Coherent Elastic Neutrino Nucleus Scattering
CEνNS in XENONnT

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PhD XENON

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The Magnificent workshop

12-14 June 2024 Valencia

On behalf XENON collaboration

XENON Collaboration

XENON is a World-wide collaboration present in 11 countries.
With ~180 Scientists from 27 Institutions, there is always a XENON researcher awake...

AMERICA

- UC San Diego – San Diego
- Houston
- The University of Chicago – Chicago
- Columbia University in the City of New York – New York City
- Purdue University – Lafayette

EUROPE

- Zurich
- KIT Karlsruhe Institute of Technology – Karlsruhe
- WWU Münster – Münster
- Uni Freiburg – Freiburg
- JG|U – Mainz
- Max-Planck-Institut für Kernphysik – Heidelberg
- Nikhef – Amsterdam
- Stockholm University – Stockholm
- Coimbra
- Subatech – Nantes
- LPNHE Paris – Paris
- INFN Torino – Torino
- Bologna
- Università degli Studi dell'Aquila – L'Aquila
- INFN LNGS – Assergi
- Napoli

MIDDLE EAST

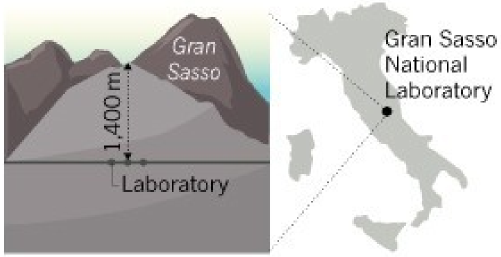
- מכון ויצמן למדע Weizmann Institute of Science – Rehovot
- جامعة نيويورك أبوظبي NYU Abu Dhabi – Abu Dhabi

ASIA

- 清華大学 Tsinghua University – Beijing
- 東京大学 The University of Tokyo – Tokyo
- Nagoya University – Nagoya
- Kobe University – Kobe

XENONnT Experiment

Located at the underground Laboratori Nationale di Gran Sasso LNGS in Italy, XENONnT is shielded from cosmic muons by ~ 1400 m of rock (3600 w.m.e), resulting in a reduction factor of 10^6.



XENON10 (25kg)

(J. Angle et al. , P.R.L.100)

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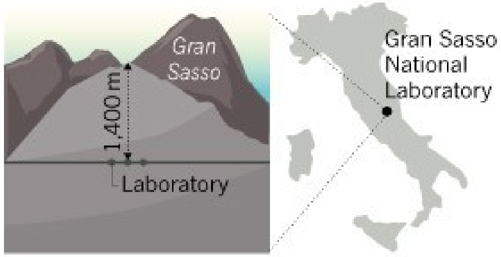

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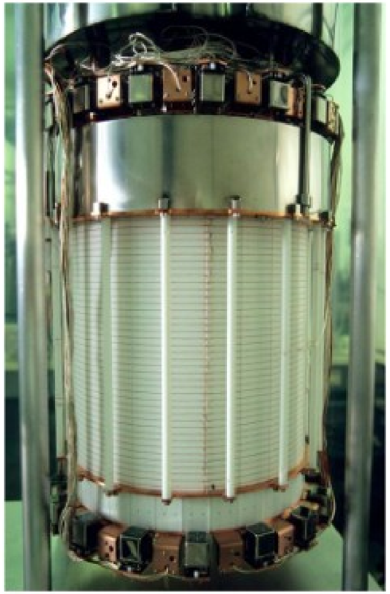

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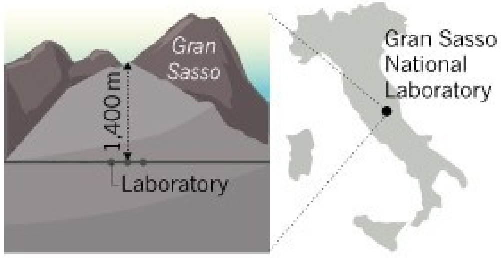

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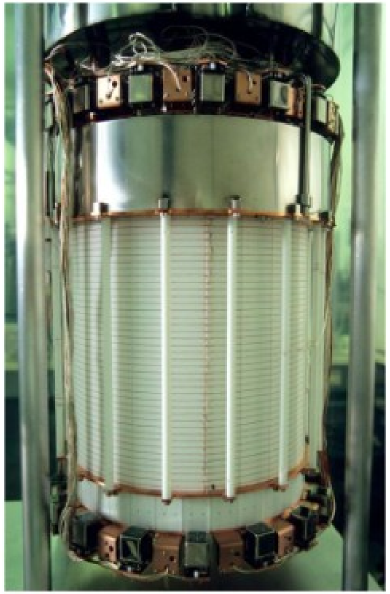

XENON1T (3.2tons)

(E. Aprile et al. P. R. L. 121)

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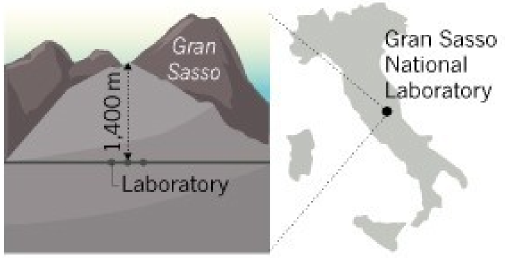

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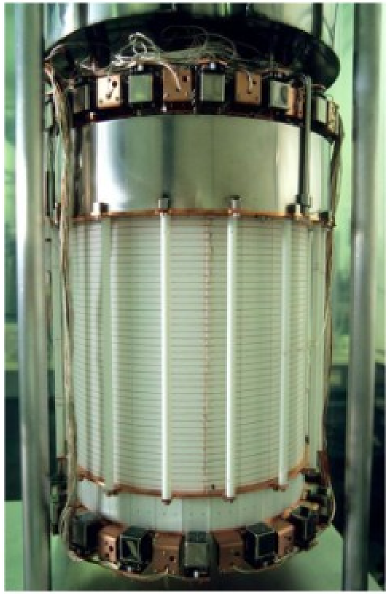

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2016

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2020

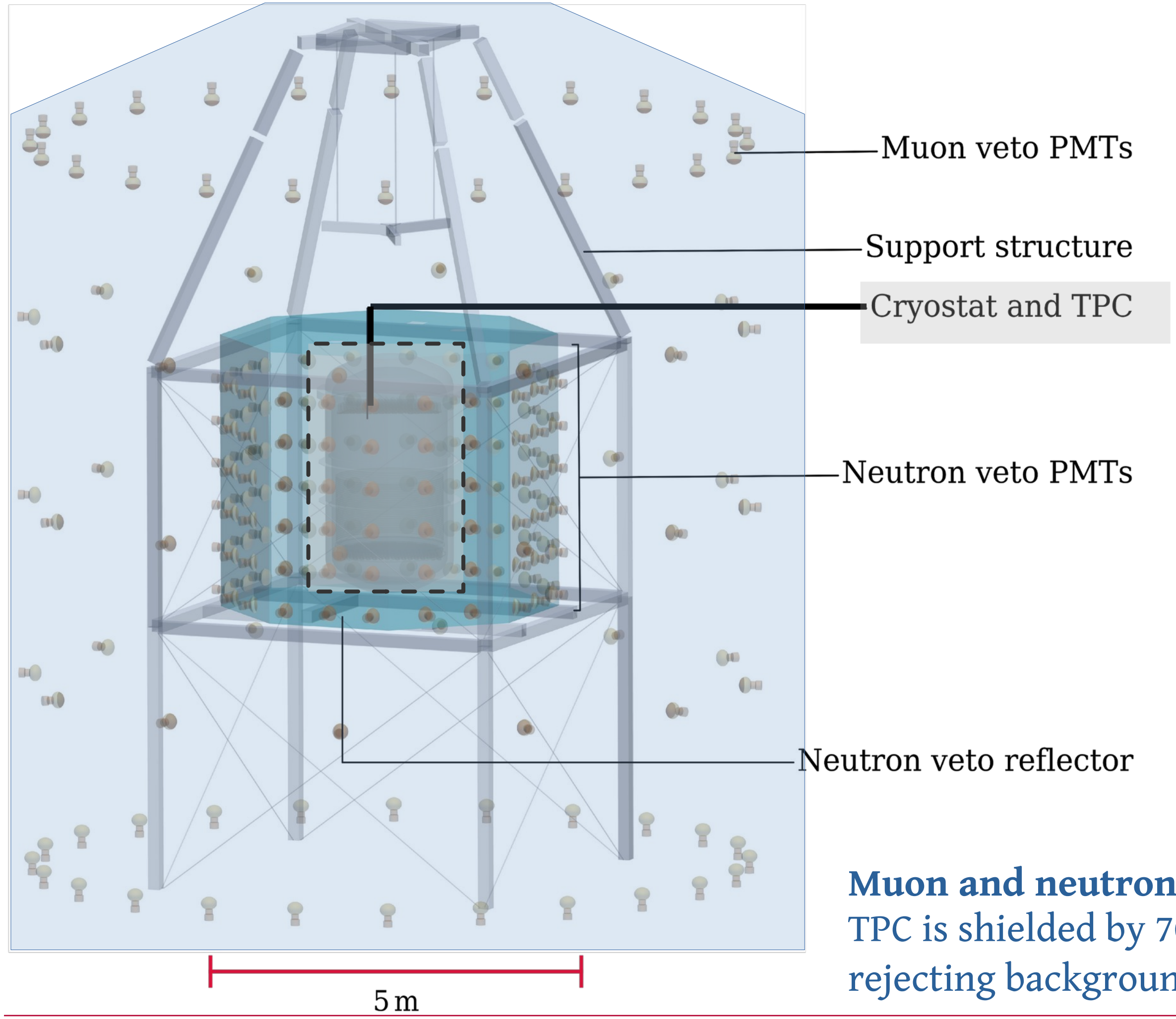
~ 20 years..

- Increasing active volume (5.9 tons LXe)
- Reducing background (~16 evts/ton×year×keV)
- Improving sensitivity 1.4×10^{-48} cm^2 (projection for 20 ton-years exposure

RUNNING (SR2 data)

2024 - 26

XENONnT Experiment Design



Muon and neutron Vetos :
TPC is shielded by 700 tons of Gd(0.02%) doped ultra-pure water, rejecting background from cosmic muons and radiogenic neutrons.

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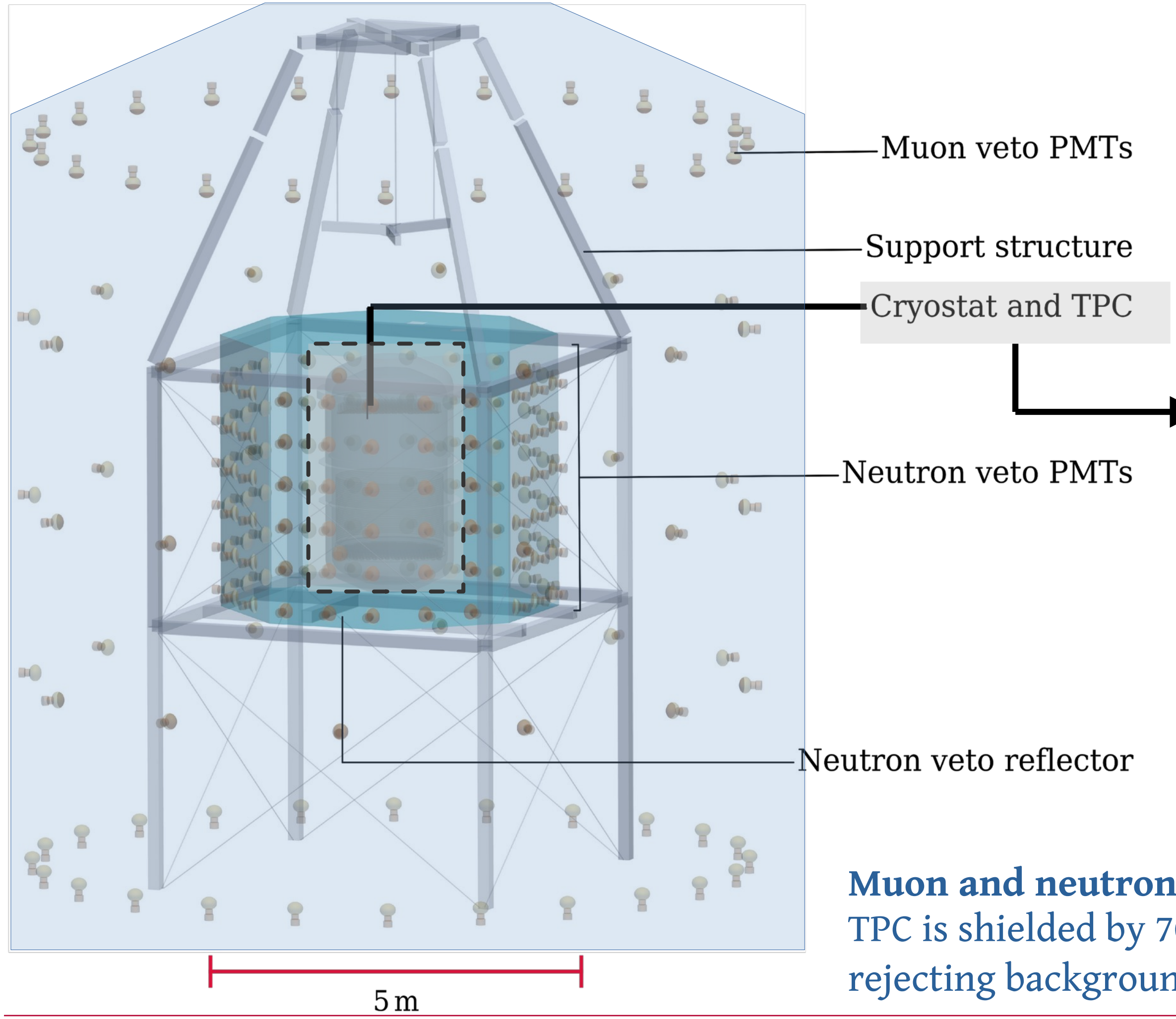
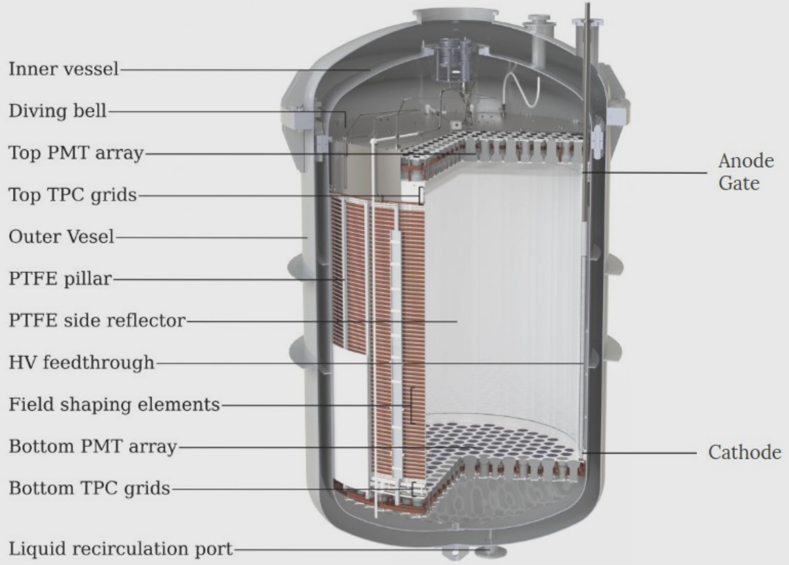


Dual Phase Time Projection Chamber **TPC :**
LXe is hosted by the cryostat inner vessel
at -96°C temperature.
Active volume is inside a stainless cylinder
(ϕ=138cm and h=146cm)



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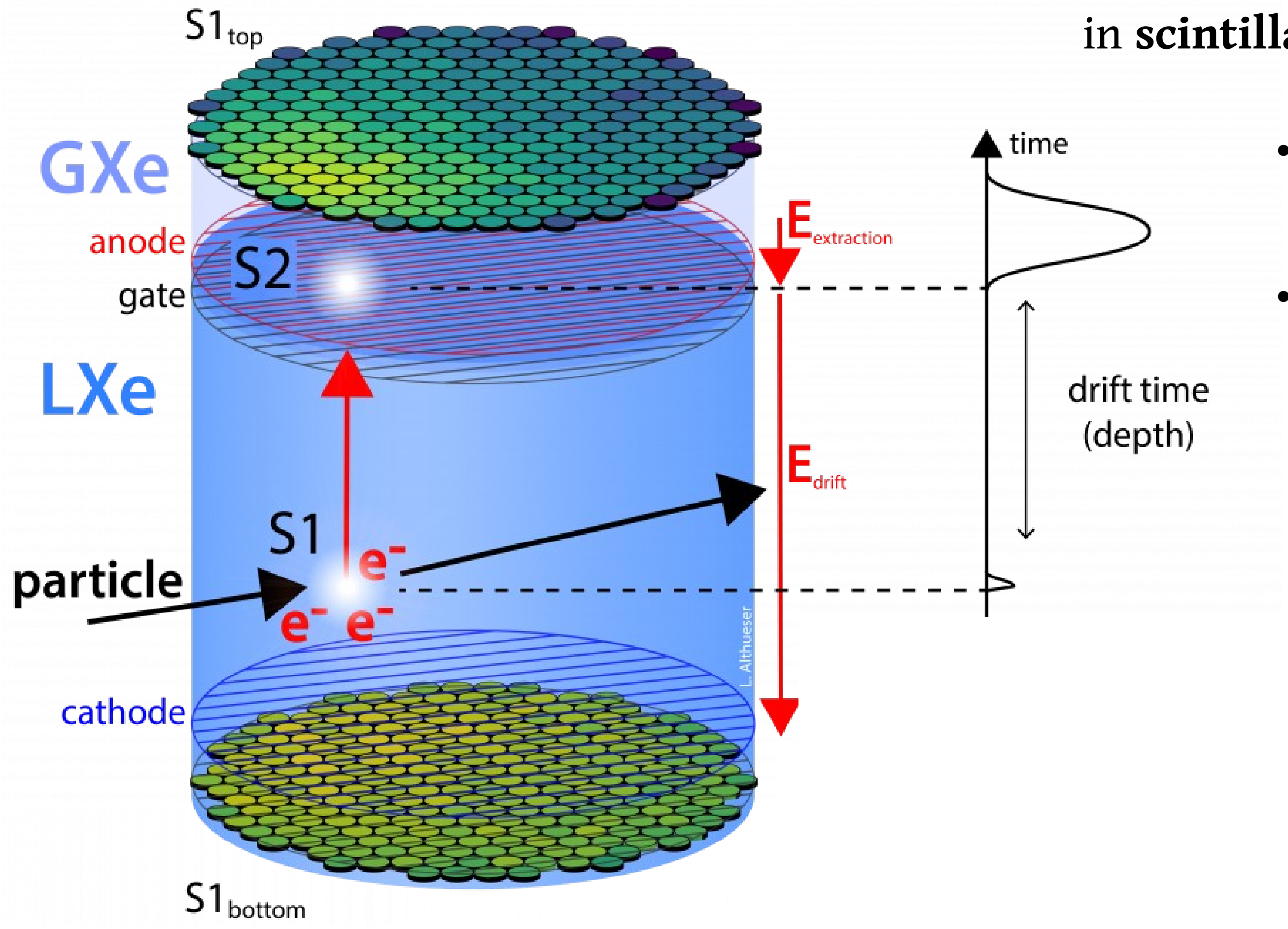
XENONnT Detection principle

Dual Phase TPC : LXe atoms excitation results in **scintillation** and **ionization** observables



- Prompt scintillation signal **(S1)** λ=177.6nm is detected by the PMTs.
- Ionization electrons are drifted by the electric field to the Liquid/Gas interface.
  An extraction-multiplication field accelerates them, producing scintillation signal **(S2),** proportional to the **number of drifted electrons**.

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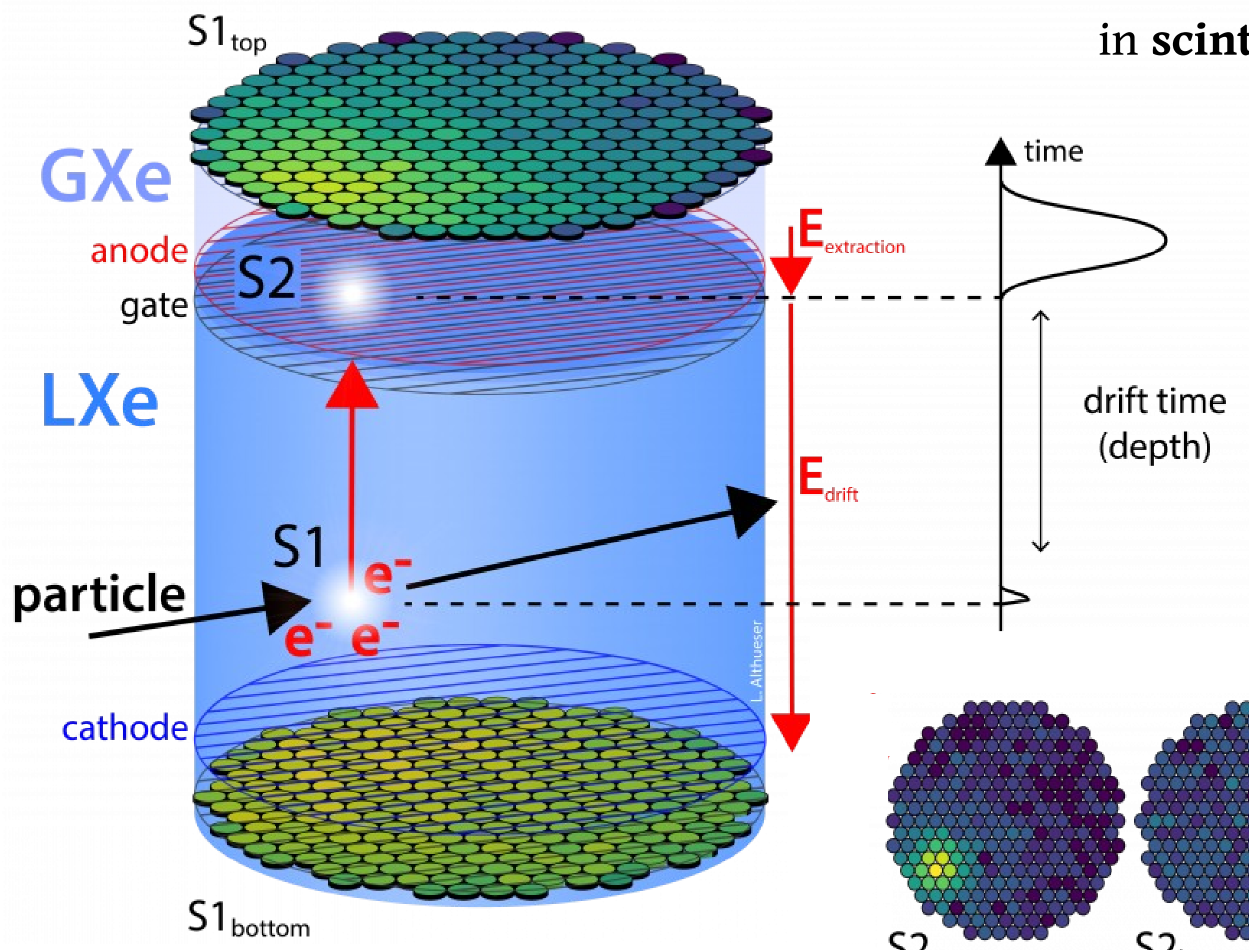

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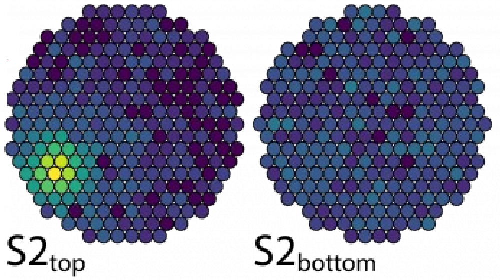

PMT array is composed by a total of **494** Hamamatsu R11410-21 3” PMTs, distributed in the top (253) and bottom (241) arrays .

XENONnT event reconstruction

- **Event energy reconstruction**

$$E = W\,(n_{ph} + n_e)$$

$$E = W\left(\frac{S1}{g1} + \frac{S2}{g2}\right)$$

W =13.7 eV

g1 = (0.152 ± 0.002) PE/γ

g2 = (16.5 ± 0.6) PE/e-

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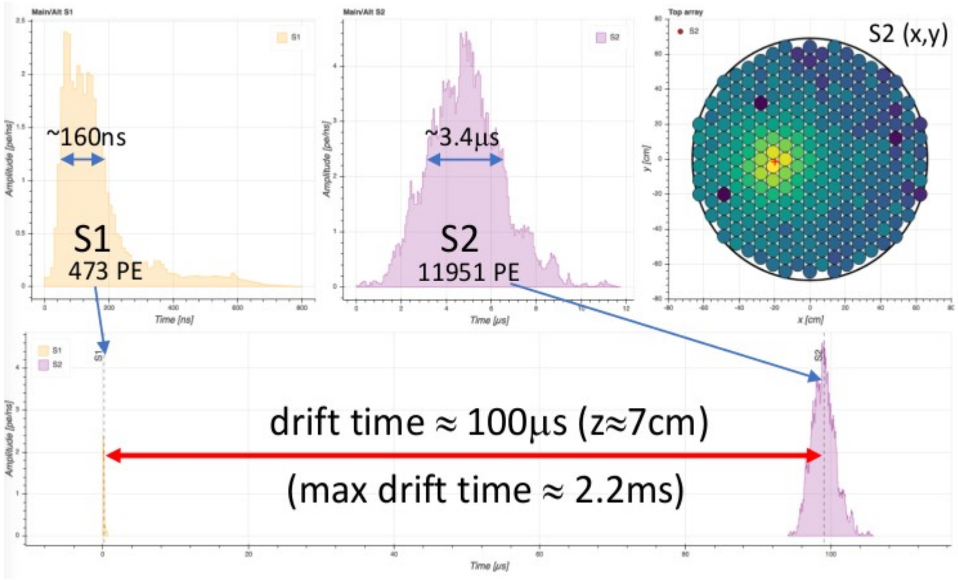

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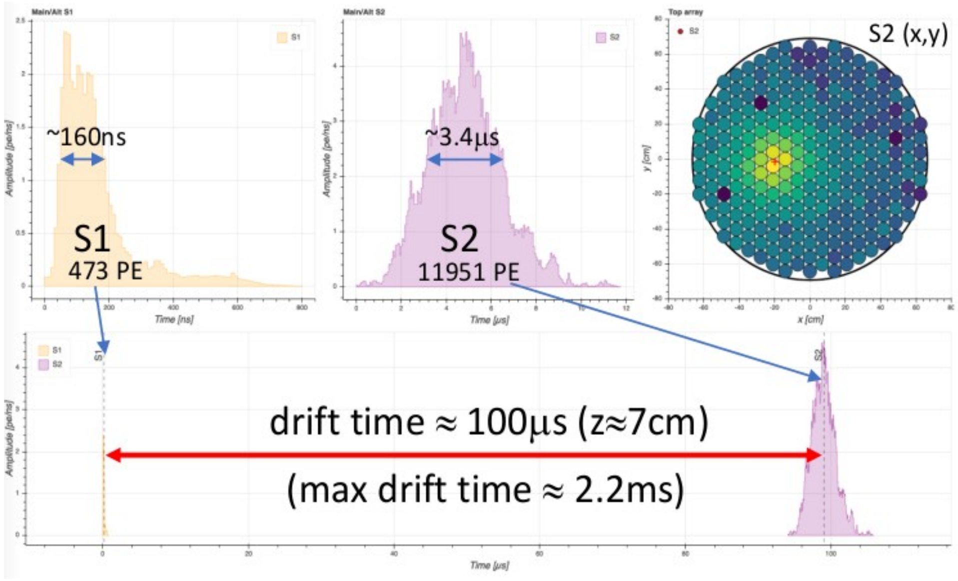
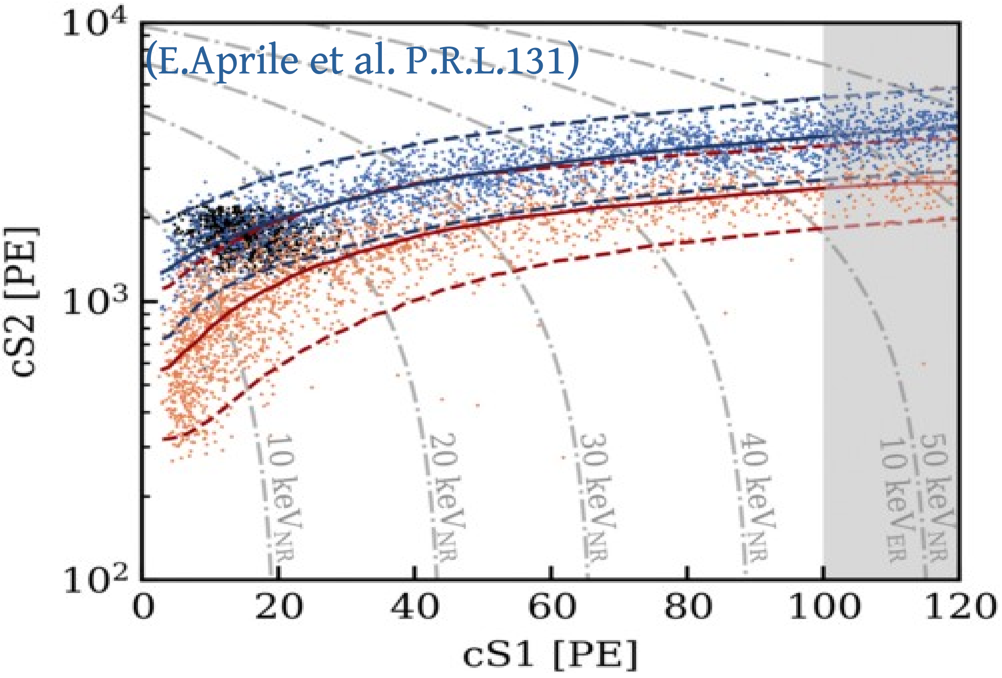


- **Particle discrimination**

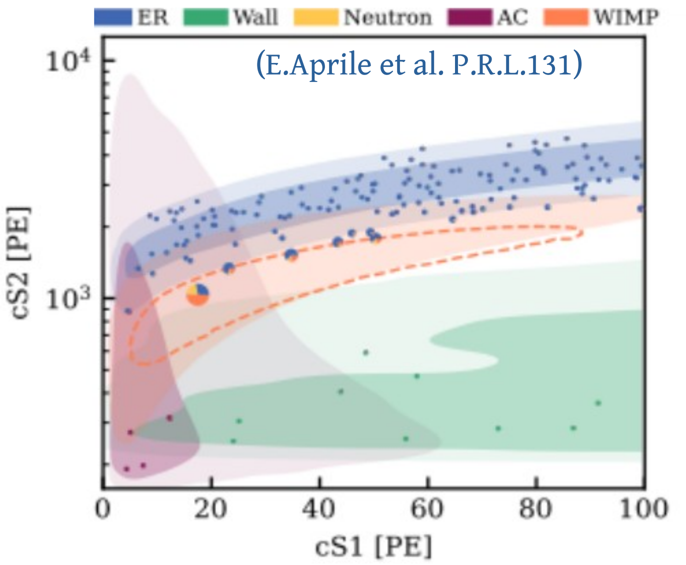
S1/S2 ratio is different from electron recoil (ER), expected from background and nuclear recoil (NR)



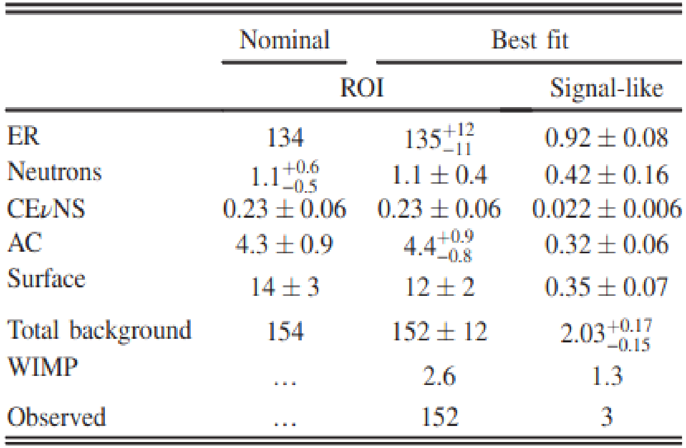
ER: Beta, gamma, pp solar neutrinos..

NR: WIMPs, neutrons , 8B solar and Supernovae neutrinos (**CEνNS**)

XENONnT background



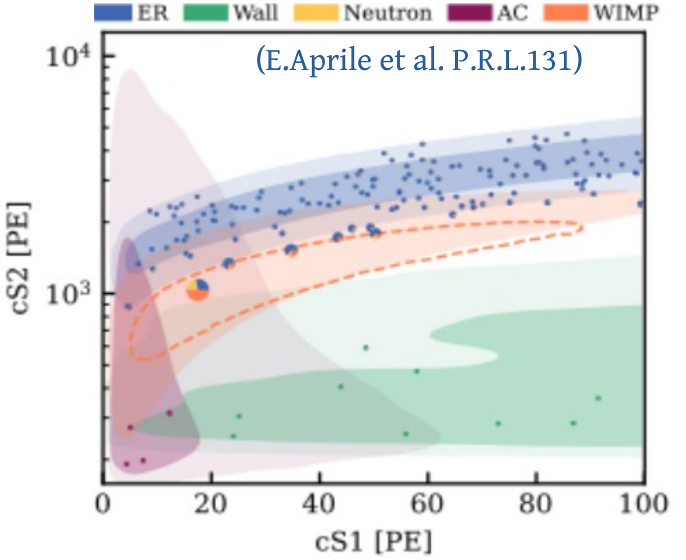
(E.Aprile et al. P.R.L.131)



	Nominal	Best fit	
	ROI		Signal-like
ER	134	135^{+12}_{-11}	0.92 ± 0.08
Neutrons	$1.1^{+0.6}_{-0.5}$	1.1 ± 0.4	0.42 ± 0.16
CEνNS	0.23 ± 0.06	0.23 ± 0.06	0.022 ± 0.006
AC	4.3 ± 0.9	$4.4^{+0.9}_{-0.8}$	0.32 ± 0.06
Surface	14 ± 3	12 ± 2	0.35 ± 0.07
Total background	154	152 ± 12	$2.03^{+0.17}_{-0.15}$
WIMP	…	2.6	1.3
Observed	…	152	3

- **ER** using S1/S2 Particle discrimination
- **Wall** events imposes fiducial cuts (~4 .18 tons)

XENONnT background



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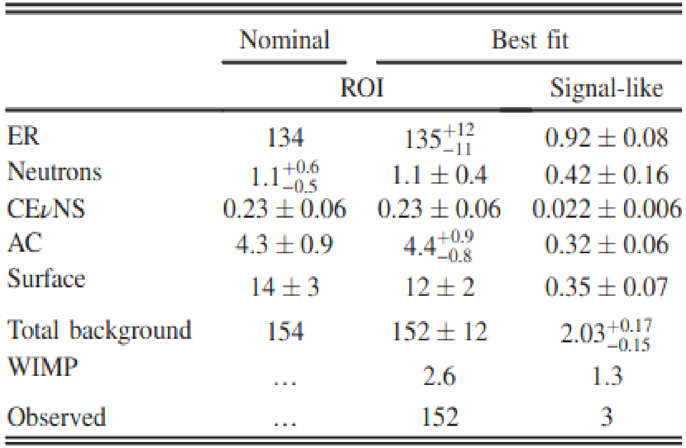

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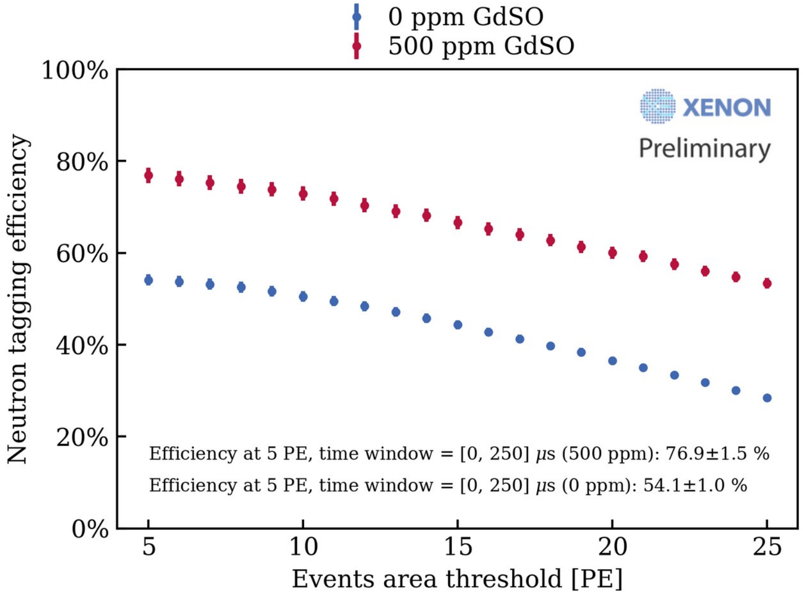
- **Neutrons** rejection from neutron veto **AmBe** calibrations results

Doped Gd(0.02%)-Water increase neutron capture detection efficiency *(Gd(0.02%)≣500pm GdSO)

Neutron capture :

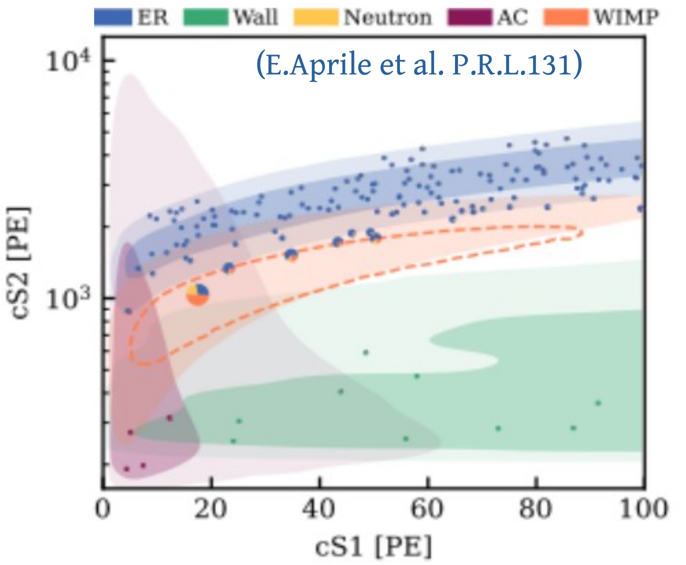
- Water 2.2 MeV gamma (200µs)
- Gd ~8 MeV gamma cascade (~30µs)



Efficiency at 5 PE, time window = [0, 250] µs (500 ppm): 76.9±1.5 %

Efficiency at 5 PE, time window = [0, 250] µs (0 ppm): 54.1±1.0 %

XENONnT background



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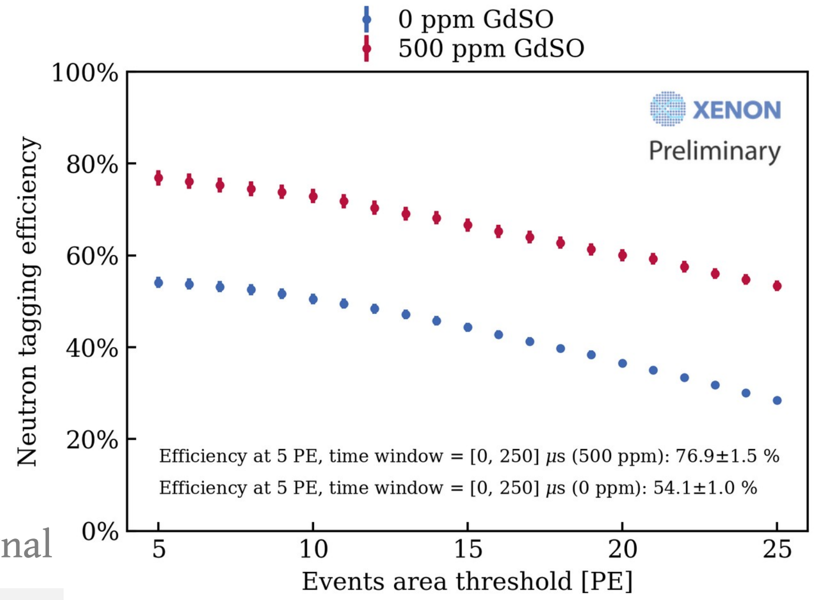
- CEνNS mimic WIMPs signal

Neutrino Fog :
Solar, Atmospheric,
DNSB

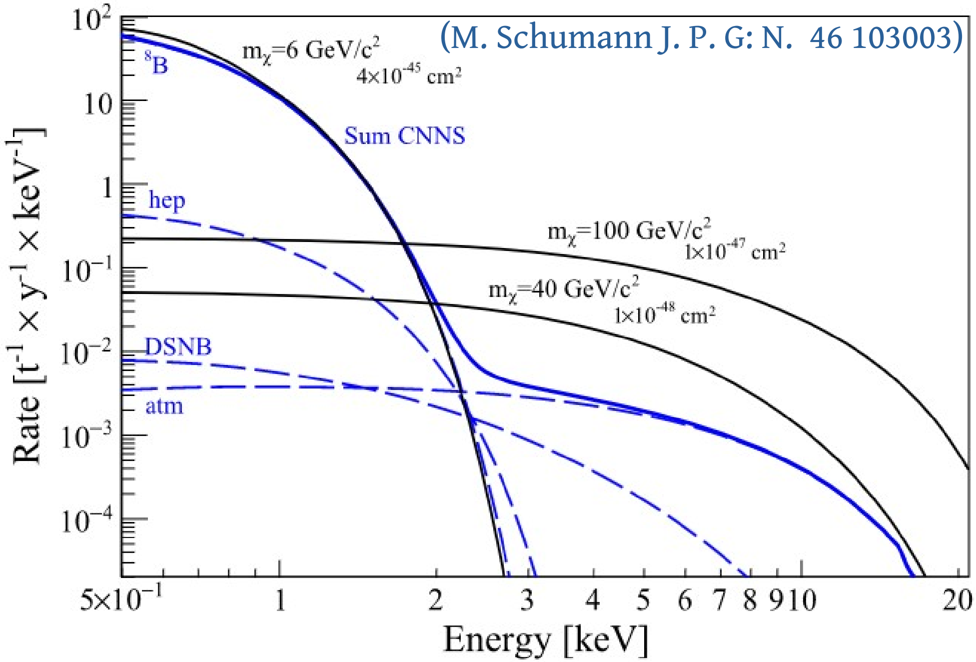


*Muons rate in Water tank 1-2/min
Muon Veto rejects almost 100 % of them

Neutrino Fog

- CEνNS induced from cosmic neutrinos produce **NR O(1)-O(10) keV**, similar of expected from WIMPs GeV/c² range.

- Spin independent **SI WIMP-nucleon** scattering and CEνNS discrimation is challenging, imposing the last sensitivity limits on the SI-WIMP interaction, represented by the ‘**neutrino fog**’



(M. Schumann J. P. G: N. 46 103003)

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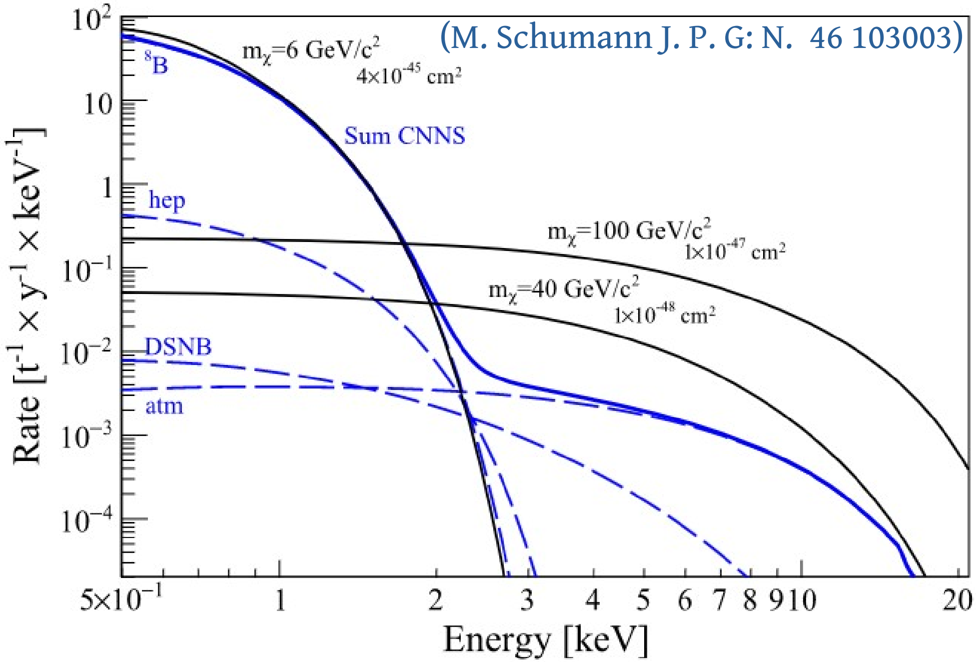

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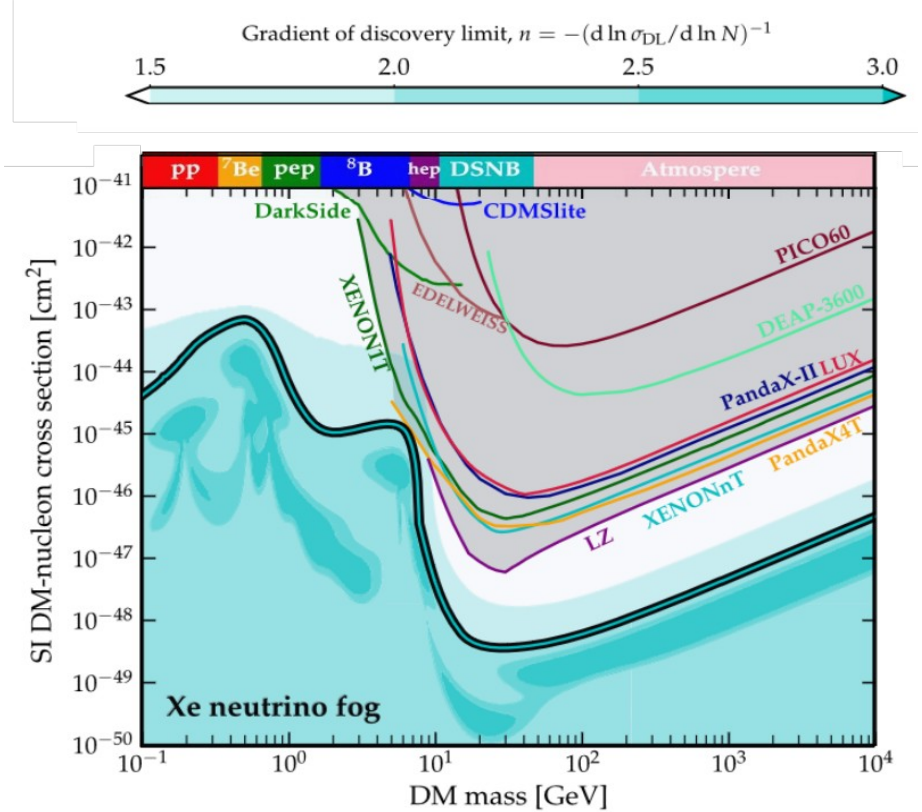


Cosmic **neutrino fluxes** and DM detectors **low NR** uncertainities, leads to a re-definition of the limits of the ‘*neutrino floor*’ into a boundary region the ‘neutrino fog’. Next generation of direct DM detectors will attempt this limits for 10-100 GeV/c² DM mass.

(See Ciaran O'Hare Talk)

CEνNS in LXe

*(Mixing angle Θw ~0.23)

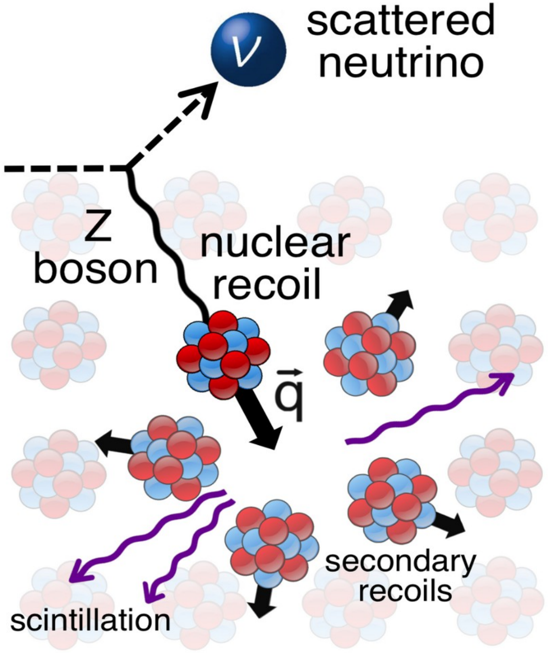
$$N - (1 - 4\sin^2\theta\omega)Z$$

α N²

Form factor
Coherence (q~RXe)

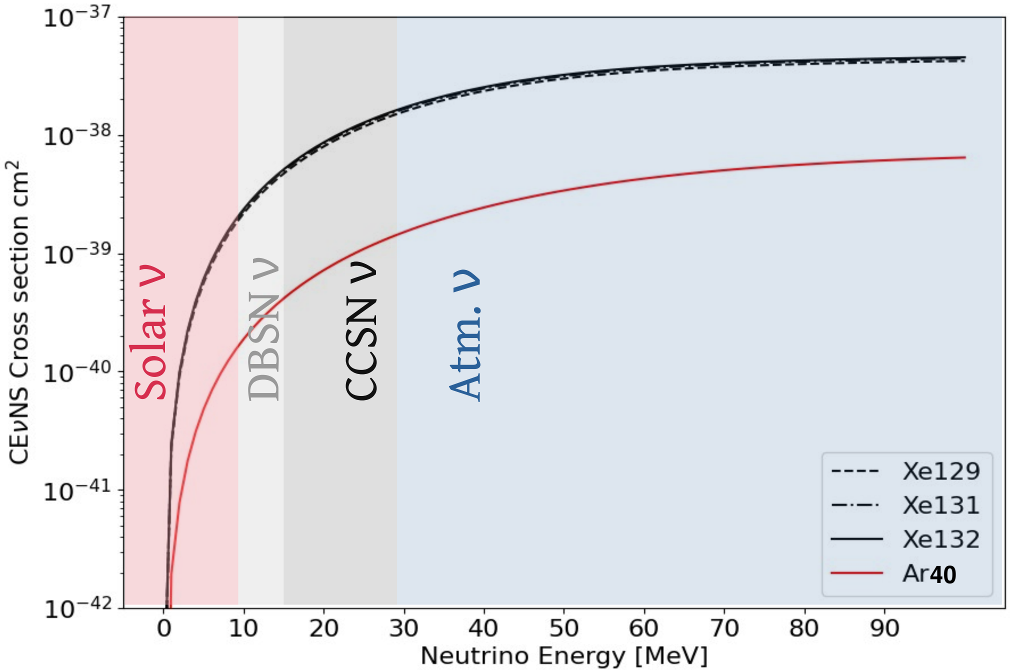
F(q=0)=1

$$\frac{d\sigma(E_\nu, E_R)}{dE_R} = \frac{G_f^2 \boxed{Q_w^2} m_N}{4\pi}\left[1 - \frac{m_N E_R}{2E_\nu^2}\right]\boxed{F^2(E_R)}$$



q~ $\sqrt{2 E_R M}$

CEVNS cross section as a function of neutrino energy

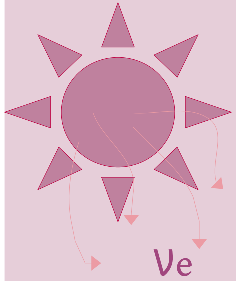


- Neutron rich natural LXe isotopes
- Heavy nuclei (A=129-132) for the most abundants isotope (>72 %)
- Larger Cross section
- Low recoils O(keV).

CEνNS from cosmic neutrinos in XENONnT

CeνNS have been Observed by **COHERENT** experiment in 2017 (arXiv.1708.01294)
Never observed from a **cosmic source…** requires High **Flux** and High **exposure**

XENONnt with 20 ton year exposure expects $\mathcal{O}(100)$ **events** /ton/ year .



Solar Neutrinos

- High, constant, measured flux of $\mathcal{O}$(MeV) neutrinos

$\phi \sim \mathbf{6.6 \times 10^{10}\ /cm^2\ s}$

- Mainly **νe** from pp-chain
- **Low NR** < 5 keV
- $\mathcal{O}$(1000) **interactions** /ton year but require **0.1-0.3 KeV** threshold
- Major contribution from the

^{8}B beta decay :

$$^8B \longrightarrow {}^8B^* + e^+ + \nu_e$$

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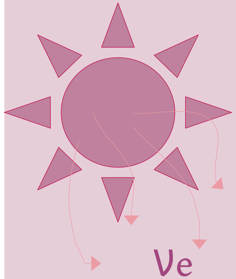

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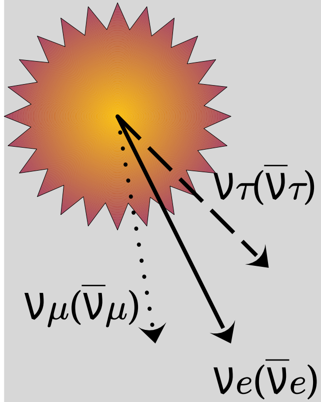


Core collapse Supernova CCSN

- Neutrino bursts of all flavor $\mathcal{O}$(10MeV)
- ~ 5×10^{53} ergs in 10 seconds
- High flux uncertainity
- NR < 20 KeV
- 2 or 3 per century in <50 kpc
- CEvNS sensitive to the entier spectrum

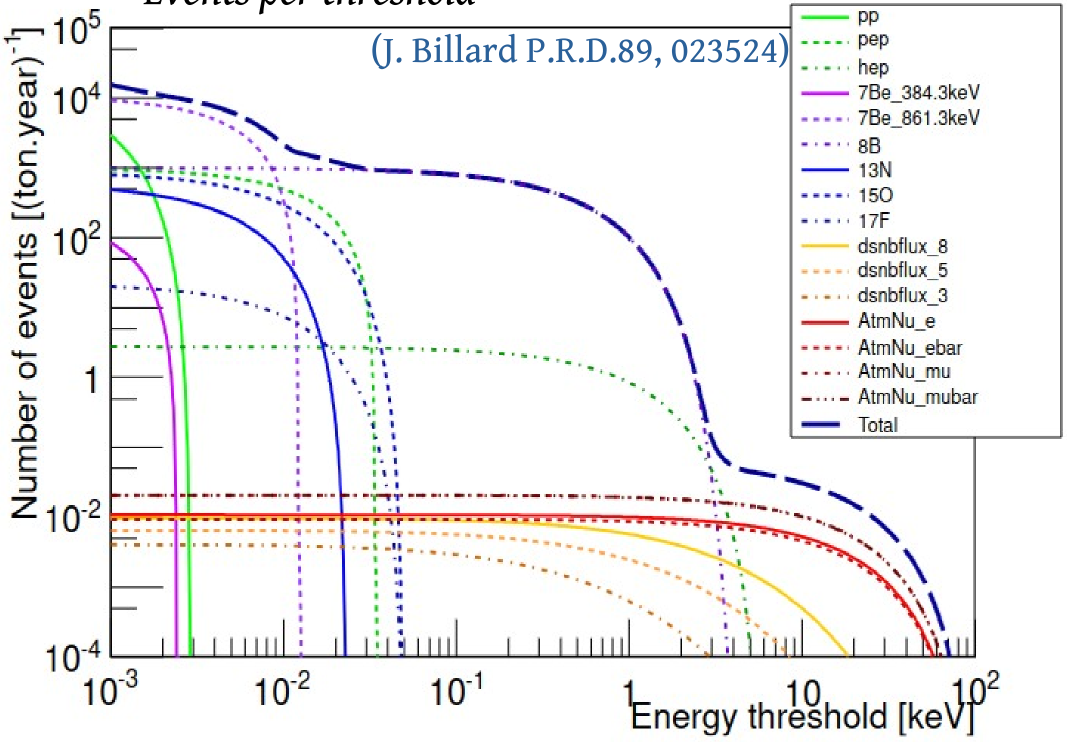
^{8}B CEνNS detection in XENONnT

Exposure ⊗ σ (CEVNS) ⊗ ν Flux ($5.25 \pm 0.20 \times 10^6$ /cm² s)

$$R = \boxed{T \times N_{Xe}} \int_{\boxed{E_{R_{th}}}}^{\infty} dE_R \int_{E_{\nu_{min}}} \frac{d\sigma(E_\nu, E_R)}{dE_R} \boxed{\frac{dN}{dE_\nu}(E_\nu)\, dE_\nu}$$

<1 keV threshold

Events per threshold



(J. Billard P.R.D.89, 023524)

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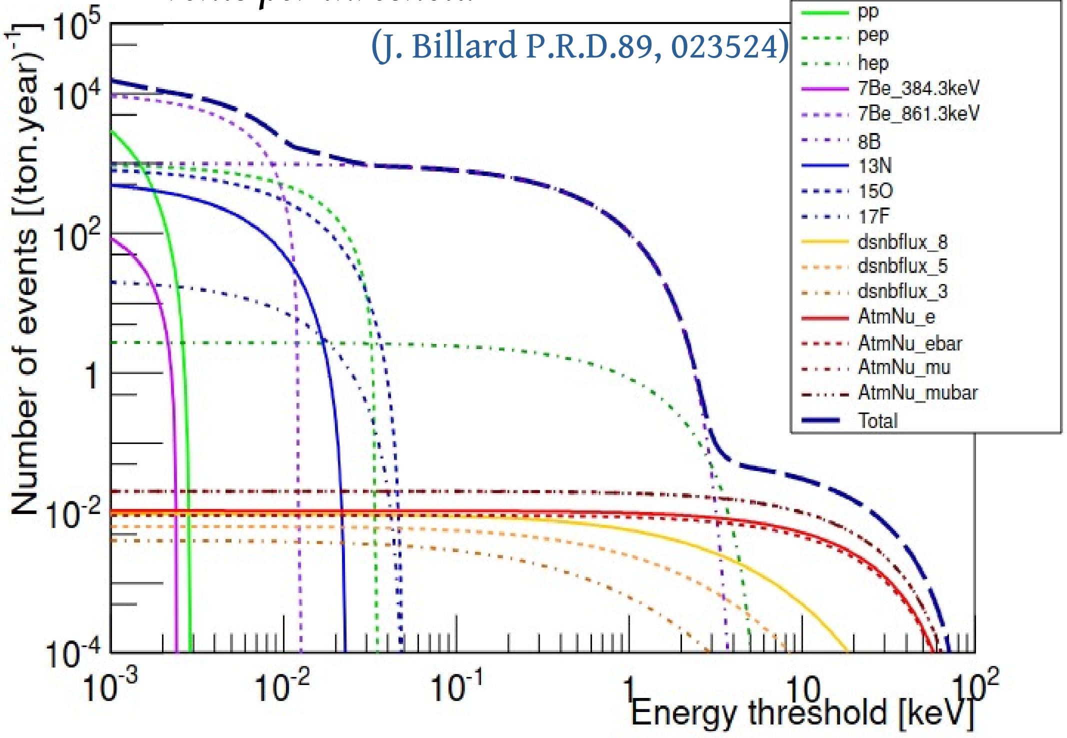
<1 keV threshold

- **^{8}B ν mean energy** <E> ~8 MeV
  - Extremly low **NR < 3 keV**
- ~**600 events**/ton per year (0.5 KeV threshold)

- Threshold reduction(<0.5KeV)
- Increase background (**AC**)
- **Low detection efficiency**

Events per threshold



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^{8}B CEνNS previous XENON1T analysis

XENONnT expected to improve ^{8}B detection efficiency of XENON1T

NR Efficiency looses in XENON1T

- S1 threshold PMT coindidences

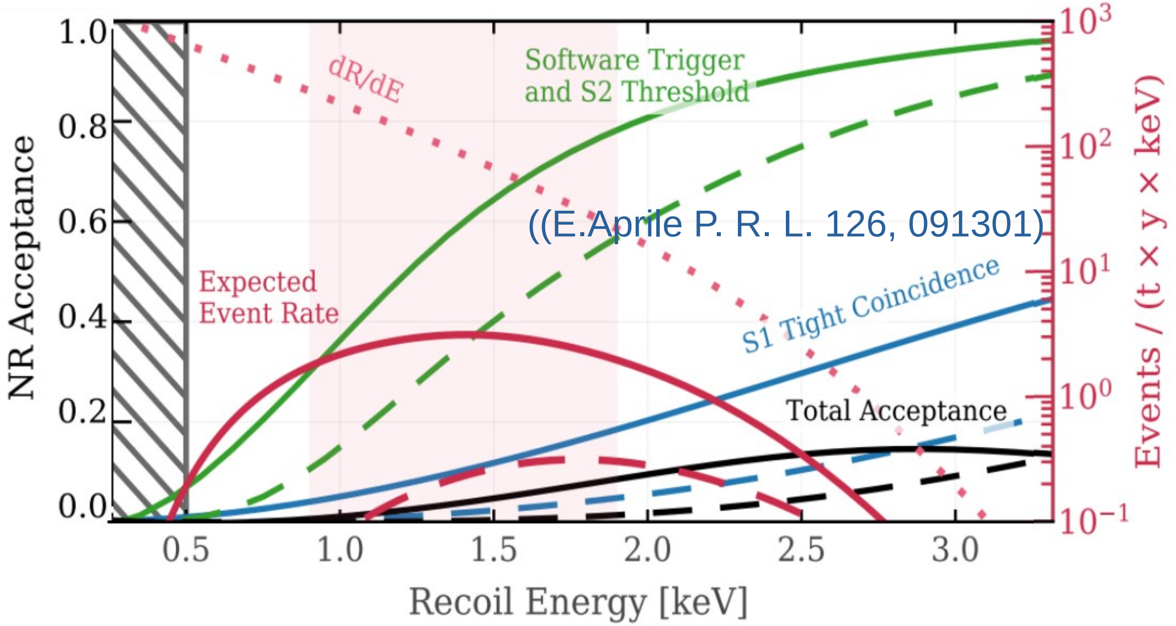
  3 PMT → 2 PMT

- S2 threshold

  200 PE → 120 PE

- Total acceptance **(>0.5KeV)**

  1 % → 5 %



((E.Aprile P. R. L. 126, 091301)

^{8}B CEνNS previous XENON1T analysis

XENONnT expected to improve ^{8}B detection efficiency of XENON1T

NR Efficiency looses in XENON1T

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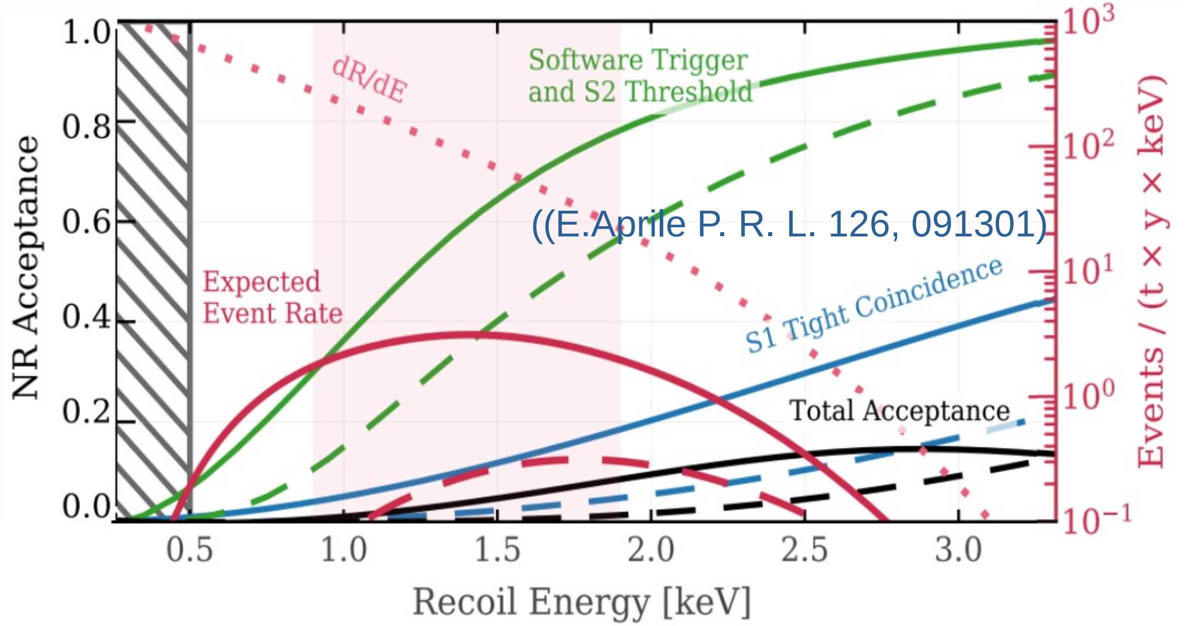

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NR improvements lead to **introduction of new background** $\mathcal{O}(10^2)$ more...
Cutting background leads to acceptance looses...

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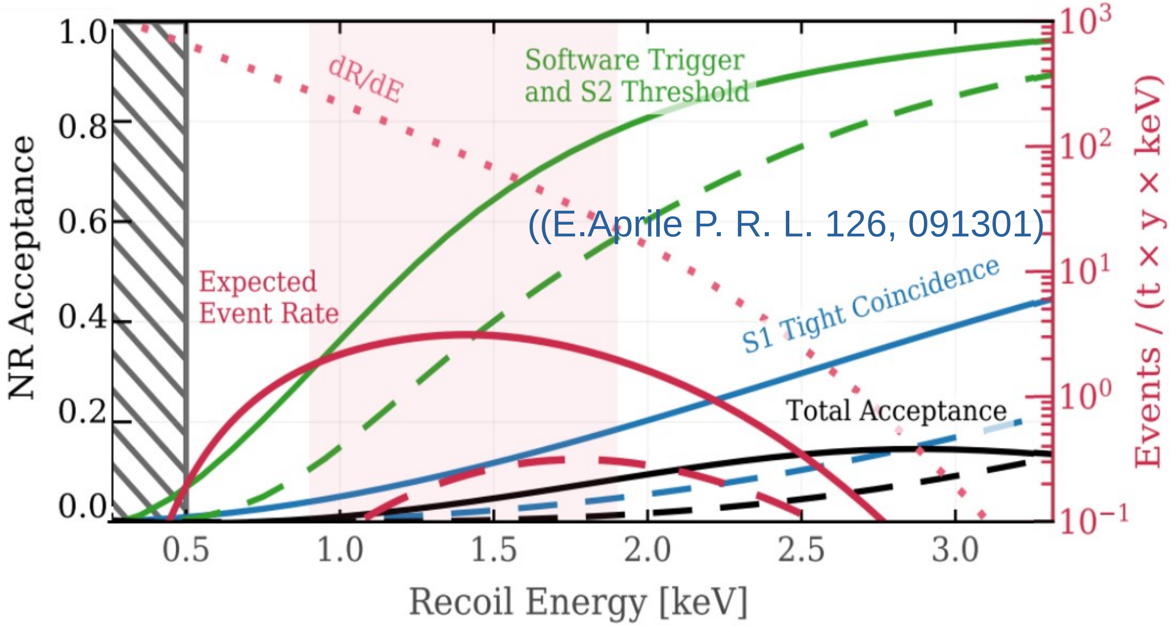

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NR improvements lead to **introduction of new background** $O(10^2)$ more...
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CEνNS background is mainly from accidental coincidences **(AC)**, i.e. randomly paired isolated S1 and S2s

^{8}B CEνNS previous XENON1T analysis

ER are negligible for ^{8}B CEVNS signal and fiducial cuts can remove Surface/Wall events.

Accidental coincidences (AC)

e⁻ maximun drif time

$$AC_{RATE} \simeq \int R_{iso_{S1}} \times R_{iso_{S2}} \times \boxed{\Delta_{e_{drift}}} dt$$

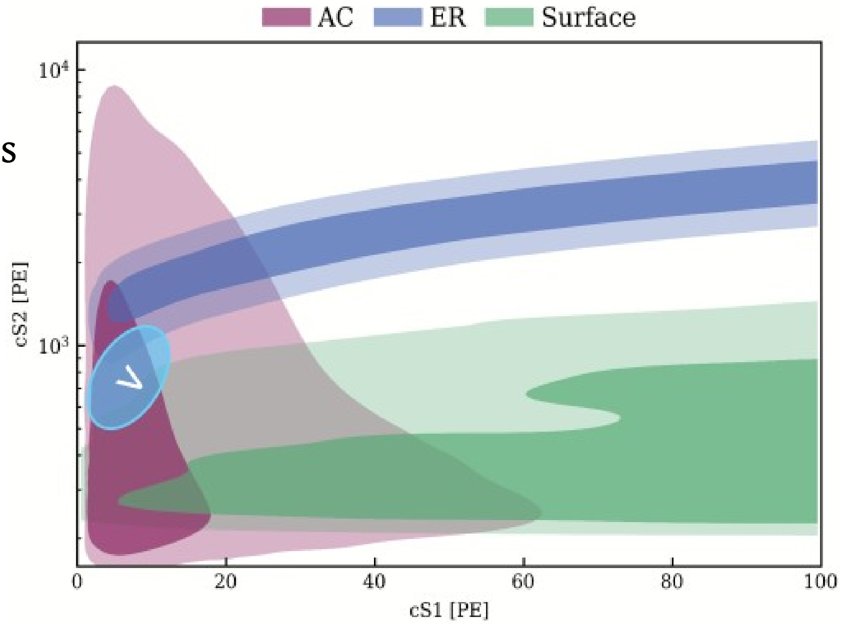
Isolated S1 and S2

Isolated S1 :

- Dark counts
- Misidentified single electrons
- Below-cathode and surface events

Isolated S2 :

- Delayed single electrons
- Misidentified afterpulses



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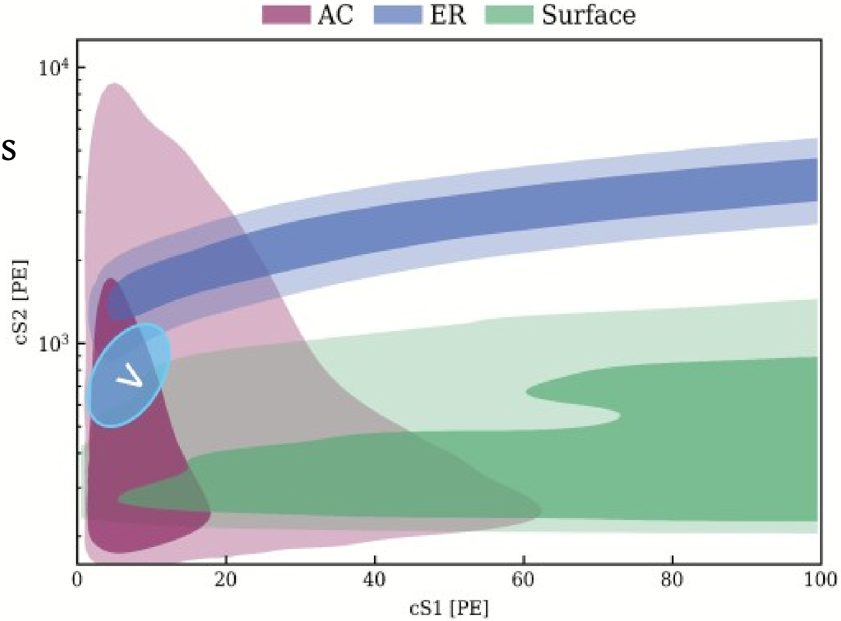
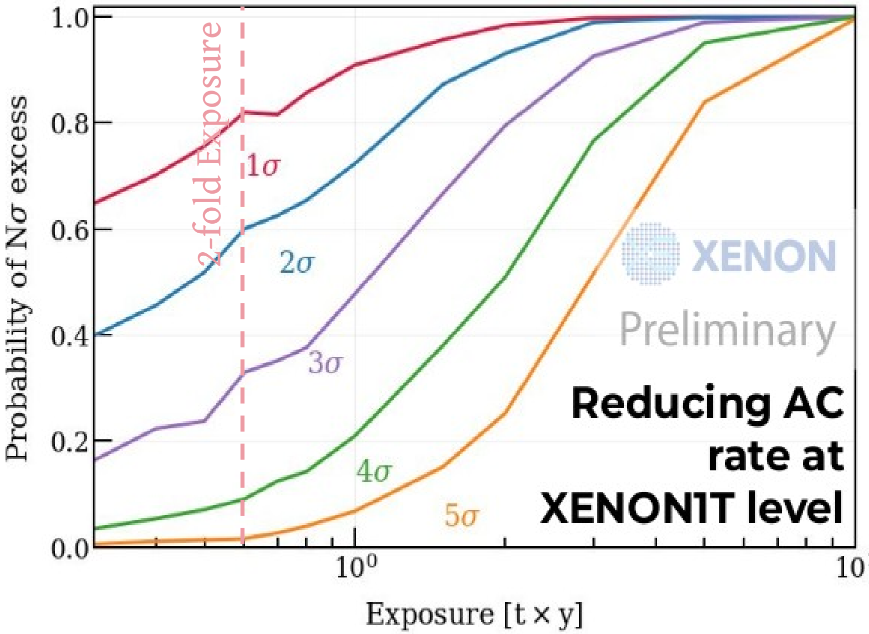


^{8}B XENON1T discovery potential

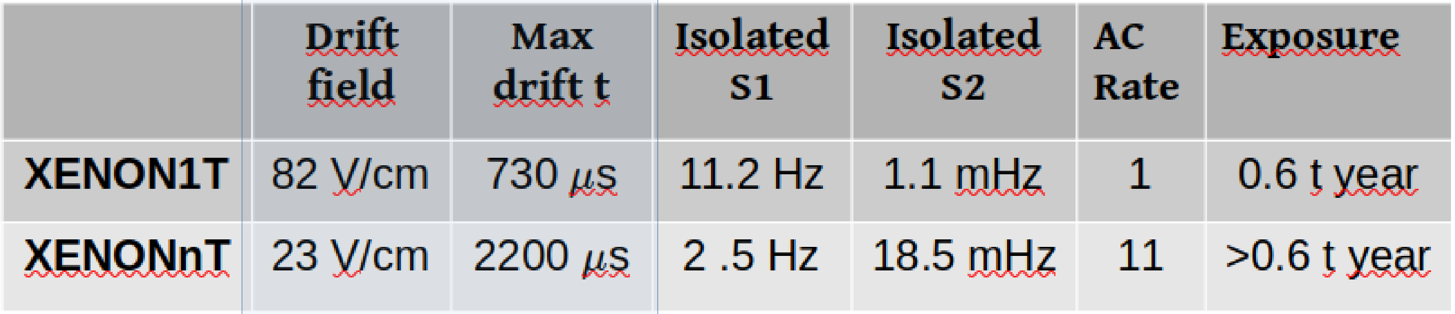


Reducing AC rate at XENON1T level

- 2-Fold coincidences 0.6 ton year exposure
- XENONnT is expected to improve exposure and signal discovery.
- Reach total efficiency ~ 1% $O(5)$ CEvNS

XENONnT improvements for ^{8}B CEνNS detection

- Triggerless DAQ
- Better LXe purity
- Lower NR threshold
- Higher exposure



	Drift field	Max drift t	Isolated S1	Isolated S2	AC Rate	Exposure
XENON1T	82 V/cm	730 μs	11.2 Hz	1.1 mHz	1	0.6 t year
XENONnT	23 V/cm	2200 μs	2 .5 Hz	18.5 mHz	11	>0.6 t year

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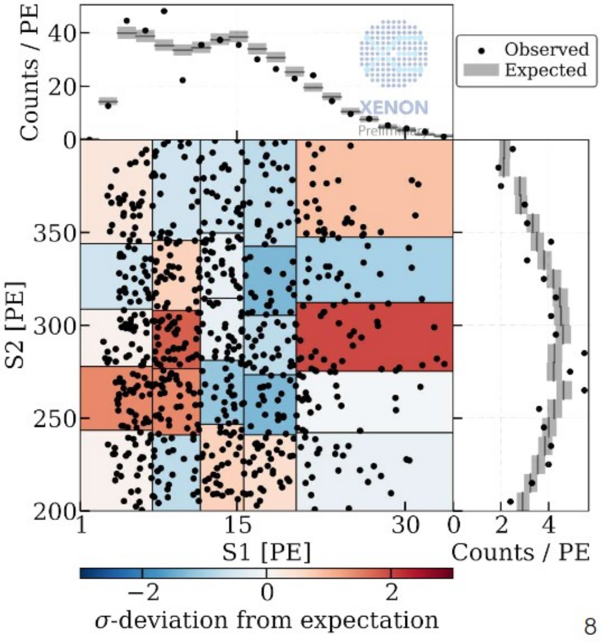
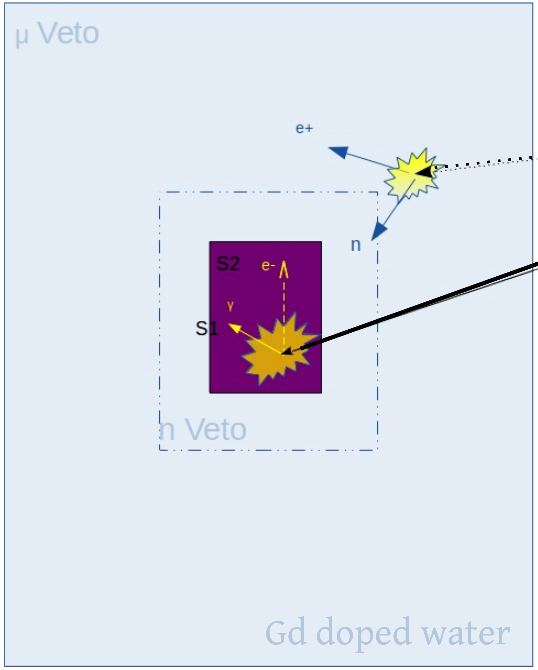


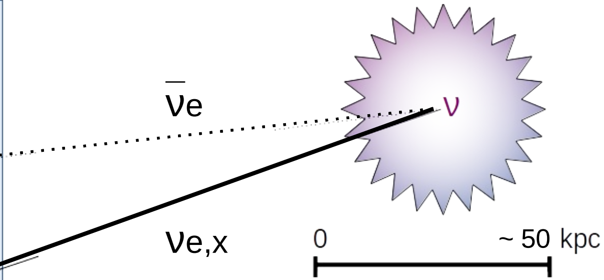
- **AC** is well understood for Science Run 0, with a 5% precision.
- Shadowing effects, affecting ‘True’ S1/S2 pairing

^{8}B CEνNS XENONnT status

- AC background reduced :
  - Larger AC rate but, better suppression AC (new approach)
  - Modelling validated in the XENONnT WIMP analysis (Science Run 0)
- NR Threshold reduced
- Performing low-threshold 2-fold coincidence analysis!

CCSN Neutrino detection in XENONnT





- CCSN progenitors 8-40 M⊙
- SN Type II, Ib and Ic
- XENONnT is sensitive to CCSN in the whole Galaxy and Magellanic Clouds (≤ 52 kpc)

- Time dependent signal (10 seconds)
- **S2-Only** (ER/NR discrimination not necessary)
- **Two** sentive volumes (**TPC** and **Vetos**)
- **Supernova Early Warning system SNEWS**

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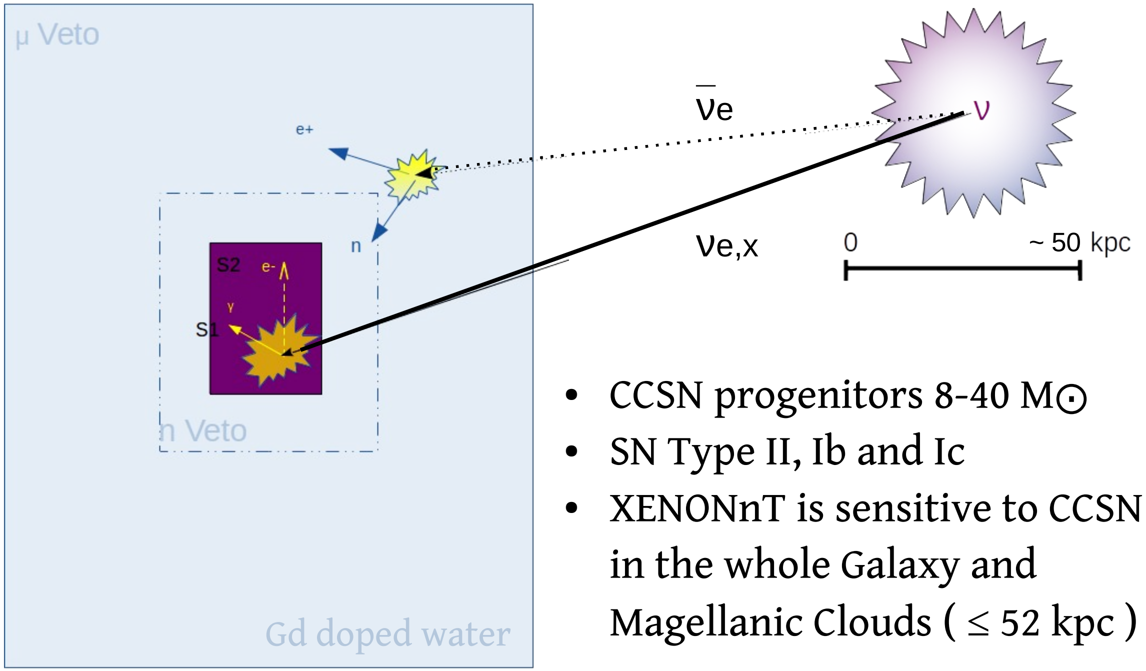

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TPC(5.9t of LXe):

- CEνNS interactions enhanced by A^2
- Sensitive to all ν flavors
- Not affected by oscillations uncertainities
- Expected ~**100-150 interactions** from an SN at 10 kpc

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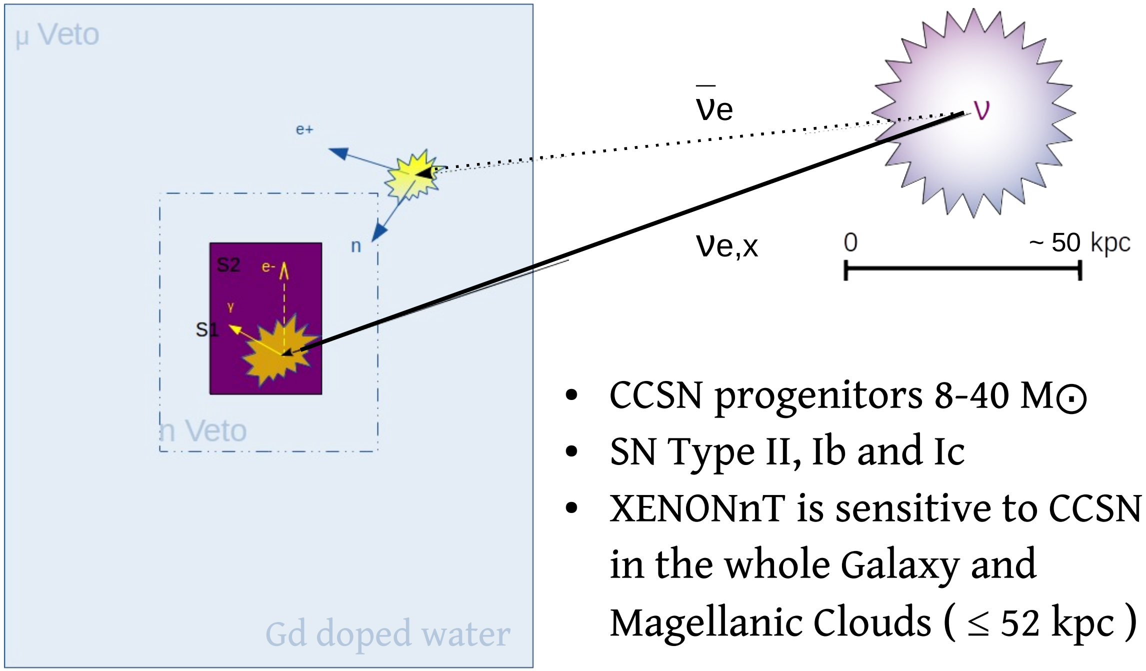

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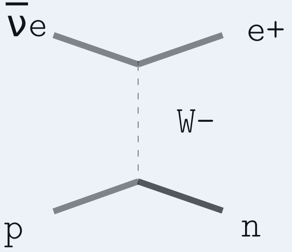
- **Supernova Early Warning system SNEWS**

Water Tank(700t Gd doped water):

- Inverse Beta Decay **IBD** interactions in (μ and n Vetos) producing Cerenkov light.



- **100 - 200 Interactions** at 10 kpc
- Sensible to 1/6 ν flux
- Ee+ ~ Eν – 1.2 MeV

CCSN CEνNS signal in XENONnT

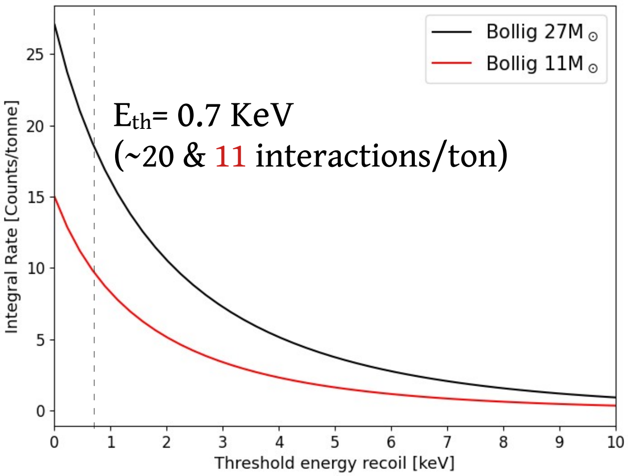
SN distance ⊗ 2D ν Flux ⊗ σ (CEVNS)

$$N_{th} = \sum_{i}^{\nu_e,\bar{\nu}_e,\nu_x} \boxed{\frac{1}{4\pi d^2}} \int_{t_1}^{t_2} \int_{E_{min}} \int_{E_{R_{th}}}^{E_{R_{max}}} \boxed{\frac{dN}{dE_{\nu_i} dt} \frac{d\sigma(E, E_R)}{dE_R}} dE dE_R dt$$

(*$x = \mu, \bar{\mu}, \tau, \bar{\tau}$)

- Time evolution of the signal allows background discrimination (**S2-Only**).
- 3 phases : ***Neutronisation*** (0-0.05s), ***Acretion*** (0.05-1s), ***Cooling*** (1-10s)
- Around **45 %** of the events are expected to be observed in the **first second.**

Number of interactions as a function of recoil energy threshold



E_{th}= 0.7 KeV
(~20 & 11 interactions/ton)

CCSN CEνNS signal in XENONnT

SN distance ⊗ 2D ν Flux ⊗ σ (CEVNS)

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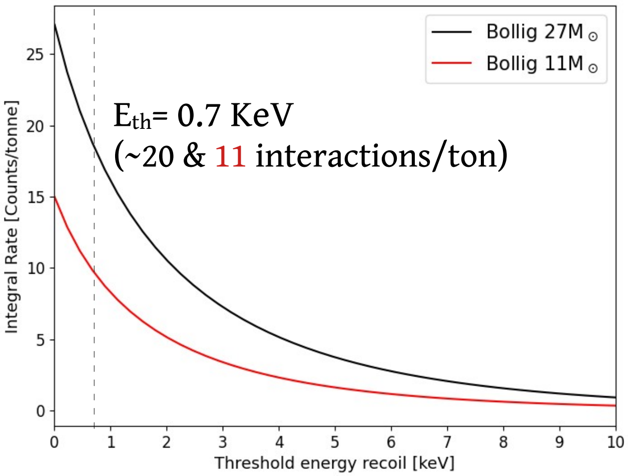
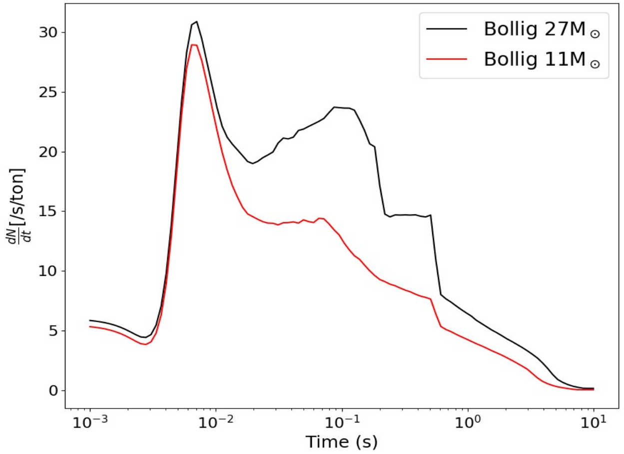
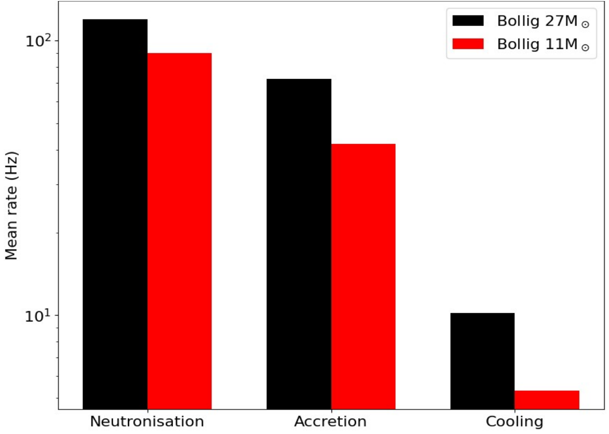


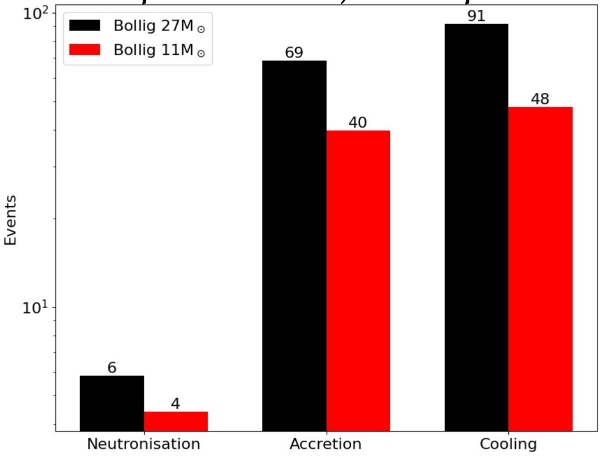
CCSN Rate Time evolution



Mean Rates for each phase



Expected events for each phase

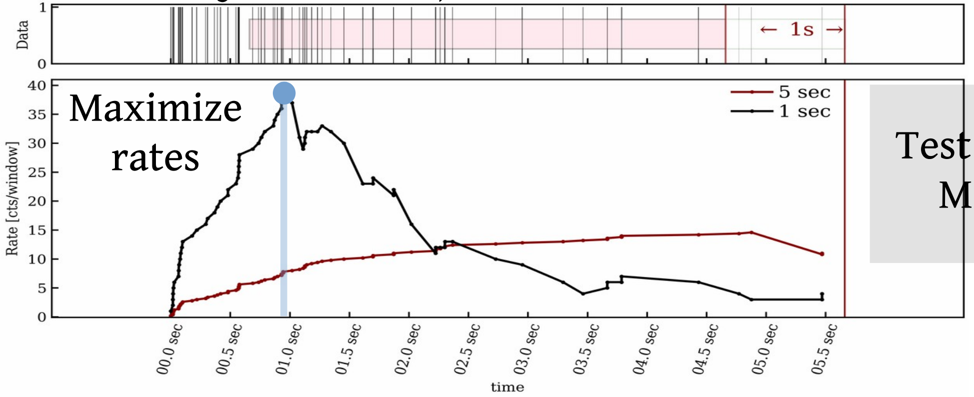


CCSN CEνNS signal simulation

Use time evolution of the CCSN ν burst can be used

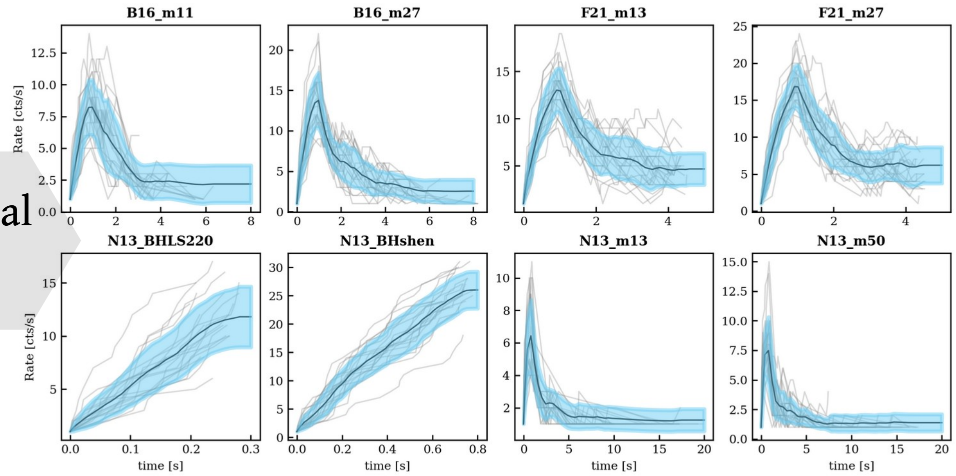
@MelihKara_SNVD_2023

CCSN Rolling window rates for 1s and 5s window



Maximize rates

Test several Models



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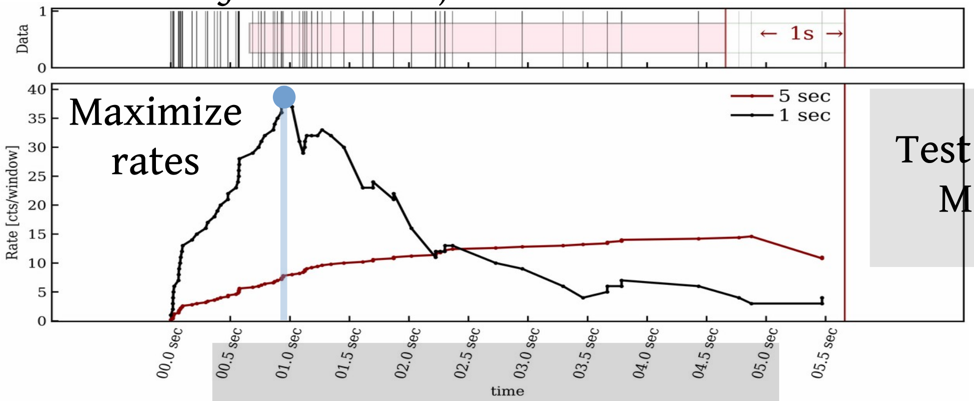

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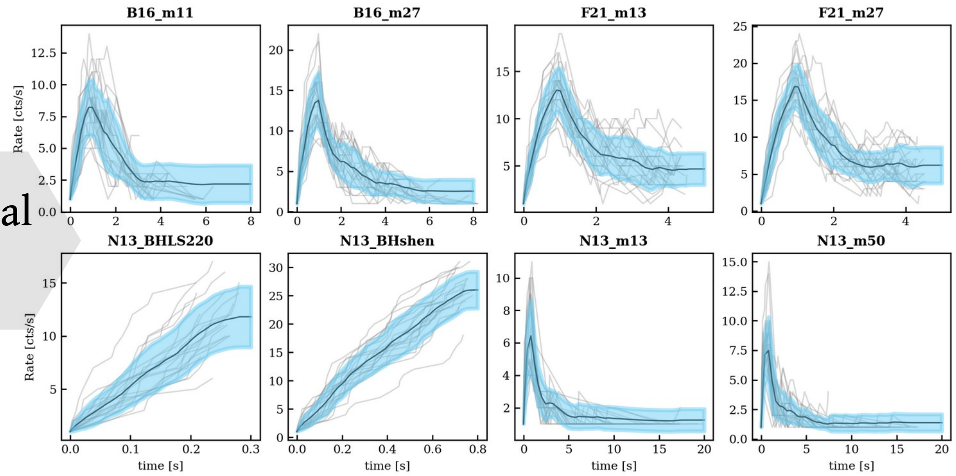

Selecting CCSN peaks and Identifying the signal

- ➢ Study the peak-rate evolution after cuts
  - Low energy recoil ROI
  - Inner detector volume (less wall background)
- ➢ Look for short-time increases in peak rate evolution

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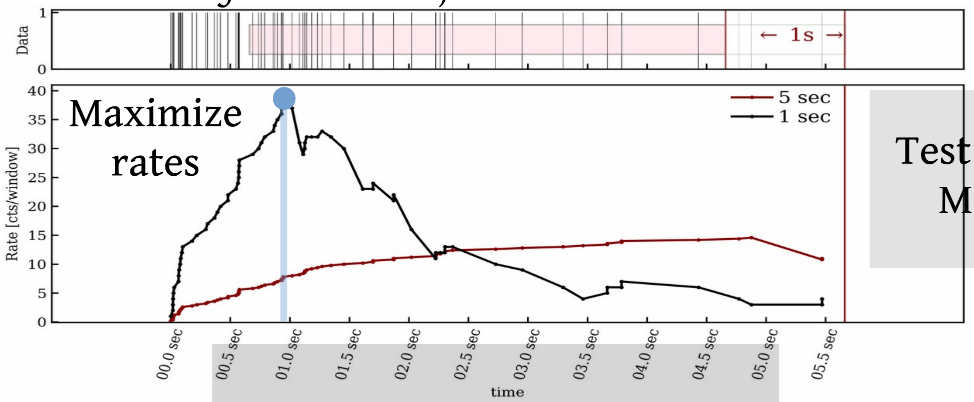

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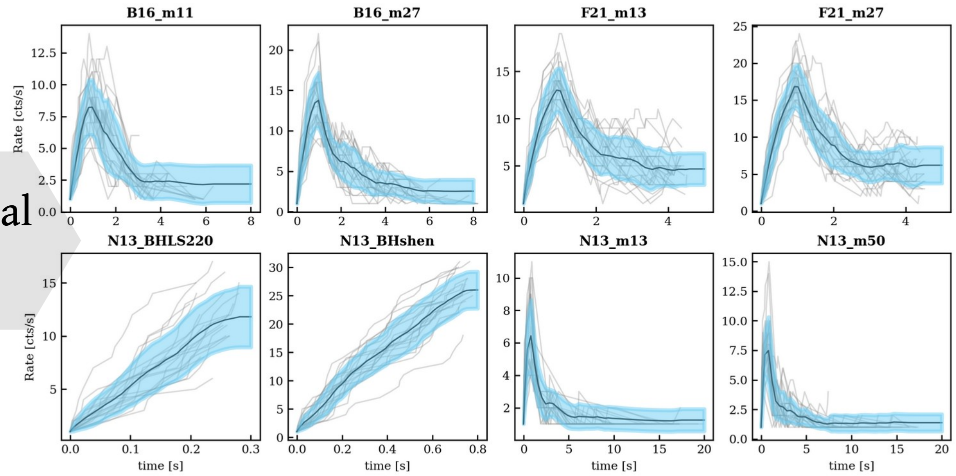

Selecting CCSN peaks
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- ➢ Study the peak-rate evolution after cuts
  - Low energy recoil (ROI, S2-Only)
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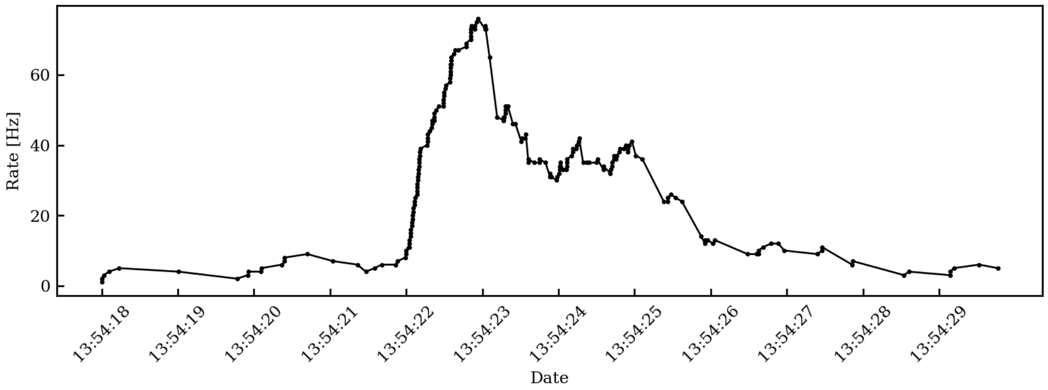
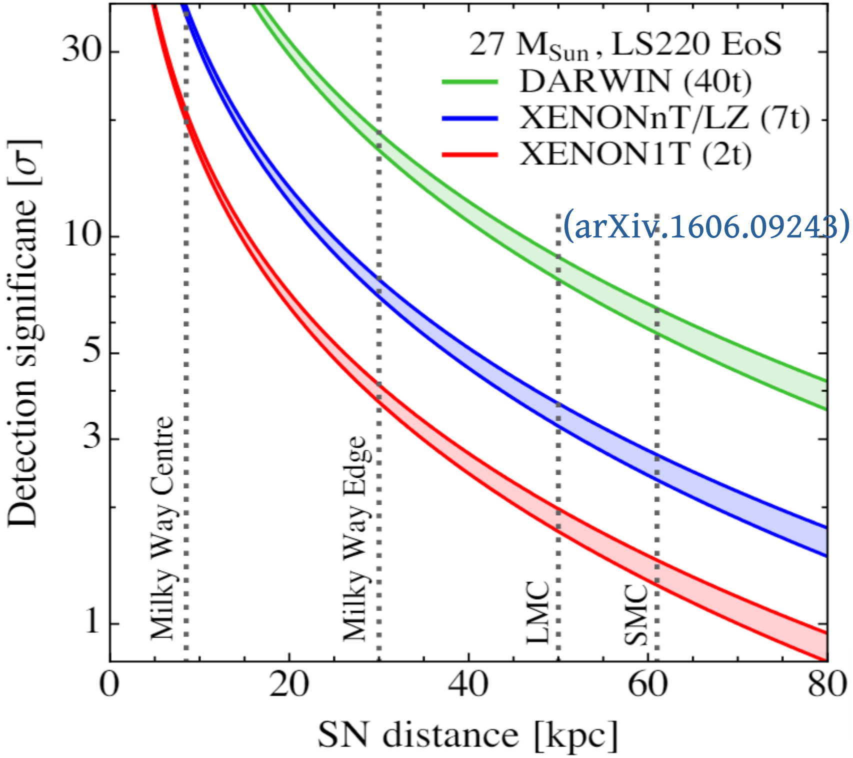
Rate evolution of the peaks surviving the selection cuts



CCSN Sensitivity in XENONnT



(arXiv.1606.09243)

- Results for 27M$_\odot$ from Bollig 2016 Model(Arxiv.1508.00785):
  - 5σ at 15 kpc in XENONnT
  - 5σ in the Milky way edge for DARWIN

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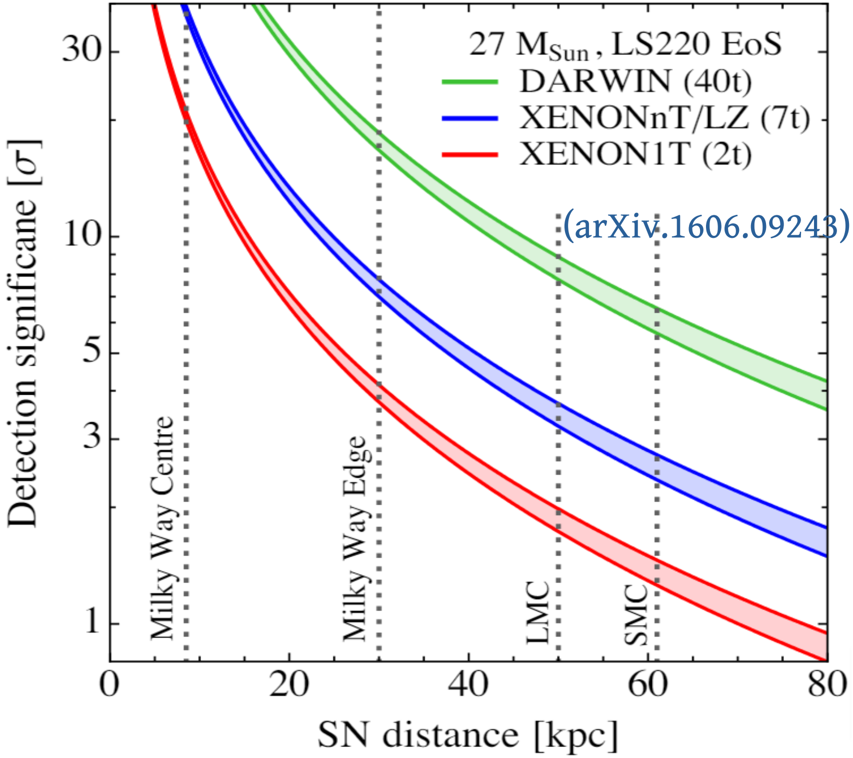

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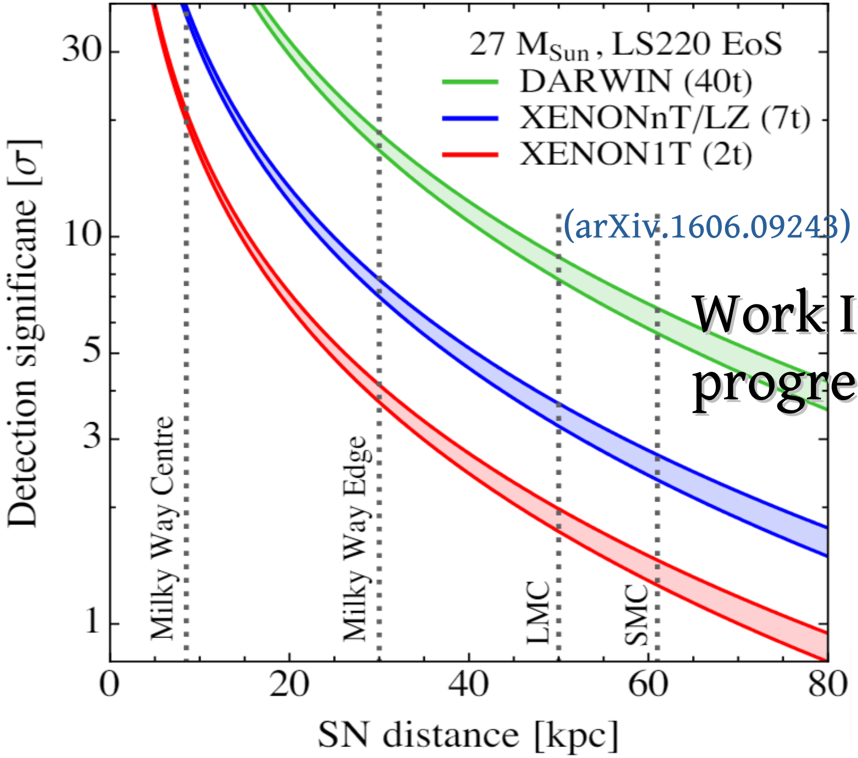
- ➢ Strongly impacted by CCSN flux uncertainities

CCSN Sensitivity in XENONnT



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Work In progress ...

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- ➢ **CEVNS TPC** sensitivity can be combined with the neutron and muon **Veto IBD** induced by CCSN $\bar{\nu}_e$:
  - **Muon Veto (~645 tonnes) :**
    - ➔ 83 events (after background cuts) at least expected at 10 kpc with > 4σ
  - **Neutron Veto (~55 tonnes)**
    - ➔ 12 events with high significance(>50σ) at 10 kpc

- ➢ **SNEWS**
  - False/True CCSN rate
  - CCSN Trigger for sending online Alarms

Thank you !

Back up

CCSN SNEWS Communications & Software Trigger

SNEWS
SUPERNOVA EARLY WARNING SYSTEM

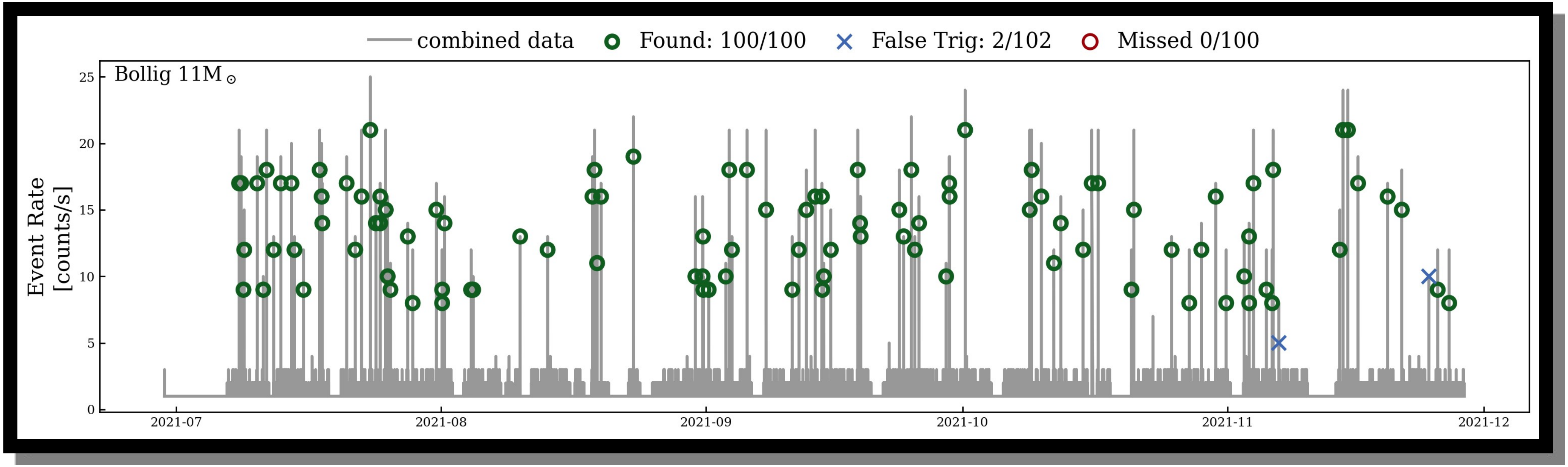
SNEWS-Comm

Heartbeat pinging

Listening incoming alerts

Sending possible observations

- We can already listen SNEWS and send ON/OFF heartbeats
- These scripts for monitoring and triggering can be deployed to a machine at LNGS
- Software Trigger needs further tuning

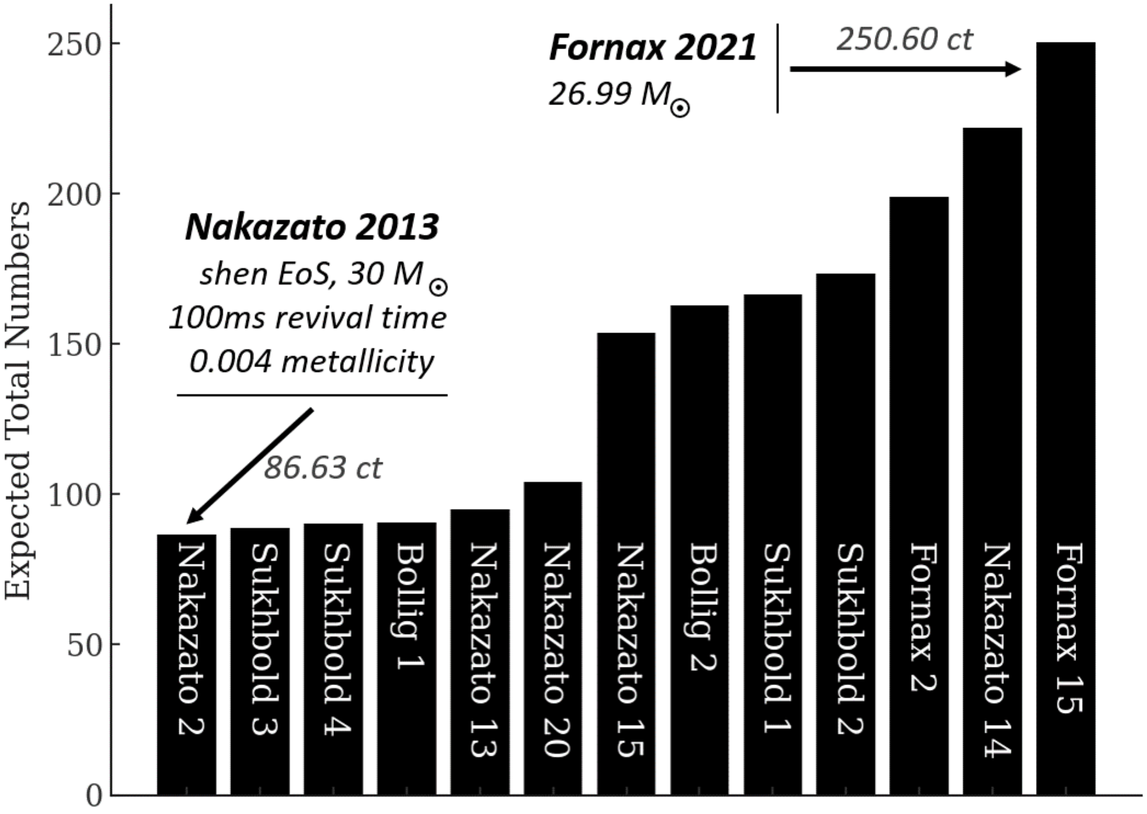


CCSN CEVNS Number of Expected interactions for different Models

CCSN neutrino flux uncertainities are high related to :

- The transport inside the SN environment (MSW effect, neutrino self-induced flavor oscillation)
- SN collapse physics
- A significant amount of CCSN Models...

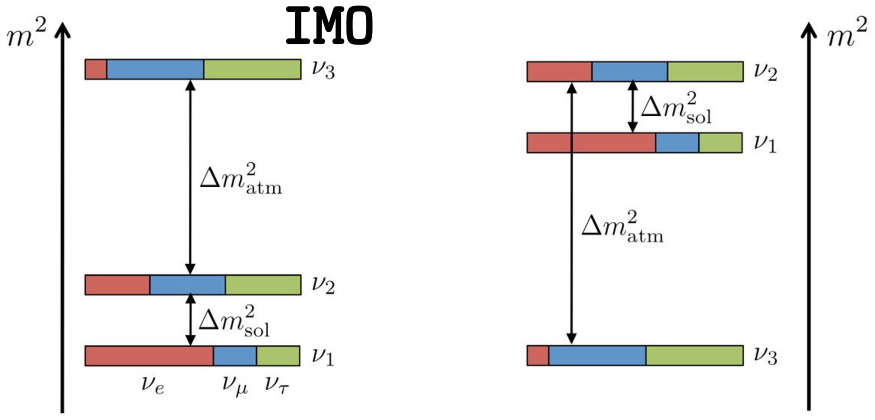
Expected total interactions for different models at 10 kpc
Assuming 0 keV threshold, 100% detection efficiency



CCSN IBD Observable Neutrino Spectrum

As SN progenitors >1kpc, observable ν oscillation effects are related to the **mass ordering : Normal NMO** or **Inverted IMO,** assuming that **neutrino self-interactions** are already accounted in CCSN Model Spectrum:

NMO **IMO**



2D Observable Spectrum

$$\frac{dN_{\bar{e}}}{dtdE_{\bar{e}}}_{\oplus} = \underbrace{\frac{1}{4\pi d^2}} \left(P_{\bar{\nu}_e\bar{\nu}_e} \frac{dN_{\bar{e}}}{dtdE_{\bar{e}}} + P_{\bar{\nu}_x\bar{\nu}_e} \frac{dN_{\bar{x}}}{dtdE_{\bar{x}}} \right)$$

d : distance

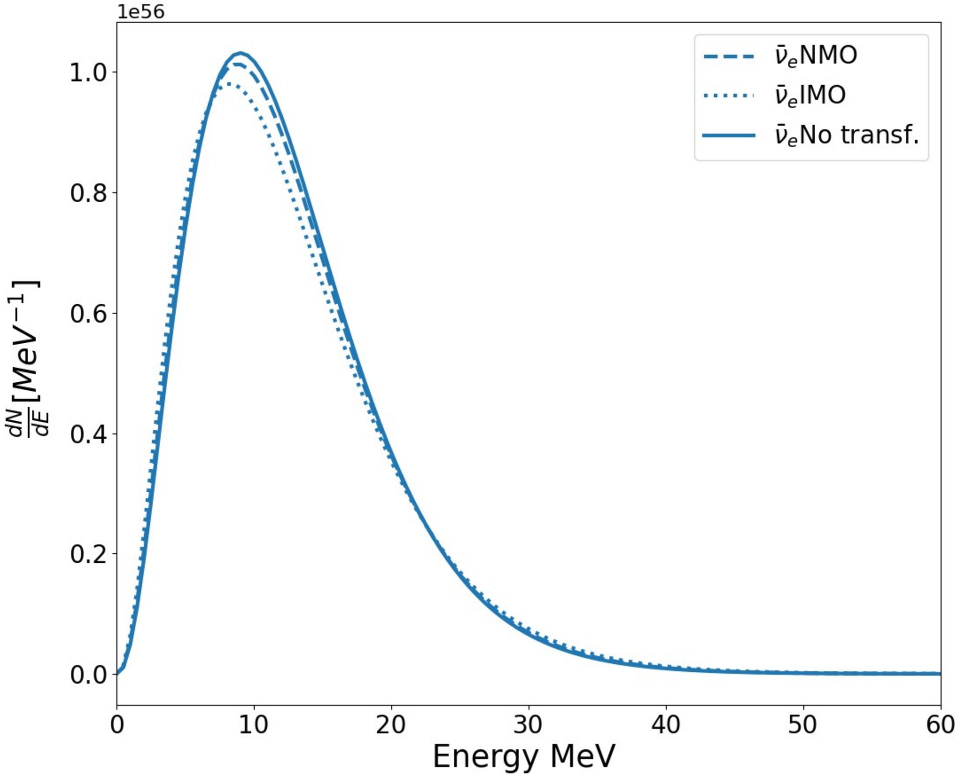
NMO $P_{\bar{\nu}_e\bar{\nu}_e} = cos^2\theta_{12}cos^2\theta_{13}$

$P_{\bar{\nu}_e\bar{\nu}_x} = 1 - P_{\bar{\nu}_e\bar{\nu}_e}$ $P_{\bar{\nu}_x\bar{\nu}_e} = \frac{1}{2}P_{\bar{\nu}_e\bar{\nu}_x}$

IMO $P_{\bar{\nu}_e\bar{\nu}_e} = sin^2\theta_{13}$

$P_{\bar{\nu}_x\bar{\nu}_x} = \frac{1}{2}(1 + P_{\bar{\nu}_e\bar{\nu}_e})$

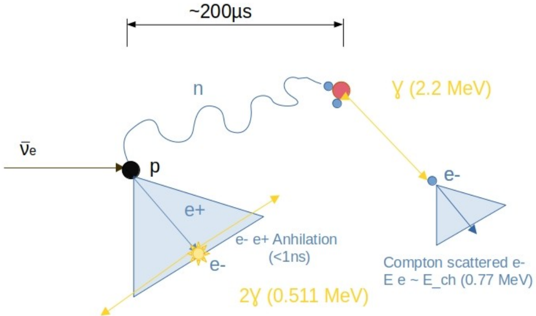
Initial differential Energy time integrated spectrum for IBD or NMO and IMO



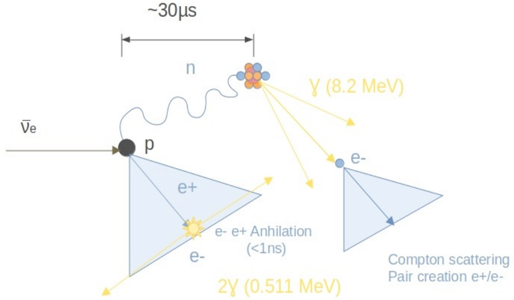
CCSN IBD Expectations in XENONnT Water Tank

2 Configurations (Water and **Gd** doped Water) into 2 Different detectors (**Muon** and **Neutron Vetos)**

1. Pure Water



2. Water with Gd 0.02 % (ϵ~ 90 %)

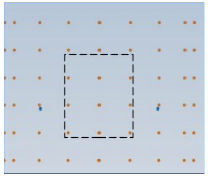


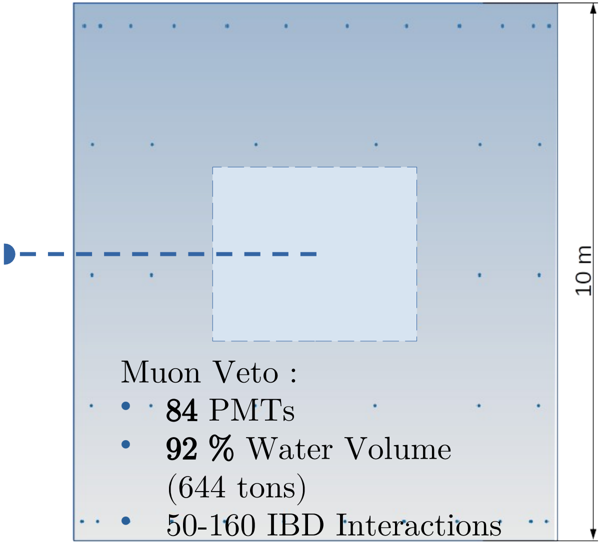
Neutron capture, particularly in Gd Water configuration contimates Positron signal. This Gd Capture has high acceptance in Neutron Veto.Neutron Capture in **Water not relevant** for **Muon Veto.**

Both detector surrounded by **reflectors**, that enhance **collection efficiency**

Neutron Veto :

- **120** PMTs
- **8 %** Water Volume (56 tons)
- 4-14 IBD Interactions

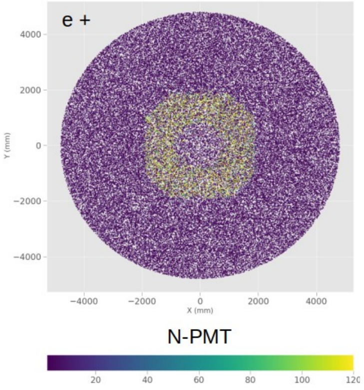


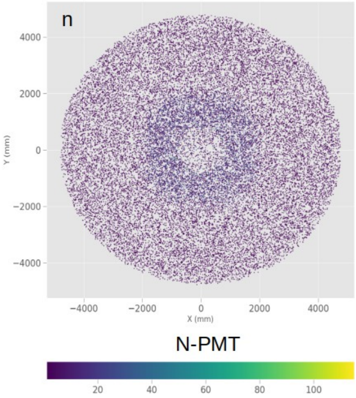


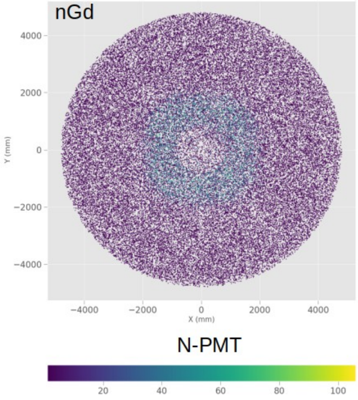
Muon Veto :

- **84** PMTs
- **92 %** Water Volume (644 tons)
- 50-160 IBD Interactions

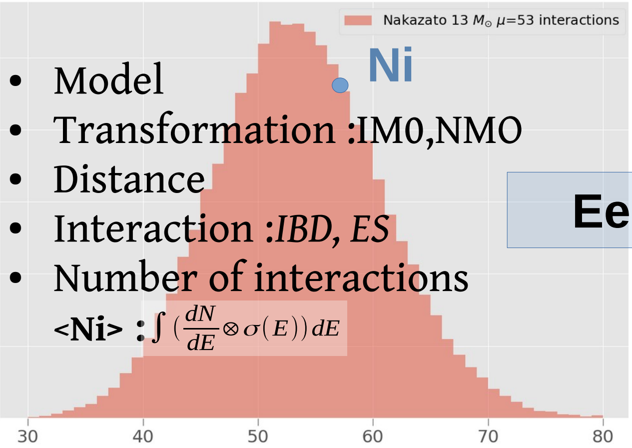
- We expect **high signifiance** for neutron Veto due to high PMT coverage, but **few events** d **<20Kpc.**
- Muon Veto can cover large distances but we expect less significance







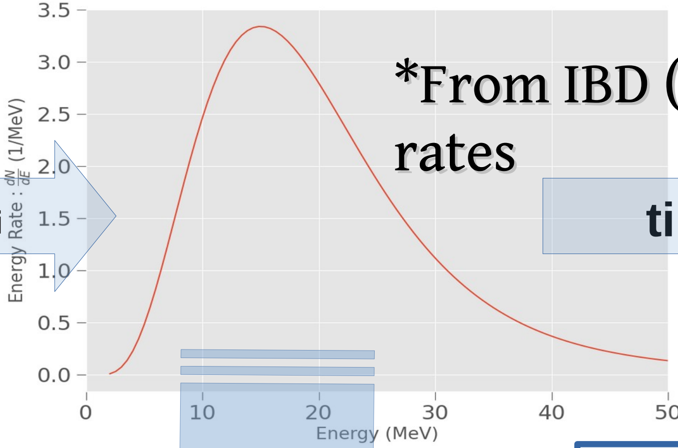
CCSN IBD SImulation in XENONnT Water Tank



- Model
- Transformation :IM0,NMO
- Distance
- Interaction :*IBD, ES*
- Number of interactions

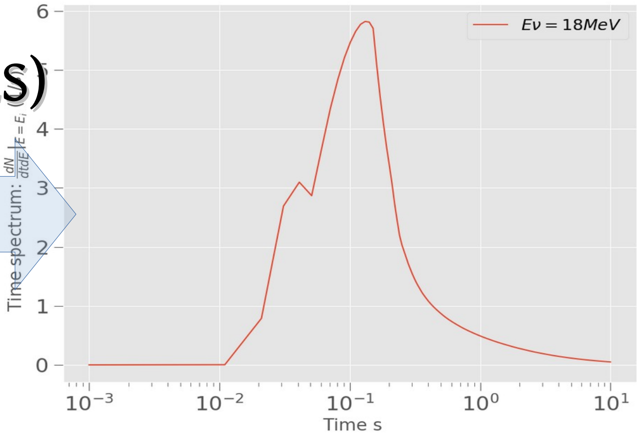
<Ni> : $\int (\frac{dN}{dE} \otimes \sigma(E))dE$

Eei



*From IBD (ES) rates

ti



GEANT4 Generator :

- **Mono-energetic $e^{+(-)}$, or n** in the IBD(ES) energy range
- Detection efficiencies
- Reconstruction of Energy Spectrum
  for each Model

Data digitalisation of GEANT4 ‘PMThits’

`‘hitlets_mv(nv)’`

`‘events_mv(nv)’`

- **Energy of $\overline{\nu}_e$, $e^{+(-)}$, n**
- **Detection efficiences**
- **Signal distributions and ROI**
- **And time …**