Fate and Dynamics of Ejecta Liberated by the Proposed DART Impact

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Key Questions

- This talk summarizes recent activities at JPL to simulate the dynamics of the DART impact ejecta as it moves through and exits the Didymos binary asteroid system.
- This work is aimed at answering several key questions relevant to the deflection experiment, and secondarily to operation of a possible observer spacecraft in the vicinity:
  - How large of a crater is produced? Over what duration? How much material is ejected?
  - What fraction of ejecta return impacts, vs. transfer impacts, vs. escapes?
  - How long does ejecta persist on way to return / transfer / escape? i.e. What are ejecta clearing timescales? vs. particle size?
  - Will there be many particles left at given times past impact (e.g.15days)?
  - With what size-frequency distribution?
  - Where do return / transfer impacting ejecta accumulate on bodies?
  - What are spatial densities and fluxes of critical quantities vs. time throughout relevant volume surrounding Didymos barycenter?

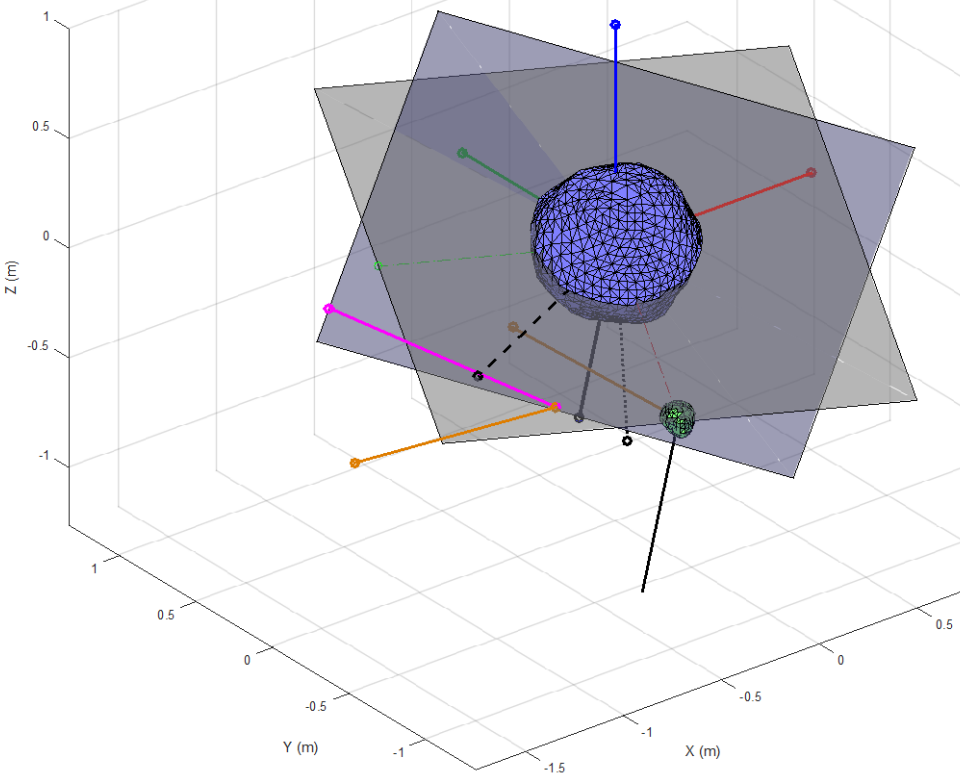
System Setup / Modeling - Didymos

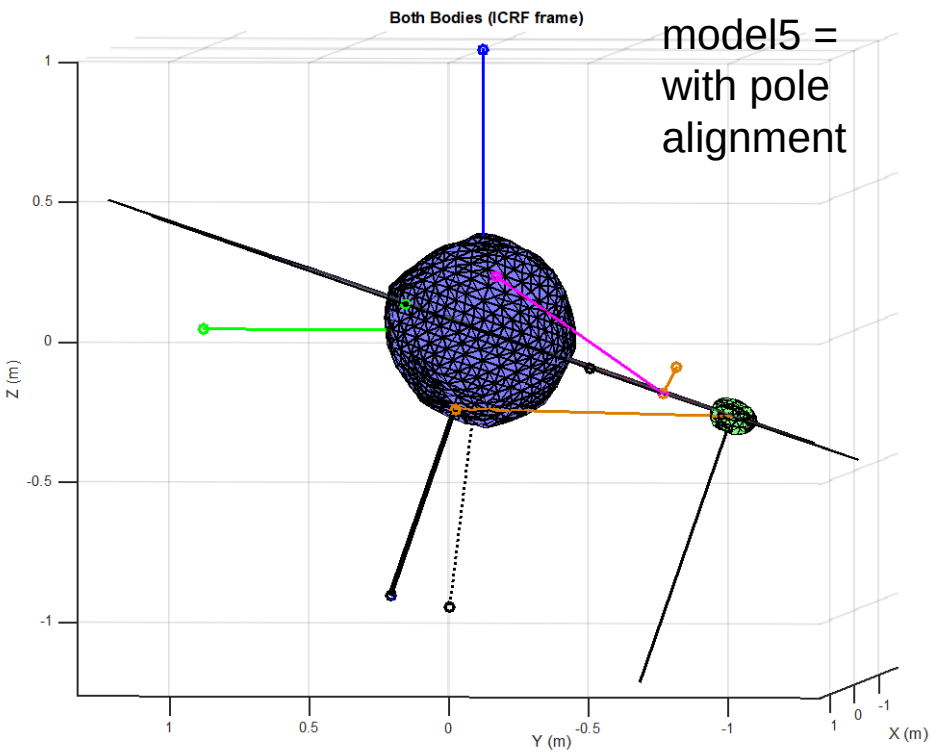
- Conformed to latest version of DRM
- Used Didymos primary (Didymain) shape model provided by Naidu & Benner as of Jan. 4, 2016 that is consistent with aligning primary spin pole & mutual orbit pole → see Naidu's talk
- Explored 3 options for Didymos secondary (Didymoon) shape:
  - mesh filling the ellipsoid with DRM's semi-axes.
  - rescaled DP107 secondary.
  - rescaled KW4 secondary.
- Propagated F2RBP dynamics of system, in cases with pole alignment and with 3° pole misalign-ment, for e_o= {0,1,2,3}%, with ω_{Bo} tweaked for most "relaxation" of dynamics

System Properties	
Didymain	GM = 34.9016 +3.7582 / -1.8125 m^3/s^2 Mass = 522.9e9 +56.3e9 / -27.2e9 kg Mean radius = 390.038 +/-39.004 m Density = 2.1040 +1.0930 / -0.6053 g/cc Spin period = 2.2600 +/- 0.0001 hr
Didymoon	GM = 0.3232 +0.0874 / -0.0579 m3/s2 Mass = 4.843e9 +1.309e9 / -0.867e9 kg Mean radius = 81.908 +12.482 / -11.702 m Density = 2.1040 +1.0930 / -0.6053 g/cc Spin period = 11.920 +0.004 / -0.006 hrs (**synchronous assum.**)
Mutual Orbit	Mean separation = 1.180 +0.040 / -0.020 km Eccentricity = 0.02 +0.01 / -0.02 Orbit period = 11.920 +0.004 / -0.006 hrs Orbit pole longitude = 310 +30/-175 deg (EMO2000) Orbit pole latitude = -84 +8/-6 deg (EMO2000) Binary obliquity = 174 +6/-8 deg.

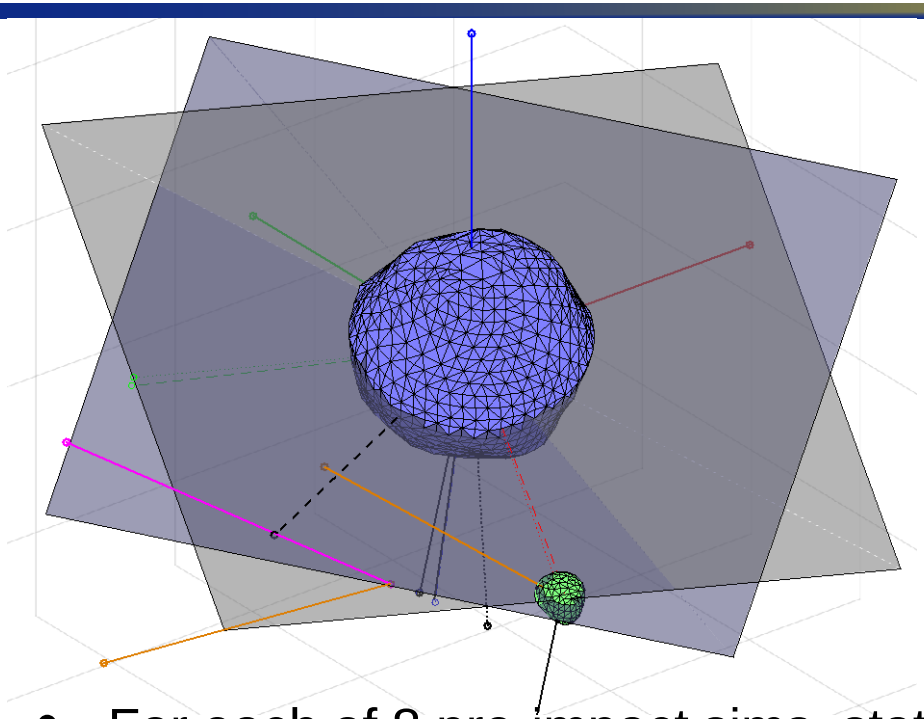
System Setup / Modeling - Didymos

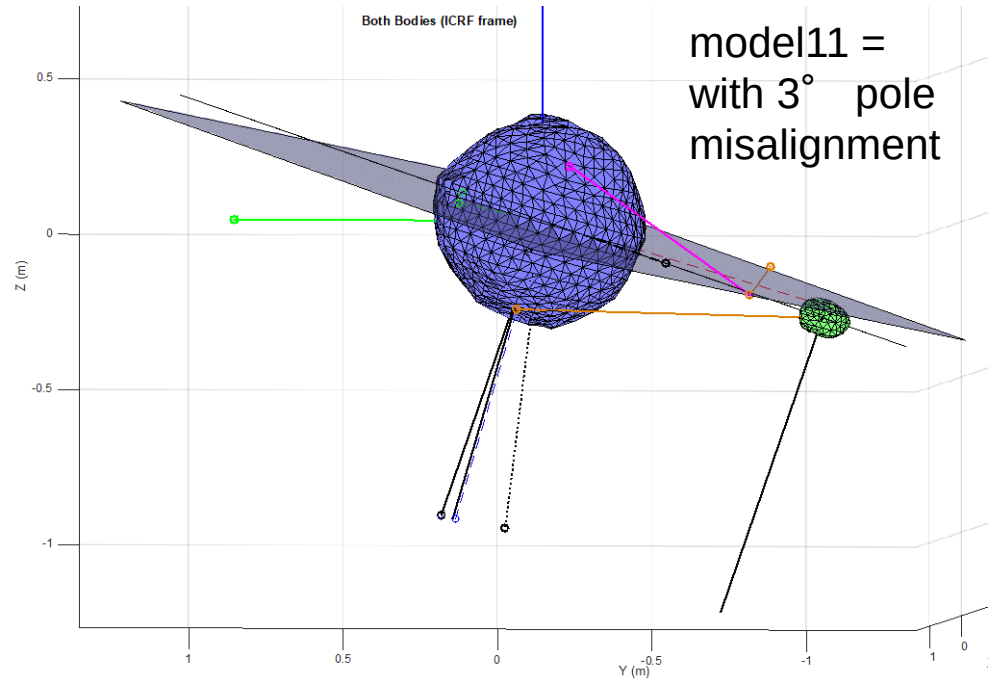
- F2RBP sims from pre-AIM-arrival epoch past impact epoch
- Relative velocity vector of DART w.r.t. inertial space at impact epoch obtained from J. Atchison @APL, along with desired critical angles (impact plane angle = -11.7157°, solar phase angle = 47.035089°, impact angle = 168.28426°)
- Initial mutual orbit "phase" of Didymoon adjusted to produce desired precise impact geometry at desired impact epoch





System Setup / Modeling - Didymos

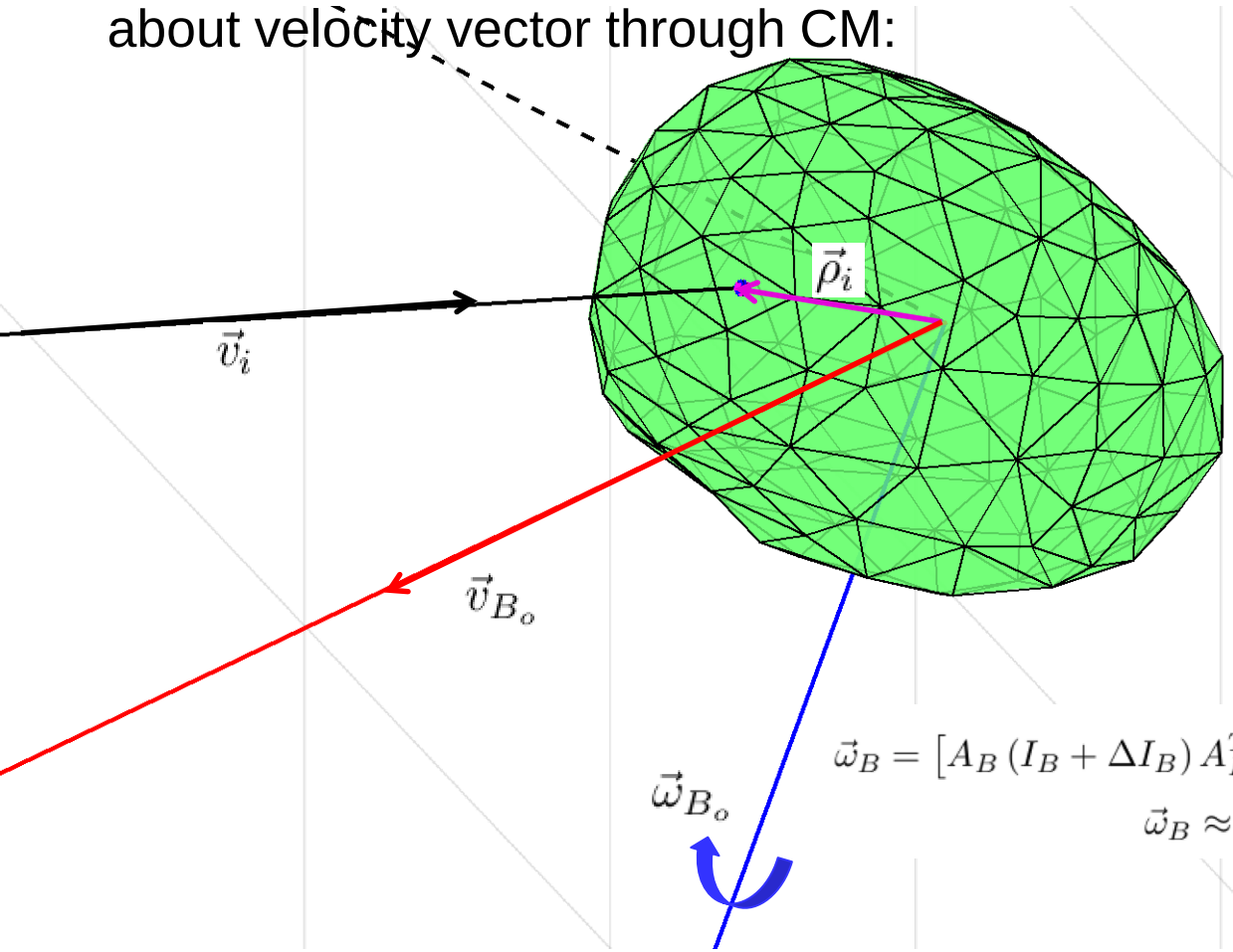


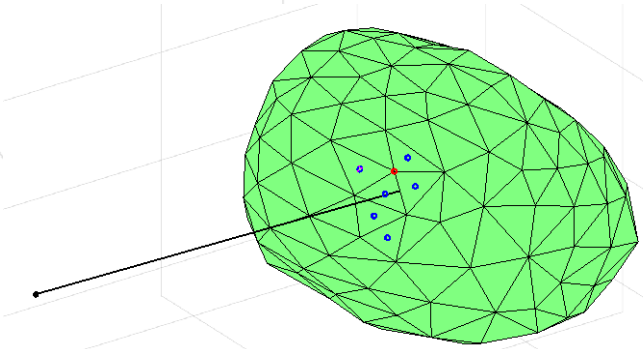


- For each of 8 pre-impact sims, state closest to impact epoch is picked off, impulsively changed to initialize post-impact sims
- Selected a few impact points compatible with expected dispersion about ideal approach path through Didymoon CM
- Also varied β={1, 1.2, 2}
- From among 96 post-impact sims, selected “low”, “moderate”, and “high” excitation cases → see Chesley’s talk
- Used each as “substrate” F2RBP motion for ejecta simulations

Impact Location & Impulse Application

- Knowledge error in impact supposedly ~1 m? (1σ?)
- Control error on impact point to be <15m w.r.t. center of figure – amplified this by 50% due to possible COF offset from CM
- Used as impact points the facet centers falling within “tube” of this radius about velocity vector through CM:





$$\vec{v}_B = \frac{\beta\, m_i\, \vec{v}_i + m_B\, \vec{v}_{B_o}}{m_i + m_B}$$

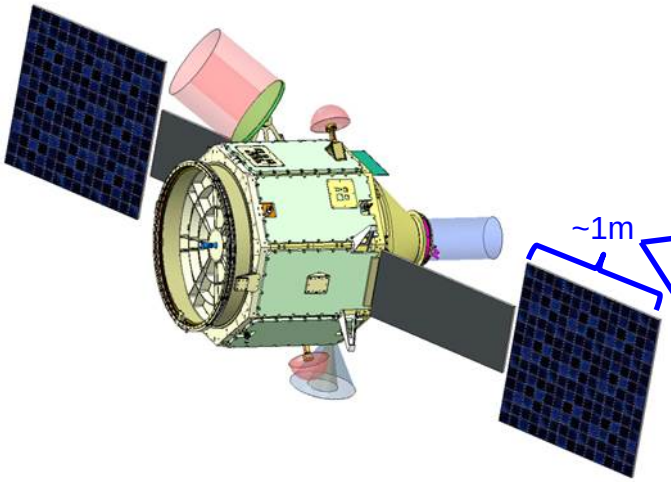
$$\vec{v}_B \approx \frac{\beta\, m_i}{m_B}\, \vec{v}_i + \vec{v}_{B_o}$$

$$\vec{\omega}_B = \left[A_B\,(I_B + \Delta I_B)\,A_B^T\right]^{-1} \left(\beta\, m_i\, \left(\vec{\rho}_i \times \vec{v}_i\right) + A_B\, I_B\, A_B^T \vec{\omega}_{B_o}\right)$$

$$\vec{\omega}_B \approx \left[A_B\, I_B\, A_B^T\right]^{-1} \left(\beta\, m_i\, \left(\vec{\rho}_i \times \vec{v}_i\right)\right) + \vec{\omega}_{B_o}$$

Methodology: Crater Excavation Physics

- Ejecta particles liberated from expanding (w/ time) circular crater footprint – centered on chosen "launch facet", displaced 0.001 body mean radii above, but kept parallel to, that facet
- However, crater modeling is consistent w/ normal impact…
- Adapted crater scaling law equations formulated as in Housen et al. 1983, *JGR* 88, B3, 2485-2499 and Housen & Holsapple 2011, *Icarus* 211,856-875
- In notation of latter paper, parameters used were:



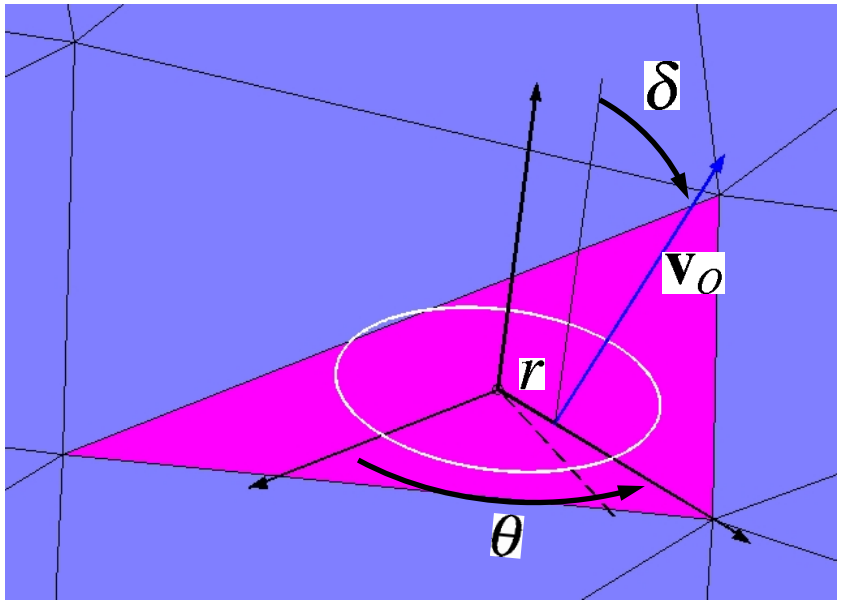
Parameter	Value	units	Param.	Value
facet ID **	171,135,167	--	ν	0.4
g **	(5.13,5.69,6.07)e-5	m s^{-2}	μ	0.41
a	0.5	m	C_1	0.55
m	300	kg	k	0.30
U	7027.1	m s^{-1}	H_1	0.59
δ	1018.59	kg m^{-3}	H_2	0.39
ρ	2103.99	kg m^{-3}	n_1	1.2
porosity	35%	n/a	n_2	1
Y	100	--	p	0.3

Methodology: Ejecta Initial Position, Velocity

- Realistically calculated impact ejecta field's initial (i.e. at launch) properties
- Position of each particle within crater footprint randomly drawn:

  θ using $2\pi \mathrm{U}$

  $0 \le r \le R_c$ using $R_c \mathrm{U}^{1/3}$
- Calculated launch time relative to time of impact t_o
- Small (1%) random deviation and constraint placed on launch radius



- Calculated initial surface-relative velocity vector magnitude
- Small (1%) random deviation, then constraint on this velocity magnitude too
- Velocity vector tilt δ computed from 4th-order polynomial fit interpolated from ejection angle data in Cintala et al. 1999, *MPS* 34, 605-623.
- Surface-relative initial state transformed into inertial barycentric i.c.'s

Resulting Crater Properties

- Cratering is consistently within the strength regime, so although local g varies, crater properties are the same:

Feature / Characteristic of Cratering Event	Value	units
impact @171, low excitation binary dynamics shape-based gravity and actual shape rotation net normal surface acceleration	5.13×10^{-5}	m s^{-2}
impact @135, moderate excitation binary dynamics , shape-based gravity and actual shape rotation net normal surface acceleration	5.69×10^{-5}	m s^{-2}
impact @167, high excitation binary dynamics , shape-based gravity and actual shape rotation net normal surface acceleration	6.07×10^{-5}	m s^{-2}
Radius of crater produced, R_c	**13.693**	**m**
Crater formation duration, T_c	**≈107**	**s**
Total mass of ejecta	**1.6204×10^{6}**	**kg**
Maximum facet-relative launch speed (at the impactor radius)	**1204.53**	**m s^{-1}**
Minimum facet-relative launch speed (at outer rim of final crater)	0	m s^{-1}

Methodology: Ejecta Propagation Approach

- On top of each substrate F2RBP motion case, did restricted "full" three body problem (RF3BP) propagation of N=1e6 ejecta particles under all relevant dynamical effects:
  - Shape-model-derived full polyhedral body gravity of both Didymoon and Didymain, per method in Werner & Scheeres 1997, *CMDA* 65, 313-344.
  - Body impact detection included, no convergence issues close to surface
  - Differential solar tide acceleration included
  - Differential Solar Radiation Pressure (SRP) acceleration included
  - For SRP, modeled shadowing by polyhedral shape models
  - Also accounted for realistic particle size-frequency distribution and particle optical properties ➔ very important w.r.t. SRP!

- All ejecta simulations run out to 60 days post-impact duration

Methodology: Particle Mass, Size Distribution

- Probability distribution functions for mass & number abundance have power law fit of form: $pdf\left(x(D)\right) = D^{-a} / 10^{b}$

  want to preserve value of this

  but can adjust this…

- Sampled quanta of mass w/ average D drawn from $pdf\left(mass(D)\right)$

$$\begin{bmatrix}\text{fraction of mass between} \\ \text{sizes } D_1 \text{ and } D_2\end{bmatrix} = \frac{D_2^{-a+1} - D_1^{-a+1}}{(-a+1)\,10^b}$$

$$D_1,\ D_2,\ a \rightarrow b\ =\ \log_{10}\left(\frac{D_2^{-a+1} - D_1^{-a+1}}{-a+1}\right)$$

Then draw with: $D\ =\ \left(D_1^{-a+1} + (-a+1)\,10^b\,U\right)^{\frac{1}{-a+1}}$

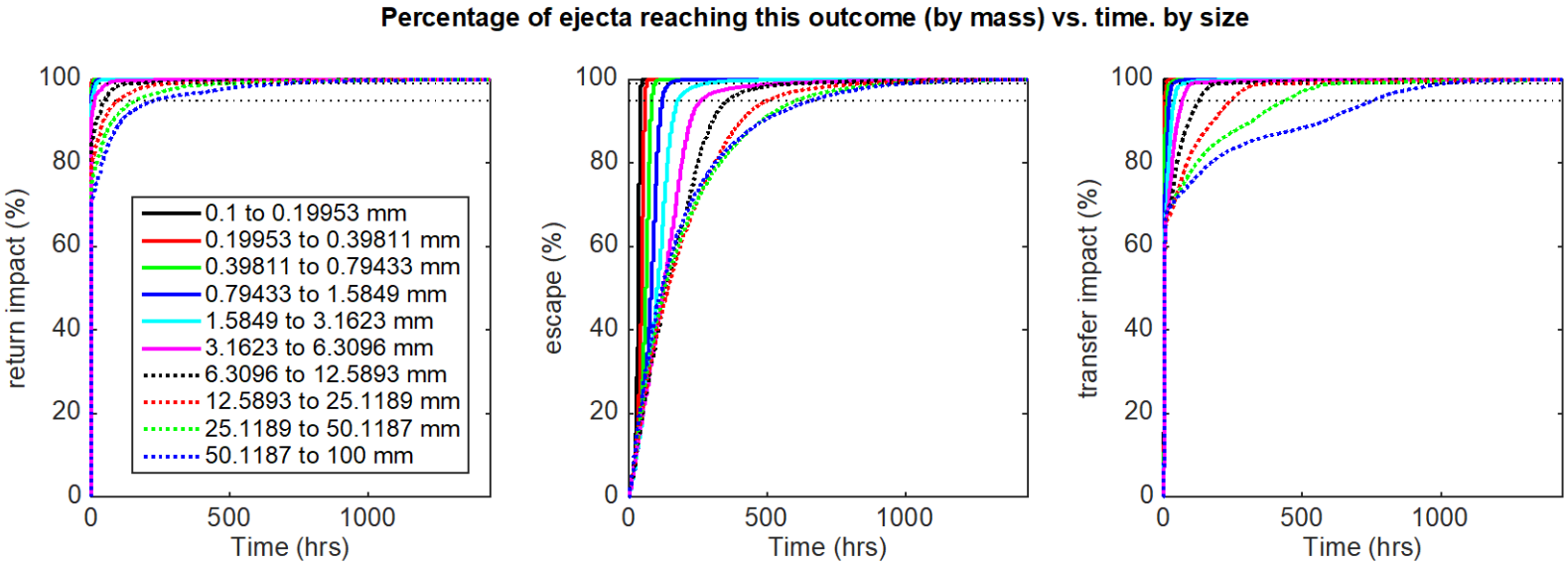
- Later switched to uniformly drawing $\log_{10} D$ (in mm) from [-1,2]

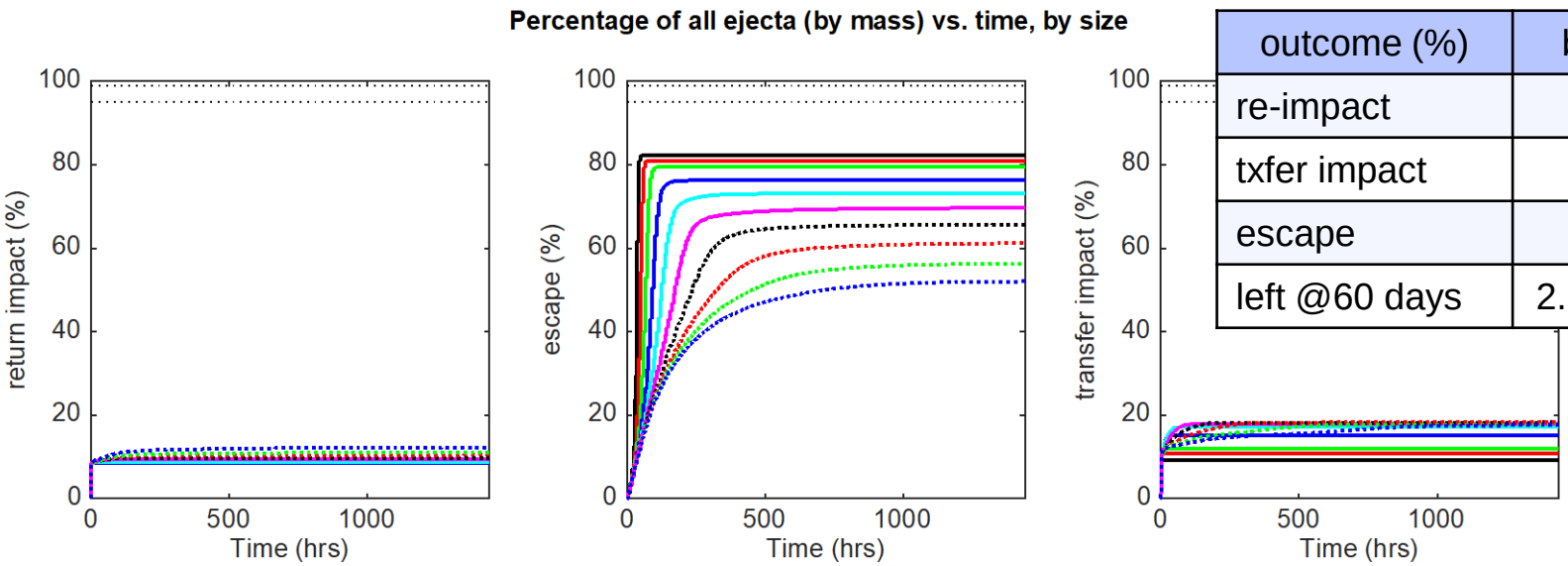
- Mass quanta sampling means we must scale each tracer particle for each mass quantum by multiplier K :

$$K_i = \frac{1}{N_i}\begin{bmatrix}\text{\# of particles in} \\ \text{interval } [D_{p_i}, D_{pp_i}]\end{bmatrix} = \frac{1}{N_i}\left(\frac{\text{total mass of ejecta}}{\text{avg. mass of particle with } D}\right)\begin{bmatrix}\text{fraction of total mass in} \\ \text{interval } [D_{p_i}, D_{pp_i}]\end{bmatrix}$$

$$K_i = \frac{3\,k\,\rho_B\,R_c^3}{N_i\,\pi\,\rho_{GRAIN}}\left(\frac{1}{D_{pp_i}^3} + \frac{1}{D_{p_i}^3}\right)\left[\frac{D_{pp_i}^{-a+1} - D_{p_i}^{-a+1}}{(-a+1)\,10^b}\right]\ \text{, for } i \in \{1, 2, \ldots, n_{bin}\}$$

Outcome Time Histories, low excitation case



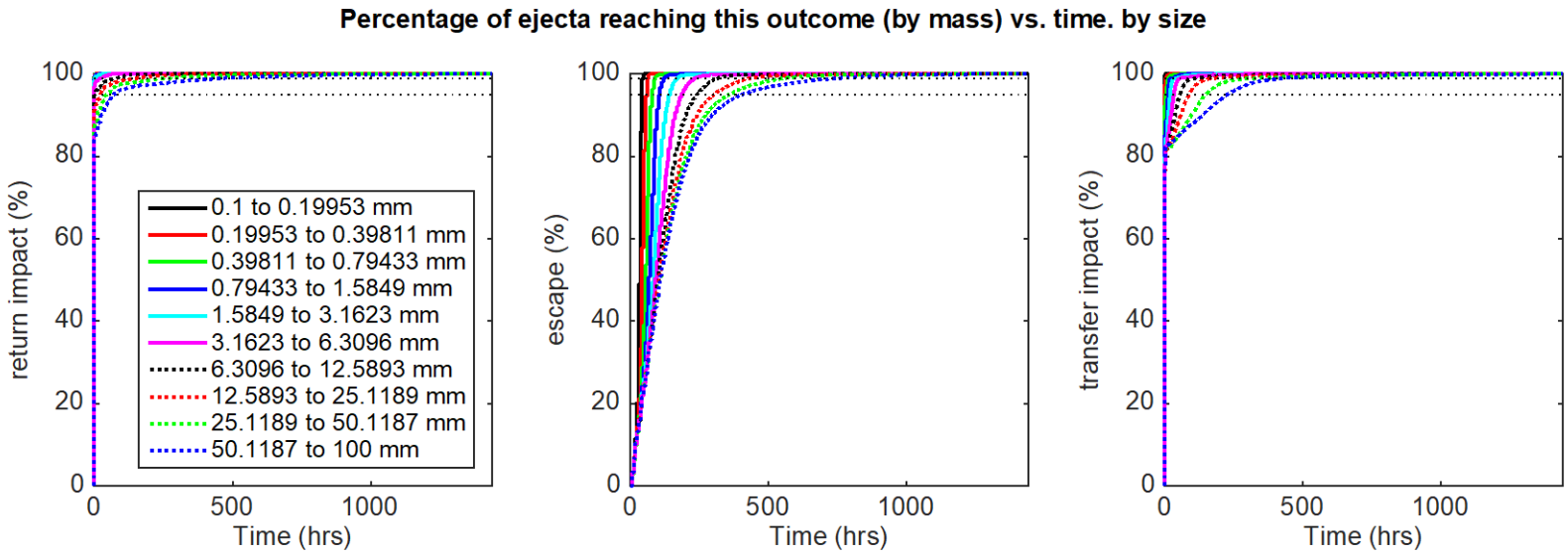


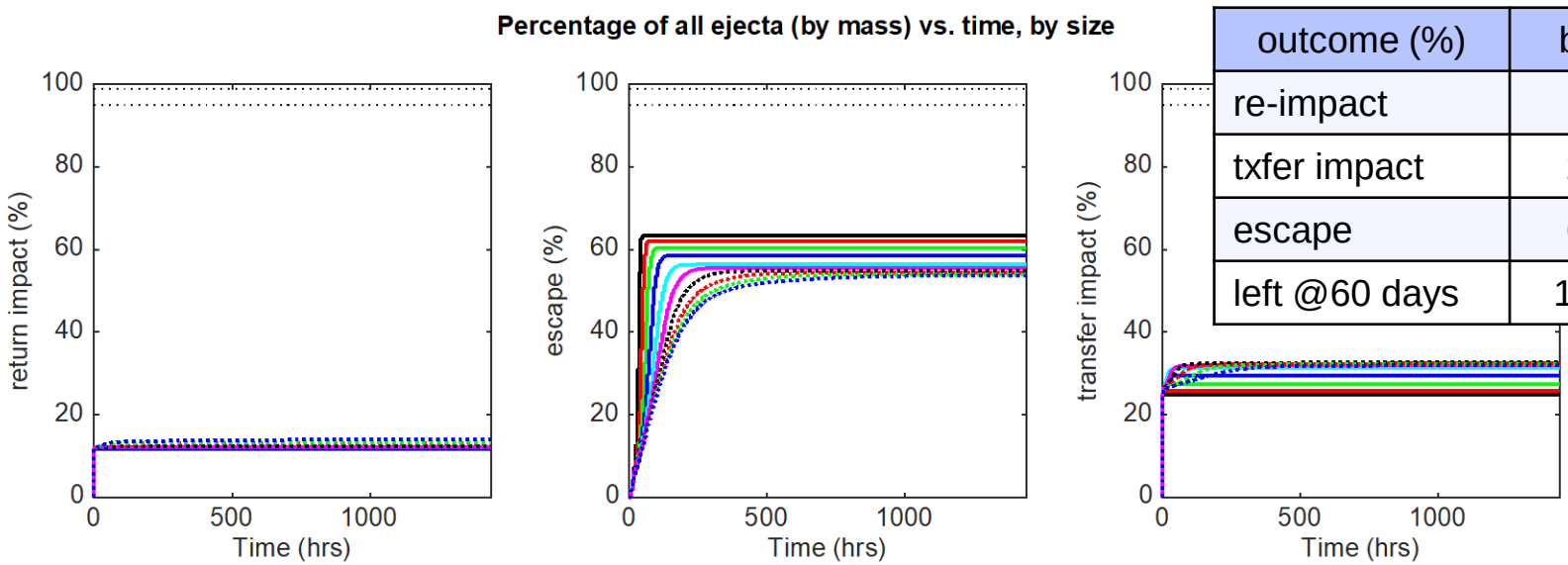
outcome (%)	by #	by mass
re-impact	8.52	10.94
txfer impact	9.34	17.55
escape	82.14	58.62
left @60 days	2.28e-3	12.88

Clearing Timescales, low excitation case

all times are in hours, to nearest 10 minutes	reached 95% of re-impact	reached 99% of re-impact	reached 95% of escape	reached 99% of escape	reached 95% of transfer impact	reached 99% of transfer impact
whole pop.:	0.1667	0.3333	48.1667	72.1667	2.3333	7.8333
1-20 :	0.1667	0.1667	42.1667	42.1667	2.1667	2.3333
21-40 :	0.1667	0.5000	54.1667	60.1667	2.8333	8.6667
41-60 :	0.1667	2.1667	78.1667	90.1667	10.5000	18.5000
61-80 :	0.1667	11.1667	114.1667	132.1667	18.3333	31.5000
81-100:	1.5000	16.3333	168.1667	240.1667	32.6667	62.3333
101-120:	10.6667	49.1667	246.1667	504.0000	61.0000	96.0000
121-140:	46.3333	103.5000	330.1667	570.0000	110.1667	184.8333
141-160:	83.8333	257.5000	480.1667	822.0000	214.8333	379.5000
161-180:	151.8333	453.1667	594.0000	972.0000	382.5000	580.5000
181-200:	211.6667	622.1667	654.0000	978.0000	688.1667	958.6667

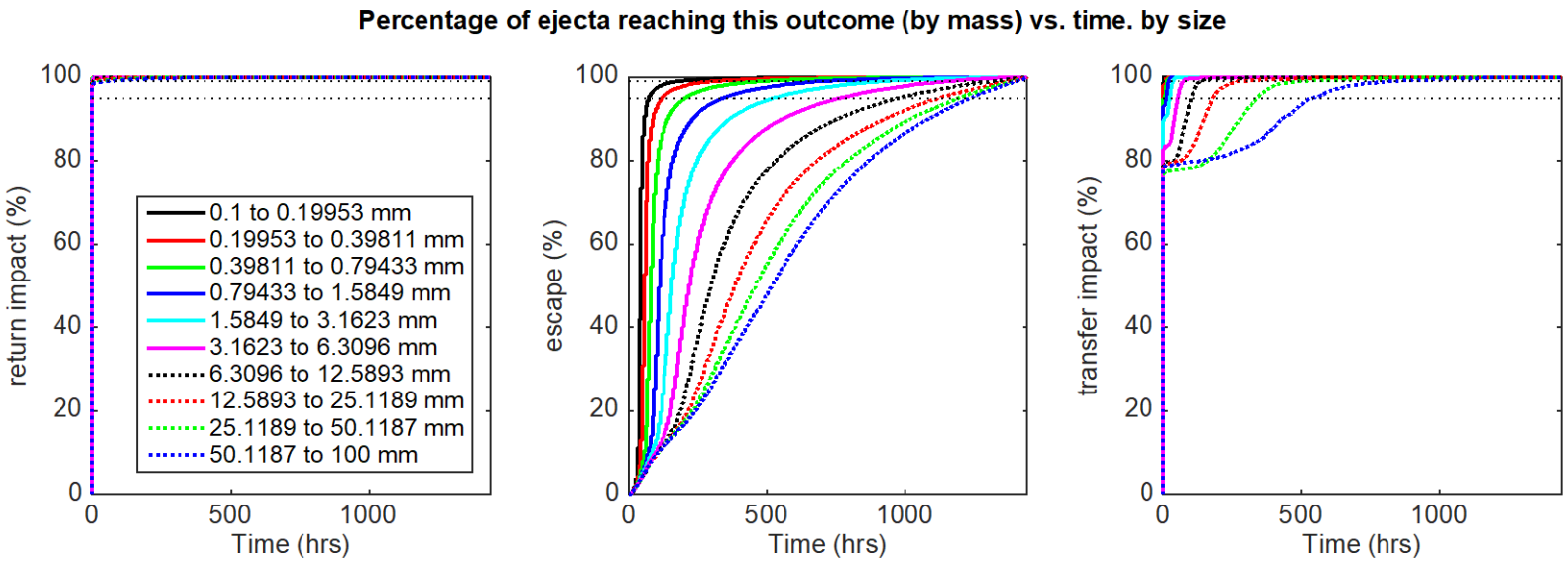
Outcome Time Histories, moderate excitation

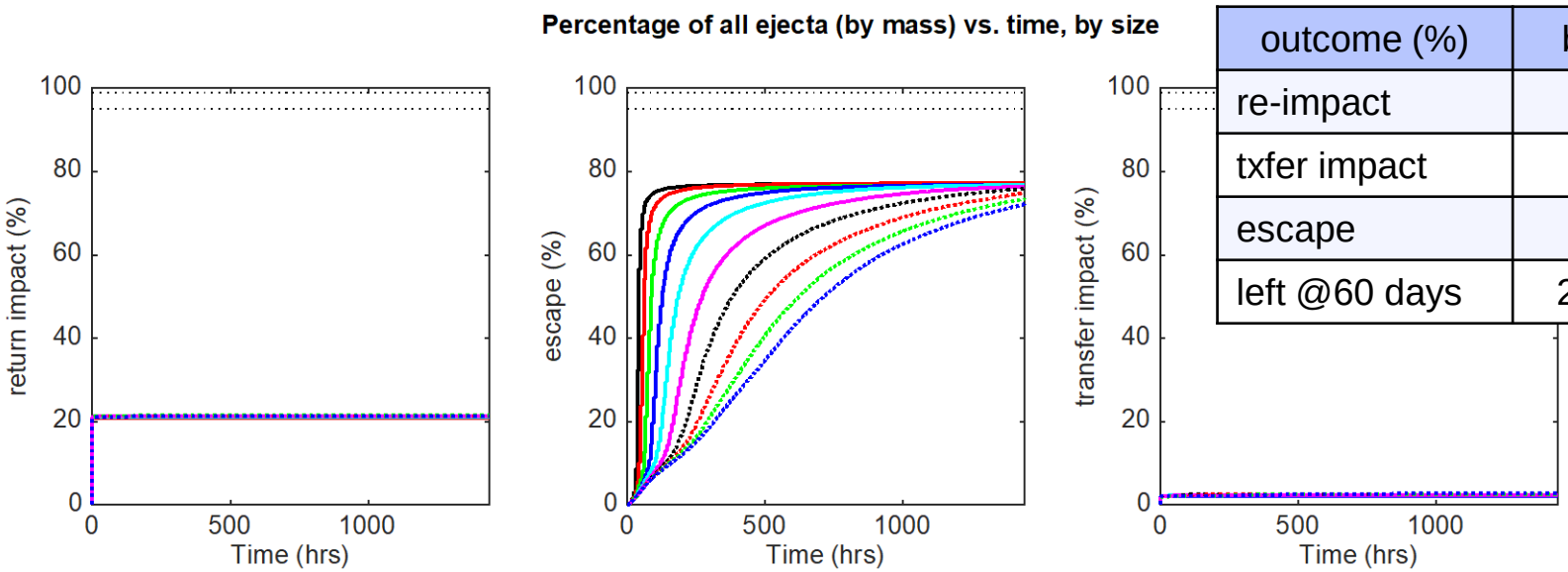




outcome (%)	by #	by mass
re-impact	11.87	13.35
txfer impact	24.93	32.02
escape	63.20	54.50
left @60 days	1.4e-6	0.13

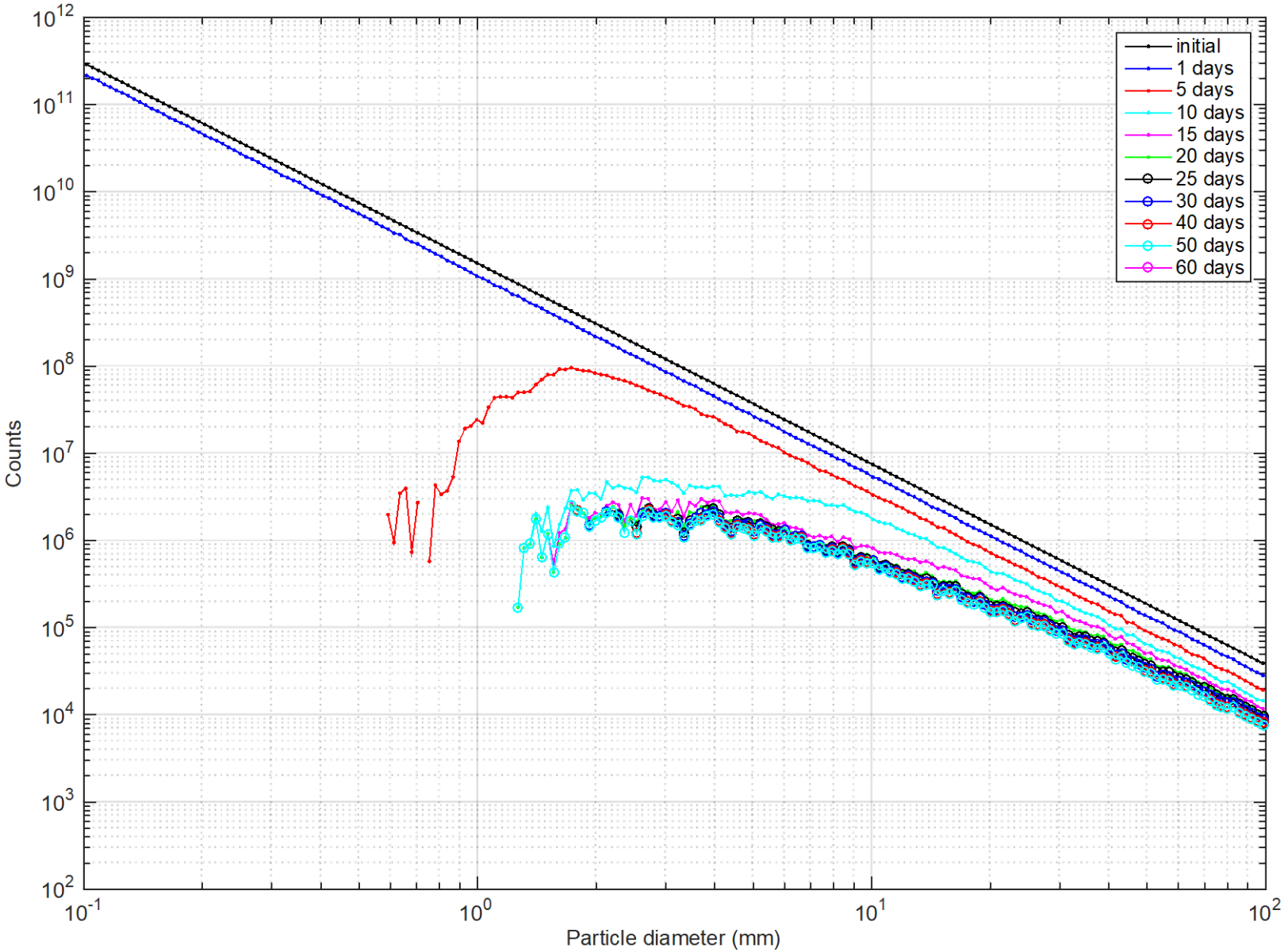
Outcome Time Histories, high excitation



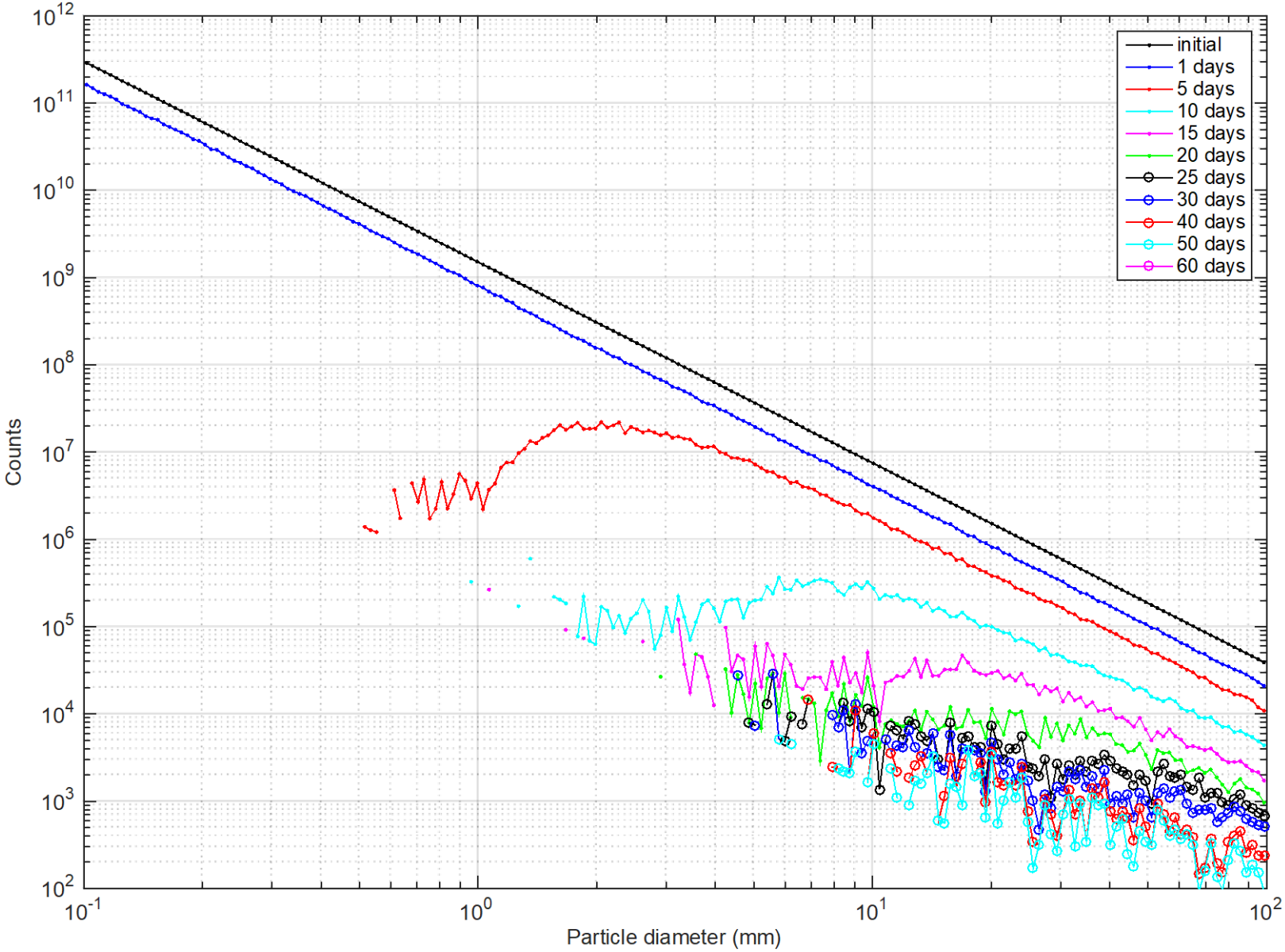


outcome (%)	by #	by mass
re-impact	20.93	21.31
txfer impact	2.08	2.58
escape	76.99	73.87
left @60 days	2.2e-5	2.25

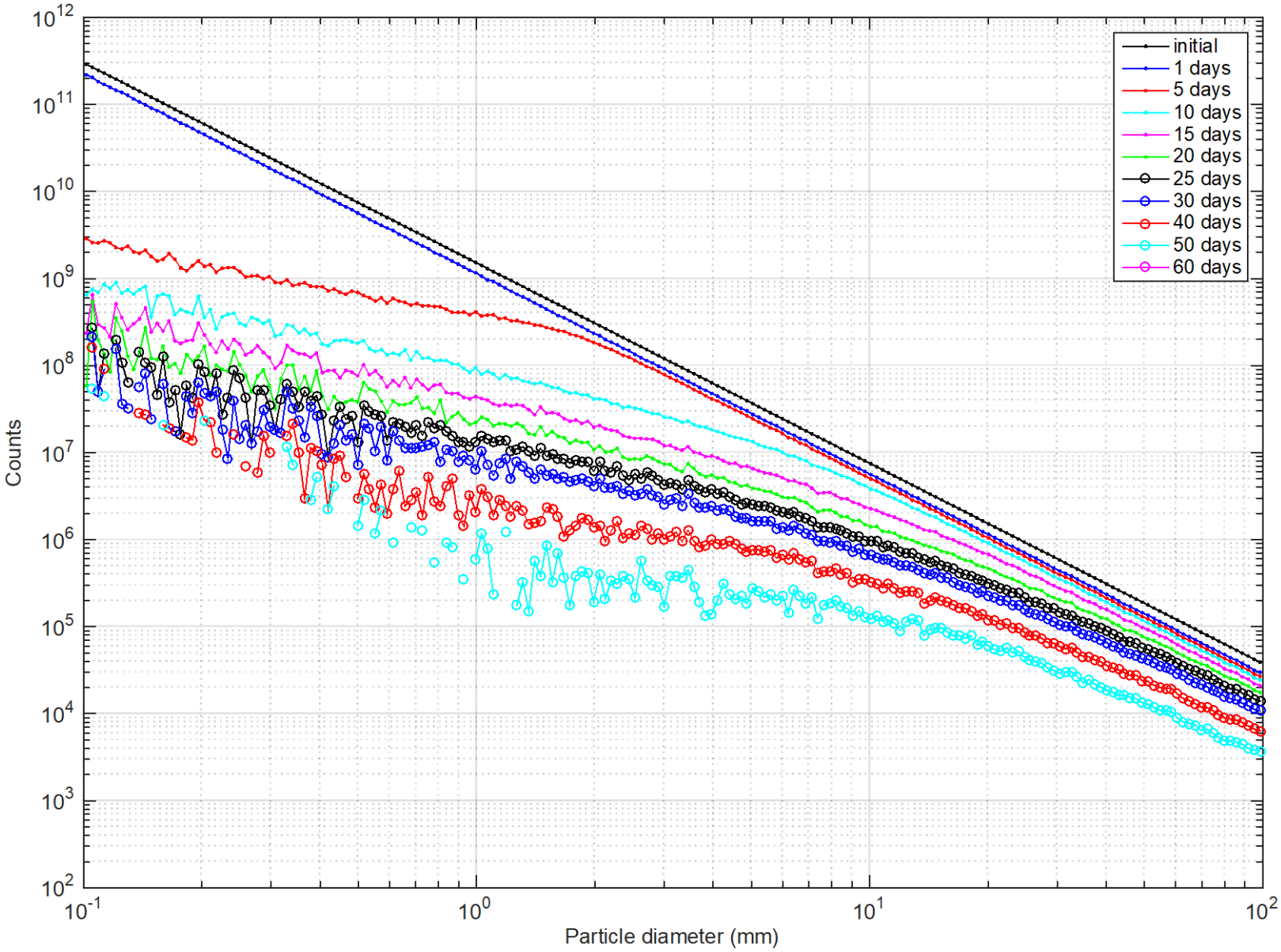
Size-Freq. Distrib. vs. Time, low excitation



Size-Freq. Distrib. vs. Time, mod. excitation

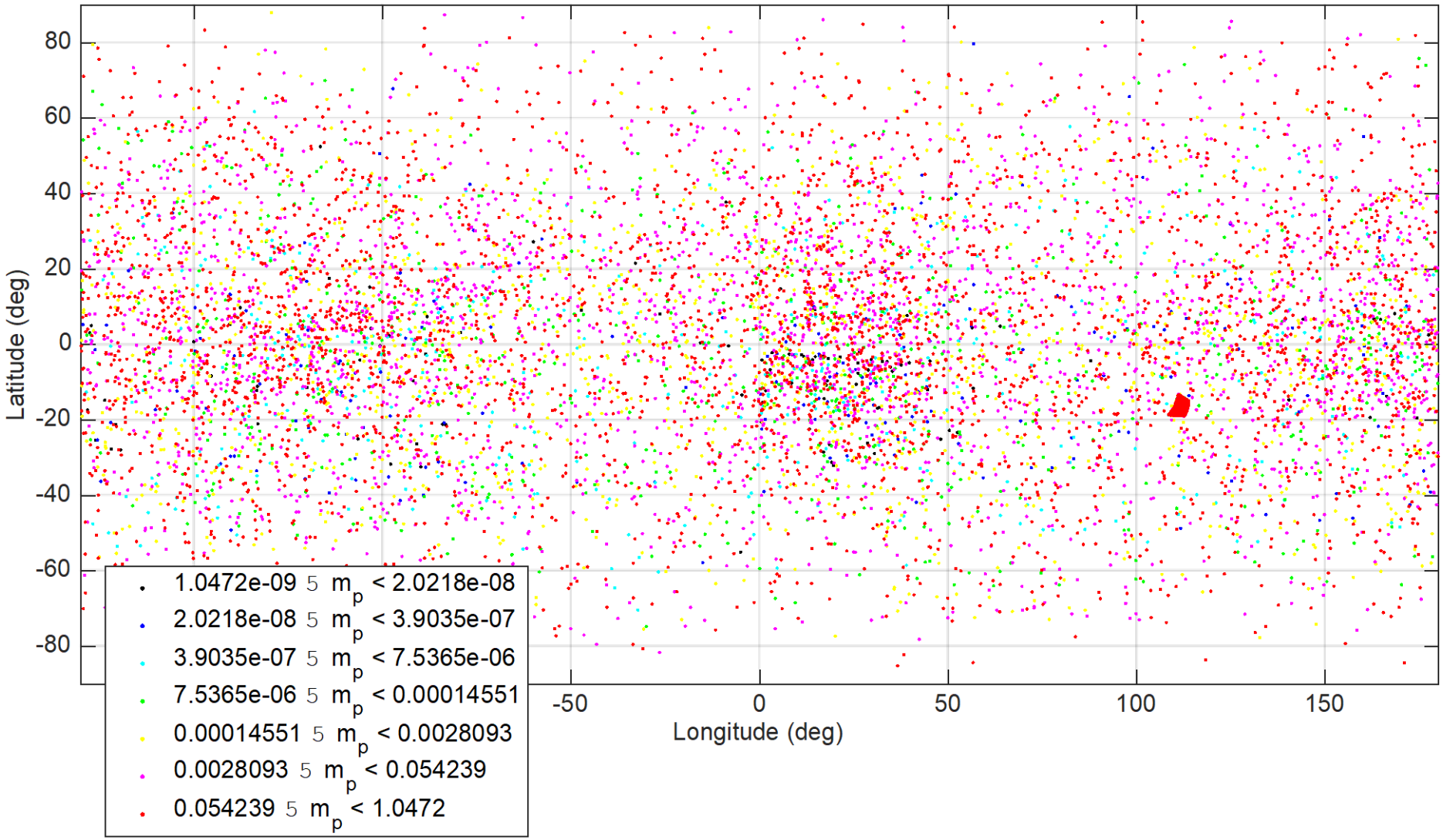


Size-Freq. Distrib. vs. Time, high excitation

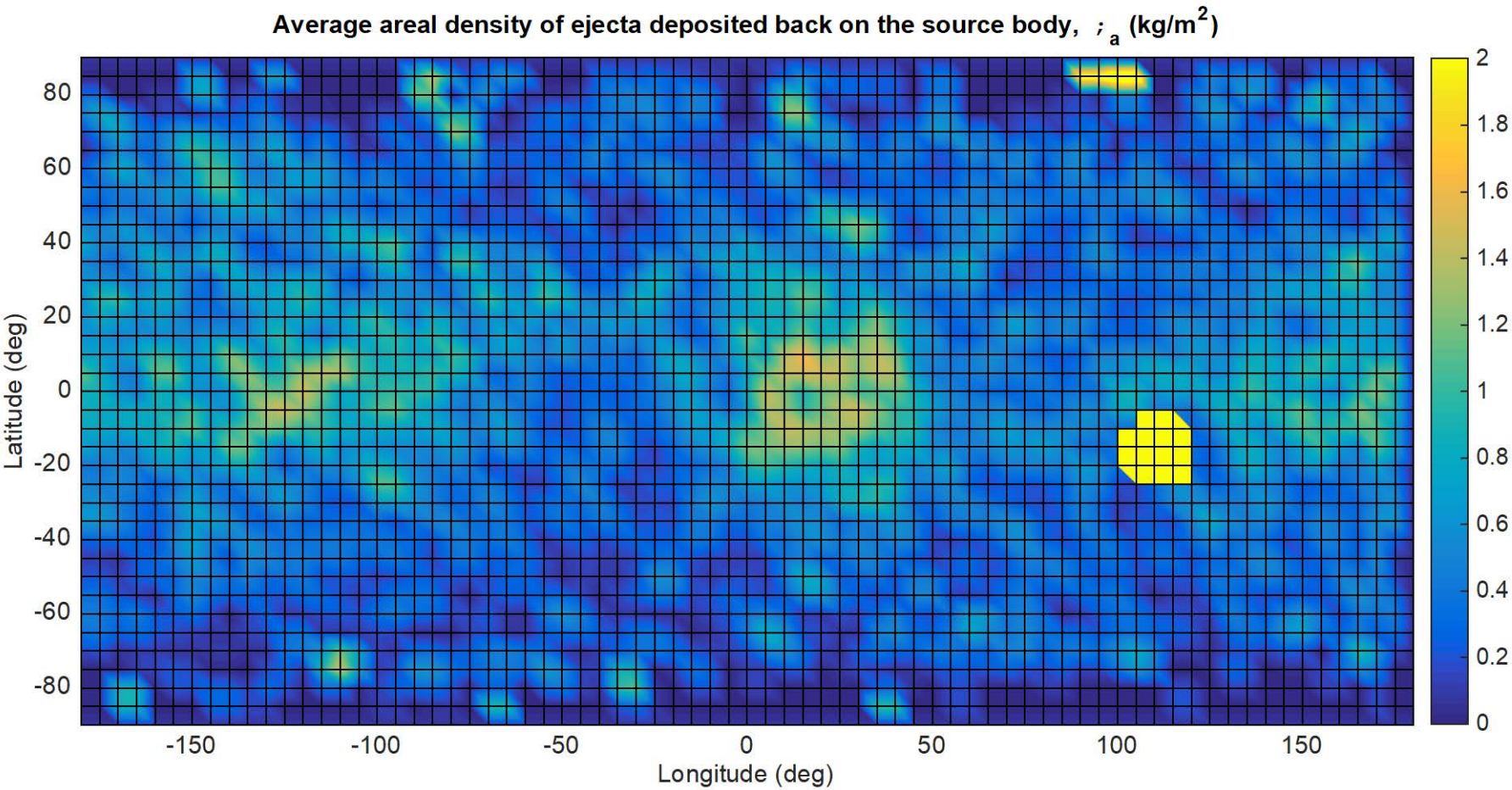


Re-Impact Locations by Size, low excitation

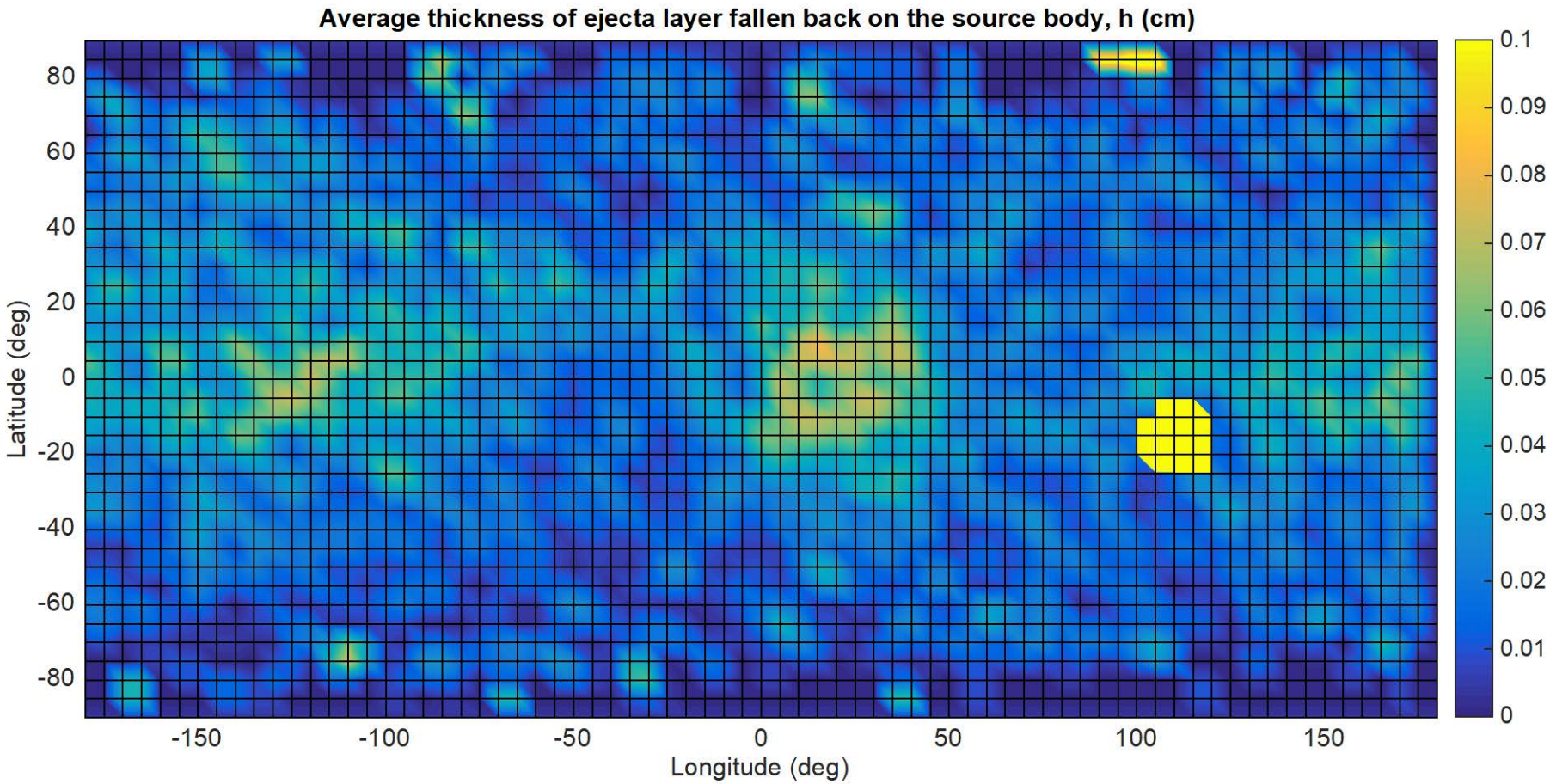
Landing locations, color coded by logarithmic bins in particle mass, for ejecta re-impacting source body



Density of Returning Ejecta, low excitation

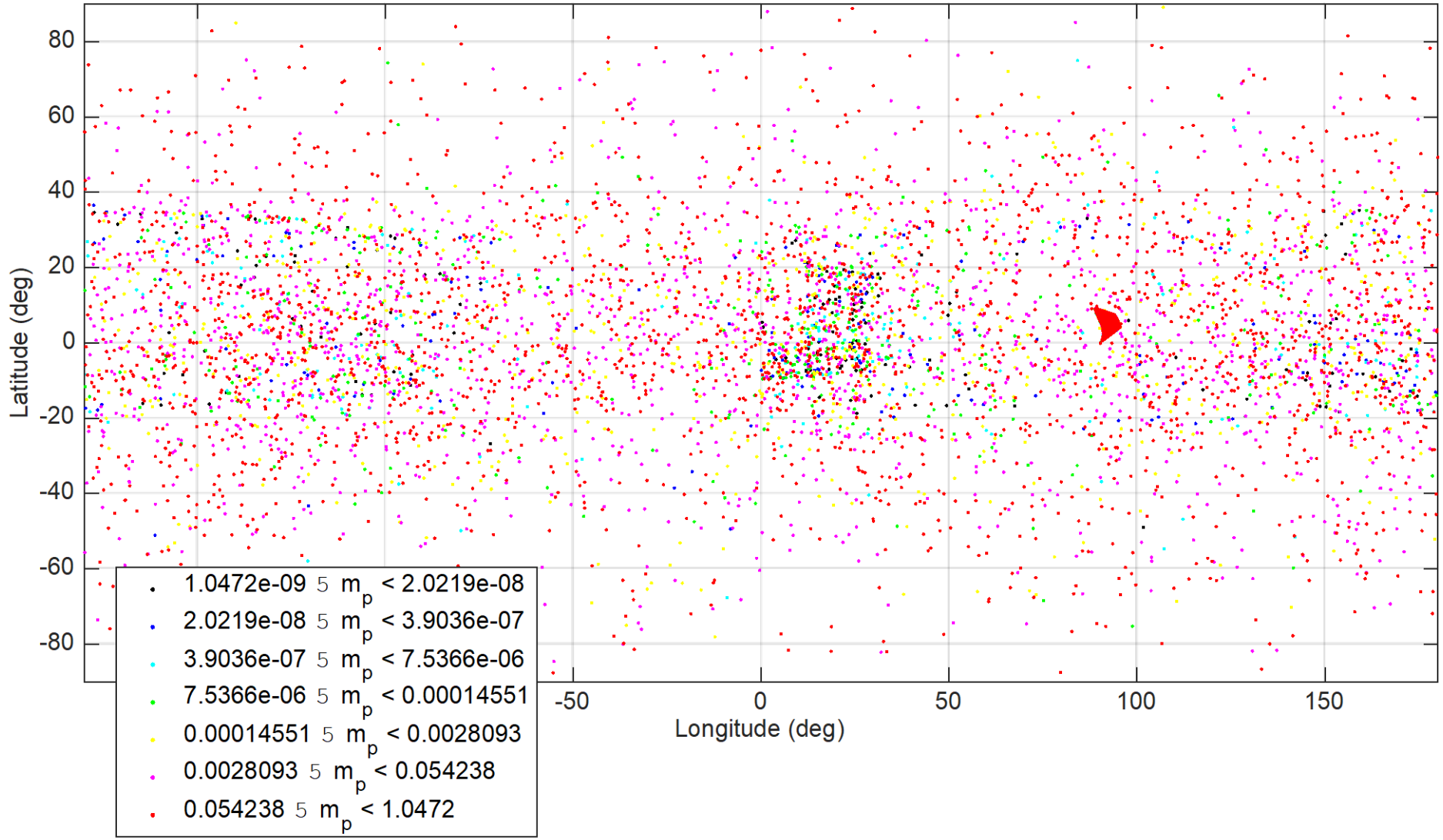


Avg. Thickness of Same, low excitation



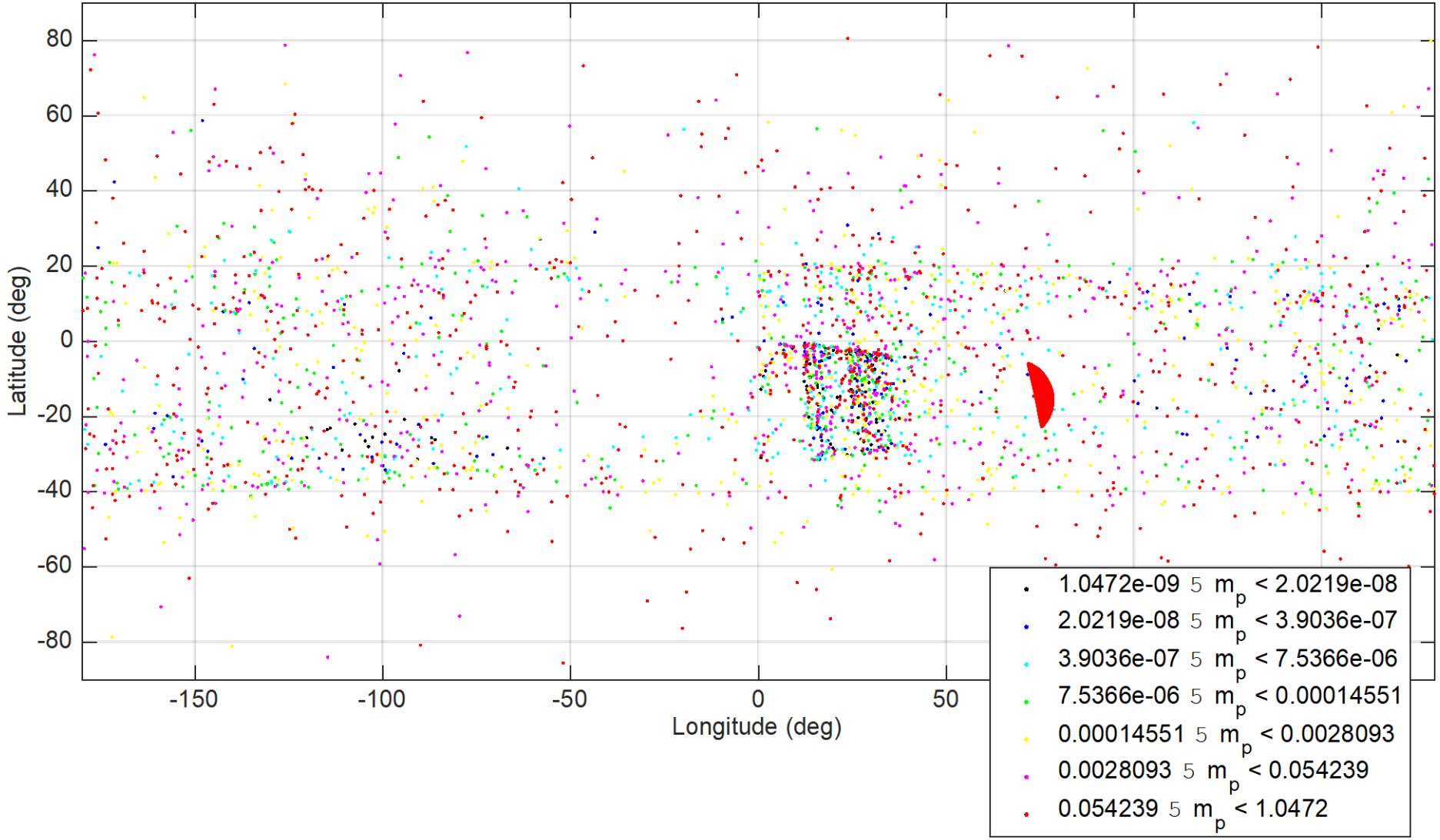
Re-Impact Locations by Size, mod. excitation

Landing locations, color coded by logarithmic bins in particle mass, for ejecta re-impacting source body

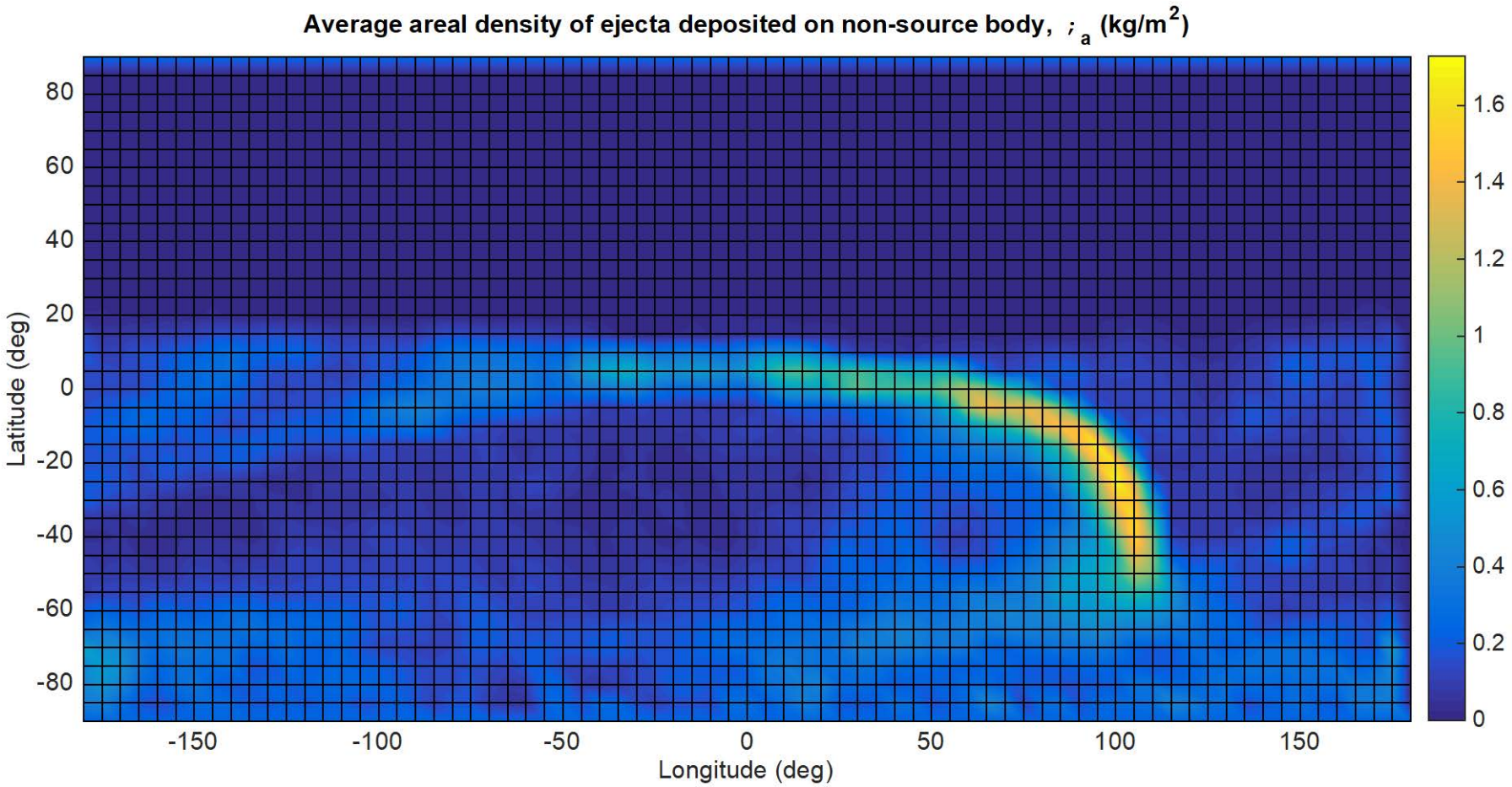


Re-Impact Locations by Size, high excitation

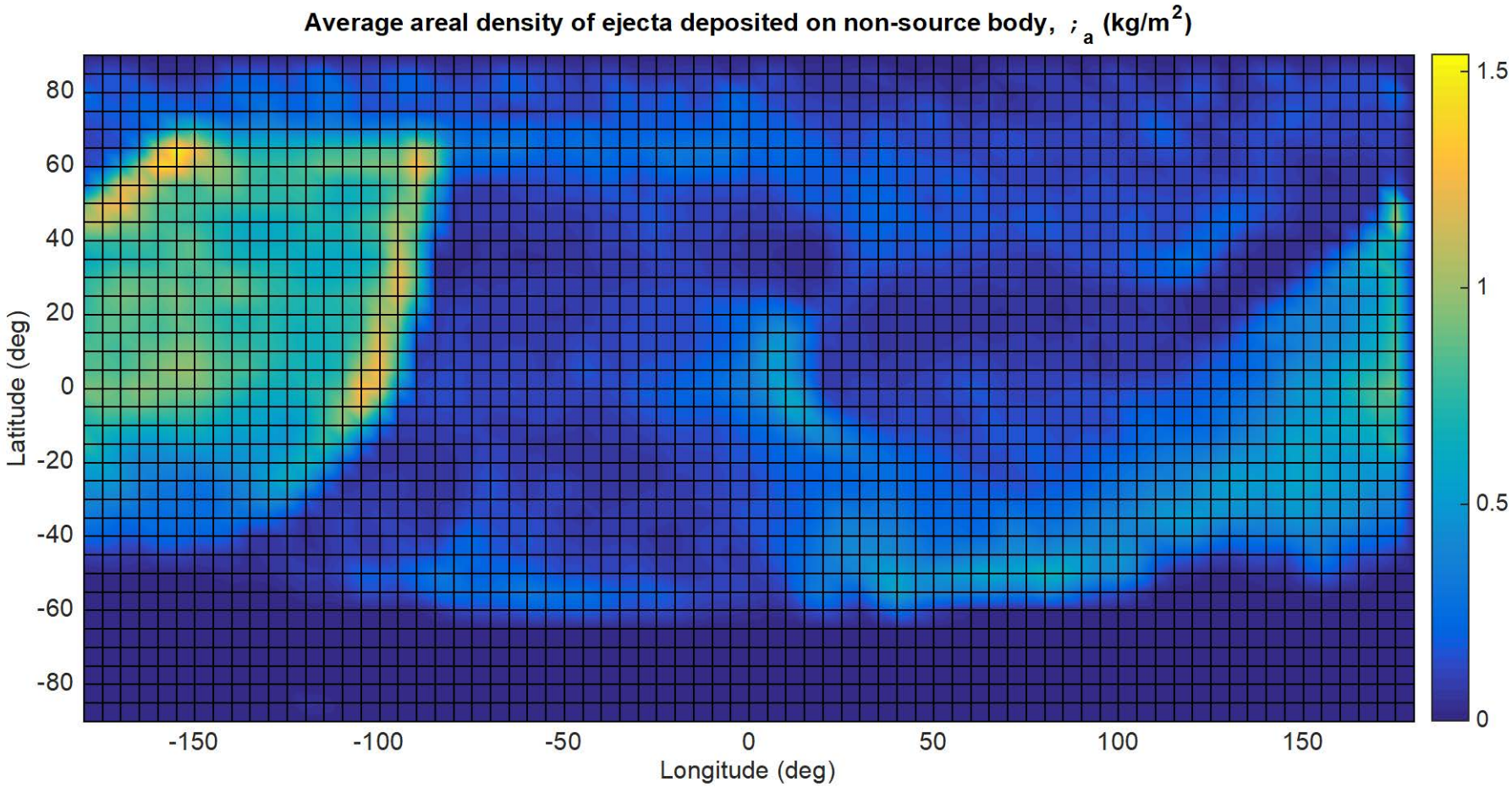
Landing locations, color coded by logarithmic bins in particle mass, for ejecta re-impacting source body



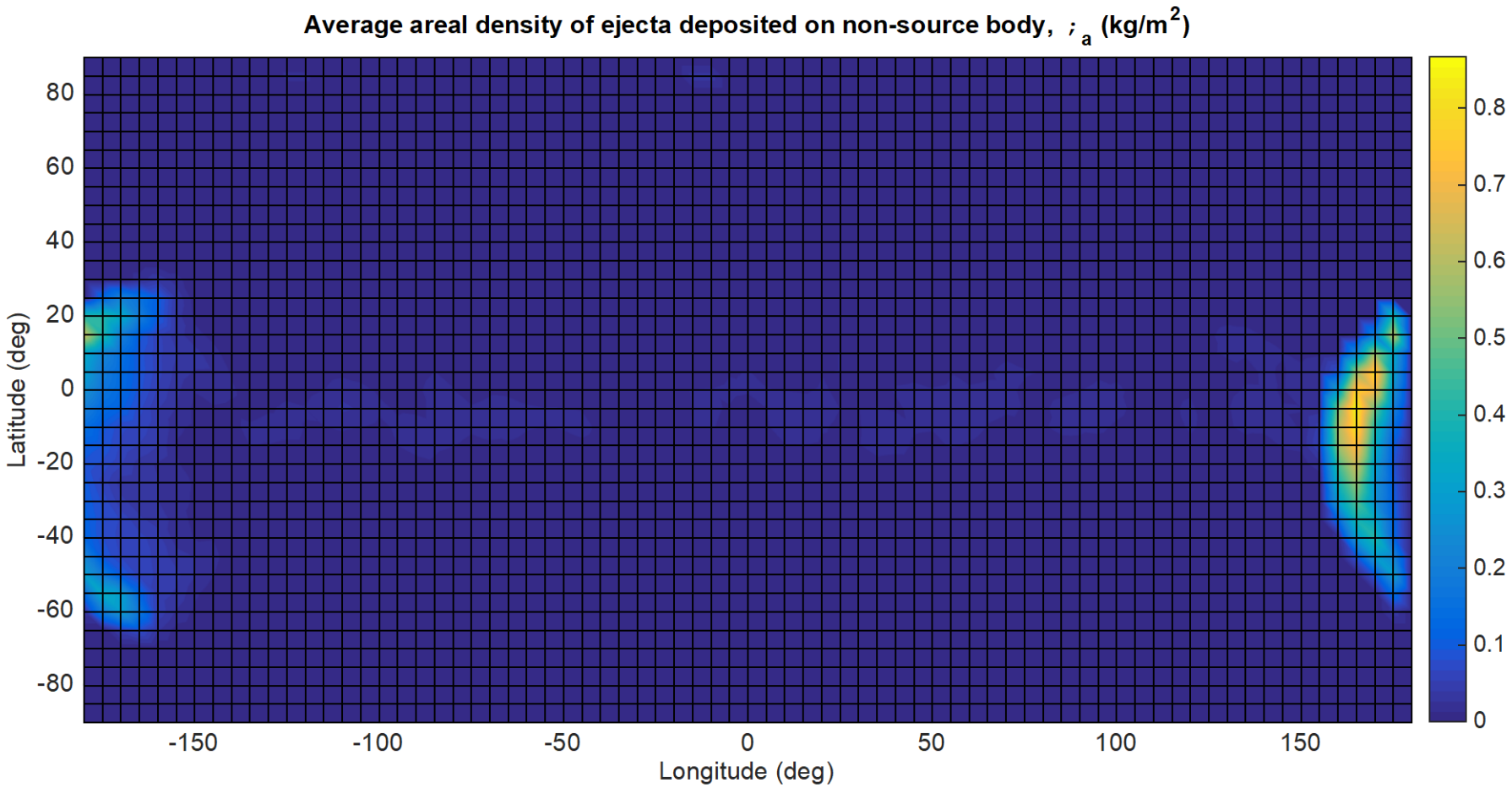
Density of Transferring Ejecta, low excitation



Density of Transferring Ejecta,mod. excitation



Density of Transferring Ejecta, high excitation



Conclusions

- Significant variation in ejecta outcomes, and time to reach them, between different cases
- Large #'s of particles, representing sizeable fraction of mass, persist to long (i.e. several weeks) duration:
  - Clearing times nonlinearly dependent on particle size as expected…
  - Only the largest ejecta persists so long…
- Strong dependence on local surface geometry at impact site
- Return-impacting material accretes mostly in $\pm 50^\circ$ lat. band, with small concentrations antipodal to impact location and on "far" side w.r.t. Didymain
- Transfer-impacting material accretes consistent with intersection/fallback of ejecta cone with Didymain surface
- Again, strong dependence on local surface geometry

Questions?

Acknowledgements:

- Asteroid (Didymain and Didymoon) models from Shantanu Naidu, et. al.
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- Supercomputers used in this investigation were provided by funding from the JPL Office of the Chief Information Officer

Backup Slides