8th IAA Planetary Defense Conference

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

Michael Aftosmis
NASA Ames Research Center
michael.aftosmis@nasa.gov

Wade Spurlock
Science and Technology Corp
NASA Ames Research Center
wade.m.spurlock@nasa.gov

Jonathan Chiew
NASA Ames Research Center
jonathan.j.chiew@nasa.gov

Lorien Wheeler
NASA Ames Research Center
lorien.wheeler@nasa.gov

Jessie Dotson
NASA Ames Research Center
jessie.dotson@nasa.gov

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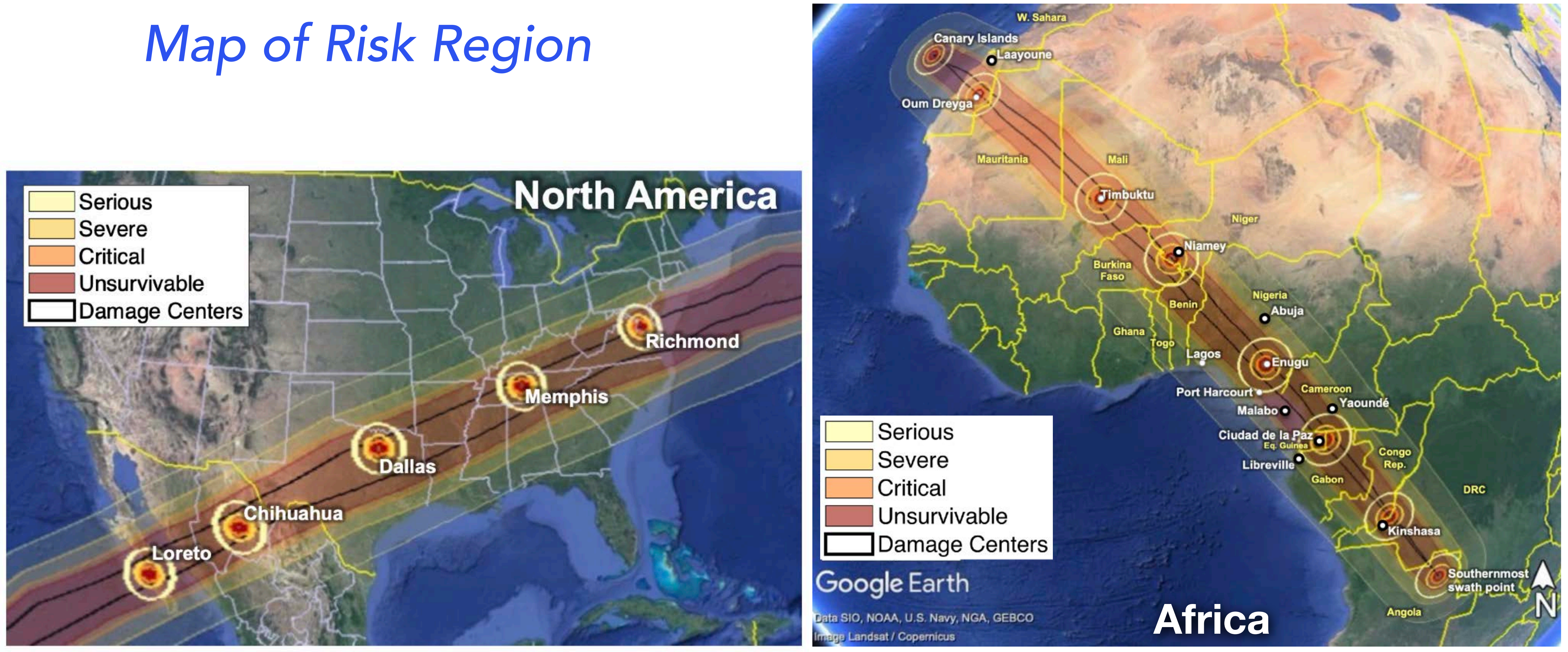
2023 PDC Asteroid Impact "Epoch 1" Scenario

ARC/TNA

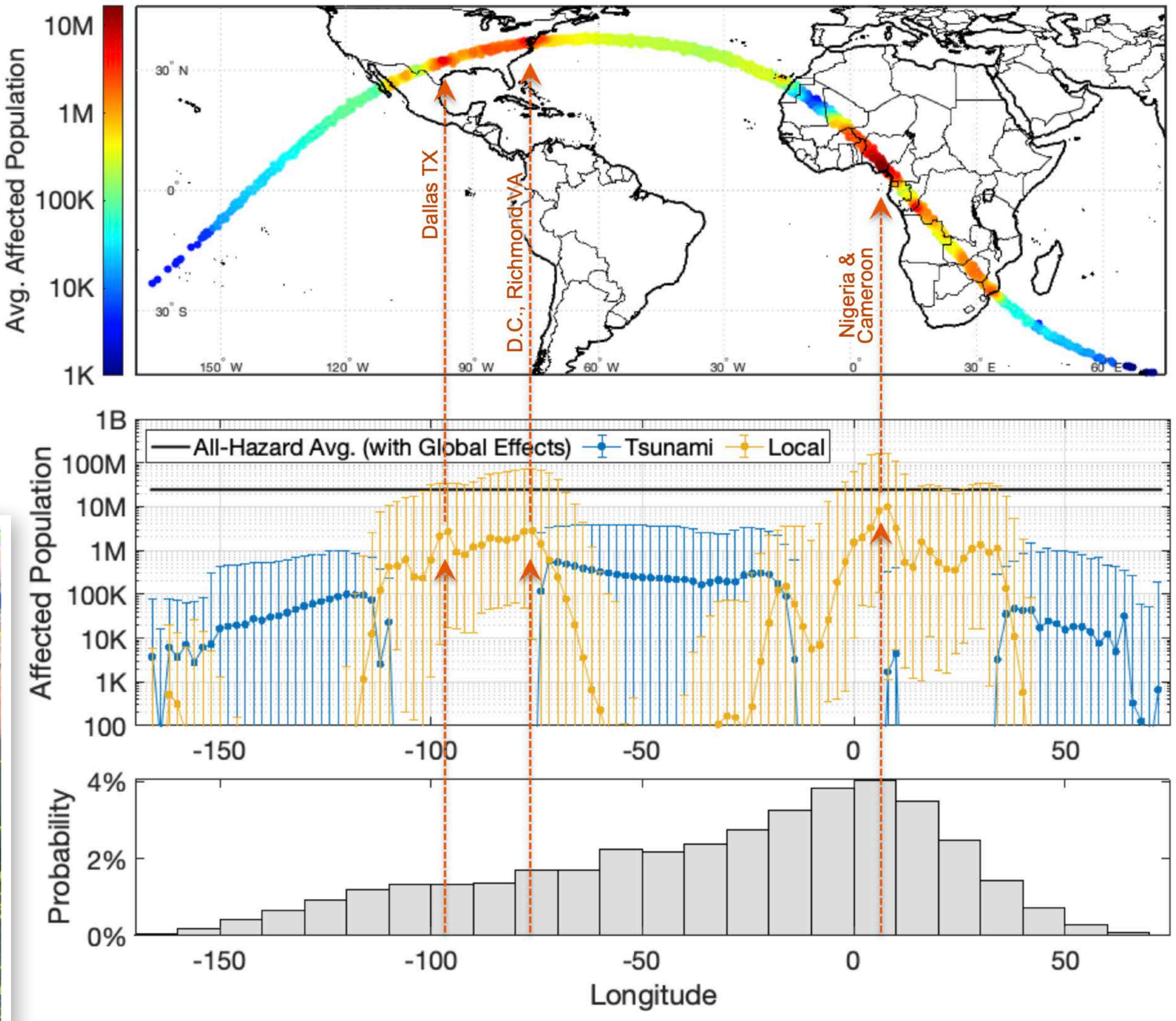
Entry modeling and probabilistic risk assessment

- 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

Asteroid Properties

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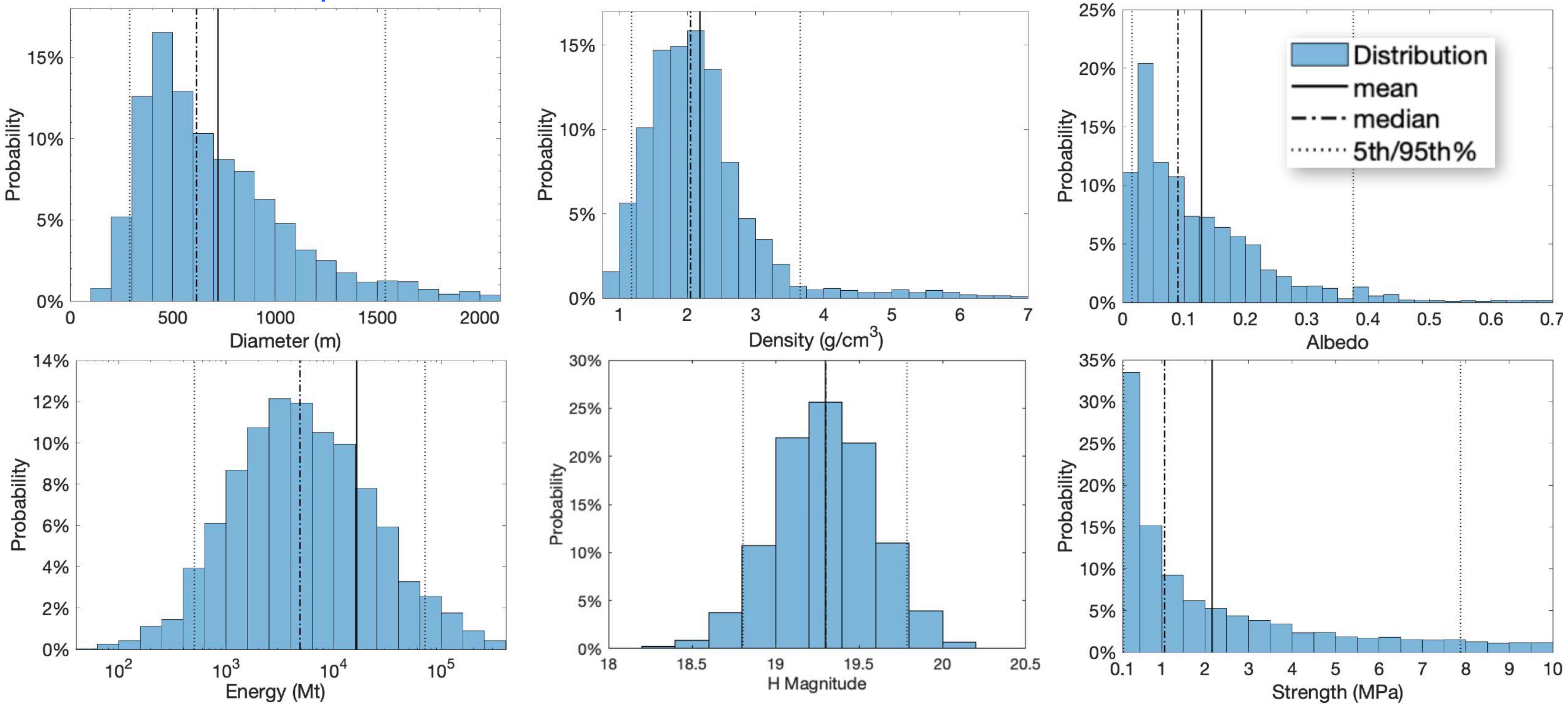
Statistical analysis and Bayesian inference to determine likely asteroid properties

- 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)

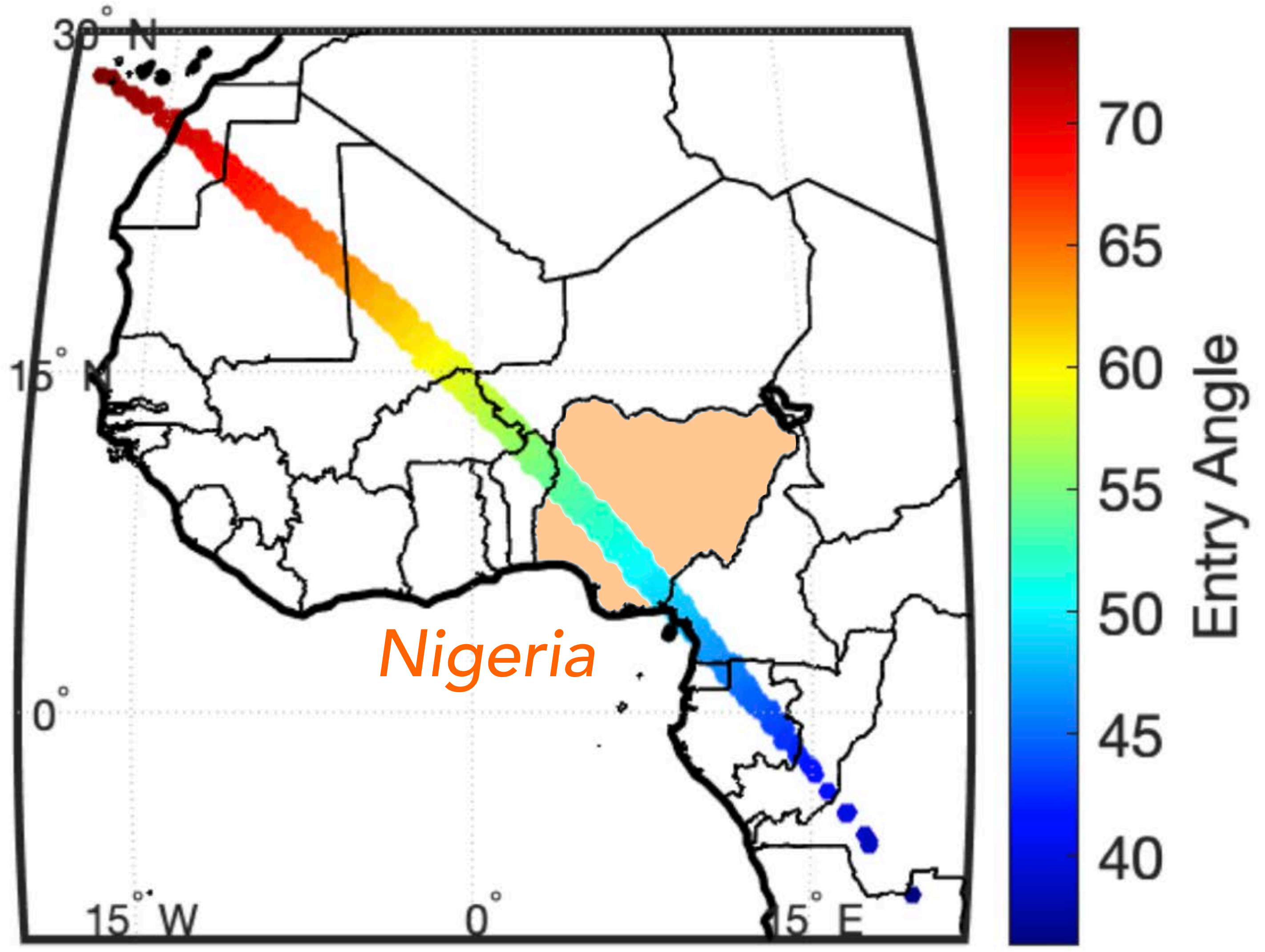


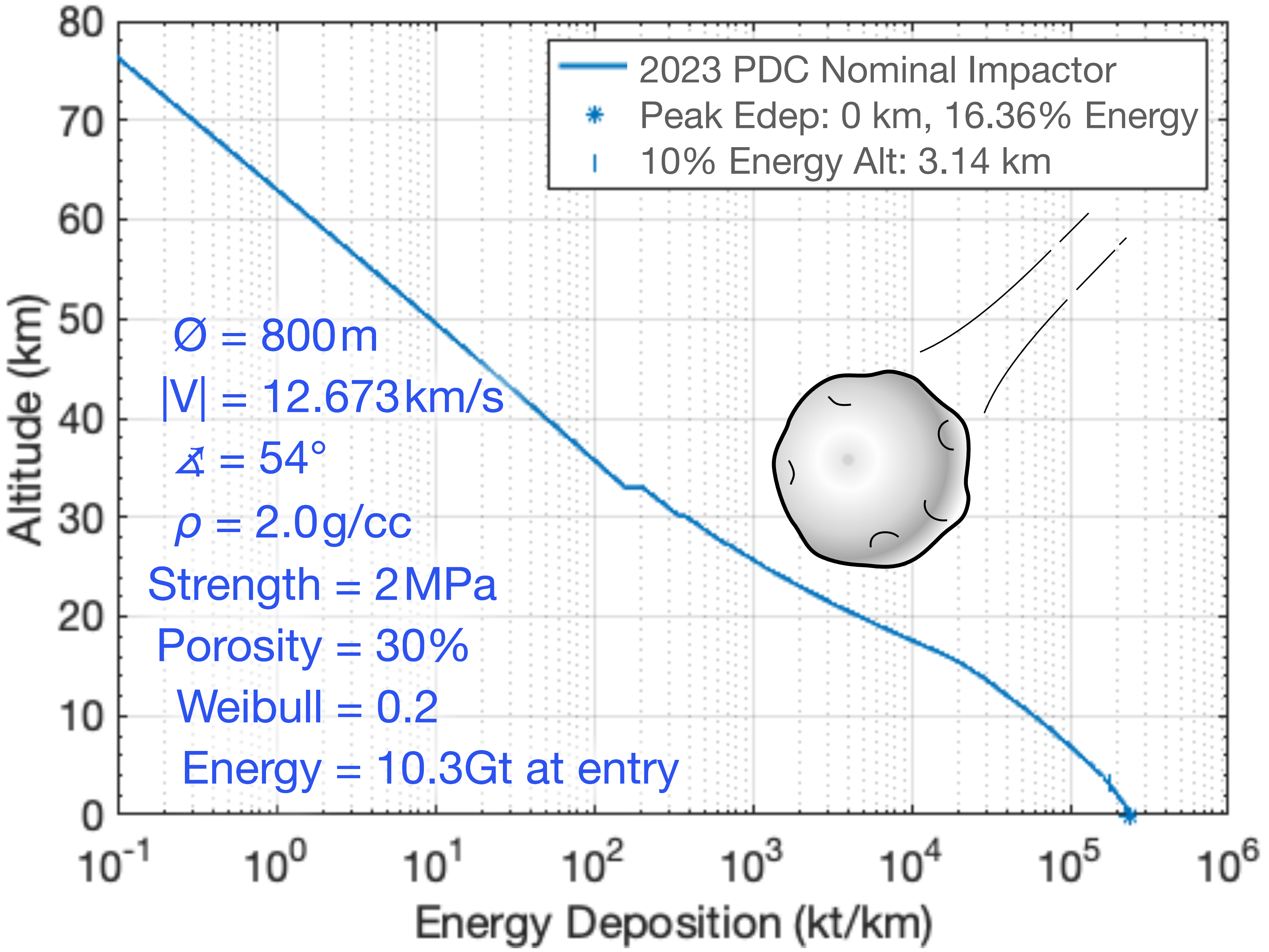
Entry and Energy Deposition

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 ~ 10 M

2023 PDC Entry Angle Map for Africa

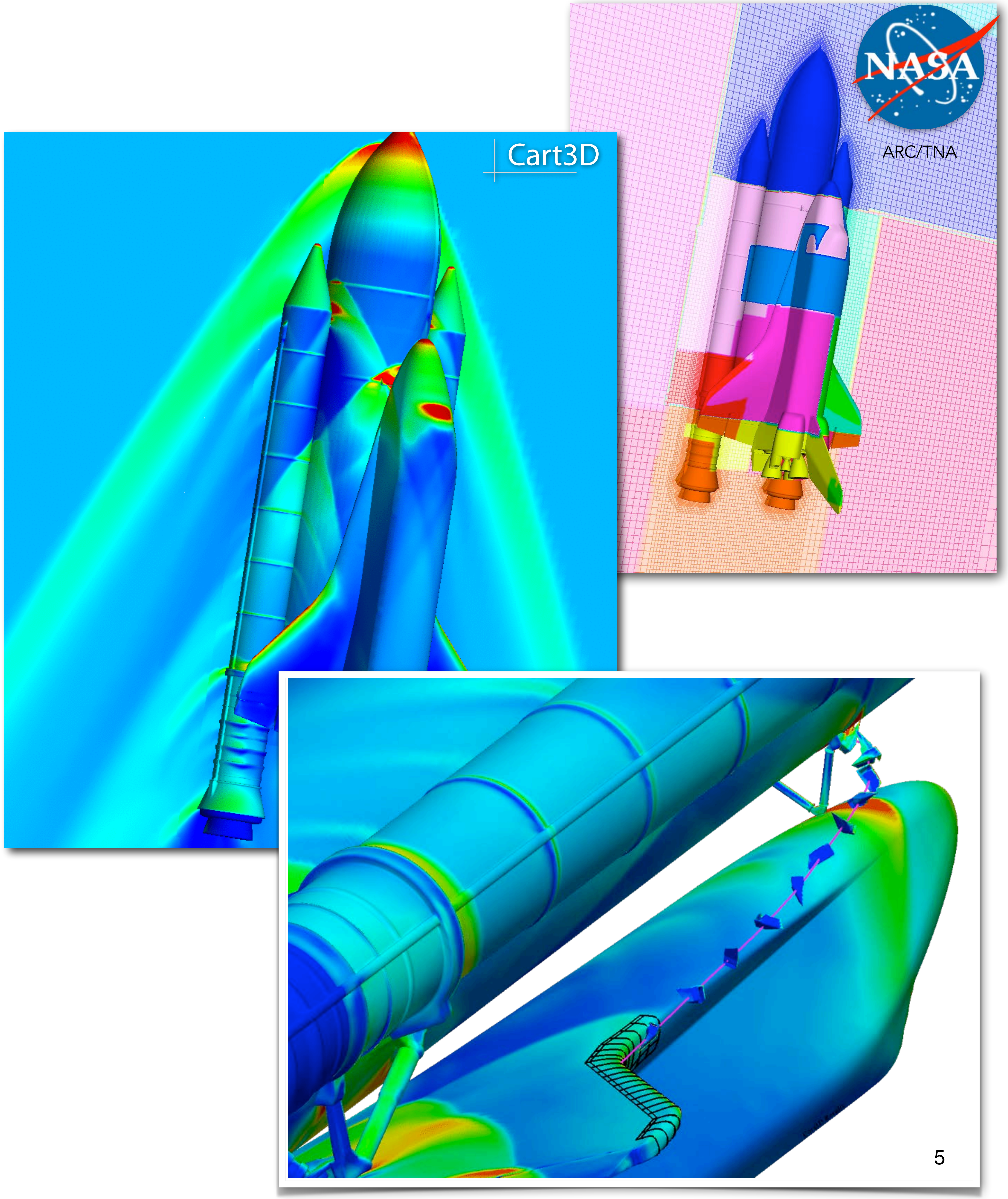




Solver Overview: Cart3D

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

- Originally developed for aerospace applications
- Fully-automated mesh generation for complex geometry
- Inviscid solver using Cartesian cells
  - Fully-conservative finite-volume method
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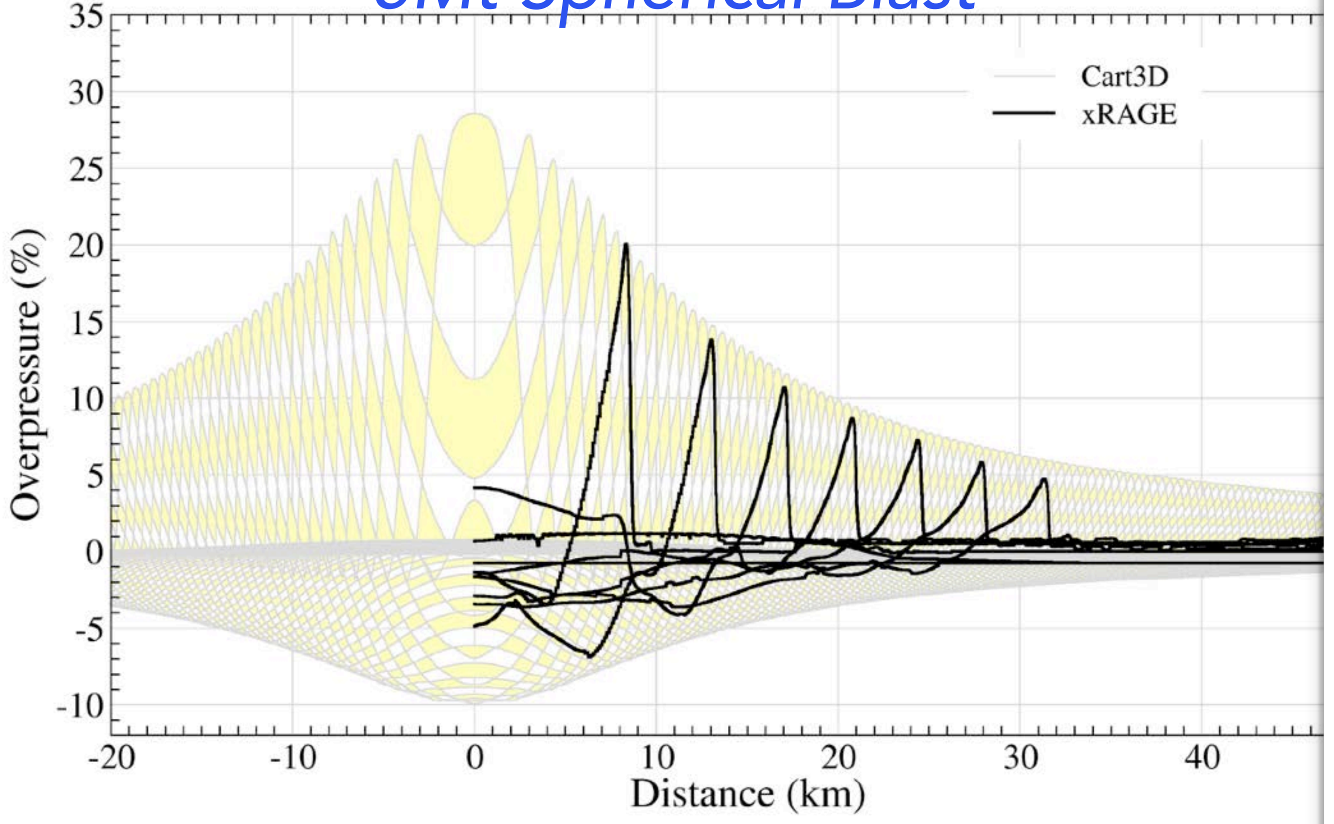
5Mt Spherical Blast



Comparison with xRAGE (DoE) at 2016 Tsunami Workshop

Chelyabinsk Ground Footprints

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

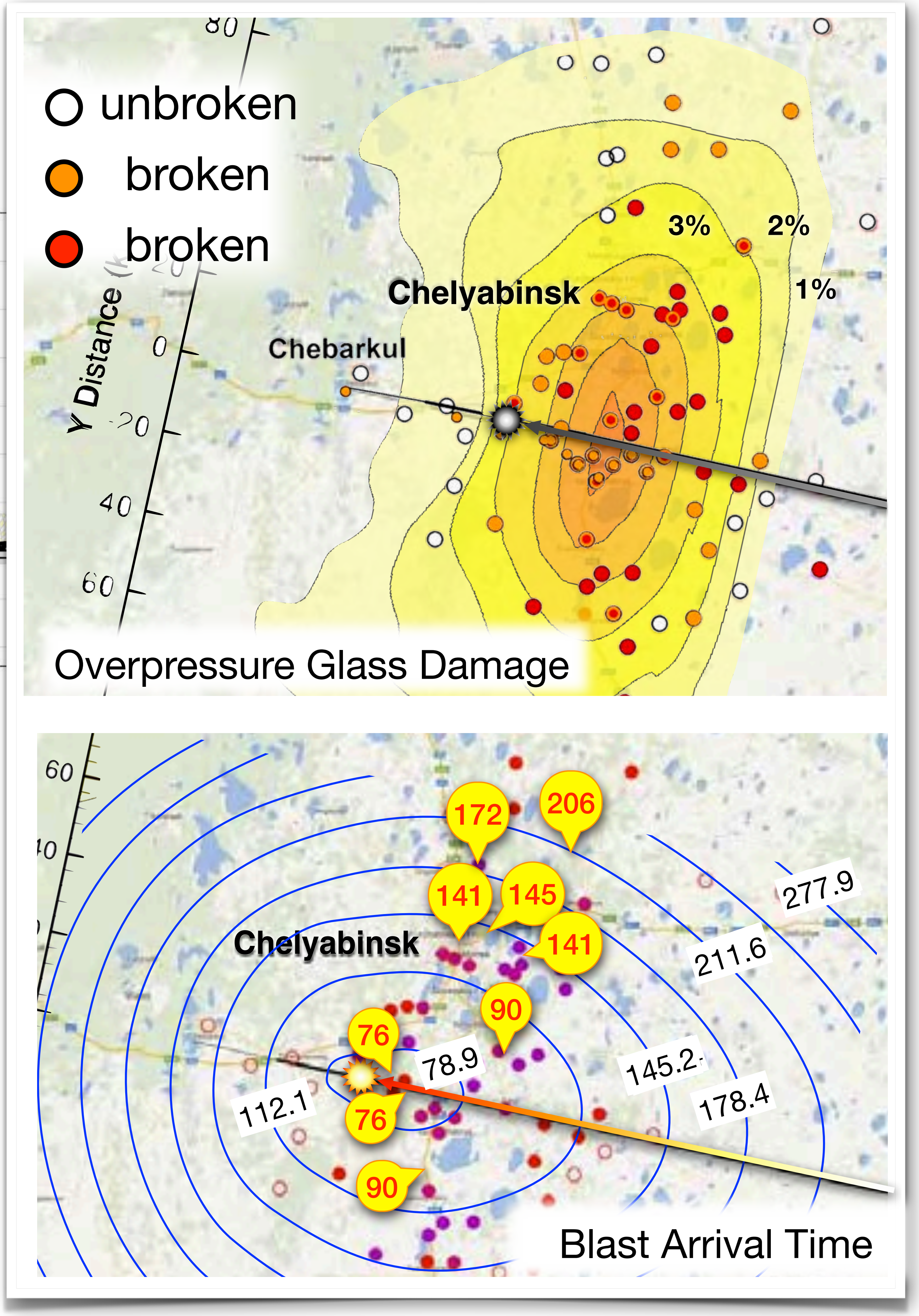


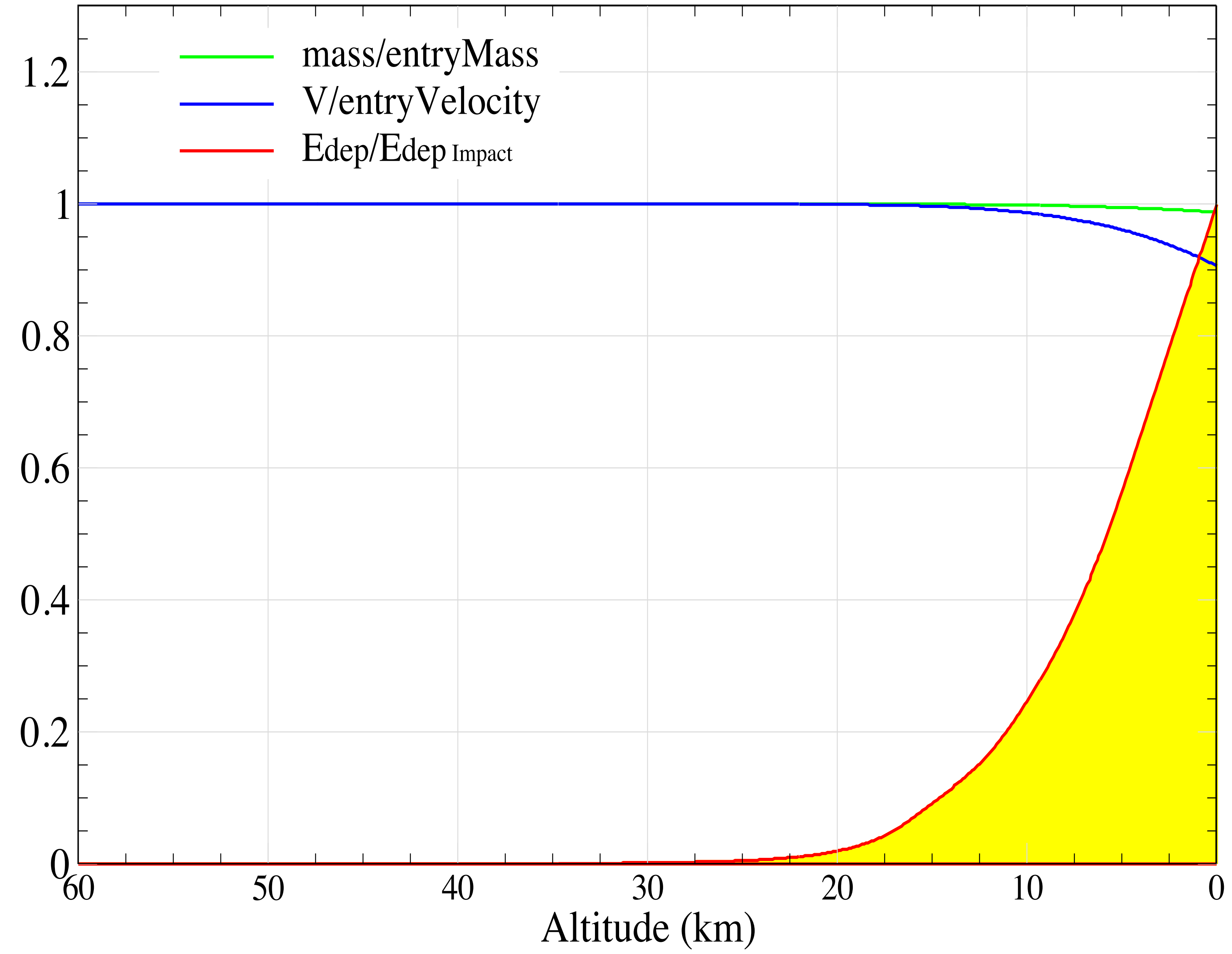
Image credit *AIAA 2016-0998, used with permission.*

2023 PDC Impactor – Simulation setup

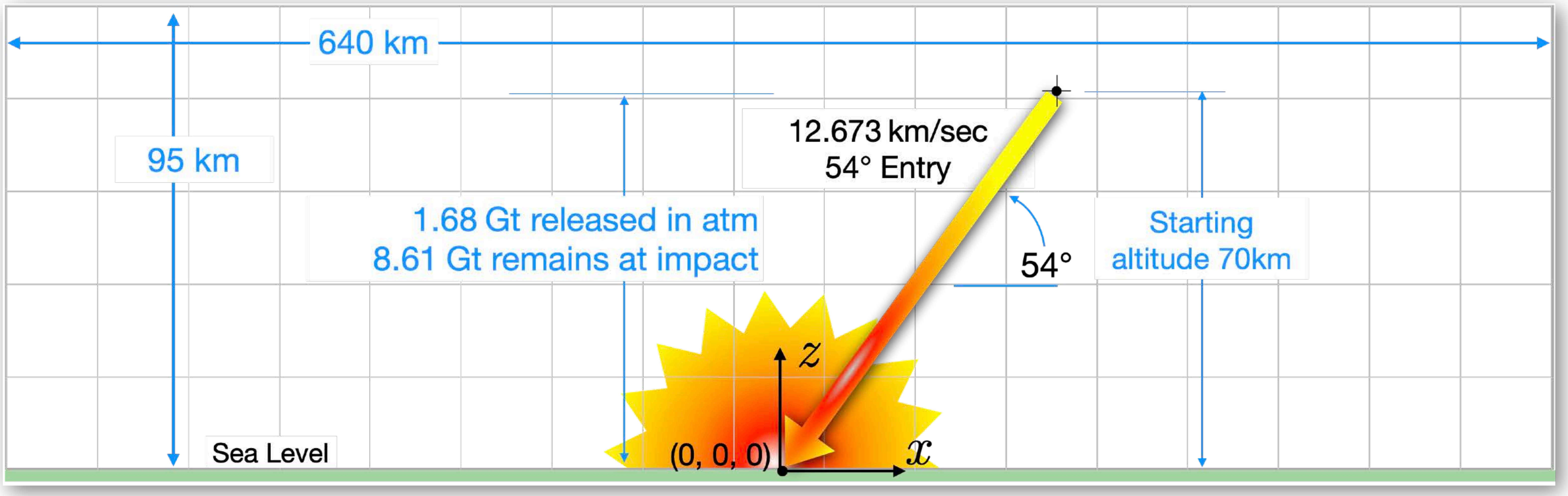
54° entry of Ø 800 m, asteroid at 12.673 km/s, ρ = 2000 kg/m³

- 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

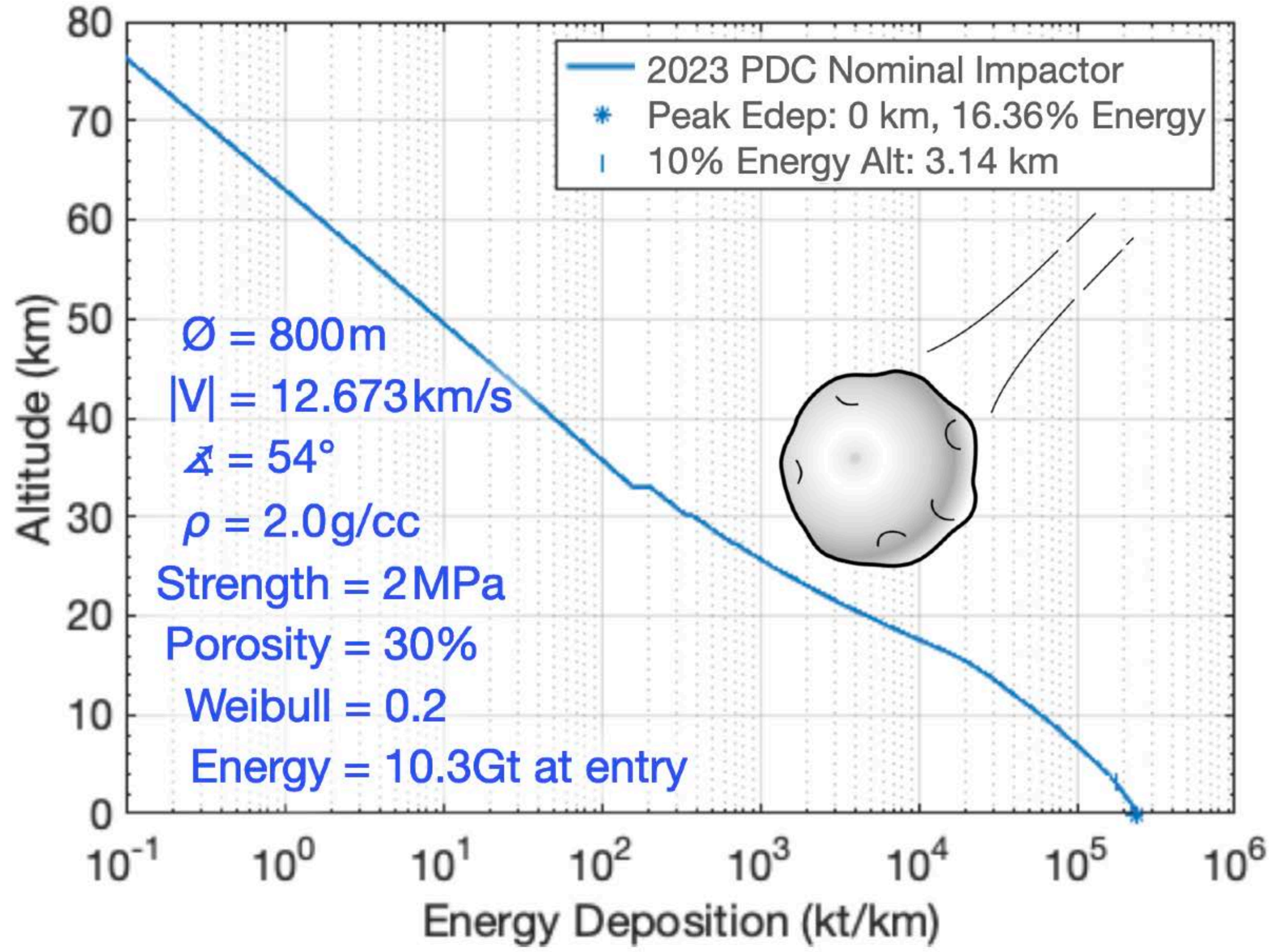
Entry Profile: energy, mass & velocity



Computational domain (not to scale)



FCM Entry Profile: 2023 PDC

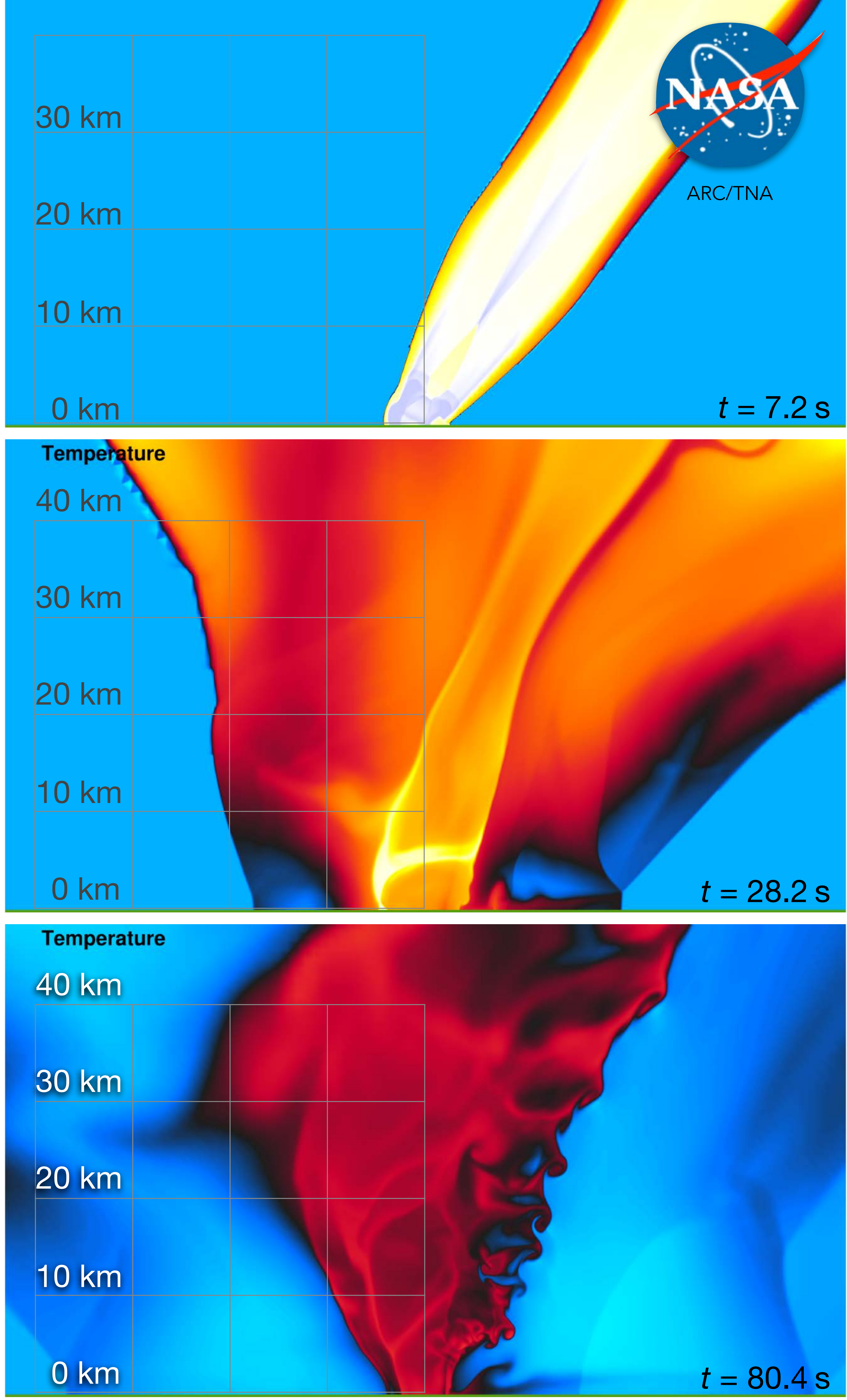


ARC/TNA

Blast Propagation for 2023 PDC

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

- 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




Temperature
54° entry of Ø 800 m asteroid at 12.67km/s
40 km
30 km
20 km
10 km
0 km
Temp. [K]
40000
10000
2500
1000
500
250

Local Mach Number

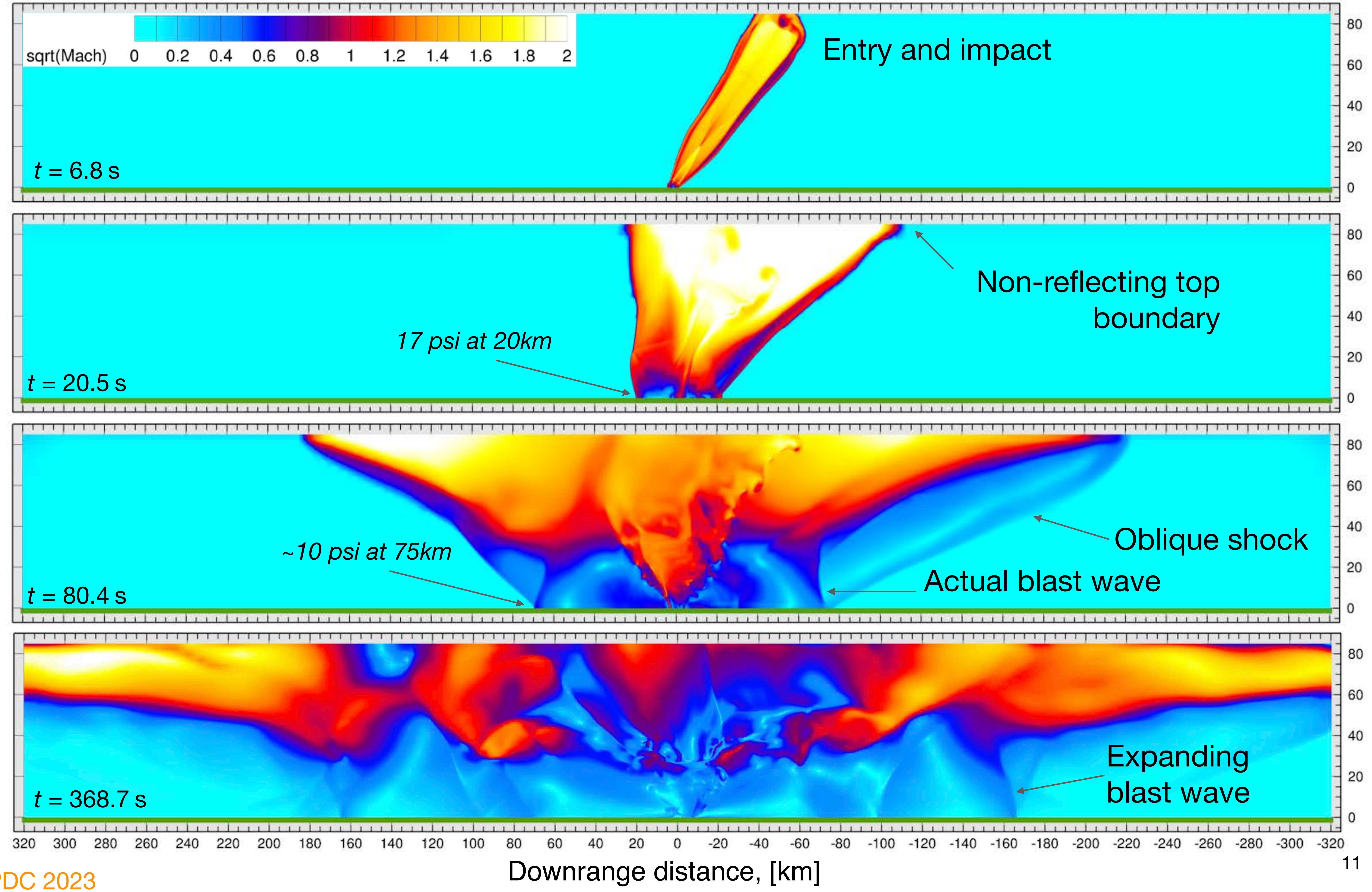
54° entry of Ø 800 m asteroid at 12.67km/s

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

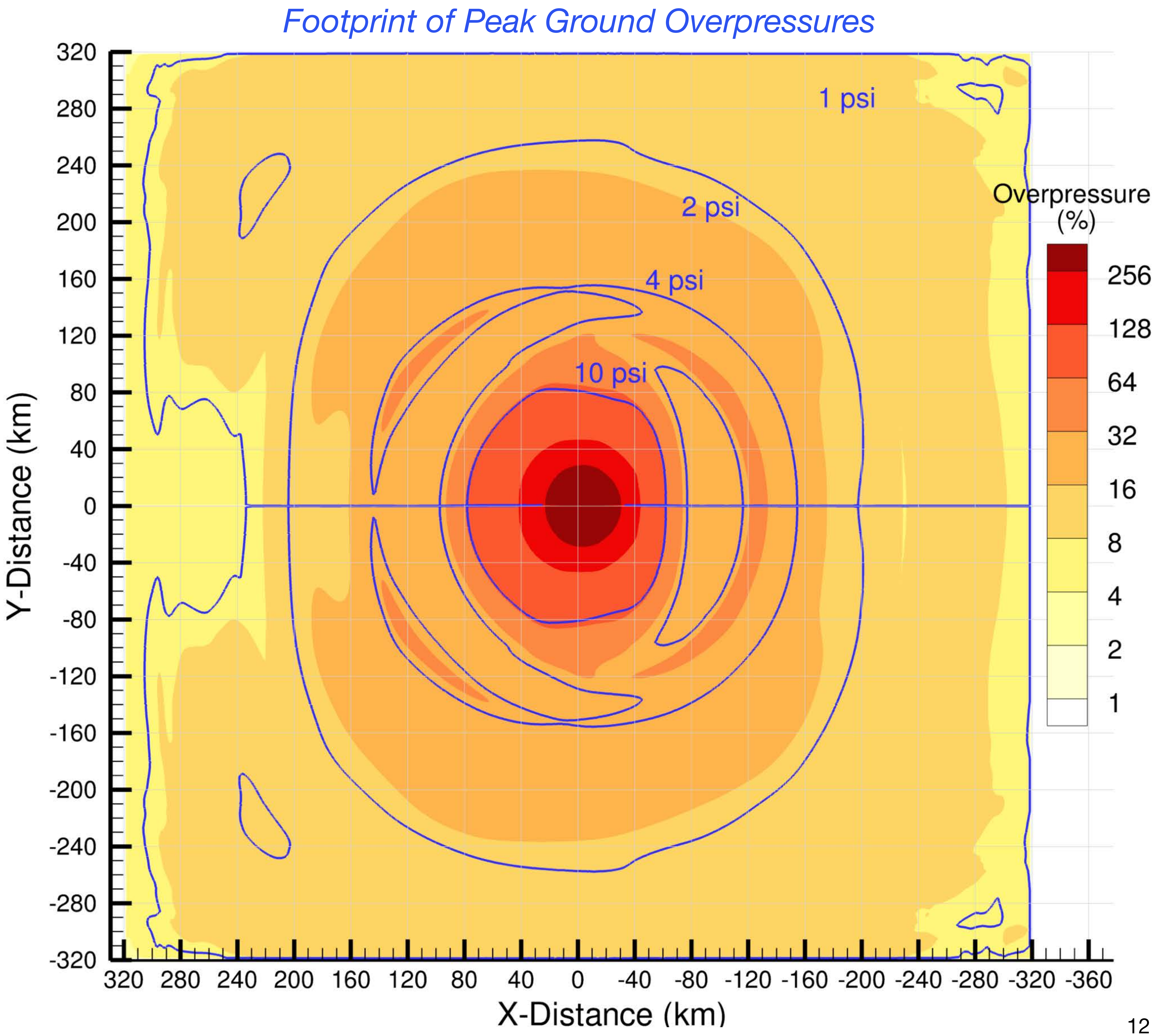


Blast Propagation for 2023 PDC

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

- Ground overpressure footprint evolves for over 12 mins to cover 640 km² of terrain
- 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 (km²)
Unsurvivable	10 psi	**74**	**17,203**
Critical	4 psi	**155**	**75,477**
Severe	2 psi	**235**	**173,494**
Serious	1 psi	*> 320*	*> 321,700*



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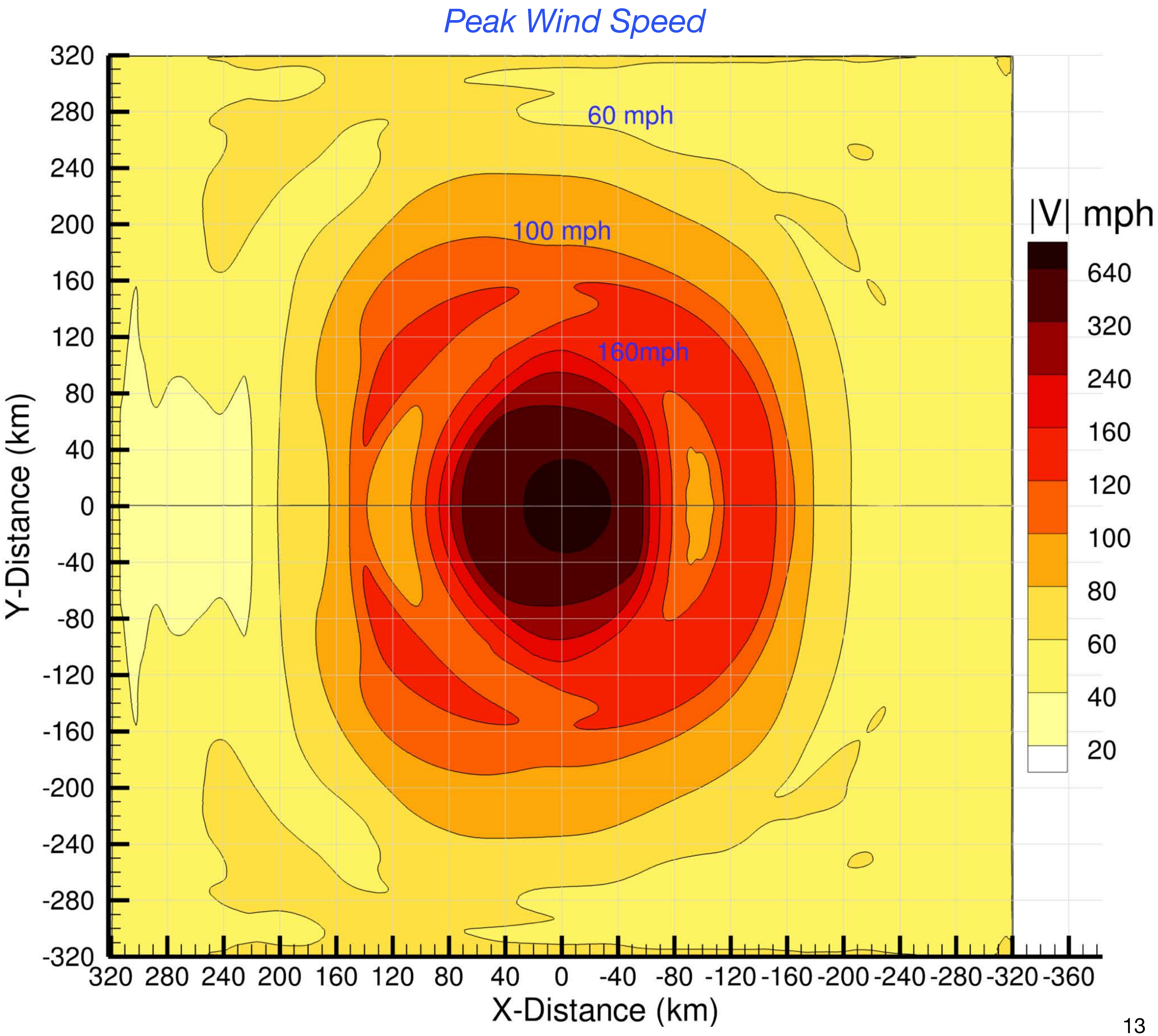
Blast Propagation for 2023 PDC

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



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Lamb Wave Formation

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

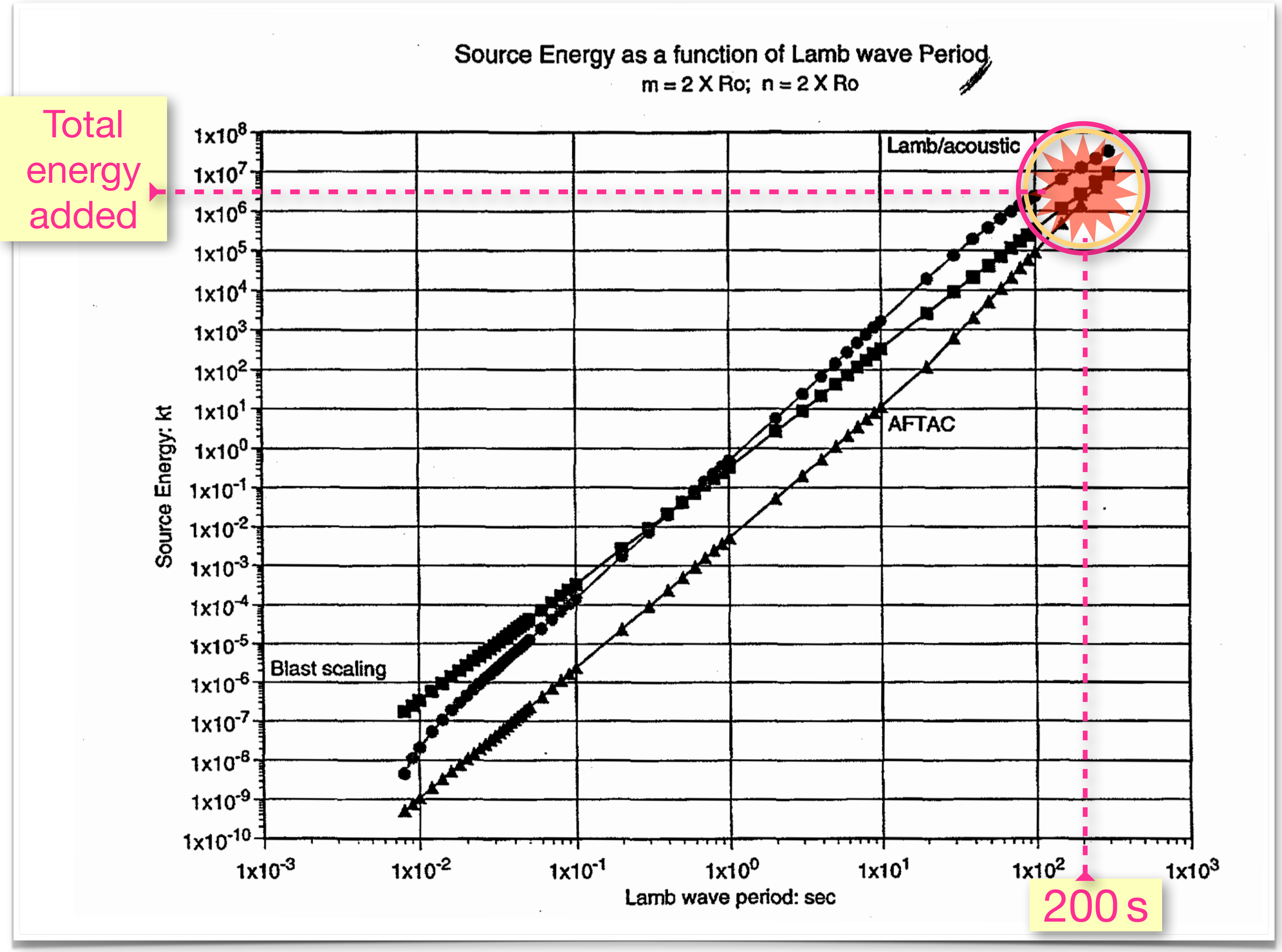
ARC/TNA

- 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

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

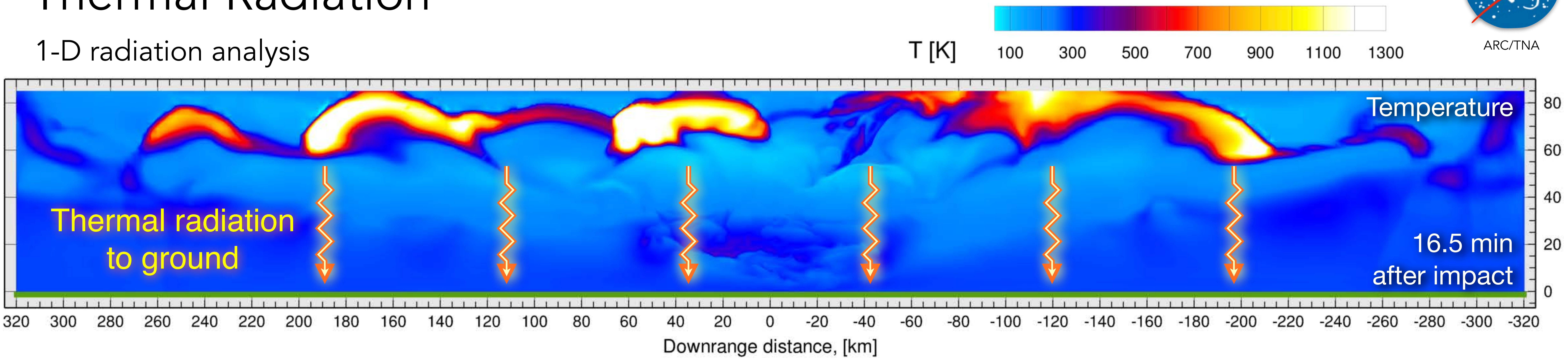
- Will resonate around the globe for several days
- Potential for triggering tsunamis far from impact



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

Thermal Radiation

1-D radiation analysis



ARC/TNA

- 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 with a little more energy, or earlier in the evolution, significant regions of the domain could ignite.

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:
  - Analysis reveals initiation of atmospheric Lamb waves with initial overpressures of ~1 psi which will travel around the globe for days after impact and raise 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 throughout the simulation domain

Acknowledgements

ARC/TNA

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