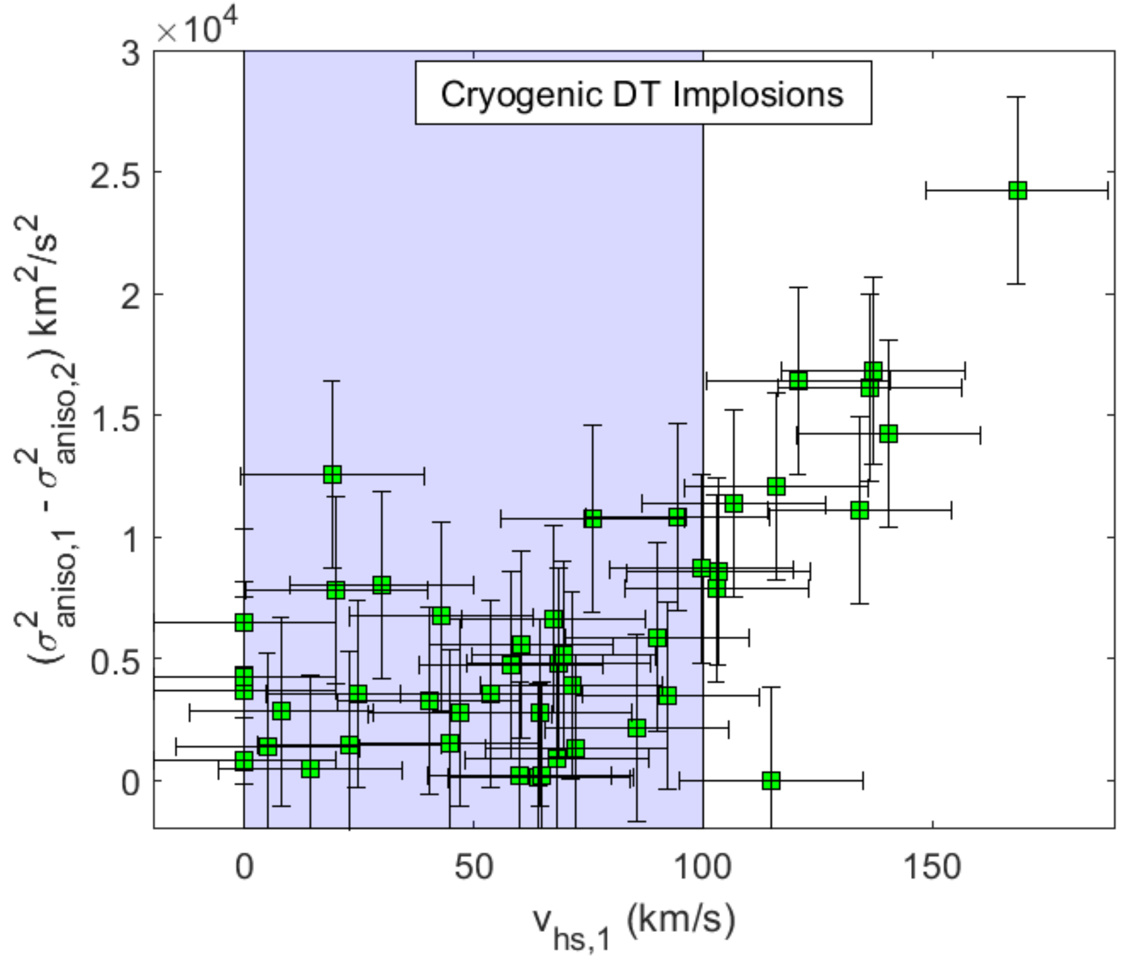
Evaluating the Residual Kinetic Energy in Direct-Drive Cryogenic Implosions on OMEGA



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Summary

Efficient conversion of the shell kinetic energy to the internal hot-spot energy is an essential requirement in ICF fusion implosions

- **The spectral moments of the neutron distribution emitted from a fusing deuterium-tritium (DT) plasma is used to interpret the hot-spot velocity and temperature of the reactants.**

- **An isotropic and anisotropic flow can introduce additional broadening of the second moment on the energy distribution of fusion-produced neutrons.[*]**

- **Hot-spot residual kinetic energy (RKE) from the presence of anisotropic flow is observed with increasing hot-spot velocity (> 100km/s).**

[*] K. Woo *et al.*, Phys. Plasmas 27, 062702 (2020).

Collaborators

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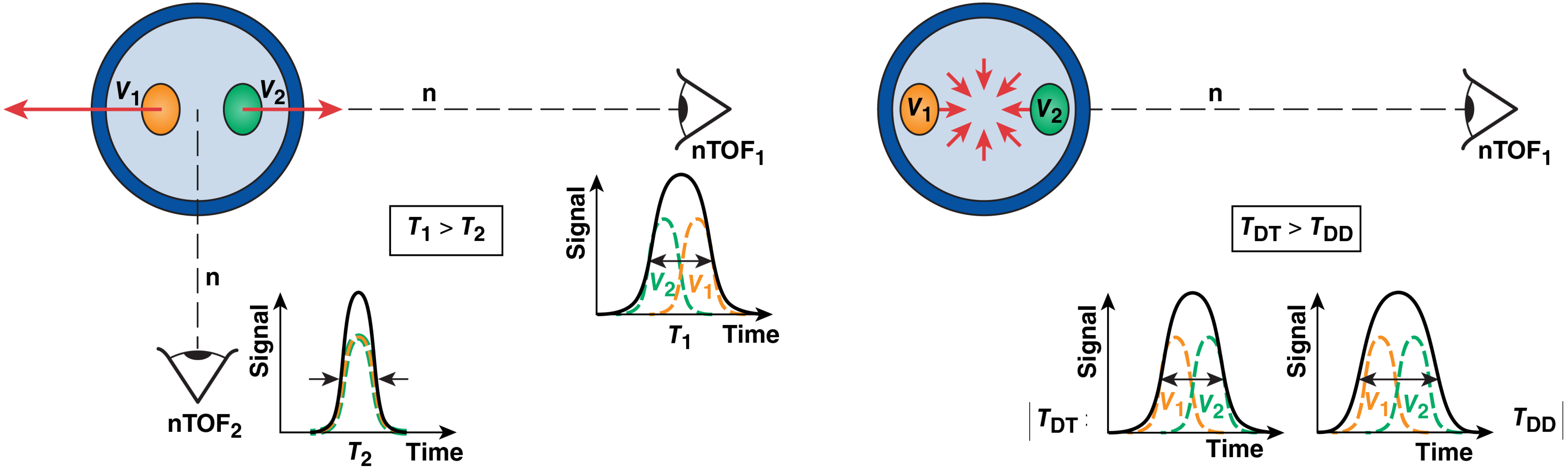
Motivation

Two different mechanism can introduce broadening on the energy distribution of fusion-produced neutrons used to infer the temperature of the reactants

Anisotropic Flow* (LOS)

Isotropic Flow



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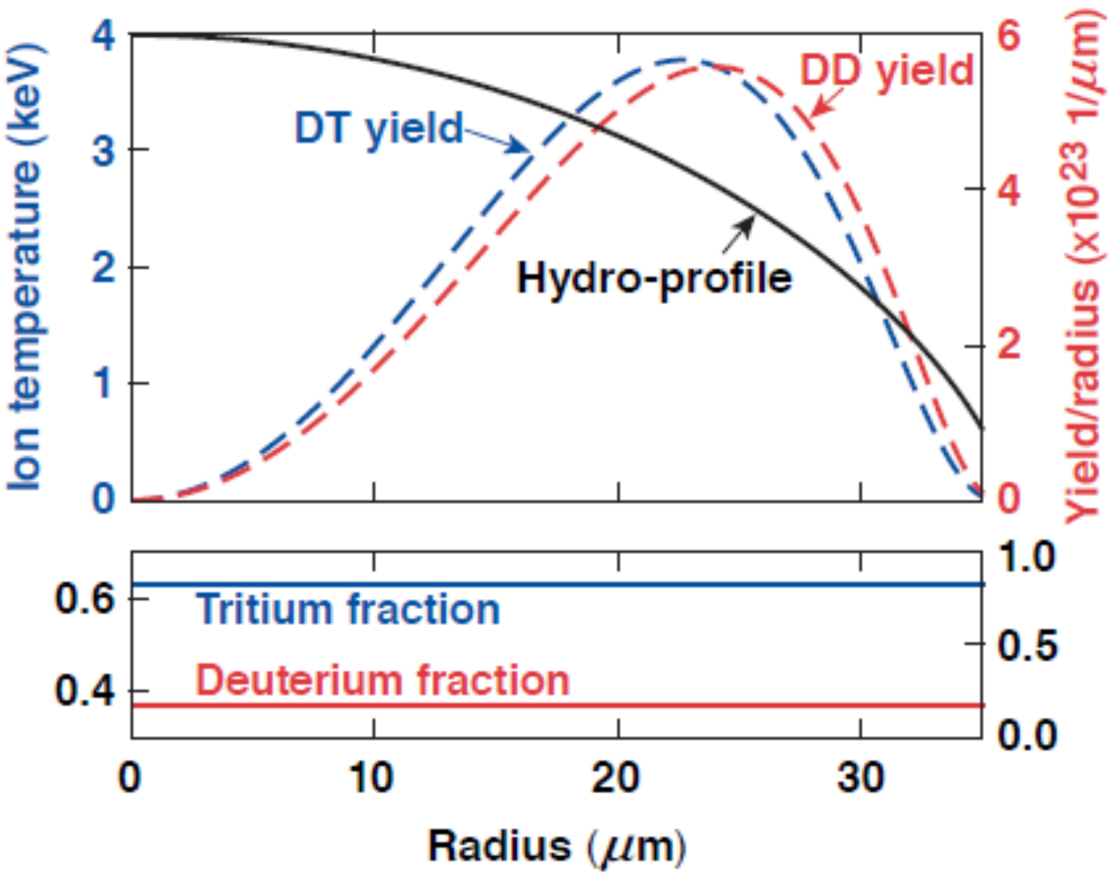
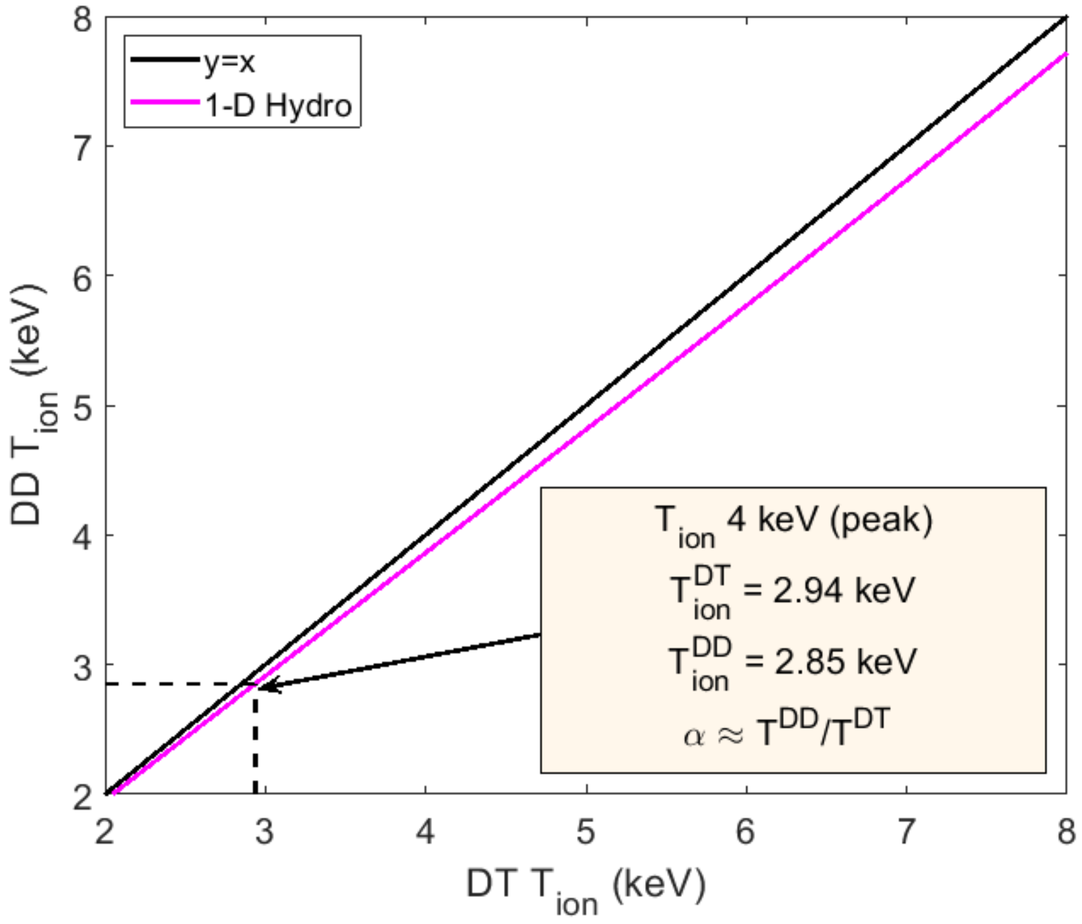
Anisotropic and isotropic flows is a signature of hot-spot residual kinetic energy (RKE) and can be determined since they have a different effect on the DT and DD ion temperatures.

*Murphy *et al.*, Rev. Sci. Instrum. 68, 614 (1997).

A 1-D model with a temperature profile from hydrodynamic simulations* can be used to calculate the DT and DD neutron-averaged ion temperature

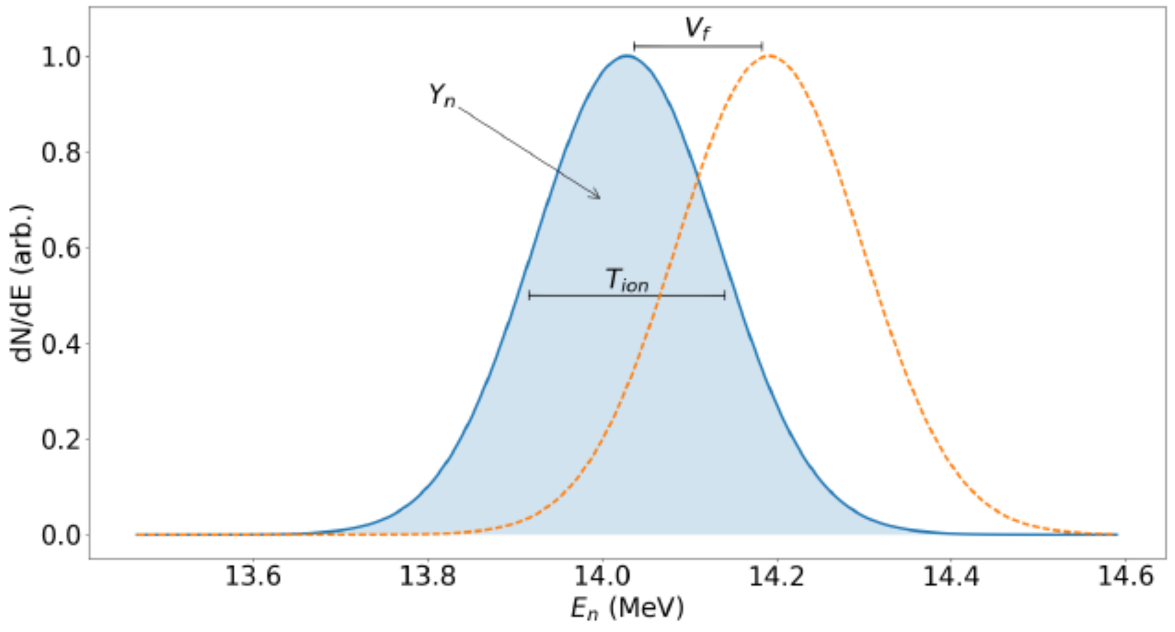




The DT and DD reactants have different sensitivities with respect to the temperature profile of the hot spot.

*R. Betti et. Al., Physics of Plasmas 9, 2277 (2002)

A generalized forward-fit technique is used to infer the spectral moments of the peak distributions from a neutron-time-of-flight (nTOF) diagnostic



The hot-spot velocity is inferred using 5 different lines-of-sight.

Two highly-collimated line-of-sight allows for accurate measurements of the primary DT and DD neutron distributions.

- **The forward-fit approach uses a semi-relativistic energy distribution dNdE*.**

$$\frac{dN}{dE} = I_0 \exp\left(-\frac{2\bar{E}}{\sigma^2}\left(\sqrt{E} - \sqrt{\bar{E}}\right)^2\right),$$

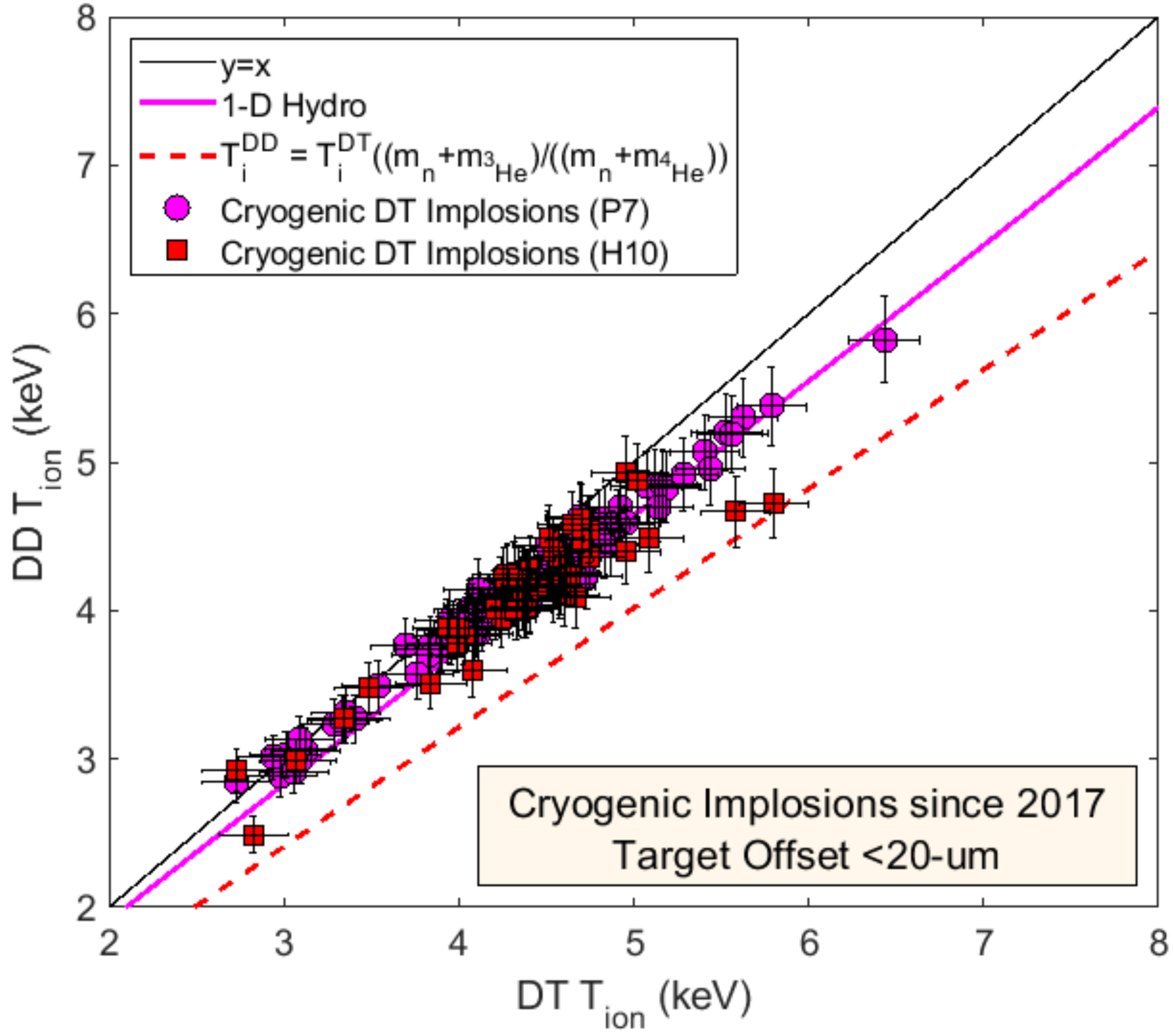
- **The line-of-sight $S(E)_{los}$ attenuation and non-linear light output $S(E)_{nlo}$ were modeled using a neutron transport code (MCNP).**

- **An energy dependent response function R(E,t)** is required for a more accurate interpretation of the time-of-flight signal in region around the DD peak distribution**.**

$$I(t) = c\left[S(E)_{los} S(E)_{nlo} \frac{dN}{dE}\frac{dE}{dt}\right] \otimes R(E,t)$$

*L. Ballabio, J. Källne, and G. Gorini, Nucl. Fusion 38, 1723 (1998).
**Mohamed et al., Submitted to Journal of Applied Physics. (2020) & GO11.00005.

Residual kinetic energy (RKE)* from the presence of isotropic and anisotropic flows can be inferred with the ion temperature from separate lines-of-sight



Unconverted hot-spot kinetic energy does not contribute to the thermal energy of the system.

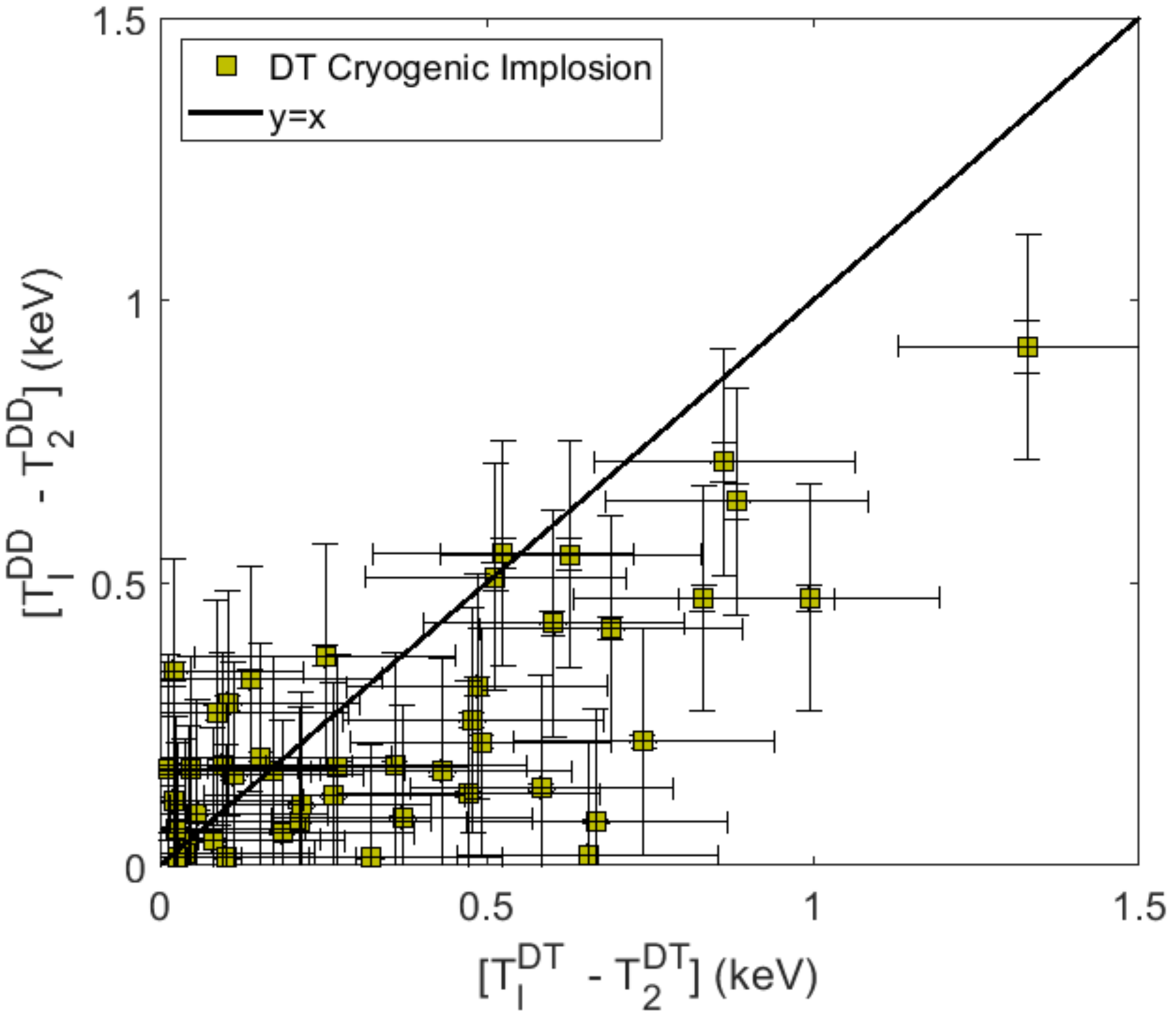
This effect will manifest itself into the additional broadening of the neutron velocity distribution (RKE $\equiv M_{DT}\ \sigma_{1,2}^2$) where 1,2 is the LOS.

$$\begin{bmatrix} T_1^{DT} \\ T_1^{DD} \\ T_2^{DT} \\ T_2^{DD} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 0 \\ \alpha & 0.8 & 0.8 & 0 \\ 1 & 1 & 0 & 1 \\ \alpha & 0.8 & 0 & 0.8 \end{bmatrix} \begin{bmatrix} T^{th} \\ M_{DT}\sigma_{iso}^2 \\ M_{DT}\left(\sigma_{aniso}^2\right)_1 \\ M_{DT}\left(\sigma_{aniso}^2\right)_2 \end{bmatrix}$$

$$\alpha = T_{DD}^{th}/T_{DT}^{th}$$

*Murphy *et al.*, Phys. Plasmas 21, 072701. (2014).

The observation of large differences in the ion temperatures along separate line-of-sight indicates that RKE is likely due to low-mode asymmetries



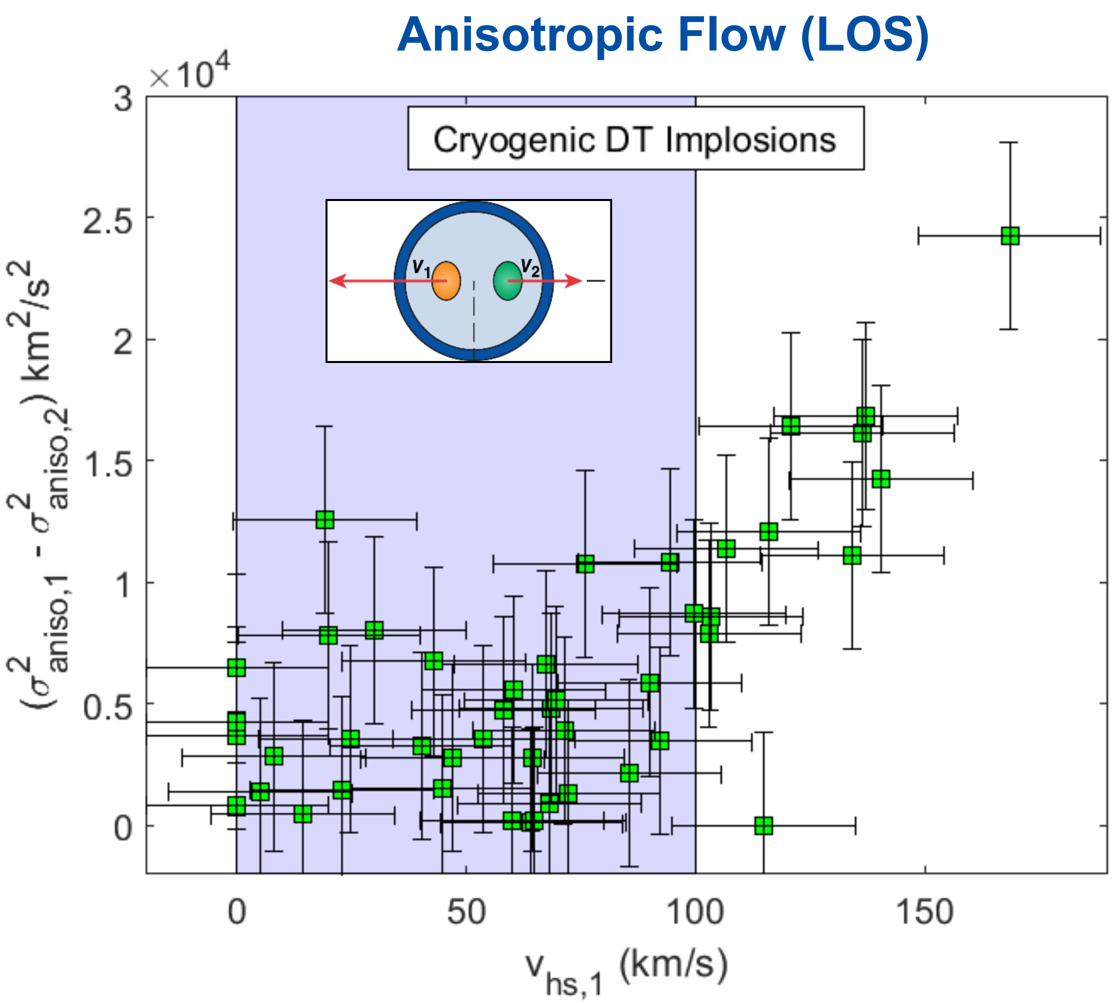
The difference in the ion temperature along two different line-of-sight is produced from anisotropic flows in the hot-spot.

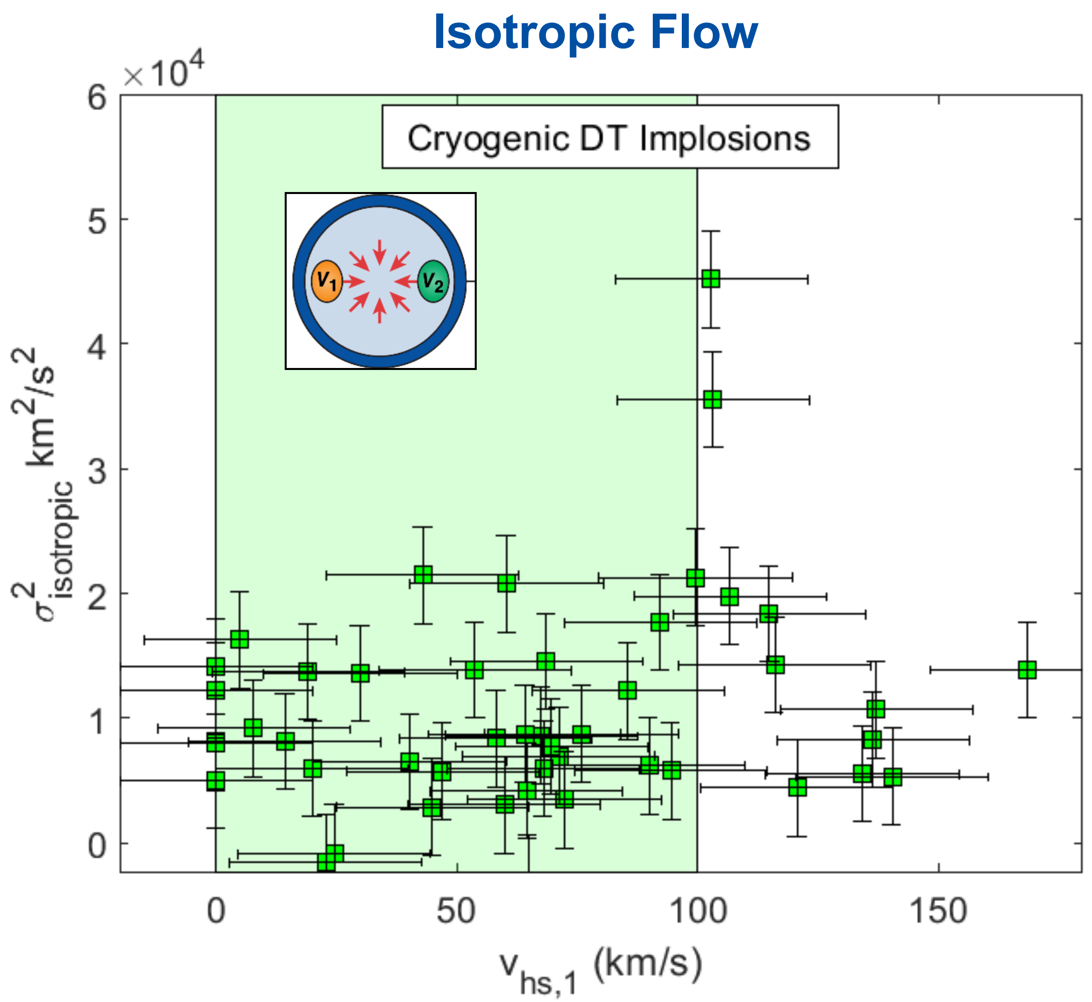
$$\frac{T_1^{DT} - T_2^{DT}}{T_1^{DD} - T_2^{DD}} = \frac{M_{DT}(\sigma_1^2 - \sigma_2^2)}{0.8M_{DT}(\sigma_1^2 - \sigma_2^2)}$$

This implies,

$$T_1^{DT} - T_2^{DT} > T_1^{DD} - T_2^{DD}$$

The residual kinetic energy due to anisotropic flows from two separate line-of-sight increases with the flow velocity of the hot-spot

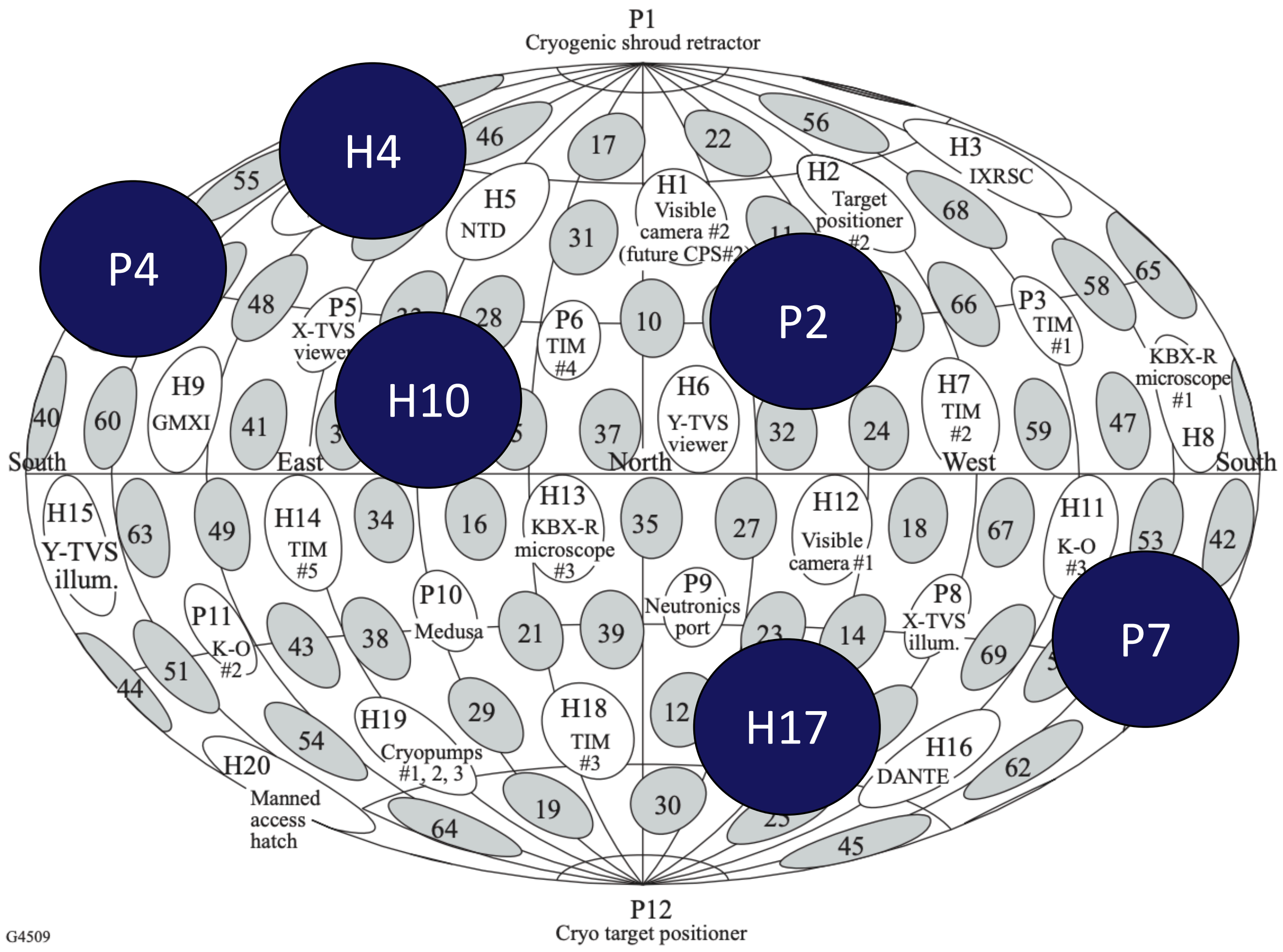




These results indicate a significant anisotropic flow is observed in OMEGA cryogenic DT implosions.

A limit on the thermal temperature will require all of the available DT and DD ion temperature and hot-spot flow experimental values

OMEGA Target Chamber



A more generalize formalization using all available measurements can be used to monitor the entire system.

2nd Moment

$$T_{los}^{DT} = T^{th} + M_{DT} Var[\vec{v} \cdot \hat{d}_{los}]$$

$$T_{los}^{DD} = \alpha T^{th} + 0.8 M_{DT} Var[\vec{v} \cdot \hat{d}_{los}]$$

1st Moment

$$\Delta V_{los} = 7.35\, T_{keV}^{th} + \langle \vec{v}_{km/s} \cdot \hat{d}_{los} \rangle^{*}$$

T_{los}^{DT} = 6 lines-of-sight (P2,P4,P7,H4,H10,H17)
T_{los}^{DD} = 2 lines-of-sight (P7, H10)
ΔV_{los} = 5 lines-of-sight (P2,P7,H4,H10,H17)

*K. Woo *et al.*, Phys. Plasmas 27, 062702 (2020).
O. Mannion, Session KI02: Invited: Inertial Confinement Fusion

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