What does a new, better nTOF buy us?

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Improving the nTOFs will drive innovation at NIF

- What does an additional nTOF get us?
  - Capturing Tion variation
    - Choose your line of sight carefully – antipodal? Fill a gap?
    - What does it take to see expected Tion anisotropy? 100 eV error bar.
  - North pole
    - Removes systematics in Tion and bulk velocity
    - Gets odd modes
    - Chance at thermal ion temperature
- What do improvements to nTOF measurements or analysis get us?
  - Moments of the peak reveal thermal and fluid state
  - 1st (shift) – bulk velocity
  - 2nd (width) – Tion and flow variance
  - 3rd (skew) – correlation of temperature and flow. Is the hot stuff moving fast?
  - 4th (kurtosis) – correlation of temperature variance and flow. Is burn happening over a broad temperature range?

Apparent Tion varies with line of sight AND antipodal Tions are the same

- Fluid velocity variance increases the apparent temperature

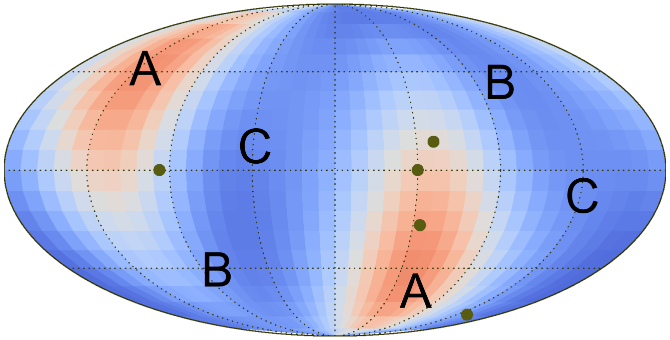
$$T_{Brysk} = \left(\frac{m_D+m_T}{k}\right)\sigma_v^2 + T_{thermal}$$

Murphy PoP

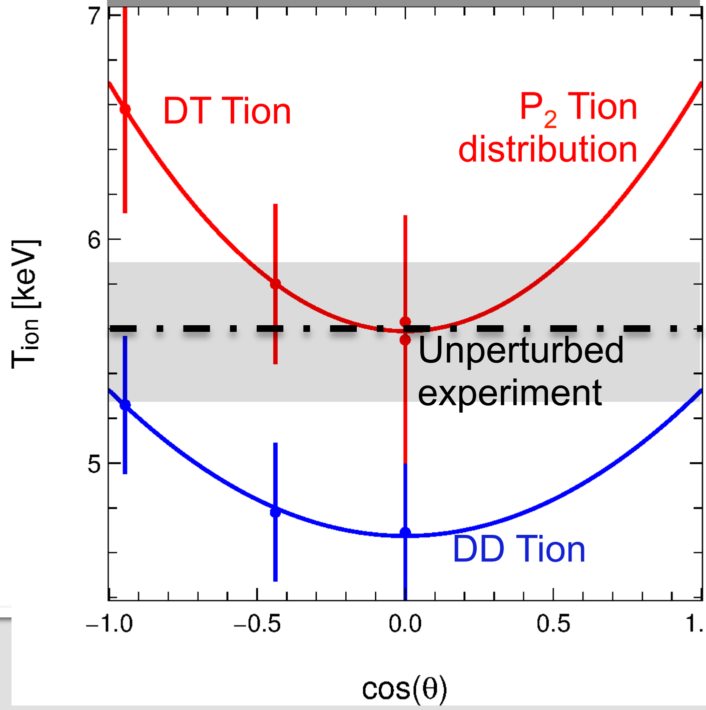
- Apparent temperature has an L=2, ellipsoidal distribution
  - Varies with line of sight
  - Equal on antipodal (opposite) lines of sight (LOS)

Some lines of sight are more valuable than others.

Simulation and theory show antipodal temps are identical



P_1 experiment suggests antipodal temps are the same

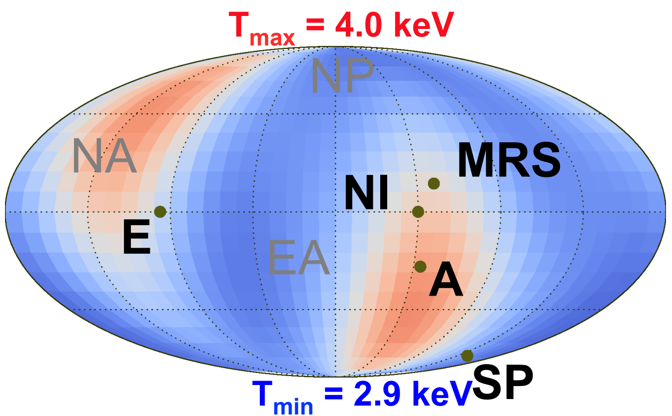


An additional nTOF increases the ability to capture differences with line of sight

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

Simulated detectors caught 55% of PTV

Antipodal temps are identical

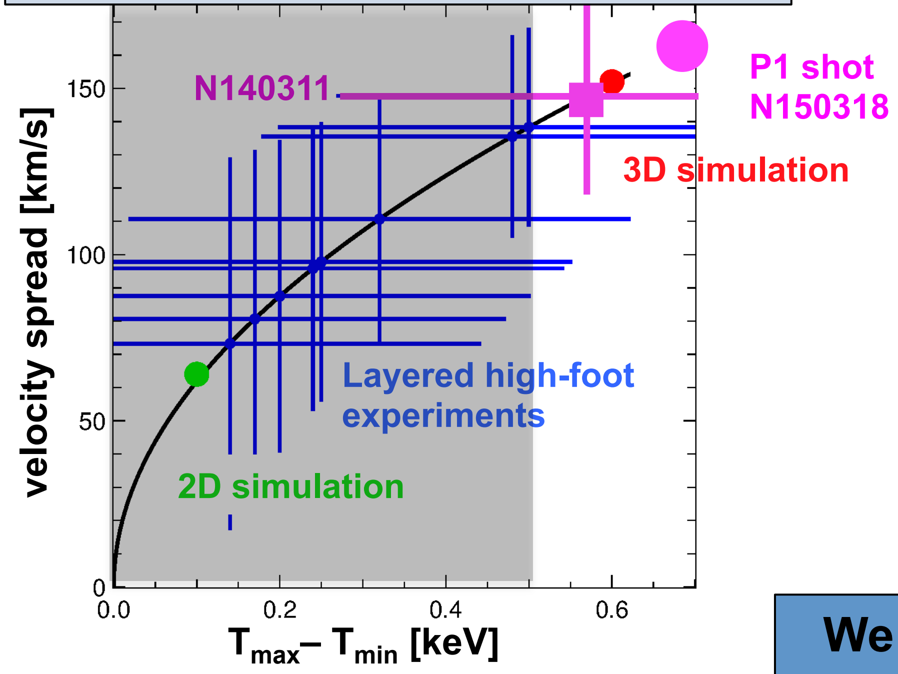


- With 4 nTOFs: capture 50 - 65% of Tion peak-to-valley (PTV)
- Add Spec NP: capture 55 - 70% (not exactly opposite SP)
- Add still another
  - antipodal specA: stays 55-70% of PTV
  - Collinear E and A: get 75 – 80 %
    - Larger percentage
    - Less variation (dependence on ellipsoid shape)

Some lines of sight are more valuable than others … for capturing PTV.

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

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



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

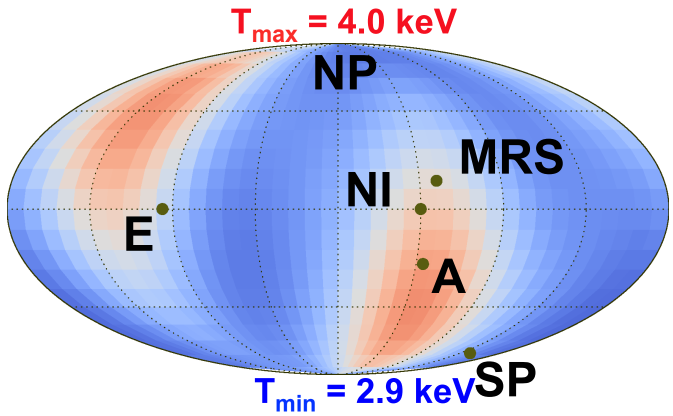
- **Post shot simulations suggest Tion anisotropy of ~ 300 - 400 eV**
- **Detectors would typically sample ~ 150-200 eV**
- **Detectors can measure down to 500 eV anisotropy (PTV)**

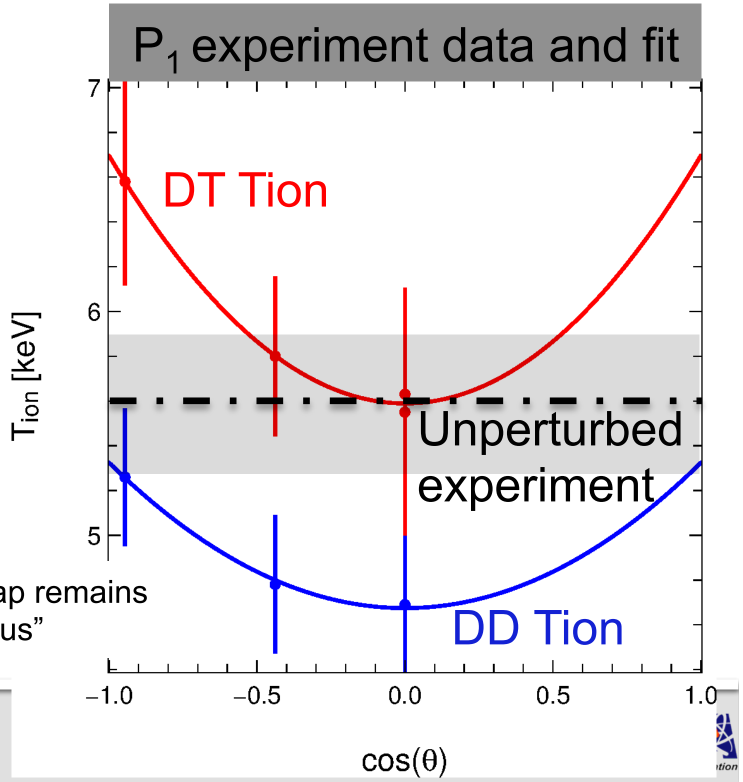
See M. Gatu Johnson paper

We need neutron spectrometers that can measure 300 eV anisotropy – that's about a 100 eV error

Antipodal nTOF removes systematic errors in analysis

- Apparent temperature should be the same on opposing sides
  - Sources of differences
    - underappreciated physics influences (scattering)
    - instrumental or analysis systematics
- Bulk velocity
  - Equal and opposite on opposing sides
  - Similar sources of differences
- Odd mode DSR
- Can shine light on
  - Tion uncertainty
  - DD and DT Tion differences
  - DD and DT bulk velocity differences
  - Polar areal density ice caps



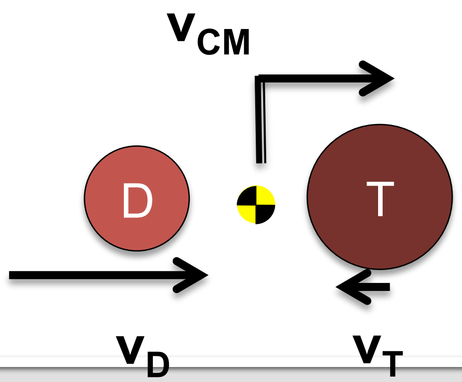


DD/DT gap remains “anomalous”

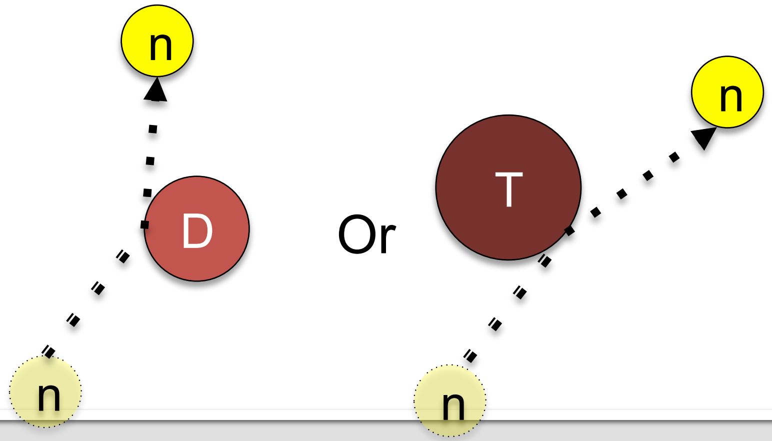
At least three effects change the neutron spectral peak location

- Center of mass drift velocity of the burning volume
- Relative kinetic energy of the fusing ions
- Scattering of the neutrons by compressed fuel
  - -scattering into the peak region by fuel
  - -scattering out of the peak region by fuel

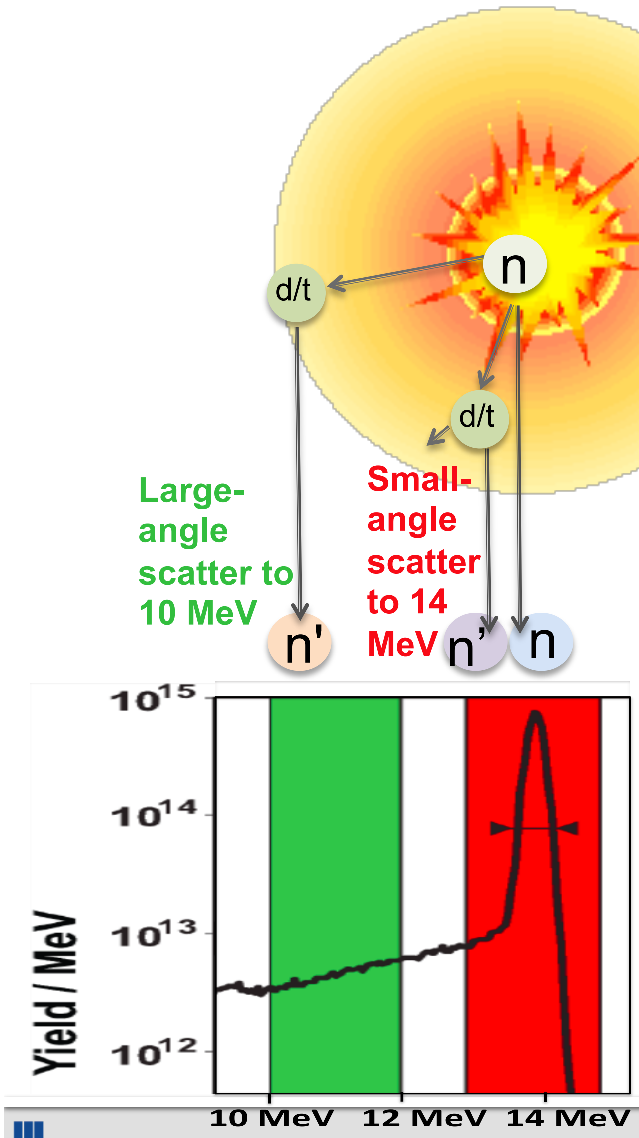
Reaction kinematics



Scattering kinematics



Neutron scattering by dense DT shifts the central peak

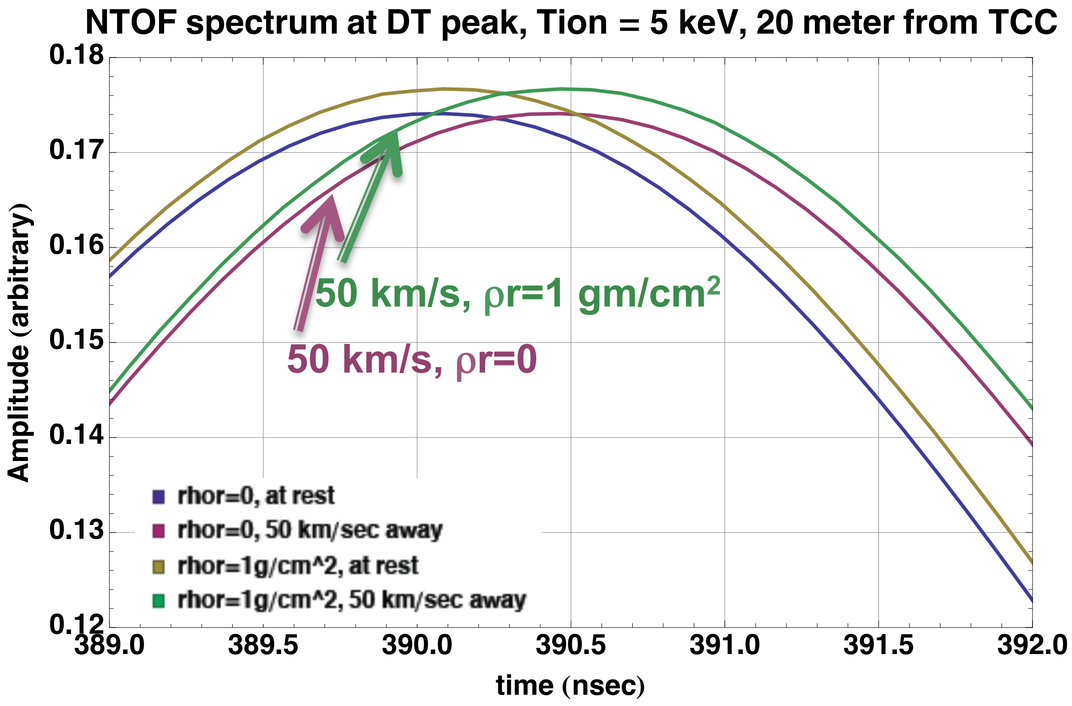


Large-angle scatter to 10 MeV

Small-angle scatter to 14 MeV

Scattering out of peak

Scattering within peak



Shift in central peak due to scattering is small

Antipodal detectors provide a better measure of drift velocity

- The centroid of the DT peak shifts
  - Mainly due to neutron-weighted bulk flow (rigid translation)
  - Smaller correction due to "Ballabio" effect – neutron boost from reactant KE

$$v_{p,i} = \underbrace{v_0 + v_{Ballabio}}_{\text{Constant over LOS}} + v_{drift,i}$$

	V_0 [km/s]	V_{drift} [km/s]	$v_{Ballabio}$ [km/s]
DT	**51233.6**	**100**	**35**
DD	**21601.9**	**100**	**70**

- Differencing opposing lines of sight leaves drift term

$$\frac{v_{p,1} - v_{p,2}}{2} = v_{drift}$$

Need 15-30 km/s precision to measure drift velocity

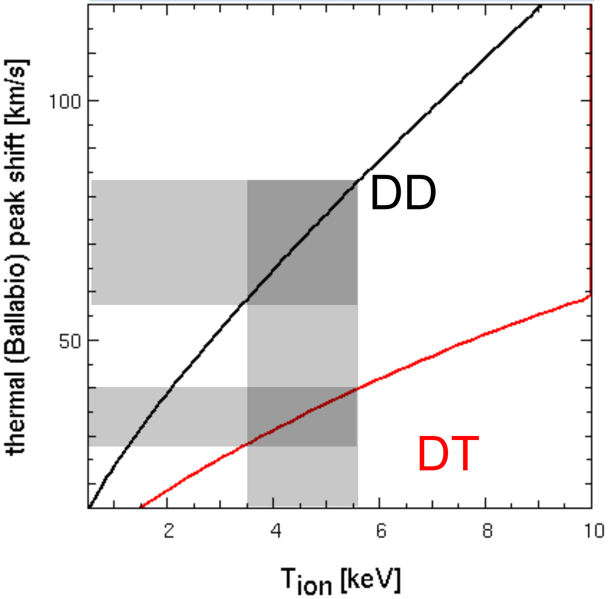
Antipodal detectors provide a measure of thermal ion temperature – in theory!

- The centroid of the DT peak shifts
  - Mainly due to neutron-weighted bulk flow (rigid translation)
  - Smaller correction due to "Ballabio" effect – neutron boost from reactant KE

$$v_{p,i} = \underbrace{v_0 + v_{Ballabio}}_{\text{Constant over LOS}} + v_{drift,i}$$

	V_0 [km/s]	V_{bulk} [km/s]	$v_{Ballabio}$ [km/s]
DT	**51233.6**	**100**	**35**
DD	**21601.9**	**100**	**70**

Ballabio shift depends only on ***thermal*** Tion



- Averaging opposing lines of sight leaves Ballabio term

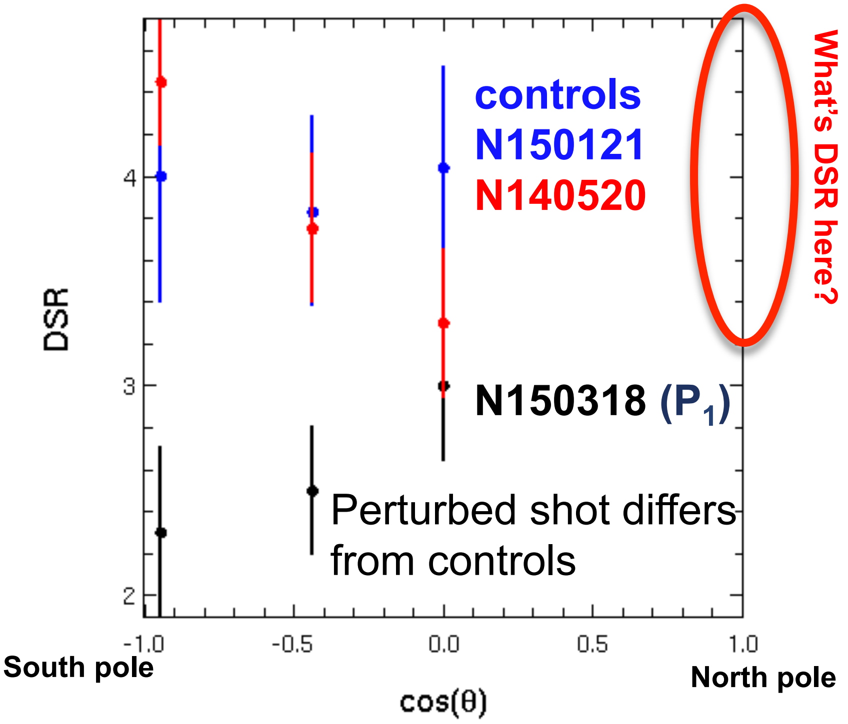
$$\frac{v_{p,1} + v_{p,2}}{2} - v_0 = v_{Ballabio}$$

DT needs 5 km/s precision
DD needs 15 km/s precision

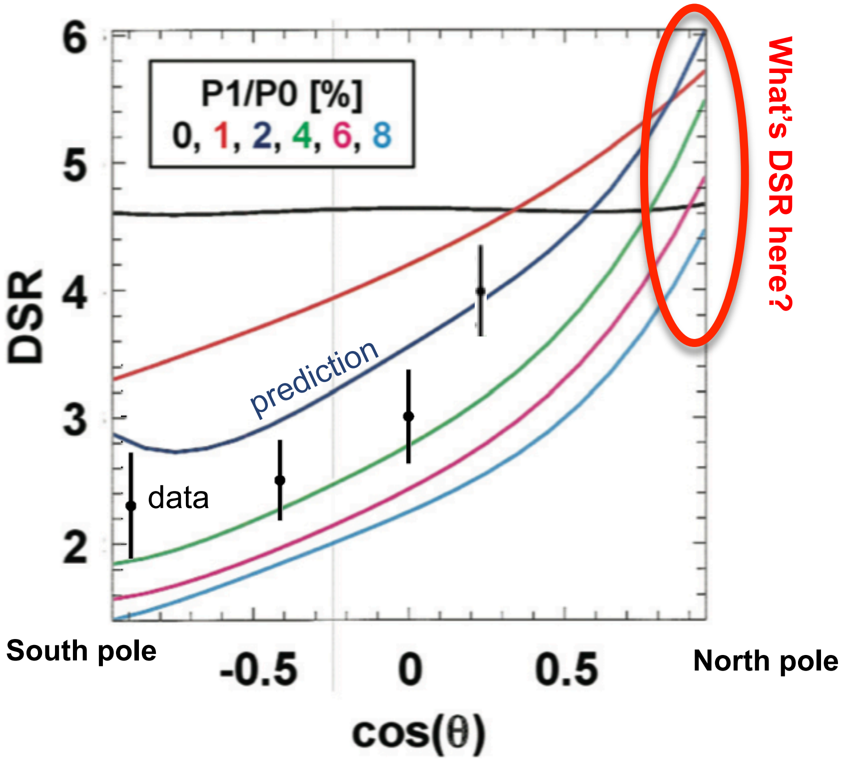
Alas, some things are harder to do in experiment than in theory

North pole nTOF measures odd modes in cold shell

- DSR in P1 shots has strong odd mode (mode 1)
- Is the north pole as predicted? Is it different from control shots?



Perturbed shot is different from control shots



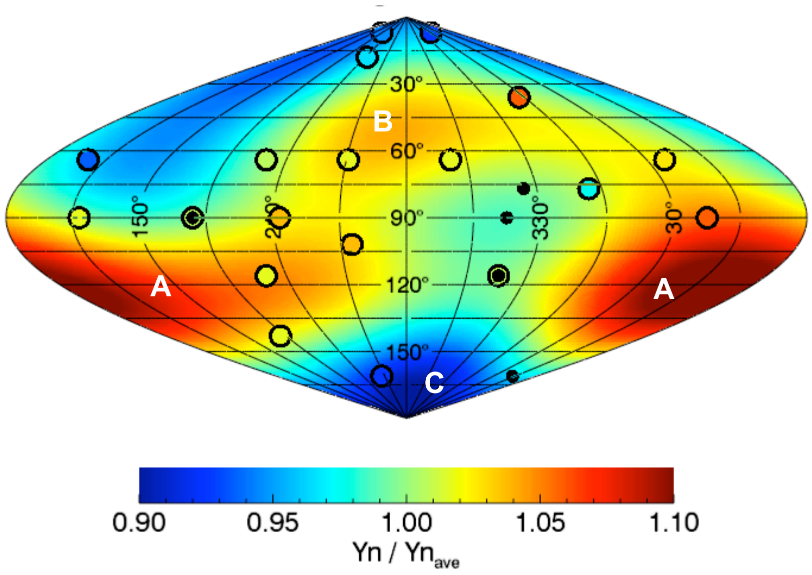
Experiments compare nicely with preshot predictions

North pole nTOF provides a missing diagnosis of DSR asymmetry

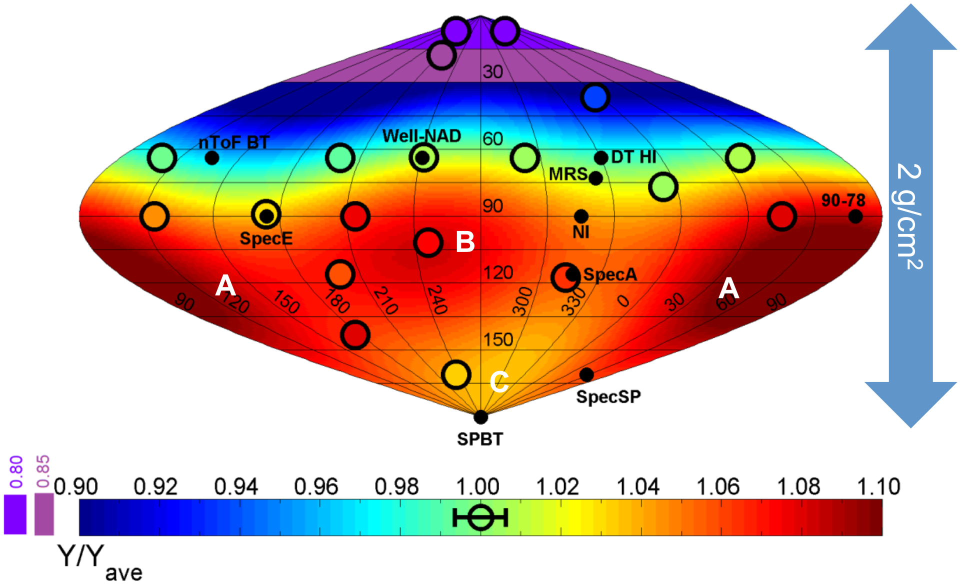
North pole nTOF could help resolve polar ice cap issues

- DSR in P1 shots has strong odd mode (mode 1)
- Is the north pole as predicted? Is it different from control shots
- Does DSR variation compare well with fNADS, especially pole to pole?

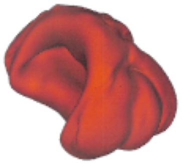
N140520 control shot



N150318 P_1 shot

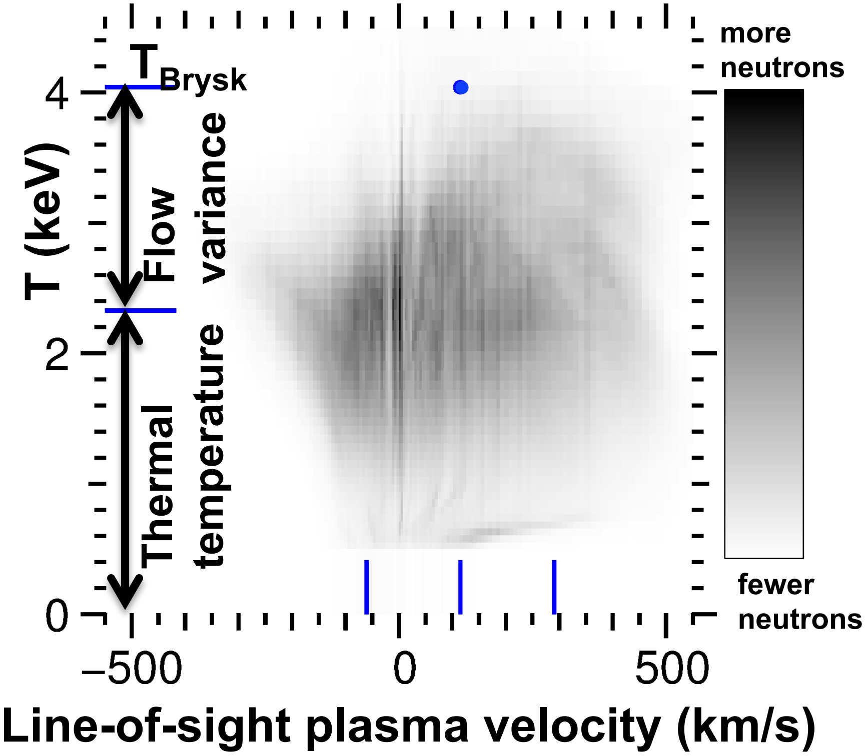


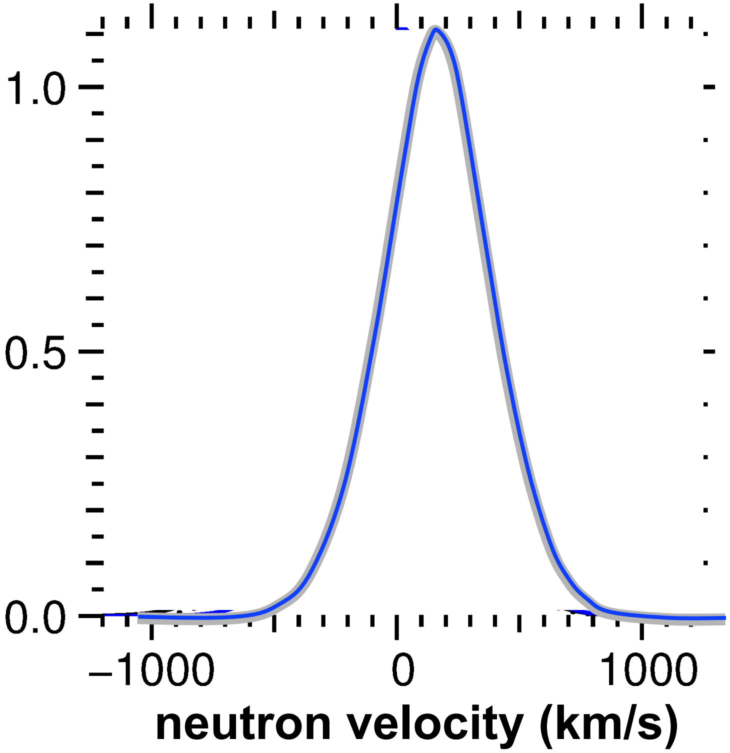
Spectral peak depends on the distribution of neutron production in temperature and velocity space



Neutrons produced over a range of temperatures and velocities

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

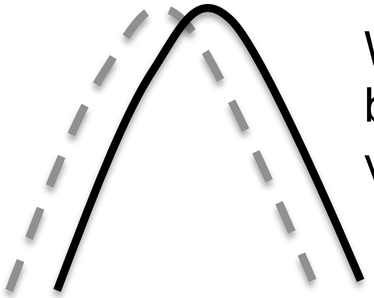




Simulations have to get a lot right to capture the temperature variation

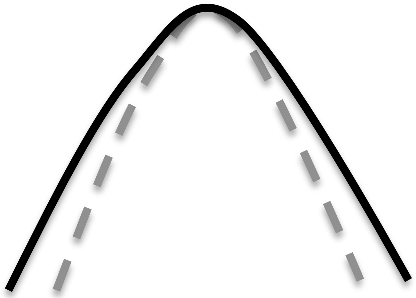
Stagnation measurements can be much more informative

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



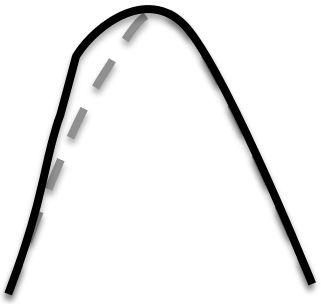
What's the bulk velocity?

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



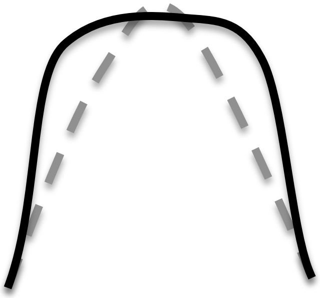
What's the apparent temp, thermal temp,residual flow?

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?

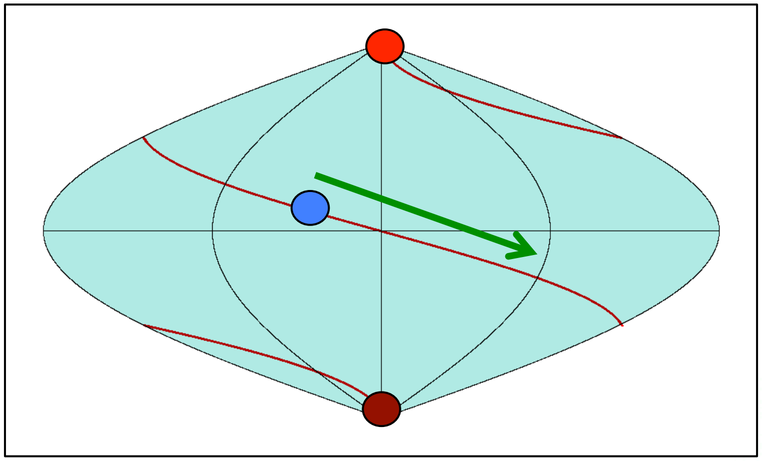
High convergence NIC capsule view at 10 KeV

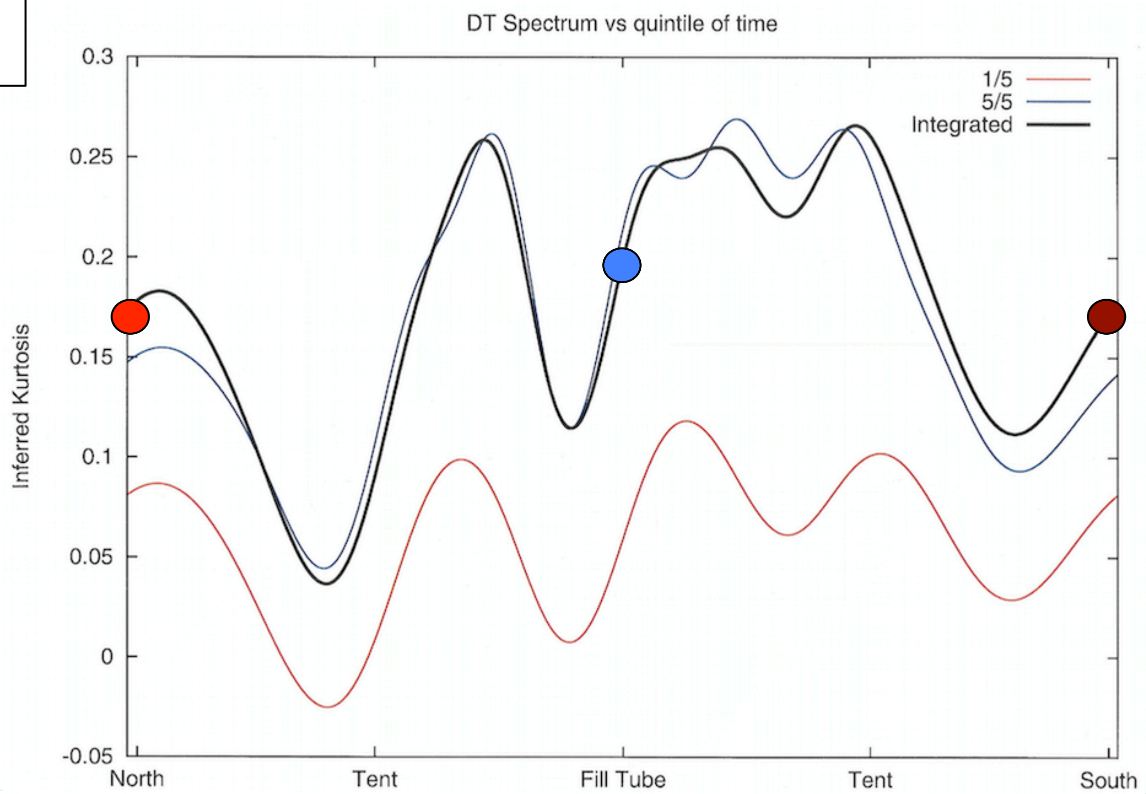
(different scales)

N120321 HYDRA hi-resolution simulation with 470M zones
by D. Clark and C. Weber

The kurtosis shows hot spot cooling and flow effects.

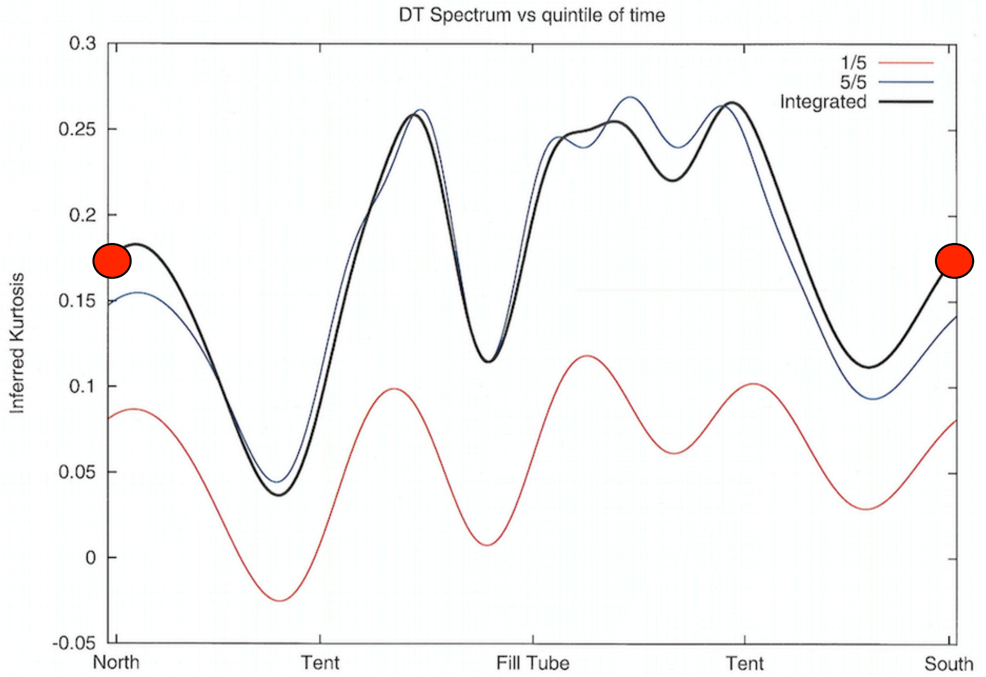
VIEW PATH





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

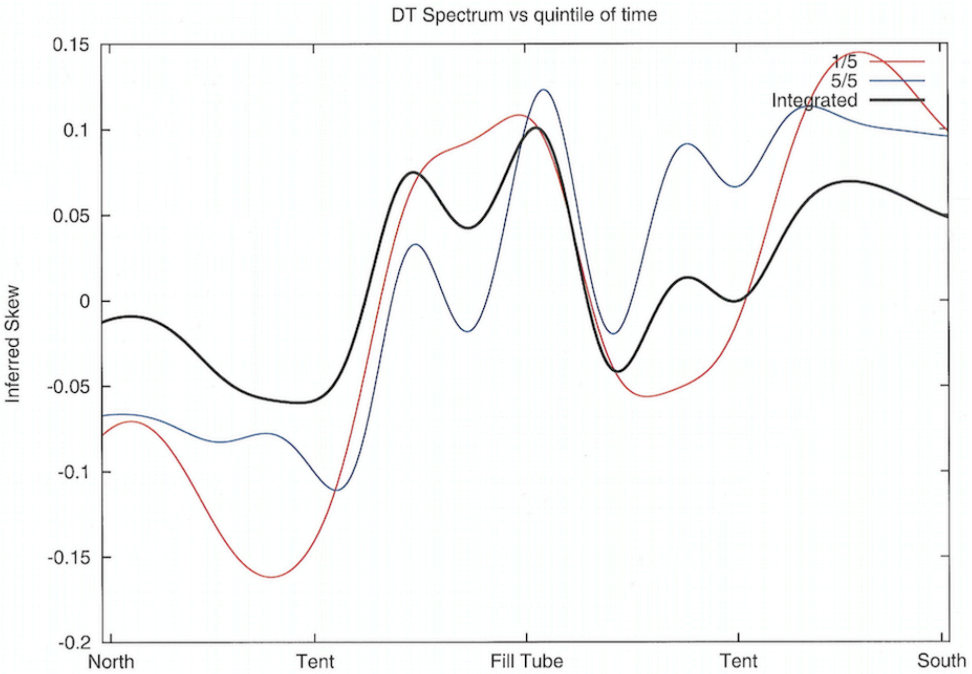


$$\mathrm{Kurt}(\omega)=\frac{\overbrace{3\,\mathrm{Var}(\tau)}^{\text{scalar}}+\overbrace{6\,\mathrm{Cov}(\tau,u_{\Omega},u_{\Omega})+\mathrm{Cov}(u_{\Omega},u_{\Omega},u_{\Omega},u_{\Omega})-3\,\mathrm{Var}(u_{\Omega})^{2}+\ldots}^{\text{Vary with line of sight (tensors)}}}{\mathrm{Var}(\omega)^{2}}$$

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% precision

1. Skew gives correlation of temperature and velocity
2. Is the hottest material moving fast? Slow?



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

Capturing the spatial variation of spectral signatures requires tradeoffs in instrument number and precision

- Consider a test case
  - 400eV PTV Tion variation
  - 15% skew variation
  - 20% kurtosis variation
- Current suite + SpecNP (50% sampling efficiency)
  - 1st moment – peak location to 15-30 km/s, needed on at least 3 LOS
  - 2nd moment – sample 200 eV PTV → 100 eV precision
  - 3rd moment – sample 7% skew PTV → 3% precision
  - 4th moment – sample 10% kurtosis PTV → 5% precision
- Current suite + SpecNP + collinear EA (75% sampling efficiency)
  - 1st moment – peak location to 15-30 km/s, needed on at least 3 LOS
  - 2nd moment – sample 300 eV PTV → 150 eV precision
  - 3rd moment – sample 12% skew PTV → 6% precision
  - 4th moment – sample 15% kurtosis PTV → 8% precision

Improving the nTOFs will drive innovation at NIF

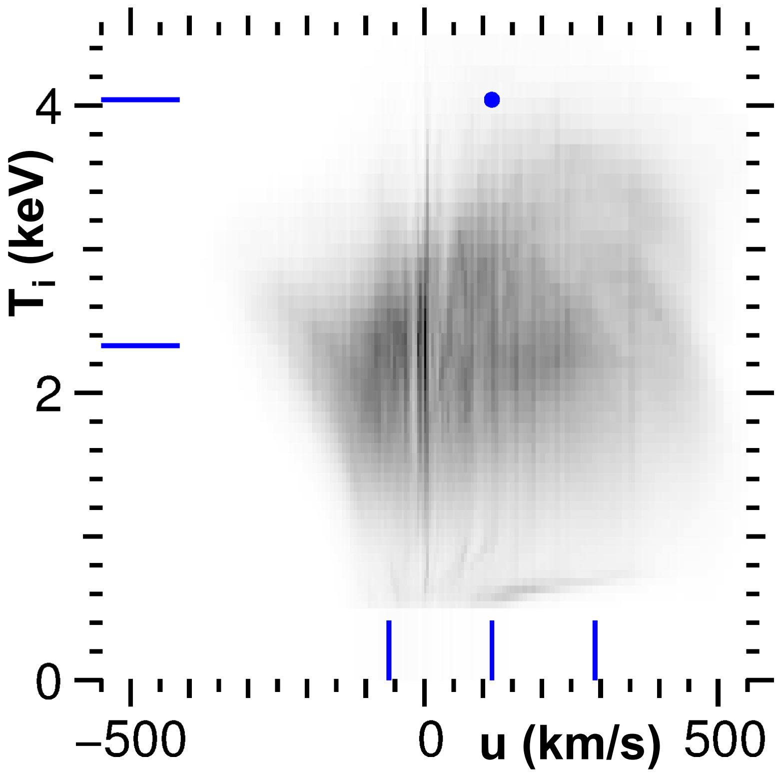
- What does an additional nTOF get us?
  - Captures peak-to-valley Tion variation

    OR

  - Removes systematics in Tion and bulk velocity
  - Gets odd modes
  - Gives a chance at thermal ion temperature
- What do improvements to nTOF measurements or analysis get us?
  - Moments of the peak reveal thermal and fluid state
  - 1st (shift) – bulk velocity
  - 2nd (width) – Tion and flow variance
  - 3rd (skew) – Is the hot stuff moving fast?
  - 4th (kurtosis) – Is hot spot burning over a broad range of temperatures?
  - Do the nuclear signatures provide a signature of asymmetry?

Neutron spectral moments and LOS dependence are important clues

burn T-u distribution (3D simulation)



u = fluid velocity component along LOS

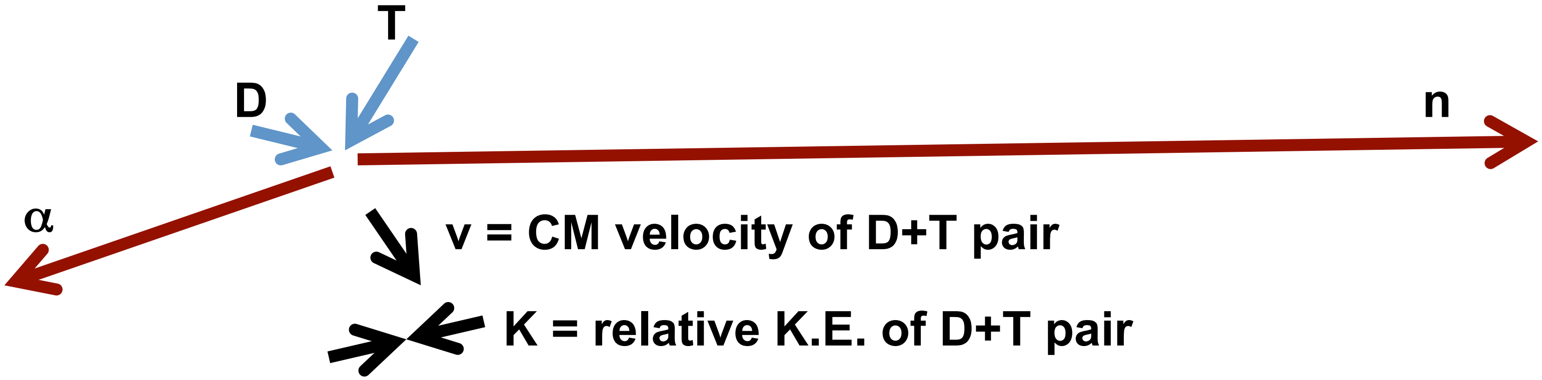
burning plasma exceedingly non-uniform, neutrons produced in wide range of T_i and fluid u

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



v = CM velocity of D+T pair

K = relative K.E. of D+T pair

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

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 ~ 14 MeV
v_0 ~ 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

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

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 velocity²
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

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

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

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

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

nth 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**

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

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

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

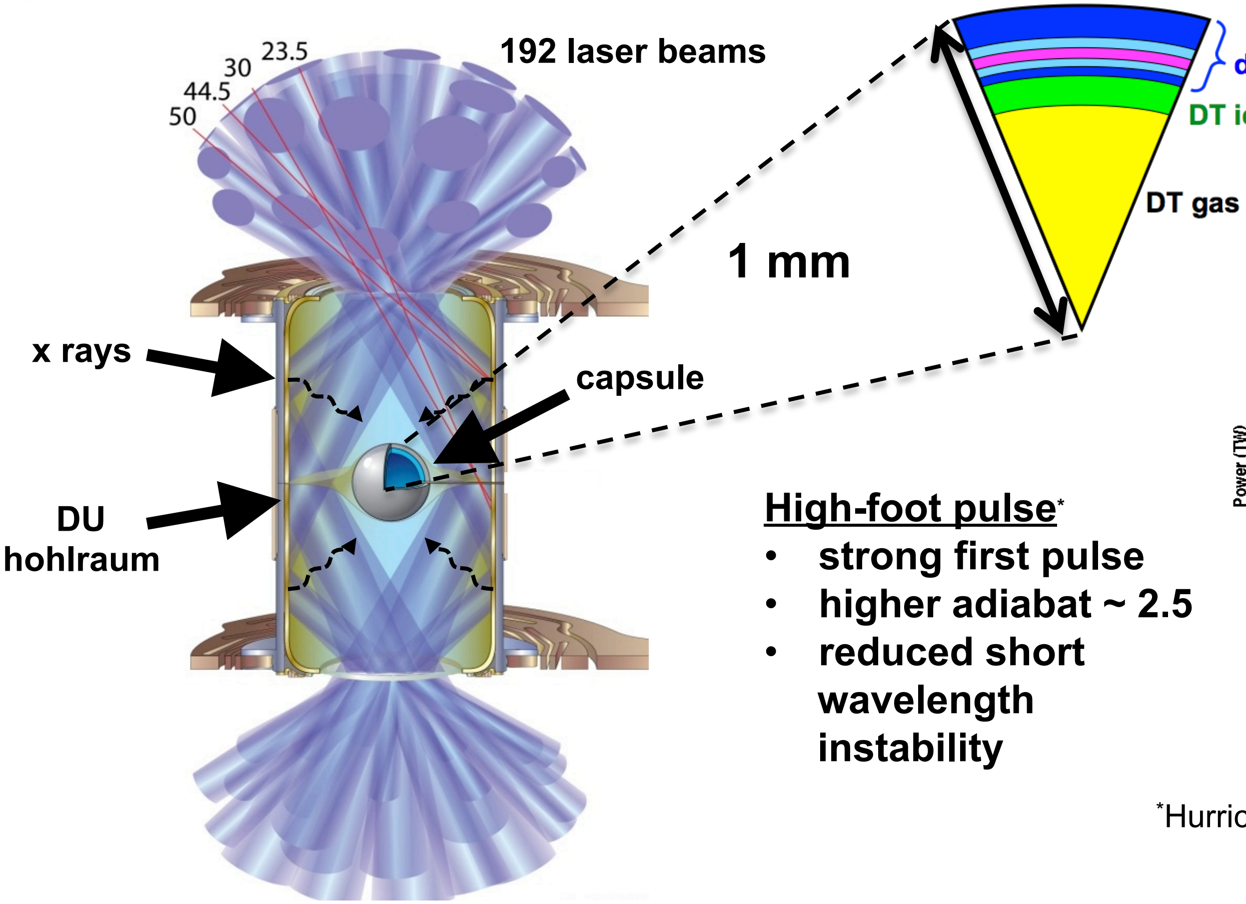
L=0, 2, 4

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

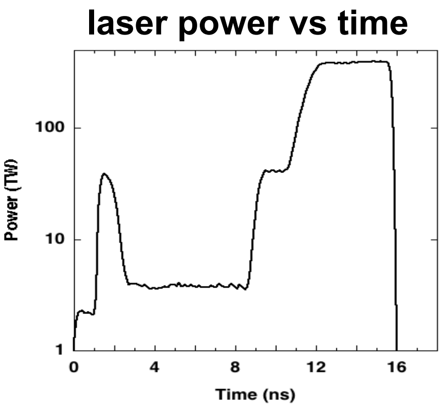
We used high-adiabat implosions with reduced high-mode instability



High-foot pulse*

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

laser power vs time



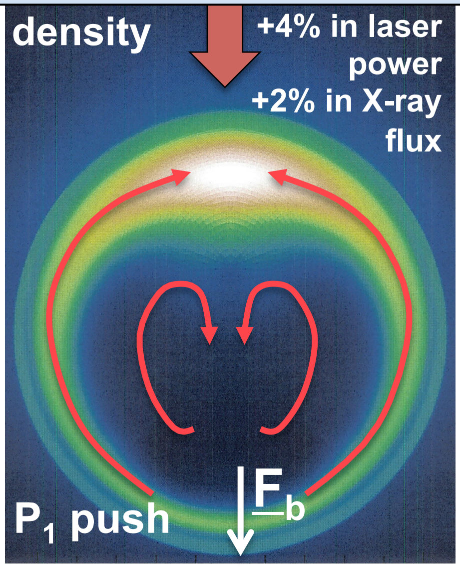
*Hurricane et al., Nature, 506, 7488 (2014)

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

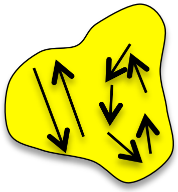
- Provide an experimental platform with asymmetric radiation flow
- Detailed measurements of the stagnating plasma
- Detailed code predictions of observable signatures (neutron spectra)

Perturbed implosions provide an integrated test of our code capabilities

We measure multiple stagnation quantities by neutron spectrometry

Ion temperature

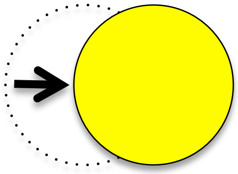
Neutron spectral peak width.
Temperature and hot spot flow.



Shear
Swirling
Velocity field variance

Bulk velocity

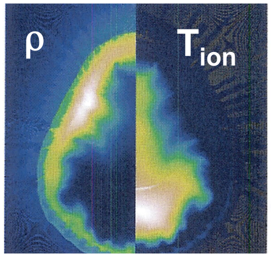
Neutron spectral peak shift.
One-sided imbalance drives this.



Rigid-body translation

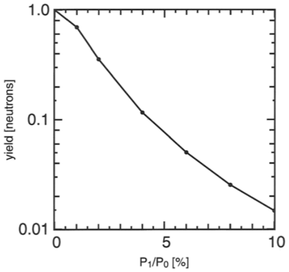
Shell uniformity

Neutron scattering.
Asymmetries perturb the shell.



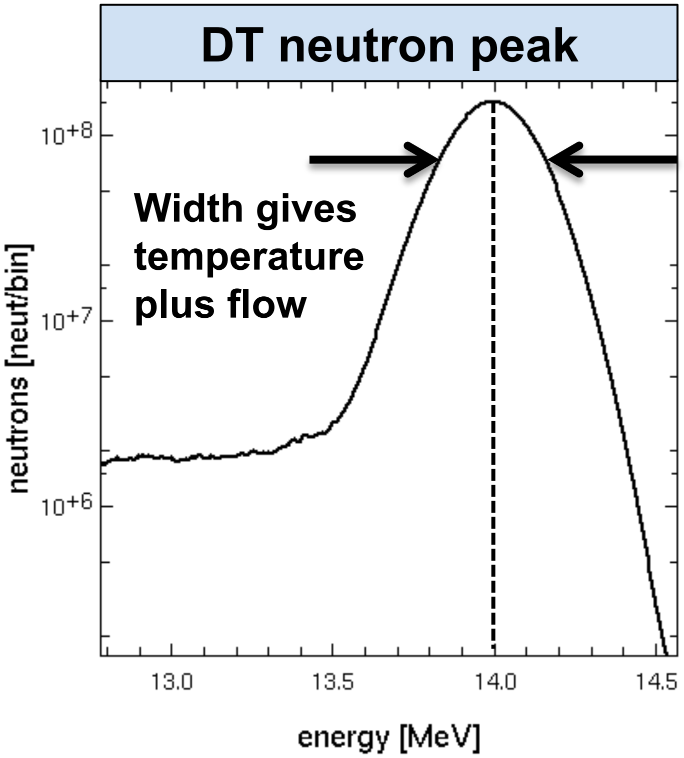
Neutron yield

Integrated performance metric.
Incomplete stagnation reduces yield.



Implosion asymmetry alters stagnation phase properties

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



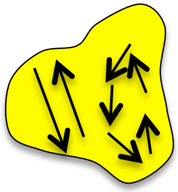
DT neutron peak

Width gives temperature plus flow

Peak is broadened by:

1. thermal temperature
2. fluid flow

Flowing hot spot:
Shear
Swirling
Velocity field variance

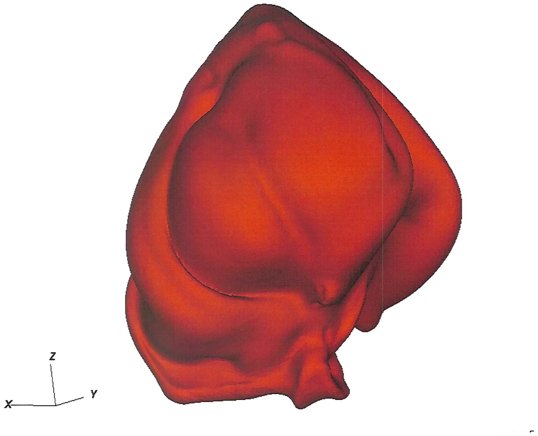


$$T_{Brysk} = \overbrace{\left(\frac{m_D+m_T}{k}\right)\sigma_v^2}^{\underline{\textit{spread}}\ \text{in fluid velocity}} + T_{thermal}$$

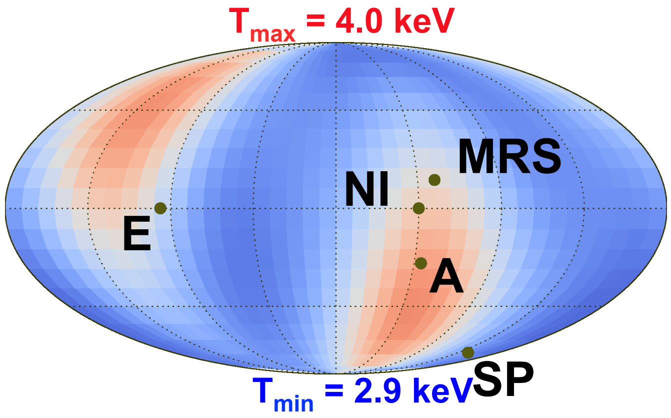
Hot spot flows increase the apparent (Brysk) temperature

Asymmetric 3D simulations show angular temperature variations due to flow

Asymmetric flow in distorted hot spot



Apparent temperature distribution from simulated peak widths



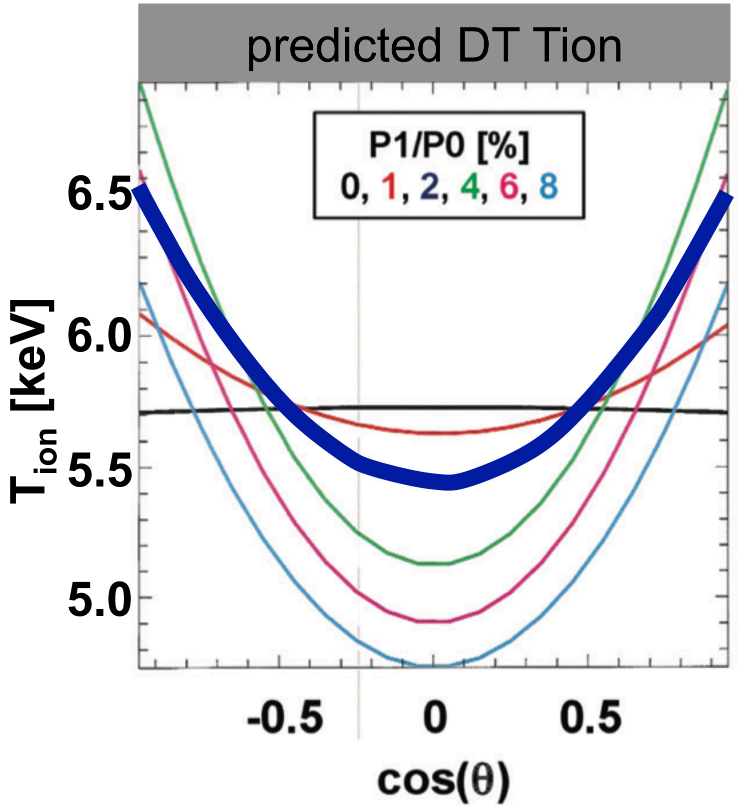
Detector	T_{Brysk}
SpecE	3.49
SpecA	3.56
SpecSP	2.96
NITOF	3.50
MRS	3.39

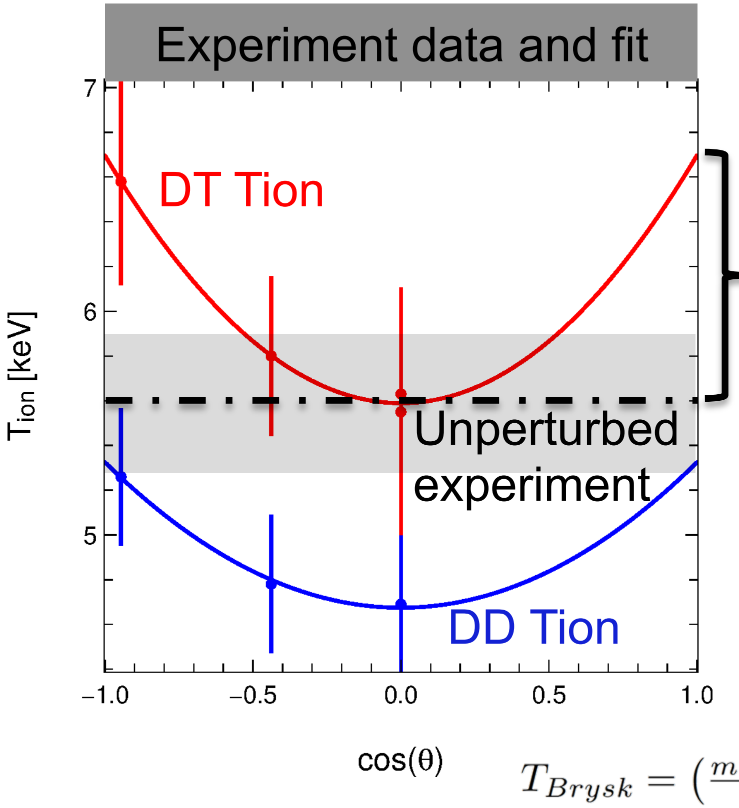
- Thermal temperature is 2.3 keV
- Apparent temperatures span 2.9 to 4.0 keV – depending on direction
- Detector array typically samples 50% of full PTV

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

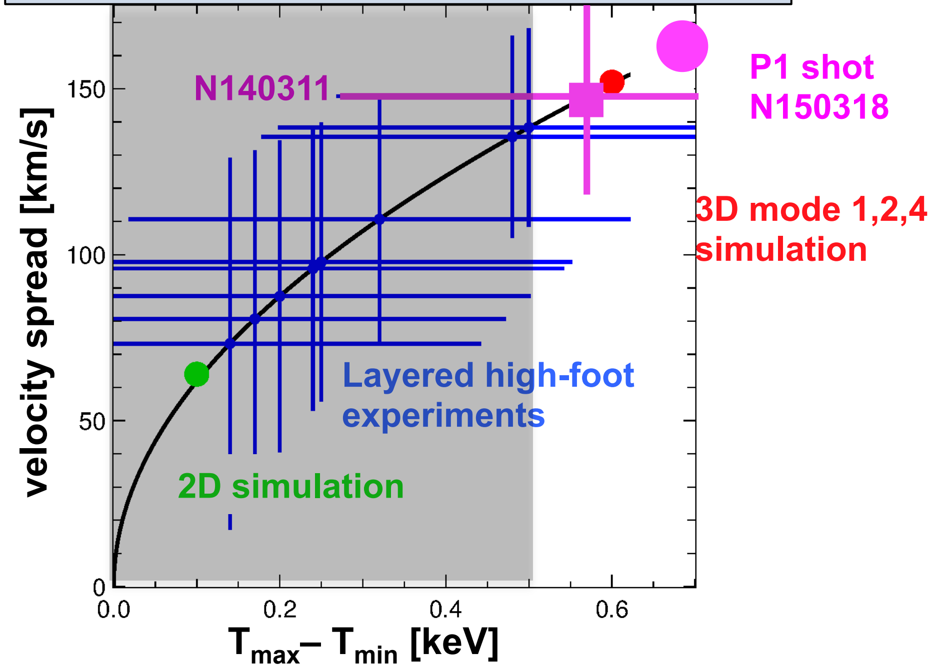
DD/DT gap
remains
“anomalous”

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

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



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

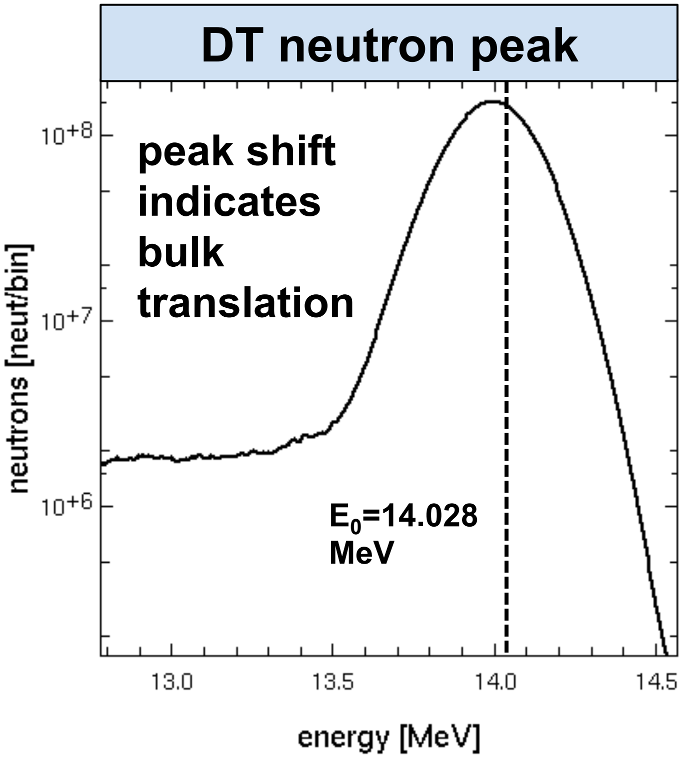
The NIF data cannot (currently) distinguish between isotropy and the expected level of anisotrop

- **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

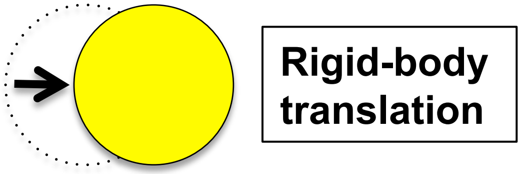
We need neutron spectrometers that can measure 300 eV anisotropy

Neutron spectrometers measure bulk velocity from spectral peak shift



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

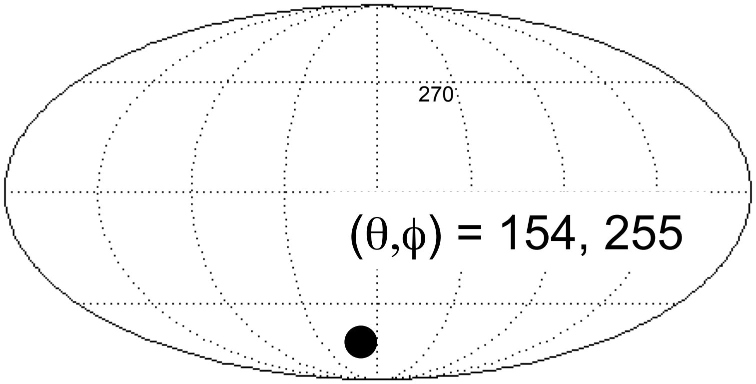
Mode 1 perturbed experiments confirm our ability to measure bulk flow velocity

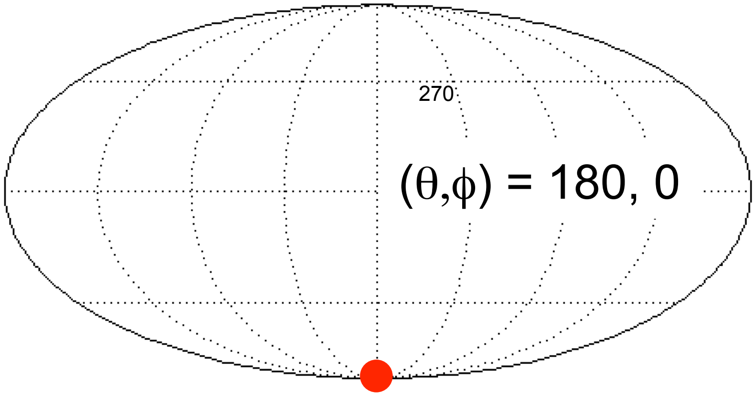
Experimental measurement

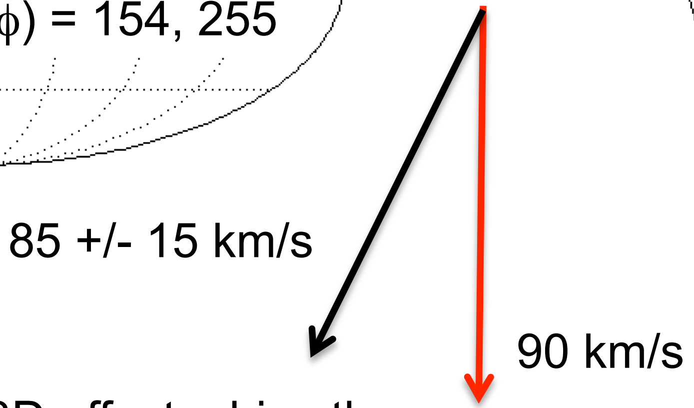
85 +/- 15 km/s resultant
26 degrees off vertical

Preshot prediction

90 km/s resultant
directly downward





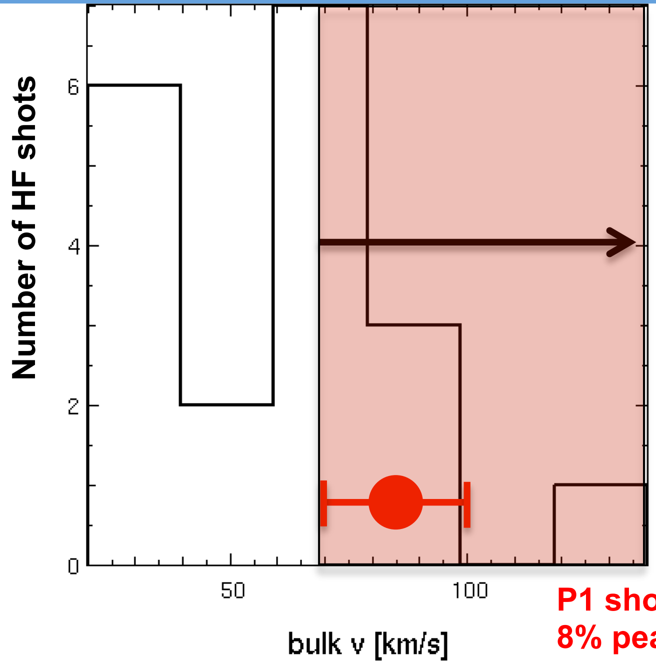


3D effects drive the
flow off axis

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

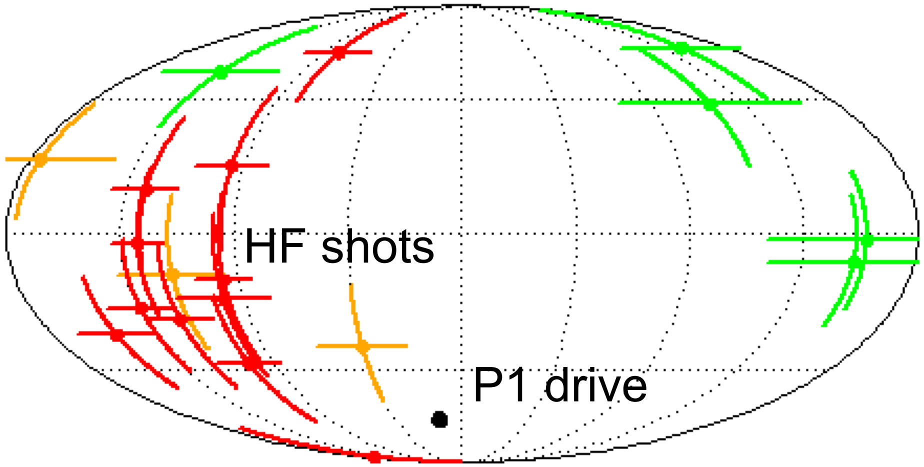
The average high foot shot bulk velocity is 70% of the intentional P_1

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



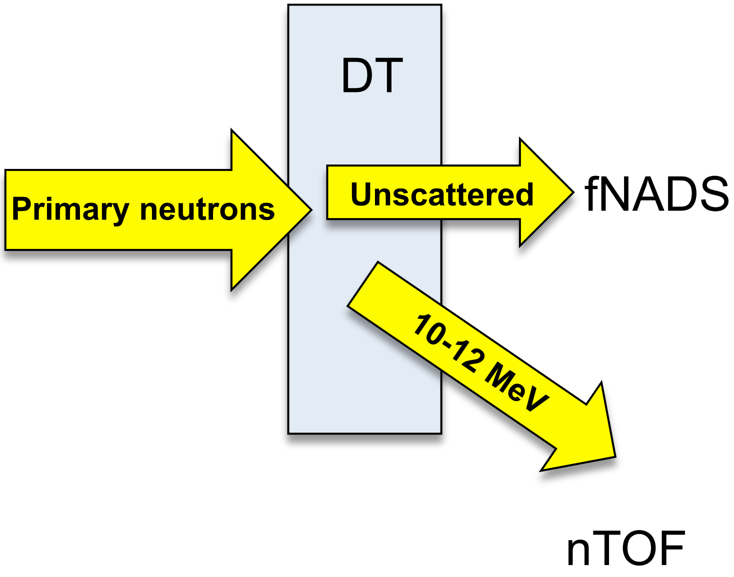
> 60 km/s
30 - 60 km/s
< 30 km/s

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

We haven't yet identified what is producing these perturbations

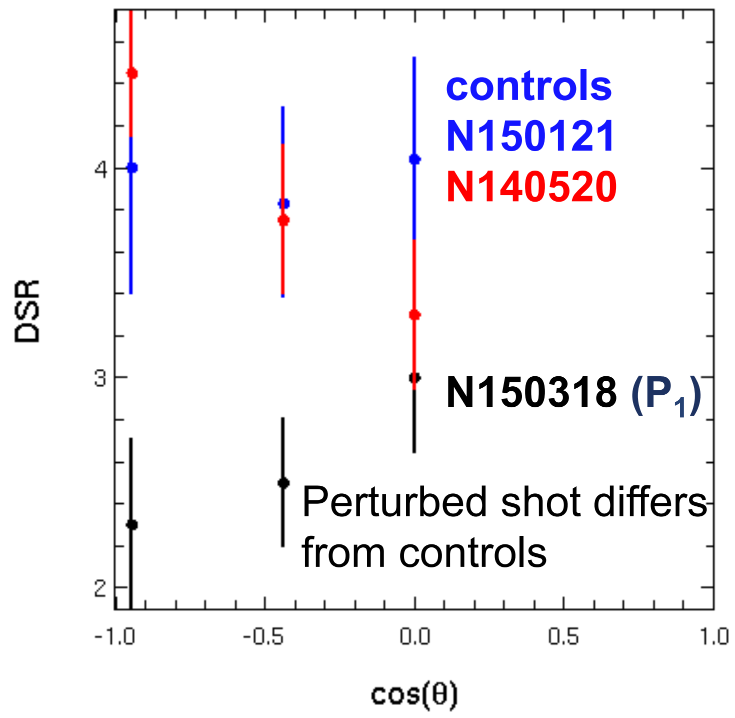
The cold shell conformation is probed by exiting neutrons

- 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

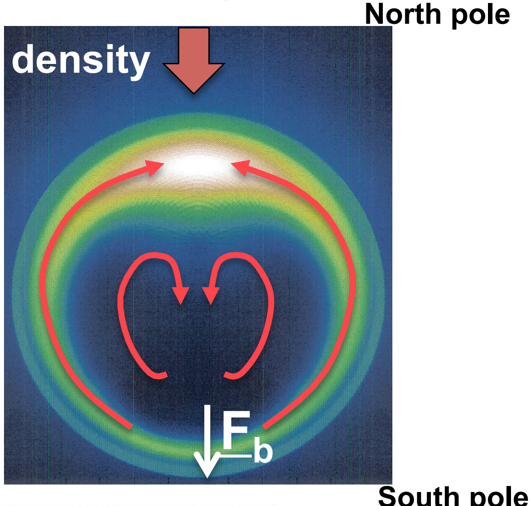


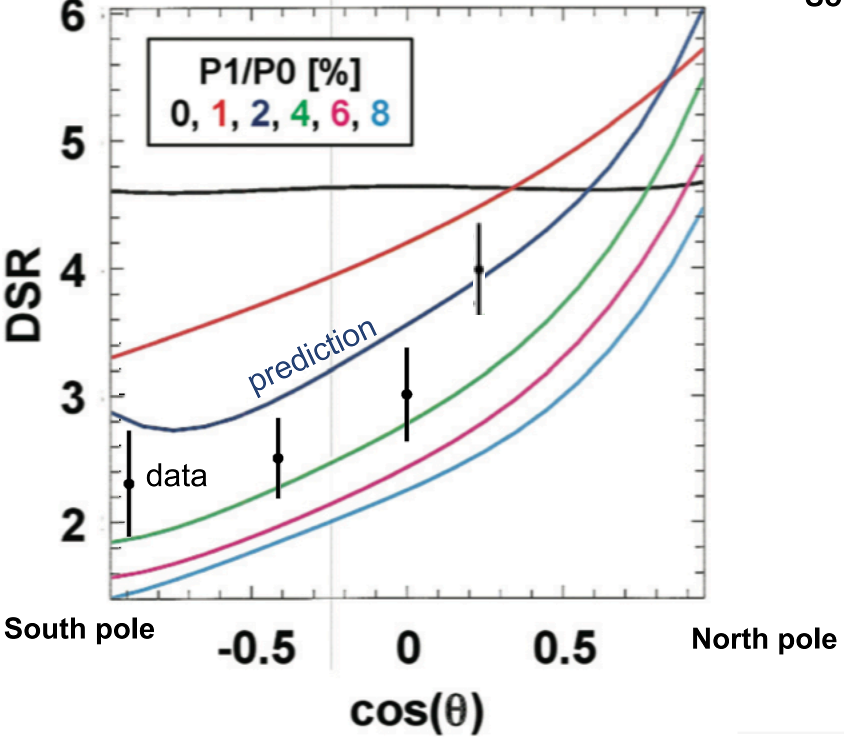
Mode 1 perturbed experiments confirm our ability to measure angular variation in DSR

Perturbed shot is different from control shots



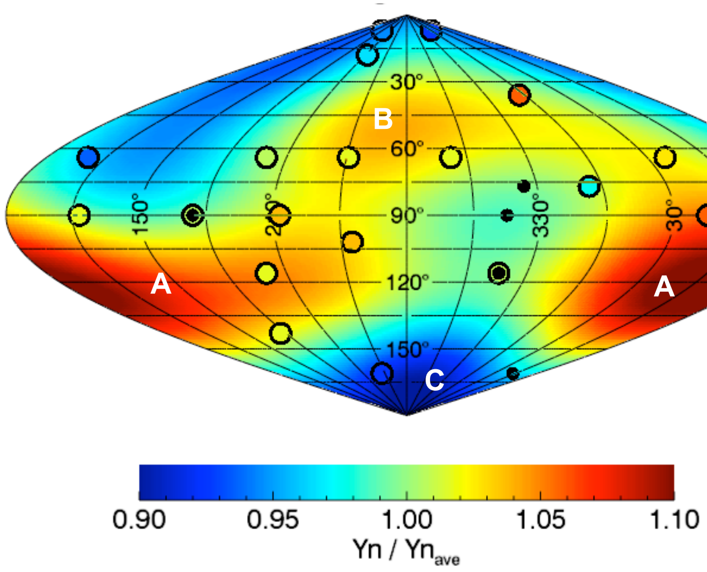
Experiments compare nicely with preshot predictions



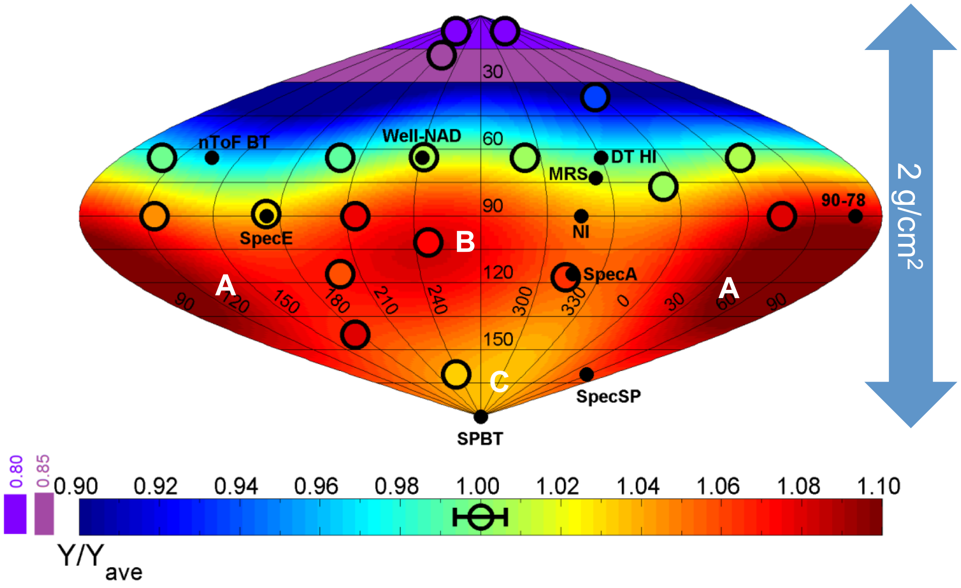


fNADS measured the predicted angular distribution of escaping primary neutrons

N140520 control shot



N150318 P$_1$ shot



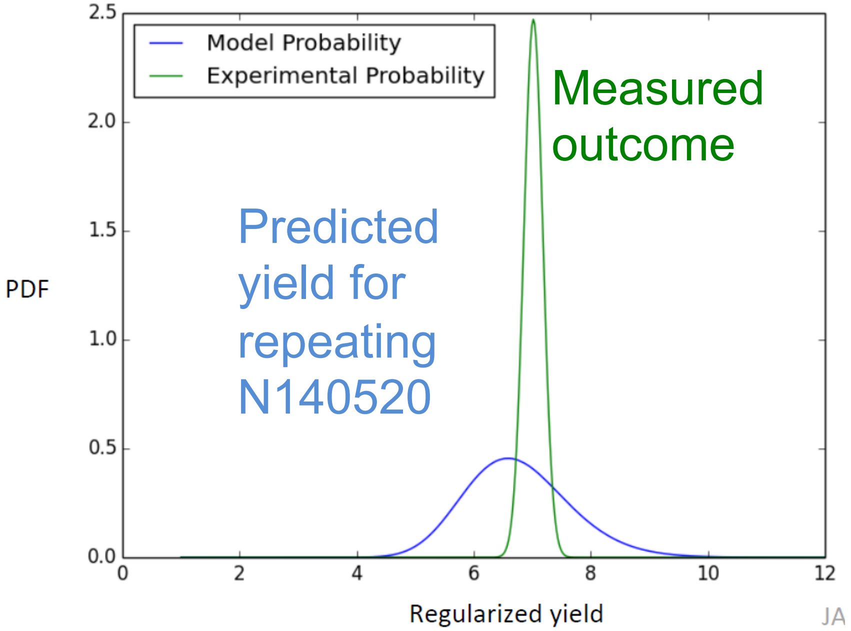
- Predicted fNADS variation of ~ 25% peak to valley → measured 30%
- Expected P$_1$ asymmetry → observed P1 plus 3D similar to control shot

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
    - $T_{\text{ion:}}$ 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



Measured outcome

Predicted yield for repeating N140520

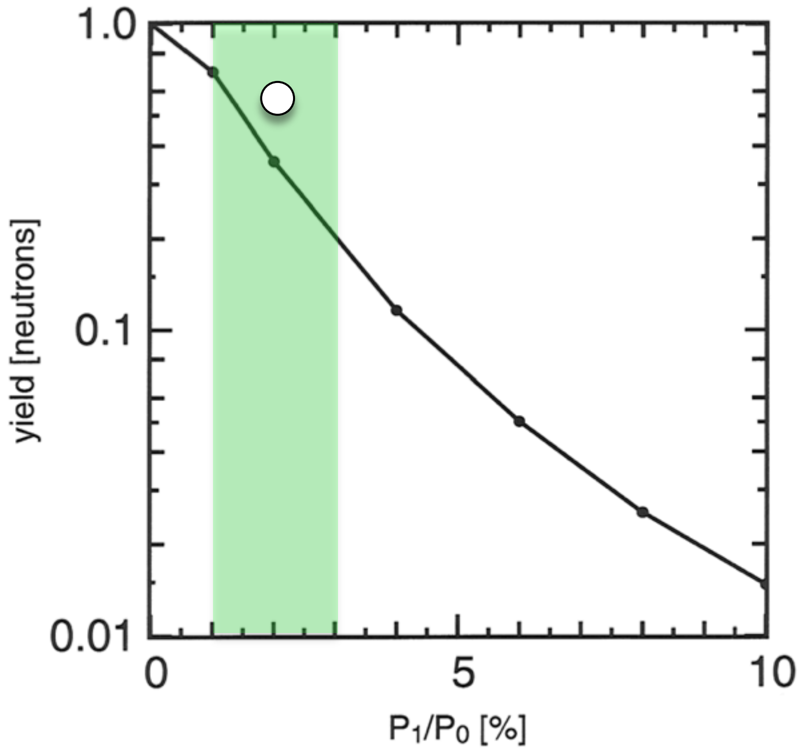
Jim Gaffney, Tammy Ma, Dan Casey, Niko Izumi, Debbie Callahan, Brian Spears

The repeatability of the platform is sufficient for testing perturbation effects

Reduction in yield was smaller than predicted by <u>single failure mode</u> simulations

- 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

<u>Control shots</u>
N140520 = 7.6e15
N150121 = 6.3e15
N150409 = 6.9e15
<u>P_1 shot</u>
N150318 = 4.8e15

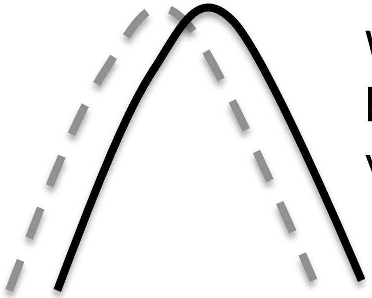


The yield is different from the controls

The yield is different from the prediction

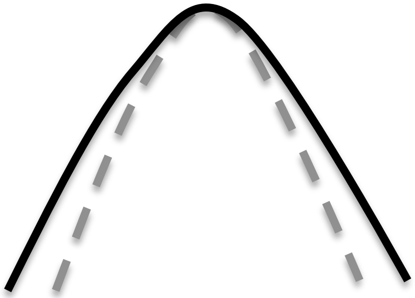
Stagnation measurements can be much more informative

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



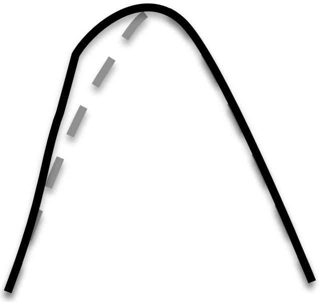
What's the bulk velocity?

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



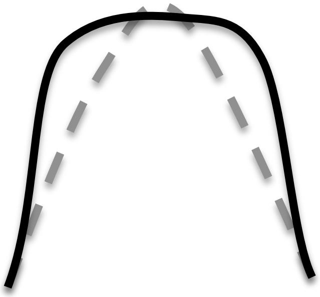
What's the apparent temp, thermal temp,residual flow?

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