TOOLS FOR

DUST ASTRONOMY

CASSINI AND BEYOND

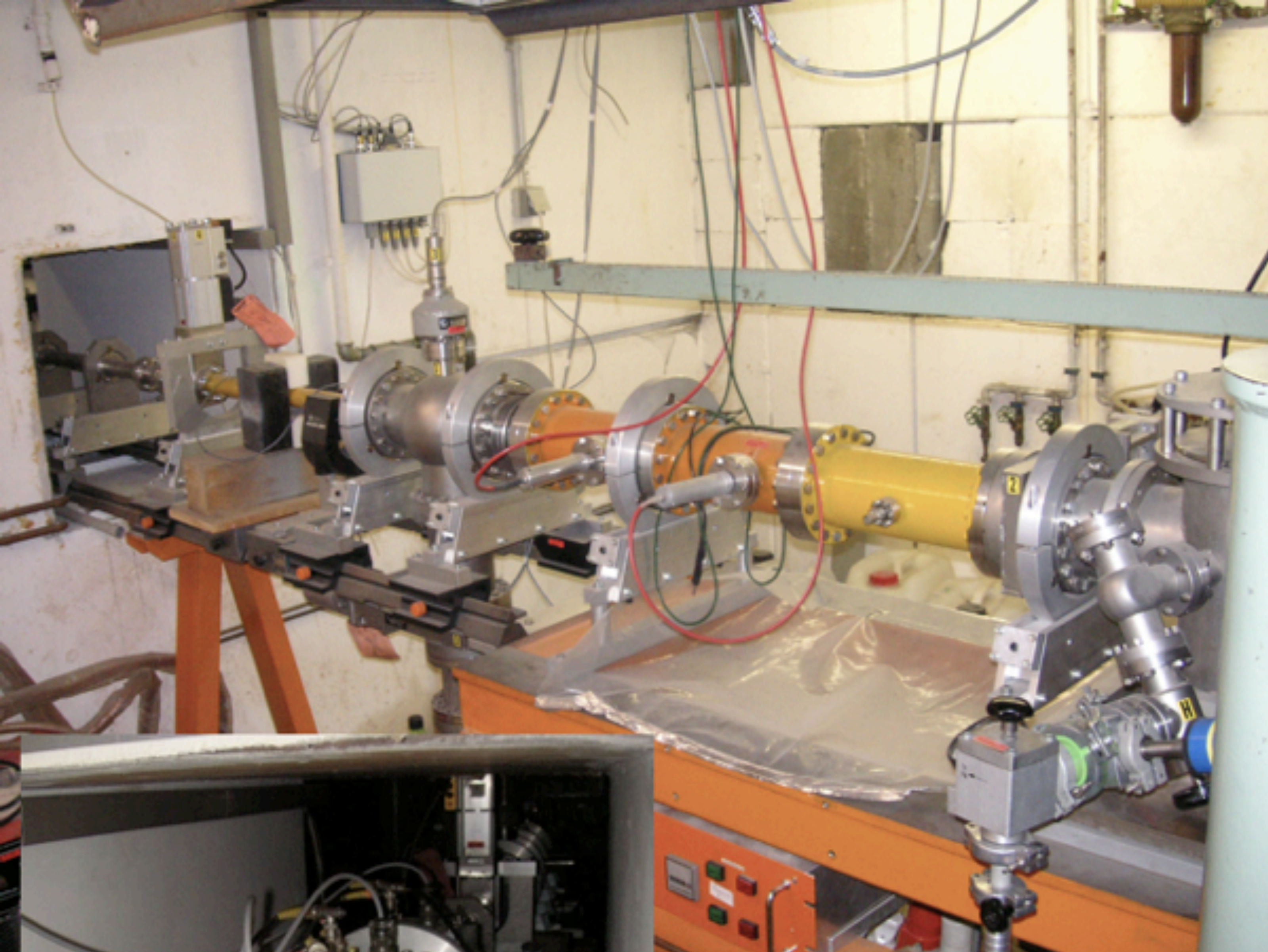
Ralf Srama

MPI Nuclear Physics, Heidelberg, Germany

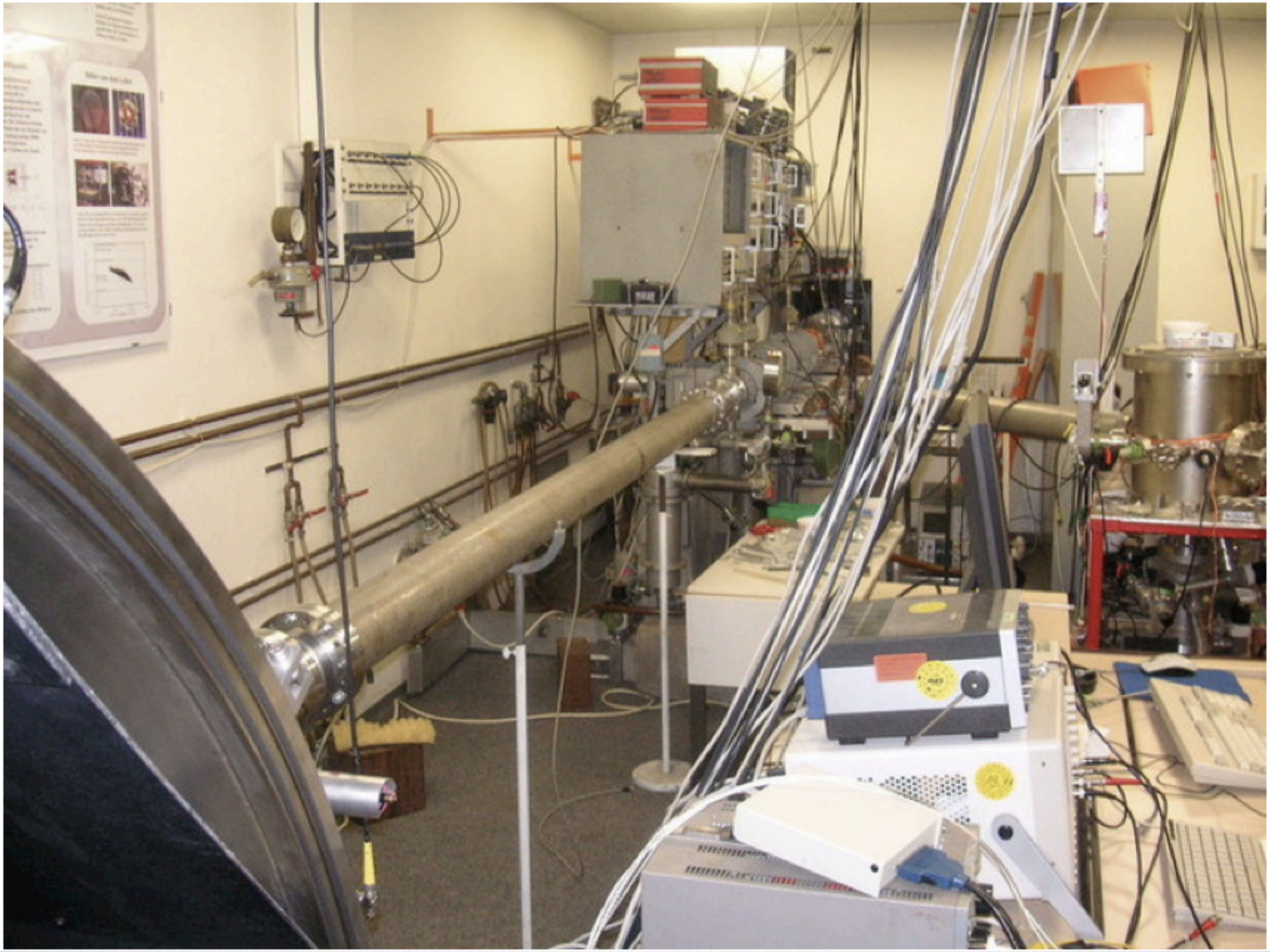
Location

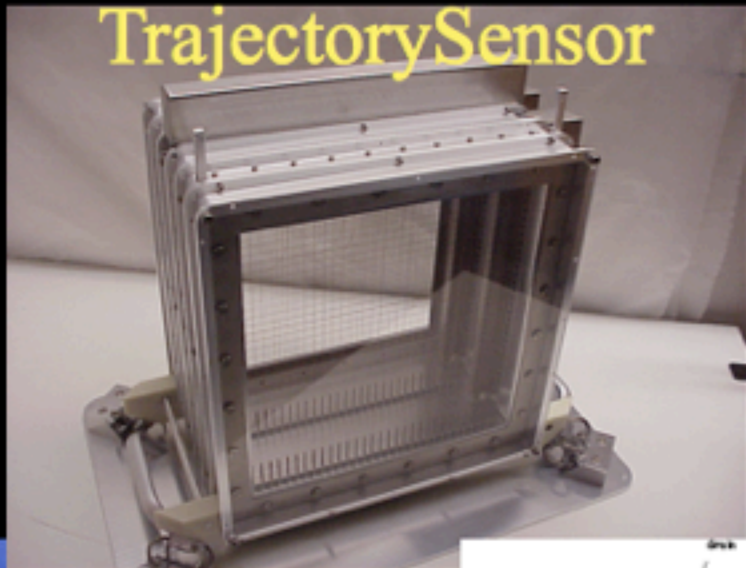
The Max-Planck-Institut für Kernphysik in Heidelberg, Germany

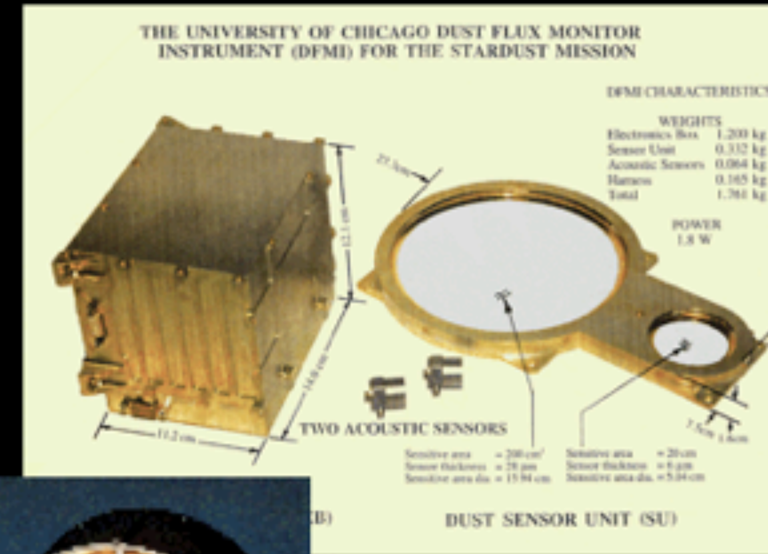
Der Beschleuniger



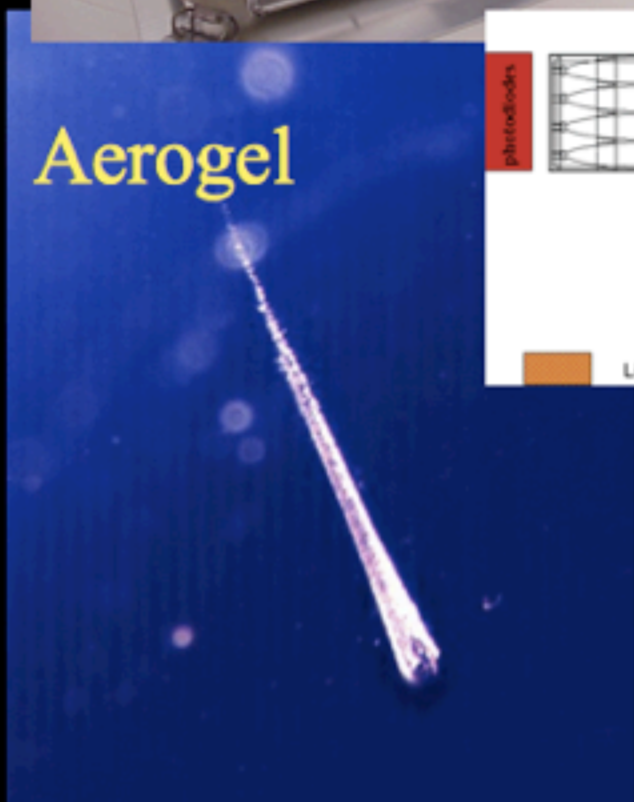
The Laboratory

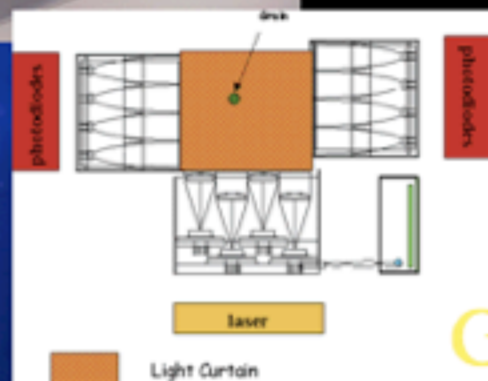






PVDF

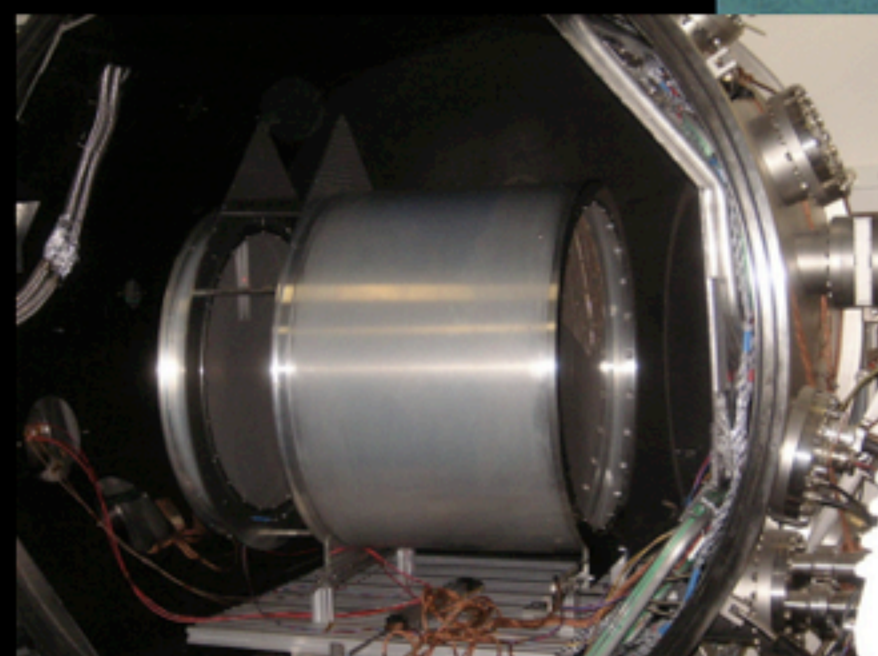




CDA

Giada

DDS



ISIDE

LAMA

CIDA

PROJEKTE

TOOLS FOR

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Spacecraft	Mass threshold [kg]	Dynamic range	Sensitive area [m^2]	References
Pioneer 8,9	$2x10^{-16}$	100	0.009	[Berg and Richardson, 1968]
Pioneer 10	$2x10^{-12}$	1	0.26	[Humes et al., 1974]
Pioneer 11	$1x10^{-11}$	1	0.26 (0.57)	[Humes, 1980]
HEOS 2	$2x10^{-19}$	10^4	0.010	[Hoffmann et al., 1975]
Helios 1,2	$9x10^{-18}$	10^4	0.012	[Dietzel et al., 1973]
Giotto PIA	$3x10^{-19}$	10^6	0.0005	[Kissel, 1986]
Giotto DIDSY	10^{-20}	10^{14}	0.1	[McDonnell et al., 1986]
VeGa 1,2 PUMA	10^{-20}	10^6	0.0005	[Kissel et al., 1986]
VeGa 1,2 DUCMA	10^{14}	10^3	0.0075	[Perkins et al., 1985]
VeGa 1,2 SP1	$2x10^{-18}$	10^5	0.0081	[Göller et al., 1987]
VeGa 1,2 SP2	$1x10^{-14}$	10^8	0.05	[Sagdeev et al., 1985]
Hiten	$2x10^{-18}$	10^4	0.01	[Igenbergs et al., 1991]
Ulysses	$2x10^{-18}$	10^6	0.10	[Grün et al., 1992a]
Galileo	$2x10^{-18}$	10^6	0.10	[Grün et al., 1992b]
Stardust CIDA	$2x10^{-18}$	10^4	0.01	[Kissel et al., 2004]
Stardust DFMI	10^{-15}	10^6	var.	[McDonnell et al., 2000]
Nozomi	$2x10^{-18}$	10^6	0.01	[Igenbergs et al., 1998]
Cassini DA	$5x10^{-19}$	10^6	0.1	[Srama et al., 2004]
Cassini HRD	$3x10^{-16}$	10^4	0.006	[Srama et al., 2004]
New Horizons	$1x10^{-15}$	10^5	0.1	[Horanyi et al., 2009]
Bepi Colombo	TBD	TBD	0.01	[Nogami et al., 2009]

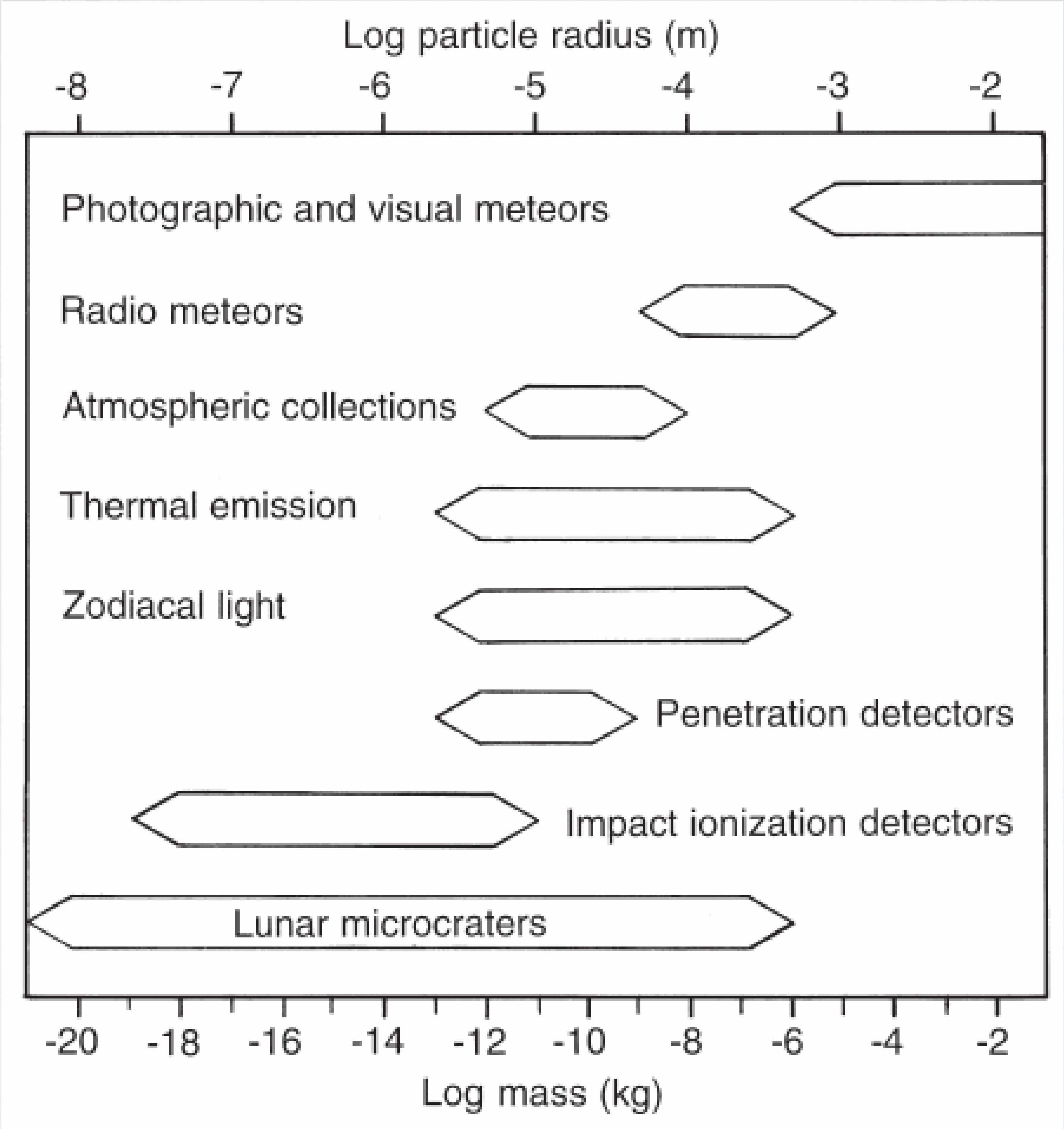

Figure 1: Different observation methods are necessary in order to cover the entire size range of micrometeoroids. Crater investigations of lunar rocks provided a broad overview of the entire dust mass range.

DUST ASTRONOMY ADVANCES

- You get dust dynamics (trajectories, orbital parameters)
- You measure local densities (not integrated along LOS)
- You measure dust charges
- You measure more sensitive (in threshold and number density)
- You measure dust composition (spatially resolved)
- You measure mass distribution
- You measure distant worlds by remote-in-situ analysis (look into moons and look into stars)

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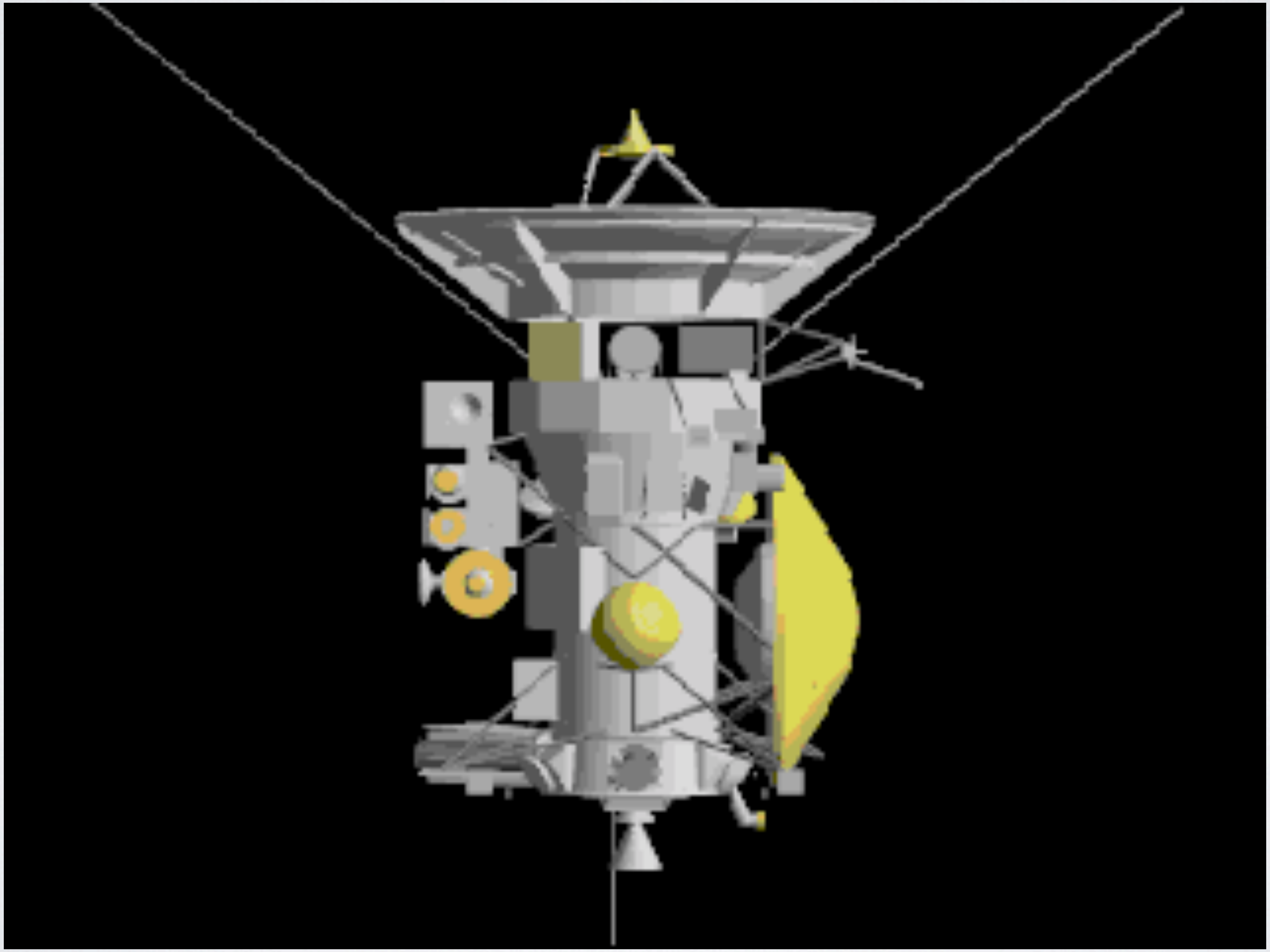
EXAMPLES (CASSINI CDA)



Cosmic Dust Analyser (CDA)

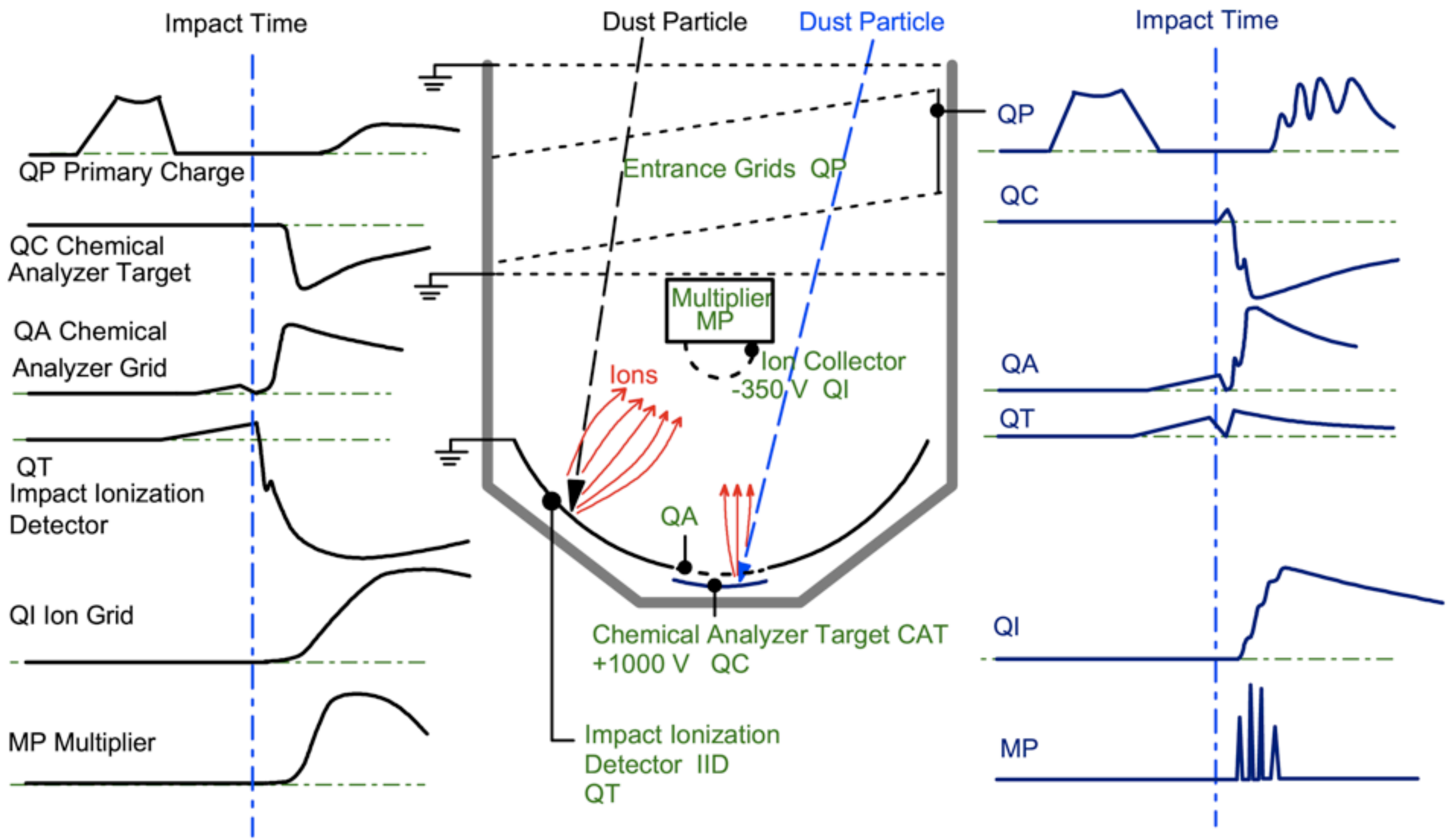
Dust detector on Cassini spacecraft:

- dust mass/velocity: impact ionisation detector
- chemical composition: time of flight mass spectrometer
- dust charge/velocity/impact angle: charge sensitive entrance grids
- high rate detector (HRD)

CDA measurement range

- Sensitive area: $0.1\ m^2$
- Dust speed: $1\text{-}100\ km\ s^{-1}$
- Dust mass: $10^{-15}\text{-}10^{-9}\ g\ (@20\ km\ s^{-1})$
- Dust charge: $10^{-15} - 10^{-13}\ C$
- Dust composition: 20-50 mass resolution
- Impact counting rate: 1/week-10000/s
  1000 times more sensitive than optical measurements

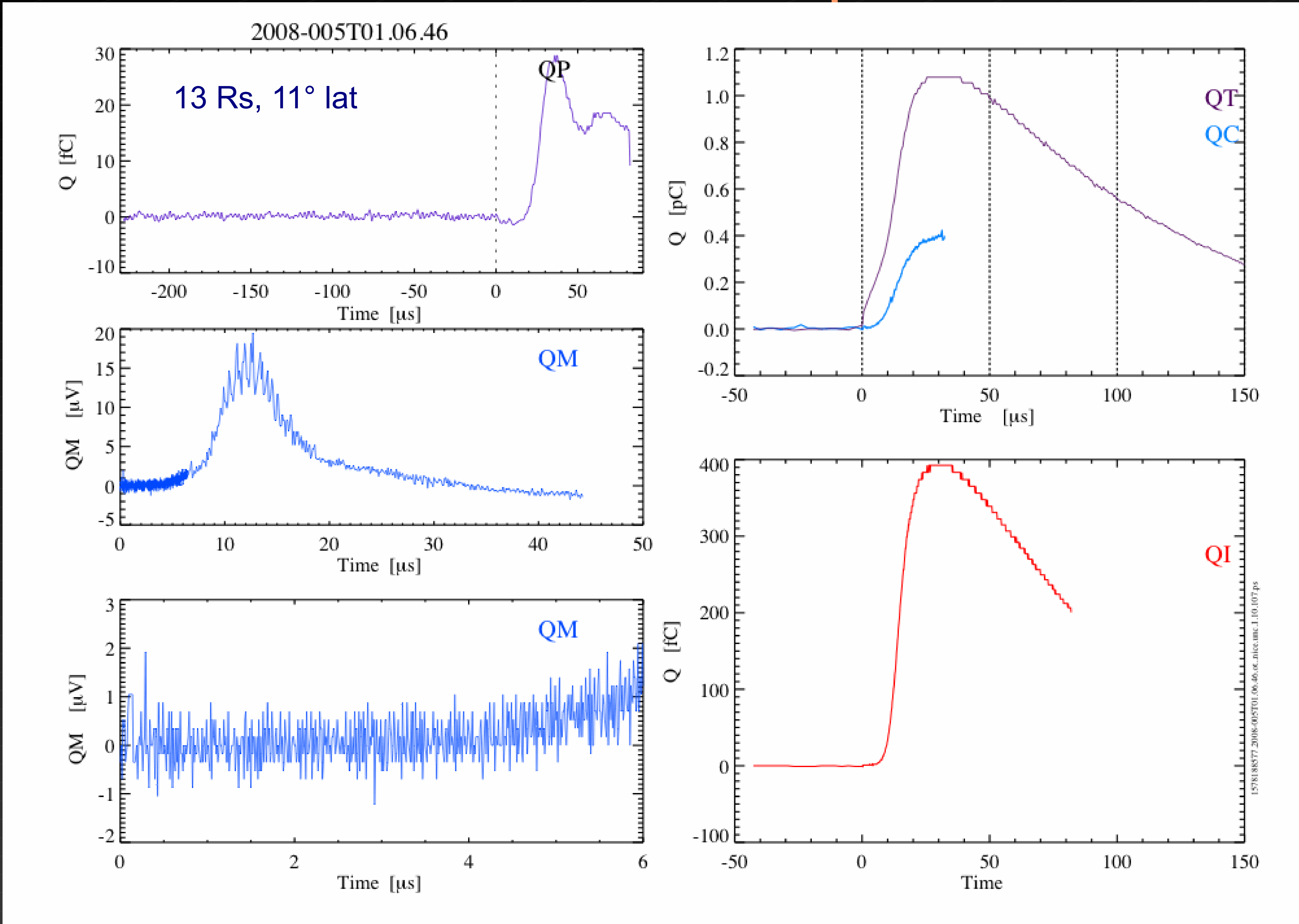
CDA finds one particle within one km^3



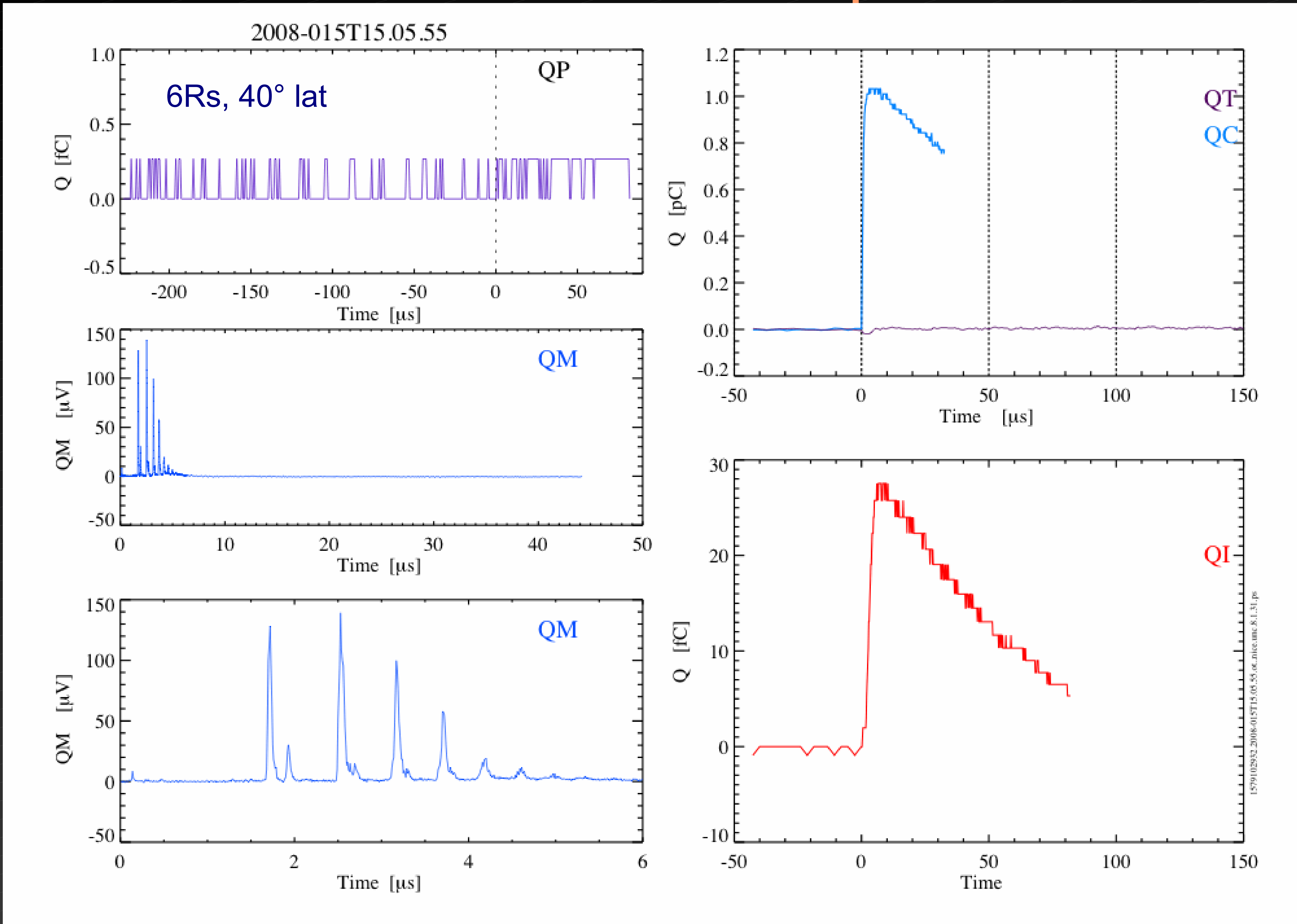
Impact onto big target (IID)

Impact onto small target (CAT)

Raw data IID impact

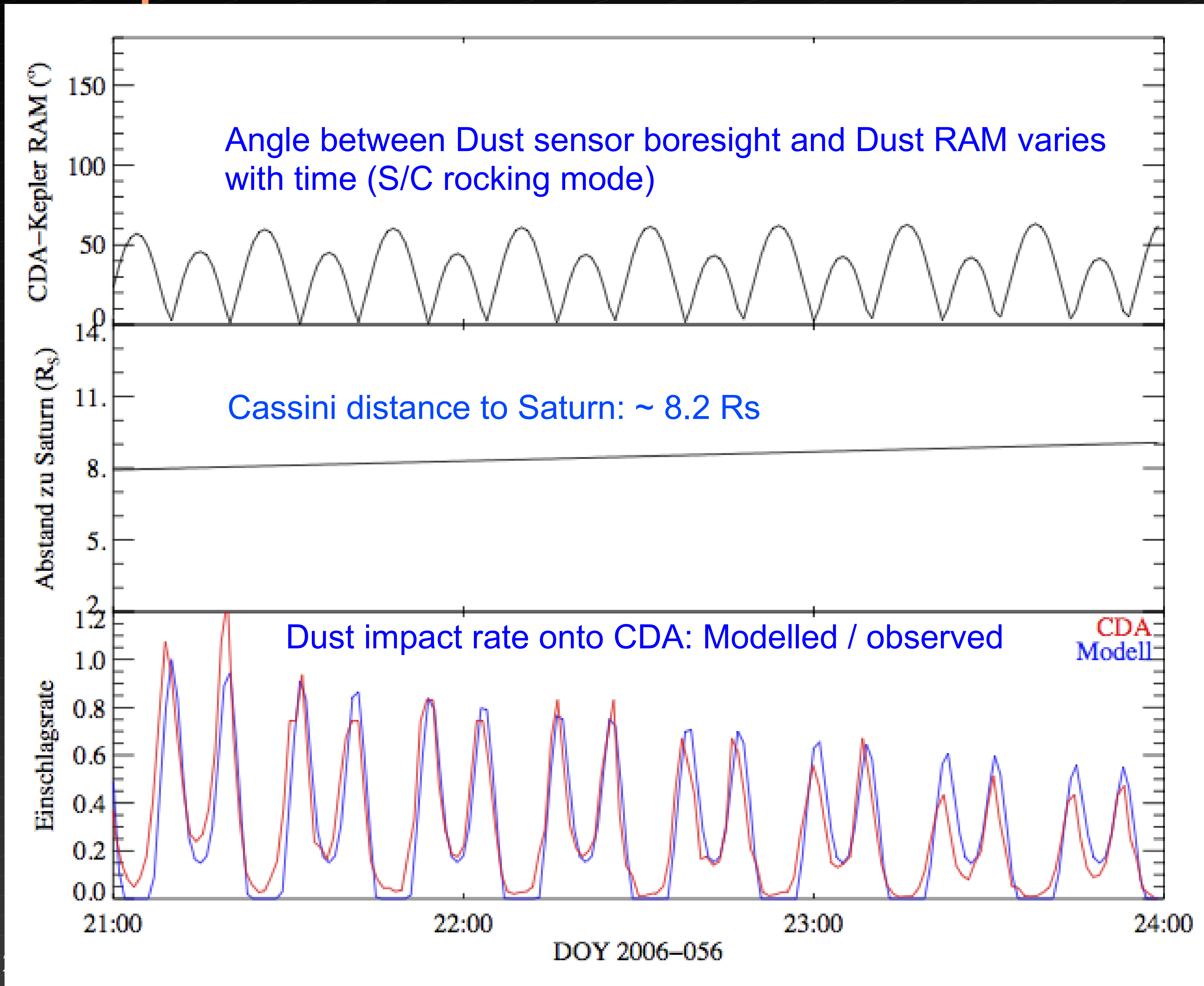


Raw data CAT impact



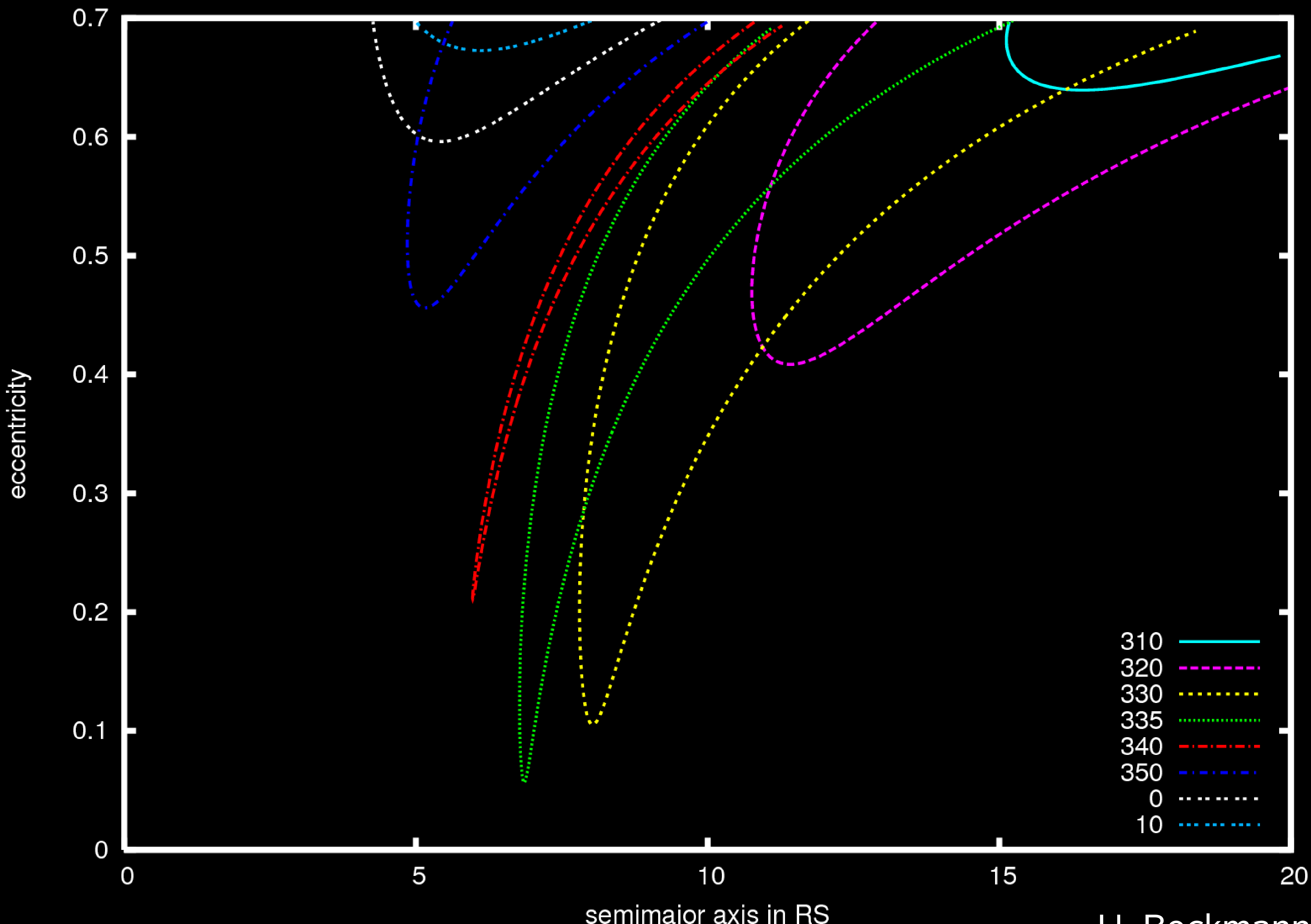
Example : DUST DYNAMICS

Compare : Model and CDA in-situ data



E ring dynamics

Dust eccentricity and semimajor axis for a given time (CDA pointing)

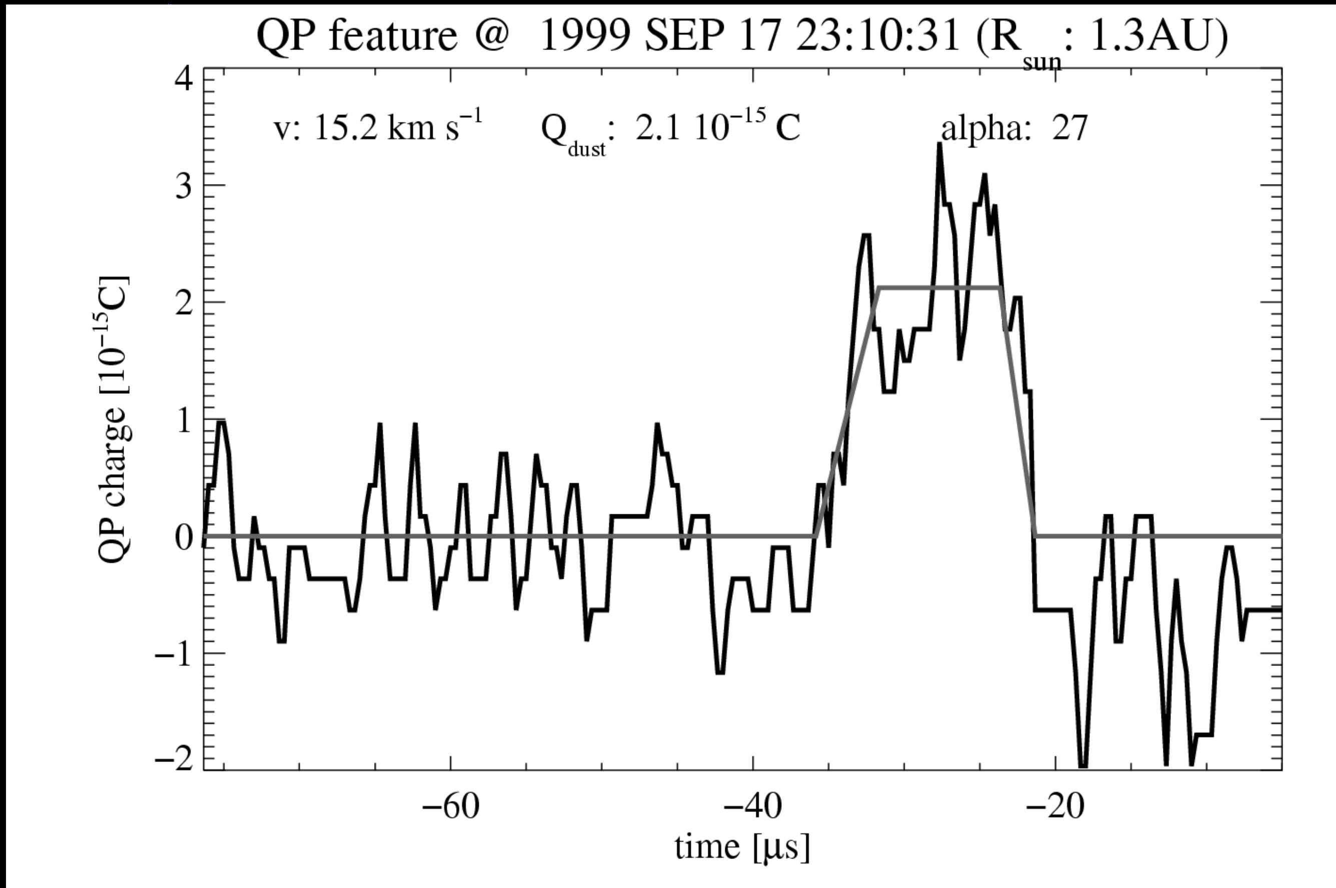


Ap

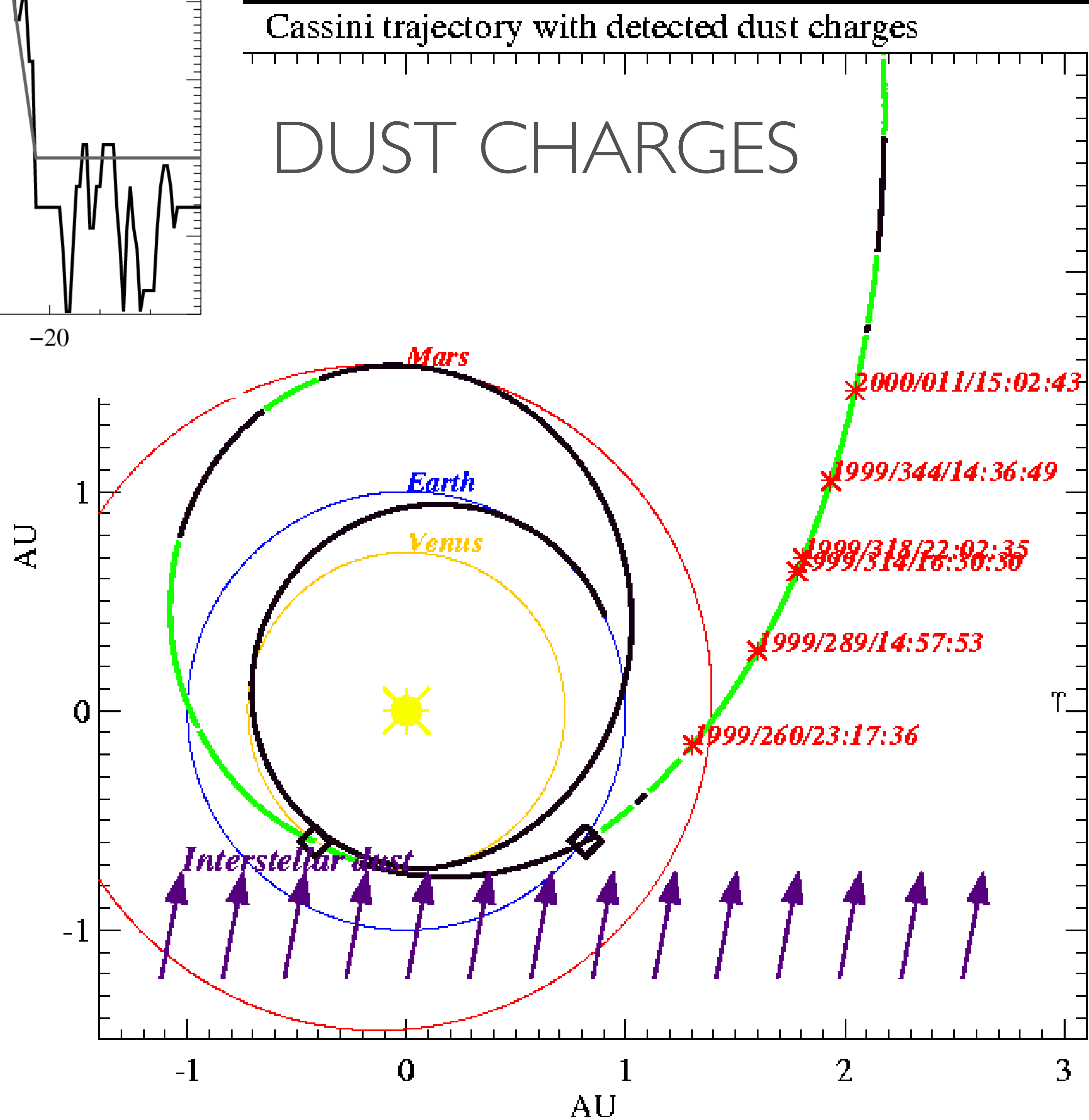
U. Beckmann

COSMIC DUST ANALYZER

Charges on interplanetary grains



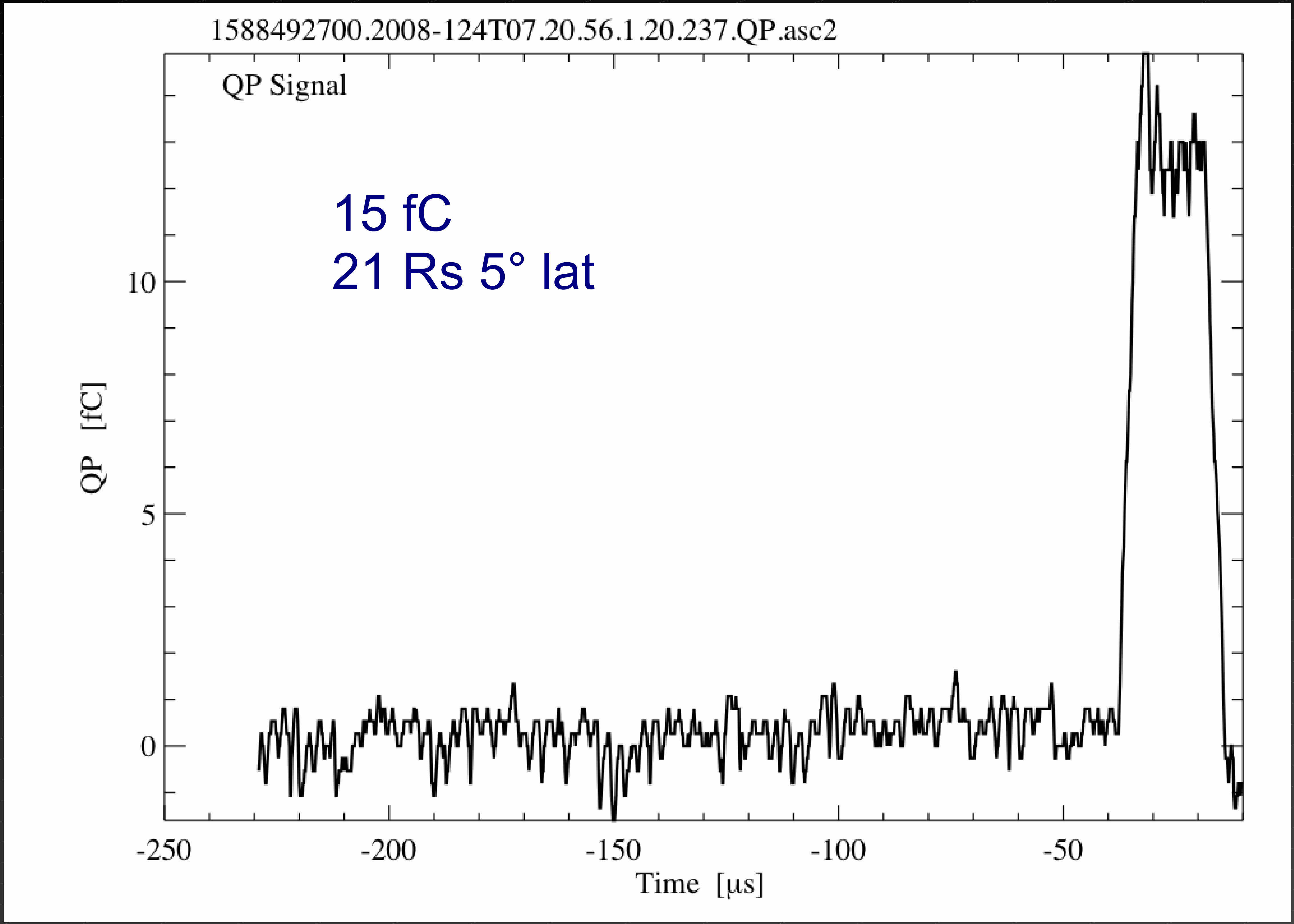
DUST CHARGES



6 particles in interplanetary space (0.8 – 4 fC)

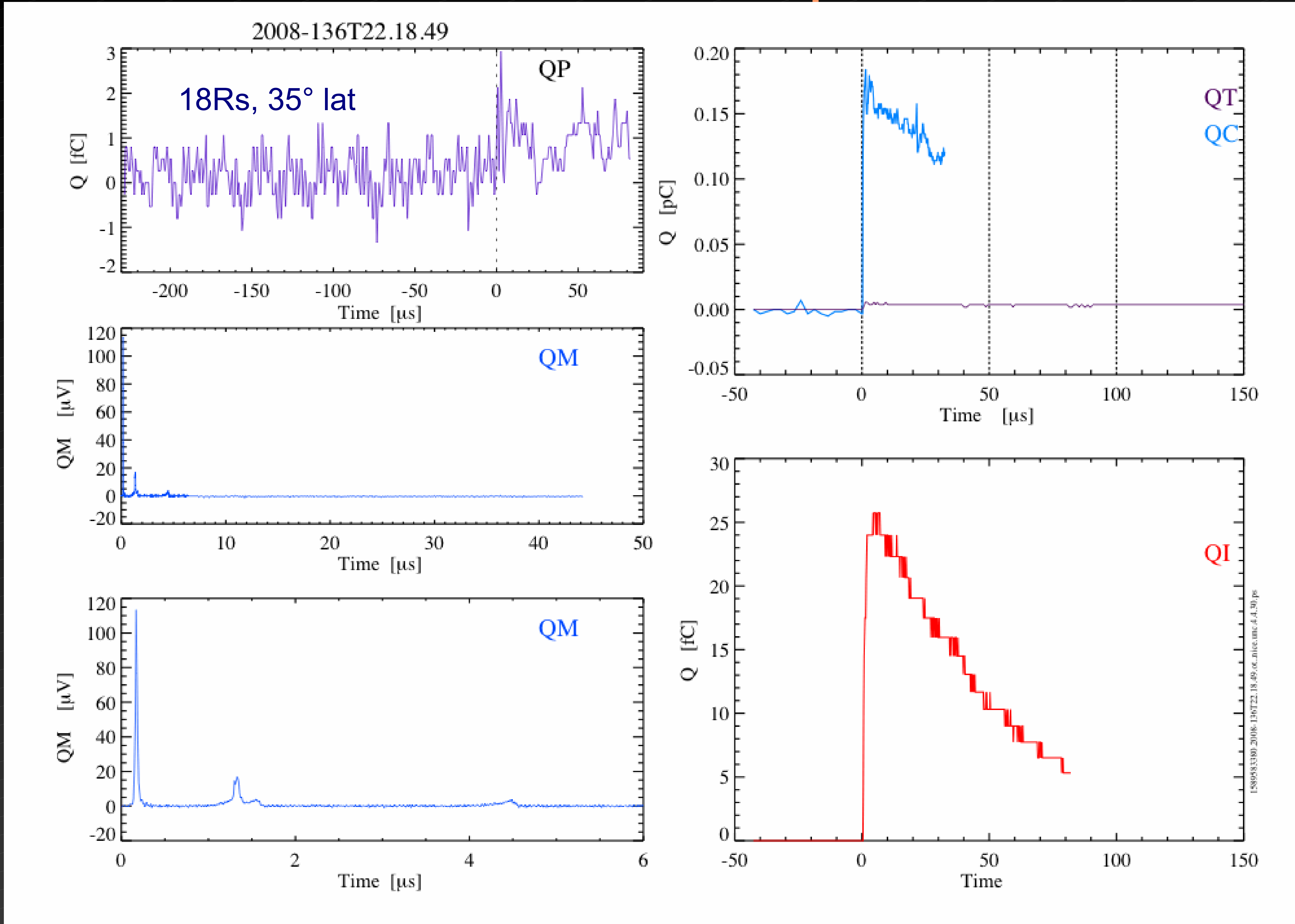
Apr. 2007

Recent impact with high primary charge

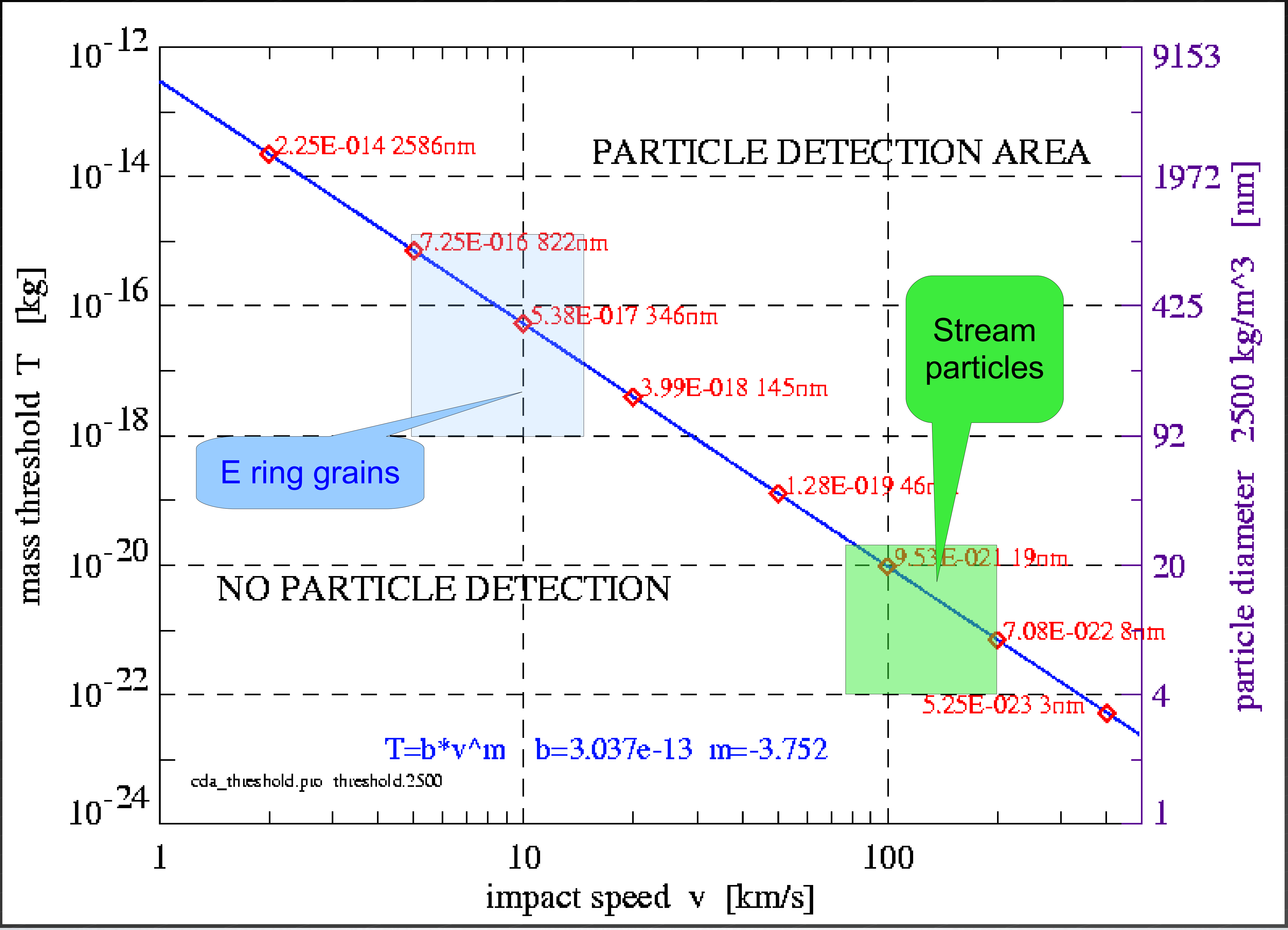


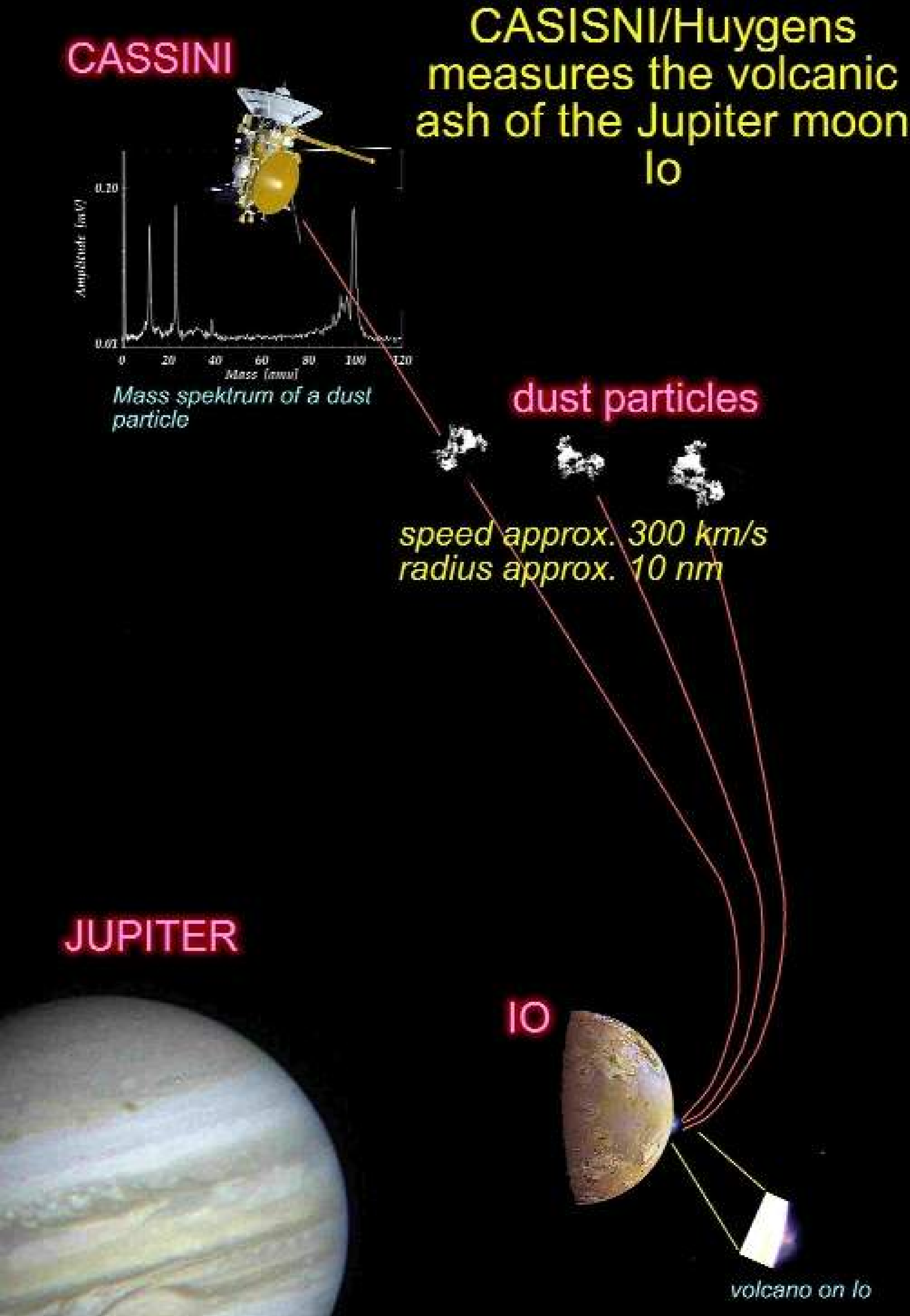
LOW DETECTION THRESHOLD (NANODUST)

Raw data stream particle



Dust detection threshold

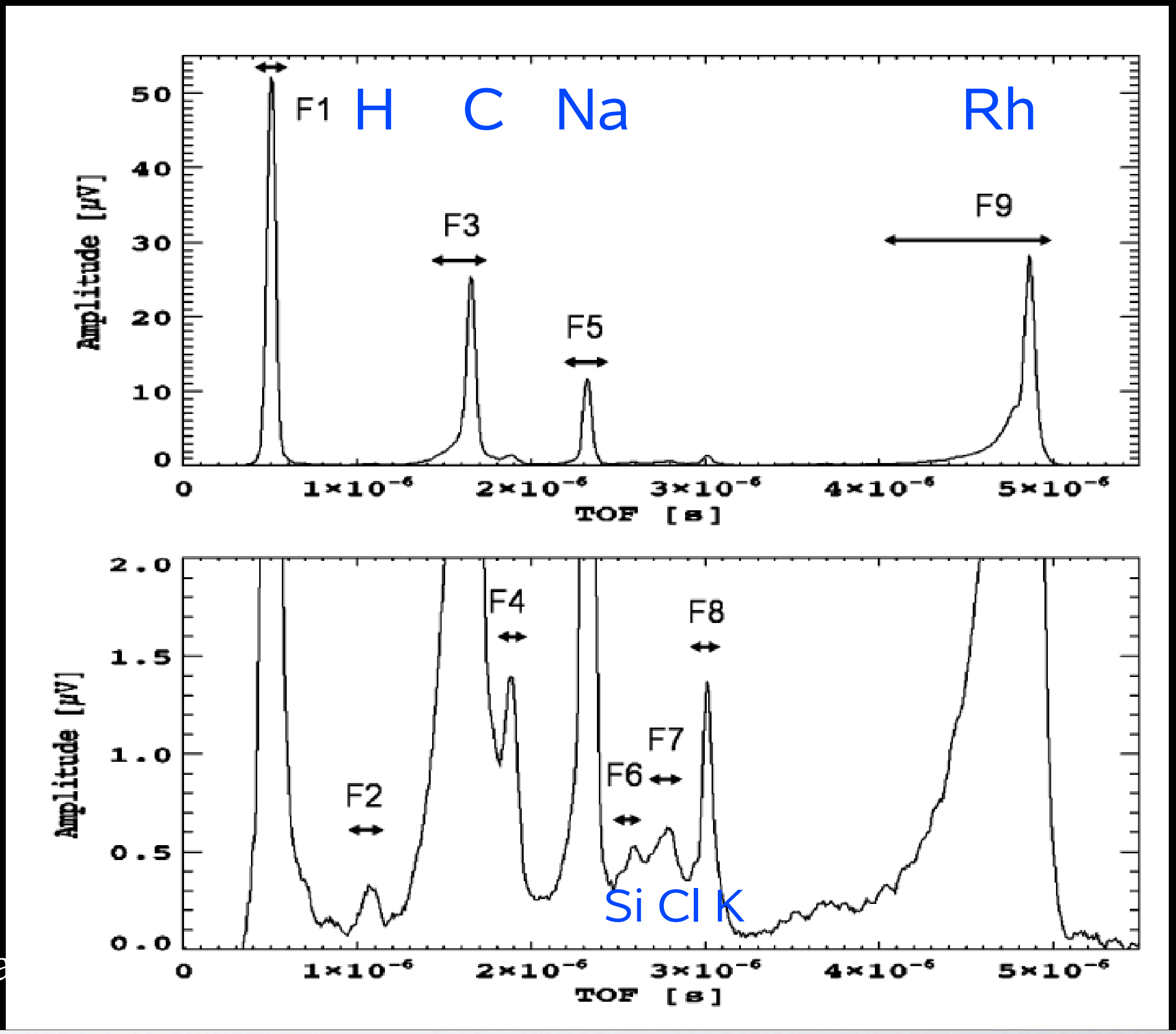




Grain speeds ~ 300 km/s

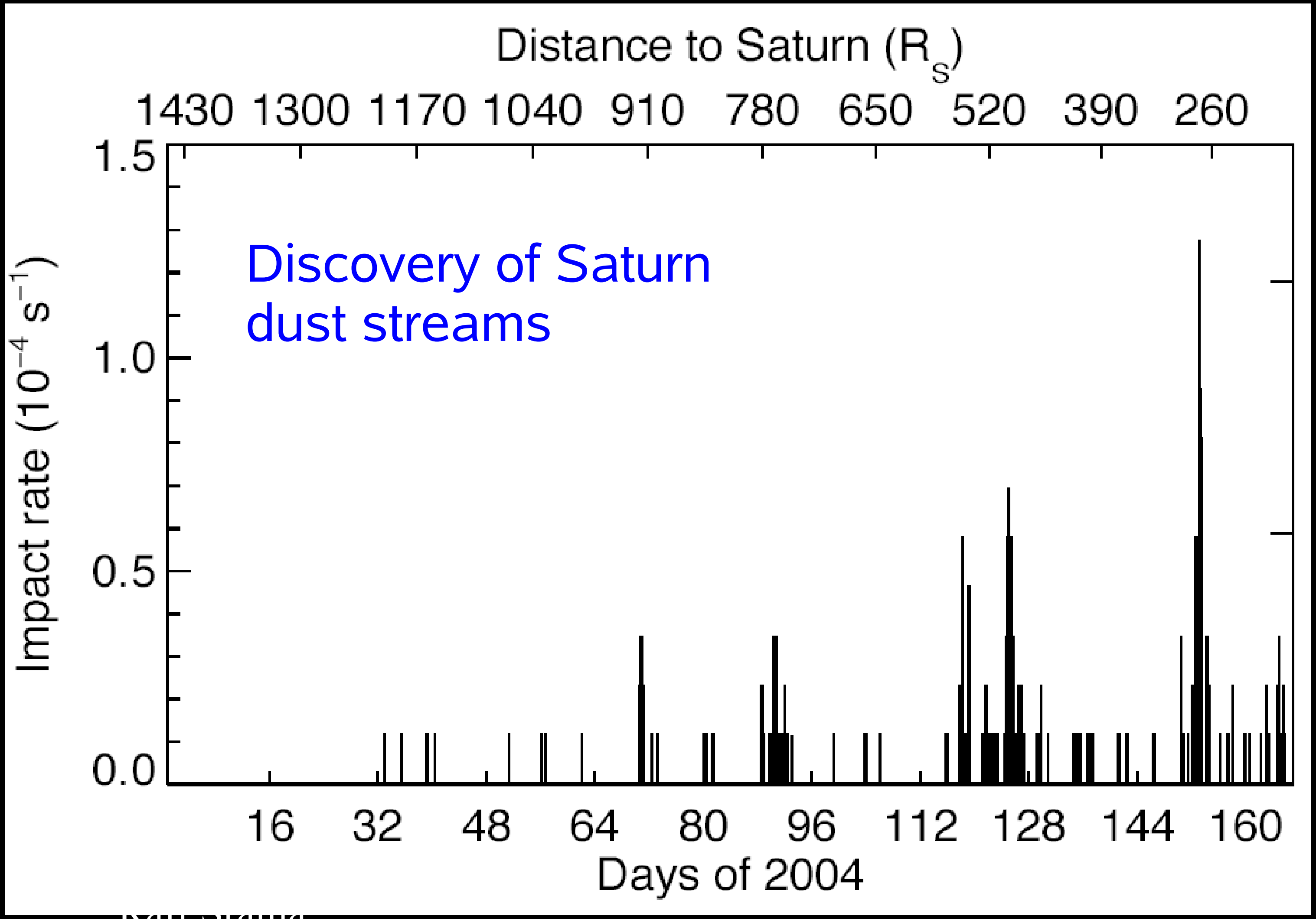
Grain sizes ~ 10 nm

Composition: sulphur, sodium, silicates ?

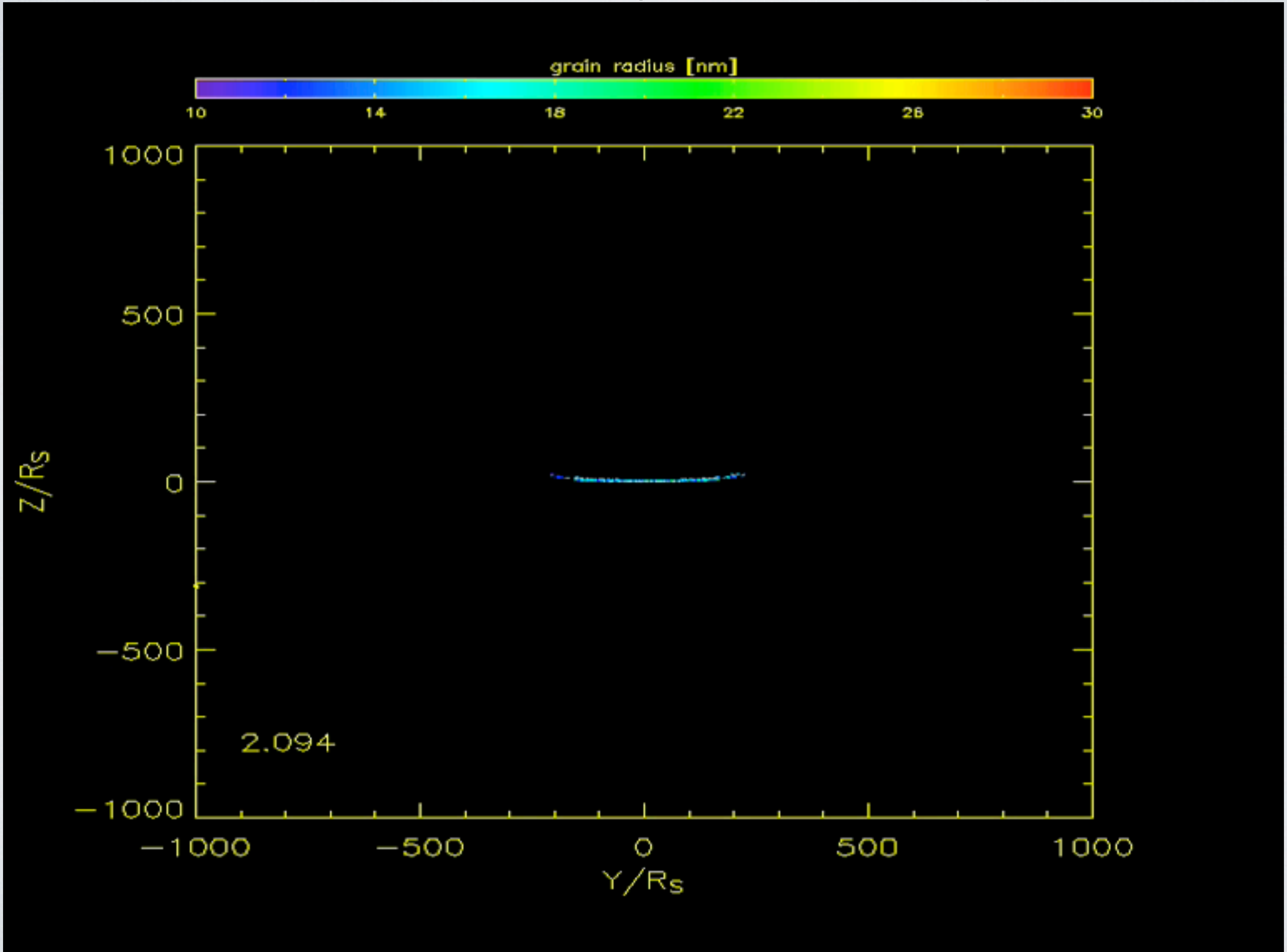


CDA Science Highlights I (Cruise)

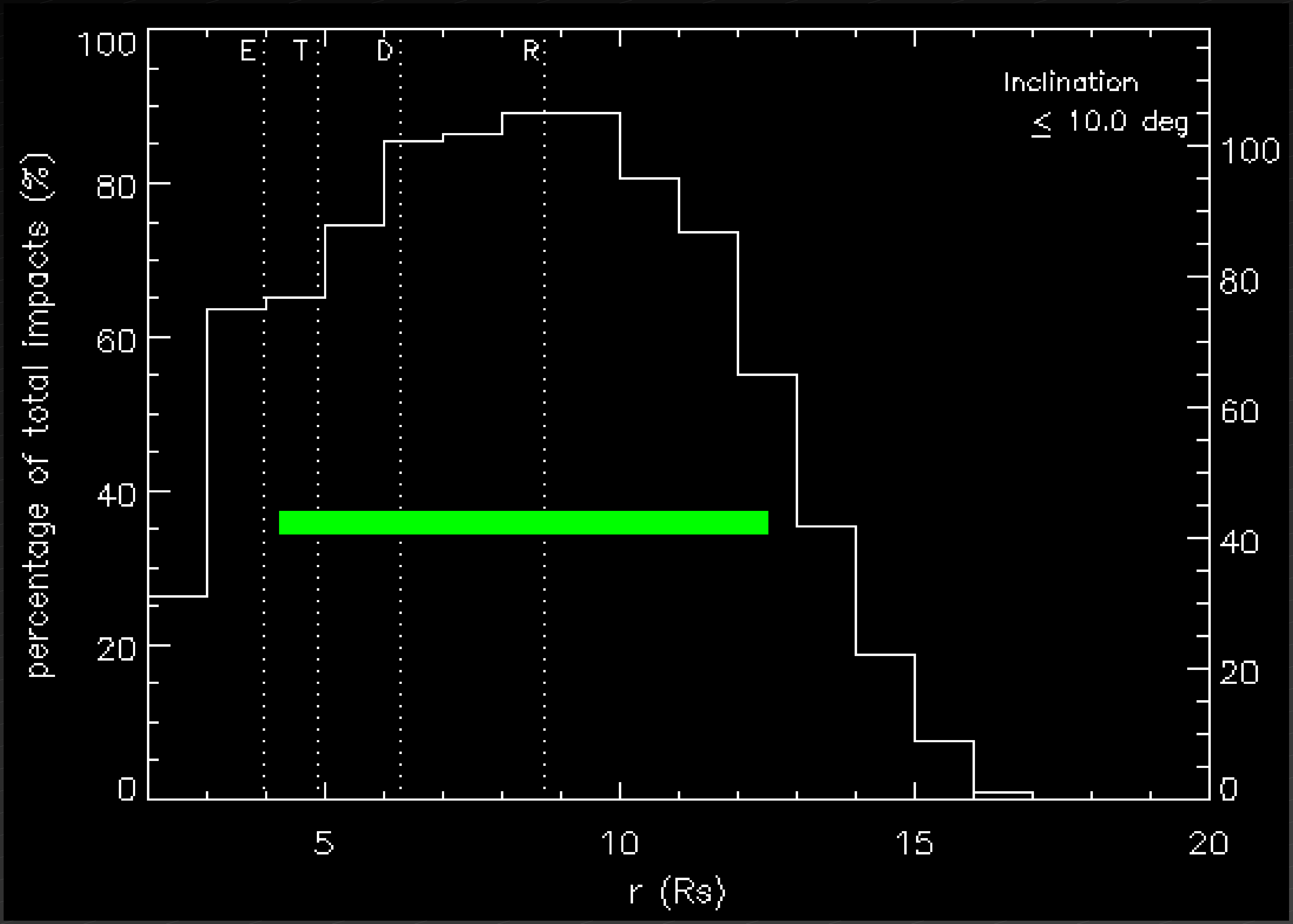
- Streams of nano-dust from Saturn : Discovery, compositon and dynamics, coupling between CIRs/CMEs and dust stream dynamics (S. Kempf, Nature)
- Origin of particles detected during the approach to Saturn is the A ring
- Composition of these particles: silicates



SIMULATION OF ESCAPING DUST STREAMS FROM SATURN (M. HORANYI)

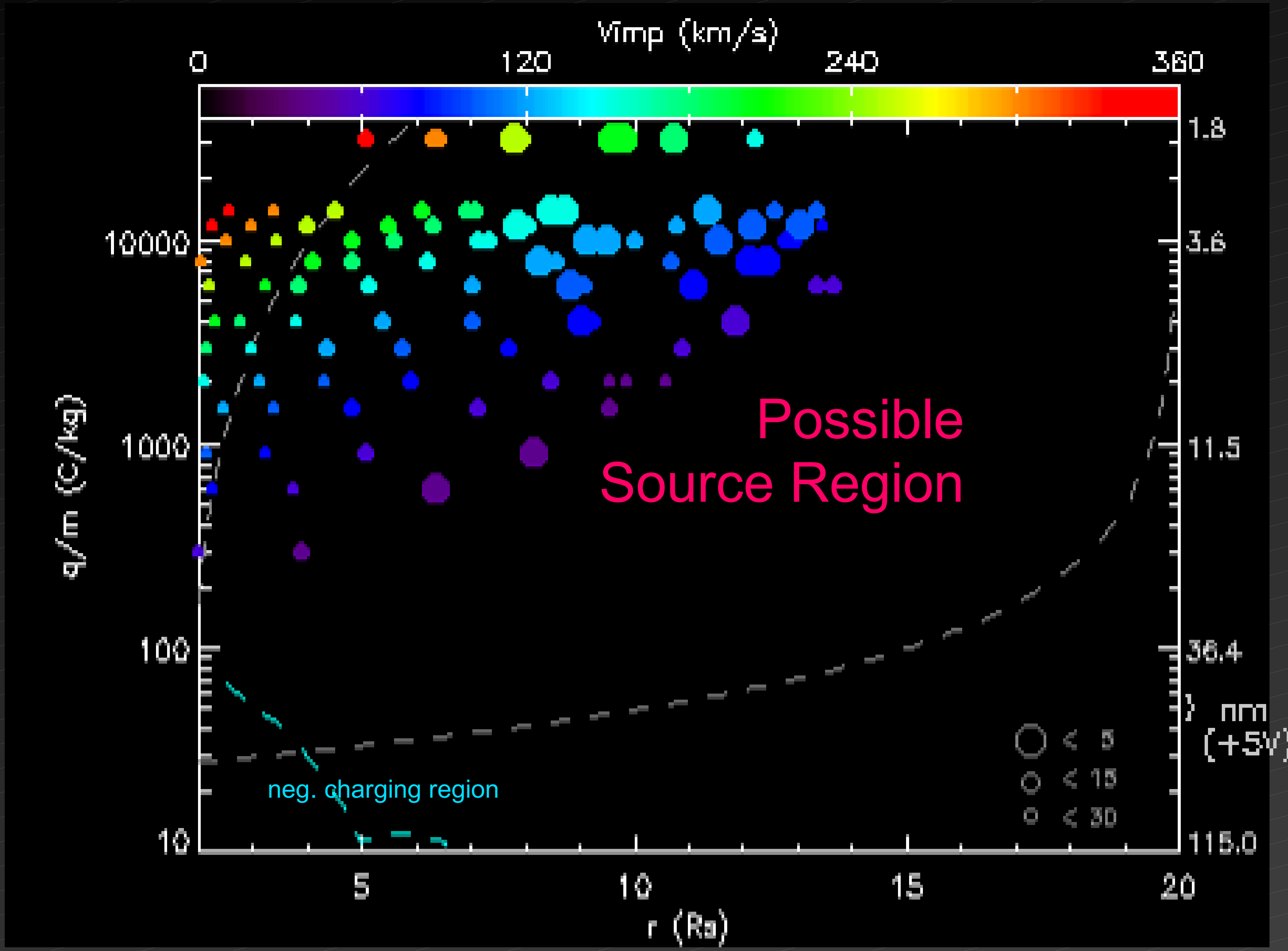


Where do the stream particles originate?



Modelling Stream Particles

Backward tracing of one stream particle impact



Origin ?

Points show solution of one stream particle impact.

- color = speed
- size = inclination

Slower grains started either from regions with greater distances (10 Rs) or they are large.

Particles can be as small as 3 nm.

Example : Composition

COSMIC DUST ANALYZER

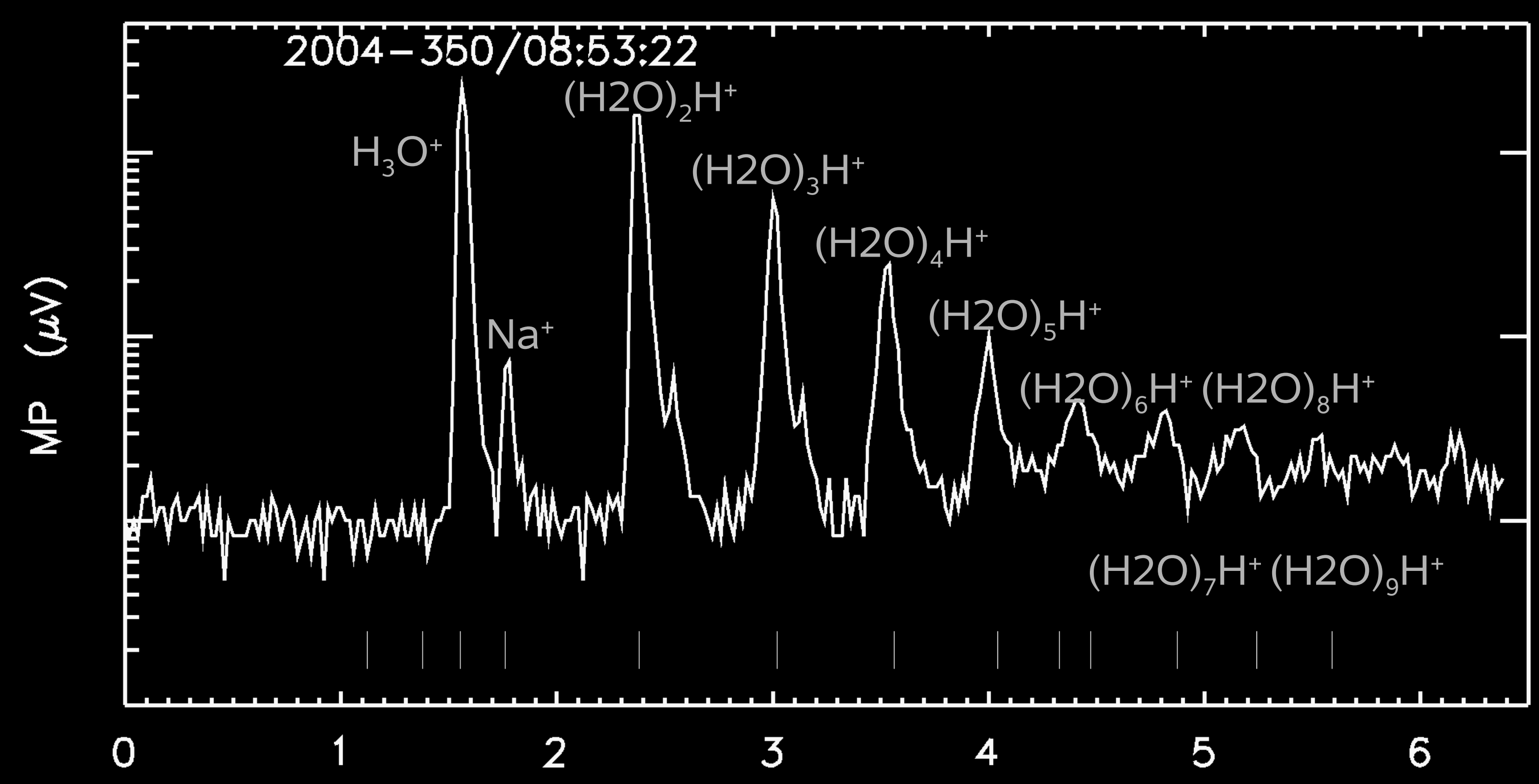
E ring particle composition

- dominated by water ice clusters
- water cluster ions $(H_2O)_xH^+$ with x up to 12
- Some Na, Si, C, Mg
- J. Hillier, F. Postberg
- Two populations:

  pure water ice (source=moon surfaces)

  water ice + silicate (source Enceladus interior?)

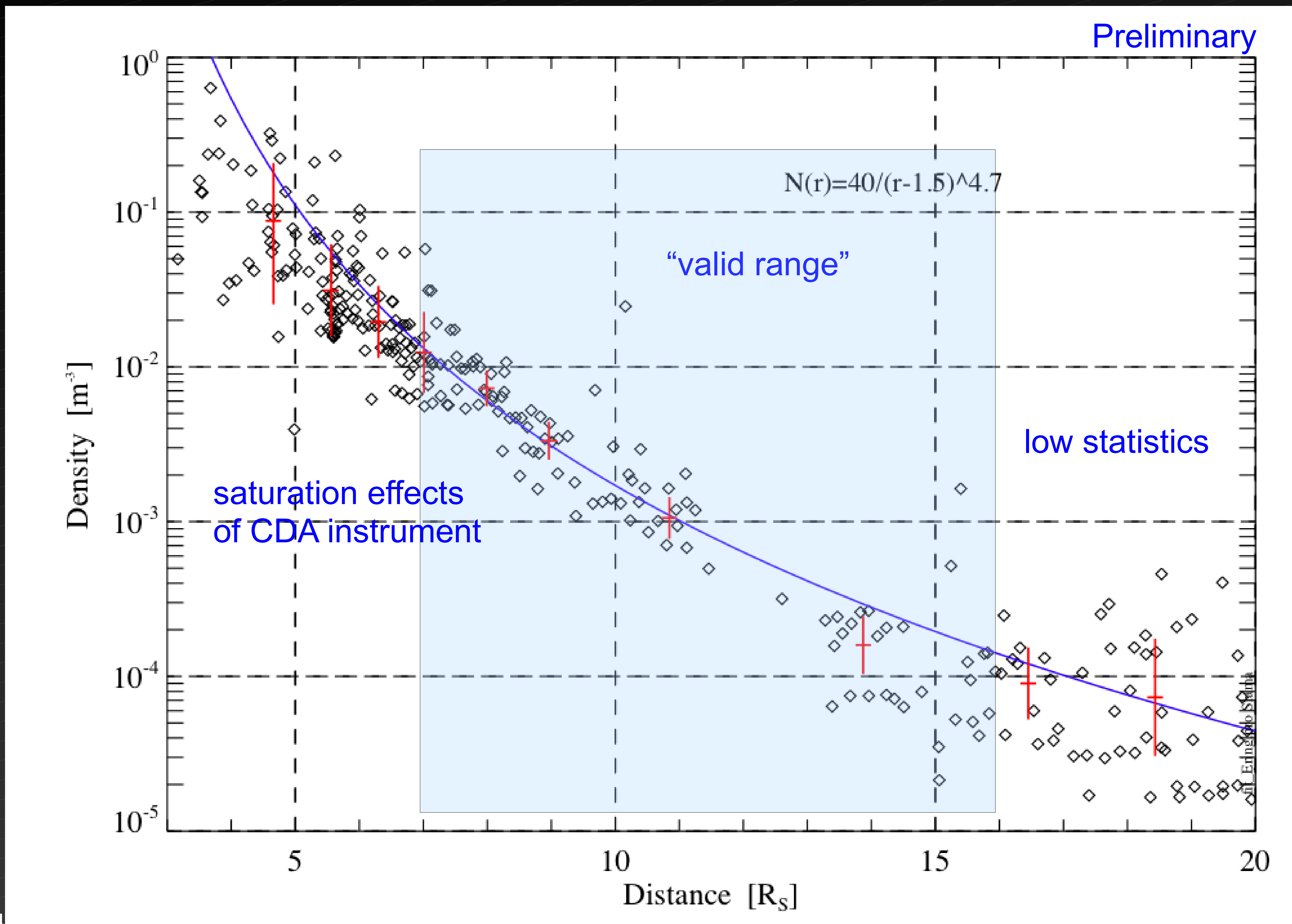
Time-of-Flight spectrum of the impact of an E ring particle



Time μs

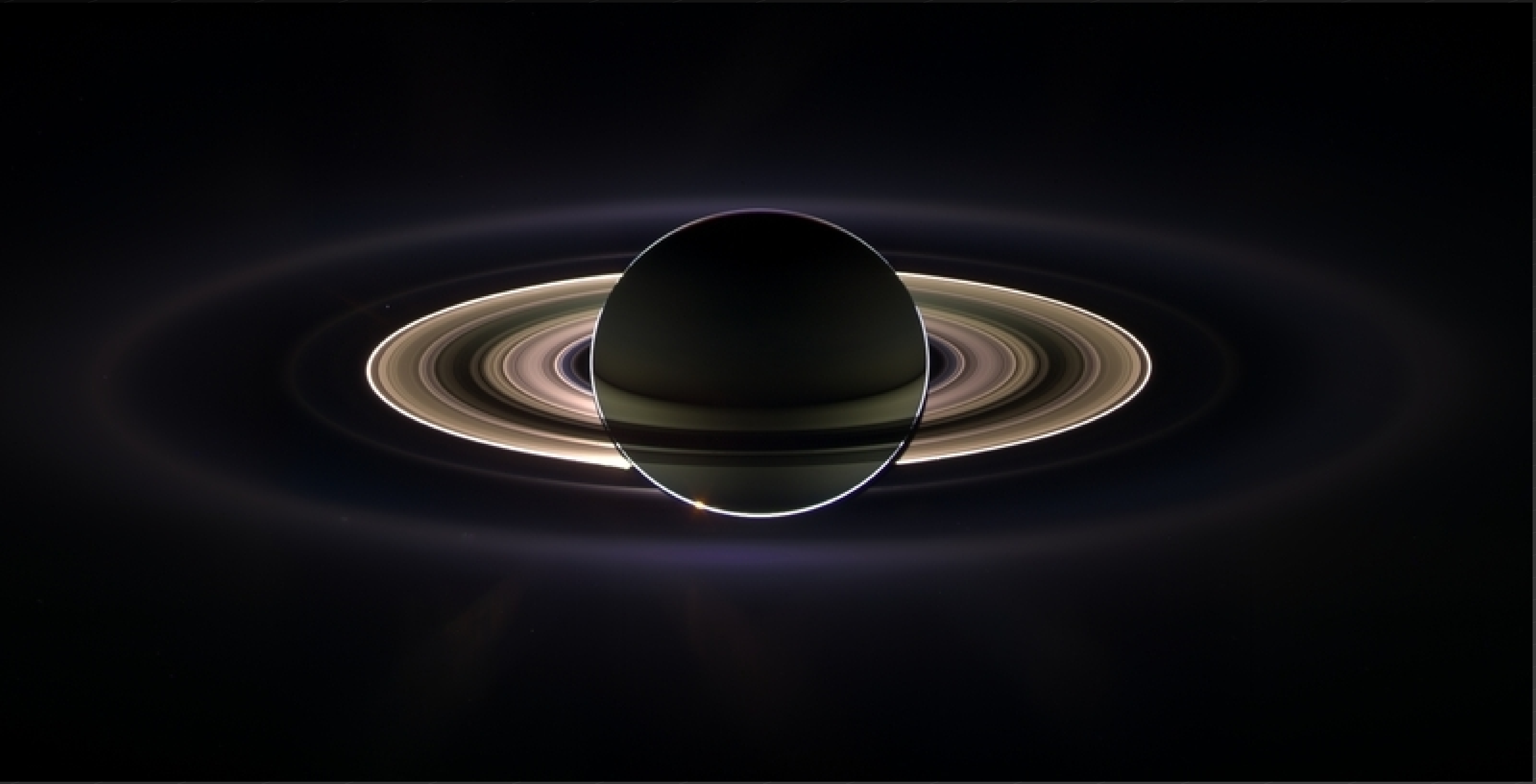
Example : Measure low number densities

Derived dust density in equatorial plane, 5 to 18 Rs
High uncertainty inside 6 Rs and outside 16 Rs



Comparison : Optical measurements

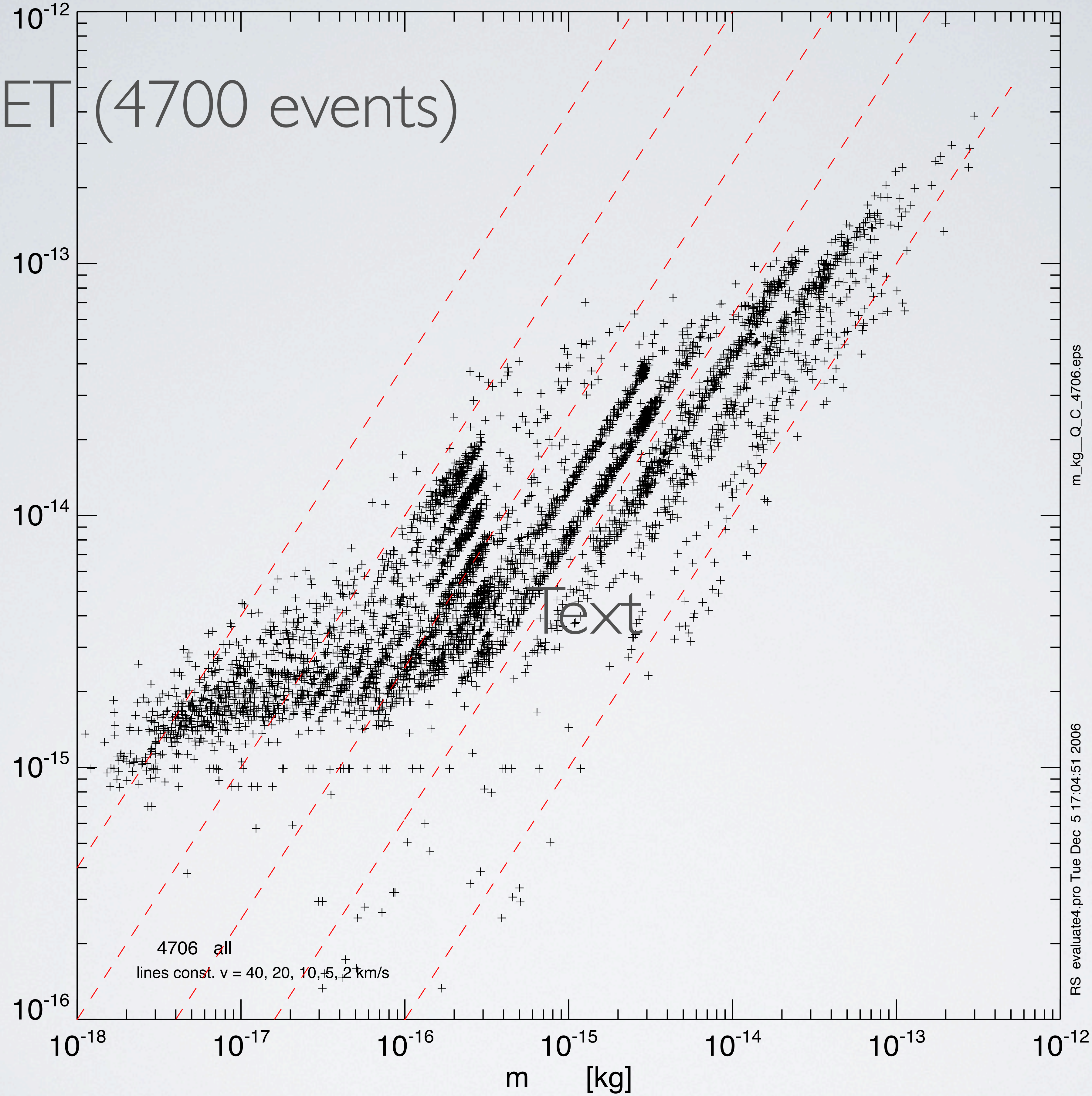
The E-Ring



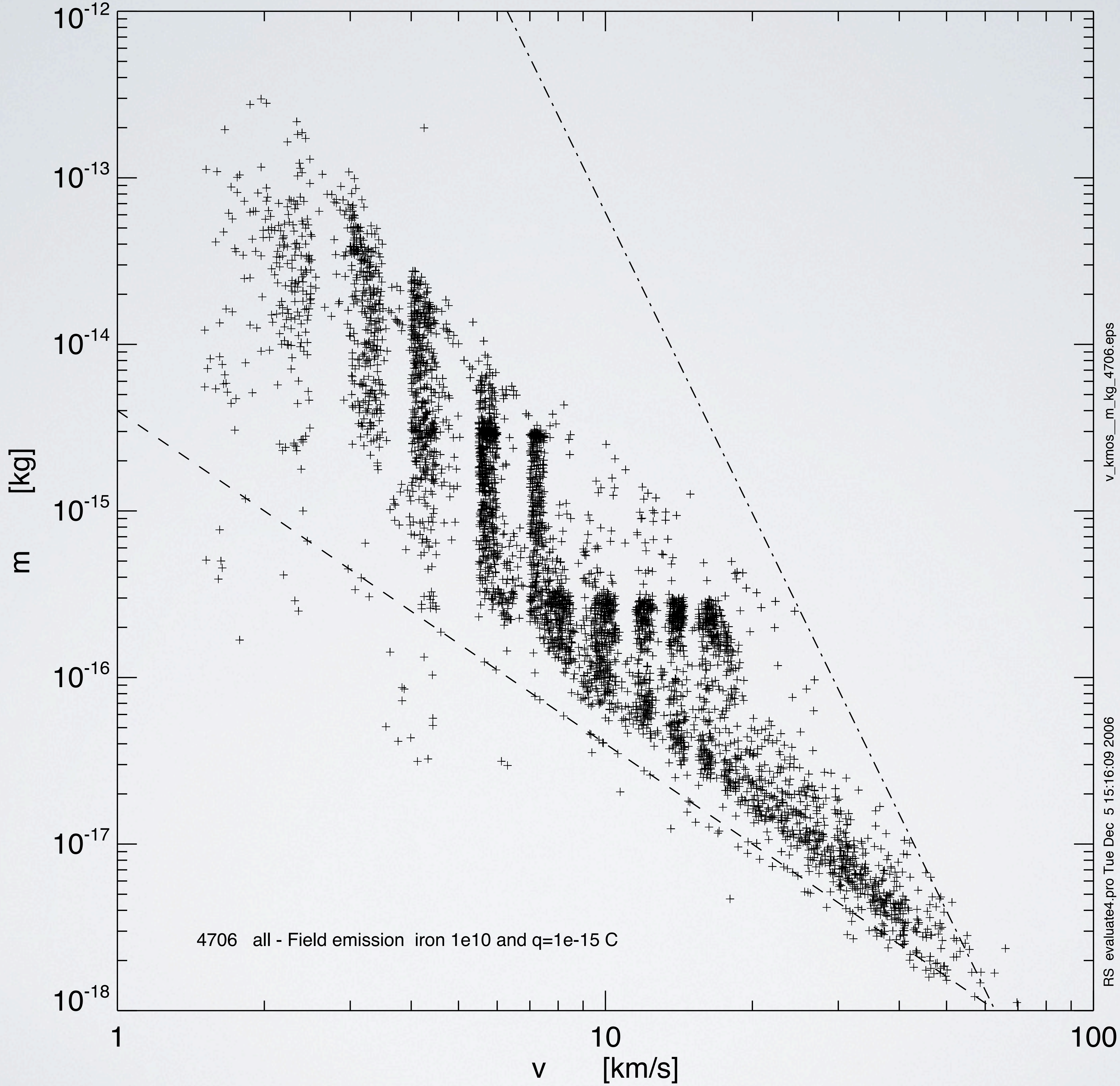
NEW CALIBRATION ONSET
(MITIGATE ACCELERATOR BIAS)

- No law of $Q \sim m^a v^b$
- Use hyperplane fit to phase space of v, Q, m
- reduce order to ensure monotonie
- cover entire speed, charge, mass range

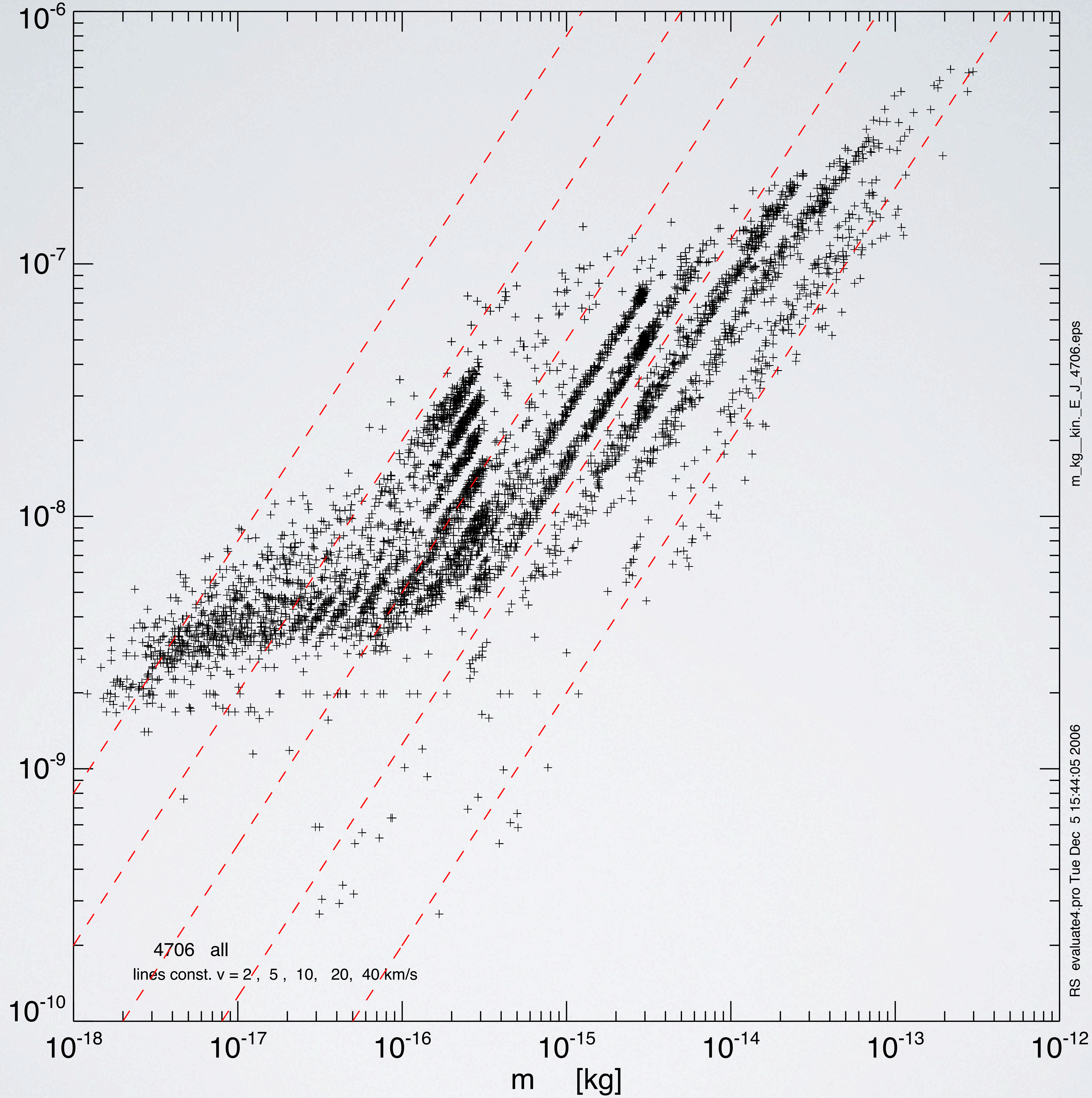
DATA SET (4700 events)



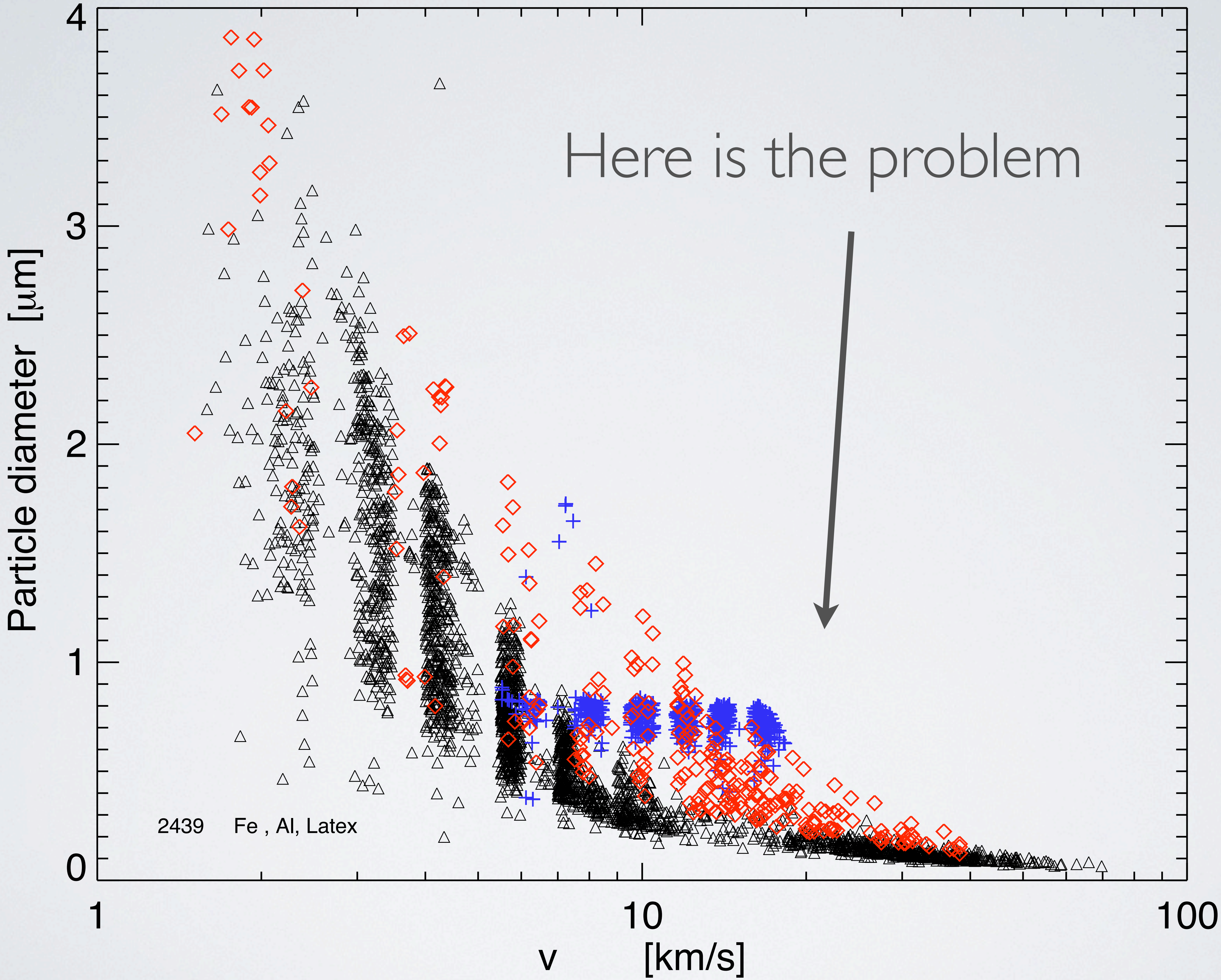
Dashed lines indicate particles with a constant speed of 40 kms−1, 20 kms−1, 10 kms−1, 6 kms−1 and 2 kms−1



10^-12
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
m [kg]
1
10
100
v [km/s]
4706 all - Field emission iron 1e10 and q=1e-15 C
v_kmos__m_kg_4706.eps
RS evaluate4.pro Tue Dec 5 15:16:09 2006



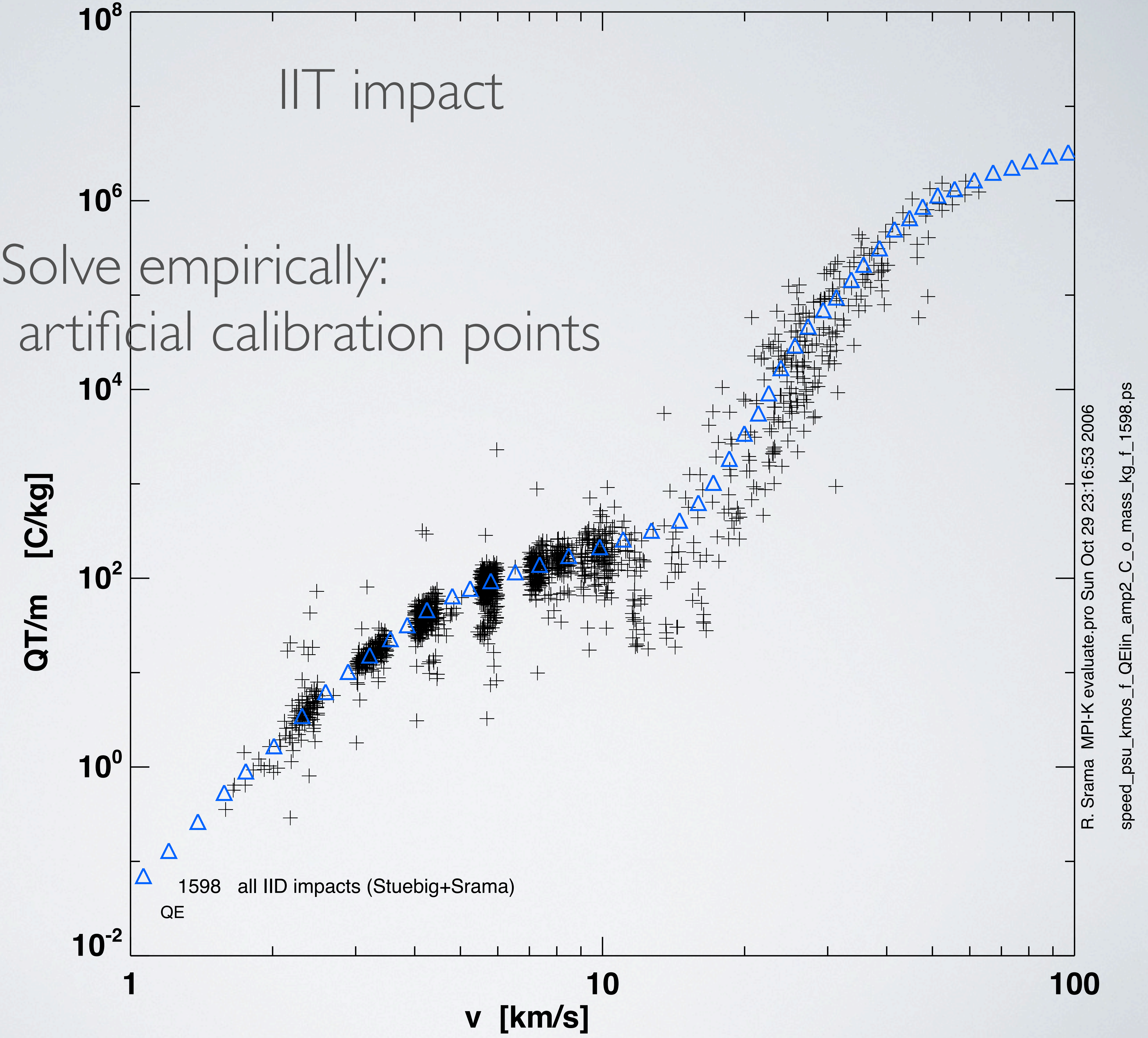
dashed lines indicate constant impact speeds of 40, 20, 10, 6, 2 kms−1

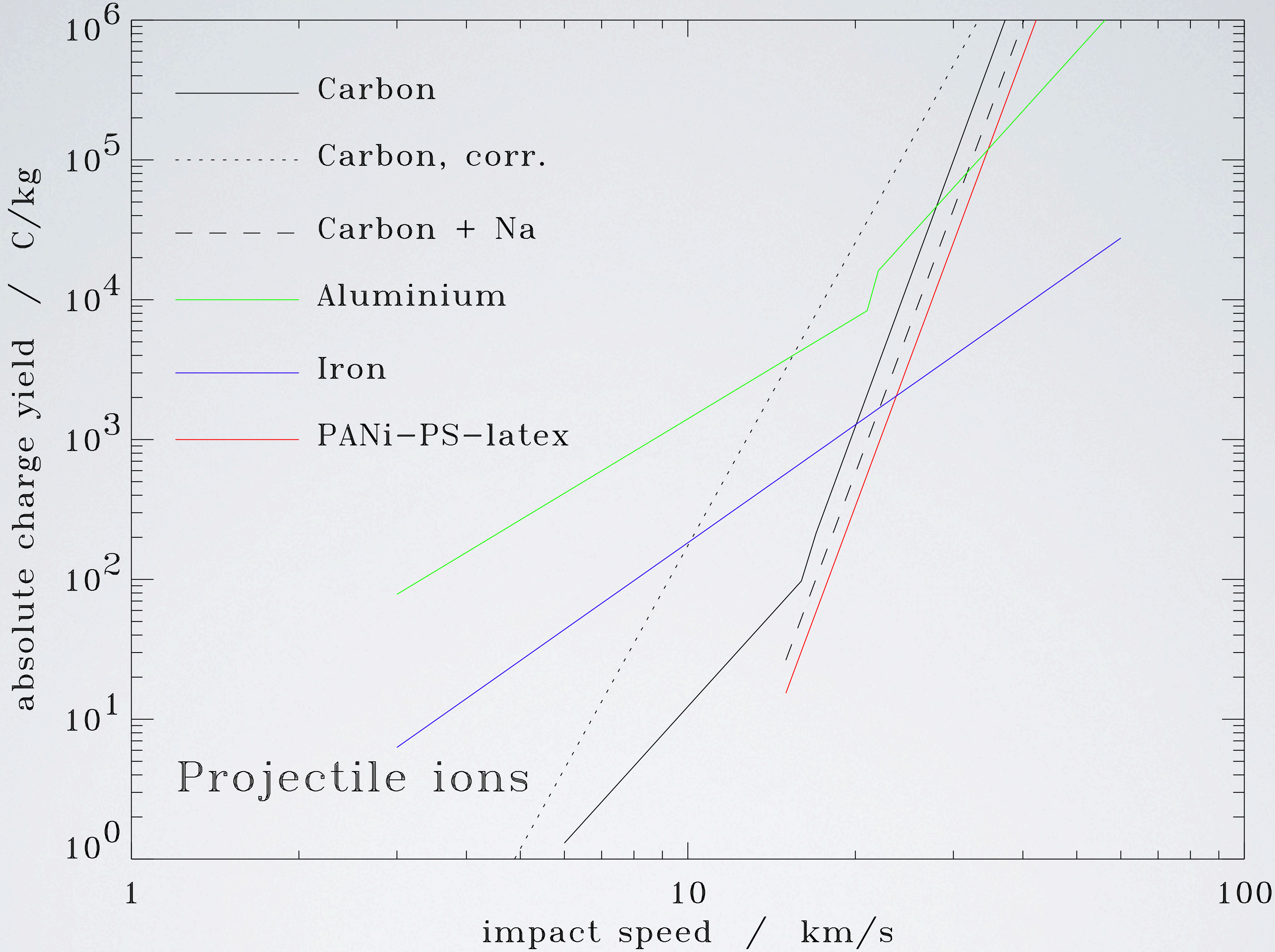


Here is the problem
Particle diameter [μm]
0
1
2
3
4
1
10
100
v [km/s]
2439 Fe , Al, Latex

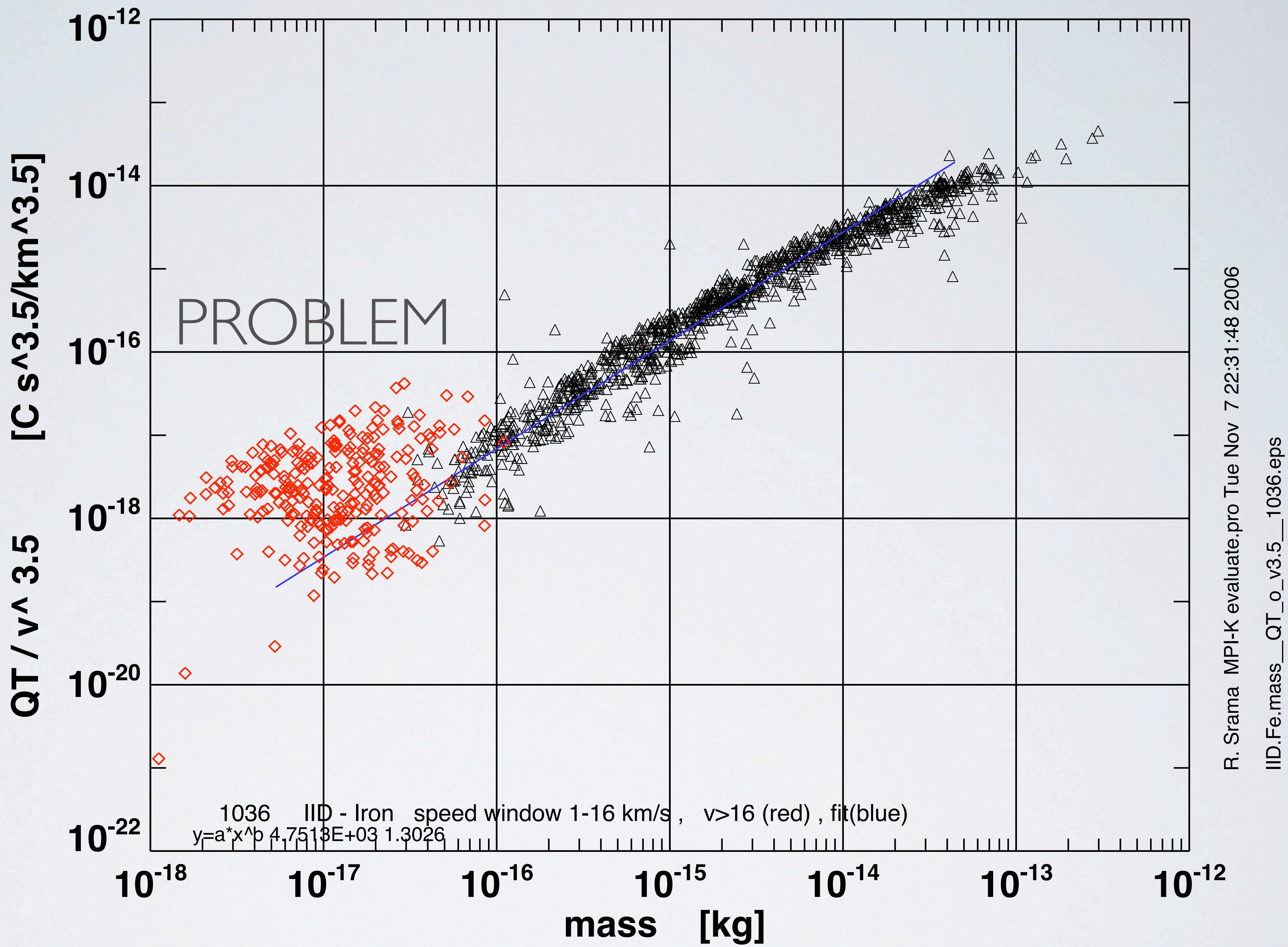
IIT impact

Solve empirically:
introduce artificial calibration points





CONSERVATIVE SOLUTION



$$\frac{QT}{v^{3.5}} = 4751 \cdot m^{1.30} \implies m = \frac{QT^{0.769}}{672 \cdot v^{2.69}}$$

HOW TO SOLVE?

- Generated charge Q is function of impact speed v
- Generated charge Q is function of projectile mass m

NEW APPROACH

of degree n to a surface and returns a parameter array k_x. The hyperplane function is defined in Eq. 3.19:

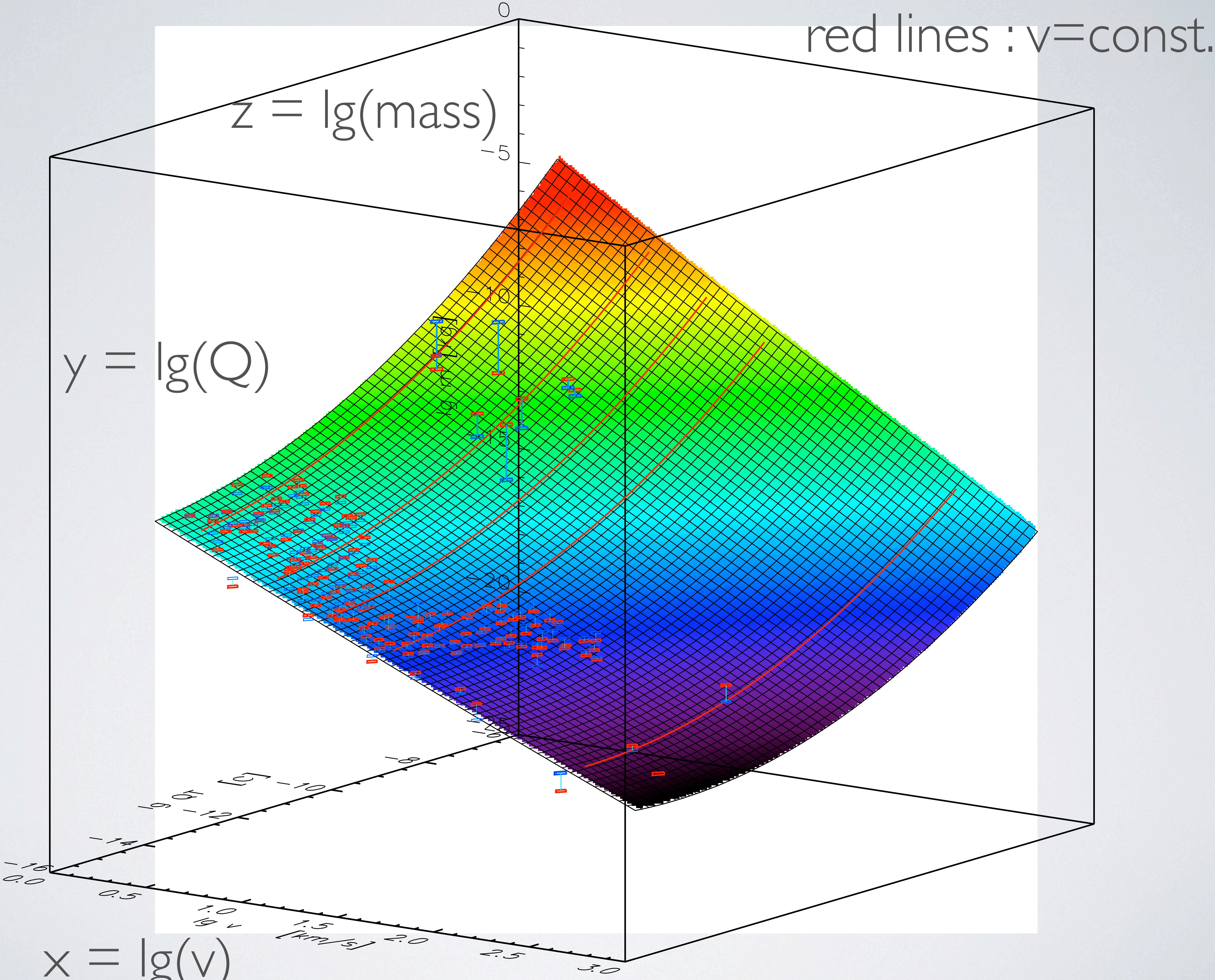
$$f(x,y) = \sum_{i,j=0}^{n} k_{j,i} \cdot x^i \cdot y^j \tag{3.19}$$

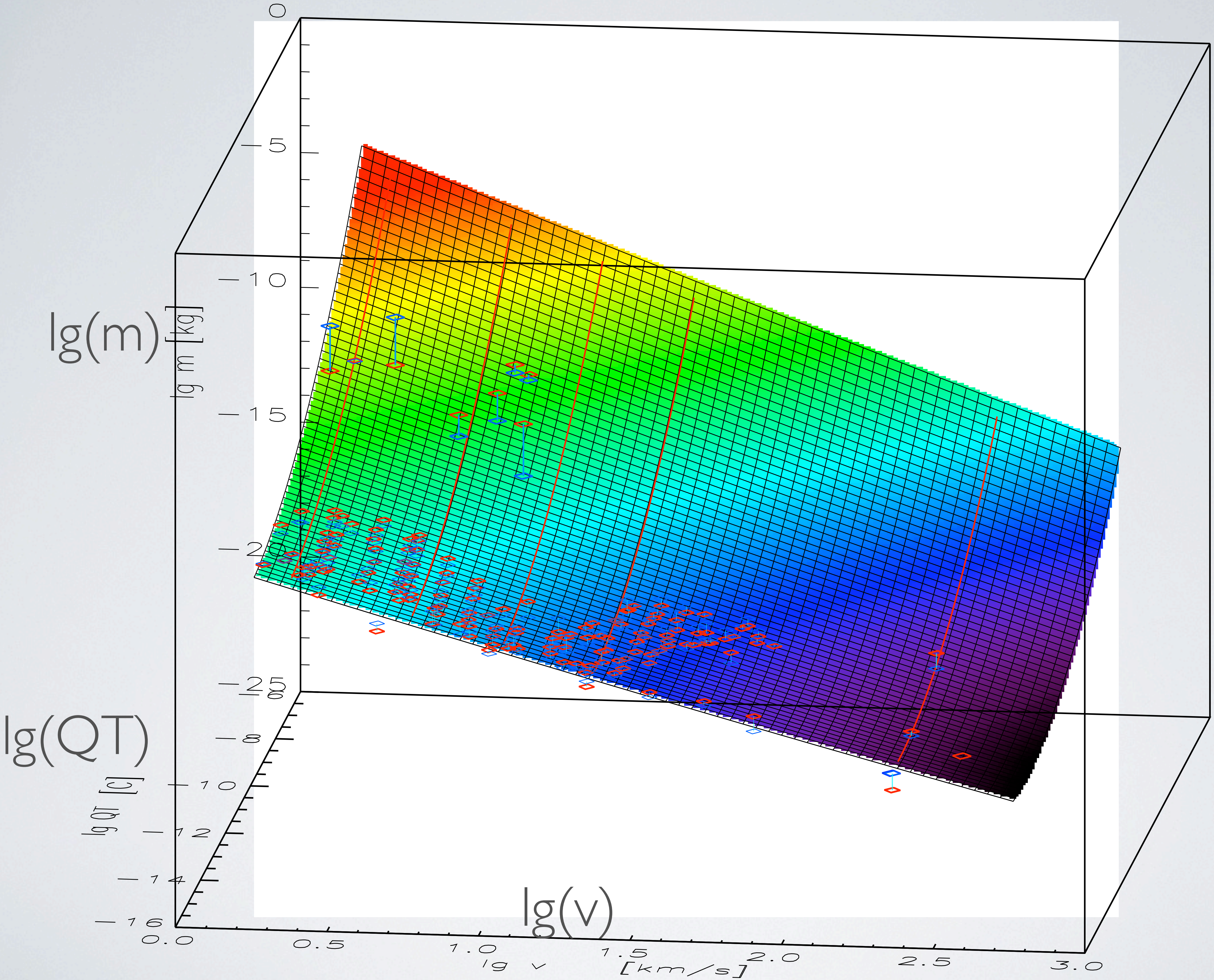
In our case, fits with a maximum degree of two are sufficient to fit the data accurately and the simplified formula uses only six parameters (Eq. 3.20):

$$f(x,y) = k_0 + k_1 \cdot y + k_2 \cdot y^2 + k_3 \cdot x + k_4 \cdot x \cdot y + k_5 \cdot x^2 \tag{3.20}$$

The function f(x,y) is nothing else than our dust mass m (in kg), whereas x is the impact speed v (in $\mathrm{km\,s^{-1}}$) and y is the impact charge Q (in C). Before applying the fit formula, we have to take the logarithms of the values of v and m. Then, the impact charge QT of IIT

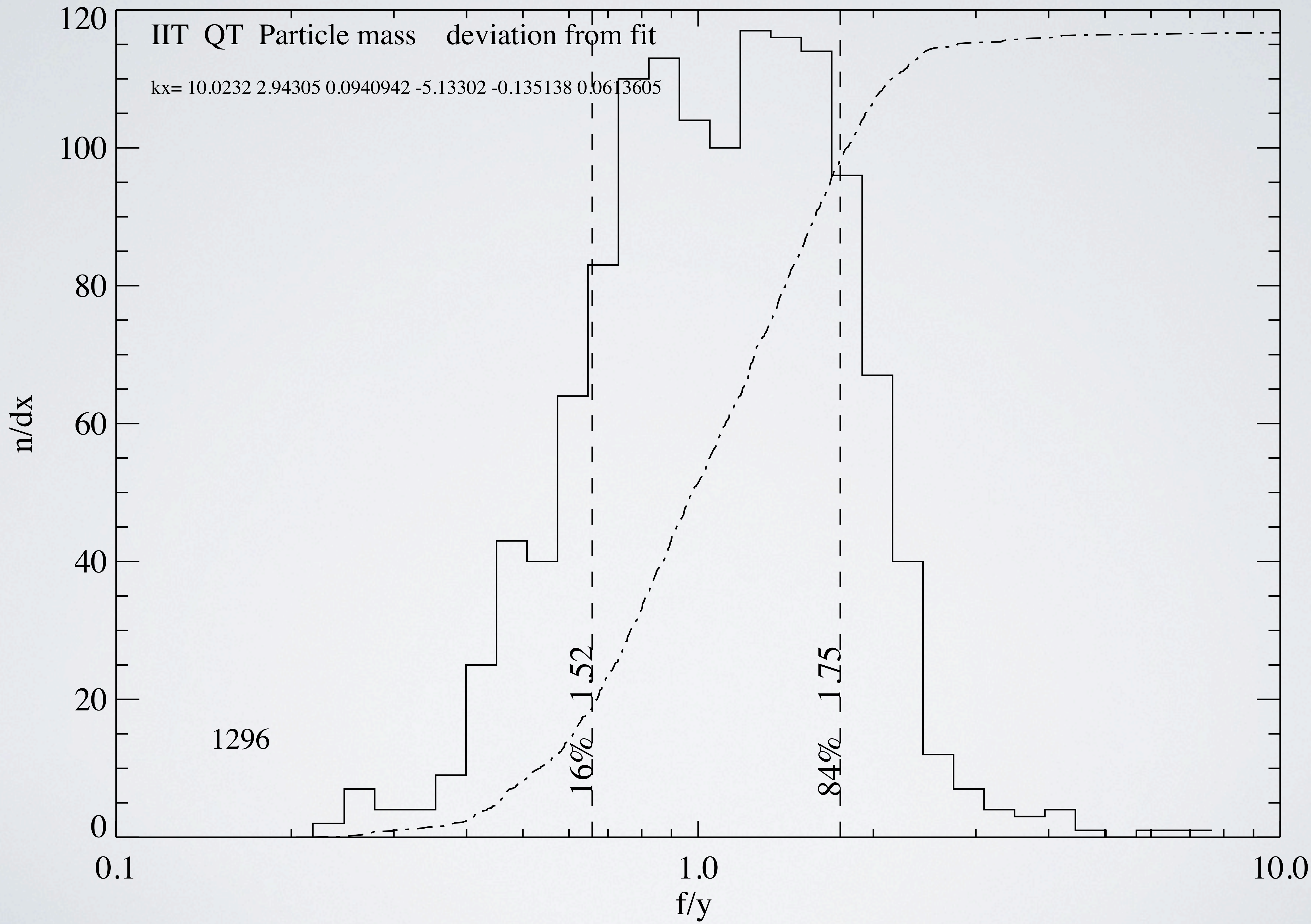
$$\begin{aligned} log(m_{QT}) \quad = \quad & 10.02 + 2.943 \cdot log(QT) + 0.0941 \cdot (log(QT))^2 - 5.133 \cdot log(v) - \\ & 0.135 \cdot log(v) \cdot log(QT) + 0.0614 \cdot (log(v))^2 \end{aligned} \tag{3.21}$$


red lines : v=const.
z = lg(mass)
y = lg(Q)
x = lg(v)
lg m [kg]
lg Q [C]
lg v [km/s]
0
−5
−10
−15
−20
−25
−8
−10
−12
−14
−16
0.0
0.5
1.0
1.5
2.0
2.5
3.0



lg(m)
lg m [kg]
0
−5
−10
−15
−20
−25
lg(QT)
lg QT [C]
−6
−8
−10
−12
−14
−16
lg(v)
lg v [km/s]
0.0
0.5
1.0
1.5
2.0
2.5
3.0

ERROR FACTOR HISTOGRAM



NOW SOMETHING COMPLETELY DIFFERENT:

DEAD TIME CORRECTION OF EVENT RATES

$$n = \frac{n'}{1 - n'\tau}$$

true event rate : n
measured event rate : n‘
dead time : tau

$$n = 8 \cdot ln\left(\frac{0.125}{\frac{1}{n'} - 1} + 1\right)$$

Real case for CDA
Dead time is 8 RTI
1 RTI = 0.125 s
but „RTI grid“

LAB TESTS WITH STOCHASTIC EVENTS

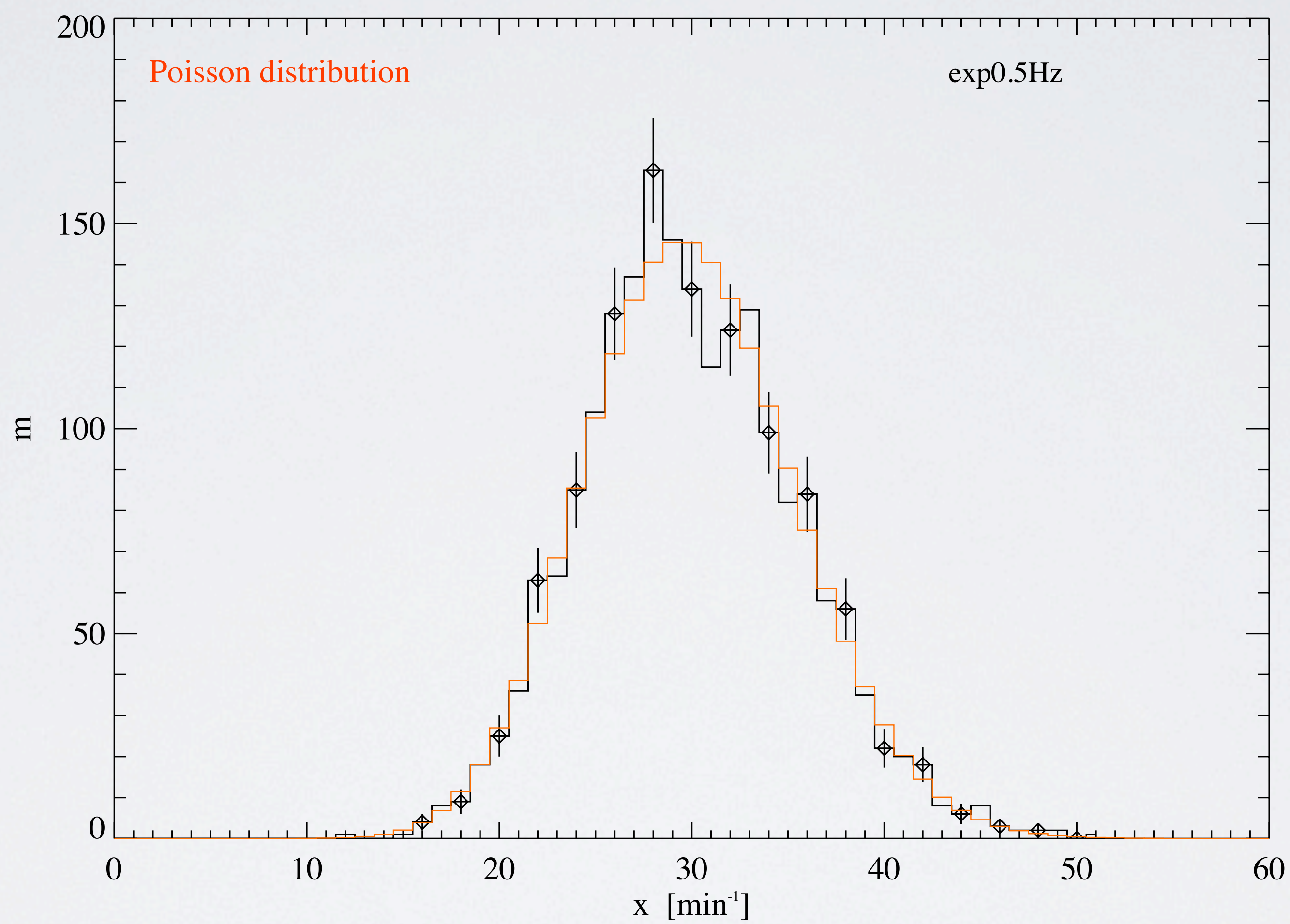
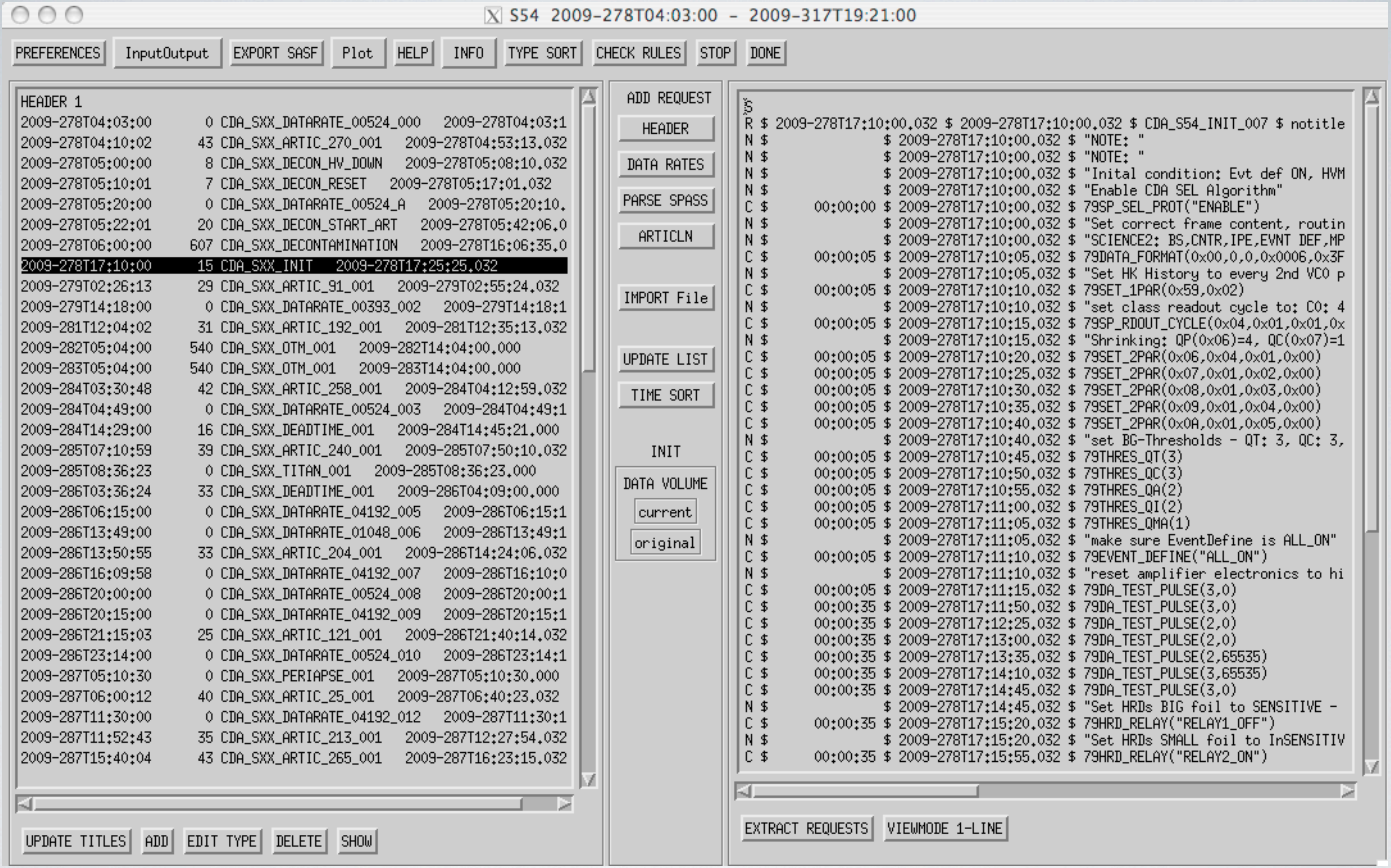


Figure 3.40: Stochastic data set (black histogram) with a maximum at 0.5 Hz and Poisson distribution function (red line). The coincidence verifies the data generation process.

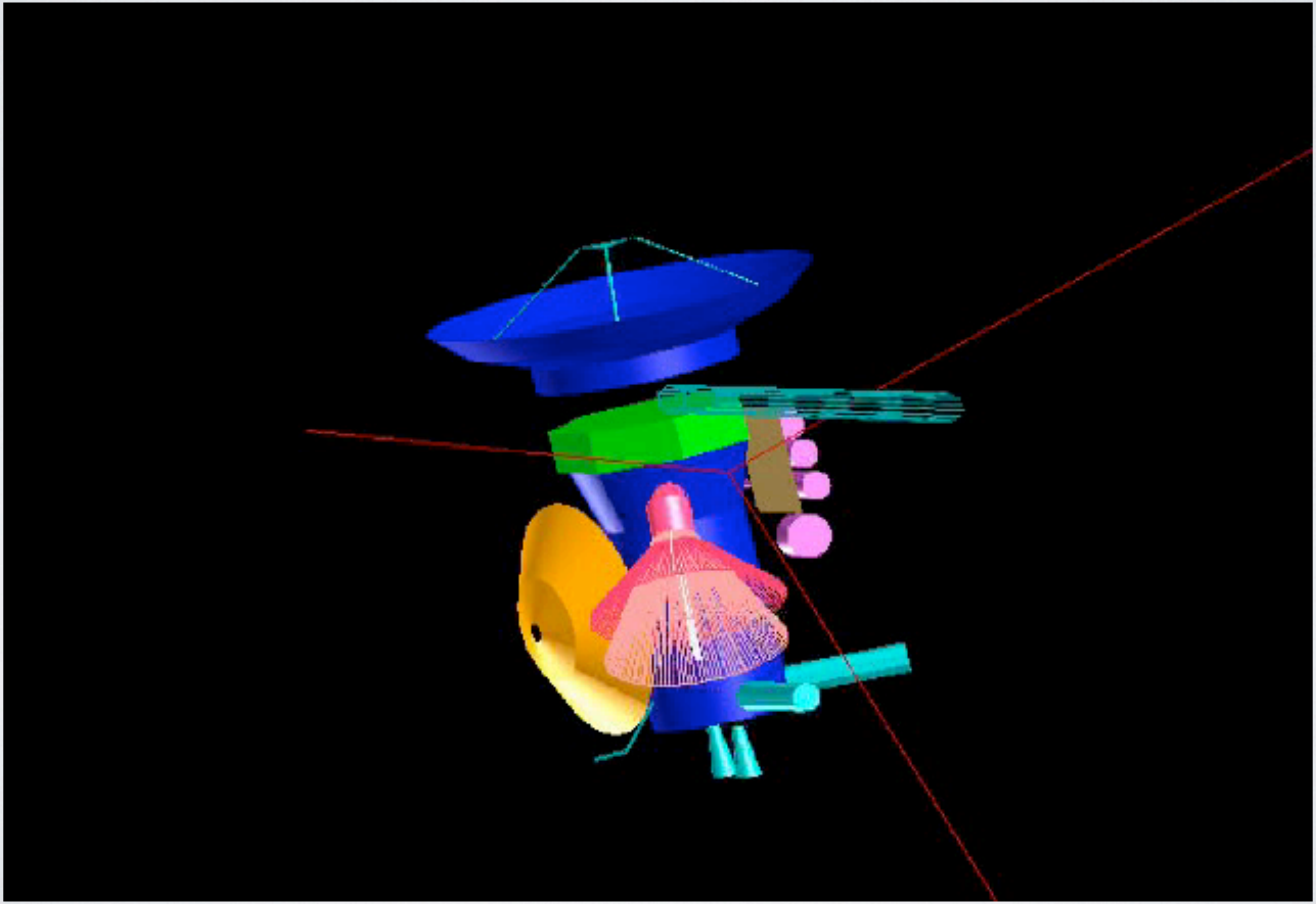
PREPARE FOR DATA RECORDING

- CDA requires high operational efforts
- CDA has to set data rate and POINTING
- CDA has to take care of manoeuvers, telemetry modes, data rates, dead times, operational modes, ...

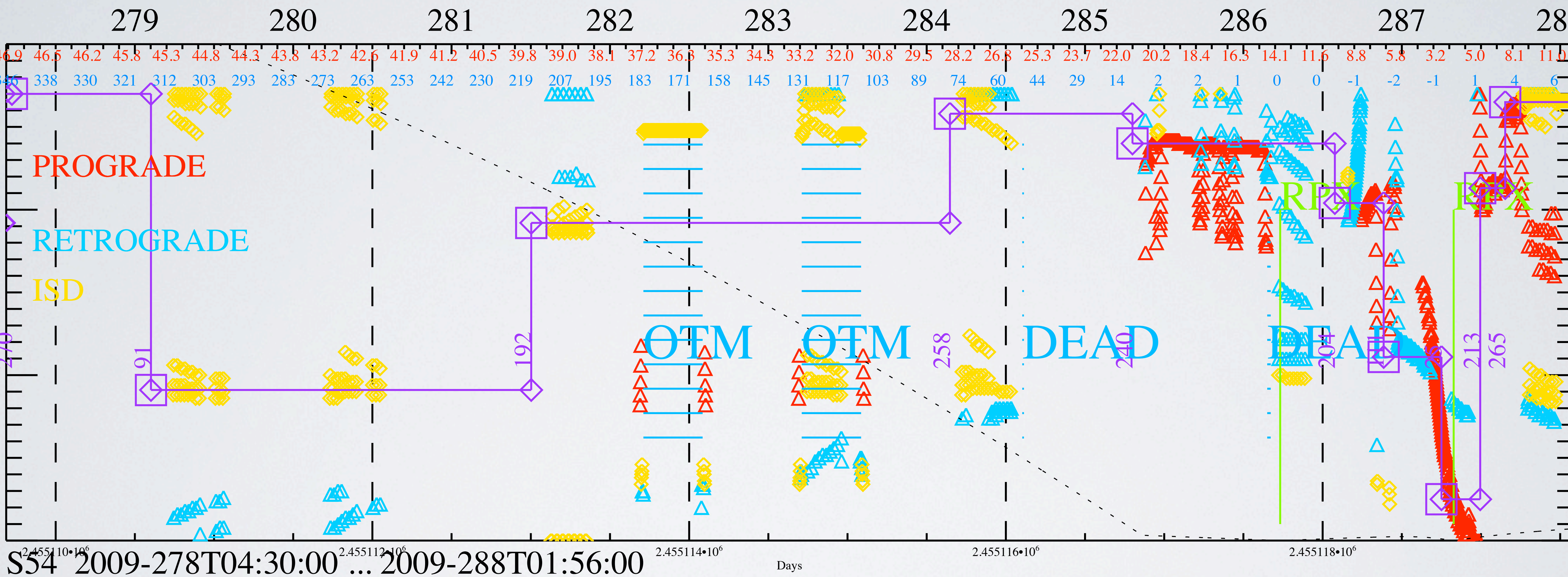


MANY TOOLS DEVELOPED FOR SCIENCE PLANNING AND OPERATIONS

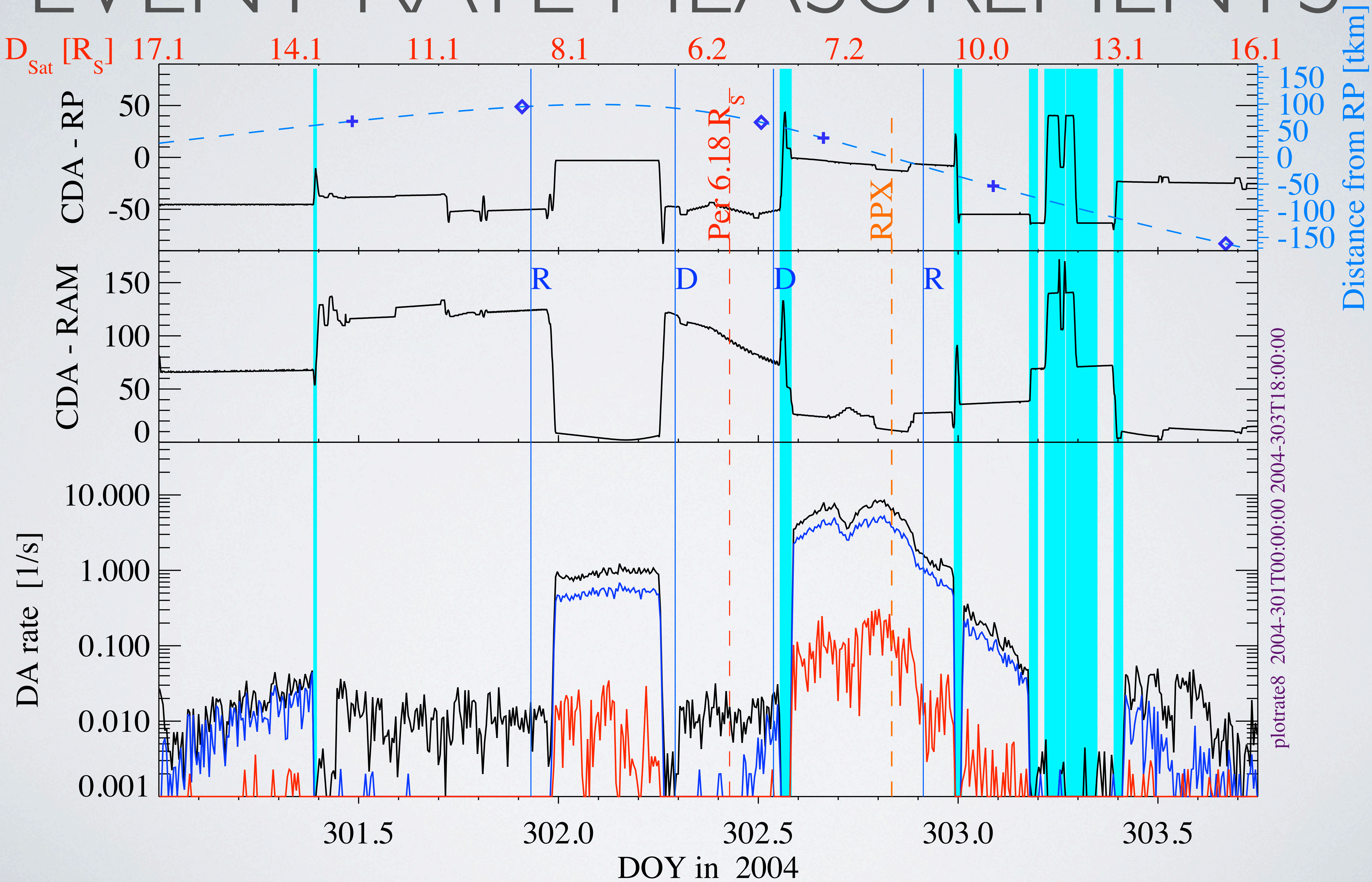
REMINDER: CDA CAN ARTICULATE



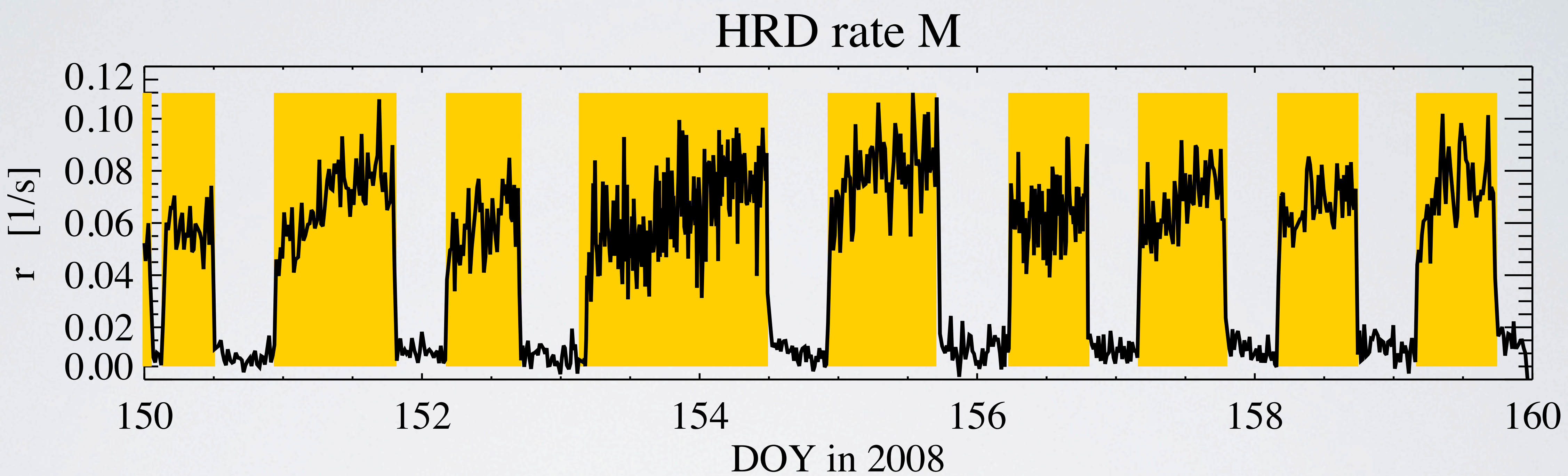
CDA POINTING PLATFORM OPERATIONS

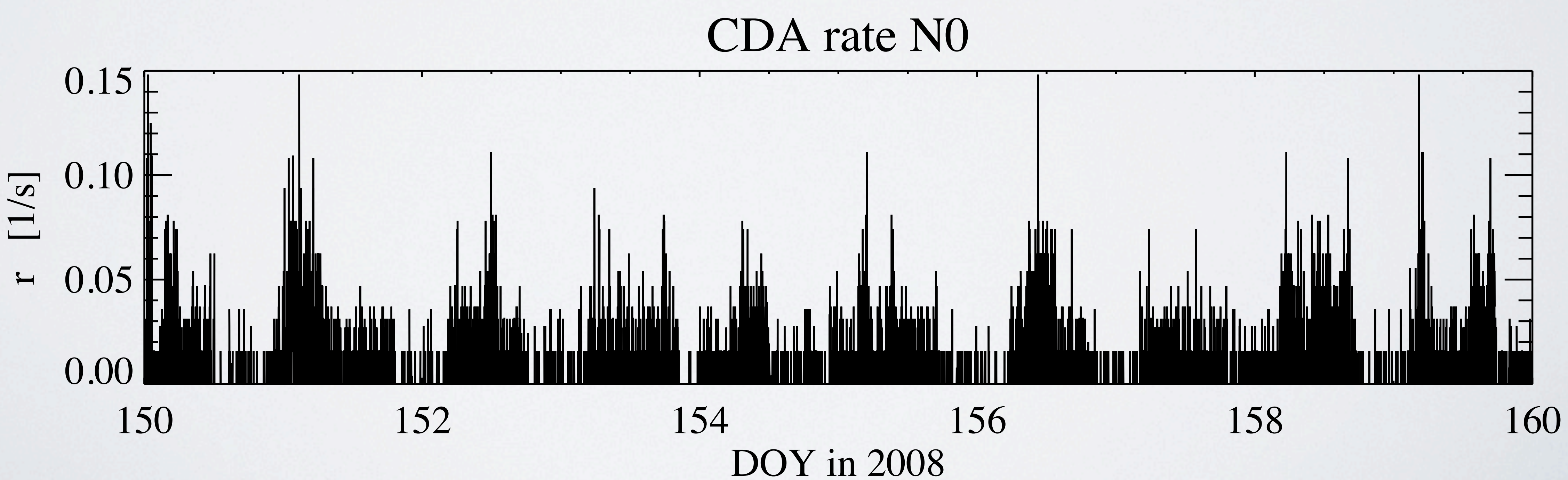


FINALLY: EVENT RATE MEASUREMENTS



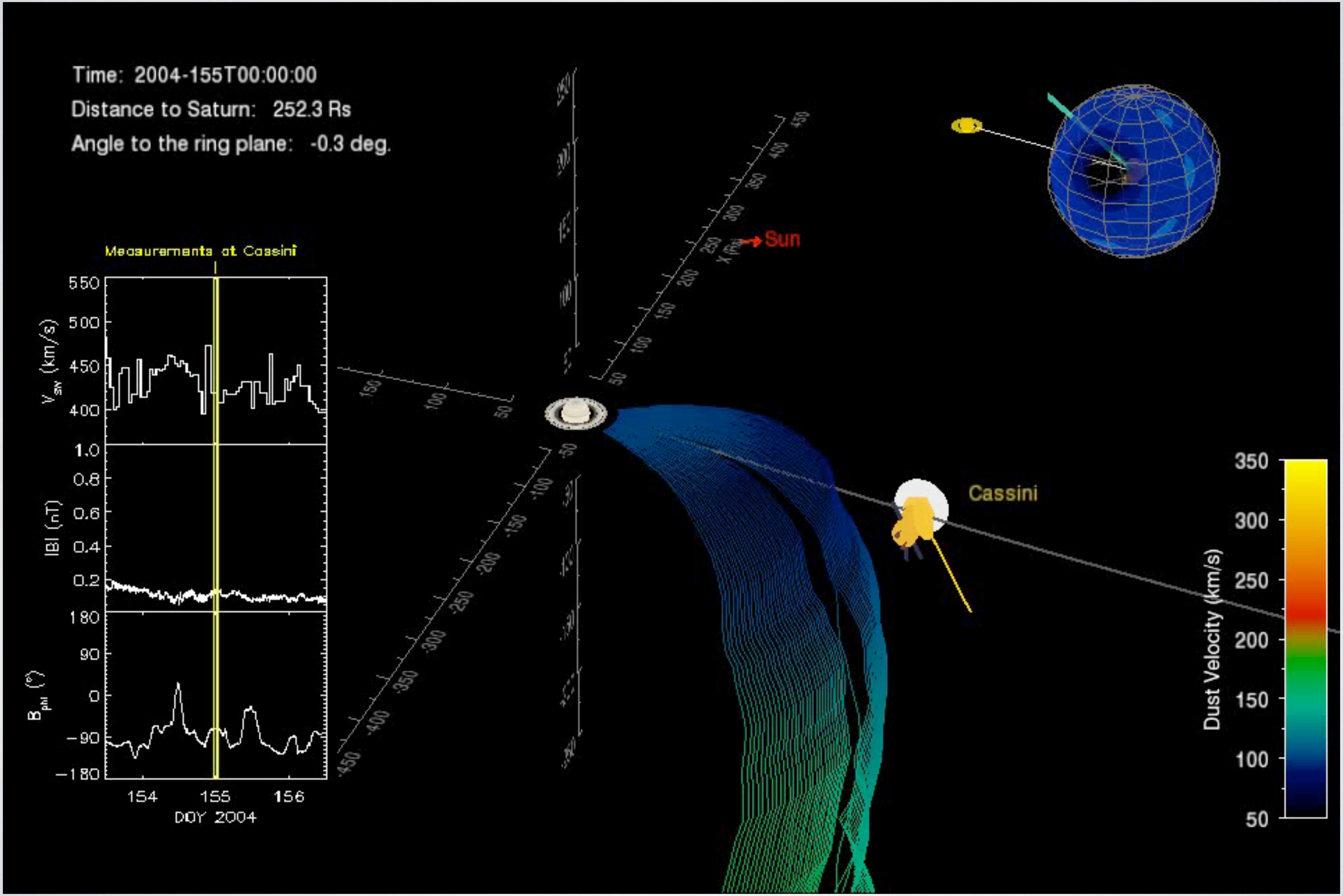
ONE SOURCE FOR NOISE: THE ONBOARD BUS





DUST STREAM MODELING

S. Hsu



OTHER EXAMPLE (WITH ROLL)

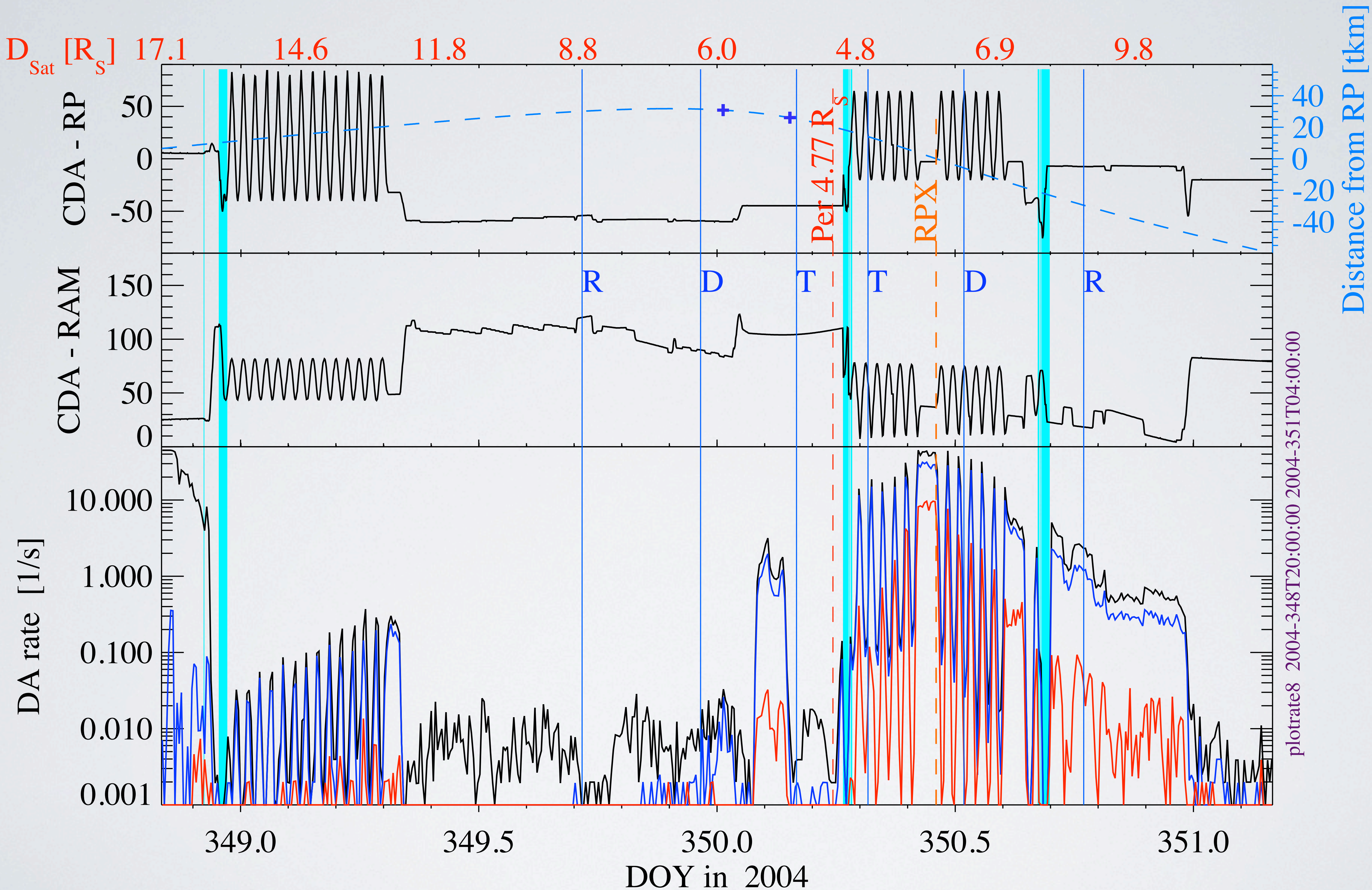
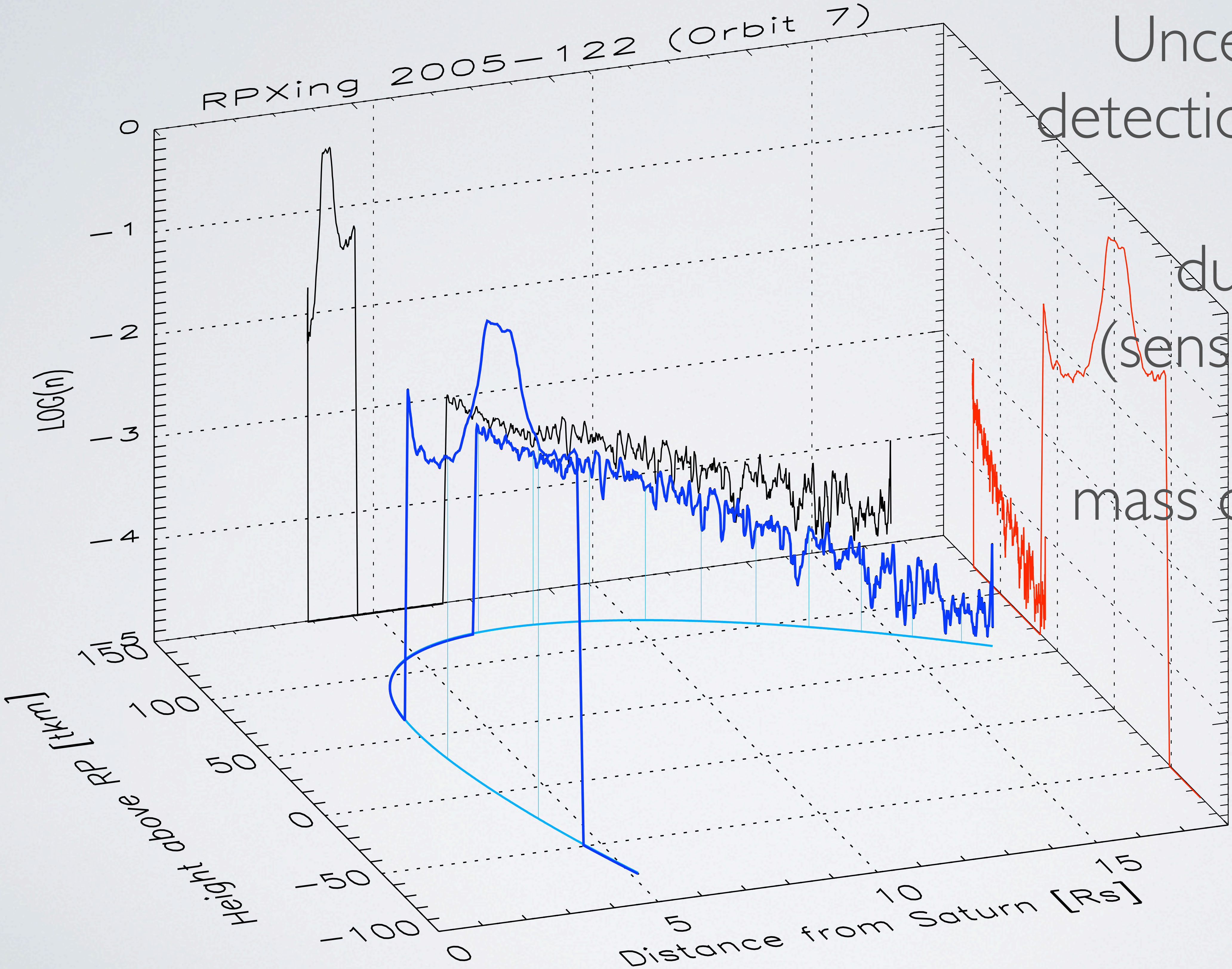


Figure 4.16: CDA pointing and dust impact rates at the inner ring plane crossing in orbit B.

TRANSLATE TO DENSITY...



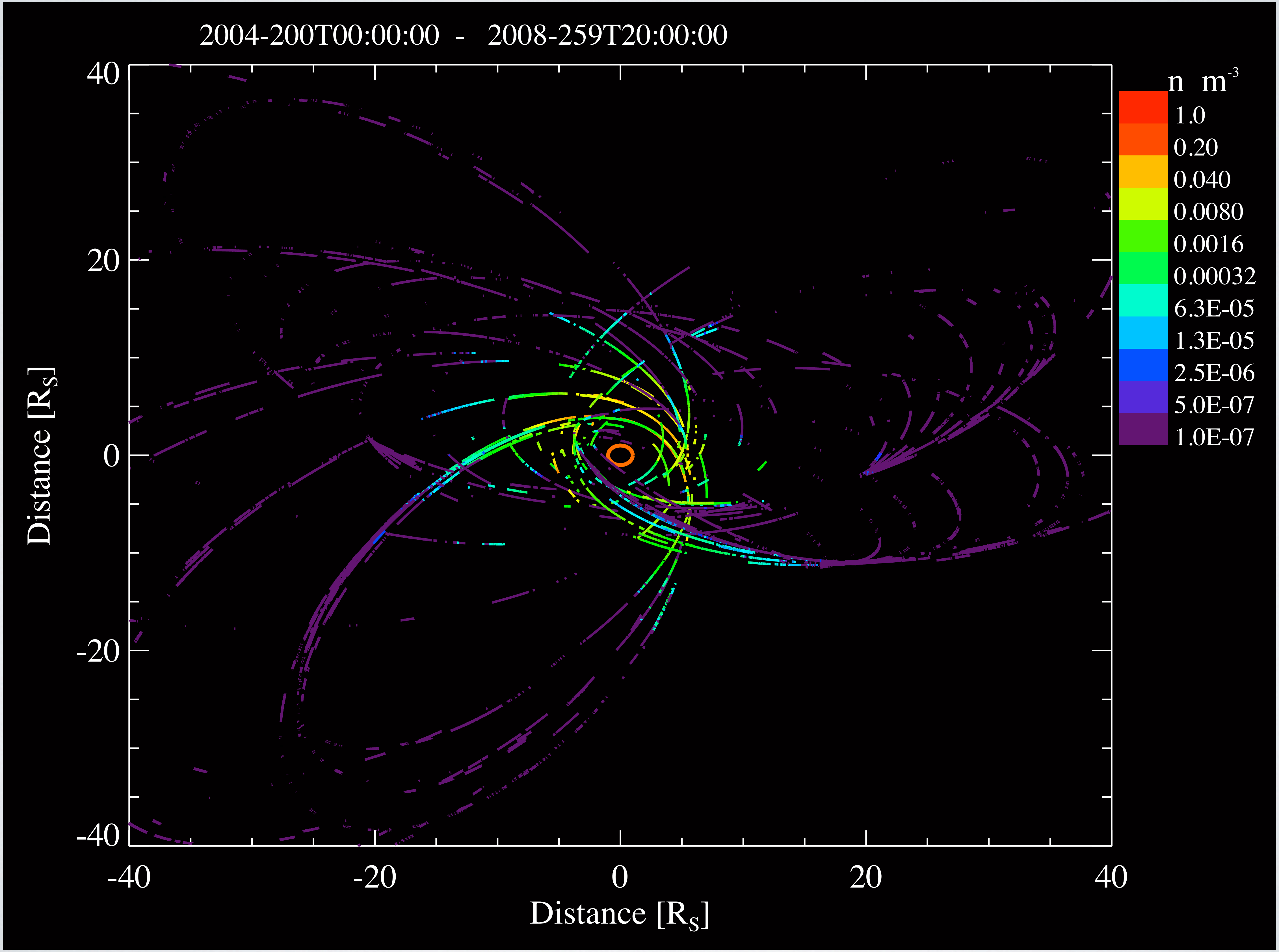
Uncertainties:

detection threshold

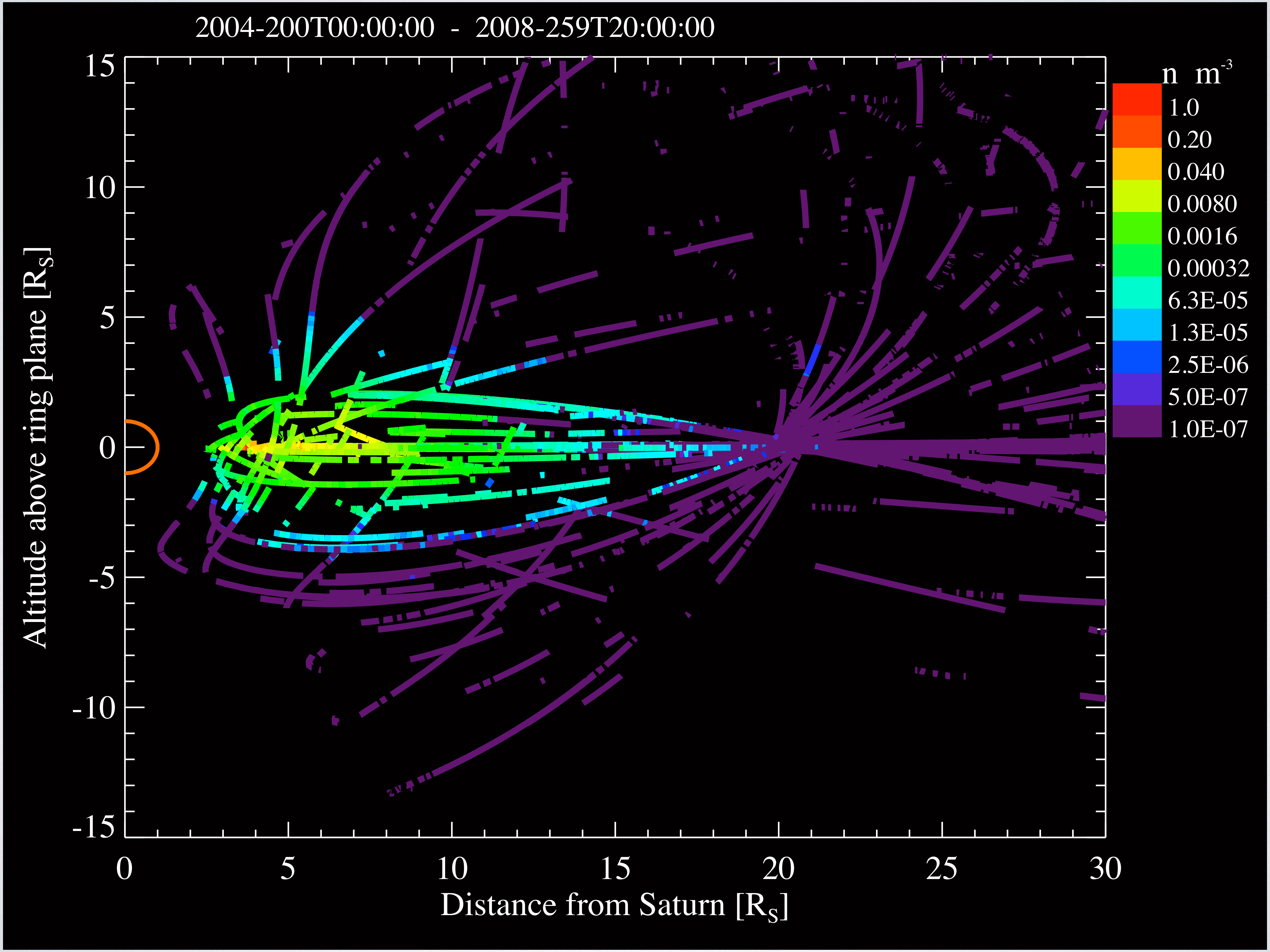
dust ram (sensitive area)

mass distribution

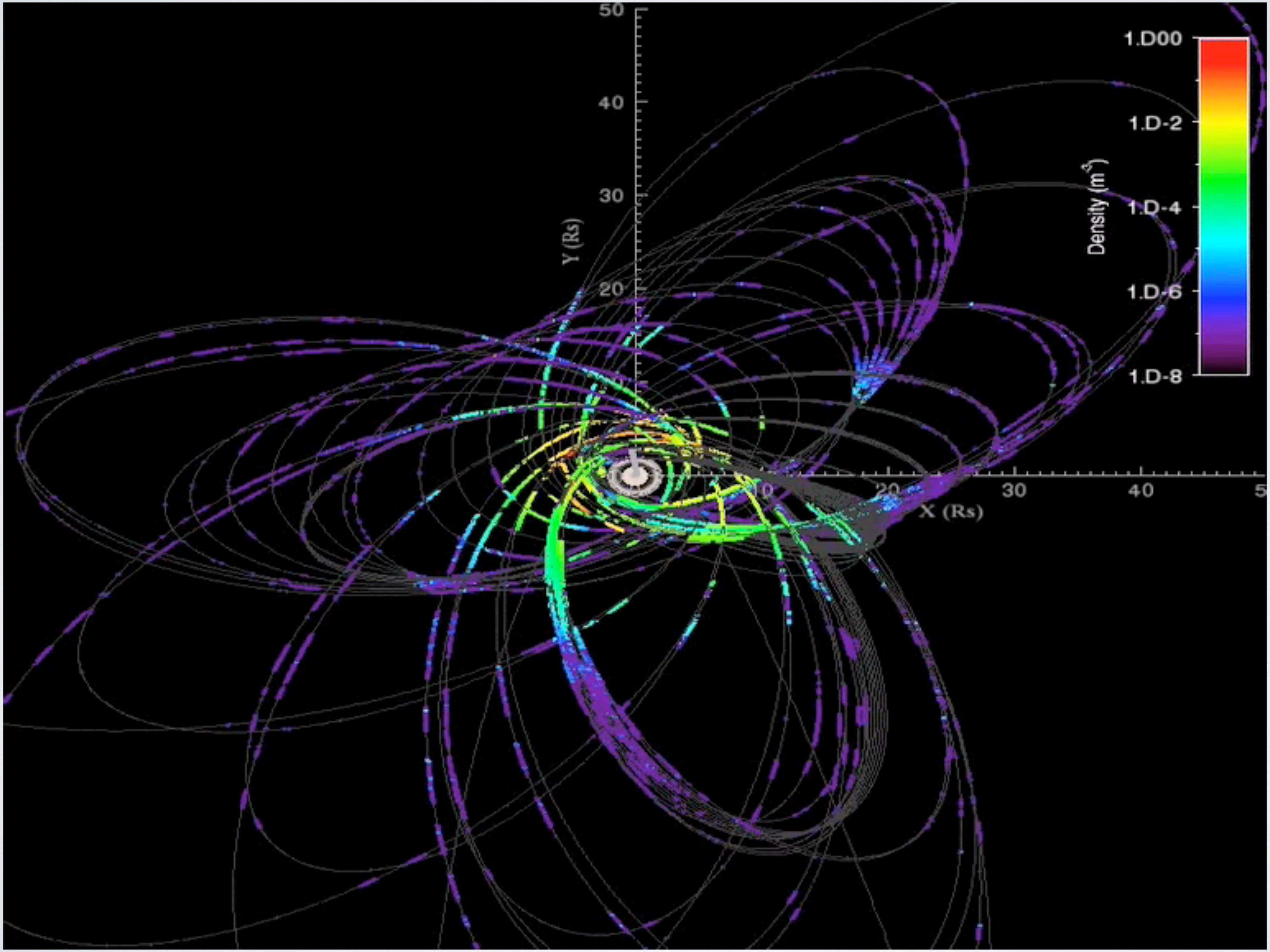
DUST DENSITY ALONG CASSINI TRAJECTORY



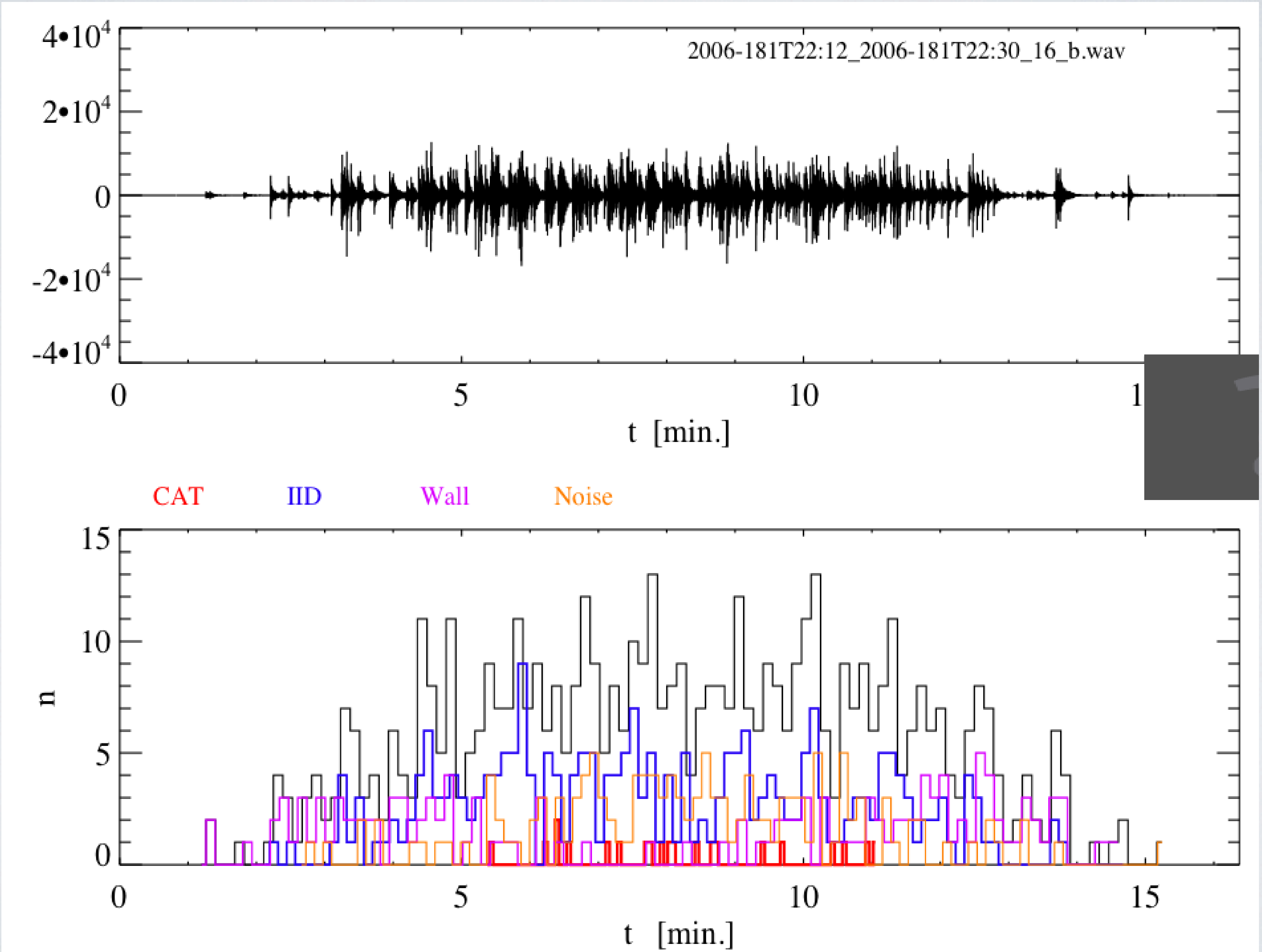
SATURN'S DUST ENVIRONMENT



3D DUST DENSITY

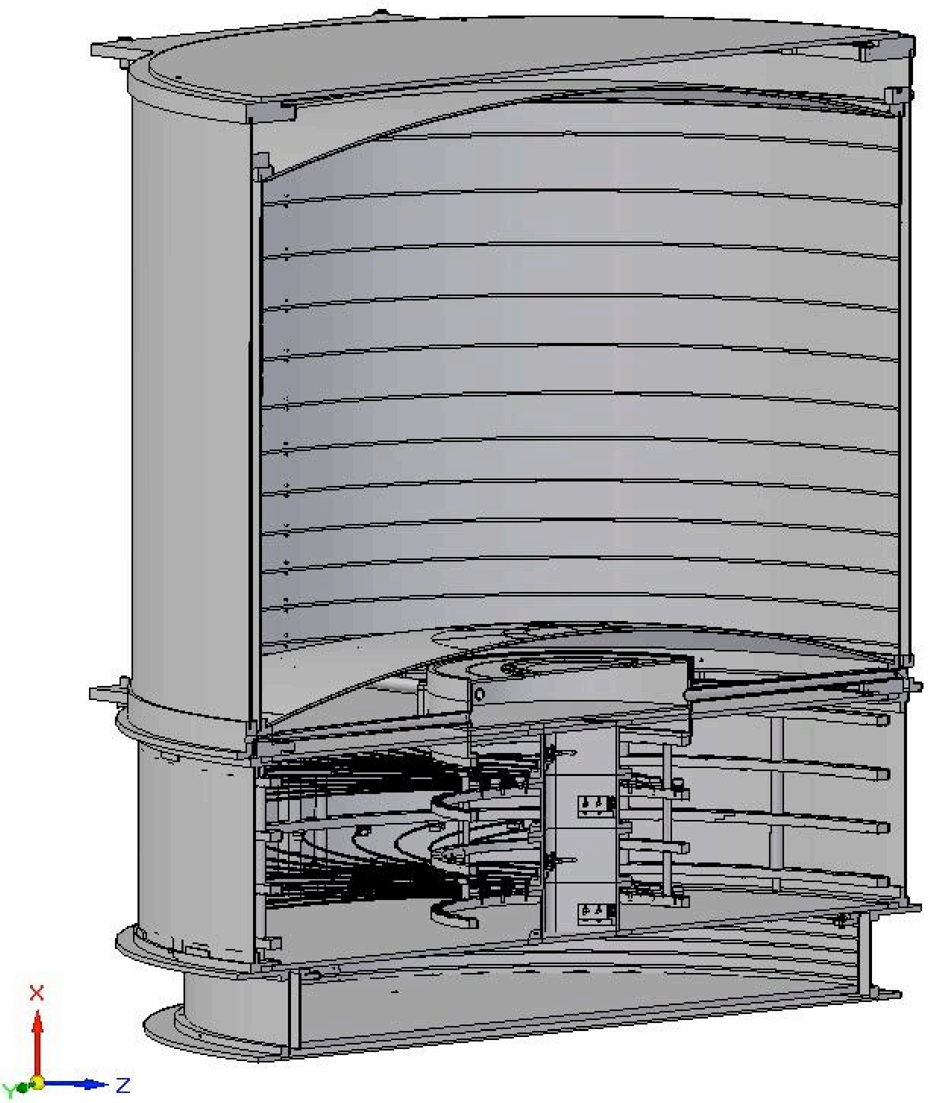


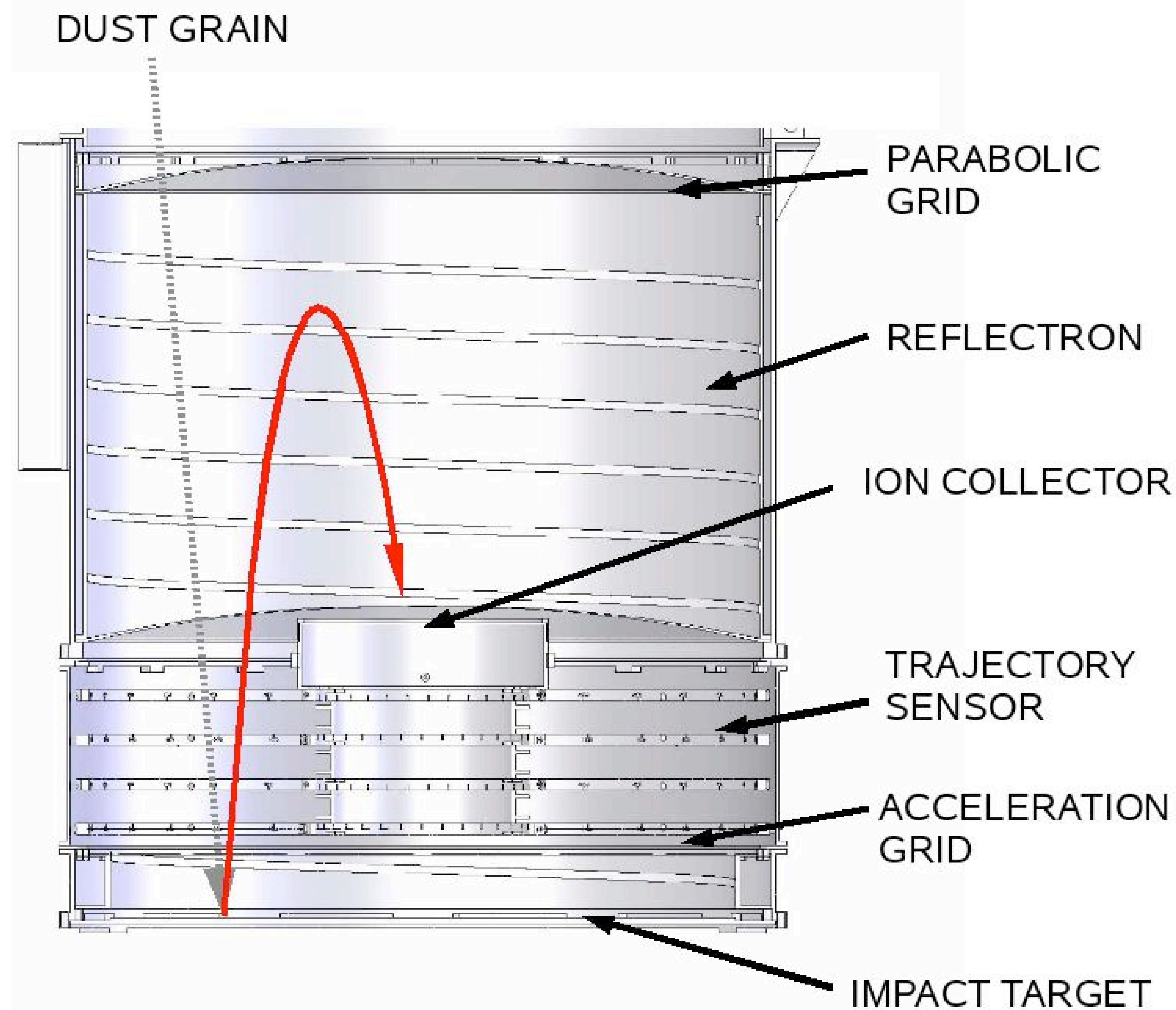
HEAR DUST IMPACTS !



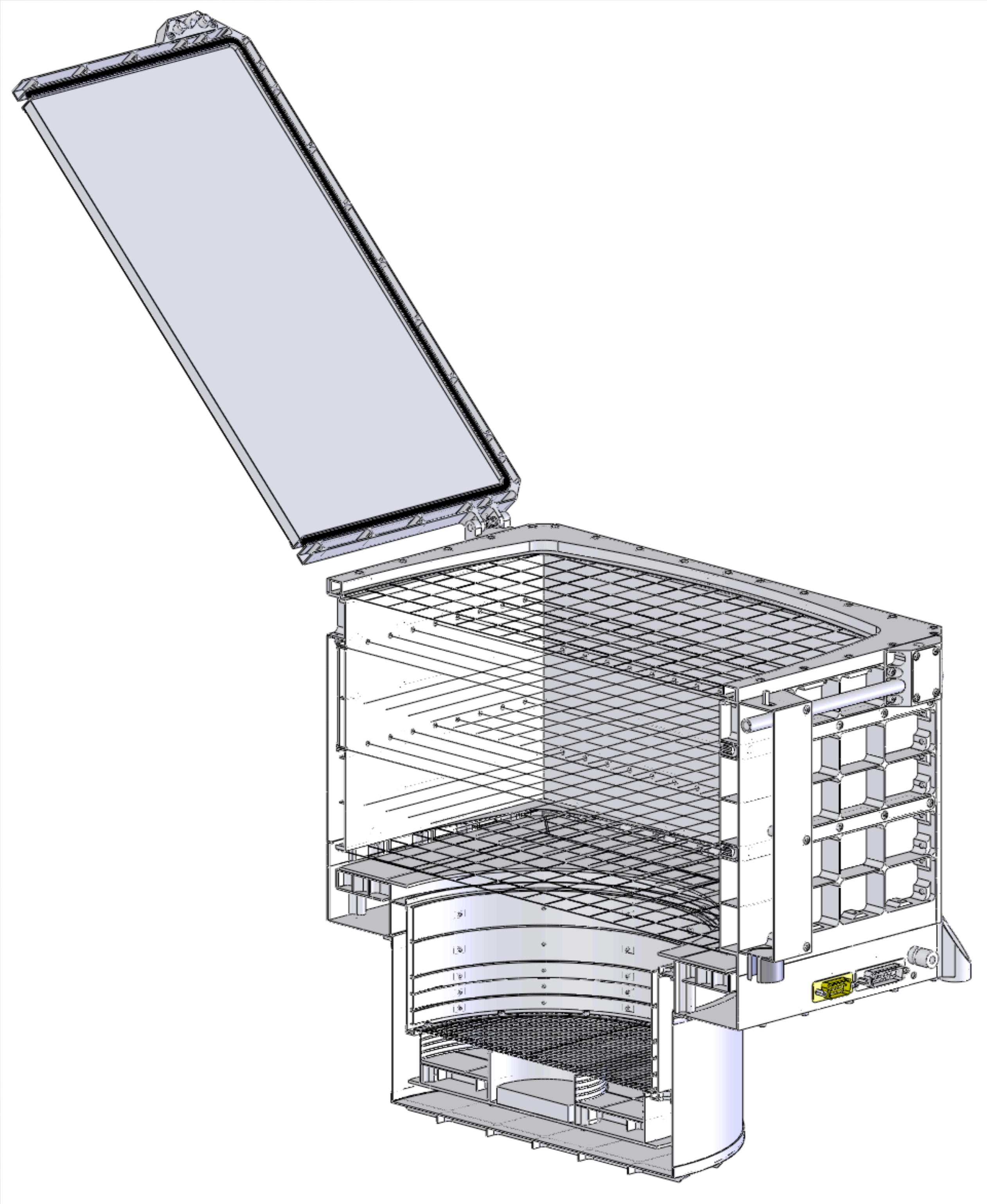
NEW INSTRUMENTATION
NEW MISSION SCENARIOS

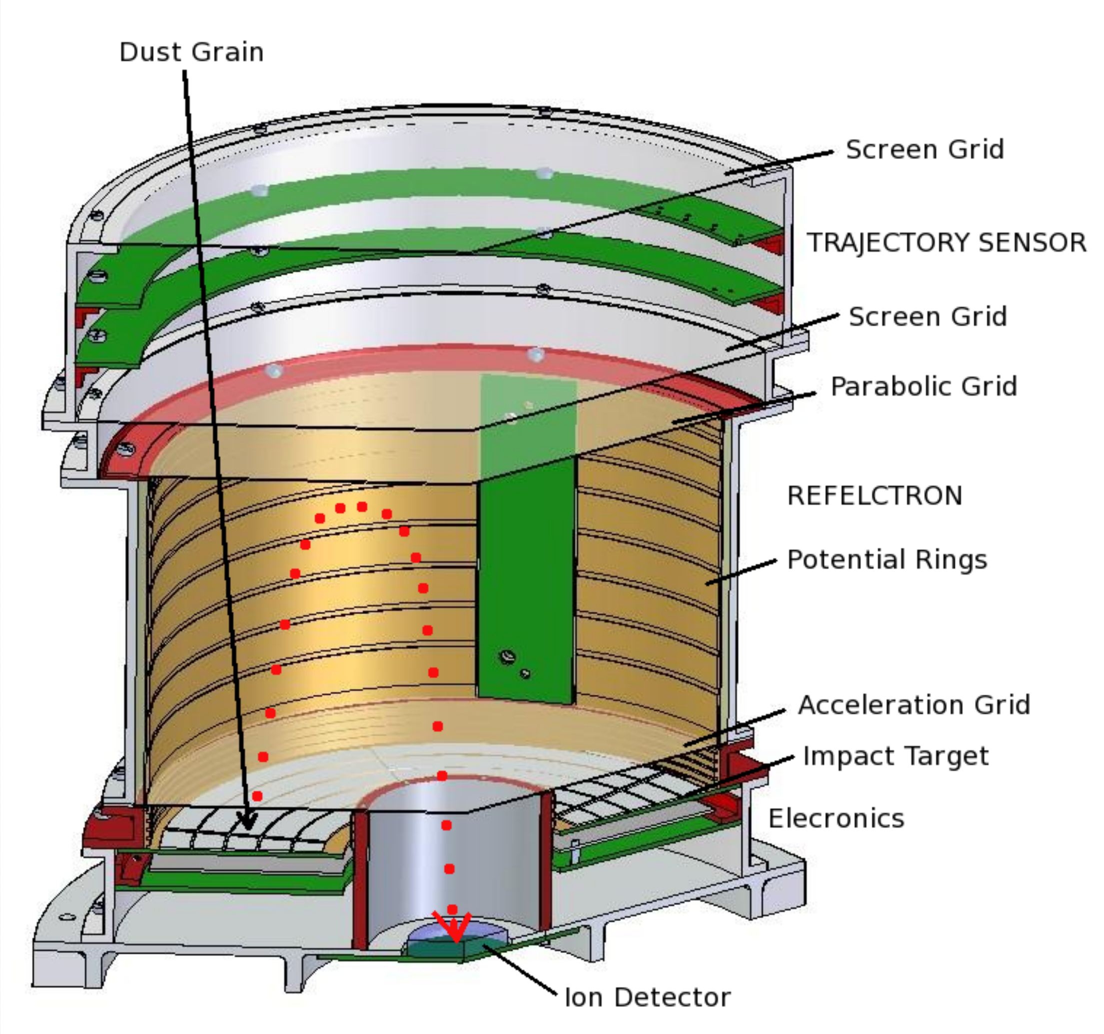
DUST TELESCOPE LARGE AREA MASS ANALYSER





LEOPARD (MOON) SODA/SUDA



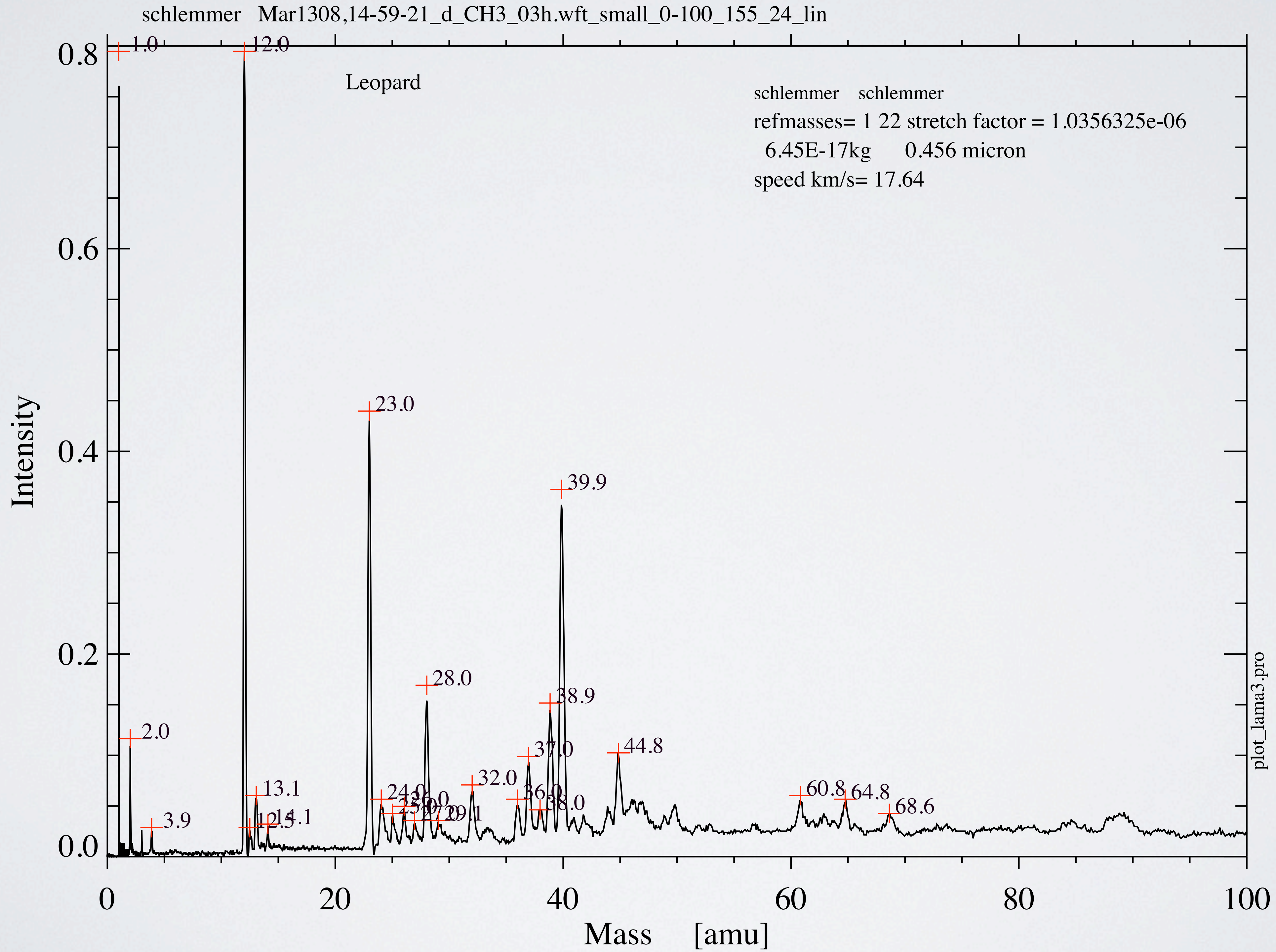


DUST TELESCOPE PROPERTIES

Table 5.4: Properties and measurement thresholds for three different Dust Telescopes DT (big), LEOPARD (medium size) and SODA (small).

Property	DT	Leopard	SODA
Mass [kg]	$\approx$22	$\approx$8	$<$2.5
Power [W]	$<$19	$<$19	$\approx$10
Area [cm^2]	2200	750	240
FOV	$\pm 38^\circ$	$\pm 50^\circ$	$\pm 45^\circ$
Datarate [kbps]	1 - 10	0.5 - 10	0.5 - 4
Dimension m^3	$0.65 \times 0.65 \times 0.72$	$0.23 \times 0.23 \times 0.35$	$0.32 \times 0.37 \times 0.35$
Dust speed [$km\,s^{-1}$]	1 - 50	1 - 50	1 - 50
Dust mass [kg]	$1 \cdot 10^{-18} - 1 \cdot 10^{-8}$	$1 \cdot 10^{-18} - 1 \cdot 10^{-8}$	$1 \cdot 10^{-18} - 1 \cdot 10^{-8}$
Dust flux [$m^{-2} s^{-1}$]	$< 1 \cdot 10^{-5}$	$< 3 \cdot 10^{-5}$	$< 6 \cdot 10^{-5}$
Dust charge [C]	$3 \cdot 10^{-16}$ - $1 \cdot 10^{-13}$	$3 \cdot 10^{-16}$ - $1 \cdot 10^{-13}$	$5 \cdot 10^{-16}$ - $1 \cdot 10^{-13}$
Dust trajectory ($1 \cdot 10^{-15}$ C)	$\pm 1^\circ$	$\pm 1^\circ$	$\pm 10^\circ$
Dust composition $\frac{m}{\Delta m}$	yes, $>$200	yes, $\approx$100	yes, $\approx$100

SODA SPECTRUM (LATEX ONTO AU)



• Analysis of the elemental and isotopic composition of individual cosmic dust grains

• Determination of the size distribution of interstellar dust

• Characterisation of the interstellar dust flow through the planetary system

• Analysis of interplanetary dust of cometary and asteroidal origin

DUNEXPRESS - SCIENCE

- Measurement of dust charges down to 1 ·10−16 C
- Determine dust trajectories with an accuracy of better than 3% in speed and 3° in direction in order to distingushi interstellar from interplanetary dust by their trajectories
- Analyse the elemetal and isotopic composition of individual cosmic dust grains at a mass resolution of m/dm > 100
- Characterise the ambient plasma conditions
- Determine the physical properties of individual dust grains

DUNEXPRESS SPACECRAFT

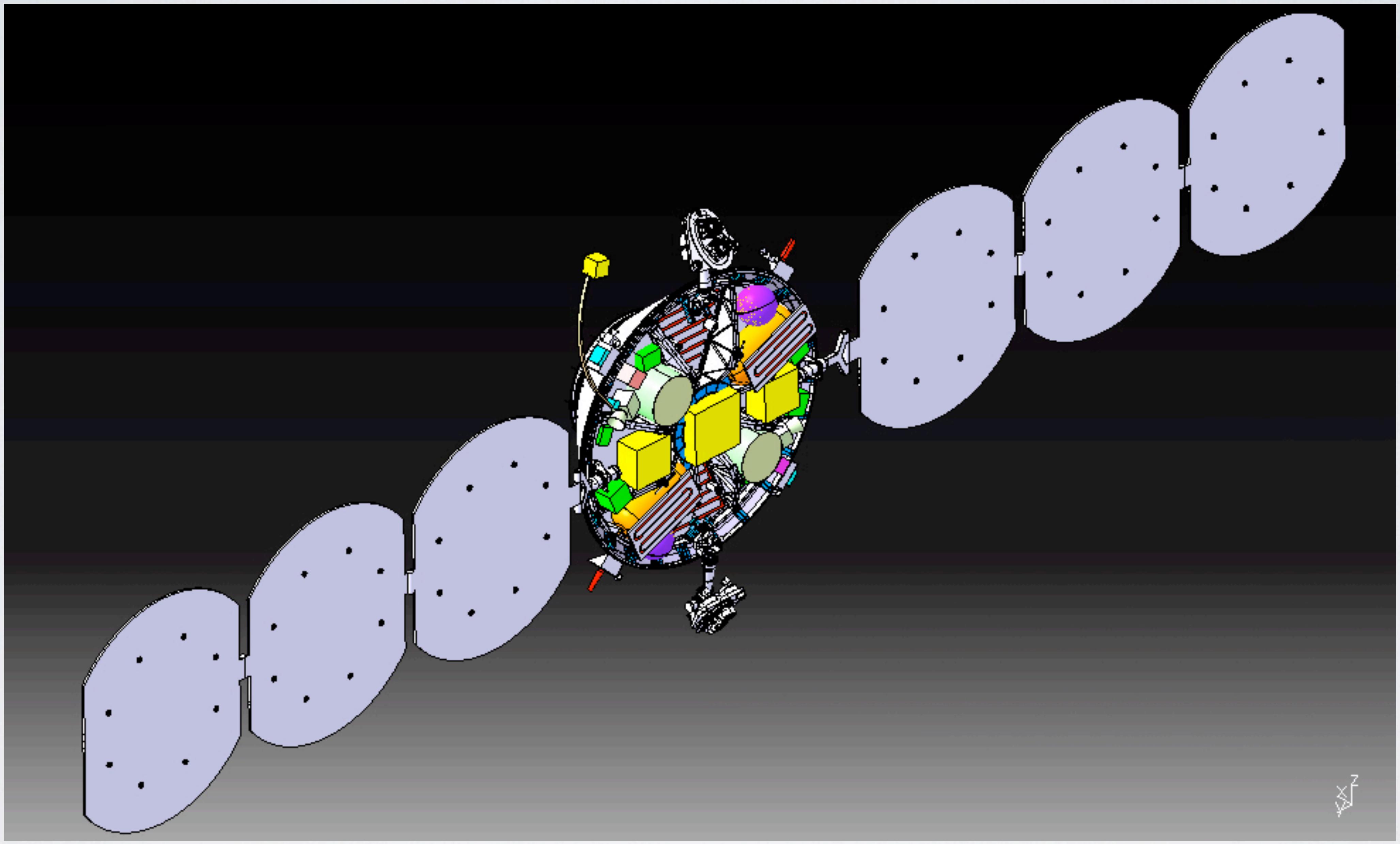


Figure 6.5: DuneXpress bus with two integrated Dust Telescopes (bright green) and three Dust Cameras (yellow boxes). The plasma monitor is mounted at a short boom (yellow box). (Dutch Space)

DUNEXPRESS MODEL-PAYLOAD

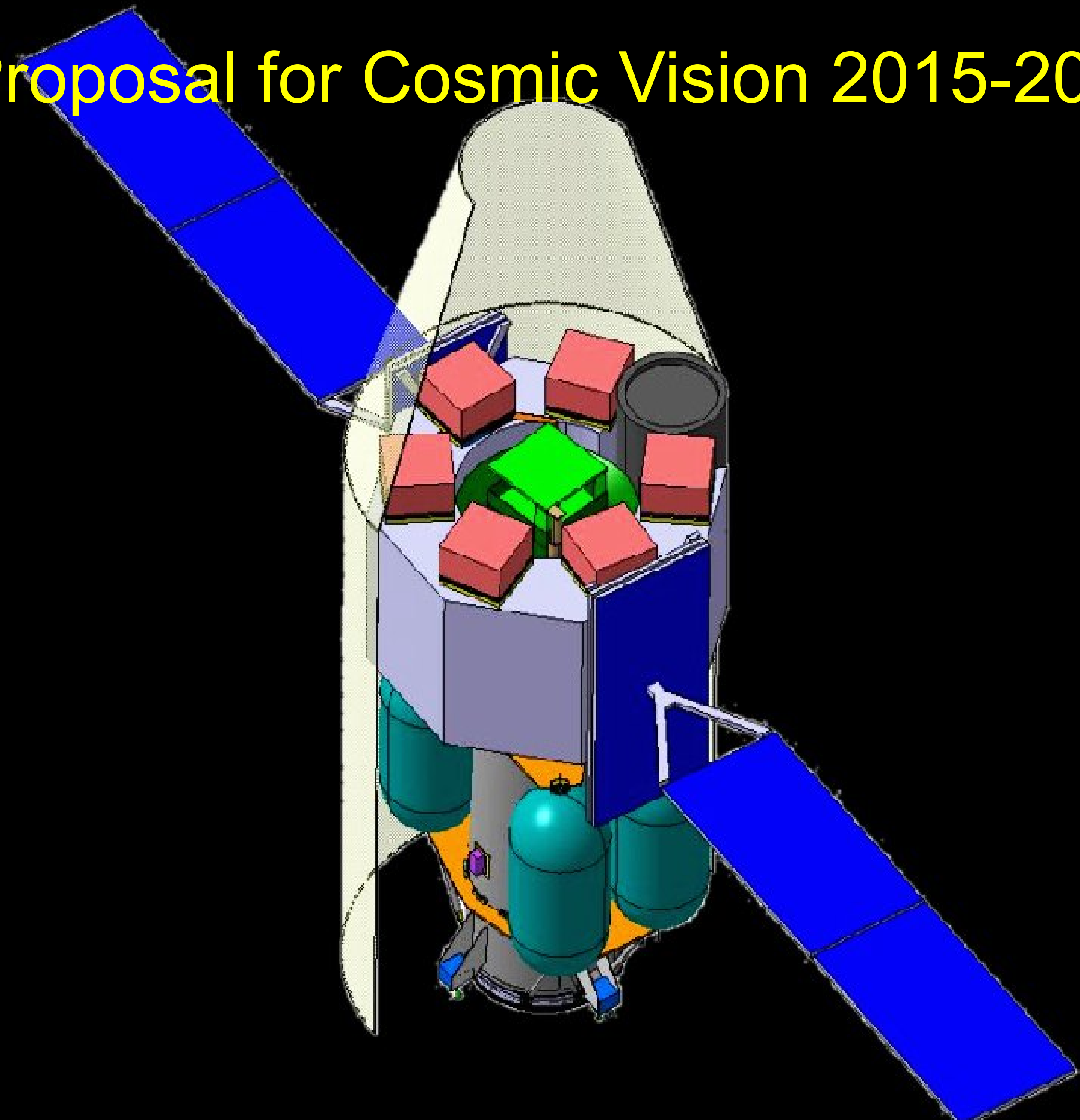
Table 6.2: Summary of the payload instruments onboard DuneXpress. Combinations of Trajectory Sensors with various impact stages (Dust Cameras, DC) are employed. Two types of Dust Telescopes (DT) provide trajectory and compositional information of impacting interstellar or interplanetary dust grains. Some instruments share a data processing unit (not shown). The total payload mass and power is 56 kg and 95 W, respectively. A further description is given in Grün et al. [2009].

Instrument	DT1	DT2	DC1	DC2	DC3	AFIDD	PLASMON
Type	LAMA1	LAMA2	PVDF	Piezo	Ionisation	Al film+MCP	Plasma
Area [m^2]	0.05	0.05	0.1	0.1	0.2	0.004	NA
Mass [kg]	15	19	4.9	5.6	8	1	1.3
Power [W]	16	25	8	< 30	9	2	1.5
Size [cm]	44×49	48×48	30×30×34	36×36×29	50×50×23	13×13×2	15×15×15

SARIM

Sample Return of Interstellar Matter

Proposal for Cosmic Vision 2015-2025



May 2009, R. Srama

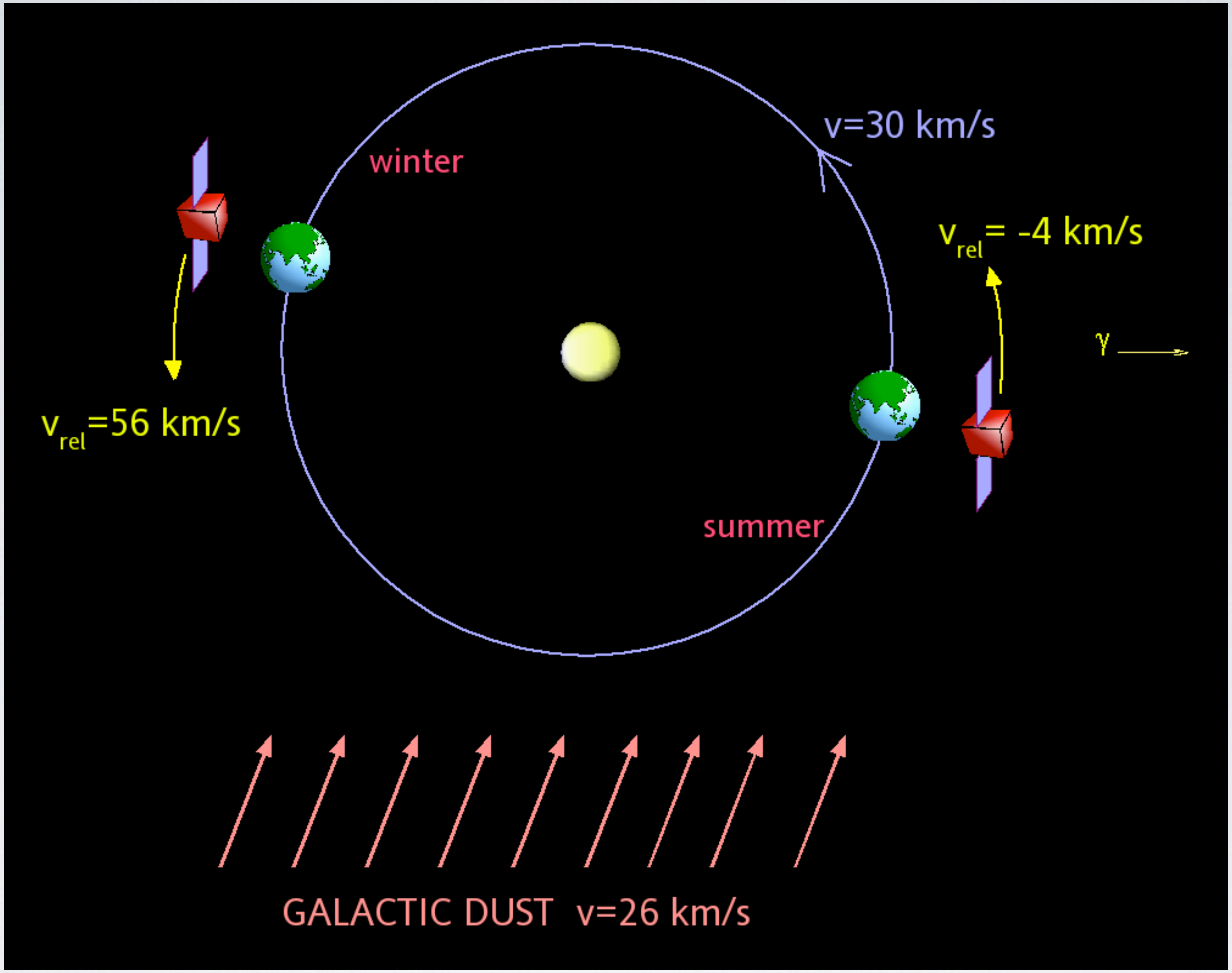
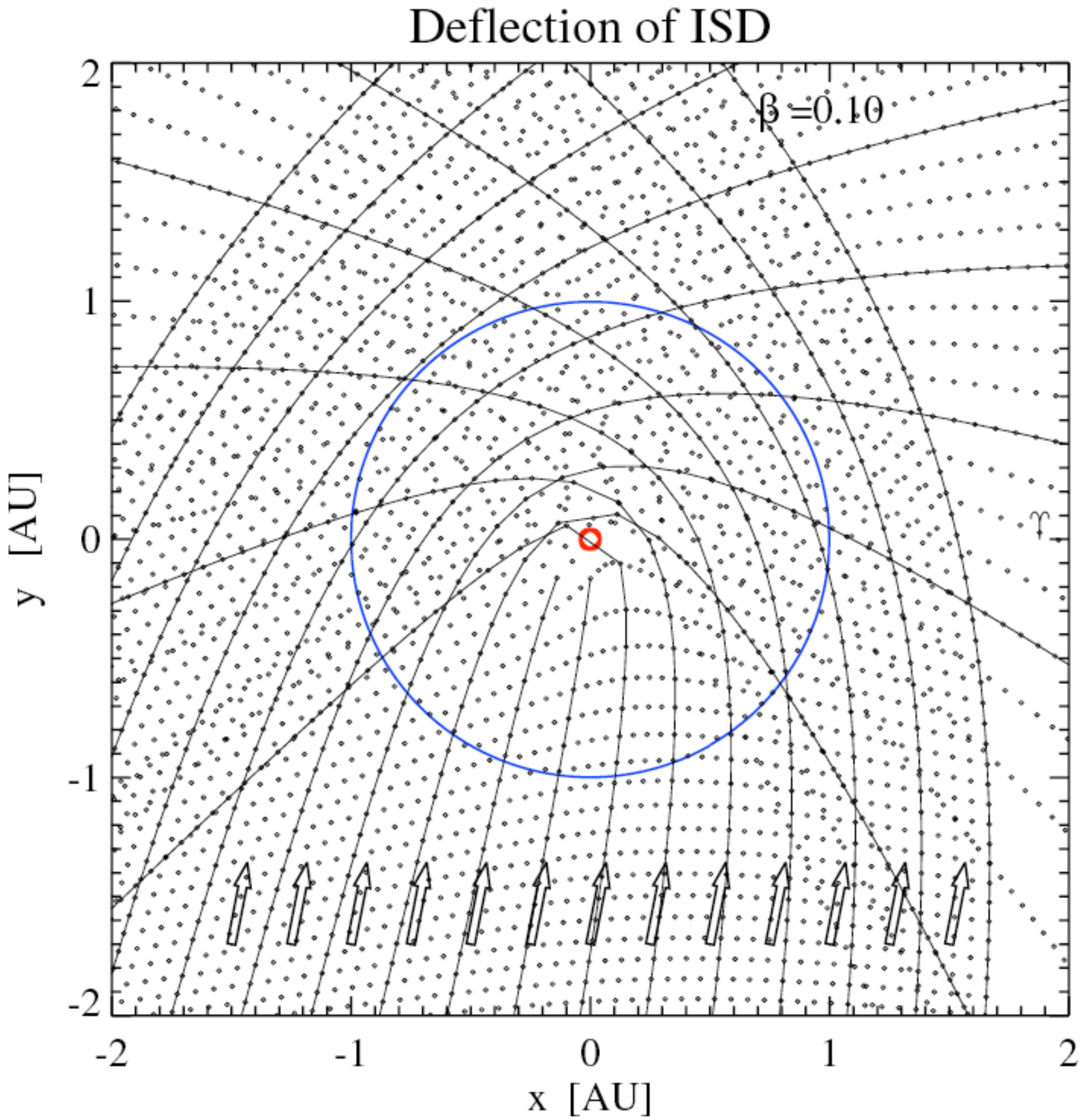


Figure 6.4: Mission scenario of DuneXpress at L2 of the Sun-Earth system. The interstellar dust flux direction, two positions of the Earth and the spacecraft are shown (right: late summer, and left: late winter). The orbital geometry leads to a yearly modulation of the interstellar flux. The corresponding fluxes are $F = 4.5 \cdot 10^{-4} \mathrm{m}^{-2}\mathrm{s}^{-1}$ in winter and $F = 6.6 \cdot 10^{-5} \mathrm{m}^{-2}\mathrm{s}^{-1}$ in summer. Further information can be found in Grün et al. [2009] and Grün et al. [2003].



Deflection of ISD
β =0.10
y [AU]
x [AU]
2
1
0
-1
-2
-2
-1
0
1
2
♈

HOW MUCH ISD DO WE GET?

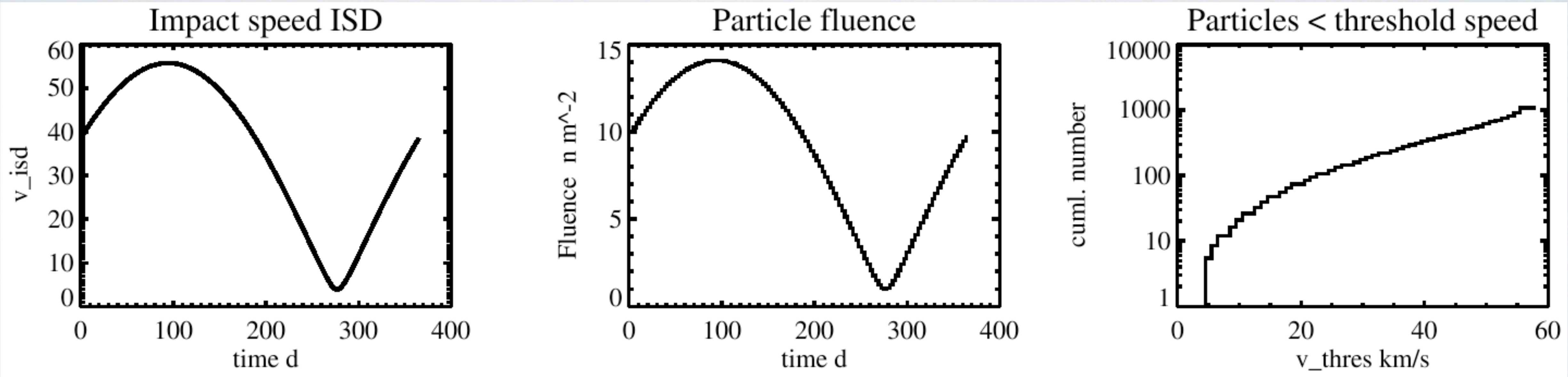


Figure 6.8: Relative impact speeds, particle fluence and cumulated number of collected interstellar dust grains below a threshold speed v_{thres} ($\beta = 1$).

WHAT IS THE EXPECTED RELATIVE IMPACT SPEED?

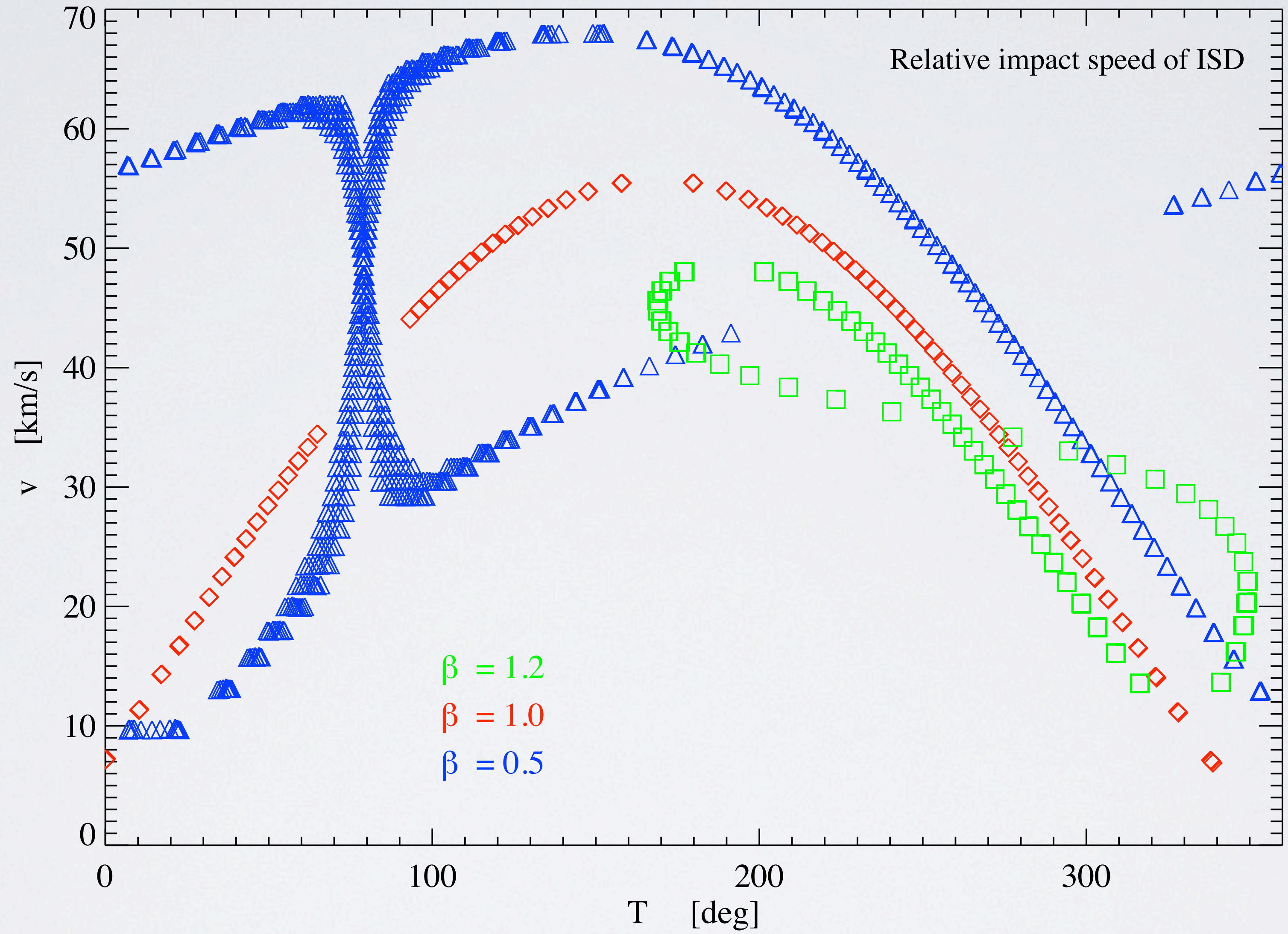
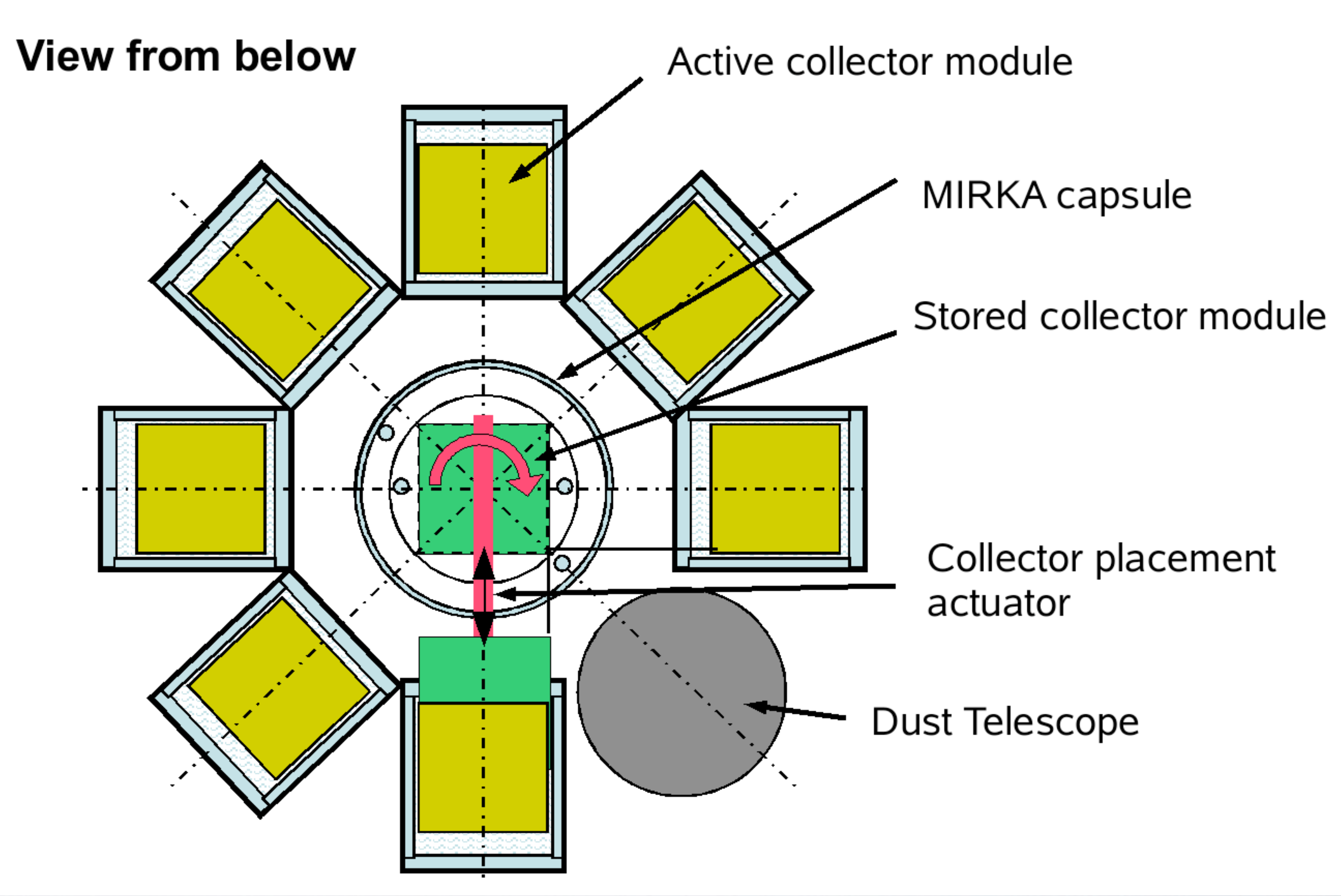
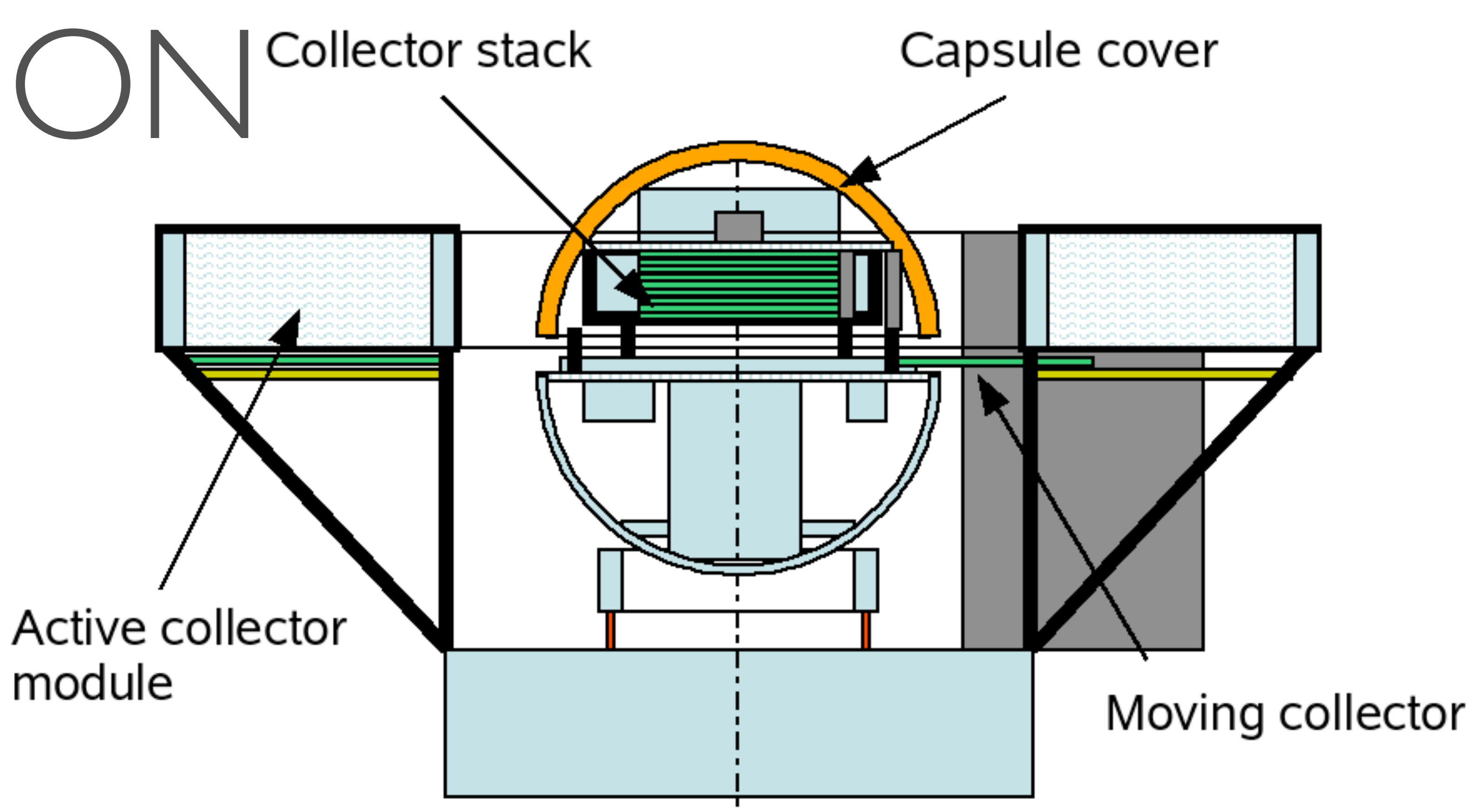


Figure 6.7: Relative impact speeds of ISD for a DuneXpress-like orbit for different angular distances from the point of periapsis (True anomaly T). The colours belong to particles with $\beta = 0.5$ (gravity dominated, big dust grains), $\beta = 1.0$ (radiation force and gravity are equal) and $\beta = 1.2$ (radiation force dominated, reflected by solar radiation pressure).

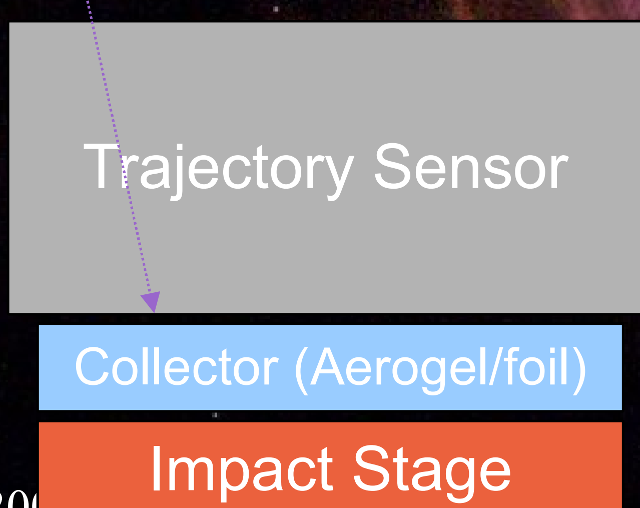
SARIM PAYLOAD CONFIGURATION





Preparation of Active Collector development

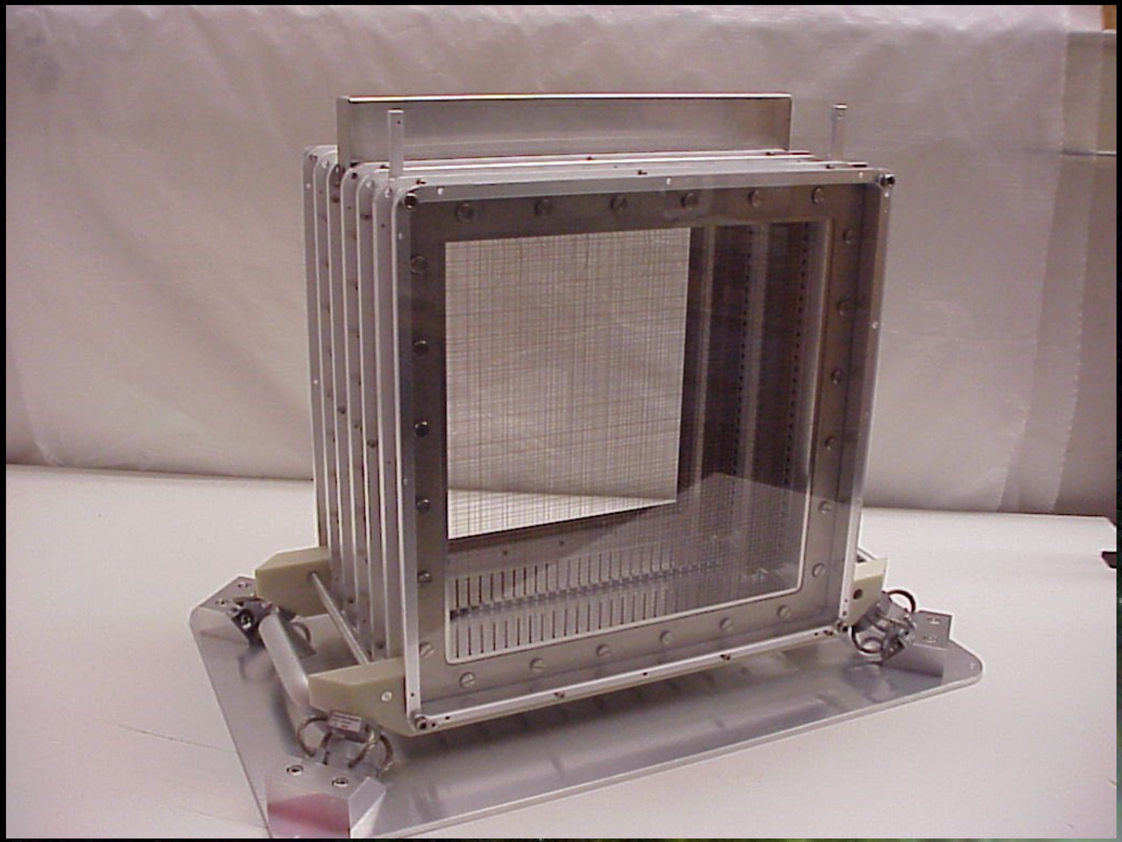
- Aerogel (10 times cleaner than Stardust)
  density gradient (2...20 mg/ml ?)
- Foils of „soft“ and „clean“ metals (aluminium)
- 7 Modules, each module is articulated individually to expose the collector during phases of interstellar dust detection.
- Each module has a collective area of 40 cm x 40 cm

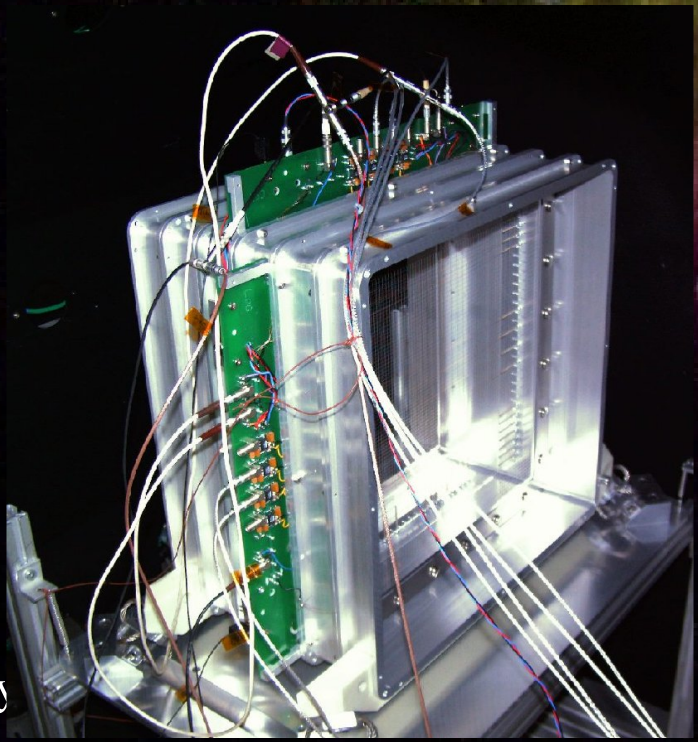


One of 7 active collector modules:

The collector will be removed during parts of the SARIM orbits

Trajectory Sensor developed

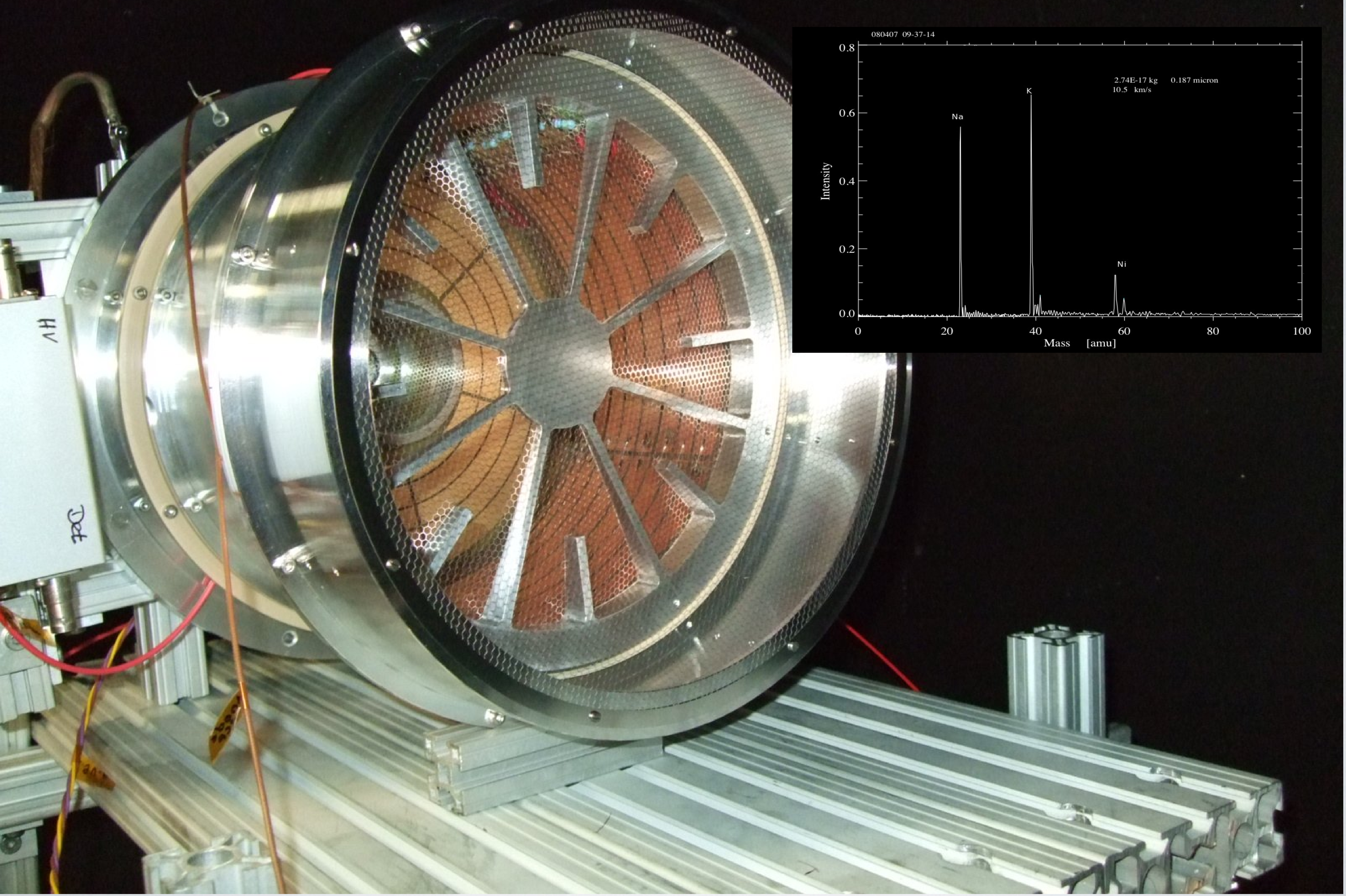




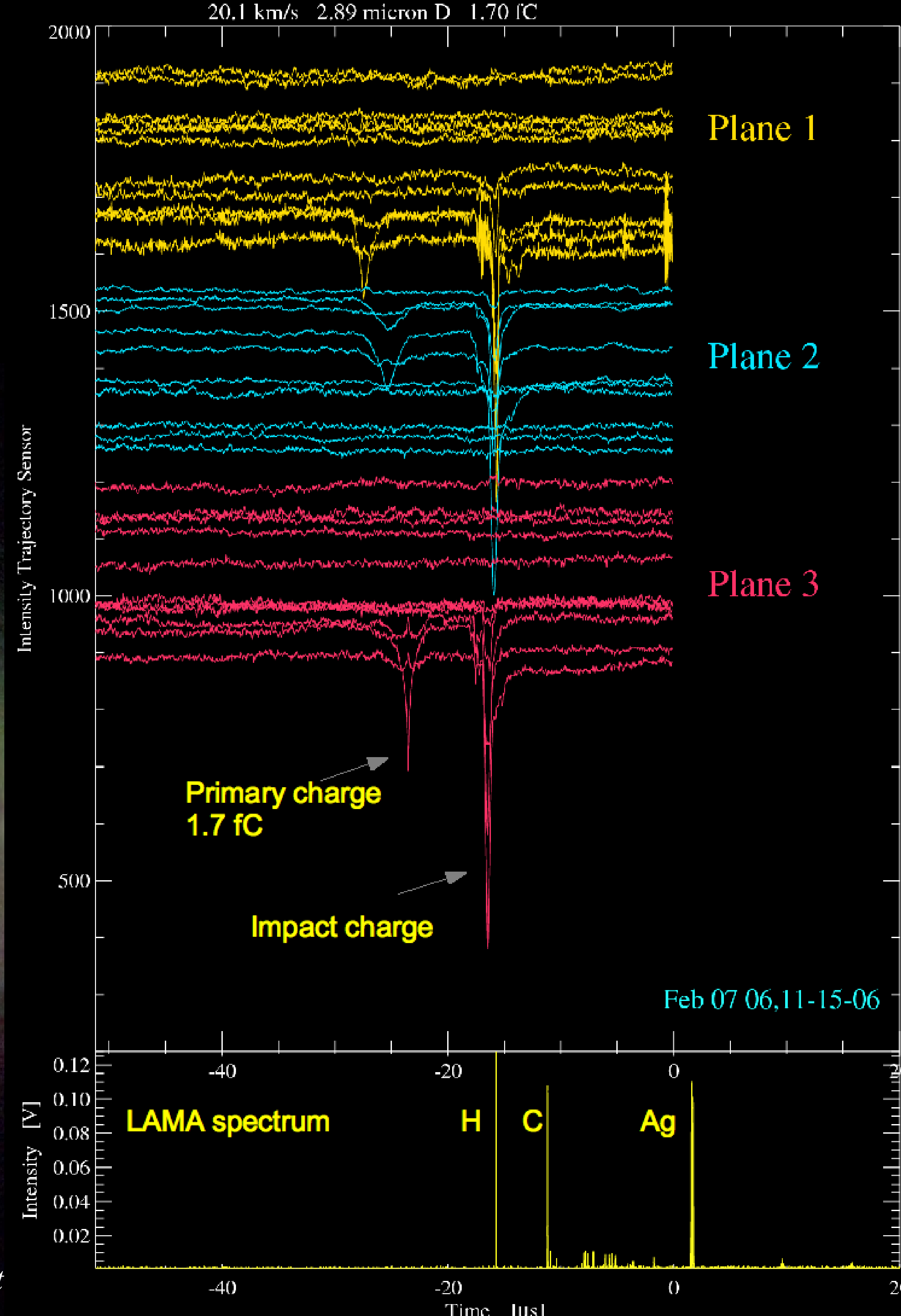
Measurement of induced charge of particle primary charge

Dimension	40 cm x 40 cm
Depth	20 cm
Sensitive area	0.14 m^2
FoV half cone	45°
Data rate	1500 bps
Mass	< 5 kg
Power	8 W
Dust speed	1 .. 100 km/s
Dust charge	0.1 fC .. 100 fC
Dust mass	10e-15 .. 10e-8 g
Dust trajectory	1°
Dust composition	N/A

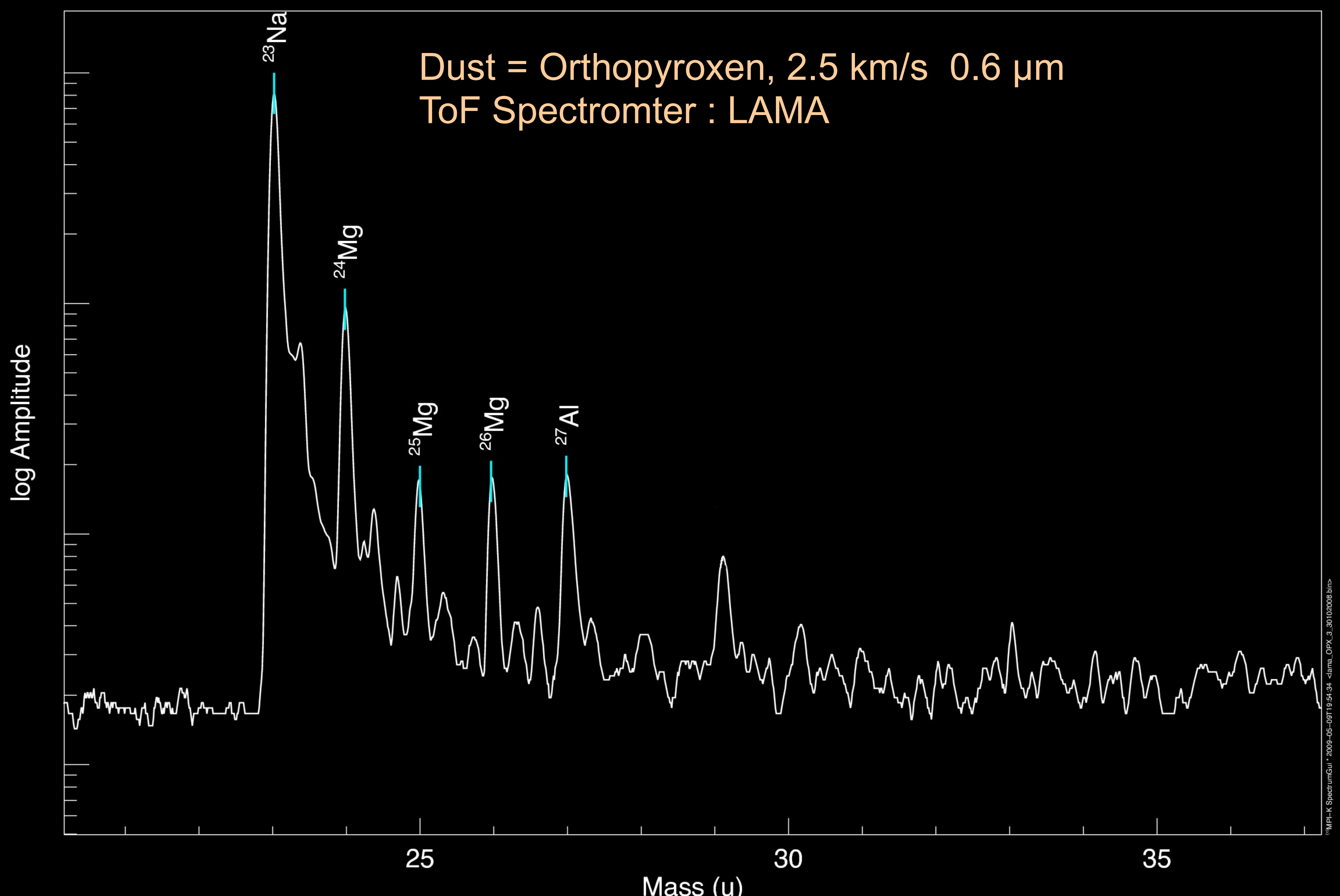
We have tested a Small Dust Telescope



- Combine trajectory sensor and TOF spectrometer
- Dust origin AND dust properties (mass, composition, charge,...)



New: Impact spectra of low-velocity impacts



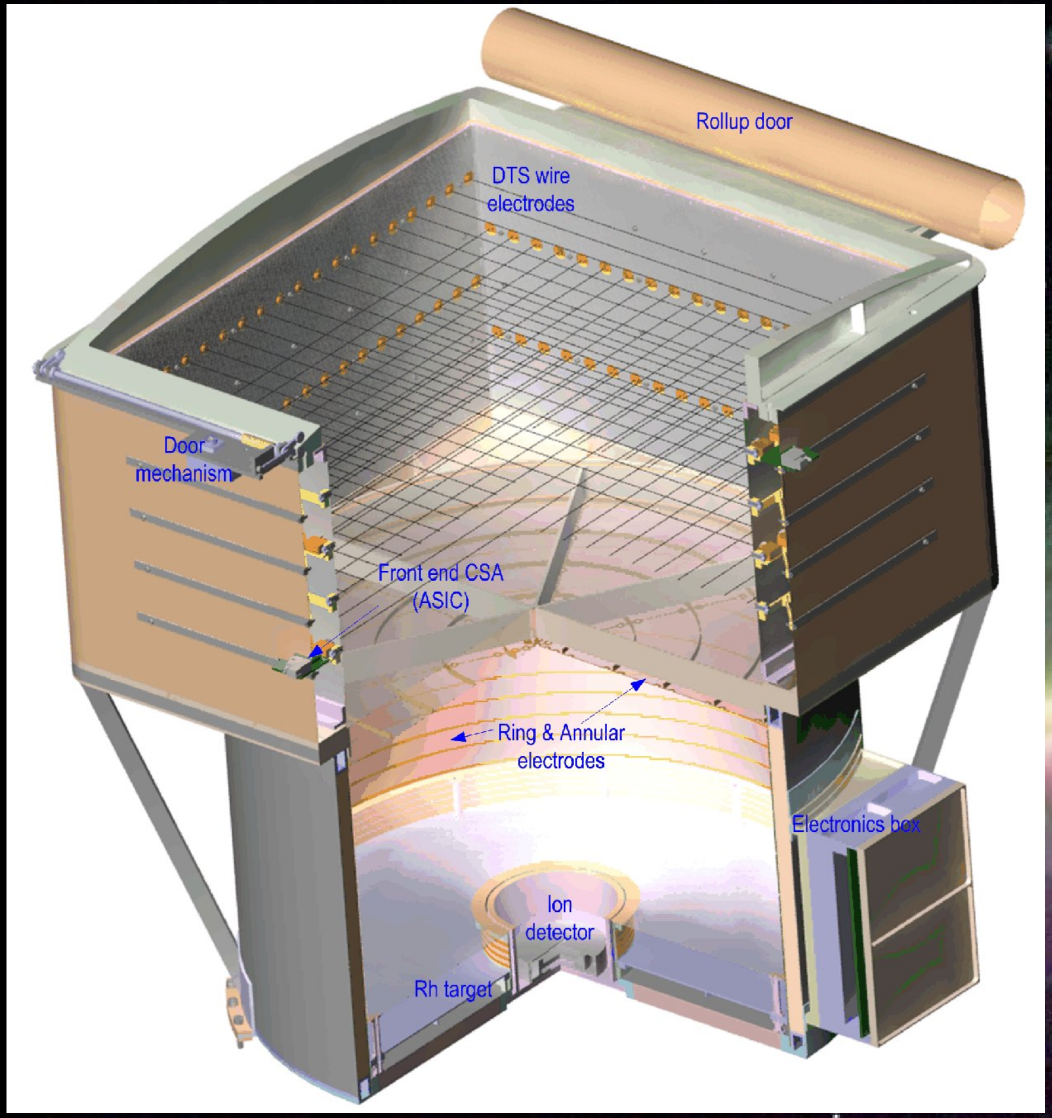
New dust sample return mission - Increments on STARDUST

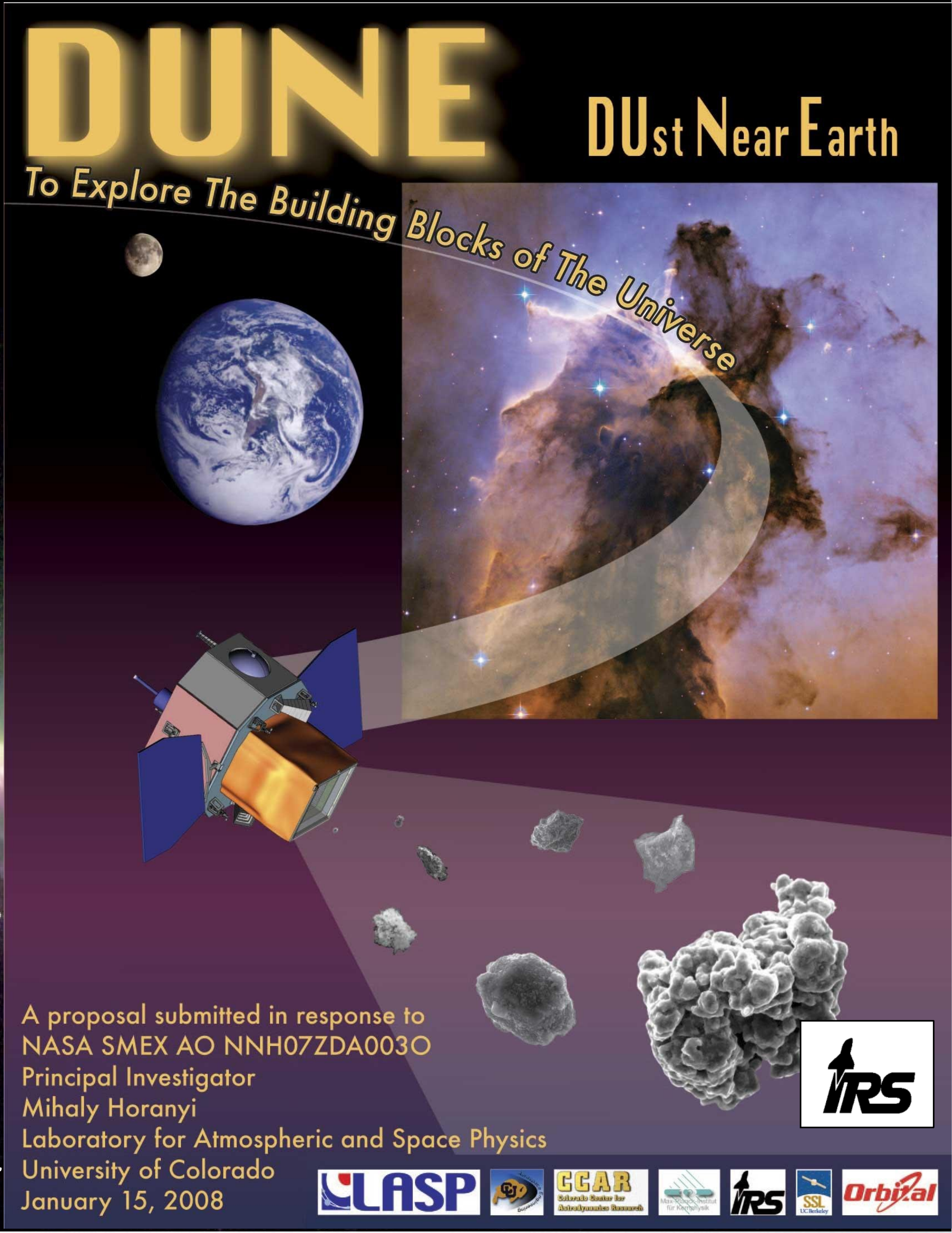
- 10 times sensitive area (collector 0.1 to 1 m^2)
- 10 times sensitive area (spectrometer 0.01 to 0.1 m^2)
- collection/detection of interstellar dust possible
- collection of dust grains in vicinity of small bodies (Hill sphere) – geyser or volcanoe activity provide a view below the surface
- Dust grains rich in alkali metals: proof of subsurface-ocean
- Determine impact time and location of individual impacts at the collector. Determine particle speed and mass of individual grains. We know where to look for particles in/at the collector.
- Combine with in-situ package (spectrometer/trajectory sensor)
- Separate interplanetary dust, interstellar dust, moon dust by trajectory analysis

Conclusion

- Targets: interstellar dust, interplanetary dust, dust from asteroid/moon surfaces, dust from moon interiors (detection of liquid water), cometary dust
- Combine dust collection with in-situ techniques, provides impact time and impact location (collector surface), grain mass, grain trajectory !
- Combine collector with in-situ compositional measurement (submicron or fast grains are problematic for collectors)

Univ. Colorado:
Dune Mission Proposal (in-situ only)





Prepare for

14 - 16 JULY , GÖTTINGEN