NIF nToF Update

NISP Meeting

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Activity since the Oct NISP Committee meeting…

- Fusion neutron spectral characterization
  - Momentum/Velocity based core functions

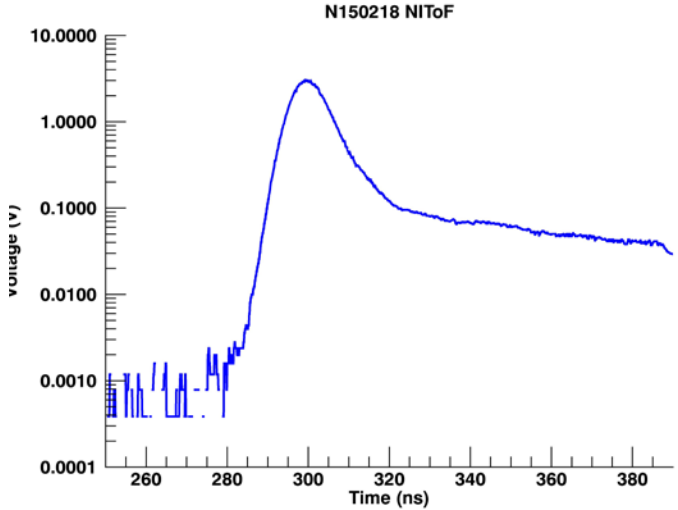
- Shell uniformity
  - Implementation of a north-pole nToF
  - T(n,n): DSR in the “backward” direction…

- Progress towards improved measurements
  - Precision nToF scoping project

- Workshop on nToF techniques at LLE
  - Synopsis of what LLNL has learned about forward fitting vs. parameterized fitting…

The product of the nToF system is a time series trace that represent the detectors response to the neutron flux…

- **Correcting for detector system response, assuming an infinitesimally short burn, and knowledge of bang-time, the long LoS nToF systems measure the neutron velocity distribution, produced in the experiment.**



The goal becomes how to interpret the plasma conditions from this neutron velocity distribution.

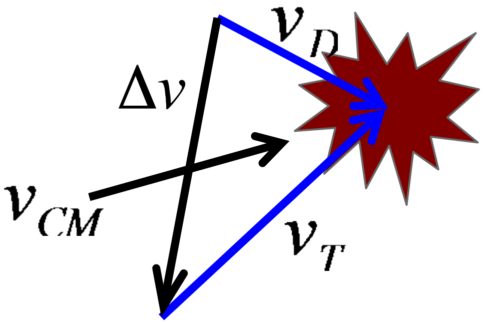
For a single fluid element, the neutron velocity distribution is nearly the LOS component of CM velocity distribution

— DT CM velocity distribution

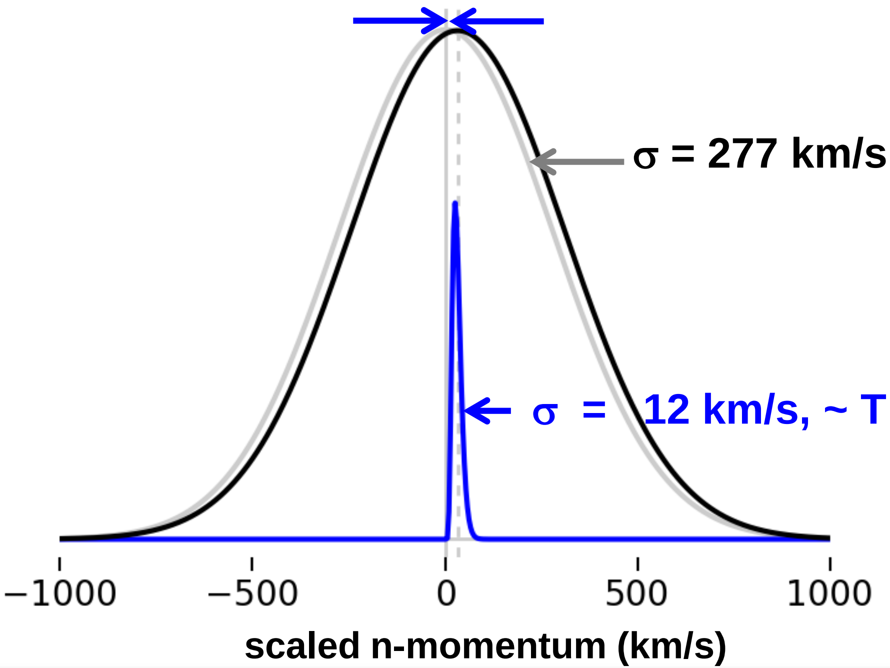
— DT neutron momentum spectrum

— Relative K.E. distribution (v-shift from Gamow peak)

Reactant CM motion makes neutron spectrum; relative motion is small correction.



single fluid element at T = 4 keV, u = 0



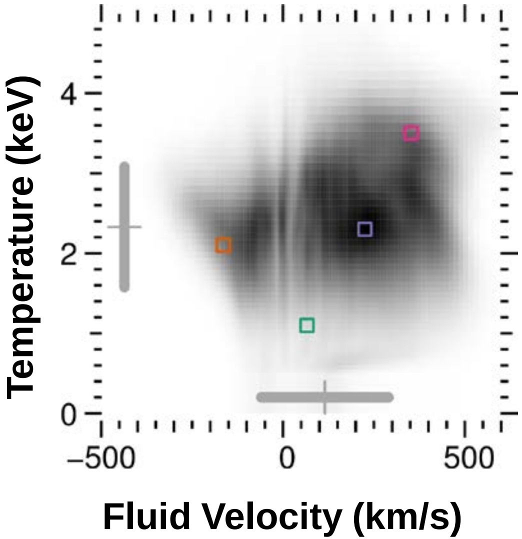
Δ = 31 km/s, proportional to T

σ = 277 km/s, ~ $T^{1/2}$

σ = 12 km/s, ~ T

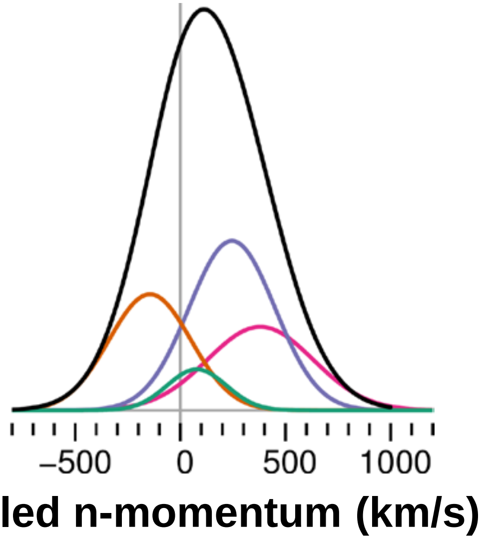
Real capsules burn at many temperatures & fluid velocities resulting in "non-Gaussian" spectra along a diagnostic LoS.

Implosion with large L=1 aimed toward diagnostic LOS



Darkness = # neutrons produced

━╋━ **mean, standard deviation**



DT spectrum for this LOS

— colors show single fluid element spectra corresponding to box of matching color in left picture

A Gaussian like spectrum in the velocity domain with "single scattering" has been used, but has fixed spectral content and assumes a static fluid…

- Velocity distribution as used in Ballabio

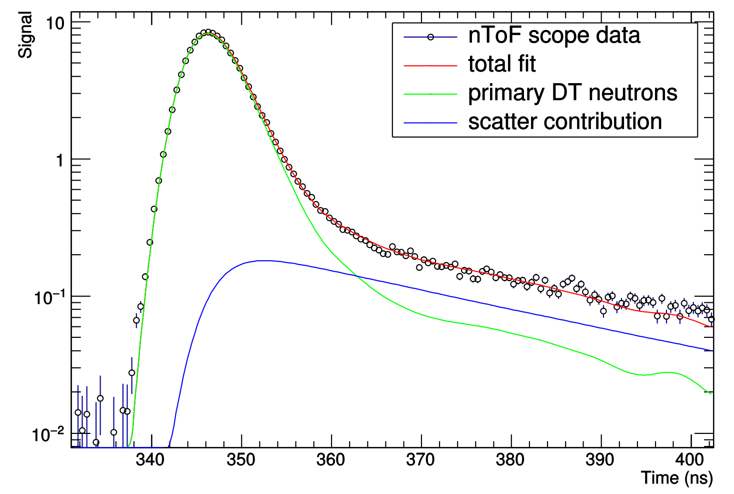
$$I_{src}\left(E\right)=\frac{1}{\sqrt{2\pi\sigma}}e^{-\frac{\overline{E}}{\sigma^2}\left(\sqrt{E}-\sqrt{\overline{E}}\right)^2}$$

  - T_{ion} influences mean and variance of the neutron energy spectrum

- A single scatter model needs to be added to asses the width of the birth spectrum

$$I(E)=A(I_{src}(E)+f_{sc}\int_E^{\infty}I_{src}(E_i)\frac{d\sigma}{d\Omega}(\cos\theta_{CM})\frac{d\Omega}{dE_i}dE_i$$

Ballabio with single scatter model fit to the data



NB: The above model presumes a static, single temperature plasma!

To address the “non-Gaussian” spectrum generalized core functions are being explored

The model is momentum-space based to facilitate physics interpretation

$$p_n = M_n \gamma \beta = \frac{M_n}{\sqrt{\left(\frac{c\Delta\tau}{L}\right)^2 - 1}} \Rightarrow x_p \equiv \frac{p_n - \mu_p}{\sigma_p}$$

$$I(x_p) = \frac{A}{2\pi\sigma_p}\left(H_o(x_p) + \frac{\gamma_3}{3!}H_3(x_p) + \frac{\gamma_4}{4!}H_4(x_p)\right)\exp\left(-\frac{x_p^2}{2}\right)$$

$$H_o(x_p) = 1$$

$$H_1(x_p) = x_p$$

$$H_2(x_p) = x_p^2 - 1$$

$$H_3(x_p) = x_p^3 - 3x_p$$

$$H_4(x_p) = x_p^4 - 6x_p^2 + 3$$

$\Rightarrow$

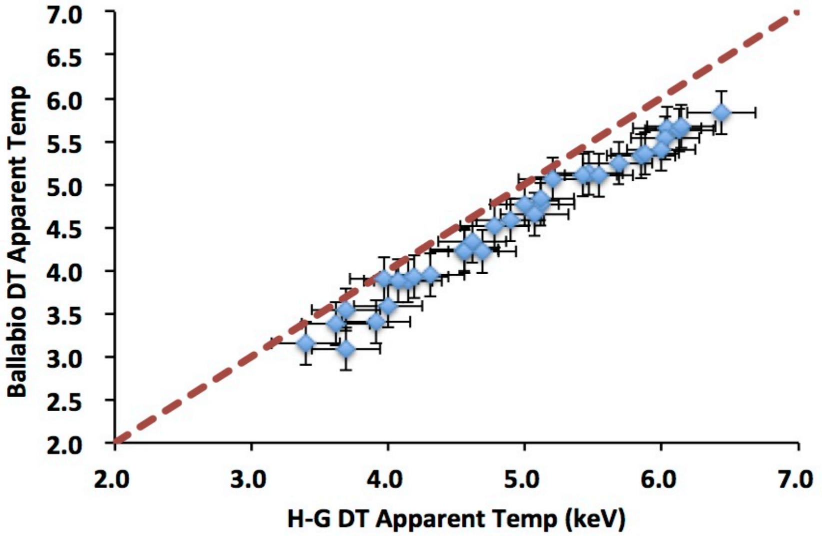
Cumulant	Quantity	Parameter
0th	Uncoll. Yield	A
1st	Mean Mom.	μ_p
2nd	Mom. Variance	σ_p
3rd	Skew	γ_3
4th	Kurtosis	γ_4

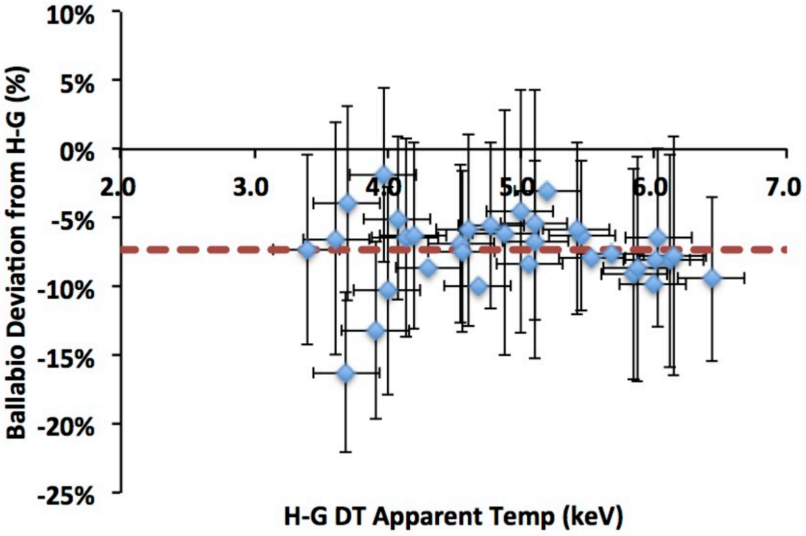
Caveats: Accuracy of higher moments are limited by the model and instrumentation

- The down-scatter model in the fit has limited accuracy
  - Actual ρR distribution affects the spectral shape

- The instrument response function needs to be known accurately
- High dynamic range recording system is required
  - Cumulants are sensitive to noise floor in the “tails”.
  - Precision nToF project is focused on understanding and quantifying these issues.

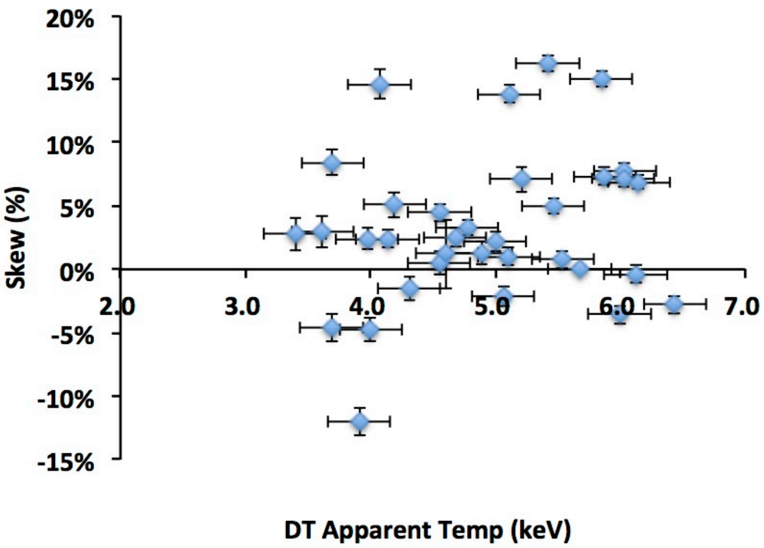
Preliminary NIToF fit results show DT weighted temperatures increase by ~7.5%...

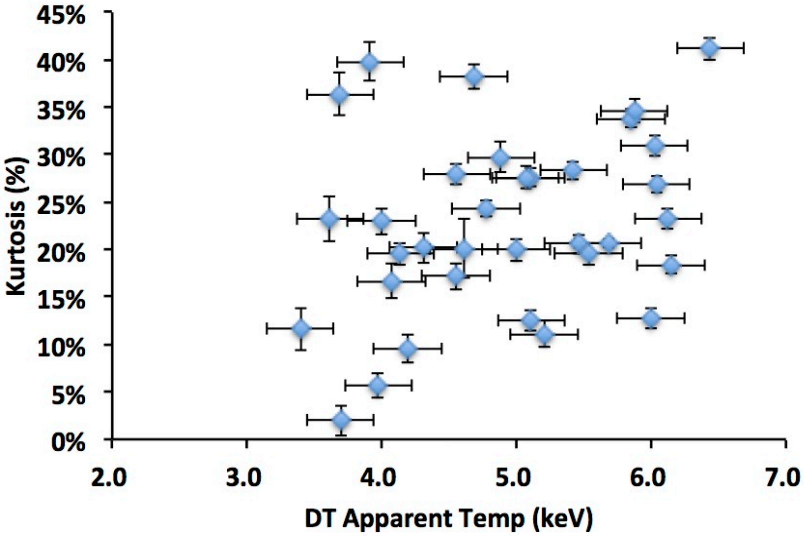




Data drawn from the NIF Hi-Foot and HDC campaigns.

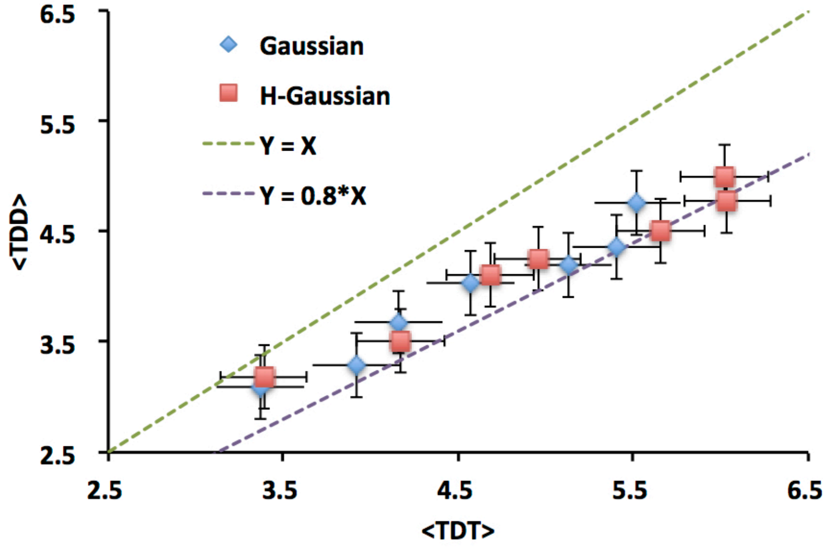
Fit results indicate the presence of skew and kurtosis in the spectrum…

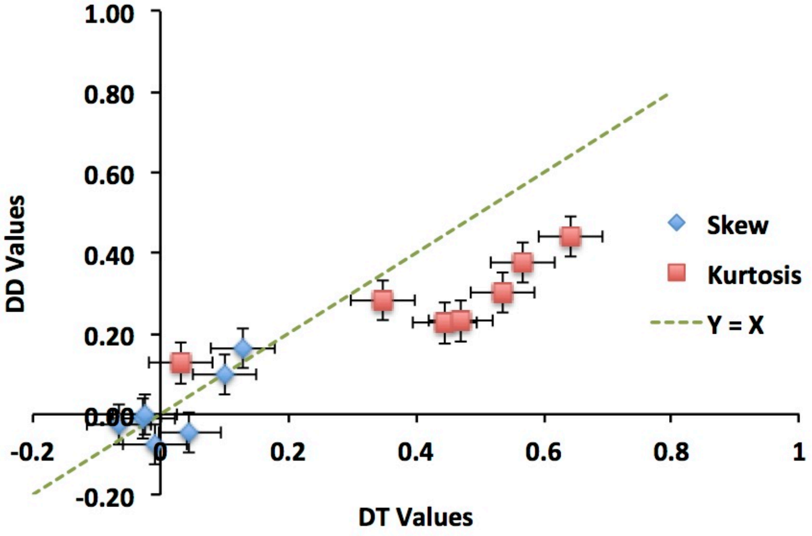




Systematic studies using new improved methods are required to understand the significance of these data.

Preliminary fits of the DD peak are now becoming available…

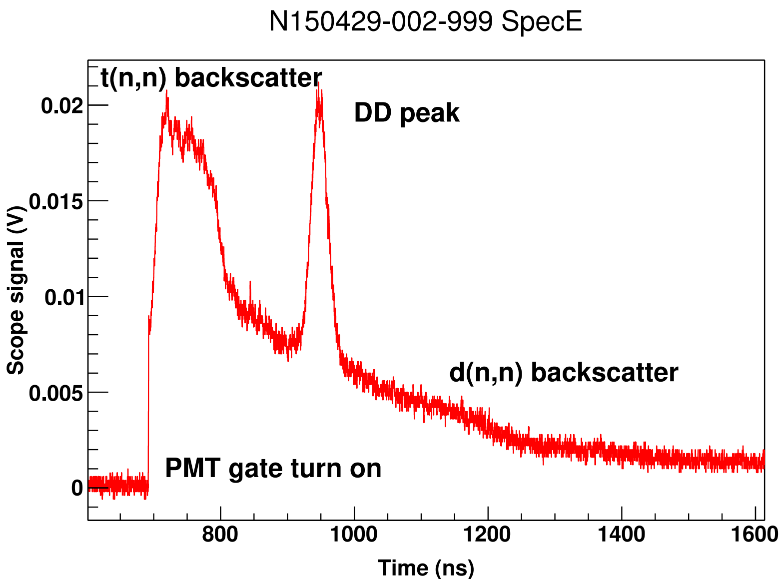




Results show a Similar increase in the neutron spectral variance for both DT and DD
Skew seems to track, but Kurtosis appears to increase more for DT than DD...
These results are not immune to systematics and are *Preliminary…*

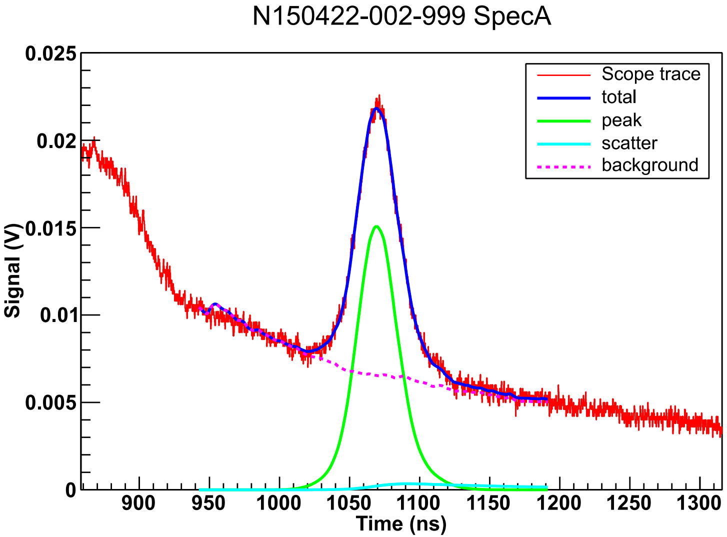
Fitting DD peak on DT shots needs to correctly address systematic issues…

- The background under the DD peak does not a fit to the DD downscatter region
  - Use DT DSR to estimate $f_{scatter}$
- The BG model is parabolic in neutron energy space, adding 3 parameters to the fit.
- Both approximations influence the estimated skew and kurtosis parameters…



Influence of background model on deduced variance, skew and kurtosis

- Fits of the model were obtained with skew and kurtosis fixed to 0 as well as with those parameters floating.
  - Background model changes significantly between those fits
  - Kurtosis is typically positive between 0.3 and 0.7, skew is close to 0.
  - As kurtosis increases, so does the variance (and therefore T_{ion})
- Study of sensitivity of kurtosis to background model is underway

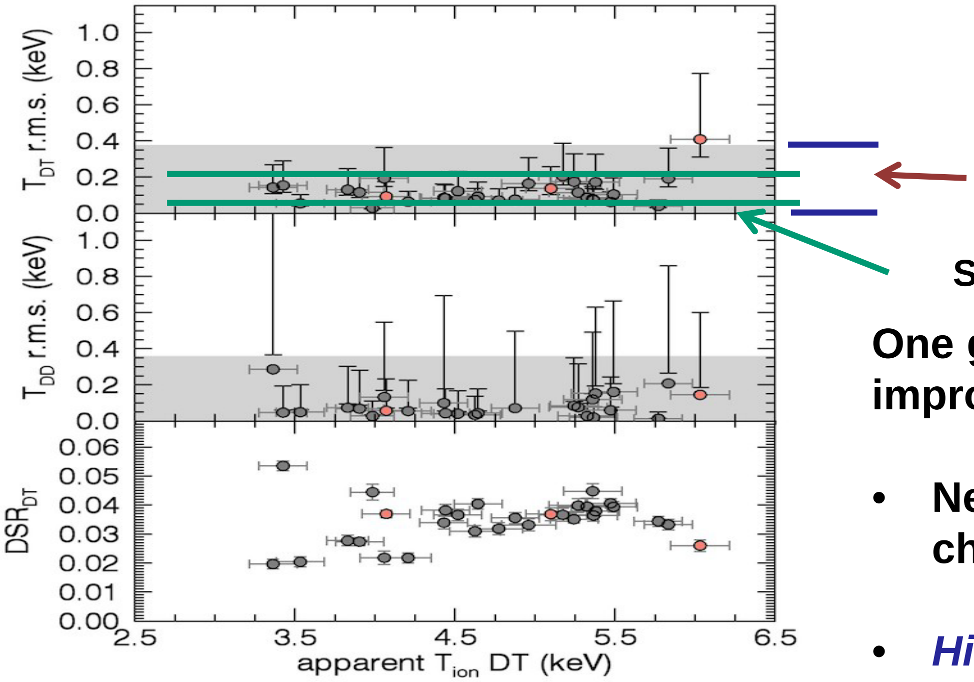


Current (Fall 2015)Precision nTof Performance Goals

- Operate at fusion yields as high as 1 x 10^{16} to 1.2 x 10^{19} (33 kJ to 40 MJ).
- Produce a linear output signal over this yield range to better than 1% accuracy.
- Measure the absolute neutron fluence at the detector to better than 0.5%.
- Measure the first 4 central moments of the DT and DD neutron peaks to the following accuracy:

Moment	Precision
1st	0.02%
2nd	100 eV
3rd	0.3%
4th	1%

Further, detector systematic uncertainties dominate LoS variability measurements



Magnitude of systematic unc.

Shot-to-shot variability of T_{ion} RMS

One goal of the Precision nToF project is to improve systematic uncertainties through:

- **New detector systems with improved characteristics**
- ***Higher sensitivity digital recording***

High Level Plan

- Define physics requirements for next generation of nToF diagnostics at HED facilities.
- Assess current detector performance in context of new requirements.
- Assess and down-select prospective technologies
- Create a 3-5 year plan to develop and implement selected technologies in facilities such as Omega, the NIF, and Z.

With the following major technical elements…

- Assessment of photo-detector impacts on system IRF
  - Linearity
  - Shift invariance

- Scope strategies to mitigate a non shift invariant IRF.
  - See A. Moore talk next

- Study the practicability of in-situ IRF generation via 2-ω fidu.

- Assessment of detector backgrounds from scattered radiation in the scintillator
  - Determine the cross over point where optical filtering cannot accommodate increased yields

- Scope new photo-detector designs to produce a shift invariant IRF.

What follows is a snapshot status report on the above plan.

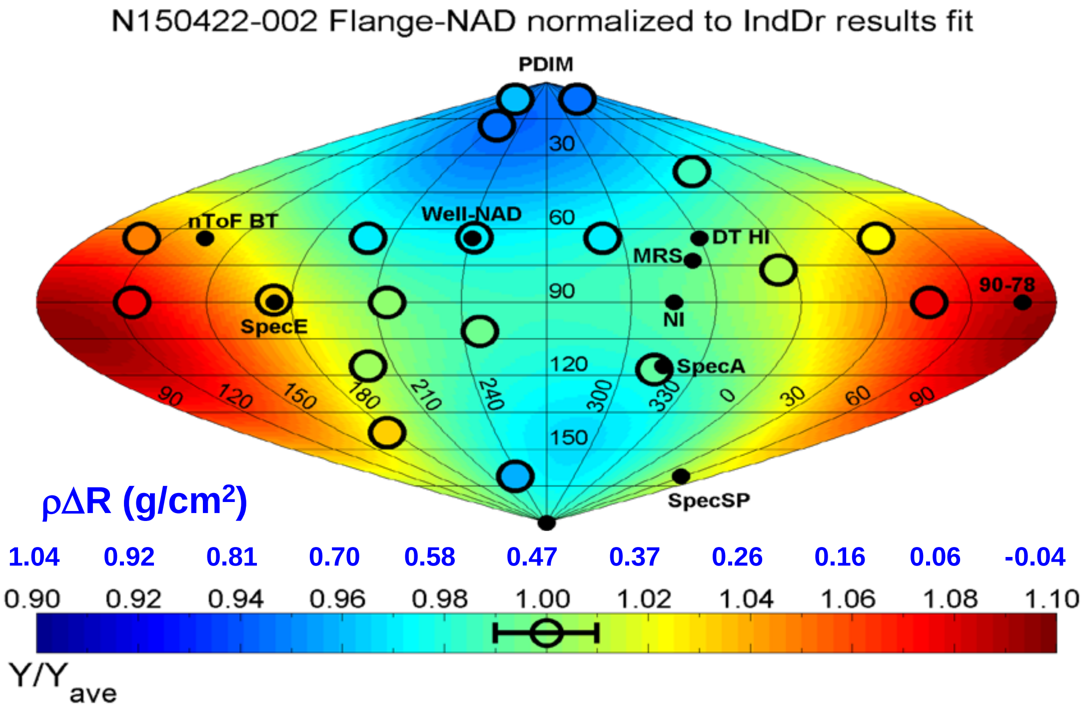
Are FNADs indicating high-mode ρΔR asymmetry?

Limited number of DSR measurements makes it challenge to quantitatively compare the measurements.

Possible to convert maps to areal density,

$$\frac{Y_n(\theta,\phi)}{\langle Y_n\rangle} = \exp\left(-\frac{N_A}{M_{DT}}\sigma\left(\rho\Delta R(\theta,\phi) - \langle\rho\Delta R\rangle\right)\right)$$

but also limited by the location and number of nTof systems.



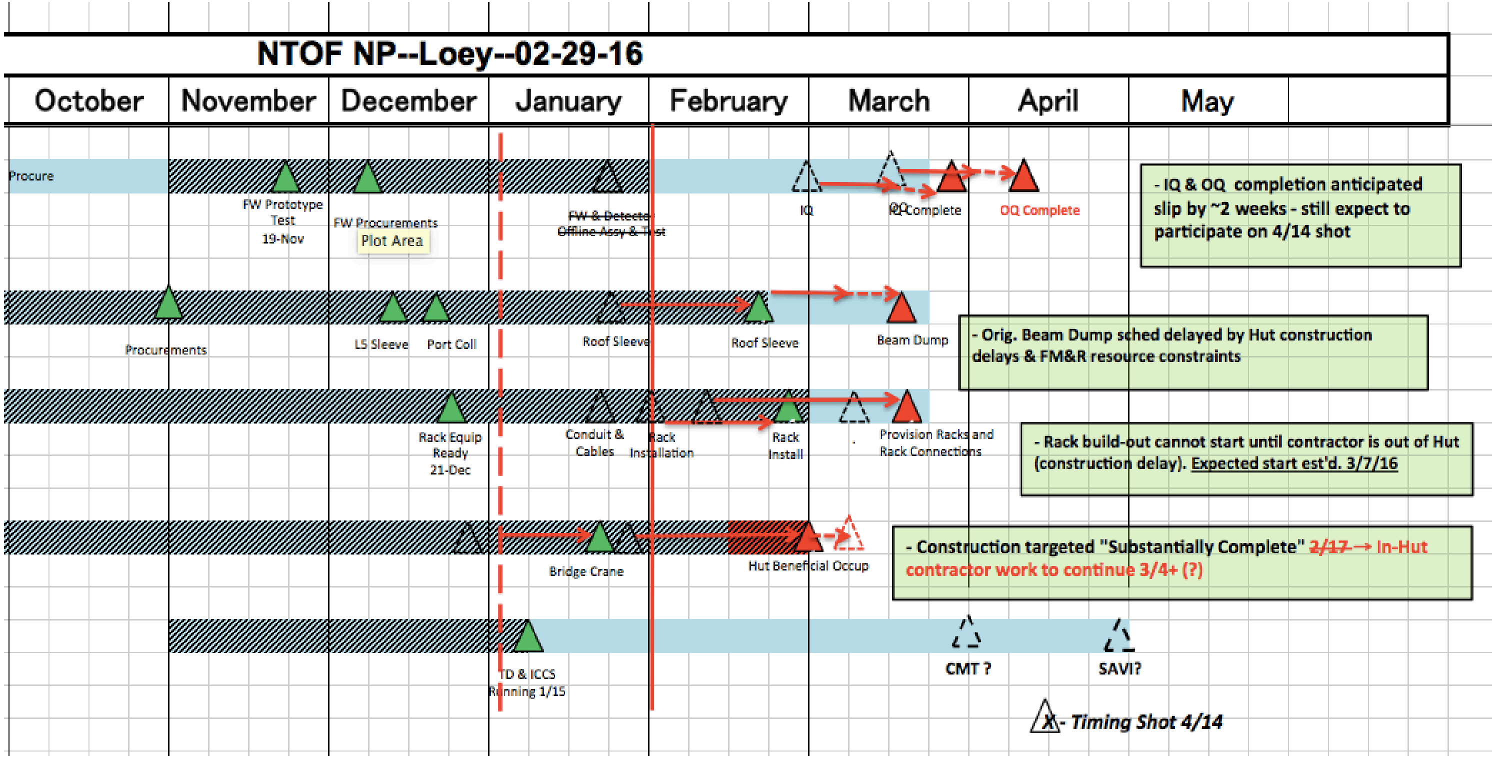
Several improvements are being pursued…

- In the near term
    - Adding a 4th SPEC nToF detector on the north pole
    - Looking at T(n,n) scattering to understand "backwards" areal density…

- Long term
    - Real time NADS – up to 50 NAD foils being viewed by a LaBr based detector coupled to an on board digitizer.

NIF North Pole nToF should be ready by mid-April to collect data…

NIF nToF NP Schedule



- IQ & OQ completion anticipated slip by ~2 weeks - still expect to participate on 4/14 shot

- Orig. Beam Dump sched delayed by Hut construction delays & FM&R resource constraints

- Rack build-out cannot start until contractor is out of Hut (construction delay). Expected start est'd. 3/7/16

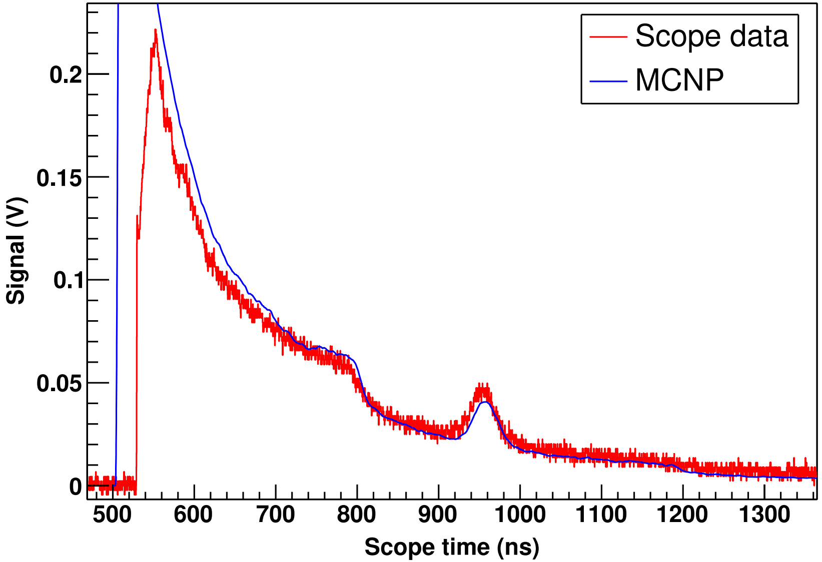
- Construction targeted "Substantially Complete" ~~2/17~~ → In-Hut contractor work to continue 3/4+ (?)

Analysis of t(n,n) backscatter edge for ρR information

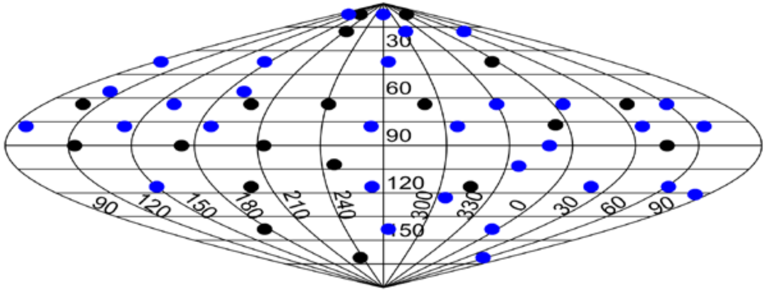
- Analysis of t(n,n) backscatter edge allows to get ρR information from a different part of the capsule than DSR

- Need a model for contributions other than scattering on tritium

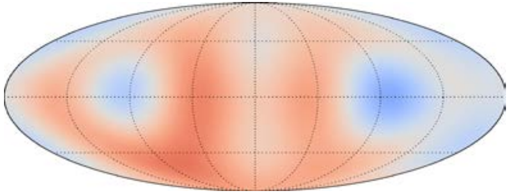
- Comparing MCNP simulations with experimental data in order to see if simulation can reproduce spectral shape seen by the nToF detector

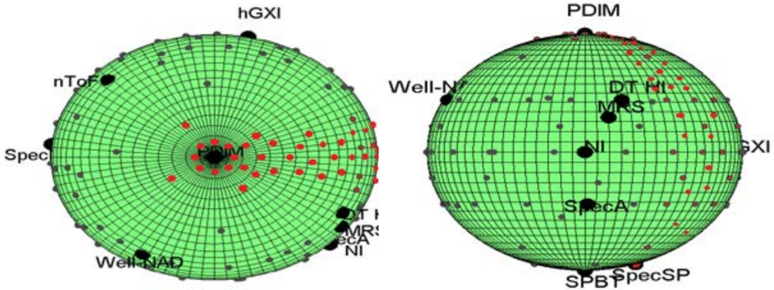


Proposed design would support a variable layout to be determined based on physics need

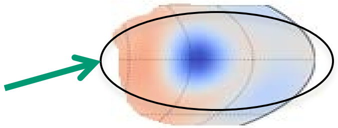


48 evenly-spaced FNADs





ℓ~8 cluster of NADs over pole and one meridian to equator



The proposed design supports either of these physics options plus more

Exploding Pusher 77358

Synthetic data

Taking the fit values from the LLNL scatter model analysis to be:

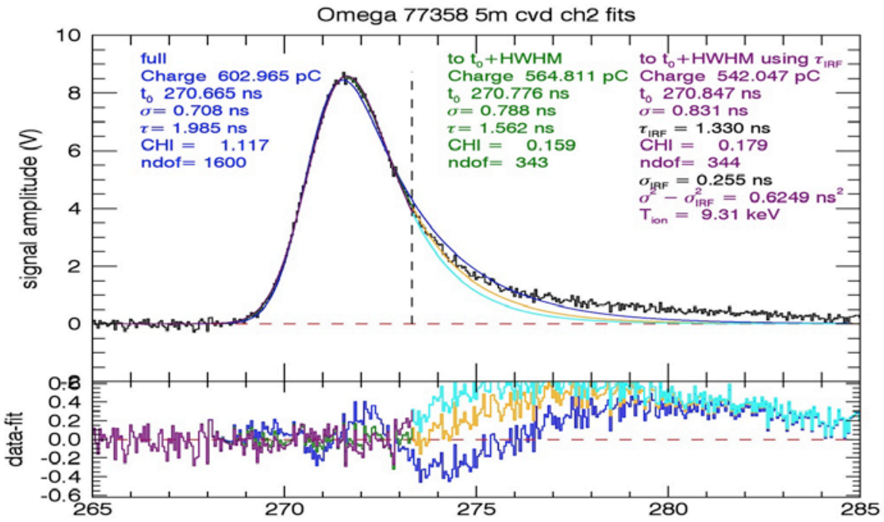
A=**15.889 V**
t_0=**270.52 ns**
T_{ion}=**9.639 keV**
f=**3.075**

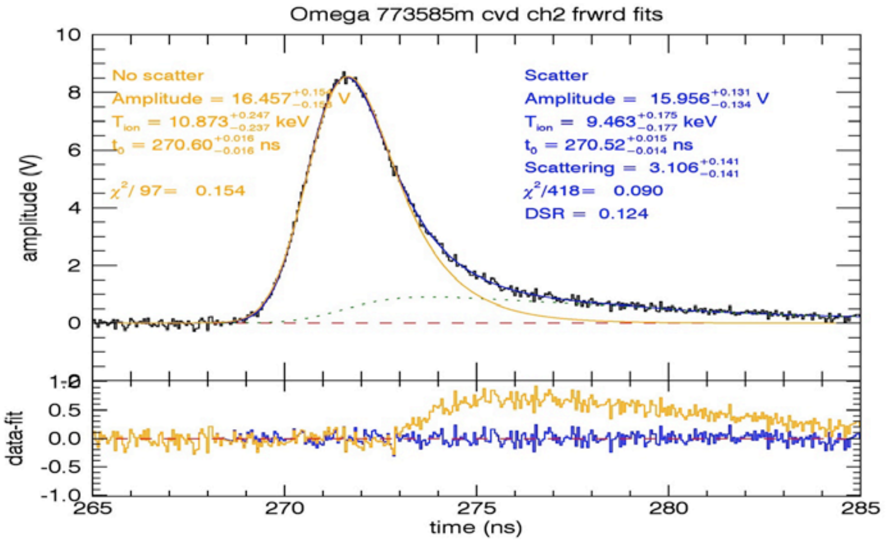
Construct a waveform using:

1)the Ballabio model plus the single scatter in the kinetic energy domain,
2)apply the detector energy sensitivity,
3)transform to the time domain,
4)apply the instrument response function,
5)add a noise term equivalent to that in the “real” data

This synthetic waveform can be fit with the different analysis methods. The amount of scattering tail can be changed to see how this might effect the various fit results.

Comparison of synthetic data fit





The input is close to the original constants. The LLNL scatter model fits the data very well, as expected. The LLE analysis model also does a good job fitting the synthetic data.

Changing the scattering coefficient

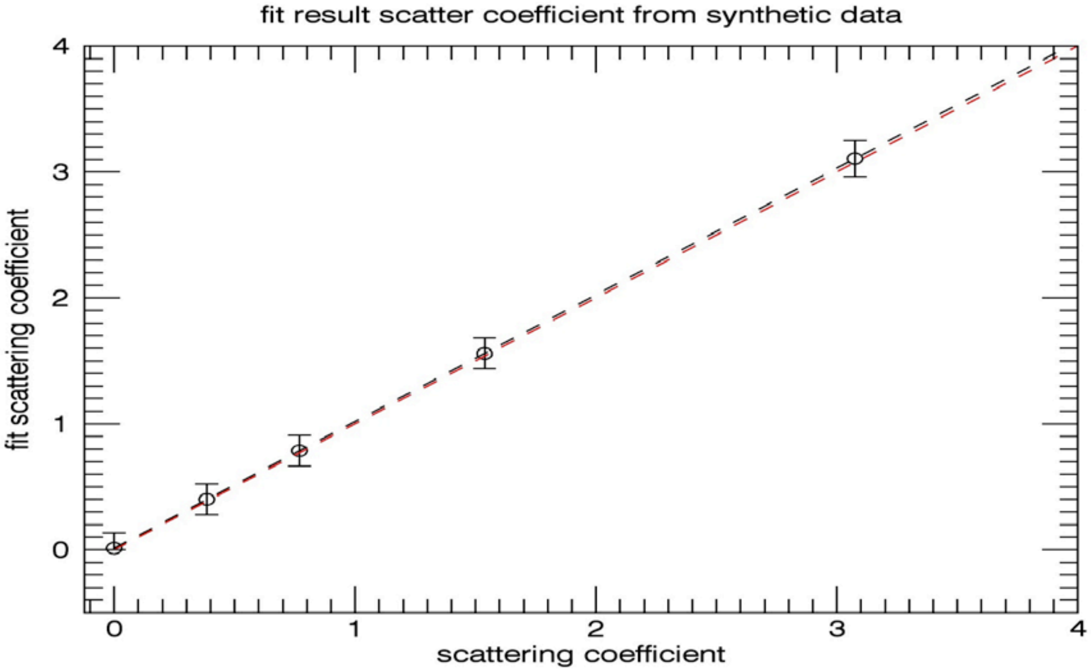
The LLNL scatter model recovers the value of the scatter coefficient used to generate the synthetic data.

The red dash line is for equality, the black dash line is a linear fit

Fit coef = 0.01±0.08 + (1.01±0.06) x True coef

All other parameters were kept equal.

The same noise value was used (0.09 V) but different random sets were produced for each value of the scatter coef.

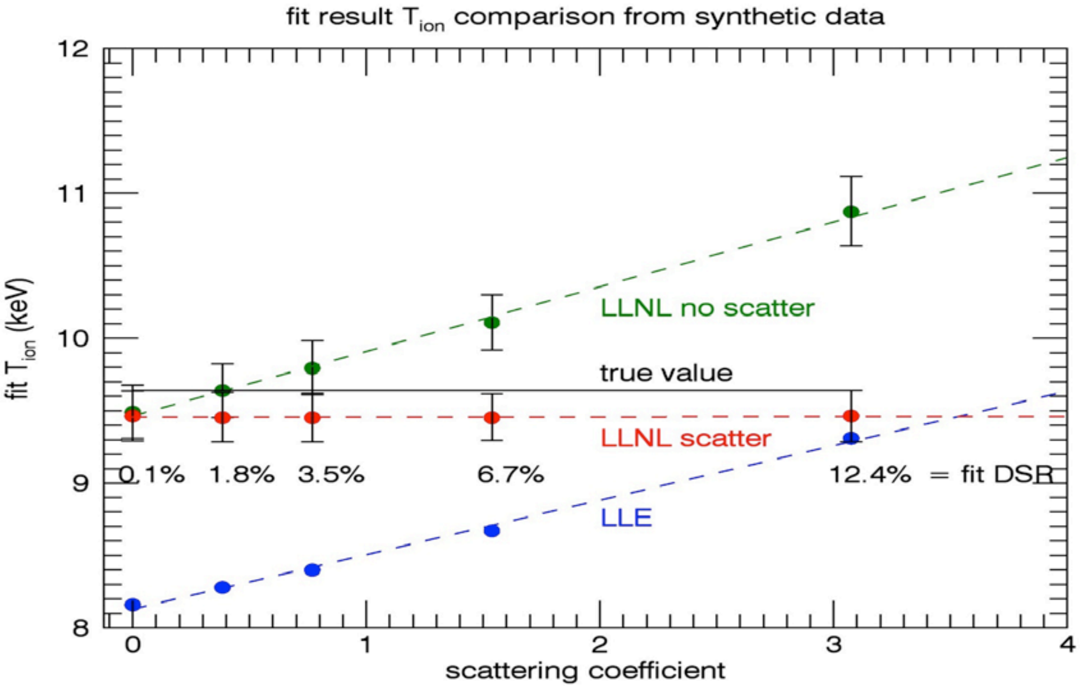


Scattering effect on T_{ion} determination

Both the LLNL no scatter model and the LLE model show a linear dependence on the amount of scattering. The “equivalent” DSR obtained from the LLNL scatter model is shown.

The LLNL scatter model is also systematically lower than the true T_{ion}, though within uncertainties (roughly 0.170 keV).

The LLNL models converge at scatter coeff = 0., as expected.



Discussion

The amount of scattering does effect the LLE analysis. There is a 1.3 keV difference in T_{ion} between the two models that do not treat scattering.

The LLE result agrees with the LLNL result at the scatter coefficient value that represents the actual scattering environment at OMEGA. This is not an accident, as the scatter background not due to physics (the assumption of the LLNL model is that the scatter is due to physics).

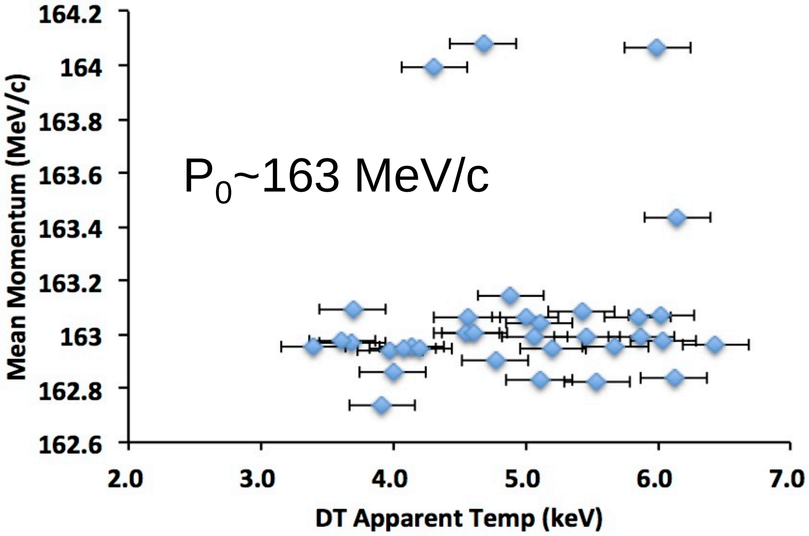
The very different calibration procedures for the LLE model and the LLNL scatter model analysis obtain results in agreement to ±0.170 keV in this synthetic data test.

If the DSR value of "12.4%" is taken as the zero point (the Exploding Pusher has vanishingly small DSR), the LLE model T_{ion} parameter has a linear dependence on the physical DSR, this analysis predicts: an 0.094 keV increase per 1% increase in DSR.

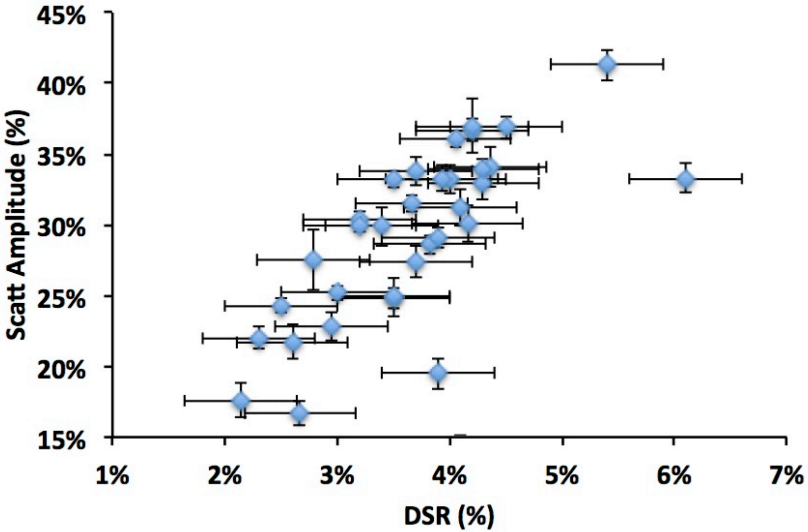
Attempts to improve the T_{ion} precision of the OMEGA nTOFs to 0.100 keV will have to address this correlation.

Backup stuff…

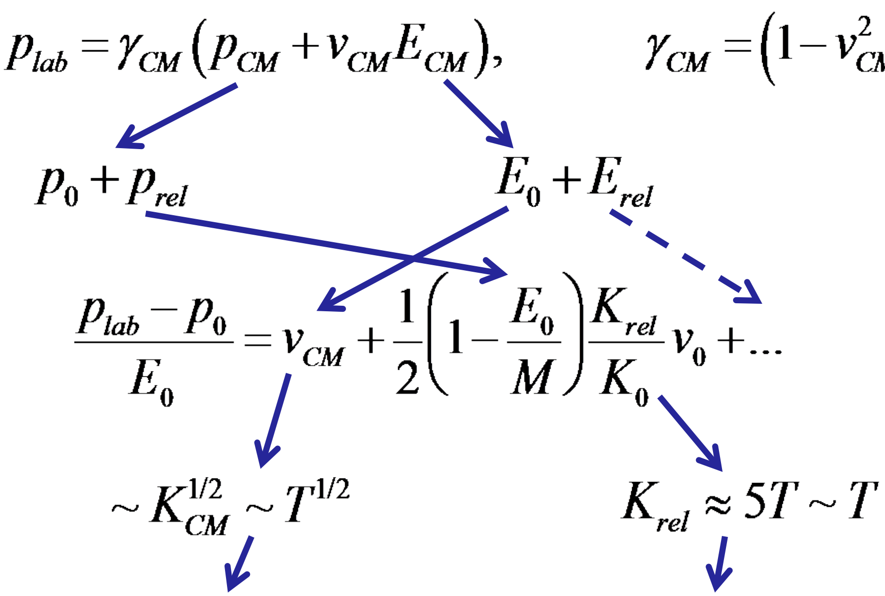
The mean momentum and relative scattering amplitude behave nominally.



P_0~163 MeV/c



Neutron peak is nearly LOS component of CM velocity distribution



$$p_{lab} = \gamma_{CM}\left(p_{CM} + v_{CM}E_{CM}\right), \qquad \gamma_{CM} = \left(1 - v_{CM}^2\right)^{-1/2} \approx 1$$

$$p_0 + p_{rel} \qquad E_0 + E_{rel}$$

$$\frac{p_{lab} - p_0}{E_0} = v_{CM} + \frac{1}{2}\left(1 - \frac{E_0}{M}\right)\frac{K_{rel}}{K_0}v_0 + \dots$$

$$\sim K_{CM}^{1/2} \sim T^{1/2} \qquad K_{rel} \approx 5T \sim T$$

(Gamow peak)

We use this shifted, scaled lab neutron momentum for spectra

$E_0 = m_n + K_0$

$p_0, K_0 =$ n-momentum, K.E. at $K_{rel} = 0$

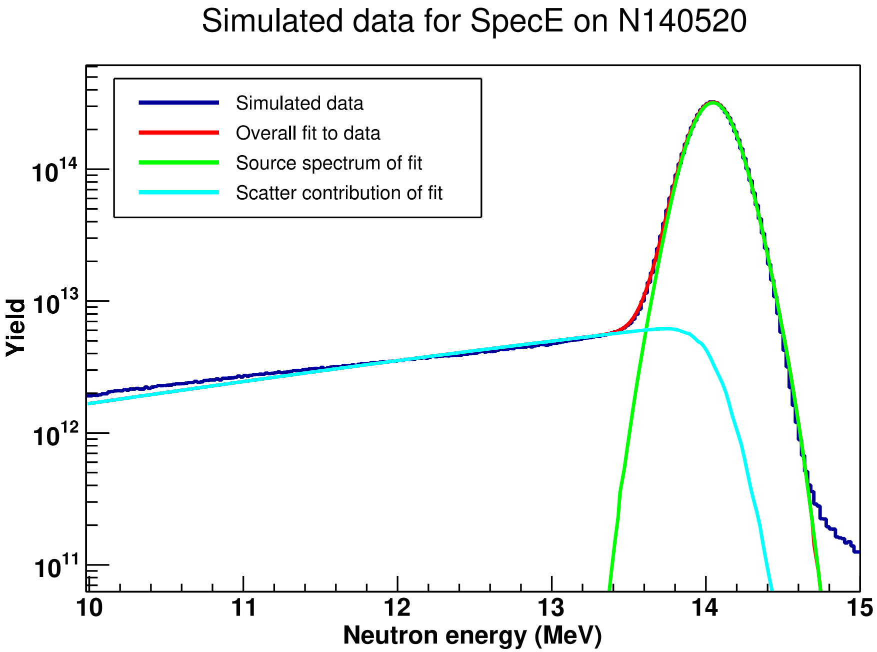
$M = m_D + m_T$

At T = 4 keV:			
	277 km/s	31.3 km/s	for DT
	310 km/s	64.3 km/s	for DD
	(std. dev.)	(centroid)	

The scattering model used in the fit has minimal impact on the deduced skew and kurtosis

- Scatter model has a simplified ρR distribution and is limited to single scatters
  - Compare fit with scatter model in simulations to fit of simulated source spectrum

Value	SpecE los simulation	SpecSP los simulation	Production spectrum
Mean	163.081	163.081	163.081
Sigma	0.8925	0.8909	0.8981
Skew	0.0307	0.0312	0.0306
Kurtosis	0.325	0.328	0.295



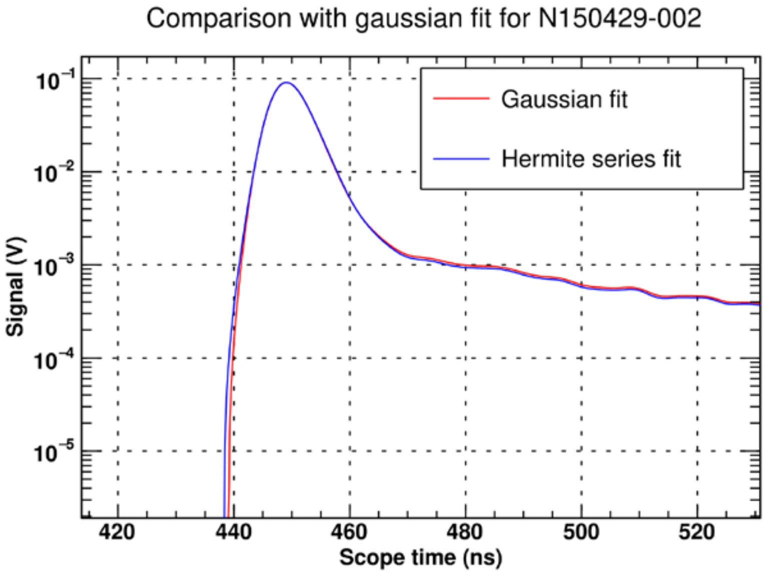
A Precisely Determined Instrument Response Function is important for determining higher moments

- Measuring skew and kurtosis is challenging

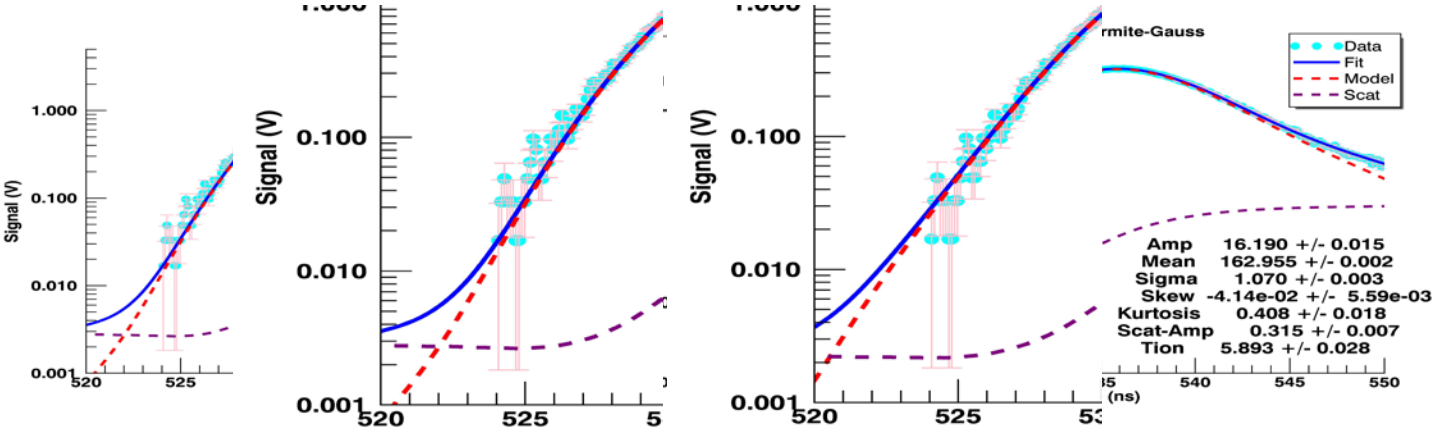
- On the right is shown a comparison of a gaussian fit with a Hermite series one

- Hermite series has a “typical” kurtosis of 0.3

- *IRF induced “wiggles” are larger than the difference between both fits:*
  - *Need more accurate IRF description*



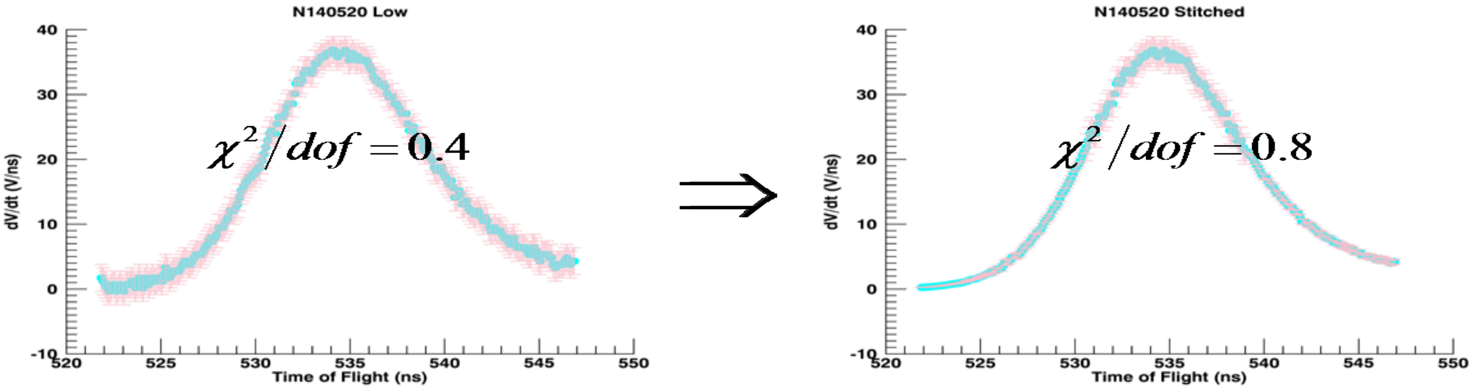
Adding extra degrees of freedom visibly improves NIToF fit quality in the region of interest…



Reduced chi-square is decreased by 2x…

Can we now take advantage of higher sensitivity data?

High & Low sensitivity data produce very low fit errors, need to consider consider a different cost function…



$$\chi^2 = \frac{1}{2\sigma_s^2}\sum_{i,j}\left(s_i-[m\otimes h]_i\right)^T C_{i,j}\left(s_j-[m\otimes h]_j\right)$$

$$\chi^2 = \frac{1}{2}\sum_{i}\left(\frac{s_i-[m\otimes h]_i}{\sigma_{s,i}}\right)^2$$

What does the NIF nToF suite measure?

- NIF nToF systems provide estimates of parameters from a model spectrum.

- Currently, the estimated parameters in the energy domain are:
  - The 0th-2nd moments
  - The strength of single elastic scatters produced by the spectrum

- These parameters are used, with certain assumptions, to infer properties of a model plasma, i.e. <TDT>, <TDD>, velocity, etc...

- Generally, the model assumptions do not hold for the experimental conditions producing the data, e.g.
  - Burn from an isochoric, isobaric, static, homogeneous, equimolar plasma.

- It is essential that the consumer of NIF <TDT> and <TDD> data understand what is being measured! – *Caveat Emptor!*

Variance is but one parameter in describing a spectrum…

Variance is but a single parameter of significance….

Summary

- The NIF nToF is

There are four nToF detector which allow to extract spectral information

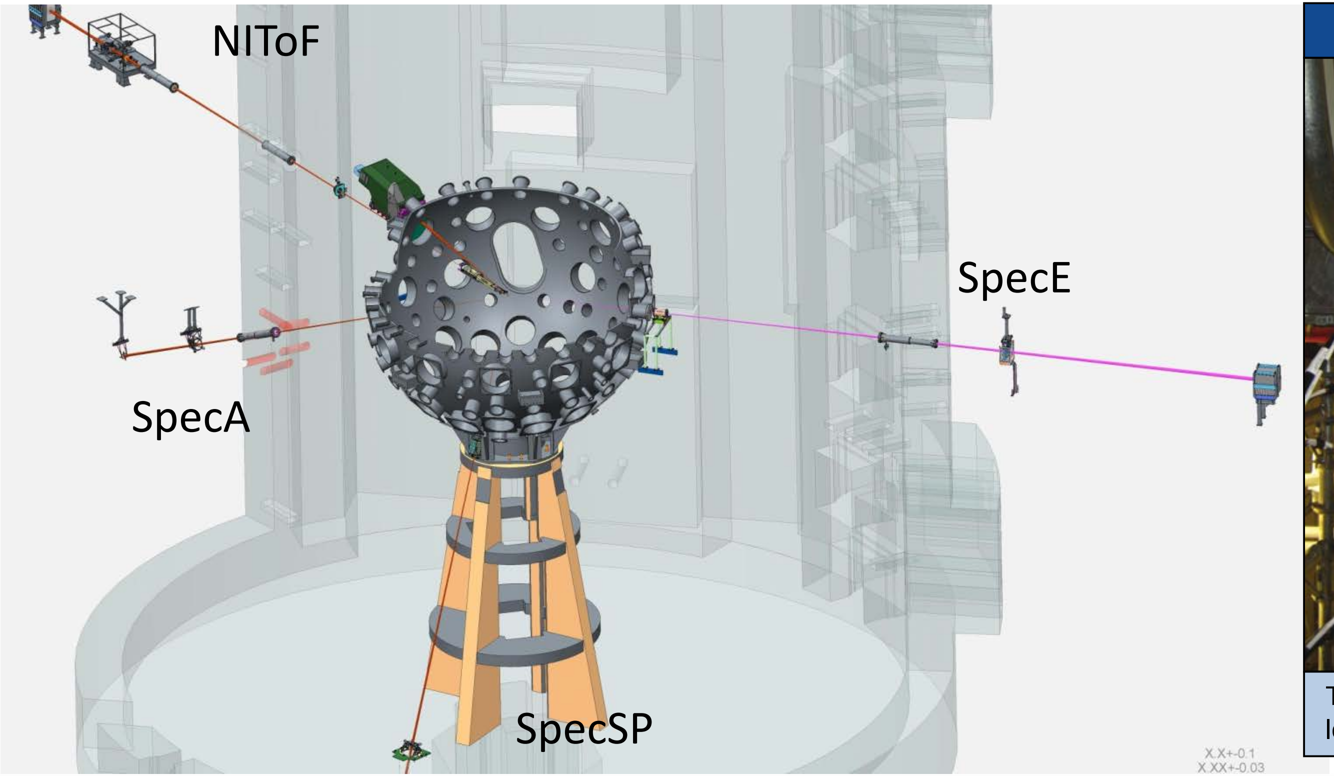
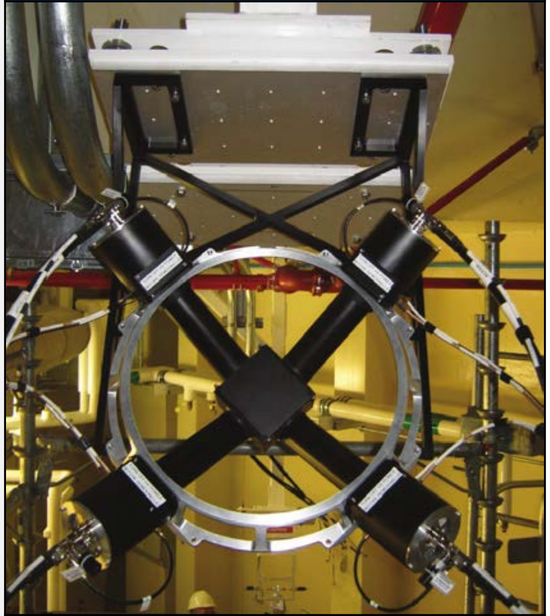


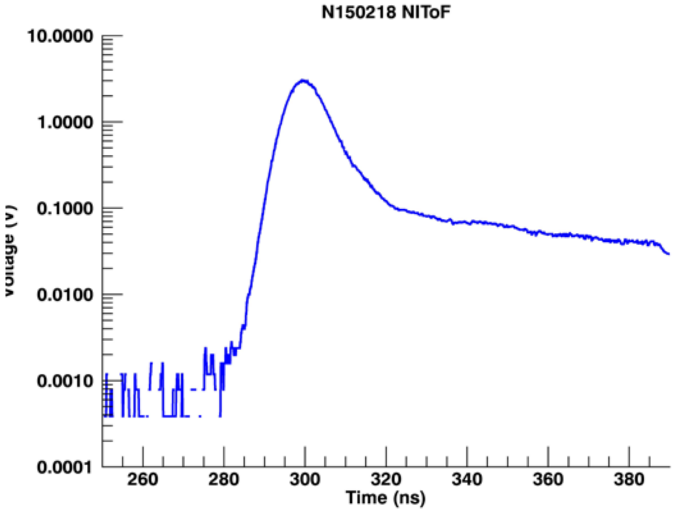
Photo of installed detector



The detectors employ 3 PMTs and a PD to look at a scintillation detector.

The product of the nToF system is a time series trace that represent the detectors response to the neutron flux…

- The nToF analysis task is to extract the moment content of the underlying neutron spectrum in the *energy domain.*
- To accomplish this goal the detector system response must be properly corrected for in both the energy and time domains.



The nToF analysis forward fits a spectrum model to the time-of-flight data to *estimate spectral moments*

- Deconvolution is mathematically ill posed problem → use forward fit of model

$$f(t) = I(E)a(E)s(E)\frac{dE}{dt} \otimes h(t) \equiv m \otimes h$$

- *I(E)* is the model in neutron energy space (more on next slide)
- a(E) is the beam line attenuation
- s(E) is the scintillator sensitivity

$$\chi^2 = \frac{1}{2\sigma_s^2}\sum_i \left(s_i - [m \otimes h]_i\right)^2$$

- *dE/dt* is jacobian transformation from time-of-flight to neutron energy
- *h(t)* is the instrument response from the detector

Using the Ballabio parameterizations, the first and second moments are related to a T_i of a static, uniform plasma.

$$I_{src}(E) = \frac{1}{\sqrt{2\pi\sigma}}\exp\left(-\bar{E}\left(\frac{\sqrt{E}-\sqrt{\bar{E}}}{\sigma}\right)^2\right)$$

Fit parameters

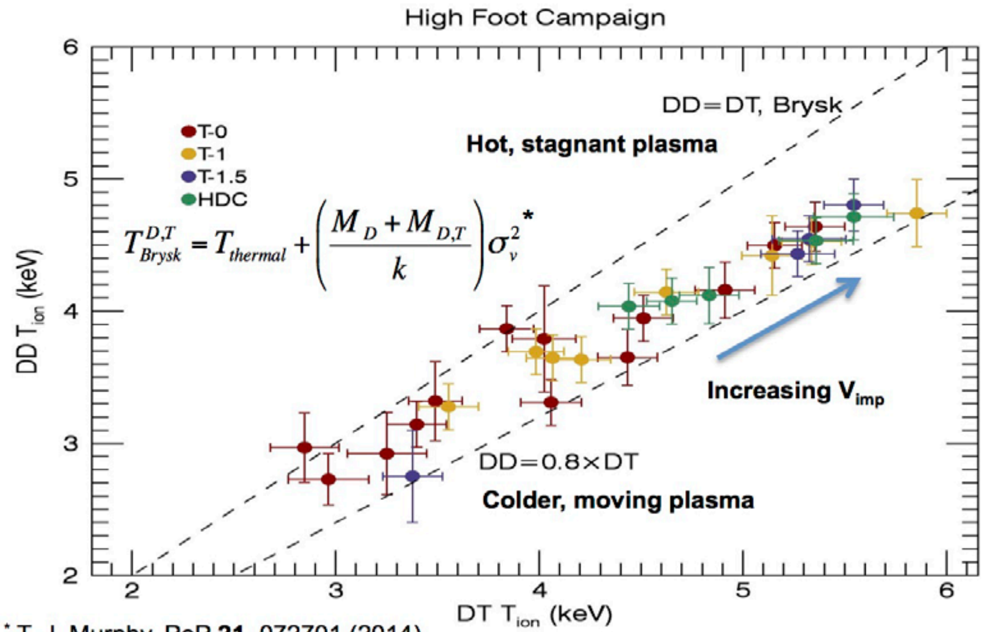
Using the relations $\bar{E} = \langle E\rangle\left[1-\frac{3}{2}\left(\frac{\sigma_{th}}{\langle E\rangle}\right)^2\right]^{1/2}$ & $\sigma^2 = \frac{4}{3}\left(\langle E\rangle\bar{E}-\bar{E}^2\right)$ gives σ_{th} & $\langle E\rangle$

$$T_i = \left(\frac{2\sqrt{2\ln 2}\,\sigma_{th}}{\omega_0\left(1+\delta_\omega(T_i)\right)}\right)^2 \qquad \langle E\rangle = E_0 + \Delta E(T_i) \Rightarrow \frac{\alpha_1}{1+\alpha_2 T_i^{2/3}} + \alpha_4 T_i$$

Const. related to E_{brysk}

Ballabio parameterized fits, different set of a for ΔE and δ_ω

When applied to NIF data interesting differences between DT and DD Ballabio apparent temperatures emerge…



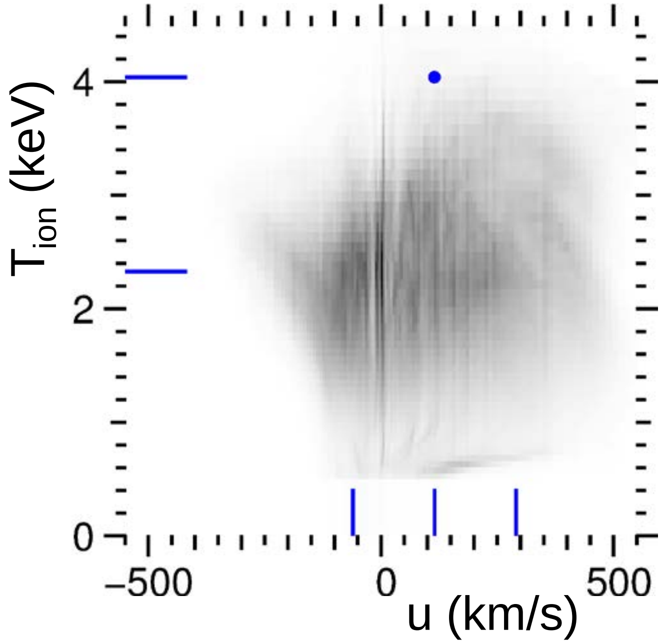
* T. J. Murphy, PoP **21**, 072701 (2014)

Is this motion broadening?
Is this a model artifact?
What do simulations show?

A more sophisticated spectral model is needed that address fluid motion at minimum…

3-D simulations show that neutrons are produced in fluid elements with varying velocity and temperatures…

burn T-u distribution (3D simulation)



u = fluid velocity component along LOS

- Burning plasma is non-uniform: neutrons are being produced in a wide range of temperature and fluid velocity
- Shift of the spectral peak only tells us the shift of mean velocity and mean energy shift due to T_{ion}
- Variance captures average T_{ion} + variance of velocity field
- Skew and kurtosis tell us about T_{ion}-velocity correlations and variations.

We need a model which allows to determine skew and kurtosis

- The Ballabio analysis assumes a static single temperature plasma → should be gaussian in neutron momentum space.

- The desired model should be perturbation on a gaussian in neutron momentum space that add skew and kurtosis to the distribution (D. Munro, Nucl. Fusion).

- The values for skew and kurtosis should be extract-able from the fit parameters since numerical integration is problematic.

- The scattering model from the Ballabio fit should be kept in order to extract the moments of the "source" distribution.