SAND2011-3032C

Fast Neutron Detection with a Neutron Scatter Camera

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LENS / CMP Joint Nuclear Physics Seminar

Indiana University, Bloomington, IN

May 6th, 2011

This work has been funded by

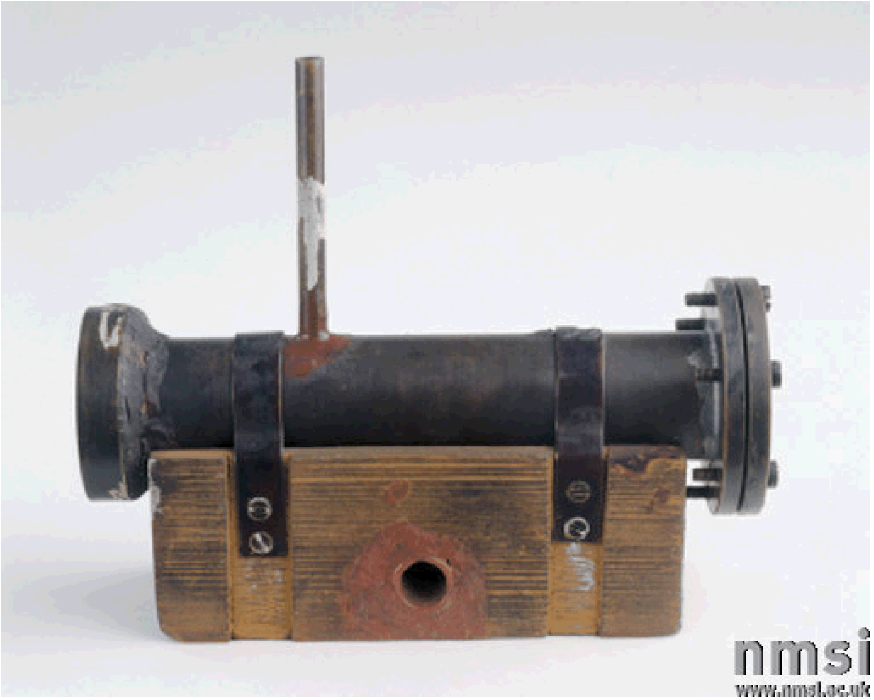
NA-221
DTRA RD-NTDL
Sandia LDRD

Motivation

- New **START** (**ST**rategic **A**rms **R**eduction **T**reaty)
  - Provisions for warhead counting & verification
  - Neutron detection included as radiation detector
  - Warhead counting
- Special Nuclear Material (SNM) detection
  - Border and cargo portal monitoring
  - Large stand-off detection exercises
- Reactor safeguards
- Neutrons in fundamental physics processes?

Why Fast Neutrons?

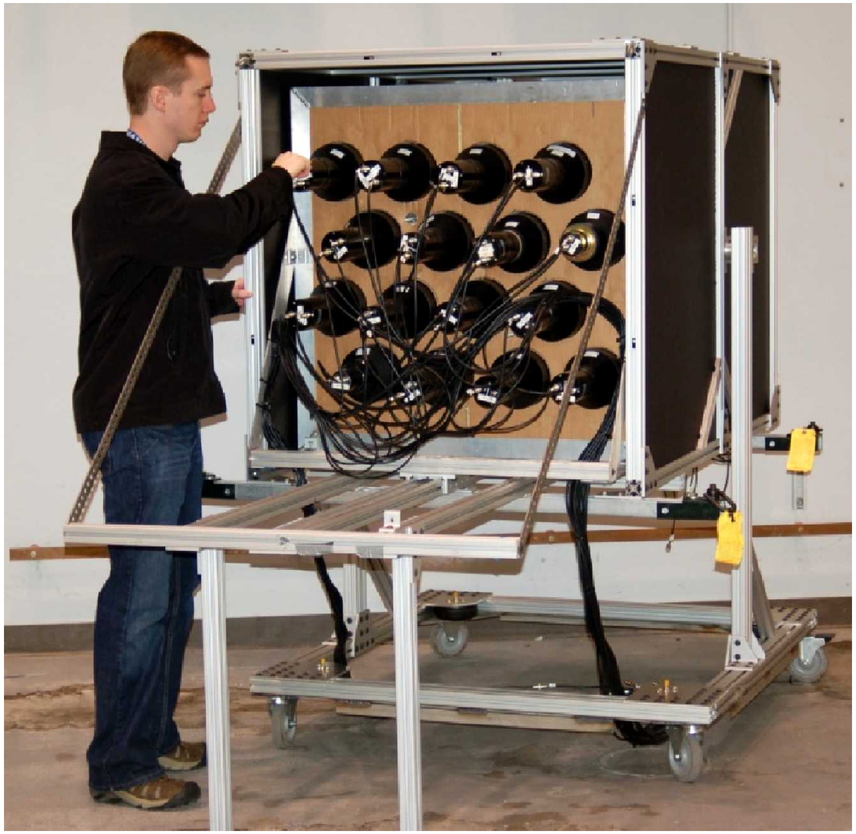
- Fast neutron penetrates
- Gammas can yield information of nearby classified materials (could violate treaty)
- Neutrons not as susceptible to this
- Long range (~100 m)
- Imaging & spectroscopy
- Replaces thermal neutron and ^{3}He tubes



Chadwick's neutron generator: Polonium alpha source striking Beryllium target

Neutron Scatter Camera

- Multi-element, 2-plane
- 0.5 – 10 MeV neutrons
- Eljen EJ-309 liquid scintillator cells - PMT coupled, ruggedized
- Front: 2” thick, 5” diam.
  - single scatters
- Rear: 5” thick, 5” diam.
  - efficient tagging
- Plane spacing variable



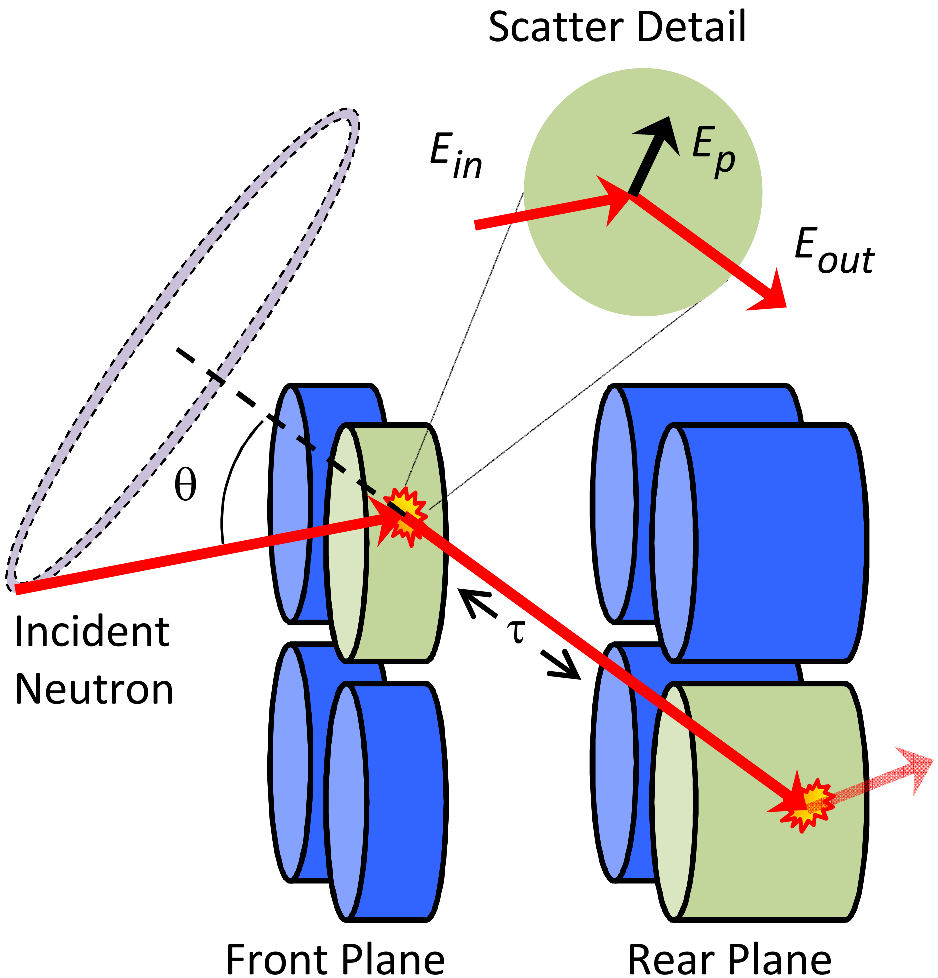
Principle of Operation

- Neutron elastic scatter on hydrogen

$$E_{in} = E_p + E_{out}$$

$$\frac{E_{out}}{E_{in}} = \sin^2 \theta$$

- Measure E_p and E_{out}
- E_{out} from TOF τ
- Can reconstruct E_{in} and position (to within a cone)



Energy Calibrations

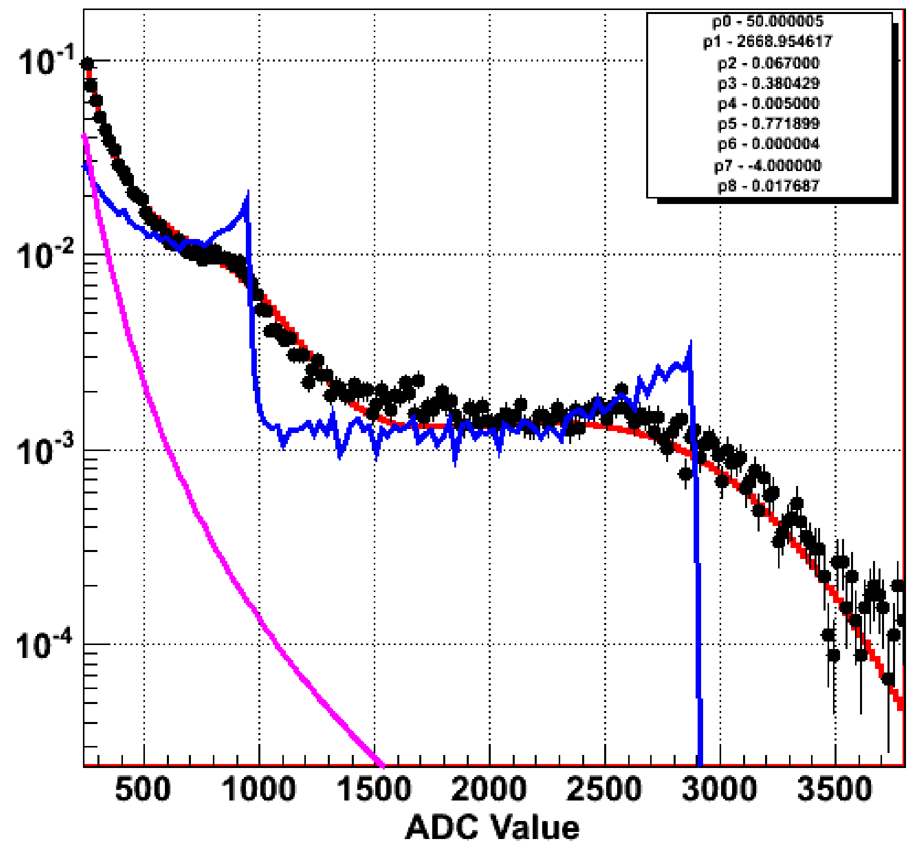
- MCNP-PoliMi generates ^{22}Na MC spectrum (--)
- Gain/offset/scale MC
- Gaussian resolution*

$$\Delta L/L = \sqrt{\alpha^2 + \beta^2/E + \gamma^2/E^2}$$

- Final MC (--)
- Power-law background

$$C(x + x_0)^n \quad (--)$$

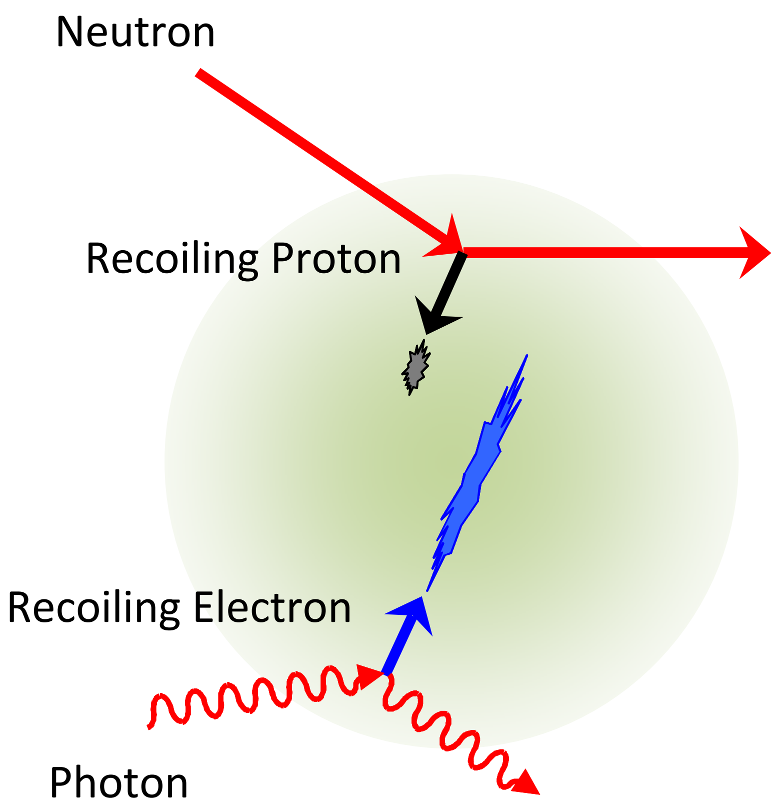
- Minuit fit to data (•)



* Dietz and Klein, Nucl. Instrum. Meth. vol. 193 (1982) pp. 549-556.

Pulse Shape Discrimination (PSD)

- Recoil proton dE/dx is much greater than electrons
- Shorter range for ion pair creation
- Liquid allows ion recombination
- Protons quenched
- Scintillation pulse shape in time differs for *e*, *p*



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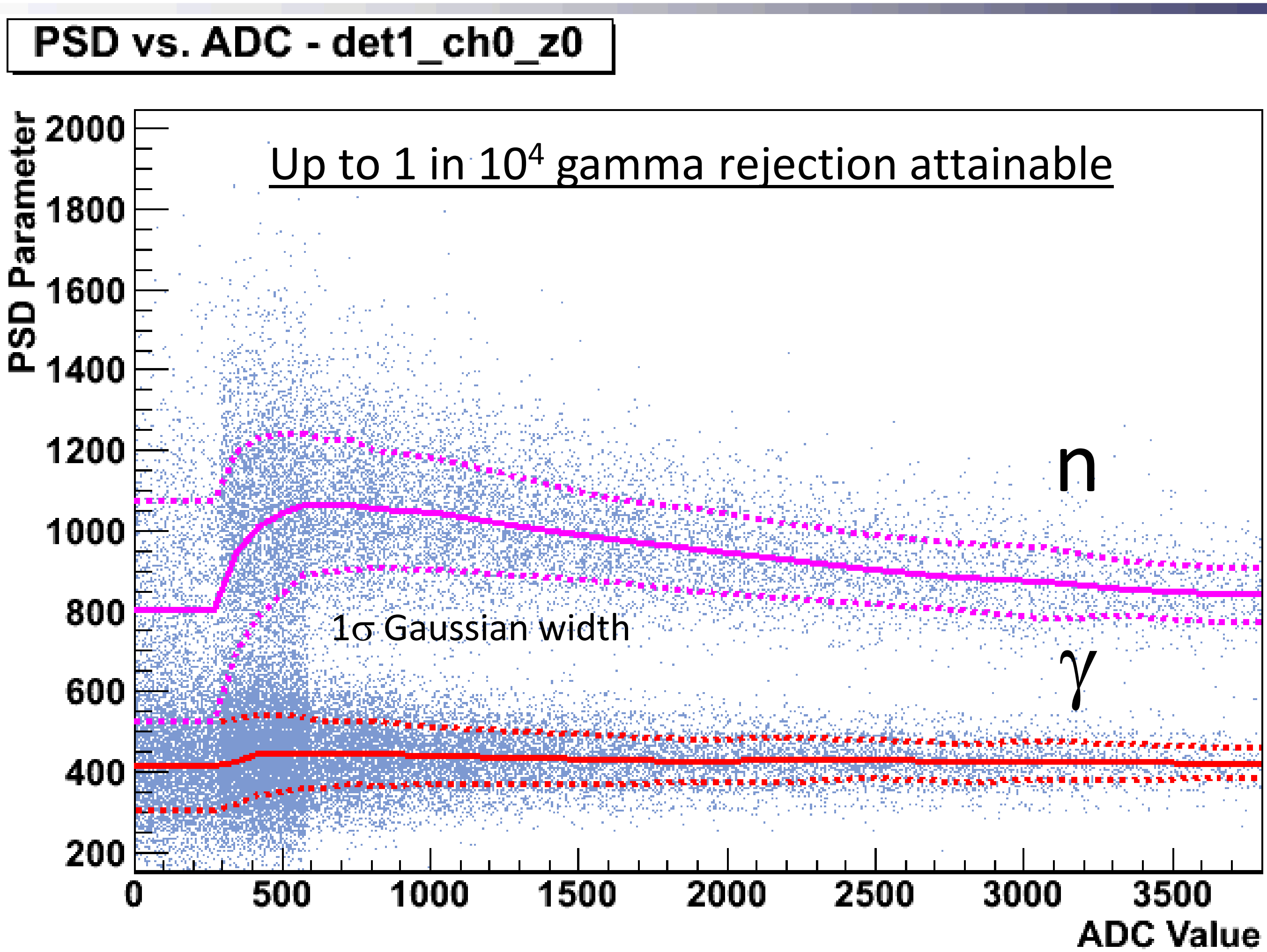
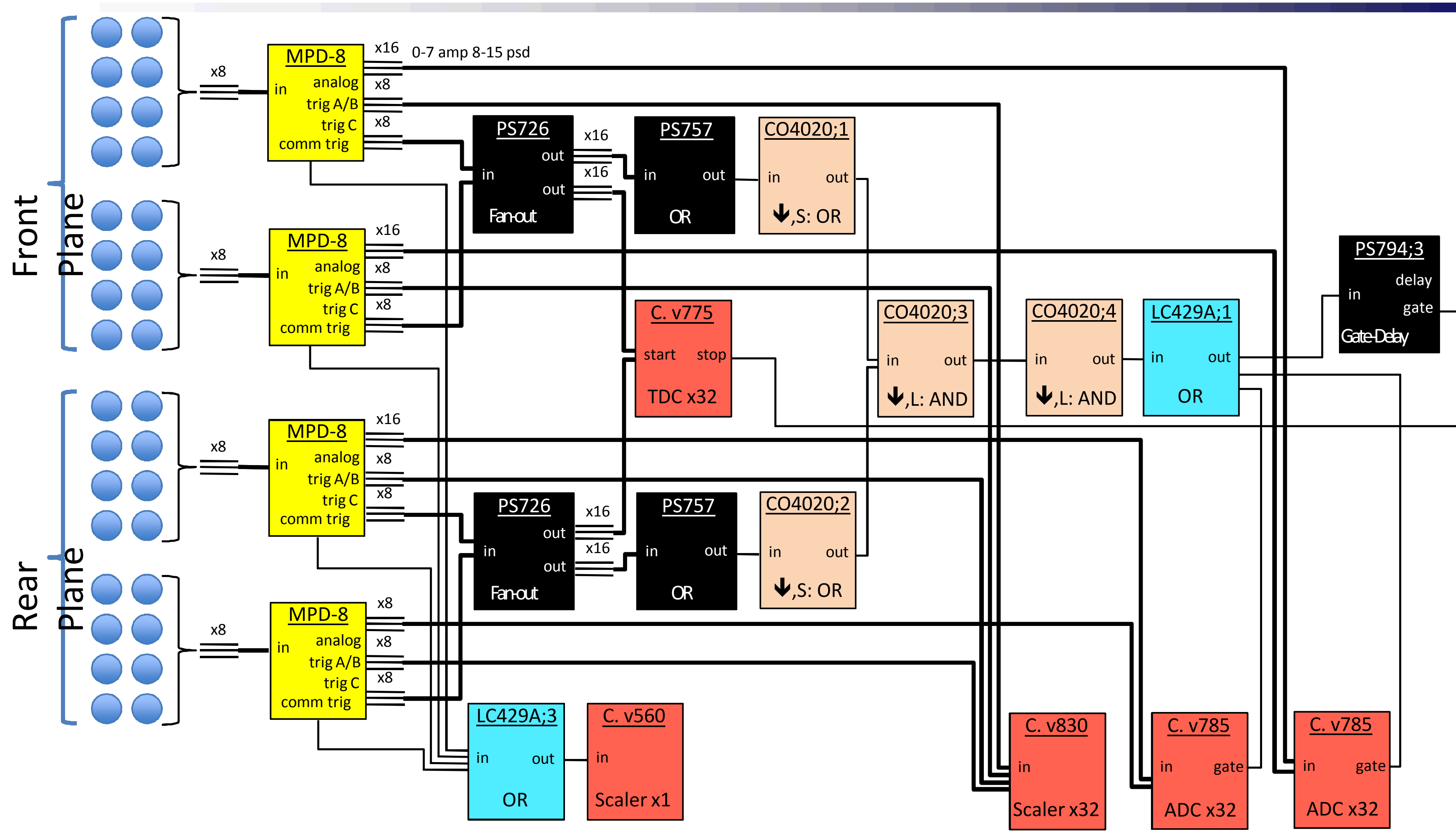
PSD Calibrations



DAQ (VME & NIM to PC)



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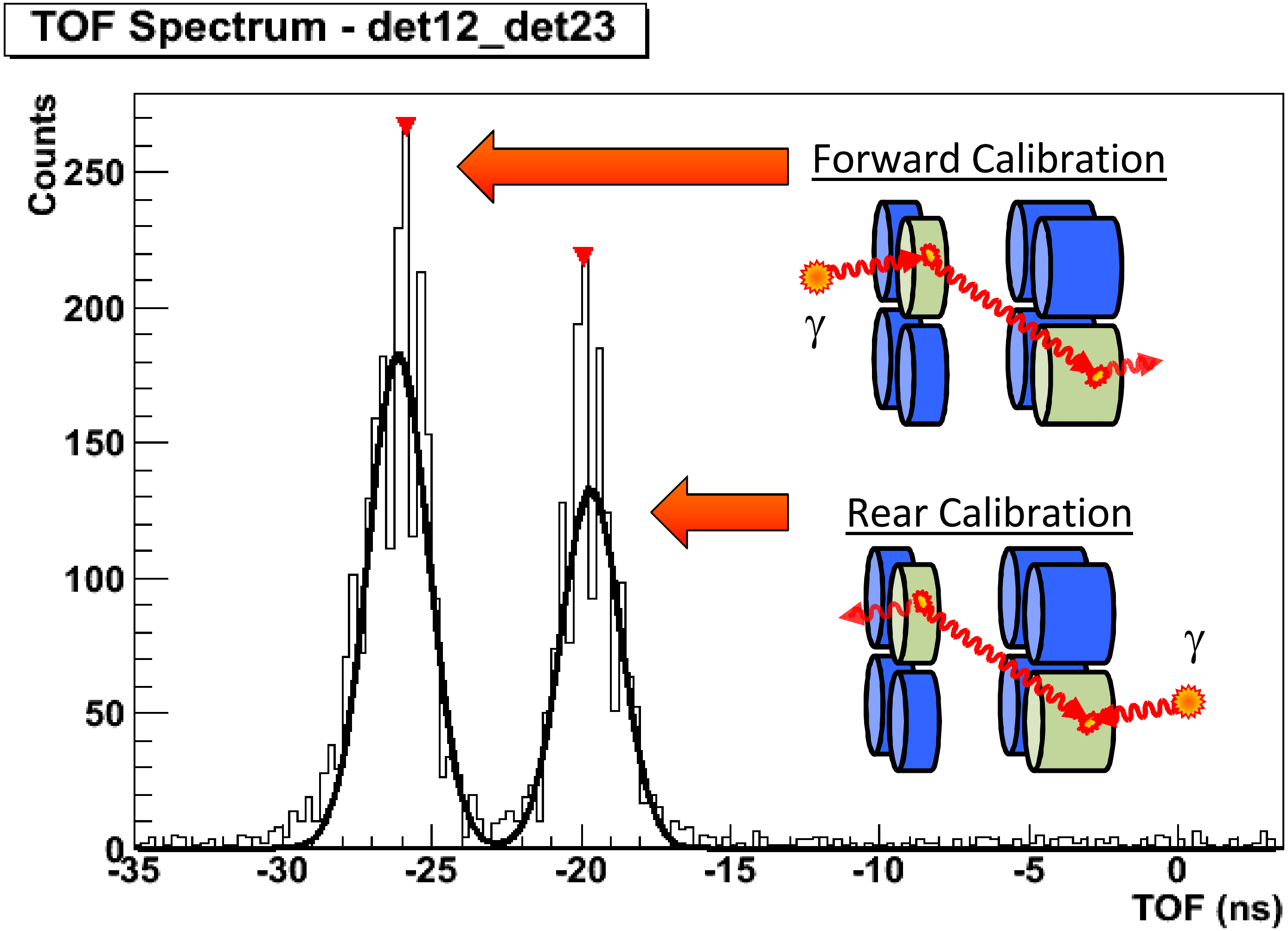
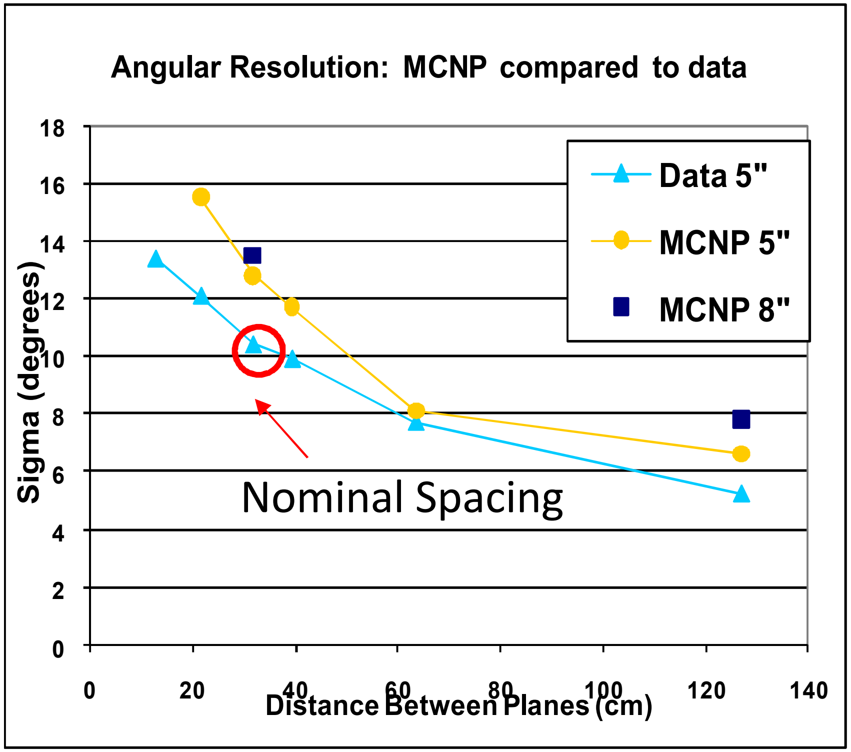
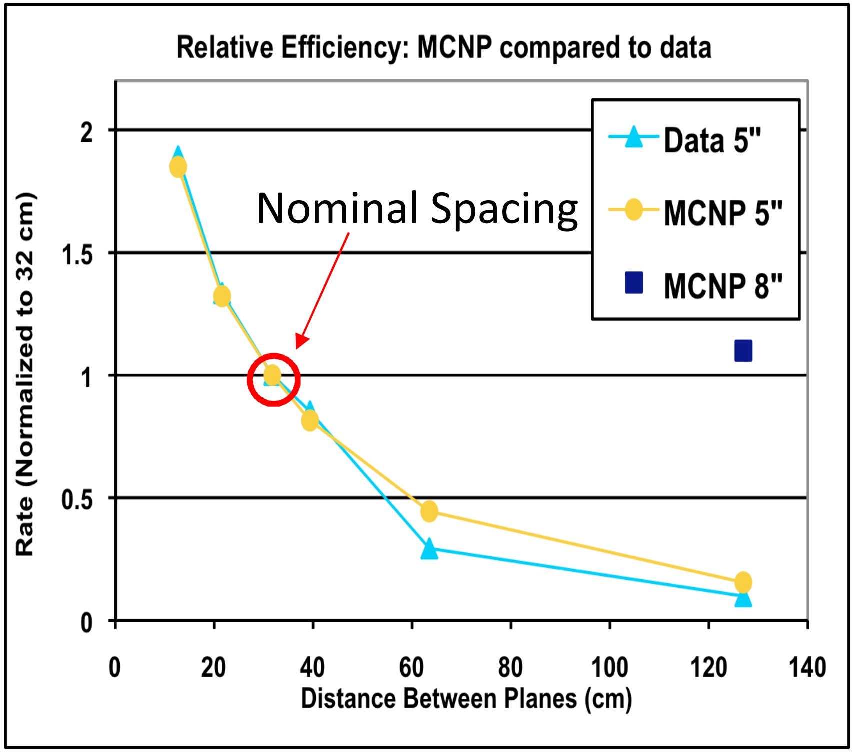
TOF Calibrations



Performance *vs.* Plane Spacing

- Angular resolution improves and detection efficiency decreases with increasing plane spacing





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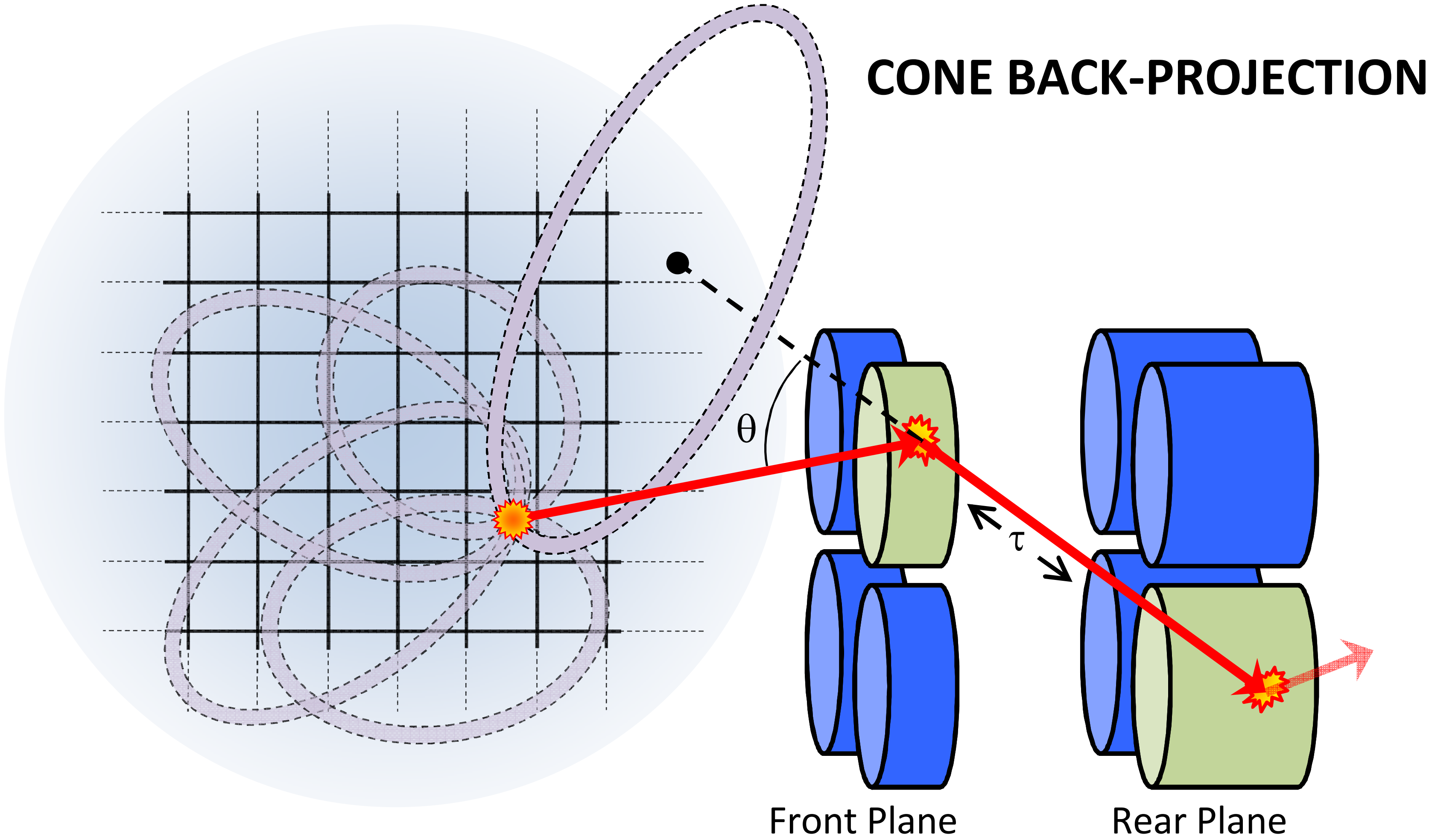
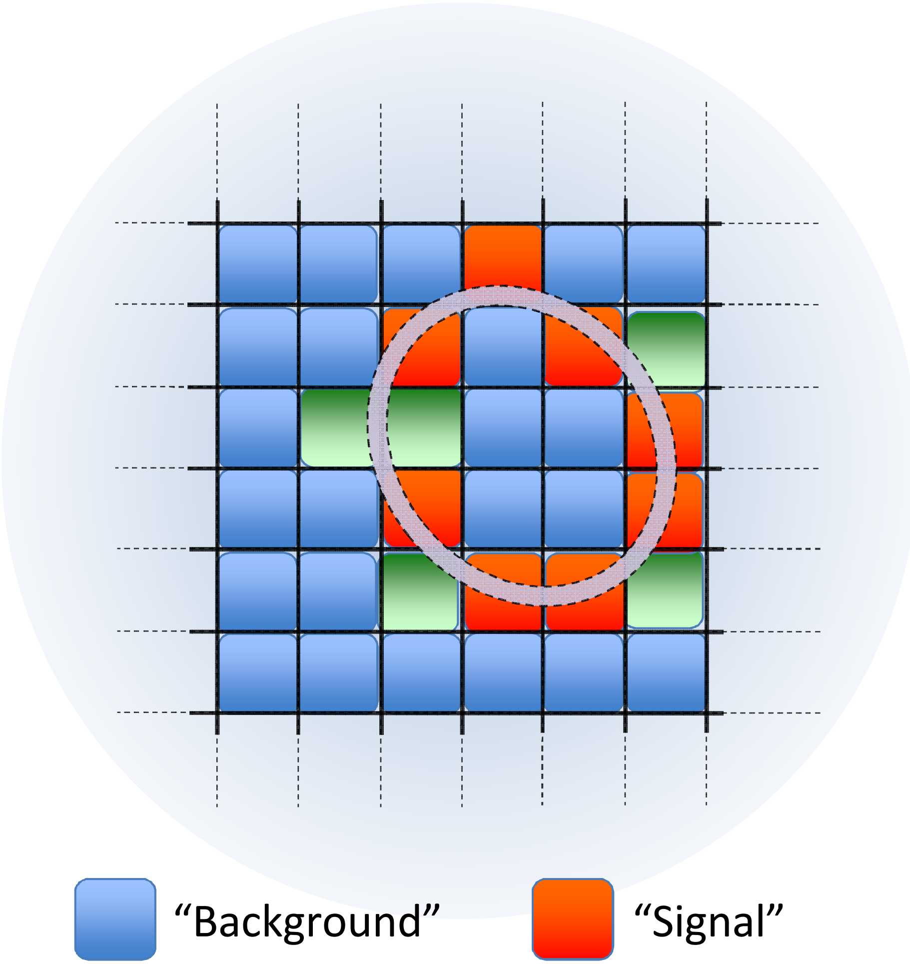
Imaging Techniques



Imaging Techniques

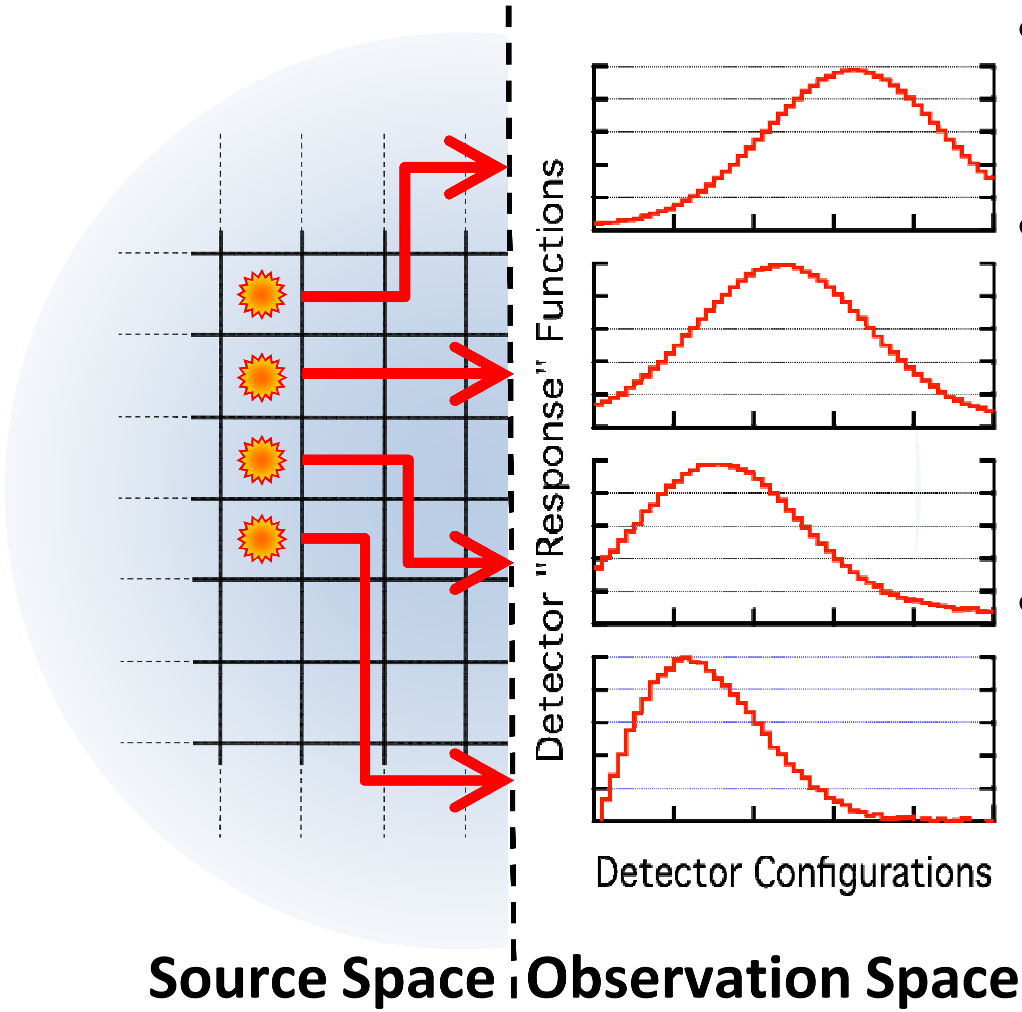


DECODE METHOD

- Similar to back-projection
- For each “cone” the areas outside of the cone are “background”
- Adding cones introductions “signal” and “background” summing
- Flattens non-signal response

L. A. Shepp and Y. Vardi IEEE Transactions on Medical Imaging, Vol. MI-1, No. 2, October 1982

Maximum Likelihood (MLEM)



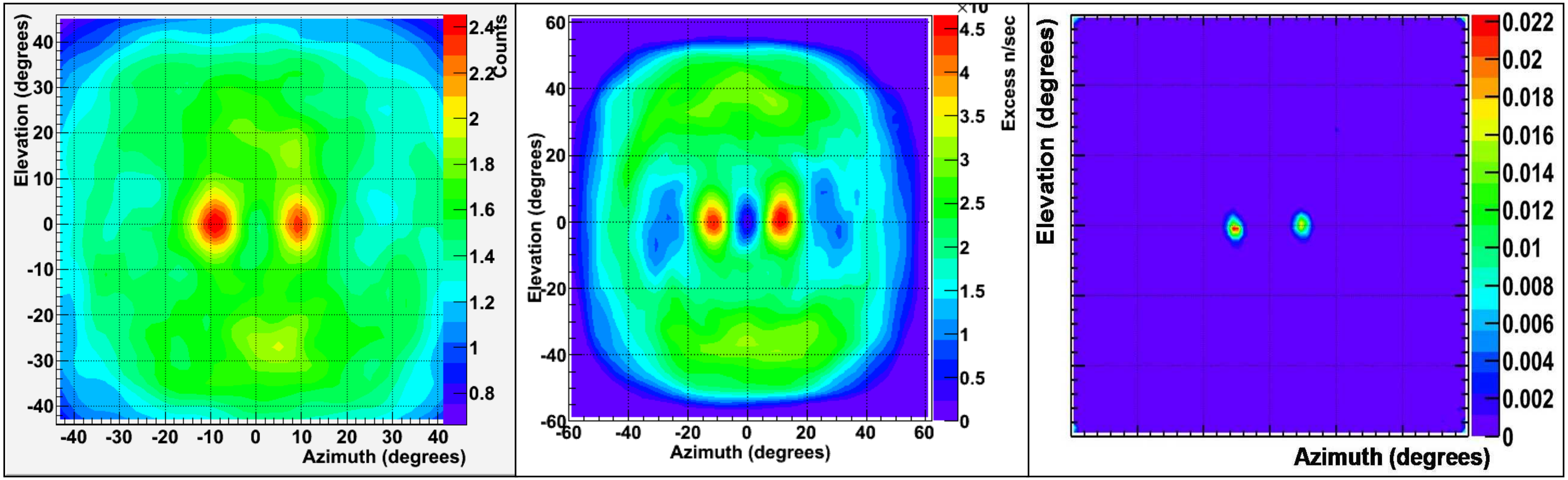
- MC useful in building this "response map"
- Spaces can be multi-dimensional $(E_{src}, \boldsymbol{x}) \rightarrow (f_i, r_i, E_{recon}, \theta, \tau \ldots)$
- Likelihood algorithm "fits" data observed to corresponding source space

L. A. Shepp and Y. Vardi IEEE Transactions on Medical Imaging, Vol. MI-1, No. 2, October 1982

Imaging Method Evolution

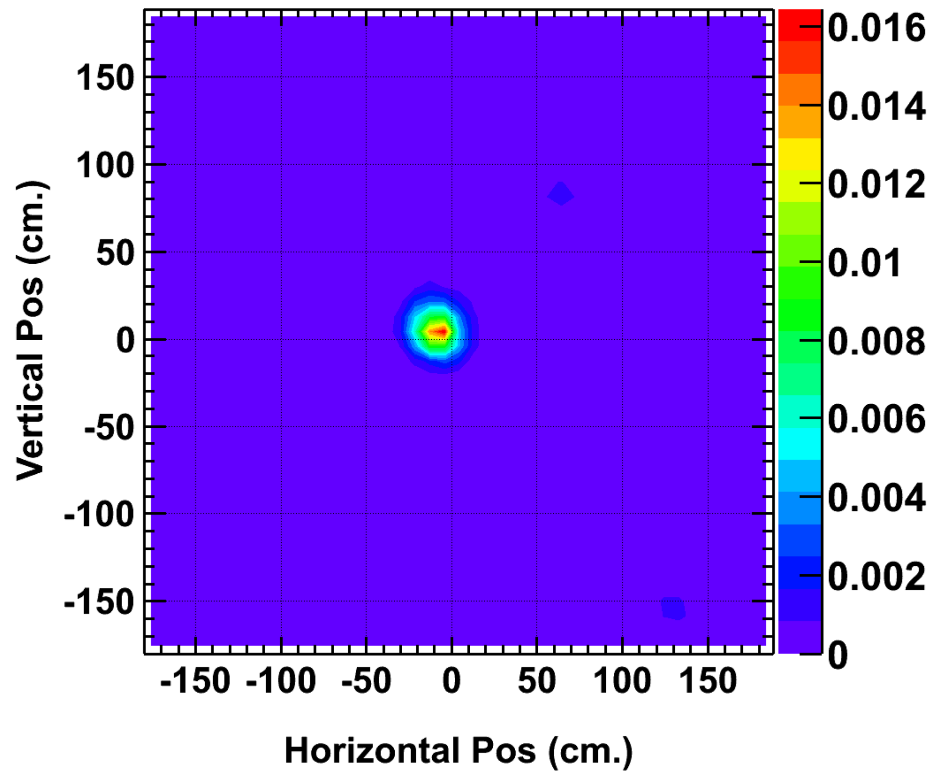
- Plane separation large for angular resolution
- "Response" is difficult to discern
- MLEM identifies source locations very well
- Simulation essential to build response maps

Cone Back-projection | "Decode" Method | MLEM Reconstruction



MLEM Subtleties

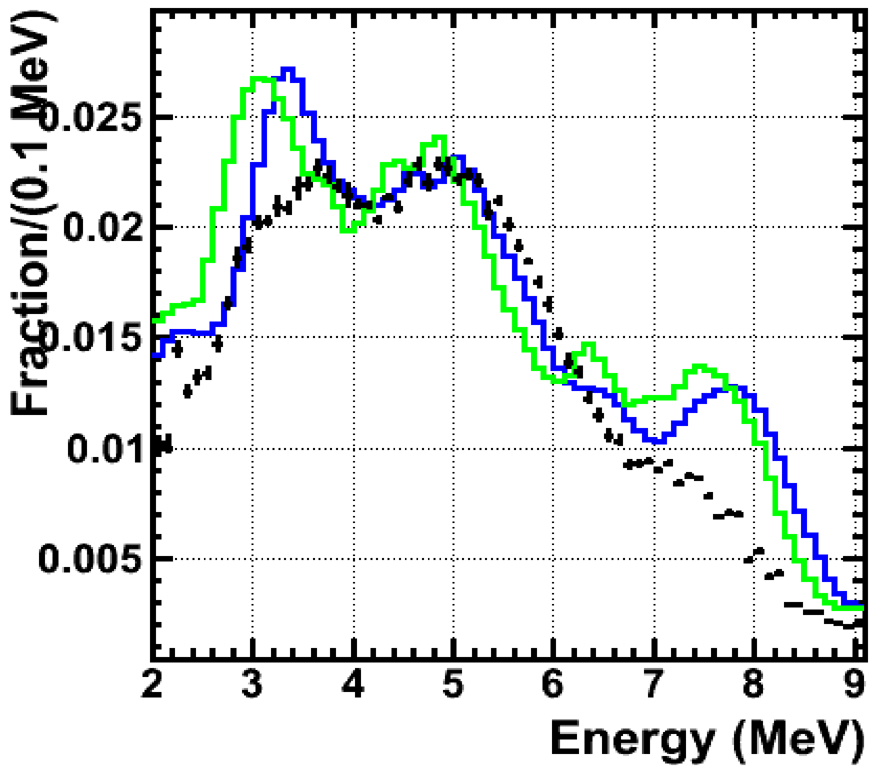
- Can't iterate indefinitely
- Artifacts appear from noise and statistical fluctuations in data
- Stopping criterion can be arbitrary?
- Regularization of response (smoothness)
- Response maps via MC is time consuming



APPLICATION STUDIES

Energy Spectroscopy

- NSC an imager, but E_{in} is also reconstructed
- (α, n) reactions have structure spontaneous fission sources do not
- AmBe: ^{241}Am α–emitter (~5 MeV); $^{9}Be(\alpha, n)^{12}C$
- MLEM reconstructs many spectral features



Green: ISO 8529-1 (2001)

Blue: Geiger and van der Zwan, NIM 131, 315 (1975)

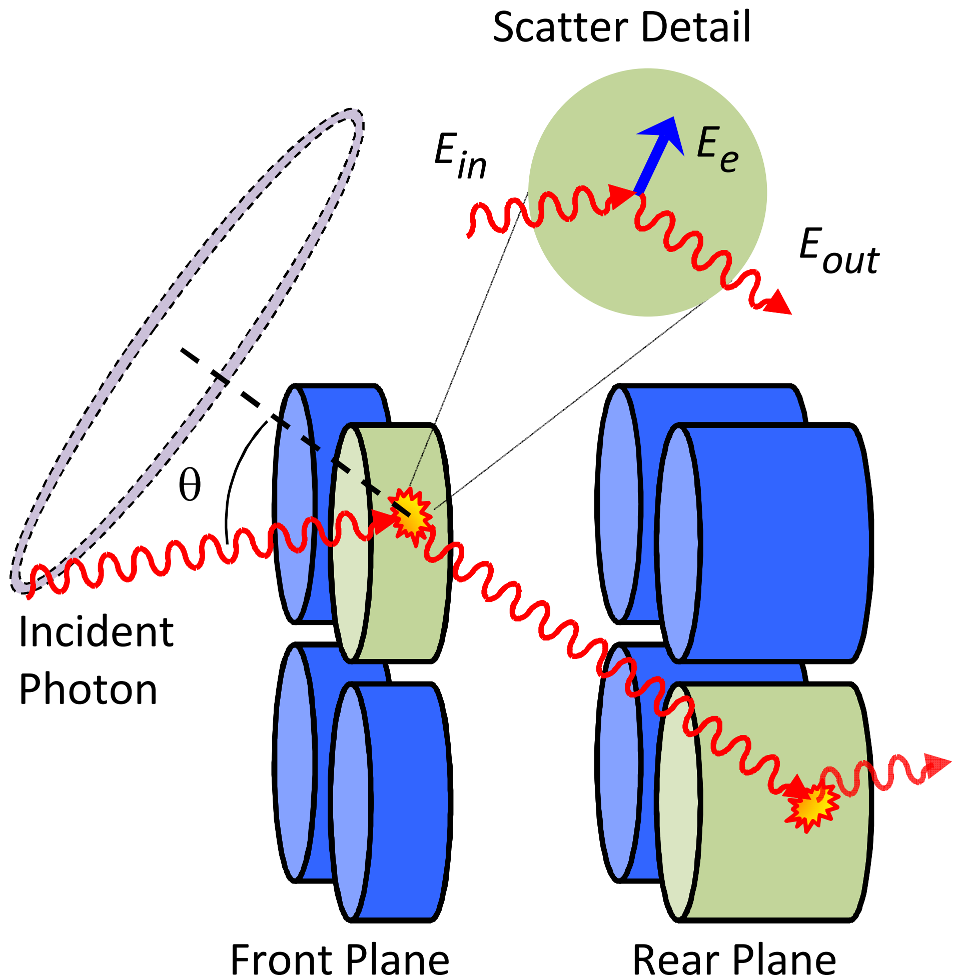
Imaging Photons

- Photons Compton scatter off electrons

$$\frac{1}{E_{out}} - \frac{1}{E_{in}} = \frac{(1-\cos\theta)}{m_e c^2}$$

- Need E_{in} because TOF is constant
  1. Assume E_{in}
  2. Calorimetric: use rear plane energy deposit E'_e

$$E_{in} = E_e + \alpha E'_e$$



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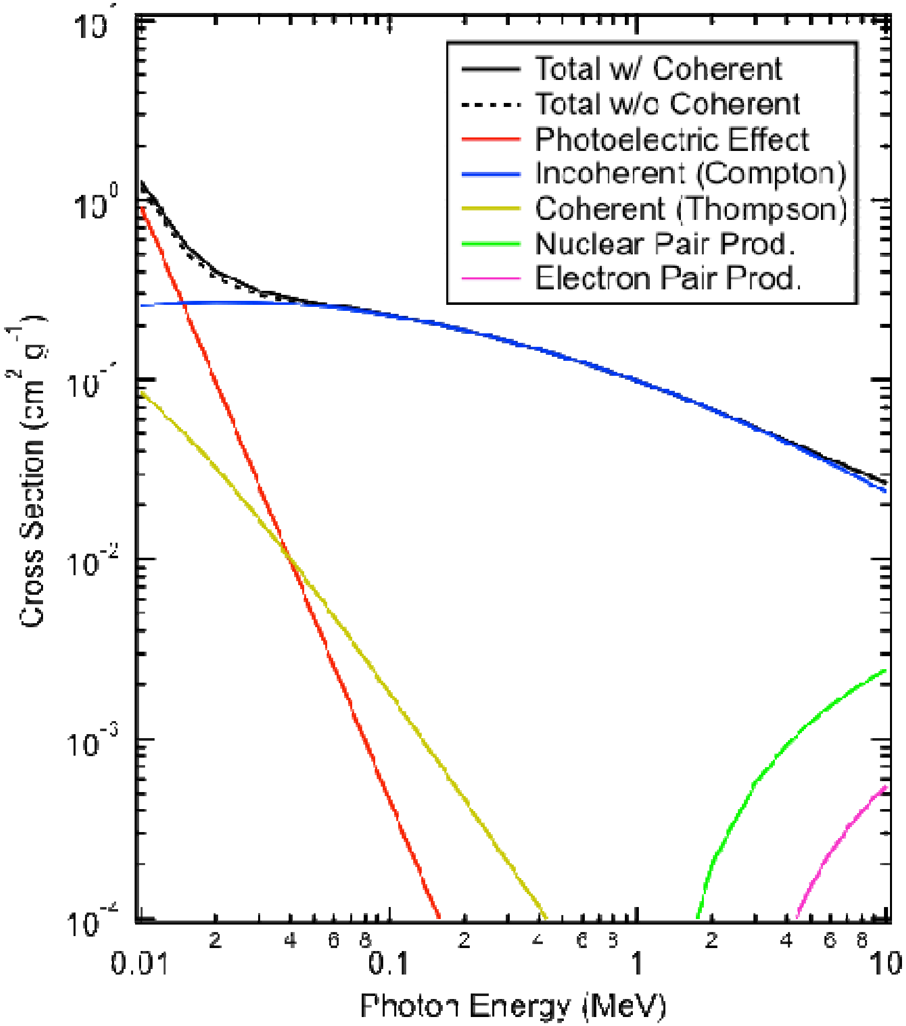
$$E_{in} = E_e + \alpha E'_e$$



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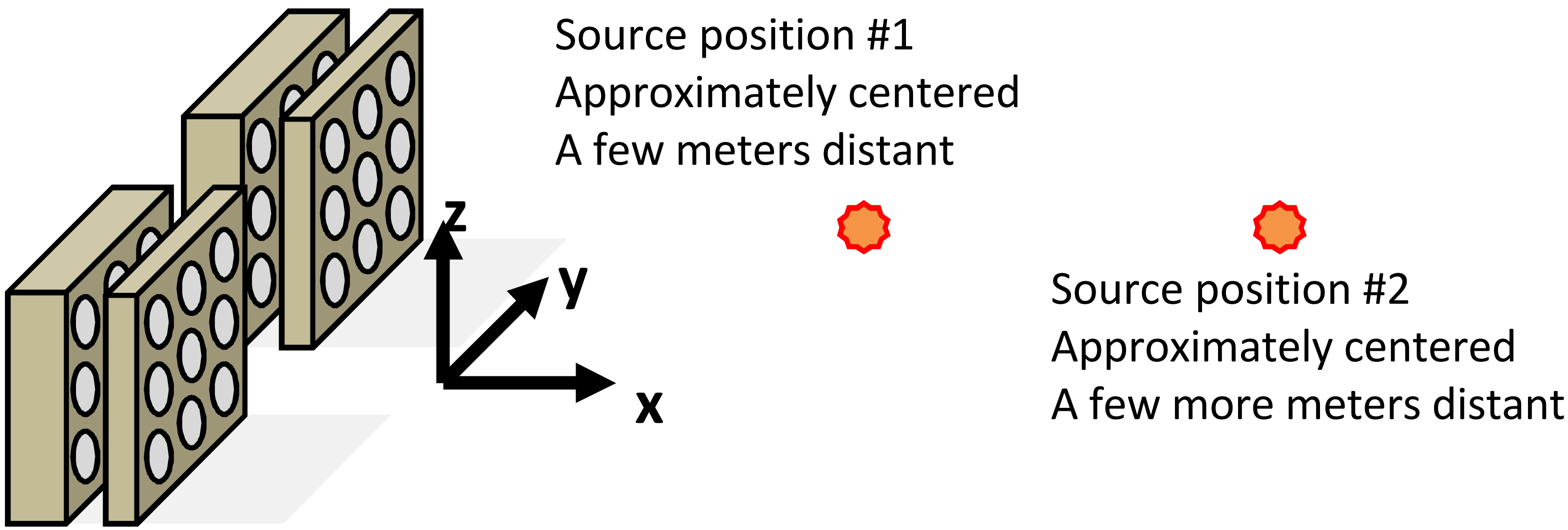
Stereo Imaging

- Two similar cameras a few meters apart (in line and roughly the same height)
- Full 3D imaging of sources?
- Neutron (^{252}Cf) and gamma (^{60}Co) sources

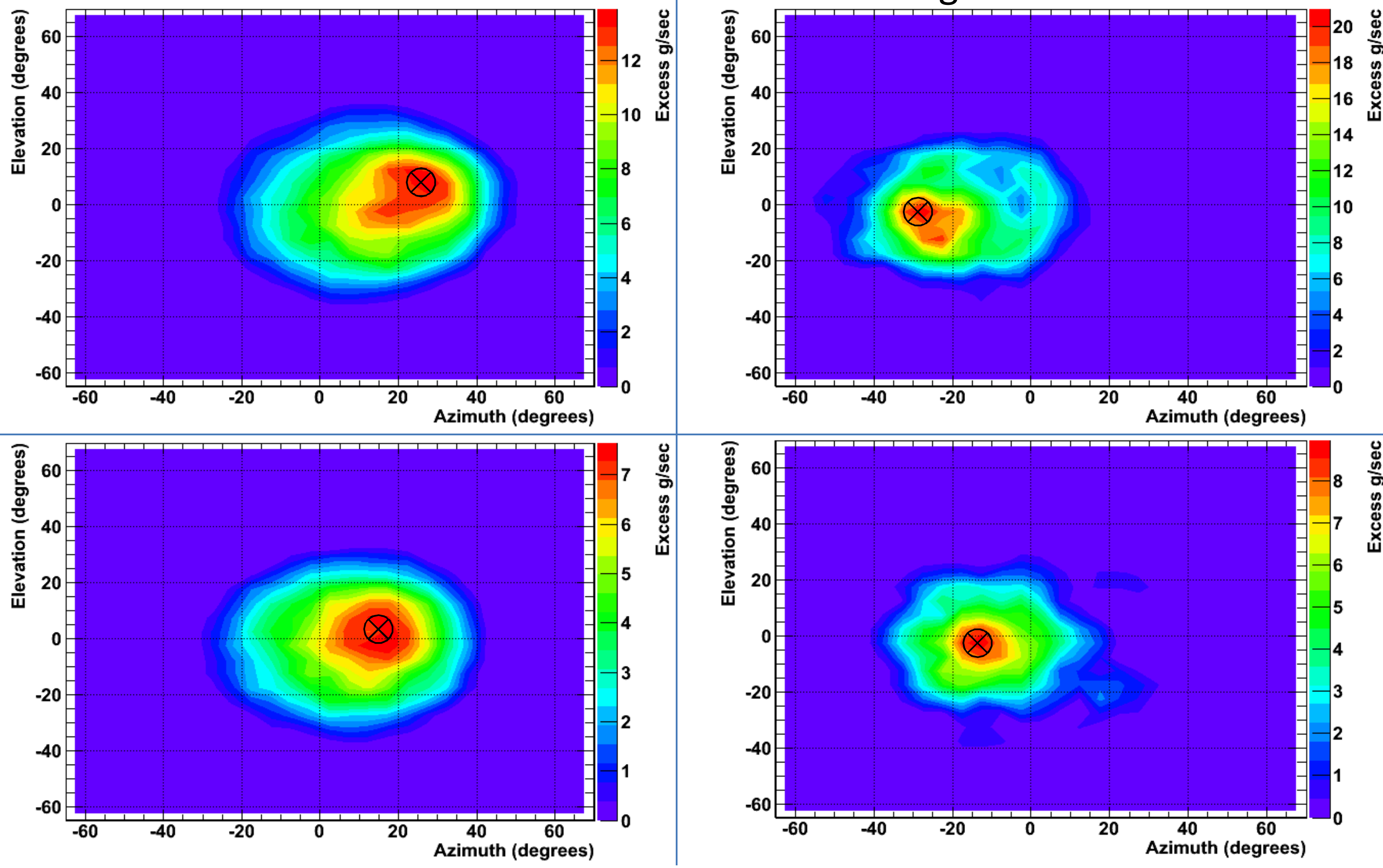


^{60}Co Stereo Images

Left Camera | Right Camera

Near Source

Far Source



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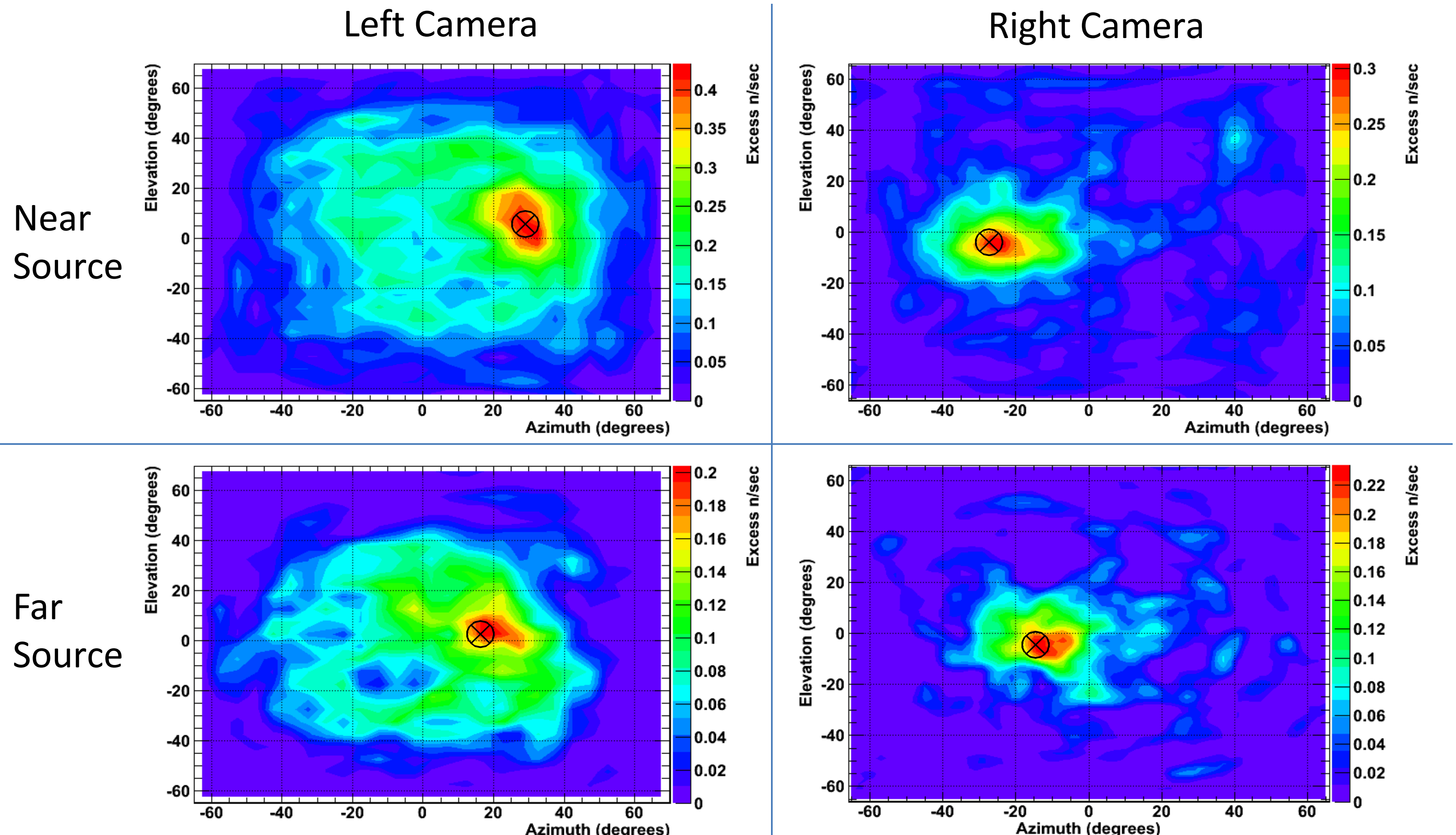
^{252}Cf Stereo Images



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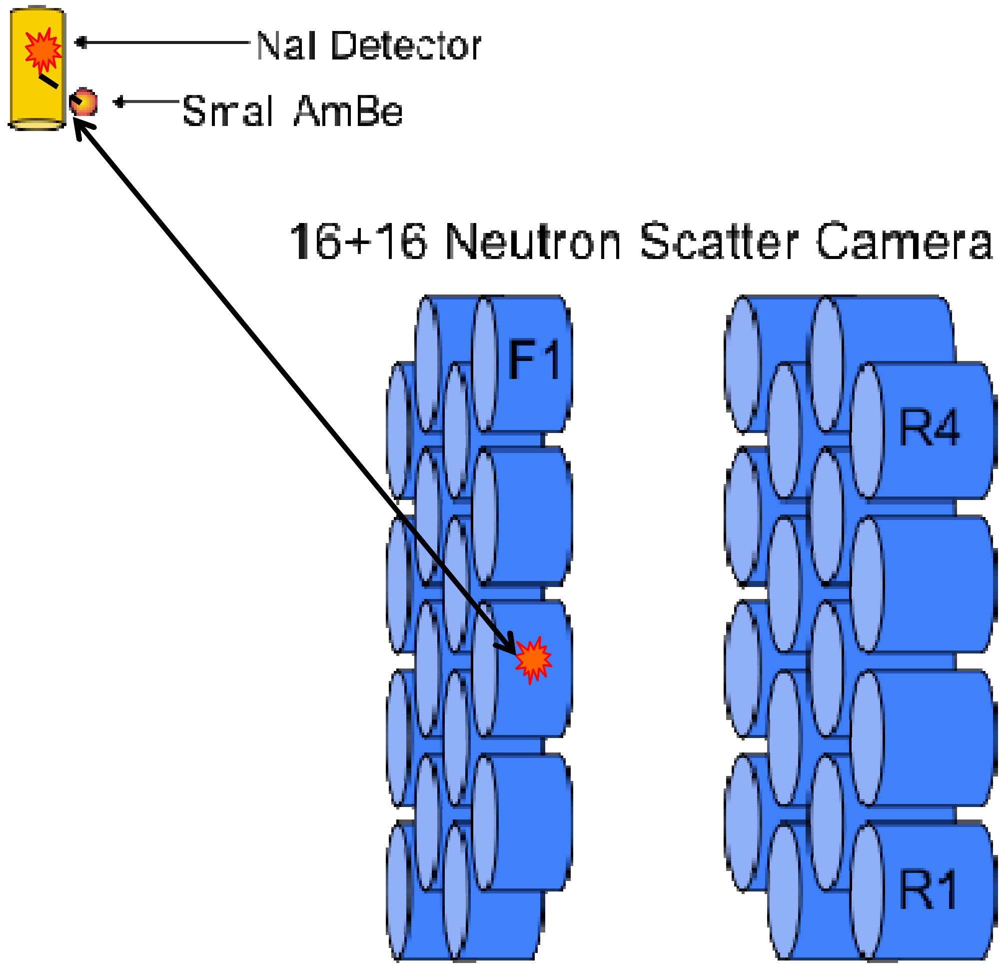
γ-Tagged, TOF n-Source

- Carbon state in AmBe can be in excited state
- 3.2 MeV, 4.4 MeV γ accompanies neutron
- TOF from γ tag gives neutron energy
- **Applications**: Light output quenching formula, radiography, etc.



Conclusions

- NSC is being used in neutron detection applications
- Neutron stand-off detection, imaging and energy spectroscopy possible
- Gamma imaging provides important expanded capabilities as well as cross checks on neutron capabilities
- Highly scalable and more applications have yet to be explored