

# Cosmogenic and reactogenic background estimations of the RICOCHET experiment



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Magnificent CE $\nu$ NS 2023 - 23/03/2023

# Summary

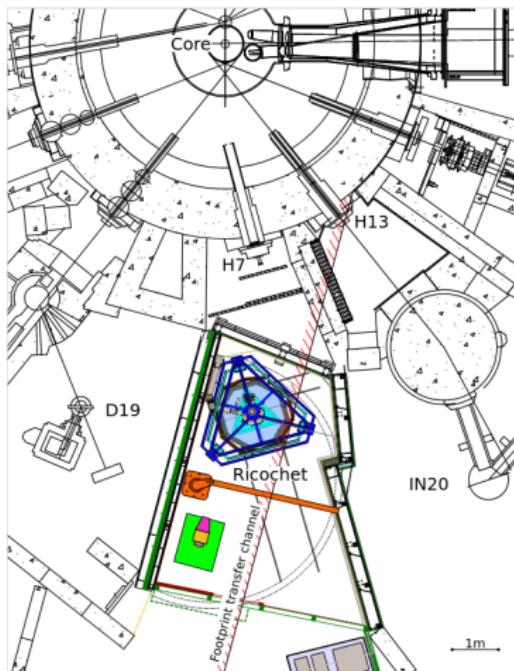
- Context
- Simulation inputs
- Simulation results
- Sensitivity studies

# Context

# Experimental site

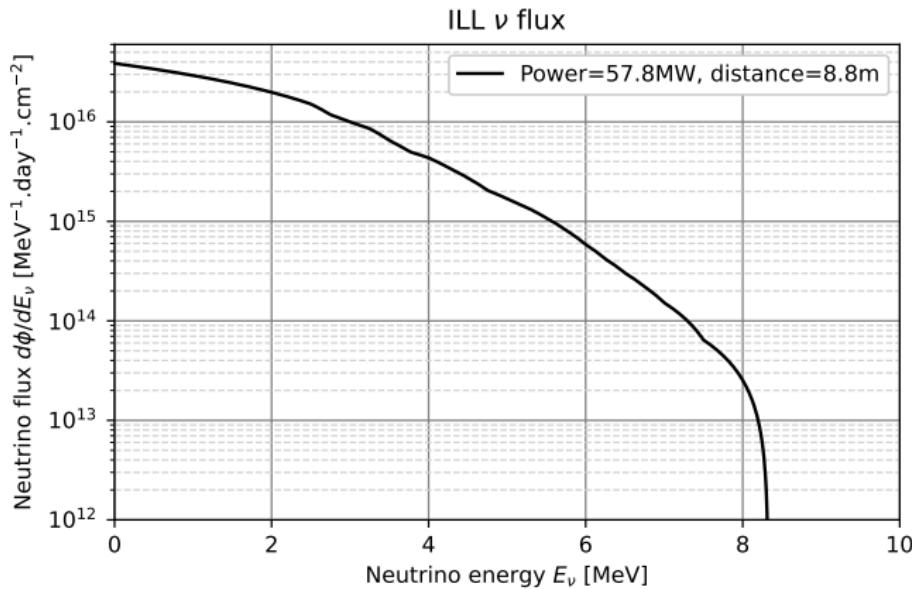
Located at the Institut Laue-Langevin (ILL) nuclear reactor, H7 site  
(former STEREO experimental site)

- Neutrino energy up to 8 MeV ;
- Very close to reactor core (8.8m) ;
- Research reactor → ON-OFF cycles (50d ON)
- Important reactogenic background from neighbour experiments ;
- Surface experiment : important cosmogenic background, partly mitigated by water transfert channel (15 m.w.e).



# Neutrino spectrum

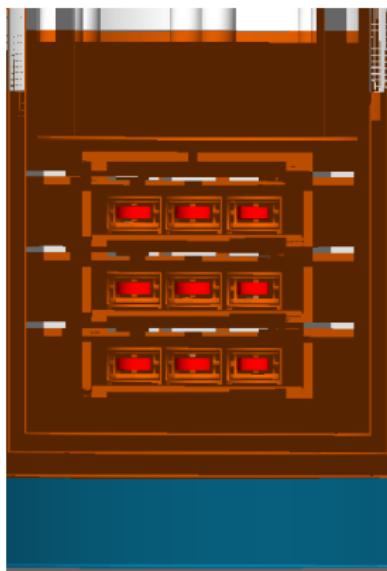
Electronic antineutrino spectrum (from STEREO measurement) :



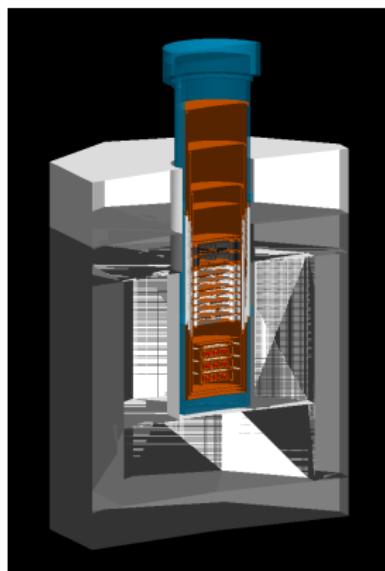
Total NR rate : 11 evts/day/kg in [50eV ; 1keV].

## Simulation inputs

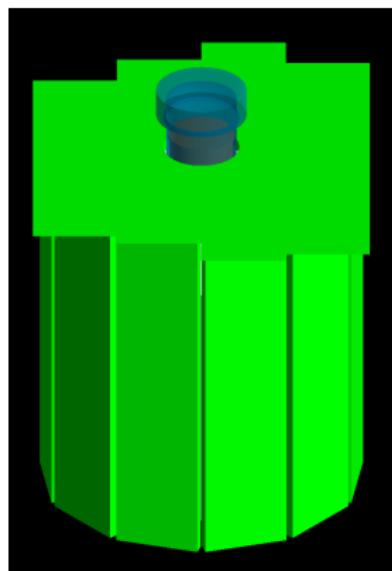
# GEANT4 geometry



CryoCube : 27 Ge  
detectors



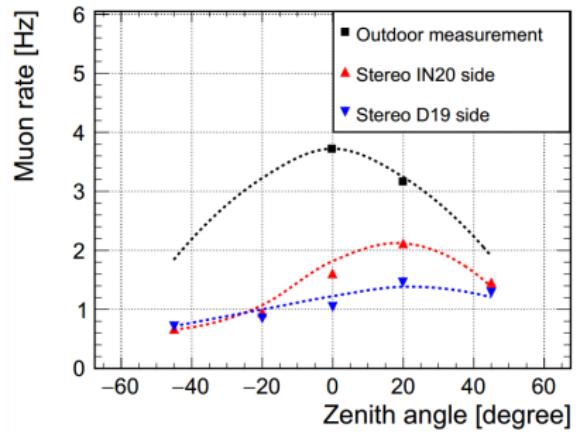
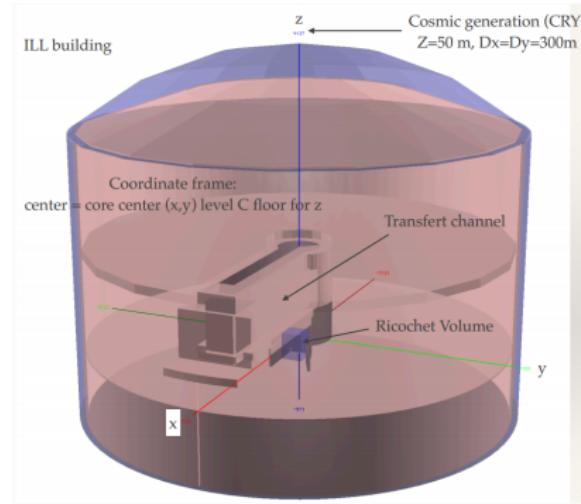
Passive shielding :  
borated PE + lead



Muon veto : pairs of  
plastic scintillators

# Cosmic rays simulation

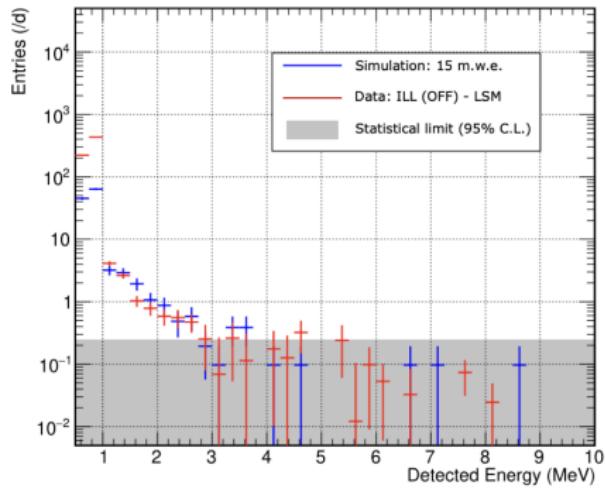
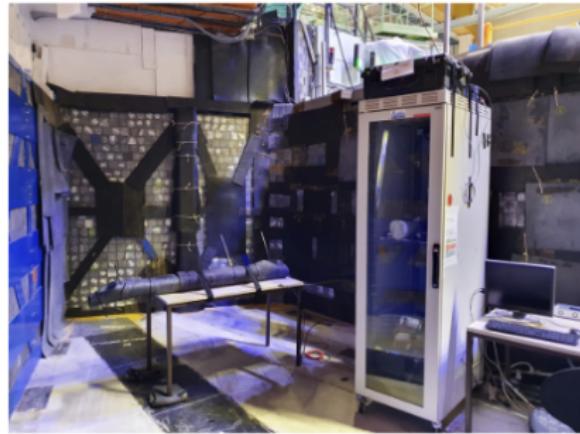
Cosmic rays are simulated using CRY software (including production of secondary particles within the reactor building).



Confirmed by on-site measurements (from STEREO experiment)  
 $\Rightarrow$  15 m.w.e overburden ( $\mu$  attenuation factor of 4).

# Cosmogenic fast neutrons

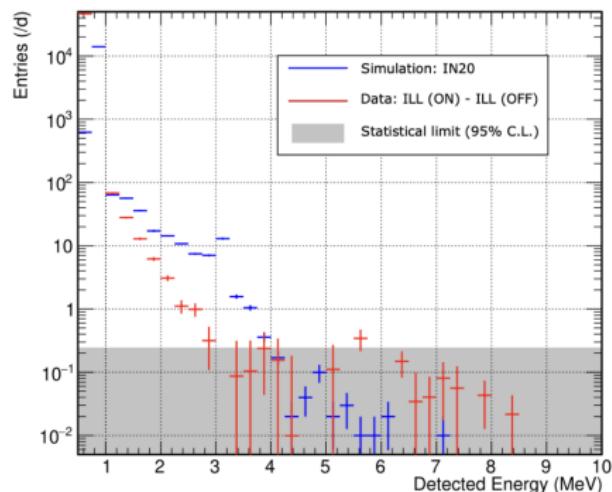
On-site measurements using  ${}^3\text{He}$  counter : on-flight neutron capture  
(arXiv:2208.01760)



→ validation of simulated neutron background !

# Reactogenic background

The same measurement during ON period gives us reactogenic fast neutron background



Measurement lower than simulation that we know overestimated (done by STEREO with a different configuration).

Gamma background input from STEREO measurement.

## Simulation results

# Simulation analysis & results

Event selection is based on the properties of the signal (neutrino interaction) : a single event, inducing a nuclear recoil in Ge detector.

Cuts applied to background events :

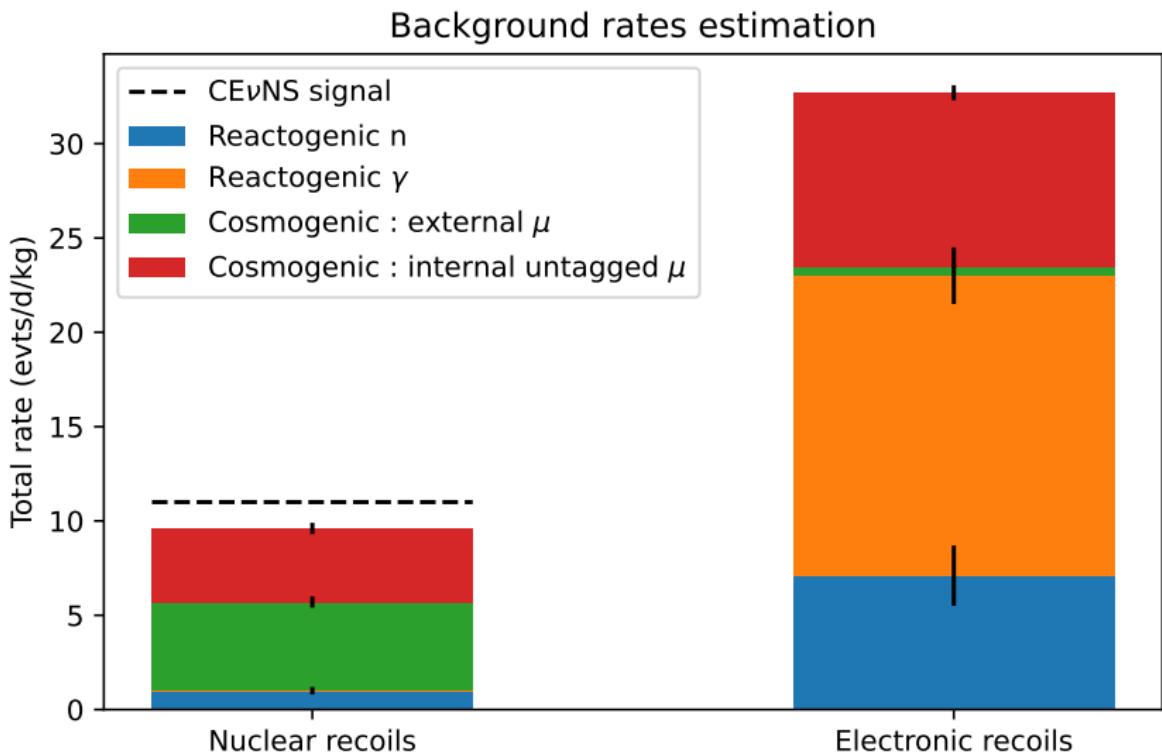
- Recoil energy : [50eV, 1keV] ;
- Unicity : only one Ge detector triggered ;
- Anticoincidence with the muon veto (30% dead time induced).

Resulting background rates :

Recoil type rate	Cosmogenic	Reactogenic	Total	$\text{CE}\nu\text{NS}$
$R_{NR}$ (evts/d/kg)	$8.4 \pm 0.4$	$1.0 \pm 0.2$	$9.4 \pm 0.5$	11
$R_{ER}$ (evts/d/kg)	$9.5 \pm 0.5$	$23.0 \pm 1.6$	$32.5 \pm 1.7$	-

$S/B > 1$ , with electronic recoil rejection factor  $\mathcal{O}(100)$

# Background composition

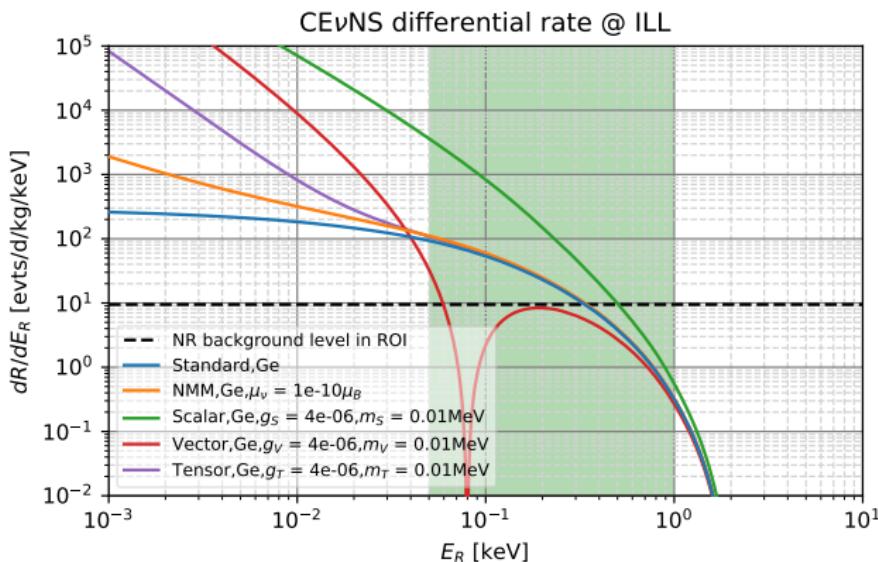


## Sensitivity studies

# Recoil spectra

Differential recoil rate calculation :

$$\frac{dR}{dE_R} = \frac{1}{m_N} \int_{E_\nu > E_{\nu,\min}} \Phi(E_\nu) \frac{d\sigma_{\nu-N}}{dE_R} dE_\nu$$



# Statistic analysis

Based on a likelihood function :

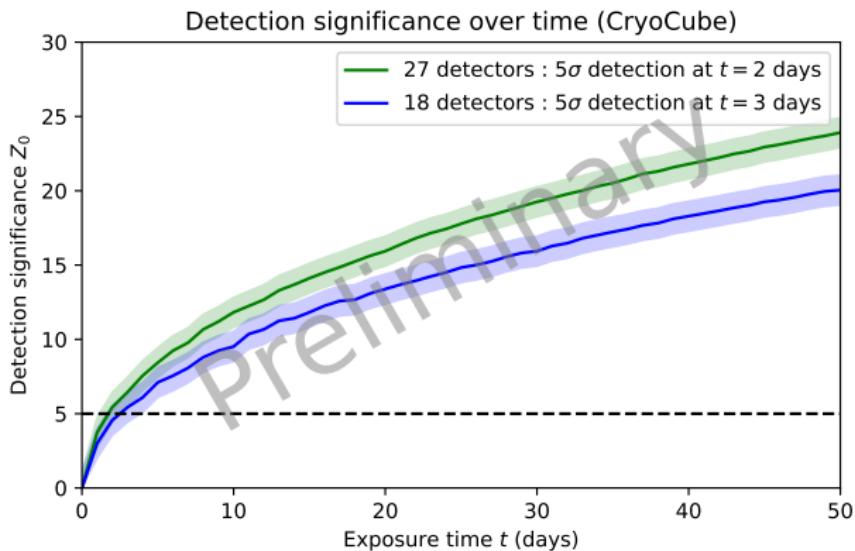
$$\mathcal{L}(\mu, \theta) = \mathcal{L}(\theta) \times \prod_i^{N_{\text{bins}}} P \left( N_{i,\text{obs}} | N_{i,\text{sig}}(\mu, \theta) + N_{i,\text{bg}}(\theta) + \Delta N_{i,\text{sig}}^{\text{cal}}(\mu, \theta_{\text{cal}}) \right)$$

Nuisance parameters and uncertainties :

- $\theta_{bg}$  : background normalisation ;  $\sigma_{bg} = 4.7\%$  (50d) or  $\sigma_{bg} = 1.9\%$  (300d).
- $\theta_{sig}$  : experimental signal normalisation ;  $\sigma_{sig} = 3\%$
- $\theta_{cal}$  : energy calibration error ;  $\sigma_{cal} = 2\%$

Assumptions : NR background only (perfect ER/NR discrimination), flat background spectrum.

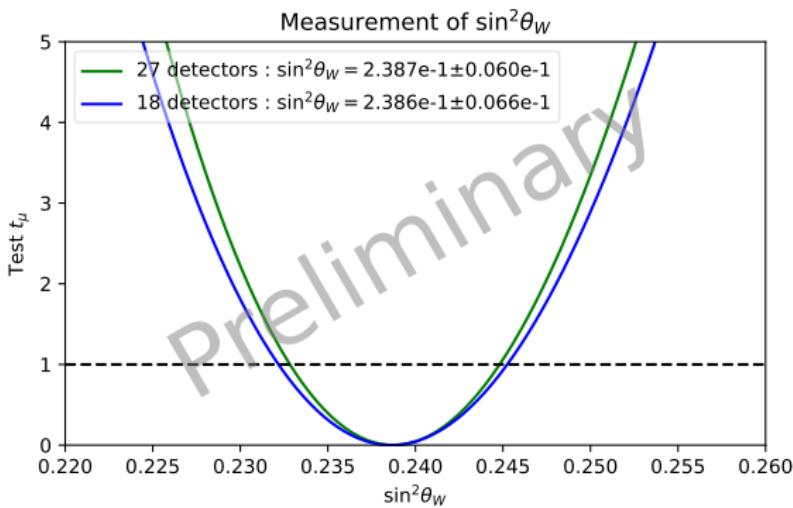
# CE $\nu$ NS sensitivity



Confirmation of CE $\nu$ NS within few days !

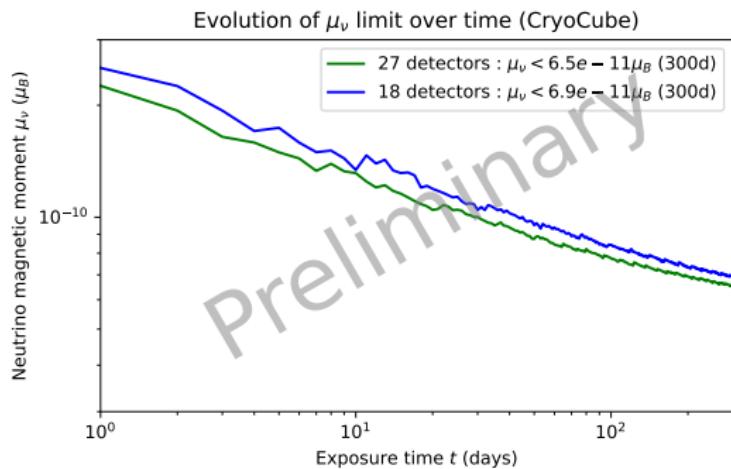
50 days precision :  $\sim 5\%$  ; 300 days precision  $\sim 2.3\%$  (18 det)

# Weak mixing angle



At 300 days :  $\sin^2 \theta_W = 0.239 \pm 0.007$  (3% precision).  
APV result :  $\sin^2 \theta_W = 0.2367 \pm 0.0018$  (PDG 2022).

# Neutrino magnetic moment



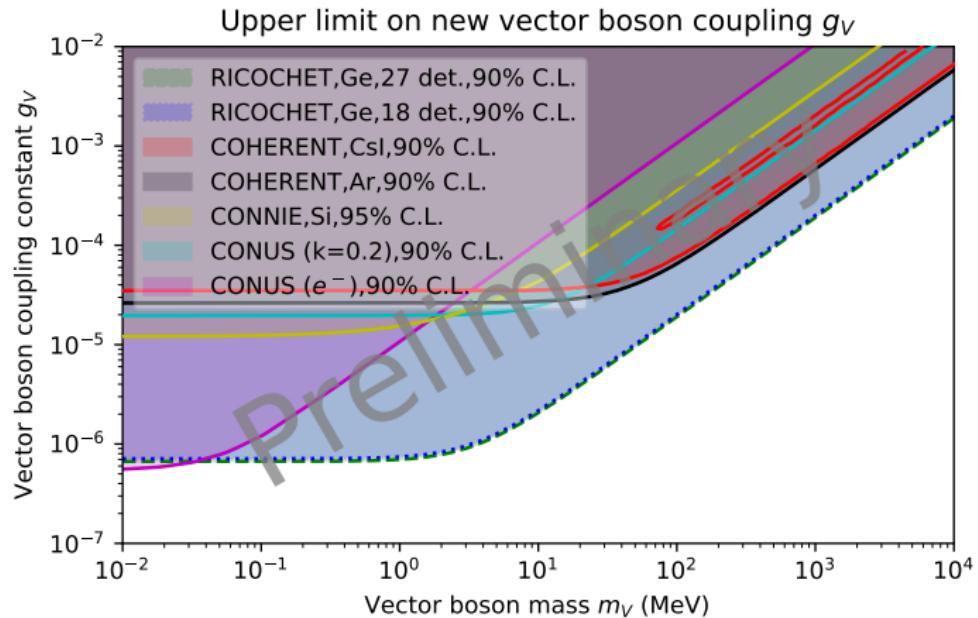
300d limit :  $\mu_\nu < 6.9 \times 10^{-11} \mu_B$  (90% C.L.)

Limits from other experiments :

- COHERENT :  $\mu_\nu < 43 \times 10^{-11} \mu_B$  (90% C.L. ; arXiv:1711.09773)
- BOREXINO :  $\mu_\nu < 2.8 \times 10^{-11} \mu_B$  (90% C.L. ; PDG 2022)

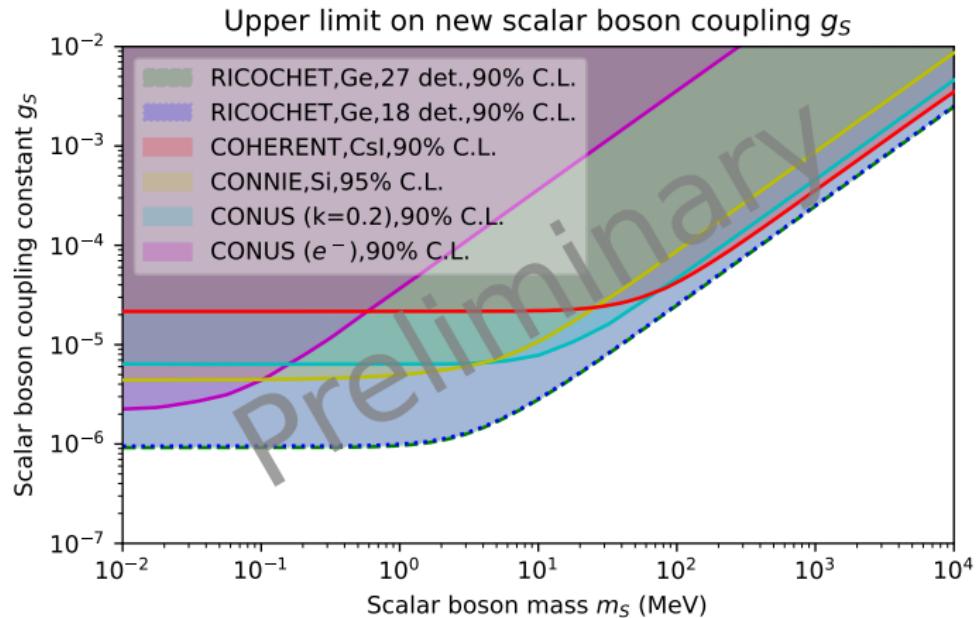
# New vector boson

Exclusion plot in phase space ( $m_V, g_V$ ) with universal coupling ( $Q_{\nu,V} = Q_{q,V} = 1$  i.e.  $g_{\nu,V} = g_{q,V}$ ) (other exp data taken on arxiv:2110.02174)



# New scalar boson

Exclusion plot in phase space ( $m_S, g_S$ ) with universal coupling ( $Q_{\nu,S} = Q_{q,S} = 1$  i.e.  $g_{\nu,S} = g_{q,S}$ ) (other exp data taken on arxiv:2110.02174)



# Conclusions & perspectives

- Many simulations performed addressing cosmogenic and reactogenic backgrounds ;
- Simulations input verified by on-site measurements ;
- Expected  $S/B > 1$  with electronic recoil rejection of 100 ;
- Expected  $5\sigma$  CE $\nu$ NS detection in one reactor ON cycle ;
- Background measurements to be done in the next few months with the outer shielding ;
- Improve sensitivity studies, including the Heat Only background.

# Thank you for your attention !



# Backup

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# Muon veto trigger rate

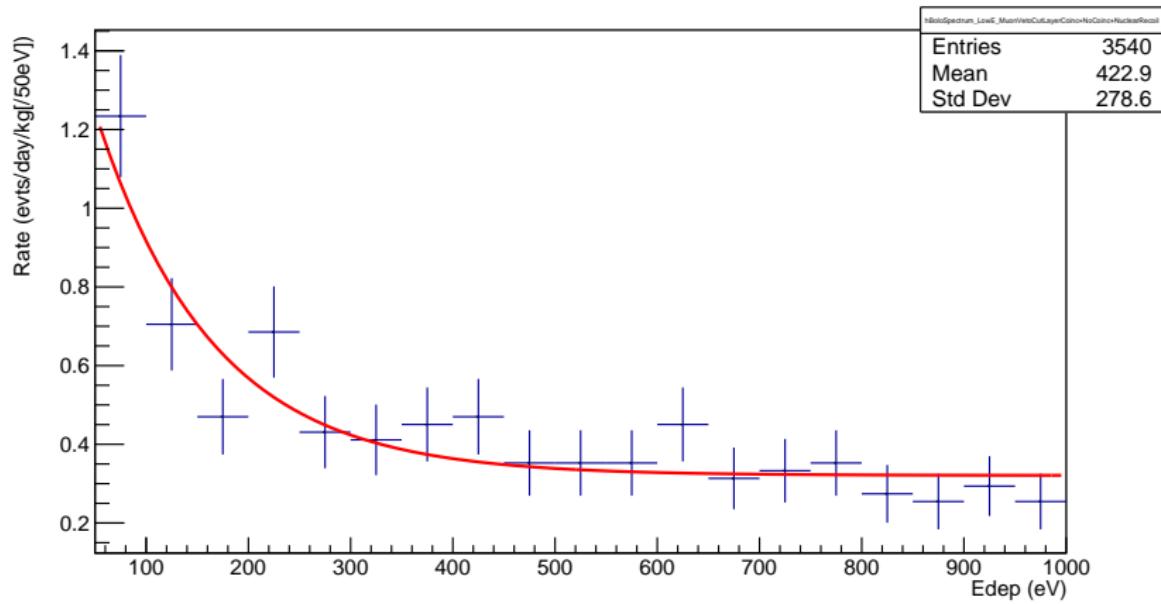
Trigger rate evaluated after coincidence with required 3 MeV deposited on both panels :

	Cosmogenic	Reactogenic	Total
$R_{veto}$ (evts/s)	$480.6 \pm 0.7$	$23.0 \pm 0.9$	$503.6 \pm 1.2$

Resulting dead time : 30%

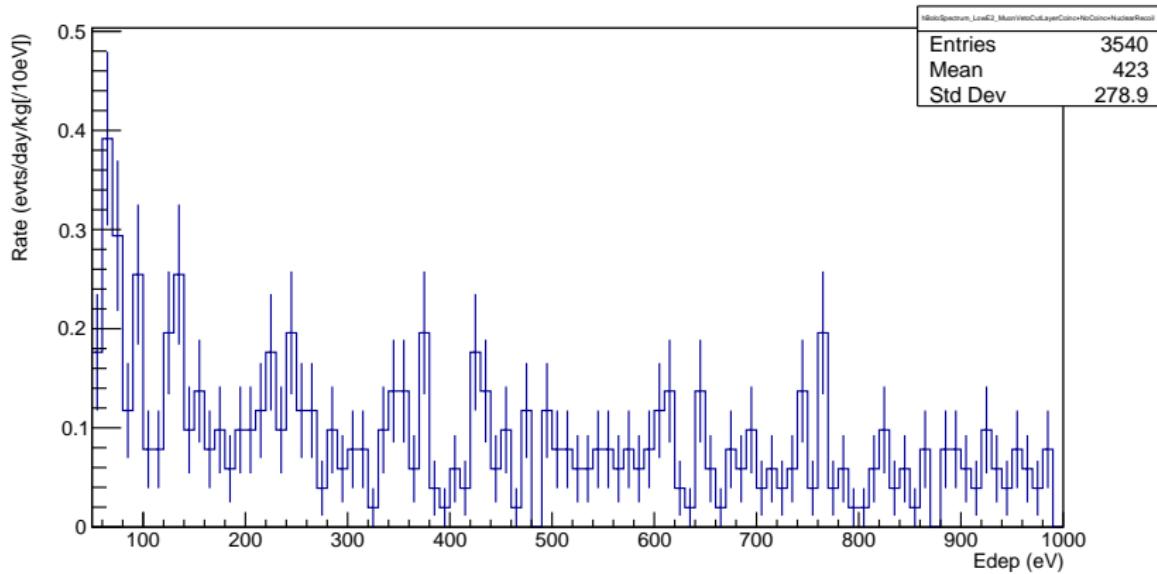
# Cosmogenic NR background spectrum

With 50eV bins



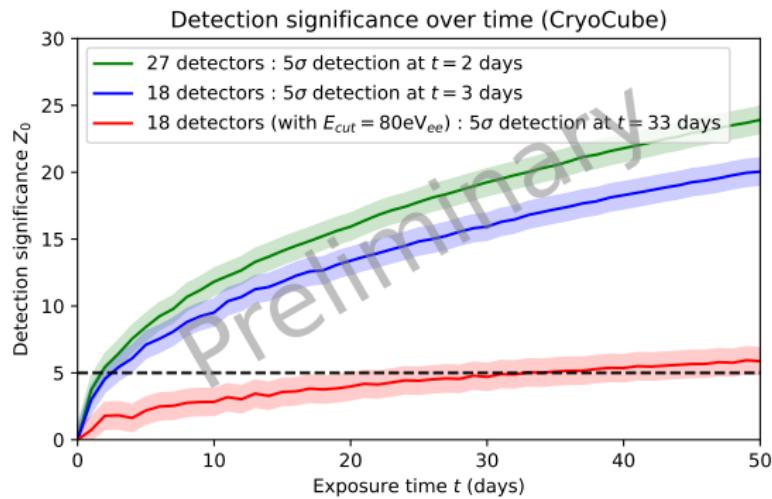
# Cosmogenic NR background spectrum

With 10eV bins :



# CE $\nu$ NS sensitivity with Heat Only

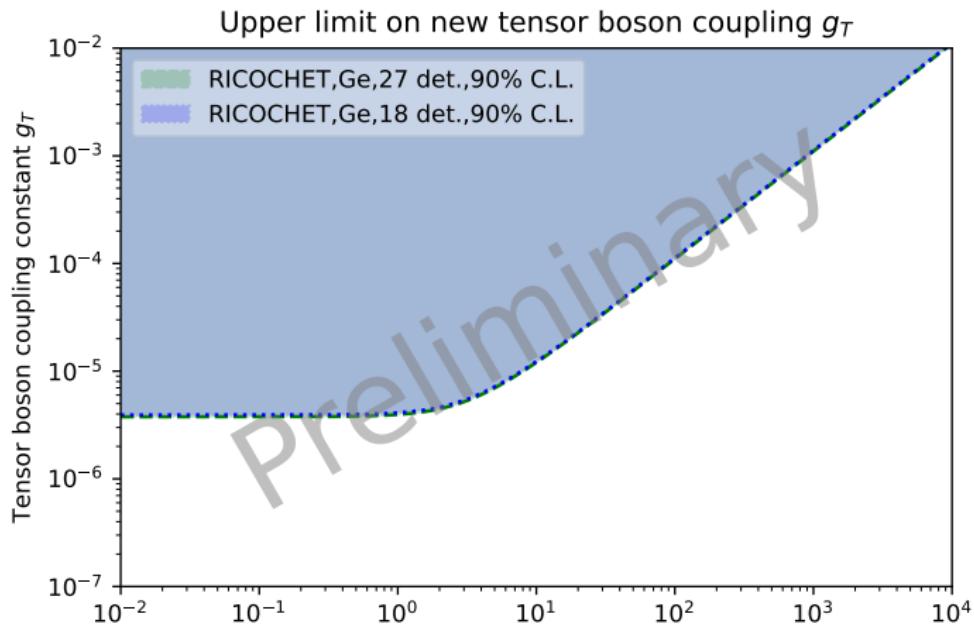
Crude estimation of Heat Only impact with higher ionisation energy threshold to remove this background :



$5\sigma$  detection still possibly in reach after 1 cycle, but with much lower precision ( $\sim 8\%$  at 300d)

# Results (additional tensor boson)

Exclusion plot in phase space  $(m_T, g_T)$  with universal coupling  
 $(Q_{\nu,T} = Q_{q,T} = 1$  i.e.  $g_{\nu,T} = g_{q,T}$ )

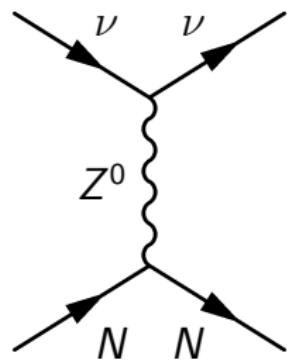


# Standard CE $\nu$ NS

Cross section of SM CE $\nu$ NS :

$$\frac{d\sigma_{SM}}{dE_R} = (\mu) \frac{G_F^2}{4\pi} Q_W^2 m_N \left(1 - \frac{m_N E_R}{2E_\nu^2}\right) F^2(E_R)$$

with  $Q_W = (A - Z) - (1 - 4\sin^2\theta_W)Z$



→ scales with number of neutrons in the nucleus.

# CE $\nu$ NS with NMM

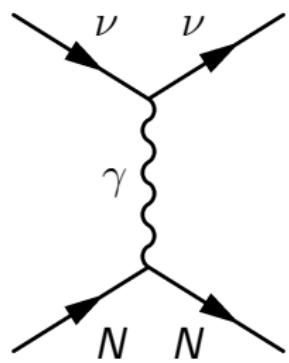
Massive neutrinos have non-zero magnetic moment.

For Dirac neutrinos :  $\mu_\nu \sim 10^{-19} \mu_B$

For Majorana neutrinos :  $\mu_\nu \sim 10^{-14} \mu_B$

If measured at  $\mu_\nu \sim 10^{-12} \mu_B \rightarrow$  hint for new physics + Majorana nature of the neutrino !

$$\frac{d\sigma_{NMM}}{dE_R} = \frac{\pi\alpha^2 \mu_\nu^2 Z^2}{m_e^2} \left( \frac{1}{E_R} - \frac{1}{E_\nu} + \frac{E_R}{4E_\nu^2} \right) F^2(E_R)$$



# CE $\nu$ NS with NGI

NGIs adds a new light boson that can be of any Lorentz-invariant structure. Lagrangian definition (below EW symmetry breaking scale) :

$$\mathcal{L}_{NGI} = \frac{G_F}{\sqrt{2}} C_{\alpha,\alpha}^{q,P} [\bar{\nu}_\alpha \Gamma^X L \nu_\alpha] [\bar{q} \Gamma_X P q]$$

with  $X = \{S, P, V, A, T\}$ ;  $\Gamma_X = \{\mathbb{1}, i\gamma_5, \gamma_\mu, \gamma_5 \gamma_\mu, \sigma_{\mu\nu}\}$ ;  $\alpha = e, \mu, \tau$  and  $q = u, d$

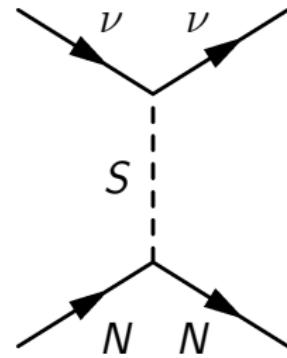
Couplings can be universal or defined with a  $U(1)$  symmetry, often related to baryon and lepton numbers (ex :  $U(1)_{B-L}$ ).

# CE $\nu$ NS with NGI

Scalar boson :

$$\frac{d\sigma_S}{dE_R} = \frac{Q_S^2}{4\pi} \frac{m_N^2 E_R}{E_\nu^2 (q^2 + m_S^2)^2} F^2(E_R)$$

with  $Q_S = g_{\nu,S} g_{q,S} (15.1Z + 14N)$



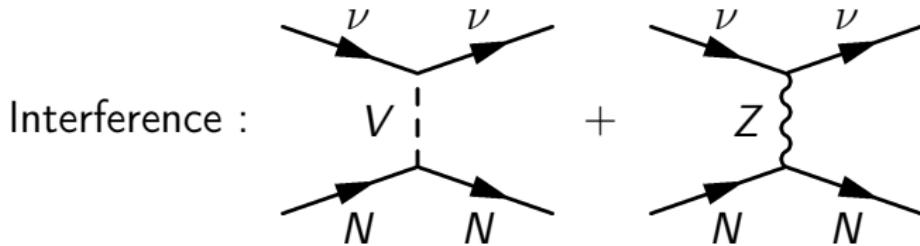
# CE $\nu$ NS with NGI

Vector boson :

$$\frac{d\sigma_V}{dE_R} \propto \frac{d\sigma_{SM}}{dE_R} \text{ with } Q_W \rightarrow Q_{tot}$$

$$Q_{tot} = Q_W - \frac{\sqrt{2}}{G_F} \frac{Q_V}{q^2 + m_V^2};$$

$$Q_V = g_{\nu,V}((2g_{u,V} + g_{d,V})Z + (g_{u,V} + 2g_{d,V})N)$$

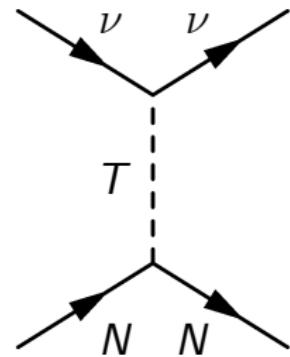


# CE $\nu$ NS with NGI

Tensor boson :

$$\frac{d\sigma_S}{dE_R} = \frac{Q_T^2}{2\pi} \frac{m_N(4E_\nu^2 - m_N E_R)}{E_\nu^2(q^2 + m_T^2)^2} F^2(E_R)$$

with  $Q_T = g_{\nu,T} g_{q,T} (0.85Z - 0.08N)$



# Statistic analysis

Profiled likelihood ratio :

$$\lambda(\mu) = \frac{\mathcal{L}(\mu, \hat{\theta})}{\mathcal{L}(\hat{\mu}, \hat{\theta})}$$

Test used for detection sensitivity  $q_0$  :

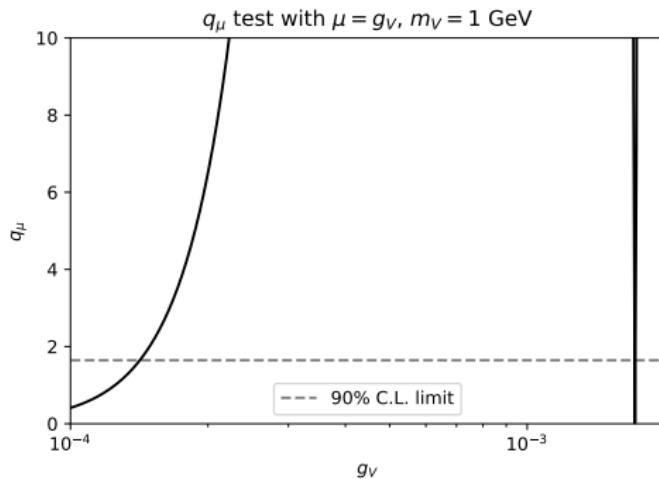
$$q_0 = \begin{cases} -2 \ln \lambda(0) & \text{if } \hat{\mu} \geq 0 \\ 0 & \text{else} \end{cases}$$

Test used for calculating upper limits  $q_\mu$  :

$$q_\mu = \begin{cases} -2 \ln \lambda(\mu) & \text{if } \hat{\mu} \leq \mu \\ 0 & \text{else} \end{cases}$$

# Nuclear weak charge degeneracy (new vector boson model)

The degeneracy band  $Q_{tot} = -Q_W$  does exist but is very thin and hard to compute numerically.



$q_\mu(g_V)$  with 401 test values of  $g_V$