CCLDAS: Colorado Center for Lunar Dust and Atmospheric Studies

Modern dust instruments for the exploration of the Moon and small bodies

Zoltán Sternovsky

Siegfried Auer, Keith Drake, Eberhard Grün, Mihály Horányi, Huy Le, Ralf Srama, and Jianfeng Xie

Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO, 80309, USA
Aerospace Engineering Sciences, University of Colorado, Boulder, CO, 80309, USA
A&M Associates, Basye, VA, 22810, USA
Institute of Space Systems, University of Stuttgart, 70569, Germany

Recent lunar missions

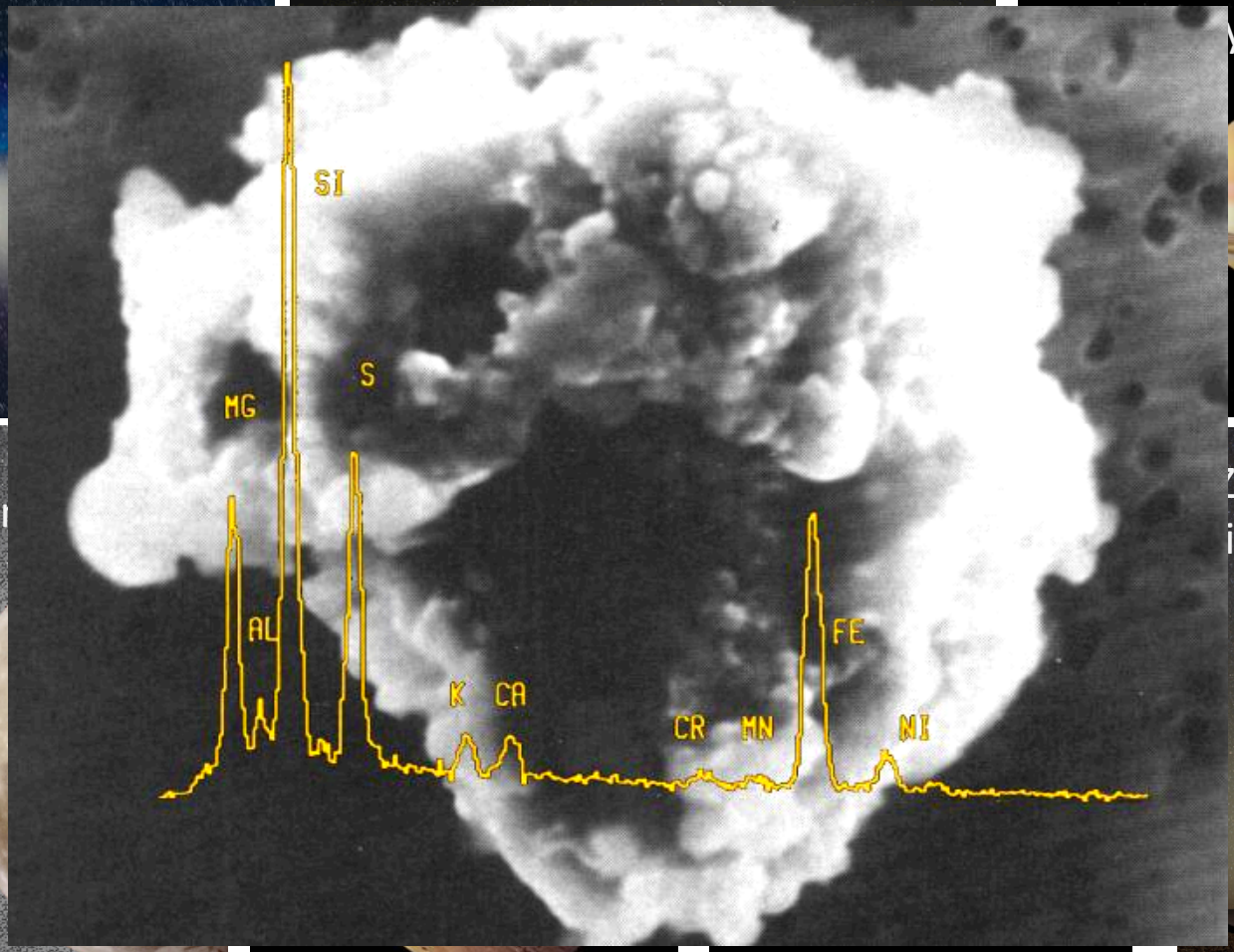
- **LADEE** – NASA, 2013, orbiter, lunar environment
- **GRAIL** – NASA, 2011-, orbiter, gravity mapping
- **Chang'e 2** – CNSA, 2010-, orbiter
- **LCROSS** – NASA, 2009, Impactor, looking for water
- **Lunar Reconnaissance Orbiter** – NASA, 2009-
- **Chandrayaan-1** - ISRO (India) Lunar Orbiter Mission (2008)
- **Chang'e 1** - CAST (China), 2007-09, orbiter
- **Kaguya (SELENE)** – JAXA, 2007-09, orbiter
- **SMART 1** – ESA (Swedish design), 2003-06 Lunar Orbiter Mission
- **Lunar Prospector** – NASA Discovery, 1998-99,
- **Clementine** - DoD/NASA, 1994, Lunar Mapping Mission

Outline

- The value of in-situ instruments
- Dust to measure
- Brief historical overview of past instruments
- LDEX for LADEE – detecting dust from orbit
- Chemical analyzers
- ELDA for slow moving dust
- Summary

Dust within the solar system

Comets



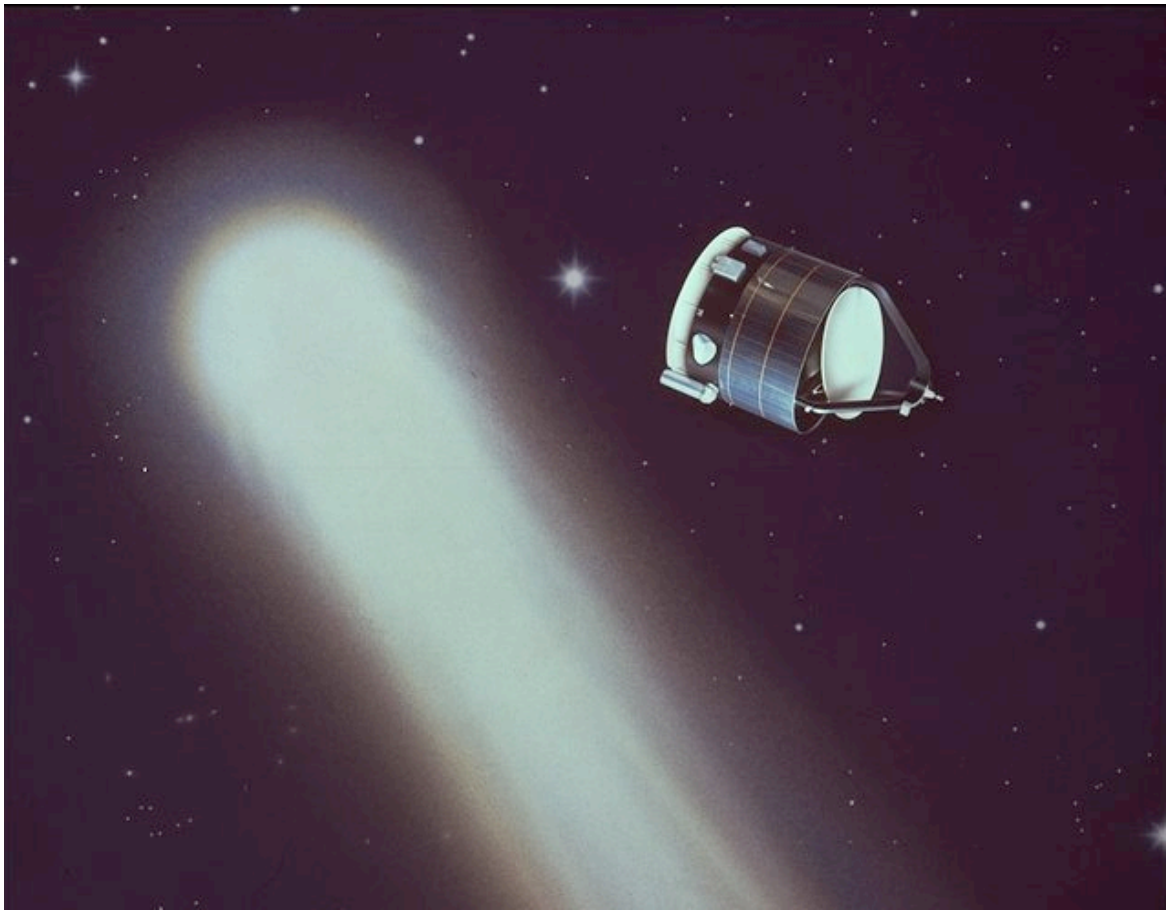
y rings

Airless moo

Active moons

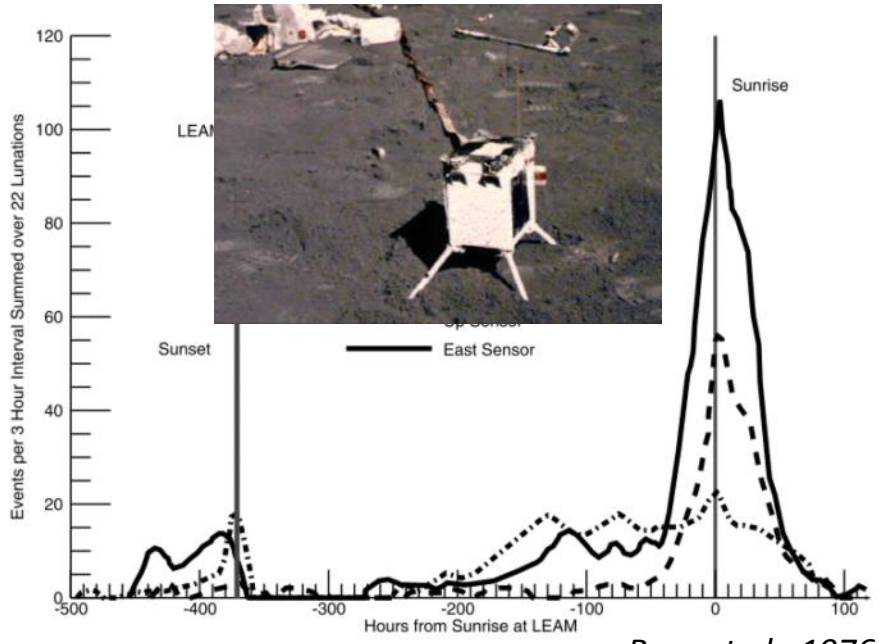
Zodiacal
ight

Giotto at Halley – the beginning of dusty plasmas

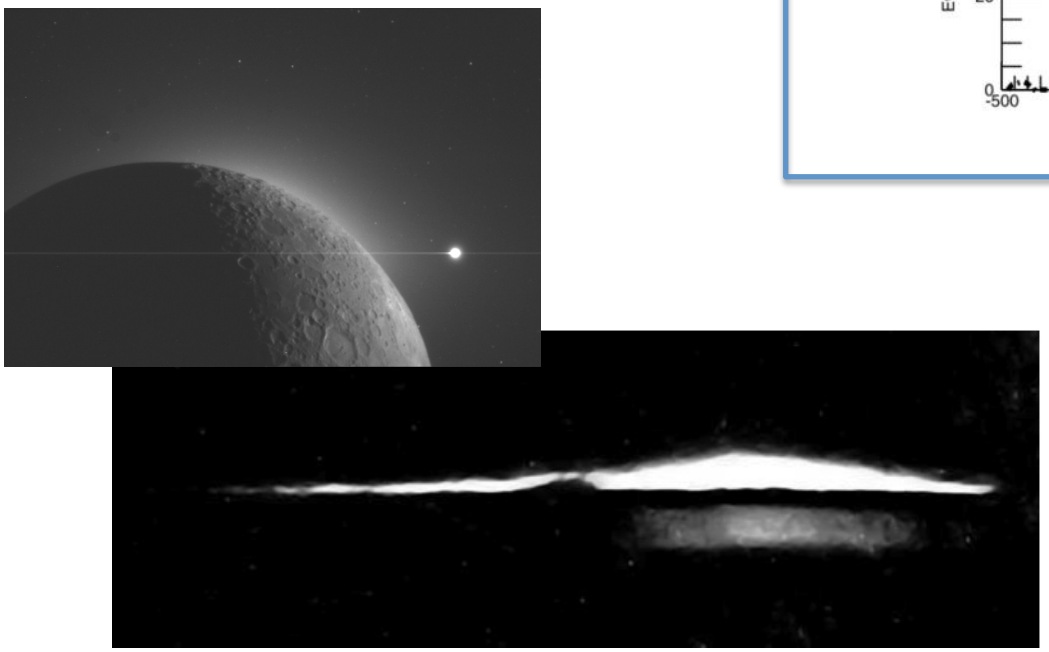


Motivation

- Lunar Ejecta and Meteorites Expt. (LEAM)
  - Large number of counts near sunrise interpreted as slow-moving, horizontally transported dust particles
  - Charging and transport due to horizontal electric fields?



Berg et al., 1976

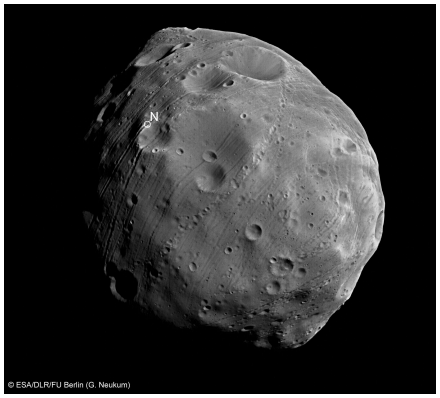


Colwell et al., 2005

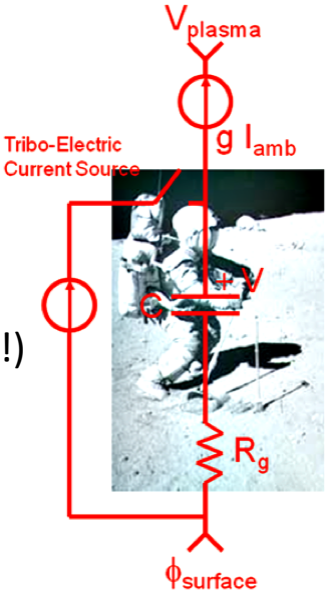
Horizon Glow

- Forward scattering of solar light detected by *Surveyor* spacecraft
- Possibly levitated dust particles
  - ~ 6 μm in radius [*Rennilson & Criswell, 1973*]

Motivation



- **Fundamental physics** and applications to other bodies
  - Plasma interaction with an unmagnetized body
    - Surface-bounded exospheres
  - Mercury, Phobos, Deimos, asteroids

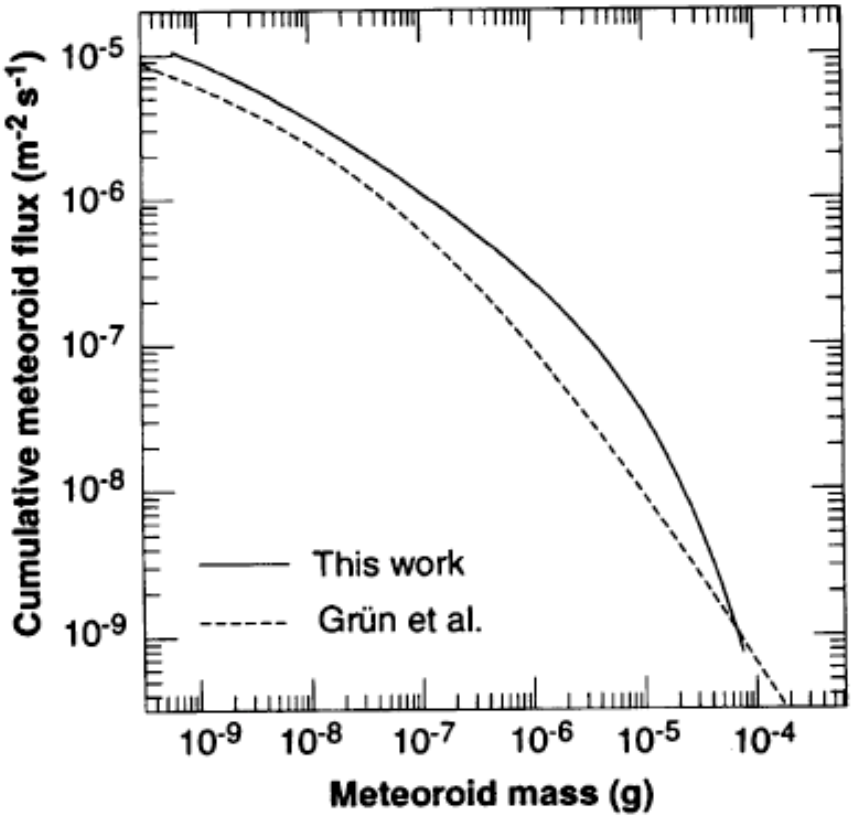


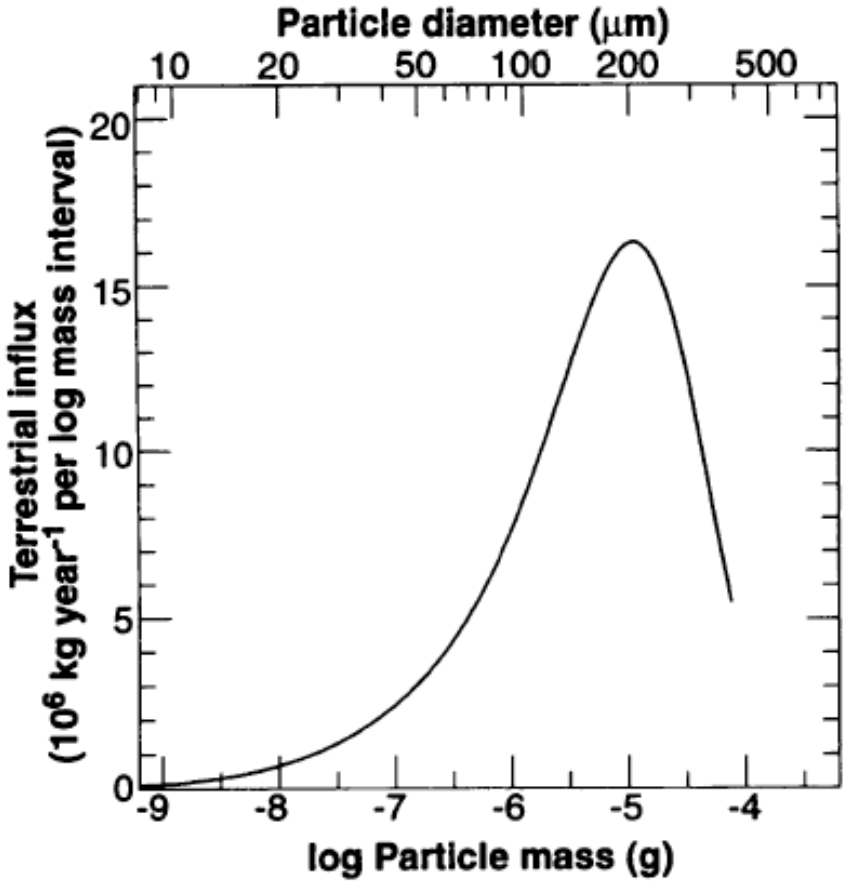
- **Human exploration** of the Moon
  - Need to understand object (ie. astronaut!) charging

- *"Dust - I think probably one of the most aggravating, restricting facts of lunar exploration is dust and its adherence to everything, no matter what kind of material…"* - E. Cernan, Apollo 17

Farrell et al., 2008

Interplanetary Dust Bombardment

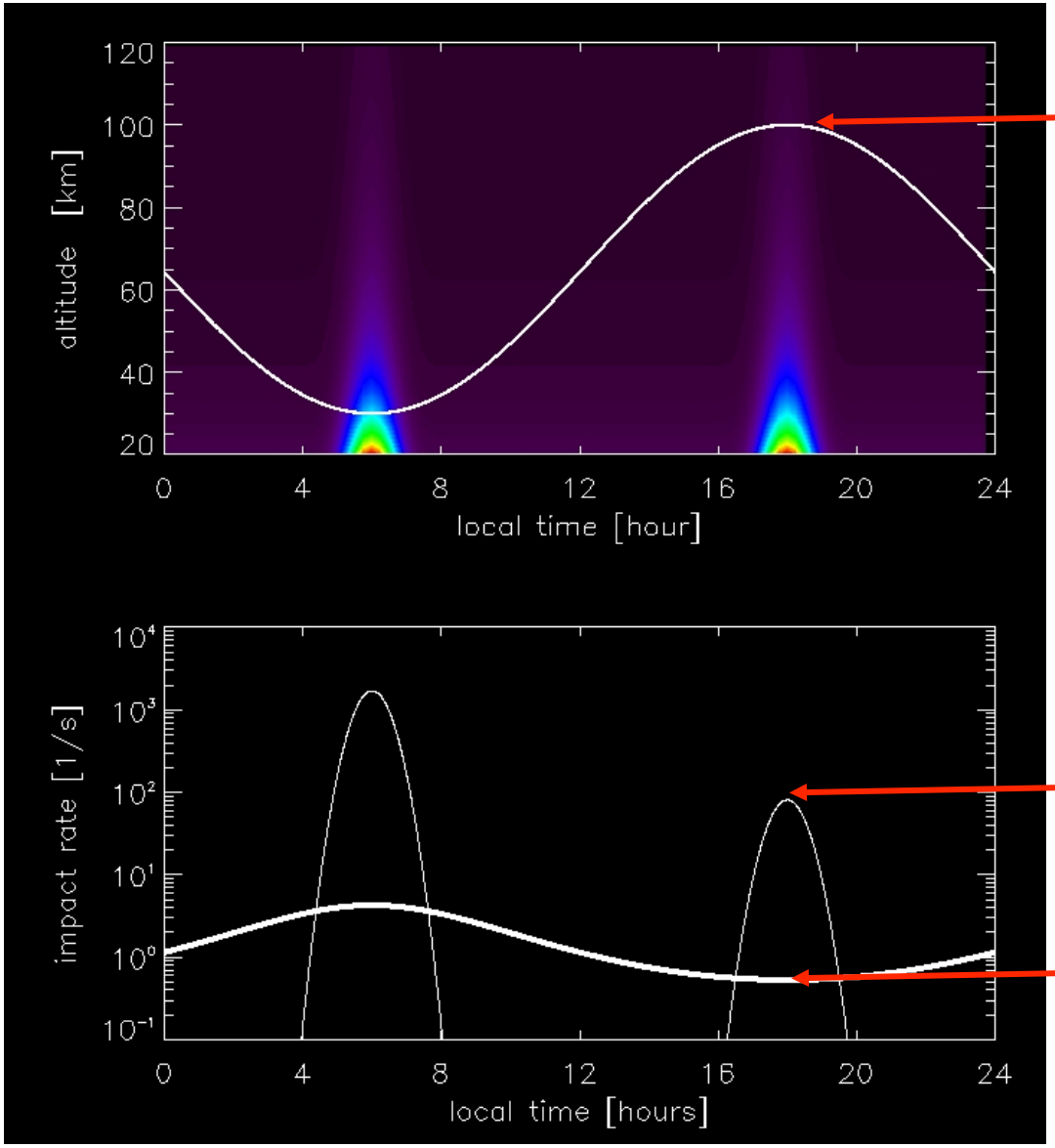




Love and Brownlee, 1993

100 ton/day @ Earth → 5 ton/day @ Moon

Expected Impact Rates



30 x 100 km orbit

Periselene over the morning terminator

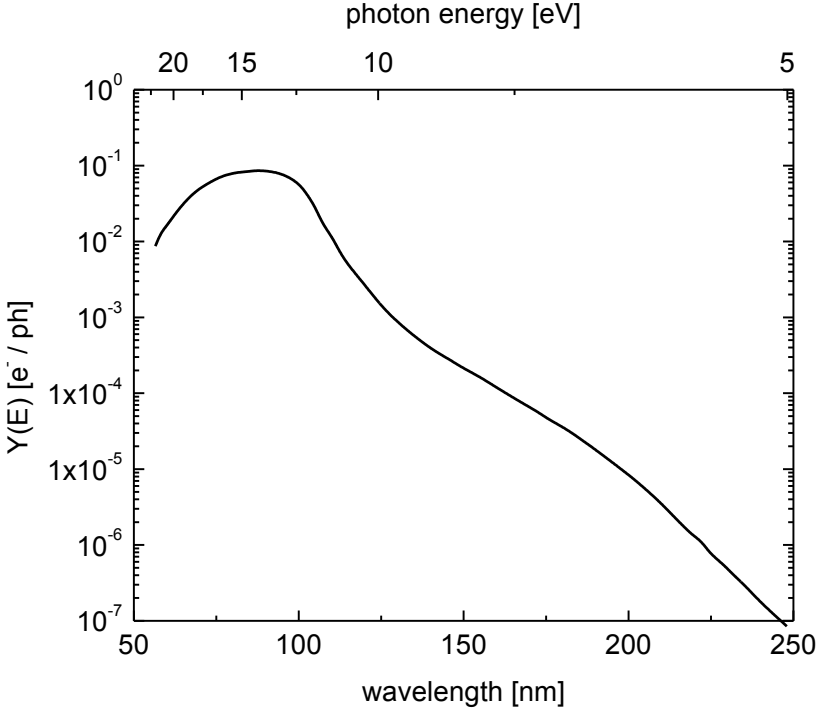
A = 100 cm^2

$\leq$0.3 micron

> 0.3 micron

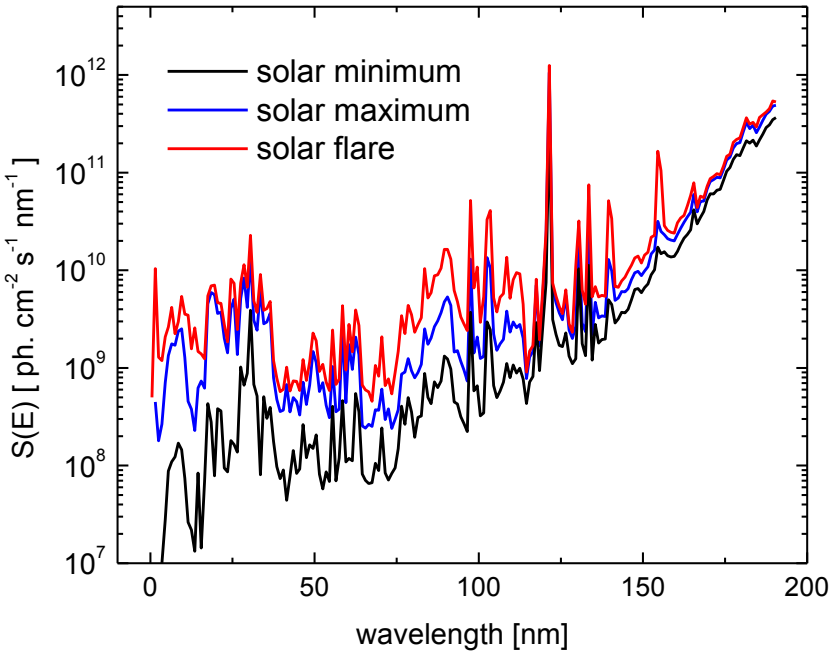
The effect of UV variability

Photoelectron yield



The photoelectric yield measured on the samples returned by the Apollo missions (after Willis et al., 1973).

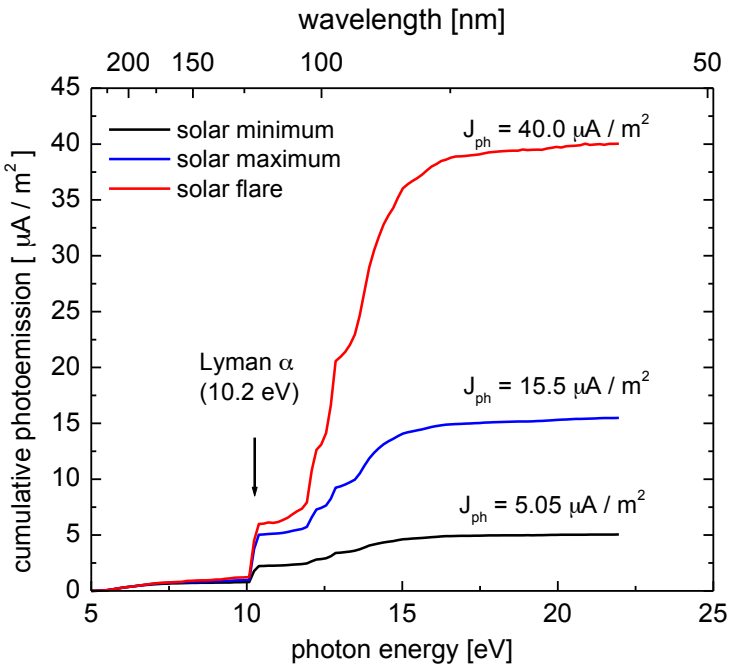
Solar spectrum variability



Variability of the VUV emission spectrum with solar activity measured at 1 AU from the Flare Irradiance Spectral Model (FISM) (Chamberlin *et al.* 2008).

The effect of UV variability 2

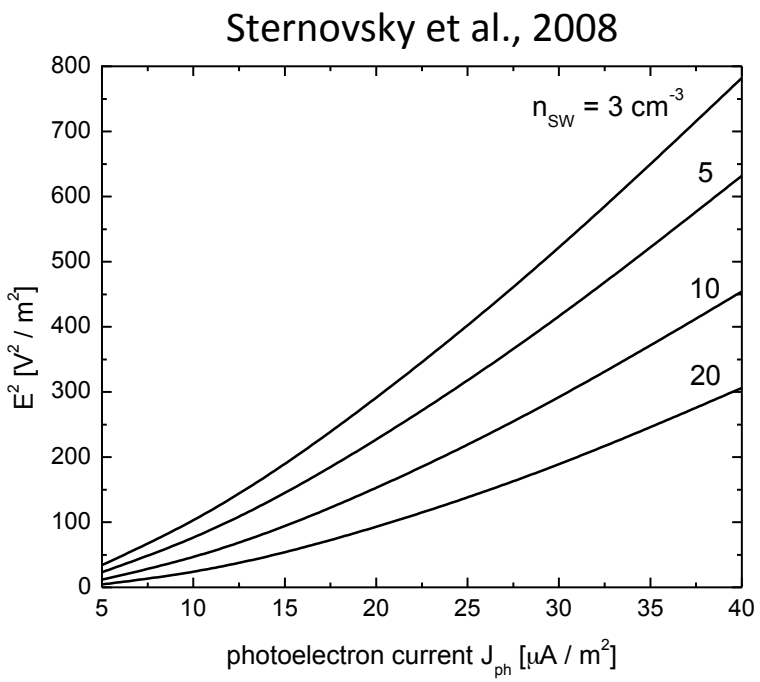
Photoelectron current from the Moon



The cumulative photoelectron current from 5 eV to 22 eV photon energy.

$$J_{ph} = q\int_{W}^{\infty} Y(E)S(\lambda)\frac{d\lambda}{dE}dE$$

E^2 is the proxy for dust mobilization



$$n_e \cong 2J_{ph,0} / \sqrt{T_{ph} / m_e}$$

$$\lambda_D = (\varepsilon_0 T_{ph} / n_e q^2)$$

$$E \cong \phi_L / \lambda_D$$

$$\sigma = E\varepsilon_0$$

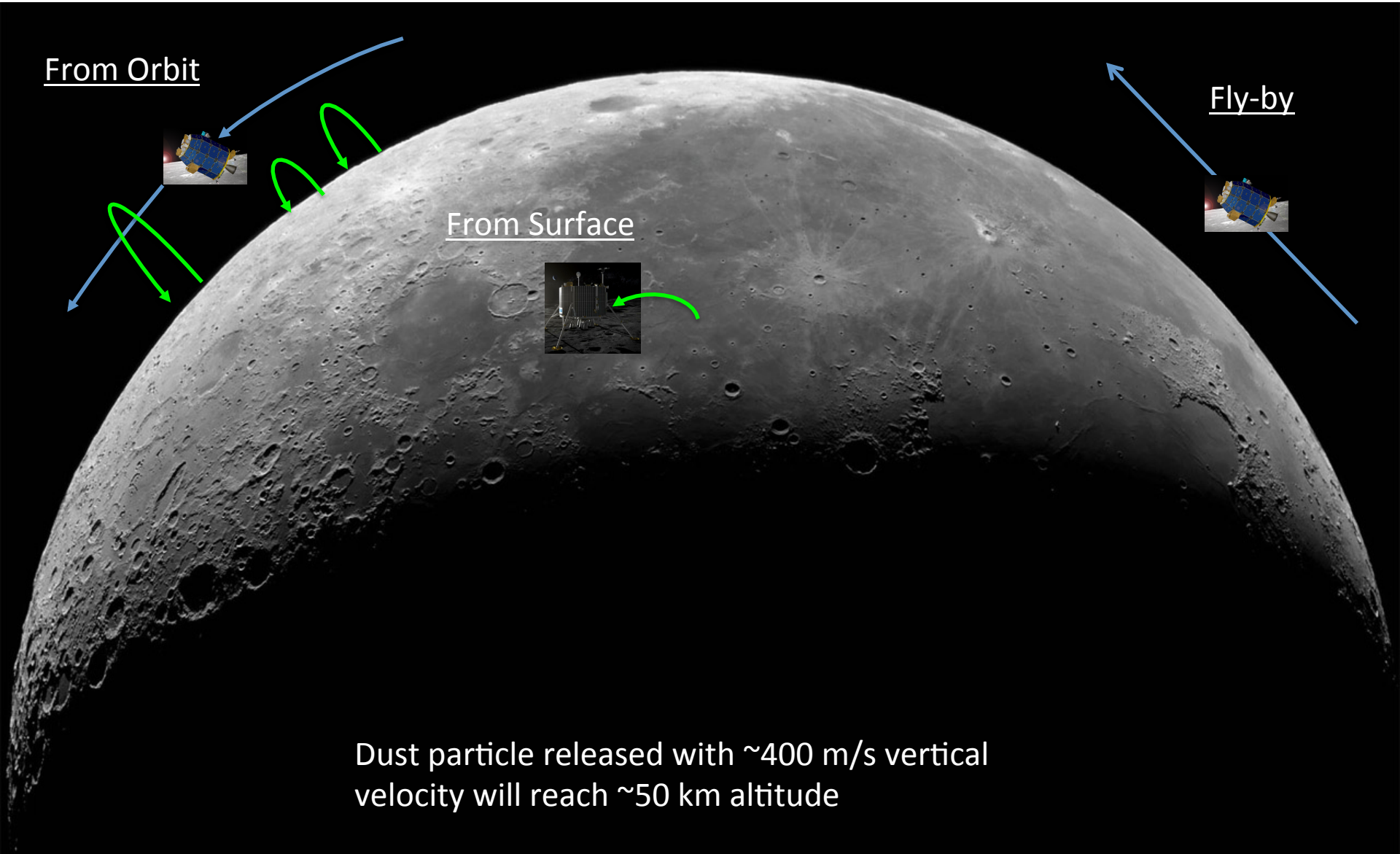
Simple model:
F_D ~ Eσ ~ E^2

Conclusion: dust mobilization should correlate with solar activity (flares)

The big questions

- What mechanisms loft dust particles and what are the characteristics of the dust populations? (density, *m* and *v* distributions, temporal variability, etc.)
  - Ejecta dust
  - Electrostatic dust lofting
- Compositional mapping

Where to detect dust

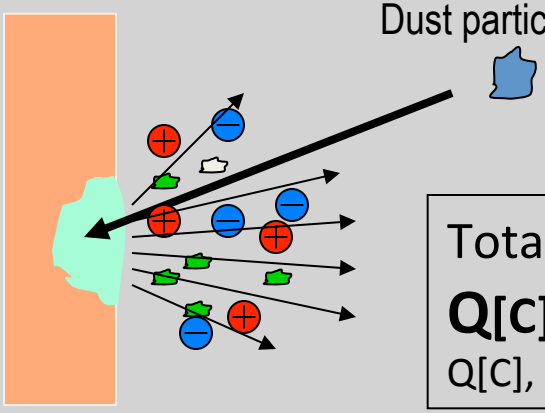


How to detect dust?

- Remote sensing
- Impact/momentum transfer
- Impact ionization (most sensitive for > 1 km/s)
  - Allows chemical composition measurements
- Charge induction (for low velocity)

Impact ionization: high sensitivity

Hypervelocity impact (> 1 km/s)

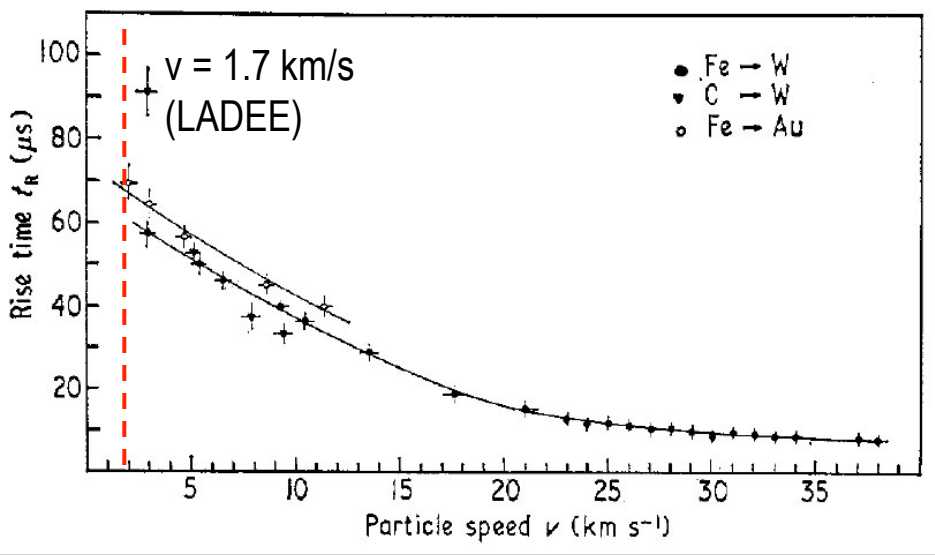


Total impact charge:

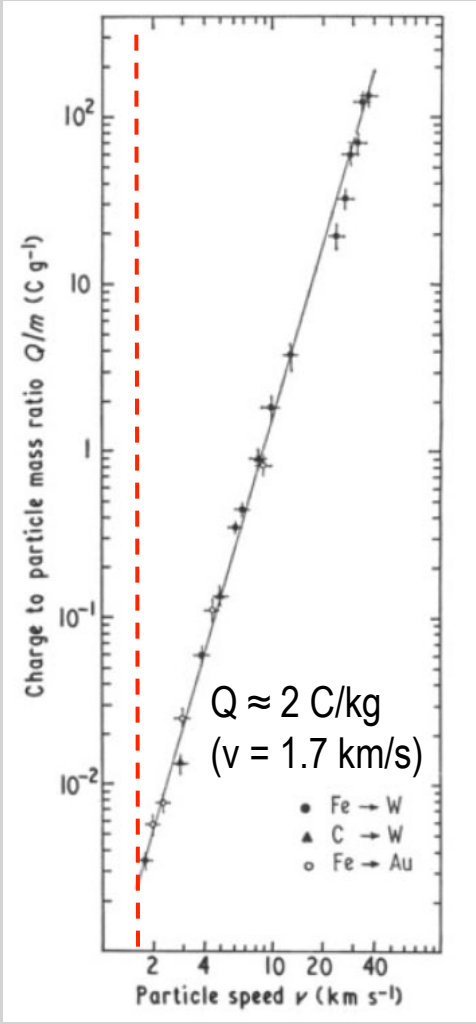
$$Q[C] \approx 0.5\, m v^{3.5}$$

Q[C], m[kg], v[km/s]

Velocity determined from signal rise-time

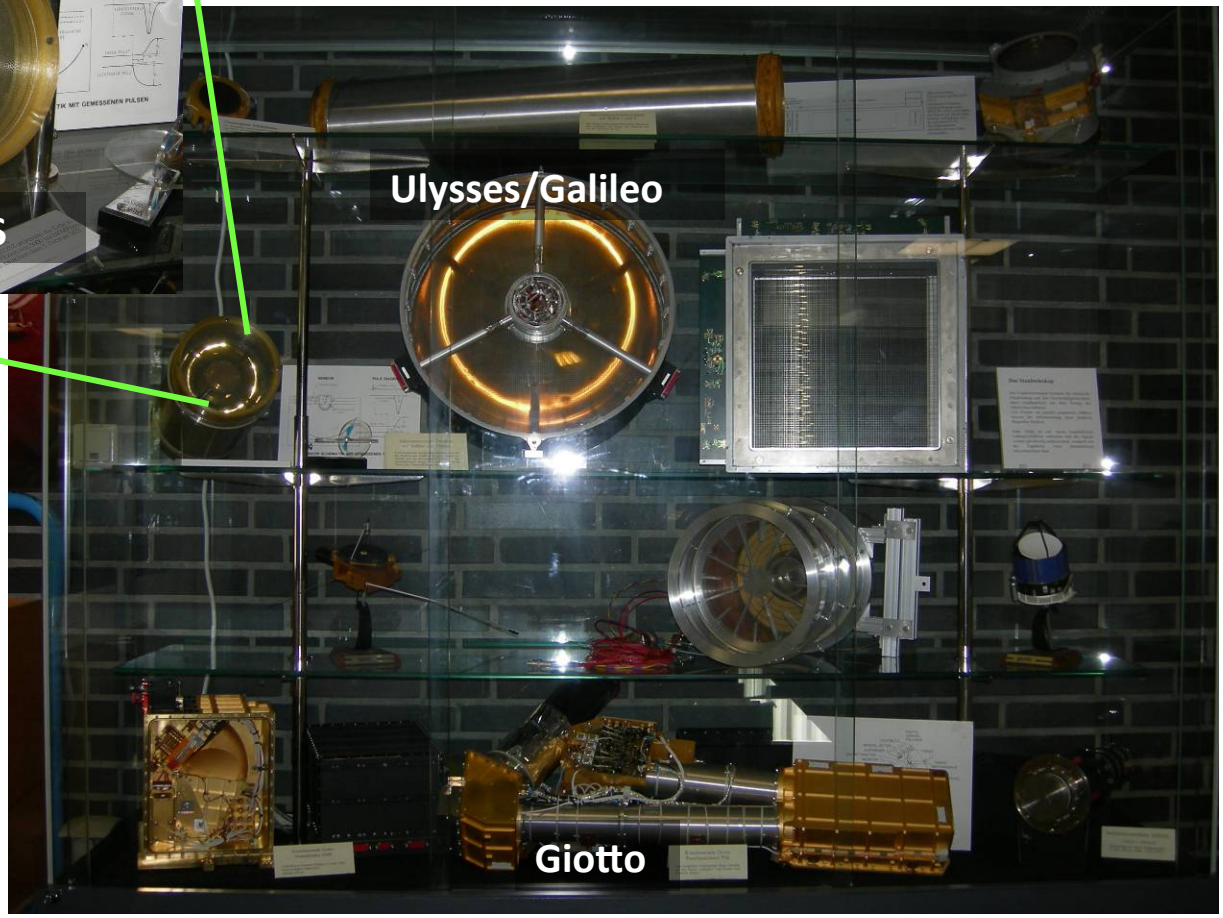


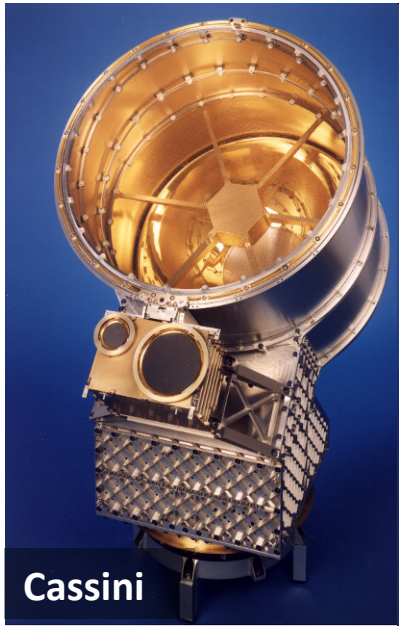
Mass determined from impact charge



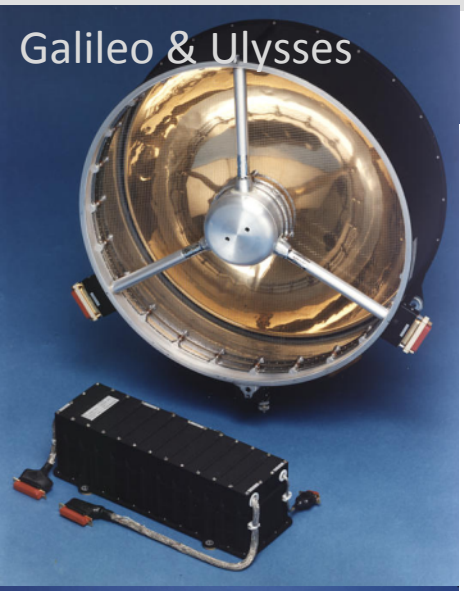
Dietzel et al., J Phys E (1973)

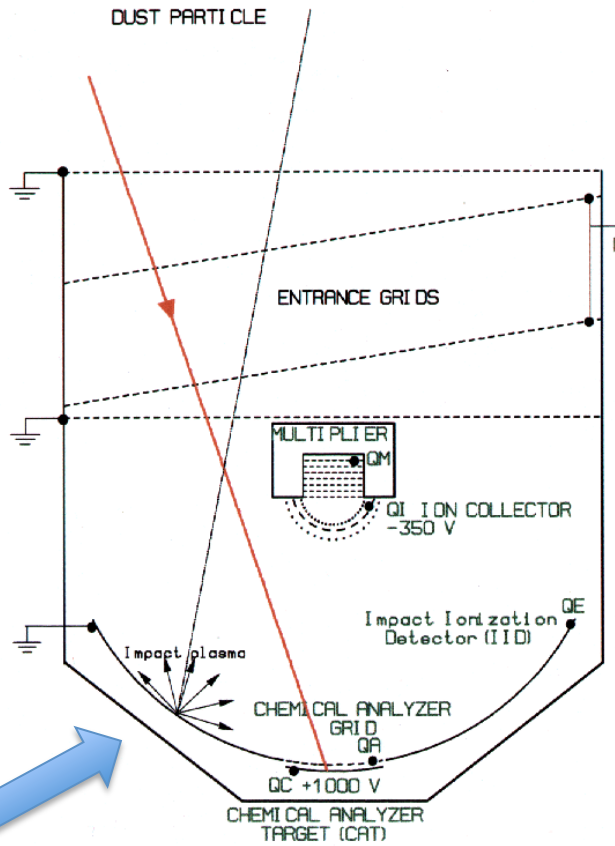
Instrument Heritage

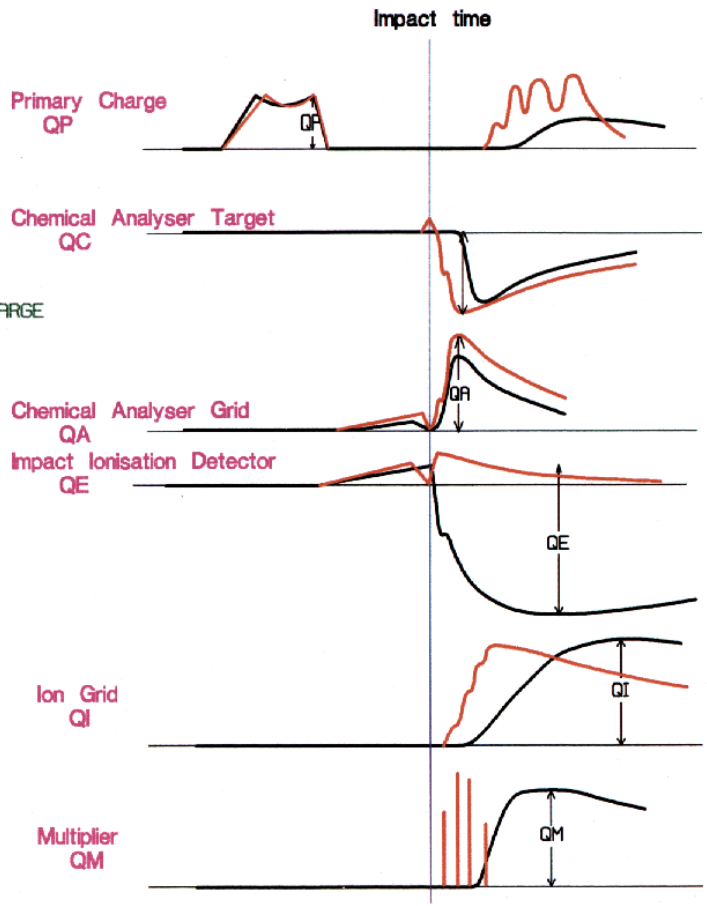




Galileo, Ulysses & Cassini dust instruments







M/dM ~ 20-30

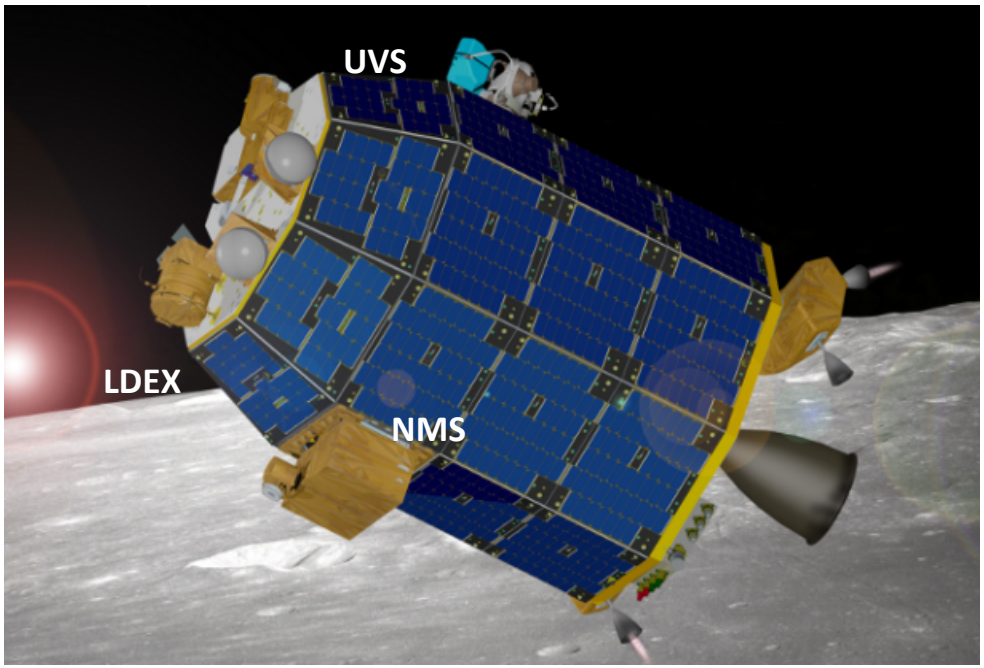
Coincident detection required!!!

LADEE: Upcoming Lunar Mission

Lunar **A**tmosphere and **D**ust **E**nvironment **E**xplorer

Launch: May, 2013

Orbit: ~50x200 km elliptical orbit, 100 days of operation



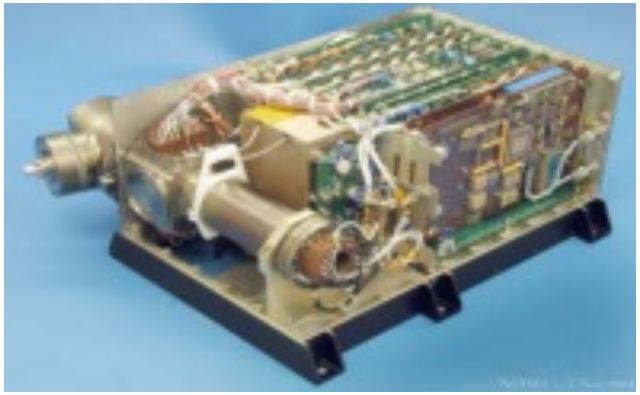
LADEE Payload

Neutral Mass Spectrometer (NMS)

MSL/SAM Heritage

SMD - Directed instrument

In situ measurement of exospheric species



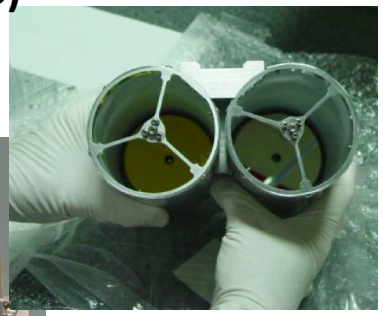
P. Mahaffy
NASA GSFC
(Directed – SMD)

300 Dalton range/unit mass resolution

UV Spectrometer (UVS)

LCROSS heritage

SMD - Directed instrument



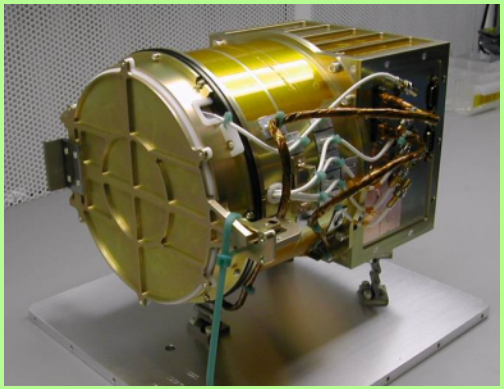
Dust and exosphere measurements

A. Colaprete
NASA ARC
(Directed – SMD)

Lunar Dust EXperiment (LDEX)

Impact ionization dust detector

HEOS 2, Galileo, Ulysses and Cassini Heritage



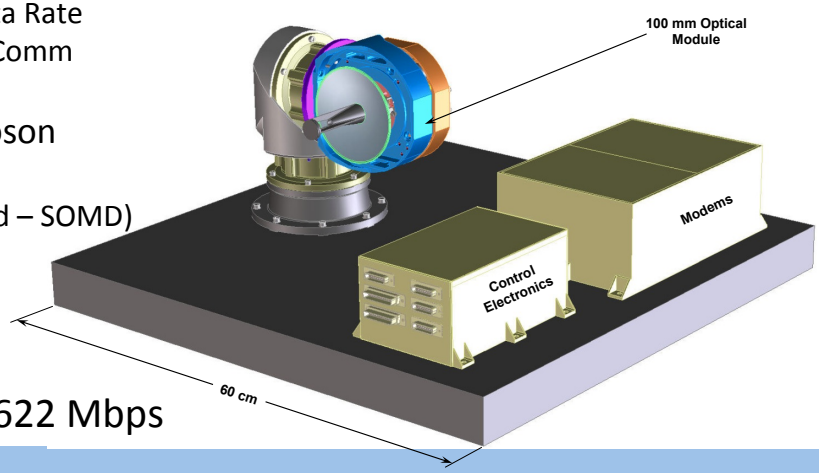
M. Horányi
LASP
(Competed – SMD)

SMD - Competed instrument

Lunar Laser Com Demo (LLCD)

Technology demonstration

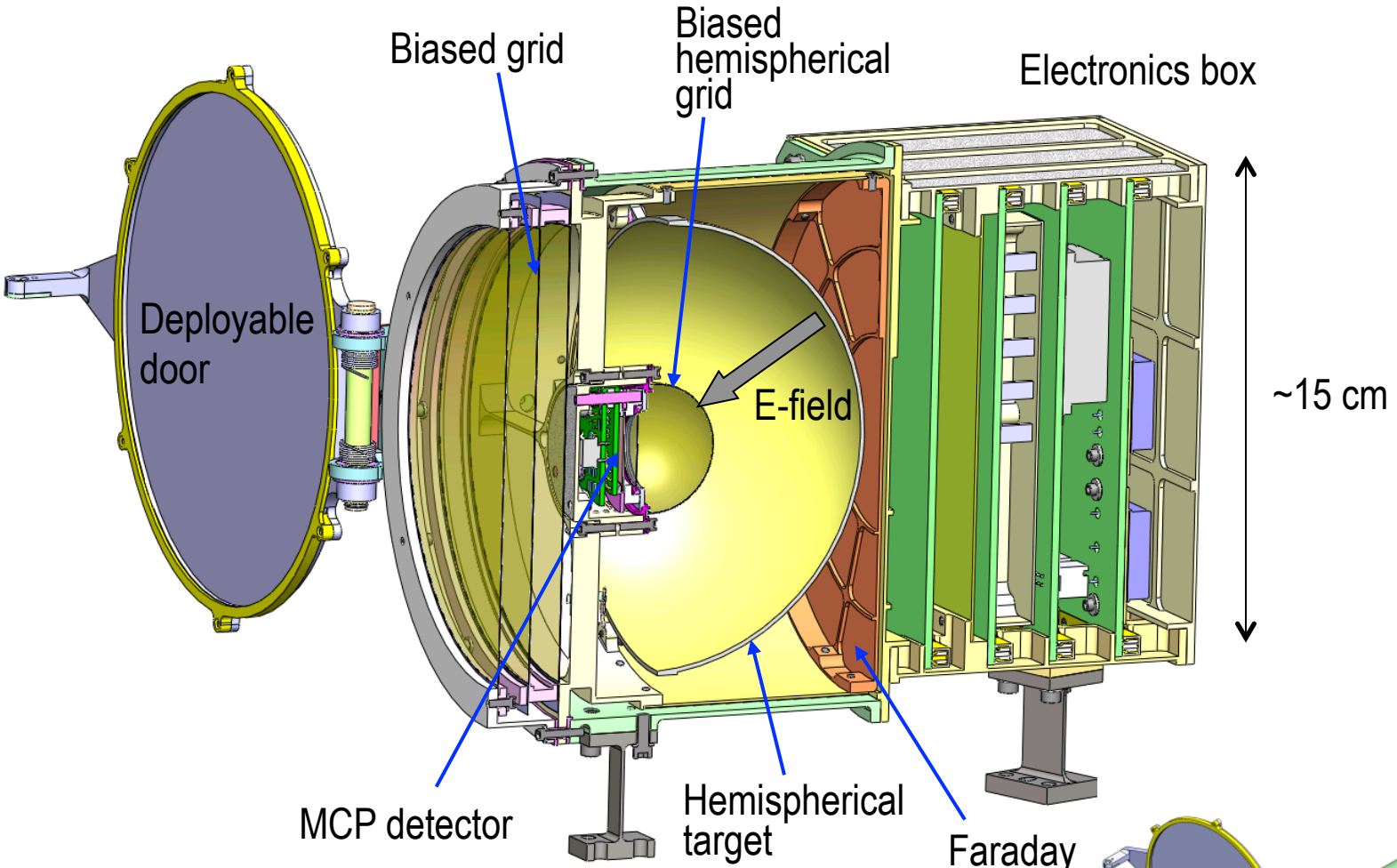
High Data Rate Optical Comm

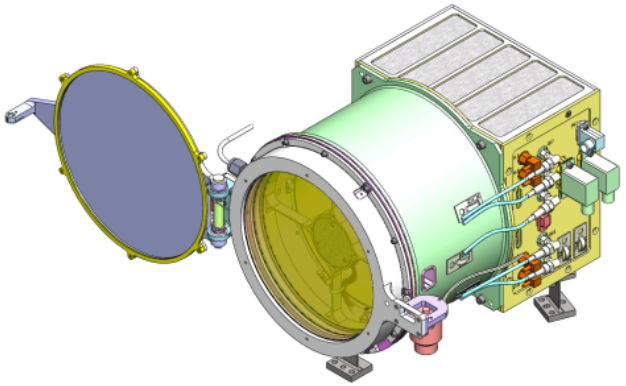


D. Boroson
MIT-LL
(Directed – SOMD)

51-622 Mbps

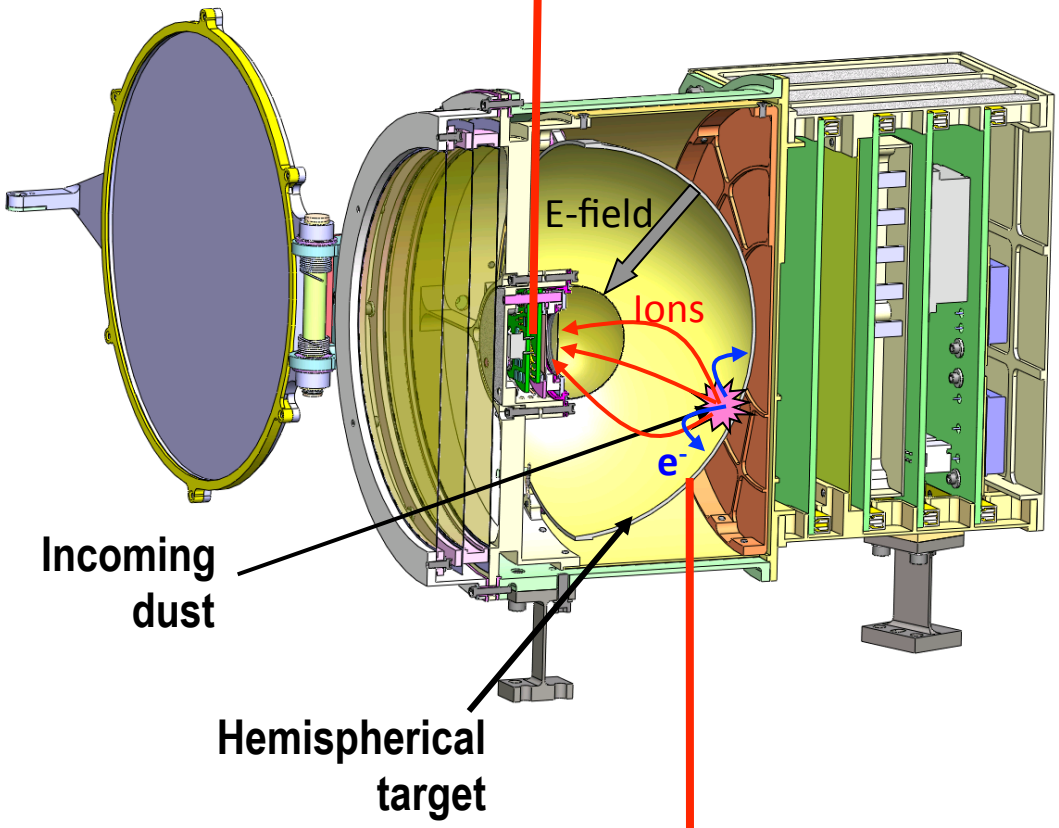
LDEX Instrument



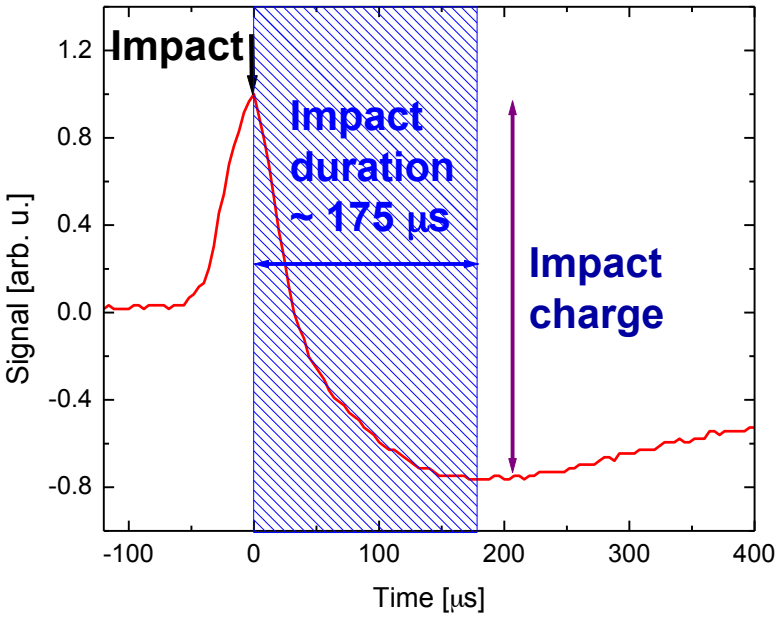


Individual Dust Impact Detection

MCP detector for ions (high sensitivity)



Impact signal from prototype instrument

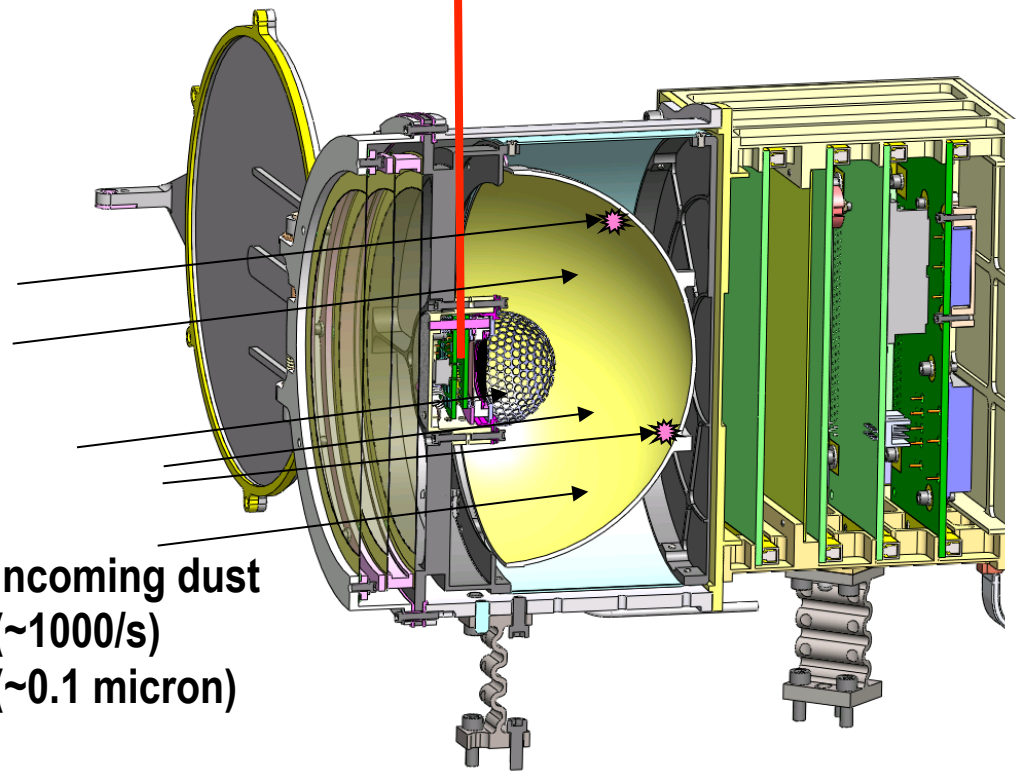


Target collects electrons (low sensitivity)

$Q \approx 0.5\ mv^{3.5}$

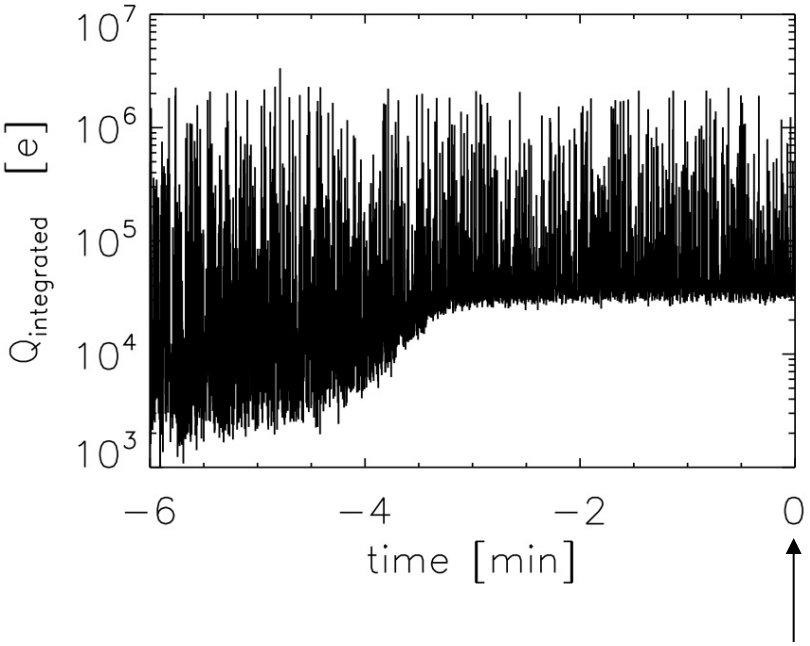
Small Particles – Collective Mass

Integrated (100 ms) charge from small dust particle impacts



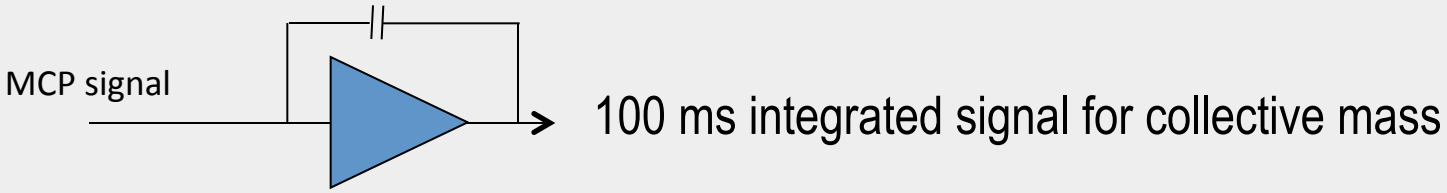
Incoming dust
(~1000/s)
(~0.1 micron)

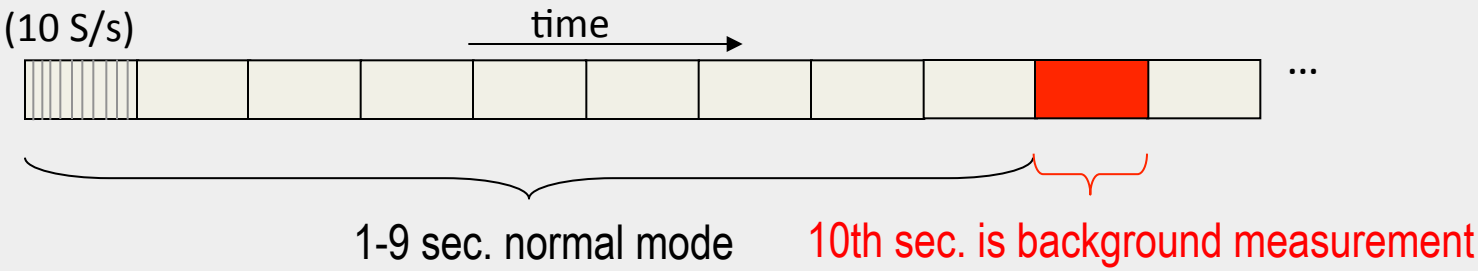
Simulated signal over the terminator region



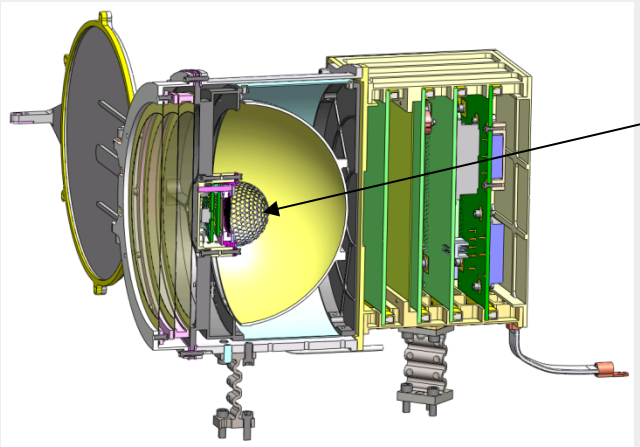
Terminator

Collective mass – background removal





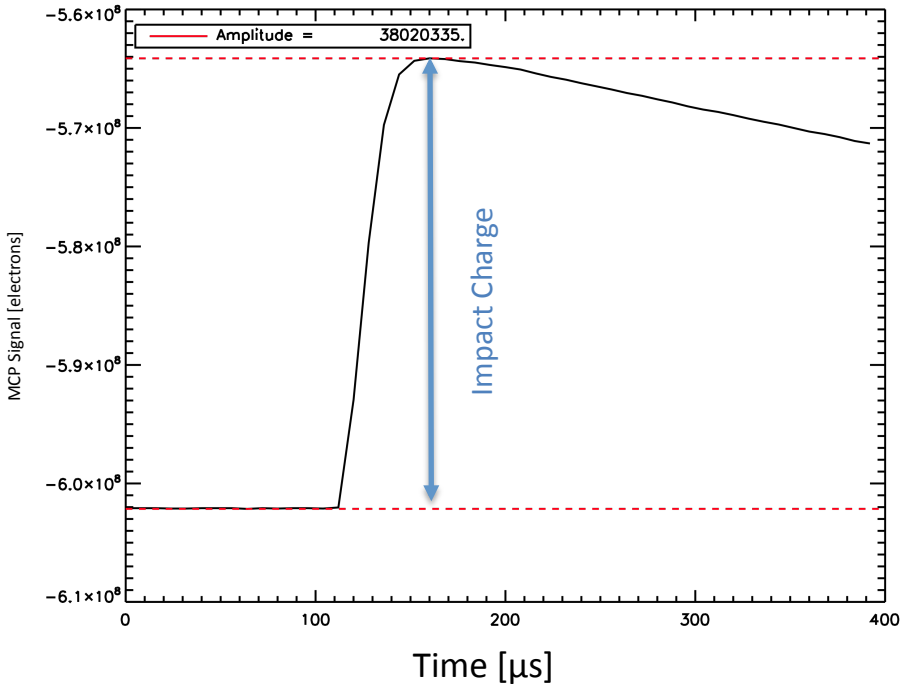
The noise background is measured by reversing the bias on the ion focusing grid and prevent ions from being collected.



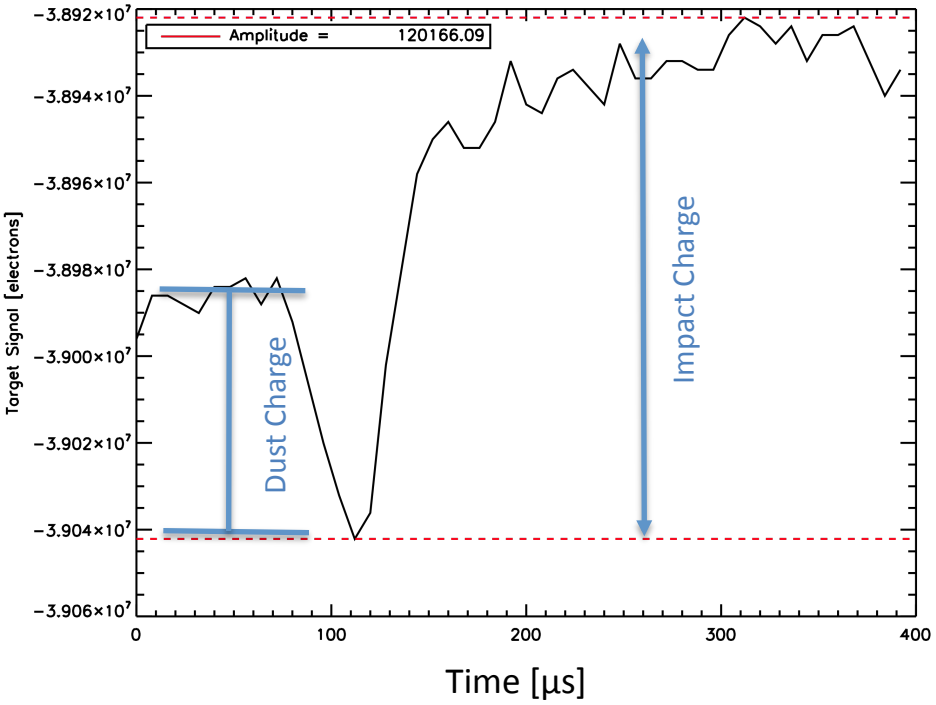
Bias changed from -200 V to +25 V

Dust Impact Signals

MCP Signal

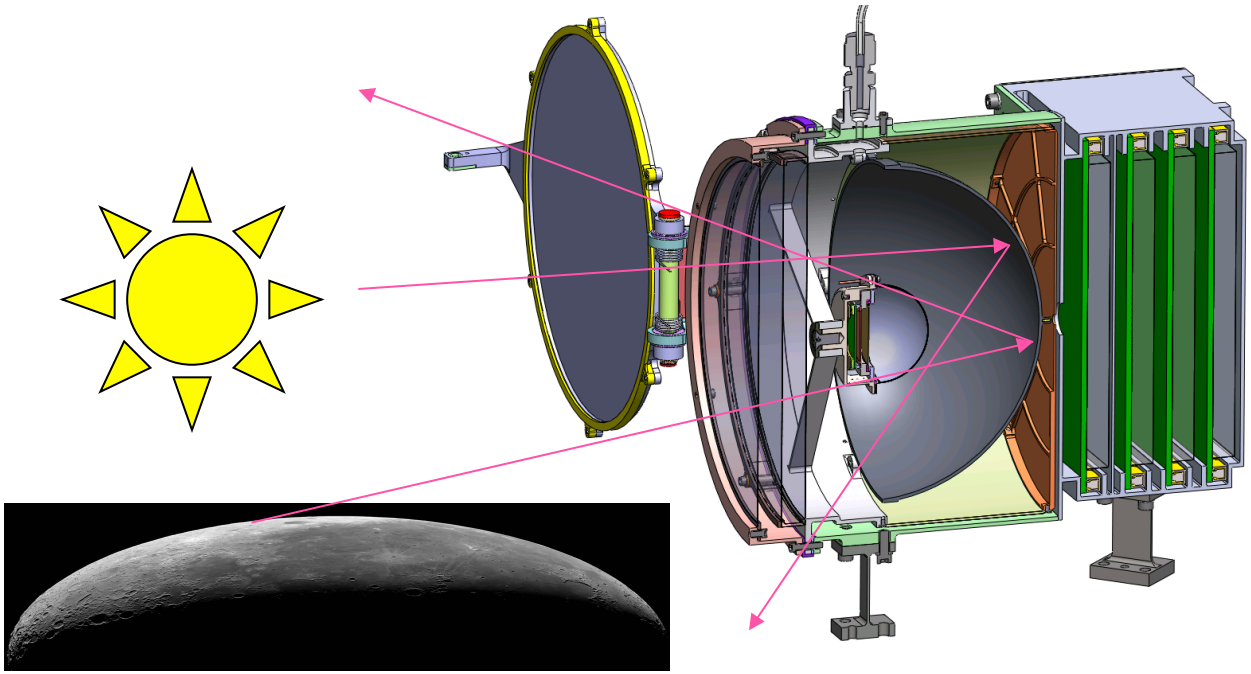


Target Signal



- Waveforms recorded (50 points, 8 μs spacing)
- MCP signal larger in amplitude
- Target signal show dust charge
- **Waveforms analyzed and impacts are validated by the preprogrammed FPGA**
  - **Time constants, duration, area-to-peak ratio, ….**
- The samples shown are for a 1.06 μm radius particle at 1.89 km/s velocity

Detection threshold is set by UV noise

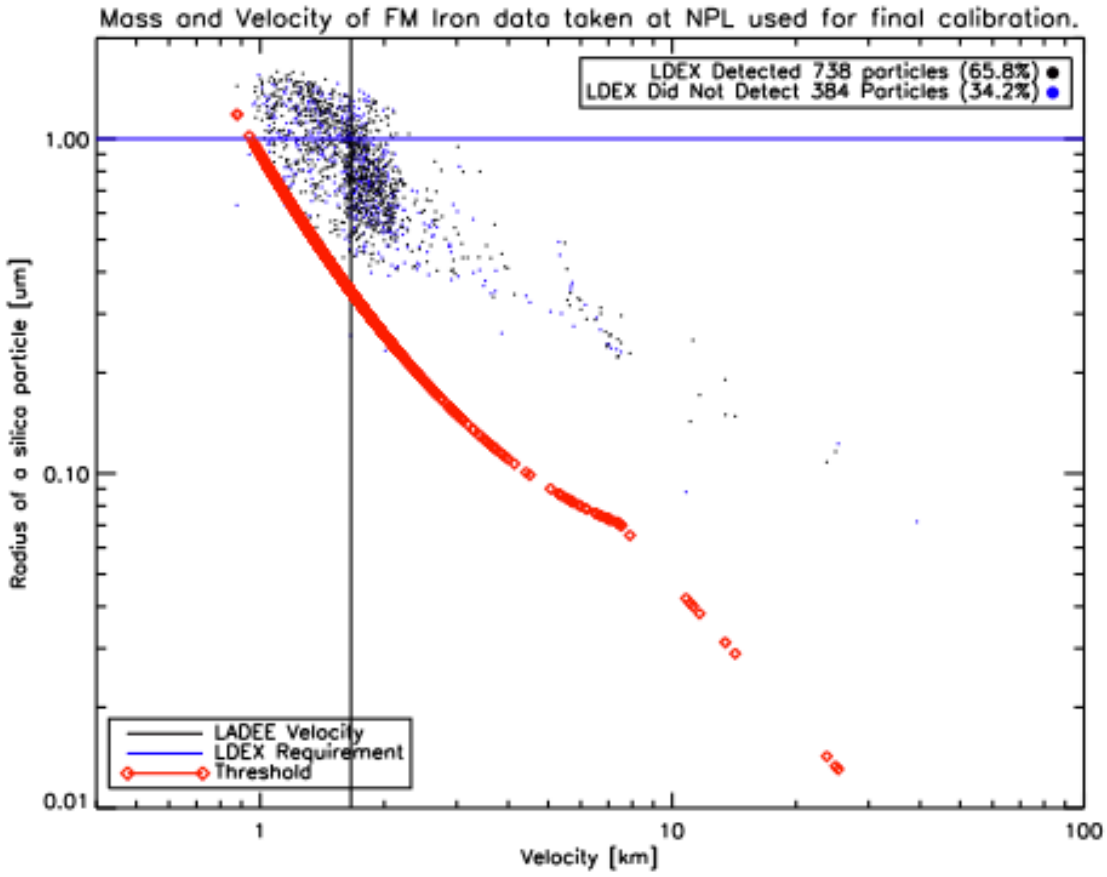


Target:
- Rh coating
- highly polished

- LDEX is designed to reject UV light (specular reflection)
- Only scattered light can reach the MCP detector
- Direct Sun exposure degrades the MCP on the timescale of 2 months
- Estimated noise from lunar backscatter is < 10^6 detected photons / s
    - limits individual particle detection (>0.16 microns)

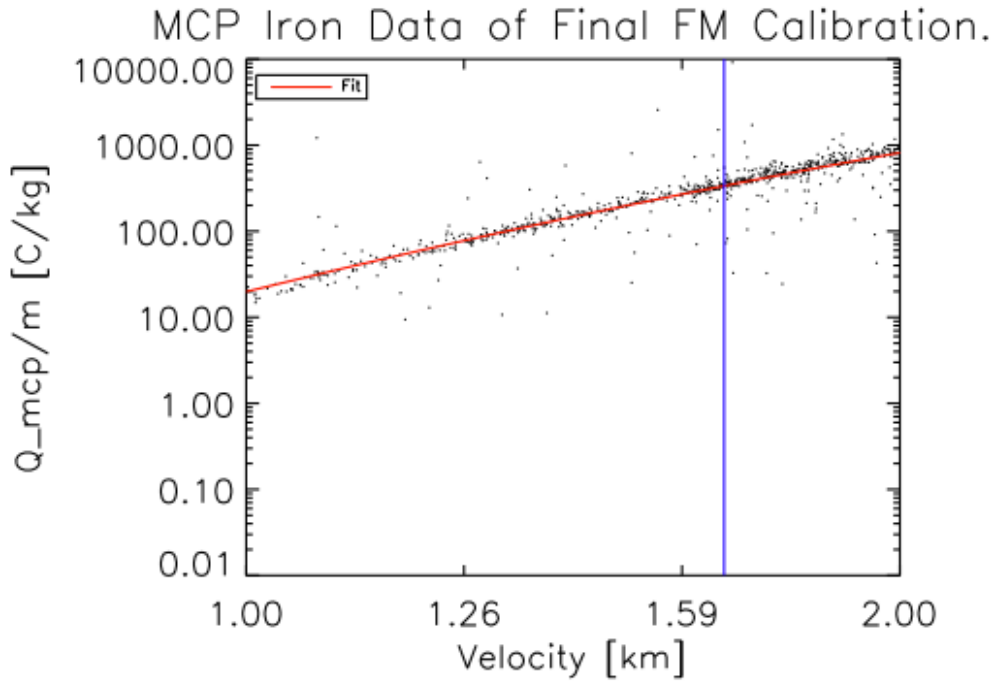
Calibration

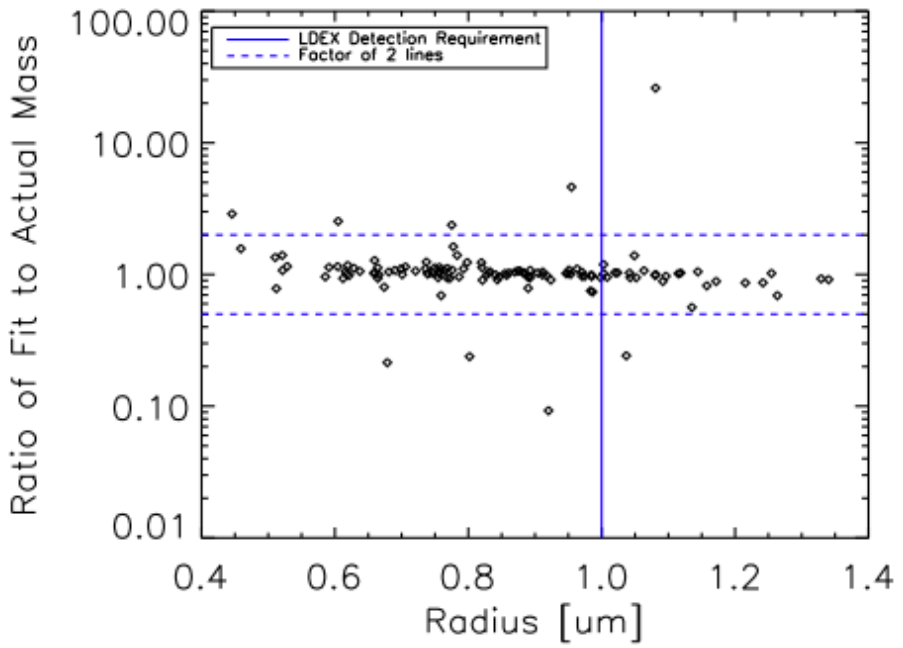
The distribution of Fe particles used for calibration



- Performed at the CCLDAS facility
- Velocity range 0.9–40 km/s
- Size range Equivalent to 0.2 – 1.6 μm for Silica
- Total number of particles shown 1122
- **Black**: particles detected by LDEX
- **Blue**: not detected by LDEX
- Red Line is nominal testing Threshold at 50 DN = 2E-13 C
- **66%** are detected by LDEX
- Dust flux is reduced by the 3 grids over the aperture (90% open area) and the 90% duty cycle of LDEX
- $(0.9)^4$ = **0.66**

MCP Calibration (Q/m vs. velocity)



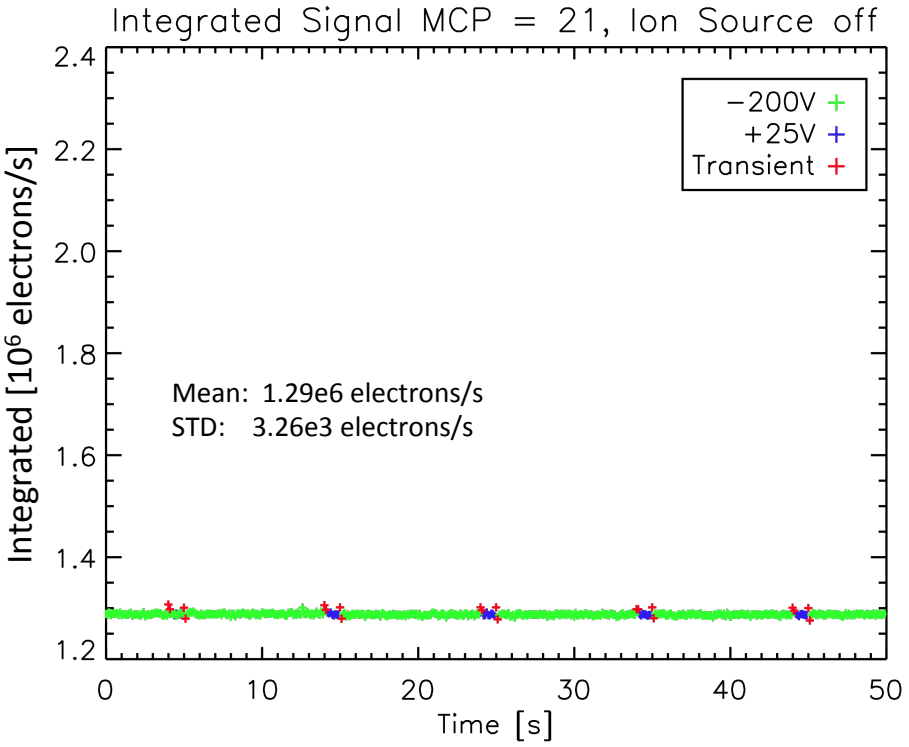


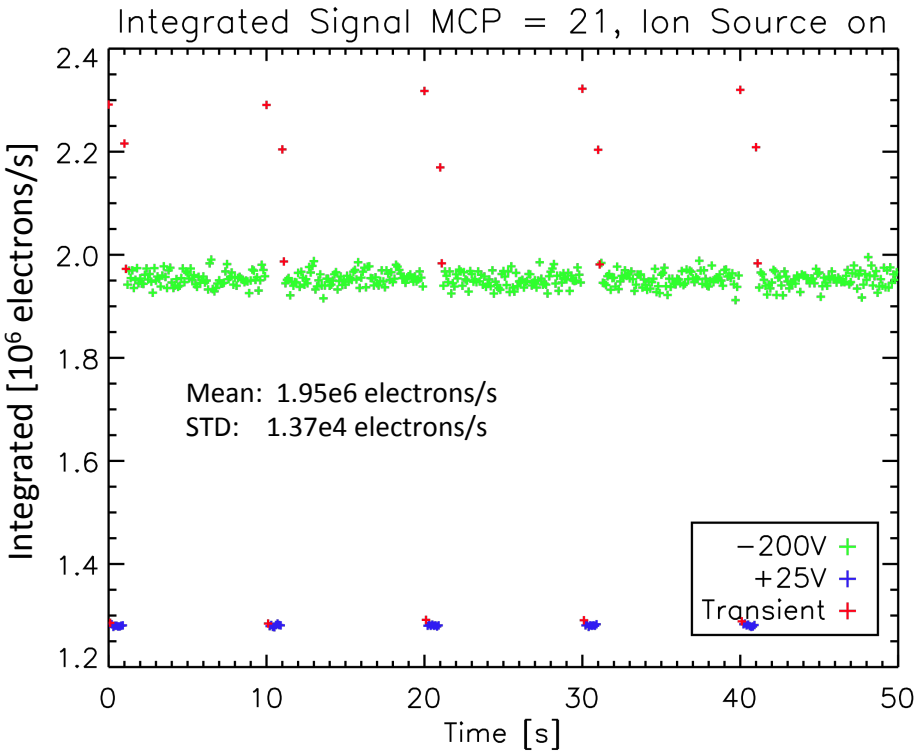
At 1.66 km/s the MCP equation is:

(Nominal 850 V biad potential on MCP)

$m = 3.0 \times 10^{-3} * Q_{mcp}$

Integrator Signal

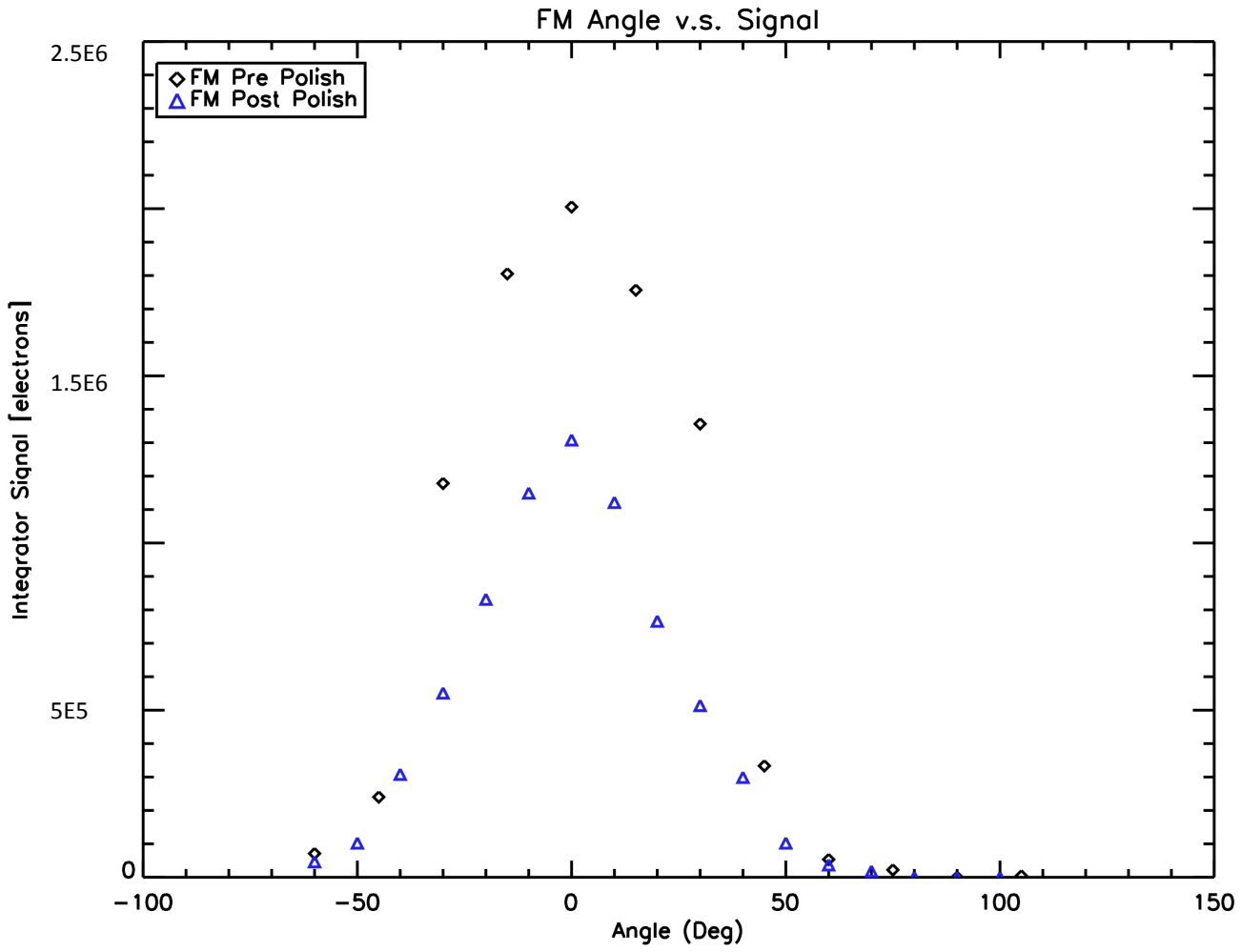




Integrator signal with nominal LDEX settings (100ms integration period) and ion source off/on. Blue and red periods are switching of the ion focusing grid.

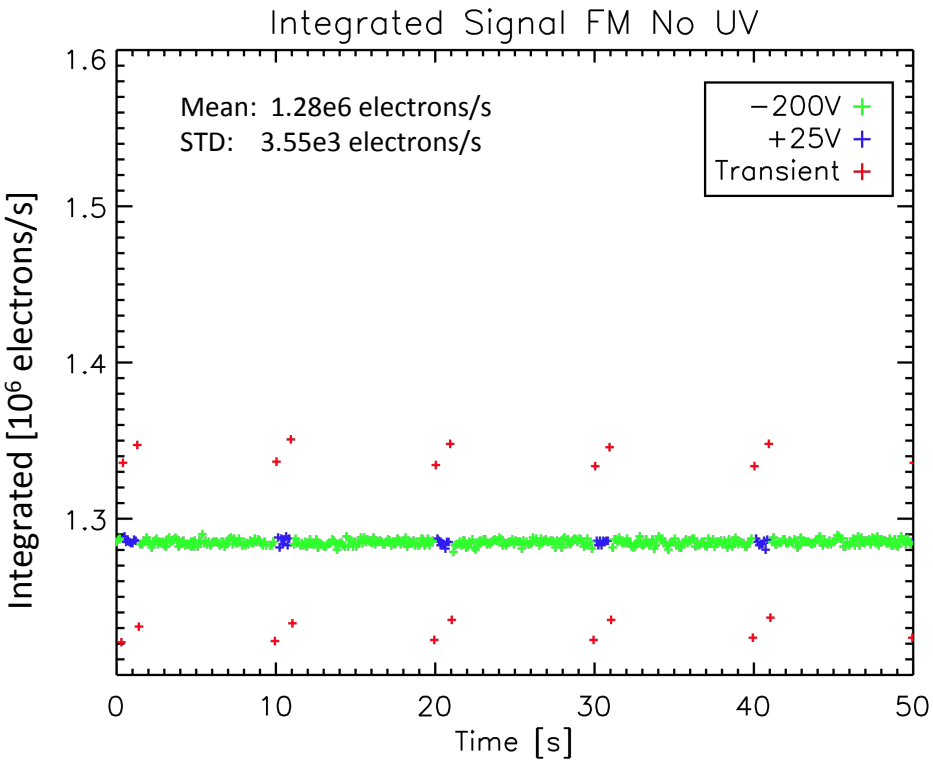
Note: The rejection of the ion signal is efficient.

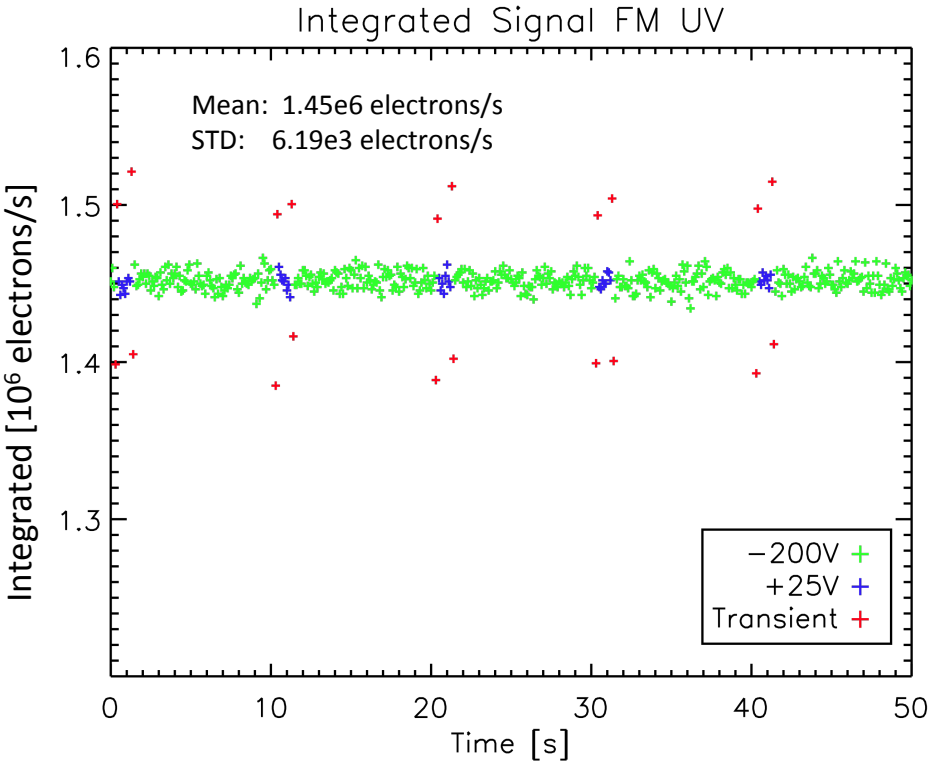
Moon UV Angle



Polishing and re-plating the target improved our UV rejection input by a factor of ~1.5.

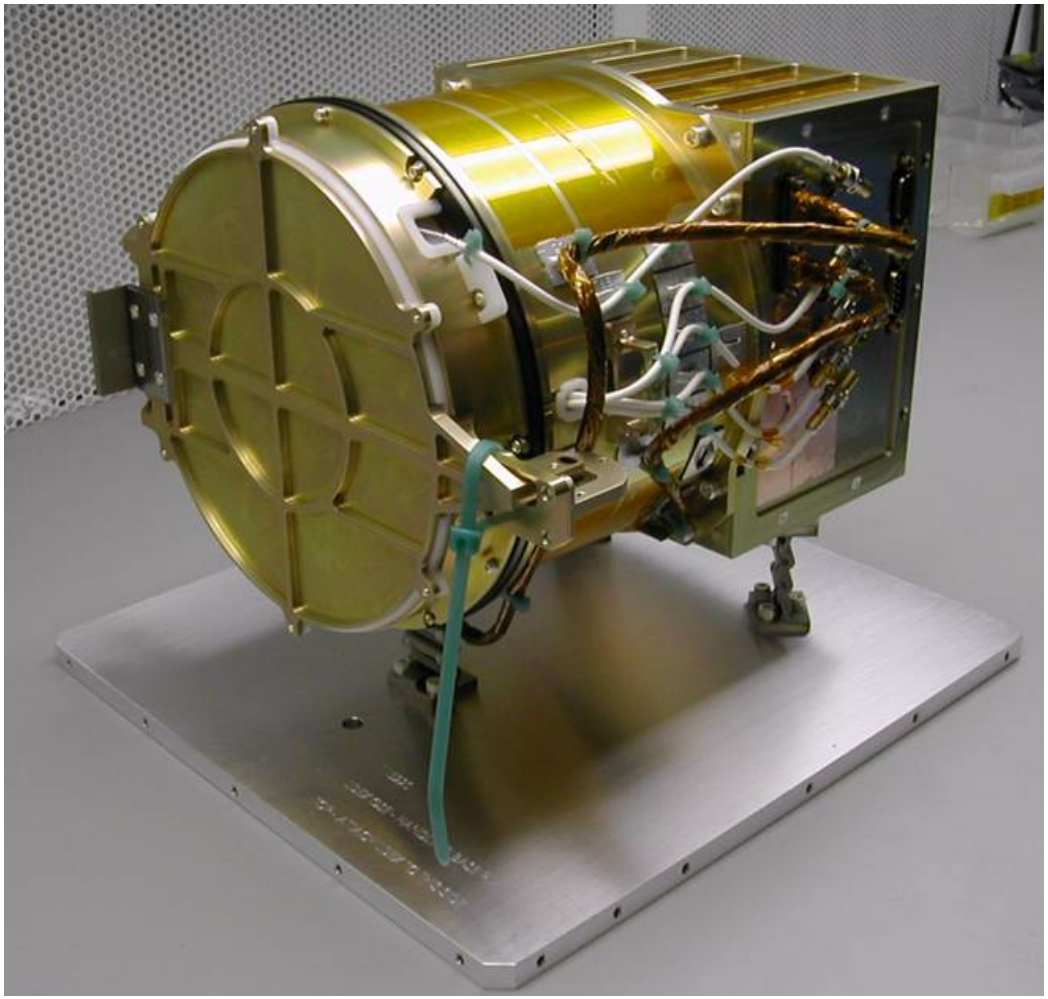
In Simulated UV environment





- Requirement: Detect 10^5 e^-/s integrated charge signal
- UV generated noise STD: 6200 e^-/s
- **Expected SNR meets the science requirements by about a factor of 2.**

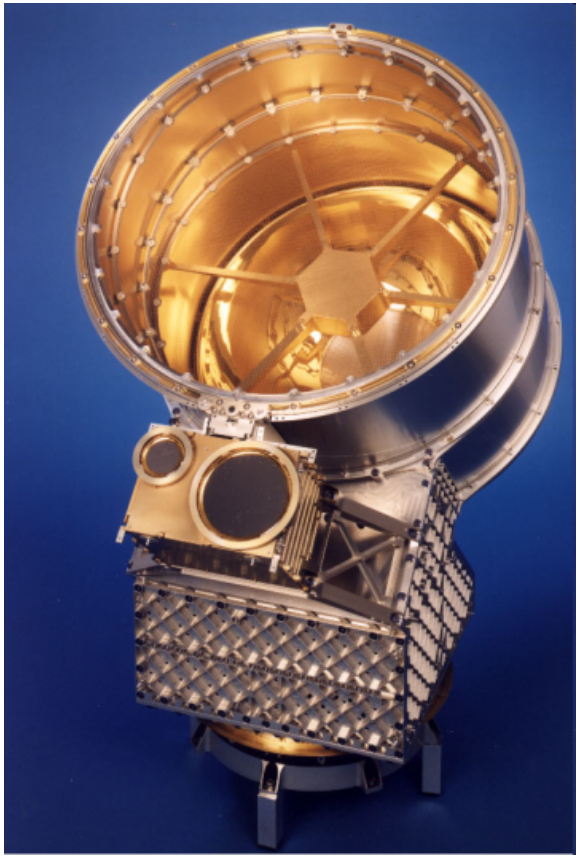
LDEX instrument



- LDEX is designed to minimize UV noise
- Individual impact detection range 0.3 – 5 micron
- Integrated signal to measure 0.1 micron particles
- Calibrated at the Heidelberg dust accelerator facility

Chemical analysis

Cosmic dust analyzer on Cassini

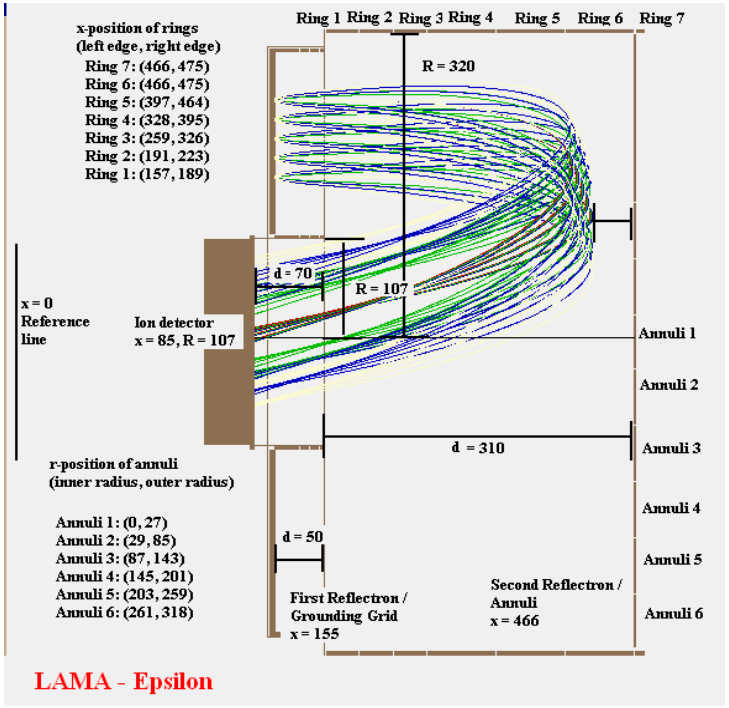


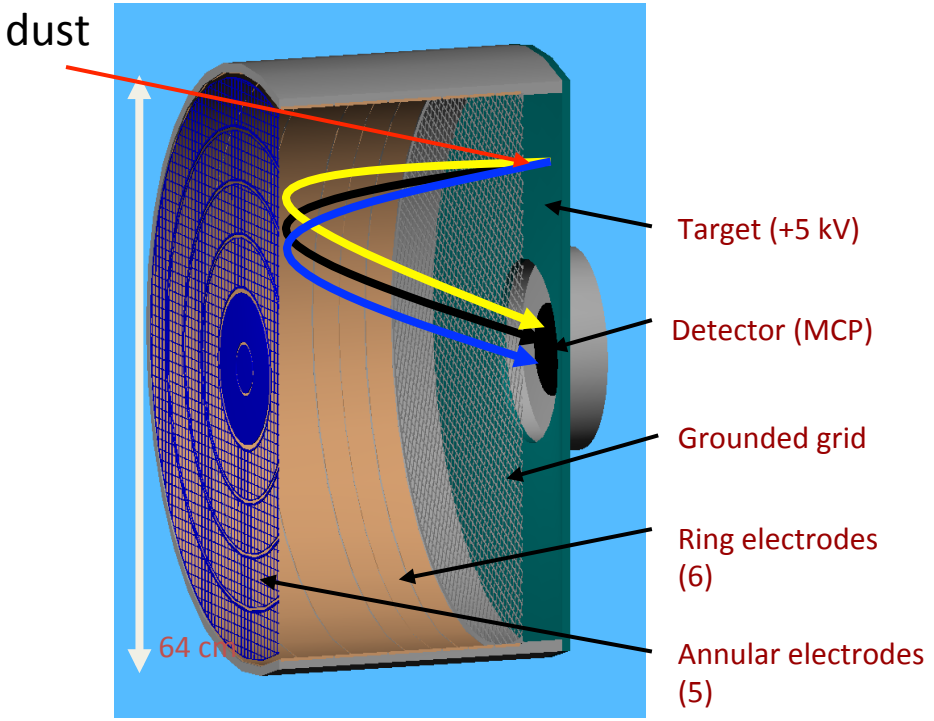
CA target: 160 cm^2
M/dM ~ 20-30

Cometary and Interstellar Dust Analyzer on Stardust

CA target: ~75 cm^2
M/dM > 100

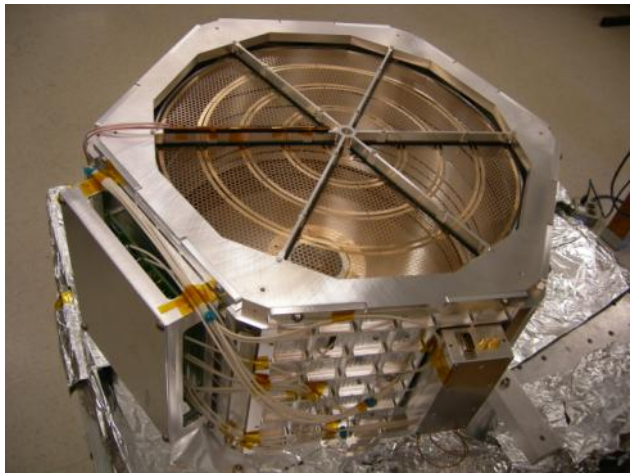
The Large Area Mass Analyzer

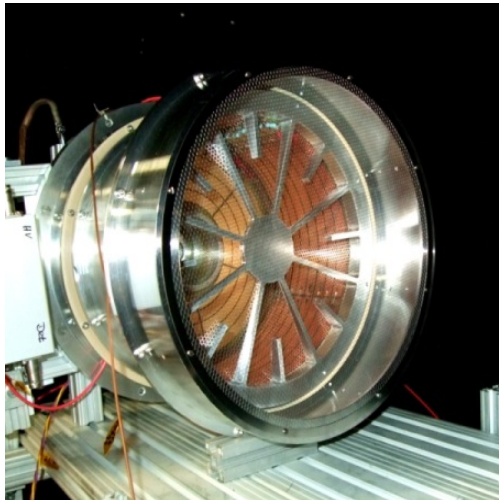


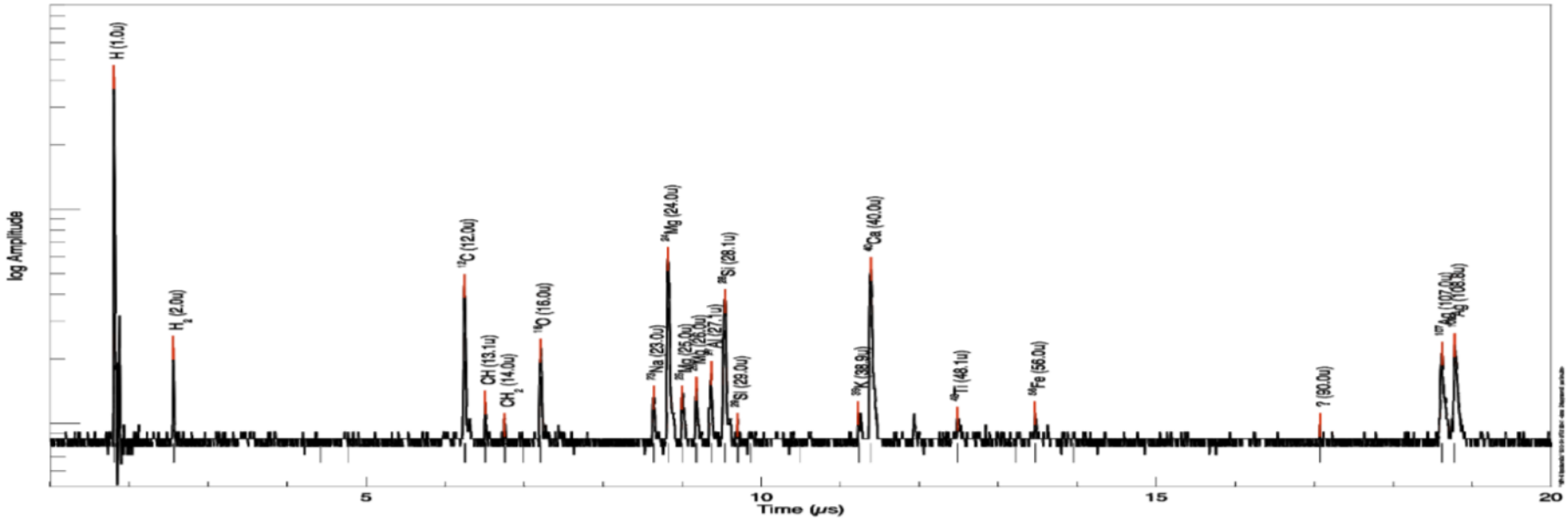


- one-stage reflectron
- flat annular grids
- *m / dm* = 200
- target area ~ 200 - 2000 cm^2

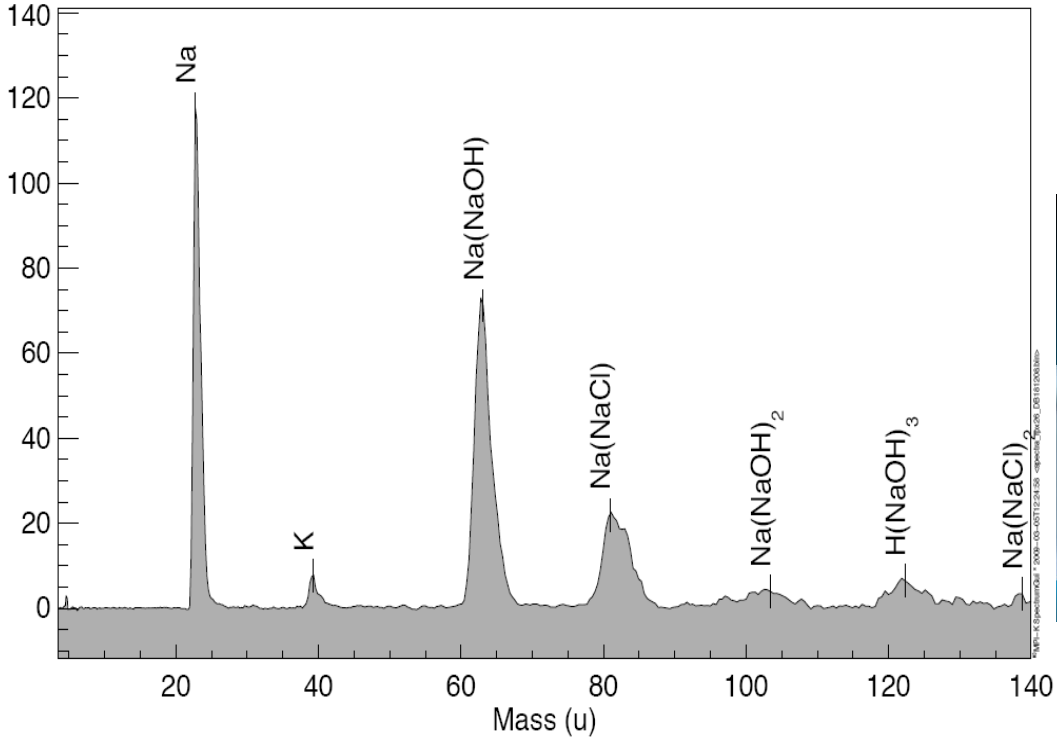
Chemical Analyzer

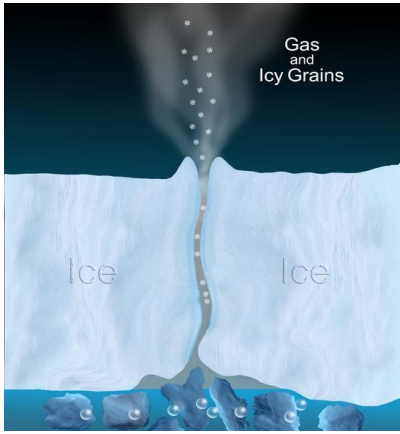






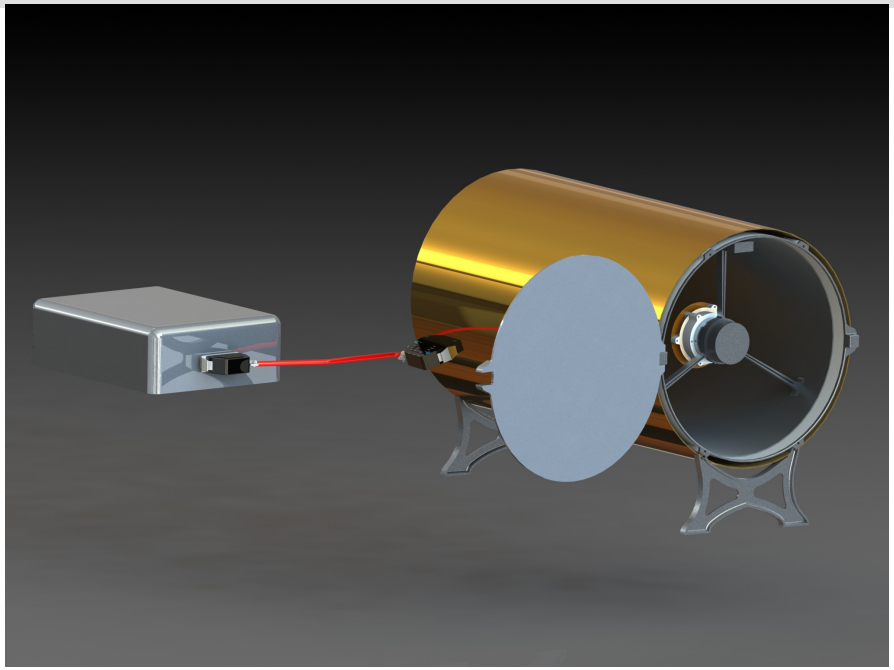
Analysis of the Plumes of Enceladus

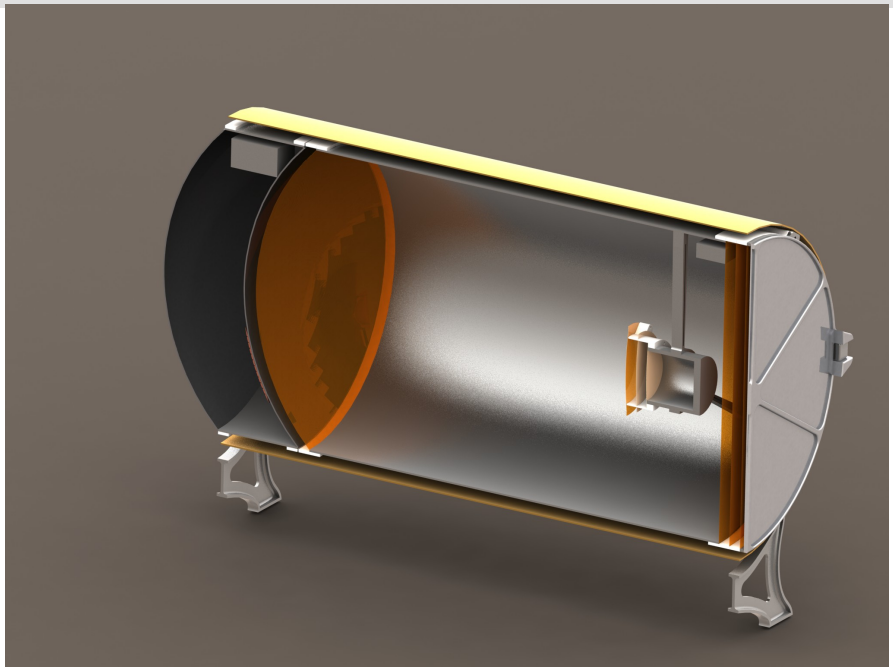




- Pronounced signatures of sodium and potassium salts in a water matrix
- NaCl and NaHCO3 are identified.
- Important implications for subsurface water reservoir (Postberg et al., Nature 2009)

Nanodust analyzer





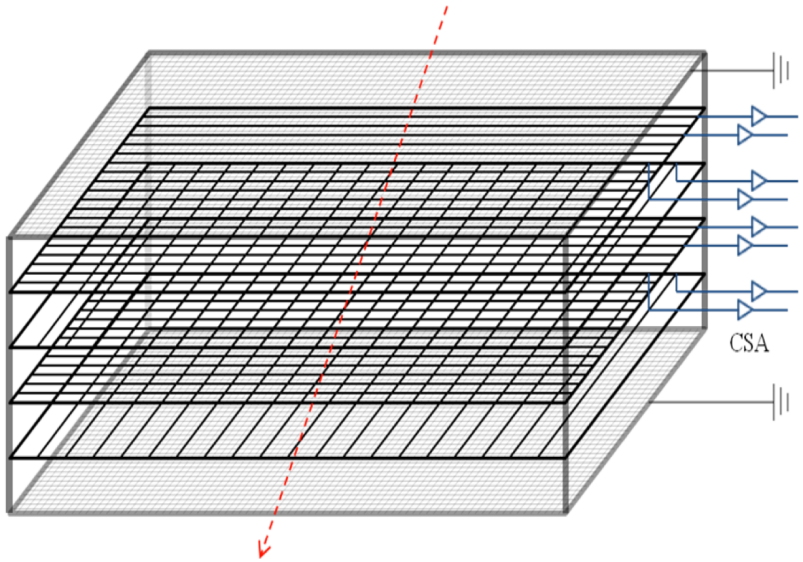
- Linear TOF - derived from CDA
- 20 cm dia impact target, 30 cm ion flight path (higher resolution)
- Developed nano-dust grains (~10 nm size, ~400 km/s velocity)
- Discovery claimed by the STEREO wave instruments
- Operation with the Sun in the FOV

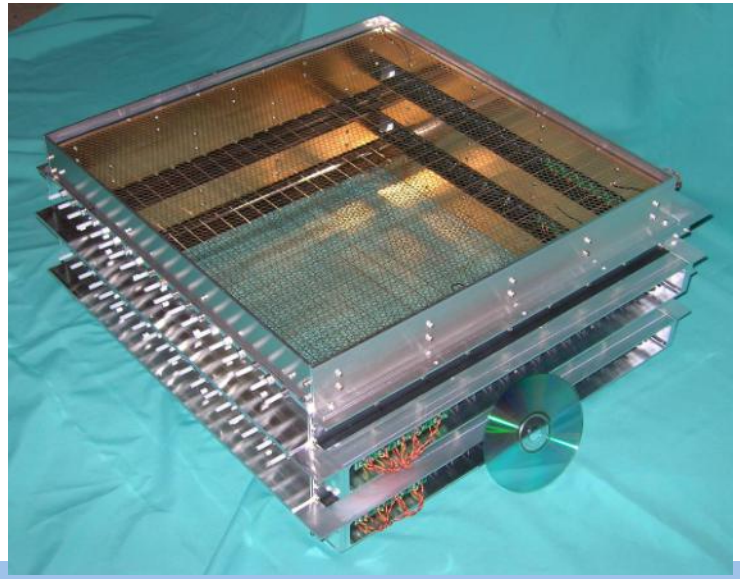
Detection of Slow Dust

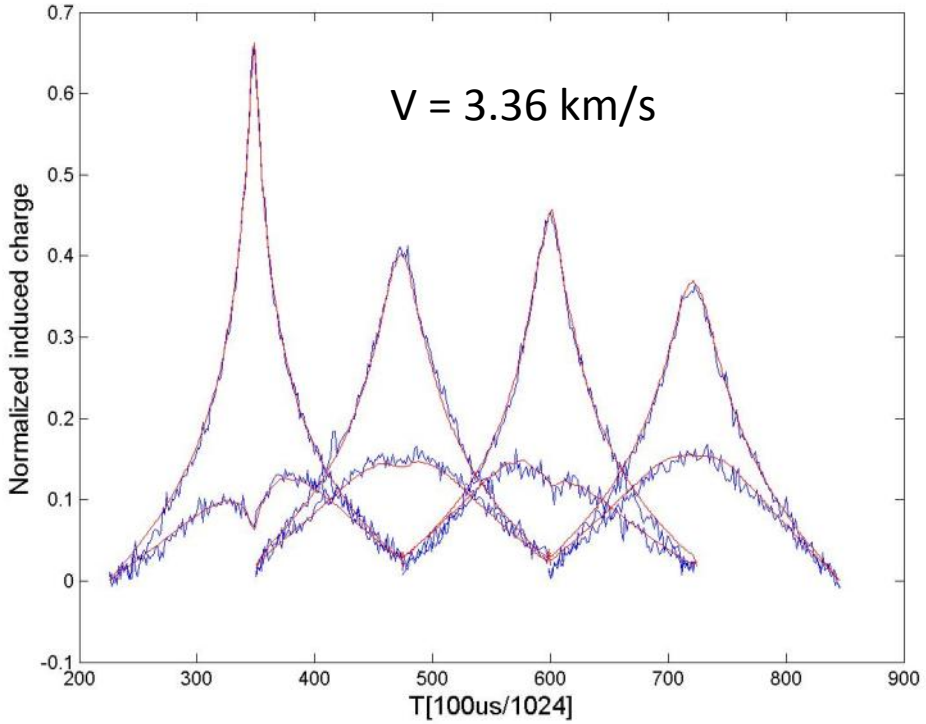
- **Impact ionization does not work well below 1 km/s**
- At hypervelocity (>1 km/s): $Q = 0.5\ m\ v^{3.5}$
  - $Q \sim 10^5$ electron for v = 1.6 km/s (1 micron dust)
- Low impact charge signal at v = 1-100 m/s
  - Q ~ 10 electrons for v = 100 m/s (1 micron dust)

- Best detection is through the charge on the dust
  - $Q = 700\ a\ \Phi$ (a in micron, Φ in volts, Q in electrons)
  - Q = 3,500 electrons for a = 1 microns, Φ = 5 V

Dust Trajectory Sensor (S. Auer)



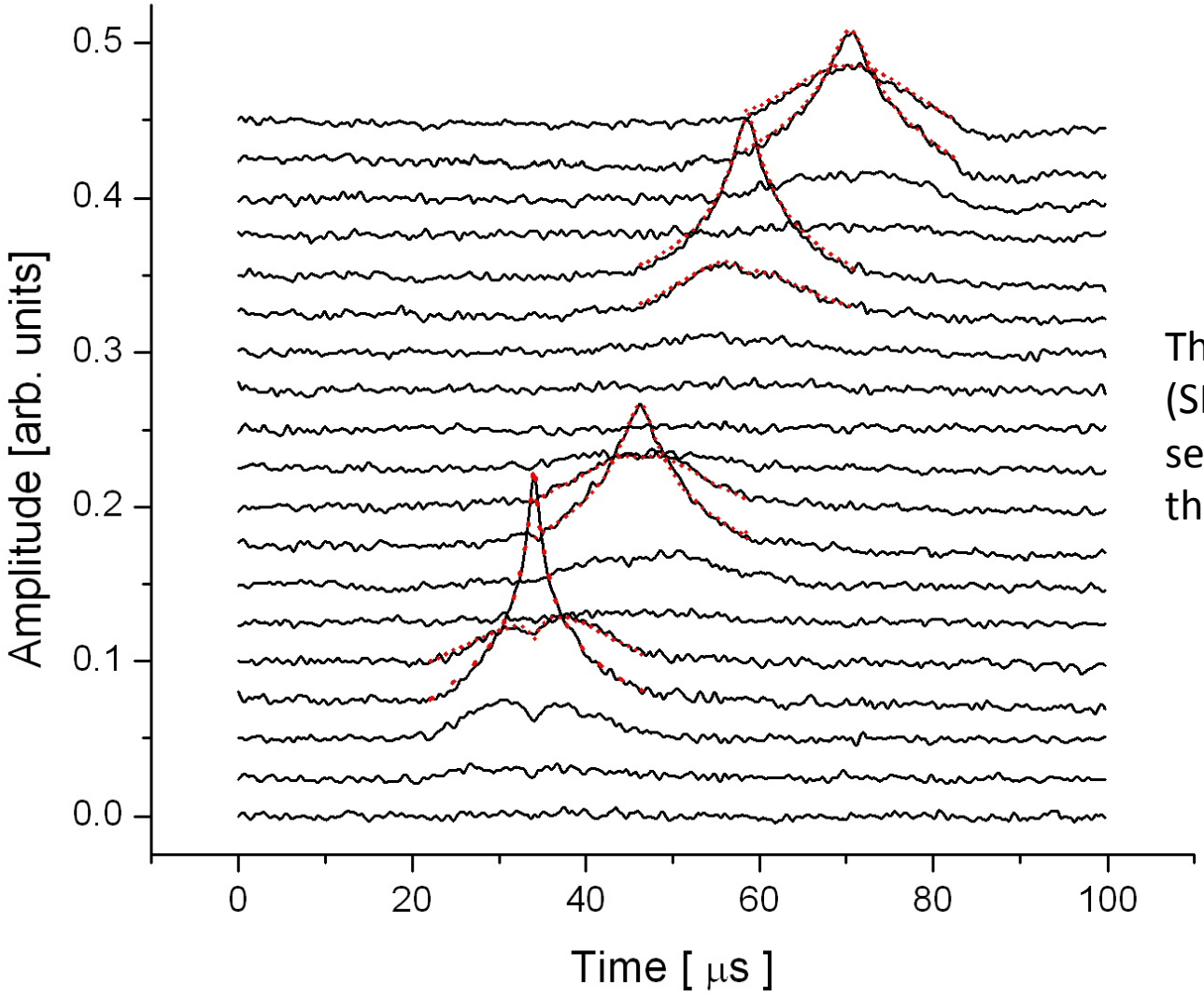




- The data analysis is done by fitting the measured signals with numerical simulations.
- Expected performance:
  - sensitivity ~ 0.3 micron radius (5V)
  - Velocity accuracy: ~ 1% or better
  - Angular accuracy: ~ 1 degree or better

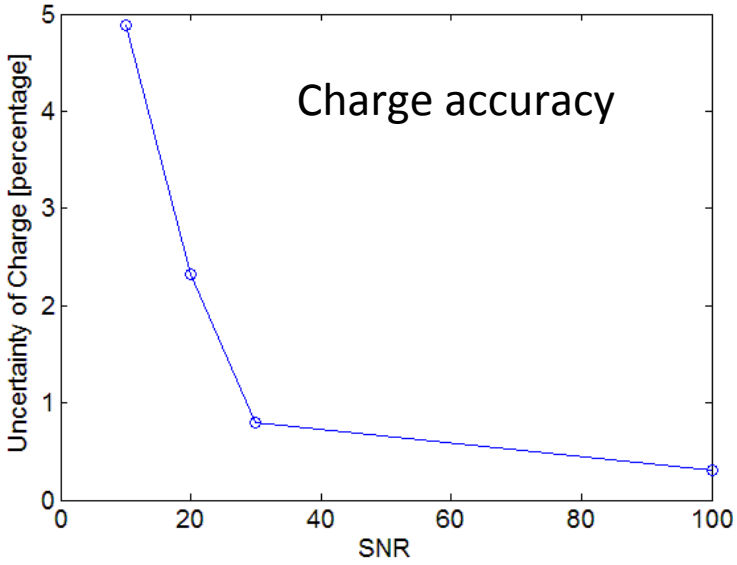
(Auer et al., 2008, 2010)

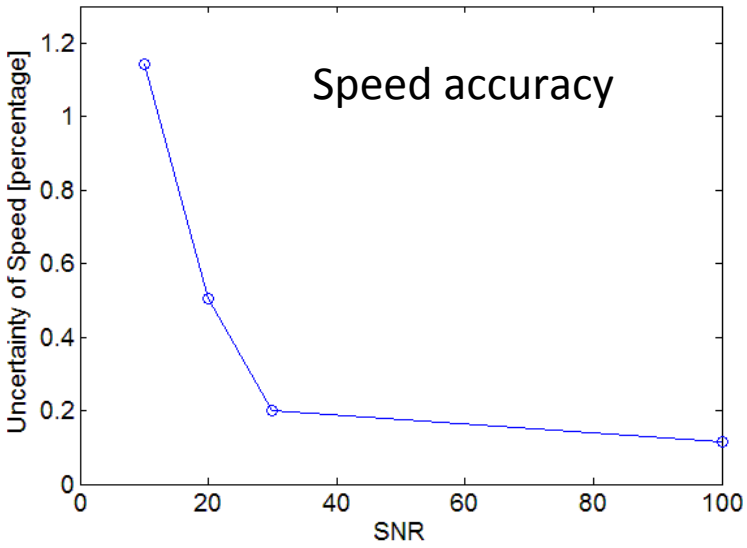
Data analysis

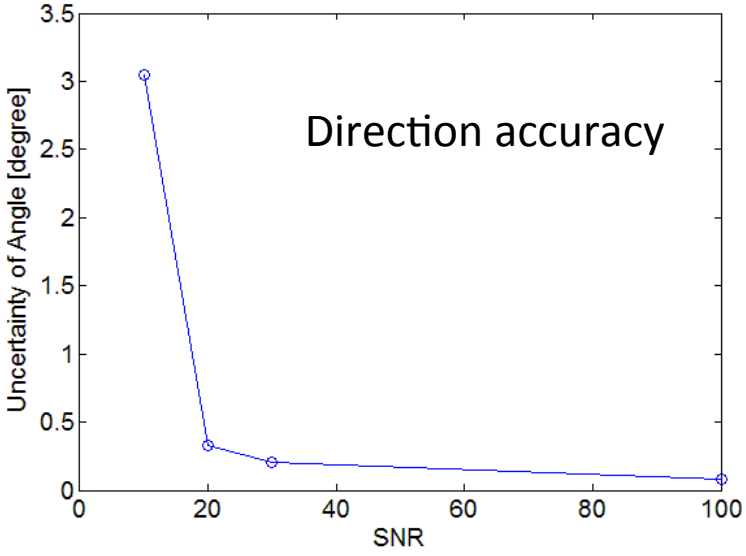


The Signal-to-Noise Ratio (SNR) determines the sensitivity and accuracy of the instrument

Accuracy analysis (Xie et al, 2011)





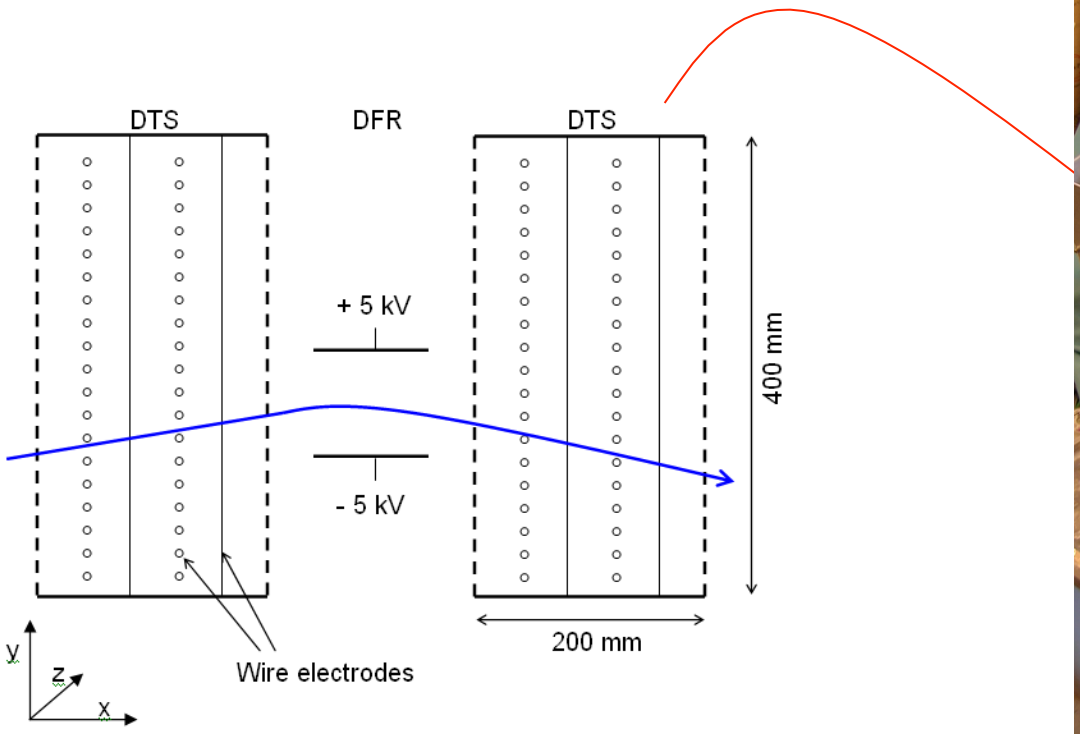


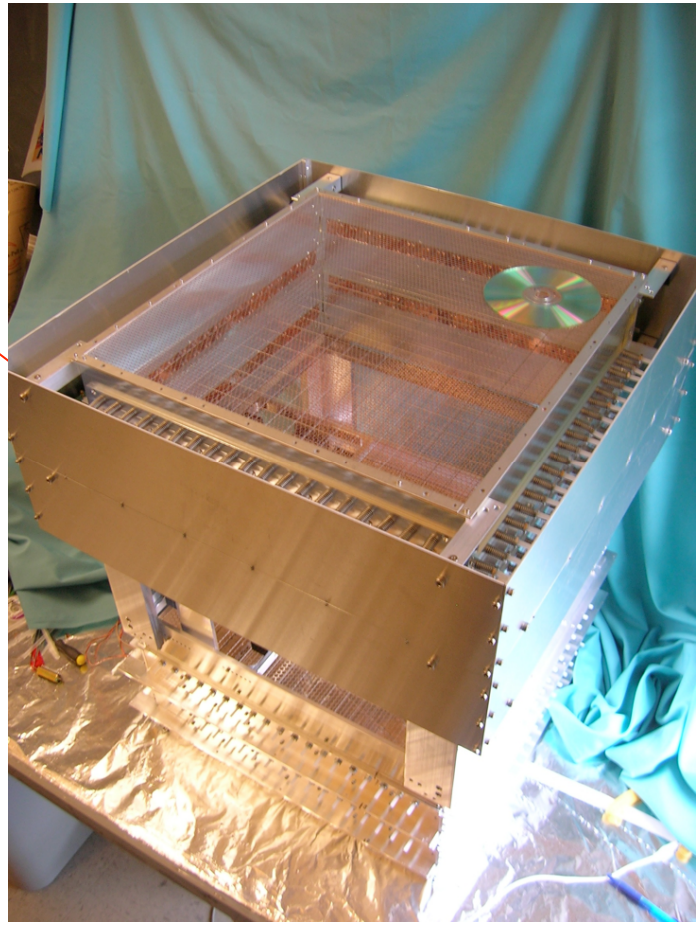
Accuracy increases with increasing SNR

Velocity: about 1 %
Angle: about 1 degree

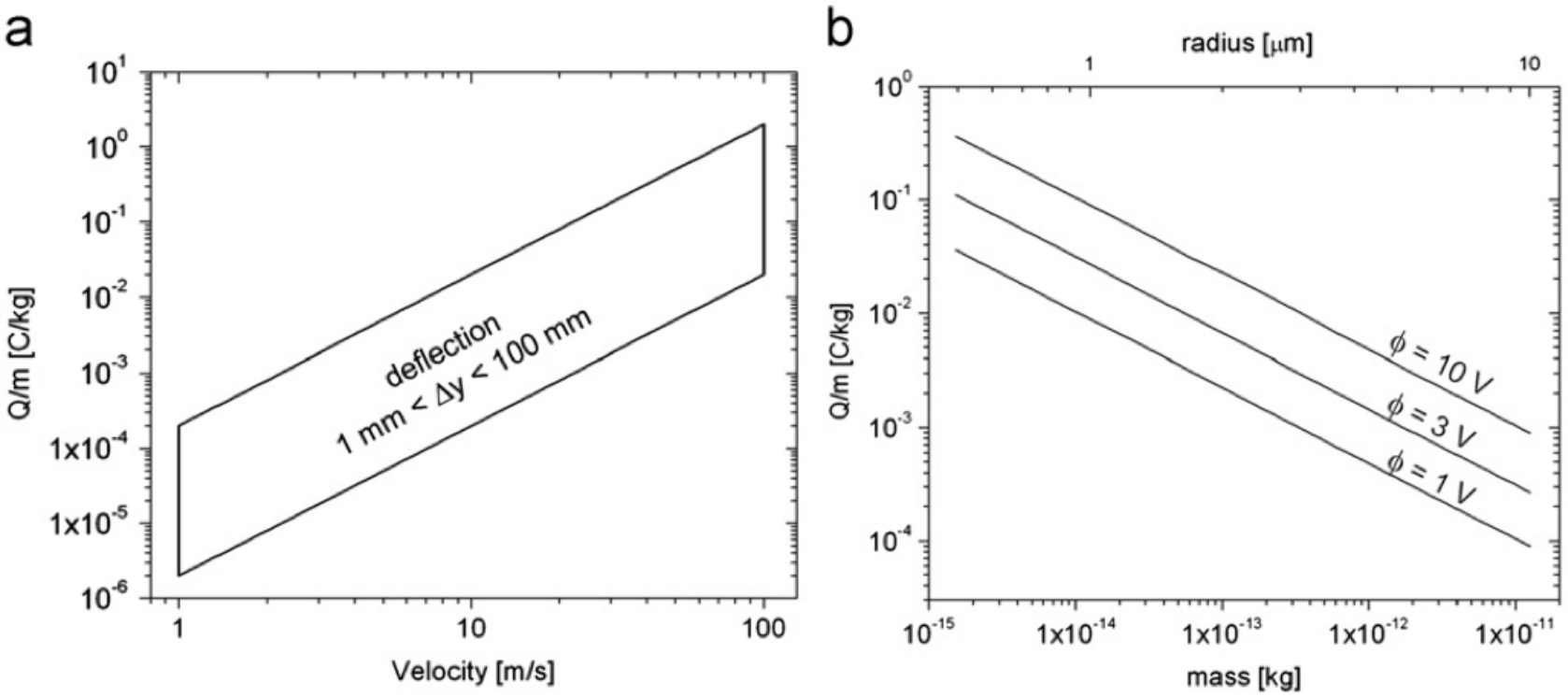
Measuring slow dust: ELDA

- Electrostatic Lunar Dust Analyzer (***ELDA***)
- Designed for low velocity (1-100 m/s), submicron and micron sized charged dust particles
- Measures: Q, m, v (charge, mass, velocity vector)





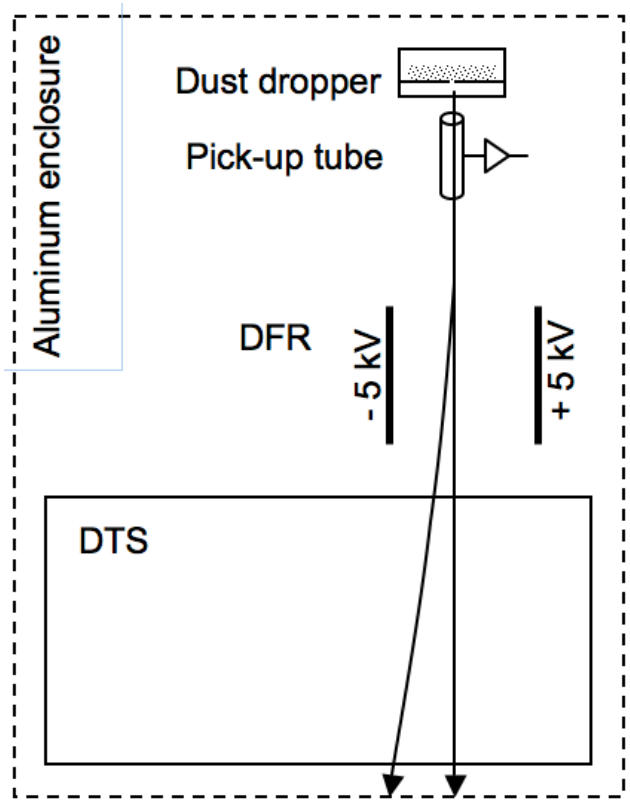
ELDA operation range



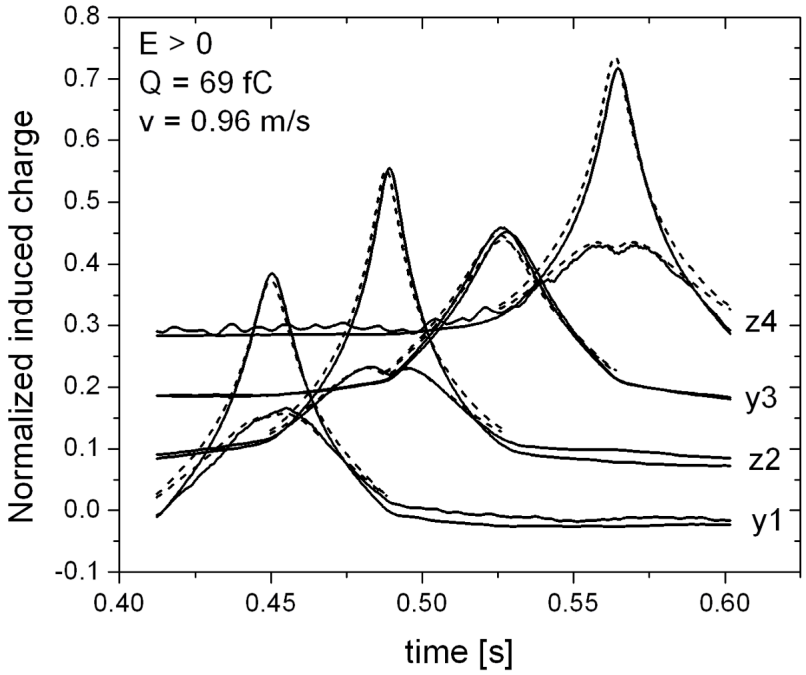
ELDA measures micron sized particles in the velocity range 1-100 m/s (approx.)

ELDA laboratory testing

Laboratory setup

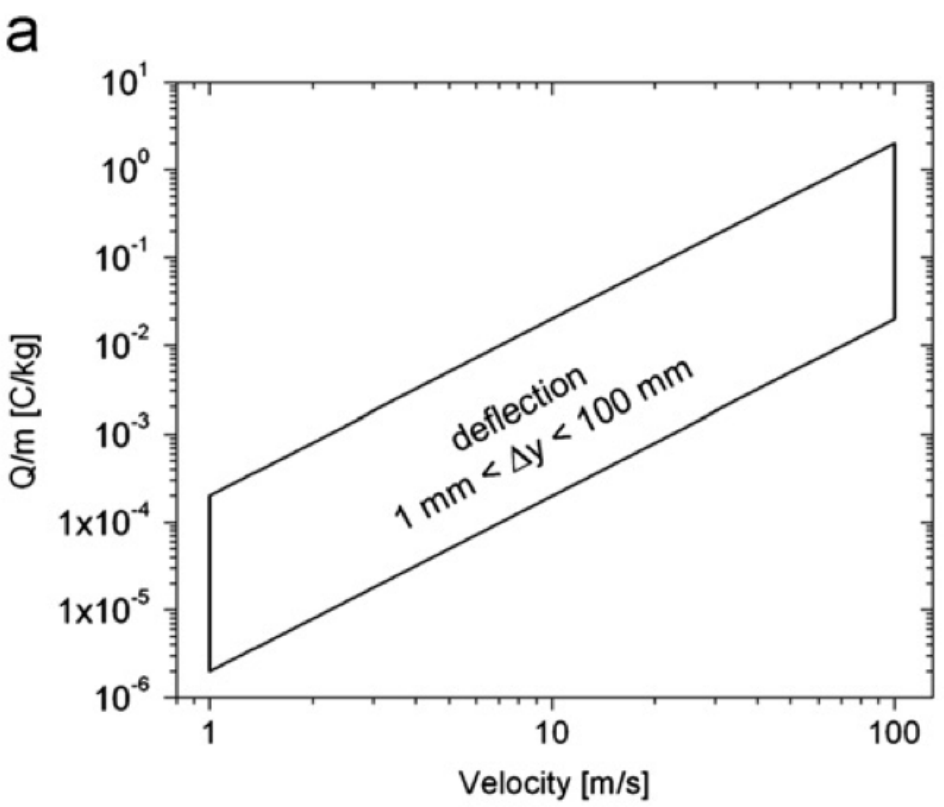


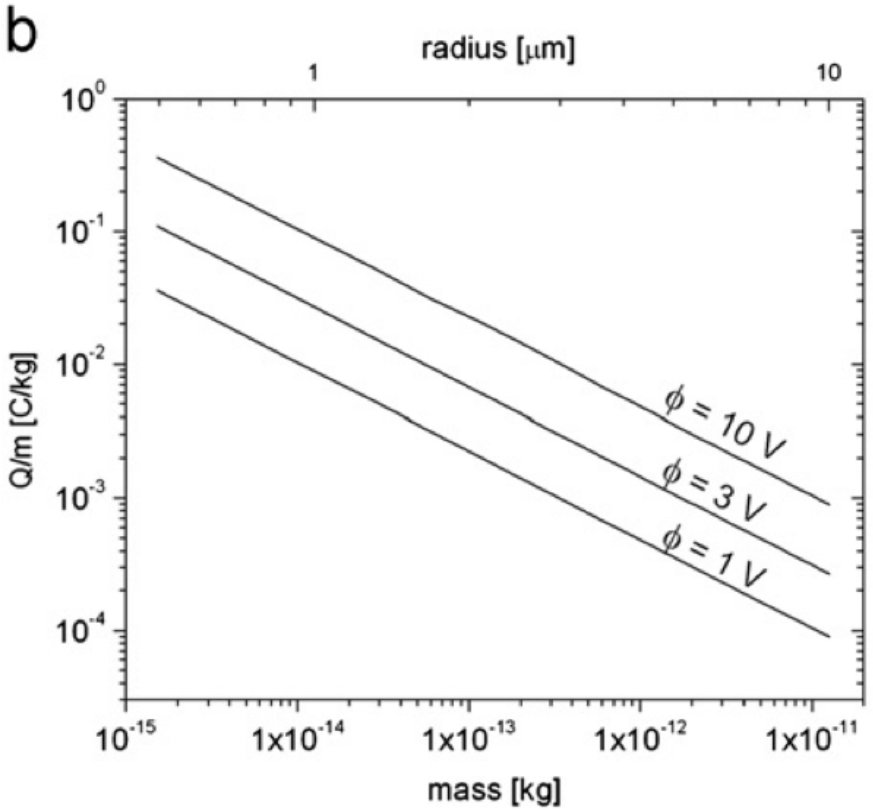
Data analysis: fitting the measured curves



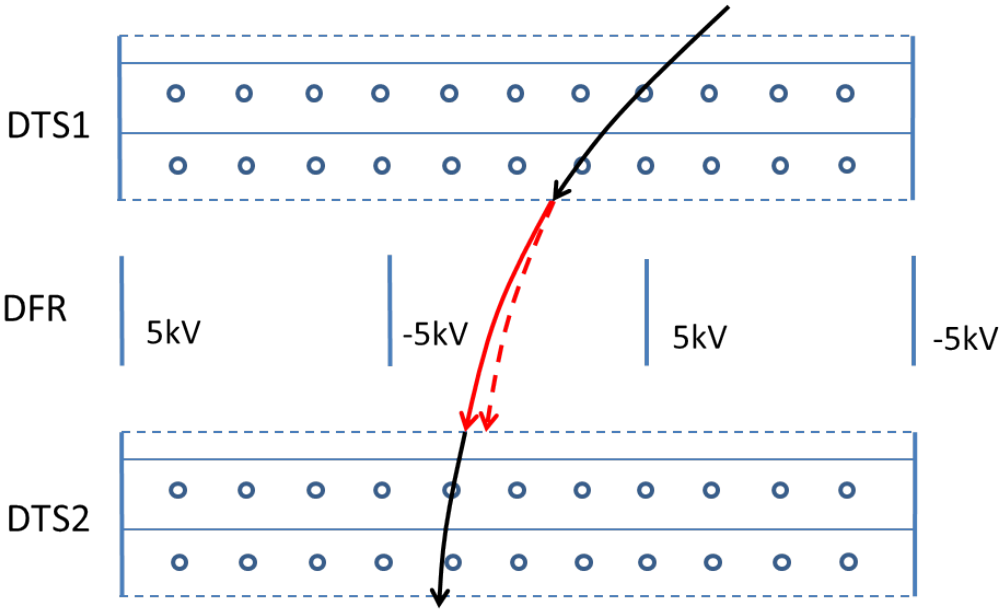
Trajectory information:
Speed: accuracy better than 1%
Angle of incidence: better than 1°

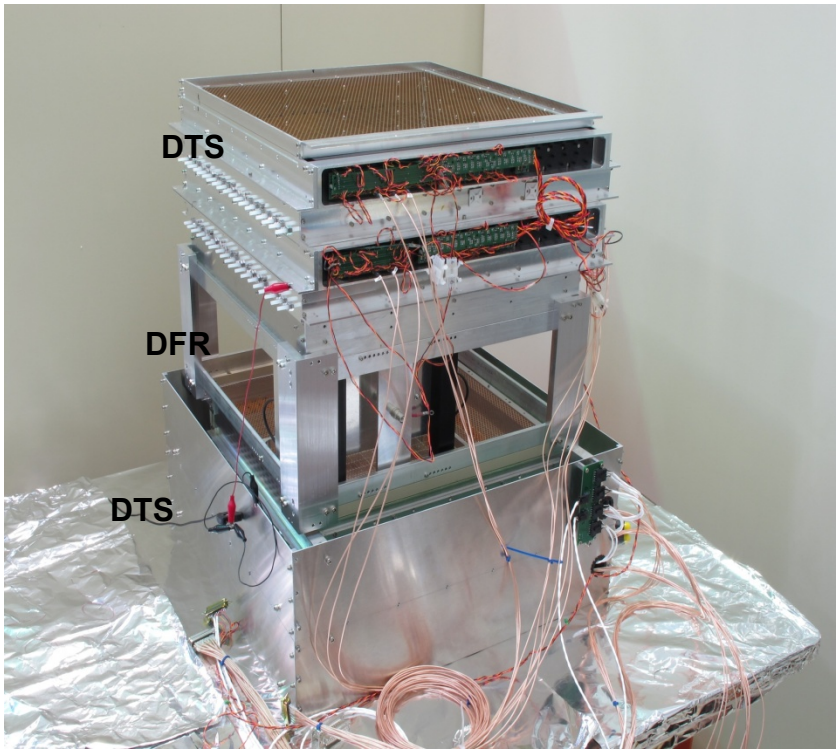
Parameter range of operation





ELDA laboratory testing

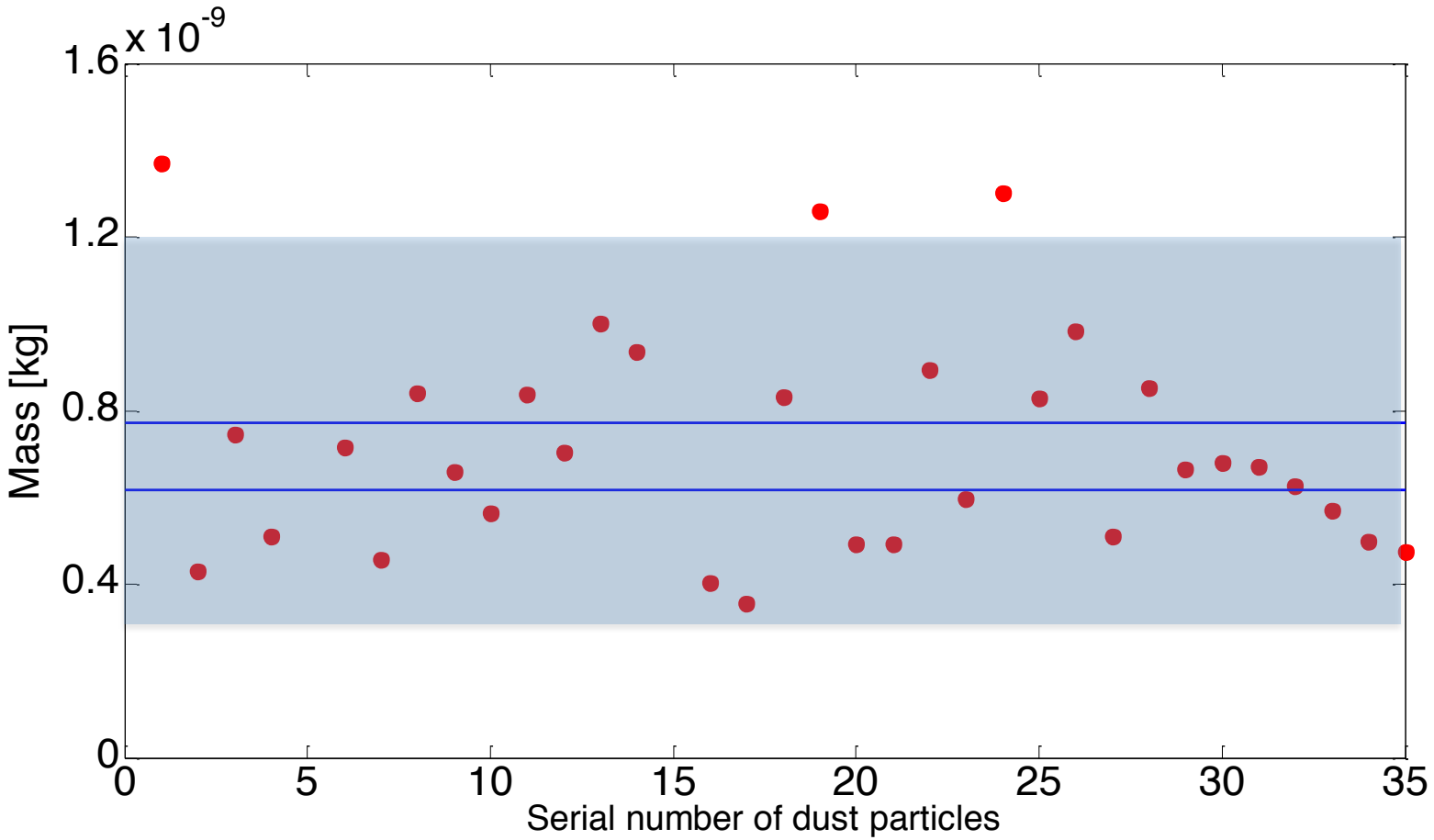




Dust sample used

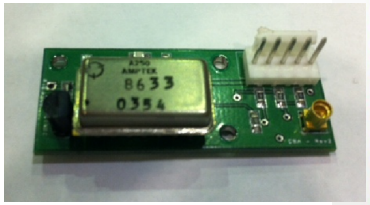
- Size r=54+/-2 microns
- Density d=1.05 g/cm^3
- Mass: m=6.18~7.12 e-10 kg
- Charge: q=0.18~2.02 e-13 C (5-10 V typical)

A factor of two accuracy in mass with ELDA

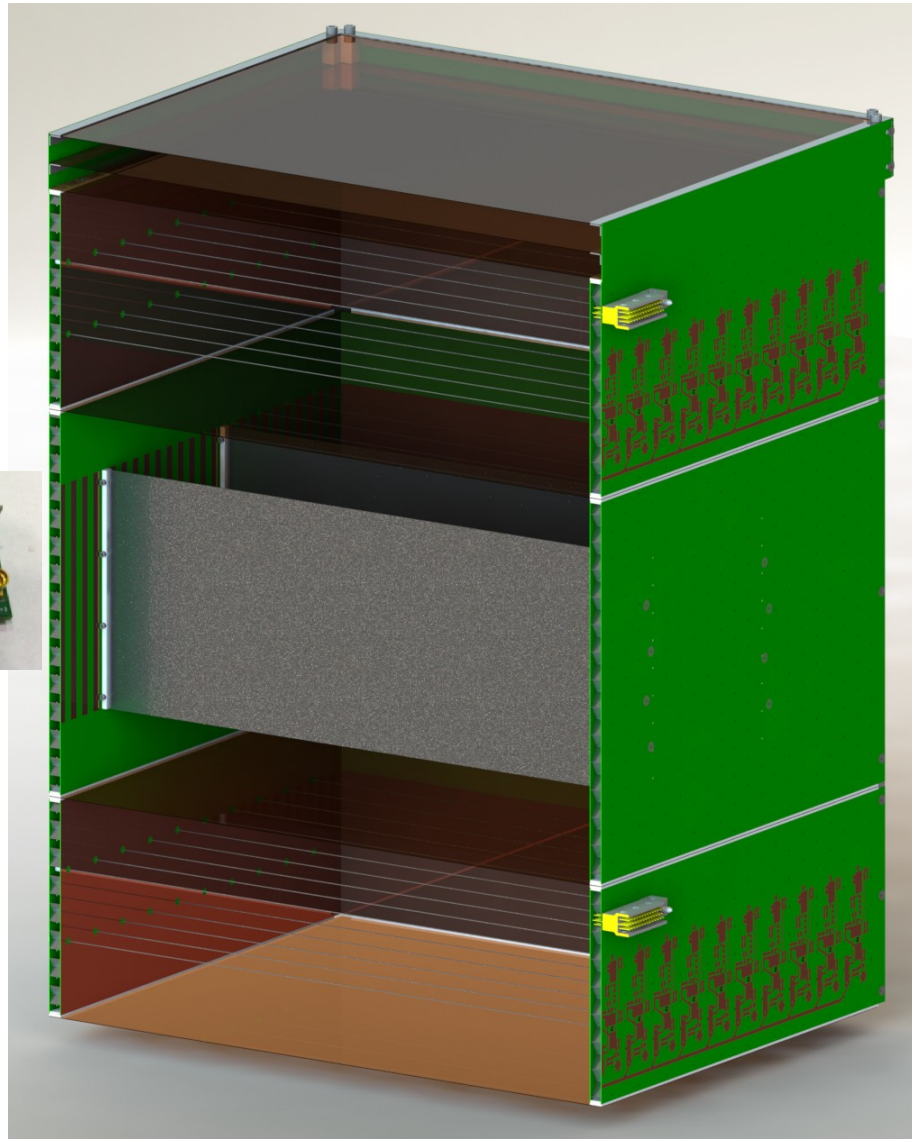


ELDA instrument study

- Low-mass ELDA design using honeycomb structures
- 26x26 cm^2 active cross section
- Mass: 2.28 kg + 1.5 kg = **3.78 kg**
- Integrated front-end electronics
- Current electronics sensitivity: 400 e^- rms noise



- Expected performance improvements to **100-200 e^- rms**
- Sophisticated trigger (>99% detection for SNR > 6.25 signals)
- Corresponding **sensitivity: 0.35 micron dust** (charged to +5 V)



Summary

- LDEX is the most sensitive dust instrument and ready for launch
- Bigger better chemical analyzer instruments are now available
- ELDA is a sensitive instrument for the detection of slow moving dust from the lunar surface