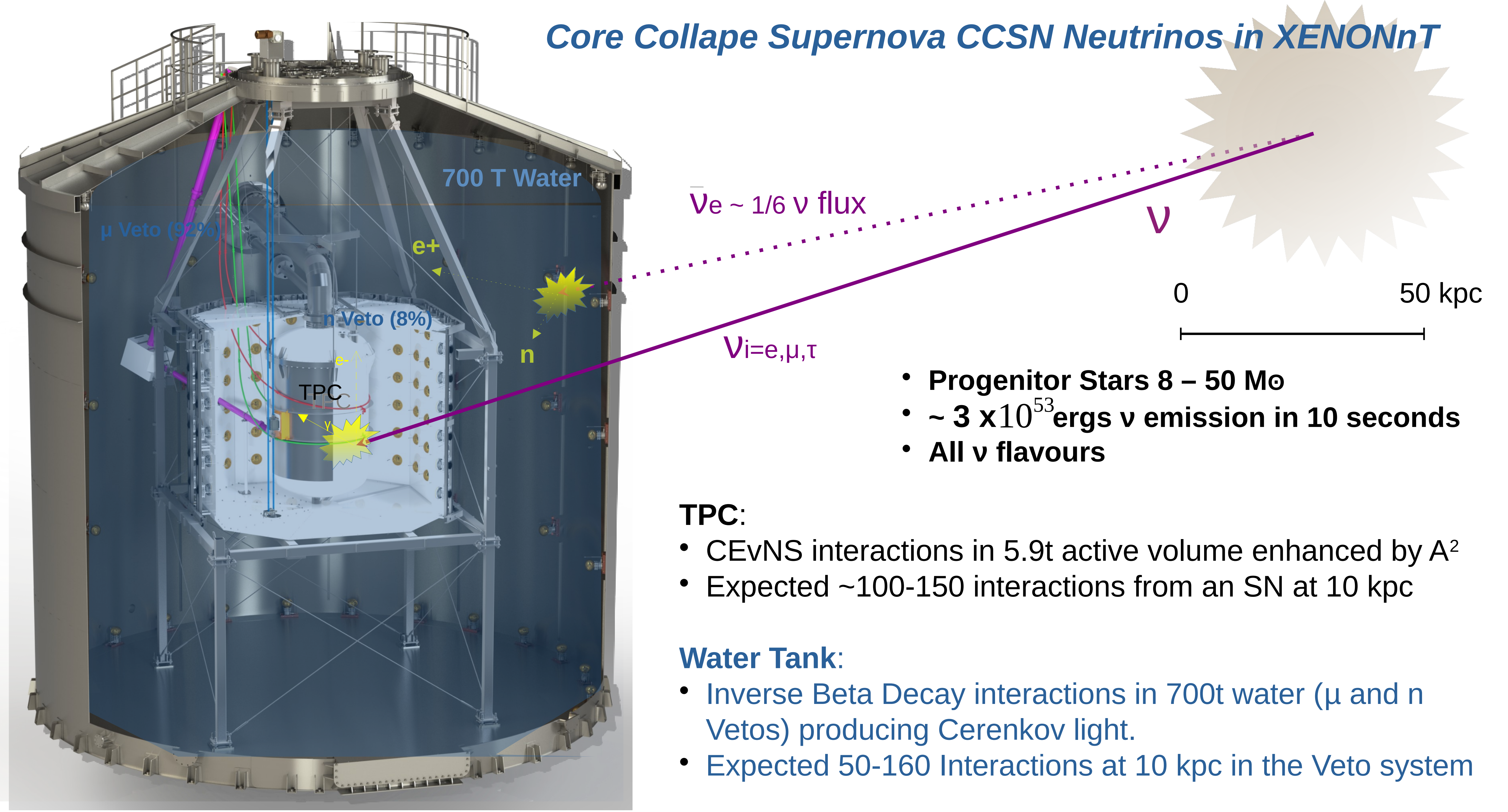
Core Collapse Supernova Neutrinos in XENONnT

Layos Daniel
LPNHE
layos.daniel@in2p3.lpnhe.fr

Melhi Kara
KIT
melih.kara@kit.edu

DMLab Meeting *16-17 /11/2023*

Core Collape Supernova CCSN Neutrinos in XENONnT



- **Progenitor Stars 8 – 50 M⊙**
- **~ 3 x10^{53}ergs ν emission in 10 seconds**
- **All ν flavours**

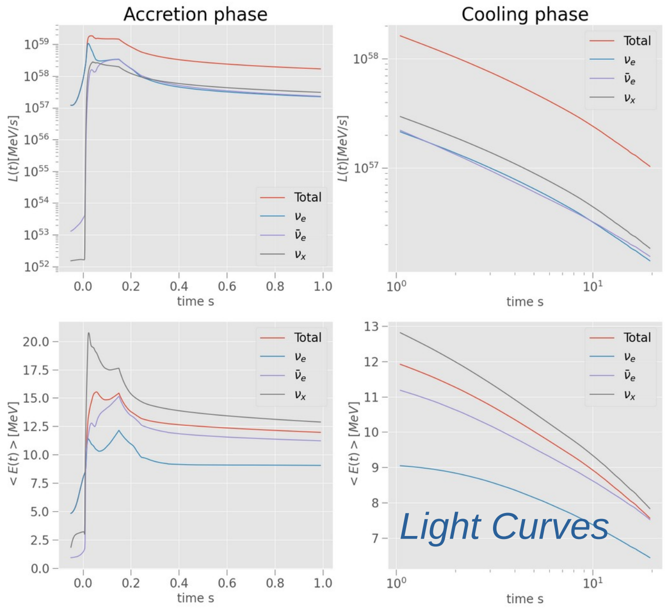
TPC:
- CEvNS interactions in 5.9t active volume enhanced by A^2
- Expected ~100-150 interactions from an SN at 10 kpc

Water Tank:
- Inverse Beta Decay interactions in 700t water (μ and n Vetos) producing Cerenkov light.
- Expected 50-160 Interactions at 10 kpc in the Veto system

CCSN Neutrino Flux and Models

SNEWPY, Astrophys.J. 925 (2022) 2

SN Flux Models are an interpolation of two phases during neutrino emission



Accretion [0, 1 s]:

- 0 - 0.05 s: ν_e
- 0.05 - 1 s: $\bar{\nu}_e$, ν_x

Cooling phase [1,10 s]

$\langle E_{\nu_e} \rangle \approx 12MeV$

$\langle E_{\bar{\nu}_e} \rangle \approx 14MeV$

$\langle E_{\nu_x} \rangle \approx 15$ MeV

$\langle \alpha \rangle$ [2, 3.5]

$N_{\nu_e} > N_{\bar{\nu}_e} > N_{\nu_x}$ with $x = \mu, \bar{\mu}, \tau, \bar{\tau}$

Neutrino Flux $$\frac{dN}{dEdt}_i = \frac{1}{4\pi d^2}\frac{L_\nu(t)_i}{< E_\nu(t)_i >}\Phi_i(E,t)\psi_i(t)$$

Neutrino energy distribution $$\Phi_i(E,t) = \frac{E^{\alpha(t)_i}}{< E_\nu(t)_i >^{\alpha(t)_i}} e^{-(\alpha(t)_i+1)\frac{E_\nu}{< E_\nu(t)_i >}}$$

Normalisation $$\psi_i(t) = \frac{1}{\int \Phi_i(E,t)dE}$$

- **d distance** of Supernovae
- **Luminosity** $L_{\nu_i}(t_{\text{pb}})$
- **Neutrino mean energy** $\langle E_{\nu_i}(t_{\text{pb}}) \rangle$
- **pinching parameter** $\alpha(t_{\text{pb}})$:

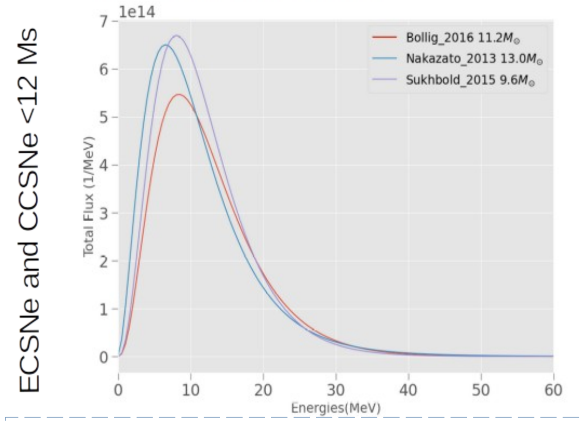
$$\alpha = \frac{\langle E_\nu^2(t_{\text{pb}})\rangle - 2\langle E_\nu(t_{\text{pb}})\rangle^2}{\langle E_\nu(t_{\text{pb}})\rangle^2 - \langle E_\nu^2(t_{\text{pb}})\rangle}$$

+ Transport effects :
- Oscillations
- MSW

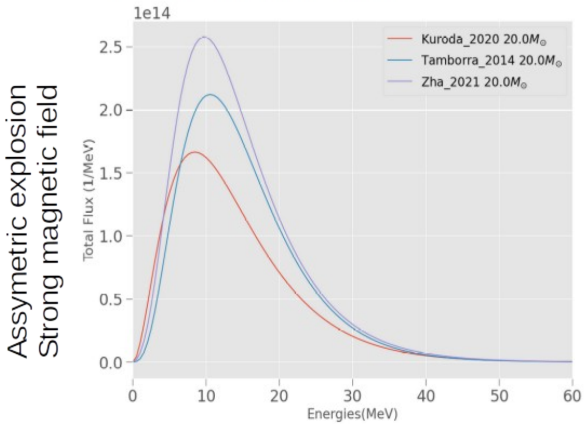
A Y Smirnov 2019

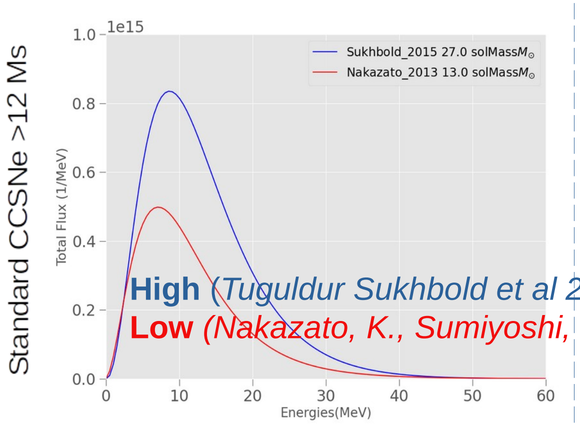
- **EOS** : LS 220, SHEN, BH…
- **Metallicity**: Solar (Z=0.02) and Small Magellanic Cloud SMC (Z=0.004)
- **Mass range** : 8-50 M⊙
- **Time burst** duration: 0.5 to 20 s

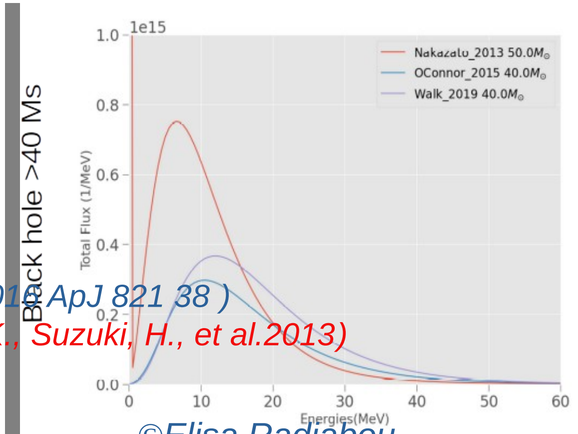
7 - 20 s neutrino burst



0 – 0.5 s neutrino burst





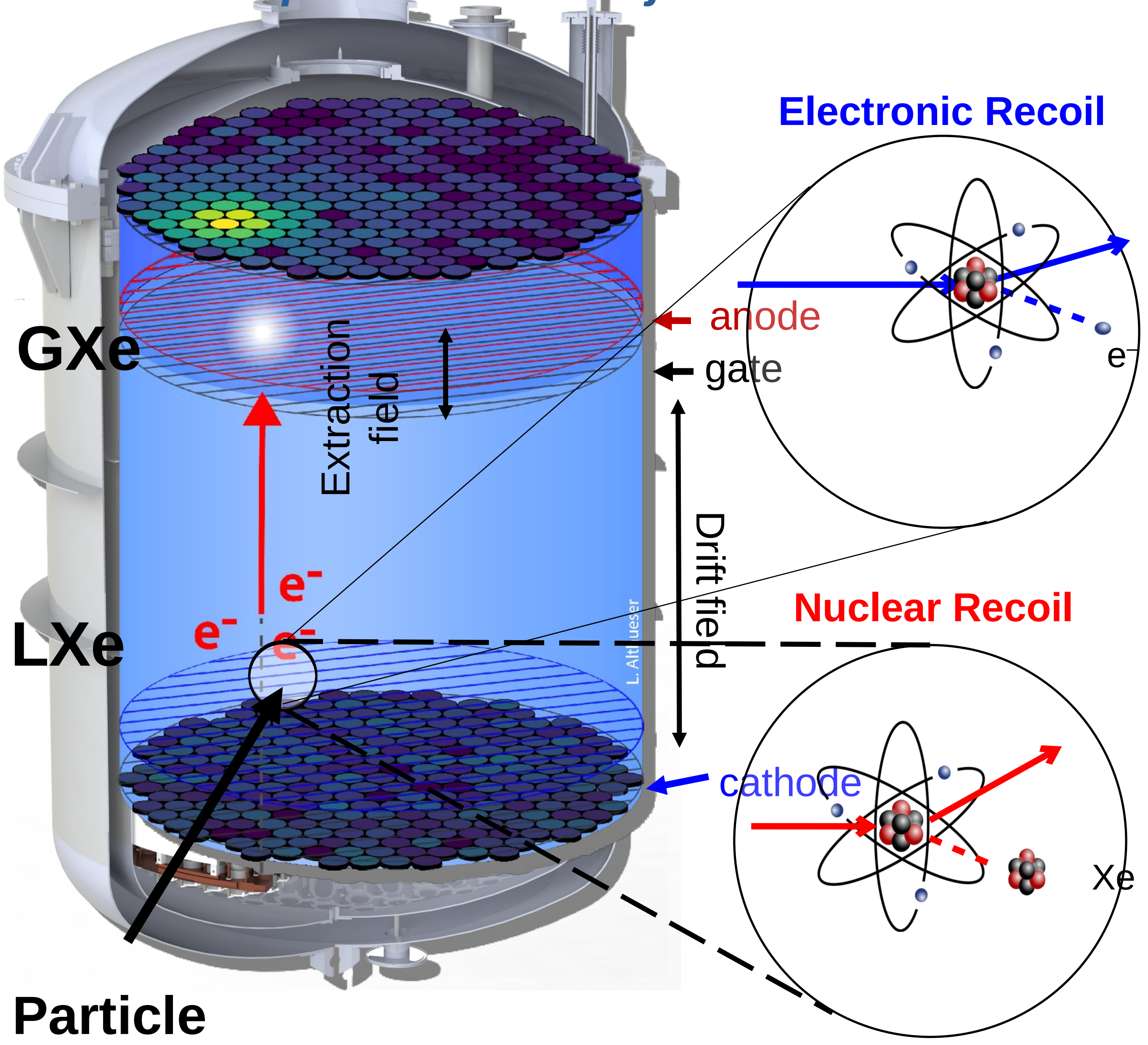


High *(Tuguldur Sukhbold et al 2016 ApJ 821 38)*

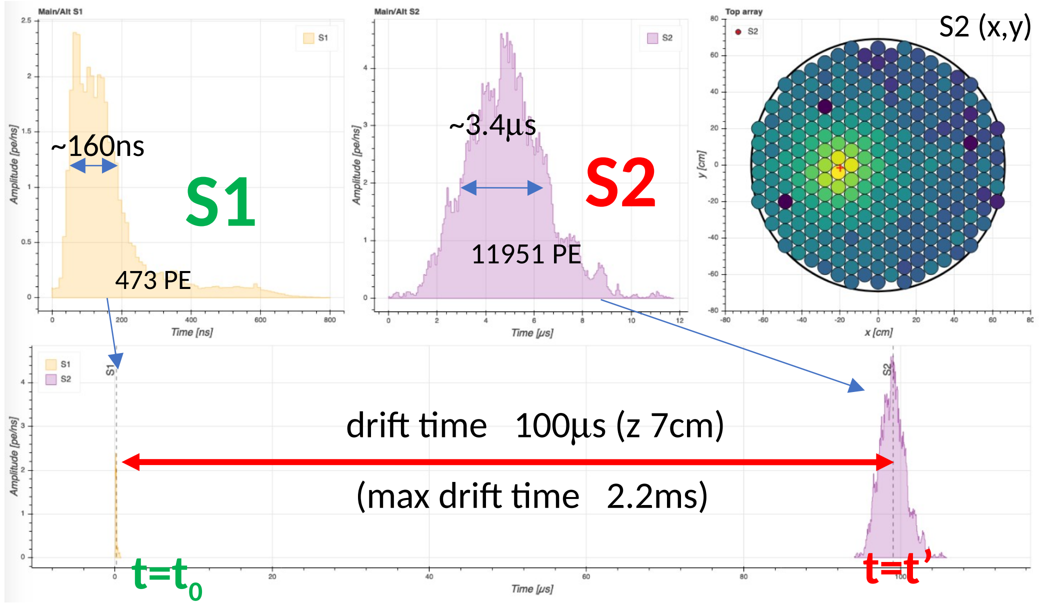
Low *(Nakazato, K., Sumiyoshi, K., Suzuki, H., et al.2013)*

©Elisa Radjabou
elisa.radjabou@gmail.com

CCSN Dual phase Time Projection Chamber TPC



ER: Beta, gamma, neutrinos
NR: WIMPs, neutrons, neutrinos (CEvNS)



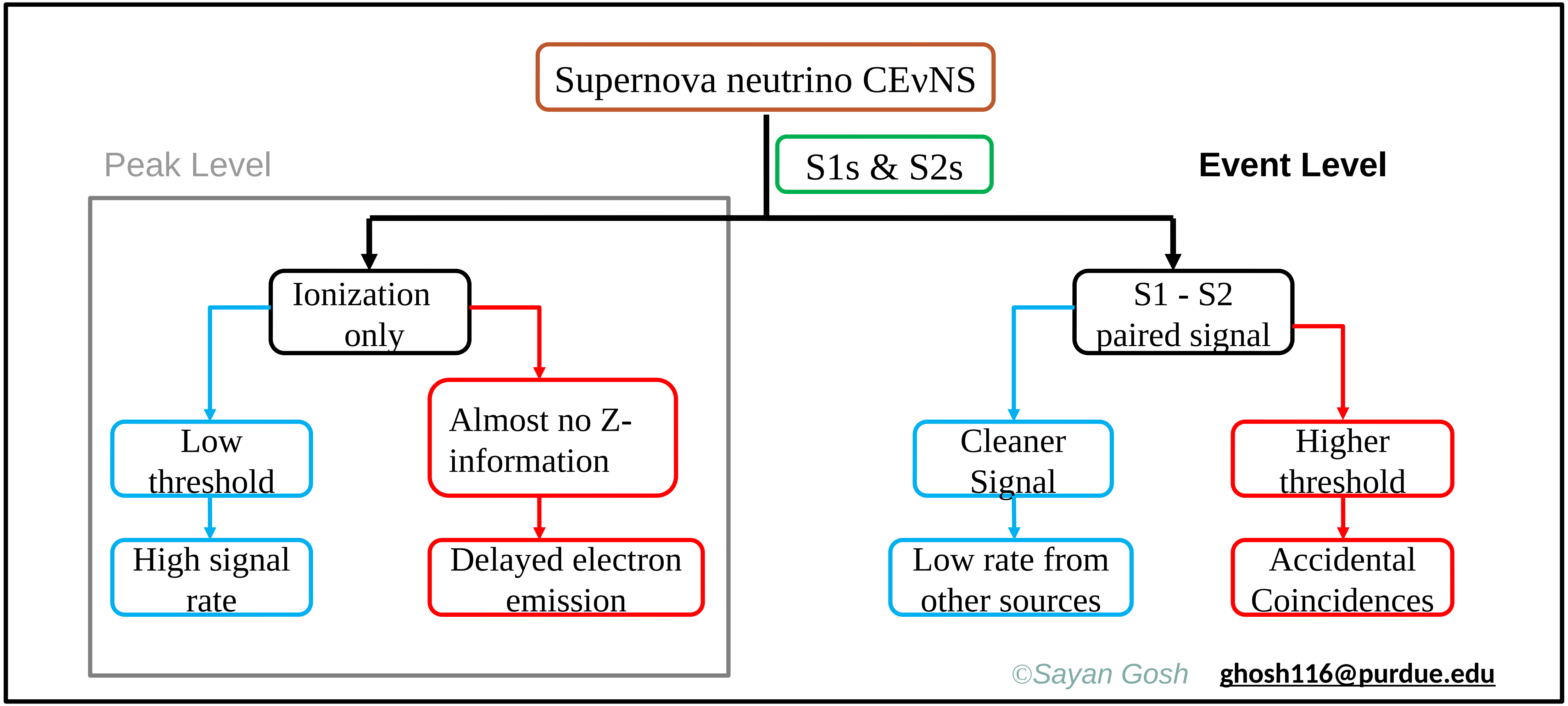
Prompt scintillation signal in LXe: S1
Proportional scintillation in GXe: S2

S1 Peak + S2 Peak ⟶ Event

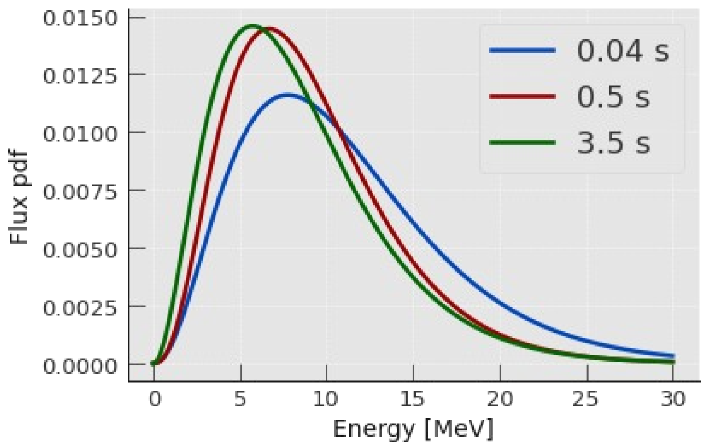
If the light yield is low (no S1), we can do an S2-only analysis

CCSN Dual phase Time Projection Chamber TPC Event and Peak Level

We can take advantage of the short signal of SN ν to discriminate it from background, and use only the **peak** corresponding to the **S2 signal** that is sensible to **lower recoils**, as expected from **CVNS** interaction.
This appraoch distinguish two different Level of analysis **Event Level** and **Peak Level.**



CCSN Simulation Chain CVNS Rates

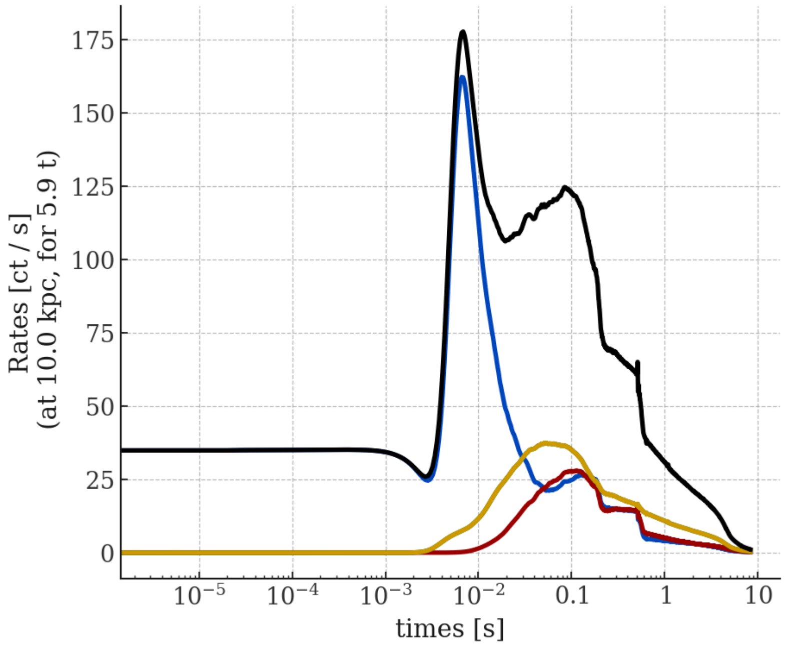


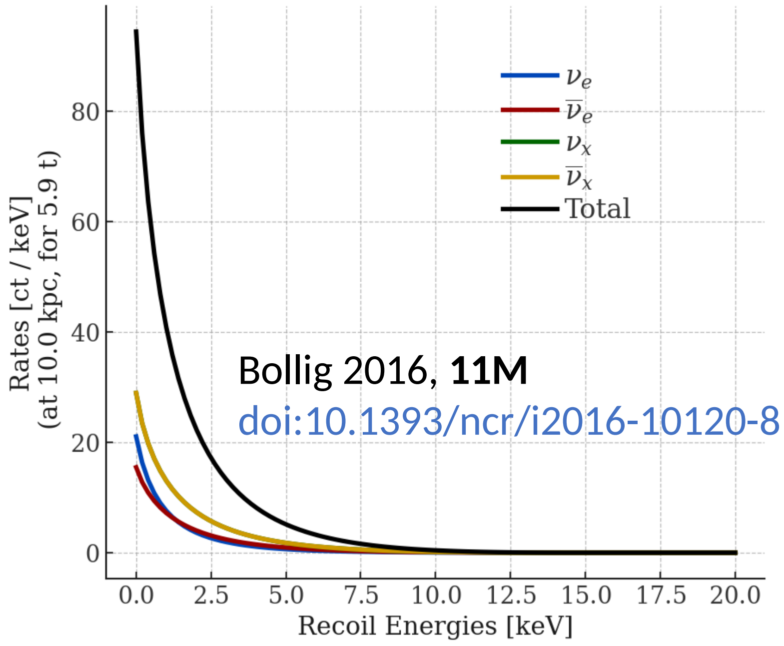
We use the physics driven supernova model fluxes from **SNEWPY**
This gives us time and energy distributions of all the flavors during the burst.

For the TPC we are flavor blind as all flavors scatter off of the nuclei in same way, spectrum is not affected by ν oscillations.

$$\frac{d^2 R}{dE_R dt_{pb}} = \sum_{\nu_\beta} N_{Xe} \int_{E^{\nu}_{min}} dE_\nu \; f_\nu(E_\nu, t, d) \; \frac{d\sigma}{dE_R}(E_\nu, E_r)$$

GitHub SNEWPY | GitHub SNAX | GitHub WFSIM





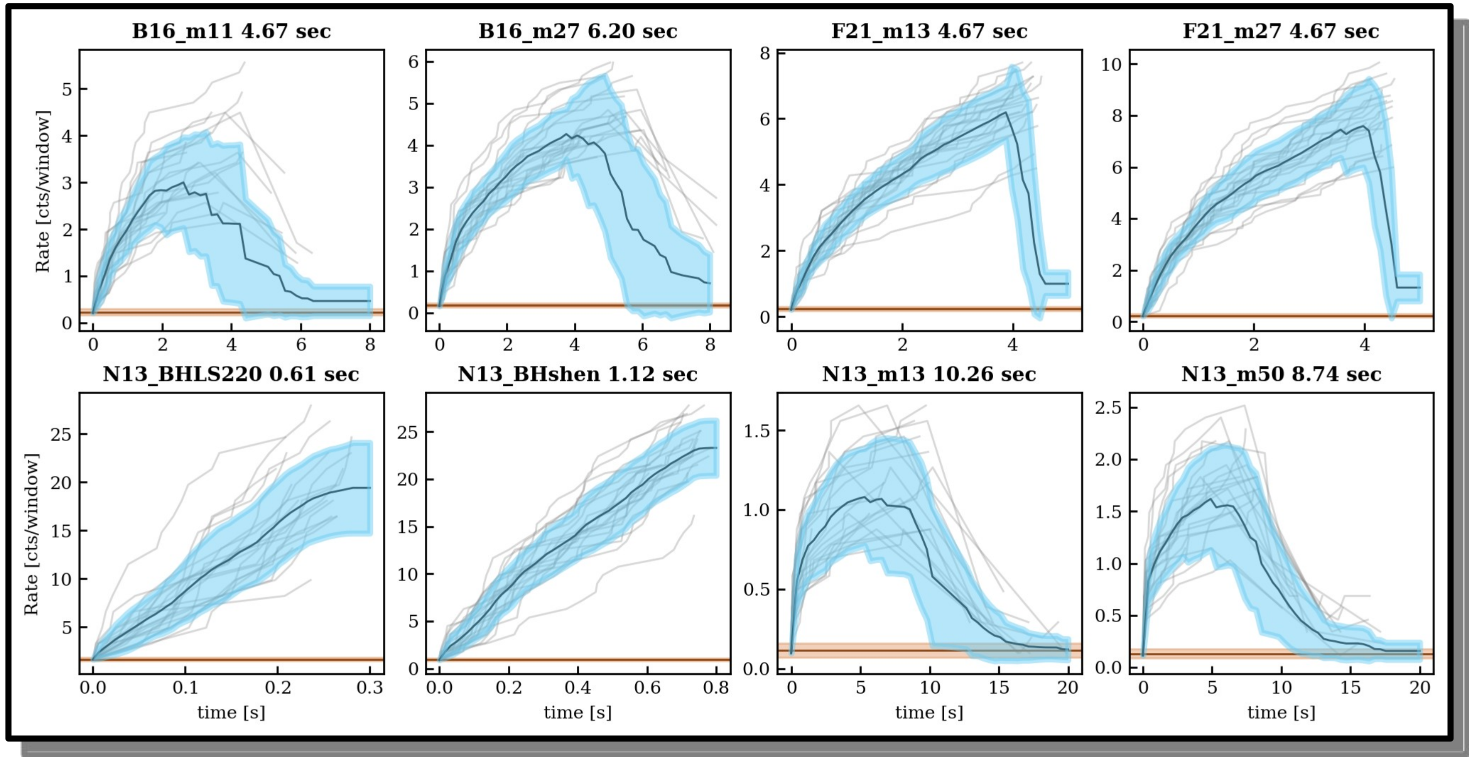
Interactions with Xe target is investigated using **SNAX** package to compute expected ***recoil energies and interaction times***.

These interactions are then simulated using **WFSIM**.

CCSN TPC Simulation Chain Time Signal

The steps for the analysis.

- Simulate the detector signal for 8 models and many times.
- Look at the ***count rates*** after applying some selection.
- Compare the rate increase against the background fluctuation in a short, rolling time window.
- Assess the likelihood of upward background fluctuation and assign a detection significance.



Cleaner background = better detection of the supernova signal.

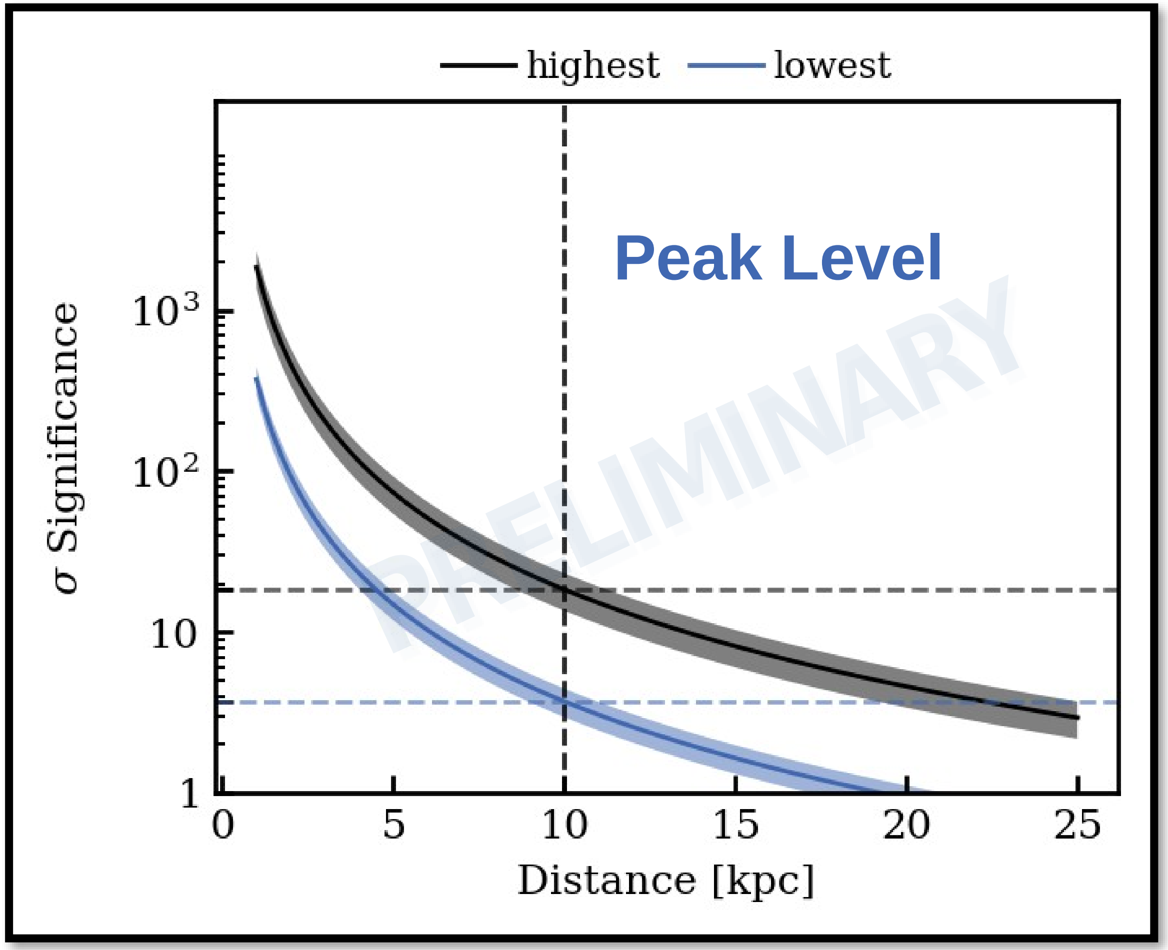
For the TPC we can do both **PEAK level** and **EVENT leve**l analysis.

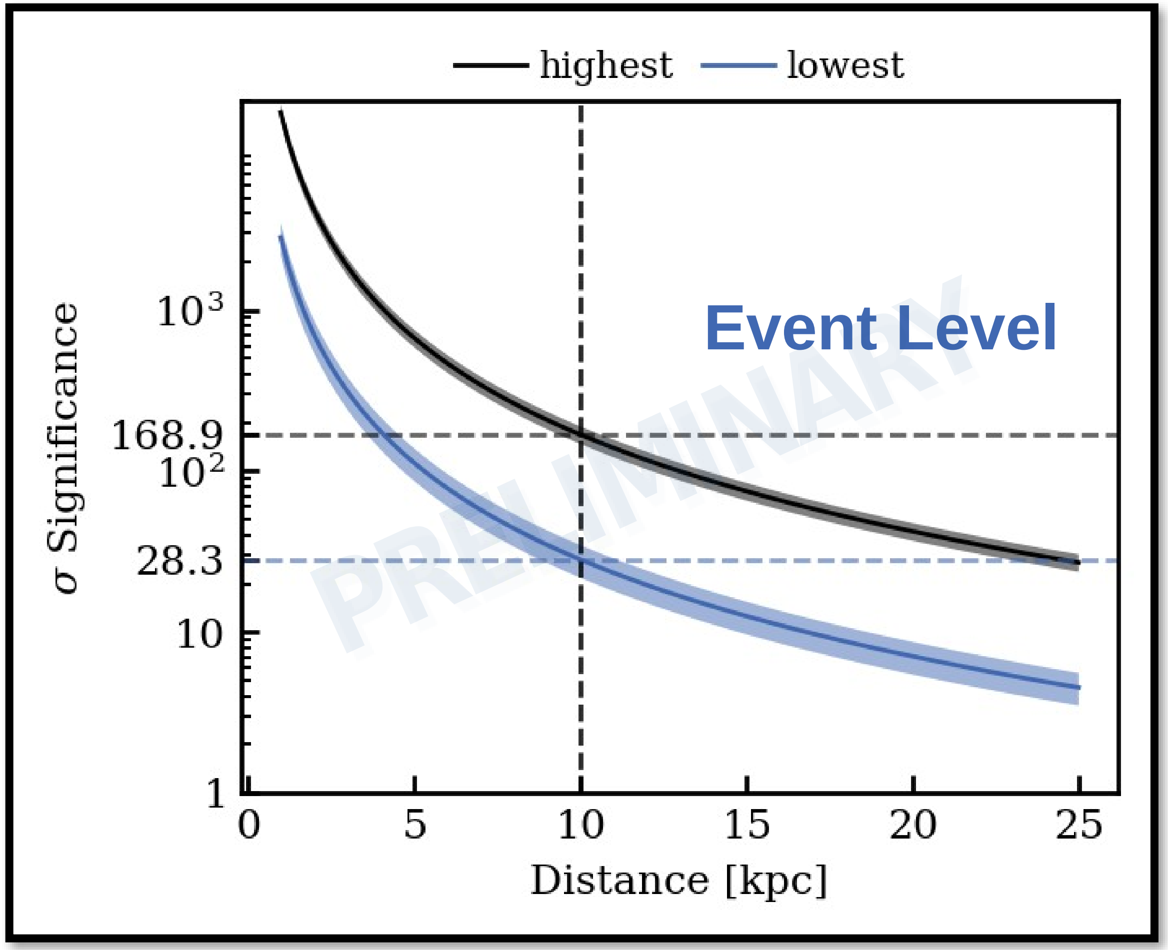
- Track the **increase in rate of all peaks**, or
- **Build events from the peaks** and track the increase in the **rate of events**

XENONnT TPC has ultra low background in the low energy nuclear recoil region.
Therefore, **events are easier to trace.**

CCSN Simulation Chain Events and Peaks

Signifiance Curves for a given SN distance for Peak and event level Analysis.
The bands corresponds to background uncertaineties.





~100 Peaks 3.7 σ at 10 kpc

Highest Fornax 2021 27 M⊙ *Fornax 2021, 2019*
Lowest Nakazato 2013 M⊙ *Nakazato 2013*

CCSN SNEWS Communications & Software Trigger

SNEWS
SUPERNOVA EARLY WARNING SYSTEM

GitHub
SNEWS-Comm

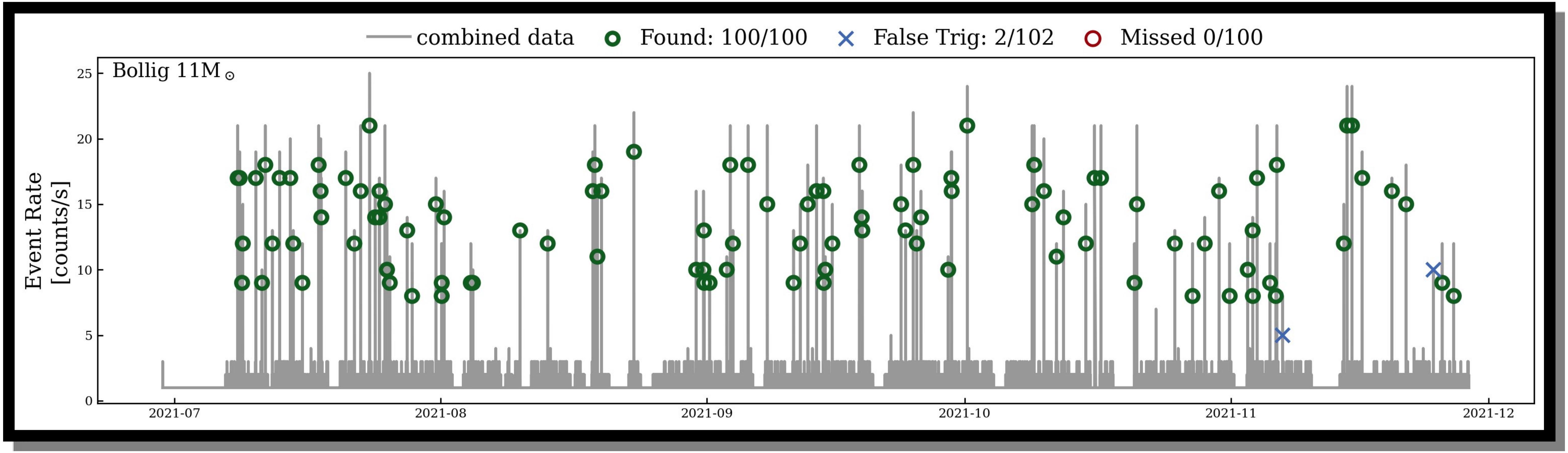
docker

Heartbeat pinging

Listening incoming alerts

Sending possible observations

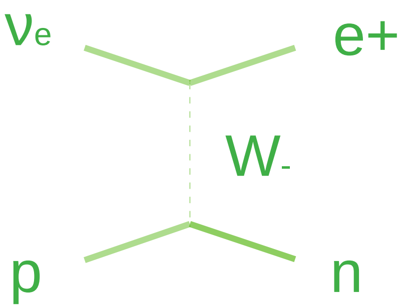
- We can already listen SNEWS and send ON/OFF heartbeats
- These scripts for monitoring and triggering can be deployed to a machine at LNGS
- Software Trigger needs further tuning



CCSN Interactions in XENONnT Water Tank

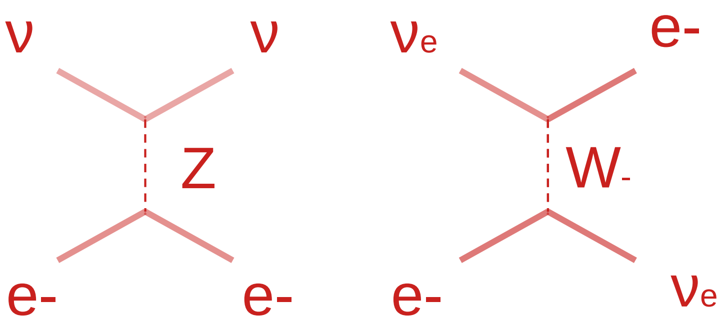
Interactions leading to **Cerenkov light** production :
NC (ES) and CC (IBD + ES)

Inverse Beta Decay (**IBD**):



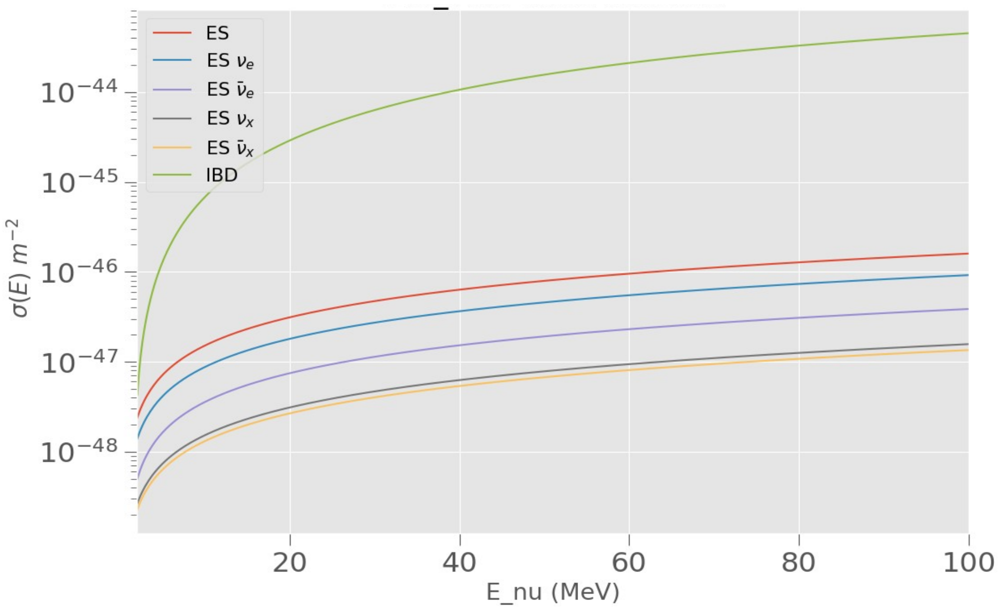
100 - 200 Interactions at 10 kpc
Sensible to 1/6 ν flux
Ee+ ~ Eν – 1.2 MeV
Directional information is lost…
(e+ emission is almost isotropic)
Neutron Capture signal

Neutrino electron elastic scattering (**ES**):

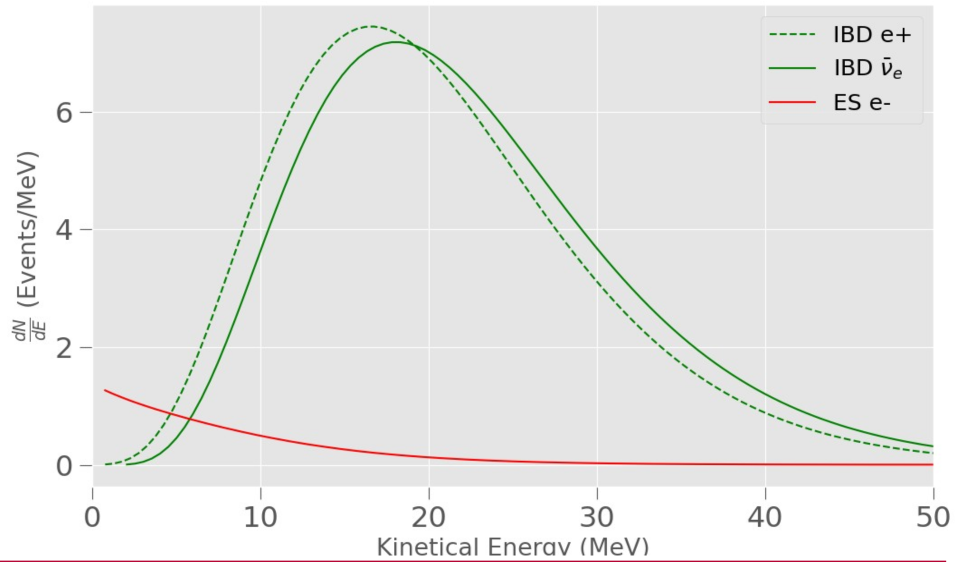


7 - 15 Interactions at 10 kpc
<Ee+> ~ 1.5 MeV
All flavors via NC
Directional information but not enough statistics

Water Tank dominant proces Cross Section



IBD e+, ν and ES e- Energy Spectrums



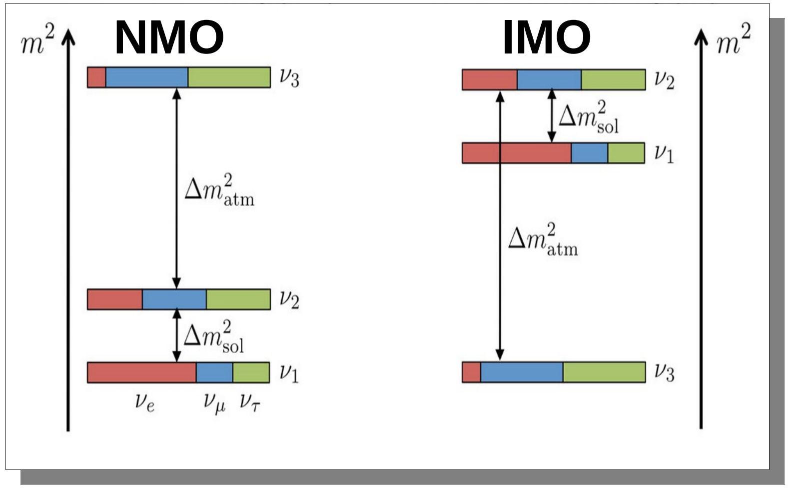
CCSN Inverse Beta Decay IBD

Detectable **Positron** Signal

$$\text{IBD threshold}: E_{\nu_{th}} = 1.806 \text{ MeV} \ll \langle E_\nu \rangle \ (\approx 18 MeV)$$

$$\text{e+ Cherenkov threshold } E_{ech_{th}} = 774 KeV \rightarrow \beta = \frac{1}{n_w} \qquad n_w = 1.33$$

IBD interaction is more sensible than CVNS to **ν mass states oscillations** as we consider **only νe** flavour.



As $\nu_\tau \approx \nu_\mu$ ($\bar{\nu}_\tau \approx \bar{\nu}_\mu$) and SN progenitors >1kpc, observable ν oscillation effects are finally related to the mass ordering hierarchy **(MO)** :

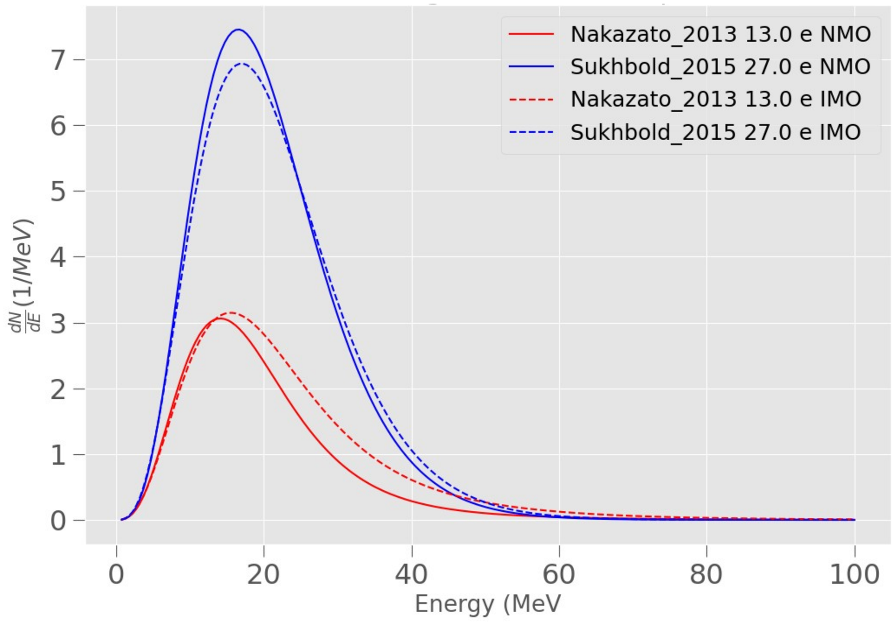
$$\frac{dN}{dtdE_{\bar{\nu}_e}} = \bar{p}_{ee} \frac{dN}{dtdE_{\bar{\nu}_e}} + \bar{p}_{xe} \frac{dN}{dtdE_{\bar{\nu}_x}}$$

2-Dimensional spectrum :

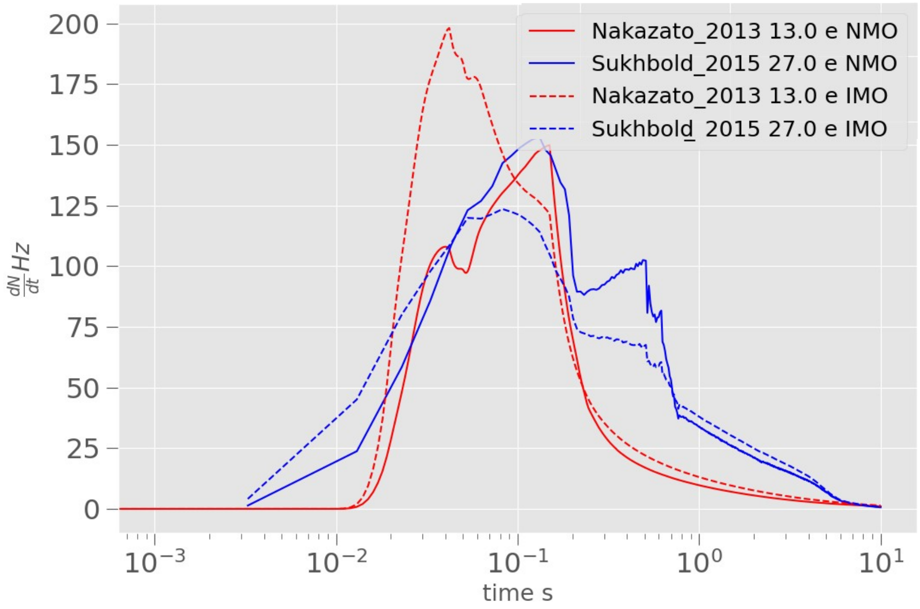
Time + Energy

$$\frac{dN}{dE_e dt}_{ibd} \propto \int_{E_{min}}^{E_{max}} \underbrace{\frac{dN}{dtdE_{\bar{\nu}_e}}}_{Time} \underbrace{\frac{d\sigma(E, E_e)}{dE_e}}_{Energy} dE$$

IBD Positron Energy spectrum



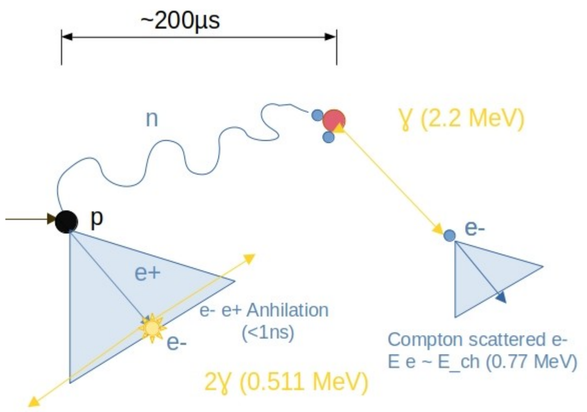
IBD Positron Time evolution rate



CCSN IBD Expectations in XENONnT Water Tank

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

Water



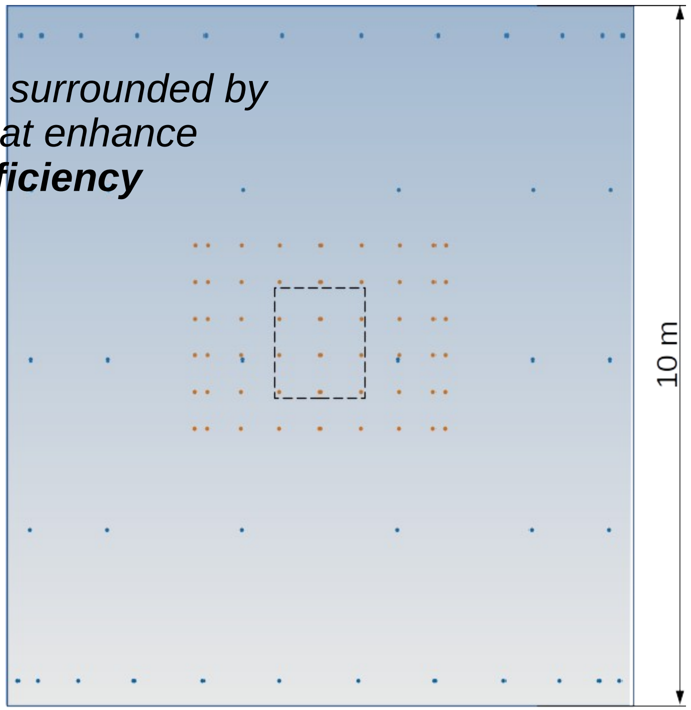
Muon Veto :

- **84** PMTs
- **92 % of 700T** Water Volume
- 50-160 IBD Interactions

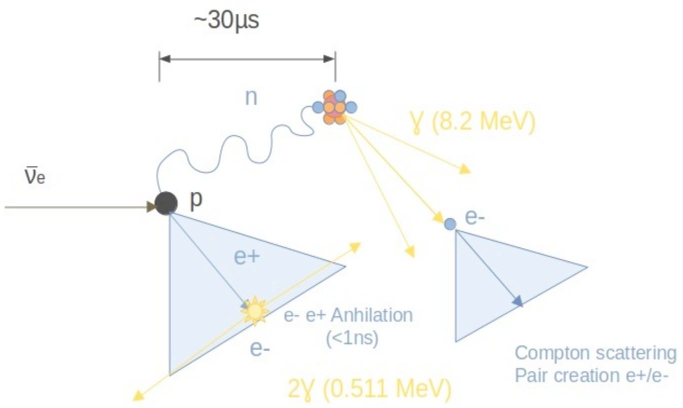
Neutron Veto :

- **120** PMTs
- **8 % of 700T** Water Volume
- 4-14 IBD Interactions

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

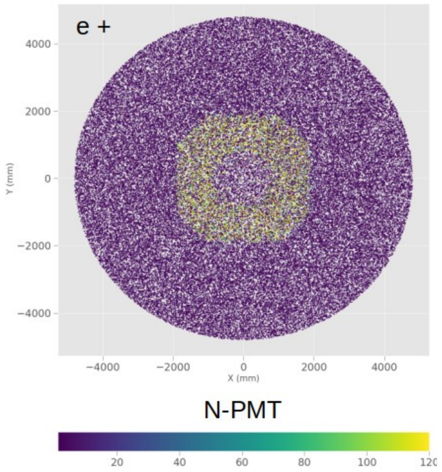


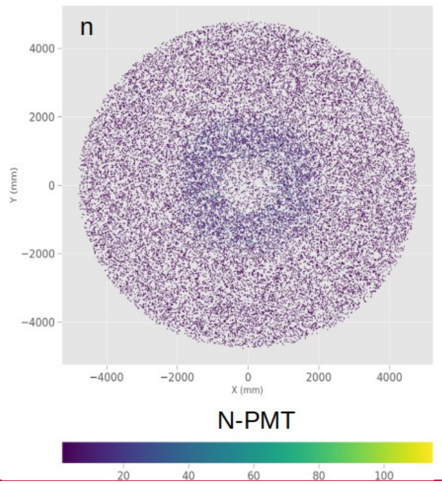
Water with Gd 0.2 % (ϵ~ 90 %)

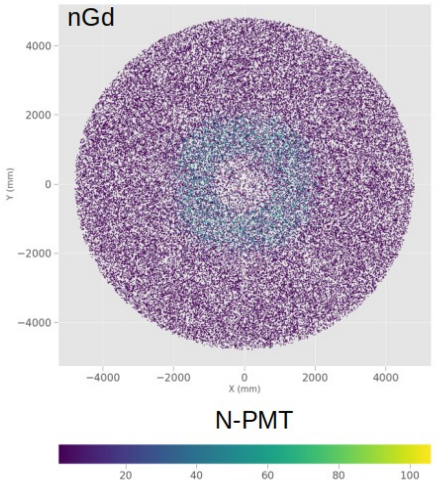


We expect **high signifiance** for neutron Veto due to high PMT coverage, but **few events** d <**20Kpc**.
Muon Veto can cover large distances but we expect less signifiance

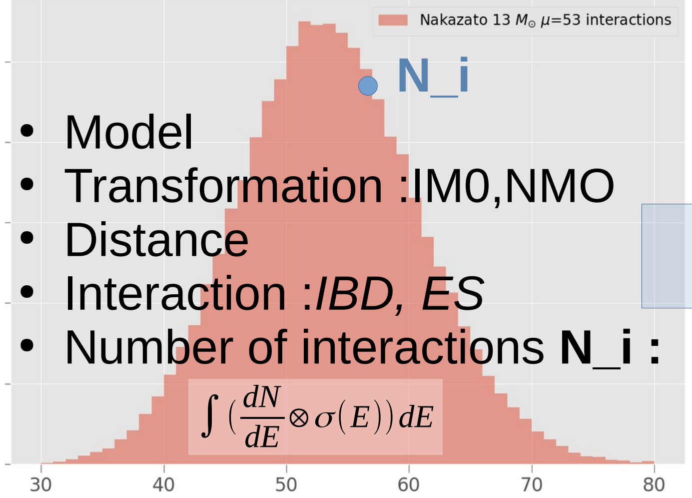
Neutron capture, particularly in Gd Water configuration contimates Positron signal. This Gd Capture has high acceptance in Neutron Veto. Neutron Capture in **Water not relevant** for **Muon Veto.**







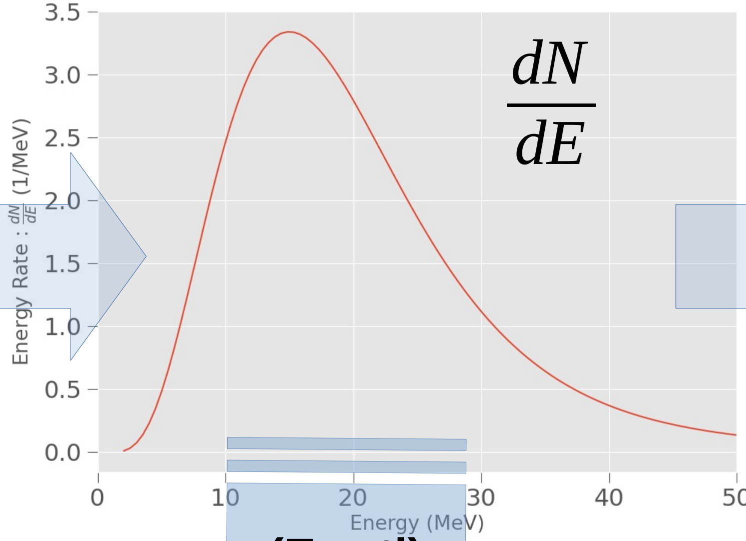
CCSN Simulation : Simulation Chain



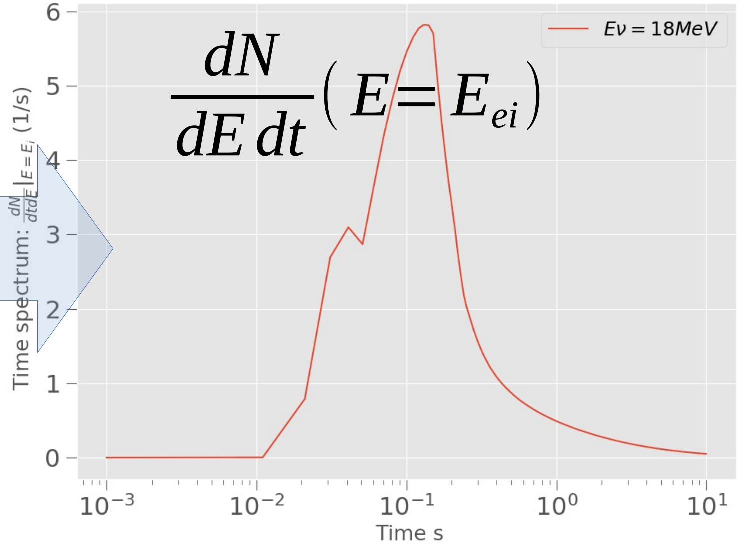
- Model
- Transformation :IM0,NMO
- Distance
- Interaction :*IBD, ES*
- Number of interactions **N_i :**

$$\int (\frac{dN}{dE} \otimes \sigma(E))\, dE$$

Eei



ti

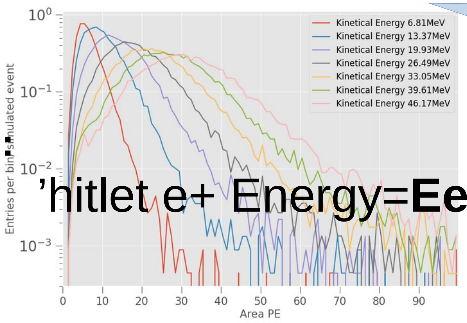


(Eei, ti)

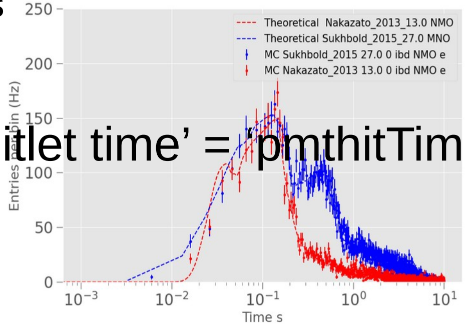
Selection of simulated hitlets (PMT hits PE)

IBD (and ES)
GEANT4 Generator :

- **PMTs response**
- for a given Positron (neutron or electron ES) Energy
- Detection efficiencies
- Reconstruction of Energy Spectrum for each Model



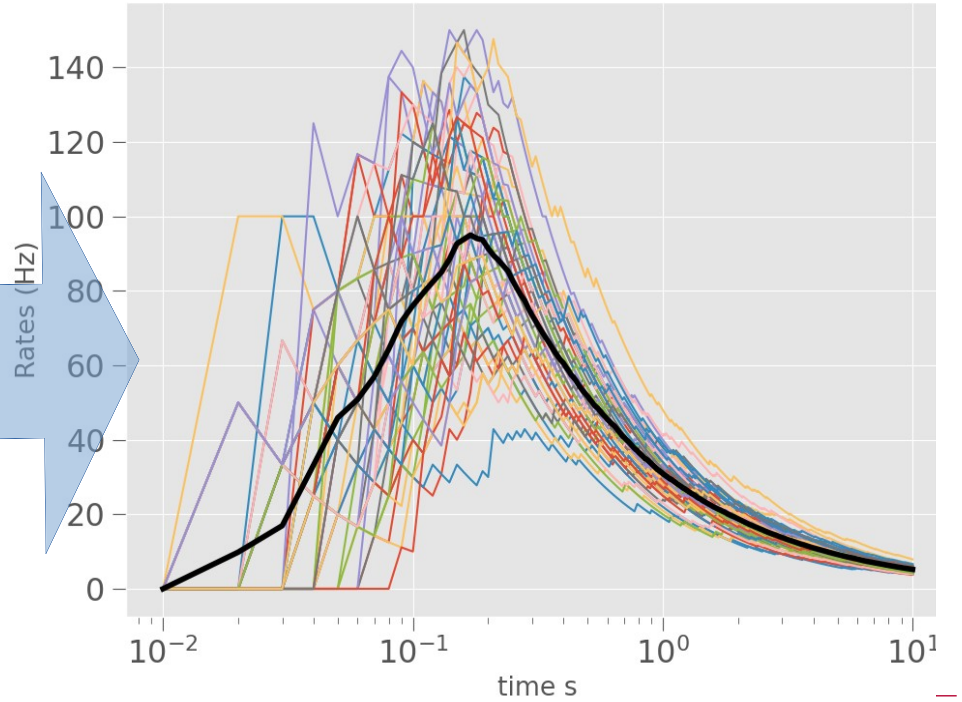
'hitlet e+ Energy=**Eei**'



'hitlet time' = 'pmthitTime' + **ti**

'hitlets_mv(nv)'

'events_mv(nv)'

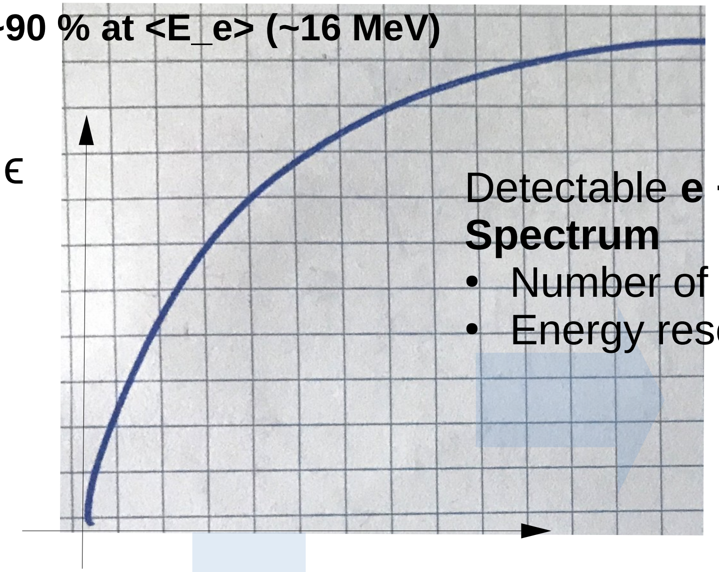


CCSN Simulation : IBD Positron Energy

Muon Veto

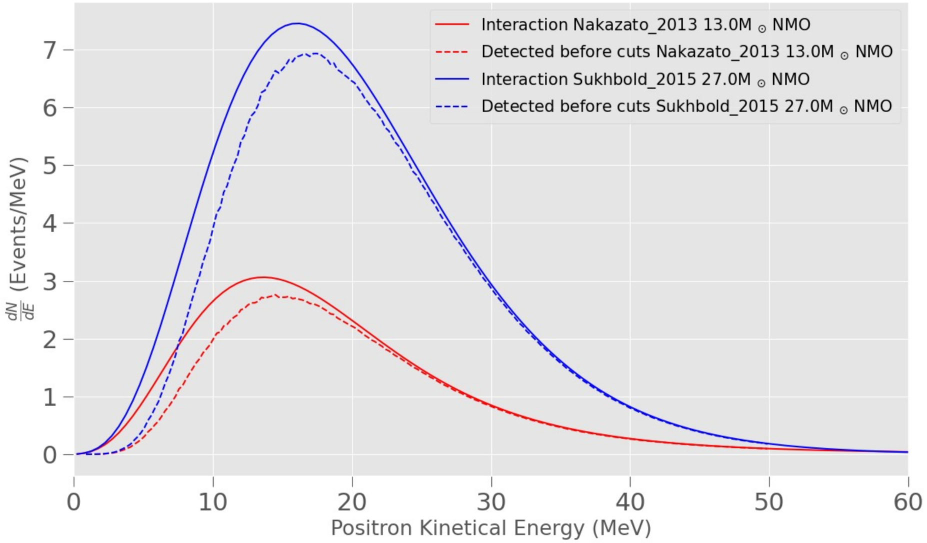
For each SN Model we extract detection efficiencies **ϵ** :

ϵ~90 % at <E_e> (~16 MeV)



Detectable **e + Spectrum**
- Number of events
- Energy resolution

NMO Detectable vs expected e+ Energy Spectrum

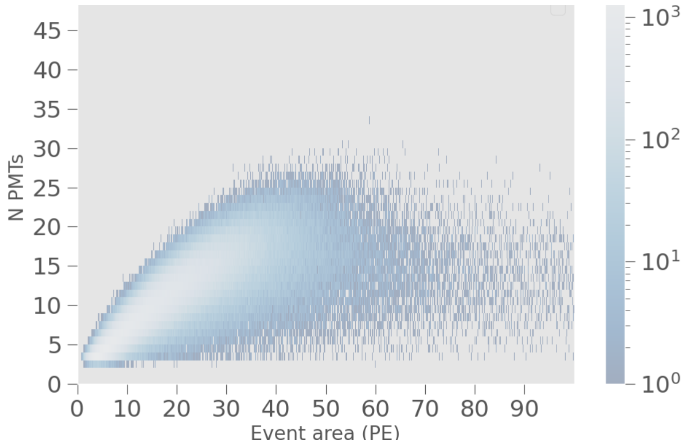


NMO events at 10 kpc
139- 52 events

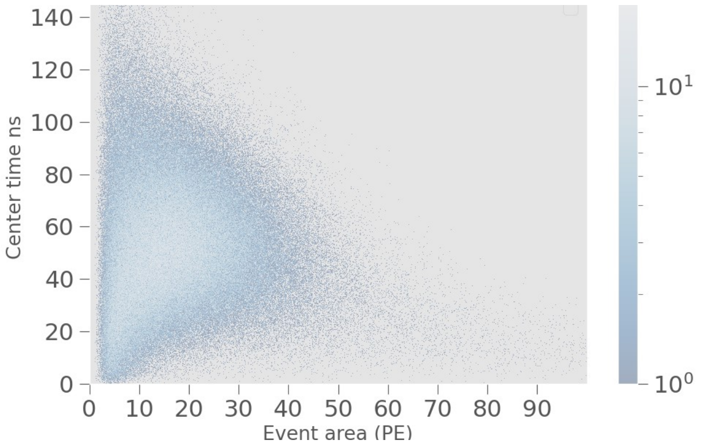
IMO events at 10 kpc
138- 64 events

e+ Region of interest **ROI**
- Event parameters :
  - Area (PE), PMTs in coincidences
  - **Center time** (*~mean time when photons arrive to PMTS)*

e+ PMT coincidence vs Event Area



e+ Center time vs Event Area



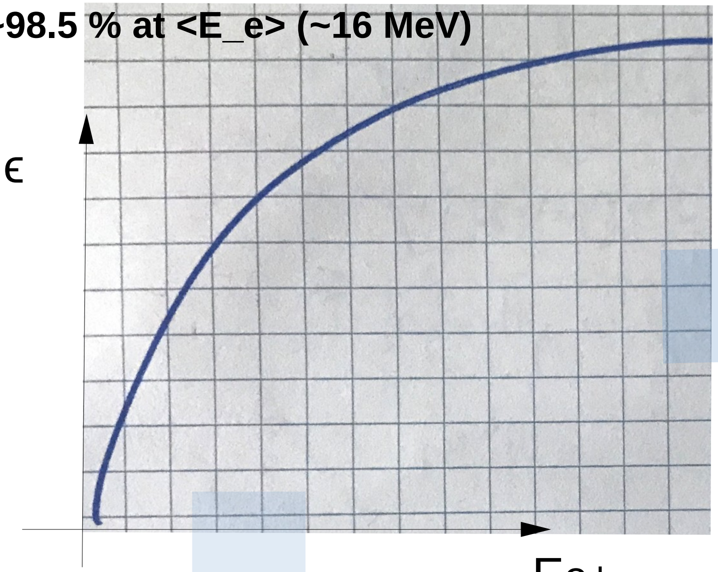
ROI
[1, 100 PE]
[2, 30 PMTs]
[0, 150 ns]

CCSN Simulation : IBD Positron Energy

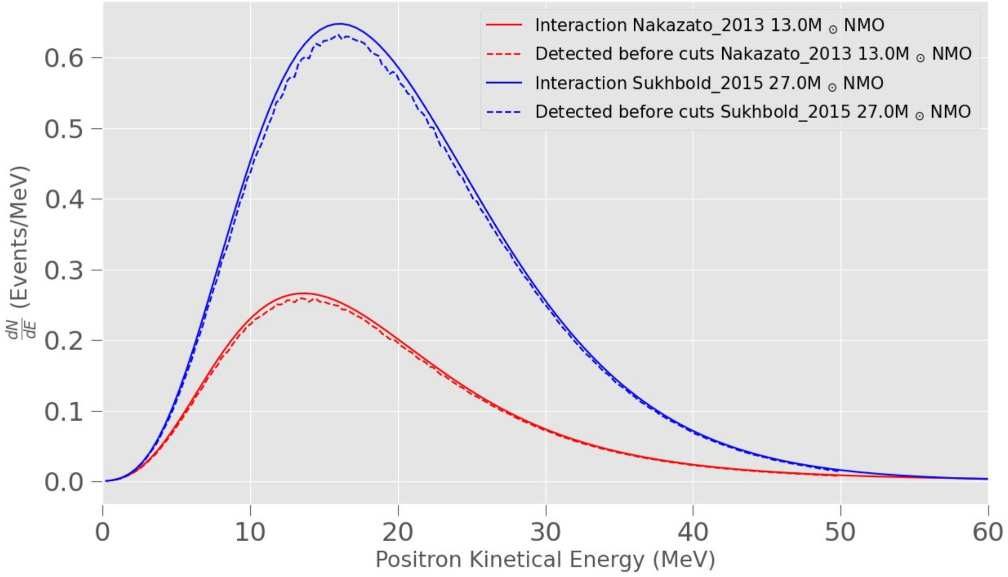
Neutron Veto

For each SN Model we extract detection efficiencies **ϵ** :

ϵ~98.5 % at <E_e> (~16 MeV)

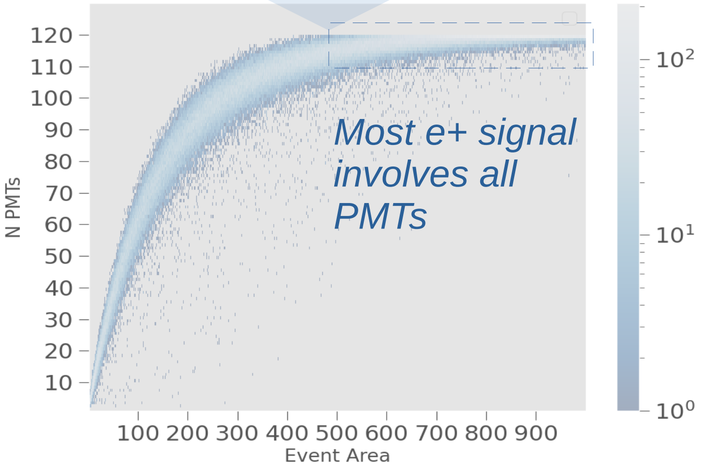


NMO Detectable vs expected e+ Energy Spectrum



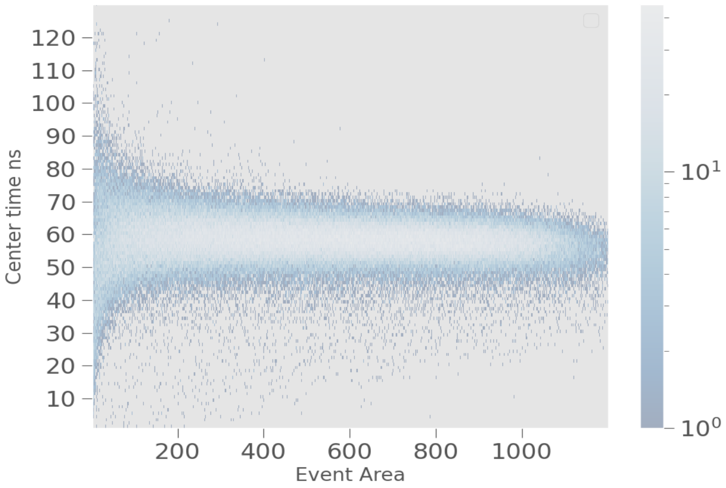
We have a very **good accuracy** of e+ energy spectrum.

e+ PMT coincidence vs Event Area



PMT array density **enlarge** the ROI in Event Area PE, and **stretch** the Center time distribution

e+ Center time vs Event Area



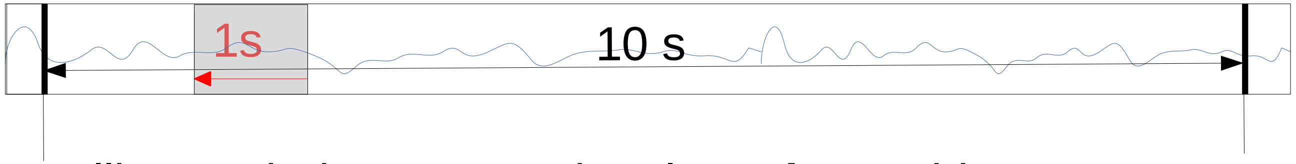
NMO events at 10 kpc
13- 5 events

IMO events at 10 kpc
13- 6 events

ROI
[1, 1200 PE]
[2, 120 PMTs]
[10, 100 ns]

CCSN Simulation : IBD Positron Time signal

Rolling Window in 10s through 100 SN Simulations.

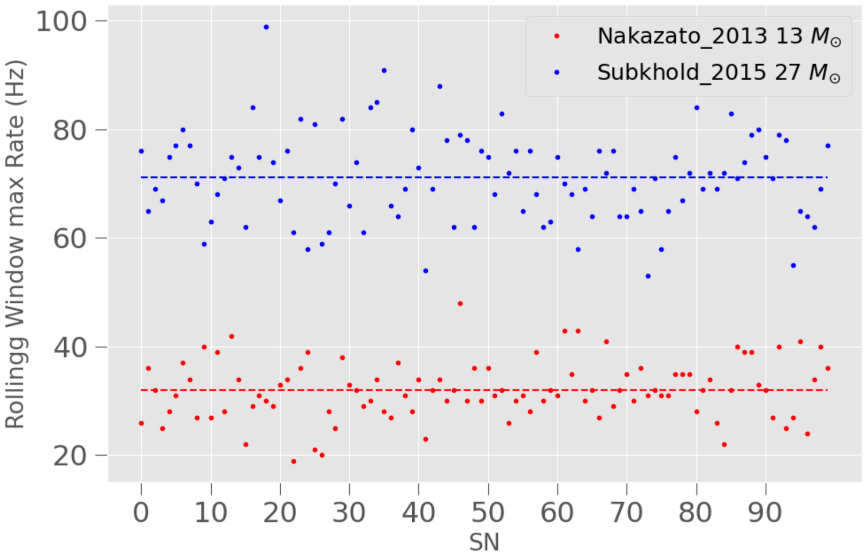


Rolling a window over a signal **maximaze** his rate.

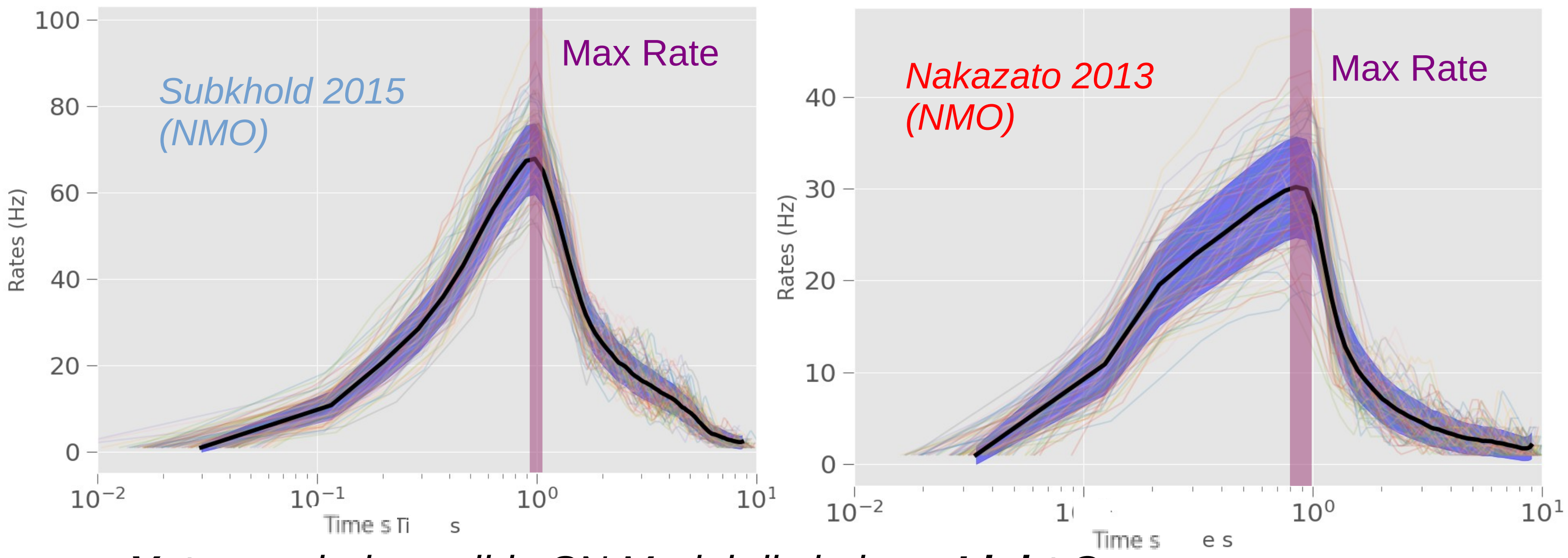
Maximun Rates characterize SN signal to be discriminated from background (also Neutron and ES signal) and happens in few **1ms.**

The choice of the **Step** of **rolling window** (1 sec here) minimize background that should keep stable.

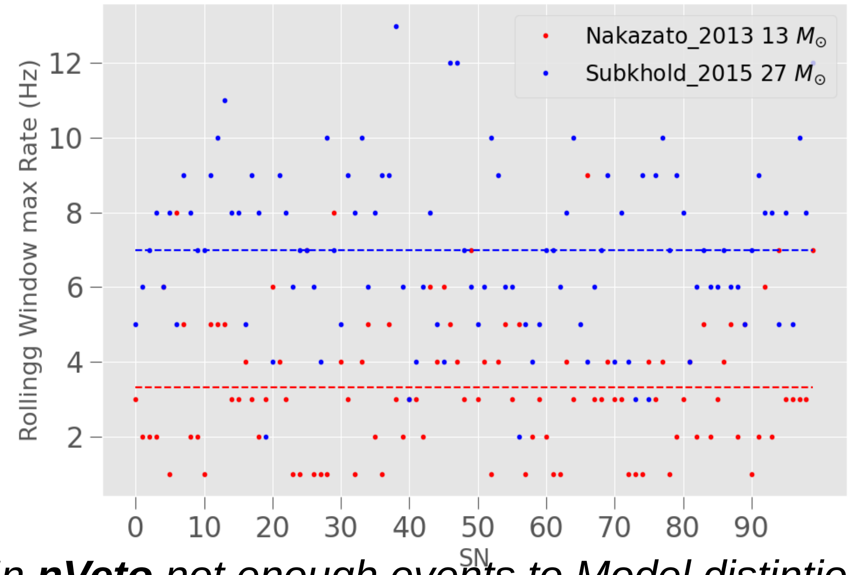
e+ Muon Veto Max rates for 100 SN



e+ Muon Veto Rolling Window Rates for 100 SN



e+ Neutron Veto Max rates for 100 SN



*e+ μ**Veto** a priori possible SN Model distintion…**Light Curves***

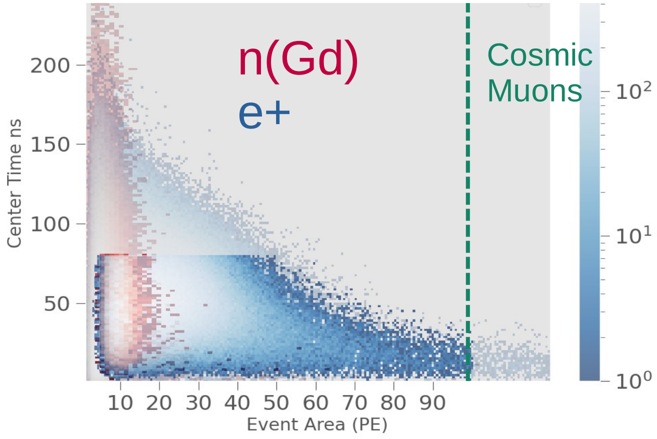
*In **nVeto** not enough events to Model distintion...*

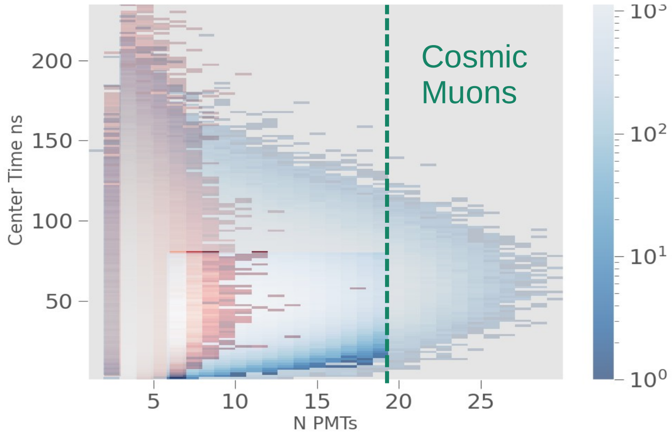
CCSN Background Model in XENONnT Water Tank : Neutron

We study the contaminato of IBD neutron considering also Muon Veto Background in ROI, composed by also neutrons, i.e. Cerenkov light from nCapture in Water (and Gd) **gamma rays**.

Only neutron in Gd Water signal is important in Muon Veto.

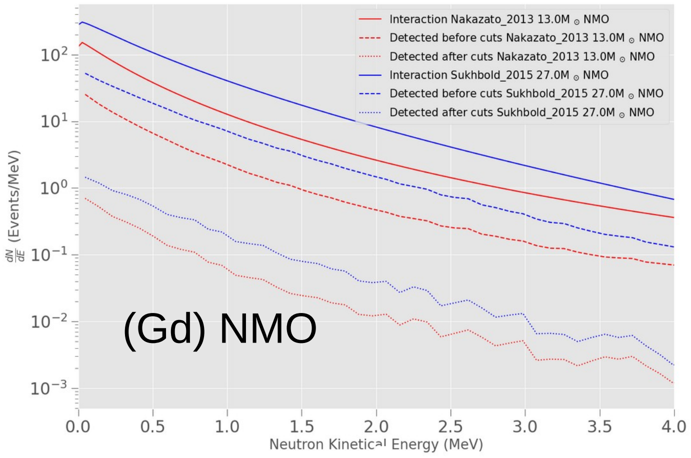
e+ and neutron center time vs Event Area and center time vs N pmt coinc.





From **IBD Neutron Spectrum**

Detectable Energy Neutron spectrum



NMO events at 10 kpc

10-26 events

IMO events at 10 kpc

12-26 events

<1 neutron (Gd) events ***After cuts*** for NMO and IMO

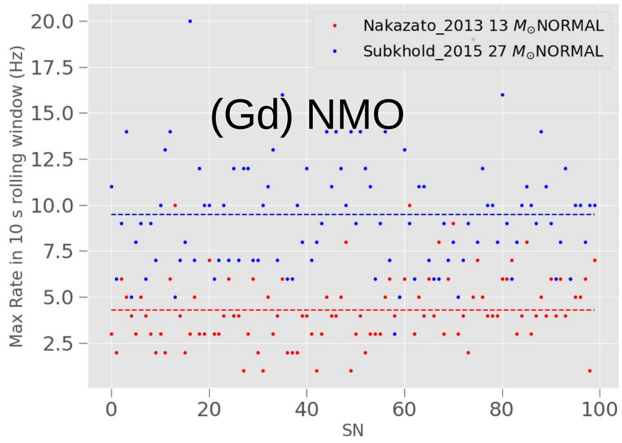
From **Maximun Rates** rolling window of 100 SN IBD neutrons

Before cuts

100/100 SN n have at least 1 event (1Hz).

Mean Max. rates : ~4.3 (4.9) and ~9.6 (9.5) Hz

Max. Rates Before cuts



After cuts

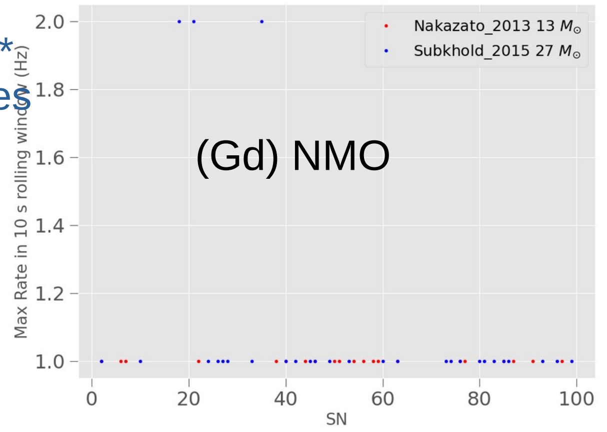
Only a fraction ~ 20 % * of SN simulated survives

22/100 NMO (25 IMO)

18/200 NMO (18 IMO)

Median of Maximun Rates ~ 1 Hz

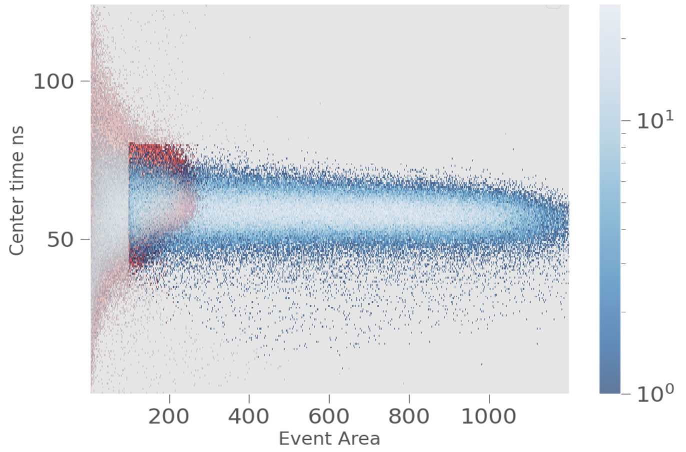
Max. Rates After cuts

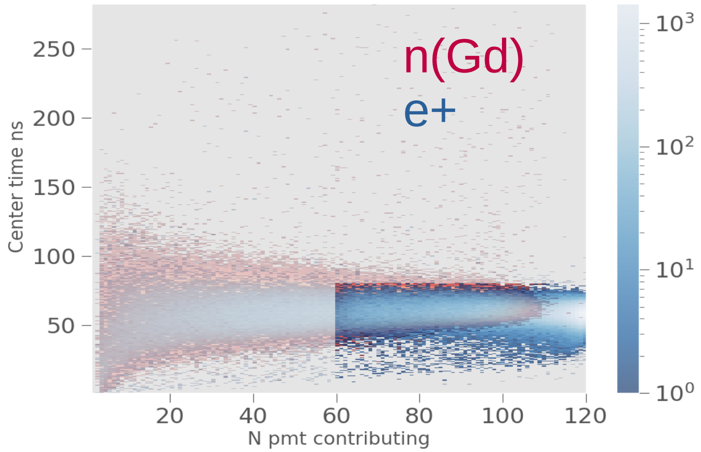


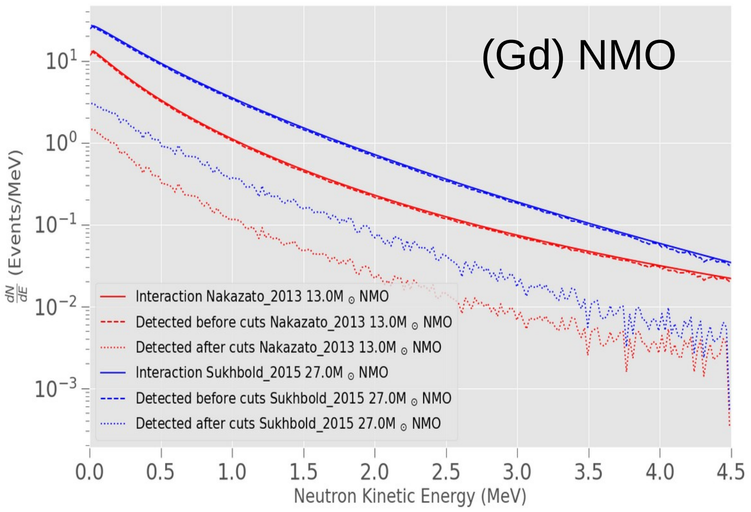
CCSN Background Model Neutron

Intrinsec neutron Veto background is composed mostly by radiogenic neutrons from detector component, that we will ad to IBD neutron signal. For neutron Veto we know signal of neutron from AmBe calibrations, but not in Water doped with **Gd**...

e+ and neutron center time vs Event Area and center time vs N pmt coinc.







We expect from Gd capture :

NMO events at 10 kpc
4-12 events

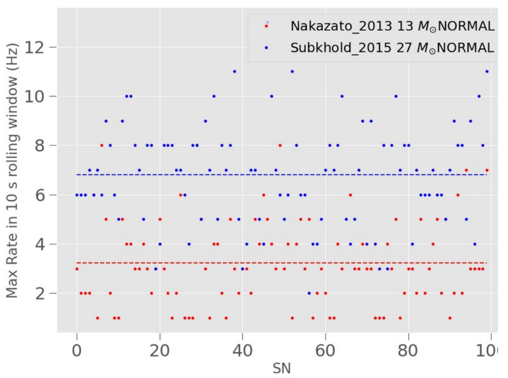
IMO events at 10 kpc
6-12 events

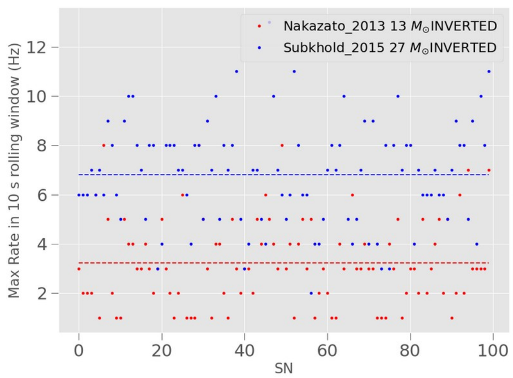
High Efficiency in Gd Capture signal.

<1 neutron (Gd) evts after cuts for NMO and IMO

We use also a **rolling window** to get **maximun rates** from **IBD** neutron signal, for the 100 SN

Before cuts



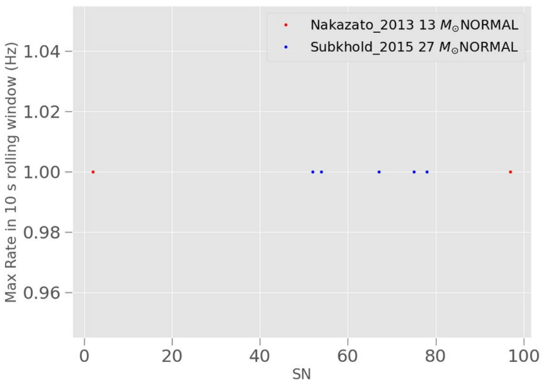


After cuts

~2- 5 % of SN simulated survives

5/100 NMO (5 IMO)
2/200 NMO (2 IMO)

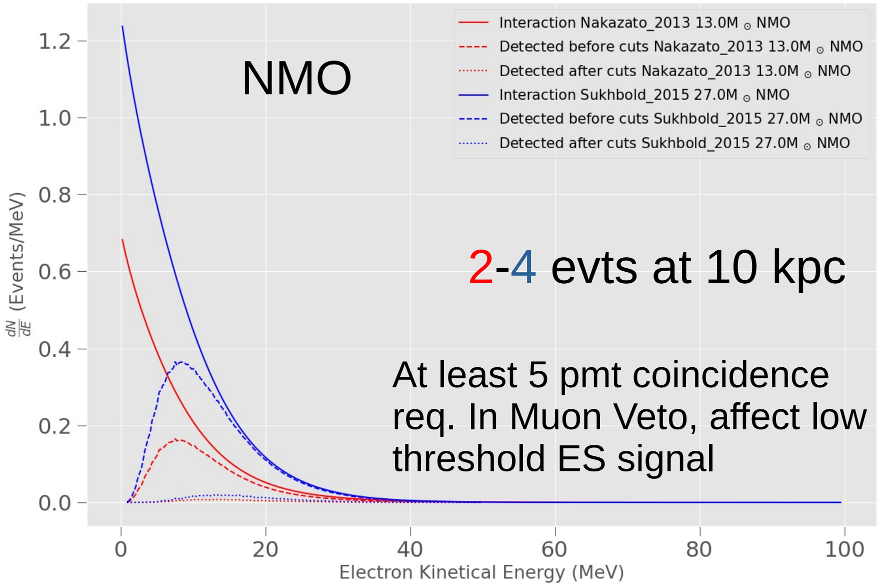
Median of Maximun Rates~ 1 Hz



CCSN Background Model : ES

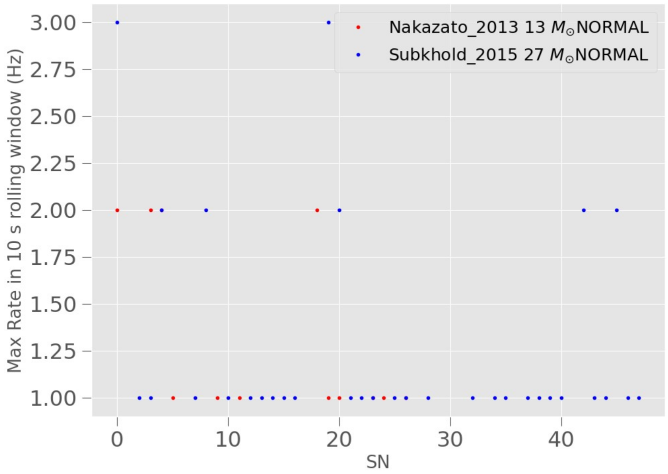
Muon Veto

ES e- Detectable energy Spectrum



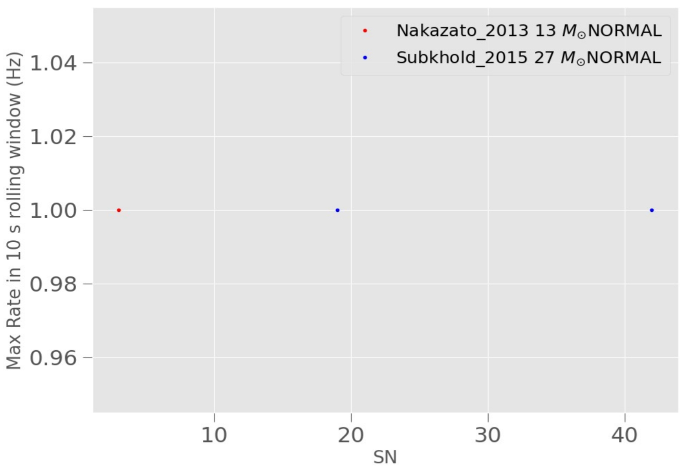
ES e- Maximun Rate in rolling window

Before Cuts



ES e- Maximun Rate in rolling window

After Cuts



Low energies of Scattered electron close to the Cerenkov threshold (223 KeV).

NMO 4 events of 14 Interactions
(2 to 5 Interactions)
IMO 5 events of 14 Interactions
(2 to 5 Interactions)

Only a fraction of simulated ES from SNν interactions generate at least 1 event **Before cuts** :

NMO (IMO)	45 (47) / 100
ES surviving	19 (25) / 100

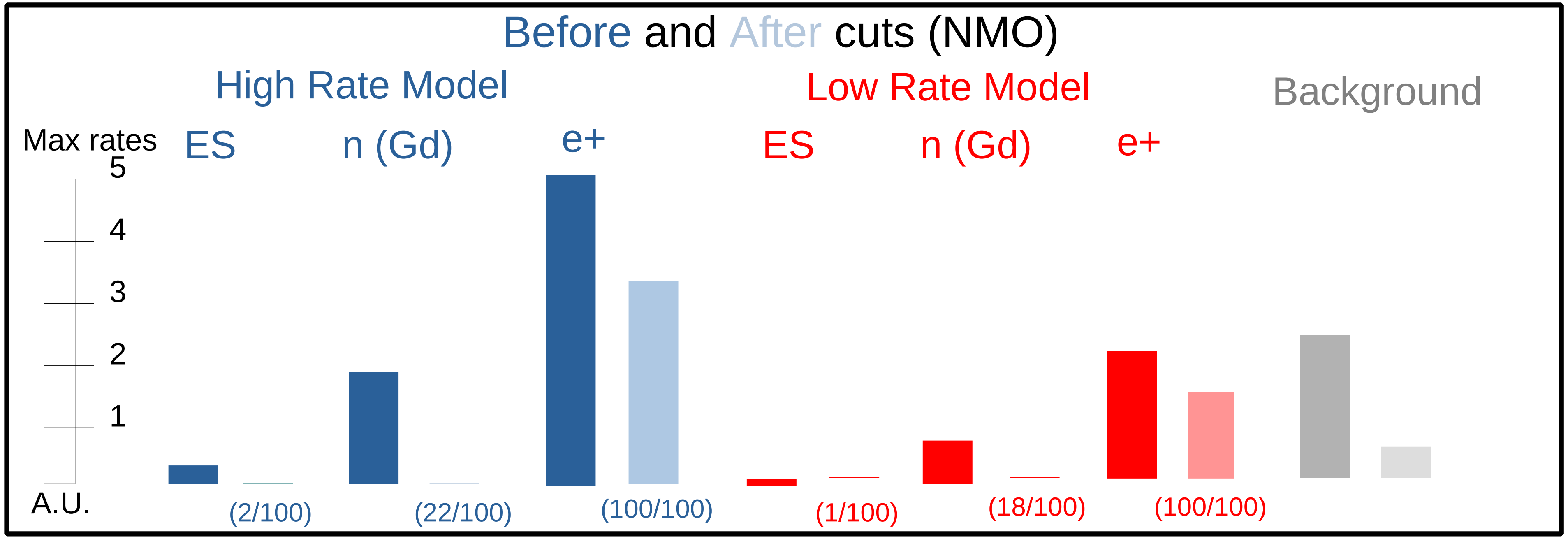
After cuts only 2/100 ES SN Survives

Neutron Veto

For this analysis we not consider ES in Neutron Veto as we expect an extremly low rate at 10 kpc:**<< 1 event at 10 kpc**
However, it should be considerer at **distances < 3 Kpc** wen we expect to have **1 ES events** (in front 45 IBD events)

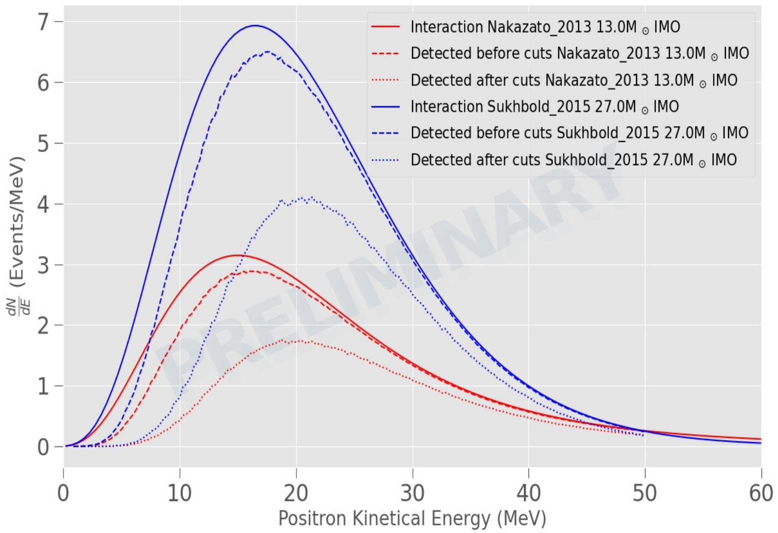
CCSN Background Model : Final e+ signal

Muon Veto maximun Rate in Rolling Window from 100 SN at 10 kpc:



We reduce **significantly ES** and **neutron (Gd)** signals after cuts in therms of Maximun rates rolling window.
At 10 kpc Low rate Model should have enough **signifiance** to consider e+ signal.

Detectable e+ Spectrum after cuts NMO



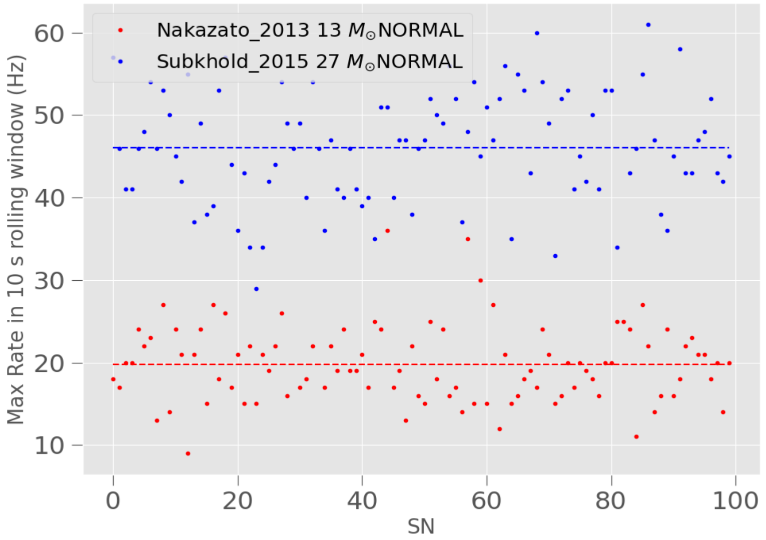
Number of events after cuts

NMO events at 10 kpc
83- 29 events

IMO events at 10 kpc
84- 39 events

We loose **energy resolution** in the low energy region of e+ spectrum

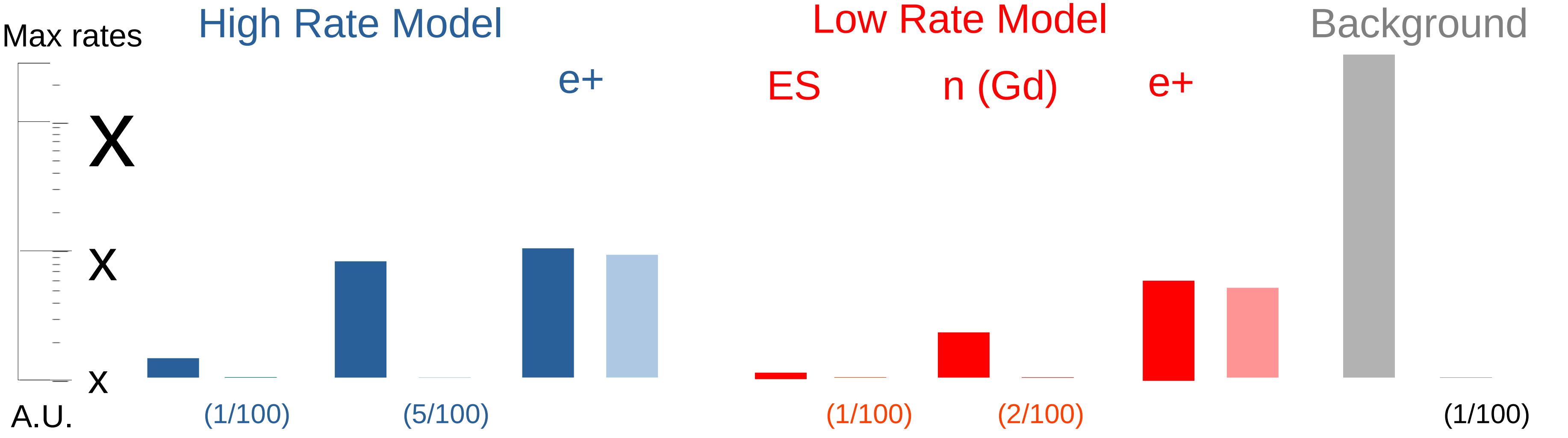
e+ Maximun rolling window Rates After cuts



CCSN Background Model : e+Final signal

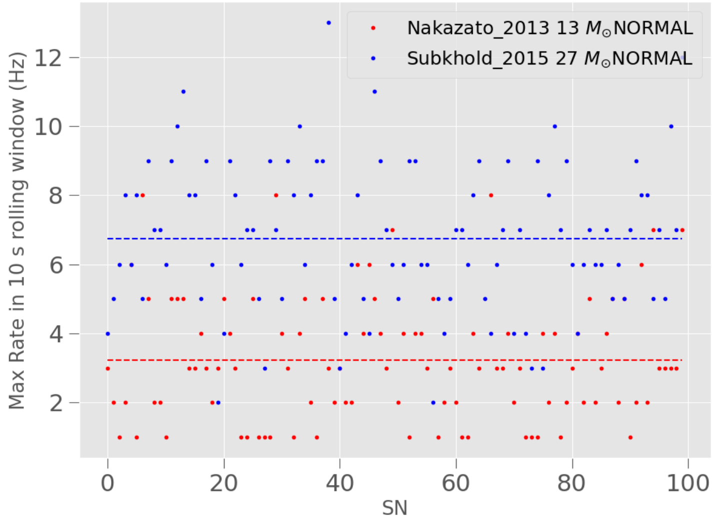
Neutron Veto maximun Rate in Rolling Window from 100 SN at 10 kpc:

Before and After cuts (NMO)



We reduce **almost completely ES** and **very significantly neutron (Gd)** signals after cuts in therms of Maximun rates rolling window.
As we excepted in the e+ ROI we reduce background without loosing a priori any e+ event (mean e+ events).

Detectable e+ Spectrum after cuts NMO



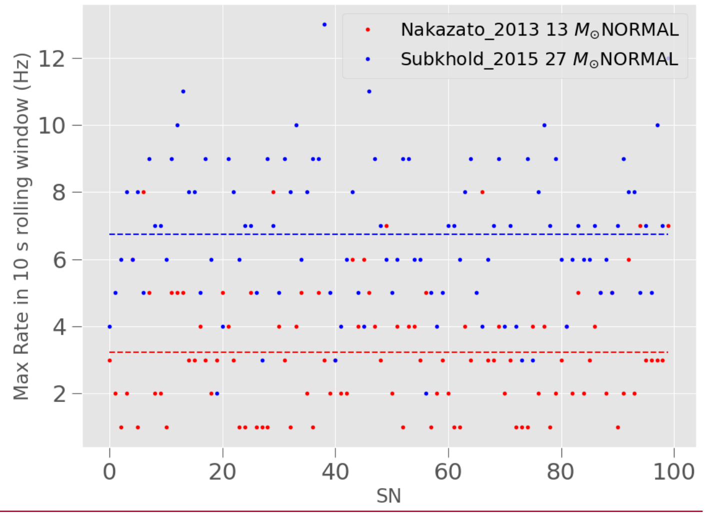
Number of events after cuts

NMO events at 10 kpc
12- 4 events

IMO events at 10 kpc
12- 5 events

Accurate detactable e+ spectrum, in terms of energy resolution. Neutron Veto signal becomes important at **distances <5 kpc (16-48 events)**

e+ Maximun rolling window Rates After cuts



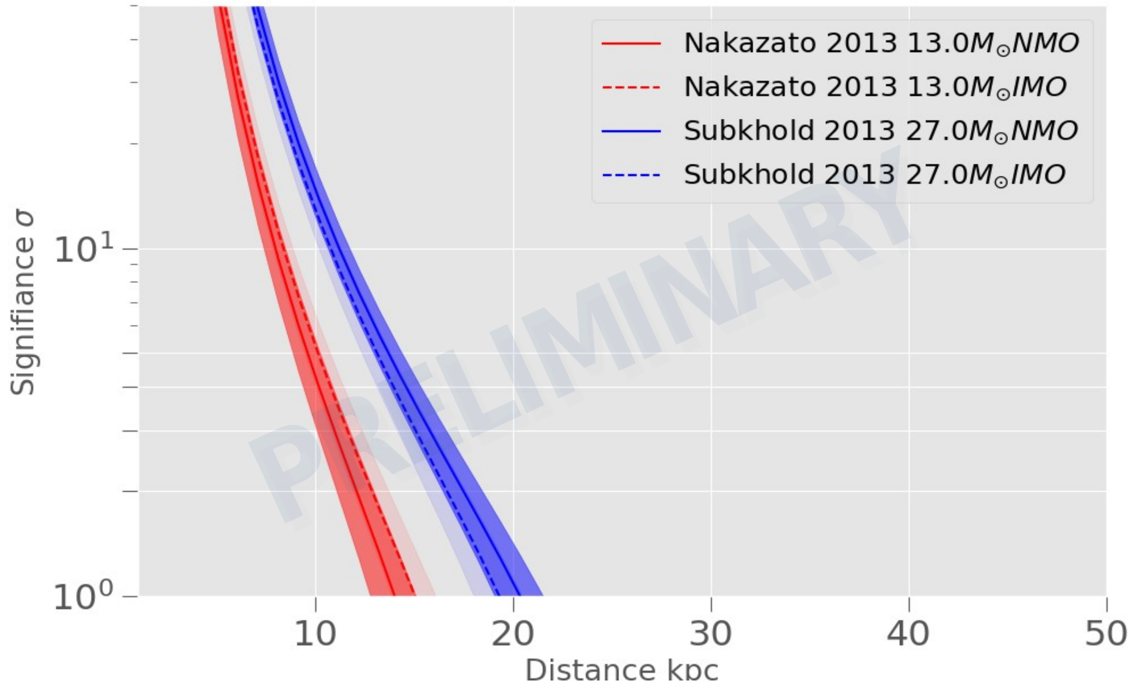
CCSN Simulation in XENONnT Water Tank : IBD Signal Significance σ

Sensititivity Curve for a given SN distance using maximum Rates :

Muon Veto : **p-value** of PDF (Background + n(Gd) + ES)

Signifiance Z(σ) $= \Phi^{-1}(1 - p)$

Cowan et al. 2010



> 4σ at 10 kpc

29 (39) events NMO (IMO)

83 (84) events NMO (IMO)

Neutron Veto :

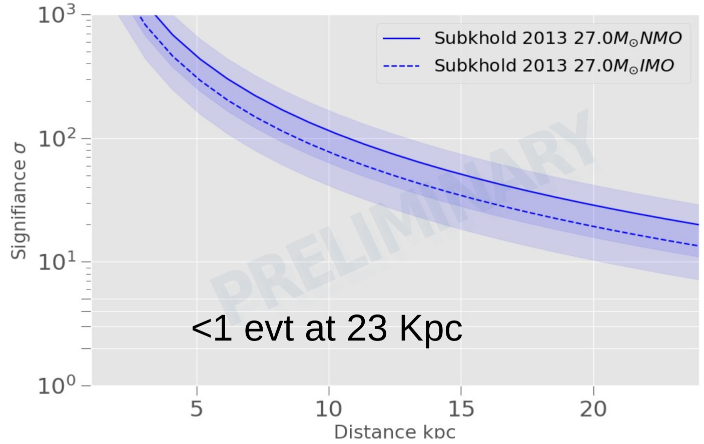
Only neutron signal contributes to Background After cuts. A priori mean of expected detected events is conserved *After cuts.*

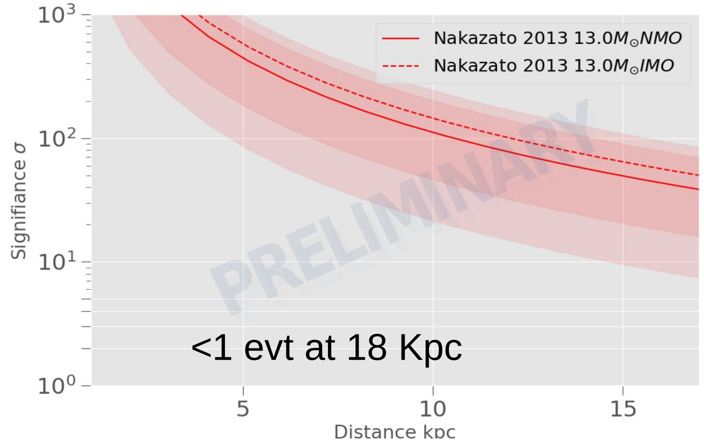
Better **PMT coverage** of Neutron Veto and Background far from ROI, gives better sensitivity to SN signal from neutron Veto, but also more to the IBD neutron one :

> 50σ at 10 kpc

12 (12) events NMO (IMO)

4 (5) events NMO (IMO)





CCSN in XENONnT: *Summary*

- Main interaction in TPC : **CevNS**
  - S2-only & event level analysis : high-significance detection
  - ~100 peaks, >30 events at least expected at 10kpc
- Main interaction in Water Tank : **IBD**
  - > 29 events at least expected at 10 kpc with > 4σ in Muon Veto
  - > 4 events with high signifiance at 10 kpc

We are working to combining them...

- (Almost) the first ever dark matter detector actively participating in SNEWS2.0
  - Include Veto Systems (LGNS Veto Network)

SNEWS
SUPERNOVA EARLY WARNING SYSTEM

- CC interactions and possible limitations under investigation

- Model discrimination through light reconstruction is needed, but also:
  - *IBD cross section (For Neutron and Muon Vetos)*
  - *SNν Flux uncertainties…*
  - *Background possible incrementation once Gd is present in Vetos*

Thank ν̄ou !

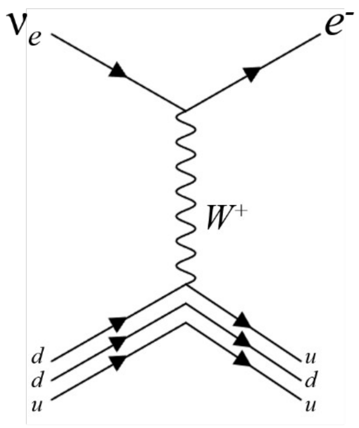
Specially Thanks to Ricardo Peres, Sayan Gosh and Andrea Molinario

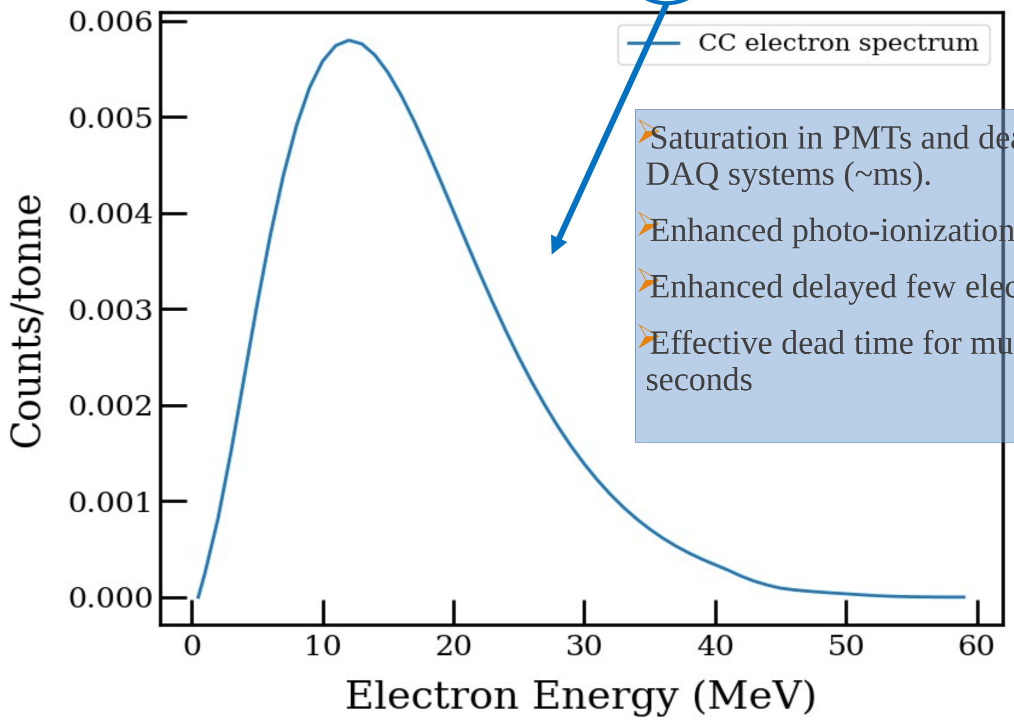
Back up

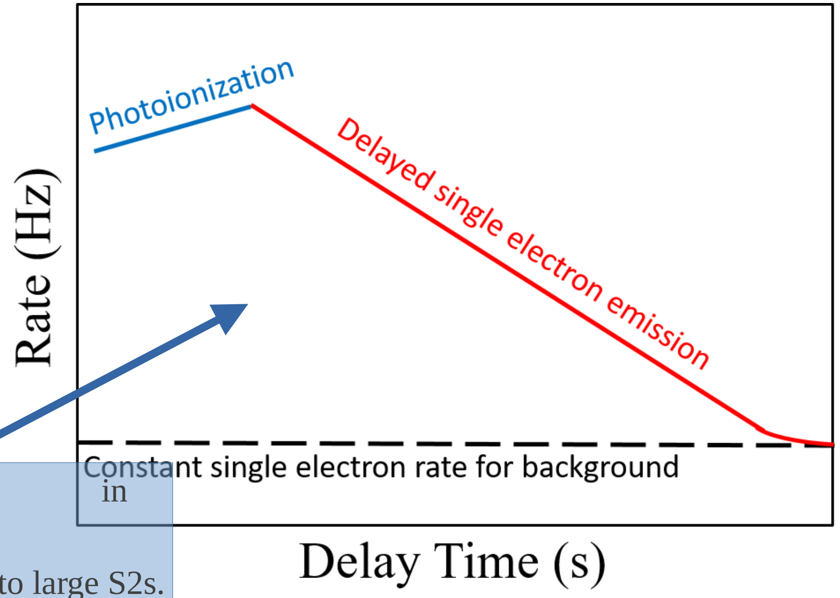
CCSN CC INTERACTIONS IN THE TPC

The CC interactions lead to emission of electrons and a daughter nucleus in an excited state ($^{132}Cs^*$ in case of ^{132}Xe).

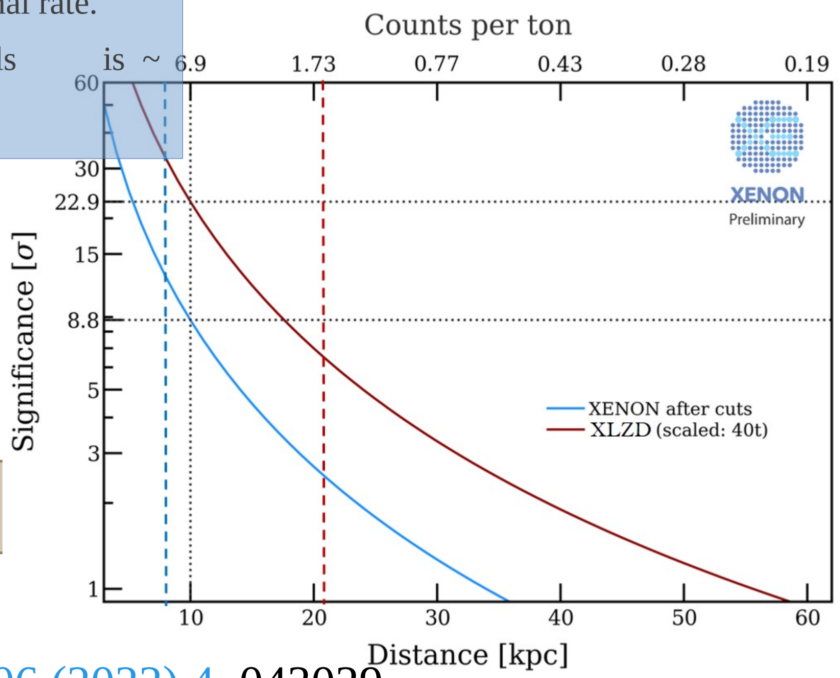
$$\nu_e + {}^{132}_{54}\mathrm{Xe} \rightarrow e^- + {}^{132}_{55}\mathrm{Cs}^*$$







- Saturation in PMTs and dead times in DAQ systems (~ms).
- Enhanced photo-ionization rate due to large S2s.
- Enhanced delayed few electron signal rate.
- Effective dead time for muon signals is ~ seconds



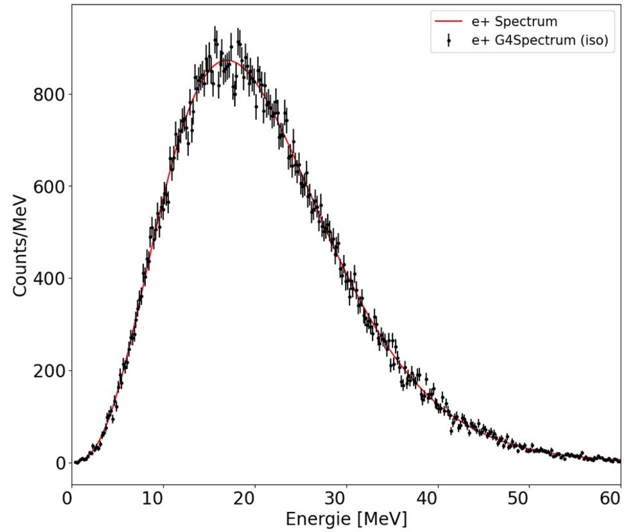
For 11 $M_\odot$ model : 4 electrons at 10 kpc are expected in XLZD (40 t).

P. Bhattacharjee, A. Bandopadhyay, S. Chakroborty, S. Ghosh, et. al., *Phys.Rev.D* 106 (2022) 4, 043029.

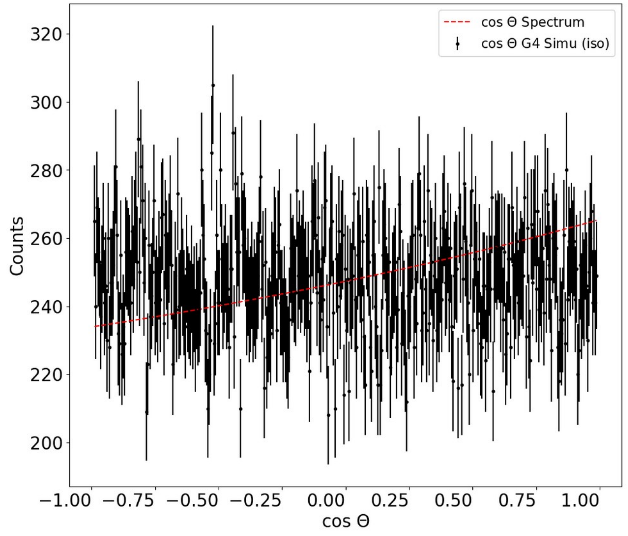
CCSN IBD POSITRON SPECTRUM

MC GEANT4 e+ Simulations

Energy e+ Spectrum



E+ ν scattering angle Spectrum



Positron Energy in the Lab frame

$$E_e = \frac{(E-\delta)(1+\epsilon)+\epsilon cos(\Theta)\sqrt{((E-\delta)^2 - m_e^2\kappa)}}{\kappa}$$

$$\epsilon = E/m_P \qquad \kappa = (1+\epsilon)^2 - (\epsilon cos(\Theta))^2$$

2D Positron rate

$$\frac{dN}{dE_e dt}_{ibd} = N_{H_2O} * f_p * \frac{1}{4\pi d^2}\int_{E_{min}}^{E_{max}} \frac{dN}{dtdE_{\bar{\nu}_e}}\frac{d\sigma(E,E_e)}{dE_e}dE$$

$$E_{min} = E_e + \delta \qquad E_{max} = \frac{E_{min}}{(1-2\frac{E_{min}}{m_p})} \qquad f_p = 2$$

$$\delta \equiv \frac{m_n^2 - m_p^2 - m_e^2}{2m_p} \qquad N_{H_2O} \approx 3.32710^{28}$$

Positron scattering angle in the Lab frame

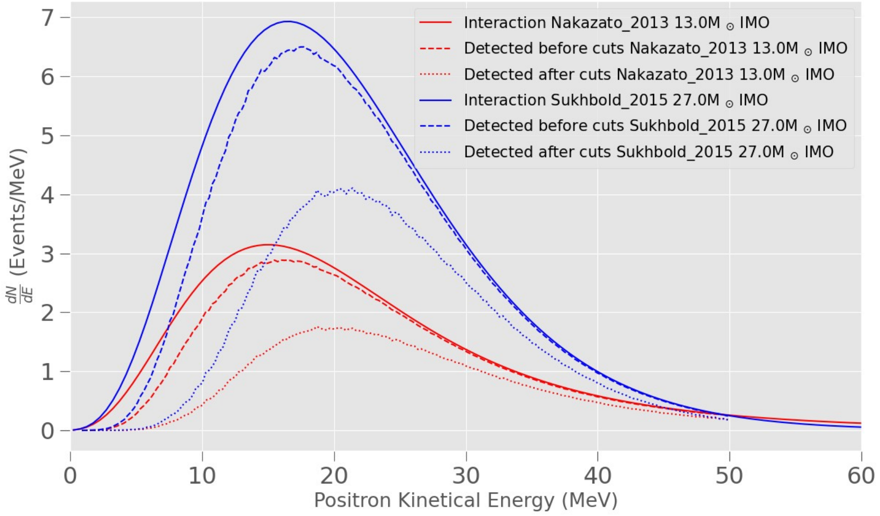
$$cos(\theta) = \frac{(m_n^2 - m_p^2 - m_e^2 + 2m_p(E_\nu - E_e) - 2E_\nu E_e)}{2E_\nu p_e}$$

$$\frac{dN}{dcos(\theta)dt}_{ibd}|_t = N_{H_2O} * f_p * \frac{1}{4\pi d^2}\int_E \frac{L(t)}{<E>(t)}\phi(E,t)\psi(t)\frac{d\sigma(E,cos(\theta))}{dcos(\theta)}dE$$

CCSN IMO e+ Energy Spectrums and Maximun Rates in Muon Veto rolling window

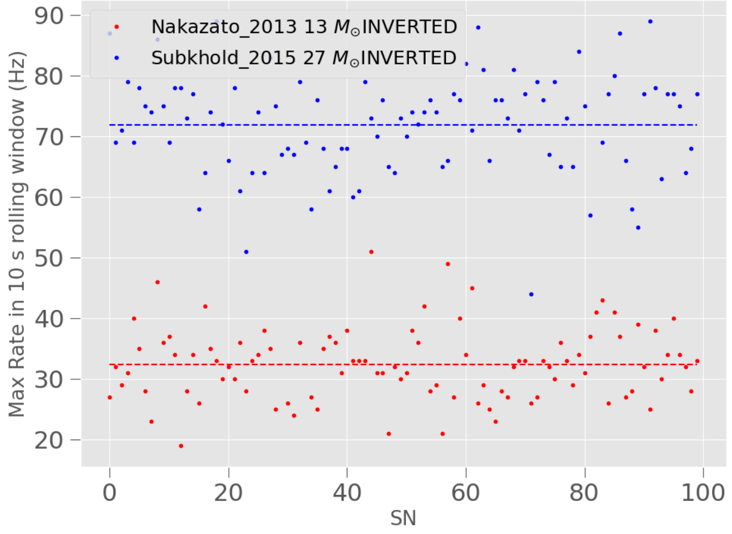
IMO e+ Detectable Spectrum

Muon Veto

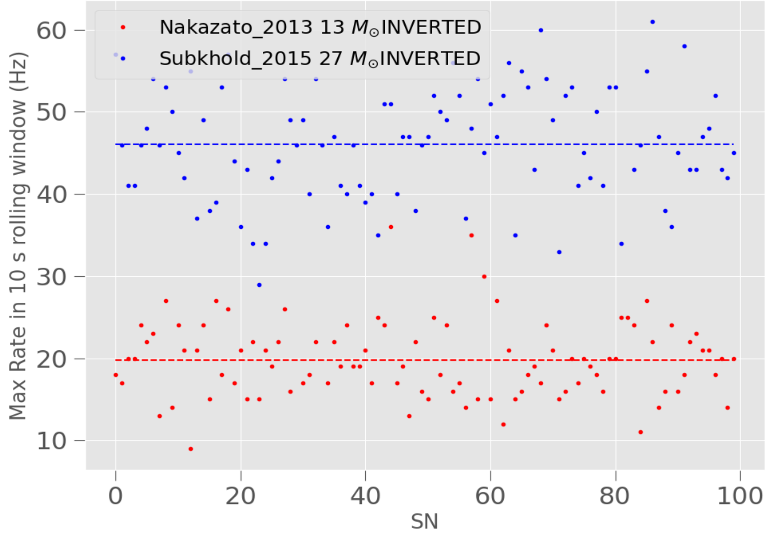


IMO e+ Rolling Window maximum Rates

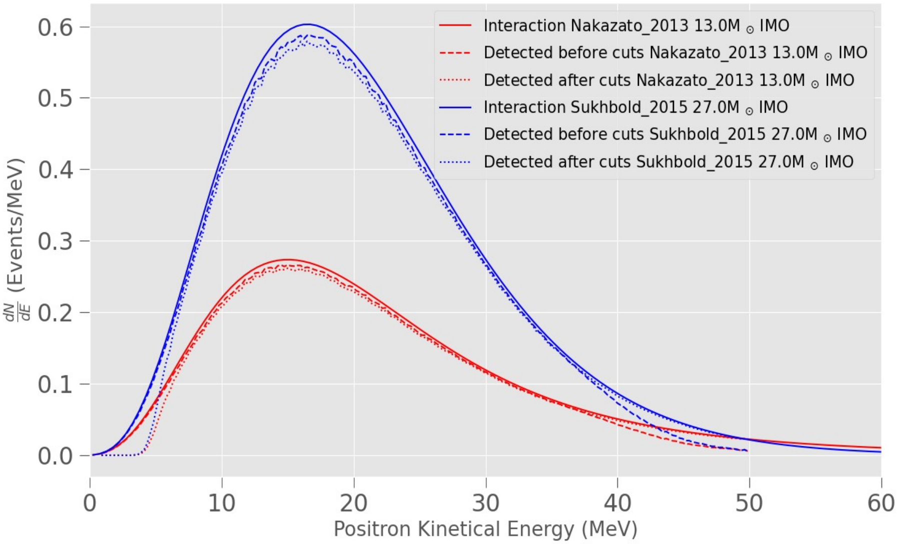
Before Cuts

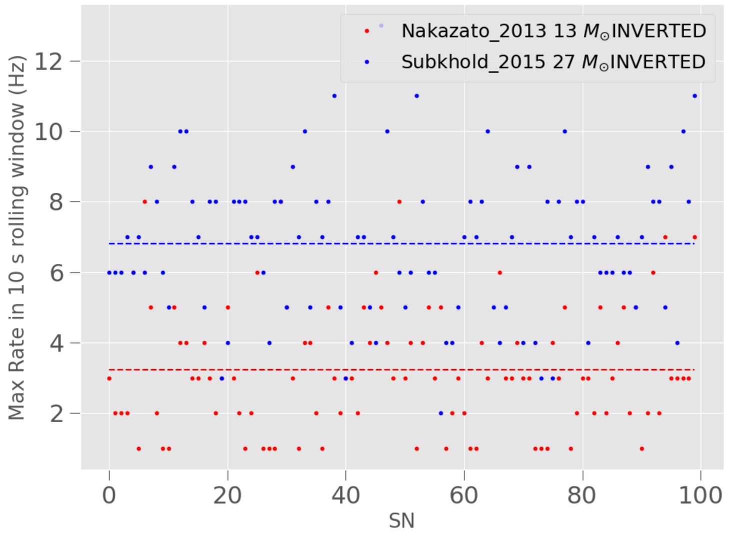


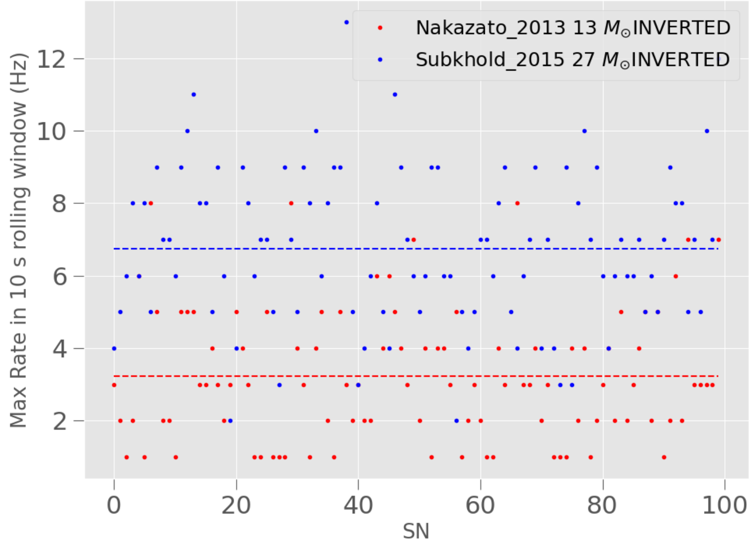
After Cuts



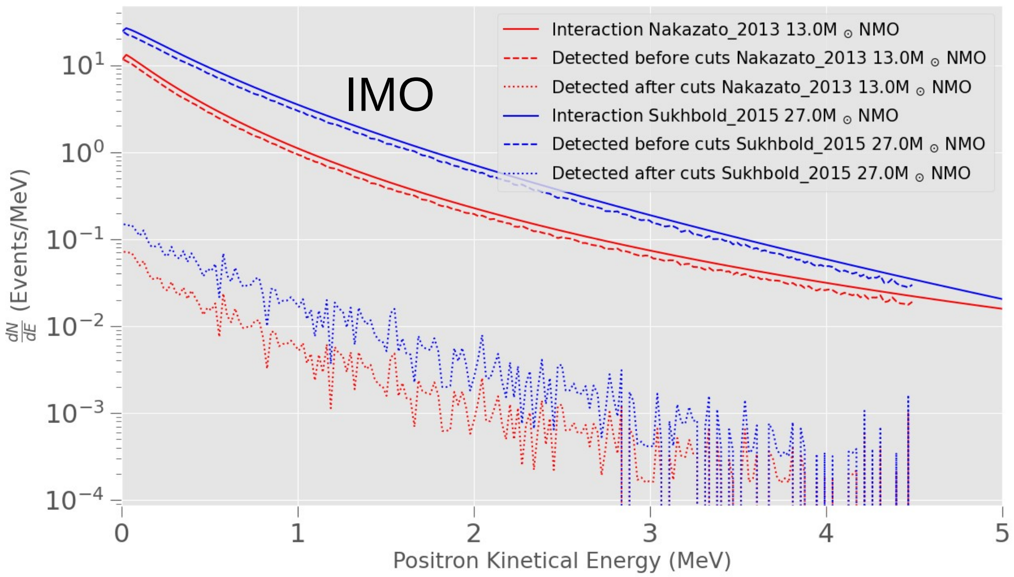
Neutron Veto

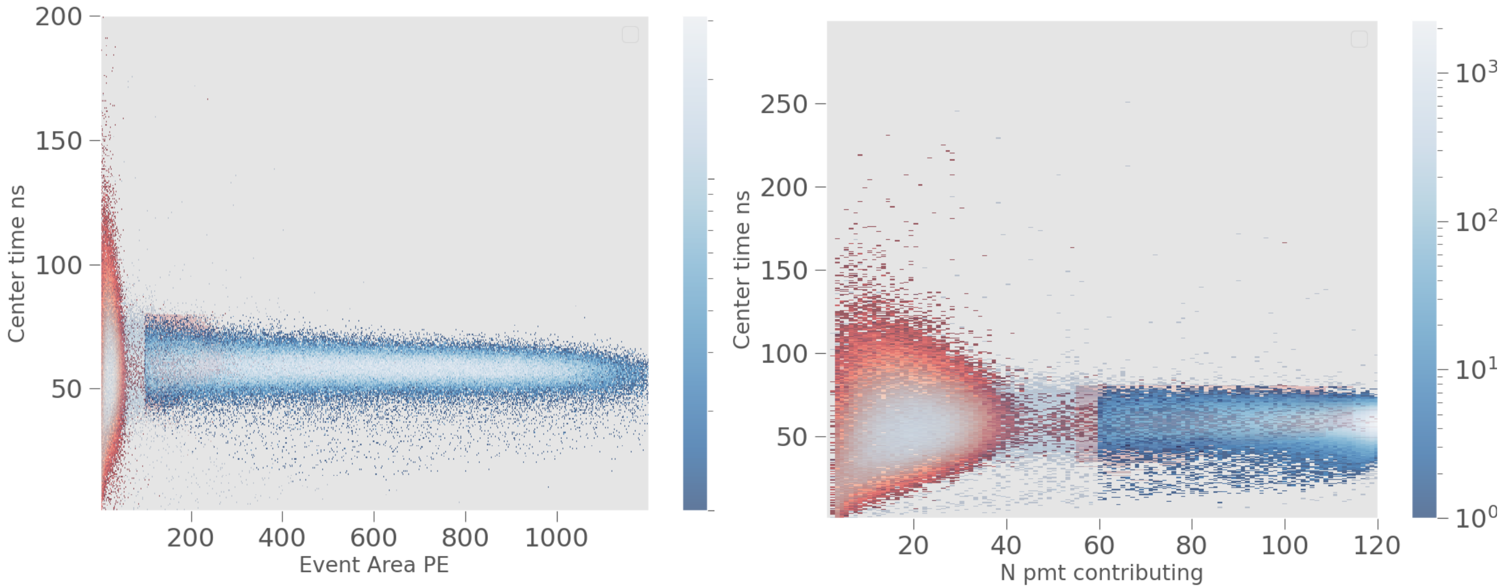


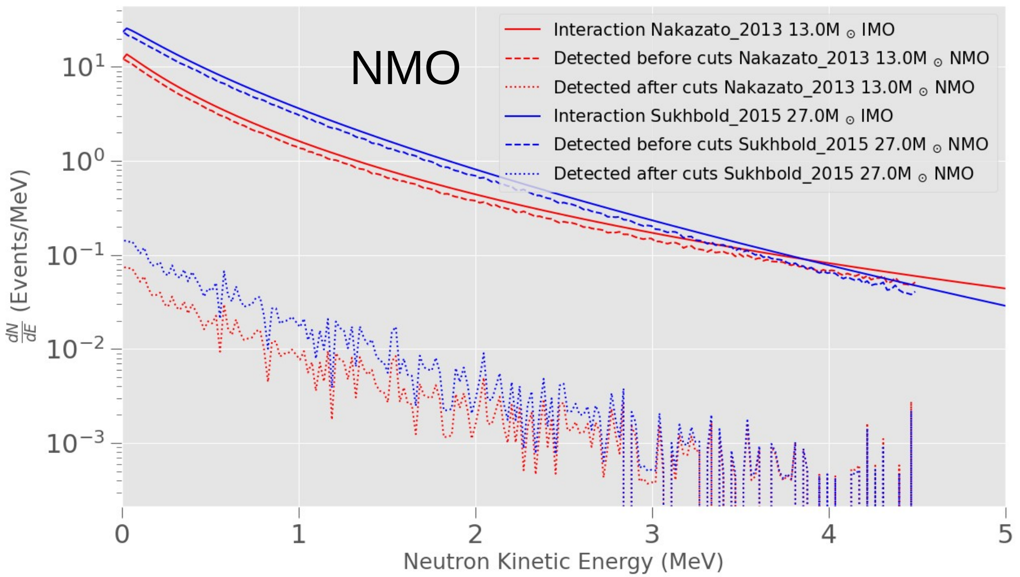




CCSN neutron Capture in Water Neutron Veto







We see that is easy to cut neutron Capture signal requiering high PMT coincidences, nCapture detection in Water needs low threshold.

We expect to have 11 (11) and 4(5) events from High and Low rate model in NMO (IMO) cases. Only 1/100 SN survives after cuts.

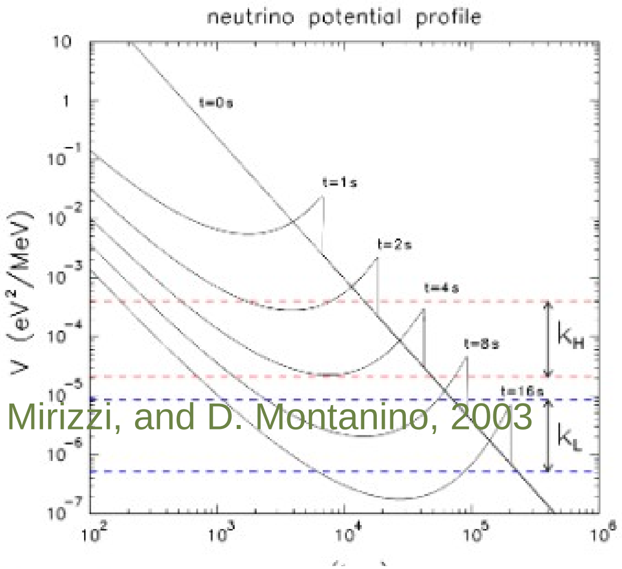
Detection efficiency is higher than Muon Veto, being more close to the Gd capture one.

CCSN neutrino oscillations

SN environnemment:

The density variation, $n_e(t)$ leads to
H(t)= $H_0 + V(t)$
MSW effect : Adiabatic or partially adiabatic neutrino flavor conversion in medium with varying density
Adiabaticity condition:

$$\gamma = \left| \frac{\dot{\theta}_m}{H_{im} - H_{jm}} \right| \ll 1$$



A. Mirizzi, and D. Montanino, 2003

1)In high densites SN medium $\frac{V}{k} \gg 1$ and $cos2(\bar{\theta}_m) \approx 1$ $\quad sin2(\bar{\theta}_m) \approx 0$

2)The assumption of $N_\mu \equiv N_\tau = N_x$ leads to non observable effects of the transformation 2-3, i.e. $\theta_{23m} = 0$ in NMO. **3 flavor oscillation case with θ_{12m} and θ_{13m}.**

3) **In Vaccum** : $\bar{P}_{ex} \propto sin^2\Delta_{ij} = sin^2 \frac{\Delta m^2_{ij} d}{2E}$
At long distances 1 pc the factor $\frac{d}{E}$ averages out: $\bar{P}_{ex} \longrightarrow \langle \bar{P}_{ex} \rangle(\theta_{ij})$

Mean Probability will **only depend on** vaccum mixing angles θ_{ij}.

For $\bar{\nu}_e$ in Normal mass ordering **NMO**

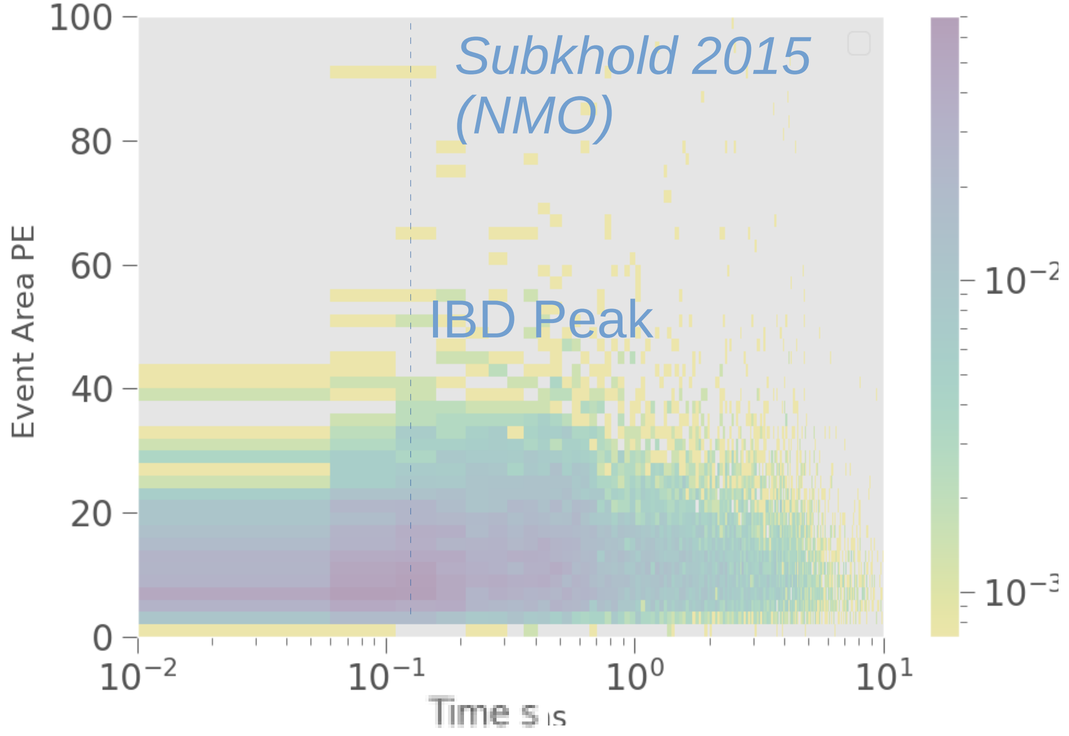
$$\bar{p}_{ee} = D_{e1} = cos^2(\theta_{12})cos^2(\theta_{13}) \qquad \bar{p}_{ex} = 1 - \bar{p}_{ee} \qquad \bar{p}_{xx} = (1 + \bar{p}_{ee})/2 \qquad \bar{p}_{xe} = (1 - \bar{p}_{ee})/2 \tag{20}$$

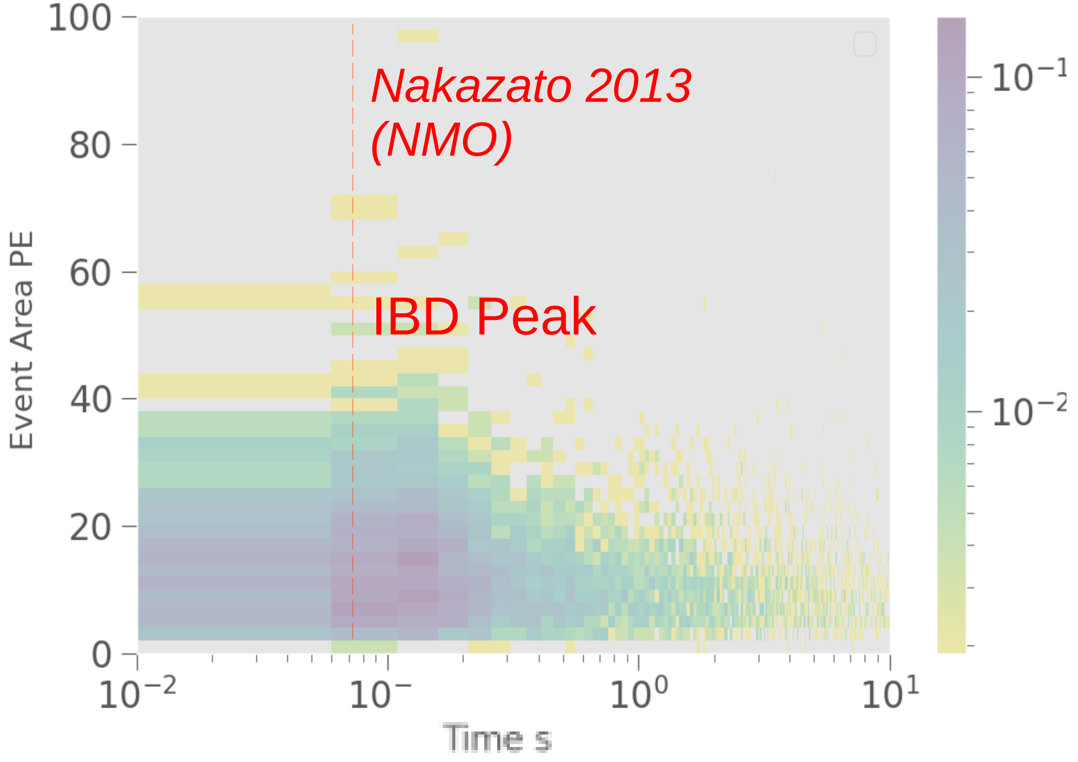
For Inverted mass ordering **IMO** :

$$\bar{p}_{ee} = D_{e3} = sin^2(\theta_{13}) \qquad \bar{p}_{ex} = 1 - \bar{p}_{ee} \qquad \bar{p}_{xx} = (1 + \bar{p}_{ee})/2 \qquad \bar{p}_{xe} = (1 - \tag{21}$$

CCSN Model Discrimination

e+ Muon Veto Event Area vs time for 100 SN





*e+ µ**Veto** a priori possible SN Model distintion…*
Light Curves we expect to have enough statistics to get Luminosities and mean energies.