Progress on understanding neutron spectral peak shapes: getting a handle on scattering effects

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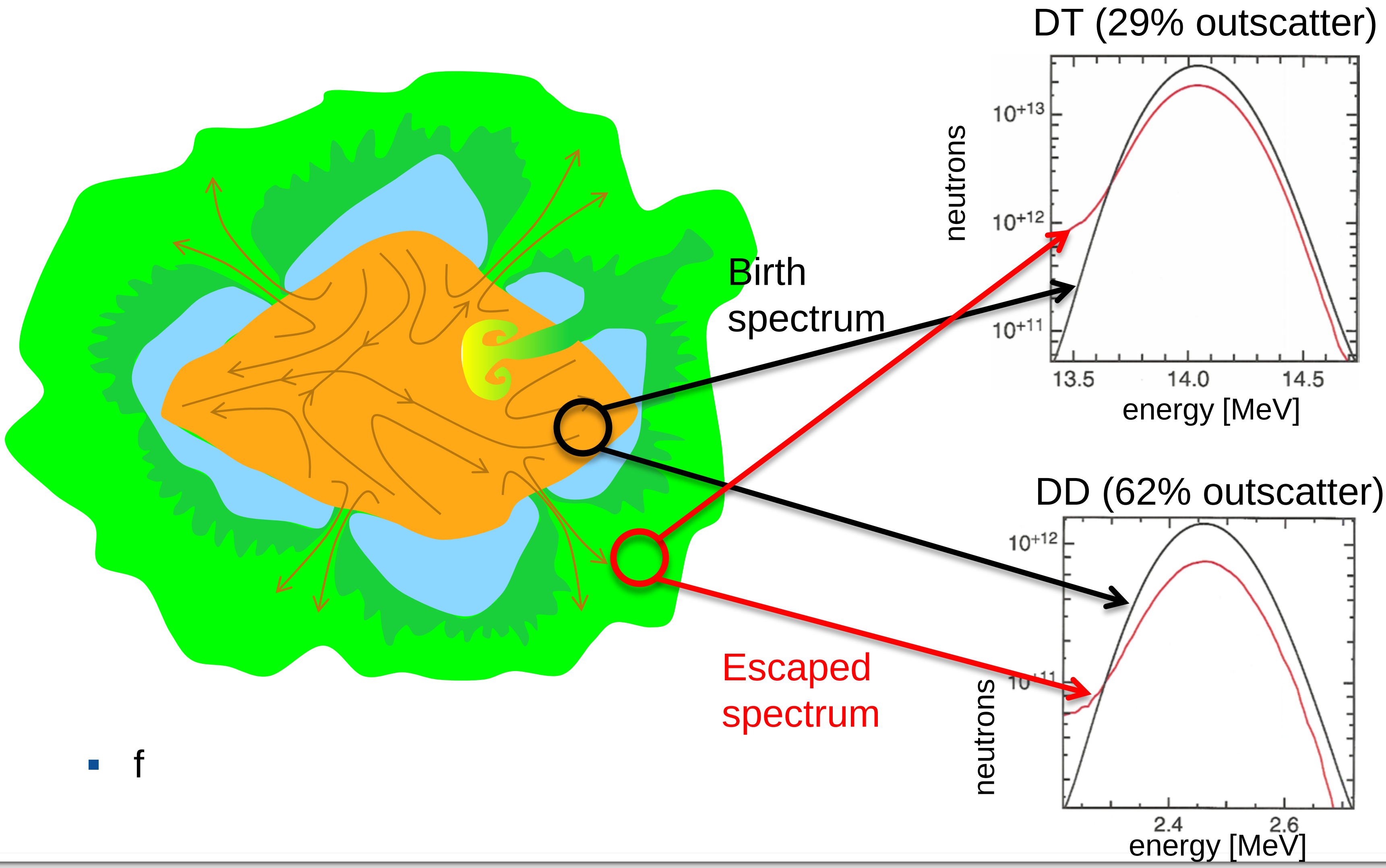
We are studying how neutron spectra deviate from Gaussian and the scattering contribution to shape



- f

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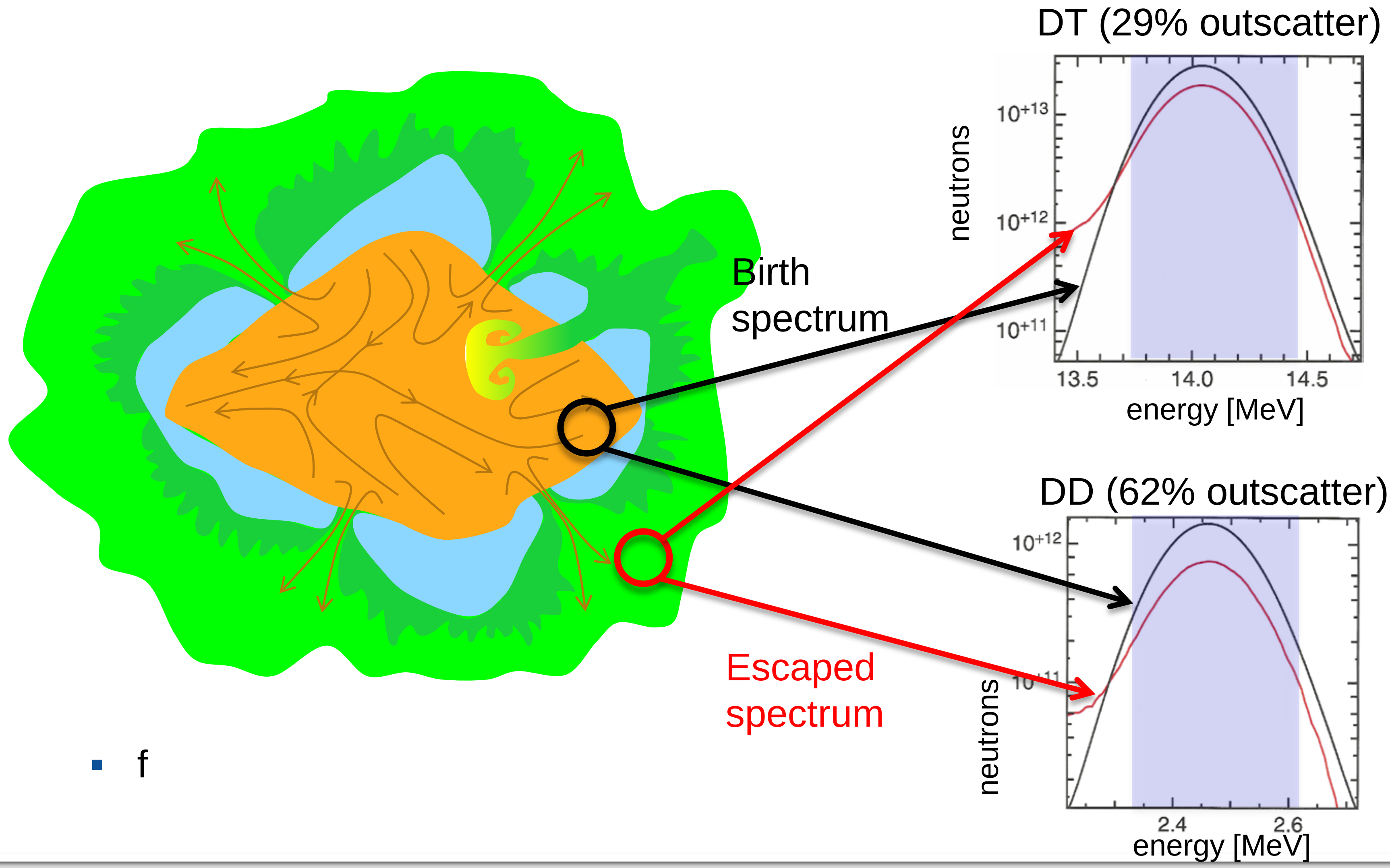

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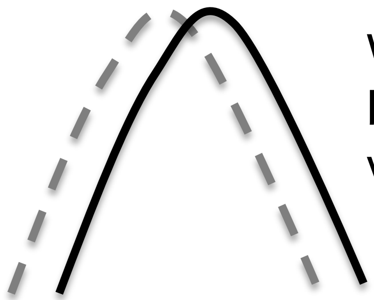
Moments of the birth peak tell us about the hot spot stagnation

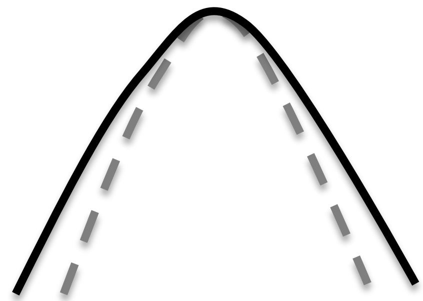
First moment – peak shift



What's the bulk velocity?

peak shift ~ f(bulk velocity, $T_{thermal}$)

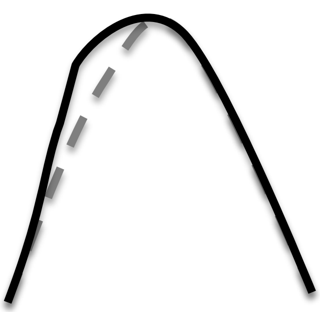
Second moment – width



What's the apparent temp, thermal temp,residual flow?

Width ~ f($T_{thermal,}$flow variance)

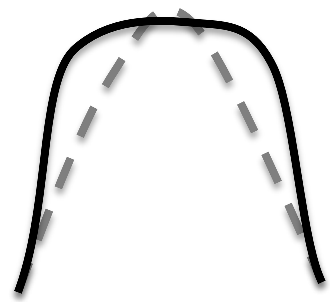
Third moment – skew



Is the hot stuff moving fast?

Skew ~ cov($T_{thermal,}$flow)

Fourth moment – kurtosis



How broad is the distribution of thermal temperatures?

Kurtosis ~ variance of Tion

Moments of the birth peak tell us about the hot spot stagnation

First moment – peak shift	Second moment – width
What's the	What's the
p	temperatures?
Skew ~ cov($T_{thermal,}$flow)	Kurtosis ~ variance of Tion

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Interpreting inertial fusion neutron spectra

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We compute cumulants to measure deviation from Gaussian spectrum

$$\mathrm{Cov}(X,Y) = \left\langle \left(X - \langle X \rangle\right)\left(Y - \langle Y \rangle\right) \right\rangle = \langle XY \rangle - \langle X \rangle \langle Y \rangle$$

$$\mathrm{Var}(X) = \mathrm{Cov}(X,X) = \langle X^2 \rangle - \langle X \rangle^2$$

$$\mathrm{Cov}(X,Y,Z,\ldots) = \left\langle \left(X - \langle X \rangle\right)\left(Y - \langle Y \rangle\right)\left(Z - \langle Z \rangle\right)\ldots \right\rangle$$

$$\mathrm{Skew}(X) = \mathrm{Cov}(X,X,X) / \mathrm{Var}(X)^{3/2}$$

$$\mathrm{Kurt}(X) = \mathrm{Cov}(X,X,X,X) / \mathrm{Var}(X)^2 - 3$$

zero for Gaussian distribution

$$\mathrm{Var}(\omega) = \langle \tau \rangle + \mathrm{Var}(u_\Omega) + 2\,\mathrm{Cov}(\kappa, u_\Omega) + \ldots$$

L=0, L=2, L=1 in direction

$$\mathrm{Skew}(\omega) = \frac{3\,\mathrm{Cov}(\tau, u_\Omega) + \mathrm{Cov}(u_\Omega, u_\Omega, u_\Omega) + \ldots}{\mathrm{Var}(\omega)^{3/2}}$$

L=1, L=3 in direction

$$\mathrm{Kurt}(\omega) = \frac{3\,\mathrm{Var}(\tau) + 6\,\mathrm{Cov}(\tau, u_\Omega, u_\Omega) + \mathrm{Cov}(u_\Omega, u_\Omega, u_\Omega, u_\Omega) - 3\,\mathrm{Var}(u_\Omega)^2 + \ldots}{\mathrm{Var}(\omega)^2}$$

L=0, 2, 4

We like math. (Apologies if you don't)

1D implosion spectral peaks are non-Gaussian

	Fractional deviation from Gaussian				
spectrum	Yield	Drift (==0)	Width	Skew (==0)	Kurtosis
1D HF birth	0.011	0.0049	0.073	0.022	0.078
1D HF escaped	0.020	-0.0024	0.13	-0.010	0.13
difference	+0.09	0	+0.057	0	+0.052
1D BF birth	0.010	0.00073	0.067	0.0034	0.07
1D BF escaped	0.016	-0.0036	0.10	-0.016	0.10
difference	+0.006	0	+0.033	0	+0.03

	Tiavg (keV)	Btifwhm (keV)	Width (keV)
HF	12.45	16.07	--
BF	11.47	13.73	14.27

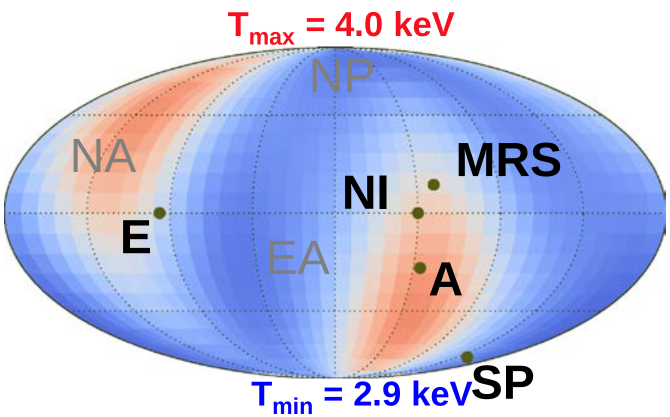
Apparent Tion (peak width) varies with line of sight

- Fluid velocity variance increases the apparent temperature

$$T_{Brysk} = \left(\frac{m_D + m_T}{k}\right) \sigma_v^2 + T_{thermal}$$

- Apparent temperature has a Y2m (ellipsoidal) distribution
  - Varies with line of sight
  - Equal on antipodal (opposite) lines of sight (LOS)

Antipodal temps are identical



Detectors catch 55% of PTV

Detector	T_{Brysk}
SpecE	3.49
SpecA	3.56
SpecSP	2.96
NITOF	3.50
MRS	3.39

Fluid motion varies the apparent temperature by up to 1 keV in DT. How about DD?

Simulations show a difference between apparent DD and DT ion temperatures likely due to scattering

Detector	Simulated T_{DT} [keV]	Simulated T_{DD} [keV]	T_{DT}-T_{DD} [eV]	Predicted T_{DD} [keV]
SpecE	3.74	2.92	820	3.45
SpecA	3.18	2.99	190	3.00
SpecSP	3.08	2.80	280	2.92
NITOF	3.67	3.33	340	3.40
MRS	3.60	3.23	370	3.43

True $T_{thermal}$ = 2.3 keV

- **We expect Tion DD and Tion DT to be related to the thermal temperature (excepting scattering effects)**
- **When we try to compare DD and DT temps in experiments we find difference to be "too large."**
- **Turns out 3D simulations have the same "too large" difference that makes the measured TDD lower than predicted.**

$$T_{Brysk} = \left(\frac{m_D+m_T}{k}\right)\sigma_v^2 + T_{thermal}$$

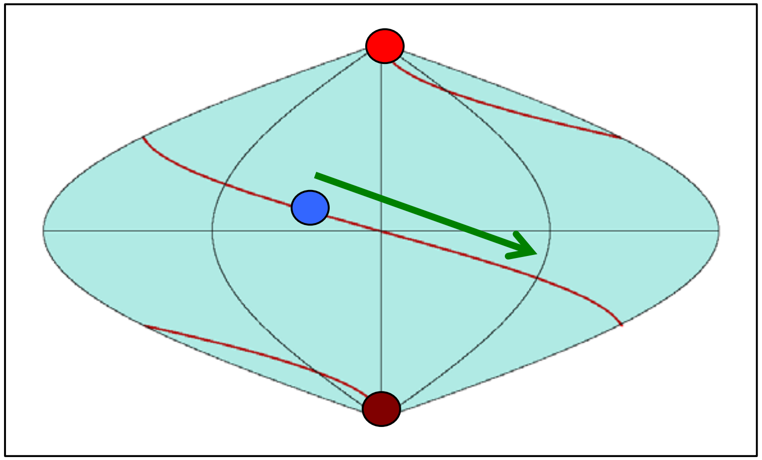
$$T_{thermal} = 5T_{DD} - 4T_{DT}$$

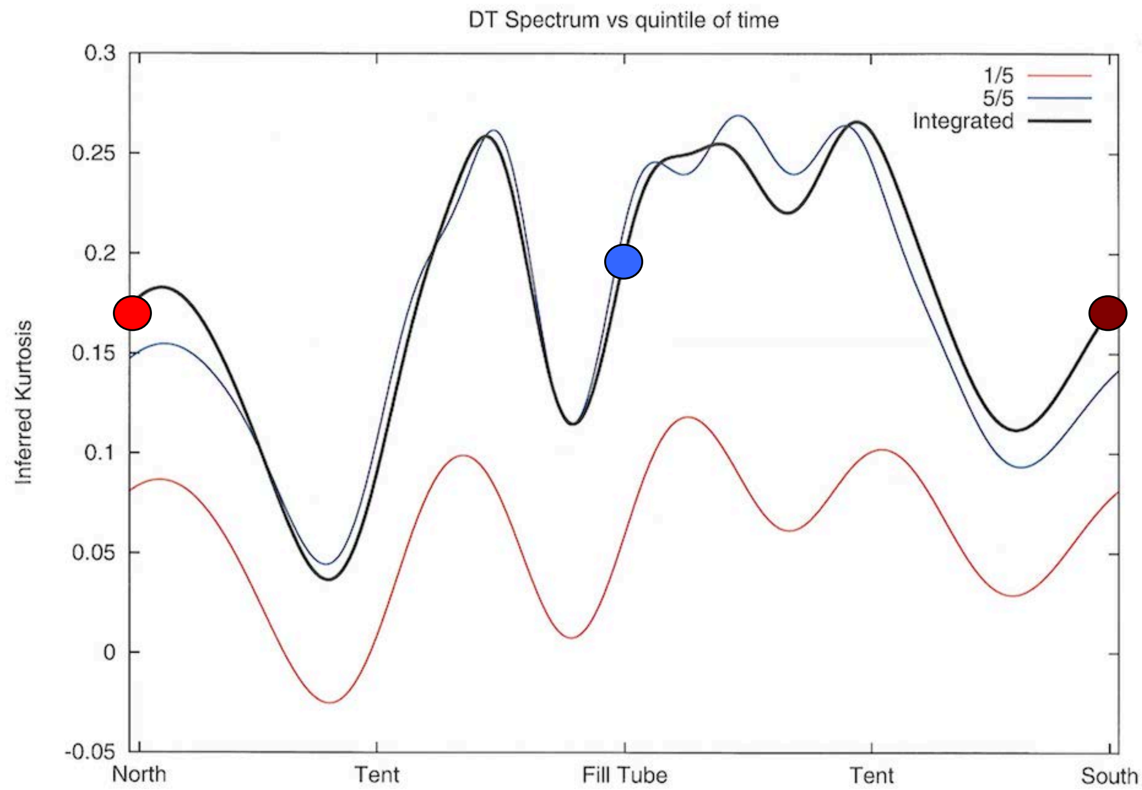
$$T_{DD}=(T_{thermal} + 4T_{DT})/5$$

Scattering alters the peak shape, likely affecting apparent temperature

The kurtosis shows hot spot cooling and flow effects.

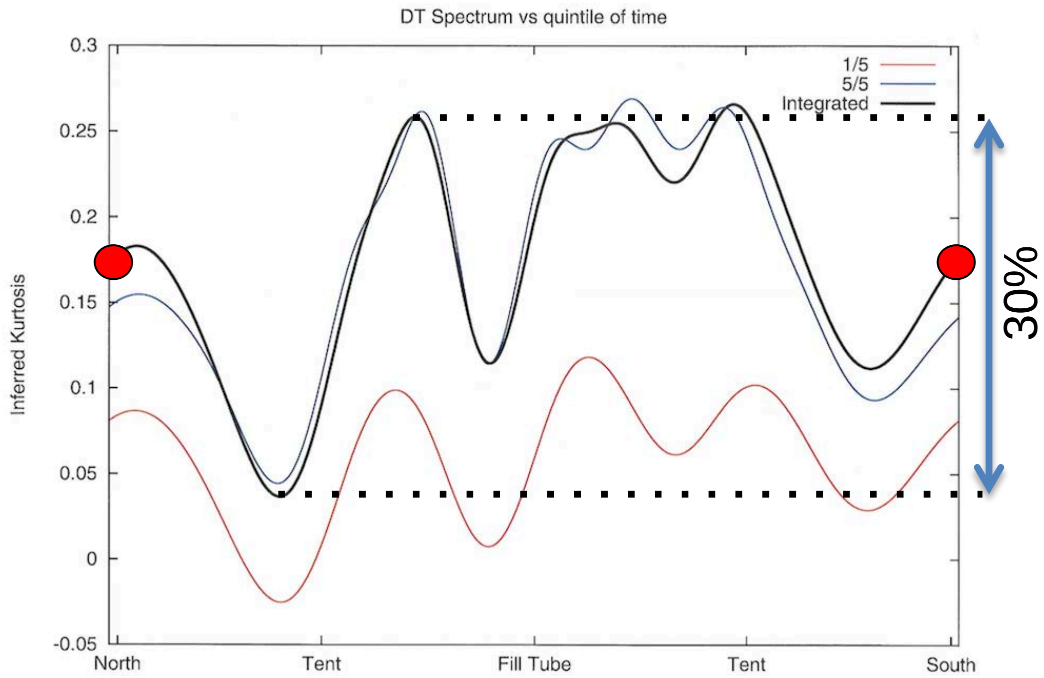
VIEW PATH





The kurtosis shows hot spot cooling and flow effects

1. Positive kurtosis suggests temperature variation during burn
2. Negative kurtosis implies velocity variation.
3. Variation with angle is due to velocity.
4. Kurtosis would be constant with LOS in a spherical or stagnant implosion



scalar — Vary with line of sight (tensors)

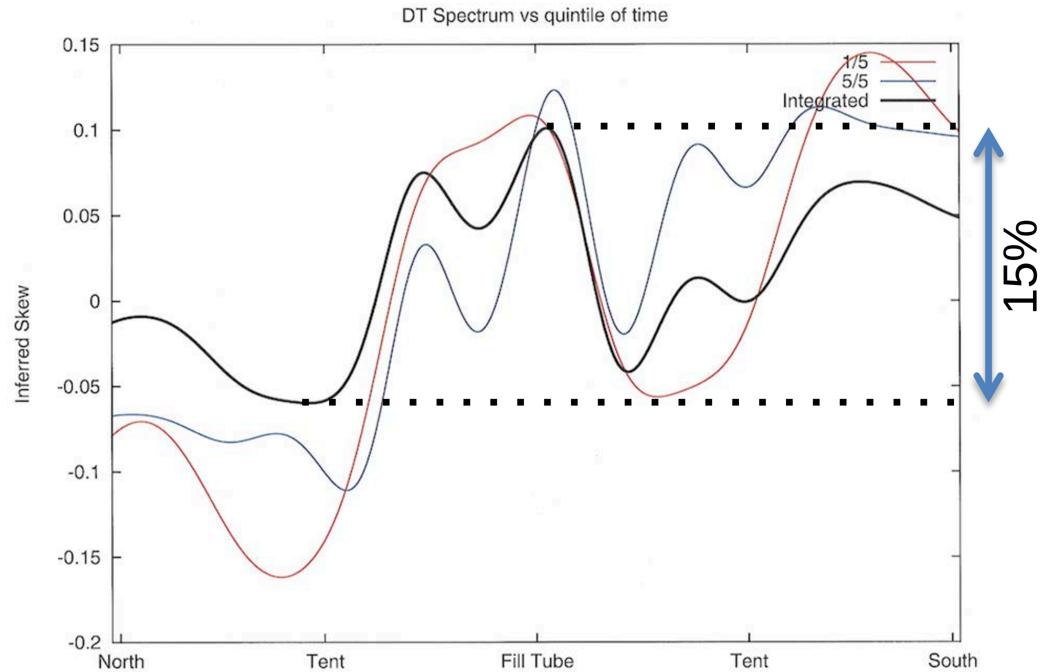
$$\mathrm{Kurt}(\omega)=\frac{3\,\mathrm{Var}(\tau)+6\,\mathrm{Cov}(\tau,u_\Omega,u_\Omega)+\mathrm{Cov}(u_\Omega,u_\Omega,u_\Omega,u_\Omega)-3\,\mathrm{Var}(u_\Omega)^2+\ldots}{\mathrm{Var}(\omega)^2}$$

L=0, 2, 4 in direction → antipodes are identical

Kurtosis variation with line of sight is another direct measure of stagnation and stagnation asymmetry – need it to ~ **5-10% precision**

Skewness measures the relationship between temperature and velocity

1. Skew gives correlation of temperature and velocity
2. Is the hottest material moving fast? Slow?
3. **Skew is zero for 1D implosions**



Vary with line of sight (tensor)

$$\mathrm{Skew}(\omega) = \frac{\overbrace{3\mathrm{Cov}(\tau, u_\Omega)}\overbrace{+\mathrm{Cov}(u_\Omega, u_\Omega, u_\Omega)+\ldots}}{\mathrm{Var}(\omega)^{3/2}}$$

L=1, L=3 in direction → antipodes measure odd modes

Skewness gives us a picture of the partition of mechanical and thermal energy – need it to ~ **3-5% precision**

Variation of moments in simulation suggest requirements for diagnostic performance and analysis

- 1st moment – peak location to 15-30 km/s, needed on at least 3 LOS
- 2nd moment – width and sampling to allow 200 eV PTV in signal
- 3rd moment – skew and sampling to 5%
- 4th moment – kurtosis and sampling to 5-10%

How are we affected by scattering?

Can we ignore it?

- How big is the error we make doing so compared to the range we'd like to measure?

Compensate for it?

- How confident can we be that this reduces uncertainty in our measurement?

Can we rely on it?

- Can simulations be predictive enough that we compare peak shapes directly?

Scattering affects some peak shape properties more than others

Scattering drives skew down

- Meaningful for DT
- Larger for DD

Scattering impact on kurtosis depends on neutron energy

- Negligible for DT
- Huge for DD

2D simulation			Skew (0.03-0.05)	Kurtosis (0.05-0.1)
DT	Spec A	birth	0.055	0.225
		escaped	-0.037	0.245
		change	-0.092	+0.020
	NIS	birth	0.019	0.261
		escaped	-0.051	0.261
			-0.070	0.000
	Spec SP	birth	0.100	0.165
		escaped	--	--
DD	Spec A	birth	0.069	0.116
		escaped	-0.111	0.583
			-0.180	+0.467
	NIS	birth	0.041	0.139
		escaped	-0.102	0.592
			-0.143	+0.453
	Spec SP	birth	0.100	0.080
		escaped	--	--

Scattering affects some peak shape properties more than others

Similar story in 3D run

Scattering drives skew down

- Meaningful for DT
- Larger for DD

Scattering impact on kurtosis depends on neutron energy

- ~~Negligible~~ Meaningful for DT
- Huge for DD

3D simulation			Skew (0.03-0.05)	Kurtosis (0.05-0.1)
DT	Spec A	birth	0.026	0.149
		escaped	-0.037	0.208
		change	-0.063	+0.059
	NIS	birth	0.026	0.141
		escaped	-0.047	0.204
			-0.073	+0.093
	Spec SP	birth	0.019	0.142
		escaped	--	--
DD	Spec A	birth	0.047	0.080
		escaped	-0.116	0.572
			-0.069	**+0.492**
	NIS	birth	0.046	0.081
		escaped	-0.114	0.581
			-0.160	**+0.500**
	Spec SP	birth	0.042	0.090
		escaped	--	--

We are applying our understanding of spectral peak shape to representative simulations

- 1D, 2D, 3D simulations; 6 LOS where appropriate
- DT and DD peaks
- Moments 0, 1, 2, 3, 4 by peak fitting
- Fit by n-parameter, Hermite polynomial
- Escaped spectrum (w/ scattering), birth (w/o scattering), escaped with correction (experimental)
- Comparison with moments of (T,u)-distribution (Munro paper)

We're trying to better understand the neutron peak shape

- Moments of the **birth** spectral peak encode joint temperature and velocity variation
  - 1st moment – peak location to 15-30 km/s, needed on at least 3 LOS
  - 2nd moment – width and sampling to allow 200 eV PTV in signal
  - 3rd moment – skew and sampling to 5%
  - 4th moment – kurtosis and sampling to 5-10%
- Scattering transforms the birth peak to the **escaped** peak
  - Reduces skew
  - Increases kurtosis
  - Slight effect in DT
  - Major effect in DD
- Much work remains

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Simulations show a difference between apparent DD and DT ion temperatures likely due to scattering

Detector	Simulated T_{DT} [keV]	Simulated T_{DD} [keV]	T_{DT}-T_{DD} [eV]	Inferred $T_{thermal}$
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True $T_{thermal}$ = 2.3 keV

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$$T_{Brysk} = \left(\frac{m_D + m_T}{k}\right)\sigma_v^2 + T_{thermal}$$

$$T_{thermal} = 5T_{DD} - 4T_{DT}$$

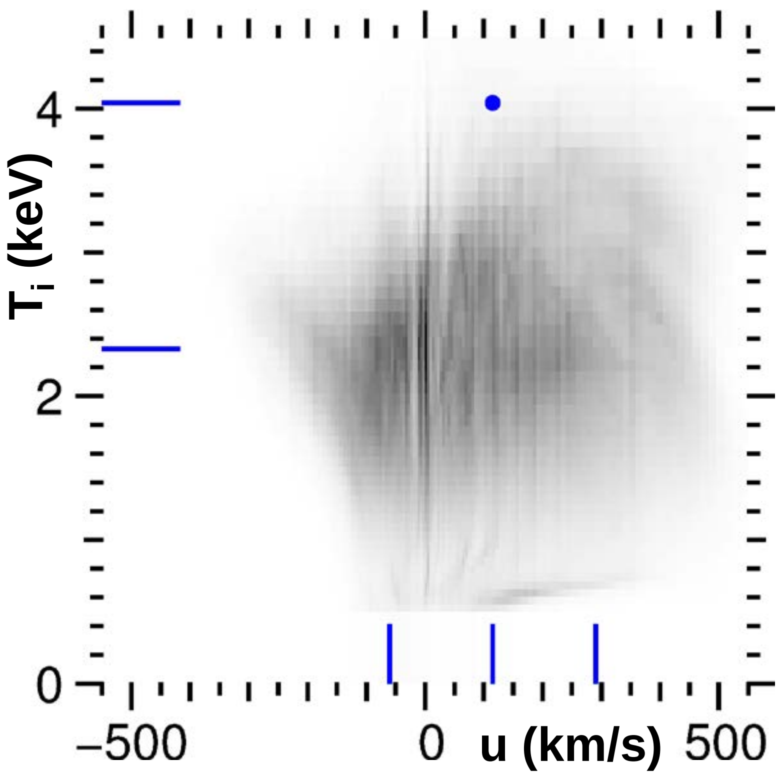
$$T_{DD} = (T_{thermal} + 4T_{DT})/5$$

- **When we try to compare DD and DT temps in experiments we find difference to be "too large."**
- **Turns out 3D simulations have the same "too large" difference that makes Tthermal look way too small.**
- **Is DD scattering to be blamed? Likely.**

Scattering alters the peak shape, affecting apparent temperature

Neutron spectral moments and LOS dependence are important clues

burn T-u distribution (3D simulation)



u = fluid velocity component along LOS

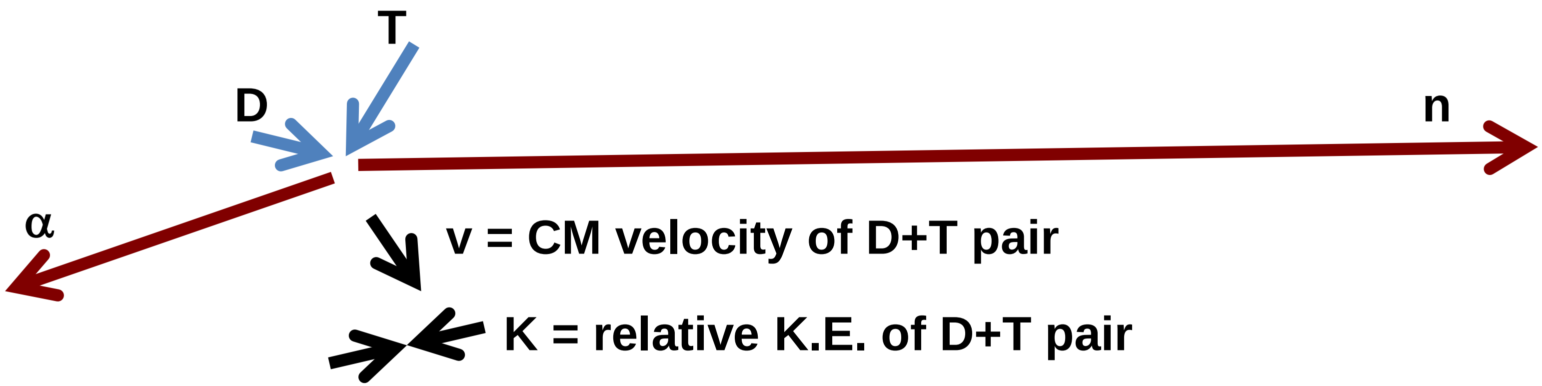
burning plasma exceedingly non-uniform, neutrons produced in wide range of T_i and fluid u

shift of spectral peak only tells us mean <u> + shift(<T_i>)

variance of spectral peak only captures <T_i> + Var(u)

skew and kurtosis of spectral peak tell us about T-u correlations and Var(T)

Each D+T (or D+D) reaction makes n with slightly different momentum



$$m^2 = E^2 - p^2 = E'^2 - p'^2$$

Lorentz invariants for neutron boost

$$E' = \gamma\left(E + \mathbf{v}\cdot\mathbf{p}\right) = \gamma\left(E + v_\Omega p\right)$$

Boost CM 4-momentum by CM v

$$p' = p + E_0 v_\Omega - \frac{v_\perp^2}{2v_0^2}v_0 + \frac{v^2 + v_\perp^2}{2}v_0 + O\left(v^3\right)$$

$E_0 = m_n + K_0$, $K_0 \sim 14$ MeV
$v_0 \sim 51000$ km/s (14 MeV)

$$\omega \equiv \frac{p'}{E_0} - v_0 = v_\Omega + \frac{p}{E_0} - v_0 - \frac{v_\perp^2}{2v_0^2}v_0 + \frac{v^2 + v_\perp^2}{2}v_0 + O\left(v^3\right)$$

Shifted, scaled neutron momentum is best variable for spectrum

$$\omega \equiv \frac{p'}{E_0} - v_0 = v_\Omega + \frac{p}{E_0} - v_0 - \frac{v_\perp^2}{2v_0^2} v_0 + \frac{v^2 + v_\perp^2}{2} v_0 + O\left(v^3\right)$$

CM velocity component
thermal motion T,
fluid motion u

p=p(K) relative K.E.
thermal motion K ~ 5T

$$M = m_D + m_T \qquad \left\langle v_\Omega^2 \right\rangle_{\text{thermal}} = \frac{T}{M} \equiv \tau$$

T in units of velocity^2

1 keV → (139 km/s)^2 DT
(155 km/s)^2 DD

$$\frac{p}{E_0} - v_0 \approx \frac{1}{v_0}\left(\frac{M}{E_0} - 1\right)\frac{K}{M} \equiv \kappa$$

K in units of velocity

10 keV → 14.7 km/s DT, 33.1 km/s DD

For given T, u, and K, can integrate over directions, Maxwellian exactly

fixed K = relative K.E. defers needing to know reaction cross section

$$\frac{dN}{d\Omega dp''_n} \sim \frac{p''^2_n}{E''_n p'_n p_n} \exp\left(-(\gamma-1)\frac{M+K}{T}\right)$$

unprimed is CM
' is fluid frame
" is lab frame

This spectrum exact Maxwell-Juttner averaged relativistic kinetics
Can also integrate momentum moments analytically

Averages over the distribution of K for given T done by expanding in K/K_0 and K/M – this averaging requires reaction cross section

Finally, average over T, u distribution

Use neutron momentum spectrum, scaled to units of velocity

$\omega = p_n / (m_n + K_0) - v_0$ **scaled and shifted neutron momentum**
- very nearly CM velocity of reacting DT pair

$4\pi \frac{dN}{d\omega\, d\mathbf{\Omega}}$ **momentum spectrum = number of neutrons per sphere within dω of "velocity" ω and within dΩ of direction Ω**

$$\langle \omega^n \rangle = \frac{\int d\omega\, \omega^n \frac{dN}{d\omega\, d\mathbf{\Omega}}}{\int d\omega\, \frac{dN}{d\omega\, d\mathbf{\Omega}}}$$

n^th moment of scaled momentum spectrum

$\tau = T / (m_D + m_T)$ **fluid temperature T as a velocity variance**

$u_\Omega = \mathbf{u} \cdot \mathbf{\Omega}$ **fluid velocity component along LOS**

$$\bar{\kappa} = \frac{1}{v_0}\left(\frac{m_D + m_T}{m_n + K_0} - 1\right)\frac{\bar{K}(T)}{m_D + m_T} \approx \bar{\omega}(T)$$

"velocity" for mean DT K.E.(T) ("Ballabio shift")

Each spectral moment constrains moments of (T,u) burn distribution

$f(T,\mathbf{u})dTd^3\mathbf{u}$ **fraction of neutrons produced in plasma at temperature T within dT, velocity u within du**

$\langle XY \rangle = \int XY\, f(T,\mathbf{u})dTd^3\mathbf{u}$ **burn average of quantity XY**

$$\int d\omega\, 4\pi \frac{dN}{d\omega\, d\mathbf{\Omega}} = 1 + \frac{2}{v_0}\langle u_\Omega \rangle + \frac{1+v_0^2}{2v_0^2}\left(3\langle u_\Omega^2 \rangle - \langle u^2 \rangle\right) + \ldots$$

LOS dependence of yield

$$\langle \omega^1 \rangle = \langle u_\Omega \rangle + \langle \kappa \rangle + (1+\tfrac{1}{2}v_0^2)\langle \tau \rangle / v_0 + \ldots$$

centroid of spectrum

$$\langle \omega^2 \rangle = \langle \tau \rangle + \langle u_\Omega^2 \rangle + 2\langle \kappa u_\Omega \rangle + \ldots$$

$$\langle \omega^3 \rangle = 3\langle \tau u_\Omega \rangle + \langle u_\Omega^3 \rangle + \ldots$$

(showing only largest contributions)

$$\langle \omega^4 \rangle = 3\langle \tau^2 \rangle + 6\langle \tau u_\Omega^2 \rangle + \langle u_\Omega^4 \rangle + \ldots$$

Compute cumulants to see deviation from Gaussian spectrum

$$\mathrm{Cov}(X,Y)=\left\langle\left(X-\langle X\rangle\right)\left(Y-\langle Y\rangle\right)\right\rangle=\langle XY\rangle-\langle X\rangle\langle Y\rangle$$

$$\mathrm{Var}(X)=\mathrm{Cov}(X,X)=\left\langle X^2\right\rangle-\langle X\rangle^2$$

$$\mathrm{Cov}(X,Y,Z,\ldots)=\left\langle\left(X-\langle X\rangle\right)\left(Y-\langle Y\rangle\right)\left(Z-\langle Z\rangle\right)\ldots\right\rangle$$

$$\mathrm{Skew}(X)=\mathrm{Cov}(X,X,X)/\mathrm{Var}(X)^{3/2}$$

$$\mathrm{Kurt}(X)=\mathrm{Cov}(X,X,X,X)/\mathrm{Var}(X)^2-3$$

skew, kurtosis zero for Gaussian distribution

$$\mathrm{Var}(\omega)=\langle\tau\rangle+\mathrm{Var}(u_\Omega)+2\,\mathrm{Cov}(\kappa,u_\Omega)+\ldots$$

L=0, L=2, L=1 in direction

$$\mathrm{Skew}(\omega)=\frac{3\,\mathrm{Cov}(\tau,u_\Omega)+\mathrm{Cov}(u_\Omega,u_\Omega,u_\Omega)+\ldots}{\mathrm{Var}(\omega)^{3/2}}$$

L=1, L=3 in direction

$$\mathrm{Kurt}(\omega)=\frac{3\,\mathrm{Var}(\tau)+6\,\mathrm{Cov}(\tau,u_\Omega,u_\Omega)+\mathrm{Cov}(u_\Omega,u_\Omega,u_\Omega,u_\Omega)-3\,\mathrm{Var}(u_\Omega)^2+\ldots}{\mathrm{Var}(\omega)^2}$$

L=0, 2, 4

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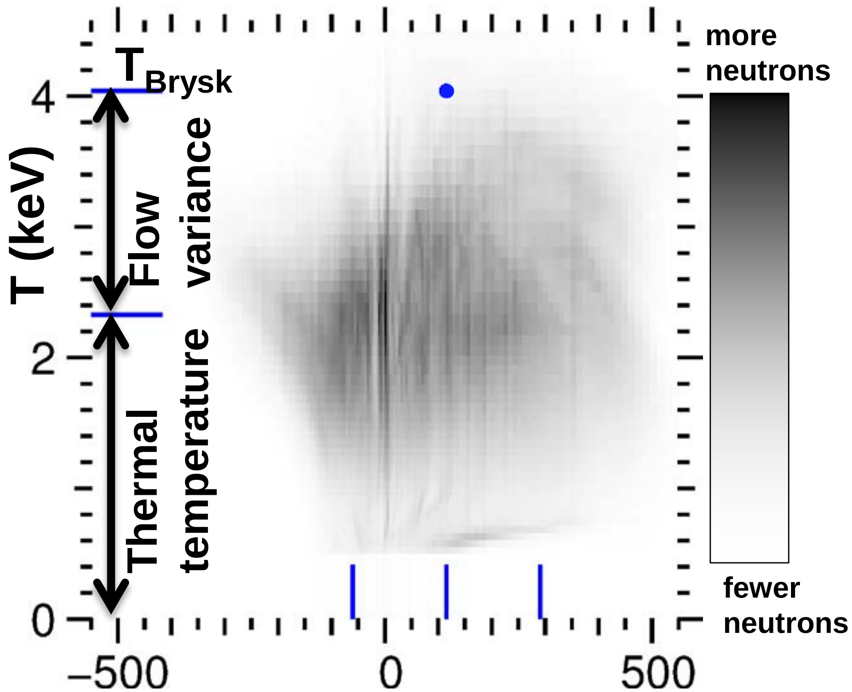
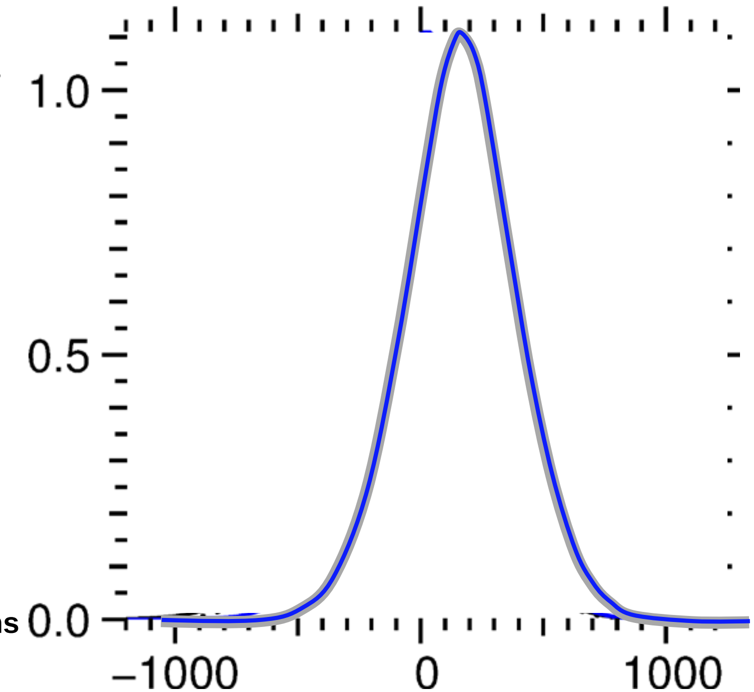
Birth peak depends on the distribution of neutron production in temperature and velocity space

Neutrons produced over a range of temperatures and velocities

Peak width records neutron-weighted thermal temperature and the flow variance





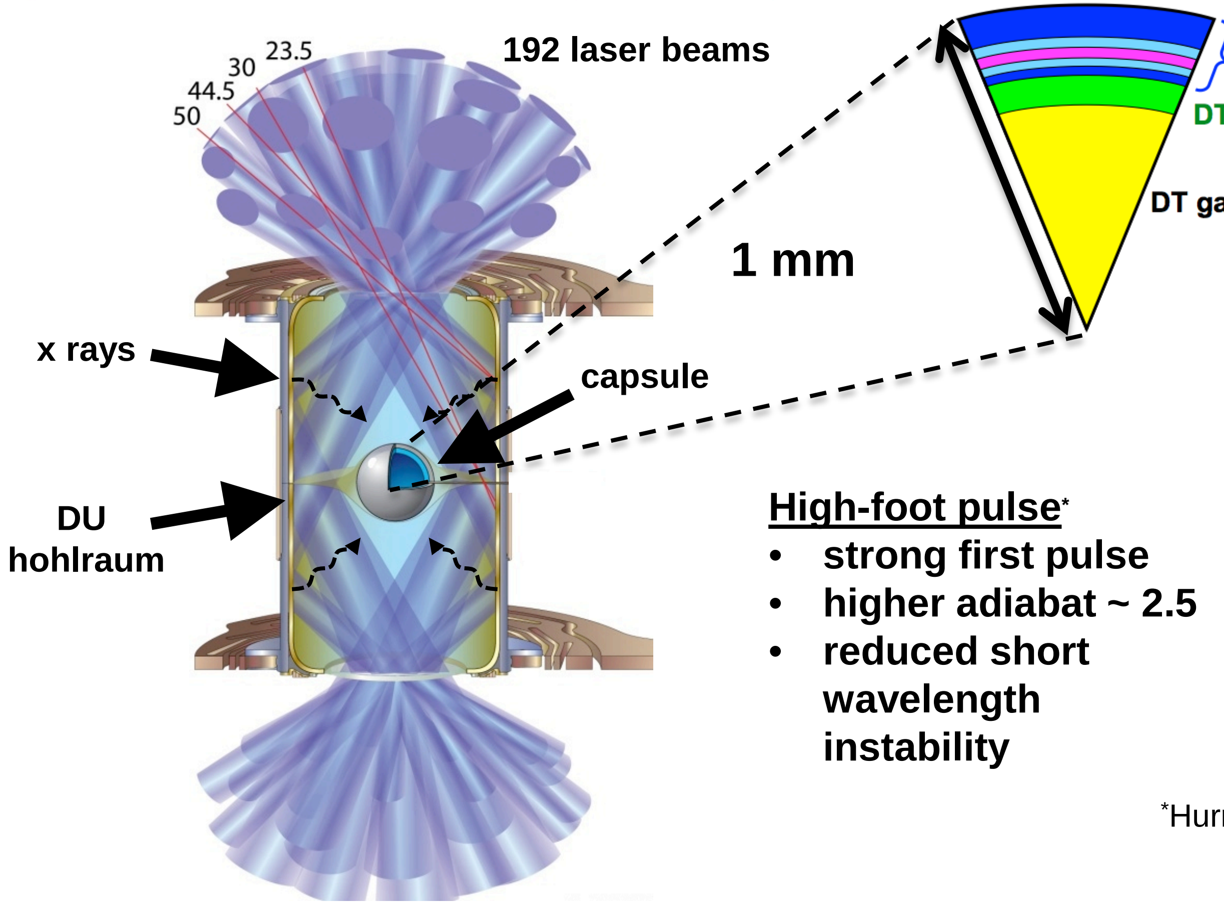
Simulations have to get a lot right to capture the temperature variation

Nuclear diagnosis at NIF provides an unprecedented picture of stagnated ICF implosions

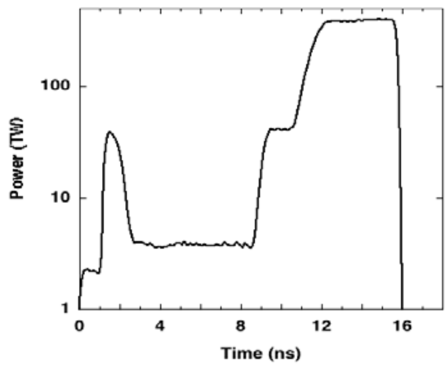
- **Hohlraum and capsule symmetry respond to large drive perturbations (P_1) as predicted**
- **Nuclear diagnostics capture the thermodynamics and flow of the hot spot and cold shell**
- **Simulated hot spot and cold shell diagnostics match experimental observables**
- **The repeatability of the high foot implosion platform supports perturbed stagnation experiments**

Our codes and diagnostics have captured the detailed effects of intentional perturbations

We used high-adiabat implosions with reduced high-mode instability



laser power vs time



High-foot pulse*

- strong first pulse
- higher adiabat ~ 2.5
- reduced short wavelength instability

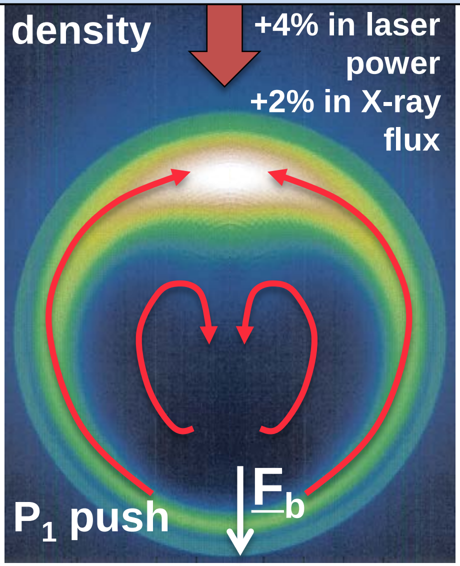
*Hurricane et al., Nature, 506, 7488 (2014)

High-adiabat implosions allow investigation of asymmetry and stagnation processes

Top-to-bottom drive imbalance (mode 1) is an ideal symmetry perturbation

- **Implosions are sensitive to mode 1**
  - **Buoyancy force on hot spot due to P_1 acceleration**
  - **Hot spot flows**
  - **Shell asymmetry**
  - **Similar flows result from ice layer asymmetry**

We performed this experiment on N150318



Spears, PoP 2014
Chittenden et al

- **Mode 1 effects are observable by nuclear diagnosis**
- **Signatures of mode 1 are present in many high foot implosions**

Asymmetrically driven implosions are relevant to the stockpile stewardship mission on NIF

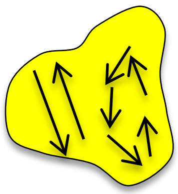
- **Provide an experimental platform with asymmetric radiation flow**
- **Detailed measurements of the stagnating plasma**
- **Detailed code predictions of observable signatures (neutron spectra)**

Perturbed implosions provide an integrated test of our code capabilities

We measure multiple stagnation quantities by neutron spectrometry

Ion temperature

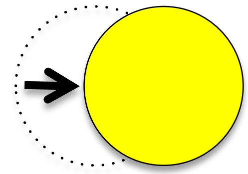
Neutron spectral peak width.
Temperature and hot spot flow.



Shear
Swirling
Velocity field variance

Bulk velocity

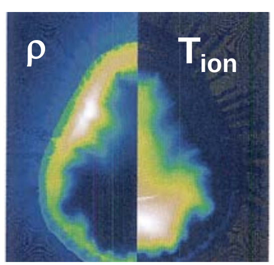
Neutron spectral peak shift.
One-sided imbalance drives this.



Rigid-body translation

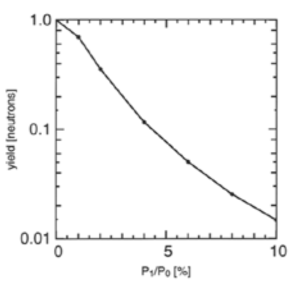
Shell uniformity

Neutron scattering.
Asymmetries perturb the shell.



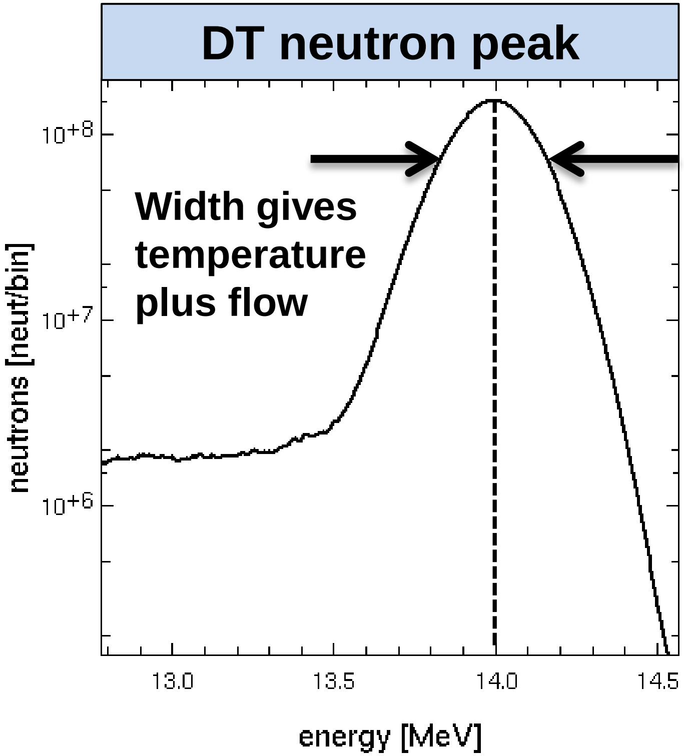
Neutron yield

Integrated performance metric.
Incomplete stagnation reduces yield.



Implosion asymmetry alters stagnation phase properties

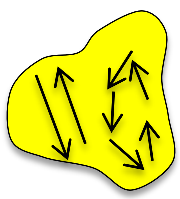
Neutron spectrometers measure *apparent* ion temperature from spectral peak width



Peak is broadened by:

1. **thermal temperature**
2. **fluid flow**

Flowing hot spot:
Shear
Swirling
Velocity field variance



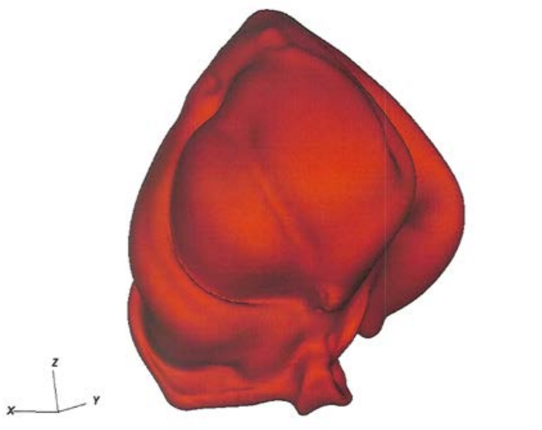
spread **in fluid velocity**

$$T_{Brysk} = \left(\frac{m_D + m_T}{k}\right) \sigma_v^2 + T_{thermal}$$

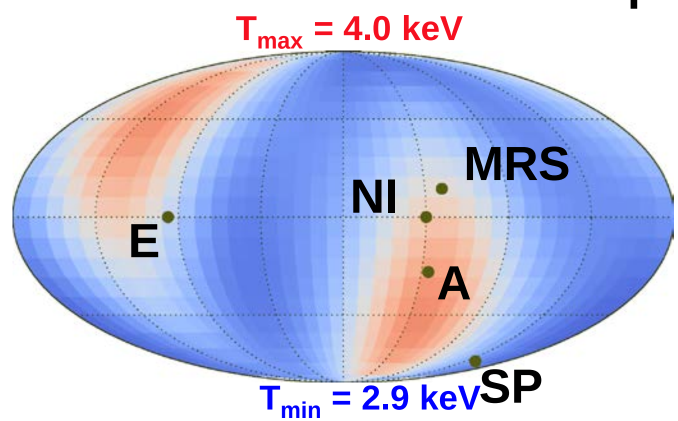
Hot spot flows increase the apparent (Brysk) temperature

Asymmetric 3D simulations show angular temperature variations due to flow

Asymmetric flow in distorted hot spot



Apparent temperature distribution from simulated peak widths



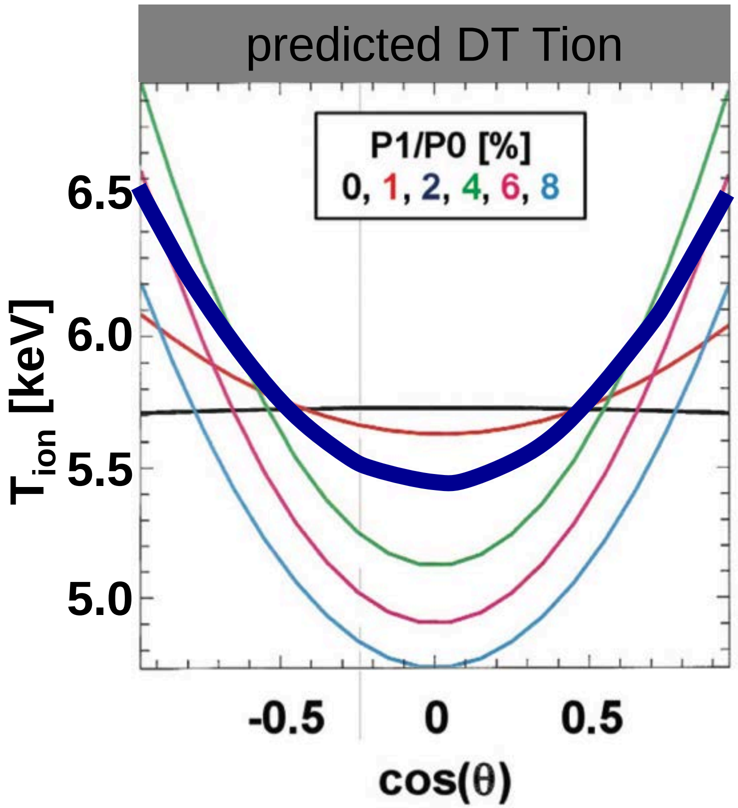
Detector	T_{Brysk}
SpecE	3.49
SpecA	3.56
SpecSP	2.96
NITOF	3.50
MRS	3.39

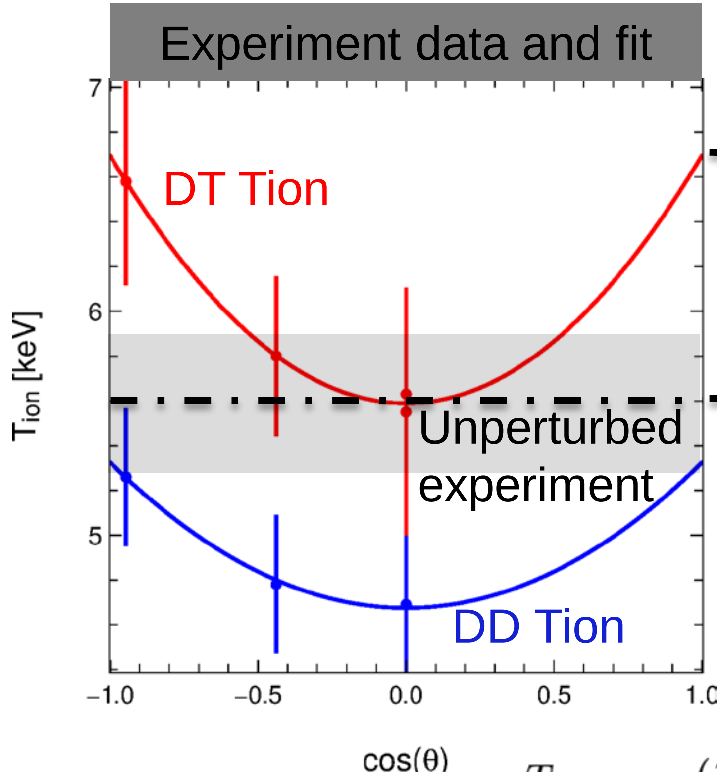
- **Thermal temperature is 2.3 keV**
- **Apparent temperatures span 2.9 to 4.0 keV – depending on direction**
- **Detector array typically samples 50% of full PTV**

Hot spot flow can be estimated from temperature differences

P_1 perturbed experiments confirm our ability to measure flow-induced temperature variation

- Preshot simulations predict 1 keV temperature variation due to flow
- Experiments show very similar variation, amplitude and shape





1 keV represents 140 km/s standard deviation in "stagnated" velocity

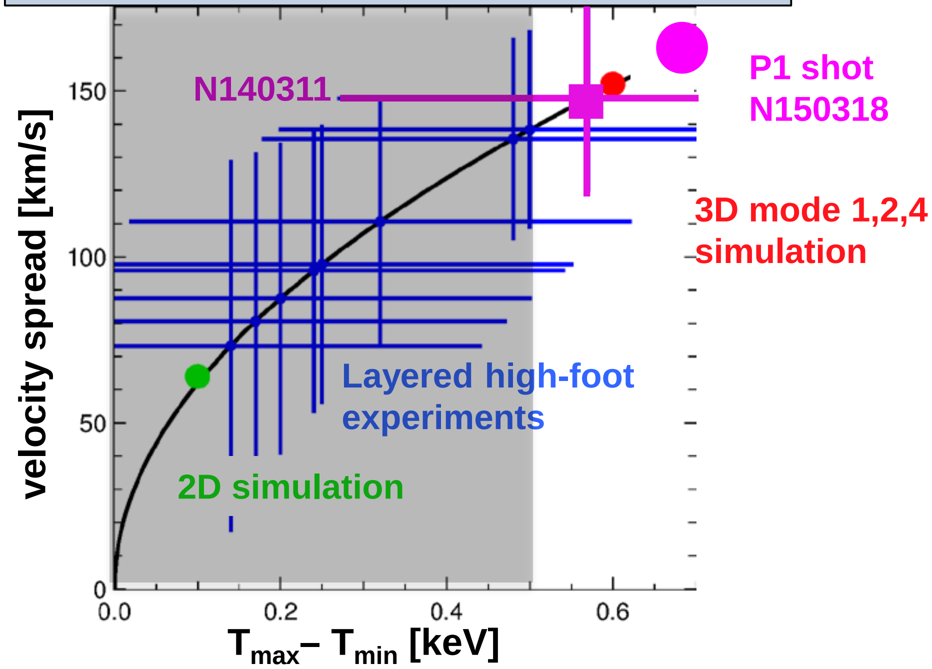
DD/DT gap remains "anomalous"

$$T_{Brysk} = \left(\frac{m_D + m_T}{k}\right)\sigma_v^2 + T_{thermal}$$

We can measure 1 keV apparent Tion anisotropy

So, is the high foot apparent T_{ion} usually isotropic or not?

Expected Tion variation is nearly observable



$$T_{Brysk} = \left(\frac{m_D + m_T}{k}\right) \sigma_v^2 + T_{thermal}$$

The NIF data cannot (currently) distinguish between isotropy and the expected level of anisotrop

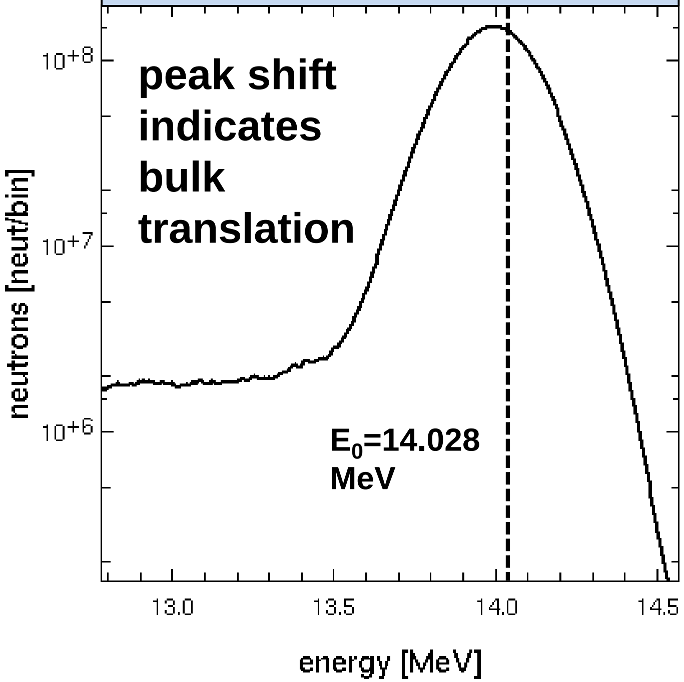
- **Post shot simulations suggest Tion anisotropy of ~ 300 - 400 eV**
- **Detectors would typically sample ~ 150-200 eV**
- **Detectors can measure down to 500 eV anisotropy**

See M. Gatu Johnson paper

We need neutron spectrometers that can measure 300 eV anisotropy

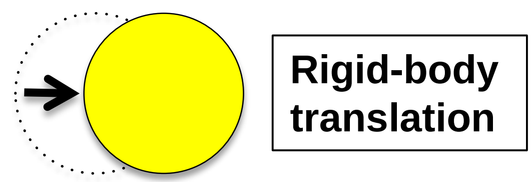
Neutron spectrometers measure bulk velocity from spectral peak shift

DT neutron peak



Primary neutron peak location gives translational or bulk velocity

Translating hot spot



$$t = \frac{d}{v_n + \bar{v}_{fluid}}$$

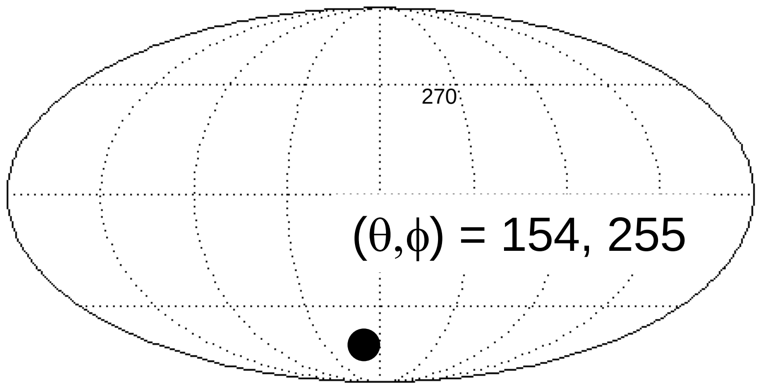
Velocity components measured on 3 nearly orthogonal lines of sight

Measure speed and direction of hot spot translation

Mode 1 perturbed experiments confirm our ability to measure bulk flow velocity

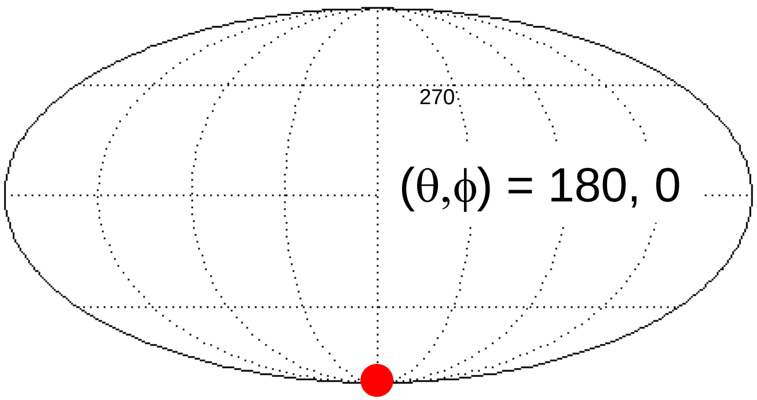
Experimental measurement

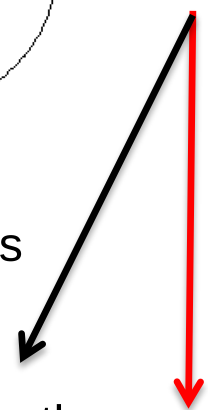
85 +/- 15 km/s resultant
26 degrees off vertical



Preshot prediction

90 km/s resultant
directly downward



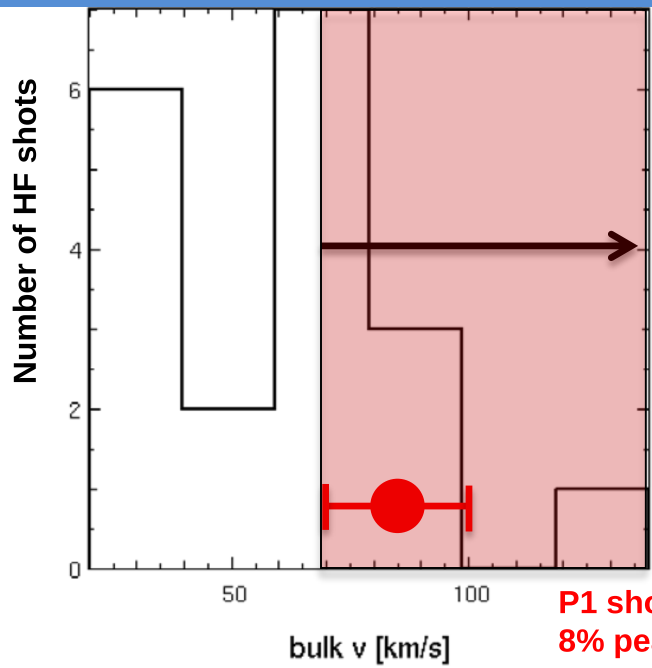


3D effects drive the
flow off axis

Composition of multiphysics effects (laser propagation, LPI, radiation transport, implosion hydrodynamics) is mainly captured by HYDRA

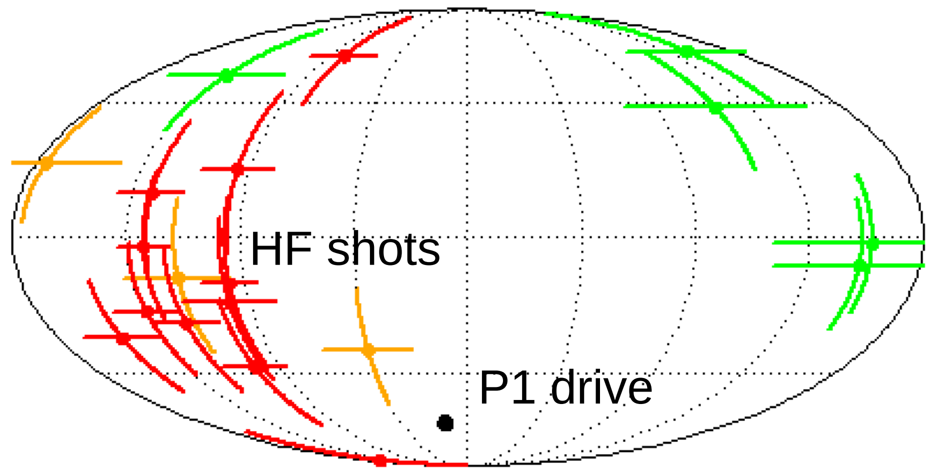
The average high foot shot bulk velocity is 70% of the intentional P_1

Average HF bulk velocity is 60 km/s; P_1 was 85 km/s



P1 shot N150318
8% peak to valley
power imbalance

Large bulk velocities tend to cluster



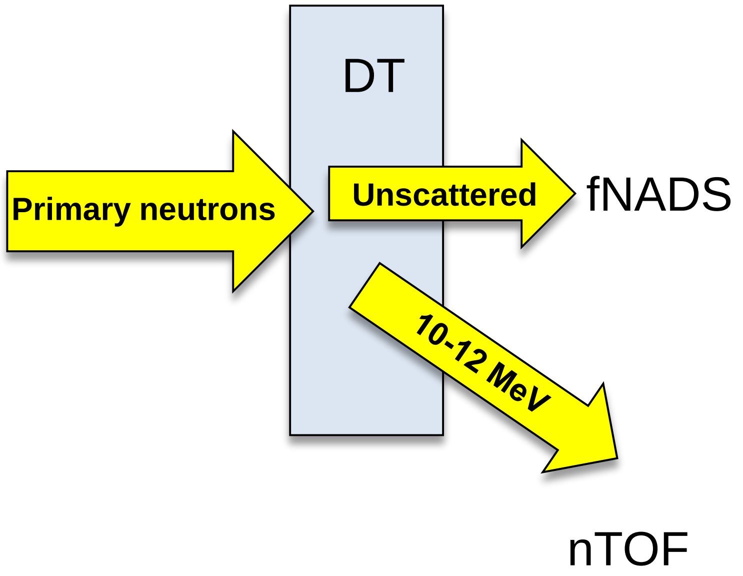
> 60 km/s
30 - 60 km/s
< 30 km/s

8 of 19 HF shots have velocities larger than the P_1 shot

We haven't yet identified what is producing these perturbations

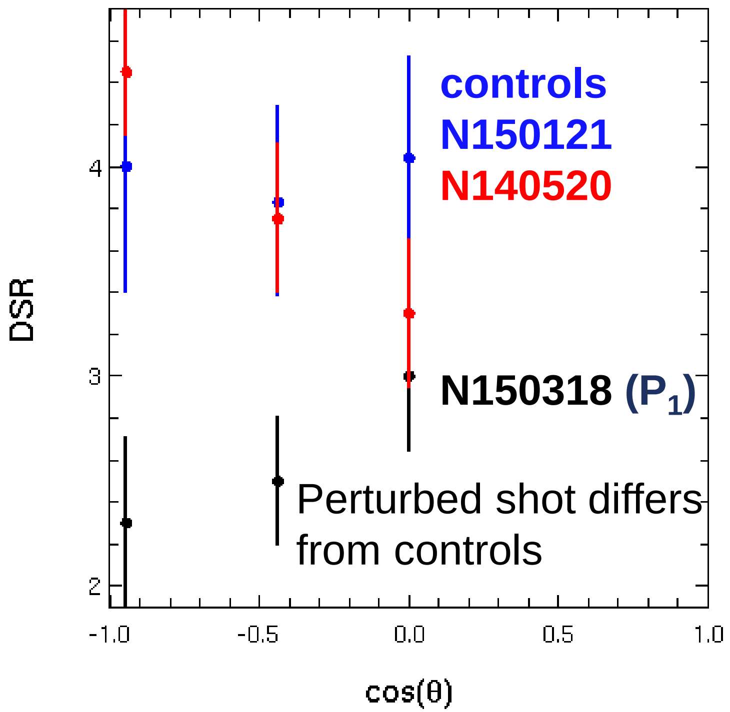
The cold shell conformation is probed by exiting neutrons

- Neutron spectrometers (nTOF) measure downscattered neutrons
  - High areal density DT scatters into 10 – 12 MeV band
  - Multiple lines of sight measure the asymmetry
- Flange Neutron Activation Diagnostics (fNADS) measure unscattered primary neutrons
  - Zr activated by neutrons above 1X.XX MeV threshold
  - 19 locations on chamber
  - Complementary to DSR

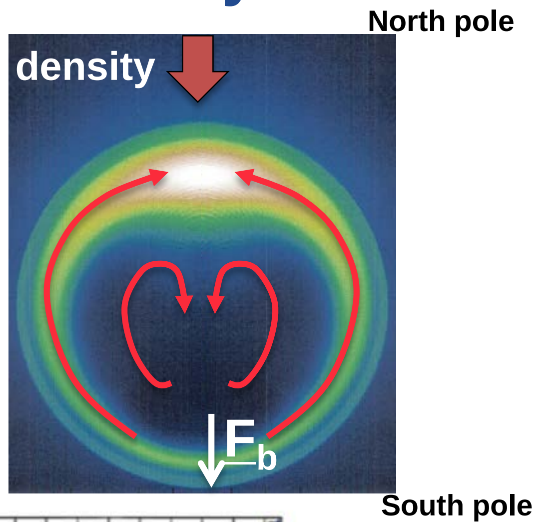


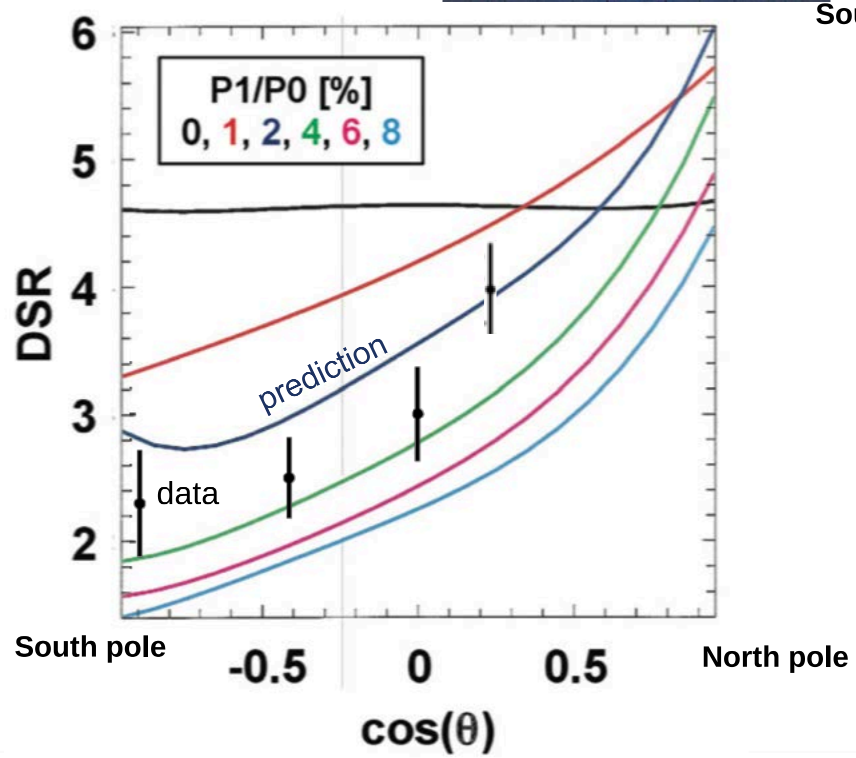
Mode 1 perturbed experiments confirm our ability to measure angular variation in DSR

Perturbed shot is different from control shots



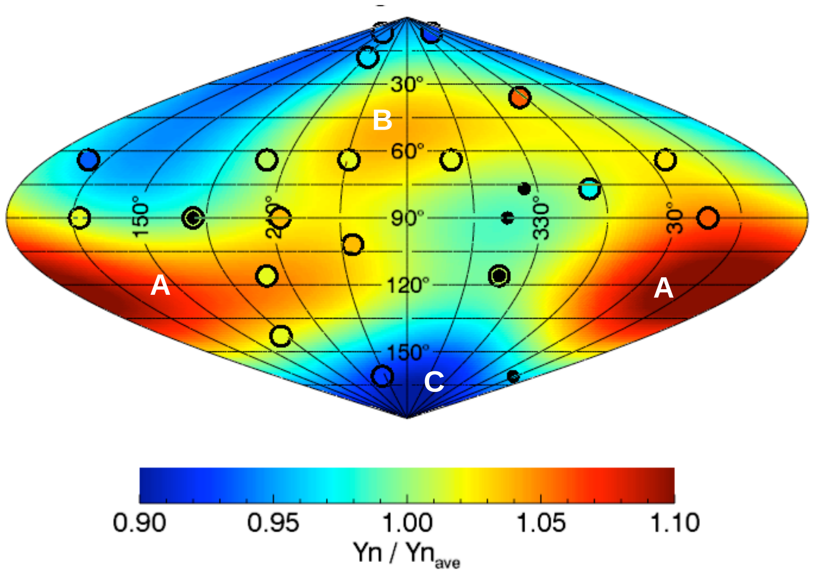
Experiments compare nicely with preshot predictions



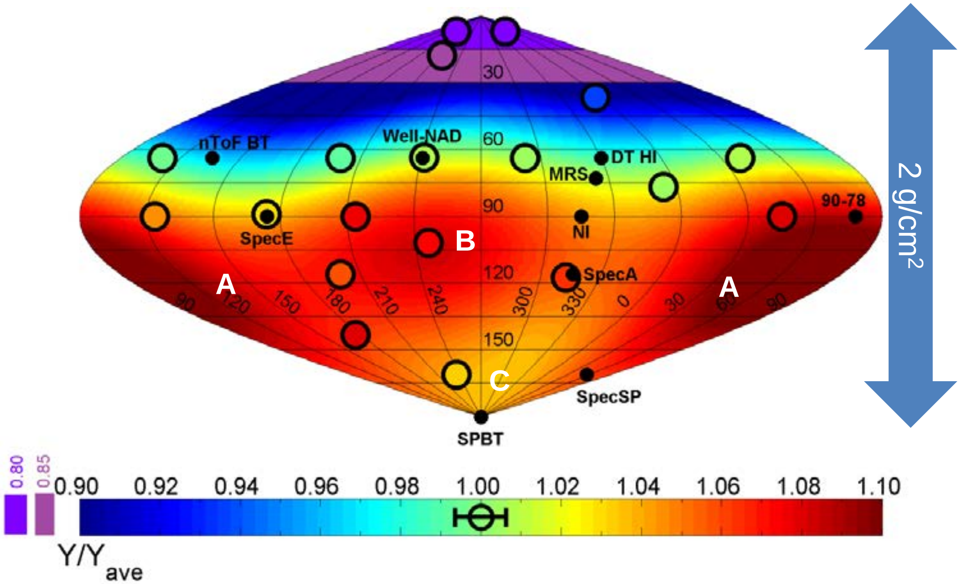


fNADS measured the predicted angular distribution of escaping primary neutrons

N140520 control shot



N150318 P_1 shot



- Predicted fNADS variation of ~ 25% peak to valley → measured 30%
- Expected P_1 asymmetry → observed P1 plus 3D similar to control shot

We can predict aspects of the cold shell areal density distribution when the perturbation is large enough

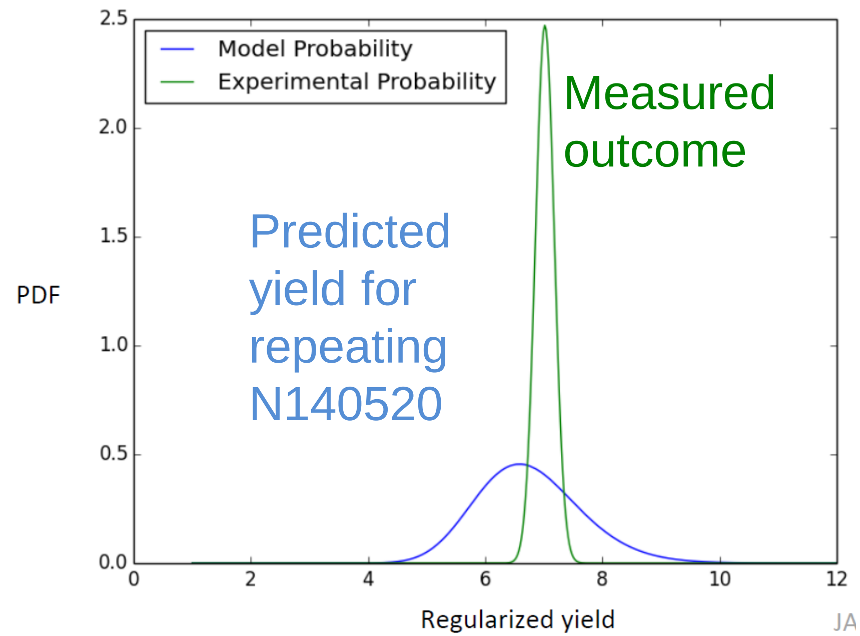
The repeatability of the unperturbed implosion supports the perturbed results

- We have 3 nominal repeats
  - Yield: μ=7.0e15, σ=0.5e15
  - T_{ion}: μ=5.44, σ =0.087
- We developed a statistical model of variability using the growing database and Callahan scaling
  - Uses both repeats and other high foot shots
  - Predicted variability compared favorably with a blind test on a repeat shot
- Stagnation properties are repeatable, even if not perfected

Calibration { N140520 = 7.6e15
N150121 = 6.3e15

Prediction 6.5e15 +/- 1e15

Outcome N150409 = 6.9e15



Jim Gaffney, Tammy Ma, Dan Casey, Niko Izumi, Debbie Callahan, Brian Spears

The repeatability of the platform is sufficient for testing perturbation effects

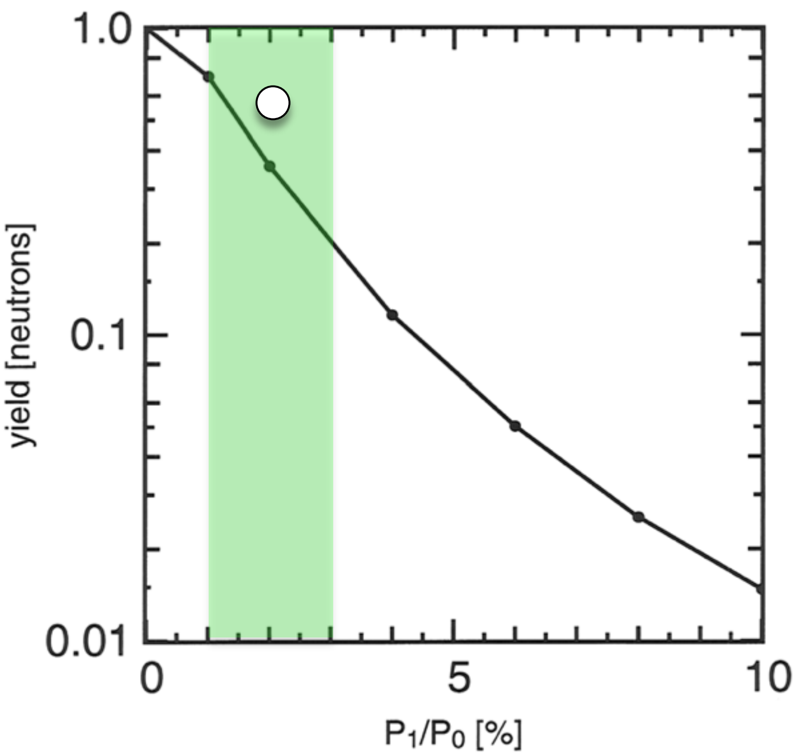
Reduction in yield was smaller than predicted by single failure mode simulations

Control shots
N140520 = 7.6e15
N150121 = 6.3e15
N150409 = 6.9e15
P_1 shot
N150318 = 4.8e15

- Control shots:7.0e15 +/- 0.5e15
- P1 shot gave 4.8 e15
  - Experiment degradation was 30%, observed 3σ reduction from control
  - Expected degradation was 60%, observed 3σ above expectations

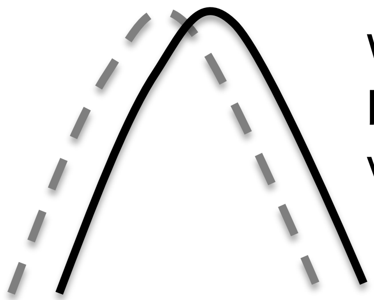
The yield is different from the controls

The yield is different from the prediction



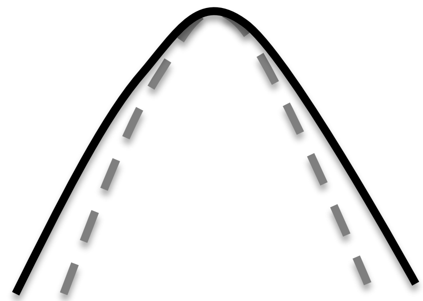
Stagnation measurements can be much more informative

First moment:
peak shift ~ f(bulk velocity, $T_{thermal}$)



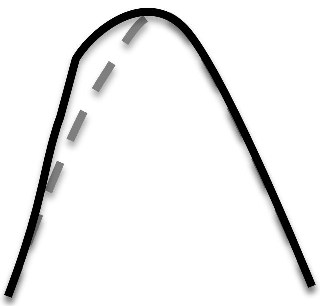
What's the bulk velocity?

Second moment:
Width ~ f($T_{thermal,}$flow variance)



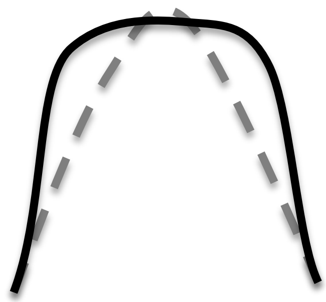
What's the apparent temp, thermal temp,residual flow?

Third moment:
Skew ~ cov($T_{thermal,}$flow)



Is the hot stuff moving fast?

Fourth moment:
Kurtosis ~ variance of Tion



How broad is the distribution of thermal temperatures?

New measurements provide increasingly detailed picture for code validation

Nuclear diagnosis at NIF provides an unprecedented picture of stagnated ICF implosions

- **Hohlraum and capsule symmetry respond to large drive perturbations (P_1) as predicted**
- **Nuclear diagnostics capture the thermodynamics and flow of the hot spot and cold shell**
- **Simulated hot spot and cold shell diagnostics match experimental observables**
- **The repeatability of the high foot implosion platform supports perturbed stagnation experiments**

Precision diagnostics, platforms, and codes are advancing our validation efforts

Lawrence Livermore National Laboratory