

宇宙探査機搭載用宇宙ダスト 検出器の開発

Development of Cosmic Dust Detectors
Onboard Space Explorers

京都大学大学院工学研究科

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自己紹介

* 福岡県福岡市出身

* 東京工業大学 原子核工学博士課程修了

「電子衝撃による窒素分子に対する電離三重微分断面積の測定」

専門分野： 原子分子物理、放射線物理・化学、加速器科学

* 宇宙ダストの研究

東大・原子力研究総合センター在職中

1997年「新世紀の宇宙塵研究」東大宇宙研の研究会がきっかけ
重照射研究設備(HIT)のバンデグラーフ静電加速器でダストを加速

現在： 京大原子核工学専攻、(兼)宇宙総合学研究ユニット

本日のお話し

- 1) 宇宙ダストについて
- 2) 宇宙機搭載用ダスト計測器
- 3) 地上でのダストシミュレーション実験

1) 宇宙ダストの分類

★ 星間起源ダスト(太陽系外・主に銀河系内) Interstellar dust

高速で太陽系内に流入、 黄道面から離れると主成分

★ 小惑星・彗星起源ダスト Interplanetary dust

黄道光の観測 (小惑星の族におけるダストバンドの検出)

★ β メテオロイド

衝突・蒸発で小さくなったダスト($< 0.1 \mu\text{m}$)が太陽放射圧で吹き飛ばされる ($\beta = \text{太陽光放射圧} / \text{重力}$)

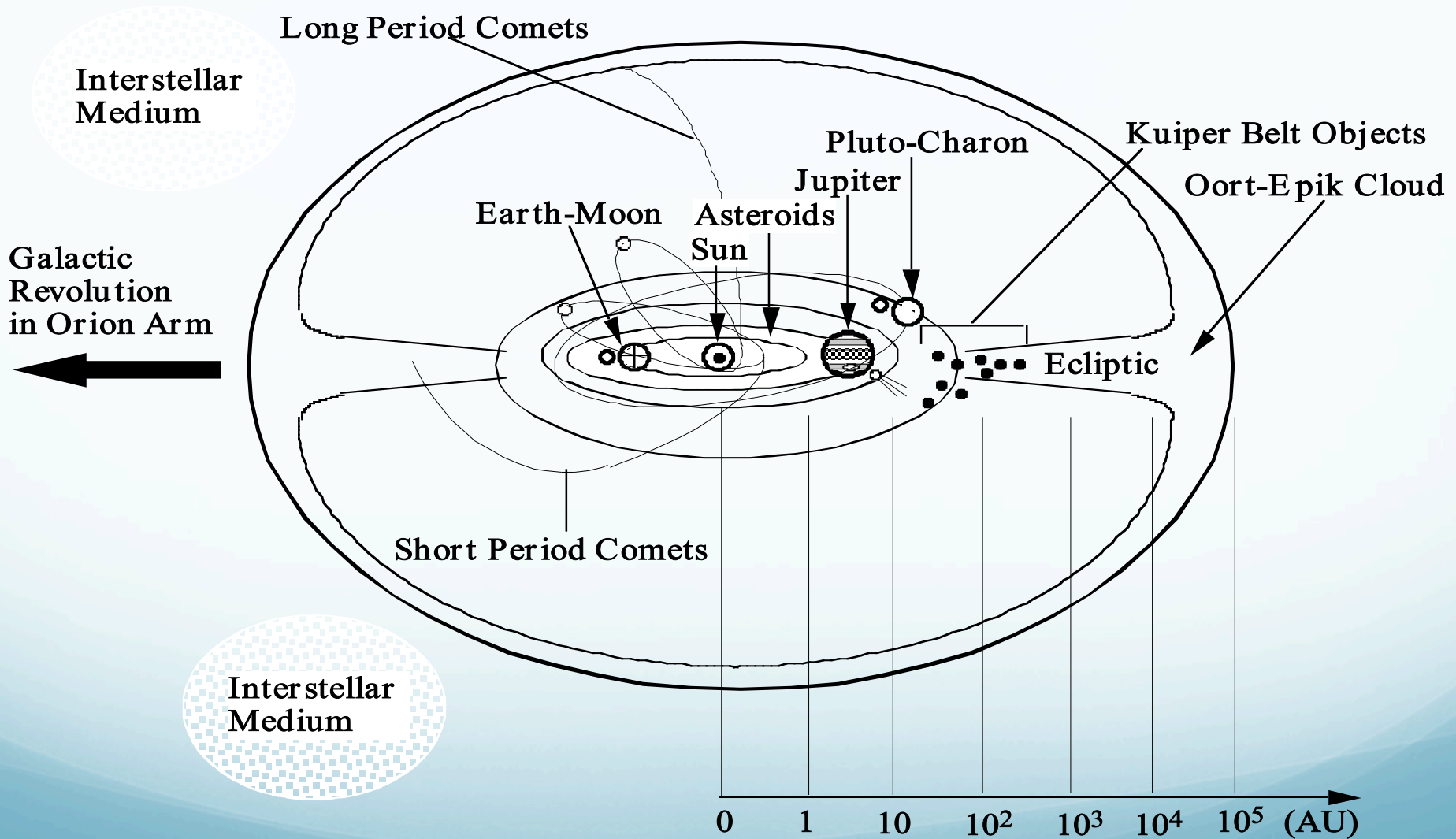
★ 周惑星ダスト

地球・火星・木星・外惑星のダストリング

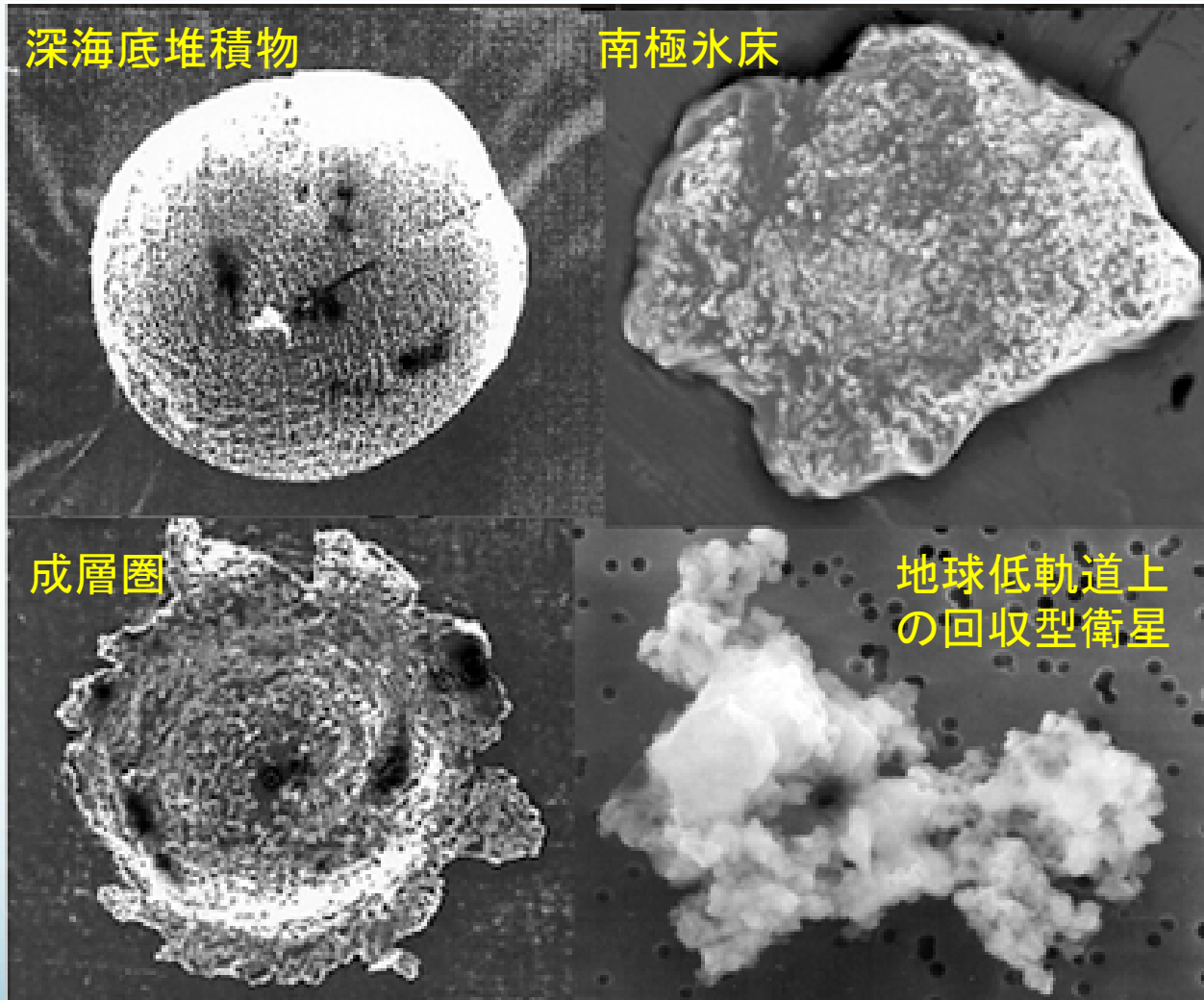
★ スペースデブリ

地球周回、 人工物起源

太陽系における宇宙塵の起源



地球近傍で採集された宇宙塵

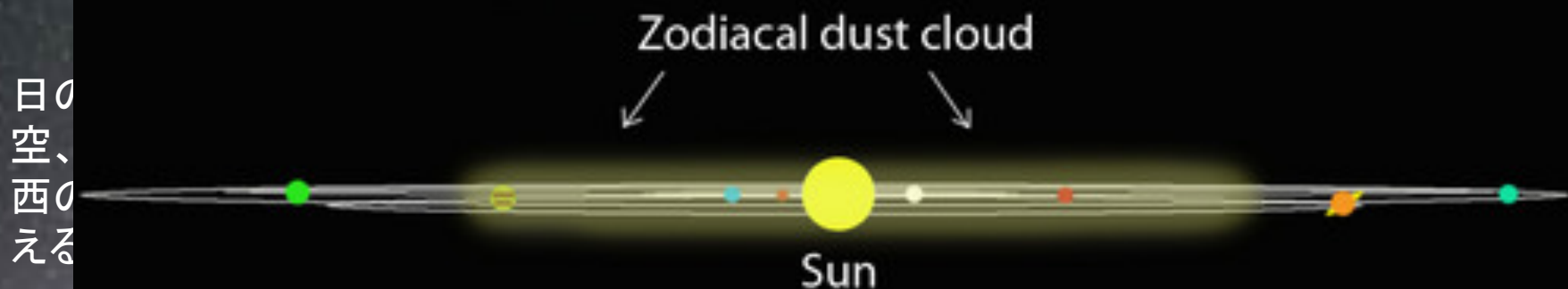


直径10～500ミクロン程度で縮尺は全て異なる

太陽系内に浮遊する
ダストが太陽光で散乱
されて光っているもの

黄道光

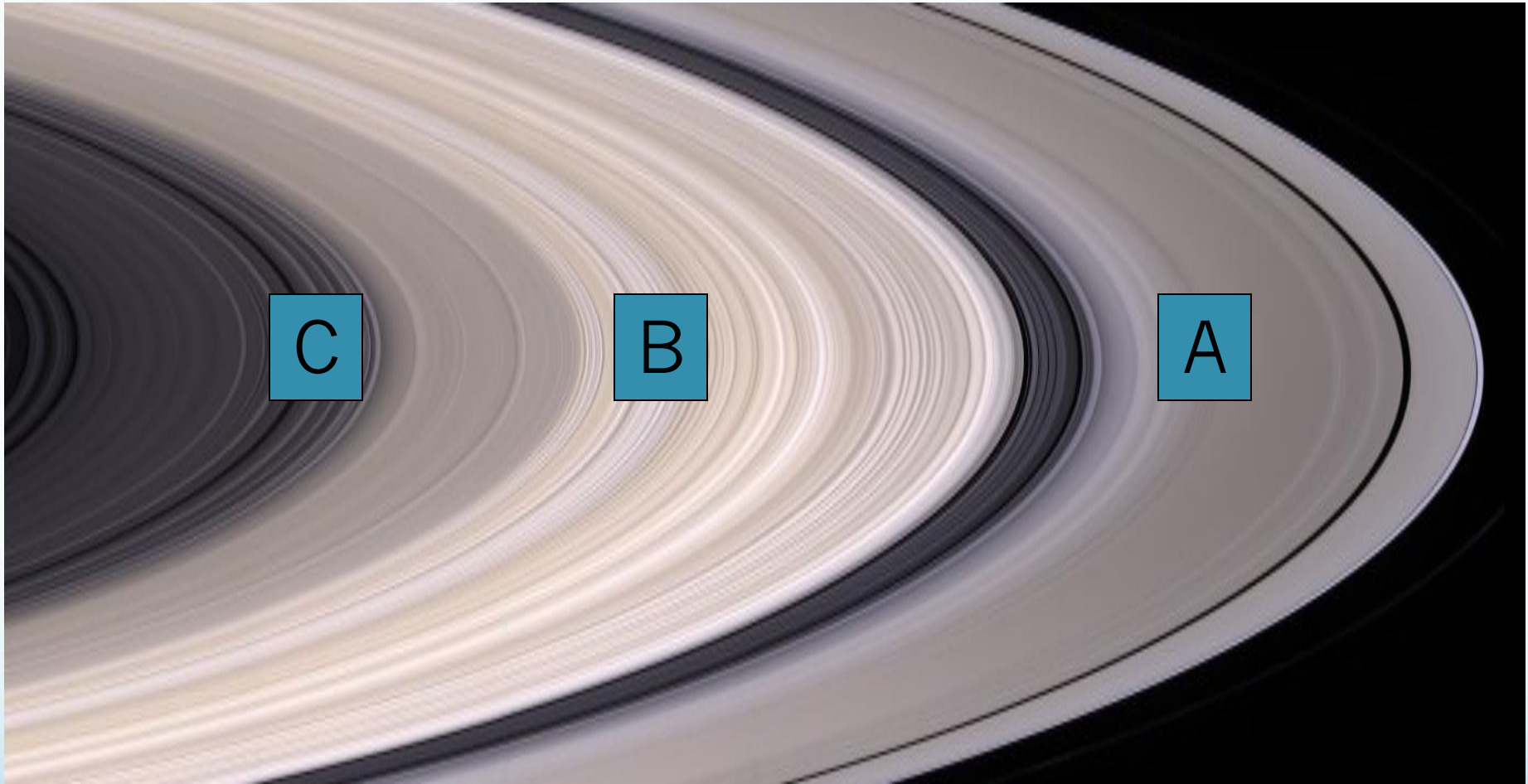
Model of zodiacal cloud



Source of zodiacal dust

- Asteroids and comets
- Inward flow by Poynting-Robertson effects

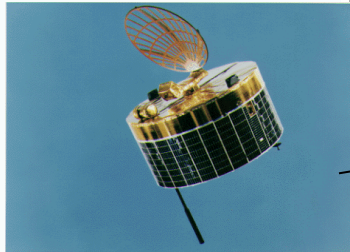
Cassini view of A, B and C rings



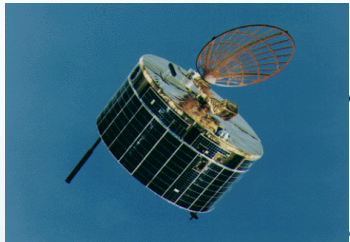
赤道から 6,630 km ~ 120,700 km 厚さ : (A) 10~30 m, (B) 5~20m, (C) ~5m
成分 : 氷 大きさ : μm (薄いリング) ~ m size

Comets = actually ejecting dust

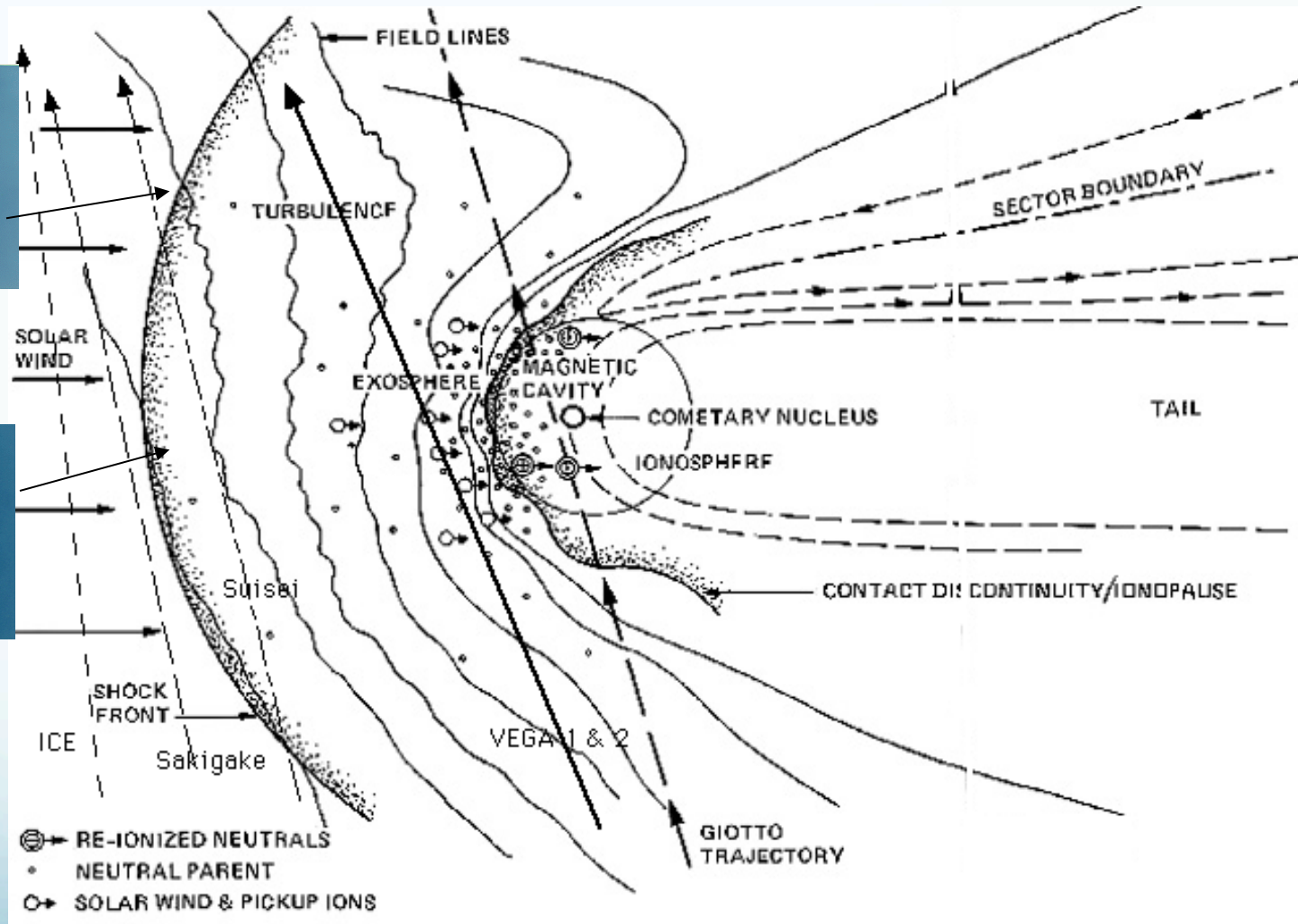
Missions to Halley's Comet



Suisei



Sakigake



Dust size change

- IDP (Asteroids, Comets) → Poynting-Robertson effect
→ Inner solar system
Frequent collisions, Evaporations
- Dust size < 1 micron
Solar radiation pressure increases a.
→ beta-meteoroids

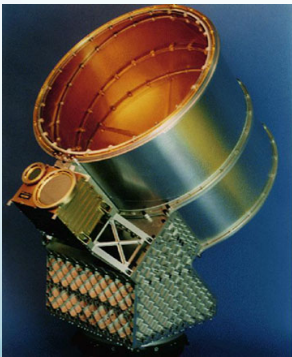
2) 宇宙機搭載用ダスト計測器

In situ measurement of space dust

Space, mass and velocity distribution, and chemical composition of dust are needed.

~ Methods of dust measurement ~

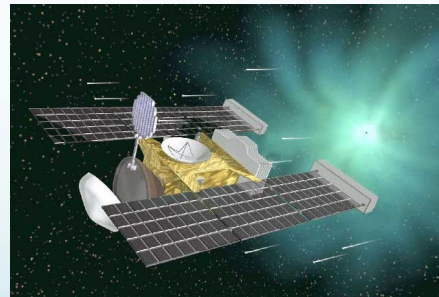
- Impact ionization detection (IID) with/without mass spectrometer
- Using Piezo-electric effect - PVDF, PZT
- Non-destructive collection, Sample return - Aerogel



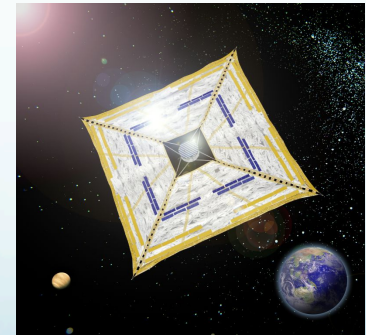
1997 Cassini IID "CDA"



1998 Nozomi IID "MDC"

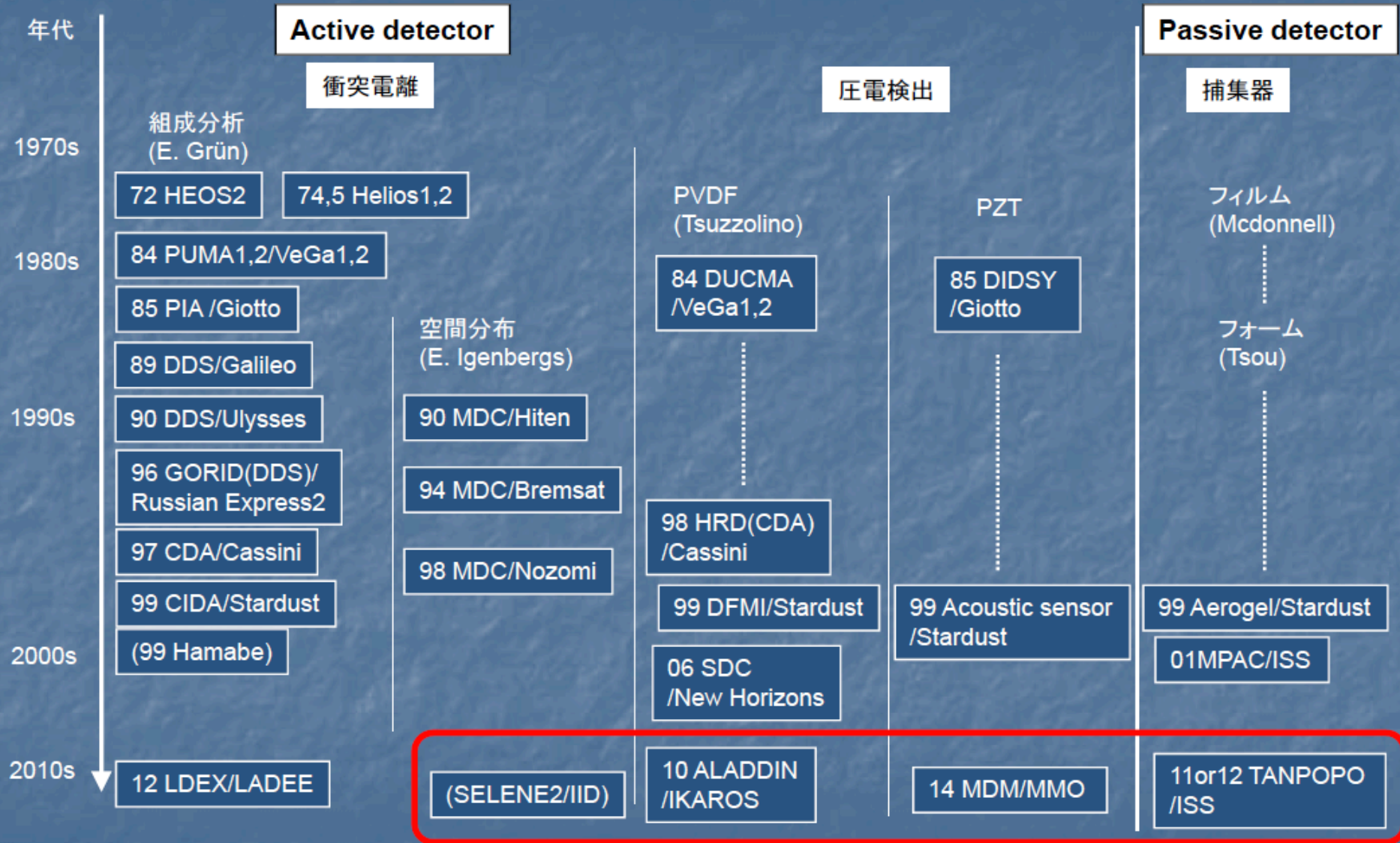


1999 Stardust IID+Mass
"PUMA", PVDF, Aerogel



2010 IKAROS PVDF
"ALADDIN"

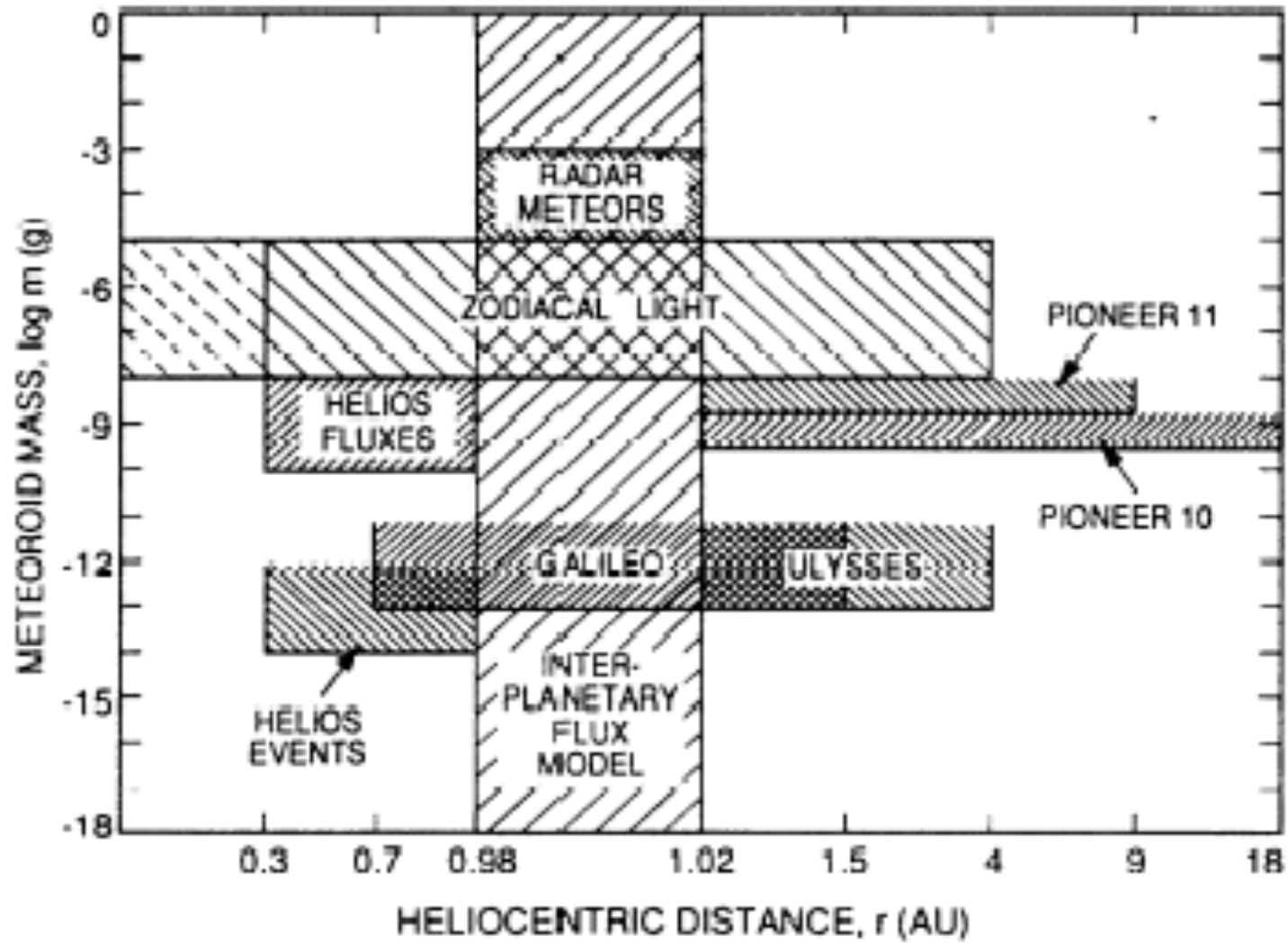
ダストその場計測の歴史



※この他の原理の計測器は省略している。
 ※70s以前はPZTや捕集板が主流であった。

今後10年間で計画されている日本のミッションに搭載予定

水 金 地 火 木 土 天



Divine (1993)

Historical dust mission of solar system

E.Grün

Spacecraft	distance range (AU)	spin axis direction	sensor orien- tation (deg.)	mass thresh- old (g)	sensitive area (m ²)	solid angle (sr)	dy- namic range
Helios 1/2	0.3–1	N	65, 134	$9 \cdot 10^{-15}$	0.012	1.23	10^4
Galileo	0.7–5.4	S, E	120	$4 \cdot 10^{-15}$	0.1	1.4	10^6
Pioneer 9	0.75–0.99	N	90	$2 \cdot 10^{-13}$	0.0074	2.9	200
Pioneer 8	0.97–1.09	N	90	$2 \cdot 10^{-13}$	0.0094	2.9	200
HEOS 2	1	var.	0	$2 \cdot 10^{-16}$	0.01	1.03	10^4
Hiten	1	N	90	$2 \cdot 10^{-15}$	0.01	1.5	$3 \cdot 10^4$
Ulysses	1–5.4	E	85	$4 \cdot 10^{-15}$	0.1	1.4	10^6
Pioneer 10	1–18	E	180	$8 \cdot 10^{-10}$	0.26 ⁽¹⁾	2.8	1
Pioneer 11	1–10	E	180	$6 \cdot 10^{-9}$	0.56 ⁽¹⁾	2.8	1

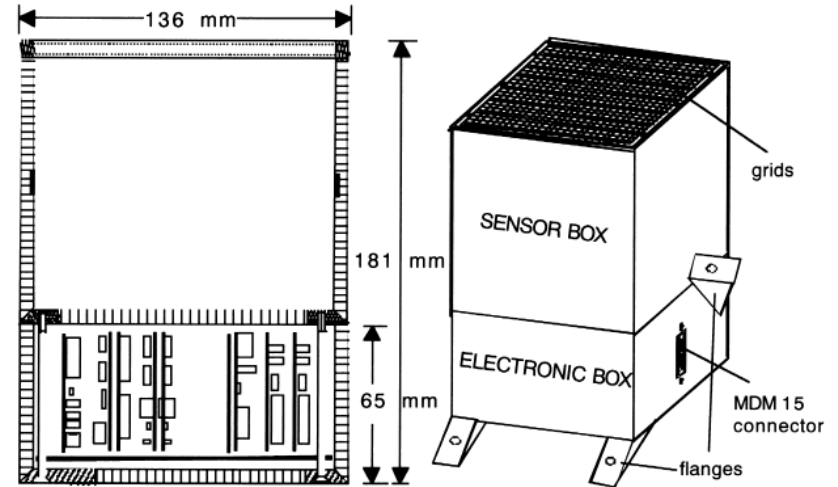
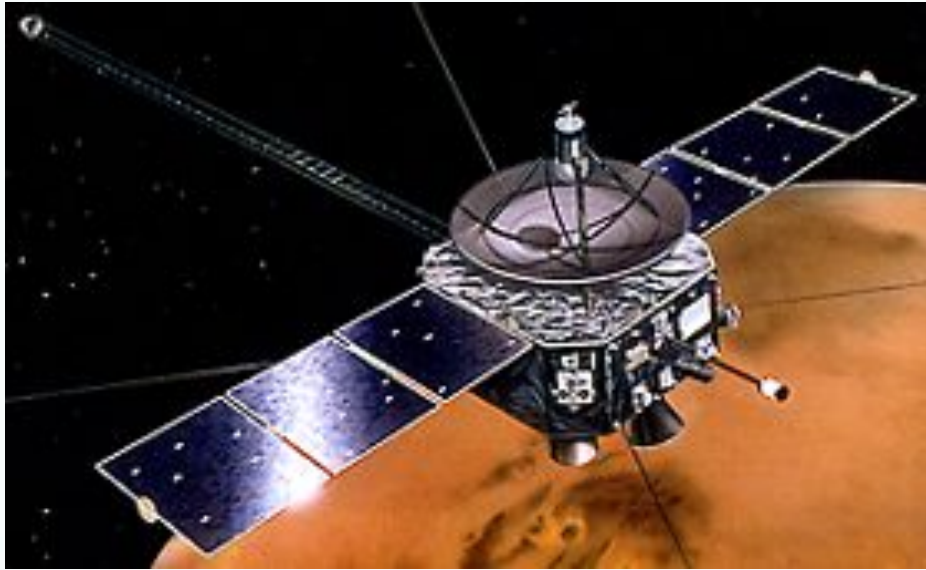
(1) initial area, actual area decreased as cells were punctured

+ Cassini, NOZOMI, IKAROS

MDM 0.31—0.47 N 90 10^{-14} 0.0064 2 10^4

Three in situ dust detectors in Japanese (inter)planetary missions

- MDC (Mars Dust Counter) on board NOZOMI
 - Impact ionization dust detector n, v, m
 - 1.0 – 1.5AU
- ALADIN onboard IKAROS
 - PVDF film dust counter n
 - 0.7 – 1AU
- MDM (Mercury Dust Monitor) onboard BepiColombo-MMO
 - Piezo electric (PZT) dust detector n, mv
 - 0.31 – 0.47AU

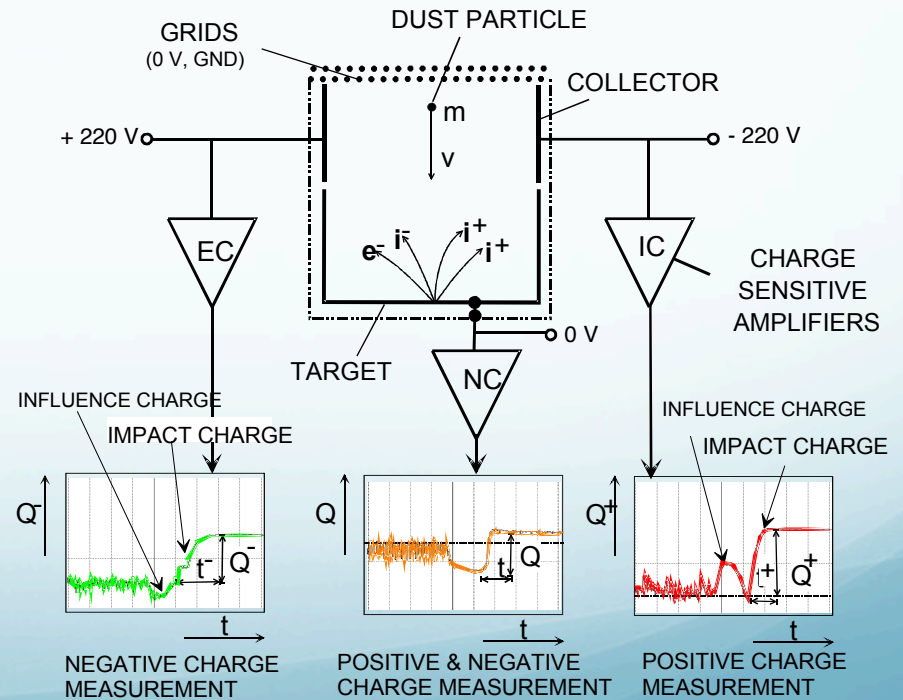


のぞみ 1998年7月4日打ち上げ

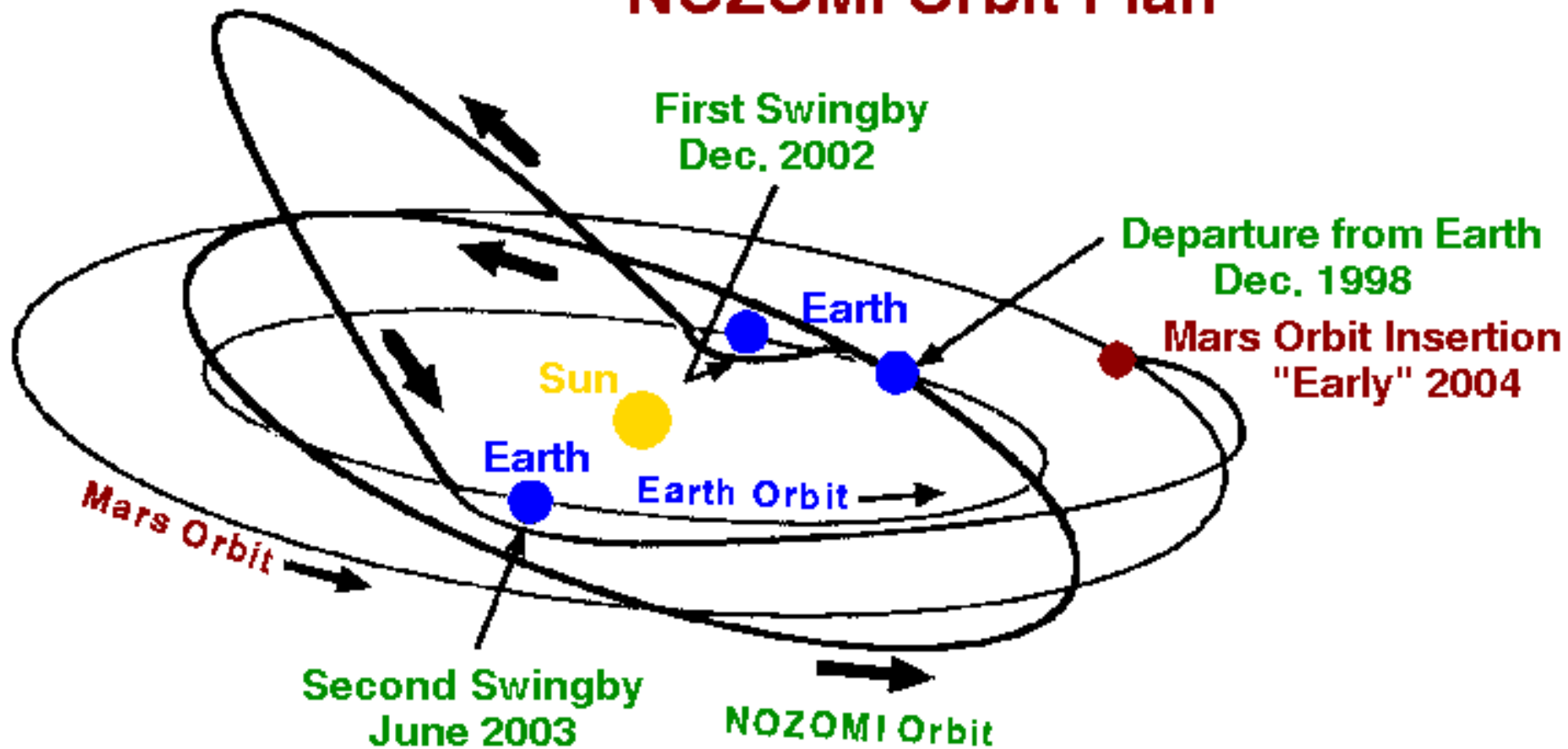
火星へ向けて飛行、2004年1月
火星周回予定であったが失敗した

Mars Dust Counter 日独で開発

Impact ionization dust detector
Dust flux, charge, mass, velocity

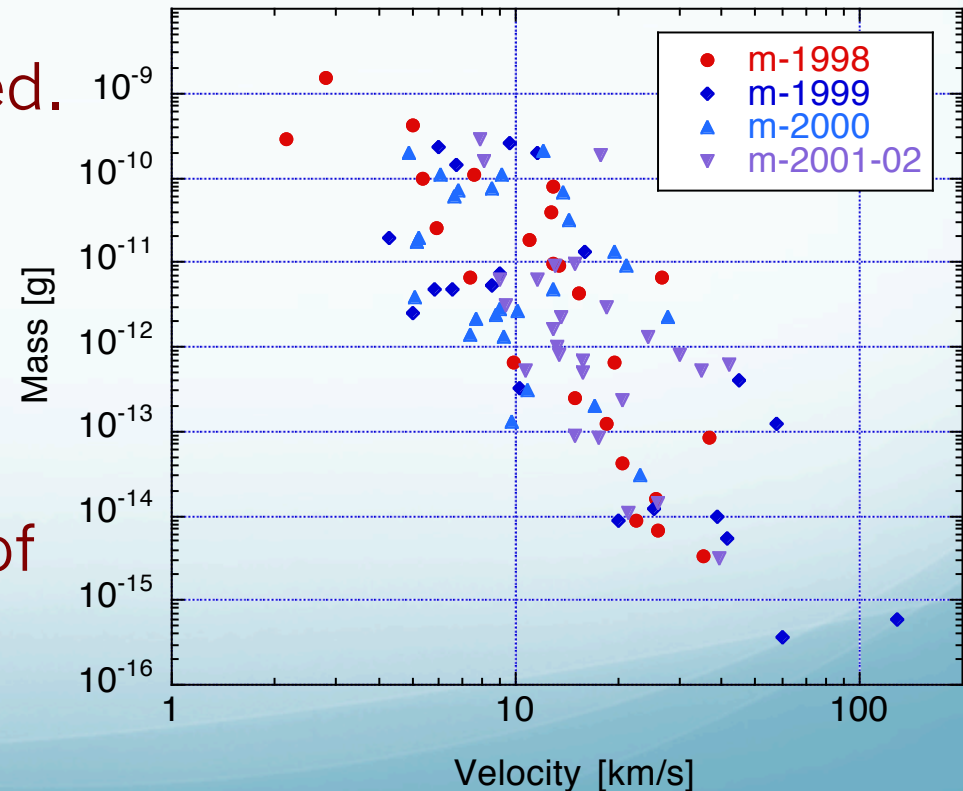
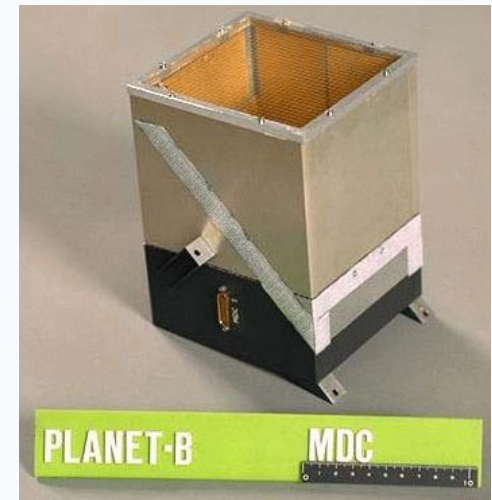


NOZOMI Orbit Plan

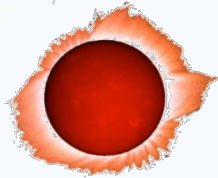


Mars Dust Counter (MDC)

- Impact-ionization type
- 730g including electronics
- 124 x 115 mm² aperture
- 4-Year operation.
- 120 dust impacts detected.
(100: v & m estimated)
- Most dust particles are Keplerian IDPs around the sun.
- A few particles probably of interstellar origin were detected in 1999.



IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun)



- May 21, 2010 Launched by H-IIA-17
- June 3-10, 2010 Deployment of the sail membrane and produced power from ultra-thin solar cells on the sail
- December 8, 2010 Venus flyby (Perihelion passage)
- December, 2010 Extended mission started
- May 2011 Aphelion passage

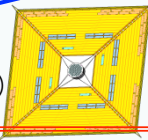
①



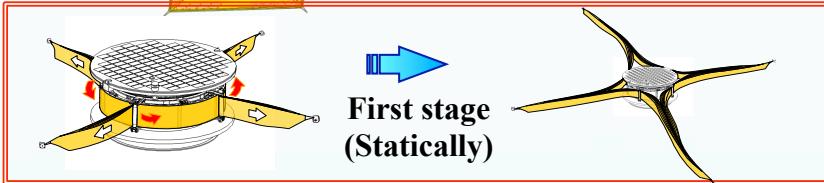
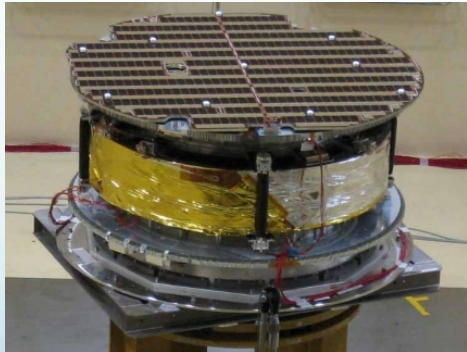
②



③

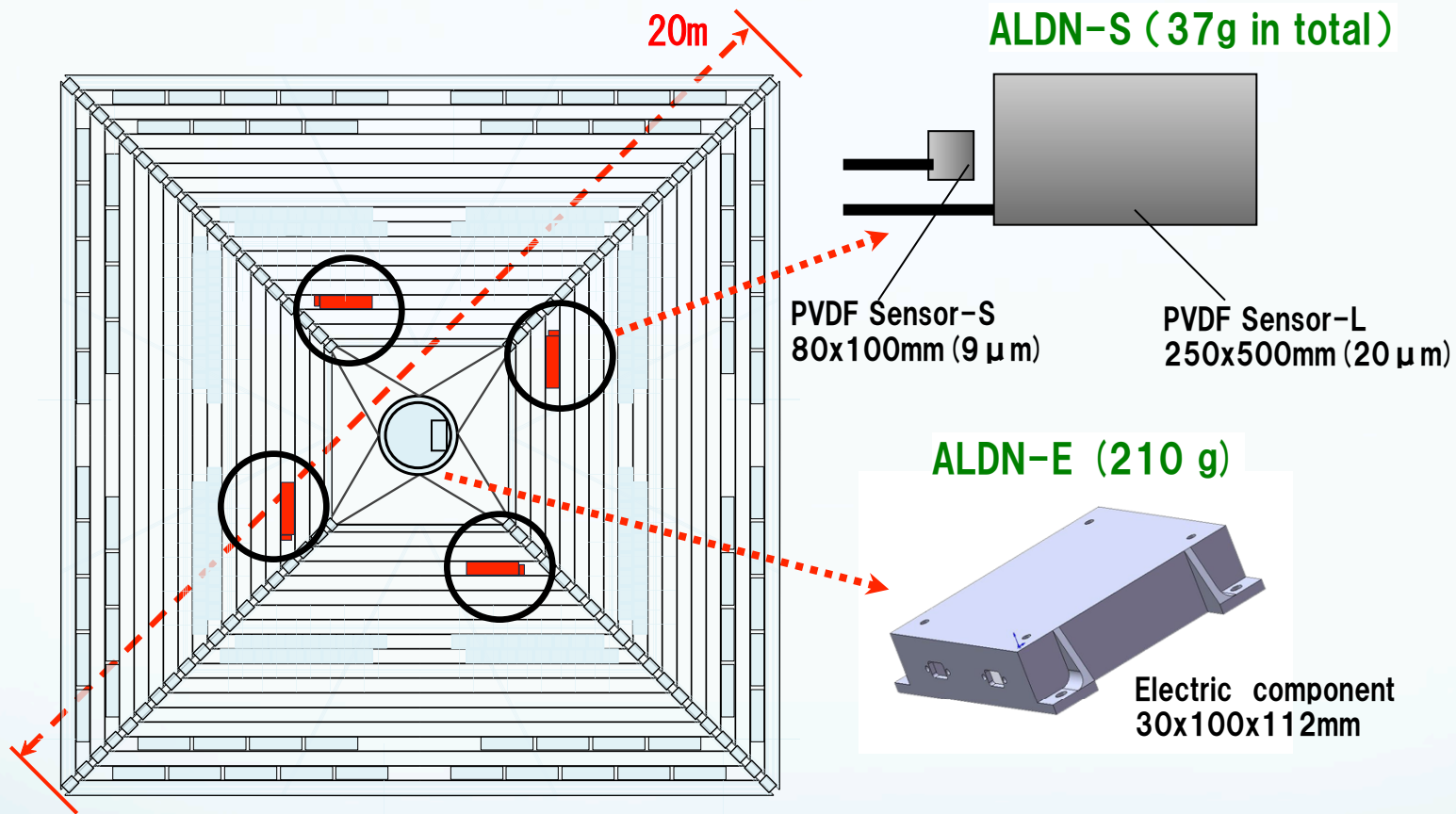


④



- Science missions are defined as extra mission success: GAP (high energy astronomy) and ALADDIN (solar system science)

IKAROS-ALLADIN System



- IKAROS-ALDN-S-PVDF :

➔ The WORLD'S LARGEST dust detector (0.54m^2) for statistically accurate measurements of dust flux with respect to heliocentric distance

- 9 micron-thick sensors: $0.01\text{ m}^2 \times 4 = 0.04\text{ m}^2$
- 20 micron-thick sensors: $0.125\text{ m}^2 \times 4 = 0.5\text{ m}^2$

Examples of Impact Candidate Data Acquired by ALADDIN

•Flight History:

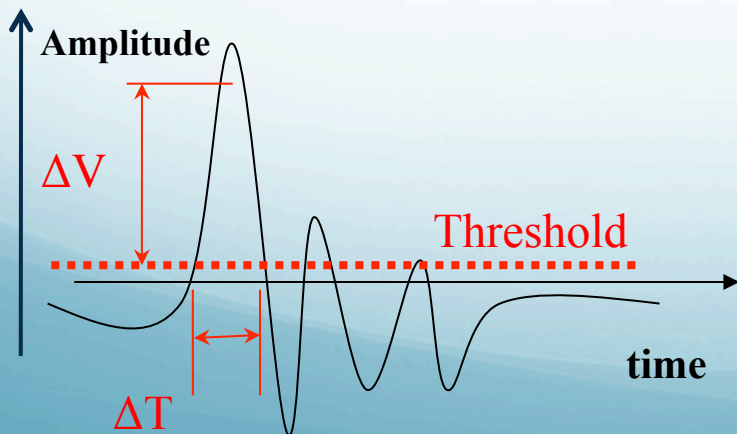
- * Detection Epoch
- * Heliocentric Distance
- * Field of View

•HK Data (Health Check):

- ALDN-E +V/I
- ALDN-E -V/I
- ALDN-E Temperature
- ALDN-S Temperature
- Cumulative Signal Counter

•Signal Data:

- Validity Flag
- Header, Channel Number
- Threshold Level
- Signal Decay Time (Delta T)
- Peak Signal Level (Delta V)



(eg., June 29, 2010)

<AOS-HK>

- * V(+) 4.93V、 I(+) 40.54mA : ALDN-E +V/I
 - * V(-) 4.95V、 I(-) 12.81mA : ALDN-E +V/I
 - * CH30 -17.8°C : ALDN-E Temperature
 - * MEM4_TEMP +81.20°C : ALDN-S Temperature
- ALDN System Healthy

<DR Data>

20100629~20100630: CNT-UP:1data

ΔV :2.65V (CH1)

<Screening Signals>

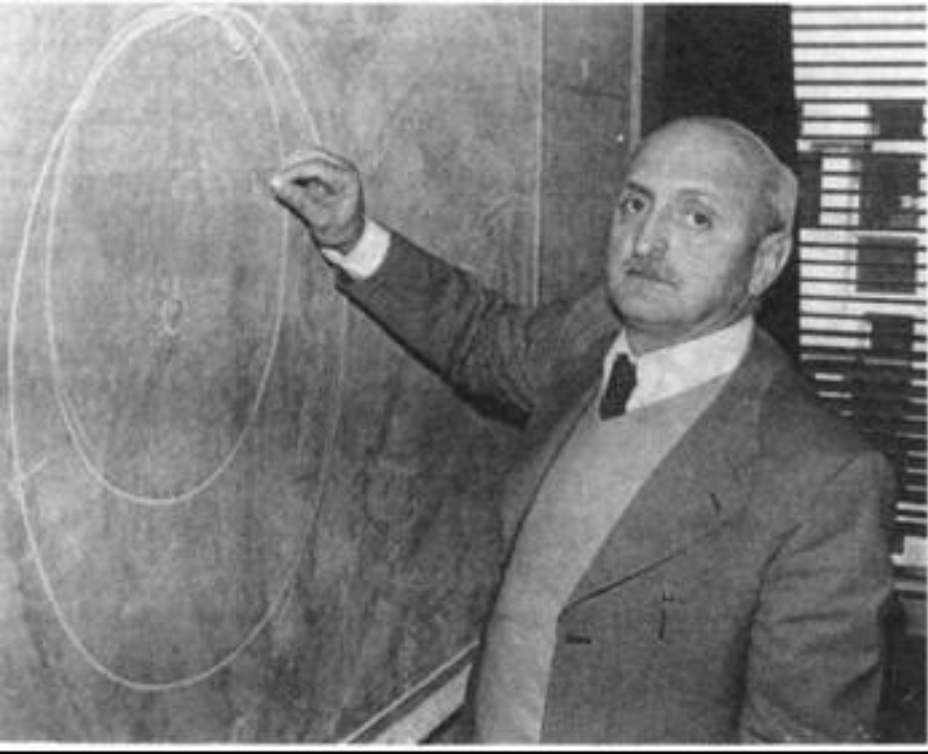
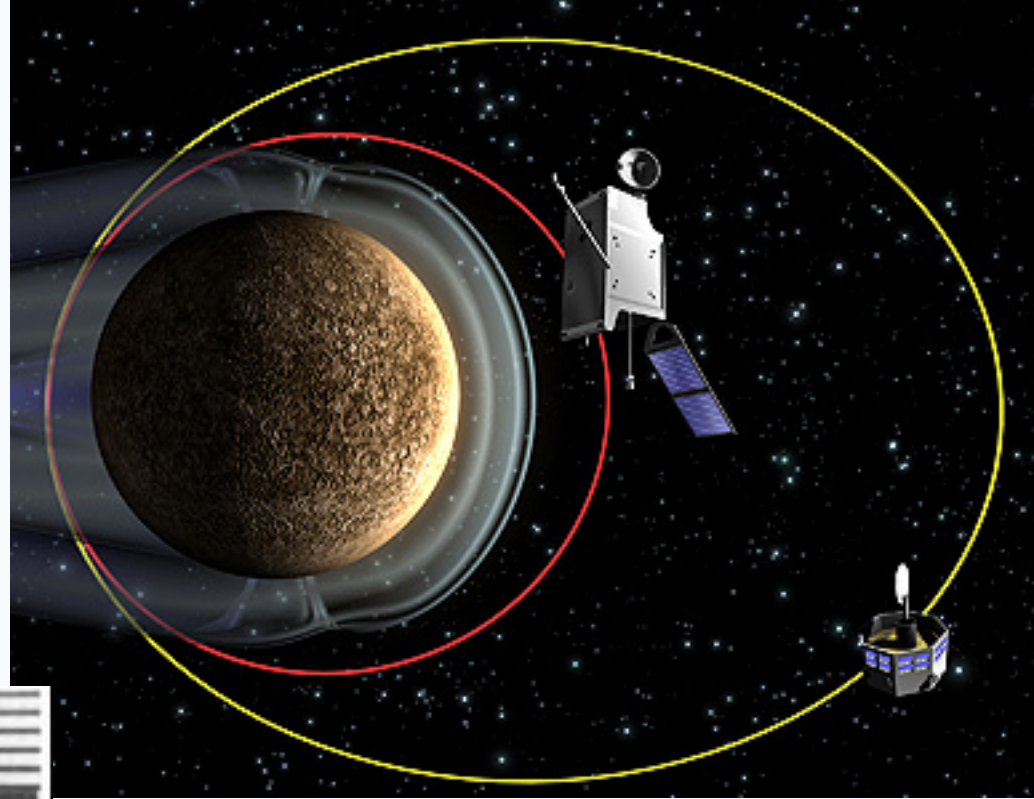
- (1) Compare with command log to identify if S/C generated noise data (RCD, SAP, etc.)
- (2) Compare decay time and peak level with HVI calibration database
- (3) Compare with other potential signals such as discharge events, high energy particles

BepiColombo

ESA /JAXA joint mercury
exploring mission

*MPO (Mercury Planetary
Orbiter) (ESA)

*MMO (Mercury Magneto-
spheric Orbiter) (ISAS/JAXA)



Launch July 2015 Ariane 5
Arrival Jan 2022
One year research from May 2022

Giuseppe (Bepi) Colombo
(1920-1984) Italy
Applied mathematician

Dust particles in the solar system

B) Cometary dust trail (trail)

A) Interstellar dust

E) Interplanetary dust

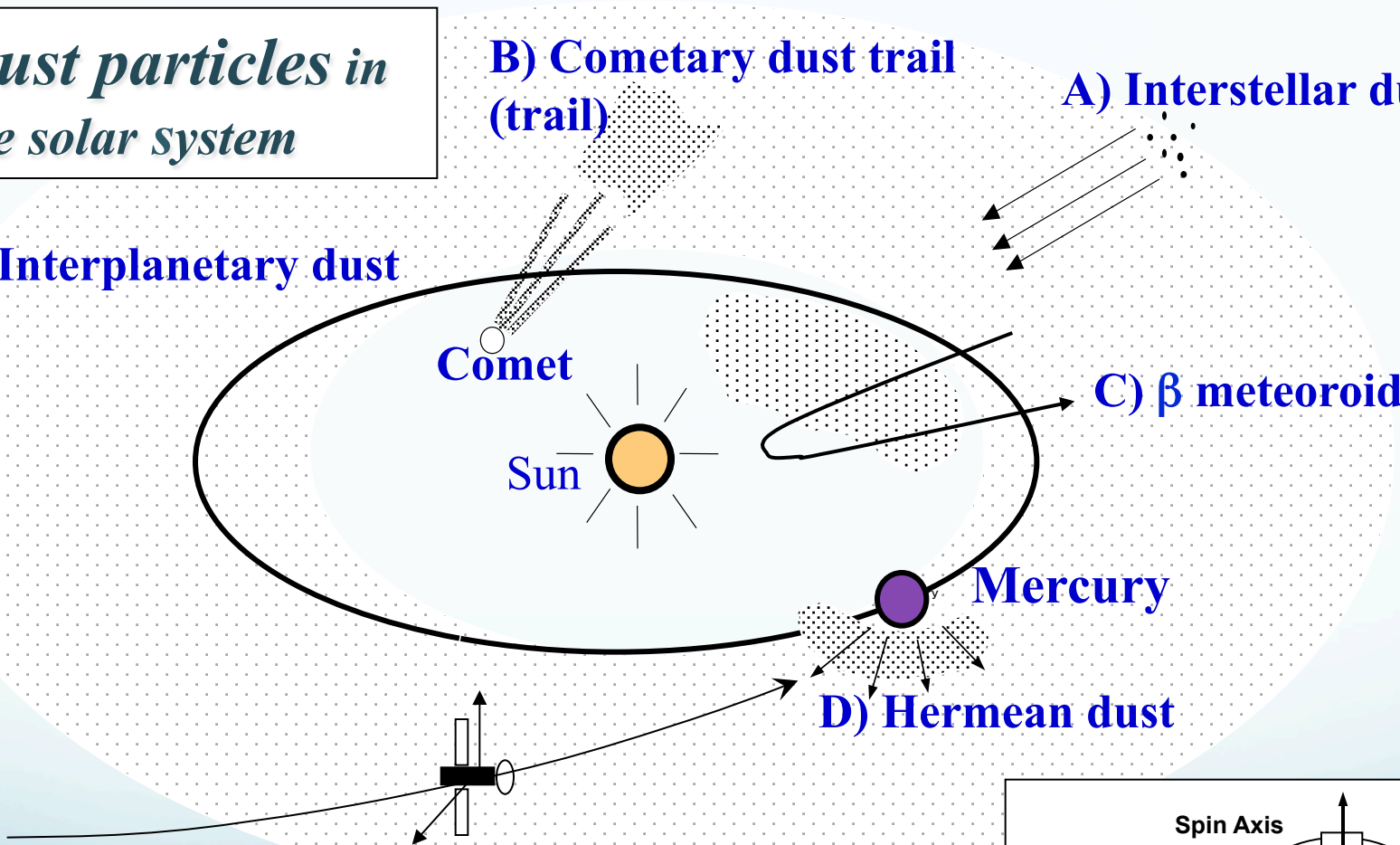
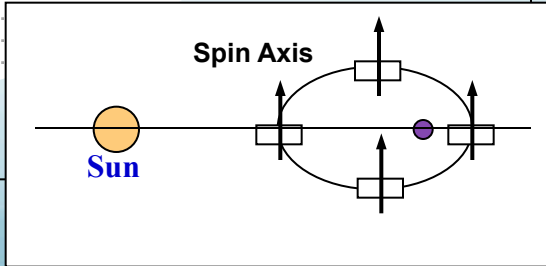
Comet

Sun

C) β meteoroids

Mercury

D) Hermean dust

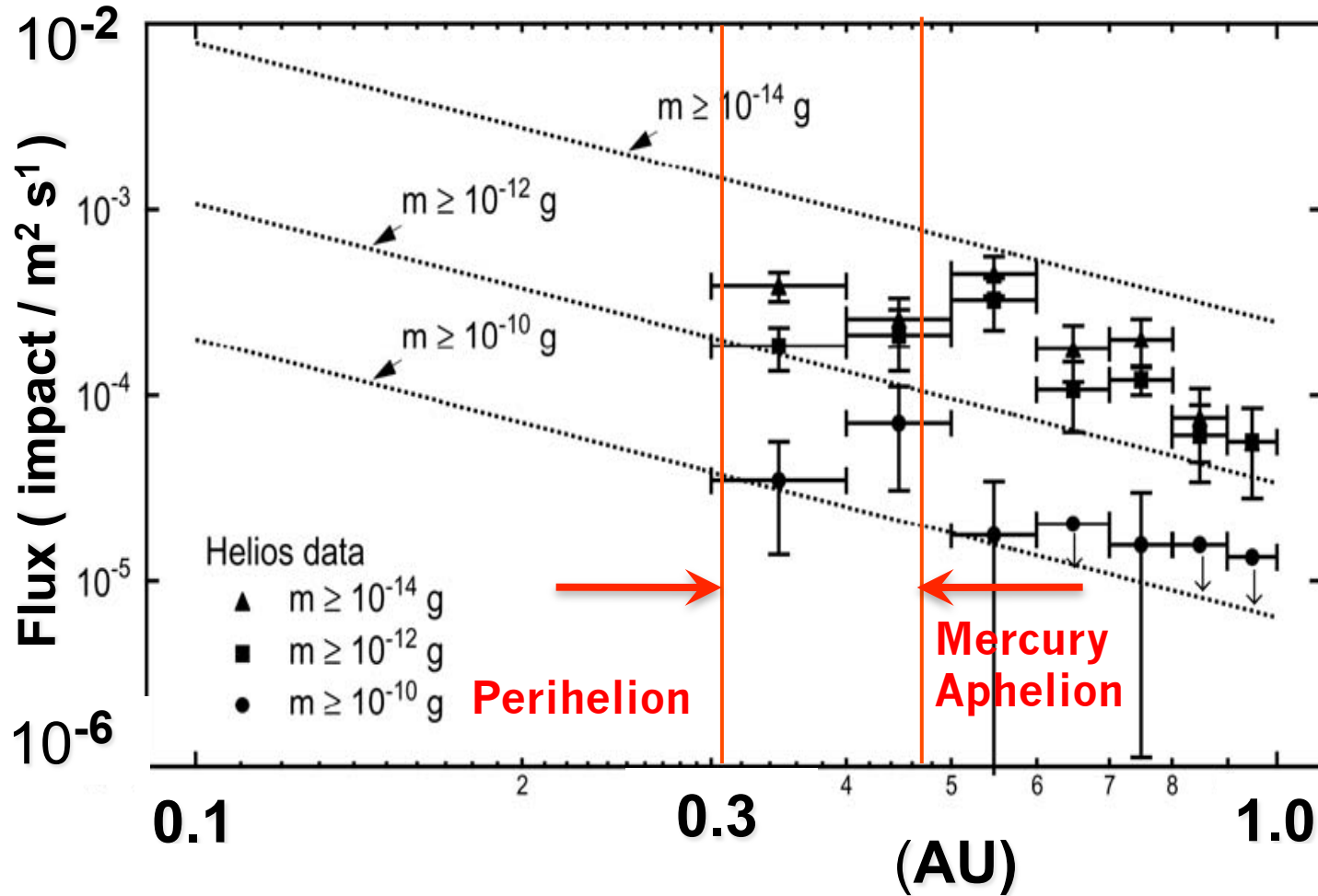


Scientific Objectives

<i>Dust Types</i>	<i>Scientific Interests</i>
Dust flux within the Inner Solar System	Confirm the flux and size distribution as a function of the heliocentric distance (0.31-0.47 AU) . In-situ measurement to constrain zodiacal dust cloud distribution model.
Cometary Dust	Possible encounters with the cometary dust trails and highly eccentric trajectories.
Beta Meteoroids	Direct flux measurement in the vicinity of Mercury (0.31-0.47 AU) help to understand mechanism and location.
Interstellar Dust	Possible detection of large interstellar dust (≥ 1 micron) coming into close to the sun.
Dust to Mercury (V orbit = 47.5 km/s V rel > 6 km/s)	<ul style="list-style-type: none"> +Investigation of temporal and directional variations of dust influx throughout Mercurian orbit to identify the key meteoroid sources. +Assessment of meteoroid impact contribution to the formation of the tenuous Na atmosphere. +Constraint to space weathering effect on the Mercurian surface. +Estimate external mass accretion rate to the Mercurian surface
Dust from Mercury (V esc.= 4.25 km/s)	<ul style="list-style-type: none"> +Search for Mercurian dust ejection (e.g., temporal dust cloud?) by meteoroid impacts, similar to the Jovian satellites. +Possible interaction with the magnetic field, similar to the Jovian satellite dust stream.

Dust Flux around Mercury Orbit

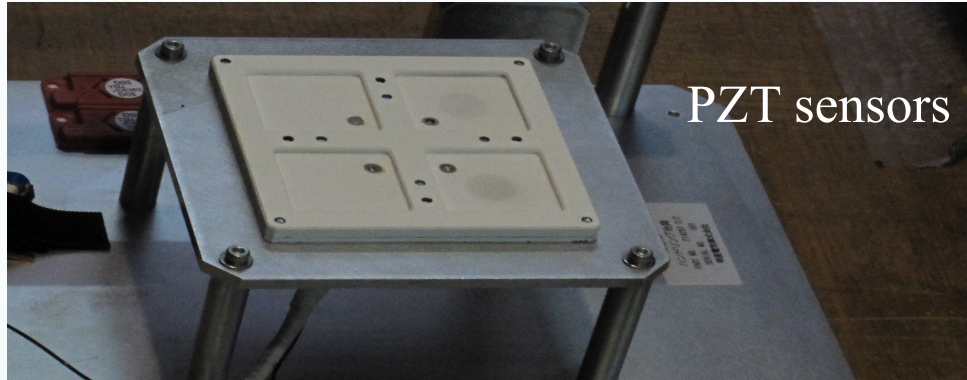
from Mann et al. 2003



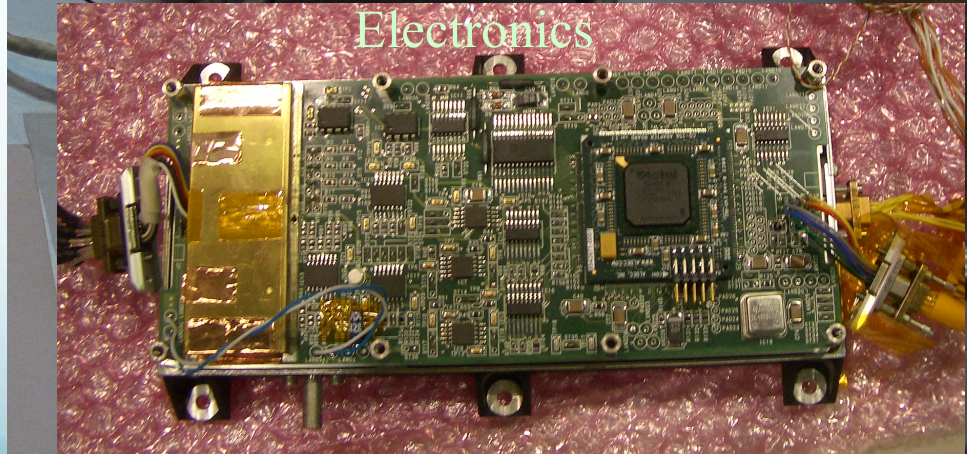
Expected impacts will be 0.5 impact/day with MDM.

MDM-S 4 PZT sensors are in the frame

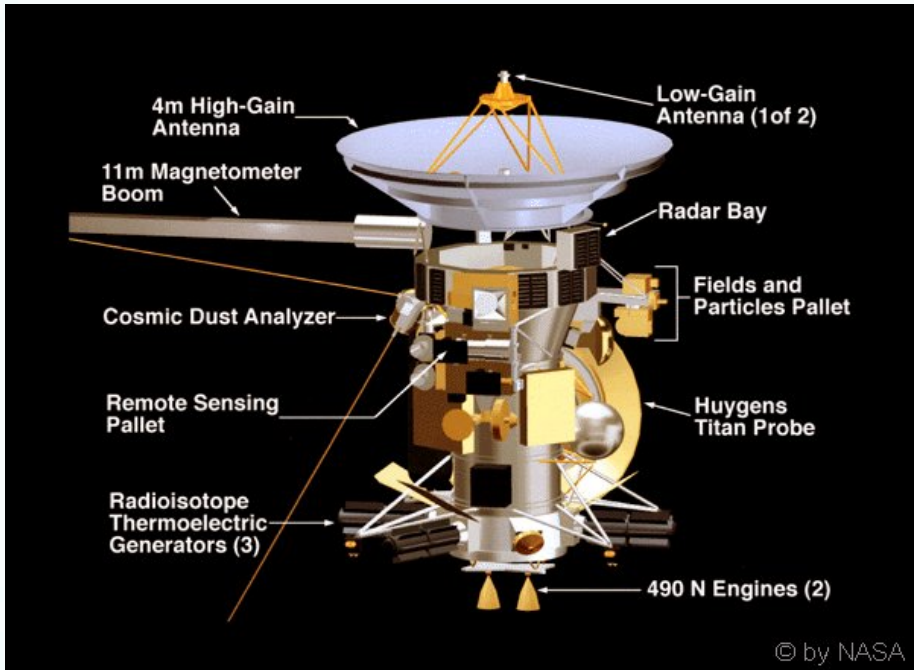
PZT(Pb-Zi-Ti): 4cm×4cm×2mm



- No need of bias power supply
- Usable at high temperature (~250°C)
- Long term stability
- Enough tolerance of radiation damage
- Easy to shape any structure



Engineering Model



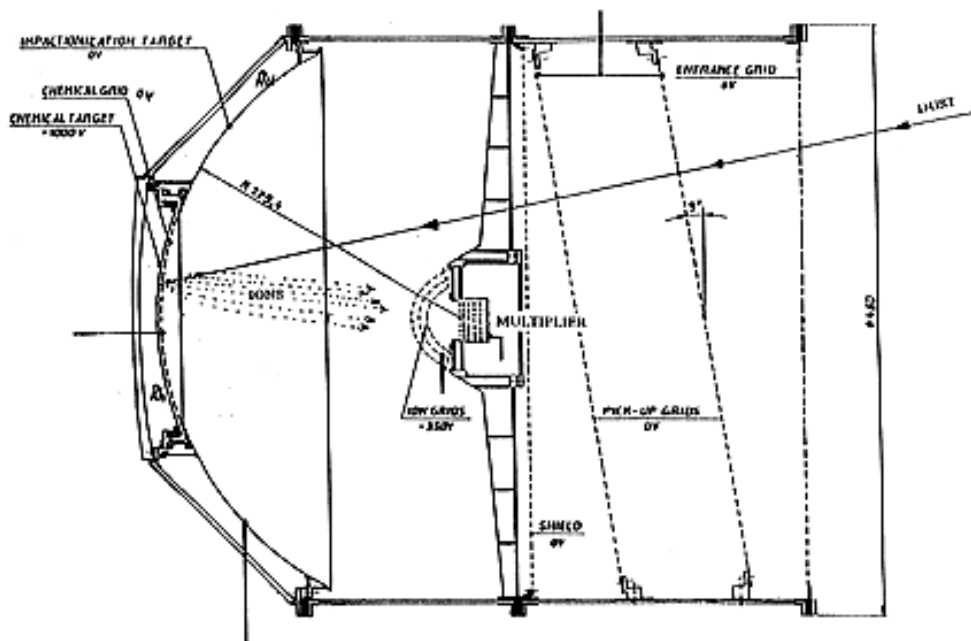
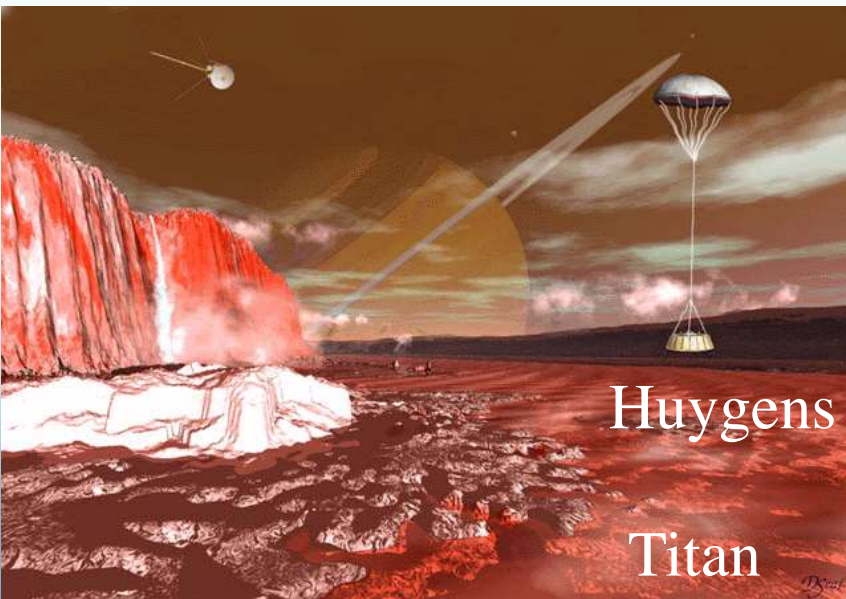
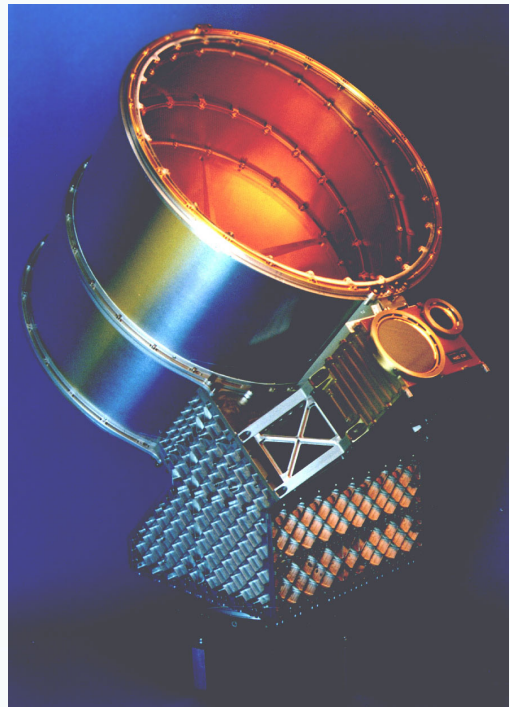
© by NASA

Cassini-Huygens

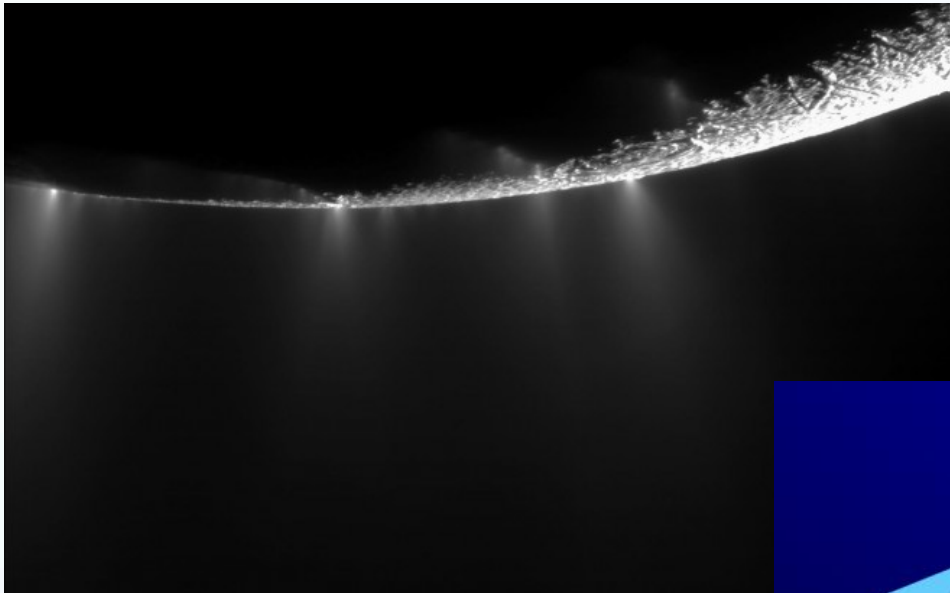
1997.10.15~
2017

2004. July 土星

Cosmic
Dust
Analyzer
(CDA)

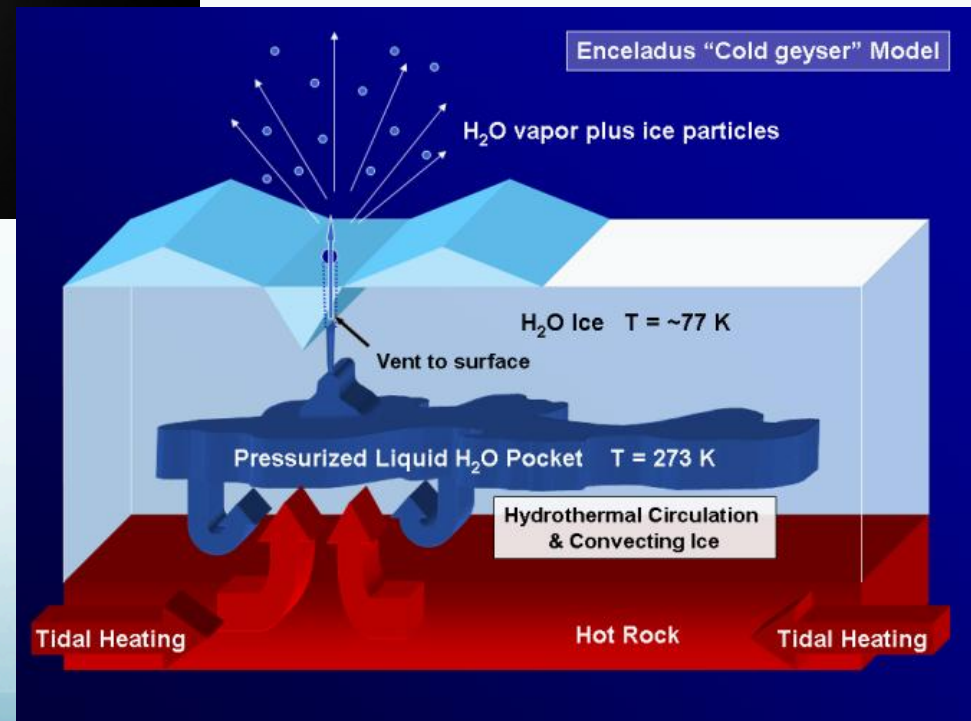


Enceladusからの水蒸気と氷粒の噴出



CDAIによる分析

氷の中にナトリウム塩を
発見

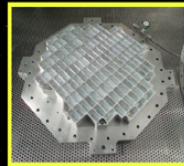


STARDUST

STARDUST plans to fly by Comet Wild2, and for the first time ever, bring pristine samples of cometary material back to Earth in the Utah desert.



Delta II Launch



Aerogel Dust Collector Grid



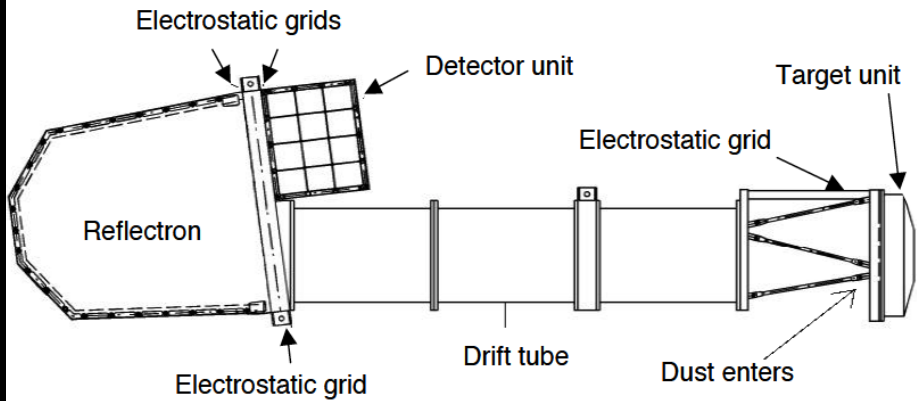
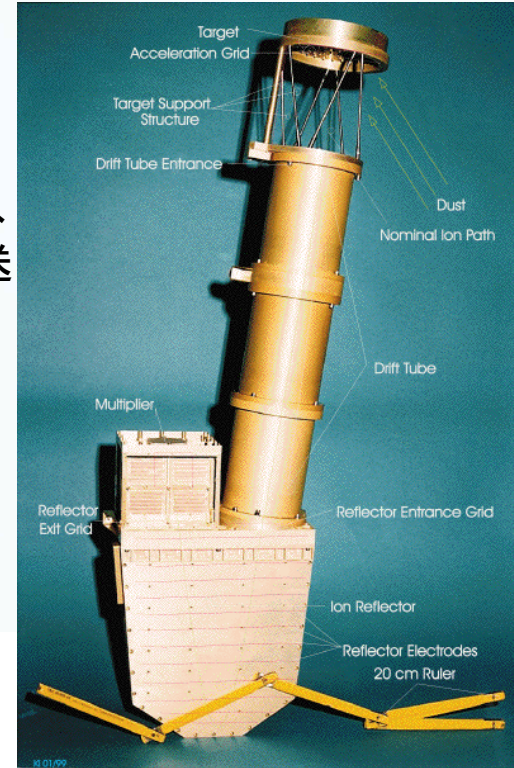
Sample Capsule Return in Utah

BRINGING COSMIC HISTORY TO EARTH

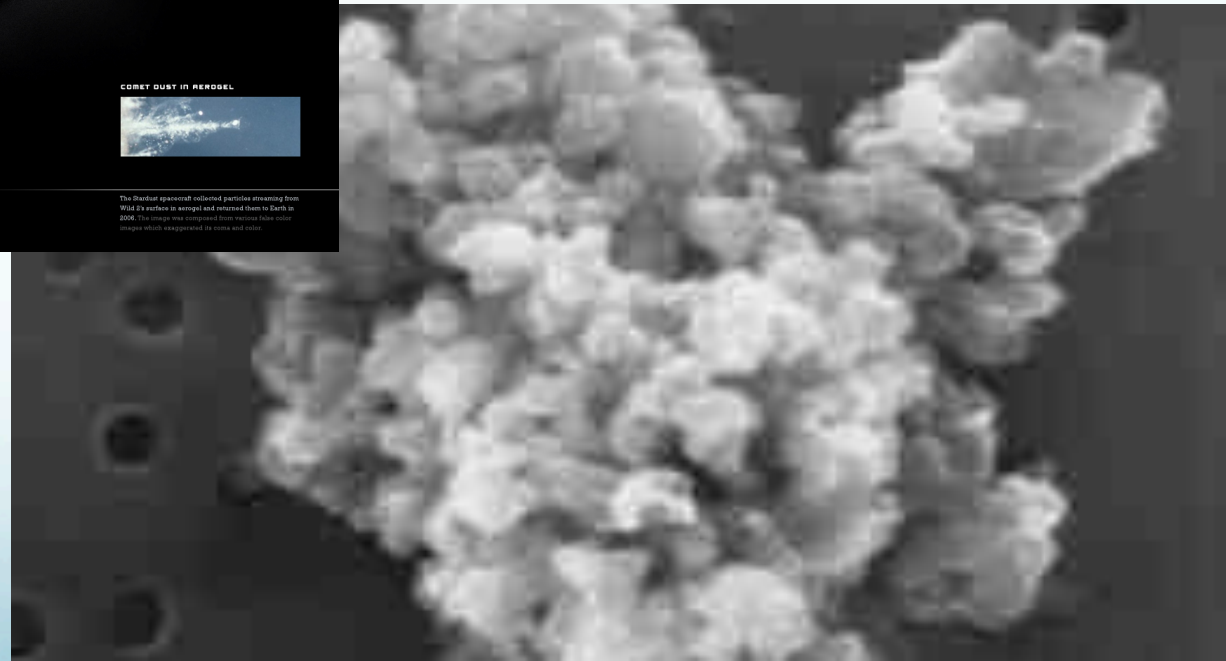
1999年2月7日～ 2011年3月24日

2004年1月に「Wild2彗星」に接近
2006年1月地球へ向けてサンプルを送る
2011年2月「Tempel1彗星」を探索

CIDA (Cosmic and Interstellar Dust Analyzer)



Sample return STARDUST from Comet Wild2



3) 地上でのダストシミュレーション実験

微粒子（ダスト）加速

加速されている微粒子の特徴

微粒子の種類: C, Ag, Al, Fe, ... (conductive)

Conductive polymer coated latex

大きさ(直径) : 10 nm ~ 10 μ m

質量 : 0.01 fg ~ 0.1 μ g ($10^7 \sim 10^{17}$ / p)

速度 : 1 ~ 100 km/s

電荷 q : +1 fC ~ 0.1 pC ($+10^4 \sim 10^6$ / e)

エネルギー E : 10 GeV ~ 1 TeV at 1 MV acceleration
($E = qV$ V: 加速電圧)

Characteristics of hypervelocity impact

* 5 ~ 100 km/s impact velocity

Impact ionization

Shock wave

Pressure ($10^5 \sim 10^8$ atm)

Temperature ($10^2 \sim 10^5$ deg)

Production of crater

production mechanism

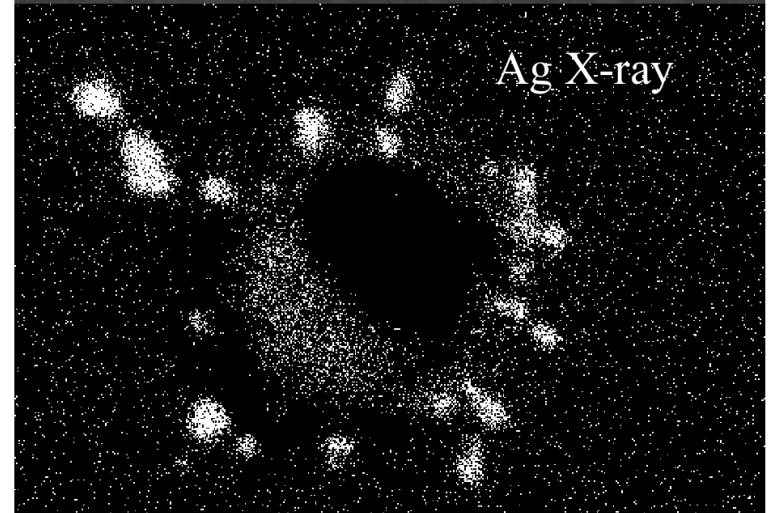
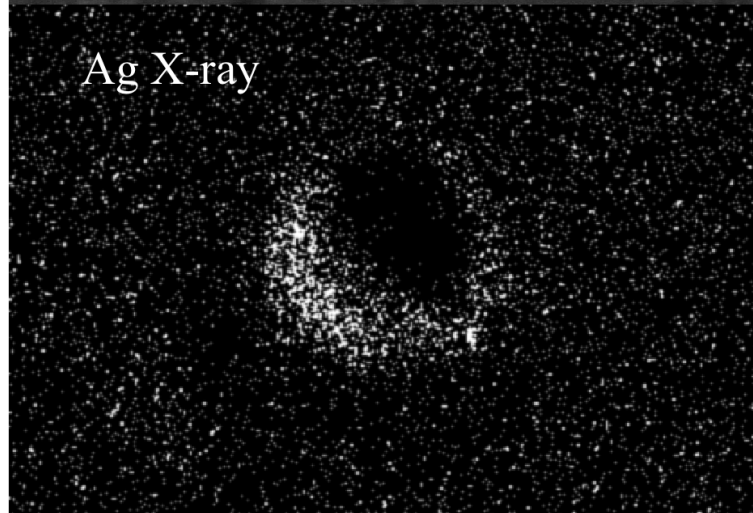
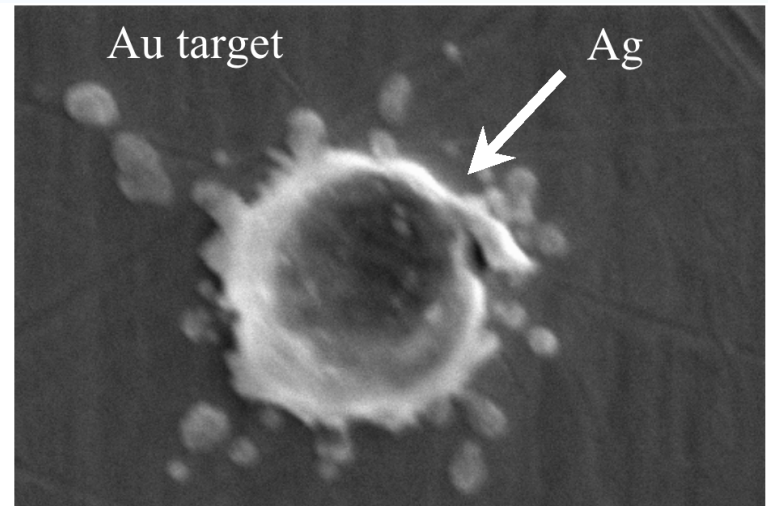
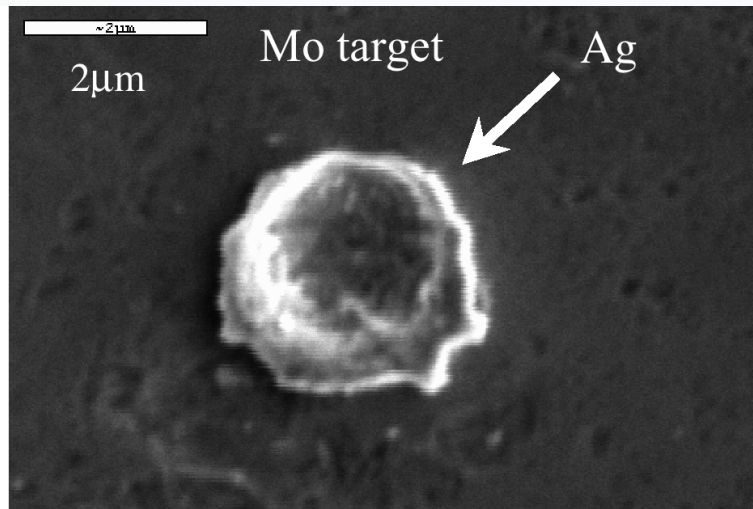
New material production by phase transition

* ~ 1000 km/s

Inertial confinement fusion

モリブデン(左)及び金(右)標的に銀粒子が衝突した痕跡

走査型電子顕微写真(上)と特性X線(下)によるマッピング



ダスト加速器施設

国内施設

100 kV: 京都大学工学研究科

200 kV: 若狭湾エネルギー研究センター (材料科学)
(~2009)

250 kV: 重イオンライナック入射器; 京都大学工学部
(~1987)

1.0 MV: 2.0 MV バン・デ・グラーフ; 京都大学 (~1987)

3.2 MV: 3.75MV バン・デ・グラーフ; 東京大学原子力
専攻HIT

国外施設

- * 0.4MV: Cockcroft-Walton type: Material Science
Institute of Nuclear Physics, Moscow State University (Russia)
- * ? MV : 6.0 MV Van de Graaff:
Los Alamos National Laboratory(U.S.A.)
- * 2.0 MV: 2.0 MV Van de Graaff: Space Science
Open University (Milton Keynes, UK)
- * 2.0 MV: 2.0 MV Van de Graaff: Space Science
Max-Planck-Institut für Kernphysik (Heidelberg, Germany)
- * 2.0 MV: 3.0 MV Van de Graaff;
Institute of Nuclear Physics, Moscow State University (Russia)
- * 2.0 MV: 2.0 MV Van de Graaff: Space Science
Concordia College (Moorhead MN U.S.A.)
- * 3.0 MV: 3.0 MV Van de Graff: Space Science
University of Colorado (Boulder CO U.S.A.)
- * 2.0 MV: 2.0 MV Van de Graaff ?
University of Stuttgart (Stuttgart, Germany)

The Open University

Milton Keynes, U.K.

2 x 2MV Van de Graaff
accelerator



↑ Reading 大学より移設

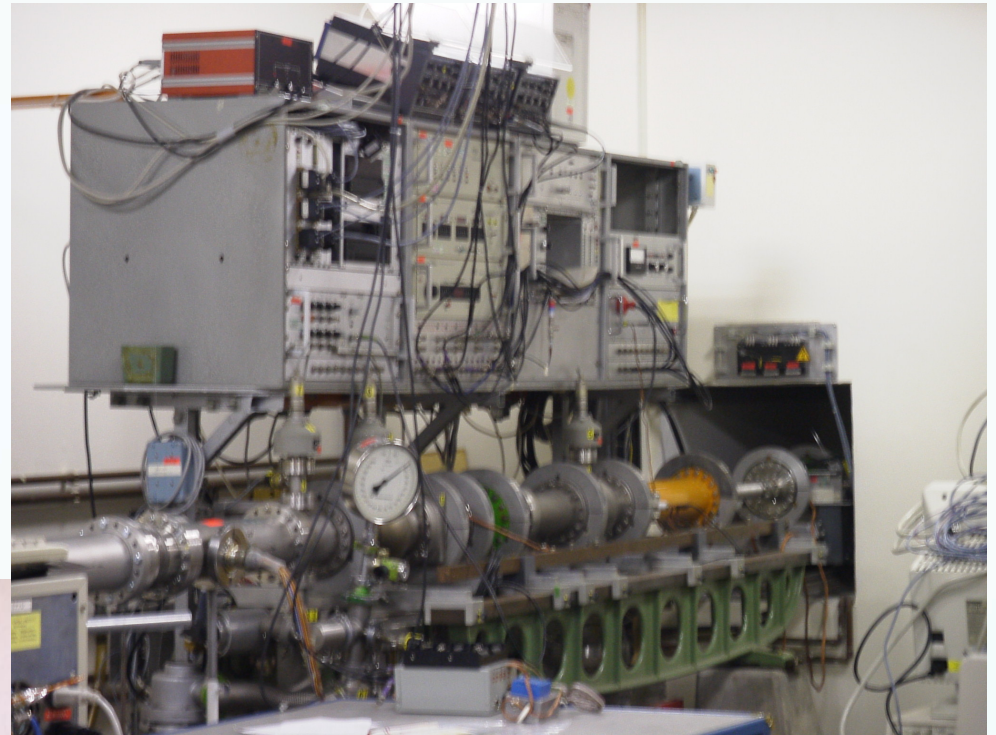
Kent 大学より移設 →

2002年11月時点での様子

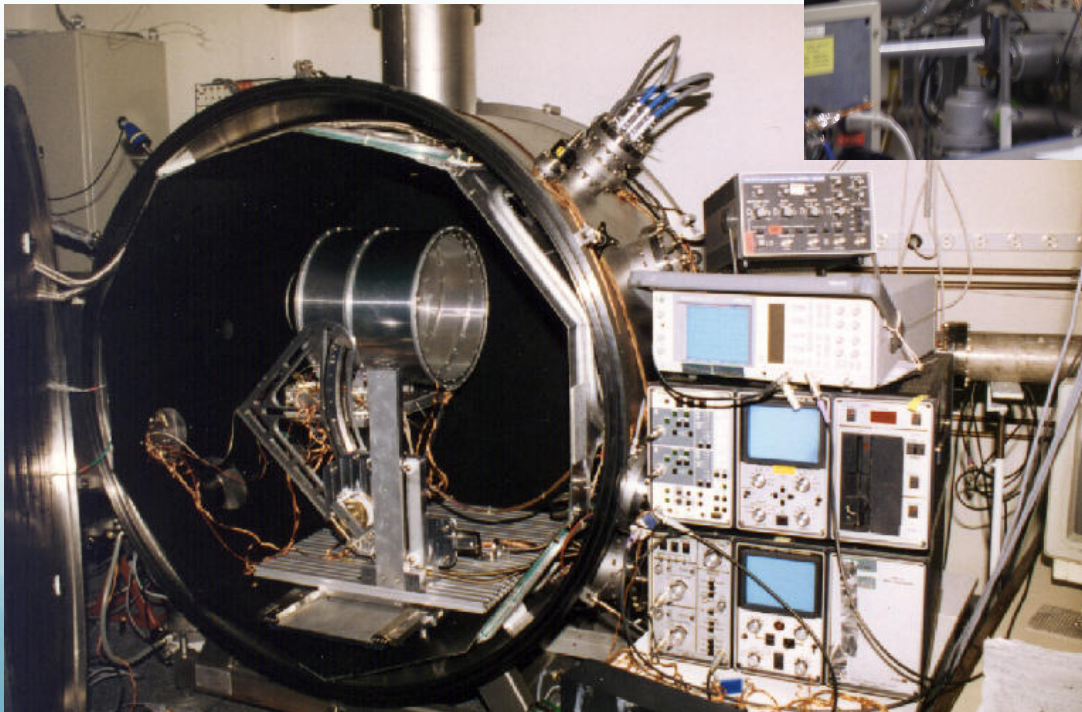


Max-Planck-Institut für
Kernphysik
Heidelberg, Germany

2MV Van de Graaff
accelerator



Beam line

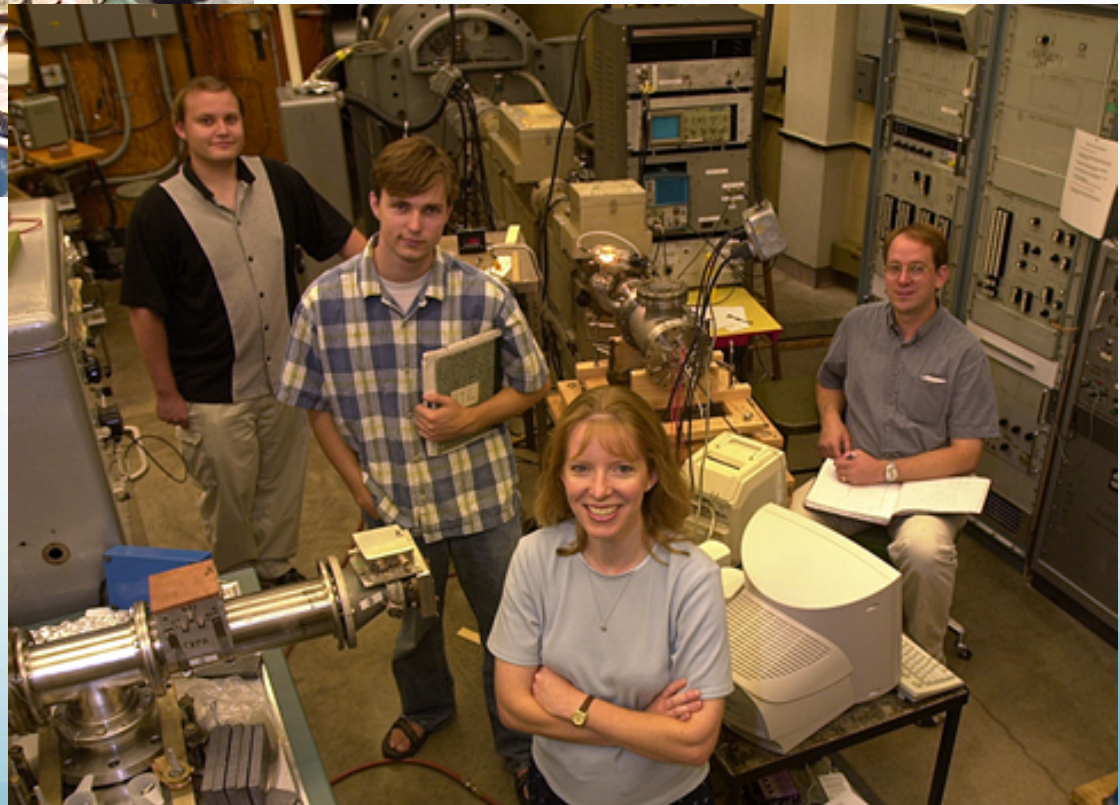
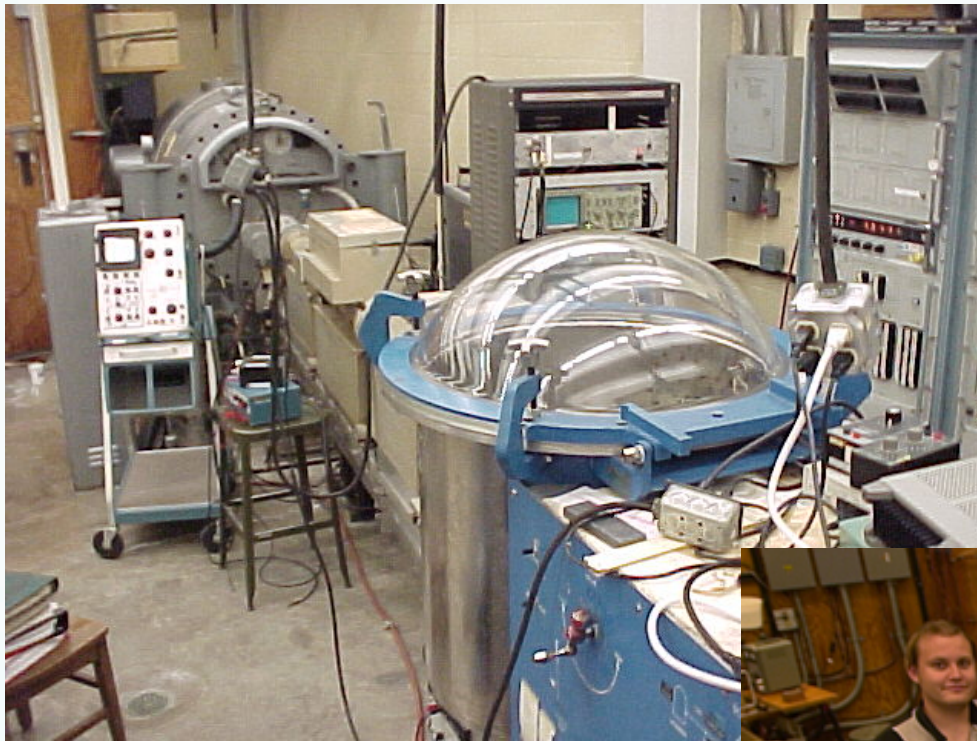


Target chamber

The Concordia College Electrostatic Hypervelocity Dust Accelerator

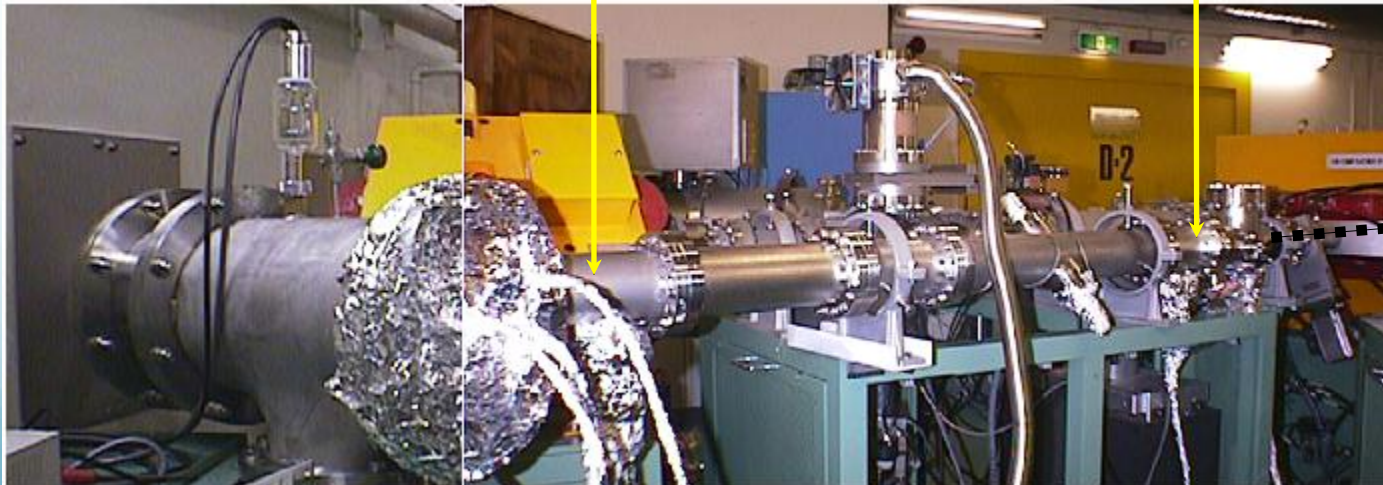
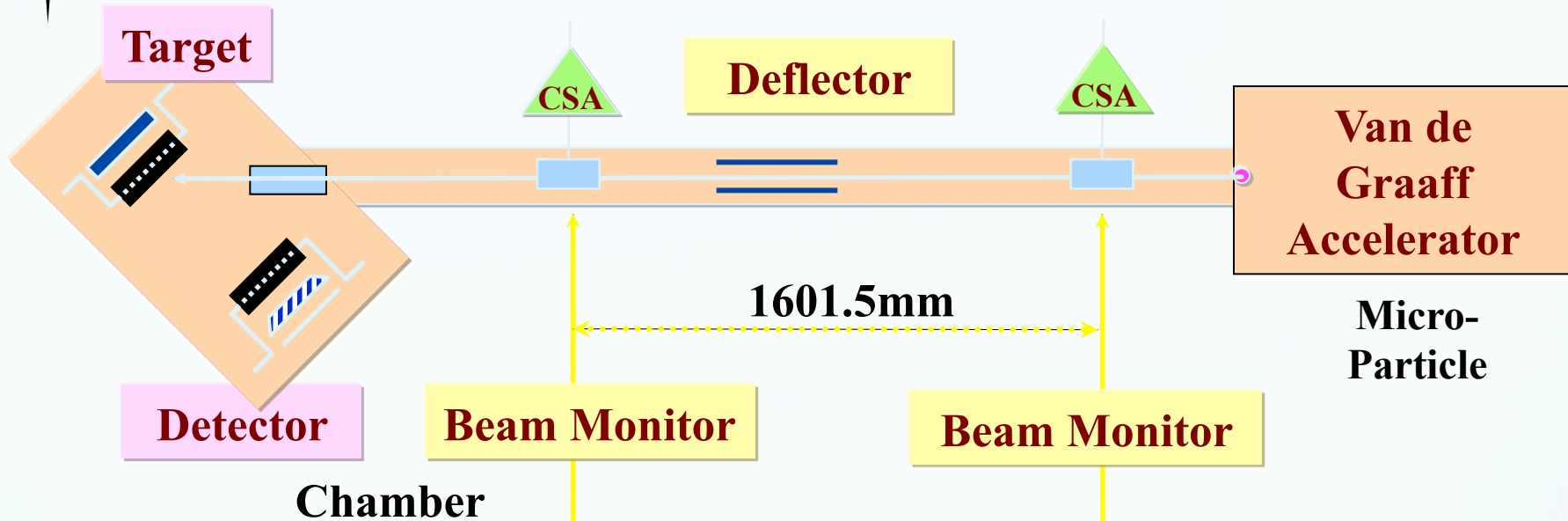
2MV Van de Graaff accelerator

Moorhead, MN, U.S.A.

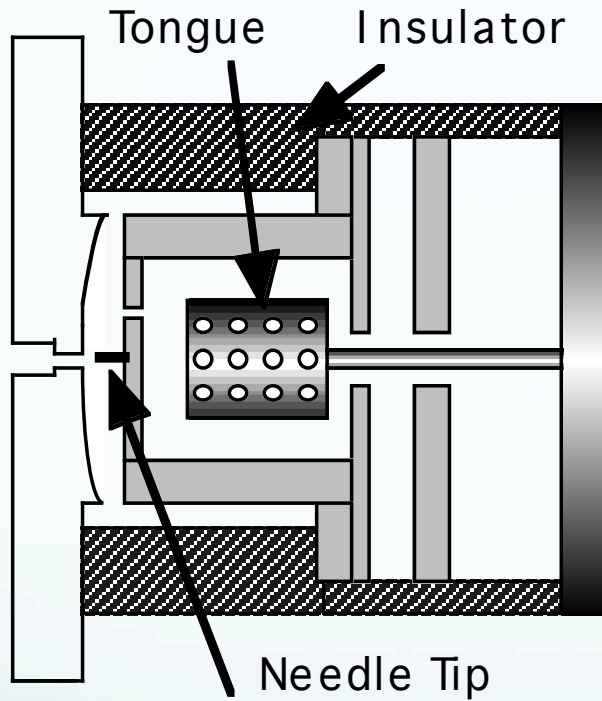


During the summer of 2001, (from left to right in the photo) Matt Matz, James Farnsworth and Heidi Manning supported Daniel Austin, Caltech, in the testing of his DustBuster Mass spectrometer.

Dust Accelerator (UT-HIT)



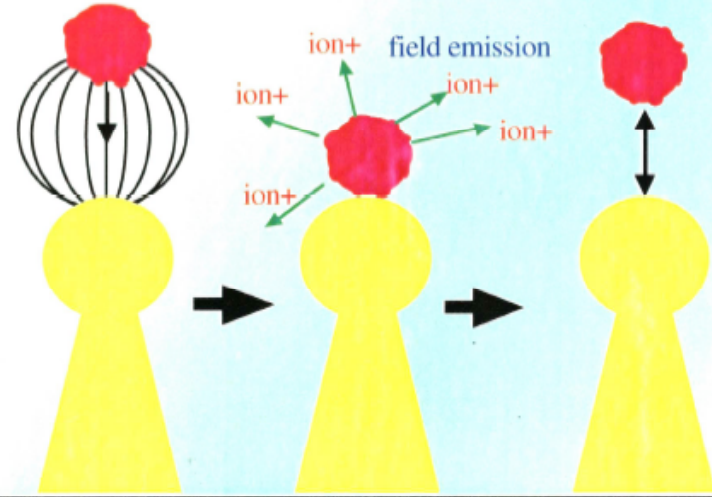
微粒子イオン源



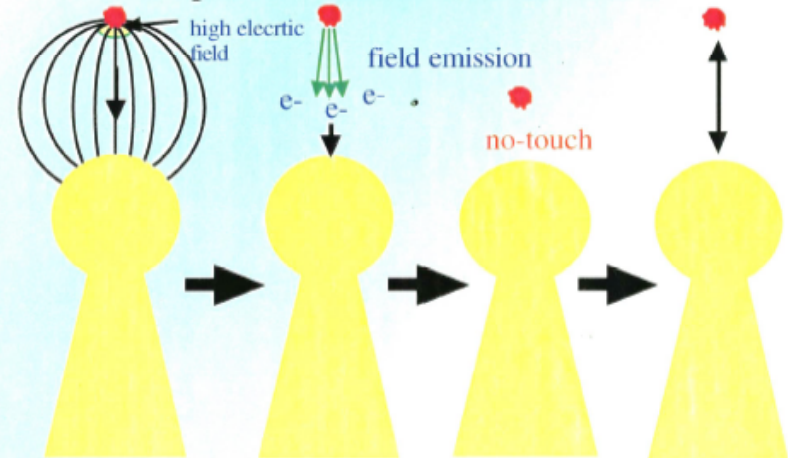
微粒子イオン源の仕組み (Top view)

Particle charge model
Keaton et al. 1990

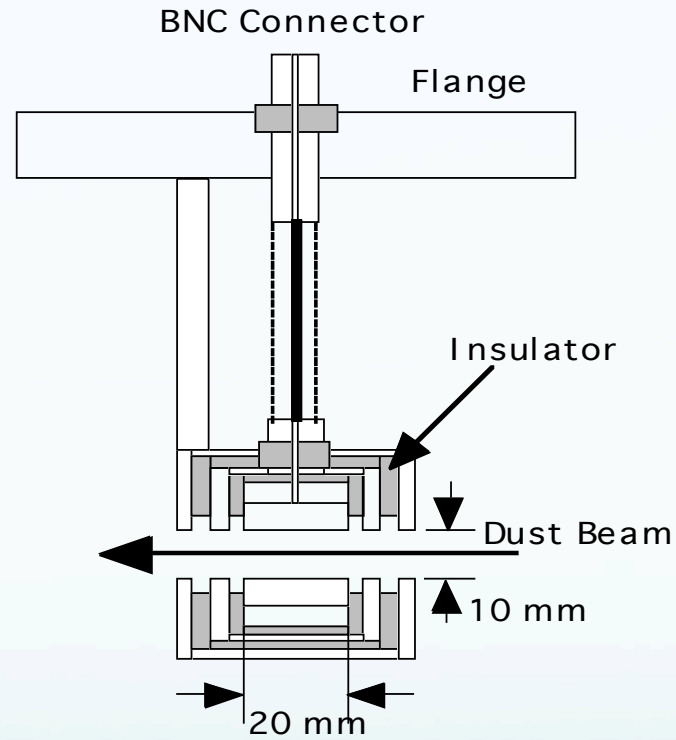
particle radius > 0.1 micron



particle radius < 0.1 micron

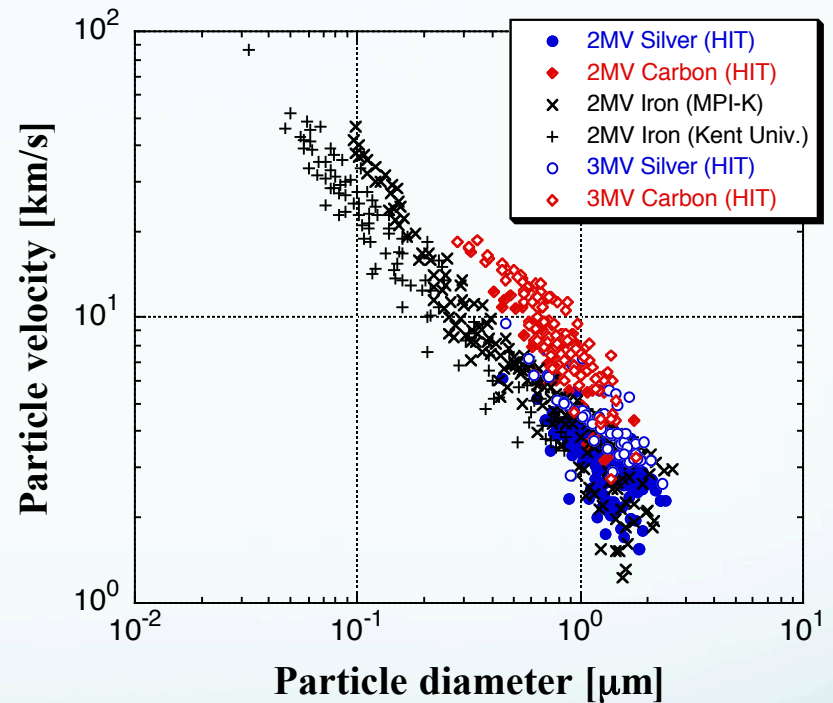
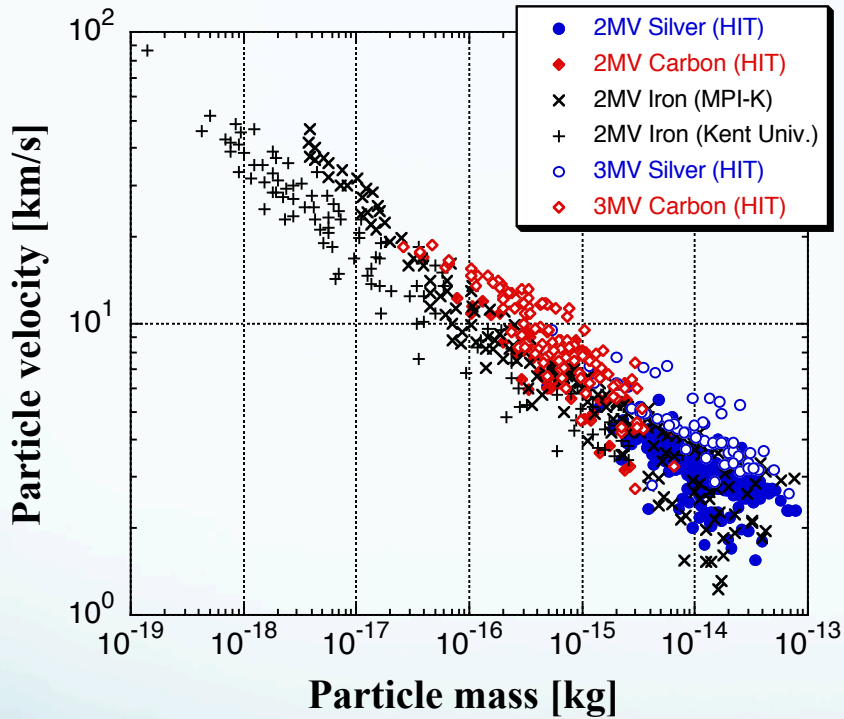


電荷測定用ビームモニター

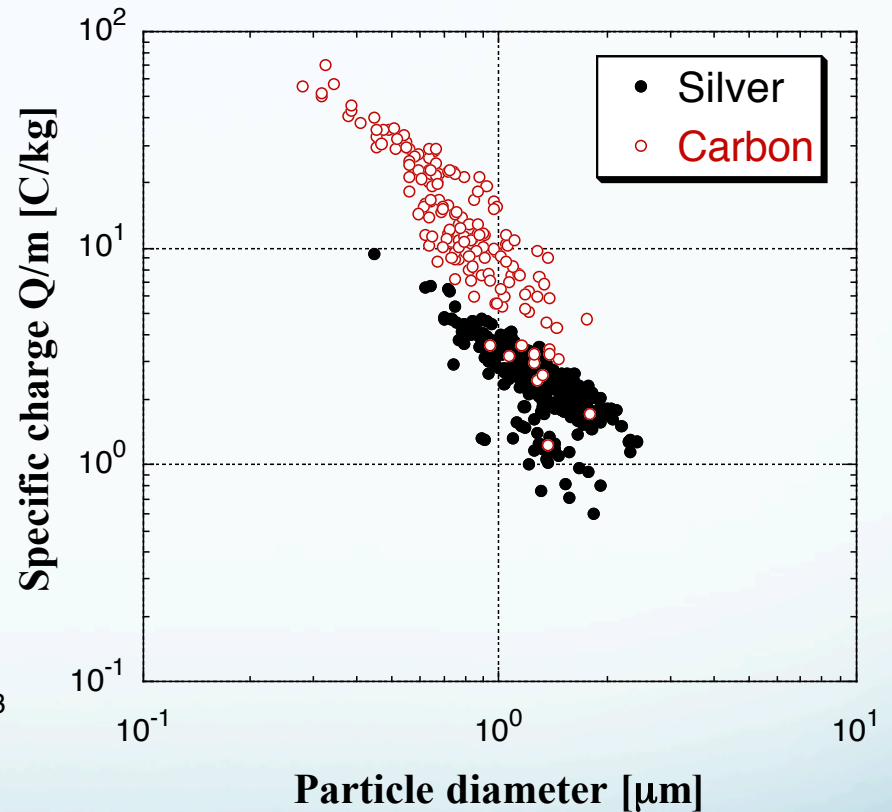
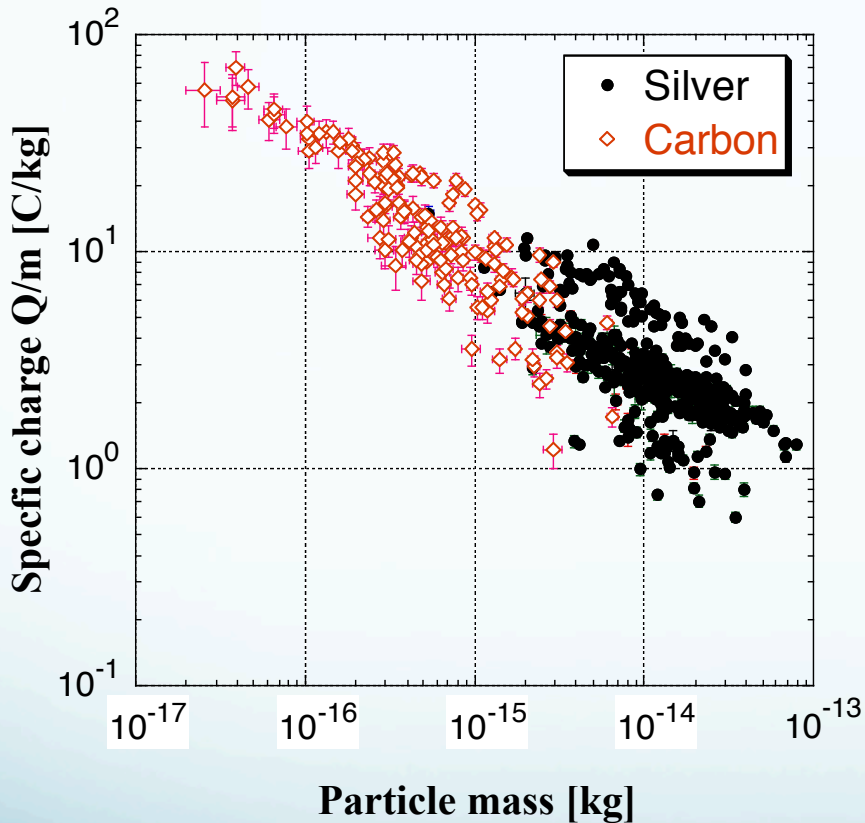


円筒コンデンサー型のビームモニター

加速された微粒子の速度と質量・直径の関係



加速された微粒子の比電荷と質量・直径の関係



Proton $Q/m \sim 10^8$ [C/kg]

超高速微粒子を用いた研究

1. 超高速微粒子の衝突電離を用いた宇宙機搭載用ダスト検出器

- ・衝突電離検出器
- ・小型TOF質量分析器の開発

2. 超高速微粒子と固体衝突における衝突ひずみ波検出

- ・水星探査機BepiColombo-MMO搭載用ダスト計測器の開発

使用実験装置

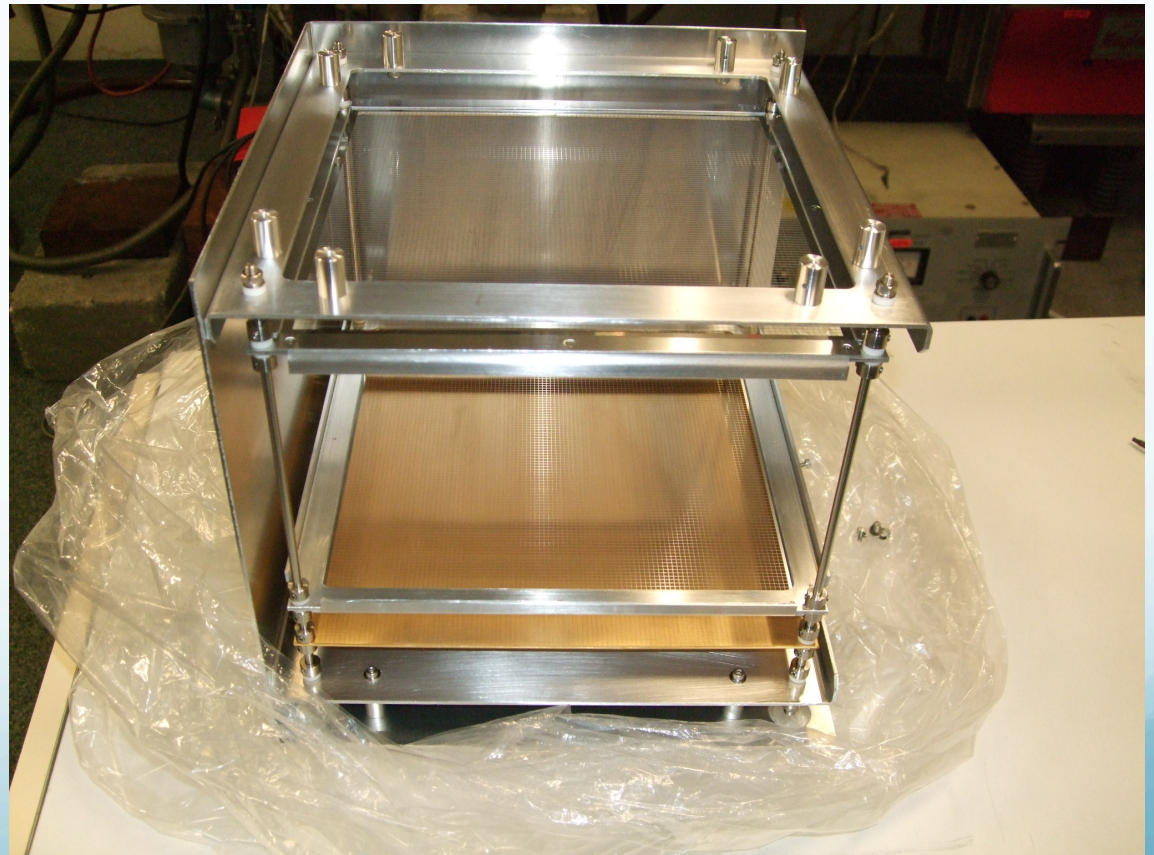
3.75MV バン・デ・グラーフ(東大工)

2.0 MV バン・デ・グラーフ(ドイツ MPI-K)

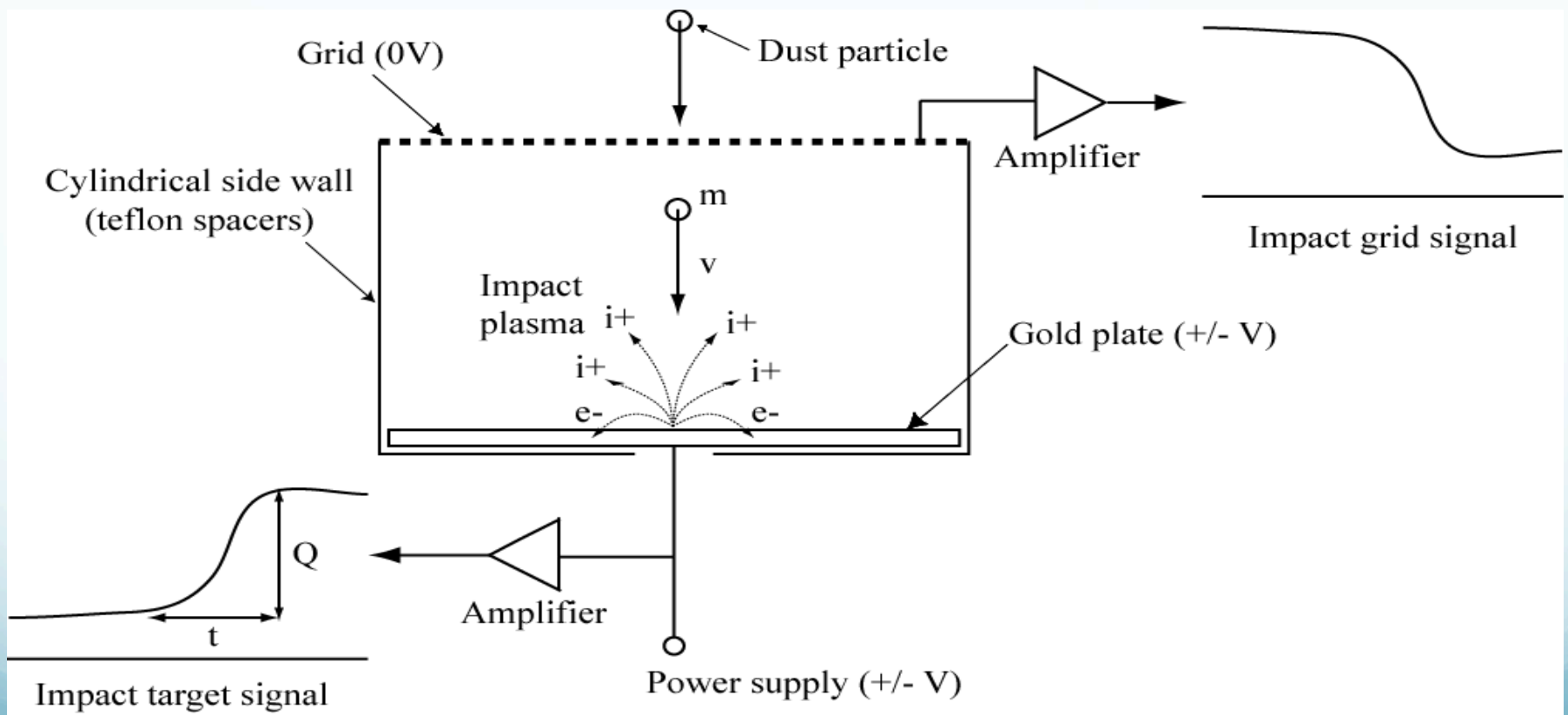
Cosmic Dust Detector

IID (Impact Ionization Dust/Debris detector)

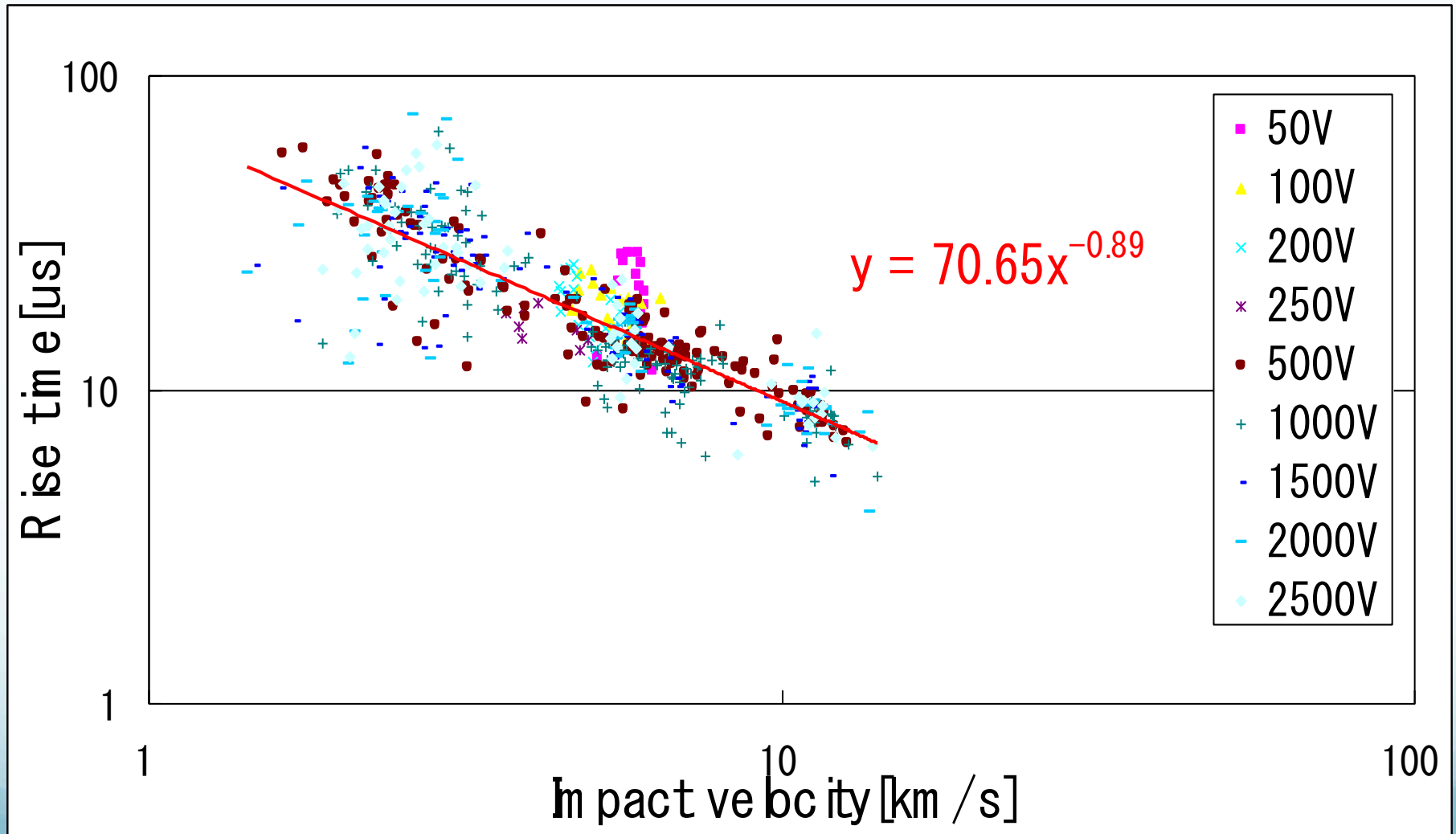
- Gold plated metal target, entrance grids set in parallel
- Large area with light mass



Principle of Impact Ionization Dust Detector



Impact velocity vs Rise time



Charge Signal → *Mass , Velocity*

$$t = c_g v^\alpha$$

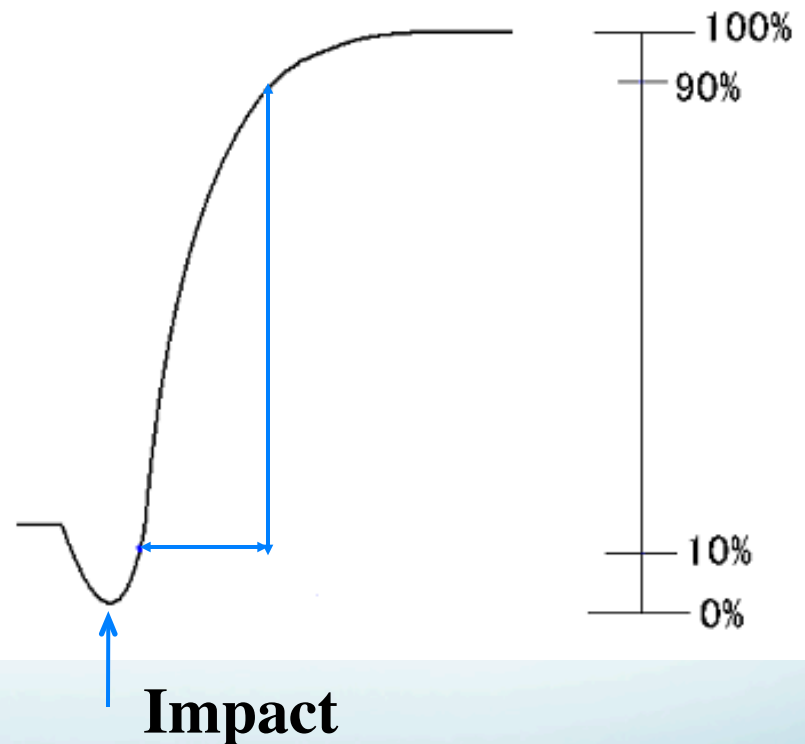
$$\pm Q/m = c_r v^\beta$$

t : Rise time v : Velocity

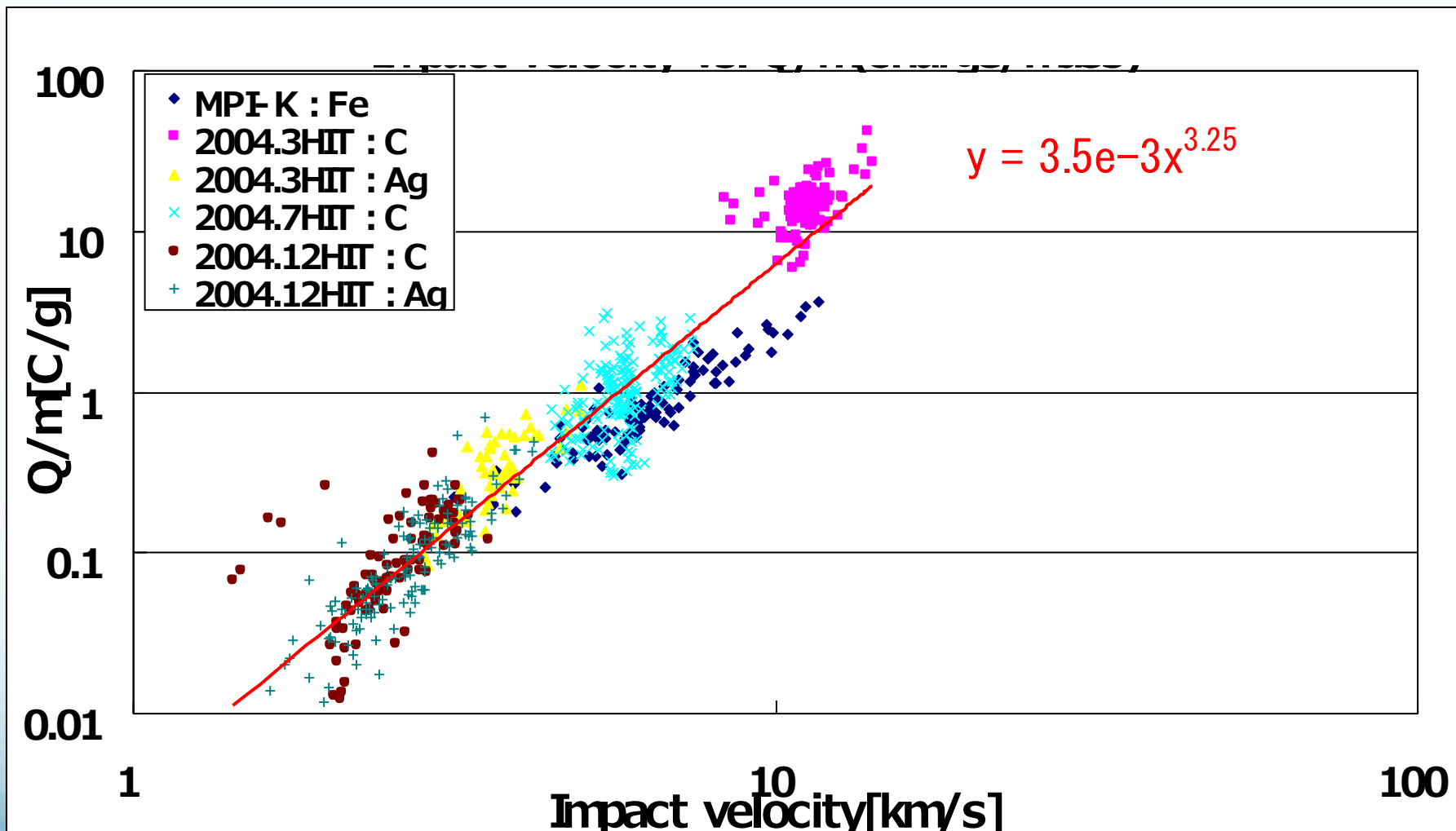
Q : Charge m : Mass

C_g, C_r, α, β : Constants

[Igenbergs et al., 1998]



Impact velocity vs Charge/mass



TOF質量分析器

開発目標

ダスト計測器

質量・速度・
飛来方向・分布
 10^{-19} g
0.01 - 0.1 m²
-
惑星、惑星間空間

測定項目

検出限界質量
有効面積
分解能
対象天体

ダスト質量分析器

化学組成
空間分布
 10^{-14} - 10^{-19} g
0.0005 - 0.005 m²
50 - 150
彗星、土星

運動量と化学組成の同時測定

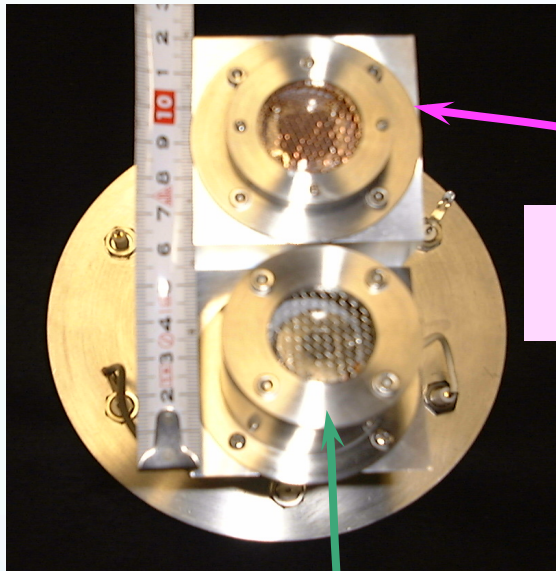
大開口径 (> 50 cm²) と高質量分解能 (> 100)

高いイオン検出率 (時間的・空間的収束)

小型 (< 40cm) ・軽量 (< 5 kg)

曲面電場を用いた飛行時間型質量分析器で実現

Reflectron (Prototype)



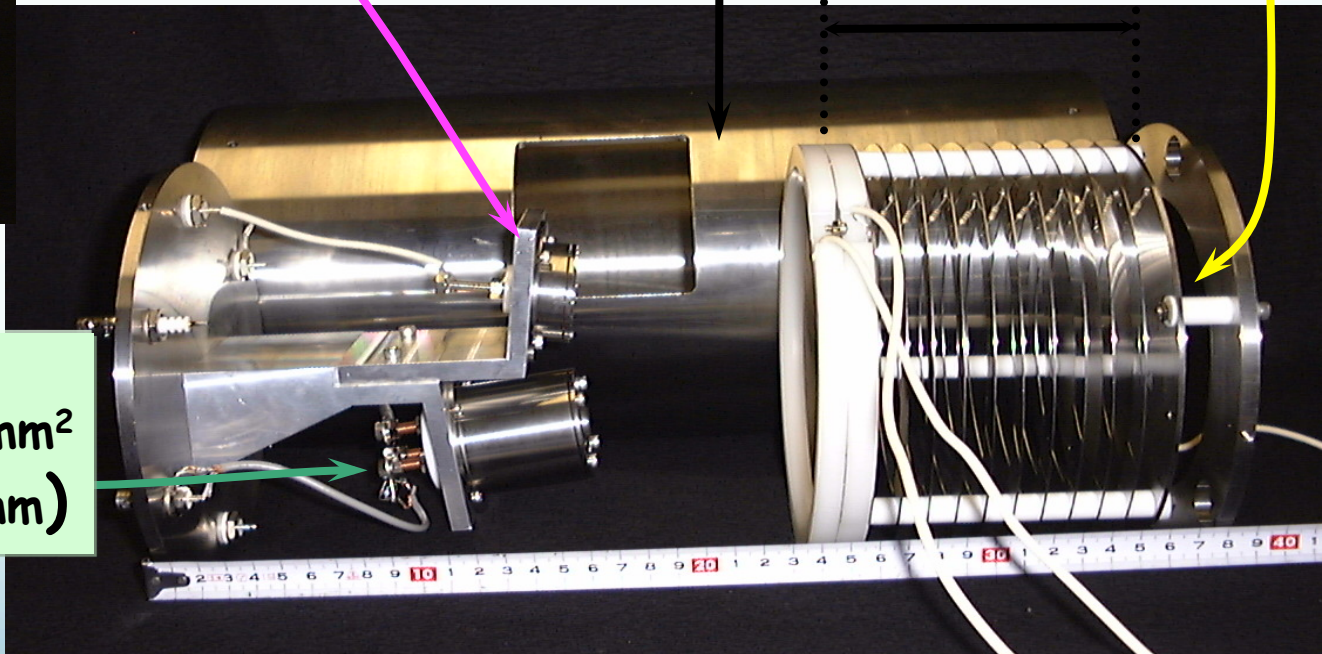
Detector (MSP)
Effective Area $\sim 57 \text{ mm}^2$
(Diameter = 8.5 mm)

Target (800 - 1200 V)
Effective Area : $18 \times 18 \text{ mm}$

Protective Tube

Reflection Plate
(1000 - 2500 V)

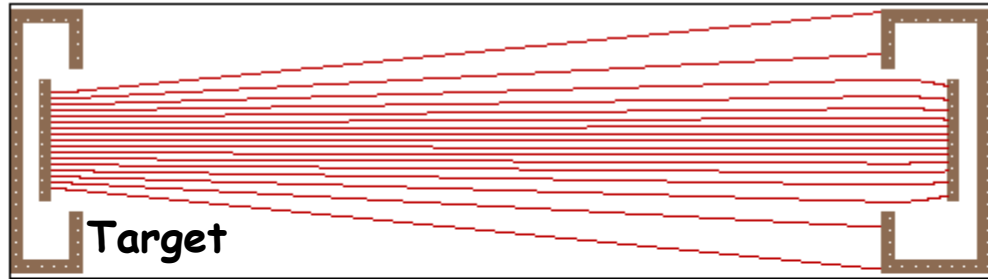
Reflecting Region
(Potential Ring)





Curved Potential TOF-MS

Linear Type



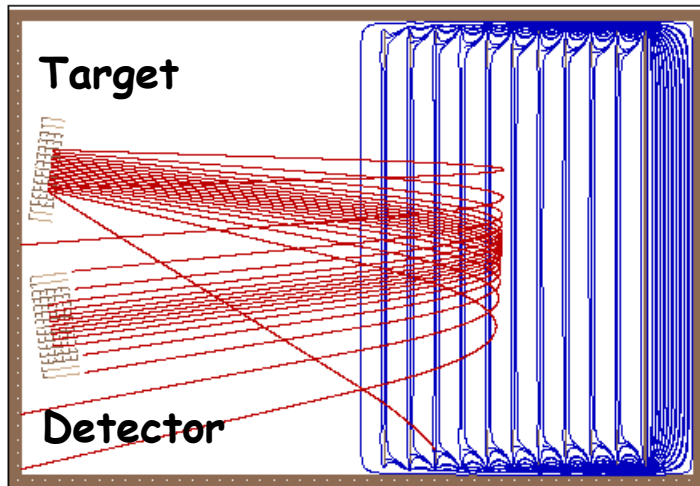
Detector

Impact Point :

$$Y = \pm 4 \text{ mm}$$

Initial Energy : 0.1 eV

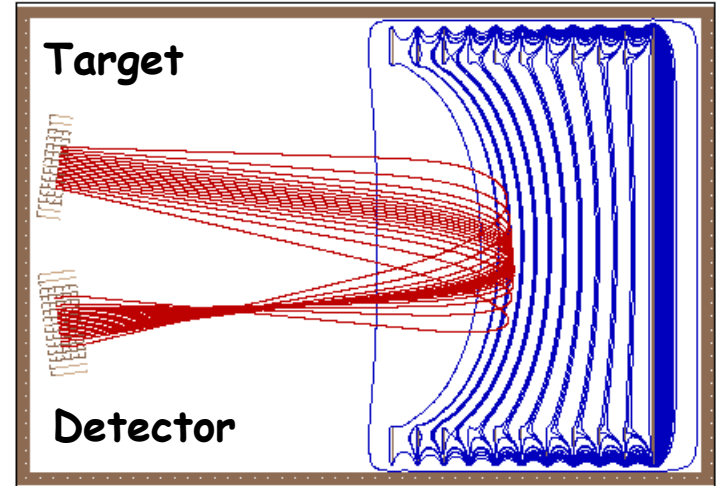
Parallel Potential Type



Target

Detector

Curved Potential Type



Target

Detector

Performance

★ Previous Reflectron vs. Curved Potential Reflectron

- Mass Resolution ($M/\Delta M$)

	Laser Irradiation	Fast Particles
Linear type	: $M/\Delta M < 100$	$M/\Delta M < 80$
Parallel type	: $M/\Delta M < 300$	$M/\Delta M \sim 500$
Curved Potential	: $M/\Delta M \sim 500$	$M/\Delta M \sim 600$

- Detection Efficiency of Ion

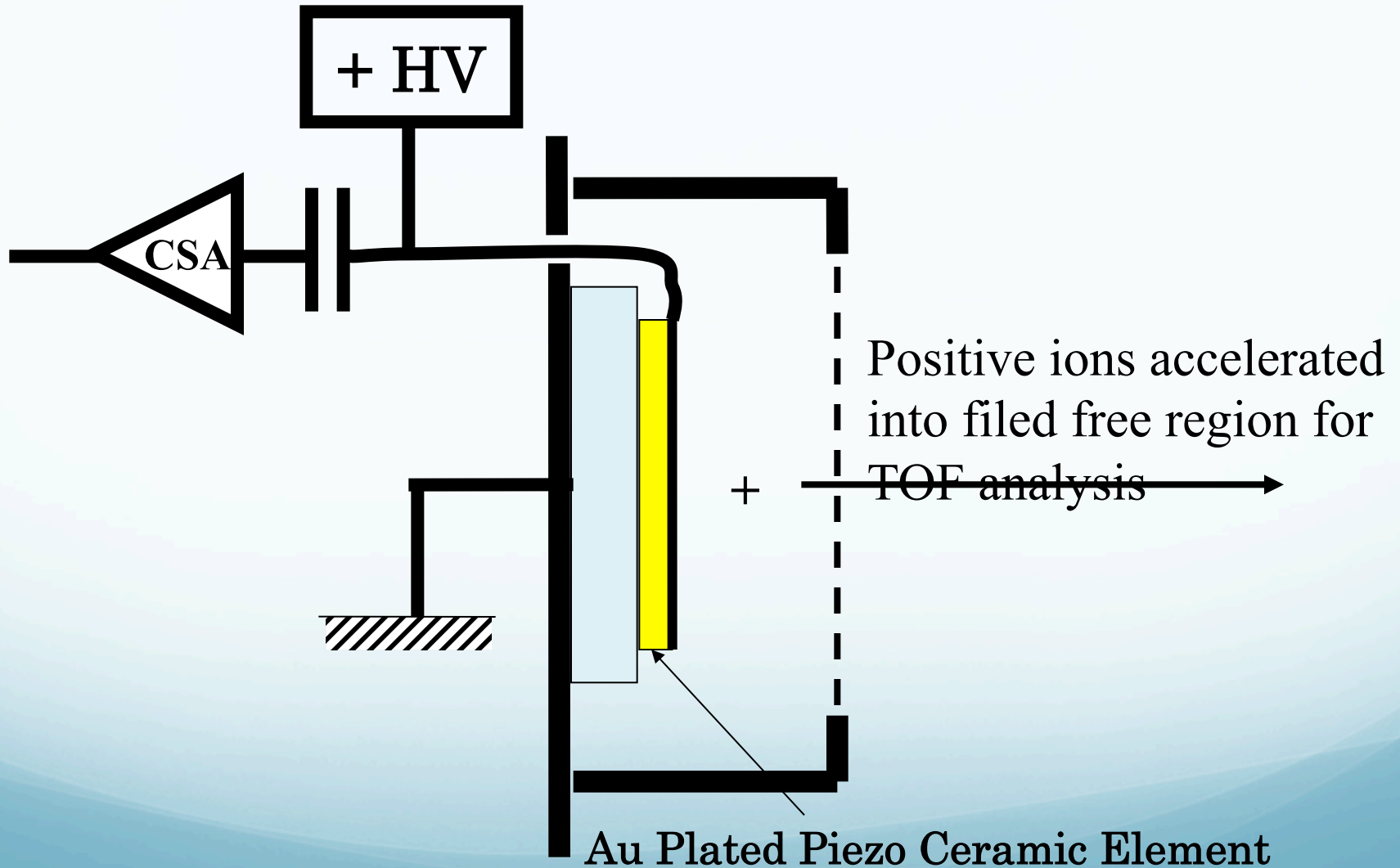
Curved Potential Type $\sim 10 \times$ Parallel Potential Type

★ Large Aperture Reflectron

Effective Area $\sim 4\text{cm}^2 \rightarrow 30\text{cm}^2$: $M/\Delta M \sim 370$

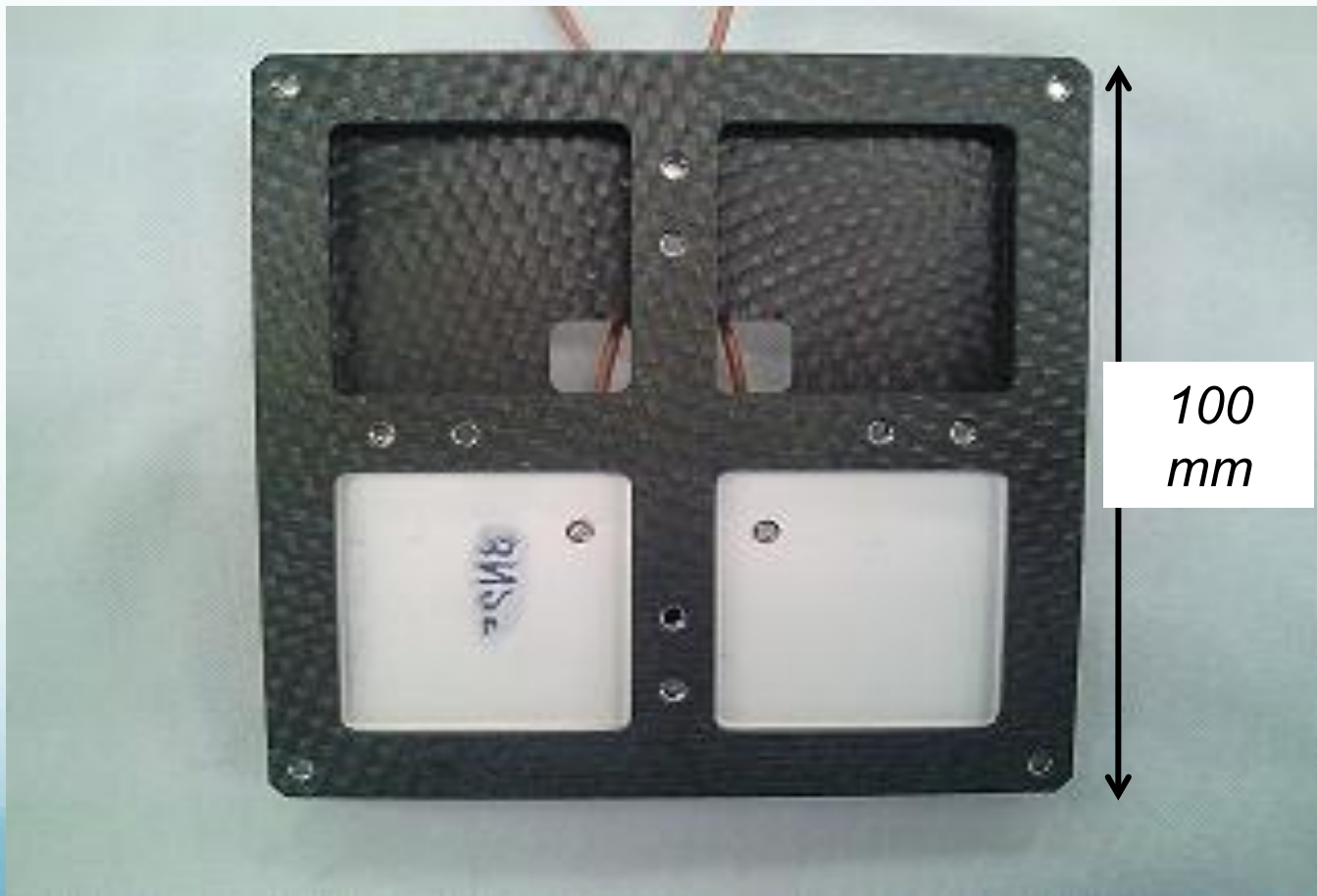
However, there is no data for impacts above 20 km/s

Schematics of target setup



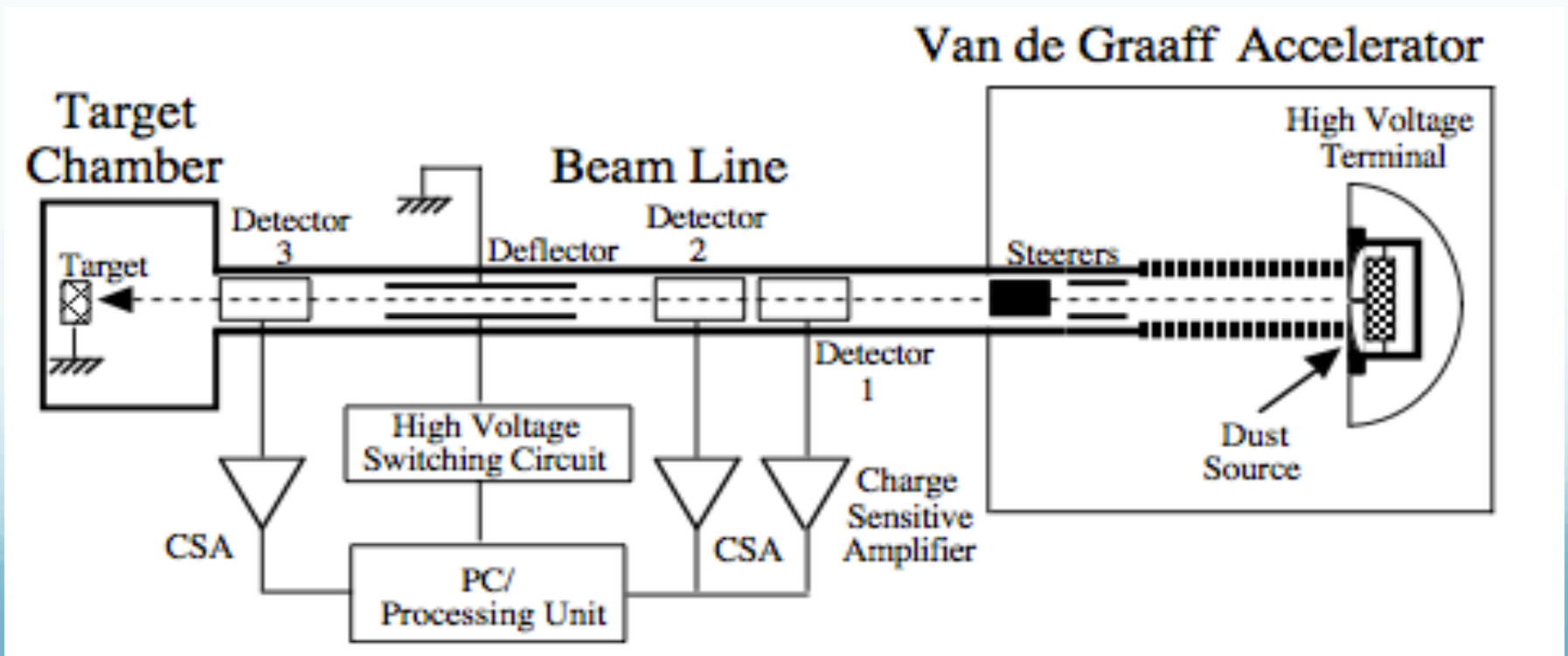
MDM-S (piezo-electric sensor & CFRP frame)

PZT(Pb-Zi-Ti): 40 mm × 40 mm × 2 mm

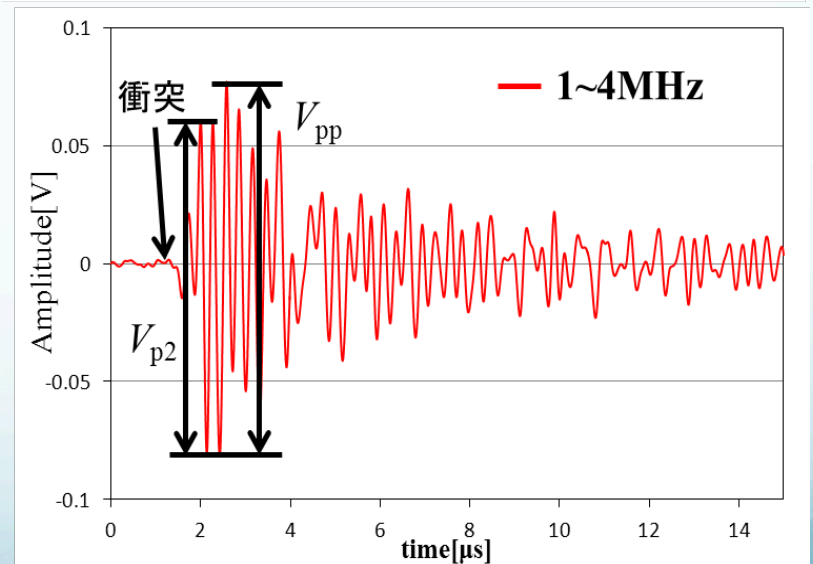
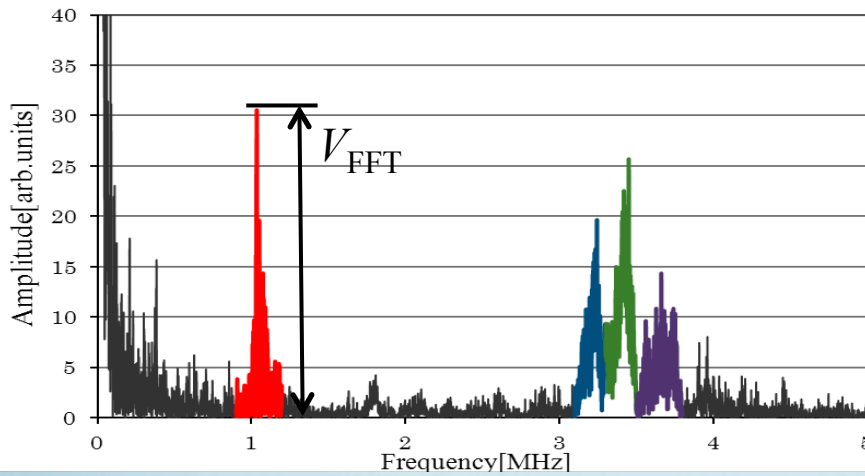
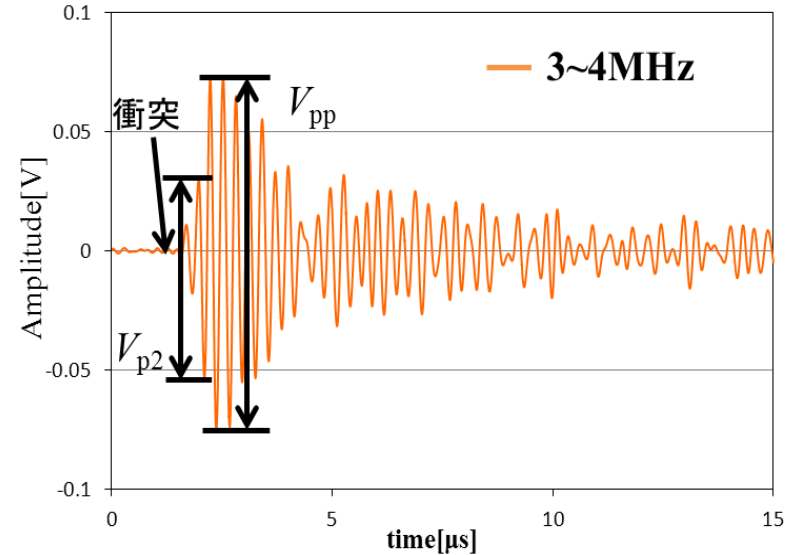
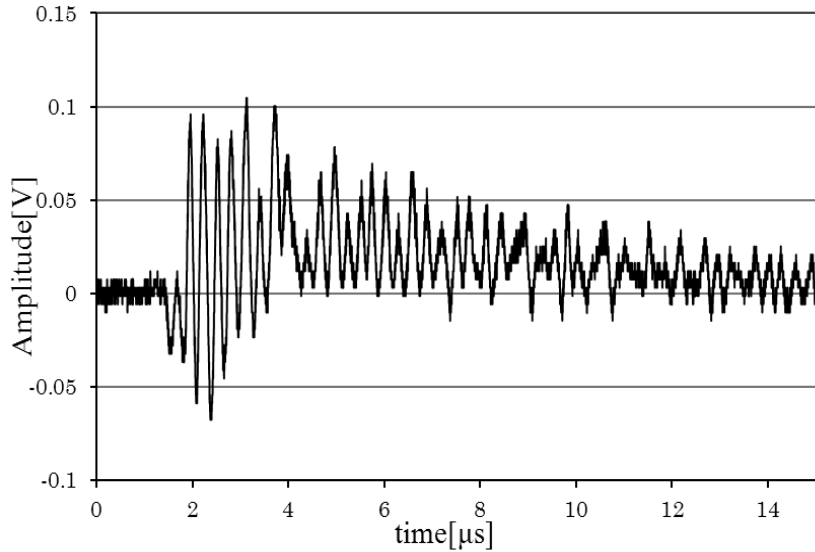


PZT sensor calibration experiment

MDM calibration experiments have been performed at MPI-K (van de Graaff), HIT (van de Graaff) and ISAS (Light-gas gun).

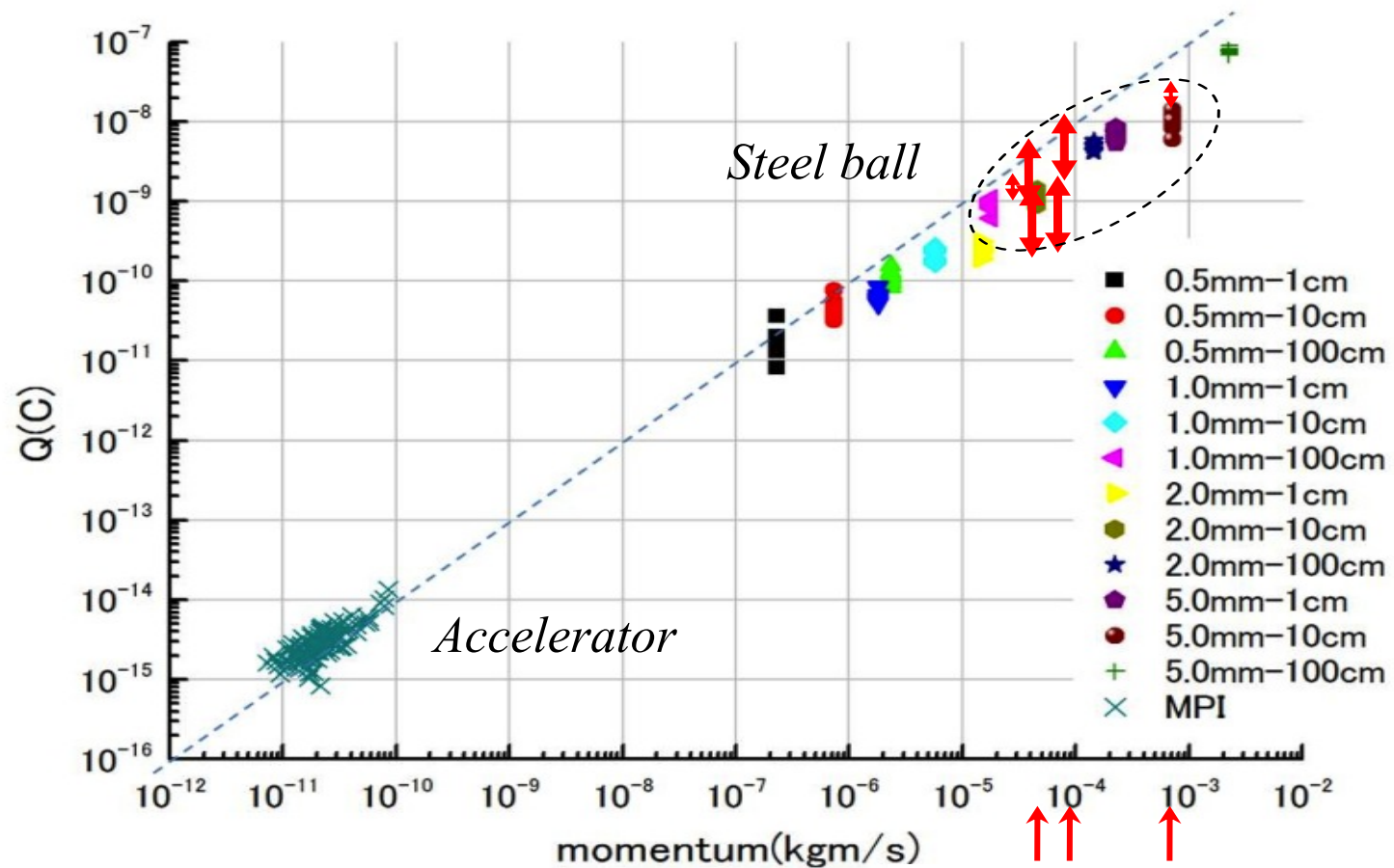


Original impact signal of dust



FFT spectrum of impact signal

Output charge vs. momentum of particles



Light gas gun

ご静聴ありがとうございました。