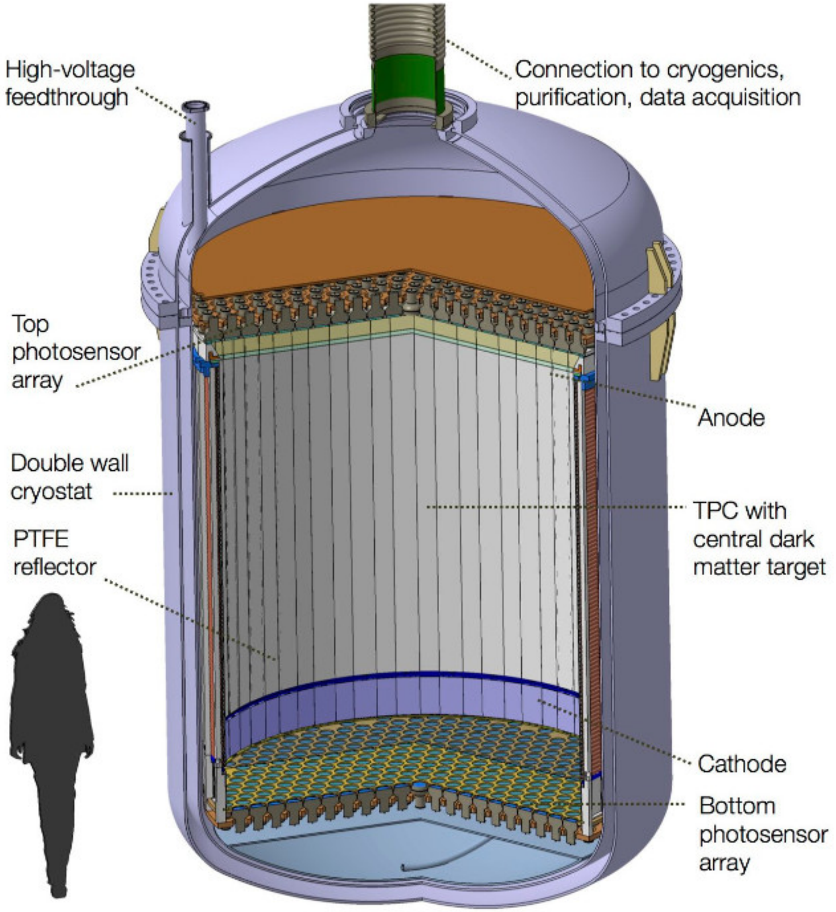
GPU-based optical simulation of the DARWIN detector

Igor Ostrovskiy

University of Alabama

Introduction

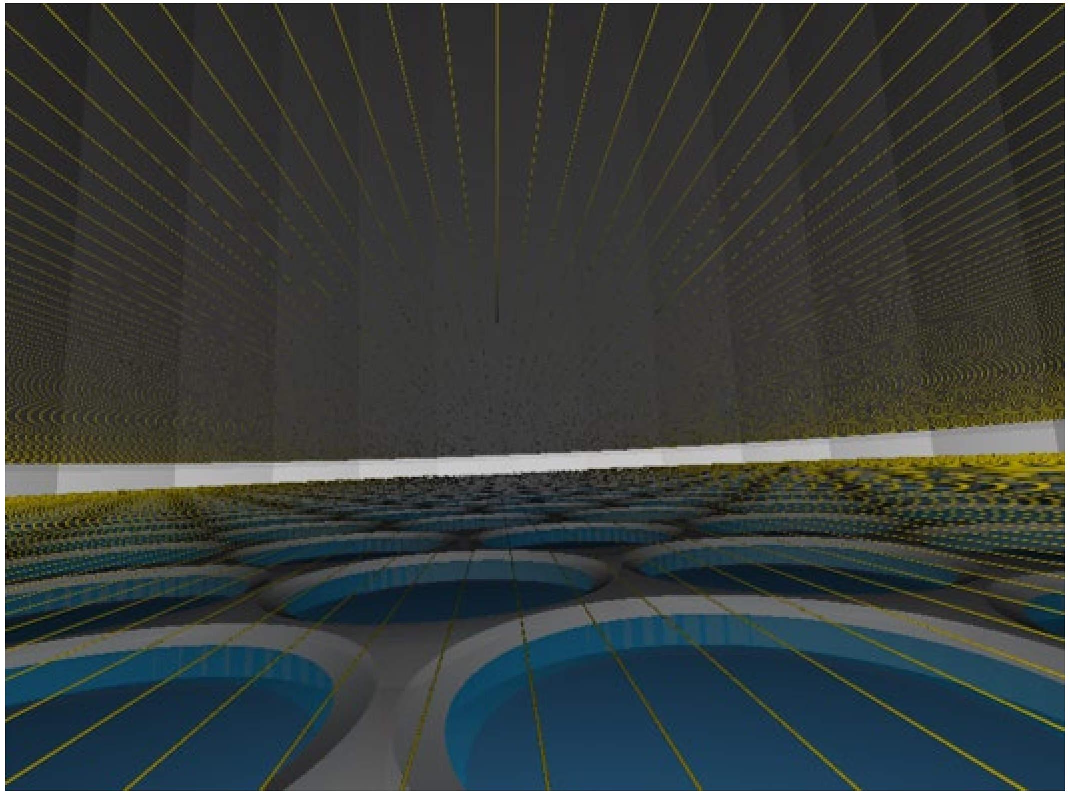
- Xenon detectors continue to grow in size and complexity
- DARWIN plans to construct 2.6 m dual-phase time projection chamber (TPC) with 40 tons of LXe to become ultimate dark matter detector[1]
  - Also enabling competitive searches for $0\nu2\beta$[2], measurements of solar νs[3], other physics
  - See DARWIN-related talks L. Baudis, R. Peres, H.-S. Wu for more details
- Optical simulations – critical step in optimizing design and maximizing discovery potential – become more time-consuming and challenging
  - Geant4-based optical simulation takes >95% of total CPU time in LZ[4]



[1] *JCAP* **11** (2016) 017, [2] *Eur. Phys. J. C* **80** (2020) 808, [3] *Eur. Phys. J. C* **80** (2020) 1133, [4] *EPJ Web Conf.* **251** (2021) 03037

Chroma

- Alternatives to Geant4: novel frameworks that use GPU to track photons
- Chroma tracks photons fast, plus it accepts geometry directly from CAD files with ease and feels like a Python script
- The last two advantages are especially helpful during design stage, where many different detector geometries may need to be investigated fast



Chroma rendering of inside of DARWIN detector. Electrode wires, light reflectors, and photosensors are visible

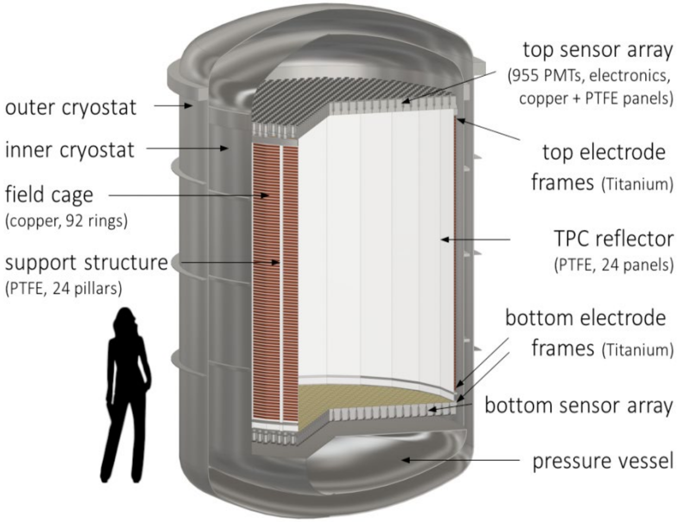
Chroma in DARWIN

- To evaluate Chroma, we simulated DARWIN and conducted several studies, which might already be interesting for the next-generation LXe rare-event searches
- First, we compared physics and speed performance to Geant4 simulation
  - After fixing a couple of issues, see <2% agreement
  - Roughly an order of magnitude faster photon tracking

Geant4 \ Chroma	GTX Titan X	TITAN Xp
Intel Broadwell	11	16
Intel Xeon	8	12
AMD Opteron	17	24

Ratio of times to track the same number of photons during a typical DARWIN simulation by Geant4 and Chroma for different hardware setups

Simulation: Baseline Design



Section view of baseline detector design

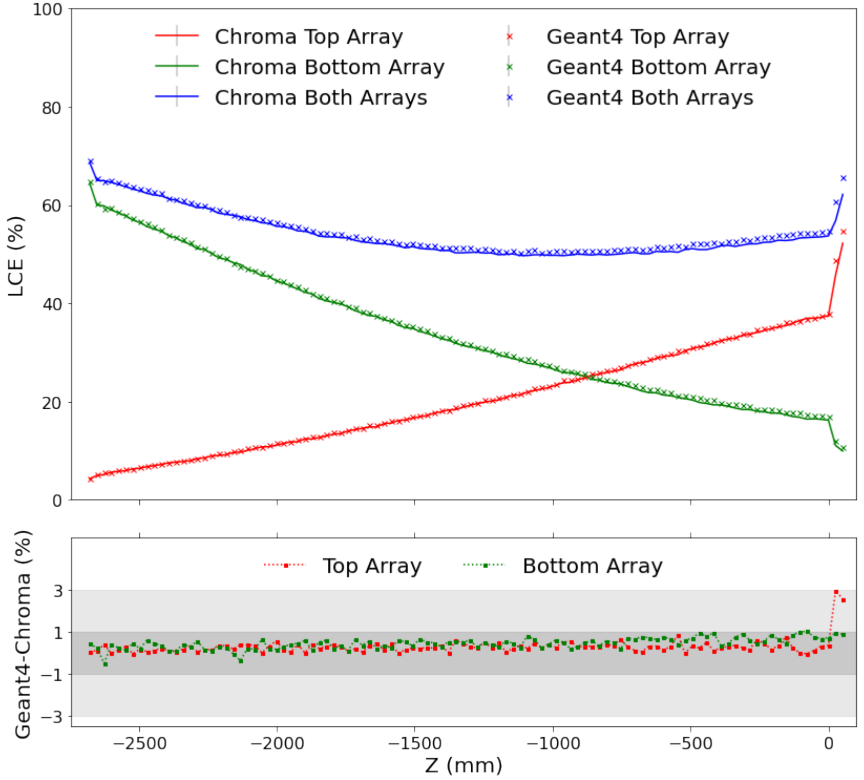
Parameter	Best-guess Value @175 nm
n_{LXe}	1.69
LXe L_{abs}, m	50
LXe $L_{Rayleigh}$, cm	36
GXe L_{abs}, m	500
GXe $L_{Rayleigh}$, m	200
PTFE in LXe R_{total}, %	99
PTFE in GXe R_{total}, %	80
PTFE R_{spec}/R_{diff}	0.05
n_{quartz}	1.60
k_{quartz}	$< 10^{-4}$
SS R_{total} %	30
SS R_{spec}/R_{diff}	2
Cu R_{total} %	45
Cu R_{spec}/R_{diff}	3.5
Al R_{total} %	90
Al R_{spec}/R_{diff}	17
Ti R_{total} %	39
Ti R_{spec}/R_{diff}	2.9

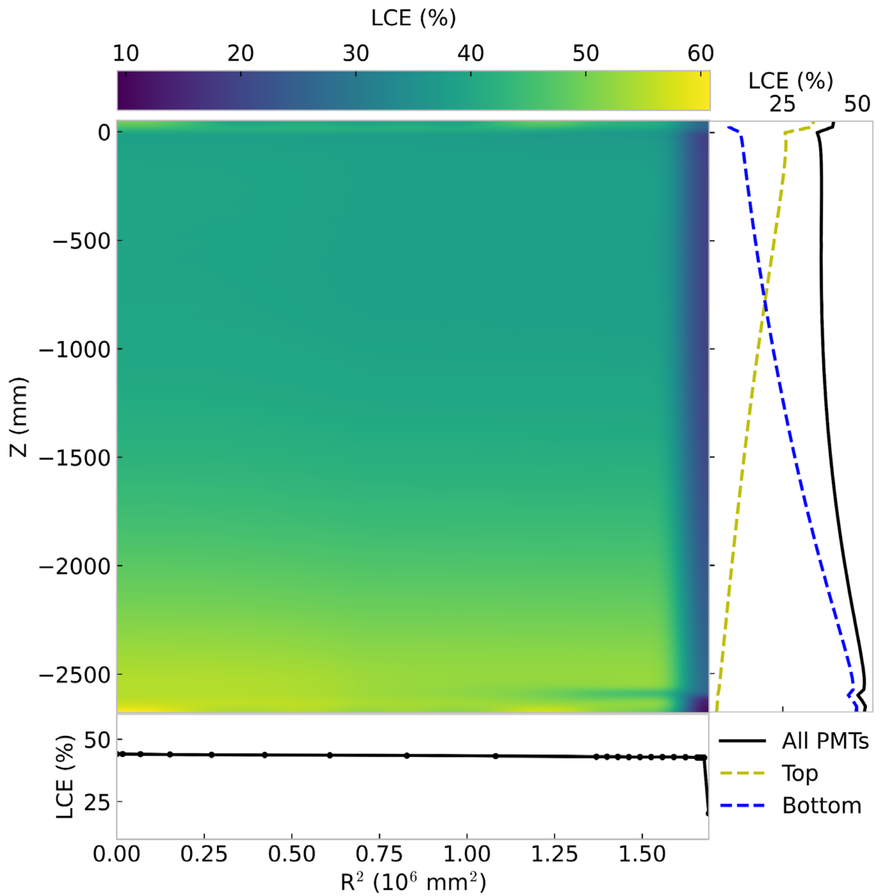
Optical properties used in simulation

$R_{spec/diff}$ – Reflectivity specular/diffuse
$L_{abs/Rayleigh}$ – Length absorption/scattering
n – Index of Refraction
k – Extinction coefficient

- 2.6 m diameter, height of TPC
- PTFE reflectors in gas, liquid phases
- Top and bottom arrays of PMTs, 955 each
- 200 μm stainless wires with 5 (7.5) mm pitch for top (bottom) electrodes
- Optical parameters based on literature or recent measurements
- Many parameters are not well constrained due to lack of data at 175 nm in LXe. Must include as systematic error
- Main parameters of interest:
    - LCE (=$N_\gamma^{hit}/N_\gamma^{tot}$)
    - τ_{90} (=window in which 90% of detected γs arrive)

Simulation: Baseline Design





- Average LCE agrees to ~0.5% abs.(~1.5% rel.) between Chroma and Geant4
- With all details switched on, average LCE for DARWIN is 43.1%
- 90% of these photons arrive within ~200 ns

Photon graveyards

Component	Absorbed photons, %
LXe (L_{abs} = 50 m)	**22.7**
Electrodes	**18.0**
Gate	7.7
Cathode	3.1
Bottom screen	2.6
Anode	1.7
Top screen	1.6
Frames	1.3
PMTs	**9.0**
Bottom PMTs	6.3
Top PMTs	2.7
PTFE reflectors	**7.2**
Total	**56.9**

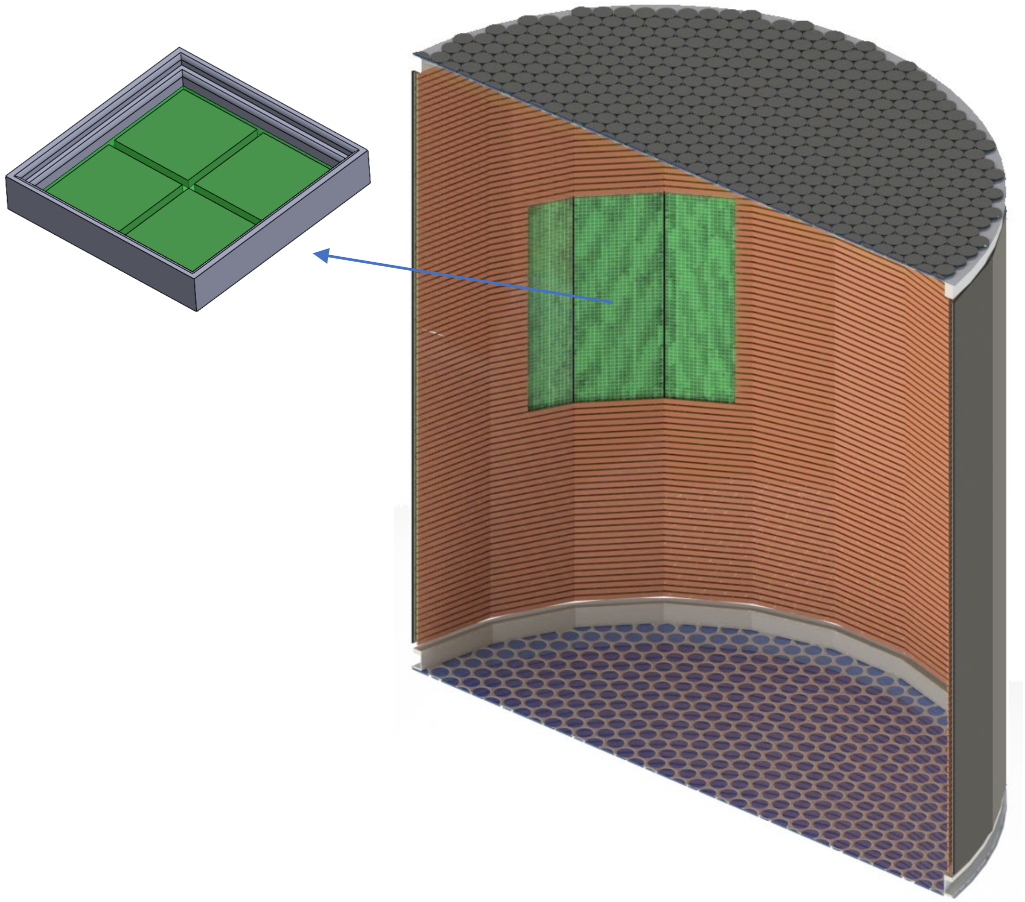
- For the assumed LXe absorption length, the largest photon sink is bulk absorption
  - L_{abs} = 50 m is taken from XENONnT's sensitivity paper. Result of recent work implies larger L_{abs} is doable
- Electrodes is the next biggest sink, motivating the next study

Reflective coatings

LXe L_{abs}, m	Scenario	Total LCE (top/bottom), %	Improvement, abs.% (rel.%)
50	Default (SS electrodes+frame)	**43.1** (14.8/28.2)	-
	Only Gate covered with Al/MgF_2	**46.0** (16.8/29.2)	+2.9 (+6.7)
	All electrodes and frames covered	**51.8** (18.6/33.2)	+8.7 (+20)
500	Default (SS electrodes+frame)	**54.0** (18.7/35.3)	-
	Only Gate covered with Al/MgF_2	**58.7** (21.8/36.9)	+4.7 (+8.5)
	All electrodes and frames covered	**67.0** (24.3/42.7)	+13 (+24)

- Substantial improvement in LCE if electrodes are covered with 90% reflective coating
- Does not matter if reflections are specular or diffuse
- Similar improvement for mesh electrodes as for wire one
- Improvement the larger the longer the L_{abs}
- Covering only gate electrode could be a cost-effective compromise

4π design



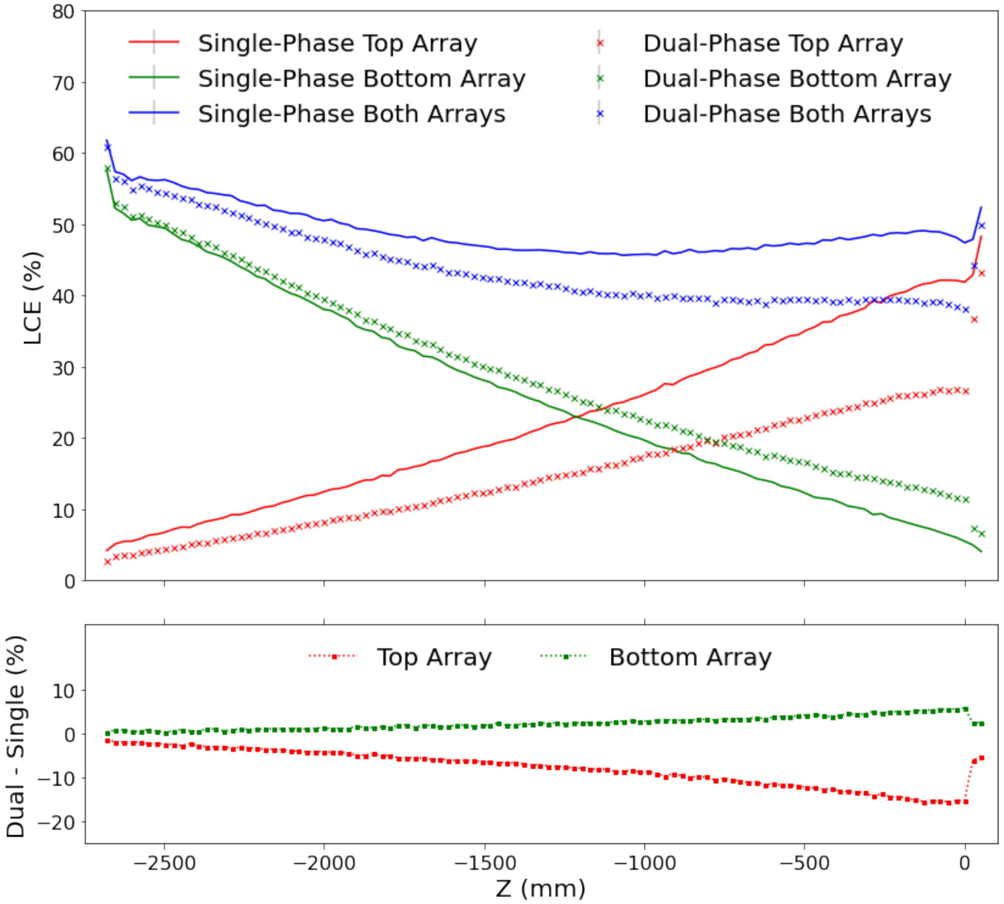
- Placing photosensors behind the field shaping rings
- VUV4 quad SiPMs or R12699-406-M4 flat PMTs
- No improvement in LCE due to rings' obstruction, loss of PTFE
- For SiPMs, surface reflections is another negative factor
    - Apart from decreased DN, SiPMs should have AR coatings to become more attractive
- Small improvement if rings are covered with reflective coatings, but only for the PMTs

Variant	FSRs	Total LCE (top/bottom/side), %
SiPMs	Cu	**22.6** (4.3/9.3/9.1)
	Al/MgF_2	**36.9** (6.1/13.0/17.9)
	No FSRs	**44.4** (3.7/8.1/32.6)
PMTs	Cu	**27.7** (4.3/9.3/14.1)
	Al/MgF_2	**46.8** (6.0/13.0/27.8)
	No FSRs	**61.2** (3.5/7.8/49.9)

Concluding remarks

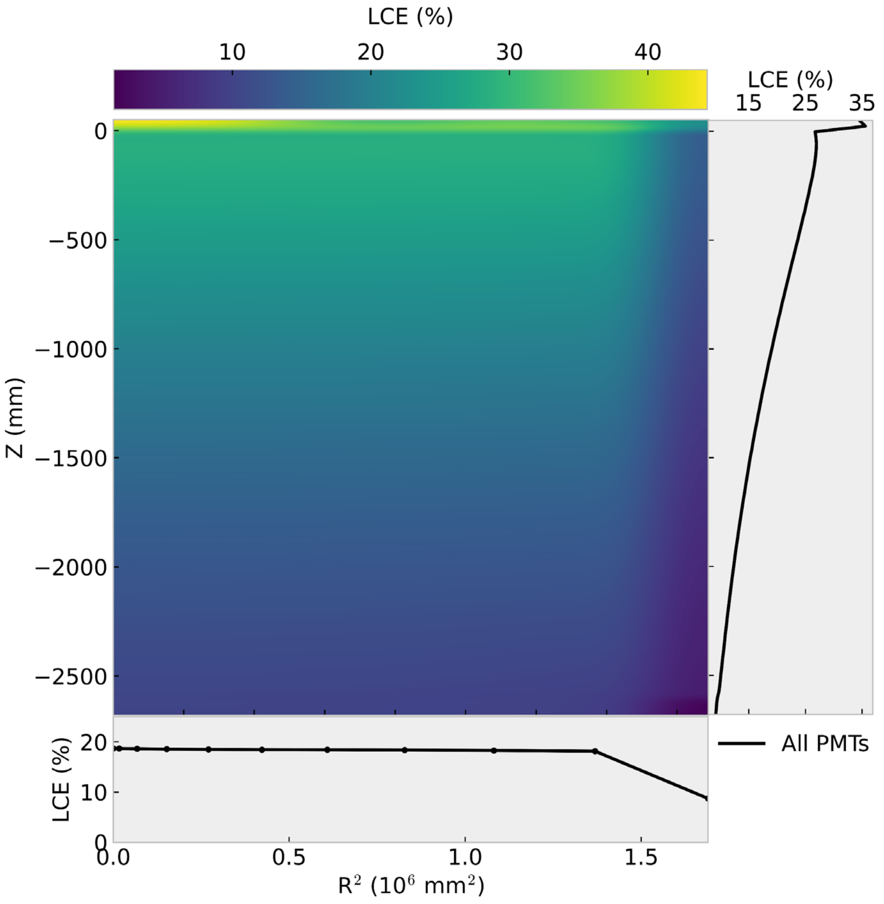
- Performed optical simulations of DARWIN with an alternative photon tracker, Chroma
  - Order-of-magnitude faster photon tracking than Geant4
  - Fast, convenient geometry implementation is an added plus for experiments without fixed design
  - Once the design is fixed, integrating Chroma (photon tracking) with Geant4 (rest of physics) should be achievable within any modular, Python-based software framework
  - Cross-validated Chroma and Geant4 to <2%
  - Several specific studies based on realistic, detailed geometry
    - Reflective coatings good, 4π coverage not so much
    - More details and other studies in arXiv preprint

Single-phase TPC



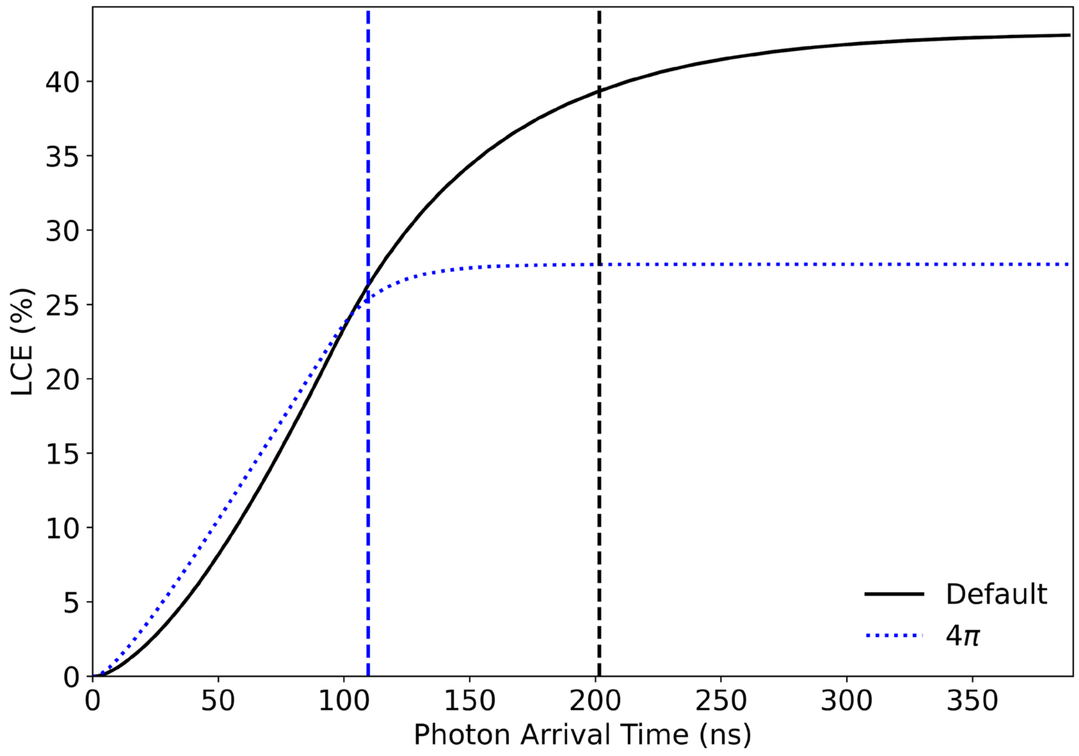
- Proportional scintillation in LXe offers several advantages
- Simplest way (not necessarily optimal) to implement and simulation this is for DARWIN to remove the GXe region
  - PMTs would collect more light and do it faster

No bottom PMT array



- Potential advantages are reduced backgrounds and halving the costs of PMTs and electronics
- The expected loss of LCE could be alleviated by extra PTFE reflector
- However, in a big detector like DARWIN, the LCE still drops too much, more than twice below the baseline level
  - Improving the L_{abs} to 500 m does not help enough
- Time to collect photons also gets worse
- Overall, a nonstarter

4π vs baseline



- 4π collects photons faster, but to have more photons total, one would have to use wider gaps between rings, coat rings with reflective films
  - Both are tricky

4π vs baseline