National Aeronautics and Space Administration

High-Fidelity Blast Modeling of Impact from Hypothetical Asteroid 2023 PDC

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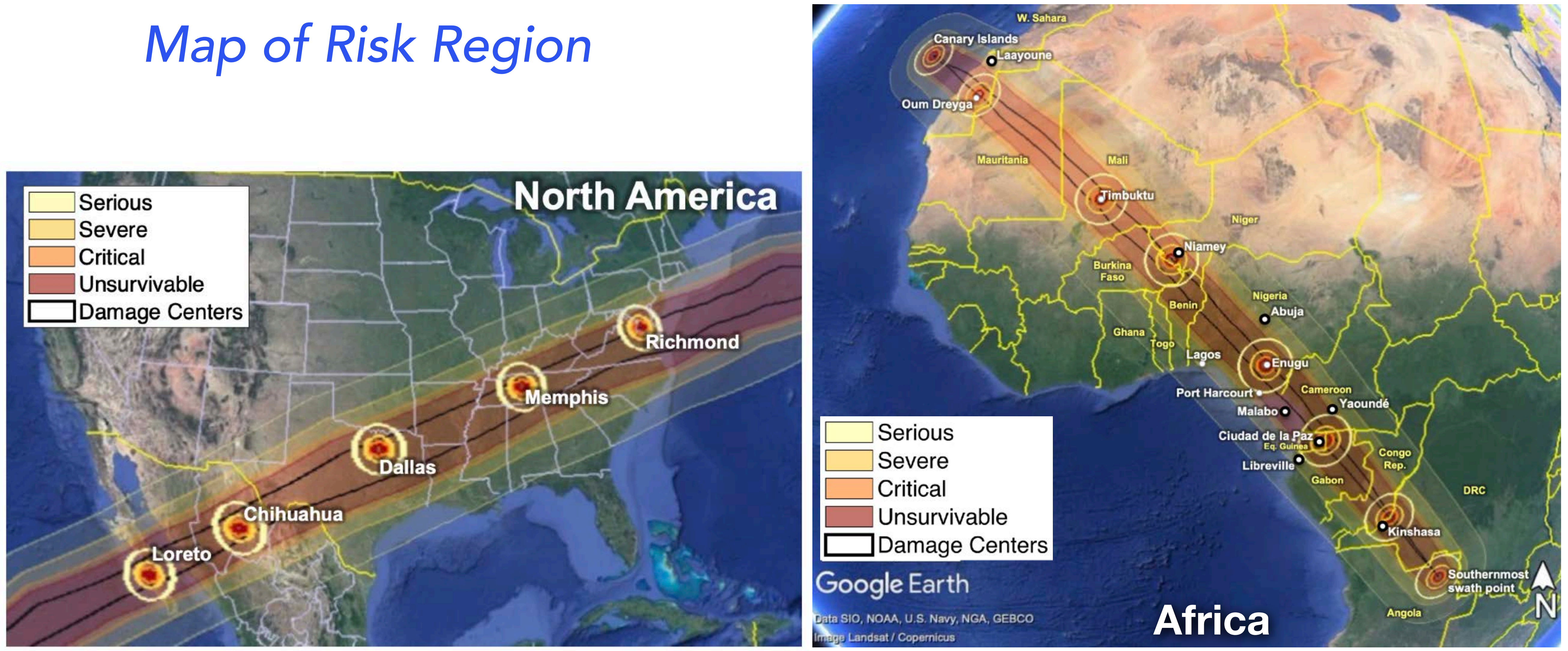
2023 PDC Asteroid Impact "Epoch 1" Scenario

Entry modeling and probabilistic risk assessment

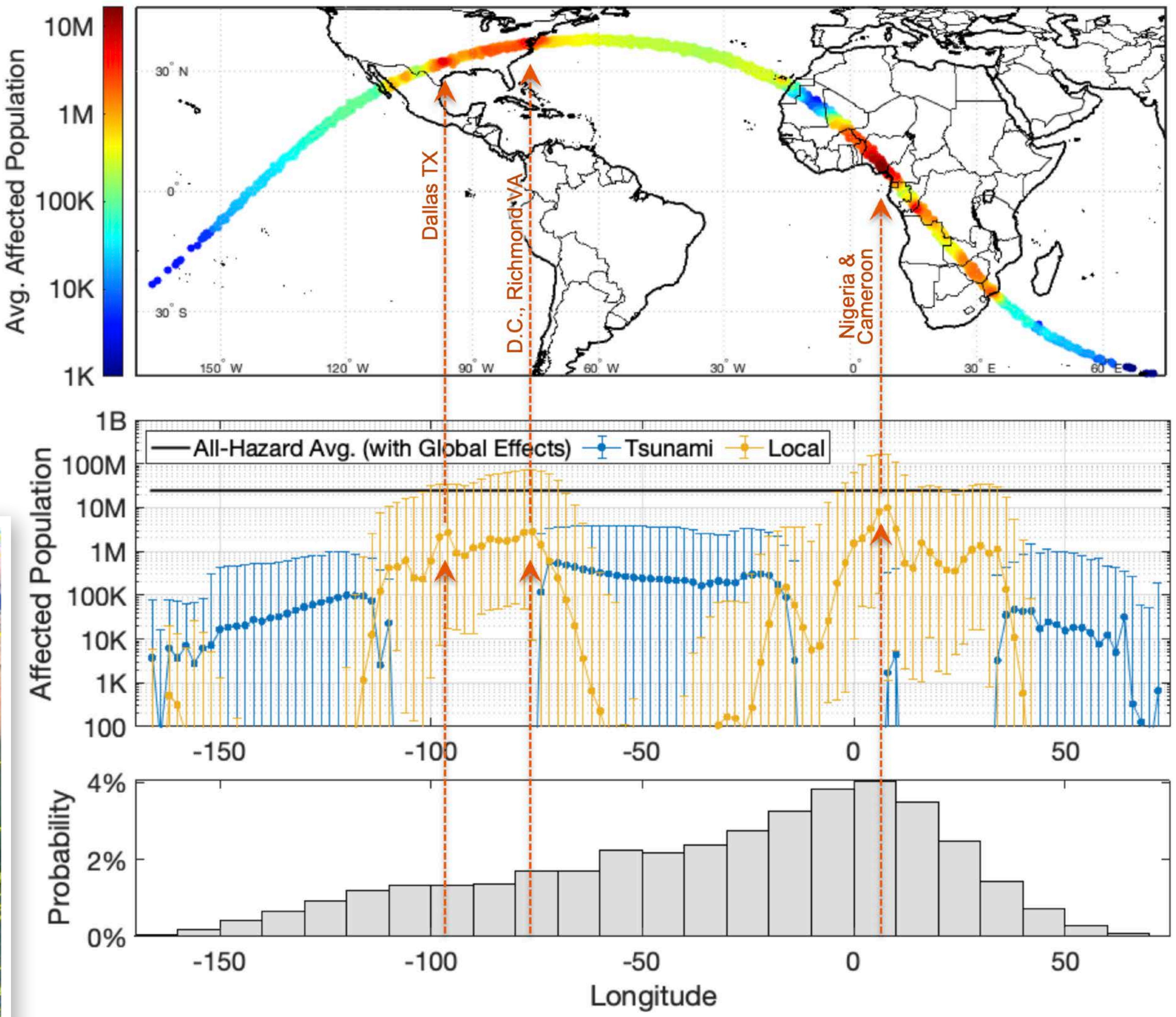
ARC/TNA

- Diameter: 150–2000 m, most likely 220–660 m, median size 470 m
- Entry speed: 12.67–12.68 km/s
- Energy range from 54-160,000 megatons (Mt)
- Wheeler et. al (PDC2023) showed the highest risk region is Nigeria & Cameroon with average affected population of ~10M

Map of Risk Region



Affected Population Ranges Along Entry Swath



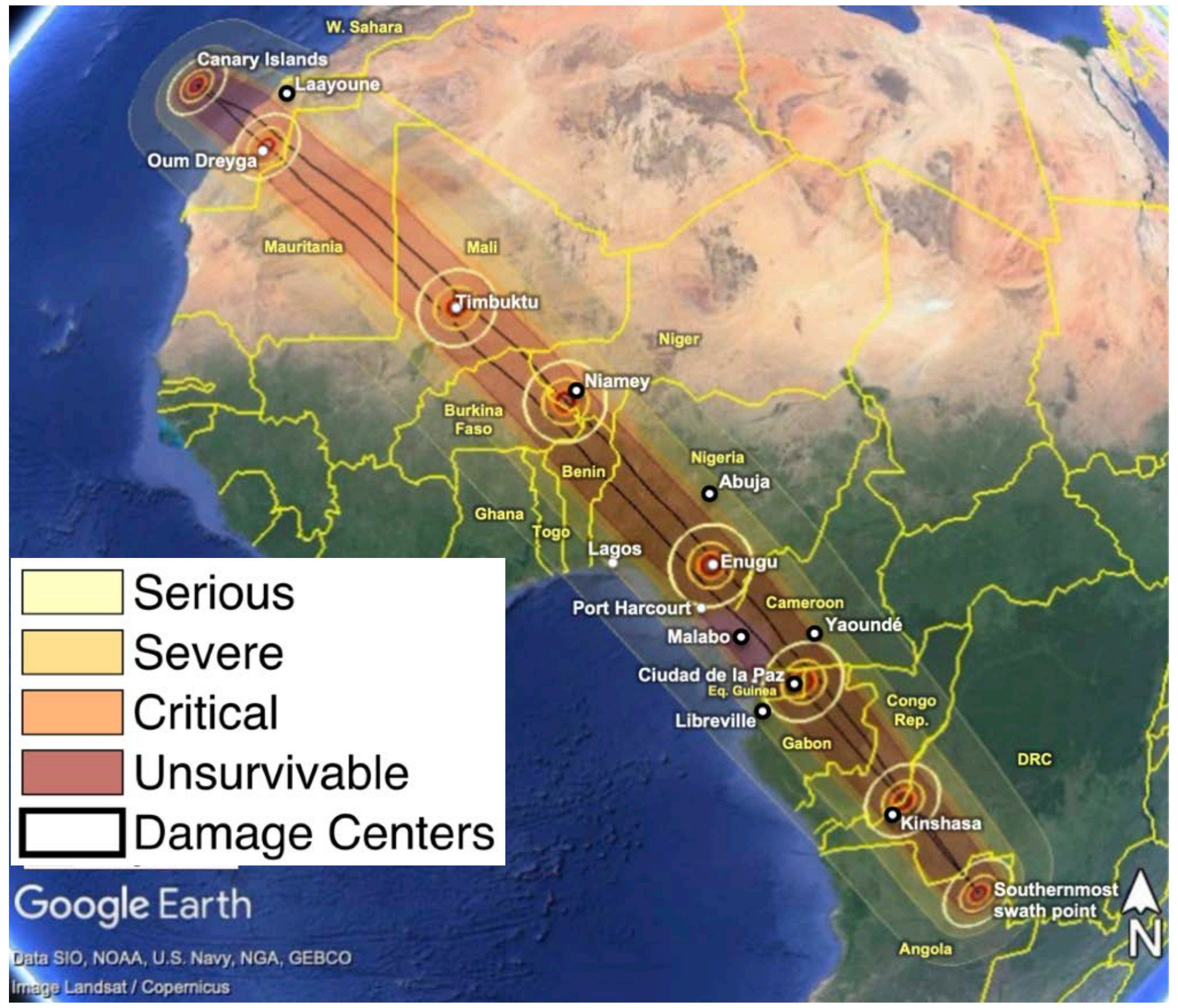
See Wheeler et al. PDC2023 for details of Epoch 1 analysis

Outline

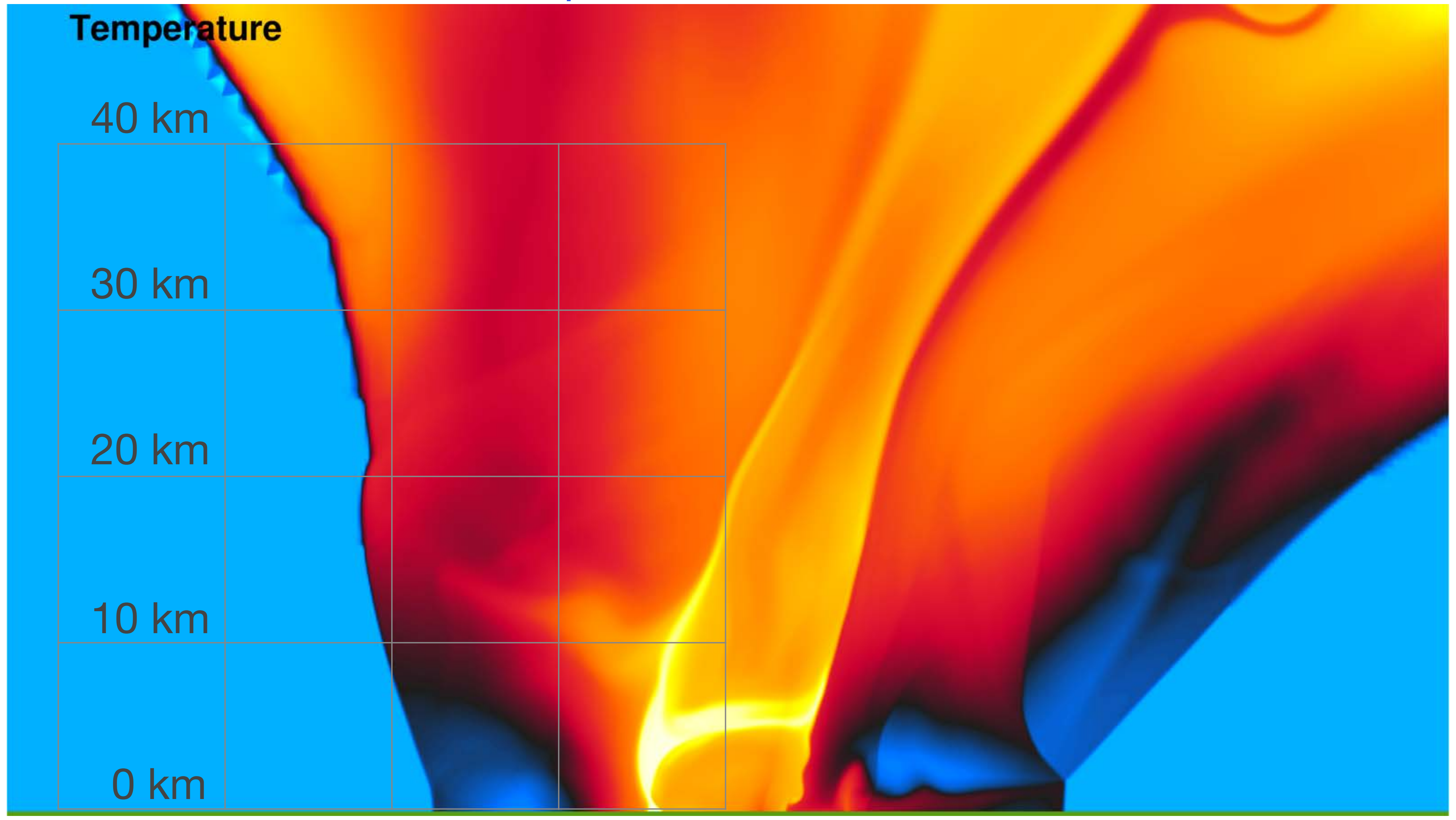
Entry modeling and probabilistic risk assessment

- Asteroid properties
- Entry and energy deposition
- Solver & simulation setup
- Results
  - Simulations and ground footprints
  - Atmospheric waves
  - Radiation analysis
- Computing resources
- Summary

Risk swath in Africa



Impact simulation



Asteroid Properties

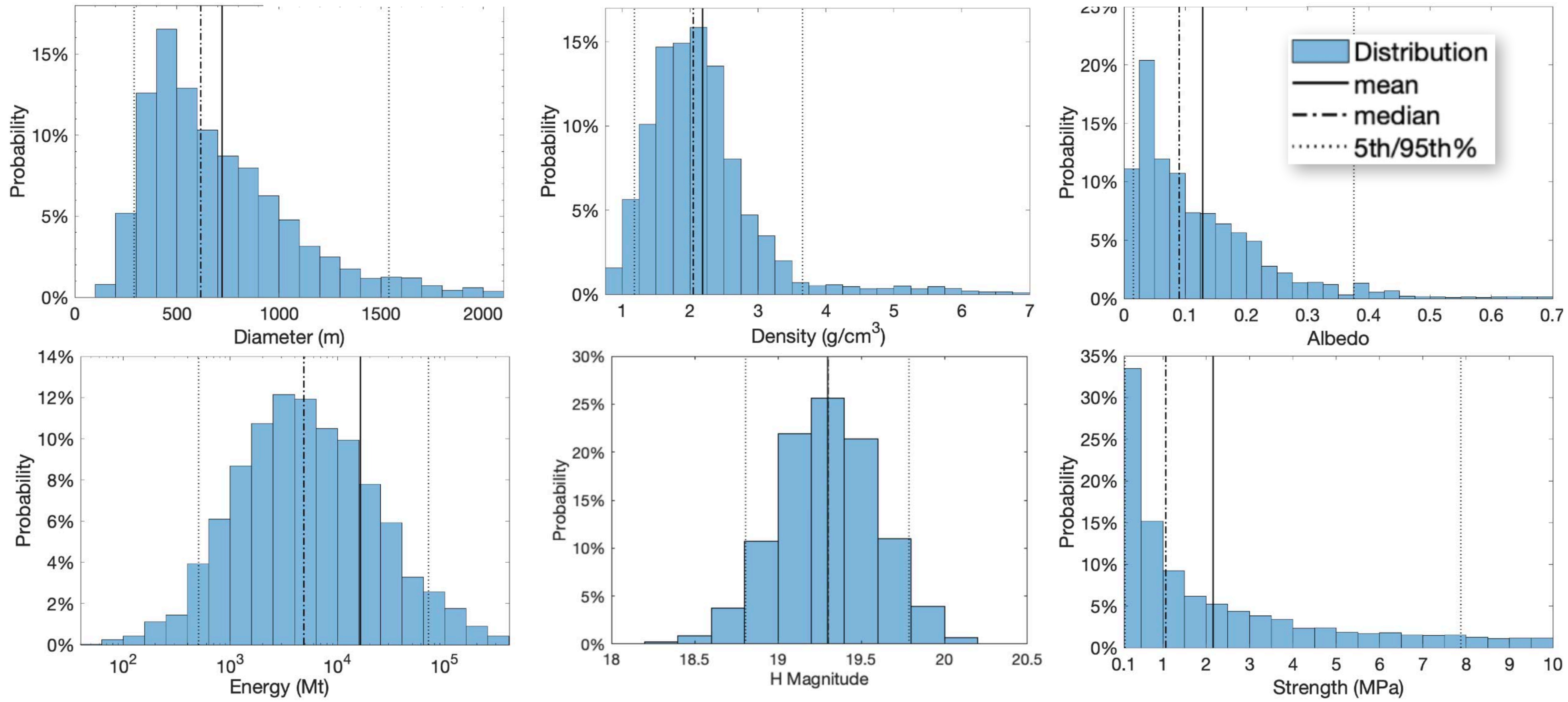
Statistical analysis and Bayesian inference to determine likely asteroid properties

ARC/TNA

- Epoch 2, PDC2023 remains faint, but have *g*, *r* and *i* band colors which inform inference for taxonomic class, density and strength
- High-fidelity simulations will focus on upper end of “most likely” (68%) range

	Mean	25%	Median 50%	75%	68% (most likley)
H magnitude	19.3	19.1	19.3	19.5	19 - 19.6
Albedo	0.13	0.04	0.09	0.17	0.01 - 0.15
Diameter Ø [m]	721	434	617	901	294 - 880
Density [g/cc]	2.2	1.6	2.0	2.5	1.3 - 2.6
Mass [kg]	8.5×10^{11}	9.6×10^{10}	2.5×10^{11}	7.5×10^{11}	$4 \times 10^{9} - 5.4 \times 10^{11}$
Energy [Mt]	16000	1800	4900	14000	76 - 10000

Property Distributions (Wheeler: PDC2023 & Dotson: PDC2023)

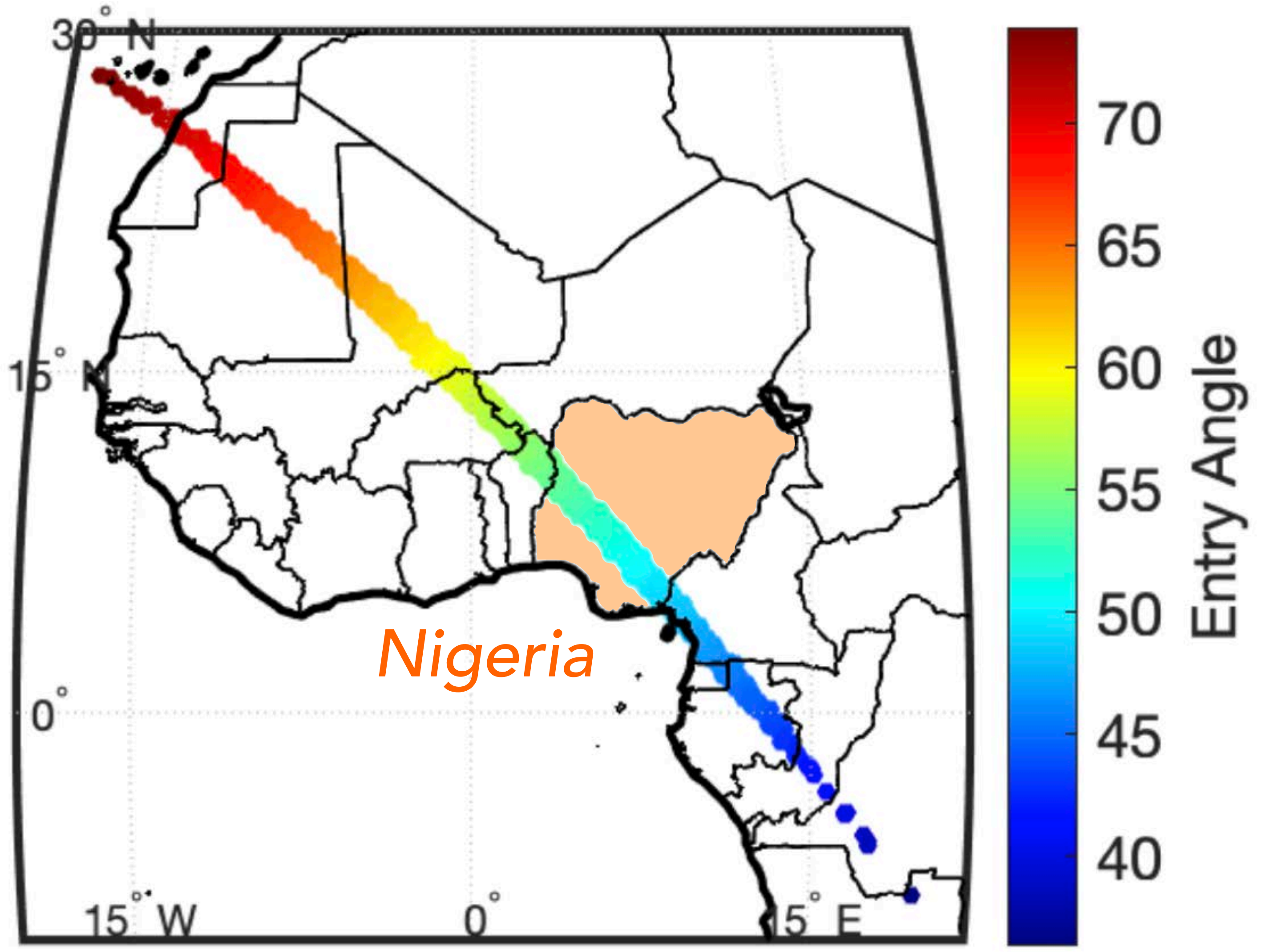


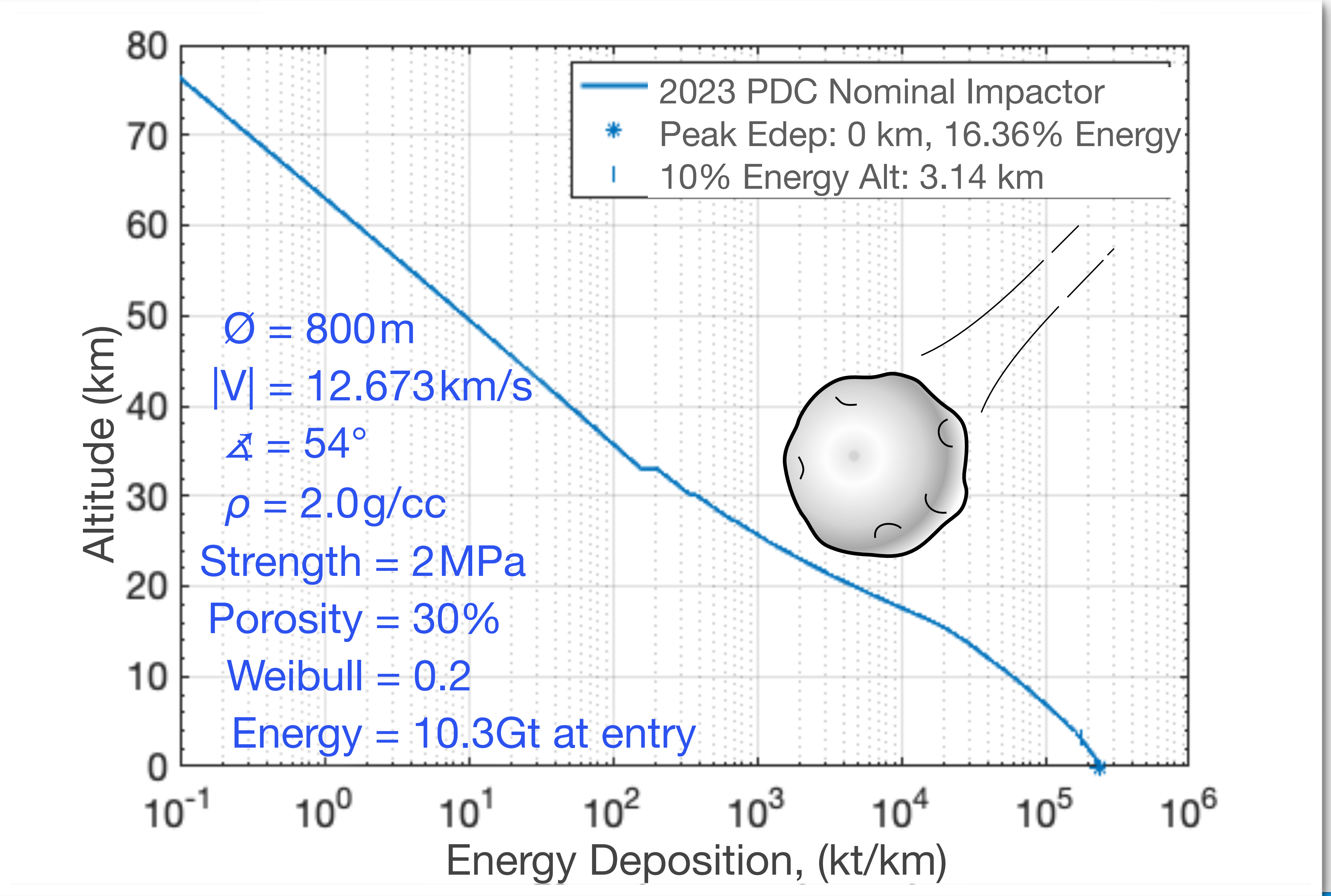
Entry and Energy Deposition

Detailed selection of entry parameters for nominal impact case

- Chose nominal impactor to be near large end of the 68% "most likely case" from risk assessment
  - H-mag 19 & albedo 0.069
  - Nominal impact case is 800m diameter @ 12.67km/s
  - Oblique entry at ∡ = 54° from horizon
- Modeled entry in FCM to get details along trajectory
- Kinetic energy at entry, E_{Tot} = 10.3 Gt
  - ~1.68 Gt deposited into atmosphere (16.36%)
  - ~8.61 Gt of ground-impacting energy (83.64%)
- FCM entry modeling parameters shown at right
- Impact in Nigeria has total affected population ~ 10M

2023 PDC Entry Angle Map for Africa

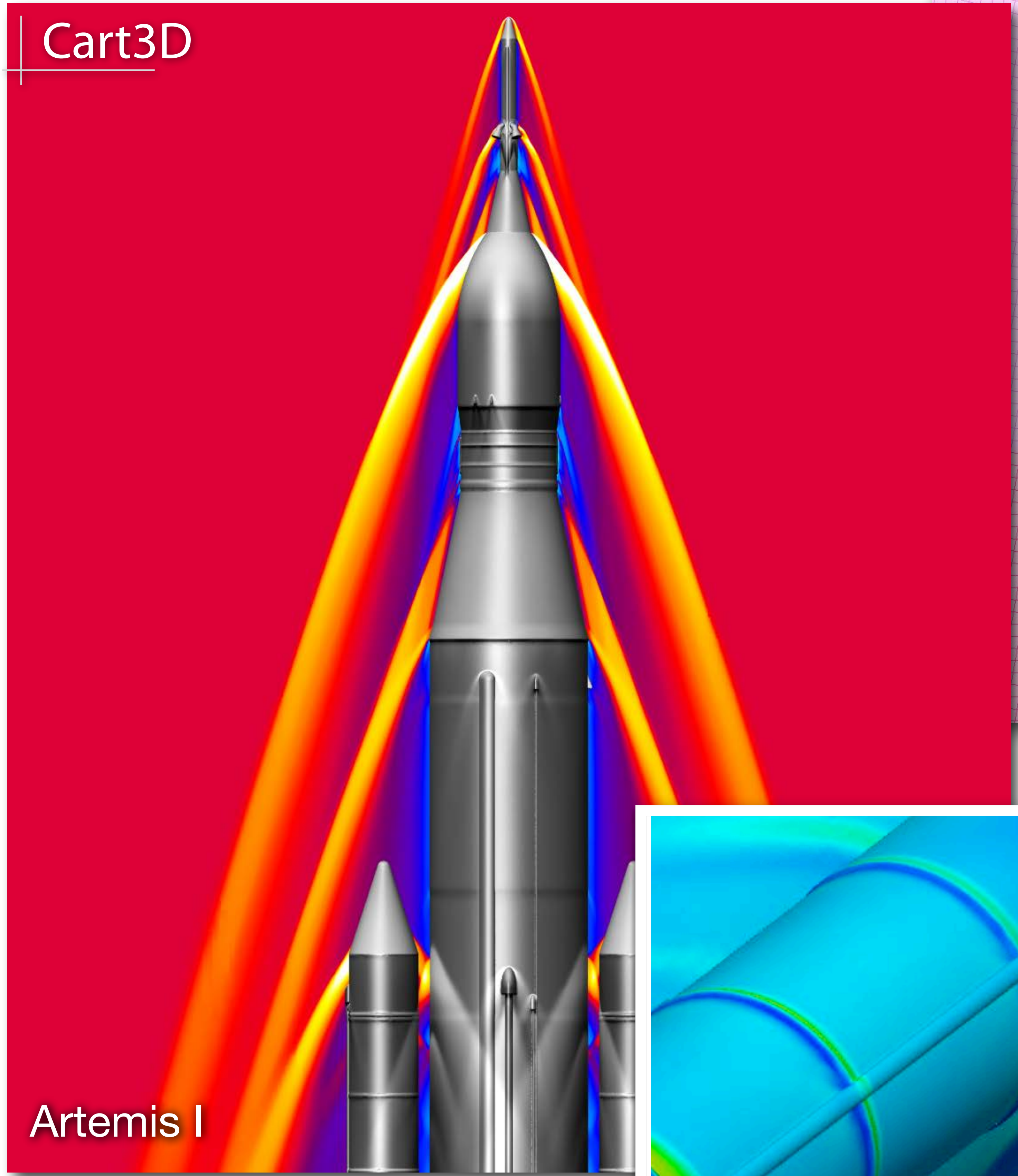


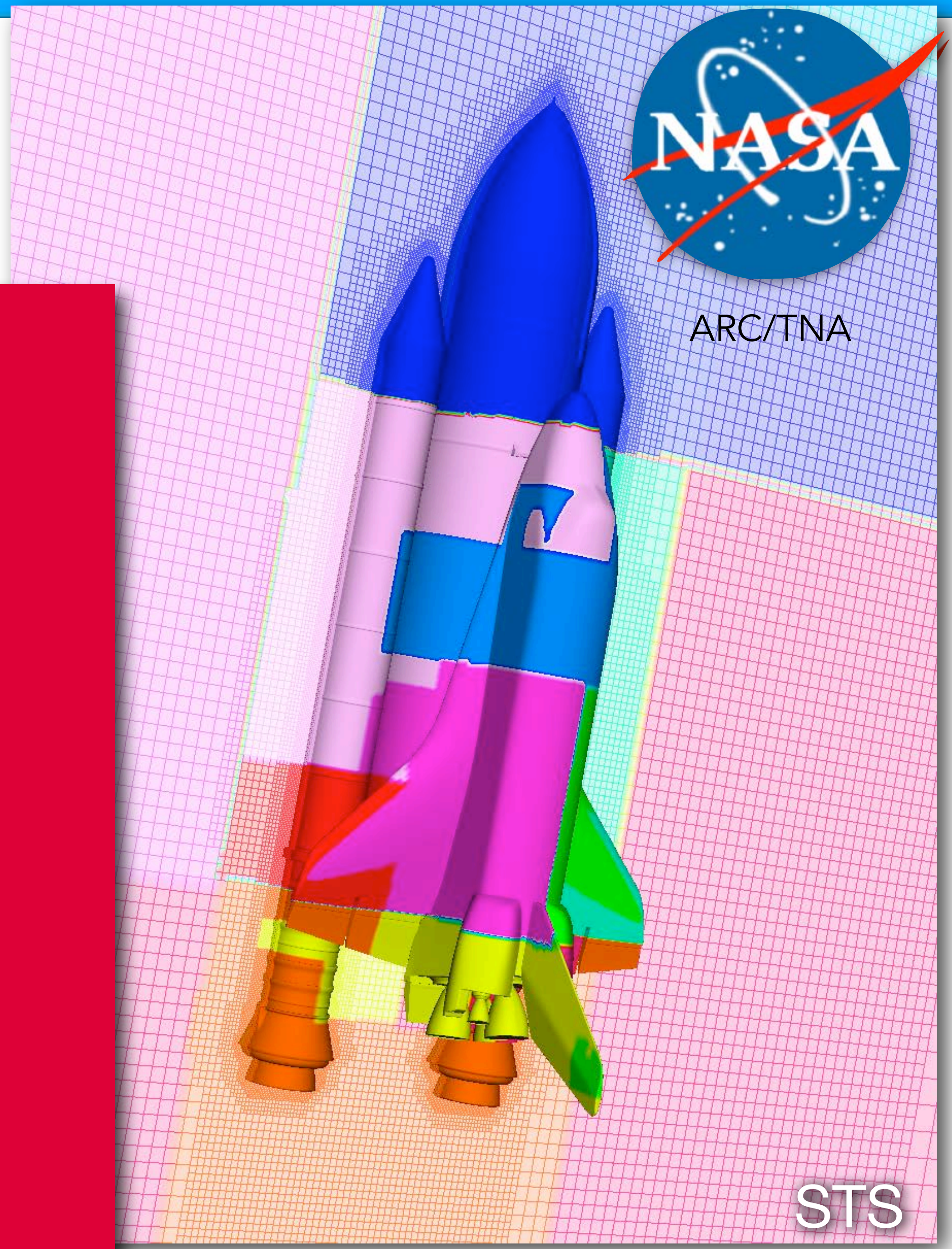


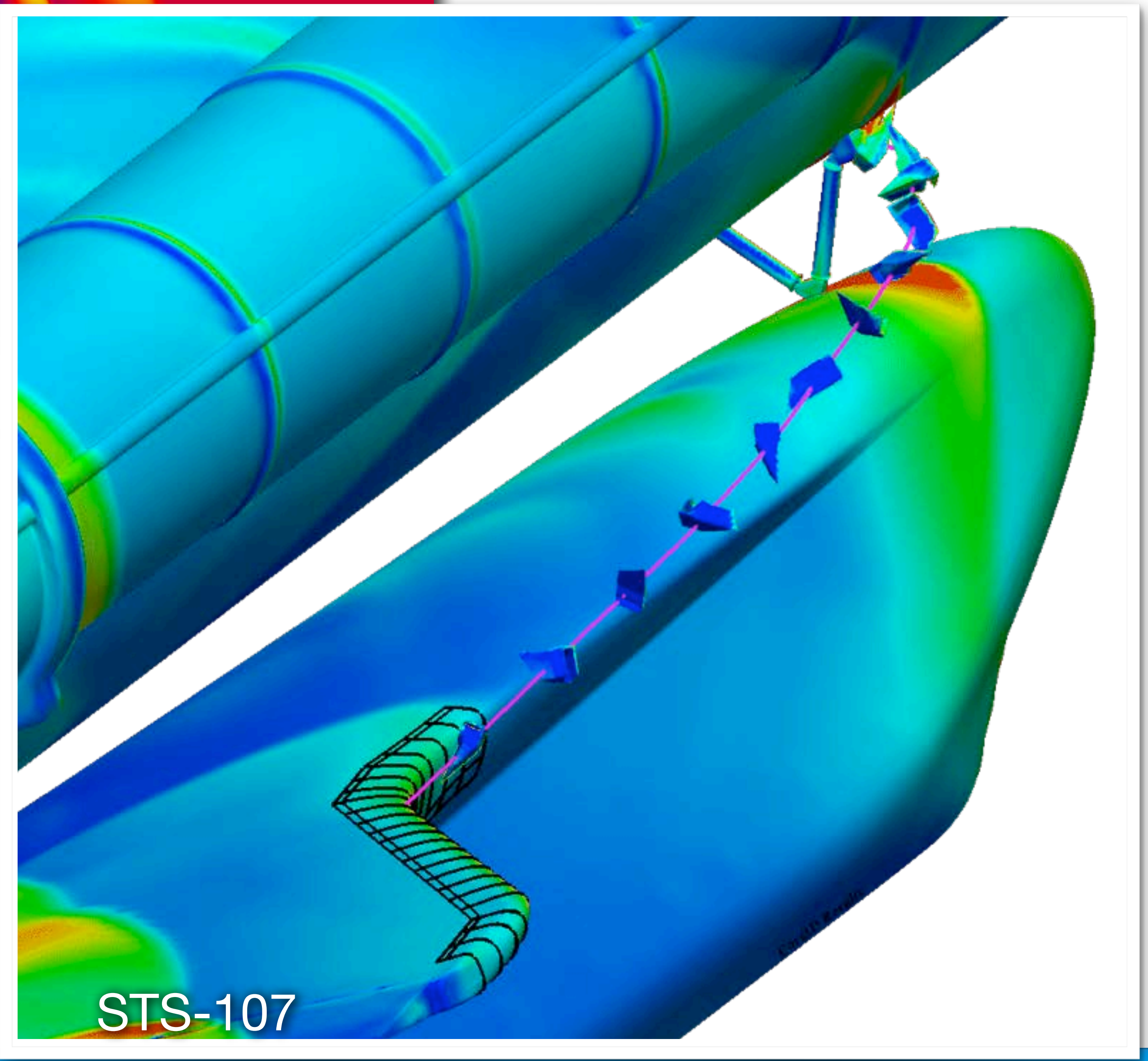
Solver Overview: Cart3D

Production solver based on cut-cell Cartesian mesh method

- Originally developed for aerospace applications
- Fully-automated mesh generation for complex geometry
- Inviscid solver using Cartesian cells
  - Fully-conservative finite-volume method
  - Multigrid accelerated 2nd-order upwind scheme
  - Dual-time approach for unsteady simulations
  - Domain-decomposition for good parallel scalability
- All runs are full 3D
  - 220-330 M cells with 20-30 k time steps
- Excellent scalability
  - Typical airburst simulations take 8-16 hrs on ~4000 cores
- One of NASA's most heavily used production solvers, large validation database, 900+ users
- Good comparisons w/ *CTH*, *xRAGE* & *ALE3D* at the 2016 Tsunami Workshop







Solver Overview: Cart3D

Extensive Validation for airburst and entry simulations

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- Fully-automated mesh generation for complex geometry
- Inviscid solver using Cartesian cells
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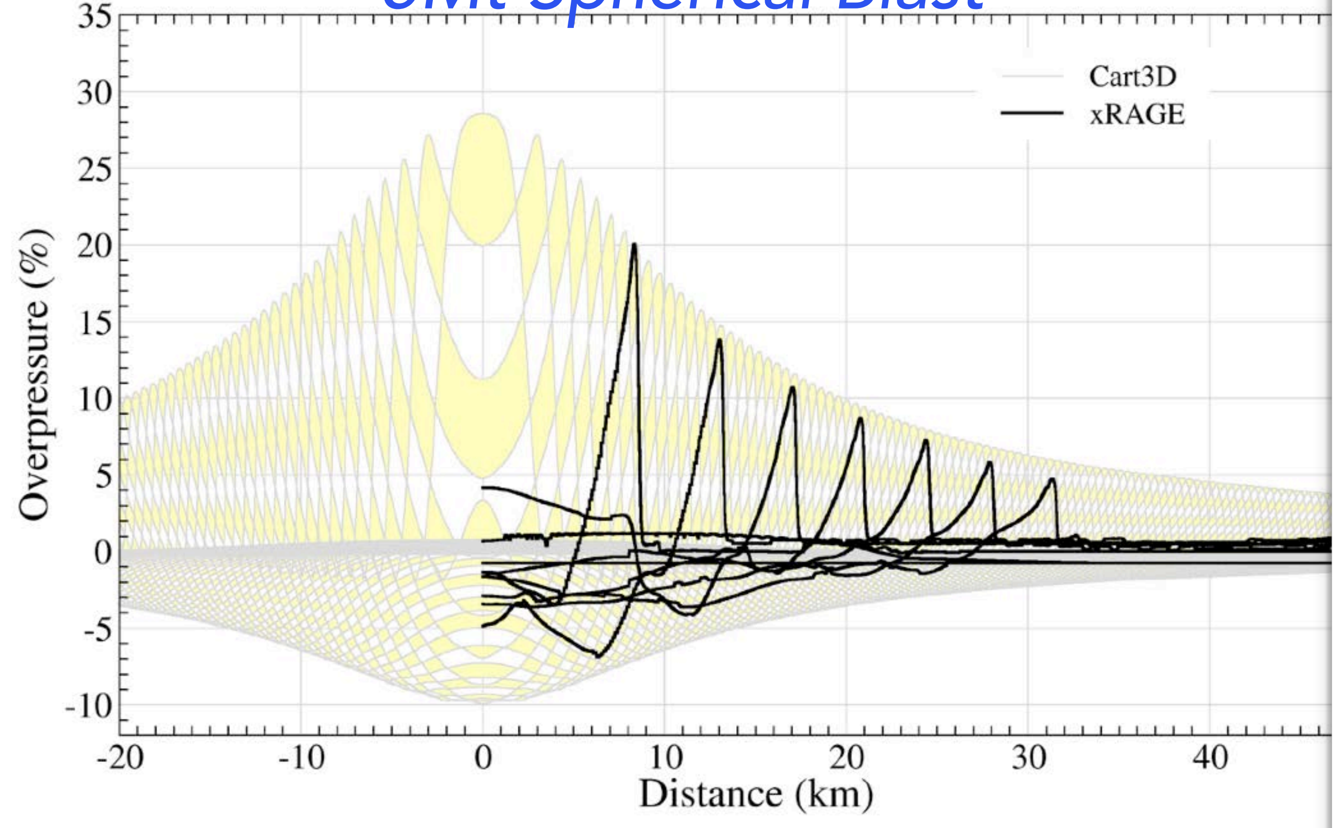
5Mt Spherical Blast



Comparison with xRAGE (DoE) at 2016 Tsunami Workshop

ARC/TNA

Chelyabinsk Ground Footprints

Chelyabinsk airburst: *AIAA Paper 2016-0998, Jan 2016*

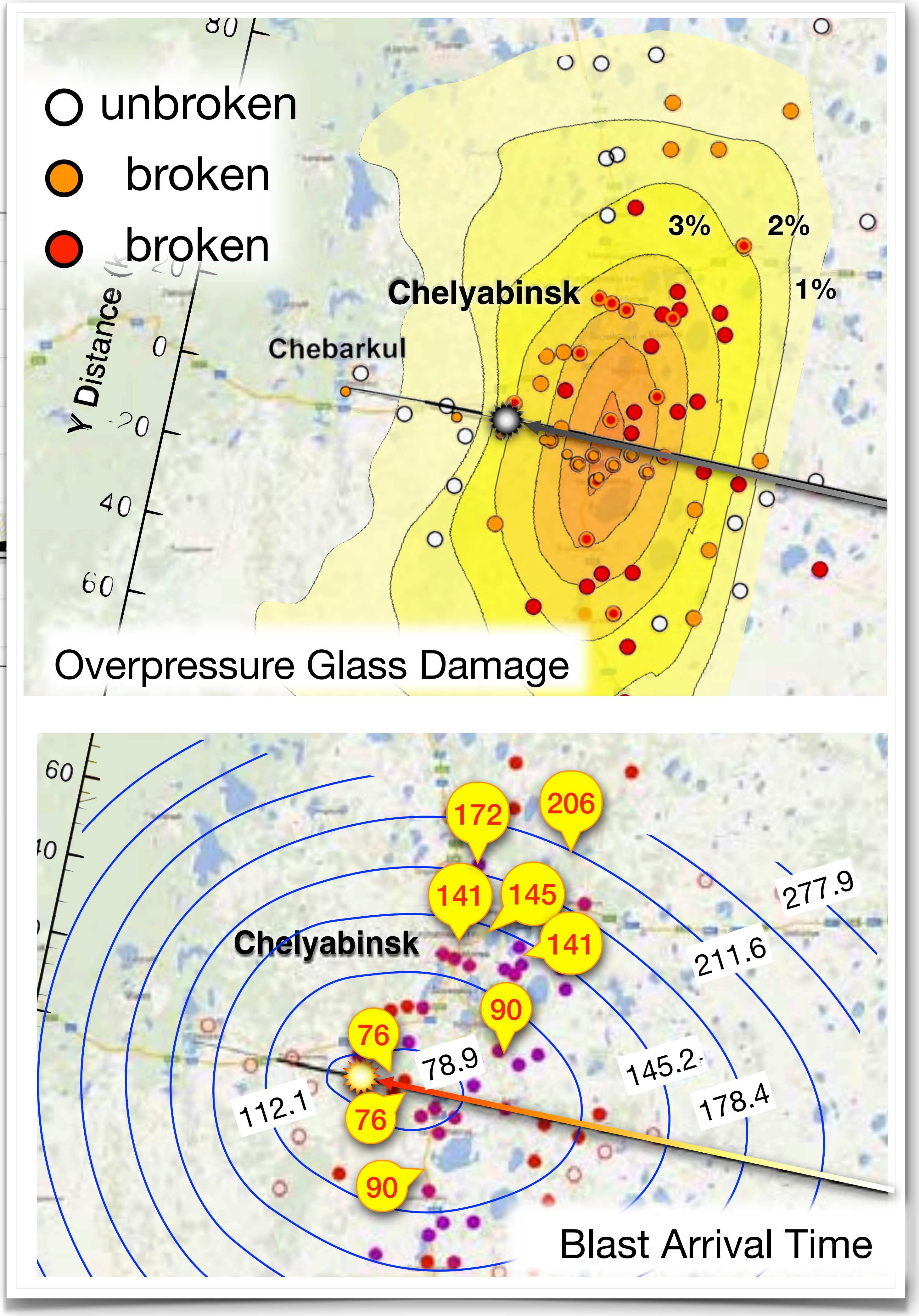


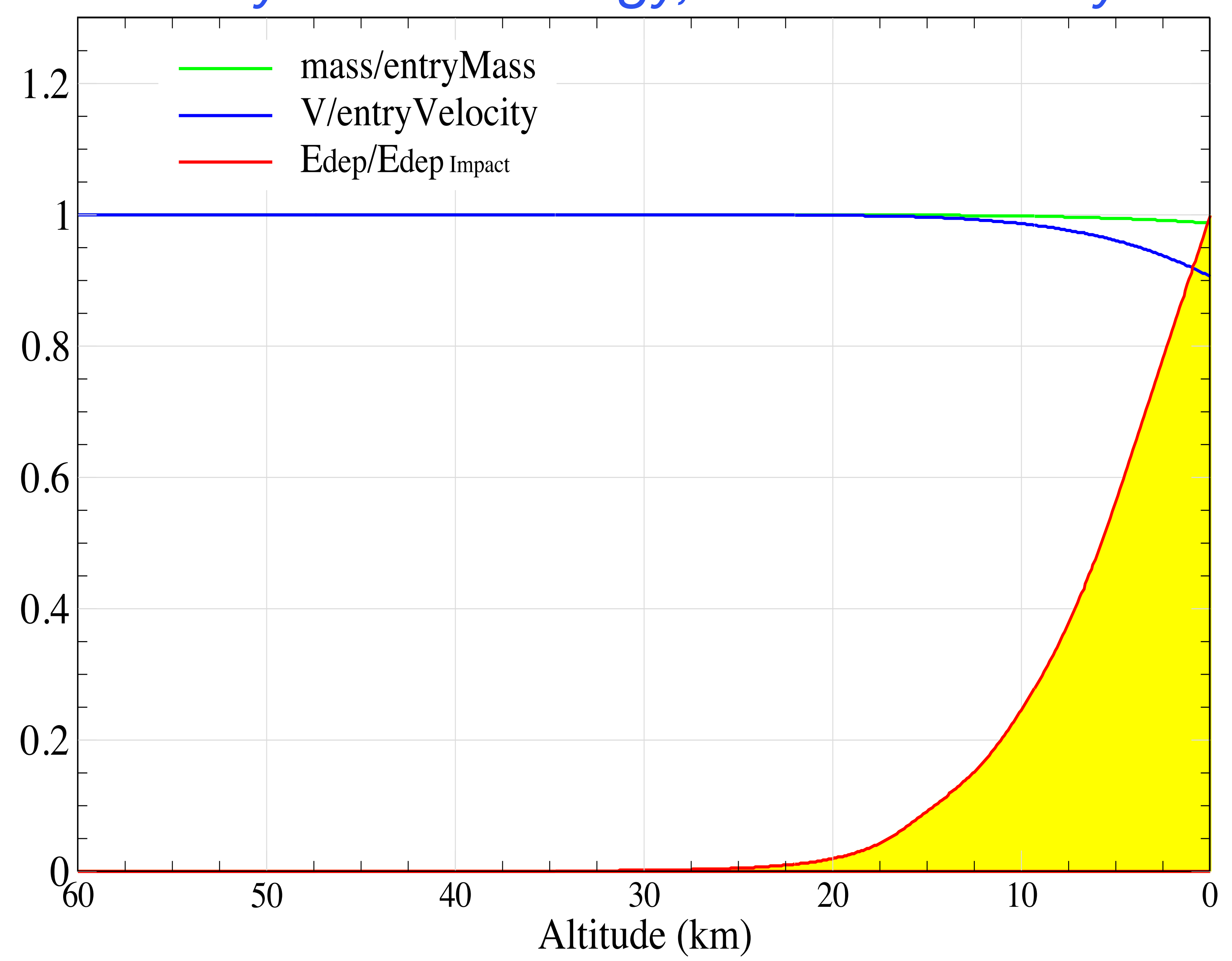
Image credit *AIAA 2016-0998, used with permission.*

2023 PDC Impactor – Simulation setup

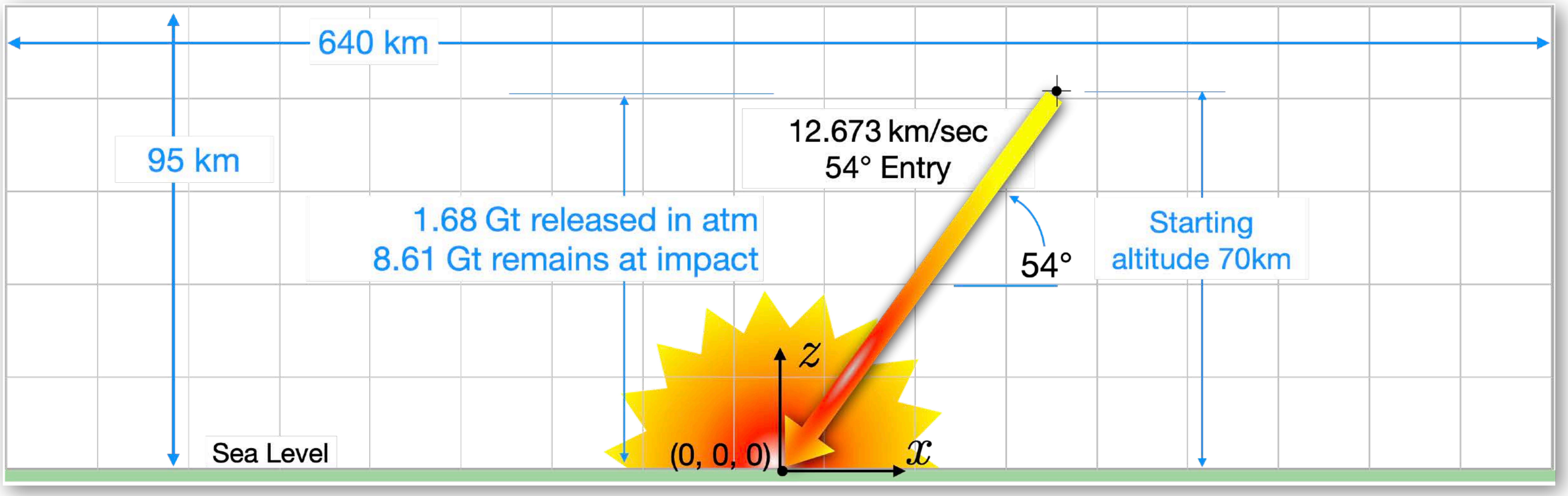
54° entry of Ø 800 m, asteroid at 12.673 km/s, ρ = 2000 kg/m³

- Entry profile from FCM with deposition of mass, momentum & energy
- E_{Tot} = 10.3 Gt, ~200 times more energy than median 2021 PDC case
  - 16.36% (1.68 Gt) of E_{Tot} released in atmosphere
  - 83.64% (8.61 Gt) of E_{Tot} remains at impact
- Impact Modeling
  - Model impact as entry + detonation
  - 2018 studies with ALE3D (Robertson) indicate 3-5% of impact energy couples to airblast

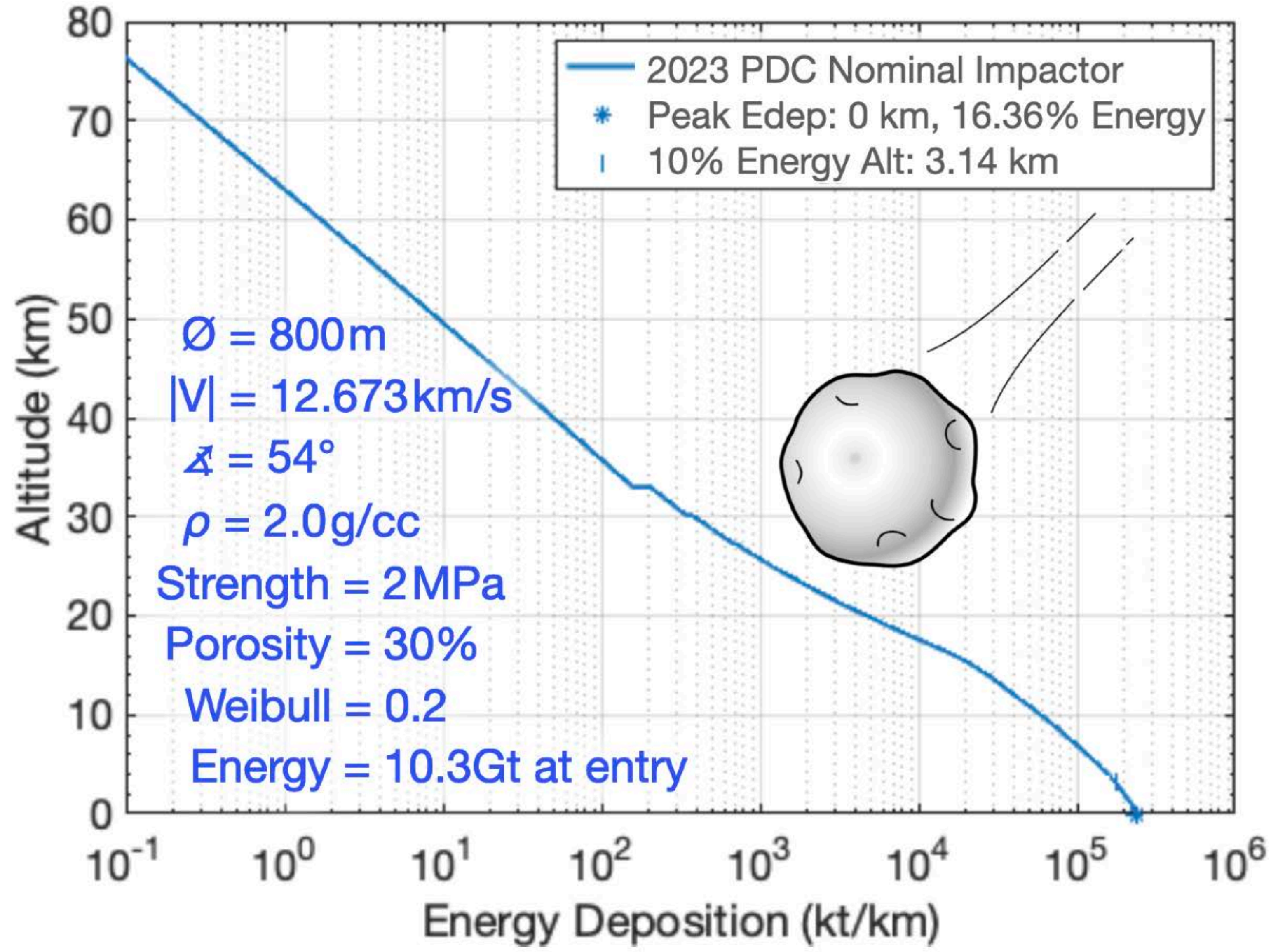
Entry Profile: energy, mass & velocity



Computational domain (not to scale)



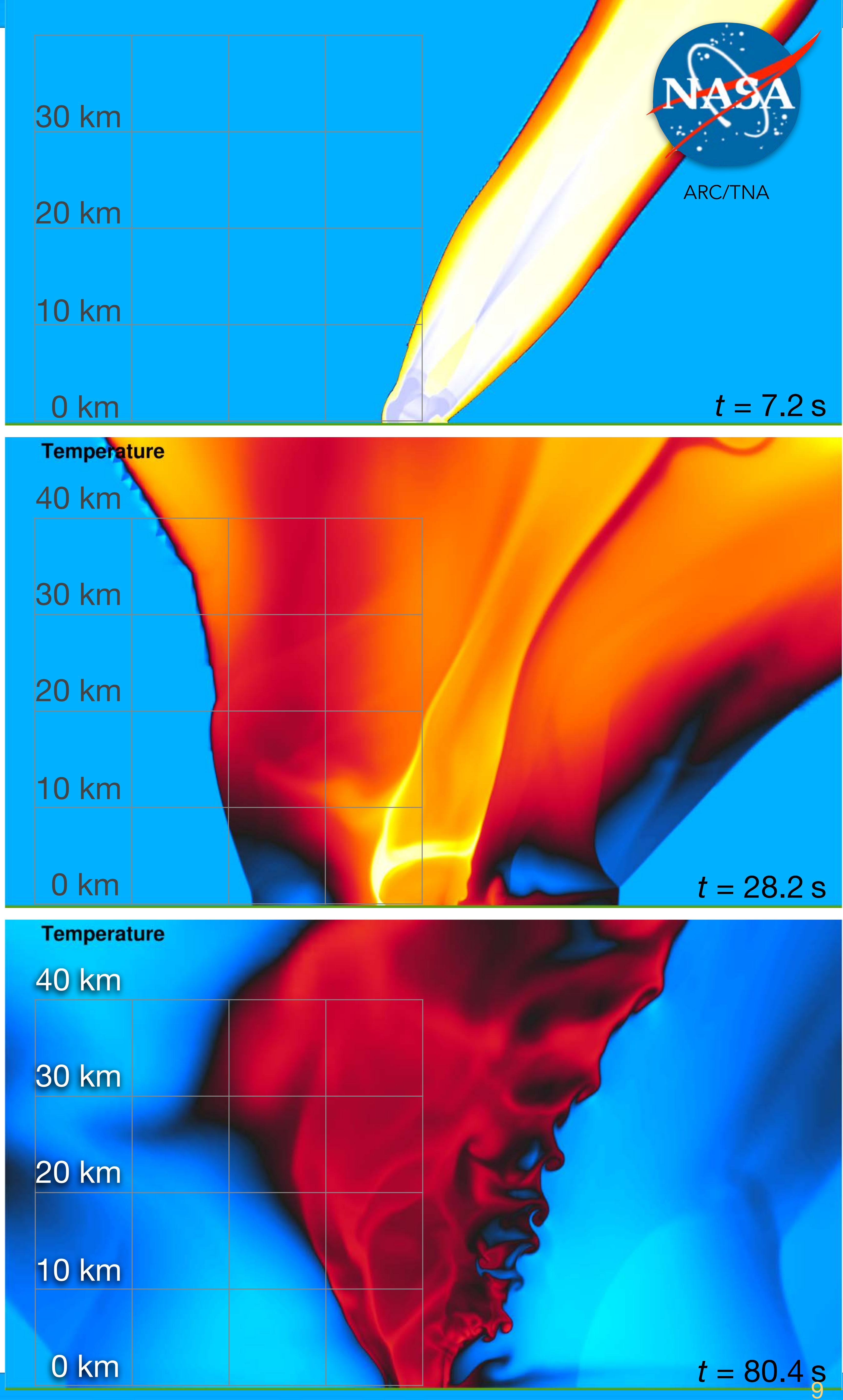
FCM Entry Profile: 2023 PDC



Blast Propagation for 2023 PDC

54° entry of Ø 800 m, asteroid at 12.67 km/s

- Full 3D simulations of the oblique entry and blast evolution
- 1.68 Gt energy deposited during entry
  - Very strong atmospheric blast
  - Ground impact at elapsed time *t* = 6.62 s
- Impact energy is 8.61 Gt
  - 95% goes into ground
  - ~5% (430.5 Mt) couples to atmosphere
  - Impact modeled as detonation (430.5 Mt) near ground
- Simulation spans more than 20 min of real time to observe atmospheric response
  - Blast first reaches downrange domain boundary (320 km from impact) about 12 min after entry



ARC/TNA

Temperature

54° entry of Ø 800 m asteroid at 12.67km/s

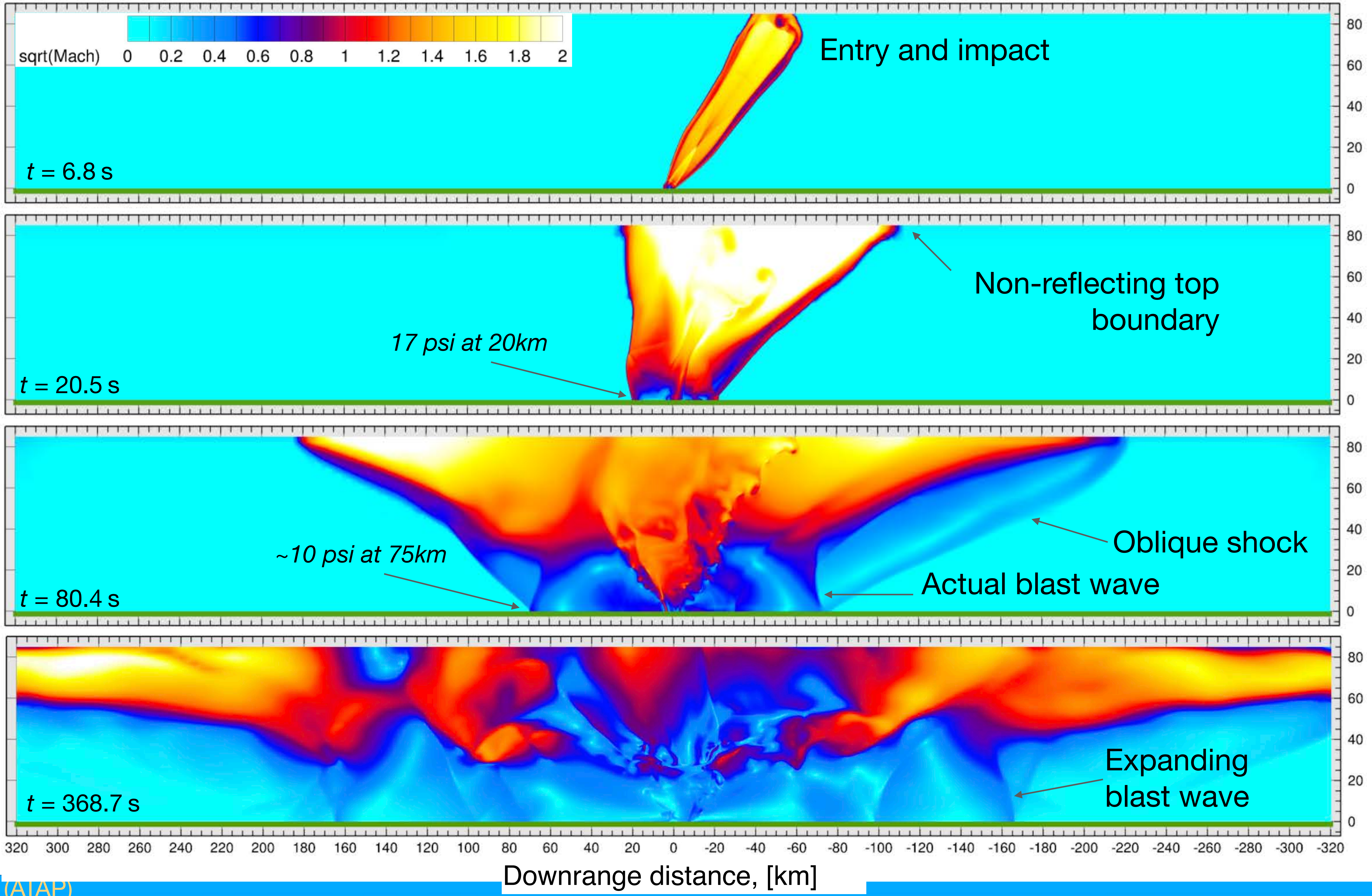

Local Mach Number
54° entry of Ø 800 m asteroid at 12.67km/s
NASA
40 km
30 km
20 km
10 km
0 km
Local
Mach No.
0
0.16
0.5
1.0
2.0
3.0
4.0

Blast Propagation for 2023 PDC

54° entry of Ø 800 m, asteroid at 12.67 km/s

ARC/TNA

- Iso-Mach contours
- Blast from entry corridor and impact disrupts entire atmosphere
- Supersonic spreading at altitude creates oblique shocks which lead the main blast on the ground
- 10 psi overpressures extend 75-80 km from impact
- 4 psi overpressure extends to ~150 km
- 1 psi overpressure extends to domain boundary
- At later times, energy release fills entire domain, and atmosphere oscillates like an elastic membrane

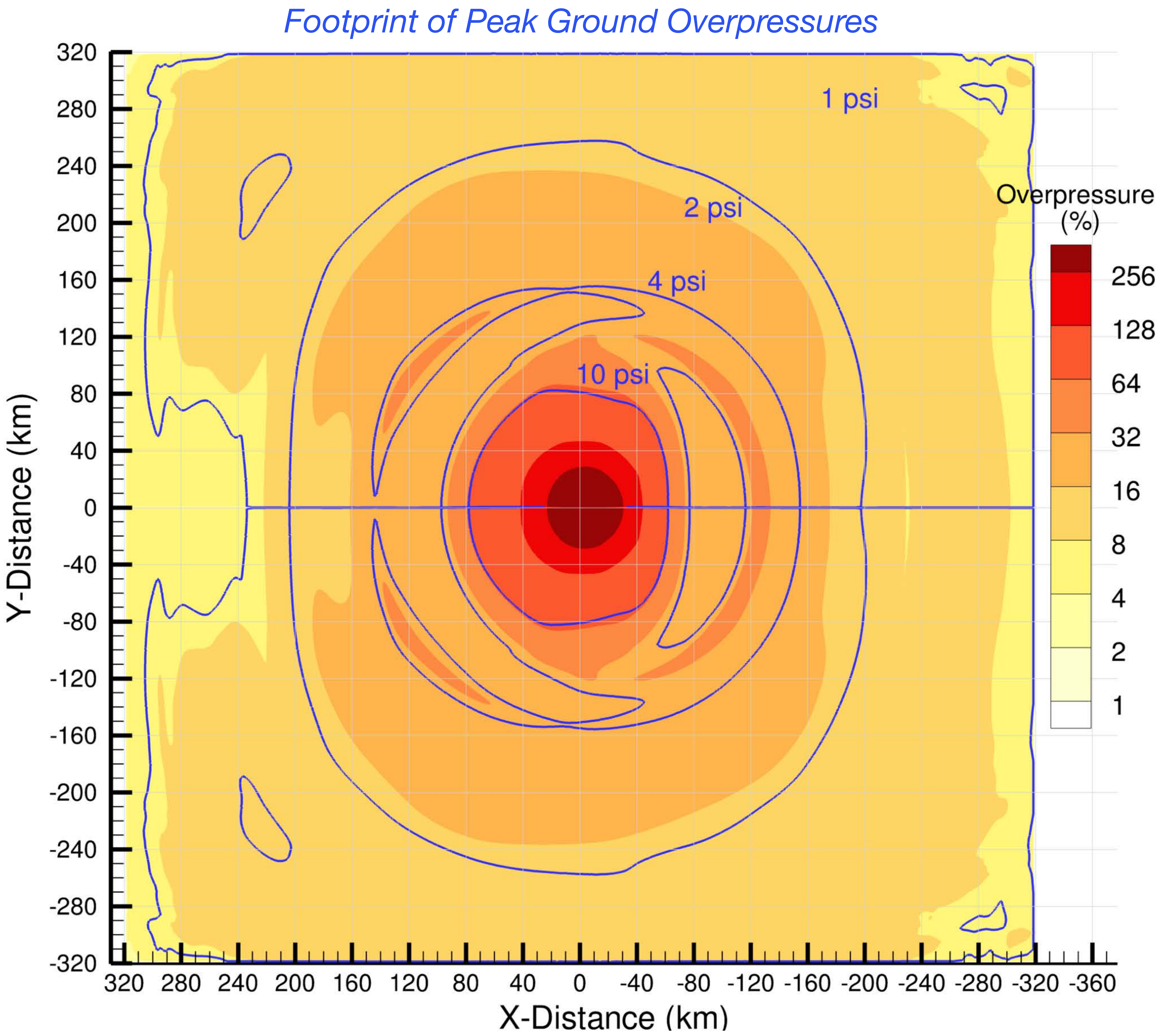


Blast Propagation for 2023 PDC

54° entry of Ø 800 m, asteroid at 12.67 km/s

- Ground overpressure footprint evolves for over 12 mins to cover the entire 640 x 640 km domain
- 10 psi contours nearly circular, mean radius of 74 km
- Lower overpressure contours slightly elliptical due to oblique entry
- 1psi contour driven by oscillation of the atm & extends > 320 km to domain boundary

		Mean blast radius (km)	Area (km^2)
Unsurvivable	10 psi	**74**	**17,203**
Critical	4 psi	**155**	**75,477**
Severe	2 psi	**235**	**173,494**
Serious	1 psi	*> 320*	*> 321,700*



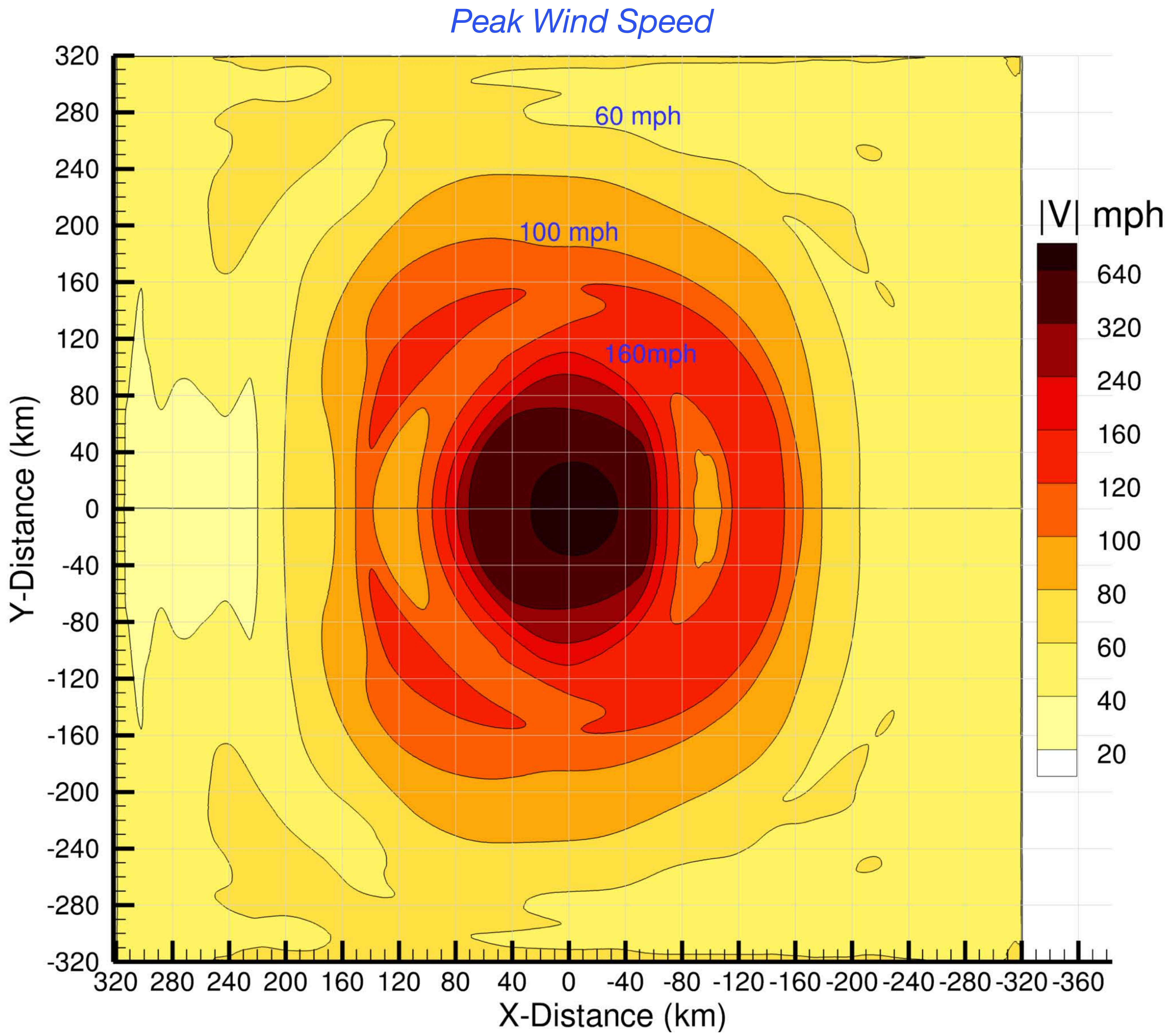
Blast Propagation for 2023 PDC

54° entry of Ø 800 m, asteroid at 12.67 km/s

- Wind is supersonic for over 15 km from impact
- Category 5 winds extend 80-100 km from impact
- Category 1-2 winds extend 180 km from impact and sustain for several minutes
- Speeds near edge likely contaminated by domain boundary conditions

Saffir-Simpson Hurricane wind scale

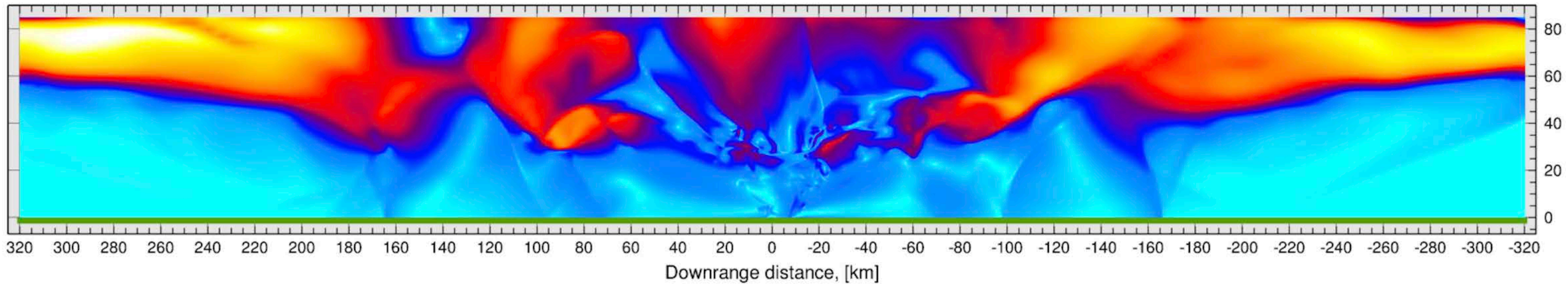
SSHWS Category	Speed (mph)	Mean radius (km)
5	157	95
4	130	140
3	111	155
2	96	180
1	74	210



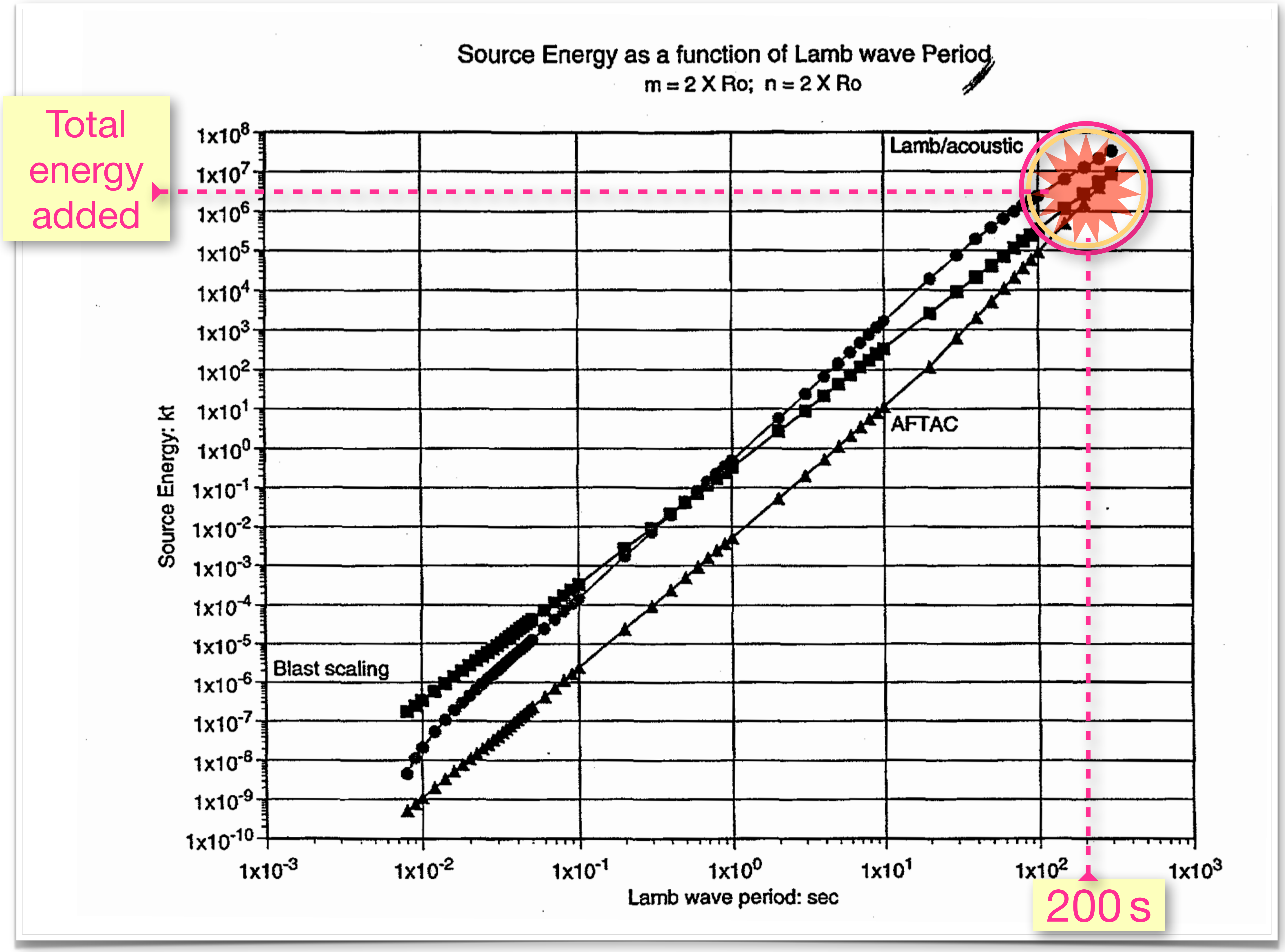
ARC/TNA

Lamb Wave Formation

54° entry of Ø 800 m, asteroid at 12.67 km/s



- Can compute the expected period of a Lamb wave from detonations in the atmosphere as a function of the energy released (Revelle, 1996)
- Well known, and is basis for
  - CTBT infrasound monitoring
  - Infrasound estimates of bolide energy release
- Observed oscillation period of upper atmosphere in simulation is around 180-240s
- Total energy in simulation is sum of E-dep during entry + energy coupling to airblast at impact
- Observed frequency in simulation matches classical prediction extremely well



Revelle & Whitaker, *"Lamb wave from airborne explosion sources: Viscous effects and comparisons to ducted acoustic arrivals."* LANL Report, LA-UR-96-3594, Dec. 1996

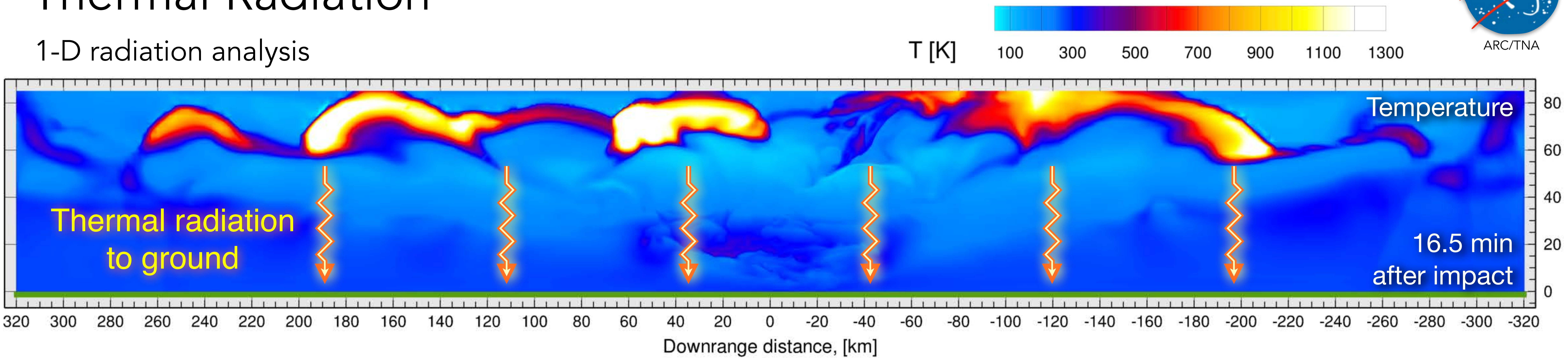
Hunga-Tonga eruption in 2022 (VEI 5-6) created Lamb wave with max. overpressure of 780Pa.

2023 PDC impact is at least an order of magnitude more energetic

- Will resonate around the globe for several days
- Potential for triggering tsunamis far from impact

Thermal Radiation

1-D radiation analysis



- Wide flat atmospheric slab (640 x 640 km) allows use of 1-D radiation approx. via *Stephan-Boltzmann Law*
- Radiative heating is $\dot{q} = \varepsilon\sigma(T_h^4 - T_c^4)A_h$, where σ is the Stephan-Boltzmann constant, $T_h = T_{\text{hot gas}}$, $T_c = T_{\text{ambient}}$
- Used emissivity, ε, of 0.1 for hot air
- Gives heating of approx. $\dot{q}$ = 77 Watts/m^2
  - Below threshold to ignite forest floors and damp leaves (Durda & Kring, 2004)
  - Below ignition threshold of fescue grass, pine needles & paper (Pitts, 2007)

Not enough energy to ignite entire domain, but easy to see that earlier in the evolution, significant regions of the domain could ignite.

Computing Resources

NASA Advanced Supercomputing Center

ARC/TNA

Simulation

- 280M cells in computational domain
- 32,000 time steps
- ~12 sub-iterations per time step (adaptive)
- 2.1M total residual evaluations

- Manufacturer: HPE
- 4 E-Cells (1,152 nodes), 16 Apollo 9000 racks (2,048 nodes)
- 13.12 Pflop/s theoretical peak
- 9.07 Pflop/s LINPACK rating (#58 on June 2022 TOP500 list)
- 172.38 Tflop/s HPCG rating (#44 on June 2022 HPCG list)
- Total cores: 308,224
- Total memory: 1.27 PB

Resources

- Aitken computer in NAS's Modular Supercomputing Facility
- 64 nodes x 128 cores: AMD EPYC Rome processors on Total of 8,192 cores
- Total wallclock time of ~8hrs per simulation
- Parallel efficiency of ~98% with each subdomain containing ~32k cells
- Estimated 0.25 Pflop/s sustained mean performance (including IO)

Summary

ARC/TNA

- **Probabilistic risk assessment** and statistical inference was used to develop a nominal impactor and entry profiles for hypothetical asteroid "2023 PDC" in sufficient detail to enable high-fidelity simulation.
- **Performed high-fidelity 3D entry simulations** for self-consistent Ø800 m asteroid entering at 12.67 km/s and 54° to compute ground overpressure footprints and maps of local maximum wind speed to drive hazard modeling using NASA's Cart3D simulation package.
- **Ground footprints show very large areas of devastation** from both blast and wind and generally exceed those predicted by the fast-running engineering methods in PAIR

Blast Severity		Mean blast radius (km)	Area (km^2)
Unsurvivable	10 psi	**74**	**17,203**
Critical	4 psi	**155**	**75,477**
Severe	2 psi	**235**	**173,494**
Serious	1 psi	*>320*	*> 321,700*

Wind Speed

Hurricane Category	Speed (mph)	Mean radius (km)
5	157	95
4	130	140
3	111	155
2	96	180
1	74	210

- In addition to local blast damage:
  - Simulations showed initiation of atmospheric Lamb waves with initial overpressures of ~1 psi which will travel around the globe for days after impact and may pose a significant tsunami threat
  - 1-D thermal analysis shows radiation from post-impact energy lingering in upper atmosphere may pose a credible ignition threat to grasslands and forests near the impact

Acknowledgements

ARC/TNA

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