Neutrino Astrophysics with JUNO

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on behalf of the JUNO collaboration

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PRISMA Cluster of Excellence

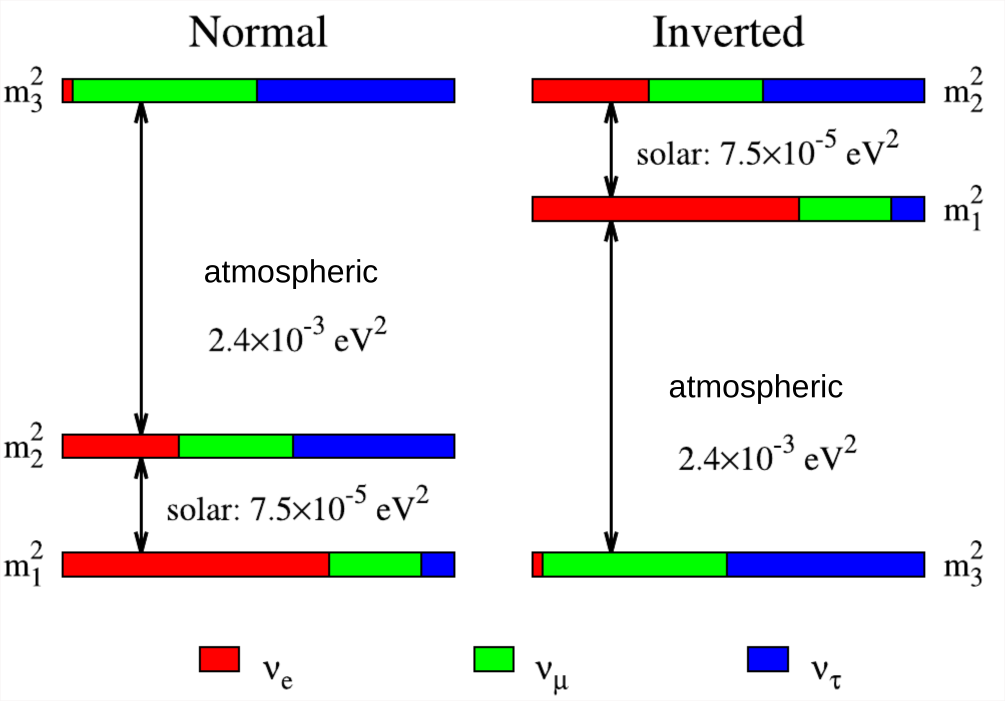
Magellan Workshop – Connecting Neutrino Physics and Astronomy

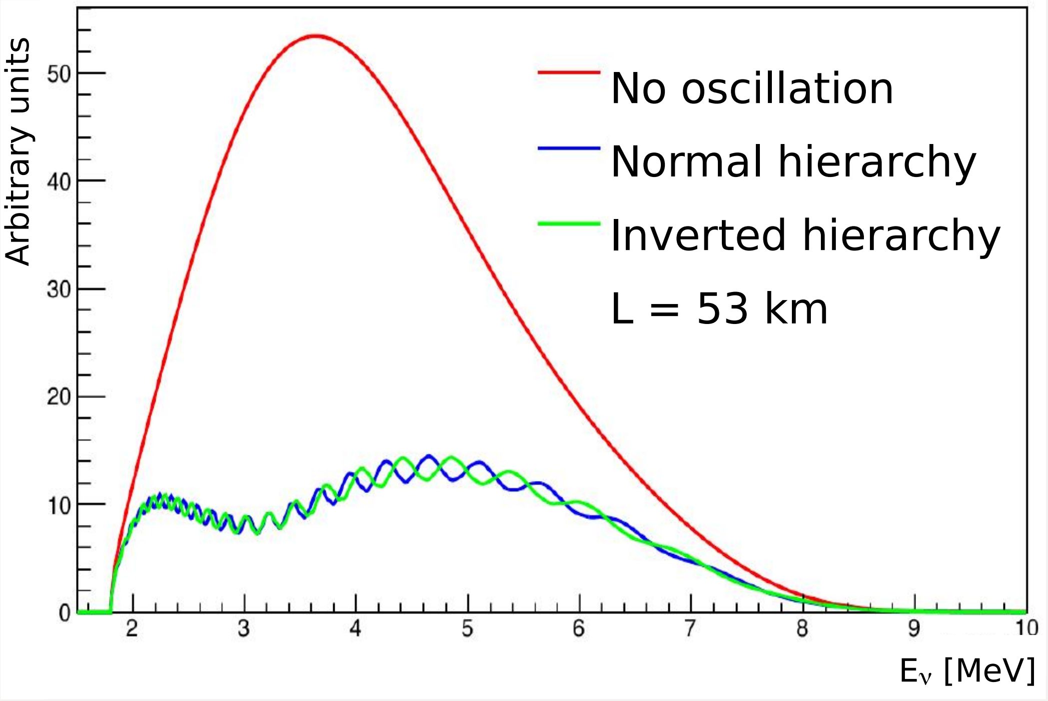
DESY, Hamburg, March 18th 2016

Outline

- Main Goal of the
  Jiangmen **U**nderground **N**eutrino **O**bservatory
- JUNO Detector Design
- Neutrino Astrophysics Program
  - Core-collapse Supernova Neutrinos (SN-ν) from a burst
  - Diffuse Supernova Neutrino Background (DSNB)
  - Solar Neutrinos (Solar-ν)
- Summary & Conclusion

Main Goal of JUNO





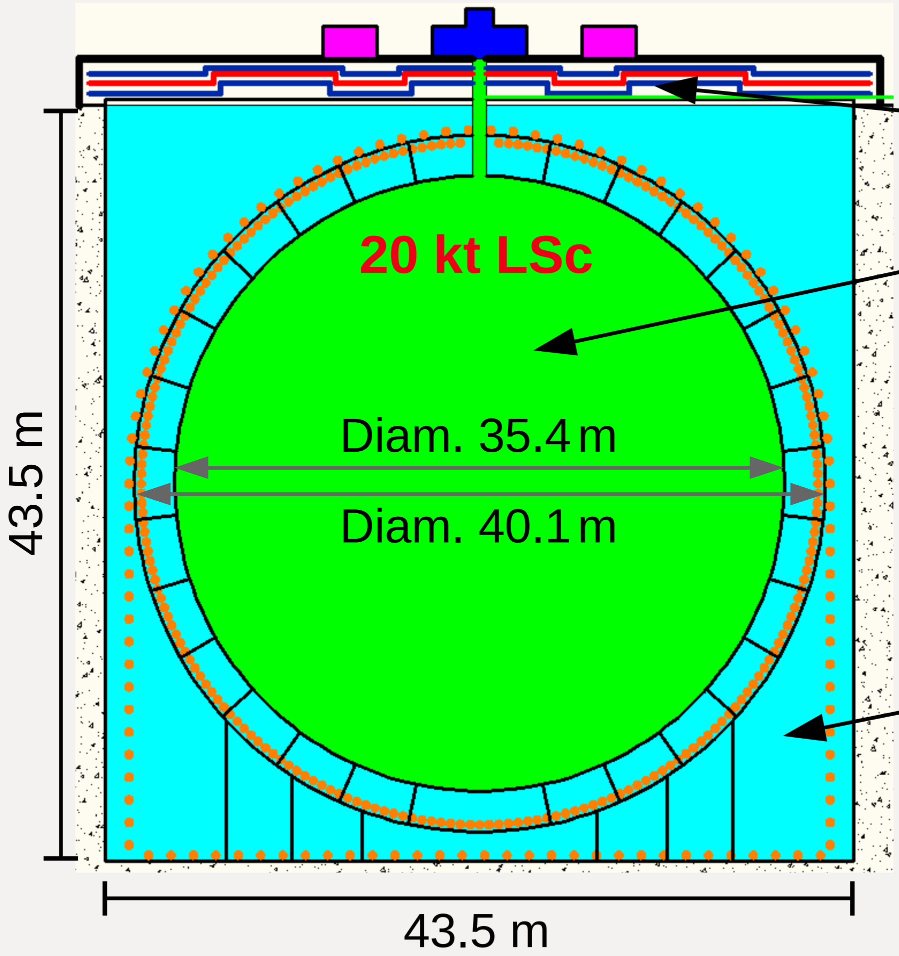
- **Goal:** determine neutrino mass ordering (MO)
- **Approach:** Investigate oscillatory fine structure in reactor $\bar{\nu}_e$ event spectrum at a baseline length of ~53 km (probe survival probability)
- **Requirements:** large target mass, low energy threshold, very good energy resolution (~3% @ 1 MeV)

"*Neutrino physics with JUNO*" - J. Phys. G 43 (2016) 030401

JUNO Detector Design

- **JUNO** will use **20 kt of liquid scintillator (LSc)**
- Primary $\bar{\nu}_e$ detection channel: $\bar{\nu}_e + p \rightarrow e^+ + n$ (IBD)

  Signature: prompt e^+ annihilation; O(ns) + delayed n-capture; O(200 μs)

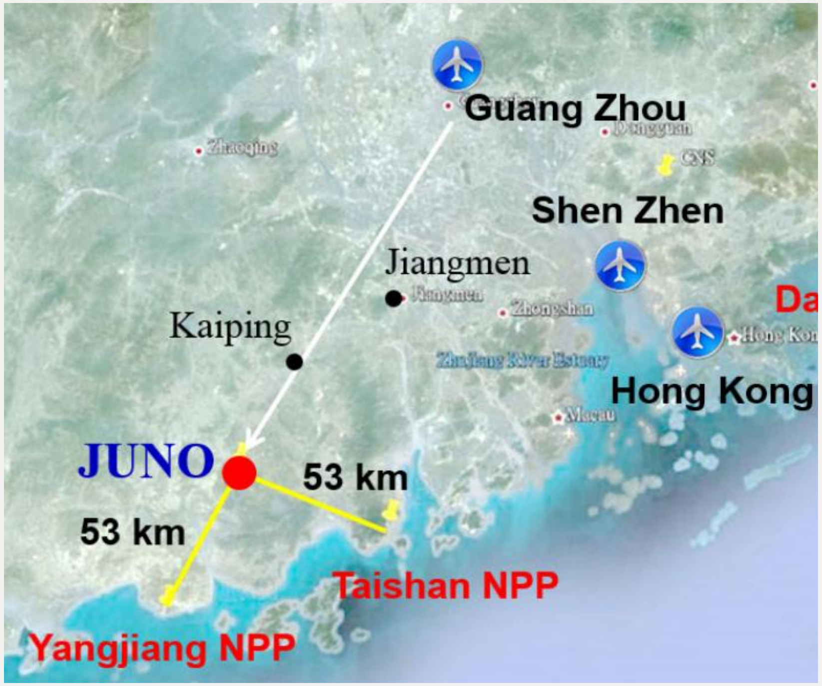


- **Top Tracker** (solid scintillator)
- **Spherical central detector**
  - 20 kt LSc in acrylic sphere
  - ~17 k 20" PMTs + ~34 k 3" PMTs

  → high, uniform photoelectron yield (~ 1200 p.e. / MeV)
- **Water Cherenkov veto**
  - ~2 k 20" PMTs

"*JUNO Conceptual Design Report*" - arXiv: 1508.07166

JUNO Experimental Site



Expected median sensitivity to neutrino MO of JUNO
6 years @ 36 GW
(~100k IBDs)

w/o precise external info: **~3σ**

w/ precise external info: **3.7–4.4σ**

- Underground site close to Kaiping in the south of China
- About 700 m overburden
  → Muon event rate: ~3 s^{-1}
- $\bar{\nu}_e$ source: 2 NPPs at 53 km distance
  10 cores with a total of 35.8 GW P_{th}
- JUNO is a funded project
  - construction started 2015
  - data taking starts ~2020
- **What else?**
- Measure some flavor oscillation parameters with sub-percent level precision
- Measure neutrinos from Earth and **extra-terrestrial sources**

Supernova Neutrino Measurement

- SN-ν measurements with JUNO benefit from
  - + very good energy resolution
  - + large target mass (20 kt LSc)
  - + **time and flavor information**

Channel	Type	Events for different $\langle E_\nu \rangle$ values		
JUNO		12 MeV	14 MeV	16 MeV
$\bar{\nu}_e + p \rightarrow e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \rightarrow \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \rightarrow \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$	CC	0.5×10^2	0.9×10^2	1.6×10^2
$\bar{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B$	CC	0.6×10^2	1.1×10^2	1.6×10^2

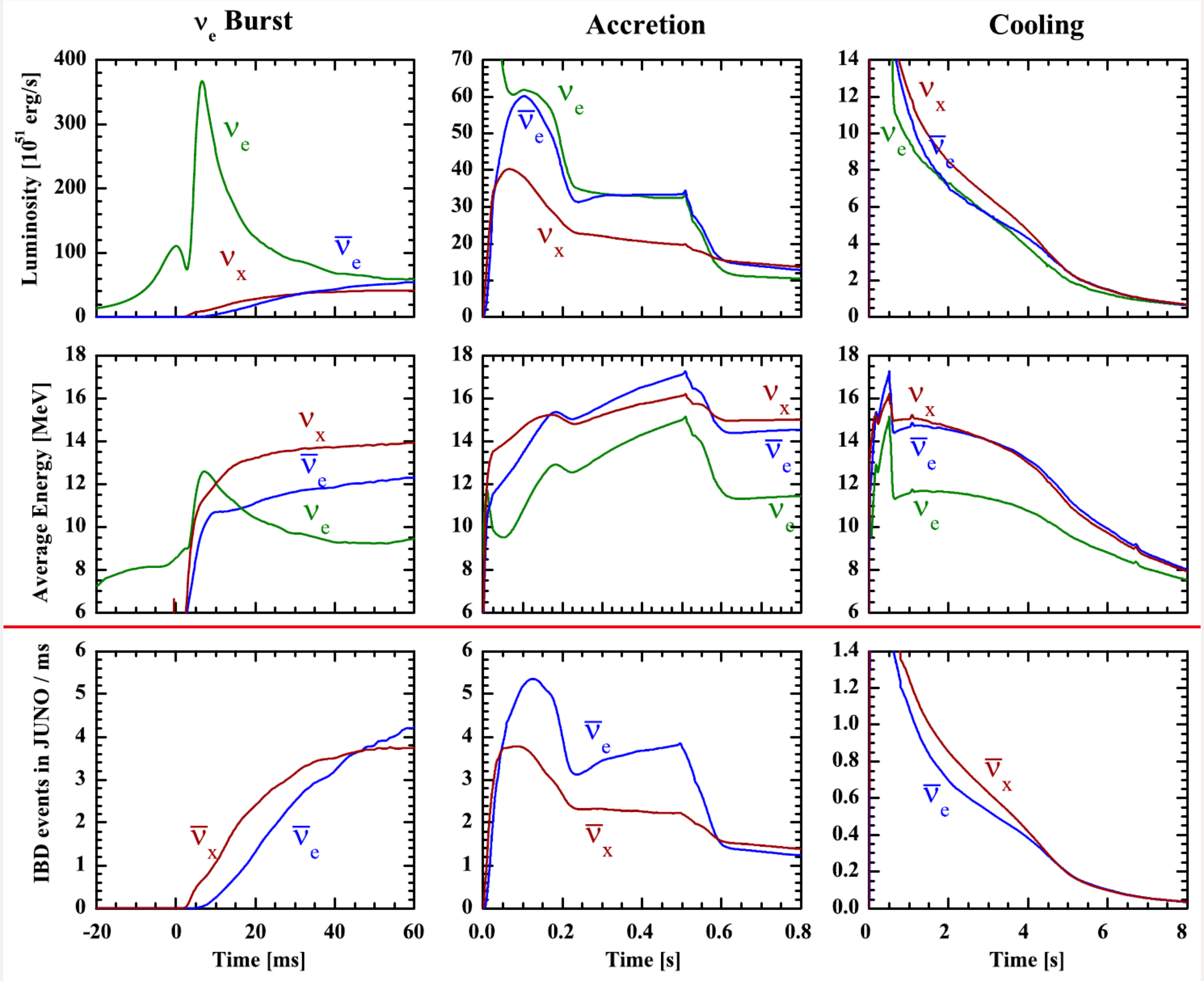
Primary channel → ($\bar{\nu}_e + p \rightarrow e^+ + n$)

LSc! → ($\nu + p \rightarrow \nu + p$)

Event counts for a core-collapse SN at a typical distance of 10 kpc.
No flavor conversion.
Proton recoil energy threshold for ν–p elastic scattering: 0.2 MeV

- High event rate in 10 s burst → background no serious concern
- Detailed neutrino “light curve“ spectra with high statistics from JUNO will allow to test core-collapse SN models

Supernova Neutrino Measurement



Spherically symmetric model from the *Garching group*

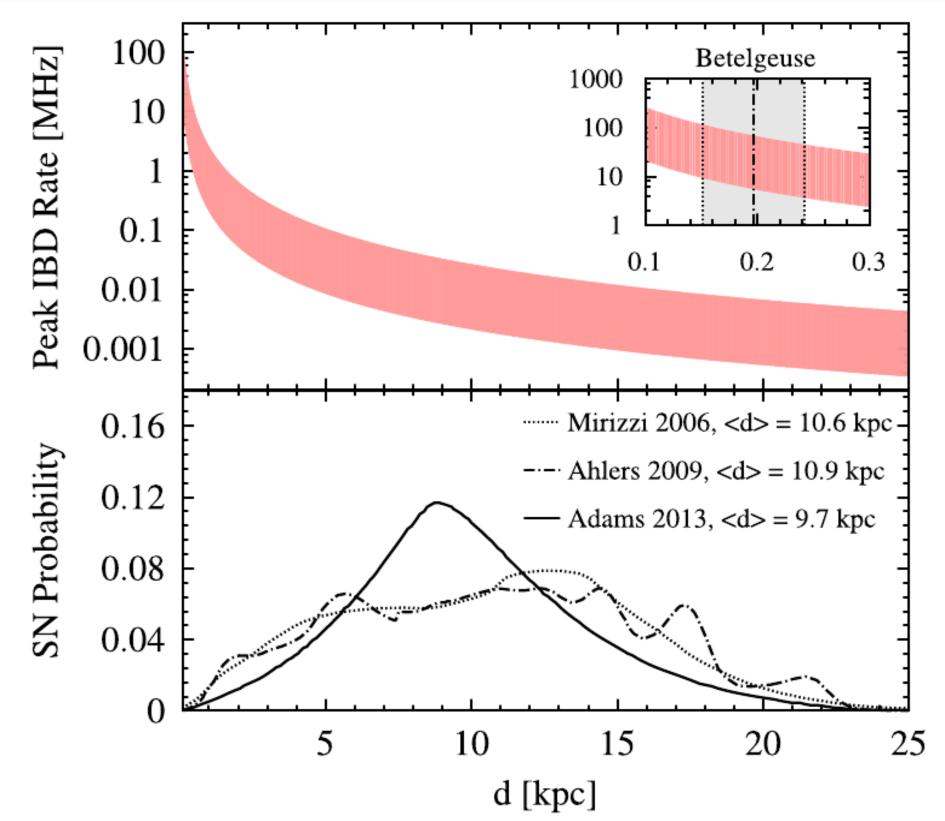
Explosion triggered by hand

27 SM progenitor star

3.24×10^{53} erg emitted in neutrinos

Supernova Neutrino Measurement

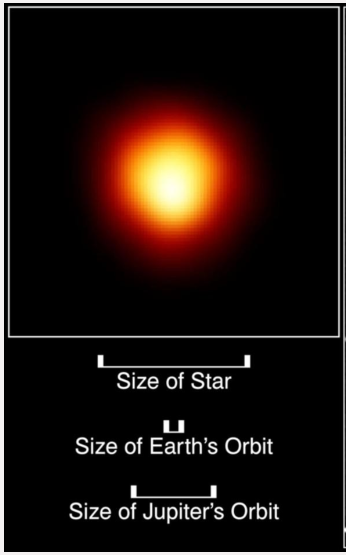
- JUNO will be sensitive only to galactic core-collaps SNe
- Only 1-3 / century expected
  → Don't miss the next one!
- Make sure the detector is not blinded by a close core-collapse SN

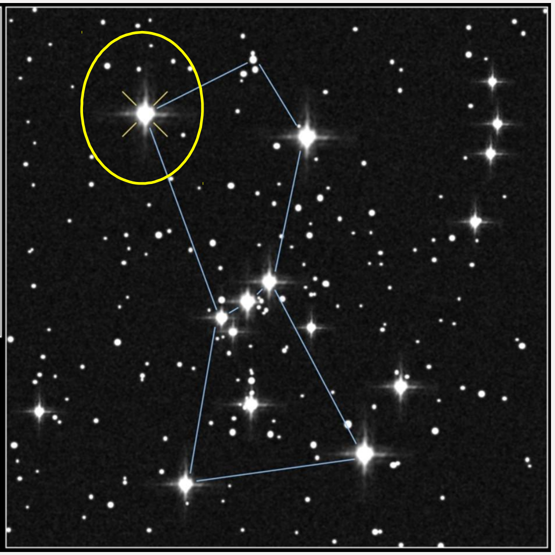


IBD events in JUNO from a core-collapse SN burst at ...

~750 kpc (Andromeda)	: O(1)
~50 kpc (LMC; SN 1987A)	: O(200)
~10 kpc (gal. SN mean dist.)	: $O(5\times10^3)$
~0.2 kpc (Betelgeuse)	: $O(10^7)$

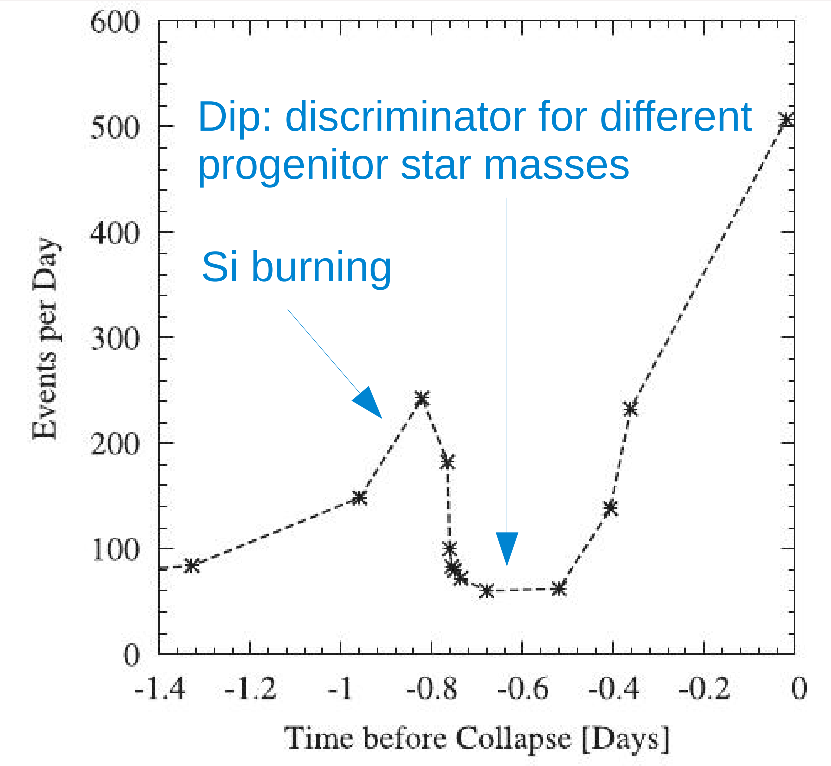
Red Supergiant Betelgeuse (Alpha Orionis)
Distance: ~197 pc Mass: ~18 SM
Expected to end its life as core-collapse SN





Supernova Neutrino Measurement

- JUNO will surely be part of the **S**uper**N**ova **E**arly **W**arning **S**ystem
- For very close progenitors (Betelgeuse): pre-SN-νs from Si burning as ultimate pre-warning system
- Locate SN (even if its visual appearance is obscured):
  - Triangulation with multiple detectors
  - Study displacement between prompt and delayed signal vertices of IBD events on a statistical basis
    - → for 5 k IBD events: ~9° uncertainty in sky coordinates

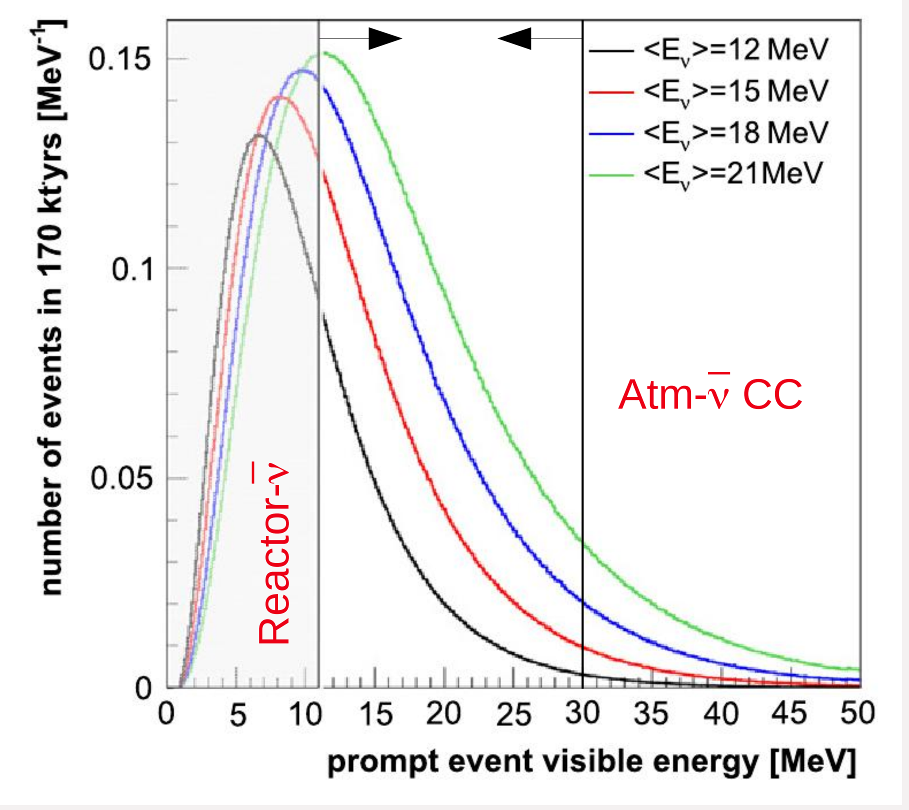


Event rate in JUNO for a massive star with 20 SM at Si burning stage; the assumed distance is 0.2 kpc (Betelgeuse)

DSNB Measurement

- **DSNB** : neutrino flux from past core-collapse events in visible universe
- Provides information on star-formation rate, average core-collapse neutrino spectrum, rate of failed SNe
- **In JUNO**: about 0.7-1.9 IBD events per year in [11; 30] MeV – after all cuts

- Most challenging background: atmospheric-ν NC interactions
  → neutron knock-out or more complex
  → neutrons produce recoil-protons
- Look for ^{11}C decay
- Performance will largely depend on power of pulse shape discrimination for the prompt signal in the LSc

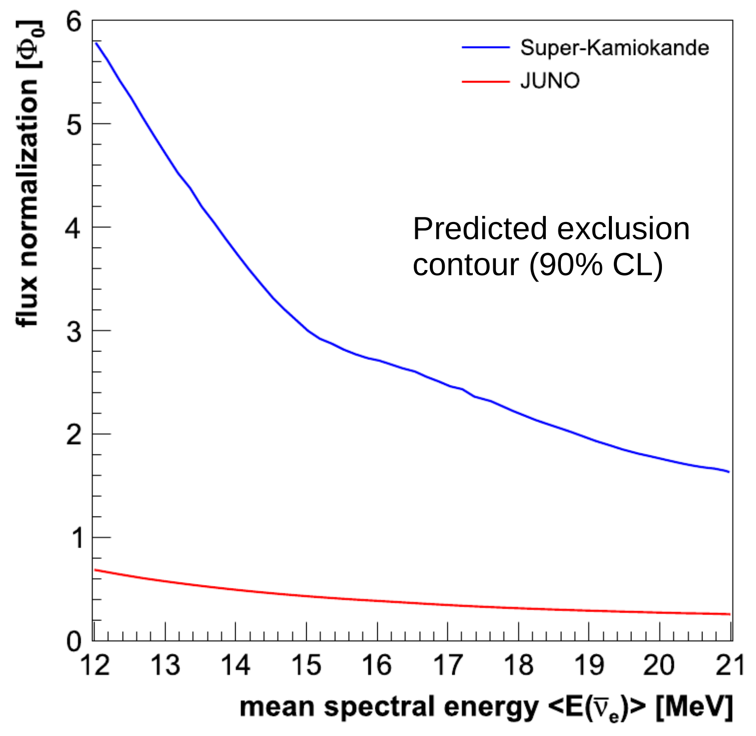


DSNB Measurement

- For favored DSNB parameters: a 3σ evidence for the DSNB signal seems within reach after 10 years of measurement

Syst. uncertainty BG	5%		20%	
$\langle E_{\bar{\nu}_e} \rangle$ **JUNO**	Rate only	Spectral fit	Rate only	Spectral fit
12 MeV	2.3 σ	2.5 σ	2.0 σ	2.3 σ
15 MeV	3.5 σ	3.7 σ	3.2 σ	3.3 σ
18 MeV	4.6 σ	4.8 σ	4.1 σ	4.3 σ
21 MeV	5.5 σ	5.8 σ	4.9 σ	5.1 σ

- If there is no positive DSNB detection after 10 years: significant improvement of current upper limit on DSNB flux



5% background uncertainty;
10 years of measurement;
$N_{det} = \langle N_{bkg} \rangle$

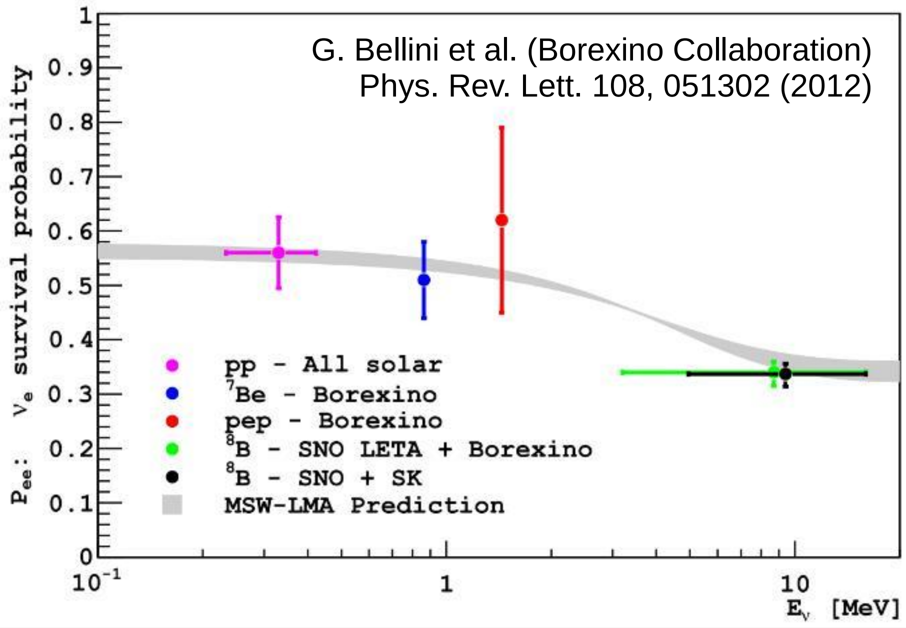
Solar Neutrino Measurement

Open issues:

1) Solar metallicity problem
2) Shape of transition from matter-dominated to vaccum-dominated region in solar ν_e survival probability

Solar-ν measurements with JUNO...

- ... benefit from ...
  + very good energy resolution
  + large target mass (20 kt LSc)
  (fiducial volume → self-shielding)
- ... but need to deal with ...
  - high radiopurity requirements
  - low overburden
  (cosmogenic background)



Solar neutrino signal rates (counts/day/kton) **JUNO**

pp ν	1378
^{7}Be ν	517
pep ν	28
^{8}B ν	4.5
^{13}N/^{15}O/^{17}F ν	7.5/5.4/0.1

[Flux model BP05(OP) – no energy cuts]

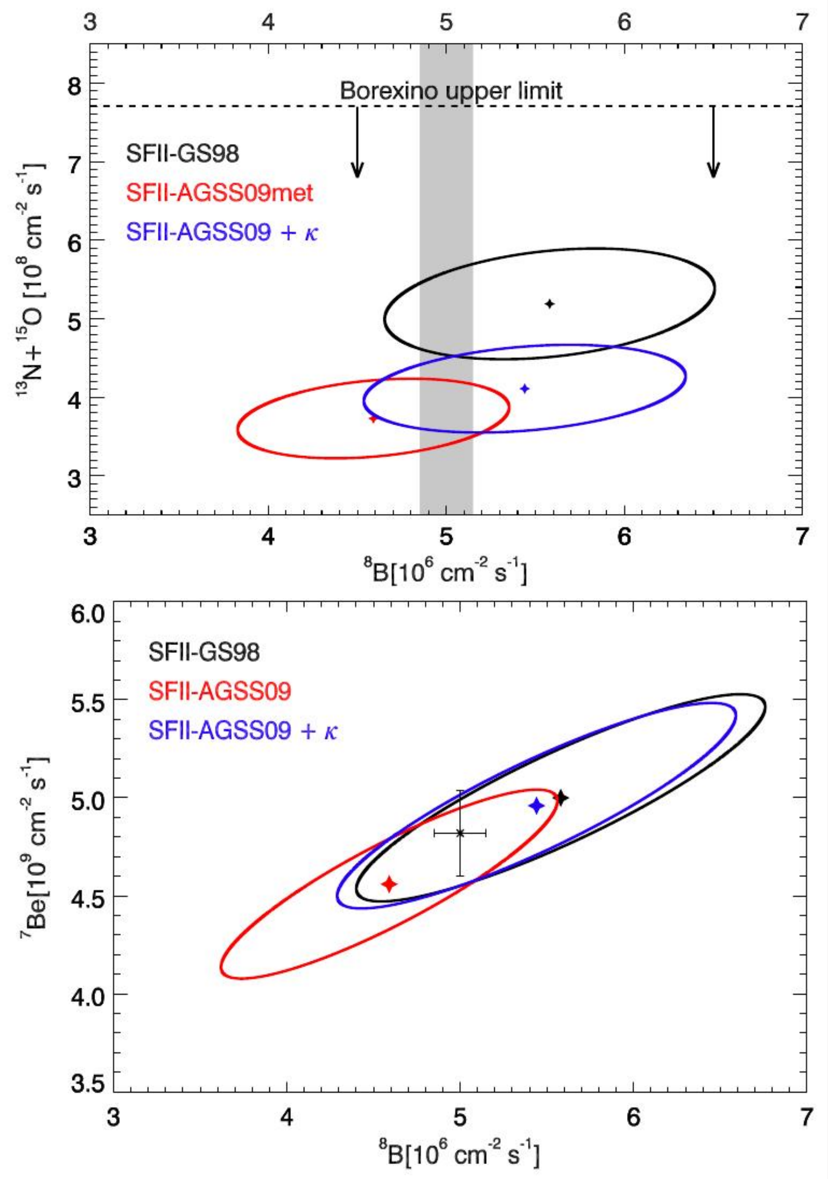
- Primary detection channel:
  ν – e elastic scattering

Solar Neutrino Measurement

- **JUNO:** focus on ^{7}Be-ν and ^{8}B-ν fluxes
- CNO-ν results alone can still yield model ambiguities, but ^{7}Be-ν / ^{8}B-ν measurements with higher statistics can help to break them
- **Moreover:** probe P_{ee} transition region with high statistics measurement of LE part of ^{8}B-ν spectrum (~3 MeV)
- Radiopurity and cosmogenic background rejection will be decisive for solar-ν program of JUNO (Borexino expertise on board!)

JUNO — Internal radiopurity requirements

	Baseline	Ideal
^{210}Pb	5×10^{-24} (g g^{-1})	1×10^{-24} (g g^{-1})
^{85}Kr	500 (counts/day/kton)	100 (counts/day/kton)
^{238}U	1×10^{-16} (g g^{-1})	1×10^{-17} (g g^{-1})
^{232}Th	1×10^{-16} (g g^{-1})	1×10^{-17} (g g^{-1})
^{40}K	1×10^{-17} (g g^{-1})	1×10^{-18} (g g^{-1})
^{14}C	1×10^{-17} (g g^{-1})	1×10^{-18} (g g^{-1})



"A special Borexino Event—Borexino Mini-Workshop" by A. M. Serenelli (Gran Sasso, 2014)

Summary & Conclusion

- JUNO aims to determine the neutrino MO by investigating an oscillatory fine structure in the reactor $\bar{\nu}_e$ survival probability at a baseline of 53 km
- It will feature a 20 kt LSc detector of unprecedented size; the construction began in 2015; data taking will start in ~2020
- In case of a galactic core-collapse SN, high event counts in JUNO with time and flavor information will allow to test SN models
- A 3σ evidence for the DSNB signal seems within reach after 10 years of measurement; the current upper DSNB flux limit will be significantly improved if no positive DSNB signal is found
- Solar-ν program depends on achieved radiopurity and cosmogenic background rejection
- ^{7}Be-ν and ^{8}B-ν measurements can help to shed light on solar metallicity / opacity problem and solar ν_e survival probability transition region

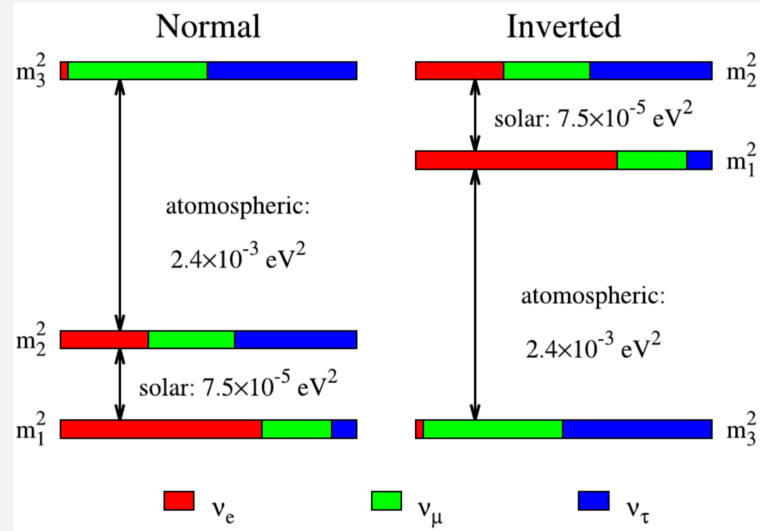
Thank you for your kind attention!

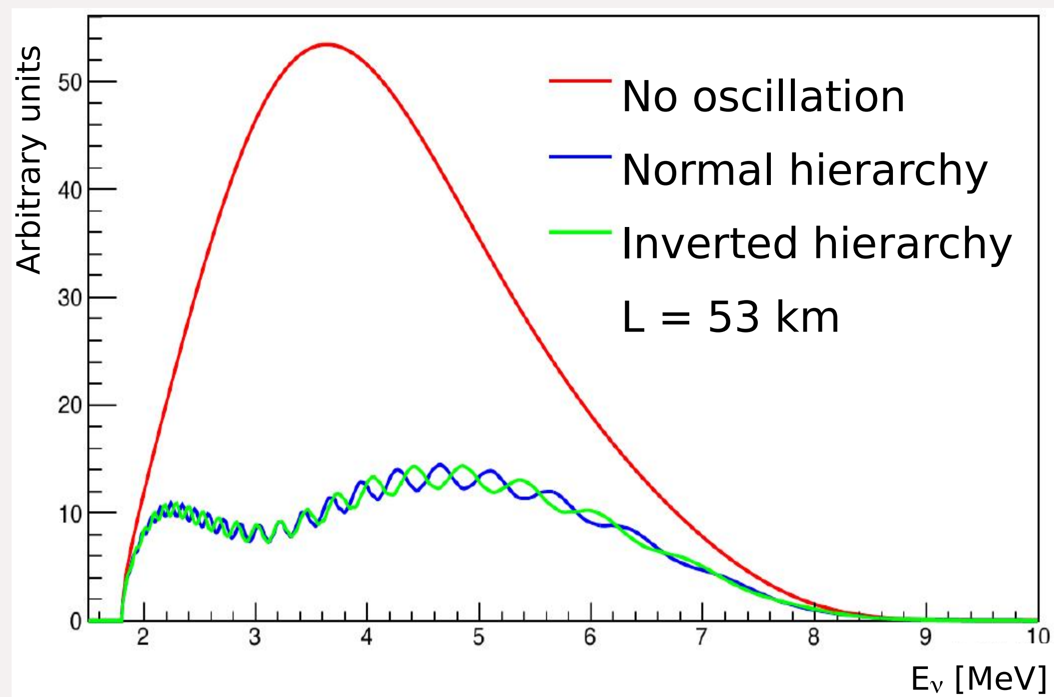
Further information

$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$
$$P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\boxed{\sin^2(\Delta_{31})}$$
$$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\boxed{\sin^2(\Delta_{32})}$$
$$\Delta_{ij} = 1.27\Delta m^2_{ij} L/E$$

$$\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$$
$$\text{NH}: |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$$
$$\text{IH}: |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$$

$$\frac{|\Delta m^2_{21}|}{|\Delta m^2_{32}|} \sim 0.03$$





Precision of $\sin^2\theta_{12}$, Δm^2_{21} and $|\Delta m^2_{ee}|$ from the nominal setup to those including additional systematic uncertainties. The systematics are added one by one from left to right.

	Nominal	+B2B (1%)	+BG	+EL (1%)	+NL (1%)
$\sin^2\theta_{12}$	0.54%	0.60%	0.62%	0.64%	0.67%
Δm^2_{21}	0.24%	0.27%	0.29%	0.44%	0.59%
$\|\Delta m^2_{ee}\|$	0.27%	0.31%	0.31%	0.35%	0.44%

“*Neutrino physics with JUNO*“ - J. Phys. G 43 (2016) 030401

$$\frac{\Delta E}{E} = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}}$$

Energy leakage & non-uniformity (a^2)

Photon statistics ($\frac{b^2}{E}$)

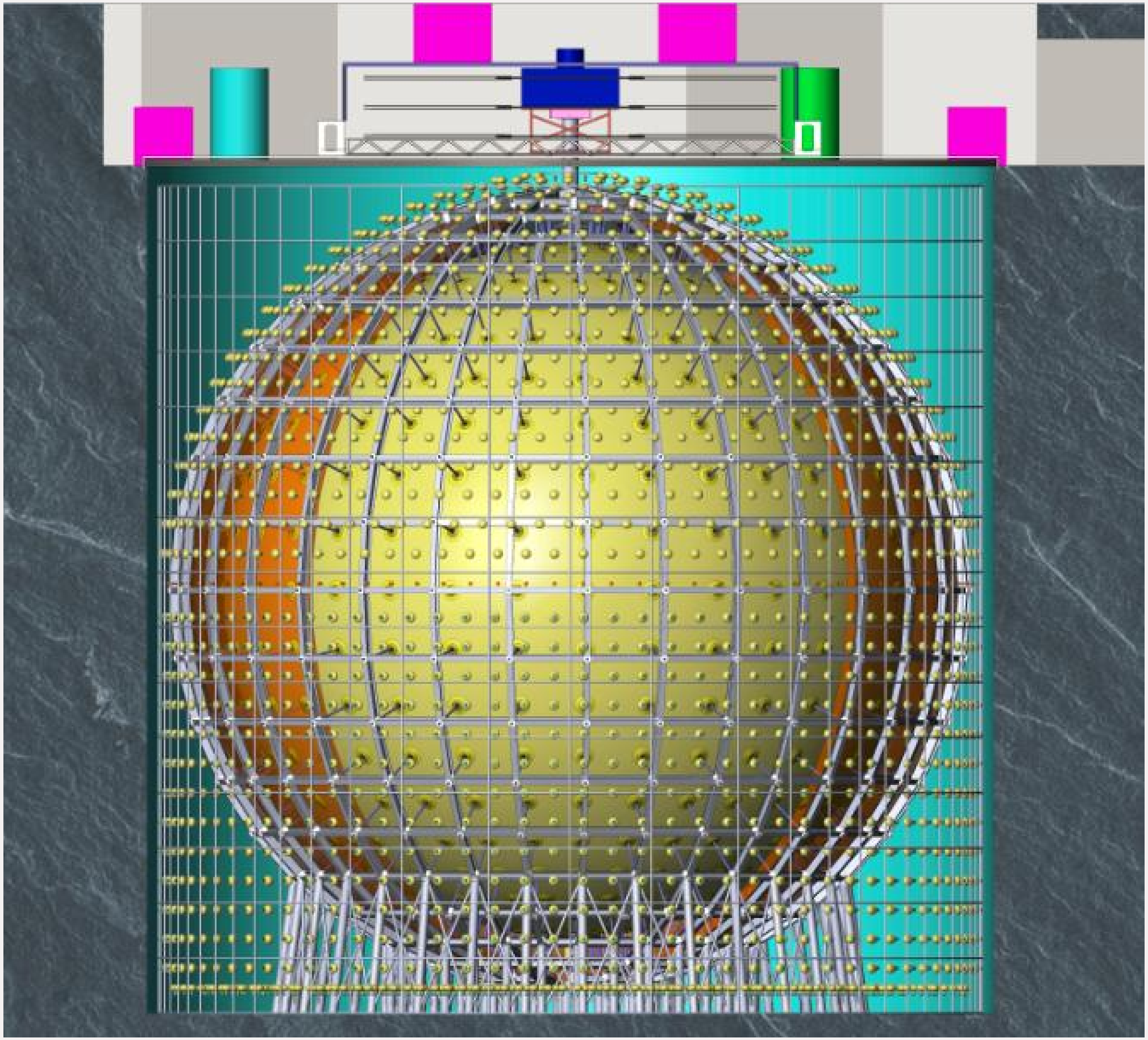
Noise (~ background) ($\frac{c^2}{E^2}$)

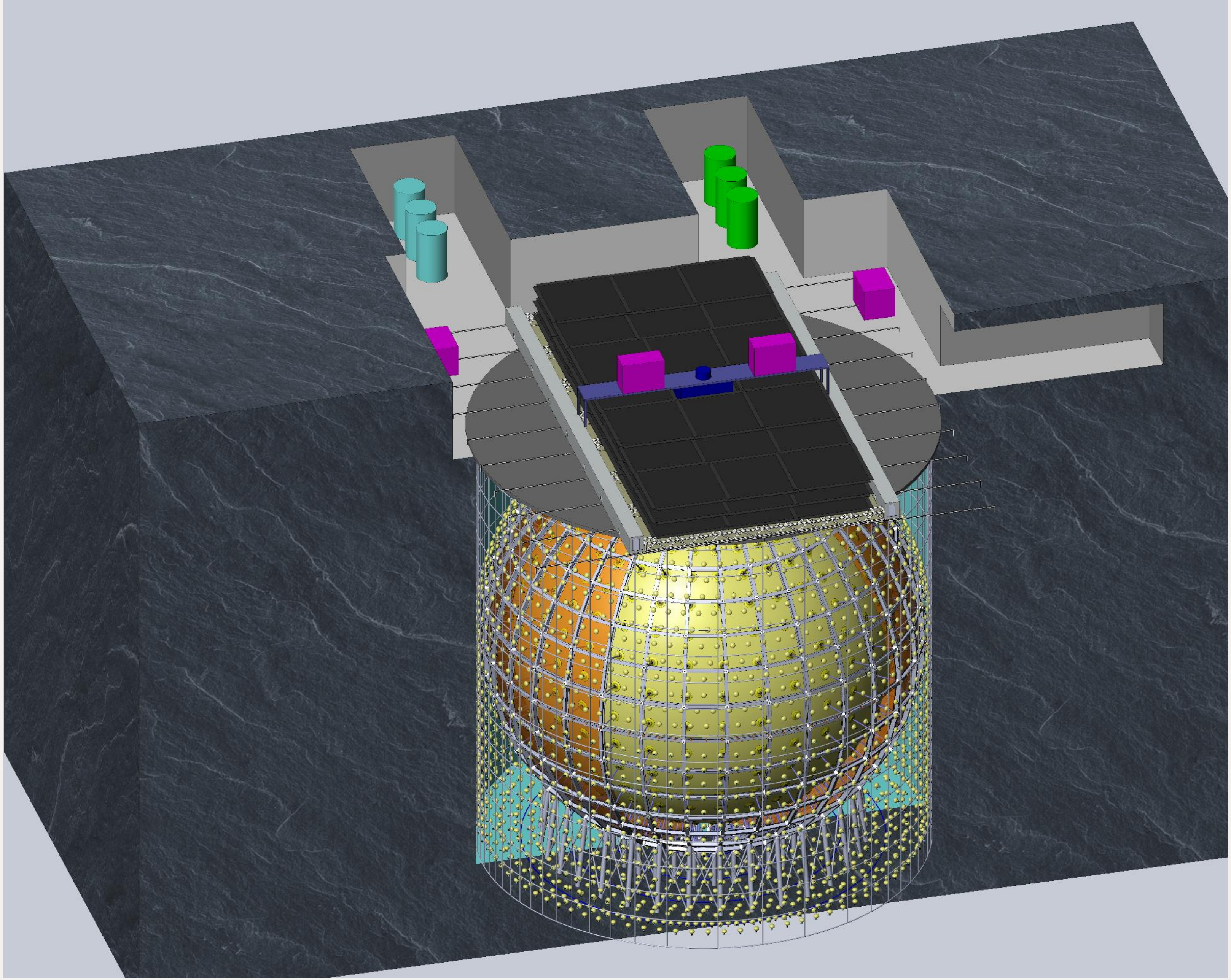
A) High, uniform photoelectron yield (~ 1200 p.e./MeV)

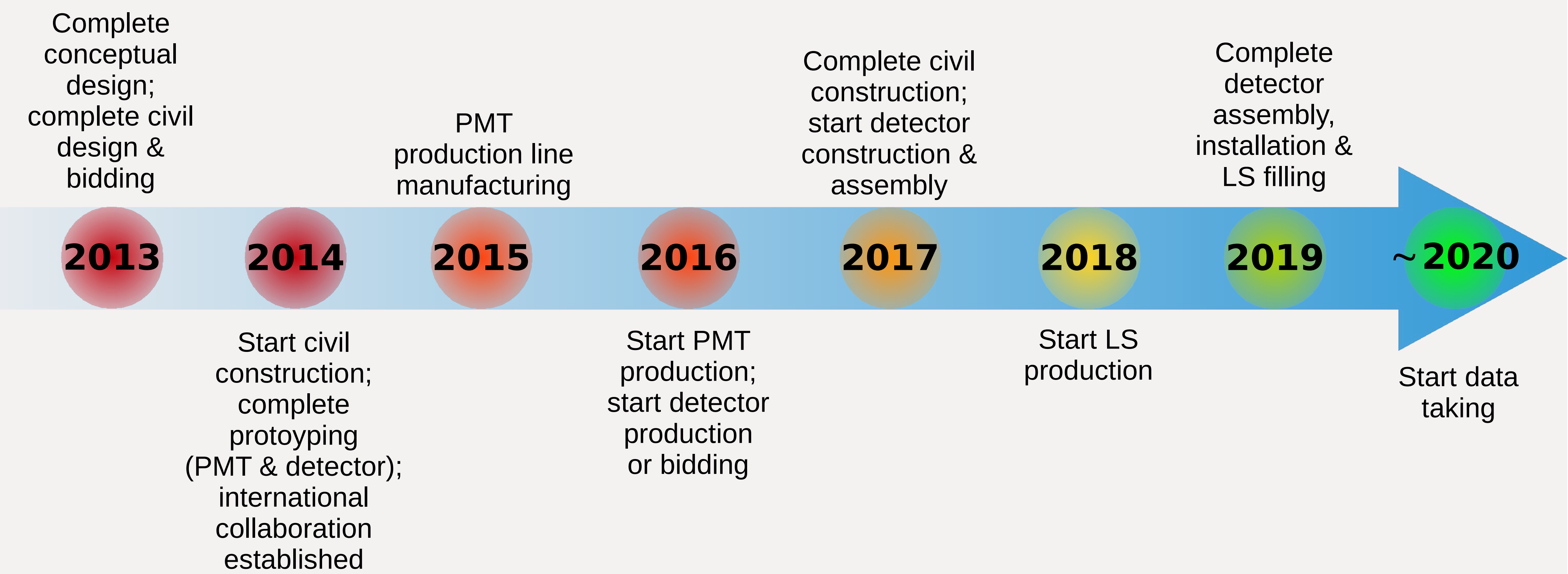
- Spherical detector
- High light yield scintillator + low attenuation (**no Gd loading**)
- High photocathode coverage (~77%)
- PMTs with high detection efficiency (~30%)

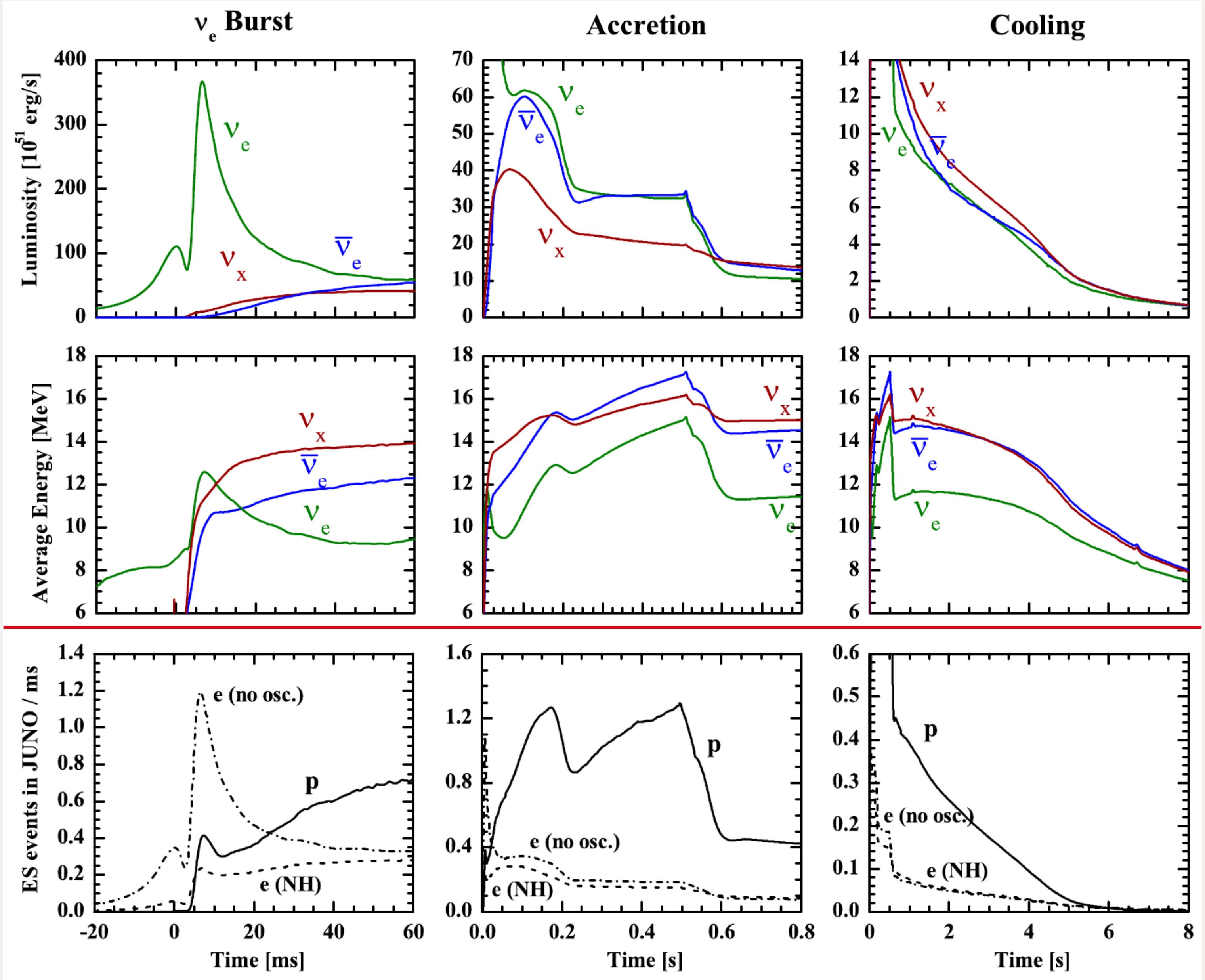
B) Low noise → Clean materials and quiet PMTs

C) Comprehensive calibration program






2013
Complete conceptual design; complete civil design & bidding
2014
Start civil construction; complete protoyping (PMT & detector); international collaboration established
2015
PMT production line manufacturing
2016
Start PMT production; start detector production or bidding
2017
Complete civil construction; start detector construction & assembly
2018
Start LS production
2019
Complete detector assembly, installation & LS filling
~2020
Start data taking



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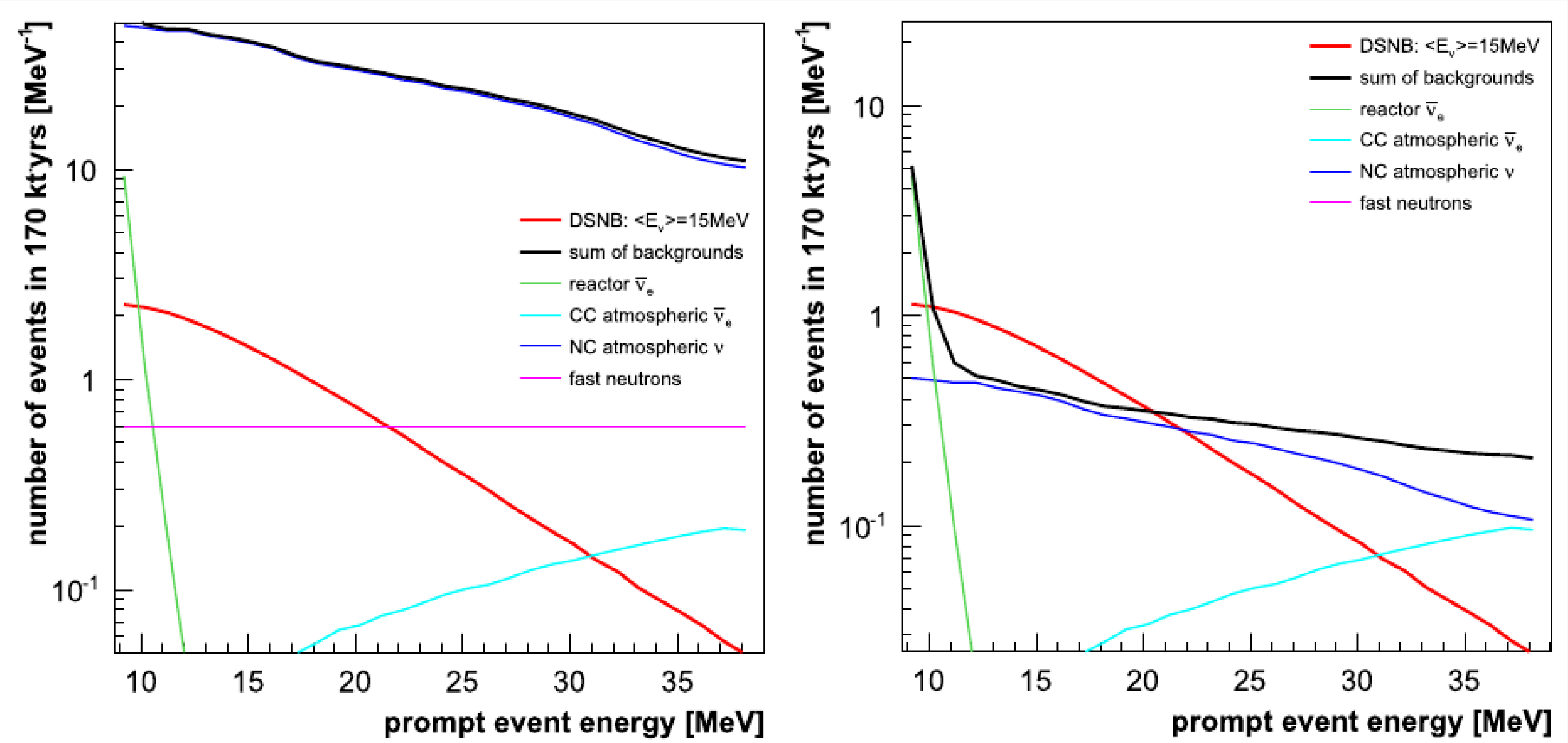
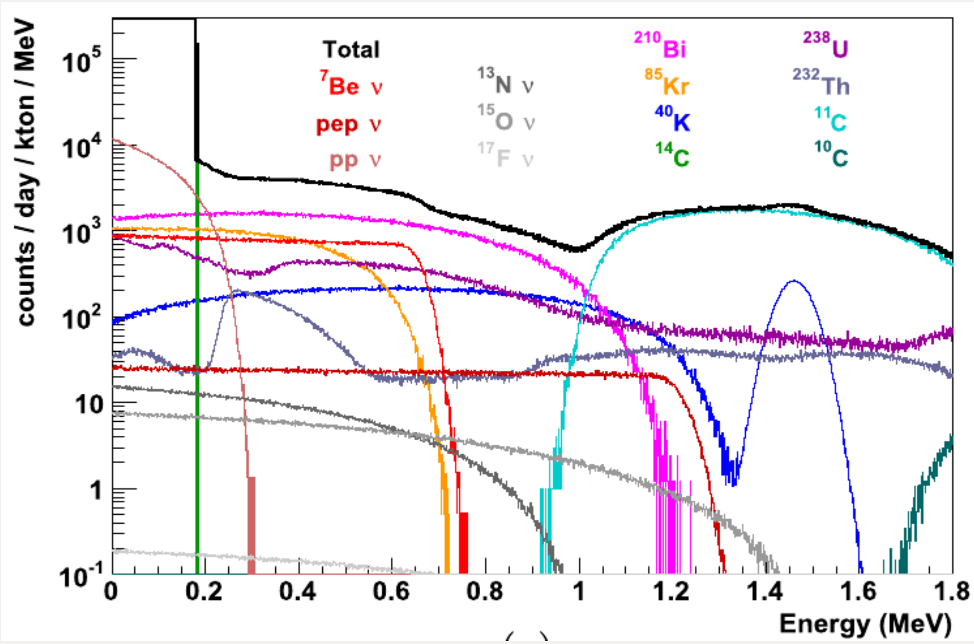
3.24x10^{53} erg emitted in neutrinos

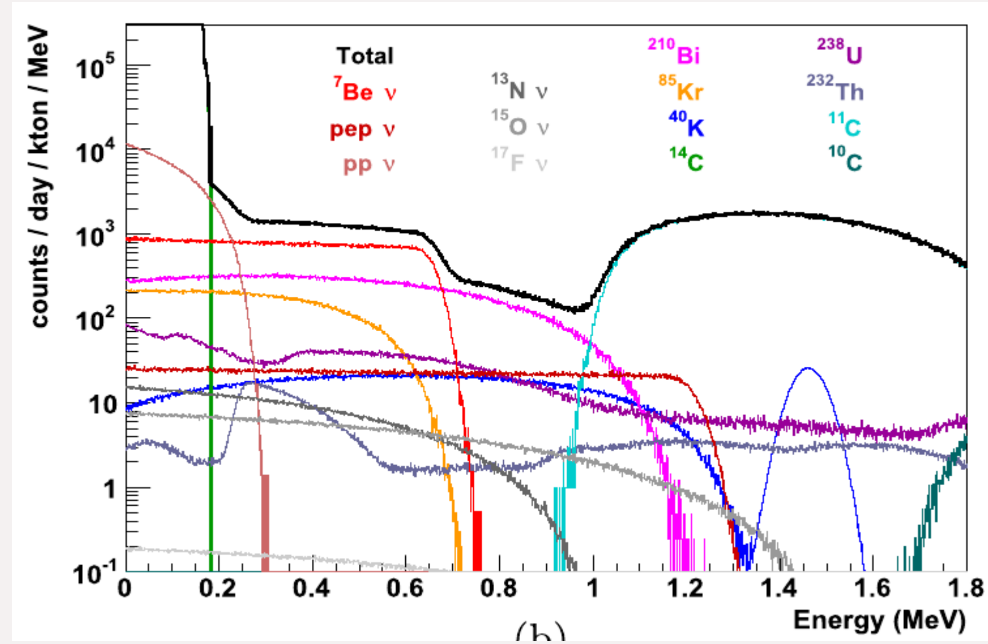


Item		Rate (no PSD)	PSD efficiency	Rate (PSD)
Signal	$\langle E_{\bar{\nu}_e} \rangle = 12$ MeV	13	$\varepsilon_\nu = 50\%$	7
	$\langle E_{\bar{\nu}_e} \rangle = 15$ MeV	23		12
	$\langle E_{\bar{\nu}_e} \rangle = 18$ MeV	33		16
	$\langle E_{\bar{\nu}_e} \rangle = 21$ MeV	39		19
Background	reactor $\bar{\nu}_e$	0.3	$\varepsilon_\nu = 50\%$	0.13
	atm. CC	1.3	$\varepsilon_\nu = 50\%$	0.7
	atm. NC	6×10^2	$\varepsilon_{NC} = 1.1\%$	6.2
	fast neutrons	11	$\varepsilon_{FN} = 1.3\%$	0.14
	Σ			7.1

10 years measurement
17 kt fiducial mass



Baseline



Ideal

JUNO

Internal radiopurity requirements	Baseline	Ideal
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	Cosmogenic background rates (counts/day/kton)
^{11}C	1860
^{10}C	35