Office of Defense Nuclear Nonproliferation Research and Development

CVT – Consortium for Verification Technology

Thrust II: Fundamental physical data acquisition and analysis

October 19, 2016

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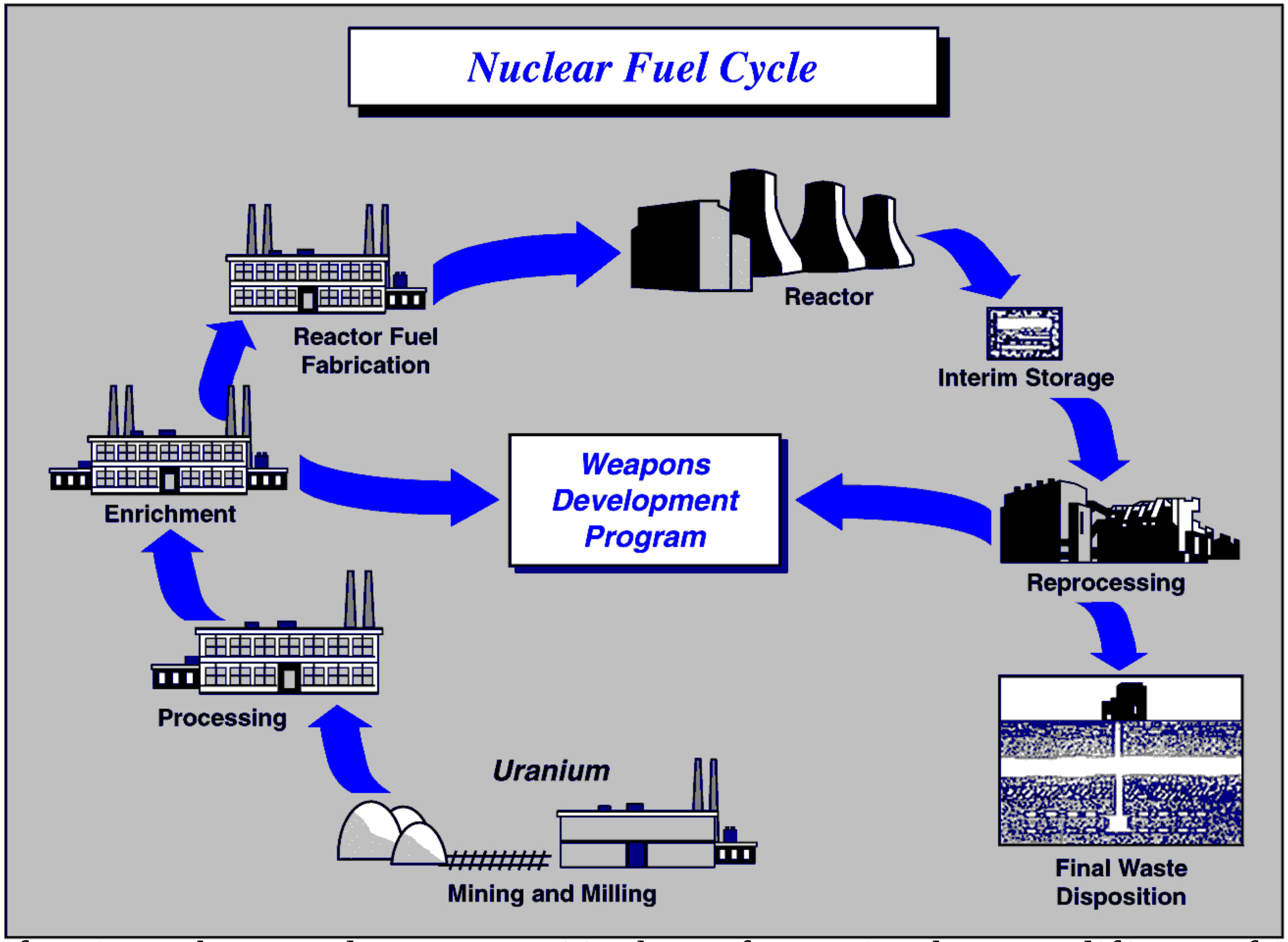
MIDAS/EECS/BME/Statistics
University of Michigan

CVT Thrust II Goals

- **Goal 1: Anomaly detection and localization (Hero, Fisher)**
  - Objective: To develop sensitive statistically based methods for detecting anomalies, e.g., material diversions from nuclear fuel cycles and cyberattacks.
  - Methods: machine learning, anomaly detection, quickest change detection, information fusion, multimodal factor analysis, nuclear fuel cycle simulation.
- **Goal 2: Fundamental physics modeling of radiation detectors (Pozzi, Hero)**
  - Objective: To simulate and experimentally validate new models for gamma and neutron detection.
  - Methods: Prompt neutron correlation analysis, monte carlo simulation of source/detector interaction physics, experimental validation.
- **Goal 3: Signal and image processing for radiation detection (Mattingly, Carin)**
  - Objective: to develop DAQ and signal processing algorithms for emerging radiation detection technologies
  - Methods: deep learning, compressive sampling, neutron scattering models, neutron track modeling, algebraic image reconstruction, experimental validation.

Nuclear fuel cycle

Objective of IAEA safeguards: "...the *timely detection* of any diversion of significant quantities of nuclear material and to deter diversion by creating the risk of *early detection*." Leonard Weiss, Bulletin of Atomic Scientists, vol. 47, no. 4, 1991.



Proliferation: Threat and Response 1997. http://fas.org/irp/threat/prolif97/meafrica.html

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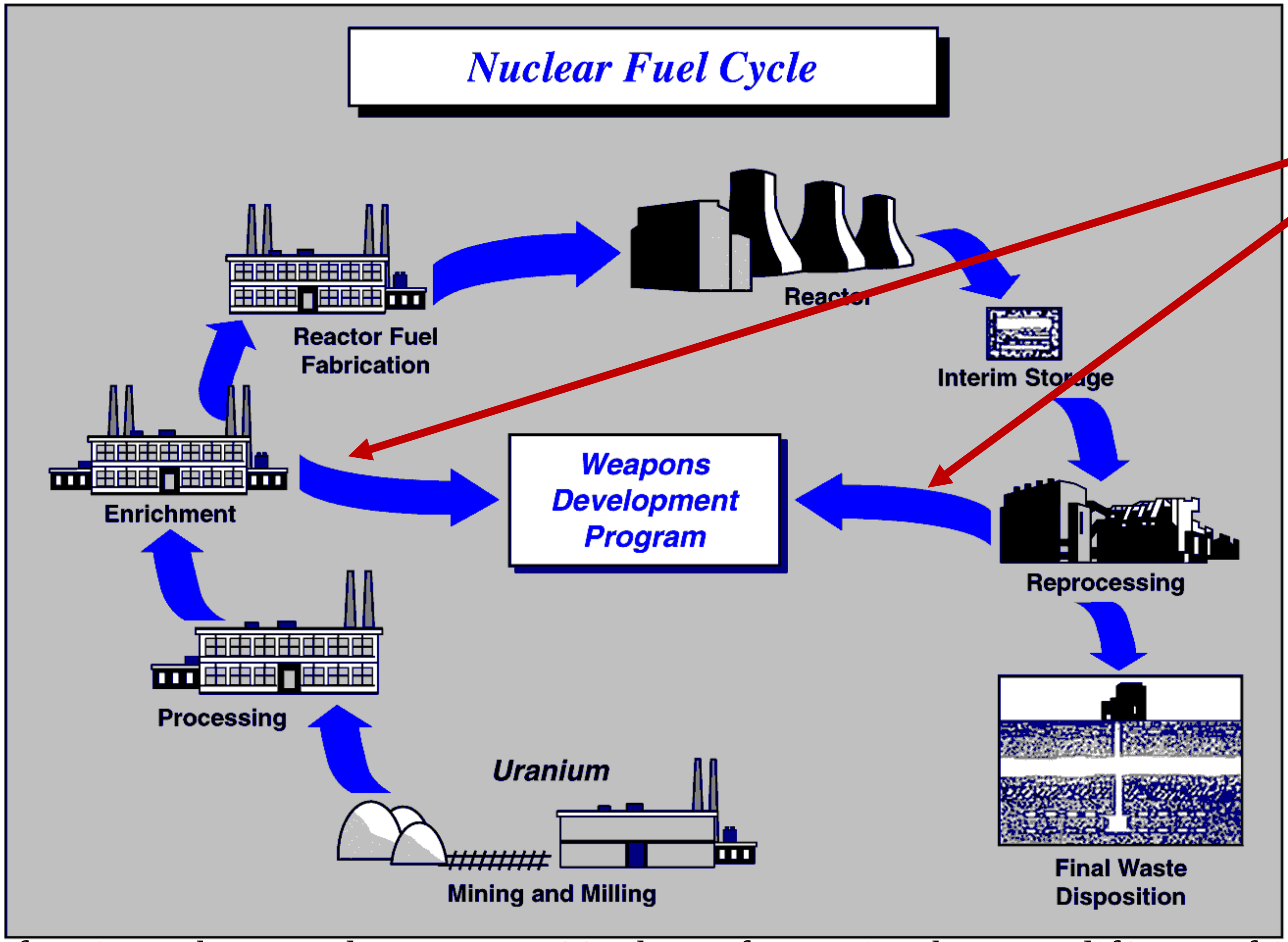

Potential diversion

Proliferation: Threat and Response 1997. http://fas.org/irp/threat/prolif97/meafrica.html

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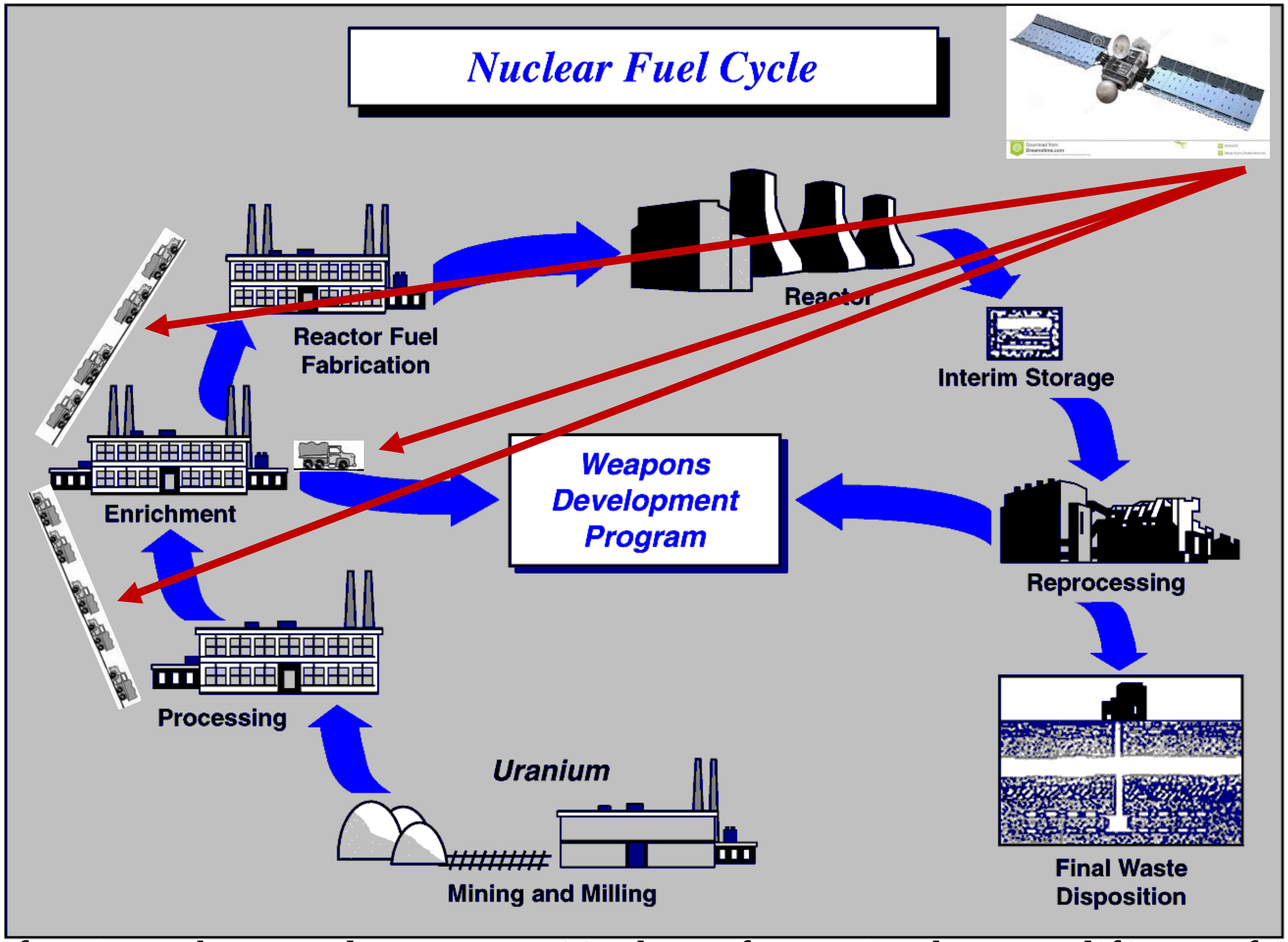

Remote Imaging
L. Carin,

Delivery/ Shipment monitoring
Y. Yilmaz

Proliferation: Threat and Response 1997. http://fas.org/irp/threat/prolif97/meafrica.html

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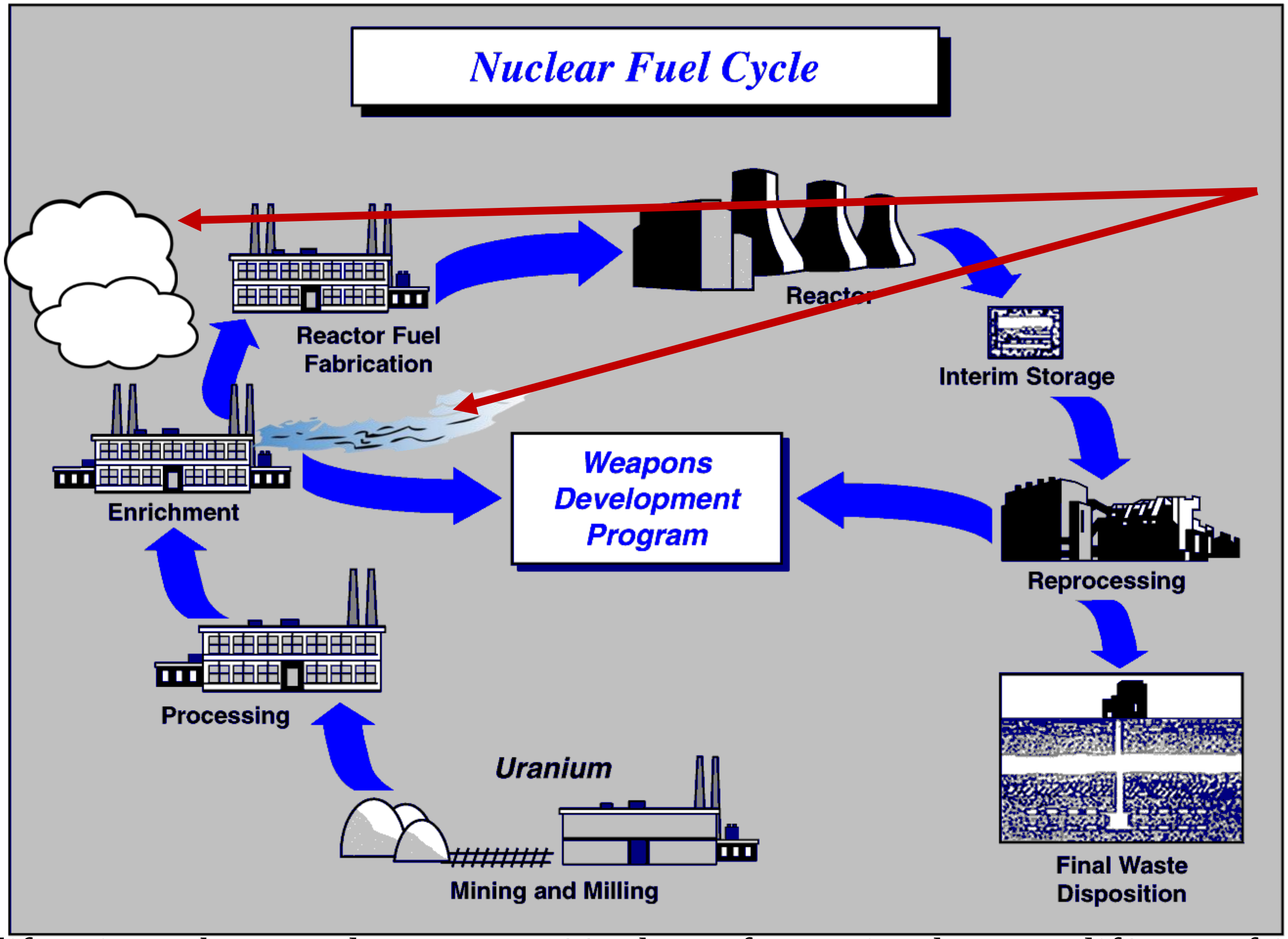

Emission monitoring
E.Hou
J. Fisher

Proliferation: Threat and Response 1997. http://fas.org/irp/threat/prolif97/meafrica.html

Nuclear fuel cycle

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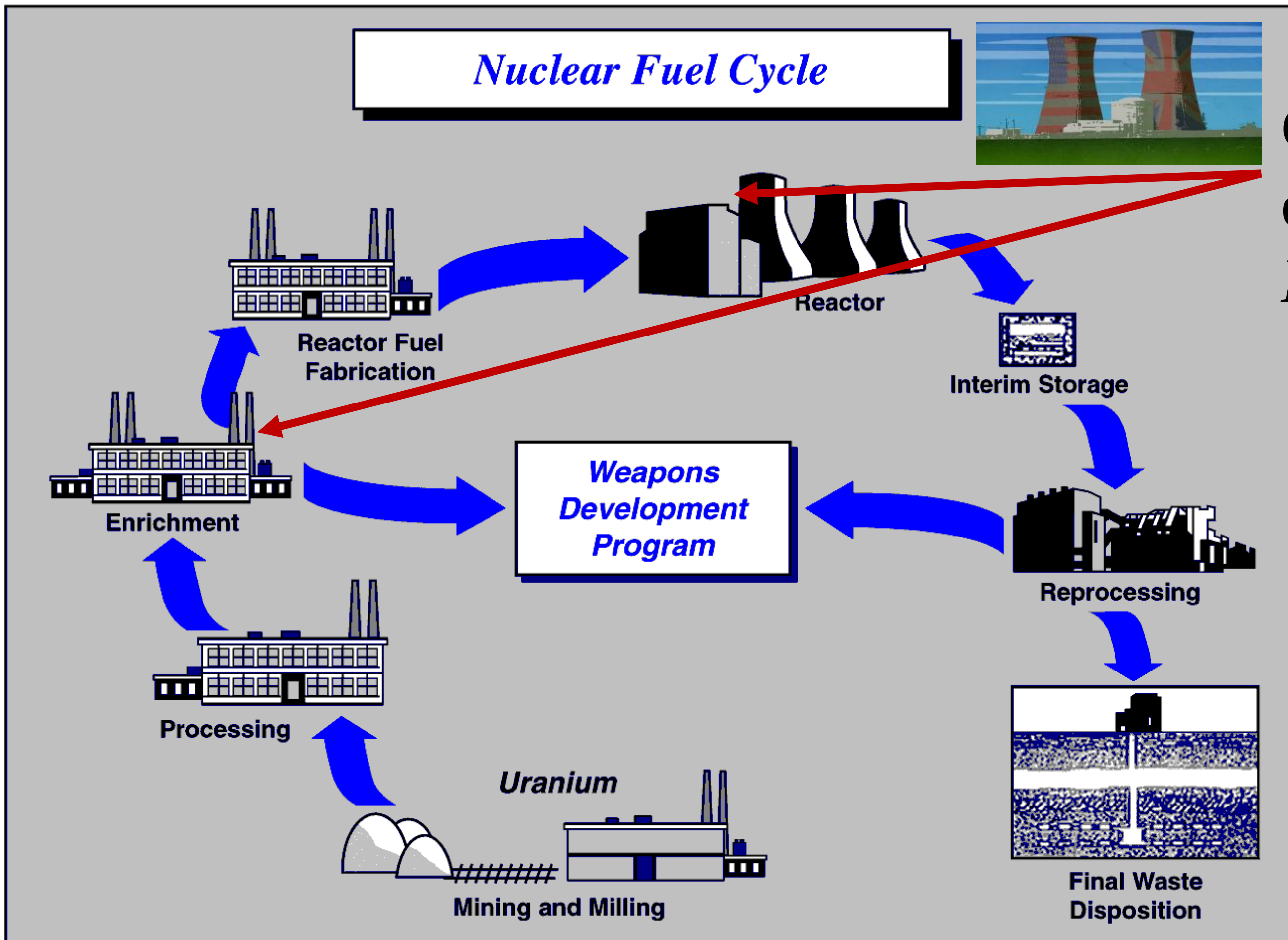

Cyberattack
detection
PY Chen

Proliferation: Threat and Response 1997. http://fas.org/irp/threat/prolif97/meafrica.html

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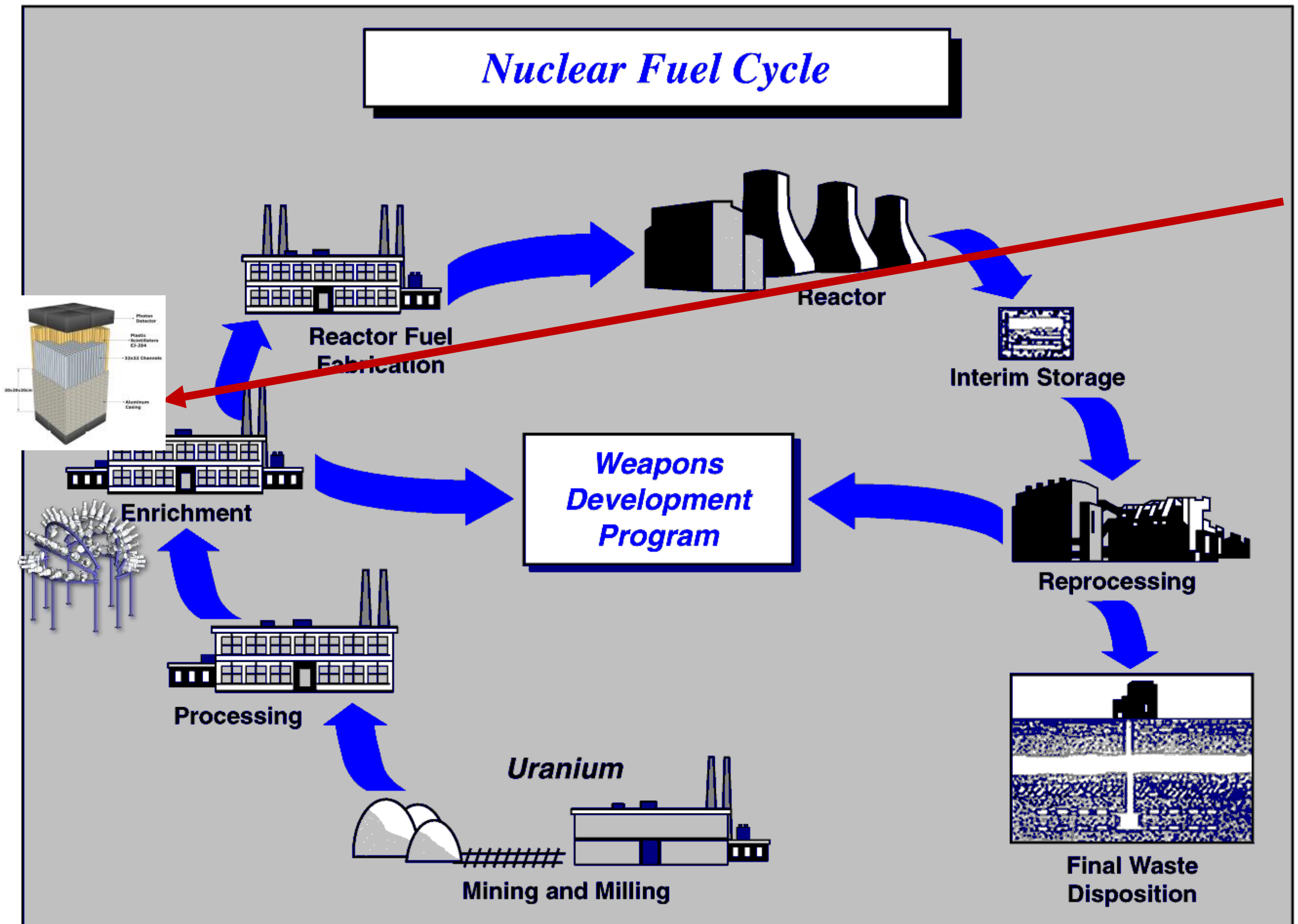


In situ radiation detection

S. Pozzi

A. Hero

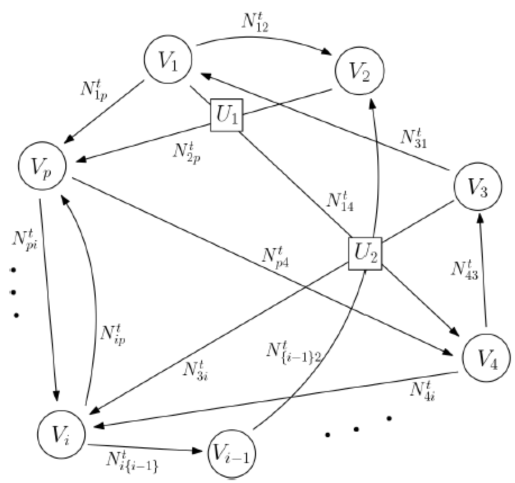
J. Mattingly

Proliferation: Threat and Response 1997. http://fas.org/irp/threat/prolif97/meafrica.html

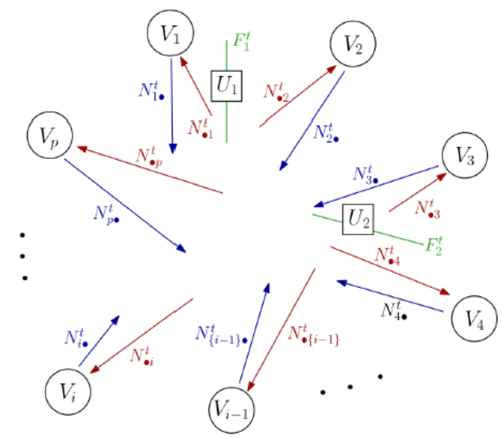
Anomaly detection
Delivery/shipment network monitoring

- **Technical challenge(Hero)**
  - Detecting anomalies in shipment patterns across fuel cycle networks is a very difficult inverse problem when traffic only partially observed.
- **Progress(Hero)**
  - A generative (Bayesian) hierarchical Gamma-Poisson model introduced that combines anomaly detection and network tomography
  - Accurate reconstruction algorithm implemented via fast EM algorithm that outperforms the standard MLE for network tomography.
  - Proposed method detects new edges (anomalies) with high accuracy.
- **Collaborations: Earl Lawrence at LANL**

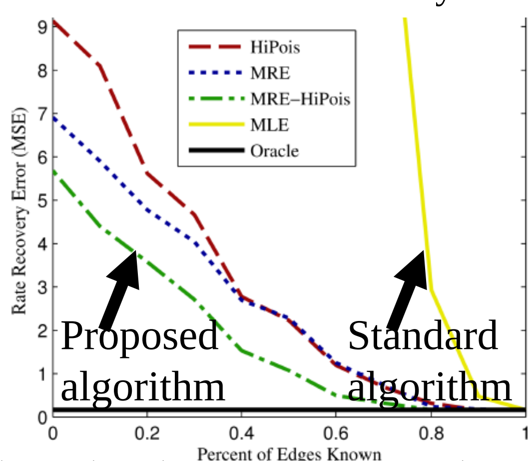
Actual network (ground truth)



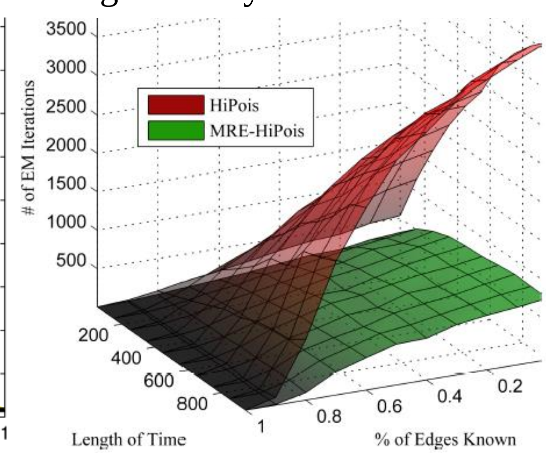
Observed network



Proposed MRE-HiPois has best reconstruction accuracy



Its implementation complexity is significantly smaller than others

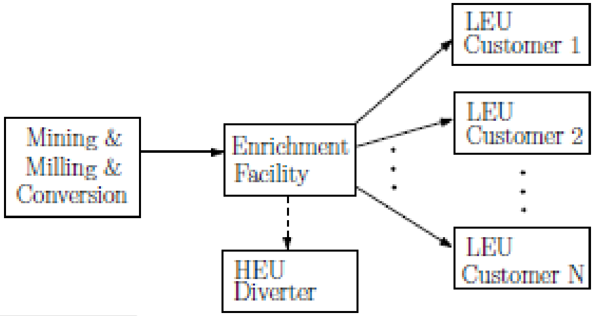


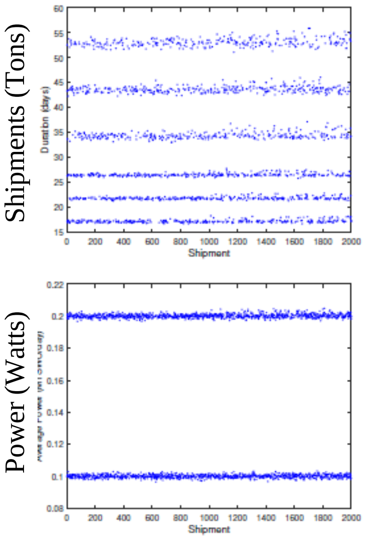
Anomaly detection
Delivery/shipment monitoring

- **Technical challenge (Hero):**
  - Combining multimodal measurements (power and shipments) to most quickly detect anomalies or diversions.
- **Progress (Hero):**
  - Proposed model for inferring unobserved HEU diverter amidst multiple observed LEU customers.
  - Formulated a multimodal CUSUM test for quickest detection of anomalies due to HEU diversion
  - Applied procedure to simulated power consumption and shipment traffic.
  - Quickest detection performance significantly beats the state of the art Kolmogorov-Smirnov,
- **Collaborations: Paul Wilson at UW**

TABLE I. Sample shipments of 1 ton with duration and average power consumption observations.

Shipment no. 	Duration (days)	Average Power Consumption (MTSWU/day)
1	17.11	0.2015
2	43.33	0.1018





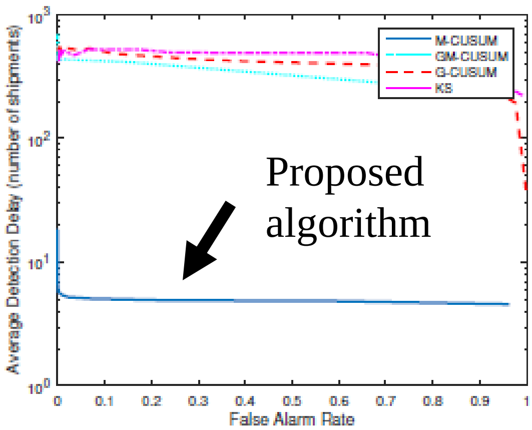


Fig. 4. Average detection delay vs. False alarm rate

Y. Yilmaz, E. Hou, A. Hero, "Diversion Detection in Nuclear Fuel Cycles from Multi-Modal Observations," ANS Workshop, Santa Fe, 2016.

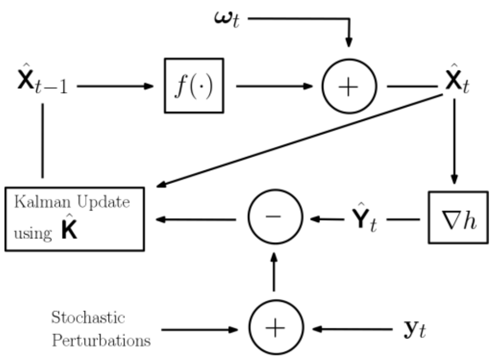
Anomaly detection
Emission monitoring: detection and tracking

- **Technical challenge(Hero, Hou)**
  - Detect anomalous nuclear facility emission patterns: heat, water, vapor
- **Progress(Hero, Hou)**
  - Emissions modeled as a spatio-temporal random field

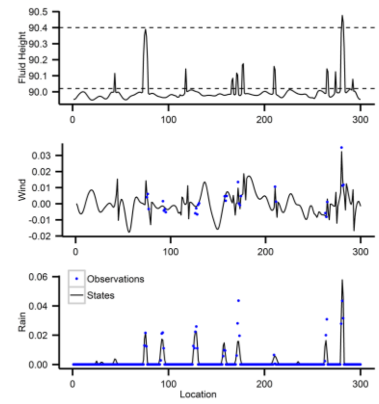
$$\mathbf{y}_t = h(\mathbf{x}_t) + \boldsymbol{\epsilon}_t \qquad \mathbf{x}_t = f(\mathbf{x}_{t-1}) + \boldsymbol{\omega}_t$$

  - Ensemble Kalman filter uses model to predict
    - o future emission patterns
    - o Posterior 95% confidence envelope
  - We detect anomalies w/ confidence
  - Anomaly detector tested on simulated shallow water ODE model.
- Collaborations: Earl Lawrence **(LANL)**

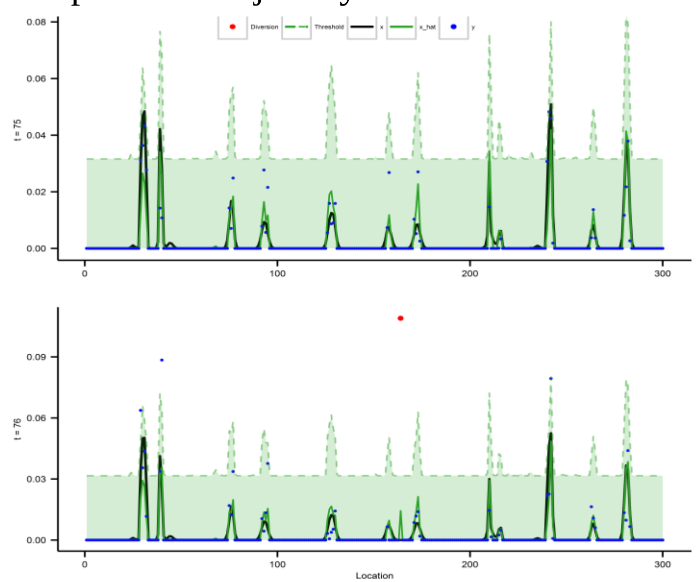
Ensemble Kalman filter



Observations



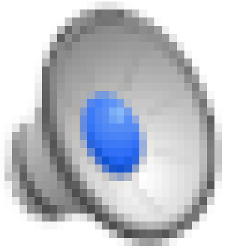
Posterior predictor trajectory with confidence envelope

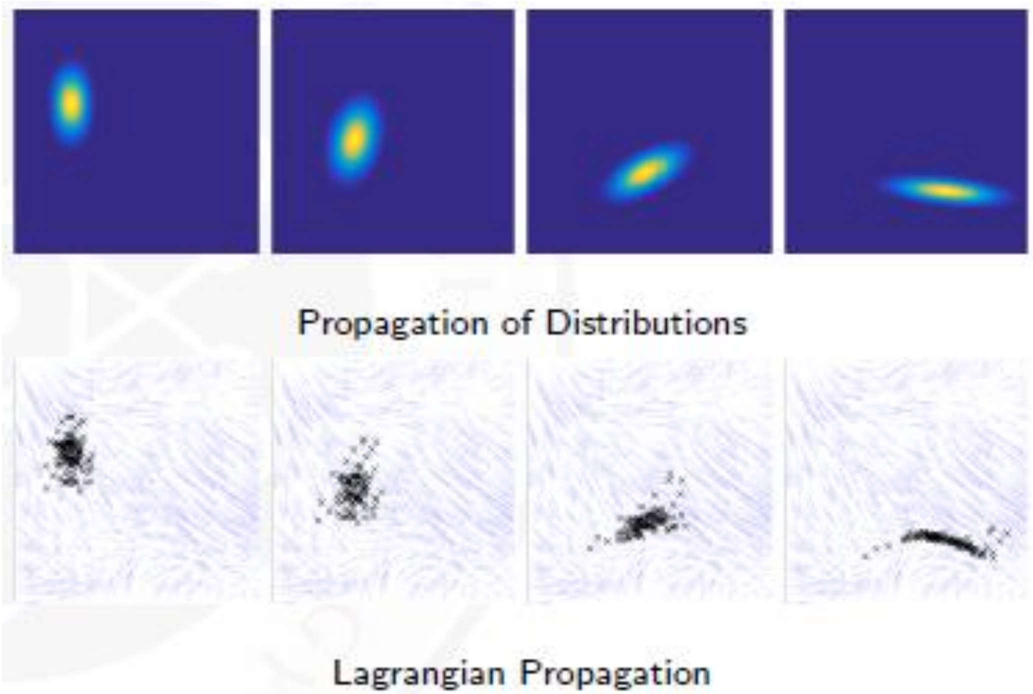


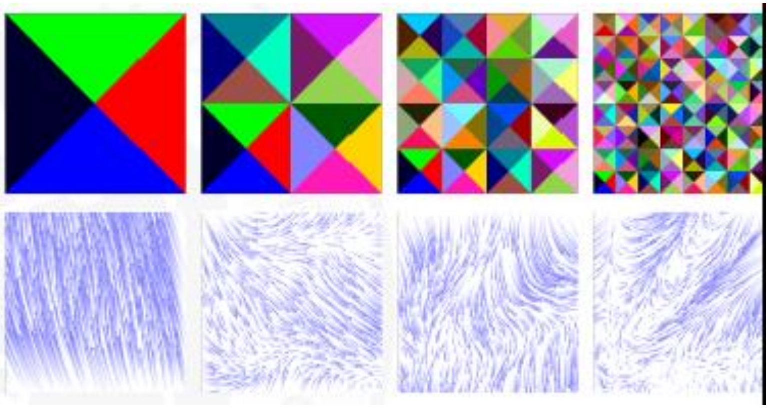
E. Hou, E. Lawrence, A Hero, "Penalized Ensemble Kalman Filters for High Dimensional Non-linear Systems," submitted, 2016.

Signal/image processing
Emission monitoring: active localization

- **Technical challenge (Fisher):**
  - Autonomous navigation for chemical source localization in complex transport medium
- **Progress (Fisher):**
  - Formulated dynamic Bayesian information planning problem
  - Developed graphical model for longitudinal; data integration
  - Introduced multiscale ODE vector field model for propagation of plume and localization density

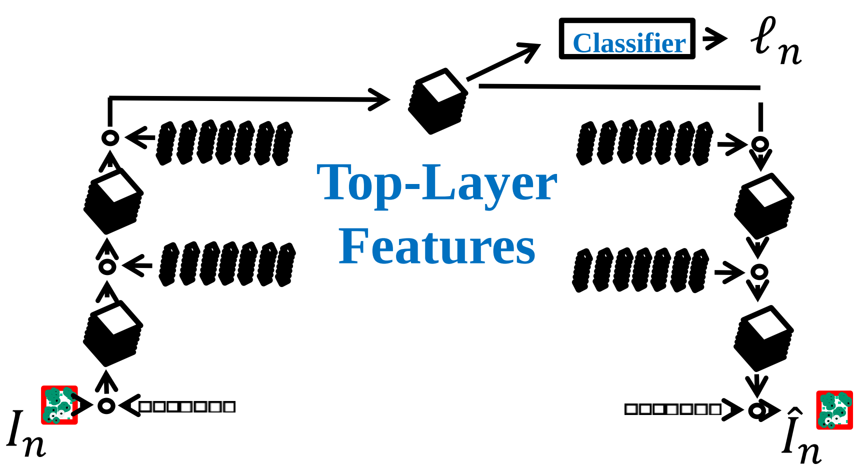






Signal/image processing
Deep learning for security and threat detection

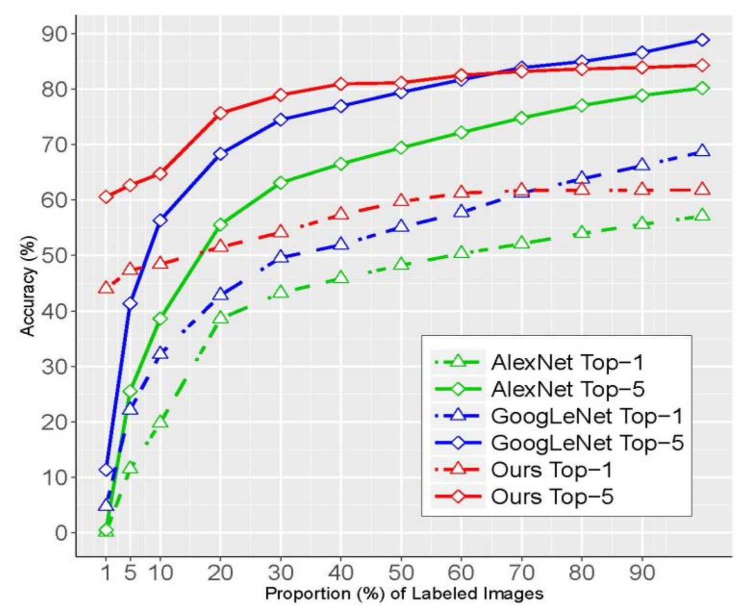
- **Technical challenge (Carin):**
  - CVT applications require classification with limited labeled (training) data → semi-supervised learning is necessary.
- **Progress (Carin):**
  - CNN image classifier developed for SSL
  - Demonstrated improvement on ImageNet
  - Variational autoencoder (VAE)
    - o Deep encoder for feature selection (CNN)
    - o Deep decoder for image reconstruction



Semi-Supervised ImageNet Analysis

1000 image classes, 1M training images

Example Images



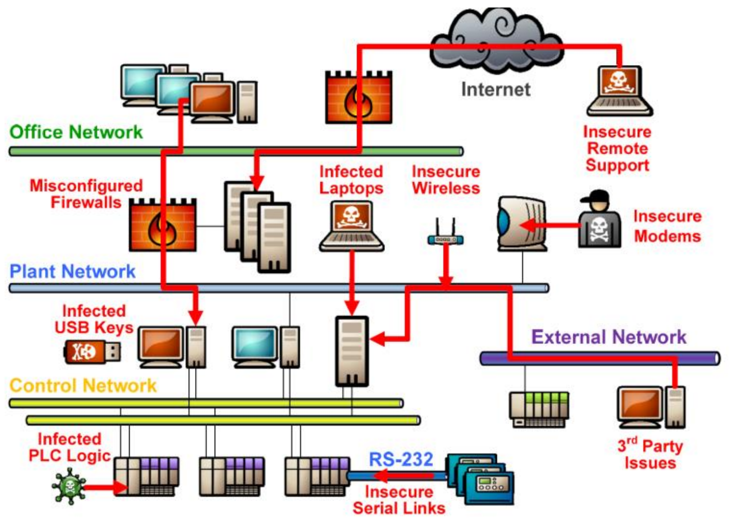
Collaborations: Tom Potok and Karen Miller at ORNL&LANL

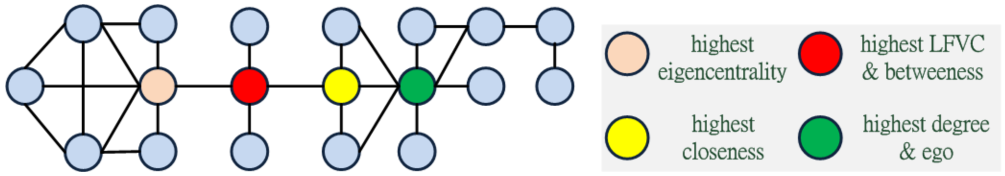
Y. Pu, X. Yuan, A. Stevens, C. Li, L. Carin, A Deep Generative Deconvolutional Image Model, Artificial Intelligence and Statistics (AISTATS), 2016

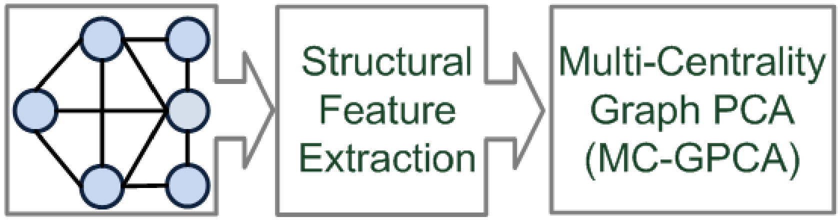
Anomaly detection
Cyber-intrusion detection

- **Technical challenge(Hero)**
  - Detecting potentially catastrophic cyber-intrusions on nuclear facilities..
- **Progress(Hero)**
  - Represent interactions between entities on network as a graph
  - Extract multi-centrality structural features to identify at-risk nodes
  - Select best combination of multicentrality features with dictionary learning
  - Implement dictionary for early detection of anomalies&attacks
  - Validate on experimental data (New Brunswick cyberintrusion data)
- Collaborations: **Sutanay Choudhury (PNNL)**

Cyber-intrusions vulnerabilities on a Nuclear Facility



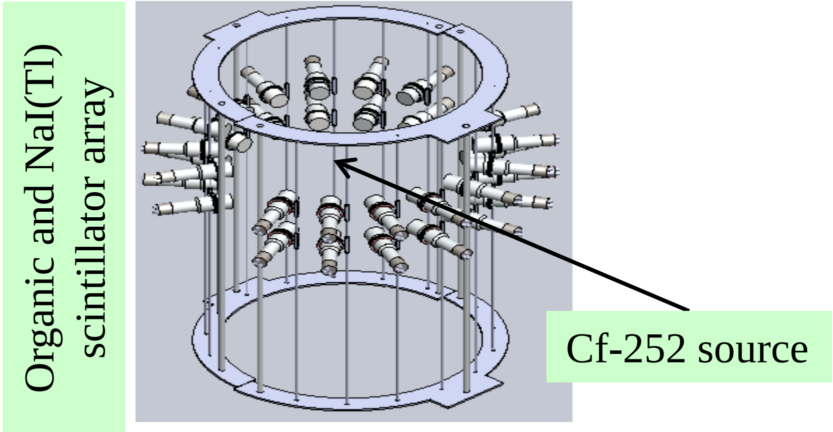




P.Y. Chen, S. Choudhury, A Hero, "Multi-centrality Graph Spectral Decompositions … Cyber Intrusion Detection," ICASSP, Shanghai 2016.

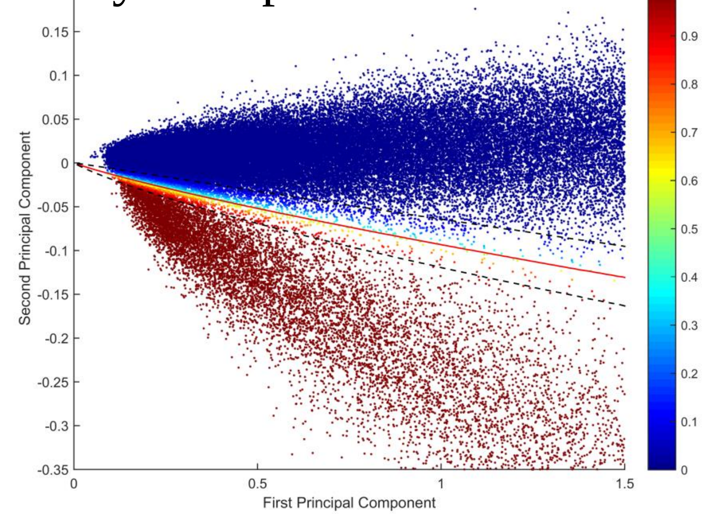
Fundamental physics modeling Correlations in Prompt Neutrons and Gamma-rays from Fission

- **Technical challenge (Pozzi):**
  - To accurately discriminate fissile materials from other radioactive sources for treaty verification.
- **Progress (Pozzi and Hero):**
  - High sensitivity neutron pulse discrimination and unfolding without time-of-flight information
  - Developed Bayes-optimal neutron unfolding and pulse discrimination algorithms
  - Tested on data generated from organic and NaI scinitillator detector array in S. Pozzi's lab.

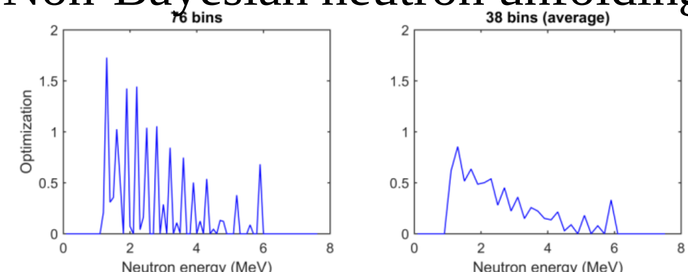


- **Collaborations: LANL, LLNL, LBNL**

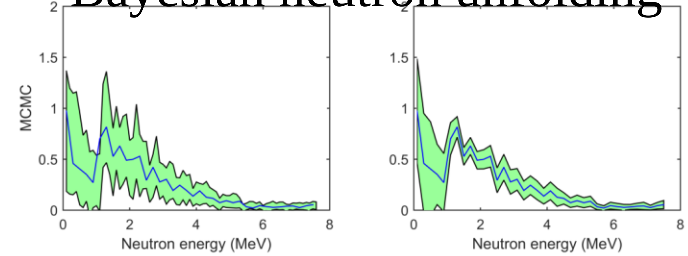
Bayesian pulse discrimination



Non-Bayesian neutron unfolding



Bayesian neutron unfolding



Conclusion

- **Thrust 2 is making progress on data analysis for diversion detection, fundamental physics modeling and signal/image processing for radiation detection.**
- **Collaborations with 6 National Laboratories reinforce CVT mission**

For more information on Thrust 2 see other presentations today:

1. P.-Y. Chen, “Multicentrality graph spectral decomposition techniques…,” (Oral)
2. J. Mattingly, “Data compression and analysis methods…,” (Oral)
3. E. Hou E. Lawrence, A. Hero, ”Penalized ensemble kalman filter methods…,” (Poster)
4. Y. Altman, A. DiFulvio, A. Hero, S. Mclaughlin, S. Pozzi, “Advanced analytic methods for neutron spectra…,” (Poster)
5. K. Liang and L. Carin, “Deep learning for complex image analysis,” (Poster)

Associated National Laboratories

- Los Alamos National Laboratory (LANL)
  - *High dimensional anomaly detection project* (LANL partner Earl Lawrence working w/ Hero)
  - *Physics of fission experiments and theory* (LANL partners Robert Haight and Patrick Talou working with Pozzi)
- Pacific Northwest National Laboratory (PNNL)
  - *Compressive sensing to transmission electron microscopy project (TEM) project* (PNNL partners Andrew Stevens and Nigel Browning working with Carin)
  - *Heterogeneous network models for cyber-security project* (PNNL partner Sutenay Choudhury working with Hero)
- Oak Ridge National Laboratory (ORNL)
  - *Neutron coded aperture fast neutron camera project* (ORNL partners Jason Newby & Paul Hausladen working witn Mattingly and Chapman, NCSU)
  - *Application of deep-learning technology to airborne imagery* (ORNL partner Thomas Potok working with Carin)
- Sandia National Laboratory (SNL)
  - *Compact single-volume neutron scatter camera project* (SNL partner Erik Brubaker working with Mattingly and Weinfurther, NCSU)
- Lawrence Livermore National Laboratory (LLNL)
  - *Large liquid scintillator array project* (LLNL partner Les Nakae working with Mattingly)
  - *FREYA Modeling of Fission Correlations* (LLNL partner Ramona Vogt working with Pozzi)
- Lawrence Berkeley National Laboratory (LBNL)
  - *FREYA Modeling of Fission Correlations* (LBNL partner Jurgen Randrup working with Pozzi)

Thrust II students and post-docs (2015-16)

- **Funded by CVT**
  - Elizabeth Hou (UM STATS): CVT Fellow
  - Charles Sosa (UM NERS), CVT Fellow
  - David Carlson (Duke ECE), CVT Fellow
  - Sue Zheng (MIT CSAIL), CVT Fellow
  - Yassin Yilmaz (UM EECS): post-doctoral fellow
  - Sijia Liu (UM EECS): post-doctoral fellow
  - Angela Di Fulvio (UM NERS), post-doctoral fellow
  - Xuejun Liao (Duke ECE), post-doctoral fellow
  - Rob Weldon (NCSU NE Ph.D. student): CVT fellow (poster)
  - Jonathan Mueller (Duke Physics), post-doctoral fellow
  - Oren Freifeld (MIT CSAIL), post-doctoral fellow

- **Funded from non-CVT sources**
  - Pin Yu Chen (UM EECS): PhD candidate **(PNNL supported)**
  - Matthew Marcath (UM NERS), Ph.D candidate (poster)
  - Tony Shin (UM NERS), M.S. student
  - Steve Ward (UM NERS), M.S. student
  - Andrew Stevens (Duke ECE), PhD student (PNNL employee)
  - Kyle Weinfurther (NCSU Nuclear Eng), PhD student (Sandia supported) (poster)
  - Pete Chapman (NCSU Nuclear Eng), Ph.D. student (supported by US Army)
  - Mudit Mishra (NCSU NE Ph.D. student): supported by NCSU Engineering fellowship
  - Ben Reed (Surrey Physics student): supported by Surrey
  - Yoan Altman (Herriot-Watt post-doc): supported by Herriot-Watt