Physics & technology of JUNO

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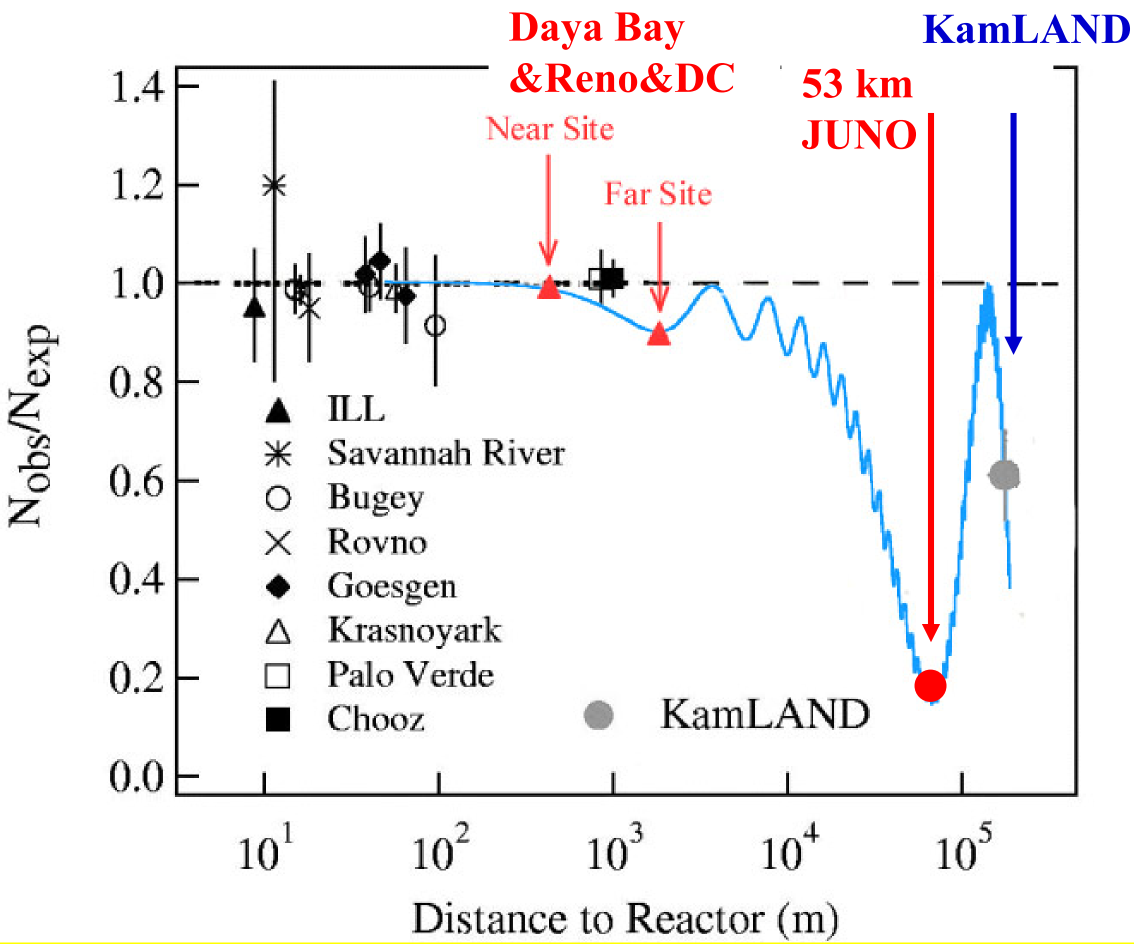
INFN – Milano

International Workshop on Outlook for INO, IICHEP and beyond
20 February, 2021

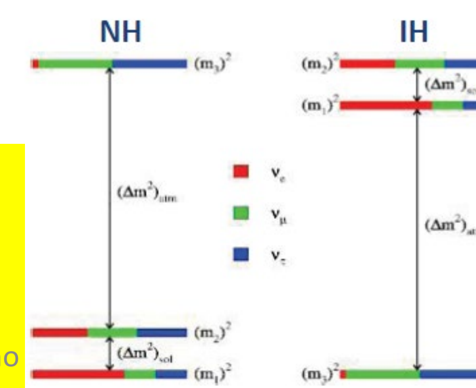
Online meeting

- Determination of the neutrino mass hierarchy with a large mass liquid scintillation detector located at medium distance – 53 km – from a set of high power nuclear complexes
- Precise measurements of oscillation parameters
- Vast astroparticle program
- Technical challenges and status of the construction

JUNO physics summary



- **20 kton LS detector**
- **~3 % energy resolution-the greatest challenge**
- Rich physics possibilities
  - ⇨ **Mass hierarchy**
  - ⇨ **Precision measurement of 3 mixing parameters**
  - ⇨ **Supernovae neutrinos**
  - ⇨ **Geoneutrinos**
  - ⇨ **Diffuse Supernovae ν's**
  - ⇨ **Atmos&sol neutrinos**
  - ⇨ **Nucleon Decay**
  - ⇨ **Exotic searches**



Neutrino Physics with JUNO, J. Phys. G 43, 030401 (2016)

The tension between the solar and KamLAND Δm^2 has further boosted the importance of the precision Δm^2_{21} measurement

The physics with a large LS spherical detector

– **LS large volume:** ➔ **for statistics**

– **High Light(PE)** ➔ **for energy resolution 1200 pe/MeV**

Both crucial for the physics capabilities

Steel Truss to support the acrylic and hold PMTs

~20000 x 20”

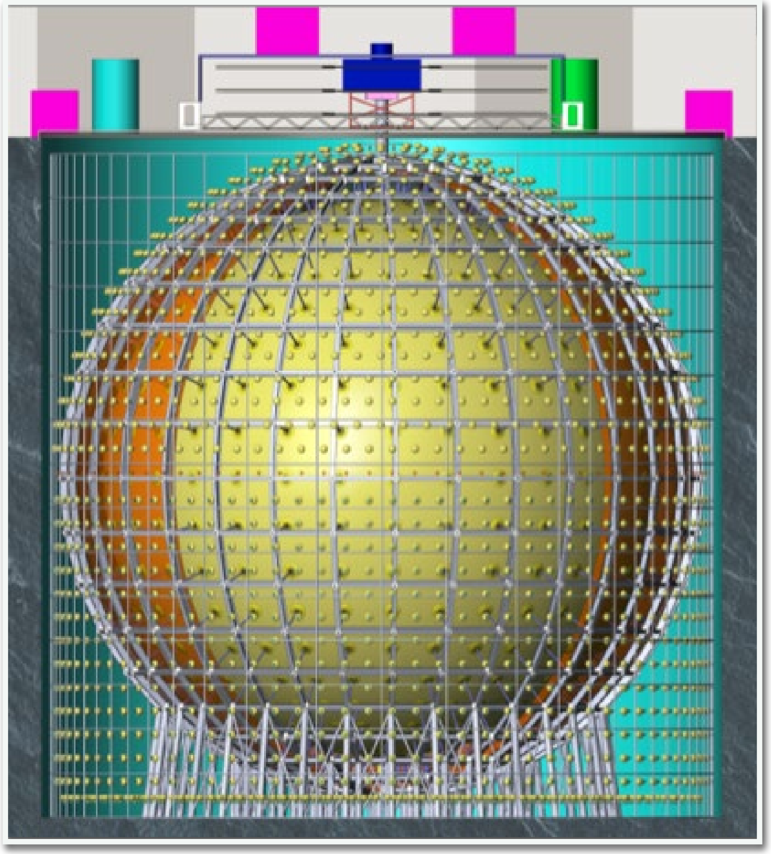
18000 Inner

2000 veto

~25000 x 3”

Acrylic Sphere

filled with 20 kt LS



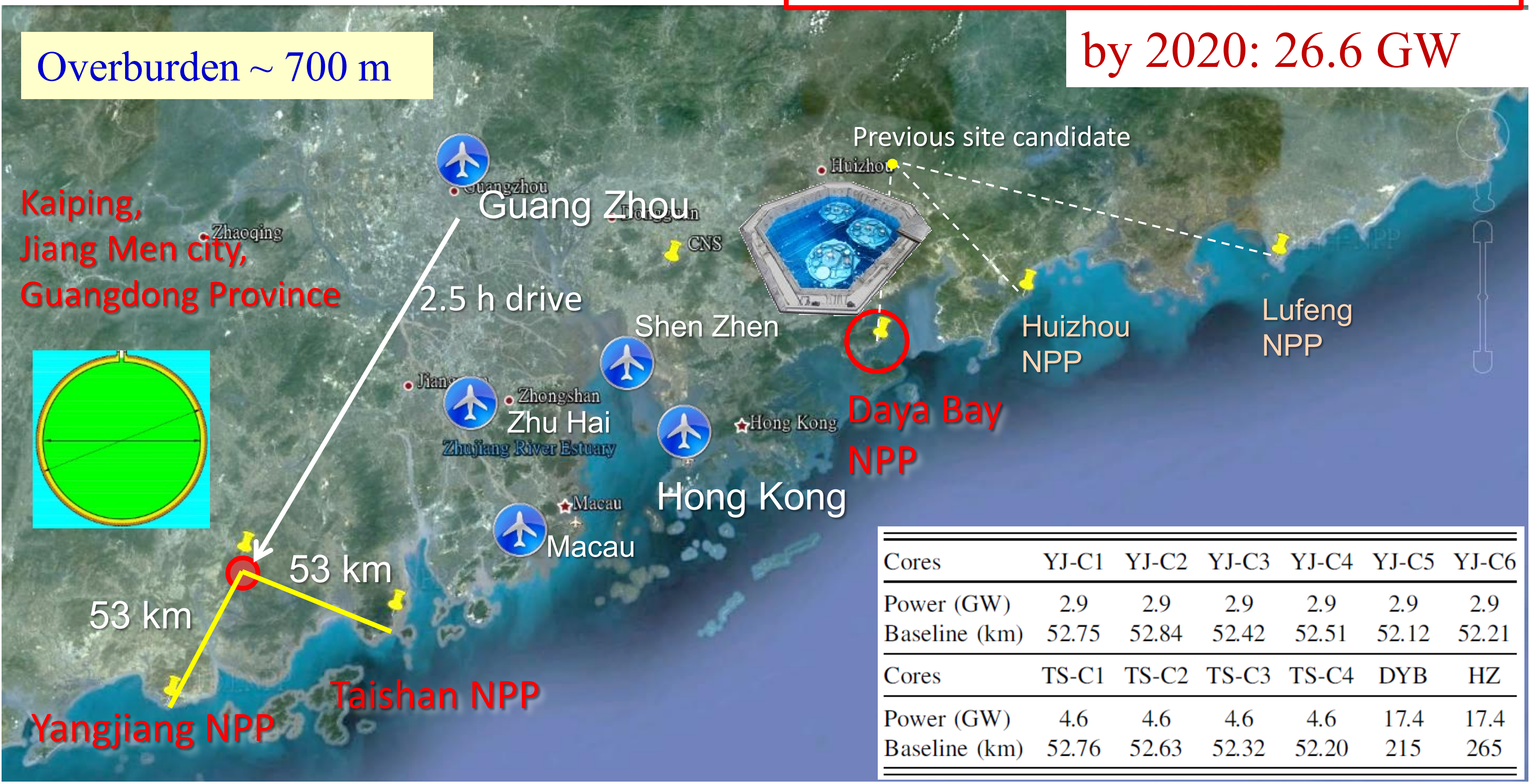
JUNO has been approved in China in Feb. 2013

Participation and contributions from several other countries:

- **Armenia**
- **Belgium**
- **Brazil**
- **Chile**
- **Czechia**
- **Finland**
- **France**
- **Germany**
- **Italy**
- **Latvia**
- **Pakistan**
- **Russia**
- **Slovakia**
- **Taiwan**
- **Thailand**
- **USA**

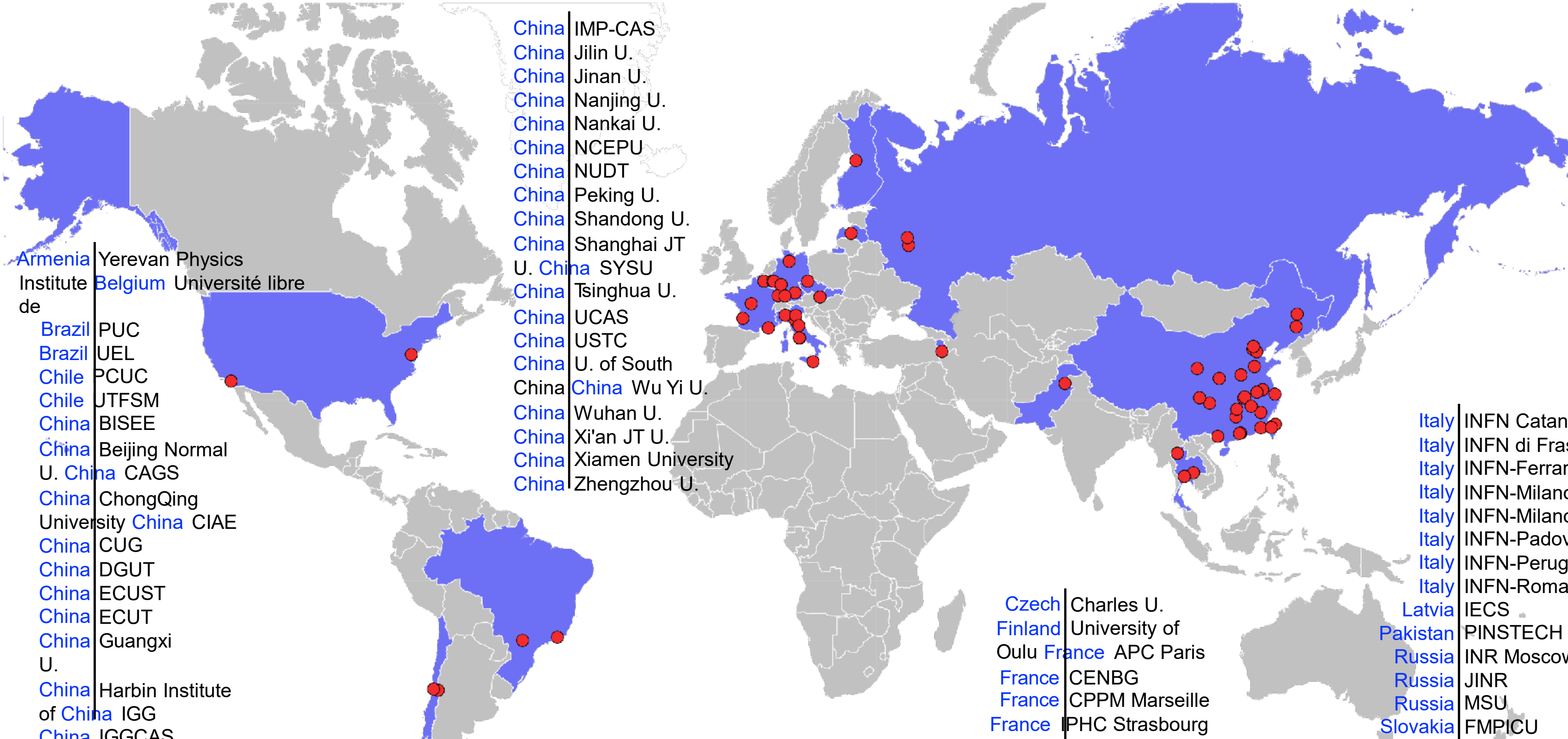
The importance of the location

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	6 built	2 built + 2 future
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

JUNO collaboration



Armenia | Yerevan Physics Institute
Belgium | Université libre de
Brazil | PUC
Brazil | UEL
Chile | PCUC
Chile | UTFSM
China | BISEE
China | Beijing Normal U.
China | CAGS
China | ChongQing University
China | CIAE
China | CUG
China | DGUT
China | ECUST
China | ECUT
China | Guangxi U.
China | Harbin Institute of China
IGG
China | IGGCAS

China | IMP-CAS
China | Jilin U.
China | Jinan U.
China | Nanjing U.
China | Nankai U.
China | NCEPU
China | NUDT
China | Peking U.
China | Shandong U.
China | Shanghai JT U.
China | SYSU
China | Tsinghua U.
China | UCAS
China | USTC
China | U. of South China
China | Wu Yi U.
China | Wuhan U.
China | Xi'an JT U.
China | Xiamen University
China | Zhengzhou U.

Czech | Charles U.
Finland | University of Oulu
France | APC Paris
France | CENBG
France | CPPM Marseille
France | IPHC Strasbourg
France | Subatech Nantes
German | ZEA FZ Julich
German | RWTH Aachen U.
German | TUM
German | U. Hamburg
German | IKP FZ Jülich
German | U. Mainz
German | U. Tuebingen

Italy | INFN Catania
Italy | INFN di Frascati
Italy | INFN-Ferrara
Italy | INFN-Milano
Italy | INFN-Milano Bicocca
Italy | INFN-Padova
Italy | INFN-Perugia
Italy | INFN-Roma 3
Latvia | IECS
Pakistan | PINSTECH (PAEC)
Russia | INR Moscow
Russia | JINR
Russia | MSU
Slovakia | FMPICU
Taiwan | National Chiao-Tung U.
Taiwan | National Taiwan U.
Taiwan | National United U.
Thailand | NARIT
Thailand | PPRLCU
Thailand | SUT
USA | UMD1
USA | UMD2
USA | UCI

Collaboration established on July 2014

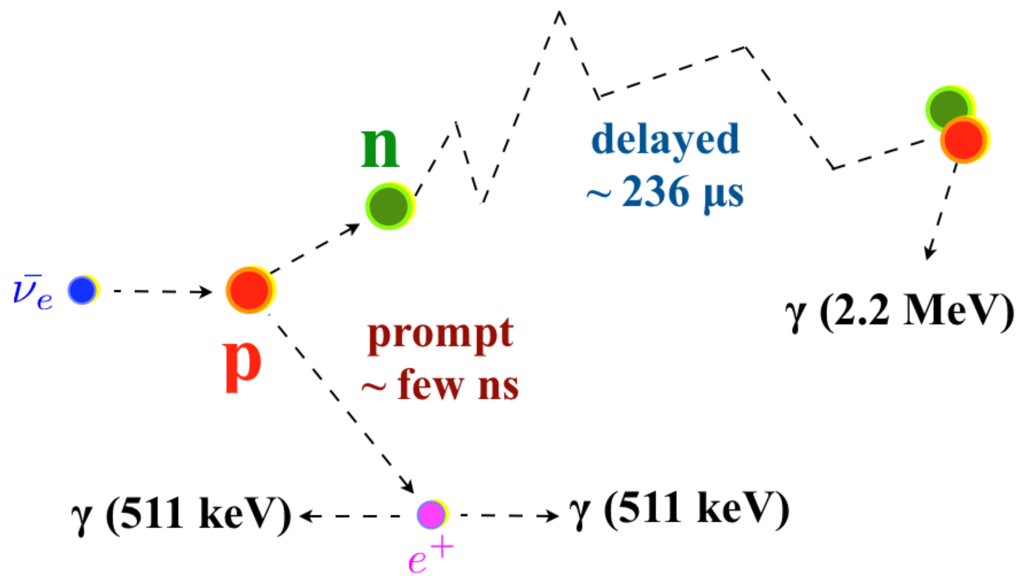
Now 77 institutions ~600 collaborators

Methodology to infer the Mass Hierarchy

The determination of the mass hierarchy relies on the identification on the positron spectrum of the "imprinting" of the anti-ν_e survival probability

Detection through the classical inverse beta decay reaction

$$\bar{\nu} + p \rightarrow n + e^+ \quad E_\nu > 1.8 \text{ MeV}$$



The time coincidence between the positron and the γ from the capture rejects the uncorrelated background

The "observable" for the mass hierarchy determination is the positron spectrum
It results that $E_{vis}(e^+) = E(\nu) - 0.8$ MeV

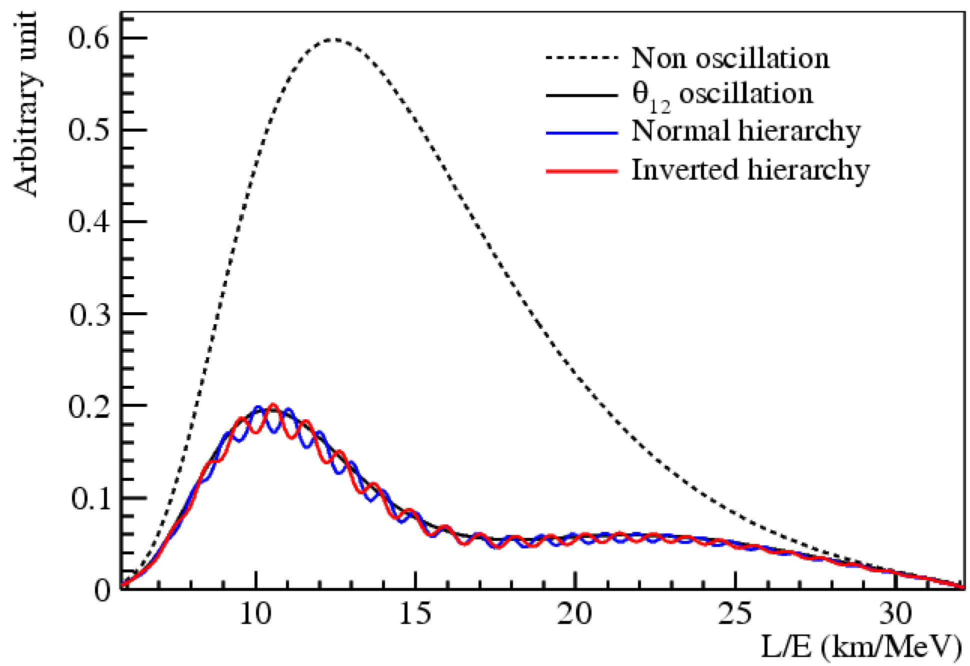
Method from Petcov and Piai, Physics Letters B 553, 94-106 (2002)

MH and Survival probability

arXiv 1210.8141

$$P_{ee} = \left| \sum_{i=1}^{3} U_{ei} \exp\left(-i\frac{m_i^2}{2E_i}\right) U_{ei}^* \right|^2$$
$$= 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21})$$
$$- \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{31})$$
$$- \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{32})$$

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu}, \quad (\Delta m_{ij}^2 \equiv m_i^2 - m_j^2)$$



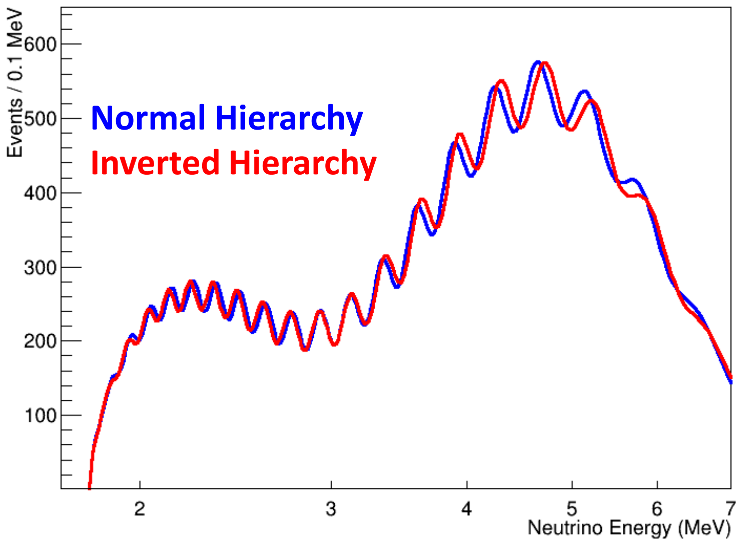
Or to make the effect of the mass hierarchy explicit, exploiting the approximation $\Delta m^2_{32} \approx \Delta m^2_{31}$:

$$P_{ee} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21})$$
$$- \sin^2 2\theta_{13}\sin^2(|\Delta_{31}|)$$
$$- \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{21})\cos(2|\Delta_{31}|)$$
$$\pm \frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin(2\Delta_{21})\sin(2|\Delta_{31}|),$$

+ NH
- IH

The big suppression is due to the "solar" oscillation → Δm^2_{21} , $\sin^2\theta_{12}$
The ripple is the "atmospheric" oscillation → Δm^2_{31} from frequency
MH encoded in the phase
"high" value of θ_{13} crucial

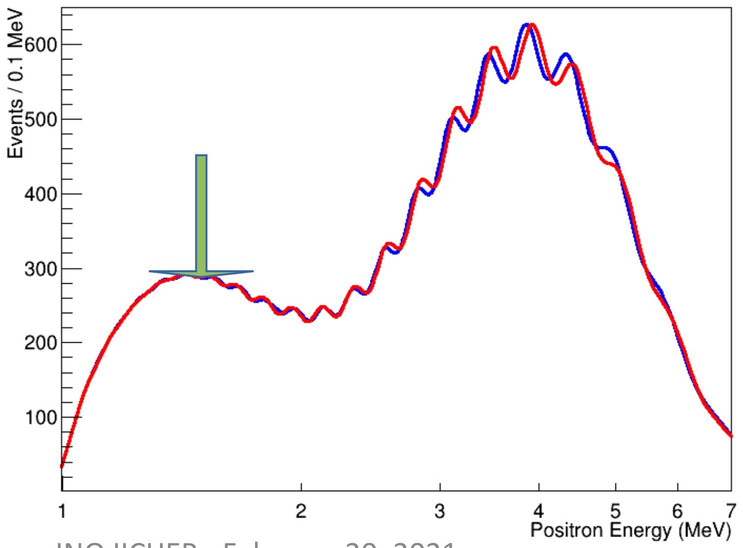
Example of Neutrino & Positron Spectra



Spectrum in term of neutrino energy – no energy resolution

Replicating sensitivity study in arXiv 1210.8141

- Three neutrino framework (no effective Δmee $\Delta m\mu\mu$)
- Baseline: 50 km
- Fiducial Volume: 5 kt
- Thermal Power: 20 GW
- Exposure Time: 5 years
- **more pessimistic than the JUNO values**



Visible energy due to inverse beta decay

- E(vis) ~ E(ν) – 0.8 MeV
- Assuming 3% / sqrt(E) resolution
- Assuming negligible constant term in resolution

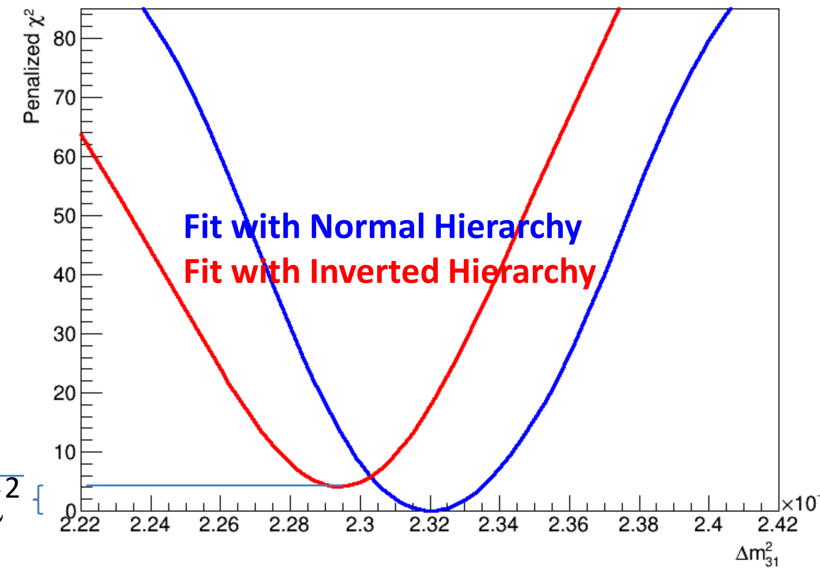
Spectrum in term of positron visible energy – with energy resolution

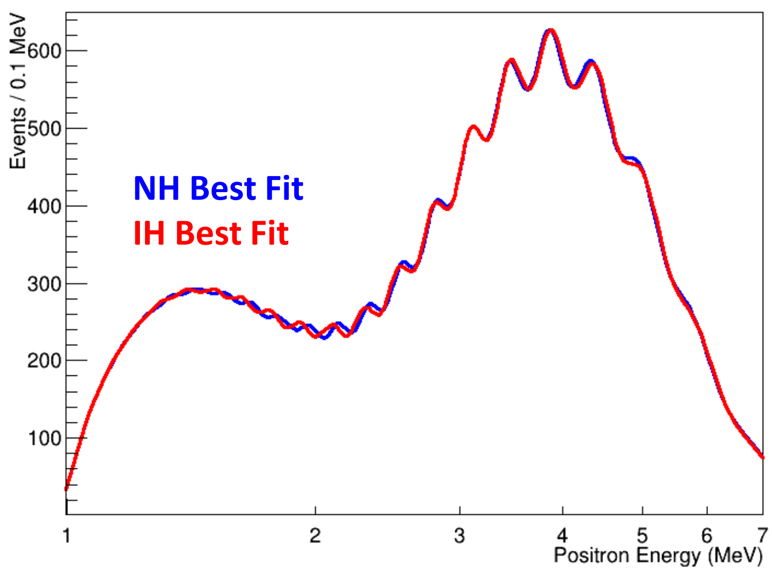
Example of χ^2 comparison – NH true

Numerical values as before
Scan of penalized (i.e. marginalized over the other minimization parameters) χ^2 vs. $|\Delta m^2_{31}|$

Case NH true- average spectrum
(no fluctuation –**Asimov data set**)
Test statistics → $\Delta\chi^2=\chi^2_{min}(NH) - \chi^2_{min}(IH)$

Fit NH minimum: $1.6\ 10^{-2}$ (practically 0)
FIT IH minimum: 4.0
$\overline{\Delta\chi^2}$ ~4.0





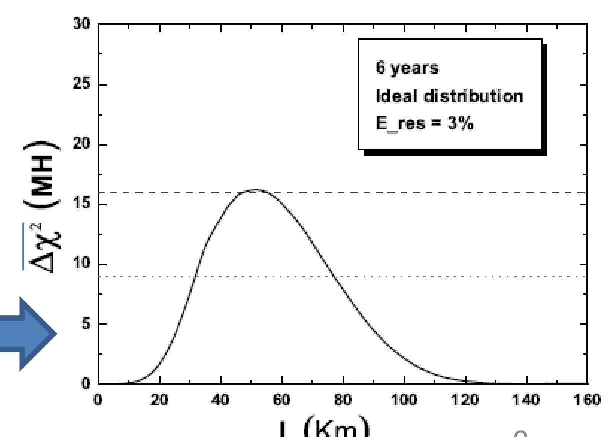
Comparison between IH/NH best fits

The best fit $|\Delta m_{31}|$ is different in the two cases

Fit almost succeeds in accommodating IH spectrum to NH data

The two solutions are fully degenerate but in a limited range of distances

Optimum distance to maximize $\overline{\Delta\chi^2}$

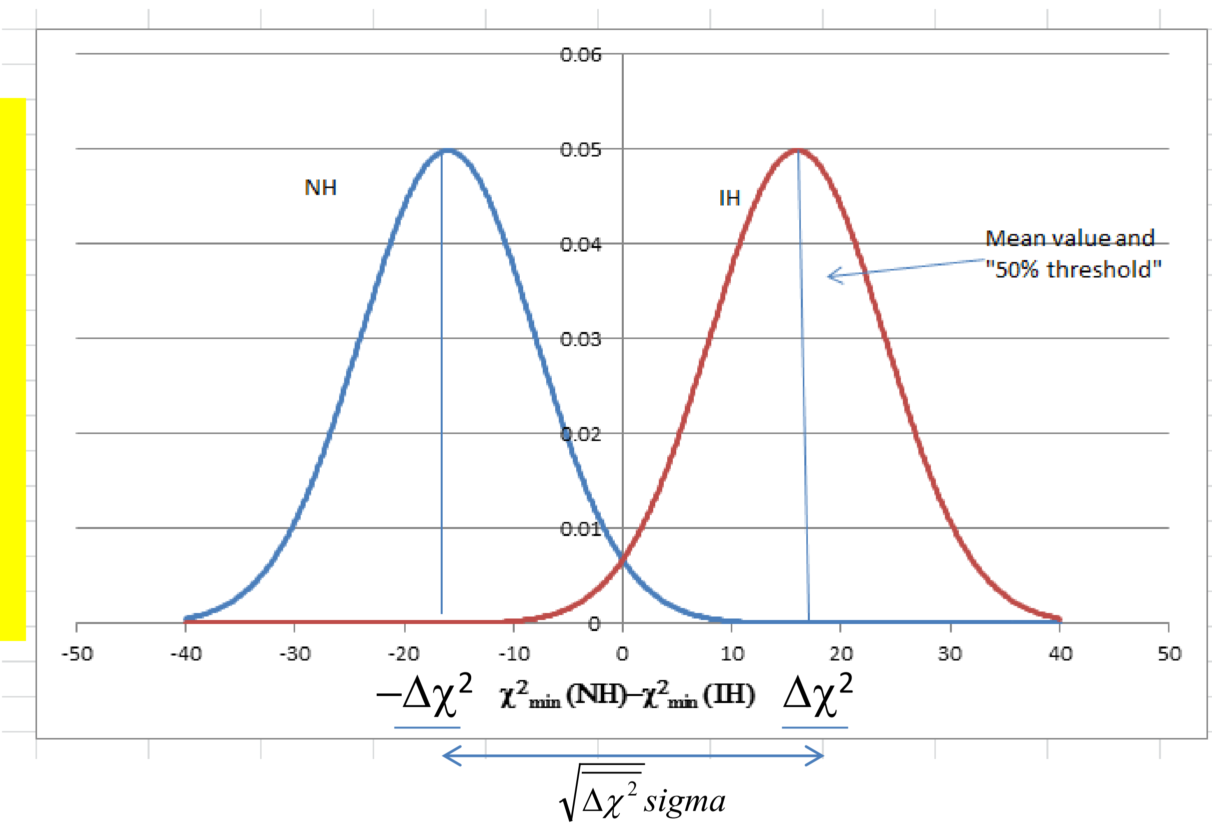


From arXiv:1303.6733v1 [hep-ex] JUNO
$\overline{\Delta\chi^2}$ can be as high as **16** @ 53 km

Distribution of test statistics and number of sigmas for discovery

- **Not unique answer**
- It depends upon the assumed framework (**frequentist or Bayesian**)
- However the actual information is fully encoded in the amount of overlap of the two Gaussian independently from how it is summarized as number of σ
- General result: sigma of each Gaussian = $2\sqrt{\Delta\chi^2}$ **arXiv: 1210.8141v2**

The mean value of the Gaussian curves is taken as representative of the **JUNO** capability at 53 Km arXiv:1303.673



The mean values of the two curves are displaced of exactly

$$\sqrt{\Delta\chi^2}\ sigmas$$

Assumed in a frequentist framework as quantification of discovery capability

arXiv:1311.4076

JUNO sensitivity to Mass Hierarchy – statistics only

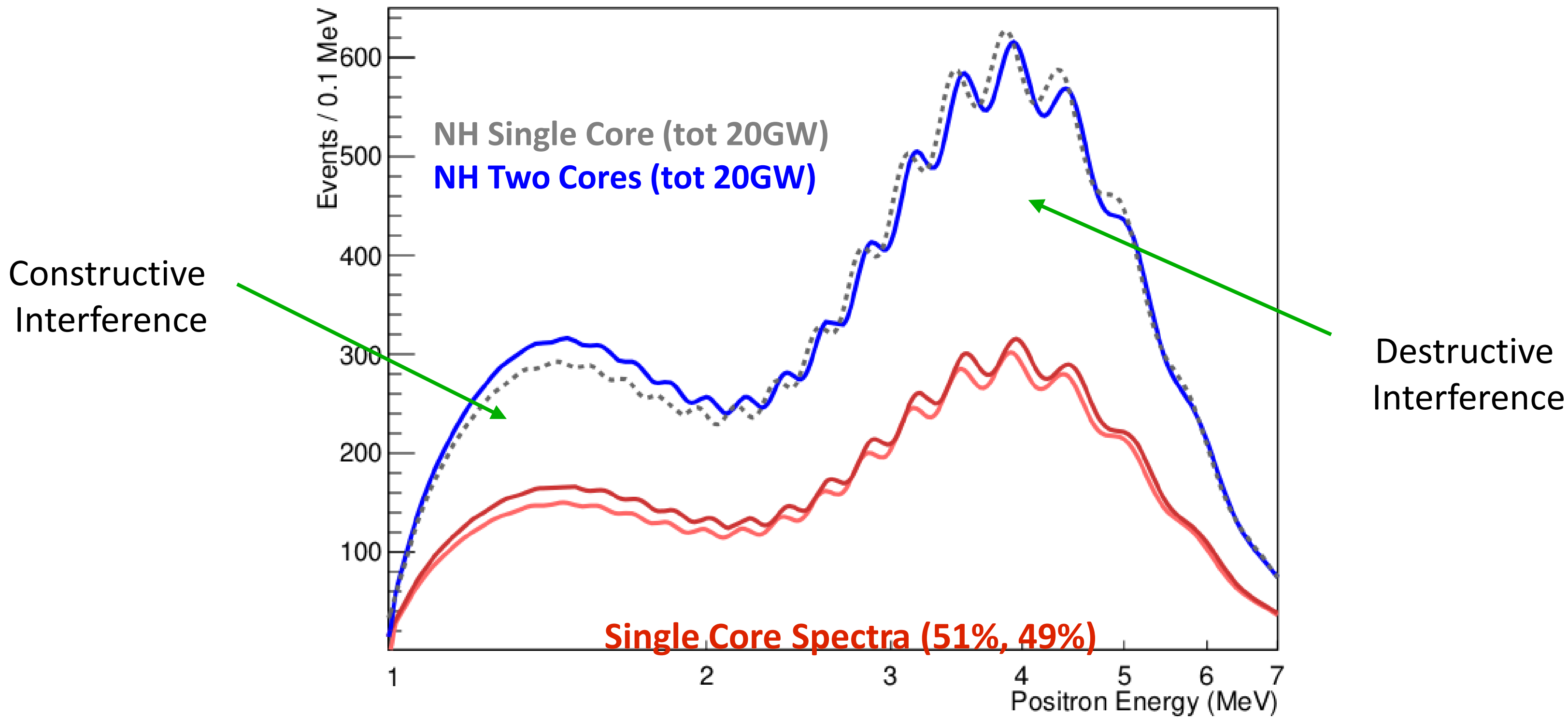
With these characteristics JUNO can achieve statistically a 4 σ sensitivity, understood with the meaning of the previous slide – spectrum with about 100000 events

- Baseline: 53 km
- Fiducial Volume : 20 kt
- Thermal Power : 36 GW
- Data taking : 6 years (8/9 with reduced Power)
- Proton content : 12% in mass
- Energy resolution : 3% @ 1 MeV

Caveat: Multiple Cores

Reduction in sensitivity might arise from actual spatial distribution of nuclear reactor cores

E.g. two cores with 51% (49%) of tot. power, placed at 53 km but with 500 m difference distance from detector

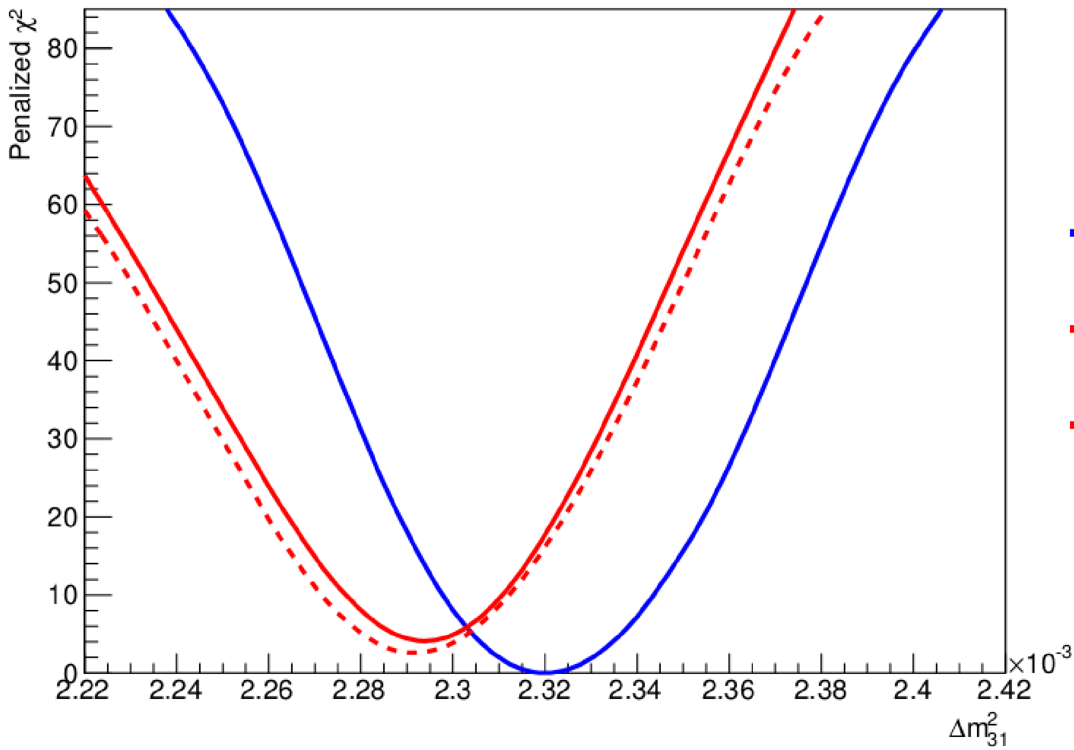


Baseline difference results in destructive interference in the most sensitive region of the spectrum

Important effect since JUNO will detect neutrinos from several cores

Multiple Cores: χ^2

Sensitivity loss is measured through the new χ^2 minimum



Best Fit NH

Best Fit IH Two Cores

Best Fit IH Single Core

For JUNO this defines the location (only two reactors) and the maximum baseline difference : 500 m

$\overline{\Delta\chi^2}$ between IH and NH in this numerical exercise is reduced from 4.0 to 2.6

In the JUNO set-up the spread of the cores is 500 m $\rightarrow$ $\overline{\Delta\chi^2}$ reduction of about **3**

Other effects

- Adverse effects
  - **Non linearity of the energy scale**

  This clearly impacts the ability to distinguish the true from false Hierarchy since distorts the experimental spectrum, therefore a very careful calibration is required better than 1% **arXiv:1307.7419**, as well as the long term stability of the detector - see also **arXiv:1508.01392**

  Other experiments already achieved <1% accuracy

(Daya Bay ~0.5%, Double Chooz 0.74%, Borexino <1% (at low energies), KamLAND 1.4%)

  - **Reactor shape uncertainty** (1%) → more on this later
  - **The statistical and shape uncertainties of backgrounds**

- Favorable element for analysis

Improved knowledge of $|\Delta m_{31}|$ by other experiments specifically T2K and NovA ~1%

Exploited by adding a pull in the χ^2 definition thus increasing globally the $\overline{\Delta\chi^2}$

This is better done using the effective parameter $\left|\Delta m^2_{\square}\right|$

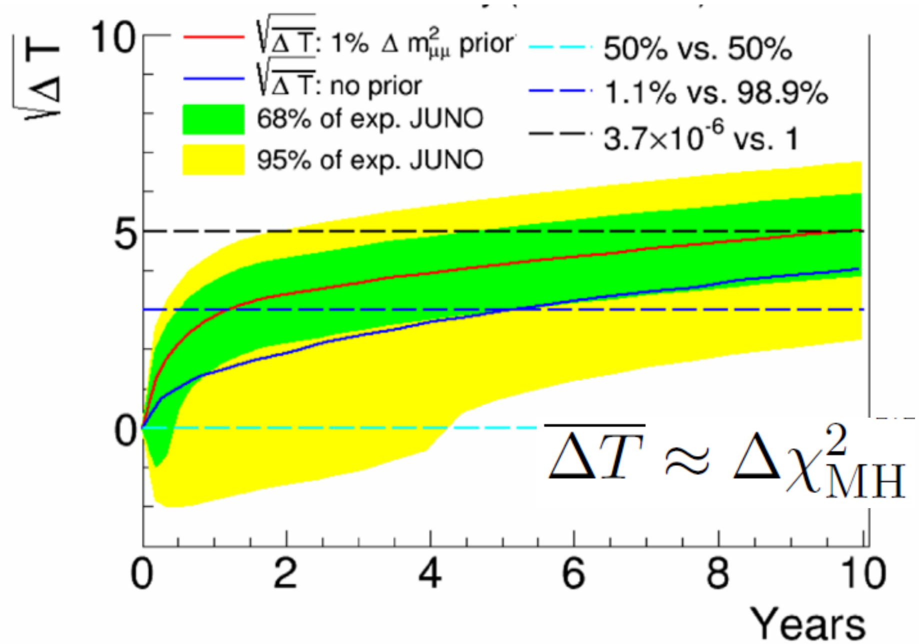
$$\Delta m^2_{\mu\mu} = \sin^2\theta_{12}\Delta m^2_{31} + \cos^2\theta_{12}\Delta m^2_{32} + \cos\delta\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\Delta m^2_{21}$$

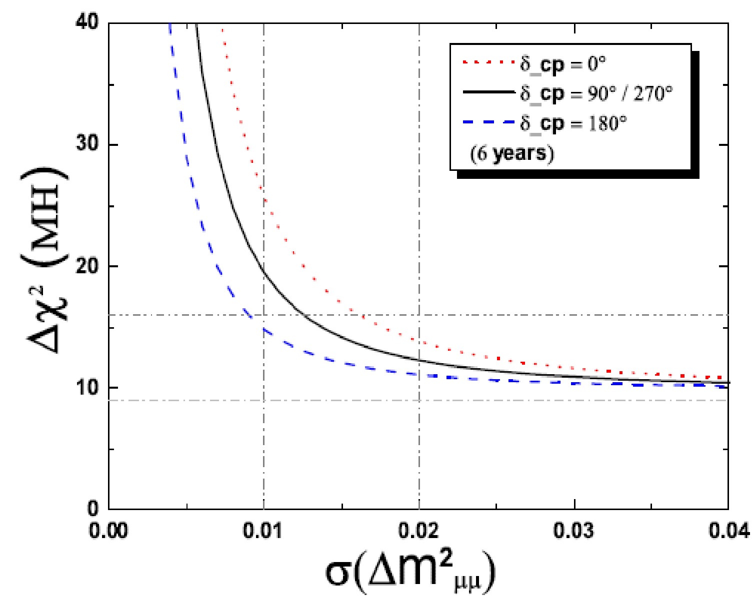
- In conclusion arXiv:1303.6733v1 demonstrates that JUNO can reach the value $\overline{\Delta\chi^2}$ in the range 15-20 → **crucially dependent upon the resolution (this assumes 3%) which is by far the challenge of the experiment**

Summary of MH Sensitivity

PRD 88, 013008 (2013)	Relative Meas.	Use absolute Δm^2
Statistics only	4σ	5σ
Realistic case	3σ	4σ

JUNO **MH sensitivity with 6 years' data (nominal power):**





	Stat.	Core dist.	DYB & HZ	Shape	B/S (stat.)	B/S (shape)	$\lvert\Delta m^2_{\mu\mu}\rvert$
Size	52.5 km	Tab. 1-2	Tab. 1-2	1%	6.3%	0.4%	1%
$\Delta\chi^2_{\rm MH}$	+16	−3	−1.7	−1	−0.6	−0.1	+(4 − 12)

Energy non linearity and residual energy scale uncertainty

Implications thoroughly discussed in the JUNO Yellow Book arXiv:1507.05613

The loss on $\overline{\Delta\chi^2}$ depends upon the assumed form of the residual non linearity and also on the procedure to deal with in the χ^2 computation - this is why is not included in the summary table $\rightarrow$ main message : calibrate as better as possible (sub percent level)

A general approach to deal with this issue devised in arXiv:1508.01392

- based on the knowledge of the residual uncertainty band and on the introduction of a corresponding pull in the χ^2 definition

Example: residual energy scale uncertainty in Day Bay calibration

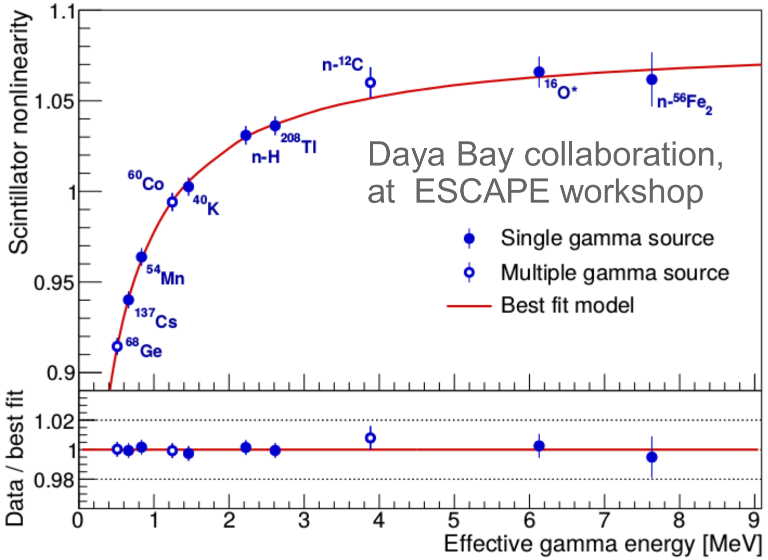
How to Control the Energy Scale Uncertainties

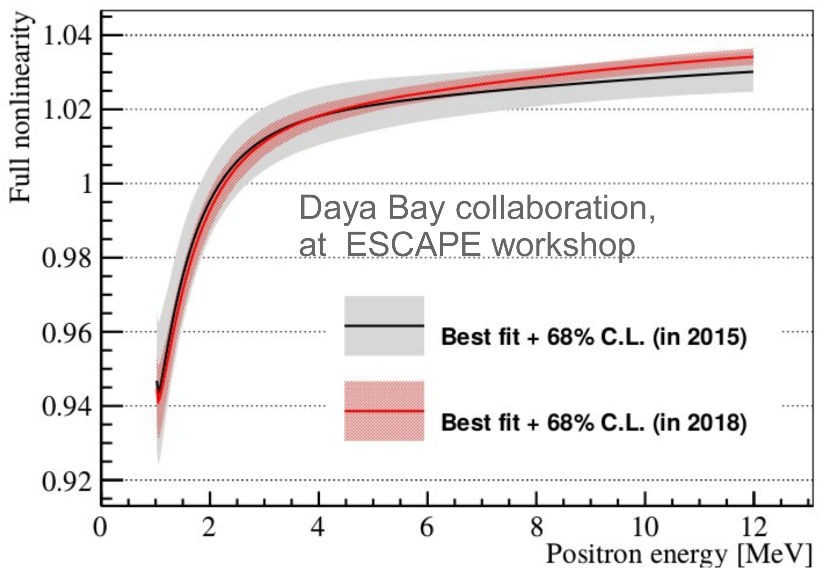
With accurate and extensive calibration procedures

Different sources, over whole energy range, continuously, ...

For more information see: Daya Bay collaboration, Phys. Rev. D 95, 072006 (2017)

Calibration results from Daya Bay at ESCAPE workshop @Heidelberg June 2018

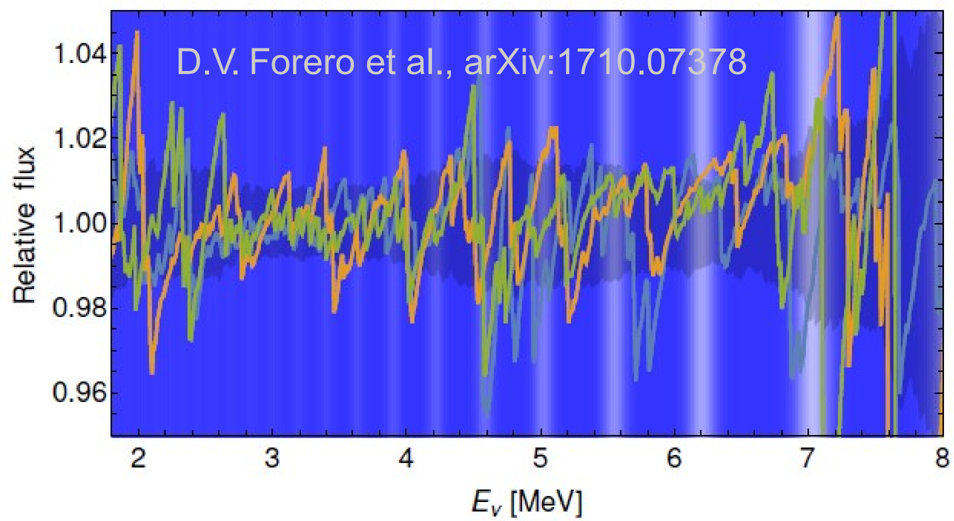




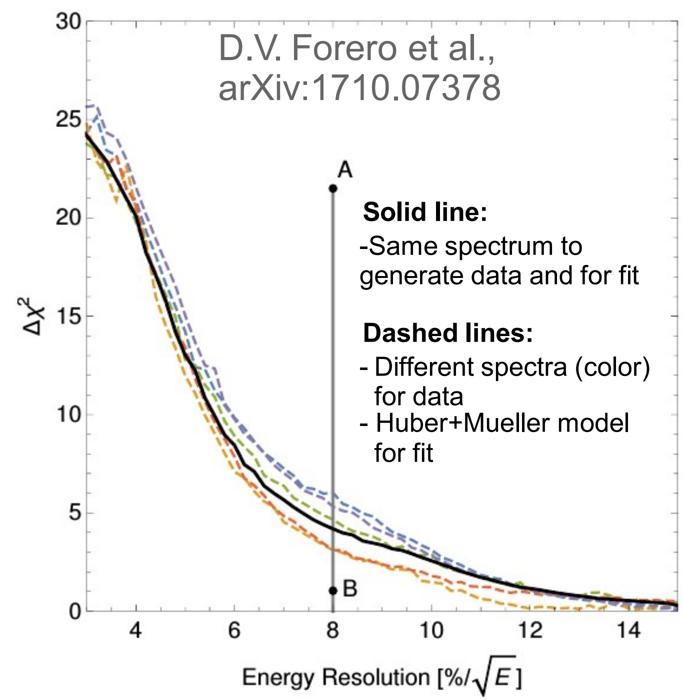
Uncertainty band substantially below 1% →MC in JUNO shows MH sensitivity unaffected

Implications of the reactor shape uncertainty

- "Standard" reactor shape uncertainty has minor impact on the sensitivity
- But reactor spectrum might show micro-structures
  (see e.g. A.A.Sonzogni, et al. arXiv:1710.00092, D. A. Dwyer &T. J. Langford, Phys. Rev. Lett. 114,012502 (2015))
- micro-structures might degrade the MH sensitivity by mimicking periodic oscillation pattern



Relative difference of 3 synthetic spectra to spectrum predicted from ILL data (Huber+Mueller model)



of reactor spectrum measurement

→ **Reactor spectrum with energy resolution at least similar to JUNO avoids in principle this potential issue**

Near TAO Detector Concept

Gd-LS in diameter of 1800 mm

- Surface 10.2 m^2
- Volume 3.05 m^3, or 2.63 ton
- 1 ton fiducial volume w/ a 25cm cut
- Event rate 30 times of JUNO
- ~30 m from the core @ Taishan
- Resolution better than 1.7%

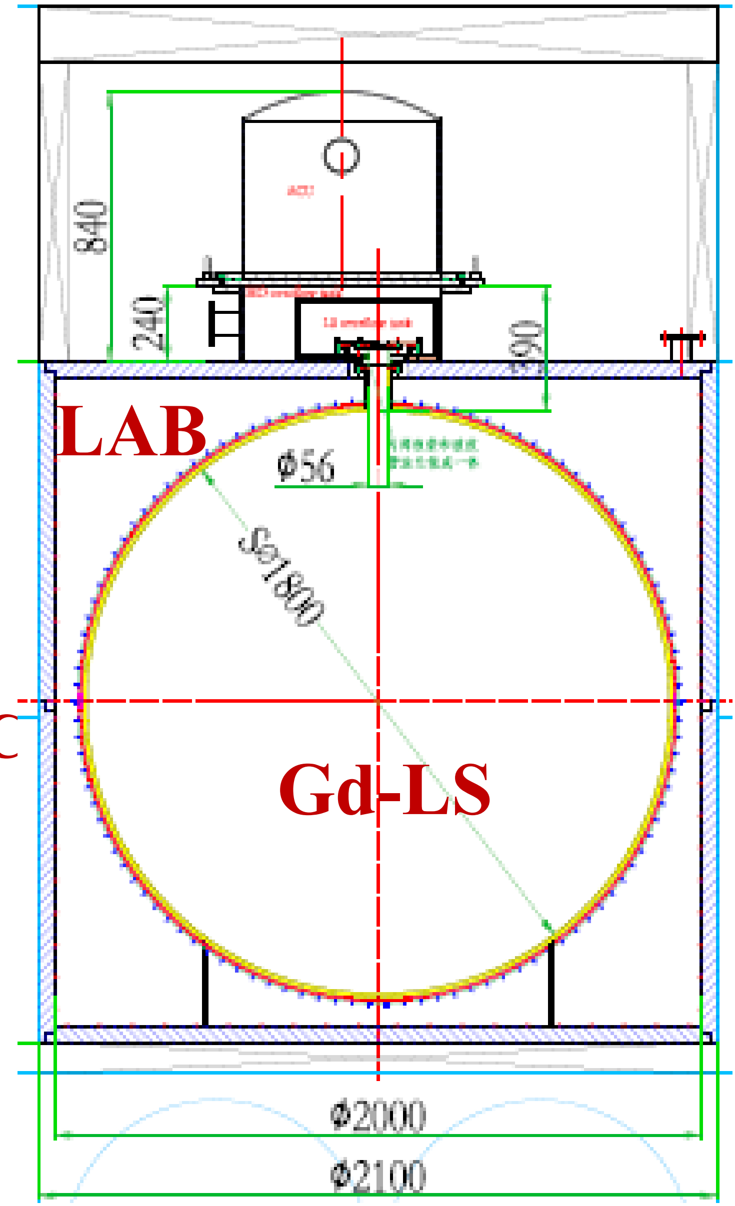
Scintillator in acrylic vessel surrounded by SiPM for optimum resolution

10 m^2 SiPM of 50% PDE, operated at -50°C

LAB+quencher as buffer

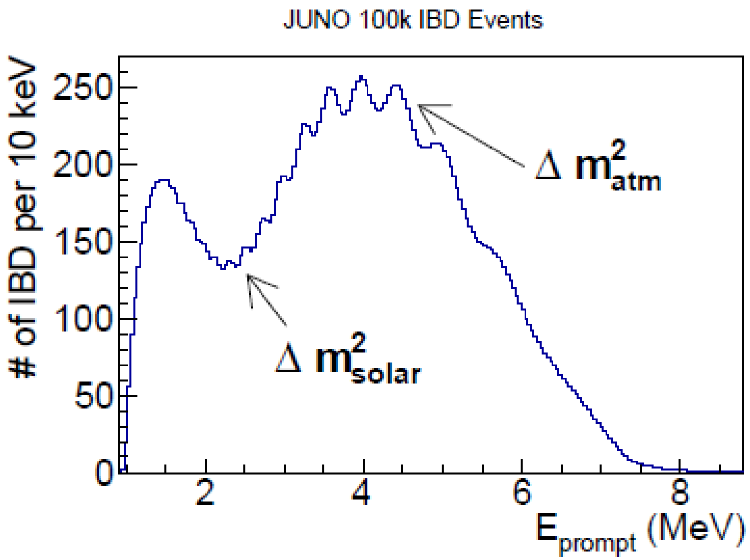
Cryogenic vessel

DYB Automatic Calibration Unit

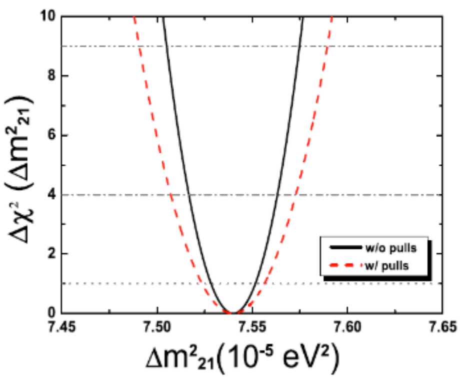


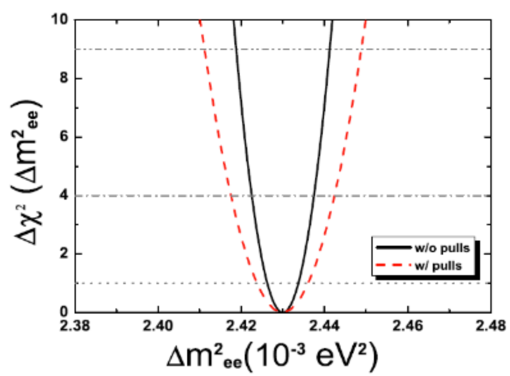
Precision Measurements

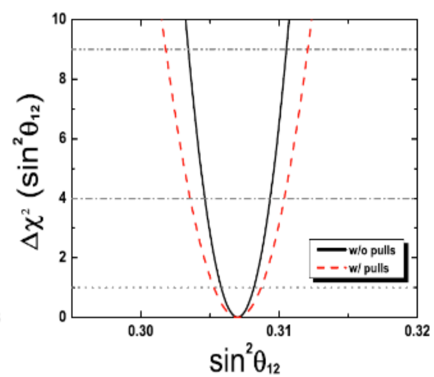
Probing the unitarity of U_{PMNS} to ~1% more precise than CKM matrix elements !

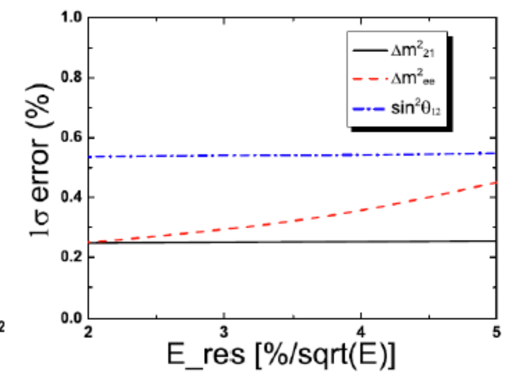


	Statistics	+BG +1% b2b +1% EScale +1% EnonL
$\sin^2\theta_{12}$	0.54%	0.67%
Δm^2_{21}	0.24%	0.59%
Δm^2_{ee}	0.27%	0.44%









0.16%→0.24%

0.16%→0.27%

0.39%→0.54%

E resolution

Correlation among parameters

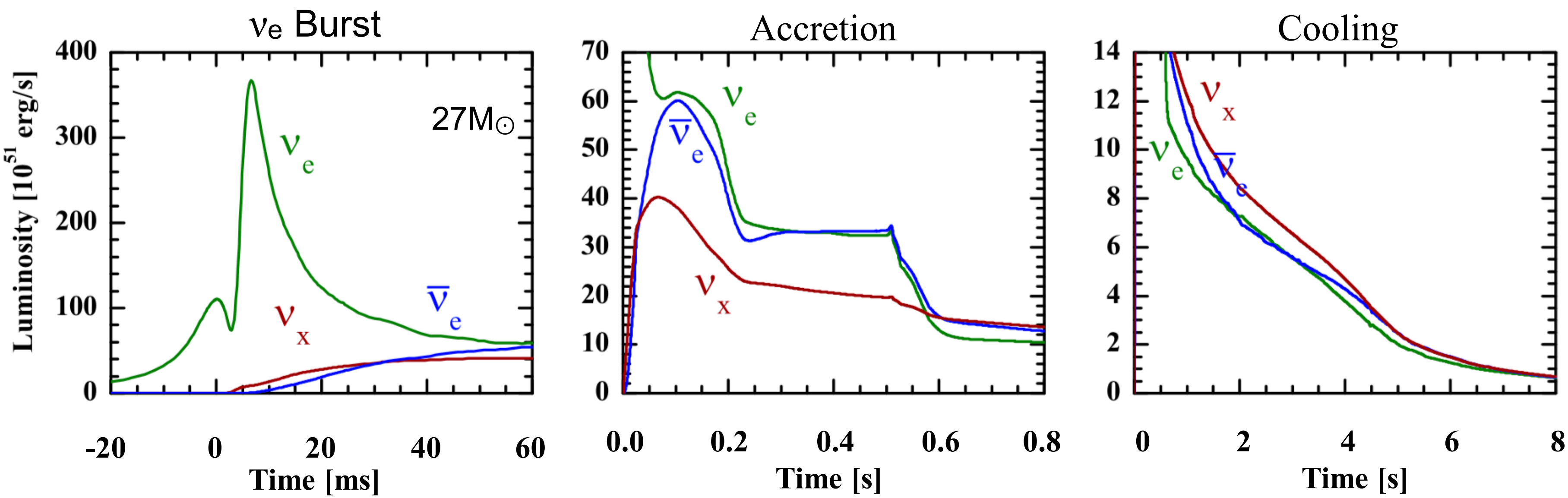
$$\Delta m^2_{ee} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

Vast physics reach beyond Reactor Neutrinos

- **Supernova burst neutrinos**
- **Diffuse supernova neutrinos**
- **Solar neutrinos**
- **Atmospheric neutrinos**
- **Geo-neutrinos**
- **Sterile neutrinos**
- **Nucleon decay**
- **Indirect dark matter search**
- **Other exotic searches**

Neutrino Physics with JUNO, J. Phys. G 43, 030401 (2016)

Supernova Neutrinos



- Typical case :huge amount of energy (3×10^{53}erg) emitted in neutrinos at 10Kpc
- 3 phases equally important ▸ 3 "experiments" teaching us about astro- and particle-physics

Bound on neutrino masses
Imprinting of the mass ordering
Collective neutrino oscillations
Constraining new physics

Process	Type	Events ⟨E_ν⟩=14MeV
$\bar{\nu}_e + p \rightarrow e^+ + n$	CC	5.0×10^3
$\nu + p \rightarrow \nu + p$	NC	1.2×10^3
$\nu + e \rightarrow \nu + e$	ES	3.6×10^2
$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$	NC	3.2×10^2
$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$	CC	0.9×10^2
$\bar{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B$	CC	1.1×10^2

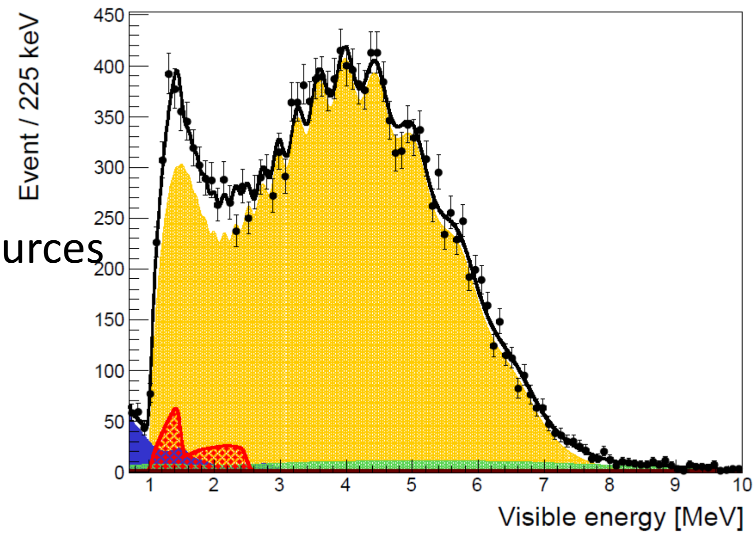
NB Other ⟨E_ν⟩ values need to be considered to get complete picture.

Expected events in JUNO for a typical SN distance of 10kpc

We need to be able to handle Betelgeuse (d~0.2kpc) resulting in ~10MHz trigger rate

Geo-neutrinos

- **Geo-neutrinos**
  - Current results
    KamLAND: 30±7 TNU *(PRD 88 (2013) 033001)*
    Borexino: 47.+8.4-7.7(stat)+2.4-1.9(sys) TNU
    (PRD 101 (2020) id.012009 *)*
    Statistically dominated errors
  - More precise measurements for multiple geological insights
    Fraction of heat flow from radioactive sources
    nature of mantle convection
    energy needed to drive plate tectonics
  - JUNO ×20 statistics
    - Huge reactor neutrino backgrounds
    - Need accurate reactor spectra



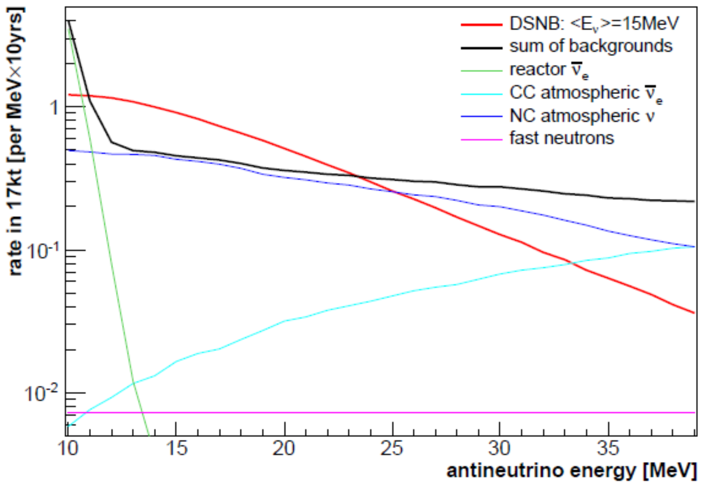
Source	Events/year
Geoneutrinos	408 ± 60
U chain	311 ± 55
Th chain	92 ± 37
Reactors	16100 ± 900
Fast neutrons	3.65 ± 3.65
^{9}Li - ^{8}He	657 ± 130
$^{13}C(\alpha, n)^{16}O$	18.2 ± 9.1
Accidental coincidences	401 ± 4

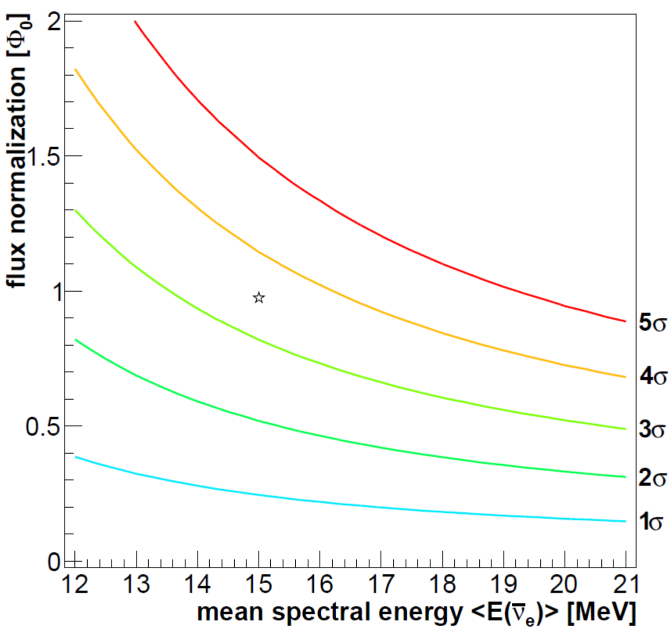
Chondritic ratio Th/U=3.9

Combined shape fit of geo-ν and reactor-ν

	Best fit	1 y	3 y	5 y	10 y
U+Th Fix ratio	0.96	17%	10%	8%	6%
U (free)	1.03	32%	19%	15%	11%
Th (free)	0.80	66%	37%	30%	21%

Diffuse Supernova Neutrinos





- DSNB: Past core-collapse events
  - Cosmic star-formation rate
  - Core-collapse neutrino spectrum
  - Rate of failed SNe

Item		Rate (no PSD)	PSD efficiency	Rate (PSD)
Signal	$\langle E_{\bar{\nu}_e} \rangle = 12\,\text{MeV}$	12.2	$\varepsilon_\nu = 50\,\%$	6.1
	$\langle E_{\bar{\nu}_e} \rangle = 15\,\text{MeV}$	25.4		12.7
	$\langle E_{\bar{\nu}_e} \rangle = 18\,\text{MeV}$	42.4		21.2
	$\langle E_{\bar{\nu}_e} \rangle = 21\,\text{MeV}$	61.2		30.8
Background	reactor $\bar{\nu}_e$	1.6	$\varepsilon_\nu = 50\,\%$	0.8
	atm. CC	1.5	$\varepsilon_\nu = 50\,\%$	0.8
	atm. NC	716	$\varepsilon_{NC} = 1.1\,\%$	7.5
	fast neutrons	12	$\varepsilon_{FN} = 1.3\,\%$	0.15
	Σ			9.2

10 Years' sensitivity

Syst. uncertainty BG	5 %		20 %	
$\langle E_{\bar{\nu}_e} \rangle$	rate only	spectral fit	rate only	spectral fit
12 MeV	$1.7\,\sigma$	$1.9\,\sigma$	$1.5\,\sigma$	$1.7\,\sigma$
15 MeV	$3.3\,\sigma$	$3.5\,\sigma$	$3.0\,\sigma$	$3.2\,\sigma$
18 MeV	$5.1\,\sigma$	$5.4\,\sigma$	$4.6\,\sigma$	$4.7\,\sigma$
21 MeV	$6.9\,\sigma$	$7.3\,\sigma$	$6.2\,\sigma$	$6.4\,\sigma$

Solar Neutrinos

Fusion reactions in solar core: powerful source of electron neutrinos O(1-10 MeV)

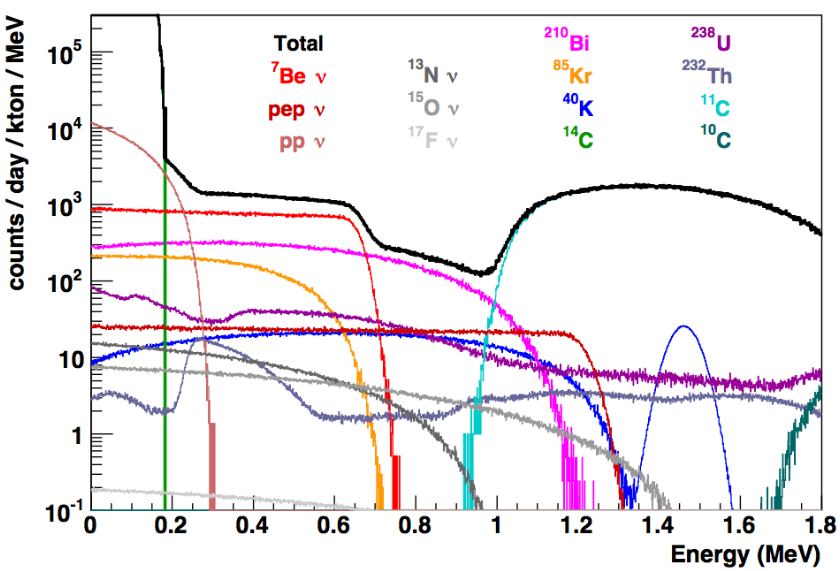
JUNO: neutrinos from ^{7}Be and ^{8}B reactions

Investigate MSW effect: Transition between vacuum and matter dominated regimes ^{8}B

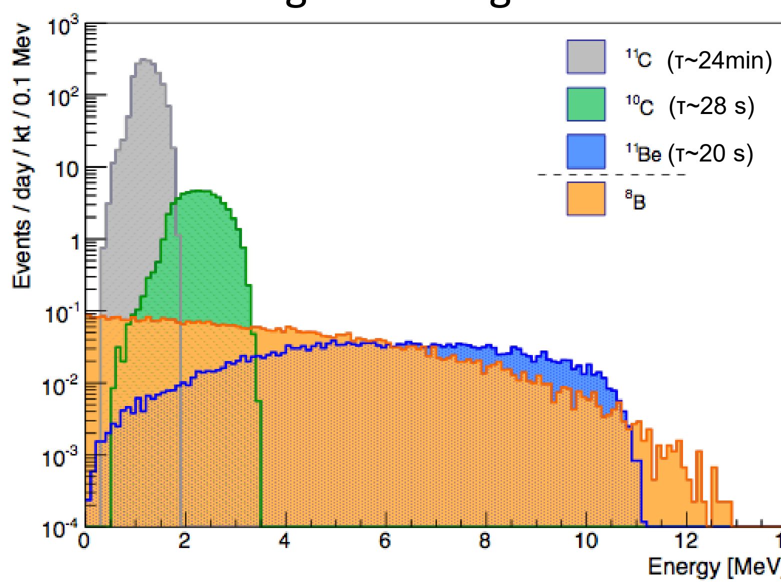
Constrain Solar Metallicity Problem:
Neutrinos as proxy for Sun composition ^{7}Be

Radiopurity requirements for JUNO LS

Liquid Scintillator	U238	Th232	K40	Pb210 (Rn222)	Ref.
Medium purity	10^{-15}	10^{-15}	10^{-16}	$1.4\cdot10^{-22}$	CTF, Borexino, KamLAND
High purity	10^{-17}	10^{-17}	10^{-18}	10^{-24}	

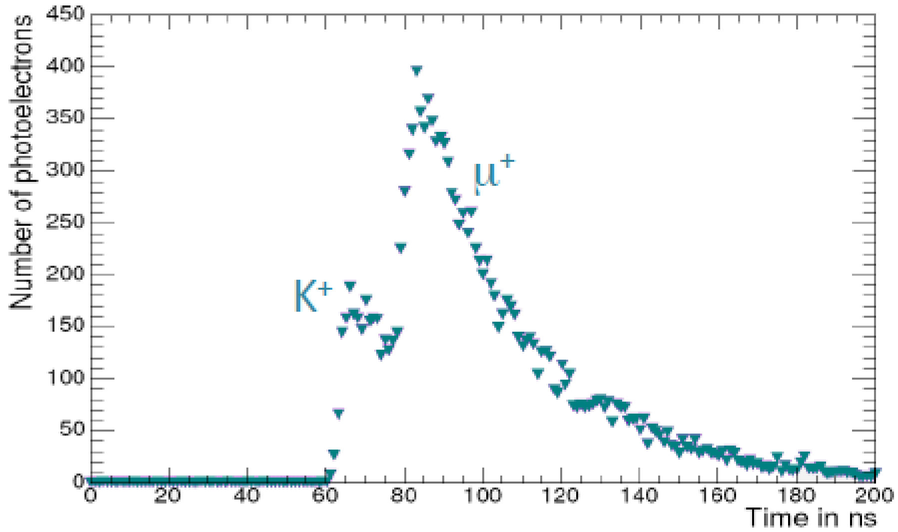


Cosmogenic background for ^{8}B



J.Phys. G43 (2016) no.3, 030401

Proton decay into $K^+\bar{\nu}$



SUSY-favored decay mode

Signature $p \rightarrow K^+ \bar{\nu}$

$\hookrightarrow \mu^+\nu_\mu / \pi^0\pi^+$

→ kaon visible in liquid scintillator!

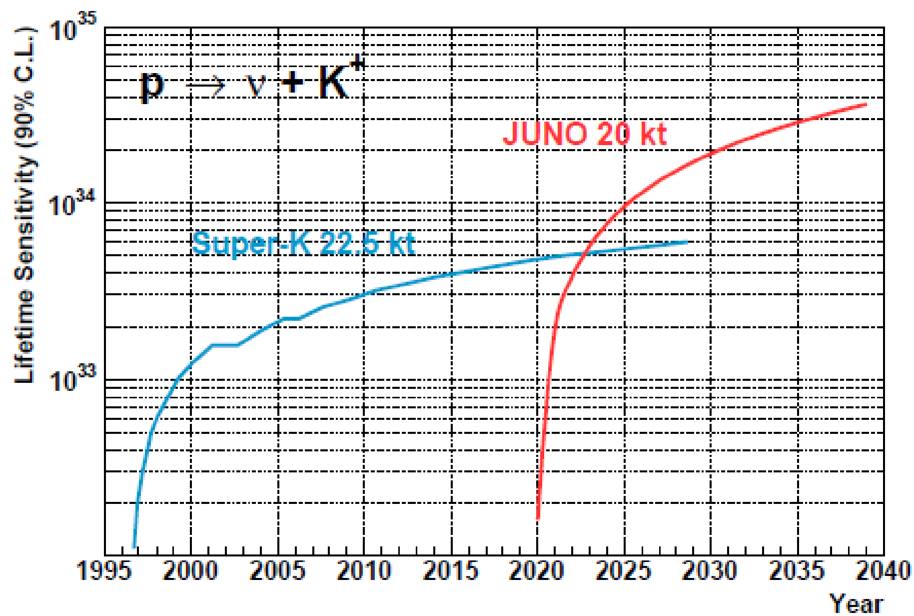
→ fast coincidence signature (τ_K = 13 ns)

→ signal efficiency: ~65% (atm. ν bg)

→ remaining background: <0.1 ev/yr

Limit if no event is observed in 10yrs (0.5 Mt·yrs):

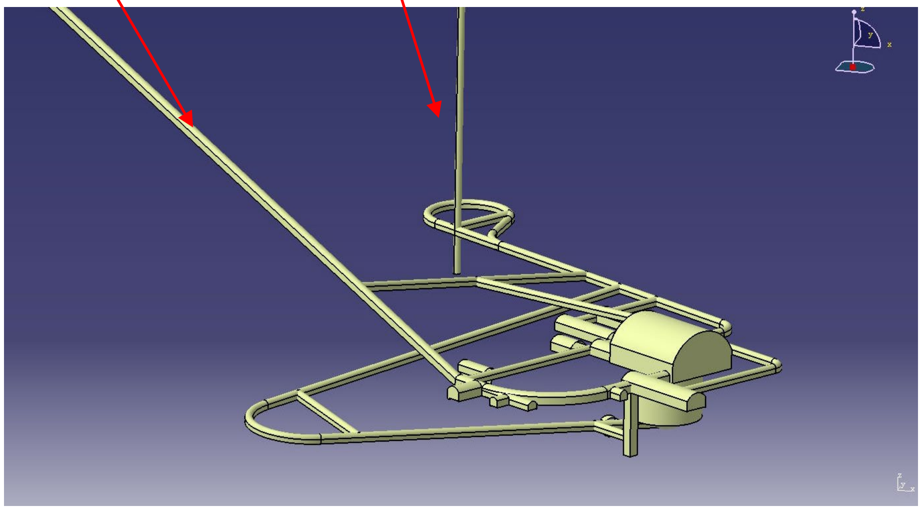
τ_p > 2x10^{34} yrs (90%C.L.)



Layout of the site

Slope tunnel

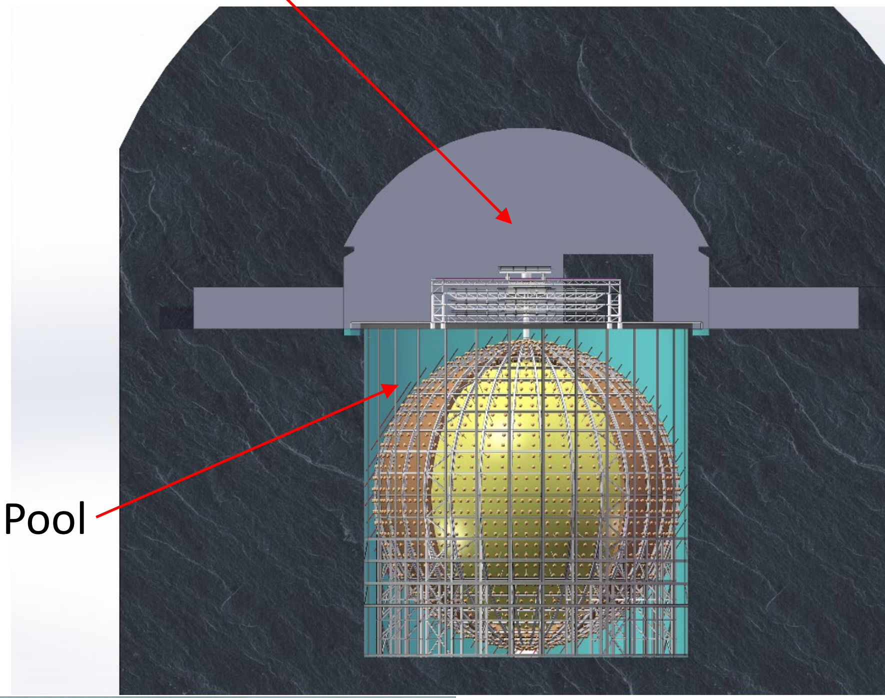
Vertical shaft



overburden ~ 700 m

Experimental Hall

Pool

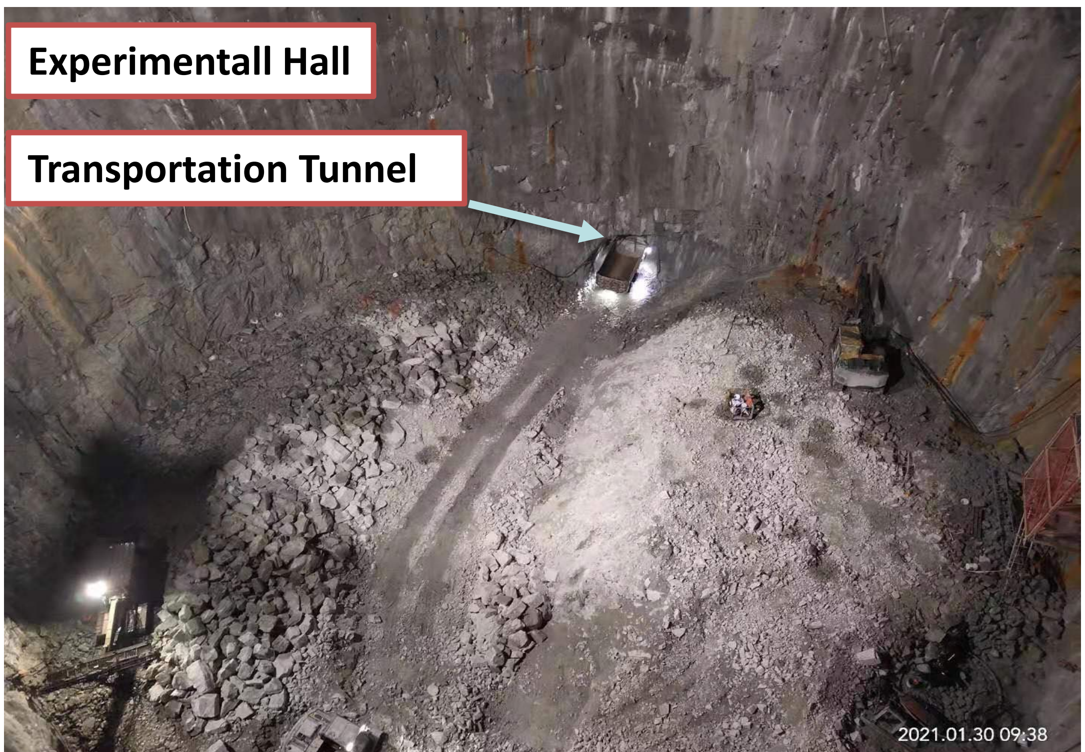


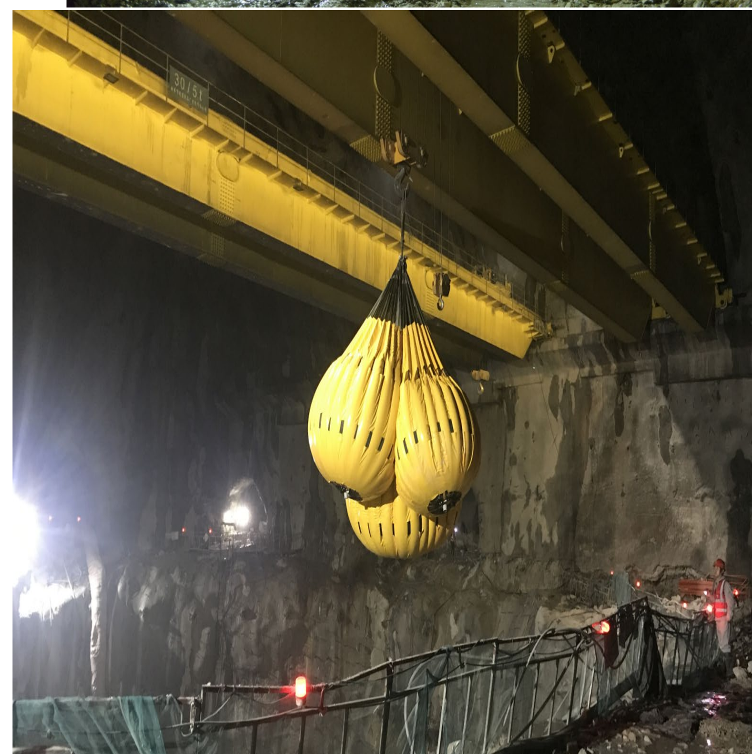
Surface buildings

Excavation of the site recently completed: experimental hall - access and service tunnels - ancillary halls

Liquid scintillator Hall

Access tunnel





External infrastructure completed

Detector's layout

Central detector

- Acrylic sphere with 20k t liquid scintillator
- PMTs in water buffer on a stainless steel truss - 18k 20" and 25k 3"
- 78% PMT coverage

Water Cherenkov muon veto

- 2000 20" PMTs
- 35 ktons ultra-pure water
- Efficiency > 95%
- Radon control → less than 0.2 Bq/m^3

Compensation coils

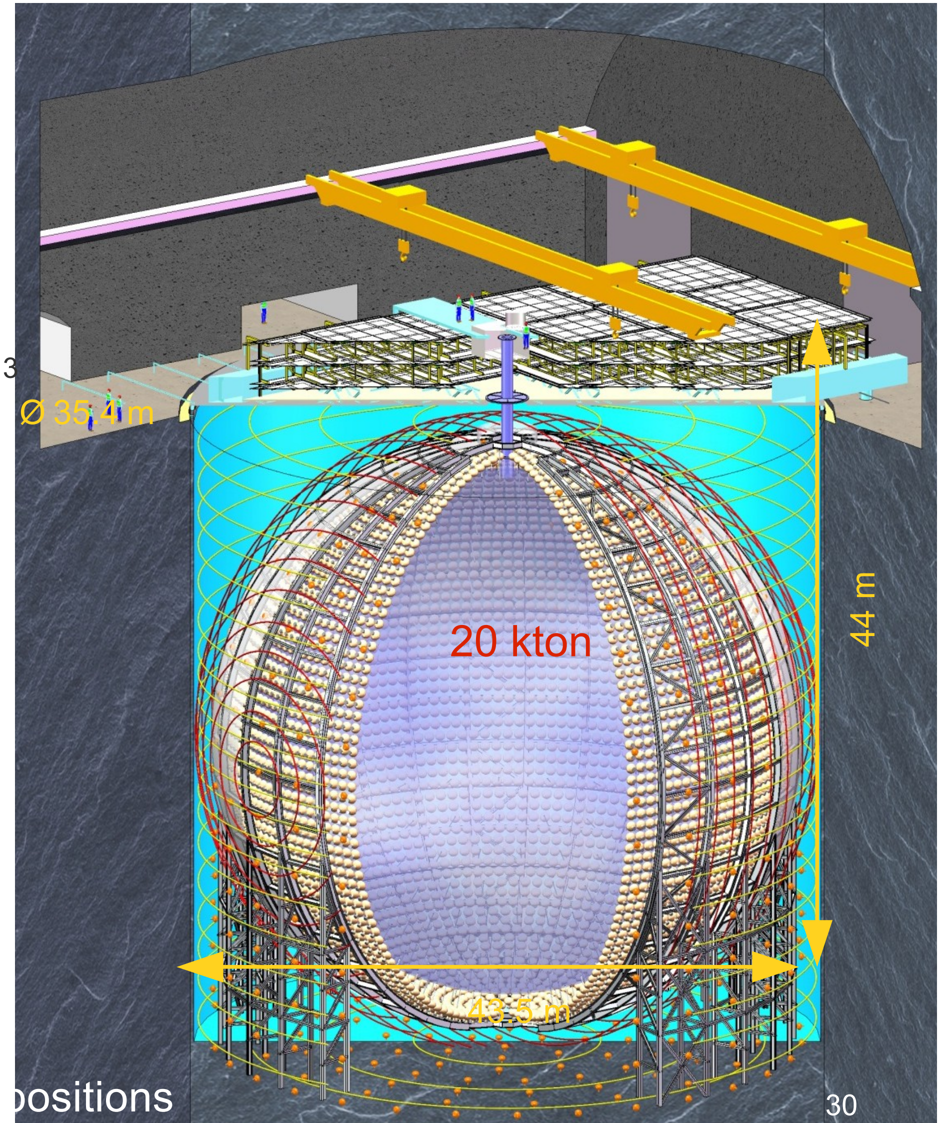
- Earth's magnetic field <10%
- Necessary for 20" PMTs

Top tracker

- Precision muon tracking
- 3 plastic scintillator layers
- Covering half of the top area

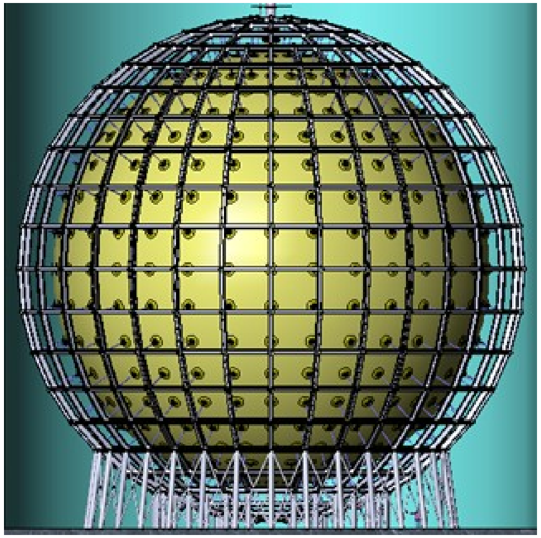
Calibration System

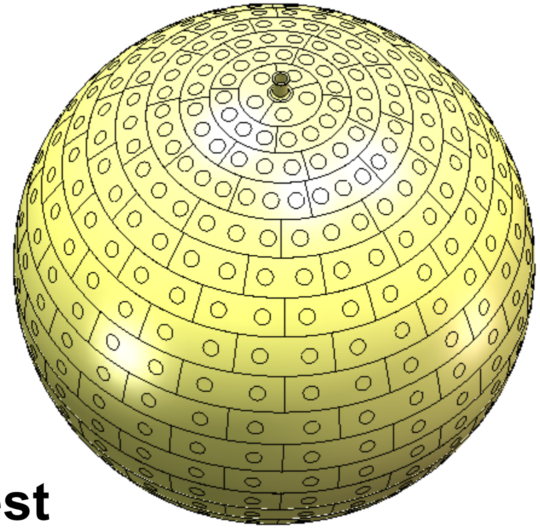
- 4 complementary sub-systems
- various particle types, ranges and positions



Central Detector

- Liquid scintillator based calorimeter
  - Req.: **3% resolution** & **<1% en. scale precision**
- **SS** supporting **PMTs** + **Acrylic Sphere**(AS)
  - Outside AS: water (shielding PMT/SS γs)
  - Inside AS: LS (scintillation matter)
- Scintillation **photon** detector:
  - 18k 20" PMTs + 25k 3" PMTs
  - 1200 pe/MeV
- Electronics:
  - **1 GHz, 14 bit**, 1~4000 p.e. dynamic range
- Coils for Earth's magnetic field compensation
- **All construction elements under realization and test**





R&D about acrylic

- **How about the life time of acrylic?**
  - Strength reduce to ~70% for 20 years @ 5.5 Mpa
  - Creep: over 100 years
- **Can the spherical panel be made?**
  - 3 companies made samples
  - 2017.2 Donchamp won the bid.
- **How about the max stress control on acrylic?**
  - ≤ 3.5 Mpa, less than 5 Mpa in Daya Bay
- **How strong the acrylic node need to be?**
  - Max pulling load: ~ 8 tons
  - Break at load: ~100 tons
- **How to control the radiation back- ground and the quality of acrylic?**
- **How to make the bulk-polymerization on site**

Thermoforming the spherical panel:
3m x 8m x 120mm

Test for bulk-polymerization

Load test of node: break at 100 tons

1:12 prototype

Status of CD elements

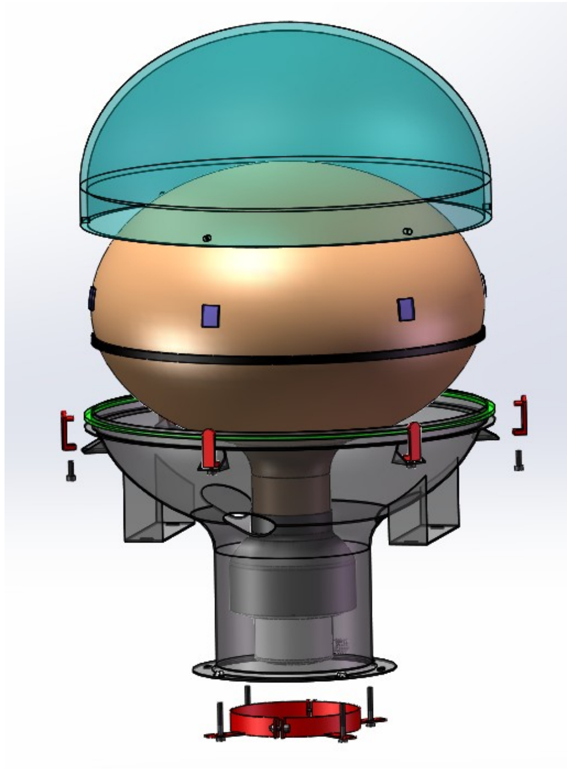
- **Acrylic Sphere**
  - Acrylic panels: mostly produced
    - Good quality on bkg., transparency…
    - Thermal forming in progress
  - Assembly & annealing: procedures understood
- **Stainless Steel Structure**
  - Production: mostly finished
  - Connection structure : 80% finished
- **Lift platform: successfully tested**
- **Filling/Overflow/Circulation System**
  - All low bkg s.s. were produced
  - All pumps and valves ordered
  - Tanks etc. : 30% finished

Photomultipliers

- **15000 MCP-PMTs from NNVT** (Northern Night Vision Technology)
- **5000 dynode PMTs from Hamamatsu**
- **Production from2016 now completed**
- **All delivered**
- **Tests close to end**

Characteristics	unit	MCP-PMT (NNVT)	R12860 (Hamamatsu)
Detection Efficiency (QE*CE)	%	27%	27%
P/V of SPE		3.5, > 2.8	3, > 2.5
TTS on the top point	ns	~12, < 15	2.7, < 3.5
Rise time/ Fall time	ns	R~2, F~12	R~5,F~9
Anode Dark Count	Hz	20K, < 30K	10K, < 50K
After Pulse Rate	%	1, <2	10, < 15
Radioactivity of glass	ppb	238U:50 232Th:50 40K: 20	238U:400 232Th:400 40K: 40

requirement

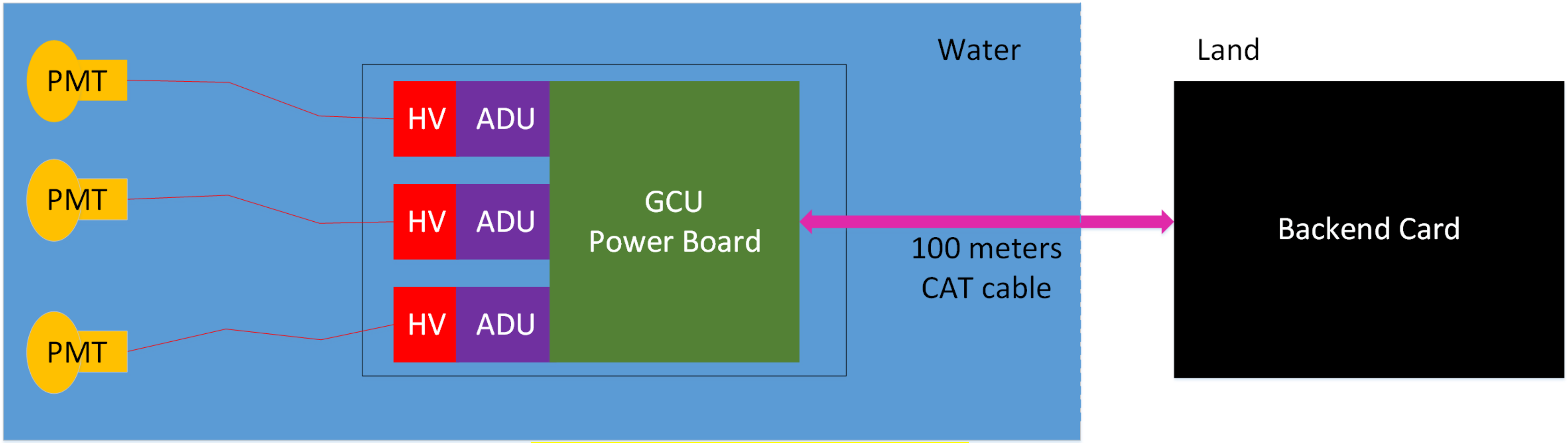


JUNO PMT with implosion protection cover

Final detection efficiency value on the whole PMT inventory: **NNVT 28.7% Hamamatsu 28.1%**

Readout Electronics

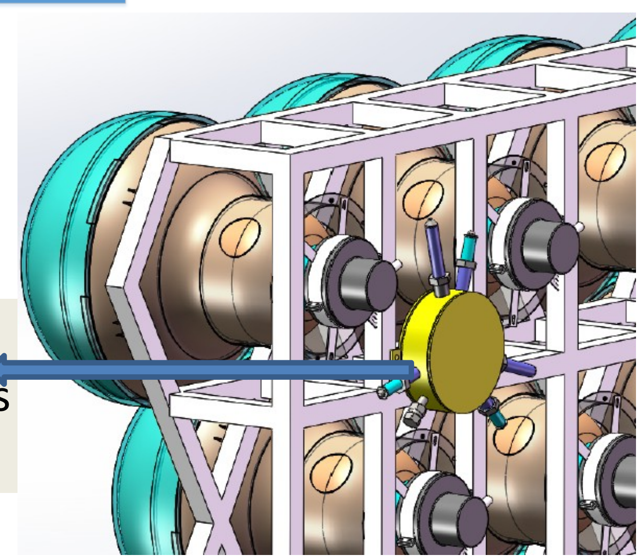
1F3 scheme



- PMT: photomultiplier tubes
- HV: High Voltage units
- ADU: Analog to Digital Unit
- GCU: Global Control Unit
- CAT cable: Category 5e cable
- High reliability needed
- Severe constraints by power consumption

PMT signals' waveform are read out by FADC, which is near PMT and guarantee the quality of the analog signals.

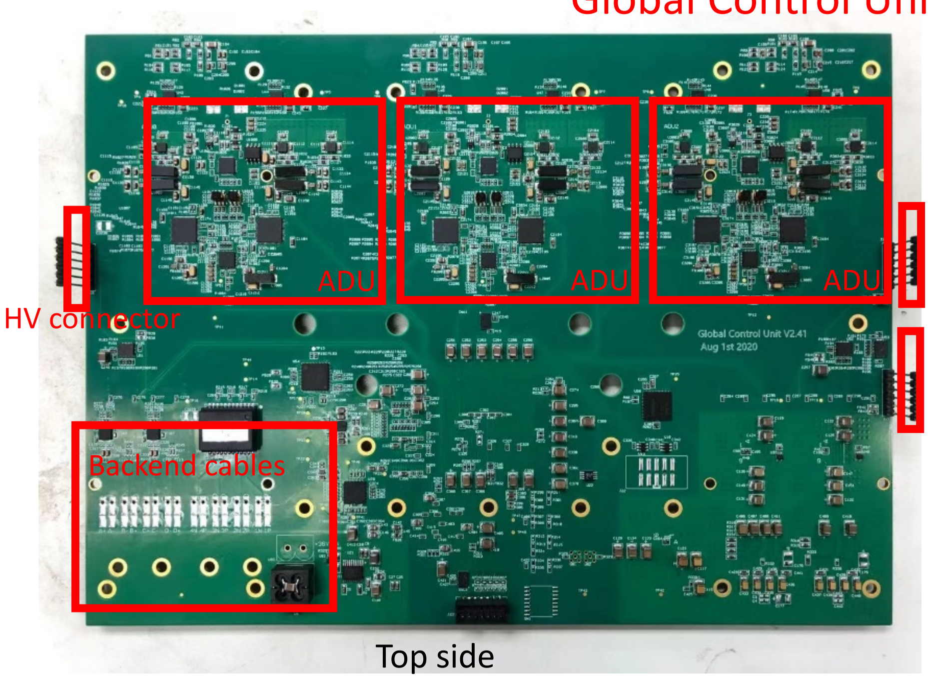
Underwater box containing the electronics 1 per 3 PMTs



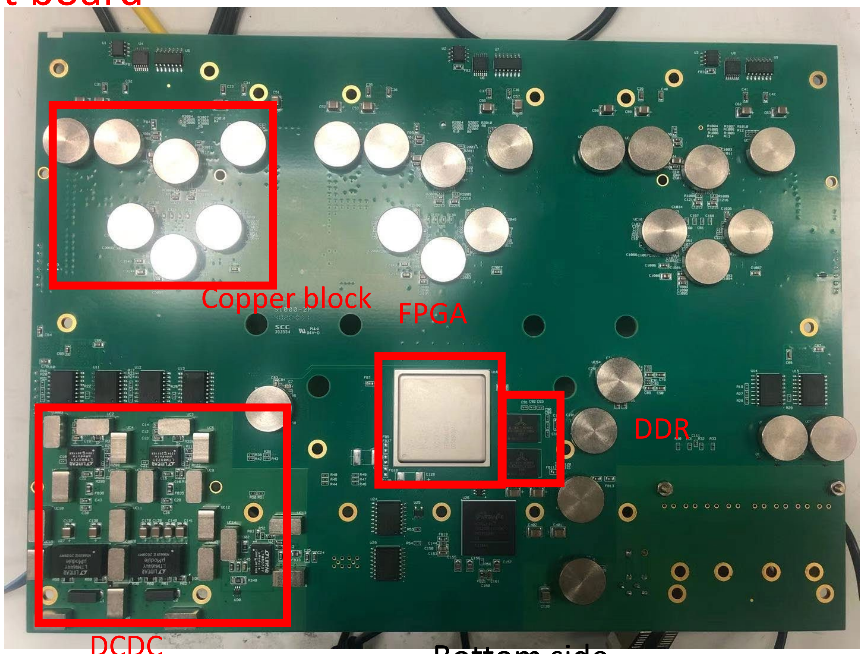
Electronics production ongoing

- Example of the board that will go in the underwater box
- Components procurement started
- Full production before the end of the year
- Integration tests are foreseen from Summer and Installation in JUNO will start at the end of 2021

Global Control Unit board

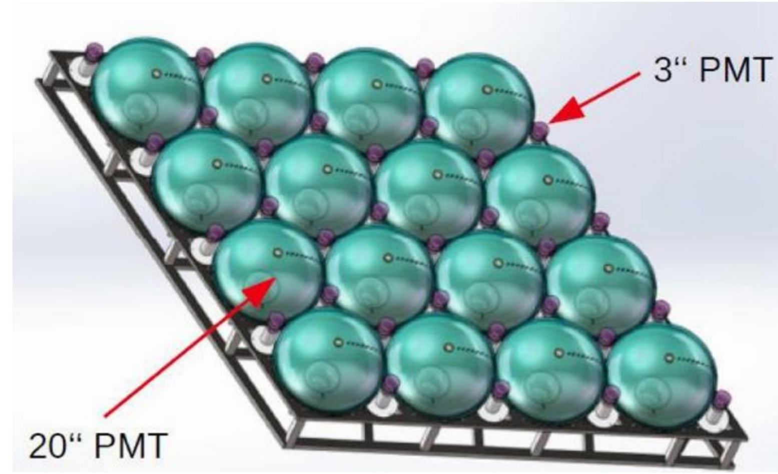


Top side



Bottom side

3“ PMTs



- **Double calorimetry**
  - Always photon counting
    → Better control of systematics
    (Calibration of non-linear response of large PMTs)
  - Increased dynamic range
    → Helps with large signals
    (e.g. muons, supernova signal)

Detector Resolution: $$\frac{\sigma_E}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}$$

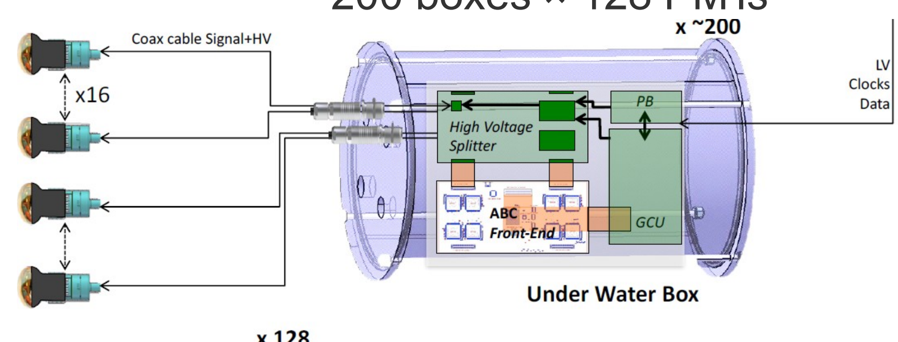
b and *c* non stochastic terms

- **25000 PMTs contracted to HZC**
- **Production ended, final test ongoing**

JUNO custom design:
XP72B22

QE 24% , P/V 3.0
SPE resolution 30%
TTS 2-5 ns

200 boxes × 128 PMTs



Under production

Veto Detectors

- **Cosmic muon flux**
  - Overburden: **~700 m**
  - Muon rate: **0.003Hz/m²**
  - Average energy: **214 GeV**
- **Water Cherenkov Detector**
  - ~4 m water shielding, Radon: **<0.2 Bq/m³**
  - ~2000 20"PMTs
  - 40 kton pure water, HDPE lining on pool
  - Similar technology as Daya Bay (**99.8% efficiency**)
- **Compensation Coil for EMF shield**
- **Top muon tracker**
  - Decommissioned OPERA plastic scintillator

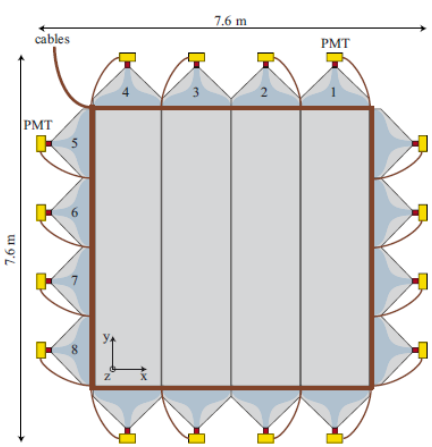
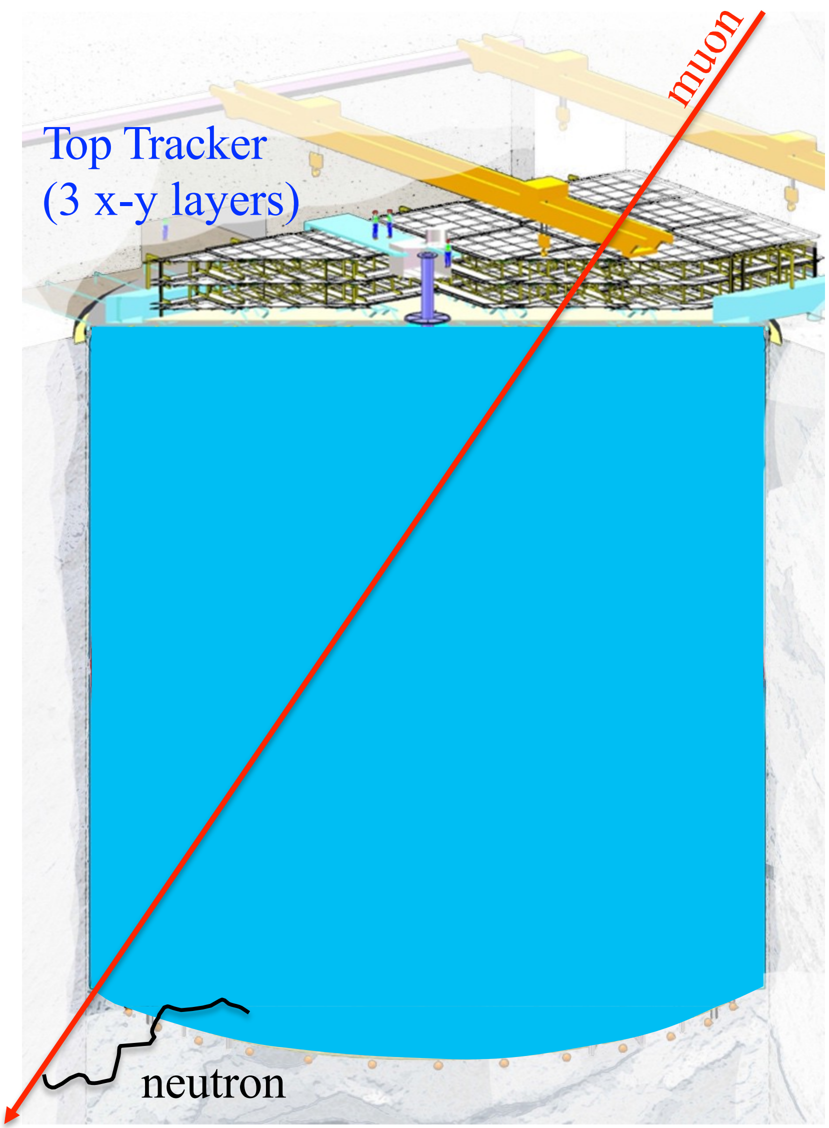
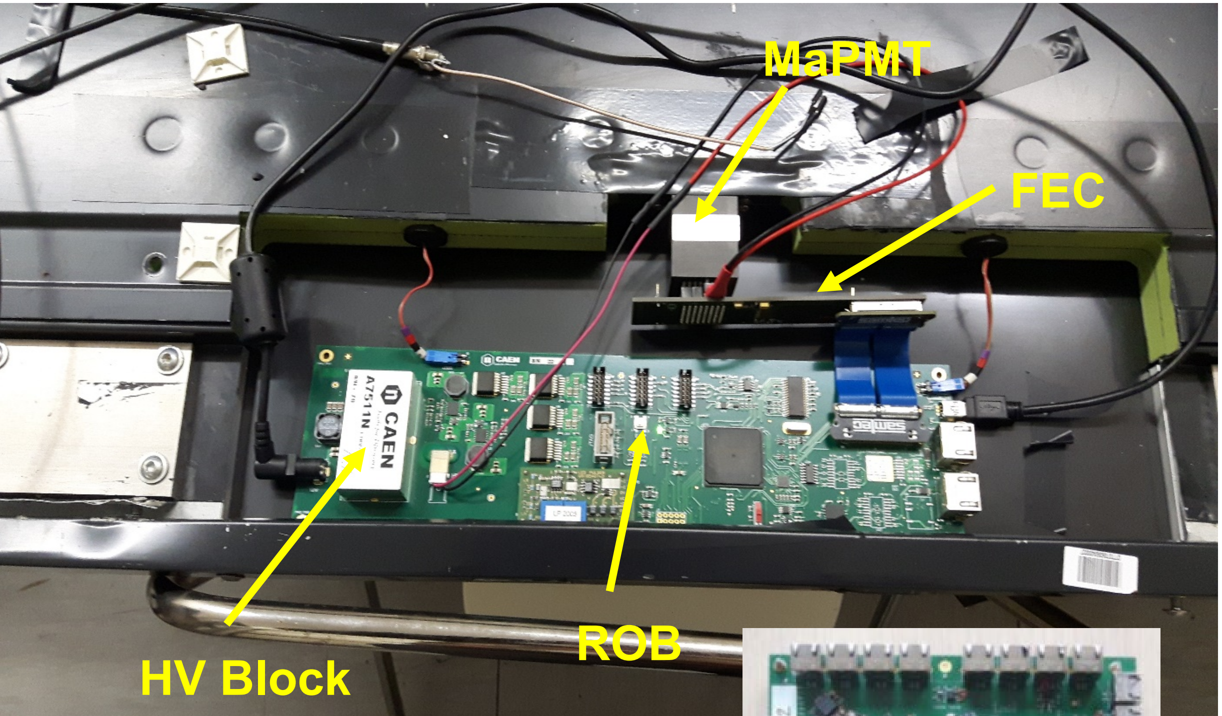


Fig. 3. Schematic view of a plastic scintillator strip wall.



Example of production: top muon tracker electronics



992 MaPMT
992 Front-End Cards
992 Read-Oout Boards
63 Concentrators

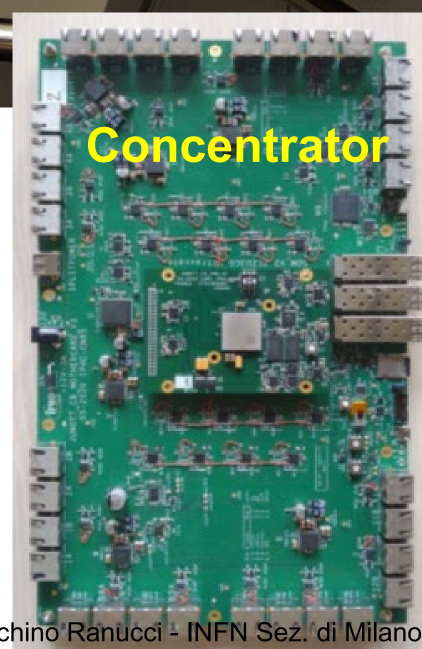
FEC: produced
ROB: Final Review asap
Component procurement started
Concentrator: prototyping

Order for 1020 ROBs already placed

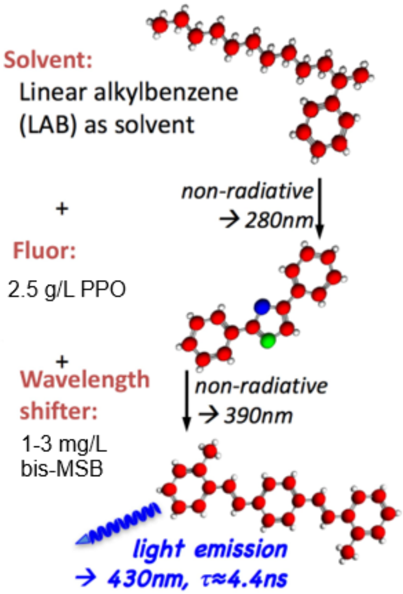
Afterwards concentrator Production

Other elements of the TT system under production

HV block
(designed for JUNO)



Scintillator and purity



- **Requirement for 3%/√E**
  - High light-yield:~10^4 photons/MeV
  - High transparency:

  Attenuation Length (A.L.) > **25m** @430nm

Purity requirements

U/Th **10^{-15} g/g** for MH **10^{-17} g/g** for Solar ν

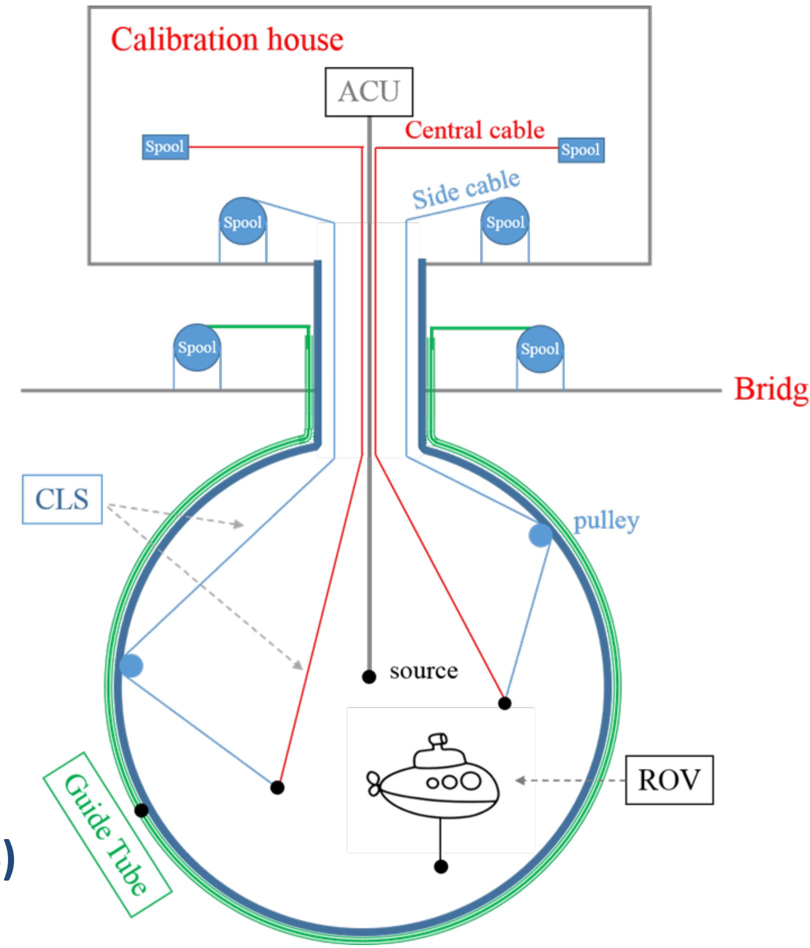
- **Storage and Purification plants**

Global background control:
Construction material, equipment & their cleanliness
Ventilation systems during the assembly & installation
Moreover: cleanliness of CD, leak check, filling with ultrapure water

- Surface storage for 5 Kt LAB
  Distillation plant ready
- Stripping plant (gas removal) ready
- Column purification via Al_2O_3 - under construction
- Water extraction plant column purification
- PPO production and pre-purification
- Mixing system
- Ultra pure nitrogen
- Ultra pure water

Calibration systems

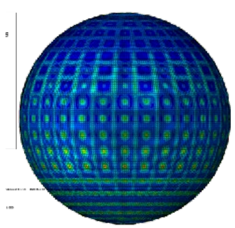
- **The goal:**
  - Overall energy resolution: ≤ 3%/√E
  - Energy scale uncertainty: <1%
- **Radioactive sources:**
  - γ： ^{40}K, ^{54}Mn, ^{60}Co, ^{137}Cs
  - e+： ^{22}Na, ^{68}Ge
  - n： ^{241}Am-Be, ^{241}Am- ^{13}C or ^{241}Pu- ^{13}C, ^{252}Cf
- **Four complementary calibration systems**
  - 1-D: Automatic Calibration Unit (ACU) → for central axis scan,
  - 2-D:
    - Cable Loop System (CLS) → scan vertical planes,
    - Guide Tube Calibration System (GTCS) → CD outer surface scan,
  - 3-D: Remotely Operated under-LS Vehicle (ROV) → full detector scan



Milestone & schedule

2014:

- International collaboration established
- Start civil construction



2015:

- PMT production line setup
- CD parts R&D

2016:

- Start PMT production
- Start CD parts production

2017:

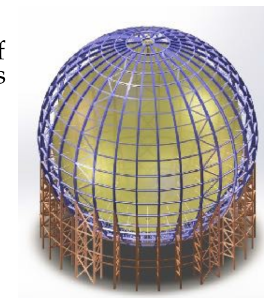
- Start PMT testing
- TT arrived

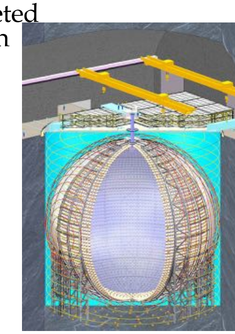
2018-19:

- PMT potting
- starts Delivery of surface buildings
- Start production of acrylic sphere

2019-2020-2021:

- Electronics production starts
- Civil work and lab preparation Completed
- Detector construction





2022:

- Detector ready for filling!

Conclusion

- The JUNO experiment provides vast physics opportunities with its **large mass** and **unprecedented energy resolution**
- Neutrino Mass Ordering sensitivity in 6-8 yrs:
  - >3σ and can **reach >4σ with 1% constraint on $\Delta m_{\mu\mu}^2$**
- **Sub-percent measurement** of $\sin^2\theta_{12}$ Δm_{12}^2 and Δm_{ee}^2
- Various astroparticle measurements
- **Several requirements: energy resolution, radiopurity, energy scale linearity**
- Near detector TAO planned for precise reference reactor spectrum
- Project well along the realization path
- Detector ready for filling: by end of **2022**