Laboratory simulation of micrometeoroid ablation

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Motivation

- Understanding Earth's **cosmic dust environment** (sources and evolution of interplanetary dust dust particles)
- Total **meteoric material input** to Earth's atmosphere
- **Sensitivity of meteor radars** to mass, composition and velocity (uncertainties of **β – ionization probability**)
- Meteoric ablation delivers **exotic material** to the MLT region (relevant to NLC/PMC, atmospheric chemistry, meteoric smoke particles, etc.)

Here we report the results on a recent experimental campaign in a newly developed experimental facility (**Thomas et al., GRL, 2016**)

The understanding of the ablation process is paramount

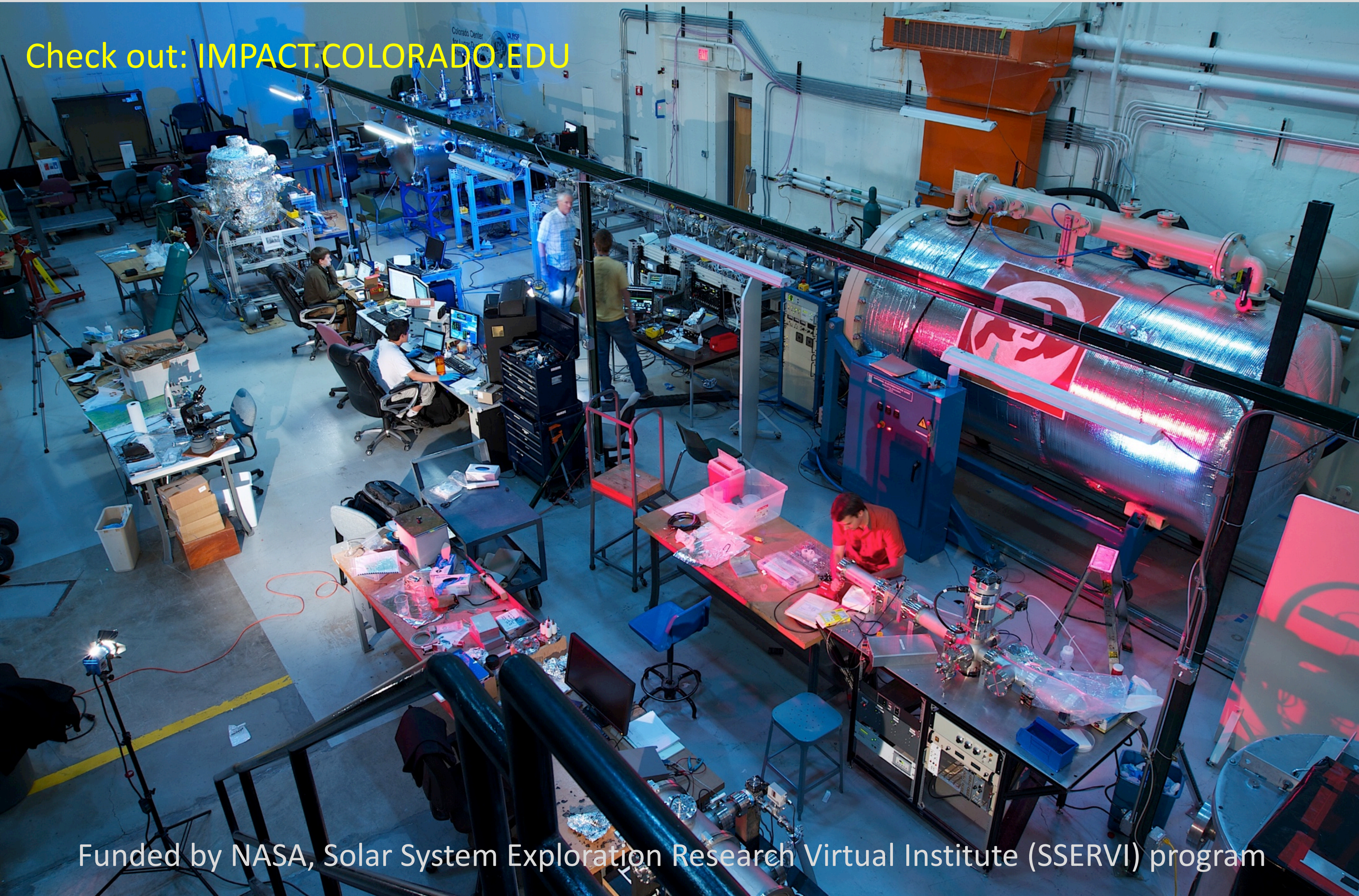
Table: Estimates of the global IDP input rate to the Earth's atmosphere (increasing order).

Technique	**IDP input [t/d]**	**Reference**	**Potential Problem**
Micrometeorites in polar ice	4 ± 1	Taylor et al. [1998]	Lower limit, since most IDPs ablate
High performance radars	5 ± 2	Mathews et al. [2001]	Possible velocity bias
Fe in Antarctic ice core	15 ± 5	Lanci et al. [2007]	Very little wet deposition by snow
Na layer modeling	10 - 30	Plane [2004]	Depends on vertical eddy diffusion
Fe/Mg in stratos. sulphate layer	22 – 104	Cziczo et al. [2001]	Data limited geographically
Aerosols at South Pole	30	Tuncel & Zoller [1987]	Data limited geographically
Optical extinction measurements	40	Hervig et al. [2009]	Questionable refractive indices
Zodiacal dust cloud model	41±14	Nesvorný et al. [2011]	Needs to be constrained by radars
Conventional meteor radars	44	Hughes [1978]	Extrapolation
Os in deep-sea sediments	101 ± 36	Peuker-Ehrenbrink [1996]	Focusing by ocean currents
Long Duration Exposure Facility	110 ± 55	Love & Brownlee [1993]	Sensitive to particle velocity
Lidar Fe/Na and vertical wind meas.	150± 38	Huang et al. [2015]	Ablation/transport model dependence
Fe in Greenland ice core	175 ± 68	Lanci & Kent [2006]	Wet deposition may be important
Ir and Pt in Greenland ice core	214 ± 82	Gabrielli et al. [2004]	Wet deposition may be important
Ir in deep-sea sediments	214	Wasson & Kyte [1987]	Focusing by ocean currents

After JMC Plane, 2012

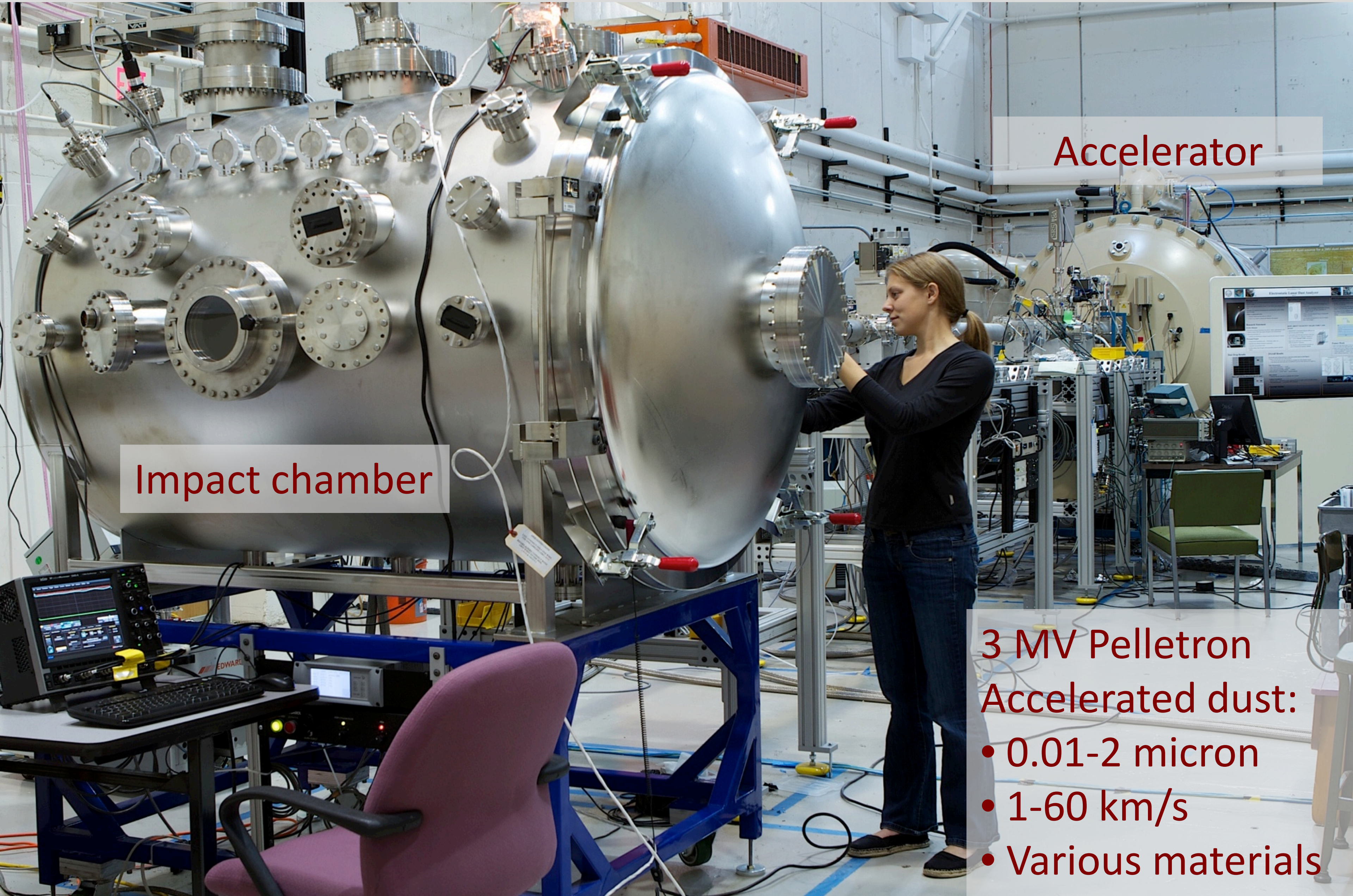
3 MV dust accelerator at LASP, Univ. of Colorado

Check out: IMPACT.COLORADO.EDU

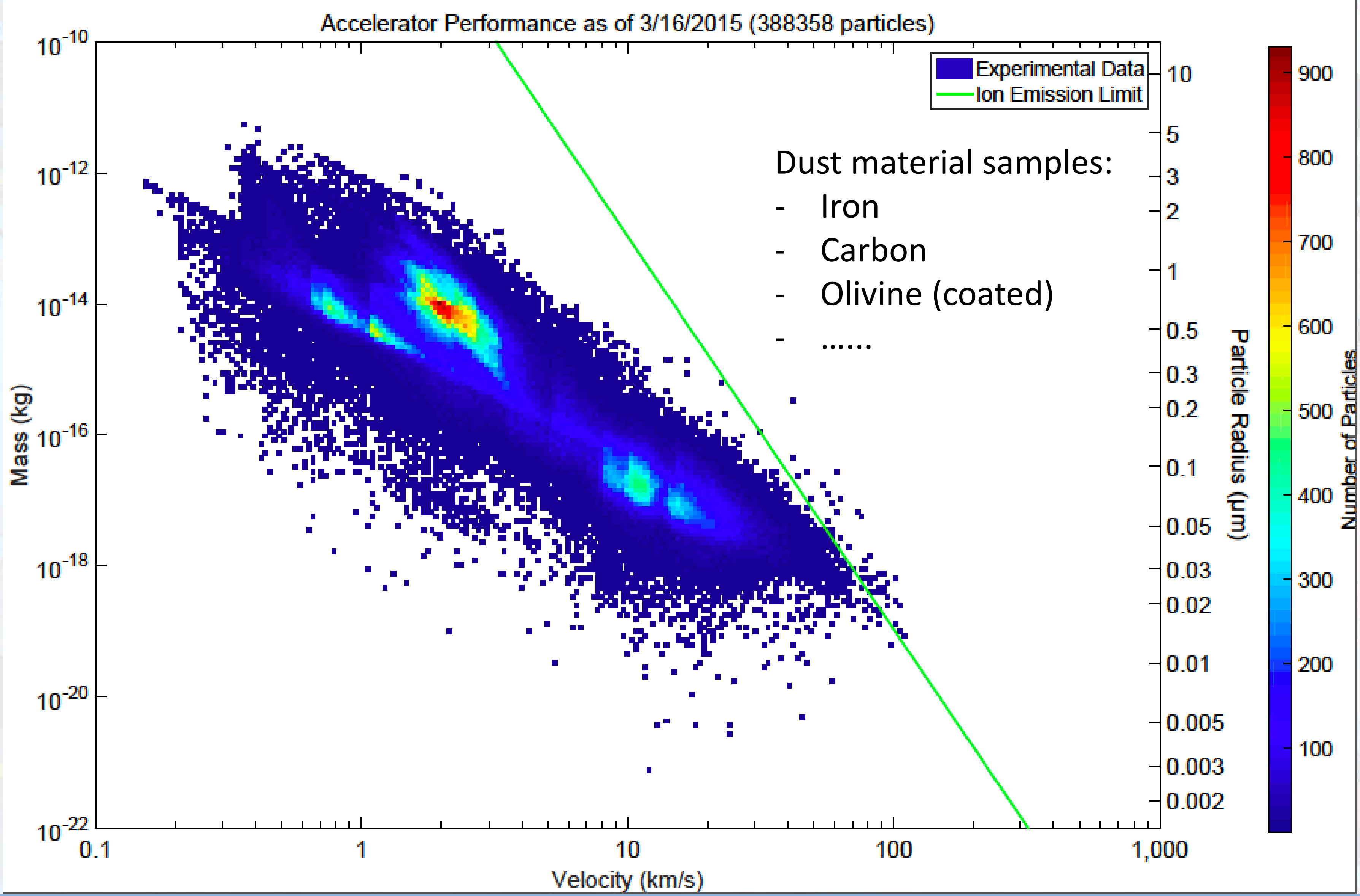


Funded by NASA, Solar System Exploration Research Virtual Institute (SSERVI) program

Testing and calibration (dust accelerator)



Particle mass vs. velocity distribution



Dust material samples:

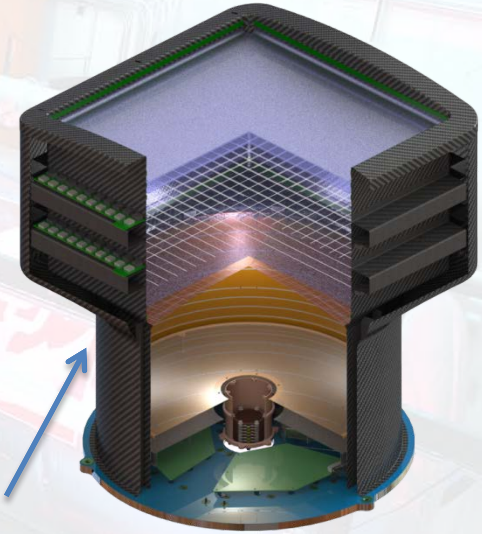
- Iron
- Carbon
- Olivine (coated)
- ……

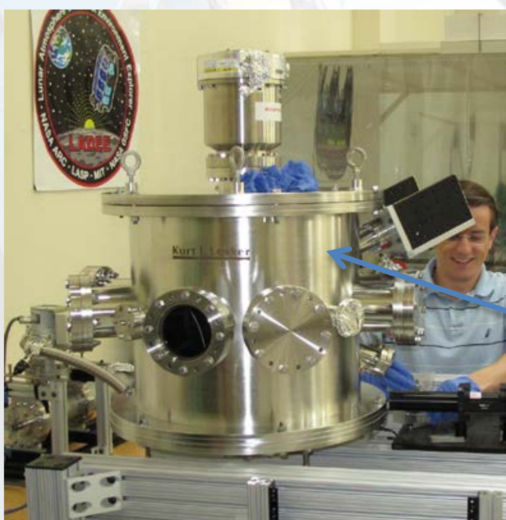
Research and development enabled by the dust accelerator

Dust detector and analyzer instrument development

Lunar Dust EXperiment on LADEE

Hyperdust: advanced dust telescope

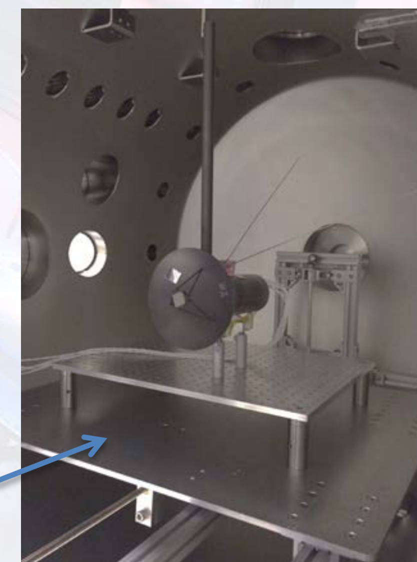




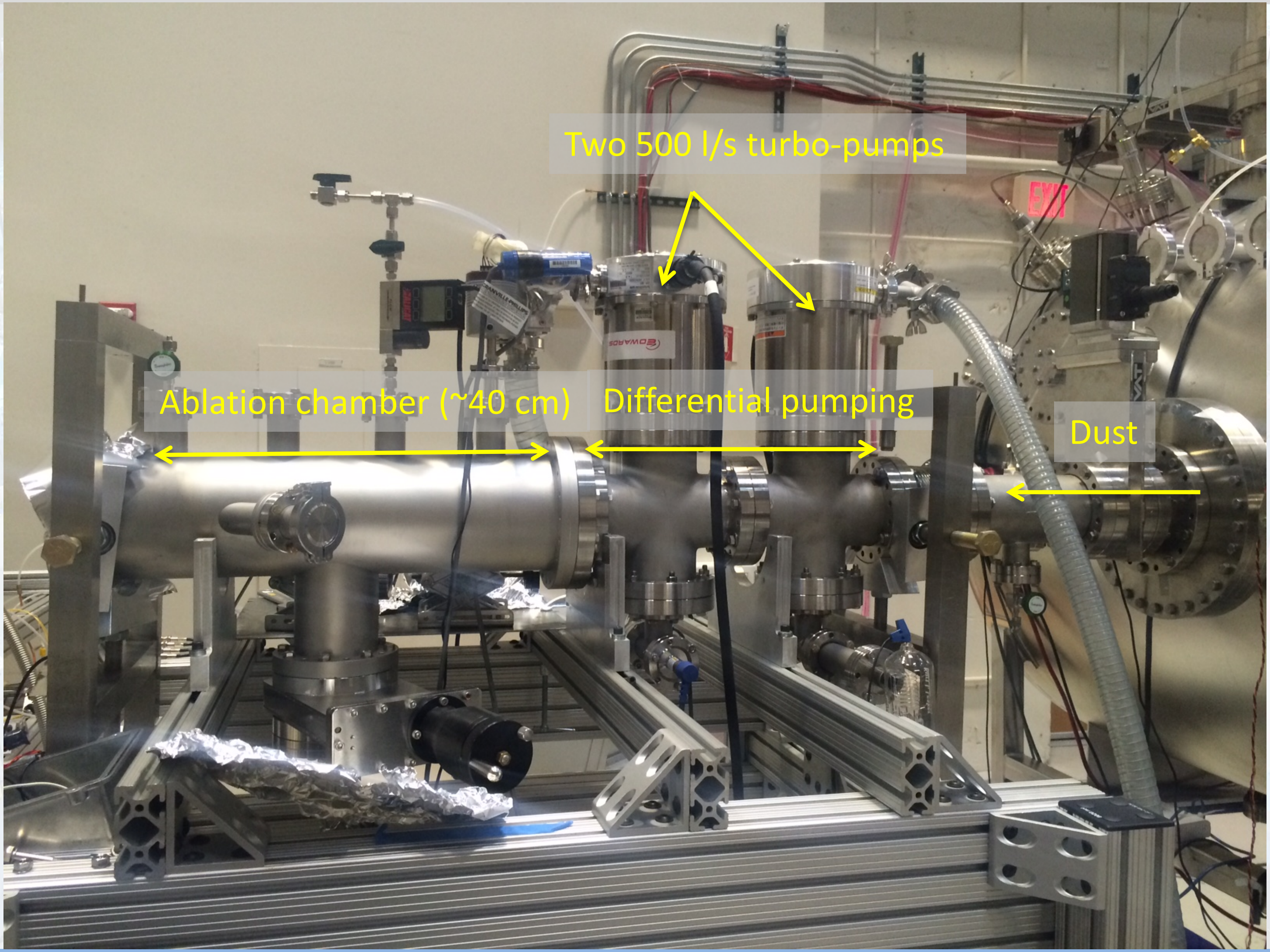
Hypervelocity impact studies

Ice target impact studies

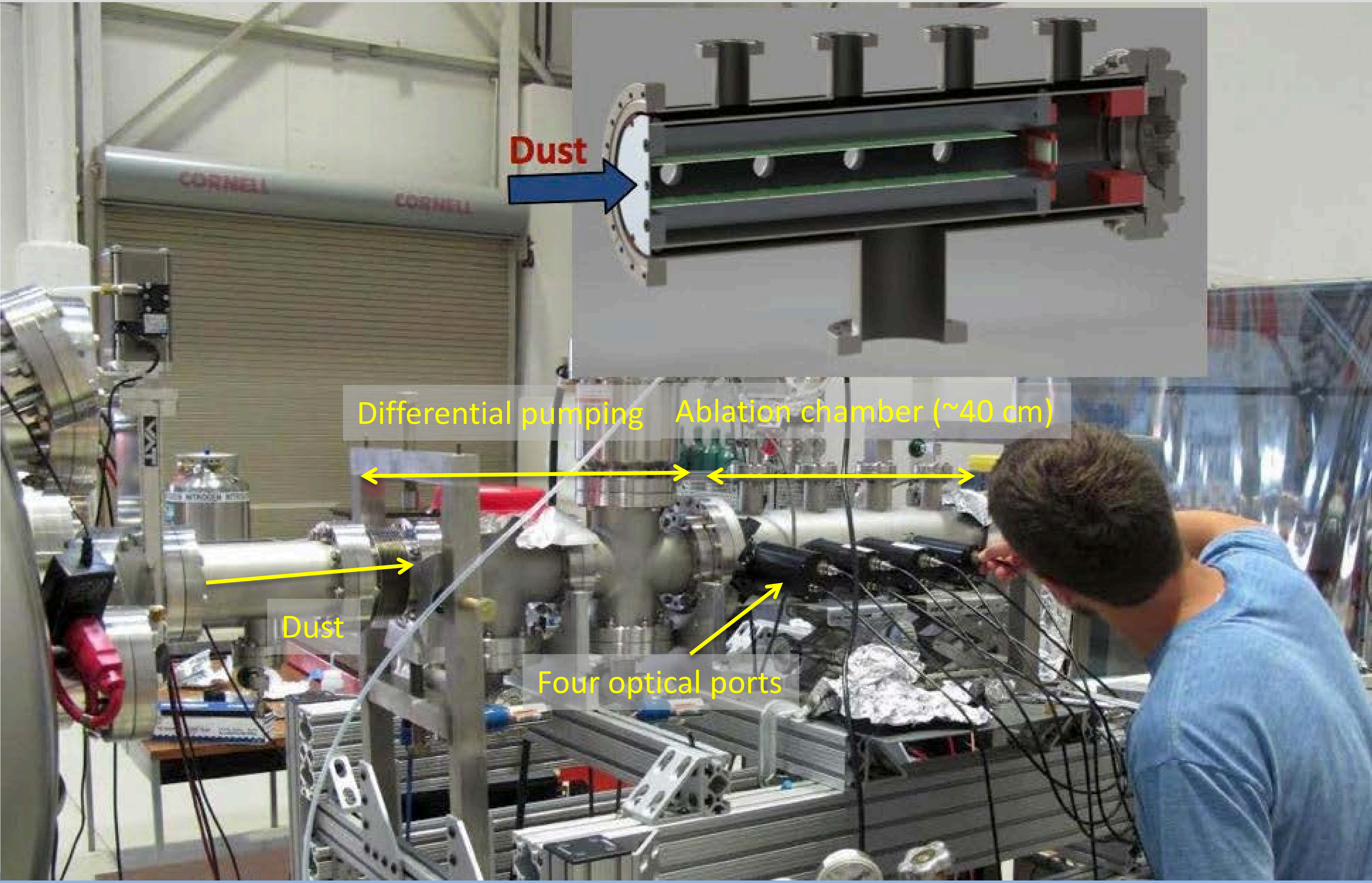
Laboratory simulation of dust impact signals detected by spacecraft



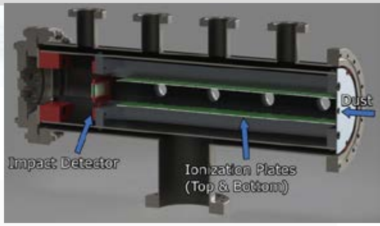
The ablation facility

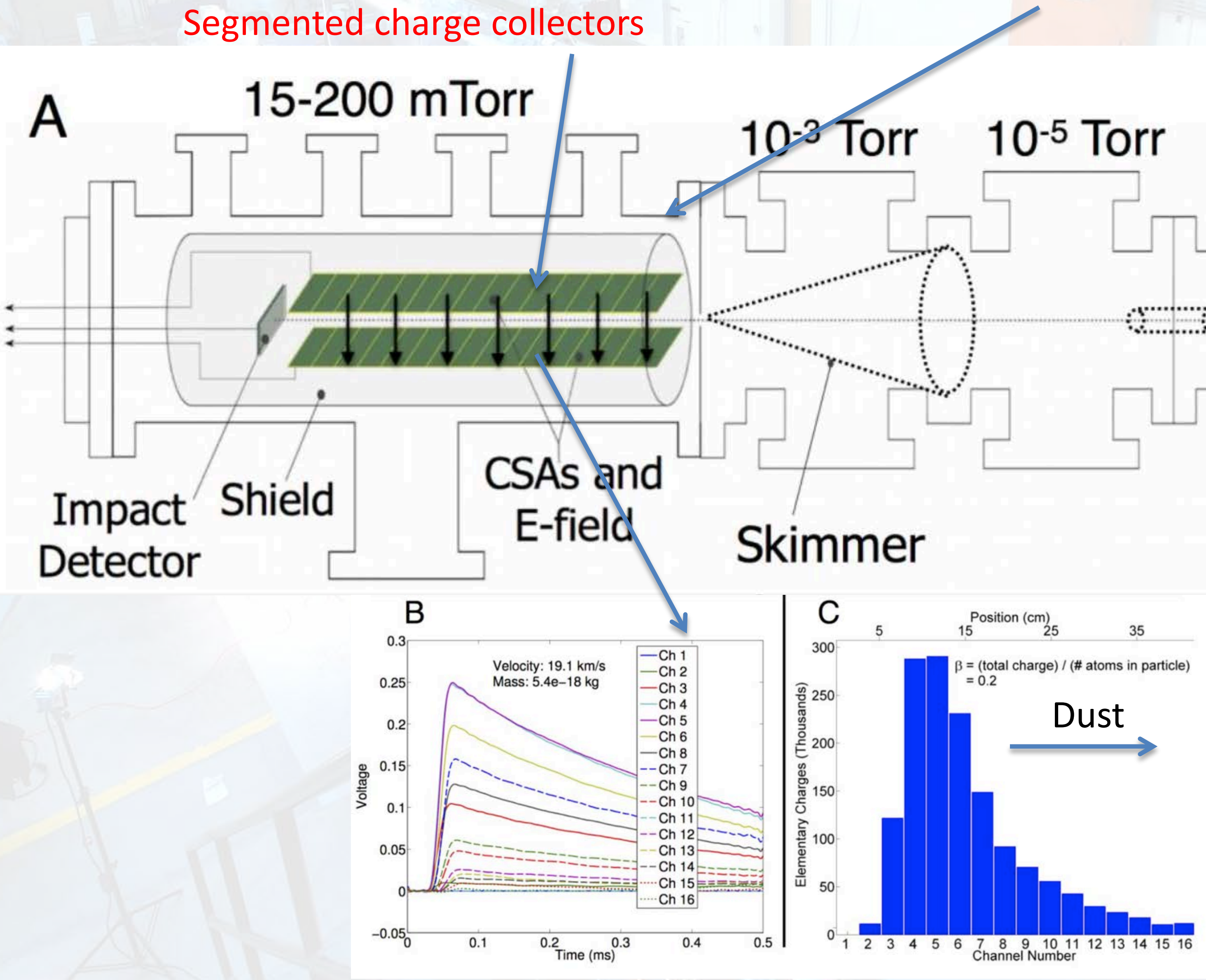
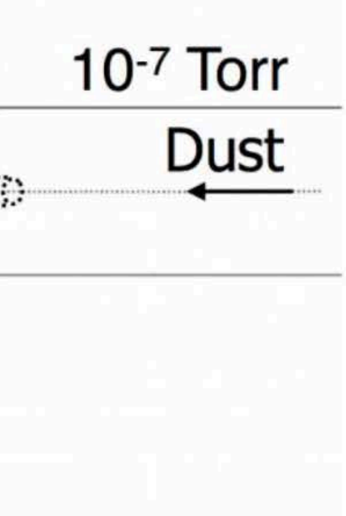


The ablation facility

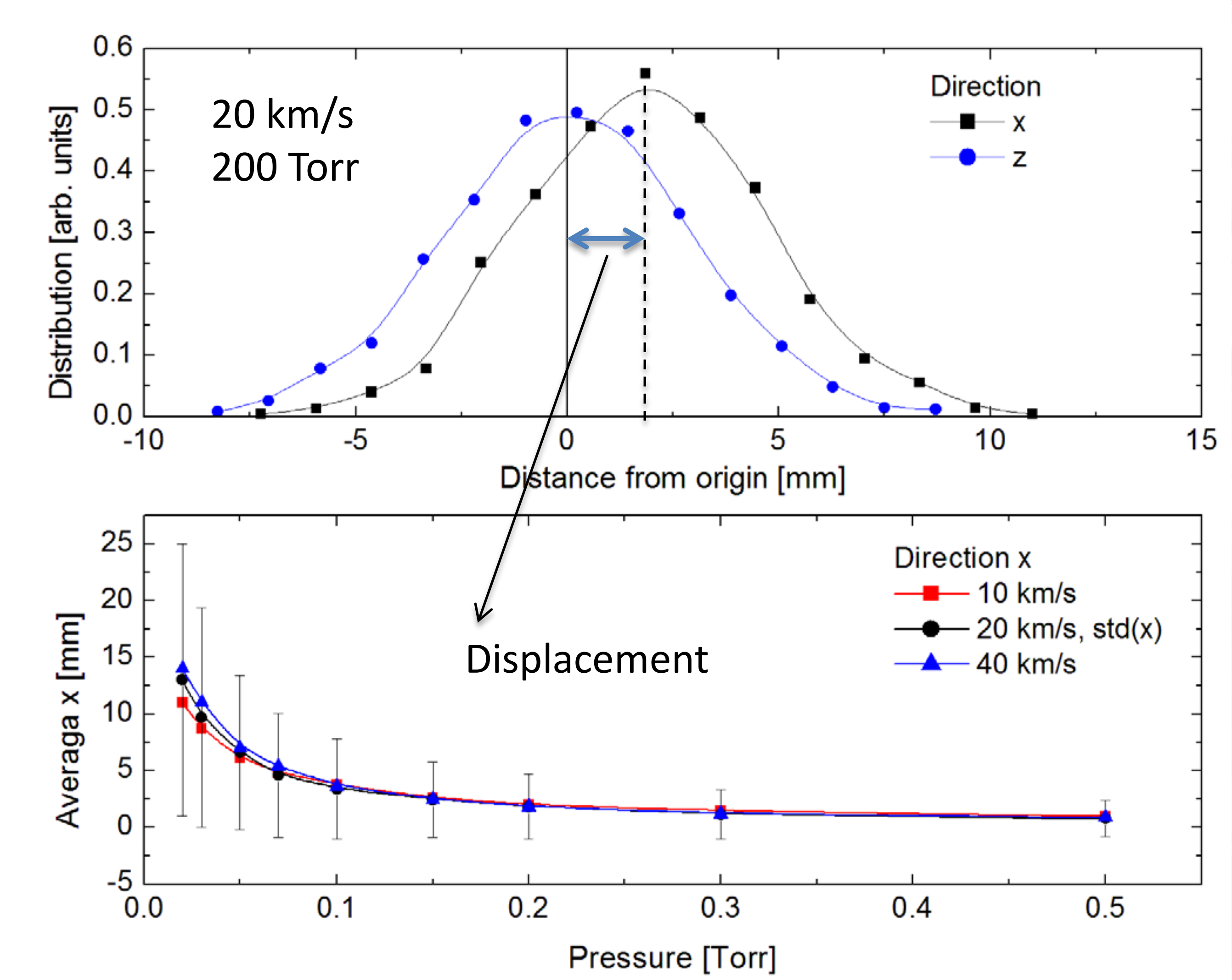


What's inside the ablation chamber



How good is the collection efficiency?

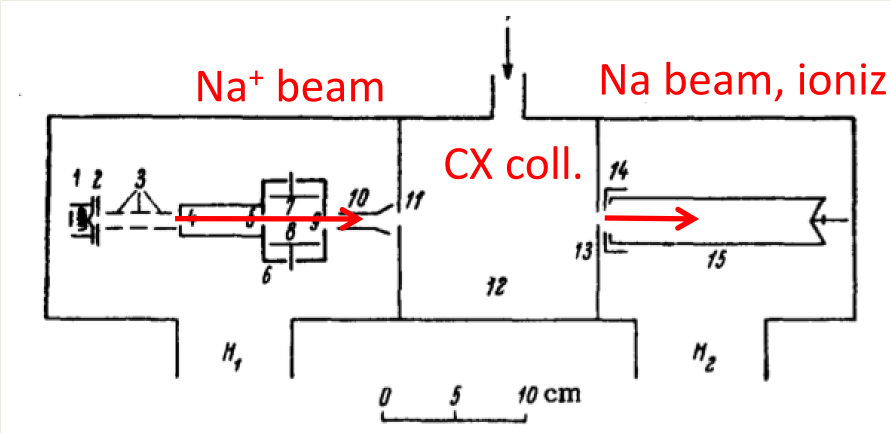


- Monte Carlo simulation (Fe + N_2)
- Hard-sphere collision model
- Ions collected close to location of birth
- >99% of ions collected

IONIZATION EFFICIENCY

Historical overview of prior measurements of ionization efficiency

1- Ionization cross section measurements



Elements: **Na, K**
Gases: N_2, O_2, etc

Bydin & Bukhteev, 1960
Moutinho et al., 1971
Cuderman et al., 1972
Kleyn et al.,1978

2- Dust accelerator/ablation measurements

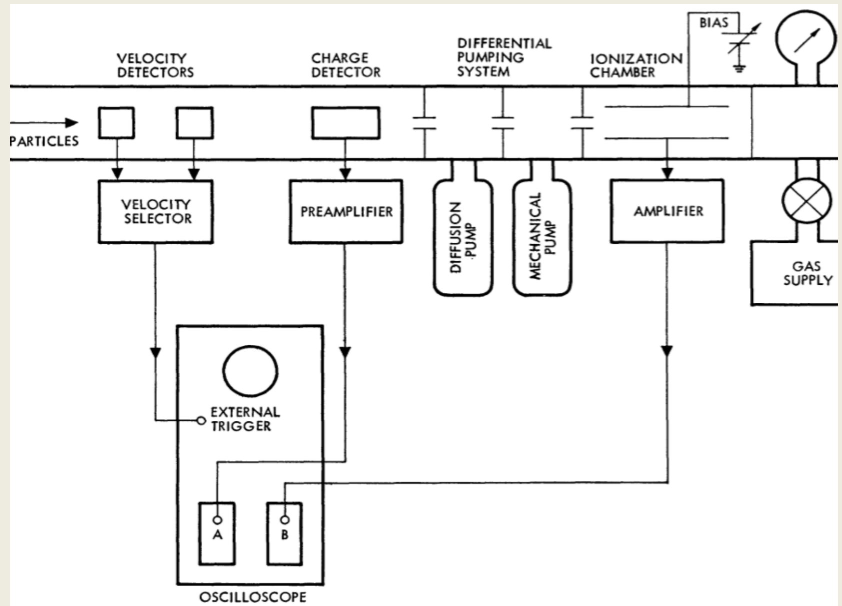


Fig. 1.—Block diagram of experimental configuration

Elements: **Fe, Cu, LaB6**
Gases: N_2, CO_2, Ar, air, etc.

Slattery and Friichtenicht, 1966
Friichtenicht et al., 1967
Friichtenicht and Becker, 1971

Jones (1997) – the standard reference

- Ionization efficiency, β_0 $$\beta_0 = \frac{\sigma_{ion}}{\sigma_{tot}} \qquad \sigma_{tot} = \sigma_{el} + \sigma_{ion}$$
- Two assumptions made
- 1: $$\sigma_{el} \sim 1/v^{0.8}$$
- 2: $$\sigma_{ion} \sim (v - v_0)^2$$
- Assumed form $$\boxed{\beta_0 = \frac{c(v - v_0)^2 v^{0.8}}{1 + c(v - v_0)^2 v^{0.8}}} \qquad \beta_0 \le 1$$
- Where $$v_0^2 = \frac{2(m + M)}{mM} \varphi_{IE}$$

Jones model – II.

$$\beta_0 = \frac{c(v - v_0)^2 v^{0.8}}{1 + c(v - v_0)^2 v^{0.8}}$$

Table 1. Ionization parameters for elements assumed to be present in the composition of a cometary meteoroid.

Element	%	p	v_0	$c\times10^6$	μ
O	45	0.617	16.7	4.66	0.57
Fe	15	0.059	9.4	34.5	2.0
Mg	9	0.082	11.1	9.29	0.86
Si	31	0.242	11.0	18.5	1.0
Cu	–	–	9.1	15.3	2.25

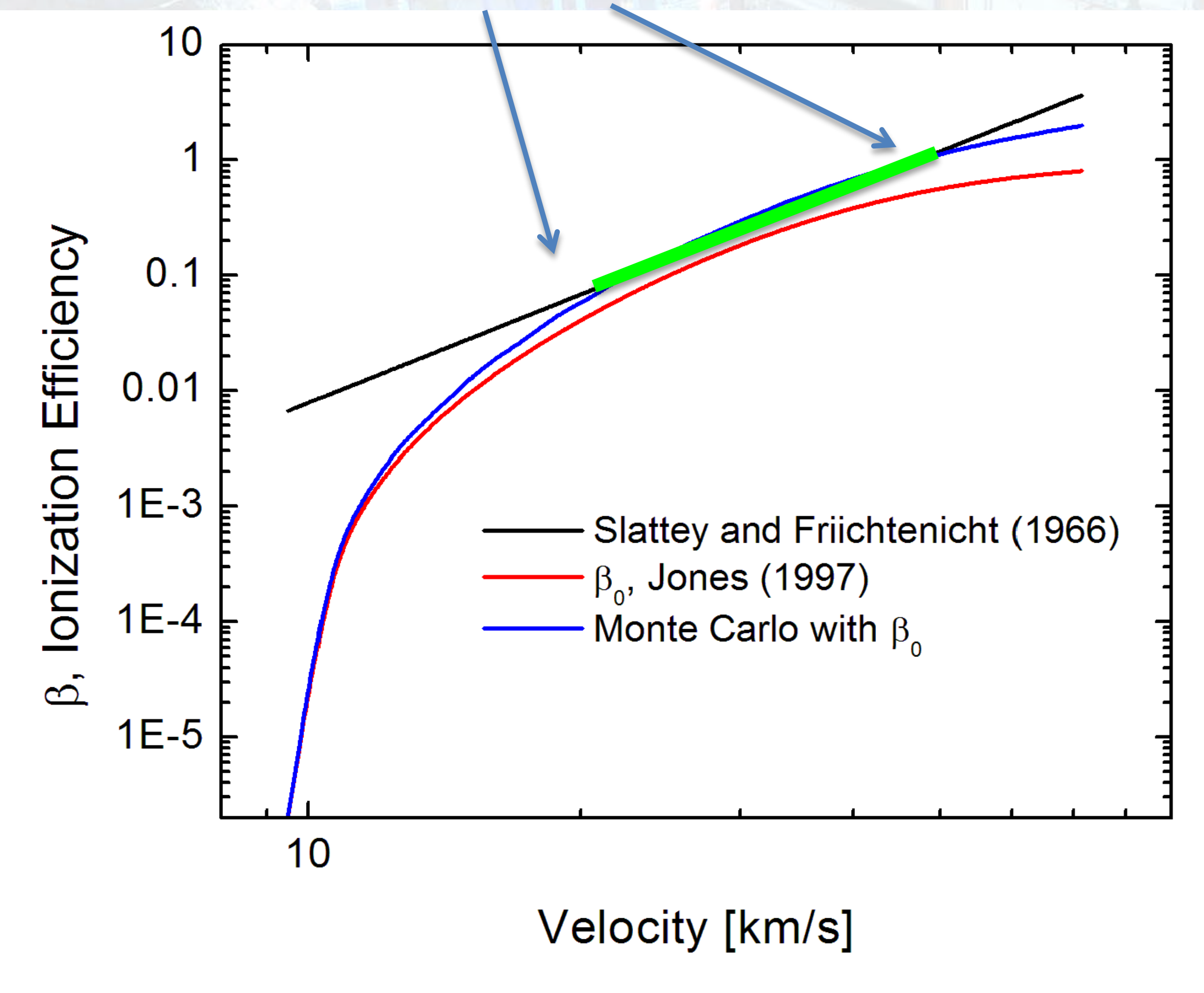
- Jones calculates β, the total ionization probability allowing subsequent ionizing collisions
- Hard-sphere collision model assumed

$$\beta(v) = \beta_0(v) + \underbrace{(1 - \beta_0(v))\frac{(1+m)^2}{2v^2\mu}\int_{v_0}^{v}\beta(v')v'dv'}_{\sim 2\text{ x at high impact velocities}}$$

Inelastic collisions ignored

Jones model – III. – Fe

Slattery & Friichtenicht (1967) data span (20 – 45 km/s)

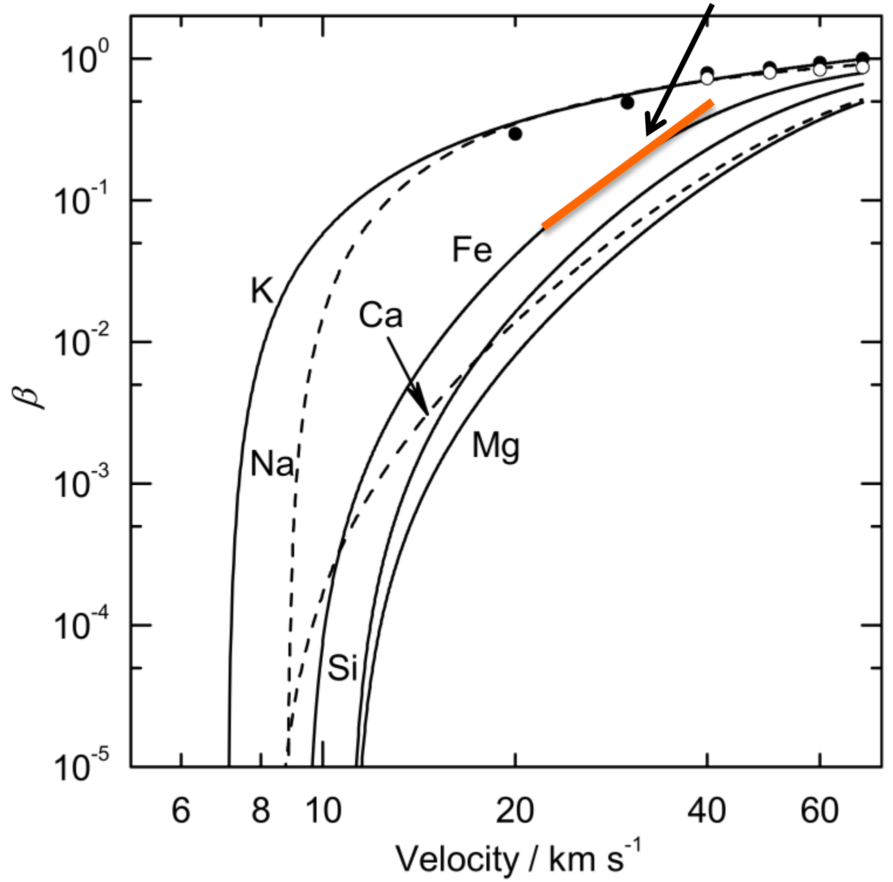


$$\beta_0 = \frac{c(v-v_0)^2 v^{0.8}}{1 + c(v-v_0)^2 v^{0.8}}$$

β - state of the art (Vondrak et al., 2008)

From Vondrak et al., 2008, for ionization in N2

Slattery and Friichtenicht (1967) data



The Jones model (1997)

$$\beta_0 = \frac{c(v - v_0)^2 v^{0.8}}{1 + c(v - v_0)^2 v^{0.8}}$$

$$v_0^2 = \frac{2(m+M)}{mM}\varphi_{IE}$$

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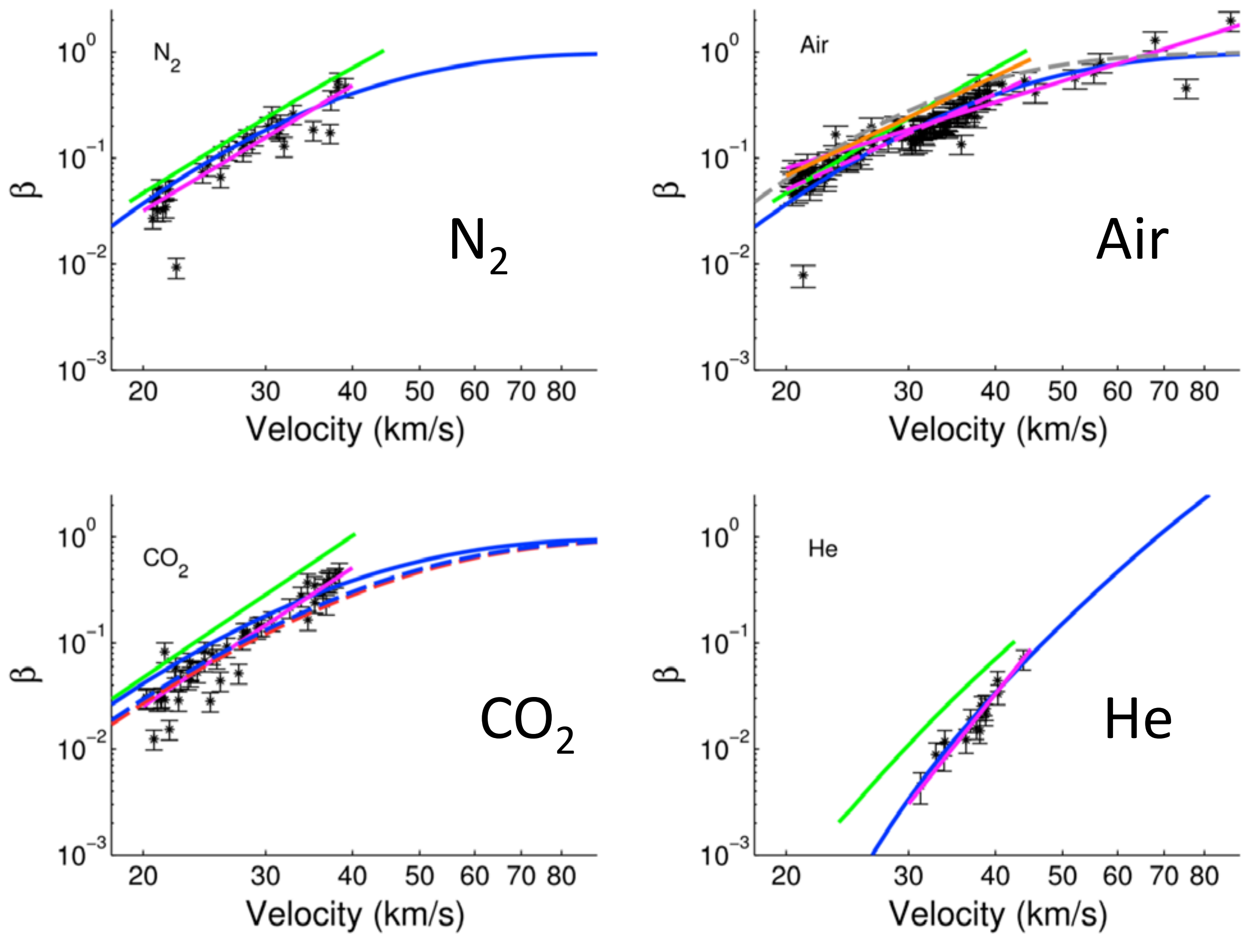
Ionization efficiency, Fe + N_2, complete ablation

Complete ablation: $\beta = (Q_{TOTAL}) / (\# \text{ atoms})$



- > 20 km/s, > 15 mTorr
- Complete ablation occurs
- Velocity change is small
- Collected pos/neg charges are equal
- Previous measurements
- New fit using Jones (1997)

Thomas et al., GRL, 2016

Ionization probability of Fe in various gases

$$\beta_0 = \frac{c(v - v_0)^2 v^{0.8}}{1 + c(v - v_0)^2 v^{0.8}}$$

Gas	Parameter $c \times 10^6$
N_2	20.4
Air	19.7 (34.5 from Jones et al. (1997)
CO_2	18.6
He	0.88

Results in Thomas et al., GRL, 2016

HOW WELL CAN WE MATCH THE ABLATION PROFILE USING MODELS?

Ablation model (after Vondrak et al., 2008)

$$\frac{dV}{dt} = -\Gamma V^2 \frac{3\rho_a}{4\rho_m R}$$

Momentum equation, **Γ = molecular drag coefficient**

$$\frac{dm_i^A}{dt} = \gamma\, p_i S \sqrt{\frac{\mu_i}{2\pi k_B T}}$$

Mass loss rate, **γ** = uptake coefficient

$$\frac{1}{2}\pi R^2 V^3 \rho_a \Lambda = 4\pi R^2 \varepsilon\sigma (T^4 - T_{env}^4) + \frac{4}{3}\pi R^3 \rho_m C \frac{dT}{dt} + L\frac{dm}{dt}$$

Energy conservation (heating) equation

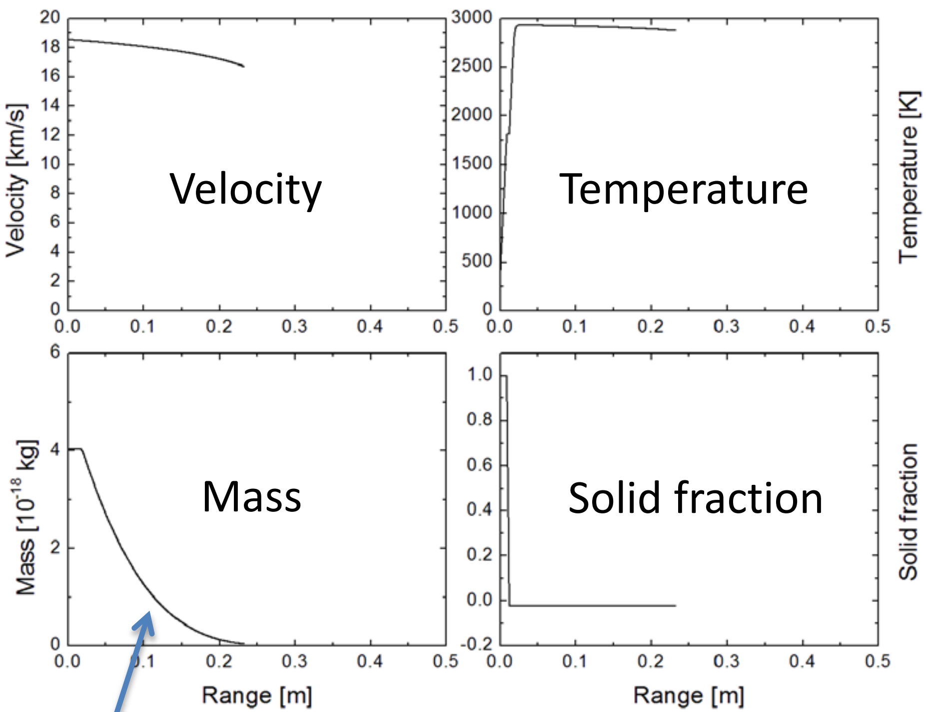
Λ – heat transfer coefficient

Ionization rate: (dm/dt) × β

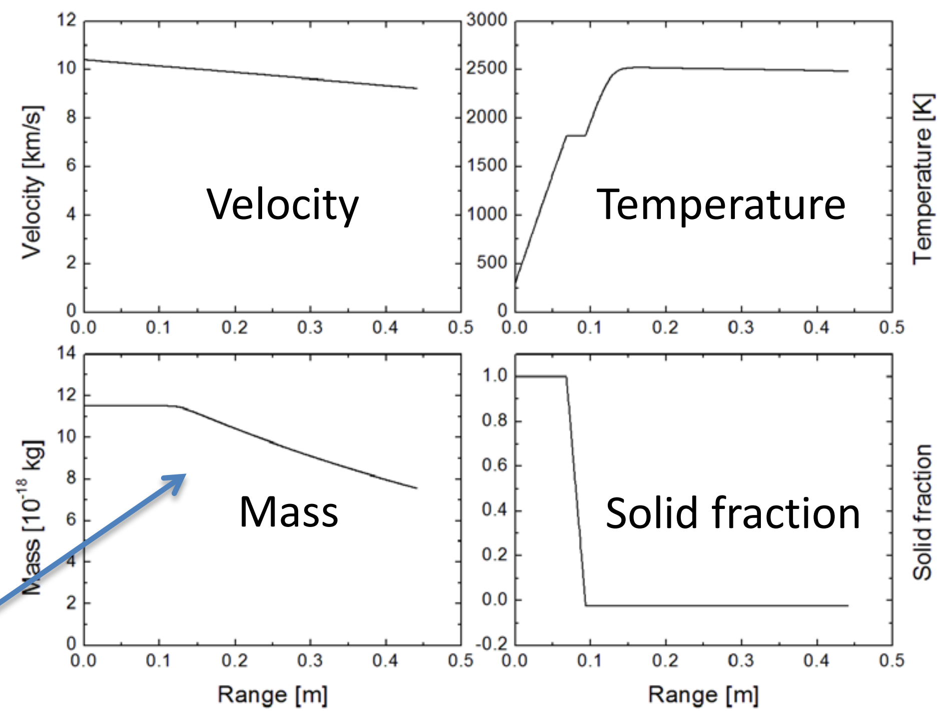
β = Ionization efficiency

Solutions to the ablation model

'Fast' particle: **18.6 km/s**, 50 nm in radius



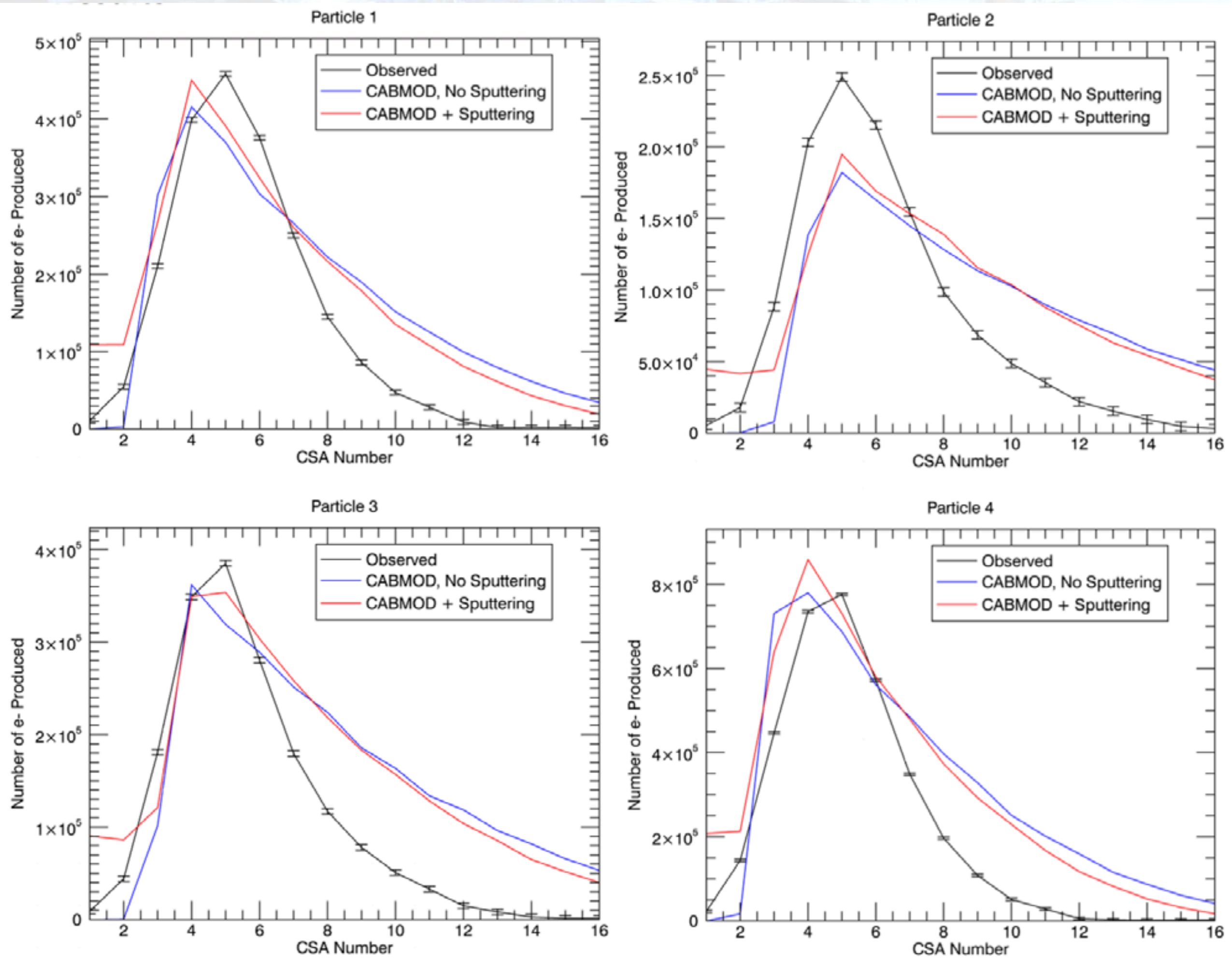
'Slow' particle: **10.4 km/s**, ~70 nm in radius



Generated charge = (dm/dx) × β

Incomplete ablation → uncertainty of mass loss

Monte Carlo analysis of experimental data

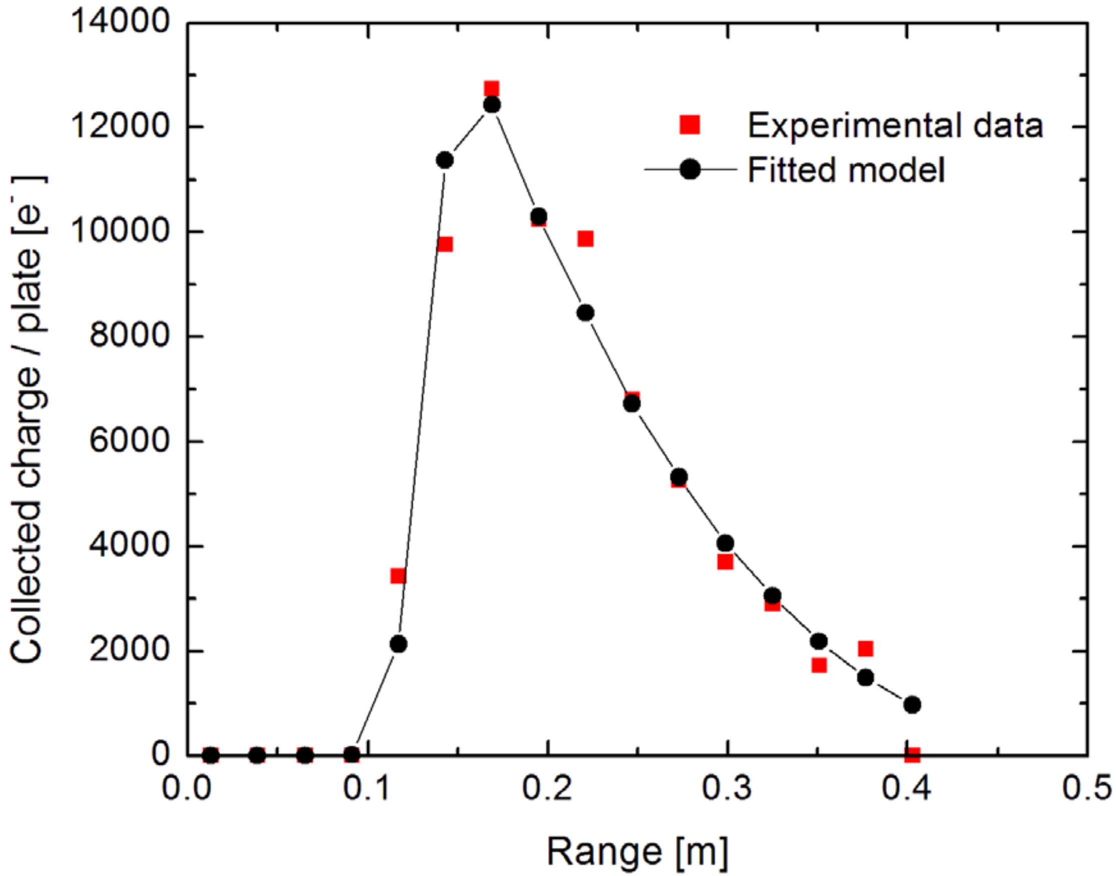


Particle 1: r_0= 39 nm, v_0= 30 km/s
Particle 2: r_0= 40 nm, v_0= 26 km/s
Particle 3: r_0= 41 nm, v_0= 29 km/s
Particle 4: r_0= 42 nm, v_0= 33 km/s

Chamber Pressure: 48.9 mTorr

Best fits: **Λ = 0.42 – 0.48**

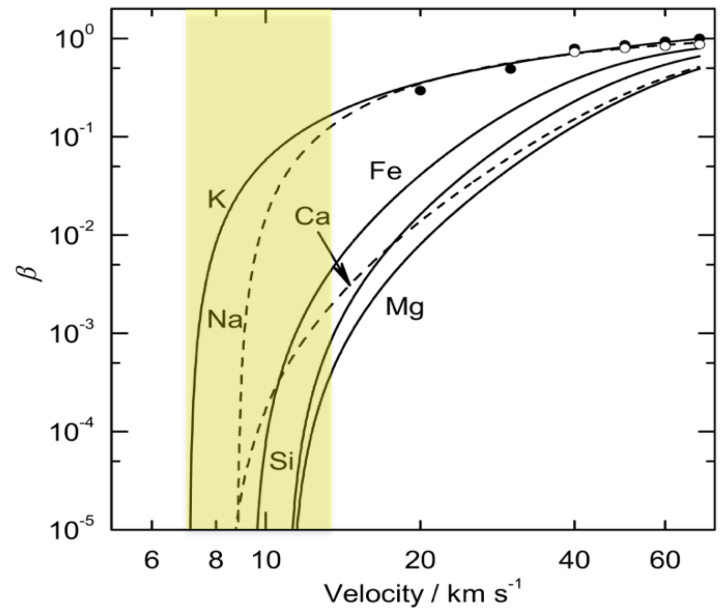
The difficulty of determining β at velocities < 20 km/s



- Velocity: **10.4 km/s**
- Radius: 70 nm
- Material: Fe
- Gas: N_2

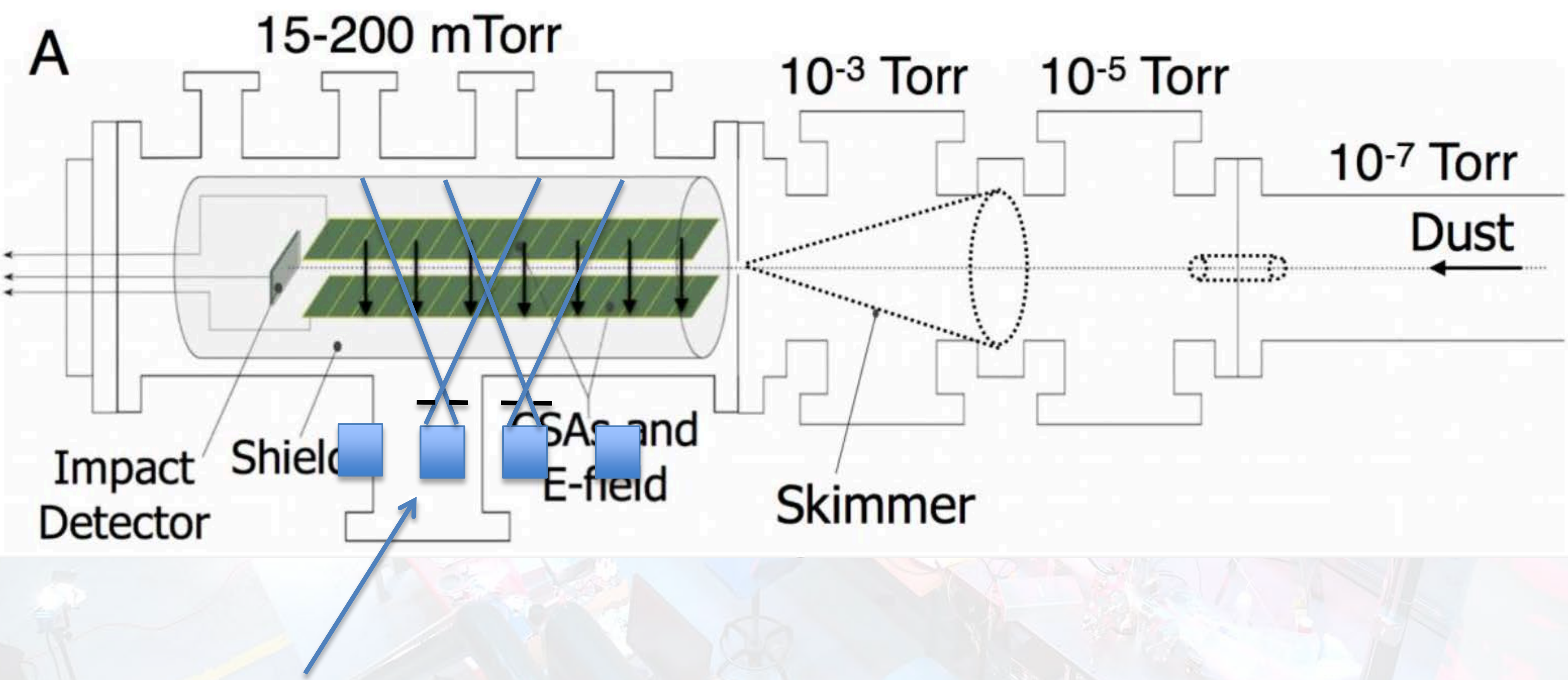
- Best fit parameters
- **Λ: ≈ 0.55**
- **Γ: ≈ 0.75**

β is strongly varying with velocity



Difficult to untangle dependence on β(v) and (Γ, Λ)

Ongoing improvements: optical velocity measurement (with the help of Bob Marshall)



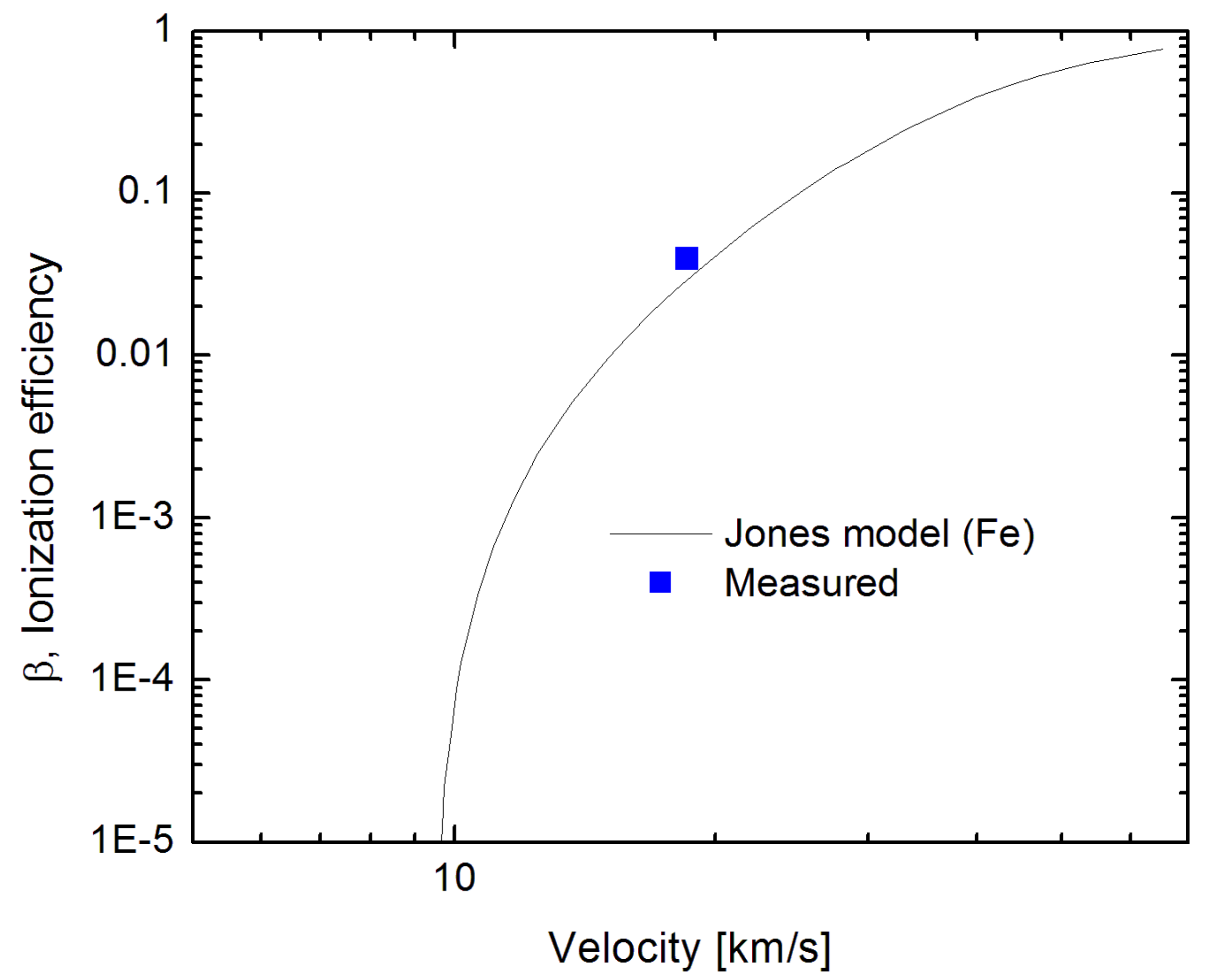
Photomultiplier detectors with overlapping Field-of-View

Summary/Conclusions

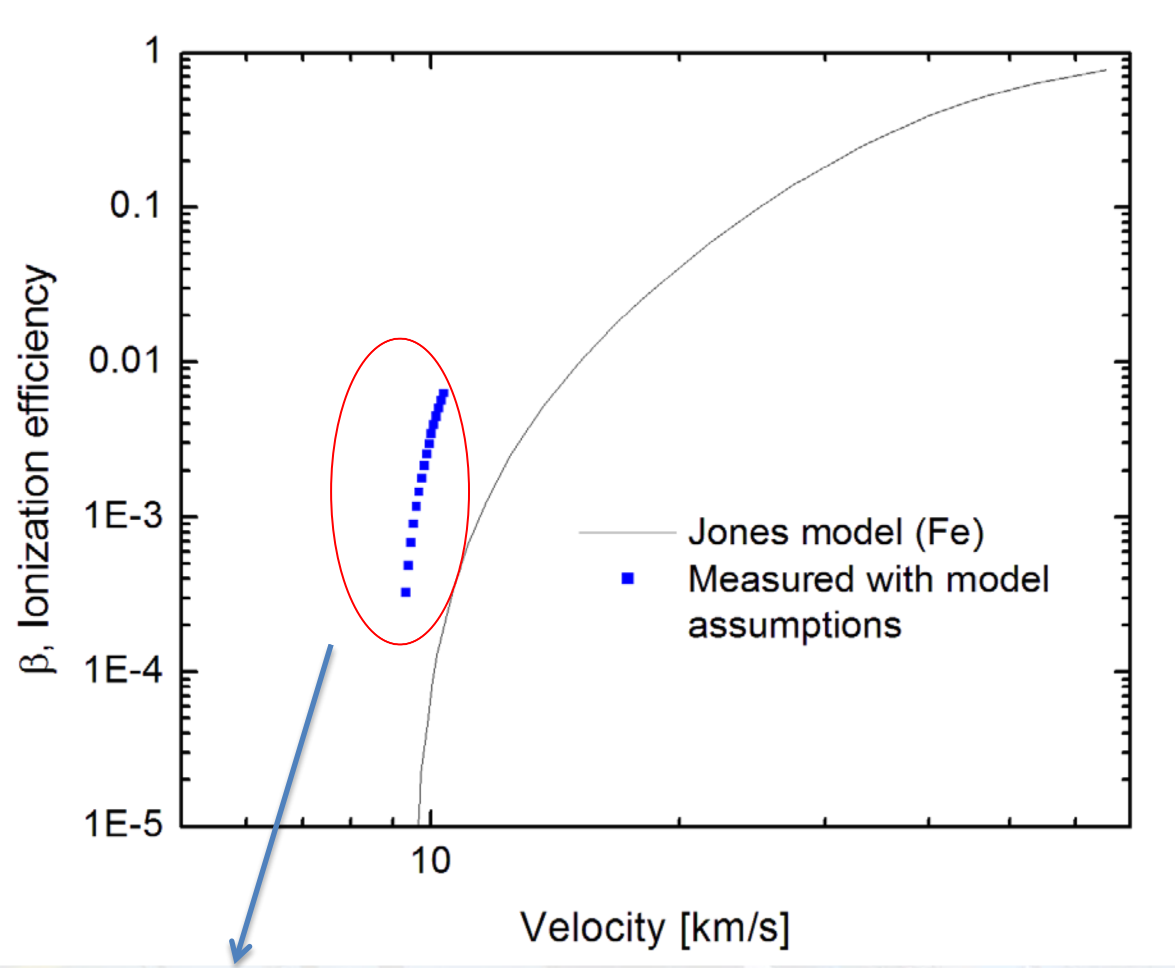
- The dust accelerator enables the **experimental investigation of the ablation process**
- First set of measurements at higher velocity and complete ablation performed, ionization efficiency determined.
- Updates to the facility under way to extend measurements to lower velocities

BACKUP SLIDES

Fast particle



Slow particle



β will depend on parameters in the ablation mode and the assumed shape of β(v)

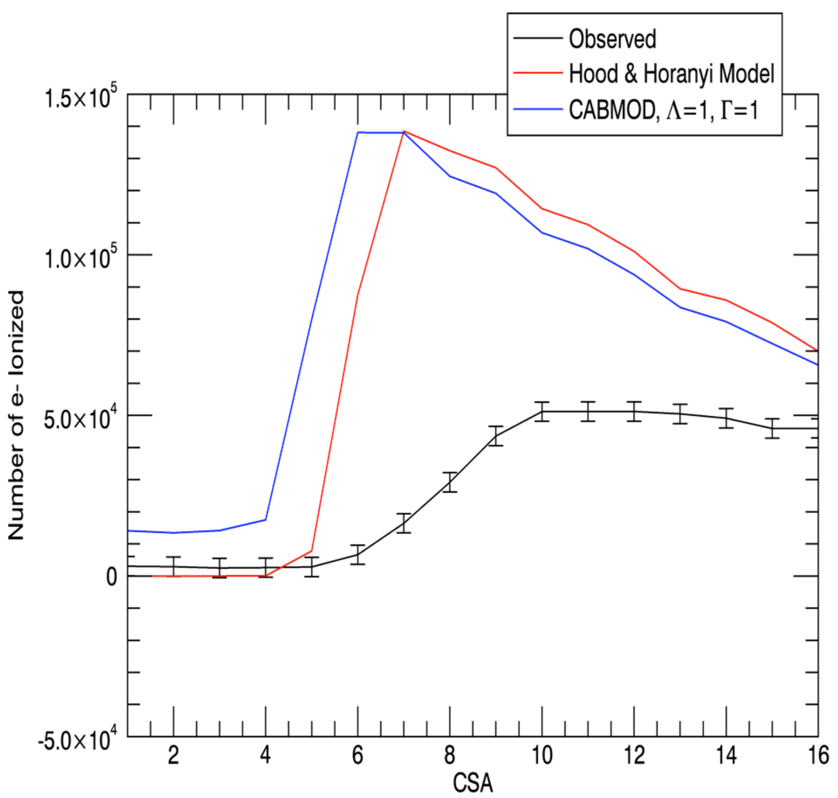
Need to consider change of velocity during the ablation process

The calculation of mass loss over each collection plate is dependent on the ablation model and parameters used (uncertainty)

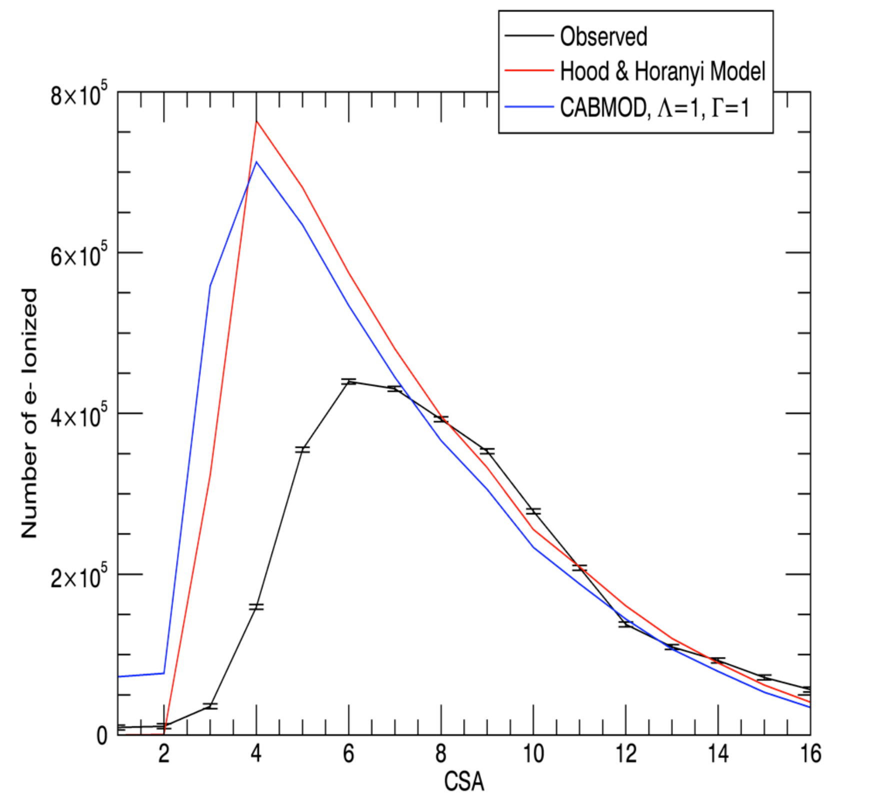
Need to analyze a large assemble of particles for reliable find the fitting parameters

CABMOD and Hood and Horanyi (1991) are similar

Compared model by Hood and Horanyi (1991) to CABMOD (Vondrak et al, 2008).



v_0 = 25.8 km/s, r_0 = 40.3 nm, P = 16.0 mTorr, N_2 Gas



v_0 = 25.1 km/s, r_0 = 57.5 nm, P = 48.9 mTorr, N_2 Gas

More careful analysis needed at low velocities