Simphony: GPU-Accelerated Optical Simulation with MC Truth Propagation for Neutrino Detectors

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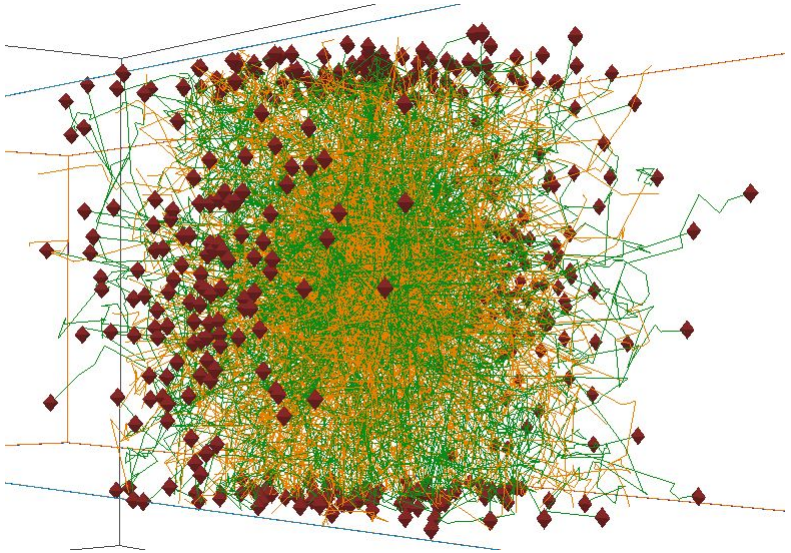
Simphony

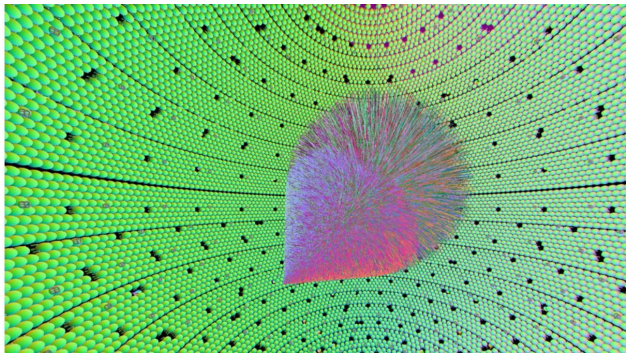
- Simphony[1]: fork of Opticks, uses NVIDIA OptiX framework to simulate photons on GPU
- Works together with Geant4:
  - Hadronic, EM etc. are done on CPU, only photons are offloaded to GPU
- Today's topics:
  - Introducing Simphony
  - Existing validation vs Geant4 for Cerenkov detectors
  - Validation results in a 14.7 kt LAr detector
  - Plans: integrating optical MC with EM on GPU



[1]github.com/BNLNPPS/simphony

Opticks[5]

- Developed by Simon Blyth for the JUNO experiment
- Uses NVIDIA's OptiX[6] ray tracing engine to implement optical photon propagation on GPUs -> simulate 10^7 photons in 1 second
- Geometries:
  - Opticks can import 10 "primitive" types (eg. box, sphere, torus…) either from GDML or Geant4 automatically

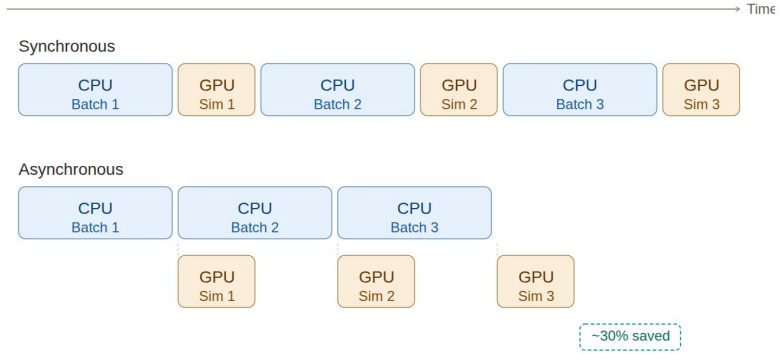


Photons simulated @ JUNO with Opticks[5]
from 200 GeV muon (~10^7 photons)

[5] Opticks: GPU Optical Photon Simulation via NVIDIA OptiX
EPJ Web of Conferences 295, 11014 (2024)
[6] https://developer.nvidia.com/rtx/ray-tracing/optix

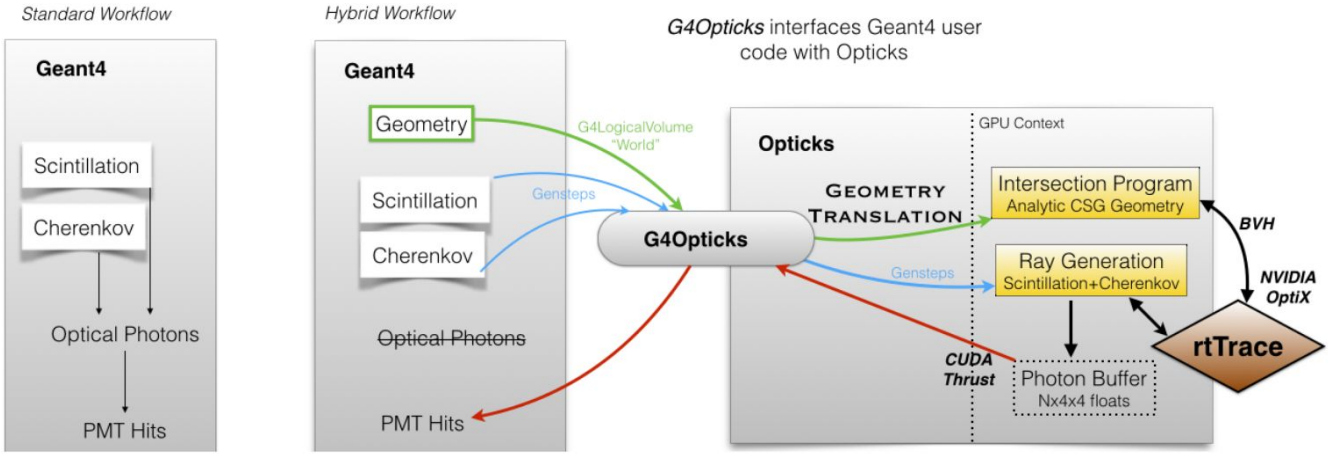
Simphony

- Maiden name: EIC-Opticks: developed for Cerenkov detectors at Electron Ion Collider
- Modifications:
  - Added wavelength shifting process to GPU
  - Added support for trapezoid volumes (G4Trd, G4Trap), cylindrical wedges and spherical wedges
  - **Added Monte Carlo truth propagation -> users can propagate information through the GPU**
  - Introduced asynchronous CPU, GPU launches
  - Created a spack package
  - Tested NERSC Perlmutter



Architecture

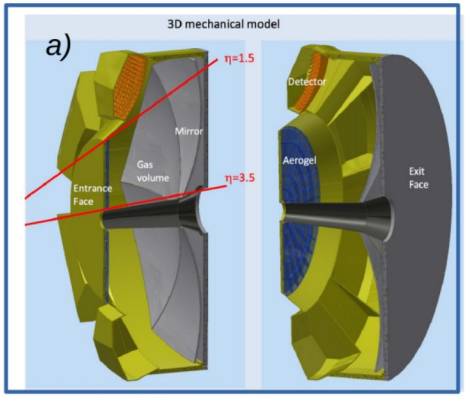
- EM, Hadronic done in Geant4 with CPU
  - For Cherenkov/scintillation, Geant4 calls G4Opticks API instead of creating photons
- G4Opticks records production distributions (position, direction, polarization, Nγ, event ID, …)
- Simphony uses these records to generate and propagate photons on the GPU with NVIDIA OptiX
- Hits are sent back through G4Opticks
- **Geometry and optical properties are translated from Geant4 to GPU → same physics,** much faster optical simulation



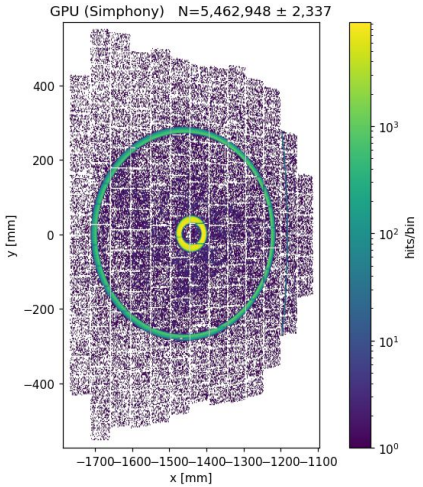
Simon Blyth, EPJ Web of Conferences 245, 11003 (2020)

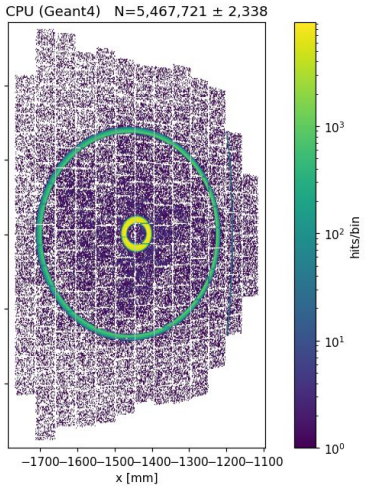
*dRICH detector

arXiv:2410.20410



- One of the Ring Imaging Cerenkov detectors planned at ePIC @ Electron Ion Collider (Brookhaven National Laboratory)
- Had to add new geometry primitive support vs. Opticks
- Dual radiator -> 2 Cherenkov cones
- Spherical mirrors
- Hit ratio: 1.0005±0.0016
- χ^2/dof = 1.02 (2D)

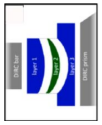




*dual Ring Imaging Cerenkov Detector

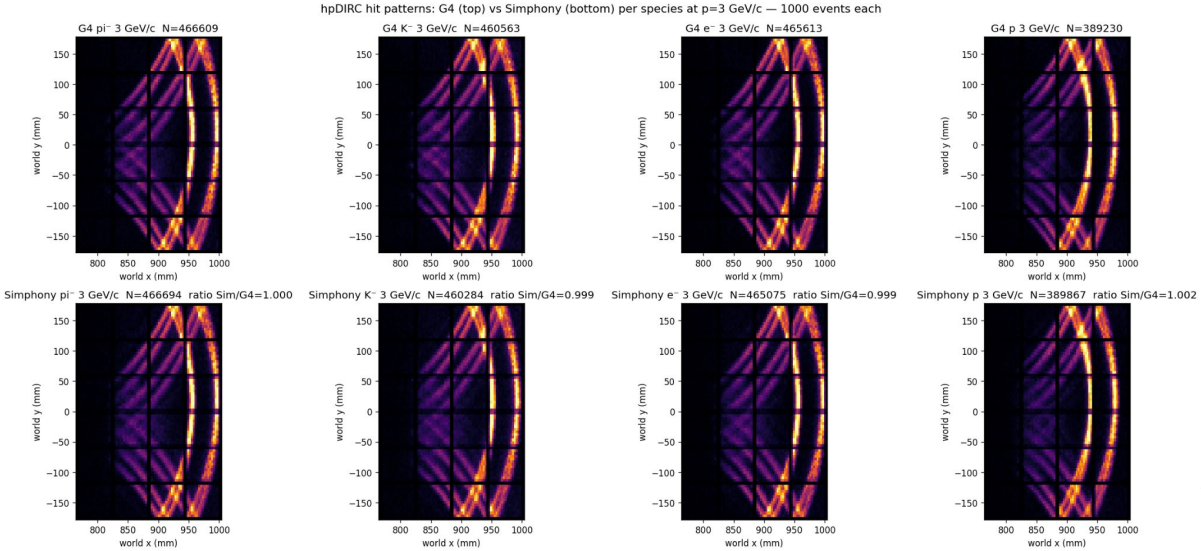
Brookhaven National Laboratory

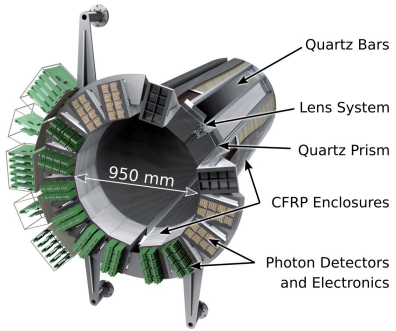
hpDIRC* detector



arXiv:2202.06457

- Implemented support for trapezoids in GPU geometry
- Long fused silica bars
- Has complex optical system
- Validated Simphony vs. G4 CPU:
  all hitmaps below have 2D χ^2/ndf: 1 - 1.5
- A third detector: pfRICH validation publication under review:
  - Galgoczi et al. : GPU acceleration of optical photon propagation in low photon yield applications: Opticks for the Electron Ion Collider (arXiv:2512.06061)



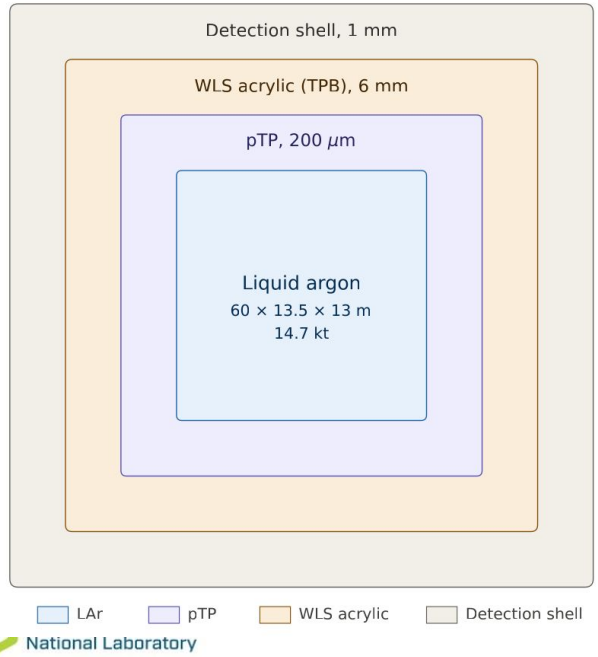


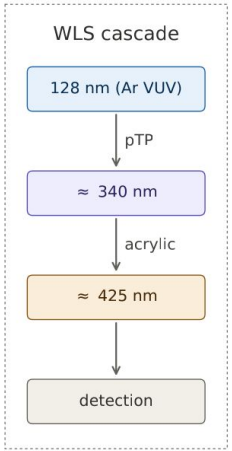
NIM A 169168

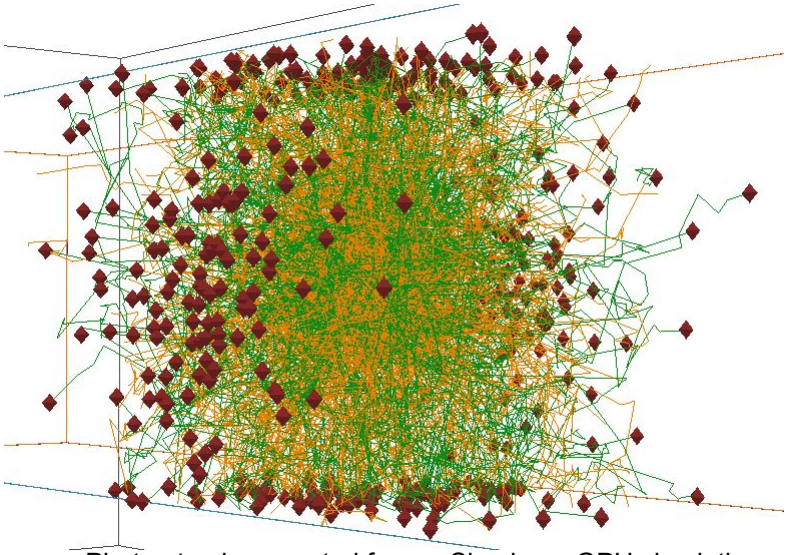
*high performance Internally Reflected Cherenkov Light (hpDIRC)

Simphony validation for noble liquid detectors

- Galgoczi et. al: “GPU optical photon Monte Carlo for noble liquid detectors: validation against Geant4 in a large liquid argon TPC benchmark” arxiv:2606.05385
- **Implemented wavelength shifting process on GPU**
- Defined a 14.7 kton LAr benchmark geometry to show the possible speed-up





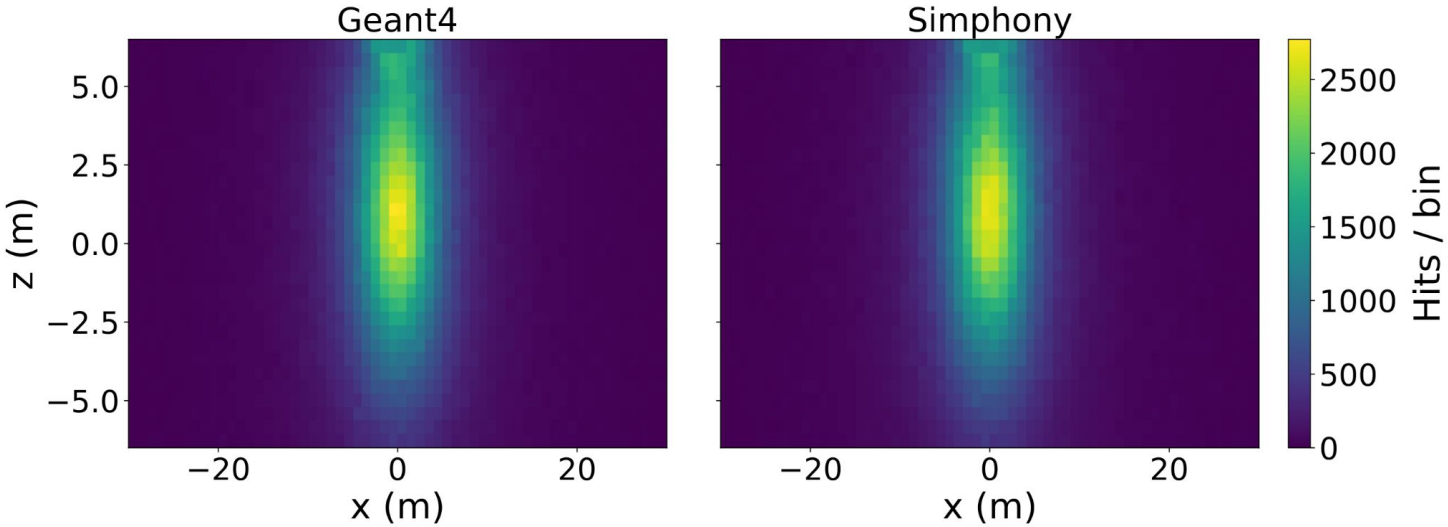


Photon tracks exported from a Simphony GPU simulation from 0.5 MeV electron in benchmark geometry

National Laboratory

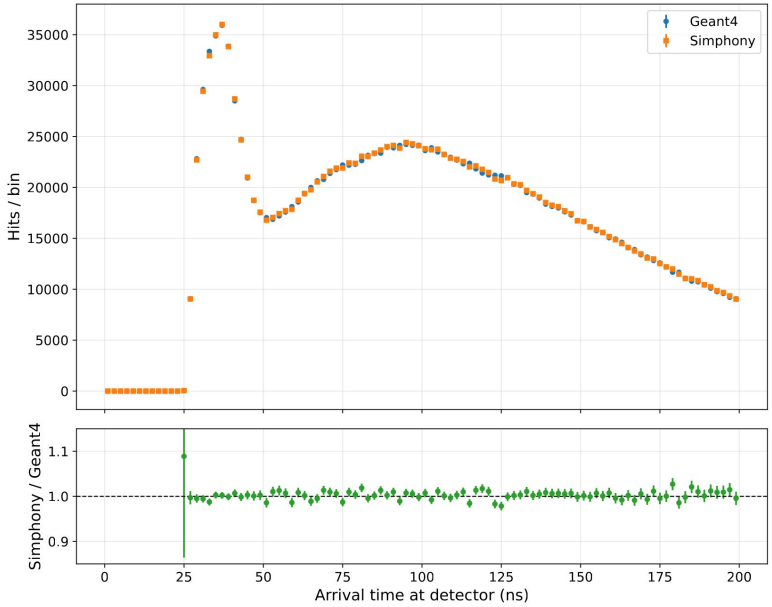
Validation

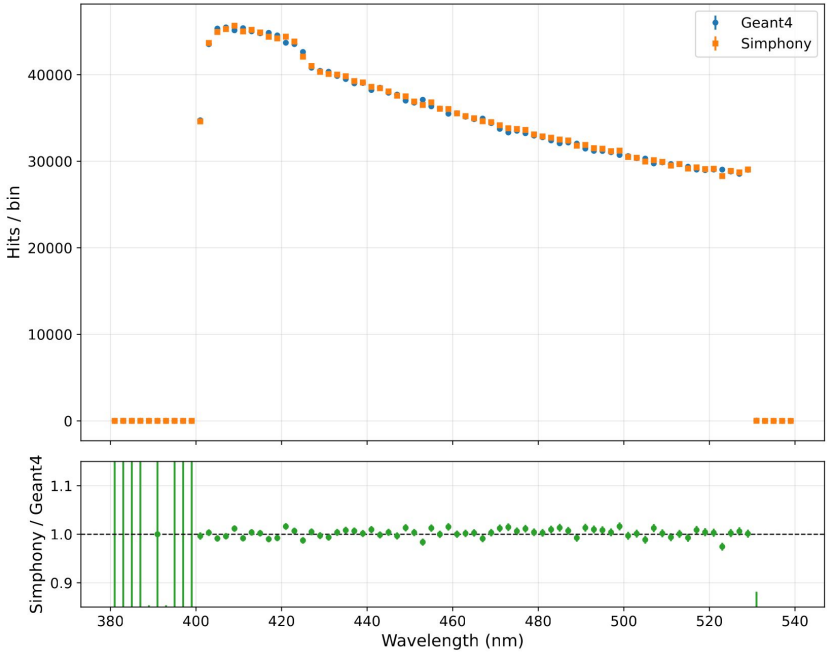
- Simulated 2.5 GeV electrons, 1 GeV muon, 400 MeV protons
- One electron produced 61 M photons
  - 2.4 M hits
  - Y face hits for a single electron:



Validation

- Simulated 2.5 GeV electrons:
  - χ^2/ndf = 0.98 for **arrival time** at photon detector and χ^2/ndf = 1.08 for **detection wavelength**
  - $Hits_{GPU}$ / $Hits_{CPU}$ = 1.0022 ± 0.0002 -> **<0.25% disagreement**
- $Hits_{GPU}$ / $Hits_{CPU}$ = 1.0017 ± 0.0008 for 1 GeV muons





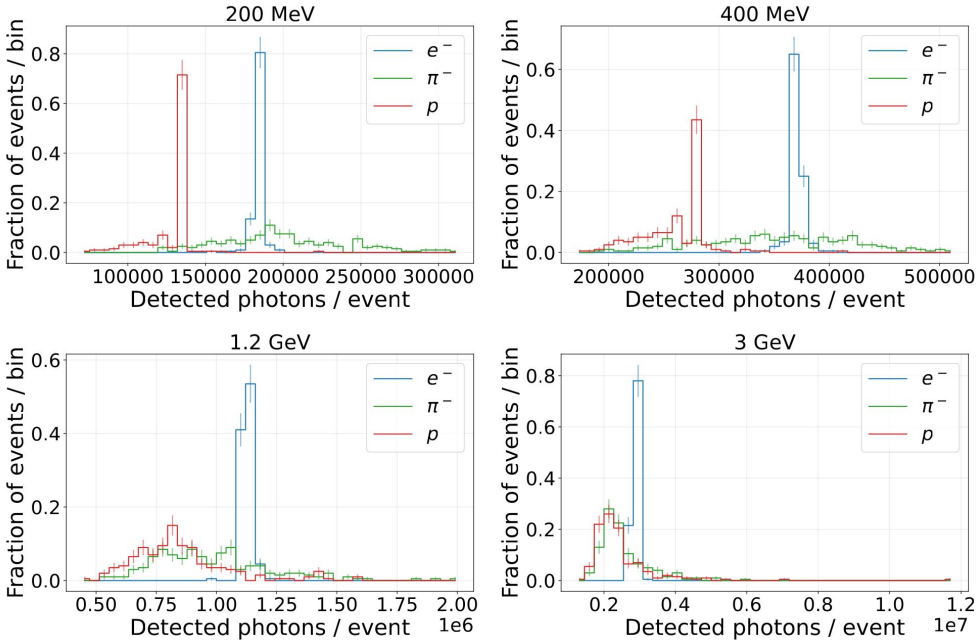
Brookhaven National Laboratory

Speed-up

- When simulating 4 electrons in one GPU call:
  - 80.2 ± 1.6 M photons s^{-1}
  - For optical simulation:
    - 1053 ± 55 x speedup compared to single thread of G4
    - time measurement included: data moving from–to GPU, GPU init., GPU sim.
  - End-to-end speed-up: EM+optical
    - 89 ± 5 x -> This shows that optical work became ~10% of the end-to-end time!
    - New bottleneck: EM simulation
- Hardware:
  - CPU: Intel Xeon w7-3445
  - GPU: RTX 4090

Illustration of capabilities

- In order to demonstrate the speed-up
- Simulated 3000 high energy events in ~4 hours on one **consumer GPU**
  - 3 species × 5 energies × 200 events
- Would have taken a CPU ~10 days
- Disclaimer:
  - No dE/dx-dependent recombination or quenching



Summary and plans

- Simphony optical GPU MC:
  - open source
  - Spack install, docker image on GitHub for setup in minutes
  - Implemented **wavelength shifting on GPU**, support for further volumes
  - Added carrying **Monte Carlo truth**: any information can be retrieved for each GPU hit
  - We have shown that **optical workload** of neutrino events in LAr can be simulated up to **1000x faster with Simphony compared to single thread G4 CPU**

- Plans:
  - Integrate into edep-sim (coming soon!)
  - We have showed that new bottleneck is EM
    - Currently integrating [1]AdePT (GPU EM MC) with Simphony
      - Soon can simulate electrons, gammas and optical photons all on GPU!
    - Expect end-to-end speed-up to increase further!

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[1]https://github.com/apt-sim/adept

Property	Value or range
Liquid argon (`G4_lAr`)	
RINDEX	1.23 → 1.6 over 2.34–11.7 eV, rising
GROUPVEL	151–244 mm/ns, dispersion corrected
RAYLEIGH	≈ 0.99 m at 128 nm (Babicz *et al.* 2020 [27]); 21-point $\lambda^4/(n^2-1)^2$ dispersion across the LAr active band
ABSLENGTH	80 m for $E \leq 7.5$ eV, 10 m for $E \geq 8.0$ eV
SCINTILLATIONCOMPONENT	truncated Gaussian, peak 128 nm, FWHM 10 nm, window 113–155 nm (Heindl *et al.* 2010 [28]); used for COMPONENT1/COMPONENT2/FAST/SLOW
SCINTILLATIONYIELD	24 000 photons/MeV
Time constants, fast/slow	7 ns / 1400 ns, with yields 0.75 / 0.25
Bulk parameters	$T = 87$ K, $\rho = 1.396$ g/cm^3, $I_{exc} = 188$ eV
Para-terphenyl (pTP, inner WLS)	
RINDEX	1.65 flat
GROUPVEL	181.7 mm/ns flat
WLSCOMPONENT	Emission peak at 340 nm, with vibronic shoulders at 400–425 nm
WLSABSLENGTH	0.5 μm at 128 nm, rising to ≥ 10 m above 340 nm
ABSLENGTH	Shared `ABSLENGTH_acrylic` table: 1 μm in the VUV → 10 m in the visible
WLSTIMECONSTANT	1.136 ns
TPB-doped acrylic (`bluewlsacrylic`, outer WLS)	
RINDEX	1.58 flat, EJ-286 PVT base
GROUPVEL	189.7 mm/ns flat
WLSCOMPONENT	Emission peak at 425 nm, with weak 530 nm tail
WLSABSLENGTH	0.1 μm in the VUV; 0.8 mm at 340–400 nm peak; ≥ 2 m above 400 nm
ABSLENGTH	Shared `ABSLENGTH_acrylic`, see pTP
WLSTIMECONSTANT	1.26 ns
SiPM surface	
EFFICIENCY	1.0 flat, idealised photon counter; UNIFIED dielectric–metal, polished finish