MULTI-GRID GENETIC ALGORITHMS FOR OPTIMAL RADIATION SHIELD DESIGN

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PhD Defense
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Overview

- The objectives
- A shield-based introduction to GA and MGGA
- Designing a shadow shield
- Designing a gamma shield
- Designing a bowtie filter
- Conclusions

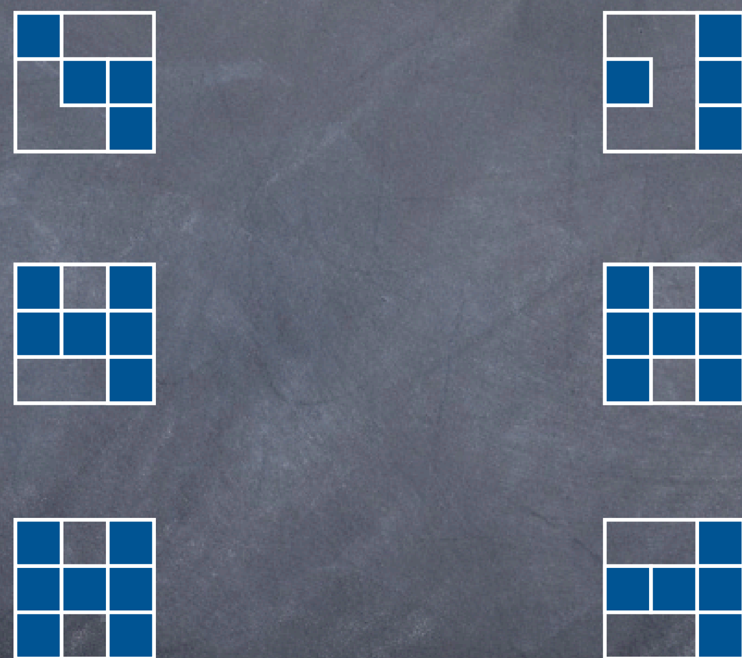
The Objectives

1. Determine if GA can be used to help find innovative shield designs

2. Determine if MGGA works, and if it can save computing resources compared to GA

Consider a Shielding Problem You Want to Explore

Start with a Bunch of Random Candidate Shields



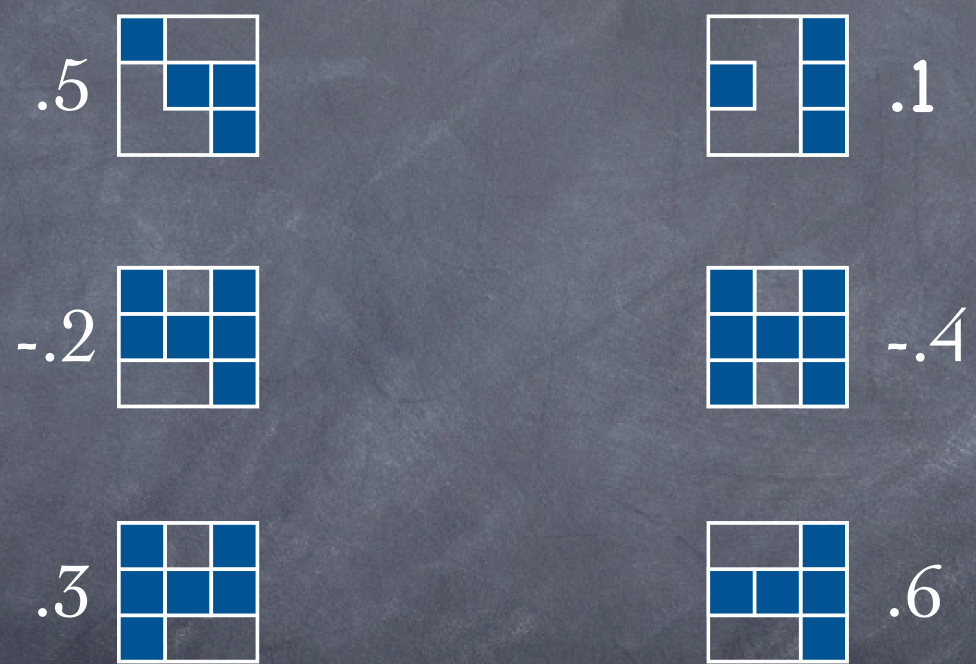
Call this a generation

Encode Each Shield into a Manageable Form

1 0 1 1 1 1 1 0 1

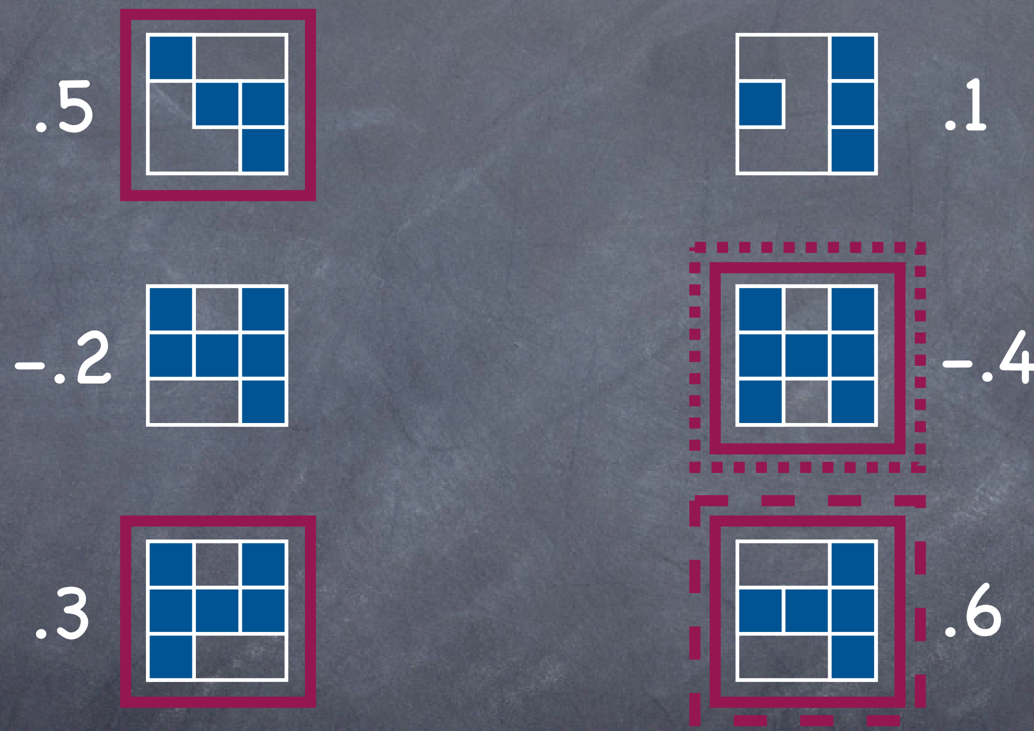
Call this encoded version a chromosome

Apply a Fitness Function



The fitness function captures your idea of what it means to be a good shield.

Pick A Shield via a Tournament

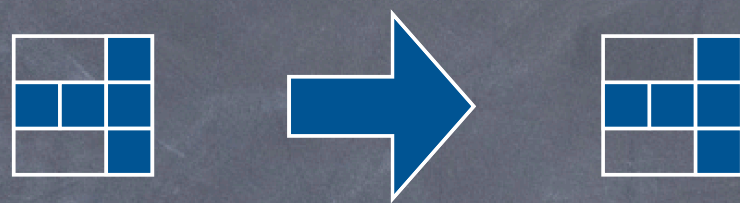


- Randomly pick several shields (4)
- Usually pick the best (75%), sometimes pick the worst (25%)

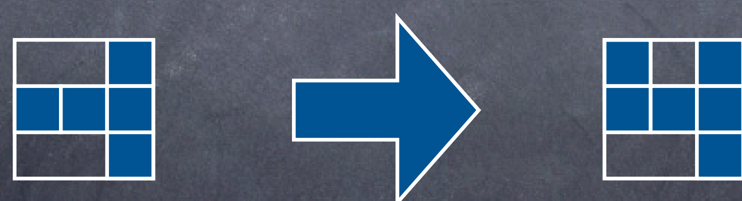
Maybe - copy (10%)

Take a tournament winner

Put it in the next generation



Maybe - mutate (20%)



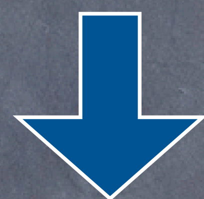
Take a tournament winner

Change it

Put it in the next generation

Maybe - combine 2 shields using crossover (70%)

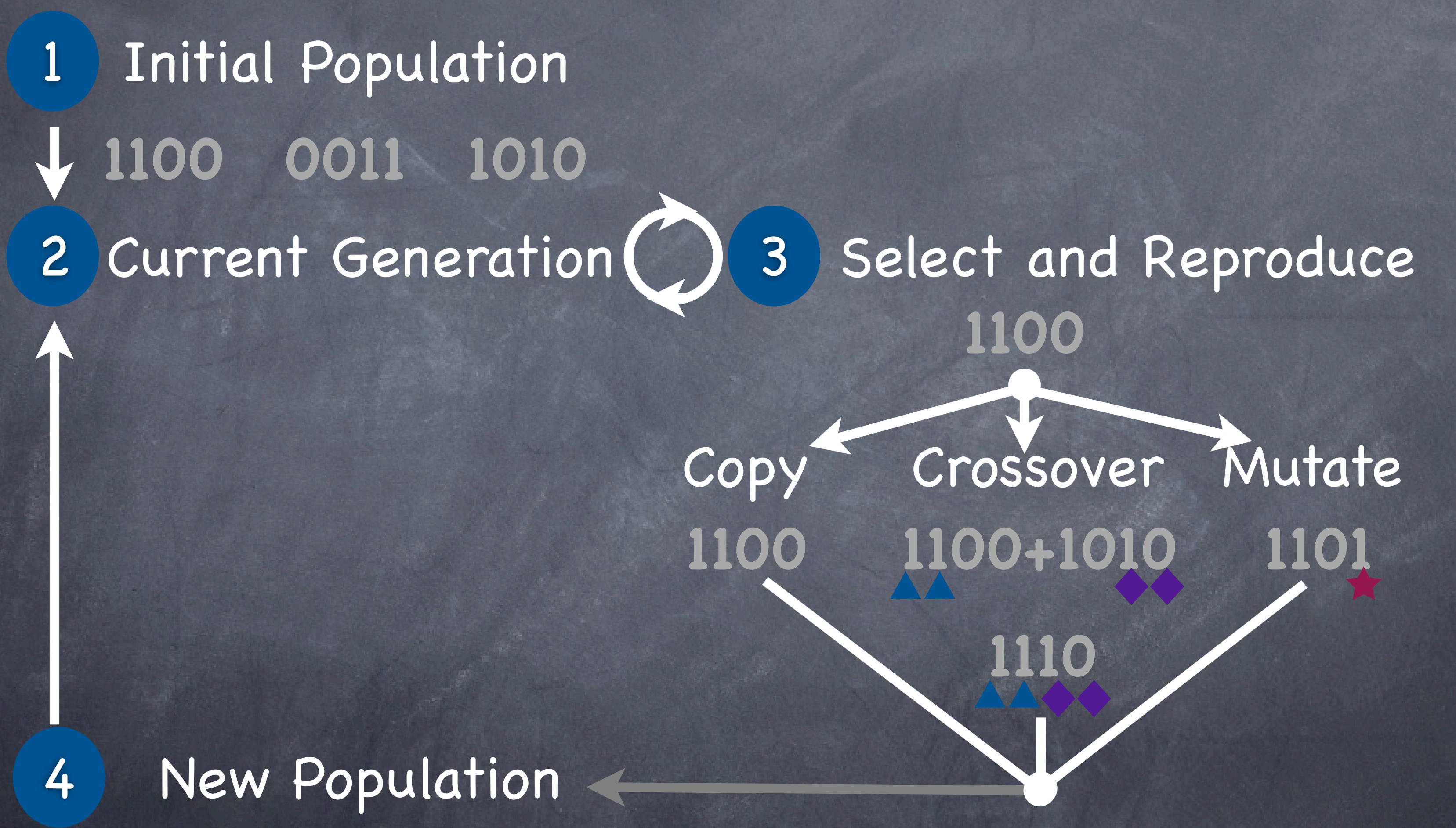
Take a tournament winner



And another tournament winner

Combine them using crossover to create two new individuals, put them in the next generation

Iterate

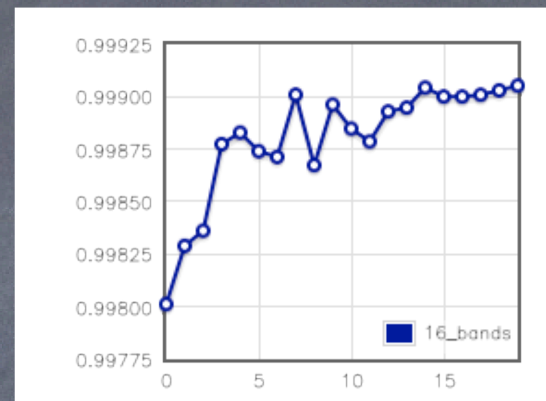


Keep iterating until your termination condition is met

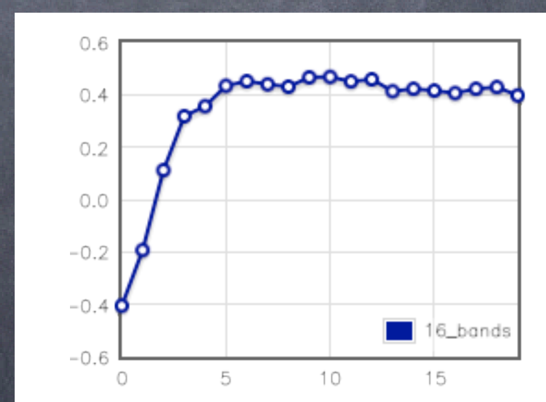
Why Does GA Work

- Chromosomes encode useful building blocks
- Crossover combines building blocks
- Mutation adds diversity to avoid local maxima
- The fitness function ranks individuals for selection

Best Fitness



Average Fitness

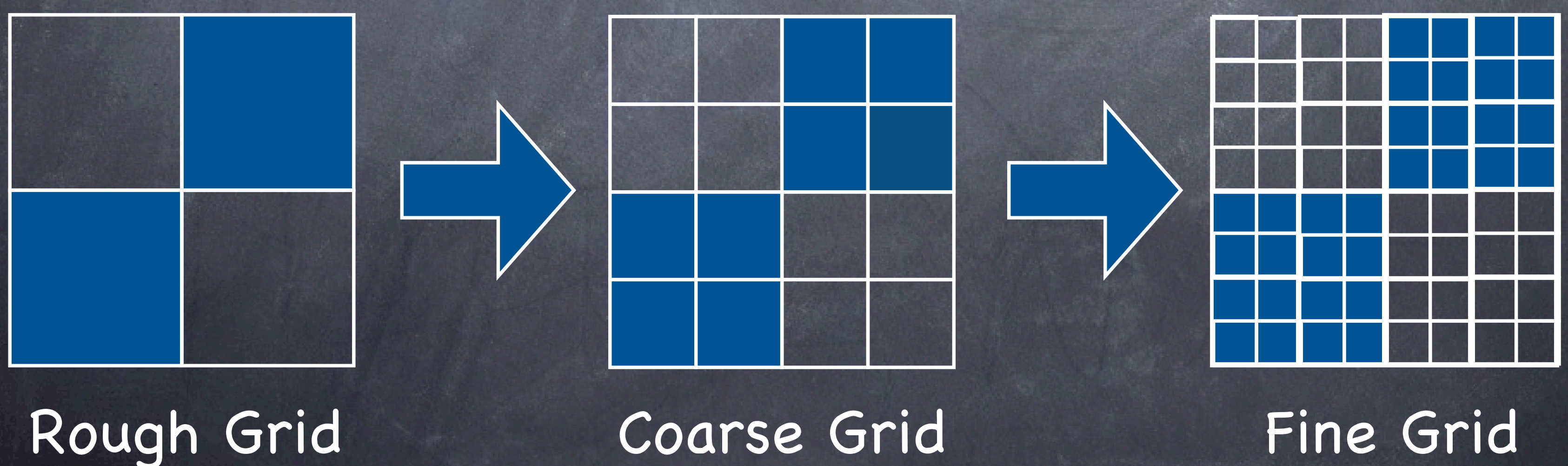


GA for Expensive Problems

- Fitness function calls can be distributed on a cluster
  - Genetik leverages the UM cluster to scavenge resources within existing constraints
- MGGA is a new meta-algorithm for GA that uses recursive refinement of the problem space to generate building blocks more efficiently - saving fitness function evaluations

Multi-Grid Genetic Algorithms

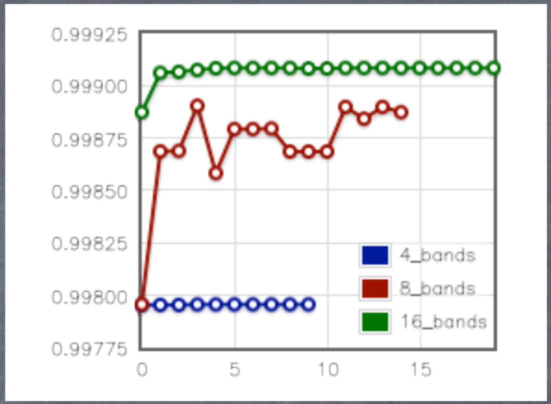
- Break the problem into phases based on geometric scaling
- Run GA on at each phase
- Translate individuals between phases



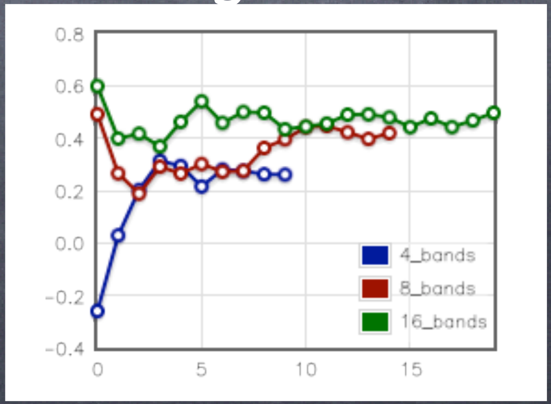
Why does MGGA Work

- Complex building blocks and parts of complex building blocks from later phases can be created in earlier phases where they are less complex
- Very large problem spaces, from later phases, are seeded with better than random individuals from the start

Best Fitness



Average Fitness



How do we shield a nuclear spacecraft?

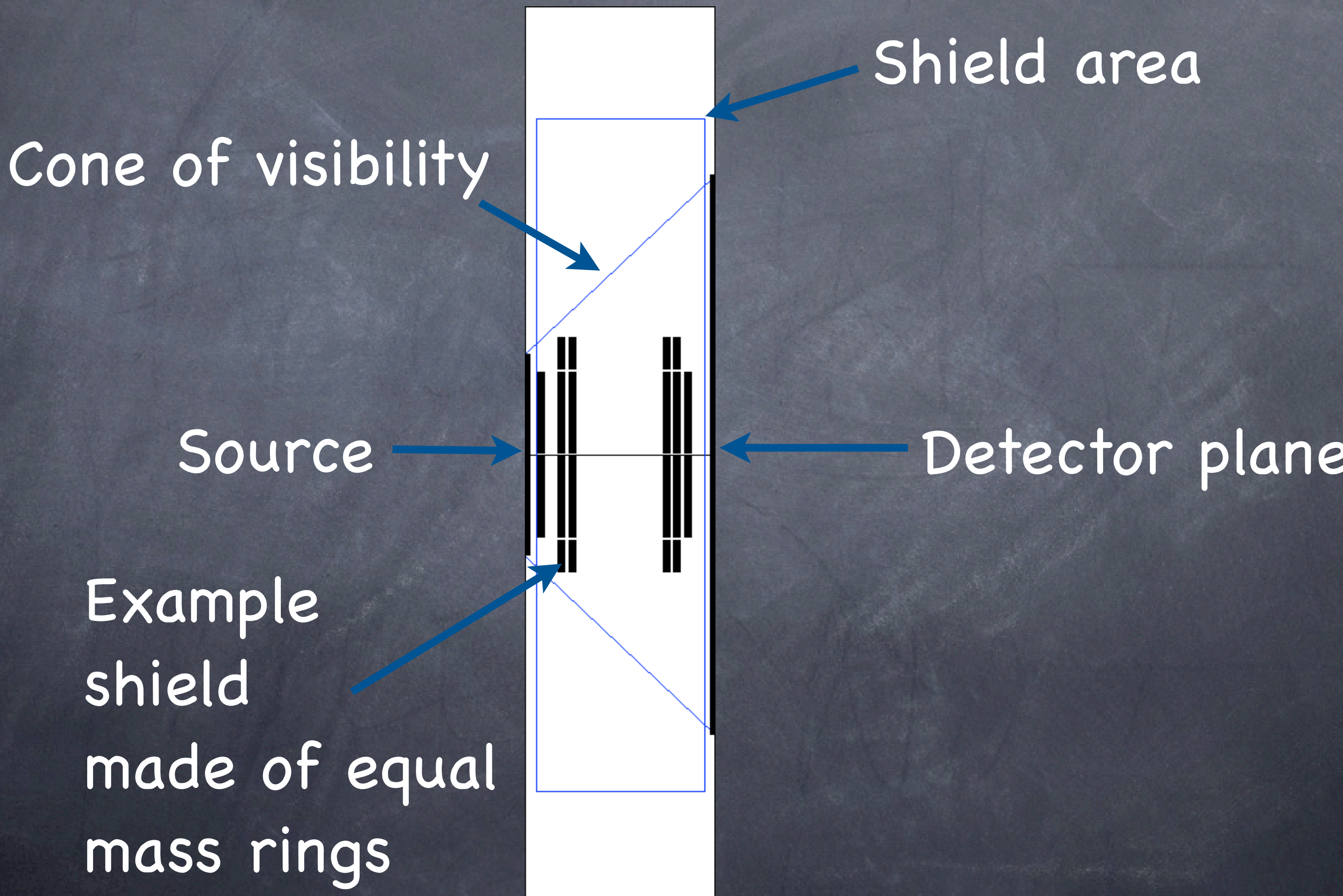
Designing A Shadow Shield

- Alpay and Holloway have discovered that the obvious shield isn't the best shield (2005)
- Splitting a shield helps, could there be an even more interesting result?
- Can MGGA help find an unexpected shield?

Obvious Shield

Improved Shield

Shadow Shield Geometry

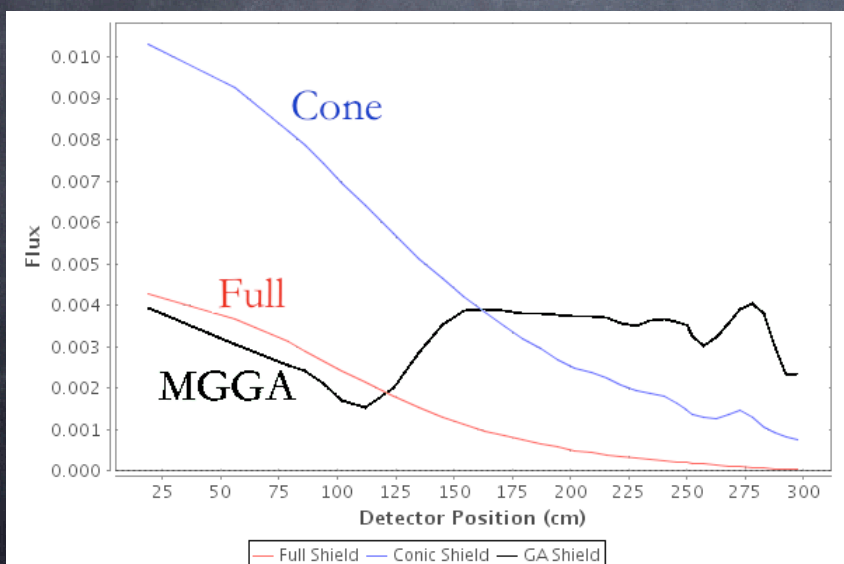


Two Fitness Functions

Max Flux

$$F(s) = \begin{cases} \min_i \left(1 - \frac{\phi_i}{\phi_i(S)}\right) & \text{if } \max_k(\phi_k(S)) < \phi_i(s) \text{ for any } i \\ 1 - \frac{m(s)}{m(S)} & \text{otherwise.} \end{cases}$$

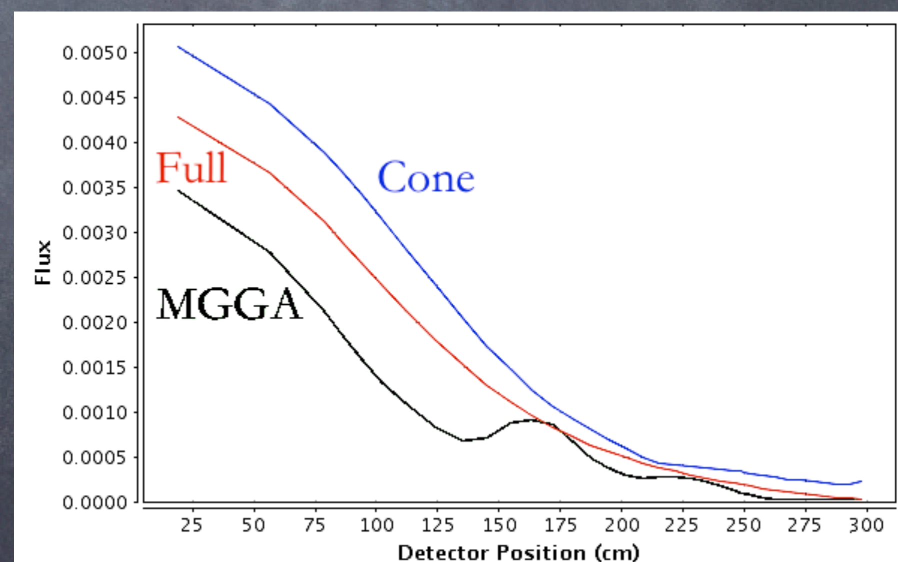
Beat the full (heaviest) shield at its worst detector



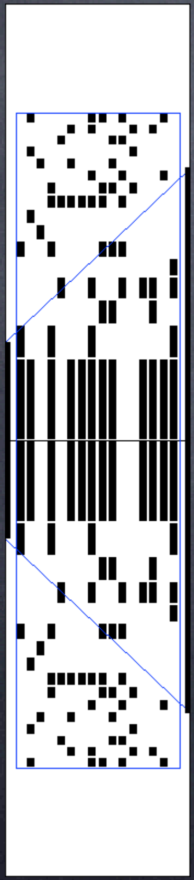
ByLocation

$$F(s) = \begin{cases} \min_i \left(1 - \frac{\phi_i}{\phi_i(S)}\right) & \text{if } \phi_i(S) < \phi_i(s) \text{ for any } i \\ 1 - \frac{m(s)}{m(S)} & \text{otherwise.} \end{cases}$$

Beat the full (heaviest) shield at each detector



Results for "Max Flux"

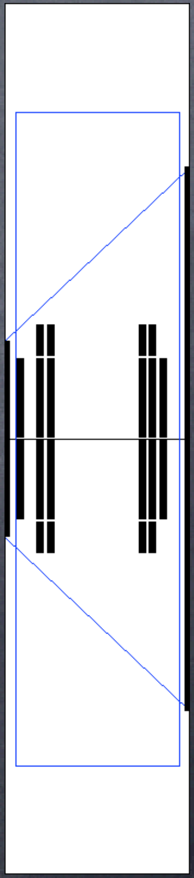


GA

- Fitness = .75
- Cells = 64
- Passed max flux
- Scored on mass
- 16x16 grid
- Tested at most 10,620 shields

MGGA

- Fitness = .96
- Cells = 10
- Passed max flux
- Scored on mass
- 2x2 -> 4x4 -> 8x8 -> 16x16 grid
- Tested at most 10,600 shields



1.16×10^{77} Possible Shields

Results for "Max Flux" 32x32

GA

- Fitness = .5
- Cells = 509
- Passed max flux
- Scored on mass
- Tested at most 15,000 shields

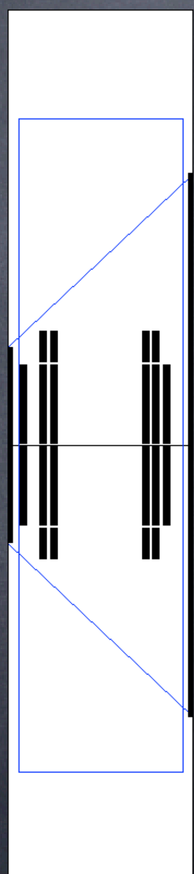
MGGA

- Fitness = .956
- Cells = 45
- Passed max flux
- Scored on mass
- Tested at most 13,000 shields

1.8 x 10^{308} Possible Shields

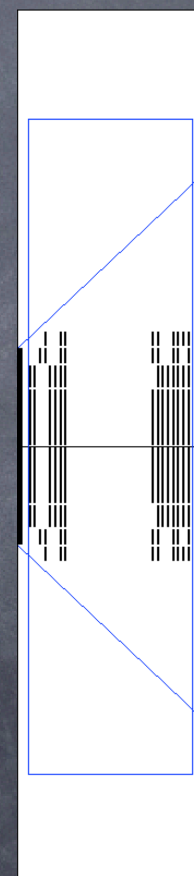
16x16 vs. 32x32

16x16



- Both have a fitness over 0.9
- Both passed flux test
- Very similar geometry

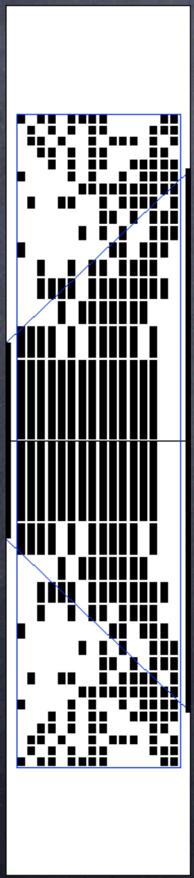
32x32



Results for ByLocation

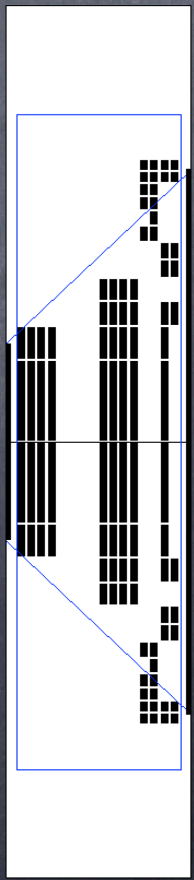
GA

MGGA



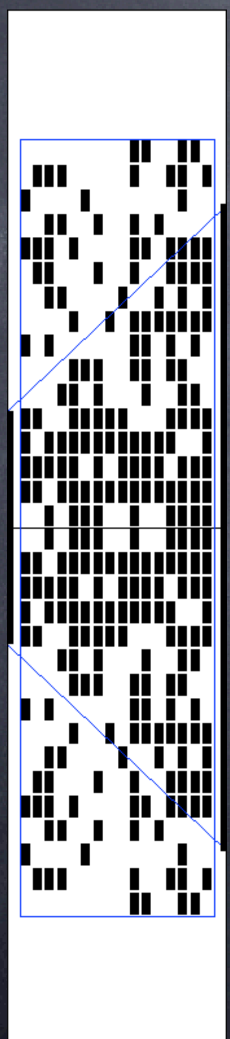
- Fitness = .45
- Cells = 140
- Passed flux by location test
- Scored on mass
- Tested at most 10,620 shields

- Fitness = .81
- Cells = 47
- Passed flux by location test
- Scored on mass
- Tested at most 10,600 shields



1.16×10^{77} Possible Shields

Non-Equal Mass Rings

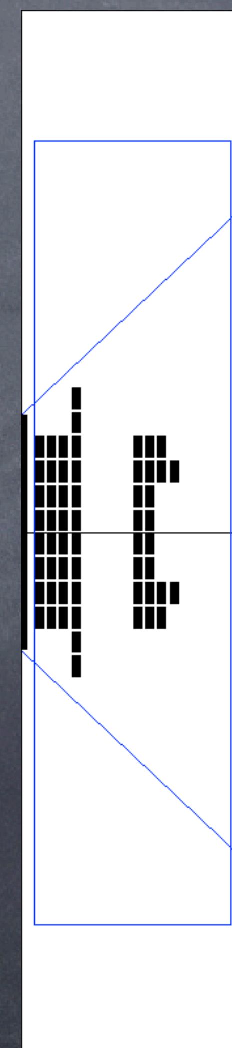


GA

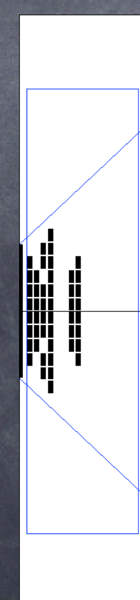
- Fitness = 0.572
- Passed flux test
- Scored on mass
- Tested at most 10,620 shields

MGGA

- Fitness = 0.9675
- Passed flux test
- Scored on mass
- Tested at most 10,600 shields



- MGGA opened up interesting scatter paths

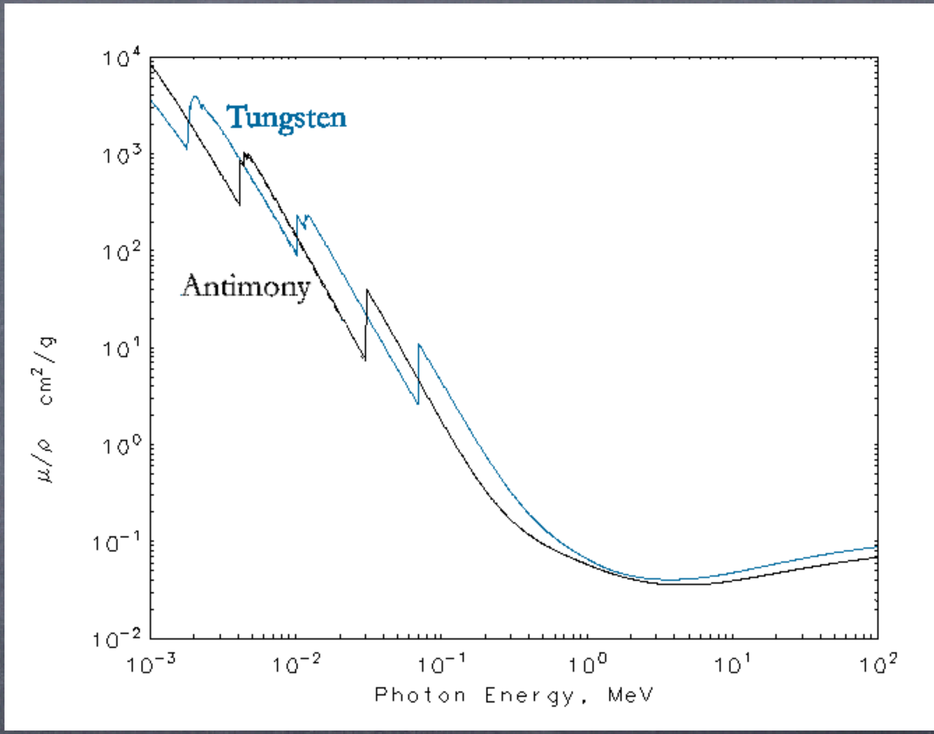


1.16×10^{77} Possibles

How do we shield radiation workers and first responders?

Designing A Gamma Shield

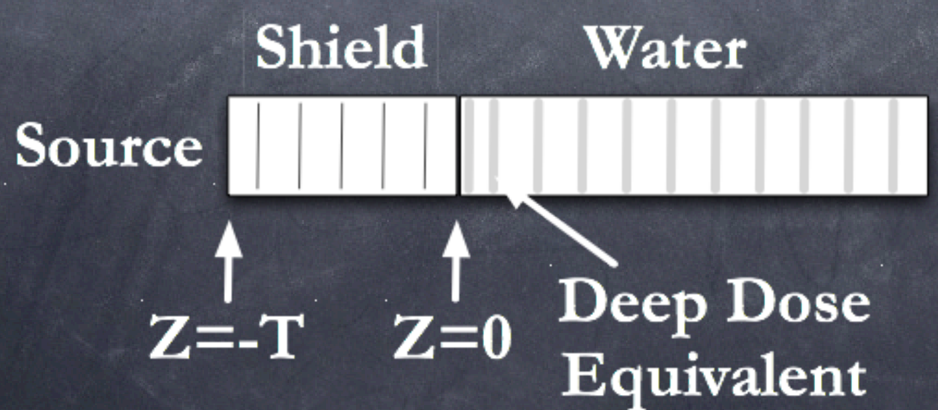
- McCaffrey, et.al. showed that low-Z/high-Z layering can beat an equal mass lead shield (2009)
- Can MGGA organize layers to take advantage of atomic physics?



$$F(s) = \begin{cases} 1 - (D(s) \times 1000) & \text{if } m(s) < m(S) \\ -\frac{m(s)}{m(S)} & \text{otherwise.} \end{cases}$$

Low Energy Setup

- Consider a shield of width T separated into layers
- Place a mono-energetic gamma source on one side
- Place water on the other side, and tally the dose at various depths



Slab Geometry Results

- <20,000 shields - GA
- <17,500 shields - MGGA
- 16 layers for GA
- 4,8 and 16 layers for MGGA
- 3.32×10^{13} possible shields

Energy	Fitness	Reduction %	Algorithm
50 kev	0.99996	79.69	GA
50 kev	0.99994	67.7	MGGA
75 kev	0.99905	83.54	GA
75 kev	0.99908	84.09	MGGA
100 kev	0.9973	31.02	GA
100 kev	0.9967	15.57	MGGA
150 kev	0.9796	1.313	GA
150 kev	0.9793	0.158	MGGA
200 kev	0.9459	1.319	GA
200 kev	0.9453	0.203	MGGA

GA 50kev

SRC	Sn	Sb	Sn	Sn	Sn	Sb	Sb	..	..	..	Sb	Sn	..	Sn	Bi	Bi

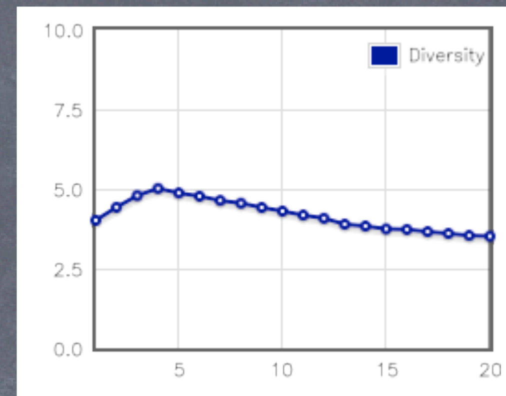
SRC	..	..	..	W	W	W	Sn	..	..	Sn	..	..	Sb	Pb	..	..

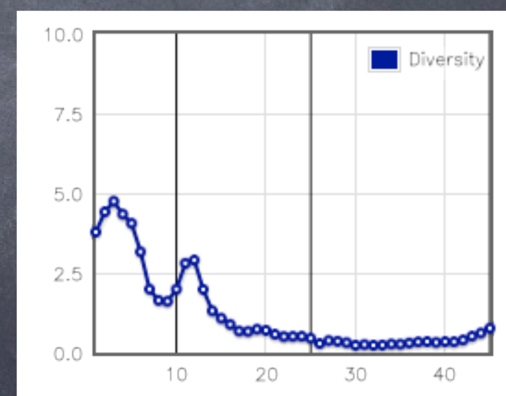
MGGA 75kev

Why isn't MGGA Winning?

- There aren't a lot of complex building blocks to carry through phases
- Later phases get locked into locally good solutions

GA





MGGA

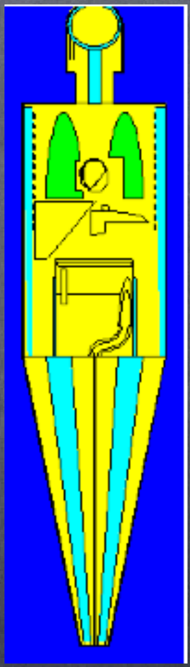
SRC	..	Sn	Sn	Sn

SRC	..	..	Sn	Sn	Sn	Sn	Sn	Sn

SRC	..	..	..	..	Sn	Sn	Sn	Sn	Al	Sn	Sn	Sn	Sn	Bi	Sn	Bi

The ORNL Phantom

- Consider a realistic human phantom
- Wrap the torso, head and groin with a shield
- Calculate a total body dose (minus the legs)
- Can a layered shield beat a lead shield of equal mass?



$$F(s) = \begin{cases} 1 - D(s) & \text{if } m(s) < m(S) \\ -\frac{m(s)}{m(S)} & \text{otherwise} \end{cases}$$

Results on the ORNL Phantom

- 16 layers for GA
- 4, 8, 16 layers for MGGA
- MGGA tested 22,500 shields
- GA tested 20,000 shields

Energy	Reduction %	Algorithm
50 kev	11.368	MGGA
50 kev	10.98	GA
75 kev	66.89	MGGA
75 kev	65.4	GA
100 kev	27.62	MGGA
100 kev	22.65	GA

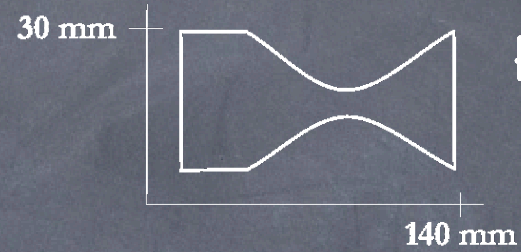
MGGA 75kev

2.65×10^{30} Possible Shields

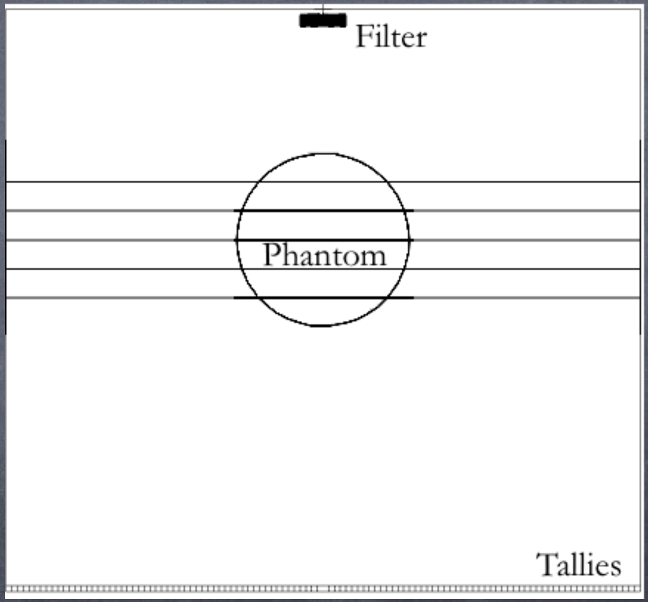
Can We Shape Fluence?

Designing A Bow-Tie Filter

- Filters are often used to shape radiation (Mail 2009)
- Can MGGA shape the profile of scattered to total flux on a target plane?

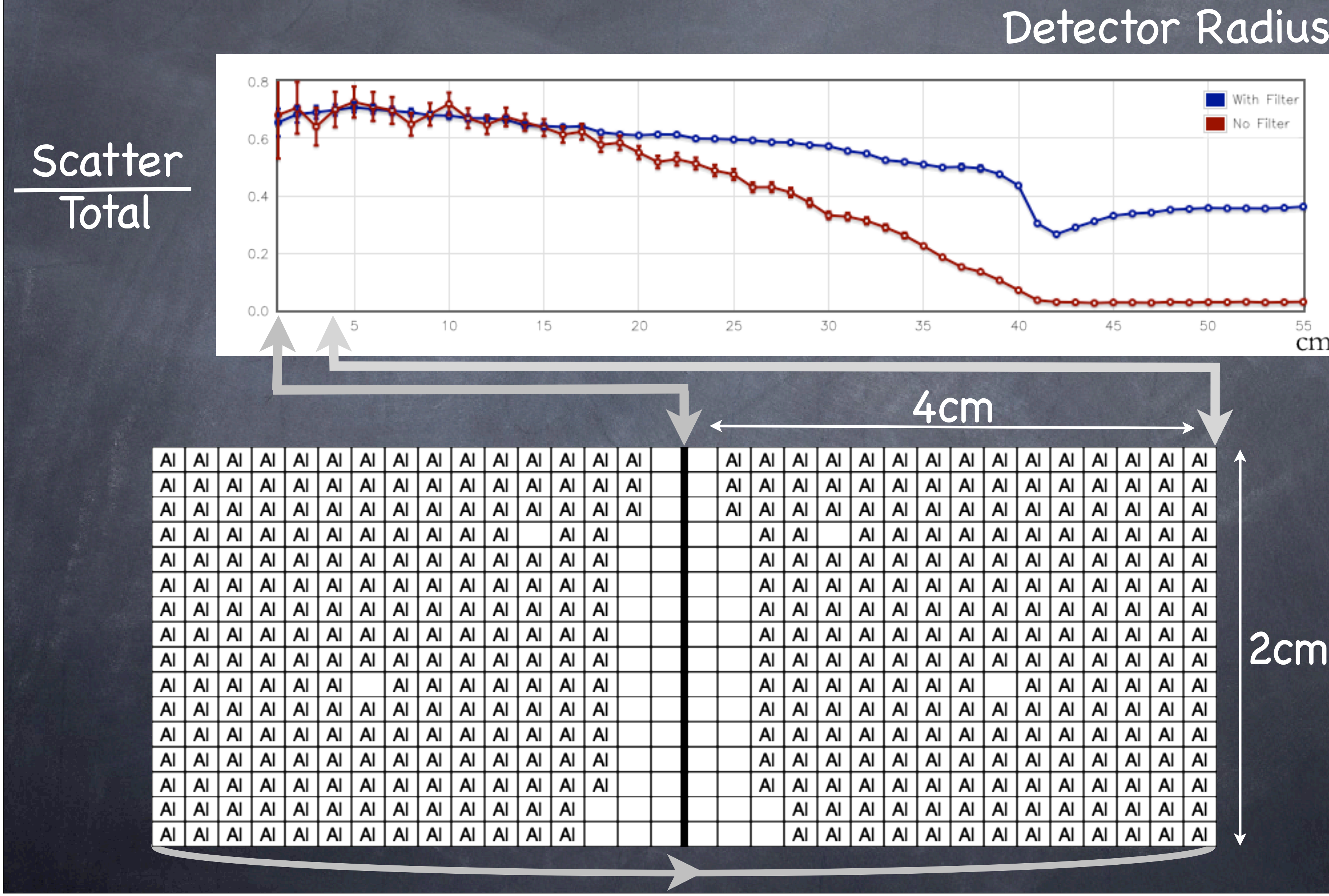


Prototypical Bowtie



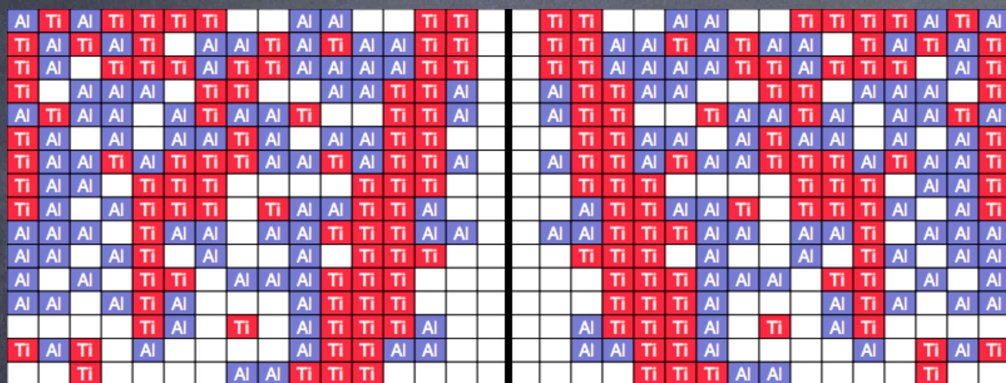
$$F(s) = \begin{cases} 1 - 1000 \times \text{count of zero tallies} & \text{if any tallies are zero} \\ 1 - \frac{1}{N}\sum_{i=0}^{N}\left(\frac{\phi_s(i)}{\phi_t(i)} - \langle\frac{\phi_s}{\phi_t}\rangle\right)^2 & \text{otherwise} \end{cases}$$

Results With Aluminum

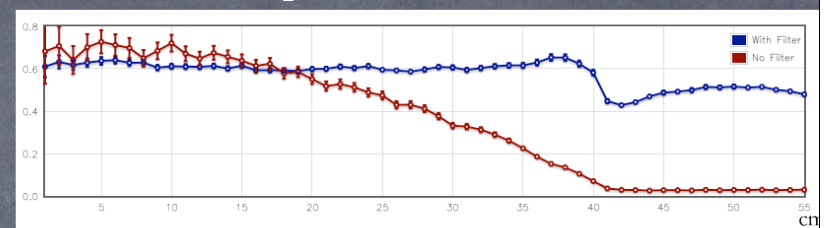


Results at 120kev

GA

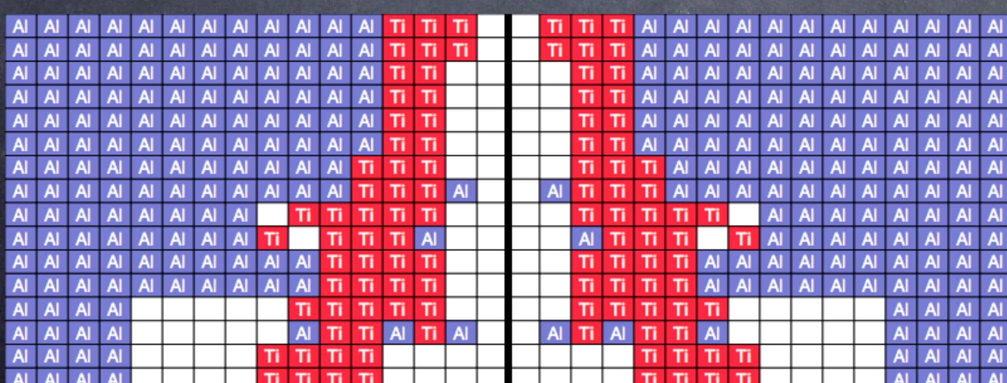


- Fitness = 0.996
- 22,500 tested
- 16x16 grid

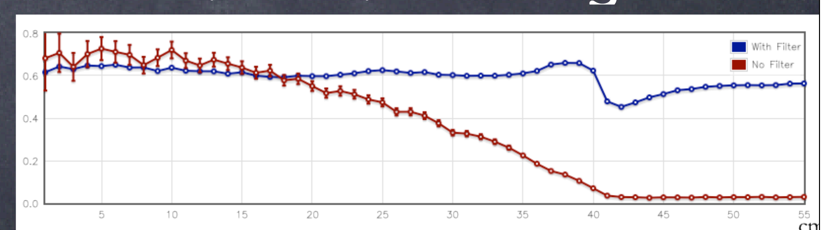


1.4 x 10^{122} Possible Shields

MGGA



- Fitness = 0.997
- 22,500 tested
- 4x4, 8x8, 16x16 grid



Future Work

- Look into different ways to tune MGGA
  - Selection during phase translations
  - Adding diversity during translations
  - Using different GA parameters at each phase (tournament selection, mutation rate)
- Investigate using physical error in fitness functions
- Simulate larger, more realistic geometries, using more computing resources

Summary

- MGGA beat GA on fitness in most cases
- MGGA beat GA on time in all cases
- MGGA provided interesting design paths
  - Detailed neutron scattering paths
  - Lightweight, layered gamma shield
  - Manufacturable multi-element bow-tie filter
- MGGA provides a powerful investigative design tool

Thank You

*This work was supported in part by DTRA grant number HDTRA1-08-1-0043

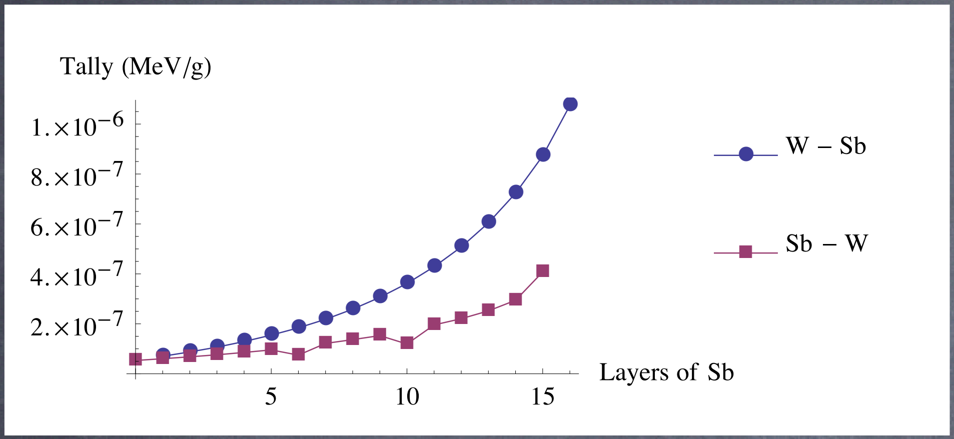
Backup Slides

Why LiH?

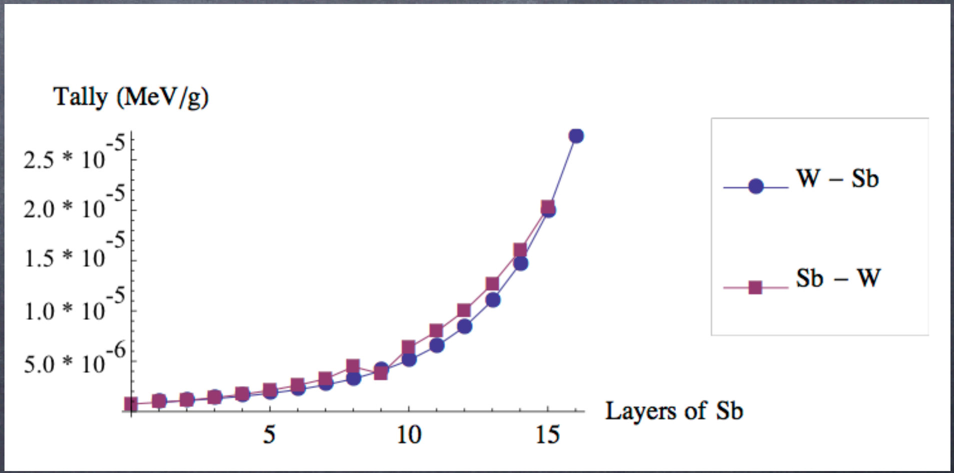
- Lightweight
- Hydrogen slows fast neutrons
- Li helps absorb slow neutrons
- Minimal gamma
- Common choice in the literature

High Z - Low Z

50 kev



100 kev



Ti-Al Cross sections