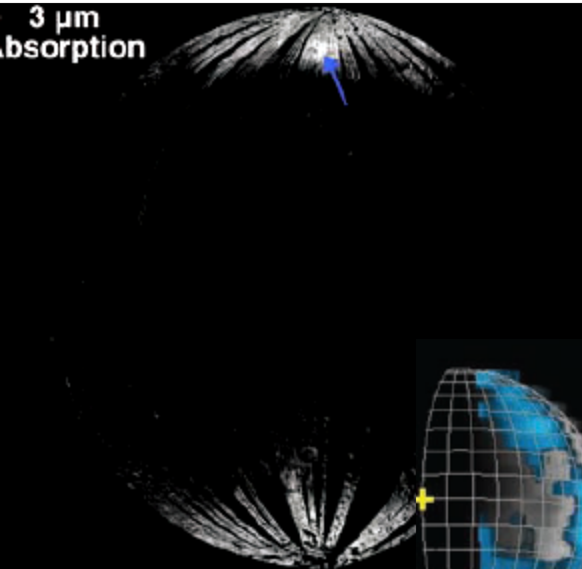
SOLAR SYSTEM EXPLORATION RESEARCH VIRTUAL INSTITUTE

A Comparison of Solar Wind Hydroxylation within and outside Lunar Magnetic Anomalies

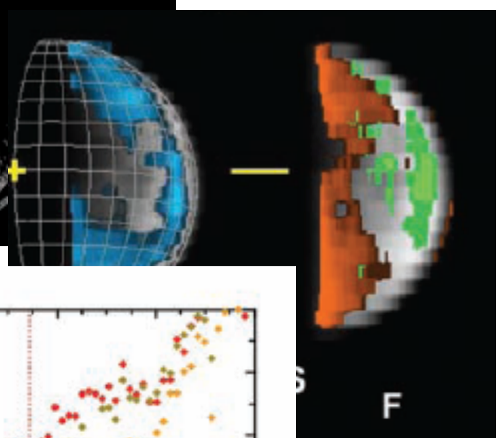
W. M. Farrell[1], D. M. Hurley[2], V. J. Esposito[3], J. L. McLain[4], M. I. Zimmerman[2]

1. NASA/Goddard Space Flight Center, Greenbelt MD; 2. Johns Hopkins University/Applied Physics Laboratory, Laurel MD; 3. NASA Goddard Summer Intern and U. South Carolina; 4. University of Maryland, College Park, MD.

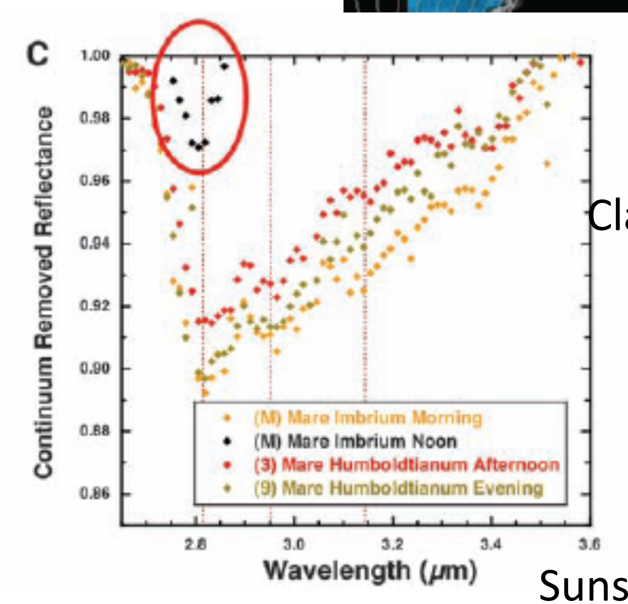
2009 – The Discovery of an OH Veneer



Pieters et al [2009]



Clark et al [2009



Sunshine et al [2009]

- Publication of Chandrayaan-1 M^3 [Pieters et al., 2009], Cassini VIMS [Clark et al. 2009], and EPOXI HRI-IR [Sunshine et al., 2009] IR observations of OH/ water content in near-surface of regolith
- Observe an absorption feature near 2.8 micron in NIR reflectance spectra
- Minimum at warm sub-solar point [McCord et al., 2011]
- Dynamic: H changing on diurnal timescales

What are the possible sources of lunar hydroxylation ?

Discussion in McCord et al 2011

1) OH in minerals: evolving view; once viewed as 'bone dry' but now find H-rich samples [McCubbin et al., 2010; Liu et al., 2012]

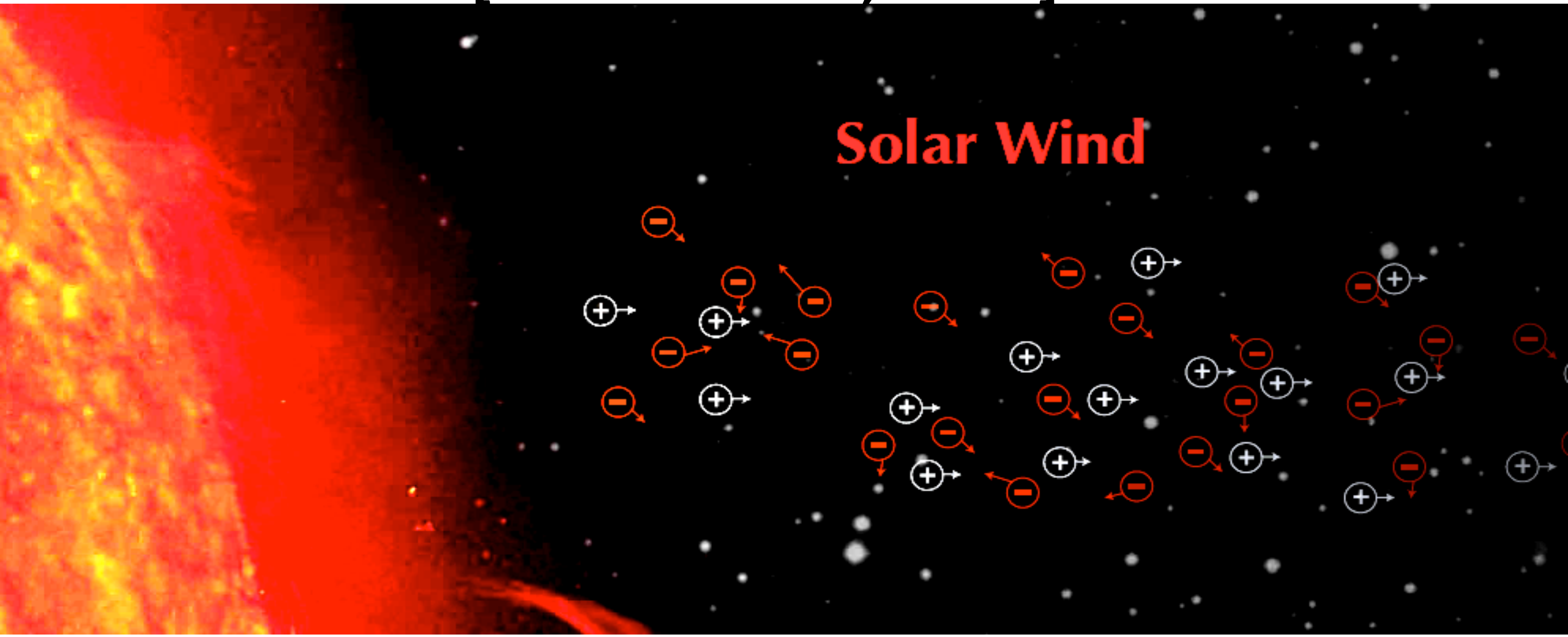
    - Recent M^3 analysis indicates mineralogical hydroxyl concentrations near pyroclastic deposits and in central peak of larger craters [Klima et al., 2013]

2) Cometary & Meteoric infall: delivery of OH bearing material

    -Is being re-examined given LADEE findings

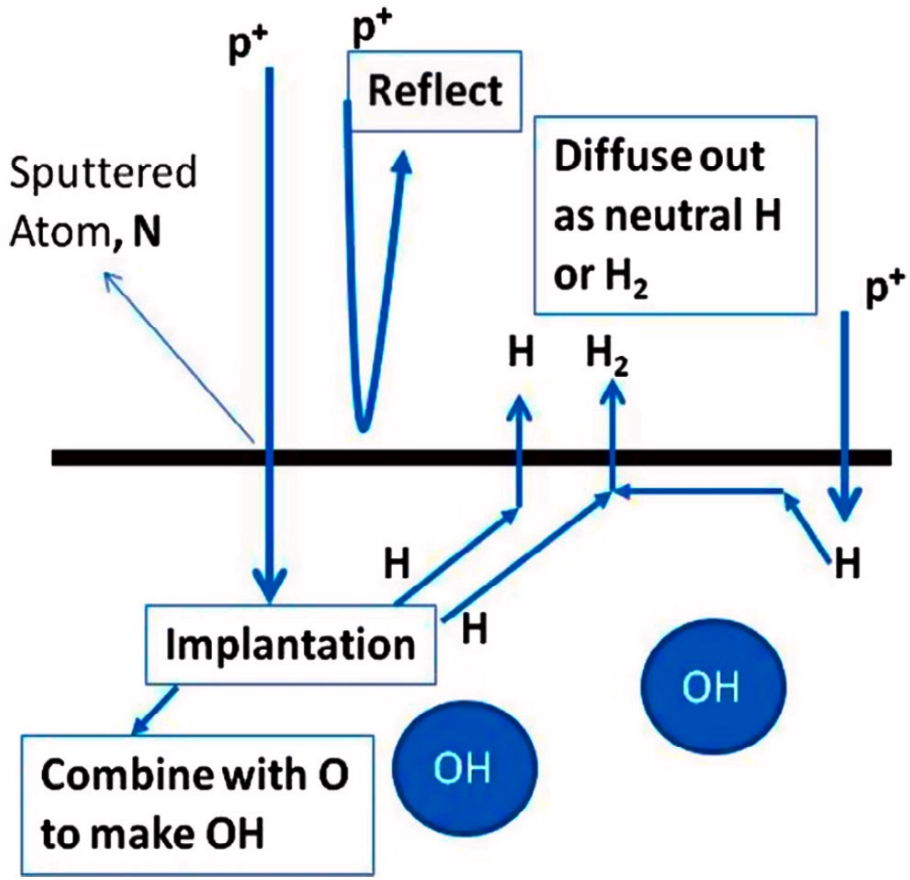
3) Solar wind implants H atoms into an oxygen-rich regolith – some of which 'loiters' [Pieters et al., 2009; Clark et al., 2009; Sunshine et al, 2009]

The Prime Suspect: Solar Wind
[McCord et al, 2011]



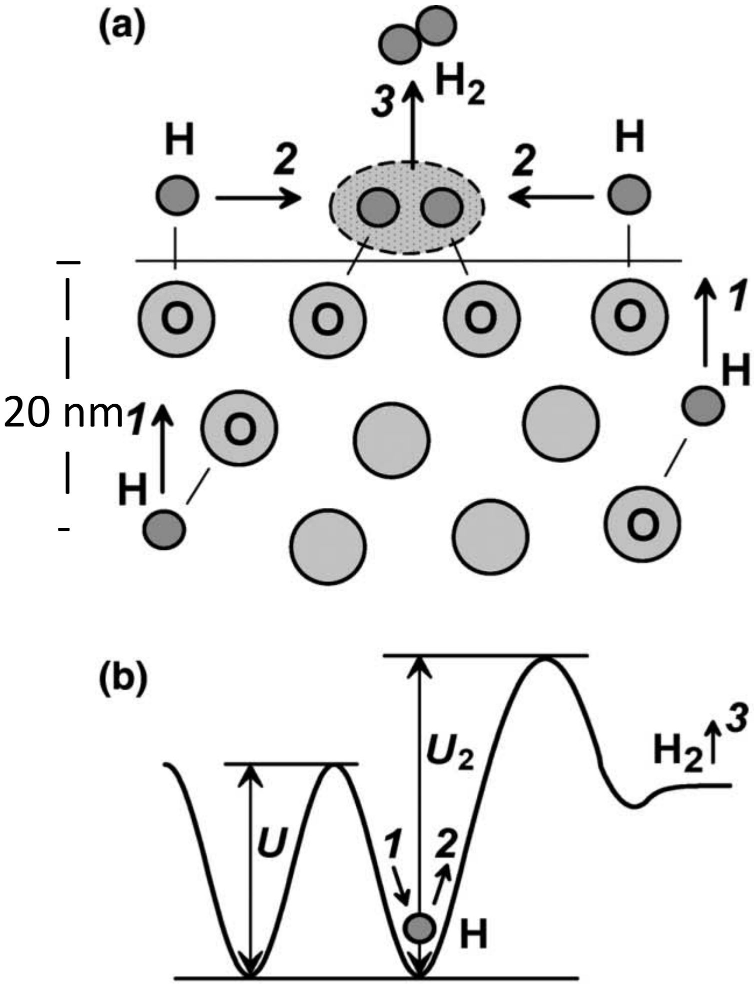
- Solar wind – tenuous ionized gas: Plasma is the 4th State of matter, most mass in universe, good example: our sun
- Protons (H^+) and electrons at $5/cm^3$ streaming at 400 km/sec, temperature near 100000K
- Airless body is a obstacle in this conductive plasma 'fluid' flow!
- 95% H^+ (few %: He^{++}, O^{+7}) incident at surface to implant, sputter, change crystal structure

H Implantation in 'Dry' Oxide-rich Lunar Regolith



- Why do some H's 'loiter' in the regolith and some allowed to leave?
- **What role does the harsh space environment perform to form OH?**

Atom-Atom Interaction



Starukhina 2001, 2006

H Residency 'Loitering' time:

$\tau = h^2 D_o^{-1} \exp(U/T)$

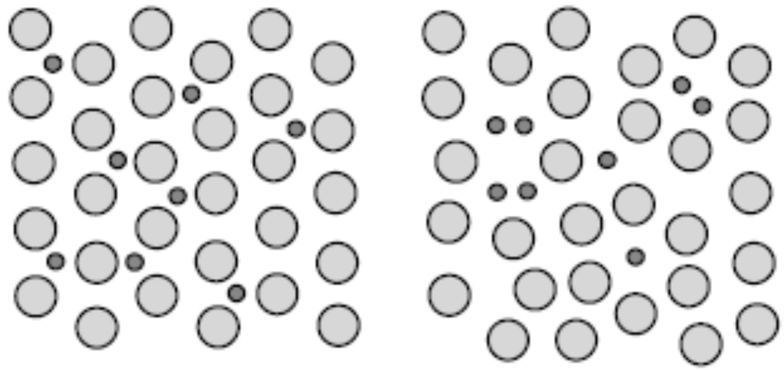
U is activation energy or 'trapping' energy related to **the inter-atomic potentials**

What is the value of U?

-Complicated question!

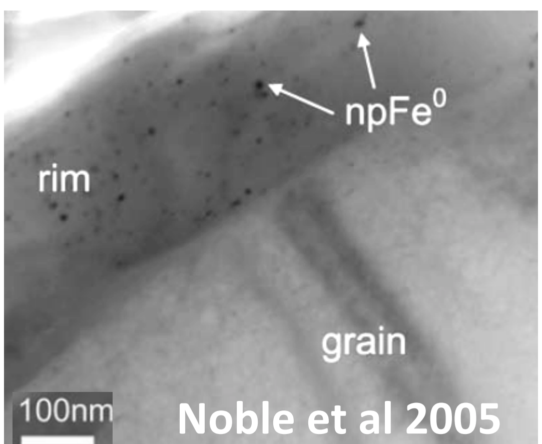
"…a wide spectrum of activation energies expects"
-Starukhina, 2006

Defects and H Diffusion



(a) (b) Starukhina 2006

- Lunar surface is oxide-rich: SiO_2, TiO_2, FeO_2
- **Non-thermal population of Defects** [Starukhina, 2006; Dyar et al., 2010]
- Vacancies yielding displacements and interstitial atoms; Channel defects
- Exposed grains have rims: amorphous crystalline structure – so damaged that original crystal destroyed
- Fink et al. 1995: Oxygen chemistry of irradiated silica will ‘hinder’ the migration of H



Noble et al 2005

Damaged crystal created via weathering in the space environment

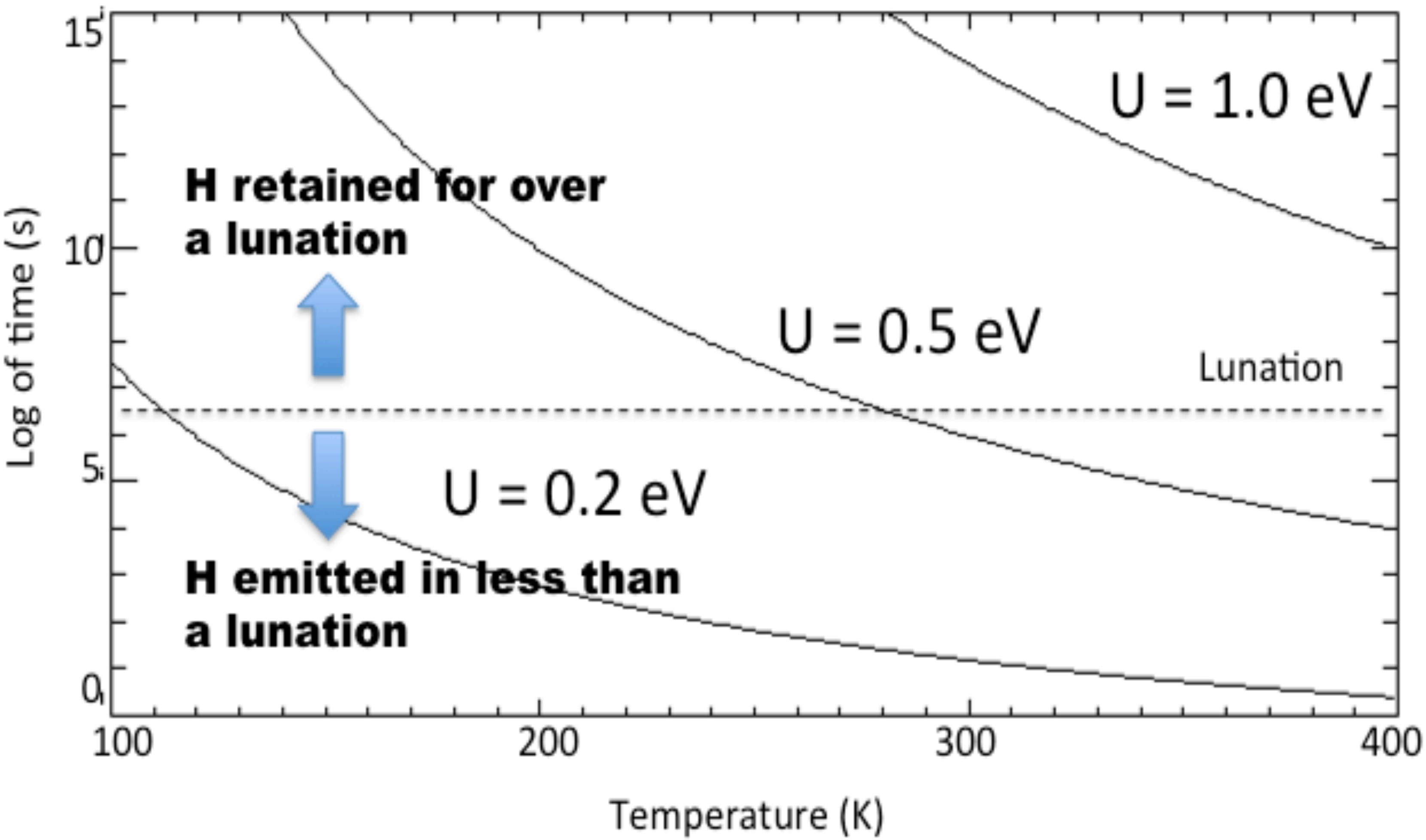
-radiation damage (tracks, channel defects)

-impact vaporization & condensation

-solar wind plasma damage (vacancy-defects) …..Self-fortifying effect

Each H implantation should have its own unique U depending on its migration history

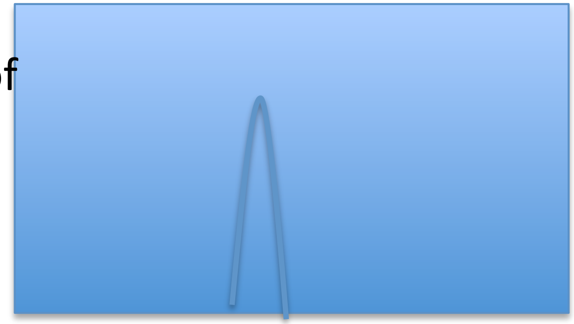
H Atom Residency Time in Irradiated Silica
($D_o = 10^{-12}\ m^2/s$, h= 20nm)



Effect of Space Weathering on a Crystal

Newly Exposed

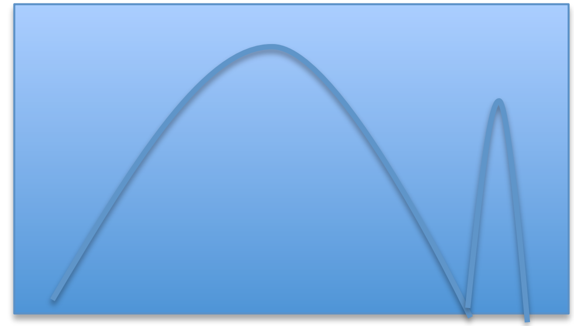
Distribution of Activation Energy, F(U)



U

$\tau = h^2 D_o^{-1} \exp(U/T)$

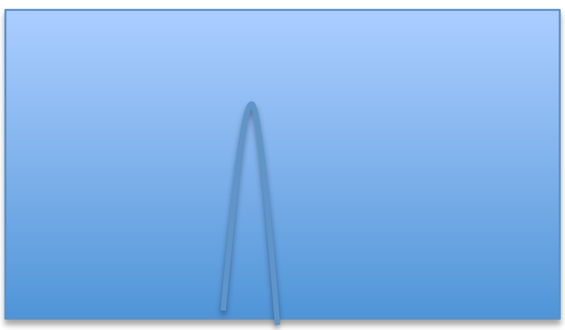
Long-Term Exposure



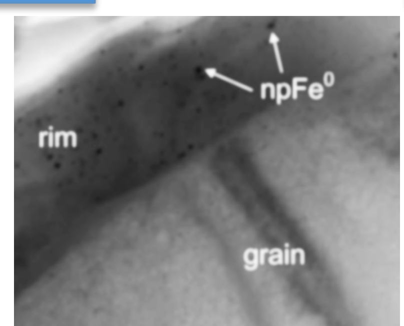
U

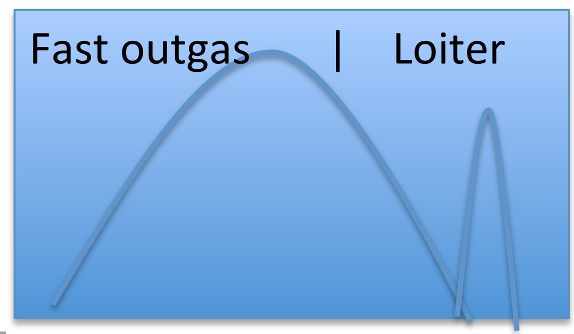
Amorphousization of the crystal lattice

Number of H Implantations



Log (τ)

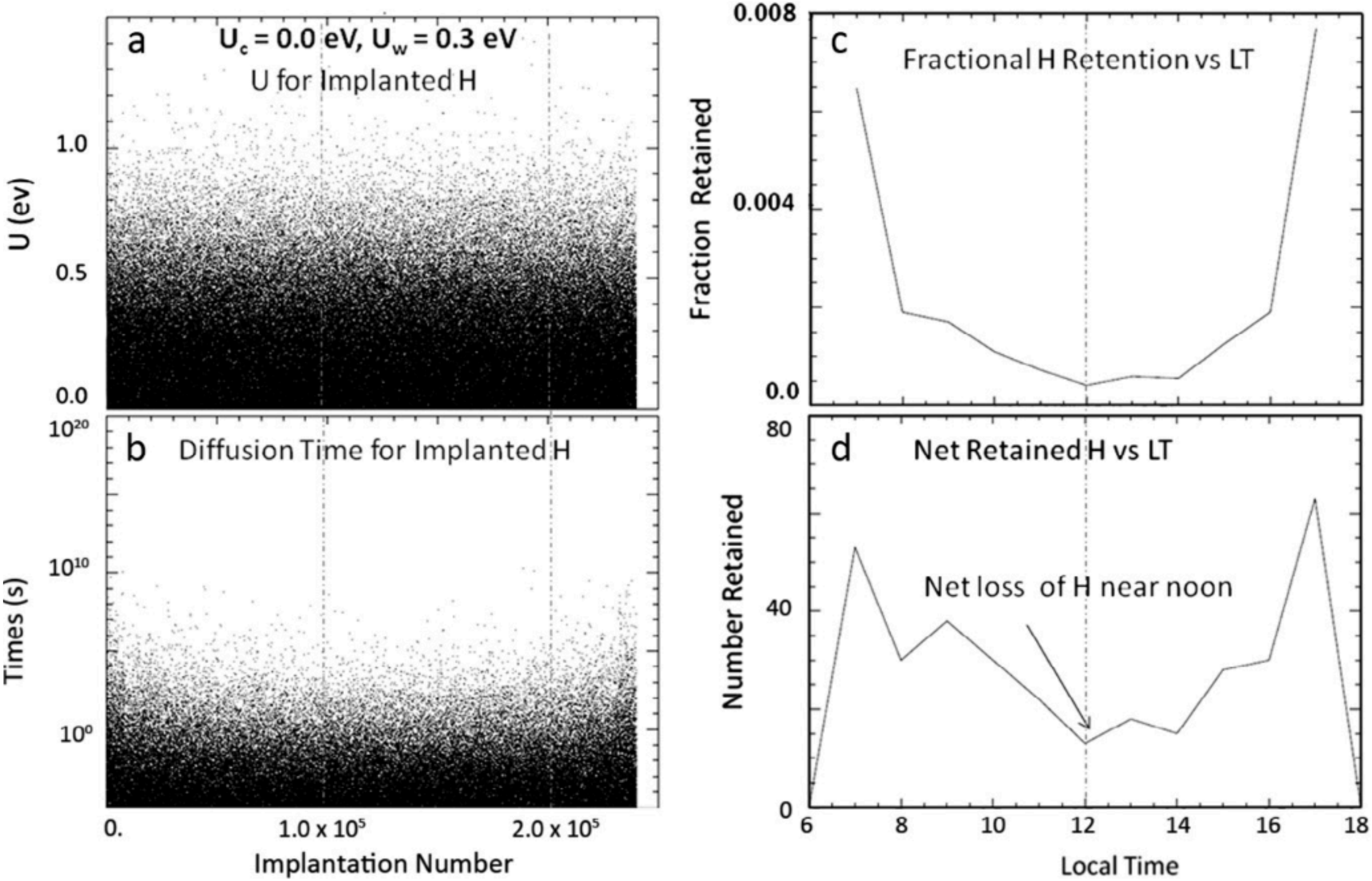




Log(τ)

As move from single value to broad distribution,
apply a **stat mech approach**

Monte Carlo H Implantations [2015 Icarus paper]



After 2015 paper, we said there must be a way to express this statistical approach analytical

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DREAM2

Statistical Mechanics of N atoms

Desorption (Barrie, 2008)

rate: $r = 1/t = -d\Theta/dt = k\Theta$

k – rate constant

Θ – fractional coverage (N/N_o)

Arrhenius Eq: $k = A \exp(-U/T)$

U- surface activation energy [eV]

T- temperature [eV]

A- Quantum frequency of bound state

Number of adsorbed molecules at T:

$$N(T) = \int_o^\infty f(U,T)\, dU$$

f(U,T) –number of molecules adsorbed with activation energy U at a given T

Average desorption rate:

$$\langle r \rangle = N^{-1} \int_o^\infty A \exp(-U/T)\, f(U,T)\, dU$$

Single U value

Distribution of U values

H-Atom Diffusion

rate: $r = 1/t = D/h^2$

D – diffusion

h – depth of implantation

Diffusion Eq: $D = D_o \exp(-U/T)$

[Starukhina, 2006]

U- volume activation energy [eV]

T- temperature [eV]

Number of implanted Hs at a given T:

$$n(T) = \int_o^\infty F(U,T)\, dU$$

F(U,T) –number of H implantations with activation energy U at a given T

Average H diffusion rate:

$$\langle r \rangle = n^{-1} \int_o^\infty D_o\, h^{-2} \exp(-U/T)\, F(U,T)\, dU$$

Application 1: Surficial H content in Dynamic Equilibrium

Continuity (Fick's law) equation with solar wind source at solar zenith angle, Z

$$dn_H/dt = n_{sw}\, v_{sw} Cos(Z)/h \quad - \langle Dn_H \rangle /h^2$$

For time-stationary equilibrium, source equals loss:

< > = Average value of quantity integrated over the spread in activation energy values

$$D_o\, h^{-2} \int_0^{\infty} e^{-U/T}\, F(U,T)\, dU = n_{sw}\, v_{sw}\, Cos(Z)/h$$

Now consider a general form of a shifted-Gaussian to describe the distribution of activated states with unknown n_H

$$F(U,T) = \frac{n_H}{\Delta U \sqrt{\pi}} \exp\left(-(U-U_o)^2/\Delta U^2\right)$$

Equilibrium H content as a function of the distribution of solar wind influx, activation energy, diffusion, and temperature - not necessarily in saturation!!

$$\boxed{n_H = n_{sw}\, v_{sw}\, Cos(Z)\, h\, D_o^{-1} \exp\left(U_o/T\right) \exp\left(-\Delta U^2/(4T^2)\right)}$$

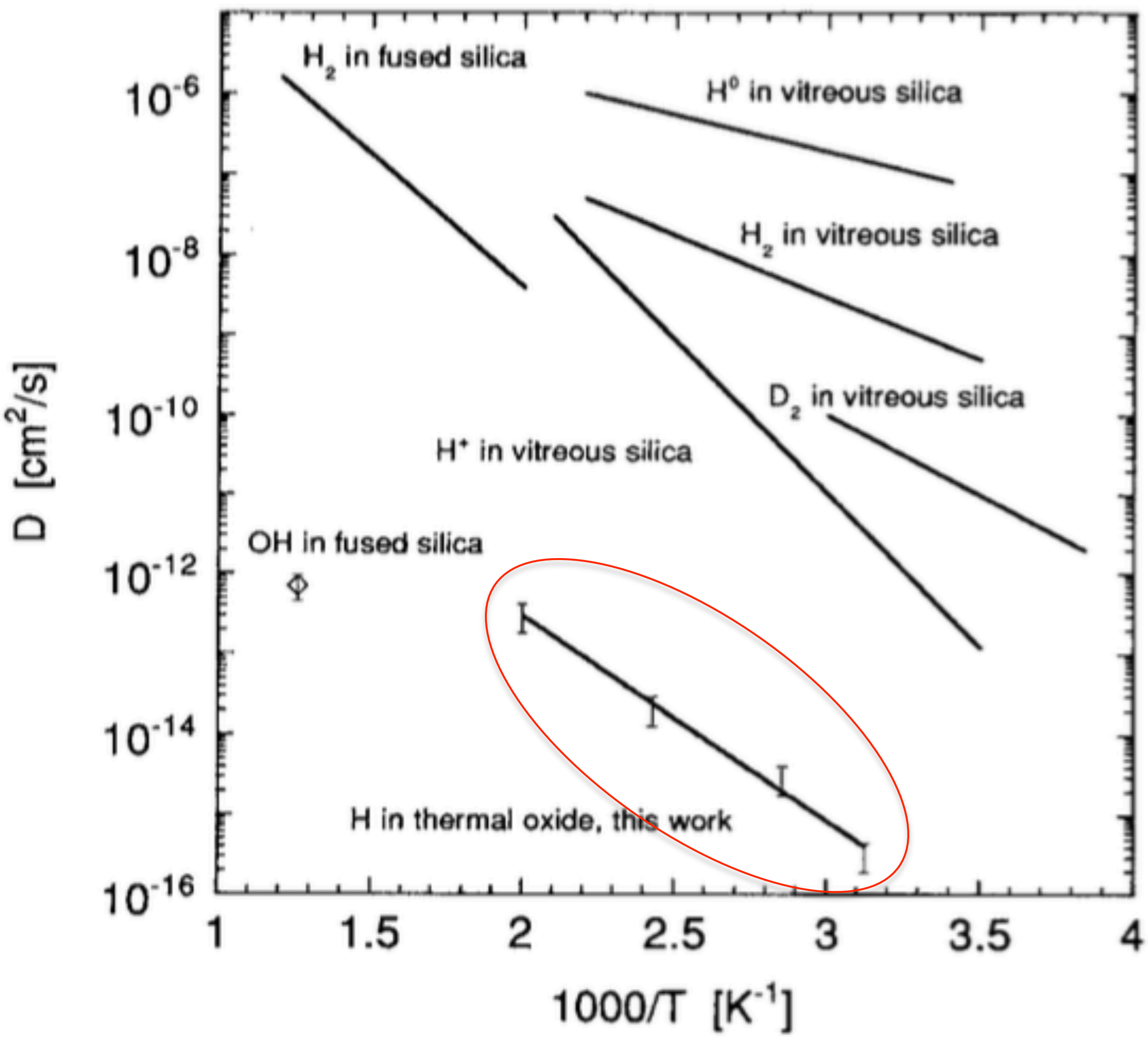
Closed analytical form for H content in layer h

What are D_o, U_o, ΔU values to use?

Hydrogen implantation and diffusion in silicon and silicon dioxide

D. Fink[1], J. Krauser[1], D. Nagengast[1], T. Almeida Murphy[1], J. Erxmeier[1], L. Palmetshofer[2], D. Bräunig[1], A. Weidinger[1]

[1]Departments FD. AT, and FH of the Hann-Meitner-Institute Berlin, Glienicker Strasse 100, D-14109 Berlin, Germany
(Fax: + 49-30/8062-2293)
[2]Institute for Experimental Physics, J. Kepler University, A-4040 Linz, Austria

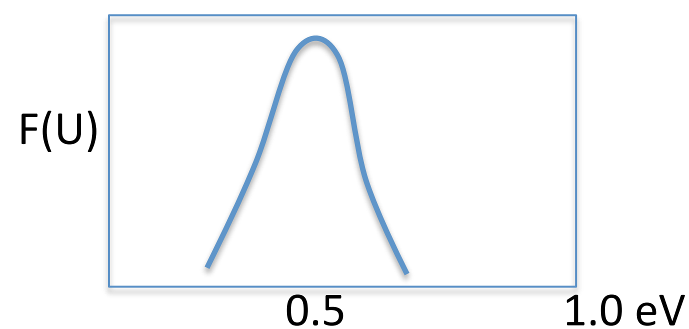


Irradiated Silica (Fink et al., 1995)

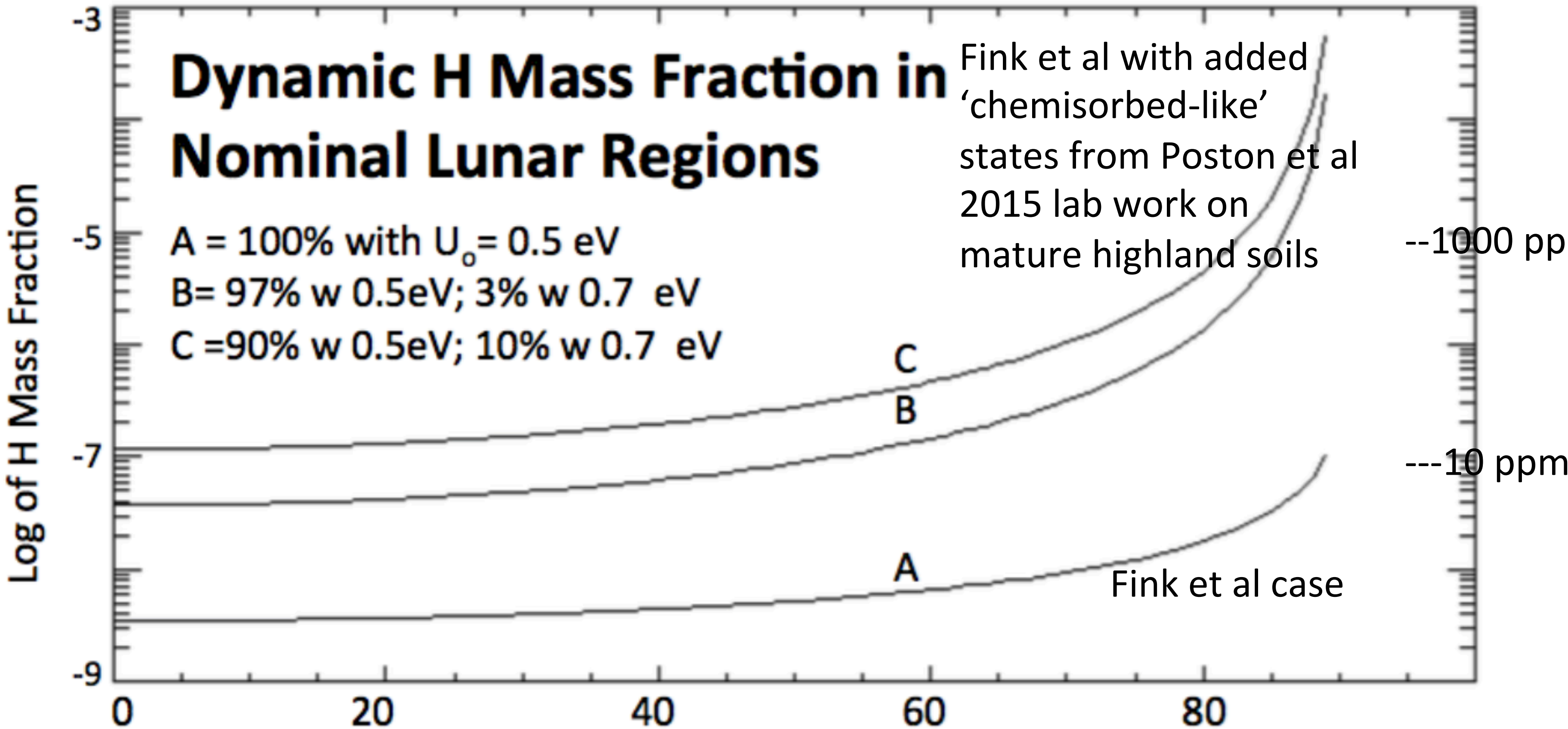
'Hindered H diffusion'

Irradiated O have a relatively stronger bond with passing H

$D_o \sim 10^{-12}$ m^2/s
$U_o = 0.52$ eV
$\Delta U = \pm 0.15$ eV



Solar Wind-Implanted H Mass Fraction

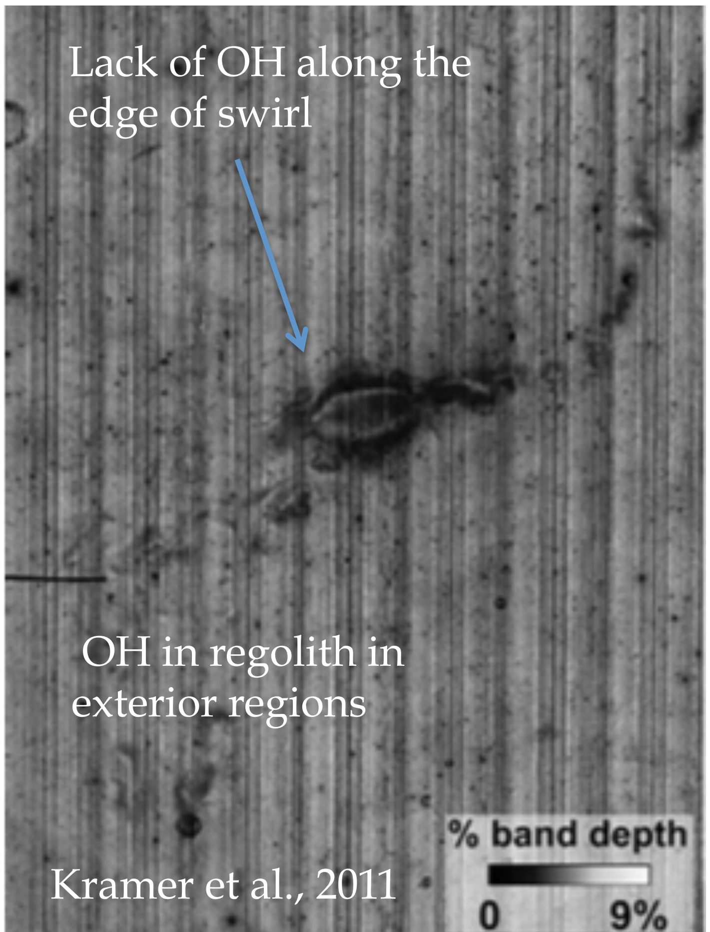


Fink-like Diffusion Parameters
D_o ~ 10^{-12} m^2/s
U_o = 0.5 eV (and U_o = 0.7 eV)
ΔU= 0.1 eV
T = 280 $\cos^{0.25}(Z)$ +100 (Crider and Vondrak, 2000)

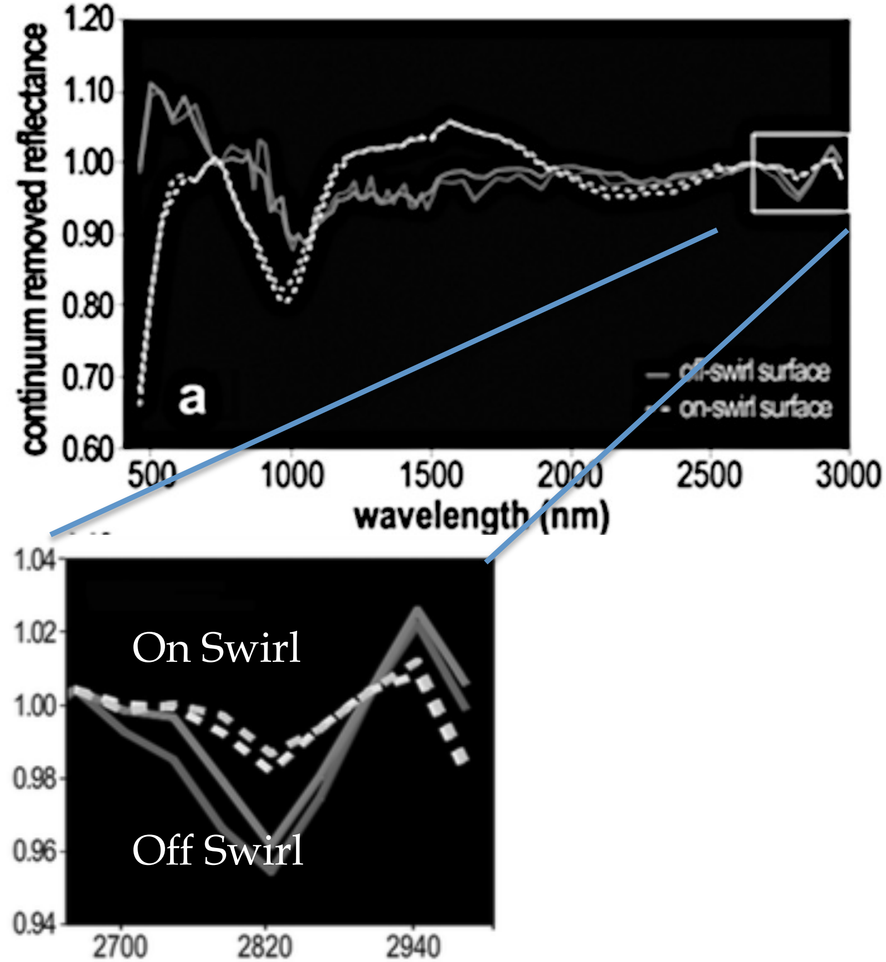
<u>Results:</u>
- Diurnal effect
- H content substantial
- H content is not saturated!!!
- If applied non-irradiated silica, H content would be substantially lower (self-fortifying effect)

Application #2: Reduced 2.8 micron IR OH signal from Mag Anomalies [Kramer et al 2011]

M^3 - 2.8 micron Reiner Gamma



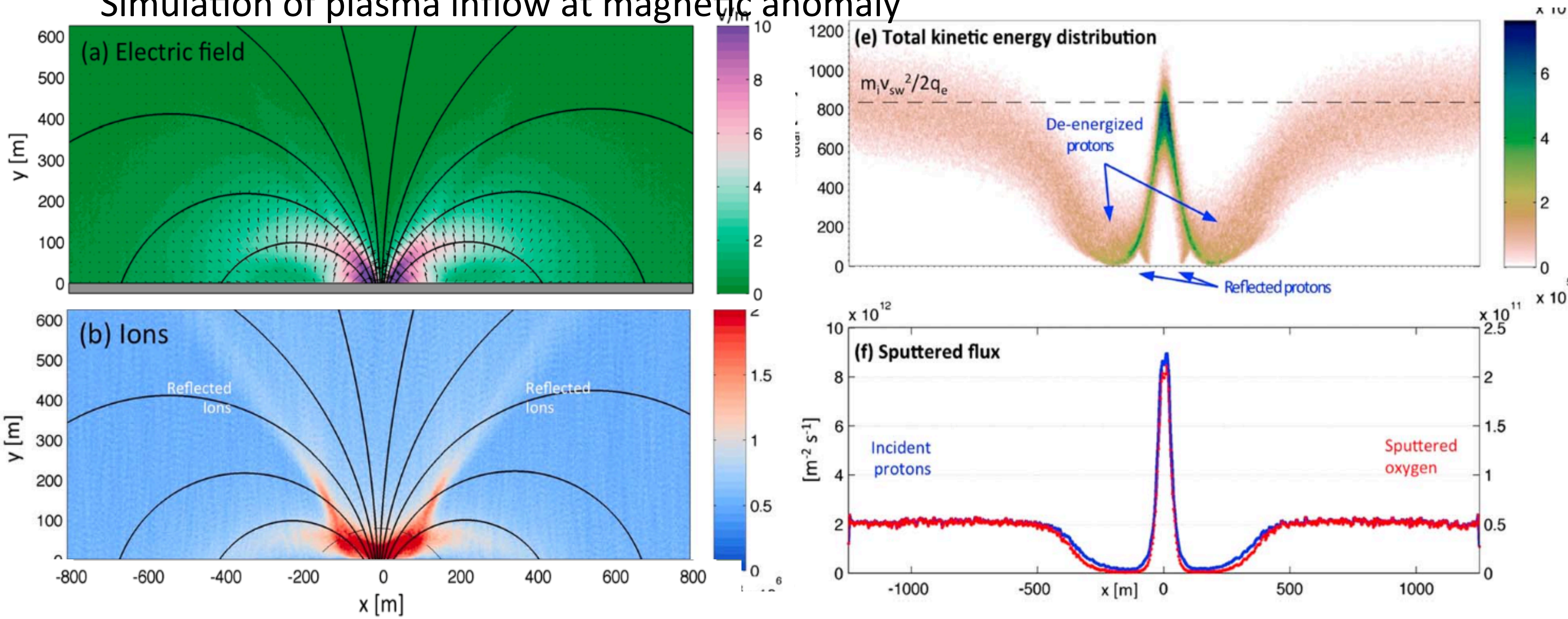
Dark = less OH



Flanks of mag anomaly appears to have less implanted H – where large tangential B

SW inflow at Magnetic Anomalies

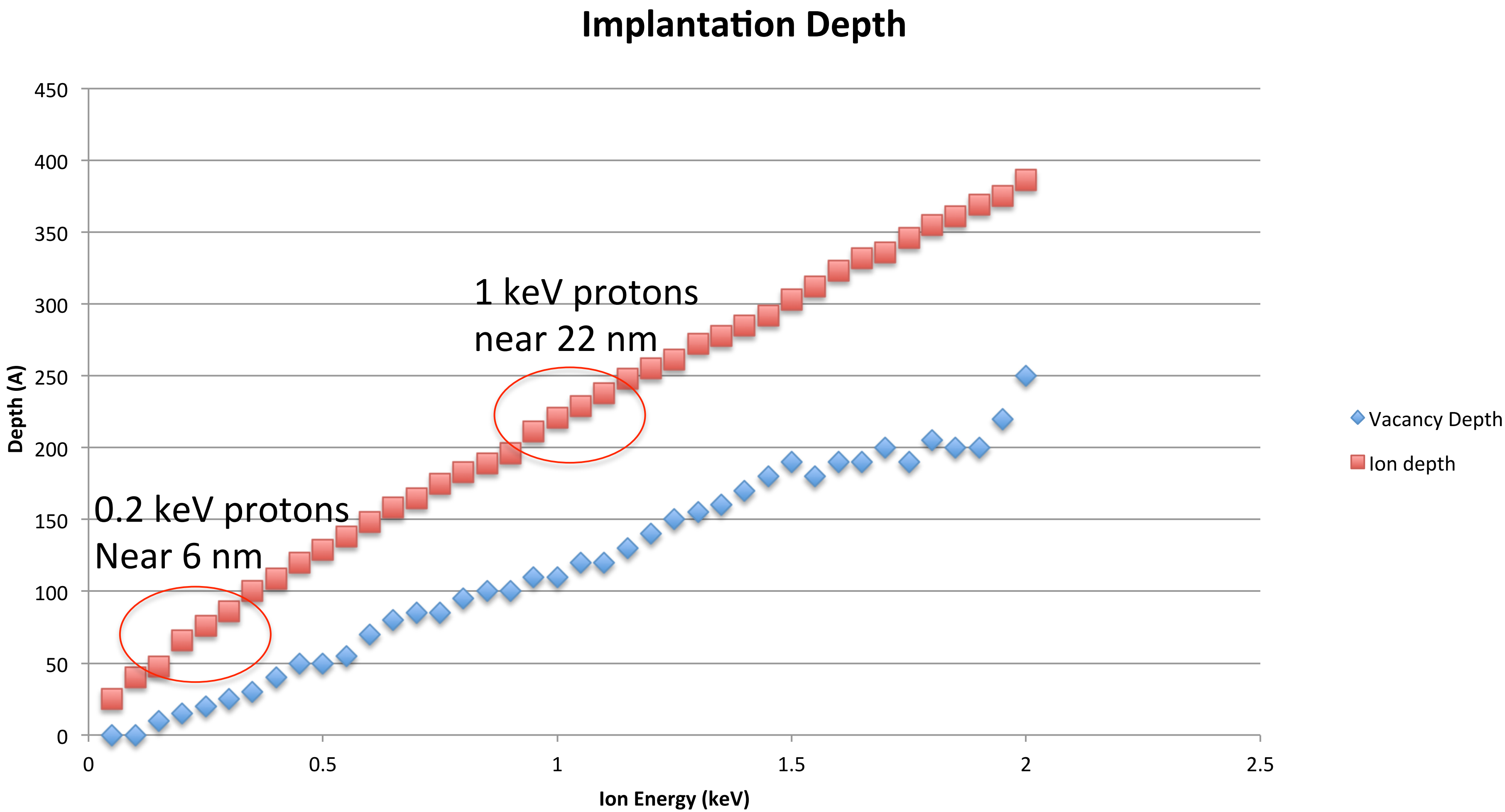
Simulation of plasma inflow at magnetic anomaly



Zimmerman et al., 2015: Development of ambipolar E-fields along flanks

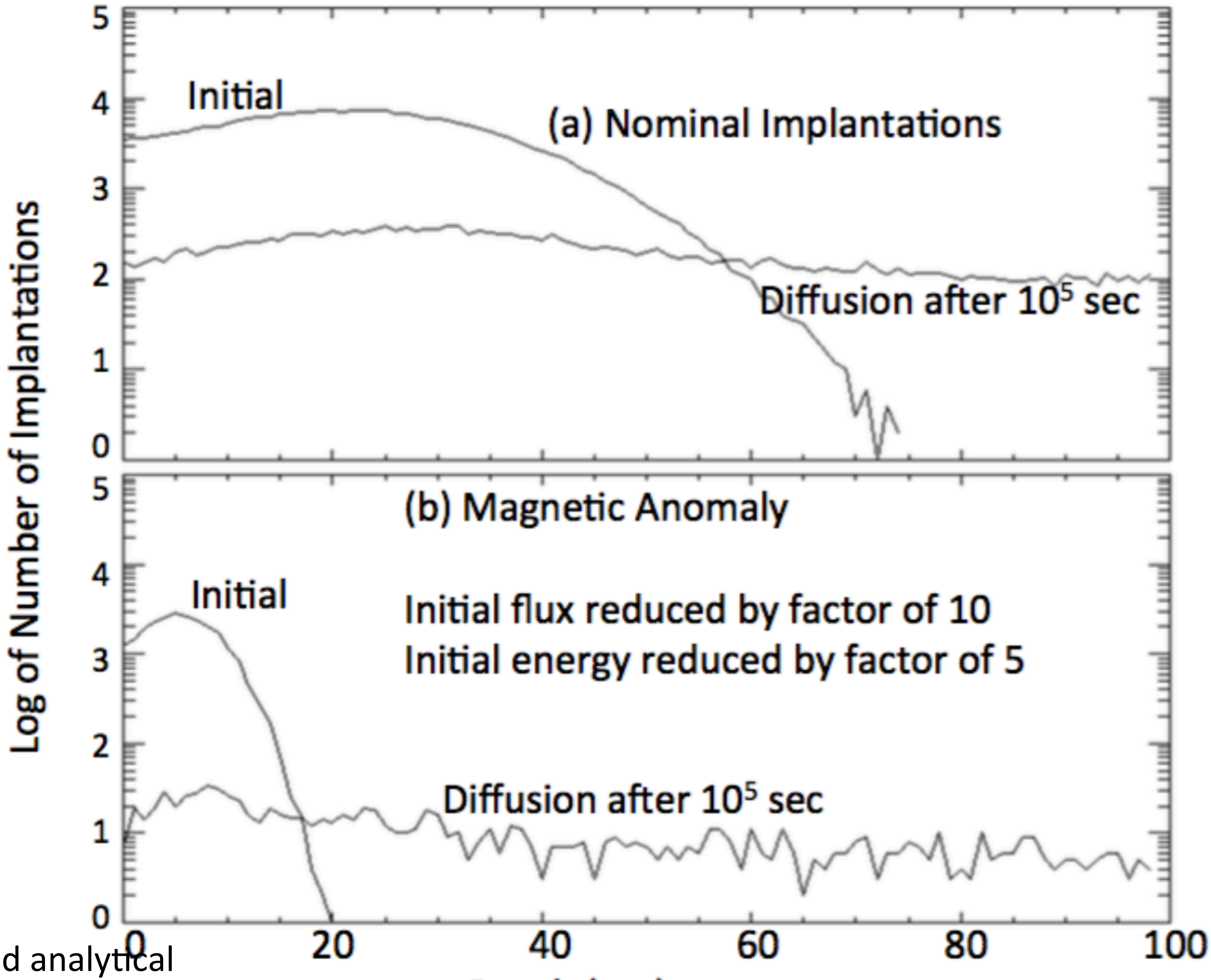
1) Reflects ions
2) Reduces ion flux to surface
3) Lowers ion energy to as low as 0.2 keV – what few ions get to surface are less potent

TRansport of Ions in Material (TRIM) Code Results

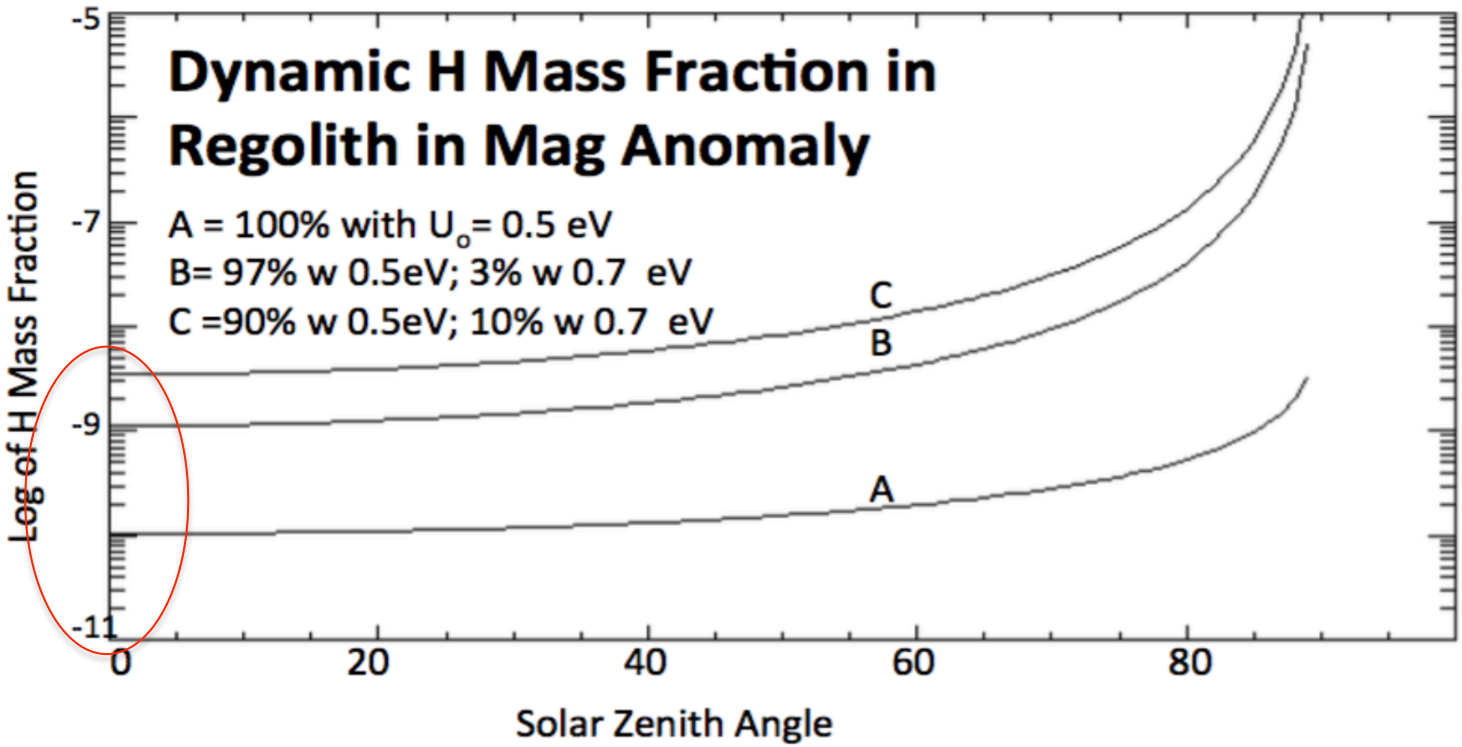


Low energy implantations stop at a depth much closer to surface

Monte Carlo Diffusion Code [used in our 2015 Icarus paper]



MC and analytical approaches in some agreement



For exact same Fink-like diffusion, obtain factor of ~50 less H atom retention in magnetic anomaly

Conclusion

- Statistical mechanics-based formalism
- An interesting solid state problem – follow-up of L. Starukhina
- Given F(U), can define H retention profile (and inverse also)
- Volumetric solar wind H content in dynamic equilibrium
- **Model predicts:** Less H atom retention in magnetic anomalies (fewer SW ion implantations at shallower depths)
- **Continuing the logic:** Should we thus expect the grain rims from mag anomalies to have a different character (shallower depth < 10 nm, less amorphous) compared to Apollo samples? Are they inherently less retentive of volatiles because of less SW damage?