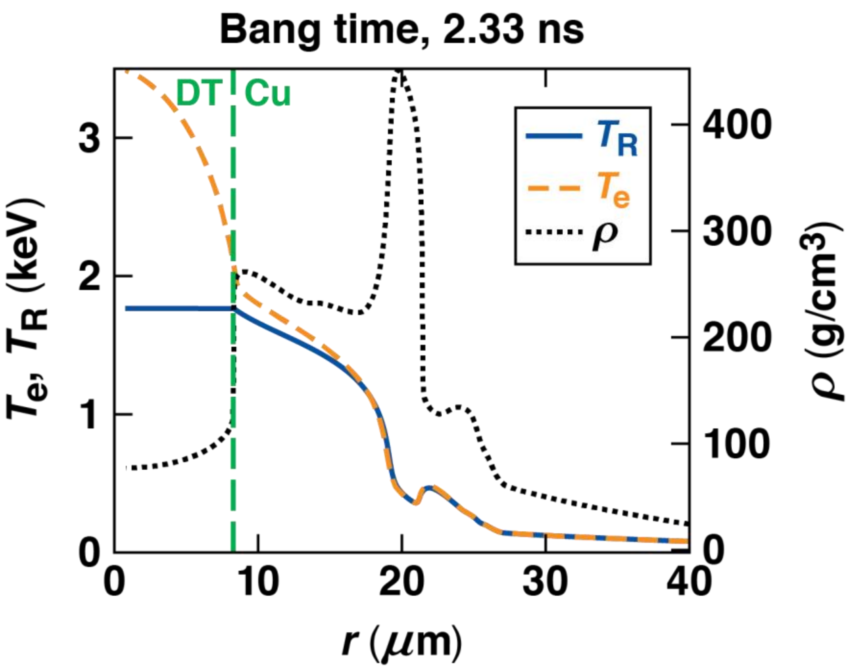
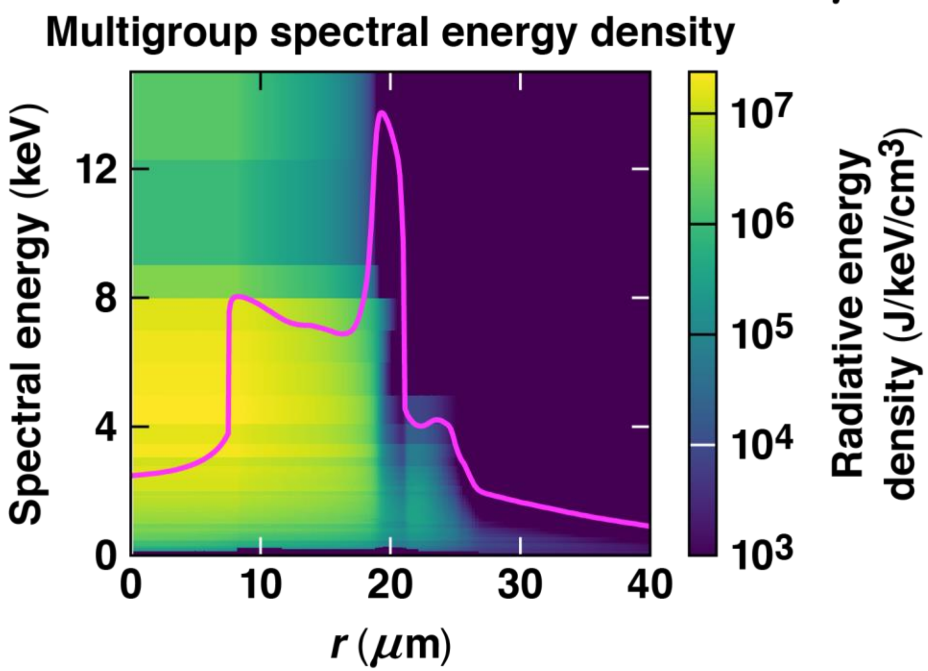
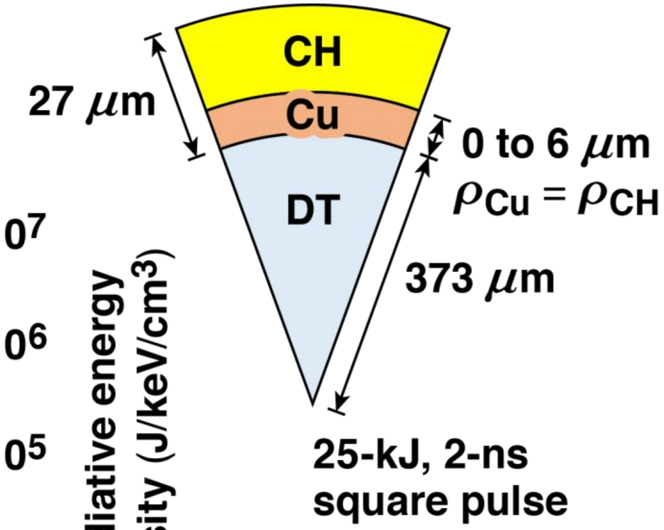
Assessment of Radiation Trapping in Inertial Confinement Fusion Implosion Experiments with High-*Z*–Lined, Single-Shell Targets







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Summary

Radiation trapping by an ICF pusher layer can be characterized in terms of a Marshak wave model

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- Radiation trapping is most apparent in simulations through a characteristic Marshak waveform, where radiation and electron temperatures are equal ($T_R = T_e$), indicating the LTE atomic-radiative limit
- The classic “textbook” Marshak wave model is generalized for a uniformly compressing pusher layer, preserving its self-similar analytic form
- The Marshak wave model is analytically transparent and describes radiation trapping in pusher layers in terms of useful characteristic quantities

Volume-ignition capsule designs rely on radiation trapping.

ICF: inertial confinement fusion
LTE: local thermodynamic equilibrium

Collaborators

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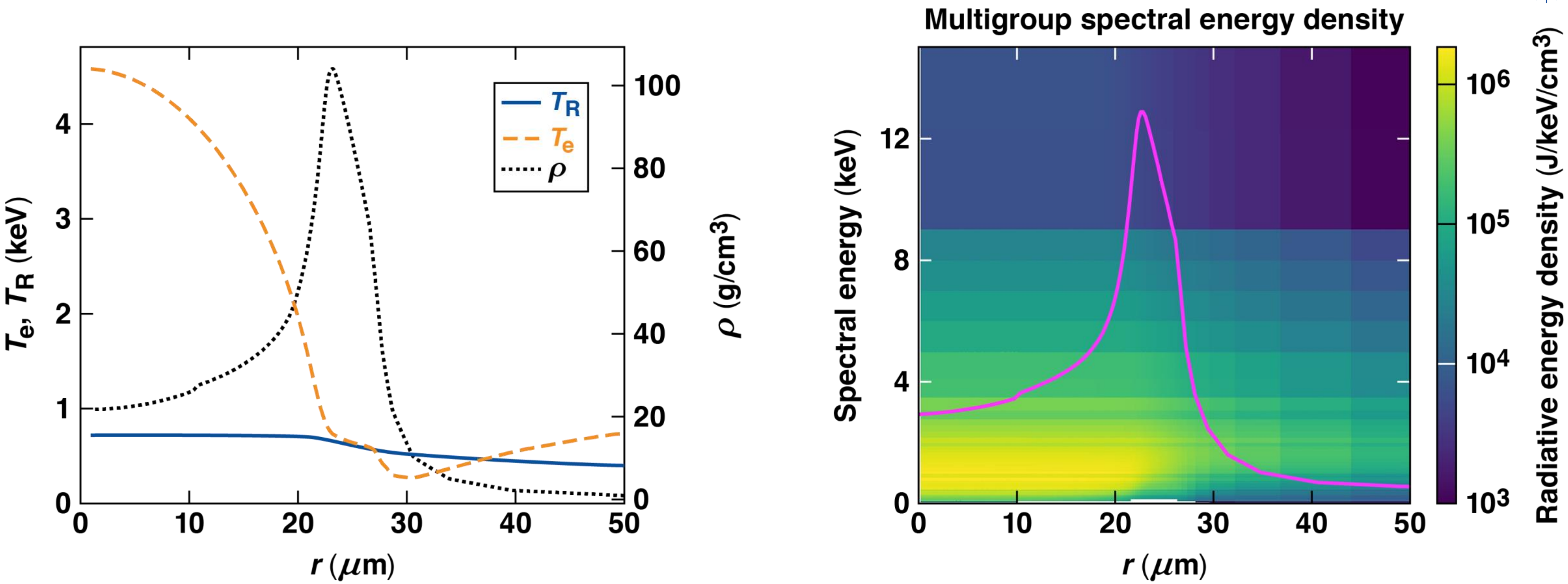
Pure-CH OMEGA-scale imploded shells do not trap radiation



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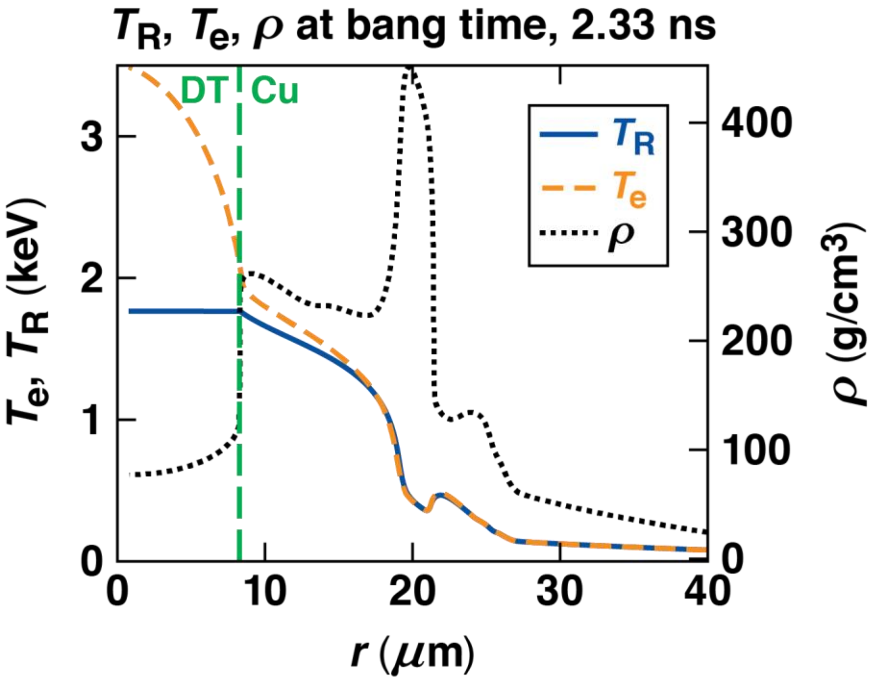
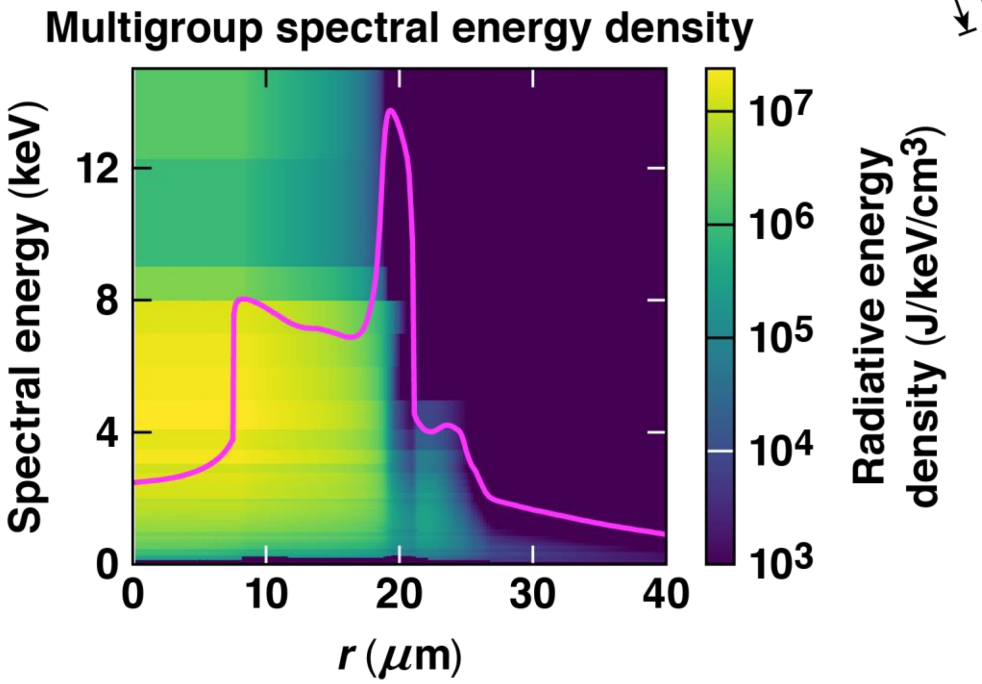
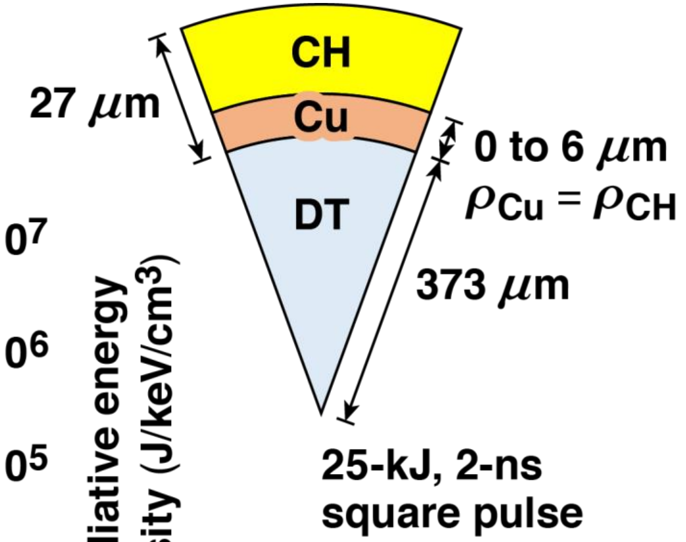
- High-yield shot 90288
- Radiation source $r < 22$ mm
- Near-free escape of radiation through CH shell

A 6-μm Cu inner-pusher layer traps radiation through bang time as seen in a *LILAC* simulation where $T_R = T_e$ indicates optically thick LTE







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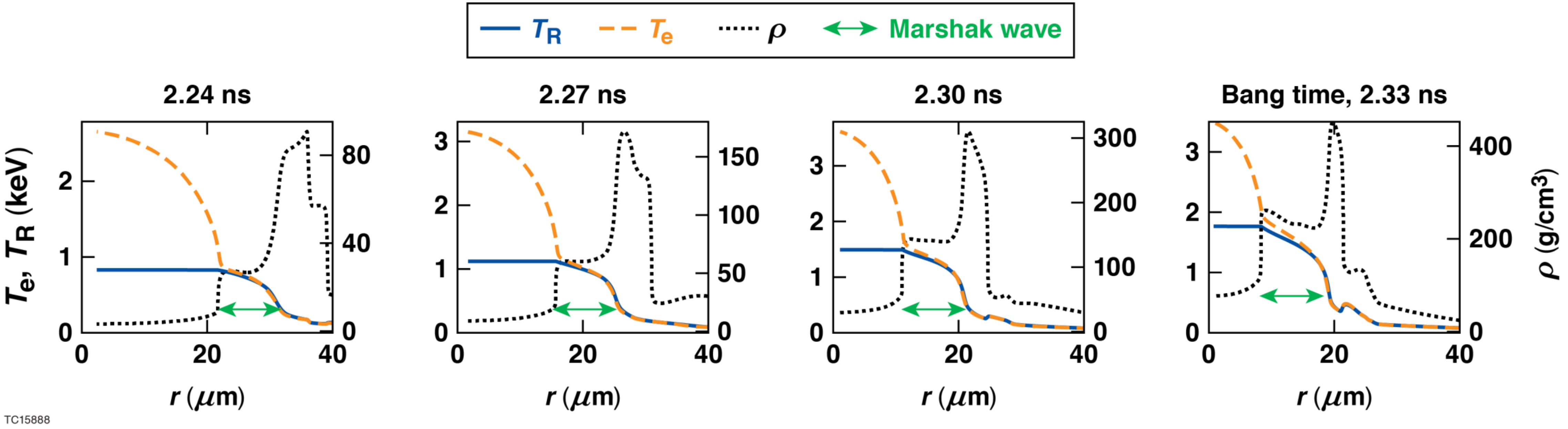
$T_R = T_e$ indicates LTE and a Planck spectrum, key assumptions underlying the Marshak wave model.

Temperature profiles of a warm OMEGA design with 6 μm Cu shows radiation trapping behind an advancing Marshak wave



Compressing ICF pusher layers requires adding adiabatic compression to the Marshak wave model.

The Marshak wave* is a self-similar solution to the Euler fluid energy equation including thermal radiation transport and adiabatic compression

Energy equation: $$\frac{1}{c}\frac{\mathrm{d}E}{\mathrm{d}t} - \frac{P}{\rho^2}\frac{\mathrm{d}\rho}{\mathrm{d}t} - \frac{\partial}{\partial \mathrm{m}}\left[\frac{4}{3\kappa}\frac{\partial}{\partial \mathrm{m}}\left(\sigma_{SB}T^4\right)\right] = 0$$

Properties of matter:** $\kappa = \kappa_0(\rho/\rho_0)^r (T/T_0)^{-n}$ $\quad C_V = C_0(\rho/\rho_0)^s (T/T_0)^q$ $\quad P = (\gamma - 1)\rho E$

Uniform adiabatic compression: $\rho(t) = \rho_0(t/t_0)^\alpha$

Marshak wave: $T(m,t) = T_0 g(m,t) h(t)$ $\quad h(t) = [\rho(t)/\rho_0]^{\gamma - 1 - s}$

New compression terms are in red

$$\xi \frac{\mathrm{d}g(\xi)^{q+1}}{\mathrm{d}\xi} - \frac{\mathrm{d}^2}{\mathrm{d}\xi^2} g(\xi)^{n+4} = 0 \qquad 0 \le \xi \le \xi_0 \qquad g(0) = 1 \qquad g(\xi_0) = 0$$

Self-similar space–time m, t dependence through the variable ξ: $$\xi = \frac{(1+\nu)^{1/2} A}{(1+q)} \frac{m}{t^{1/2}} \left(\frac{t_0}{t}\right)^{\nu/2} \qquad A^2 = \frac{3(4+n)}{32(1+q)} \frac{\kappa_0 C_0 T_0}{\sigma_{SB} T_0^4} \qquad \nu = \alpha\left[\frac{(\gamma-1)(3+n-q)}{(q+1)} - s - r\right]$$

Wavefront position $m_0(t)$ at $\xi = \xi_0$: $$m_0(t) = \xi_0 \frac{1+q}{(1+\nu)^{1/2}} \frac{t^{1/2}}{A} \left(\frac{t}{t_0}\right)^{\nu/2}$$

The Marshak wave profile and trajectory are described approximately but completely.

* R. E. Marshak, Phys. Fluids 1, 24 (1958).
** A. P. Cohen, G. Malamud, and S. I. Heizler, Phys. Rev. Res. 2, 023007 (2020).

The Marshak wave model yields several useful characteristic quantities

- Optical thickness time scale: The time of formation of a τ = 1 trapping layer is the key time scale

$$t_{\tau=1} = \left[\frac{6(1+\nu)}{\xi_0^2(4+n)}\frac{\varepsilon_{th}}{\varepsilon_R}\frac{1}{c\kappa_0}t_0^{\alpha\psi}\right]^{1/(1+\alpha\psi)} \qquad \psi = \frac{(\gamma-1-s)(3-n-q)}{(1+q)} + r - s \qquad \varepsilon_R = \frac{4\sigma_{SB}T_0^4}{c} \qquad \varepsilon_{th} = \frac{C_0 T_0}{1+q}$$

- The trapped flux varies on this time scale

$$F_R(t) \approx \frac{\xi_0^2(4+n)}{3(1+q)} c\varepsilon_R (t_{\tau=1}/t)^{1/2} \left(\frac{t}{t_0}\right)^{\frac{\alpha}{2}\left[\frac{(\gamma-1)(5+n+q)}{(1+q)} - r - s\frac{(4+n)}{(1+q)}\right]} \left(\frac{t_{\tau=1}}{t_0}\right)^{\frac{\alpha}{2}\left[\frac{(\gamma-1)(3-n-q)}{(1+q)} + r - s\frac{(4-n)}{(1+q)}\right]}$$

- Again, compression sets the time scale t_0 and the power-law index α

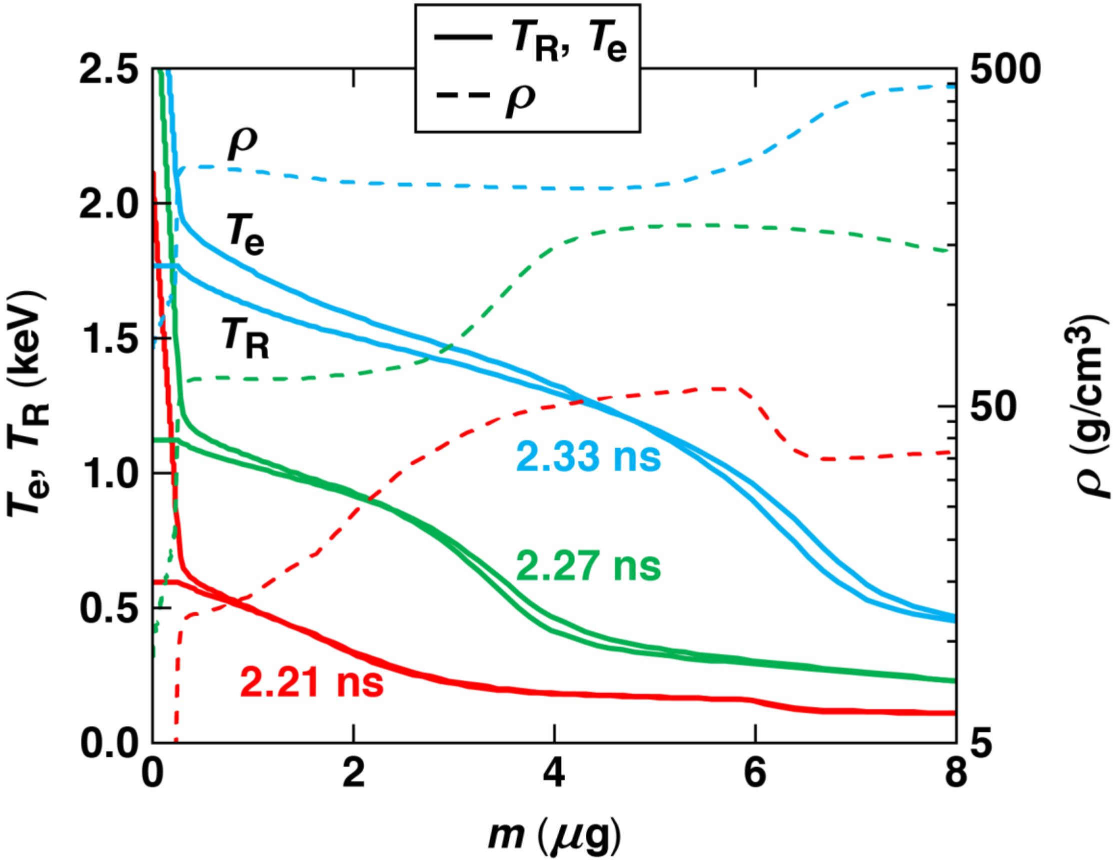
$$\rho(t) = \rho_0(t/t_0)^{\alpha} \qquad \nu = \alpha\left[\frac{(\gamma-1)(3+n-q)}{(q+1)} - s - r\right]$$

- Again, γ is the adiabatic index, *n* and *r* are opacity indices, and *q* and *s* are specific heat indices

Short "τ = 1" Marshak wave formation times for Cu are short relative to the pusher hydro time, but far too long for a pure CH shell

$$t_{\tau=1} = \frac{6}{\xi_0^2(4+n)}\frac{\varepsilon_{th}}{\varepsilon_R}\frac{1}{c\kappa_0}$$

	t sim (ns)	T_0 (keV)	ρ (g/cm³)	t (τ = 1) (ps)
Cu	2.21	0.60	12.8	5.5
Cu	2.27	1.12	60.5	3.6
Cu	2.33	1.77	239.0	2.7
CH	2.33	1.12	57.0	66.8



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The "τ = 1" formation time is a parameter that anticipates the effectiveness of radiation trapping in an imploding pusher layer.

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