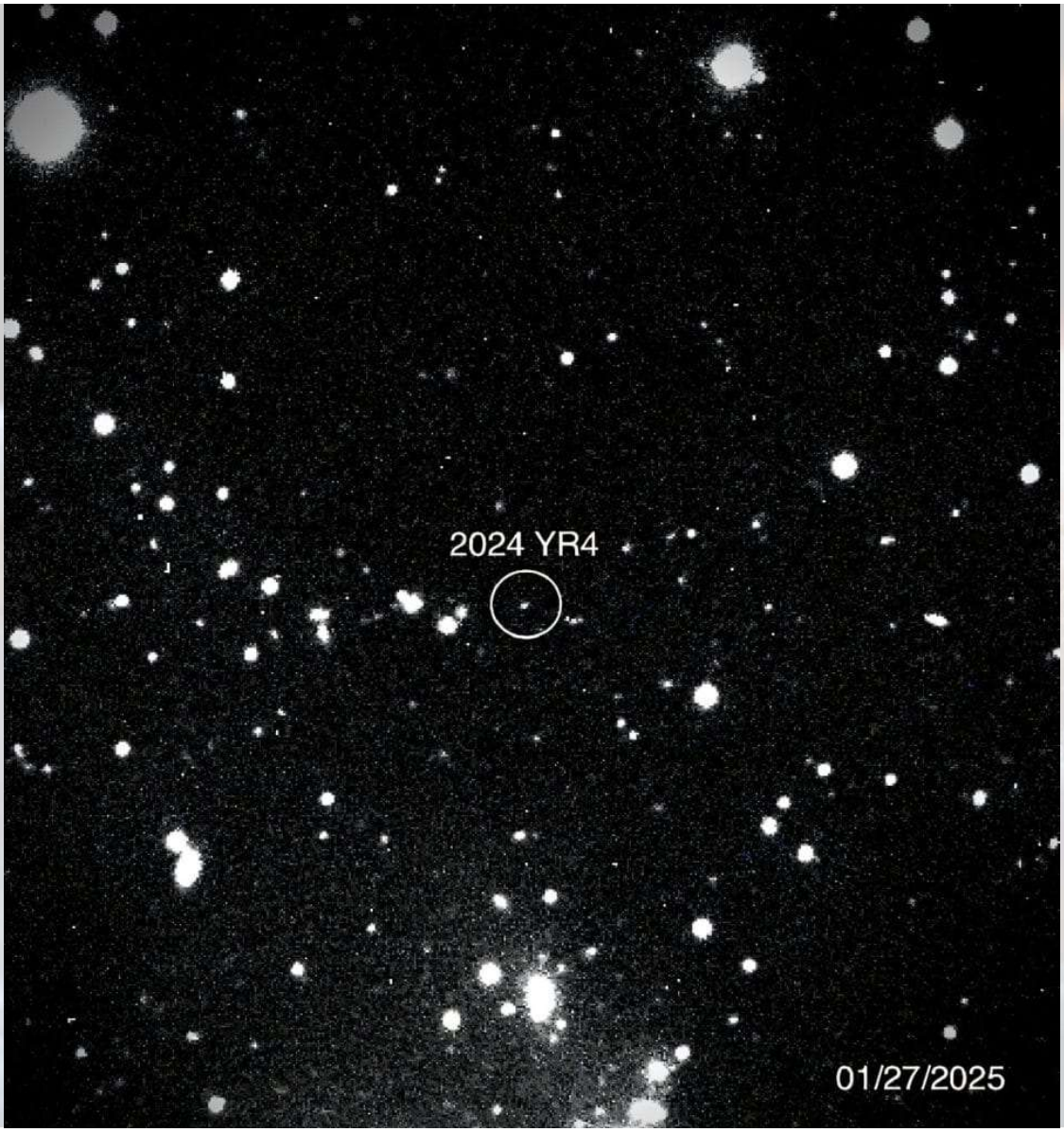
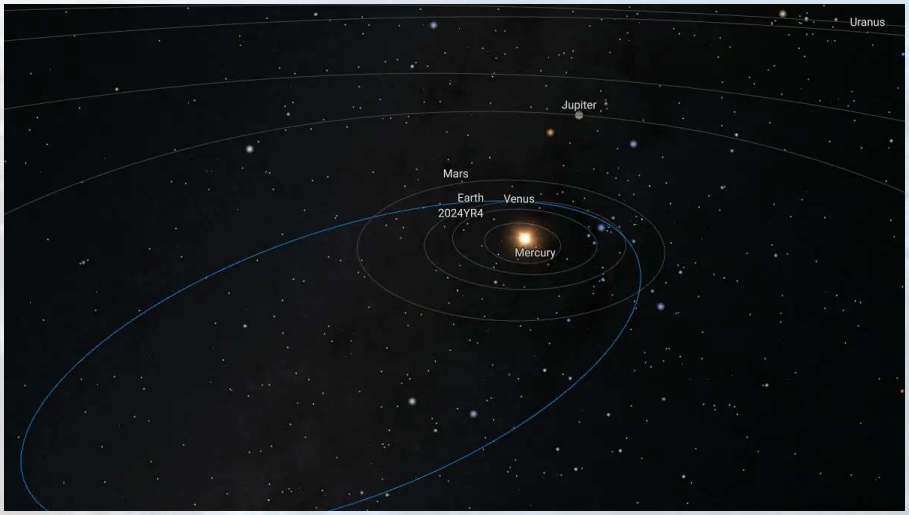
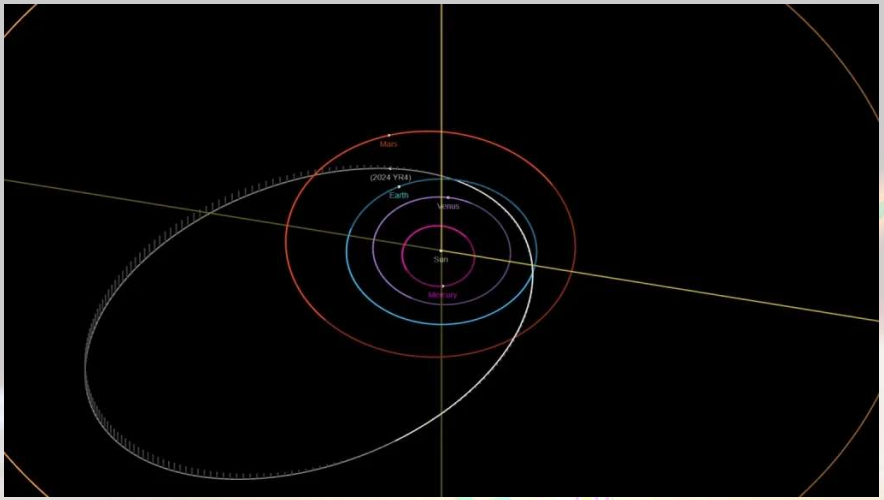


The **Asteroid 2024 YR4** was detected on **December 27, 2024**, by the **ATLAS** (Asteroid Terrestrial-impact Last Alert System). With an estimated **diameter** ranging from **40 to 90 meters (55 m, aprox)**, its potential impact could release **up to 8 megatons of TNT—over 500 times more powerful than the Hiroshima bomb.**

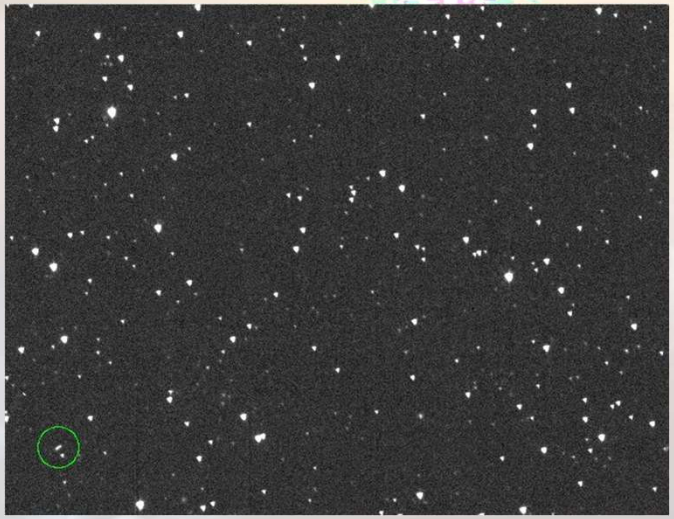
Given this significant threat, the asteroid has been classified as **level 3** on the **Torino Scale**, a system used to assess the risk of impact from celestial objects, ranging from 0 to 10.



2024 YR4 orbit diagram - January 29, 2025. Image credit: ESA/NEOCC, The Watchers

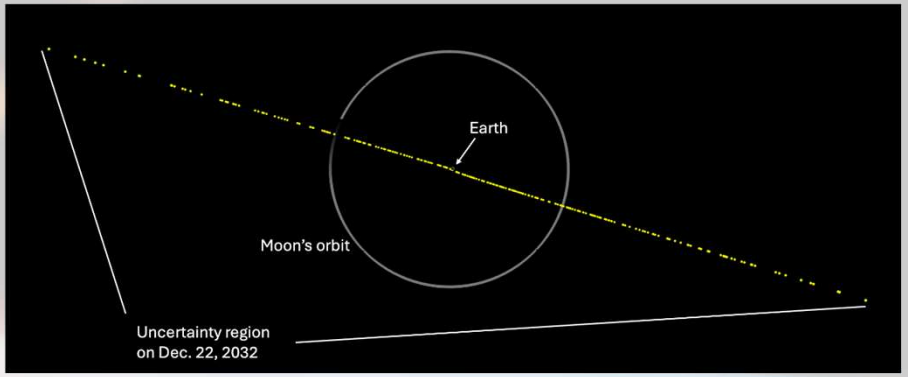


Asteroid 2024 YR4 orbit simulation graphic. Image credit: NASA/JPL

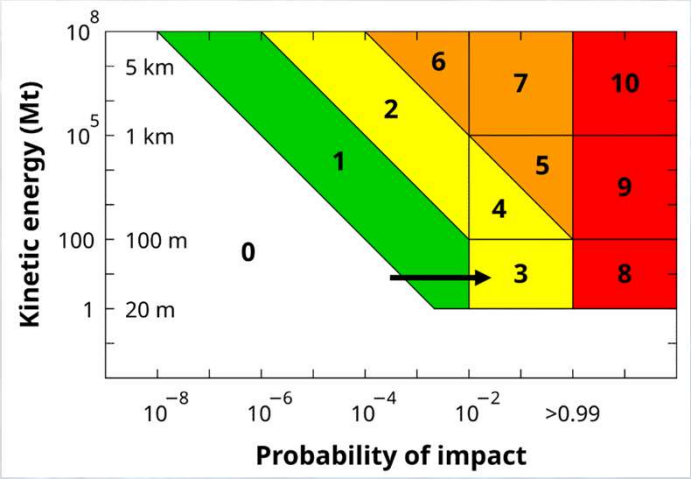


Discovery images of 2024 YR4. Credit: ATLAS

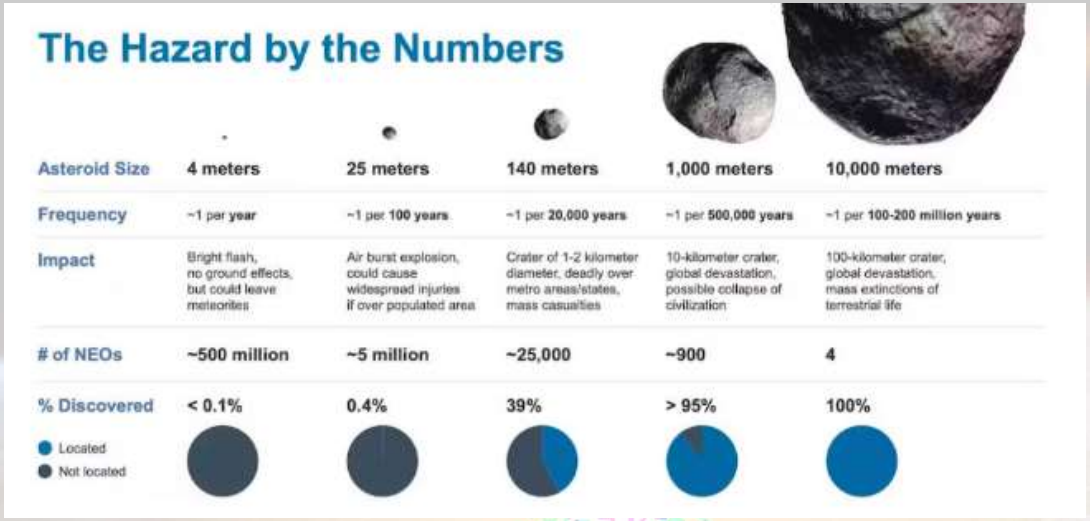
https://cneos.jpl.nasa.gov/news/news210.html

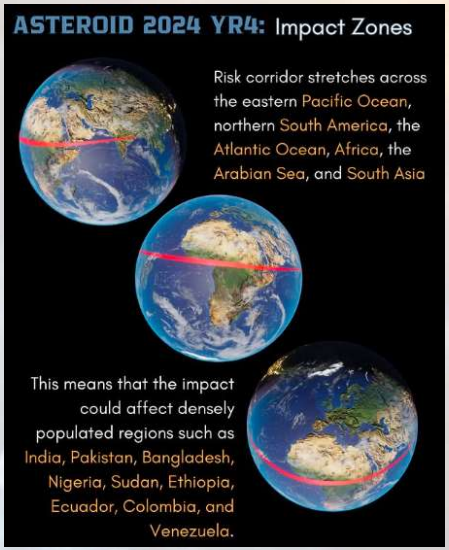


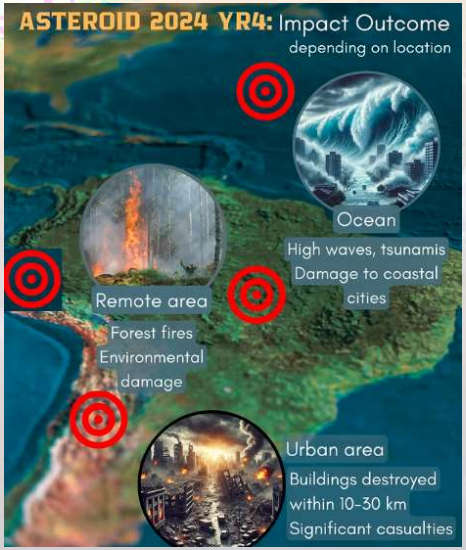
The yellow dots show the position uncertainty of asteroid 2024 YR4 when it encounters Earth in 2032, based on observations up to January 31, 2025 (orbit solution 40). Only 1.6% of this region intersects the Earth, which is the small dot at the center of the Moon's orbit.



Torino Scale diagram. The black arrow represents the evolution for 2024 YR4, which started with a Torino Scale of 0. As the probability of impact increased, it reached Torino Scale 1 on December 29, and then 3 on January 27, 2025.







Torino Impact Hazard Scale

No Hazard (White Zone)	0	The likelihood of a collision is zero, or is so low as to be effectively zero. Also applies to small objects such as meteors and bodies that burn up in the atmosphere as well as infrequent meteorite falls that rarely cause damage.
Normal (Green Zone)	1	A routine discovery in which a pass near the Earth is predicted that poses no unusual level of danger. Current calculations show the chance of collision is extremely unlikely with no cause for public attention or public concern. New telescopic observations very likely will lead to re-assignment to Level 0.
Meriting Attention By Astronomers (Yellow Zone)	2	A discovery, which may become routine with expanded searches, of an object making a somewhat close but not highly unusual pass near the Earth.
Meriting Attention By Astronomers (Yellow Zone)	3	A close encounter, meriting attention by astronomers. Current calculations give a 1% or greater chance of collision capable of localised destruction.
Meriting Attention By Astronomers (Yellow Zone)	4	A close encounter, meriting attention by astronomers. Current calculations give a 1% or greater chance of collision capable of regional devastation.
Threatening (Orange Zone)	5	A close encounter posing a serious, but still uncertain threat of regional devastation. Critical attention by astronomers is needed to determine conclusively whether or not a collision will occur.
Threatening (Orange Zone)	6	A close encounter by a large object posing a serious but still uncertain threat of a global catastrophe. Critical attention by astronomers is needed to determine conclusively whether or not a collision will occur.
Threatening (Orange Zone)	7	A very close encounter by a large object, which if occurring this century, poses an unprecedented but still uncertain threat of a global catastrophe. For such a threat in this century, international contingency planning is warranted.
Certain Collisions (Red Zone)	8	A collision is certain, capable of causing localized destruction for an impact over land or possibly a tsunami if close offshore. Such events occur on average between once per 50 years and once per several 1000 years.
Certain Collisions (Red Zone)	9	A collision is certain, capable of causing unprecedented regional devastation for a land impact or the threat of a major tsunami for an ocean impact. Such events occur on average between once per 10,000 years and once per 100,000 years.
Certain Collisions (Red Zone)	10	A collision is certain, capable of causing global climatic catastrophe that may threaten the future of civilization as we know it, whether impacting land or ocean. Such events occur on average once per 100,000 years, or less often.

Planetary Defense via Hypervelocity Penetrators

FISO Telecon 1-17-23

UCSB

π – Planetary Defense via Fragmentation

New Method of Multimodal Planetary Defense

Papers:

4 papers and articles published

4 PDC 2023 papers submitted – June 2023

2023 NT1 (7/13/23) paper on arXiv and submitted ApJ

Papers currently in preparation

Ground effects codes - GPU optimization

Nuclear penetrator mitigation including "hole drilling" with sequential passive penetrators

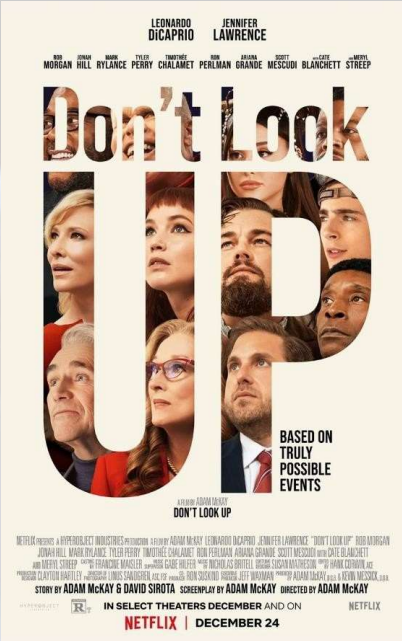
Radiological ground effects of nuclear mitigation

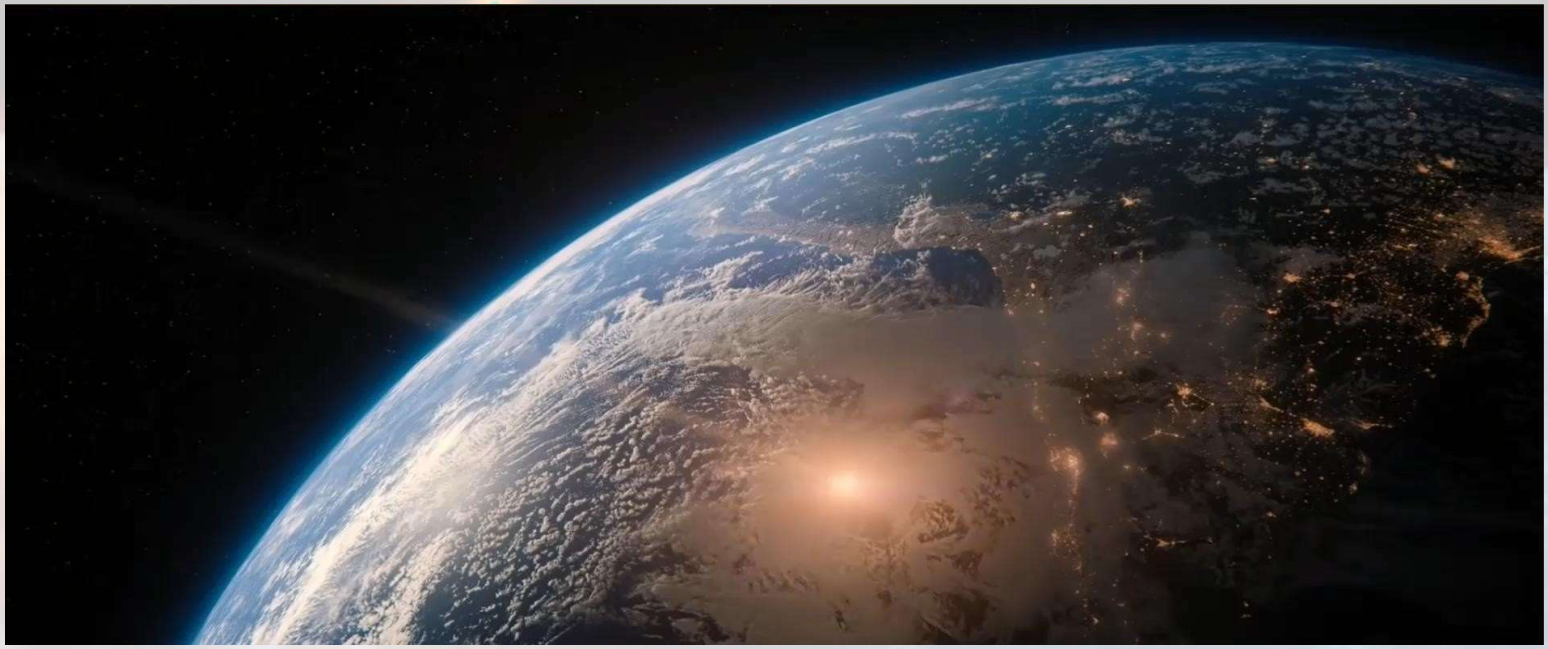
Talks:

4 PDC 2023 (UN Sponsored – Vienna); Ames Global Effects; + 9 Colloquia

Large amount of social media coverage

Don’t Look Up (2021)





“NASA Alerts: Asteroid 2024 AS1 Hurtling Towards Earth, Sparks Global Interest” – Jan 9, 23:53 EST

18 km/s, Closest approach (yesterday) 1.5 x LD – small ~ 13m

Team Members

University of California, Santa Barbara
Philip Lubin, Alexander N. Cohen, Brin Bailey, Jeeya Khetia, Dharv Patel, Jasper Webb, Jon Suen.
~30 undergraduate researchers + several high school students.

NASA Ames Research Center
Darrel Robertson

Johns Hopkins University (APL)
Angela Stickle (DART)

University of New Mexico/LANL
Mark Boslough

New Mexico Tech.
Sasha Egan

Sandia National Laboratory
Elizabeth Silber

IBM (Emeritus)
Richard Garwin

Los Alamos National Laboratory (LANL)
Irina Sagert, Oleg Korobkin

University of Utah
Glenn Sjoden

Private Space

Commentary on New Ideas

Arthur C Clarke on reactions to Revolutionary Ideas

"Every revolutionary idea seems to evoke three stages of reaction. They may be summed up by the phrases:

1 It's completely impossible.

2 It's possible, but it's not worth doing.

3 I said it was a good idea all along."

Relative threat level per Lifetime

C.R. Chapman & D. Morrison, 1994, Nature 367, 33-40

Cosmic threat: roughly all humanity dies every 100 million years) $10^{10}/10^{8}$ = 100 people/yr =10,000 people per human lifetime

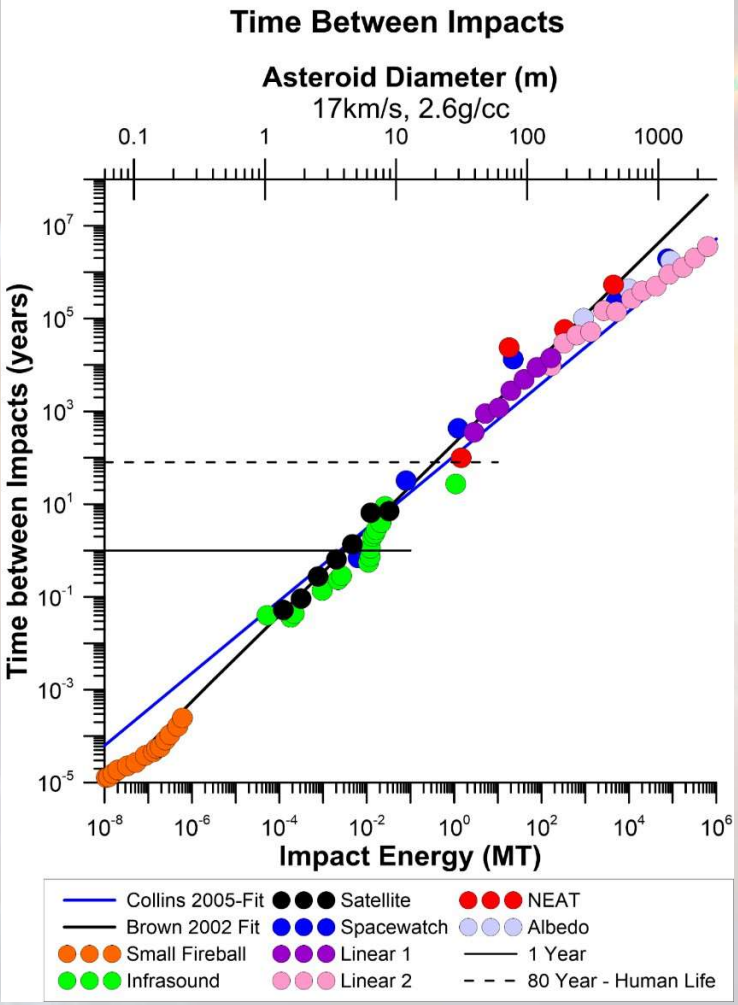
~ 10^{-6} (one chance per million) of a person dying per lifetime

- Motor vehicle accident = 1 in 100 (1% chance of dying and 50% chance of being injured – 1.3M killed/ 50M injured/yr)
- Homicide = 1 in 300
- Fire = 1 in 800
- Firearms accident = 1 in 2,500
- Electrocution = 1 in 5,000
- Passenger aircraft crash = 1 in 20,000
- Flood = 1 in 30,000
- Tornado = 1 in 60,000
- Venomous bite or sting = 1 in 100,000
- **Asteroid/comet impact = ~1 in 200,000+ (but Episodic!)**
- Fireworks accident = 1 in 1 million
- Food poisoning by botulism = 1 in 3 million
- Drinking water EPA limit of tricholoethylene = 1 in 10 million
- Grant writing 1/3
- Social media – watching news - Unity

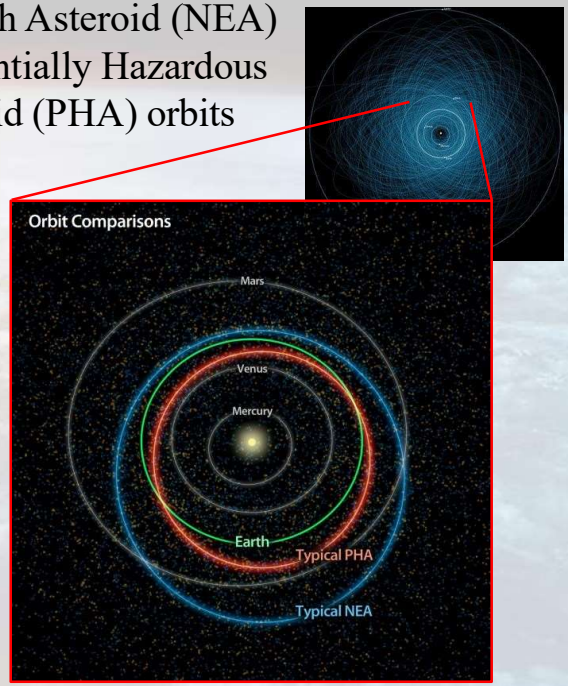
Tunguska June 30, 1908 – 3-30 MT estimated
~ 10^{8} trees blown down over 2000 km^2 from acoustic shock wave

Time Between Asteroid Hit vs Yield (MT)

10 KT event/yr – 1 MT event/lifetime



Near Earth Asteroid (NEA) and Potentially Hazardous Asteroid (PHA) orbits



PHA < 8MKm from Earth

Daily Drive-by Shootings – 100 ton/day

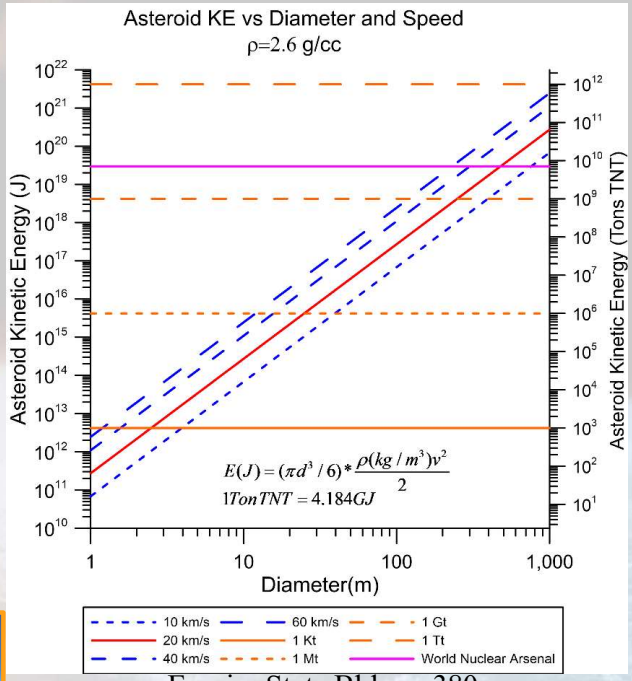
Asteroid KE comparison to existing/past NED's

Even smaller asteroids impact with energies comparable to strategic nuclear weapons.

B83 thermonuclear bomb, max yield 1.2MT.

B61 thermonuclear bomb, max yield 0.4MT.

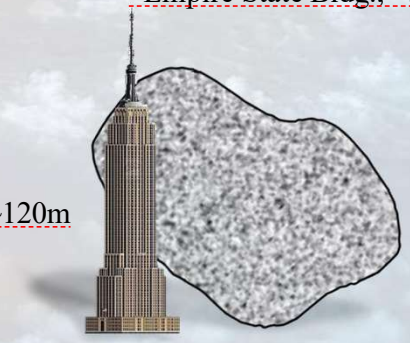
Tsar Bomba, 50/100MT, largest nuclear weapon ever detonated.



Empire State Bldg., ~380m

Starship, ~120m

Falcon 9, ~70m



20m

50m

100m

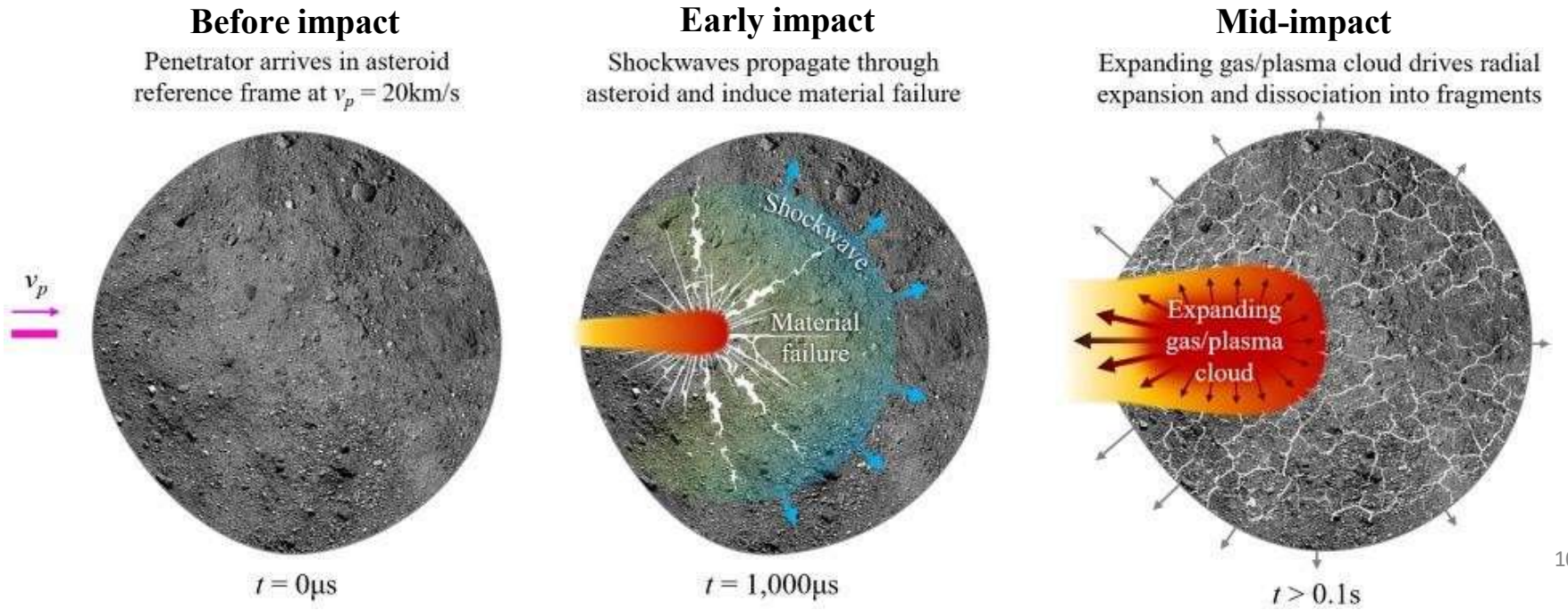
Apophis, 370m

0.5MT **10MT** **100MT** **4GT, ½ world arsenal**

π ("Pulverize It"): why it works

Hypervelocity impact to disassemble threat

- Hypervelocity penetrator induces a strong shockwave that pulverizes material
  - Can use multiple penetrators for very large/strong threats
- Impactor vaporizes itself and target material, forming a high-pressure gas/ion cloud that expands rapidly, acting as a gas-expansion engine for complete disassembly
- Target is blown apart into a fragment cloud → threat is mitigated



Multi Modal Operation – Short to Long Warning

1) Short time warning – minutes to days intercept – terminal defense (15m to 100m diam threats)

- *Fragment to <15m and use Earth's atmosphere as body armor – shock waves de-correlated*
- *Sum of all optical pulses below combustion limit – no fires*
- *Shock waves de-correlated – virtually no damage – possibly some minor window damage*
- *Ex: 100m diam (~100 Mt >> Tunguska) can be mitigated with 1 day intercept*
- *Ex: 20m (0.5 Mt - Chelyabinsk) can be mitigated with 100 sec intercept (10m/s disruption)*

2) Moderate time warning – 10-60 day intercept (100 – 500m – Apophis, Bennu)

- *Fragment to <15m and spread fragment cloud over large area on Earth (~ 1000 km radius)*
- *Earth's atmosphere is used as body armor*
- *Ex: 350m diam (~Apophis) (~ 4 Gt ½ Earth nuclear arsenal) can be mitigated with 10 day intercept*
- *Ex: 500m diam (~Bennu) (~ 8 Gt > Earth nuclear arsenal) can be mitigated with 20 day intercept*

3) Longer time warning (>75 day intercept) (600-1000m threats)

- *Fragment ideally to <15m but less restrictive*
- ***Fragment cloud spreads to be larger than the Earth - Virtually all fragments miss the Earth***
- *Residual fragments that will hit the Earth smaller than 15m are not a threat – atmosphere mitigates*
- *Residual fragments > 15m can be dealt with as in option 1) terminal defense IF needed*

4) Long term warning and existential threat (>100 day intercept and >1& <15km diameter)

- *Fragment using NED penetrator array – pure fission (eg W82 class NED) looks feasible - based on nuclear artillery technology already designed, developed and tested. Sequential penetrator option allows better NED effectiveness and possibly thermonuclear class penetrators if needed. These are internal and NOT standoff detonations.*
- *Possible use of "sequential following penetrators" to allow "hole drilling" for better NED coupling and lower "g" forces for devices such as B61-11 NED physics package – 4 kt/kg @ 350 Kt yield*
- *Fragment cloud spreads large enough to miss Earth for virtually all fragments.*

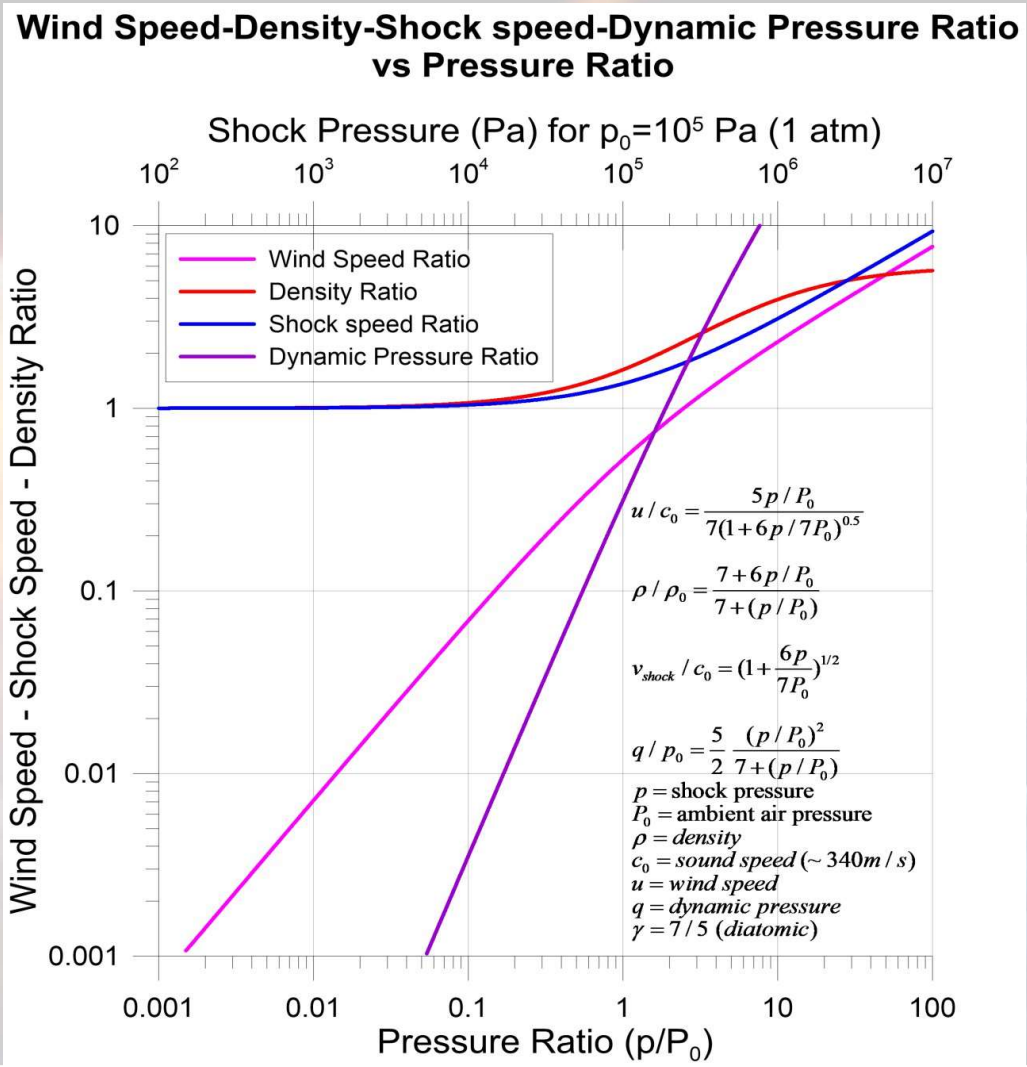
5) Long term warning (> 1 year) – asymmetrical fragmentation/ enhanced deflection option

- *Asymmetrical fragmentation to get extreme deflection enhancement - use energy not momentum.*
- *Blast off part of target to use it ("push") against itself – NOT like current deflection techniques but synergistic. See mode 6 below.*
- *Depending on target size can use kinetic only, kinetic with conventional explosives or NED penetrators for extreme threats.*
- *Use of penetrator to drive mass ejection via an induced "rocket exhaust" mode where the high temperature and pressure vaporized/ plasma created inside the bolide exists through the penetrator initiated "exhaust nozzle" to form a rocket engine using the bolide as "fuel".*

6) Long term warning (> 1 year) – classical deflection

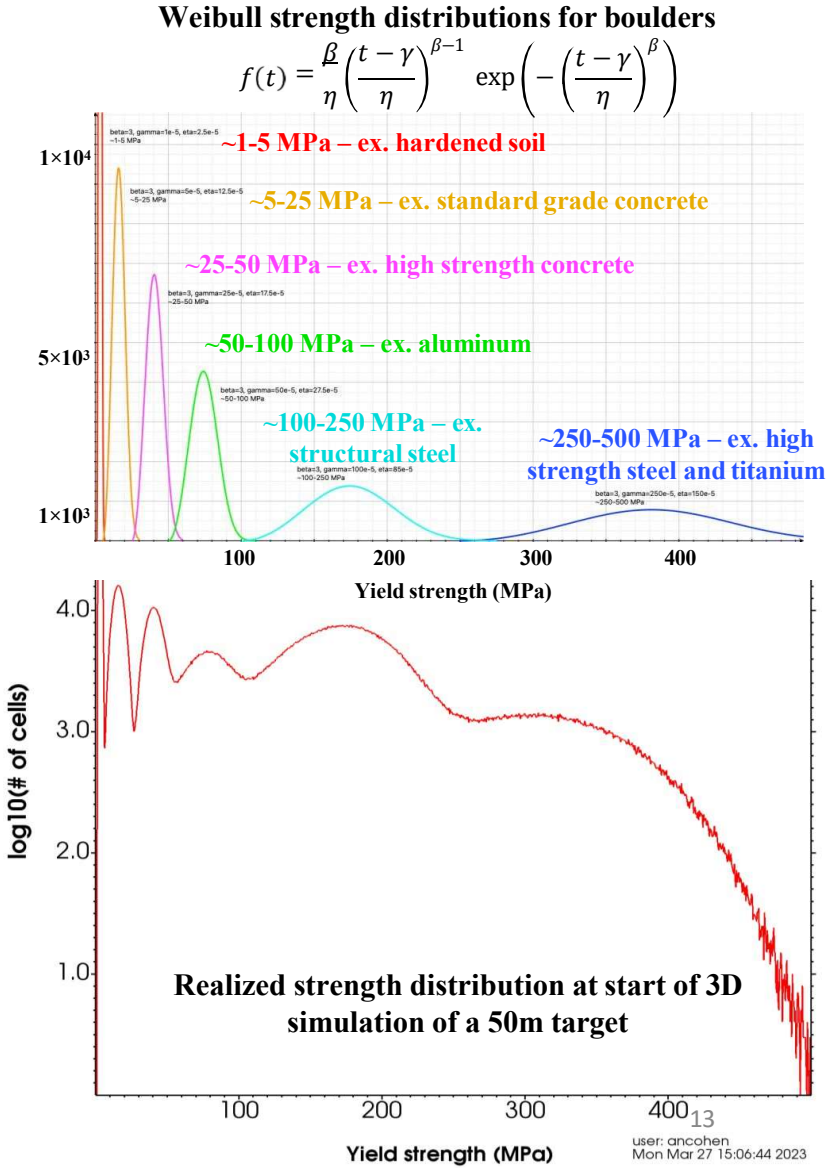
- *If desired the same system can also be used as a classical deflector -complete multimodal use.*
- *Simple penetrator reconfiguration allows the same system to be used as a classical deflector.*
- *In general this mode is not needed as mode 5 (enhanced deflection) is superior but it is available.*

Shock Wave Physics – Weak to Strong Shock Regime

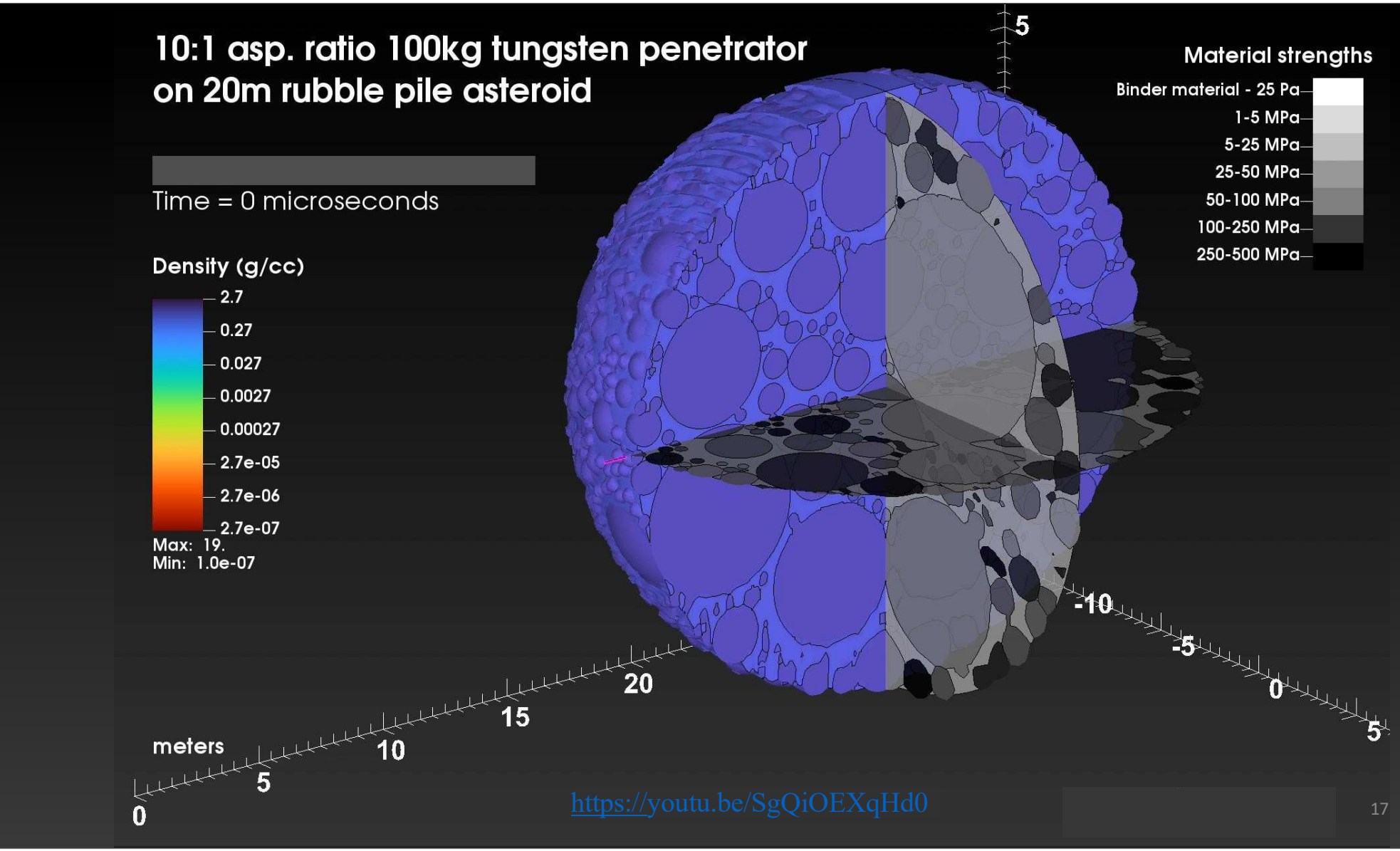


Hypervelocity impact simulations

- Two-phase LEOS granite tabular equation of state used for asteroid materials, with density 2.6 g/cm^3, porosity 40-50%.
- Spherical boulder distribution set inside weak (~25 Pa) binder material [1].
- Weibull distribution of yield strengths within asteroid materials allows for realistic simulation of fracture dynamics, along with porous crush model.
- Baseline projectile is a 100 kg 10:1 aspect ratio tungsten cylinder arriving in the reference frame of the target at 20 km/s.
- Extremely conservative – early DART results suggest higher strength materials.

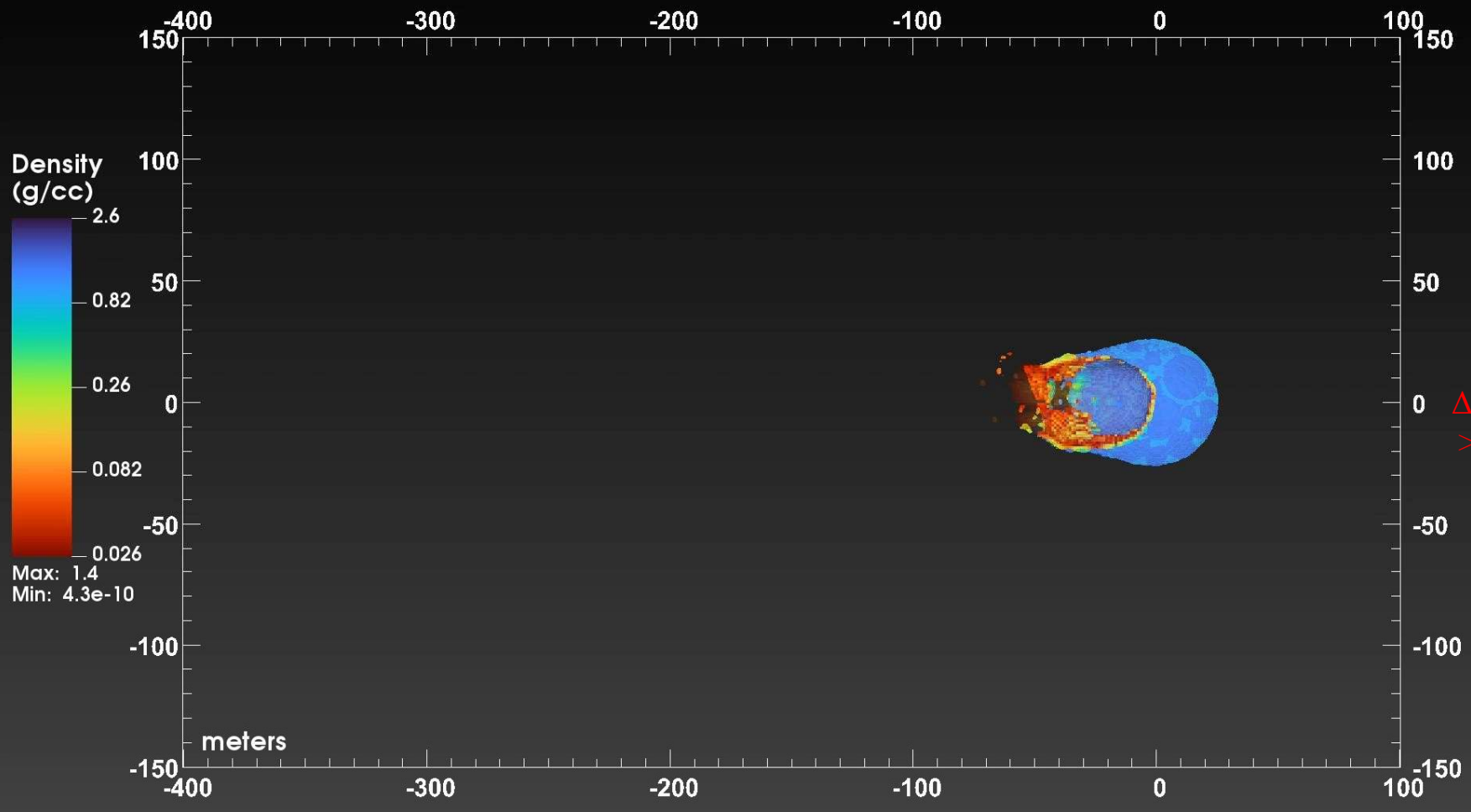


[1] Sánchez, P. and Scheeres, D.J. (2014), The strength of regolith and rubble pile asteroids. Meteorit Planet Sci, 49: 788-811. https://doi.org/10.1111/maps.12293



https://youtu.be/SgQiOEXqHd0

10:1 asp. ratio 100kg tungsten penetrator on 50m rubble pile asteroid



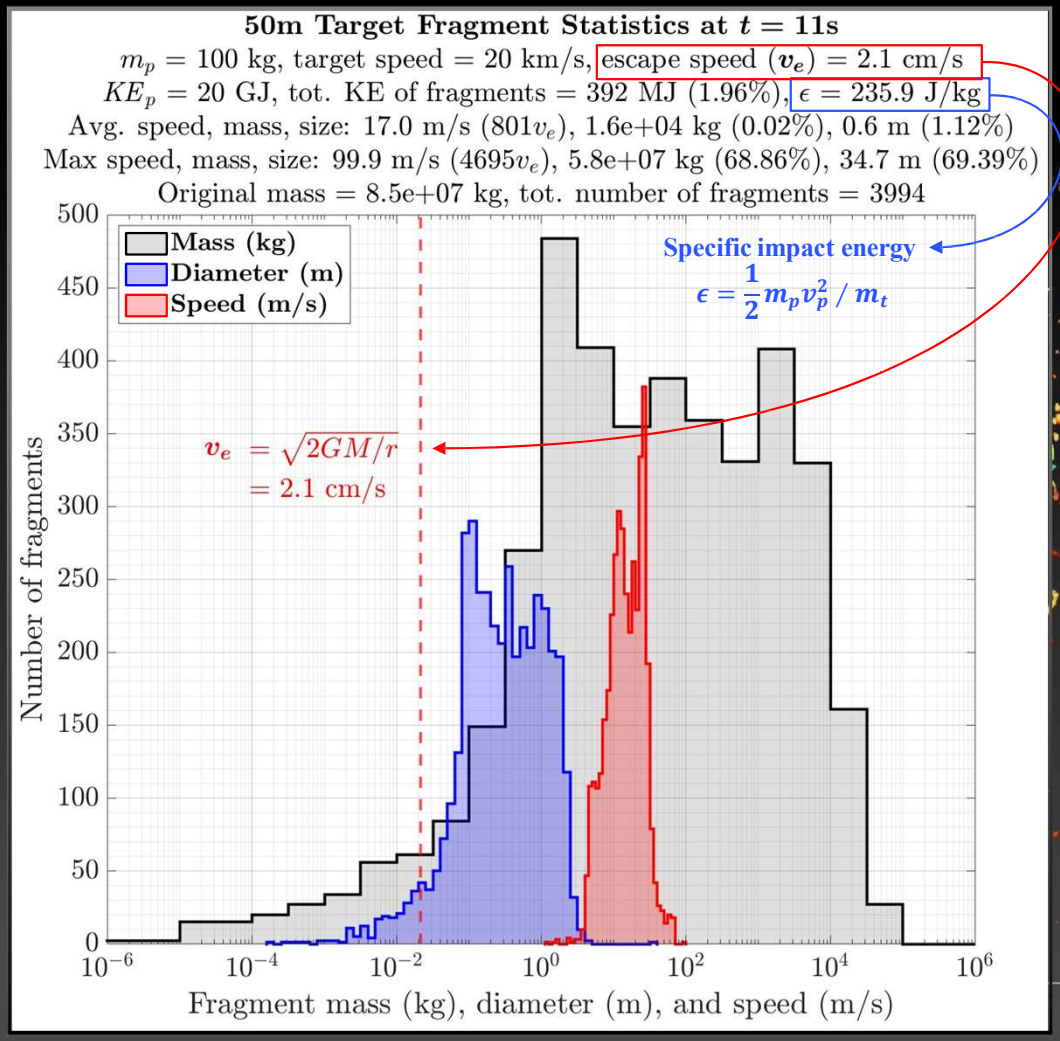
Δv ~1.5m/s
>> escape

time = 1 seconds

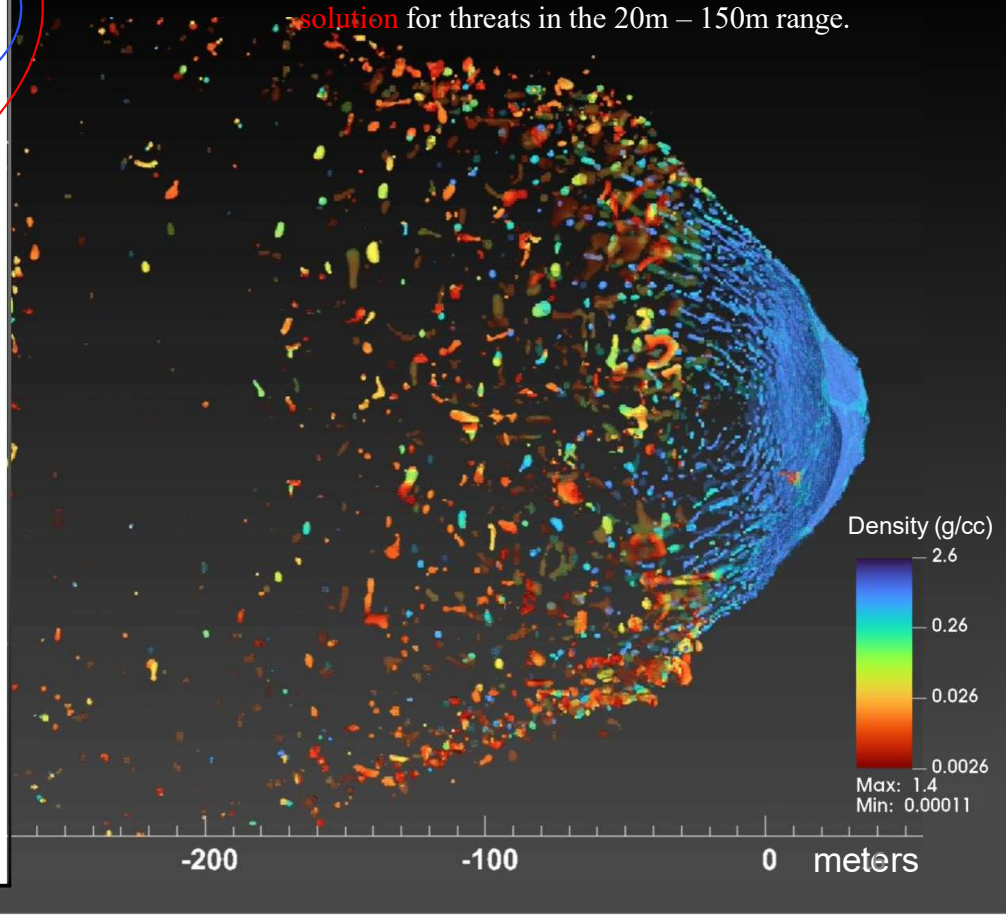
https://youtu.be/TFED08VRLdY

50m rubble pile asteroid – **single 100kg** 10:1 asp. ratio 20km/s tungsten penetrator – t = 11s

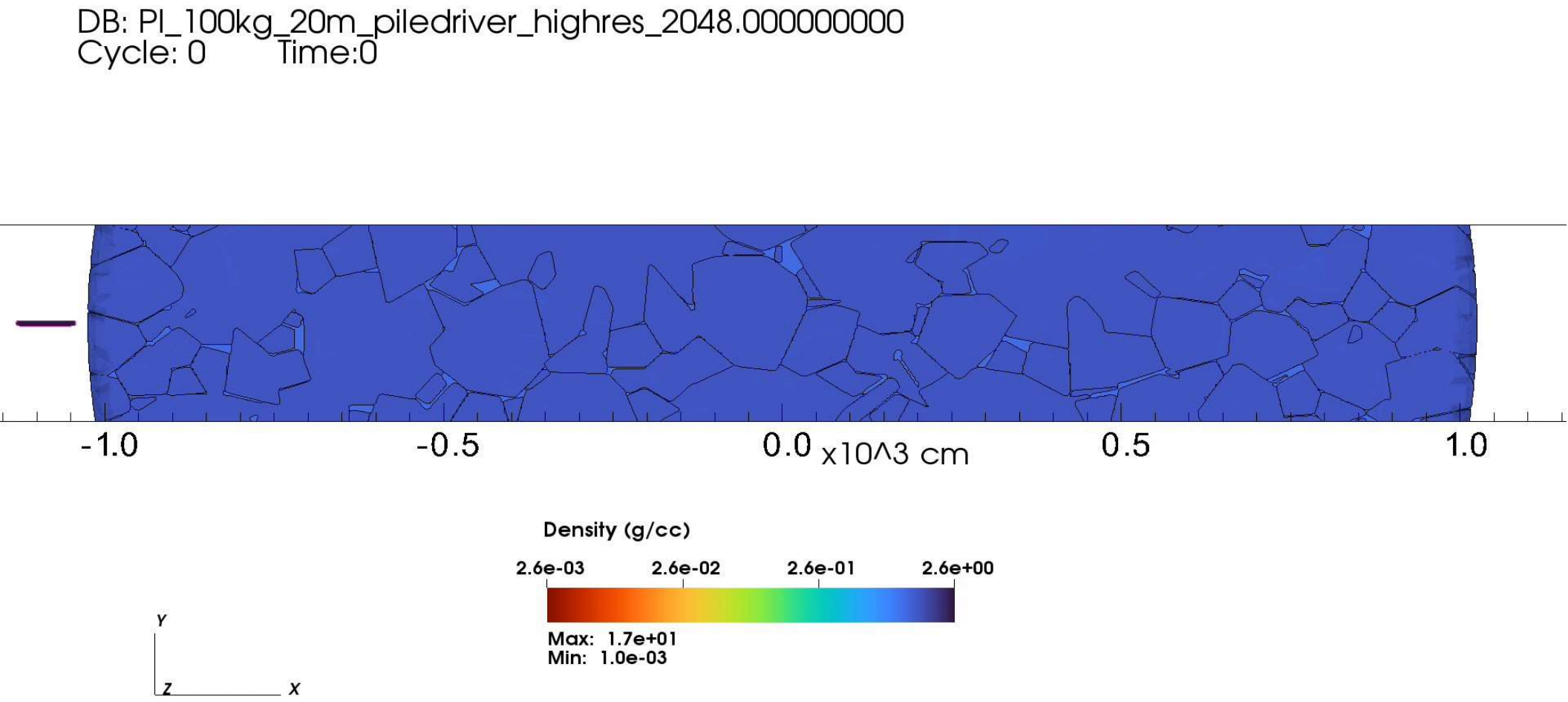
Shows catastrophic disruption and near complete volumetric material failure



- Results suggest single 100kg penetrator is sufficient to mitigate 50m bolide – scale to 100m, 8x100kg should suffice.
- 25x100kg penetrators in single Falcon 9 can achieve $C_3 > 0$ (escape), which can act as a single-launcher, passive-penetrator solution for threats in the 20m – 150m range.



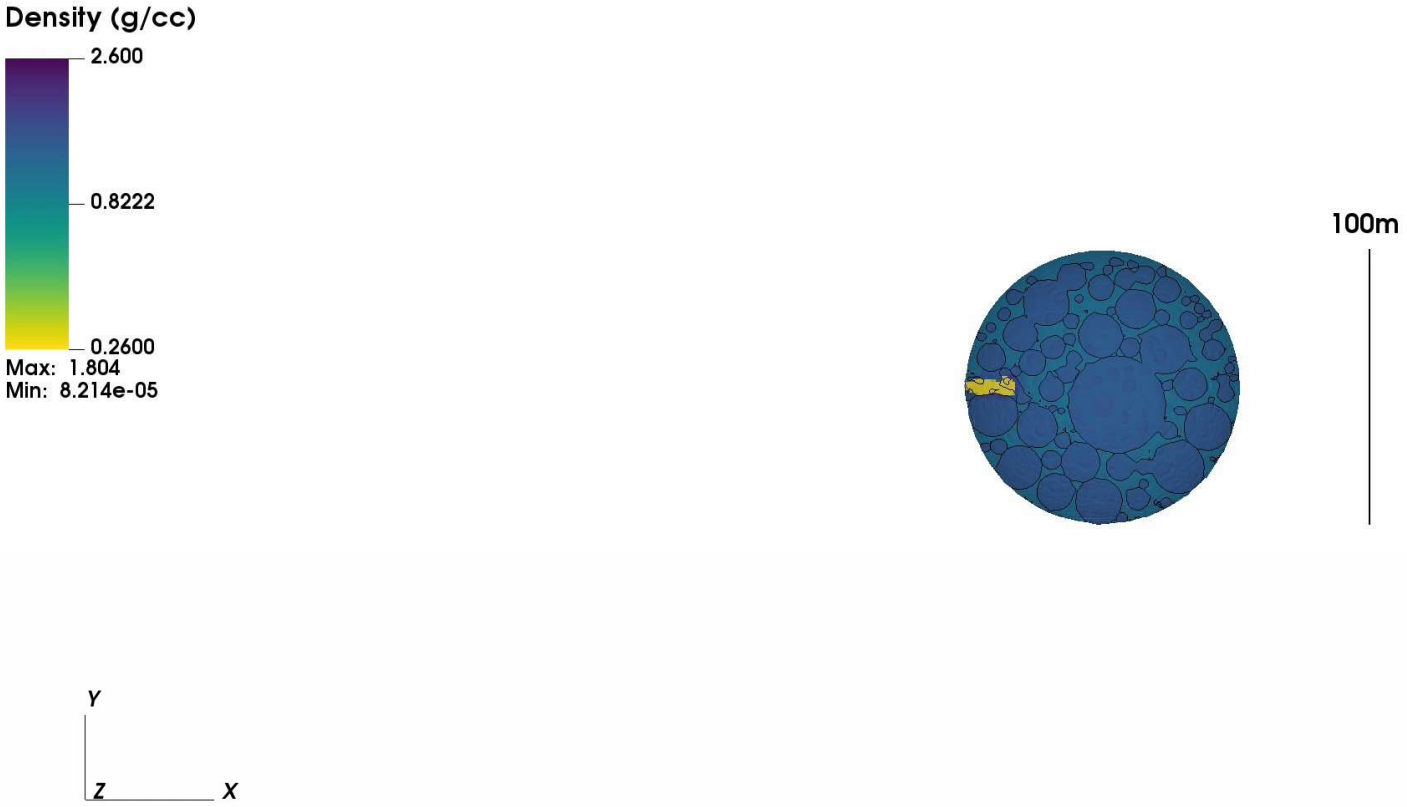
5x 100kg Sequential penetrators – for deep deposition of explosive/NED if necessary – very large threats



https://youtu.be/aqR64eGuGBw

Falcon 9 $C_3 > 0$ – 2500kg payload (passive) 20 km/s closing – on 100m– to 10 sec Target is destroyed

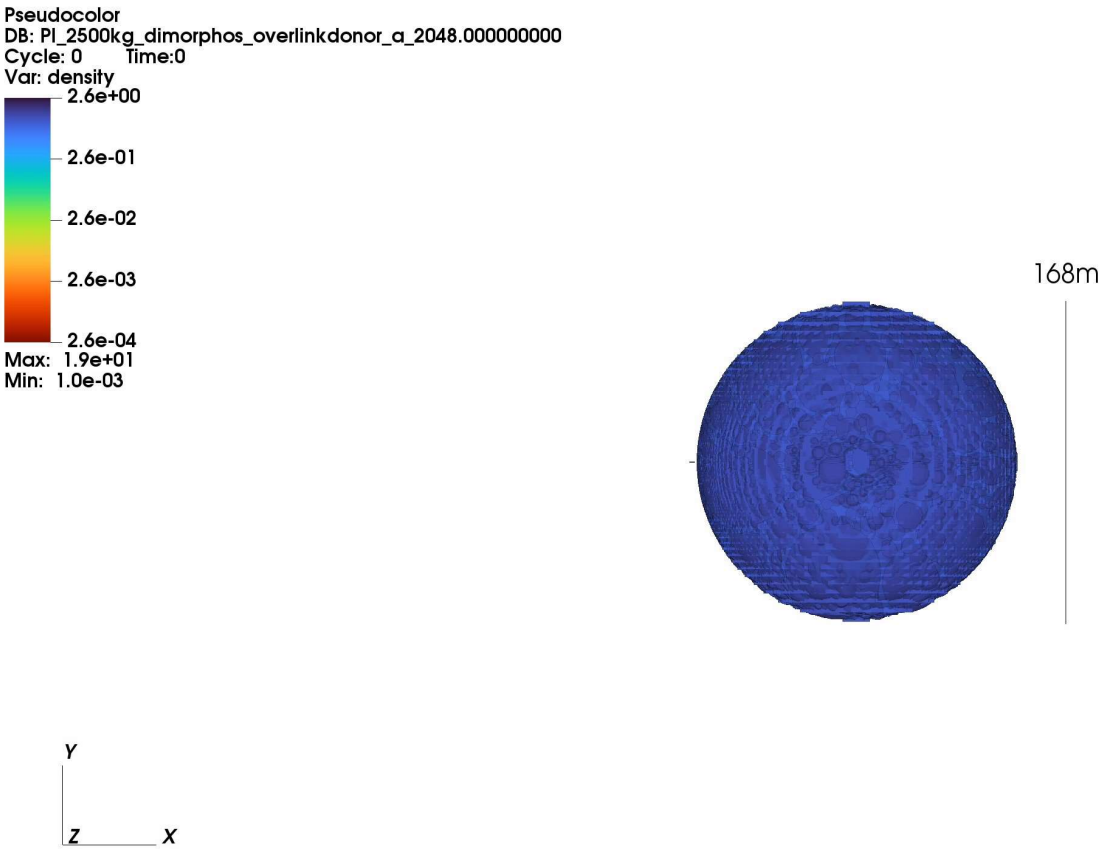
DB: Pl_2500kg_100m_overlinktarget_a_2048.000005604
Cycle: 5604 Time:10001.6



https://youtu.be/dnhVZelqgfE

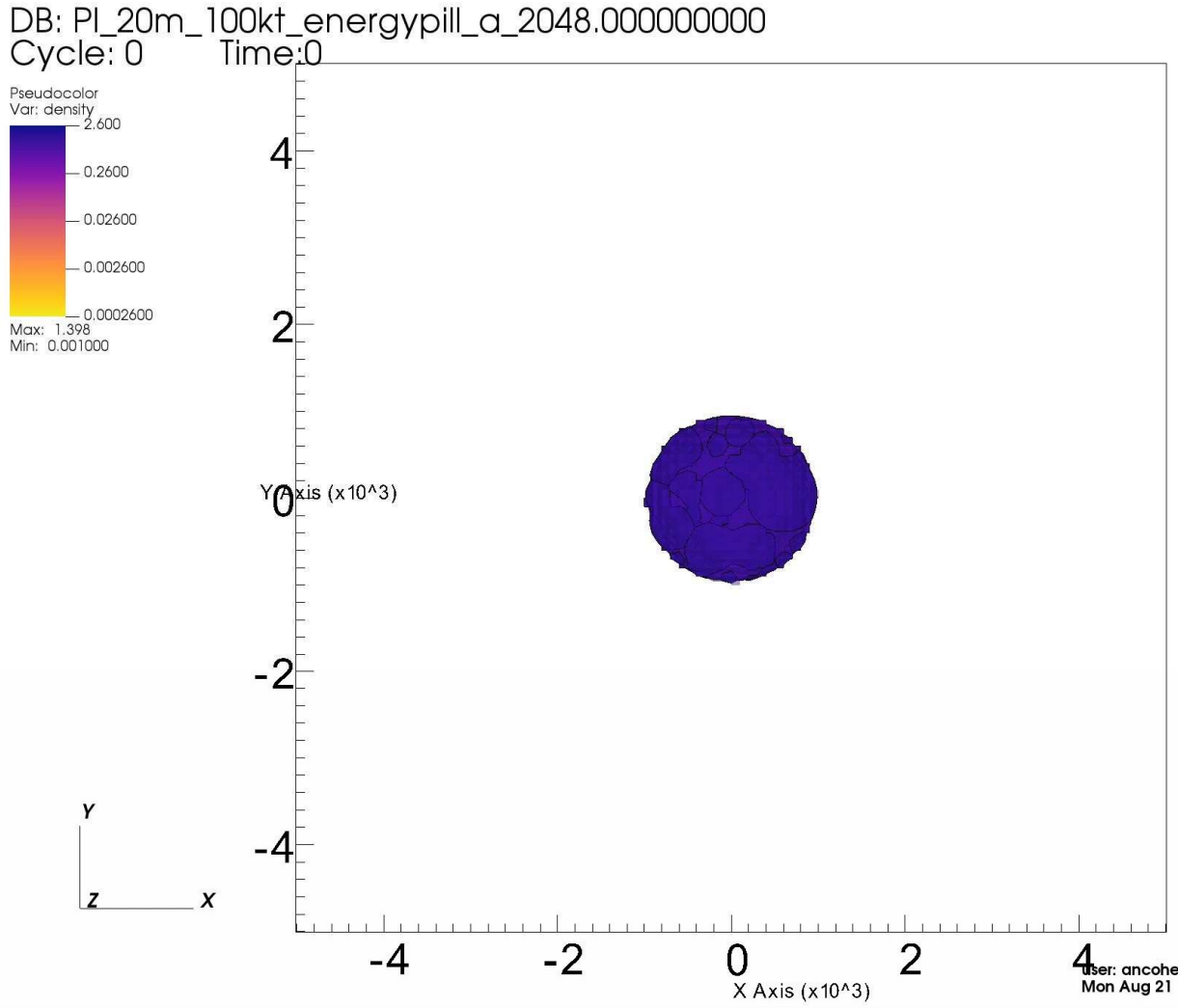
user: ancohen
Tue Aug 29 21:30:07 2023

Falcon 9 $C_3 > 0$ – 2500kg payload (passive) – Dimorphos (DART target) 20 km/s – to 10 sec
Large Fraction is destroyed – very large effective "beta" >1000



https://youtu.be/LYNfVmw0a2s

Nuclear Mitigation Simulations Started - Example of 110 kT NED in small 20m target (computational reasons)
Many more simulations to come. Looks like 1km threat can be destroyed with stockpile NED.

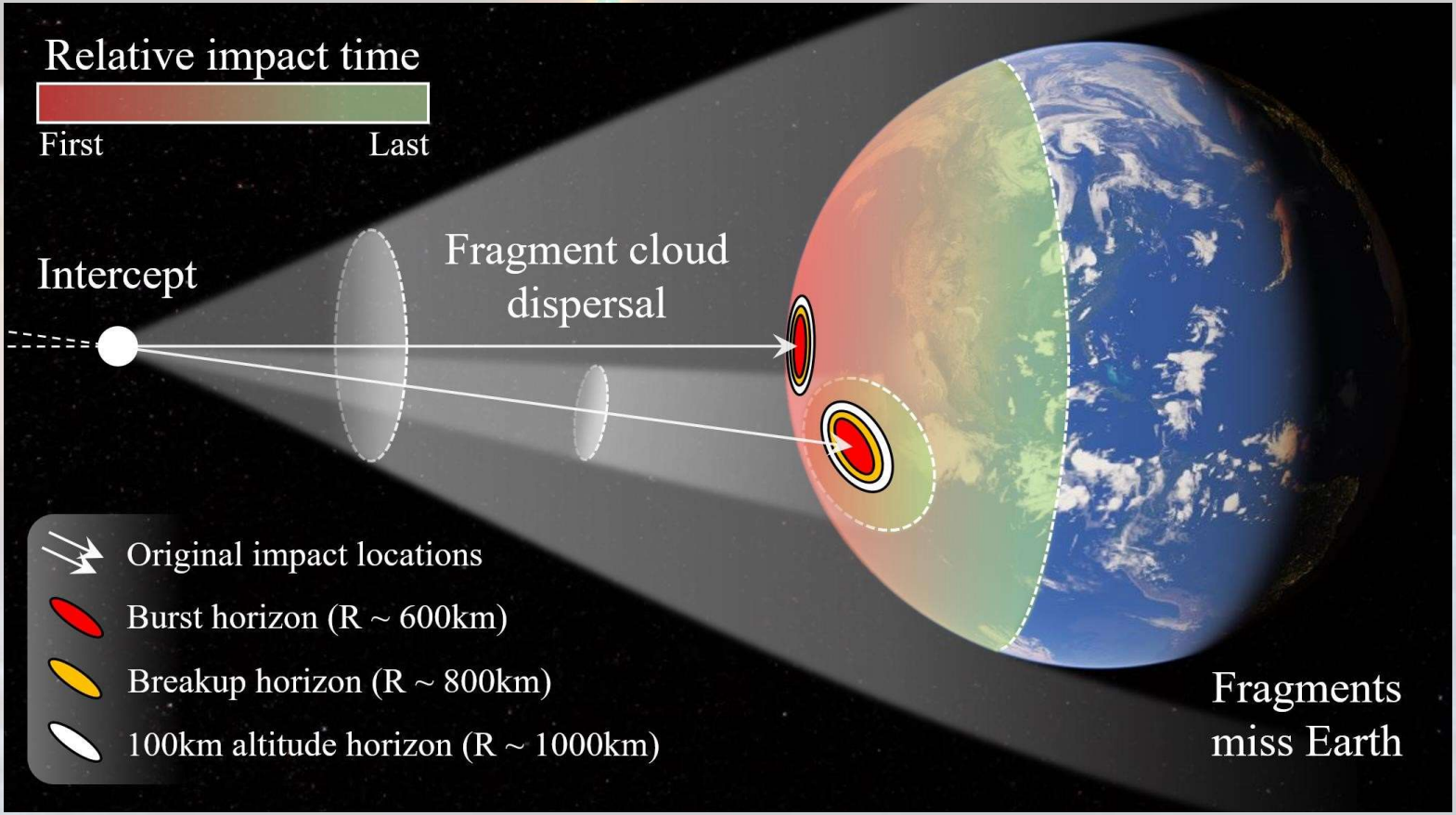


https://youtu.be/F0Az7jRi2jI

Fragments distribute energy of target

Fragments airburst in Earth's atmosphere → creates spatially and temporally de-correlated shockwaves

Results in small acoustical shockwaves and optical pulses at observer



Why this works: acoustic de-correlation

Shockwaves from individual fragments arrive at different times for any arbitrary observer due to varying slant distances and burst times for each fragment

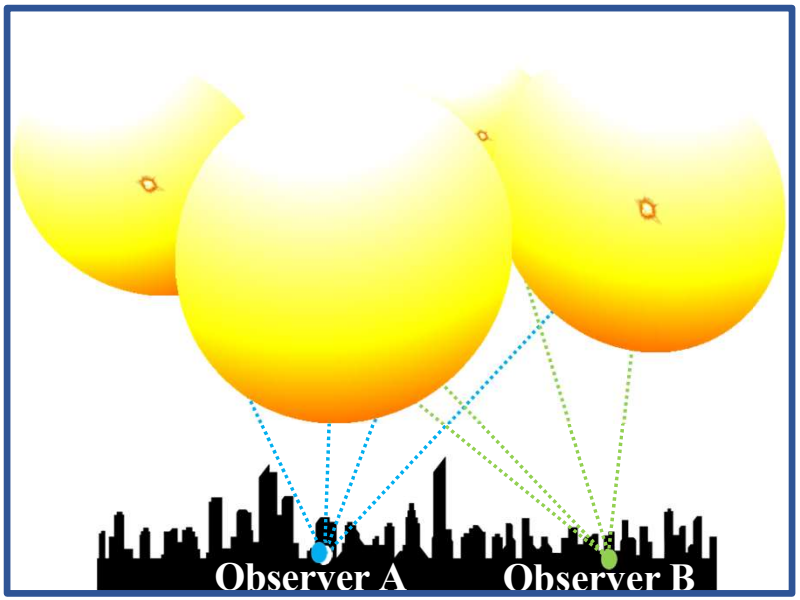
Unmitigated threat:
Extremely large blast wave and optical pulse, causing large-scale damage

https://skyandtelescope.org/astronomy-news/tunguska-100-years-and-counting/

With PI

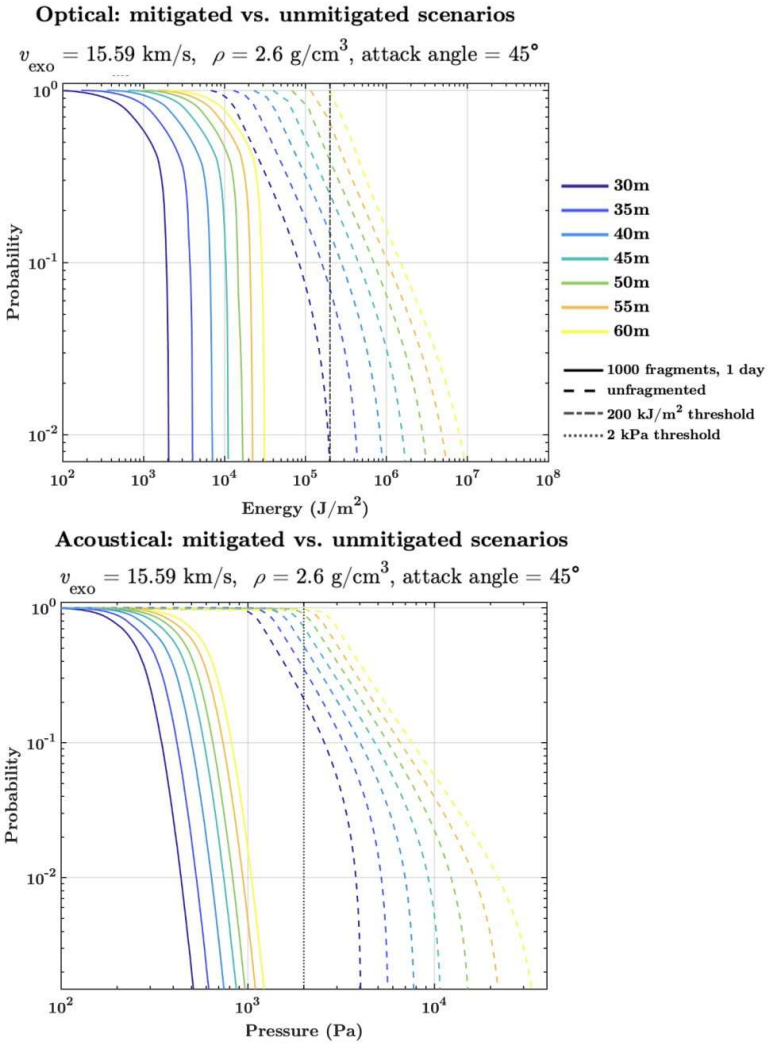
Mitigated:
Total impact energy of target is distributed into de-correlated shockwaves

Small individual shockwaves arrive at different times for any arbitrary observer on Earth's surface

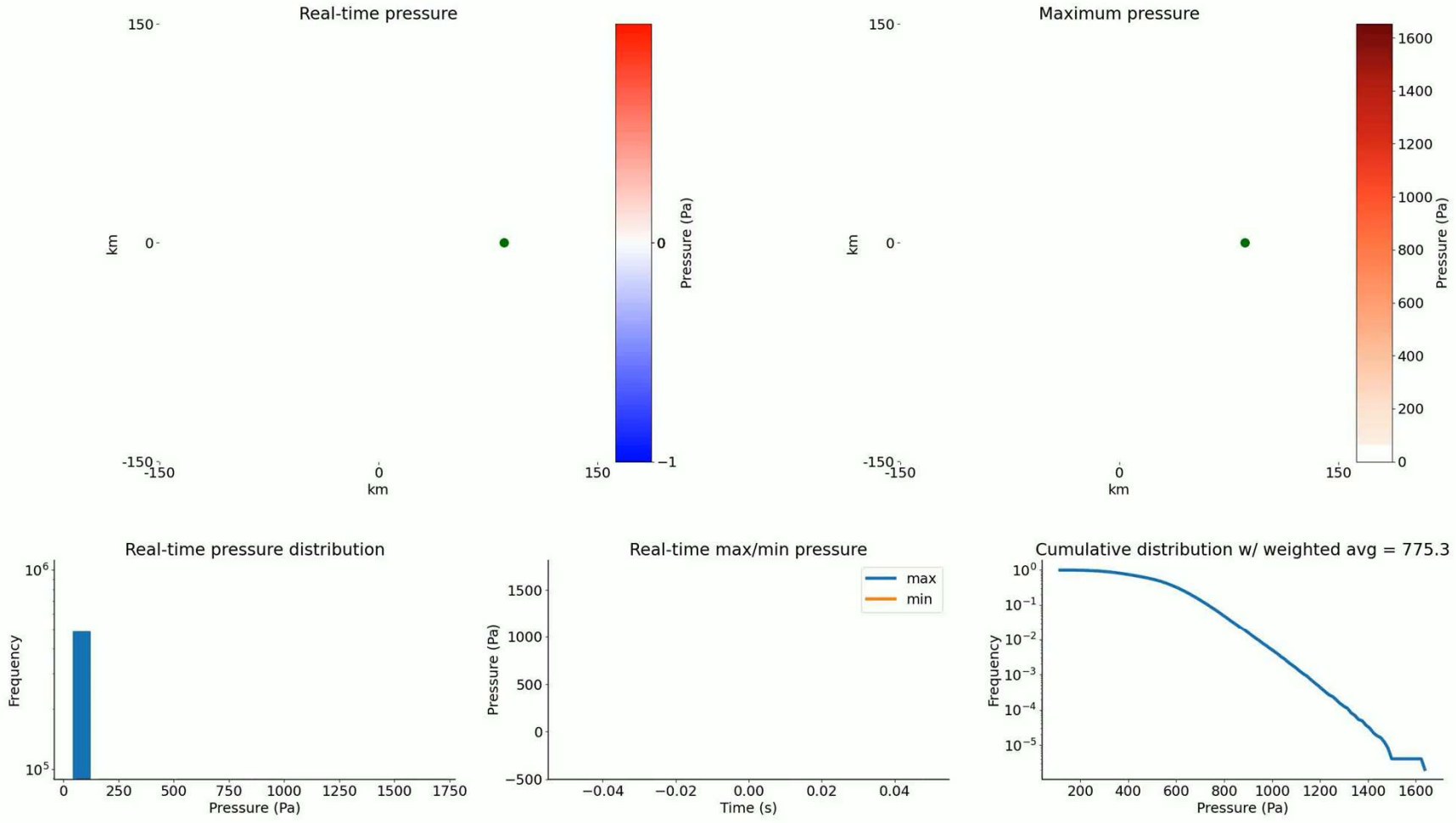


Ground effects simulations

- Simulations show that ground effects of airbursts from mitigation via the PI method are vastly lower than their unmitigated counterparts
  - Scenarios designed to keep optical energy for each burst < 0.2 MJ/m^2 and cumulative shockwave over-pressure at any given ground point < 2 kPa
- Ground effects can be decreased by increasing number of fragments or increasing intercept time
  - Increases the spatial and temporal distribution of the parent bolide's energy
- In longer warning timescales (intercept < ~70 days), the fragment cloud misses Earth entirely
  - Yields no ground effects

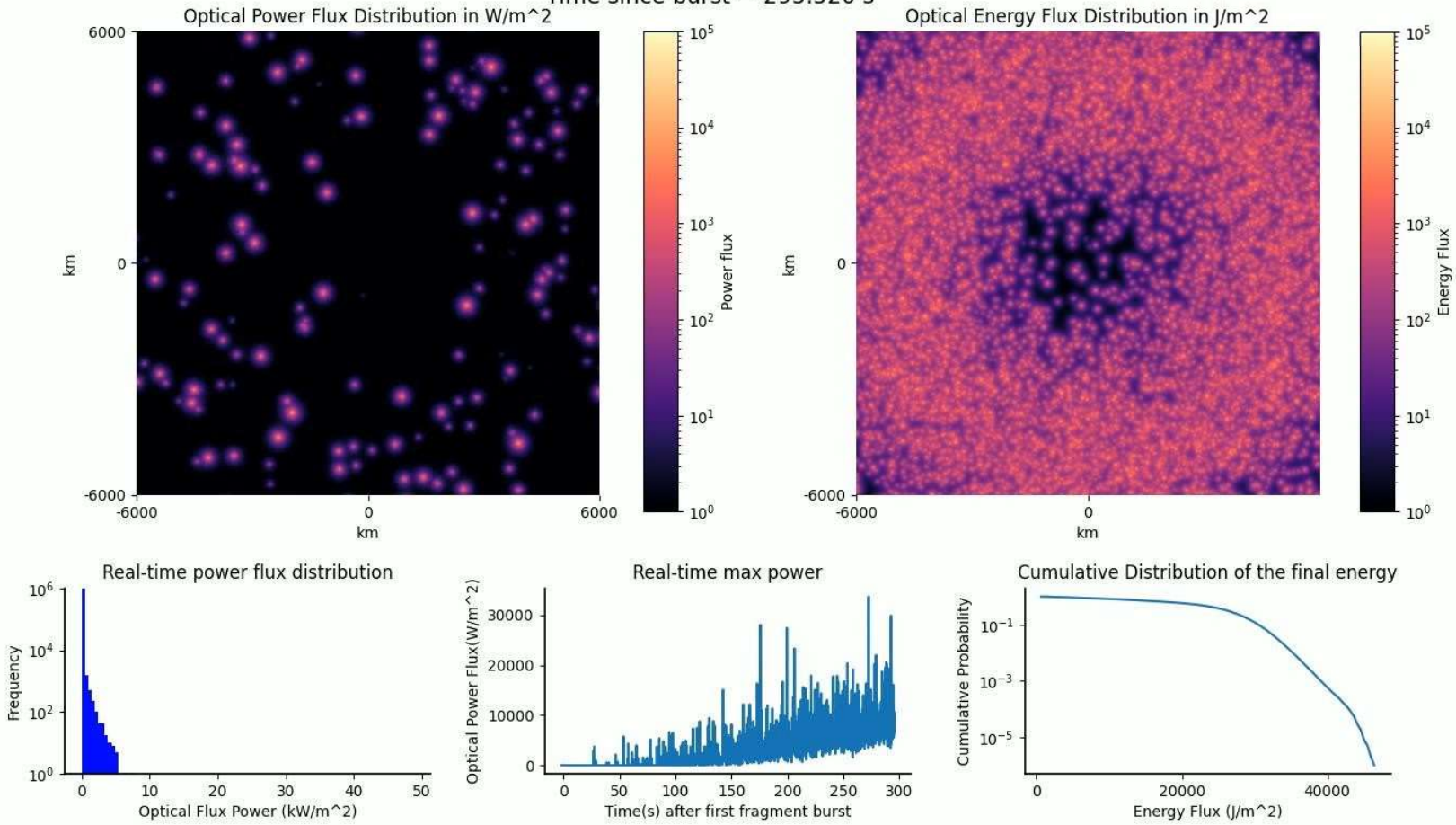


Cumulative distribution functions of the ground effects for a variety of mitigated (solid lines) versus unmitigated scenarios (dashed lines), taken from our 2023 NT1 paper (currently in preparation for submission).



https://youtu.be/ew1O5oXkJjc

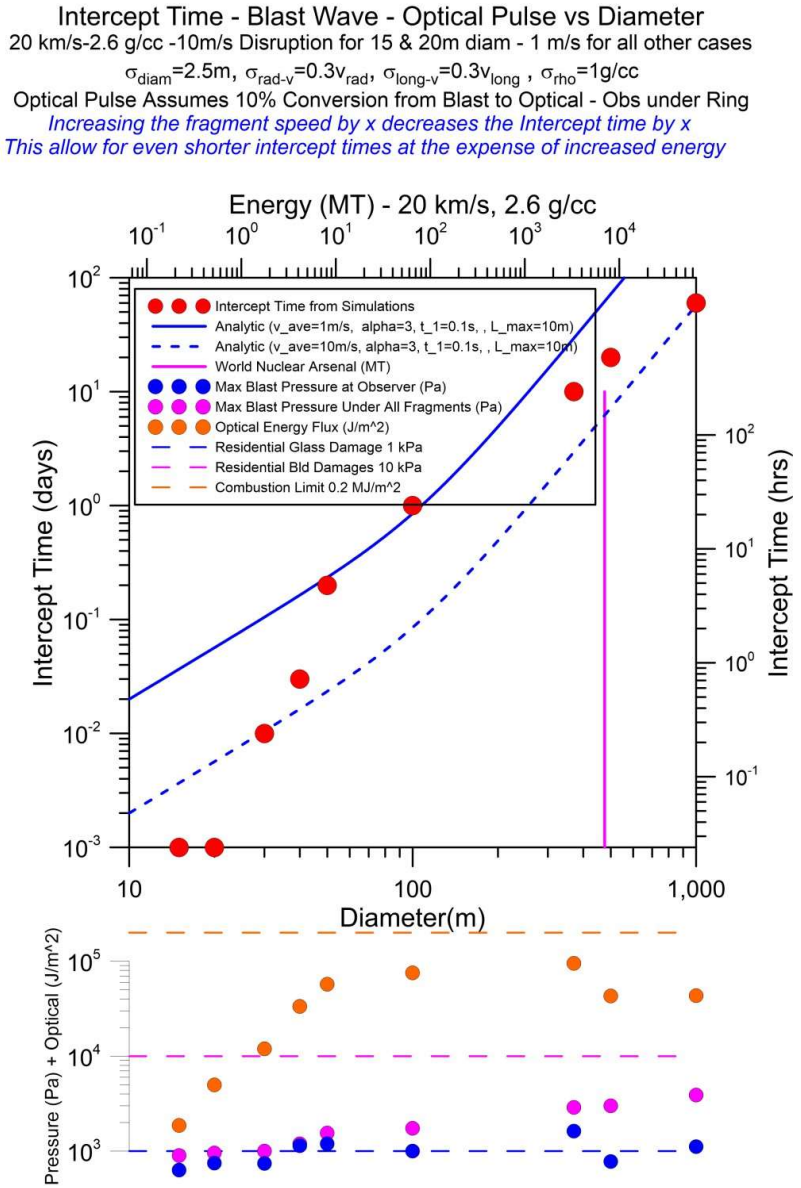
Very large 800-meter diameter asteroid – optical pulses



https://youtu.be/1Tza23EpveQ

Method summary

- PI is an extremely effective method for planetary defense that can operate in:
  - Short-warning terminal interdiction scenarios (hours-to-days intercept prior to impact; 15 – 100 m threats)
  - Long-warning time scales (months-to-years intercept; 100 – 1000 m threats)
- Plot: simulation results of mitigation via PI
  - Red: threat diameter vs intercept time (longer is better when possible)
  - Orange: maximum optical energy flux; all values < 0.2 MJ/m^2, the combustion point for dry grass/paper
  - Blue: maximum blast wave pressure at observer; all values < 2-3 kPa, the point of residential glass breakage
  - Pink: maximum blast wave pressure under all fragments; most < 2-3 kPa; all < 10 kPa, the point of residential building damage

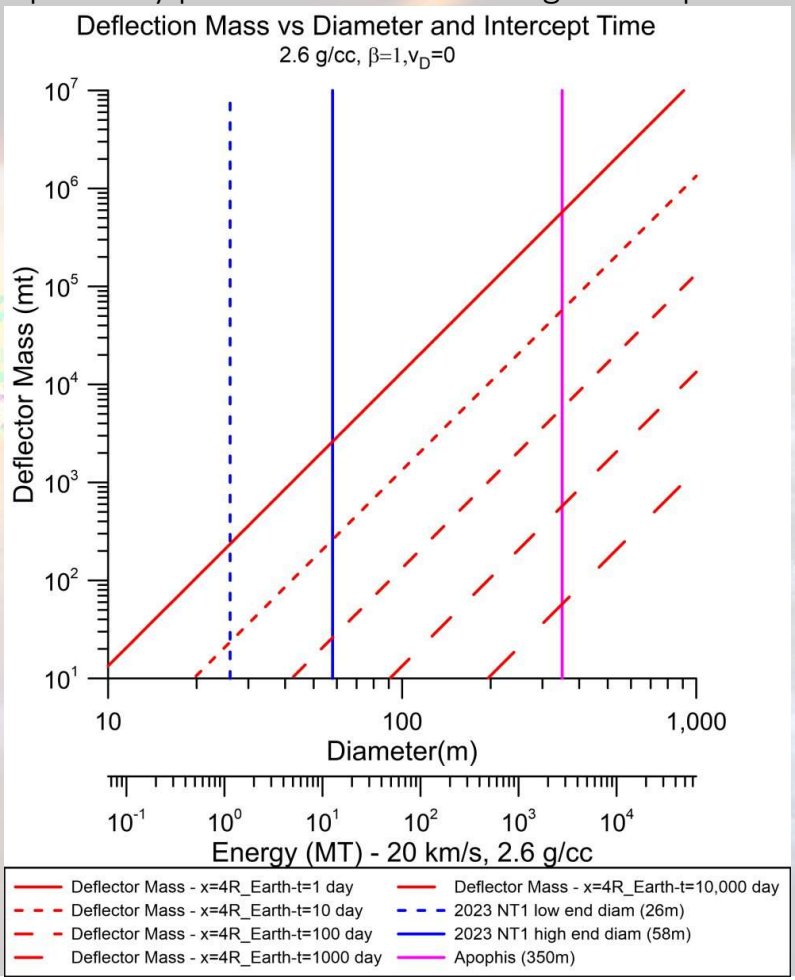


Deflection Mass Comparison

Emphasis here is to miss Earth

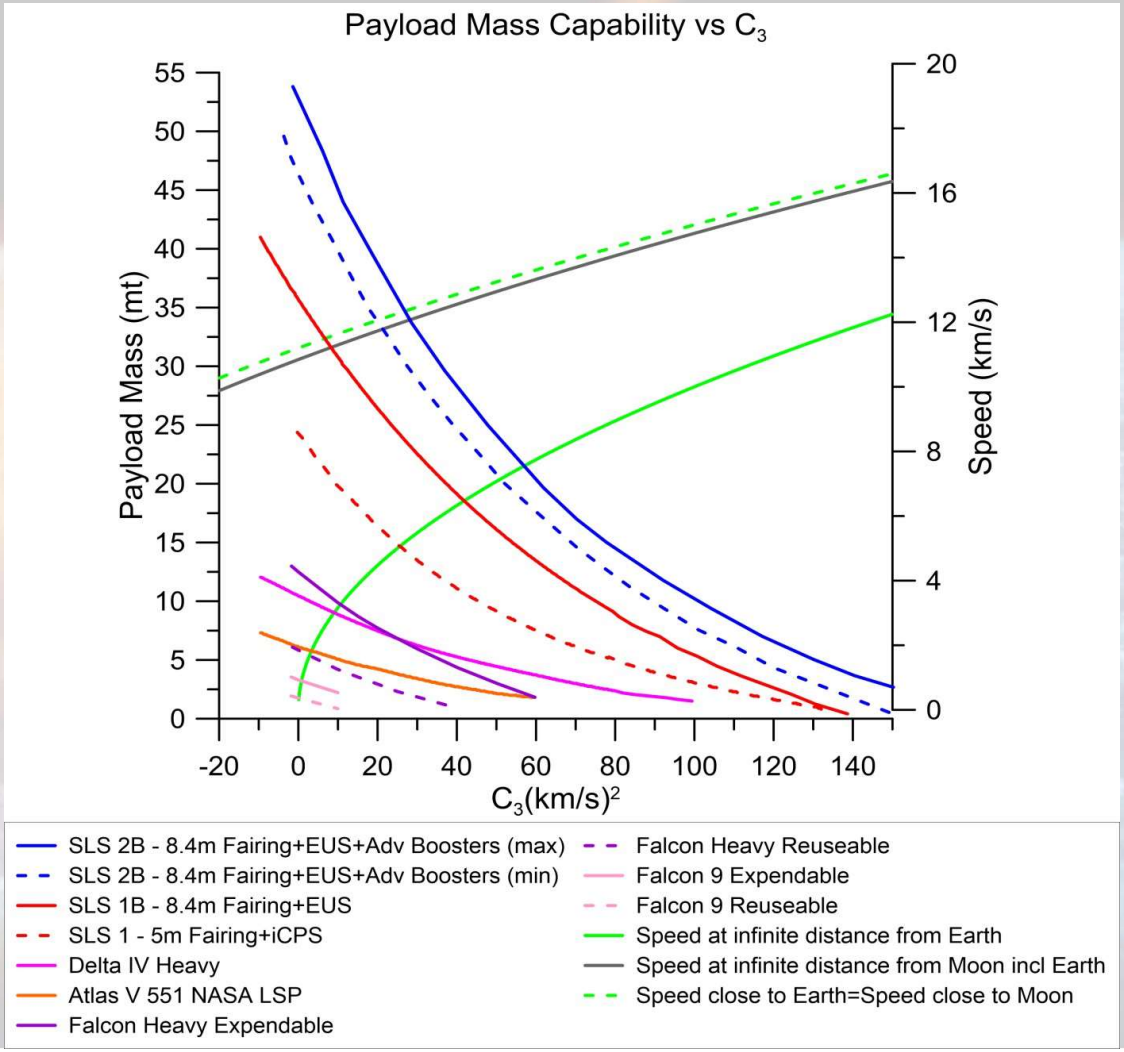
For small threats and long warning/ intercept:

If the impact point can be precisely predicted and IF moving the hit point is acceptable then more flexibility



Current Suitable Launch Vehicles

Falcon 9 (expendable) achieves 2.5 mt @ threat with C3 ~ 10 $(km/s)^2$ (v ~ 3 km/s) - Sufficient



LEO, GEO, Lunar Solid Booster – Minuteman III

Upper Stage Removed

Cannot escape Earth surface but can escape LEO, GEO, Lunar Basing – NOTE Payload Delivered is Sufficient

Likely Non-trivial Political Issues!

Stage 1 **Thiokol Tu-122 Thiokol** **I_{sp} (s)**	**Stage 2** **Aerojet SR19** **I_{sp} (s)**	**Payload(kg)**	**Stage 1 Delta_v (km/s) vs payload** **Thrust 792 kN (sea level)** **Burn 60 sec**	**Stage 2 Delta_v (km/s) vs payload** **Thrust 268 kN (vac)** **Burn 66 sec**	**Total delta_v (km/s) No grav vs payload**	**C_3 (km/s)^2 vs payload**	**Lunar Surface Launch** **Speed far from Moon w/Earth grav (km/s)** **vs payload**	**Earth Geosync Launch** **Speed far from Earth (km/s)** **vs payload**
262 (vac)	288 (vac)	500	2.92	5.02	7.94	-62.5	7.43	6.64
237 (sea level)		1000	2.84	4.26	7.10	-75.1	6.53	5.61
Stage 1 Alpha	**Stage 2 Alpha**	1500	2.75	3.73	6.49	-83.4	5.86	4.81
0.099	0.11	2000	2.68	3.33	6.01	-89.3	5.33	4.15
		3000	2.54	2.76	5.30	-97.4	4.51	3.03
Stage 1 m_begin (kg)	**Stage 2 m_begin (kg)**	4000	2.41	2.36	4.78	-102.6	3.88	1.98
23077	7032	5000	2.30	2.07	4.38	-106.3	3.37	0.49

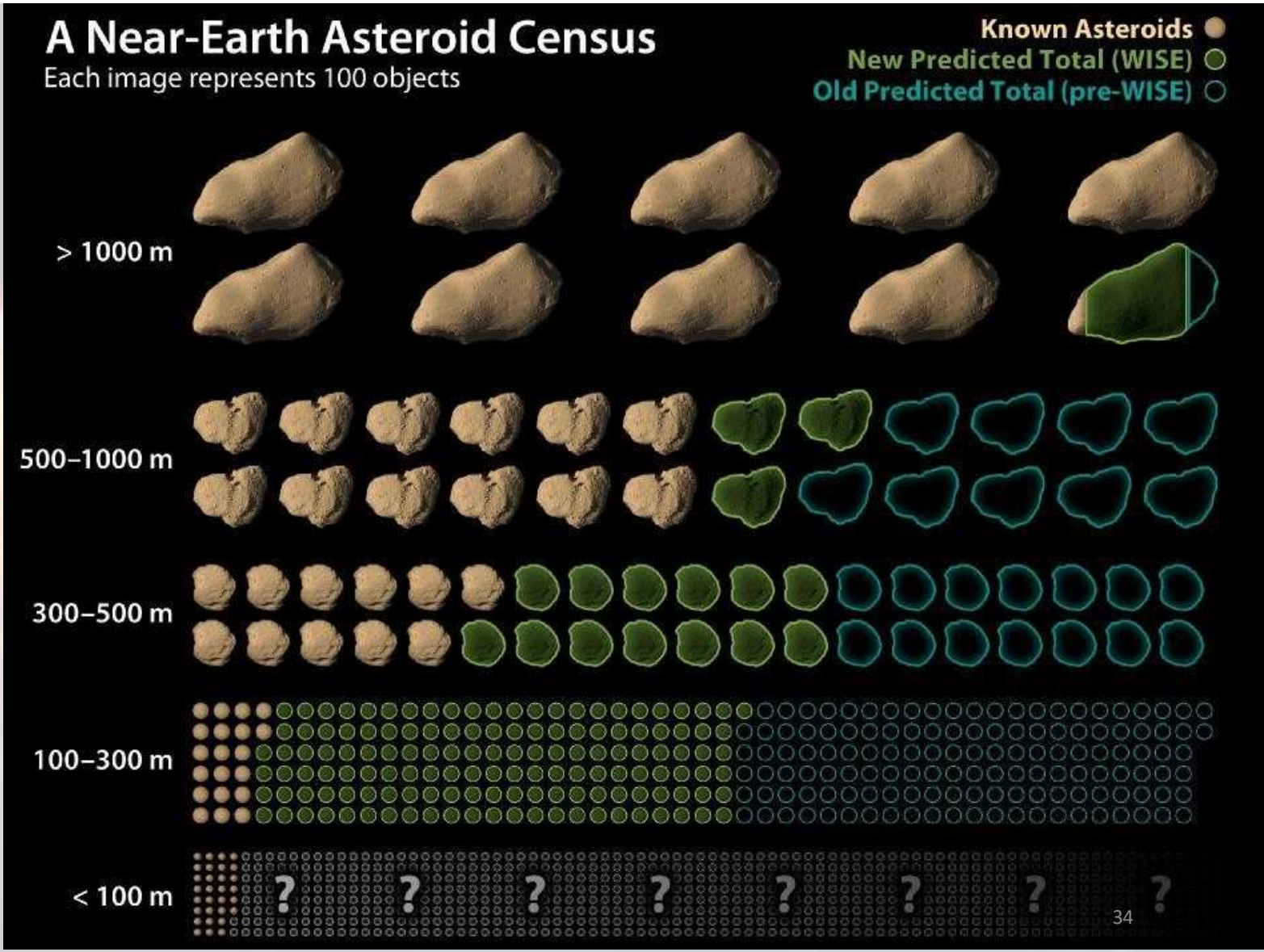
Better Situational Awareness is Key

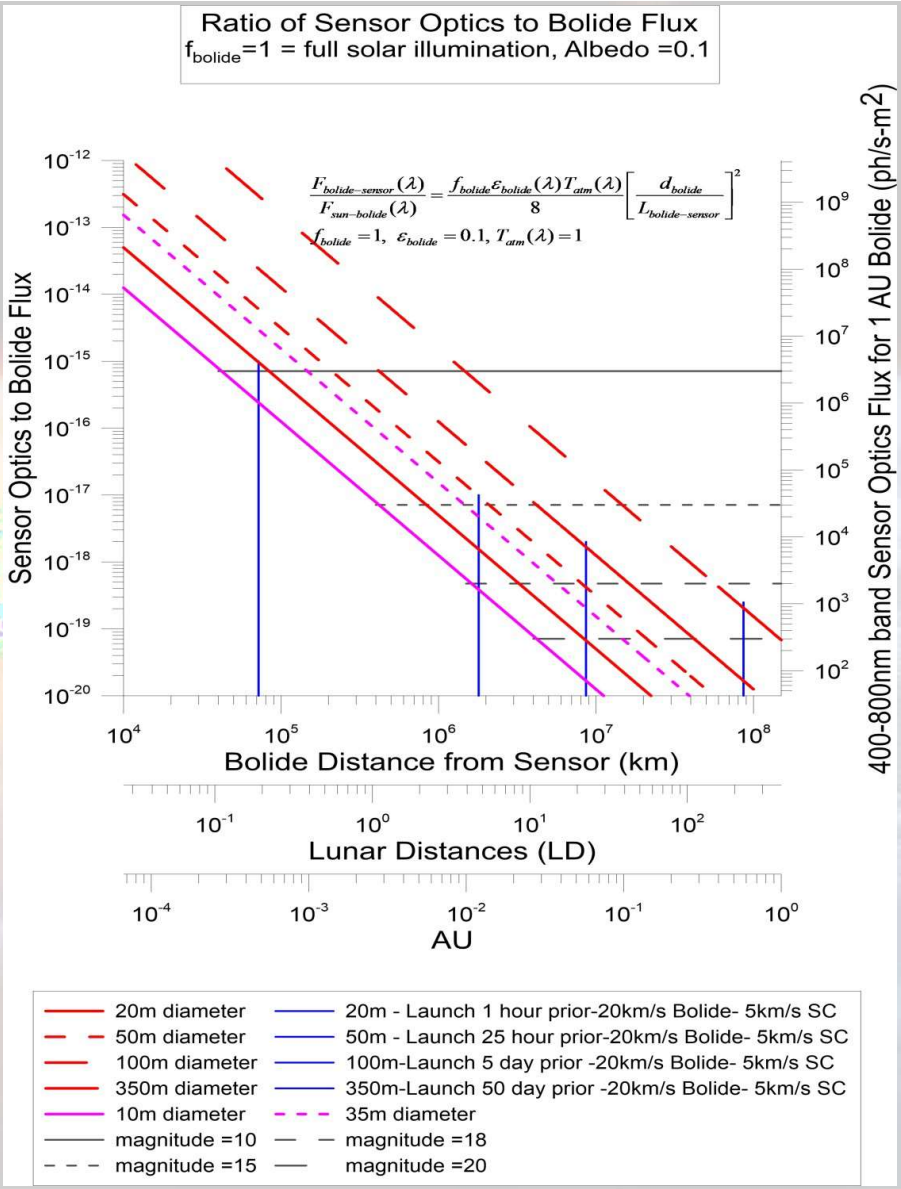
- 2023 NT1 passed by Earth July 13, 2023 (1/4 lunar) detected July 15!
  - Sunward threat - Estimated 30-60m diameter – if impacted 2-10 MT yield
- We have decent awareness of threats > 300m (very good > 1 km)
  - **Mark your calendar Friday the 13th – April 2029 – Apophis comes inside geosync**
  - **~ 4 GT if impact (comparable to all nuclear weapons combined) – repeat offender**
- Poor awareness <200m
- Virtually no awareness <100m (~ 100 MT)
- Need much better surveys in both visible and IR (3-10μ)
  - IR - NEO Surveyor (L1 - 2028 launch – 12 year mission) 0.5m (4-10μ - 2 band)
    - Goal is find "most" >140m threats
  - ATLAS Asteroid Terrestrial-impact Last Alert System vis sky 1/day
    - Four 0.5m telescopes – 45m threat – 1 week, 140m, 4 week warning
    - As for any ground based – night only – thus day and sunward threats not seen
  - LSST (Rubin)
    - Observable sky every 3 nights
    - Expect 66% detection of >140m diam within 1.3 AU – NOT for short term warning

Situational Awareness = POOR for <1km objects

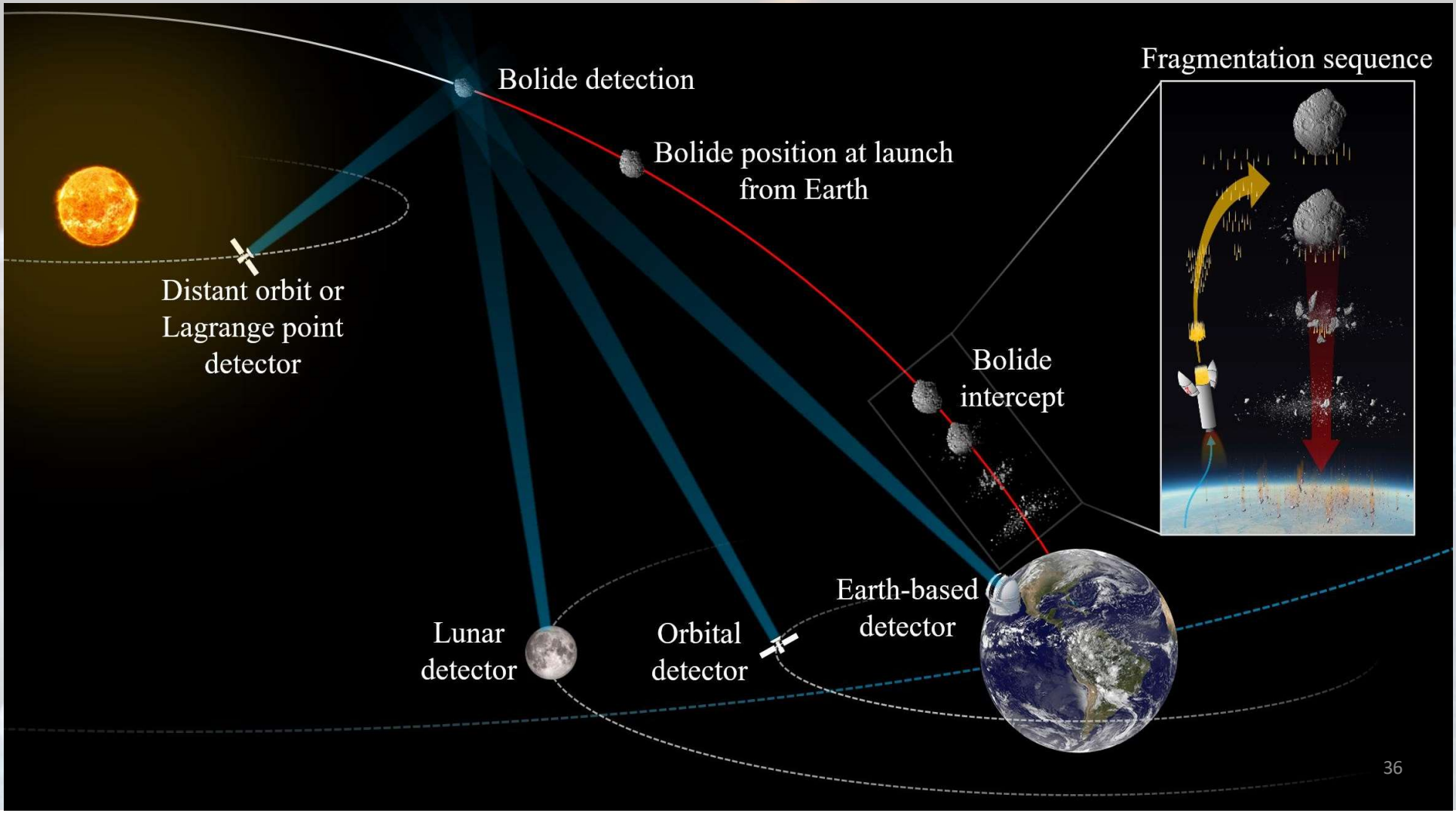
Extremely poor for<300m

100m~100Mt
50m ~ 10Mt




Ratio of Sensor Optics to Bolide Flux
f_bolide=1 = full solar illumination, Albedo =0.1
$\frac{F_{bolide-sensor}(\lambda)}{F_{sun-bolide}(\lambda)} = \frac{f_{bolide}\varepsilon_{bolide}(\lambda)T_{atm}(\lambda)}{8}\left[\frac{d_{bolide}}{L_{bolide-sensor}}\right]^2$
$f_{bolide}=1,\ \varepsilon_{bolide}=0.1,\ T_{atm}(\lambda)=1$
Sensor Optics to Bolide Flux
400-800nm band Sensor Optics Flux for 1 AU Bolide (ph/s-m2)
Bolide Distance from Sensor (km)
Lunar Distances (LD)
AU
20m diameter
50m diameter
100m diameter
350m diameter
10m diameter
magnitude =10
magnitude =15
20m - Launch 1 hour prior-20km/s Bolide- 5km/s SC
50m - Launch 25 hour prior-20km/s Bolide- 5km/s SC
100m-Launch 5 day prior -20km/s Bolide- 5km/s SC
350m-Launch 50 day prior -20km/s Bolide- 5km/s SC
35m diameter
magnitude =18
magnitude =20

Ideally want Combined Earth, Lunar and Space Detection



Recent papers on PI

Lubin, P. "PI – Terminal Planetary Defense", ASR, 2023
https://arxiv.org/abs/2110.07559

Lubin, P. and Cohen, A., "Asteroid Interception and Disassembly for Terminal Planetary Defense", ASR, 2023
https://www.sciencedirect.com/science/article/pii/S0273117722009395

Lubin, P. and Cohen, A, "Planetary Defense is Good – but is Planetary Offense Better?", Scientific American, October, 2021
https://www.scientificamerican.com/article/planetary-defense-is-good-but-is-planetary-offense-better

Lubin, P. et al "PI – Planetary Defense Program Overview", PDC 2023 – submitted to Acta Astronautica, 2023

Cohen, A., P. et al " Asteroid Disruption ALE3D Simulations for Planetary Defense via the PI Method.", PDC 2023 – submitted to Acta Astronautica, 2023

Bailey, B. et al "Acoustical Ground Effects Simulations from Bolide Disruption via the PI Method", PDC 2023 – submitted to Acta Astronautica, 2023

Patel, D. et al "Optical Ground Effects Simulations from Bolide Disruption via the PI Method", PDC 2023 – submitted to Acta Astronautica, 2023

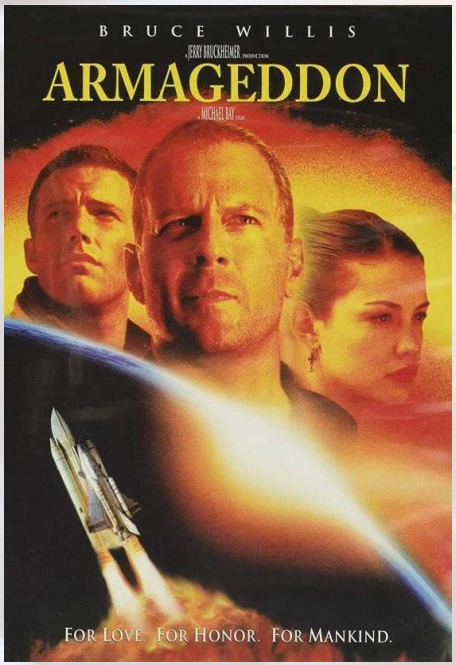
Bailey B. et al , "2023 NT1 – A Cautionary Tale" – submitted to Ap J Letters 2023

Armageddon (1998)

An Asteroid the Size of Texas

Good idea – REALLY bad physics

Not enough nuclear weapons on Earth to take apart >40 km assuming 100% efficiency



Conclusions

- The PI method is an extremely effective planetary defense strategy that can be used for a wide range of threat scenarios (20 – 1000 m diameter)
  - Allows for **very rapid response** if needed
  - Can provide mitigation of very large threats for long-warning scenarios, with **much faster response time** and **much less launch mass** than other methods (i.e., deflection)
  - Options for purely passive, active (conventional explosive) penetrators and for nuclear penetrators
- Testable method that uses existing technologies and modest resources
  - Capable with current generation of launch vehicles
- Allows for a logical roadmap to a robust PD system
  - Path towards a **single-launcher solution** with **at-the-ready capability**
  - Goal: the PI method becomes synergistic with existing mitigation strategies (such as deflection), which may be logistically favorable in some threat scenarios (particularly those with especially long warning times)
- Long-term program with long-term consequences
- Allows for a very robust Earth defense system with existing technologies
  - New heavy lift (SLS, Starship ….) are useful for large threats IF only passive penetrators
    - **NED's allows for a single small launch vehicle like the Falcon 9 or Heavy to take on threats to 1km diameter using combined passive (sequential hole drilling) penetrators and NED**
    - **NOT like standoff nuclear which is a deflection via X-ray driven surface ablation**