Hydrogen in Astrophysics and in Laboratory Astrophysics

Valerio Pirronello

DMFCI
Università di Catania
Catania, Sicily
Italy

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Work performed together with

G. Vidali	Syracuse University	
O. Biham	Jerusalem University	
L. Ling		Syracuse
C. Liu		
J. Roser		
L. Shen		
I. Furman		Jerusalem
N. Katz		
A. Lipshtat		
H. Perets		
E. Congiu (Cagliari)		Catania
G. Manicò		
G. Ragunì		


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Interstellar Medium

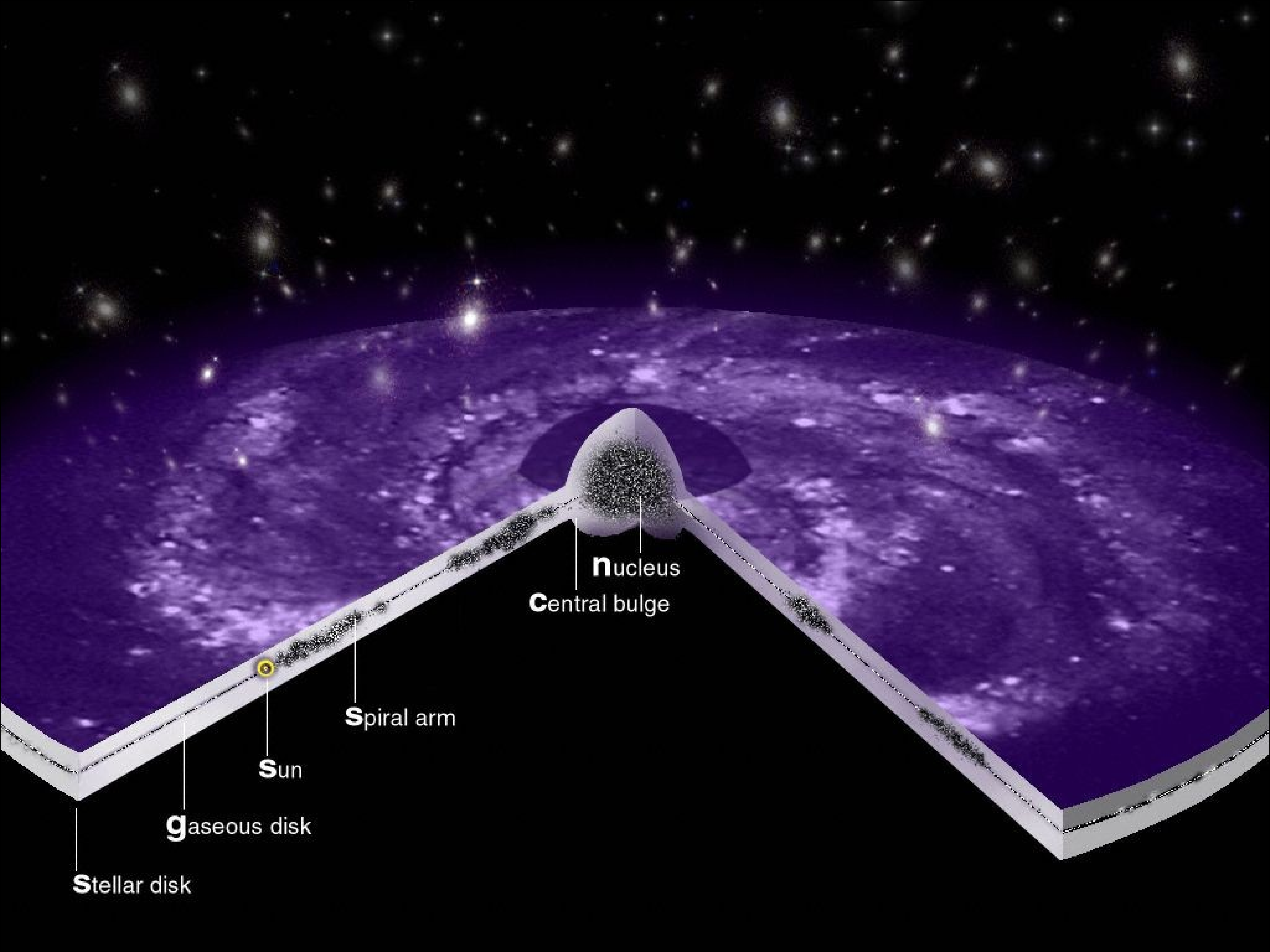
M_{ISM} = 10 % M_{Galaxy} (visible)

Gas & Dust

M_{GAS} = 99 % M_{ISM}

M_{DUST} = 1 % M_{ISM}

Condenses in clouds that settles in the galactic plane


nucleus
central bulge
spiral arm
sun
gaseous disk
stellar disk

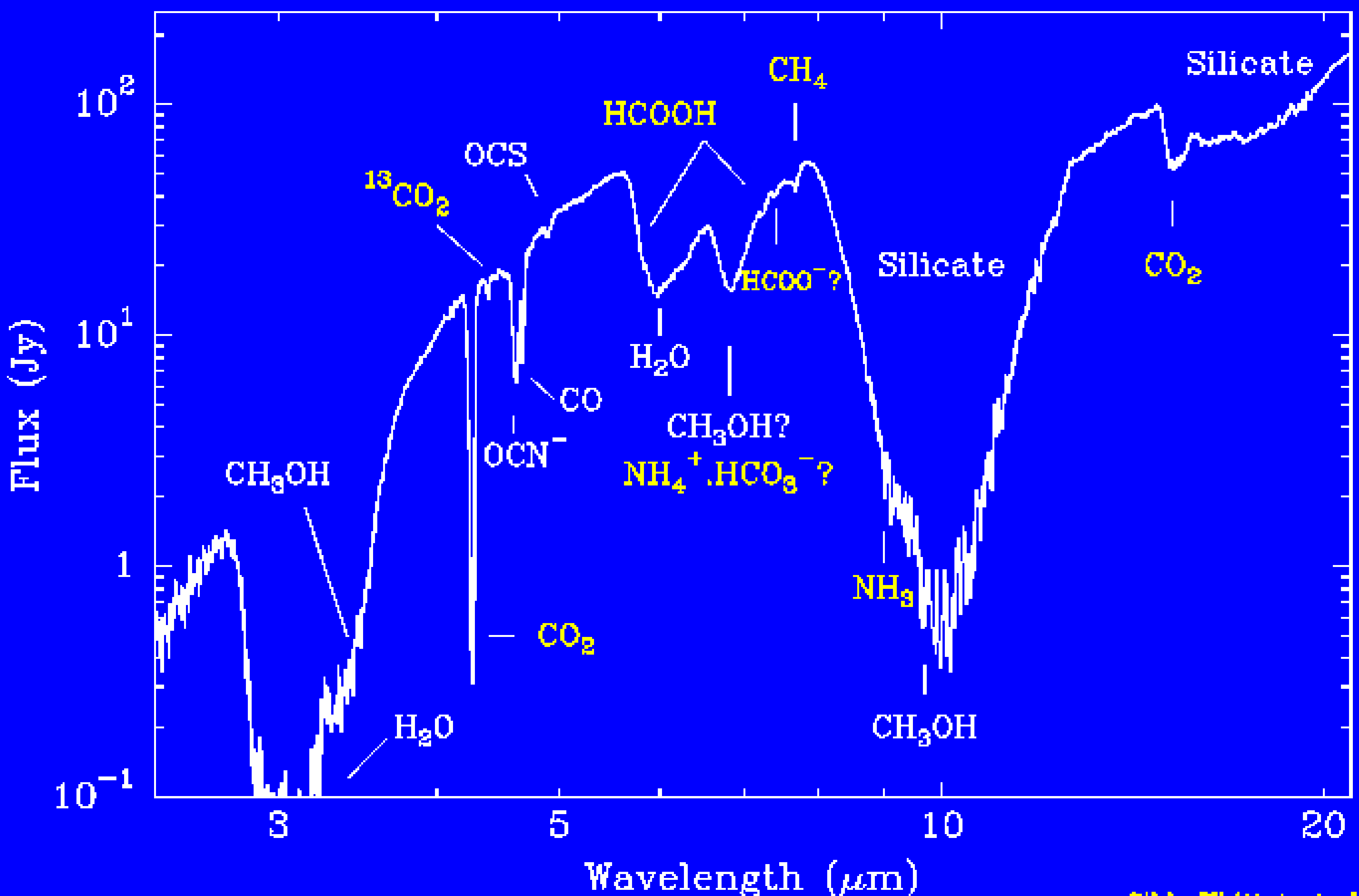
Multiple Phases of the ISM

Component	T_g (K)	n (cm^{-3})	M ($10^9 M_{Sun}$)
Molecular	10 - 20	10^2 - 10^6	≈ 2.5
Cold atomic	50 - 100	10 - 50	> 6.0
Warm atomic	8000	0.2 - 0.5	
Warm ionized	8000	0.2 - 0.5	≈ 1.6
Hot ionized	10^6	0.001	

Observed Molecules

- Diffuse Clouds (UV from stars)
  - H_2, CO, CH, ……
- Dense Clouds (almost NO UV)
  - H_2, CO, …, H_2O, … H_2CO, … HC_9N

W33A: INVENTORY OF ICES



Gibb, Whittet et al. 2000
Schutte et al. 1999

Surface Reactions

H_2 (Waterloo, Syr-Catania-Jerusalem, UCL, Munich, Odense, Cergy)

CO_2 (Syr - Catania)

H_2CO, CH_3OH + deuteration (Sapporo)

H_2O (Cergy – Catania)

Importance of H_2

- The **most abundant** molecule in space
- Once ionized by Cosmic Rays **triggers** gas phase reactions schemes **that form** other molecular species
- Provides an efficient **cooling mechanism** for clouds, helping star formation, shaping the galaxies

The Dust Role

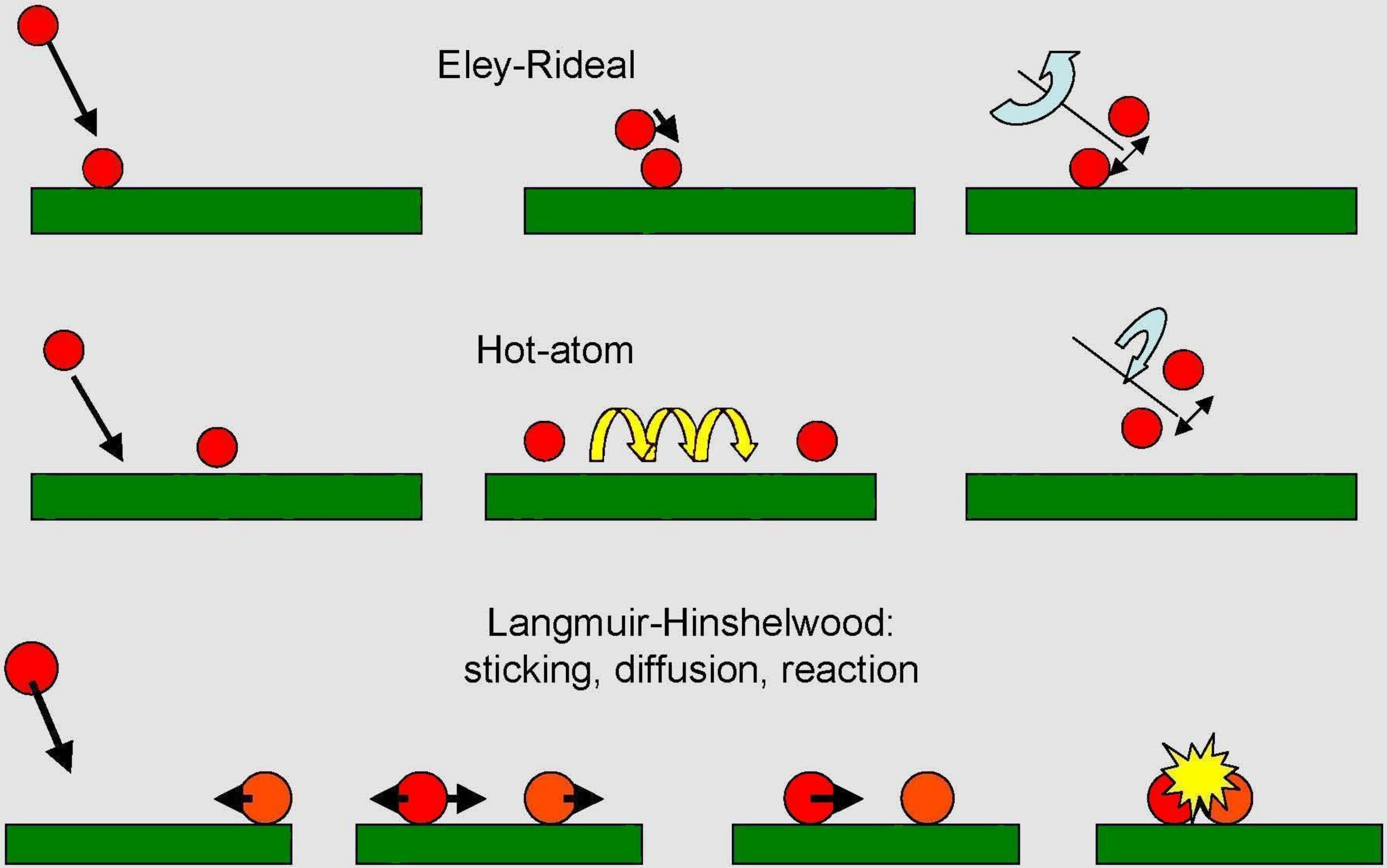
H_2 **does not form in the gas phase by the radiative association of two neutral H atoms**

A third body has to absorb the excess energy

Interstellar grains act as

CATALYSTS !

Mechanisms of reaction



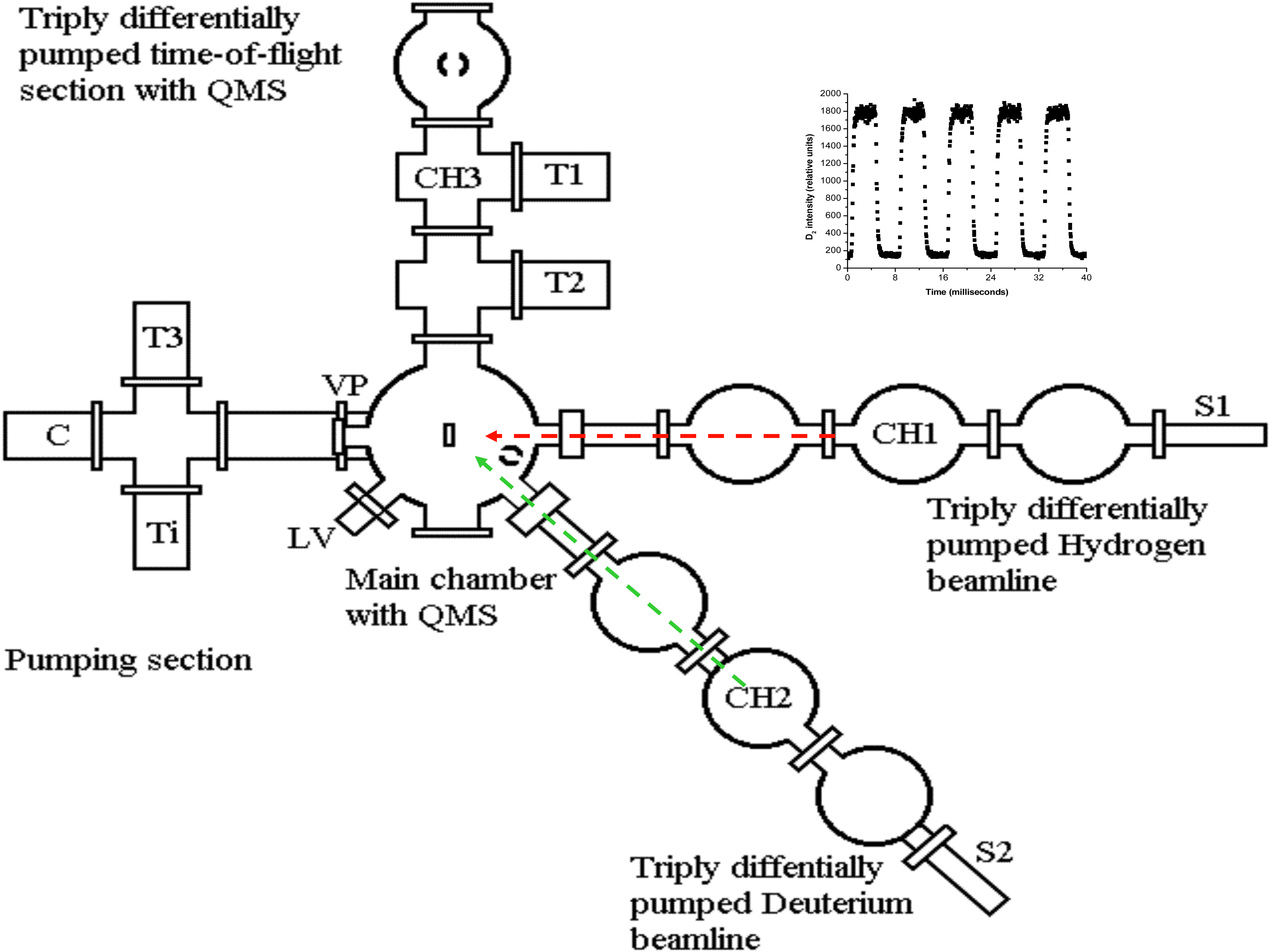
Hollenbach & Salpeter

Assumed tunneling assures enough mobility

$$R_{H_2} \sim 1/2\,(n_H\, v_H\, A\, S\, \gamma)\, n_g$$

Hollenbach et al. ApJ 163, 165 (1971)

but Smoluchowski (1979)…..



Triply differentially pumped time-of-flight section with QMS
CH3
T1
T2
T3
C
Ti
VP
LV
Main chamber with QMS
Pumping section
CH1
S1
Triply differentially pumped Hydrogen beamline
CH2
S2
Triply diffentially pumped Deuterium beamline
D2 intensity (relative units)
Time (milliseconds)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
8
16
24
32
40

Experimental Conditions

Low kinetic energy of H atoms ~150-300 K

Low flux of H atoms < 10^{12} atoms cm^{-2} s^{-1}

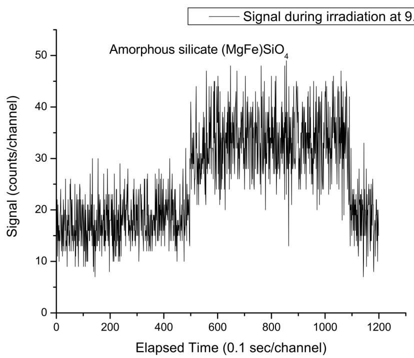
Low sample temperature 5 K - 40 K

Low background pressure 10^{-10} torr

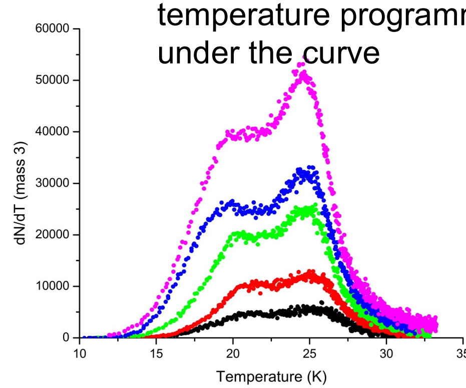
Two atomic beams

Catalytic Efficiency

The number of molecules coming off during irradiation is proportional to the area under the trace



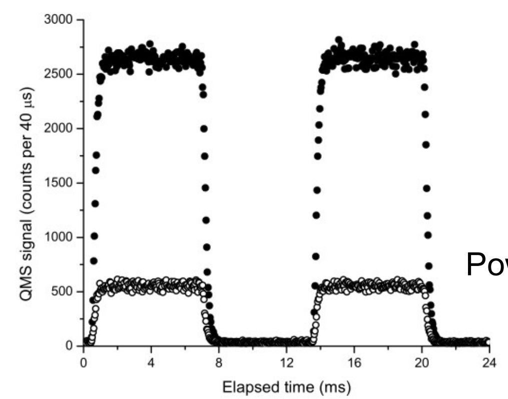
The number of molecules coming off during the temperature programmed desorption is proportional to the area under the curve



$$\gamma = \frac{N_{irr} + N_{des}}{N_{beam}}$$

Number of atoms going to the sample during the irradiation phase

Power OFF



Power ON

Change in the signal level of D_2 with RF power ON and OFF in the dissociation source; from this, the number of atoms in the beam can be calculated.

Quantitatively

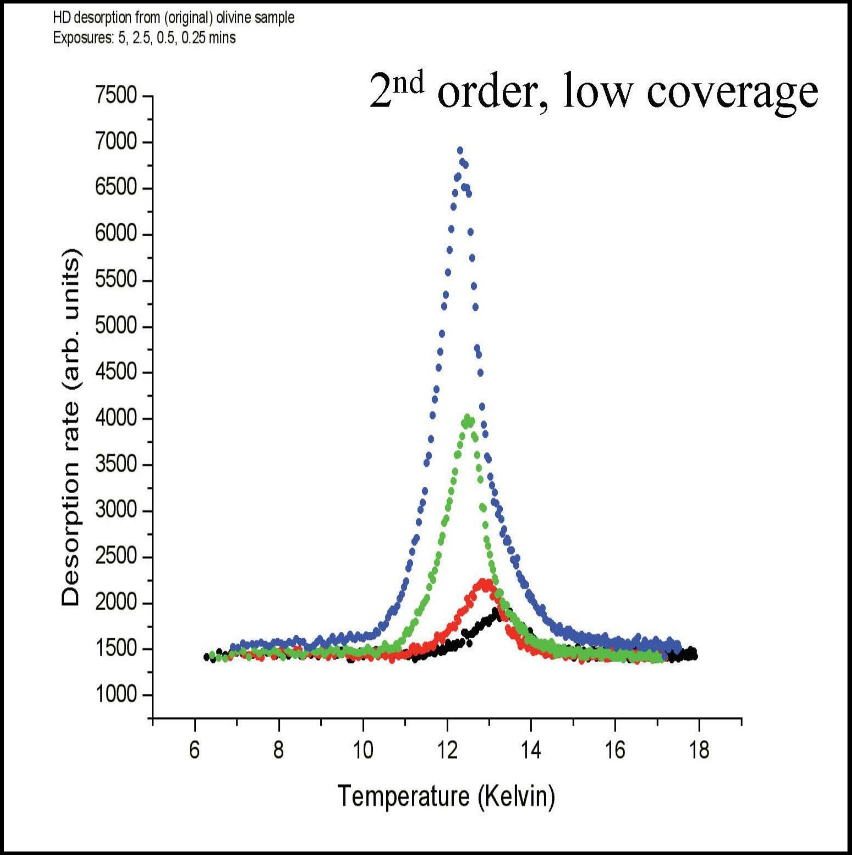
At grain temperatures

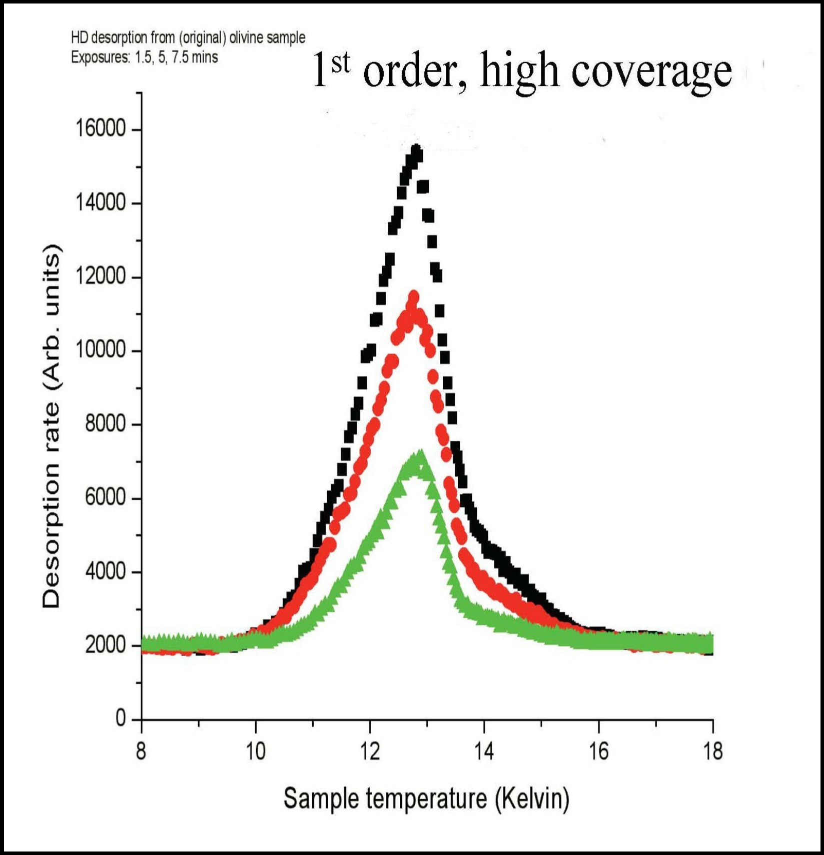
observations require $S\gamma = .3$

- Amorphous Carbon OK !
- Polycrystalline Olivine NO !
- Amorphous Olivine ?

YES !

Polycrystalline Olivine

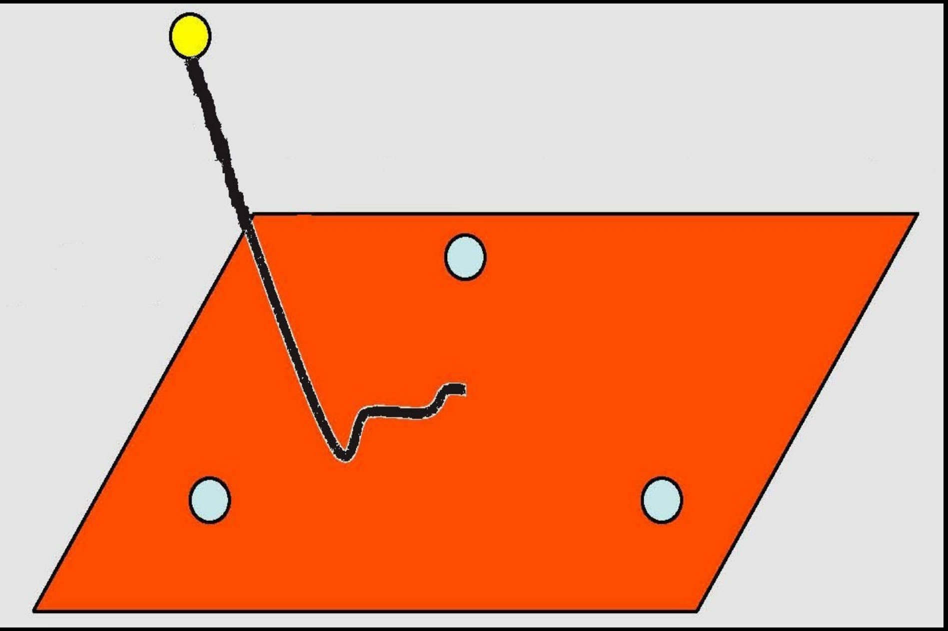


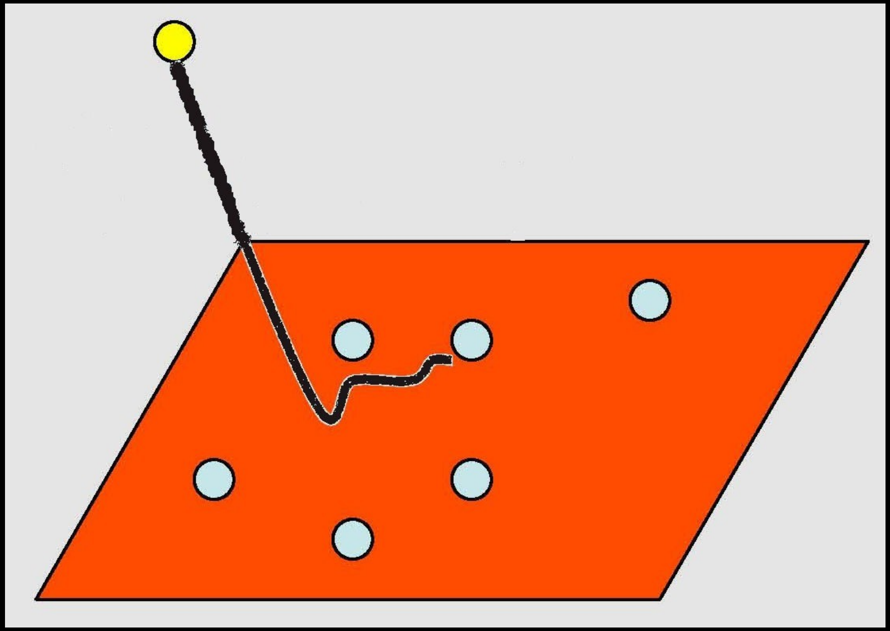


Pirronello et al. (1997a,b)

L-H

Hot Atom





- Low coverage
- High coverage

At low H atom coverage

$$R_{H_2} \sim 1/2\,(n_H\, v_H\, A\, S\, t_H)^2\, n_g\, \alpha$$

$t_H = \nu^{-1} \exp(E_{des}/kT)$ **H residence time**

$\alpha = \nu \exp(-E_{diff}/kT)$ mobility provided by <u>thermal hopping</u> or <u>thermally assisted tunneling</u>

Pirronello et al. ApJ 483, L131 (1997b)

A simple model (Biham et al., 1998)

on a single grain

$$dN_H/dt = n_H v_H A S - p N_H - \alpha N_{H2}$$

$$r_{H2} = \frac{1}{2} \alpha N_{H2}$$

in steady state

$$\Phi A S - p N_H - \alpha N_H^2 = 0$$

$$dN_H/dt = 0$$

$$r_{H2} = \frac{1}{2} \alpha N_H^2 =$$

$$= \frac{p^2 + 2\alpha\Phi A S - p(p^2 + 4\alpha\Phi A S)^{\frac{1}{2}}}{4\alpha}$$

A simple model 2 (Biham et al., 1998)

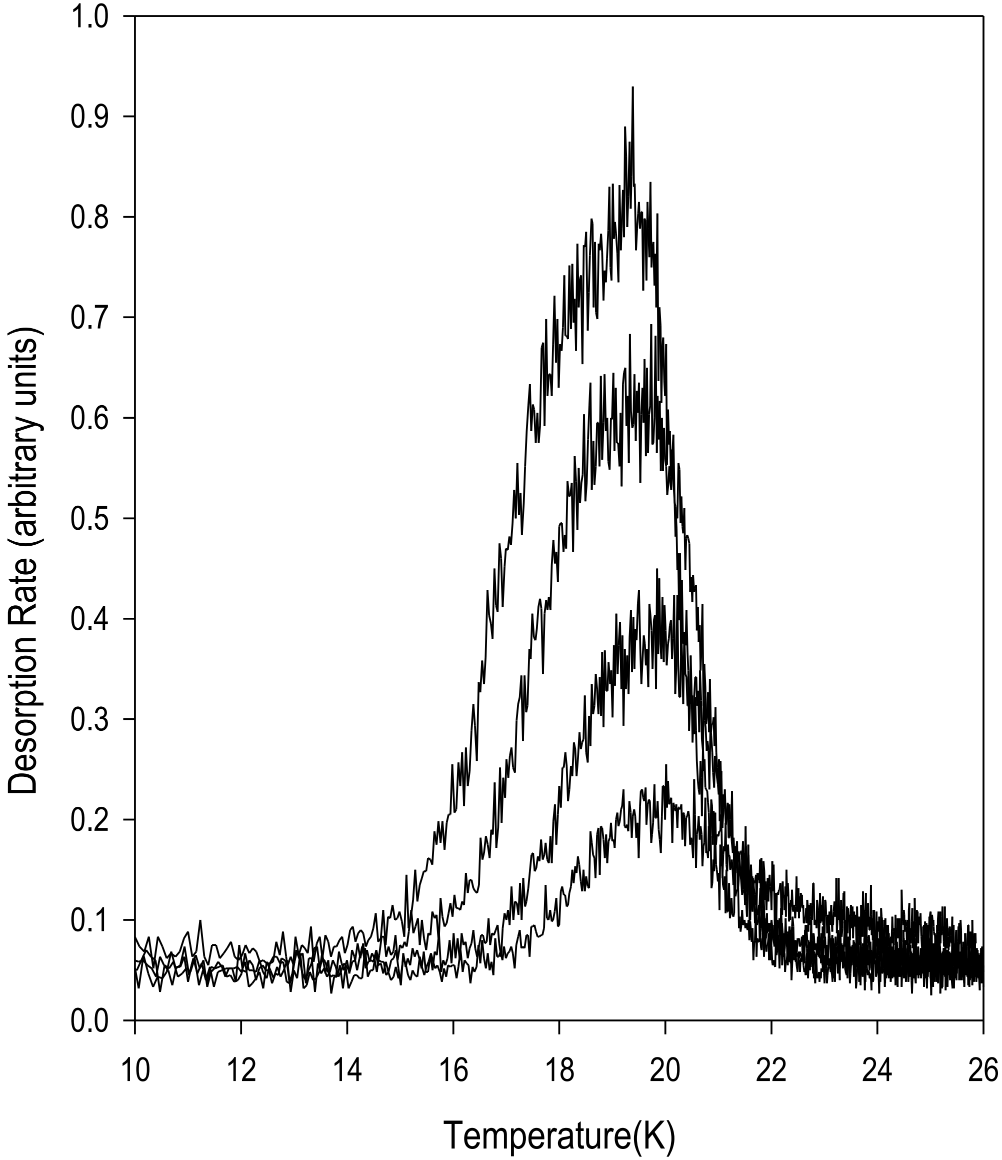
two limiting cases

a) $p^2 << 2\alpha n_H v_H AS$ → $r_{H2} = ½\, n_H v_H AS$

(Hollenbach et al. 1971)

b) $p^2 >> 2\alpha n_H v_H AS$ → $r_{H2} = ½\, (n_H v_H AS t_H)^2\, \alpha$

(Pirronello et al., 1997b)



Amorphous Carbon

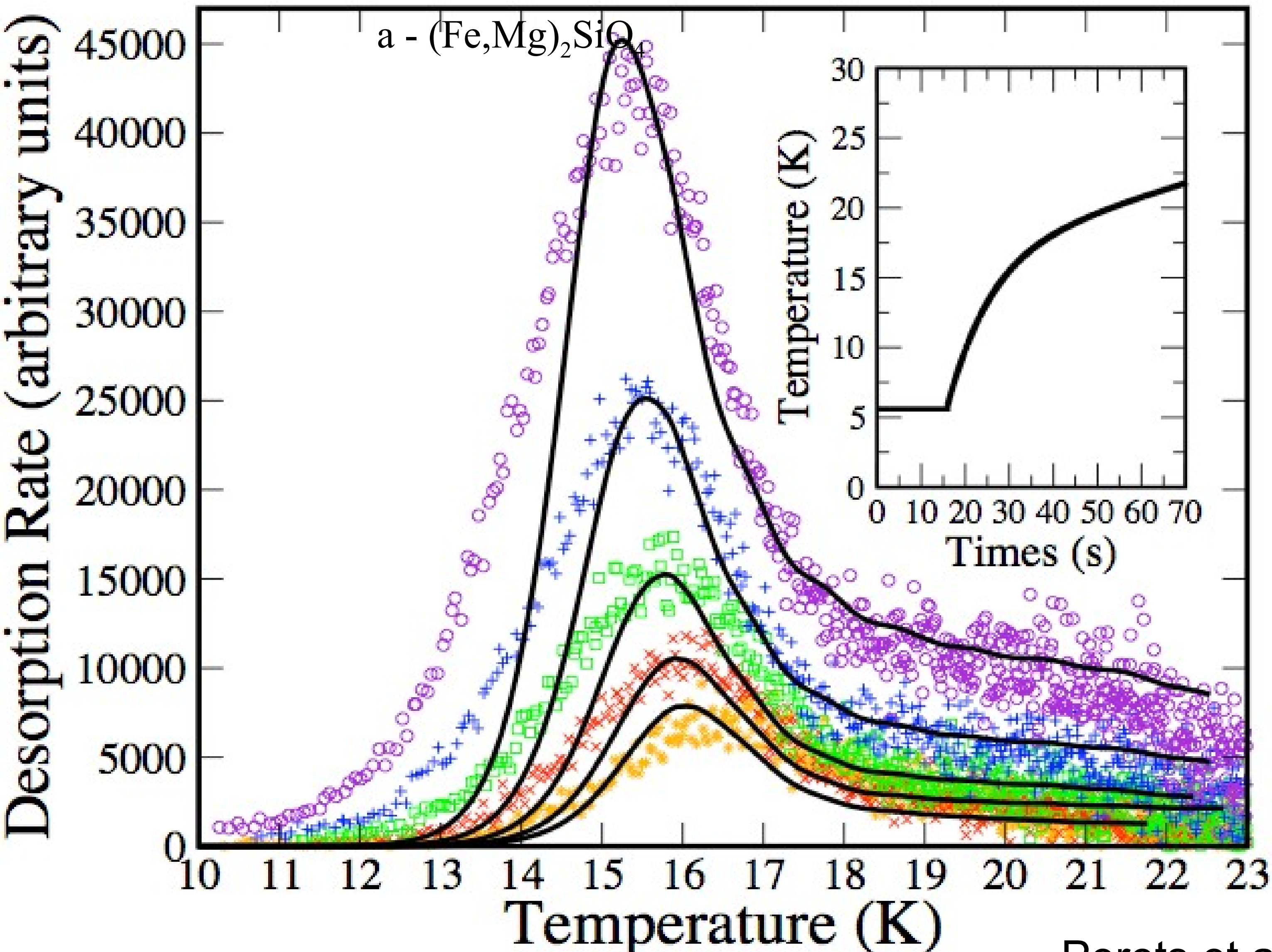
Pirronello et al. A&A 344, 681 (1999)

Energy Barriers (meV)

	E_{diff}	E_{des}
polycrystalline Olivine	24	32
amorphous Carbon	44	57

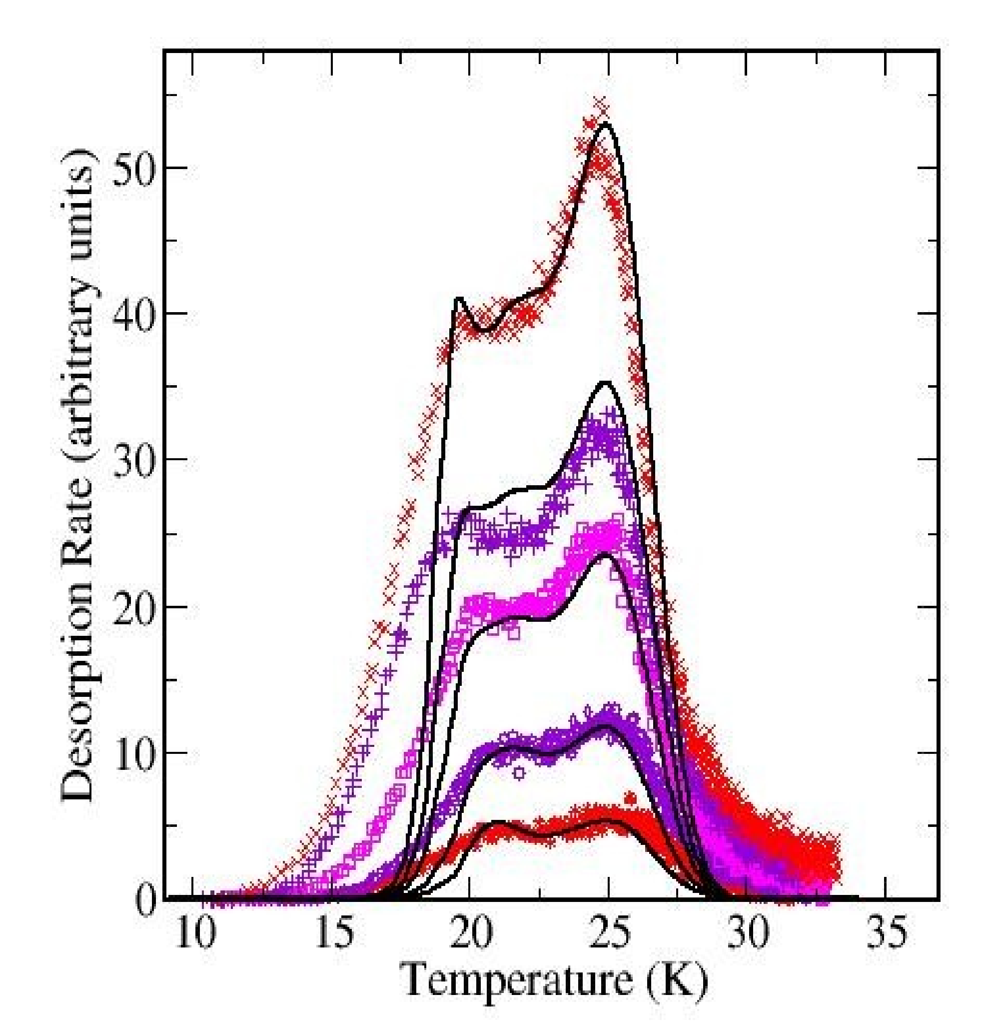
Katz et al. (1999)
Cazaux & Tielens (2004)
Perets et al. (2005)

a - $(Fe_{x=0.5},Mg_{x=0.5})_2SiO_4$



Perets et al. 2007

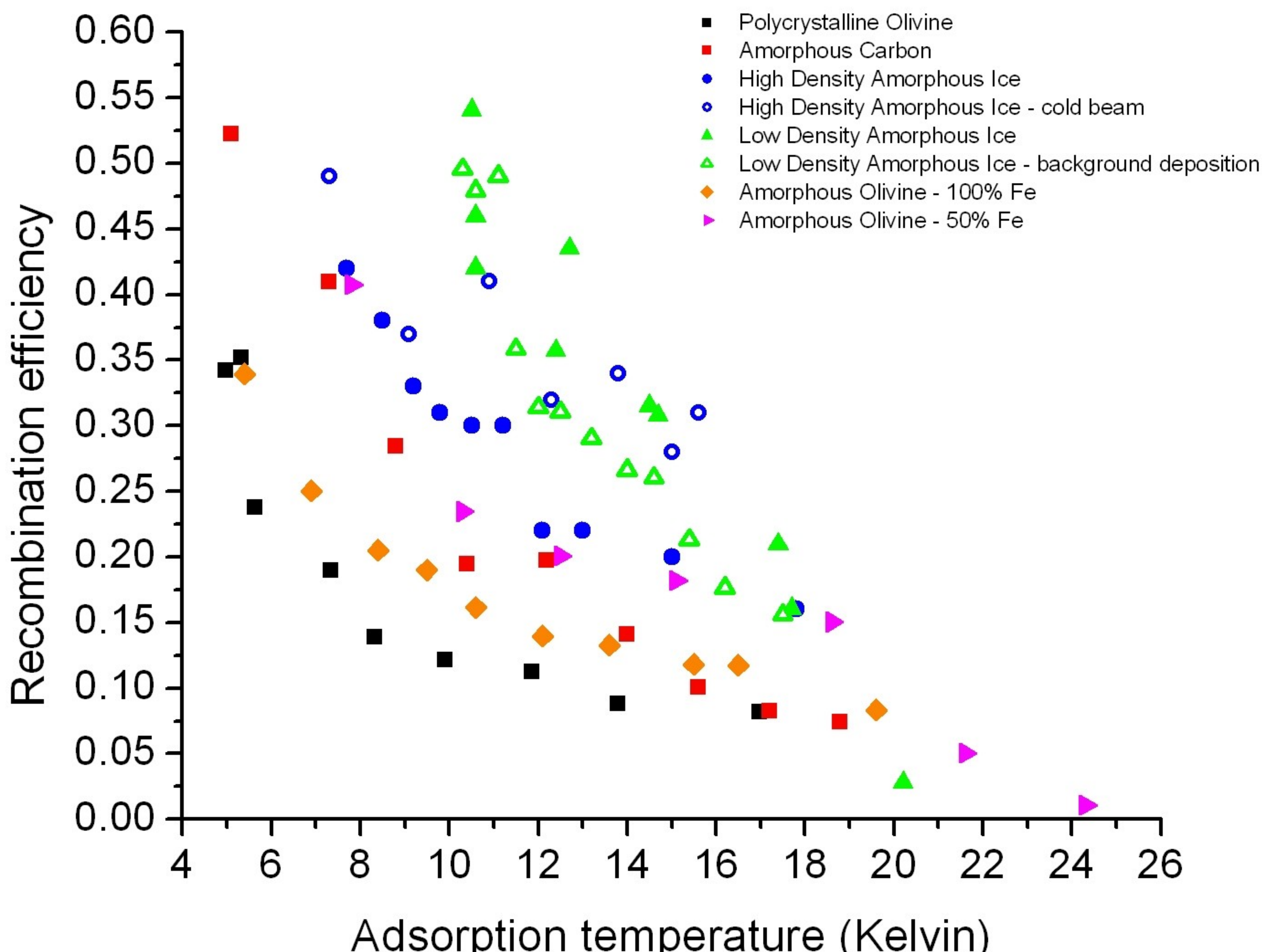
TPD Experiment on Low Density Ice (LDI)



Right peak
First order

Left peak
Second order

(Perets et al. 2005)

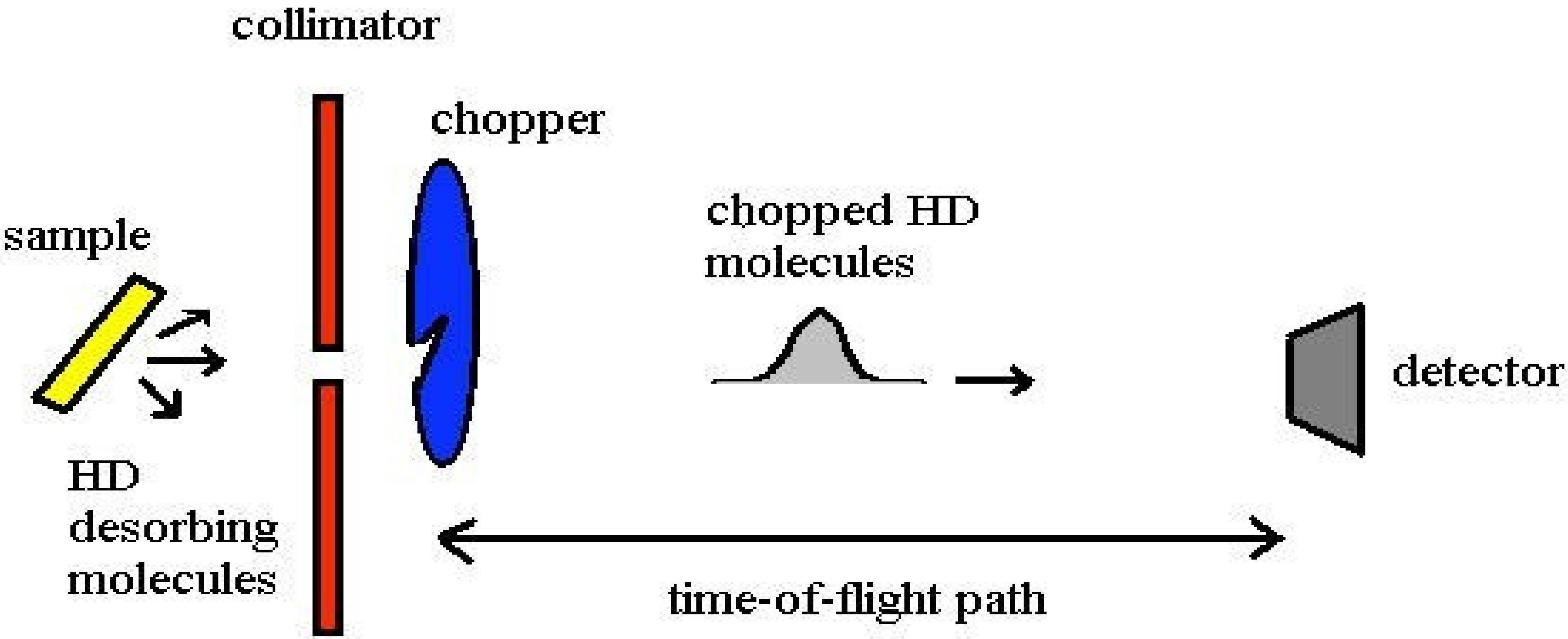

Polycrystalline Olivine
Amorphous Carbon
High Density Amorphous Ice
High Density Amorphous Ice - cold beam
Low Density Amorphous Ice
Low Density Amorphous Ice - background deposition
Amorphous Olivine - 100% Fe
Amorphous Olivine - 50% Fe
Recombination efficiency
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
4
6
8
10
12
14
16
18
20
22
24
26
Adsorption temperature (Kelvin)

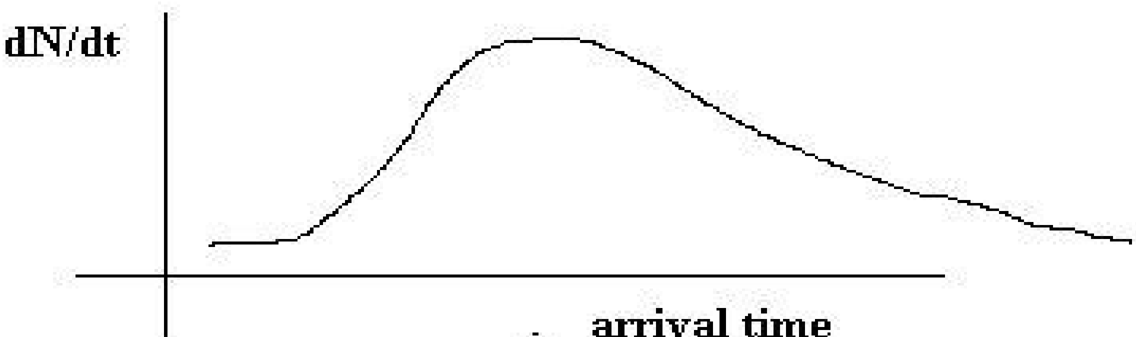
Energetics

Formation energy

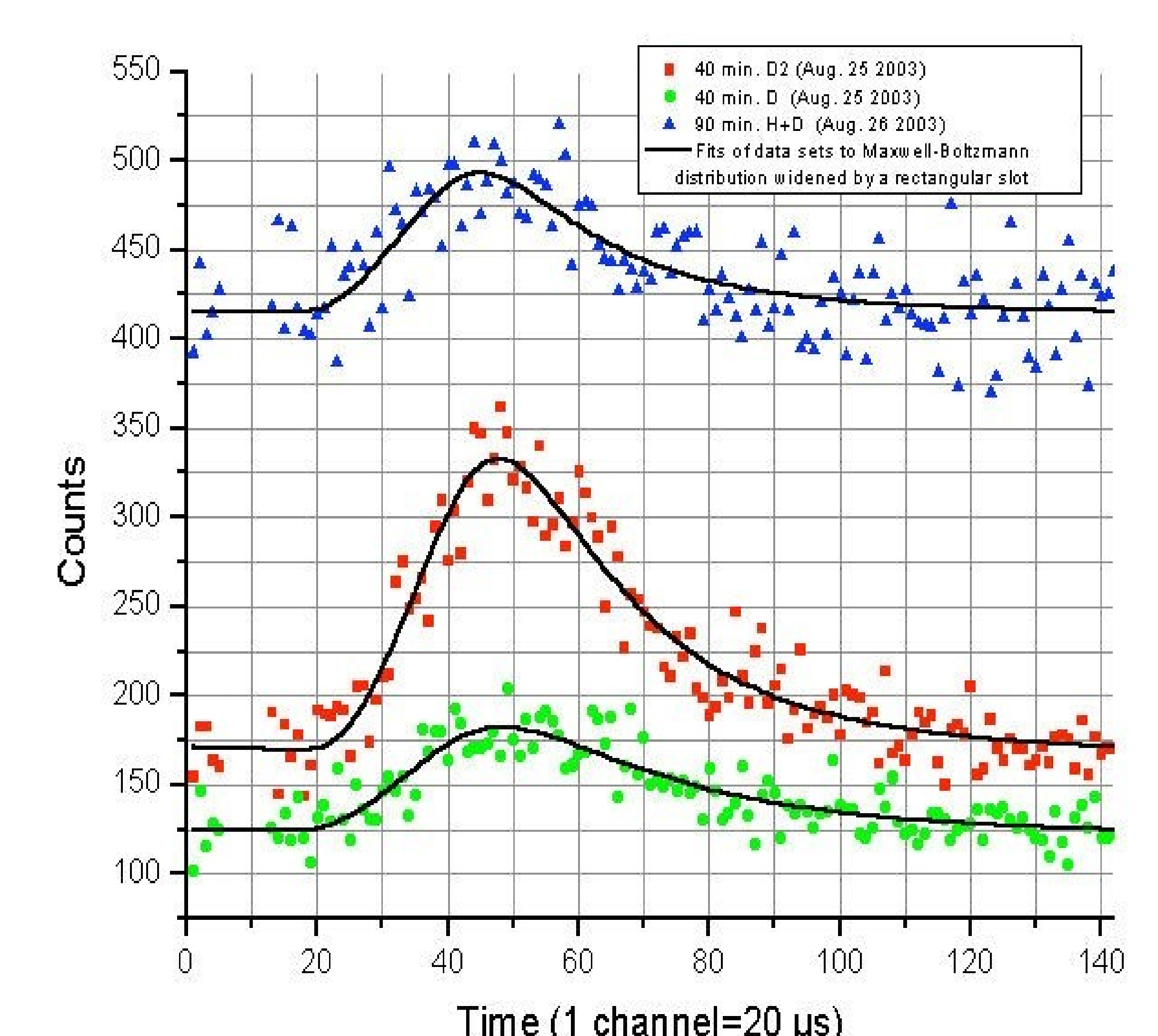
- To the grain
- To formed molecule: excitation, kinetic
- Astrophysical relevance

Schematics of time-of-flight measurements





Tof Spectra



Spectra obtained at high coverages

Summary on H_2 Formation

On realistic surfaces:

- <u>At high coverage</u> H_2 molecules may be formed by the Hot Atom Eley Redial mechanism before H atoms accomodate on the grain

- Some H_2 molecules are immediately released in the gas phase, most remain on the grain

- Depending on the surface a Temperature Window exists in which H ad-atoms are mobile (thermal hopping or thermally assisted tunnelling), may encounter and form H_2 by Langmuir - Hinshelwood mechanism (even <u>at very low coverage</u>)

- In the ISM grains are inside such a Temperature Window

- a-Carbon & a-Silicates efficiencies are high enough to explain observed abundances of molecular hydrogen in space !