Three main research axes:
- **dark matter** (direct detection)
- **solar/reactor neutrinos** (oscillation, Sun dynamics)
- **double beta decay**

<table>
<thead>
<tr>
<th></th>
<th>Solar/reactor neutrinos</th>
<th>ββ decay</th>
<th>dark matter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy range</strong></td>
<td>few MeV</td>
<td>few MeV</td>
<td>0.1÷100 keV</td>
</tr>
<tr>
<td><strong>Signal level (expected)</strong></td>
<td>1 t⁻¹ day⁻¹</td>
<td>&lt; 1 t⁻¹ yr⁻¹</td>
<td>&lt; 1 t⁻¹ yr⁻¹</td>
</tr>
<tr>
<td><strong>Background level (goal)</strong></td>
<td>1 t⁻¹ day⁻¹</td>
<td>10⁻² kg⁻¹ keV⁻¹ yr⁻¹</td>
<td>10⁻² kg⁻¹ keV⁻¹ day⁻¹</td>
</tr>
</tbody>
</table>

Background suppression and rejection are crucial:
- **underground** laboratories (10⁻⁶ cosmic flux)
- construction with **radio-pure** materials
- **assay** of all the detector components
- active/passive **shielding**
- excellent understanding of **detector response**
GEANT4 is an essential tool for:
- **design** phase of an experiment (minimize backgrounds)
- understand the **detector response**
- predict **background** levels and induced features
- **simulate the signal** (fitting data)

Focus on experiments using scintillators (Borexino & noble liquid dual-phase TPCs)

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Diagram:
1) **Simulation of detector response**
2) **Physical processes**
3) **Particle tracking**
   - **Radioactive backgrounds**
4) **Cosmogenic background**
   - **Signal**

---

*Paolo Agnes, ENSAR2 Workshop, CIEMAT*
Optical Simulations in GEANT4

300 t liquid scintillator; 2 nylon vessels separate different target regions (PC + PPO / and pure PC).

2000 PMTs are pointing towards the center
The light is produced in the core by scintillation (40000 ph/MeV) and Cherenkov effect
The light is wavelength shifted by PPO and propagated through the detector

The detected light yield is ~ 500 PE/MeV
The scintillation light emission is not simulated at the molecular level, but the energy spectrum is sampled.

The emission is intrinsically non-linear (quenching due to ionization), separate tuning.

**Optical response** depends on several parameters, some of them are known, some of them are measured in independent setups (but the experimental conditions may vary...), some of them are unknown.

Iterative tuning: sources of known energy / position, relative observables. Resolve correlations.

Iterative parameter tuning

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expected value</th>
<th>Tuned value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_{PC}$</td>
<td>1</td>
<td>1.35</td>
</tr>
<tr>
<td>$\Lambda_{nylon}$</td>
<td>1</td>
<td>0.75</td>
</tr>
<tr>
<td>$\Lambda_{DMP}$</td>
<td>1</td>
<td>1.1</td>
</tr>
<tr>
<td>$\Lambda_{PPO}$</td>
<td>1</td>
<td>1.15</td>
</tr>
<tr>
<td>$R_{SSS}$</td>
<td>0.49*</td>
<td>0.55</td>
</tr>
<tr>
<td>$R_{SSS}^{spike}$</td>
<td>0.4*</td>
<td>0.12</td>
</tr>
<tr>
<td>$R_{cathode}$</td>
<td>0.1*</td>
<td>0</td>
</tr>
<tr>
<td>$R_{\mu-\text{metal}}$</td>
<td>0.4*</td>
<td>0.4</td>
</tr>
<tr>
<td>$R_{PMT \text{ ring}}$</td>
<td>0.6*</td>
<td>0.75</td>
</tr>
<tr>
<td>$R_{PMT \text{ ring}}^{spike}$</td>
<td>0.8*</td>
<td>0.88</td>
</tr>
<tr>
<td>$R_{\text{conc. int.}}$</td>
<td>0.88 [44]</td>
<td>0.95</td>
</tr>
<tr>
<td>$R_{\text{conc. int.}}^{spike}$</td>
<td>0.8*</td>
<td>0.985</td>
</tr>
<tr>
<td>$R_{\text{conc. ext.}}$</td>
<td>0.88 [44]</td>
<td>0.95</td>
</tr>
<tr>
<td>$R_{\text{conc. ext.}}^{spike}$</td>
<td>0.8*</td>
<td>0.975</td>
</tr>
<tr>
<td>$R_{\text{nylon ring}}$</td>
<td>0.4*</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Light observed by PMTs with and without concentrator

Light observed in detector halves near and far from interaction

The optical tuning,

- Together with the tuning of the **energy scale** and **time profile** response (position reconstruction) with accuracy better than 1%.

===> **Spectral fit** and sensitivity to different component of solar neutrino flux.

The optical simulation of a detector is fundamental for improving one experiment’s sensitivity.

**GEANT4** has a fundamental role in modeling the detector response:
- optics classes and methods allow **great accuracy**
- possible **improvements**: documentation, inheritance of optical properties,

*Nature 562, 505 (2018)*
Detection in dual-phase TPC

**Scintillation:** $> 5$ PE/keV
**Ionization:** $\sim 1/ (20 \text{ eV})$
**Gas Multiplication:** $> 10$

3D vertex reconstruction for fiducialization
Ionization / Scintillation to discriminate backgrounds

**GEANT4 default ionization / scintillation mechanisms are not enough**

Energy deposition → Heat
- Excitation
  - $\text{Ar}^*$
  - $\text{Ar}_2^*$
- Singlet
- Triplet
- $\text{S}_1$
- Ionization
  - $\text{Ar}^+$
  - $\text{Ar}_2^+$
  - $\text{Ar}^{**}$
- Electrons
- Recombination
  - $\text{S}_2$
Modeling the Recombination Probability

Develop standalone classes to simulate these mechanisms

Two effective models describing the **track geometry** are joint
Free parameters (absolute yield, e-/excitons ratio, recombination...) fit to **data from independent calibration** setups

- **Thomas-Imel** for short tracks
- **Doke-Birks** for long tracks

---

**Scintillation yield at null field for recoiling electrons vs \( \gamma \) energy**

**Ionization yield for nuclear recoils at 730 V/cm drift field**

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*Paolo Agnes, ENSAR2 Workshop, CIEMAT*
In Argon: **PARIS (Precision Argon Recoil Ionization and Scintillation)** developed by the DarkSide-50 collaboration (*JINST*,12,10.1088(2017))

**S1**

- $^{83m}$Kr peak (41.5 keV)
- $^{39}$Ar spectrum (565 keV end point)

**S2**

- Internal calibrations:
  - $^{37}$Ar at 2.8 keV
  - $^{83m}$Kr at 41 keV
  - $^{39}$Ar in [80, 565] keV

**PhysRevD.97.112005**

**validation w external experiments**

**validation w external sources**
The ionization signal

Number of electrons that **survive recombination**

Simulation of ionization **electron transport** is not necessary
Projected at the liquid/gas interface (diffusion, e- lifetime)

**Calibration** of **S2 light yield** per electron relatively easy (thanks to samples of single electrons, due to impurities).

**Time profile**: extraction time + drift in the gas + scintillation time profile (distinguish S1/S2…)

---

Time profile of ionization signal for many e⁻
Radioactivity from materials or intrinsic to the target.
- Exploit energy/position correlation
- Compute leakage of known backgrounds in ROI
- Predict unanticipated backgrounds
- Calibrate the detector response over wide energy range

GEANT4 excellent for $\beta$ and $\gamma$ bgs (RDM coupled with spatial generator)
Beta and Gamma Background

GEANT4 excellent for $\beta$ and $\gamma$ bgs (RDM coupled with spatial generator)

Radioactivity from materials or intrinsic to the target.
- Exploit energy/position correlation
- Compute leakage of known backgrounds in ROI
- Predict unanticipated backgrounds
- Calibrate the detector response over wide energy range

Background model extrapolated at low energy (ionization only): excellent data/MC agreement

==> world-leading exclusion on WIMP-nucleon cross section for light WIMPs (2 to 6 GeV/c$^2$)

PRL 121, 081307 (2018)
Particular attention in dark matter experiments: a neutron (single sited, low energy nuclear recoil) can mimic dark matter!

Two classes of radiogenic neutrons are particularly interesting:
- spontaneous fission (high multiplicity, gammas)
- (alpha, n) neutrons due to U and Th in detector materials.

Dark Matter experiments are usually equipped with passive shields or active vetoes (DarkSide-50)

Example: $^{10}$B loaded Liquid Scintillator
Tagging efficiency measure with neutron sources: > 99%
Radiogenic neutron background

Intensive campaigns to assess radiogenic n background.
- **Statistics** in-situ is extremely **small**

**Production rates** are subjected to large uncertainties
- SOURCES-4A
- TALYS + SRIM

\[10^{-5} \div 10^{-9} \text{n/decay}\]

Generation in materials

**Propagation** through the detector geometry

Single sited interactions in active target

**Capture in materials**

Detection of capture products

**Neutron propagation/interaction/capture is very accurate** in GEANT4 using HP physics list.

However, large **uncertainties**

What about data/MC in **DarkSide-50**?

- Measured veto tagging efficiency of 99.6% (neutron source)
- Accumulated 500 days of statistics

**Expect ~10 neutrons** before looking in the veto: **Find 1 or 2**

==> Overestimated production rates?
==> correlated γ that interact in the TPC/Veto?

==> a lot of activities ongoing!
Some **problems** with models for nuclear de-excitation after capture:
- FS (G4NDL) approach does not conserve energy, conserves $\gamma$ multiplicity
- Photon evaporation conserves energy, does not conserve $\gamma$ multiplicity

Gd-based technology from neutrino physics (DoubleChooz, Super-Kamiokande) will be used for **DarkSide-20k** & **LZ** vetoes

This affects neutron tagging efficiency

Other nuclides are affected: Cu
Cosmic rays can reach the depth of underground laboratories and interact with materials:
- neutrons from **spallation** (MeV to GeV)
- **radionuclides** (us to s lifetime)

Extensive work is required in order to predict the background induced by cosmic muons. Simulate muons crossing a few meters of rock to fully develop showers.

Two simulation codes available:
- **GEANT4**
- **FLUKA**

**Caveat**: a prediction within a factor of 2 is acceptable

In general:
*une both and consider discrepancy as systematics*

Also:
Mixed approach is possible
## Cosmogenic activation in LAr

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Q value [MeV]</th>
<th>Half-life [s]</th>
<th>Decay mode</th>
<th>Yield per vertical muon</th>
<th>Yield [day^{-1} (10 kton)^{-1}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^8$B</td>
<td>16.96</td>
<td>0.77</td>
<td>$\beta^+$</td>
<td>9.3e-5</td>
<td>0.32</td>
</tr>
<tr>
<td>$^9$B</td>
<td>15.47</td>
<td>0.13</td>
<td>$\beta^+$</td>
<td>9.4e-6</td>
<td>0.032</td>
</tr>
<tr>
<td>$^{18}$N</td>
<td>13.90</td>
<td>0.62</td>
<td>$\beta^-$</td>
<td>1.0e-5</td>
<td>0.034</td>
</tr>
<tr>
<td>$^7$Li</td>
<td>13.61</td>
<td>0.18</td>
<td>$\beta^-$ (49%), $\beta^-n$ (51%)</td>
<td>2.9e-4</td>
<td>0.99</td>
</tr>
<tr>
<td>$^8$Li</td>
<td>12.98</td>
<td>0.84</td>
<td>$\beta^-$</td>
<td>1.4e-3</td>
<td>4.8</td>
</tr>
<tr>
<td>$^{11}$Be</td>
<td>11.51</td>
<td>13.76</td>
<td>$\beta^-$ (55%), $\beta^-\gamma$ (45%)</td>
<td>1.0e-4</td>
<td>0.34</td>
</tr>
<tr>
<td>$^8$He</td>
<td>10.66</td>
<td>0.12</td>
<td>$\beta^-\gamma$ (84%), $\beta^-n$ (16%)</td>
<td>7.2e-5</td>
<td>0.25</td>
</tr>
<tr>
<td>$^{16}$N</td>
<td>10.42</td>
<td>7.13</td>
<td>$\beta^-$ (28%), $\beta^-\gamma$ (72%)</td>
<td>4.6e-4</td>
<td>1.6</td>
</tr>
<tr>
<td>$^{15}$C</td>
<td>9.77</td>
<td>2.45</td>
<td>$\beta^-$ (37%), $\beta^-\gamma$ (63%)</td>
<td>1.2e-4</td>
<td>0.41</td>
</tr>
<tr>
<td>$^{26}$Na</td>
<td>9.35</td>
<td>1.07</td>
<td>$\beta^-\gamma$</td>
<td>1.1e-4</td>
<td>0.38</td>
</tr>
<tr>
<td>$^{27}$Na</td>
<td>9.01</td>
<td>0.30</td>
<td>$\beta^-\gamma$</td>
<td>2.1e-5</td>
<td>0.072</td>
</tr>
<tr>
<td>$^{17}$N</td>
<td>8.68</td>
<td>4.17</td>
<td>$\beta^-$ (5%), $\beta^-n$ (95%)</td>
<td>1.3e-4</td>
<td>0.45</td>
</tr>
<tr>
<td>$^{30}$Al</td>
<td>8.57</td>
<td>3.62</td>
<td>$\beta^-$</td>
<td>4.1e-4</td>
<td>1.4</td>
</tr>
<tr>
<td>$^{23}$F</td>
<td>8.48</td>
<td>2.23</td>
<td>$\beta^-$ (30%), $\beta^-\gamma$ (70%)</td>
<td>1.2e-5</td>
<td>0.041</td>
</tr>
<tr>
<td>$^{16}$C</td>
<td>8.01</td>
<td>0.75</td>
<td>$\beta^-n$</td>
<td>2.1e-5</td>
<td>0.072</td>
</tr>
<tr>
<td>$^{31}$Al</td>
<td>7.99</td>
<td>0.64</td>
<td>$\beta^-$ (65%), $\beta^-\gamma$ (35%)</td>
<td>9.7e-5</td>
<td>0.33</td>
</tr>
<tr>
<td>$^{29}$Mg</td>
<td>7.61</td>
<td>1.30</td>
<td>$\beta^-$ (27%), $\beta^-\gamma$ (73%)</td>
<td>1.8e-5</td>
<td>0.062</td>
</tr>
<tr>
<td>$^{40}$Cl</td>
<td>7.48</td>
<td>81</td>
<td>$\beta^-$ (85%), $\beta^-\gamma$ (15%)</td>
<td>7.9e-3</td>
<td>27</td>
</tr>
<tr>
<td>$^{20}$F</td>
<td>7.02</td>
<td>11.16</td>
<td>$\beta^-\gamma$</td>
<td>5.8e-4</td>
<td>2.0</td>
</tr>
<tr>
<td>$^{34}$P</td>
<td>5.38</td>
<td>12.43</td>
<td>$\beta^-\gamma$</td>
<td>3.4e-3</td>
<td>12</td>
</tr>
<tr>
<td>$^{38}$Cl</td>
<td>4.92</td>
<td>2234</td>
<td>$\beta^-$</td>
<td>0.031</td>
<td>110</td>
</tr>
</tbody>
</table>

This table lists the isotopes, their corresponding Q values, half-lives, decay modes, yield per vertical muon, and yield per day for 10 kton. The yield per day is calculated using the number of vertical muons and the decay rate of each isotope. The decay modes are indicated for each isotope, with $\beta^-$ for beta decay, $\beta^-\gamma$ for beta plus gamma decay, and $\beta^-n$ for beta plus neutron decay. The Q values indicate the energy released in the decay process, with higher values indicating more energized decays.
## Cosmogenic activation in LAr

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Q value [MeV]</th>
<th>Half-life [s]</th>
<th>Decay mode</th>
<th>Yield [per vertical muon]</th>
<th>Yield [day⁻¹ (10 kton)⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>⁴¹Ar</td>
<td>2.49</td>
<td>6.6e3</td>
<td>(\beta^-)</td>
<td>0.474</td>
<td>1600</td>
</tr>
<tr>
<td>³⁹Ar</td>
<td>0.57</td>
<td>8.5e9</td>
<td>(\beta^-)</td>
<td>0.354</td>
<td>1200</td>
</tr>
<tr>
<td>³⁸Ar</td>
<td></td>
<td></td>
<td>stable</td>
<td>0.274</td>
<td>940</td>
</tr>
<tr>
<td>³⁷Cl</td>
<td></td>
<td></td>
<td>stable</td>
<td>0.048</td>
<td>160</td>
</tr>
<tr>
<td>³⁹Cl</td>
<td>3.44</td>
<td>3.3e3</td>
<td>(\beta^-)</td>
<td>0.044</td>
<td>150</td>
</tr>
<tr>
<td>³⁴S</td>
<td></td>
<td></td>
<td>stable</td>
<td>0.034</td>
<td>120</td>
</tr>
<tr>
<td>³⁶Cl</td>
<td>0.71</td>
<td>9.5e12</td>
<td>(\beta^-)</td>
<td>0.032</td>
<td>110</td>
</tr>
<tr>
<td>³⁵S</td>
<td>0.17</td>
<td>7.5e6</td>
<td>(\beta^-)</td>
<td>0.024</td>
<td>82</td>
</tr>
<tr>
<td>³⁶S</td>
<td></td>
<td></td>
<td>stable</td>
<td>0.024</td>
<td>82</td>
</tr>
<tr>
<td>³⁷Ar</td>
<td>0.81</td>
<td>3.0e6</td>
<td>EC</td>
<td>0.030</td>
<td>100</td>
</tr>
<tr>
<td>³⁵Cl</td>
<td></td>
<td></td>
<td>stable</td>
<td>0.014</td>
<td>48</td>
</tr>
<tr>
<td>³³S</td>
<td></td>
<td></td>
<td>stable</td>
<td>0.012</td>
<td>41</td>
</tr>
<tr>
<td>³²P</td>
<td>1.71</td>
<td>1.2e6</td>
<td>(\beta^-)</td>
<td>0.010</td>
<td>34</td>
</tr>
<tr>
<td>³³P</td>
<td>0.25</td>
<td>2.2e6</td>
<td>(\beta^-)</td>
<td>0.010</td>
<td>34</td>
</tr>
<tr>
<td>³⁰Si</td>
<td></td>
<td></td>
<td>stable</td>
<td>0.010</td>
<td>34</td>
</tr>
</tbody>
</table>

### Graphs

1. **Electron Kinetic Energy vs. Time Delay**
   - **dN/dE [MeV⁻¹, day⁻¹ (10 kton)⁻¹]**
   - **Nuclear species**:
     - ⁴¹Ar, ³⁸Ar, ³⁷Ar, ³⁶Cl, ³⁵Cl, ³³S, ³²P, ³³P, ³⁰Si
   - **Time Delay [s]**
   - **Total**

2. **Time Delay vs. Yield**
   - **tdN/dt [permuon]**
   - **Nuclear species**:
     - ⁴¹Ar, ³⁸Ar, ³⁵Cl, ³⁶Cl, ³⁵S, ³³S, ³²P, ³³P, ³⁰Si
   - **Time Delay [s]**
   - **Total**

**arXiv:1811.07912**
Some discrepancy between physics lists. In general agreement within a factor of 2

Both the codes show underestimation of some nuclei (\(^{11}\)C, the most important cosmogenic background in BX)

Agreement better than factor of 2 is difficult.

**Missing a dedicated list for comic muons sims** (shower development, activation, decay)
Underground experiments heavily rely on Monte Carlo simulations.

**GEANT4** is a complete toolkit to:
- simulate and understand the detector response (iterative tuning of **optical** parameters)
- implement and tune the physics processes (development of **new classes** based on independent observations)
- simulate the known background sources (**neutron** production and **cosmic rays**)
- improve the detector sensitivity