Core-Collapse Supernova neutrinos detection with the 3" PMT system of the JUNO experiment

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34 years ago, for the first time, neutrinos from a Core-Collapse Supernovae (SN1987A) were detected, opening a new era in the study of Supernova…

What can neutrinos learn us about Supernova ?

The expanding remnant of SN1987A, a Type II supernova in the Large Magellanic Cloud. NASA image

Outline

I. Neutrinos and Core-Collapse Supernova (CCSN)

II. The JUNO experiment and its 3” PMT system

III. CCSN neutrinos events detection

Neutrinos and Core-Collapse Supernova (CCSN)

Neutrinos and Core-Collapse Supernova

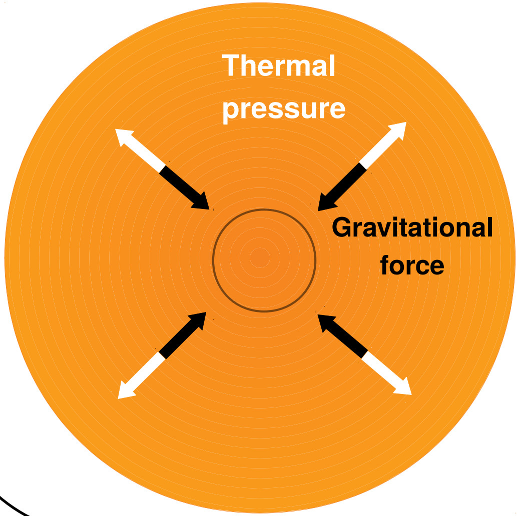
Life and Death of Massive Stars (in an nutshell)

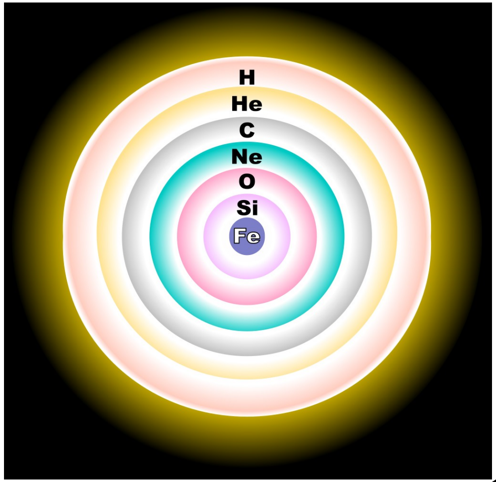
We are interested in stars with a mass M > $8M_\odot$

1. Balance between the gravitational compression and thermal pressure from fusion reactions → **Equilibrium**

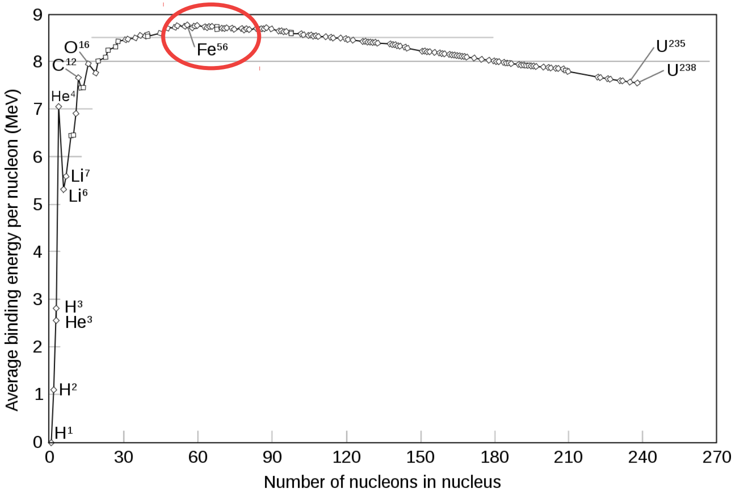
2. Fusion reactions create increasingly heavy elements

3. The elements are divided into layers. At some point, the core is made of ^{56}Fe





Problem : fusioning ^{56}Fe nuclei consumes more energy than it produces, thermal pressure drops in the core…



→ What is going to compensate for gravitational force ?

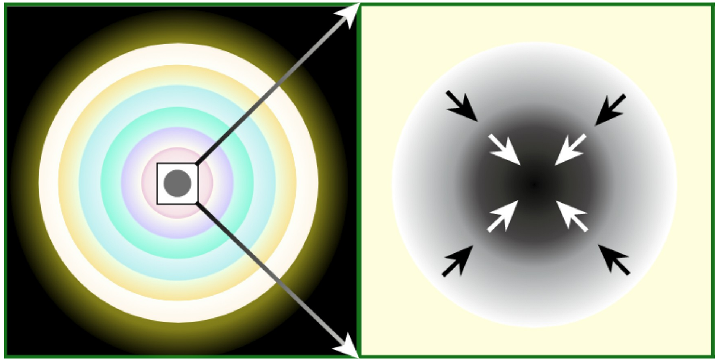
Neutrinos and Core-Collapse Supernova

Life and Death of Massive Stars (in an nutshell)

We are interested in stars with a mass $M > 8M_\odot$

Fusion keeps going in uper layer, more and more Iron produced

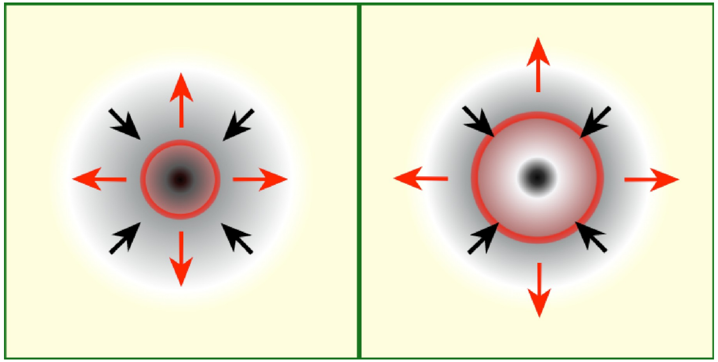
When the **core mass reaches the Chandrasekhar limit ($M > 1.4\ M_\odot$)**, it collapses !



Size of the core goes from $\approx 10^3$ to ≈ 10 km

The material on top infalls at supersonic velocities

The **core bounces** and an outwarding shockwave is formed



According to numerical simulations, the shockwave stalls at ≈200km from the core

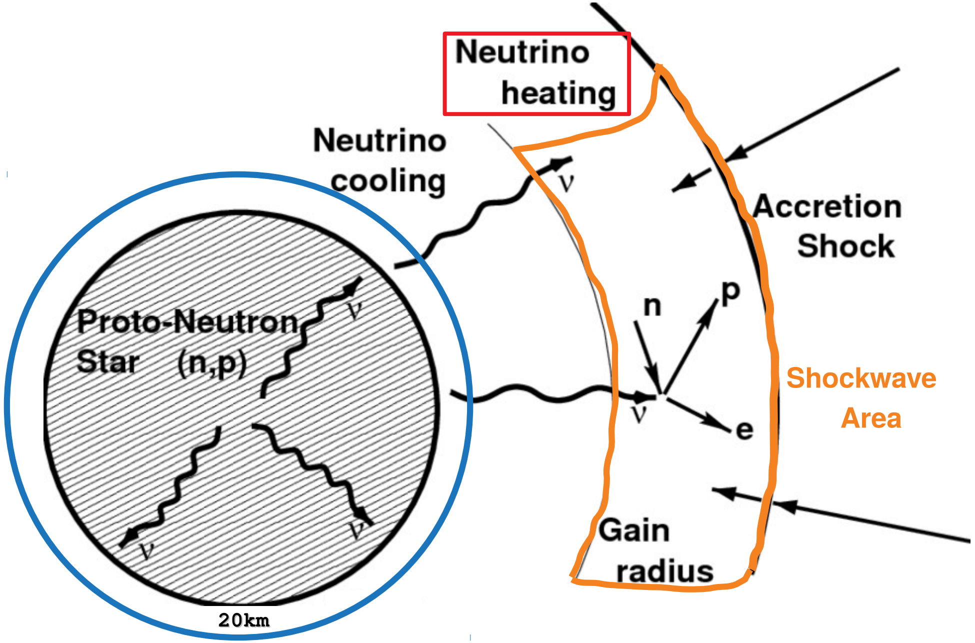
→ **No explosion triggered !**

However, we do observe explosions, how ?

Neutrinos and Core-Collapse Supernova

The role of neutrinos in Supernova explosions

- Many **neutrinos produced by various nuclear reaction** occuring in the core (Proto-Neutron star)
- Most widely accepted explosion models state that the neutrinos revive the stalling shockwave : Neutrino heating



In this scope, **CCSN neutrino flux, energy spectra etc.** have been extensively computed

Neutrinos and Core-Collapse Supernova

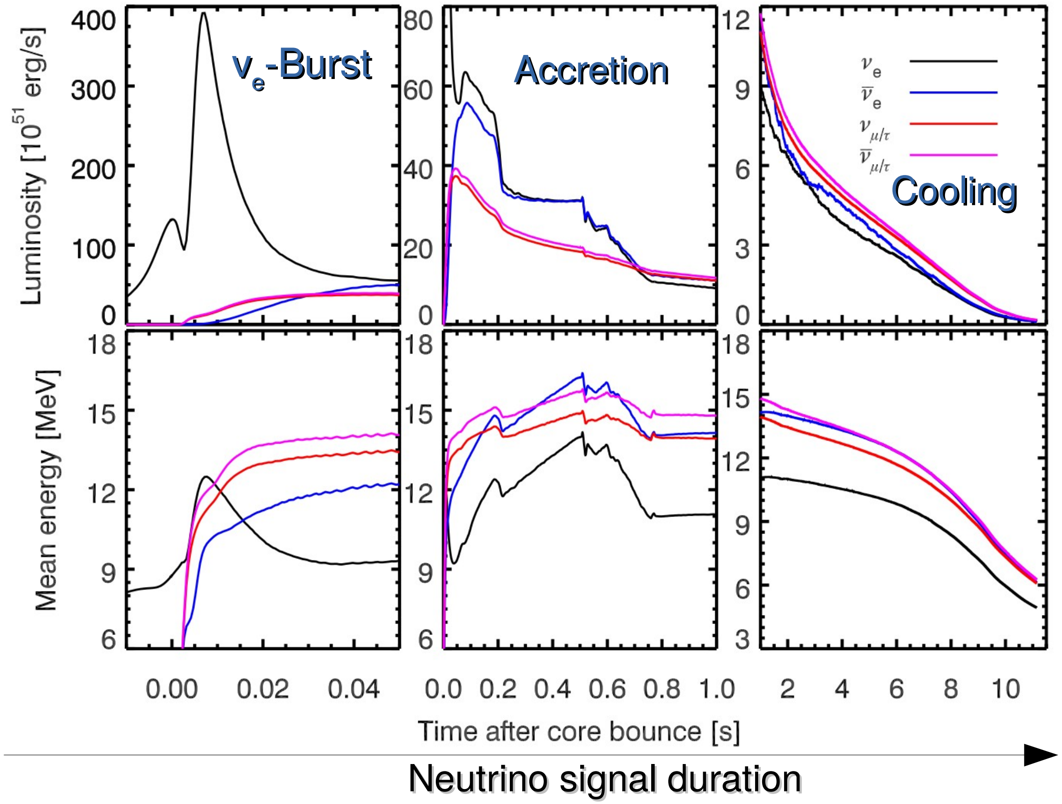
CCSN neutrino signal characteristics [arXiv:1702.08713]

1. ν and $\bar{\nu}$ of **all flavors** are emitted

2. Average energy : ≈15 MeV
   Maximum energy ≈100 MeV

3. Emission divided into 3 phases

4. Duration of the signal : ≈10s



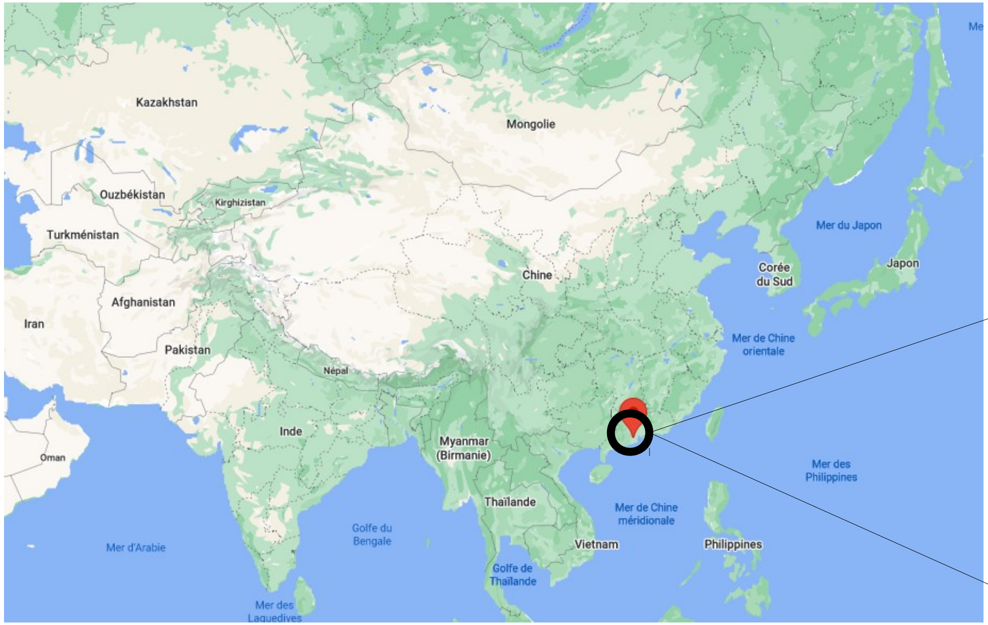
Next step is to detect these neutrinos and compare the data to the models !

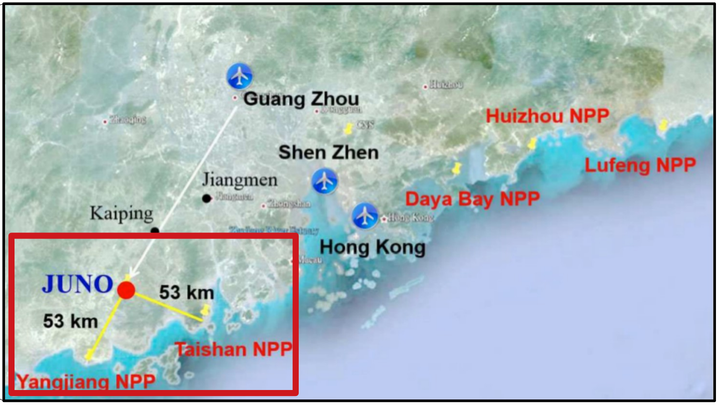
The JUNO experiment and its 3” PMT system

The JUNO experiment and its 3” PMT system

The JUNO collaboration

- International collaboration
- ≈600 collaborators
- 77 institutes

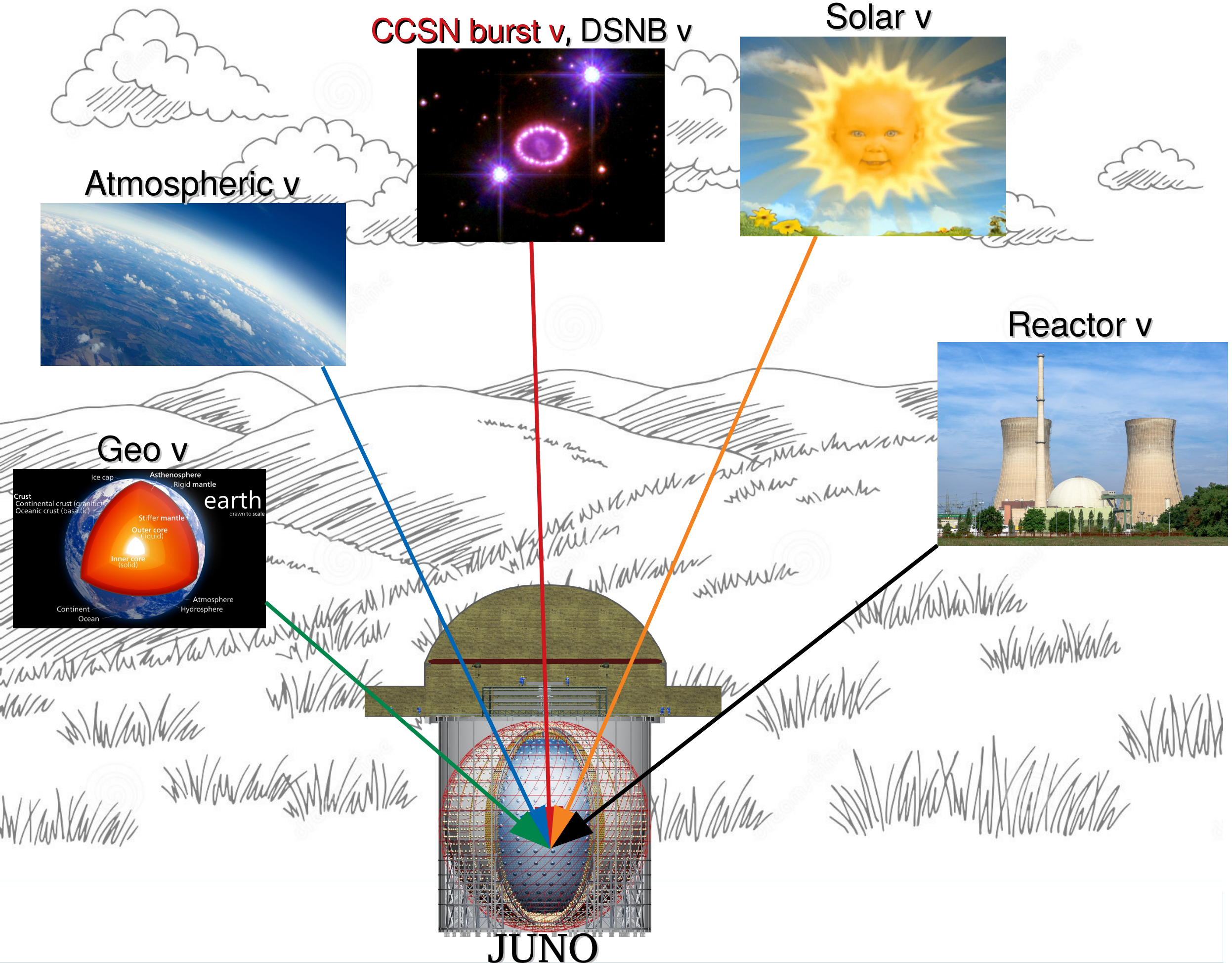




Detector currently under construction in China

The JUNO experiment and its 3” PMT system

Physics Programm

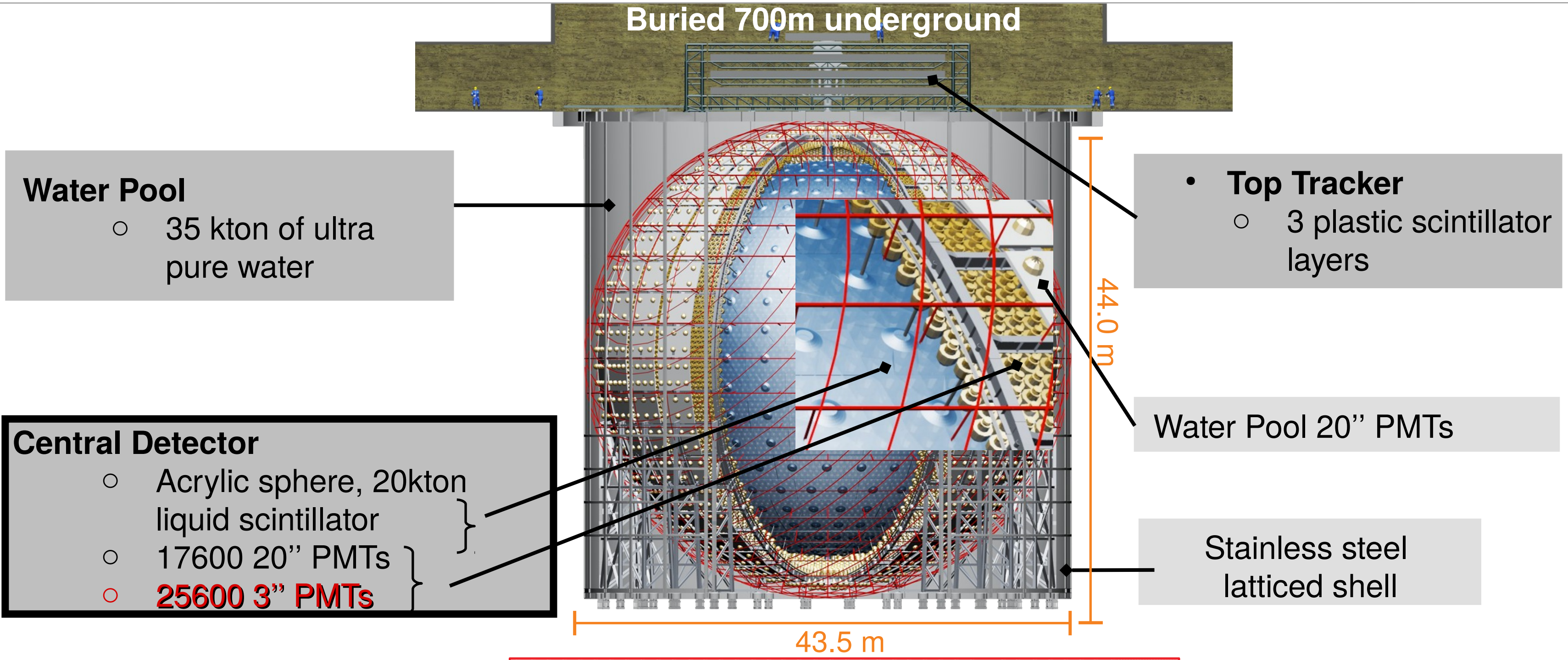


Physics Programm

- Neutrino Mass Ordering
- Neutrino oscillation parameter measurement (θ_{12}, Δm^2_{21}, θ_{13} and Δm^2_{32})
- **CCSN Neutrinos**
- Diffuse Supernova Neutrino Background (DSNB) flux measurement
- Solar Neutrino Flux Measurement
- Atmospheric Neutrinos, Geo-Neutrinos, Proton Decay...

The JUNO experiment and its 3” PMT system

The JUNO detector



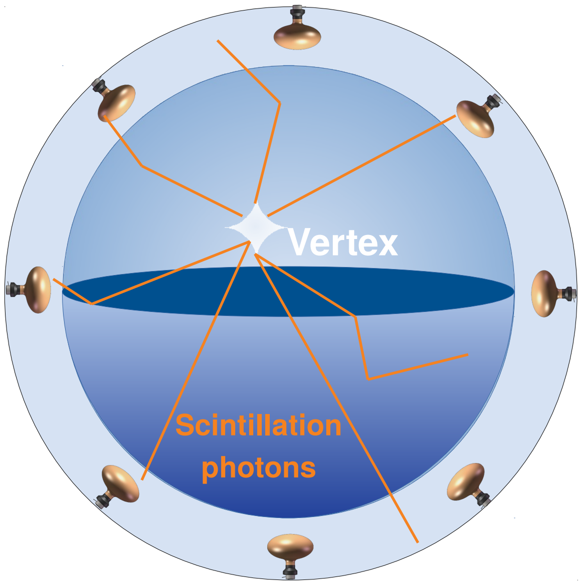
Energy Resolution requirement : $3\%/\sqrt{E(MeV)}$

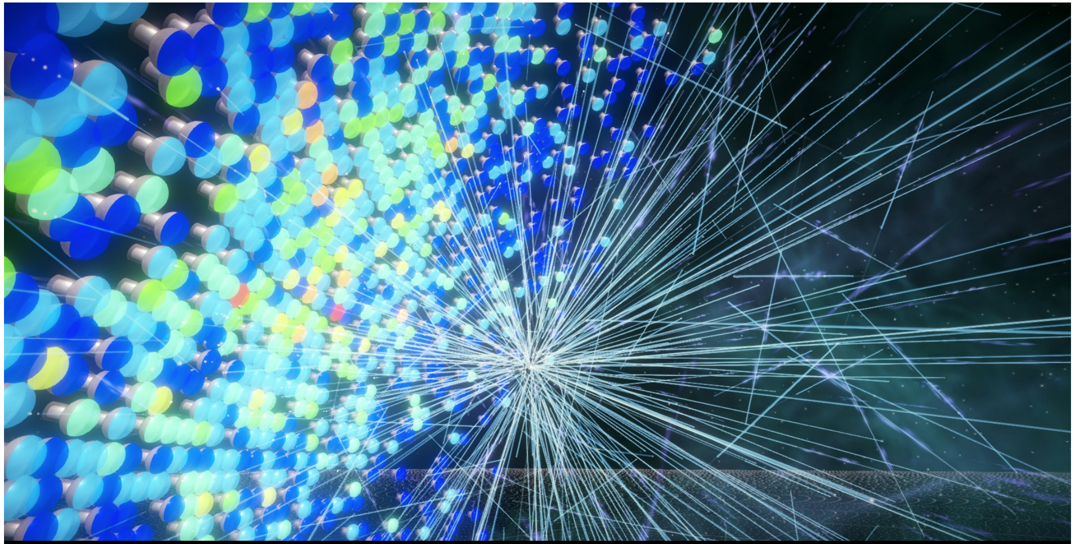
1. The **Top Tracker** : A muon veto, it aims at precisely measure their trajectories
2. The **Water Pool** : Protect the Central Detector from the external radiogenic background, also used as a muon veto
3. The **Central Detector** : the ν-target, we want the neutrinos to interact in the liquid scintillator

The JUNO experiment and its 3” PMT system

Liquid scintillator detection principle

1. Neutrinos will elastically or inelastically interact with the LS components
2. Charge particles involved in the interaction excite the LS molecules
3. The molecules will de-excite through fluorescence and phosphoresence and emit “scintillation photons”





Event display from ELAINA (Event Live Animation with unIty for Neutrino Analysis)

The event detection/reconstruction is based on the information provided by the PMTs (*time* and *charge*)

The JUNO experiment and its 3” PMT system

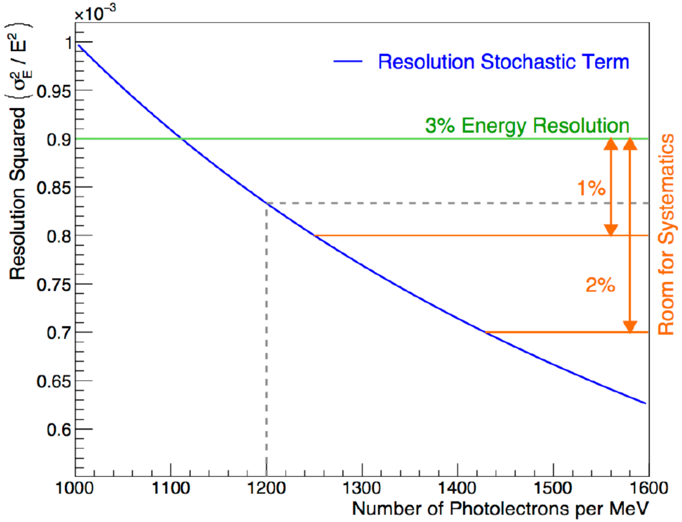
Why do we need 2 types of PMTs ? - The 3” PMT system purposes

1. Dual Calorimetry for Mass Ordering determination

- 20” PMTs : 1200 p.e/MeV → Low **stochastic** fluctuations but non-linearity at high charge
- 3” PMTs : 40 p.e/MeV + photo-counting regime → Linear system to correct for 20” PMTs non-linearity (**systematic error**)

Energy resolution model → $$\frac{\sigma_E}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2} = 3\% \ (@\ 1MeV)$$

Stochastic term — Non-stochastic terms



2. Perform quasi-independent physics analyses

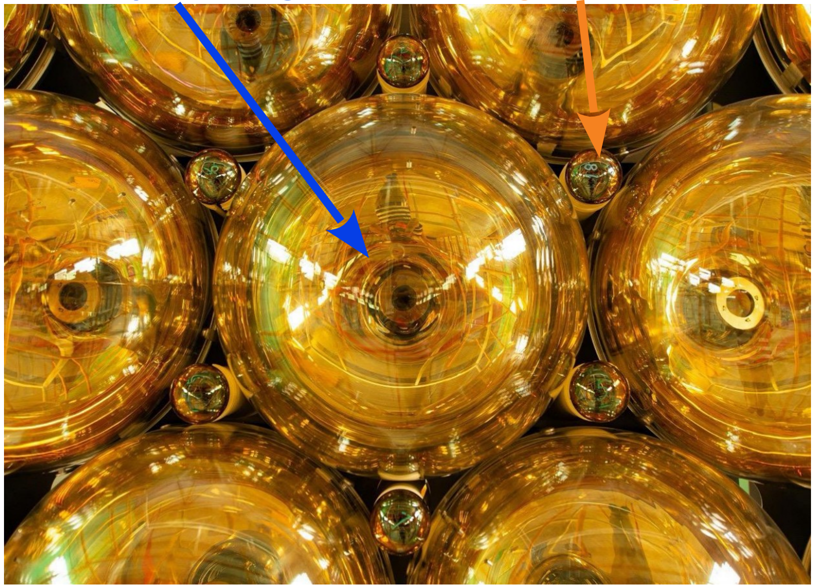
- **Measure the solar parameters** (θ_{12}, Δm^2_{21})
- CCSN burst neutrino detection
- Proton decay
- Muon reconstruction

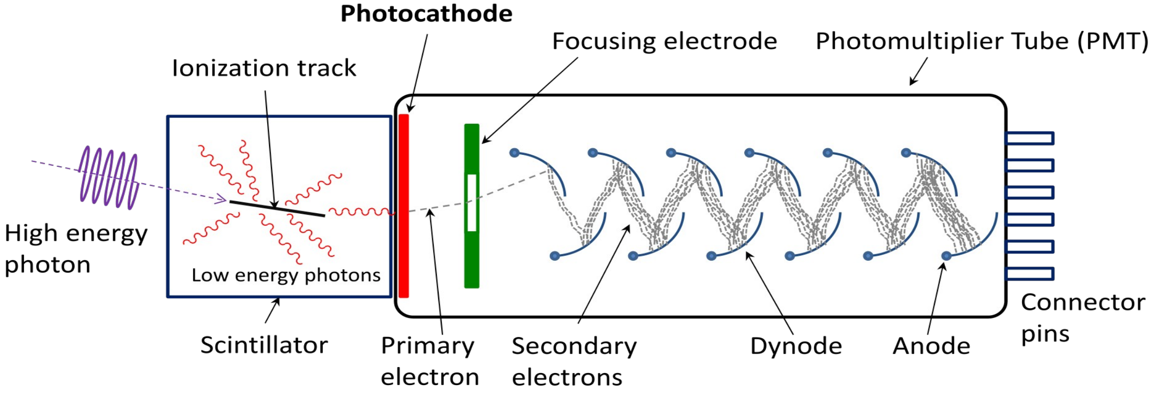
The JUNO experiment and its 3” PMT system

The 3” PMT system

1. The PMTs convert the scintillation photons into photoelectrons (p.e) by photoelectric effect
2. The photoelectron signal is amplified and then readout by an electronic system

20” PMTs   3” PMTs





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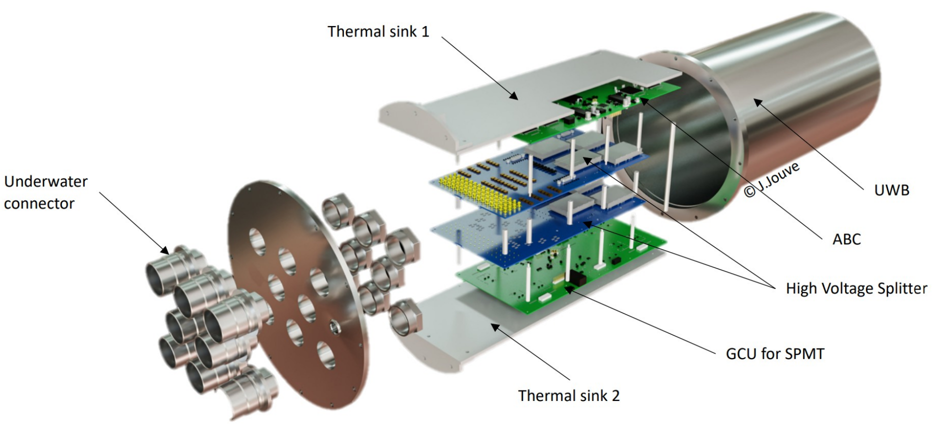
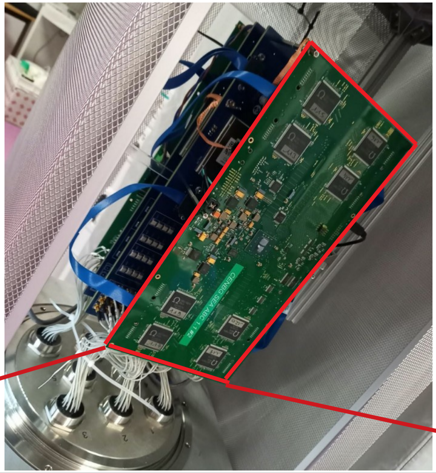


The electronics are stored in a waterproof box (20 years underwater operation)



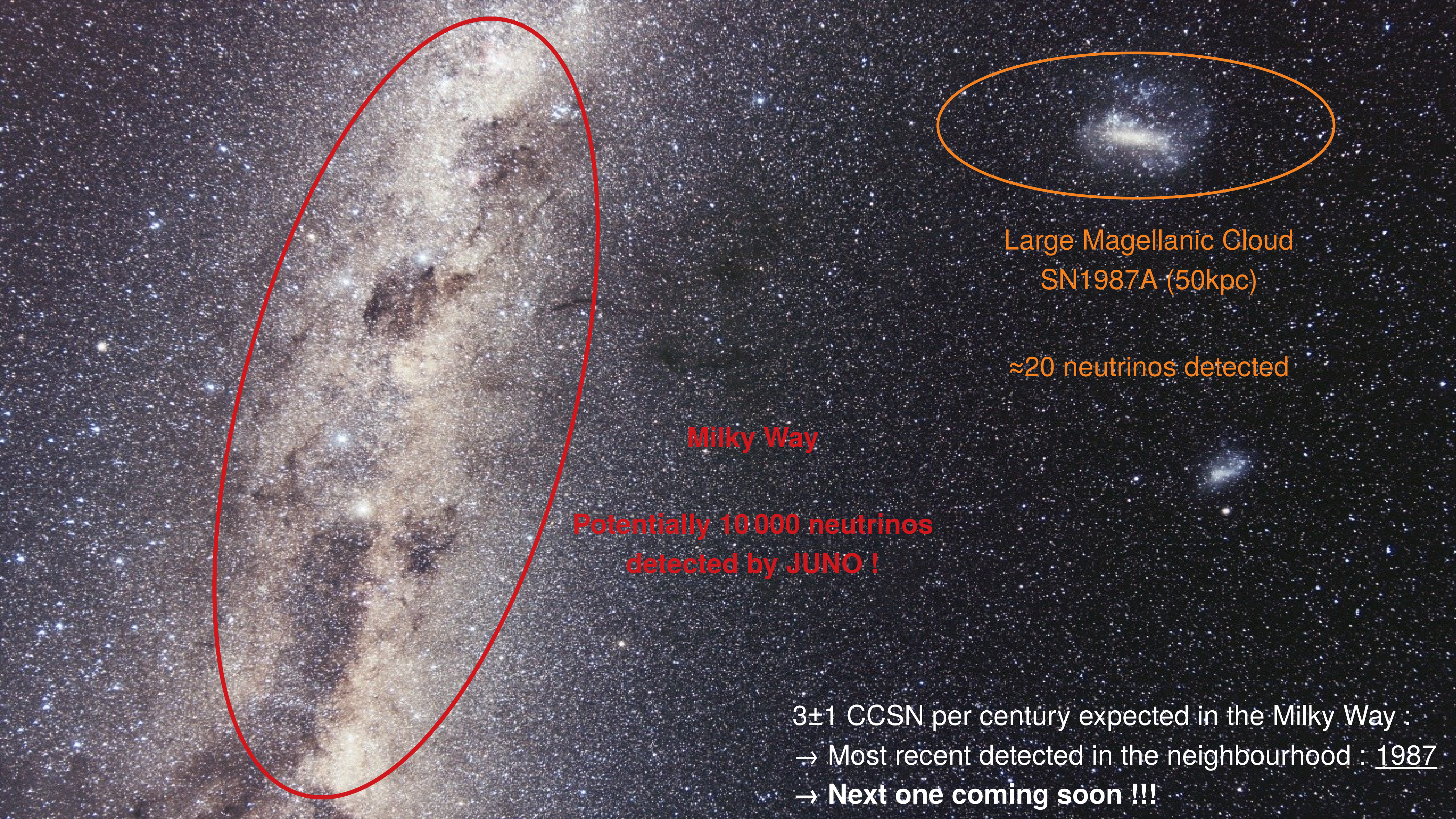
Validation of a new charge calibration method for CATIROC (important for the event reconstruction)

+ Study the impact of its performances with a simulation code

CATIROC : **C**harge **A**nd **T**ime **I**ntegrated **R**ead**O**ut **C**hip

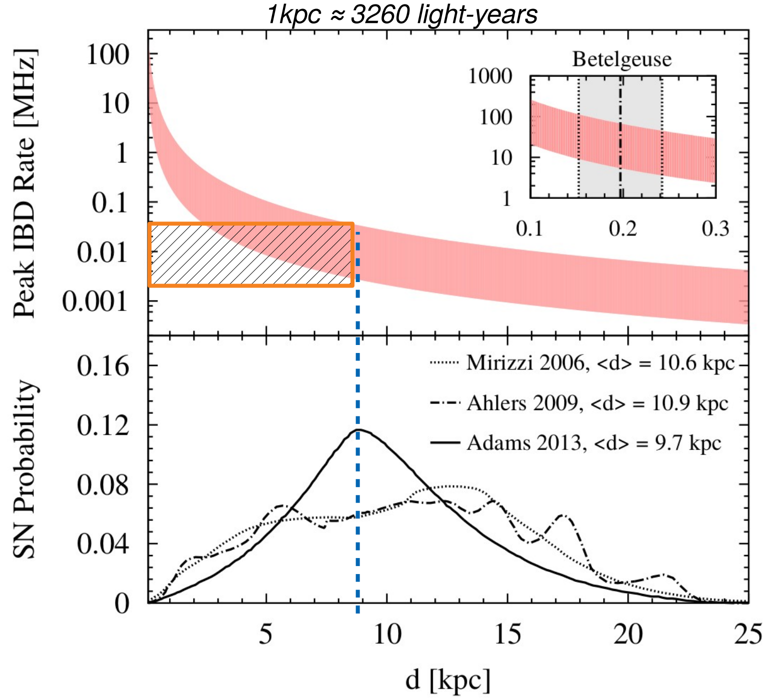
S. Conforti et. al, CATIROC: an integrated chip for neutrino experiments using photomultiplier tubes, JINST, May 2021]

CCSN neutrinos events detection


Large Magellanic Cloud
SN1987A (50kpc)
≈20 neutrinos detected
Milky Way
Potentially 10 000 neutrinos detected by JUNO !
3±1 CCSN per century expected in the Milky Way :
→ Most recent detected in the neighbourhood : 1987
→ **Next one coming soon !!!**

CCSN neutrinos events detection

Expected signal in JUNO



Most probable distance to the CCSN is **≈10kpc**

The **event rate** could reach **several tens of kHz**

For a closer CCSN, the event rate could reach several MHz !

→ Challenging for electronics and DAQ

Neutrinos interaction channels in JUNO

Channel	Type	Num. event expected (SN@10kpc)
$\overline{\nu}_e + p \to e^+ + n$	CC	$\simeq 5000$
$\nu + p \to \nu + p$	NC	$\simeq 2000$
$\nu + e^- \to \nu + e^-$	NC	$\simeq 300$
$\nu +^{12} C \to \nu +^{12} C^*$	NC	$\simeq 300$
$\nu_e +^{12} C \to e^- +^{12} N$	CC	$\simeq 100$
$\overline{\nu}_e +^{12} C \to e^+ +^{12} B$	CC	$\simeq 100$

6 different detection channels → **Sensitive to the 3 neutrinos flavor** !

Energy range of the events : [0 ; 100] MeV

CCSN neutrinos events detection

Event reconstruction - Vertex

The reconstruction of the events is mandatory if we want to compare the data to the models predictions

→ Vertex reconstruction serves 2 main purposes : Factor the geometry biases in energy reconstruction and Event selection

Based on the number of p.e collected by the 3” PMTs and on the collection time of the scintillation photons

Classified

- Radial resolution : **a few tens of cm in a 35.0 m diameter detector**.
- Efficiency is not 100% → Problem in the reconstruction of the **events occuring at the detector borders** *(ML technics to fix that, Leonard's talk)*
- The resolution gets better at higher energies (≈10cm)

CCSN neutrinos events detection

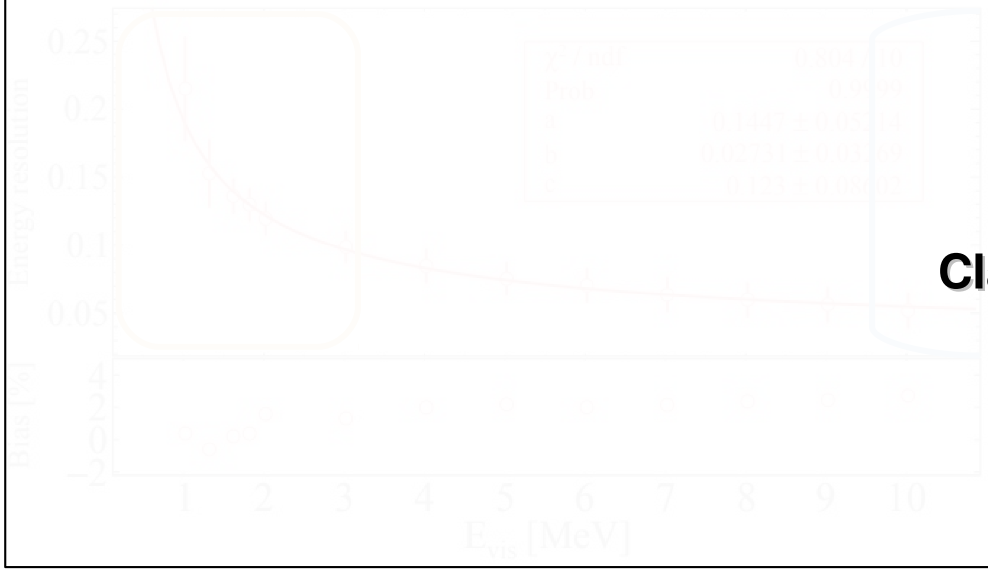
Event reconstruction - Energy

The reconstruction of the events is mandatory if we want to compare the data to the models predictions

→ Energy reconstruction for CCSN neutrino energy spectra reconstruction

Based on the number of p.e collected by the 3” PMTs

Classified



- Energy resolution >10% in the lower range [0;3] MeV
- Energy resolution < 5% in the higher range [10;…] MeV
  → OK for CCSN neutrinos energy spectra
- The bias is < 5% on the full energy range

CCSN neutrinos events detection

Event selection

Once the events are reconstructed, we need to select them to identify the different interaction channels to retrieve the neutrino flavor

Neutrinos interaction channels in JUNO

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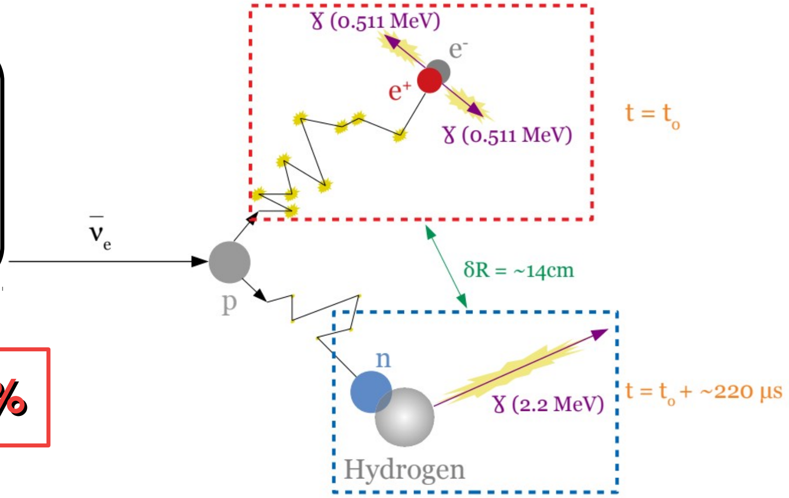
$\nu_e +^{12} C \rightarrow e^- +^{12} N$	CC	$\simeq 100$
$\overline{\nu}_e +^{12} C \rightarrow e^+ +^{12} B$	CC	$\simeq 100$

Most important channel is the Inverse Beta Decay [IBD] ($\overline{\nu}_e + p \rightarrow e^+ + n$)

→ 5000 evts

→ Selection based on the Spatial and Temporal coincidence of a Prompt and a Delayed signals : powerfull selection criteria



Current selection algorithm : Purity > 95% and Loss ≈ 5%

Purity = # correct IBD / # IBD selected ------- Loss = # Missed IBDs / Total # IBDs

Conclusion & Outlooks

- **Neutrinos are promising messengers for the study of CCSN**

- The JUNO detector aims at solving the Neutrino Mass Ordering but is **also designed for the detection of the next galactic CCSN**

- CCSN neutrinos can be **studied with two complementary PMT systems**, my work is focus on the **analysis performed with the 3" PMTs**

- **Reconstruction algorithms** have been developed and are currently being used to perform **event selection**

→ Next step is to perform energy spectra unfolding