SAND2021-13979C

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Diagnosing Ion Distributions using Primary Neutron Spectra

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Related talks:

BI01.00003 – E. P. Hartouni - *Monday A.M.*

GO07.00007 – A. S. Moore – *This session*

GO07.00010 – O. M. Mannion – *This session*

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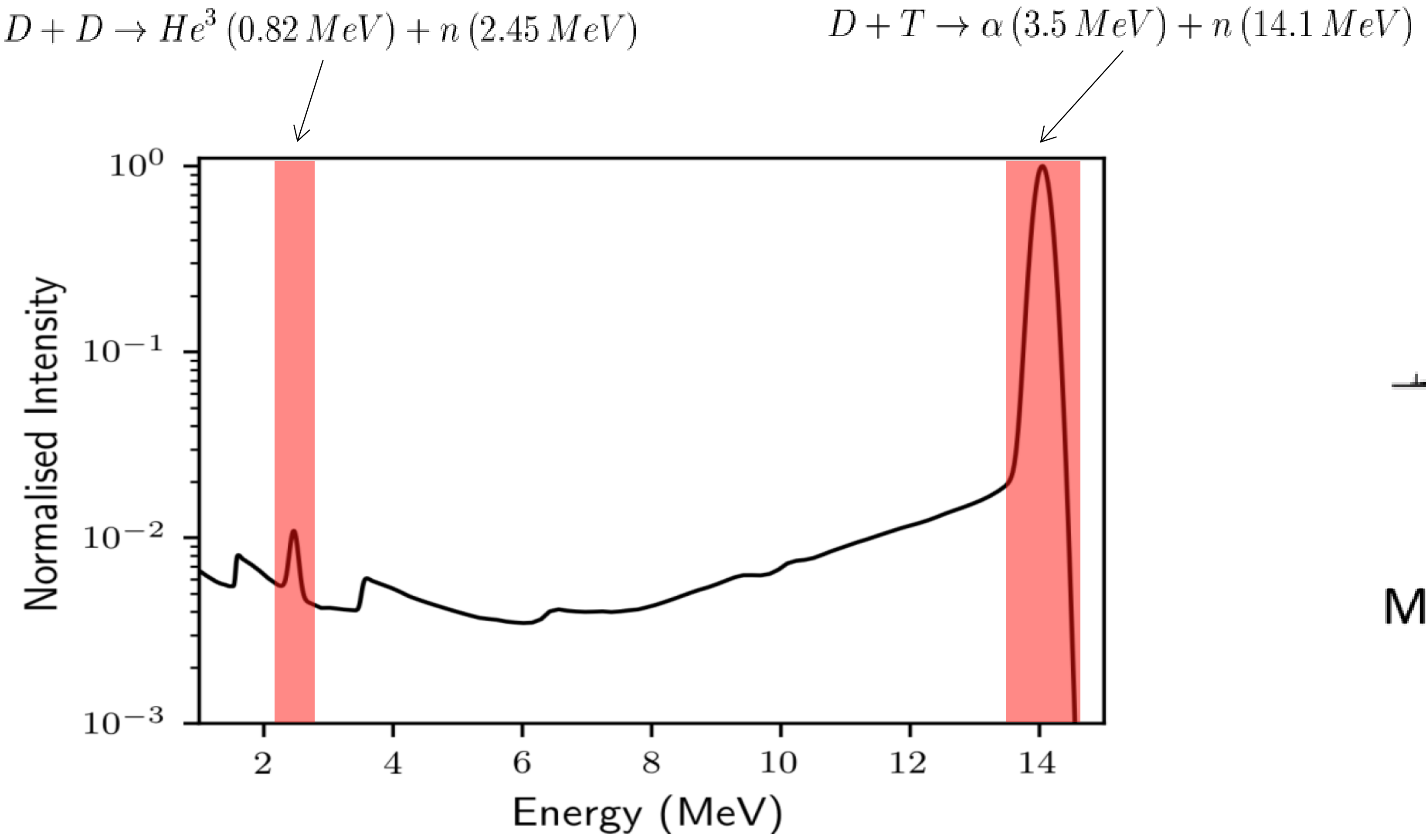
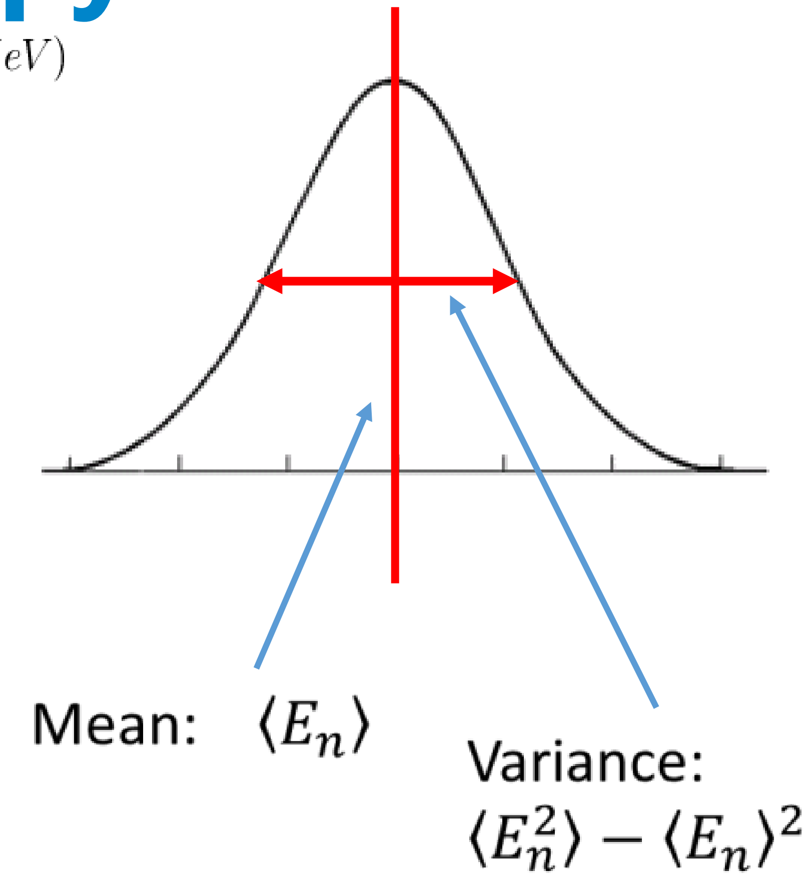
Primary Neutron Spectroscopy





Assumptions:

- Scattering does not are primary peak shape
- Secondary, tertiary & break-up reactions are negligible

$\Longrightarrow$

Mean & variance are dependent only on ion velocity distributions

Primary Neutron Spectroscopy

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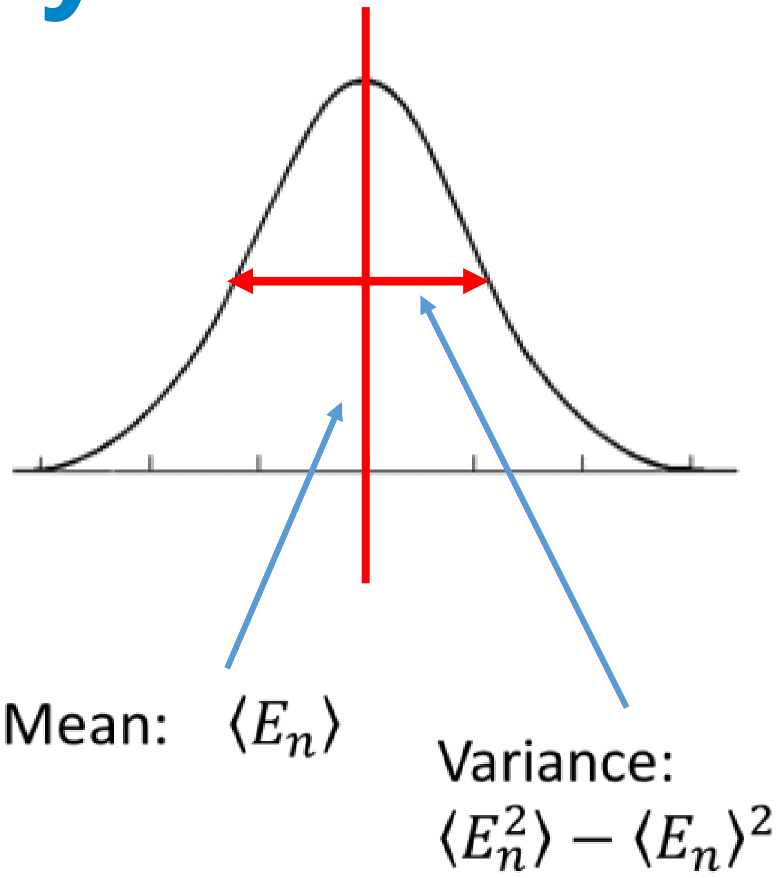
Recent measurements of $\langle E_n \rangle$ and $\langle E_n^2 \rangle - \langle E_n \rangle^2$

BI01.00003 – E. P. Hartouni
GO07.00007 – A. S. Moore } NIF Cryogenic DT
GO07.00010 – O. M. Mannion - OMEGA Exploding Pusher DD & DT



Can we calculate ion velocity distributions from these measurements?

- No unique solution since we do not measure He^3/He^4 spectra
- Measurements are time & space integrated $\Longrightarrow$ we seek “burn-averaged” distributions
- Theory is mature if we assume Maxwellians, e.g. Munro *Nuc. Fusion* [2016]
- *Recent measurements do not agree with Maxwellian theory, indicating non-Maxwellian distributions*

Primary spectra & Reactivity Weighting

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Cross-section

Reactivity definition: $$\langle \sigma v \rangle = \int v_r \sigma f_1 f_2 d^3\overrightarrow{v_1} d^3\overrightarrow{v_2}$$

Distribution functions

$\overrightarrow{v_{cm}}$ – net momentum of collision

K – energy of collision

Reactivity weighting: $$\langle E_n \rangle = \frac{\int E_n v_r \sigma f_1 f_2 d^3\overrightarrow{v_1} d^3\overrightarrow{v_2}}{\langle \sigma v \rangle}$$

$$\overrightarrow{v_{cm}} = \frac{m_1\overrightarrow{v_1} + m_2\overrightarrow{v_2}}{m_1 + m_2}$$

Reaction kinematics: $$E_n = F(Q, v_{cm}, K, \mu)$$

$$= \frac{1}{2} \quad {}_{12} \quad {}^{2}$$

Shift of $\langle E_n \rangle$: $$\Delta E = \alpha \langle K \rangle + \beta \langle v_{cm}^2 \rangle + \cdots$$

α, β, γ – functions of particle masses

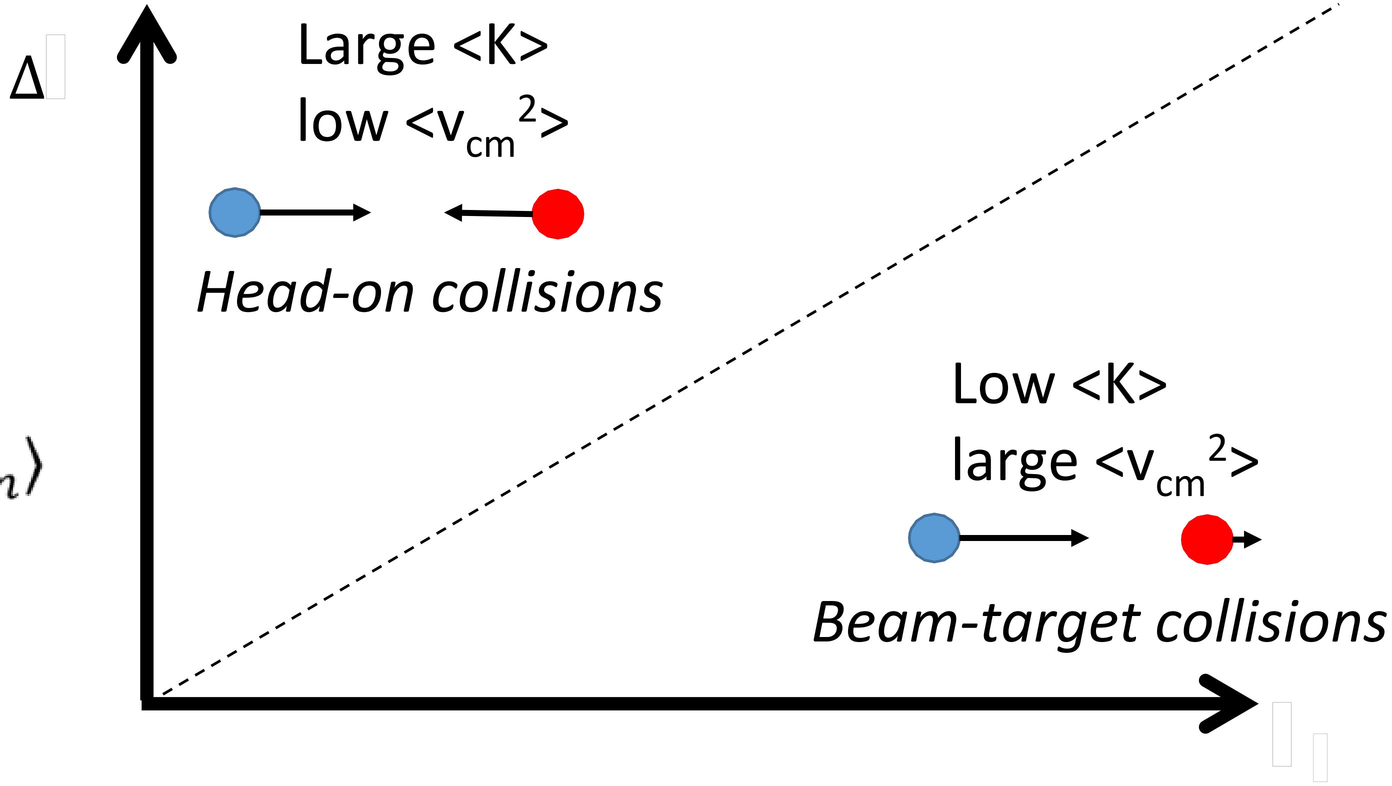
Scaled $\langle E_n^2 \rangle - \langle E_n \rangle^2$: $$T_s = \gamma \langle v_{cm}^2 \rangle + \cdots$$

Observed $\langle E_n \rangle$ *and* $\langle E_n^2 \rangle - \langle E_n \rangle^2$ *are dependent on* $\langle K \rangle$ *and* $\langle v_{cm}^2 \rangle$

$\Delta E - T_s$ Parameter Space

$$\Delta E = \alpha\langle K\rangle + \beta\langle v_{cm}^2\rangle$$

$$T_s = \gamma\langle v_{cm}^2\rangle$$



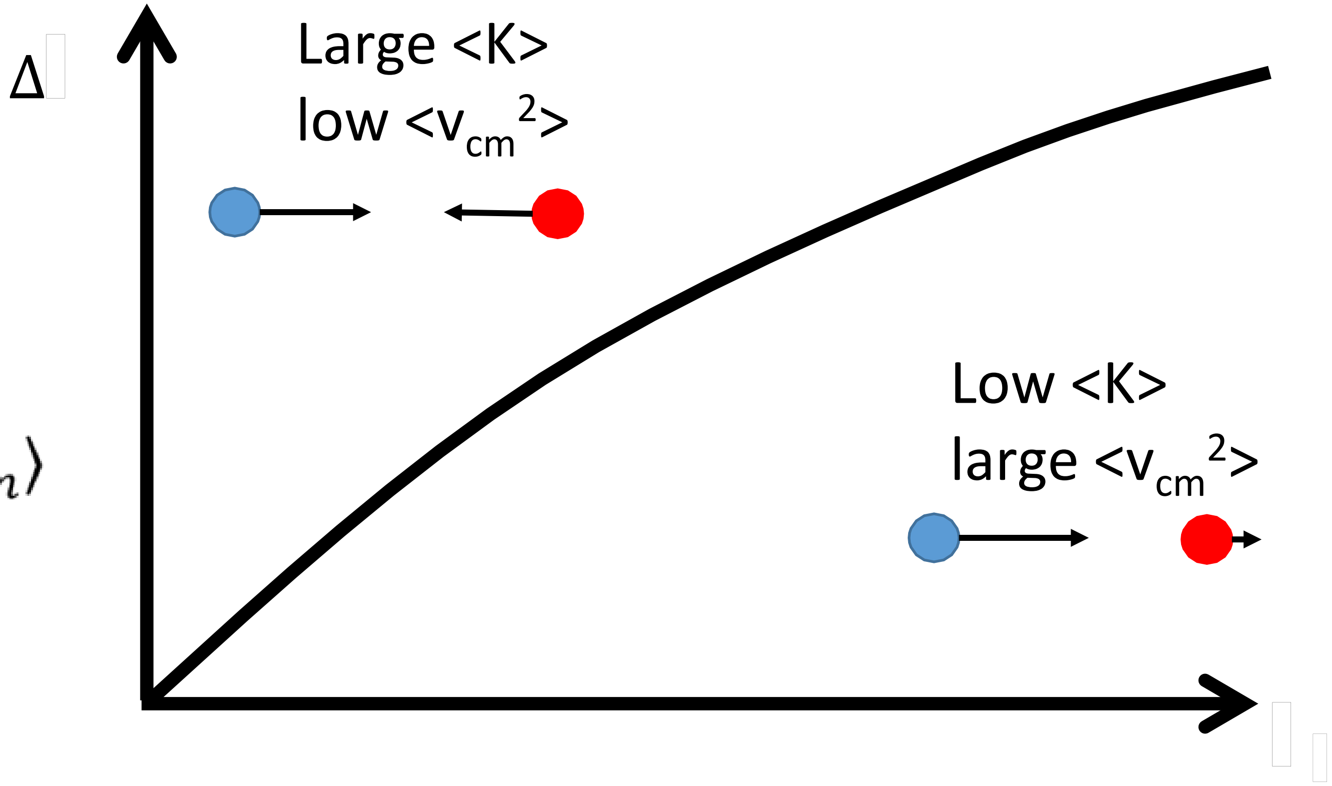
$\Delta E - T_s$ for Maxwellian

- Maxwellian is defined by a single parameter (temperature T)
- Varying T defines a locus of points in $\Delta E - T_s$ space
- $T = T_s$ for a Maxwellian

$$f_{1,2} \propto exp\left(-\frac{m_{1,2}}{2T} v^2\right)$$

$$\Delta E = \alpha \langle K \rangle + \beta \langle v_{cm}^2 \rangle$$

$$T_s = \gamma \langle v_{cm}^2 \rangle$$



$\Delta E - T_s$ for Maxwellian with flow

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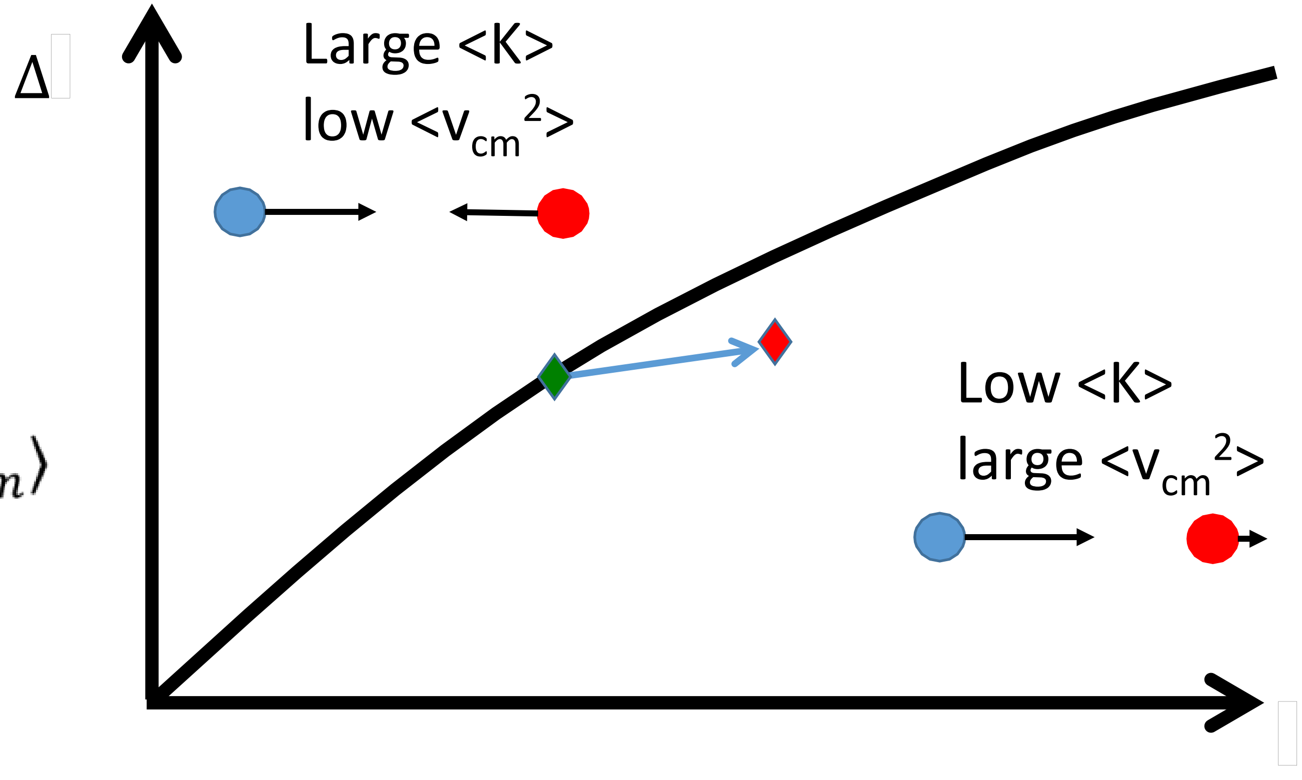
- Fluid velocity increases $\langle v_{cm}^2 \rangle$ but not $\langle K \rangle$
- Points shifted right/below Maxwellian locus in $\boldsymbol{\Delta E - T_s}$ space

$$f_{1,2} \propto exp\left(-\frac{m_{1,2}}{2T}(\vec{v} - \overrightarrow{v_f})^2\right)$$

$$\Delta E = \alpha\langle K \rangle + \beta\langle v_{cm}^2 \rangle$$

$$T_s = \gamma\langle v_{cm}^2 \rangle$$



Hydrodynamic models can only access right/below Maxwellian locus

$\Delta E - T_s$ for Maxwellian with flow

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$$f_{1,2} \propto exp\left(-\frac{m_{1,2}}{2T}\left(\vec{v} - \overrightarrow{v_f}\right)^2\right)$$

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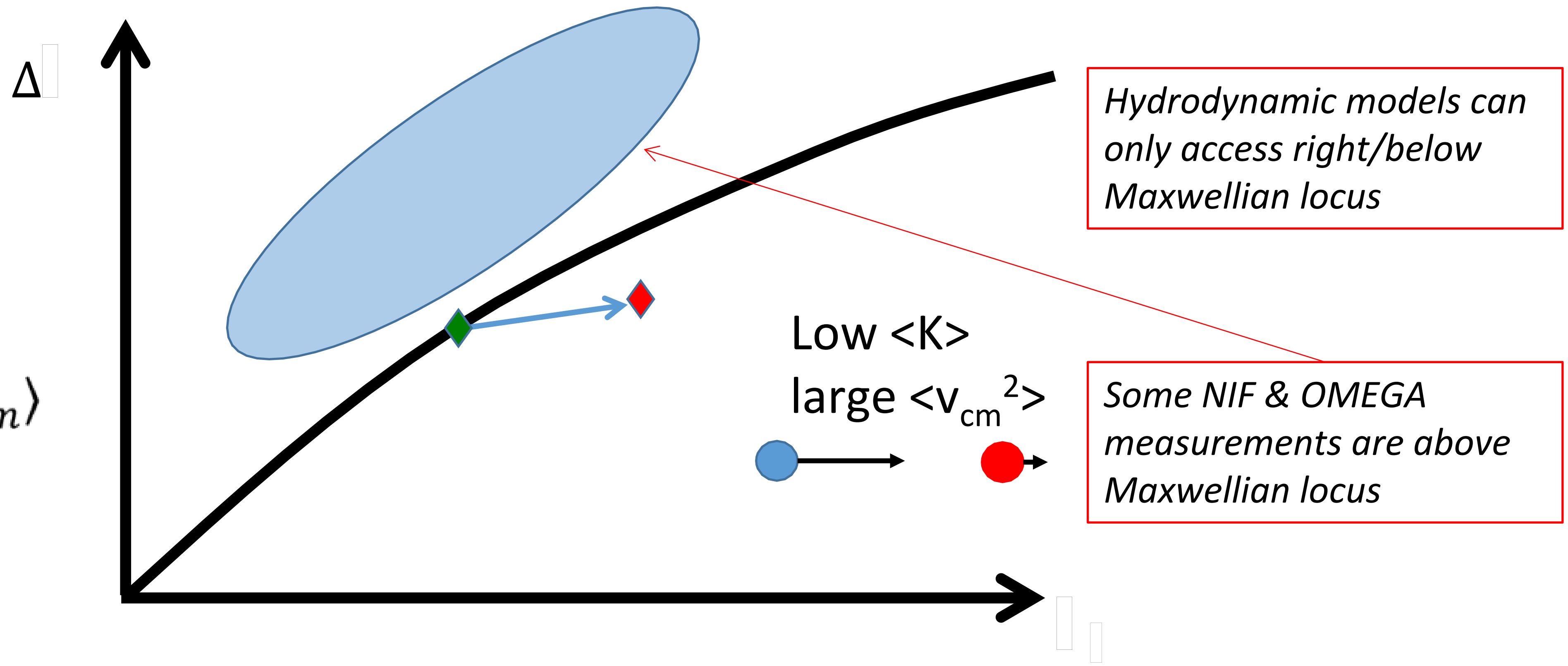
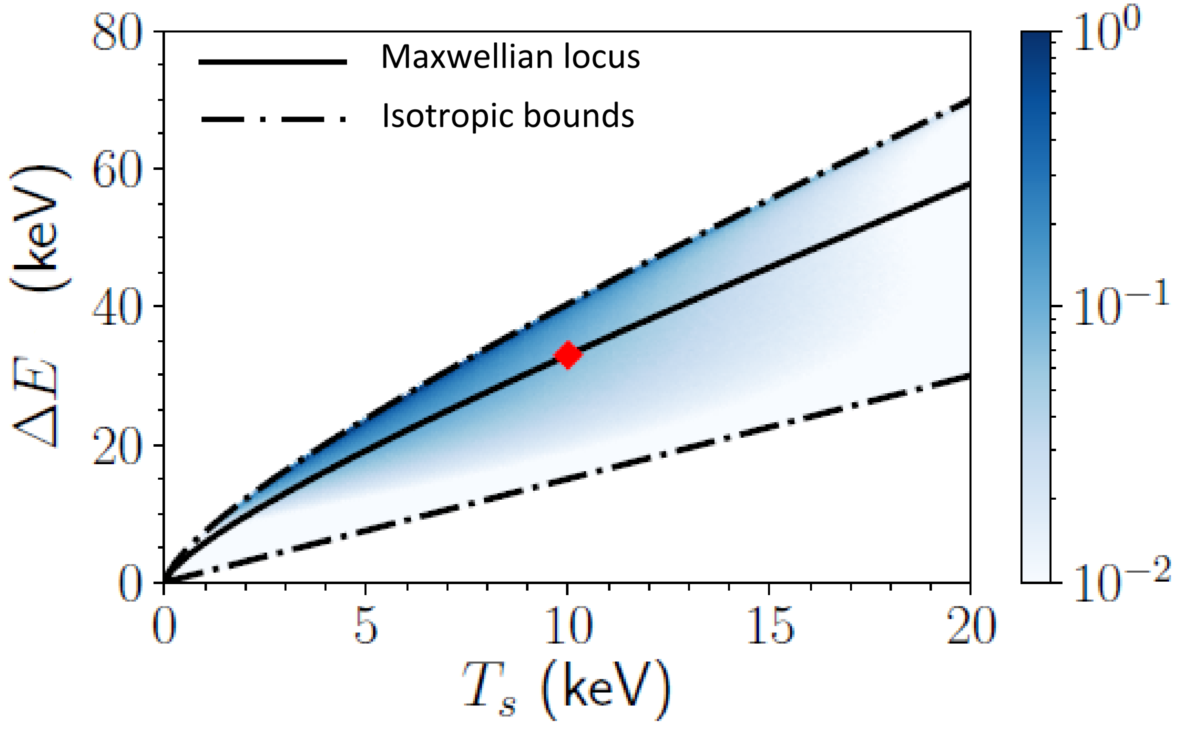


Energy Decomposition of Maxwellian

- The energy decomposition of a Maxwellian occupies a broad region in $\Delta E - T_s$ space
- Region has upper and lower bounds
- These bounds exist for any *isotropic* distribution in velocity space



Energy decomposition of a Maxwellian with T = 10 keV

Isotropic Distributions

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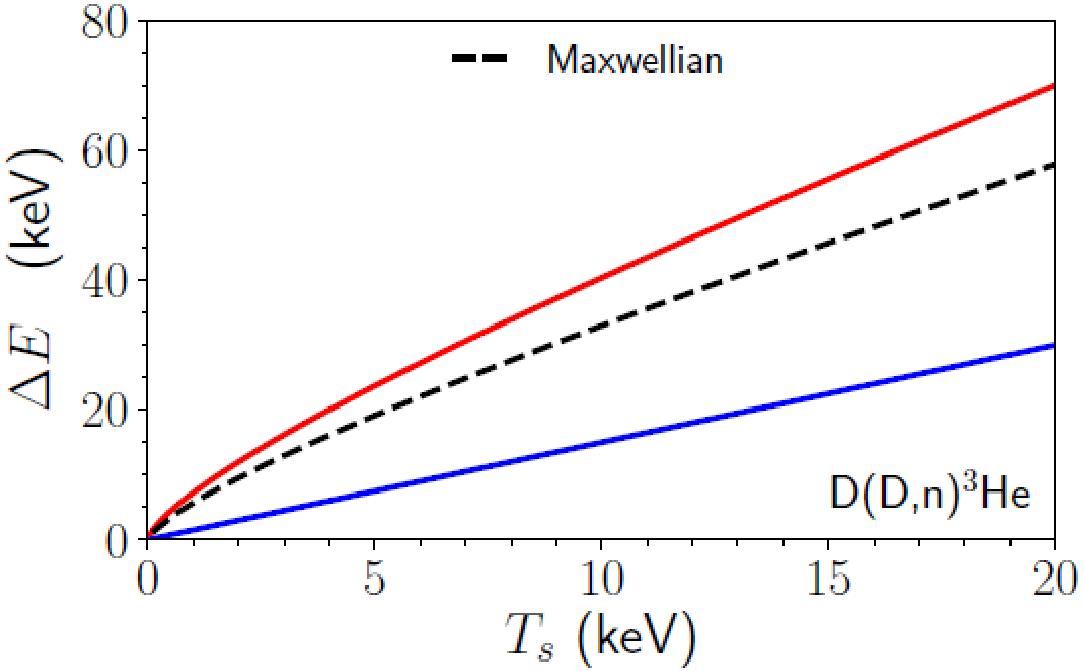
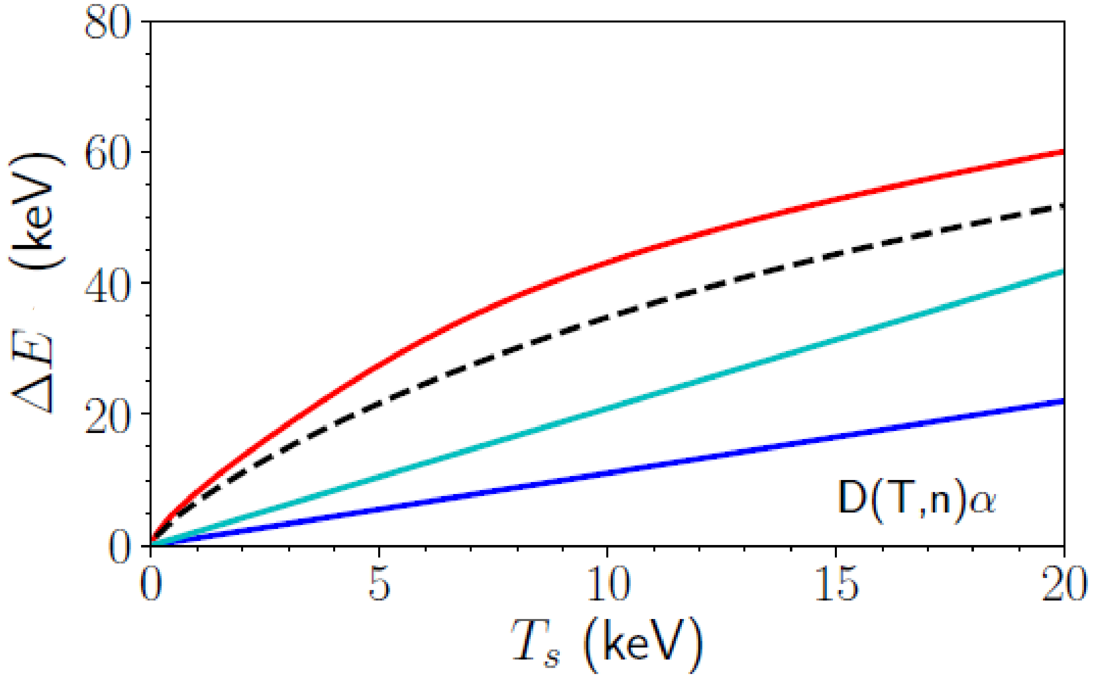
Region above red curves only accessed by *anisotropic, non-Maxwellian* distribution functions

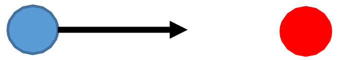




Upper Bound:
Energies for which $min|\overrightarrow{v_{cm}}| = 0$

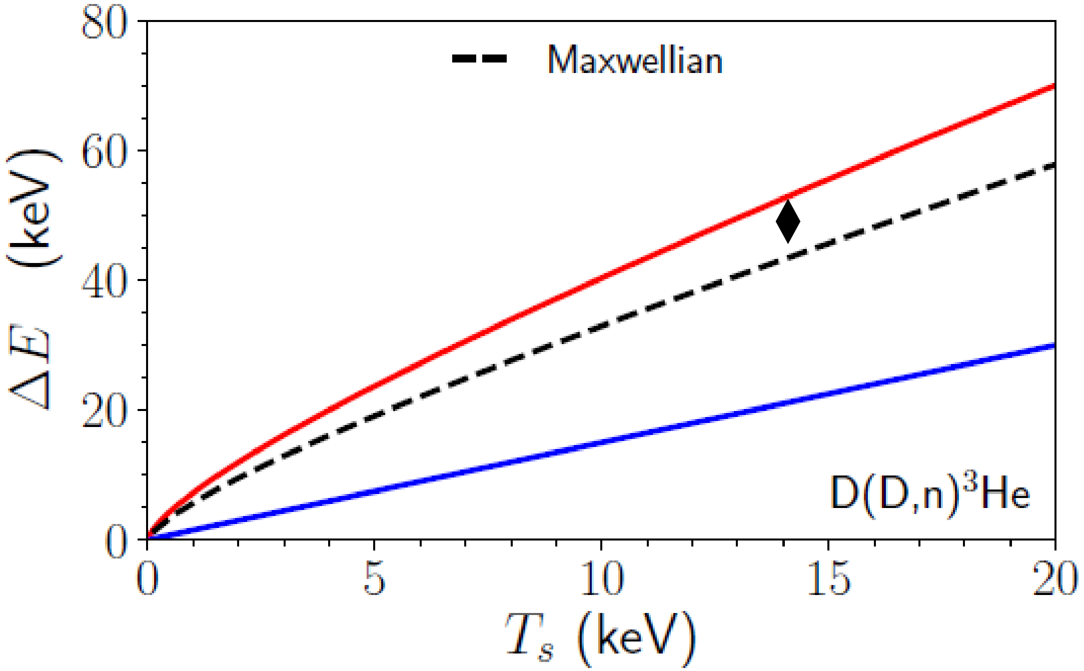
Lower Bound:
Target particle is stationary
stationary D
stationary T

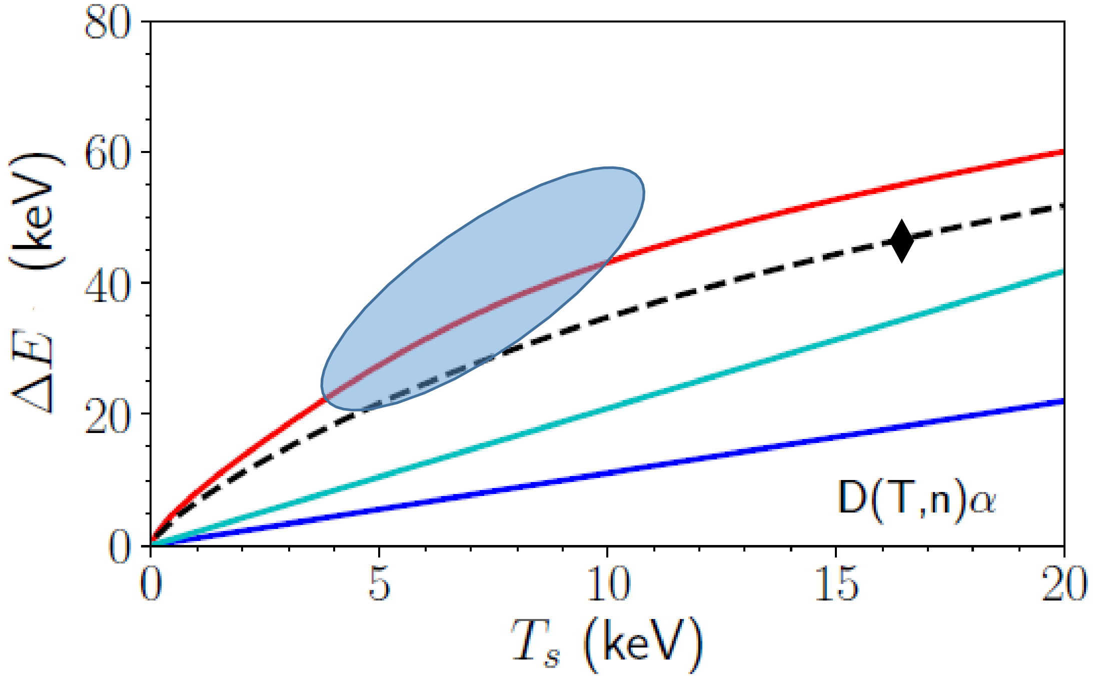
Head-on collisions



Beam-target collisions

Experimental Measurements





♦ **OMEGA Exploding Pushers:**
DD spectra imply non-Maxwellian distributions, ion kinetic simulations (iFP) match these spectra

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NIF Cryogenic:
DT spectra imply non-Maxwellian distributions including some anisotropic

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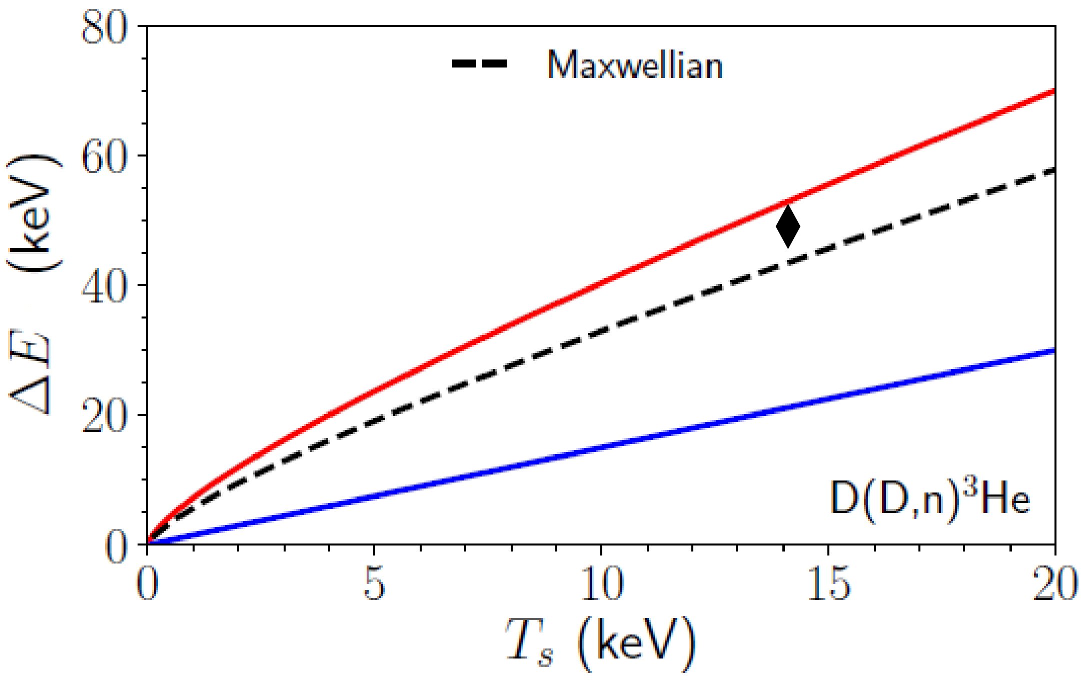
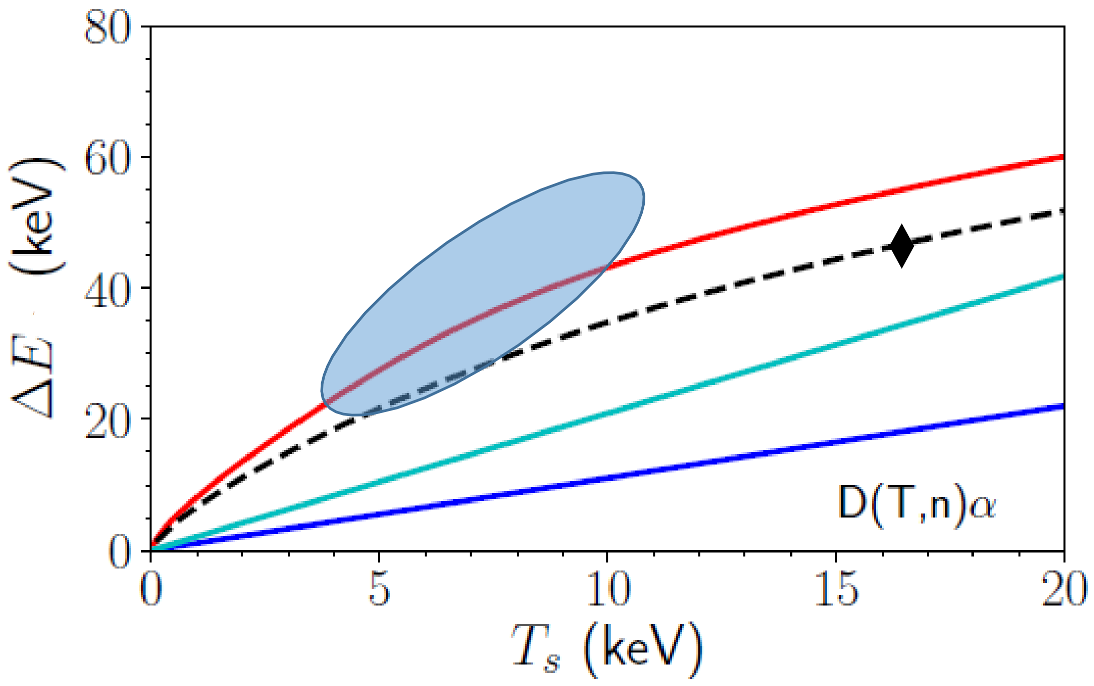
GO07.00007 – A. S. Moore

Conclusions





- $\boldsymbol{\Delta E - T_s}$ space of primary neutron spectra can characterize ion velocity distributions
- Measurements on NIF & OMEGA show direct evidence of non-Maxwellian distributions
- NIF data shows evidence of anisotropic velocity distributions

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