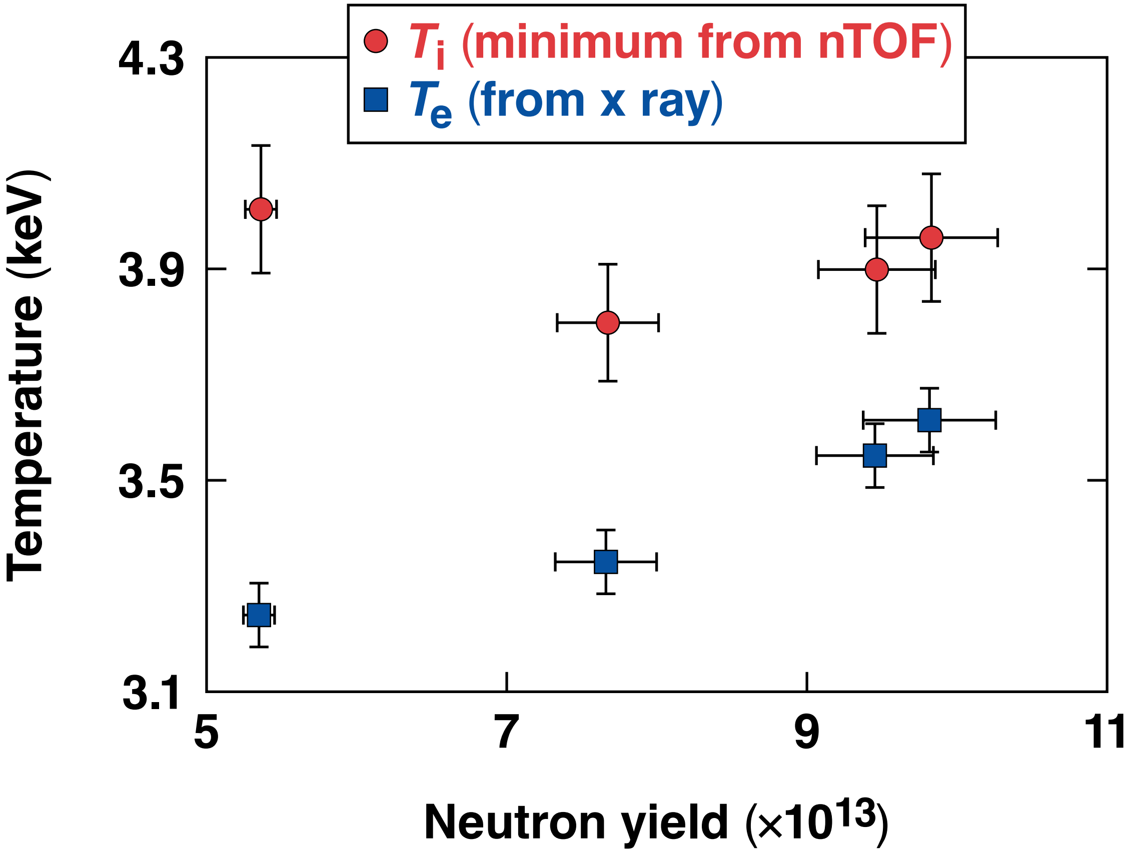
Using the 10 to 20 keV X-Ray Spectrum to Infer an Electron Temperature (T_e) as an Implosion Diagnostic on OMEGA



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Summary

Preliminary hot-spot electron temperatures have been obtained by 10 to 20 keV x-ray measurements on OMEGA direct-drive cryogenic implosions

- The electron temperature is inferred from fitting the log slope of the x-ray spectrum, with choice of photon energy determining spatial weighting
- As a stagnation metric to study hot-spot formation, T_e complements the hot-spot ion temperature (T_i) inferred from neutron diagnostics
- Preliminary x-ray measurements show the expected increase of neutron yield with electron temperature, in contrast to measured ion temperatures

A spectral imaging diagnostic is being developed to diagnose the hot-spot T_e on every DT cryogenic implosion.

Collaborators

**R. C. Shah, S. P. Regan, C. Sorce, R. Epstein, I. V. Igumenshchev, V. Gopalaswamy,
A. R. Christopherson, W. Theobald, P. B. Radha, and V. N. Goncharov**

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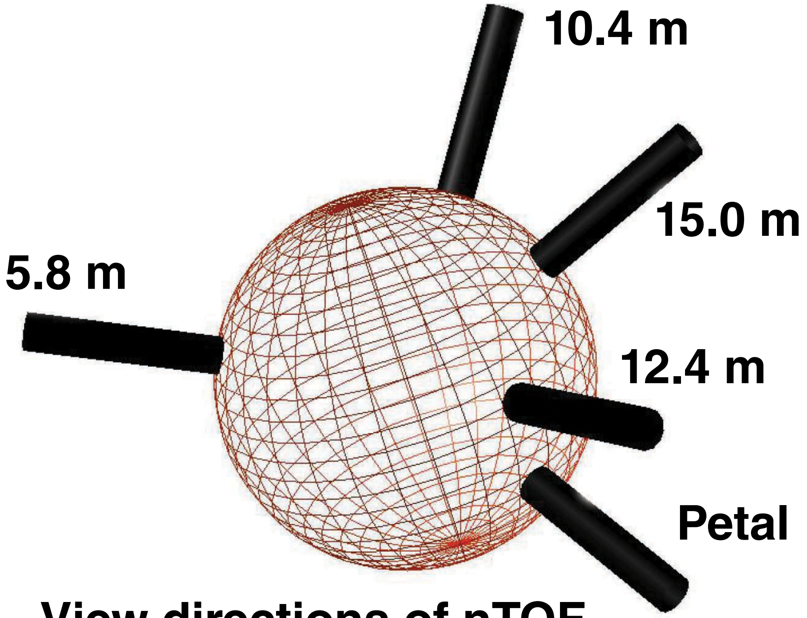
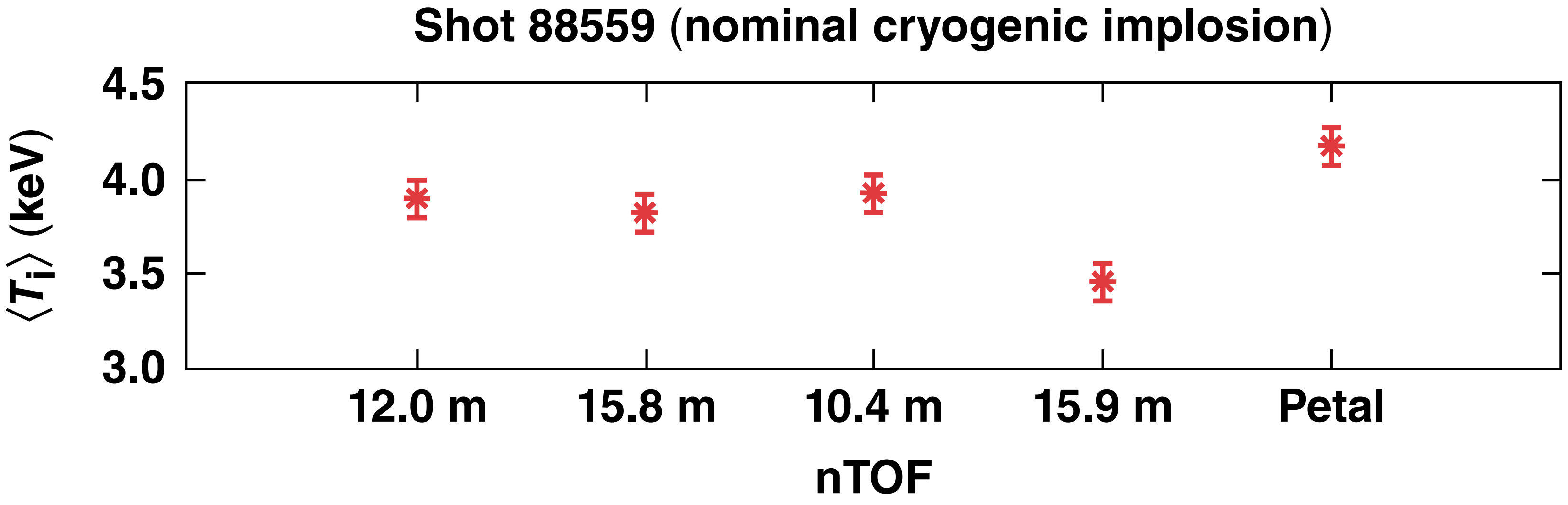
Neutron-weighted ion temperatures are biased by hot-spot fluid motions*

- **Inferred T_i is obtained from the neutron spectrum, constructed by neutron time-of-flight (nTOF) measurements**



View directions of nTOF orientations on OMEGA



- **Fluid motion affects neutron time-of-flight and consequently induces T_i variation**

There exists a need for diagnosing the hot-spot temperature without bias from hot-spot motion.

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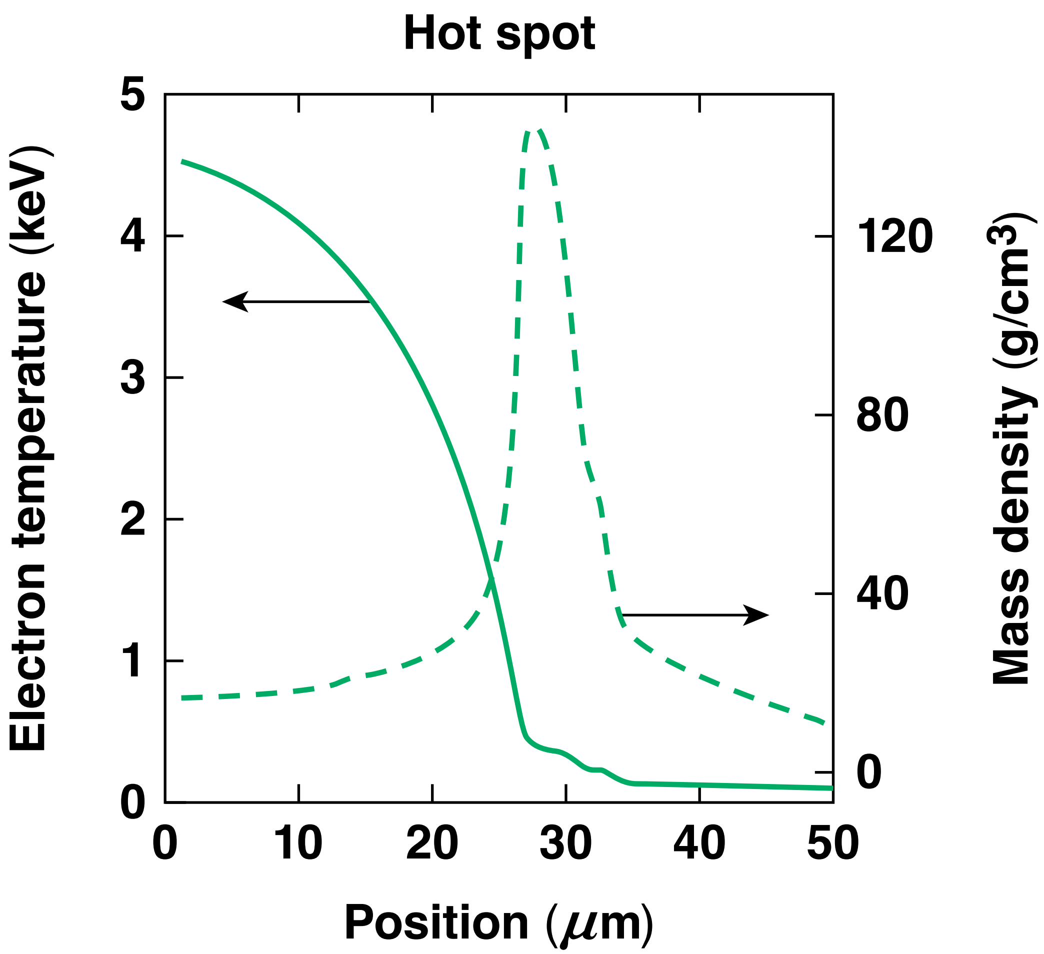
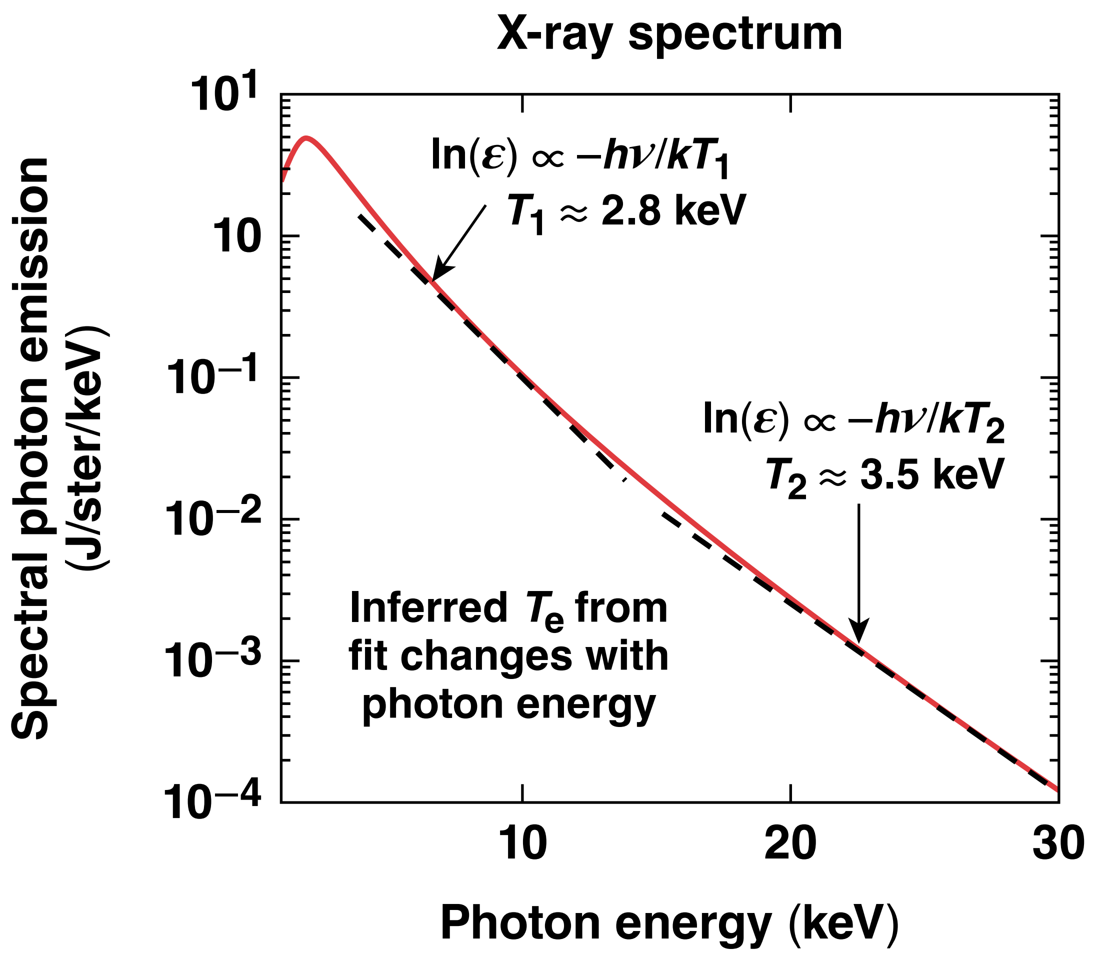
*T. J. Murphy, R. E. Chrien, and K. A. Klare, Rev. Sci. Instrum. 68, 610 (1997);
*C. Forrest *et al.*, BO6.00005, this conference.

E27217a

The x-ray spectrum offers a robust measure of emission-weighted, inverse temperature (i.e., $\langle 1/kT \rangle$)





$\ln(\varepsilon) \propto -h\nu/kT_1$

$T_1 \approx 2.8$ keV

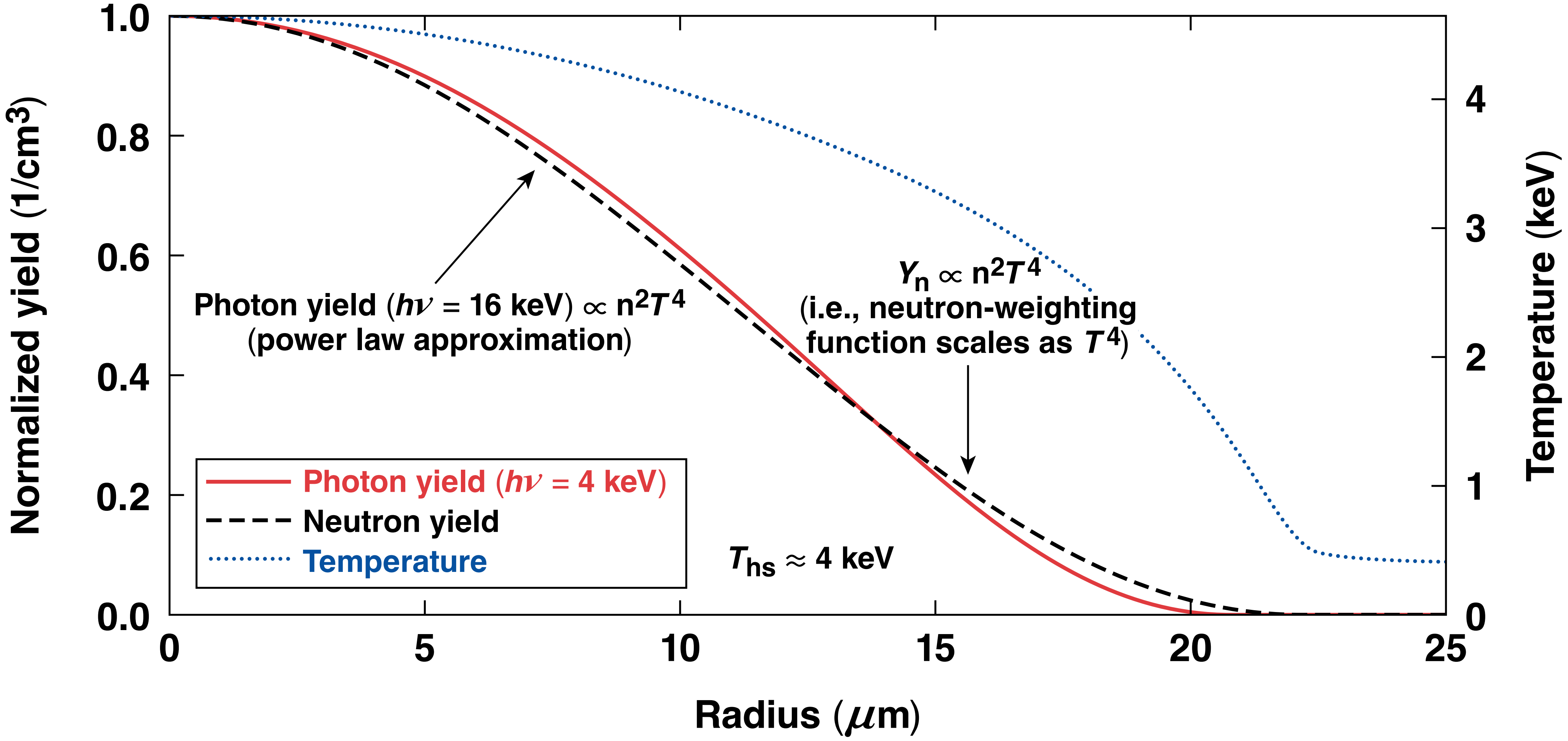
$\ln(\varepsilon) \propto -h\nu/kT_2$

$T_2 \approx 3.5$ keV

Inferred T_e from fit changes with photon energy

TC14544

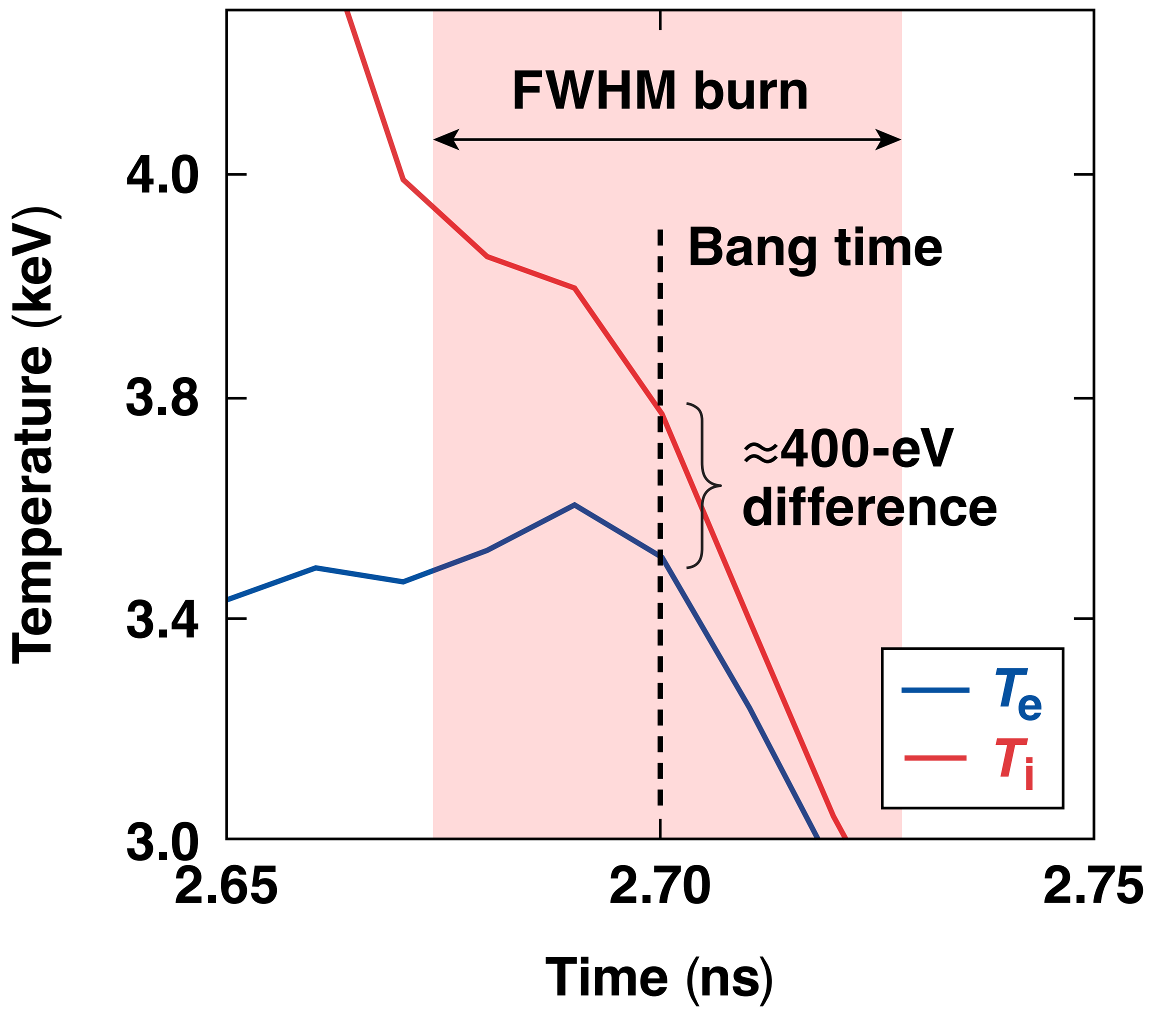
Using x rays at $h\nu \approx 4\ kT_{hs}$ gives an emission weighting that approximates neutron weighting



TC14545

For OMEGA-scale implosions, T_e and T_i are not in equilibrium during neutron production time

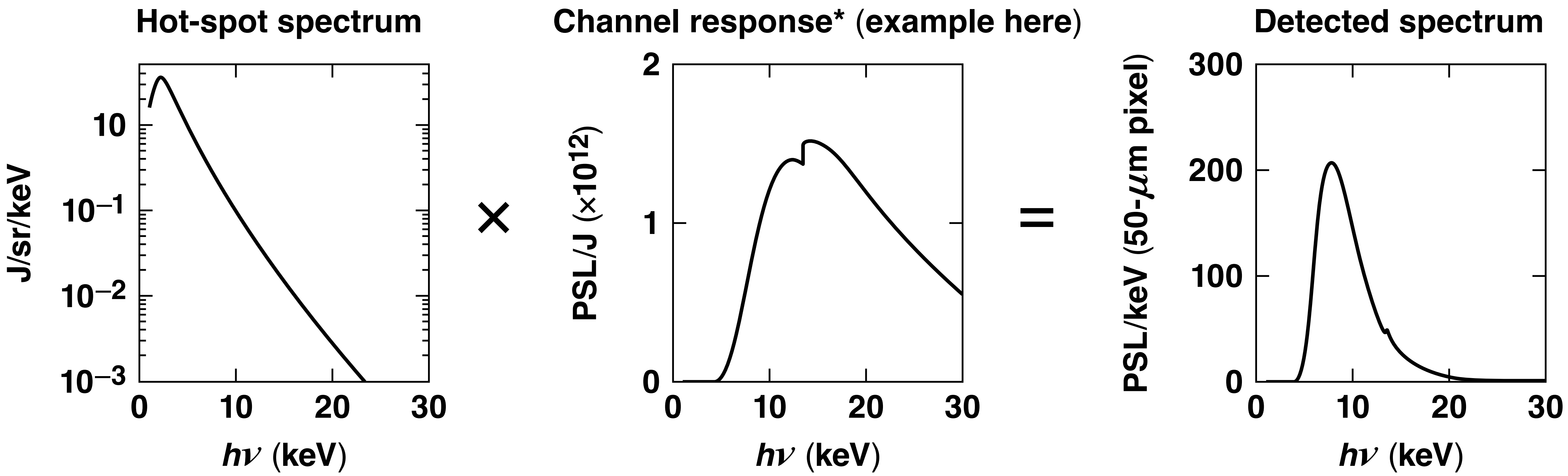
Neutron-weighted temperature versus time



- Despite $T_e \neq T_i$, we are still exploring approaches to link the measured electron temperature to ion temperature

TC14546

Transmission through known filters is being used to measure the electron temperature and absolute x-ray signal



- Mean channel energies range from 10 to 20 keV to have best fit near $h\nu = 4\ kT_{\mathrm{hs}}$ (≈ 15 keV)
- Coronal emission contribution is discriminated using imaging
- The filter-inferred electron temperature technique also in use at the National Ignition Facility**

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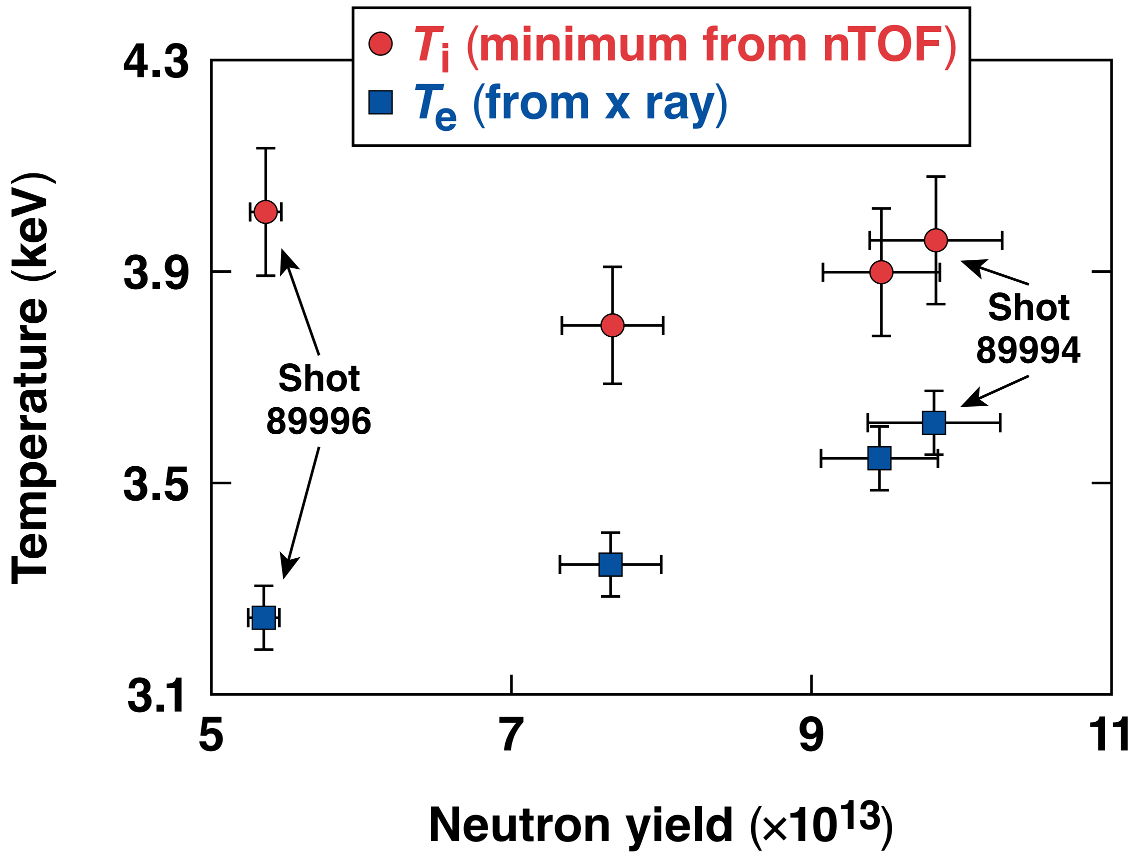
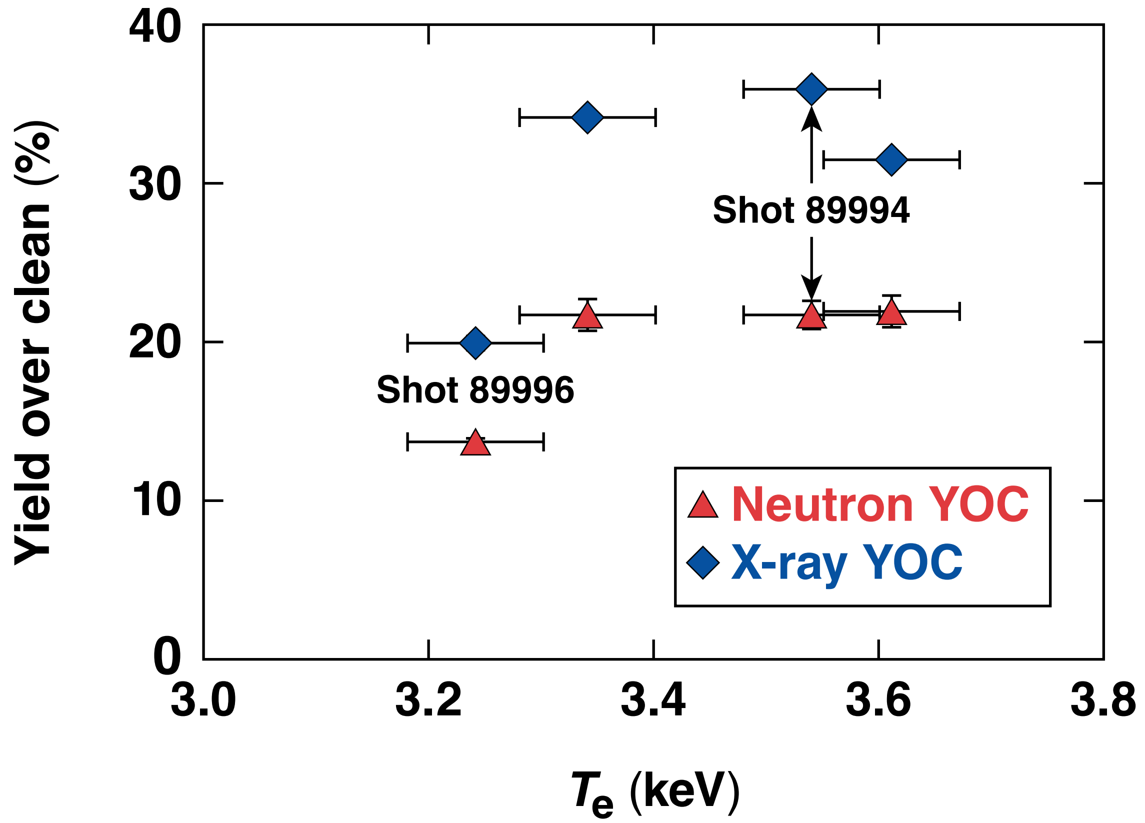
*M. J. Rosenberg *et al.*, "Image-Plate Sensitivity to X Rays at 2 to 60 keV for Spectrometers on OMEGA and the National Ignition Facility," submitted to Review of Scientific Instruments.

**L. C. Jarrott *et al.*, Rev. Sci. Instrum. 87, 11E534 (2016).

Preliminary x-ray measurements show an increase of neutrons and x-ray yield with electron temperature





The inferred T_e robustly diagnoses hot-spot internal energy compared to min (T_i).

- The absolute signal and inferred T_e will be used to infer ablator mix amounts*

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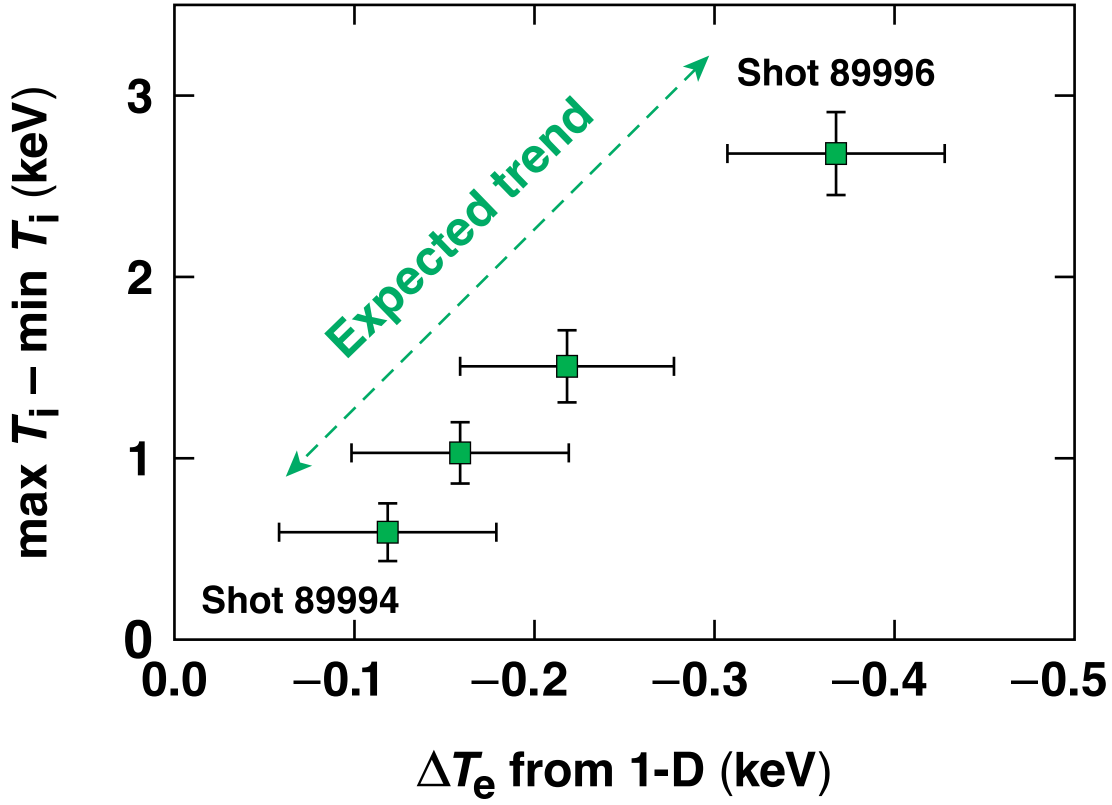
*T. Ma *et al.*, Phys. Rev. Lett. 111, 085004 (2013);
R. Epstein *et al.*, Phys. Plasmas 22, 022707 (2015).

TC14548

T_i variation (a signature of hot-spot fluid motion) increases with T_e degradation from 1-D

- **Large variations in T_i measurements imply the presence of hot-spot asymmetries (i.e., degradation from 1-D)**
  - **correlated to yield loss in the experiment***
- **As a consistency check, T_i variation should also scale with T_e degradation from 1-D**



TC14555

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[*] V. Gopalaswamy, TI3.00002, this conference (invited).

Preliminary hot-spot electron temperatures have been obtained by 10 to 20 keV x-ray measurements on OMEGA direct-drive cryogenic implosions

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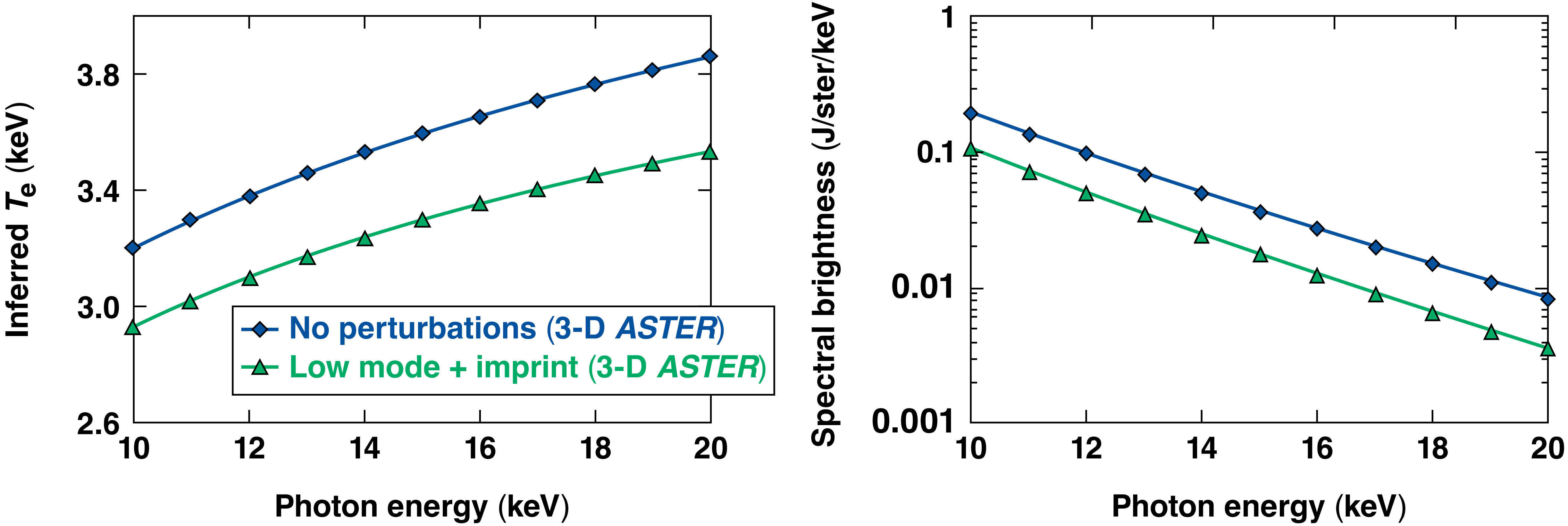
Backup

Three-dimensional *ASTER** simulations show T_e and x-ray yield decrease from 1-D

No perturbations: $\langle T_i \rangle = 4.67$ keV, $Y_n = 4.1 \times 10^{14}$

Low-mode imprint: $\langle T_i \rangle = 4.35$ keV, $Y_n = 2.0 \times 10^{14}$



TC14549

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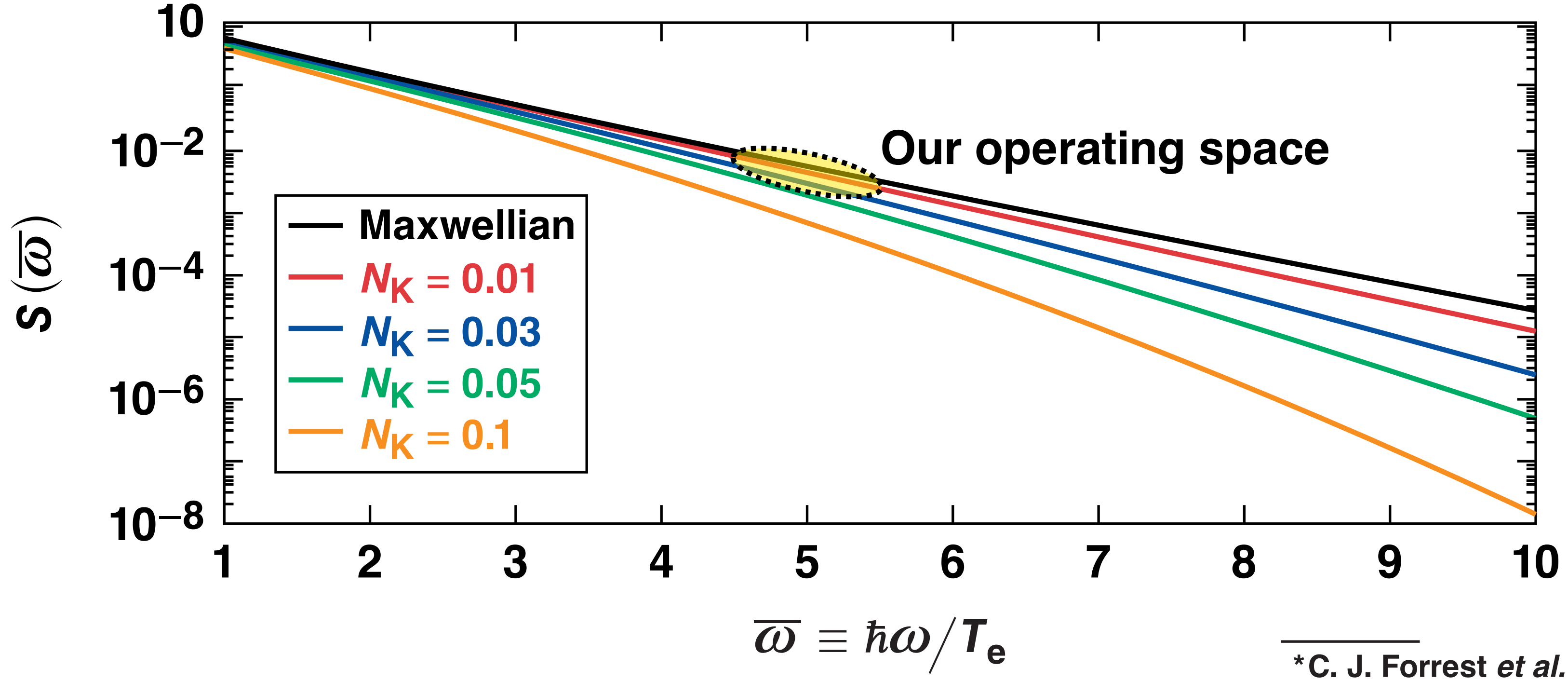
*I. V. Igumenshchev *et al.*, Phys. Plasmas 23, 052702 (2016).

Data suggest kinetic effects at $h\nu$ = 10 to 20 keV would be weak, but more analysis would be beneficial

- We assume that 10- to 20-keV photons emit from a Maxwellian electron distribution
- Validity of the Maxwellian approximation is based on the smallness of the Knudsen number $N_K = \lambda_e / R_h$
- For OMEGA cryo implosions during burn, N_K was found to be ~0.003* (data support)

Single T_e x-ray spectrum for various N_K**



The study should be repeated with more relevant T and ρ profiles

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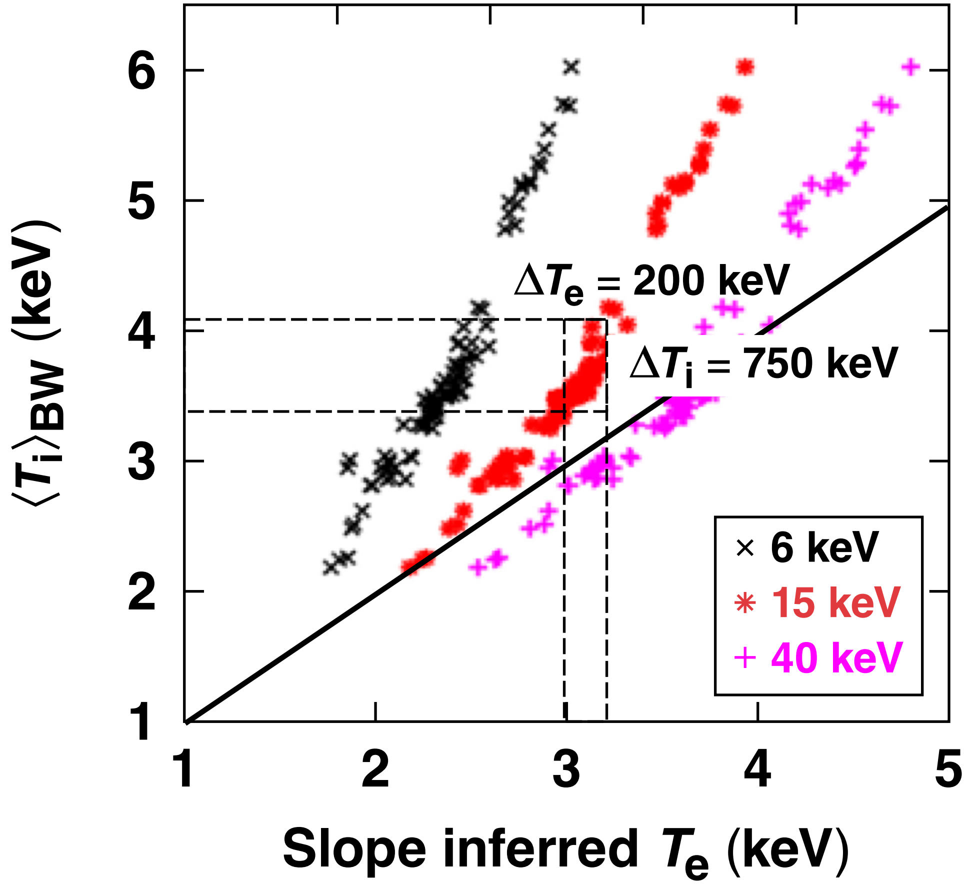
[*] C. J. Forrest *et al.*, Phys. Rev. Lett. 118, 095002 (2017).

[**] G. Kagan *et al.*, "Inference of the Electron Temperature in Inertial Confinement Fusion Implosions from the Hard X-Ray Spectral Continuum," to be published in Contributions to Plasma Physics.

TC14550

LILAC simulations suggest poor correlation between inferred T_e and burn-weighted T_i for T_i measurement surrogacy



- Each point on the left is a post-processed *LILAC* simulation from 1-D CRYO database*

T_e and T_i will be independent metrics.

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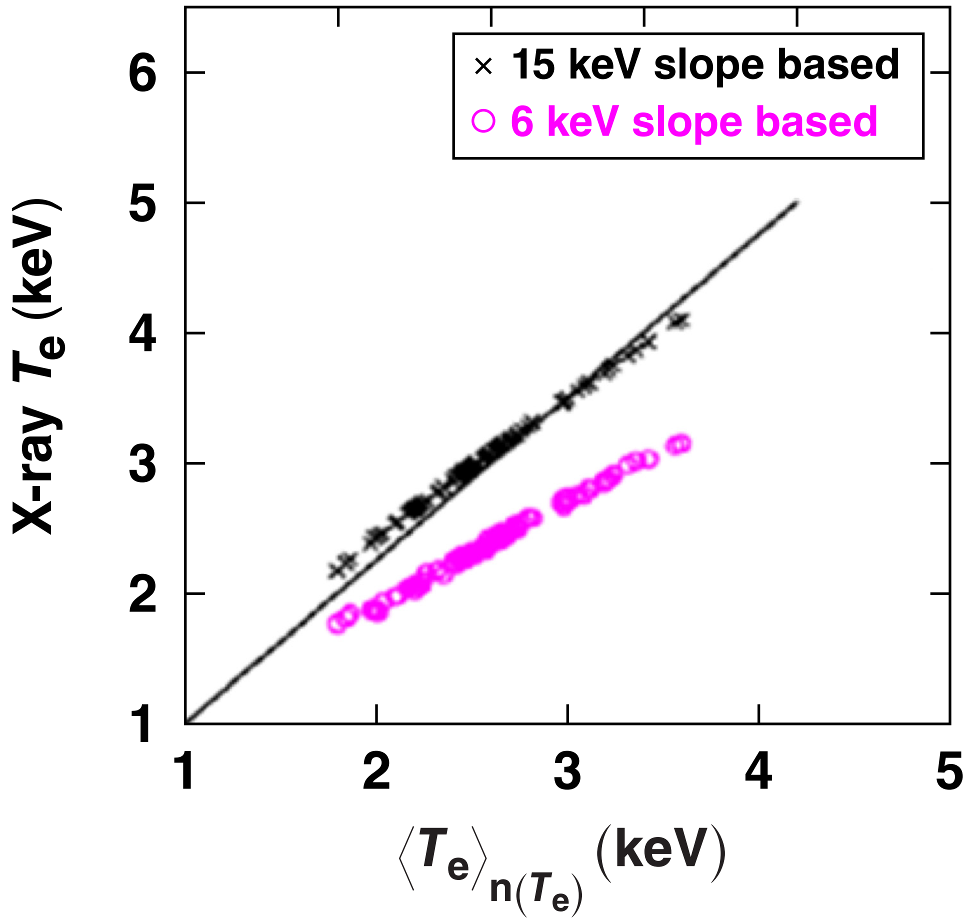
*Created and organized by V. Gopalswamy

TC14551

In 1-D, there is robust correlation between the slope-inferred electron temperature and the emission averaged electron temperature at $h\nu$ = 15 keV

1-D *LILAC* + *SPECT3D*: x-ray versus direct parameter



- Should compare experimentally inferred $\langle T_e \rangle$ to calculated $\langle T_e \rangle$

TC14552

With the inclusion of a Gaunt Factor, the harmonic mean temperature includes a small correction factor

$$I_{hv} = \int Cn^2 g_{FF} e^{-hv/kT} dV$$

Slope of ln(I_{hv}) = $\frac{\partial}{\partial(hv)} \ln(I_{hv}) = \frac{1}{I_{hv}} \int Cn^2 g_{FF} e^{-hv/kT} \left(\frac{1}{g_{FF}} \frac{\partial}{\partial(hv)} g_{FF} - \frac{1}{kT} \right) dV$

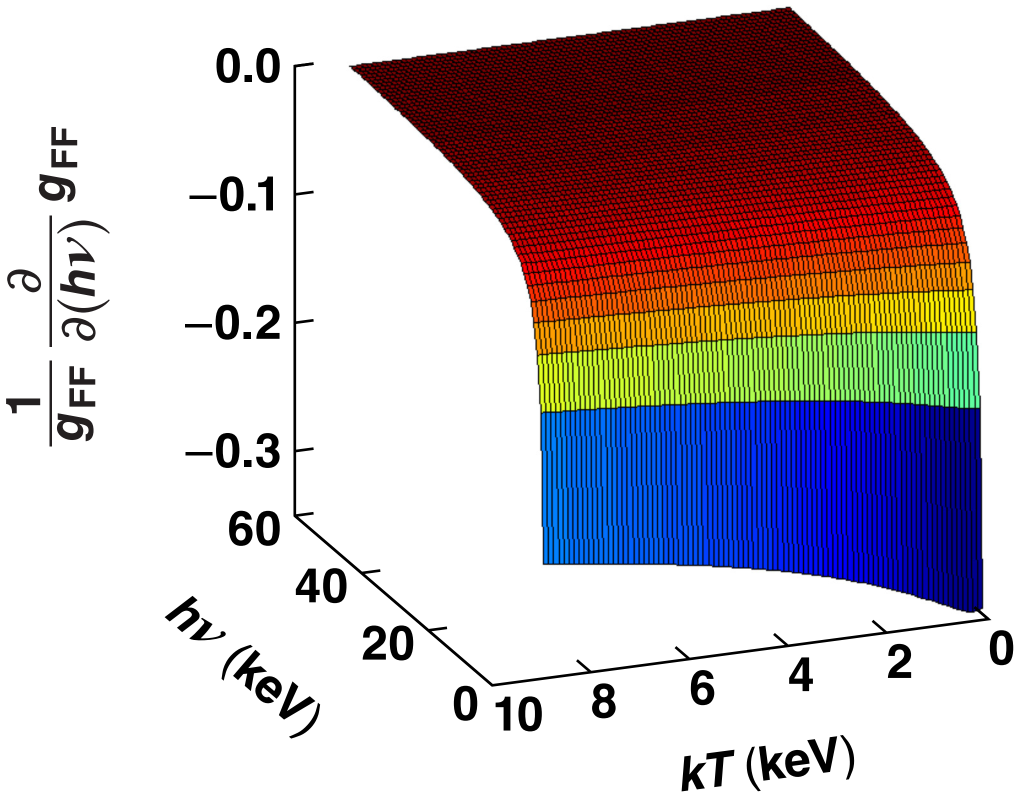
Slope of ln(I_{hv}) $= \left\langle \frac{1}{g_{FF}} \frac{\partial}{\partial(hv)} g_{FF} \right\rangle - \left\langle \frac{1}{kT} \right\rangle$

For ICF hot-spot conditions, $\left\langle \frac{1}{g_{FF}} \frac{\partial}{\partial(hv)} g_{FF} \right\rangle$ can be approximated as $\approx -1/2hv$

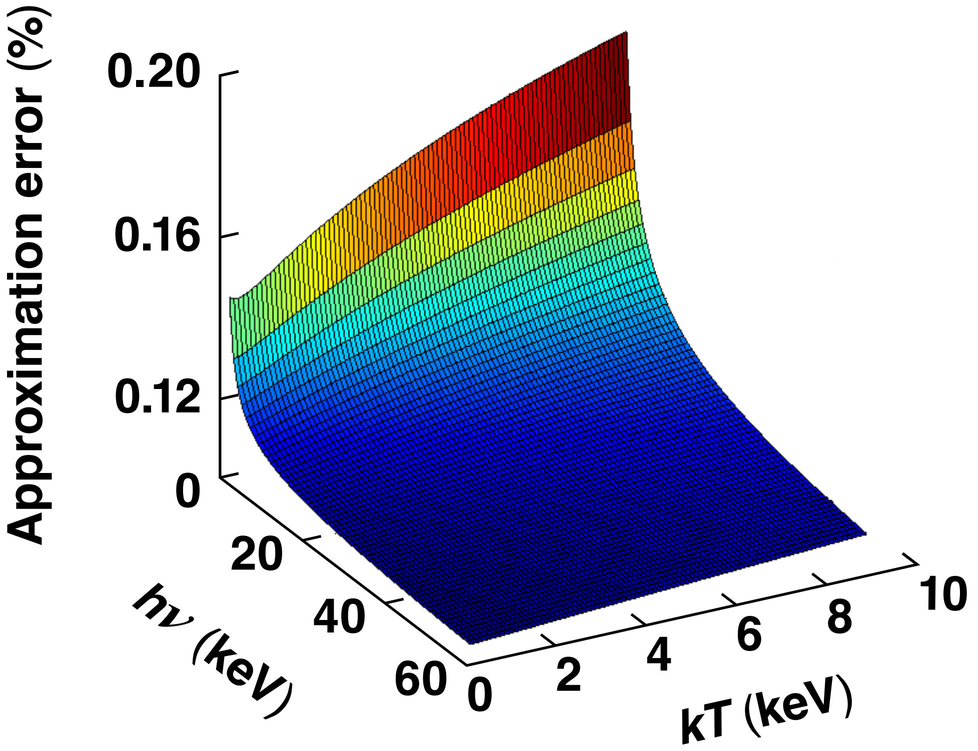
TC14553

Using the asymptotic gaunt factor approximation for inferring T_e introduces little error compared to using a more exact form*

$\frac{1}{g_{FF}}\frac{\partial}{\partial(h\nu)}g_{FF}$ versus temperature and x-ray energy



Percent error with approximate form $g_{FF} = \frac{2\sqrt{3}}{\pi}\beta\left(\frac{kT}{h\nu}\right)^{1/2}$



TC14554

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*W. J. Karzas and R. Latter, Astrophys. J. Suppl. Ser. 6, 167 (1961).