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Correlated Gamma-Neutron Signatures

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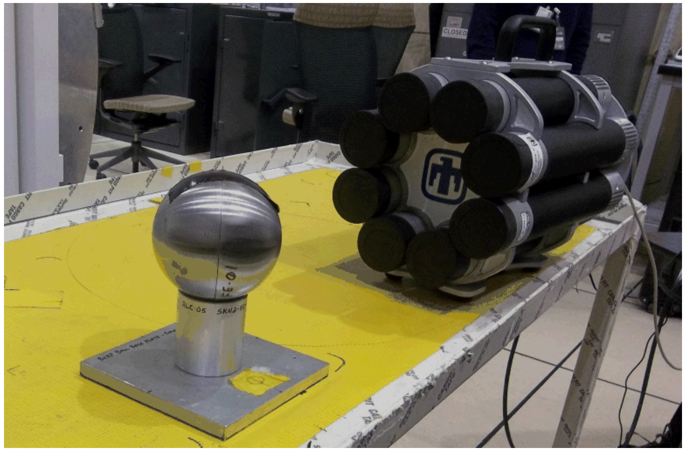
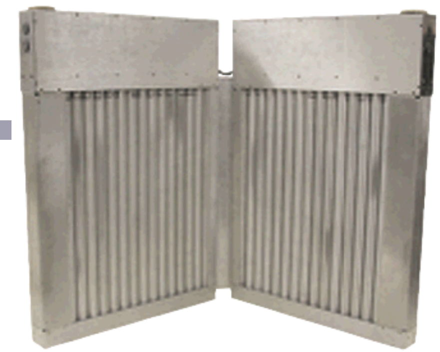
Correlated Gamma-Neutron Signatures

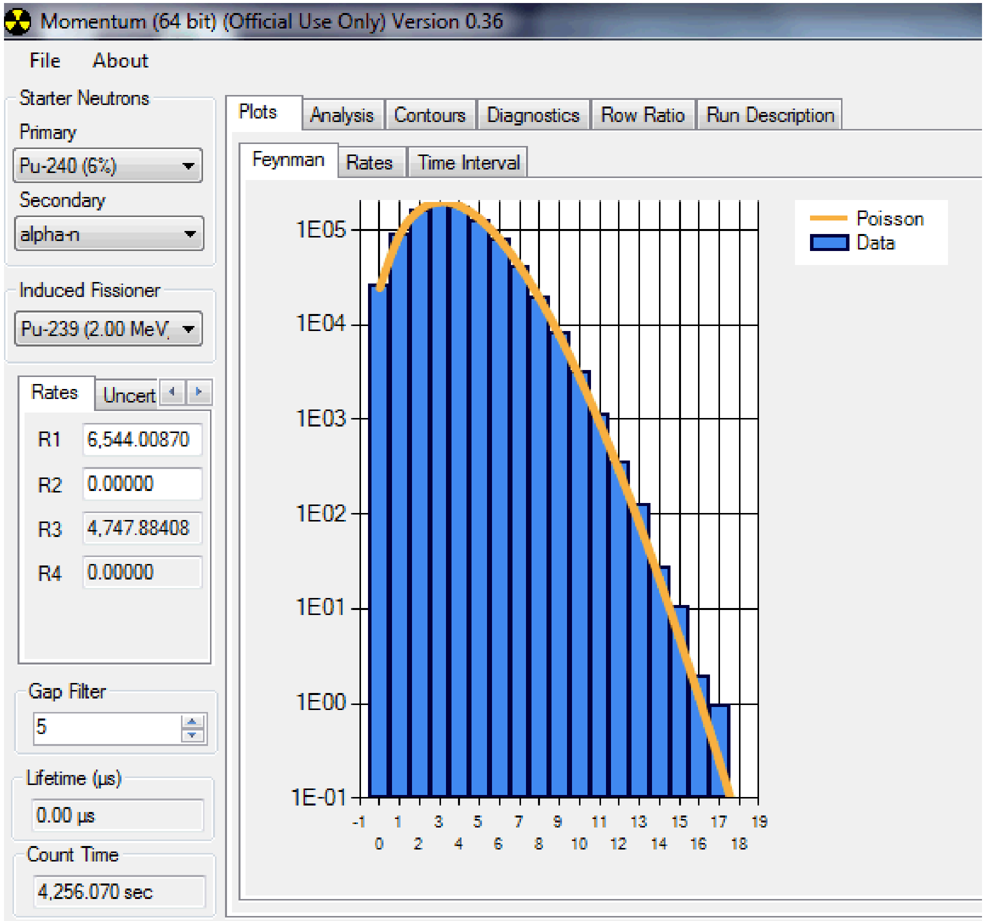
- Sandia has developed compact systems for fissile material characterization with emphasis on gamma-neutron inter-event timing:
  - Liquid scintillator arrays
  - Stilbene array
  - Double-scatter imaging (MINER)
- These systems have different operational characteristics that can benefit:
  - Search and localization missions
  - Device diagnostic applications
  - Warhead and dismantlement confirmation



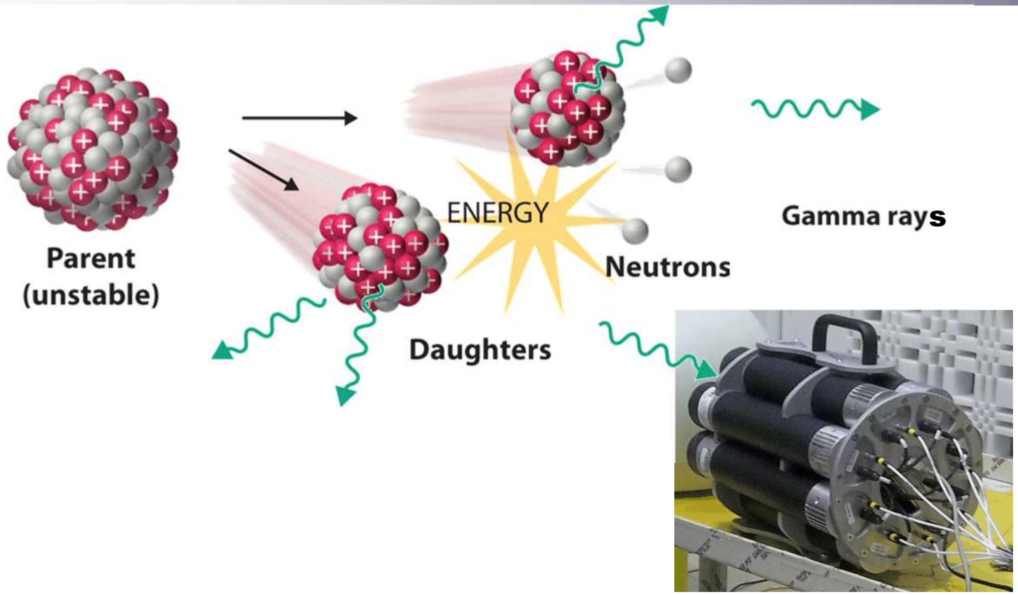
Motivation

- Multiplicity analysis requires:
  1. High efficiency
  2. Strong knowledge of the efficiency
     a) Distance to the source.
     b) Neutron energy spectrum.
  3. Properties of neutron emitting material (multiplicity, cross sections, etc.)
     a) Isotopics
     b) Alpha, n
- Focus on techniques based on fission chain timing:
  1. Can be low efficiency
  2. Does not require knowledge of that efficiency
  3. Can statistically identify the contributions due to spontaneous fission/alpha, n and fission chains.



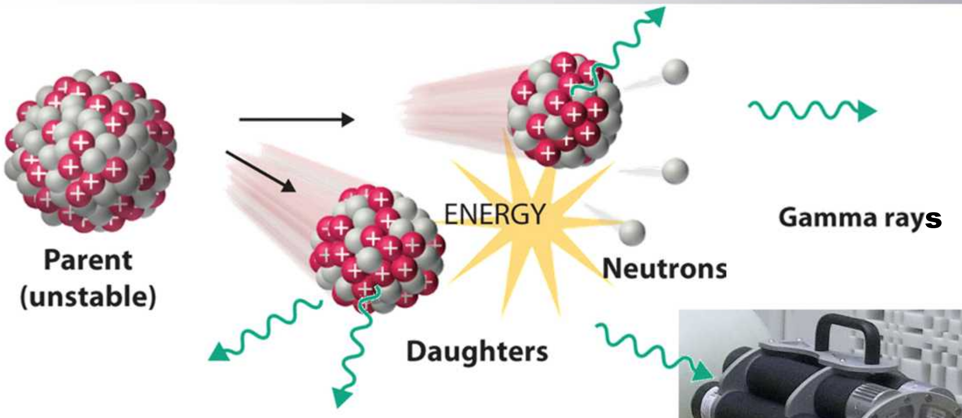


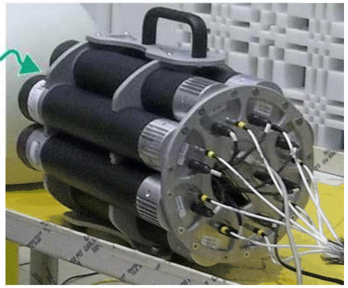
Neutron-gamma correlation – same fission

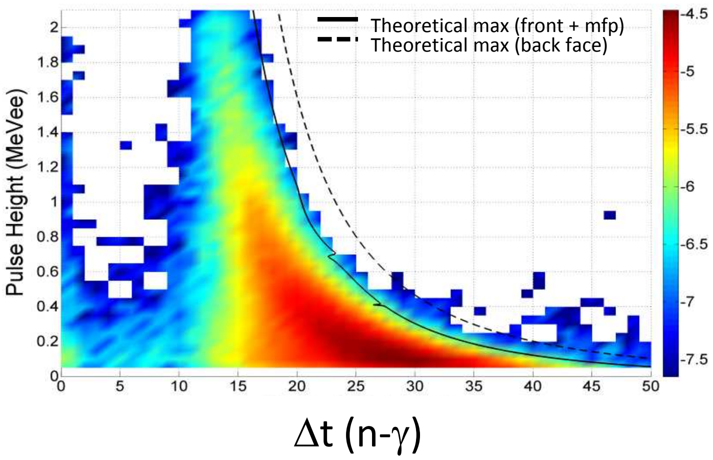


- Neutrons and gamma-rays are emitted nearly simultaneously during the fission process.
- Minimum correlation equals two:
    1. Gamma-gamma: great for timing, but a lot of detector cross talk and uncorrelated background.
    2. Neutron-neutron: without event by event energy, too much uncertainty in expected timing correlation.
    3. Gamma-neutron: gamma starts precise clock, neutron creates certainty that fission has taken place (also more penetrating).

Neutron-γ correlation – same fission

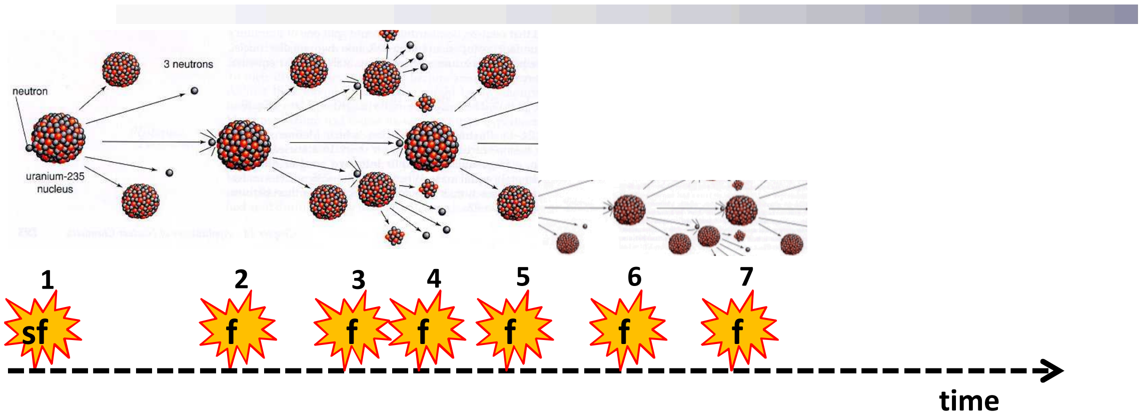


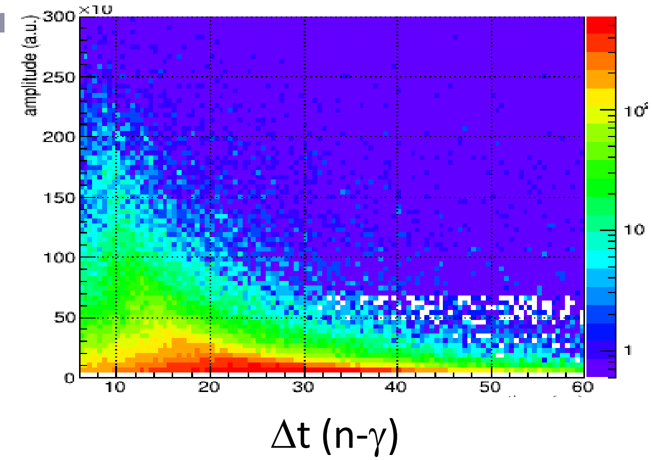




1. A gamma-ray starts the clock.
2. A correlated neutron's arrival time and energy (or fraction thereof) are recorded.
3. The neutron's arrival time is determined by its energy and distance (distance can be determined from the data). This defines the upper edge of an energy vs. Δt distribution.
4. The distribution under this edge is determined by the neutron energy distribution and the detector's response (organic scintillator).

Fission chain correlation

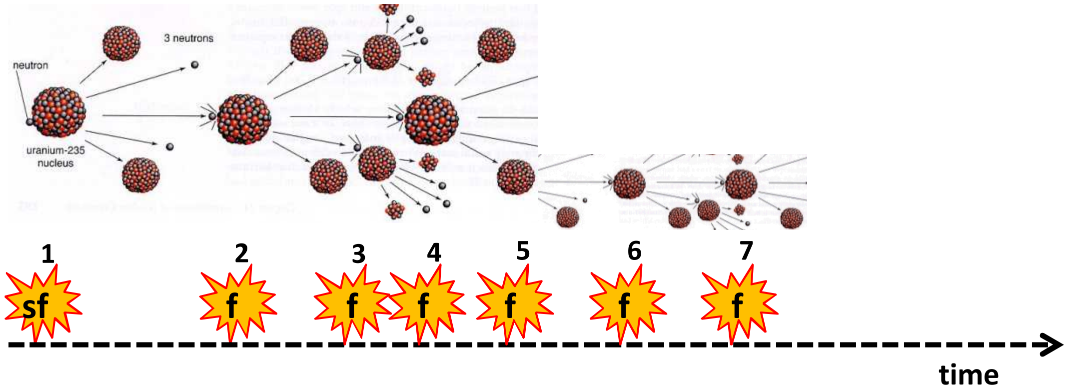


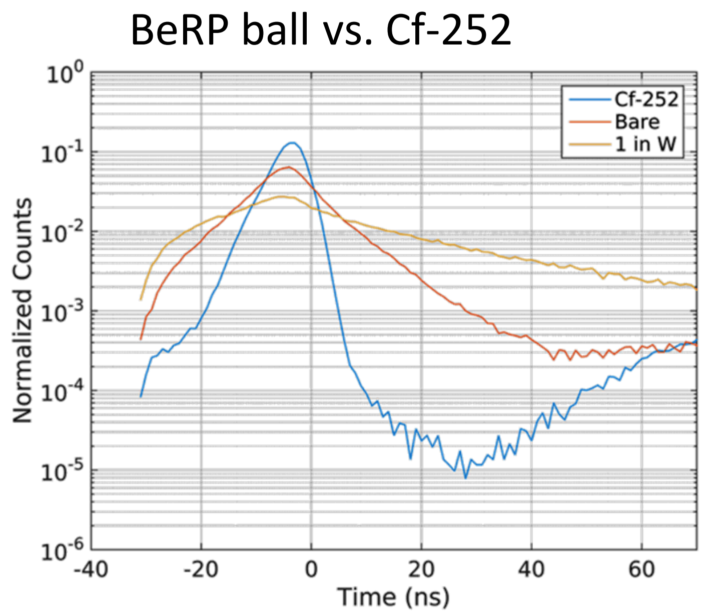


- Probability of measuring one gamma and one neutron is the same for all fissions and fission pairs.
  - Knowledge of absolute detector efficiency not required

- For a chain with N fissions:
  - N ways to get two correlated particles from the same fission (energy-time distribution as shown above).
  - $\binom{N}{2}$ ways to get two correlated particles from different fissions (energy-time as shown in plot above + spread due to fission).
  - Since the ratio of these two components is dependent on the average fission chain length, this technique is sensitive to small changes in multiplication.

Neutron-γ correlation – fission chain

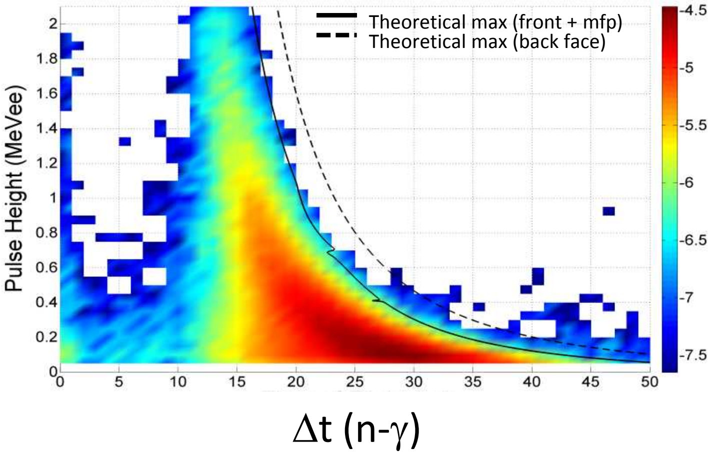


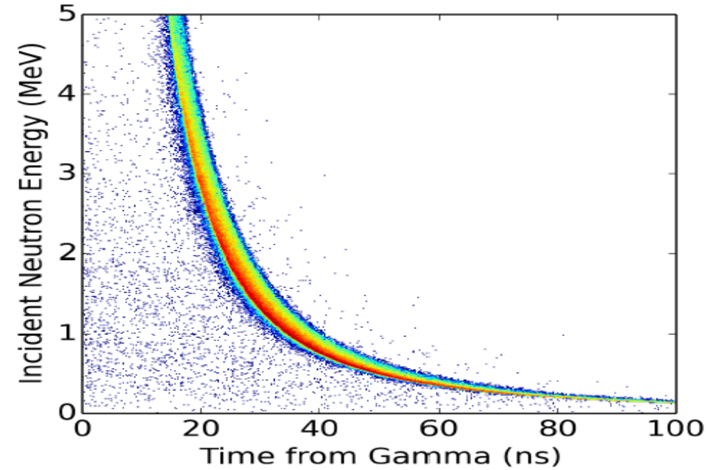


- Using the neutron's energy, the time delay due to neutron travel time can be subtracted out revealing the fission chain spread.
- This is well fit by a gamma distribution (sum of exponential random variables follows a gamma distribution).
- k: shape parameter, θ: rate parameter (empirically determined so far).

$$f(x;k,\theta) = \frac{x^{k-1}e^{-\frac{x}{\theta}}}{\theta^k \Gamma(k)}$$

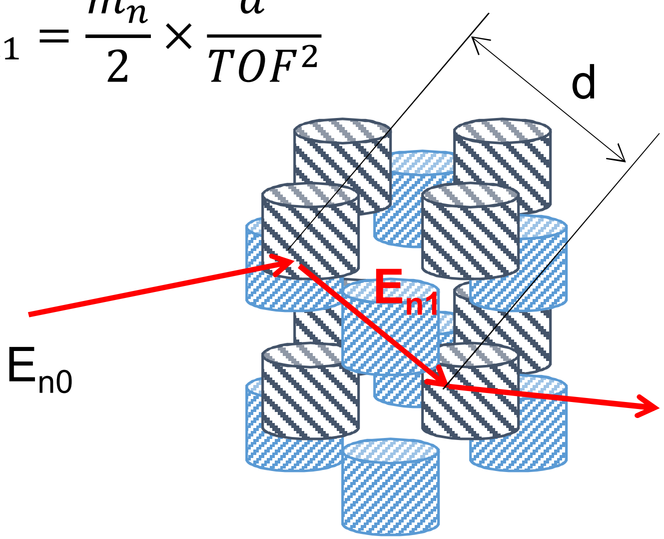
γ-n timing + imaging





$$E_{n0} = E_d + E_{n1} \qquad cos^2\theta_{n1} = \frac{E_{n1}}{E_{n0}}$$

$$E_{n1} = \frac{m_n}{2} \times \frac{d^2}{TOF^2}$$



MINER: the Mobile Imager of Neutrons for Emergency Response

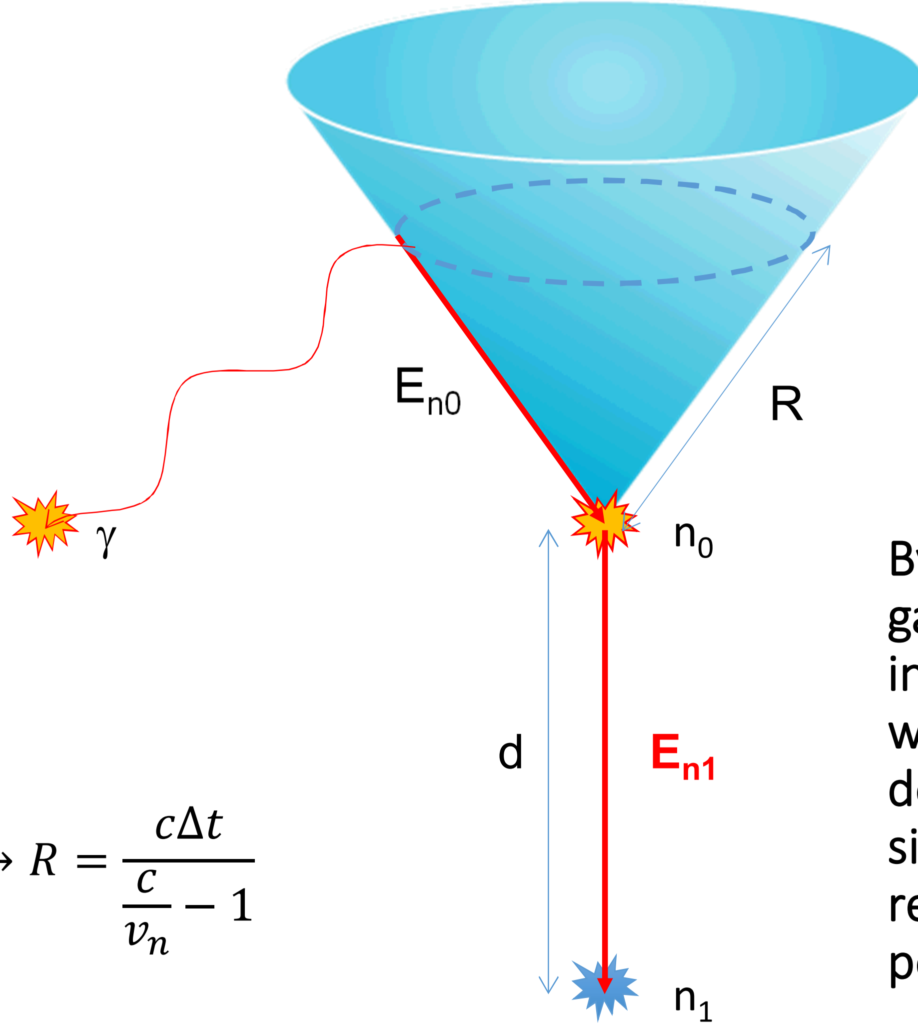
16 independent 3"x3" EJ-309 liquid scintillator cells

γ-n-n 3-D reconstruction

$$E_{n0} = E_d + E_{n1}$$

$$E_{n1} = \frac{m_n}{2} \times \frac{d^2}{TOF^2}$$

$$cos^2\theta_{n1} = \frac{E_{n1}}{E_{n0}}$$

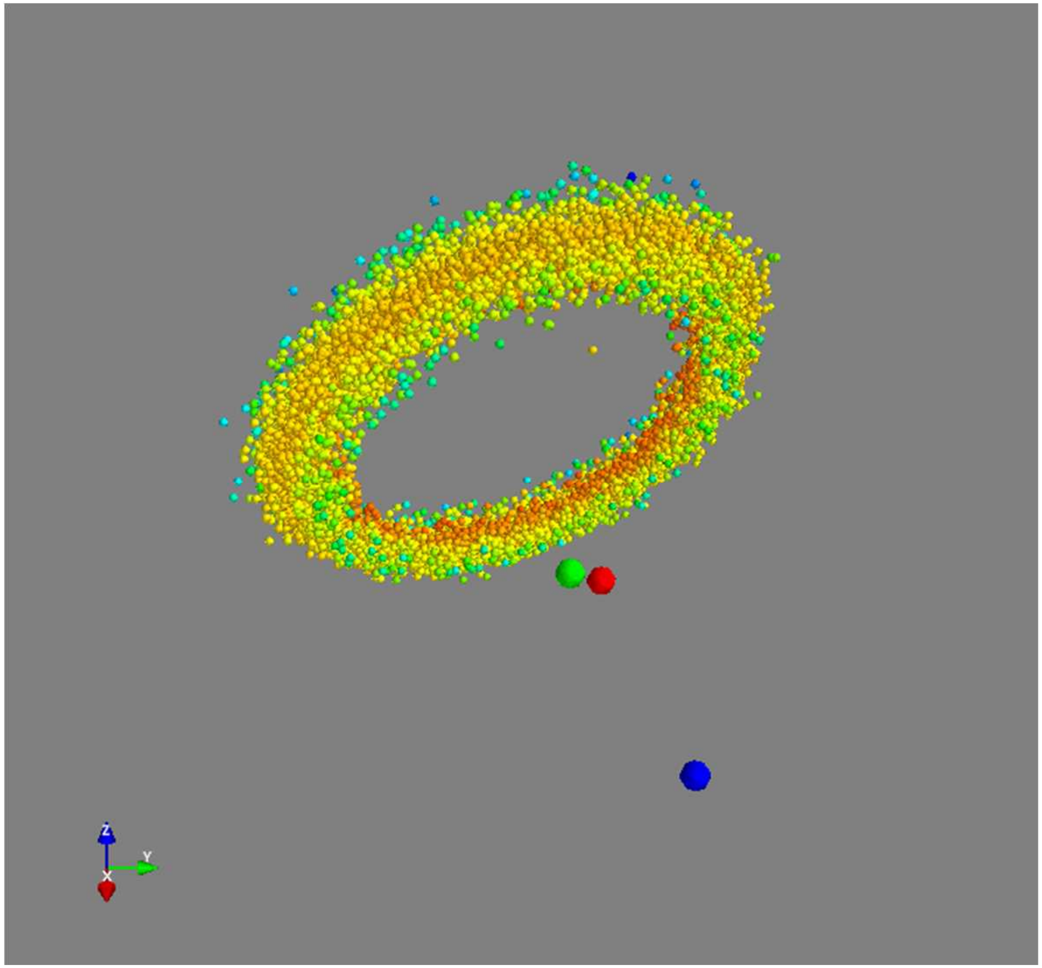


$$\Delta t_{n-\gamma} = \frac{R}{v_n} - \frac{R}{c} \rightarrow R = \frac{c\Delta t}{\frac{c}{v_n} - 1}$$

By combining the gamma-neutron inter-event time with a neutron double scatter, single sided 3-D reconstruction is possible!

γ-n-n 3-D reconstruction

Single correlated event backprojection



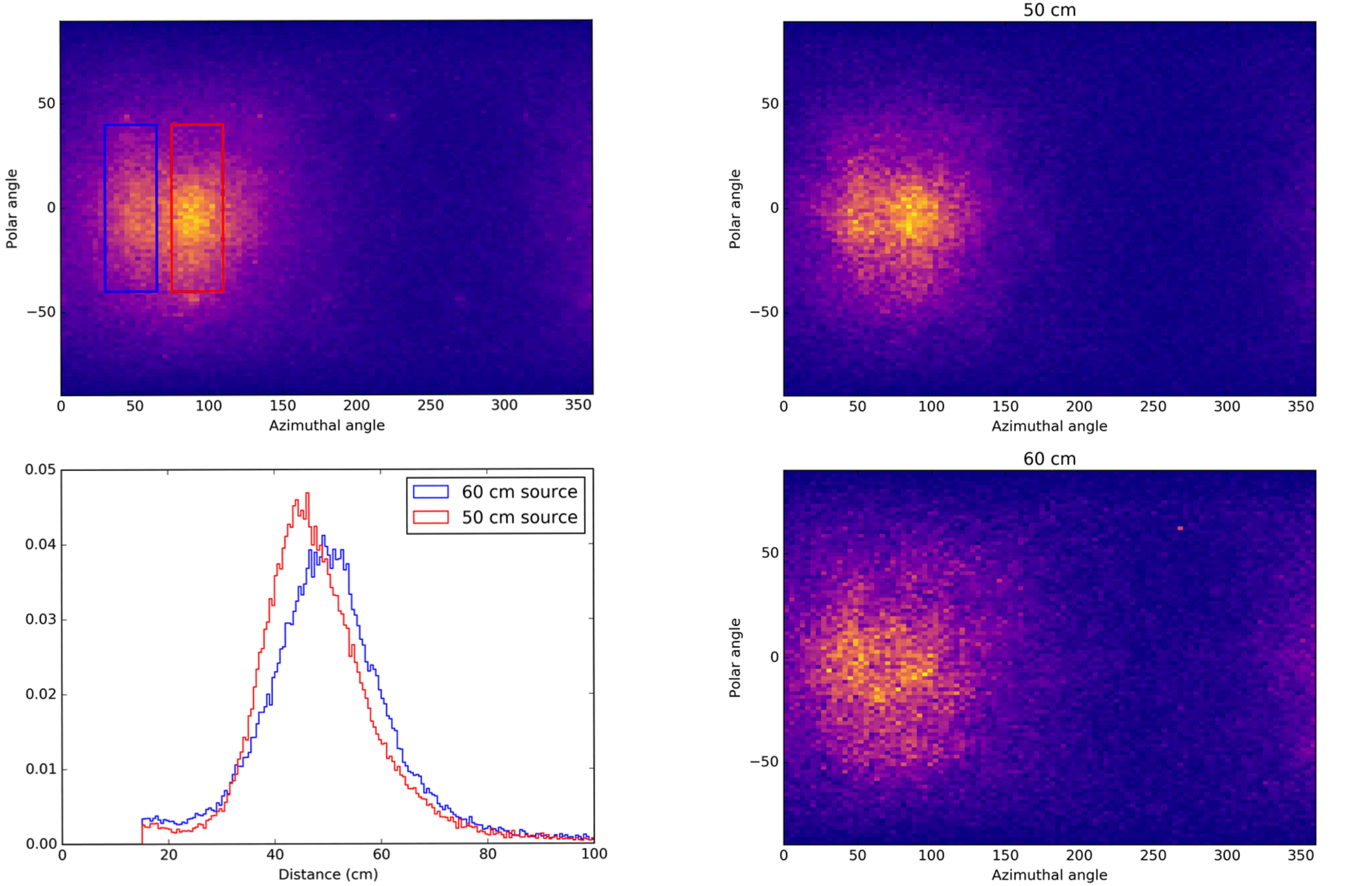
$$\cos^2\theta_{n1} = \frac{E_{n1}}{E_{n0}}$$

+

$$R = \frac{c\Delta t}{\frac{c}{v_n} - 1}$$

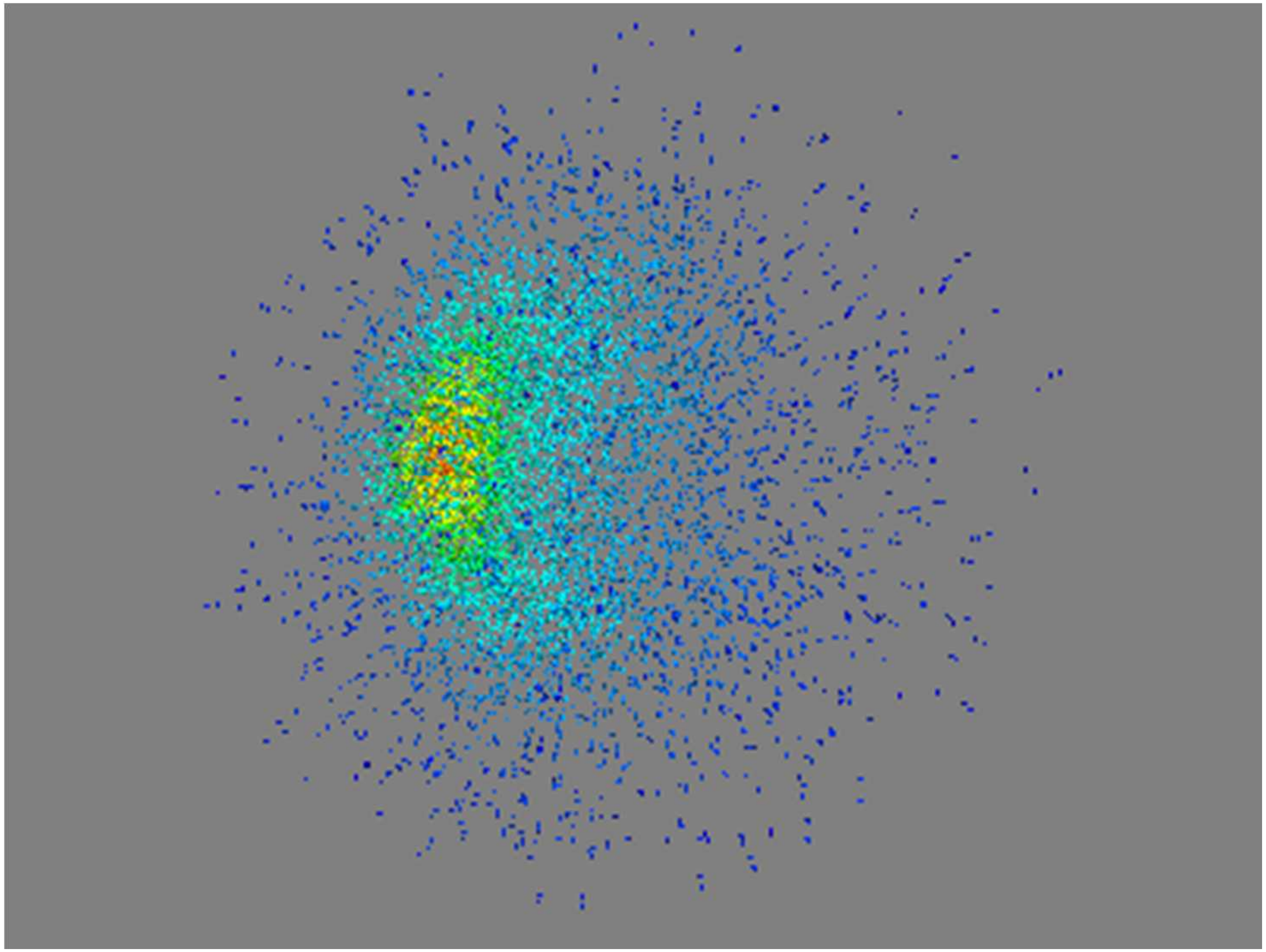
γ-n-n 3-D reconstruction

Prelim results (backprojection), Cf-252 at 50 & 60 cm



γ-n-n 3-D reconstruction

Stochastic Origin Ensemble Reconstruction
(~10,000 events with MINER, Cf-252 at 50cm and 60 cm)



$$cos^2\theta_{n1} = \frac{E_{n1}}{E_{n0}}$$

+

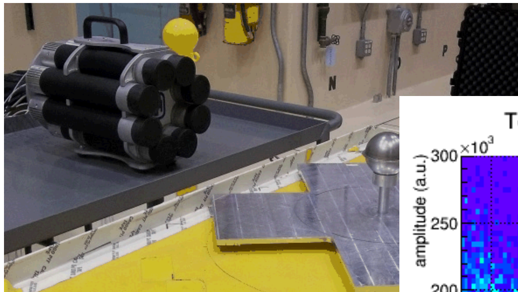
$$R = \frac{c\Delta t}{\frac{c}{v_n} - 1}$$

Some topics for collaborative efforts

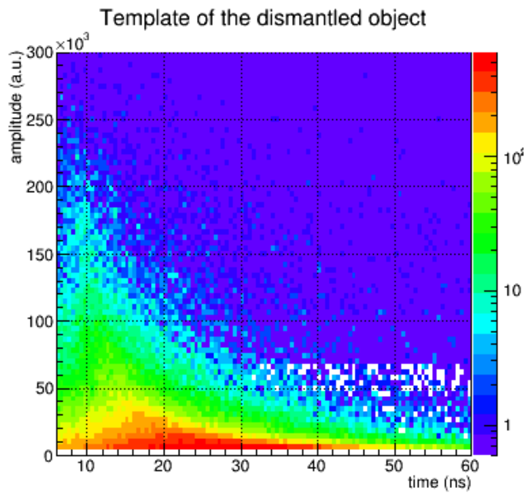
- Studies using correlated event timing have shown promise, but more work is needed to make them useful to the mission space.
  - Hardware development:
    - Optimization of organic scintillator-based detectors for fast timing + PSD (SiPMs?).
    - Optimization for combined correlated timing + imaging.
  - Algorithm development:
    - Combined neutron multiplicity counter + fast timing to break ambiguities in solution space.
    - Quantitative analysis – catching up with multiplicity and moving beyond emperical.
    - Improved single-view 3-D reconstruction.
  - Joint technology demonstrations:
    - Existing detection systems have measured SNM at the DAF, but not yet participated in Emergency Response relevant activities.

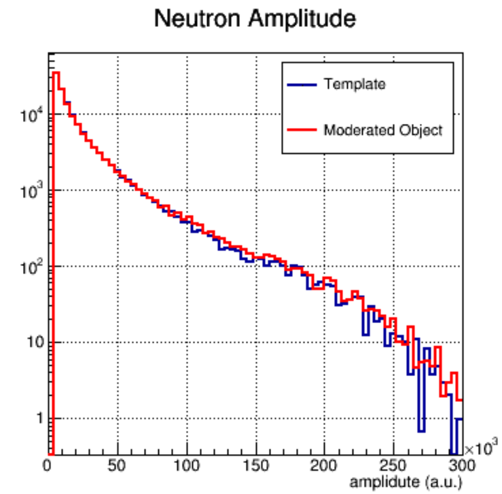
Additional material

BeRP ball (bare vs.moderated): Ignoring rate differences



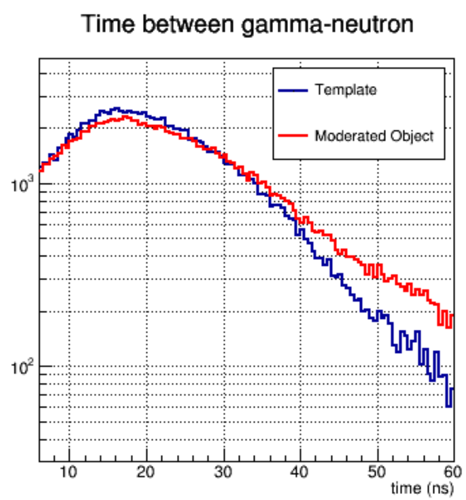
Bare BeRP ball

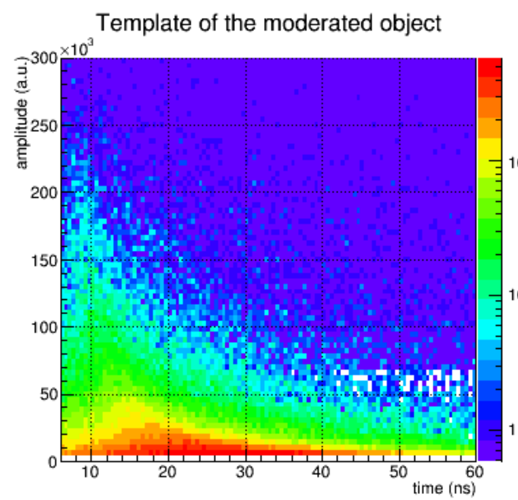




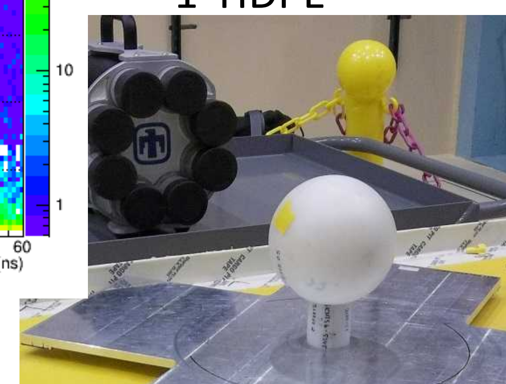
Total rate of valid events for:

- Template - 74.3 Hz
- Moderated object - 97.8 Hz

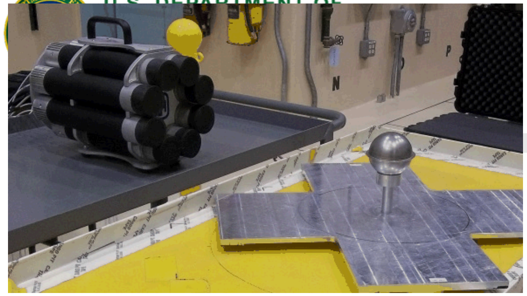


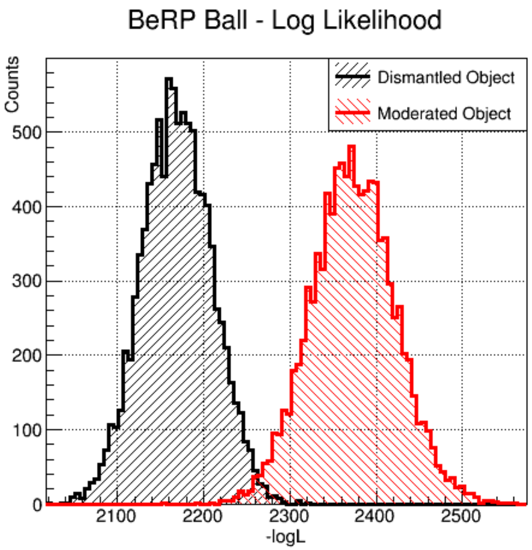


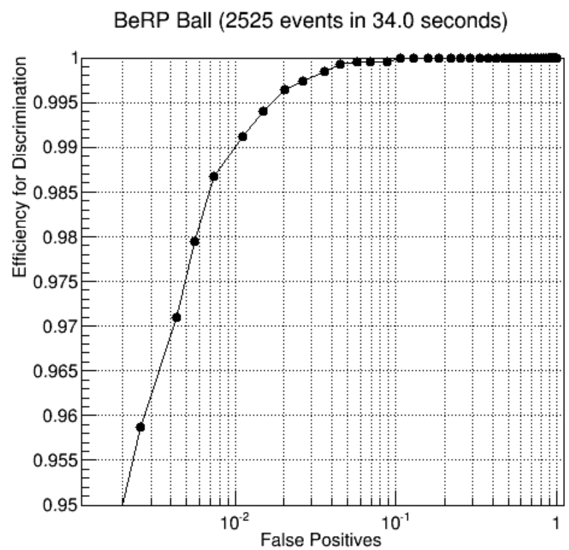
BeRP ball + 1"HDPE

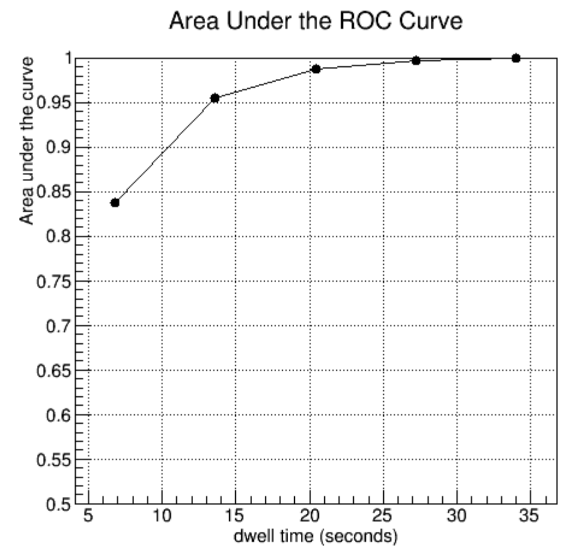


BeRP ball (bare vs.moderated): Ignoring rate differences



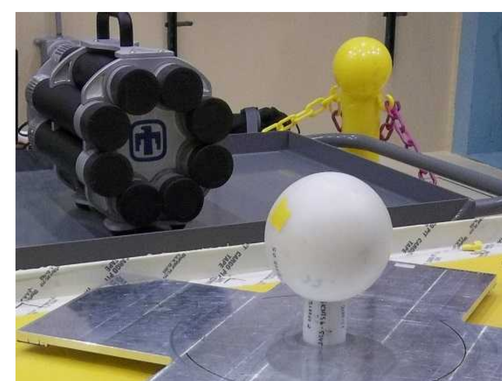






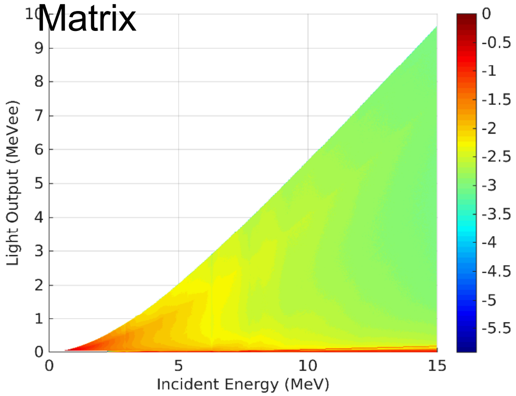
Using a log likelihood template metric:

- 99% discrimination efficiency
- 1% false positives
- In 34 seconds of dwell time.

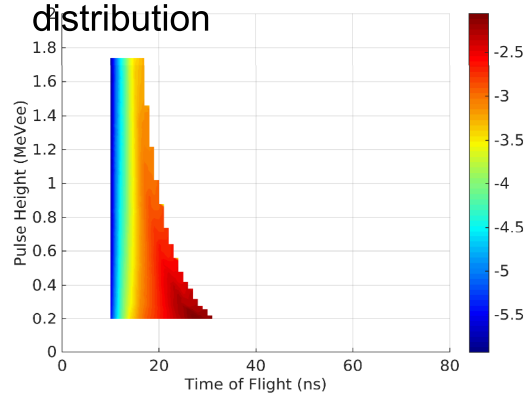


Building analytical model, gamma distribution and Monte Carlo justification

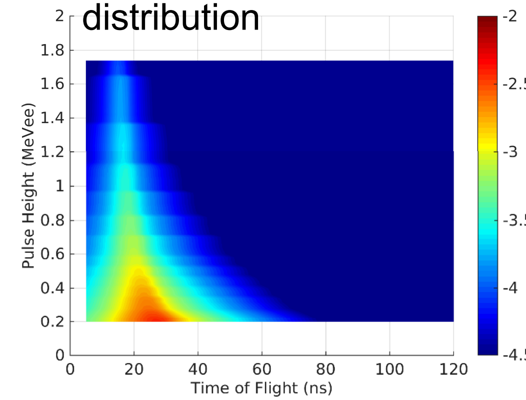
3x3 EJ-309 Response Matrix

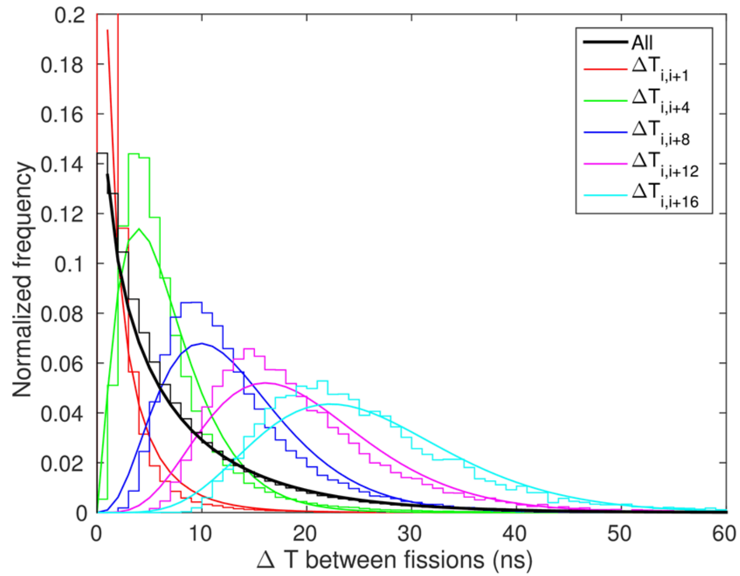


Same fission TCPH distribution

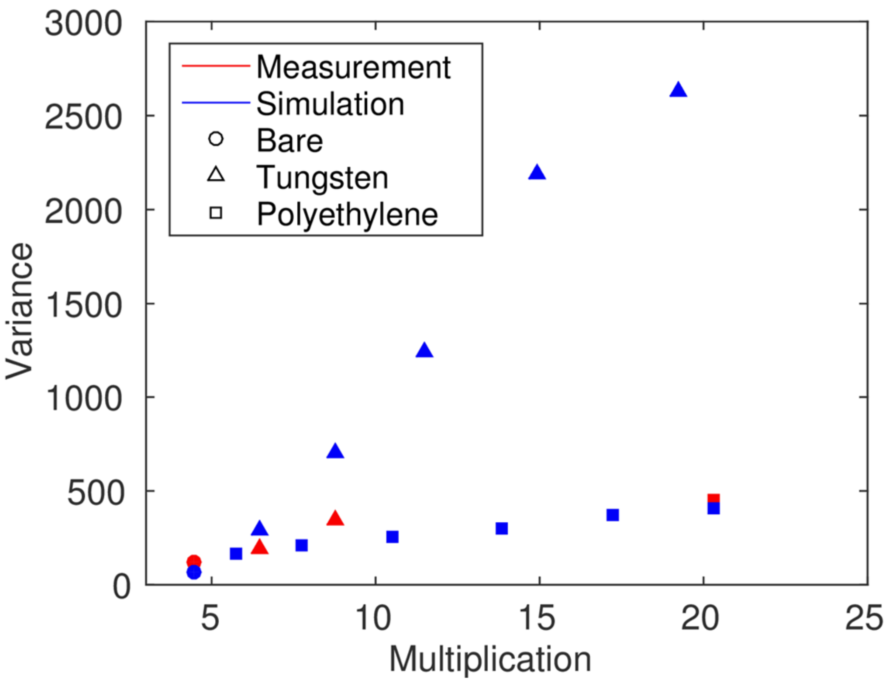


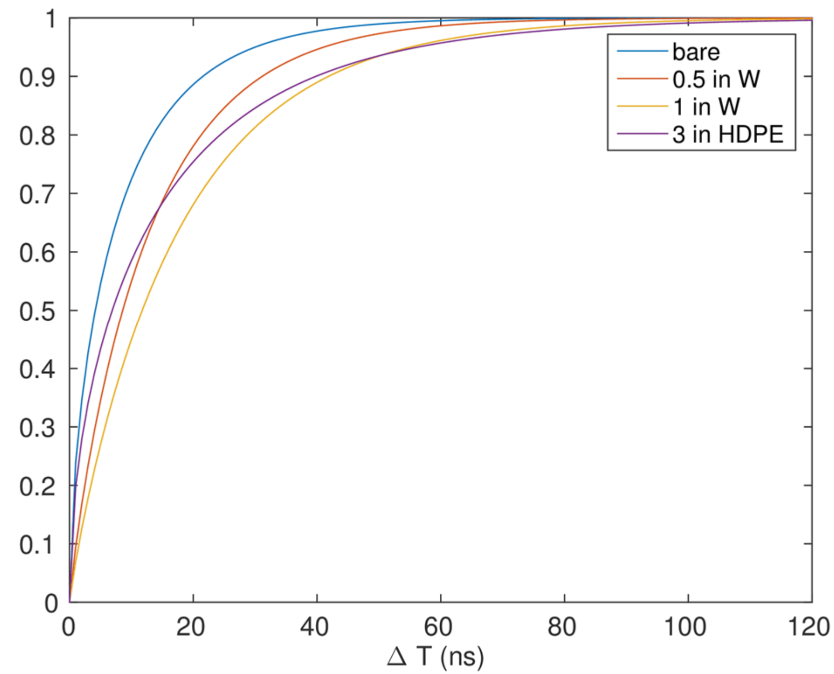
Spread TCPH distribution





Trends gamma distribution parameters





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