Fine-grained Regolith Loss on Sub-Km Asteroids

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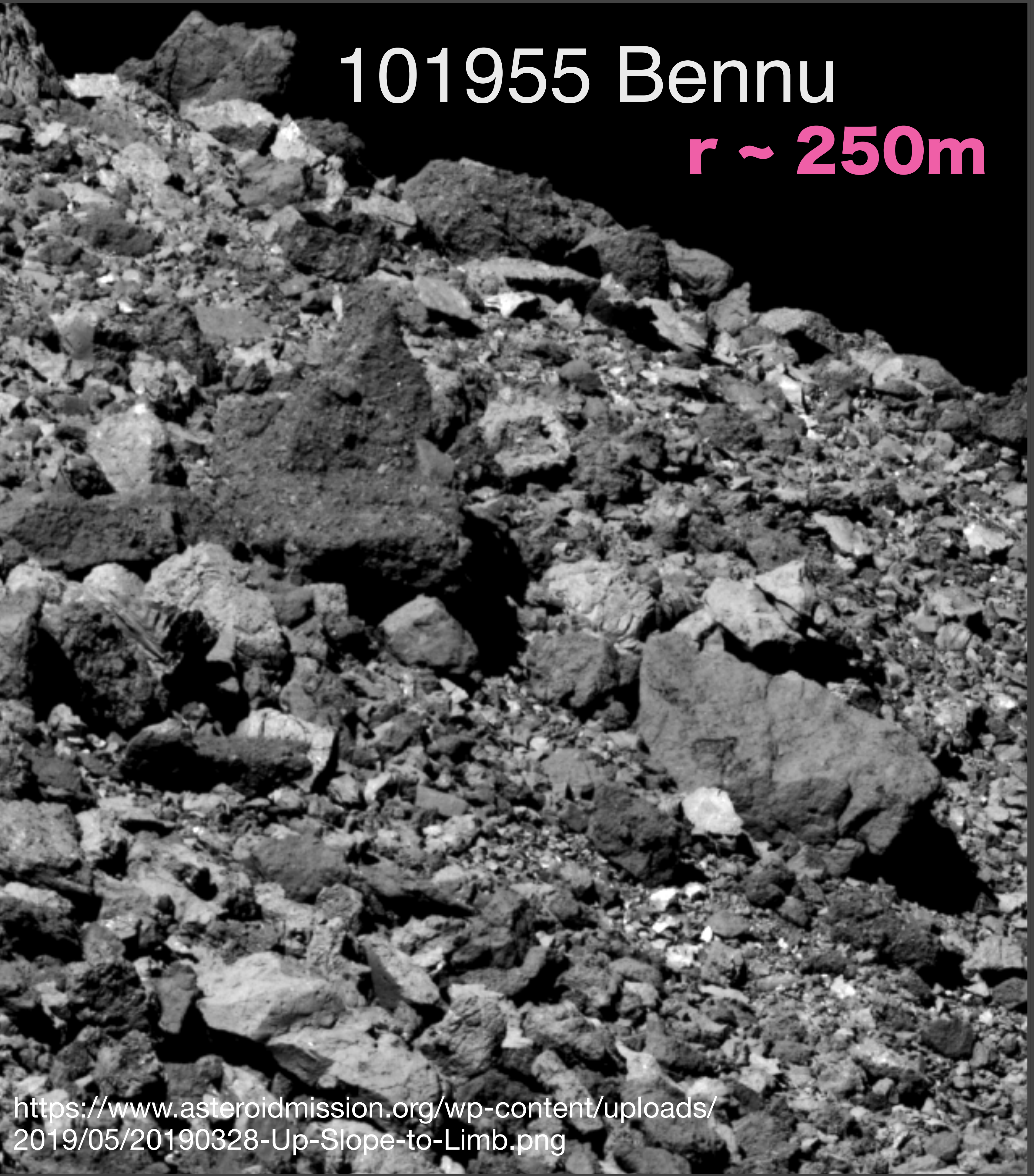
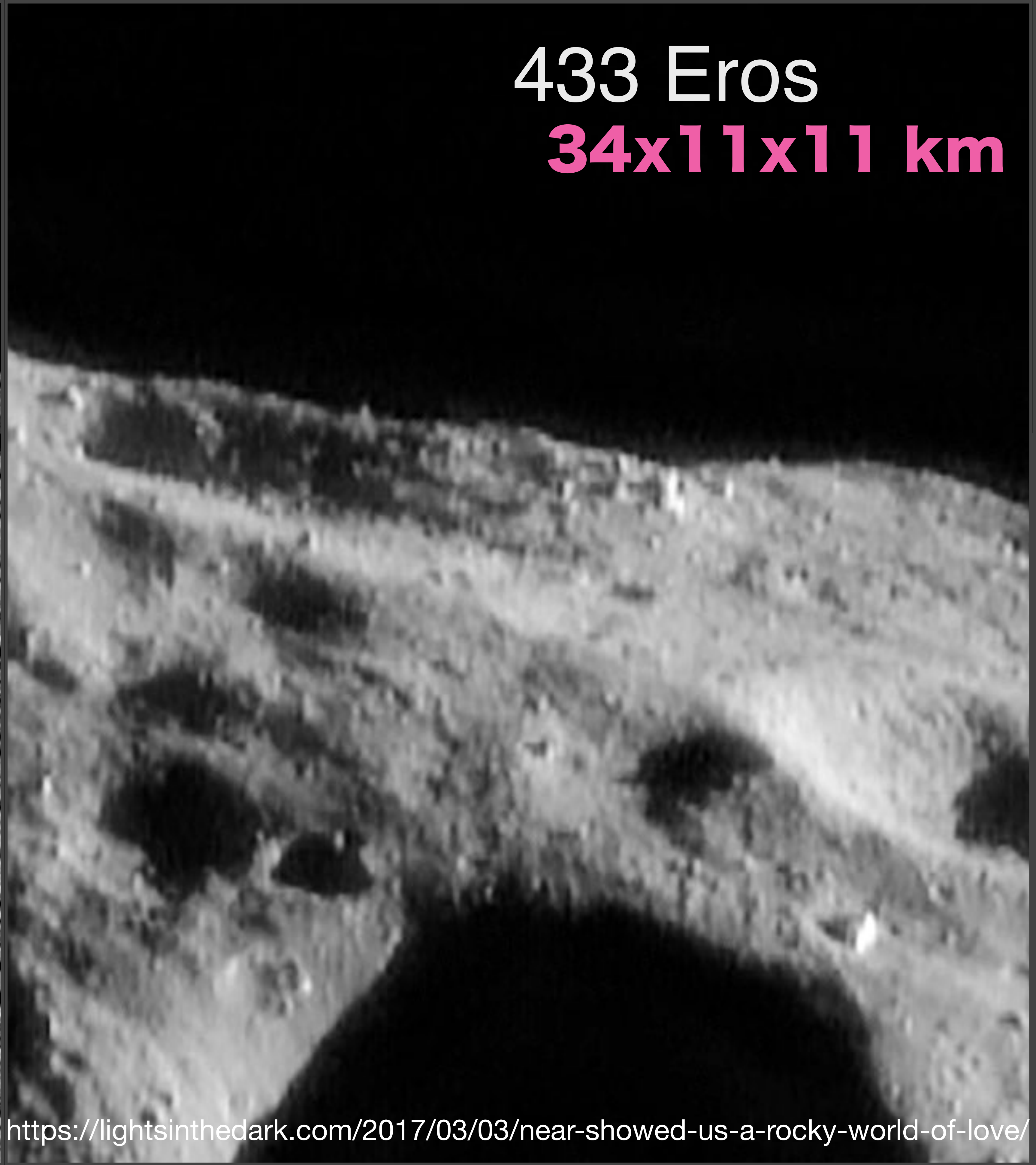
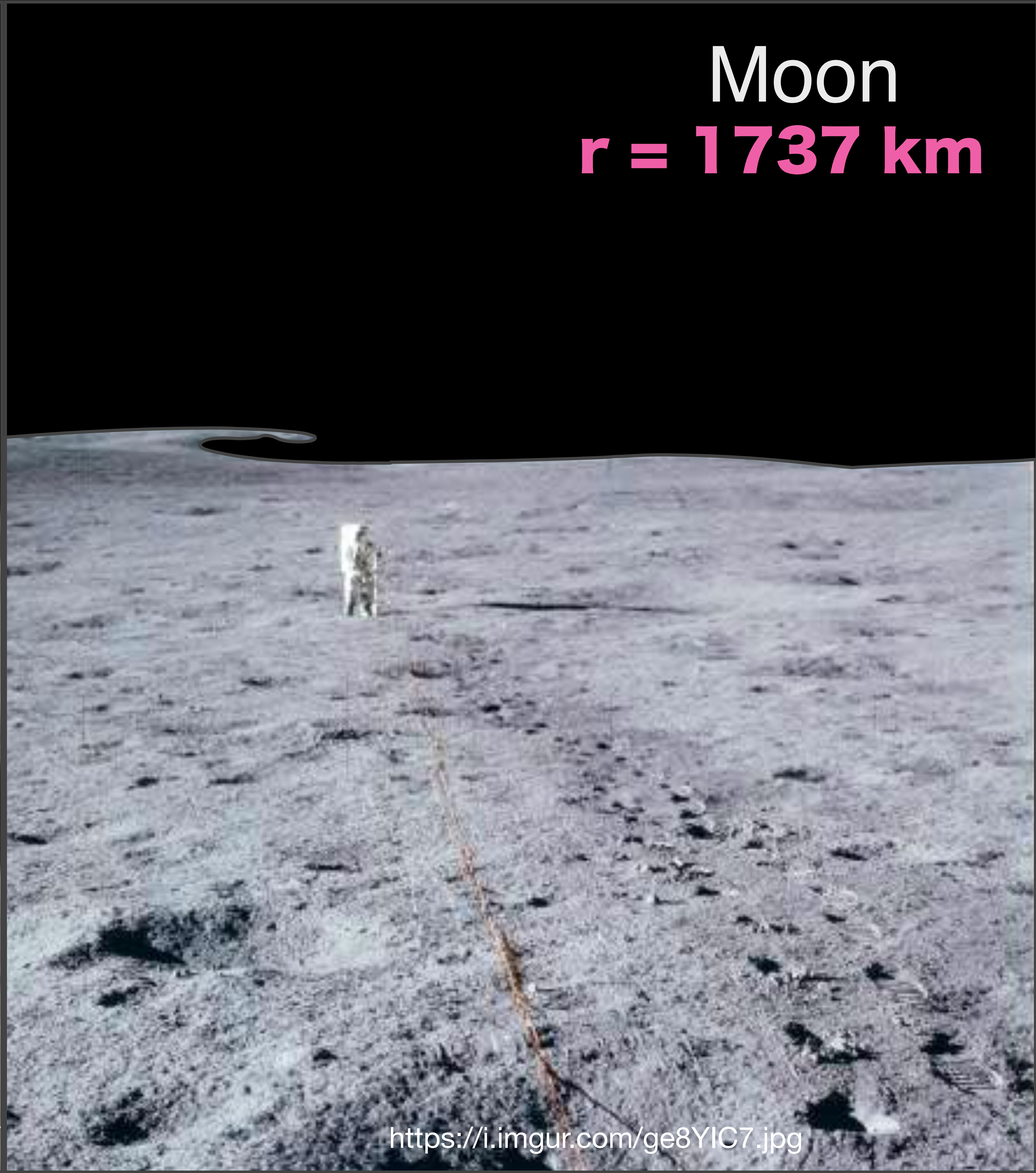






Production/ Destruction

e.g., fragmentation

Transport

e.g., currents, wind,…

https://www.nps.gov/articles/coastal-processes-sediment-transport-and-deposition.htm

sand destruction?

sand production?

sand removal?

sand deposition?

Defying Gravity

10x magnification

101955 Bennu

V_{esc}: $2x10^{-1}$ m/s

r ~ 250 m

433 Eros

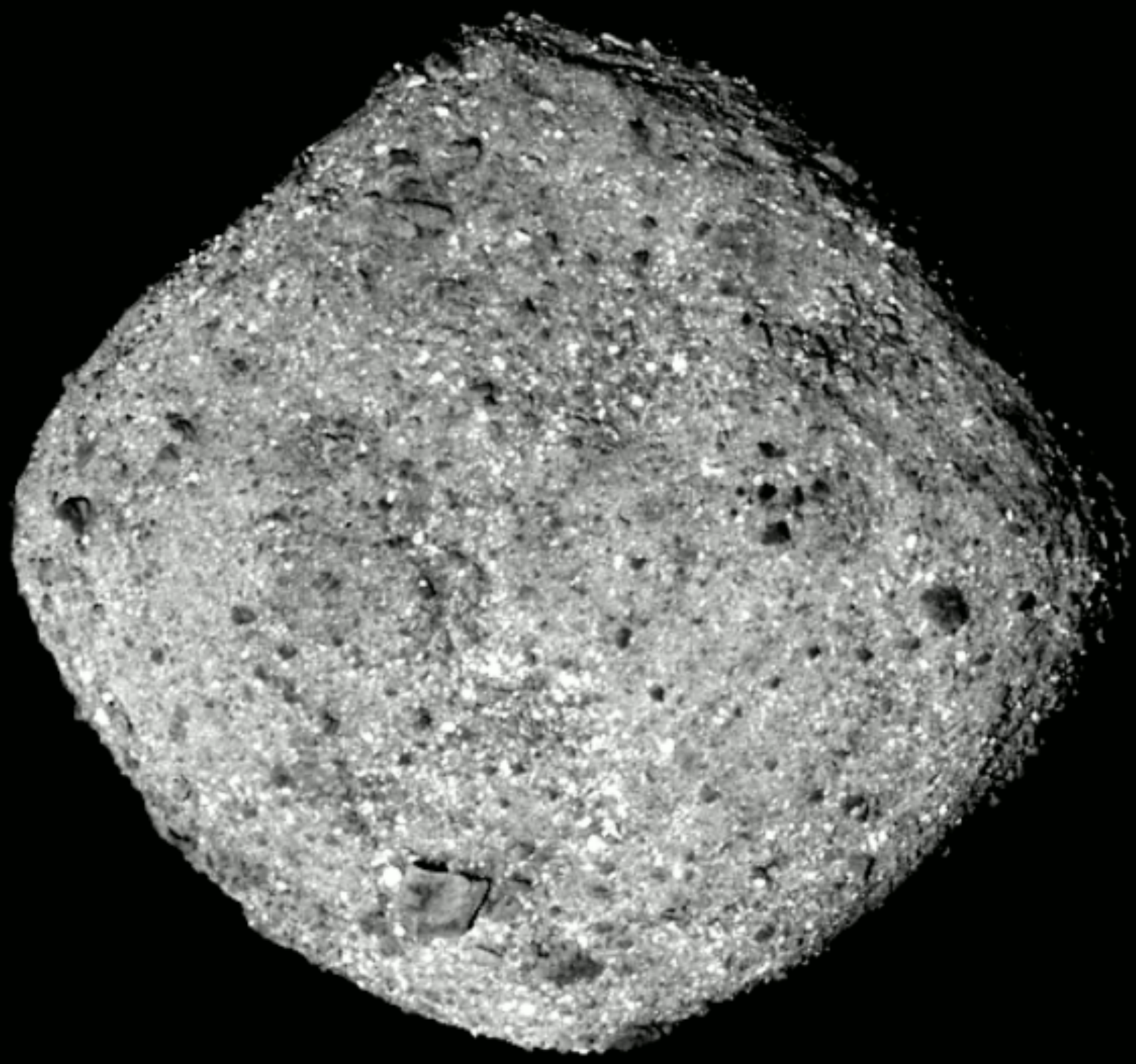
$V_{esc} = 1x10^{1}$ m/s

34x11x11 km

Moon

$V_{esc} = 2.4x10^{3}$ m/s

r ~ 1737 km

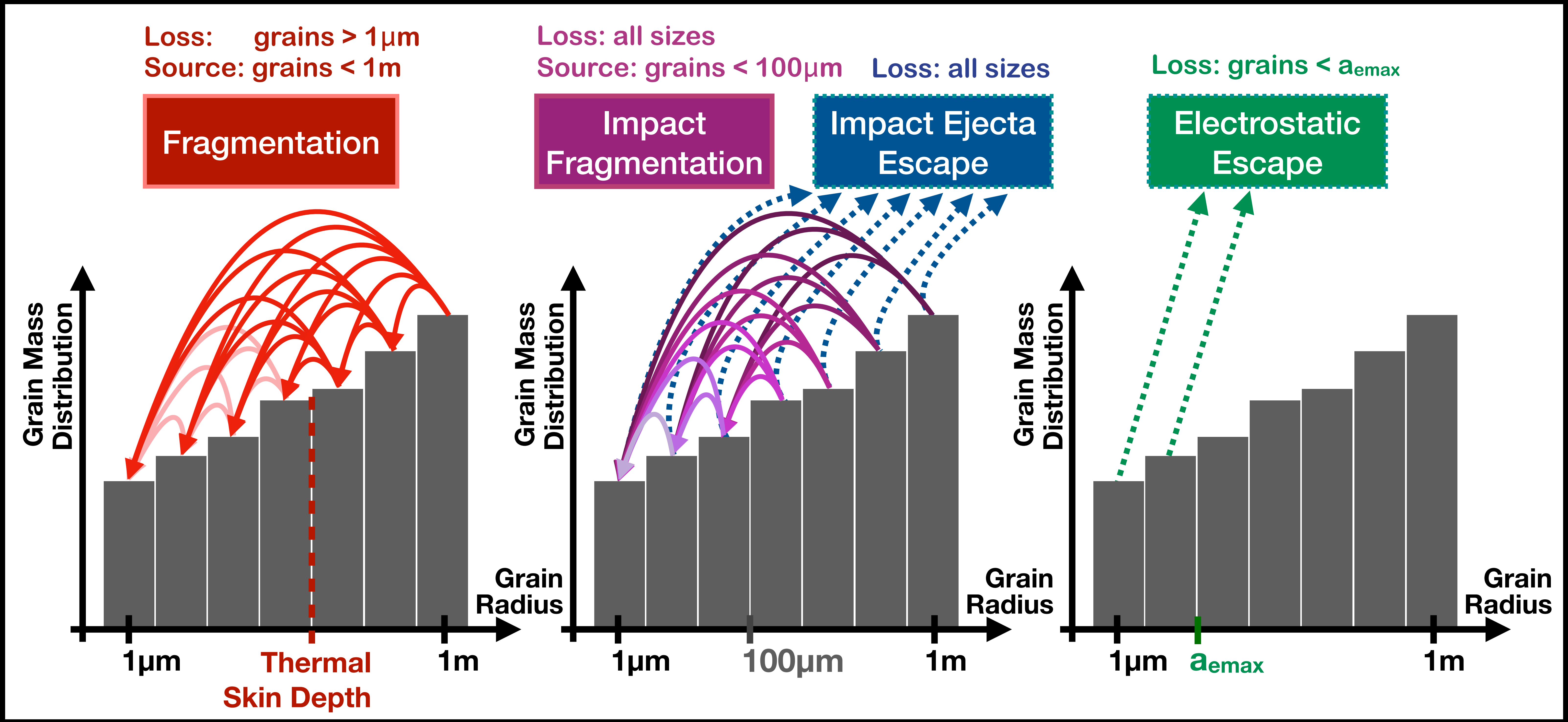


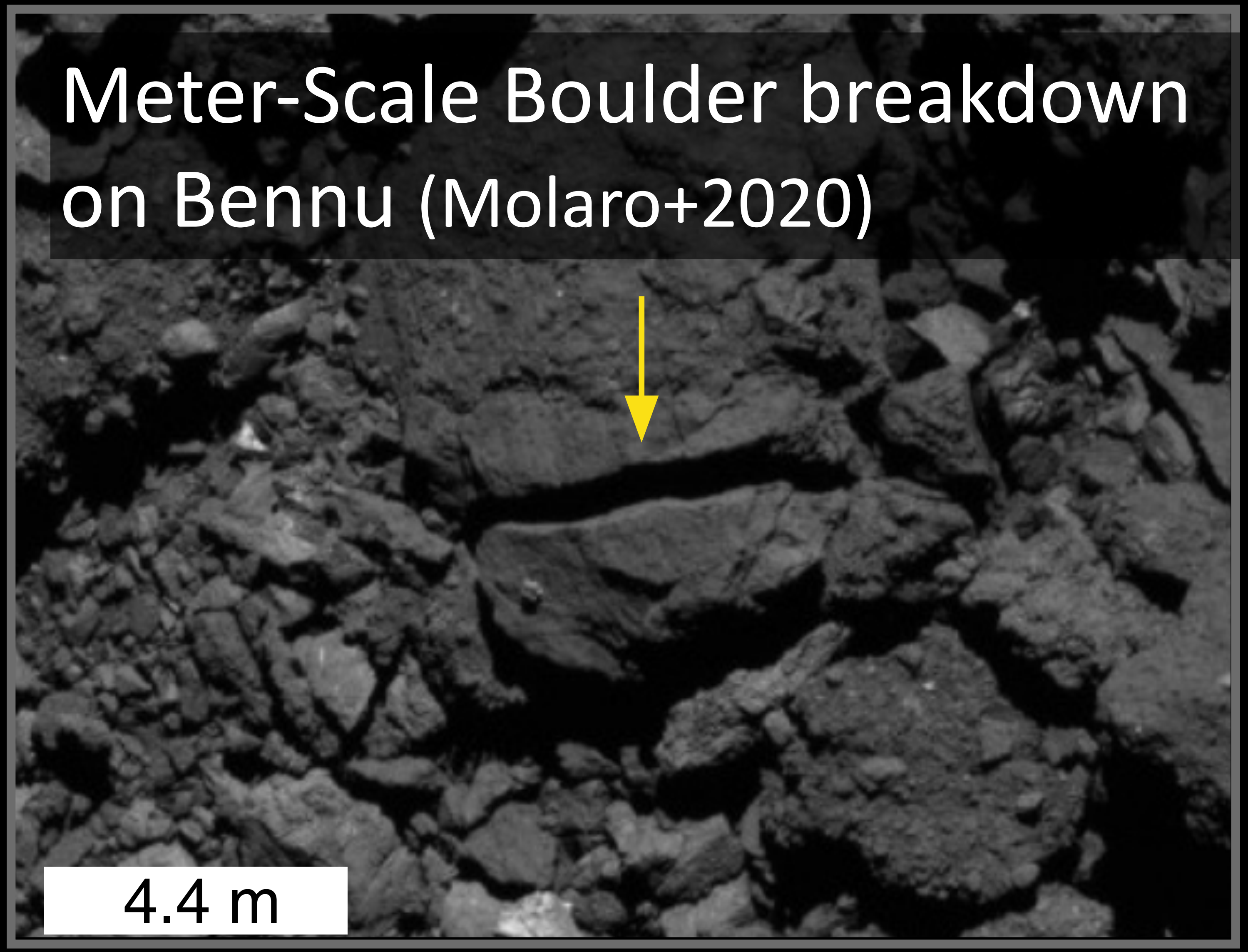
https://commons.wikimedia.org/wiki/File:Asteroid-Bennu-OSIRIS-RExArrival-GifAnimation-20181203.gif

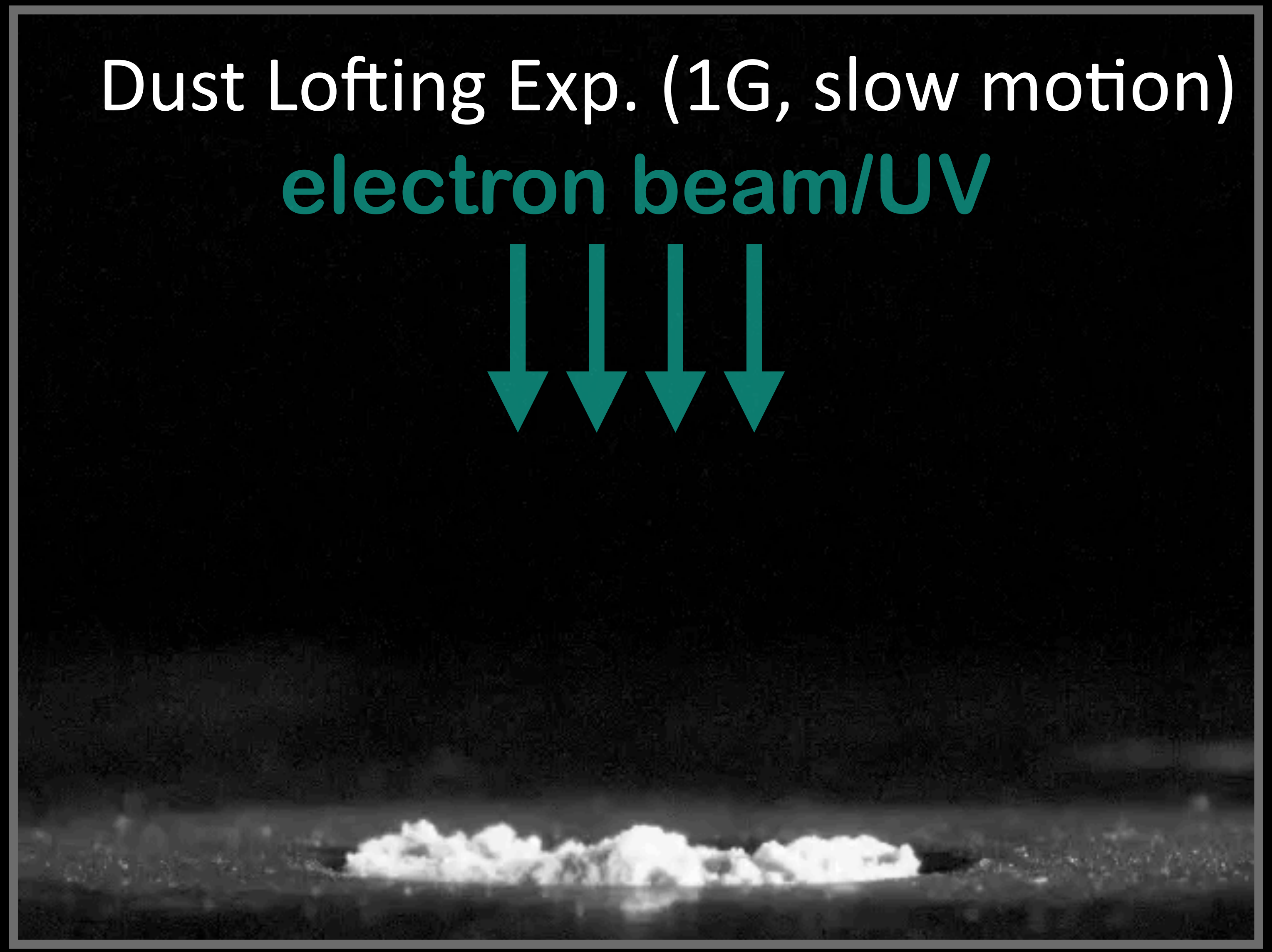
http://ircamera.as.arizona.edu/NatSci102/NatSci102/movies/

https://thumbs.gfycat.com/DefiniteGiddyGraywolf-size_restricted.gif

Regolith Processes on Asteroids



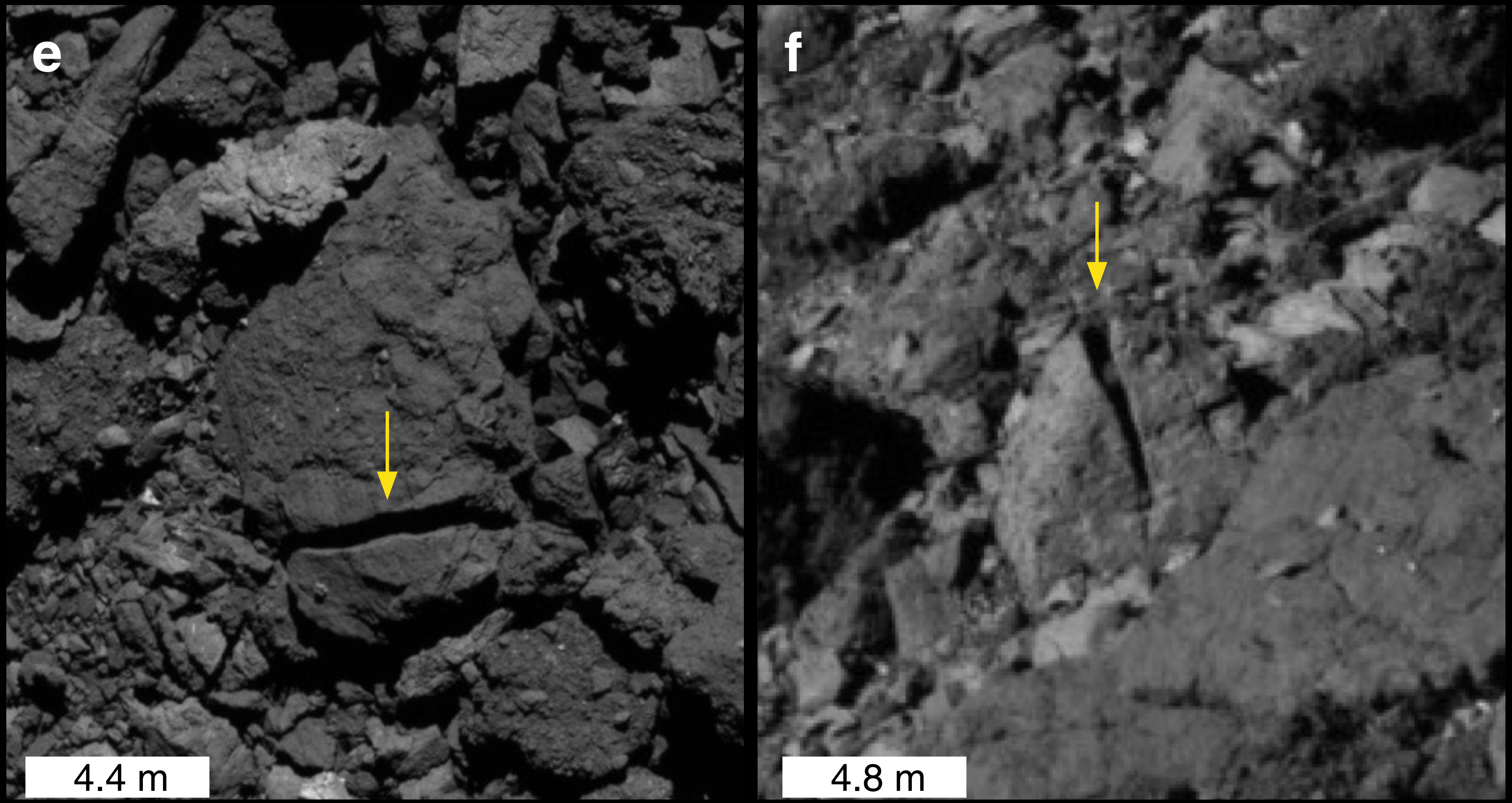




$v_{loft} \lesssim 1$ m/sec

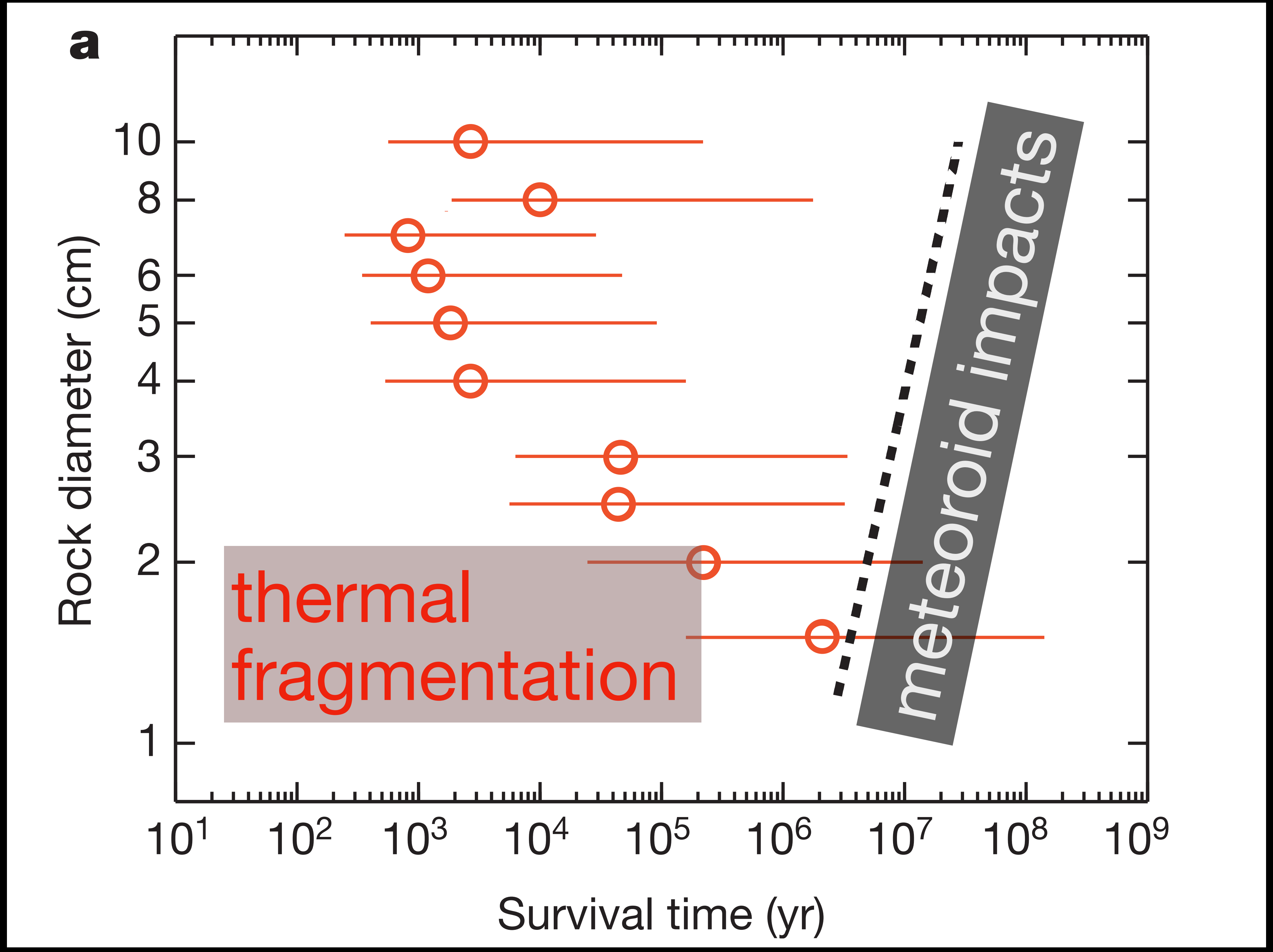
Process 1 - Thermal Fragmentation

- Independent of object size / gravity
- Production rate ~ thermal cycle & temperature change



Meter-Scale Boulder breakdown on Bennu (Molaro+2020)

Fragmentation caused by thermal fatigue is more effective than impacts (Delbo+2014).

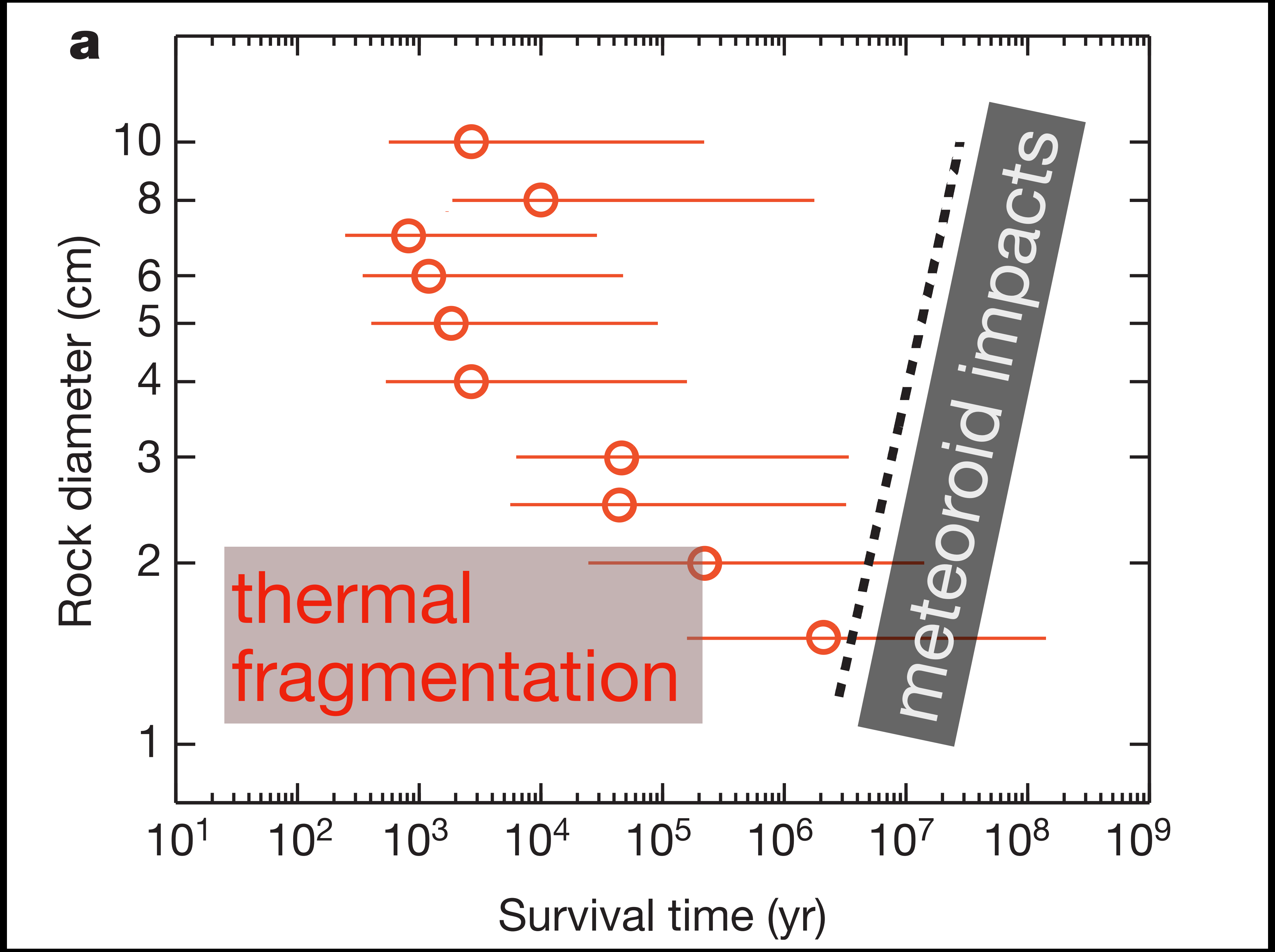


Process 1 - Thermal Fragmentation

- Independent of object size / gravity
- Production rate ~ thermal cycle & temperature change

Twain Harte Dam Rock Exfoliating (Colins+18)

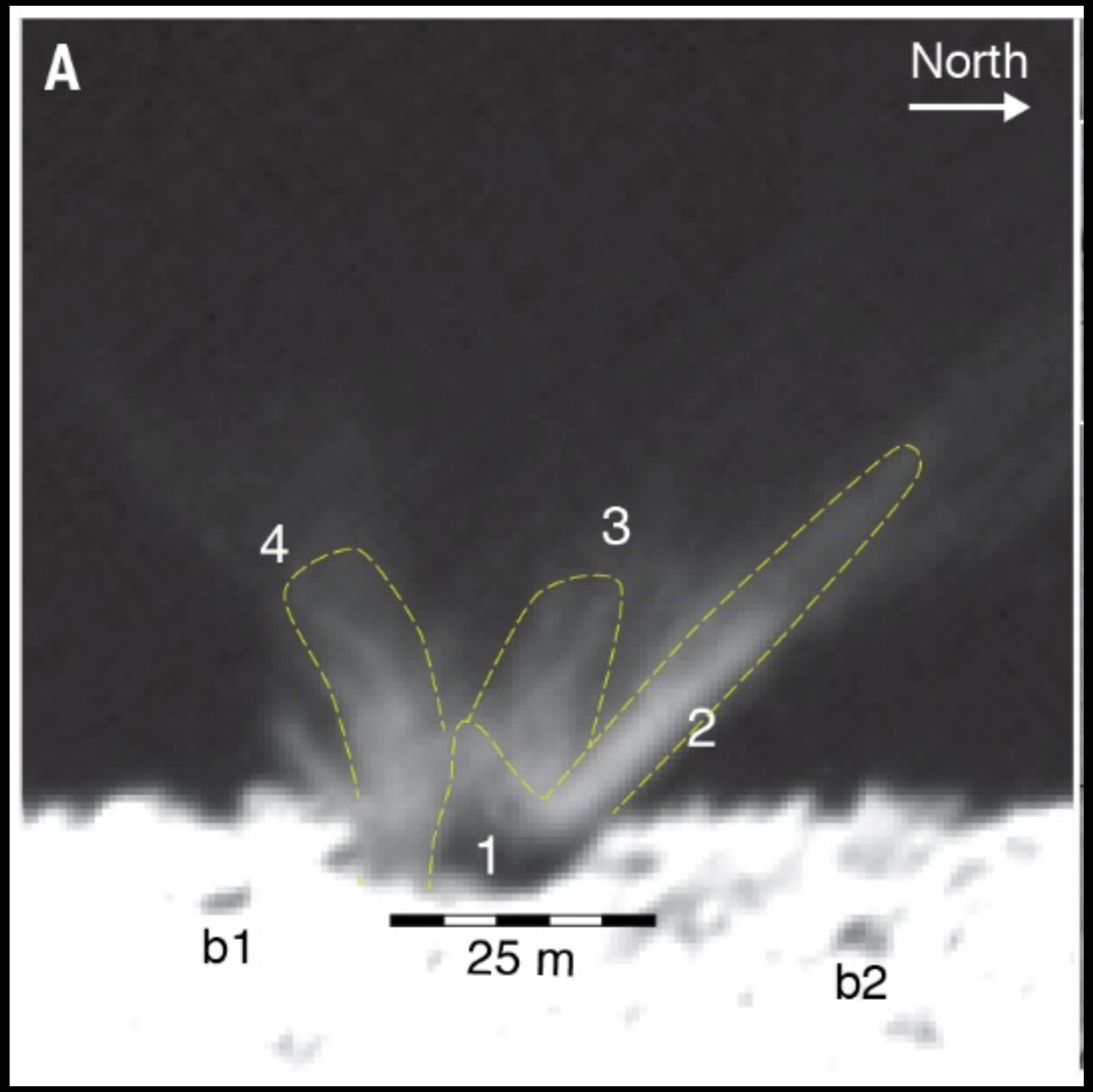
Fragmentation caused by thermal fatigue is more effective than impacts (Delbo+2014).

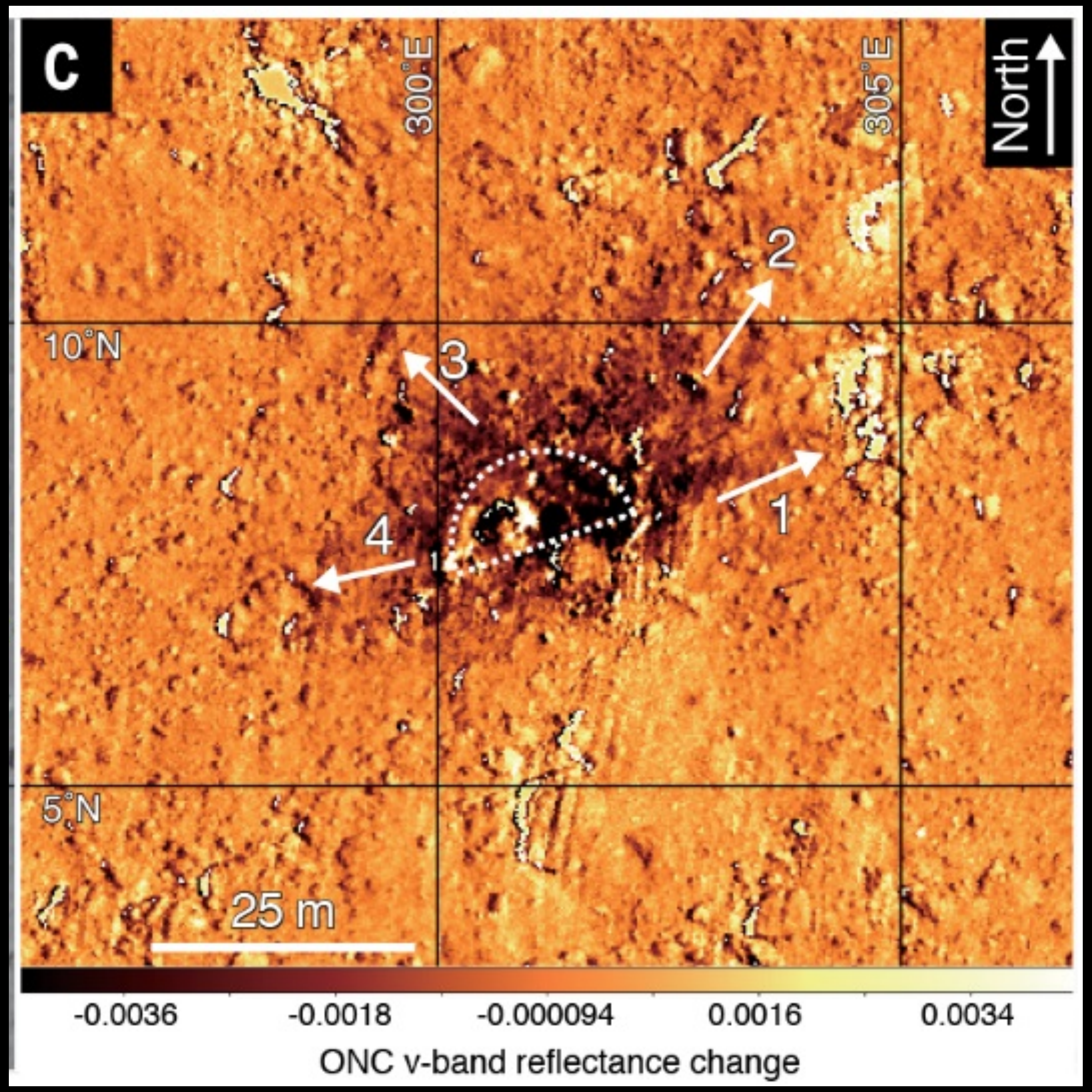


Process 2 - Meteoroid Impacts

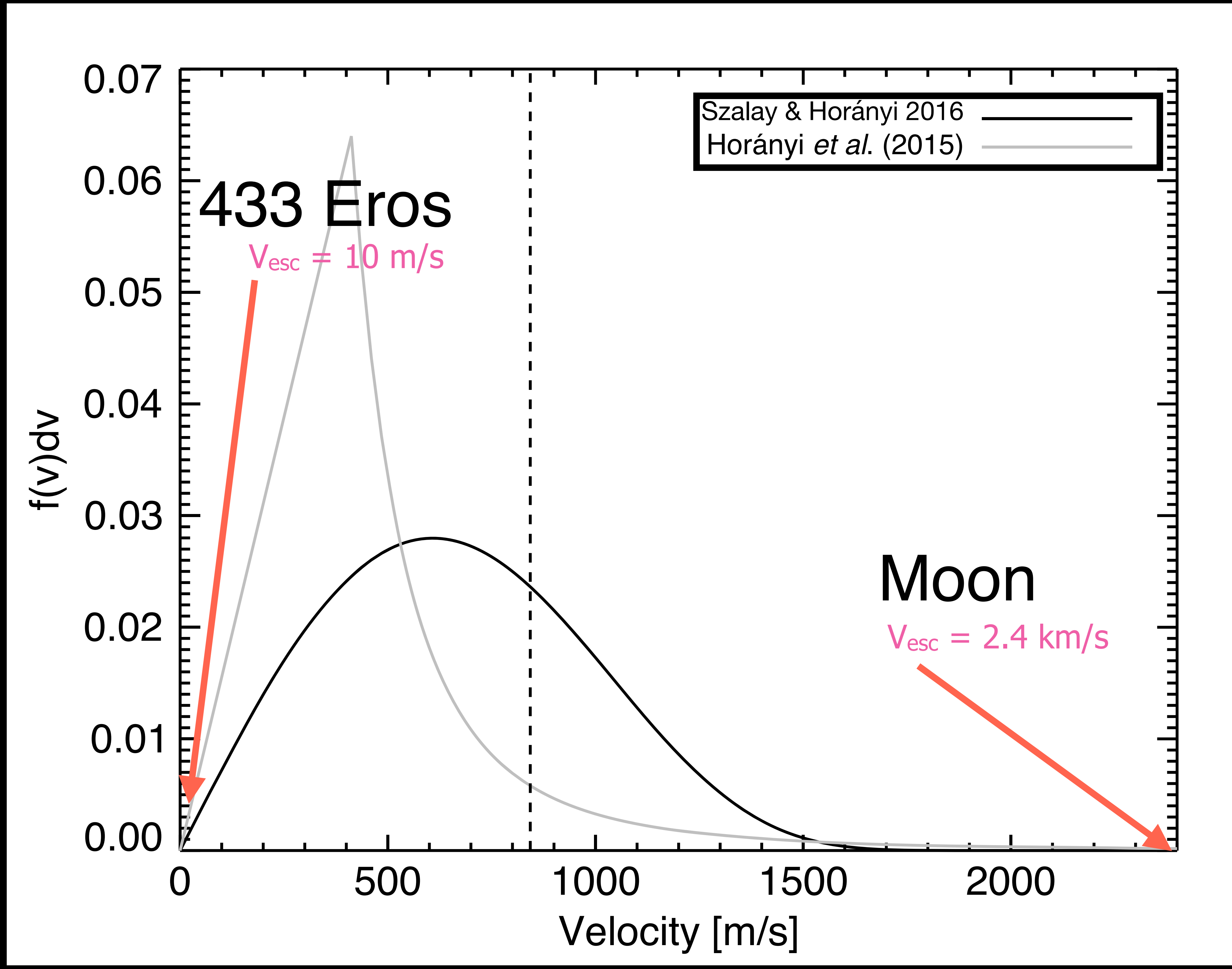
- Meteoroid impacts are both source and sink (depending on ejecta speed & object gravity)
- Fast ejecta: 5×10^{-12} kg m^{-2} sec^{-1} (LADEE mission, Horányi+2015)
- Slow ejecta + thermal fragmentation: 5×10^{-10} kg m^{-2} sec^{-1} (~10x lower than terrestrial soil production)

100 m/Myr





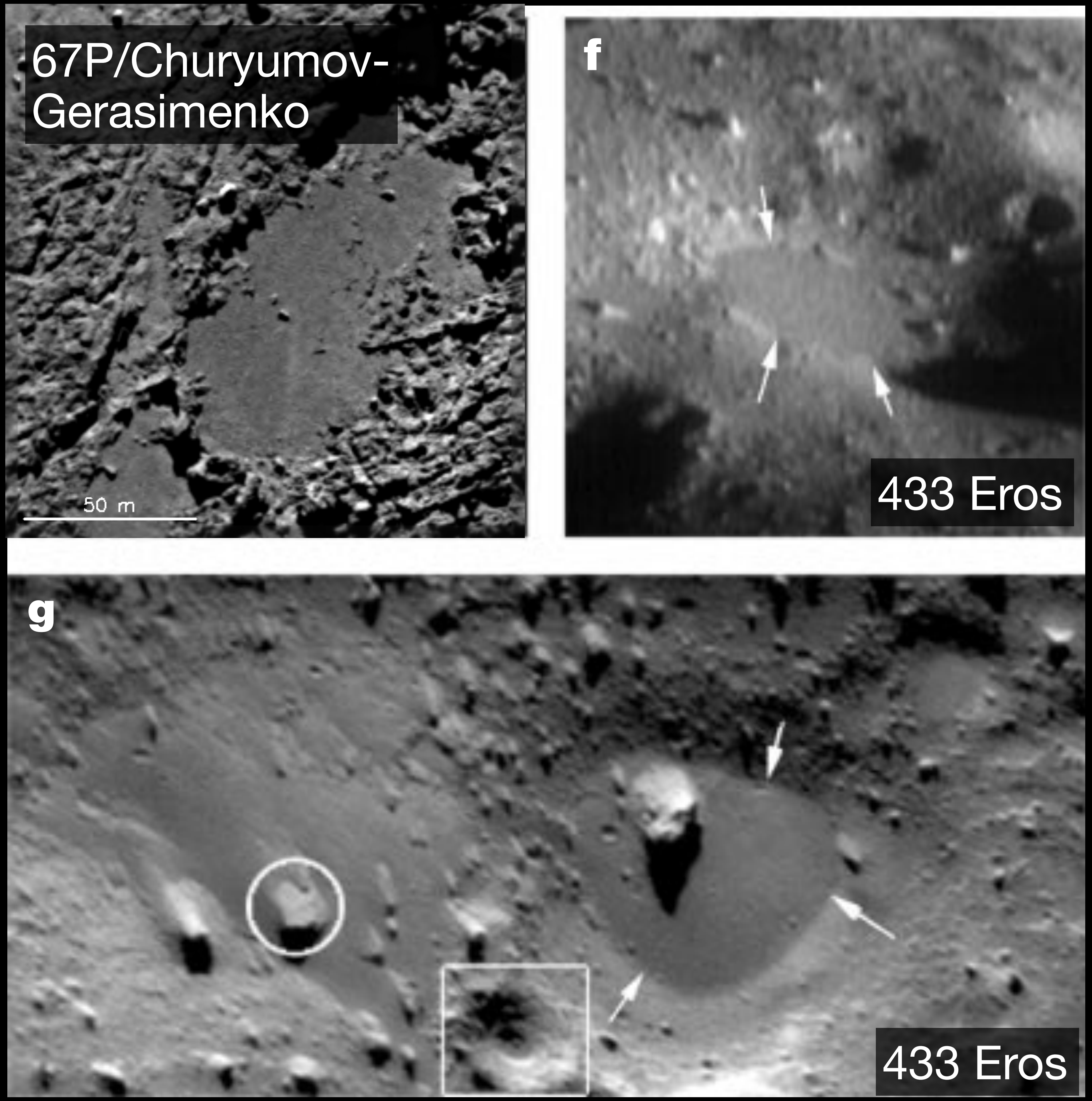
Hayabusa 2 - Small Carry-on Impactor (Arakawa+2020)



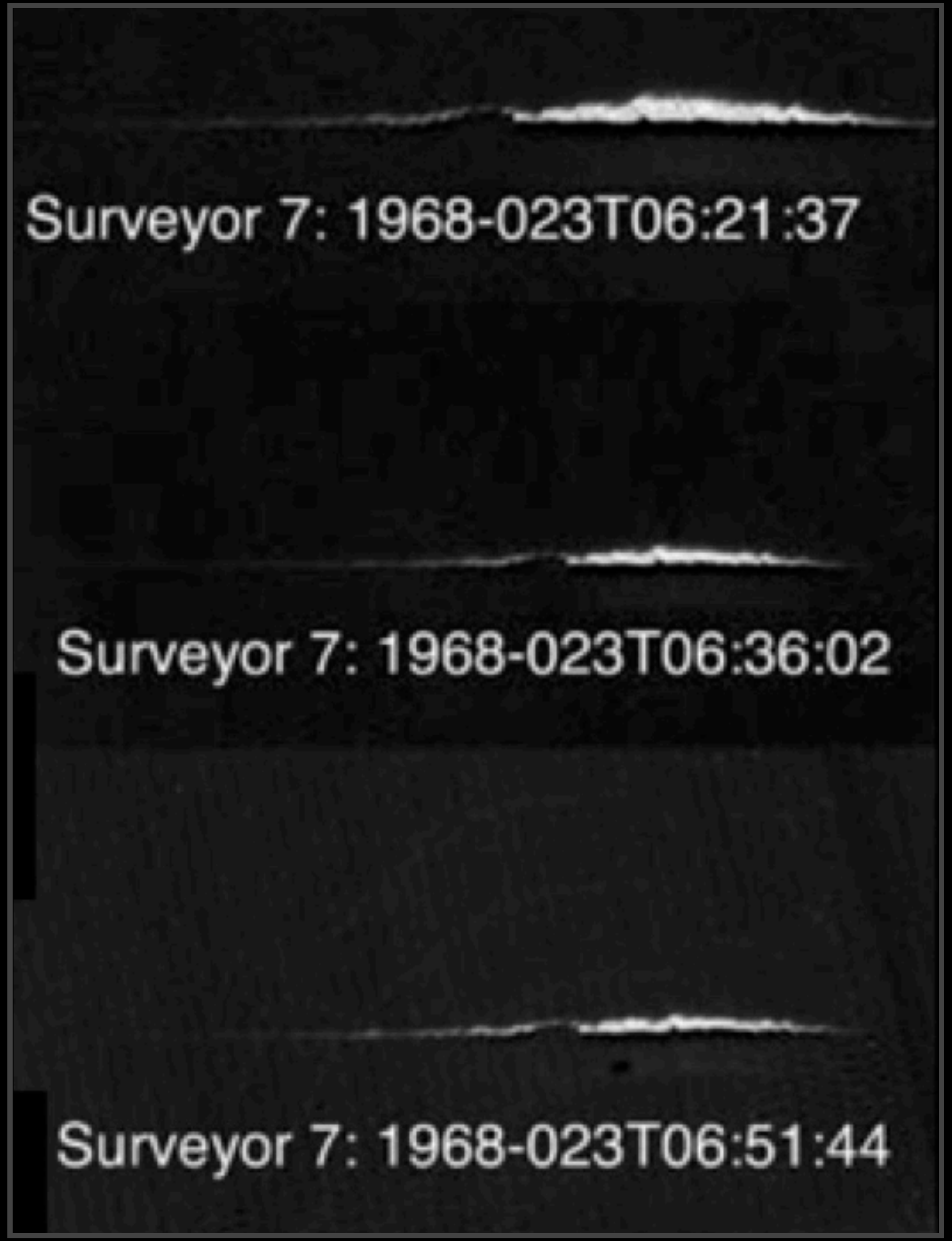
High-speed Impact Ejecta Speed Distribution (Szalay & Horányi 2016)

Process 3 - Electrostatic Dust Transport

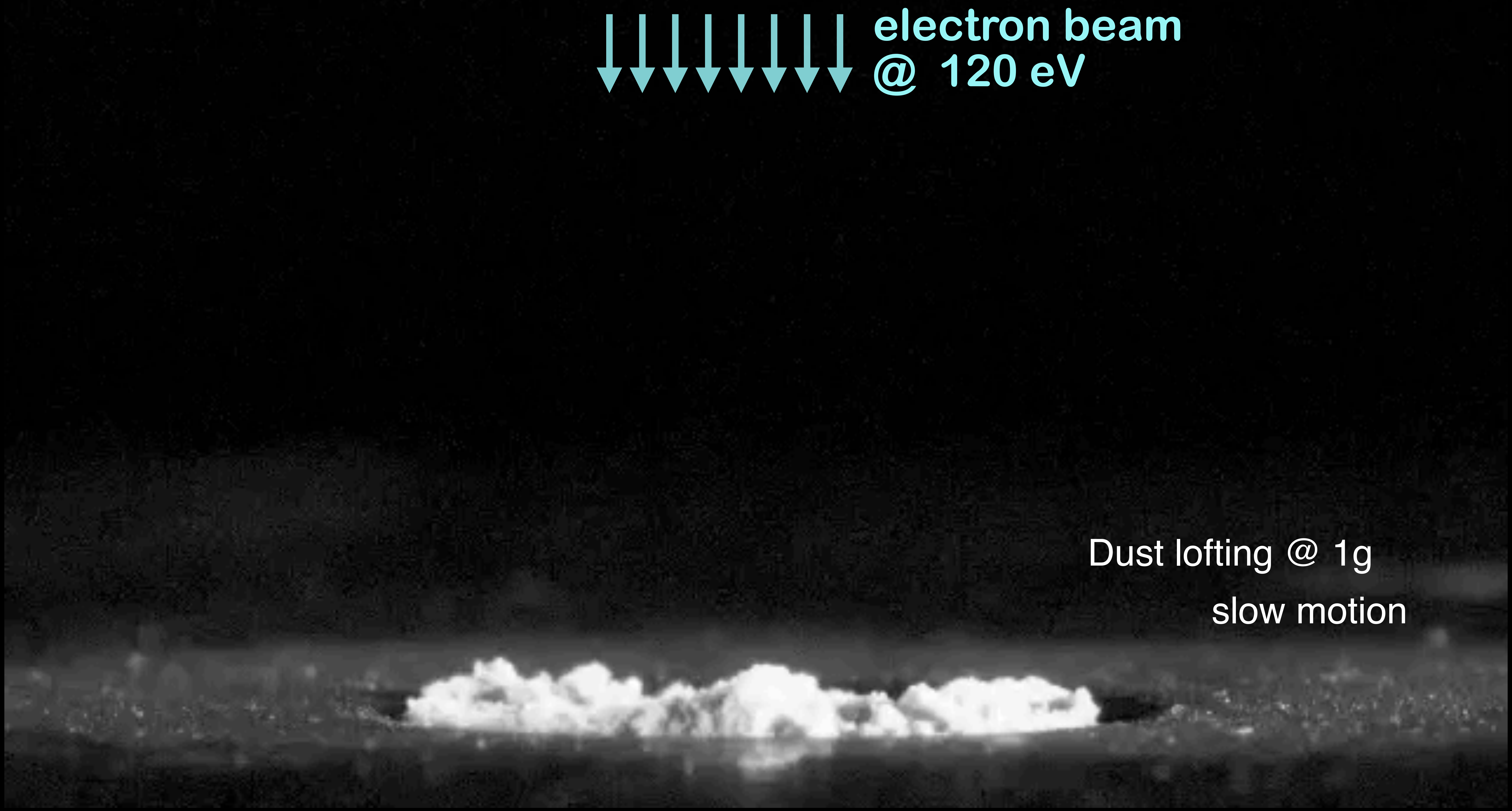
Ponded deposits on airless bodies (Robinson+2001; Thomas+2015)



Lunar Horizon Glow (Criswel 1973)

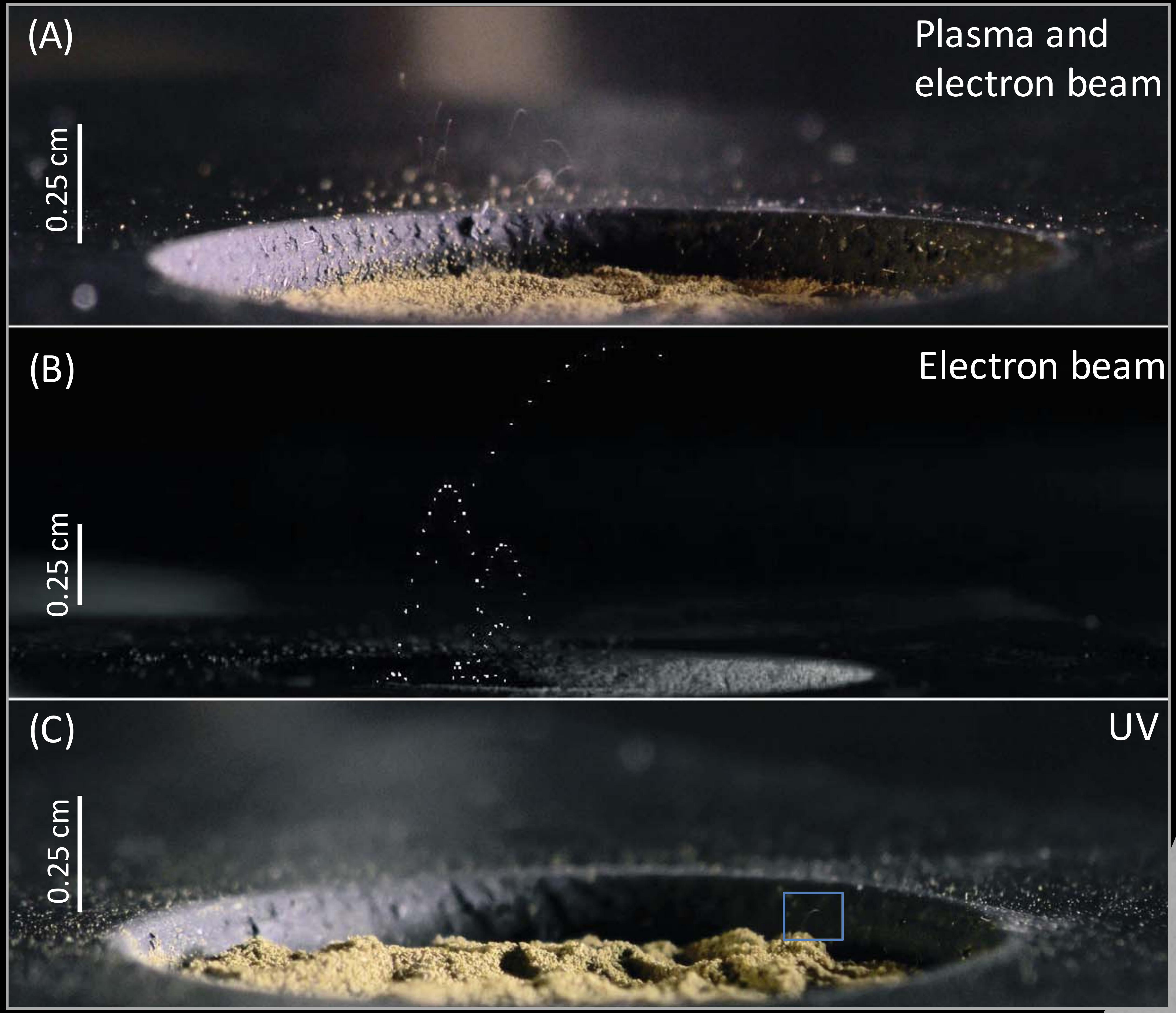


Process 3 - Electrostatic Dust Transport



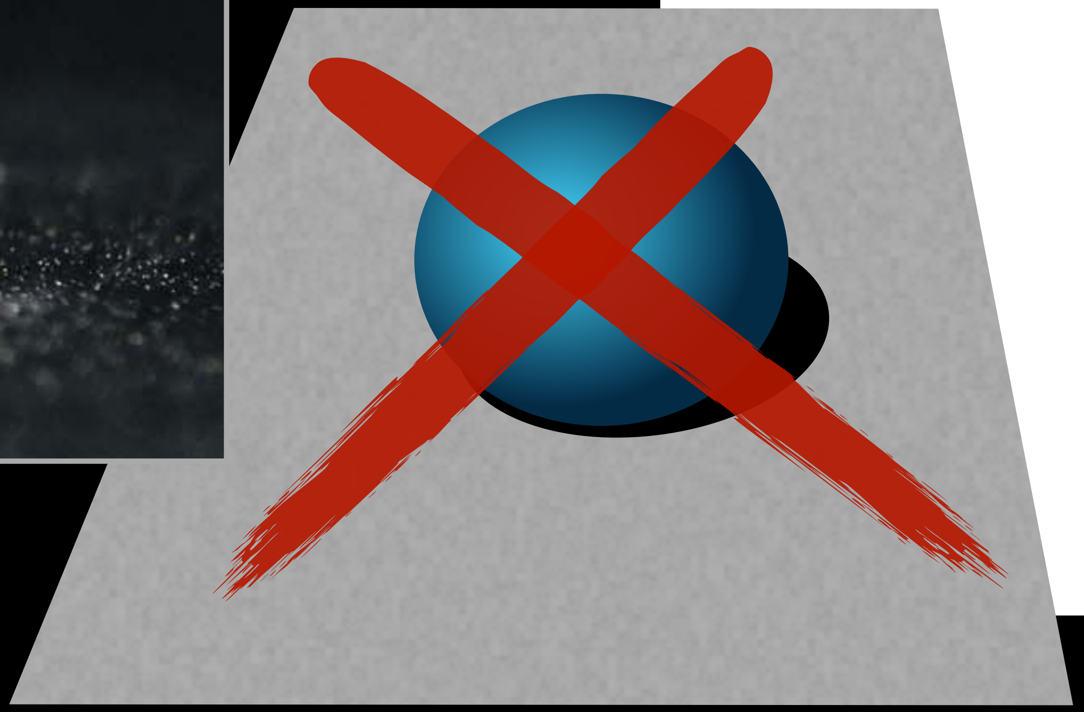
Process 3 - Electrostatic Dust Transport

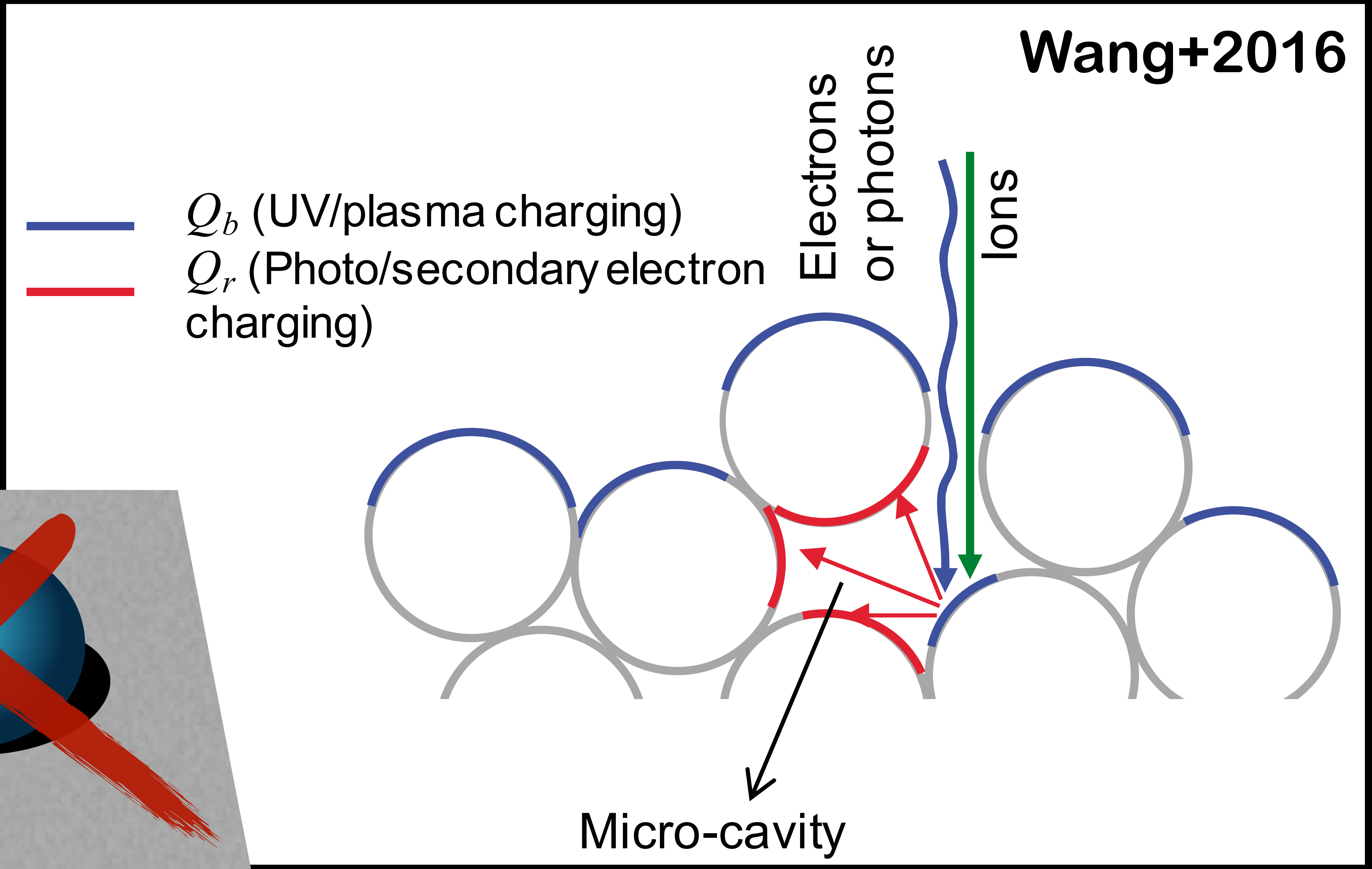
Patched Charge Model



The charging of regolith particle is significantly enhanced with the presence of microcavities, allowing electrostatic repelling force to overcome inter-particle cohesion.

Key ingredients: ionization radiation, microcavity



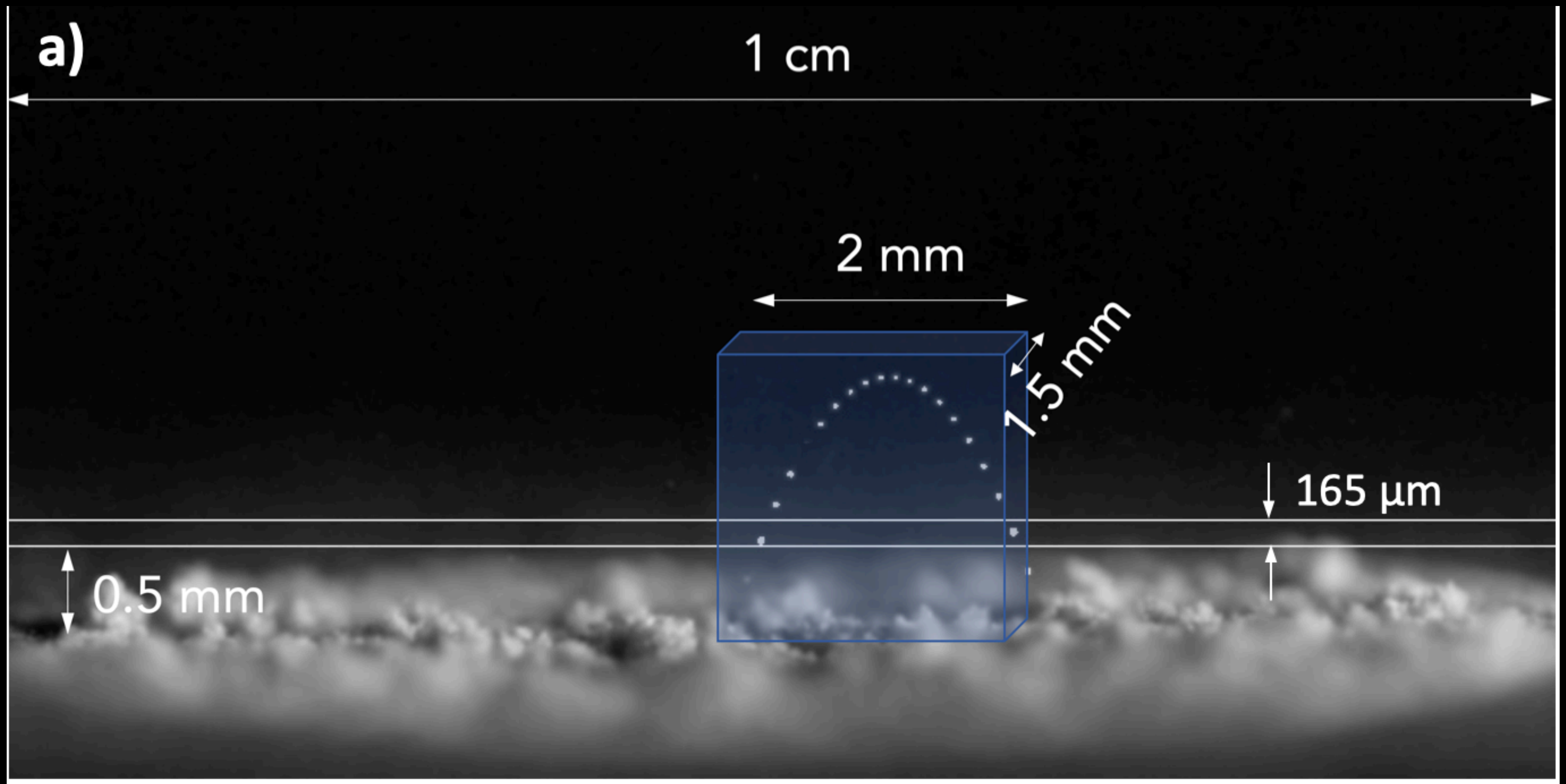


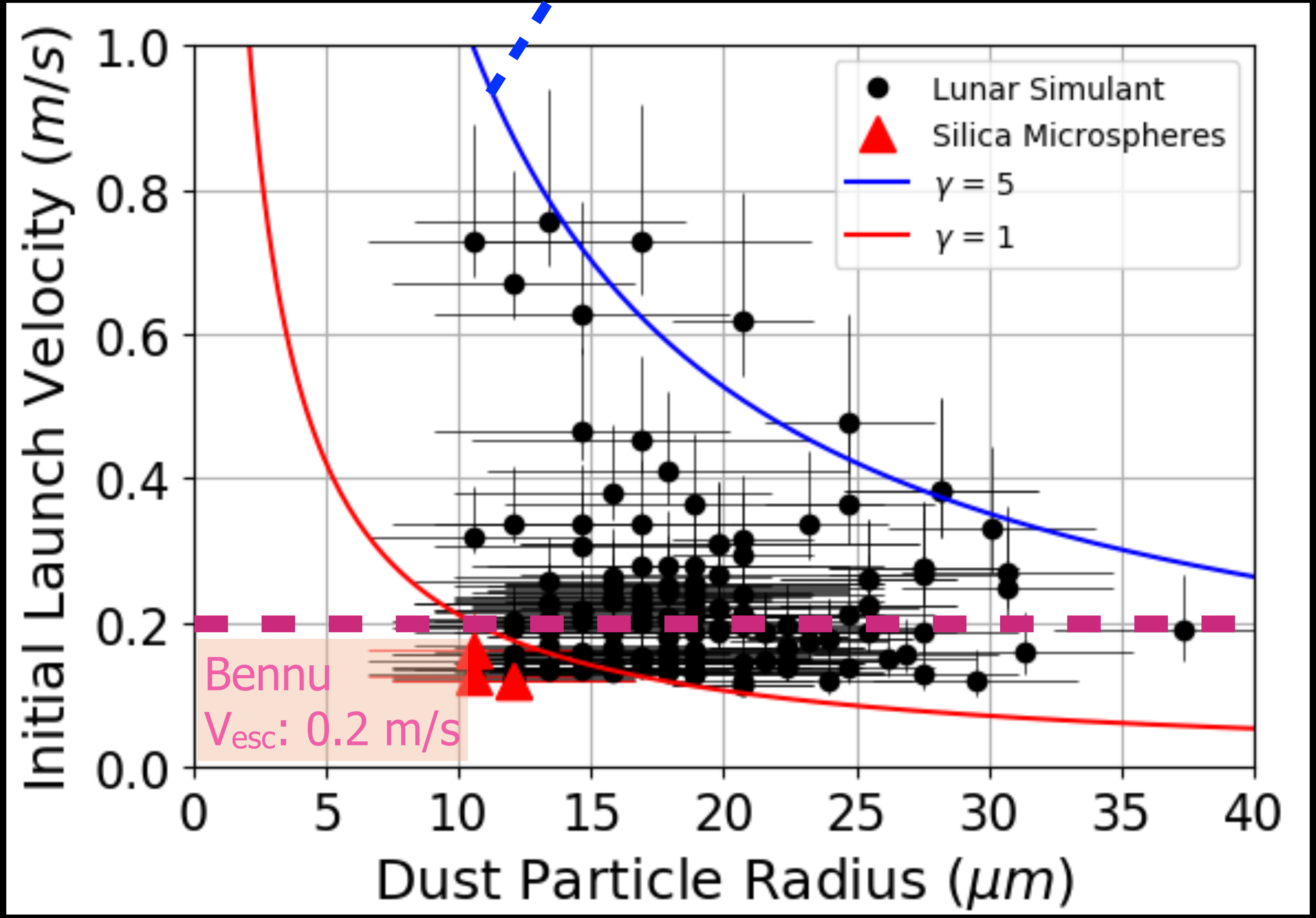
Process 3 - Electrostatic Dust Transport

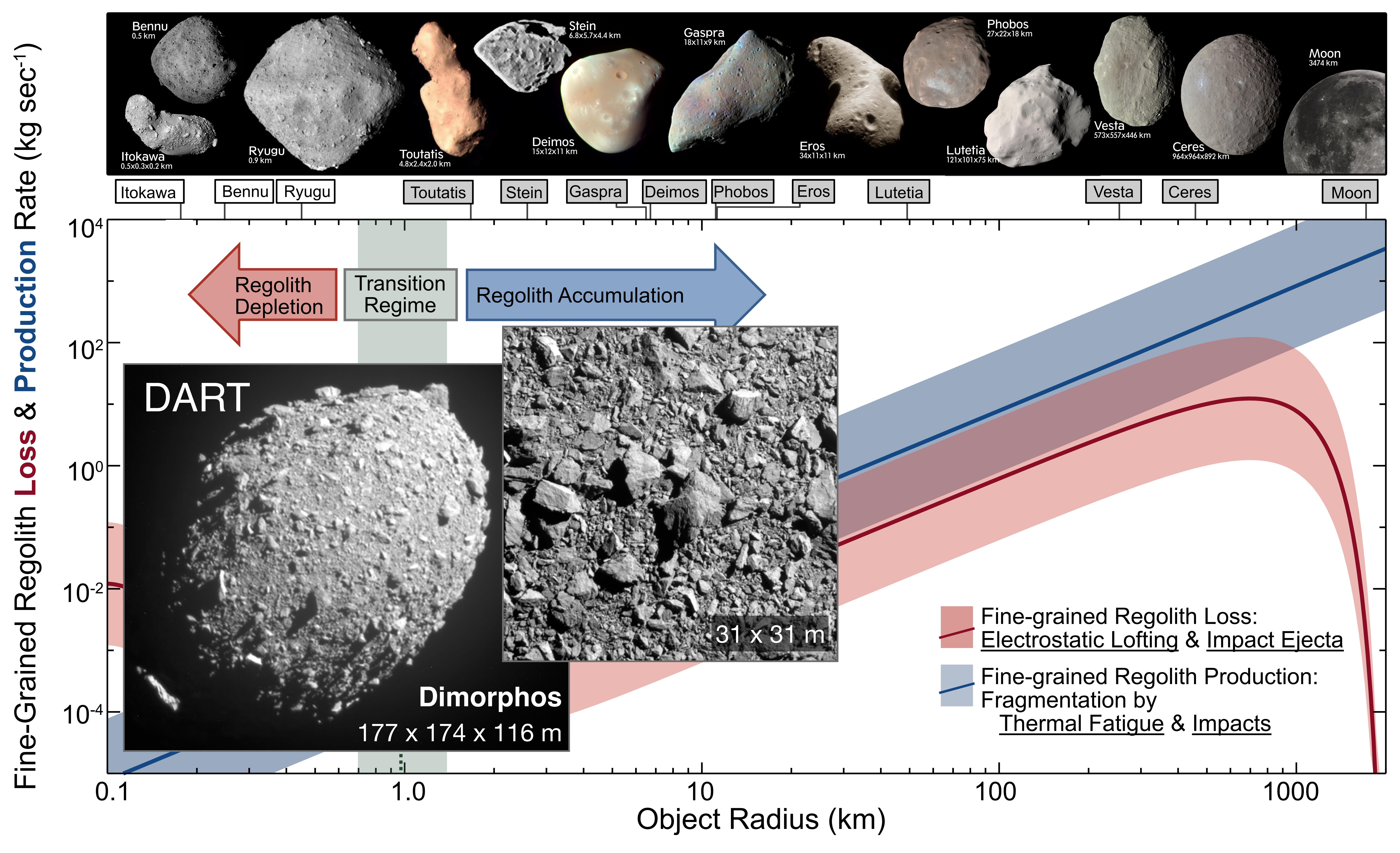
Lofted Grain Size-Speed Relation

$$v_{EL}^{max} = 11.5/\, a_{\mu m}\, m\, s^{-1}$$

Reconstructed grain trajectory
(Carroll+2020)

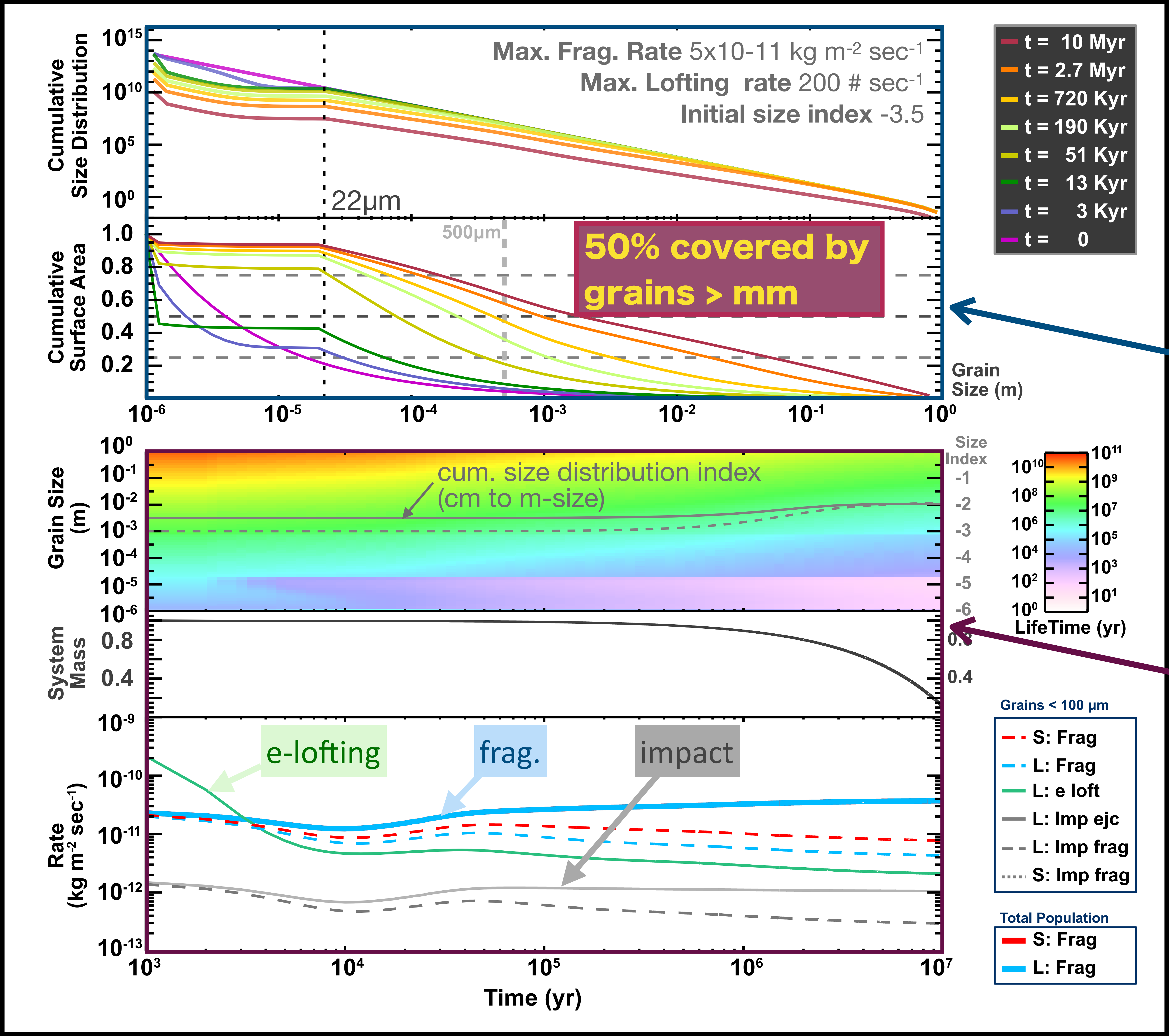






Bennu
0.5 km
Ryugu
0.9 km
Itokawa
0.5x0.3x0.2 km
Toutatis
4.8x2.4x2.0 km
Stein
6.8x5.7x4.4 km
Deimos
15x12x11 km
Gaspra
18x11x9 km
Eros
34x11x11 km
Phobos
27x22x18 km
Lutetia
121x101x75 km
Vesta
573x557x446 km
Ceres
964x964x892 km
Moon
3474 km
Itokawa
Bennu
Ryugu
Toutatis
Stein
Gaspra
Deimos
Phobos
Eros
Lutetia
Vesta
Ceres
Moon
Regolith Depletion
Transition Regime
Regolith Accumulation
DART
Dimorphos
177 x 174 x 116 m
31 x 31 m
Fine-grained Regolith Loss: Electrostatic Lofting & Impact Ejecta
Fine-grained Regolith Production: Fragmentation by Thermal Fatigue & Impacts
Fine-Grained Regolith Loss & Production Rate (kg sec⁻¹)
10⁴
10²
10⁰
10⁻²
10⁻⁴
0.1
1.0
10
100
1000
Object Radius (km)

Asteroid radius: 0.5 km @ 1AU

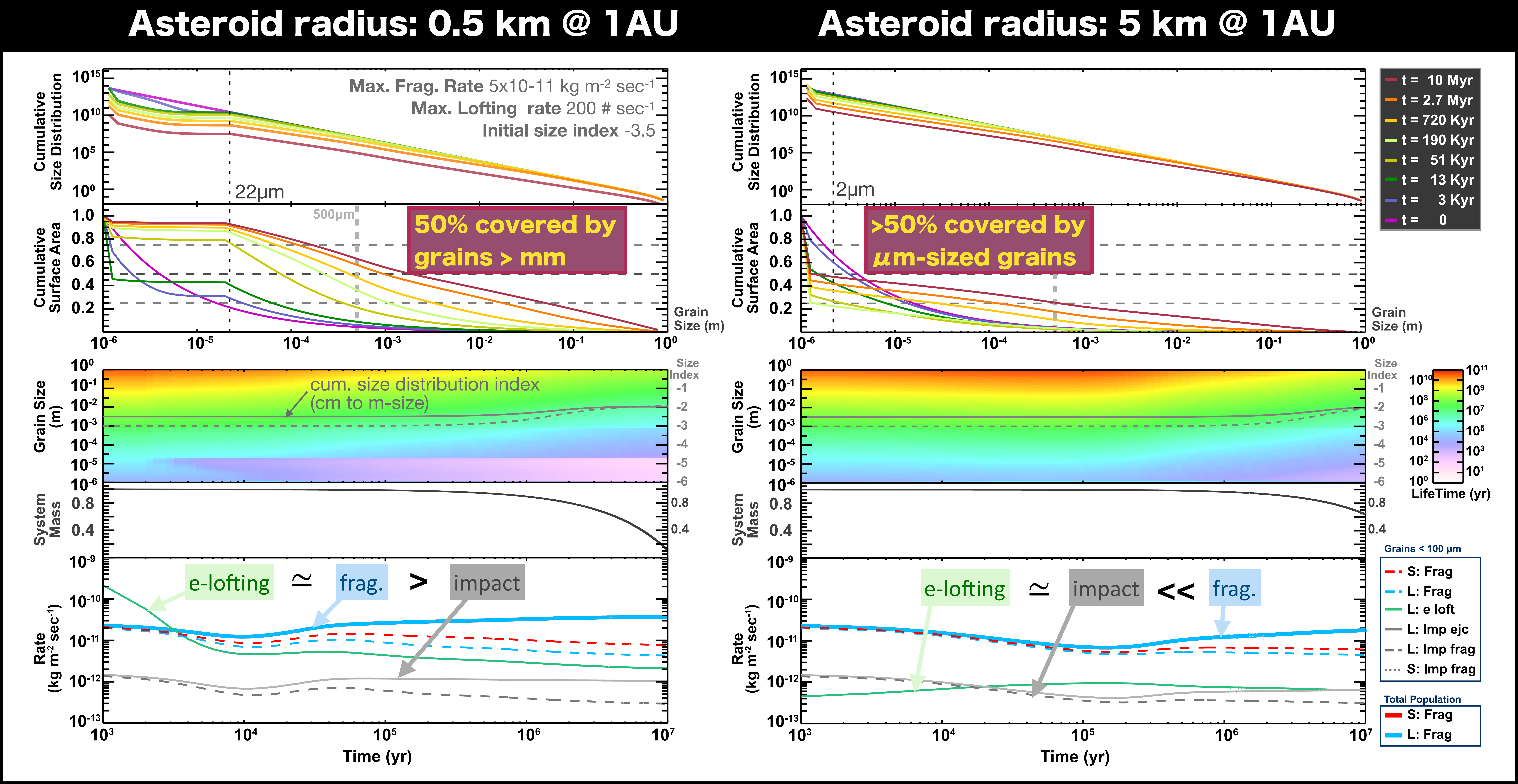


- Asteroid Regolith Size Evolution Modeling
  - Fragmentation
  - Meteoroid Impacts
  - Electrostatic dust lofting

$$\frac{dM_i}{dt} = S_{\mathrm{frag}} - L_{\mathrm{frag}} - L_{\mathrm{eloft}} - L_{\mathrm{imp,f}} + S_{\mathrm{imp,f}} - L_{\mathrm{imp,ej}},$$

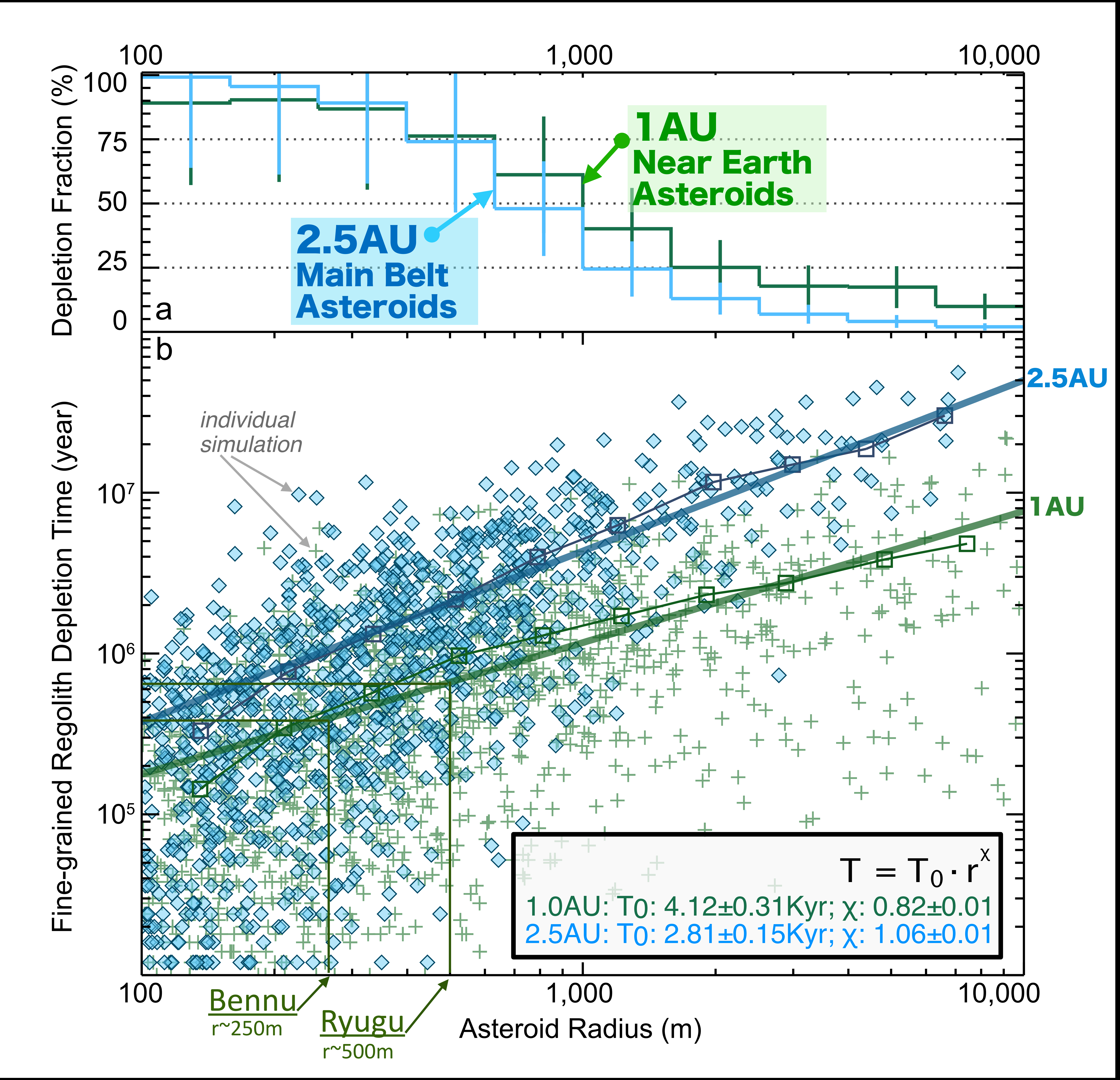
- Grain Size/Area Distribution (upper panels)
  - Grains < 22 µm lost by e-lofting
  - 50% area covered by grains > mm
  - **Coupled regolith size evolution**: larger grains are increasingly eroded after losing coverage/protection from fine grains

- Grain Lifetime & Processing Rates (lower panels)
  - µm-sized grain lifetime: **<10^3 yr**
  - Cum. size index: -3 to -2 (cm to m-sized)
  - Processing rates **vary** with regolith grain size distribution
  - Fragmentation is the dominant process



Asteroid radius: 0.5 km @ 1AU
Asteroid radius: 5 km @ 1AU
Max. Frag. Rate 5x10-11 kg m-2 sec-1
Max. Lofting rate 200 # sec-1
Initial size index -3.5
22μm
2μm
500μm
50% covered by grains > mm
>50% covered by μm-sized grains
Cumulative Size Distribution
Cumulative Surface Area
Grain Size (m)
cum. size distribution index (cm to m-size)
Size Index
System Mass
Rate (kg m-2 sec-1)
Time (yr)
LifeTime (yr)
e-lofting ≃ frag. > impact
e-lofting ≃ impact << frag.
t = 10 Myr
t = 2.7 Myr
t = 720 Kyr
t = 190 Kyr
t = 51 Kyr
t = 13 Kyr
t = 3 Kyr
t = 0
Grains < 100 μm
S: Frag
L: Frag
L: e loft
L: Imp ejc
L: Imp frag
S: Imp frag
Total Population
S: Frag
L: Frag

Asteroid Regolith Evolution Modeling



- A Monte-Carlo approach to examine the average regolith evolution path of asteroids < 10 km radius
- Fine-grained regolith is considered depleted *when > 50% area is covered by grains > 0.5 mm*
- **Results**
  - Sub-km asteroids likely lose fine-grained regolith (>75% simulated asteroids with radii < 600m)
  - Fine-grained regolith depletion timescales for small asteroids are only a few Myrs, much shorter than their dynamical lifetime (NEAs: ~10 Myr; MBAs: ~100 Myr).
  - Because the higher UV flux, fine-grained regolith loss is more significant for NEA than MBA.

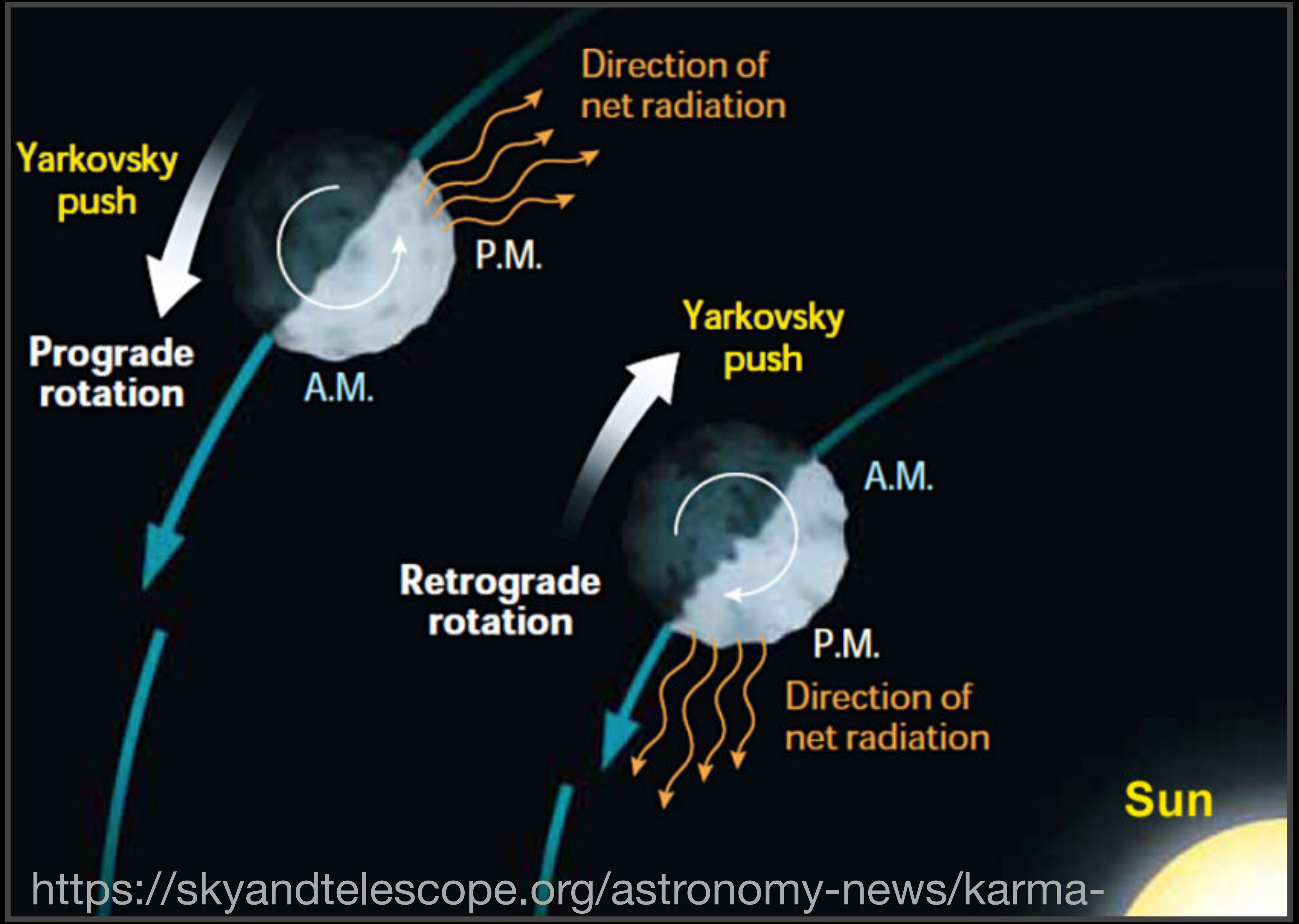
Implications

Effects on Orbital Evolution

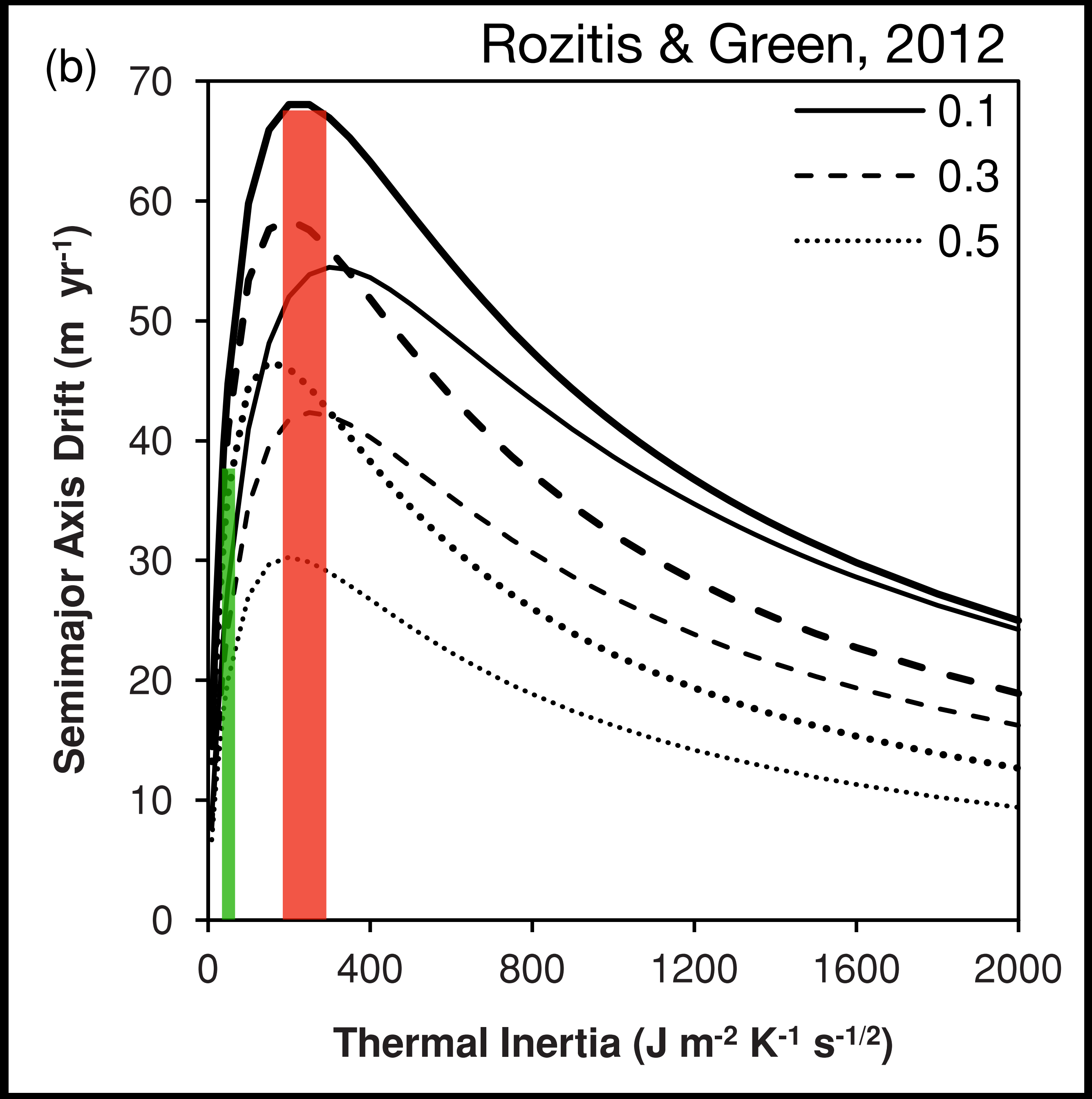
- The NEAs is supplied through the inward transport of MBAs by orbital resonances with Jupiter and Saturn, which is determined by the Yarkovsky drift of small MBAs to resonance orbits (Bottke+06).

(fine-grained rich) (fine-grained poor)

- Increasing thermal inertia from 50 to 200-300 J m^{-2} K^{-1} $s^{-1/2}$ leads to ~2x faster Yarkovsky drift (Rozitis & Green, 2012), allowing asteroids without fine-grained regolith to reach orbital resonance with the giant planets .
- Small MBAs depleted in fine-grained regolith are more likely to be de-orbit and become NEA, due to higher Yarkovsky drift.



https://skyandtelescope.org/astronomy-news/karma-family-might-send-asteroids-near-earth/



Implications

Effects on VIS-NIR Spectra

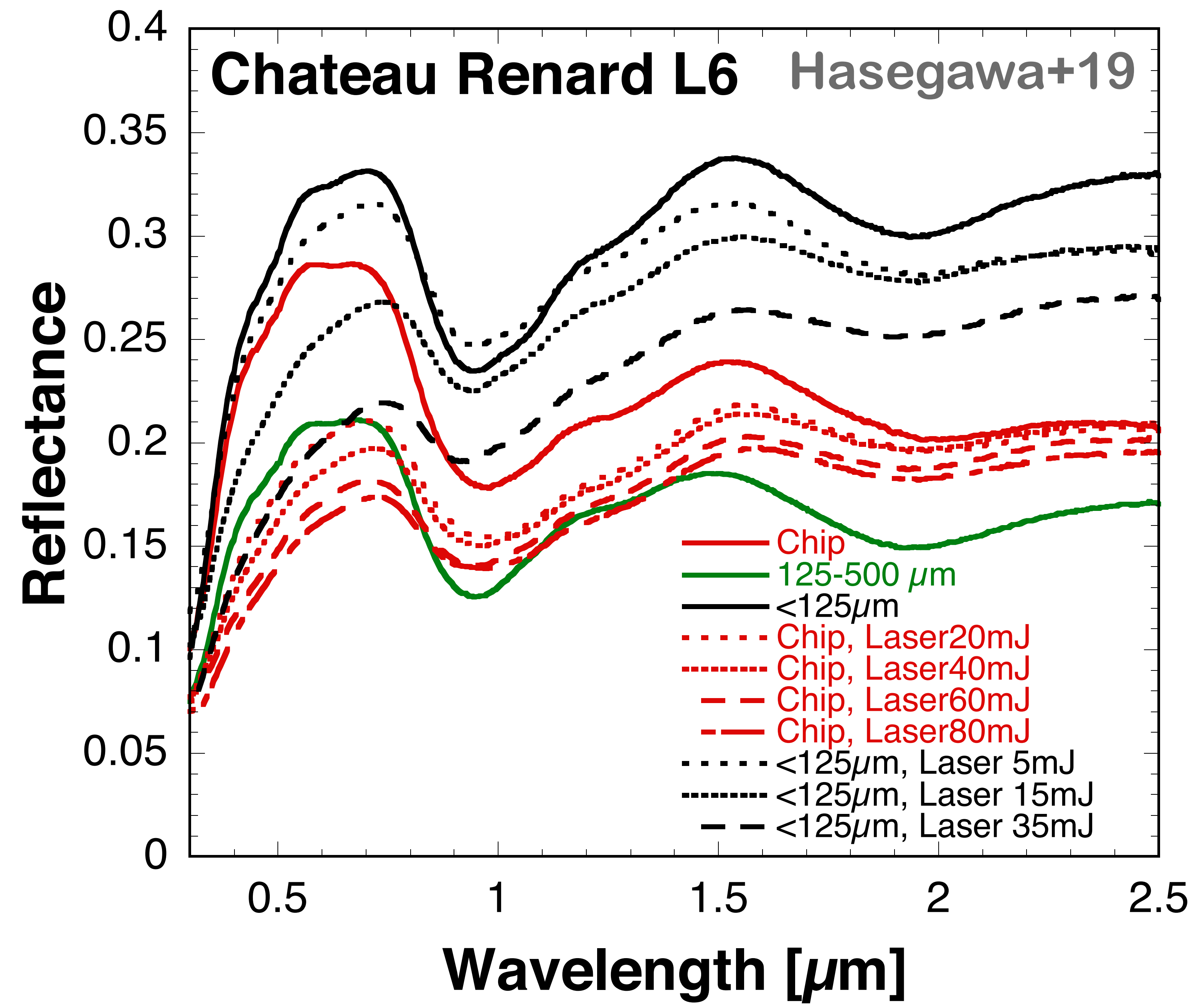
- Grain size vs. Space weathering (SpWe)

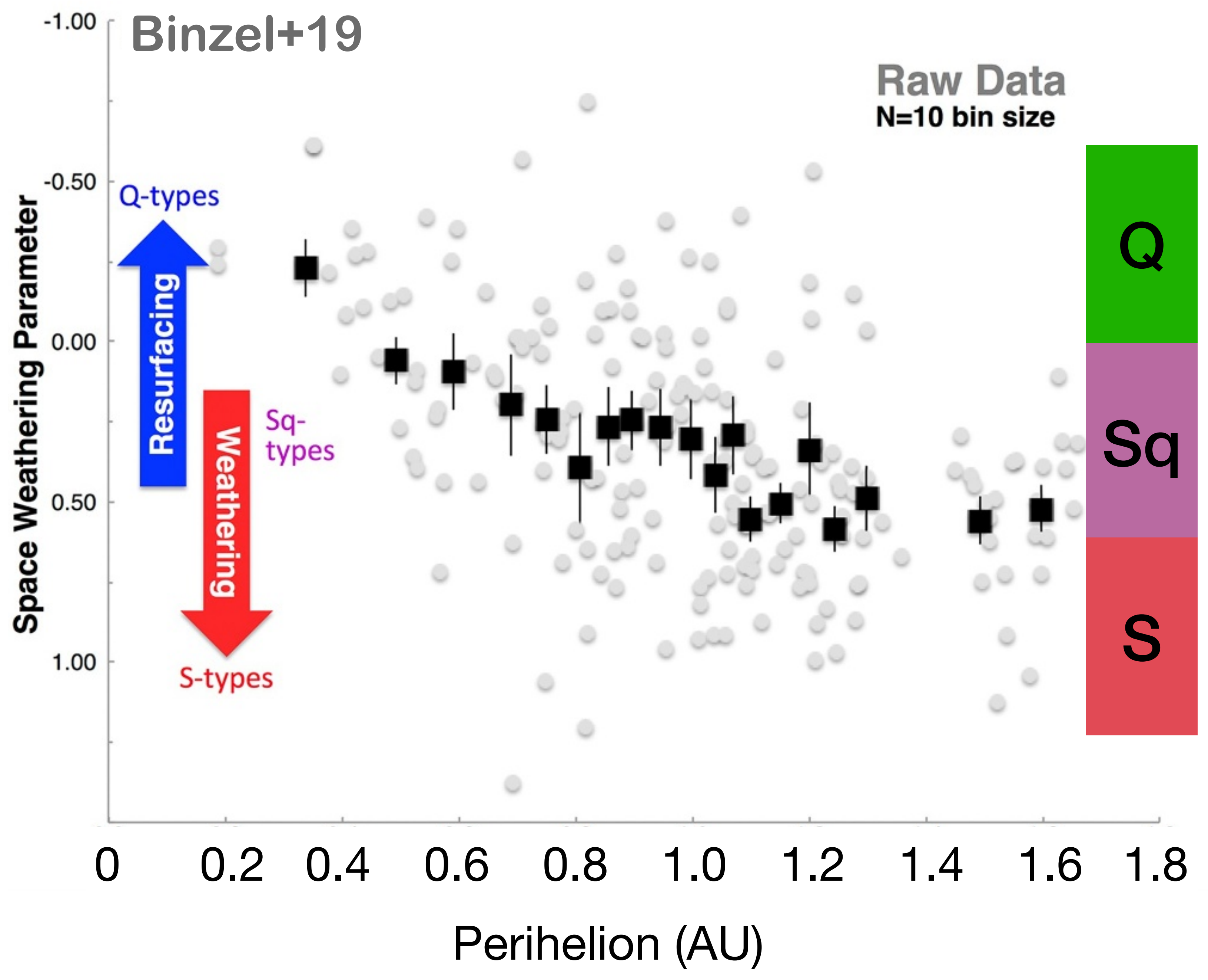
- Removing fine-grained material leads to a coarser surface
  ➡ bluer spectra
- Increasing SpWe ➡ redder spectra

- S-complex (S, Sq, Q-types) asteroids

- Current hypothesis: ordinary chondrite (OC) composition with different degree of SpWe.
- Q-type: mostly with diameter < 5 km & at lower perihelion (Binzel+04;+19)
- More Q-type NEA than MBA (Lin+15)
- Large OC grains with SpWe show Q-type spectra (Hasegawa+19)

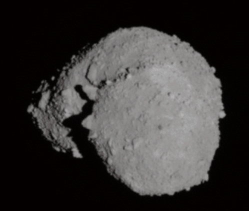
➡ *S-Q transition may reflect the abundance of fine-grained regolith*, in addition to other effects (DeMeo+23)





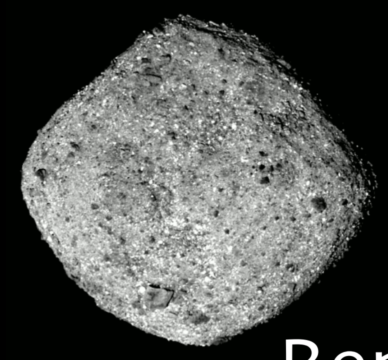
Summary

- Processes considered in asteroid regolith size evolution simulation:
  (1) thermal fragmentation, (2) meteoroid impacts, & (3) electrostatic dust lofting.
- Low-speed (~ m/s) electrostatic dust removal drives a coupled regolith loss on sub-km asteroids.
- Modeling results are consistent with recent mission results:



  - Surface residence time for grains 10s µm is than **$< 10^3$ yrs**, consistent with Itokawa particles (Nagao+11, Noguchi+14)

  - Modeled regolith cum. size distribution indices range from **-3** to **-2**, consistent with Bennu & Ryugu results (e.g., Michikami+19, Burke+21).

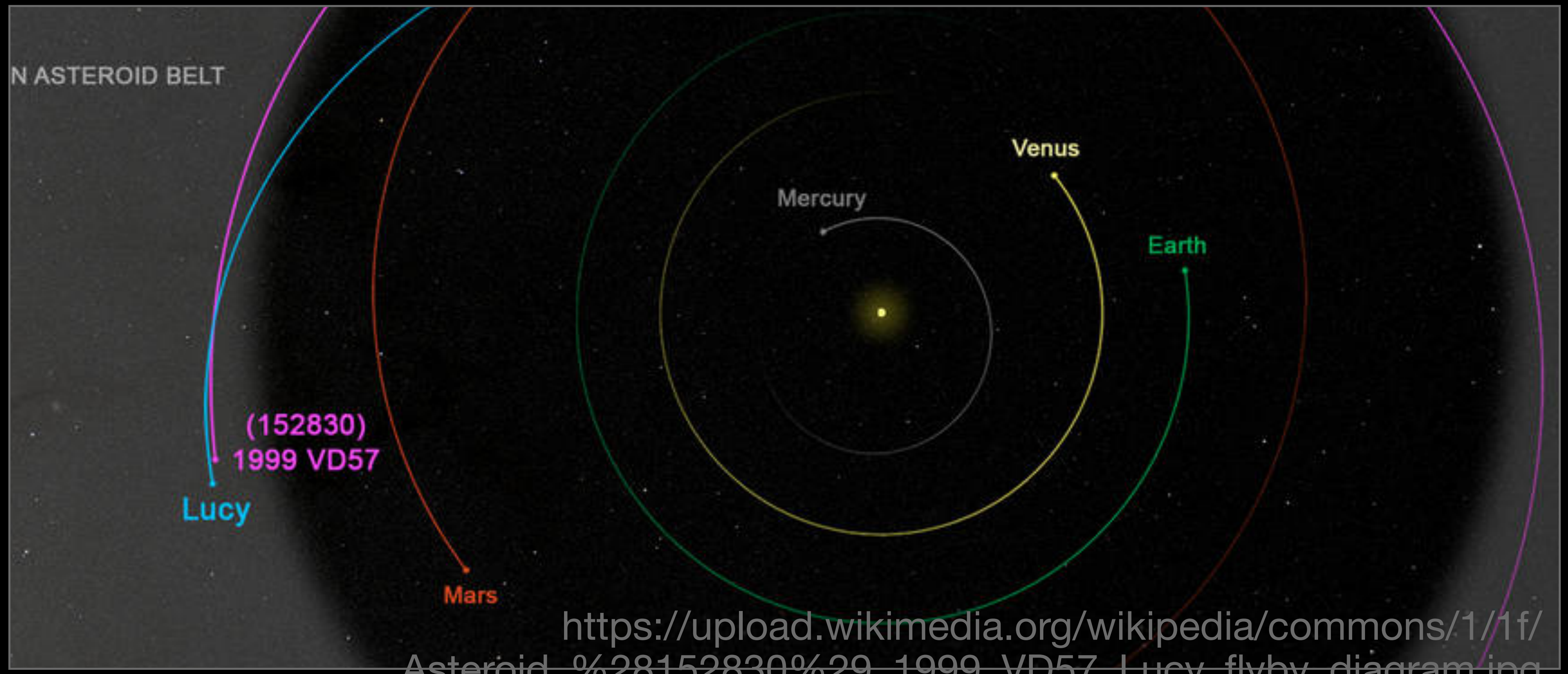


- Sub-km asteroids likely deplete in fine-grained regolith and show a boulder-rich scenery.
- Depletion timescale: **1.1/4.3 Myr** @ 1AU/2.5AU for 1-km-radius asteroids << dynamical lifetime.
- Implications: The orbital evolution and surface reflectance spectra of small asteroids are likely coupled to their regolith evolution, related to the delivery of NEAs and distributions of S-complex asteroids.

Ongoing / Future Work

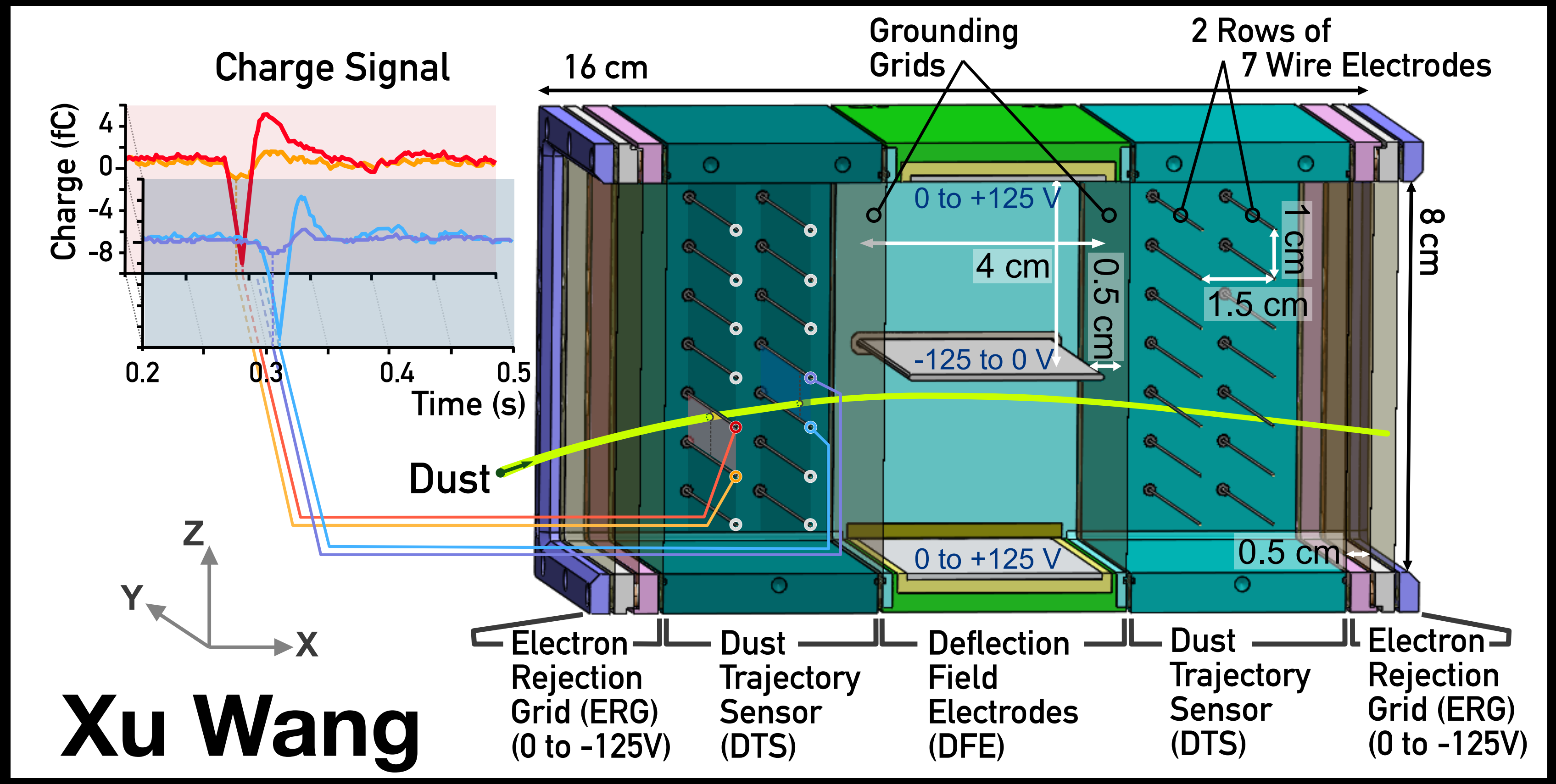
- **Reflectance Spectroscopy + eDust Transport**
  - Size-sorting effect on regolith reflectance spectra
  - See **Elena Opp**'s presentation

- **Lucy images of small Main Belt Asteroids**
  - 152830 Dinkinesh
    - C/A 450 km on 2023/11/01
    - Dimension: 0.82 km
    - Semi-major axis: 2.19 AU
  - 52246 Donaldjohanson
    - C/A 922 km on 2025/04/20
    - Dimension: 3.9 km
    - Semi-major axis: 2.38 AU

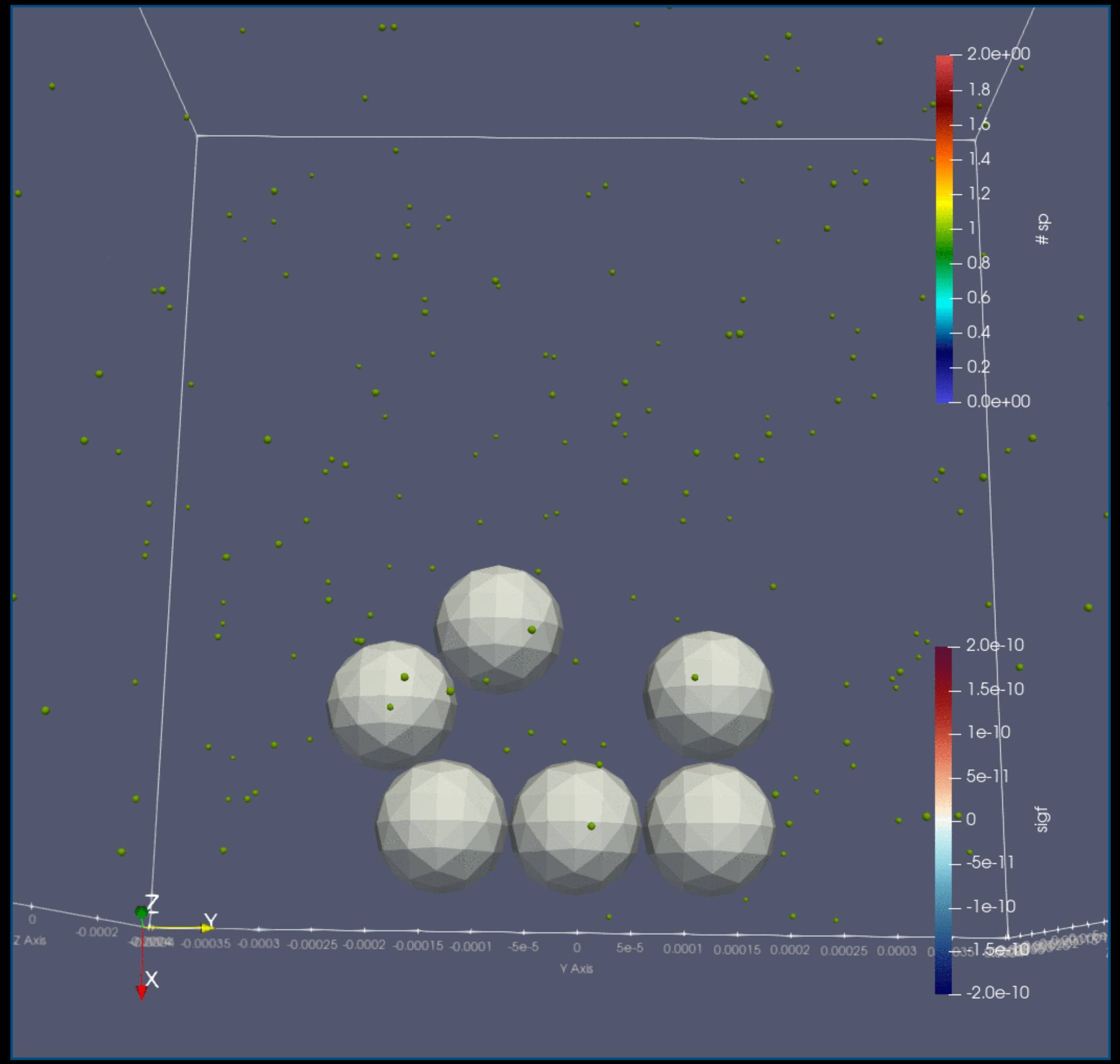


https://upload.wikimedia.org/wikipedia/commons/1/1f/Asteroid_%28152830%29_1999_VD57_Lucy_flyby_diagram.jpg

- **Electrostatic Dust Analyzer**



- **PIC-simulation of eDust Lofting**



Jan Deca