Emmett and Gladys W. Technology Fund

PI
Terminal Planetary Defense

P. Lubin
Physics Dept. – UC Santa Barbara
lubin@ucsb.edu
www.deepspace.ucsb.edu
www.deepspace.ucsb.edu/Projects/pi-terminal-planetary-defense
www.researchgate.net/profile/Philip_Lubin

131 page *Technical paper: "PI – Terminal Defense for Humanity" – Lubin, P. ASR - submitted*
arxiv.org/abs/2110.07559
"Rapid Response Planetary Defense" - Lubin, P and Cohen, A. – ASR – submitted
"Planetary Defense – Pie in the Sky or Easy as PI" Sci American – Lubin and Cohen – Oct 2021
www.scientificamerican.com/article/planetary-defense-is-good-but-is-planetary-offense-better

Terminal Defense Appears Feasible

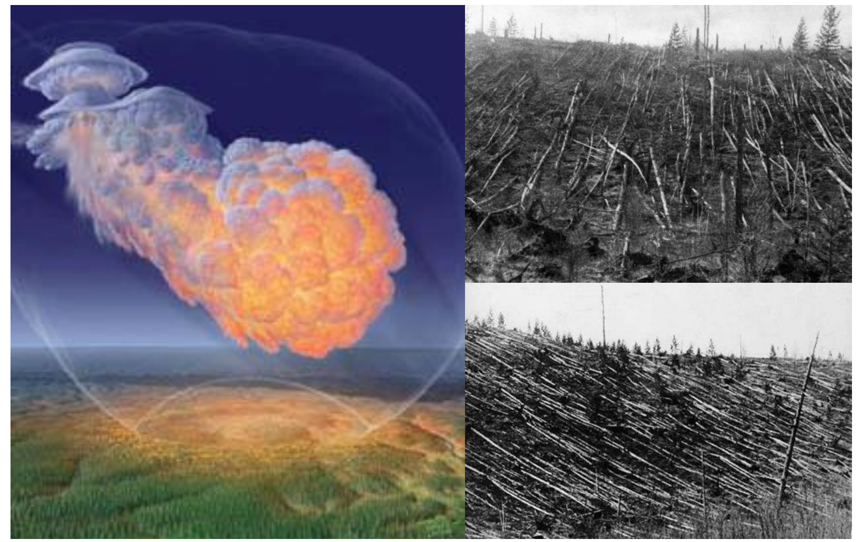
- **Up to 1km class can be mitigated**
- **Ex: 100m diameter with 1 day prior to impact**
- Technique – "slice and dice" – penetrator array
- **Conclusion: low residual damage** from:
  - Acoustic (Blast Wave)
  - Optical Flash
  - Explored secondary issues such:
    - dust (nuclear winter) – negligible
    - EMP – negligible
- Technology is here now
- **US can begin now to develop practical PD**

The Problem – Impacts are Real

→No Current Defense←

Chelyabinsk, Russia (0.5 Mt)
February 15th, 2013

Tunguska, Russia 3-30 Mt
June 30th, 1908



Asteroid/comet air bursts are similar to nuclear blasts in total energy. Common impact energies are comparable to strategic NED-class nuclear warheads, while less common larger impact energies can exceed significant fractions of the global nuclear arsenal.

Relative threat level per Lifetime

C.R. Chapman & D. Morrison, 1994, Nature 367, 33-40 (roughly all humanity dies every 100 million years)

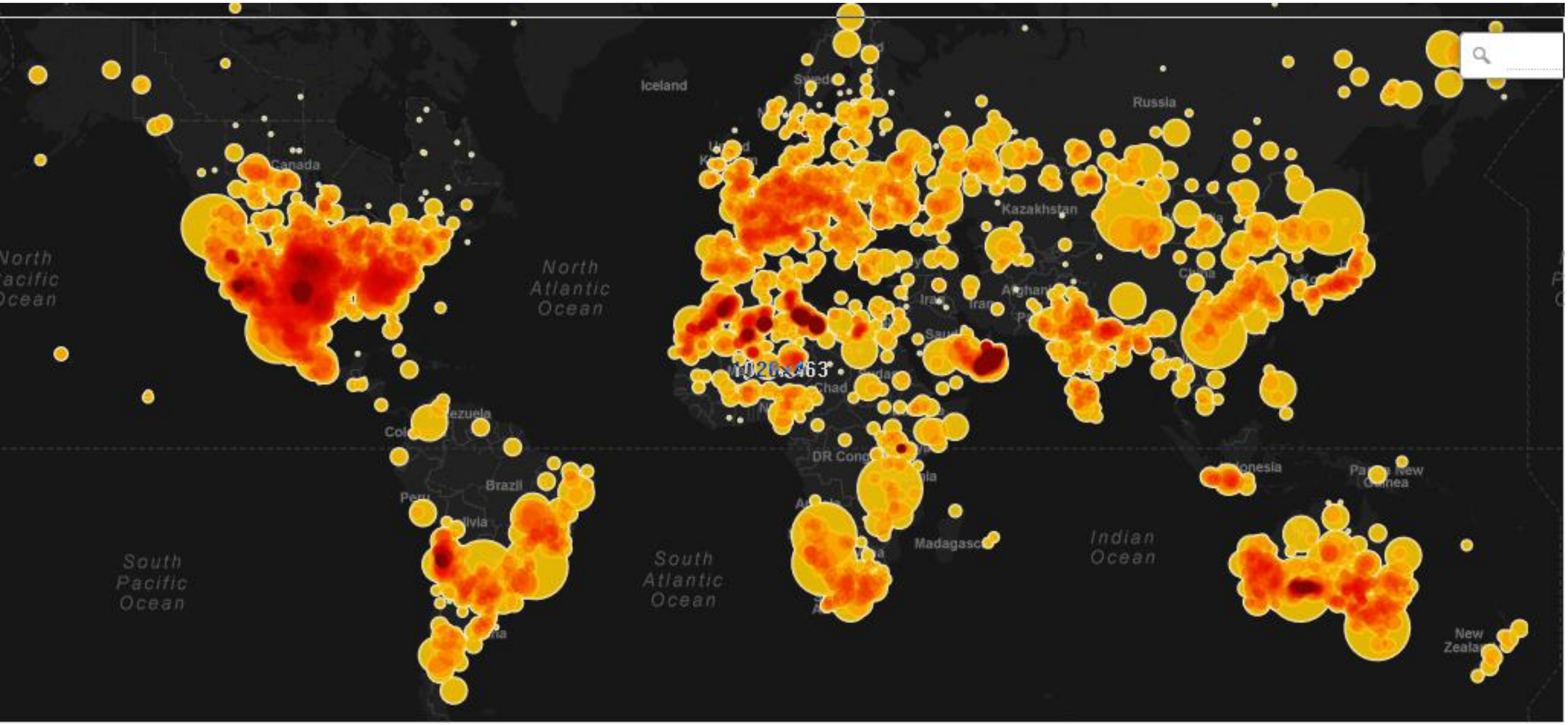
$10^{10}/10^{8}$ = 100 people/yr $=10^{4}$ people per human lifetime ~ 10^{-6} chance of a person dying per lifetime

- Motor vehicle accident = 1 in 100
- 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
- Stress from writing proposals = unity

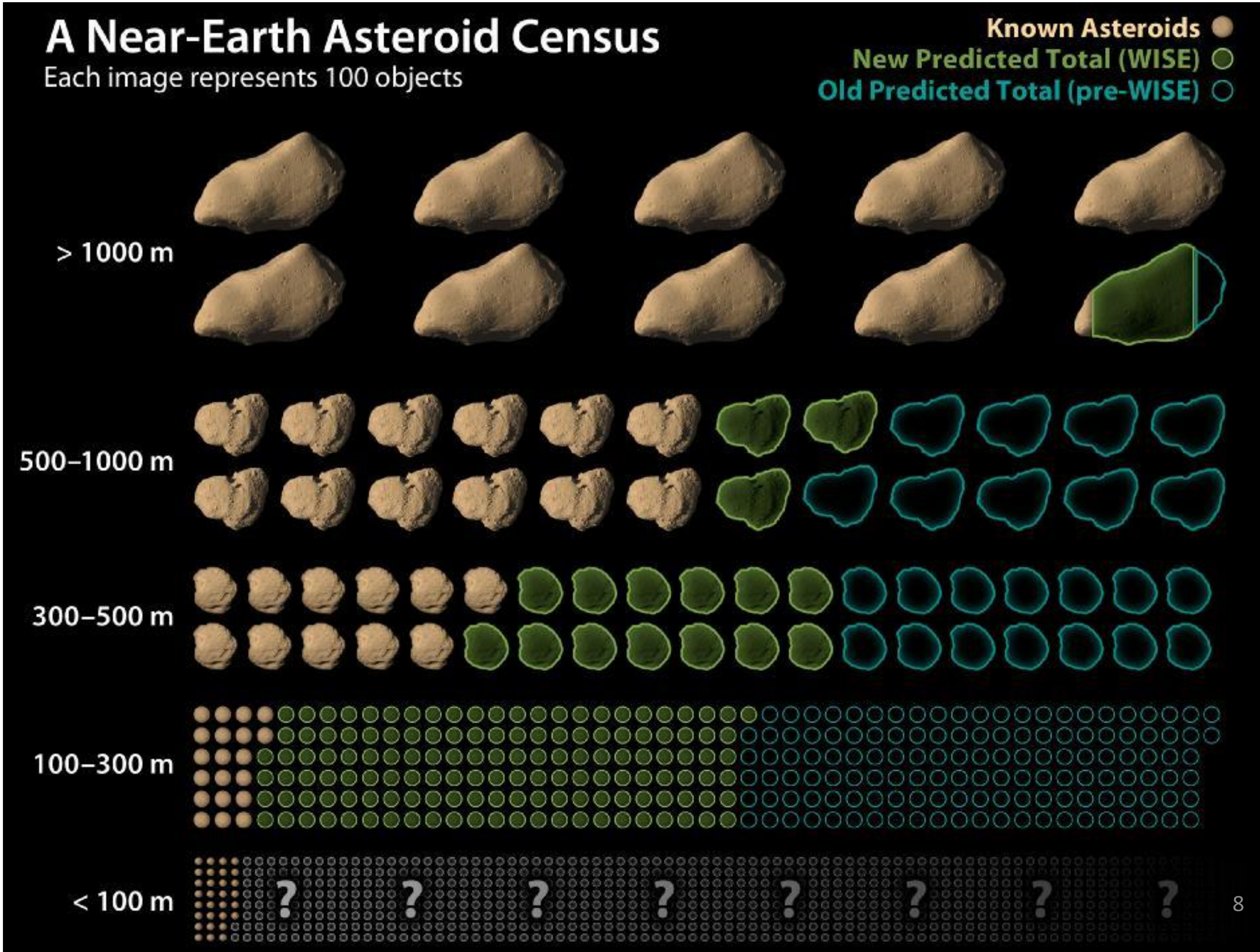
The Scale of the Problem

34,513 Noted Points of impact - Last 4000 years

On a typical non eventful day >100 Tons hits



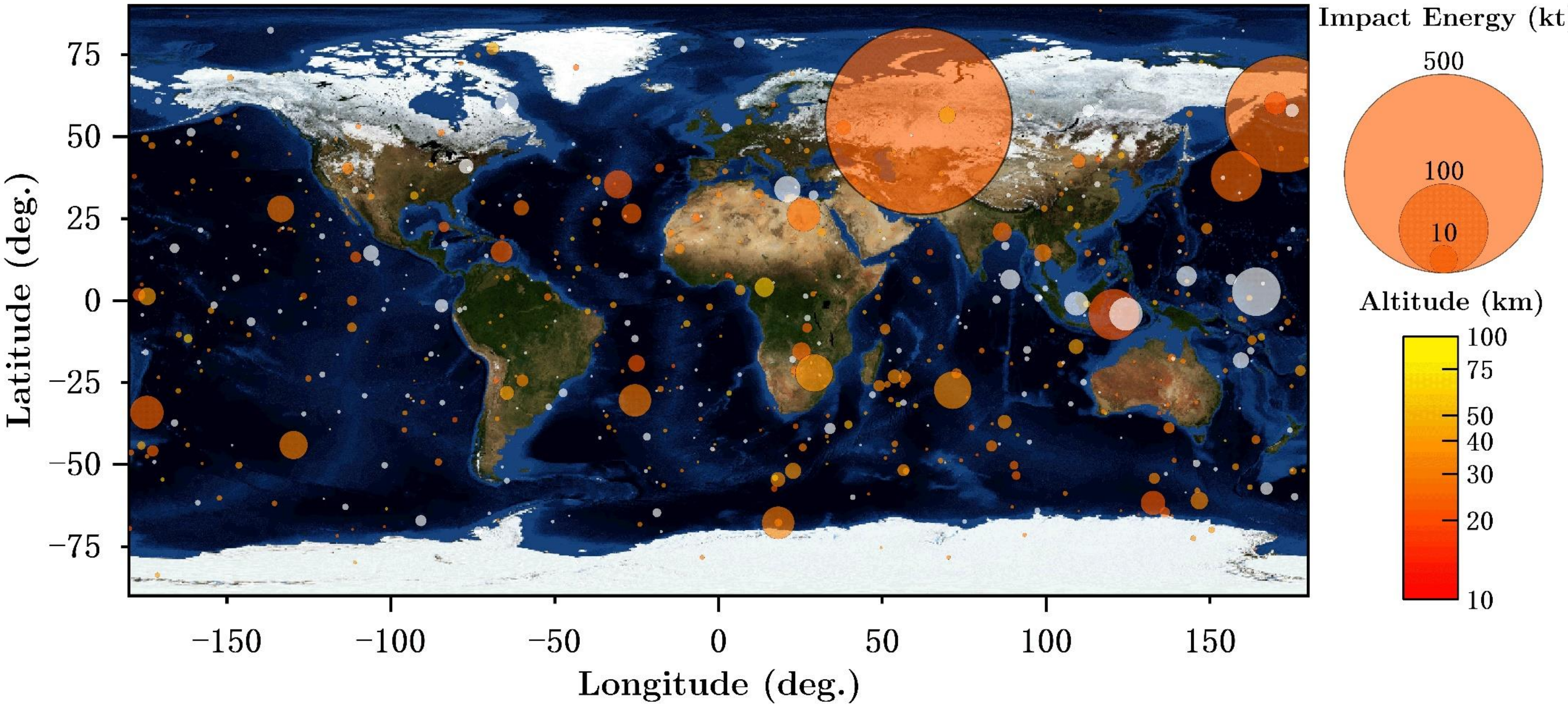
We Have Yet to Detect Many Threats



Recent Hits – From CNEOS Infrasound Data

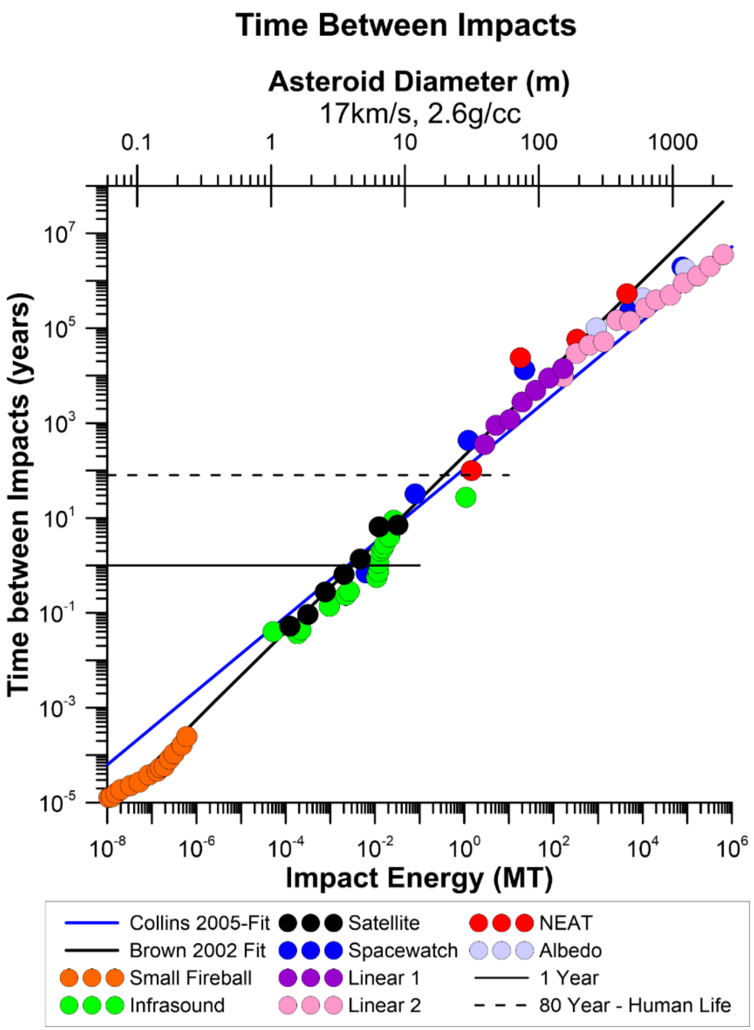
Large circle is 2013 Chelyabinsk Event (0.5MT)

Approx. 20yrs of data shown

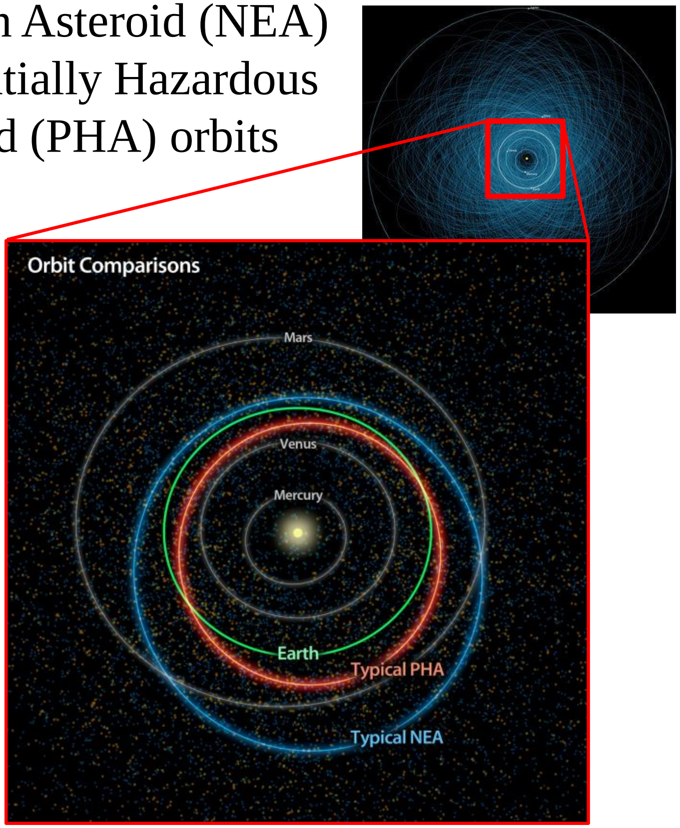


Time Between Asteroid Hit vs Yield (MT)

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

Previous Mitigation Ideas

- “Duck and Cover”
- Impactor to “bump” – change orbit to miss
- Gravity Tractor – change orbit
- Ion deflection – change orbit
- Laser Ablation – change orbit (UCSB)
- NED deflection – change orbit

What If We Could Develop a Rapid Response General Purpose PD System?

The Solution π – Pulverize It

- **Accept the hit** – atmosphere is your “bullet proof vest”
  - BUT disassemble to ~ 10m (or less) diameter fragments
- Use Earth’s atmosphere to absorb&disperse the energy
  - Analogous to body armor
- **Use asteroid’s speed (typ. 20km/s) against itself**
- Place penetrator array “in front of asteroid”
- Penetrators disassemble asteroid (typ. 20km/s)
- **Temporally de-correlate acoustic blast waves**
  - Fragments are typ. <10m diameter
  - **SUM of fragment blast waves do little harm**
  - **SUM of fragment optical pulses do little harm**

The Solution

Kinetic impactor array “slices and dices” target.

Earth’s atmosphere is our body armor – absorbs fragments.

Spatially distribute energy to de-correlate blast waves.

(2) Penetrator array is deployed and expands into conical distribution. Individual penetrators may be passive kinetic impactors or active explosives.

(1) Launch vehicle carries compact penetrator array to intercept location. Safe intercept times and choice of launch vehicle vary depending on target size.

(3) Target strikes array of penetrators, outer layers of target “peeled” off. Subsequent penetrator waves ultimately reduce target to cloud of <10m fragments.

(4) Fragments enter atmosphere and burst at ~30km altitude. Fragment cloud spatially and temporally distributes energy of impact, which de-correlates blast waves and vastly reduces danger.

The Earth Can Take It

Why This System Works

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

Single impactor generates extremely large blast wave and optical pulse which causes damage on a vast scale.

VS.

Multiple fragments distribute total impact energy into spatially and temporally de-correlated blast waves which greatly mitigates risk of damage.

Earth's atmosphere acts as a "bullet proof vest," while the asteroid disassembly converts a single "bullet" into a "buckshot."

Two Primary Damage Modes

Air burst – never allow for ground hit

Relevant Asteroid energy is similar to large NED

- 20m Chelyabinsk – 0.5 MT
  - Similar to strategic NED
- 50m Tunguska – 10 MT
  - comparable to largest US NED test

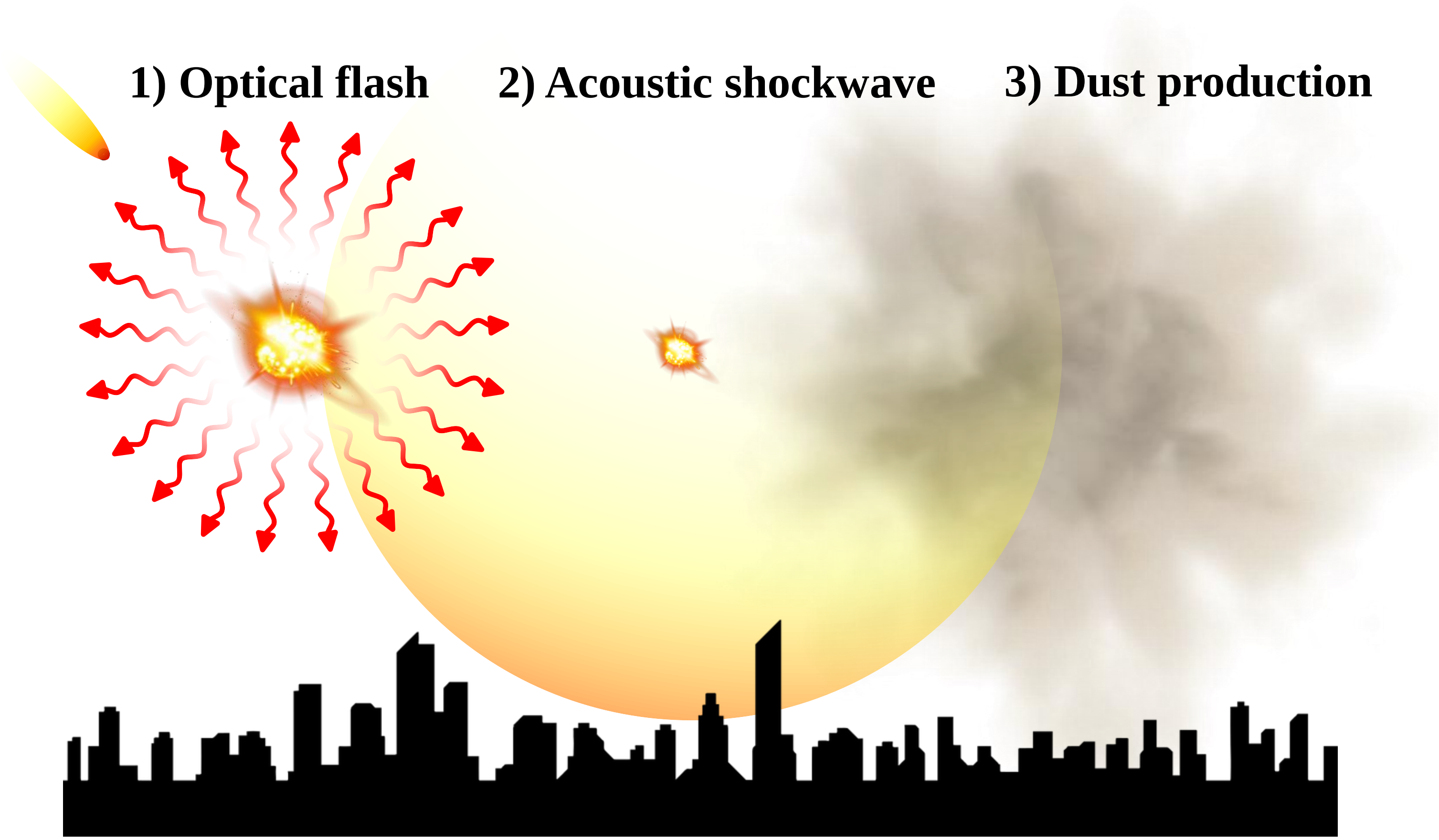
B61 thermonuclear bomb, max yield 0.4MT, similar to total energy of Chelyabinsk event.

1. Acoustic Signature – blast wave destruction
   - Can lead to significant building and personnel effects
   - If peak pressure exceeds 10 kPa → residential damage
   - Keep peak pressure below 2 kPa to avoid glass damage
2. Optical Signature – combustion concern
   - Combustion danger if > 0.2 MJ/m^2

Building and window damage after Chelyabinsk event.

Two Primary Damage Modes in Air burst

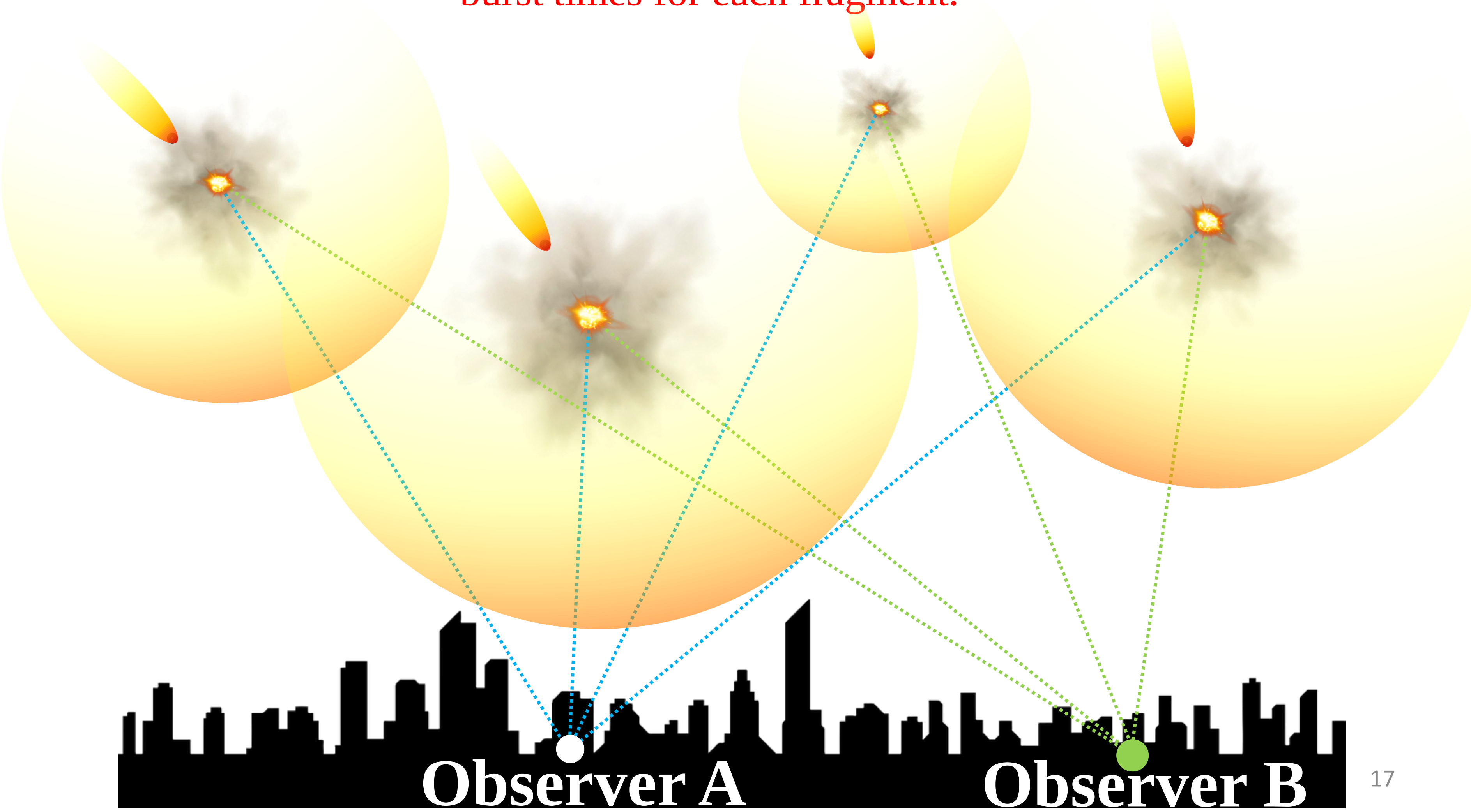
Acoustic and Optical Pulses – Dust is Minimal



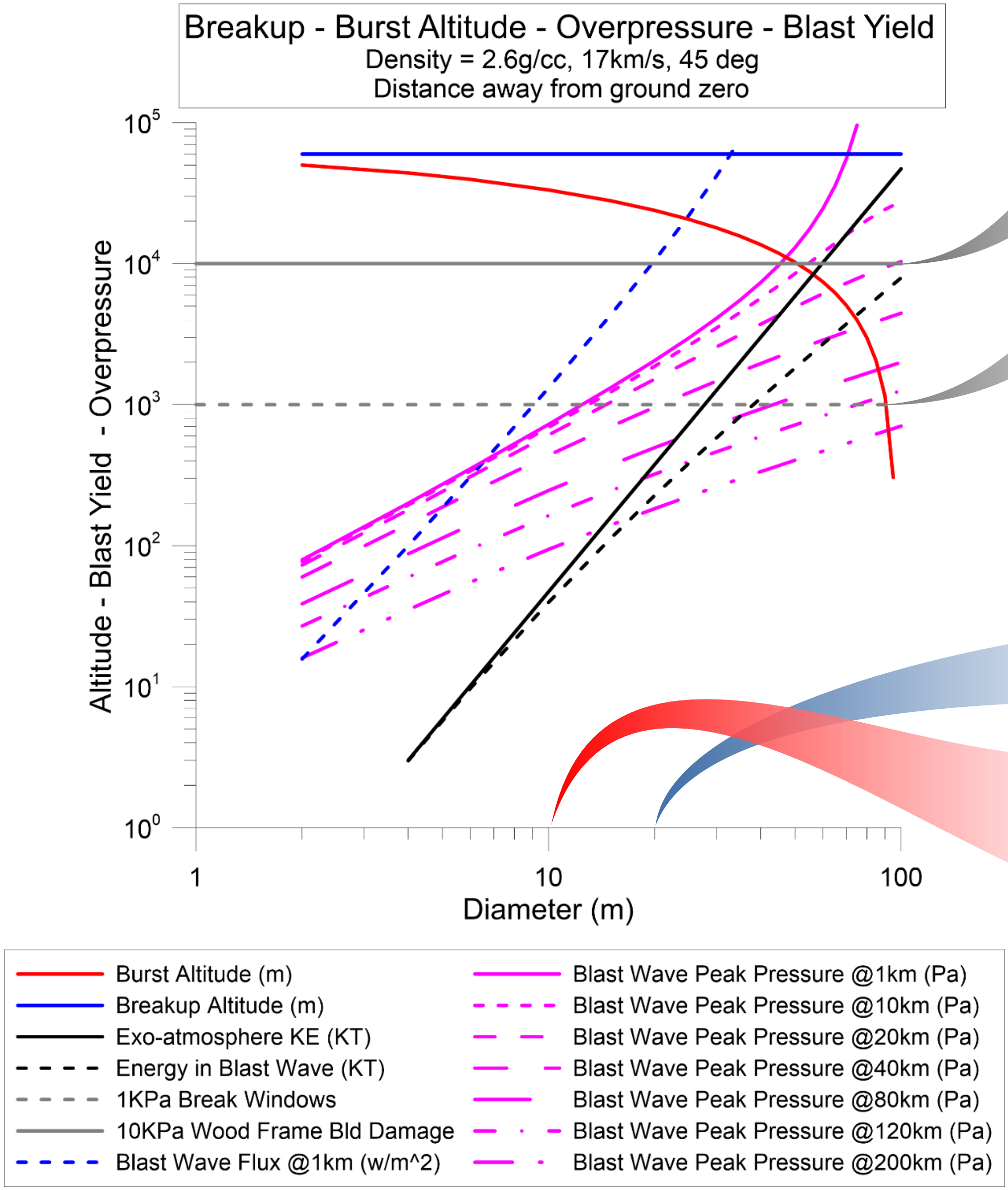
System is designed to mitigate all of the above.

Why Does This Work – Acoustic de-correlation

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



Solution – Keep fragments below ~10m to mitigate blast wave



10kPa: wooden frame building damage threshold

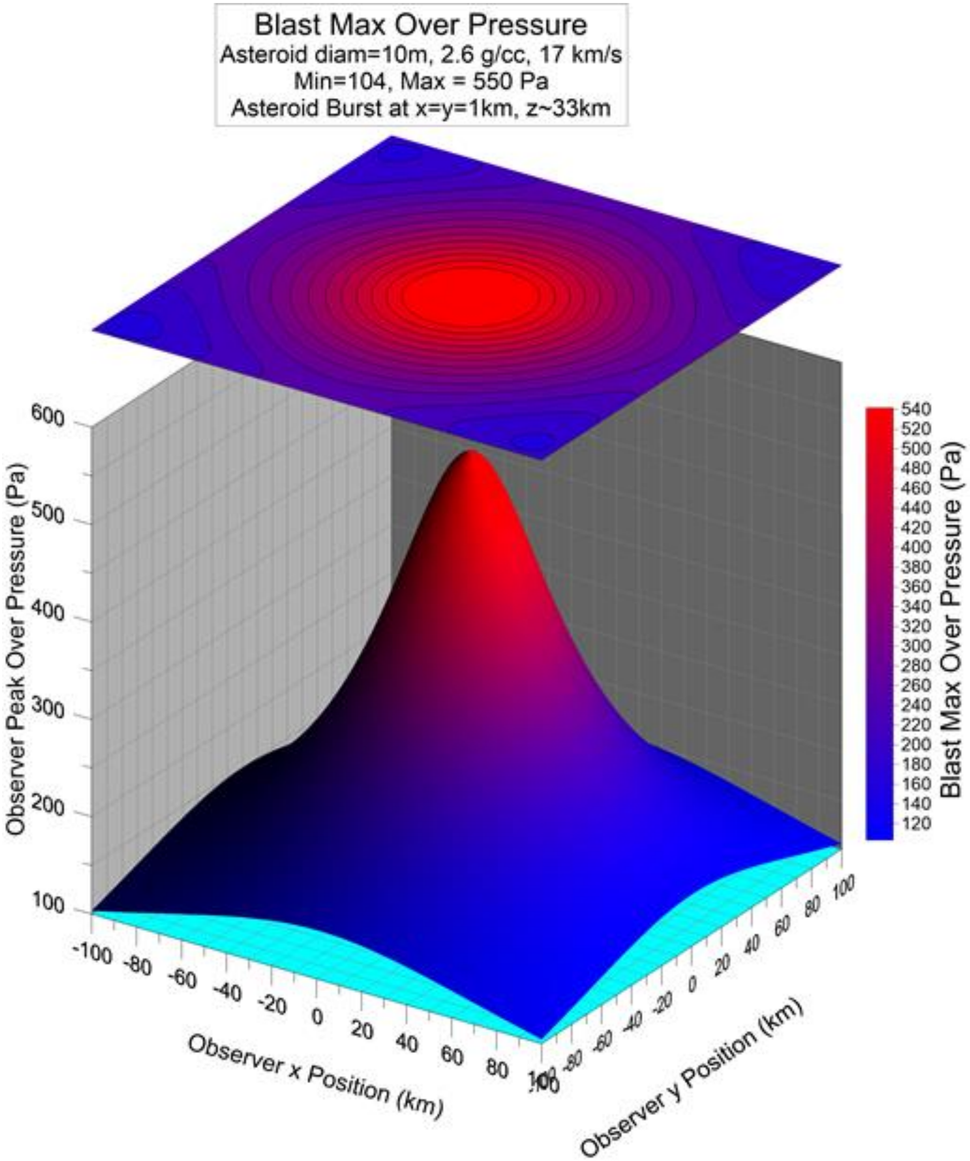
1kPa: window damage threshold

Window damage after ~20m meteor air burst over Chelyabinsk, Russia.

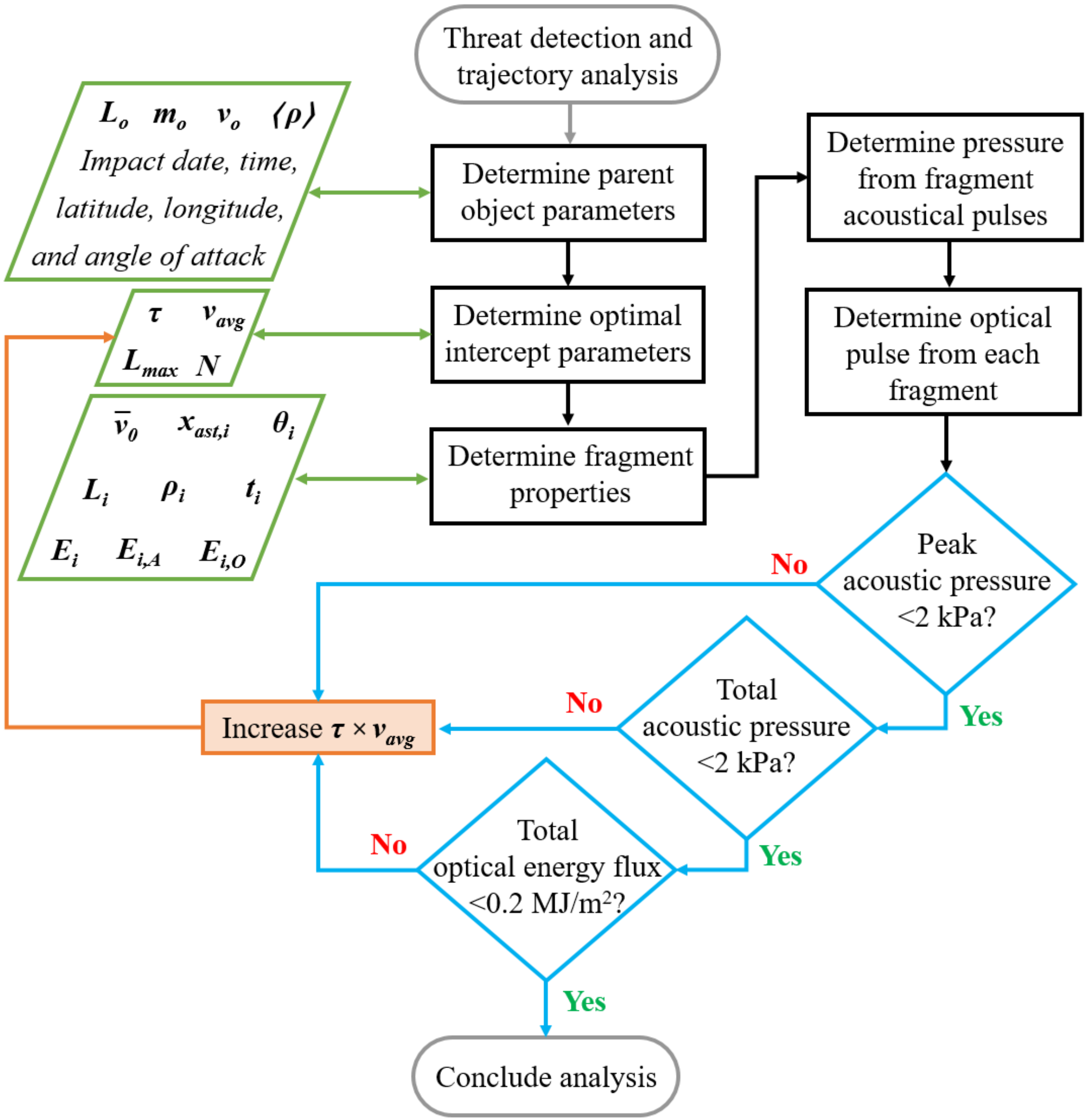
KEY: 10m stony asteroid fragments stay below window damage threshold based on data from nuclear tests and small asteroid impacts. Smaller fragments are better if feasible.

Fragmenting to 10m scale results in vastly reduced blast pressure

10m fragment shown – pressures well below window damage threshold can be achieved.

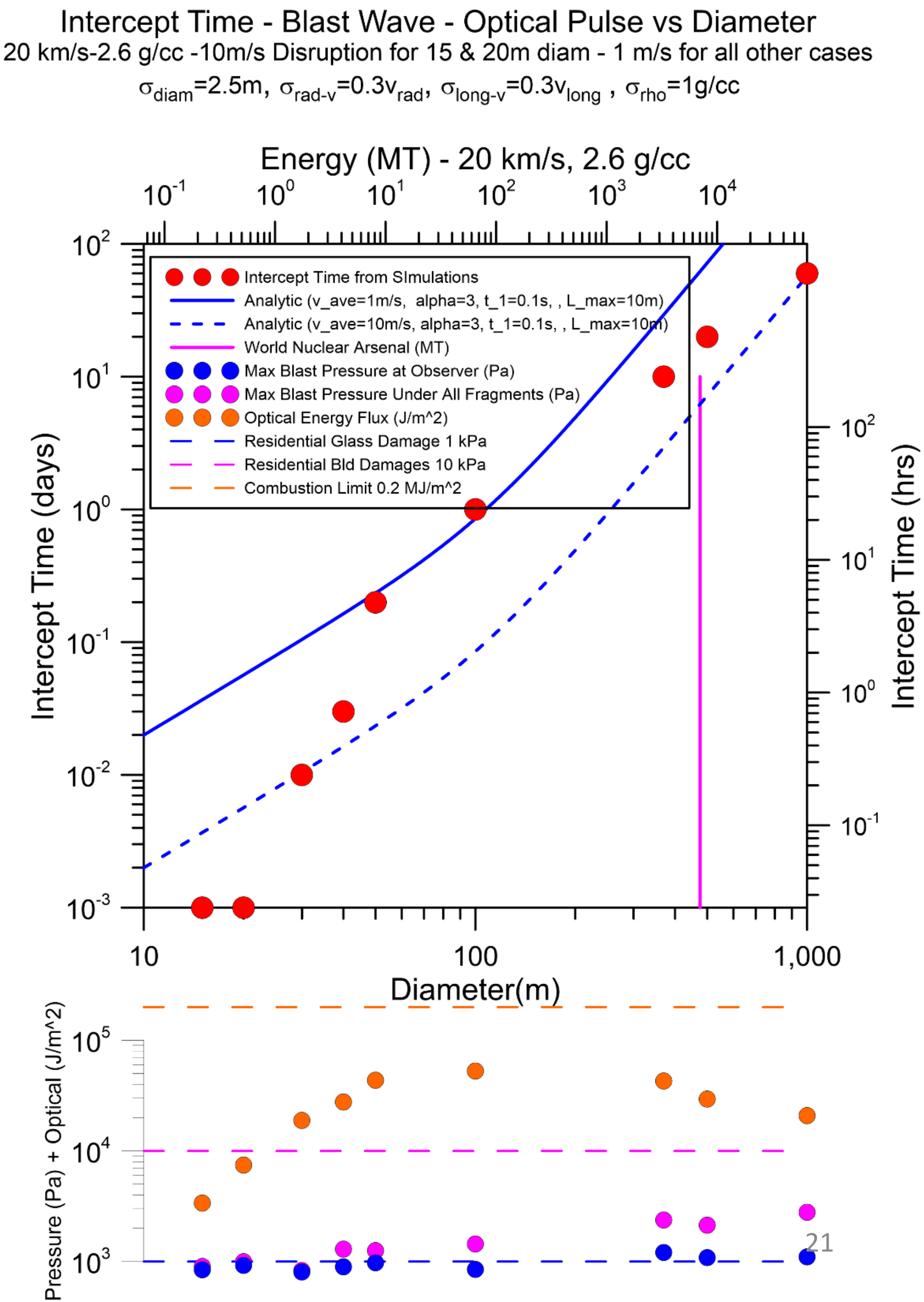


Simulation Logic Diagram



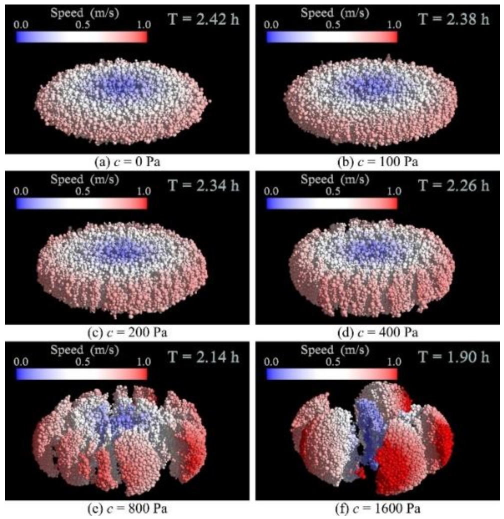
Summary

- Intercept time vs diam
  - **Red dots**
- Product of $\tau * v_{disruption}$ is key metric
  - Can trade τ and $v_{disruption}$
  - Allows even fast response IF needed
- 10m/s for 15,20m 100 s intercept
- 1m/s for 15,20m 15 min intercept
- 1m/s for all others
- Observer Optical pulse <0.2MJ/m^2
  - **Orange dots**
- Observer Acoustic pulse <1 Kpa
  - **Blue dots**
- Worst Acoustic pulses under fragments <2 Kpa
  - Magenta dots
- Zero time intercept for 20m
  - 100 sec shown for 15,20m
  - Zero time works for ≤ 20m
    - Burst altitude dispersion with fragment diameter variation allows zero time for ≤ 20m

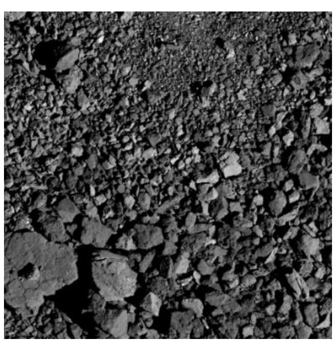


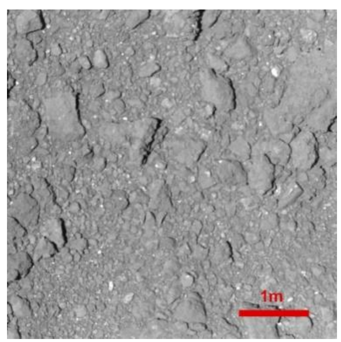
Asteroids CAN be Disassembled

Disassembly energy required is very modest

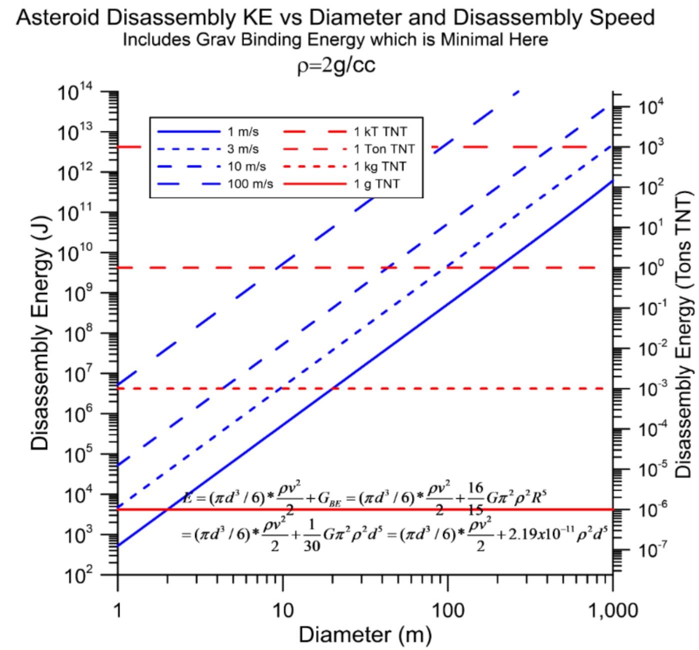


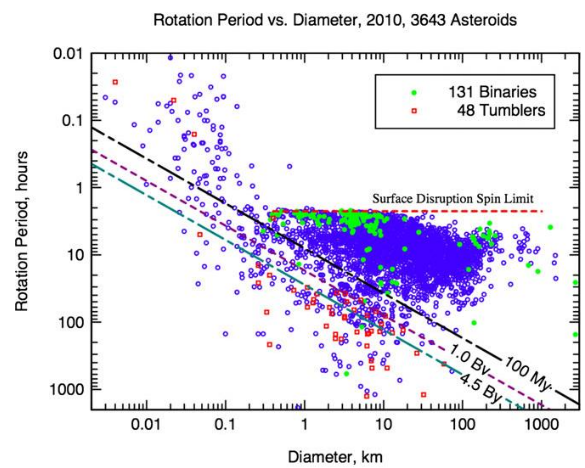
(left) Asteroid self-disassembly thresholds for various inter-particle cohesion values c and rotational periods T.
Yun Zhang *et al* 2018 *ApJ* **857** 15. https://doi.org/10.3847/1538-4357/aab5b2





(left) Image taken by the OSIRIS-REx spacecraft of the loosely bound, rubble pile-like surface of the asteroid Bennu (~500m). (right) Image taken by the Hayabusa spacecraft of a similar composition found on the surface of the asteroid Ryugu (~900m).

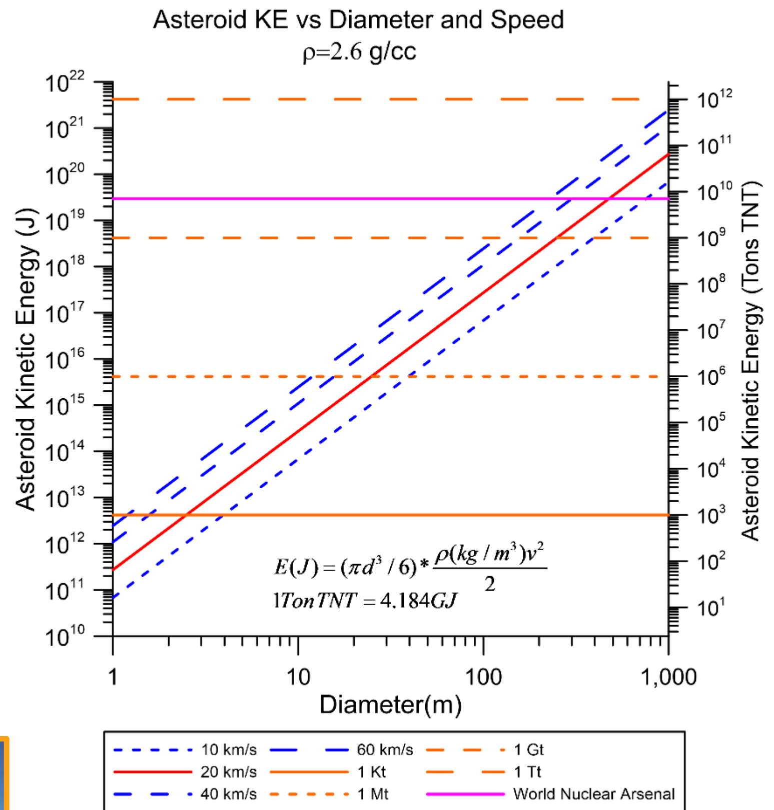




Sánchez, P. and Scheeres, D.J. (2014), Meteorit Planet Sci, 49: 788-811. https://doi.org/10.1111/maps.12293

Asteroid KE comparison to existing/past NED's

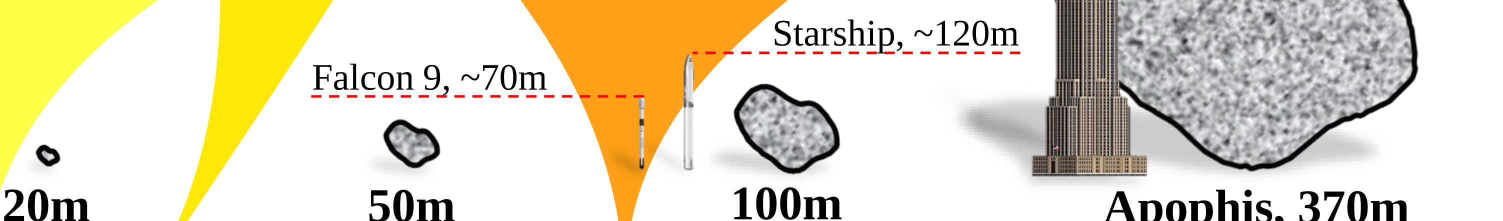
Even smaller asteroids impact with energies comparable to strategic nuclear weapons.



B83 thermonuclear bomb, max yield 1.2MT.

B61 thermonuclear bomb, max yield 0.4MT.

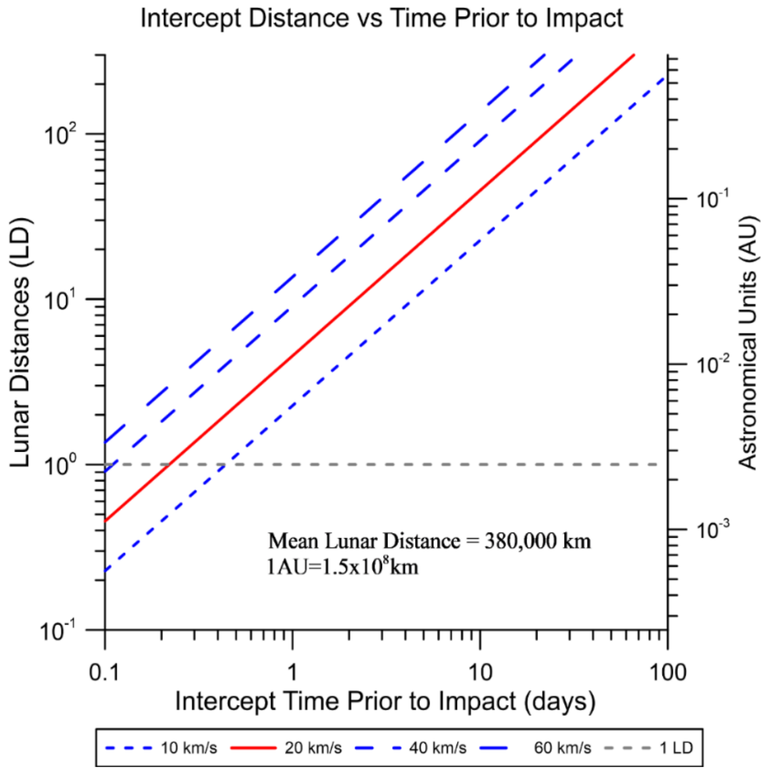
Tsar Bomba, 50/100MT, largest nuclear weapon ever detonated.

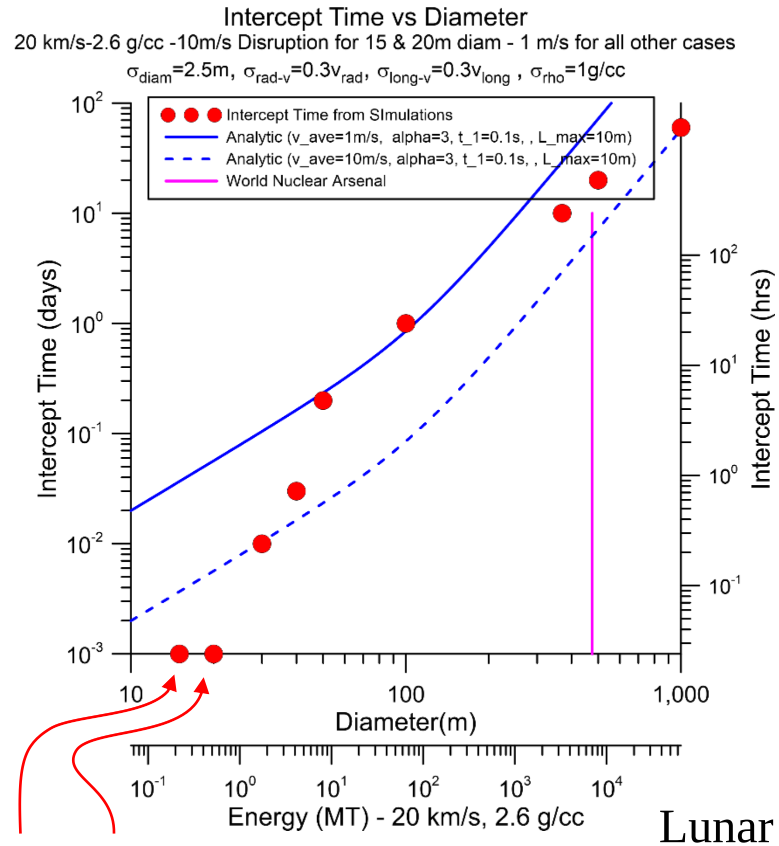


0.5MT **10MT** **100MT** **4GT, ½ world arsenal**

Response times can be remarkably short

Intercept Distance vs Time – Zero Time Intercept Possible for ≤ 20m Diameter





15m 20m
100s intercept possible!

GEO
(~36,000 km)

Lunar Distance
(1 LD ≈ 380,000 km)

Short Term Response Scenarios

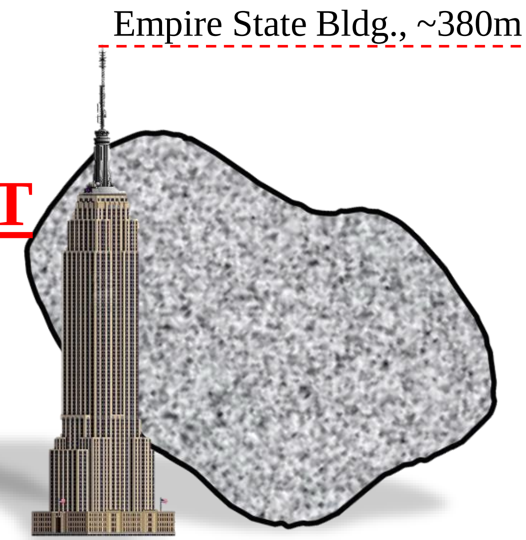
- 20m (0.5 MT) – fragment into 20 pieces
  - 1-10m/s disruption - ~ 200 kg TNT equivalent KE
  - **→1-15 min prior to impact intercept (Inside GEO)!**
- 50m (10 MT) – fragment into 100 pieces
  - 1m/s disruption - ~ 30 kg TNT equivalent KE
  - **→5 hour prior to impact intercept (One LD~ 10xGEO)**
- 100m (100 MT) – fragment into 1000 pieces
  - 1m/s disruption - ~ 250 kg TNT equivalent KE
  - **→1 day prior to impact intercept (3x LD)**
- Apophis 370m (4 GT) – fragment into 30000 pieces
  - >1/2 World arsenal)
  - 1m/s disruption - ~ 10 ton TNT equivalent KE
  - **→10 day prior to impact intercept (30x LD)**

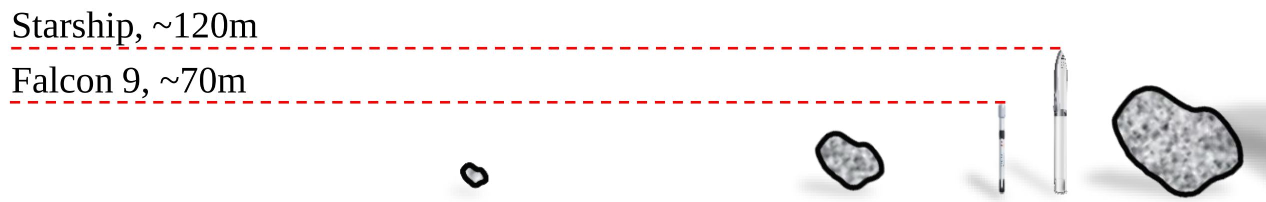
Short Term Response Scenarios

Note that Penetrator KE is energy NOT mass

20 km/s asteroid → 1 t penetrator mass ~ 50t TNT

All building blocks exist already – no miracles required.





Target size	20m	50m	100m	Apophis (370m)
Penetrator KE (kg TNT*)	**200 (4 kg mass)** (for 10m/s disruption)	**30 (<1 kg mass)** (for 1m/s disruption)	**250 (5 kg mass)** (for 1m/s disruption)	**10,000 (200 kg mass)** (for 1m/s disruption)
Intercept time	**<15 minutes**	**5 hours**	**1 day**	**10 days**
Capable launch vehicles **(conservative)**	ICBM interceptor New small booster	New small booster Falcon 9 Delta IV SLS	New small booster Falcon 9 Starship SLS	Starship SLS

***Minimum equivalent mass TNT required for disassembly → 1 t penetrator mass =50 t TNT @ 20km/s asteroid←**

Depending on coupling efficiency the interceptor could be very small in all cases shown

Solid Booster- Minuteman III- Interceptor

3rd stage removed

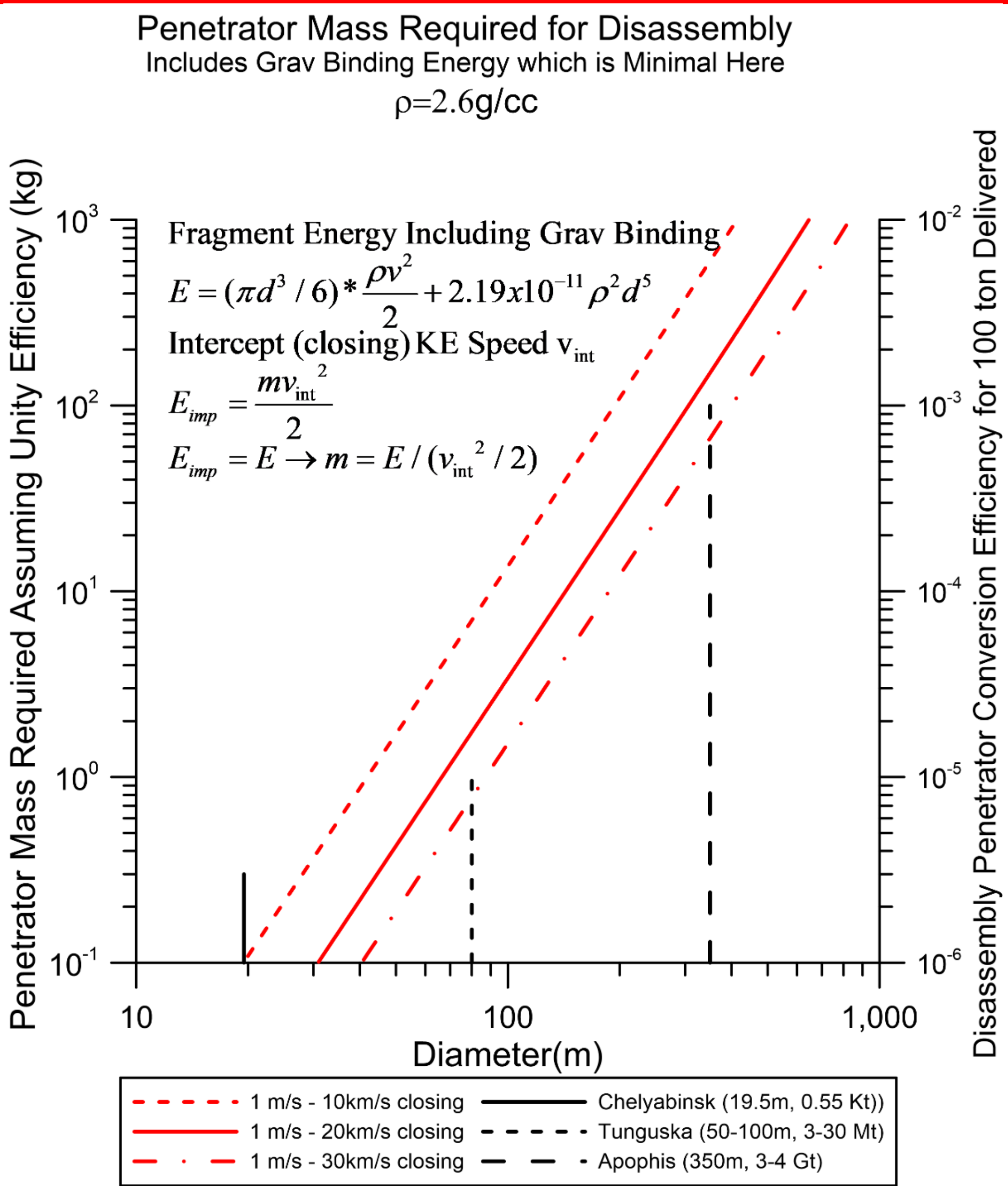
Lunar, GEO, MEO, LEO Basing Option

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**

Penetrator Mass - KE to Disrupt

The Coupling Efficiency is Important to Understand – Explosive Filled Penetrators May Help

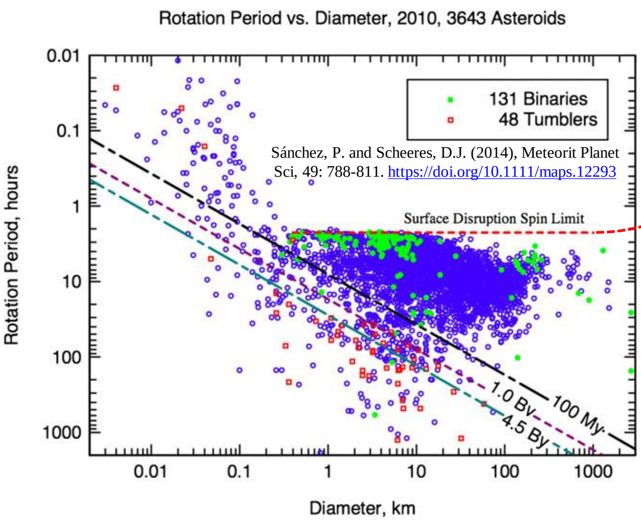
At 20 km/s 1 kg mass penetrator = 48 kg TNT equivalent energy (1 ton mass =48 t TNT)



Next Steps Needed

- **Design and Optimize penetrator array/ system** (AFRL/RW/DOE labs (LANL, LLNL)
  - **Extended hypervelocity (HV) penetrator 4D simulations (UNM, APL, Ames)**
  - **Ground testing of HV penetrator w/wo explosives**
    - **Low cost – rapid feedback**
    - **Test against asteroid "mockup" – (concrete + rocks…)**
    - **Feedback into modeling to validate/ models and 4D super computer simulations**
    - **Simulation and testing of small explosive penetrators – cluster bomb approach**
    - **Simulation and testing of surface contact explosives/ "balls" – successive erosion approach**
- **Work on spacecraft – interceptor deployment** (AFRL/RV, SSC/ Development Core)
  - Trajectory and mission design
  - Explore existing and upcoming booster options – are they sufficient?
- **Ground and space testing on asteroid simulators/ real asteroids** (US Space Command)
  - Lots of space opportunities
- **Explore terminal defense small detection/tracking** (AFRL/RV, MDA, Space Command, USSF (Space Force), NorthCom and StratCom)
  - **Possible lunar synergy**
    - Explore lunar based/ component of PD system
    - **Infrared telescope for active and passive detection and tracking**
    - LIDAR – laser based active illumination
- **Explore in space targets for disassembly/ full sys testing** (Space Command/ NASA)

Ground Testing Options

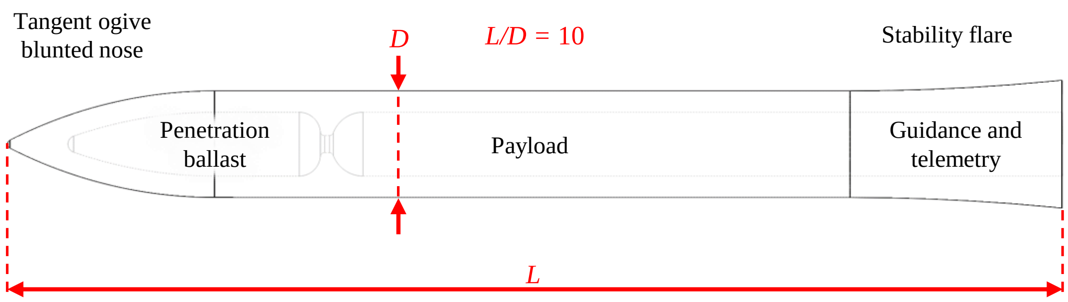


Observations suggest that virtually all asteroids larger than 100m in diameter are gravitationally bound.

This offers an opportunity to fabricate loosely bound asteroid simulants to use as targets for prototype penetrators.

Envisioned ground testing program:

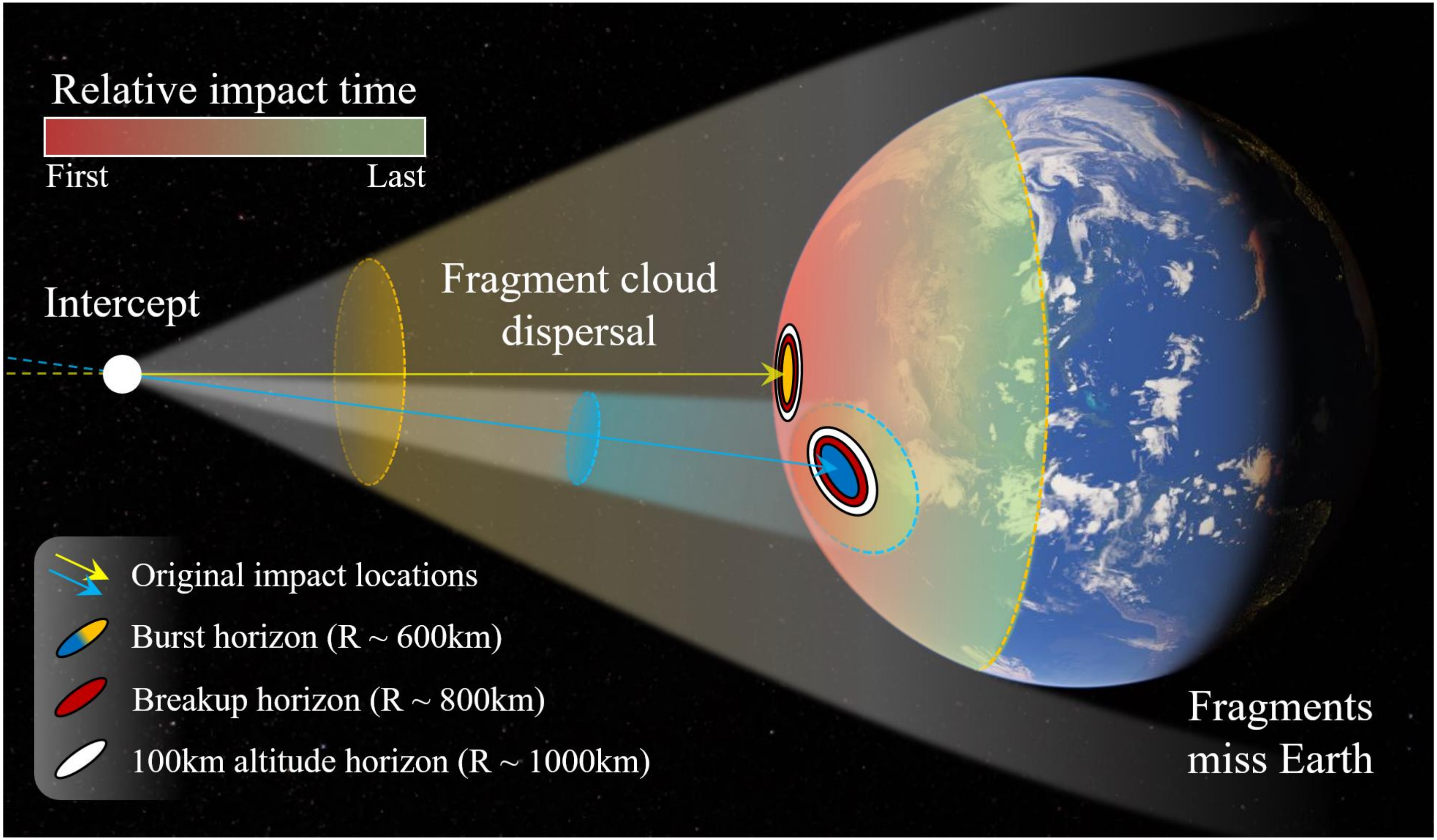
- **Fabrication of high aspect ratio asteroid simulant targets (ex. 100m x 3m x 3m).**
- **Rail guns, gas guns, or rockets are viable options for propulsion of penetrator prototypes.**
- **Terrestrial experiments provide opportunity to explore passive and explosive penetrator designs**.



Example of a simple penetrator design similar to an B61-11 NED penetrator.

Ground testing is fundamentally limited by atmospheric and propulsive constraints. Penetrator designs informed by ground experiments will require in-situ testing and demonstration, such as during future known asteroid close approaches.

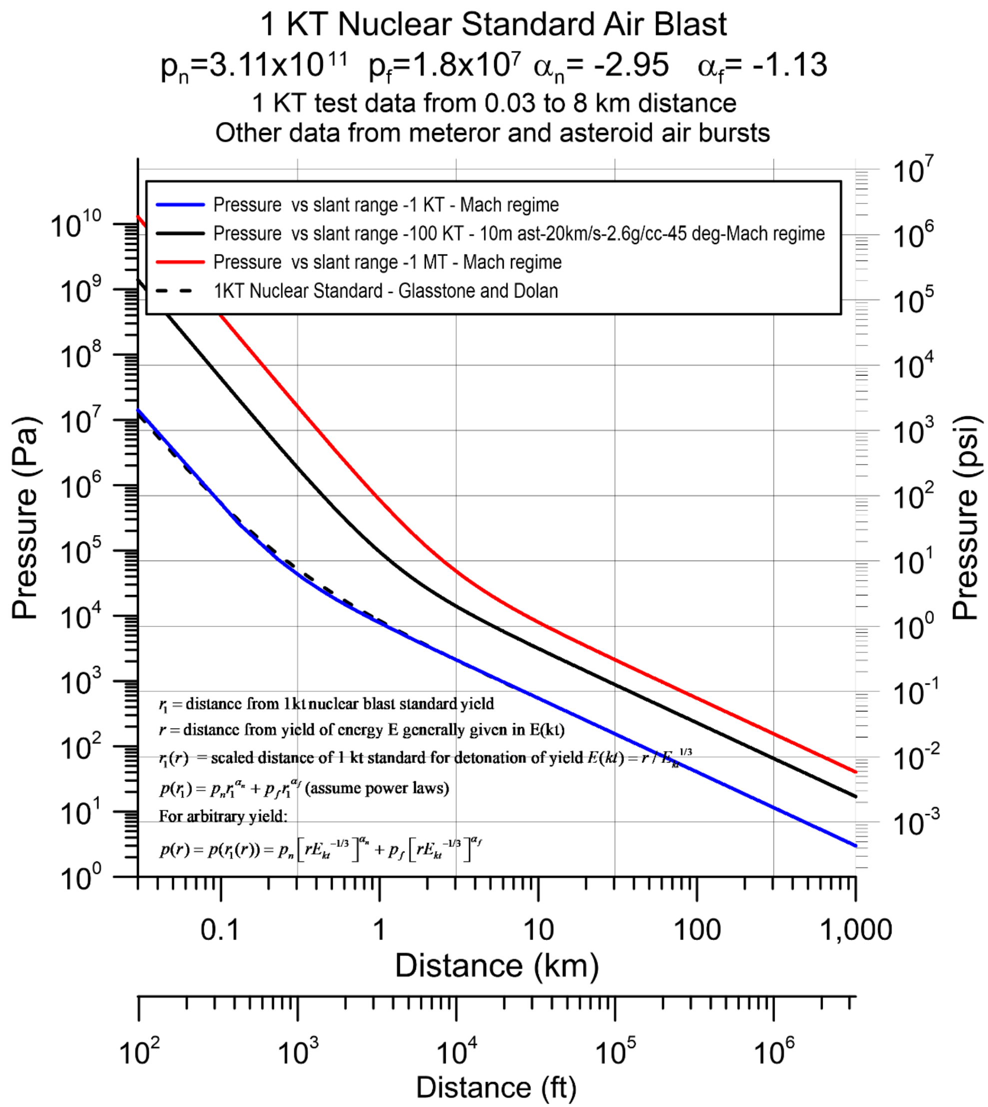
Asteroid Fragment Clouds



Individual fragment impacts are distributed over large fractions of the Earth's surface.

Blast Wave Significant but Drops Rapidly with Distance

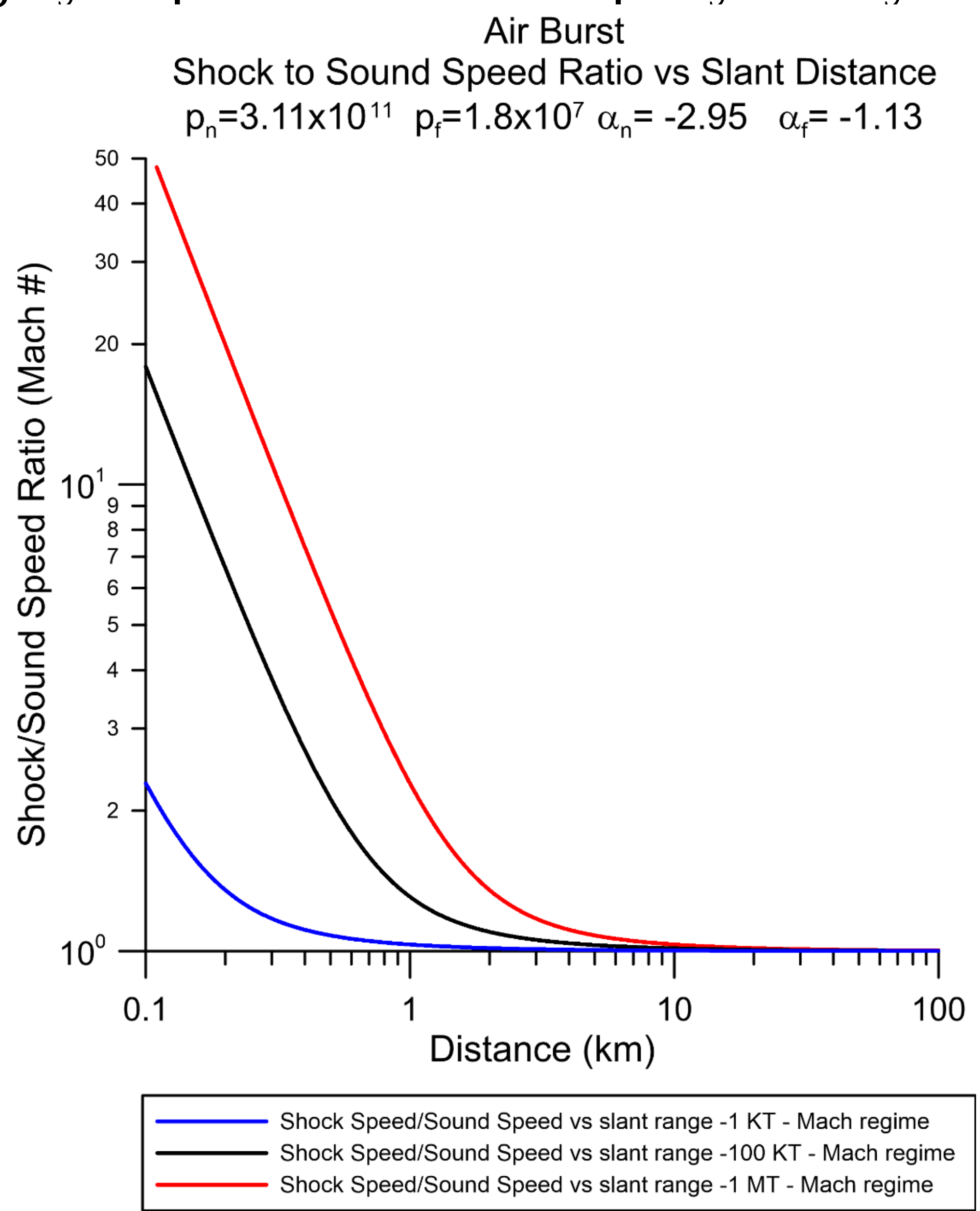
Chelyabinsk ~ 1 MT NED (at 50% NED yield to shockwave conversion)



Problem: Must Keep Blast Wave Pressure Below 1-2 kPa to avoid glass breakage

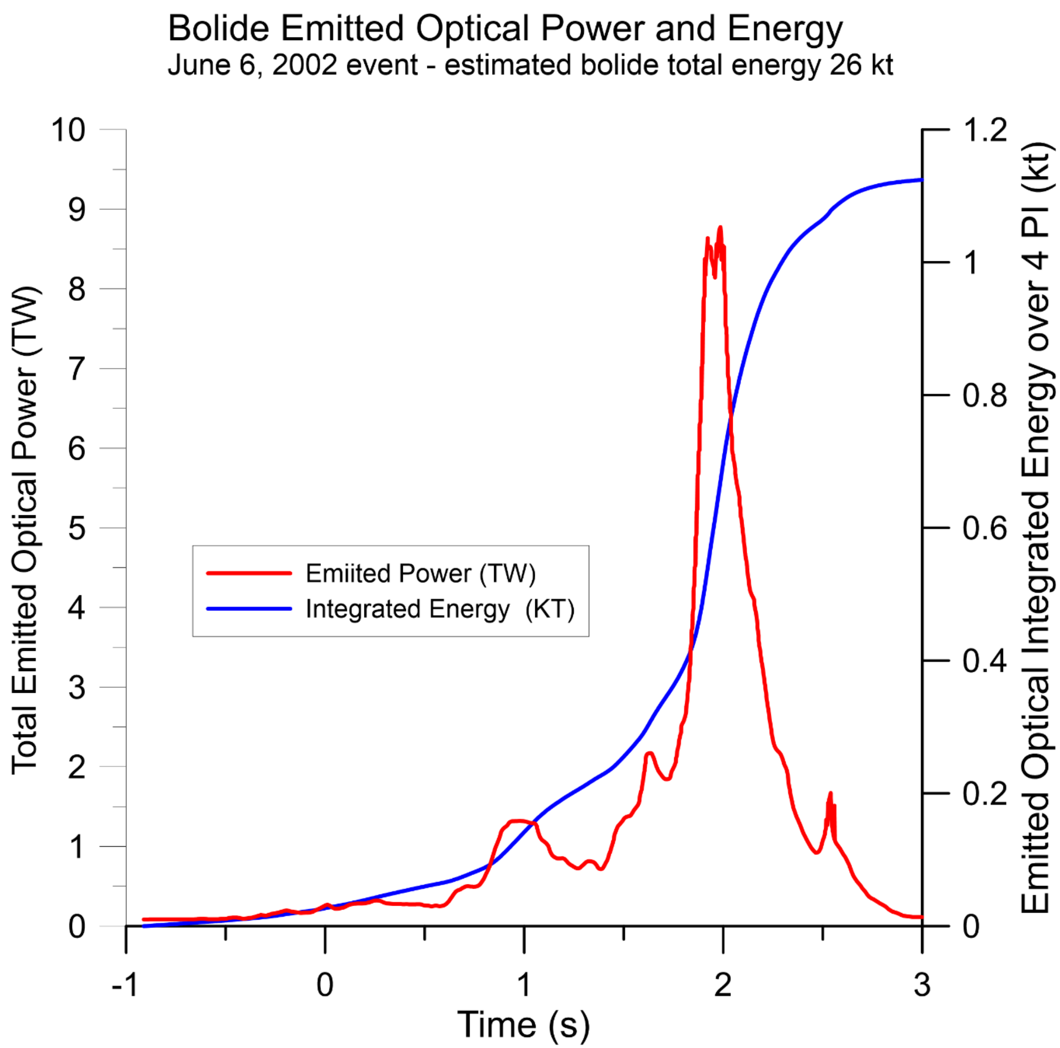
Blast Wave Speed

Shock Start Highly Supersonic Then Rapidly Decay to Near Mach 1



Measured Bolide Optical Signature

~4-15% of Blast Energy goes into Optical Pulse



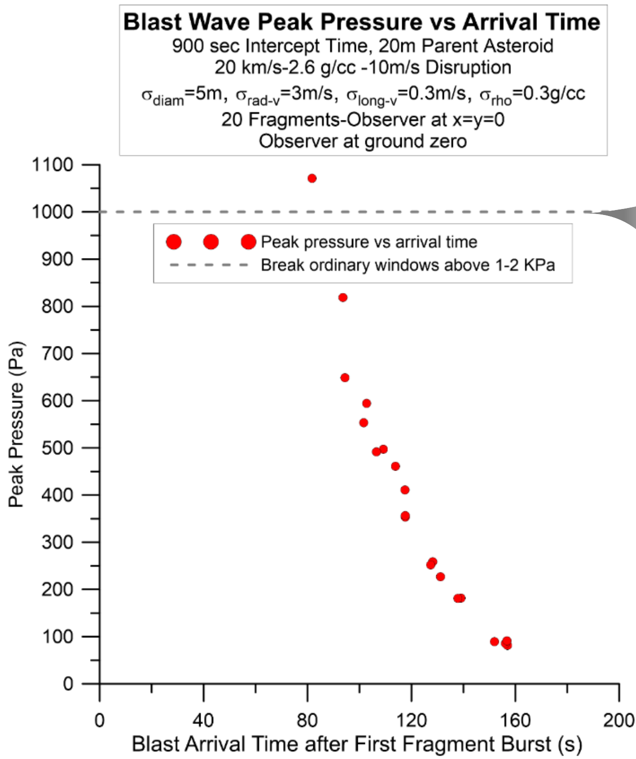
Problem: Must Keep Optical Flash Below 0.2 MJ/m^2

Acoustic Signature

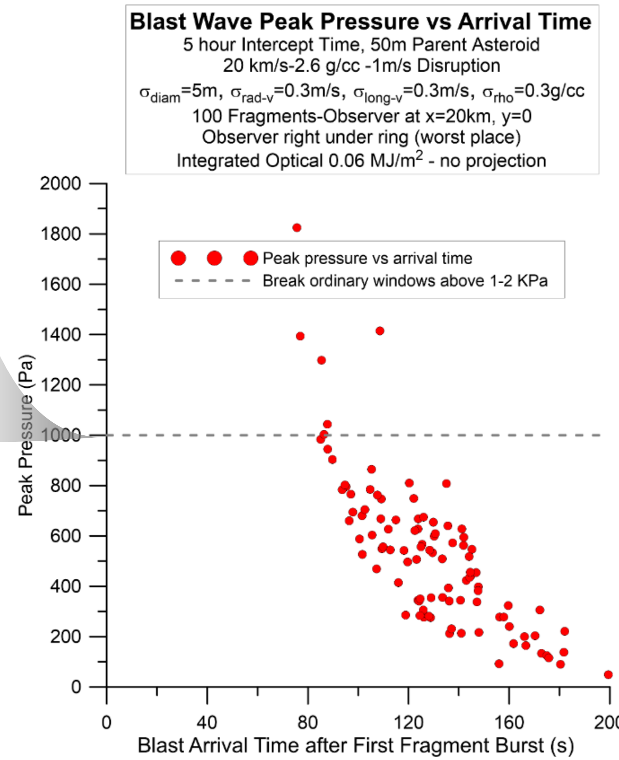
Even in extremely short-term interdiction scenarios, few fragments cause any window damage.

20m (15min@1m/s or 100s@10m/s disruption)

50m (5 hour@1m/s disruption)



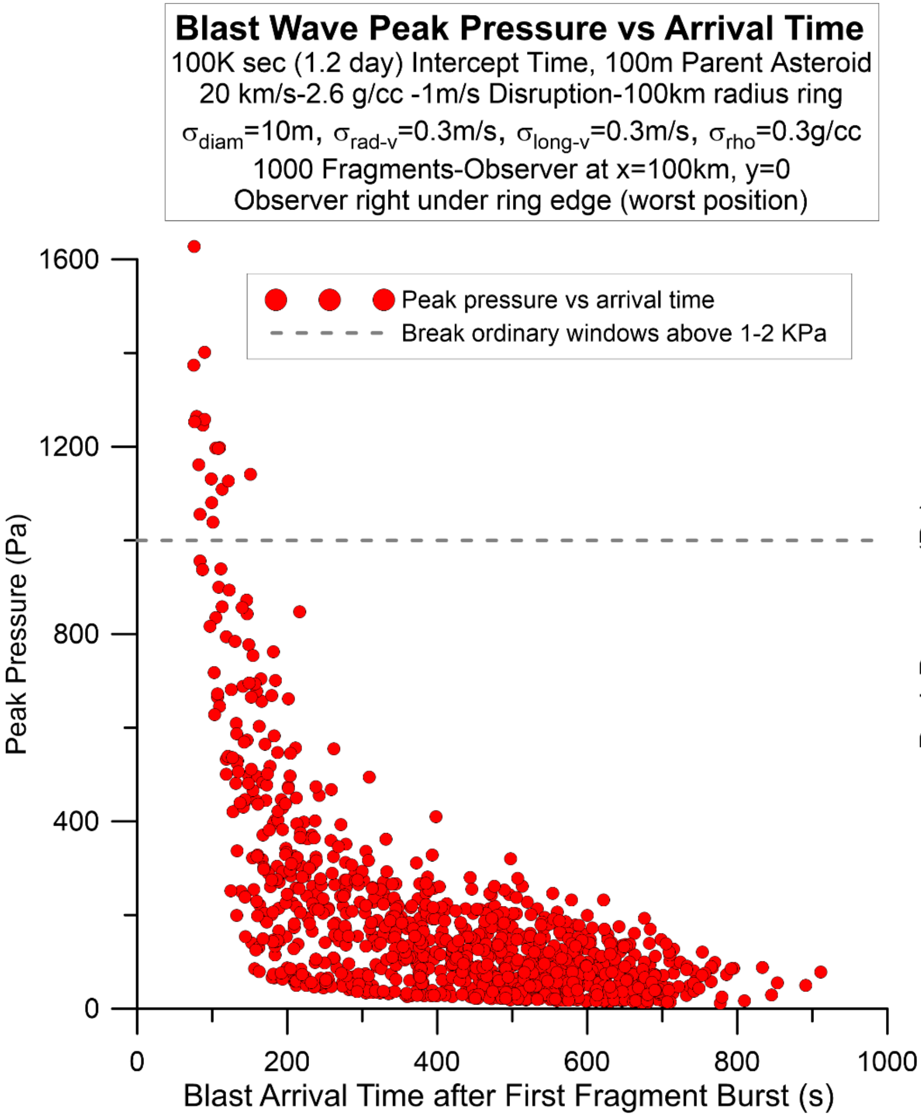
Window damage after ~20m meteor air burst over Chelyabinsk, Russia.

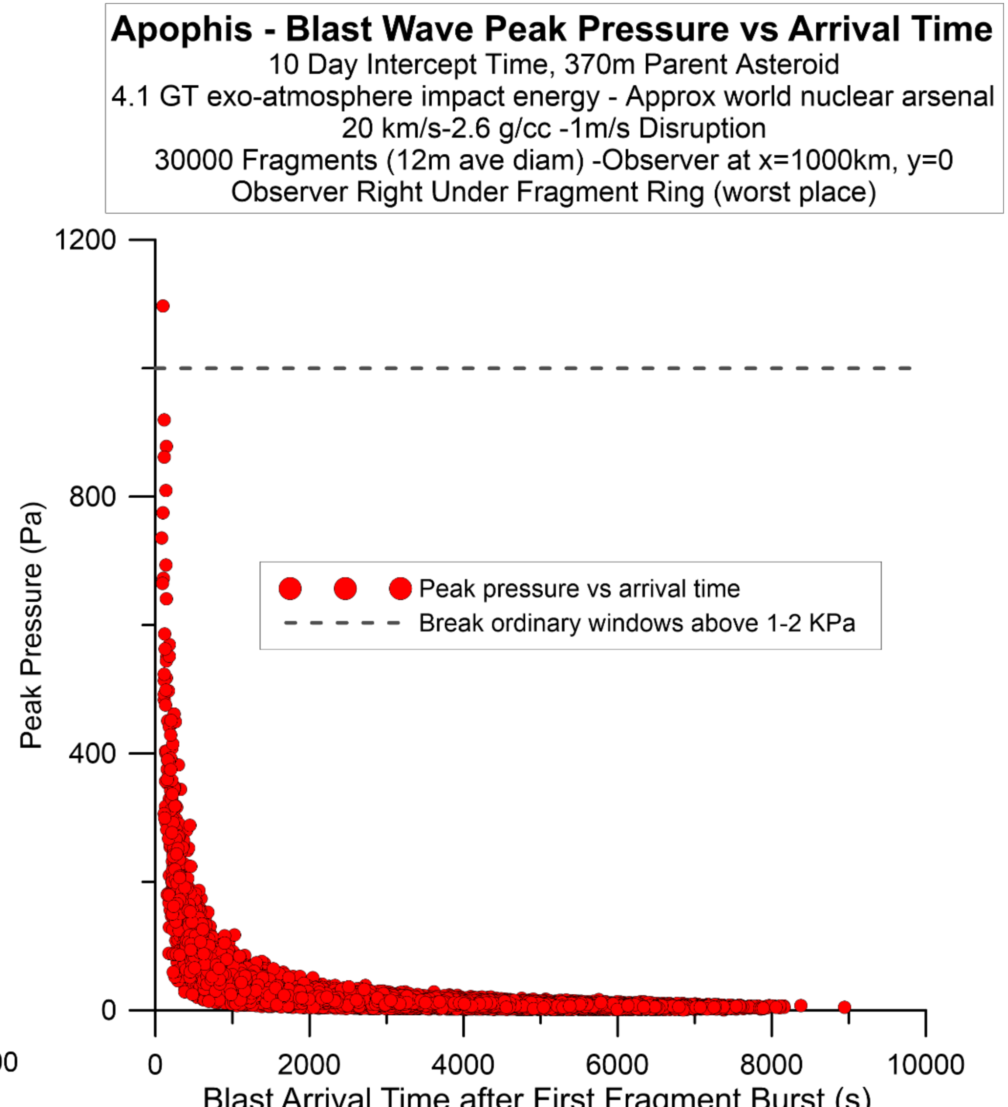


In either case, very few fragments create blast waves with pressures great enough to damage windows. Further confidence can be gained by ensuring that no fragments are larger than 10m.

Two Examples – Acoustic Signature

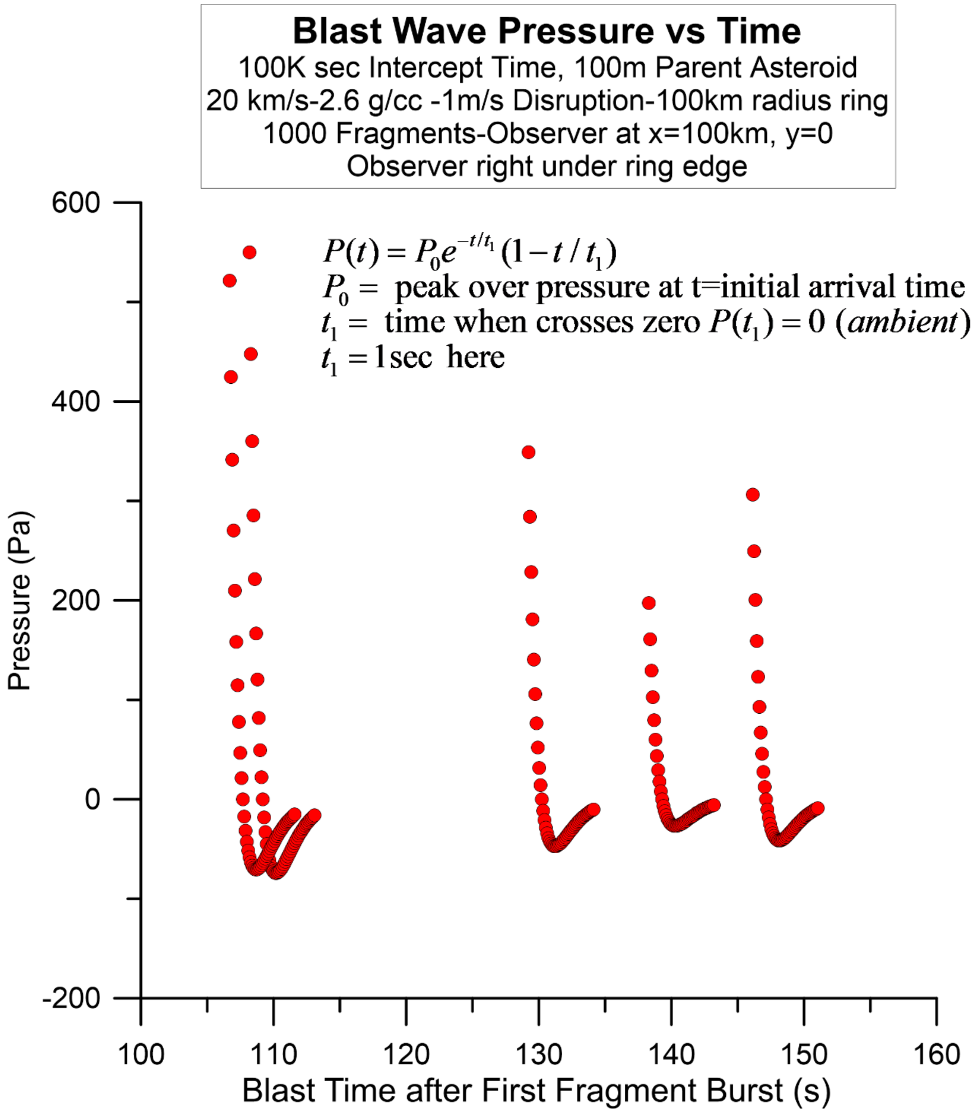
100m (1 day) and Apophis (10 day)





Blast Waves Rarely Correlate Due to Long Travel Time

100m (1 day) Blast Wave De-Correlation



Fragmentation Design so that Optical Pulse Will Not Causes Fires

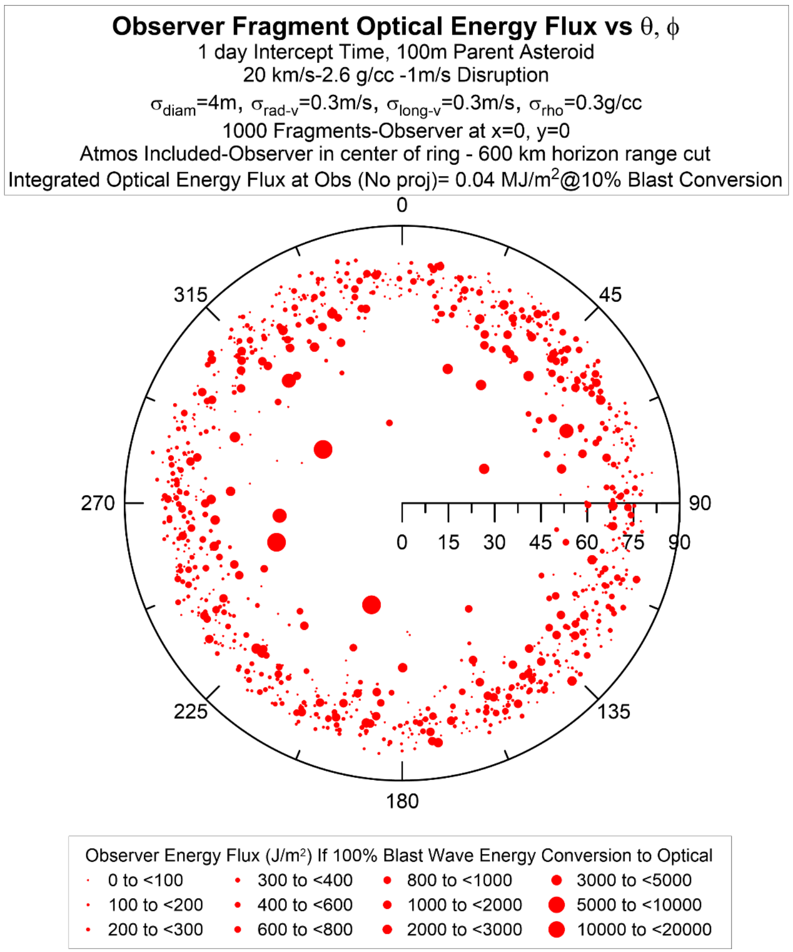
(forest, building, not even paper)

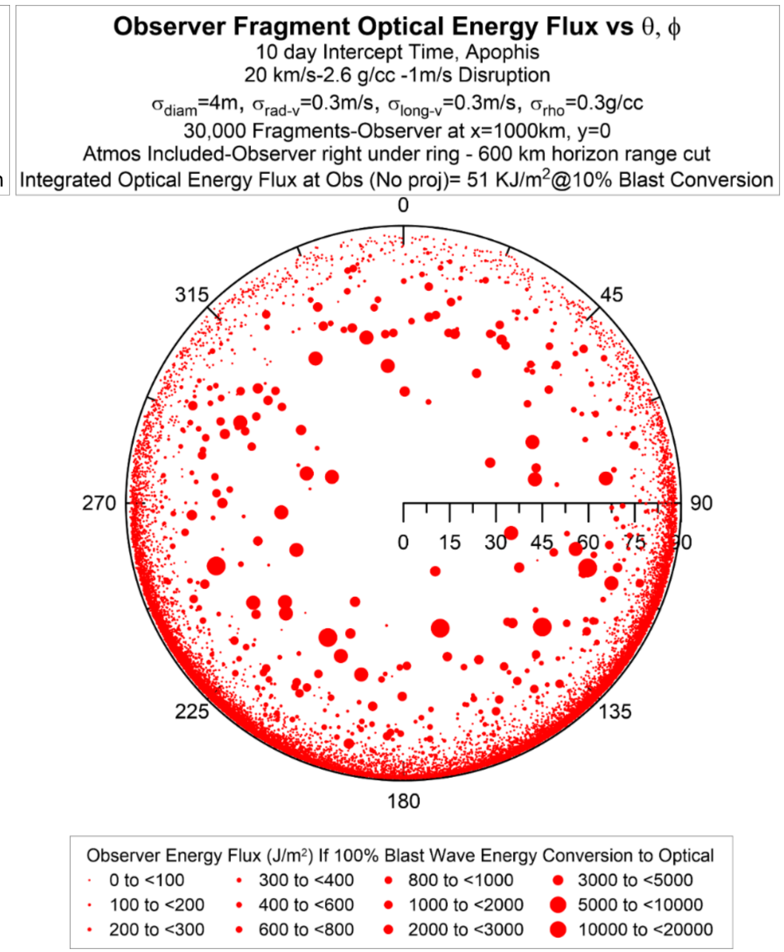
Advise to stay indoors or wear dark glasses

Optical Signature

100m (1 day) and Apophis (10 day)

Keep observer optical energy below 0.2 MJ/m^2 to avoid combustion





Dust production from air burst events

Comparison to volcanic dust production

Mt. St. Helens eruption
May 19th, 1980
Approximately 540 million metric tons of ash and dust were released into the atmosphere.

Krakatoa eruption
May 20th, 1883
Approximately 45km^3 (~100 billion metric tons at 3g/cm^3) of volcanic ash released into atmosphere.

Worst case scenario: Apophis (370m) intercept results in its entire volume, ~0.026 km^3, being converted to atmospheric dust upon air bursting. For a density of 2.6 g/cm^3, this amounts to approximately 68 million tons of material, only 0.1% the mass of material released by Krakatoa and 13% of the Mt. St. Helens eruption.

Conclusion: even in cases where the entirety of the impactor's mass is converted to atmospheric dust, the amount of dust produced by air burst events is small compared to that produced by volcanic eruptions.

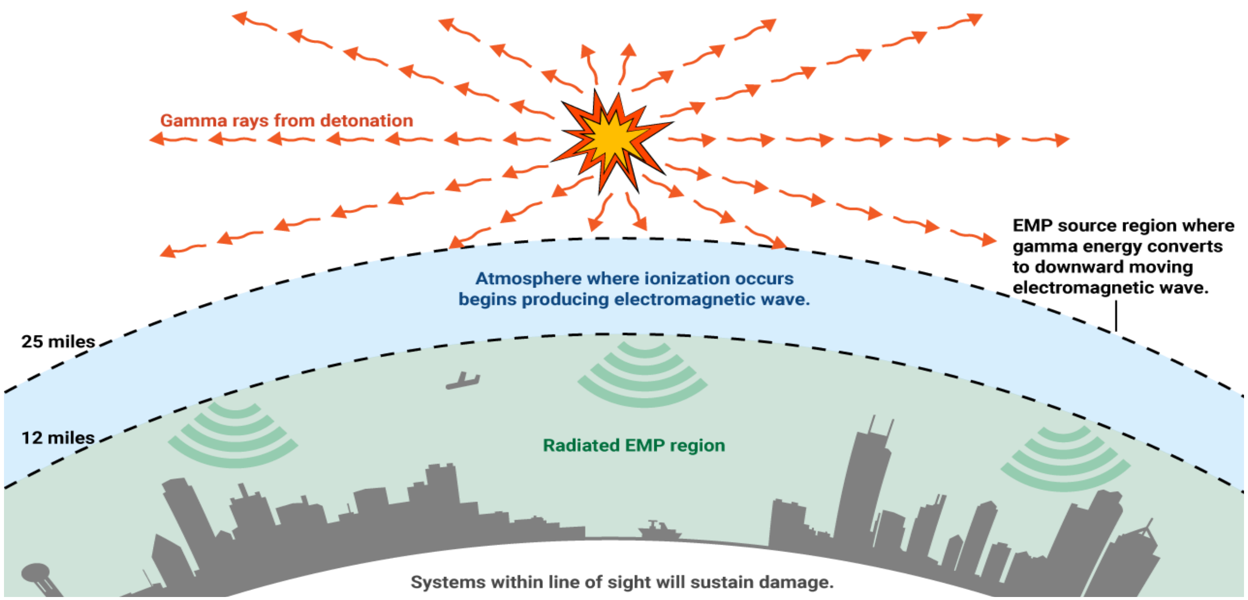
Electromagnetic Pulse (EMP)

High altitude detonation of nuclear devices are known to sometimes cause severe electromagnetic signatures known as EMP's, some of which can be strong enough to disrupt communications and power systems.

Since asteroid air bursts do not possess a radiative component (i.e. they do not produce high energy photons like a nuclear device), they will not produce "classic" EMP's as illustrated below.

However, the air around the object is ionized during atmospheric entry before the air burst, which can produce small EM effects similar to lightning. Since these effects are not coherent, unlike the case for a nuclear device.

No EMP damage is expected from fragmented bodies.



Source: Congressional Commission to Assess the Threat of Electromagnetic Pulse to the United States of America

Graphic redesign by Geopolitical Futures

Proposed Apophis Intercept Demonstration Mission (2029/2036)

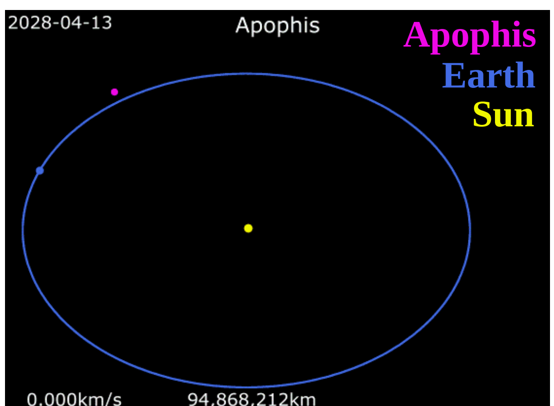
370m asteroid, avg. orbital speed 30km/s.

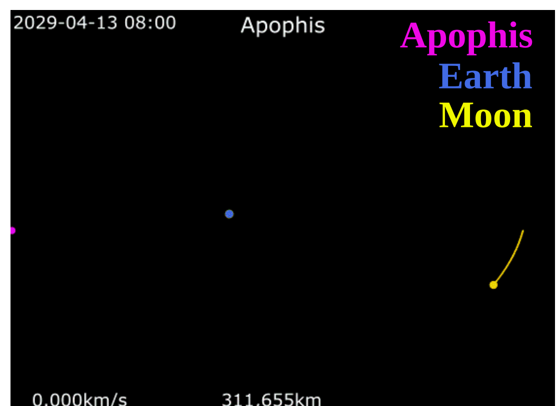
April 13th, 2029: Apophis extremely close approach, within GEO orbits.
March 27th, 2036: Apophis close approach, ~0.3AU.

Instrumented kinetic penetrator experiment (single or set of multiple penetrators) to study asteroid interior composition, inform penetrator design, and demonstrate payload delivery to desired depth.

Additional future close approaches in 2051 and 2066 offer potential opportunities to mitigate threat entirely by pro-actively destroying the asteroid.

Apophis orbit around Sun and 2029 close approach.





Apophis 2029 close approach relative to Earth-Moon plane.

https://en.wikipedia.org/wiki/99942_Apophis
Data source: HORIZONS System, JPL, NASA

Conclusions

- New mitigation approach makes planetary defense feasible
- General purpose but also allow very rapid response if needed
- No technological “show stoppers” – no miracles needed
- Synergy with current generation of launch vehicles
- Allows for a logical roadmap to a robust PD system
- Proactive vs passive approach to PD
  - Consider mitigating threats before they are a real threat (ex. Apophis)
  - Many threats come close to Earth in orbits prior to impact
- Synergy with long range asteroid detection
- Options for lunar operations, intercept+detection (IR, LIDAR)
- Options for LEO, MEO, GEO deployment
- Long term program with long term consequences