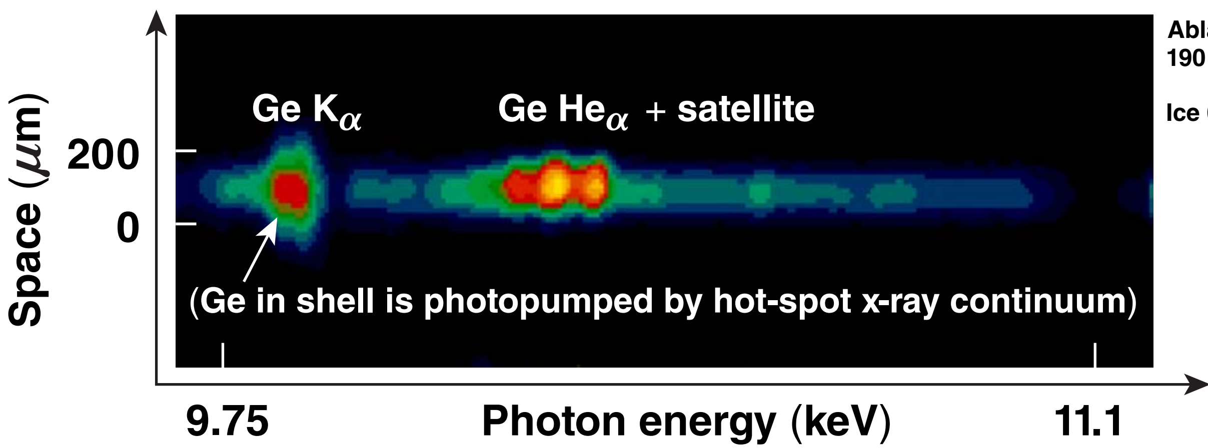
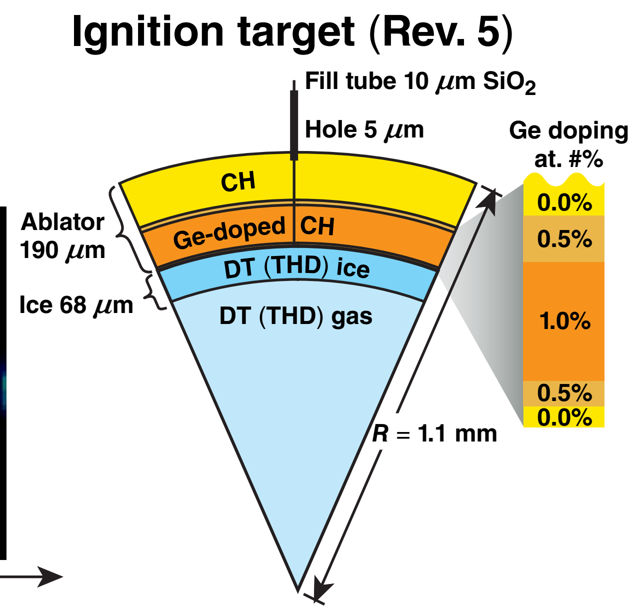
Hot-Spot Mix in Ignition-Scale Implosions at the National Ignition Facility (NIF)





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American Physical Society
Division of Plasma Physics
Salt Lake City, UT
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Summary

Hot-spot mix in NIF ignition-scale implosions is diagnosed with Ge K-shell spectroscopy

- Hydrodynamic instabilities are predicted to mix CH and Ge ablator mass deep into the hot spot at ignition time (hot-spot mix)*
- The hot-spot mix mass was estimated from the Ge K-shell line brightness using a detailed atomic physics model
- Predictions of a simple mix model are consistent with the experimental results

The inferred amount of hot-spot mix mass for NIF ignition-scale implosions is comparable to or below the 75-ng requirement.**

N. Izumi *et al.*, CO8.00013.
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B. A. Hammel *et al.*, GP9.00114.
K. J. Peterson *et al.*, PO6.00006.
M. A. Barrios *et al.*, PO6.00009.

*B. A. Hammel *et al.*, Phys. Plasmas 18, 056310 (2011).
**S. W. Haan *et al.*, Phys. Plasmas 18, 051001 (2011).

NIC mix working group collaboration

R. Epstein[1], B. A. Hammel[2], L. J. Suter[2], J. E. Ralph[2], H. Scott[2], M. A. Barrios[2], D. K. Bradley[2], D. A. Callahan[2], C. Cerjan[2], G. W. Collins[2], S. N. Dixit[2], T. Doeppner[2], M. J. Edwards[2], D. R. Farley[2], S. Glenn[2], S. H. Glenzer[2], I. E. Golovkin[3], S. W. Haan[2], A. Hamza[2], D. G. Hicks[2], N. Izumi[2], J. D. Kilkenny[2,7], J. L. Kline[4], G. A. Kyrala[4], O. L. Landen[2], T. Ma[2], J. J. MacFarlane[3], A. J. MacKinnon[2], R. C. Mancini[5], R. L. McCrory[1,6], N. B. Meezan[2], D. D. Meyerhofer[1,6], A. Nikroo[7], K. J. Peterson[8], T. C. Sangster[1], P. Springer[2], and R. P. J. Town[2]

[1]Laboratory for Laser Energetics, University of Rochester
[2]Lawrence Livermore National Laboratory
[3]Prism Computational Sciences
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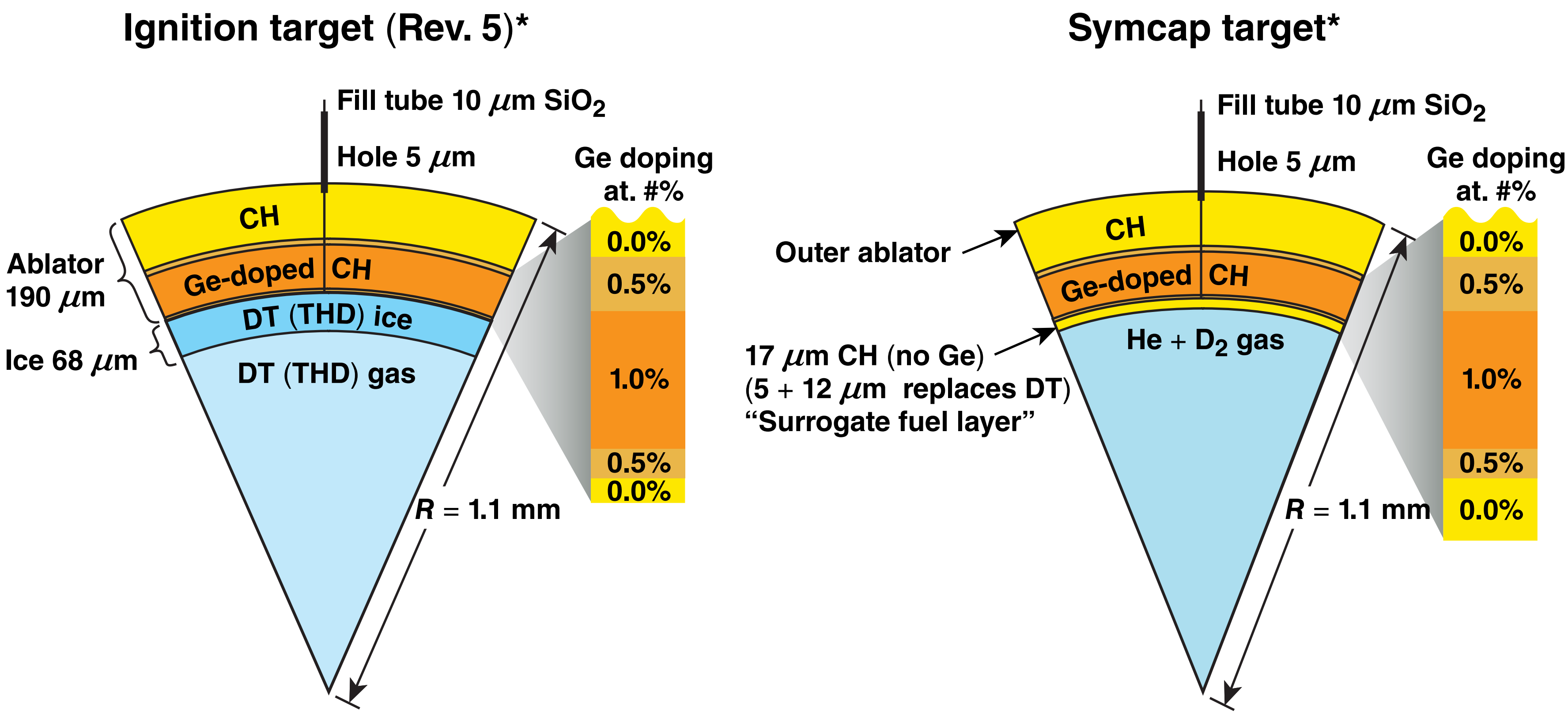
[7]General Atomics
[8]Sandia National Laboratories

The NIF Rev. 5 ignition capsule has a Ge dopant in the ablator to minimize x-ray preheat of the shell closest to the DT ice



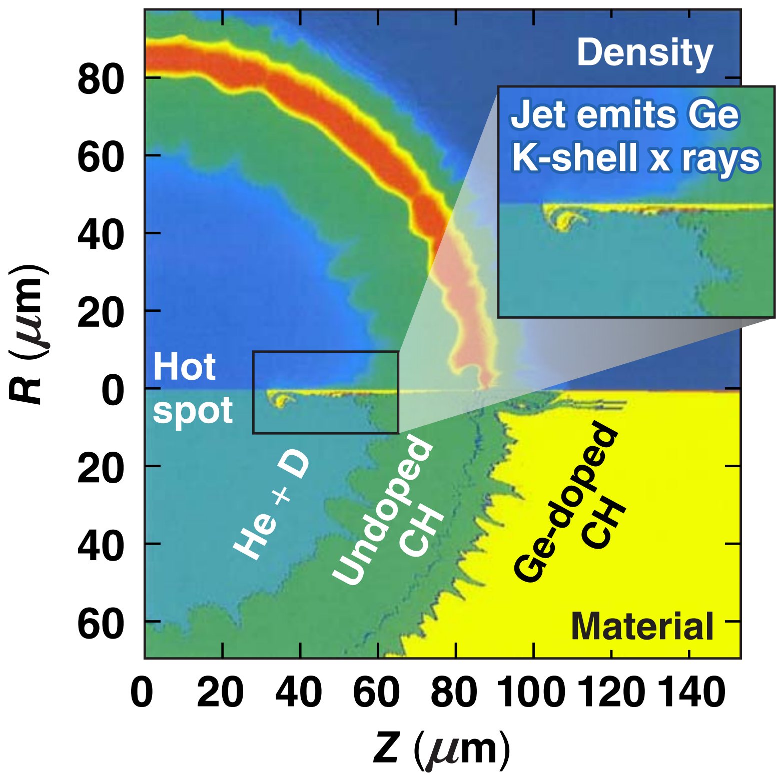
Hot-spot mix mass is diagnosed in DT, THD, and symcap NIF ignition-scale implosions.

E19895b

*D. S. Clark *et al.*, Phys. Plasmas 17, 052703 (2010).

Hydrodynamic instabilities are predicted to mix Ge and CH ablator mass deep into the hot spot at ignition time*

HYDRA 2-D simulation of symcap (perturbation on-axis)



- High ℓ-mode (50 to 200) surface perturbations
- If the seeds are large enough, they can drive jets of ablator into the hot spot
- Simulations indicate the hot-spot mix mass is from the 1% Ge-doped layer of CH ablator
- Simulations set surface-finish requirements to keep hot-spot mix <75 ng**

Ge dopant in the ablator provides a spectroscopic signature of hot-spot mix.

B. A. Hammel *et al.*, GP9.00114.

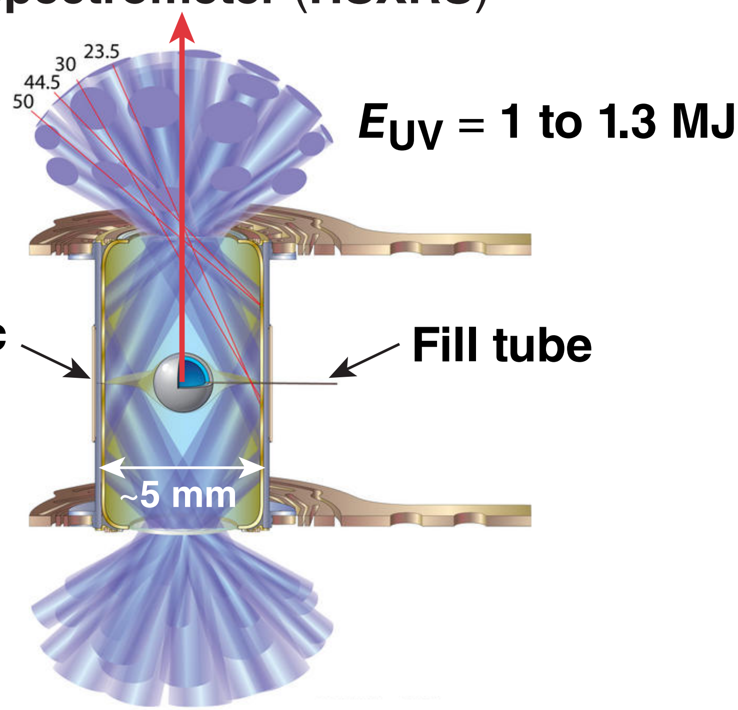
*B. A. Hammel *et al.*, High Energy Density Phys. 6, 171 (2010).
**S. W. Haan *et al.*, Phys. Plasmas 18, 051001 (2011).

E19877b

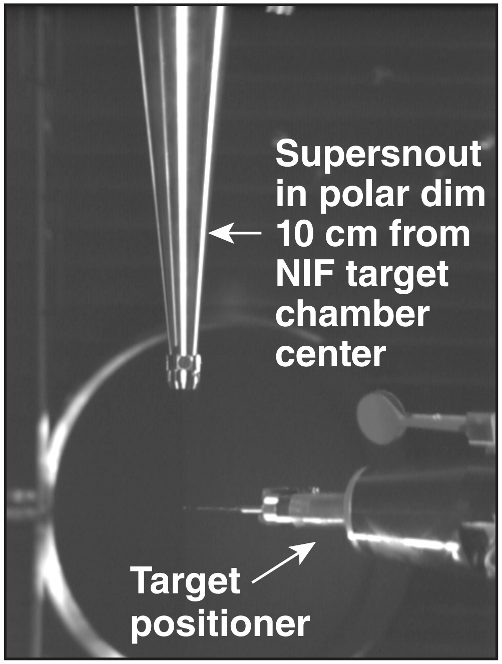
A time-integrated x-ray spectrometer with 1-D spatial resolution was fielded on the NIF specifically to look for Ge emission caused by mix

Absolute photometric calibration of HSXRS (9.75 to 13.1 keV) relates Ge K-shell emission-line brightness to the hot-spot mix mass.

Supersnout containing the hot-spot x-ray spectrometer (HSXRS)



Supersnout on the NIF

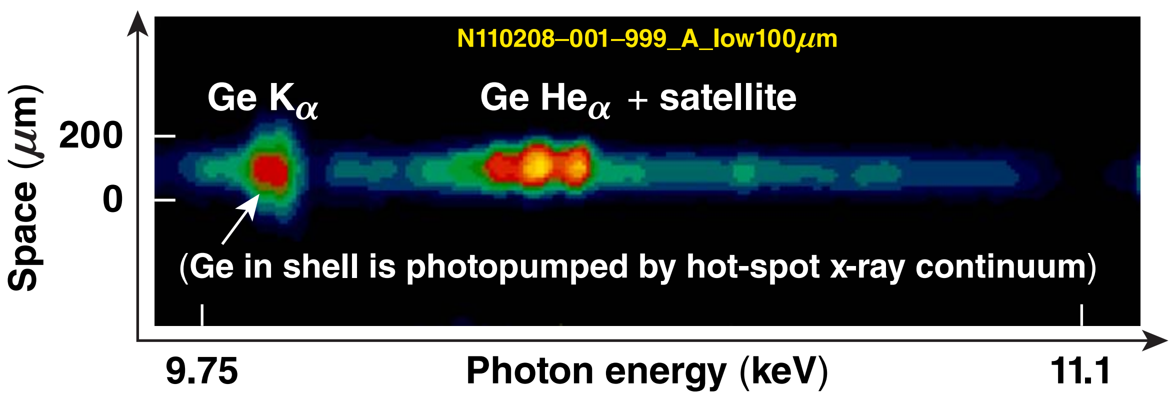


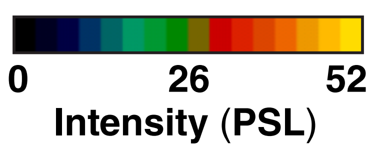
Supersnout in lab

E20073a

1-D spectral imaging provides clear evidence of Ge-doped material mixing with the hot spot

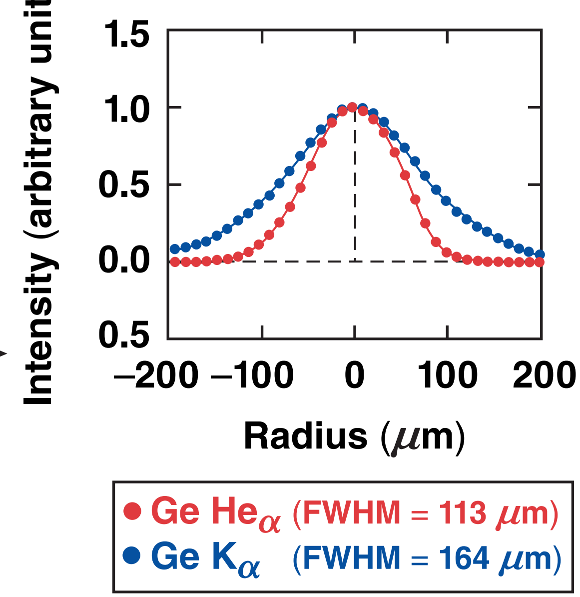
Background subtracted 1-D spectral image (N110208)





- Time integrated
- 100-μm spatial resolution
- 12-eV spectral resolution

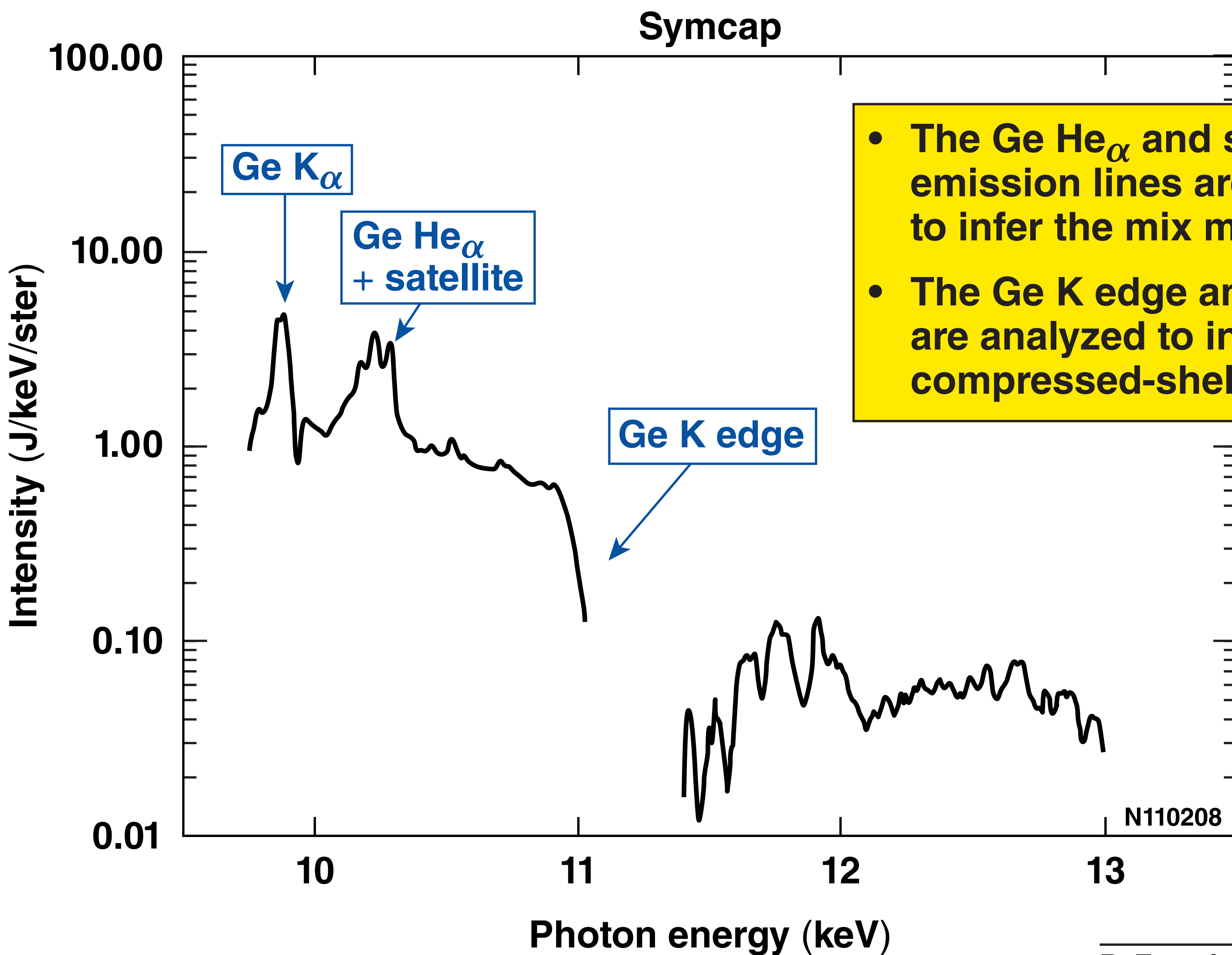
Spatial profiles



The Ge He_α emission is emitted from the mix mass and Ge K_α emission is from the cold, dense shell.

E19995a

The absolutely calibrated x-ray spectrum is spatially integrated and the x-ray continuum is modeled

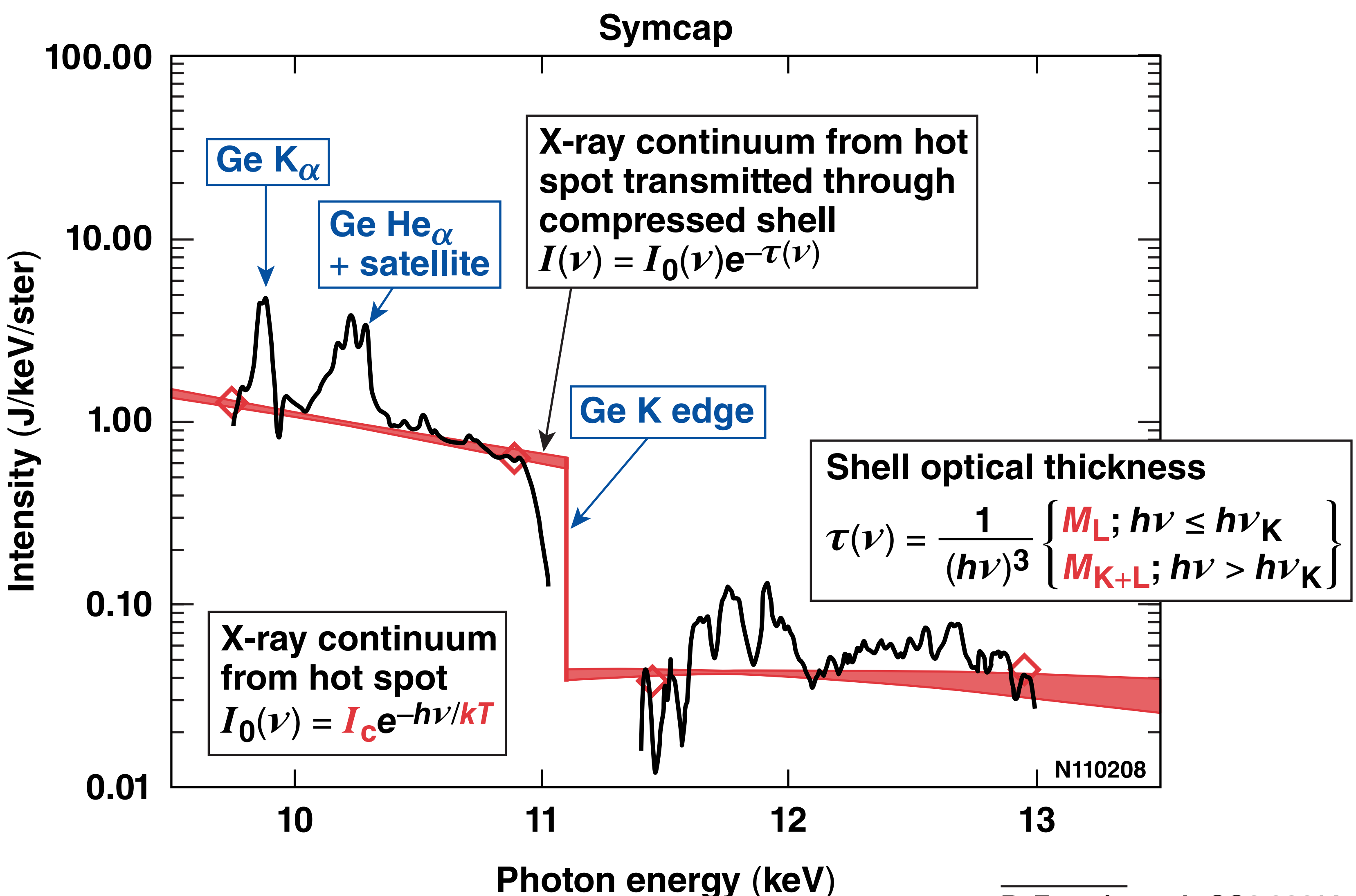


- The Ge He_α and satellite emission lines are analyzed to infer the mix mass
- The Ge K edge and Ge K_α are analyzed to infer compressed-shell conditions

E19882d

R. Epstein *et al.*, CO8.00014.

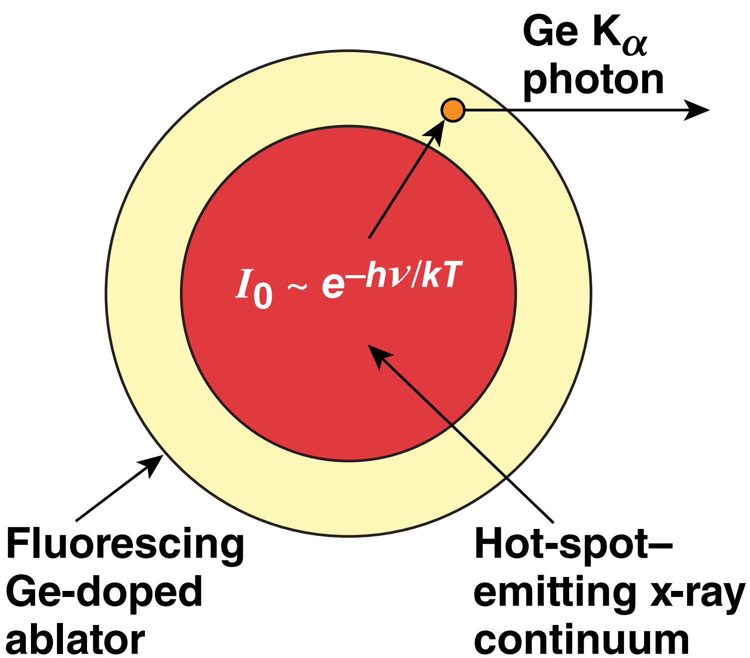
The absolutely calibrated x-ray spectrum is spatially integrated and the x-ray continuum is modeled

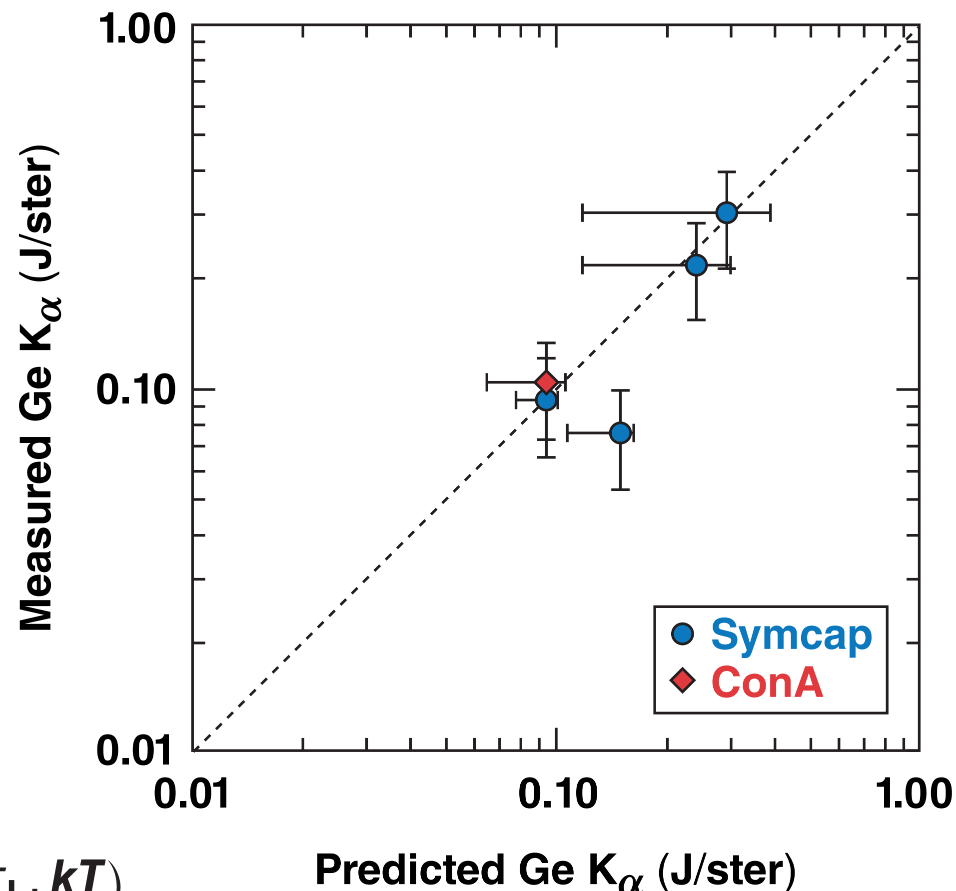


E19882e

R. Epstein *et al.*, CO8.00014.

X rays above the Ge K-edge photopump the Ge-doped ablator, producing Ge K_α emission





$$\int I_{K_\alpha} dh\nu = \Delta I_{\text{K edge}}\, kT \;\; \omega_{K_\alpha} F(\tau_K, \tau_L, kT)$$

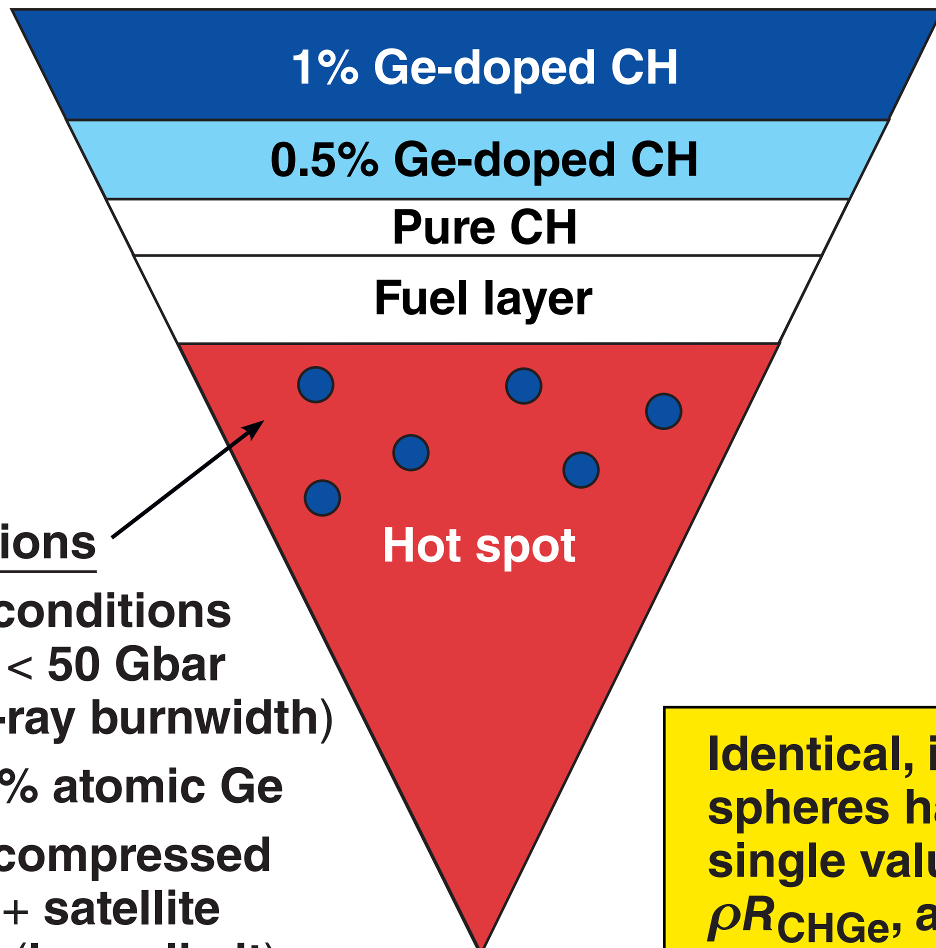
Ge K_α brightness can be used to diagnose shell areal density.

E19997a

R. Epstein *et al.*, CO8.00014.

The mix mass is modeled as multiple spheres of ablator mass with uniform plasma conditions and areal density

Target near peak compression



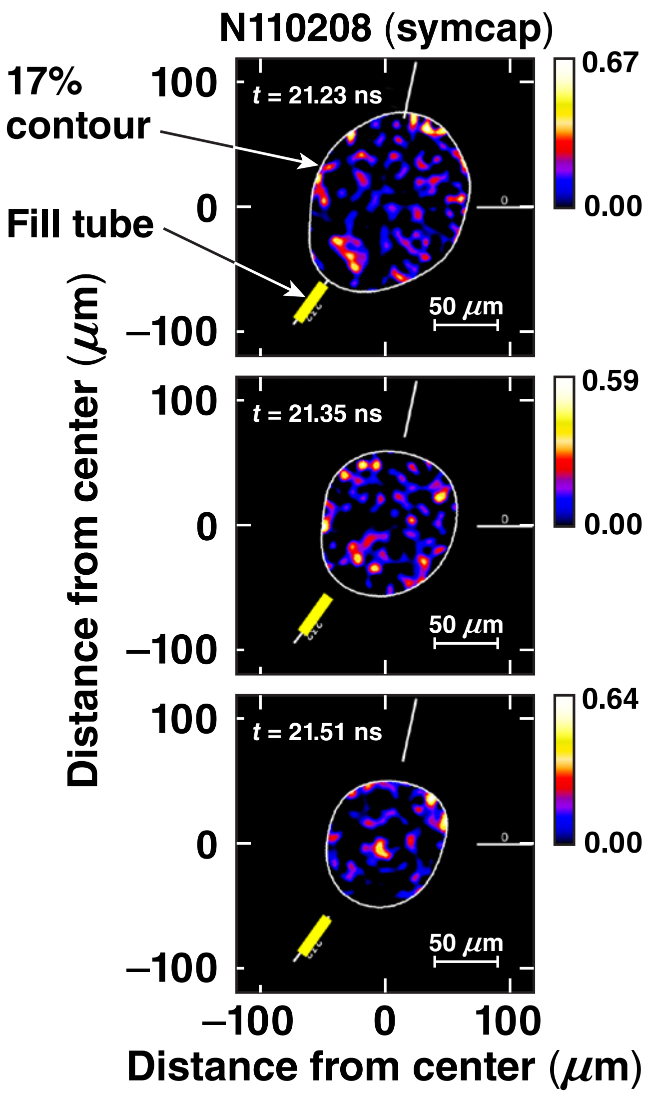
Mix-mass assumptions

1. uniform plasma conditions with 10 Gbar < P < 50 Gbar lasting 250 ps (x-ray burnwidth)
2. CH doped with 1% atomic Ge
3. transmission of compressed shell for Ge He$_\alpha$ + satellite spectrum is 30% (lower limit)

Identical, independent spheres have the same single values of n_e, T_e, ρR_{CHGe}, and ρR_{Ge}.

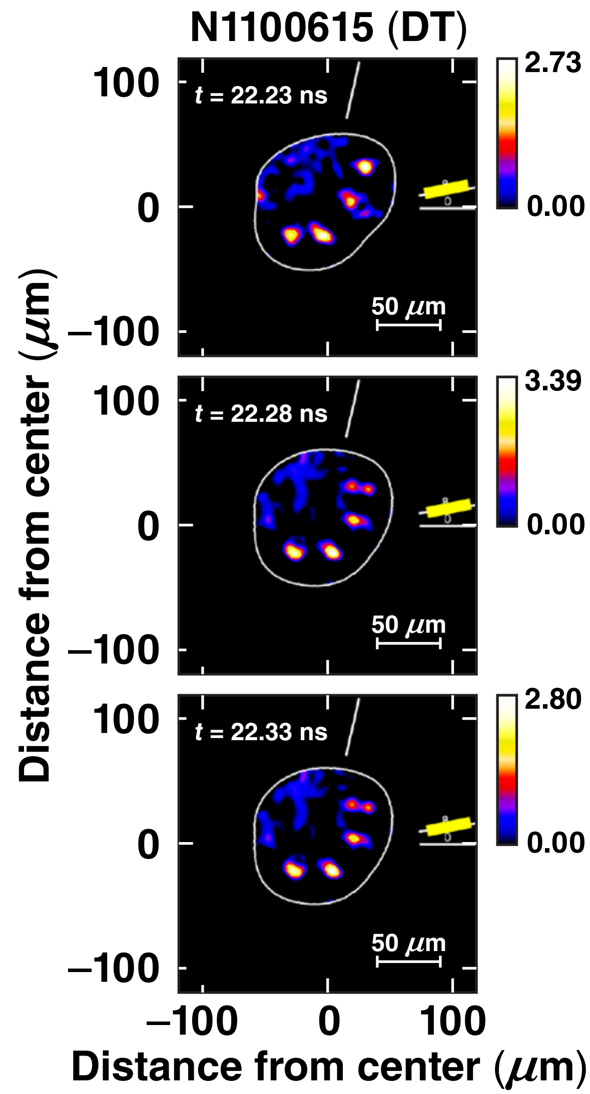
E19884b

Bright spots* in x-ray imploded core images are consistent with heterogeneous mixing of ablator material into the hot spot



Fourier-analyzed, gated, broadband implosion images taken along hohlraum axis around peak compression**

Bright spots persist in time



E20332

**M. A. Barrios *et al*., PO6.00009.

*G. A. Kyrala *et al*., Rev. Sci. Instrum. 81, 10E316 (2010).

A detailed atomic physics model is used to estimate the amount of mix mass from the Ge K-shell line brightness

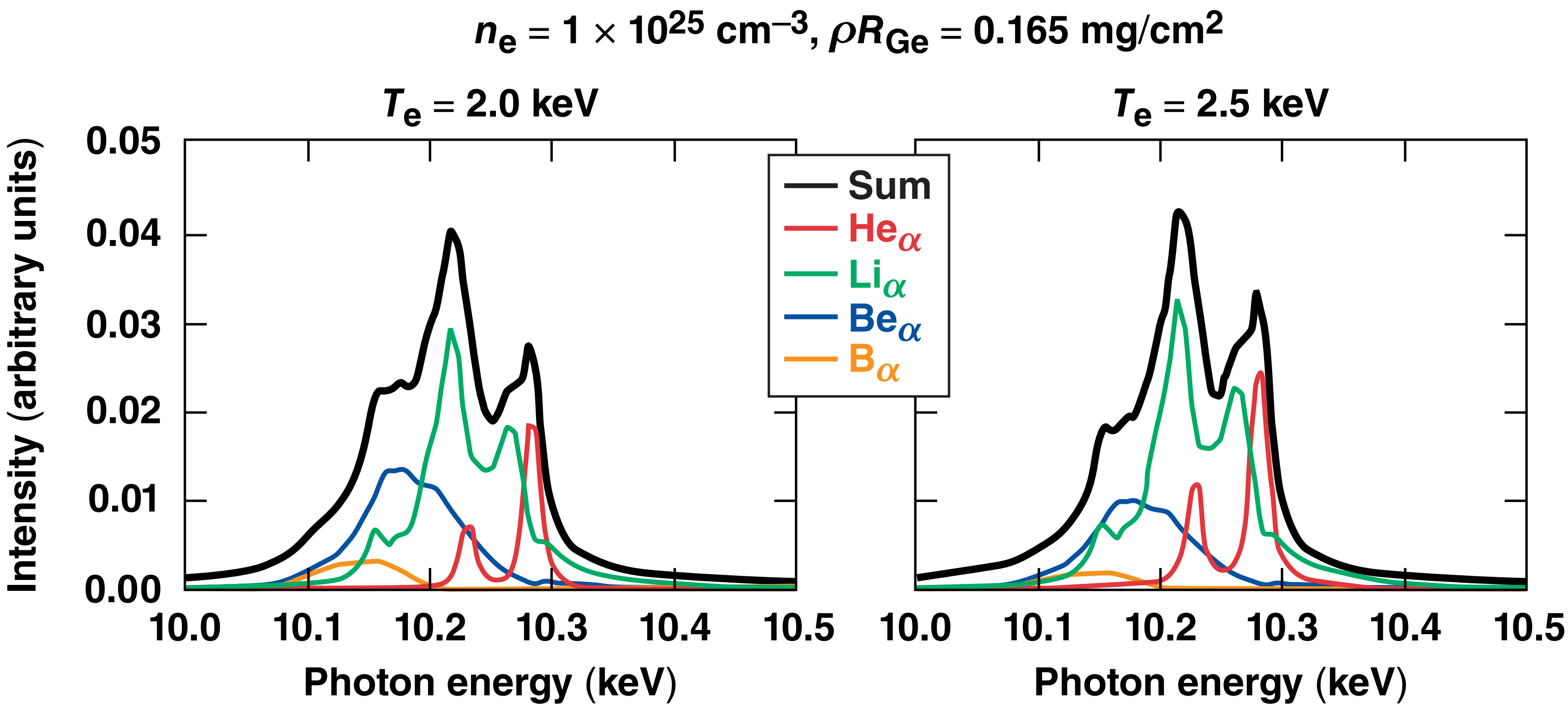
- T, ρ – dependent emissivity model* gives the total emission per Ge mass within the He_{α} + satellite feature
- Spectral fit includes self-absorption–coupled level kinetics, which gives an estimate of ρR_{Ge}
- The Ne through H-like species are represented with detailed-configuration accounting (DCA)
  - all single excitations through $n = 10$
  - all double excitations through $n = 3$
  - important resonance-line-emitting configurations are split
- The Stark-broadened Ge line shapes were calculated using the MERL** code

Measured spectra are compared with modeled spectra for 7068 combinations of n_e, T_e, and ρR_{Ge}.

*J. J. MacFarlane *et al.*, High Energy Density Phys. 3, 181 (2006).
**R. C. Mancini *et al.*, Comput. Phys. Commun. 63, 314 (1991).

E19883a

The calculated spectral line shapes are sensitive to variations in the electron temperature

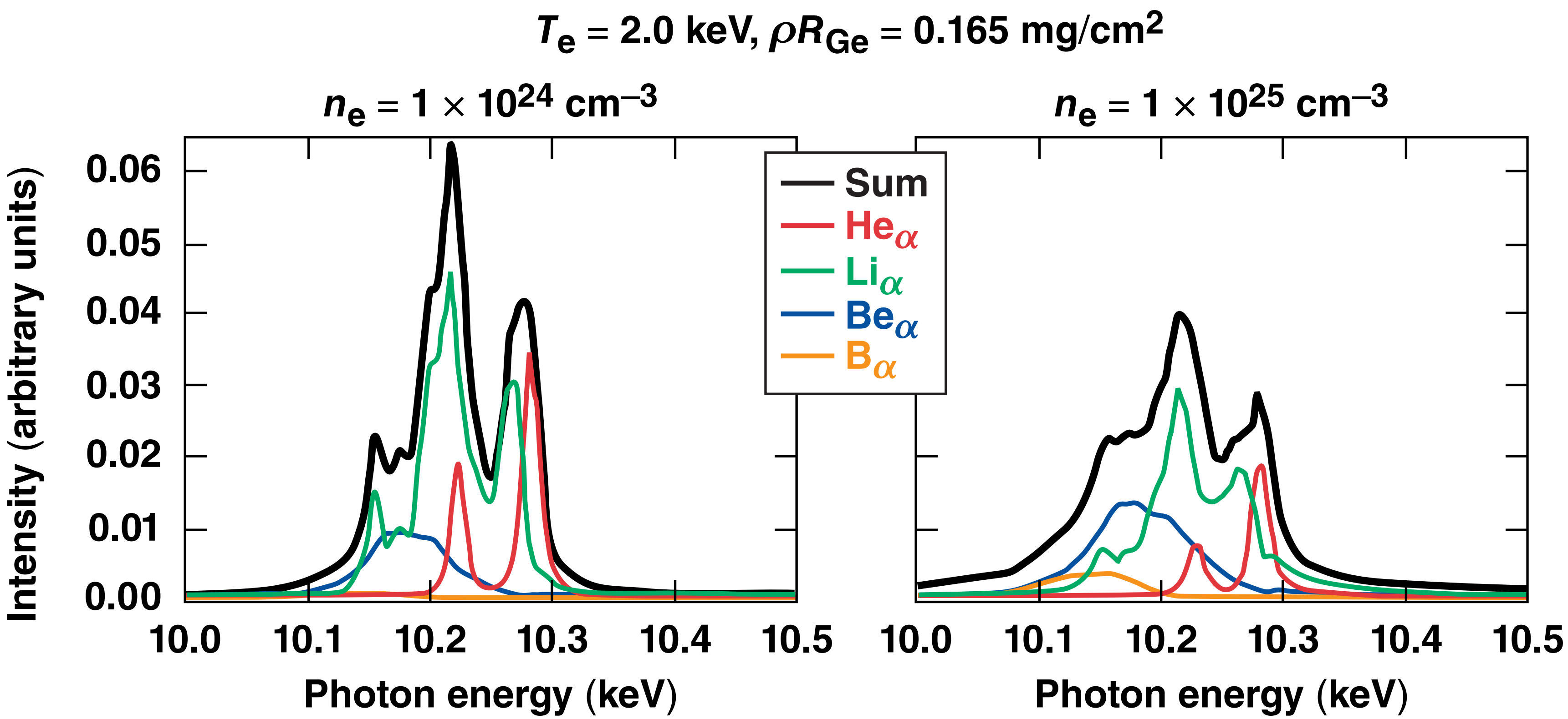


- HSXRS response function has been applied

Spectral feature contains Ge B-like to Ge He-like charge states.

E19885a

The calculated spectral line shapes are sensitive to variations in the electron density



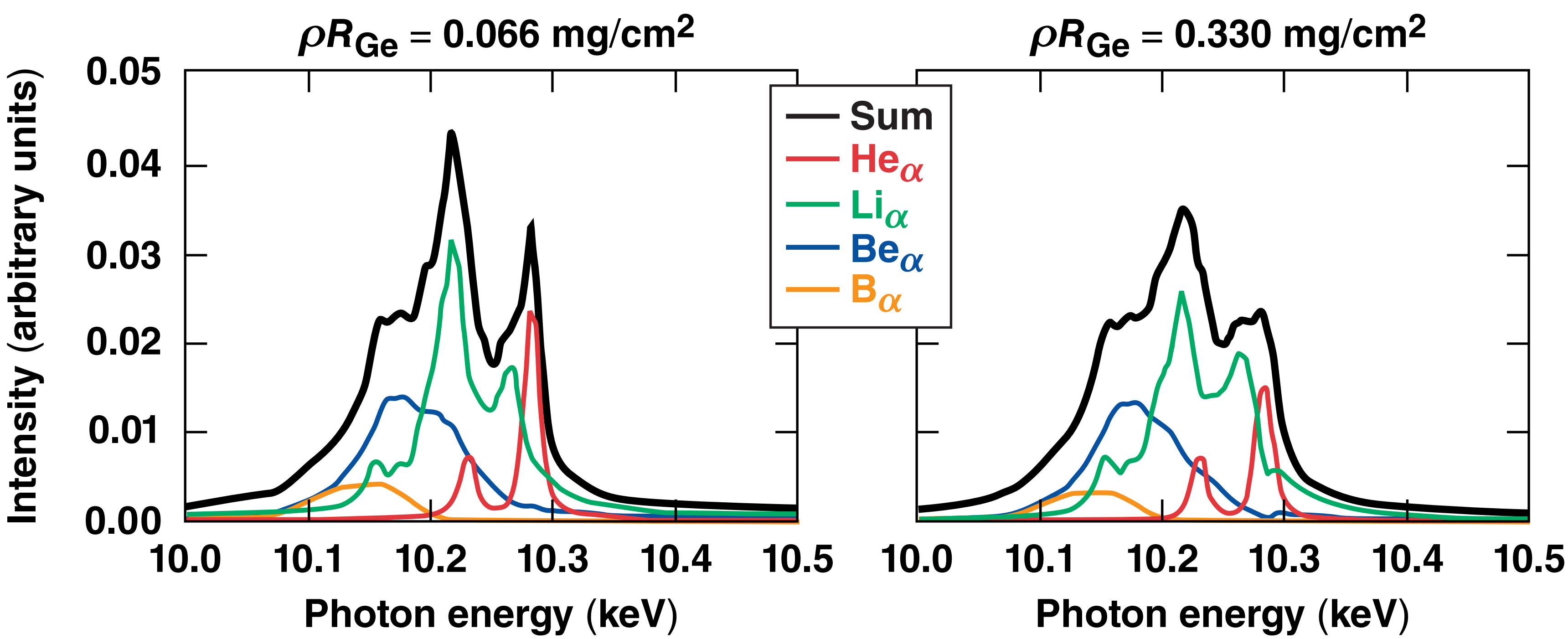
- HSXRS response function has been applied

Spectral feature contains Ge B-like to Ge He-like charge states.

E19886b

The calculated spectral line shapes are sensitive to variations in the Ge areal density

$n_e = 1 \times 10^{25}$ cm^{-3}, $T_e = 2.0$ keV



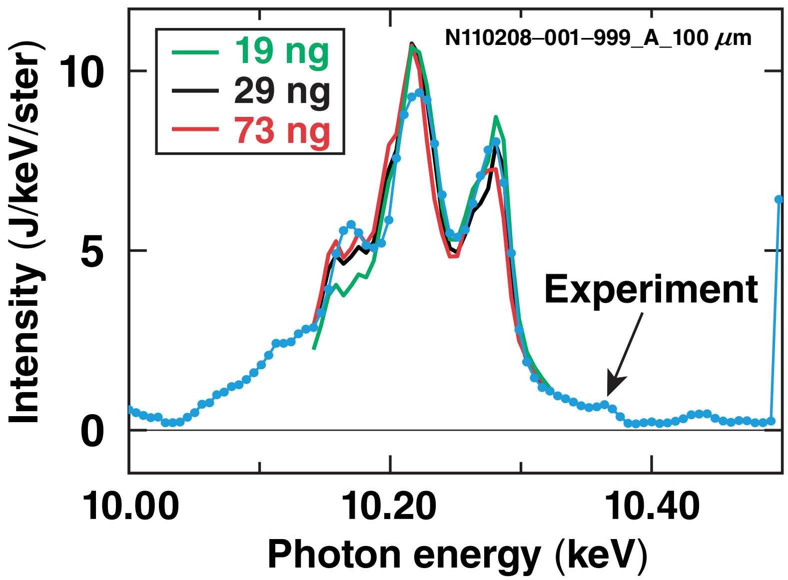
- HSXRS response function has been applied

Spectral feature contains Ge B-like to Ge He-like charge states.

E19887a

Hot-spot mix mass is determined from inferred n_e, T_e, and ρR_{Ge} and absolute brightness of Ge He$_\alpha$ and satellite spectrum

Symcap: $n_e = 1.0\ (+0, -0.5) \times 10^{25}\ cm^{-3}$
$T_e = 2.3\ (+0.4, -0.3)$ keV
$\rho R_{Ge} = 0.125\ (+0.025, +0.1)\ mg/cm^2$
Mix mass = 29 (–10, +44) ng



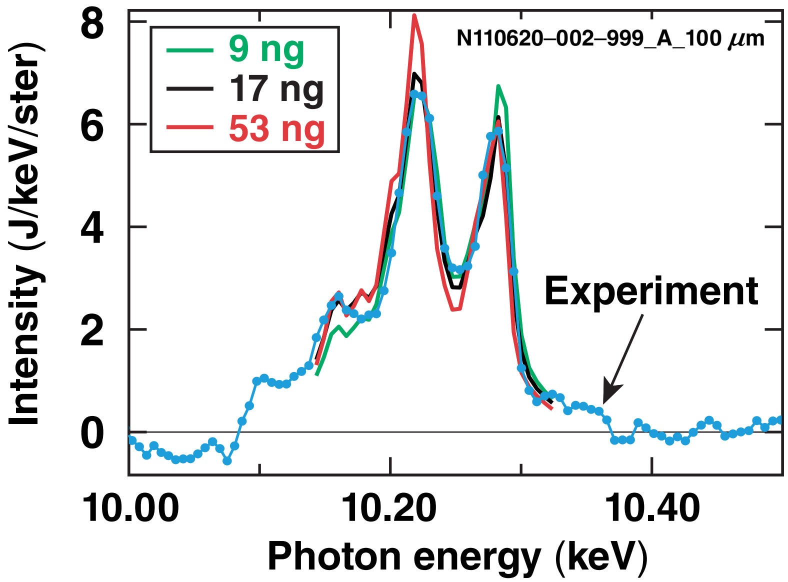
- Spectrum was corrected for shell attenuation
- Sphere diameter ~ μm and number of spheres ~10^2 to 10^4

Mix-mass density: $n_e \rightarrow \rho_{CHGe}$ assuming $Z = 3.75$
Radius of sphere: $R = \rho R_{CHGe}/\rho_{CHGe}$
Mix-mass in sphere: $M_{sphere} = 4\pi R^3\ \rho_{CHGe}/3$
Total mix mass: M_{total} = (measured brightness/brightness per sphere) M_{sphere}

E20504

Similar analysis is performed for cryogenic layered DT and THD implosions

DT: n_e = 0.8 (+0.2, –0.5) × 10^{25} cm^{-3}
T_e = 2.4 (+0.6, –0.3) keV
ρR_{Ge} = 0.075 (+0, –0) mg/cm^2
Mix mass = 17 (–8, +36) ng



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Radius of sphere: $R = \rho R_{CHGe}/\rho_{CHGe}$
Mix mass in sphere: $M_{sphere} = 4\pi R^3 \rho_{CHGe}/3$
Total mix mass: M_{total} = (measured brightness/brightness per sphere) M_{sphere}

E20505

Hot-spot mix mass inferred from x-ray spectroscopy is typically within the 75-ng allowance*

Shot	CH Ge mix mass (ng)
N100929	74 (–48, +55)
N110121	67 (–47, +110)
N110201	15 (–12, +285)
N110212	20 (–17, +265)
N110603	18 (–14, +23)
N110608	63 (–44, +65)
N110615	15 (–10, +56)
N110620	17 (–8, +36)
N101004	14 (–7, +30)
N110208	29 (–10, +44)
N110211	20 (–8, 24)
N110612	79 (–39, 300)

THD
DT
Symcap

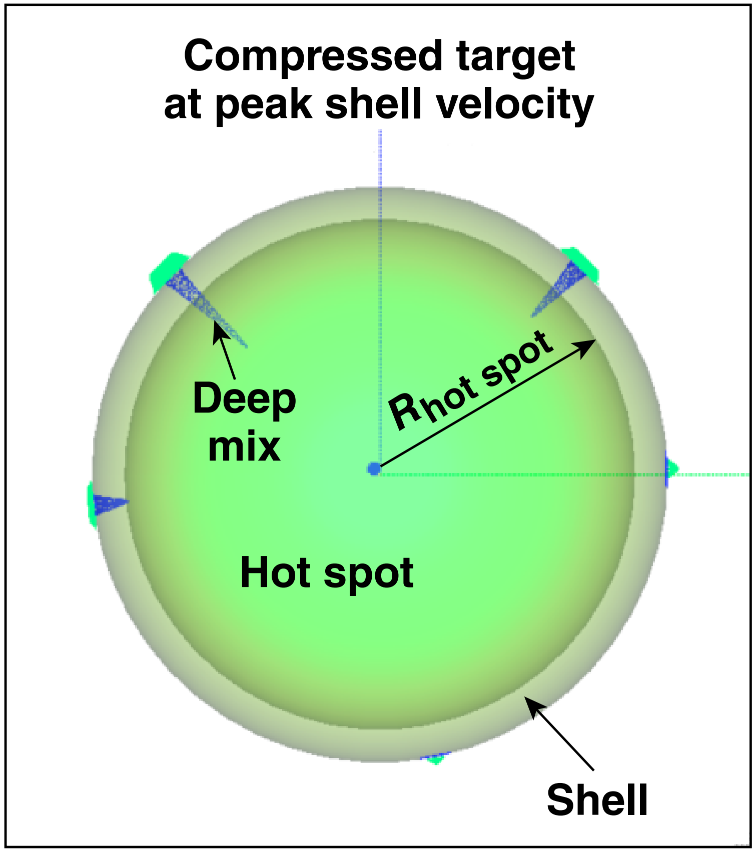
<75 ng

There is a requirement for ignition, set from multidimensional radiation–hydrodynamic simulations, that the hot-spot mix mass be less than 75 ng.*

E20511

*S. W. Haan *et al.*, Phys. Plasmas 18, 051001 (2011).

The mix mass is estimated with a model that combines linear analysis with detailed simulations of perturbation growth



Mix-mass model*

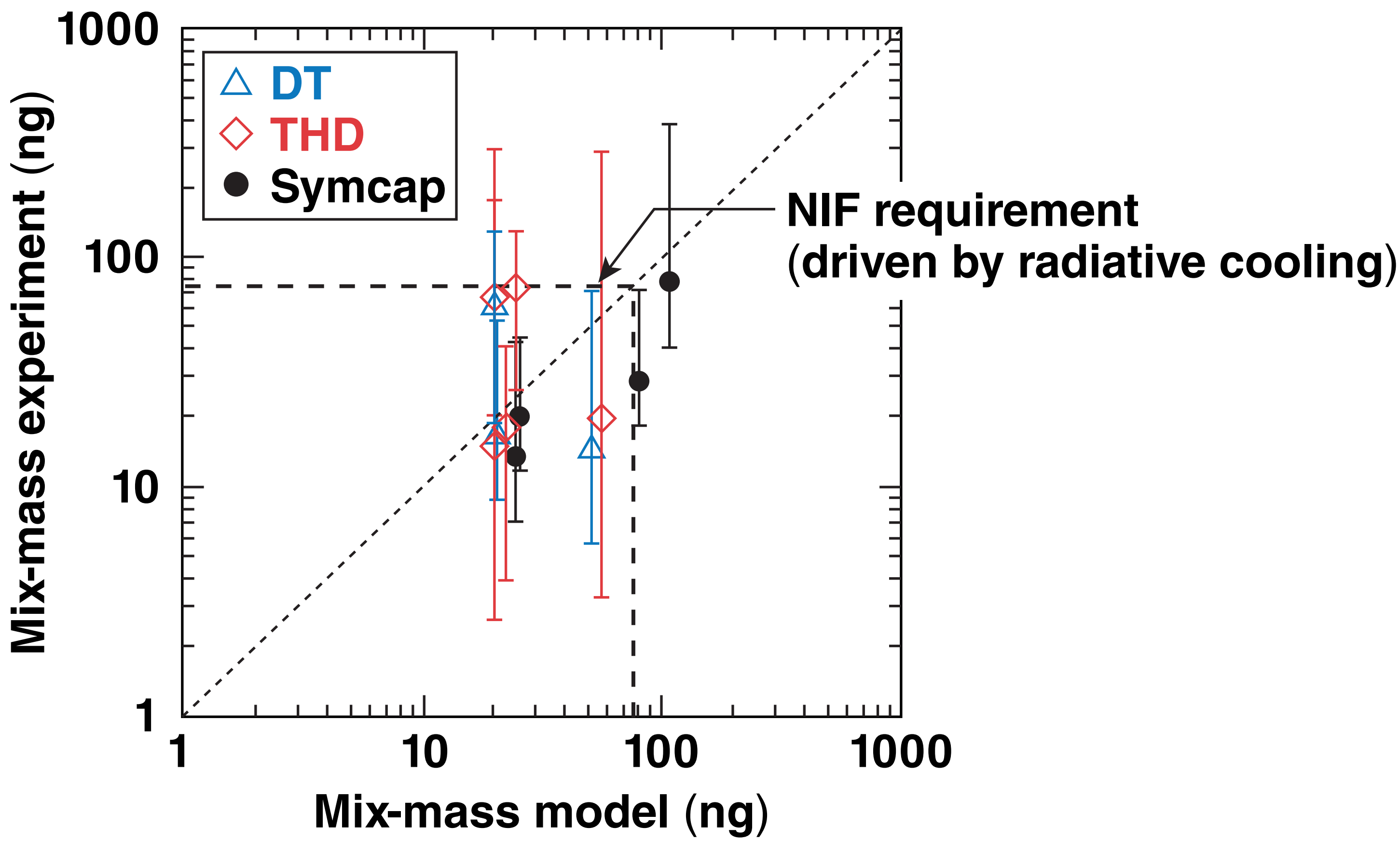
1. Transform capsule surface maps into ℓ space
2. Multiply by growth factors at peak velocity
3. Transform back to physical space
4. Find volume of ablator inside the hot spot
5. Multiply by density calibrated with detailed bump simulations (~10 g/cc)
6. The resulting mass is an estimate of what gets into the hot spot

Based on 2-D simulations, 20 ng of mix mass is added for the fill-tube jets.

E19890a

*J. Ralph, Bull. Am. Phys. Soc., T05.5 (2010).

The inferred amount of hot-spot mix for ignition-scale implosions is comparable to or below the 75-ng requirement

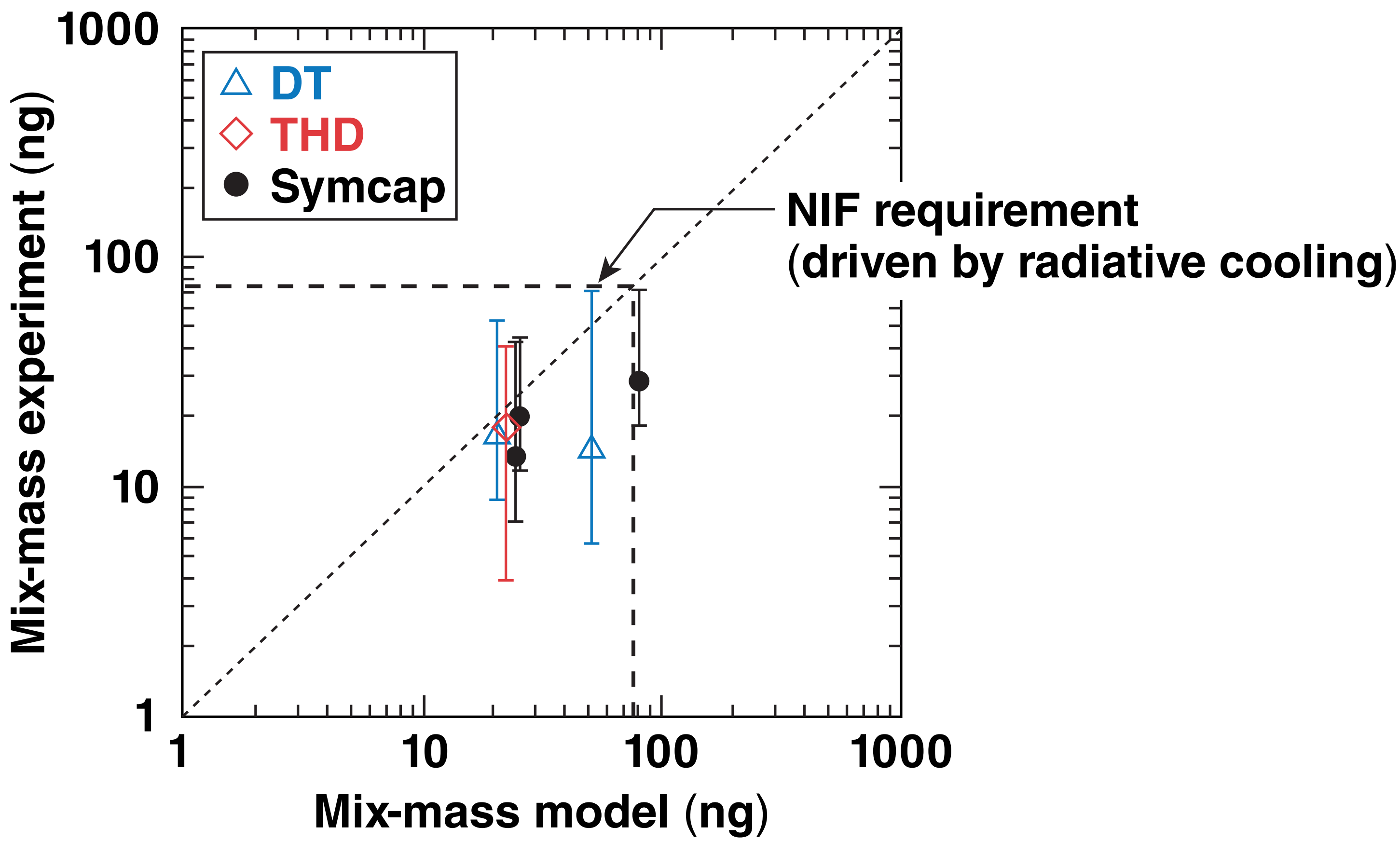


Further efforts may be needed to control hot-spot mix:

1. Reduce capsule surface-mass perturbations
2. Reduce the growth factors of hydrodynamic instability
3. Change the ablator material (e.g., Cu-doped Be)

E20075a

The inferred amount of hot-spot mix for ignition-scale implosions is comparable to or below the 75-ng requirement



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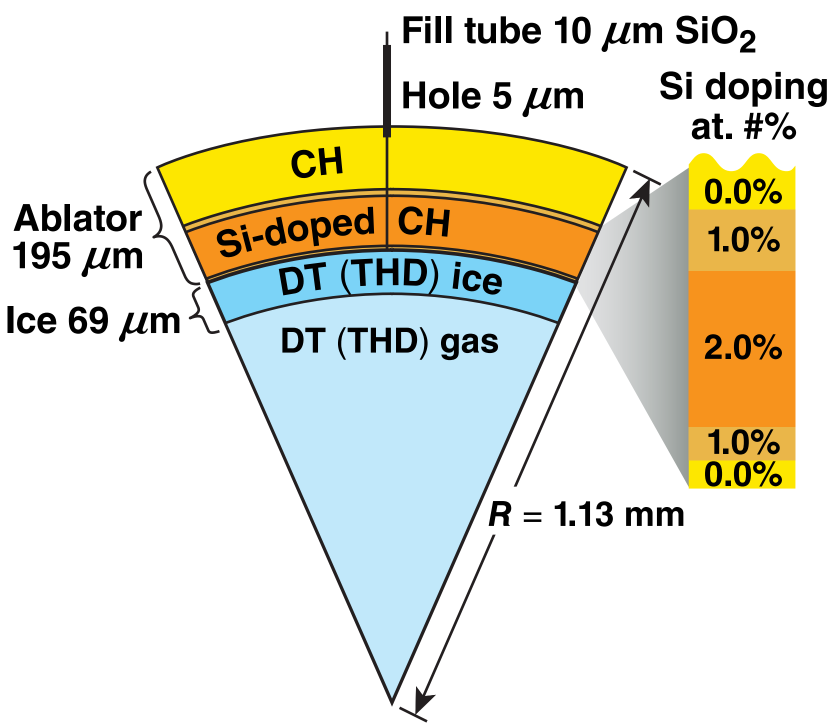
E20075a

The Ge dopant in the Rev. 5 ablator of the ignition target design has been replaced with a Si dopant*

Ignition target with Si-doped plastic ablator



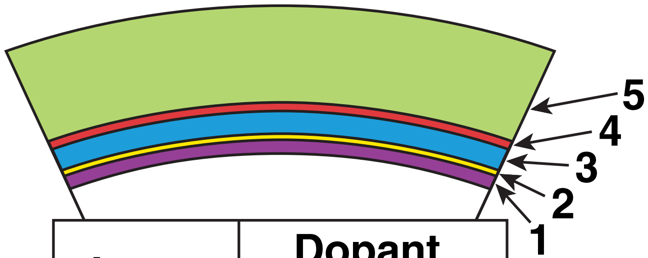
Variants of this capsule doped with trace amounts of Ge and Cu will be used to diagnose hot-spot mix with x-ray spectroscopy.

*S. Glenzer, BI3.00001.
*D. Callahan, BI3.00002.
*D. Hicks, BI3.00003.
*B. Spears, BI3.00006.

E20512

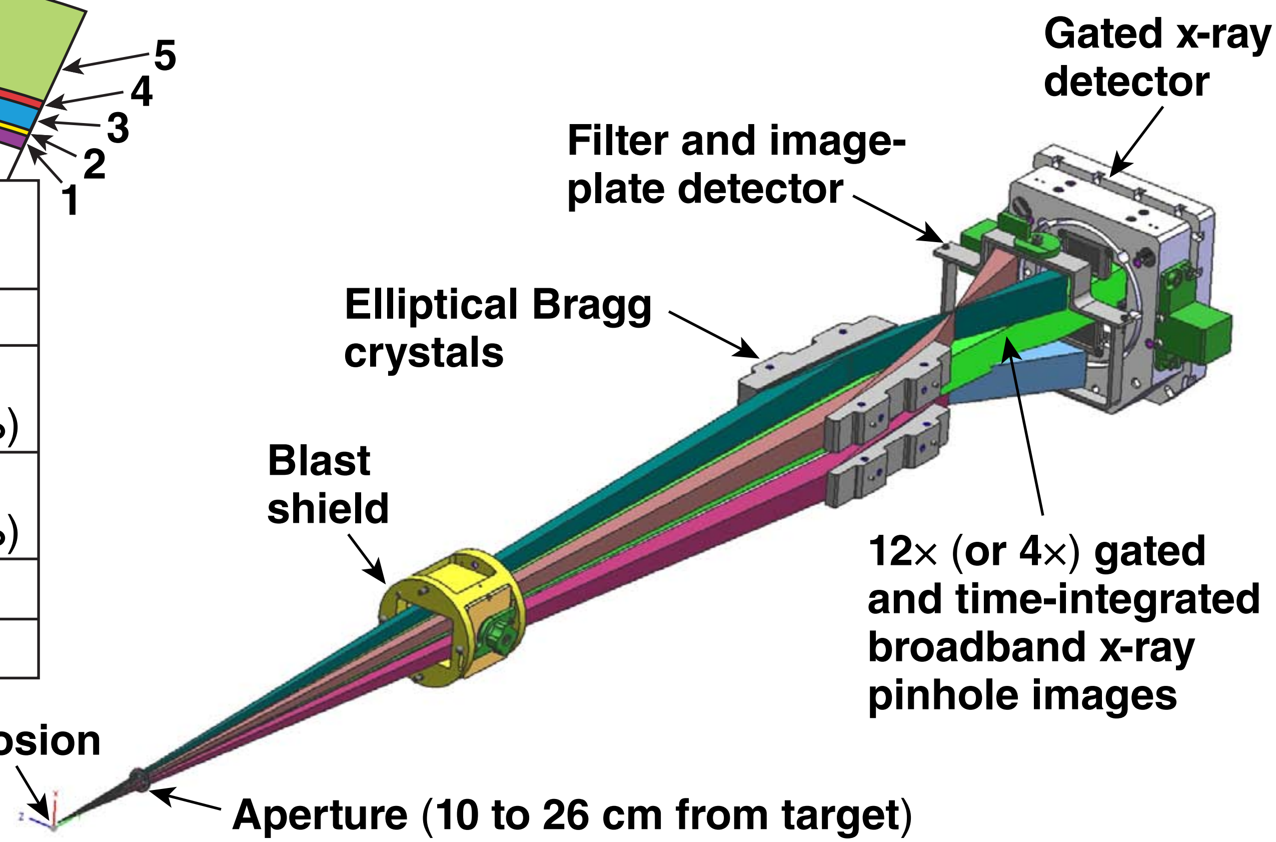
Hot-spot mix will be examined with Cu and Ge ablator dopants in NIF ignition-scale implosions

Cu, Ge, Si-doped CH ablator



Layer	Dopant (atm. %)
1	Cu (0.1%)
2	Si (0.7%) Ge (0.15%)
3	Si (1.7%) Ge (0.15%)
4	Si (1%)
5	None

Supersnout II (5.75 to 16.5 keV)



X-ray radiography of imposed surface perturbations will be studied in future experimental campaigns.*

E19892a

*K. J. Peterson *et al.*, PO6.00006.

Summary/Conclusions

Hot-spot mix in NIF ignition-scale implosions is diagnosed with Ge K-shell spectroscopy

- Hydrodynamic instabilities are predicted to mix CH and Ge ablator mass deep into the hot spot at ignition time (hot-spot mix)*
- The hot-spot mix mass was estimated from the Ge K-shell line brightness using a detailed atomic physics model
- Predictions of a simple mix model are consistent with the experimental results

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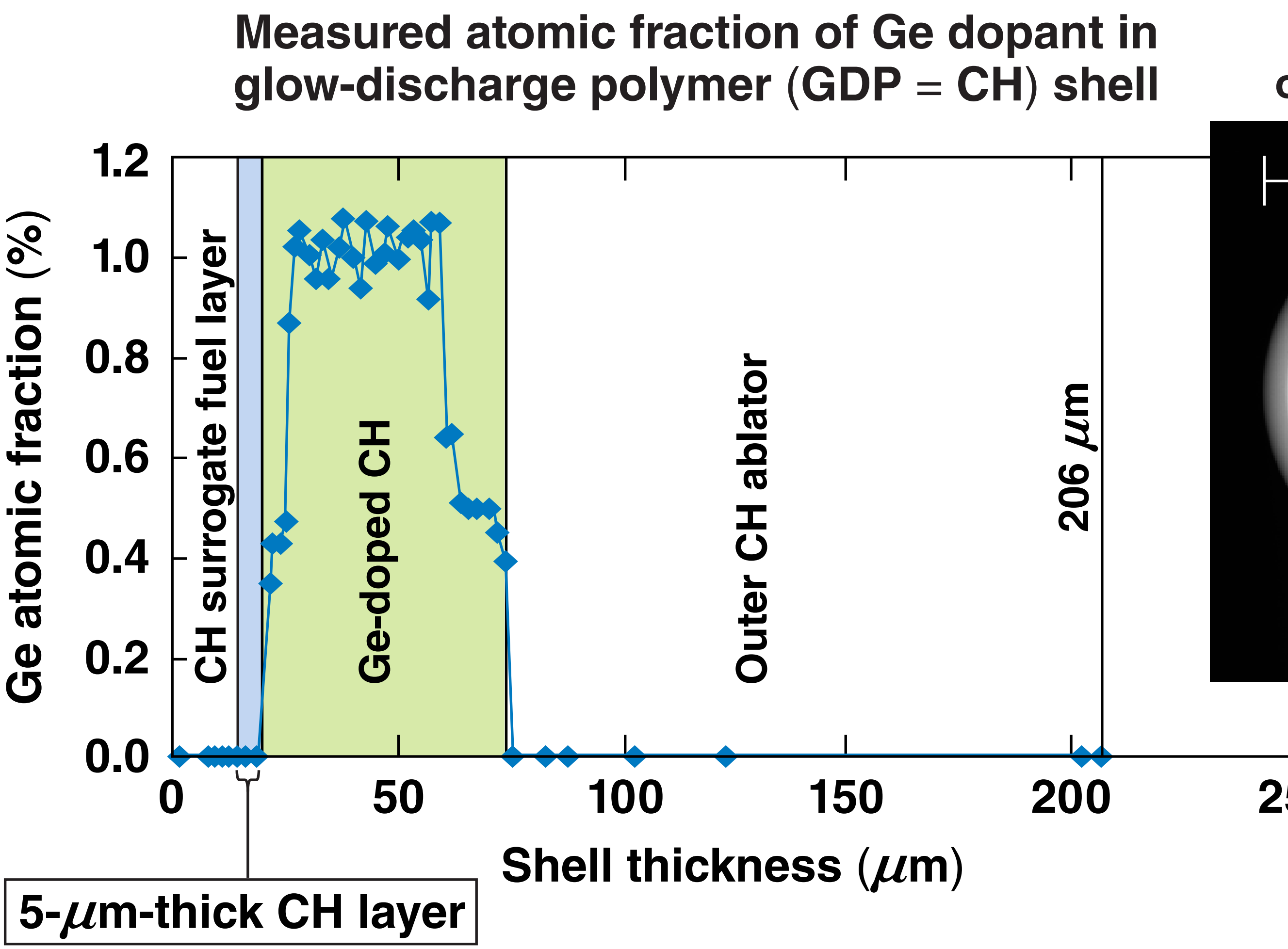
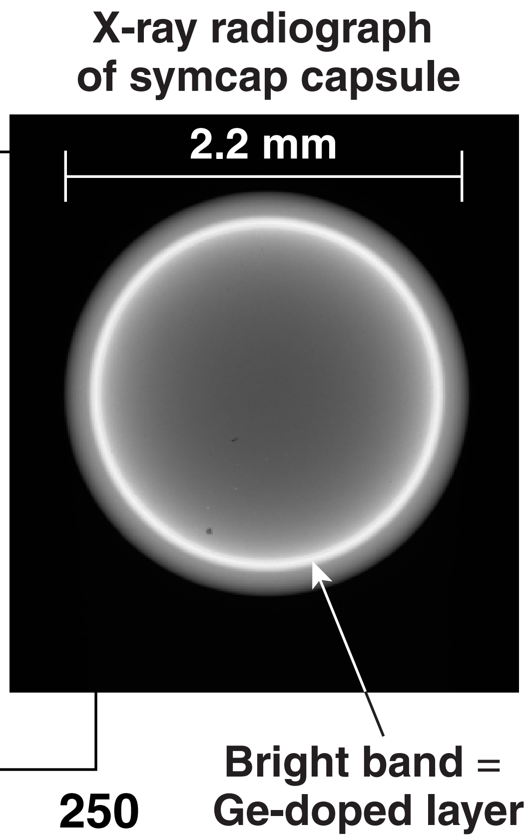




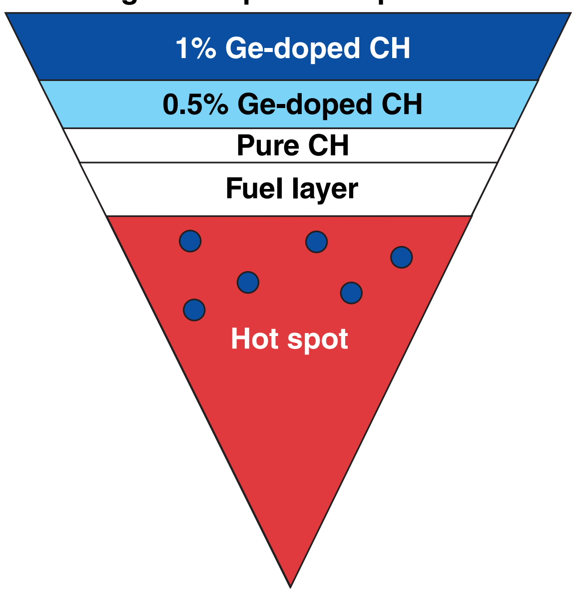
Ge dopant in the ablator provides a spectroscopic signature of hot-spot mix.

E19876

Hot-spot mix mass was diagnosed on four NIF symcap implosions

Shot	Mix n_e ($\times 10^{25}$ cm^{-3})	Mix T_e (keV)	Mix ρR_{Ge} (mg/cm^2)	CH Ge mix mass (ng)
N101004	0.8 (+0.2, –0.5)	2.4 (+0.6, –0.3)	0.150 (–0, +0.25)	14 (–7, +30)
N110208	1.0 (+0, –0.5)	2.3 (+0.4, –0.3)	0.125 (+0.025, +0.1)	29 (–10, +44)
N110211	0.9 (+0.1, –0.4)	2.0 (+0.3, –0.2)	0.150 (–0, +0.125)	20 (–8, 24)
N110612	0.9 (+0.1, –0.5)	2.2 (+0.5, –0.5)	0.075 (+0.025, –0)	79 (–39, 300)

Target near peak compression



Sphere diameter ~ μm

Number of spheres ~ 10^2 to 10^4

- Hot-spot mix-mass analysis assumes uniform plasma conditions with 10 Gbar < P < 50 Gbar lasting 250 ps, 1% atomic Ge dopant, and 30% shell transmission

E19889a

Hot-spot mix mass was diagnosed on eight NIF cryogenic-DT or THD layered implosions

Shot	Mix n_e ($\times 10^{25}$ cm^{-3})	Mix T_e (keV)	Mix ρR_{Ge} (mg/cm^2)	CH Ge mix mass (ng)
N100929	0.4 (+0.6, +0.1)	1.7 (+0.2, –0.2)	0.075 (+0, –0)	74 (–48, +55)
N110121	0.3 (+0.6, +0.1)	2.1 (+0.3, –0.5)	0.075 (+0, –0)	67 (–47, +110)
N110201	1.0 (+0, –0.4)	1.6 (+0.8, –0.5)	0.2 (–0.1, +0.15)	15 (–12, +285)
N110212	0.5 (+0.1, +0.1)	1.6 (+0.8, –0.5)	0.075 (–0, +0.15)	20 (–17, +265)
N110603	0.4 (+0.6, +0)	1.9 (+0.6, –0.3)	0.075 (+0.025, –0)	18 (–14, +23)
N110608	0.4 (+0.6, +0)	2.0 (+0.4, –0.3)	0.075 (+0, –0)	63 (–44, +65)
N110615	0.9 (+0, –0.5)	2.2 (+1,0, –0.5)	0.075 (+0, –0)	15 (–10, +56)
N110620	0.8 (+0.2, –0.5)	2.4 (+0.6, –0.3)	0.075 (+0, –0)	17 (–8, +36)

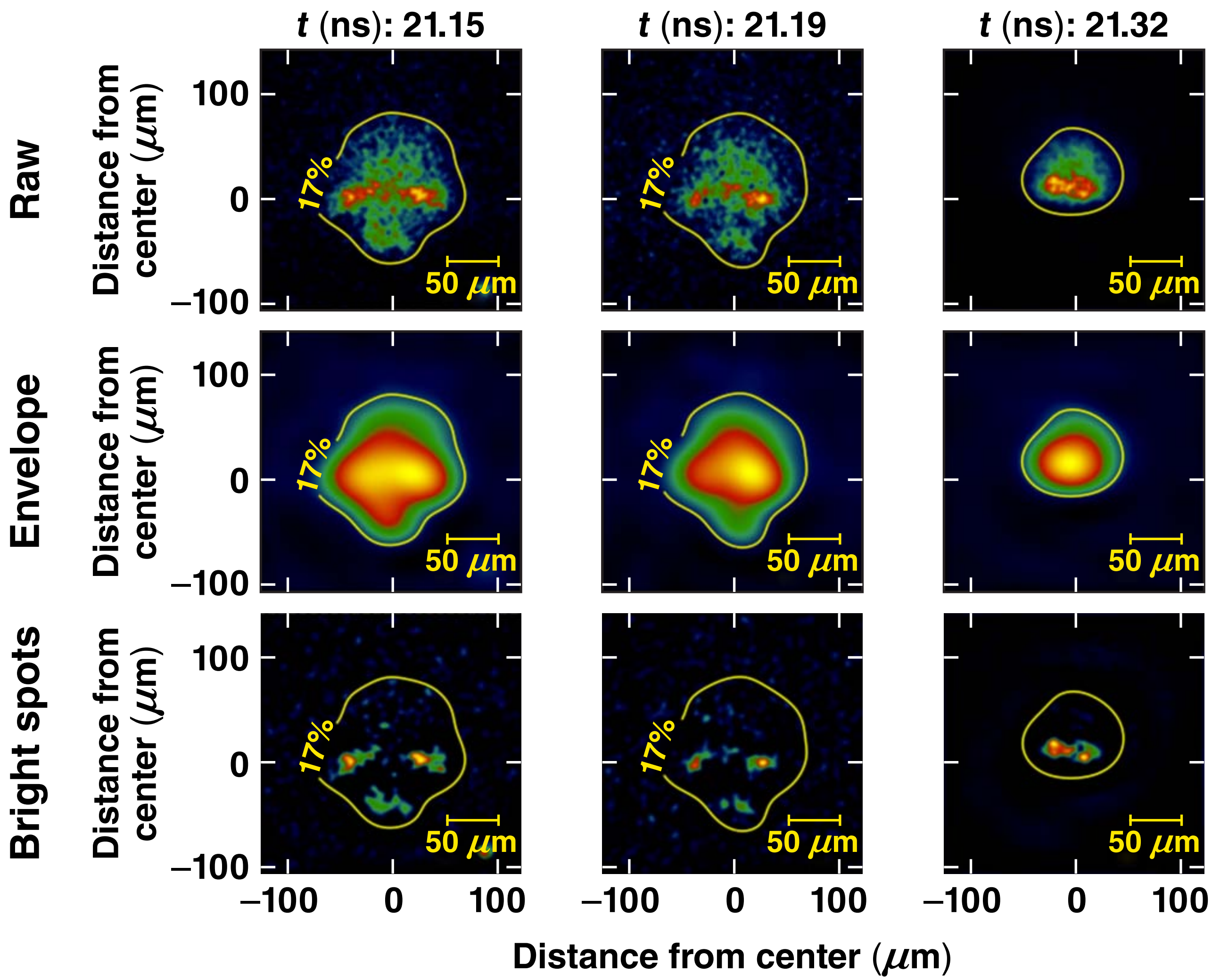
THD
DT

Sphere diameter ~ μm

Number of spheres ~ 10^2 to 10^4

- Hot-spot mix-mass analysis assumes uniform plasma conditions with 10 Gbar < P < 50 Gbar lasting 250 ps, 1% atomic Ge dopant, and 30% shell transmission

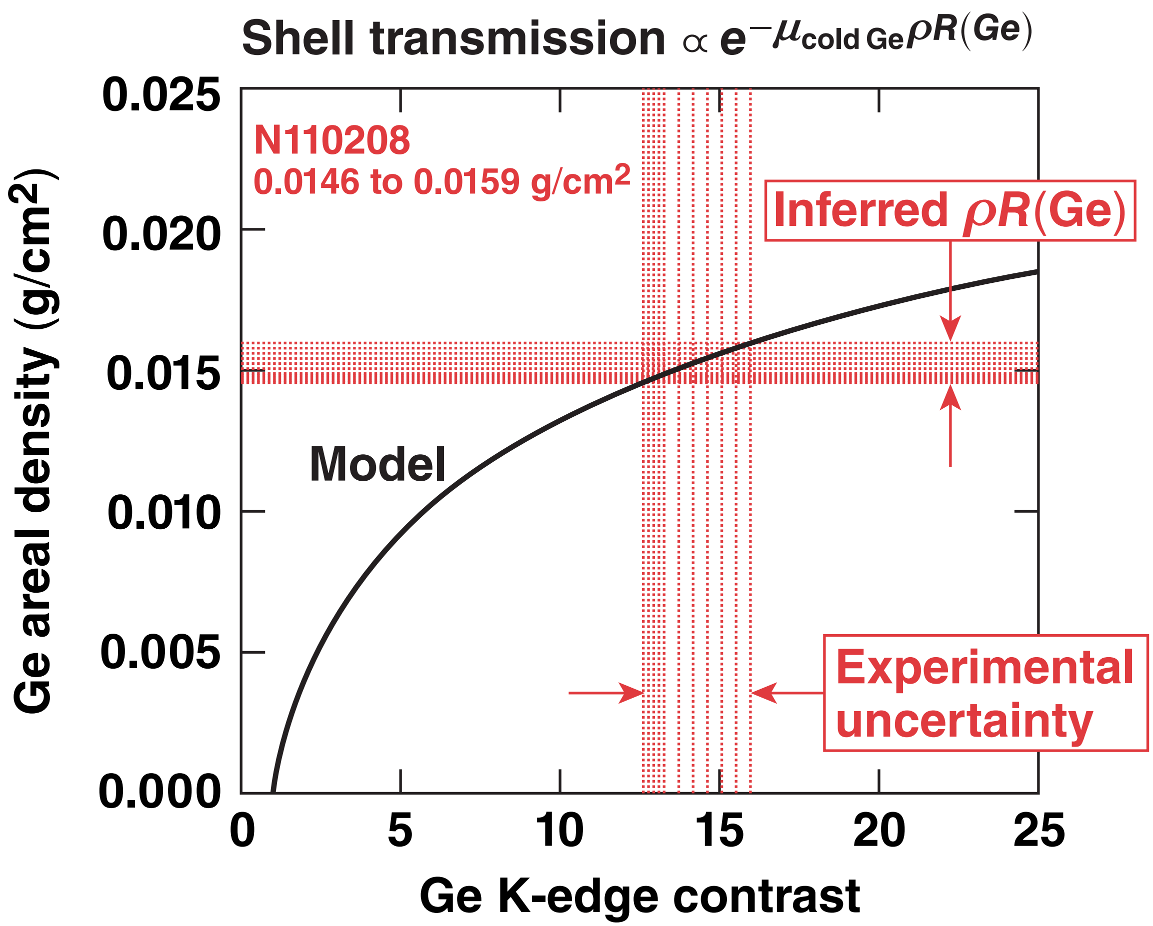
The bright spots in the gated images could be evidence of ablator material jets in the hot spot



Fourier analysis is used to filter envelope and bright spots from raw image.

E19994

The Ge K-edge contrast and cold Ge opacity are used to diagnose the areal density of Ge-doped ablators



$$\frac{\rho R(\text{CH Ge})}{\rho R(\text{Ge})} = \frac{\text{mass}(\text{CH Ge})}{\text{mass}(\text{Ge})} = \begin{Bmatrix} 18.9 \text{ for } 0.5\% \text{ atomic fraction} \\ 9.9 \text{ for } 1.0\% \text{ atomic fraction} \end{Bmatrix}$$

E19996