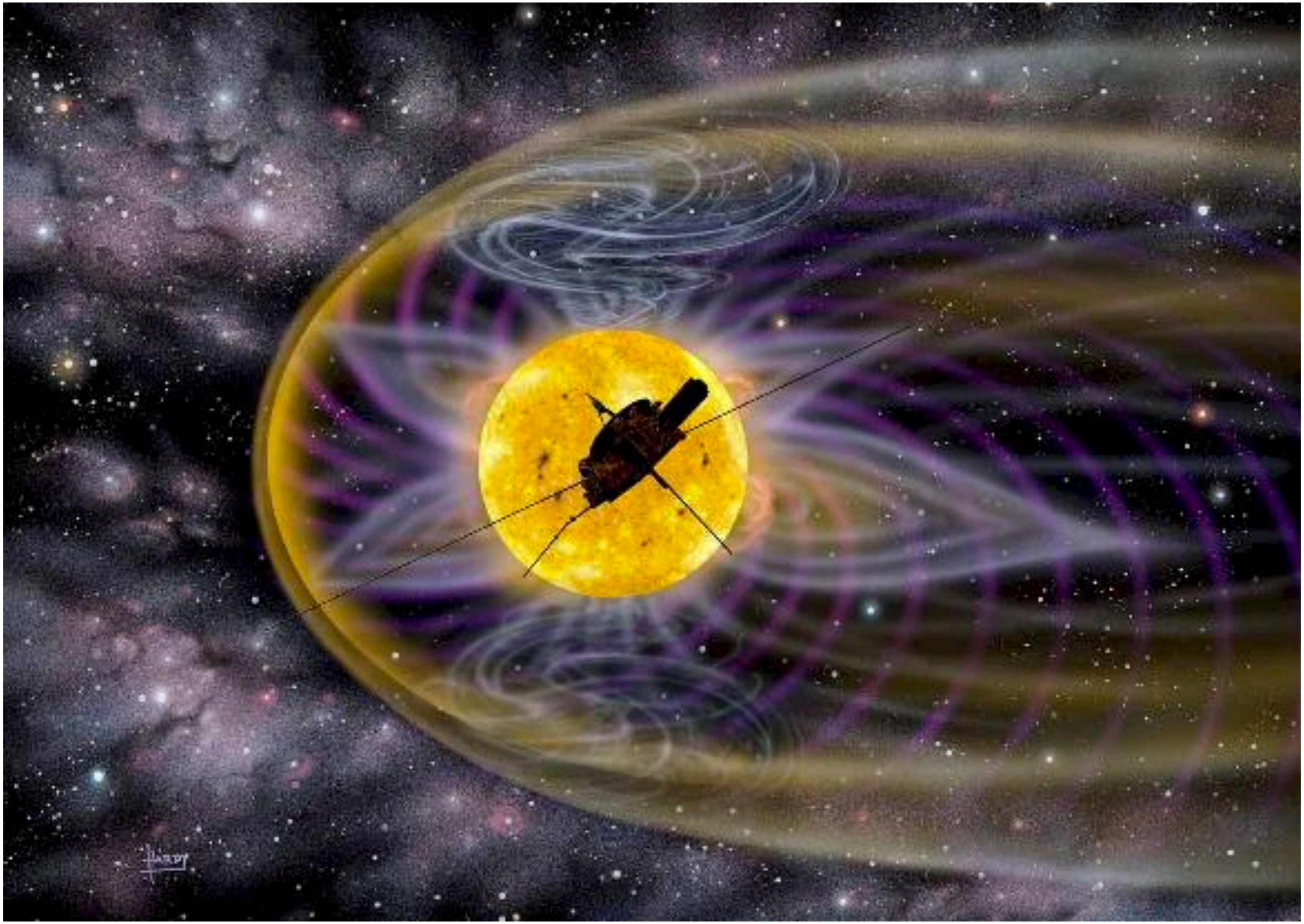
Impact! When Particles and Satellites Collide

Sigrid Close

CEDAR 2016

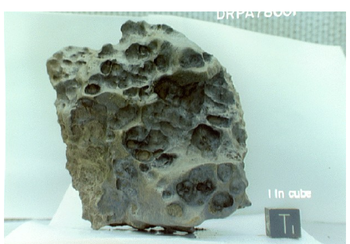
Space Environment



http://www.cea.inpe.br/wiser/about.html

Hypervelocity Particles

- **Meteoroids**
  - Speeds
    - 11 to 72.8 km/s (interplanetary)
    - 30-60 km/s (average)
  - Densities
    - ≤1 g/cm^3 (icy) or
      > 1 g/cm^3 (rocky/stony)
  - Sizes
    - < 0.3 m (meteoroid)
    - < 62 μm (dust)

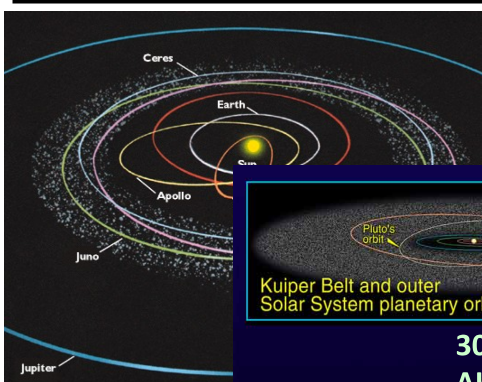


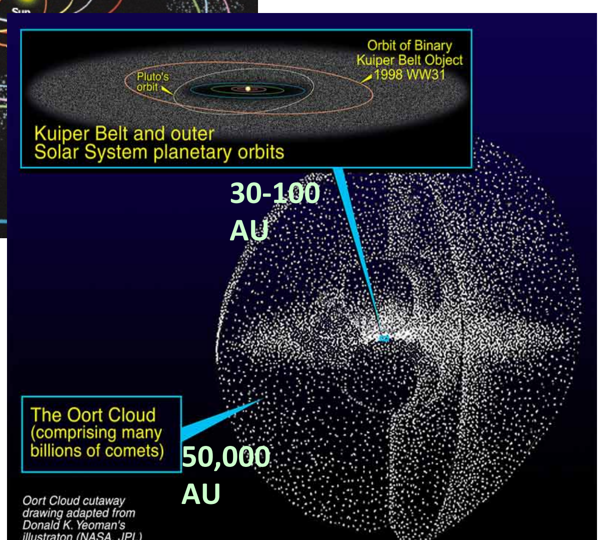
- **Space Debris**
  - Speeds in Low Earth Orbit
    - < 12 km/s
    - 7-10 km/s (average)
  - Densities
    - > 2 g/cm^3
  - Sizes
    - < 10 cm (small)

Probability of Impact? Effects from Impact?

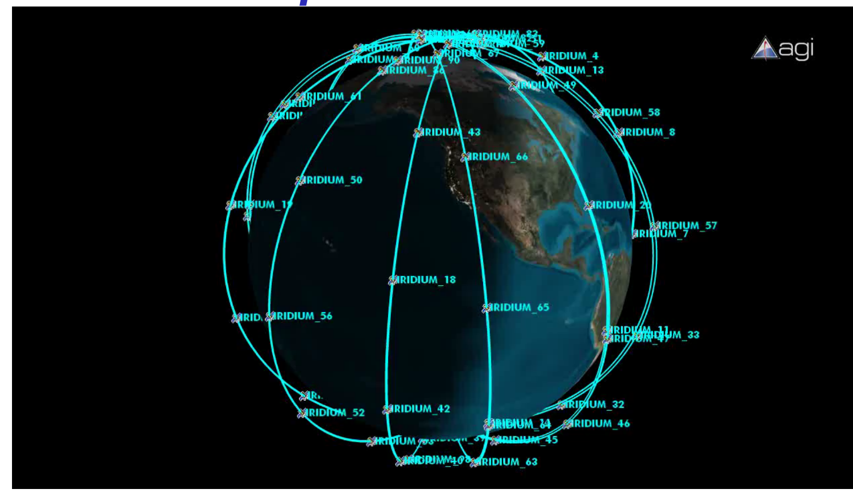
Sources

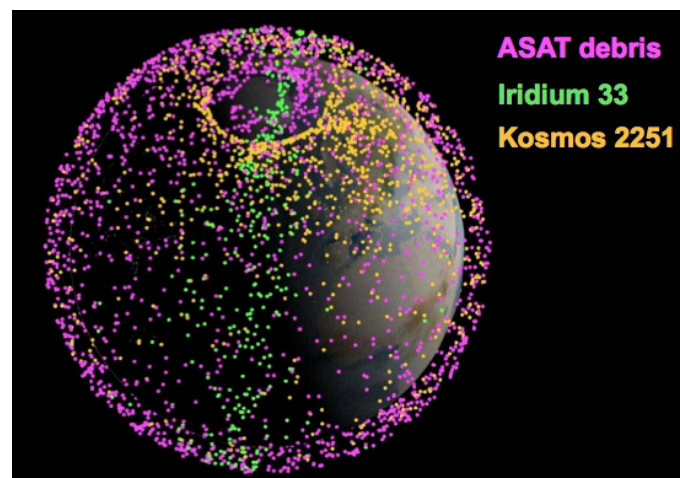
Meteoroids





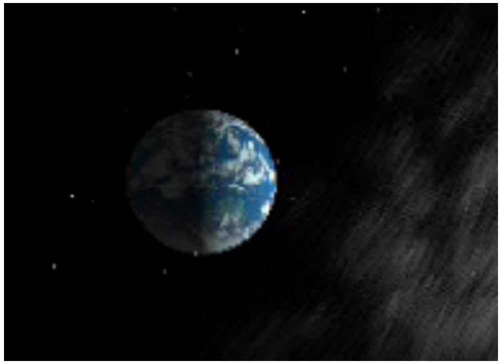
Space Debris



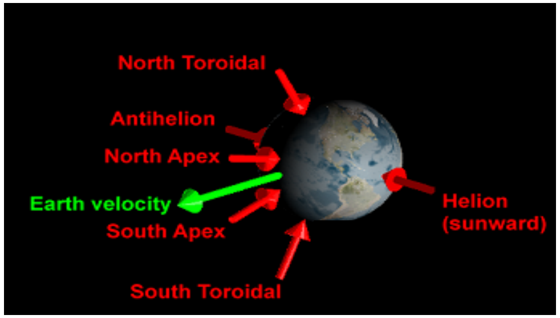


Characterization

Meteoroids

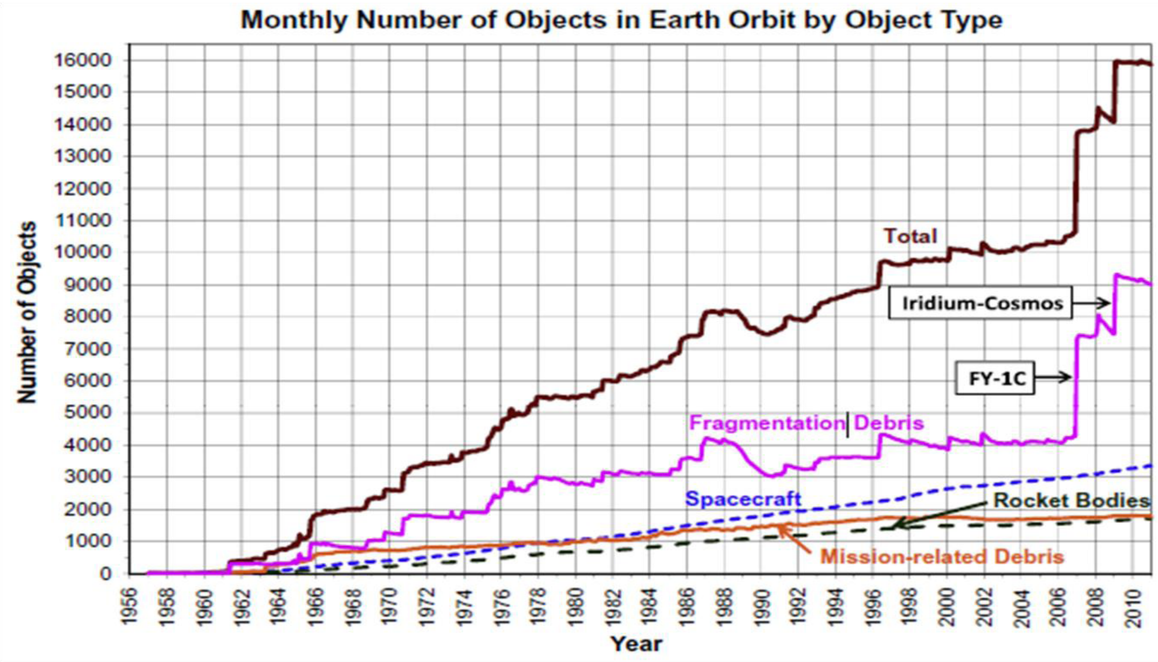


- **Showers**
  - Specific parent body
  - Named for radiant



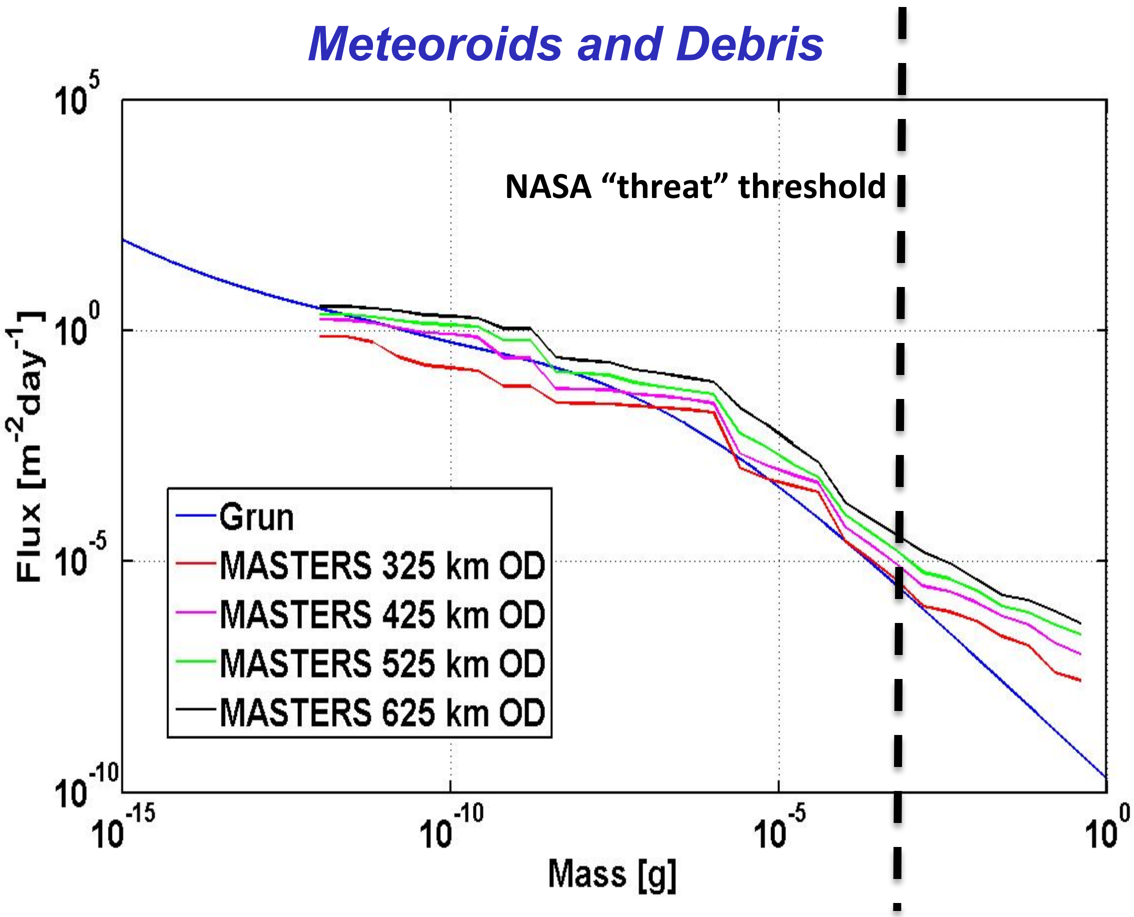
- **Sporadics**
  - Quasi-continuous
  - Grouped by location

Space Debris



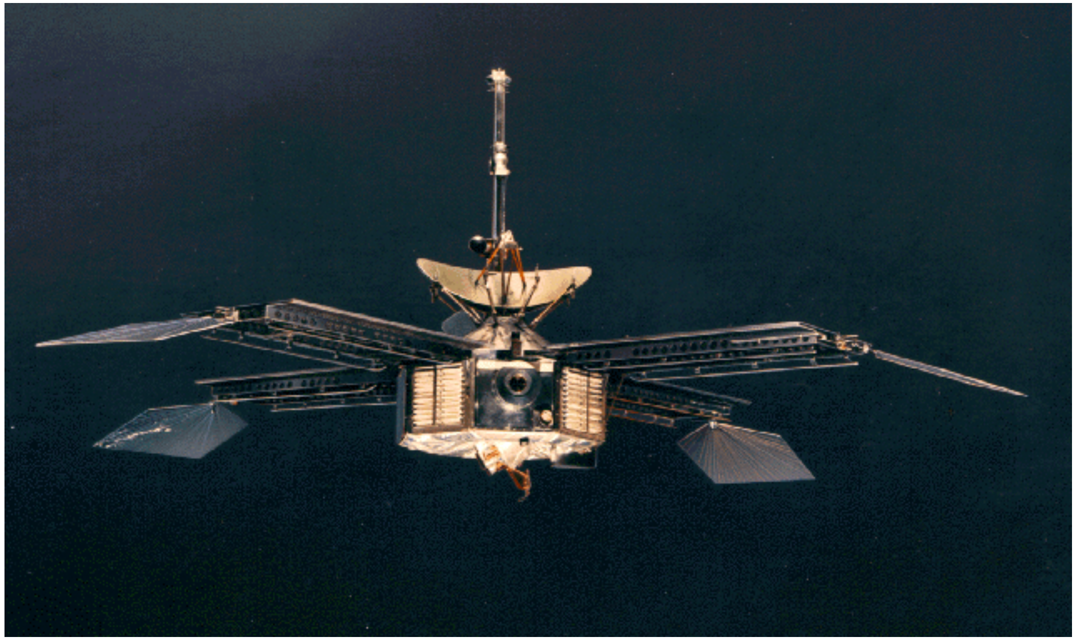
Liou et al., 2013

Flux



~ 1 ng-sized particle will impact 1 m^2 spacecraft once per day

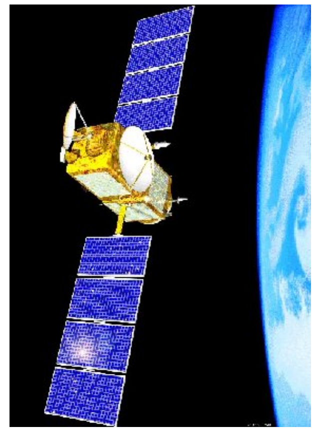
Mariner 4 – 1967



http://science.nasa.gov/science-news/science-at-nasa/2006/23aug_mariner4/

- **September: 17 meteoroid impacts in 15 minutes**
  - Temperature drop
  - Attitude changed
- **December: 83 meteoroid impacts over the course of 1 day**
  - Attitude perturbations
  - Degradation of signal strength

Spacecraft Anomalies

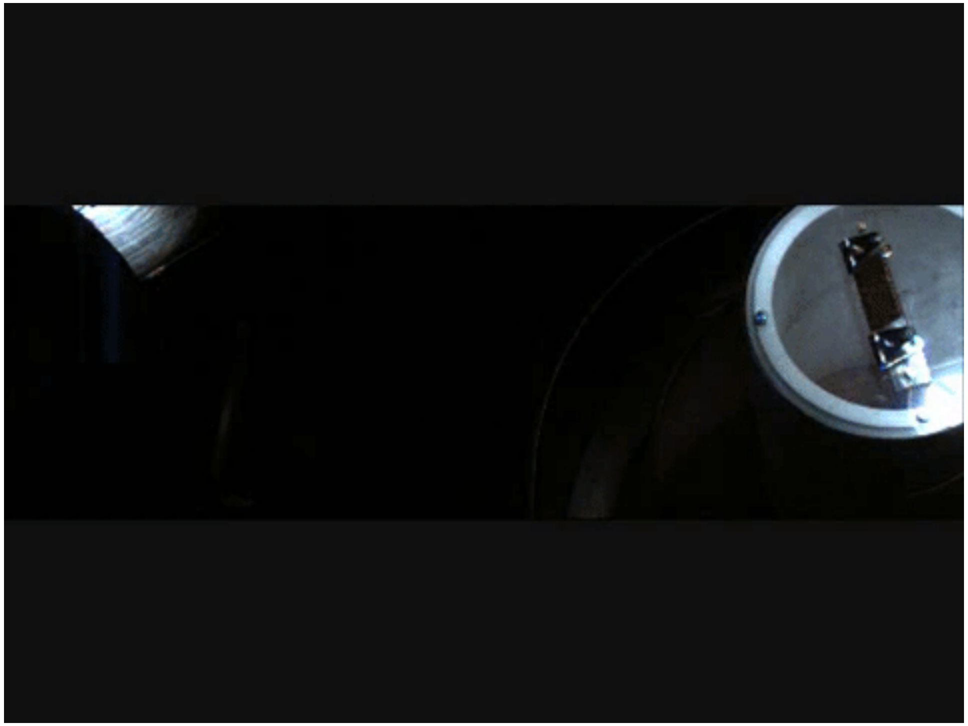
Olympus 1993	Landsat 5 2009	JASON-1 2002	ADEOS II 2003	ALOS 2011
				
ESA	NASA	NASA	JAXA	JAXA

NGDC Database: Anomaly Diagnosis
Electron Caused EM Pulse (Deep Dielectric Charging) - 490
Electrostatic Discharge (Surface Charging) – 1072
Single Event Upset - 822
Radio Frequency Interference – 8
Unknown - 2587

Goel *et al.*, 2006

Space Environment and Hypervelocity Impact Plasma

- **Mechanical damage: "well-known", larger (> 120 microns), rare**
- **Electrical damage: "unknown", smaller, more numerous**
  - ElectroStatic Discharge (ESD)
  - ElectroMagnetic Pulse (EMP)



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NRC Report

Limiting Future Collision Risk to Spacecraft

Released September 2011

"Recommendation: The NASA meteoroid and orbital debris programs should establish a baseline effort to evaluate major uncertainties in the Meteoroid Environment Model regarding the meteoroid environment in the following areas:

(1) meteoroid velocity distributions as a function of mass;

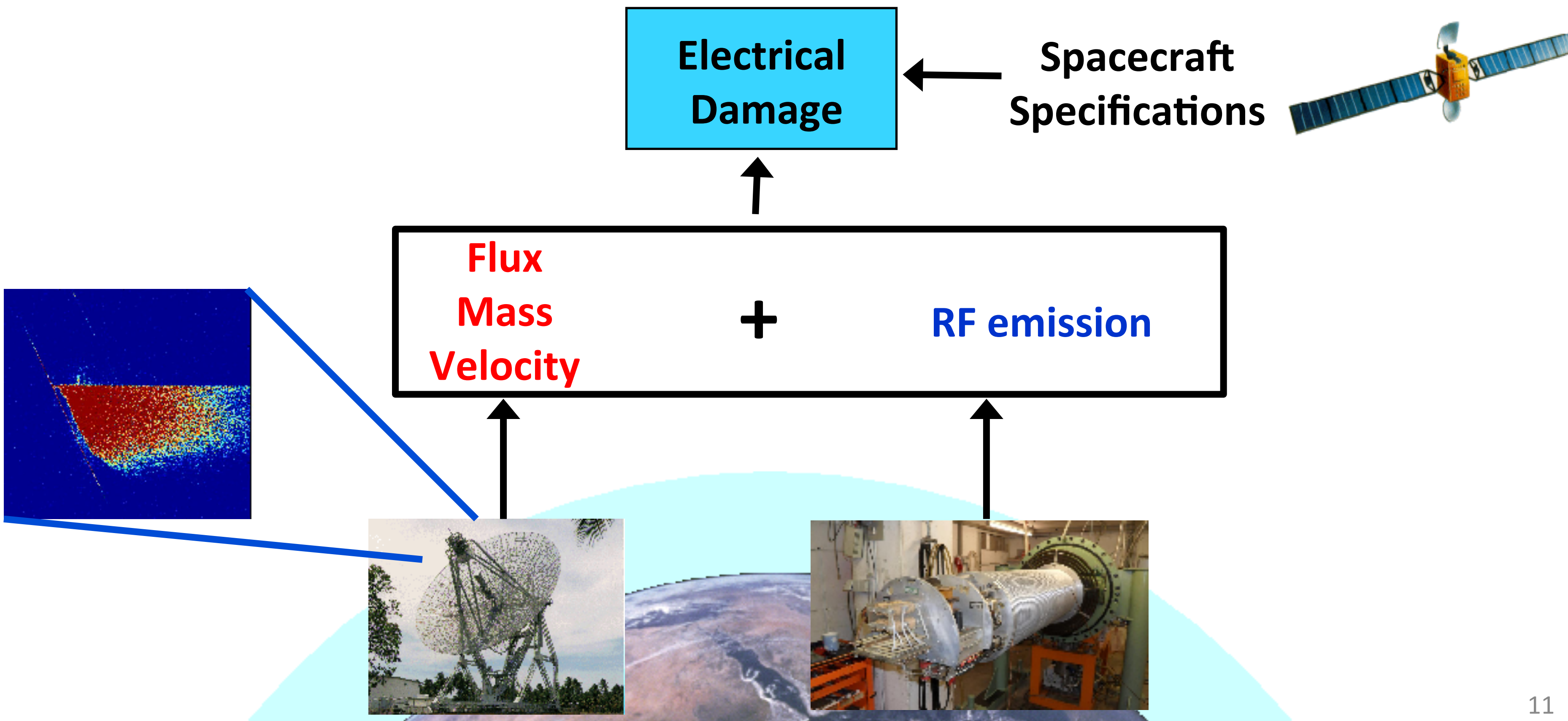
(2) flux of meteoroids of larger sizes (>100 microns);

(3) effects of plasma during impacts, including impacts of very small but high-velocity particles; and

(4) variations in meteoroid bulk density with impact velocity."

Spacecraft Threat Characterization

- **Particle impacts in atmosphere:** **characterize particles**
- **Particles impacts on spacecraft:** **characterize effects**



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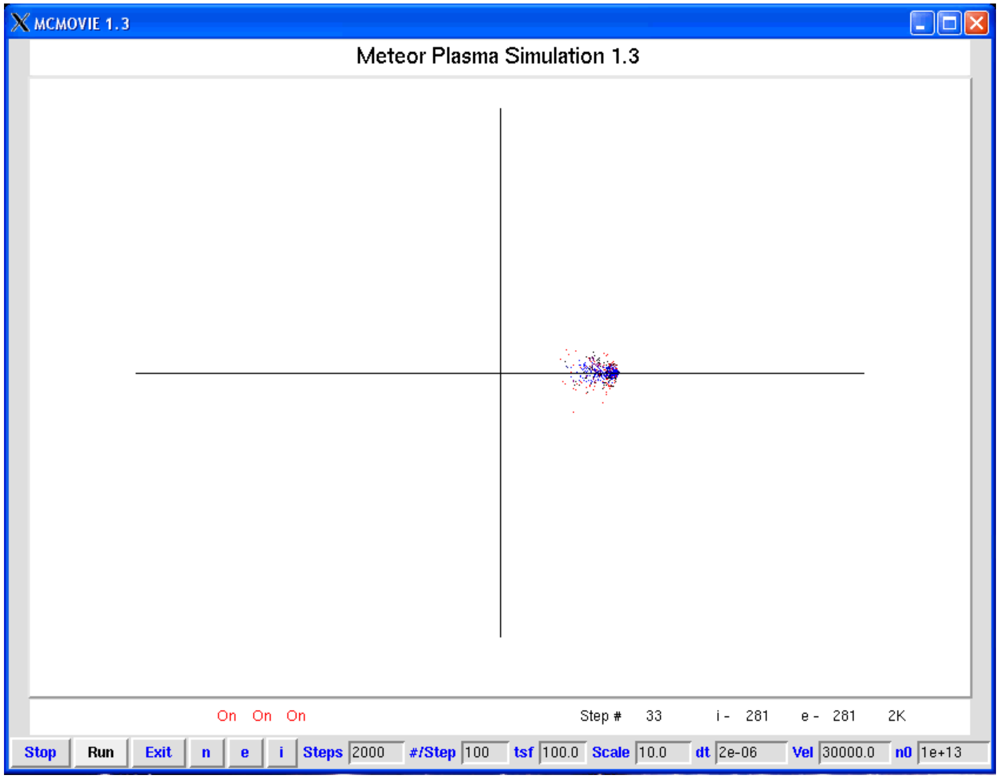
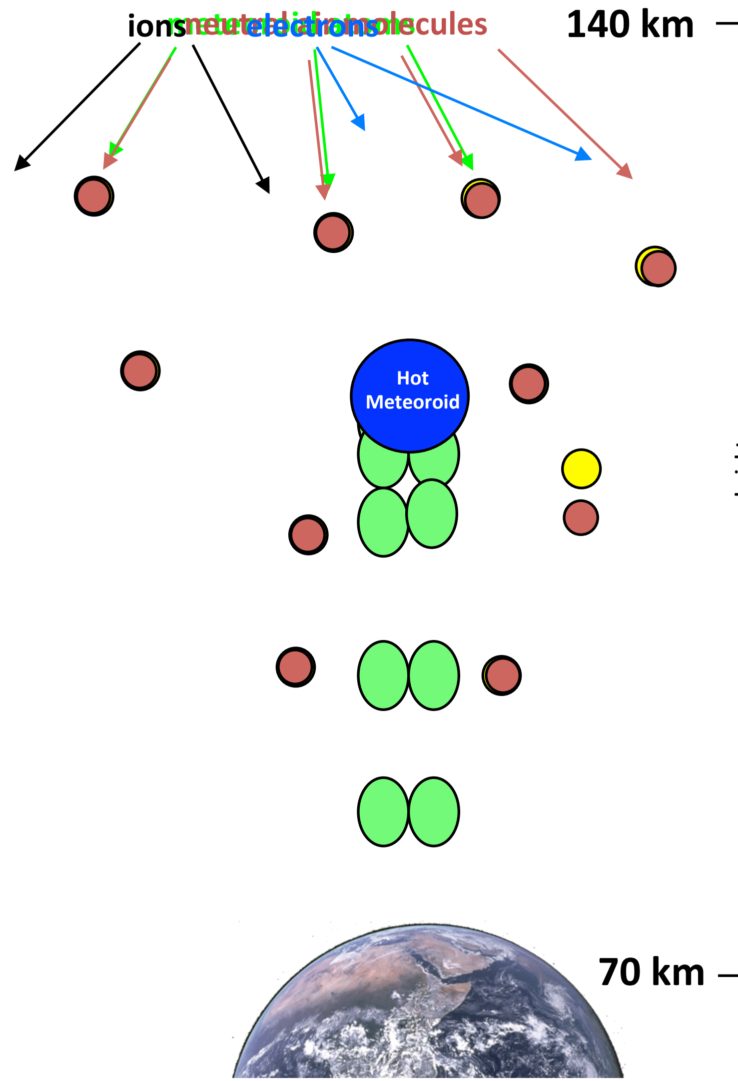
Outline

- Introduction
- **Impacts in Atmosphere**
- Impacts on Spacecraft
- Conclusion

Meteoroids and Meteors





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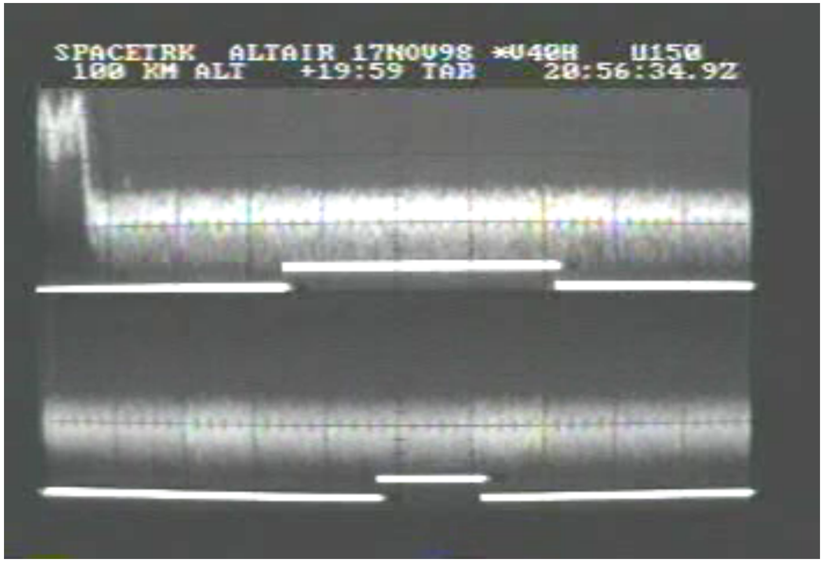
Ground-Based Radar Data

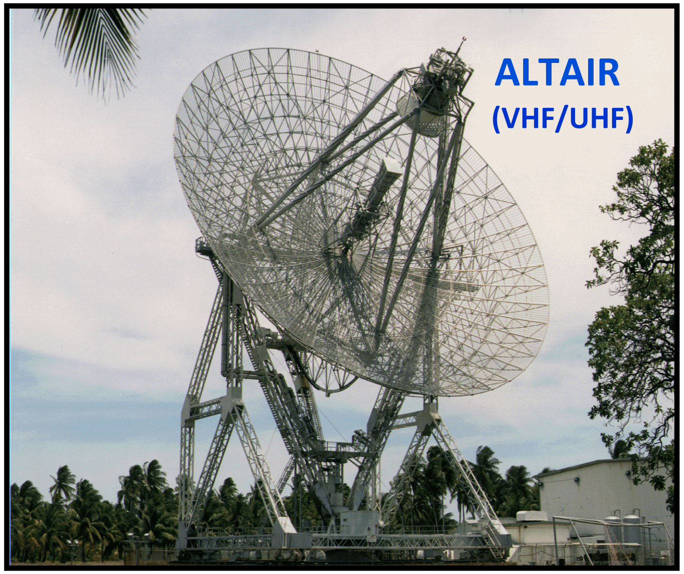
- **High-power large-aperture (HPLA) meteor observations**
  - ALTAIR
  - Arecibo Observatory
  - MIT Haystack
  - EISCAT



ARPA Long-range Tracking and Instrumentation Radar (ALTAIR)

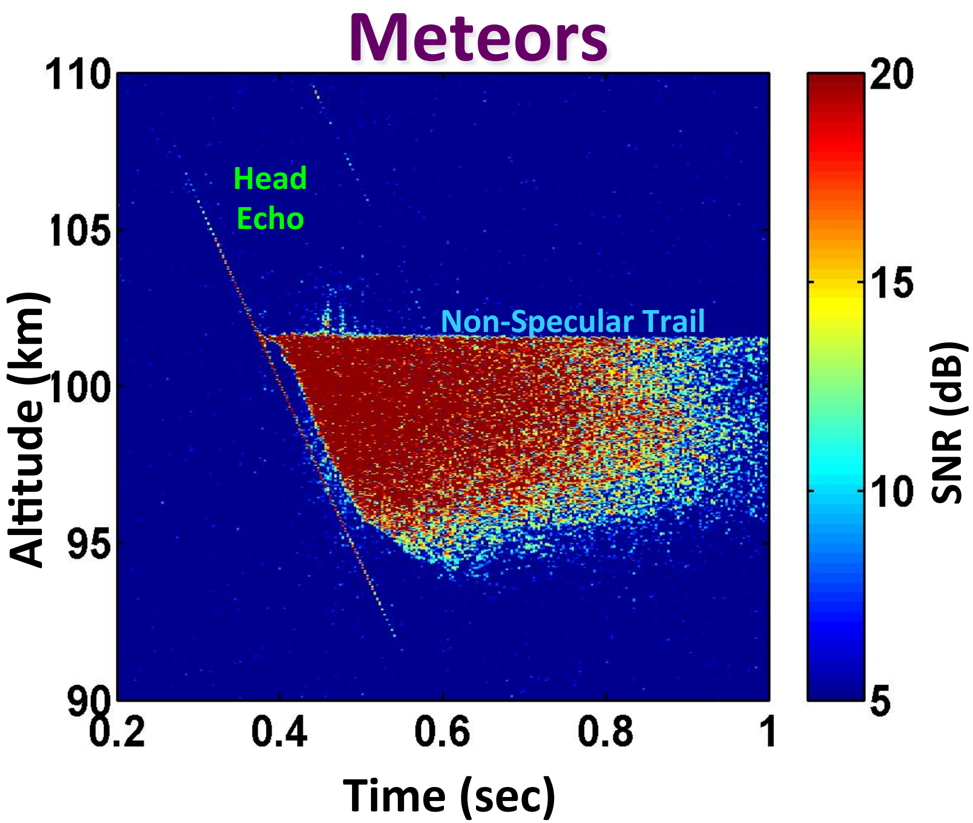
- High sensitivity, well-calibrated
- Dual frequency
- Interferometric capabilities
- High range resolution
- Circularly polarized

Frequency	160 MHz	422 MHz
Antenna Diameter	46 m	46 m
Beamwidth	2.8°	1.1°
Peak Power	6.0 MW	6.4 MW
Xmit. Polarization	RC	RC
Rec. Polarization	LC, RC	LC, RC
Range Resolution	30 m	7 m
Sensitivity	64 dB	81 dB
IPP	.003 sec	.003 sec



*(*Single pulse S/N for 1 square meter target at 100 km range)*

ALTAIR Radar Data



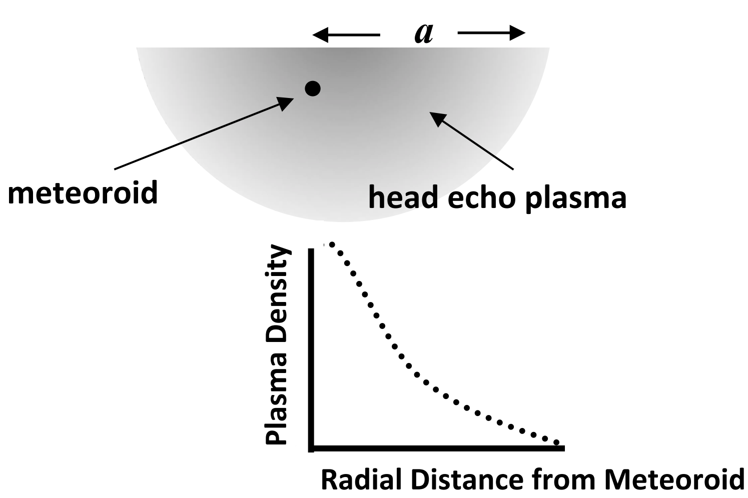
- Head Echo
  - Plasma around meteoroid
  - Velocity of meteoroid
- Trail
  - Plasma behind meteoroid
  - Velocity of wind

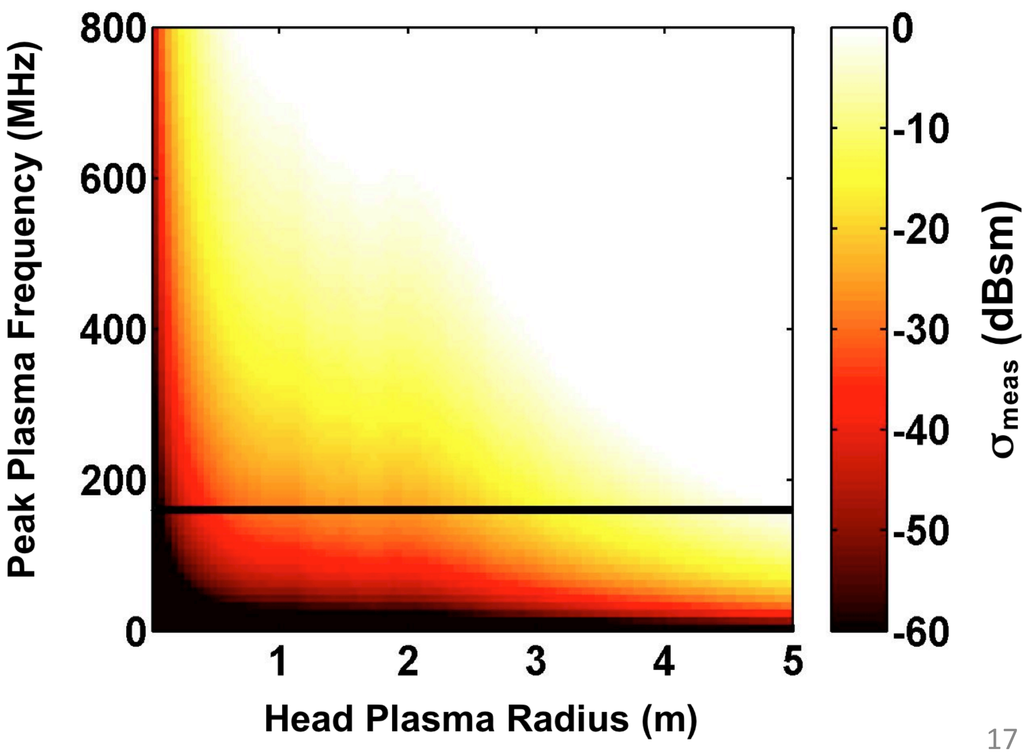
Scattering Model

- **Correlate radar signal strength (*R*) with meteor plasma density**

$$-\frac{1}{R_n} = 2 - \frac{n h_n^2(kr) A_n r^{2n+1}}{2(n+1) j_n(kr) B_n}$$

$$\sigma_{meas} = \sum_n \frac{\lambda^2 (n + \frac{1}{2})^2}{\pi} \cdot |R_n|^2$$





Meteoroid Mass, Radius and Density

- **Mass from scattering model**

$$m = \int \frac{q\mu v}{\beta} dt$$

- **Ballistic parameter from deceleration**

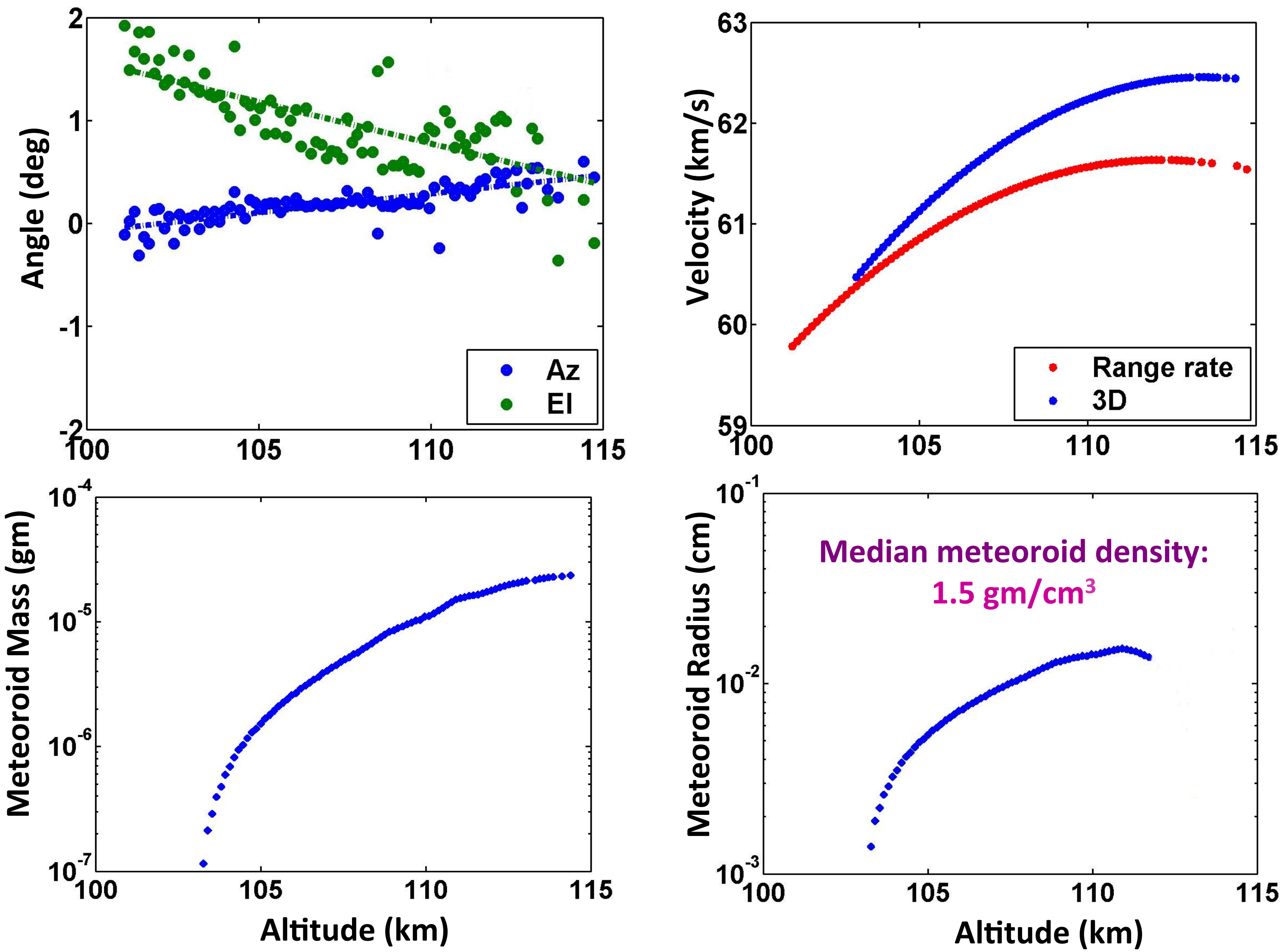
$$\frac{m}{\pi r^2} = -\frac{(v\gamma\rho \sec\chi)}{dv/dh}$$

- **Density from spherical distribution**

$$\delta = \frac{3m}{4\pi r^3}$$

q	Electron line density (m^{-1})
μ	Meteoroid molecular mass (gm)
v	Head echo velocity (m/s)
β	Ionization probability
r	Meteoroid radius (m)
γ	Dimensionless drag coefficient
ρ	Air density (gm/m^3)
χ	Angle between path and zenith
h	Head echo altitude (m)
δ	Meteoroid density (g/m^3)

Methodology



Data

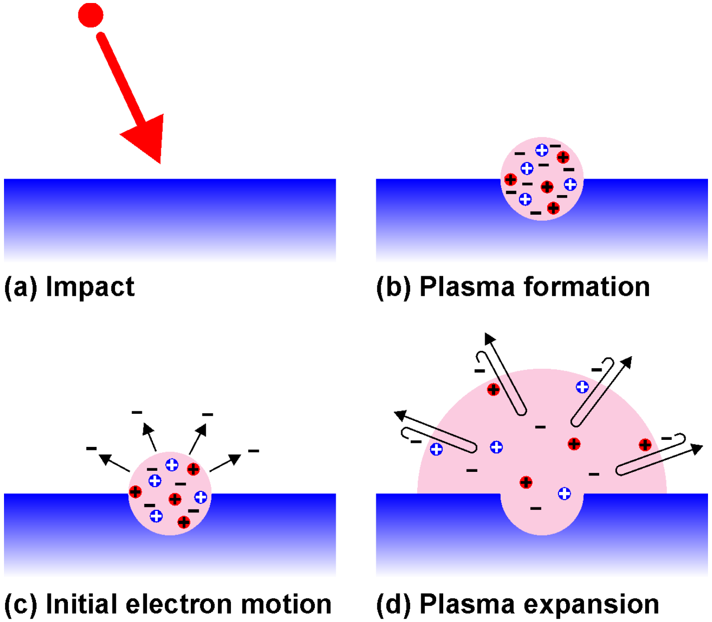
Data + Models

Outline

- Introduction
- Impacts in Atmosphere
- **Impacts on Spacecraft**
  - Theory
  - Space Experiments
  - Ground Experiments
- Conclusion

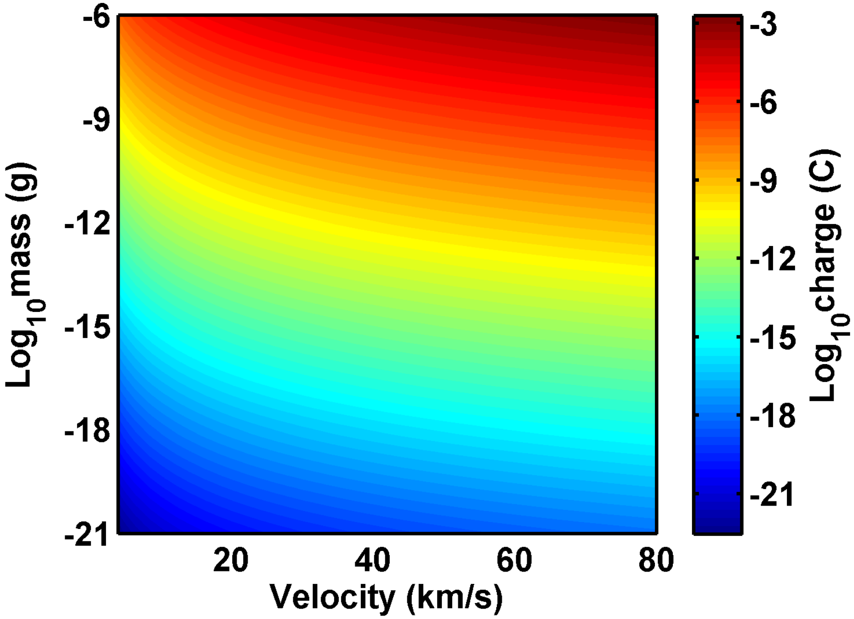
Plasma Generation

Charge Production



Charge : $$q = 0.1m\left(\frac{m}{10^{-11}}\right)^{0.02}\left(\frac{v}{5}\right)^{3.48}$$

McBride and McDonnell, 1999



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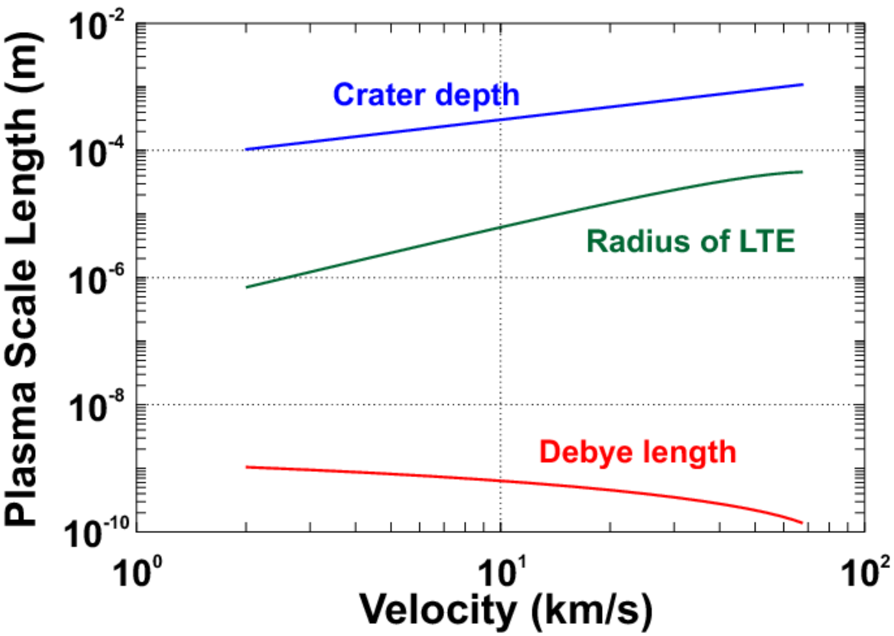
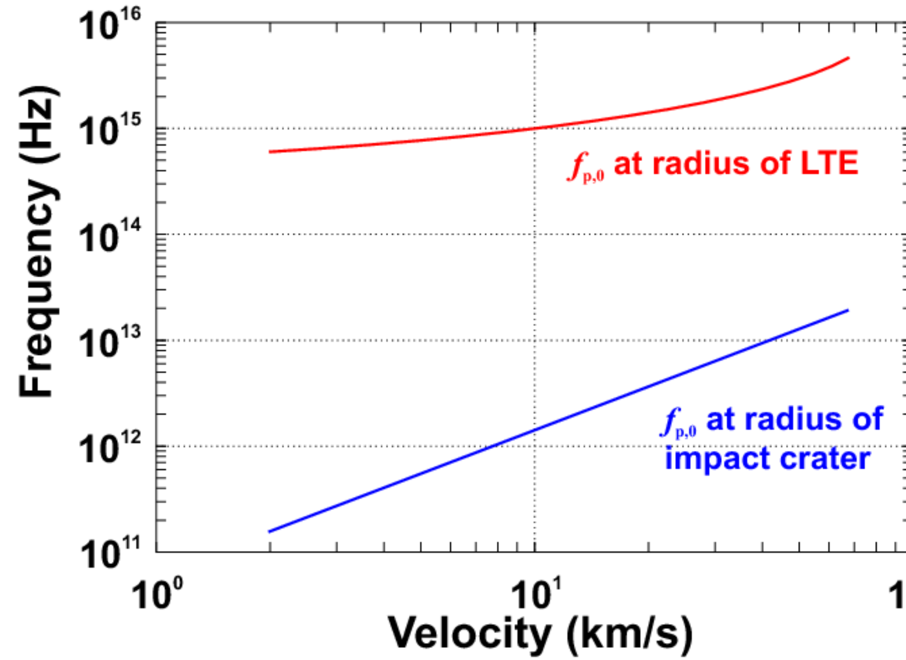
Characteristic Plasma Parameters





Density:

$$n_e(t) = \frac{n_{e,o}}{\left(1 + {c_s t}/{r_o}\right)^3}$$

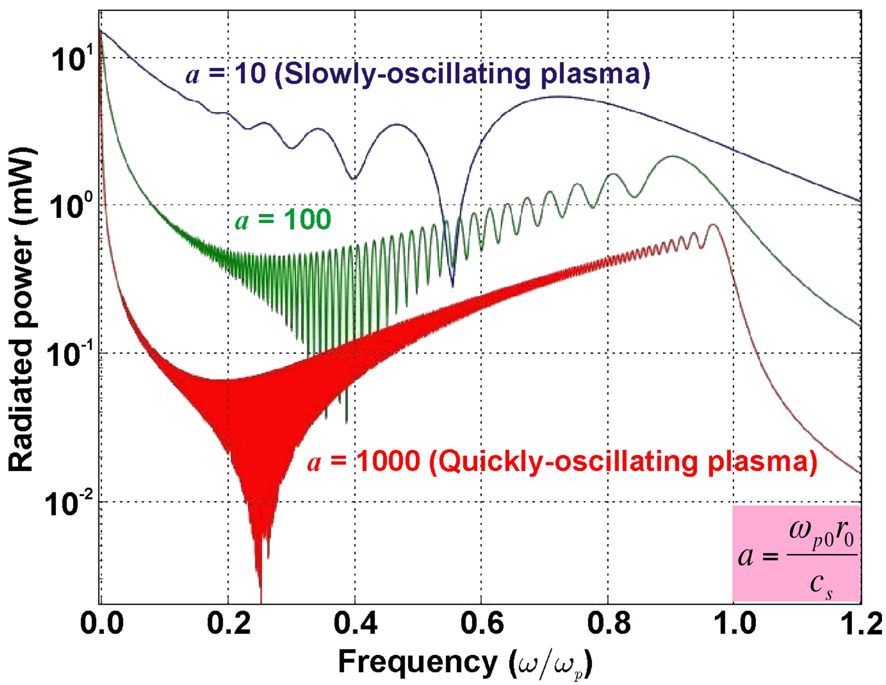
Dynamics:

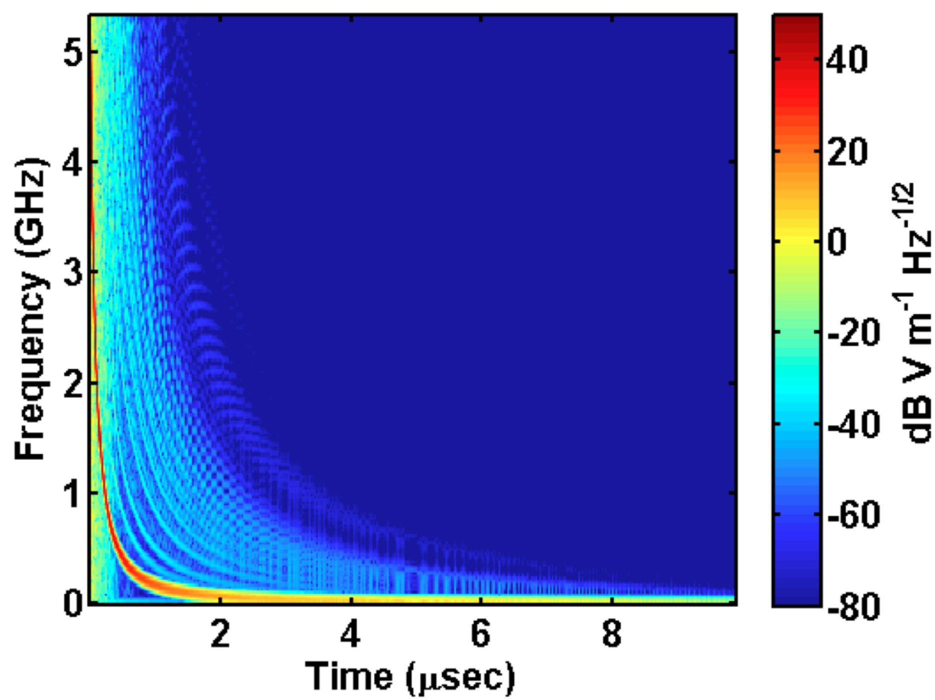
$$\ddot{\xi}(t) = -\frac{e^2 n_e \xi(t)}{m_e \varepsilon_o} = -\frac{\omega_{p,o}^2 \xi(t)}{\left(1 + {c_s t}/{r_o}\right)^3}$$

$$\xi(t) = -\frac{v_{th,e}}{\omega_{p,0}} \left(1 + \frac{c_s t}{r_o}\right)^{3/4} \sin\left(\omega_{p,0} \frac{r_o}{c_s} \left[1 + \frac{c_s t}{r_o}\right]^{-1/2}\right)$$

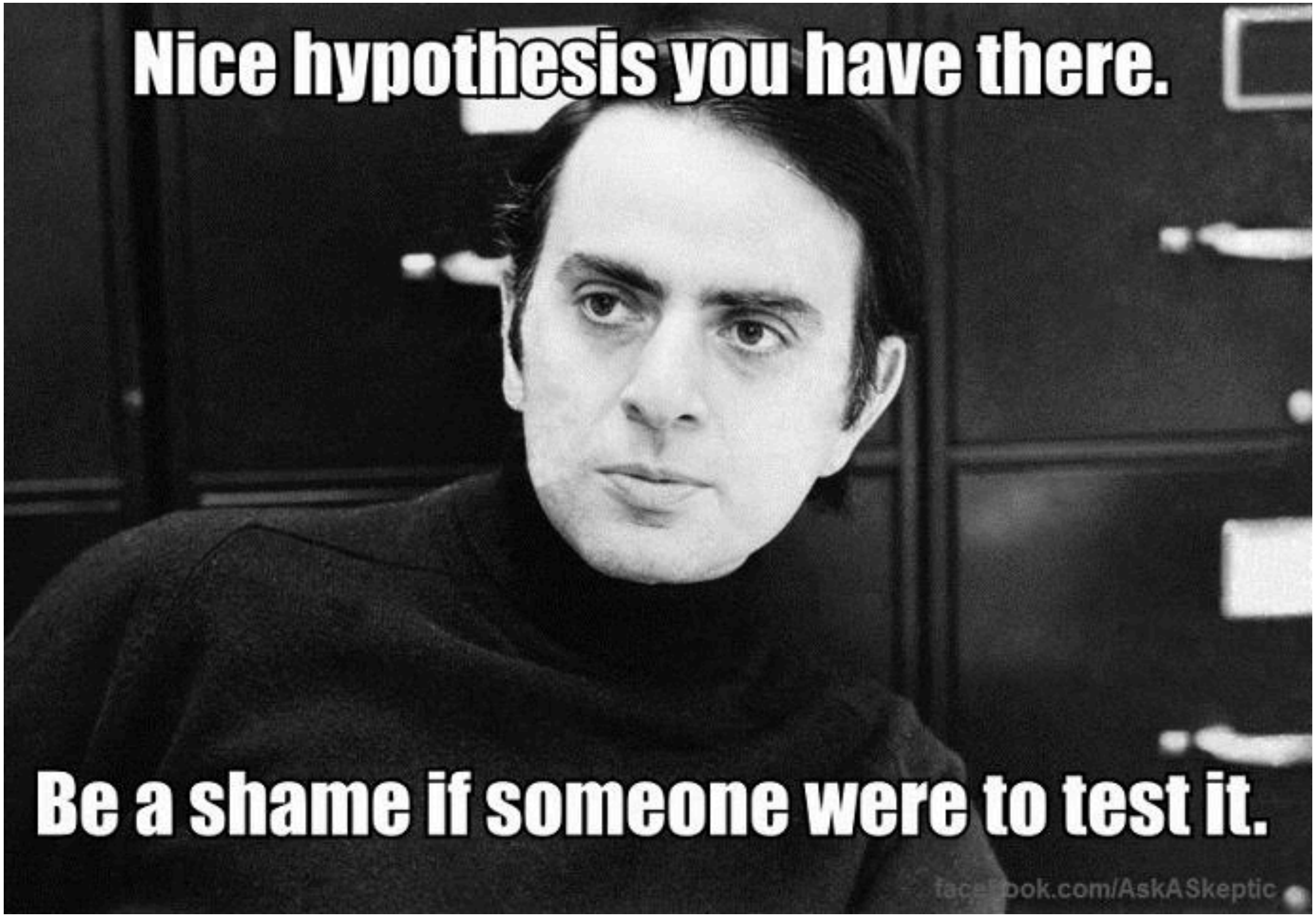
RF Emission: EMP from Theory

$$P = \frac{\omega_{p,o}^4 \left(\frac{v_{th,e}}{\omega_{p,o}}\right)^2 e^2 N \sin^2\left(\omega_{p,o}\frac{r_0}{c_s}\left[1+\frac{2c_s t}{r_0}\right]^{-1/2}\right)}{6\pi e_0 c^3 \left(1+\frac{c_s t}{r_0}\right)^{9/2}}$$

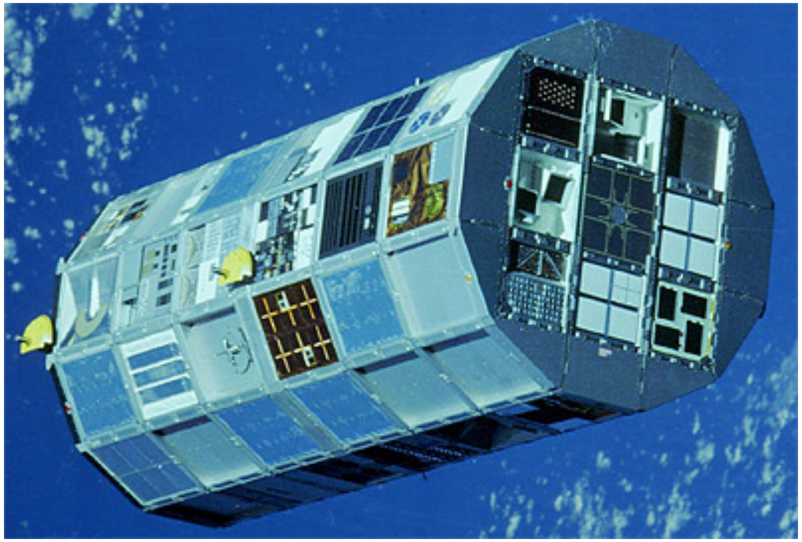




Close *et al.*, 2010

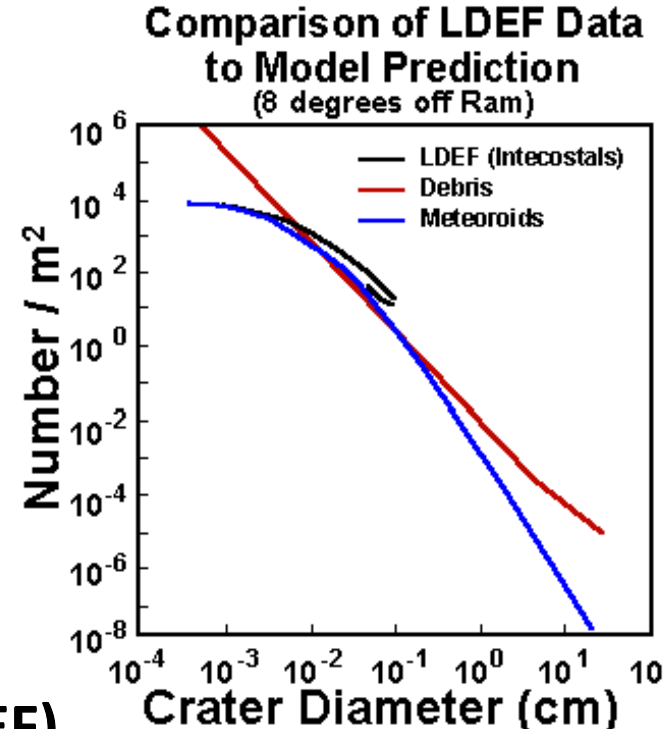

Nice hypothesis you have there.
Be a shame if someone were to test it.
facebook.com/AskASkeptic

Low Earth Orbit Dust Detectors



http://space.skyrocket.de/img_sat/ldef-1__1.jpg

δ_p



- **Long Duration Exposure Facility (LDEF)**
- **Mission: effects of space environment on satellites**
  - **Meteoroids and debris:** $\frac{D_C}{D_P} = C\left(\frac{\delta_p}{\delta_t}\right)^{0.333} v^{0.666}$
- **Lifespan**
  - **Sent into LEO by Challenger in 1984**
  - **Returned by Columbia in 1990**

Interplanetary Dust Detectors

Spacecraft	Mass threshold (kg)	Dynamic range	Sensitive area (m^2)	Reference
Pioneer 8/9	2×10^{-16}	10^2	0.010	Berg and Richardson (1968)
Pioneer 10	2×10^{-12}	—	0.26	Humes *et al.* (1974)
Pioneer 11	1×10^{-11}	—	0.26 (0.57)	Humes (1980)
HEOS 2	2×10^{-19}	10^4	0.010	Hoffmann *et al.* (1975)
Helios 1 and 2	9×10^{-18}	10^4	0.012	Dietzel *et al.* (1973)
Ulysses	2×10^{-18}	10^6	0.10	Grün *et al.* (1983)
Galileo	2×10^{-18}	10^6	0.10	Grün *et al.* (1992)
Cassini	5×10^{-19}	10^6	0.10	This work

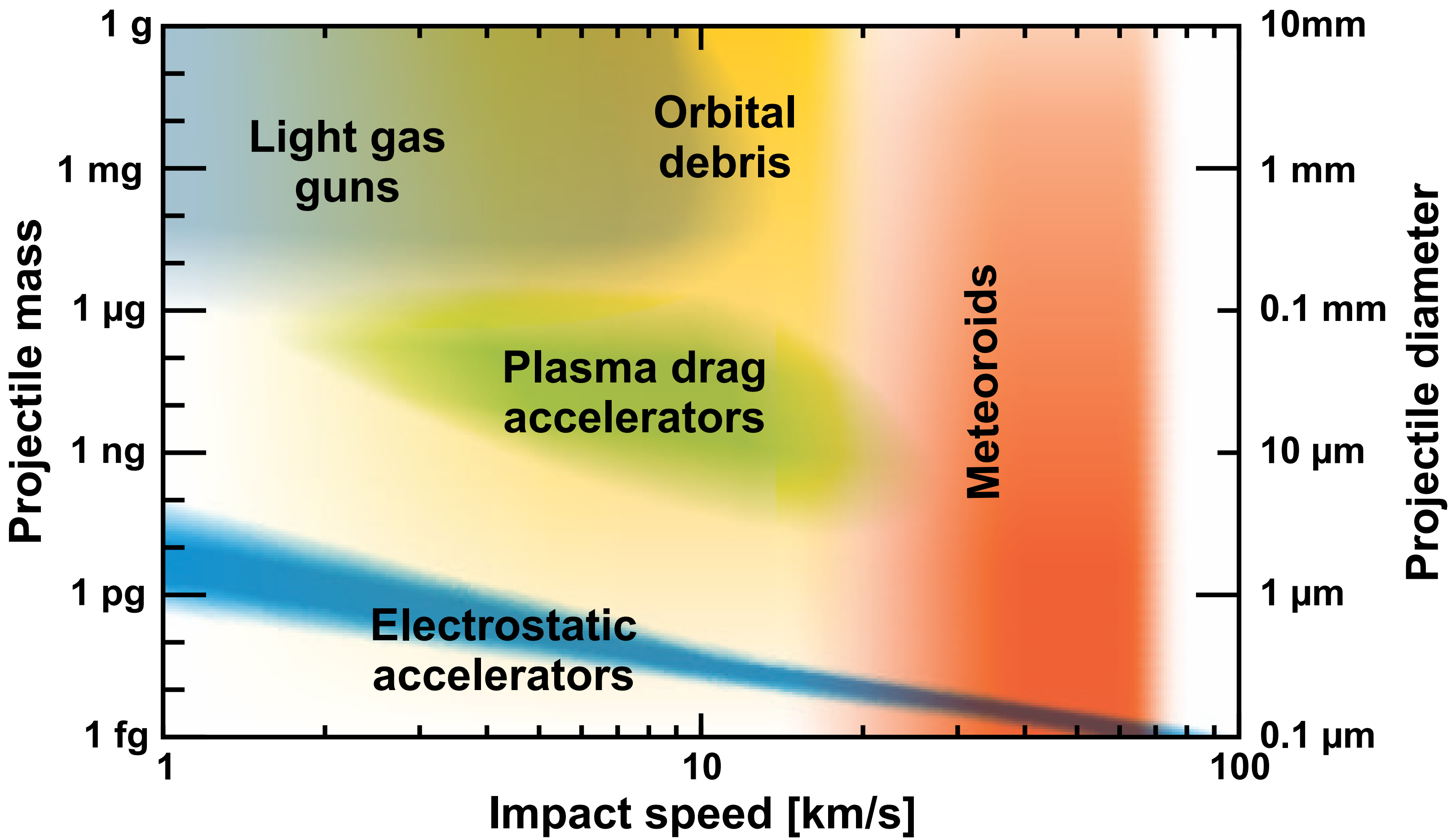
The mass thresholds refer to 20 km/s impact speed. The Pioneer 10 and 11 detectors are threshold detectors. Srama *et al.*, 2002

"Surprisingly, the plasma wave experiment on board the Voyager 2 spacecraft picked up charge signals from expanding plasma clouds generated by dust impacts onto the spacecraft during its passage through Saturn's ring plane"

Gurnett *et al.*, 1983

Ground-Based Facilities

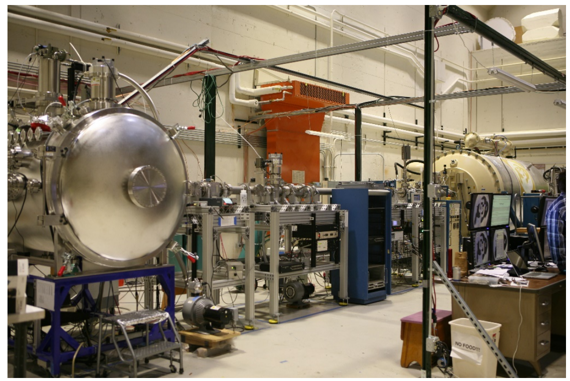
- *Advantage*: controlled experiment and knowledge of impactor
- *Disadvantage*: can't fully reproduce particle parameters



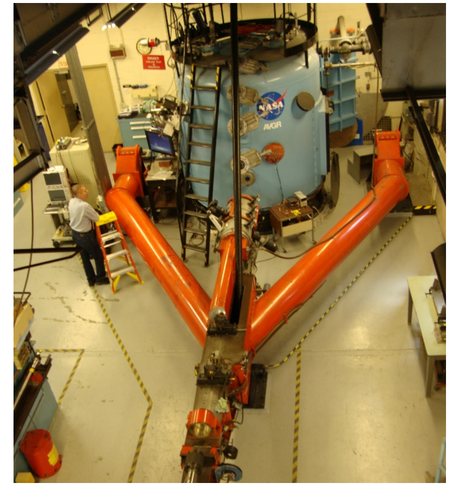
Lee *et al.*, 2012

Ground Based Testing

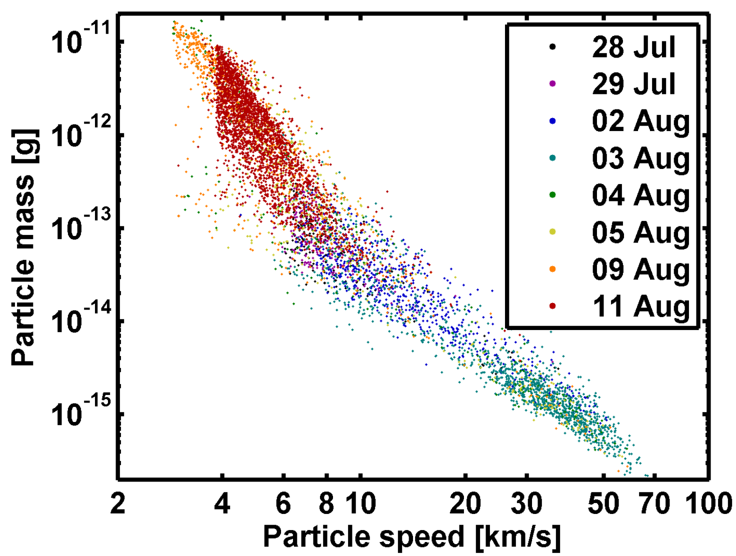
Max Planck Institute (MPI)

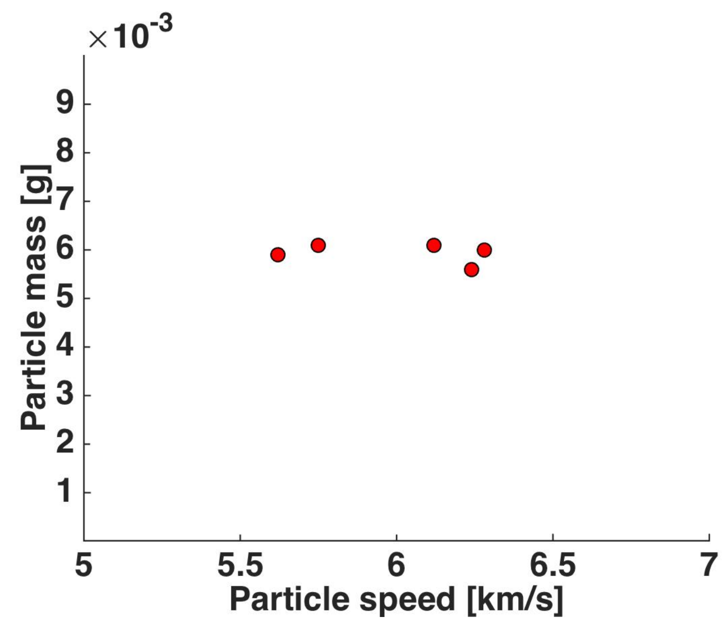


Colorado Center for Lunar Dust Acceleration Studies (CCLDAS)

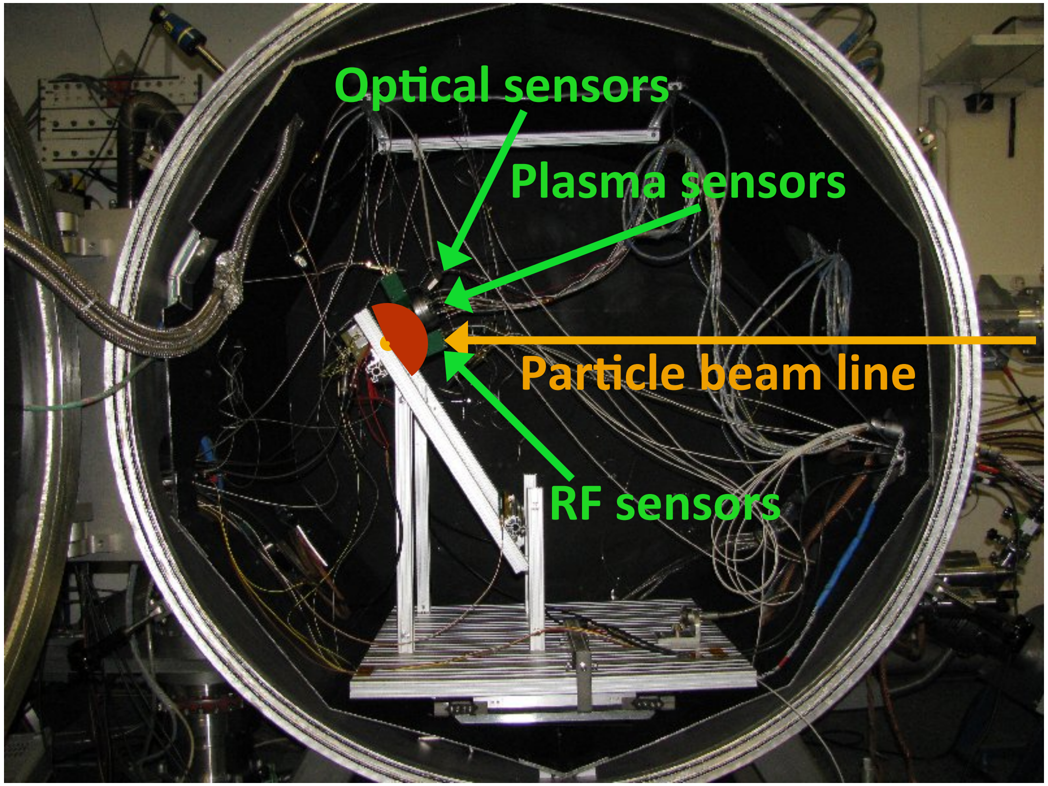


NASA Ames Vertical Gun Range (AVGR)



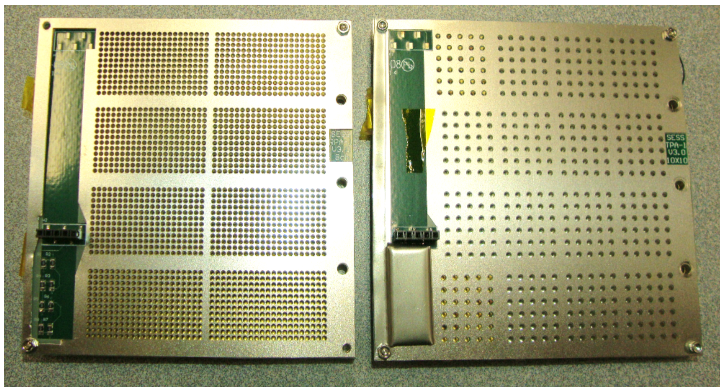


Chamber

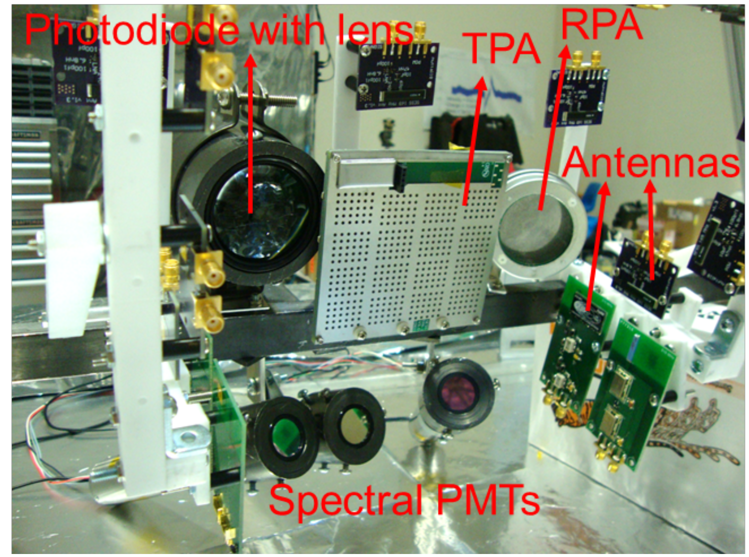


- **1.4 m diameter**
- **10^{-6} to 10^{-5} mbar**

Sensors

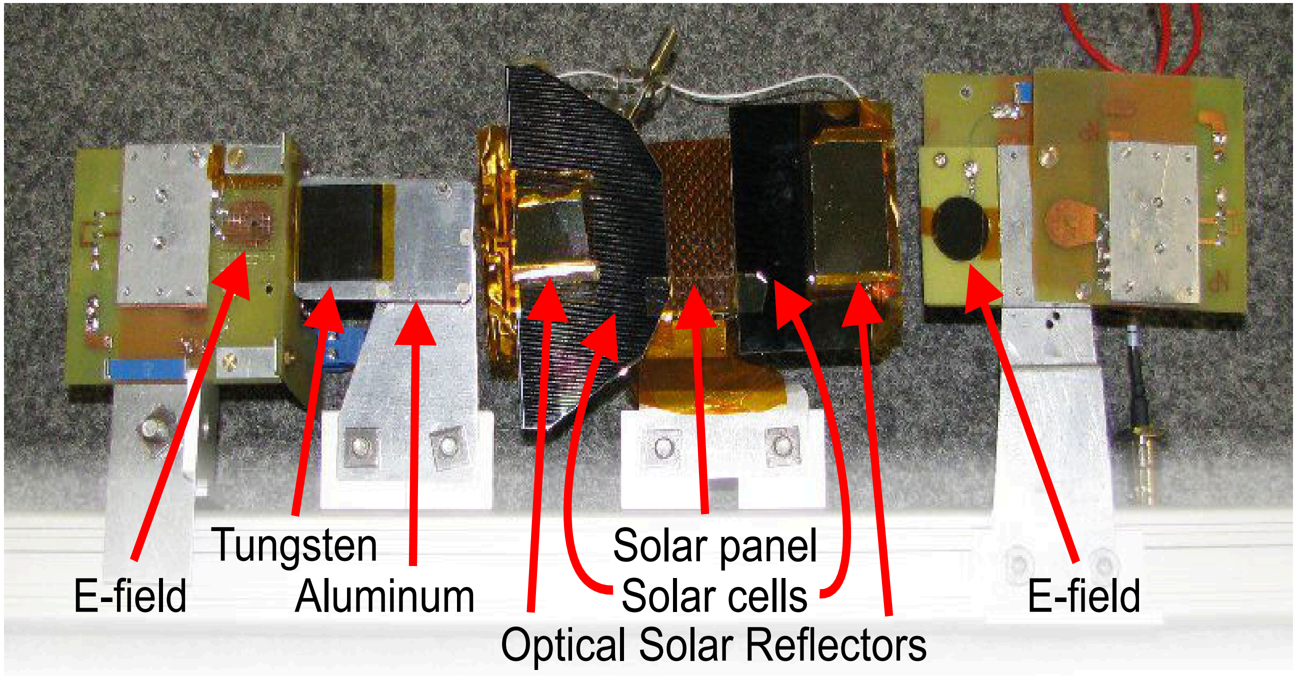


Goel *et al*., 2015

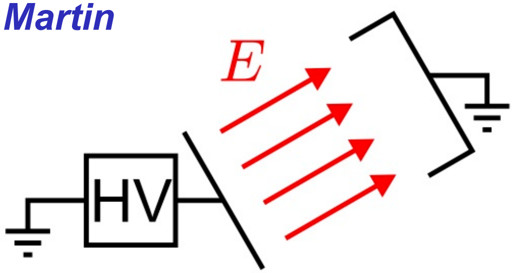


- **All-optical Photomultiplier Tube (PMT), spectral PMT with filters, photodiode with lens**
- **Plasma: Retarding Potential Analyzers (RPAs), 16 channel Transient Plasma Analyzer (TPA), 8 channel TPA**
- **RF: 165 MHz, 315 MHz, 916 MHz patch antennas**

Targets

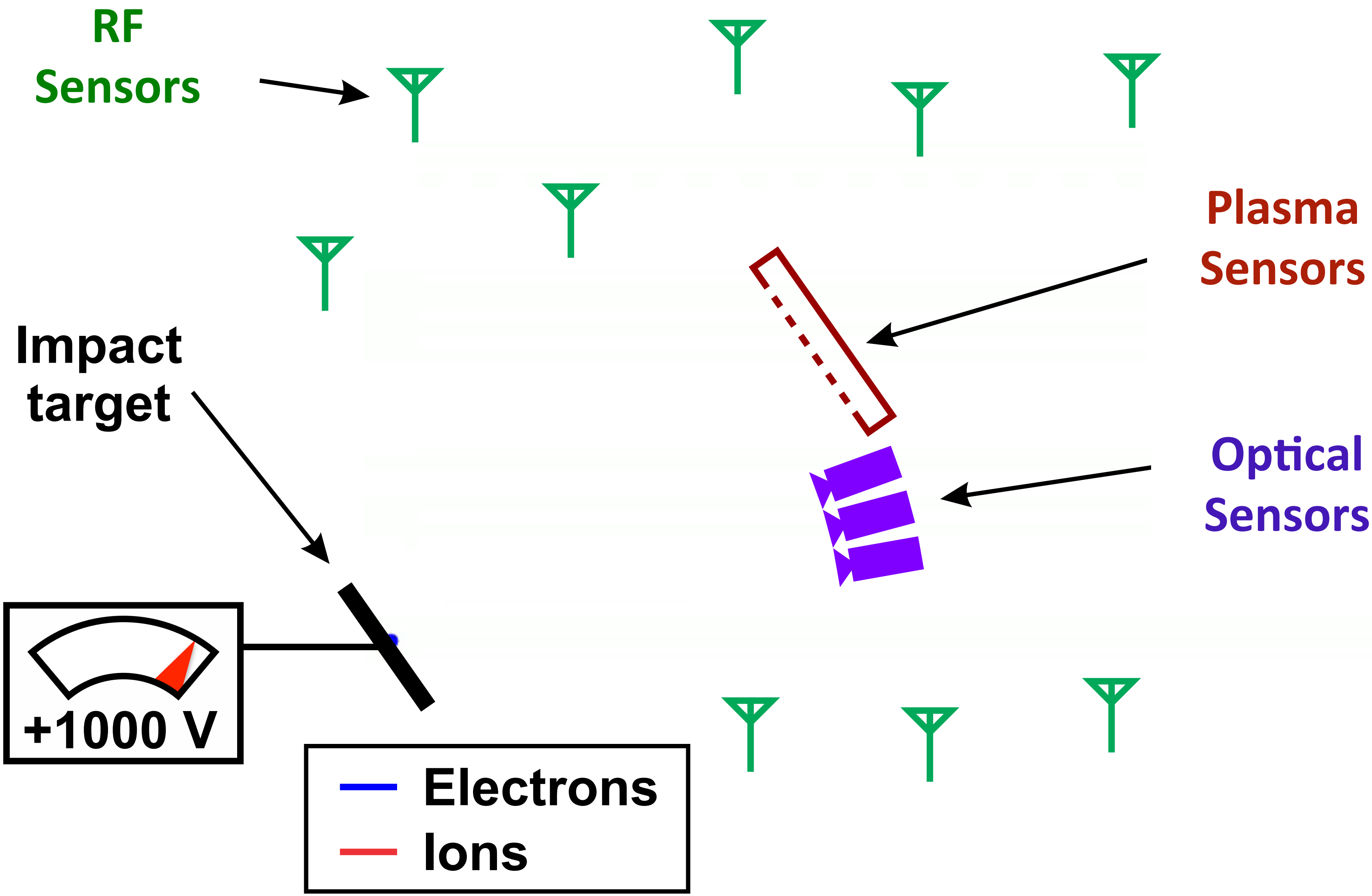


Donated by J. Likar of Lockheed Martin

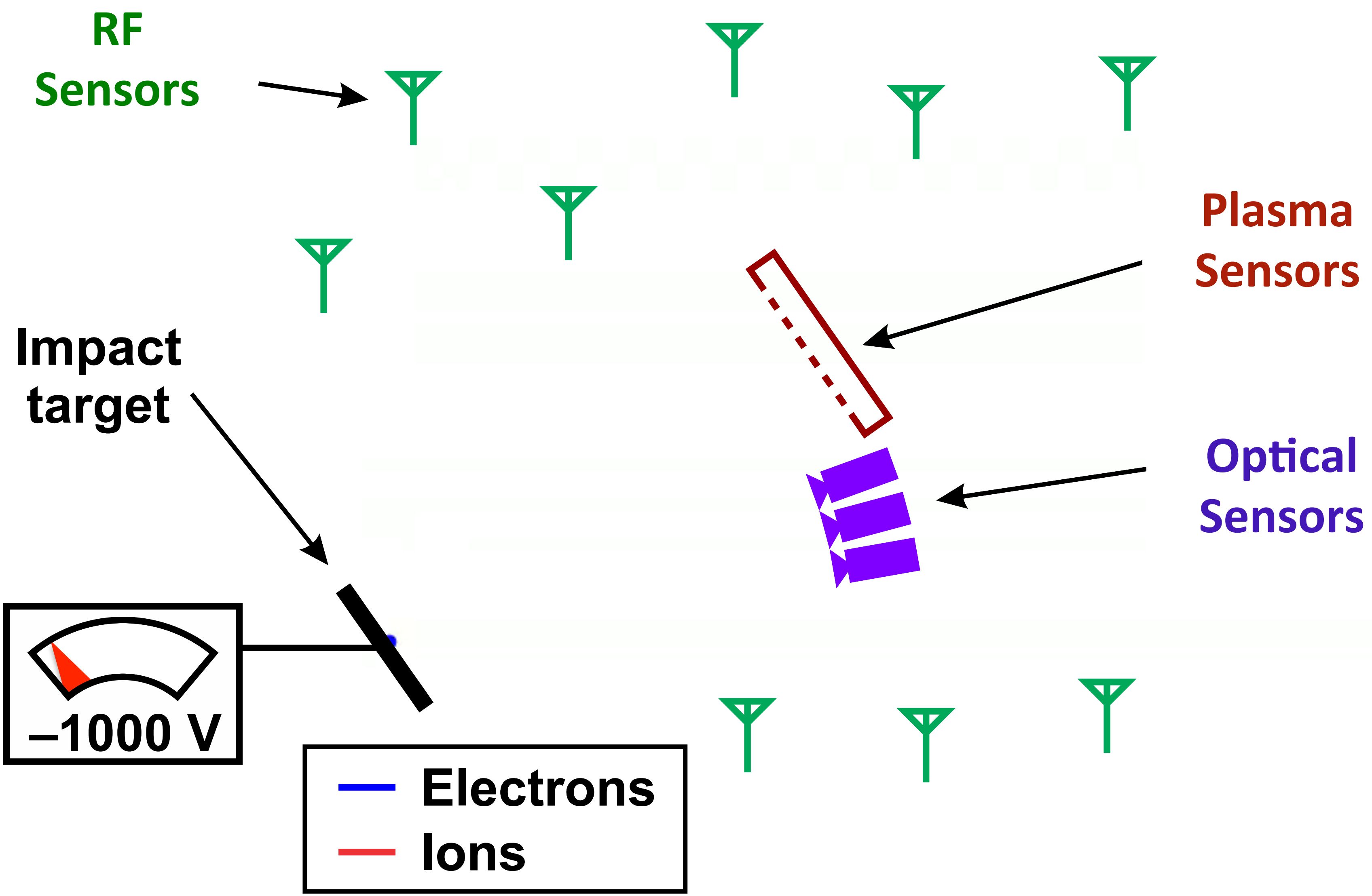


- **E-field target/sensors developed by SRI**
- **Electrical bias applied to targets to simulate spacecraft charging**

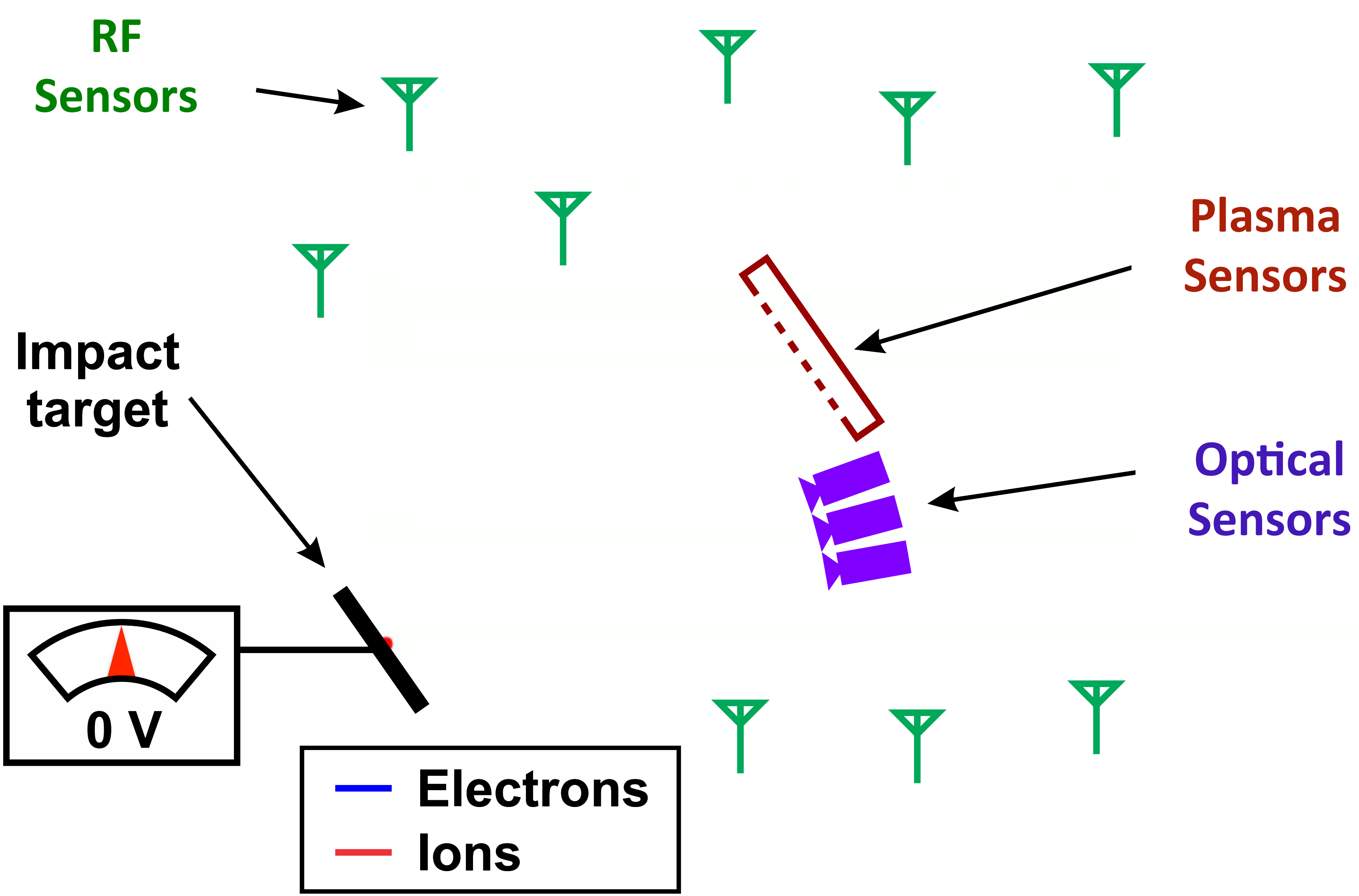
Positive **bias on target**



Negative bias on target

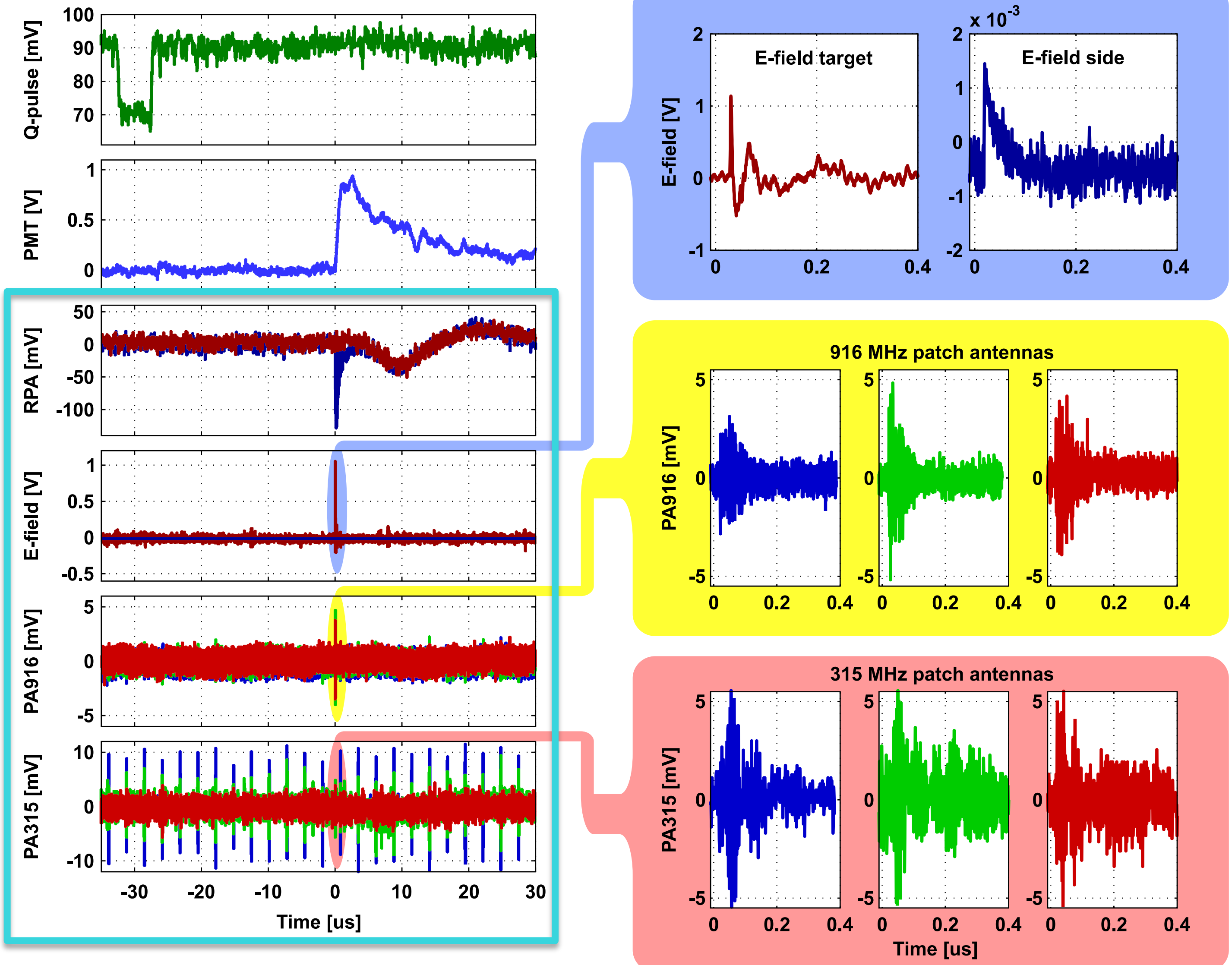


Neutral bias on target



Multi-Sensor Data

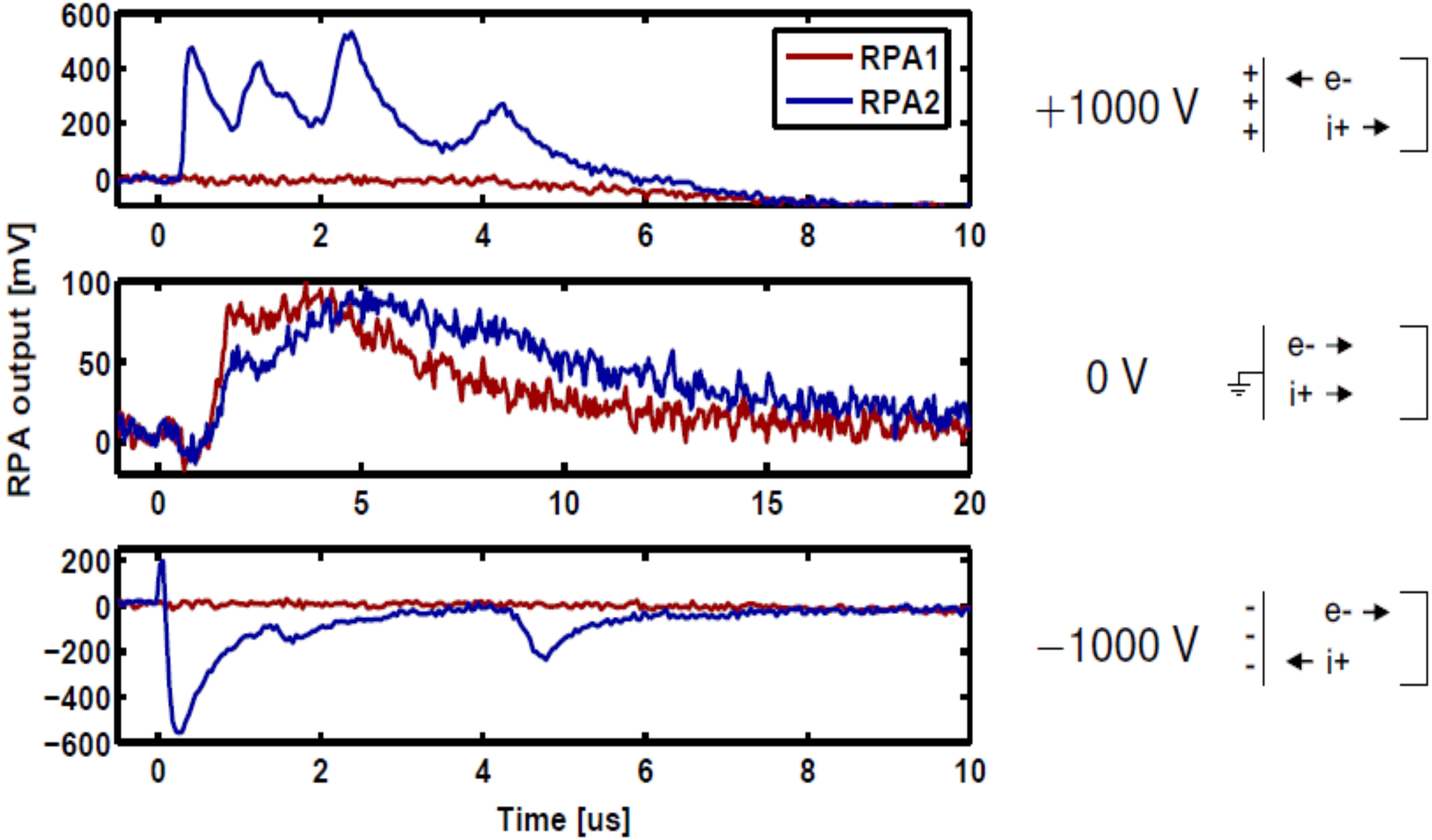
v = 39.4 km/s
m = 1.45 x 10^{-15} g
Target = Tungsten (grid)
Bias = +1000 V



Close *et al.*, 2013

Sample Plasma Data

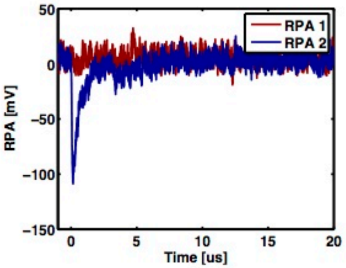
RPA Data: Dependence on Bias



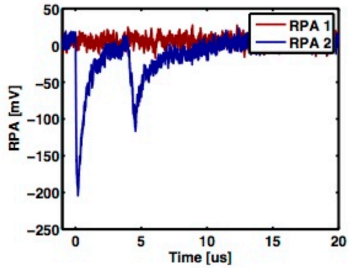
Lee *et al.*, 2013

RPA Data: Dependence on Target Type

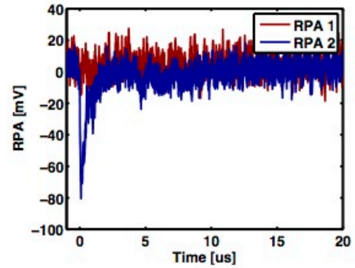
Solar Panel



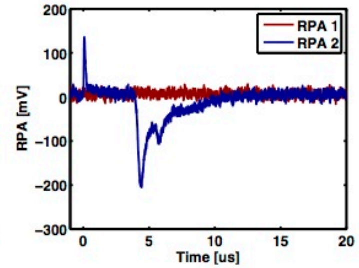
Solar Cell (uncoated)



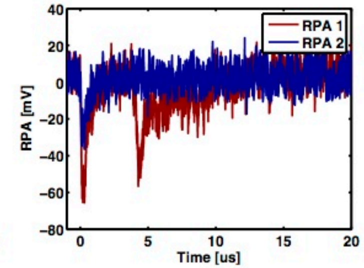
Solar Cell (conductive)



OSR (standard)



OSR (conductive)



Target	Negative Ions
Solar Panel	No
Solar Cell (uncoated)	Yes
Solar Cell (conductive)	No
OSR (standard)	Two species
OSR (conductive)	Yes

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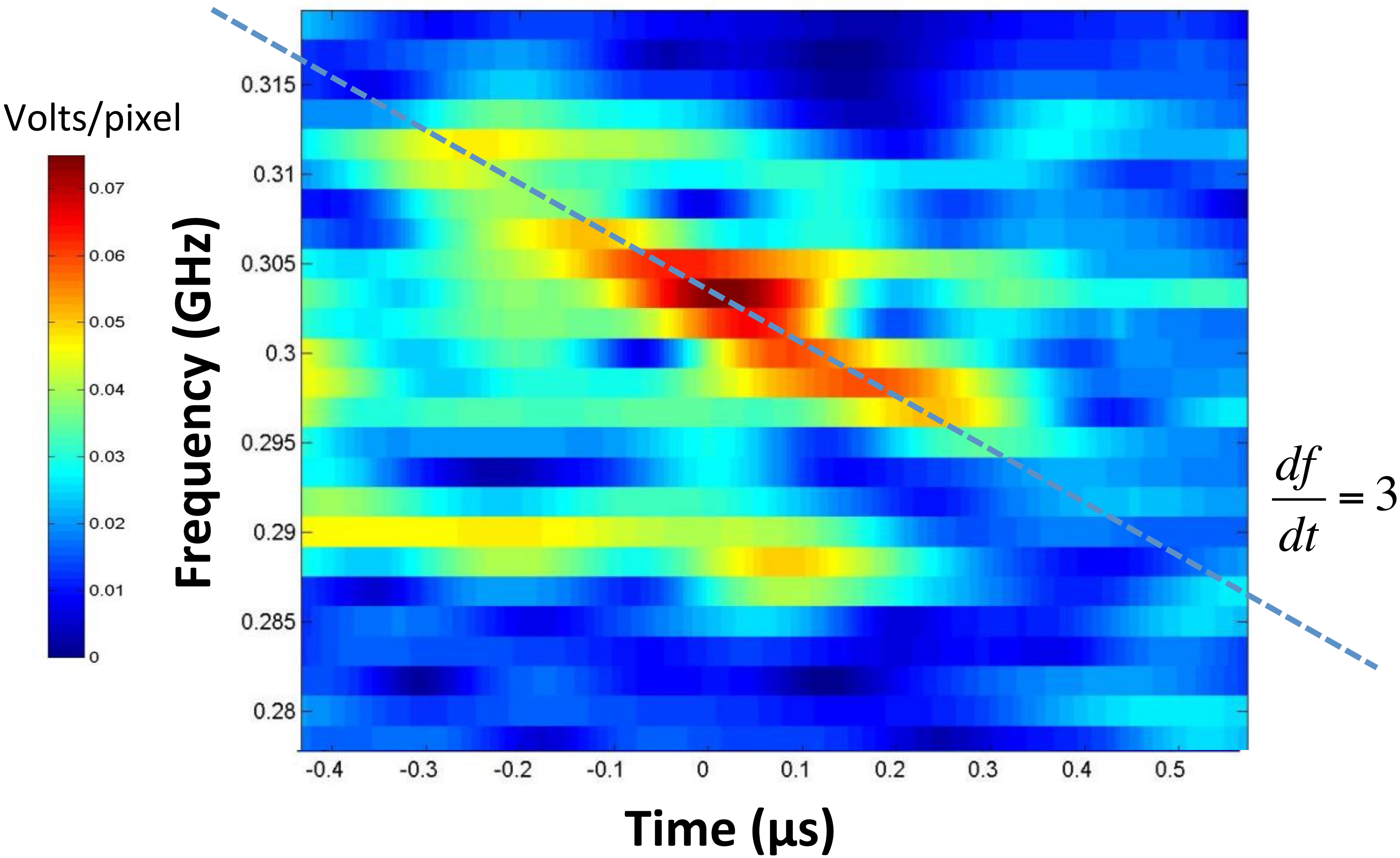
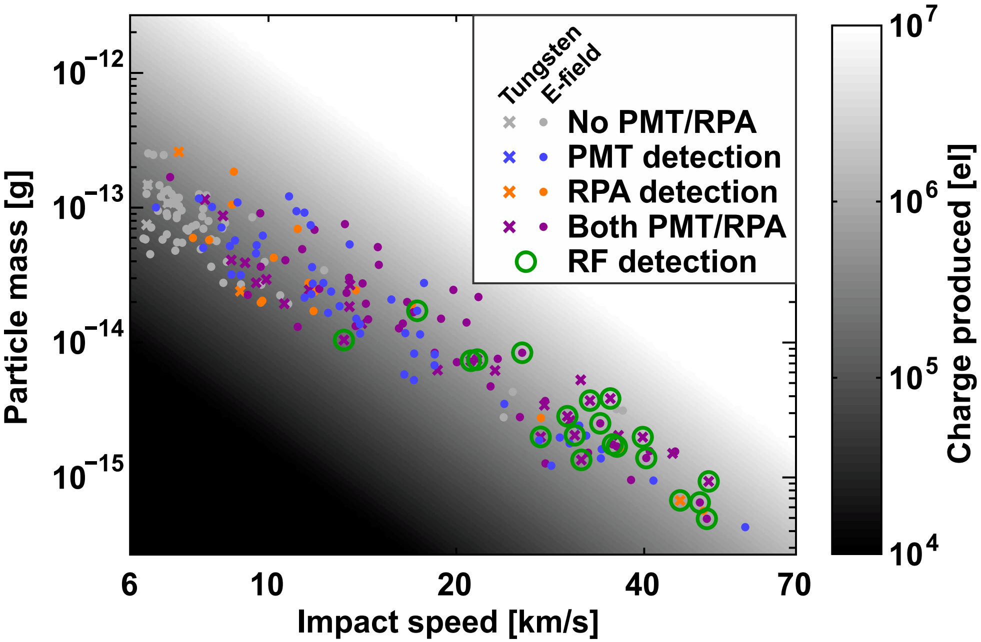
Sample RF Data

RF Data: Dependence on Frequency

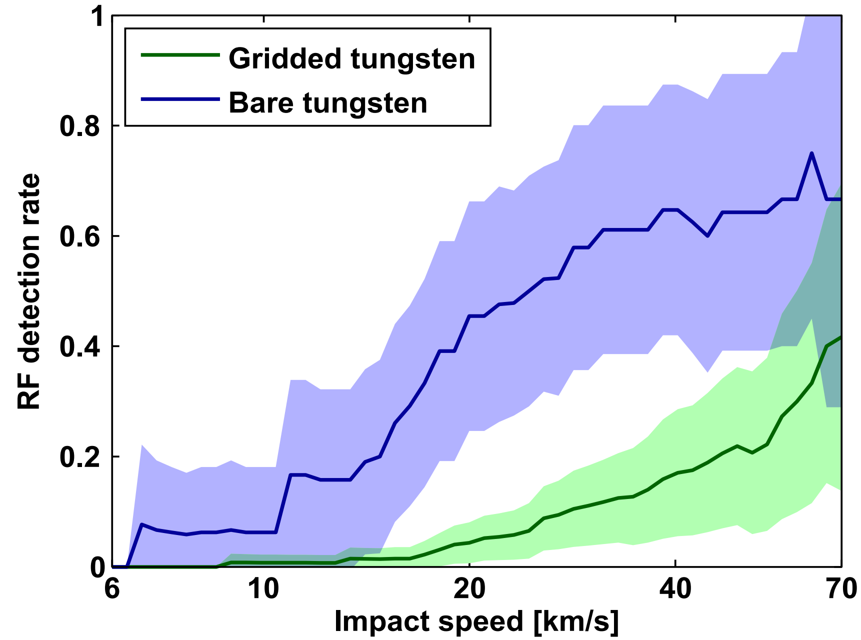


$$\frac{df}{dt} = 30 \text{ MHz} / \mu s$$

RF Data: Dependence on Speed

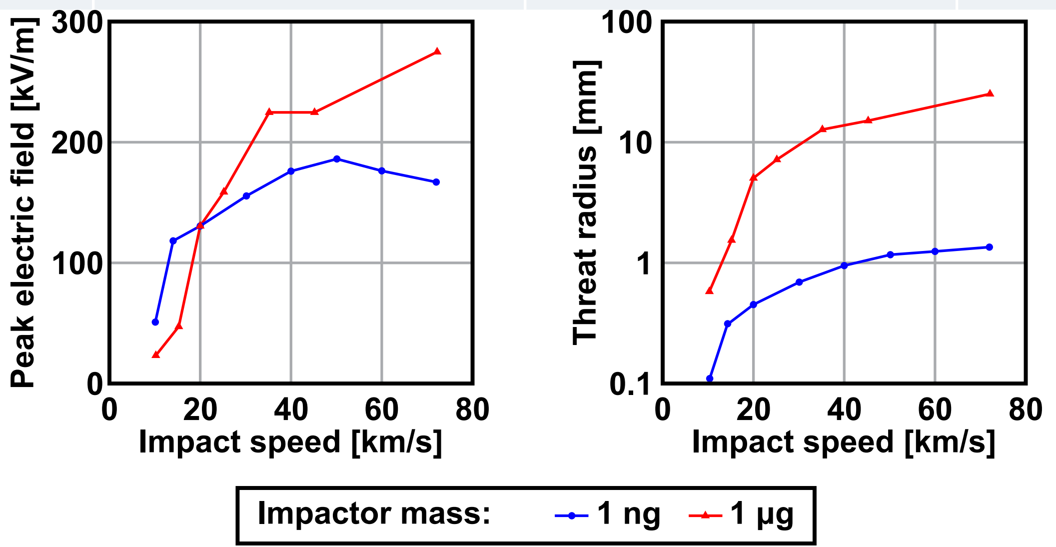


Cumulative Distribution



Threat to Spacecraft Electronics

Quantity	Ground Based Tests (1.4 fg, 40 km/s)	Impact in Space (1 ng, 60 km/s)	Impact in Space (1 µg, 60 km/s)
Electric field (V/m)	3.2×10^{-3}	2.0×10^{5}	3.0×10^{7}
Peak power (W)	7.5×10^{-7}	2.7	2.7×10^{3}
Total kinetic energy of incoming particle (J)	1.1×10^{-9}	1.8×10^{-3}	1.8
Energy (J)	3.8×10^{-14}	1.4×10^{-7}	1.4×10^{-4}



Outline

- Introduction
- Impacts in Atmosphere
- Impacts on Spacecraft
- **Conclusion**

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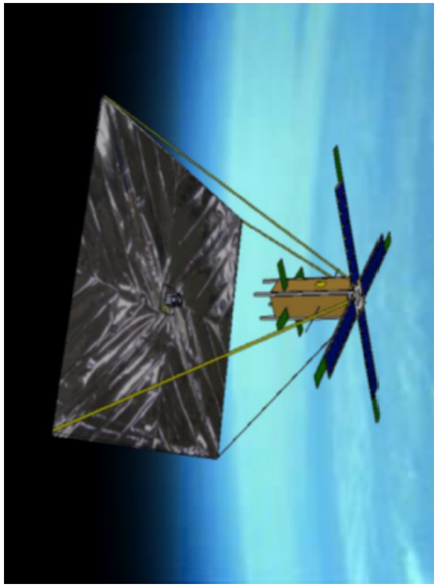
Summary

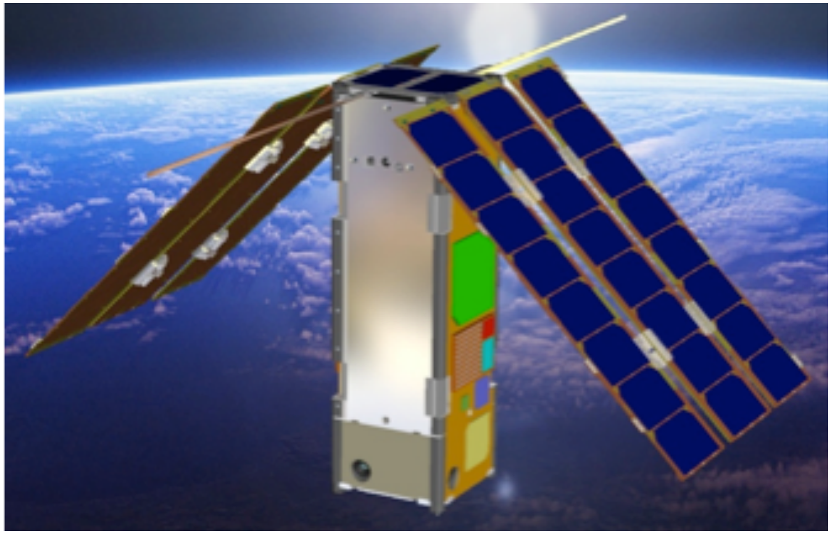
- Hypervelocity impact physics still poorly understood
- Remote sensing of plasma provides characterization of particle
- Data from spacecraft impacts (both space and ground) provides characterization of electrical effects
  - Multi-sensor approach: optical, plasma, RF
  - Strong dependence on speed, target type, biasing conditions
  - RF associated with expanding plasma
- Implications for spacecraft failure still largely unknown

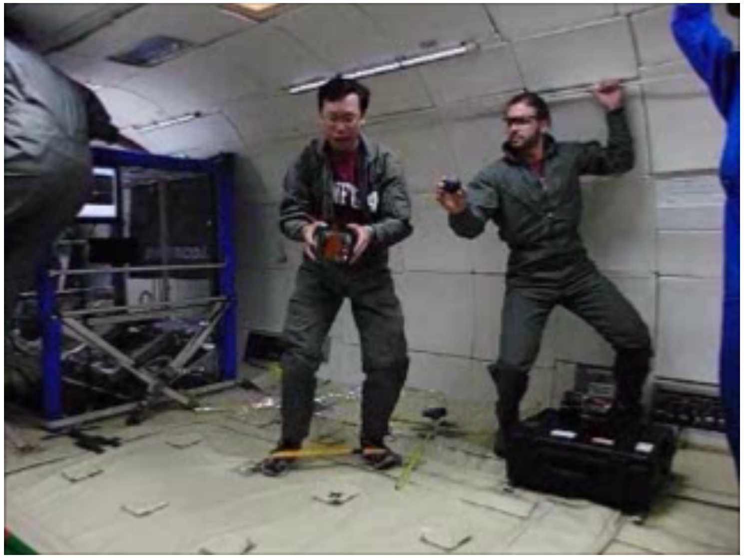
Thank You!

BACKUP

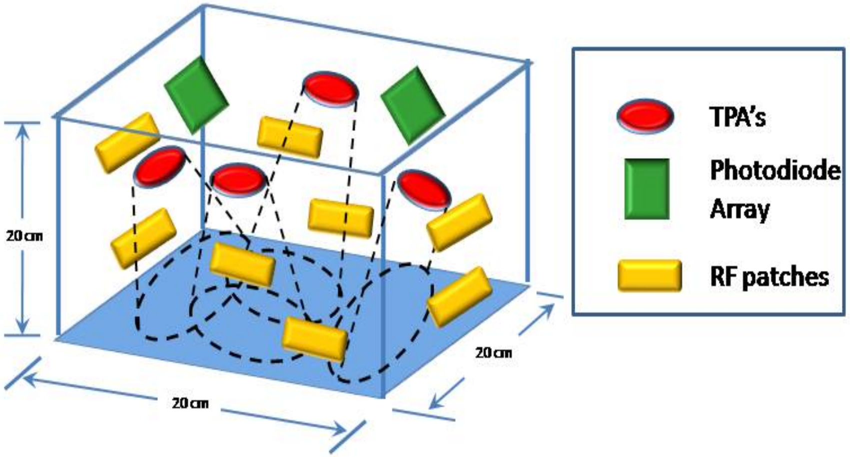
Space Experiments



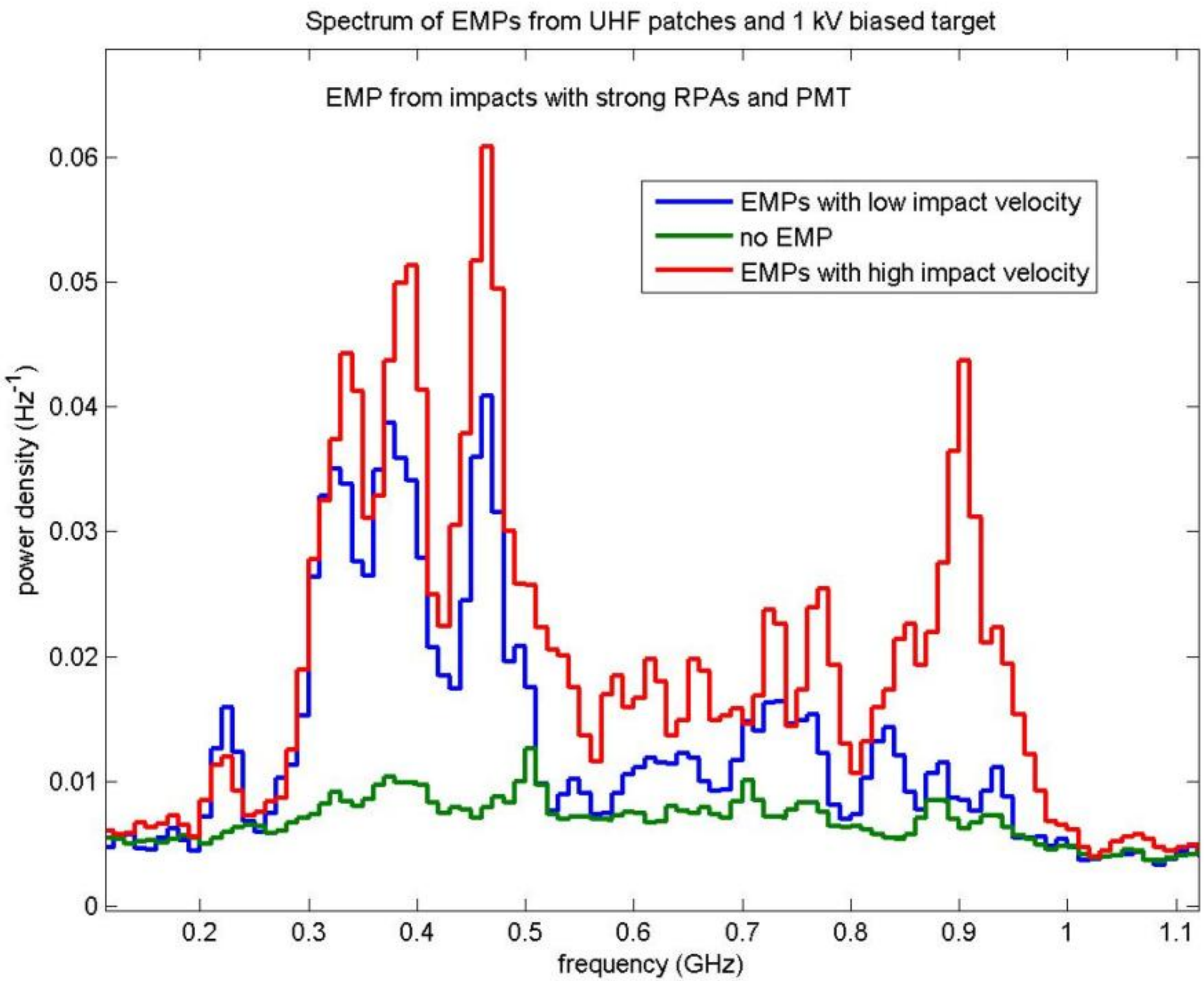




ISS Hypervelocity Impact Instrument Module

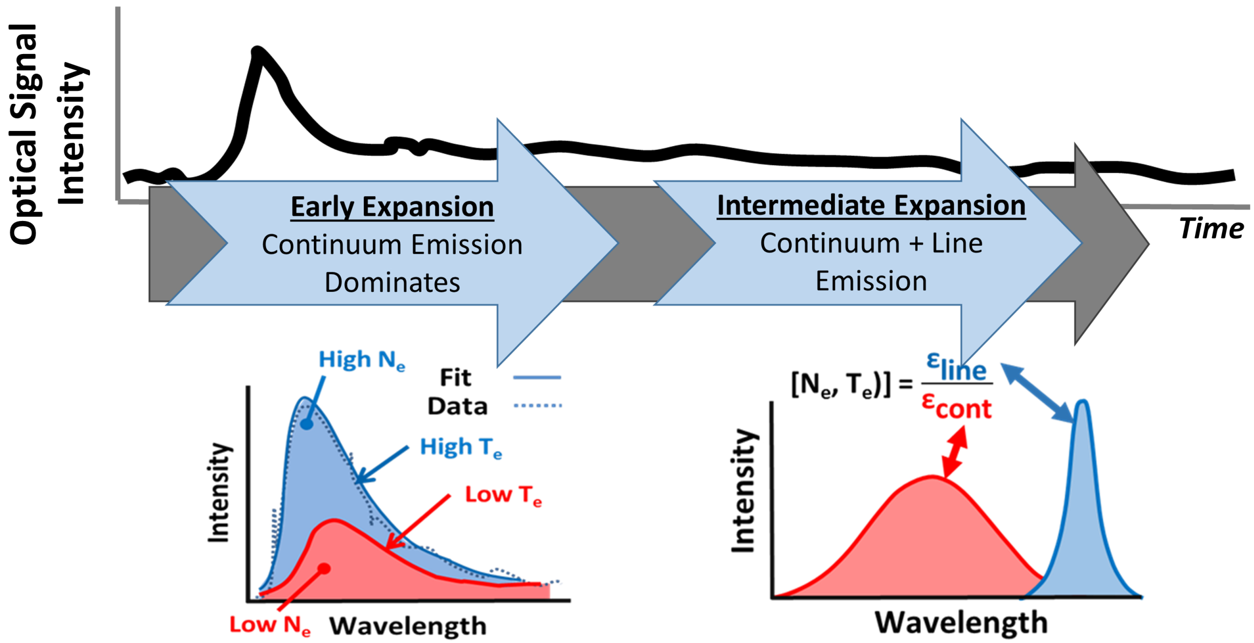


RF Characteristics: Dependence on Speed



Optical Data

Optical Emission Model



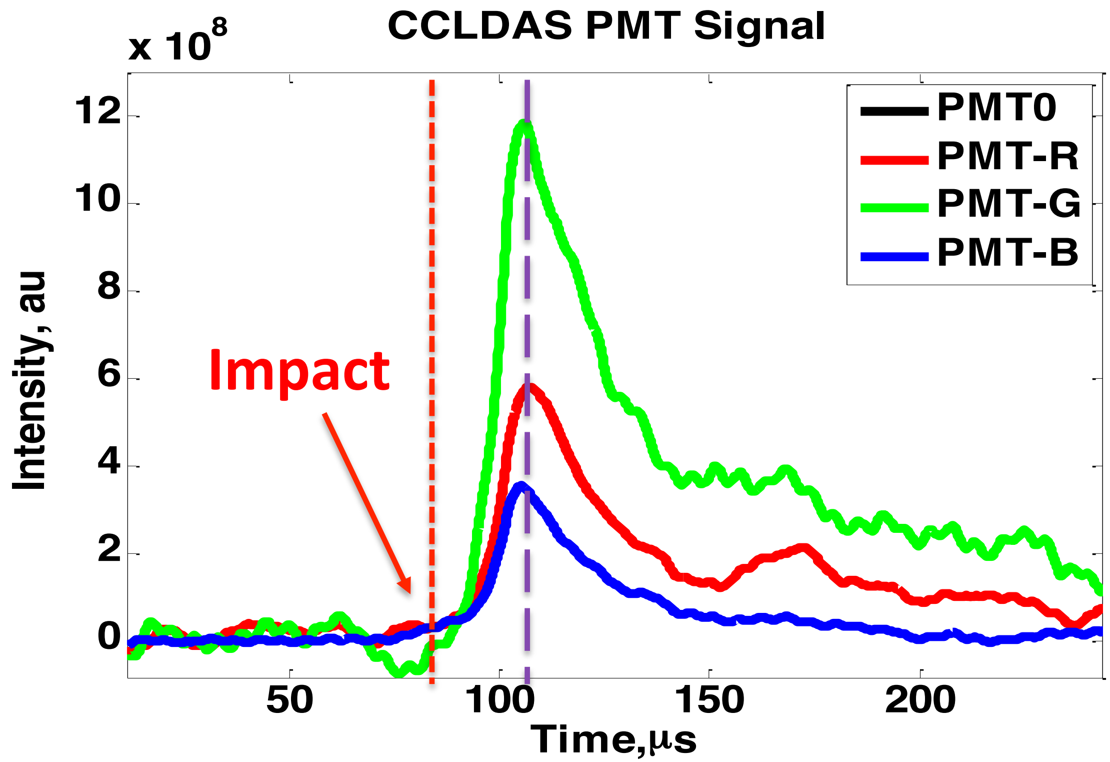
Blackbody Radiation Model

$$\varepsilon_{Conti}(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{\exp(\frac{hc}{\lambda kT}) - 1}$$

Continuum-to-line Ratio Model

$$\varepsilon_{total} = \varepsilon_{line} + \varepsilon_{continuum}$$

PMT: Negatively Biased Target

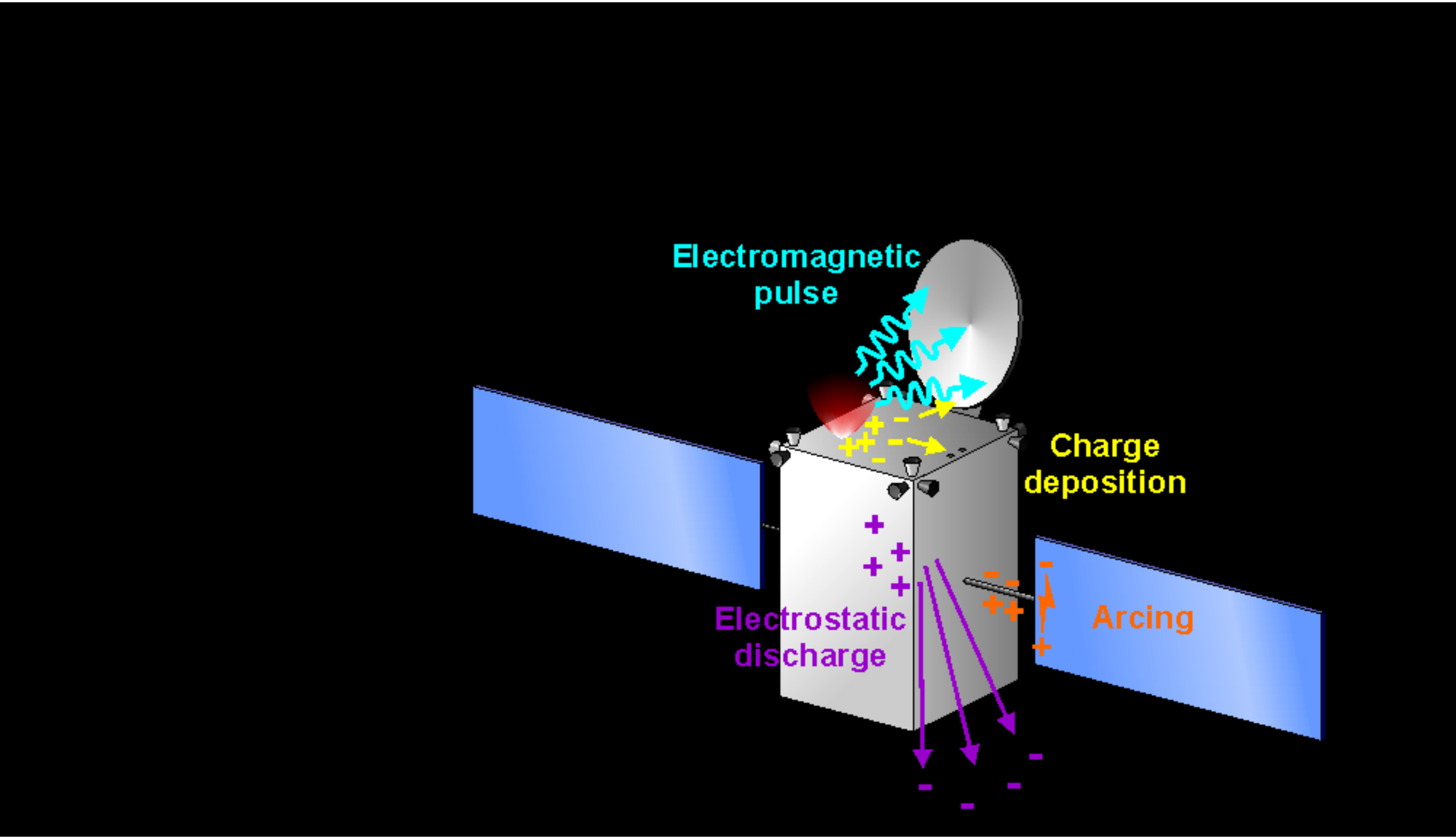


Research Goal

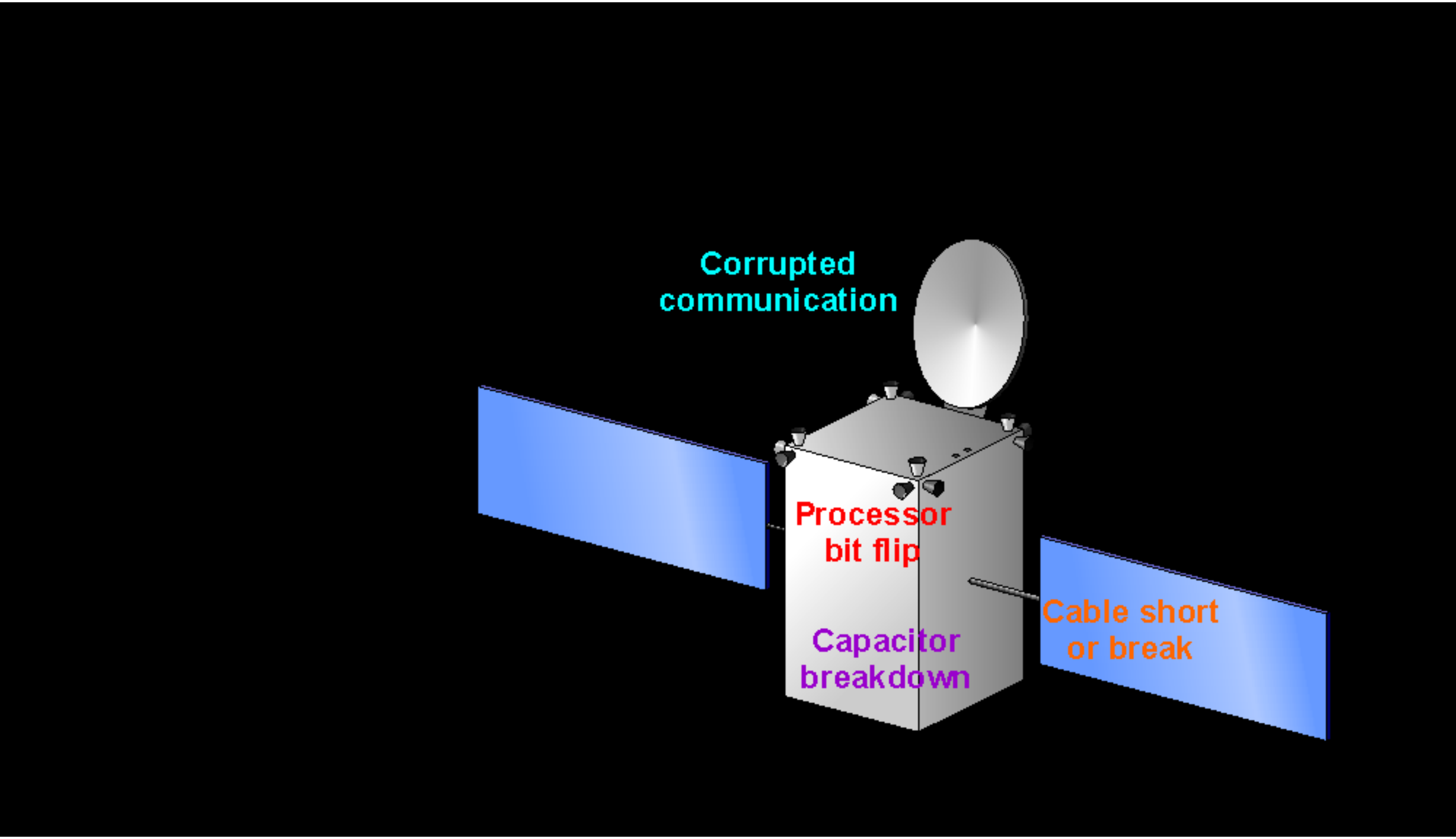
- **Spacecraft are routinely impacted by hypervelocity particles with possibility of damage**
  - **Mechanical: "well-known", larger, rare**
  - **Electrical: "unknown", smaller, more numerous**
    - **Electrostatic Discharge (ESD)**
    - **Electromagnetic Pulse (EMP)**

- **Goal:** ***characterize plasma and potential radio frequency (RF) emission from hypervelocity impacts to assess possibility of spacecraft damage***

Results of Hypervelocity Impact



Effects from Hypervelocity Impact



Possible Failures ?