Progress on Supernova Neutrinos Studies with JUNO

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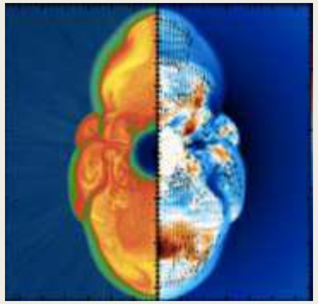
Motivation Summary

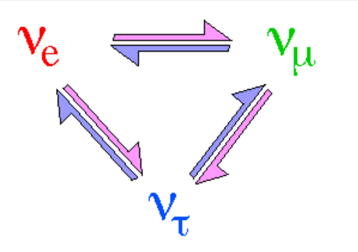
- The core-collapse supernova explosion is still not well understood… numerical studies ongoing

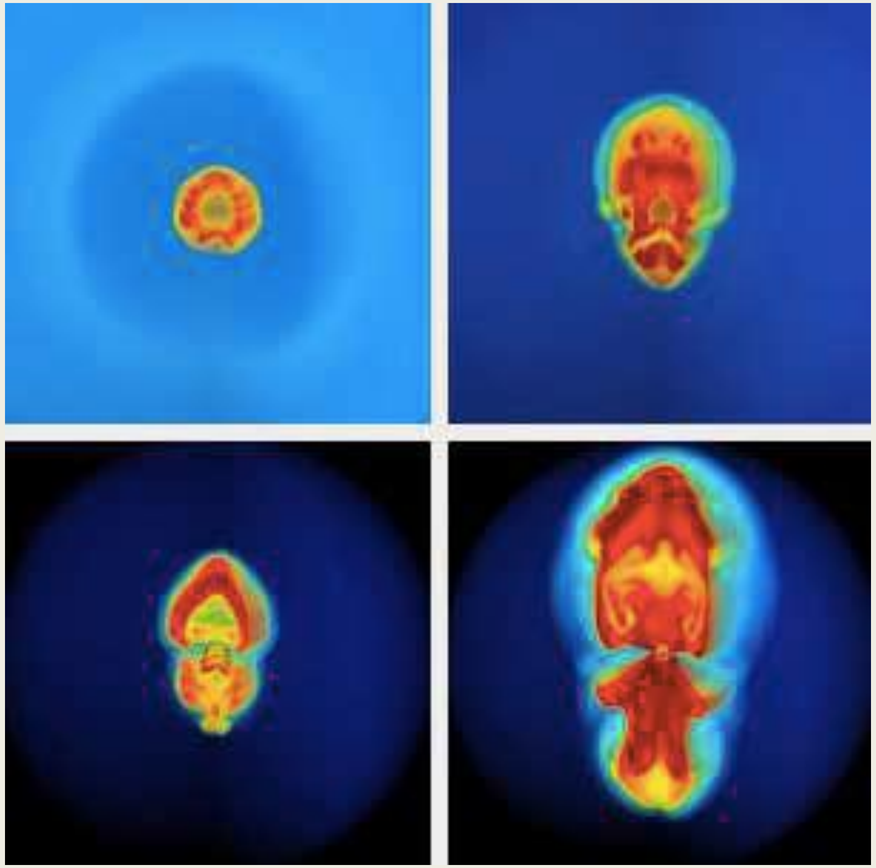
CORE COLLAPSE PHYSICS



WHAT CAN WE LEARN FROM THE NEXT NEUTRINO BURST???

NEUTRINO and OTHER PARTICLE PHYSICS





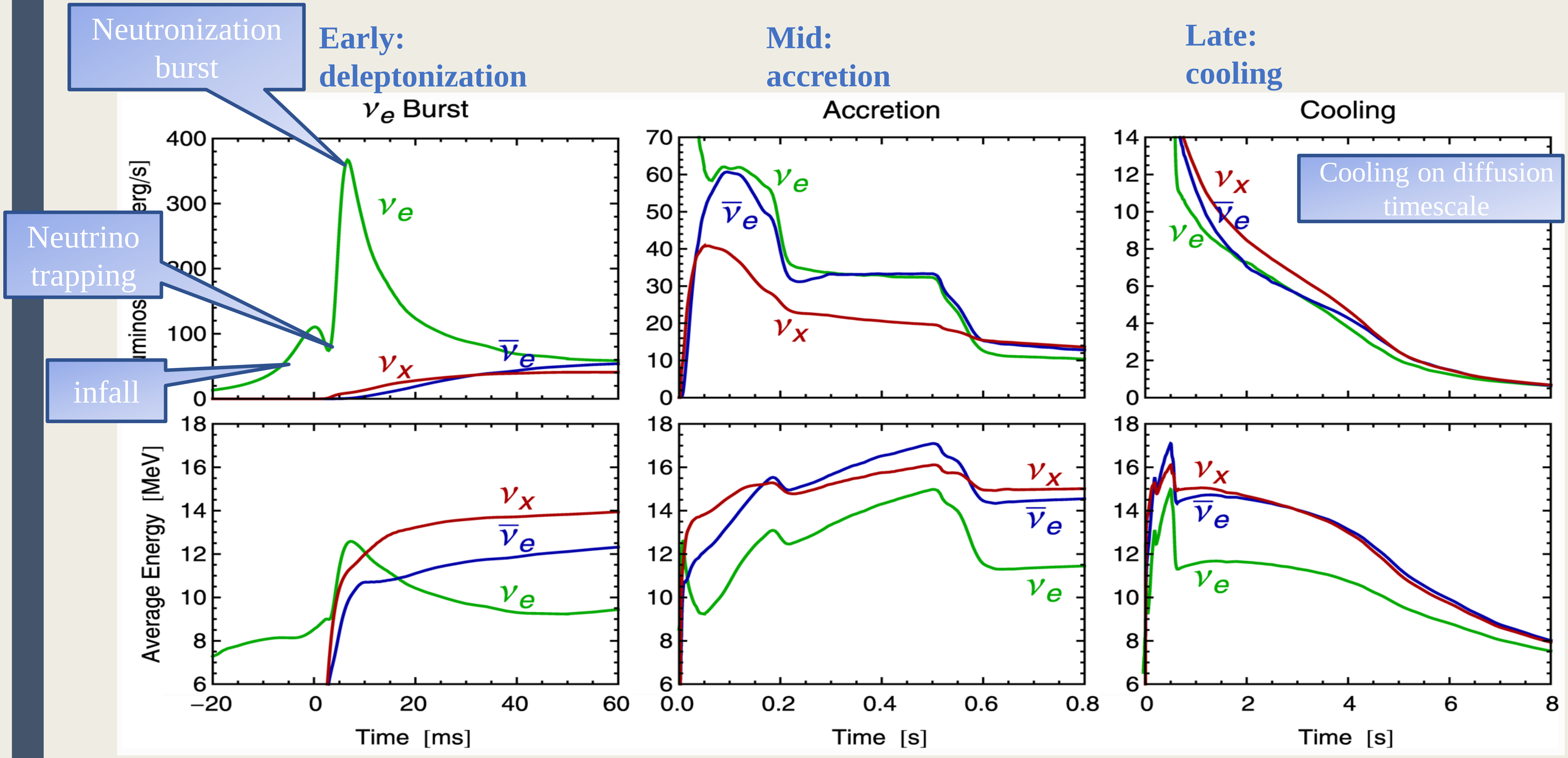
Marek & Janka

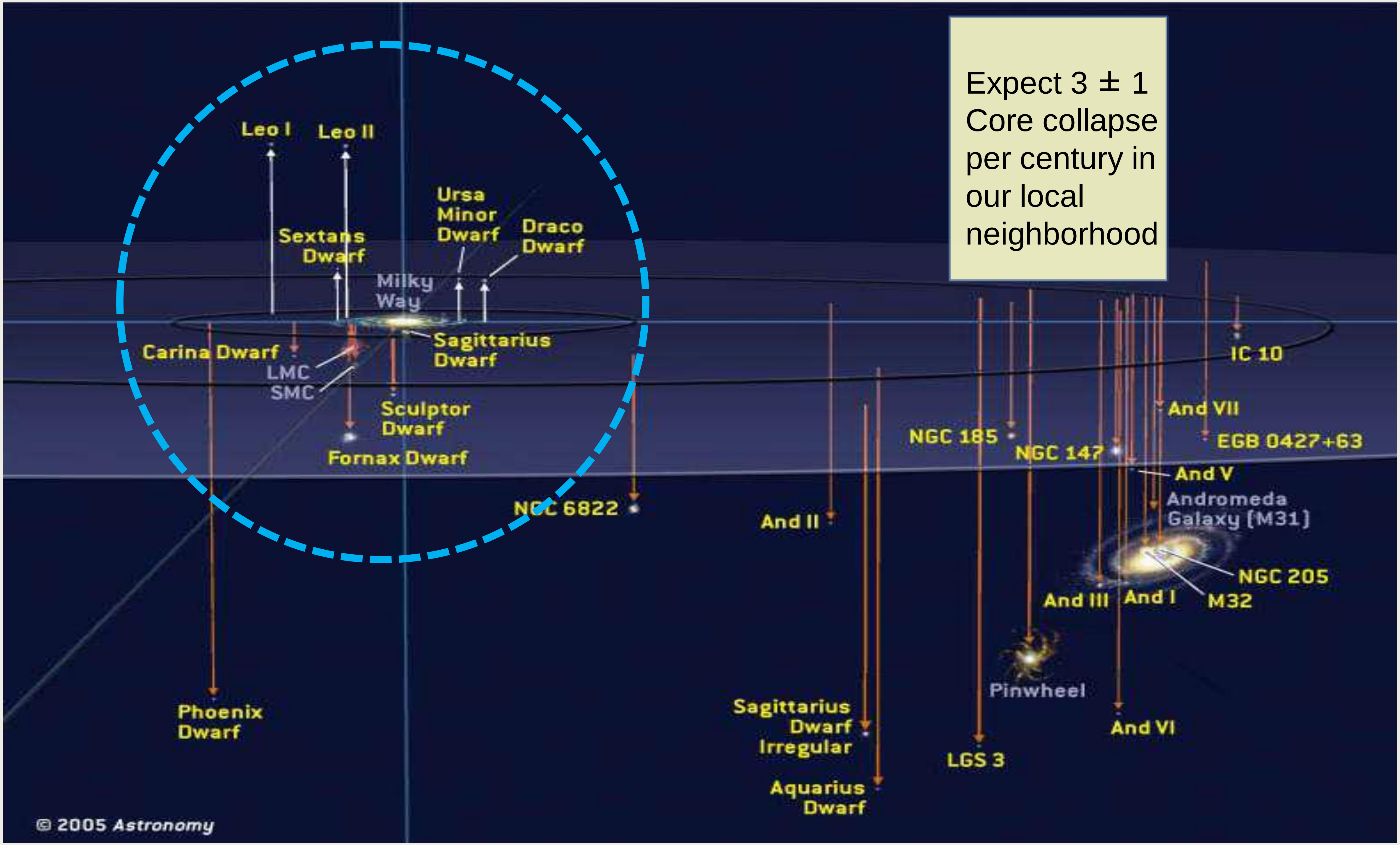
- explosion mechanism

Proto- nstar cooling,
black hole formation
accretion

ν absolute mass (not competitive)
ν mixing from spectra: flavor conversion in SN/Earth
(mass hierarchy)
other ν properties: sterile n's,
magnetic moment,...

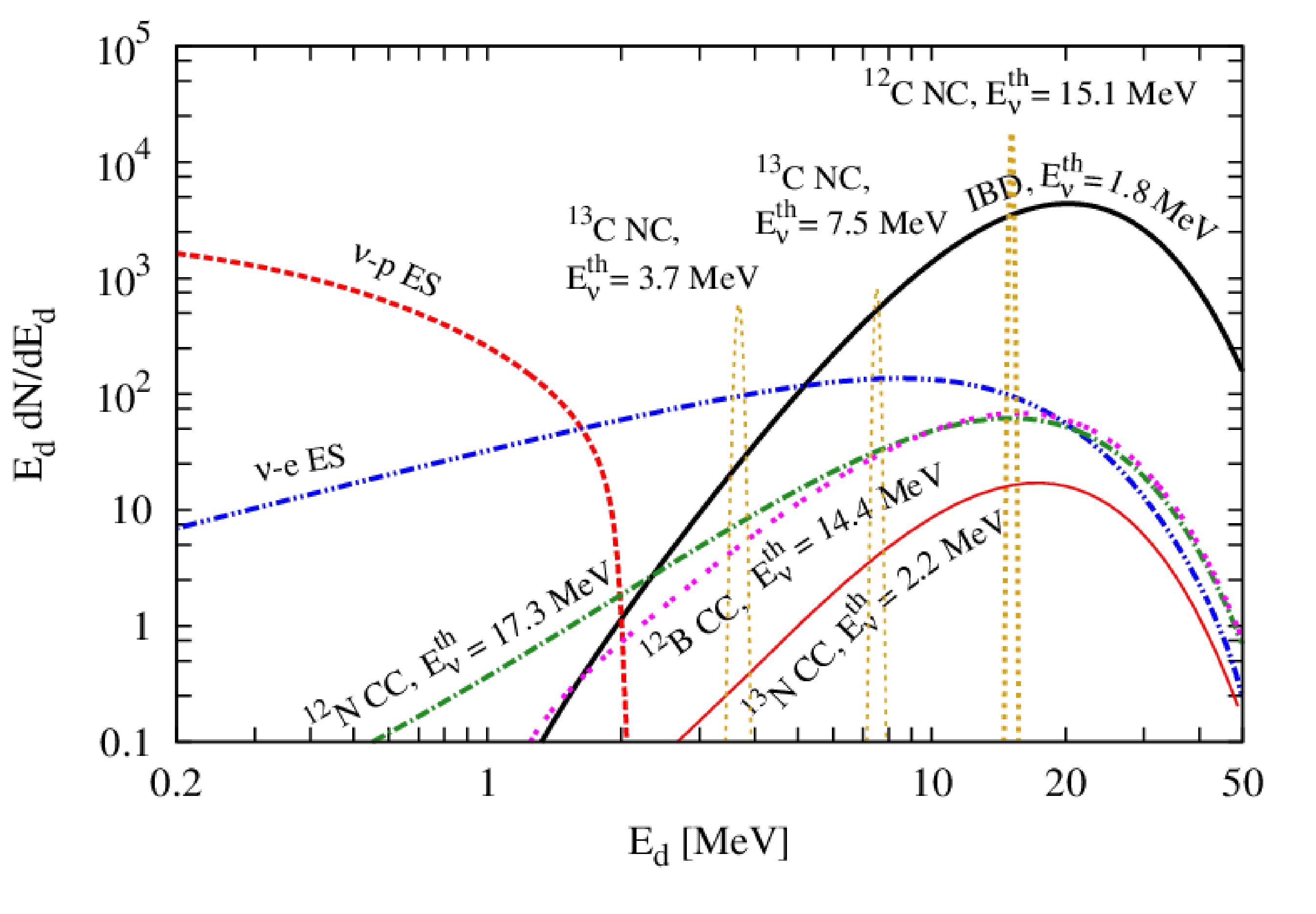
Expected neutrino luminosity and average energy vs time



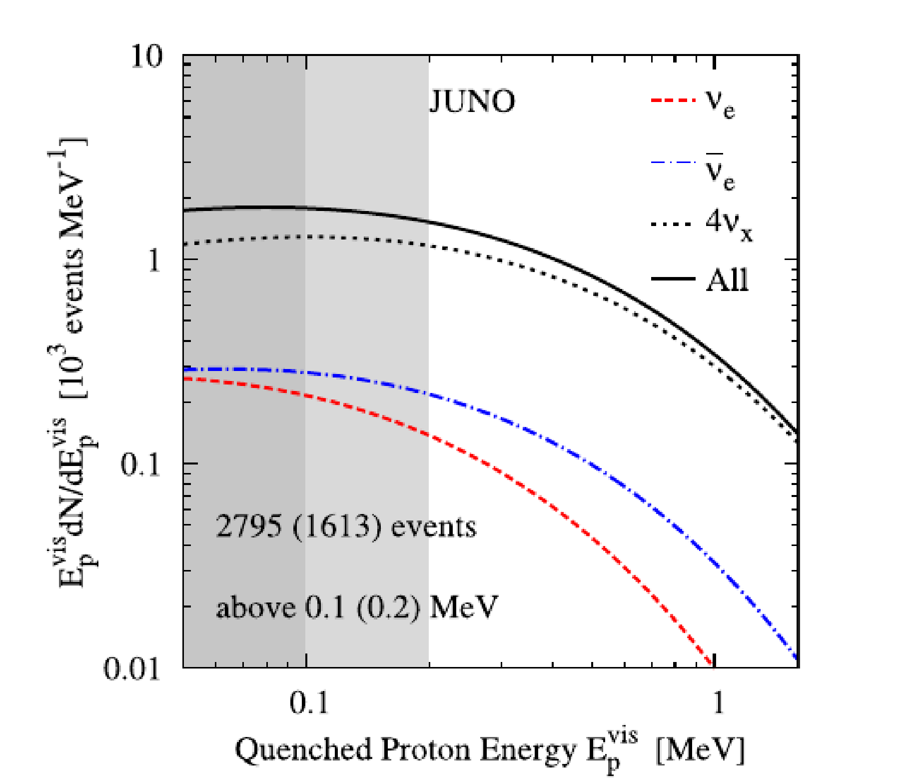


Expect 3 ± 1 Core collapse per century in our local neighborhood

Neutrino Spectrum from a CoreCollapse SN



$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$



- **IBD** dominates at high energy range → **GOLDEN CHANNEL**
- pES more consistent in low energy range

Channels of Detection

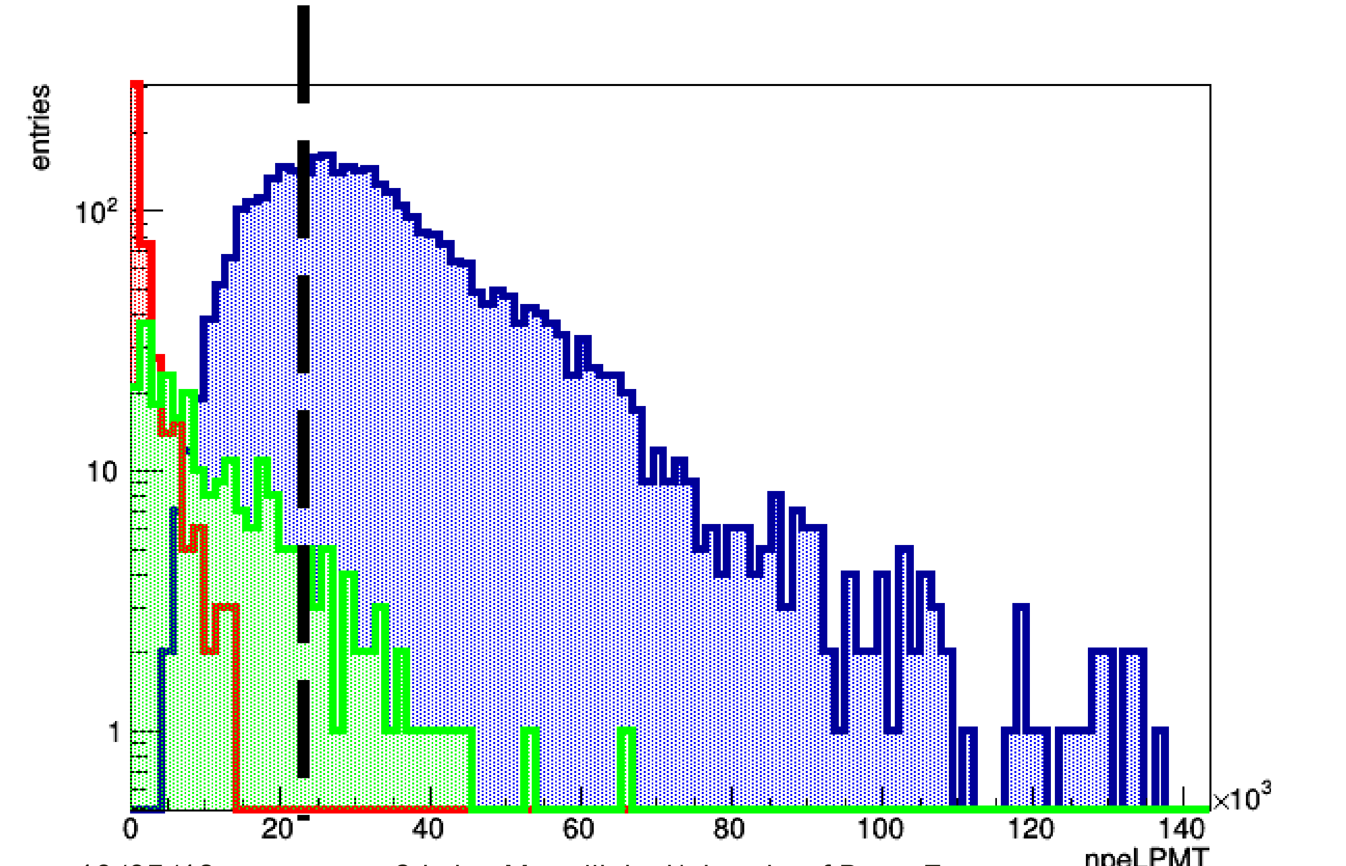
Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	6.0×10^2	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\text{C} \to \nu + {}^{12}\text{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\text{C} \to e^- + {}^{12}\text{N}$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\overline{\nu}_e + {}^{12}\text{C} \to e^+ + {}^{12}\text{B}$	CC	6.0×10^1	1.1×10^2	1.6×10^2

Table: Numbers of neutrinos events in JUNO for a SN at a typical distance of about 10 kpc, where stands for neutrinos and antineutrinos of all flavours. Three representative values of the average neutrino energy = 12 MeV, 14 MeV and 16 MeV are taken for illustration, where in each case the same average energy is assumed for all flavours and neutrino flavour conversions are not considered. For the elastic neutrino-proton scattering , a threshold of 0.2 MeV for the proton recoil energy is chosen.

What's been done

- Using the SN neutrino generator implemented in the JUNO Software (J18v1-Pre1), we generated a SN sample

■ $M = 20\ M_{\odot}$	Z= 0.004	D= 10 kpc



- ➢ **NPE for Large PMT** distribution for the three main channels is shown on the left
- ➢ Evident different distributions of the Number of PE for the three main channels

This net separation at high energy allows us to select a fiducial cut on the Energy, therefore directly on our observable

$$NPE_{LPMT} > 20 \times 10^3$$

Unfolding of Observed Spectra

- We need an unfolding algorithm to extract the energy spectrum
- Starting selecting the observables of interest, we want to reconstruct the original neutrino energy

In our case the probability of having an $\overline{\nu_e}$ of a given energy E_ν coming from an IBD is:

$$P_{IBD}(E_{\overline{\nu}_e}) \propto \int_{E_{min}}^{E_{max}} P_{IBD}\left(E_{\overline{\nu}_e} \middle| E_0\right) \cdot P_{IBD}(E_0) \cdot dE_0$$

IBD Channel

Where the conditional probability $P_{IBD}\left(E_{\overline{\nu}_e} \middle| E_0\right)$ is the detector response matrix:

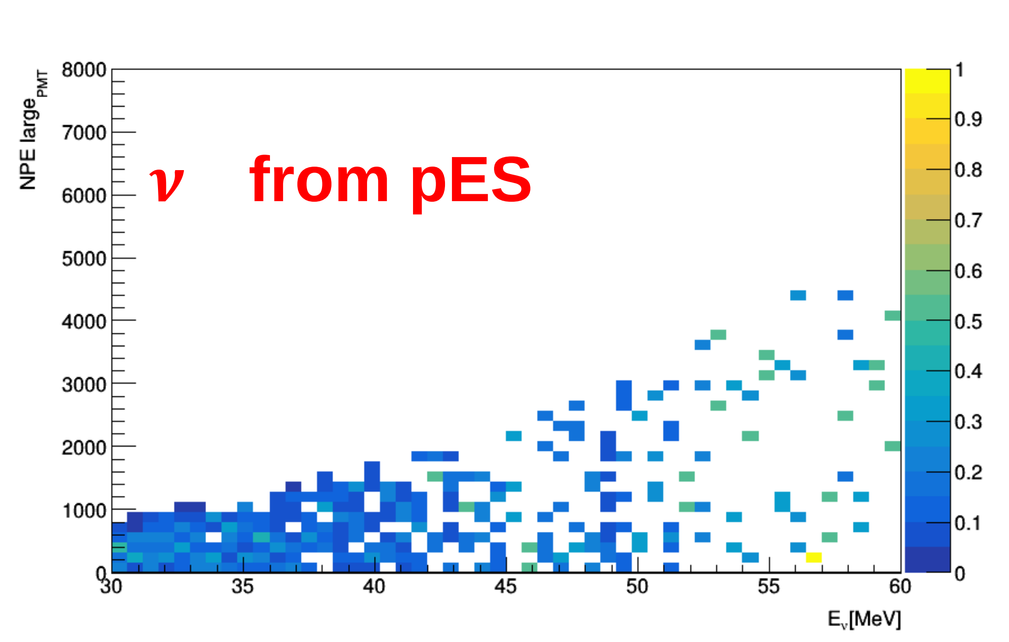
$$A_{ji} = P_{IBD}\left(N_{PE_j} \middle| E_{\nu_i}\right)$$

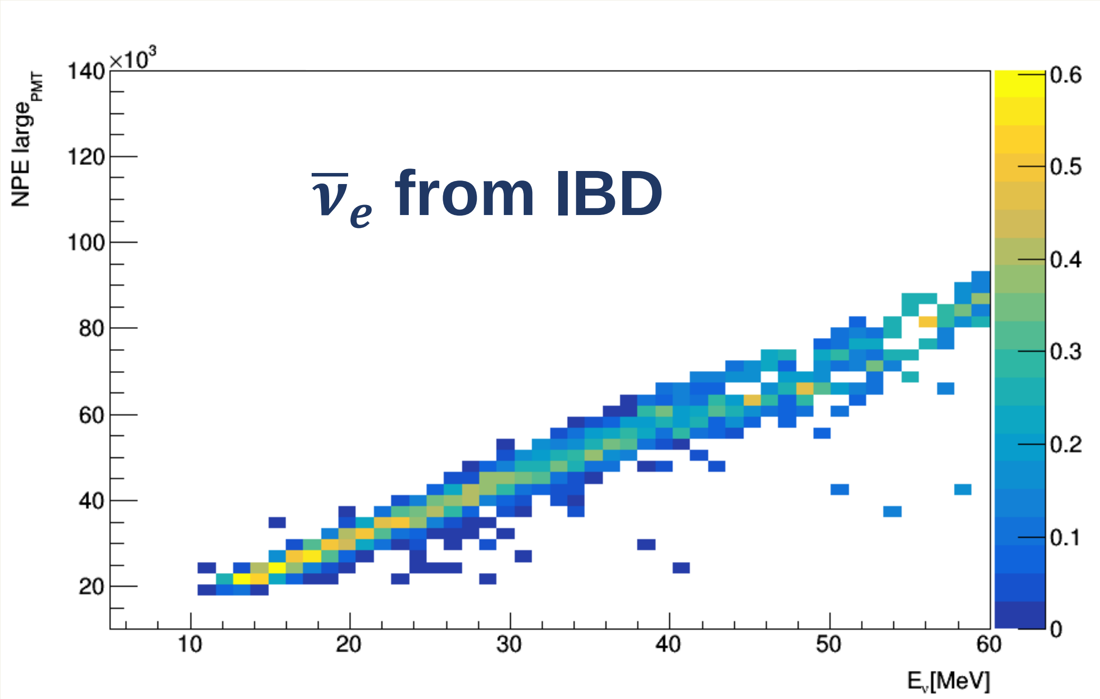
Using N_{PE} as an energy estimator and $\sum_j A_{ji} = 1 \cdot \epsilon$

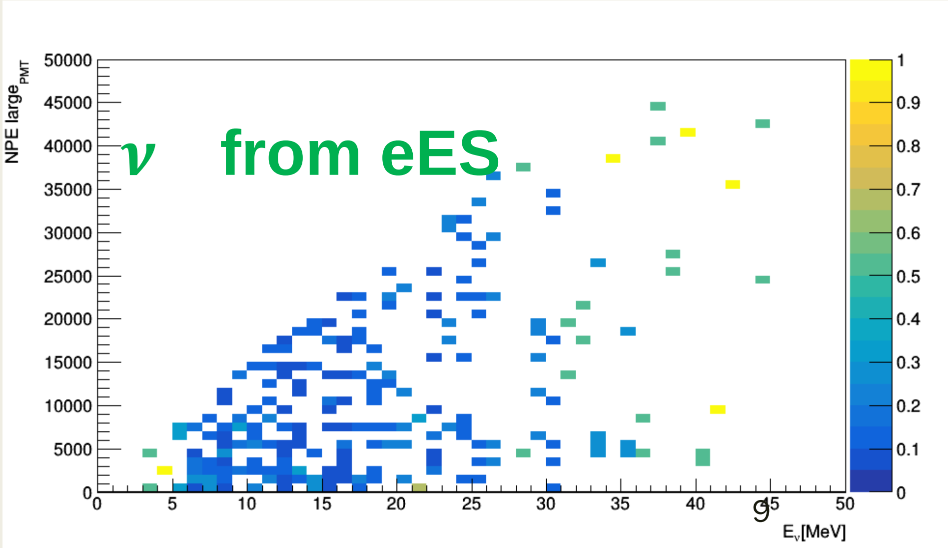
Spectrum Unfolding

- For each channel we can build the likelihood matrix **A,** and the 3 main channels for a CC SN are:

- $\bar{\nu}_e$ **from IBD**
- ν **from pES**
- ν **from eES**



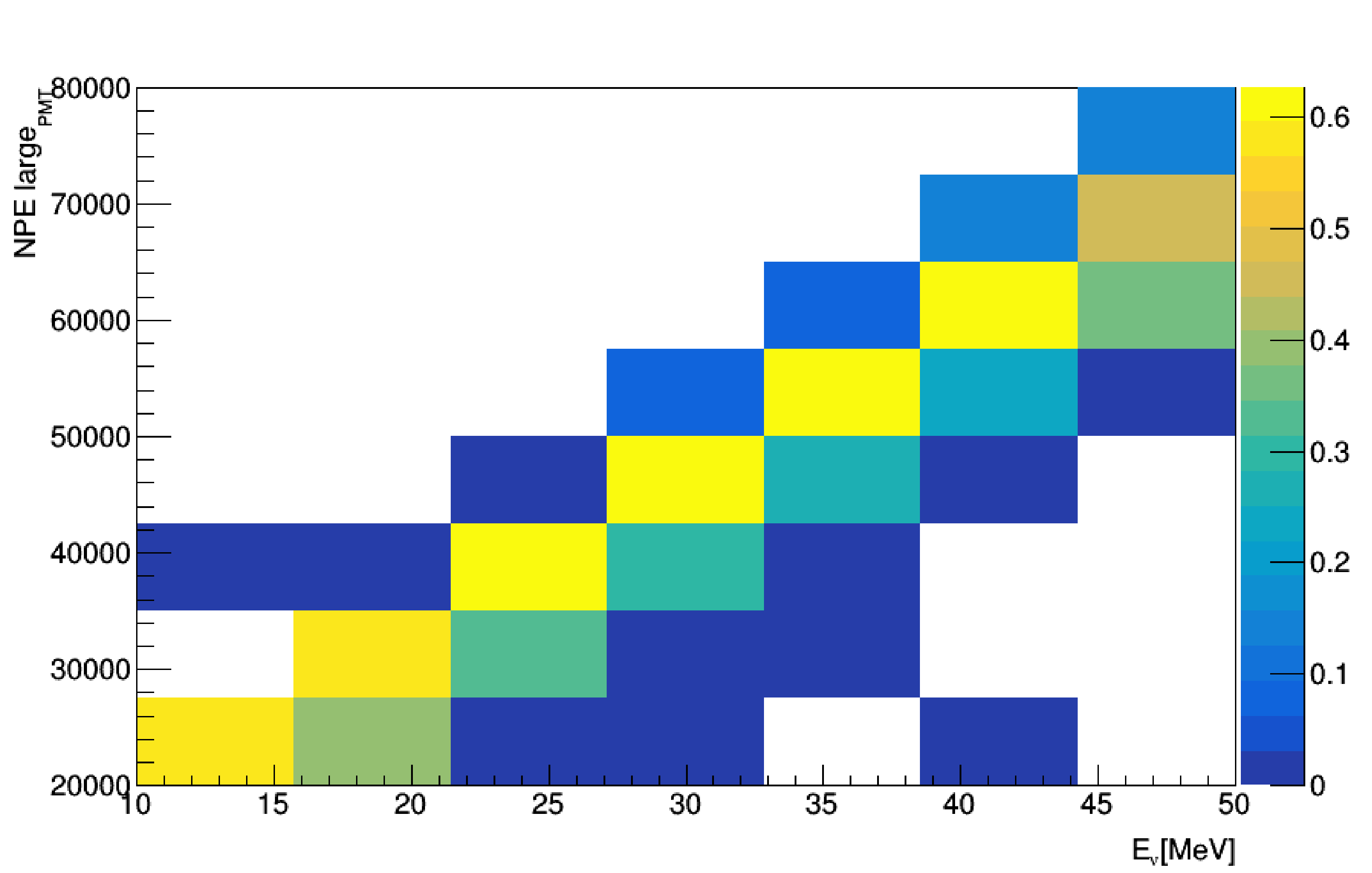




Spectrum Unfolding

- Based on the fiducial cut and on the result of the likelihood matrix, the $\bar{\nu}_e$ from IBD has been considered

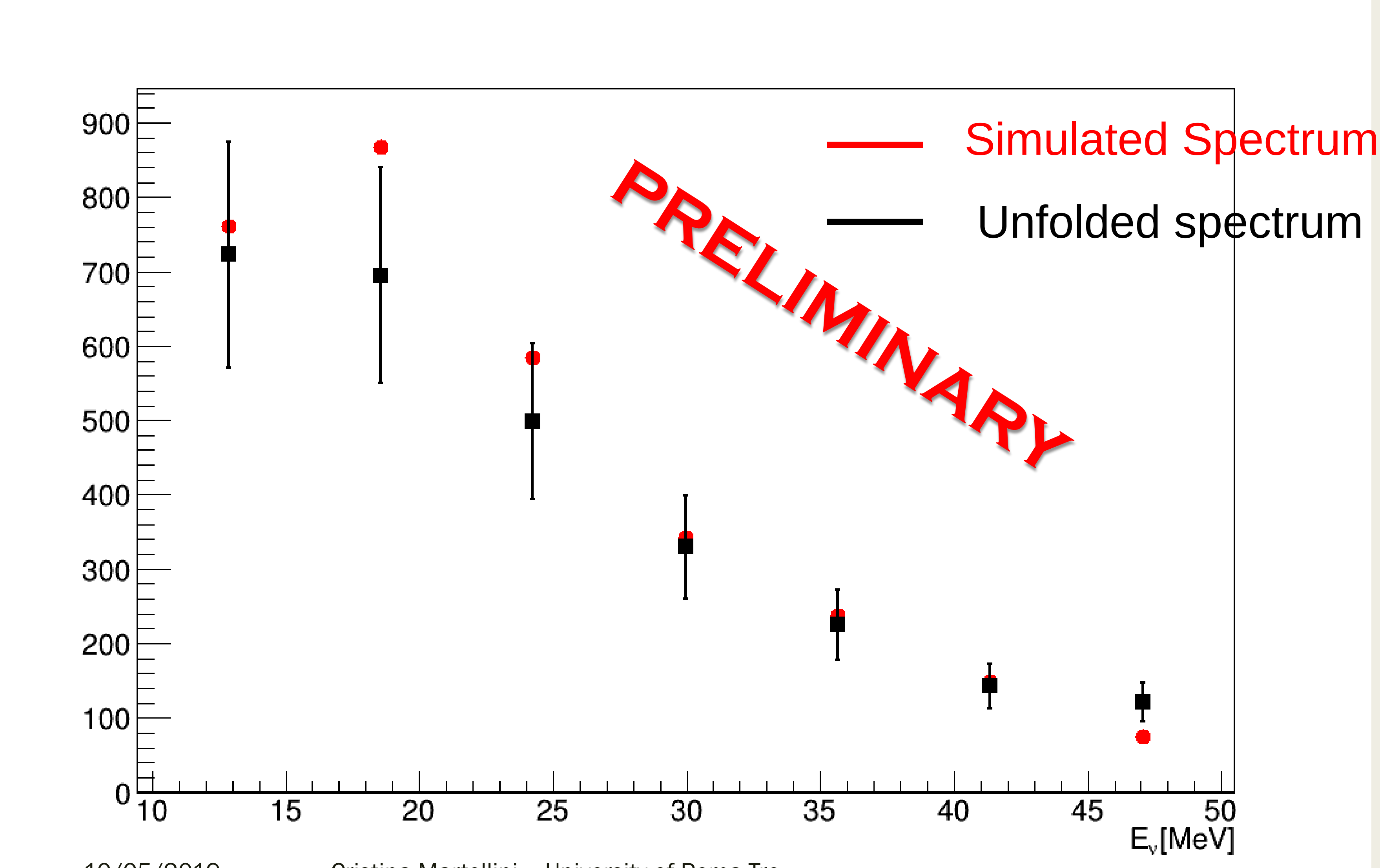
Selecting a region of interest of : $NPE_{LPMT} > 20000\ NPE$



- **We selected 7 energy bins for the spectrum unfolding**

Spectrum Unfolding

- We selected an Energy Range of **10 MeV – 50 MeV**



- Uncertainties to be refined
- Introduction of the model uncertainties as a next step

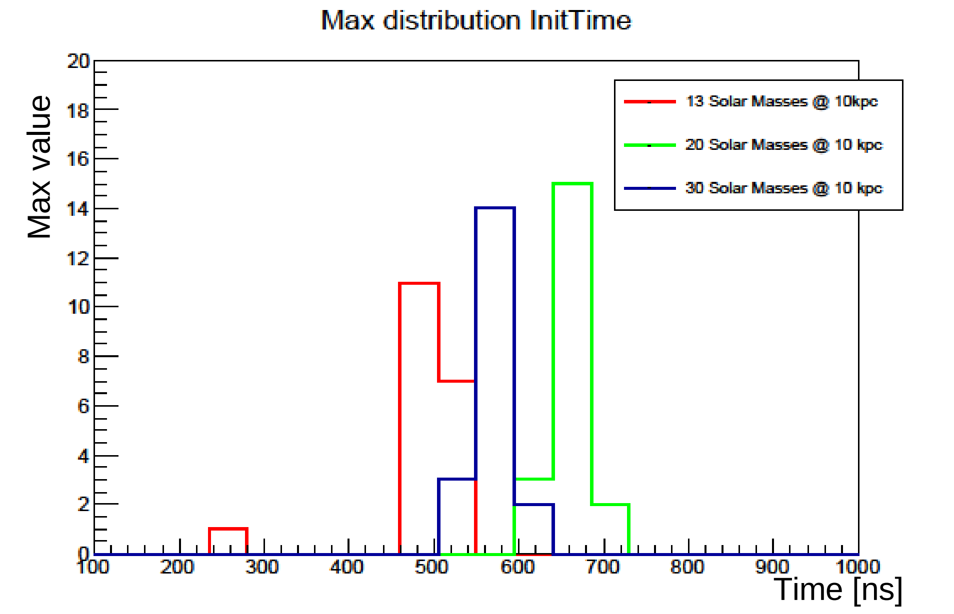
What's been done next

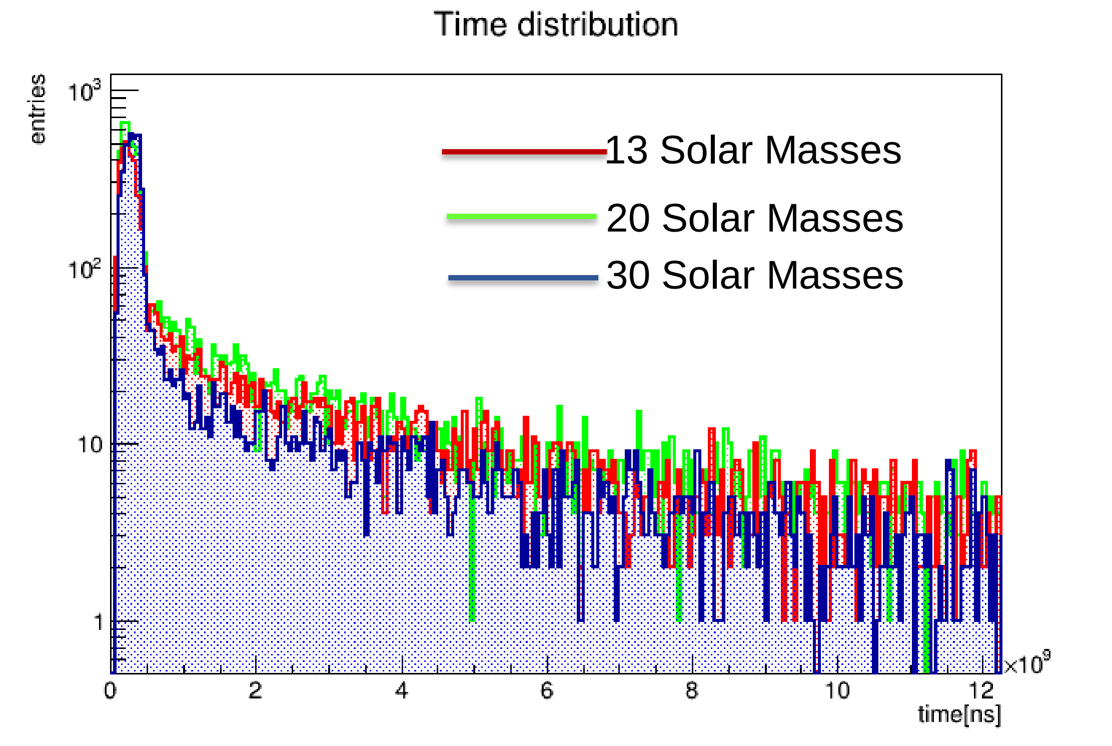
- Using the SN neutrino generator implemented in the JUNO Software (J18v1-Pre1), we generated different samples of three different SN:
  - M = $13_{M_\odot}$ M= $20_{M_\odot}$ M= $30_{M_\odot}$

For each of these samples we carried out two different approaches:

- First we simulated all of them at the same distance → D= 10 Kpc

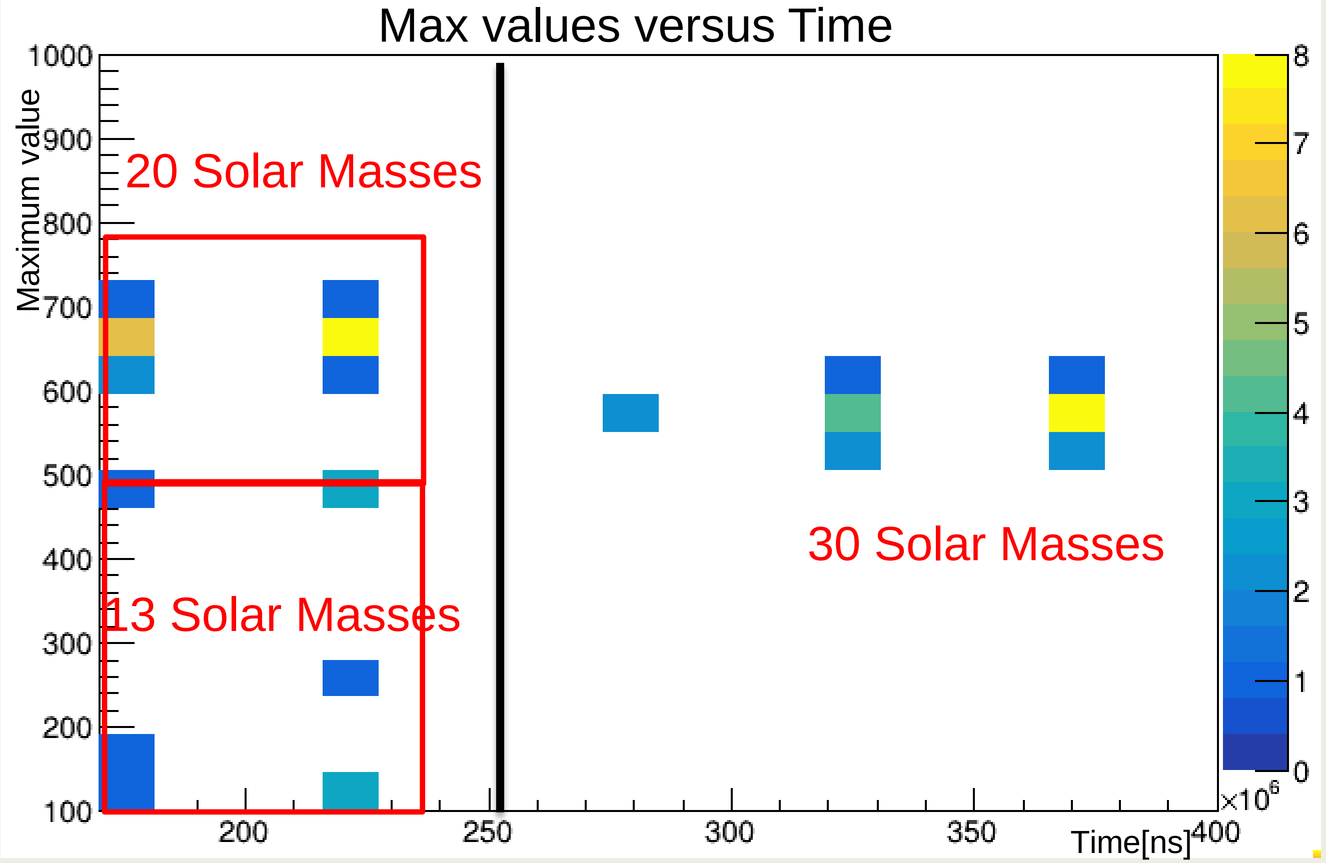
and look for a correlation as a function of time





What's been done next

Given the fact that the time distributions are basically undistinguishable, but they differ on the maximum values of the distributions



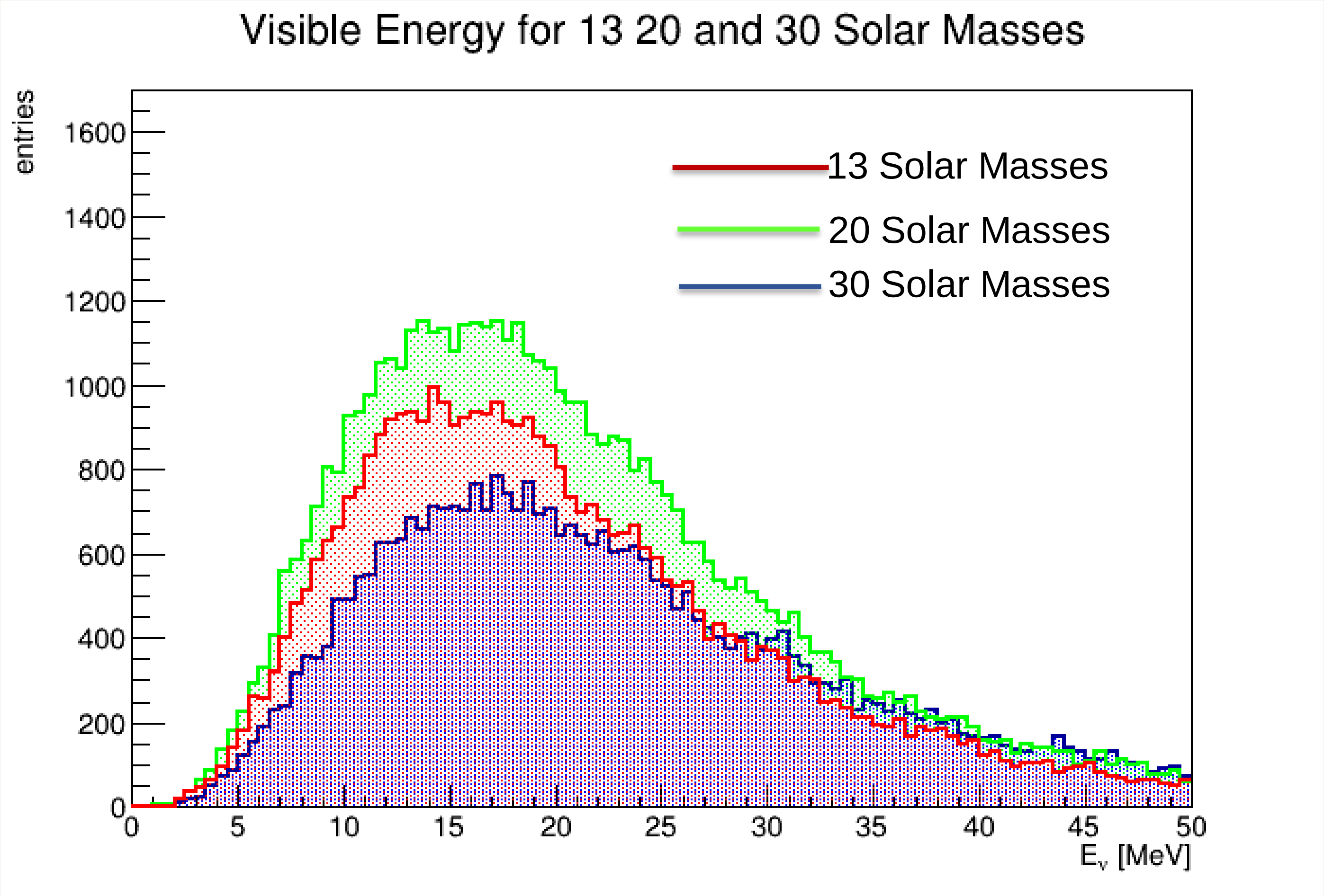
We built a matrix to have a look at the maximum values of the 3 distributions as a function of the time

What's been done next

- In first approssimation we are able to identify different SN type in distance through the Energy spectra

- Identify different masses progenitors is still under study

- In first approssimation we can identify SN which go to NS or BH. For what concerns distinguish different progenitors at the same distance that goes to NS we are still working on the algorithm



Summary and Conclusions

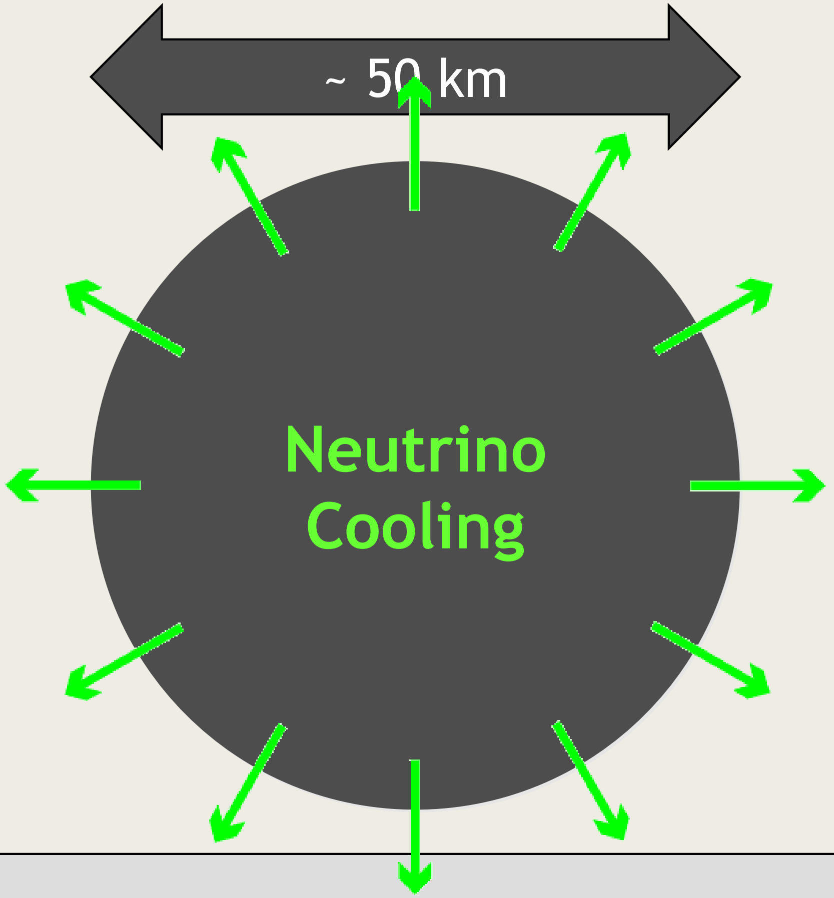
- CCSN neutrino events can be studied in separated channels
- Energy spectrum features for the different channels allowed us a first fiducial cut
- A further improved discrimination tool needs to be developed to isolate the different channels of the SN
- Further studies are needed on the other channels through the Bayesian approach to establish the possibility of different channels likelihood construction.
- The preliminary results from the unfolded spectra show promising prospectives

THANK YOU FOR YOUR ATTENTION

BACK UP SLIDES

Introduction to Supernova neutrinos

Newborn Neutron Star



Proto-Neutron Star

$\rho \approx \rho_{nuc} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

Gravitational binding energy

$E_b \approx 3 \times 10^{53}$ erg $\approx$ 17% $M_{SUN}\, c^2$

This shows up as

99% Neutrinos

1% Kinetic energy of explosion
(1% of this into cosmic rays)

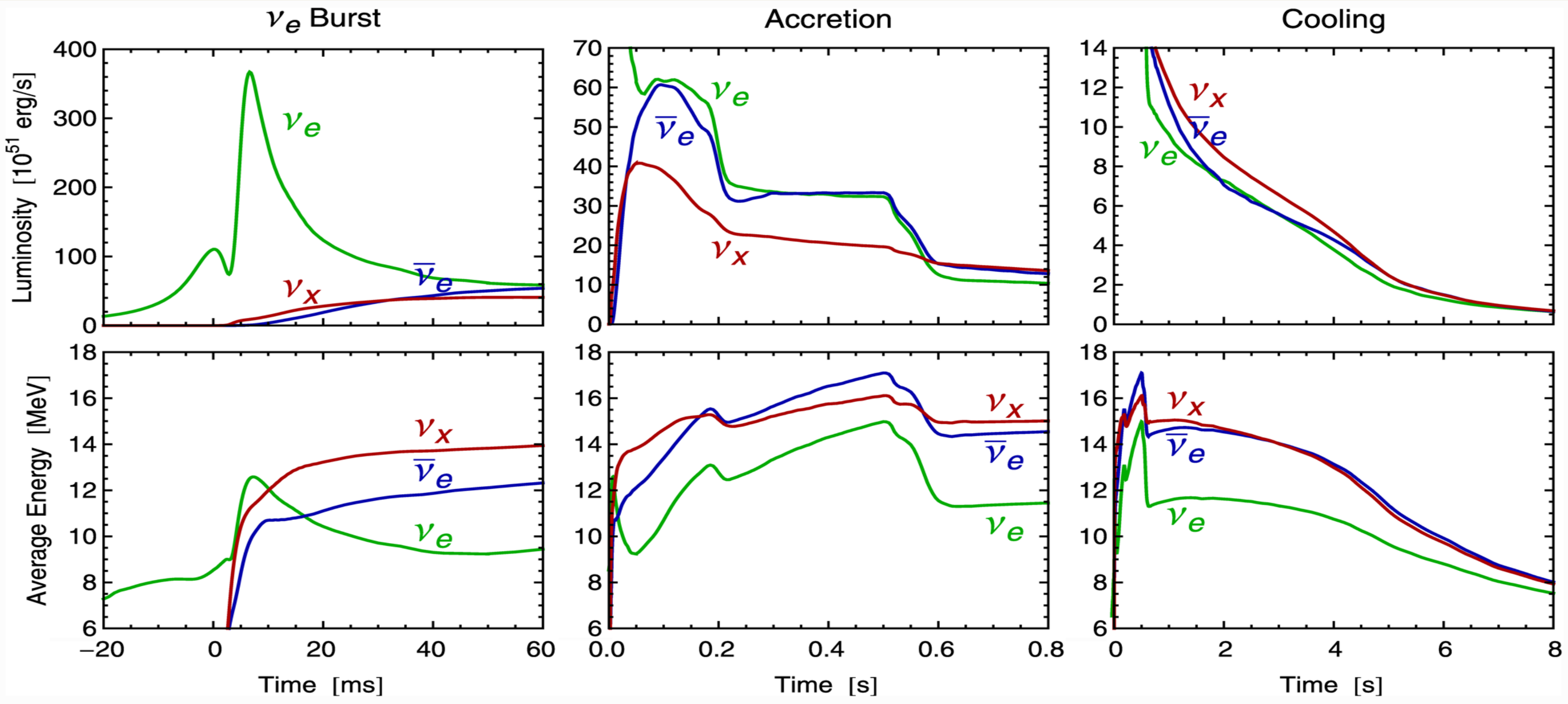
0.01% Photons, outshine host galaxy

Neutrino luminosity

$L_\nu \approx 3 \times 10^{53}$ erg / 3 sec
$\approx 3 \times 10^{19}\ L_{SUN}$

While it lasts, outshines the entire visible universe

Expected neutrino luminosity and average energy vs time



Supernovae Models

- We chose three different progenitors masses

M = 13 $M_\odot$ → Z= 0.02, Z= 0.004 → t_{revive}= 300 ms $\begin{cases} 2\ kpc \\ 10\ kpc \\ 20\ kpc \end{cases}$

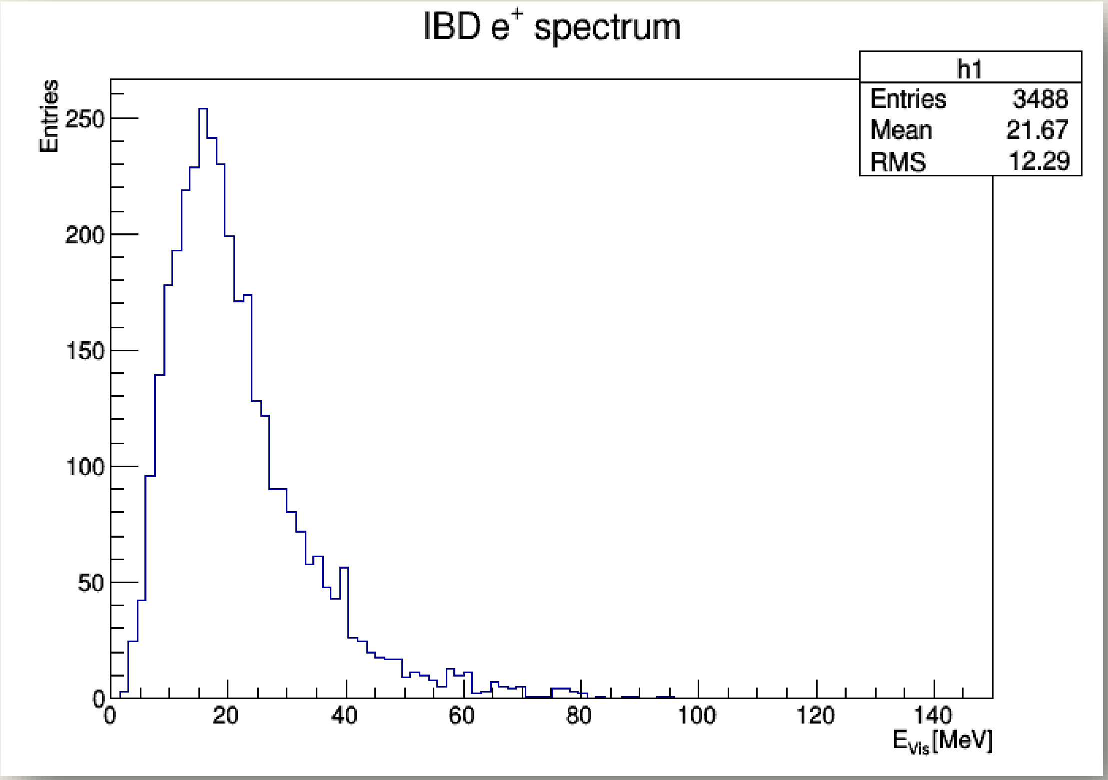
M = 20 $M_\odot$ → Z= 0.02, Z= 0.004 → t_{revive}= 300 ms $\begin{cases} 2\ kpc \\ 10\ kpc \\ 20\ kpc \end{cases}$

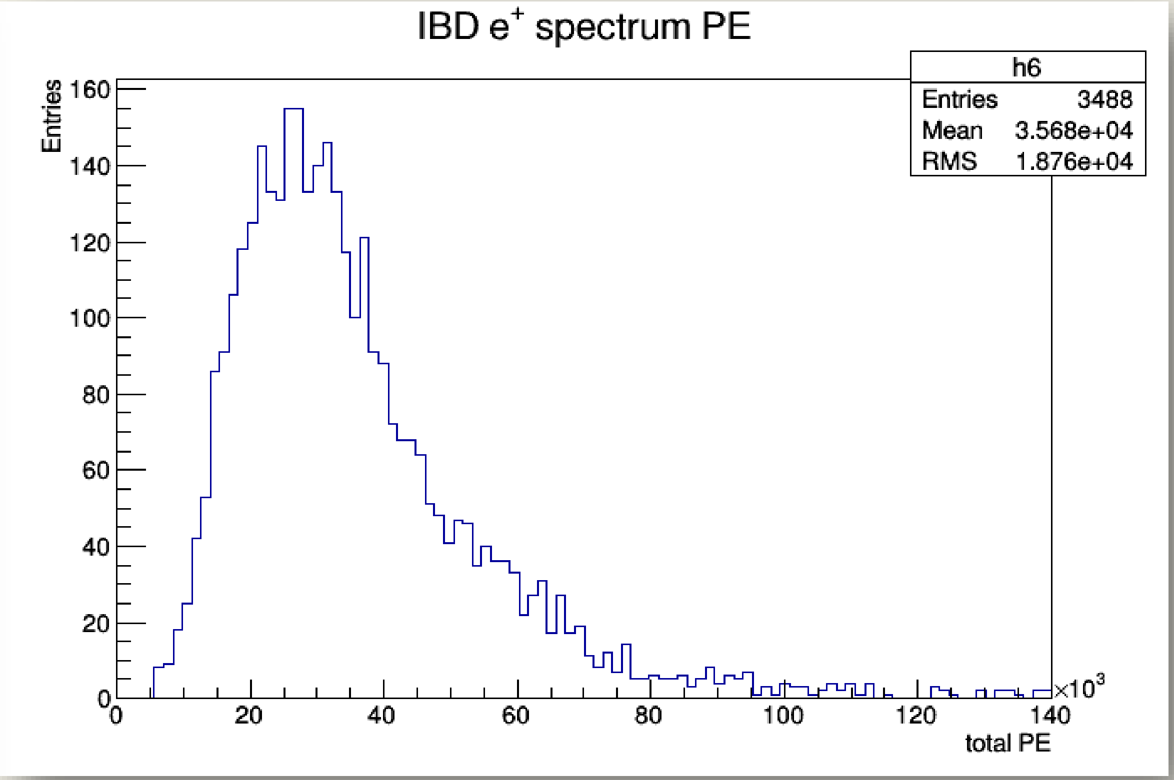
M = 50 $M_\odot$ → Z= 0.02, Z= 0.004 → t_{revive}= 300 ms $\begin{cases} 2\ kpc \\ 10\ kpc \\ 20\ kpc \end{cases}$

18 Supernova bursts!

Supernova Example Spectra

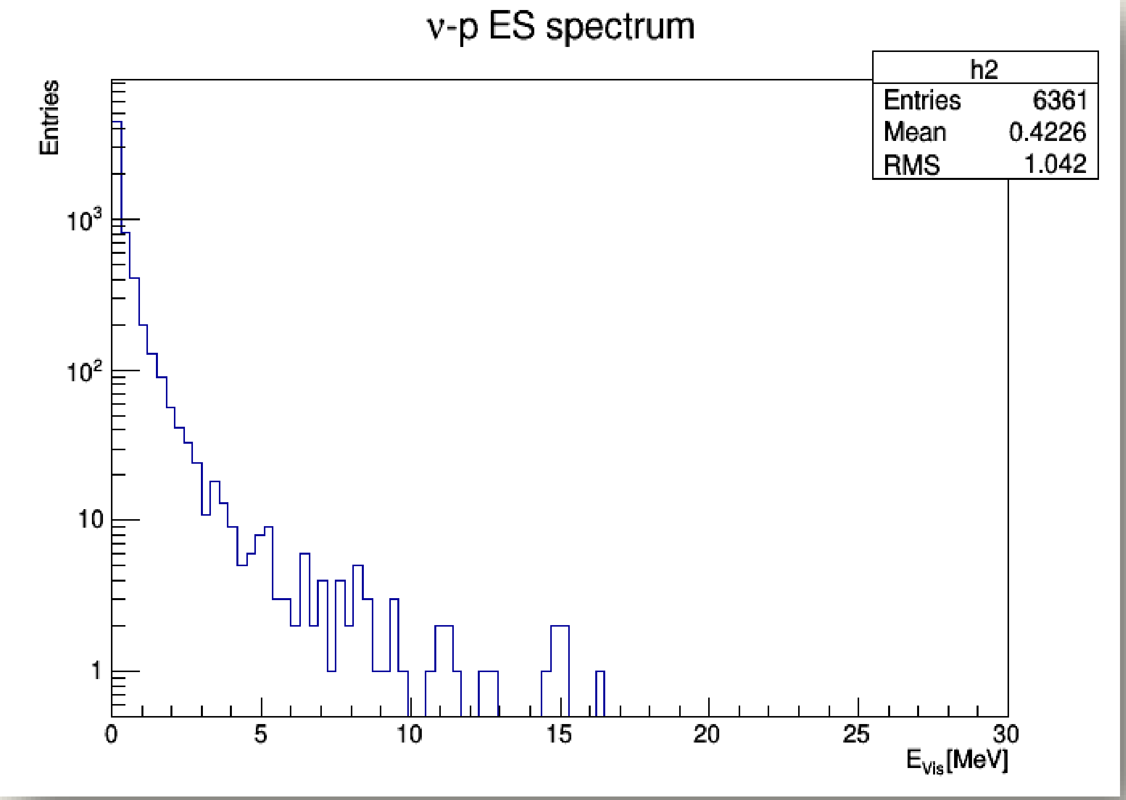
- $M = 20\ M_{\odot}$ Z= 0.004 D= 10 kpc

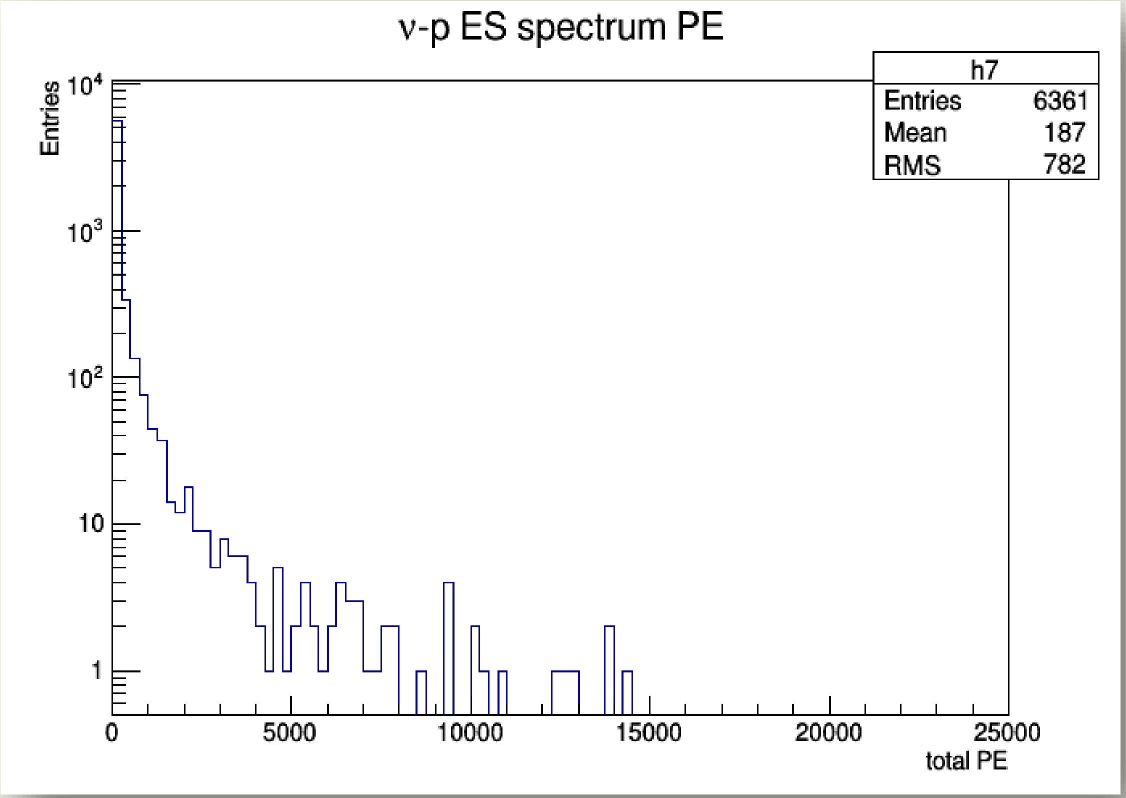




p spectrum from $\nu - p\ ES$

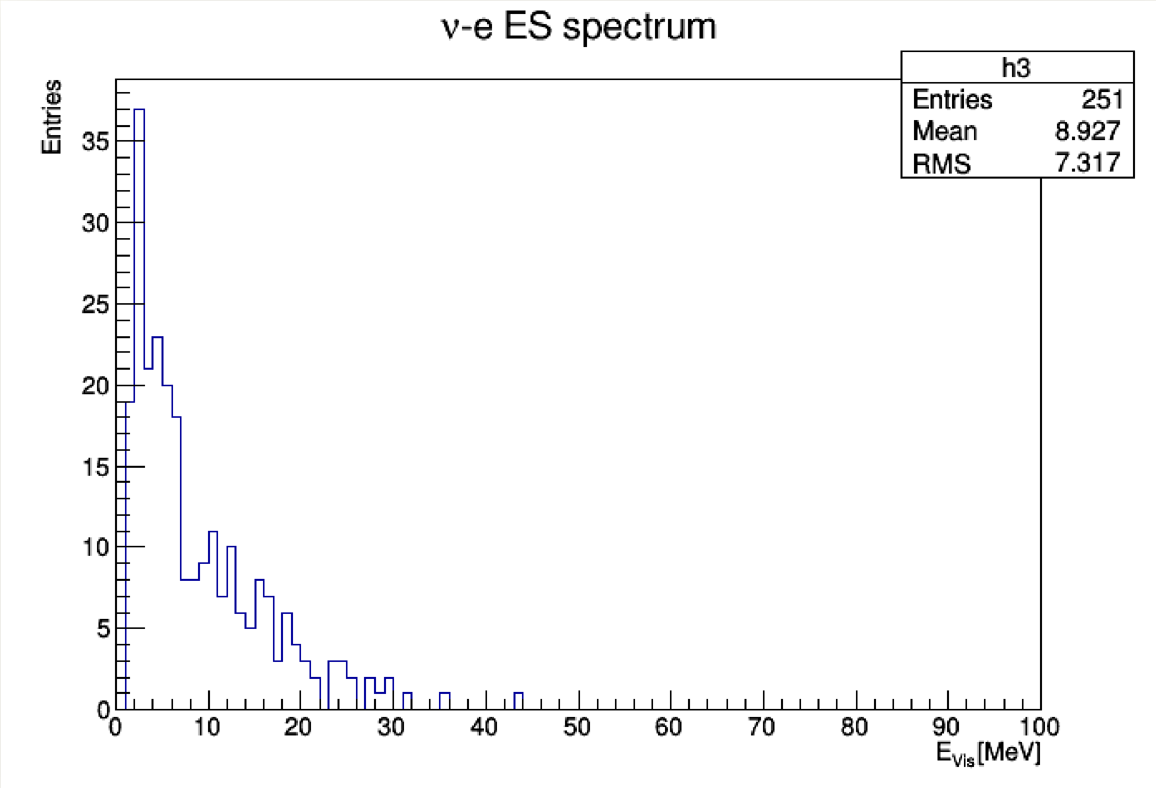
- $M = 20\ M_{\odot}$ Z= 0.004 D= 10 kpc

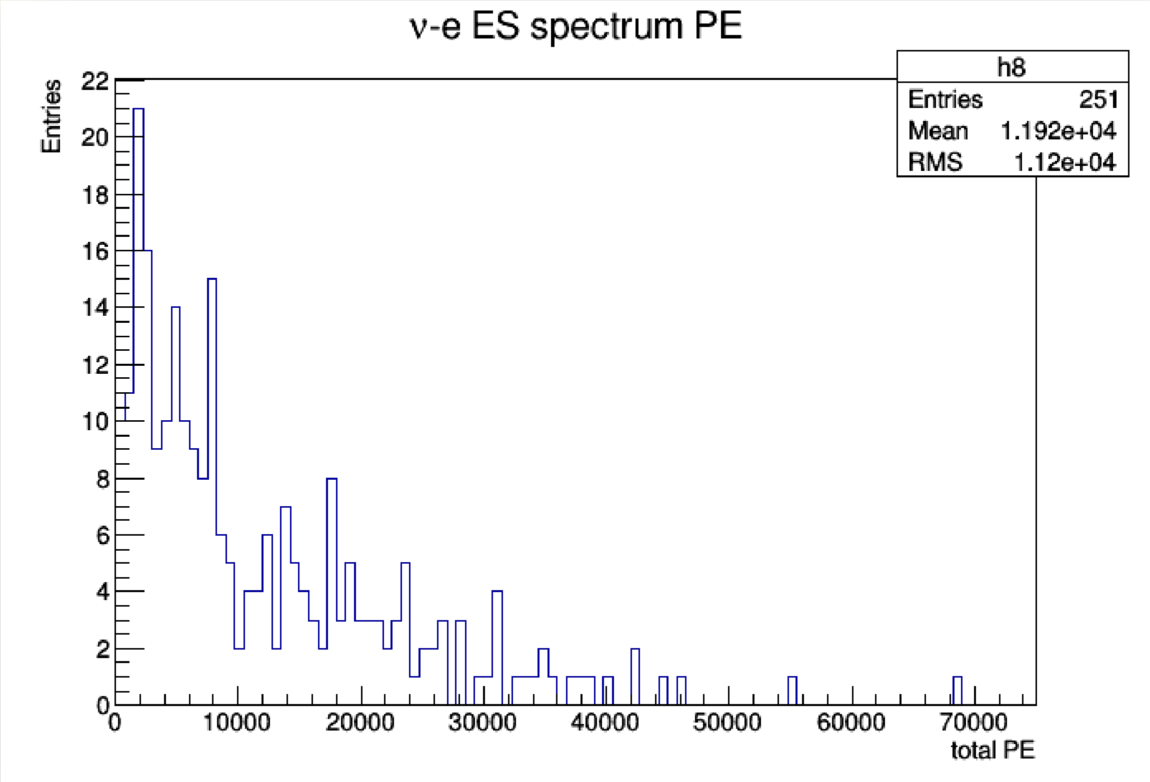




e^- spectrum from $\nu - e$ ES

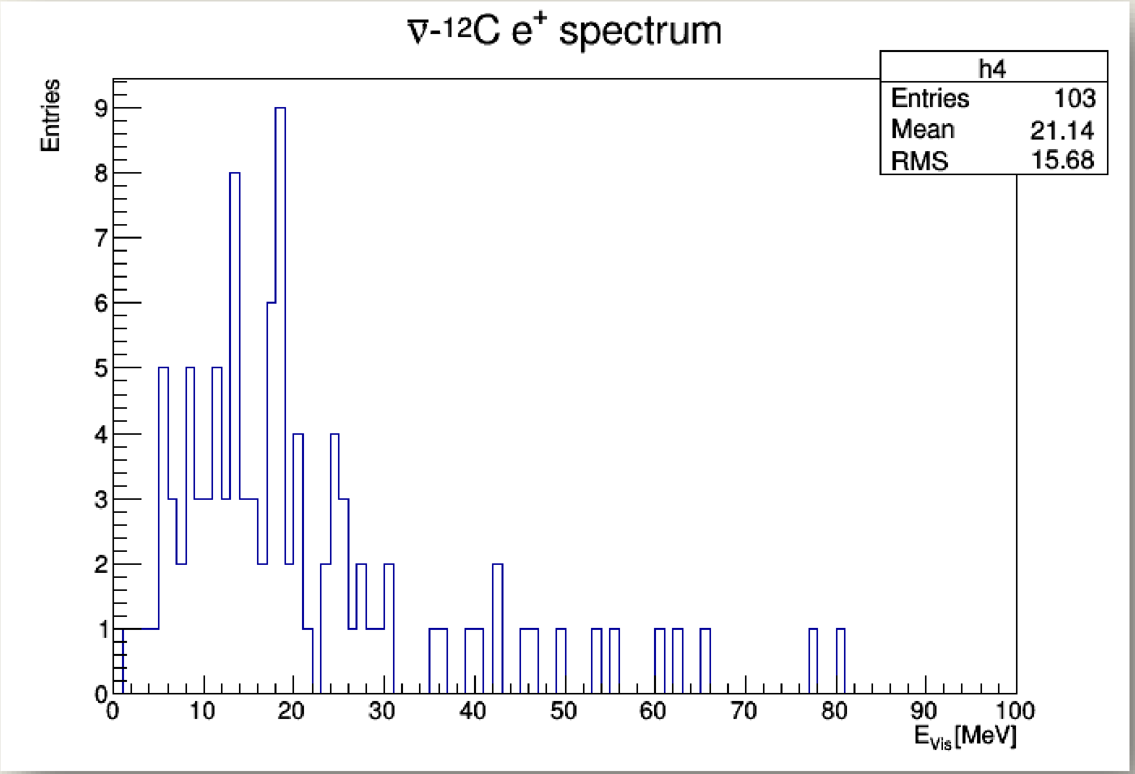
- $M = 20\ M_{\odot}$ Z= 0.004 D= 10 kpc

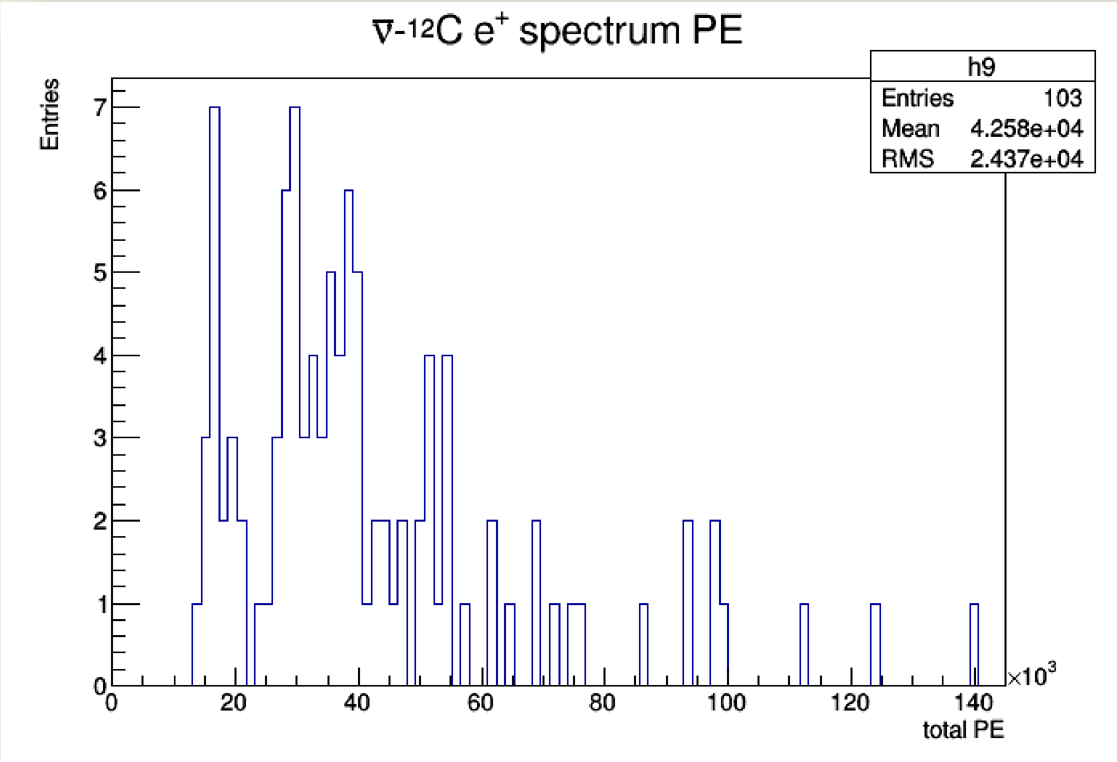




e^+ spectrum from $\bar{\nu} - {}^{12}C$ scattering

- $M = 20\, M_\odot$ Z= 0.004 D= 10 kpc





e^{-} spectrum from $\nu - {}^{12}C$ scattering

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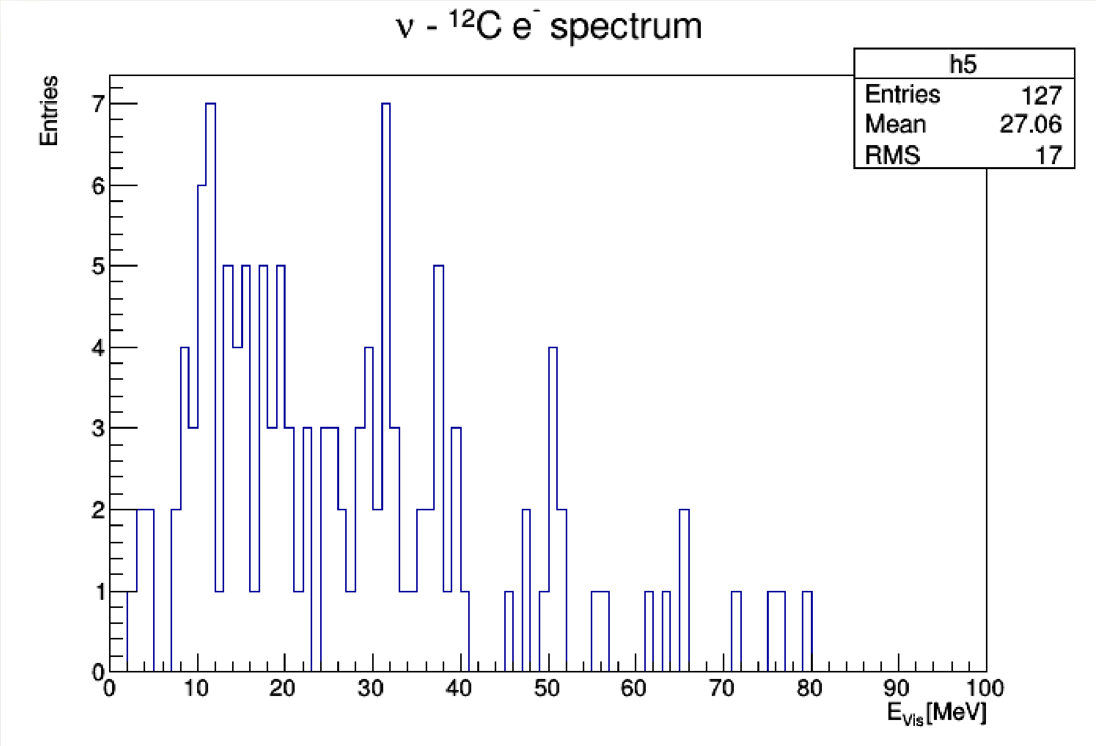
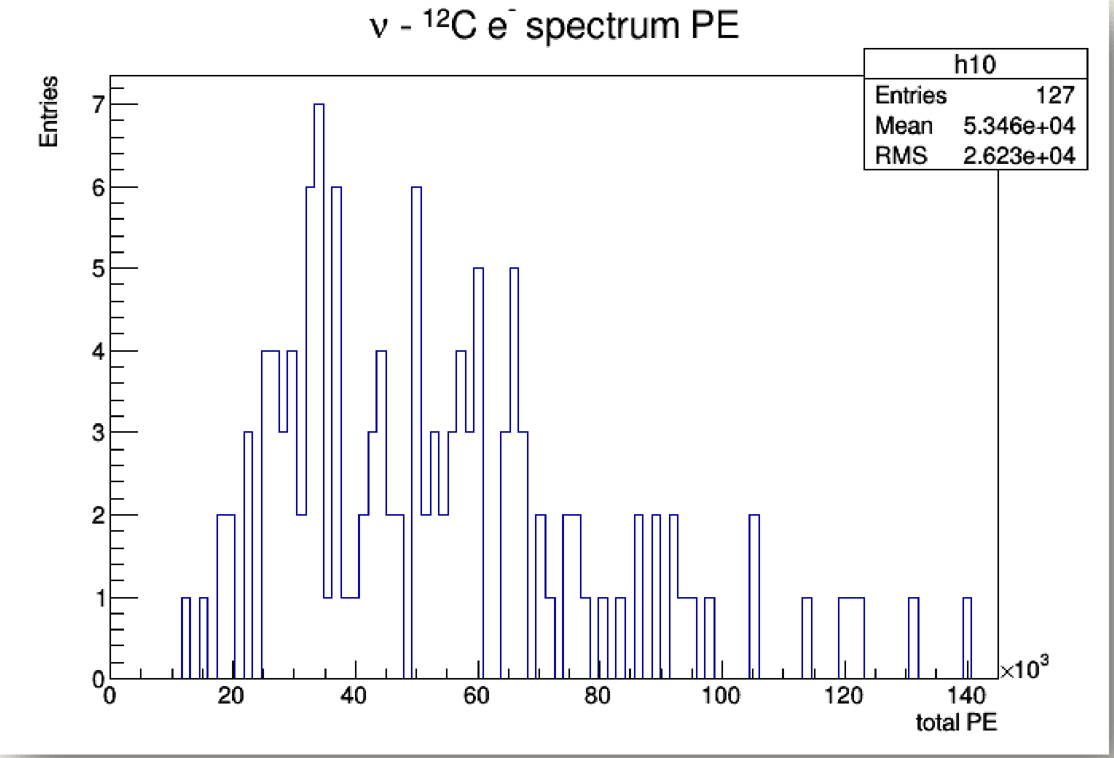
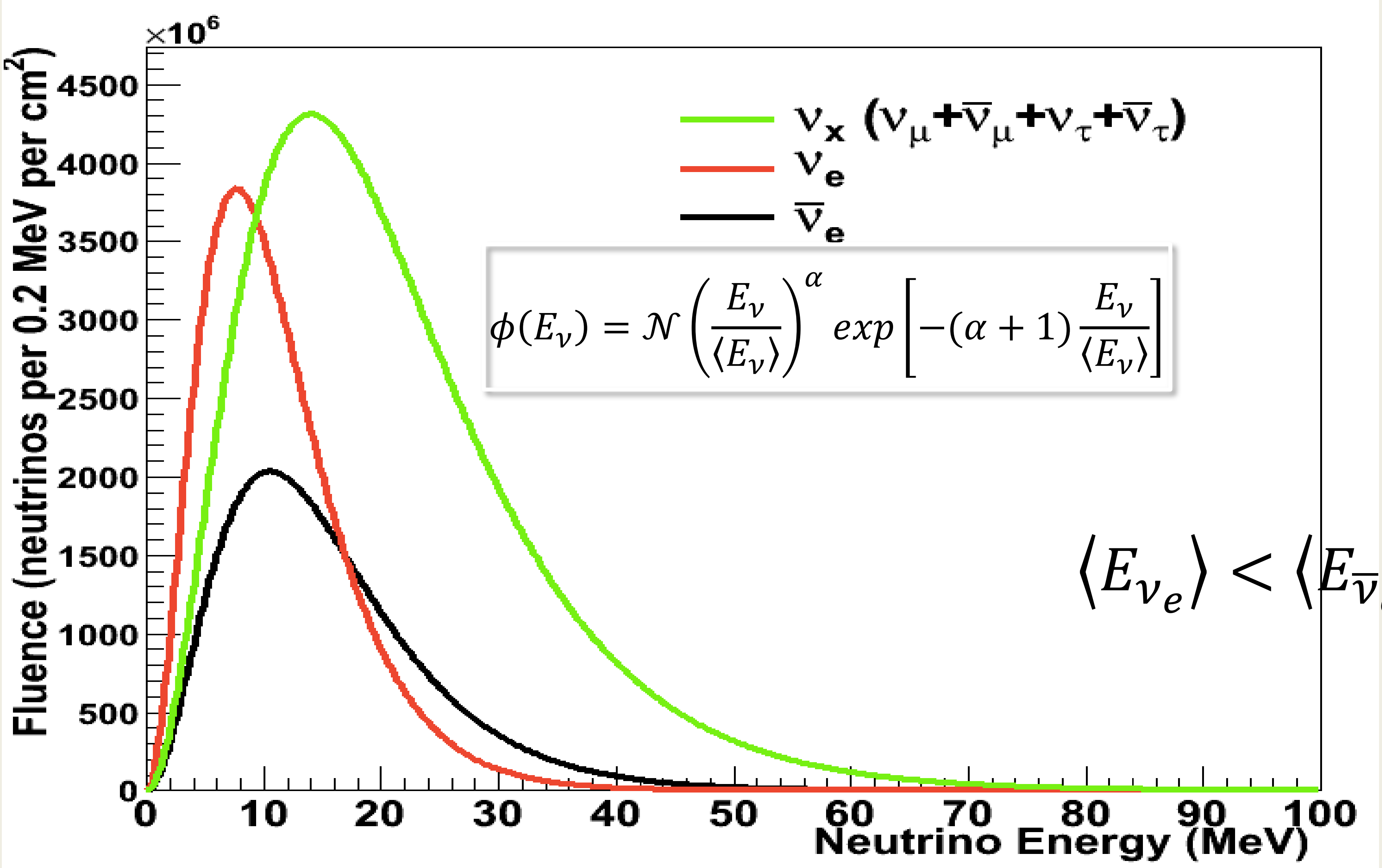




Neutrino Spectrum from a CoreCollapse SN



$$\phi(E_\nu) = \mathcal{N}\left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^{\alpha} exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu\rangle}\right]$$

$$\langle E_{\nu_e}\rangle < \langle E_{\bar{\nu}_e}\rangle < \langle E_{\nu_x}\rangle$$

Unfolding of Observed Spectra

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IBD Channel

$$P_{pES}(E_\nu) \propto \sum_{flavor=1}^{3} \int_{E_{min}}^{E_{max}} P_{pES}^{flavor}(E_\nu|E_0) \cdot P_{pES}^{flavor}(E_0) \cdot dE_0$$

pES Channel

Flux Models

- Supernova Neutrino Database

  Intp2013.data $M = 20\ M_{\odot}$ $Z = 0.004$ $t_{revive} = 300\ \text{ms}$

- We have different progenitor masses M= 13, 20, 30 and 50 $M_{\odot}$
- Different progenitors metallicities Z= 0.02 and 0.004
- Different shock revival time t_{revive} = 100, 200 and 300 ms

We started to run different simulation to create some relevant statistic to study

Analysis Goals

- JUNO has the capability to detect the SN neutrino events and to act together with other neutrino experiment as an alert system
- Reconstructing the SN neutrino spectra give us the chance to learn useful informations on the SN evolution mechanisms

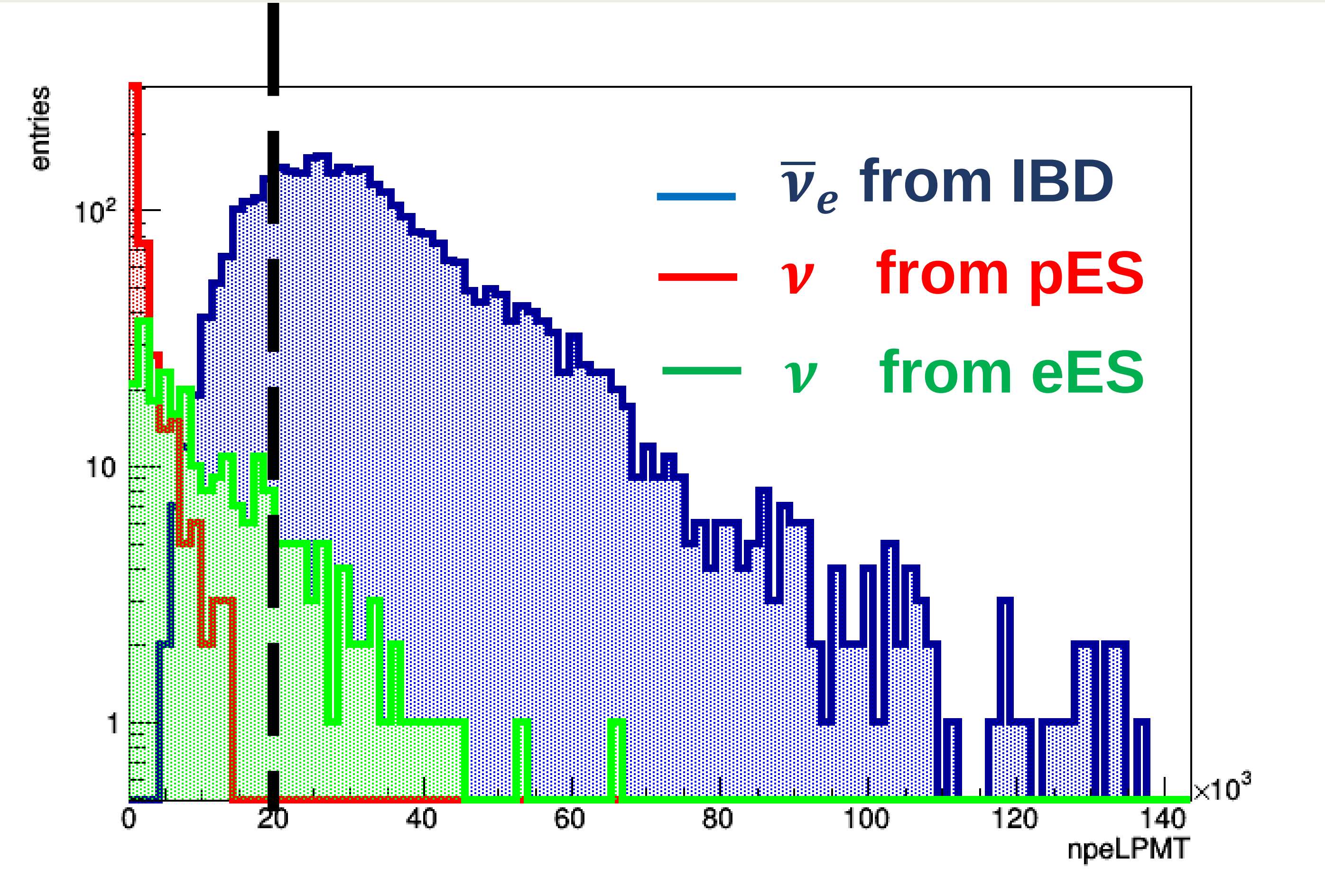
Next Steps:

- Build a discrimination alghoritm for the different classes of events involved in a burst
- Develop an UNFOLDING METHOD to extract the SN physical parameters

Channels separation

- **NPE for Large PMT** distribution for the three main channels is shown below

- Evident different distributions of the Number of PE for the three main channels



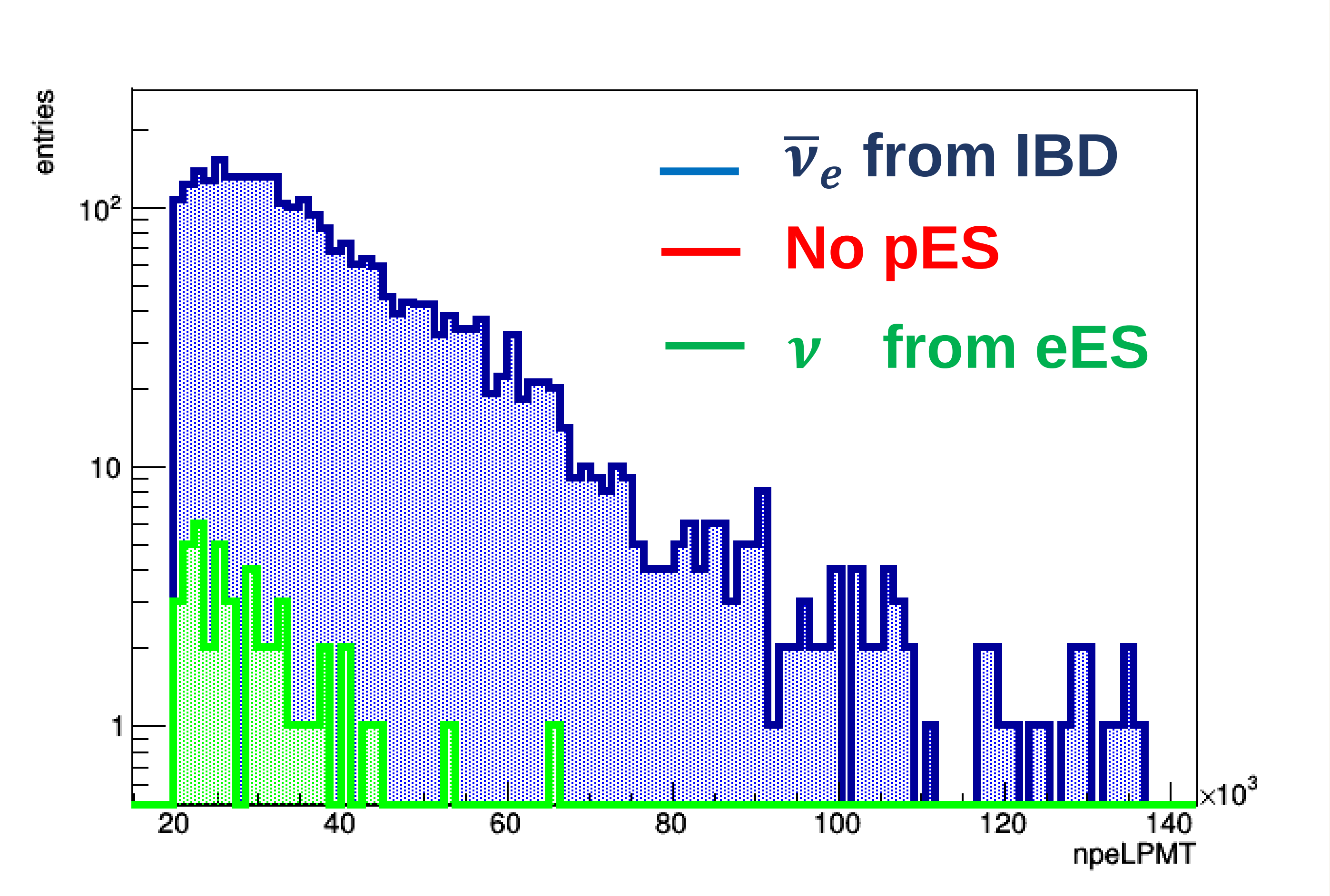
$$NPE_{LPMT} > 20 \times 10^3$$

- As expected $\bar{\nu}_e$ events from IBD seem more defined at higher energies

This net separation at high energy allows us to select a fiducial cut on the Energy, therefore directly on our observable

Channels separation

- **NPE spectra** after preliminary cut



- With a first fiducial cut in energy we completely eliminated any contribution of the proton elastic scattering to the IBD distribution

$$NPE_{LPMT} > 20 \times 10^3$$

Generator

- We used the Supernova Generator implemented in the JUNO Software (J18v1-pre1) under : offline/Examples/Generator/Supernova

- Flux models:
  - *Numerical simulated data (Japan Group)*
  - *Currently just few set of data (Supernova Neutrino Database)*

- We set a distance once we chose our fluxfile and we set NH or IH

- New Garching Models from the German group have been implemeted into Sniper

2 INDIPENDENT SAMPLES

We will run more simulations to compare the two models and the independency of the analysis

- $M = 20\ M_{\odot}$ Z= 0.004 D= 10 kpc