Asteroid Deflection via Standoff Nuclear Explosions

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Qualifications and disclaimers

- Subject of this presentation is using nuclear explosives for asteroid deflection

- Most of the work was performed together with a summer student in 2005 (JC Sanders - then a senior in the Oregon State U. Physics Department, now a graduate student at UT Austin)

- This is a technical talk and does not reflect policy of DOE, NNSA, or anyone else

- LLNL does not have an asteroid deflection program

- I am not advocating nuclear explosives development or deployment in anticipation of possible future deflection requirements

- I am not advocating deflection capability as a motivation for maintaining or expanding the US nuclear weapons stockpile

The Threat: The Earth has and will suffer collisions with large Near-Earth Objects (NEO's)

www.thedayofthelordisathand.com/asteroid2.jpg

- **Estimated NEO population 960±120 objects of d>1km and 24500±3000 objects of d > 100m**

- **723 classified by Near-Earth object Program as "Potentially Hazardous Asteroids" (Earth Minimum Orbit Intersection Distance MOID < 0.05AU and d > ~150m) Y ~ 10^5 GT**

Impact energies can be huge: Expect blast, fires, earthquakes, tsunamis, solar light extinction, etc…

Impact energy: $Y_{MT} = 50 \rho_{g/cc} R_{100m}{}^{3} v_{10km/s}{}^{2}$

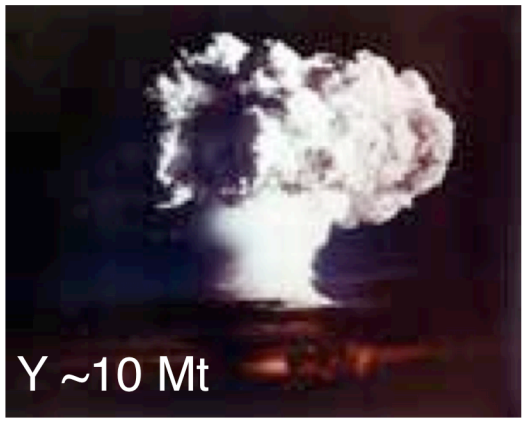


Photo courtesy of National Nuclear Security Administration / Nevada Site Office

Impactor Diameter (m)	Yield (MT)	Interval (yr)	Consequences
<50	<10	< 1	Meteors in upper atmosphere most don't reach surface
75	10-10^2	1000	Irons make craters like Meteor Crater; stones produce airbursts like Tunguska; land impacts destroy area size of city
160	10^2-10^3	5000	Irons,stones hit ground; comets produce airbursts; land impacts destroy area size of large urban area (New York, Tokyo)
350	10^3-10^4	15,000	Land impacts destroy area size of small state; ocean impact produces mild tsunamis
700	10^4-10^5	63,000	Land impacts destroy area size of moderate state (Virginia); ocean impact makes big tsunamis
1700	10^5-10^6	250,000	Land impact raises dust with global implication; destroys area size of large state (California, France)

'The Impact Hazard', Morrison, Chapman and Slovic, *Hazards due to Comets and Asteroids* http://seds.lpl.arizona.edu/nineplanets/nineplanets/meteorites.html

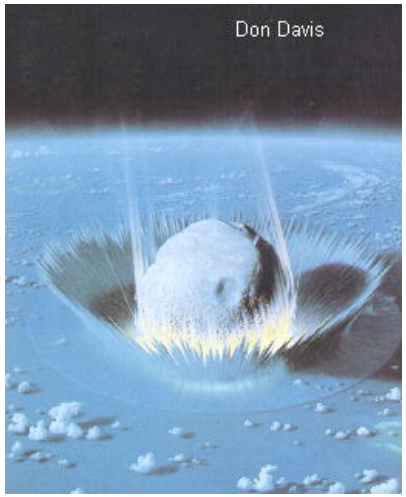
Past NEO-Earth impacts have resulted in devastating local and global effects

http://www.meteorite.com/meteor_crater/index.htm

- Barringer crater: 50,000BC
- Nickel-Iron d ~ 50m
- Y ~ 20-40 MT
- Fireball to ~ 10 km
- Hurricane-force winds to ~ 40 km

http://en.wikipedia.org/wiki/Tunguska_event

- Tunguska event: 1908
- Stony d ~ 60m
- Airburst @ 6-10km
- Y ~ 10-15MT,
- Leveled 2150 km^2 of forest



- KT impactor
- d ~ 10 km
- Y ~ 10^5 GT
- 145-180km crater
- Mass extinctions?

Several mitigation schemes have been proposed

Continuous momentum transfer

- Chemical rockets
- Ion propulsion
- Mass drivers
- Mirrors
- White paint

Impulsive momentum transfer

- Conventional explosives
- Kinetic impact
- Pulsed laser or particle beam
- Nuclear explosives

Most deflection schemes require very long lead times for global-catastrophe-scale NEO's

Required deflection velocity vs. lead time with impulsive momentum transfer

Time to impact	Required $\Delta V(cm/s) \sim R_{\oplus}/t$
month	~ 100
year	~ 10
decade	~ 1
century	~ 0.1
millennium	~ 0.01

For lead times on the order of years or decades, only nuclear explosives can realistically avert collisions with kilometer-scale NEO's

*Chemical propellant/explosive: $\Delta V_{cm/s} \sim \frac{1}{10^4} \frac{m_{tons}}{(2R_{km})^3}$

*Ion drive: $\Delta V_{cm/s} \sim \frac{1}{10^2} \frac{m_{tons}}{(2R_{km})^3}$

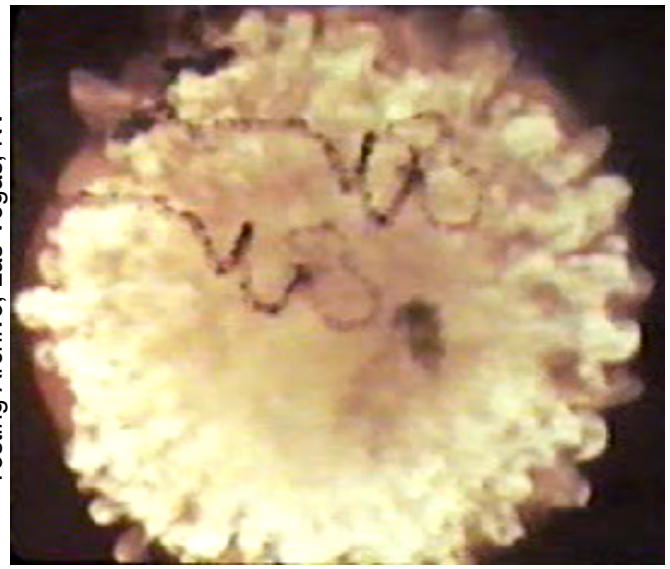
Kinetic: $\Delta V_{cm/s} \sim \frac{1}{10^3} \frac{m_{tons}}{(2R_{km})^3}$

*NIF (2r=1km,ΔV=1cm/s): ~ 10^3 yrs @ 4 shots/day or ~ month @ 1Hz

Standoff nuclear explosive device (NED): $\Delta V_{cm/s} \sim \frac{\sqrt{Y_{MT}}}{R_{km}^{\ 2}}$

*Dave Dearborn, UCRL-PROC-202922

The nuclear option: Deflection vs. destruction



U.S. Department of Energy Nuclear Testing Archive, Las Vegas, NV

Destruction

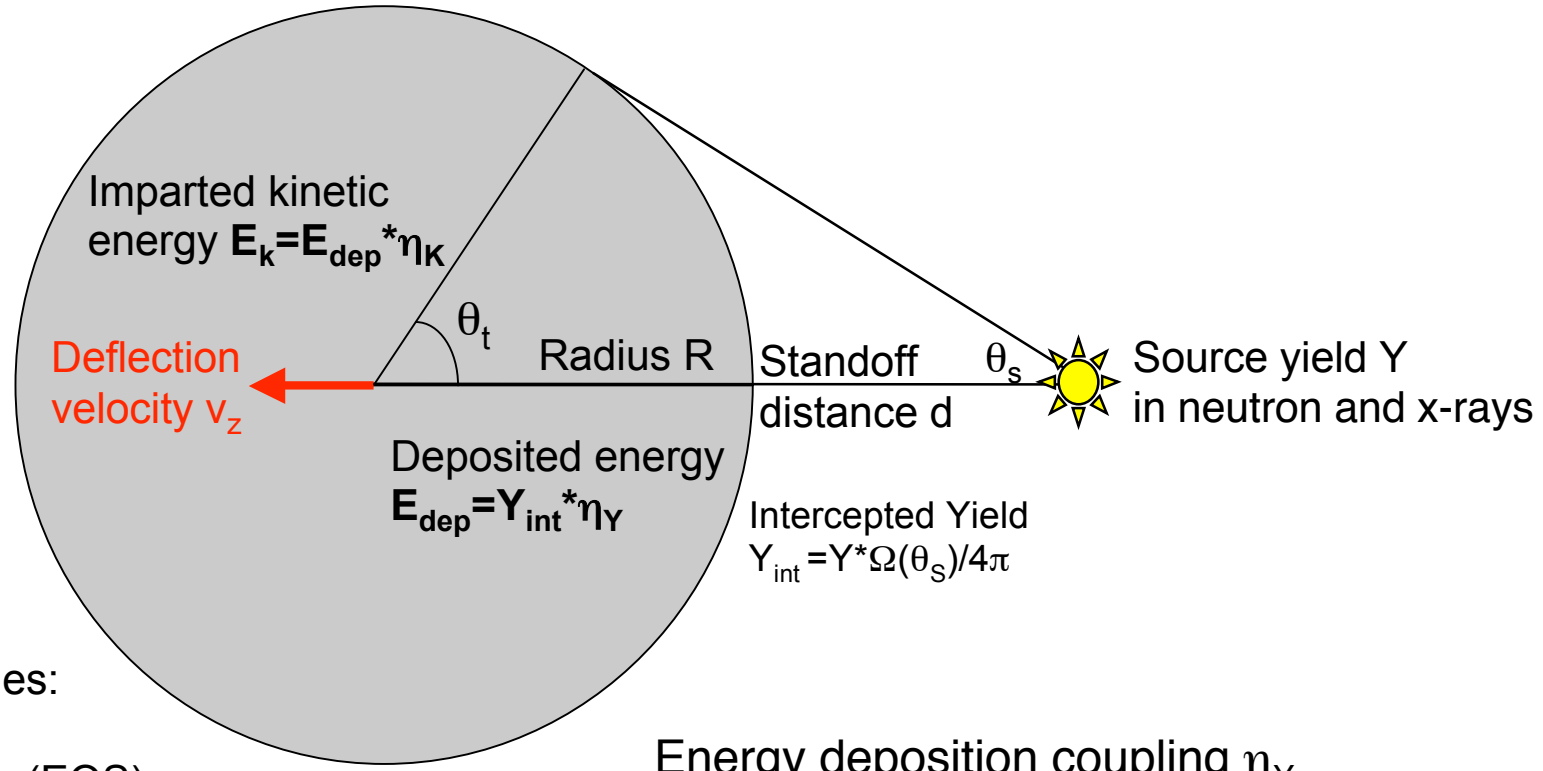
- Standoff, surface, and subsurface options
- Deeply buried detonation gives maximum source yield coupling efficiency (~1)
- Must ensure that no large (> ~10 meters) fragments survive
- Likely requires detailed knowledge of material properties or very conservative yield estimates
- Effective for smaller targets (~ 10^2 meters)
- For details, see T.J. Ahrens & A.W. Harris, Nature 360, 429 (1992).

Deflection

- Requires standoff detonation
- Requires knowledge of output energy coupling
- Less sensitive to material properties?
- Best option for larger targets (> a few x 10^2 meters)

Deflection of idealized NEO by standoff nuclear detonation: Parameters and method

Kinetic energy coupling η_K obtained from radiation hydrodynamics code Cale



Material properties:
Density (ρ)
Equation of state (EOS)
Strength model
Failure model

Energy deposition coupling η_Y obtained from Monte Carlo transport code TART

Simple analytic model

- Momentum and energy conservation:

  $MdV = (dm)v$

  $\beta dE_{dep} = MdV^2 + (dm)v^2$

- Consider only the z-component of momentum due to axial symmetry:

  $dp_z = dp\cos\theta$

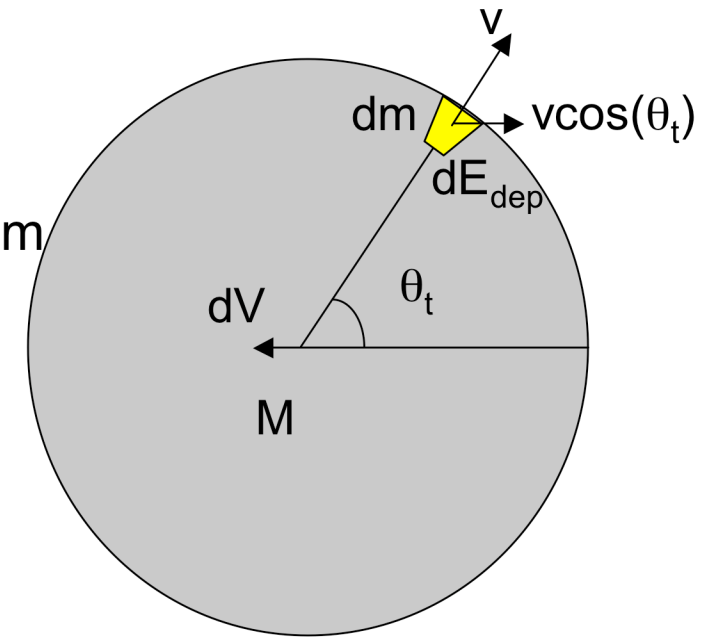
$$p_z = 2\pi\sqrt{\beta\rho}\iint\sqrt{\varepsilon_{dep}(r,\theta)}r^2\sin\theta\cos\theta dr d\theta$$

- Assume a solution for the deposited energy density:

$$\varepsilon_{dep}(r,\theta) = \varepsilon_0 e^{-\frac{R-r}{\lambda_{eff}}}\cos\left(\frac{\pi}{2}\frac{\theta}{\theta_t}\right)$$

- The solution for the momentum thus becomes:

$$p_z = R\sqrt{\rho\lambda_{eff}\beta E_{dep}} \times f(\theta_t) = R\sqrt{\rho\lambda_{eff}\beta\eta_Y Y} \times g(\theta_t)$$



Simple analytic model

The function $f(\theta_t)$ has the form:

$$f(\theta_t) = \sqrt{\pi \frac{1-(\theta_t/\pi)^2}{1-2(\theta_t/\pi)^2-\cos(\theta_t)}} \frac{1-(\pi/4\theta_t)\sin(2\theta_t)}{1-(4\theta_t/\pi)^2}$$

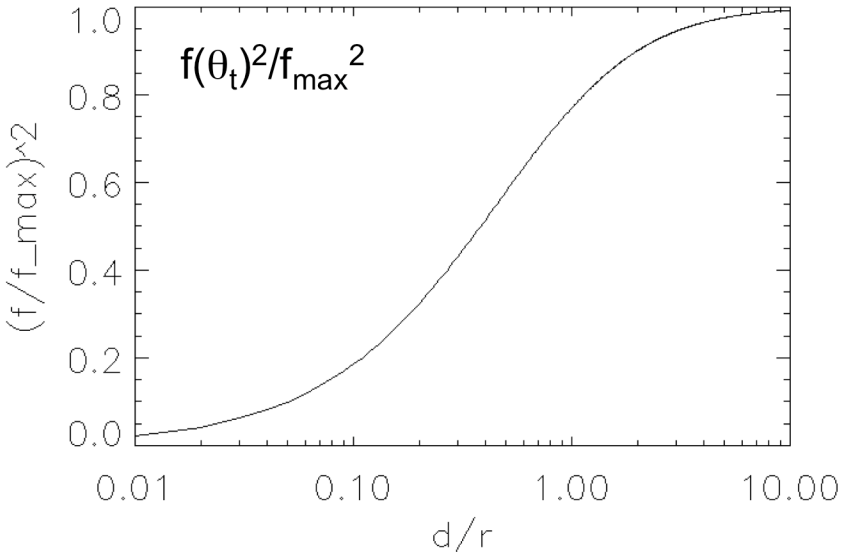
Predicted KE coupling parameter

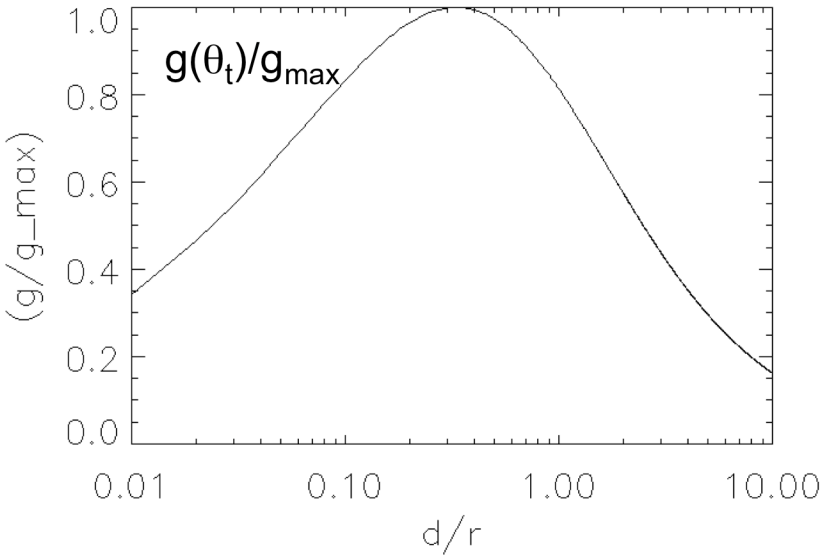
$$\eta_K = \frac{\beta\lambda_{eff}}{R}\left(\frac{f(\theta_t)}{f_\infty}\right)^2$$

Predicted deflection velocity

$$v_{z(cm/s)} = \frac{9.88}{R^2_{(km)}}\sqrt{\lambda_{eff(cm)}\beta\eta_Y Y_{MT}/\rho_{g/cc}}\,\frac{g(\theta_t)}{g_{\max}}$$

$\Rightarrow$ Optimal standoff distance d/R = 0.33





Relationship between the model parameters η_K and β

- β tells how much of the deposited energy goes into kinetic energy in either direction

$$\beta E_{dep} = 2(E_K + e_K)$$

- η_K tells how much of the deposited energy goes into deflection kinetic energy

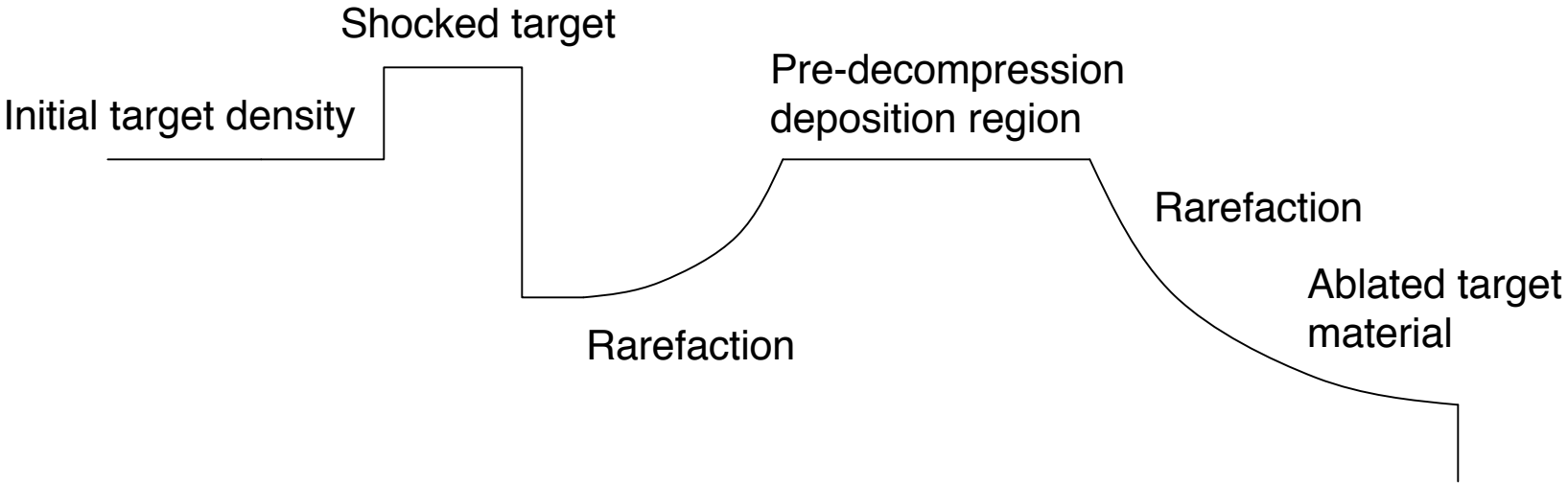
$$\eta_K E_{dep} = E_K$$

- The two are related by the ratio of directional kinetic energies

$$\beta/2\eta = 1 + e_K / E_K \sim 1 + M/m \sim M/m \sim R/\lambda_{eff}$$

- Geometry determines the proportionality constant: $\eta_K = \frac{\beta \lambda_{eff}}{r} \left(\frac{f(\theta_t)}{f_\infty} \right)^2$

Parameter β can be calculated within a shock tube model

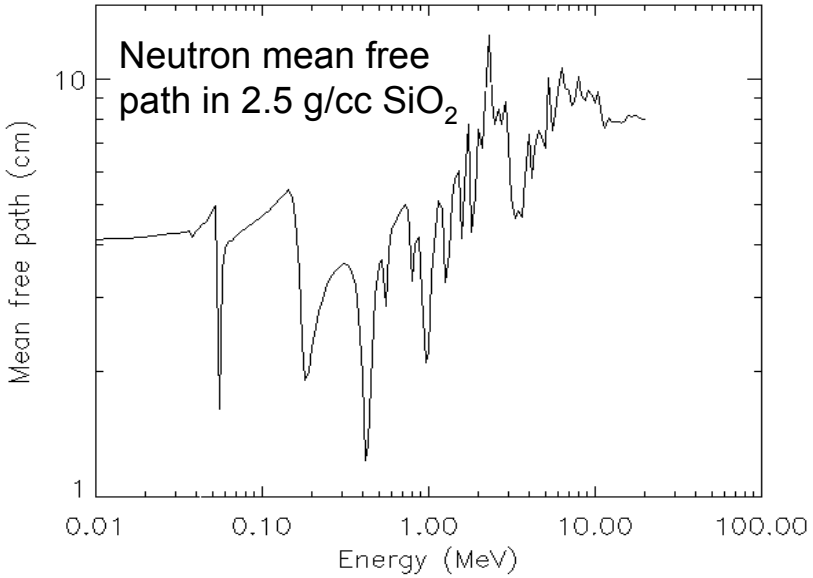


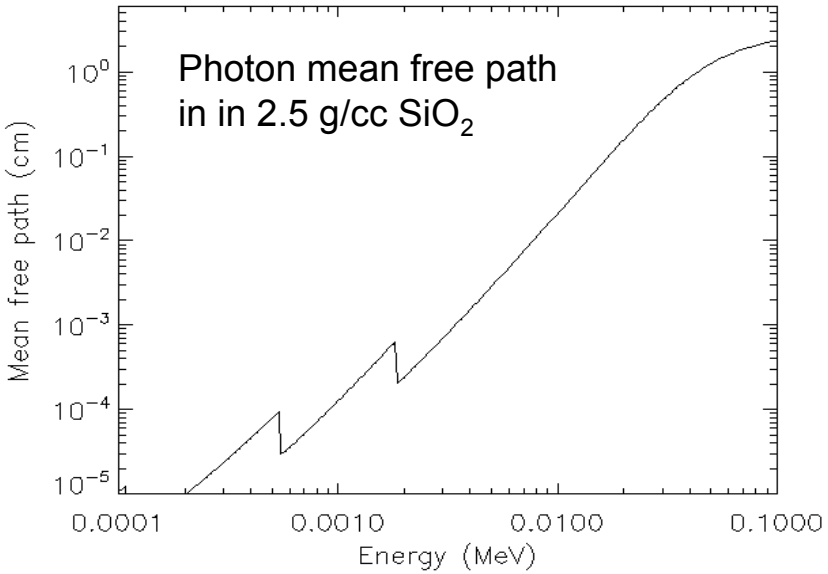
- Ideal gas approximation

- Shock tube model predicts $\beta = 0.0395\ \alpha/\gamma$
  - γ is the adiabatic index
  - $\alpha \equiv 1-(Q-P_0)/\varepsilon_{dep}$ is accounts for energy expended in melting, vaporizing, ionizing material in the deposition region

The yield coupling η_γ is obtained from TART simulations

- LLNL Monte Carlo Radiation Transport Code
- Uses [1]ENDF/B-VI Release 8 neutron cross-sections and [2]ENDL97 photon cross-sections
- Used spherical target geometry with 1, 300, and 72000 zones; typically used target radius R=500m and a standoff distance of d=0.002R-5R
- Used 5 different target materials: SiO_2, Fe, FeNi, Granite, and H_2O
- Typically used 2.5e5 particles x 40 batches = 1e7 neutrons or 1e6 particles x 100 batches = 1e8 photons





[1]UCRL-ID-127776, [2]UCRL-ID-50400

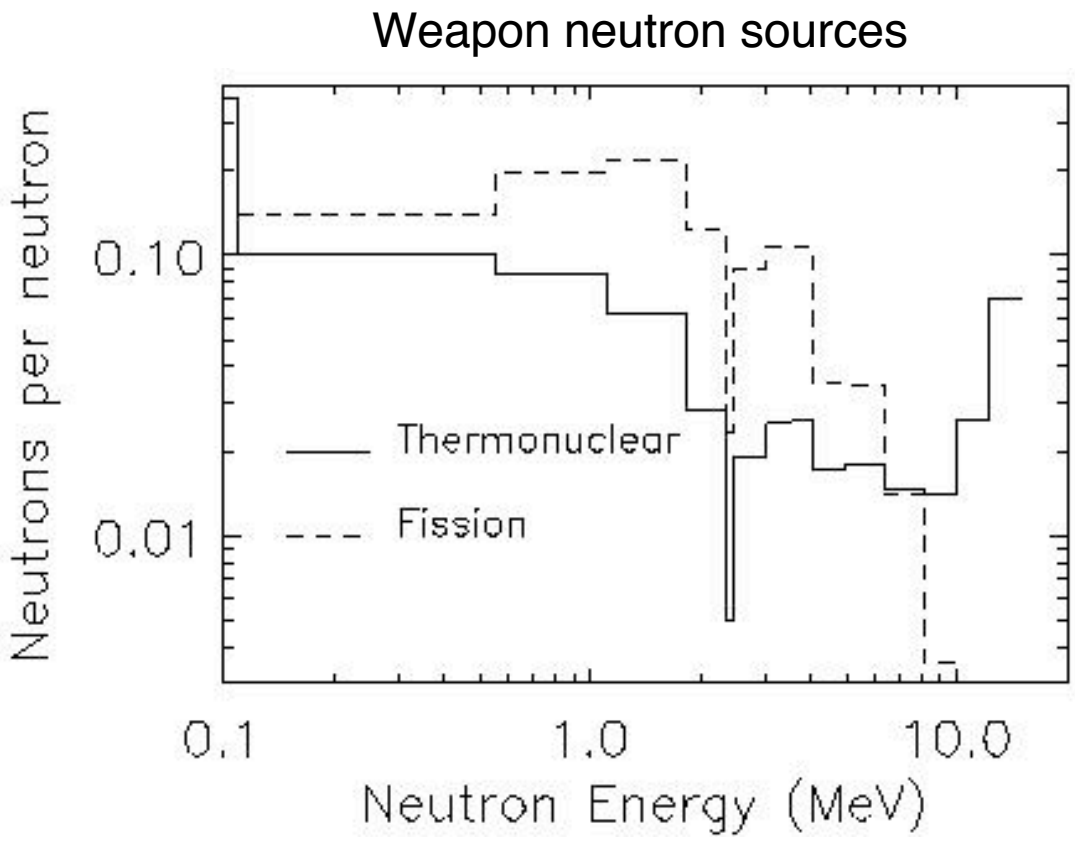
Several different sources were used in TART simulations

Neutron source spectra

- **Fission**
- **14.1 MeV monoenergetic**
- **Fission weapon***
- **Fusion weapon***

Photon source spectra

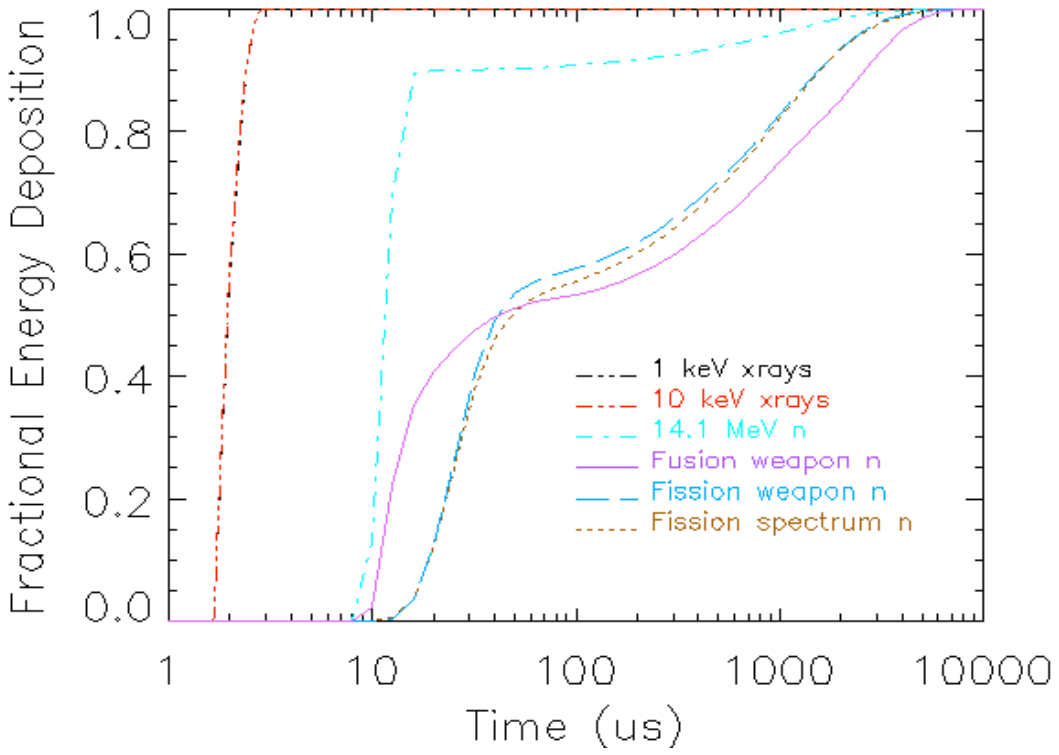
- **1 keV blackbody**
- **10 keV blackbody**



*E.A. Straker and M.L. Gritzner, "Neutron and Secondary Gamma-Ray Transport in Infinite Homogeneous Air", ORNL4464, 1969.

Time-dependence of the energy deposition

Energy deposition in SiO2 for various sources

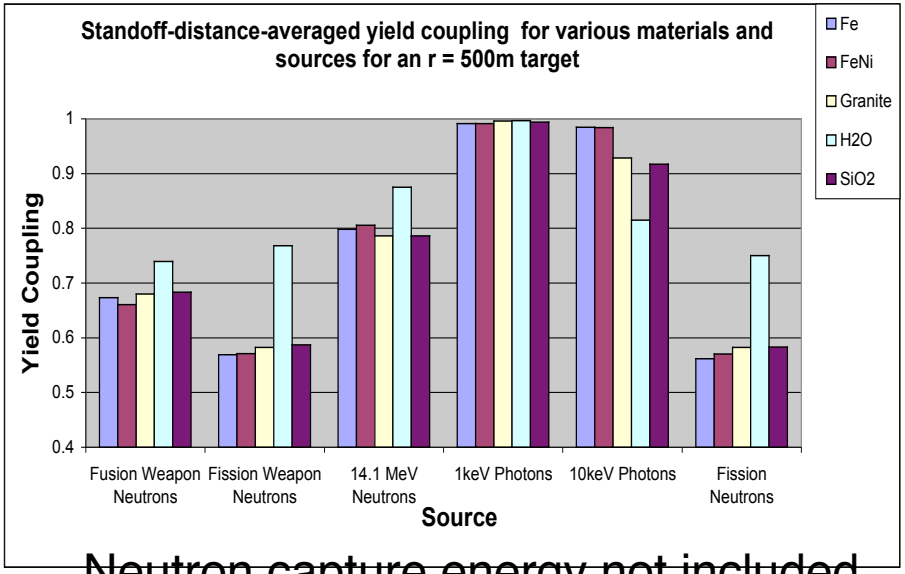


- **Photon deposition time is significantly faster than neutron deposition times**

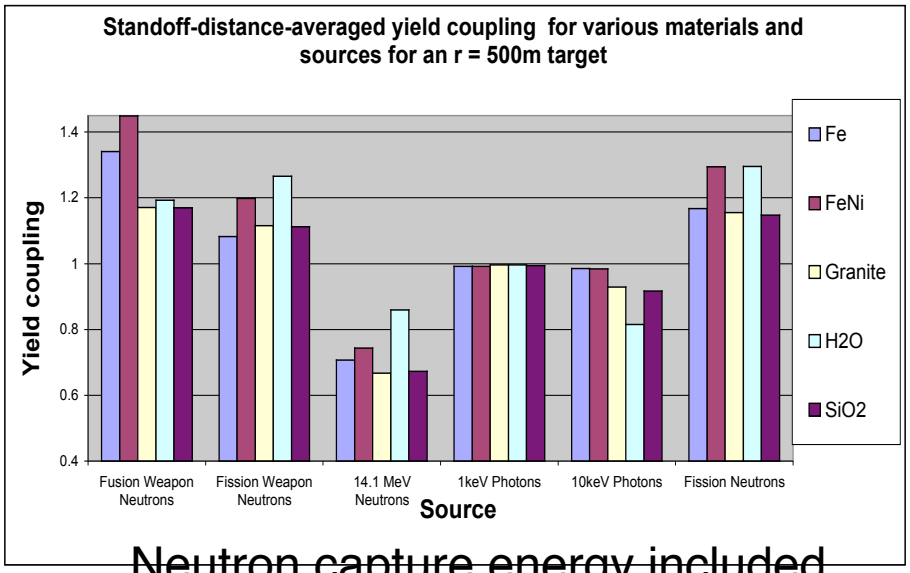
- **Neutron deposition includes early time KE deposition and late-time capture energy deposition**

Yield coupling parameter η_Y

Coupling η_Y of various spectra of photons and neutrons for five materials commonly found in asteroids and comets



Neutron capture energy not included



Neutron capture energy included

- **High energy neutrons couple better than low energy neutrons when capture energy is neglected due to increased penetration**
- **Low energy neutrons couple better than high energy neutrons when capture energy is included because capture energy is proportionally greater at low initial energies**
- **X-ray yield coupling is nearly unity for all materials at 1 keV and greater than 0.8 at 10 keV**

TART results are input into the model to give comparative predictions of deflection efficiency

The model predicts that the product $\lambda_{eff}\eta_Y$ determines the kinetic energy coupling:

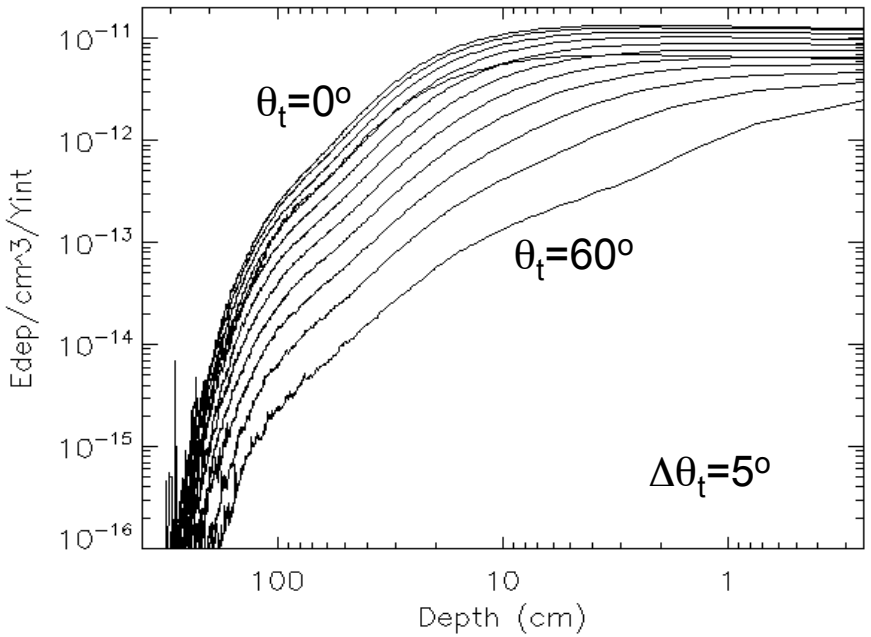
$$v_{z(cm/s)} = \frac{9.88}{R^2_{(km)}}\sqrt{\beta\lambda_{eff(cm)}\eta_Y Y_{(MT)}/\rho_{(g/cc)}}\,\frac{g(\theta_t)}{g_{\max}}$$

2.5 g/cc SiO_2 at r = 500 m, d = r			Capture energy not included		Capture energy included
Source	λ_{mfp}(cm)	η_{Y0}	$(\eta_{Y0}\,\lambda_{mfp}/\rho)^{1/2}$	η_Y	$(\eta_Y\,\lambda_{mfp}/\rho)^{1/2}$
1keV Photons	1.00E-04	0.99	0.00629	0.99	0.00629
10 keV Photons	1.80E-02	0.92	0.0814	0.92	0.0814
1.5 MeV Neutrons	5.0	0.23	0.678	1.32	1.62
2 MeV Neutrons	5.7	0.29	0.813	1.26	1.69
14.1 MeV Neutrons	6.6	0.78	1.43	0.67	1.33

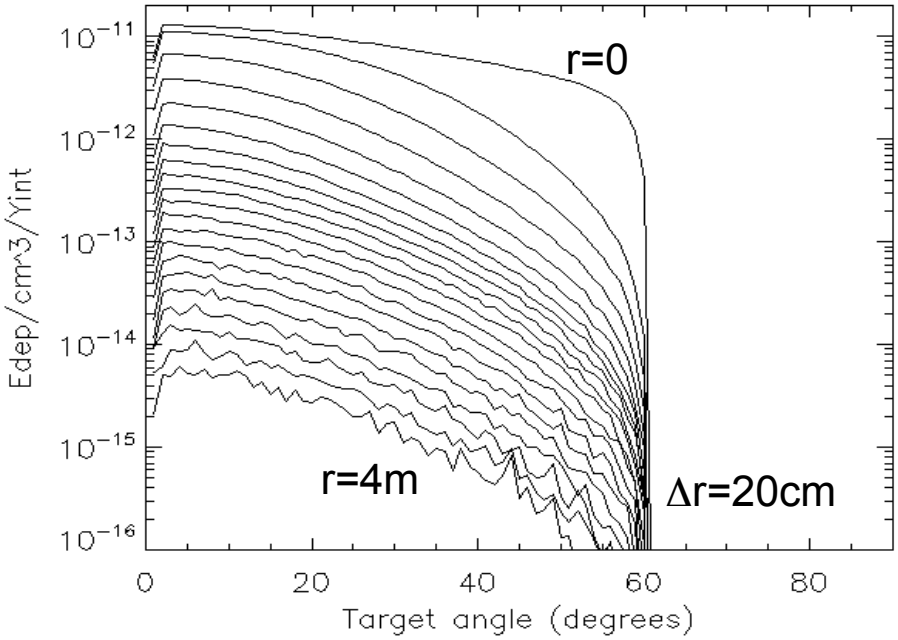
- Higher energy photons are more efficient than lower energy photons
- Neutrons are only ~10-20 times more effective than the 10 keV blackbody
- For neutrons, higher energy particles are more efficient if capture energy is neglected. The reverse is true if capture energy is included.
- It is important to determine if late-time capture energy contributes to target deflection

TART provides spatially dependent energy deposition for interpolation onto hydro mesh

Energy deposition as a function of penetration depth for 14.1MeV monoenergetic neutrons



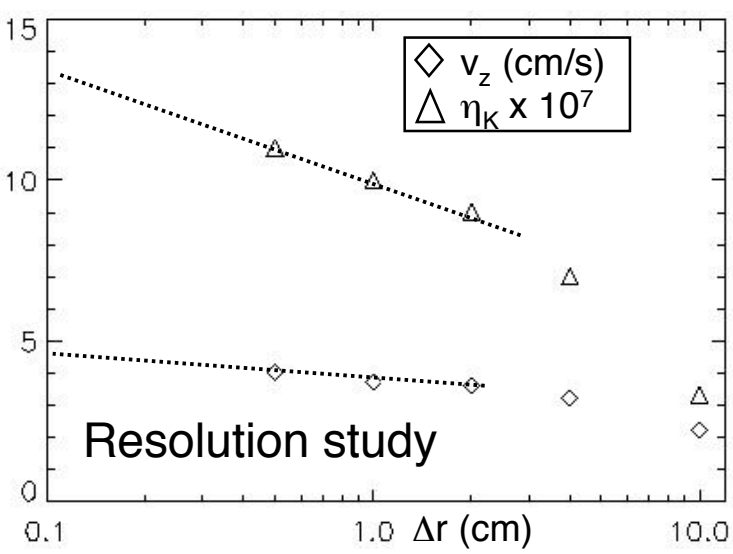
Energy deposition as a function of solid angle for 14.1MeV monoenergetic neutrons

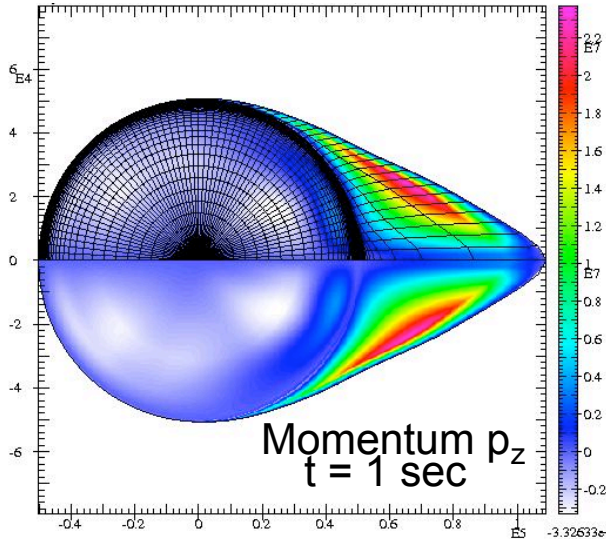


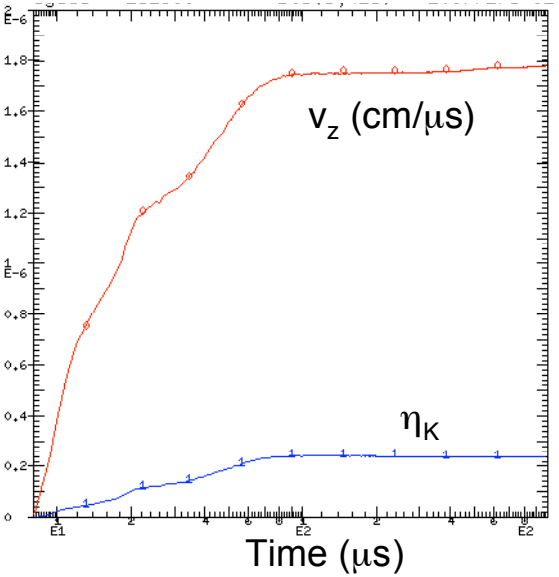
Deposition region depth chosen so that energy deposition falls off by 4 orders of magnitude through the deposition layer; typically 2-4 m for neutrons, 10 cm for 10 keV photons, and 0.6 mm for the 1 keV photons.

The kinetic energy coupling η_K is obtained from Cale simulations

- LLNL radiation hydrodynamics Arbitrary Langrangian-Eulerian (ALE) code
- Uses finite differencing to solve the Euler equations
- TART energy deposition output is interpolated and sourced into the Cale mesh







- Zoning study shows slow logarithmic divergence of v_z with decreasing radial resolution Δr in the deposition region.
- At Δr = 0.5 cm, there are 13.2 zones per 14.1 MeV neutron mean free path.

- 2.5 g/cc SiO_2 asteroid
- 14.1 MeV neutron source
- Y = 5 MT
- Stand-off distance d = r = 500m

Kinetic energy coupling vs. source and material

14.1 MeV neutron source @ Y = 5 MT

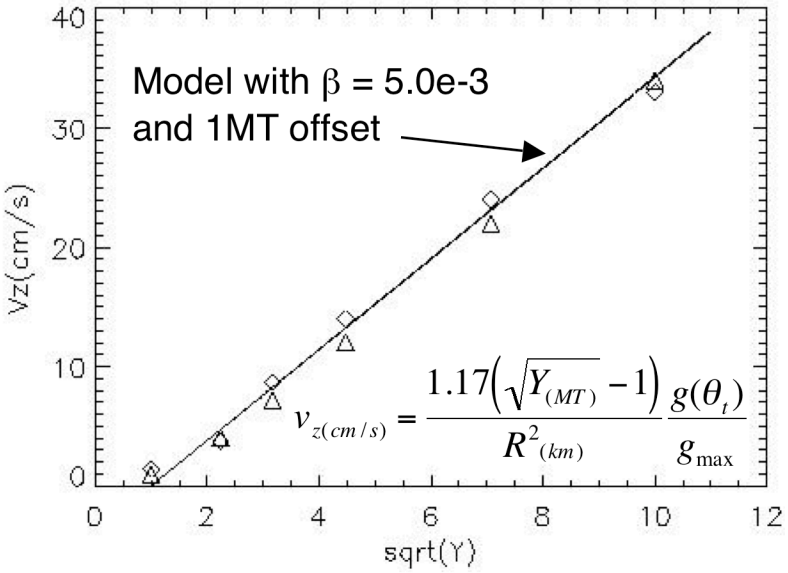
Material	EOS	Strength model	Failure model	η_K	β	v_z(cm/s)
H2O	Two-phase	Const. strength+melt	None	2.7E-05	8.8E-02	25
SiO2	QEOS	Tabular U vs P	None	5.9E-06	1.5E-02	9.2
SiO2	QEOS	Tabular U vs P	Brittle	3.4E-07	8.7E-04	2.2
Fe	QEOS	Steinberg-Guinan	Ductile	1.2E-06	9.3E-03	2.4

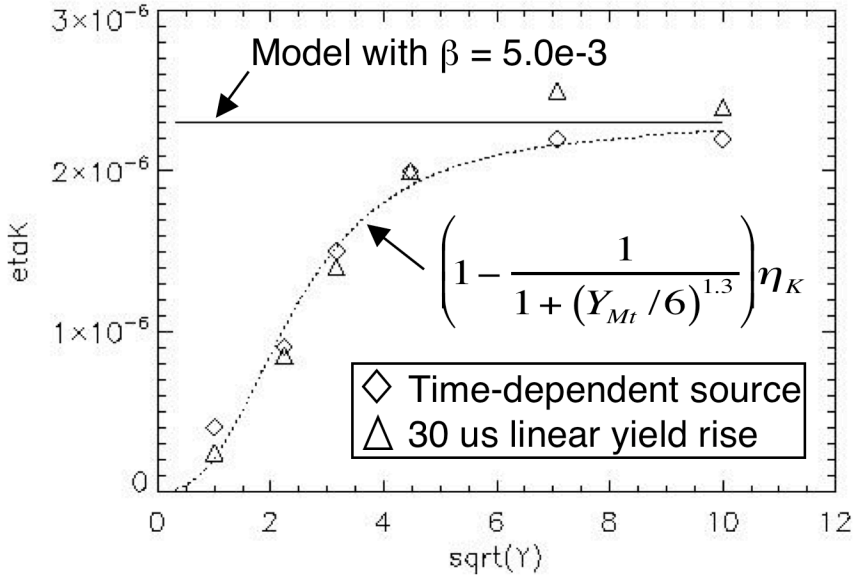
2.5 g/cc SiO_2 target

Source @ Y = 5 MT	λ_{eff}(cm)	$(1.8\eta_Y \lambda_{mfp} / \rho)^{1/2}$	v_z(cm/s)	η_K(e-7)
Fission weapon (FW) neutrons	33	5.3	4.5	10.0
Thermonuclear weapon (TNW) neutrons	30	5.1	4.0	8.5
14.1 MeV neutrons	25	3.5	3.5	9.0
10 keV blackbody x-rays	3.0e-2	0.14	1.1	0.63
1 keV blackbody x-ray	4.0e-4	0.018	0.25	0.029 @ 5μs

- η_K is sensitive to the presence of a failure model
- Neutron KE coupling depends weakly on source spectrum
- X-ray KE coupling depends strongly on photon temperature
- Cale predicts that v_z from x-rays at 10 keV is of order the neutron result

Kinetic energy coupling vs. yield for TN weapon neutron source

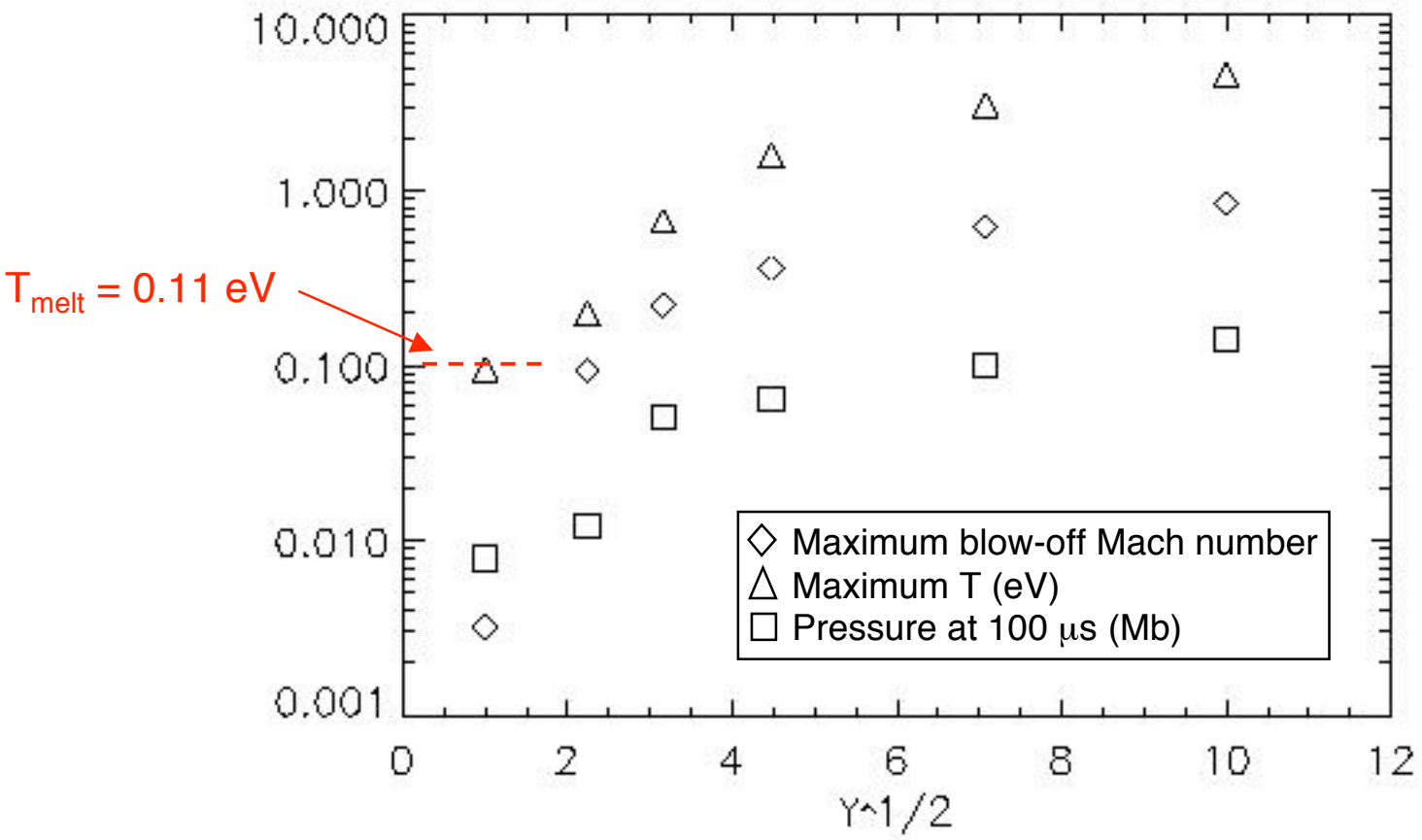




- Cale results agree with the model-predicted deflection velocity with β = 5.0e-3, a yield offset of 1 MT, and a 1/√5 multiplicative factor
- At high yield (Y ≥ 50 MT), Cale results agree with the model-predicted η_K with β = 5.0e-3
- At low yield, the model under-predicts η_K Cale relative to the simulations
- Cale predicts no significant difference between the time-dependent source and the 30 μs linear rise yield source
- Cale predicts that the neutron capture energy contributes equally throughout the yield range considered

2 cm radial zoning for time-dependent source
10 cm radial zoning for ts=30us source

Deflection velocity goes to zero when the target asteroid is not heated above the melt temperature



With the TN weapon source at d = r = 500 m, yields below 1 MT do not heat the target surface enough to cause melting

Kinetic energy coupling vs. standoff distance for 14.1 MeV neutron source

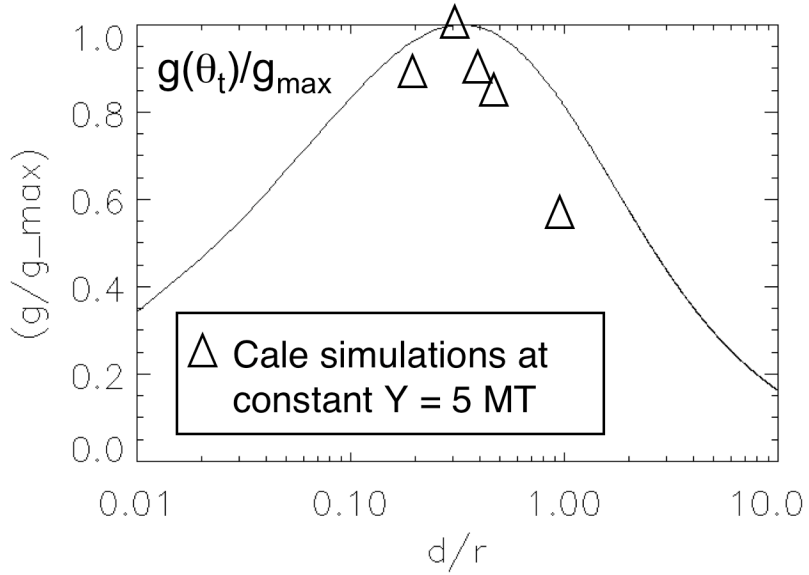
For a given source and target, the model predicts:

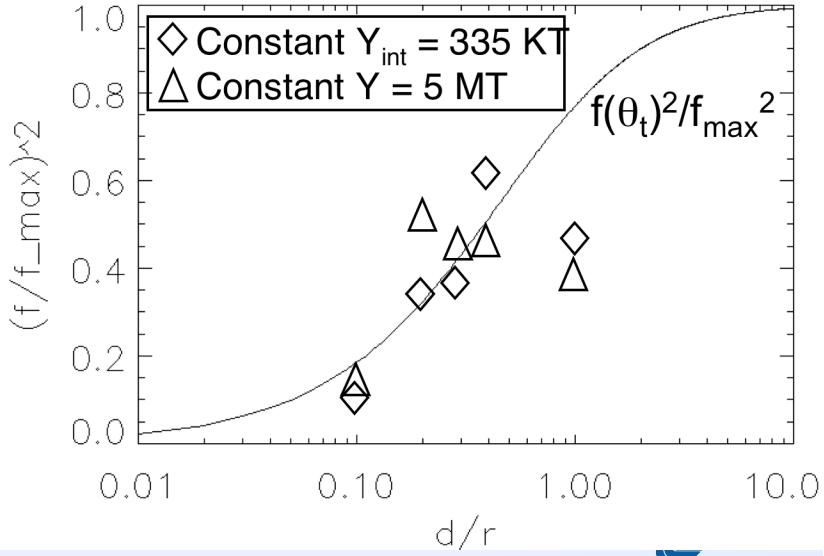
$$v_z \propto \frac{g(\theta_t)}{g_{\max}} \qquad \eta_K \propto \left(\frac{f(\theta_t)}{f_\infty}\right)^2$$

- Cale simulations agree with the model-predicted position of the $g(\theta_t)$ peak but find a narrower width
- Cale simulations agree qualitatively with the model-predicted $f(\theta_t)$ except at large stand-off distances

d/r	Y	Y_{int}	η_K(e-7)	v_z(cm/s)
0.2	1.50	0.335	1.8	1.6
0.3	1.97	0.335	2.8	2.1
0.4	2.29	0.335	2.9	2.1
0.5	2.63	0.335	4.0	2.5
1.0	5.00	0.335	3.3	2.2
0.2	5.00	1.12	2.3	3.4
0.3	5.00	0.852	3.9	3.9
0.4	5.00	0.750	3.6	3.5
0.5	5.00	0.637	3.7	3.3
1.0	5.00	0.335	3.3	2.2

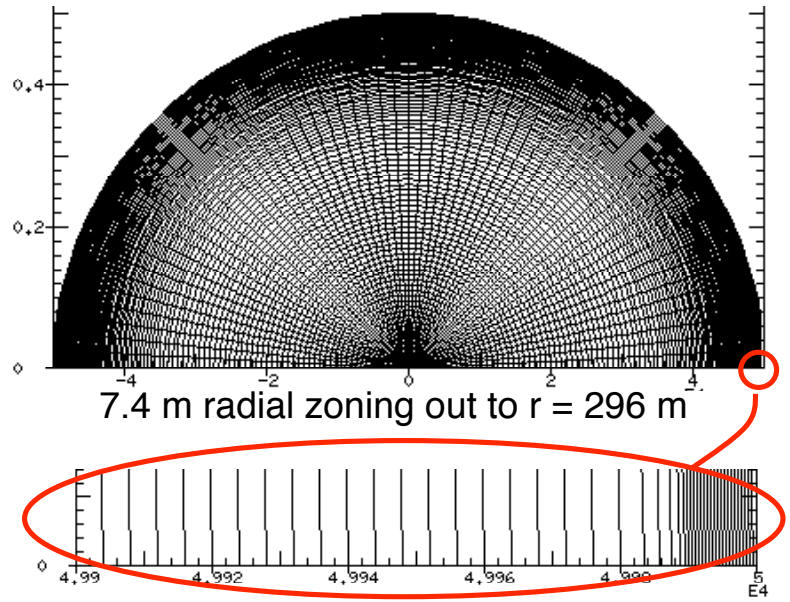
10 cm radial zoning





Combined neutron and photon sources

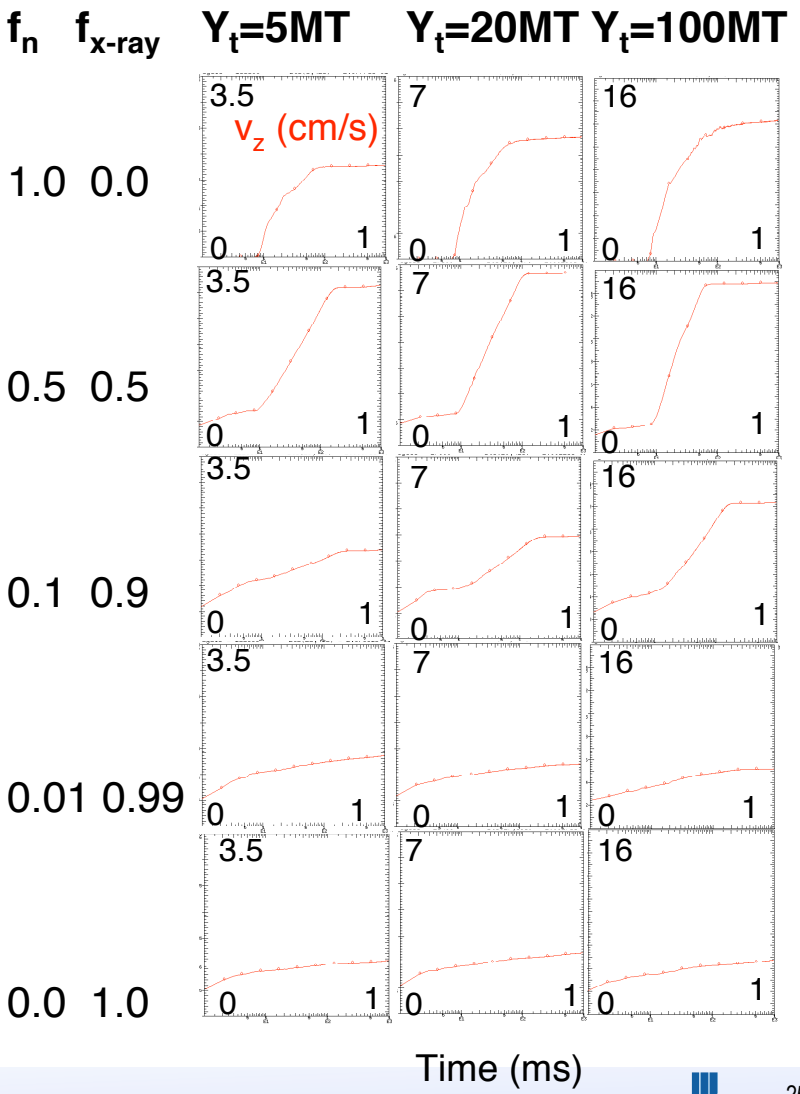
Mesh plots at 1/2 the actual radial resolution



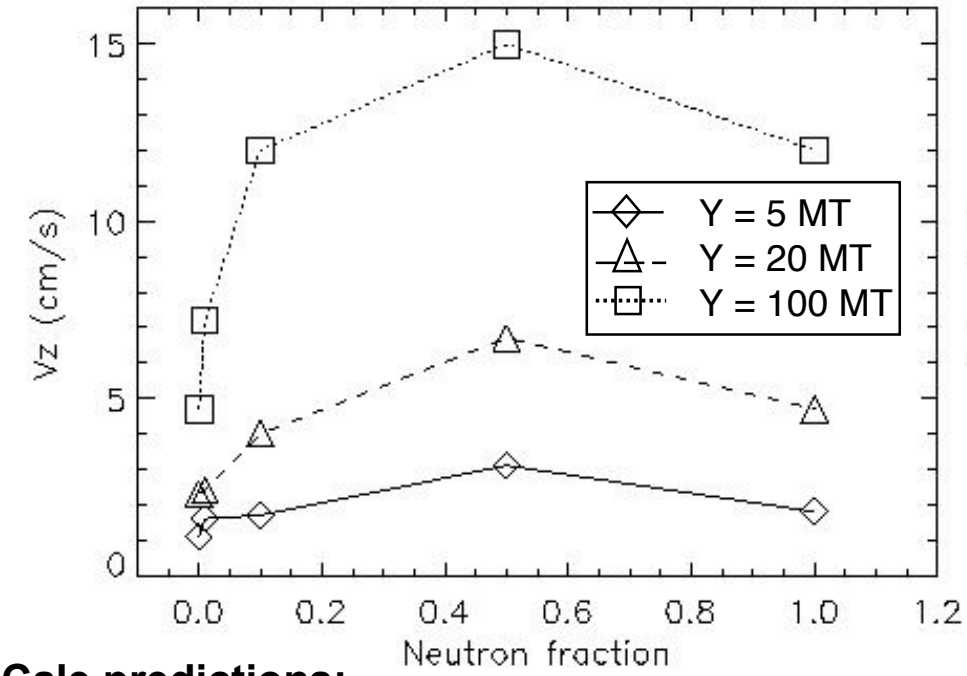
2 cm zoning in 4 m neutron deposition layer

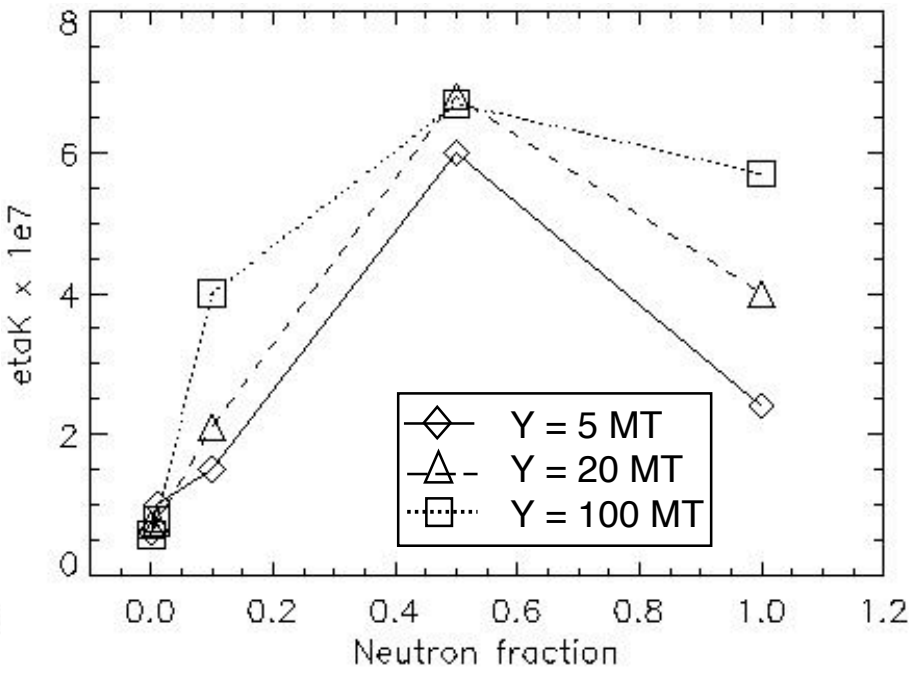
2.5 mm zoning in 10 cm x-ray deposition layer

- Distinct neutron and x-ray deposition regions
- Neutron source: Monoenergetic 14.1 MeV
- Photon source: 10 keV blackbody
- Should repeat with 1 kev photon source



Combined neutron and photon sources





Cale predictions:

- High energy neutrons are only 1.6 -2.6 times more effective than 10 keV x-rays despite model-predicted v_z ratio of 25 at constant β (shallower deposition $\Rightarrow$ higher T $\Rightarrow$ higher β)
- Presence of x-ray blow-off increases effectiveness of neutron energy deposition
- Neutron fractions of 10% and 100% are equally effective over the range of total yields considered

Should repeat calculation series with 1 kev photon source

t = 1000 μs

Needed improvements and future directions

Simulations

- Resolution of the resolution problem
- Direct (dynamic) sourcing of x-ray energy into Cale
- Consider neutron propagation through x-ray blow-off
- Improved material modeling in hydro calculations
- Consider realistic target geometries (including 3D)
- Allow internal structure ("Rubble pile" targets)
- Consider multiple sources
    - For fixed Y divided into n pulses, $\Delta v \sim \Sigma \Delta v_i \sim \Sigma (Y/n)^{1/2} \sim (nY)^{1/2} \sim n^{1/2} \Delta v_{n=1}$

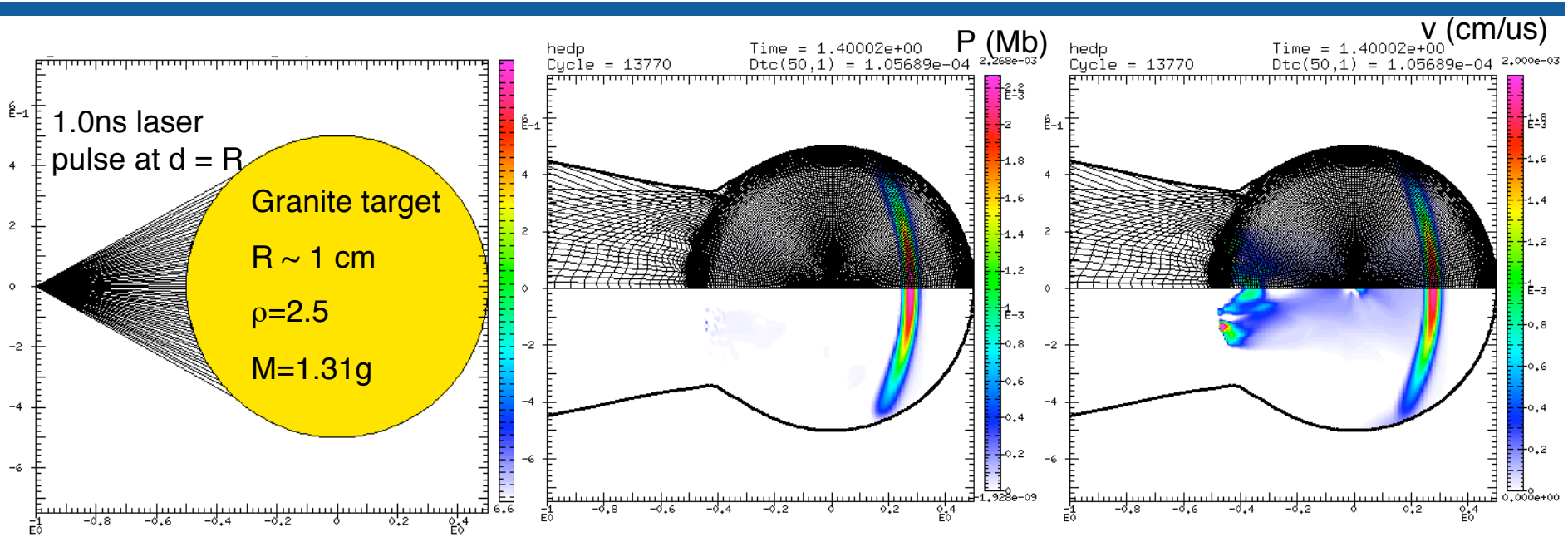
Analytic model

- Include EOS modeling
- Better description of x-ray energy deposition. A better fit to the photon TART runs is $\mathrm{Exp}\{-[(R-r)/\lambda_{eff}]^{0.4}\}$

Experiments?

- Can we measure the kinetic energy coupling efficiency?

Asteroid deflection in the laboratory?



	R	Yint	Yeff	Y_{int}/M (J/g)	P_{max} (kBar)	λ_{eff}	λ_{eff}/R	v_{def} (cm/s)	η_K	Tstop (us)
	0.5km	6.71MT	100MT	22	120	30cm	6e-4	33	2.2e-6	1000
003	1.5cm	1.034kJ	15.4kJ	29	160	3 μm	2e-4	10	2.7e-7	12.8
001	0.5cm	1.034kJ	15.4kJ	790	890	10 μm	2e-3	88	6.4e-7	2.50

Conclusions

- Without mitigation, Earth will experience future collisions with large NEO's
- Earth-asteroid collisions can cause (and have caused) devastating local and global effects
- Kilometer-scale NEO's can be deflected by megaton-class nuclear explosives with lead times of order one decade and by 100 megaton-class nuclear explosives with lead times of order one year
- Both x-ray and neutron energy deposition can be effective in deflection
- Cale simulations predict that neutron capture energy can make a significant contribution to the deflection velocity
- Material properties are important, but uncertainties in kilometer-scale targets can likely be compensated for by conservative required yield estimates
- Laser-driven laboratory experiments might be used to measure kinetic energy coupling efficiencies and validate models