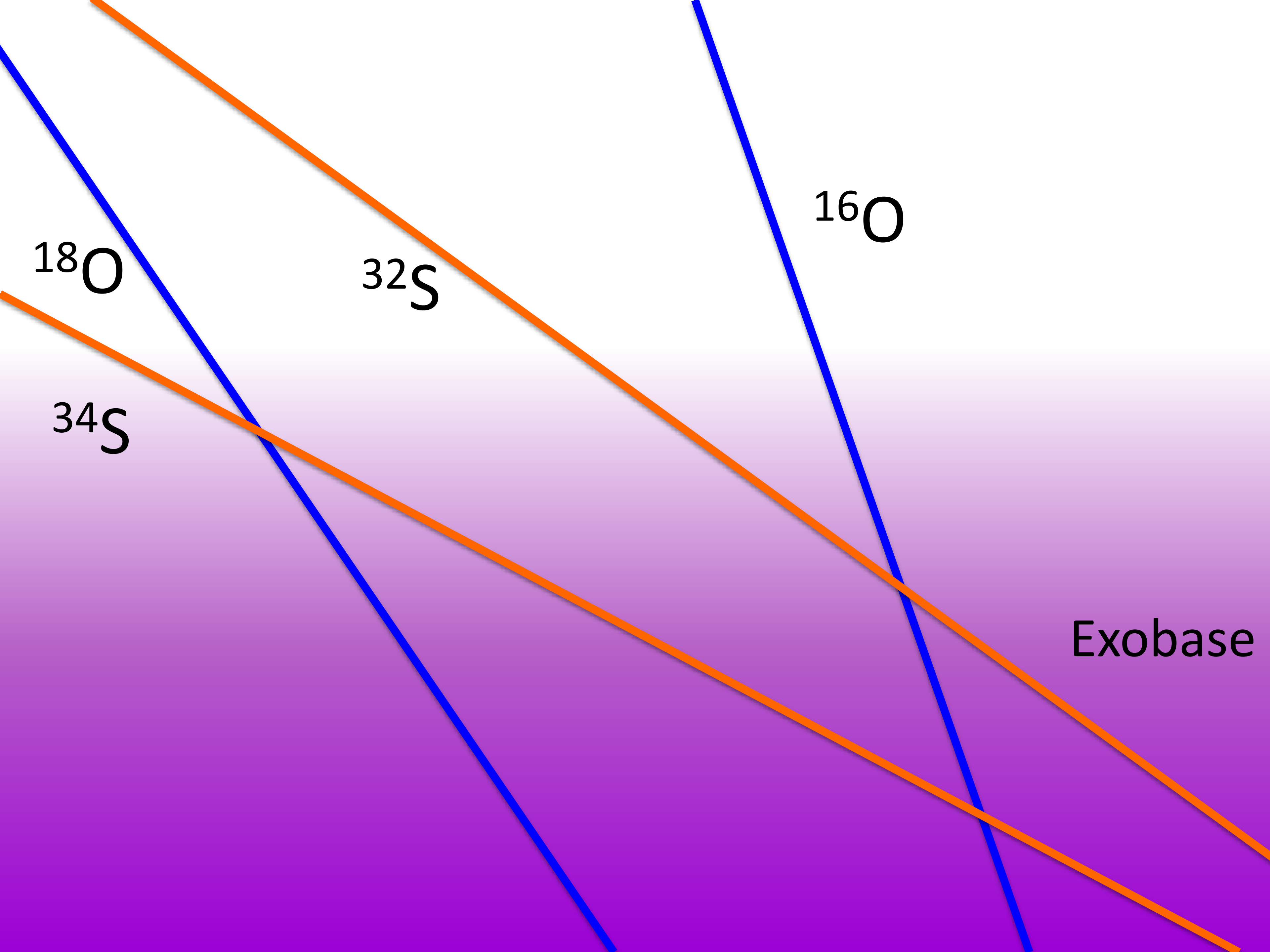
reported escape fluxes (x 10^{26} per second)

	canonical*	Moses et al 2002**
O	180	110
S	90	200
Na	3	50
NaCl	6	4
SO2	10	0
Cl		30

sum **1.1e6 g/s = 2 km of lost S over 4 Gyr**

*~~scaled from Na.~~ mass flux based on mass-loading

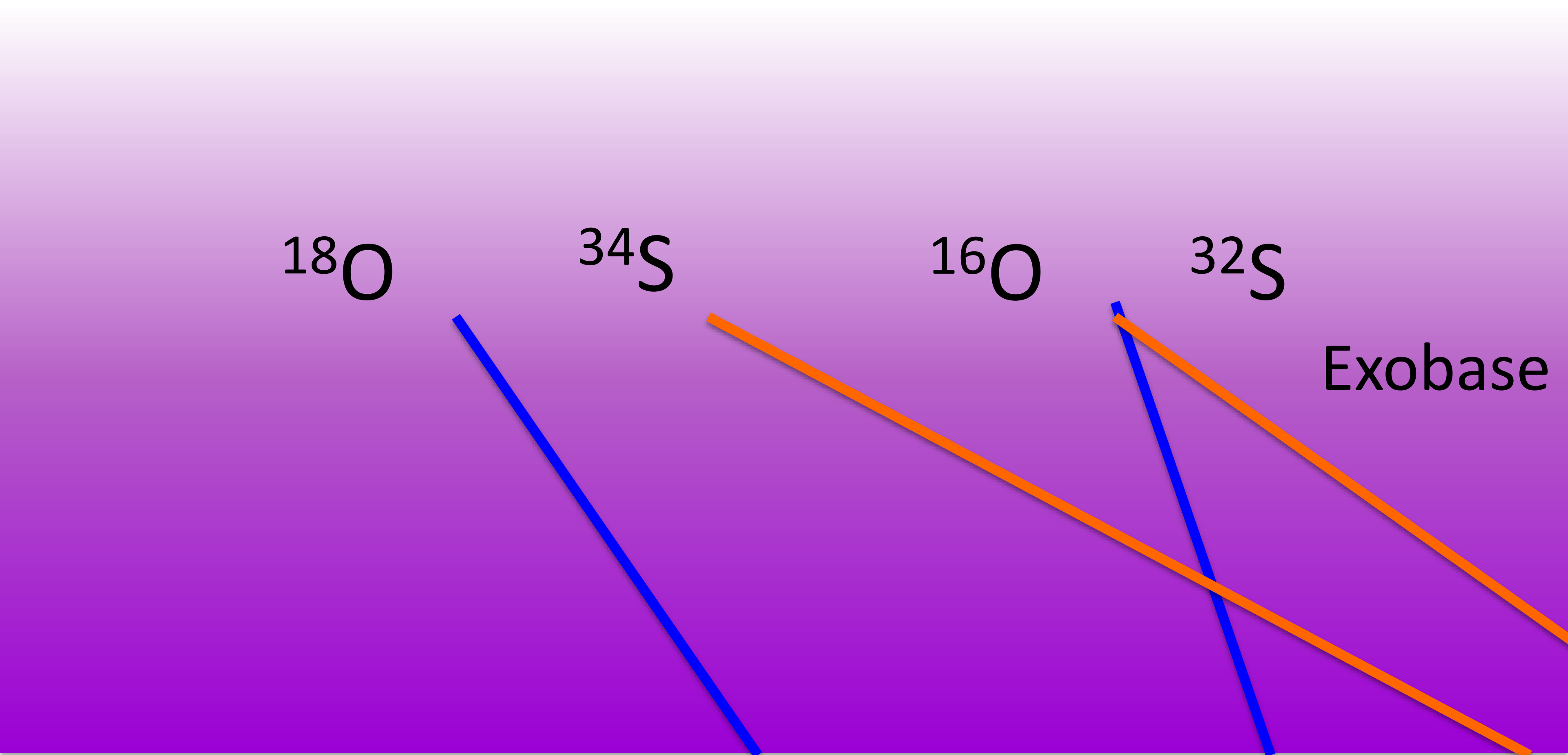
**diffusion-limiting flux, global Pelean atm assumed



^{16}O
^{18}O
^{32}S
^{34}S
Exobase

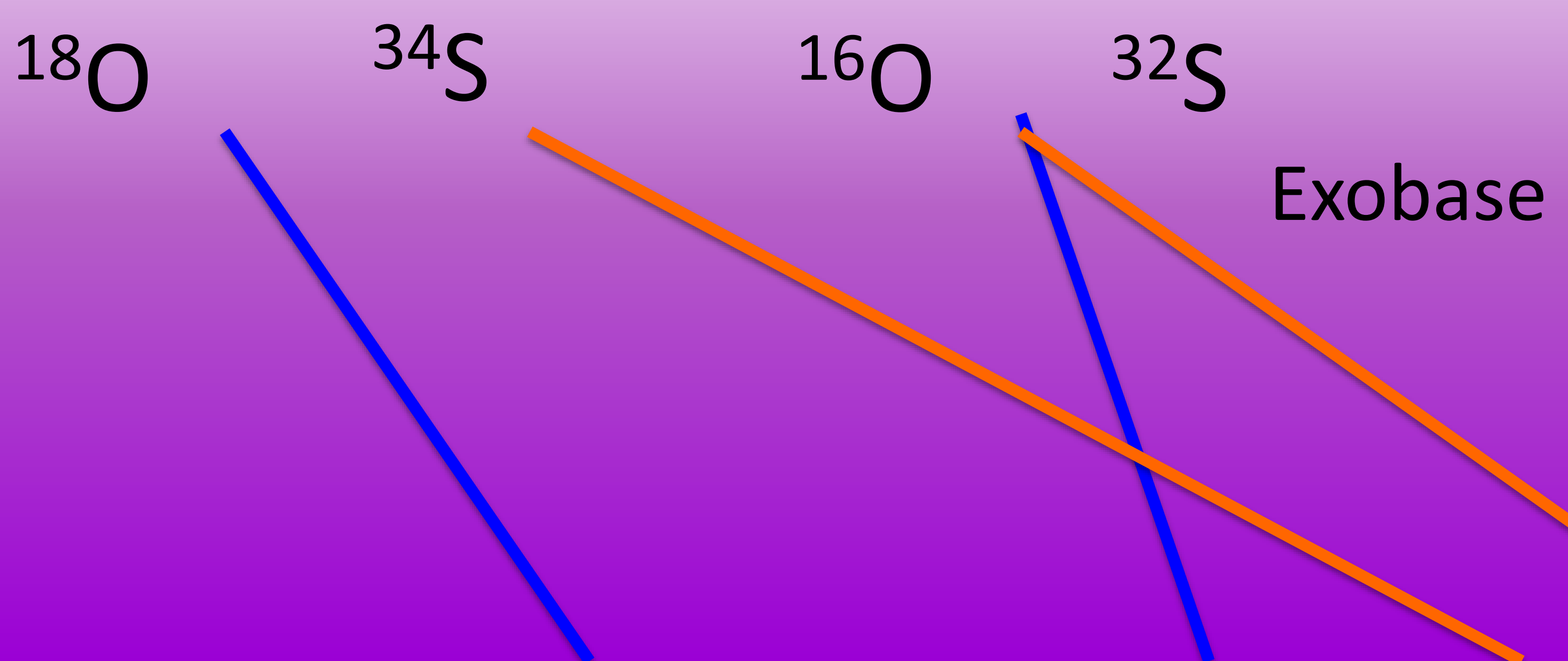
Sputtering picks off atoms ~~above~~ in general vicinity of the exobase

- which leaves the atmosphere enriched in heavier isotopes **and** enriched in **S** vs **O**



Ion pickup will prefer to pick off ions ~~above the exobase~~

- which goes the other way, favoring **S^+** escape over **O^+** escape because **S** is much easier to ionize. Na is much easier to ionize still.



some observations:

- escape takes place from the top of the atmosphere
  no Ca, Fe, Si, Mg in the torus
- plumes enable escape of NaCl and products of S_n
  escape of Na is probably restricted to plumetops
- two kinds of plumes:
  Promethean, driven by SO_2 vapors
  Pelean, driven by S_n vapors
- the atmosphere and plumes are substantially heated
  solar UV alone would heat a plume by 1-4 K/s
  particle heating is said to be bigger,
  Joule heating is said to be bigger still

more speculations, mostly re isotope fractionation

- 2 km sulfur is 0.16% of Io’s mass.
  this seems like a lot to me – its 10X the sulfur of BSE
- it seems reasonable to expect that S and O
  escape stoichiometrically as SO_2.
  This is similar to what is inferred of H and O (H_2O)
  escaping from Mars and Venus.
  We should expect feedbacks between escape,
  atmospheric chemistry, and volcanism to maintain this
- isotopic fractionation of S and O should be correlated
- isotopic fractionation is sensitive to the relationship
  between the exobase and the homopause.

My guess is that neither will be well-defined, in which
case fractionation will not be extremely sensitive to mass