Simulations, Backgrounds, and Sensitivity Report

DELight Collaboration Meeting UFR 18.06.2025

Francesco Toschi and Eleanor Fascione

Simulations Working Group Report

Simulations WG (Working Group)

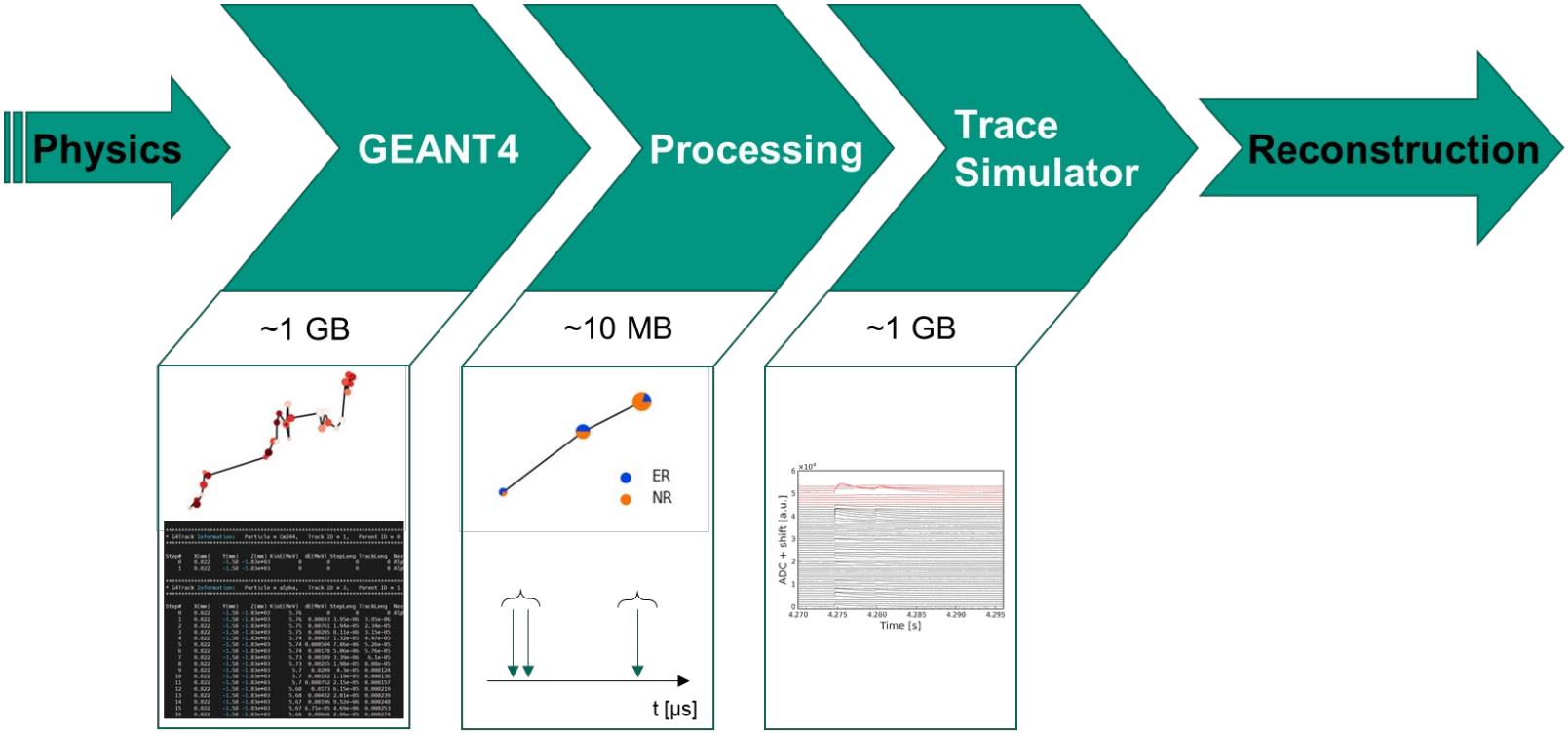
- Development and maintenance of
  - GEANT4 framework;
  - post-simulation processing tools;
  - simulation of traces.

- “Logistics” of simulations: production, bookkeeping and storage.

- Informing design and development of the detector.

Meeting: same time slot of general DELight meeting, alternating (**Tue. @ 13:30**)

SimsWG @ last CM (Sept. 2024)



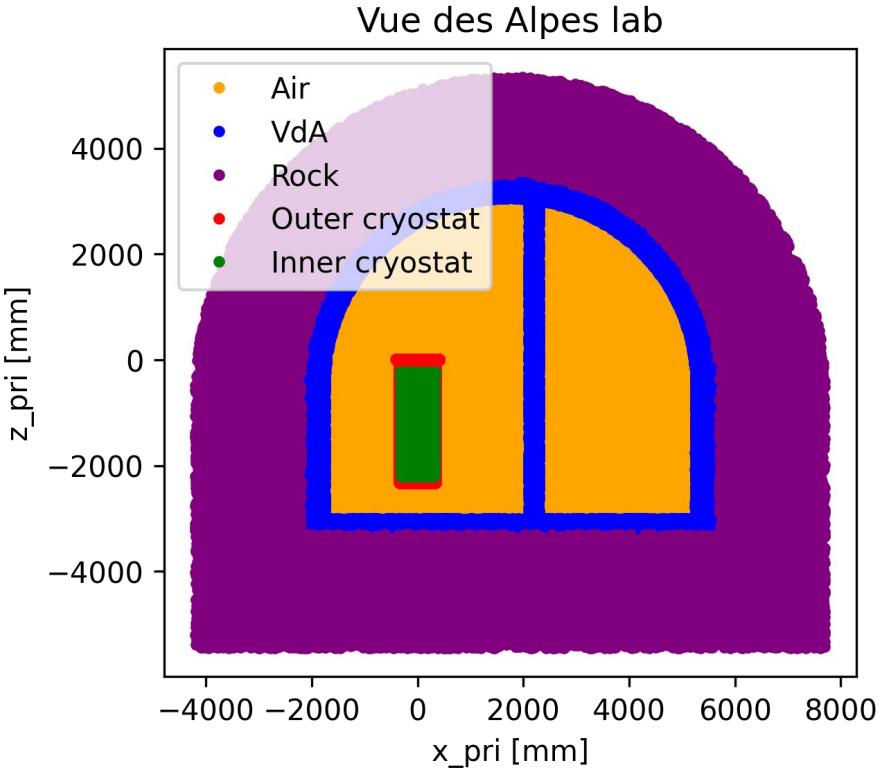
GEANT4

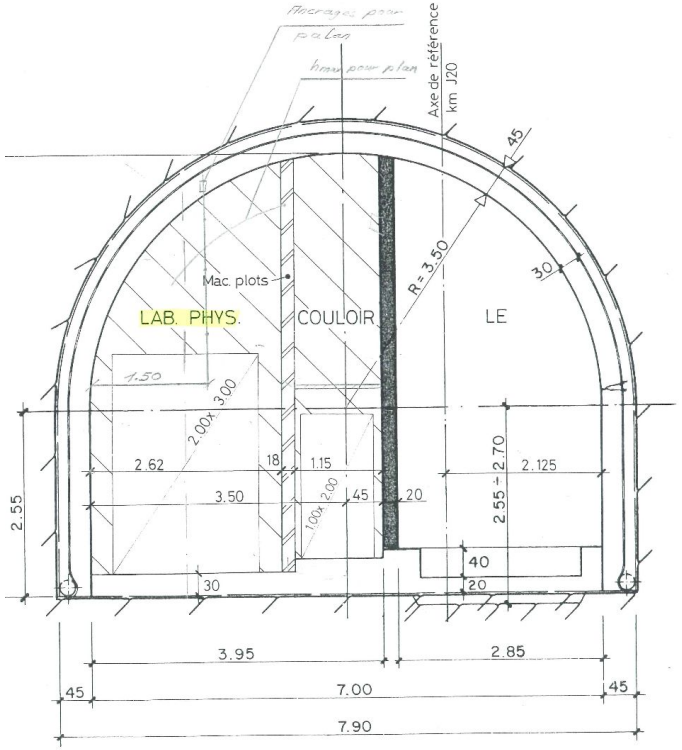
- Used on HD farm (env via *cvmfs*) and KIT kalinka (env in */home/ws/ks0116*)
- On GitLab, current version is **v0.2.0**
- Main changes are related to geometry

Name	Mass [kg]	Mass Error [kg]	Material	Density [kg/m³]	Is Sensitive?
Air	2.5942e+02	1.12e-01	G4_AIR	1.20	No
Cell	1.0296e+01	1.49e-02	G4_Cu	8960.00	No
CopperRing_He	3.3735e+00	6.34e-03	G4_Cu	8960.00	No
CopperRing_Vacuum	6.7462e-01	1.24e-03	G4_Cu	8960.00	No
Feedthrough	1.5079e-02	7.41e-06	G4_GLASS_PLATE	2400.00	No
FilmBurner_Cu	2.6222e+01	5.10e-02	G4_Cu	8960.00	No
FilmBurner_SS	9.5002e-01	4.42e-04	G4_STAINLESS-STEEL	8000.00	No
Fridge	4.2005e+02	1.73e+00	G4_Cu	8960.00	No
HeliumTarget	1.7182e-01	9.51e-05	liquidHelium	145.00	Yes
InnerCryostat	2.0645e+02	1.13e+00	G4_STAINLESS-STEEL	8000.00	No
MMCPhononCollector_0000	6.2617e-07	1.78e-09	G4_Al	2699.00	Yes
MMCPhononCollector_2000	3.2227e-07	8.04e-10	G4_Al	2699.00	Yes
MMC_0000	4.2975e-03	2.44e-06	G4_ALUMINUM_OXIDE	3970.00	Yes
MMC_2000	2.2113e-03	1.41e-06	G4_ALUMINUM_OXIDE	3970.00	Yes
OuterCryostat	3.6519e+02	2.35e+00	G4_STAINLESS-STEEL	8000.00	No
PTRs	9.4480e+00	5.53e-02	G4_STAINLESS-STEEL	8000.00	No
Rock	2.4683e+06	2.05e+03	Limestone	2710.00	No
SQUID_0000	7.3394e-06	1.51e-09	G4_Si	2330.00	No
SQUID_2000	7.3395e-06	1.22e-09	G4_Si	2330.00	No
Shielding	1.6934e+02	1.63e-01	G4_Pb	11350.00	No
ShieldingShell	2.1158e+01	2.88e-02	G4_Cu	8960.00	No
SupportingStructure	1.3830e+02	1.69e+00	G4_Al	2699.00	No
Vacuum	8.4290e-23	4.88e-26	Vacuum	0.00	No
VdA	2.5106e+05	4.00e+02	G4_CONCRETE	2300.00	No
World	8.0000e-19	9.95e-25	interGalactic	0.00	No

Work by **Kathrin Gerbig** (UHD) and **Jens Reininghaus** (UFR)

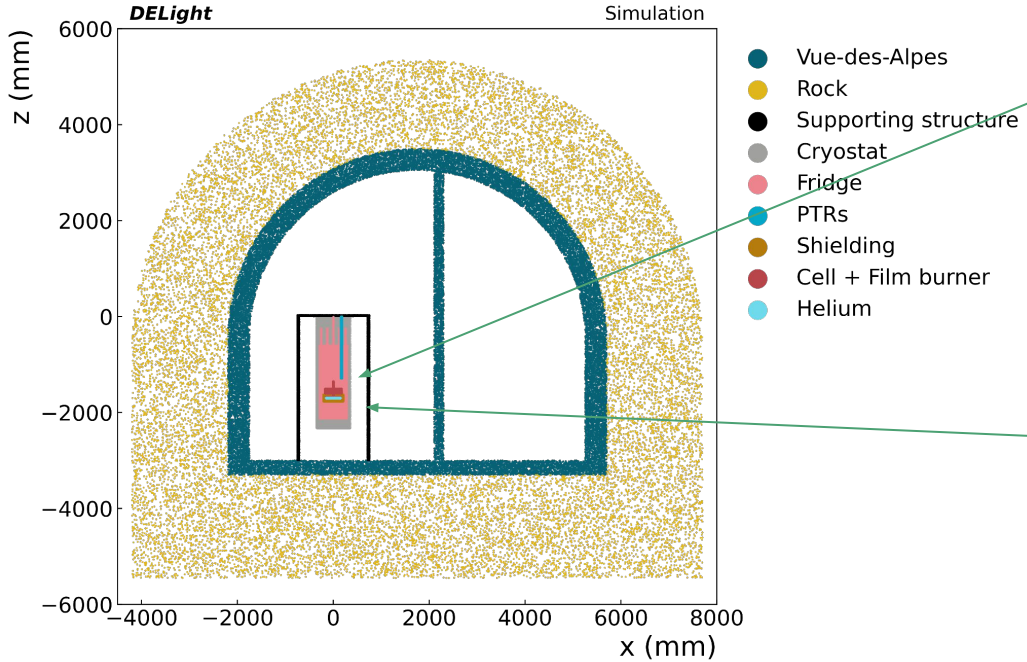
Vue-des-Alpes implementation

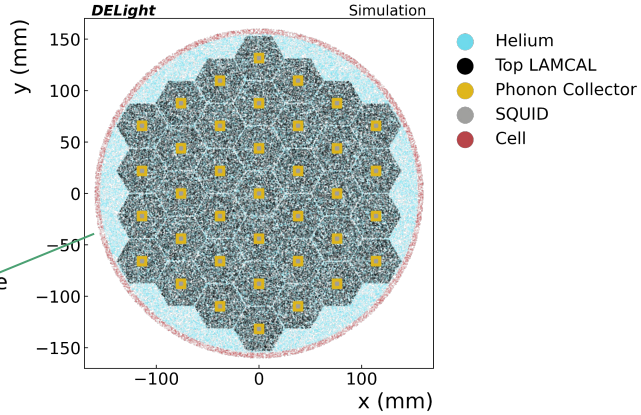


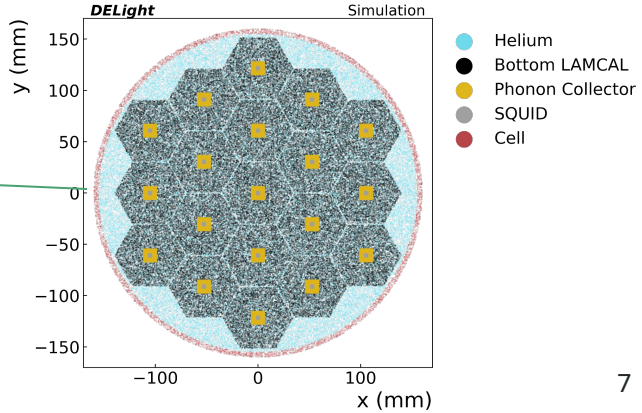


RU geometry


Physics
GEANT4
Processing
Trace Simulator
Reconstruction

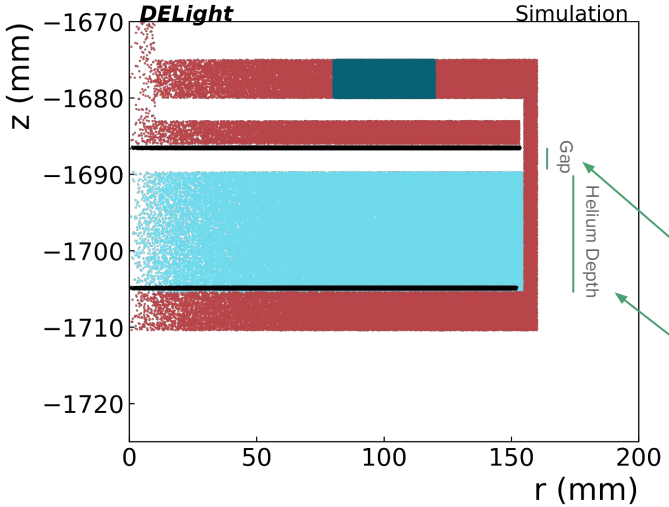

DELight
Simulation
z (mm)
x (mm)
Vue-des-Alpes
Rock
Supporting structure
Cryostat
Fridge
PTRs
Shielding
Cell + Film burner
Helium

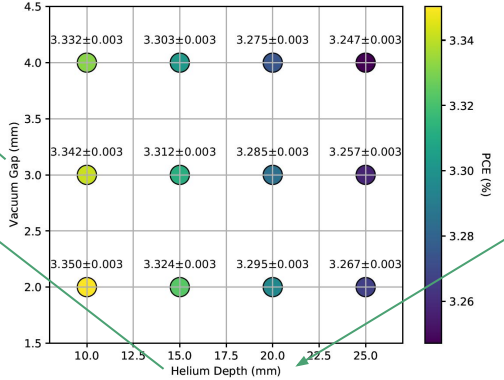

DELight
Simulation
y (mm)
x (mm)
Helium
Top LAMCAL
Phonon Collector
SQUID
Cell

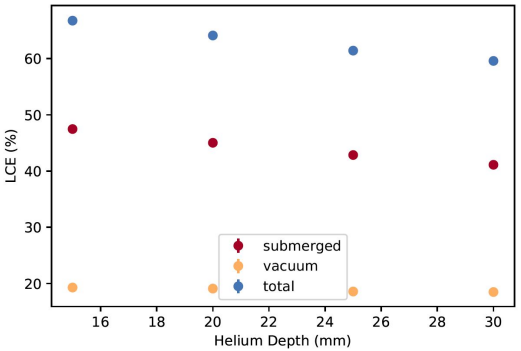

DELight
Simulation
y (mm)
x (mm)
Helium
Bottom LAMCAL
Phonon Collector
SQUID
Cell

“Pancake” geometry

Given the extreme aspect ratio, changes in vacuum gap or helium height have marginal impact on collection efficiency.

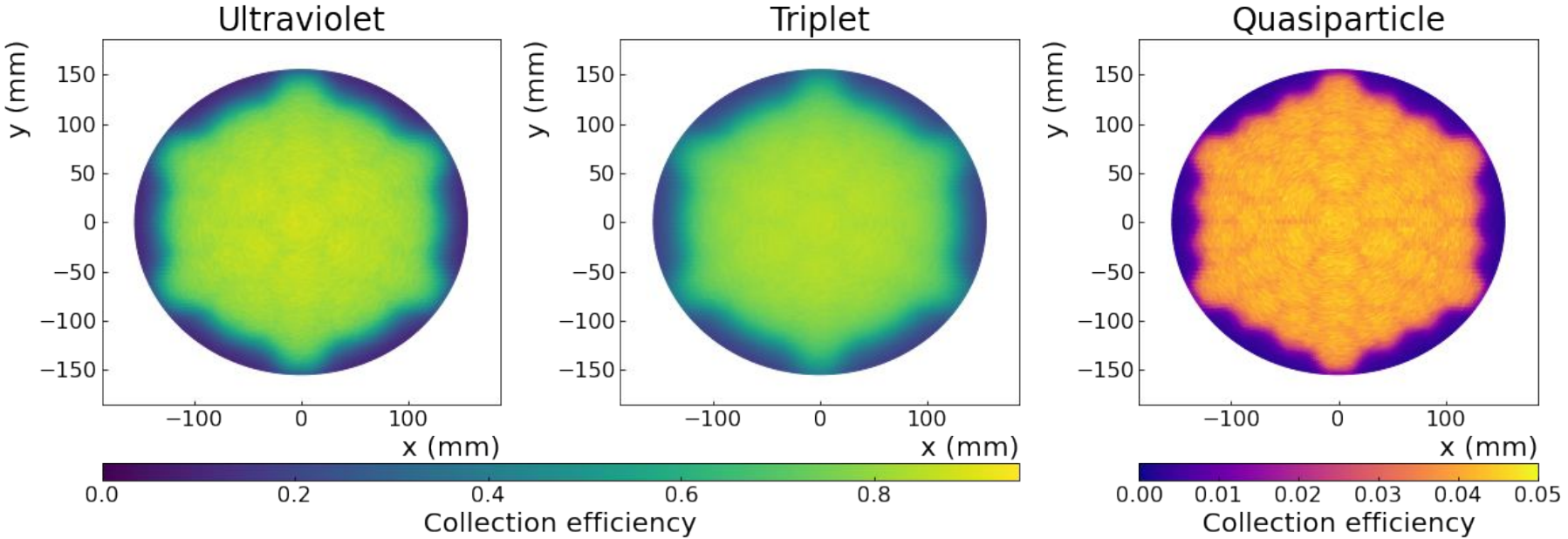






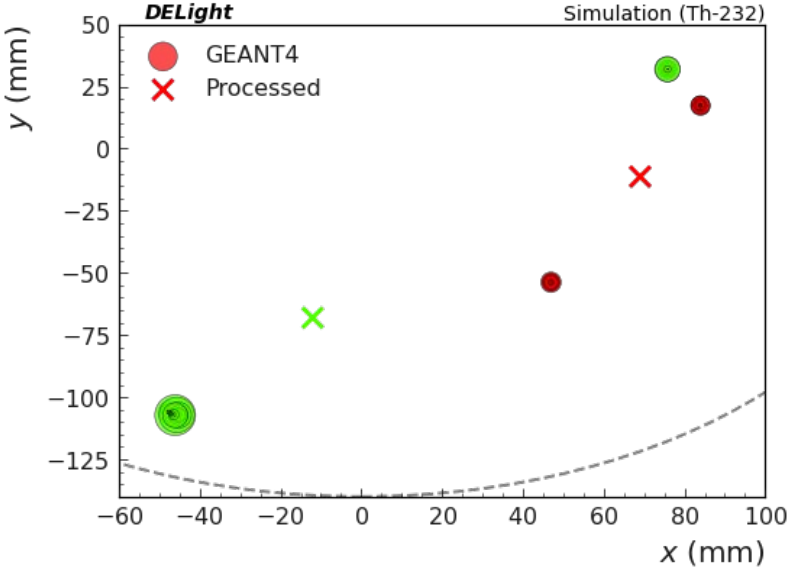
Collection efficiency maps

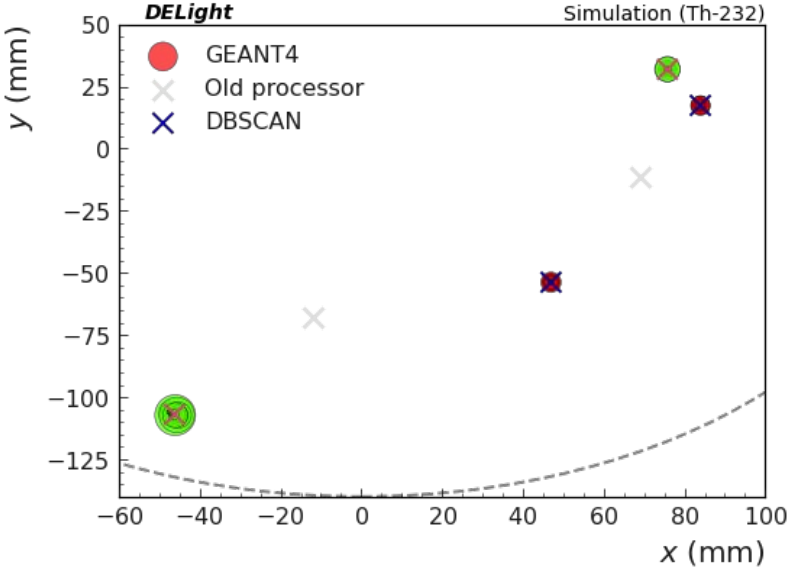
The structure of the bottom (UV/triplet) and top (quasiparticle) LAMCAL arrays is evident in the collection efficiency maps.



The new processor: SPASS

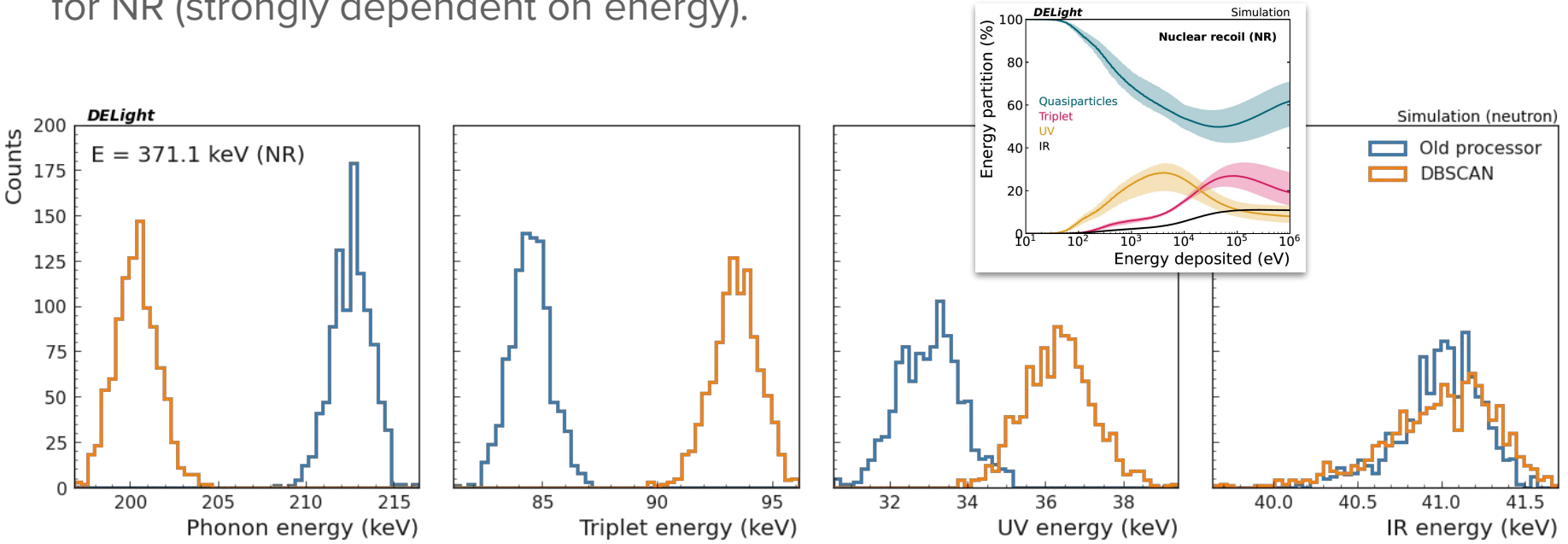
From time-only clustering (procDEL) to space-time clustering (**SPASS**): based on DBSCAN algorithm, allowing for proper partitioning.





The new processor: SPASS

Impact on signal partitioning: limited for ER (flat yields with energy), very important for NR (strongly dependent on energy).

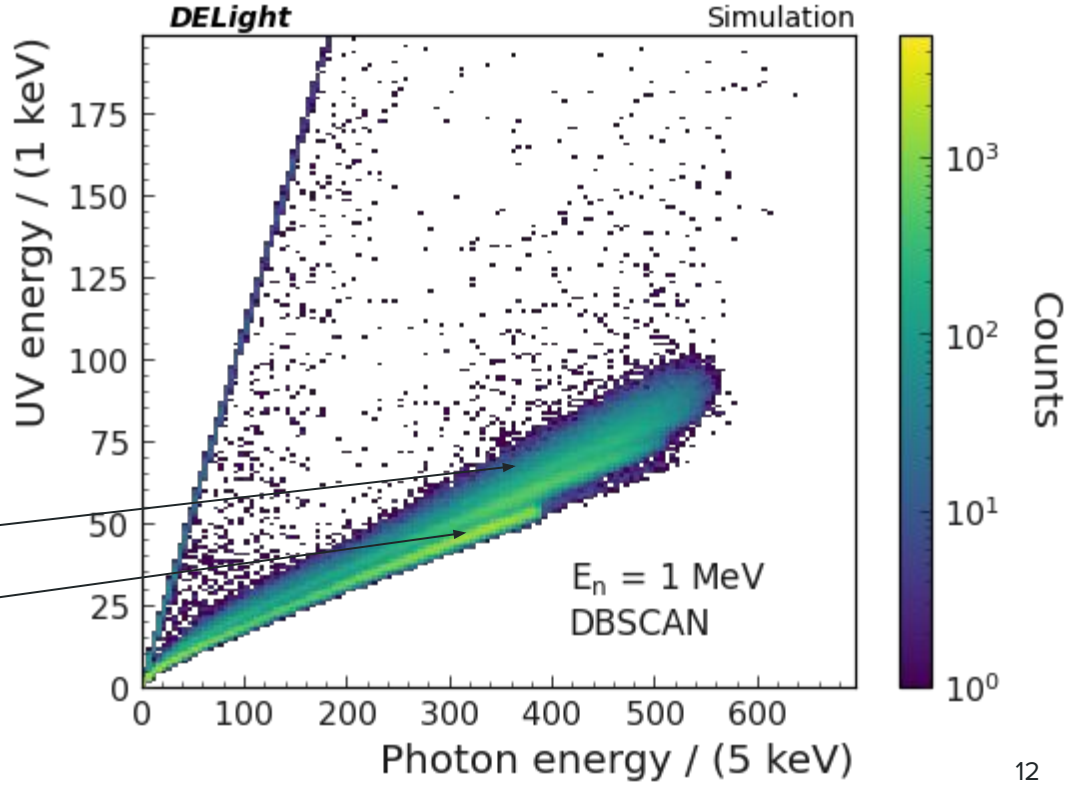


The new processor: SPASS

Potential to discriminate multiple- vs. single-scattering!

Need to investigate

Possible thesis!



TraceSimulator

- Not much new since tool was introduced
- Ongoing debugging with Benedikt and Dowling
- Aiming to have a validated simulator for RU geometry soon

People needed! (see Benedikt's report)

Backgrounds

Previously… on Backgrounds

Radiogenics (ER and NR)

Surface cosmics

MMC cosmogenic contamination

CEvNS

Photonuclear

See slides from last collaboration meeting, Francesco's detailed slides (ER, NR)

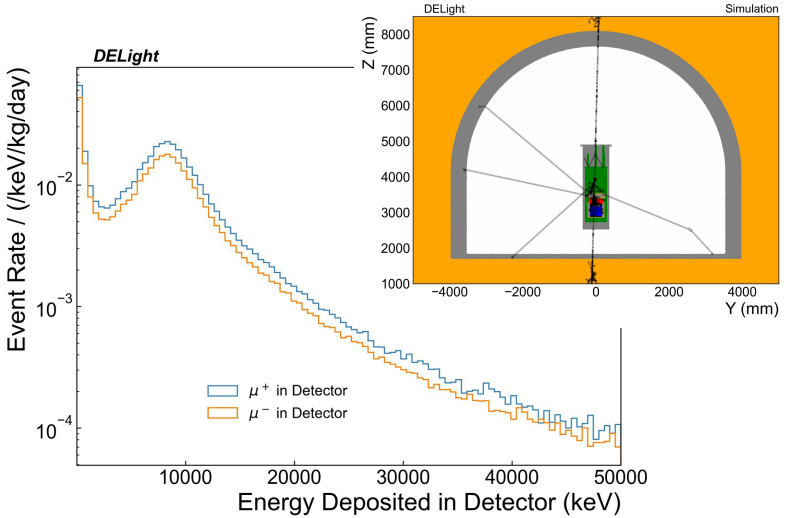
Work by **Jens Reininghaus** (UFR)

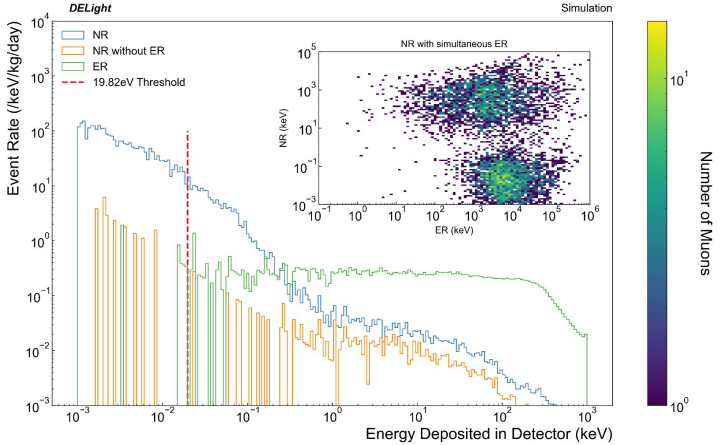
Muons at VdA

- v0 geometry, rate estimated for pancake
- Limestone rock around lab
- Theoretical muon flux model, agrees with measurement at GeMSE

See first slides and update

Depositions	Rate [/day]
All	$615.1 \pm 37.4_{(sys)} \pm 0.8_{(stat)}$
ER	$612.8 \pm 37.3_{(sys)} \pm 0.8_{(stat)}$
NR	$6.78 \pm 0.41_{(sys)} \pm 0.09_{(stat)}$
NR<1keV, no ER	$0.040 \pm 0.003_{(sys)} \pm 0.007_{(stat)}$





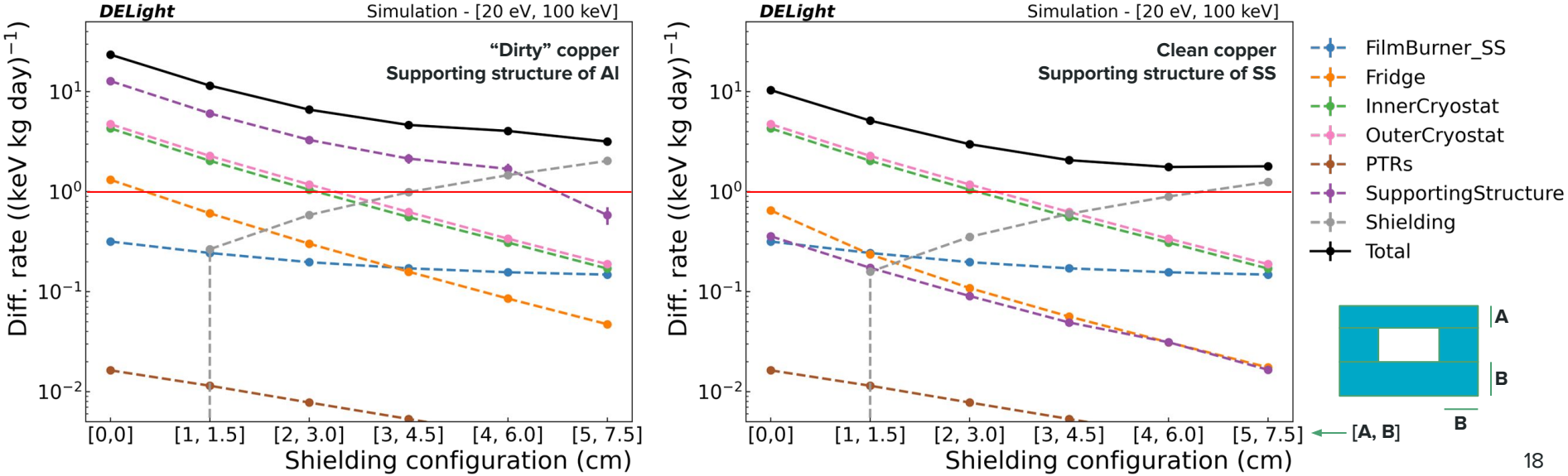
Updated Radiogenic Backgrounds

With the updated RU geometry, radiogenic backgrounds must be re-run

New studies to optimize the thickness of the internal shielding in progress

Shielding optimization - preliminary results

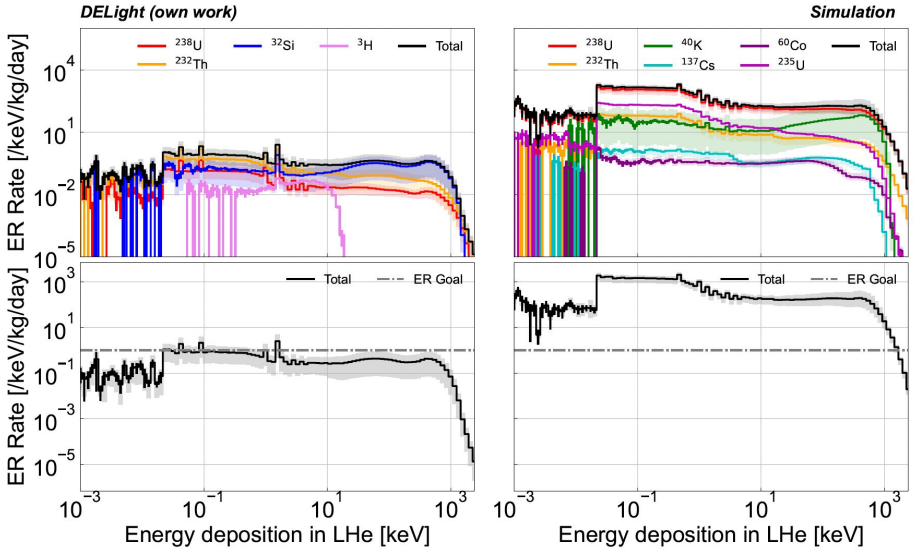
Preliminary optimization studies for the inner shielding show that already copper, if close to the active volume, can lead to an excessive background.



LAMCAL Radiogenic Backgrounds

Dependent on wafer material (sapphire vs. silicon), using currently available literature

- Not much for literature for sapphire
- Waiting for GeMSE assays
- Some background (≅10%) may be removed by large coincident signal
- Near/surpassing goal background
- SuperCDMS assumes only ^{32}Si and ^{3}H for silicon - is this more realistic?
- Not taking into account sensor material, only wafer



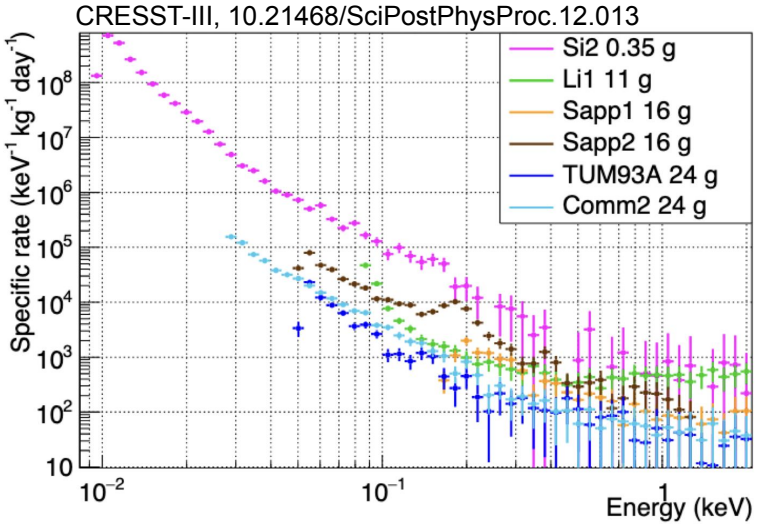
Important Note

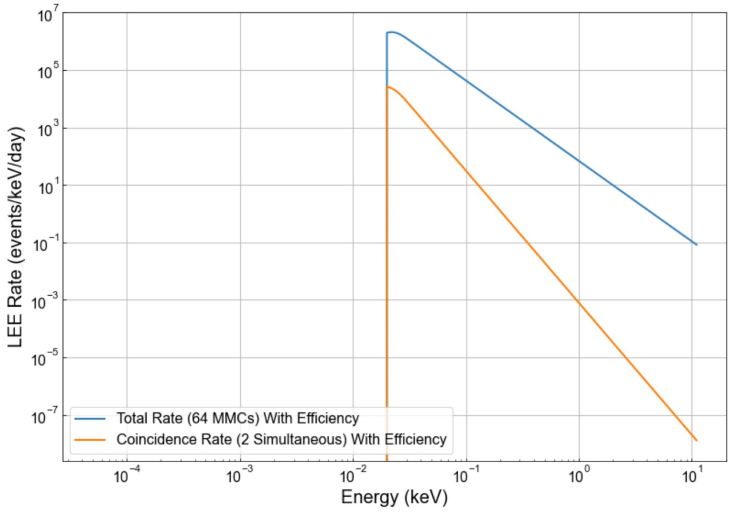
Radiogenic backgrounds will make reaching the goal background levels for phase-I **challenging**

Low Energy Excess

Expect to see the low energy excess (LEE) in DELight LAMCALs

Can be partly discriminated by requiring a coincidence in at least 2 sensors (probably in quasiparticle channel)

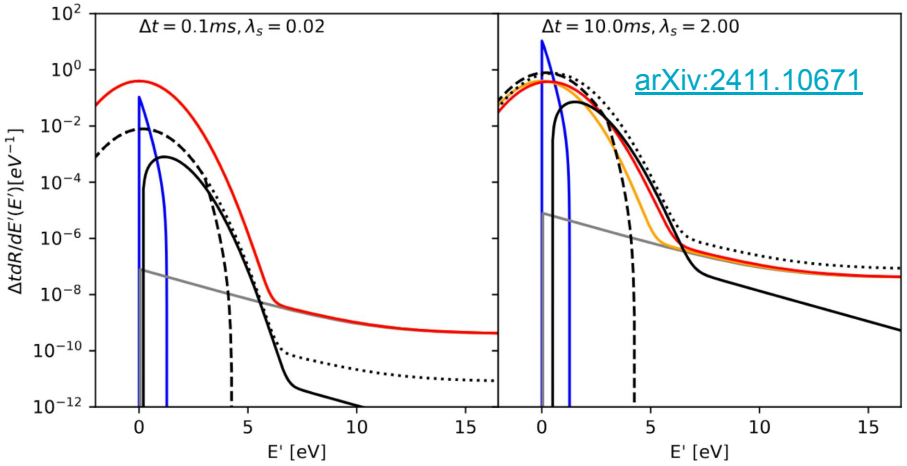




Low Energy Excess

Even with rejecting the majority of LEE events via requiring coincident signal, LEE can have an impact on the shape of the DM spectrum

Effect is similar to noise boosting (DM signals coincident with an LEE event will be ‘boosted’ to a measured higher energy)

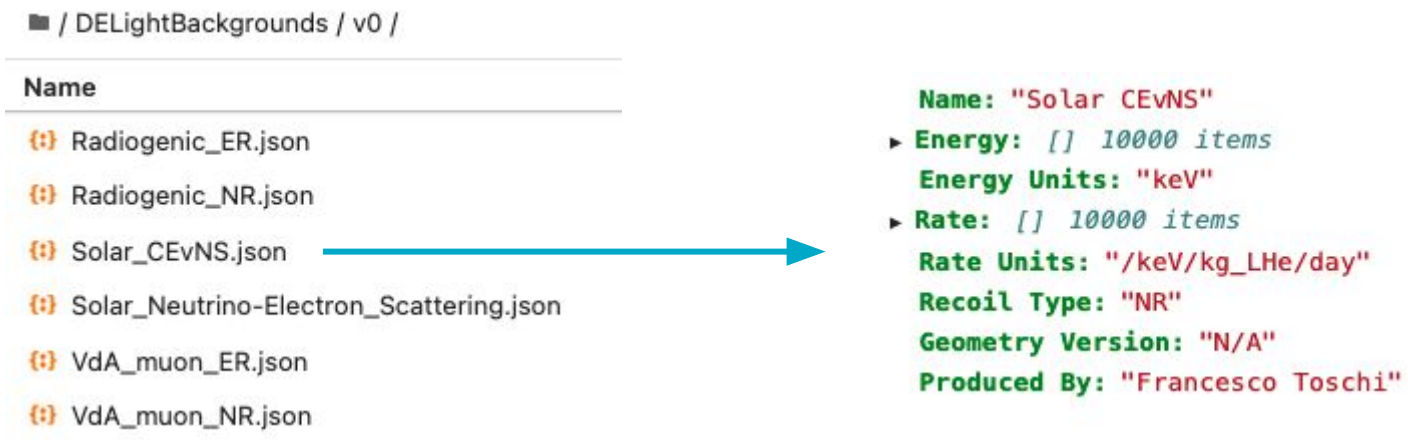


Raw background
Raw background, with noise
Raw DM recoil spectrum
Detected DM spectrum, 3σ smear
Detected DM spectrum, ‘Pyle method’
DM + background spectrum

DELightBackgrounds

A new gitlab repository, DELight Backgrounds, for the collection and versioning of the DELight background model

Preliminary v0 implemented, already out of date



DELightBackgrounds - Material Activities

Radiogenic background rates are based on material-dependent activities

DELightBackgrounds provides a library of assay results in activities.yaml and python class Radiogenics to load the activities for materials based on configuration files

- geometry.yaml - material and mass of each geometry component
- config.yaml - which activity from activities.yaml to use for a given material

Radiogenic background json files provide the ‘Total’ background assuming a default set of activities, but also provide the rates for each geometry component and isotope assuming an activity of 1Bq

Sensitivity Projections

The Sensitivity Code

Inputs

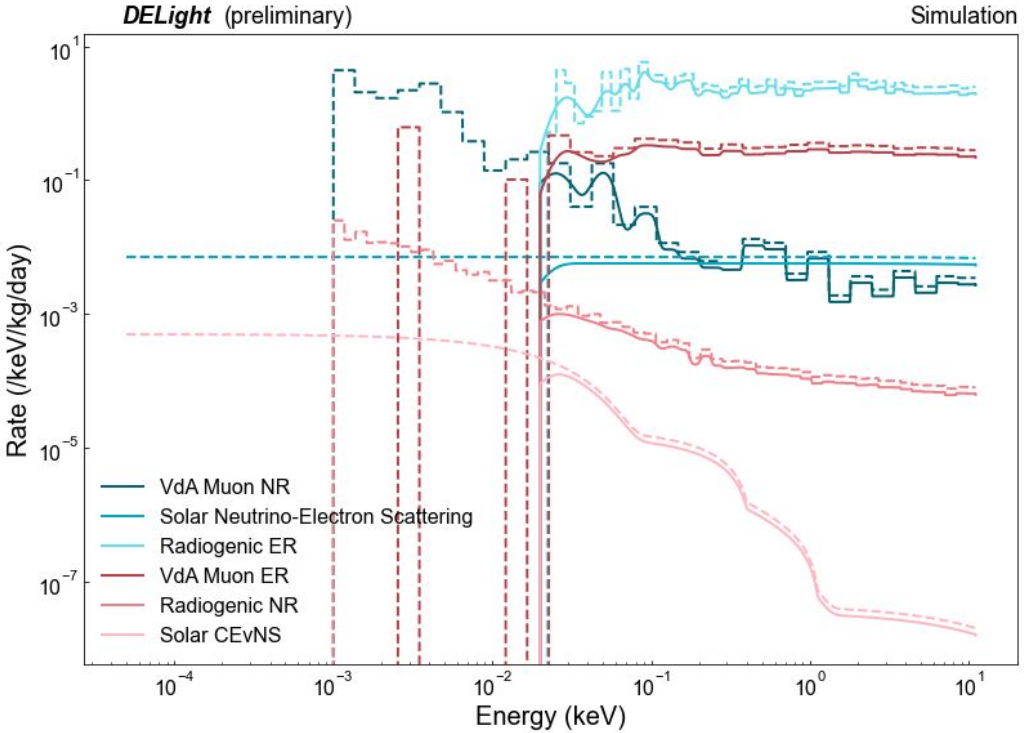
- Run configuration (duration & duty cycle, target mass, energy threshold, detector resolution, energy-dependent efficiency)
- Backgrounds

Detector response is applied to background and dark matter spectra - next slide

Limit methods - run over a given set of dark matter masses for N experiments drawn from the background model

- Optimum interval (OI)
- Profile likelihood ratio (PLR), 1 and 2 sided test statistics

Detector Response



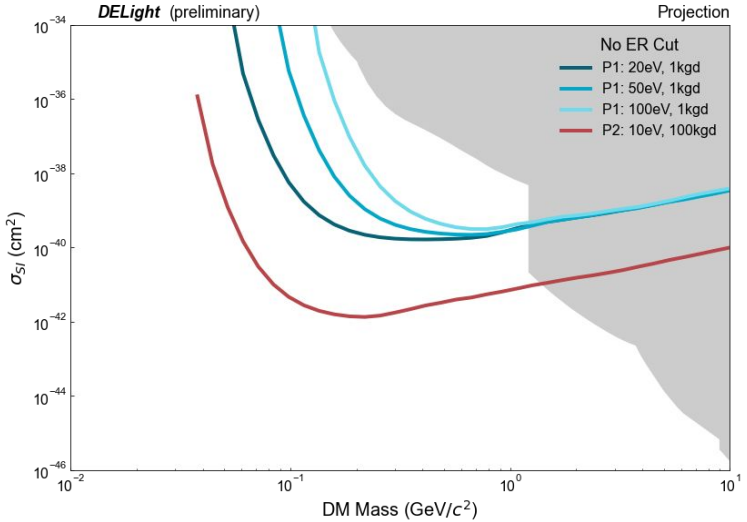
Applied to background and signal spectra

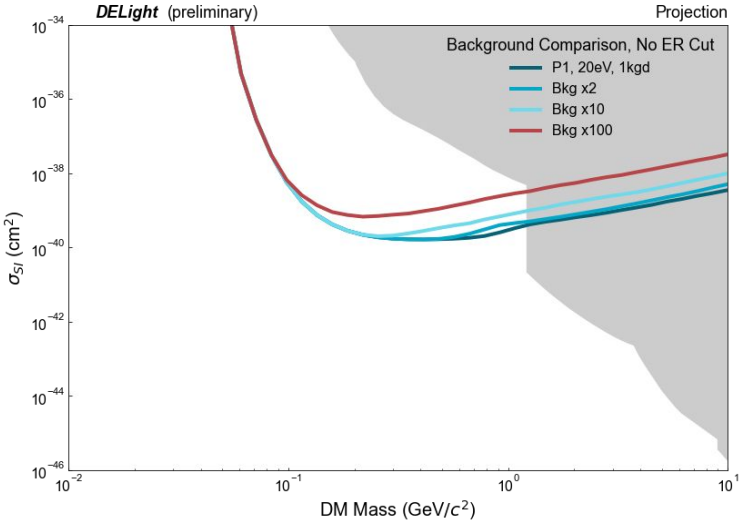
- Input: spectra as function of ‘true’ energy deposited in LHe
- Resolution smearing
- Trigger efficiency
- Recoil-type dependent efficiency e.g. ER discrimination cut

DELight Goal Background Projections

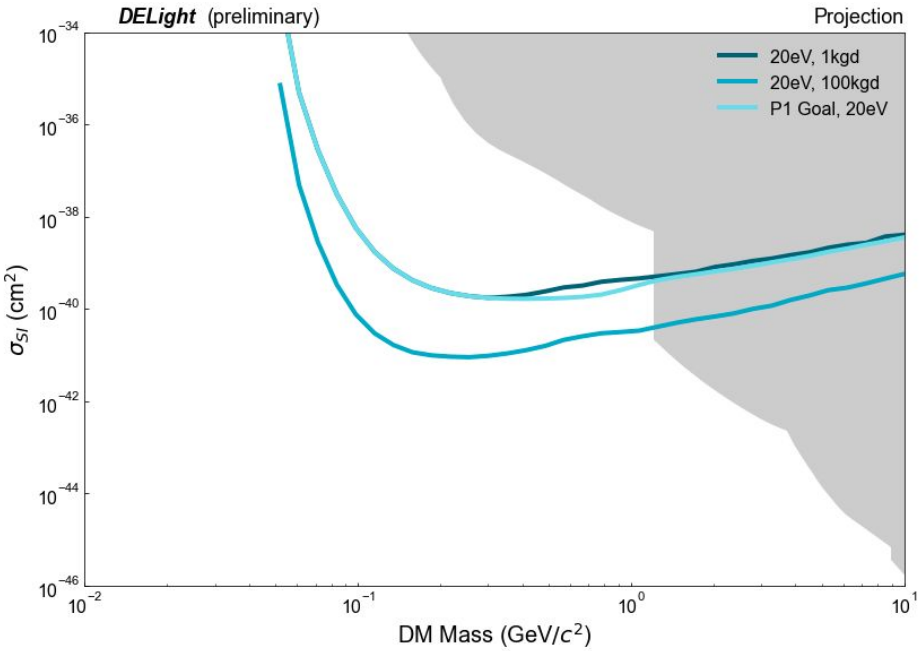
PLR limits demonstrating impact of threshold (left) and background rate (right)

- Phase-I ER: 1 /keV/kg/day, NR: 0.1/keV/kg/day
- Phase-II ER: 0.1 /keV/kg/day, NR: 0.001/keV/kg/day)

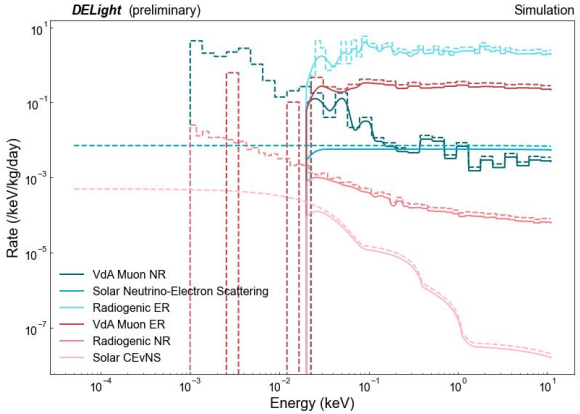




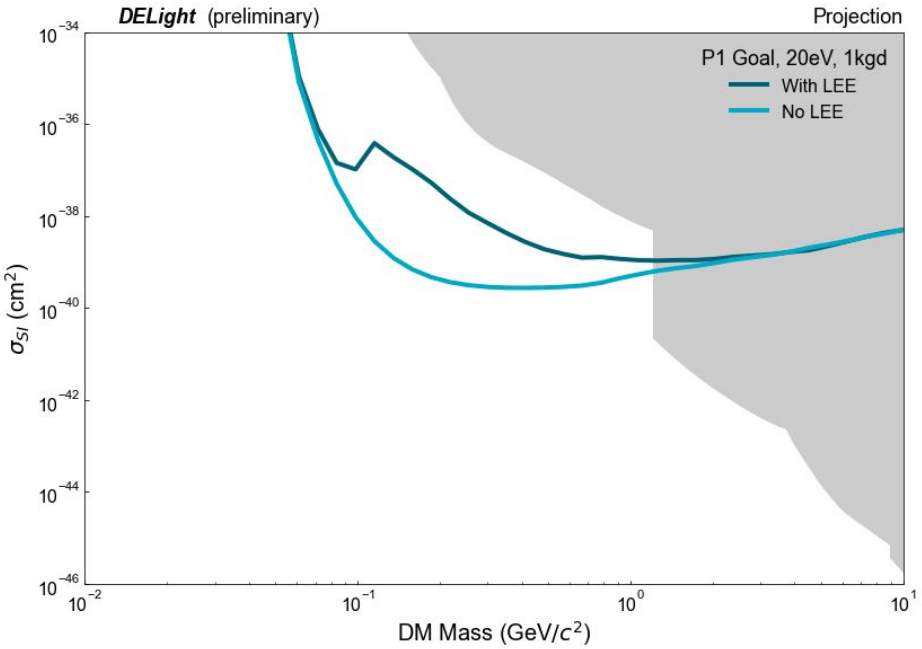
Preliminary - Projections with Full Background Model



"Full" background model still missing MMC contaminants, photonuclear backgrounds, and updated radiogenic backgrounds

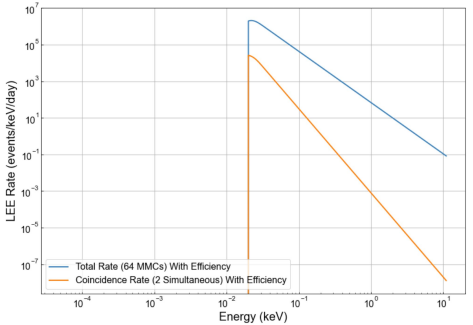


Preliminary - Impact of LEE



Assumption: LEE rate and spectral shape similar to that observed by CRESST, and 2-sensor coincidence (conservative, 2 events within 10ms)

Shape fixed in PLR - should be allowed to vary?



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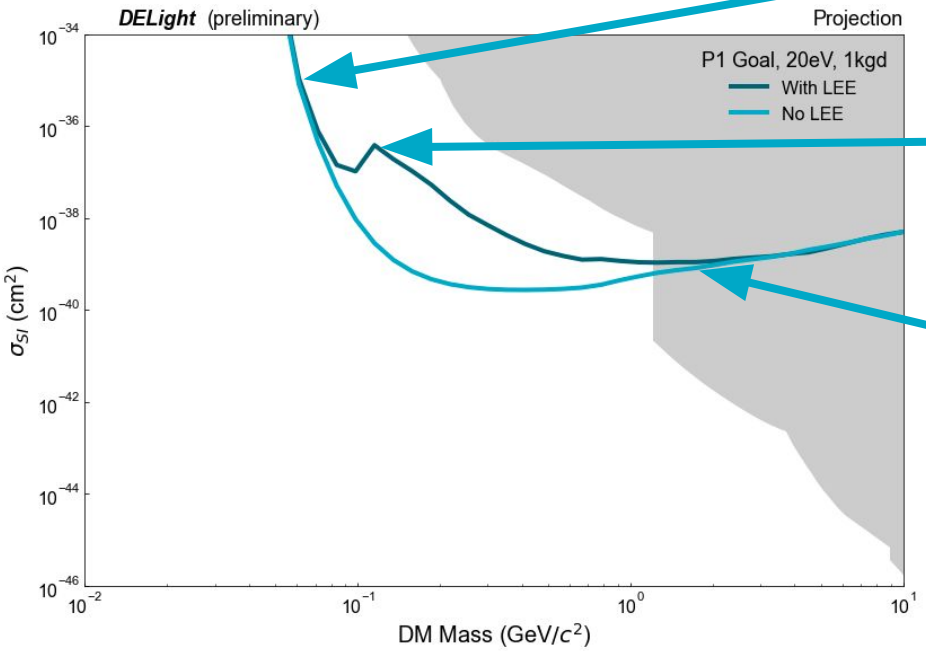

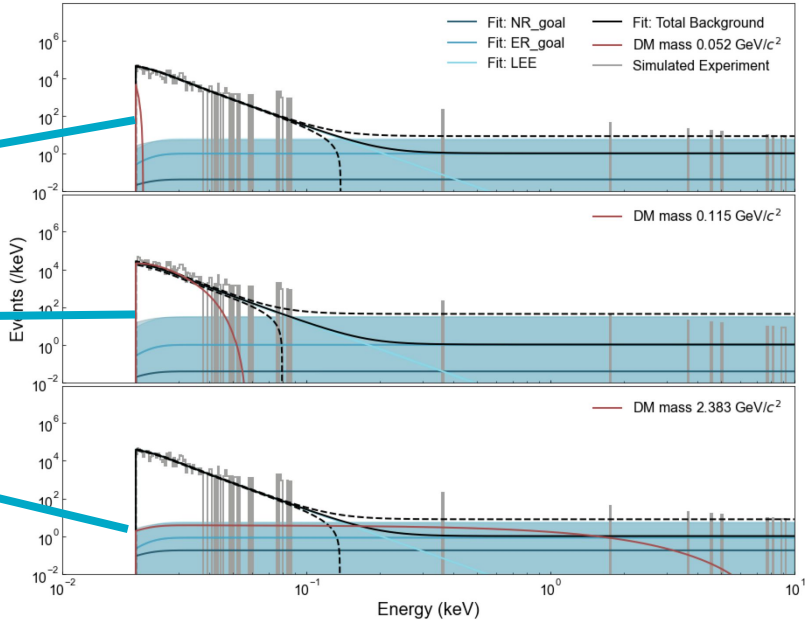

As expected, sensitivity weakens where DM model is most similar to LEE

Sensitivity Paper - What Do We Still Need?

In progress:

- Finalized background model
- V2 geometry collection efficiency maps (ER discrimination cut & energy calibration model)
- Detector response as function of ‘calibrated energy’
- Impact of NR calibration uncertainty
- Constraints/uncertainties on known backgrounds
- For LEE studies - ability for shape of LEE background to fluctuate
- PLR limit calculation based on simulated test statistic distribution rather than Wilk’s theorem

Decisions on conventions

- PLR limits: one or two sided test statistic?
- Noise boosting limitation - 3σ cut off or newer method proposed by Pyle et al?

Sensitivity Paper

Should we include sensitivity for the LAMCALs as detectors themselves?

- Sensitive to electron-scattering DM
- Dark absorption models
- Spin-dependent (sapphire)