Sustainable HEP 2026 — 5th Edition

Reducing simulation-related emissions in rare-event searches through optimised event biasing

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Birmingham Gaseous Detectors Laboratory

DM Direct Detection Landscape

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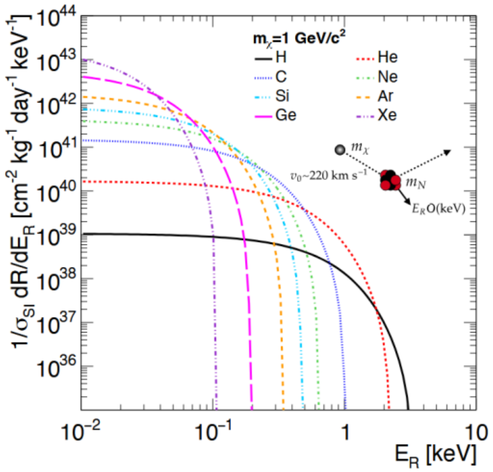
DM direct detection now reaching two extreme frontiers:

- High exposure, **extremely low background**
- Low recoil energies, **very low thresholds**

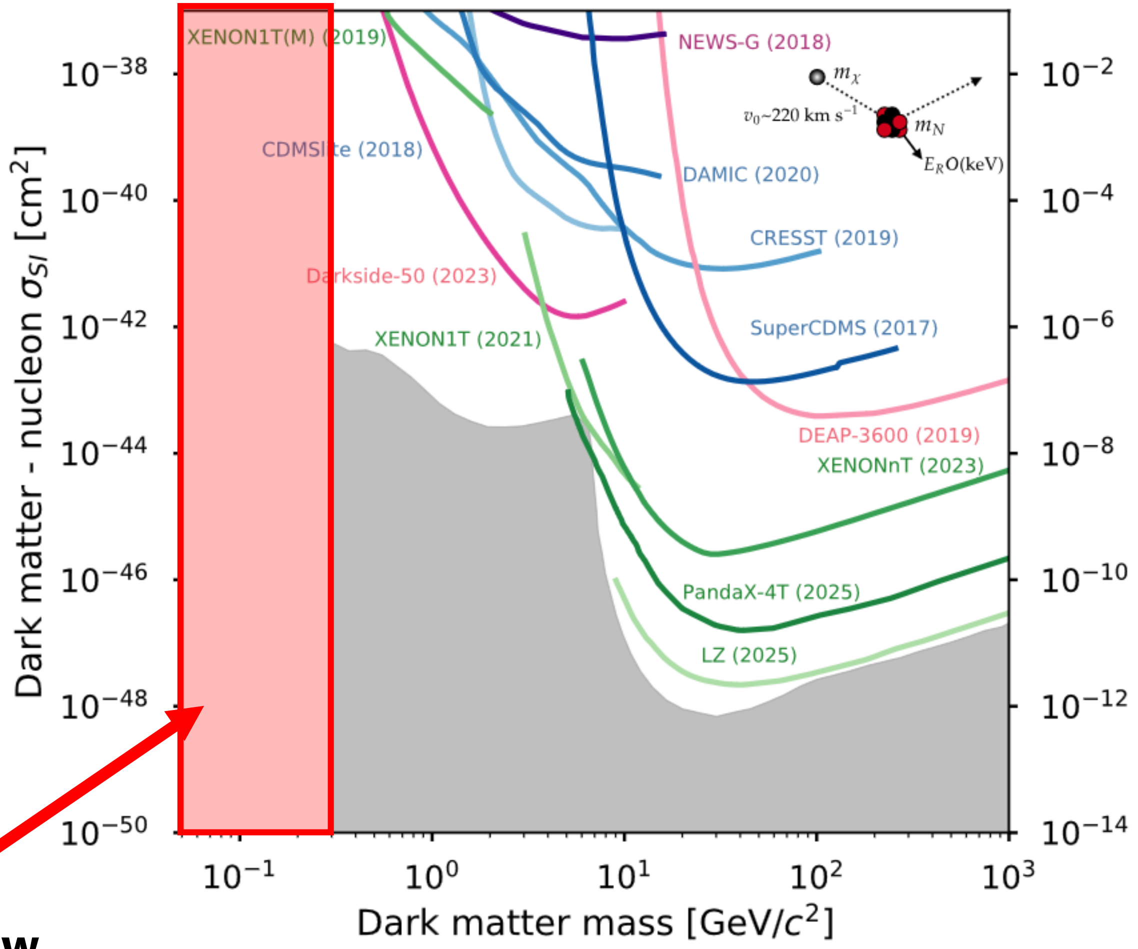
Background simulations **computationally expensive** without event biasing

- Particularly for **shielding studies – ~ 1 in 1 million events survive**

How can we best **optimise our biasing** to reduce computational load, thus **manage our carbon footprint**



Unexplored low mass region – light dark matter



Higher Exposure

Lower Threshold/Lighter Nuclei

Simulation Biasing Schemes

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Biasing or “variance reduction” techniques aim to reduce the relative uncertainty (RU) of a simulation, for a given computation time

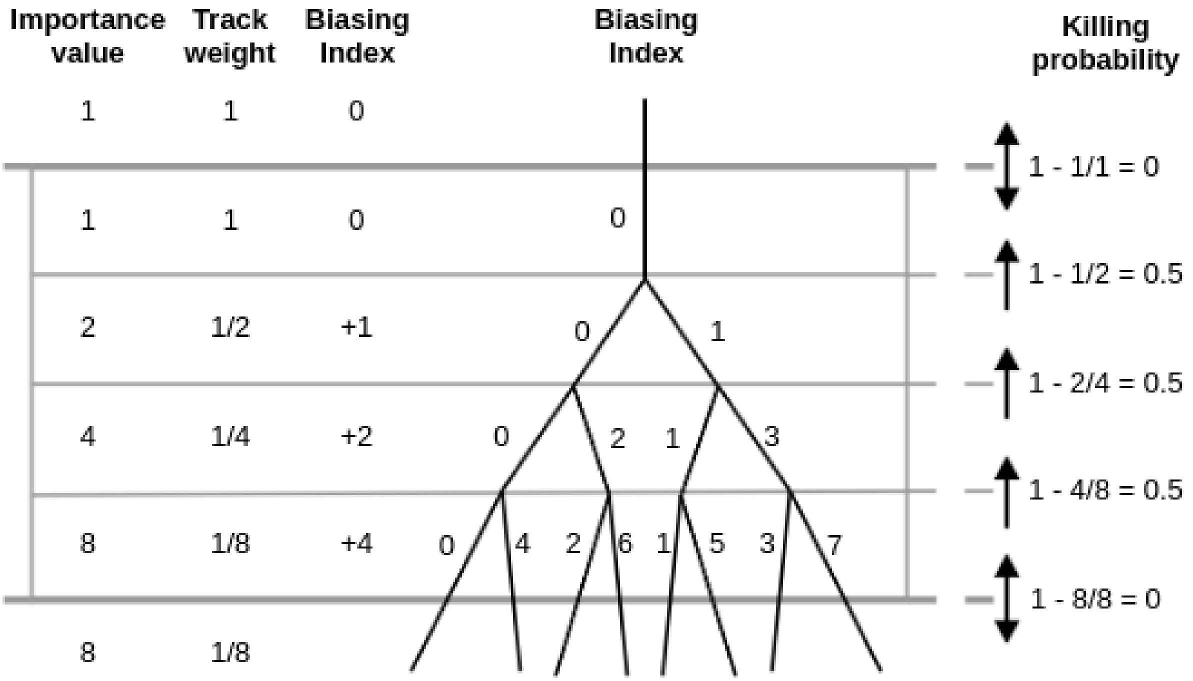
- Modify natural sampling procedure to focus on “important” events
- To compensate for this modification, particles are given statistical weights

$$w_{\text{biased}}\mathbf{pdf}_{\text{biased}} = w_{\text{unbiased}}\mathbf{pdf}_{\text{unbiased}} \qquad n \times w_{\text{biased}} = w_{\text{unbiased}}$$

Range of techniques w/ GEANT4 implementations:

- **Importance splitting –** Geant4 example *biasing/B02*
- Forced collisions – Geant4 example *biasing/GB02*
- Cross-section enhancement – Geant4 example *biasing/GB01*
- Reverse Monte-Carlo – Geant4 example *biasing/reverse/MC01*
- Many more!

Importance Splitting/Killing Biasing



Zatschler et al. NIMA, doi.org/10.1016/j.nima.2025.170766

Questions from user:

- How to keep account of different track/splitting topologies?
- **How do we optimise layer count? General rule?**

Principles:

- Split volume into **layers assigned importances $\boldsymbol{I}$**
- Particles crossing boundaries forward get **split according to $\boldsymbol{N_{split} = I_{post}/I_{pre}}$**
- Particles going backward get killed with prob. $\boldsymbol{p_{kill} = 1 - I_{post}/I_{pre}}$
- Particles given **statistical weights $\boldsymbol{w = 1/I}$** from final layer
- For m layers, if $\boldsymbol{I = 2^m}$, $\boldsymbol{N_{split} = 2}$, $\boldsymbol{p_{kill} = 0.5}$, $\boldsymbol{w = 1/2^n}$ – most common config.

Building on the Biasing Scheme

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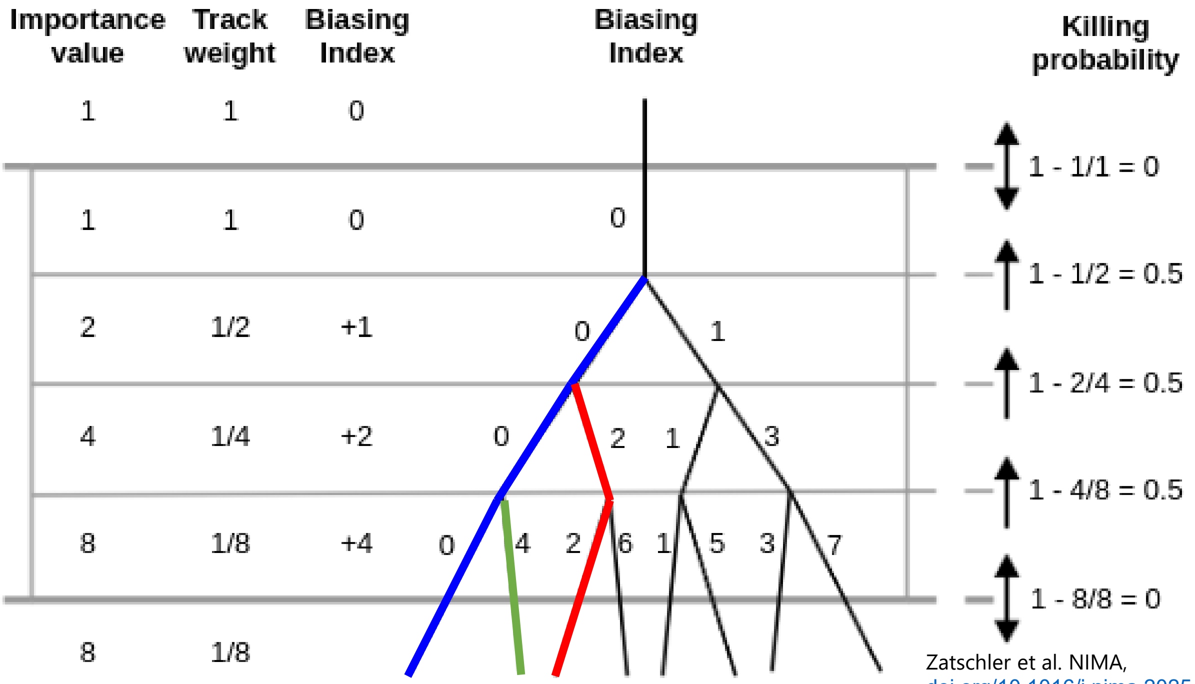

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Introduce a Biasing Index (B), according to implementation in Zatschler et al., NIMA 1080 (2025) 170766

$$\mathcal{B}_{\text{copy}} = \mathcal{B}_{\text{original}} + I/2$$

- Unique topologies - i.e. those not created by physics processes, can be tracked independently
- Consider collection of hits from **different indices** as **distinct** detector hits
- Sum the **shared weight** from each **distinct** collection/hit to reconstruct background rate

Secondaries not belonging to biased particle type inherit parent particles biasing index

Implementation for DarkSPHERE-30

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Utilise geometry in DarkSPHERE-30 background simulations as testbed

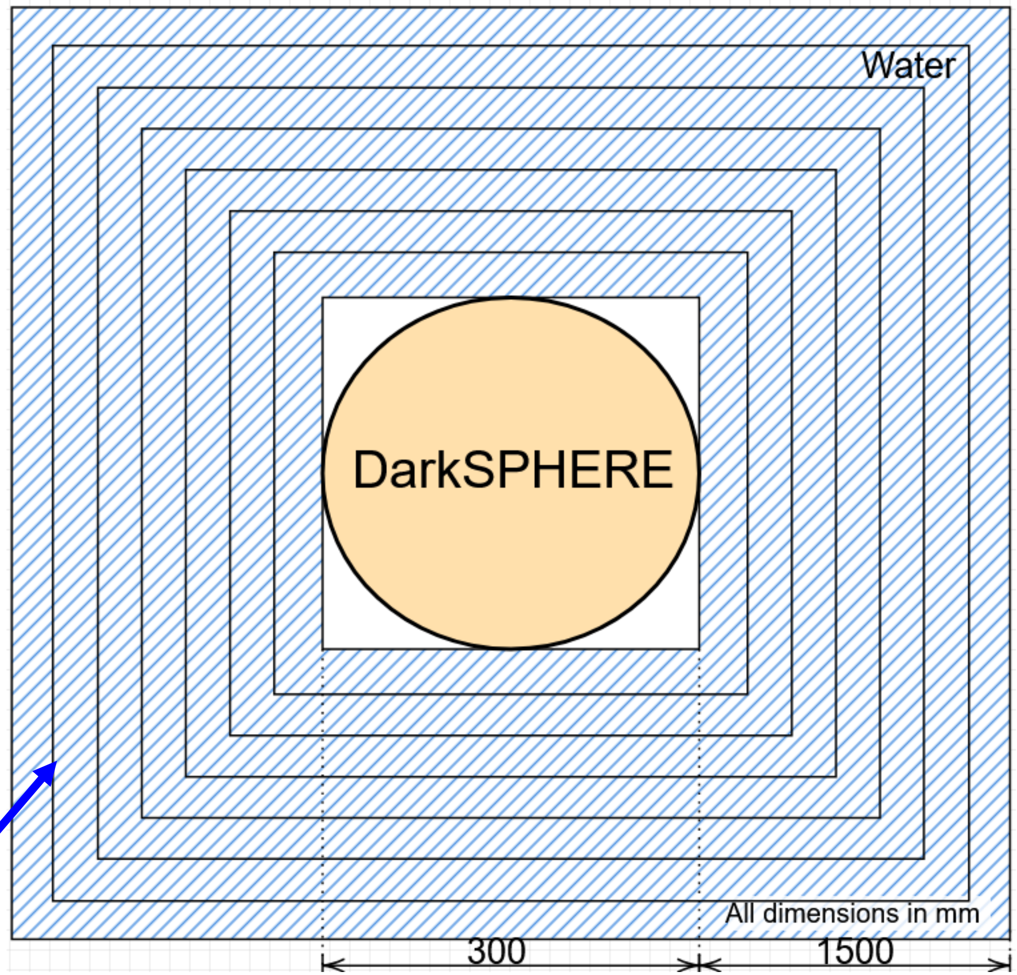
- 14 cm rad. He:C_4H_{10} (10%:90%) at 2 bar, encased in copper (1 cm thick)
- Surrounded in 1.5m thick water shielding
- Cubic air-gap between shielding and sphere

Biasing layers defined such that:

$$t_{\text{shield}} = M \times t_{\text{layer}}.$$

Importances defined such that:

$$I = 2^m,\ N_{\text{split}} = 2 \text{ and } p_{\text{kill}} = 0.5.$$



Equally thick layers fill shielding volume
NOT part of physical volumes

Understanding Optimal Performance

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Parameter of interest is probability of interaction with detector:

$$Pr_{\text{interaction}} = \frac{\sum w}{N_{\text{primary}}}.$$

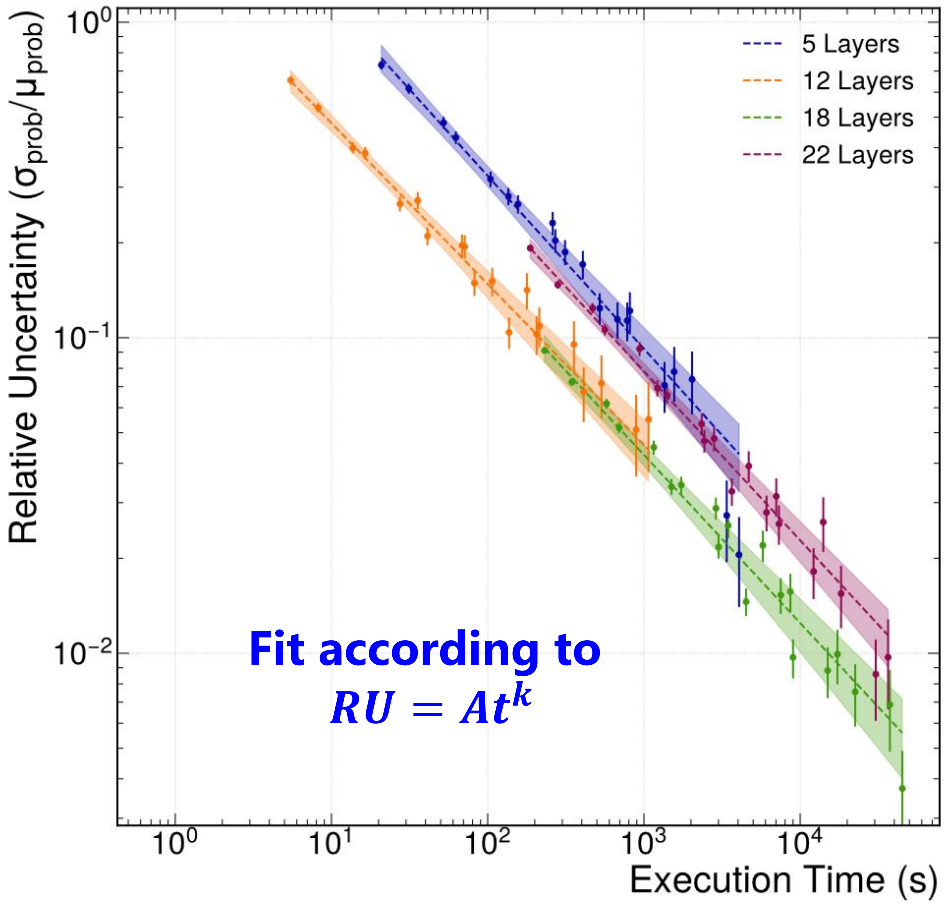
Probability is calculated for differently sized ensembles of simulation results

- Means and SDs used to define relative uncertainty (RU) as basis of comparison between layer amounts:

$$\text{R.U.} = \frac{\sigma_{\text{Pr}}}{\mu_{\text{Pr}}}.$$

RU vs. Execution time curves produced and fit to determine trends for computational efficiency ➜ reduced CO2 footprint

Expectation: at fixed times, RU decreases until reaching a high enough number of layers, then increases



Optimal Performance: Photons

Expectation: at fixed times, RU decreases until reaching a high enough number of layers, then increases

Clearly observe trend by comparing RUs at fixed execution times:
- 300 s for 2750 keV & 100 s for 1461 keV

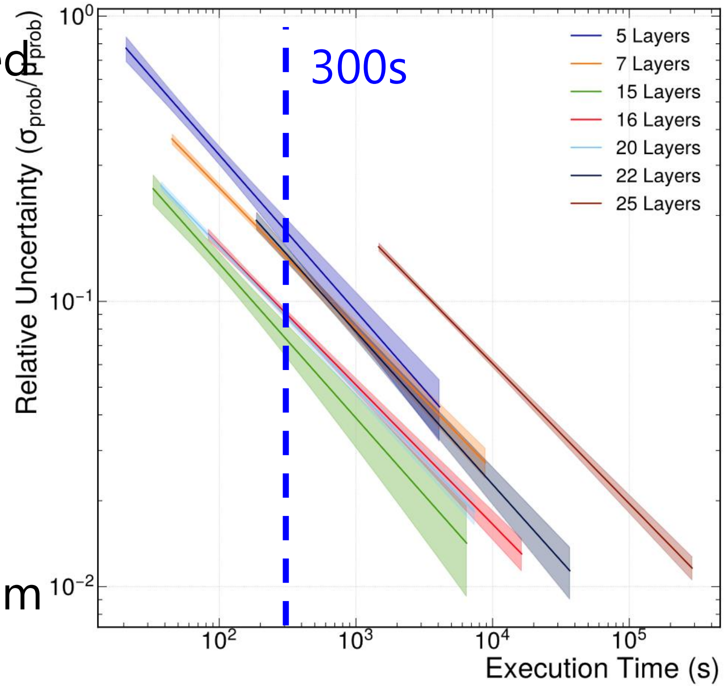
Parabolic trends observed - **turning points** represent **optimal amount of layers**

Link to physics for predictability
- Define $t_{layer} = x \times \lambda^{\gamma}_{H_2O}$
- ($\lambda^{\gamma}_{H_2O}$=24.05 cm 2750 keV, $\lambda^{\gamma}_{H_2O}$=17.14cm 1461 keV)

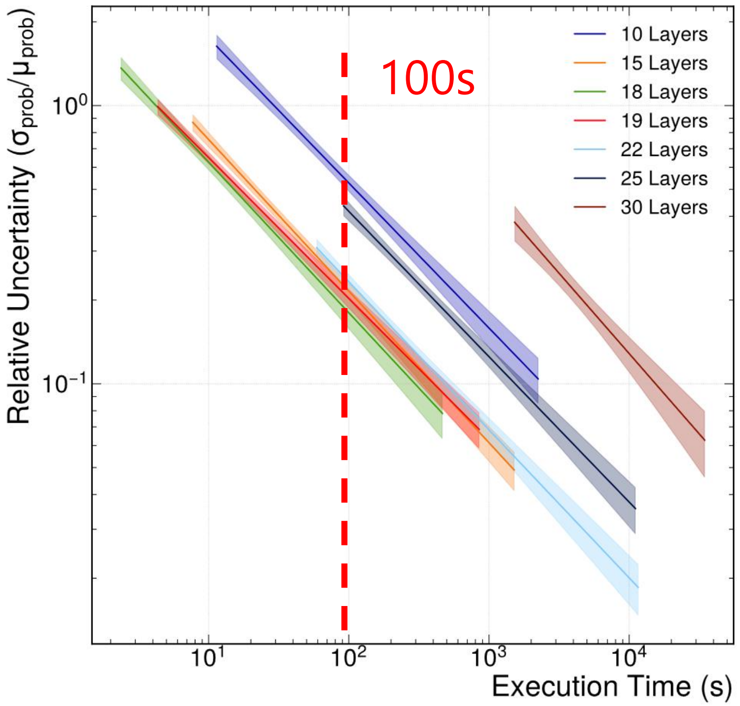
14 layers @ 2750 keV: $(0.45 \pm 0.03)\lambda^{\gamma}_{H_2O}$

18 layers @ 1461 keV: $(0.48 \pm 0.02)\lambda^{\gamma}_{H_2O}$

2750 keV



1461 keV



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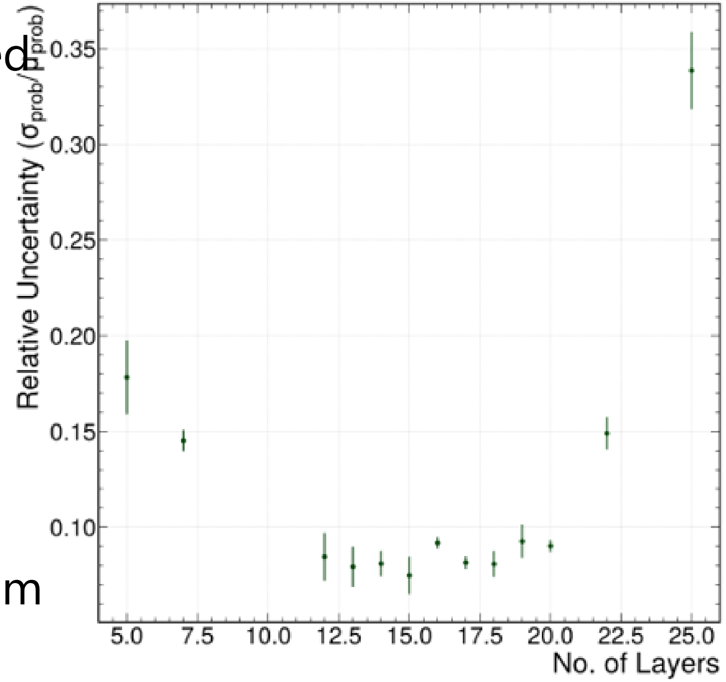

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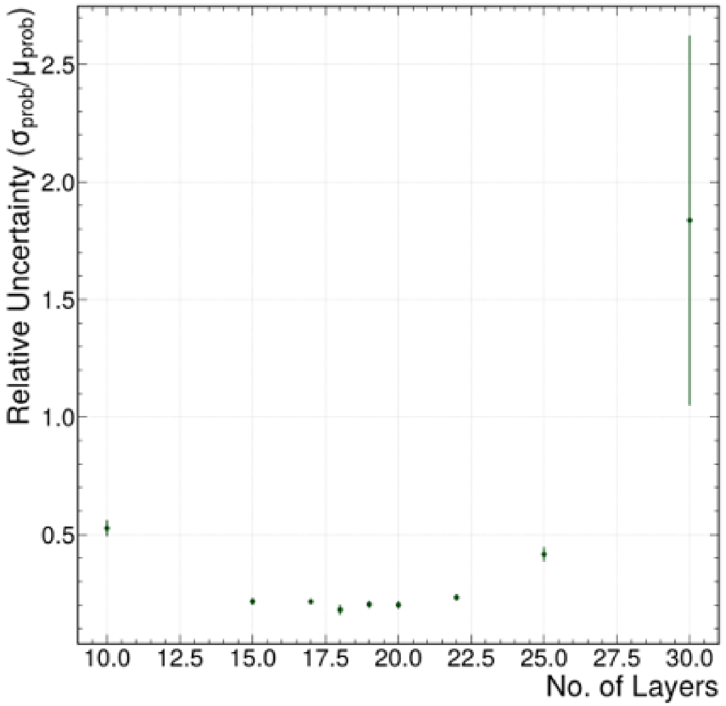

Note: λ **here refers to mean free path**, not rad. length (X_0) which would be ~36 cm at 2750 keV, e.g.

Optimal Performance: Neutrons

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Can we extend this guidance to other particle types?

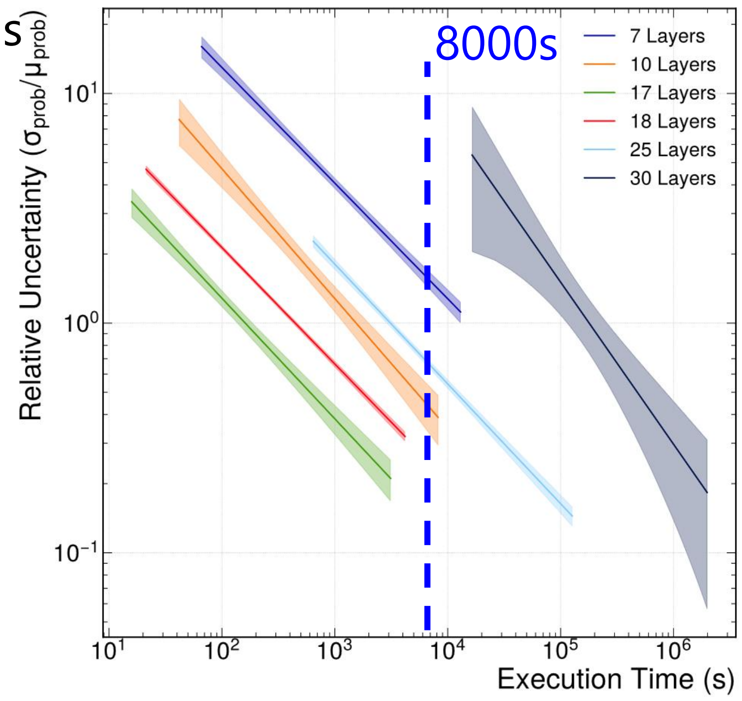
Process used for photons repeated for neutrons

Fits match expectation, and parabolic trend seen at fixed times:
- 8000 s for 10 MeV & 300 s for 5 MeV

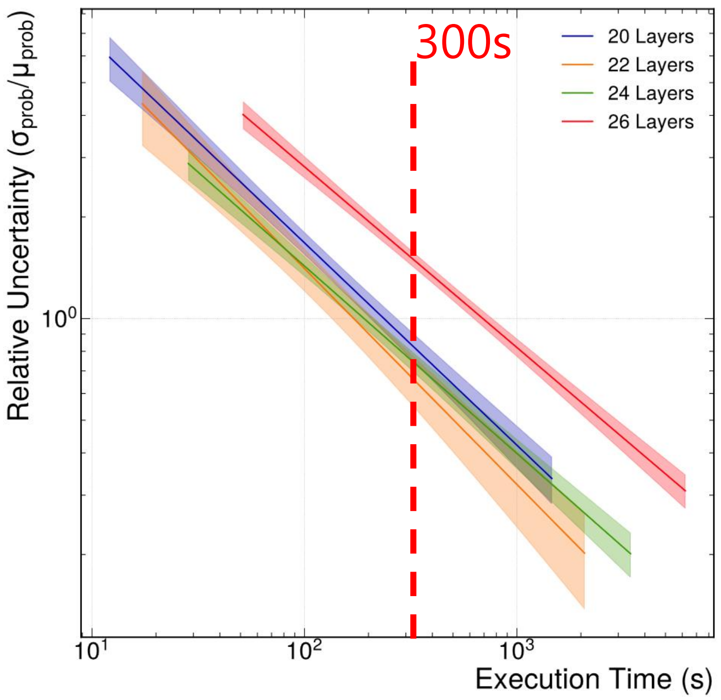
Turning/optimal points ($\lambda^n_{H_2O}$=9.62 cm @ 10 MeV, $\lambda^n_{H_2O}$=7.14 cm @ 5 MeV):
- **18 layers @ 10 MeV: $(0.92 \pm 0.05)\lambda^n_{H_2O}$**
- **23 layers @ 5 MeV: $(0.91 \pm 0.03)\lambda^n_{H_2O}$**

Same behaviour seen for neutrons, for different values

10 MeV



5 MeV



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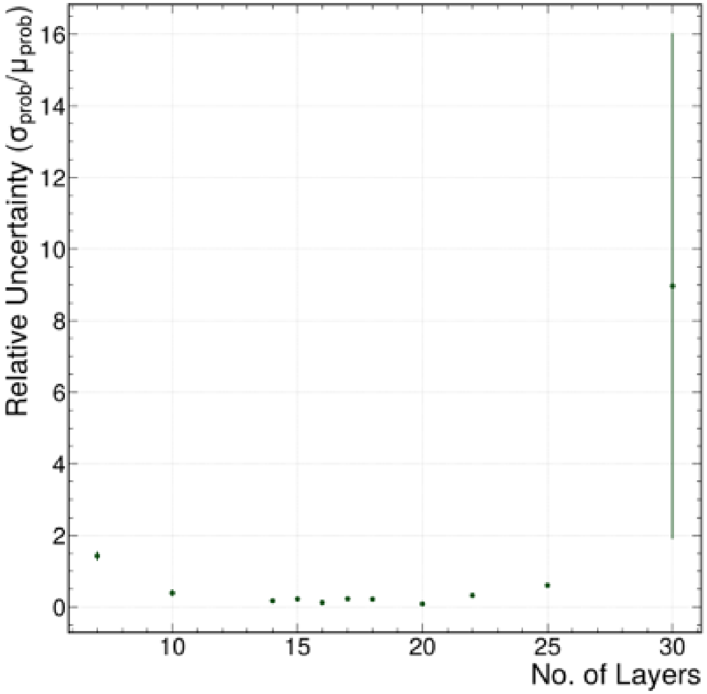

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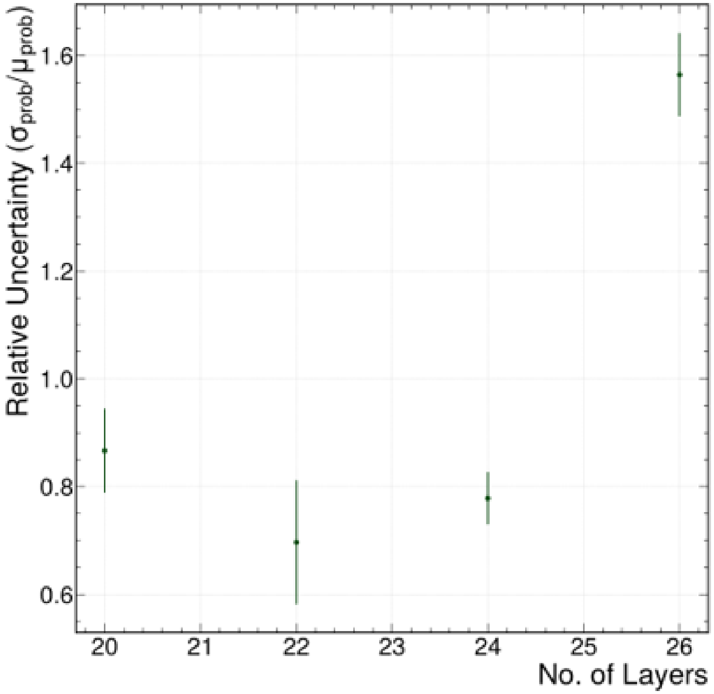


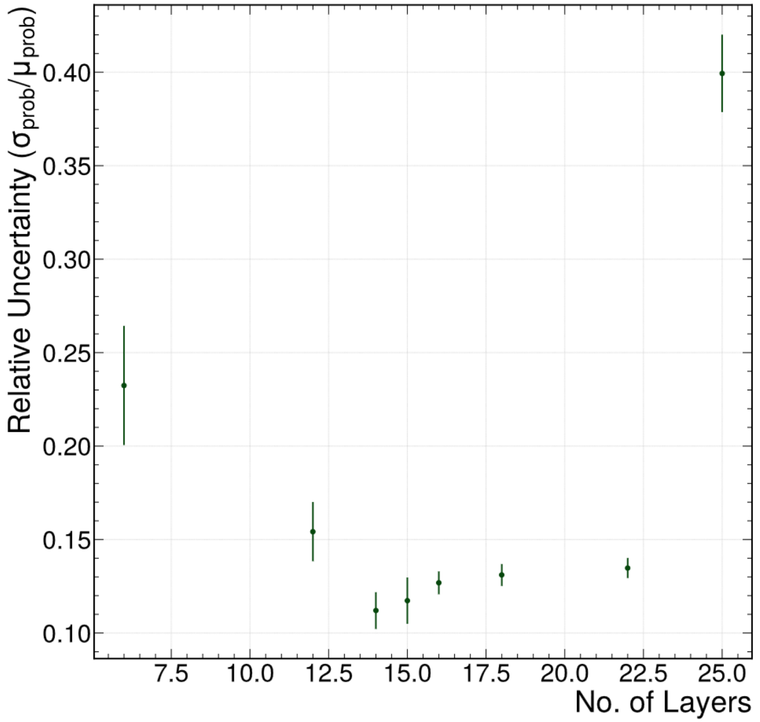
Generalising Optimisation Guidance

Test for generalisation over:
- Shielding material
- Shielding thickness

Photon simulations @ 1461 keV:
- Lead not water, 13.2 cm thick
- Water shielding 120 cm thick

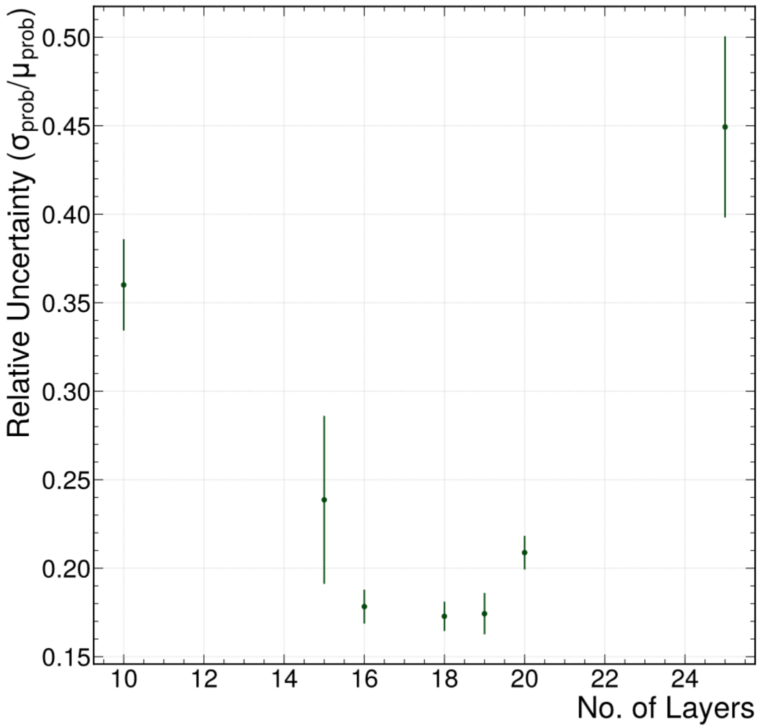
Outcome:
- **18-19 layers for Lead shielding** $(0.44 \pm 0.02)\lambda^{\gamma}_{Pb}$
- **14-15 layers for 120 cm water** $(0.50 \pm 0.03)\lambda^{\gamma}_{H_2O}$

Matches predictions – generalise over shielding material and thickness



Different thickness (120 cm) @ 1461 keV

Predict: optimal @ $\sim 0.48 \times \lambda^{\gamma}_{H_2O}$ or 14-15 layers



Lead (13.2 cm) @ 1461 keV

Predict: optimal @ $\sim 0.48 \times \lambda^{\gamma}_{Pb}$ ($\lambda^{\gamma}_{Pb} = 1.66$ cm) or 18-19 layers

What is the Computational Gain?

Have seen for 2750 keV photon case:
- At **300s ~0.08 RU achieved** in most optimal case
- Compared to **~0.18 at 5 layers, ~0.34 at 25 layers**
- For **unbiased: ~0.5 for 300s**

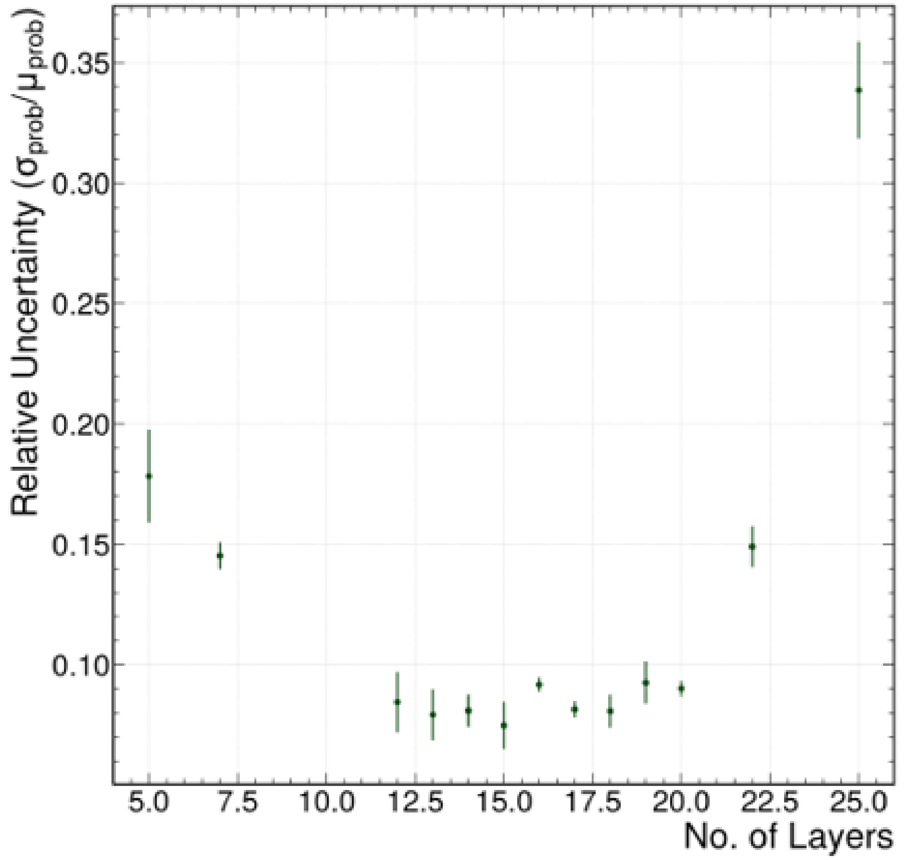
Gain in computational efficiency key for managing CO2 footprint

What is the computational gain of optimal case?

Set 0.08 as fixed RU:
- Optimal case takes 300 s to reach 0.08 RU
- 5 layers takes ~1268 s
- 25 layers takes ~5544 s
- **Unbiased takes ~30000 s**

How does this translate to a reduced CO2 footprint?

2750 keV



Computing Footprint in HEP

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Computing footprint a large proportion of professional footprint

- Relatively higher for researchers engaged in rare-event searches

Can estimate footprint:

$$\text{Footprint }[\text{gCO}_2\text{e}] = \boxed{f_{\text{PUE}}} \times \boxed{n_{\text{WPC}}} \times \boxed{f_{\text{conv}},}$$

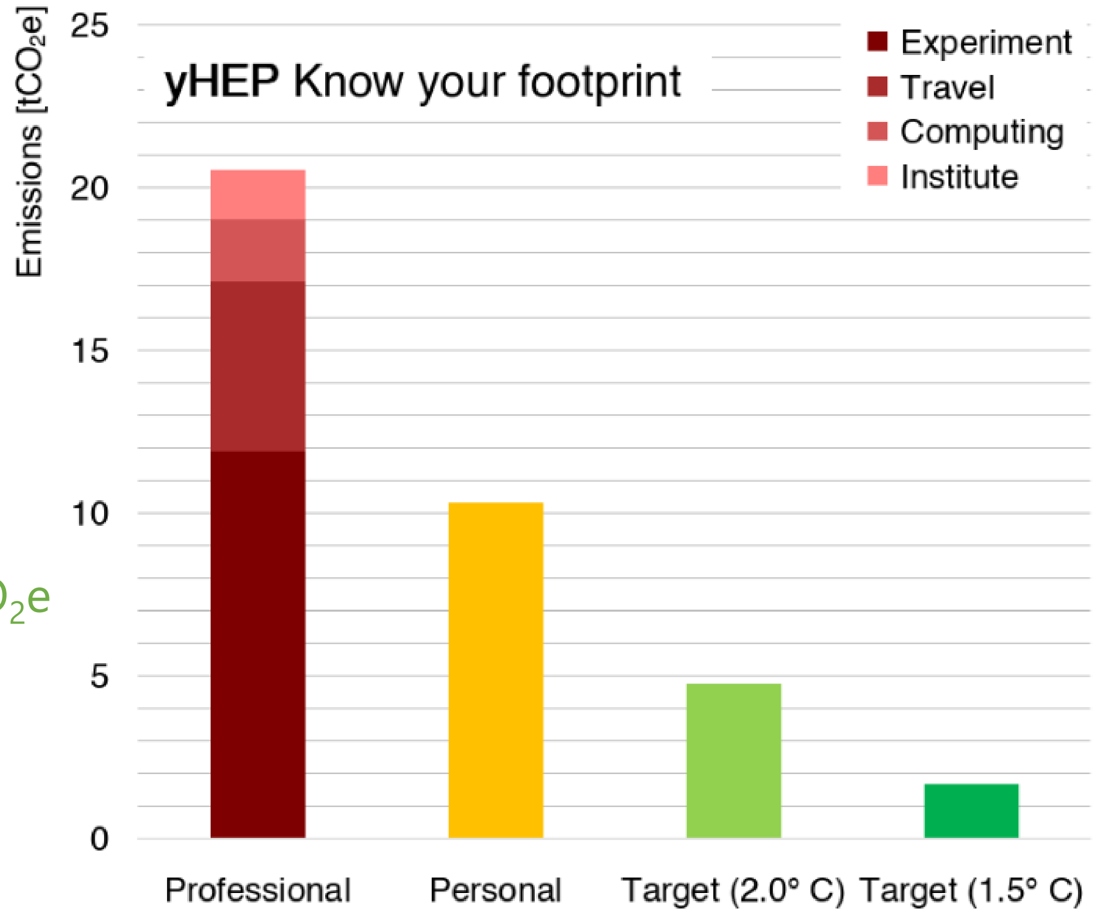
Power Usage Effectiveness of a HPC cluster

Conversion of kWh to gCO_2e (grid dependent)

$$n_{\text{WPC}} = \boxed{p_{\text{CPU-core}}} \times \boxed{t_{\text{core-h}},}$$

Power consumption of CPU core in kW

Workload of core in hours



V.S Lang et al. arXiv:2403.03308, doi:10.1038/s44168-025-00232-7

Reduced Footprint due to Optimised Biasing

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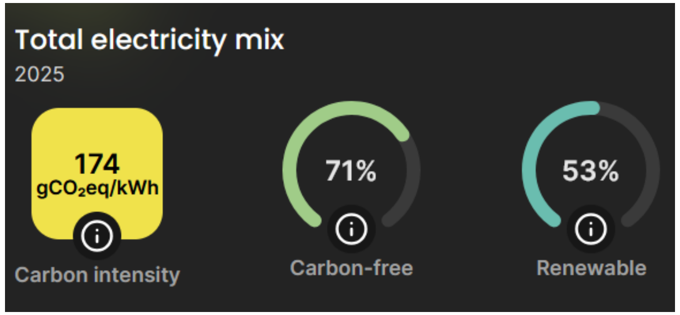
The computational gain from optimal biasing over an unbiased, under/over-biased simulation is large
- Expect large reduction in carbon footprint too!

Utilise Birmingham cluster for comparison:
- $f_{PUE} = 1.5$ (global average)
- $f_{conv} = 174$ gCO_2e/kWh
- $p_{CPU-core} = 6.25$ W
- t_{core-h} will vary between 3 cases, based on time taken to reach fixed RU



Time taken to reach fixed RU of 0.081 used for comparison

$$\text{Footprint [gCO}_2\text{e]} = 1.63 \times t_{\text{core-h}}.$$

Note: footprint is calculated on per core basis

Biasing Level	Footprint [gCO_2e/core]	Factor Increase on Optimal
Optimal (14L)	0.135	N/A
Under-biased (5L)	0.571	4.23
Over-biased (25L)	2.510	18.59
Unbiased	13.58	$\sim 10^2$

Large decrease in footprint if optimal layers used!

Summary

DM searches are requiring increasingly low backgrounds to achieve high exposure and low thresholds

Shielding simulations increasingly intractable without event biasing
- Need **optimised biased simulations, improve computational efficiency,** and **manage carbon footprint**

Commonly used biasing scheme: **Importance Splitting/Killing**
- **Specific guidance on optimal layer configurations is lacking**

DarkSPHERE-30 detector as a test-bed, more specific guidance found:
- At high enough numbers of layers, **relative uncertainty reverses expected trend**
- **Optimal point is turning point in this trend**, corresponding to **certain layer thicknesses**:
    - **$\sim 0.45\lambda^{\gamma}_{H_2O}$ for photons & $\sim 0.91\lambda^{n}_{H_2O}$ for neutrons**
- **Generalisable to different shielding materials and thicknesses**

Using optimal layer thickness can yield a **factor of ~100 reduction in computing carbon footprint**
- **Poorly optimised biasing can also lead to larger footprints**

Full publication to be submitted (on arXiv) very soon!!!