FW/CADIS-Ω: An Angle-Informed Hybrid Method for Deep-Penetration Radiation Transport

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October 19, 2016

Departmental Colloquium

University of Tennessee, Knoxville

Berkeley
UNIVERSITY OF CALIFORNIA

Who am I?

Oregon State University
College of Engineering

Berkeley
UNIVERSITY OF CALIFORNIA

FHR
Fluoride Salt Cooled High Temperature Reactor

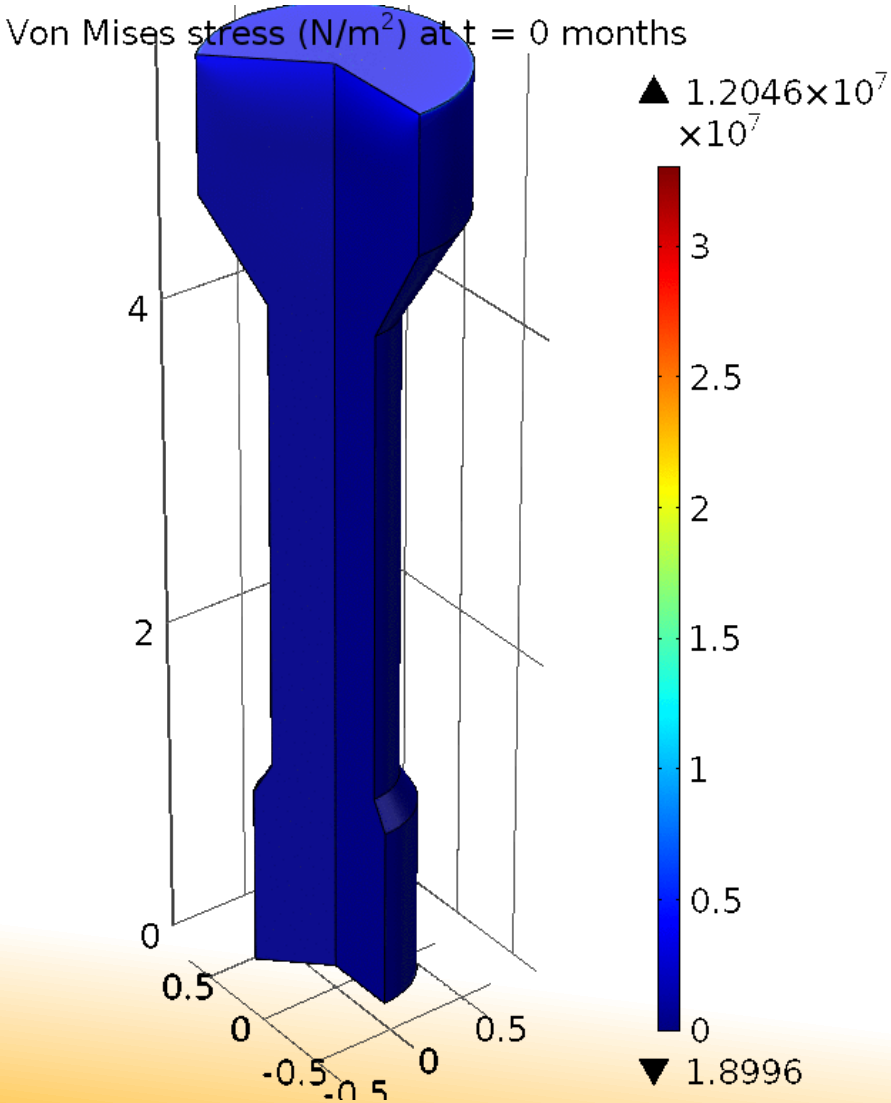
BGC
Berkeley Geochronology Center

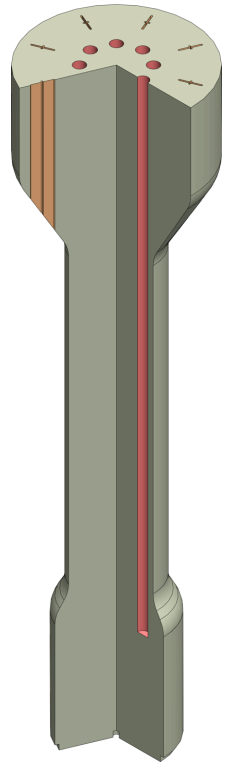
SUERC
Scottish Universities Environmental Research Centre

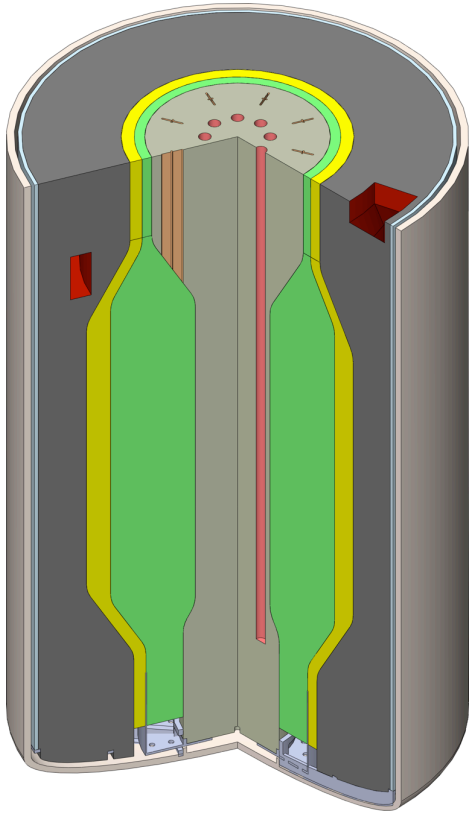
BERKELEY
Institute for Data Science

Oak Ridge National Laboratory

Research Highlights: FHR







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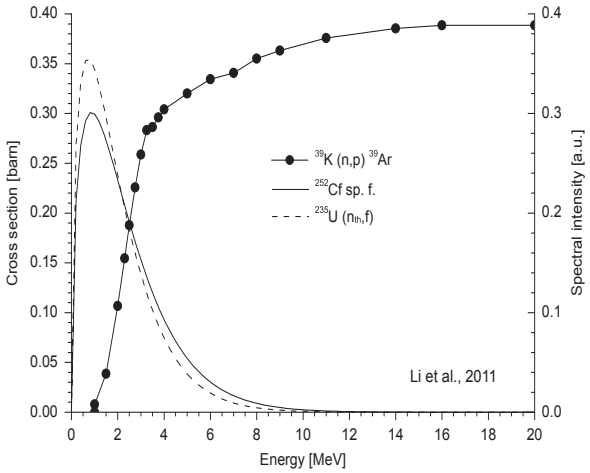
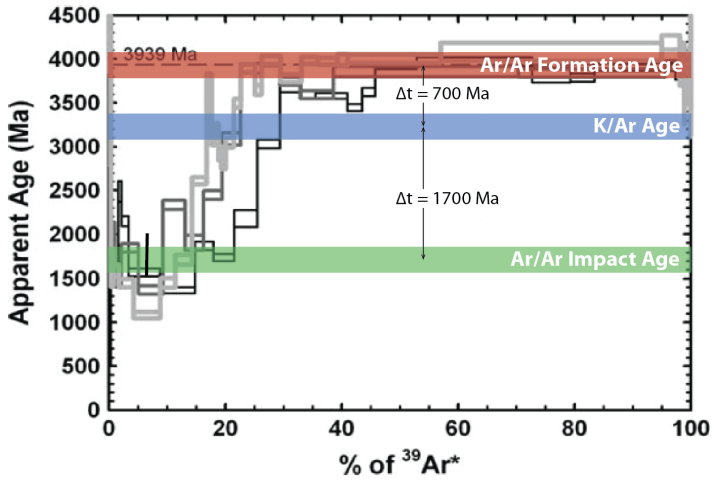
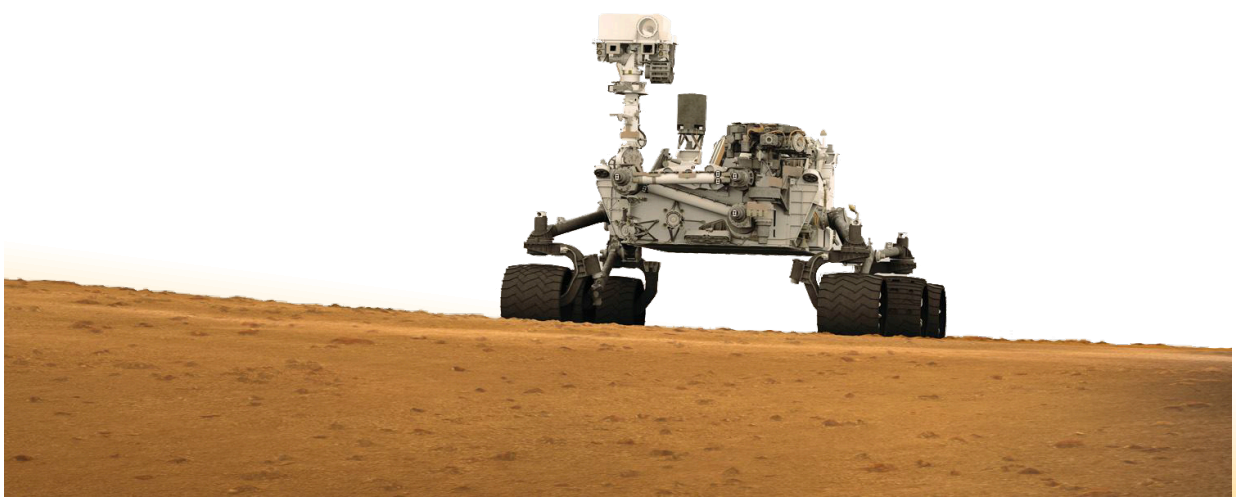
Research Highlights: SUERC & BGC







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Present Work

Hybrid Methods for Strongly Anisotropic Deep-Penetration Radiation Transport

Talk Outline

- Introduction and motivation
- Hybrid methods background
  - Adjoint and importance
  - CADIS / FW-CADIS
  - Existing state of angle-informed methods
- The Ω method
  - Method theory
  - Software implementation
  - Results on an example problem

Motivation

Variance Reduction

Hybrid Methods

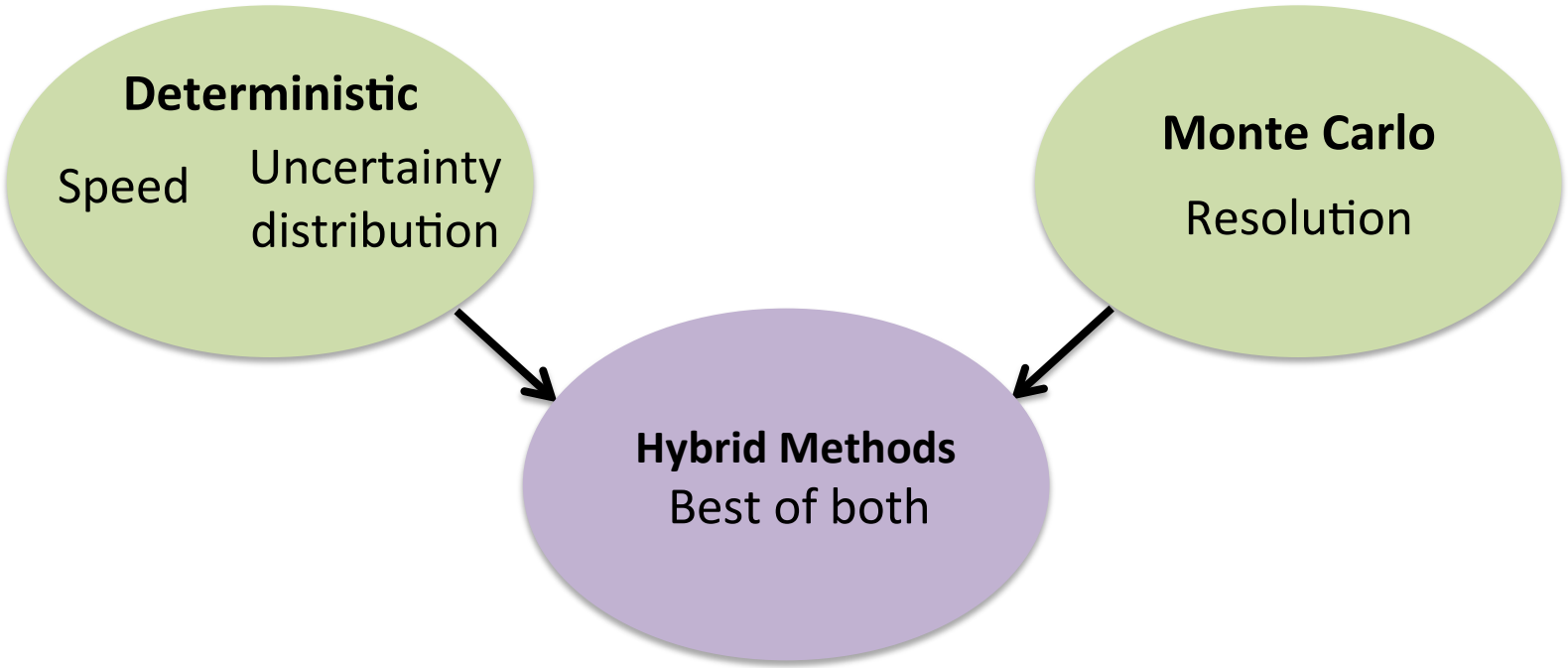
My Work

- Radiation shielding has applications in a number of fields
- "Analog" Monte Carlo for these types of problems is not ideal
  - Lots of particles → good statistics
  - Good shielding → very few particles
- Hybrid methods leverage benefits of deterministic codes to accelerate Monte Carlo
- A number of problems have strong angular anisotropies
  - The importance of a particle (whether it is likely to contribute to a result) varies with direction
  - Tracking in a low-importance direction is inefficient

Research Objectives

1. Create a new method to capture angular information in an importance map for Monte Carlo variance reduction
2. Compare the new method against existing hybrid methods
3. Determine the sensitivity of the new method to deterministic calculation fidelity and problem geometry

Hybrid Methods: Introduction



- Deterministic calculation used to generate importance map
- Importance map -> Monte Carlo -> improves precision and speed
- Importance: contribution to a tally
- Common solution: use deterministically-obtained adjoint solution for importance map

Adjoint and Importance

Forward NTE

$$\hat{\Omega}\cdot\nabla\psi(\vec{r},E,\hat{\Omega})+\Sigma_t(\vec{r},E)\psi(\vec{r},E,\hat{\Omega})=$$
$$\int_{4\pi}\int_0^{\infty}\Sigma_s(E'\rightarrow E,\hat{\Omega}'\rightarrow\hat{\Omega})\psi(\vec{r},E',\hat{\Omega}')dE'\,d\hat{\Omega}'+q_e(\vec{r},E,\hat{\Omega})$$

Adjoint NTE

$$-\hat{\Omega}\cdot\nabla\psi^{\dagger}(\vec{r},E,\hat{\Omega})+\Sigma_t(\vec{r},E)\psi^{\dagger}(\vec{r},E,\hat{\Omega})=$$
$$\int_{4\pi}\int_0^{\infty}\Sigma_s(E\rightarrow E',\hat{\Omega}\rightarrow\hat{\Omega}')\psi^{\dagger}(\vec{r},E',\hat{\Omega}')dE'\,d\hat{\Omega}'+q_e^{\dagger}(\vec{r},E,\hat{\Omega})$$

Reversal of energy

Reversal of direction

- The adjoint solution can be used to make an importance map for a desired outcome
- An exact adjoint solution can be used to obtain a zero variance Monte Carlo solution

Adjoint and Importance

Notation definition:

$$\langle a \;\; b \rangle = \int a(P) b(P) dP$$

Detector response:

$$\begin{aligned} R &= \langle \sigma_d \, \psi \rangle \\ &= \langle q^\dagger \, \psi \rangle \\ &= \langle q \, \psi^\dagger \rangle \end{aligned}$$

Point source:

$$q(\vec{r}, E, \hat{\Omega}) = \delta(\vec{r} - \vec{r}_0)\delta(E - E_0)\delta(\hat{\Omega} - \hat{\Omega}_0)$$

Response = adjoint flux:

$$R = \psi^\dagger(\overline{r_0}, E_0, \hat{\Omega}_0)$$

CADIS (Consistent Adjoint Driven Importance Sampling)

Biased source distribution

$$\hat{q}(\vec{r},E)=\frac{\phi^{\dagger}(\vec{r},E)q(\vec{r},E)}{R}$$

Starting weight of the particles

$$w_0(\vec{r},E)=\frac{q(\vec{r},E)}{\hat{q}(\vec{r},E)}=\frac{R}{\phi^{\dagger}(\vec{r},E)}$$

Weight window target values

$$w(\vec{r},E)=\frac{R}{\phi^{\dagger}(\vec{r},E)}$$

(Forward Weighted) FW-CADIS

- Reduces variance for global solutions by creating an even particle distribution across problem
- Different adjoint source for different goals

For the calculation of:	Expression	Adjoint source
Energy and spatial dependent flux (global problem)	$\phi(\vec{r},E)$	$q^{+}(\vec{r},E)=\dfrac{1}{\phi(\vec{r},E)}$
Spatial dependent total flux (semi-global)	$\int \phi(\vec{r},E)\,dE$	$q^{+}(\vec{r})=\dfrac{1}{\int \phi(\vec{r},E)\,dE}$
Spatial dependent total dose (semi-global)	$\int \phi(\vec{r},E)\sigma_d(\vec{r},E)\,dE$	$q^{+}(\vec{r},E)=\dfrac{\sigma_d(\vec{r},E)}{\int \sigma_d(\vec{r},E)\phi(\vec{r},E)\,dE}$

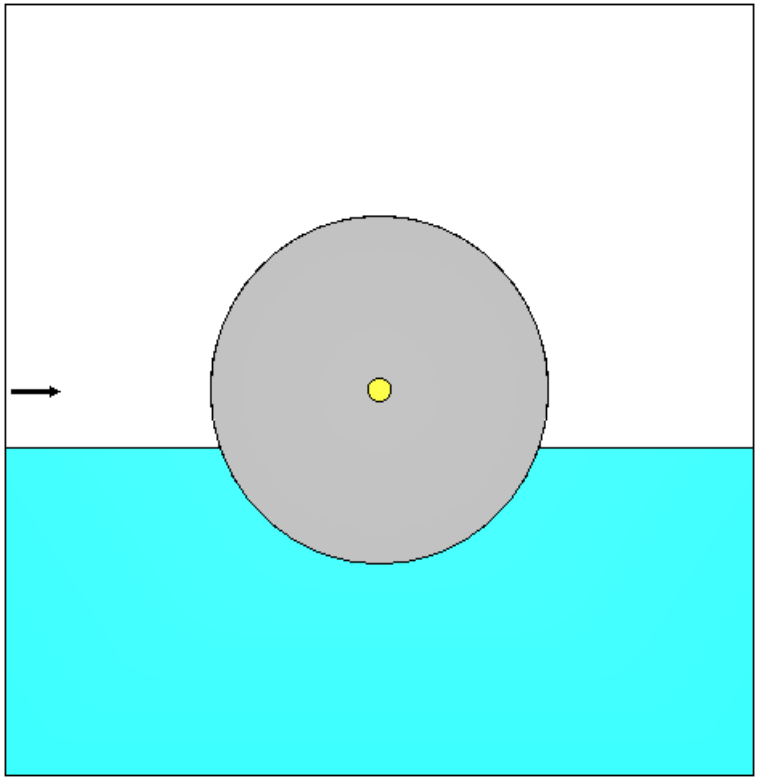
These methods are great, but.....

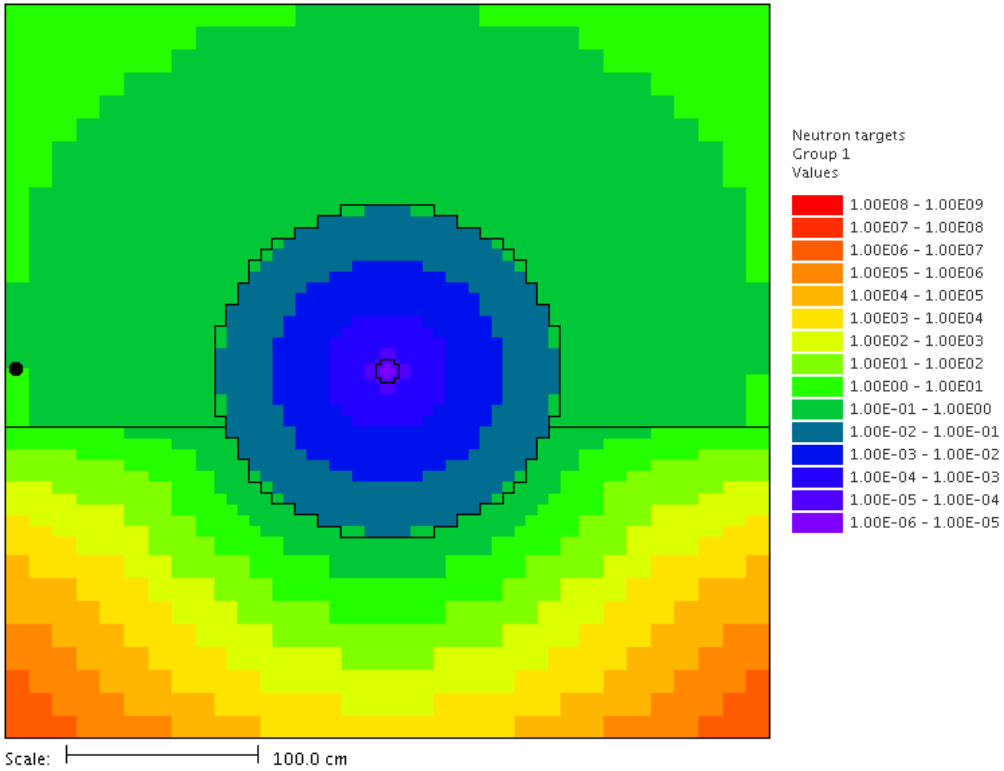
CADIS

FW-CADIS

They don’t capture angle

Angular Information Matters





Existing Angle-Informed Biasing

- Local Importance Function Transform (LIFT)
- AVATAR
- Simple angular CADIS
  - With directional source biasing
  - Without directional source biasing
- Automatic WW generator (MCNP)

Research Project Outline

1. Implement method to adjust adjoint scalar flux to get an angle-informed importance map
2. Compare methods to traditional CADIS and FW-CADIS
   - Success metrics: FOM, uncertainty distribution
3. Characterize and test the method
   a. Use validation problems to determine limitations
   b. Use challenge problems with increasing complexity to show applicability

Implementation: The Ω Flux

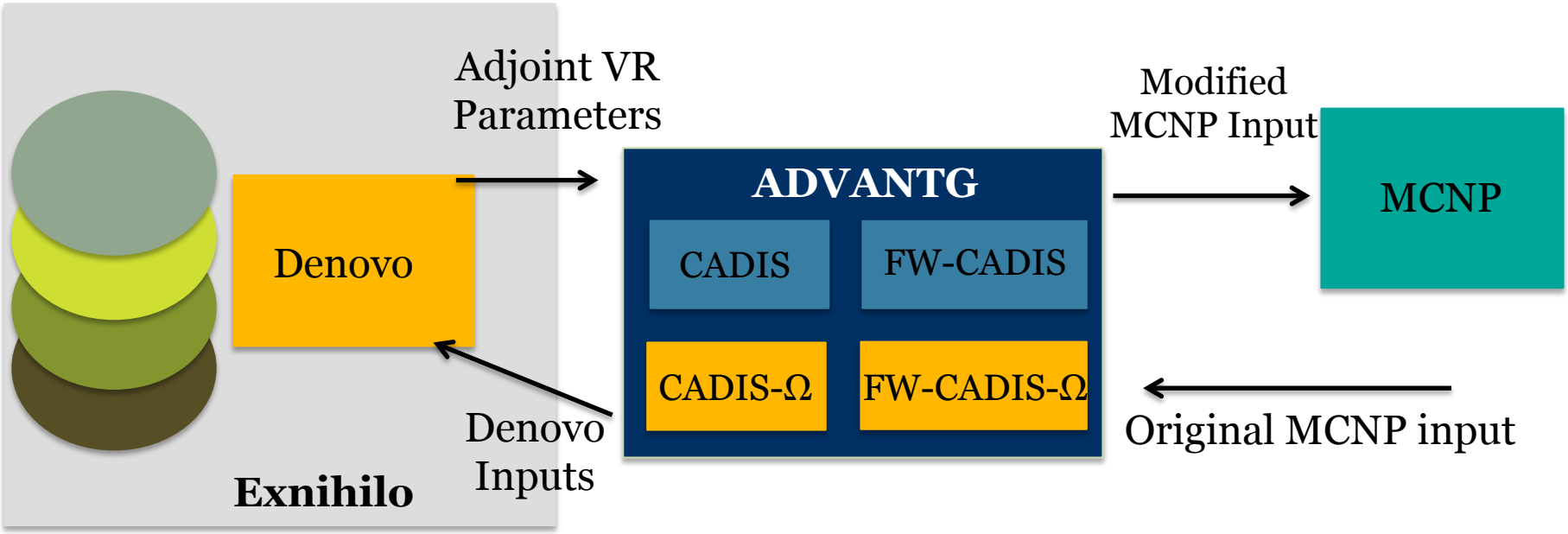
Uses angular flux → more angular information is captured in importance map

$$\phi_{\Omega}^{+}(\vec{r},E)=\frac{\int \psi(\vec{r},E,\hat{\Omega})\psi^{+}(\vec{r},E,\hat{\Omega})\,d\hat{\Omega}}{\int \psi(\vec{r},E,\hat{\Omega})\,d\hat{\Omega}}$$

Generates adjusted adjoint scalar flux → can be adapted for existing hybrid methods

Weights adjoint by the forward flux → importance map includes direction of particle flow

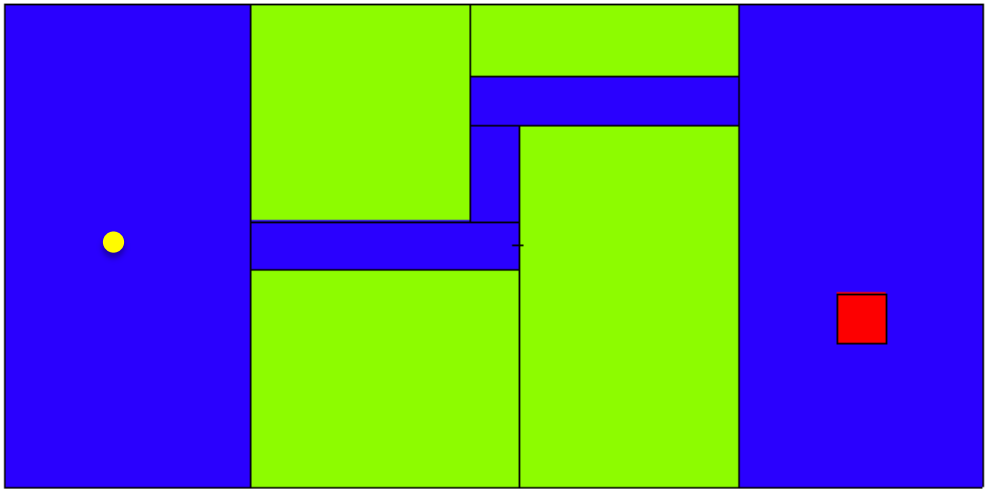
Our System:


Adjoint VR
Parameters
Modified
MCNP Input
Denovo
ADVANTG
CADIS
FW-CADIS
MCNP
CADIS-Ω
FW-CADIS-Ω
Denovo
Inputs
Original MCNP input
Exnihilo

Results: Simple Labyrinth

Problem specific:

- 10 MeV point source
- NaI detector
- Concrete barrier
- Air
- Vacuum boundary conditions



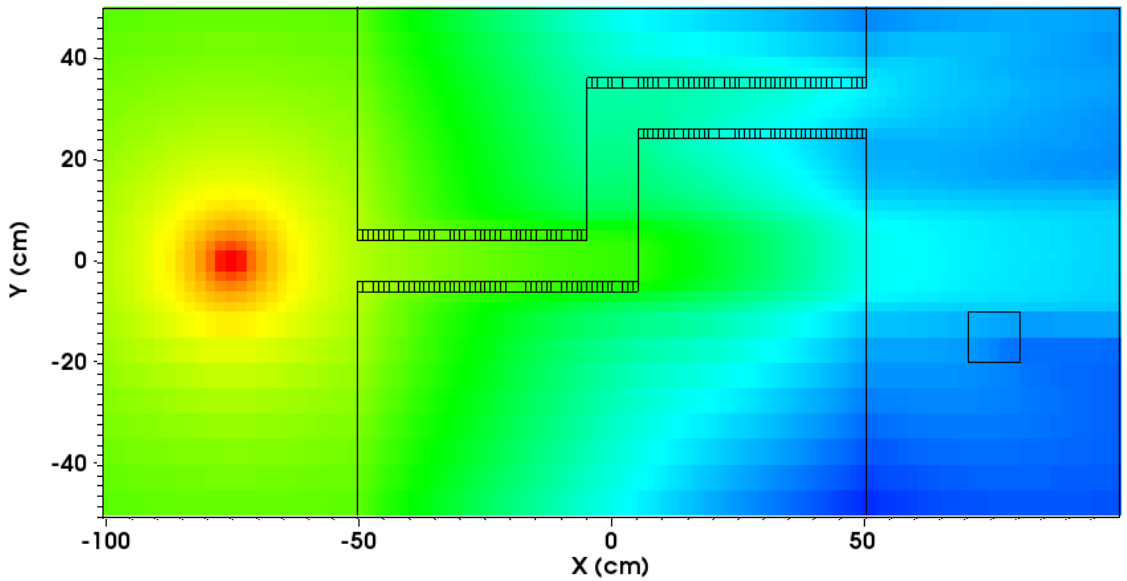
Monte Carlo Specific:

- NaI reaction rate tallied with track length tally (f4)
- Tally refined by energy bin (consistent with advantg binning)

Denovo Specific:

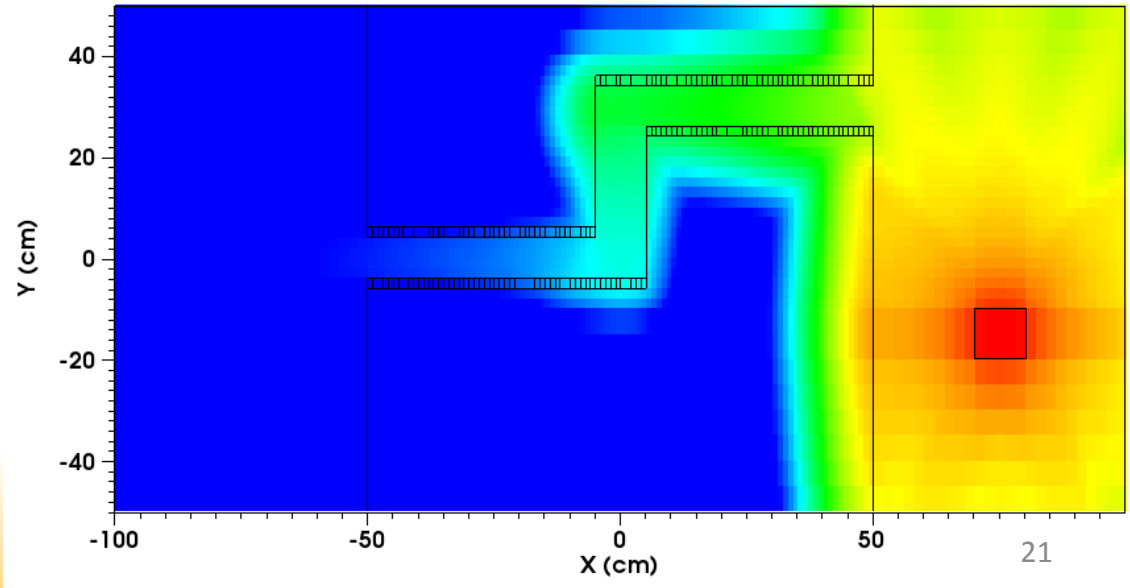
- 27g19n XS library
- QR quadrature
- SC (Step Characteristic) spatial solver
- P_N order 3

Forward and Adjoint fluxes



Forward Flux
(group 00)

Adjoint Flux
(group 26)



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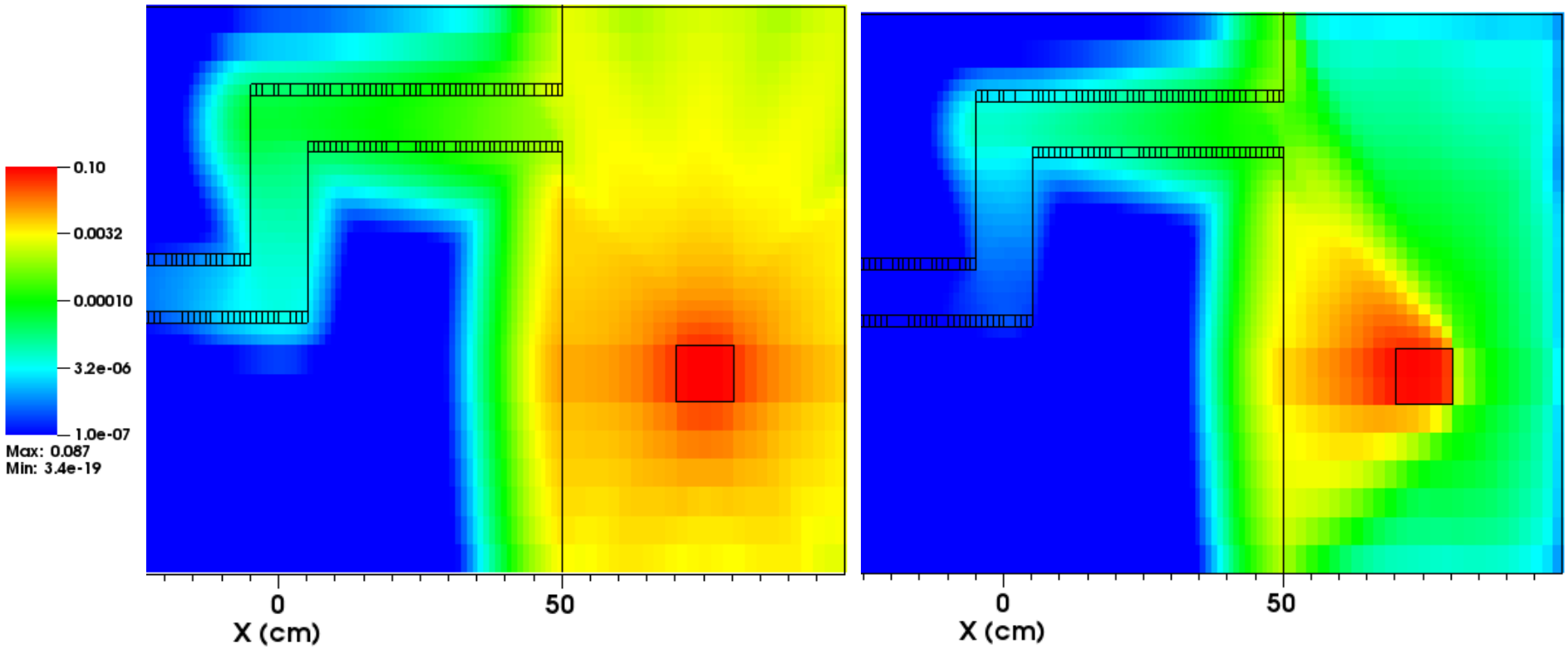
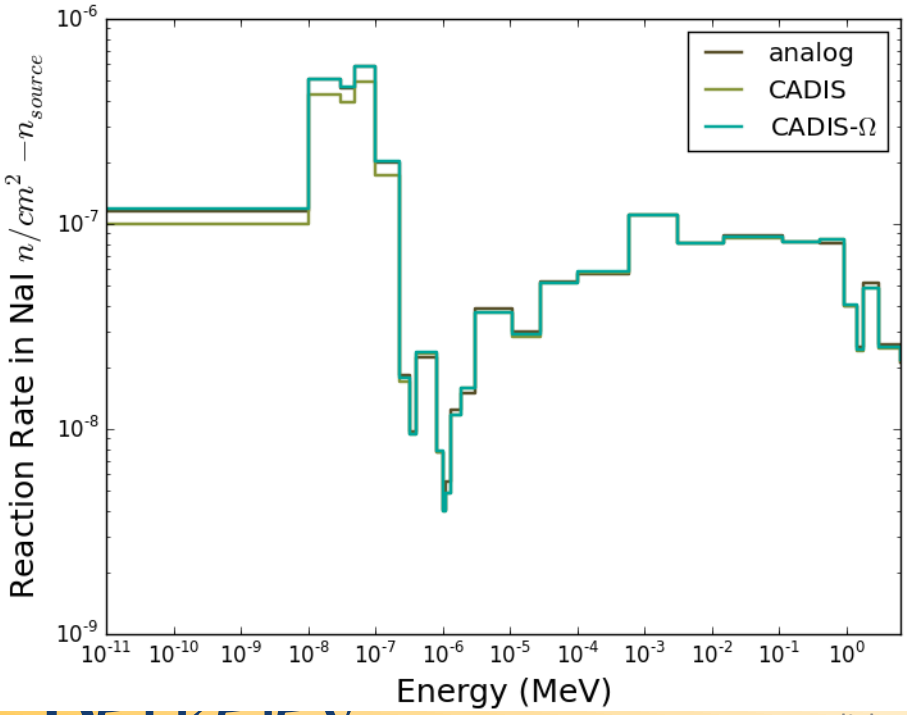
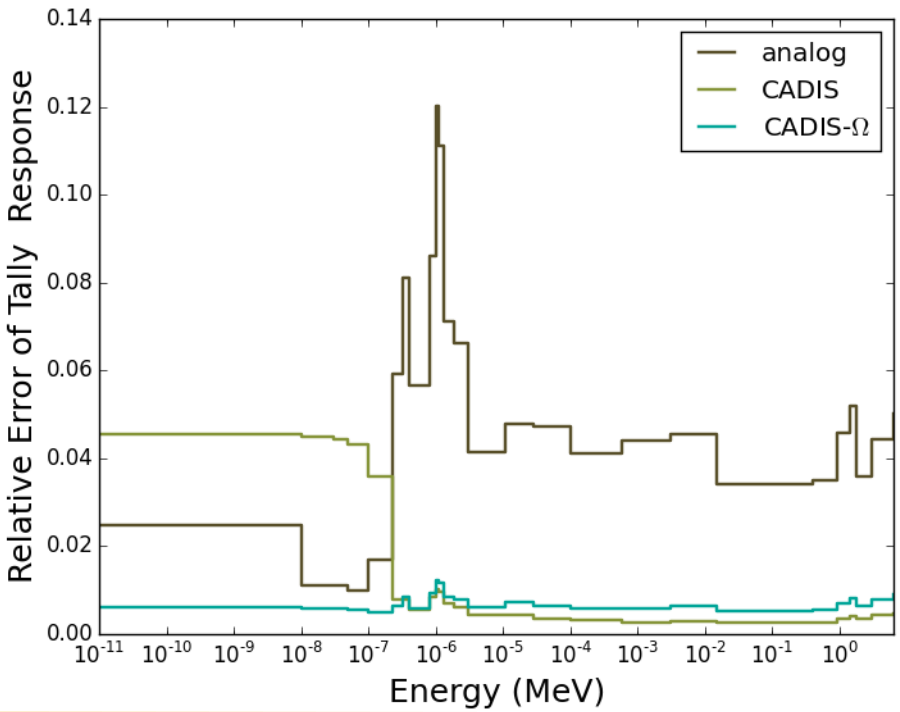
CADIS and CADIS-Ω Importance Maps



Results

… Indicate that CADIS-Ω outperforms CADIS for this problem





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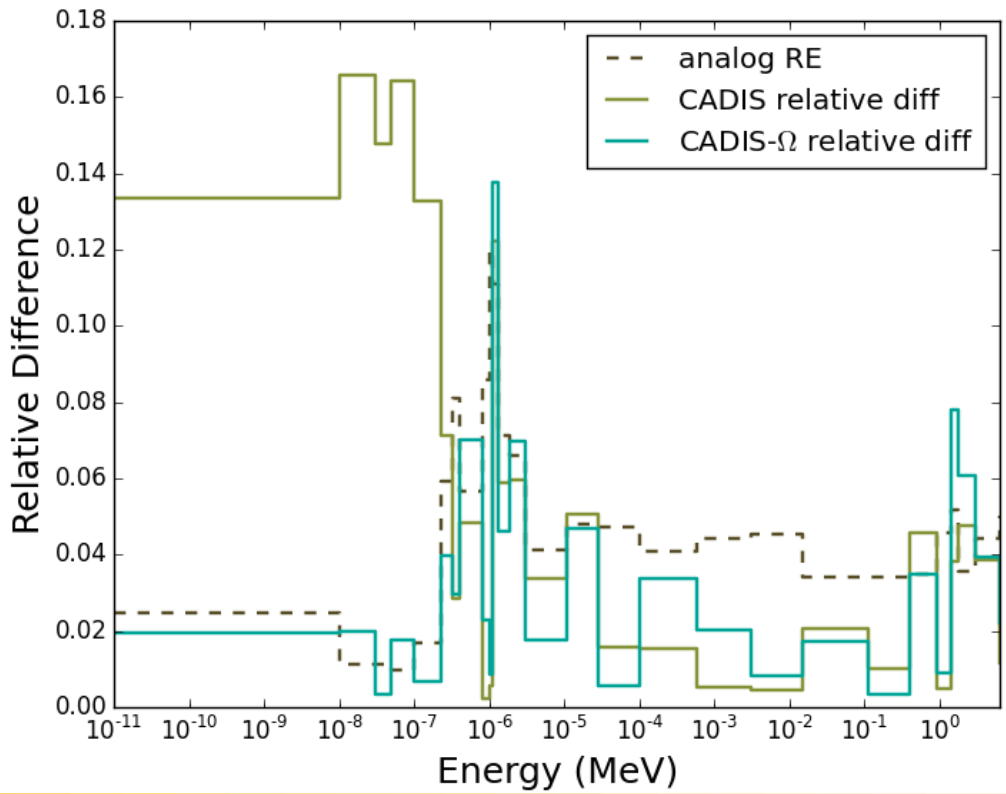

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Results Varying P_N Order

Table I: Method Performance Change with P_N Order				
P_N Order	**Type**	**MCNP time** (minutes)	**Denovo time** (minutes)	**Monte Carlo FOM**
Two	Analog	62.4	0.0	523.0
	CADIS	409.7	40.3	12.0
	CADIS-Ω	326.2	80.7	138.0
Three	CADIS	483.4	41.5	5.1
	CADIS-Ω	408.9	83.0	145.0
Four	CADIS	400.7	45.5	6.2
	CADIS-Ω	266.6	91.0	291.0

Results Varying Quadrature Order

Table II: Method Performance Change with Quadrature Order				
Quadrature Order	**Type**	**MCNP time** (minutes)	**Denovo time** (minutes)	**Monte Carlo FOM**
Six	Analog	62.4	0.0	523.0
	CADIS	3325.5	22.0	2.20E-02
	CADIS-Ω	558.1	43.9	122.0
Ten	CADIS	483.4	41.5	5.1
	CADIS-Ω	408.9	83.0	145.0
Fourteen	CADIS	514.4	76.0	3.2
	CADIS-Ω	423.1	152.0	129.0

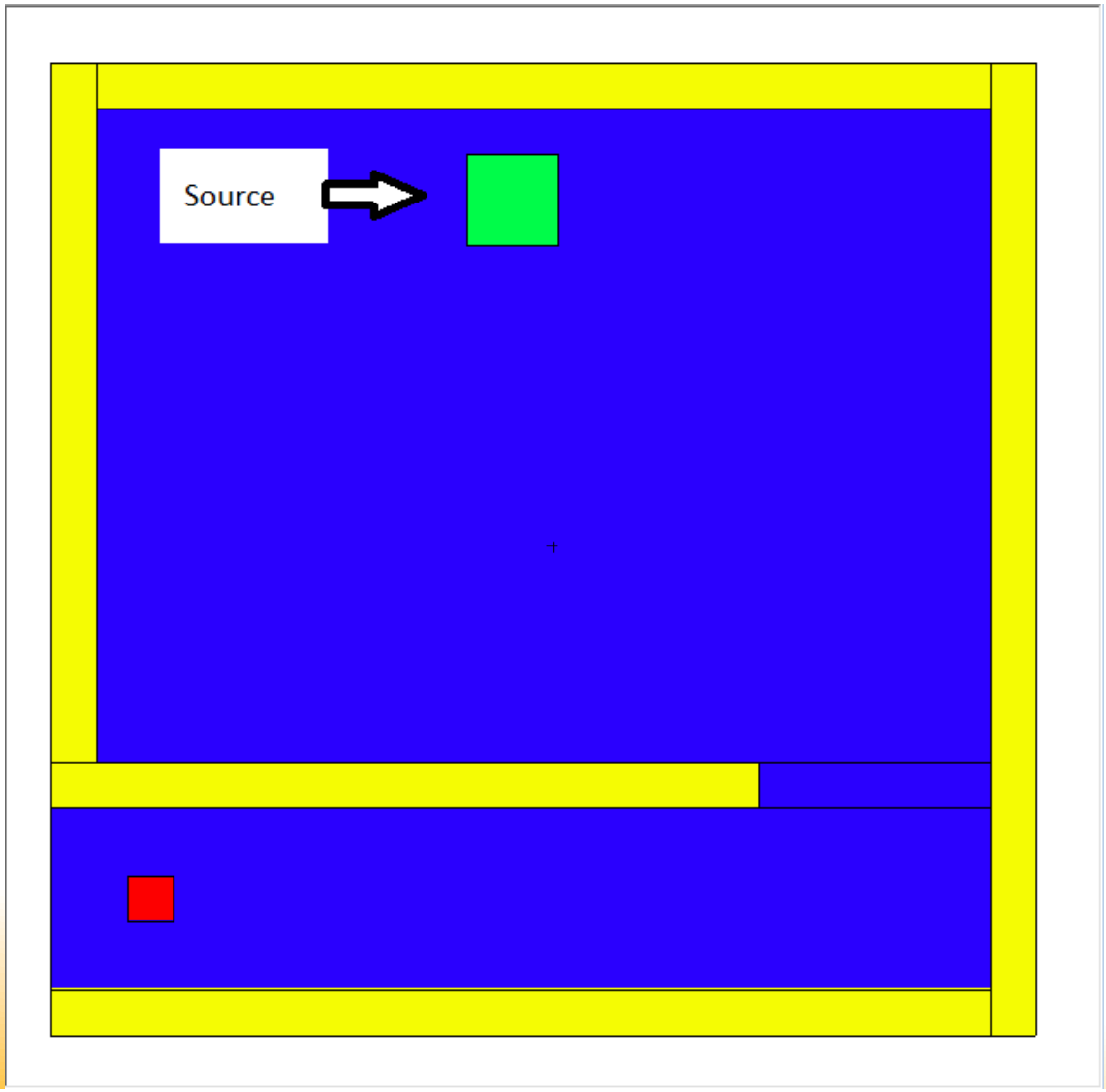
Testing The Method: Characterization Problems

Increasing complexity

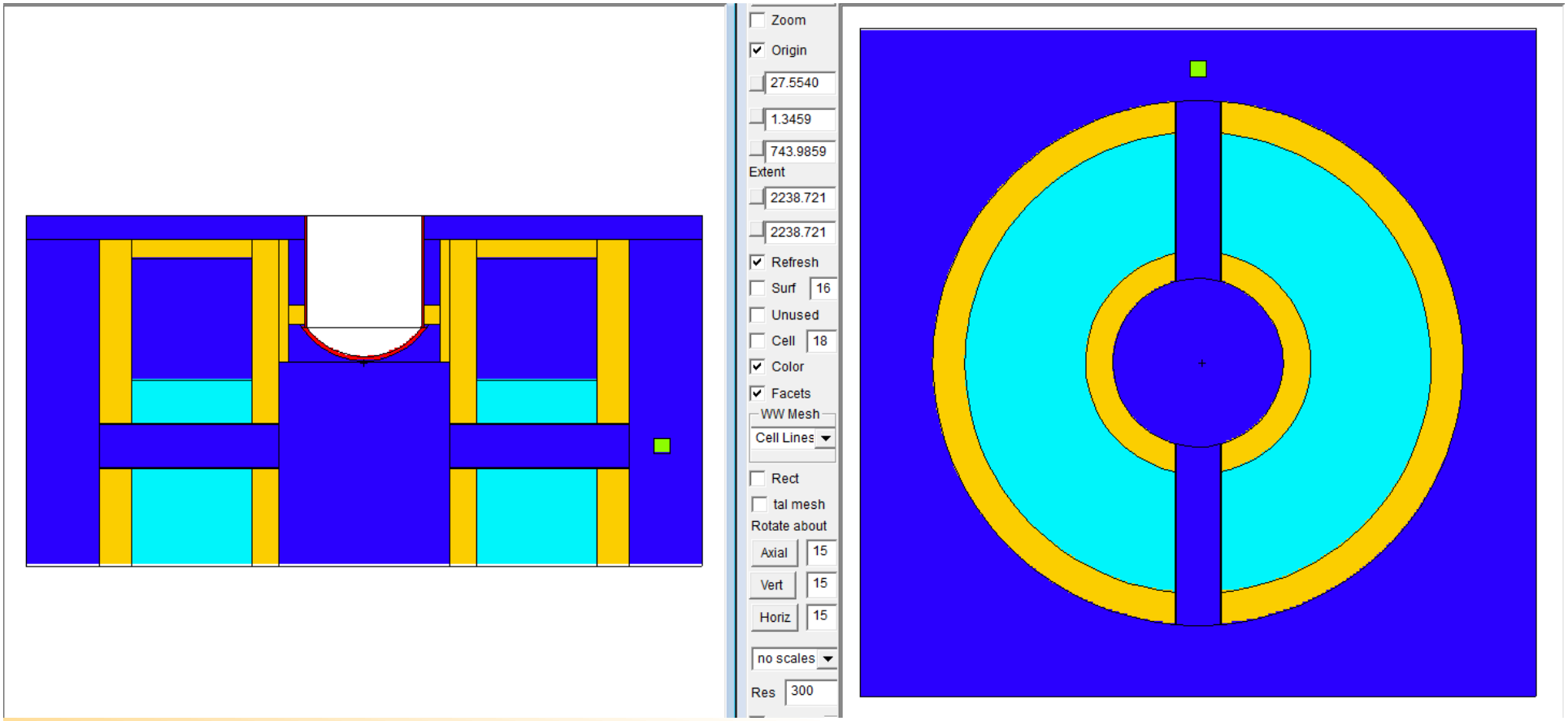
Problem Name	Problem Coverage			
	Streaming Paths	Highly Scattering	Highly Heterogeneous	Mono-Directional Source
Streaming Channel	X		X	X
Metal Plate		X	X	
Spherical Boat	X	X	X	X
Labyrinth Variants	X	X	X	

Challenge Problems

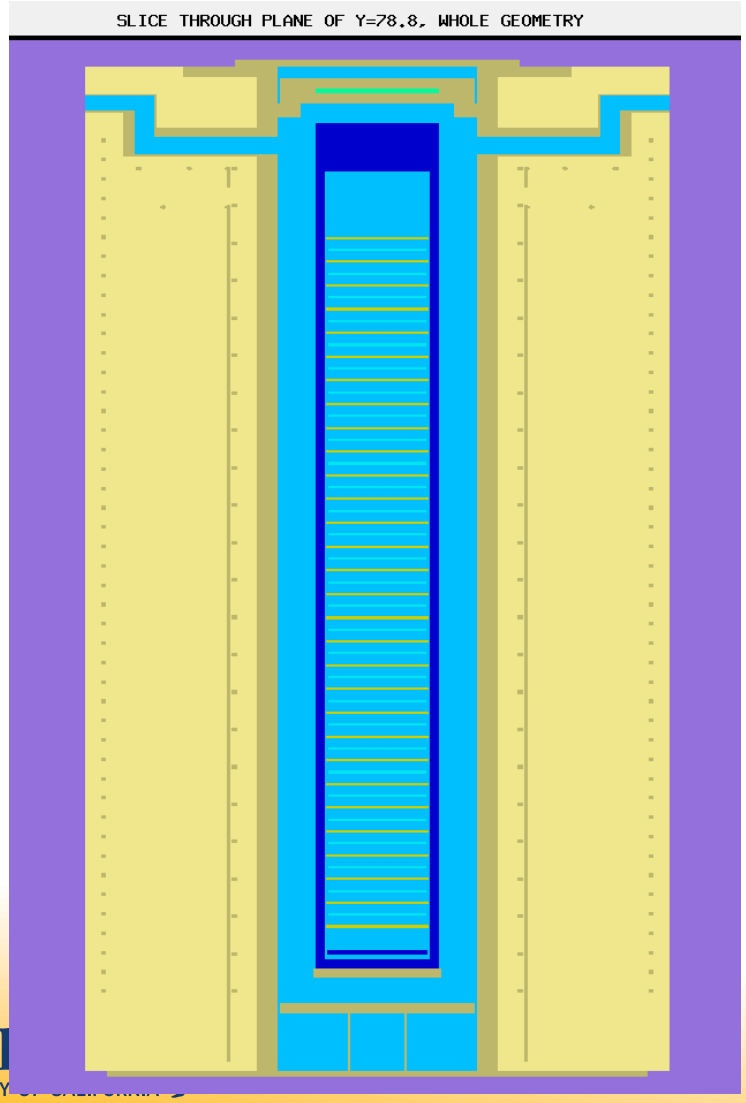
Simple Geometries with Real World Applications

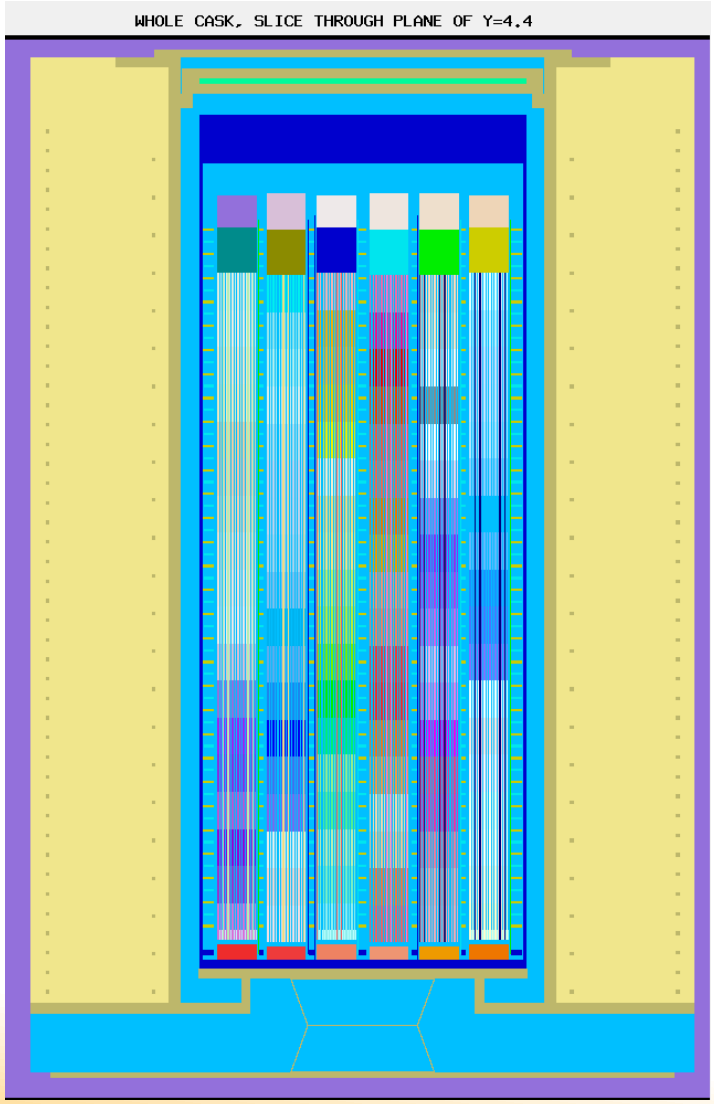


.. And Extended to Increasingly Complex Systems



.. To Show Applicability to Real World Problems





Concluding Remarks

The CADIS-Ω method:

- Captures problem physics more effectively by normalizing the contributon flux by the forward flux.
- Demonstrates an ability to more **evenly distribute the uncertainty** distribution in an f4 tally.
- Has significantly **stronger performance than CADIS** for a deep-penetration shielding problem.
- Exhibits a **dampening of ray effects** in regions where the forward and adjoint fluxes are perpendicular.
- Has effective **capture of streaming behavior** out of problem ducts.
- Does **not completely negate low-importance regions** (e.g. the region behind the detector in the void BC problem)
- FOM comparison to the analog MC maze is consistently lower; for other problems this may not be the case.

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Dr. Seth Johnson

Dr. Tom Evans

Questions?

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AVATAR

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Simple Angular CADIS

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18/19 : Denovo

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21: Ray Effects Image

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