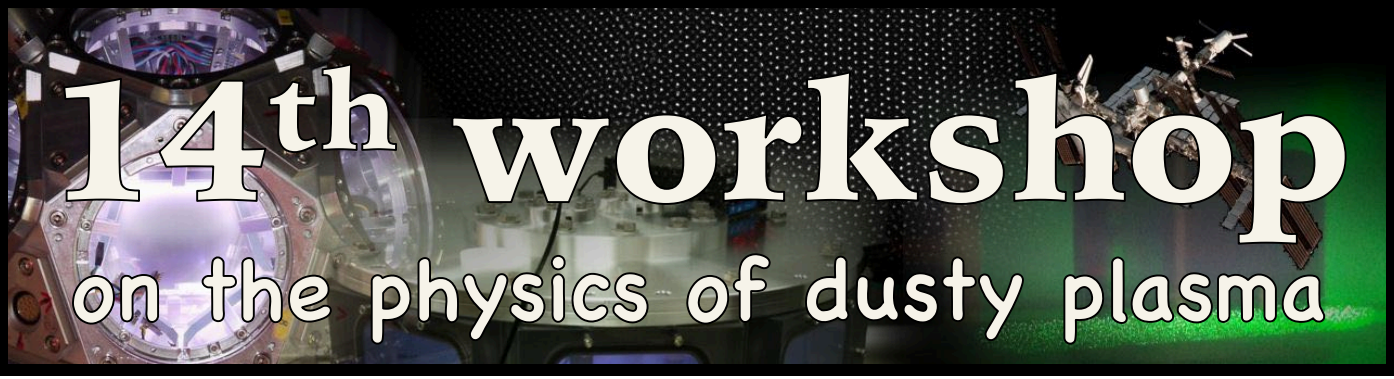
Charged Dust Measurements by the Lunar Dust Experiment

M. Horanyi, U. of Colorado, Boulder

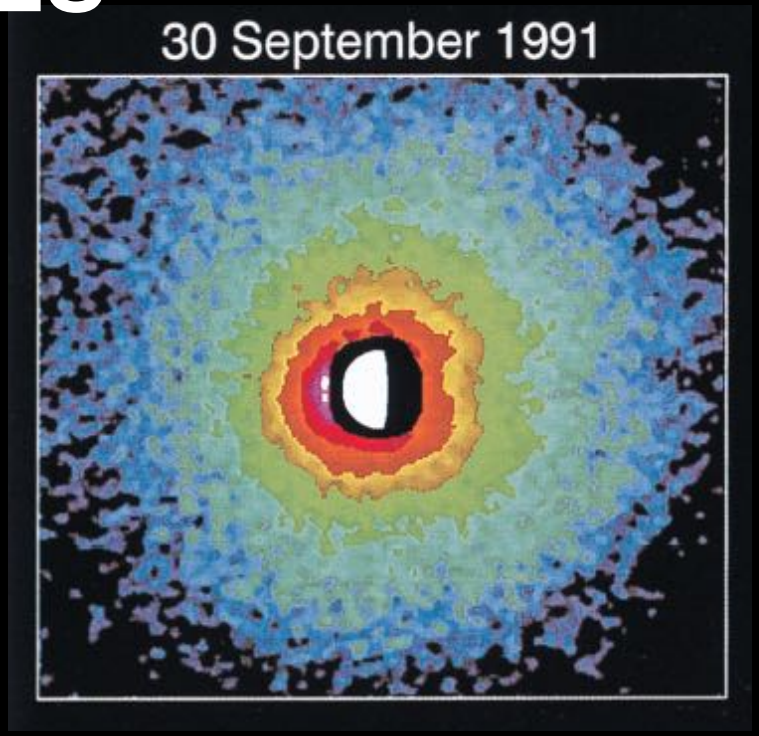
1) Lunar Atmosphere and Dust Environment Mission
2) LDEX instrument
3) Science results
   a) average ejecta cloud
   b) response to meteoroid showers
   c) lofted horizon glow particles
   d) charge detection on single grains
4) Summary



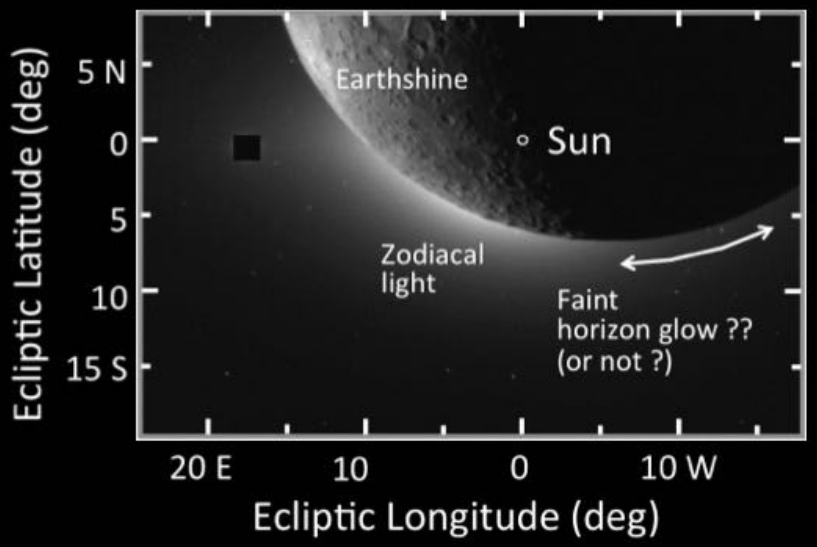
LADEE SCIENCE OBJECTIVES

- Determine composition of the lunar atmosphere, investigate processes controlling distribution and variability - sources, sinks, and surface interactions.

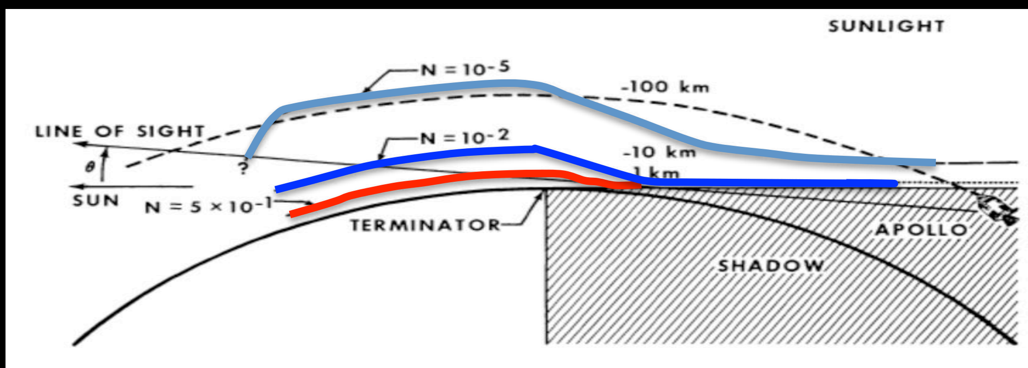
- Characterize lunar exospheric dust environment, measure spatial and temporal variability, and influence on the lunar atmosphere.

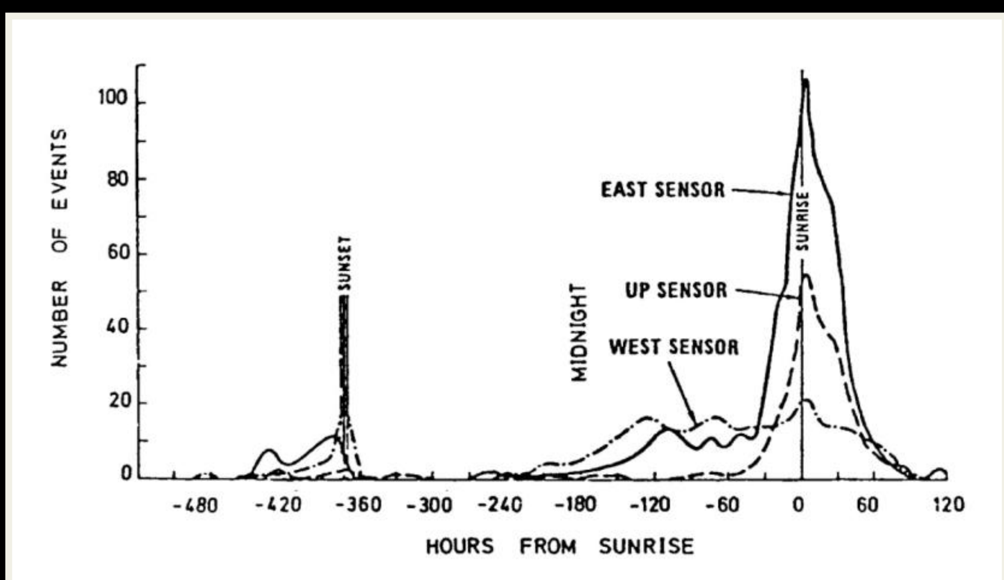


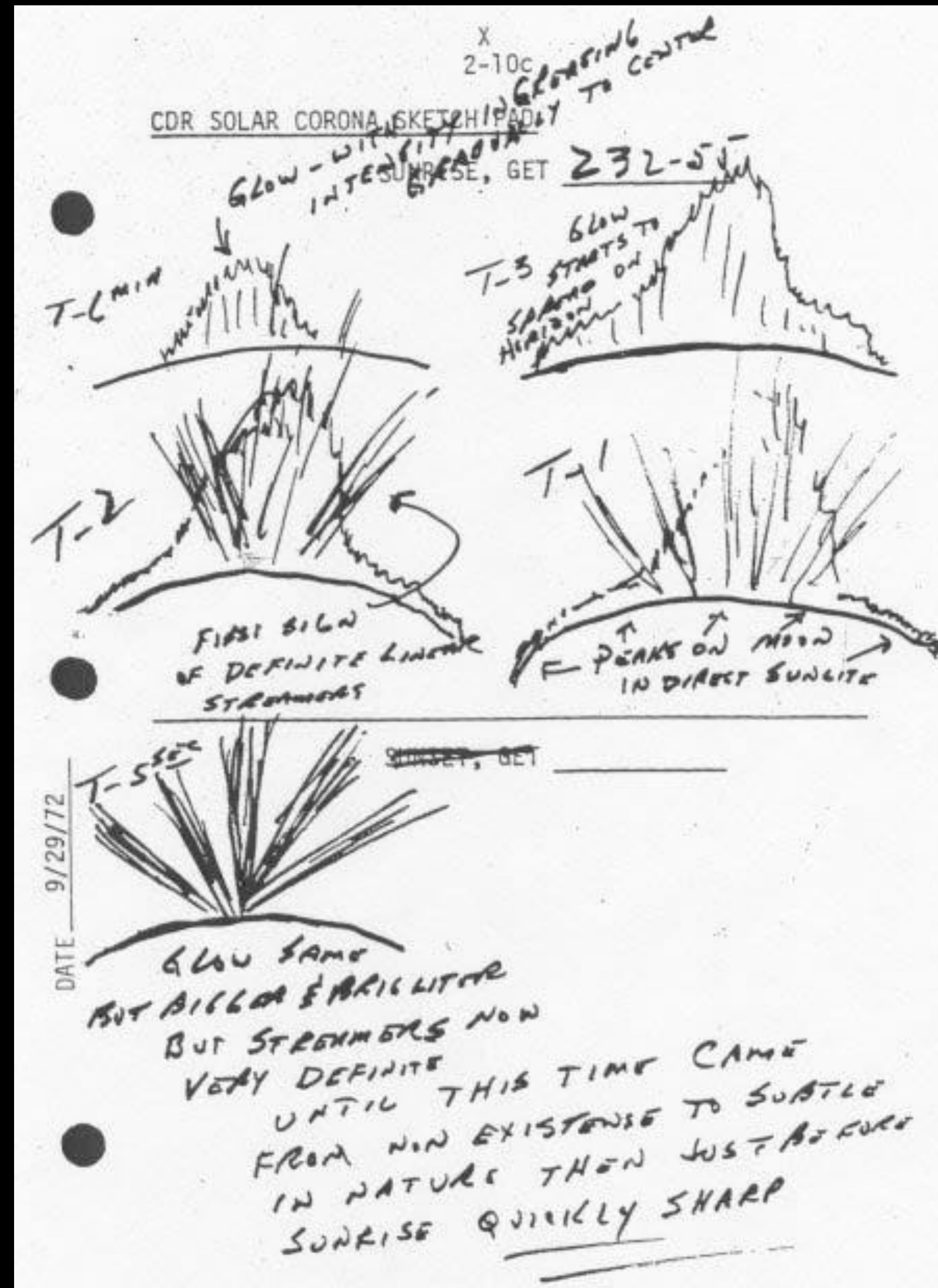
Sample Star Tracker Image – Orbit 193

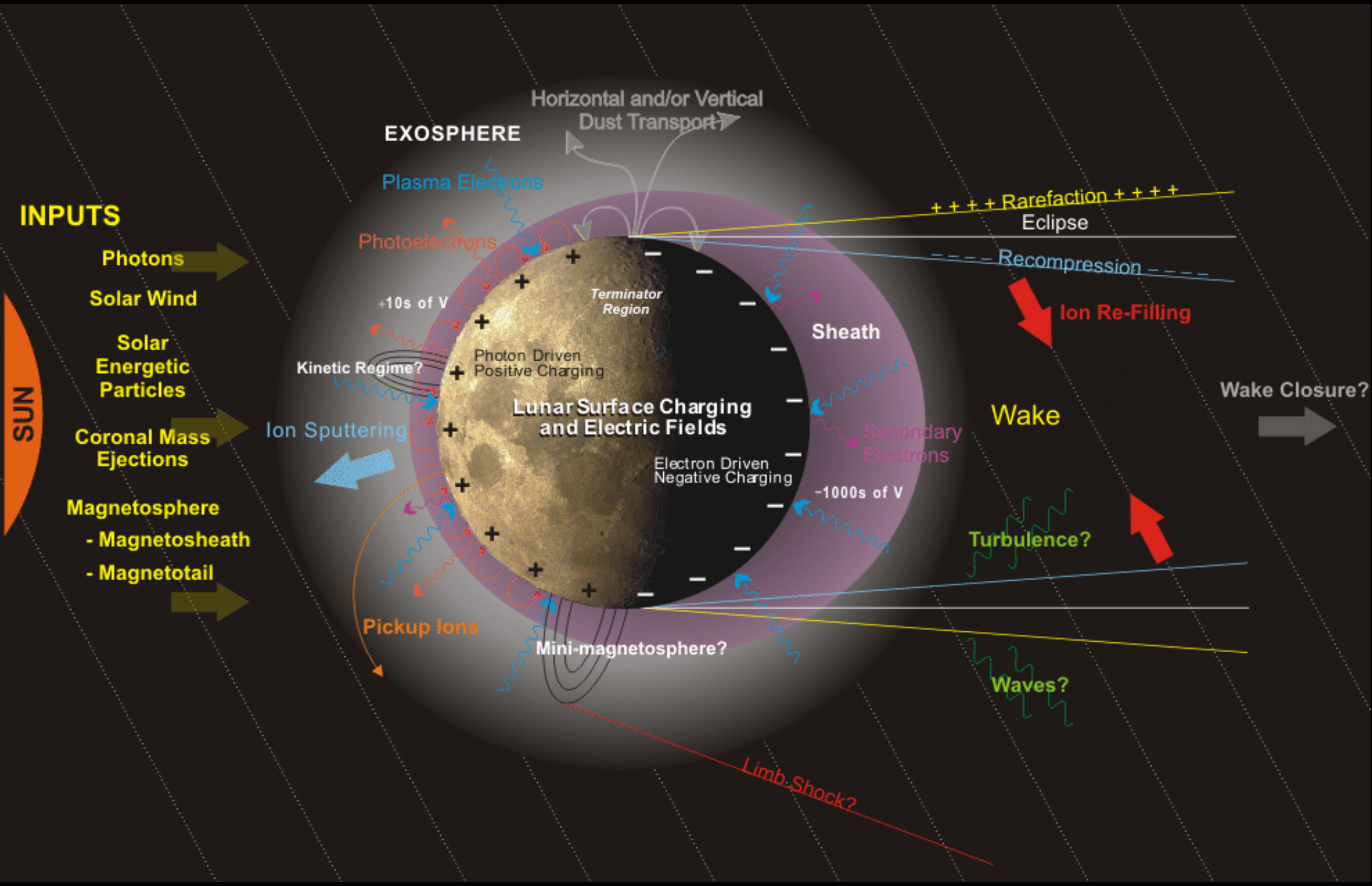



Surveyor 7: 1968-023T06:21:37

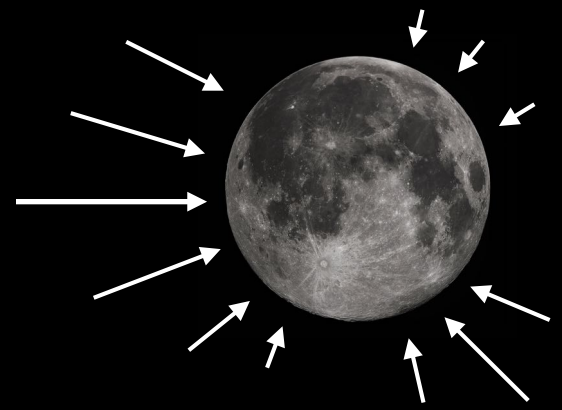

SUNLIGHT
N = 10-5
-100 km
LINE OF SIGHT
N = 10-2
-10 km
1 km
SUN
N = 5 × 10-1
TERMINATOR
APOLLO
SHADOW


NUMBER OF EVENTS
HOURS FROM SUNRISE
EAST SENSOR
UP SENSOR
WEST SENSOR
SUNSET
MIDNIGHT
SUNRISE
0
20
40
60
80
100
-480
-420
-360
-300
-240
-180
-120
-60
0
60
120

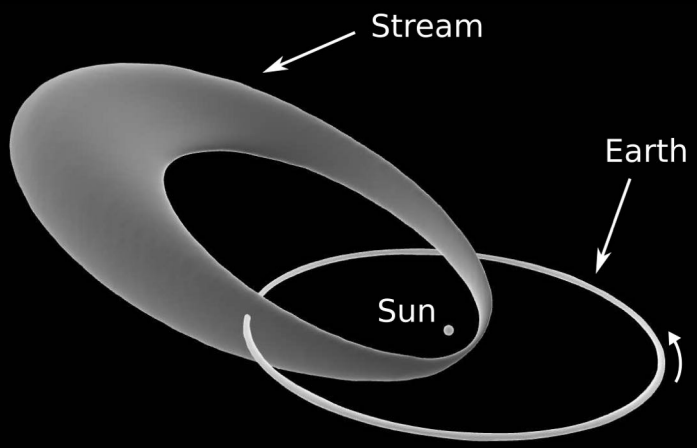

X
2-10c
CDR SOLAR CORONA SKETCH PAD
SUNRISE, GET 232-55
T-6 MIN
T-3 GLOW STARTS TO SPREAD ON HORIZON
T-2
FIRST SIGN OF DEFINITE LINEAR STREAMERS
T-1
PEAKS ON MOON IN DIRECT SUNLITE
T-5 SEC
SUNSET, GET
DATE 9/29/72
GLOW SAME BUT BIGGER & BRIGHTER BUT STREAMERS NOW VERY DEFINITE
UNTIL THIS TIME CAME FROM NON EXISTENSE TO SUBTLE IN NATURE THEN JUST BEFORE SUNRISE QUICKLY SHARP


INPUTS
Photons
Solar Wind
Solar Energetic Particles
Coronal Mass Ejections
Magnetosphere
- Magnetosheath
- Magnetotail
SUN
EXOSPHERE
Horizontal and/or Vertical Dust Transport
Plasma Electrons
Photoelectrons
+10s of V
Terminator Region
Sheath
Kinetic Regime?
Photon Driven Positive Charging
Lunar Surface Charging and Electric Fields
Ion Sputtering
Secondary Electrons
Electron Driven Negative Charging
-1000s of V
Pickup Ions
Mini-magnetosphere?
Limb Shock?
+ + + + Rarefaction + + + +
Eclipse
Recompression
Ion Re-Filling
Wake
Wake Closure?
Turbulence?
Waves?

Meteoroid Sources

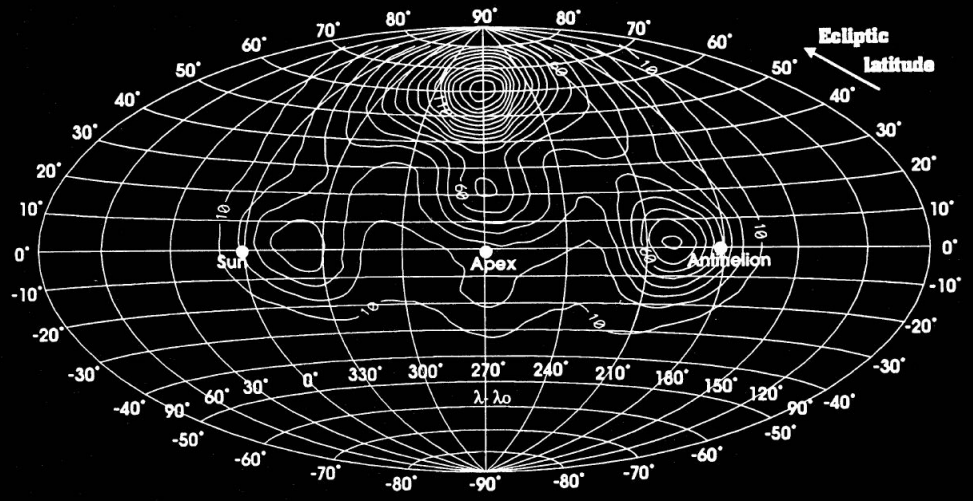


Meteor Showers



Barensten and Lefevre, 2006

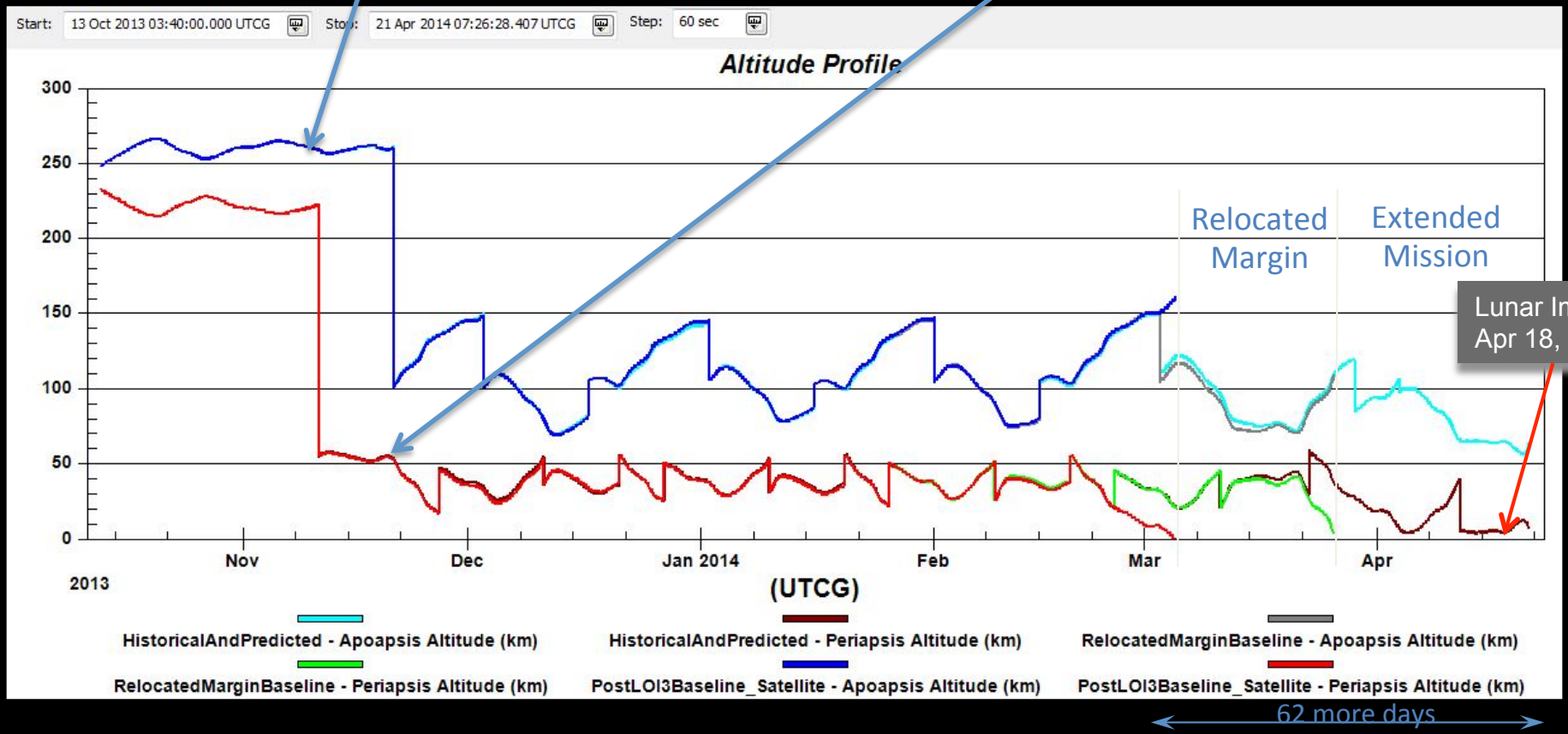
Sporadic Meteoroids



Jones and Brown, 1993

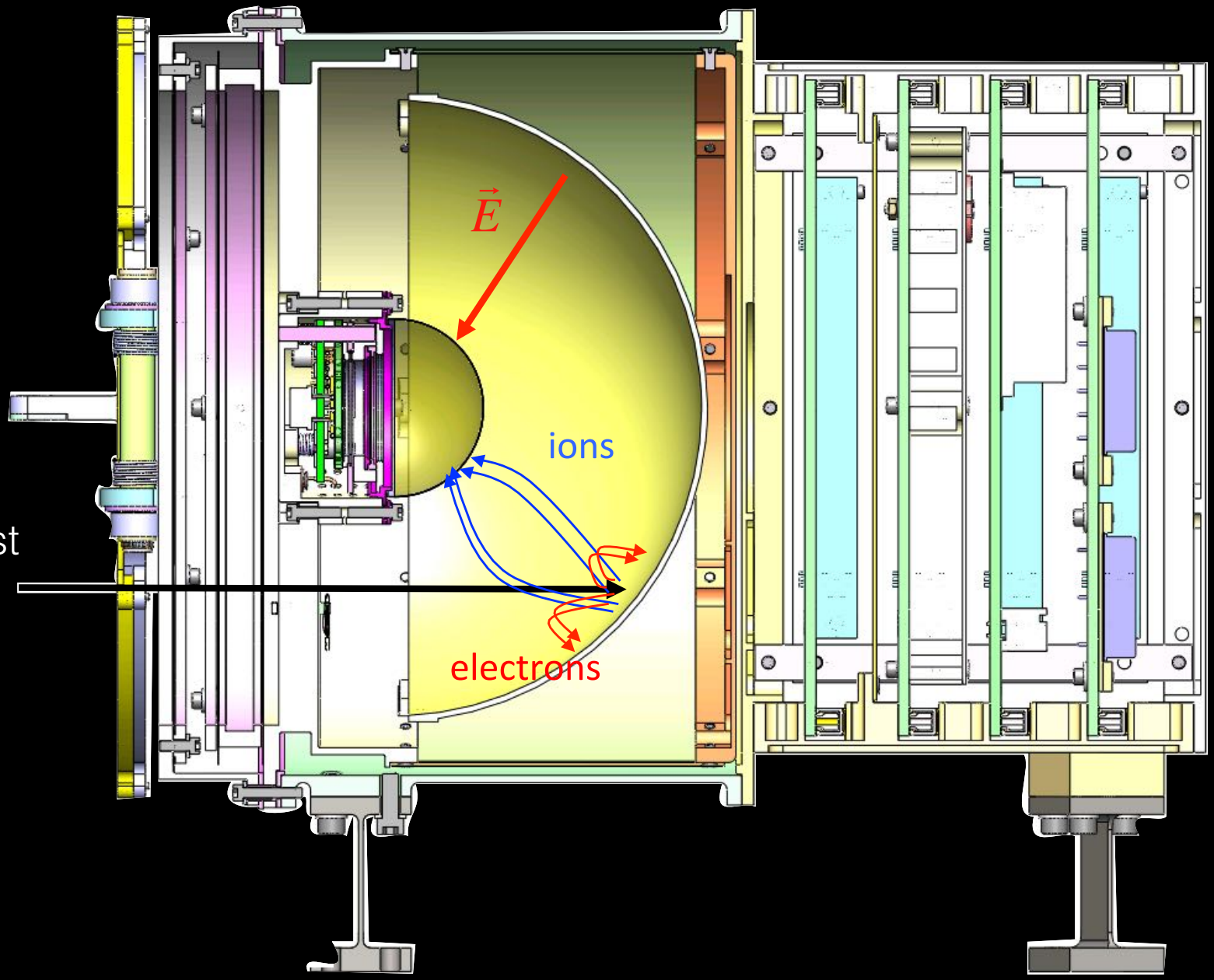
LADEE's Science Orbit

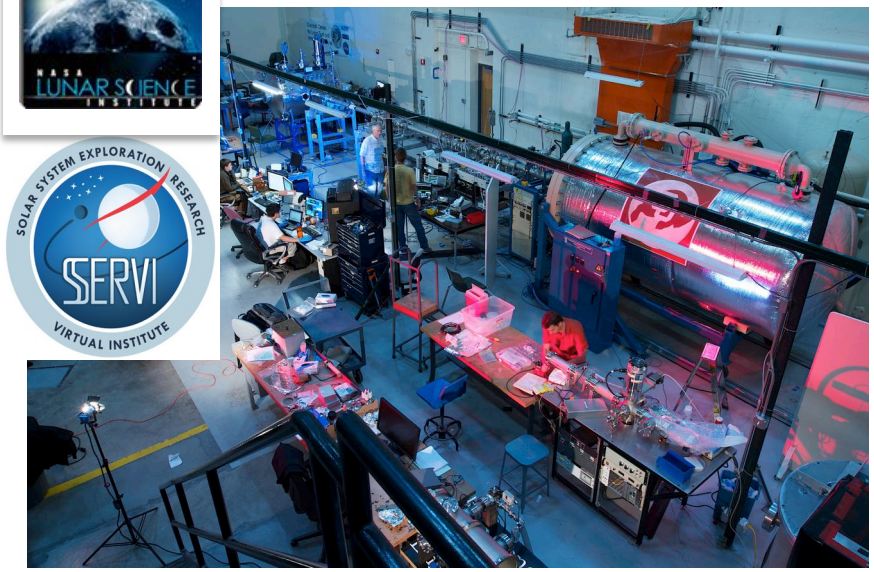
- Maneuvers have been very accurate – no corrections needed
- Result: Good delta-V margins!

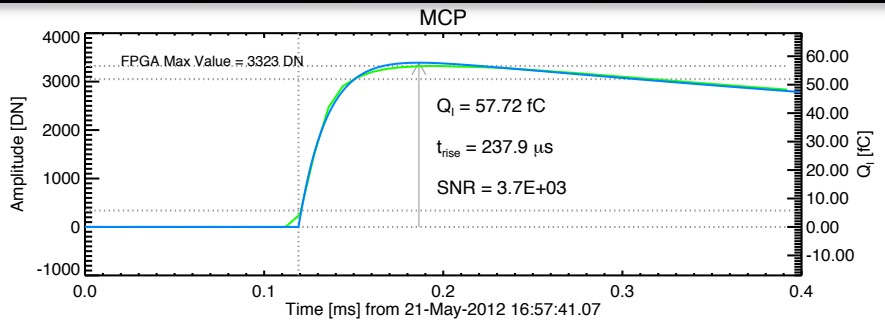


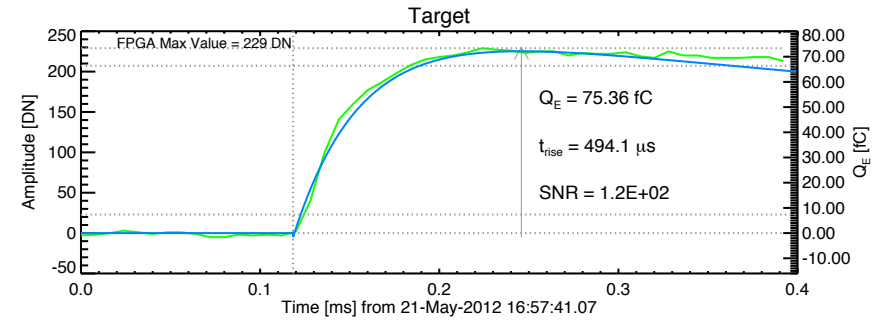
NASA Ames Research Center
NASA Goddard Space Flight Center

LDEX






MCP
FPGA Max Value = 3323 DN
Q_I = 57.72 fC
t_{rise} = 237.9 µs
SNR = 3.7E+03
Amplitude [DN]
Q_I [fC]
Time [ms] from 21-May-2012 16:57:41.07


Target
FPGA Max Value = 229 DN
Q_E = 75.36 fC
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SNR = 1.2E+02
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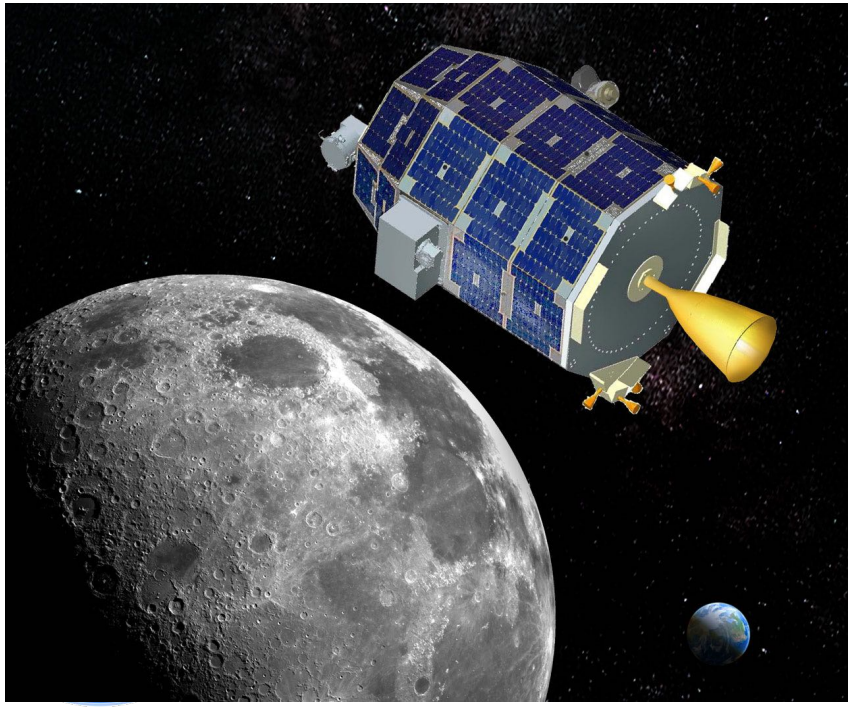
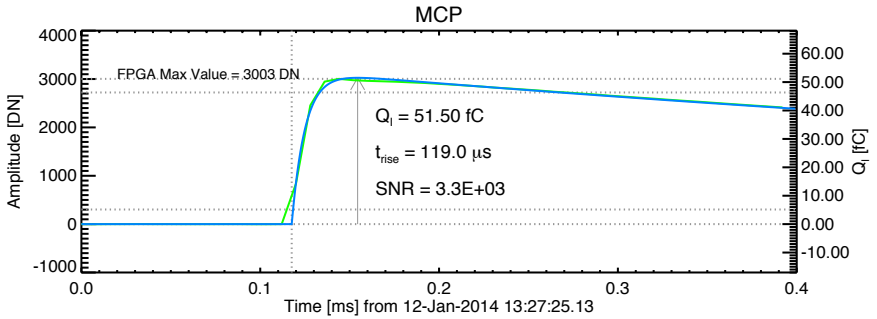
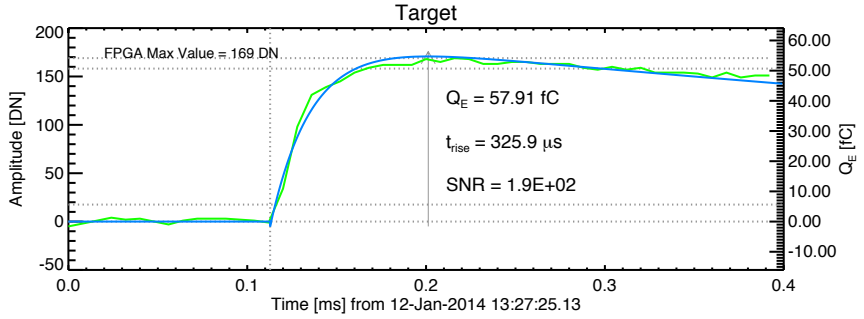
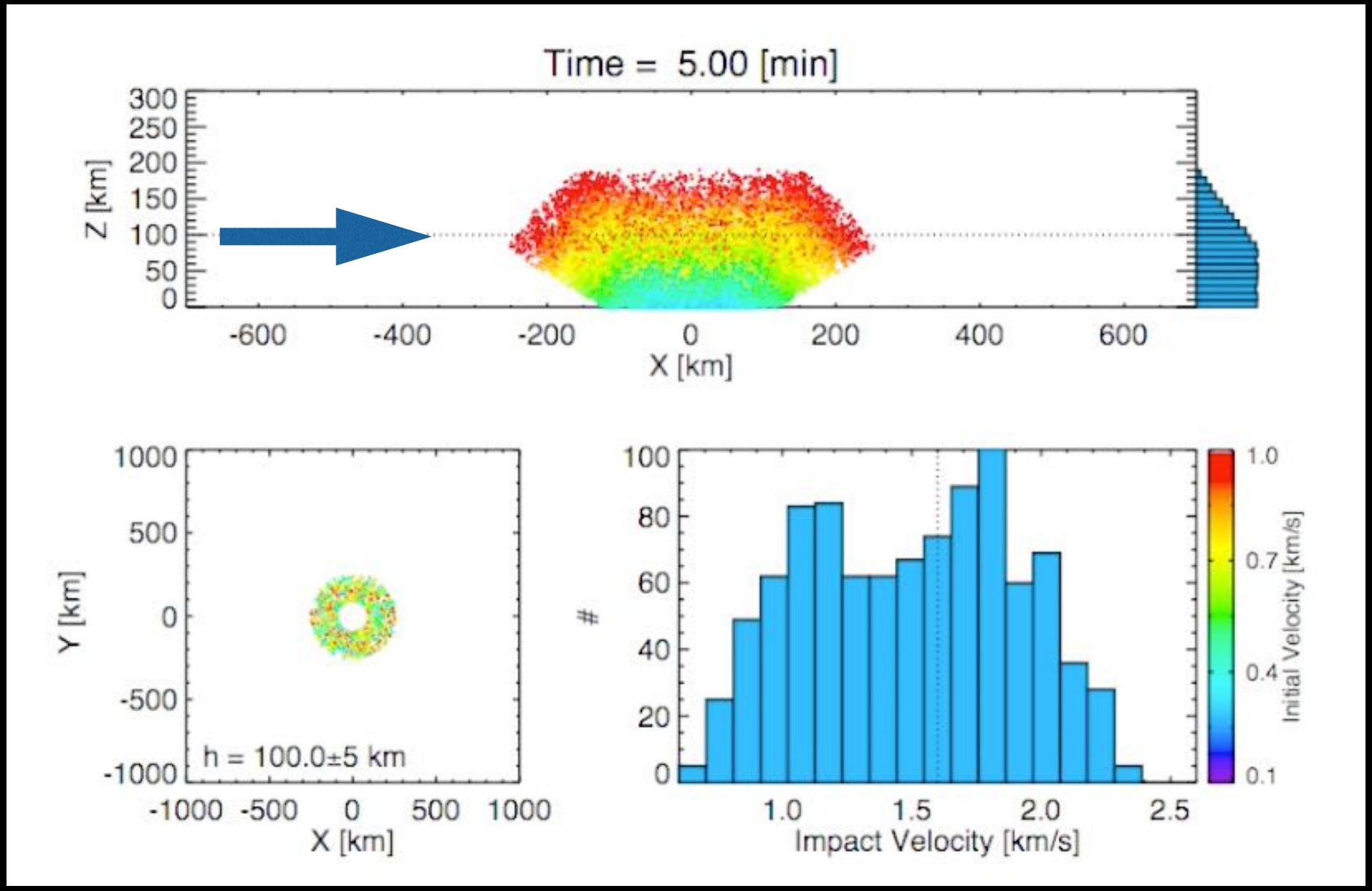
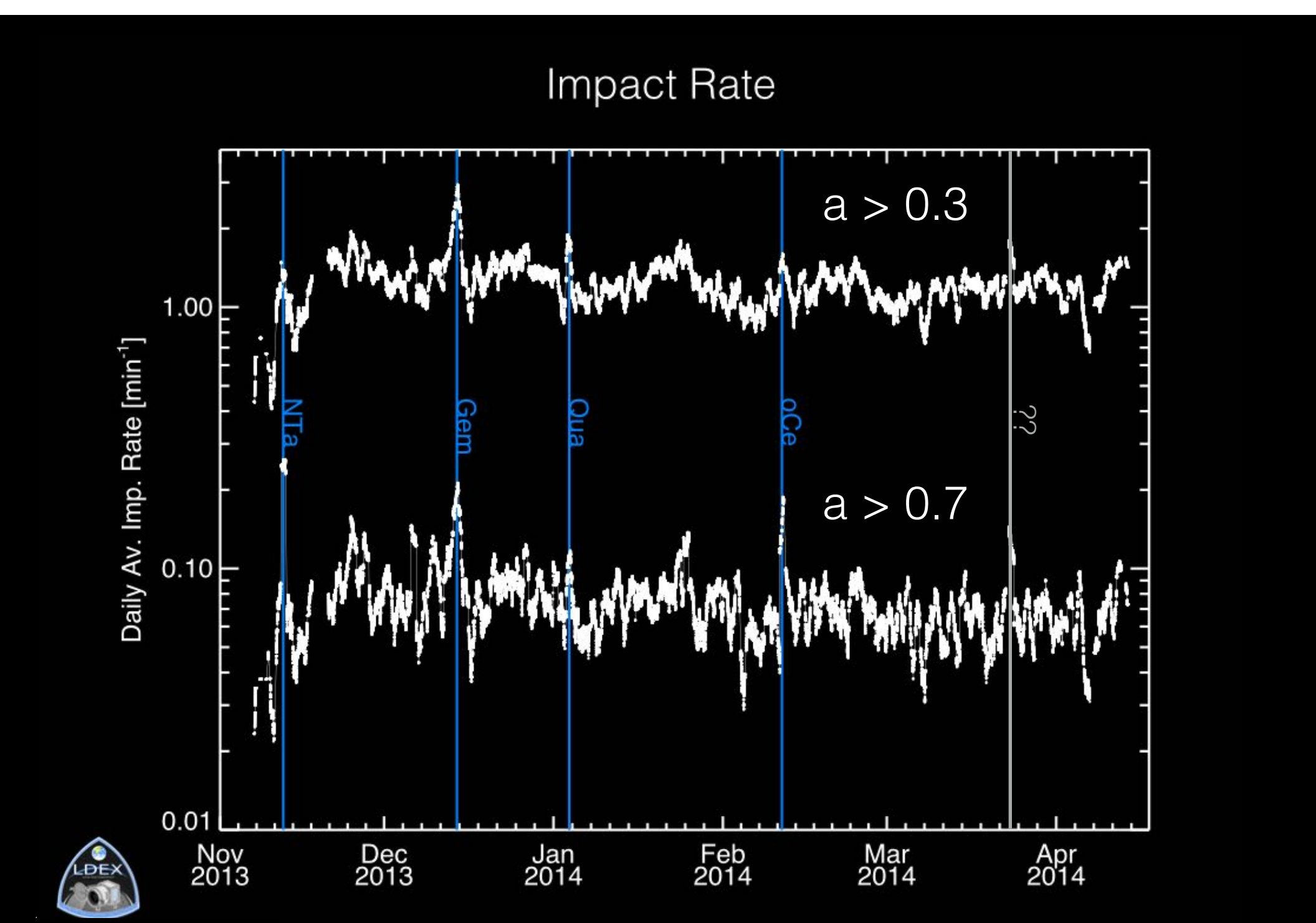



MCP
FPGA Max Value = 3003 DN
Q_I = 51.50 fC
t_{rise} = 119.0 µs
SNR = 3.3E+03
Amplitude [DN]
Q_I [fC]
Time [ms] from 12-Jan-2014 13:27:25.13

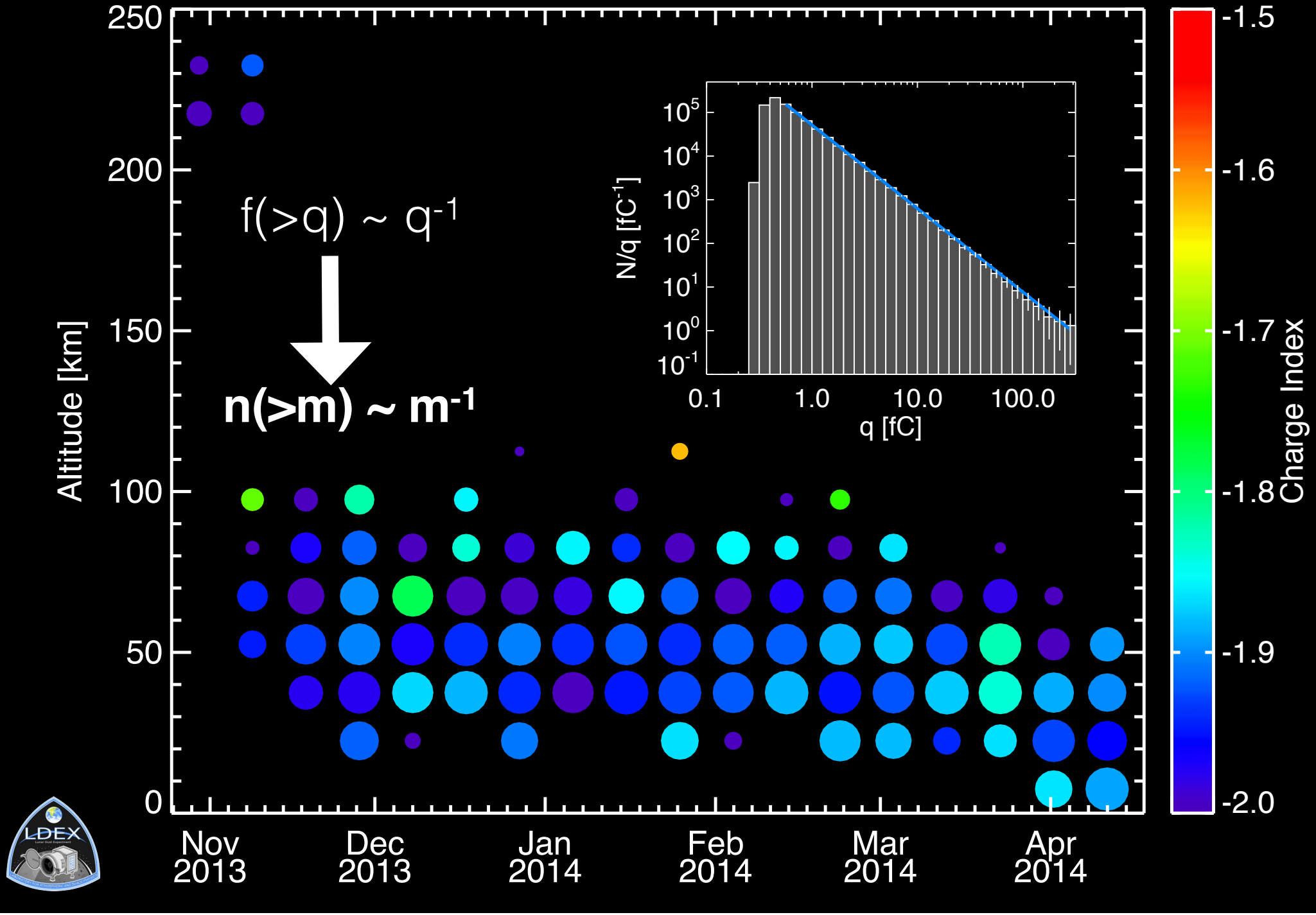

Target
FPGA Max Value = 169 DN
Q_E = 57.91 fC
t_{rise} = 325.9 µs
SNR = 1.9E+02
Amplitude [DN]
Q_E [fC]
Time [ms] from 12-Jan-2014 13:27:25.13


Time = 5.00 [min]
Z [km]
300
250
200
150
100
50
0
-600
-400
-200
0
200
400
600
X [km]
Y [km]
1000
500
0
-500
-1000
h = 100.0±5 km
-1000 -500 0 500 1000
X [km]
#
100
80
60
40
20
0
1.0
1.5
2.0
2.5
Impact Velocity [km/s]
1.0
0.7
0.4
0.1
Initial Velocity [km/s]

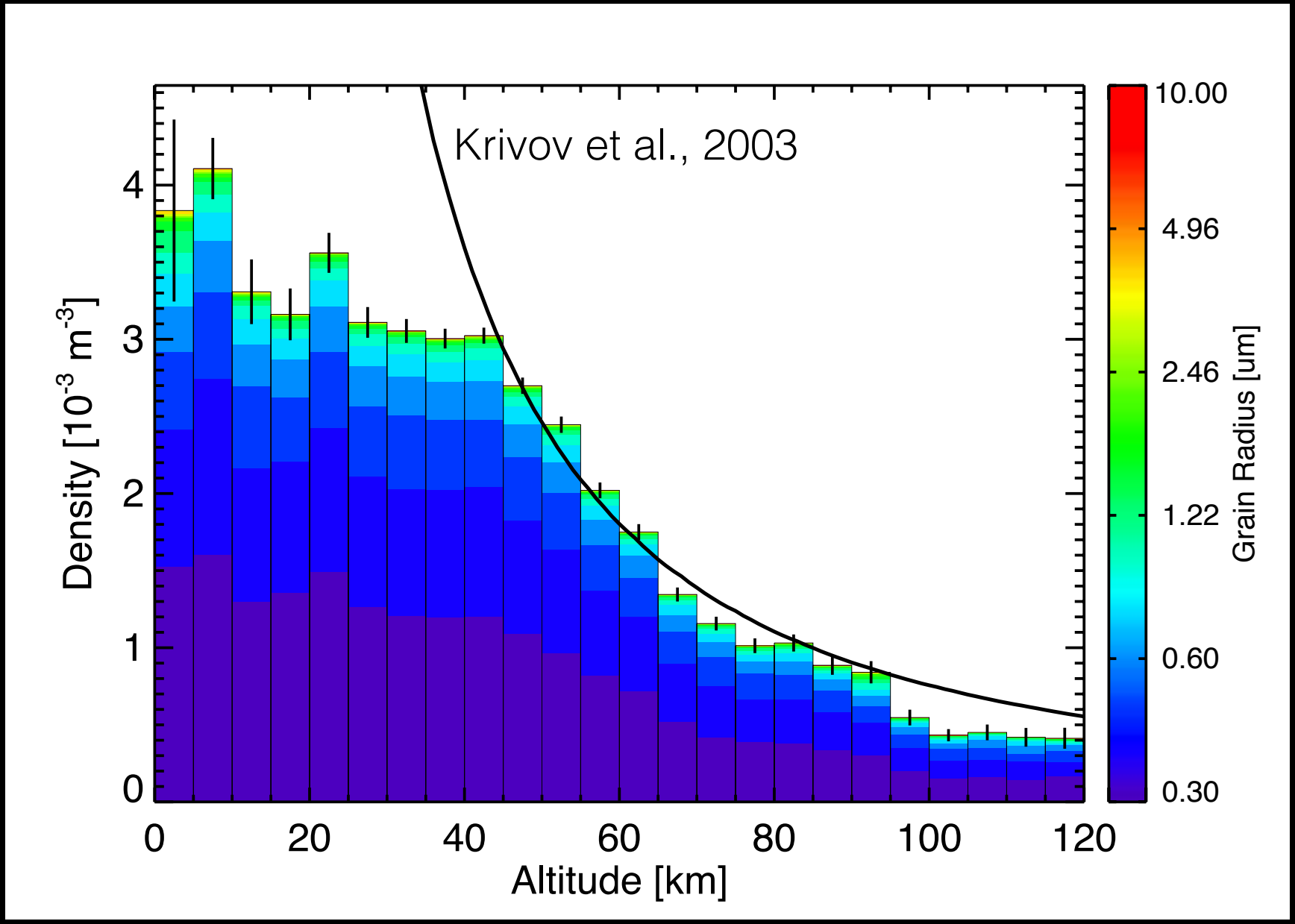


Northern Taurids (NTa); Geminids (Gem); Quadrantids (Qua); Omicron Centaurids (oCe)

Slope of Impact Charge Distribution vs. Time & Altitude



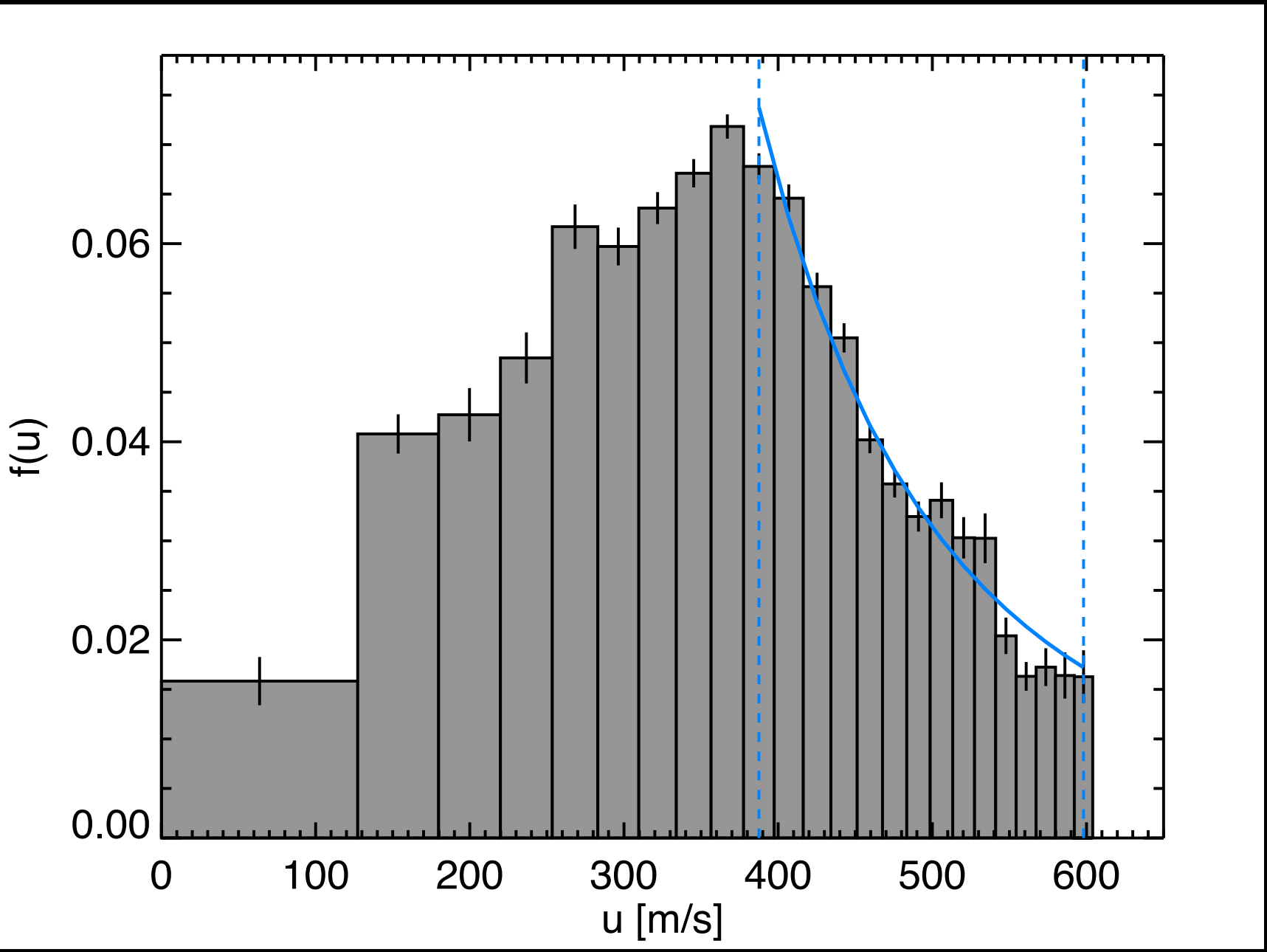
DENSITY


Krivov et al., 2003
Density [10^-3 m^-3]
0
1
2
3
4
0
20
40
60
80
100
120
Altitude [km]
10.00
4.96
2.46
1.22
0.60
0.30
Grain Radius [um]

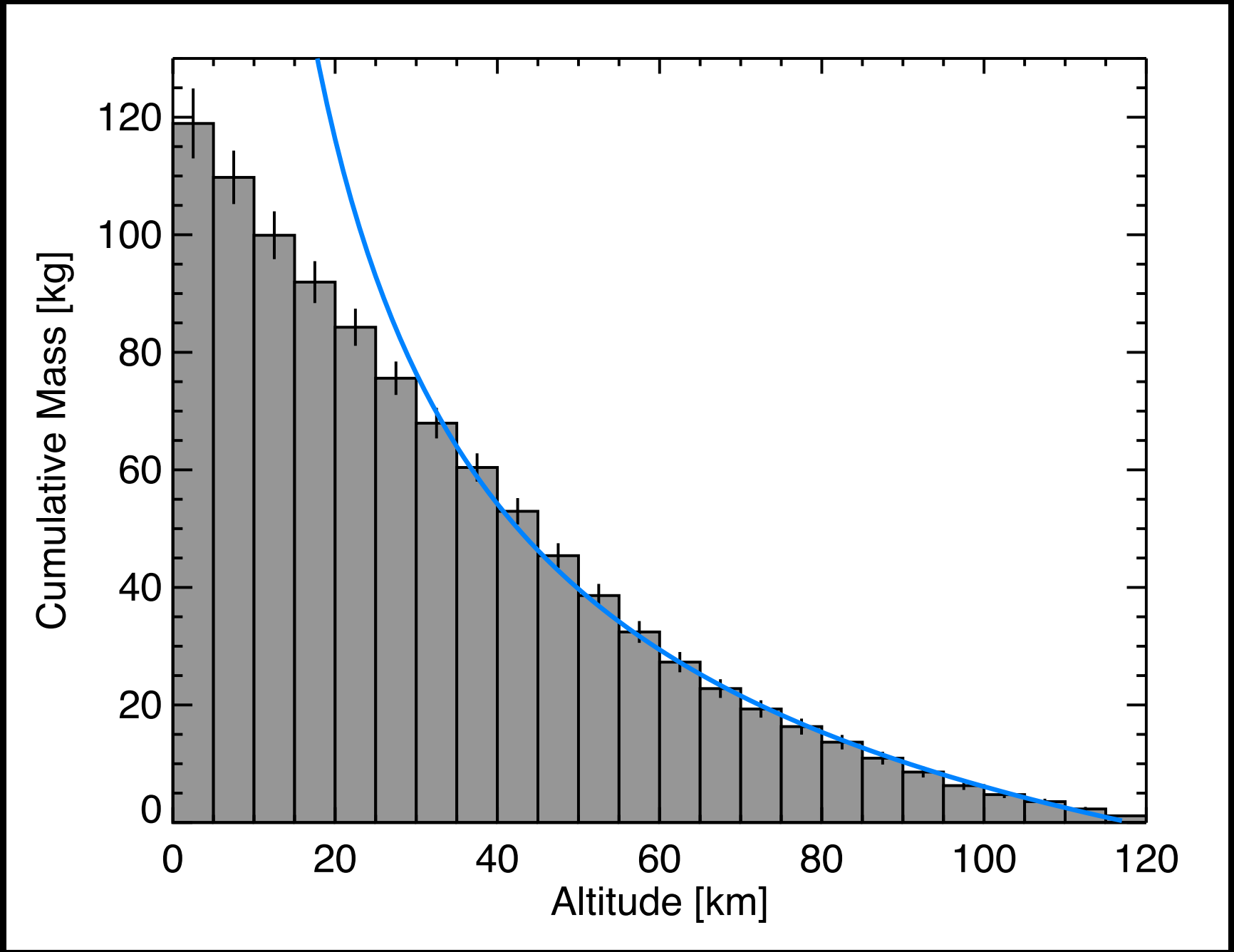
Parameter	Definition	Value
mass distribution	$N^+(>m) \propto m^{-\alpha}$	$\alpha = 0.91 \pm 0.003$
smallest mass*	m_{min}	$3 \cdot 10^{-16}$ kg
largest mass**	m_{max}	10^{-8} kg
speed distribution	$f_u(u) \propto u^{-\mu}$	$\mu = 3.4 \pm 0.1$
minimum speed	u_0	130 m/s
maximum speed	$u_{max} = 2 \cdot v_{escape}$	4.8 km/s
impactor speed	v_{imp}	20 km/s
ratio of ejecta/impactor kinetic energy	K_e/K_i	20%
ratio of ejecta/impactor mass	Y	1000
initial velocity maximum cone angle	ψ_0	30°

*radius $a_{min} = 0.3$ μm; **$a_{max} = 100$ μm

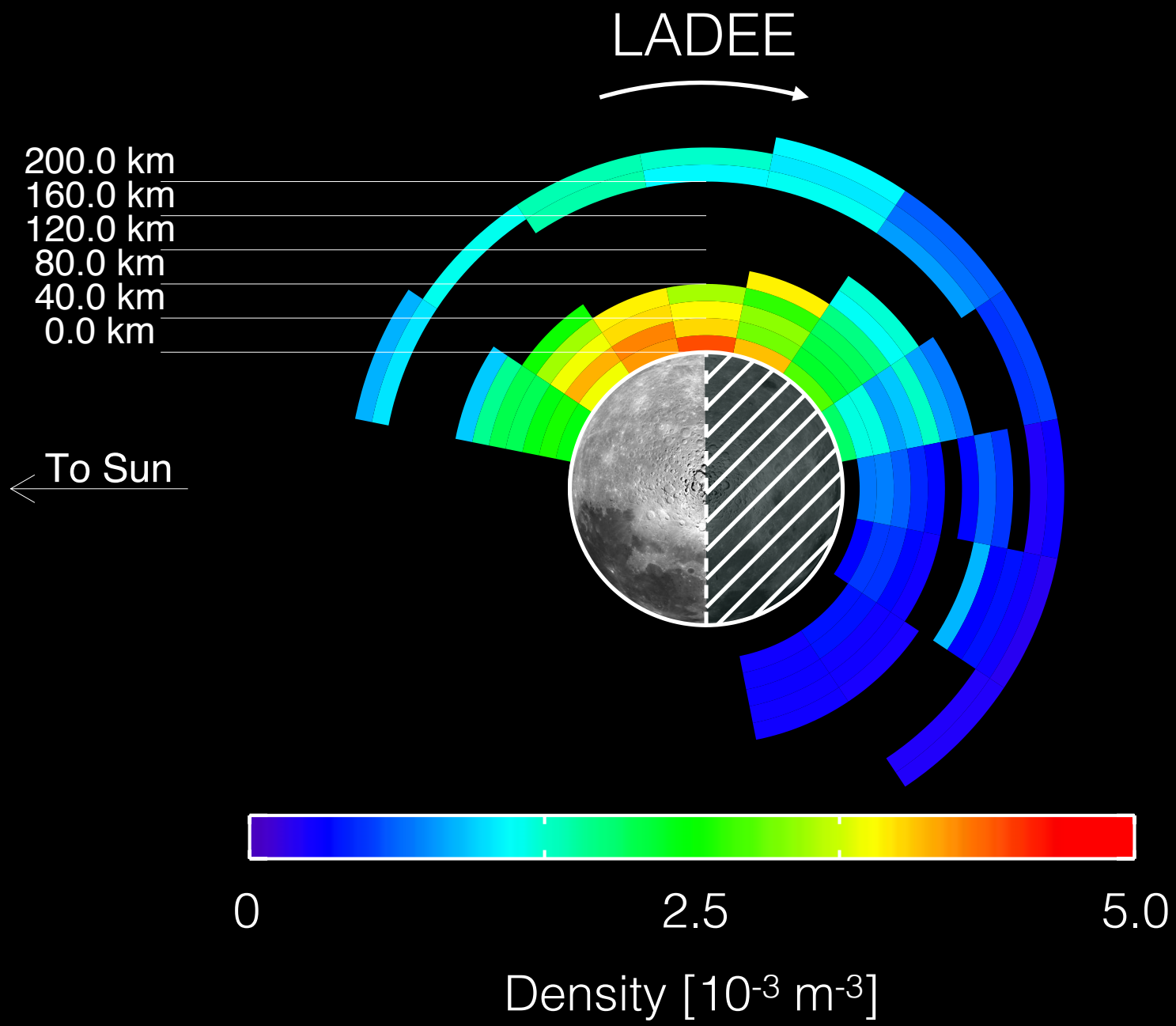
INITIAL SPEED

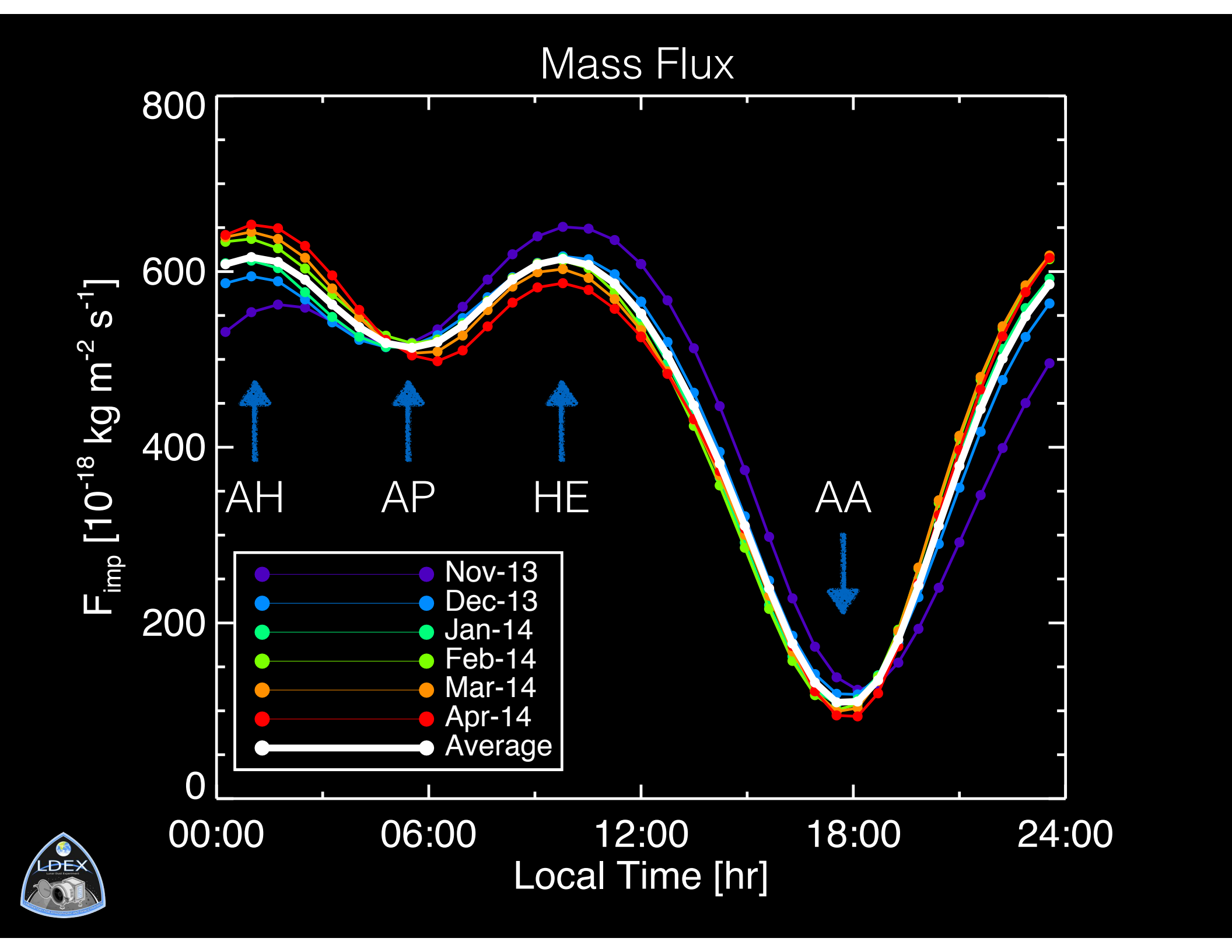


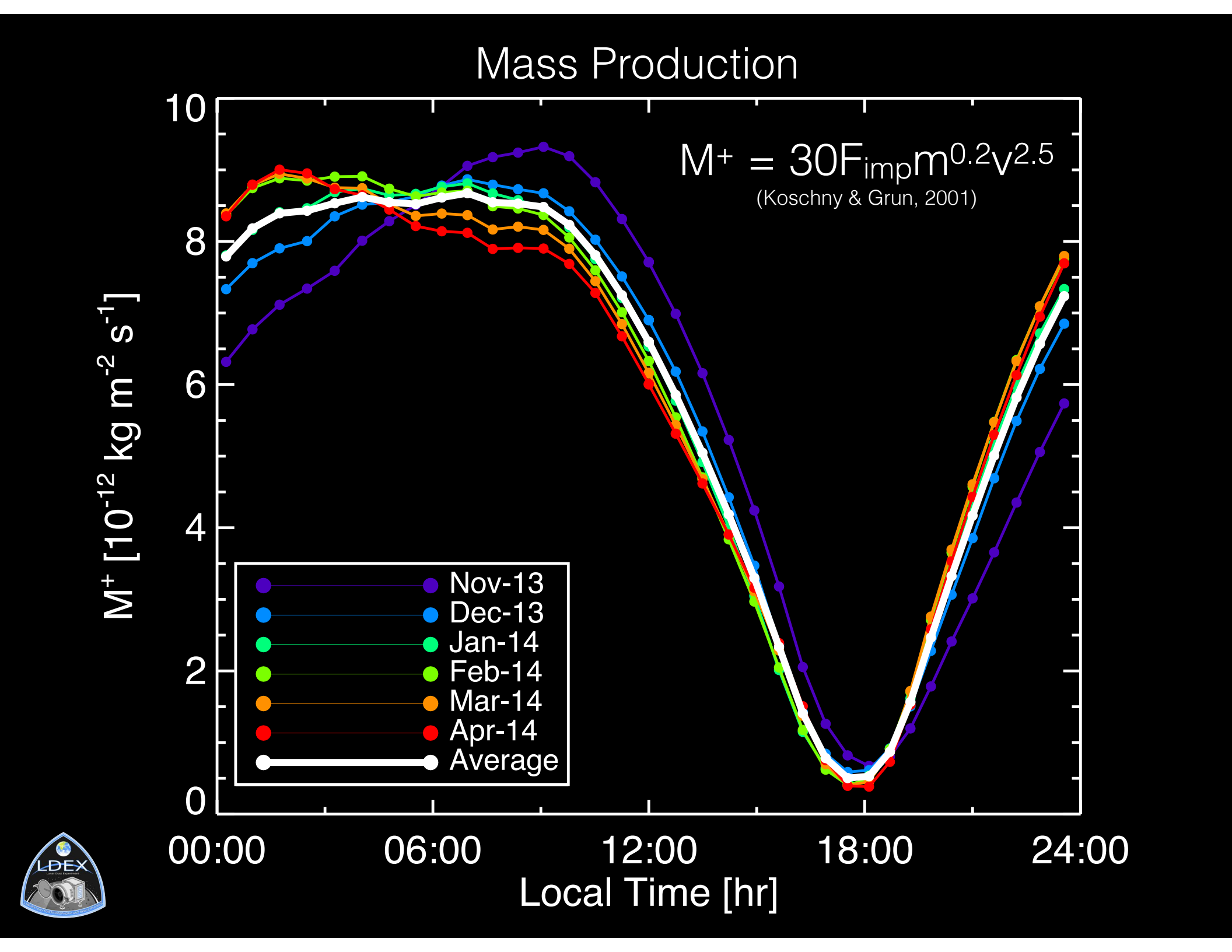
MASS

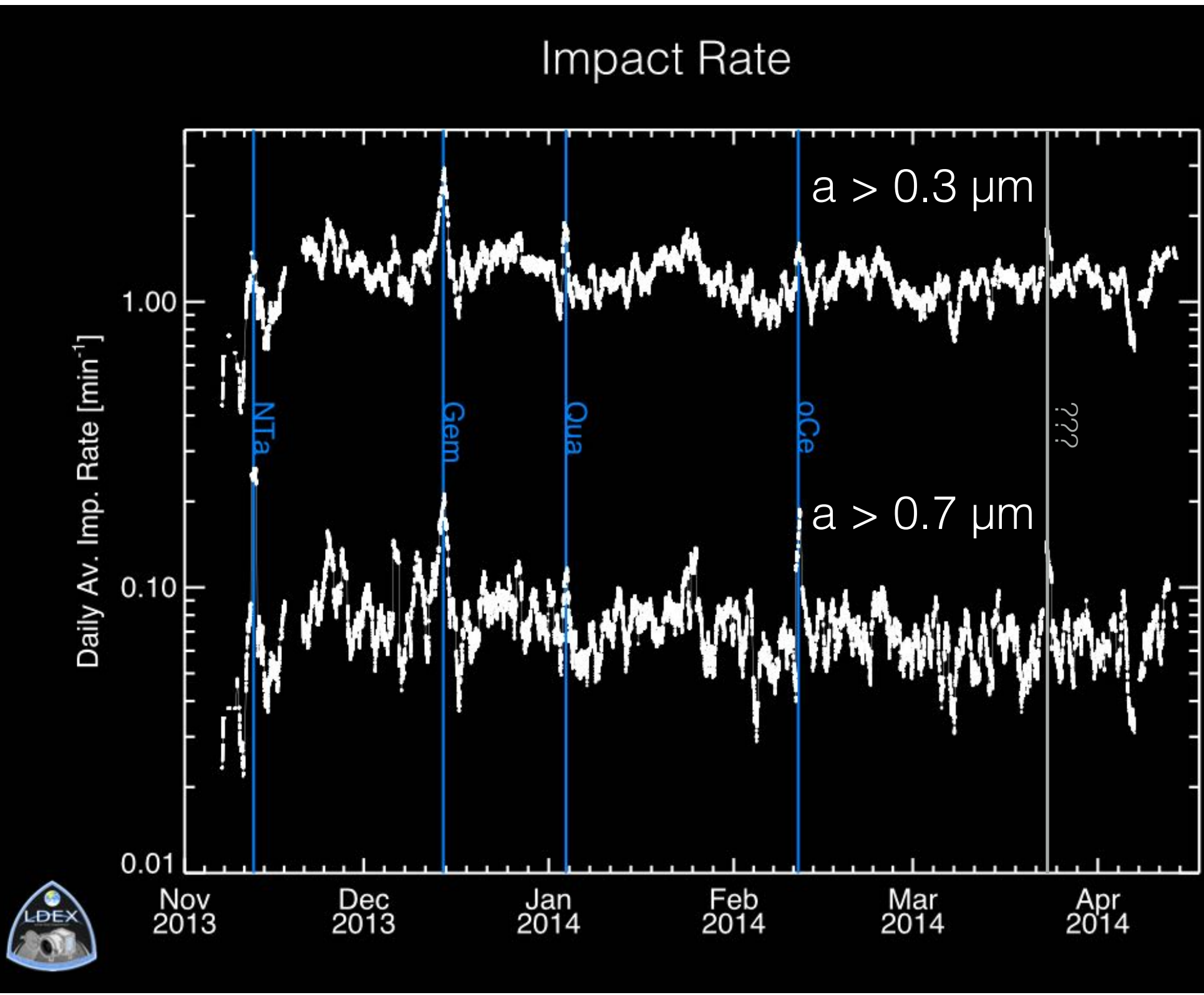

Cumulative Mass [kg]
0
20
40
60
80
100
120
Altitude [km]
0
20
40
60
80
100
120

Density (a > 0.3 μm)



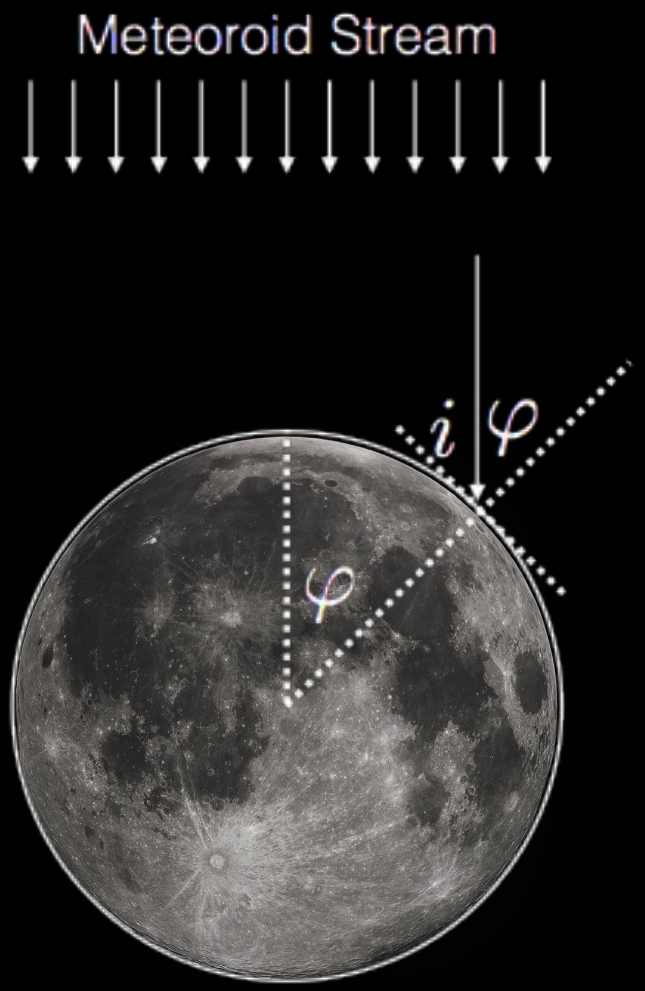

Mass Flux
800
600
400
200
0
F_{imp} [10^{-18} kg m^{-2} s^{-1}]
AH
AP
HE
AA
Nov-13
Dec-13
Jan-14
Feb-14
Mar-14
Apr-14
Average
00:00
06:00
12:00
18:00
24:00
Local Time [hr]
LDEX


Mass Production
$M^+ = 30F_{imp}m^{0.2}v^{2.5}$
(Koschny & Grun, 2001)
M^+ [10^{-12} kg m^{-2} s^{-1}]
10
8
6
4
2
0
Nov-13
Dec-13
Jan-14
Feb-14
Mar-14
Apr-14
Average
00:00
06:00
12:00
18:00
24:00
Local Time [hr]
LDEX

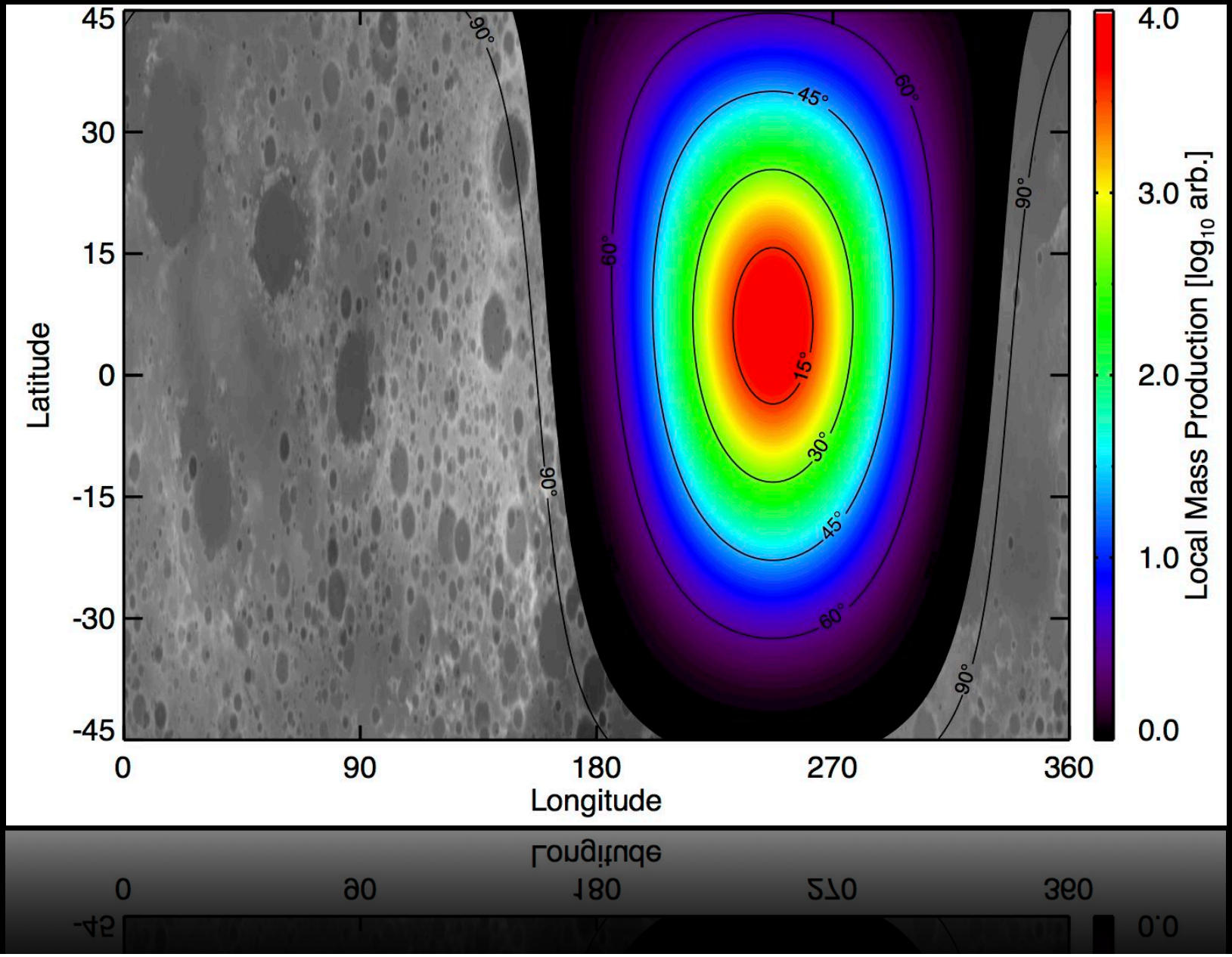

Impact Rate
a > 0.3 μm
a > 0.7 μm
Daily Av. Imp. Rate [min-1]
1.00
0.10
0.01
NTa
Gem
Qua
oCe
¿¿¿
Nov 2013
Dec 2013
Jan 2014
Feb 2014
Mar 2014
Apr 2014
LDEX

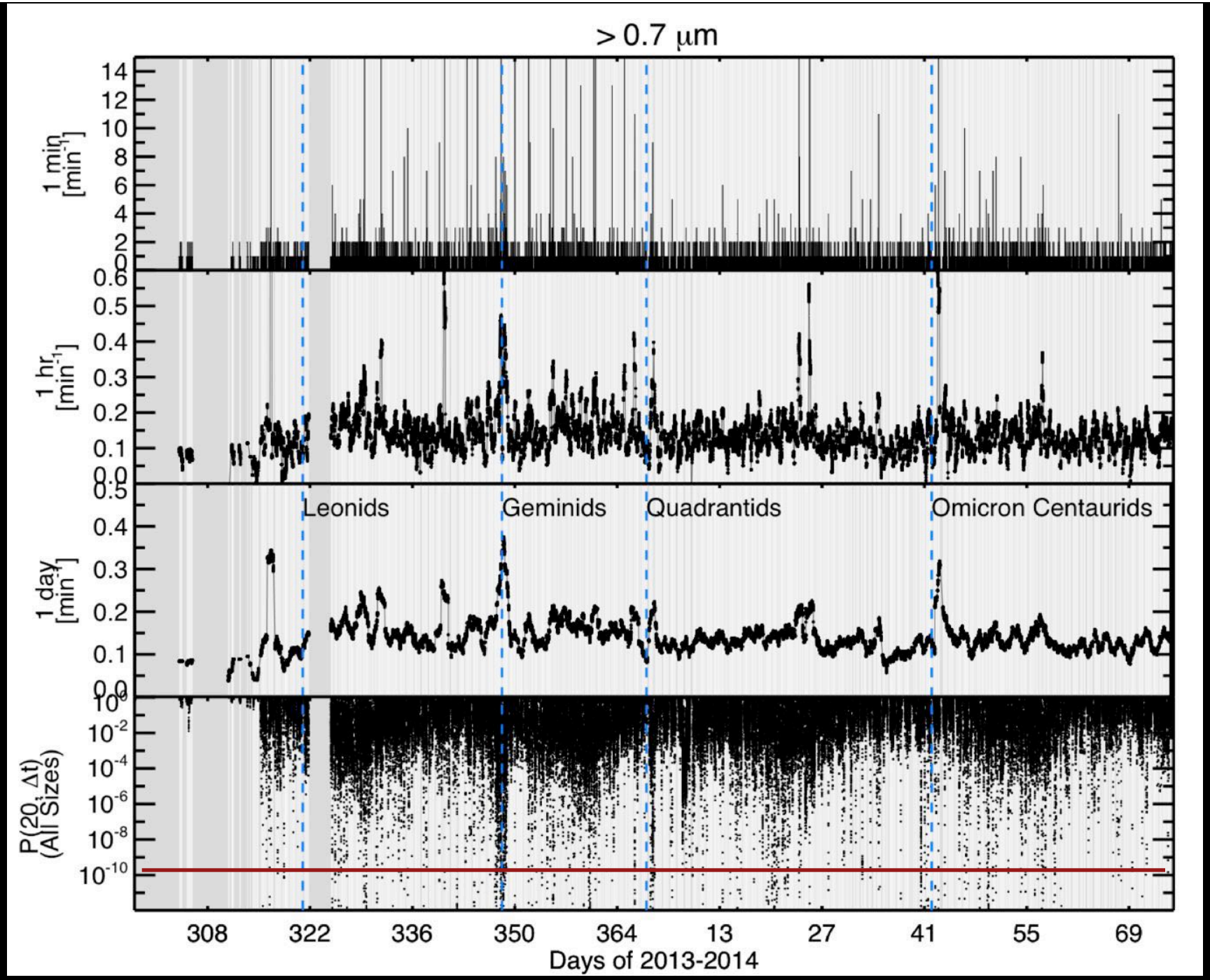
Lunar Angular Response

$$M^{+}(\vec{r}, \vec{F}, v, \varphi) \propto \cos^{3} \varphi$$



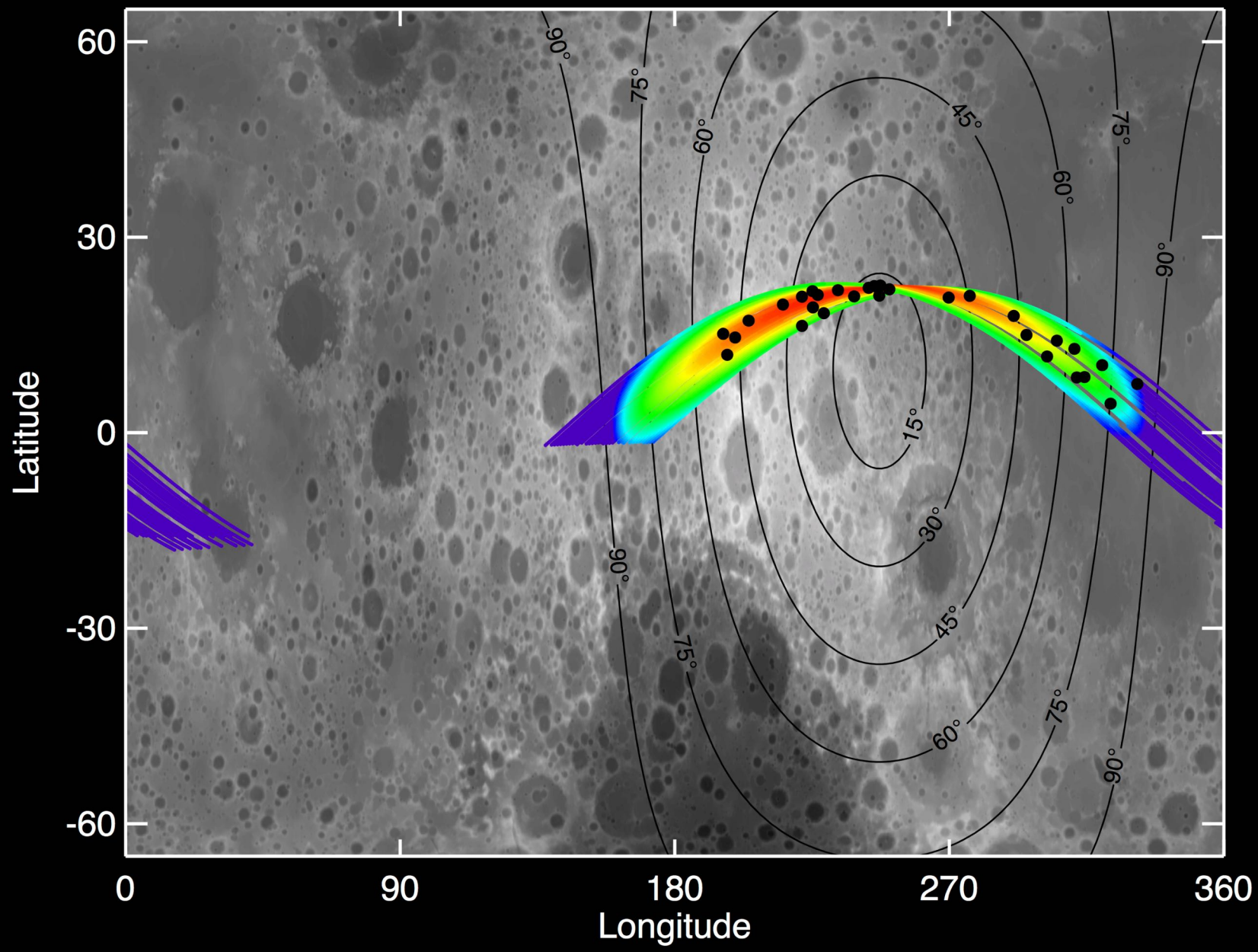
Geminids Mass Production





$$P(n,T) = 1 - e^{-\mu T} \sum_{\ell=0}^{n-1} \frac{\mu T}{\ell!}$$

Geminids Trajectory Overlay



Searching for small lofted dust

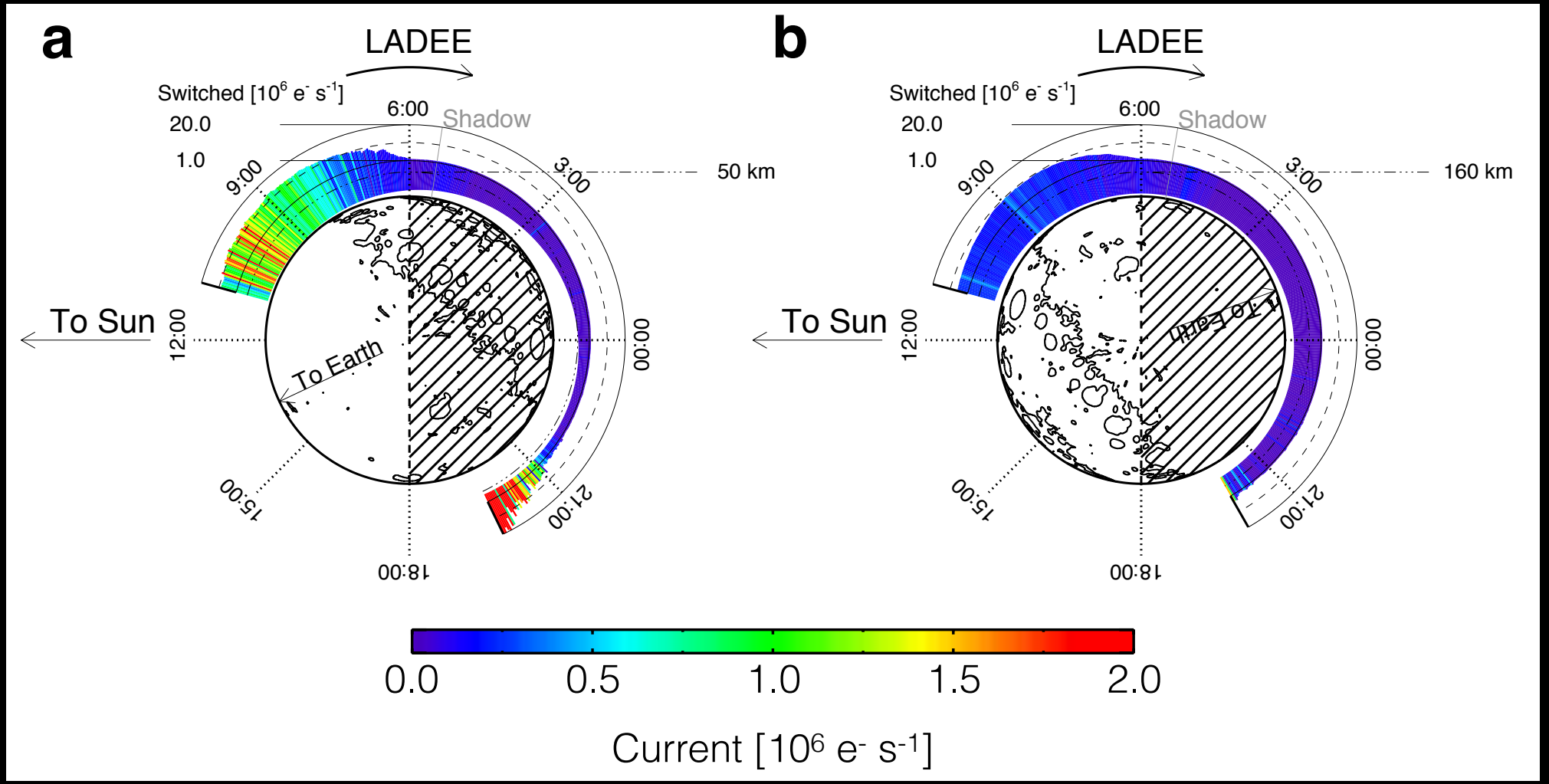
Current Definitions

Current	Definition
J_N	Nominal current, taken 9 of every 10 seconds
J_S	Switched current, taken 1 of every 10 seconds
J_D	Dust current, desired science quantity
J_ν	Photoelectron current
J_H	High energy ion current
J_L	Low energy ion current
J	Residual, low energy current

$$J_N = J_D + J_\nu + J_H + J_L$$

$$J_S = J_\nu + J_H$$

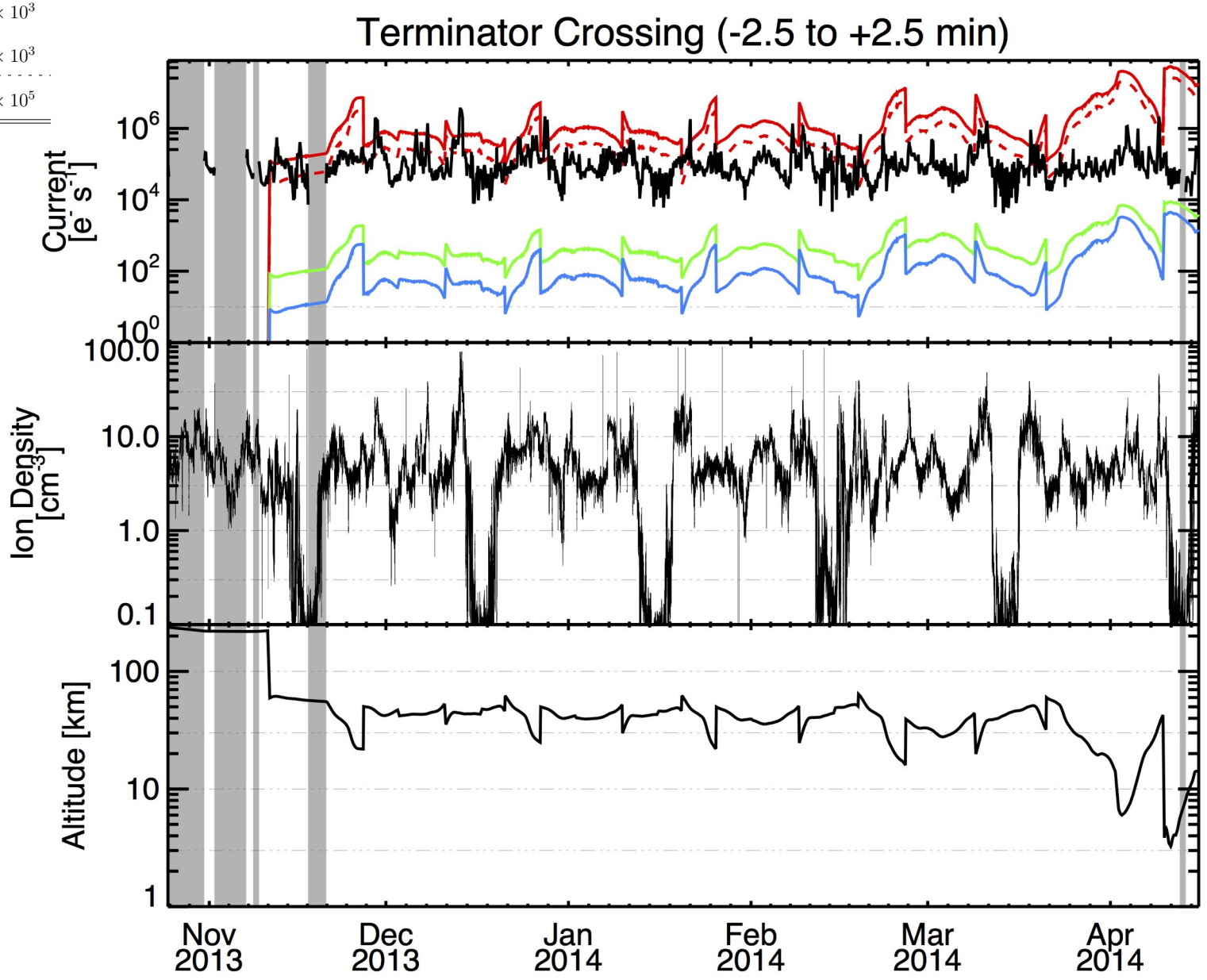
$$J = J_N - J_S = J_D + J_L$$


a
LADEE
Switched [10^6 e^- s^-1]
20.0
1.0
6:00
Shadow
9:00
3:00
50 km
To Sun
12:00
00:00
To Earth
15:00
21:00
18:00
b
LADEE
Switched [10^6 e^- s^-1]
20.0
1.0
6:00
Shadow
9:00
3:00
160 km
To Sun
12:00
00:00
To Earth
15:00
21:00
18:00
0.0
0.5
1.0
1.5
2.0
Current [10^6 e^- s^-1]

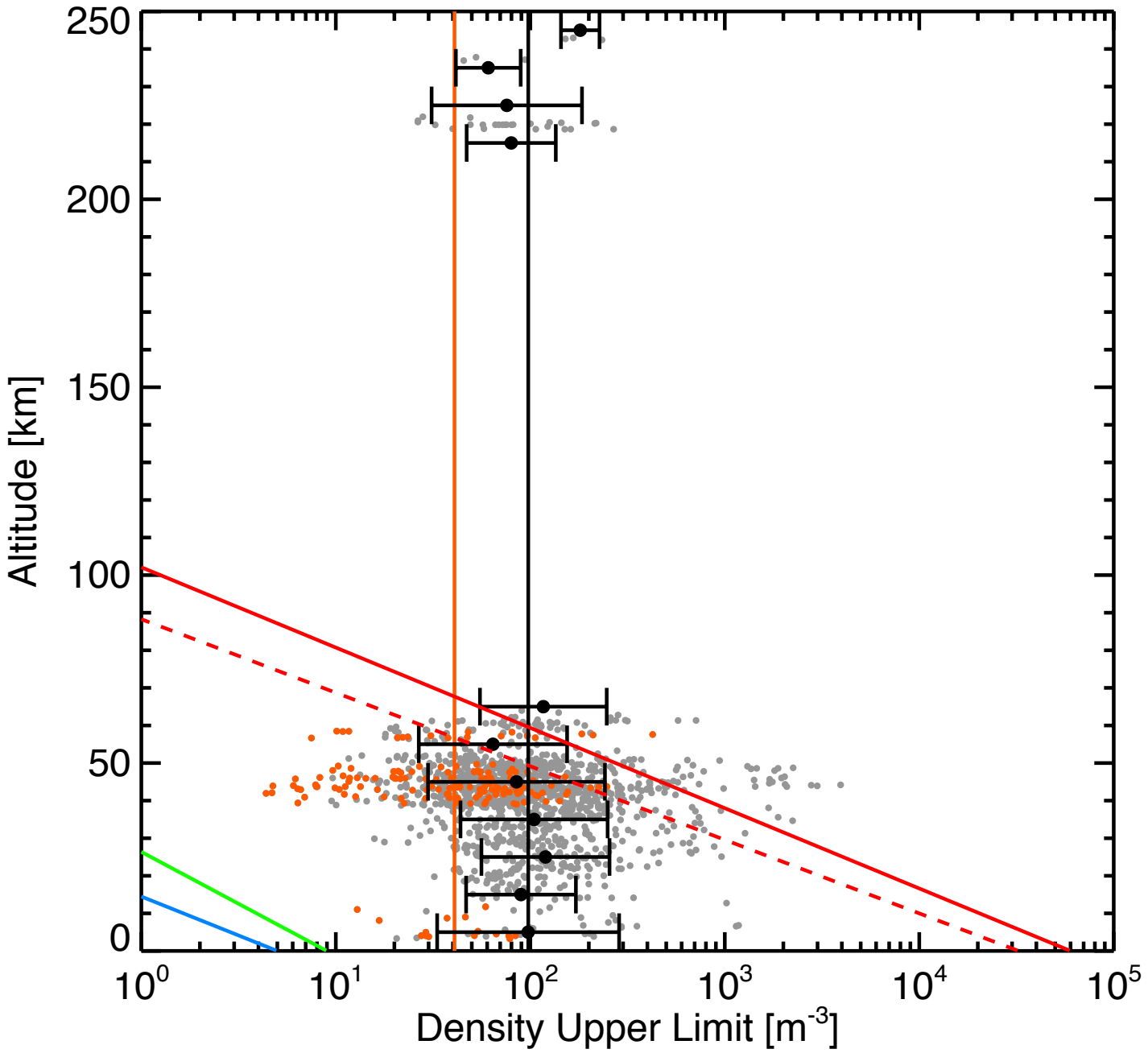
Source	n_0	z_0	h	J(3 km)
	[m^{-3}]	[km]	[km]	[e^-s^{-1}]
McCoy [1976]	6×10^4	9.28	0	6×10^7
Glenar et al. [2011]	1×10^4	8.50	10	3×10^7
Glenar et al. [2014]	9	12.00	0	9×10^3
Feldman et al. [2014]	5	9.00	0	5×10^3
LADEE/LDEX				1×10^5

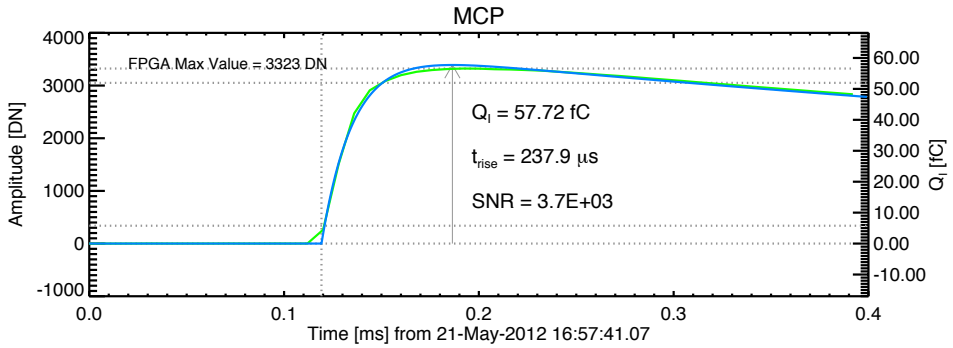
Clementine

LRO



Much smaller than expected density …. independent of altitude!

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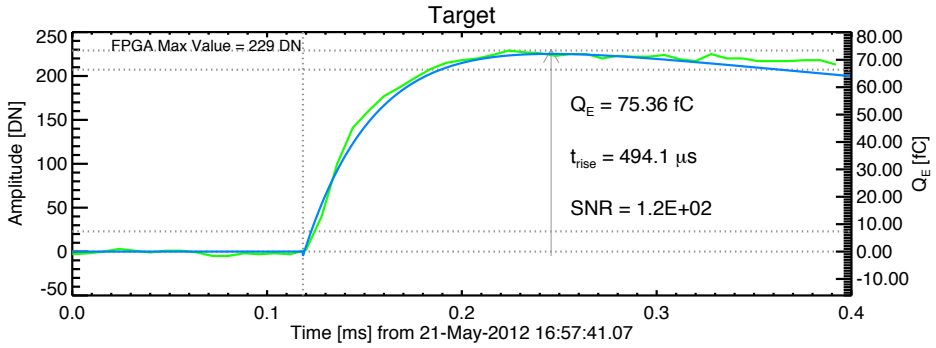
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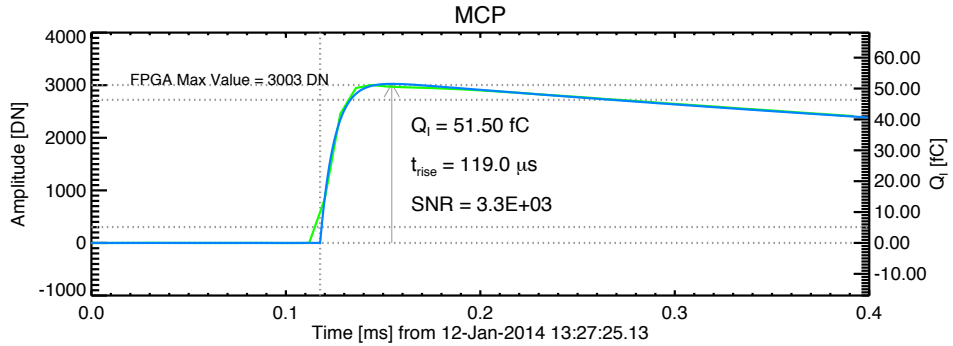
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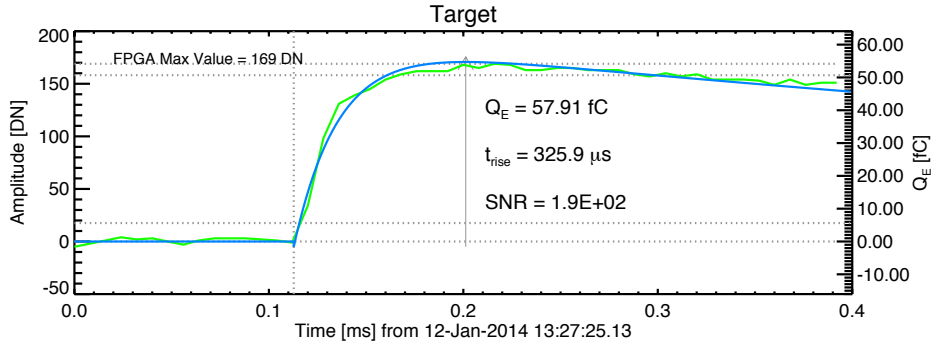
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SNR = 1.9E+02
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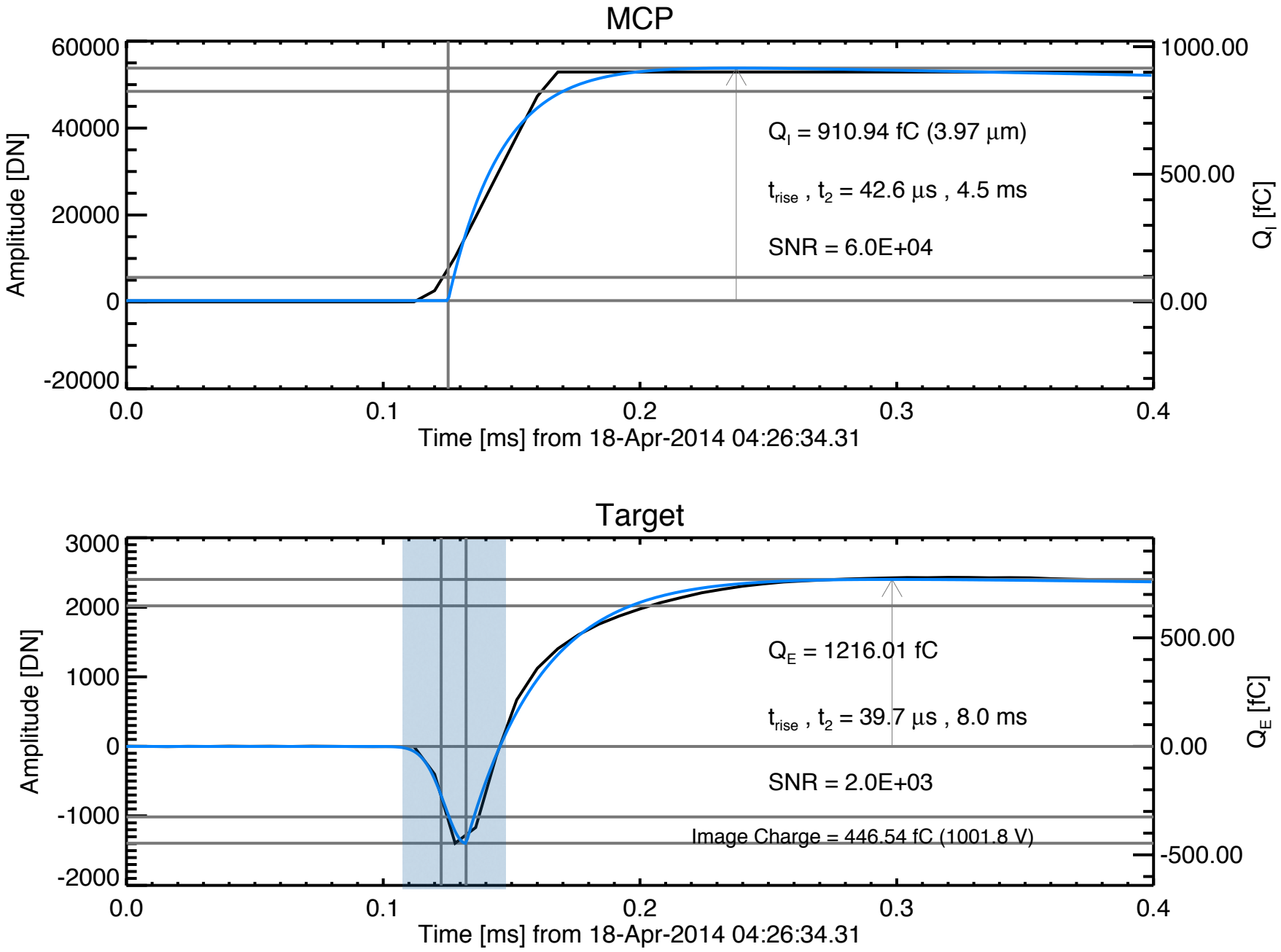
Time [ms] from 12-Jan-2014 13:27:25.13

Charge on a single dust grain



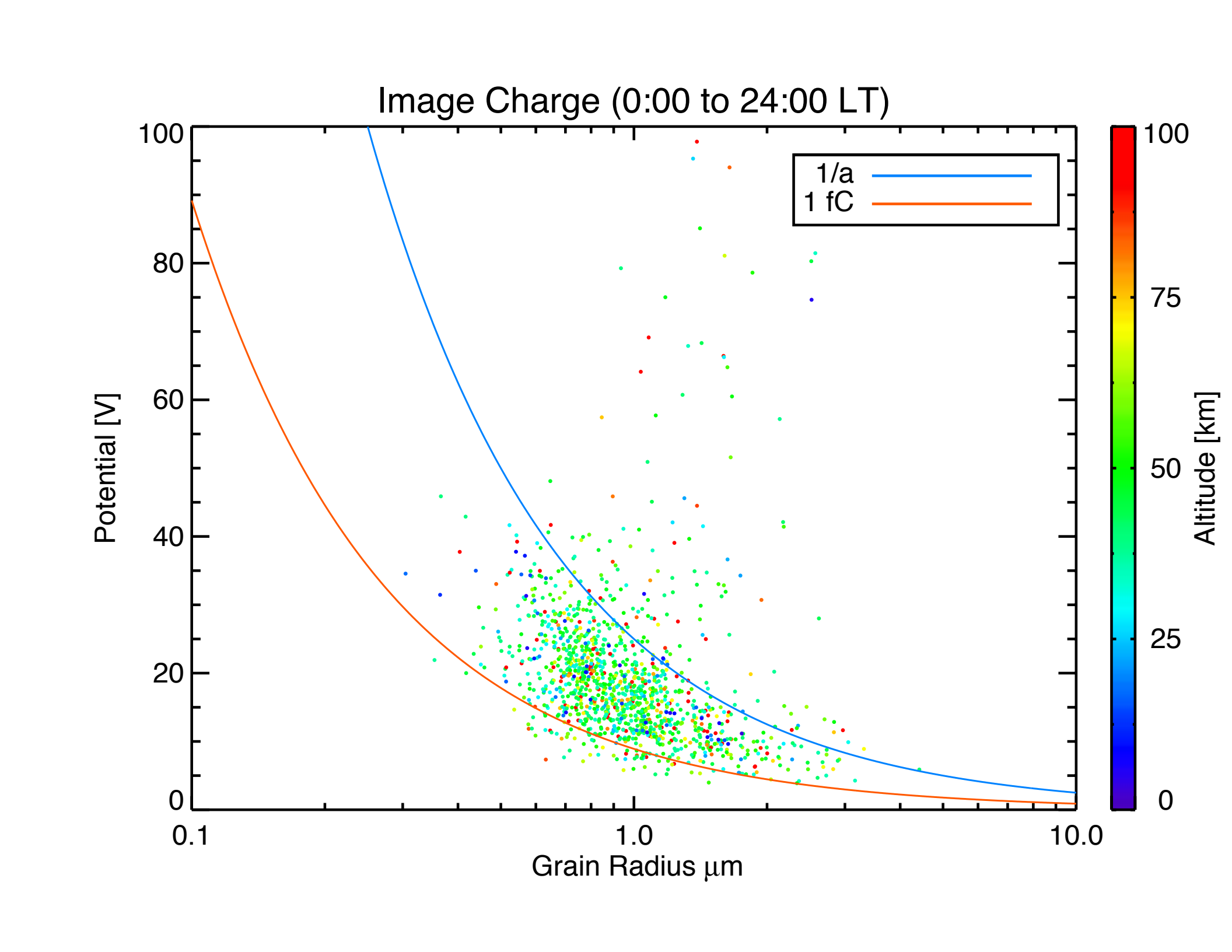
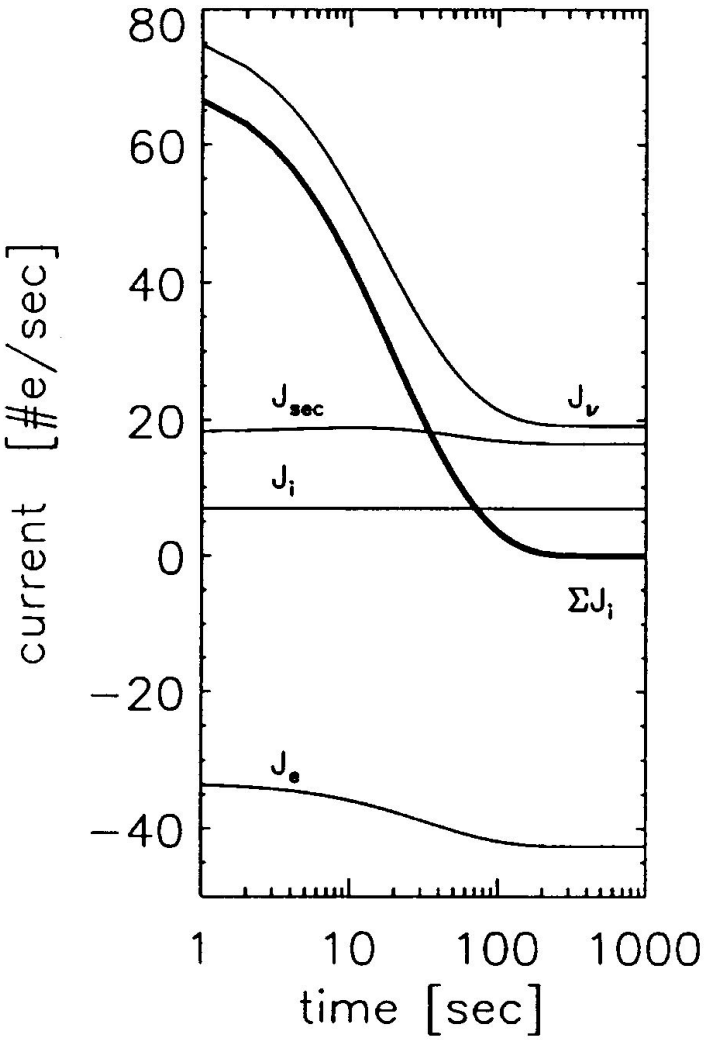
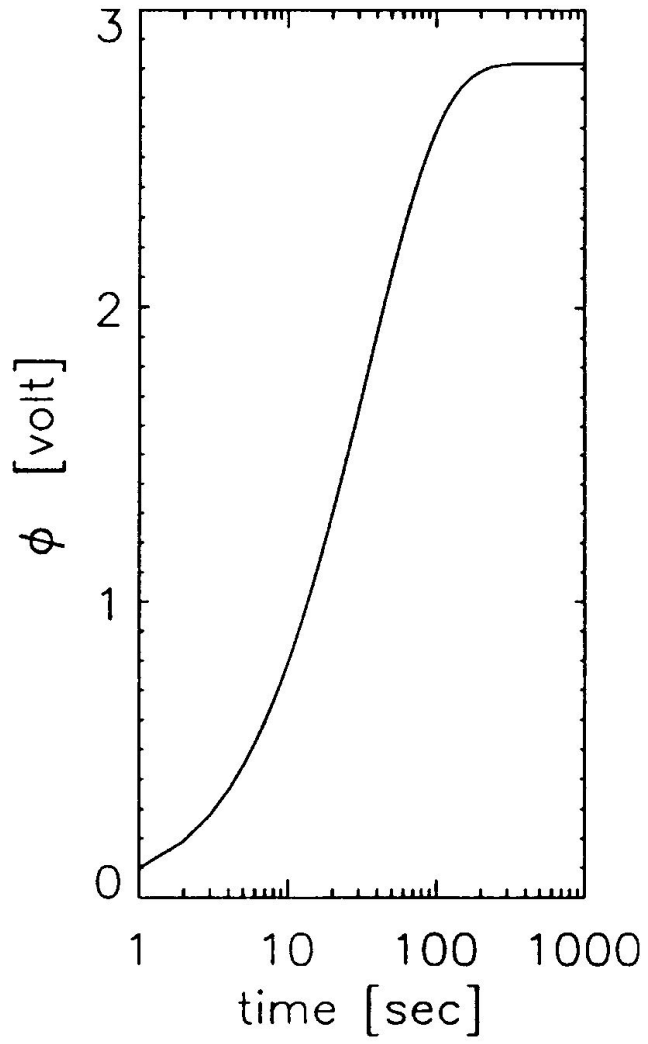


Image Charge (0:00 to 24:00 LT)
Potential [V]
100
80
60
40
20
0
0.1
1.0
10.0
Grain Radius μm
1/a
1 fC
Altitude [km]
100
75
50
25
0

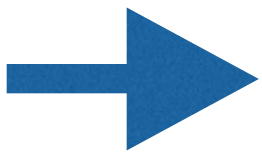
Charging currents in the solar wind at 1 AU





$$\tau \simeq \frac{2 \text{ minutes}}{a_\mu}$$

$$t_{rise} = \left(\frac{2h}{g_m}\right)^{\frac{1}{2}}$$



4 min to 50 km

SUMMARY

1) There is a permanently present asymmetric dust ejecta cloud engulfing the Moon.

2) The dust density increases during meteoroid showers.

3) There is no evidence of lofted small particles over the terminators.

4) LDEX detected unexpectedly large charges on grains at low altitudes.

5) Similar dust clouds are expected above all airless bodies, including Mercury, asteroids, the moons of Mars: Phobos and Deimos.

6) The Colorado dust accelerator is available to the community.
(impact.colorado.edu)