Status of the SoLid experiment

EOS be.h Equinox meeting

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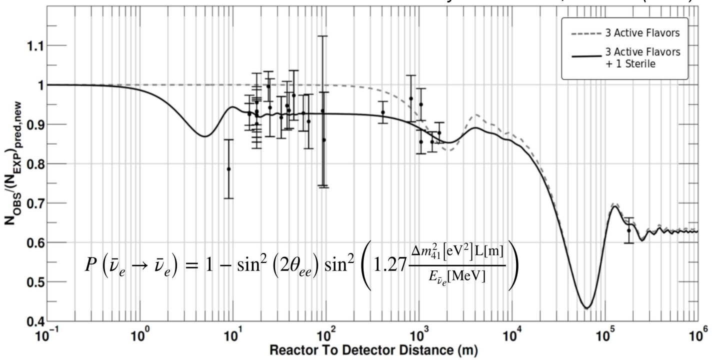
Overview

- Introducing the SoLid experiment
- Background description
- Signal selection
- Alternative analysis: Heavy Neutral Leptons
- Upgrade to the Phase 2 detector

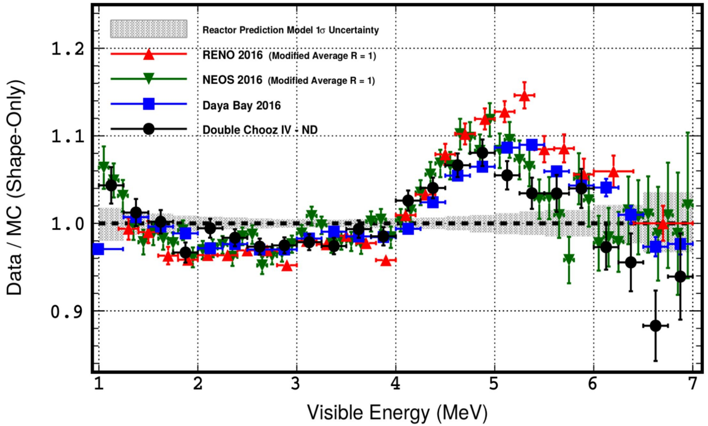
Introducing the SoLid experiment

Physics motivation

Phys. Rev. D 83, 073006 (2011)

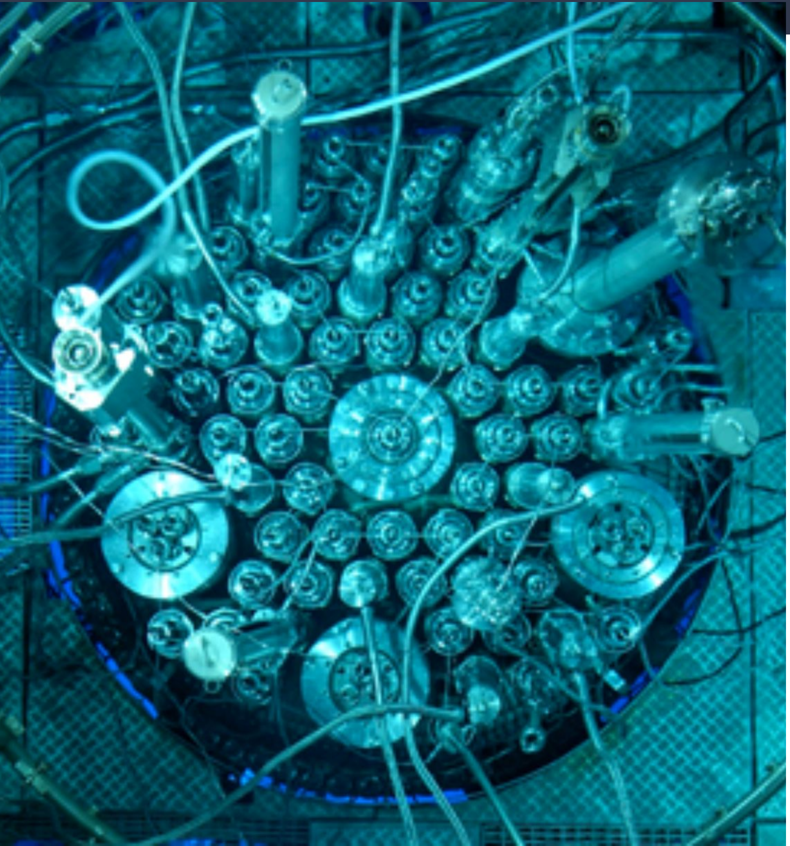


Nature Phys. 16, 558 (2020)



- Reactor antineutrino anomaly
  - Consistent deficit observed at short (< 1 km) baselines compared to predictions
  - Deficit could be explained by an additional (sterile) neutrino of $\Delta m^2 \cong$ 1-10 eV^2
  - Sterile neutrino hypothesis given more weight by unrelated anomalies (Gallium, LSND)
- Reactor antineutrino spectrum distortion, a.k.a. the 5 MeV bump
  - Excess observed at 5 MeV by most large reactor experiments
  - Among the fissile isotopes in commercial reactors, ^{235}U is considered most likely
- Also an anti-proliferation component

The BR2 reactor



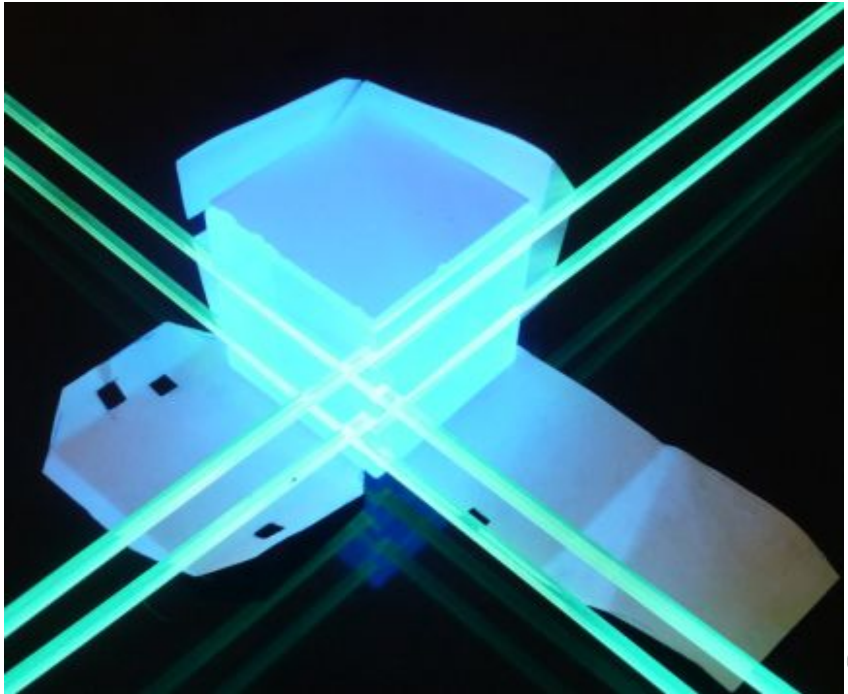
- Belgian Research Reactor 2
- Located on the SCK-CEN site in Mol, Belgium
- Rated for 50 - 100 MW_{Th}
  - Typically 60 MW_{Th}
  - 5 or 6 month-long reactor cycles per year
- Highly enriched ^{235}U
- Compact conical core
  - ∅ ~ 0.5 m
  - h ~ 1 m
  - Experimental hall starts as close as 5.5 m from the core
- Low neutron and gamma backgrounds in experimental hall
- 37 m above sea level, 6-8 m MWE overburden

The SoLid detector

A highly segmented modular antineutrino detector using dual solid scintillators and multiplexed readout

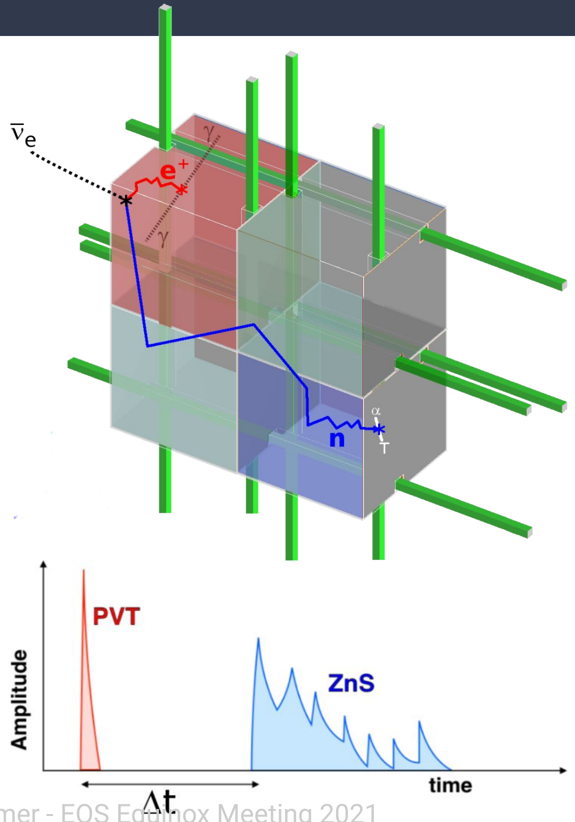
- Highly segmented
  - Built from 12.800 optically isolated cells
  - Each cell measures 5 x 5 x 5 cm^3
- Modular
  - 16 x 16 cells make a plane
  - 10 planes make a module
  - Detector consists of 5 modules
- Dual solid scintillators
  - PVT cube as neutrino target and for positron and gamma detection
  - $^{6}LiF:ZnS(Ag)$ layers for neutron capture and detection
- Multiplexed readout
  - 64 WLS fibres bring light from the cells to the edge of the detector
  - Each fibre is read out by a SiPM
  - 3200 fibre-SiPMs pairs service 12800 cells

Antineutrino detector



The SoLid detector

A highly segmented modular antineutrino detector using dual solid scintillators and multiplexed readout



Antineutrino detector

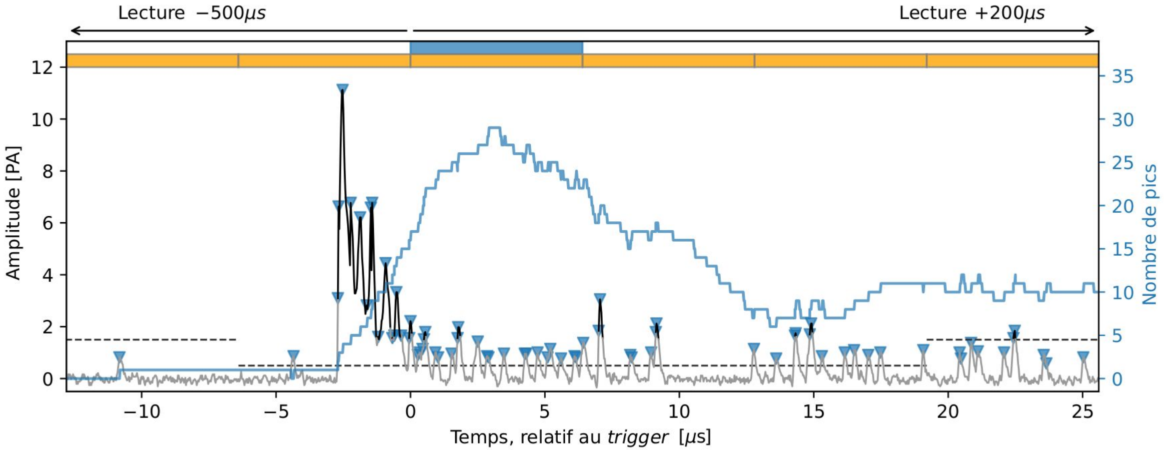
- Inverse beta decay reaction: $\boldsymbol{\nu}$ + p → n + e^+
- Prompt signal from e^+ scintillation and annihilation gammas in PVT
  - Fast scintillator, very brief pulse (few ns)
  - Provides $\boldsymbol{\nu}$ interaction cube
- Delayed signal from capture of thermalised neutron on ^{6}Li
  - n + ^{6}Li → α + ^{3}H
  - α and ^{3}H scintillate in ZnS(Ag)
  - Slow scintillator, extended pulse (10s μs)
  - Neutron cube close to $\boldsymbol{\nu}$ cube
  - Neutron capture time: τ = 68 μs

Trigger system

- Random trigger
  - Operates at 1 Hz

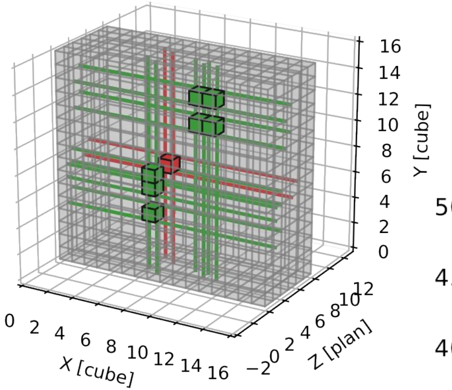
- Threshold trigger
  - Triggers signal above 2 MeV threshold
  - Coincidence required between horizontal and vertical fibre, within 75 ns

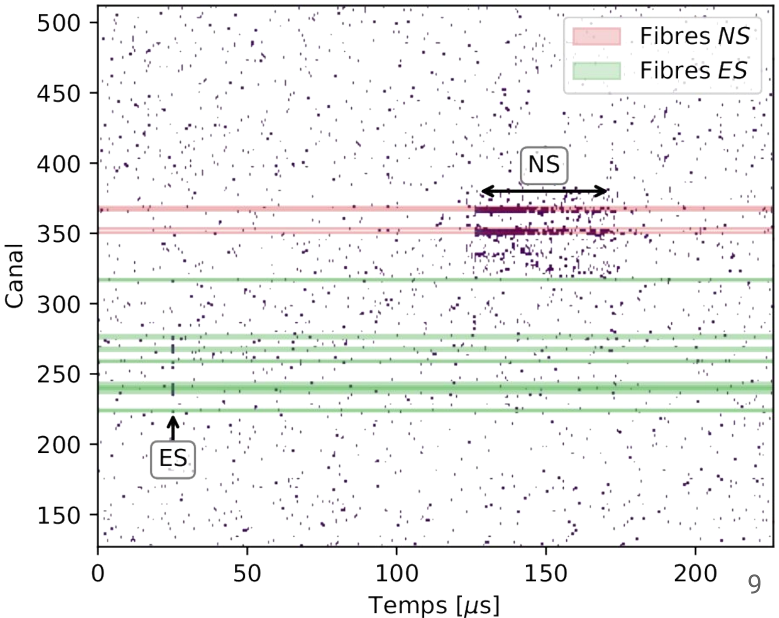
- Neutron trigger
  - Targets neutron scintillation in ZnS(Ag)
  - Counts peaks over threshold in rolling time window



Data collection

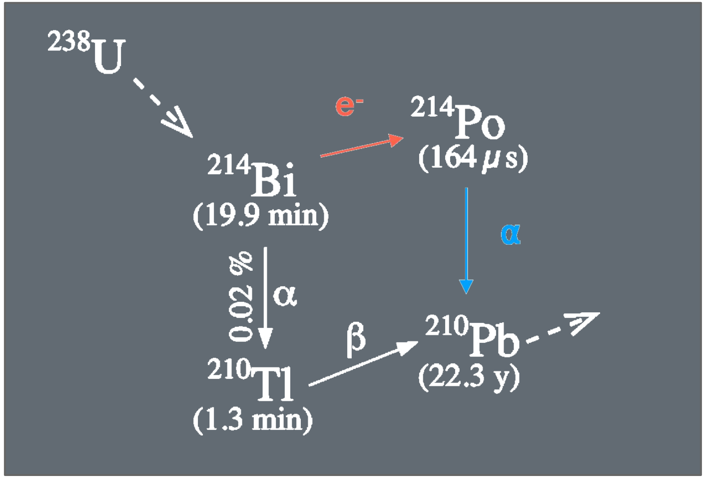
- Random trigger
  - Reads full detector for 13.6 μs
  - Saves raw waveforms
- Threshold trigger
  - Reads triggering plane for 13.6 μs
  - Suppresses signal below ~100 keV
- Neutron trigger
  - Reads triggering plane and 3 or 4 neighbouring planes (either side)
  - Reads 500 μs before and 200 μs after trigger
  - Suppresses signal below ~100 keV





Background description

Backgrounds: BiPo



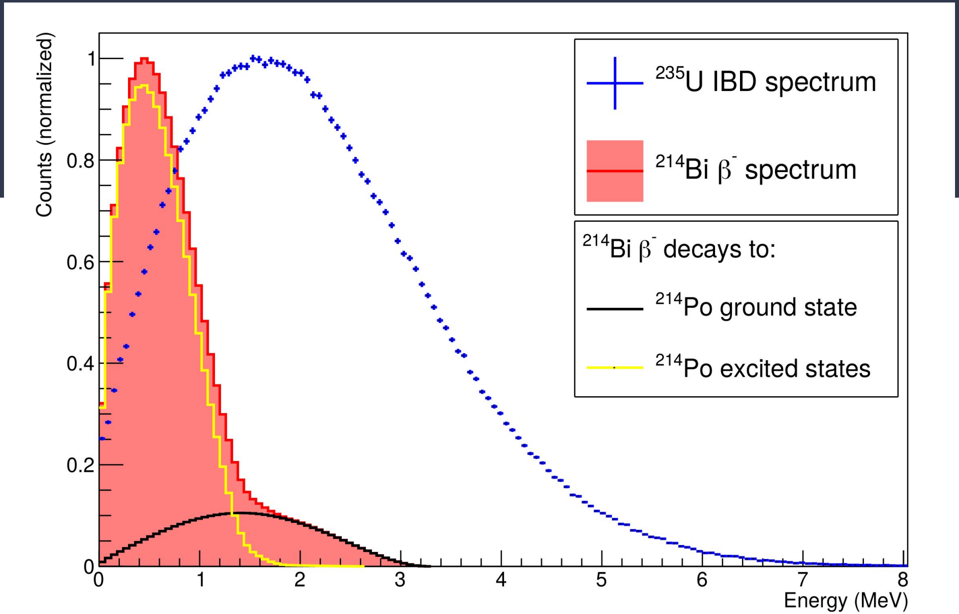
Radioactive decay sequence in the Uranium series:

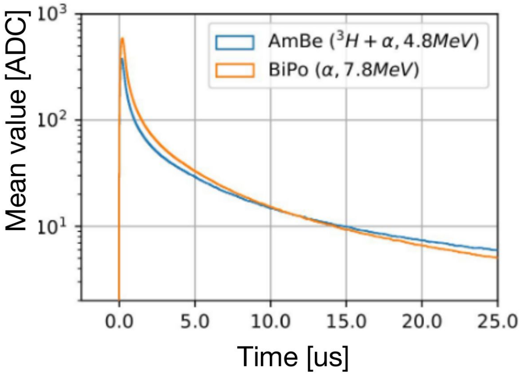
1. ^{214}Bi $\rightarrow$ ^{214}Po + e$^-$ Q = 3.27 MeV
   e$^-$ mimics prompt signal
2. ^{214}Po $\rightarrow$ ^{210}Pb + α $t_{1/2}$ = 168 μs
   α mimics delayed signal when in ZnS

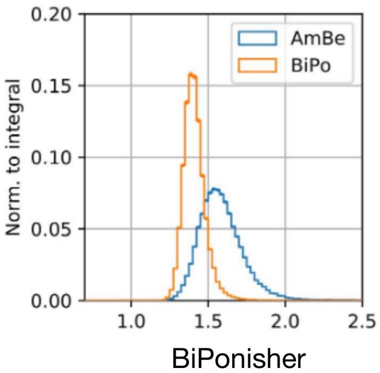
- Internal constant contamination in ZnS layers
- External variable source: ^{222}Rn release from concrete

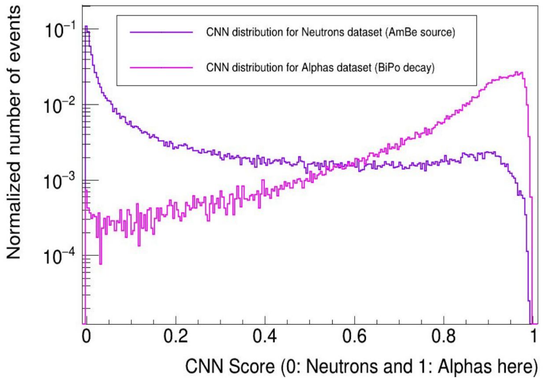
Backgrounds: BiPo

- Exploit difference between IBD's α + ^{3}H and BiPo's single α
  - Different energies (4.8 MeV vs 7.8 MeV)
  - 2 particles vs only 1
  - ➢ Slightly different scintillation pattern: 'BiPonisher' and 'BiPonator'
- Lack of annihilation gammas
- Limited energy range
- Differences in ΔT and topology





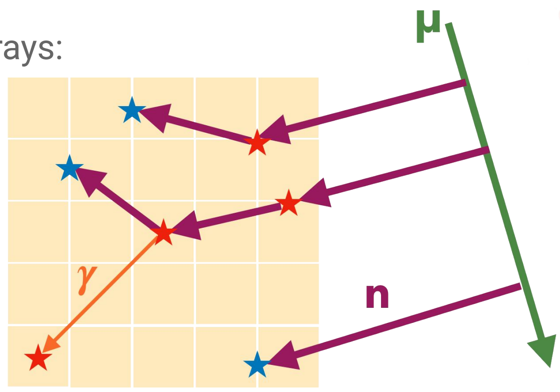


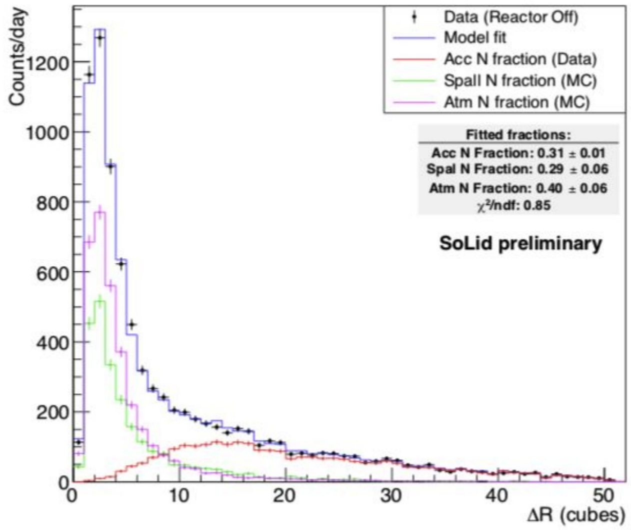


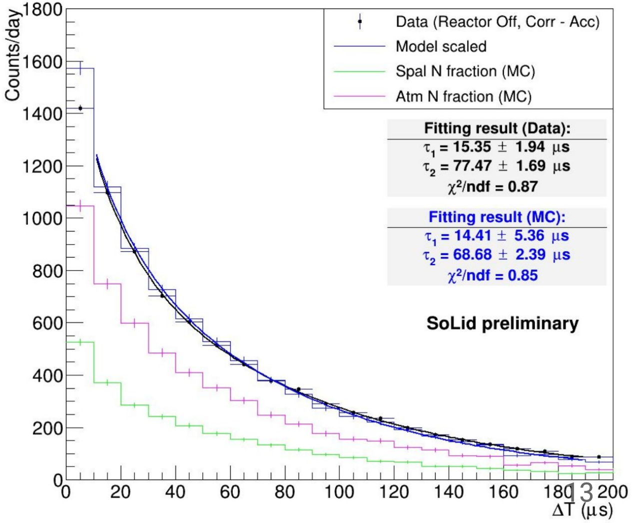
Backgrounds: cosmic neutrons

High energy neutrons created by cosmic rays:

1. Recoil on nuclei in the detector
   Recoil mimics prompt
2. Neutron thermalises and captures
   Identical to IBD neutron capture
- High rate due to low overburden
- Pressure dependent rate
- Main source of background
  - Low overburden
  - Exponentially decreasing energy spectrum over IBD energy range (and beyond)
  - High variety of topologies
  - Virtually identical ΔT to IBD

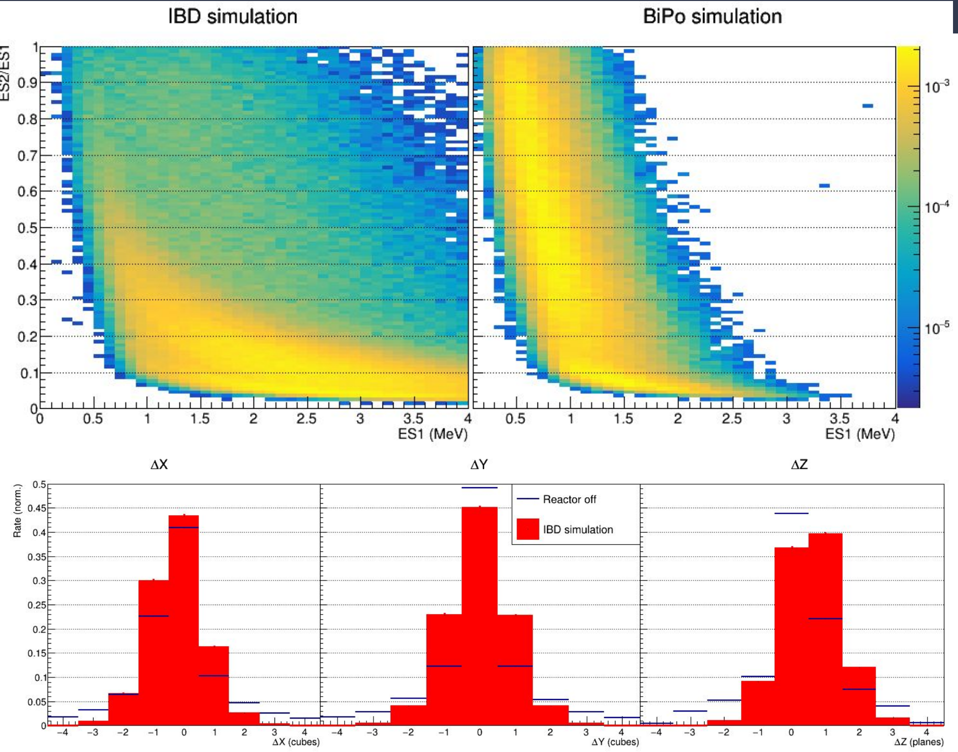






Signal selection

Basic sequential selections



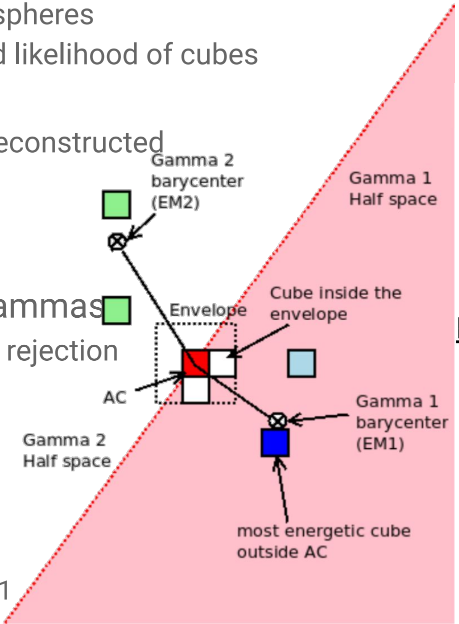
- Prompt requirements
  - Energy
  - Energy balance
  - Spatial spread
- Delayed requirements
  - BiPonisher/BiPonator
- Coincidence requirements
  - ΔT
  - ΔX, ΔY, ΔZ, ΔR

➔ ~ 10% IBD efficiency, S/B ≅ 0.06

Higher level selection

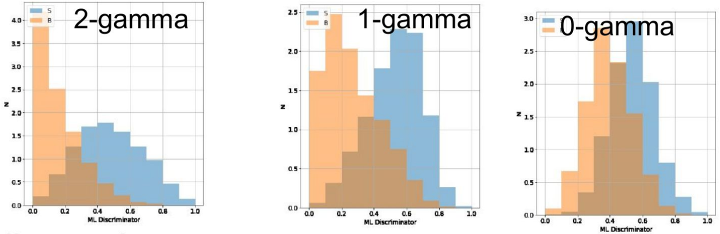
Annihilation gammas (Topology):

- Method:
  - Find highest energy cluster
  - Split detector in hemispheres
  - Tracking by minimized likelihood of cubes
- Adds variables
  - Number of gammas reconstructed
  - Energy
  - Opening angle
  - Distances
- Classification in 0, 1, 2 gammas
  - Improved background rejection

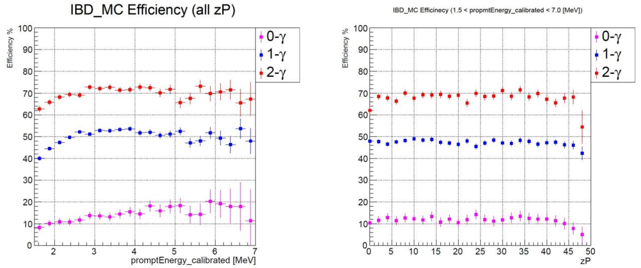


Machine learning:

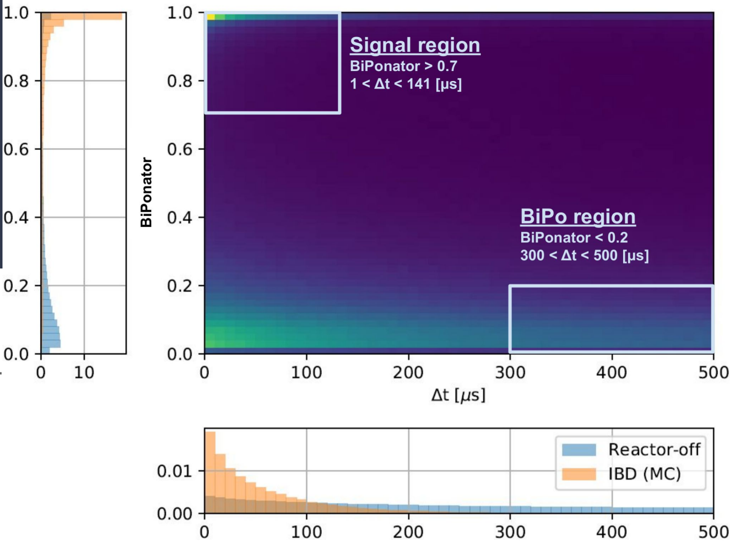
- Improved background rejection, dual approach (no cutting edge)
  - uBDT
  - GBDT



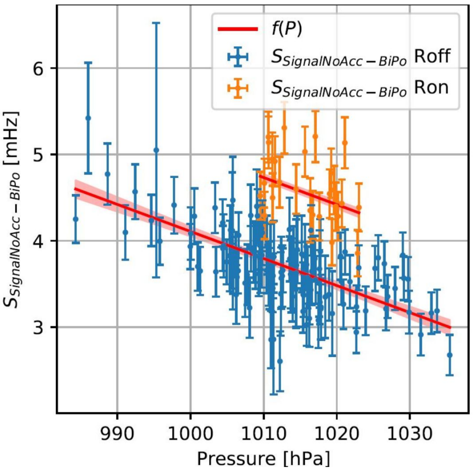
Efficiency flatness



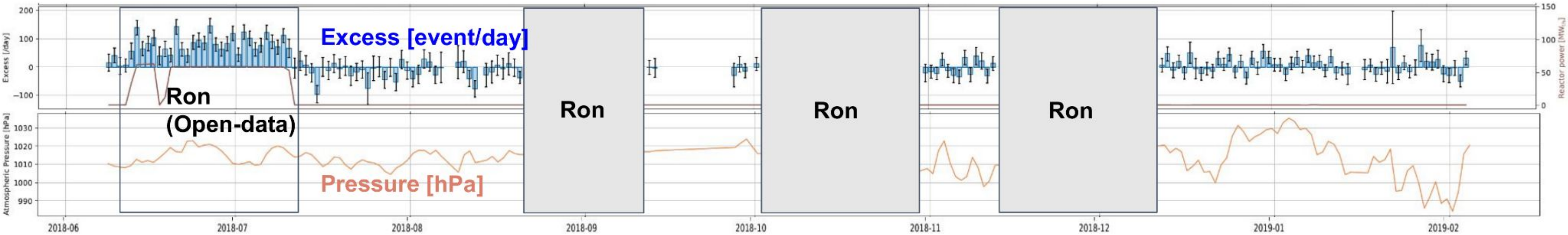
Neutrino signal in data



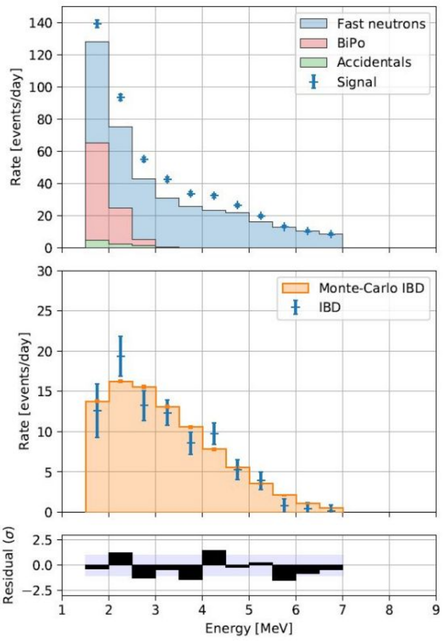
- BiPo varies with Rn releases
  - Can be determined in situ from high ΔT and low BiPonisher coincidence data

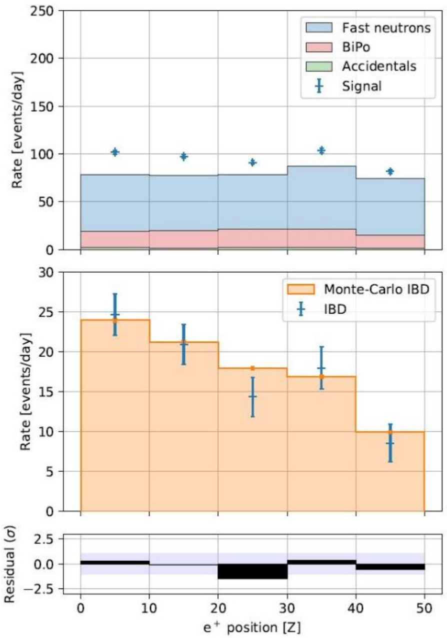


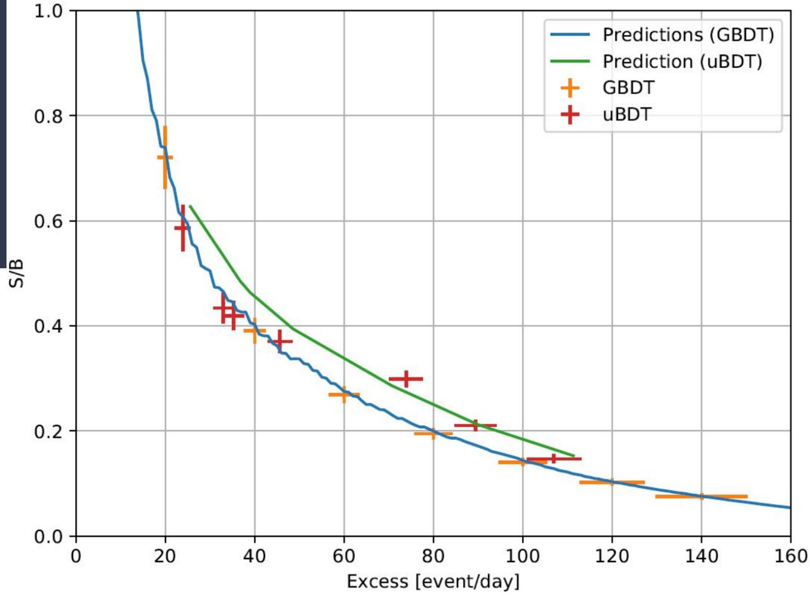
- Cosmic neutron rate varies with atmospheric pressure
  - Pressure dependence established during reactor off period
  - Extrapolated rate subtracted from reactor on period



Neutrino excess



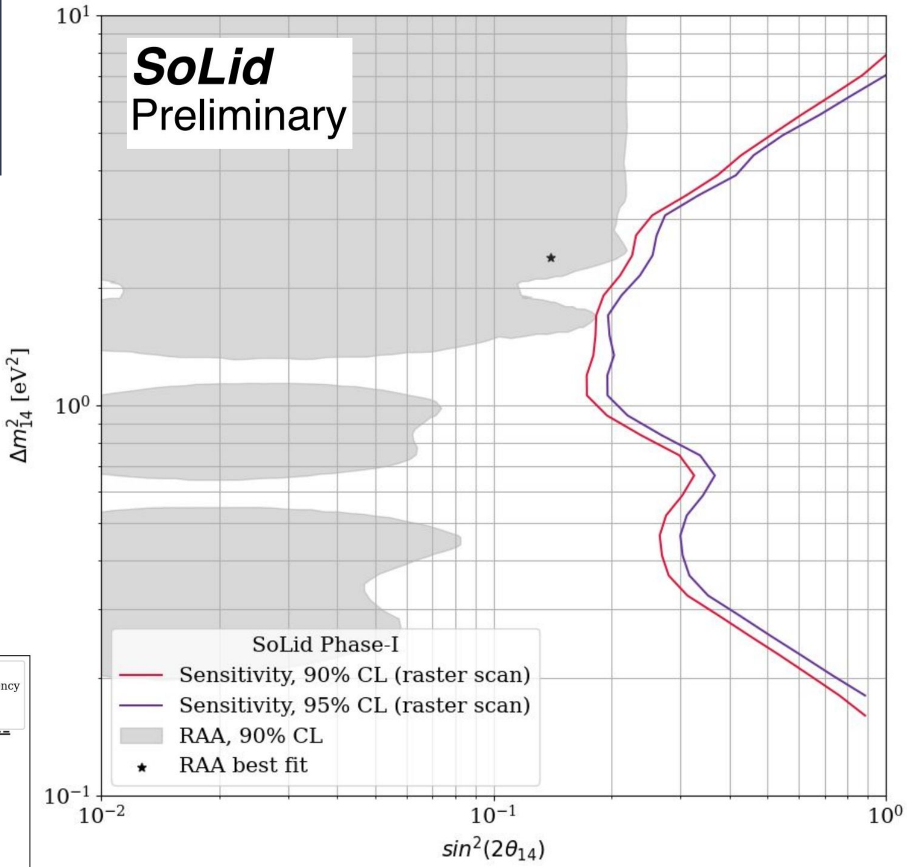


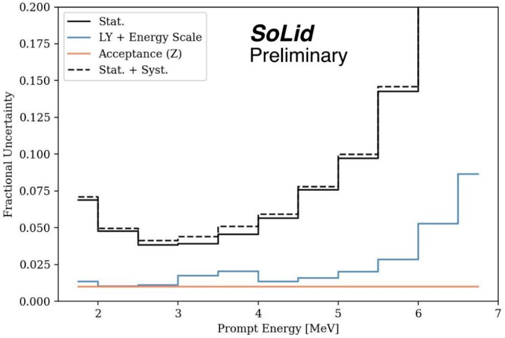


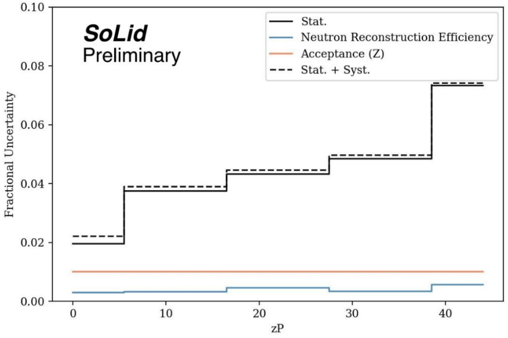
- Observed excess consistent with IBD simulations
  - ~9 % efficiency, S/B ≈ 0.2
- We are sitting on a lot more data
- Background subtraction works well
- Systematic uncertainties under way
- A major detector upgrade took place last year

Oscillation sensitivity

- Feldman-Cousins construction to estimate sensitivity to sterile neutrino oscillations
- Systematic uncertainties related to light yield, energy scale and neutron capture efficiency are currently taken into account
- Ongoing effort to assess the impact of remaining systematics and improve sensitivity with new analysis techniques



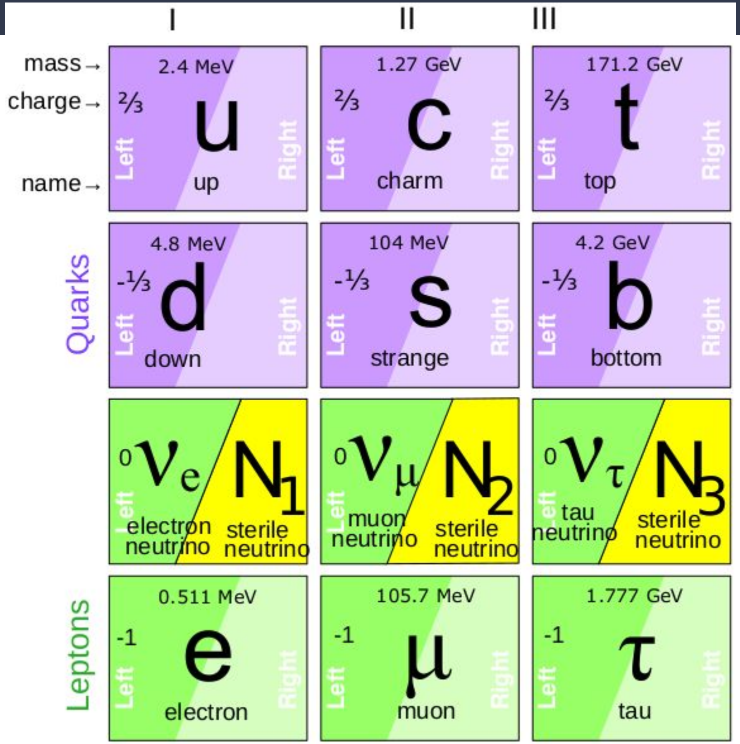




Alternative analysis:
Heavy Neutral Leptons

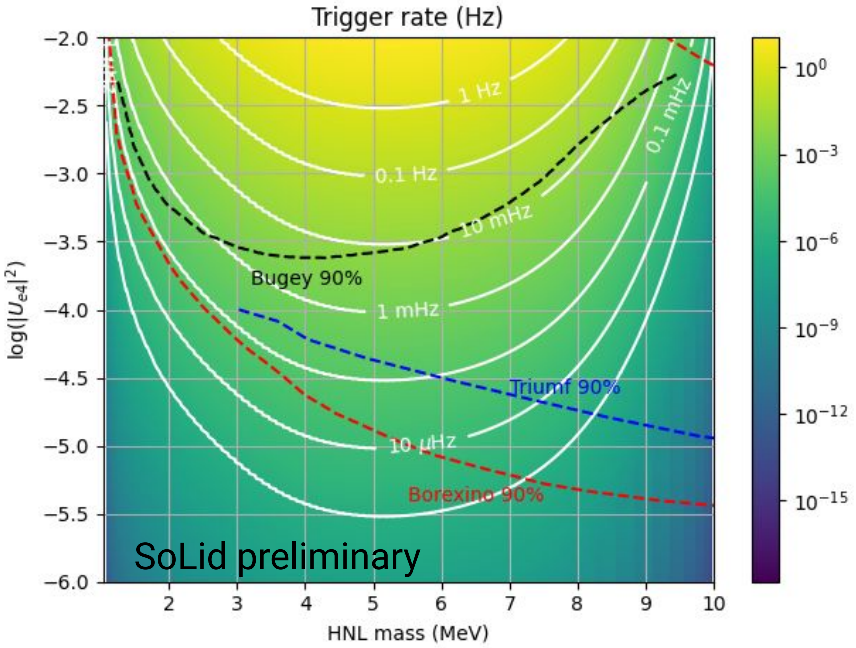
Heavy neutral leptons

- nuMSM introduces 3 right handed neutrinos
- Virtually no mass limit HNLs
- Resolves significant issues
  - Neutrino masses (seesaw)
  - Universe's baryon asymmetry
  - Dark matter candidates
- Sterile, only produced via mixing
- Small mixing angle, low production rate
- Unstable, detect decay products
  - Radiative $N_i \rightarrow \nu_j + \gamma$
    $N_i \rightarrow \nu_j + \gamma + \gamma$ *if m(N_i) > m(ν_j)*
  - Invisible $N_i \rightarrow \nu_j + \nu_k + \overline{\nu}_k$
  - e^+e^- mode $N_i \rightarrow \nu_j + e^+ + e^-$ *if m(N) > 2m_e = 1.022 MeV*



SoLid as HNL detector

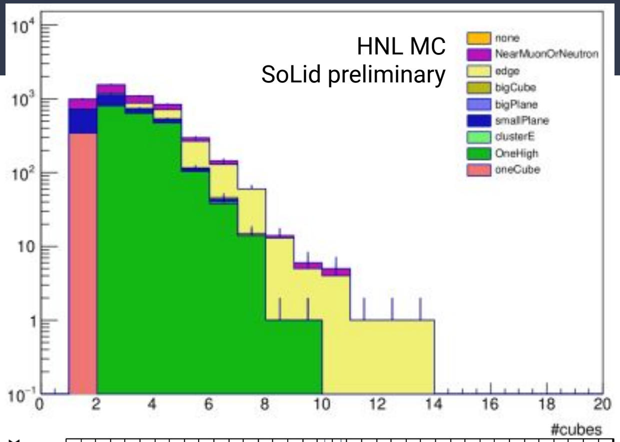
- BR2 as neutrino source
  - ~ 60 MW_{Th} → 12×10^{18} ν/s (12 EBq)
  - 12 EBq is isotropic, need to apply geometric efficiency (~ 0.13 %) → 16 PBq
  - Small mixing angle → Less Bq
  - Long decay time → Even fewer Bq
- Mass range limited by ^{235}U ν spectrum and e^+e^- decay mode requirement
  - 1.022 MeV < m(N) ≲ 9 MeV
- No neutron in e^+e^- decay → rely on threshold trigger
  - Minimum 2 MeV visible energy
  - Single plane only

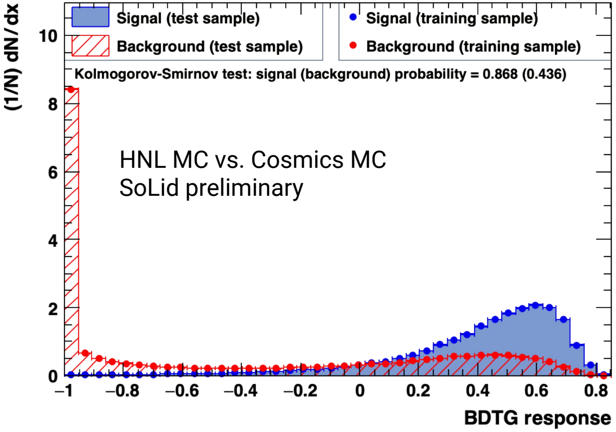


Signal selection

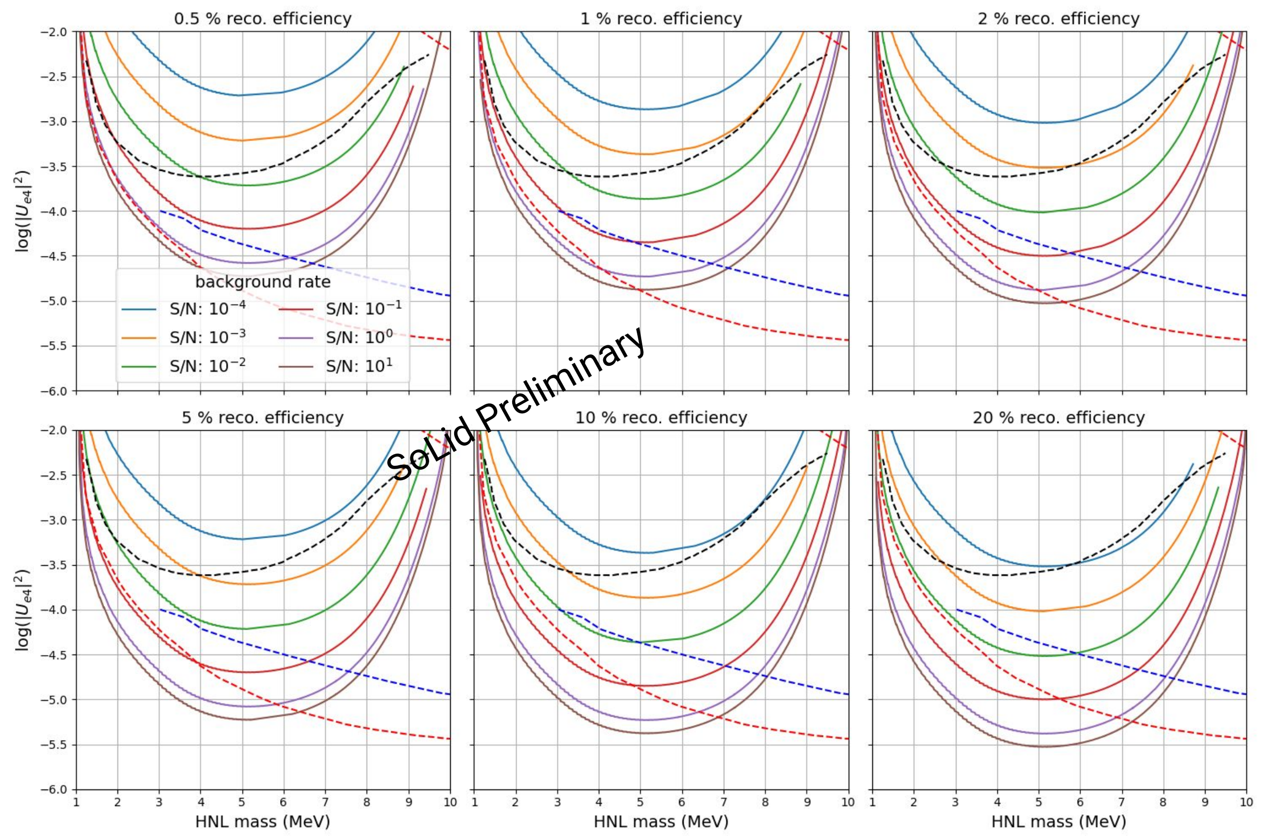
- Background simulations
  - Cosmics, BiPo: recycled from IBD analysis
  - Single gammas: HNL specific, WIP
- Signal simulation using Pythia
  - Several HNL masses
  - Full reactor spectrum

- Preliminary list of variables composed
  - Neutron/muon/alpha veto
  - Fiducialization
  - ES energy
  - ES spatial spread
  - Still being refined/expanded
- Manual and TMVA optimizations under way





SoLid's potential



- Various reconstruction efficiencies and S/B ratios compared with current exclusion limits
- Preliminary cut based analysis at 30% eff. and 10^{-5} S/B
- Also working on GBDT approach (not even preliminary figures there)

Upgrade to the Phase 2 detector

Detector upgrade

- July to November 2020: SiPM upgrade
  - Took place in Antwerp
  - Data taking since half November 2020
  - 44% more light collected
  - Preliminary analysis indicates improved S/N at higher IBD efficiency
- Ongoing: Firmware update