5th International Solar Neutrino Conference

Solar neutrinos with the JUNO experiment

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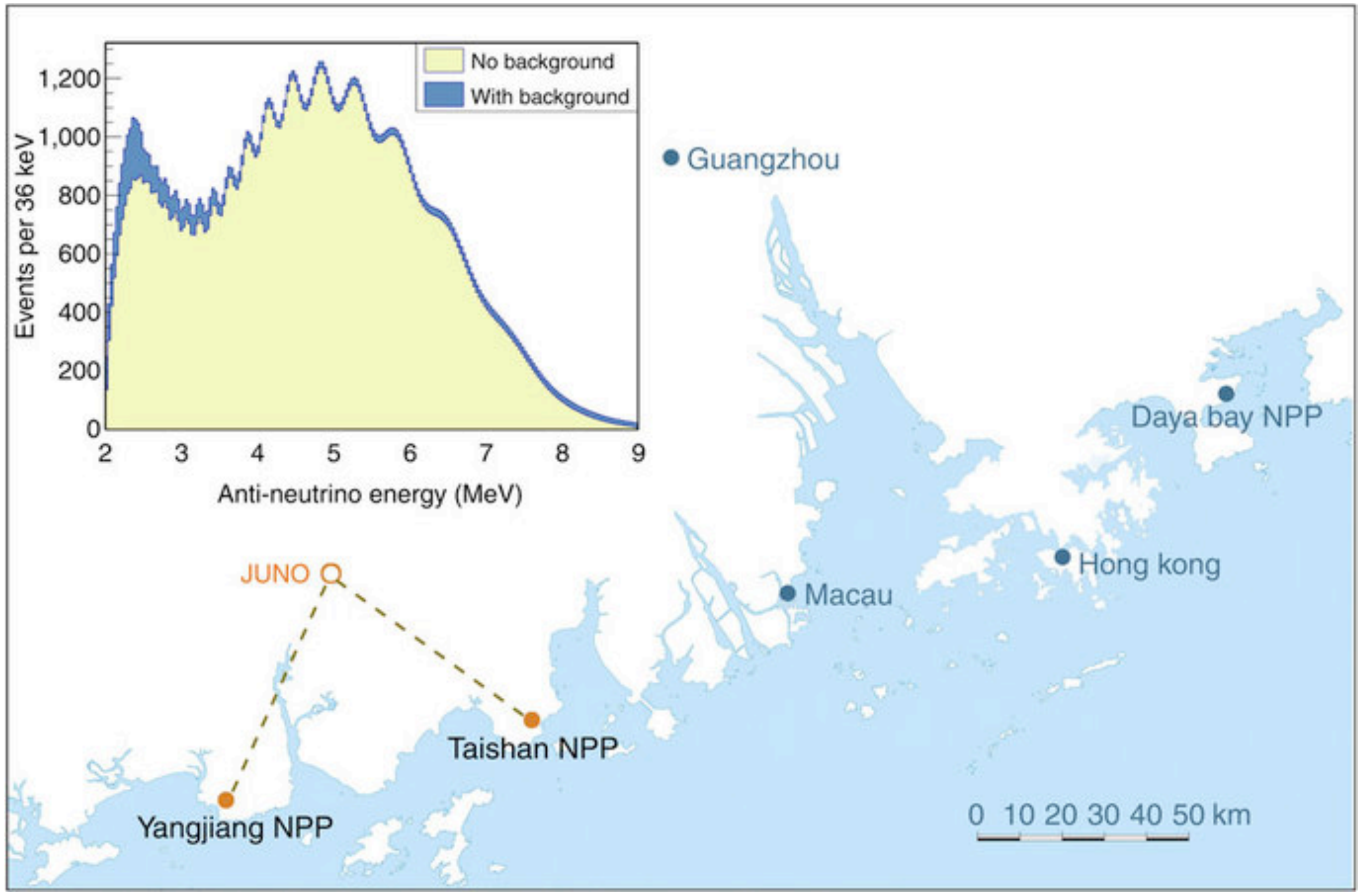
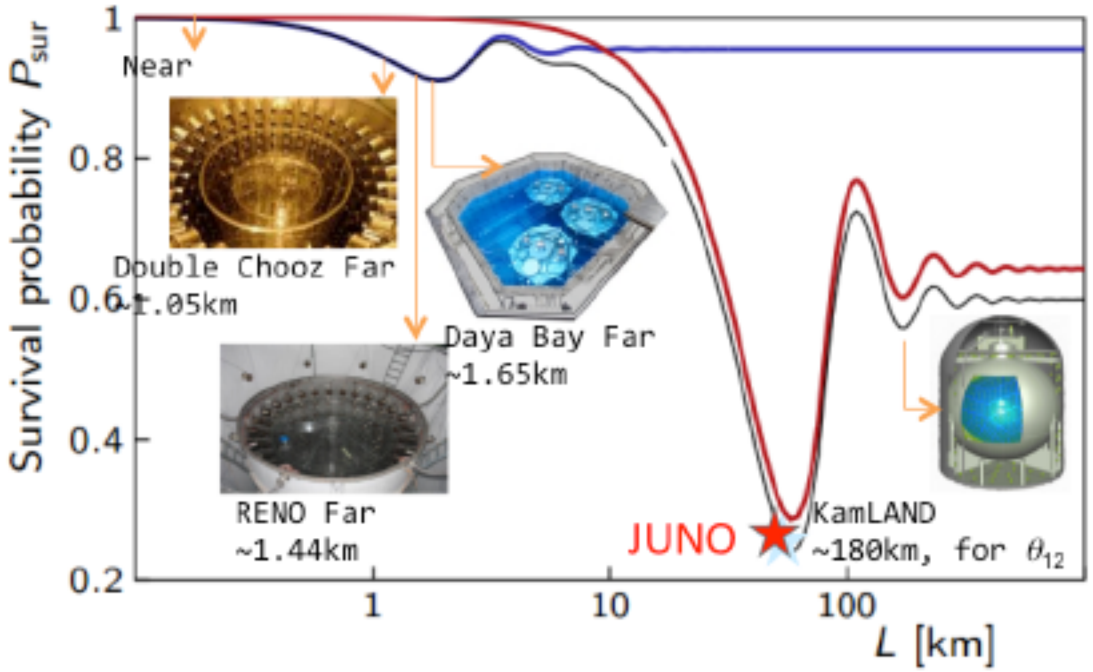
on behalf of the JUNO Collaboration

JUNO

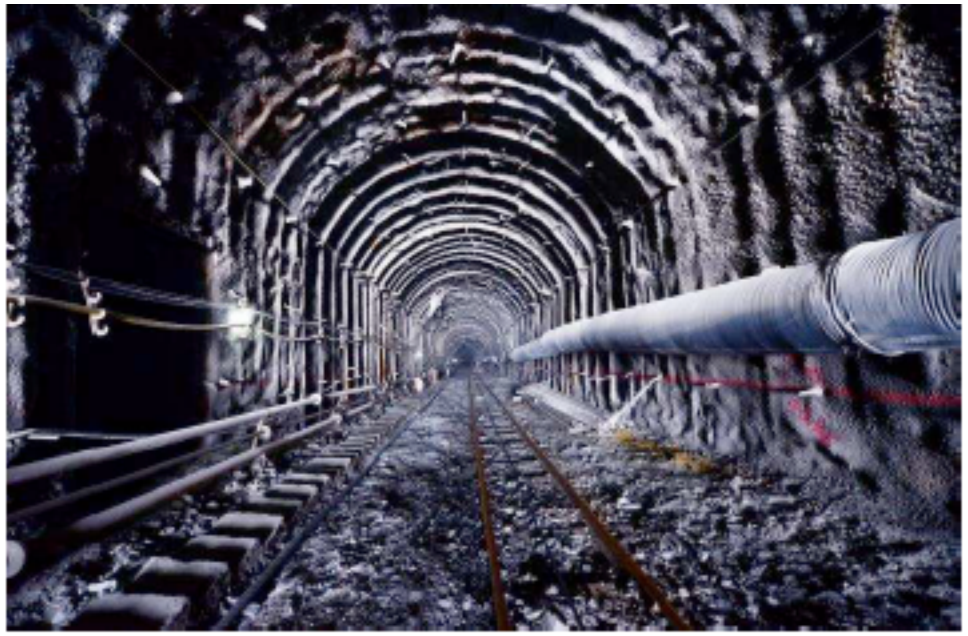
- The Jiangmen Underground Neutrino Observatory in China
- at distance (~50 km) from 2 power plants optimized for maximum $\bar{\nu}_e$ disappearance
- Facility and detector construction: 2015-20
- expected starting date for data taking: end 2020
- total thermal power available by 2020: 26.6 GW



	Yangjiang	Taishan
Exp. Power$_{Th}$	17.4 GW	18.4 GW
Exp. N of cores	6	4

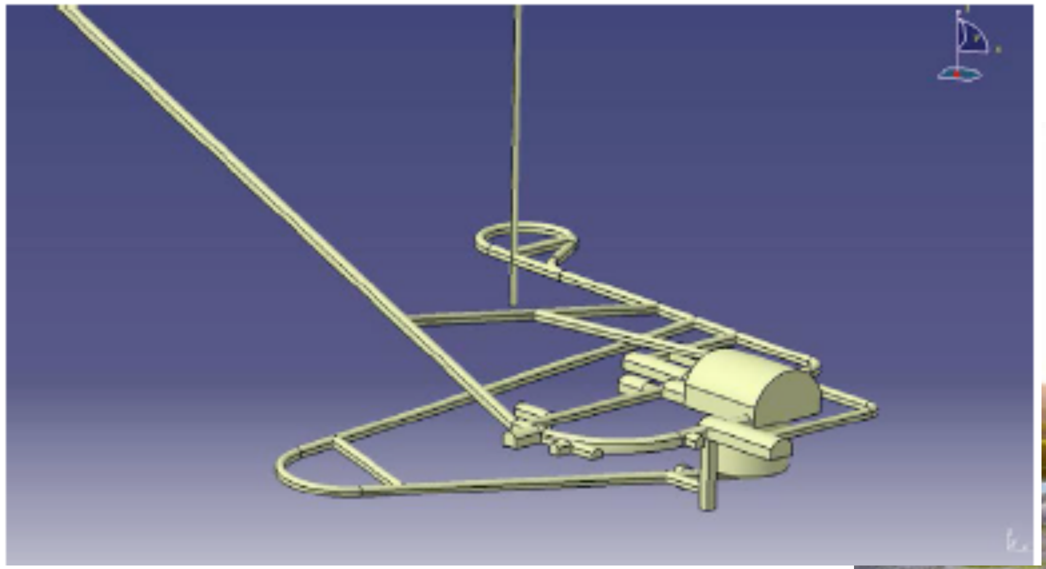


JUNO civil construction



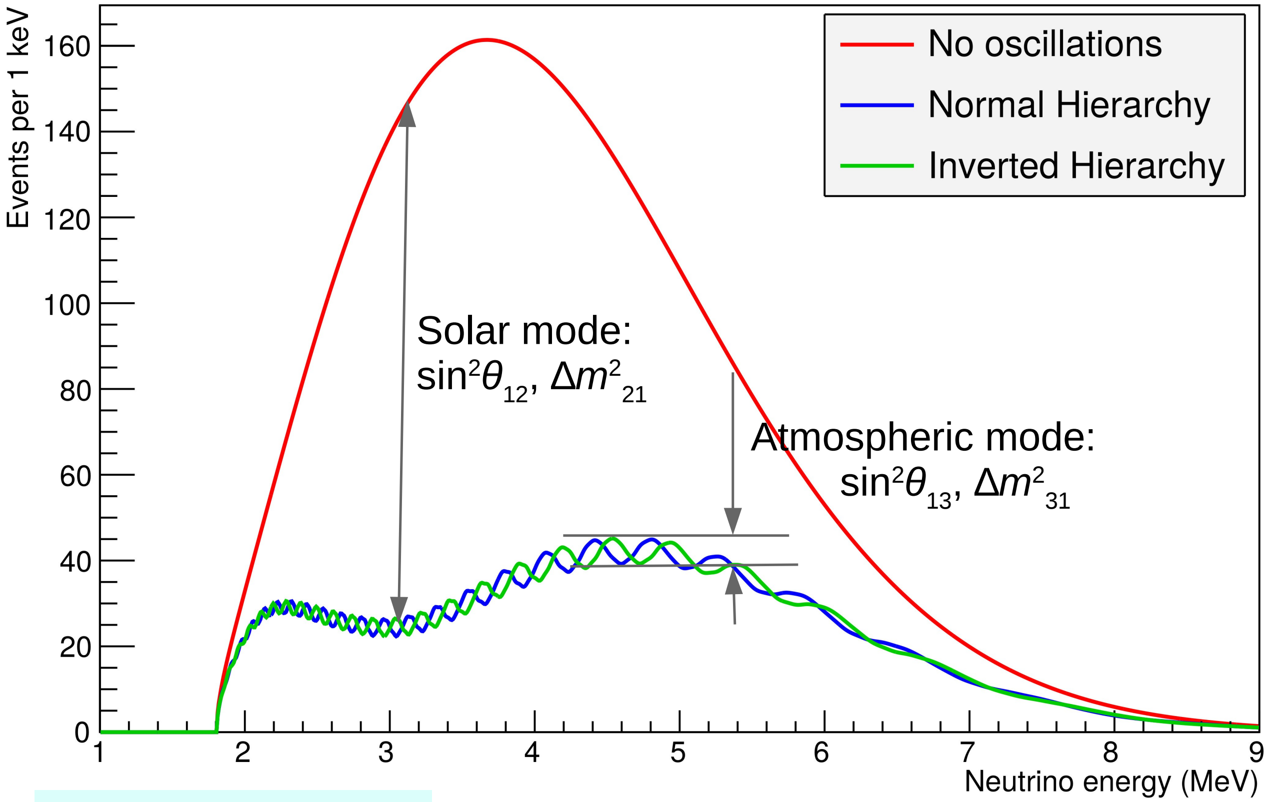
- 1340m slope tunnel excavated
  - initial delays on account of underground water leaks now under control

- **Overburden to JUNO: ~700m (~1900 m.w.e.)**

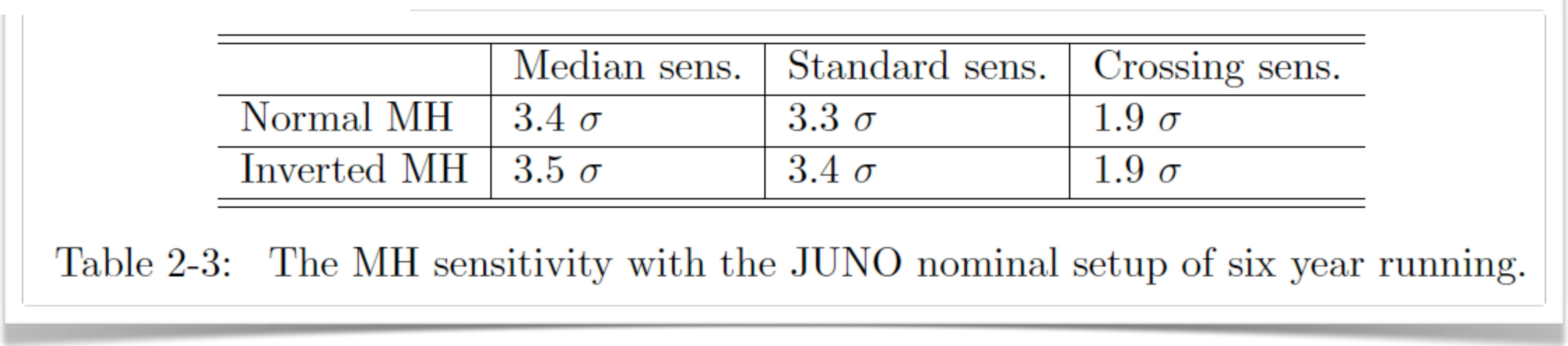


What drives the detector design?

MH from reactors: main topic



Courtesy **Y. Malyshkin**



	Median sens.	Standard sens.	Crossing sens.
Normal MH	3.4 σ	3.3 σ	1.9 σ
Inverted MH	3.5 σ	3.4 σ	1.9 σ

Table 2-3: The MH sensitivity with the JUNO nominal setup of six year running.

- *Inverse Beta Decay: E_{vis} ~ E(ν)–0.8 MeV*
- **$\Delta\chi^2$** method to determine correct hierarchy

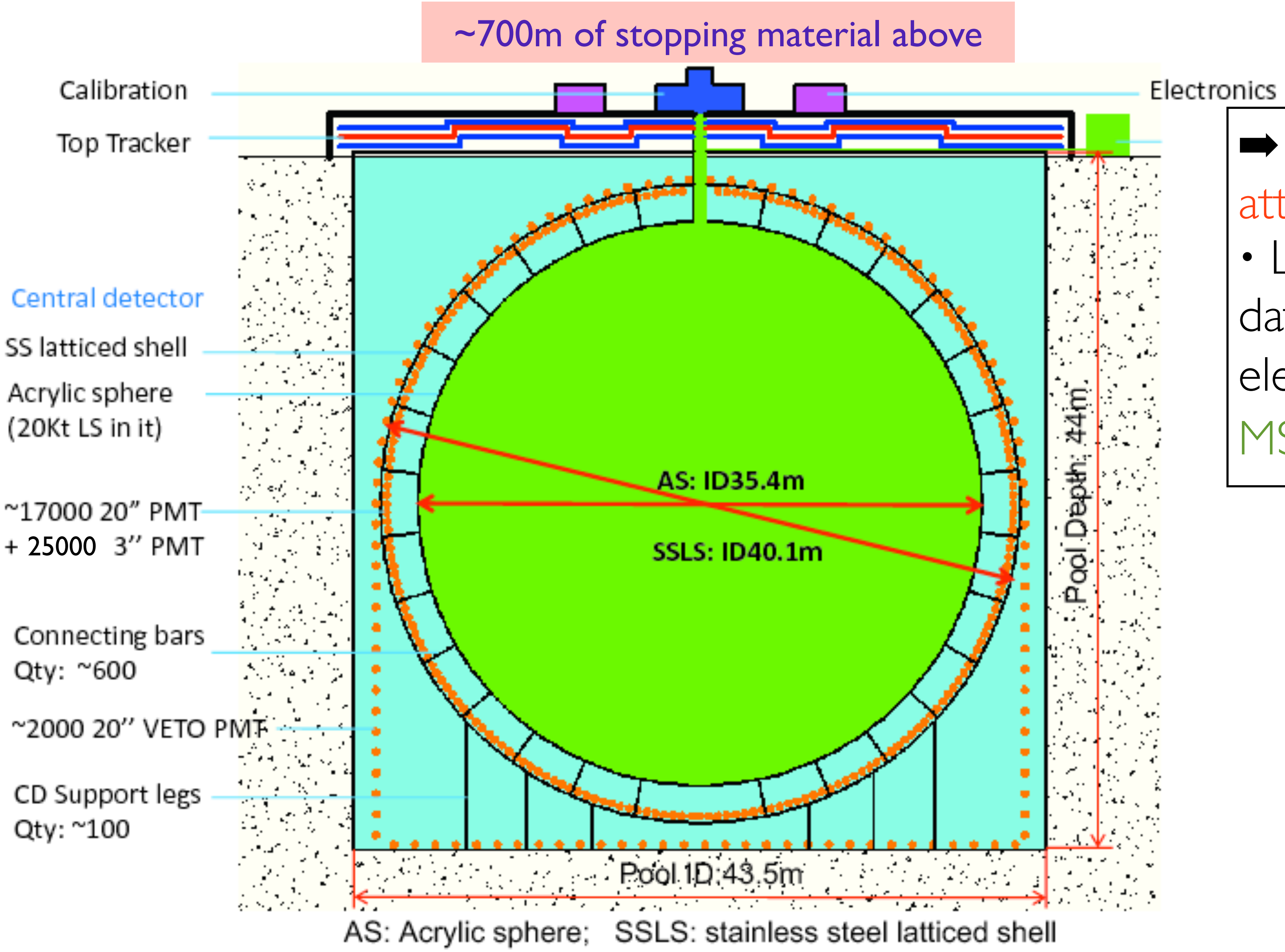
➡ Required energy resolution to determine hierarchy at 3**σ** level in 6 years, with current baseline and parameters, is **~3%/1 MeV**

➡ "Success" depends on keeping <u>linearity and uniformity of E response </u>under control

From such goals originate certain requirements...

Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
Target mass	20 ton	~300 ton	~1 kton	~20 kton
Optical coverage	~12%	~34%	~34%	~75%
E resolution	~7.5%/√E	~5%/√E	~6%/√E	~3%/√E
Light yield	~160 p.e/MeV	~500 p.e./MeV	~250 p.e./MeV	~1200 p.e./MeV

JUNO detector

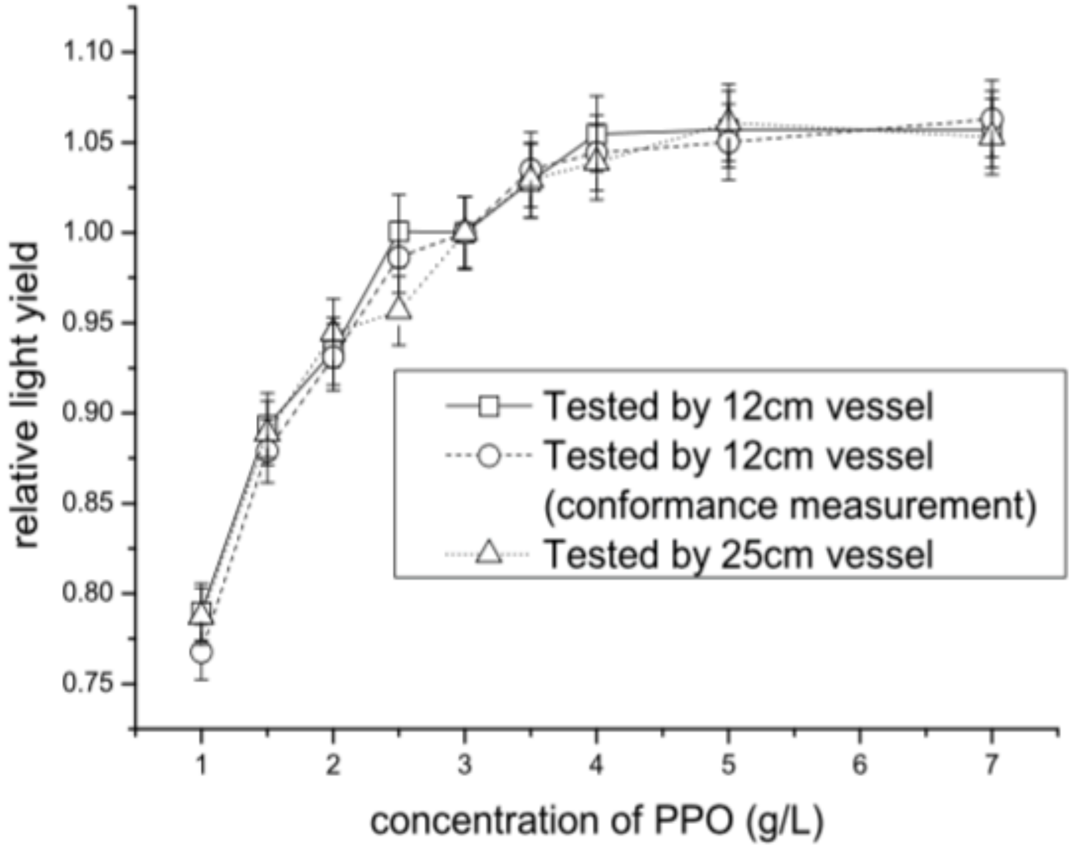


➡ maximize photon statistics and minimize attenuation of IBD prompt signal

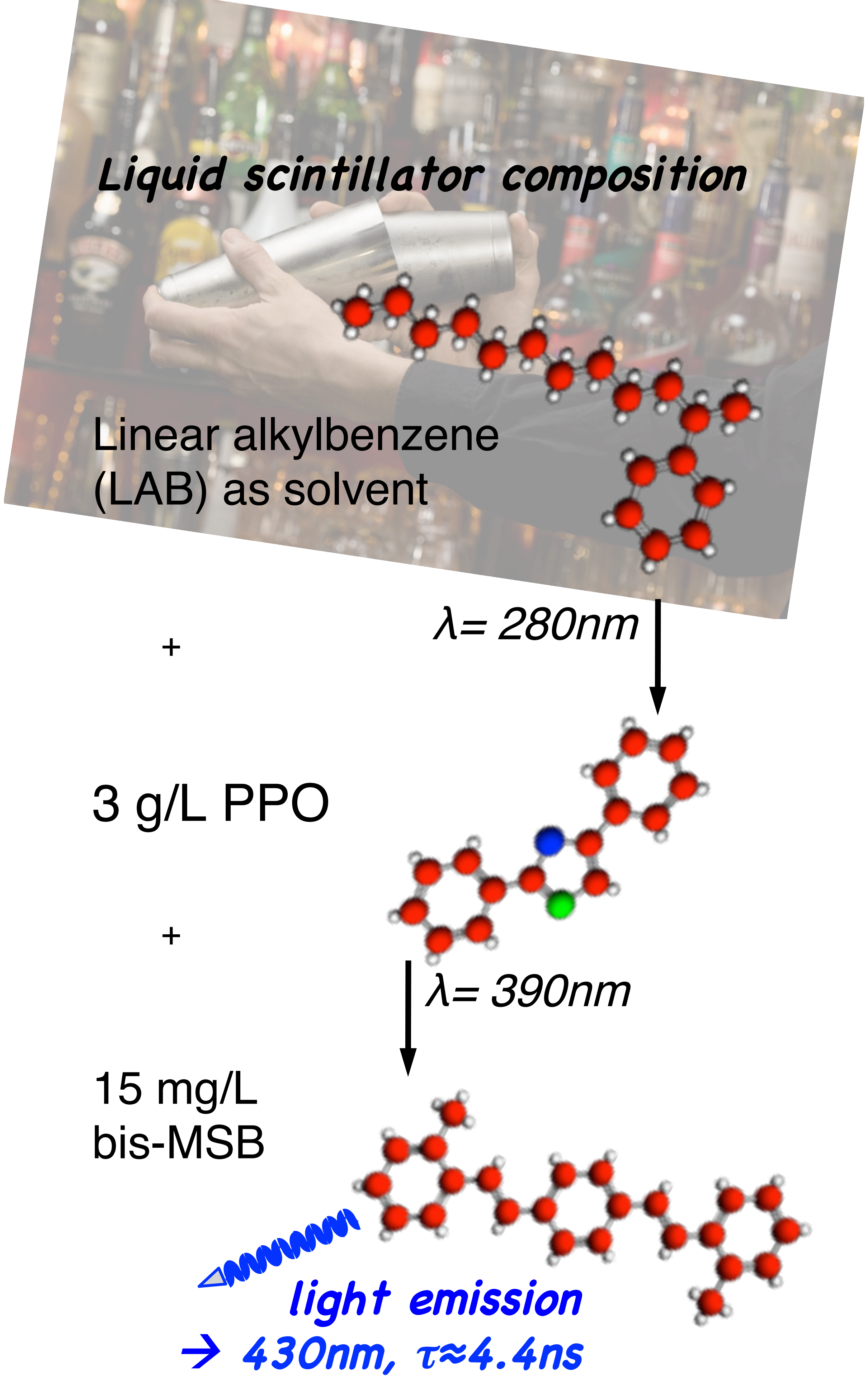
- Largest volume of liquid scintillator to date: >98% **LAB** (solvent, ~1200 photo-electrons/MeV) + **PPO** (solute) and bis-MSB (λ shifter)

20 kt liquid scintillator

- High light yield to reduce σ(E) from statistical fluctuations: ~10^4 scintillation photons/MeV
  - ➡ pure organic solvent (LAB)
    - ✓ safer and cheaper than Pseudo-cumene previously largely used, but worse particle discrimination
  - ➡ high fluor (PPO) concentration



- High transparency: > 20m
  - ➡ add wavelength shifter (bisMSB)



Liquid scintillator composition

Linear alkylbenzene (LAB) as solvent

λ= 280nm

\+

3 g/L PPO

\+

λ= 390nm

15 mg/L bis-MSB

light emission

→ 430nm, τ≈4.4ns

Cf V.Lozza and Z.Whang yesterday

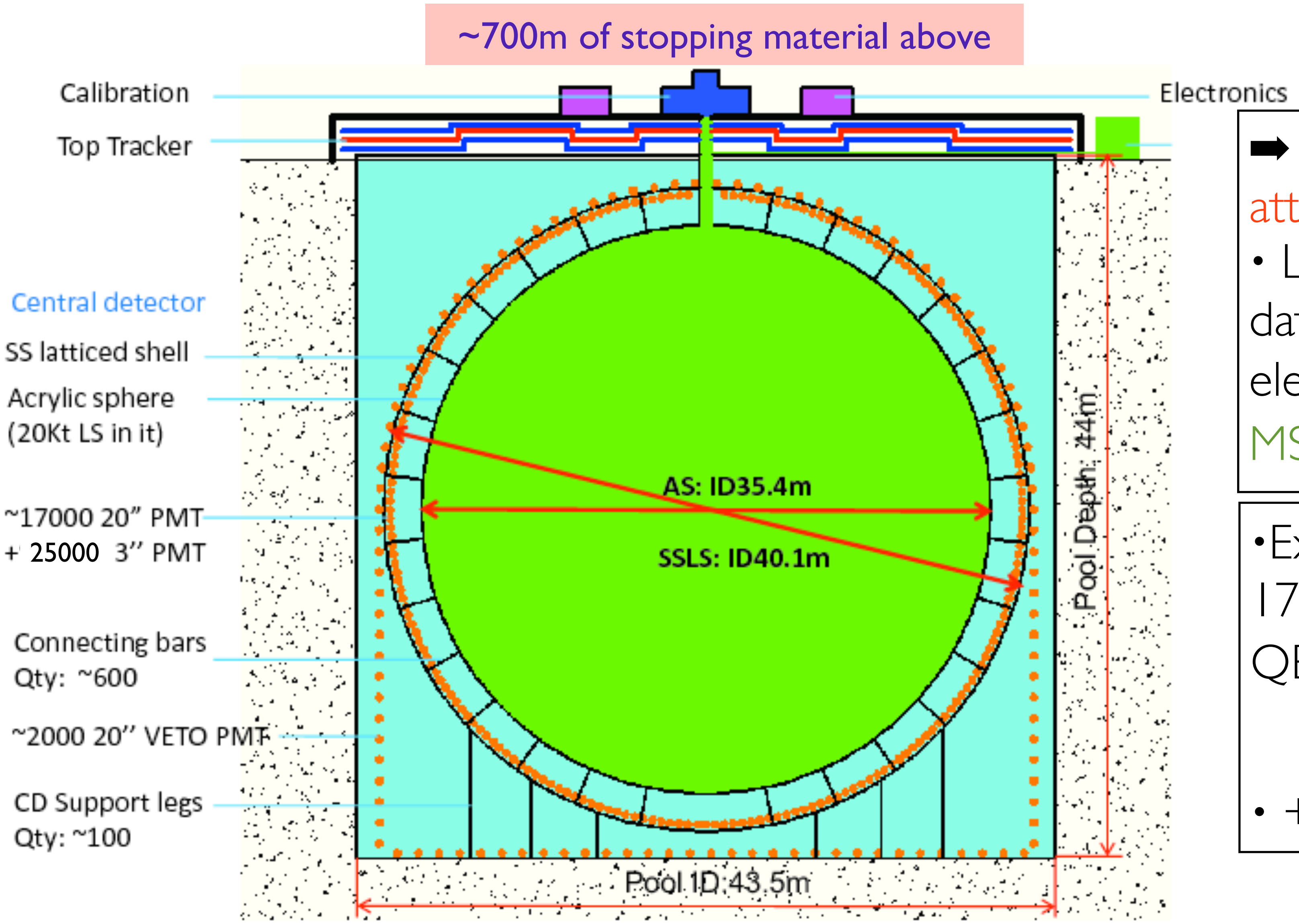
Liquid scintillator: purification

- Two main constraints determine need for LS purification (for IBD):
  - attenuation length: > 20 m at λ=430 nm (for 3g/L PPO in LAB)
  - **radio-purity: 10^{-15} g/g (^{238}U, ^{232}Th) and 10^{-17} g/g (^{40}K)**

4 different purification strategies developed and will be put in place:

attenuation length	radio-purity
Al_2O_3 column plant based on the "absorption" technique to remove optical impurities in LAB	
Distillation plant is to remove heavy metal, improve transparency	• Water extraction is to remove ^{238}U, ^{232}Th, ^{40}K • Gas Stripping plant remove the impurities : Ar, Kr, Rn • +Distillation plant

JUNO detector


~700m of stopping material above

AS: Acrylic sphere; SSLS: stainless steel latticed shell

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- Largest volume of liquid scintillator to date: >98% **LAB** (solvent, ~1200 photo-electrons/MeV) + **PPO** (solute) and bis-MSB (λ shifter)

- Extended photo-coverage (~75%) from 17k **micro-channel plate** PMT (⌀=20'', QE ~ 30% at 420 nm)
  - larger collection eff and good TTS for vertex position reconstruction (bkg rejection)
- + 25k "conventional" PMT (⌀=3'')

20'' PMT status

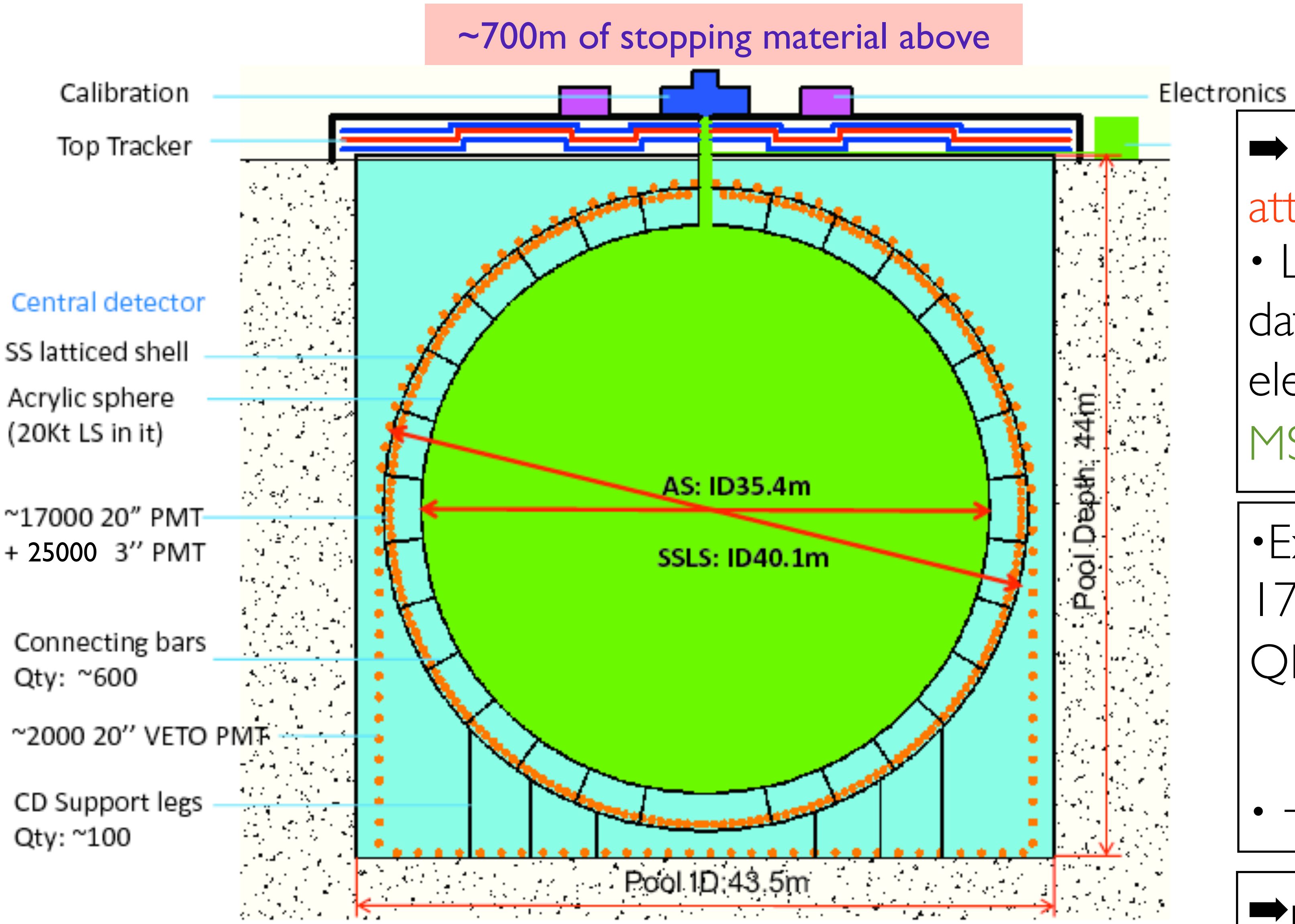
- To maximize photo-coverage use large (20'') PMT
- Ordered 15k "NNVT" MCP-PMT
- + 5K Hamamatsu R12860 "conventional dynode"
- resilience: equipped with protective mask to prevent generation of shock waves if one PMT explodes under water pressure

NNVT

R12860

Quantity	Unit	**NNVT**	**R12860**	Important for
collection mode		Reflection+Transmission	Transmission	
Quantum efficiency (400 nm)	%	30	30	E resolution
Relative detection efficiency	%	110	100	E resolution
TTS	ns	12	3	Vertex position (against bkgs)
Anode dark current	KHz	20-30	10-50	Need for a trigger
After pulse fraction	%	3	10	
Glass radioactivity	ppb	^{238}U: 50 ^{232}Th: 50 ^{40}K: 20	^{238}U: 400 ^{232}Th: 400 ^{40}K: 40	Background

JUNO detector



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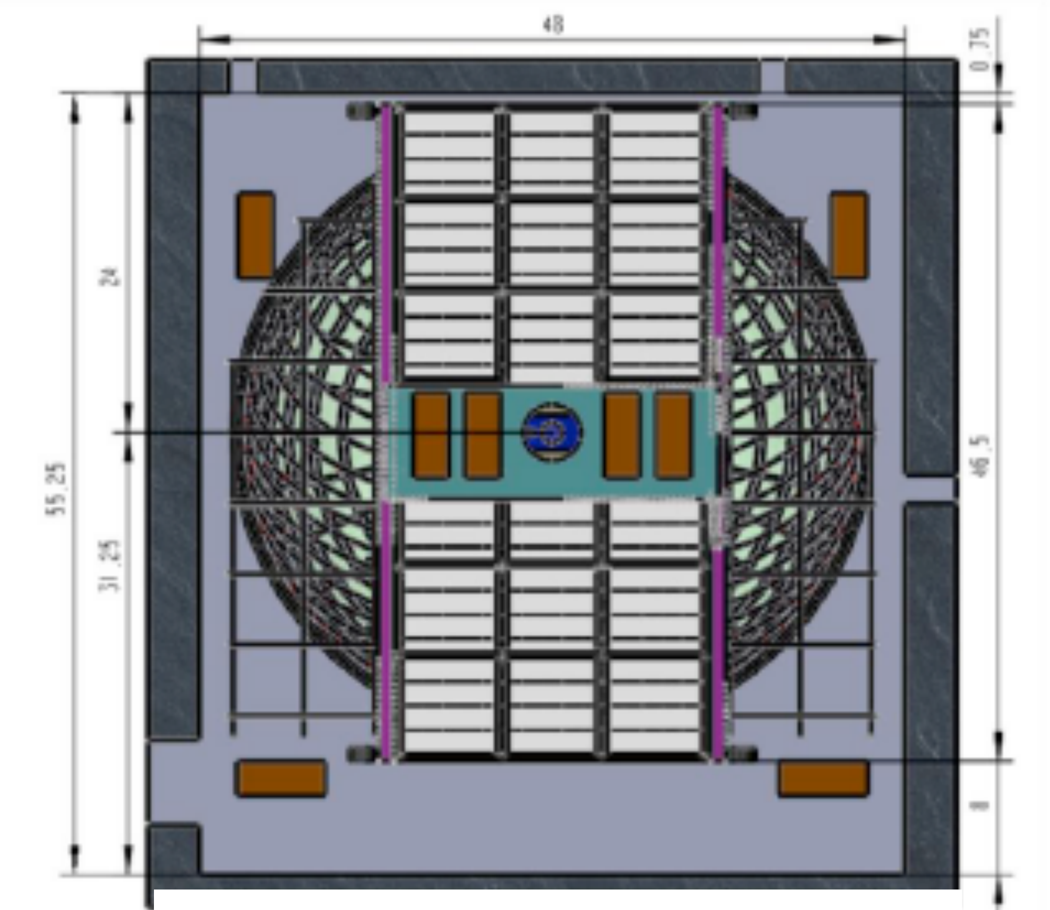
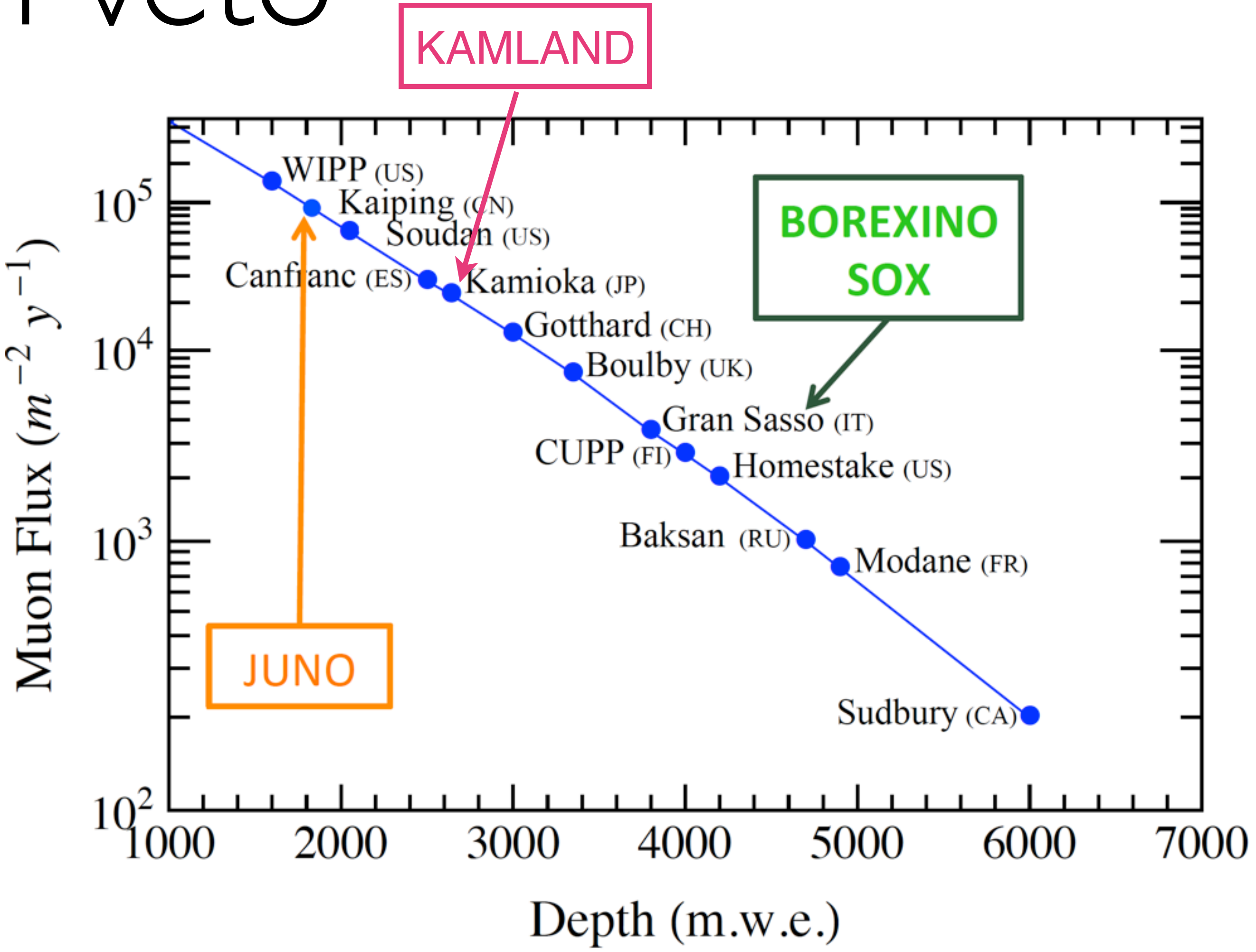
➡minimize cosmic ray bkg + shield against cavern radioactivity

  - veto activity from incoming muons and photons by surrounding water buffer (Cherenkov) and top scintillators

Muon veto



the OPERA Target Tracker


KAMLAND

BOREXINO SOX

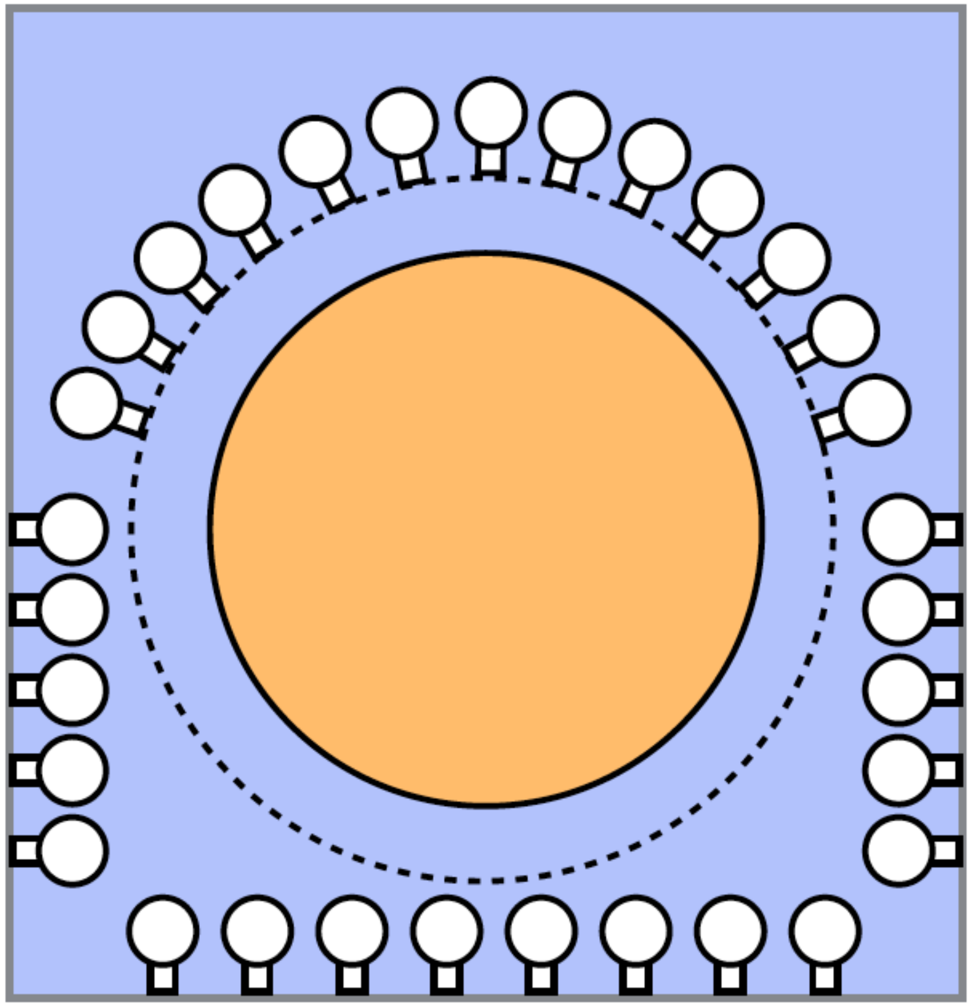
JUNO

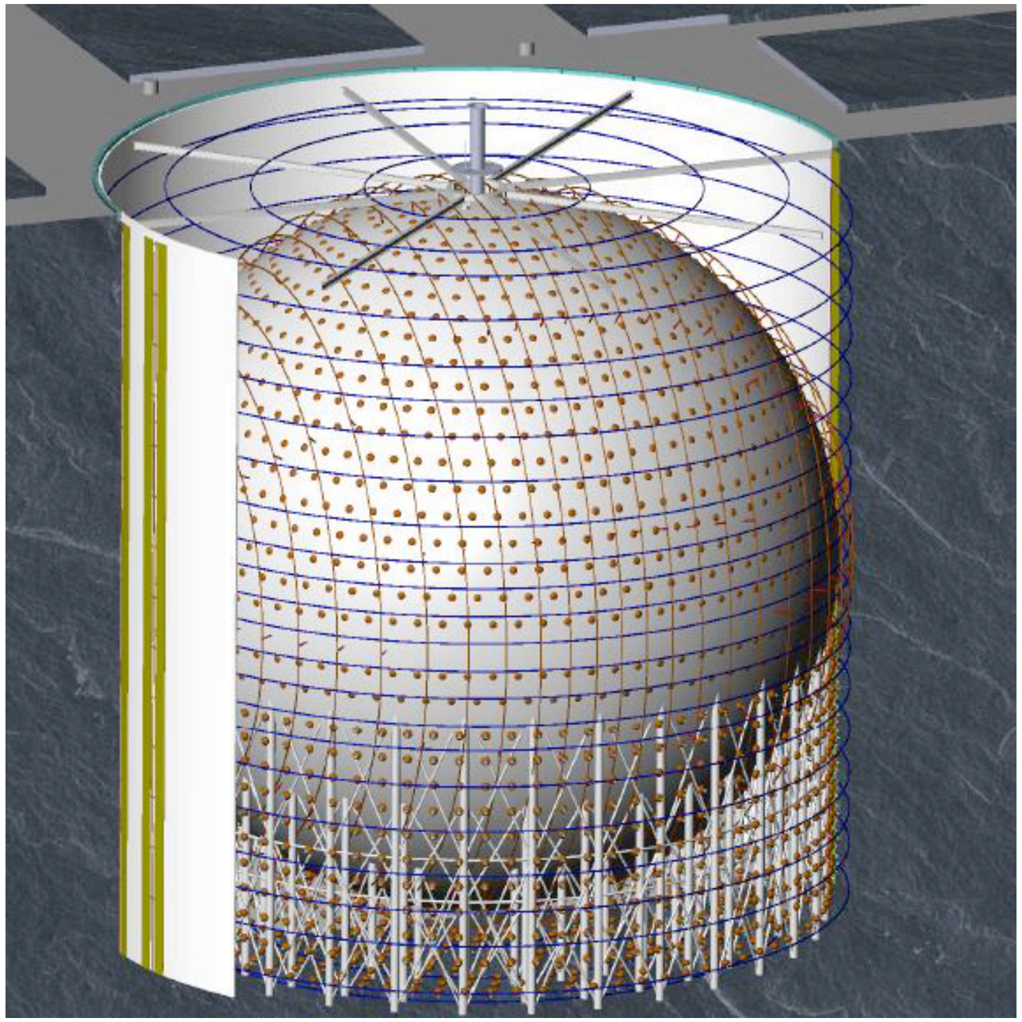
Overburden	Muon flux	$< E_\mu >$	R_μ in CD	R_μ in WP
748 m	0.003 Hz/m^2	215 GeV	3.0 Hz	1.0 Hz

- Unscreened muons can interact with ^{12}C in LS and produce lighter isotopes (esp. ^{9}Li and ^{8}He)
- Top Tracker: geometrical coverage ~50%
  - veto + provide "calibration" sample to study performance of tracking algorithms (reject un-vetoed muons passing through central detector off-line)

- Top Tracker has been shipped to near-JUNO site for aging tests

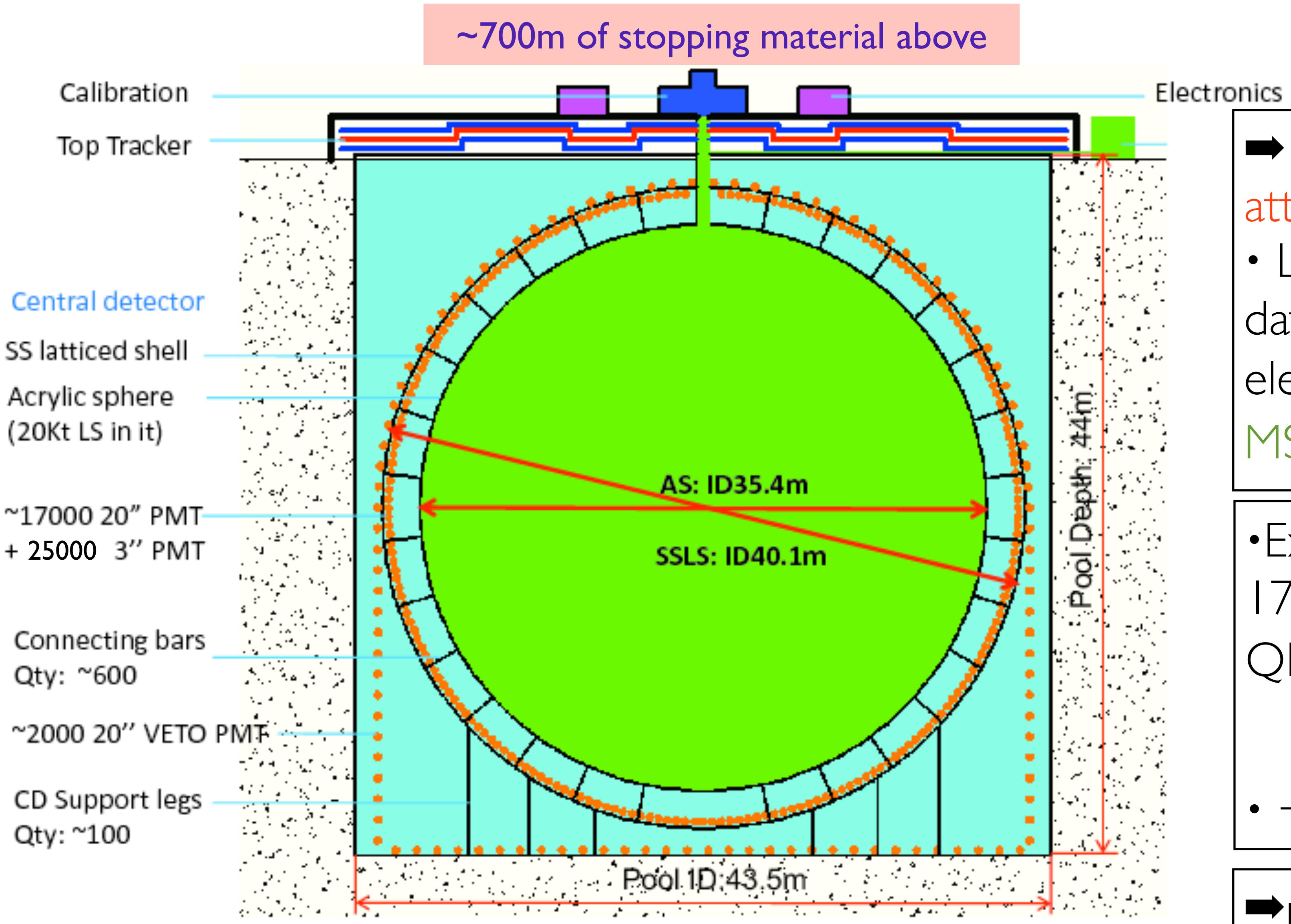
Water pool





- Even if LS is purified, surrounding environment intrinsically radioactive + there is cosmogenic bkg
- Stop β and α through passive veto
- Look for "Outside-in" *n* close to muon Cherenkov radiation in 35 kton of ultra-pure water around central sphere
- Light collected by 2k 20" PMTs
  - veto system efficiency expected to be > 95%

JUNO detector



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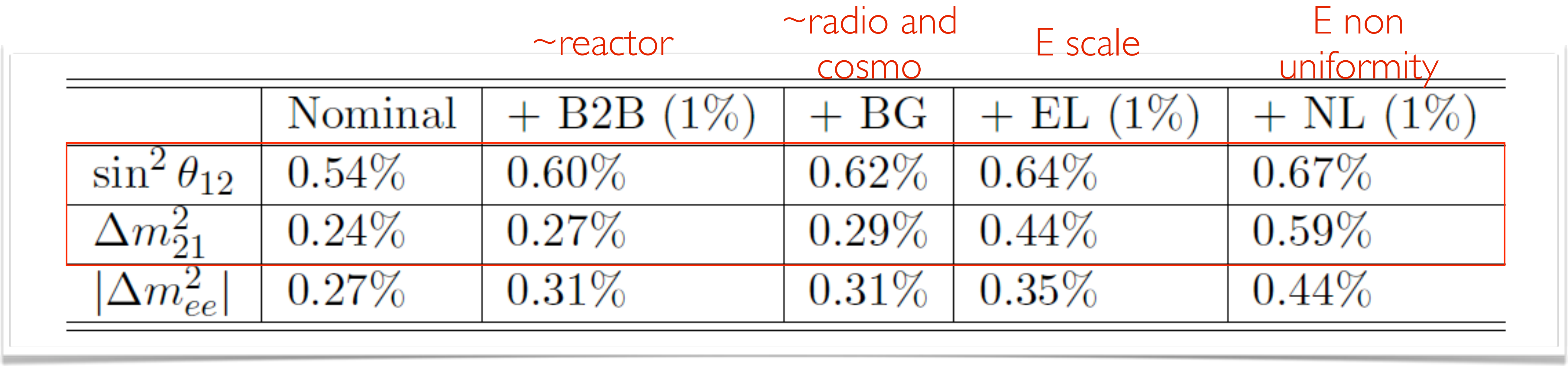
➡minimize cosmic ray bkg + shield against cavern radioactivity

- veto activity from incoming muons and photons by surrounding water buffer (Cherenkov) and top scintillators

➡front-end electronics under water with challenging design and testing currently under-way for resilience

- Mature design
- 2016-2017 – Detector component production
- 2016-2019 – PMT production
- 2018-2019 – Detector assembly and installation
- 2020 – Filling

Solar oscillation parameters - expectations



	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%
$\lvert\Delta m^2_{ee}\rvert$	0.27%	0.31%	0.31%	0.35%	0.44%

Impact on solar neutrino parameters from reactor neutrino oscillations with a:

- large mass
- detector positioned right after a full oscillation cycle

- JUNO will contribute significantly to global fits to “1-2” parameters

Solar neutrinos at JUNO

(J. Phys. G 43 (2016) 030401)

- Caveat: with an "evolving" detector, all figures are preliminary and analyses still *in nuce*
- I am presenting main advantages and issues in JUNO

Main goals, pros and issues

◉ Goal: new measurements of ^{7}Be and ^{8}B fluxes to help constrain metallicity in Sun-like stars

- Signature for solar neutrinos will be "singles" from ES:

$$\nu_{e,\mu,\tau} + e^{-} \rightarrow \nu_{e,\mu,\tau} + e^{-}$$

✓ JUNO has large exposure ideal to enhance statistics

✓ Unprecedented E_{res} (e.g. isolate ^{7}Be from "shoulder" in ES e^{-} spectrum)

➡ JUNO shallower than previous "solar experiments" (relies on "double coincidence" to reject bkg in reactor physics)

➡ Large "monolithic" liquid scintillator with no directionality

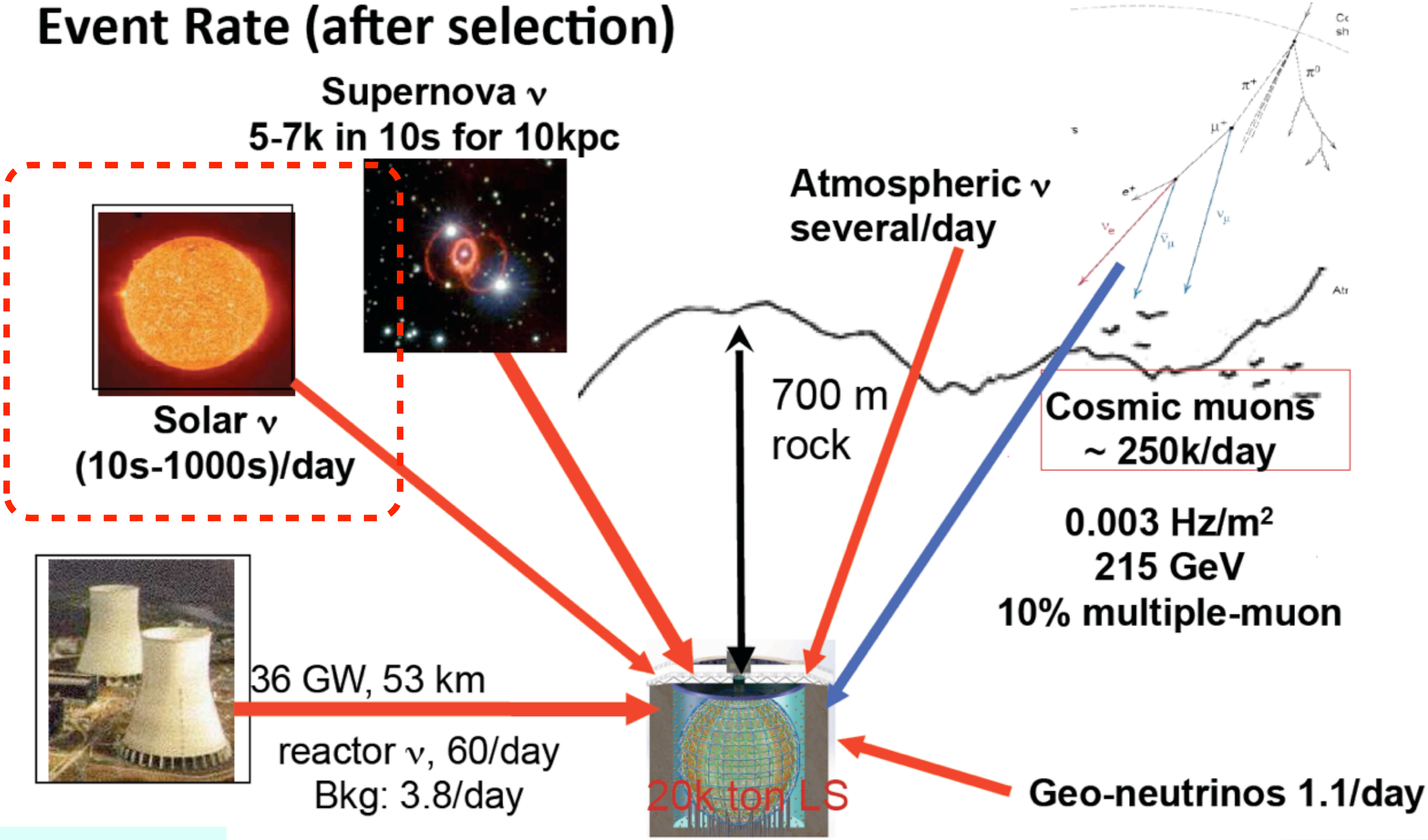
  - Only statistical rejection of (esp.) β and γ bkg

➡ Radio-purity (for ^{7}Be/low ^{8}B) and event-by-event cosmogenic veto (upper part of ^{8}B spectrum) capabilities will be the main challenges

  - also, dedicated triggers and study of ^{14}C-^{14}C overlap might be needed for low E (pp and ^{7}Be)

What one will see...

Event Rate (after selection)



Supernova ν
5-7k in 10s for 10kpc

Solar ν
(10s-1000s)/day

Atmospheric ν
several/day

700 m
rock

Cosmic muons
~ 250k/day

0.003 Hz/m²
215 GeV
10% multiple-muon

36 GW, 53 km

reactor ν, 60/day
Bkg: 3.8/day

20k ton LS

Geo-neutrinos 1.1/day

Y. B. Hsiung at NNN16

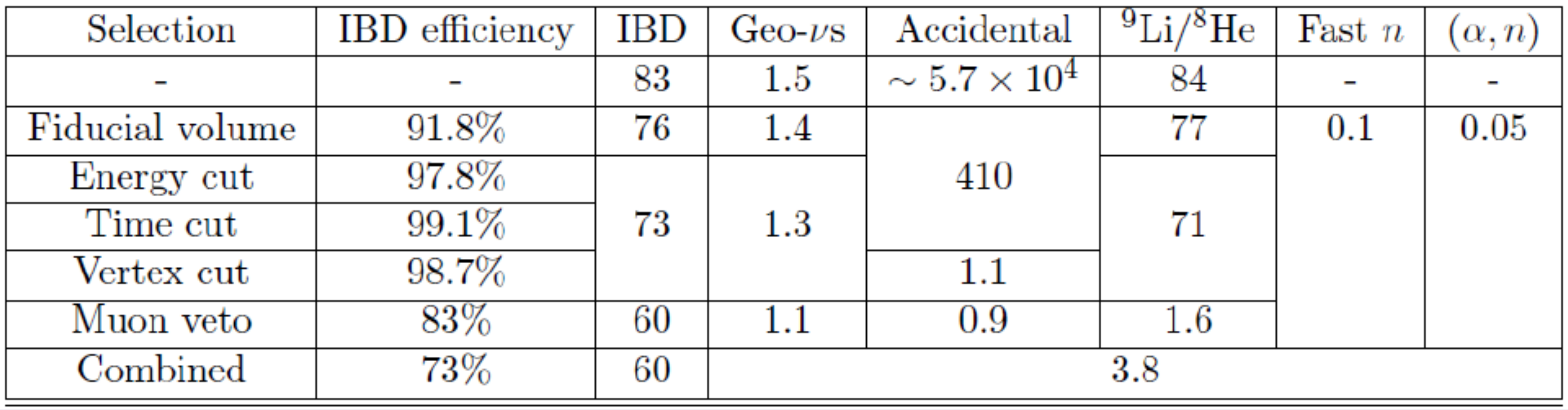
J. Phys. G 43 (2016) 030401

Background rates

Geo:1.8%

Acc: 1.5%

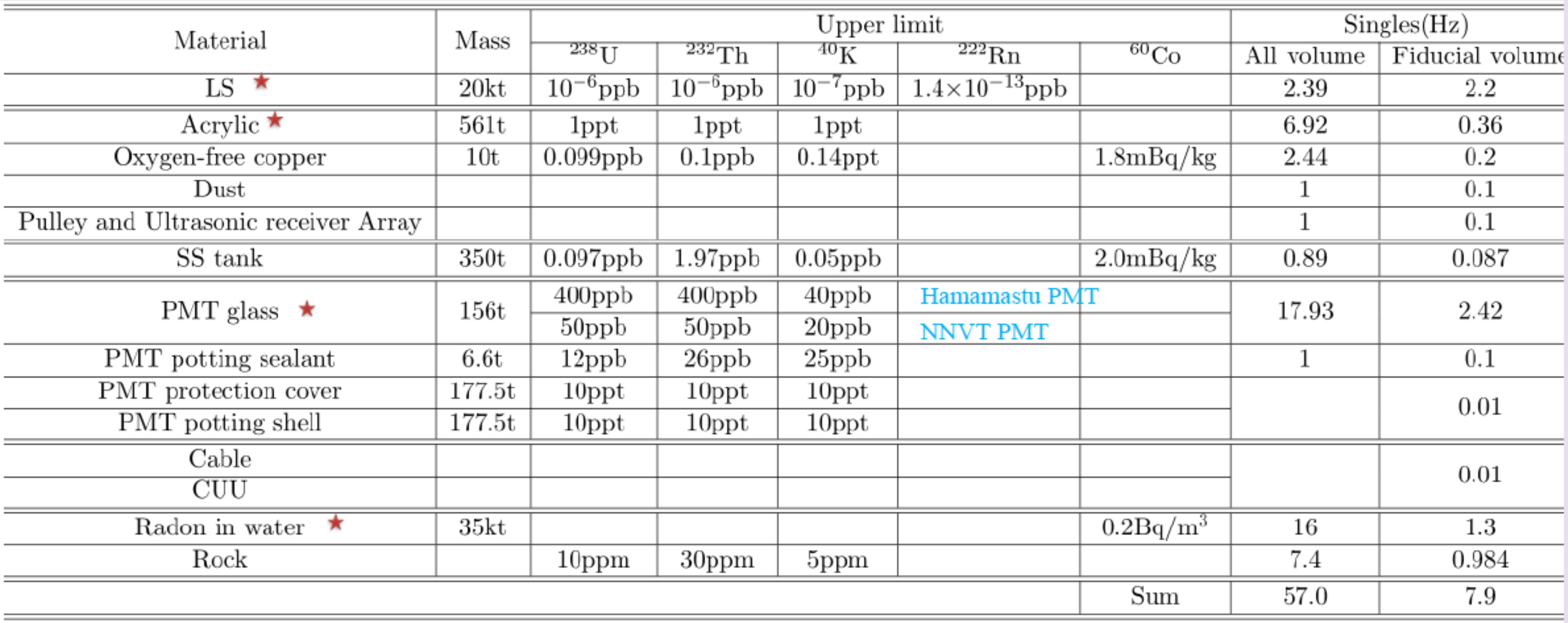
^{9}Li/^{8}He: 2.7%



Selection	IBD efficiency	IBD	Geo-νs	Accidental	^{9}Li/^{8}He	Fast n	(α, n)
-	-	83	1.5	$\sim 5.7 \times 10^{4}$	84	-	-
Fiducial volume	91.8%	76	1.4	410	77	0.1	0.05
Energy cut	97.8%	73	1.3		71		
Time cut	99.1%						
Vertex cut	98.7%			1.1			
Muon veto	83%	60	1.1	0.9	1.6		
Combined	73%	60	3.8				

Expected upper limit for each material (Preliminary)

N/day



Material	Mass	Upper limit					Singles(Hz)	
		^{238}U	^{232}Th	^{40}K	^{222}Rn	^{60}Co	All volume	Fiducial volume
LS ★	20kt	10^{-6}ppb	10^{-6}ppb	10^{-7}ppb	1.4×10^{-13}ppb		2.39	2.2
Acrylic ★	561t	1ppt	1ppt	1ppt			6.92	0.36
Oxygen-free copper	10t	0.099ppb	0.1ppb	0.14ppt		1.8mBq/kg	2.44	0.2
Dust							1	0.1
Pulley and Ultrasonic receiver Array							1	0.1
SS tank	350t	0.097ppb	1.97ppb	0.05ppb		2.0mBq/kg	0.89	0.087
PMT glass ★	156t	400ppb	400ppb	40ppb	Hamamastu PMT		17.93	2.42
		50ppb	50ppb	20ppb	NNVT PMT			
PMT potting sealant	6.6t	12ppb	26ppb	25ppb			1	0.1
PMT protection cover	177.5t	10ppt	10ppt	10ppt				0.01
PMT potting shell	177.5t	10ppt	10ppt	10ppt				
Cable								0.01
CUU								
Radon in water ★	35kt					0.2Bq/m^{3}	16	1.3
Rock		10ppm	30ppm	5ppm			7.4	0.984
						Sum	57.0	7.9

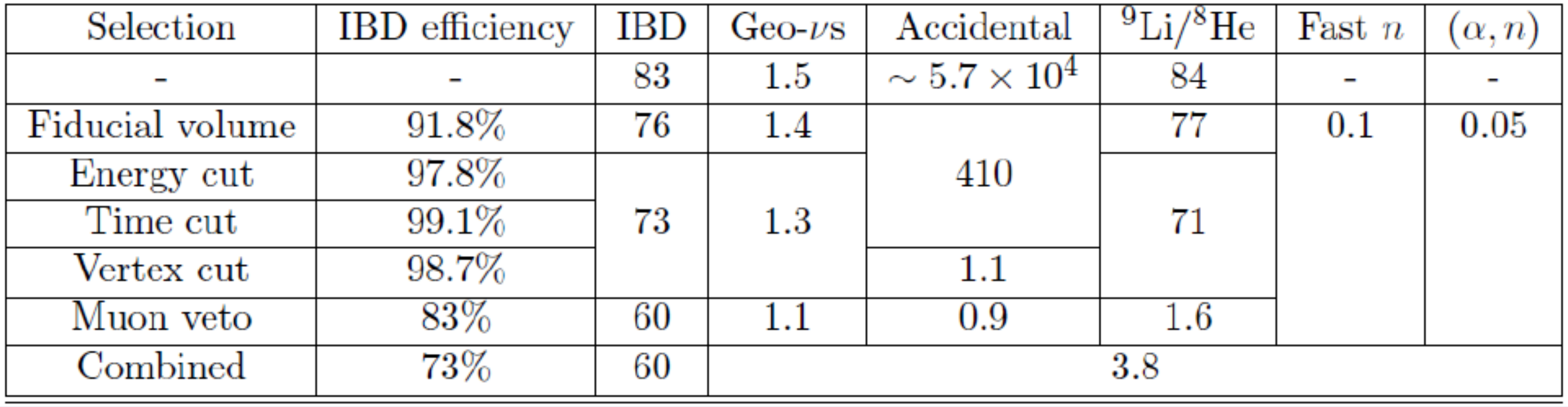
➢The most critical materials are shown with “stars” in the material column.

Background processes

Geo:1.8%

Acc: 1.5%

^{9}Li/^{8}He: 2.7%



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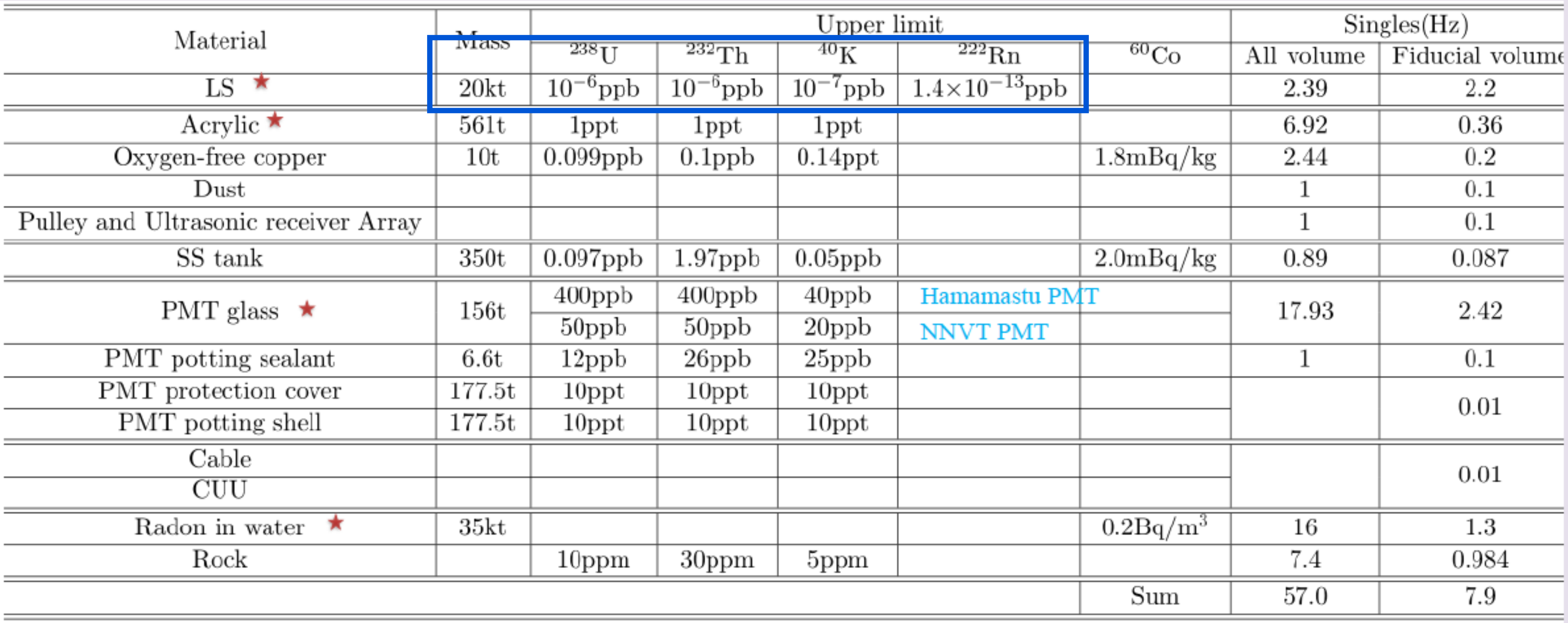

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L.Ludhova, ECAP Seminar

Radio-purity scenarios

- Two scenarios assumed in projections so far
  - “**baseline**”: minimum requirement, S/B ~ 1/3, about the same as KamLAND highest solar phase purity, *factor 10 better than “goal for IBD” (slide 9)*
  - “**ideal**”: S/B ~ 2/1, similar to Borexino phase-I
    - but both KL and Bx reached better than “ideal” for ^{238}U and ^{232}Th from start

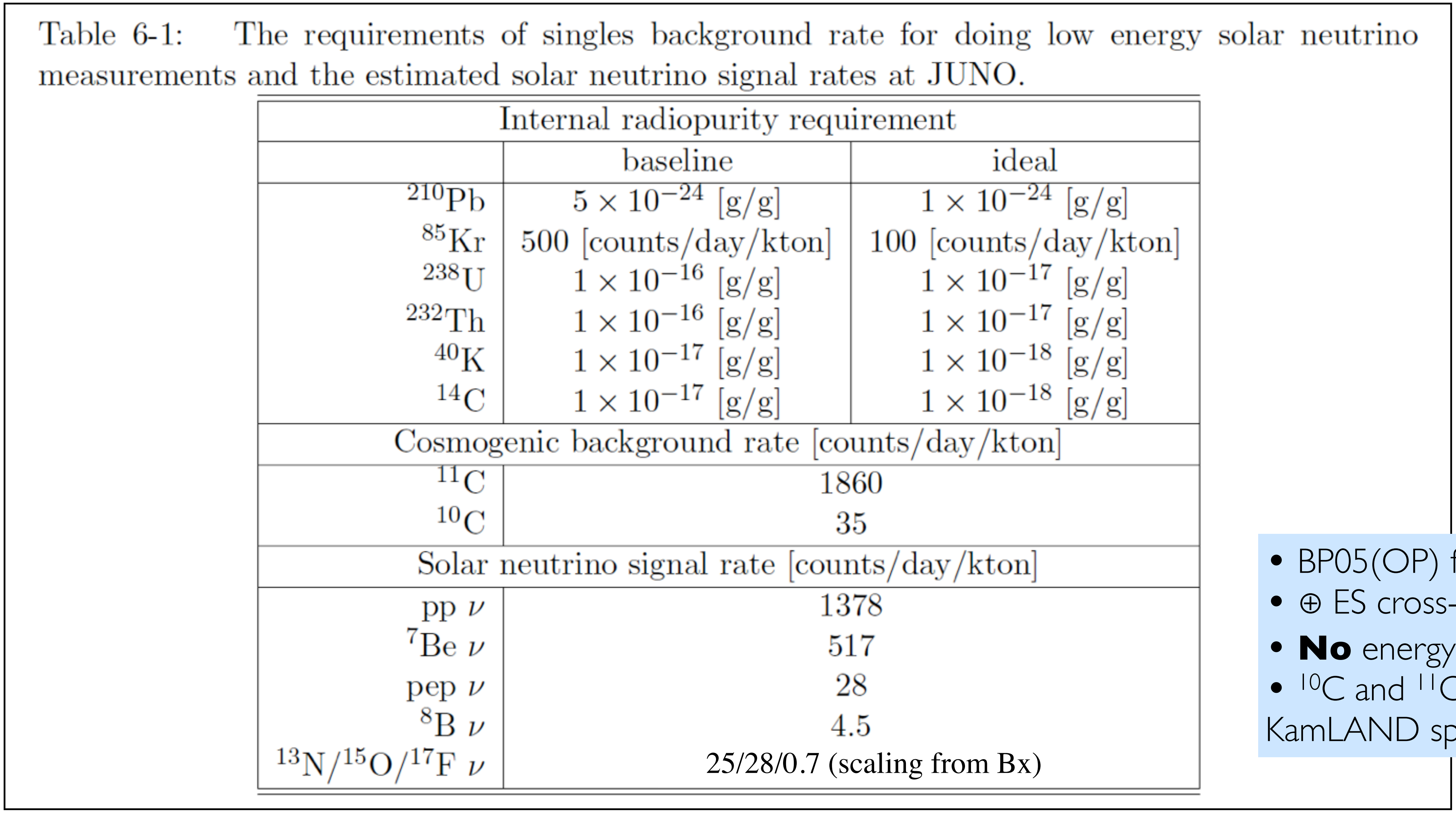


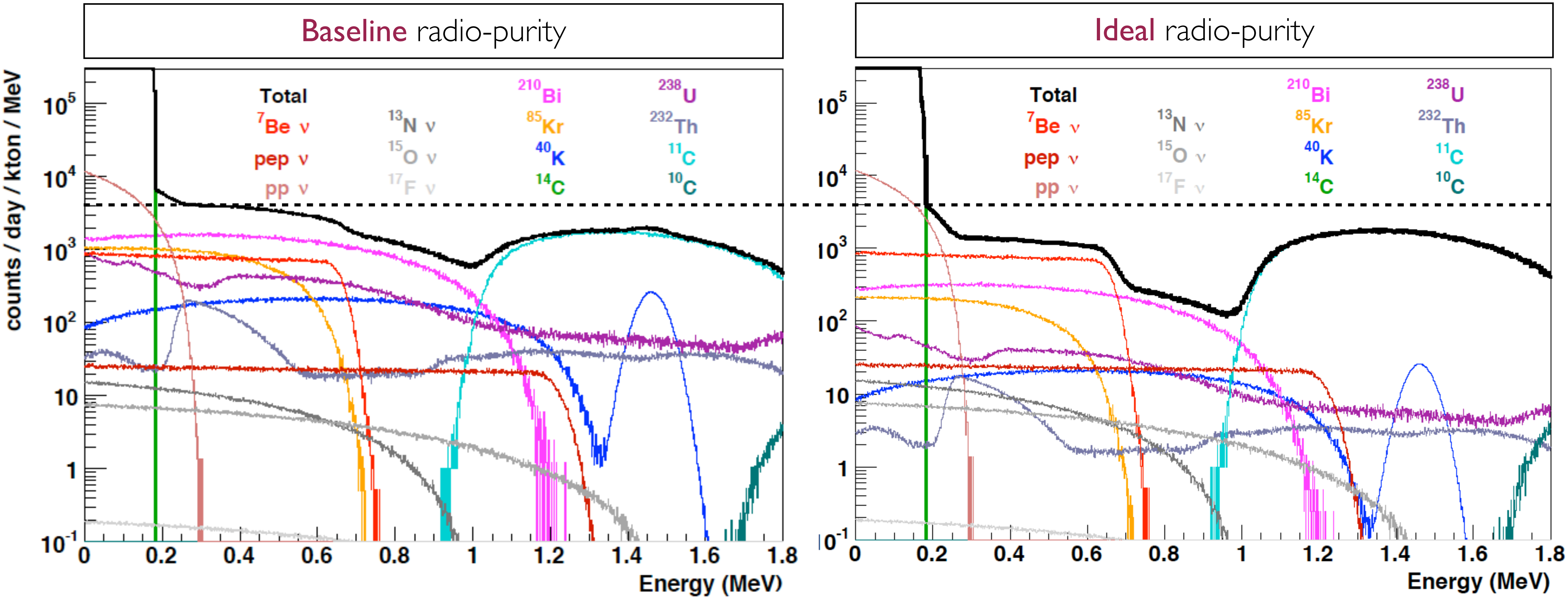
Table 6-1: The requirements of singles background rate for doing low energy solar neutrino measurements and the estimated solar neutrino signal rates at JUNO.

Internal radiopurity requirement		
	baseline	ideal
^{210}Pb	5×10^{-24} [g/g]	1×10^{-24} [g/g]
^{85}Kr	500 [counts/day/kton]	100 [counts/day/kton]
^{238}U	1×10^{-16} [g/g]	1×10^{-17} [g/g]
^{232}Th	1×10^{-16} [g/g]	1×10^{-17} [g/g]
^{40}K	1×10^{-17} [g/g]	1×10^{-18} [g/g]
^{14}C	1×10^{-17} [g/g]	1×10^{-18} [g/g]
Cosmogenic background rate [counts/day/kton]		
^{11}C	1860	
^{10}C	35	
Solar neutrino signal rate [counts/day/kton]		
pp ν	1378	
^{7}Be ν	517	
pep ν	28	
^{8}B ν	4.5	
^{13}N/^{15}O/^{17}F ν	25/28/0.7 (scaling from Bx)	

- BP05(OP) flux
- ⊕ ES cross-sections
- **No** energy threshold cuts
- ^{10}C and ^{11}C scaled x0.9 from KamLAND spallation measurmt’s

- Obviously realistic numbers only after activity measurements and MC tuning completed
- Also in-situ determination with first data will be an important constrain!

^{7}Be

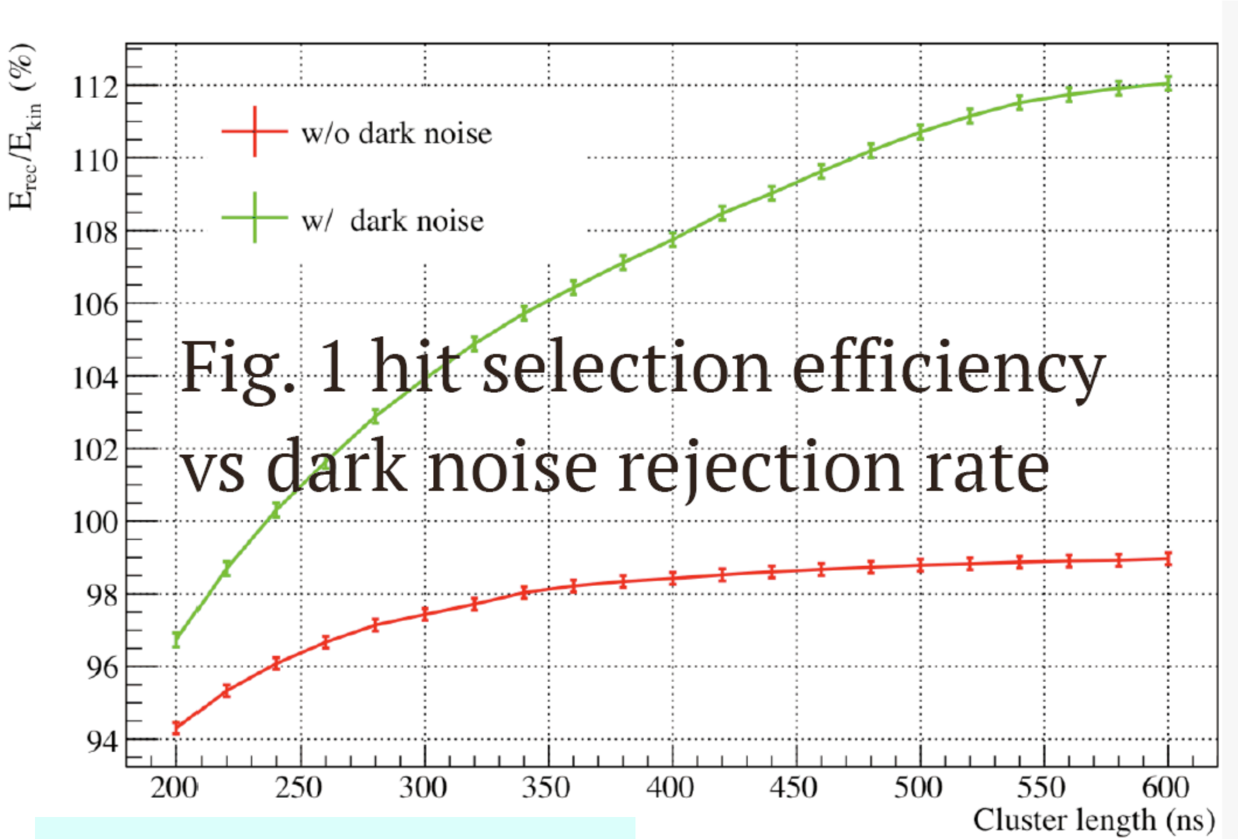

Baseline radio-purity

Ideal radio-purity

- Here only internal LS radioactivity considered
  - External γ neglected because can be removed by fiducial volume cut
- ^{238}U and ^{232}Th assumed at secular equilibrium *(10^{-16} or 10^{-17} g/g)*
- Considered here, out of equilibrium: ^{210}Pb ➞ ^{210}Bi ➞ ^{210}Po+β^{-} +ν
  - will be key point in extracting ^{7}Be spectrum at "shoulder"
  - ^{210}Po ➞ ^{206}Po+α not included here: studying now Pulse Shape Discrimination to reject it
    - but α quenching to low energies might make it hard wrt JUNO benchmark E_{thr}
- Effect of dark noise and ^{14}C at PMT waveform not yet included here
  - *see next slide*

Dark noise and pile-up

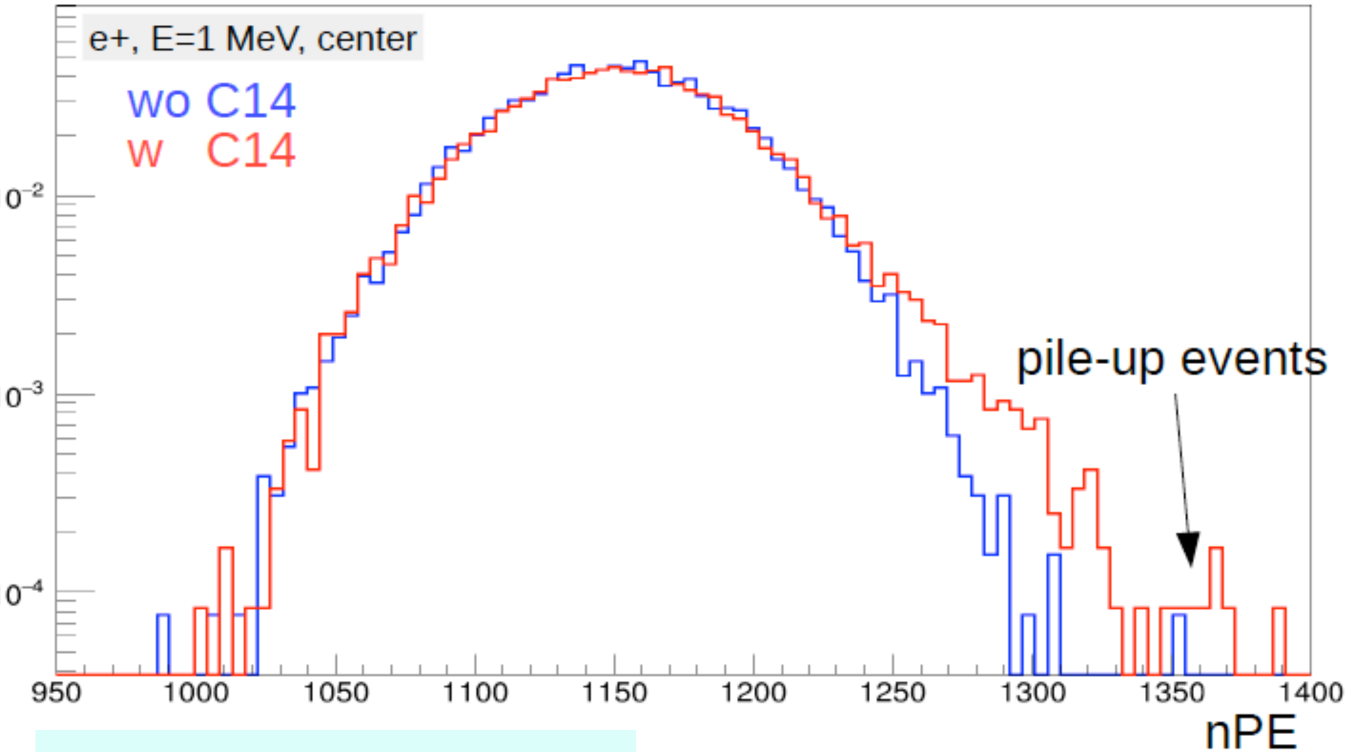
- **Dark noise** (O(10 kHz)) overlapping with signal on PMT waveform will impact energy linearity and resolution, especially at ^{7}Be e^{-} energies
- Rate of ^{14}C is such that **pile-up** with signal could bias energy estimation
- Specific algorithms like "clusterization" a la Borexino being developed
  - Group hits likely to belong to one physics event <u>based on hit arrival time</u>



X. Ding et al at Neutrino18

Optimization of algorithm (fixed cluster size, time window length, etc..) ongoing

assumed ^{14}C/^{12}C ratio of 10^{-17} and $1/\tau=4\times10^{-12}$ Hz
➔ Total: 40 kBq of ^{14}C decays
➔ **5% pile-up events expected**

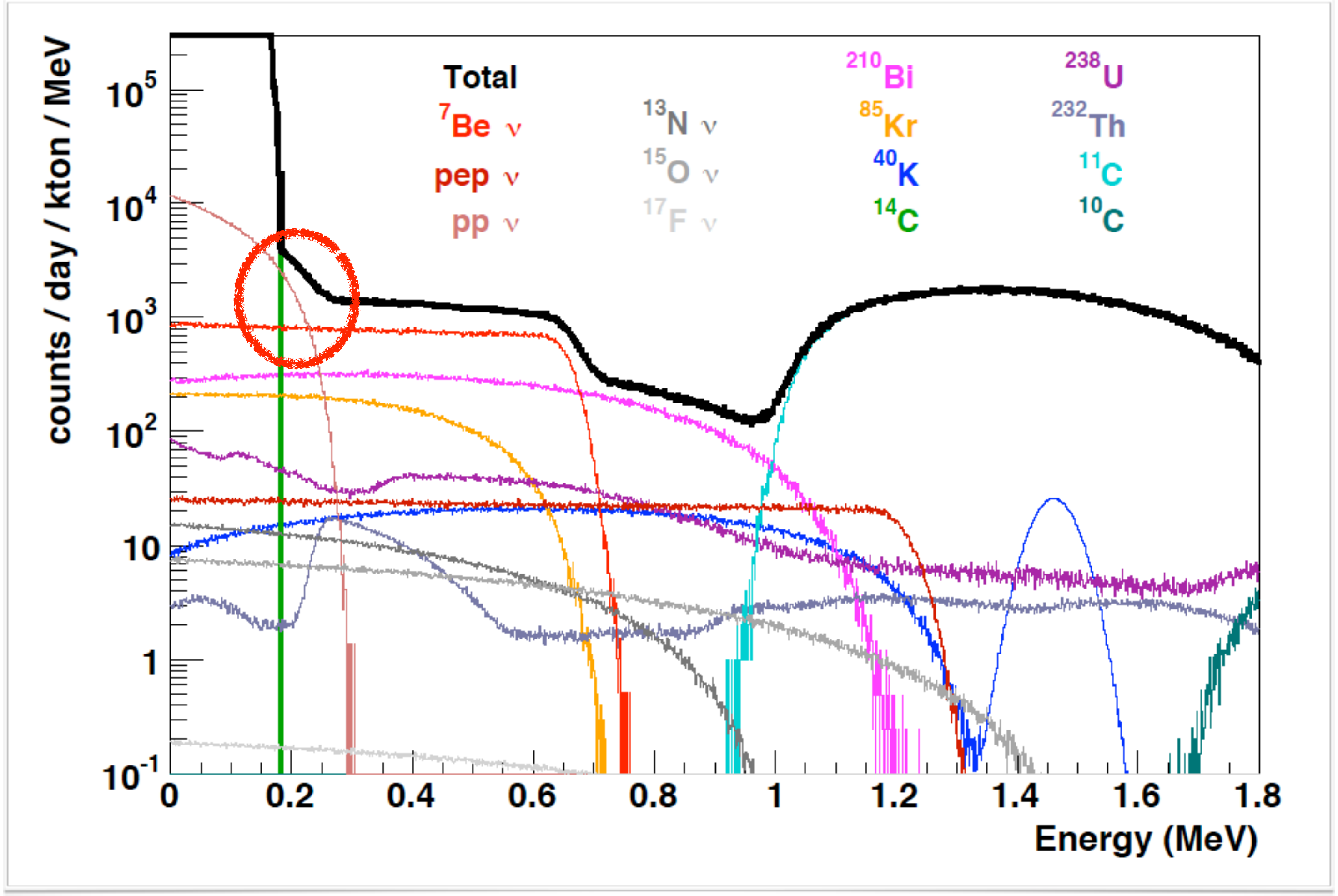


P. Kampmann et al at DPG18

pp?

- if ^{14}C pile-up is correctly modeled and rejected
- if clusterization removes dark noise contribution effectively
- if quenched **α** from Po is identified and rejected by PSD
- by developing dedicated low-energy triggers which go below the current "N(PMT) majority" trigger corresponding to ~ few hundreds of keV

then



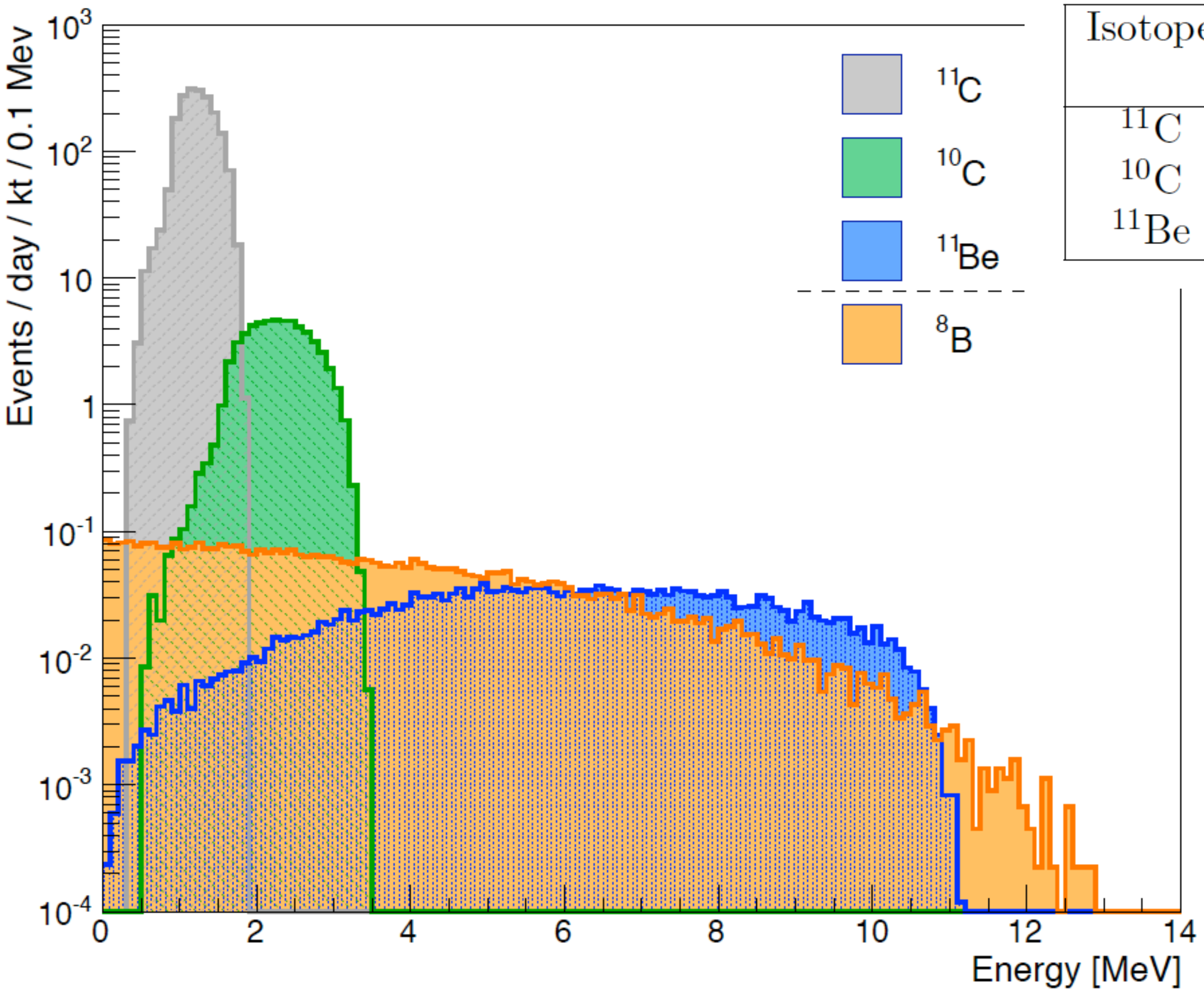
- pp can be isolated in a window ~160 keV - ~230 keV
- will therefore only benefit from mature techniques validated *in-situ* with first data

^{8}B vs radioactive bkgs...

- Mostly ^{208}Tl from ^{232}Th in the LS and in the PMT glass
    - decays β^{-} to ^{208}Pb with τ~3 min and Q=5 keV
    - hard to estimate, especially if we are out of secular equilibrium
    - and Bi-Po might be hard to detect because of α quenching to low energies
- Expect we'll need to control ^{232}Th to 10^{-17} g/g to "follow" ^{8}B at E(ES e^{-}) ≪ 5 MeV
- Contamination from PMT glasses and rest of material can be suppressed by means of fiducial volume
    - but pay a price in acceptance (up to 5m of FV needed?)

…and ^{8}B vs cosmogenic bkgs

- Spallation of cosmic muons on carbon nuclei in the LS molecules
  - Muon rate ~4Hz in JUNO central detector at expt. site depth
  - Signals from short-lives isotopes ($\tau \lesssim 1$s) can be targeted thanks to effective muon tracking (but watch out for bundles, showers, etc..)
  - preliminary idea: veto cylindrical volume with R=1m for 6.5s

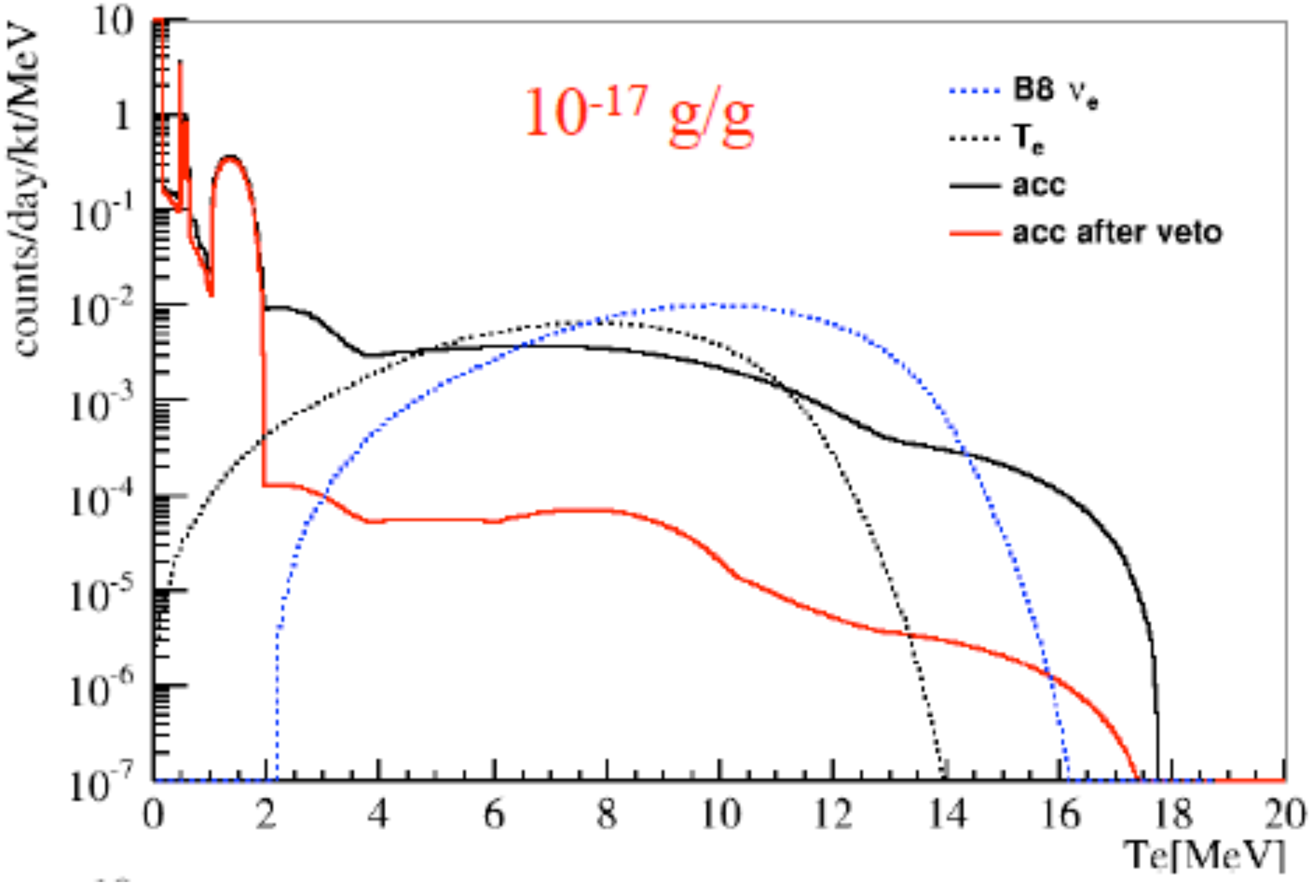


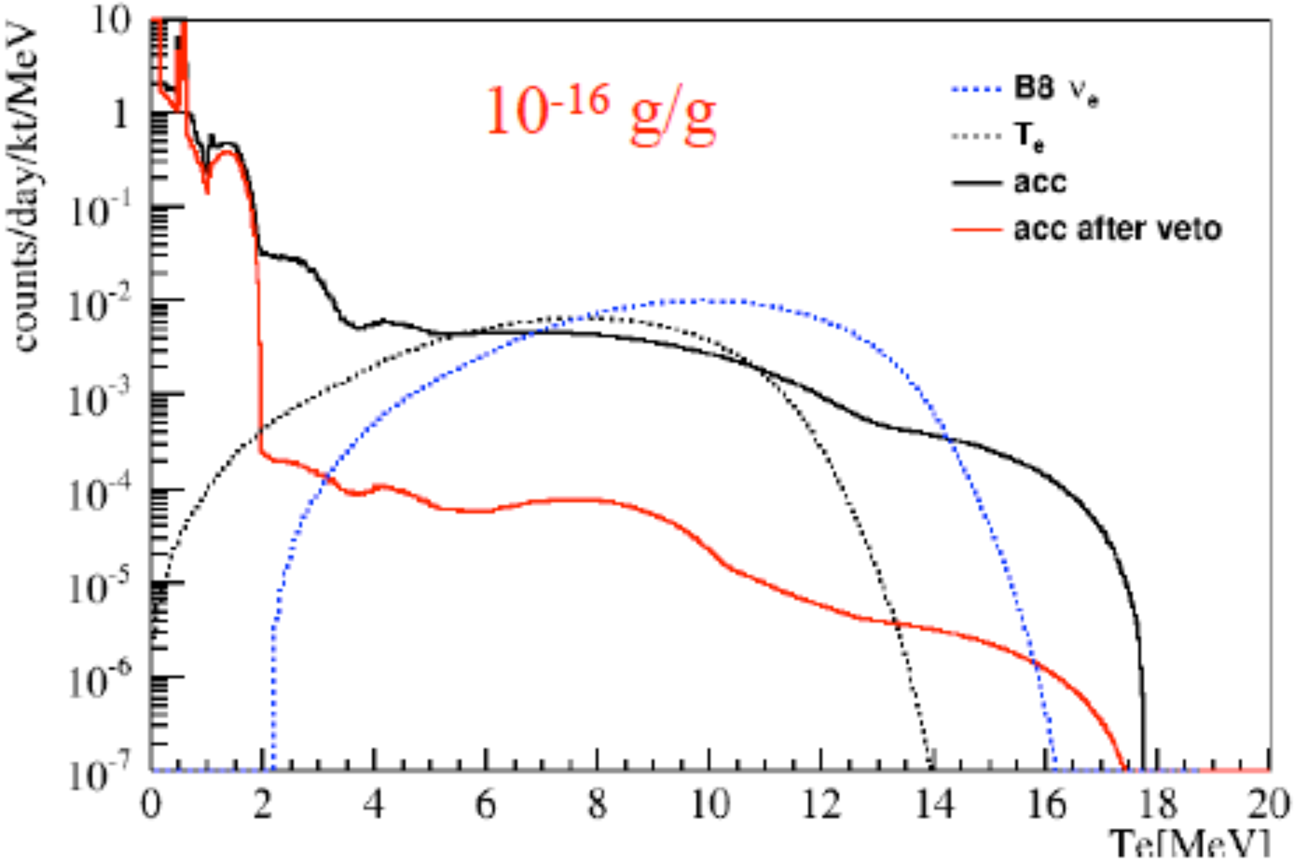
Isotope	Decay Type	Q-Value [MeV]	Life time	Yield [109, 305] 10^{-7} $(\mu\,\mathrm{g/cm^2})^{-1}$	Rate [cpd/kton]
^{11}C	β^{+}	2.0	29.4 min	866	1860
^{10}C	β^{+}	3.7	27.8 s	16.5	35
^{11}Be	β^{-}	11.5	19.9 s	1.1	2

- Relevant bkgs with τ>2s
- cannot be suppressed with a muon veto (without too much detector dead time…)
- Fitted together with ^{8}B
  - spectrum here assumes $E_{res} = 3\%/\sqrt{E}$
  - ^{10}C and ^{11}C scaled x0.9 from KamLAND spallation

…and ^{8}B vs cosmogenic bkgs /2: CC

- Idea to use also CC $\nu_e + {}^{13}\mathrm{C} \rightarrow e^- + {}^{13}\mathrm{N}$ E_th=2.2MeV
- Gives a "double":
  - prompt electron with $E_{kin}=E_\nu-2.2$ MeV
  - delayed from ^{13}N β^+ decay (Q=2.2 MeV, τ=862.8s)
  - a position-based association could reduce cosmogenic bkgs considerably





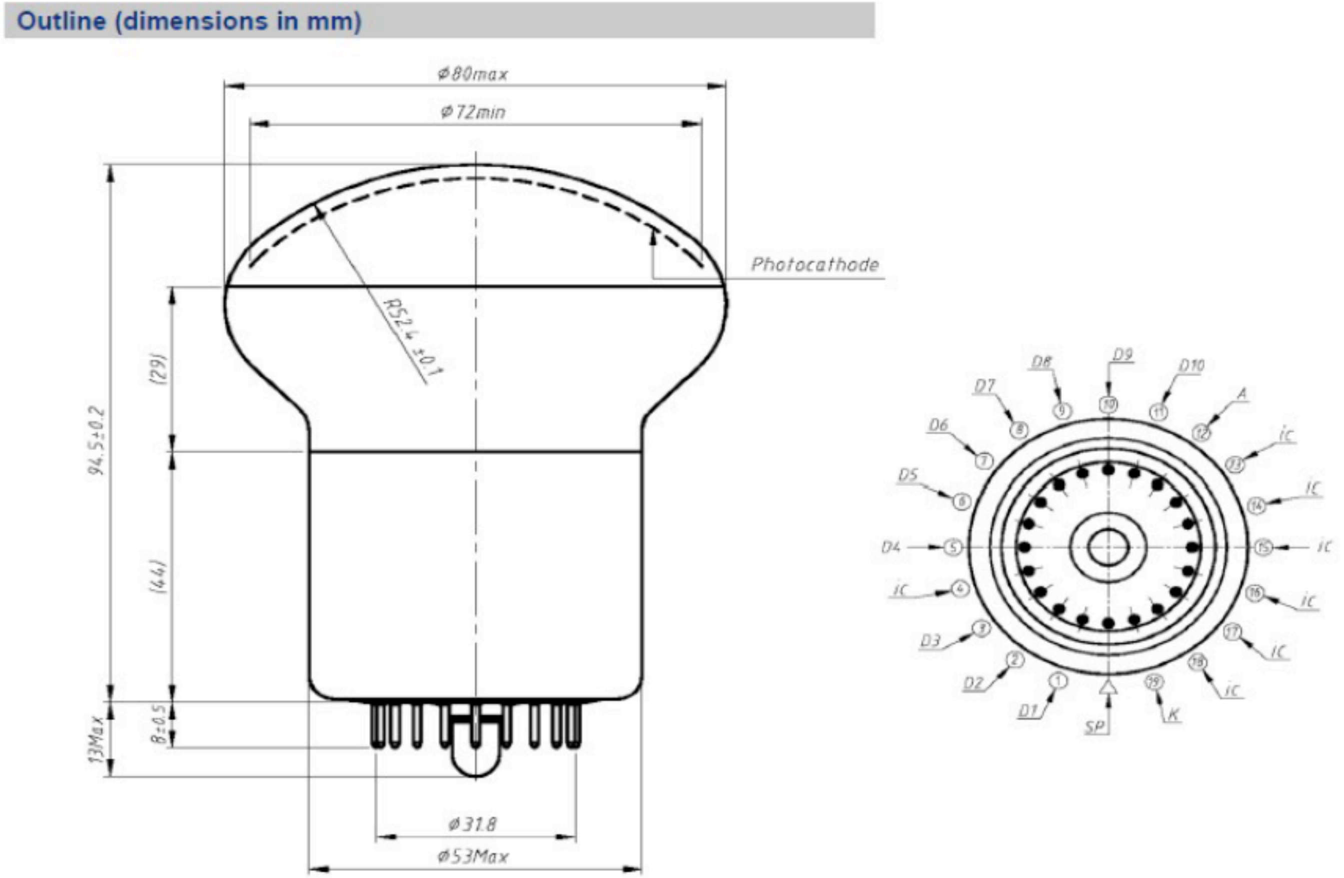
Some preliminary estimates for an IBD like CC

Conclusions

- The JUNO experiment is on course to start operations within next few years
- The collaboration is mostly focusing on designing and building the experiment
  - not much focus on analyses yet
  - especially those which depend crucially on low E bkgs, to be estimated better in situ
- With its unprecedented size and energy resolution, JUNO will complement nicely other scintillator measurements of solar fluxes
  - but several issues along the way
  - algorithmic studies to identify and reject bkgs on-going

Additional material

3’’ PMT status



Outline (dimensions in mm)

K: cathode
A: anode

sp: short pin
Dn: dynode

n: plane of symmetry of the multiplier
ic: internal connection

- Bidding *completed* and 26k XP72B22 ordered from HZC-Photonics
- custom-made: new development with improved TTS (based on KM3Net design)

E_{res}: calibremus, calibremus, calibremus...

- Keeping uncertainty on energy scale < 1% crucial to keep total σ(E)/E~3% at 1 MeV
  - uniformly in the detector
- JUNO envisaged complementary methods for E response determination across detector and for various energy loss mechanisms

- 1D: Automatic Calibration Unit (ACU)

→ along z axis

- 2D: Cable Loop System (CLS)

→ over vertical planes by means of pulleys

- Guide Tube Calibration System (GTCS)

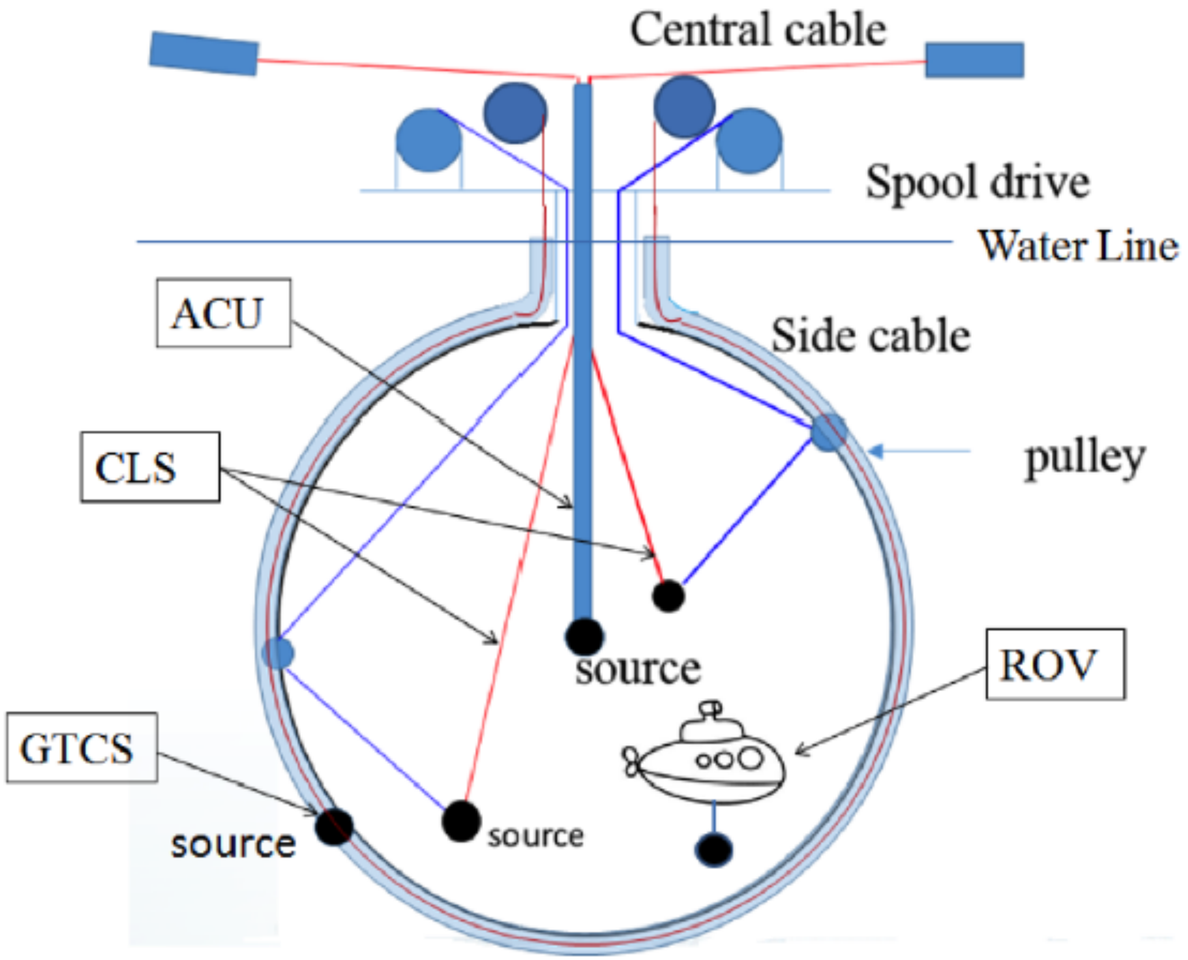
→ to probe outer CD surface

- 3D: Remotely Operated under-LS Vehicle (ROV)

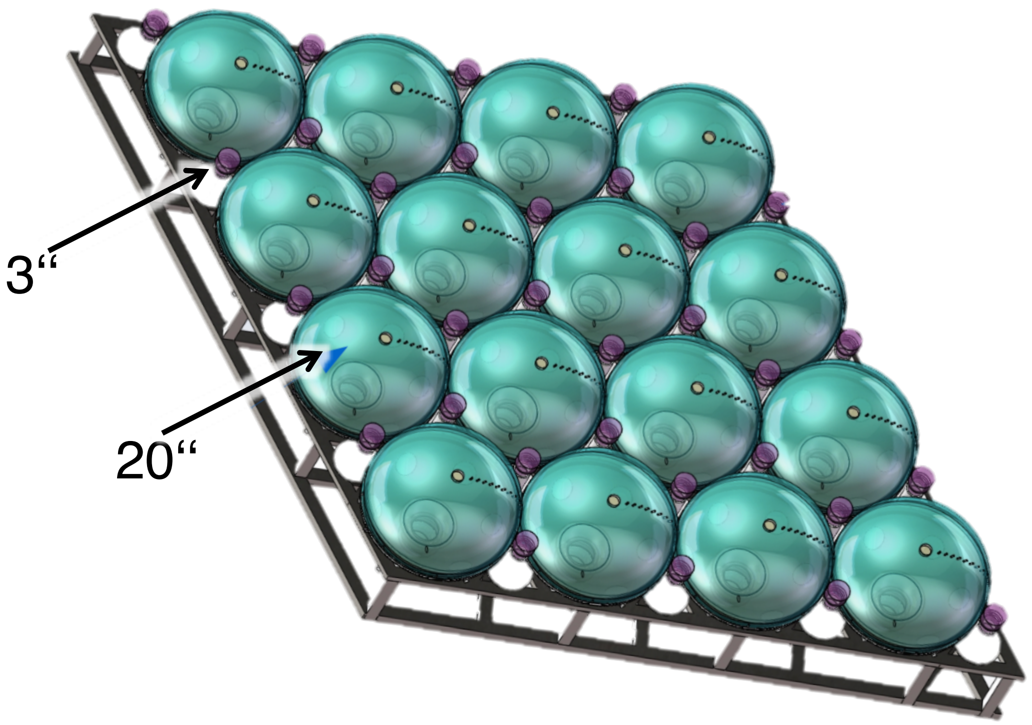
→ whole detector volume scanned

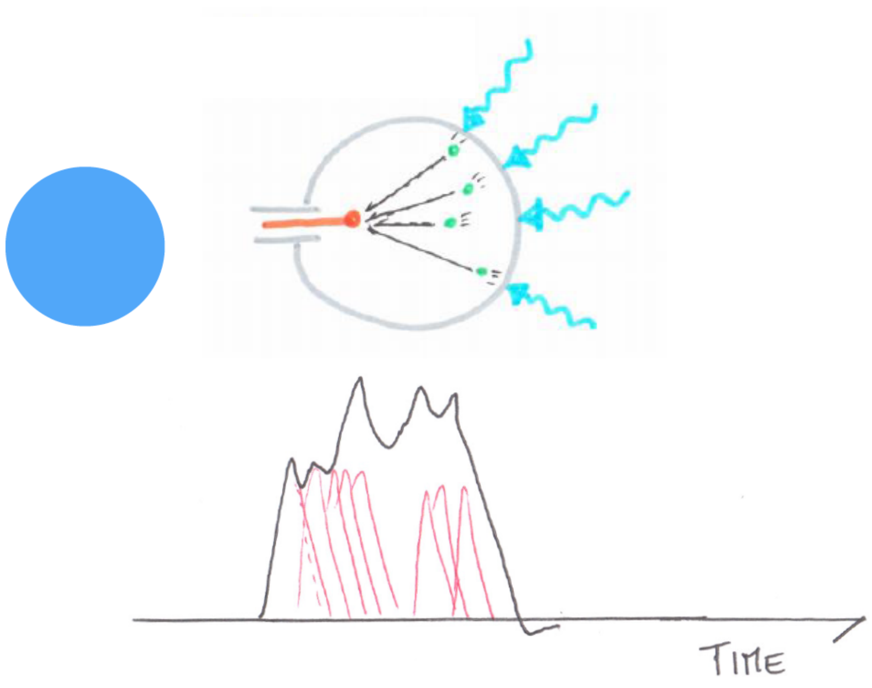
Using known radio-active sources:

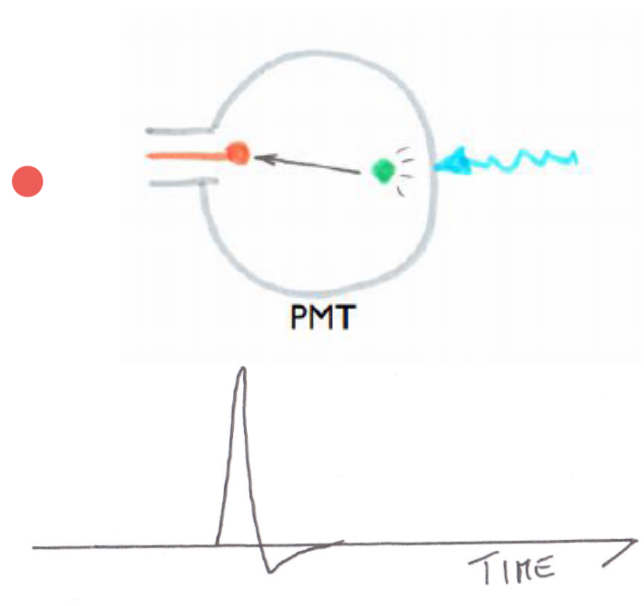
- ^{40}K, ^{54}Mn, ^{60}Co, ^{137}Cs (γ)
- ^{22}Na, ^{68}Ge, (e^{+})
- ^{241}Am-Be, ^{241}Pu-^{13}C, ^{241}Am-^{13}C (n)



Dual read-out







✓ 75% photo-coverage and collects ~1200 p.e./MeV

➡ but depending on event E and position, PMT could be "flooded" by p.e. and waveform saturate

→ loss of linearity

➡ and large cathode → high dark rate

➡ 2.5% photo-coverage and collects ~50 p.e./MeV

✓ but operating in photon counting mode allows for complementary, unbiased event E determination

✓ and lower dark rate

- ❋ *Multi-calorimetric approach* reduces non-stochastic terms ("systematics") in the energy resolution dependence (≤ 3% @ 1MeV in total)
- ❋ allows to extend the dynamical range in N(p.e.)
- ❋ and improve time and vertex resolution for muon reconstruction (showers saturate 20" PMT)

JUNO's MH reach

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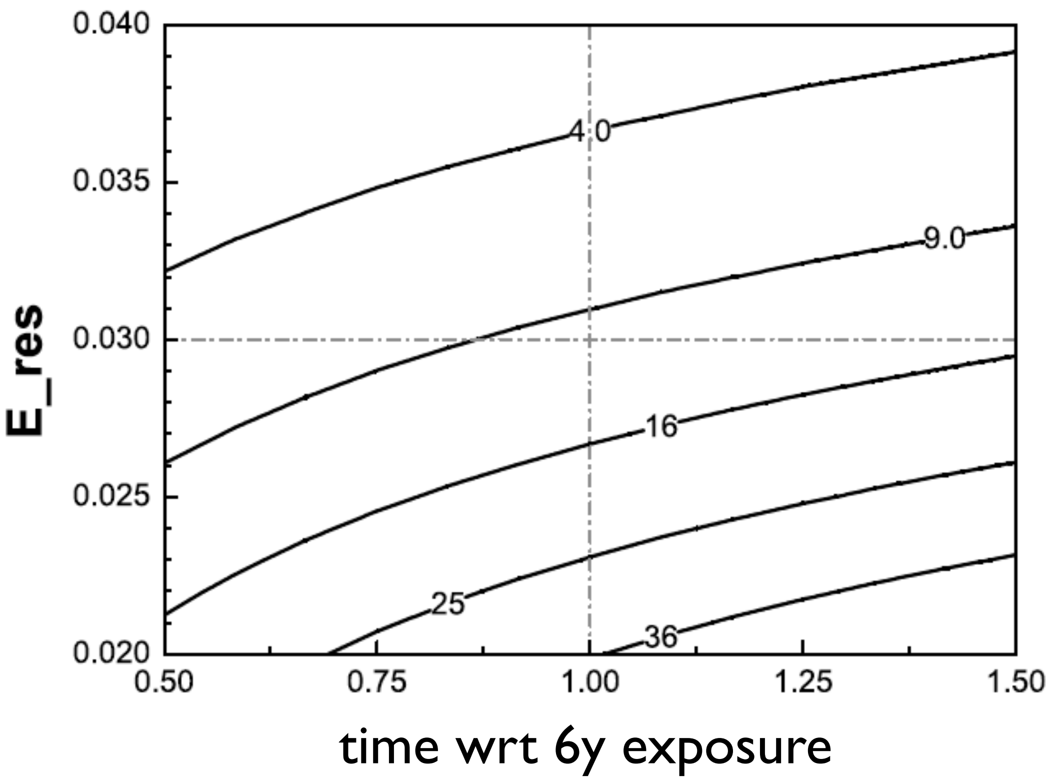
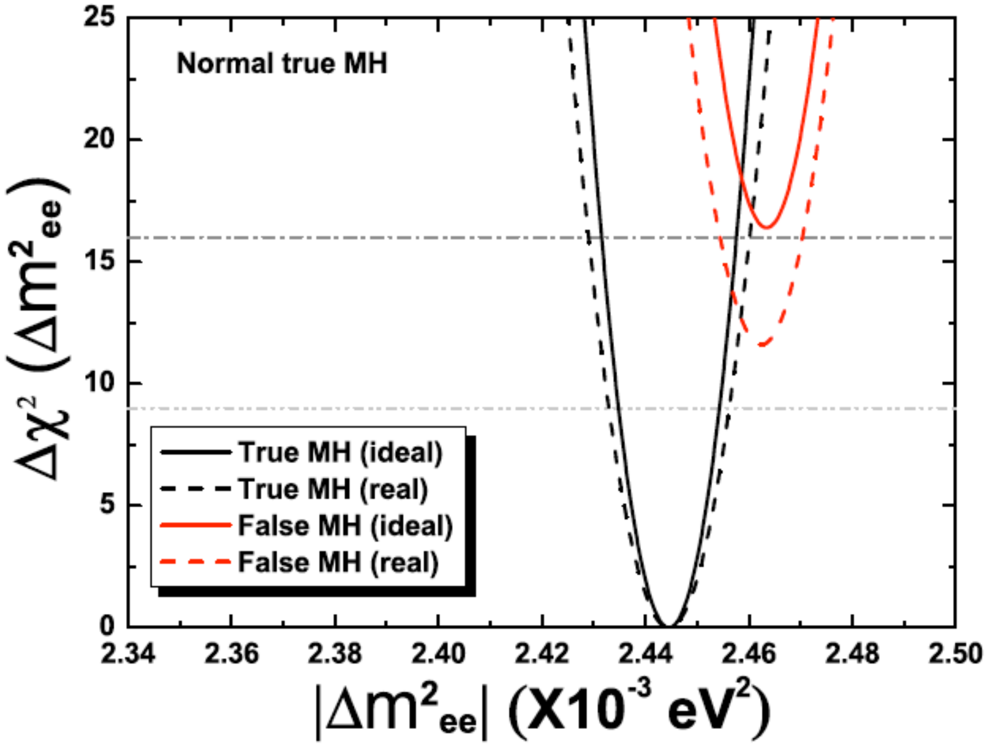
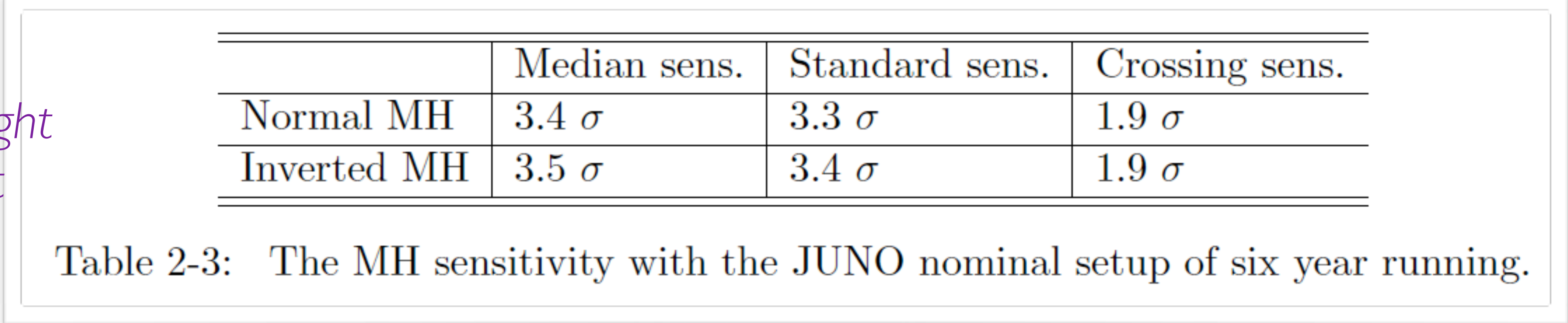
higher photo-statistics, smaller syst effects





**assumes 36 GW, might be 26 GW at start*



	Median sens.	Standard sens.	Crossing sens.
Normal MH	3.4 σ	3.3 σ	1.9 σ
Inverted MH	3.5 σ	3.4 σ	1.9 σ

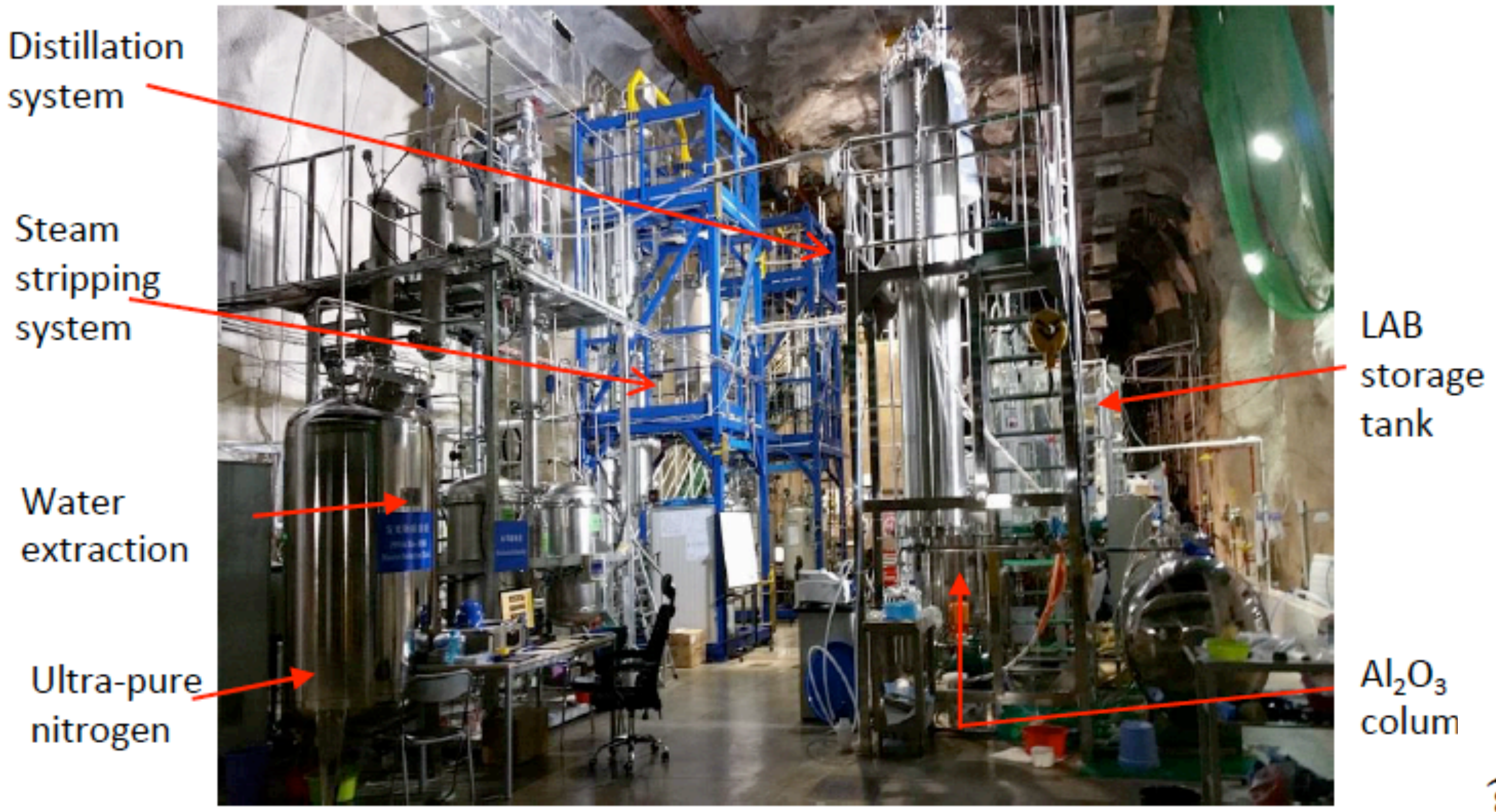
Table 2-3: The MH sensitivity with the JUNO nominal setup of six year running.

- "Success" depends on keeping linearity and uniformity of E response under control
- Not only stochastic term: it can be shown that constant term b has more impact on MH sensitivity than a
  - ➡ *non-uniformity of response in 20 KTon = challenge!*

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

Scintillator purification: tests

- Pilot plant in the Daya Bay LS hall and has run in Feb-Mar '17
    - filled Daya Bay detector with sample LAB and purified with alumina
    - optimization of fluorescent material to get the final "cocktail"



goal A.L. attained as result of purification, after "realistic operations"