Status and physics potential of the JUNO experiment

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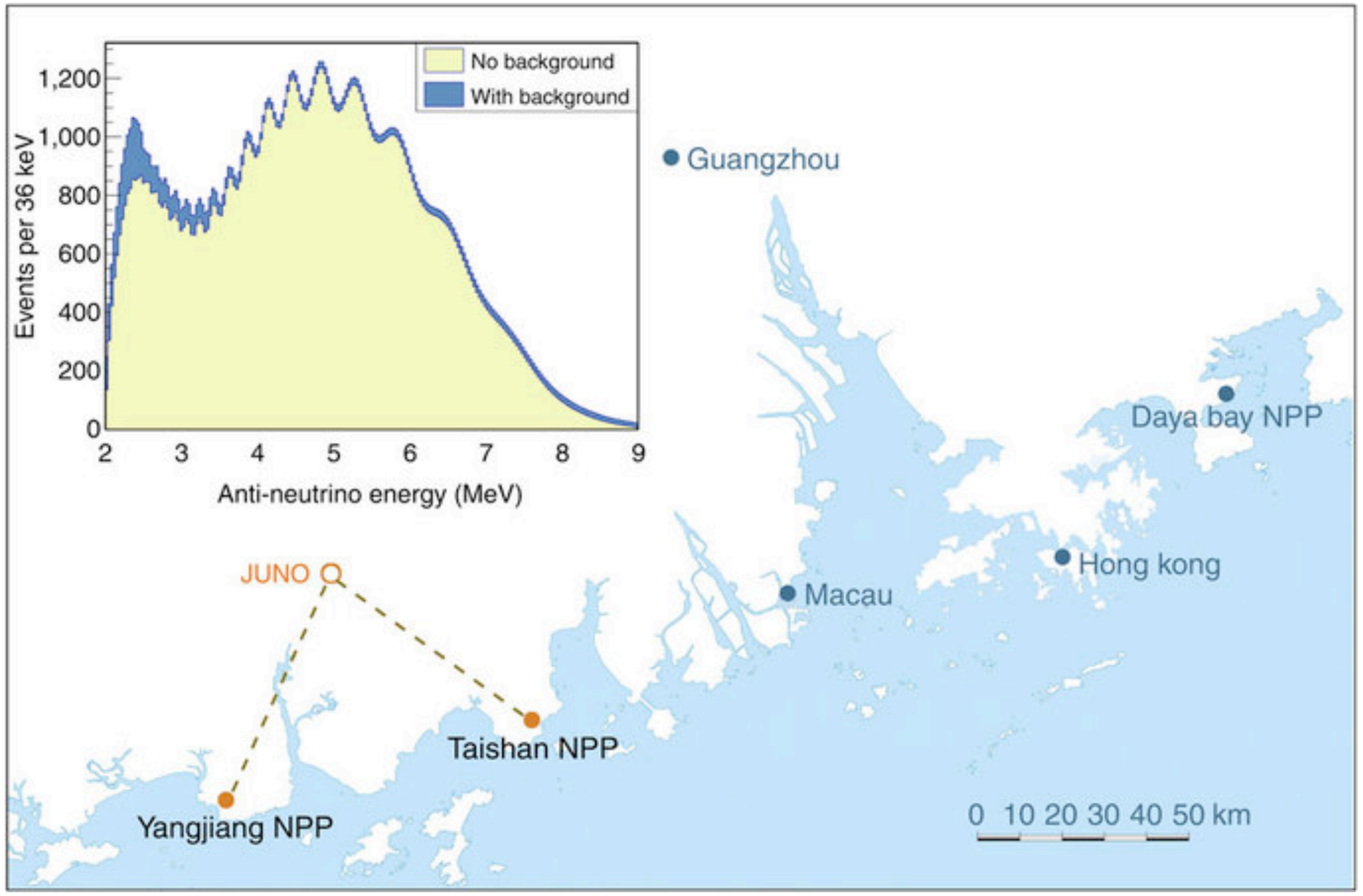
JUNO

- The Jiangmen Underground Neutrino Observatory in China
- Anti-neutrino reactor experiment
  - at a distance (~50 km) from 2 power plants
  - Facility and detector construction: 2015-20
  - expected starting date for data taking: end 2020

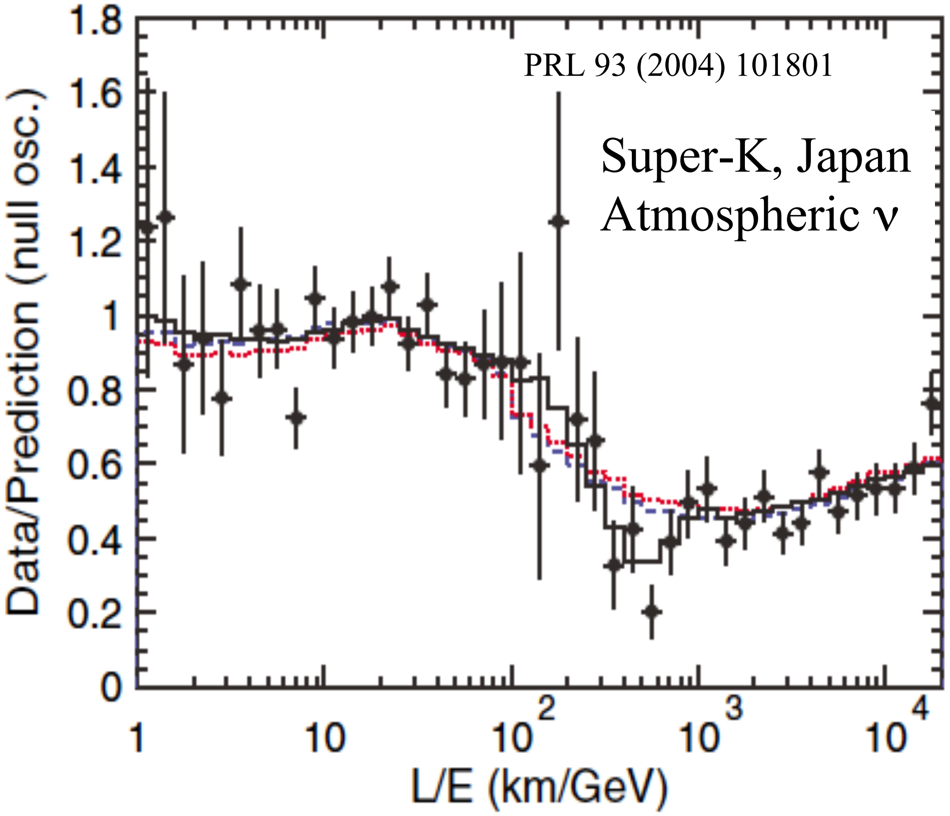


	Yangjiang	Taishan
Exp. Power$_{Th}$	17.4 GW	18.4 GW
Exp. N of cores	6	4

- total thermal power available by 2020: 26.6 GW

What drives the detector design?

Neutrino flavour oscillations



- We know since ~20 years that neutrinos oscillate
- This can only happen if at least 2 of the 3 flavours of neutrinos <u>have a mass</u>

t=0 $$|\nu(t=0)\rangle = |\nu_\mu\rangle = U_{\mu 1}\,|\nu_1\rangle + U_{\mu 2}\,|\nu_2\rangle + U_{\mu 3}\,|\nu_3\rangle$$

t>0 $$|\nu(t>0)\rangle = U_{\mu 1}\,e^{-iE_1 t}\,|\nu_1\rangle + U_{\mu 2}\,e^{-iE_2 t}\,|\nu_2\rangle + U_{\mu 3}\,e^{-iE_3 t}\,|\nu_3\rangle \neq |\nu_\mu\rangle$$

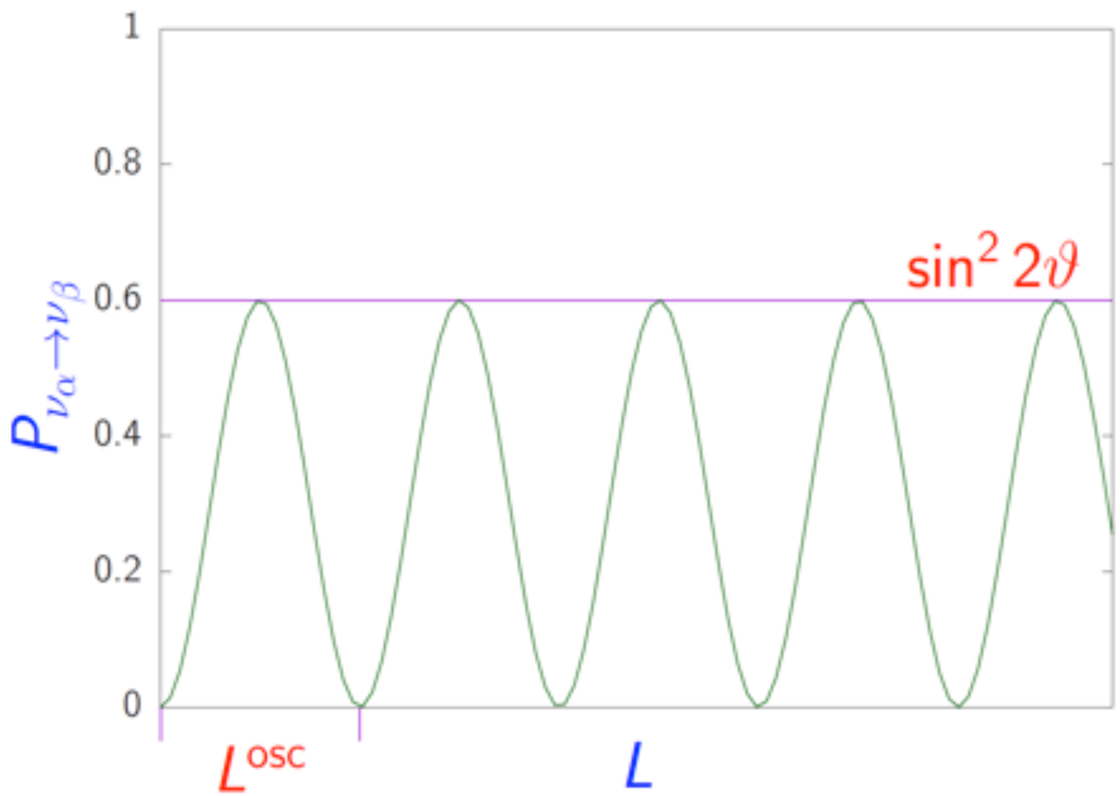
$$E_k^2 = p^2 + m_k^2$$

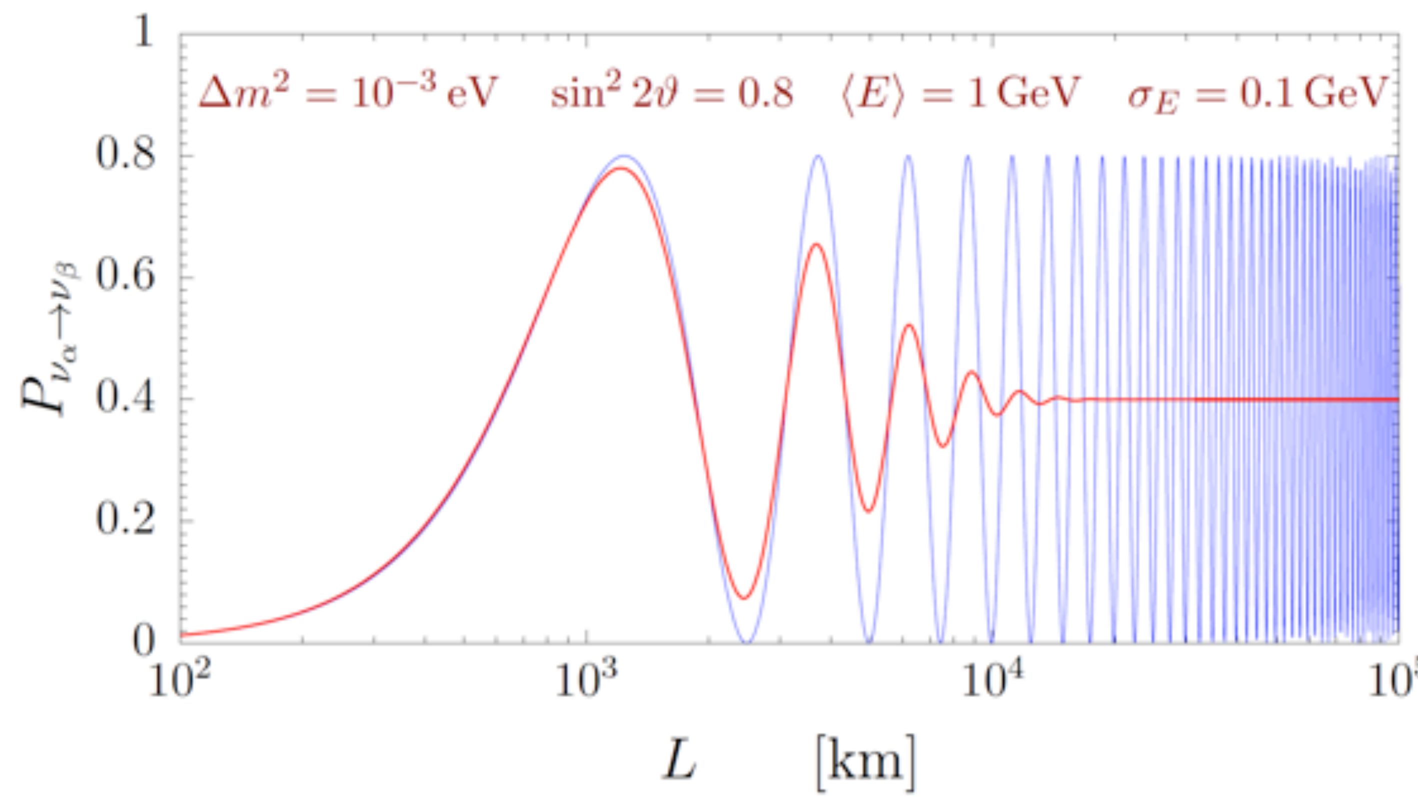
$$P_{\nu_\mu \to \nu_e}(t>0) = |\langle \nu_e | \nu(t>0)\rangle|^2 \sim \sum_{k>j} \mathrm{Re}\left[U_{ek}\,U_{\mu k}^*\,U_{ej}^*\,U_{\mu j}\right] \sin^2\left(\frac{\Delta m_{kj}^2 L}{4E}\right)$$

transition probabilities depend on U and $\Delta m_{kj}^2 \equiv m_k^2 - m_j^2$

$$\begin{array}{cccc} \nu_e \to \nu_\mu & \nu_e \to \nu_\tau & \nu_\mu \to \nu_e & \nu_\mu \to \nu_\tau \\ \bar{\nu}_e \to \bar{\nu}_\mu & \bar{\nu}_e \to \bar{\nu}_\tau & \bar{\nu}_\mu \to \bar{\nu}_e & \bar{\nu}_\mu \to \bar{\nu}_\tau \end{array}$$

2ν-mixing: $P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\vartheta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \implies \boxed{L^{\text{osc}} = \frac{4\pi E}{\Delta m^2}}$





Tiny neutrino masses lead to observable macroscopic oscillation distances!

$$\frac{L}{E} \lesssim \begin{cases} 10\,\frac{\text{m}}{\text{MeV}}\,\left(\frac{\text{km}}{\text{GeV}}\right) & \text{short-baseline experiments} & \Delta m^2 \gtrsim 10^{-1}\,\text{eV}^2 \\ 10^3\,\frac{\text{m}}{\text{MeV}}\,\left(\frac{\text{km}}{\text{GeV}}\right) & \text{long-baseline experiments} & \Delta m^2 \gtrsim 10^{-3}\,\text{eV}^2 \\ 10^4\,\frac{\text{km}}{\text{GeV}} & \text{atmospheric neutrino experiments} & \Delta m^2 \gtrsim 10^{-4}\,\text{eV}^2 \\ 10^{11}\,\frac{\text{m}}{\text{MeV}} & \text{solar neutrino experiments} & \Delta m^2 \gtrsim 10^{-11}\,\text{eV}^2 \end{cases}$$

Neutrino oscillations are the optimal tool to reveal tiny neutrino masses!

Three-Neutrino Mixing Paradigm

Standard Parameterization of Mixing Matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$c_{ab} \equiv \cos\vartheta_{ab}$ $\quad s_{ab} \equiv \sin\vartheta_{ab}$ $\quad 0 \leq \vartheta_{ab} \leq \frac{\pi}{2}$ $\quad 0 \leq \delta_{13}, \lambda_{21}, \lambda_{31} < 2\pi$

OSCILLATION PARAMETERS

- 3 Mixing Angles: $\vartheta_{12}, \vartheta_{23}, \vartheta_{13}$
- 1 CPV Dirac Phase: δ_{13}
- 2 independent $\Delta m^2_{kj} \equiv m^2_k - m^2_j$: $\Delta m^2_{21}, \Delta m^2_{31}$

2 CPV Majorana Phases: $\lambda_{21}, \lambda_{31} \iff |\Delta L| = 2$ processes

Current experimental knowledge

NuFIT 3.0 (2016)

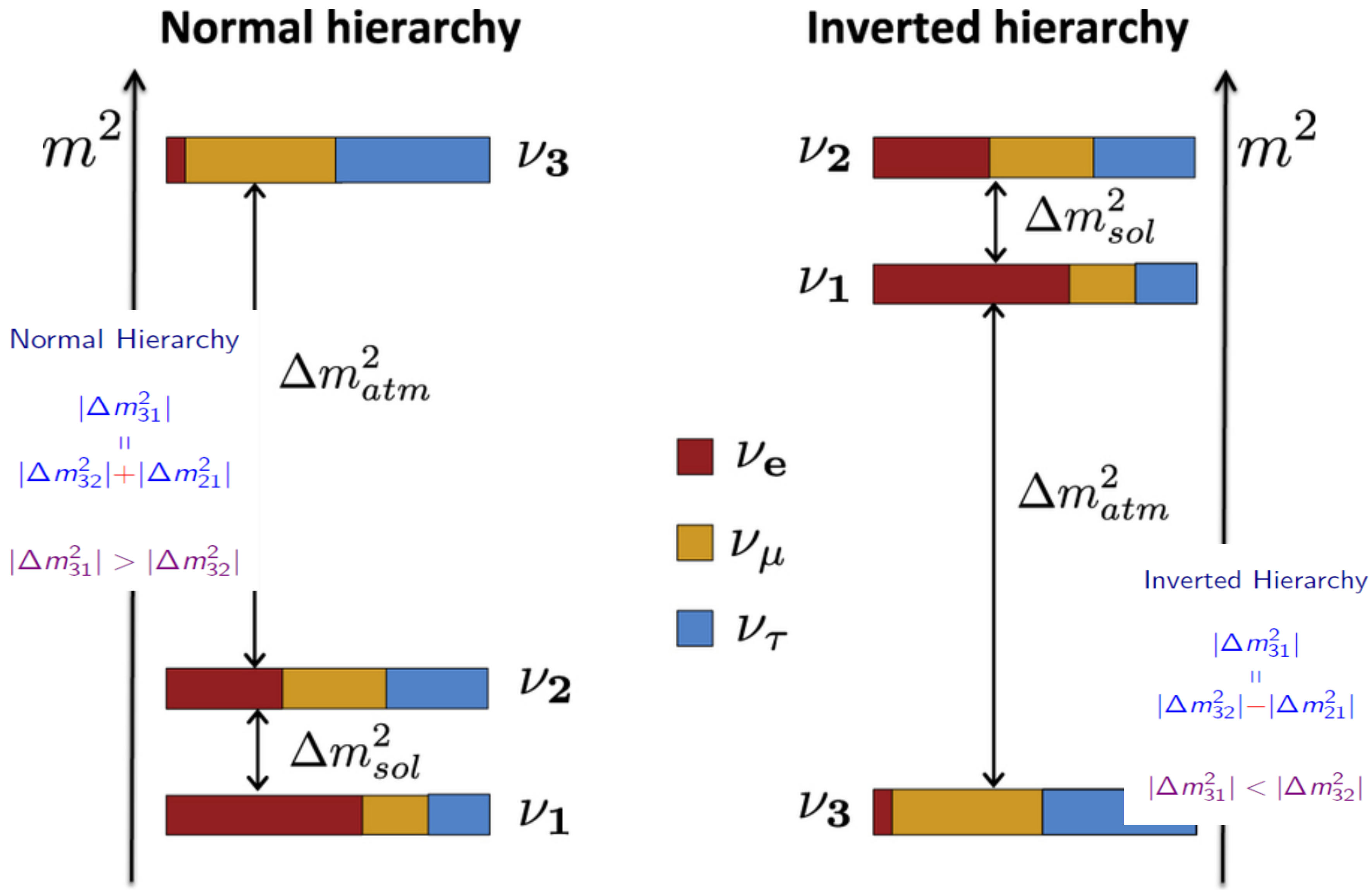
	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.83$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$	$0.587^{+0.020}_{-0.024}$	$0.393 \to 0.640$	$0.385 \to 0.638$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$	$50.0^{+1.1}_{-1.4}$	$38.8 \to 53.1$	$38.4 \to 53.0$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$	$0.02179^{+0.00076}_{-0.00076}$	$0.01953 \to 0.02408$	$0.01934 \to 0.02397$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$	$8.49^{+0.15}_{-0.15}$	$8.03 \to 8.93$	$7.99 \to 8.91$
$\delta_{\rm CP}/^\circ$	261^{+51}_{-59}	$0 \to 360$	277^{+40}_{-46}	$145 \to 391$	$0 \to 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \to -2.399$	$\begin{bmatrix}+2.407 \to +2.643 \\ -2.629 \to -2.405\end{bmatrix}$

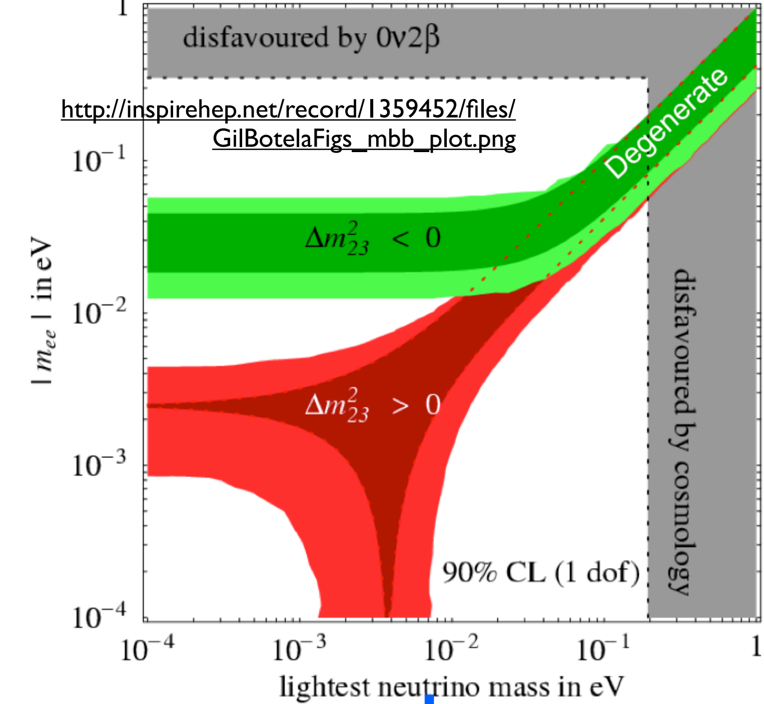
Three-flavor oscillation parameters from our fit to global data as of August 2016. The normalization of reactor fluxes is left free and data from short-baseline reactor experiments are included. The numbers in the 1st (2nd) column are obtained assuming NO (IO), *i.e.*, relative to the respective local minimum, whereas in the 3rd column we minimize also with respect to the ordering. Note that $\Delta m^2_{3\ell} = \Delta m^2_{31} > 0$ for NO and $\Delta m^2_{3\ell} = \Delta m^2_{32} < 0$ for IO.

Open Problems

- $\vartheta_{23} \lesseqgtr 45^\circ$?
  - T2K (Japan), NOνA (USA), ...
- CP violation ? $\delta_{13} \approx 3\pi/2$?
  - T2K (Japan), NOνA (USA), DUNE (USA), HyperK (Japan), ...
- Mass Ordering ?
  - JUNO (China), RENO-50 (Korea), PINGU (Antarctica), ORCA (EU), INO (India), ...

Let's focus on the mass ordering





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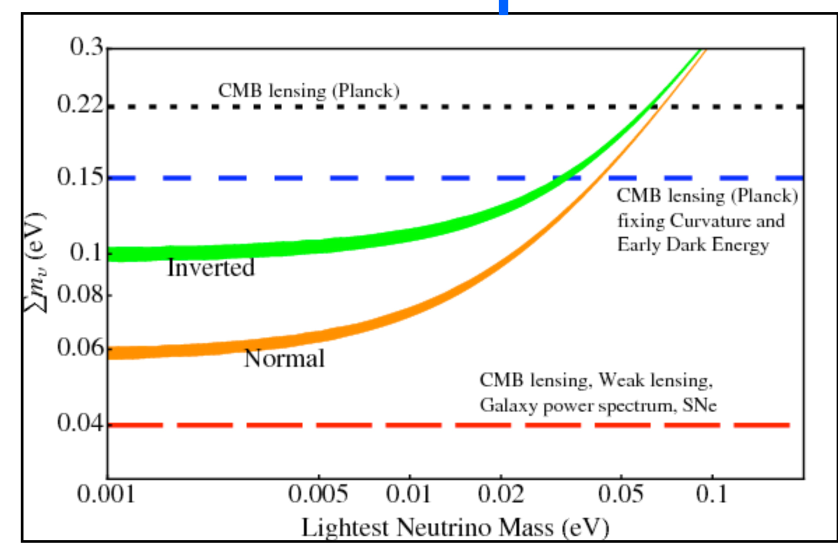

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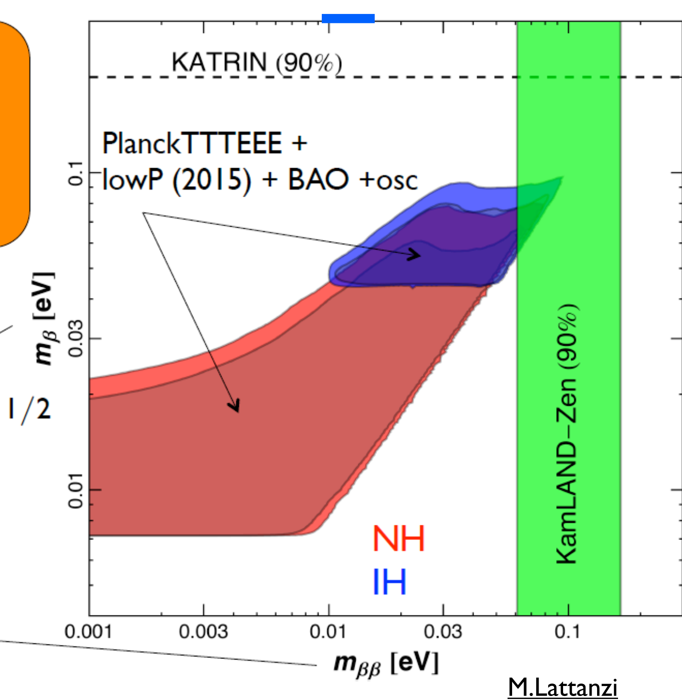
Cosmology constraints can be combined with data from oscillation experiments



$$m_\beta \equiv \left[\sum |U_{ei}|^2 m_i^2\right]^{1/2}$$

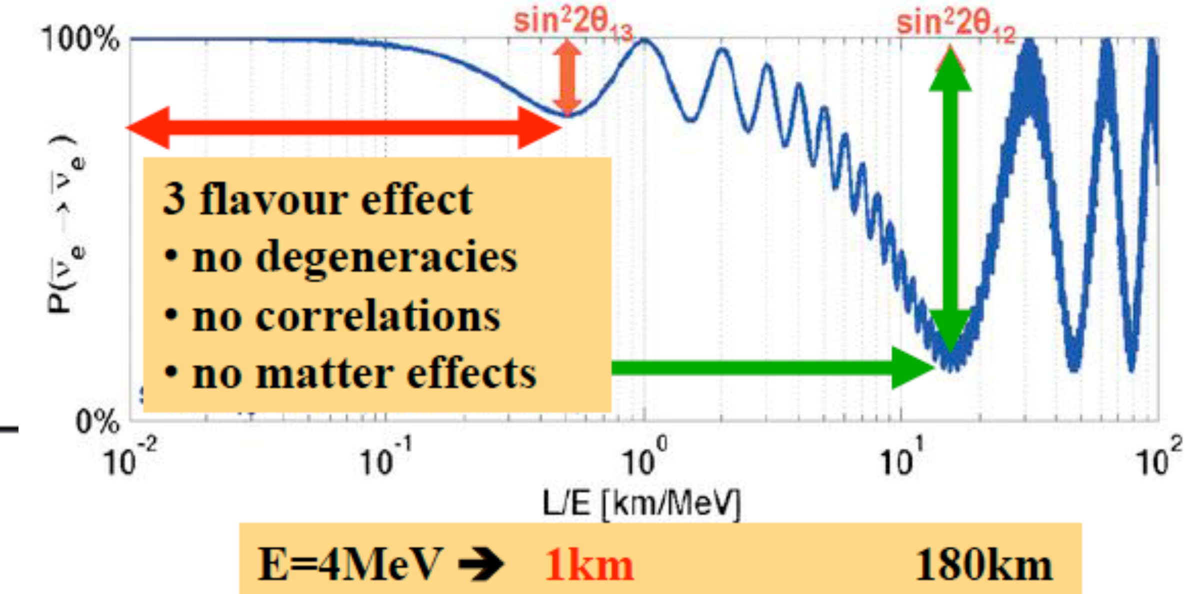
$$m_{\beta\beta} \equiv \left|\sum U_{ei}^2 m_i\right|$$

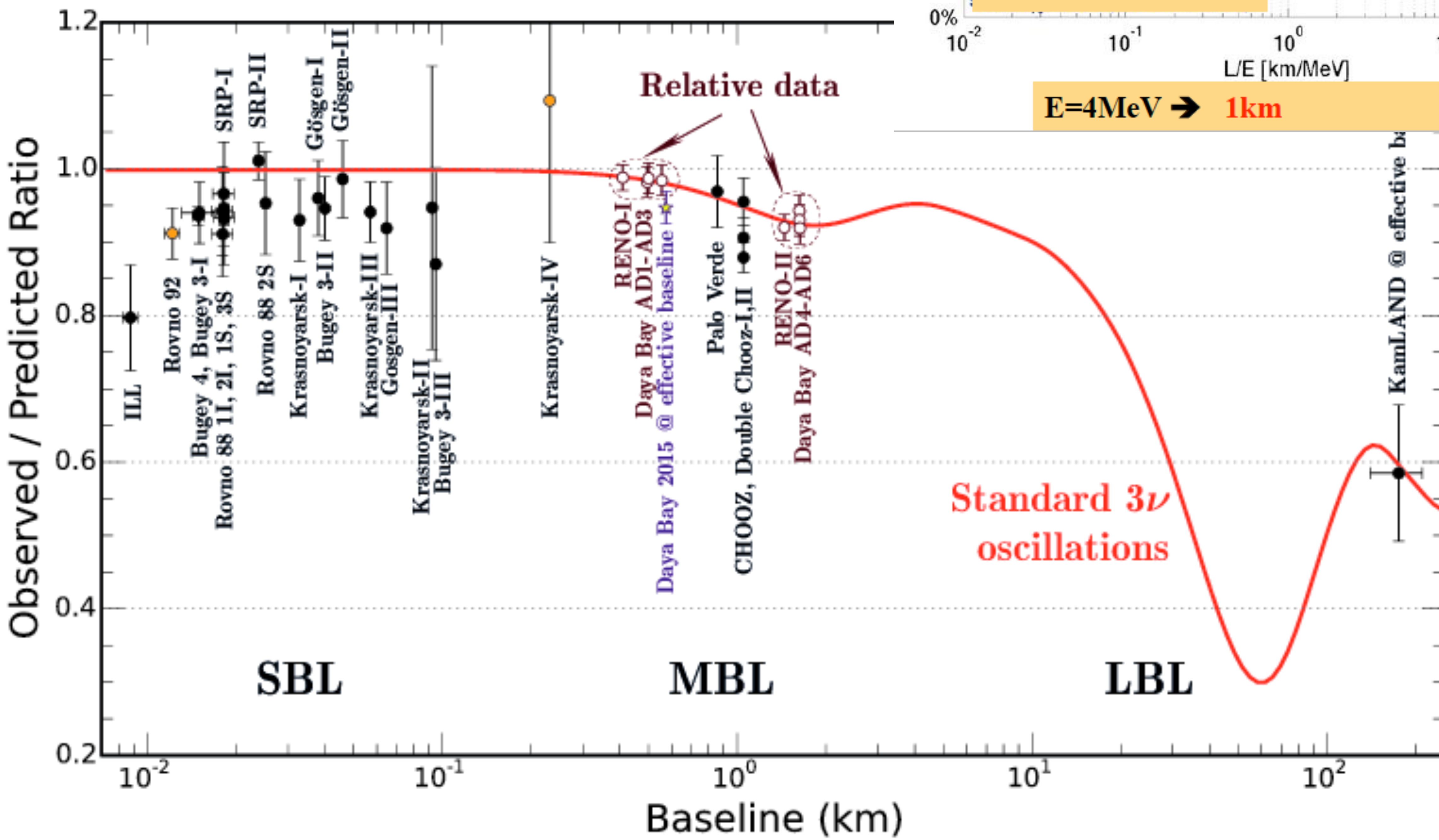
The ordering of the masses of neutrinos is important per se
and entangled with several other aspects e.g.

- their Dirac vs Majorana nature
- absolute masses and effect on early universe

Survival probability after mixing

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} - \left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)^2 \cos^4 \theta_{13} \sin^2 2\theta_{12}$$





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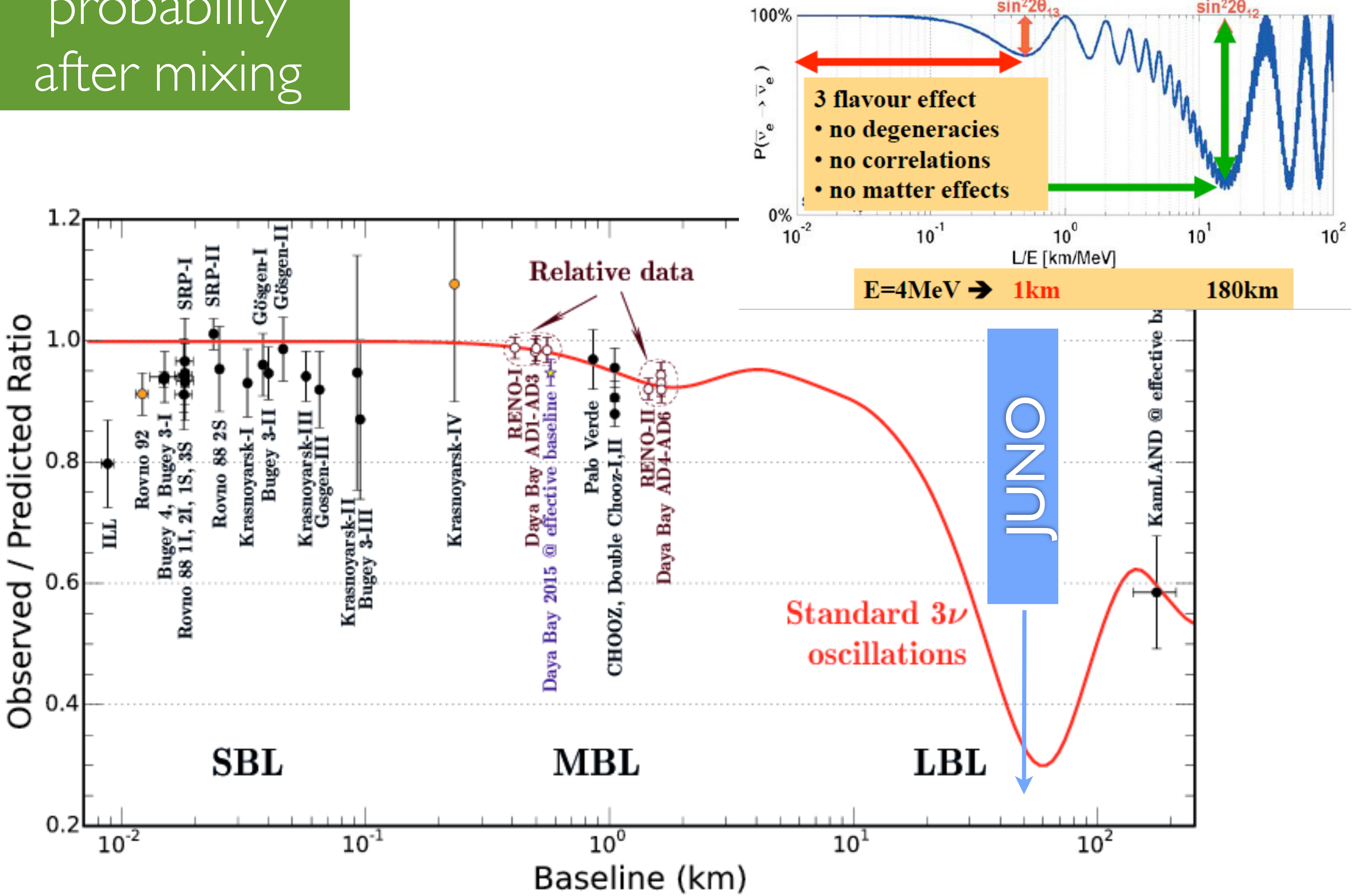
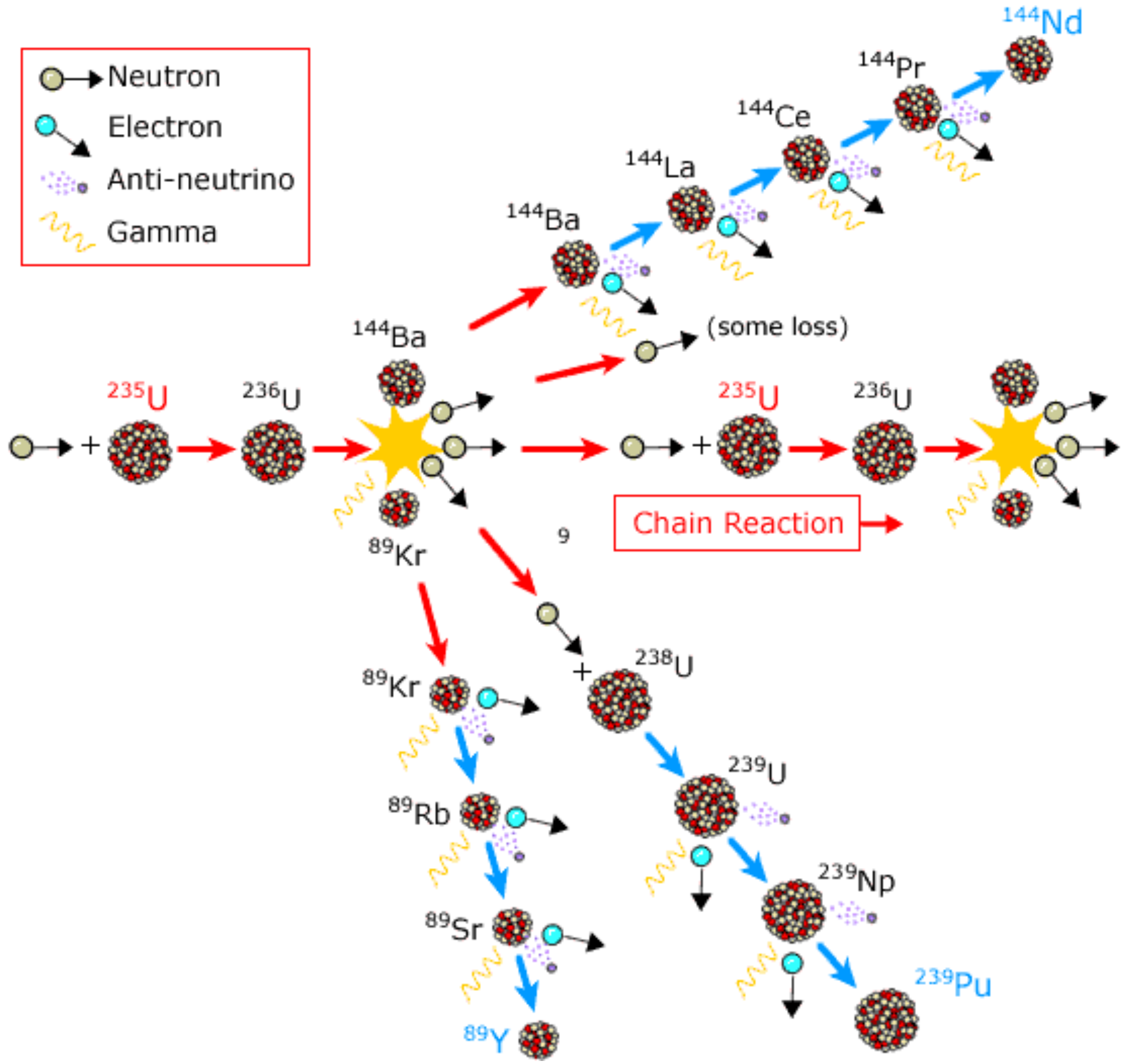
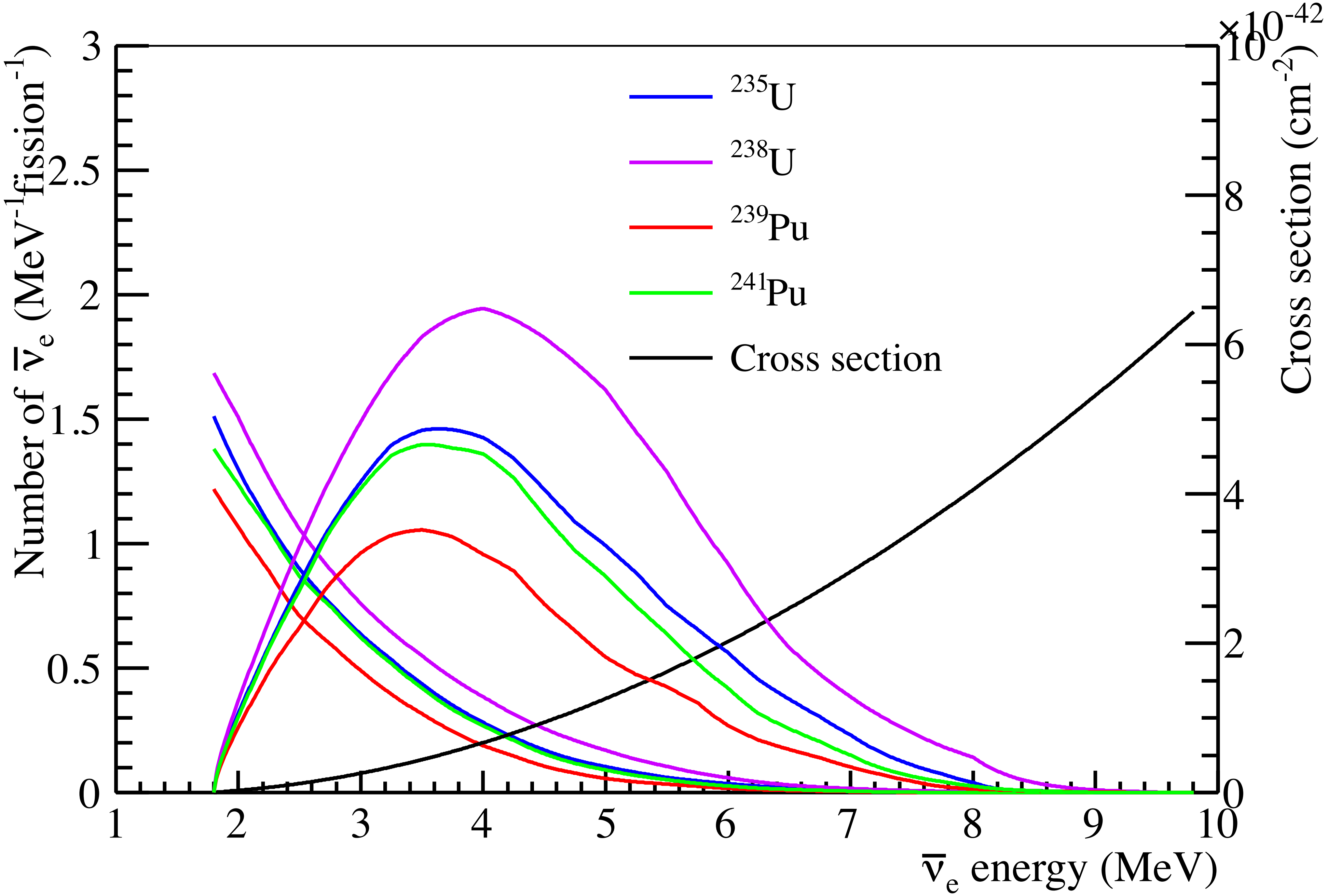


$\bar{\nu}_e$ production at reactors



typically about 10^{20}/s ν_e emitted

Flux



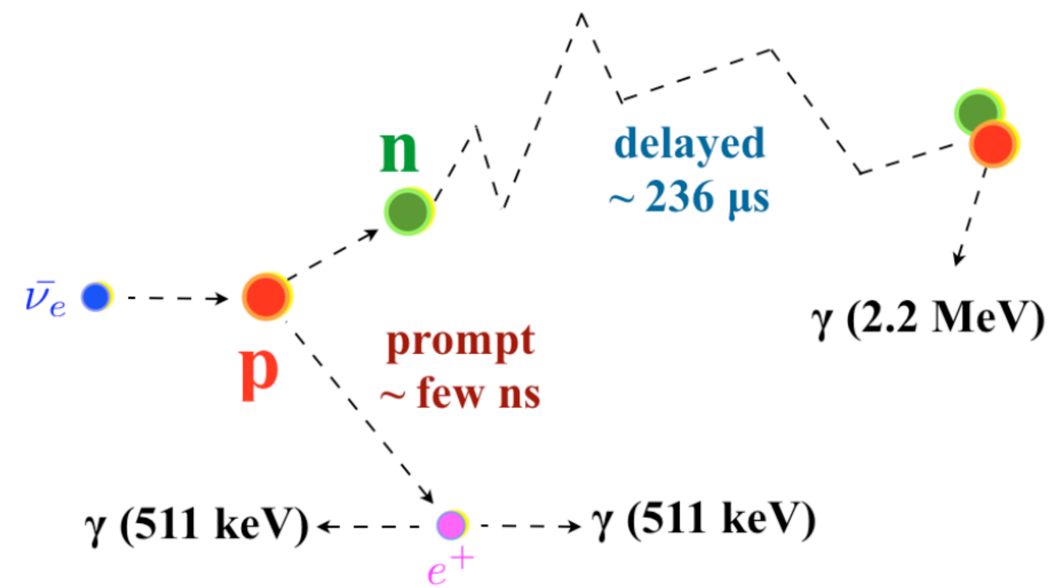
- **BUT: more than 800 nuclides from the fission of ^{235}U and others: ^{238}U, ^{239}Pu, ^{241}Pu, ...**
  → many instable fission products
  → reactor is during steady operation in a flow equilibrium

→

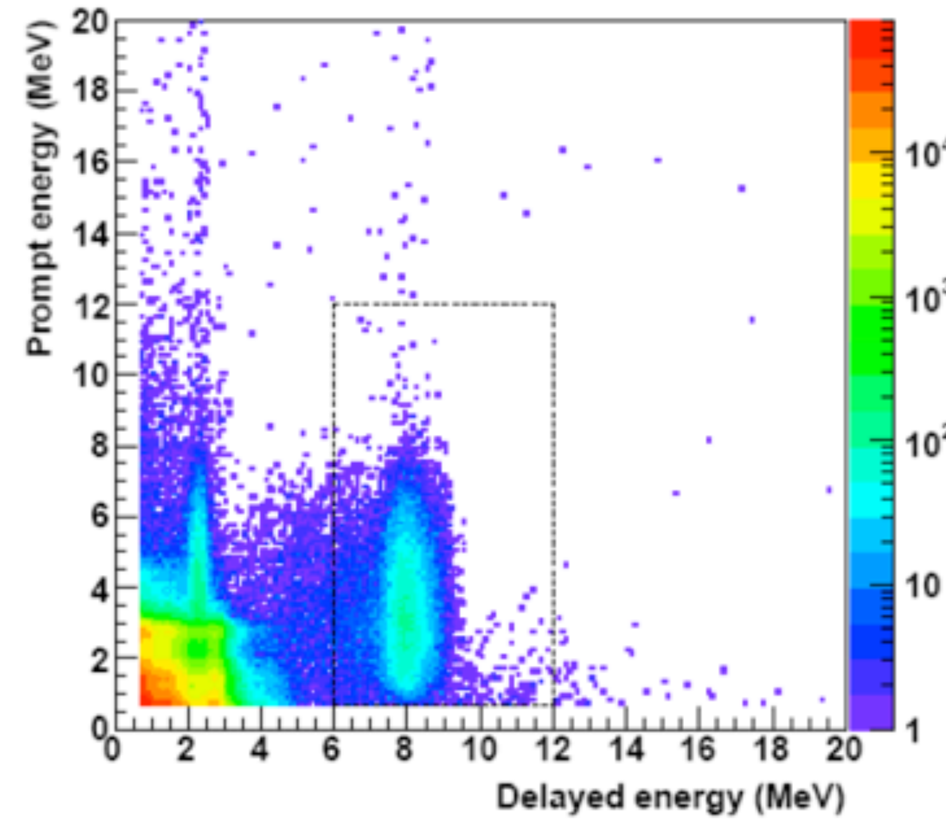
Uncertainties on the overall flux

Event Signature and Backgrounds

- **Signature:** $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Prompt: e^+, 1-10 MeV,
  - Delayed: n, 2.2 MeV@H, 8 MeV @ Gd



- **Backgrounds**
  - Uncorrelated: random coincidence of γγ, γn or nn
    - ✓ γ from U/Th/K/Rn/Co… in LS, SS, PMT, Rock, …
    - ✓ n from α-n, μ-capture, μ-spallation in LS, water & rock
  - Correlated:
    - ✓ Fast neutrons: n scattering - n capture
    - ✓ $^{8}He/^{9}Li$: β decay -n capture
    - ✓ Am-C source: γ rays - n capture
    - ✓ α-n: $^{13}C(\alpha,n)^{16}O$



Example from Daya Bay

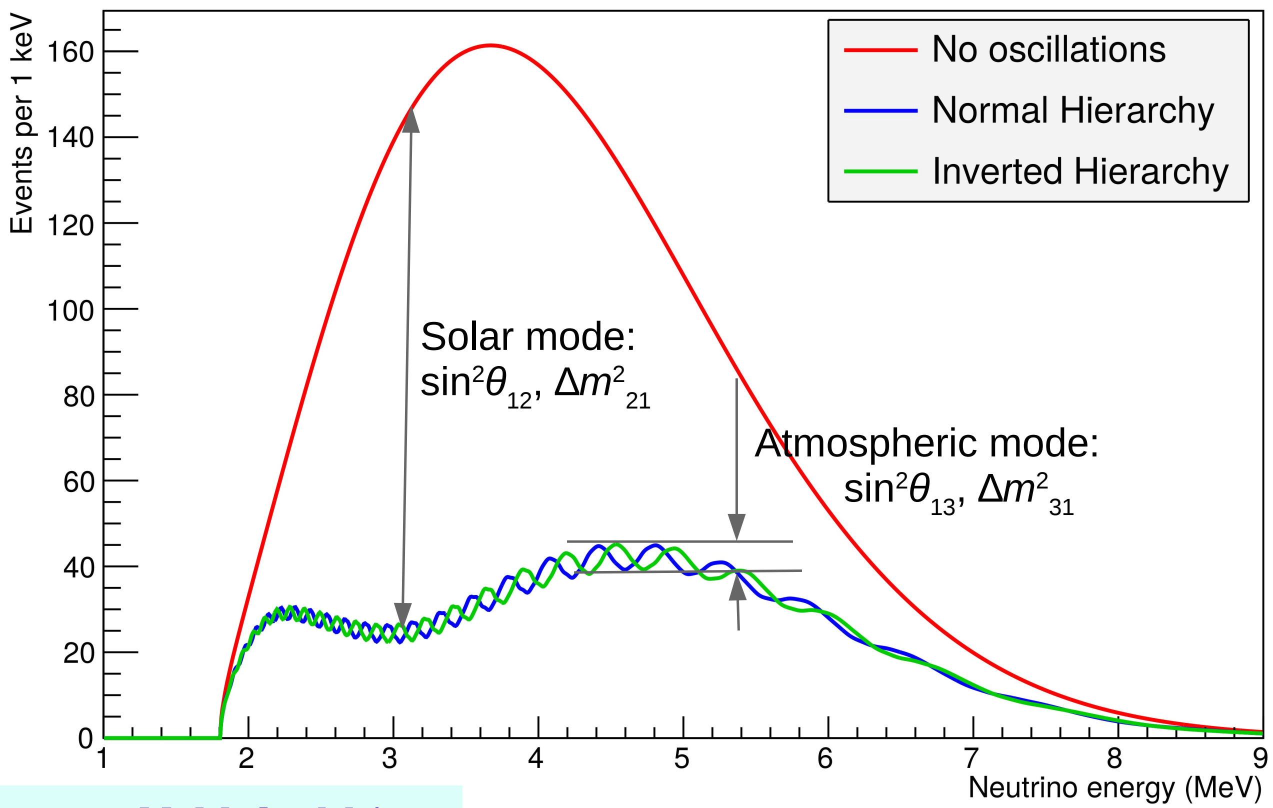
MH from reactors

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

+ NH
- IH

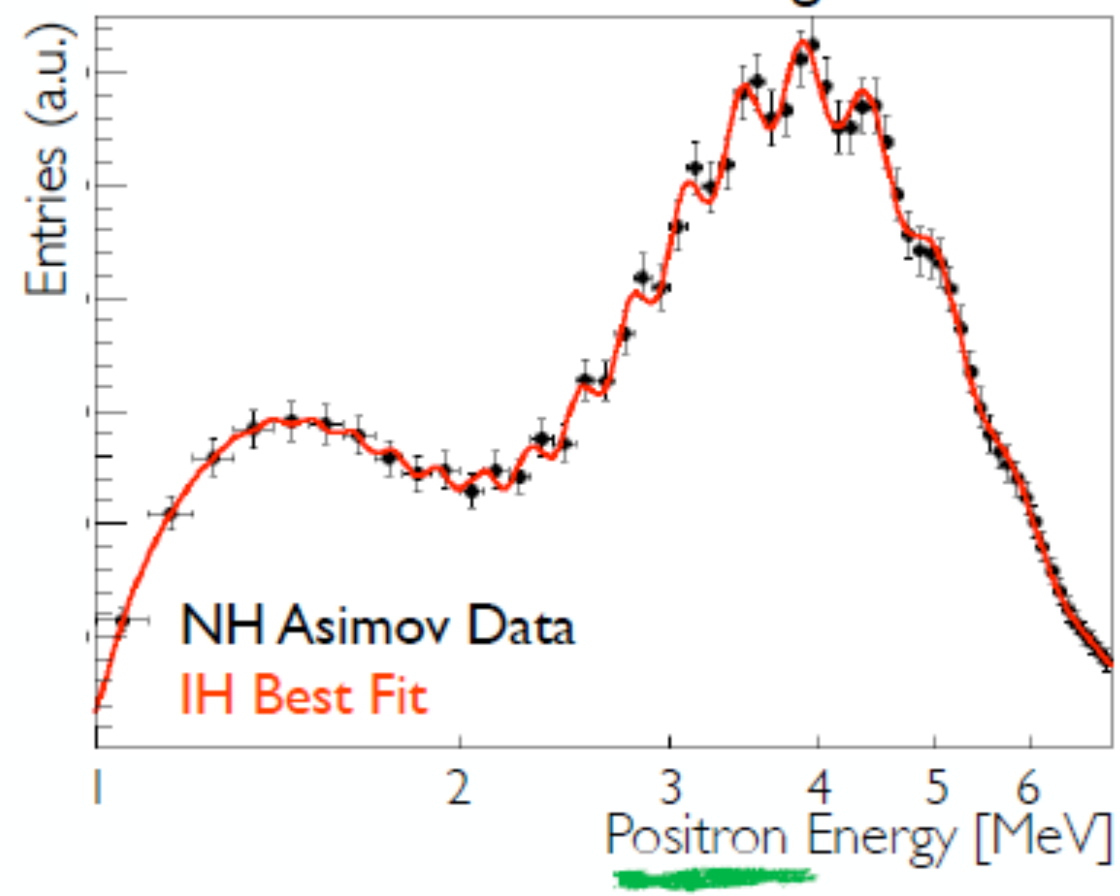
$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E_\nu}, \quad (\Delta m^2_{ij} \equiv m_i^2 - m_j^2)$$

survival probability at higher orders



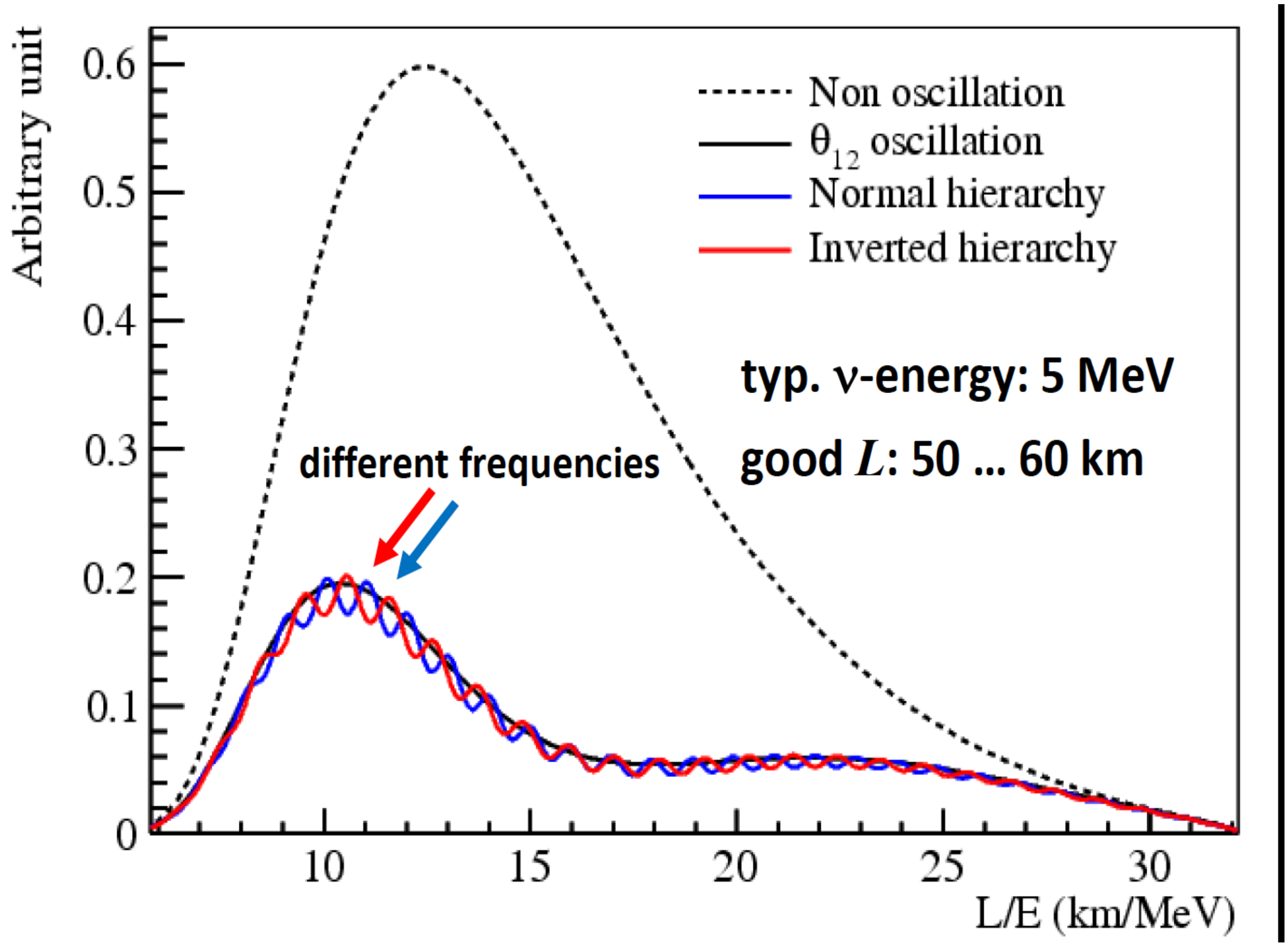
Courtesy **Y. Malyshkin**

Fit model against data



- JUNO will determine MH by reconstructing the E(**ν**) spectrum and fitting it with the two signs in the survival probability at fixed L
- *baseline* statistical method: $\Delta\chi^2_{min}$ of the two fits to disentangle the two mutually exclusive MH hypothesis (arXiv1210.8141)

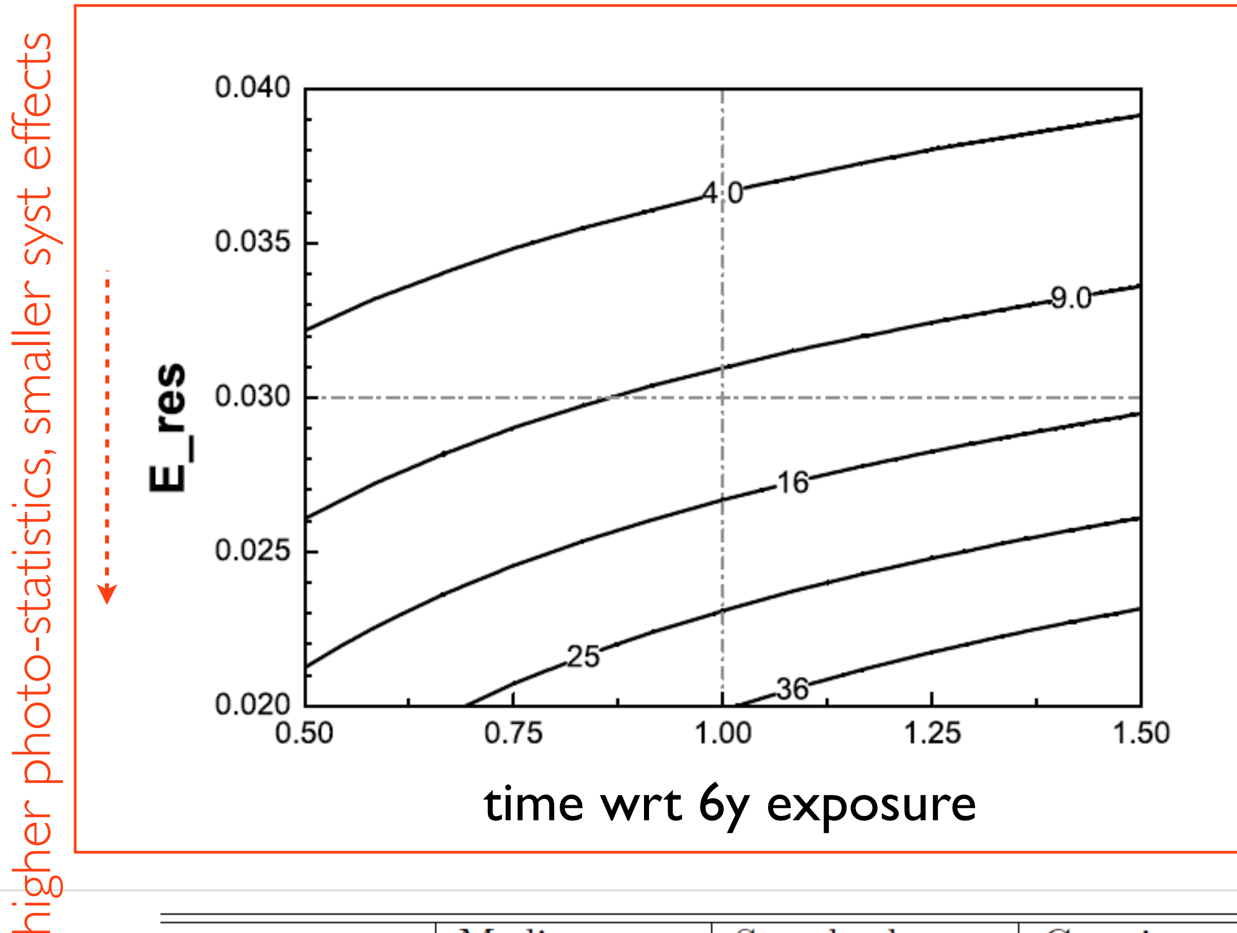
Main challenge: Energy resolution

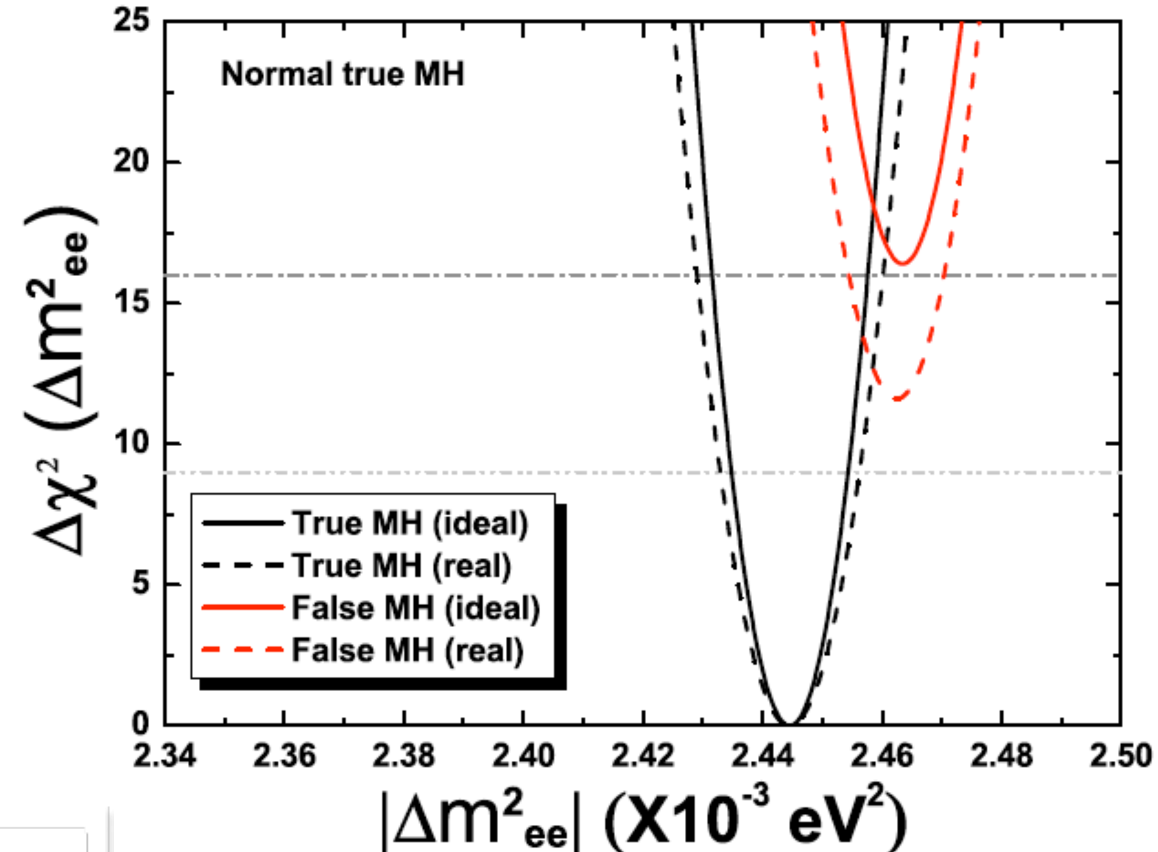


Because fitting involves separating the red vs blue curves with data, the single most important performance aspect will be the resolution on the energy measurement

JUNO's MH reach

J. Phys. G 43 (2016) 030401





	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.

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

- "Success" depends on keeping <u>linearity and uniformity of E response</u> 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!*

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

MH: facilities and prospects

An example of projections

JHEP 1403, 028 (2014)

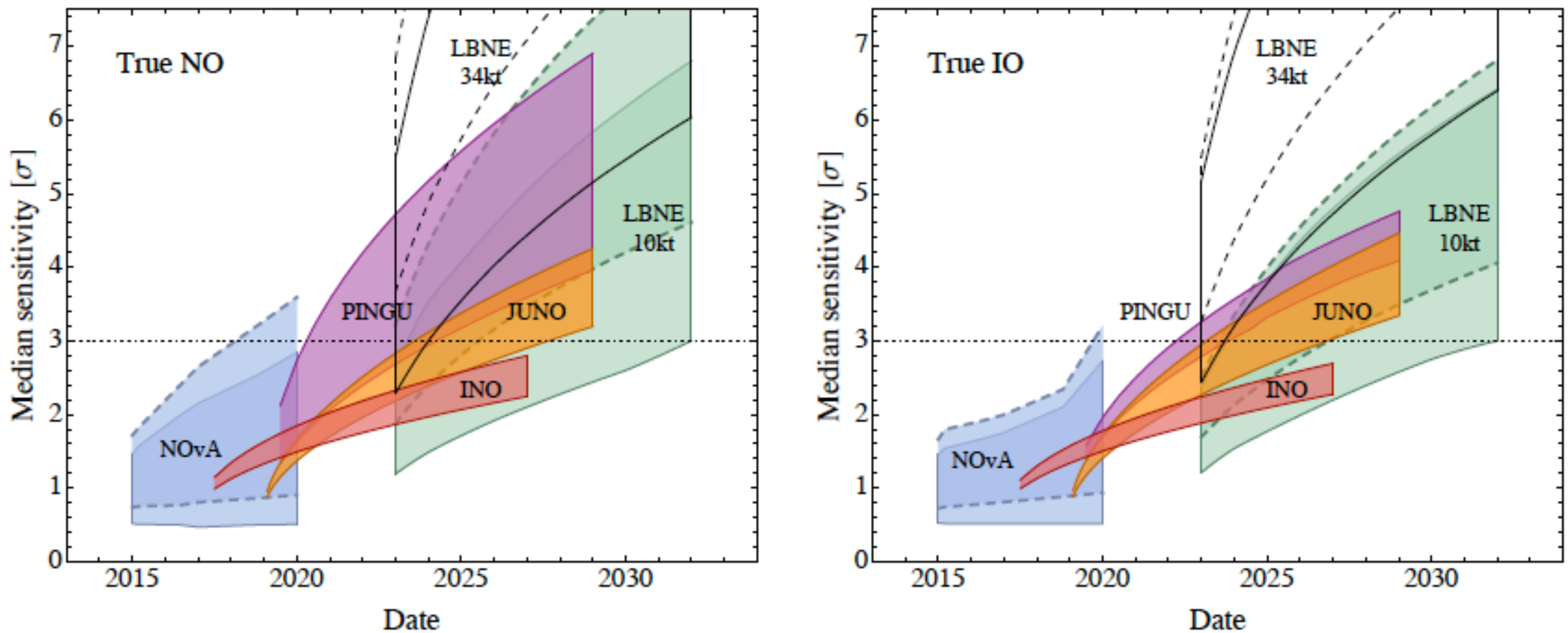


FIG. 12: The left (right) panel shows the median sensitivity in number of sigmas for rejecting the IO (NO) if the NO (IO) is true for different facilities as a function of the date. The width of the bands correspond to different true values of the CP phase δ for NOνA and LBNE, different true values of θ_{23} between 40° and 50° for INO and PINGU, and energy resolution between $3\%\sqrt{1\ \mathrm{MeV}/E}$ and $3.5\%\sqrt{1\ \mathrm{MeV}/E}$ for JUNO. For the long baseline experiments, the bands with solid (dashed) contours correspond to a true value for θ_{23} of 40° (50°). In all cases, octant degeneracies are fully searched for.

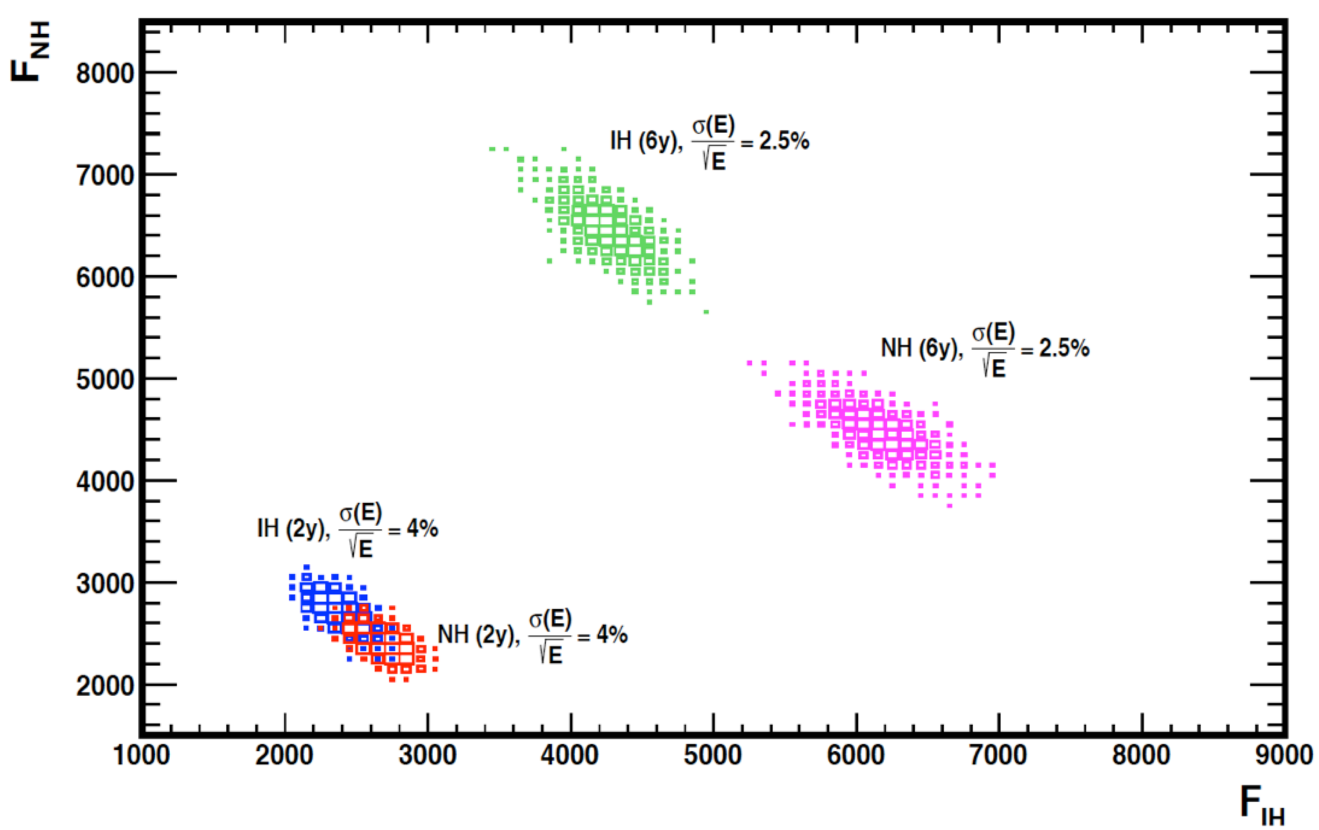
"A new way to determine the neutrino mass hierarchy at reactors"

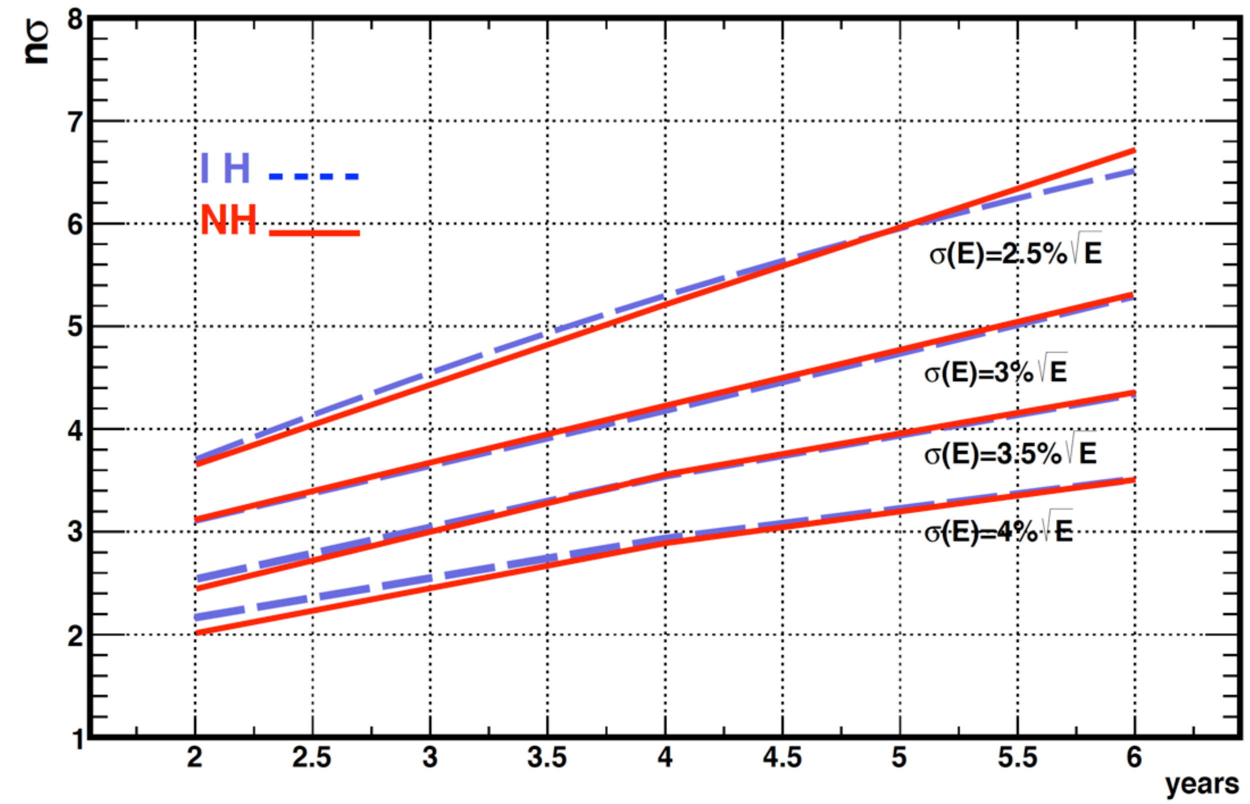
L.Stanco, G.S. et al, arXiv: 1707.07651v2 [hep-ph]

- $\Delta\chi^2$ not *a priori* best estimator; allows extracting from data also Δm^2_{atm} but fit could partially cancel discrimination power of data set
- A new estimator is proposed, with a well defined pdf, which counts and compares yields (no fit) extracted from same energy spectrum
  - "success" **still** depends on well known E response

$$
\begin{aligned}
F_{IH} &= \int_{1.8}^{8.0} (N_{obs} - N_{IH})\, dE_\nu \quad \text{in } I^+ \text{ when } N_{obs} > N_{IH} \quad (10)\\
&+ \int_{1.8}^{8.0} (N_{IH} - N_{obs})\, dE_\nu \quad \text{in } I^- \text{ when } N_{obs} < N_{IH}\\
F_{NH} &= \int_{1.8}^{8.0} (N_{obs} - N_{NH})\, dE_\nu \quad \text{in } I^+ \text{ when } N_{obs} > N_{NH} \quad (11)\\
&+ \int_{1.8}^{8.0} (N_{NH} - N_{obs})\, dE_\nu \quad \text{in } I^- \text{ when } N_{obs} < N_{NH}
\end{aligned}
$$

"Proof of principle" of method with some systematic uncertainties incl'd; not final performance





- New linear estimator promising in *decoupling* two MH at >5σ with 6y and E_{res}=3%
- but as-is identification depends on external input of Δm^2_{atm} : will need further developments

Oscillation parameters: projections

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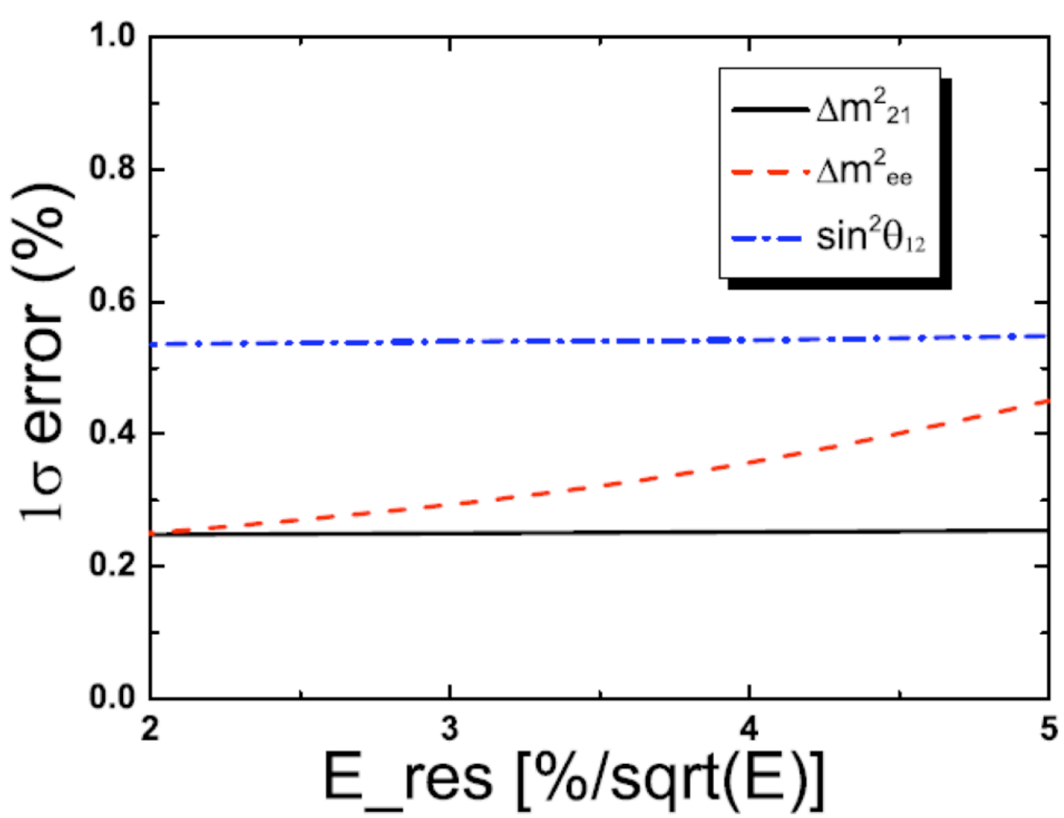
	Nominal	+ B2B (1%) ~reactor	+ BG ~radio and cosmo	+ EL (1%) E scale	+ NL (1%) E non uniformity
$\sin^2\theta_{12}$	0.54%	0.60%	0.62%	0.64%	0.67%
Δm^2_{21}	0.24%	0.27%	0.29%	0.44%	0.59%
$\lvert\Delta m^2_{ee}\rvert$	0.27%	0.31%	0.31%	0.35%	0.44%

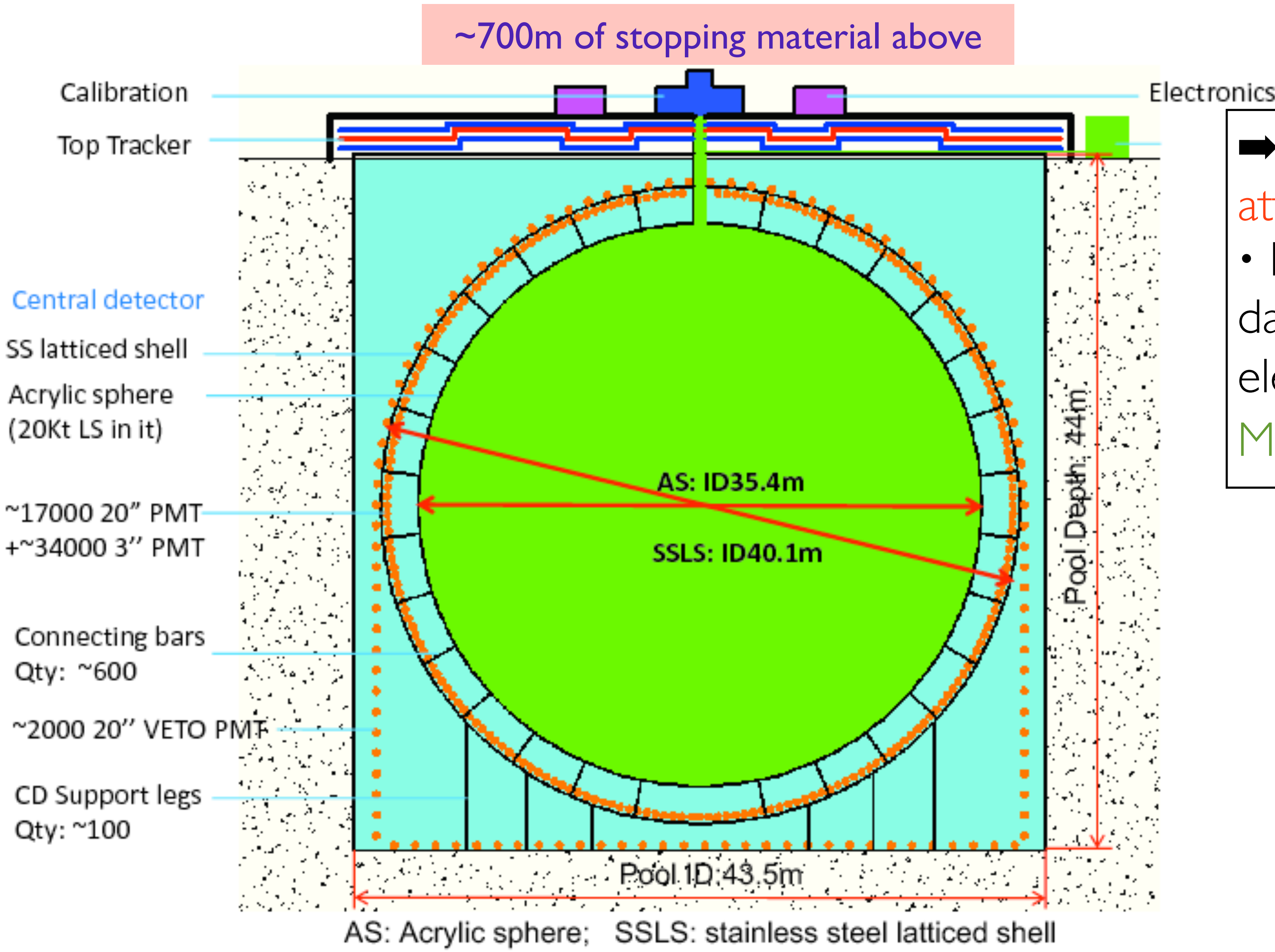


- <0.7% uncertainty on oscillation parameters
- dependence of precision on energy resolution studied
- bkgs sub-dominant in oscill. measurements (double coincidence)

From such goals descend some constraints...

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

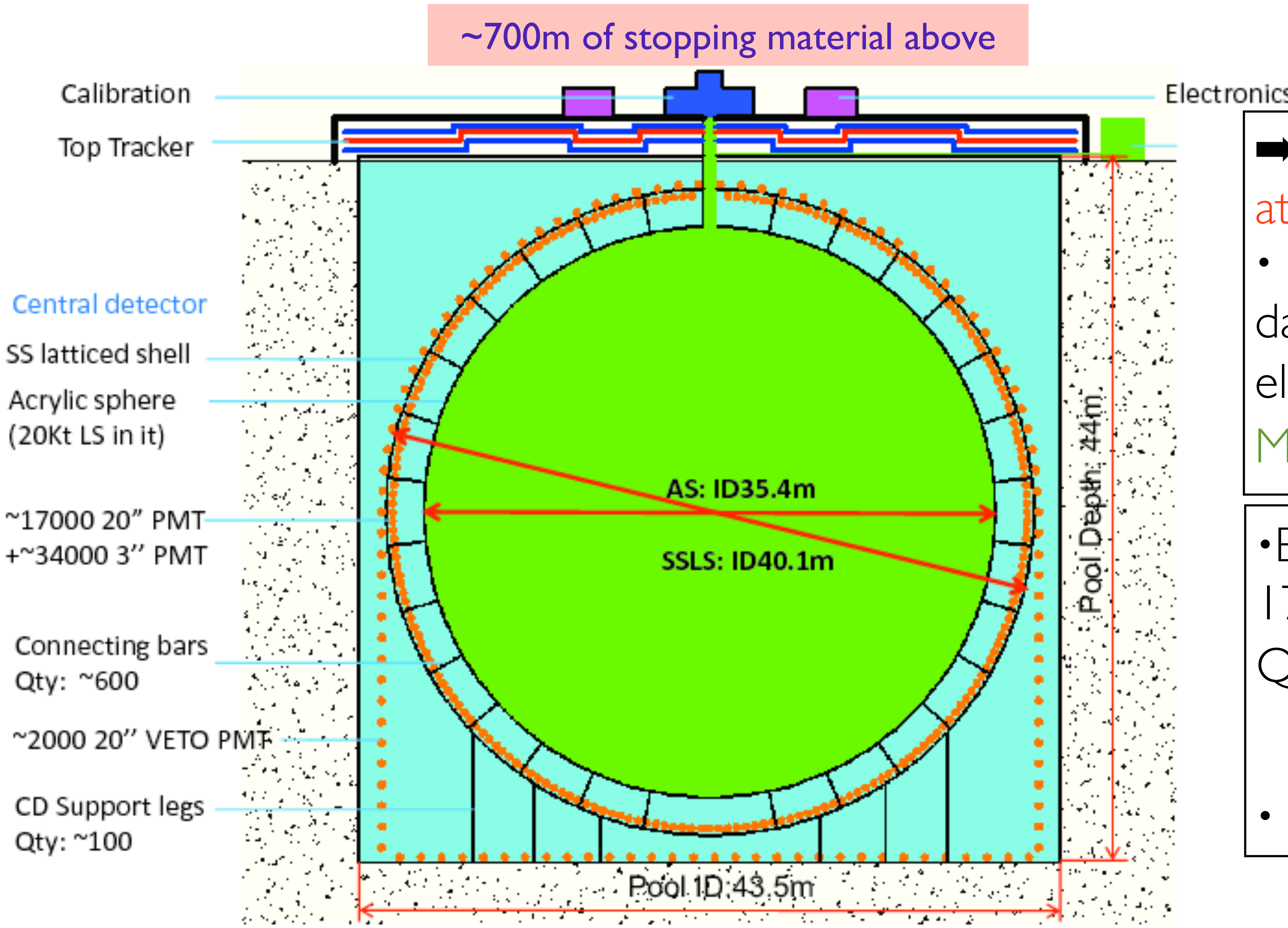
JUNO detector



➡ 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)

JUNO detector



AS: Acrylic sphere; SSLS: stainless steel latticed shell

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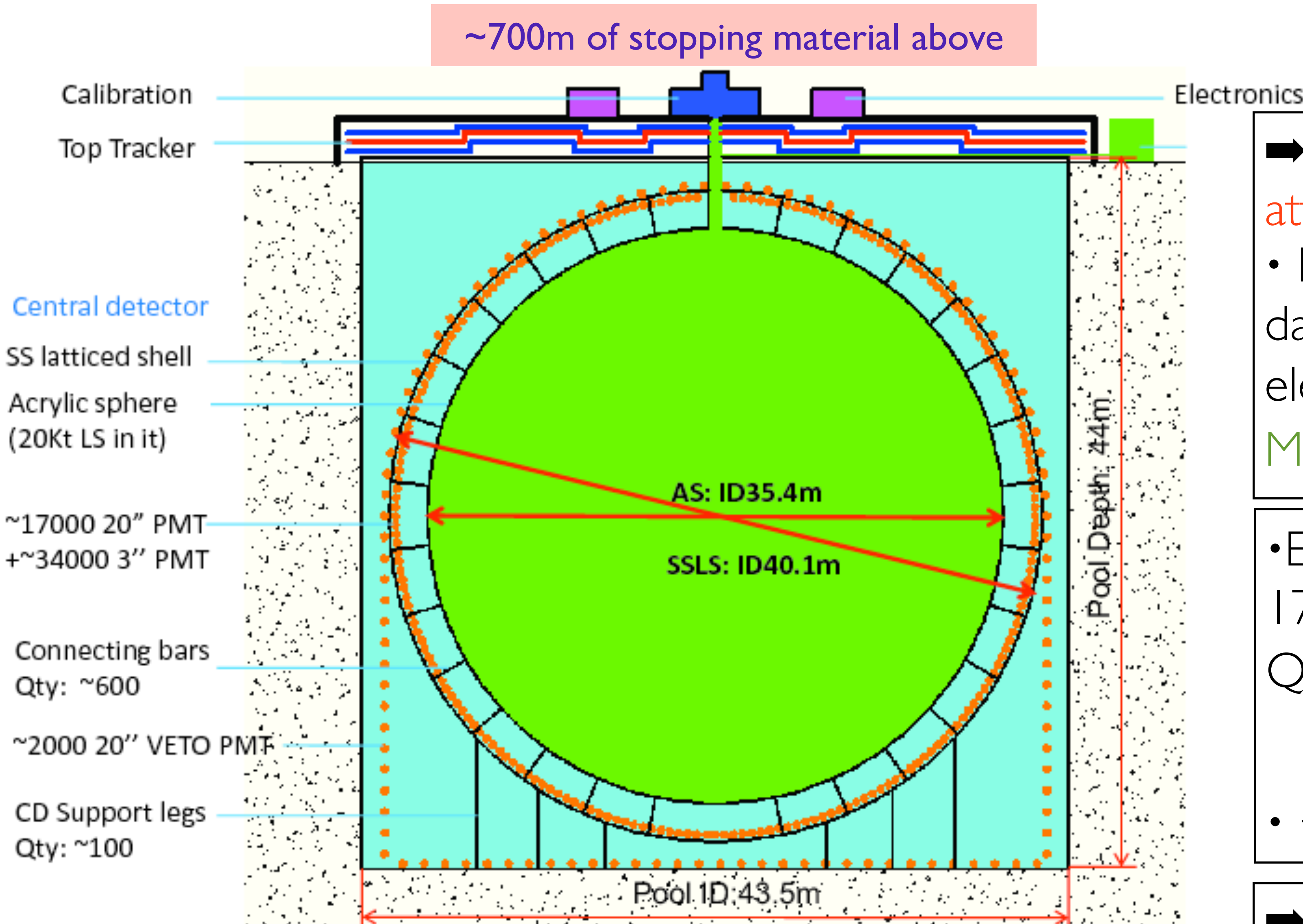
- Extended photo-coverage (~75%) from 17k **micro-channel plate** PMT (⌀=20", QE ~ 30% at 420 nm)
  - larger collection eff and good TTS for vertex position reconstruction (bkg rejection)
- + 25k "conventional" PMT (⌀=3")

JUNO detector



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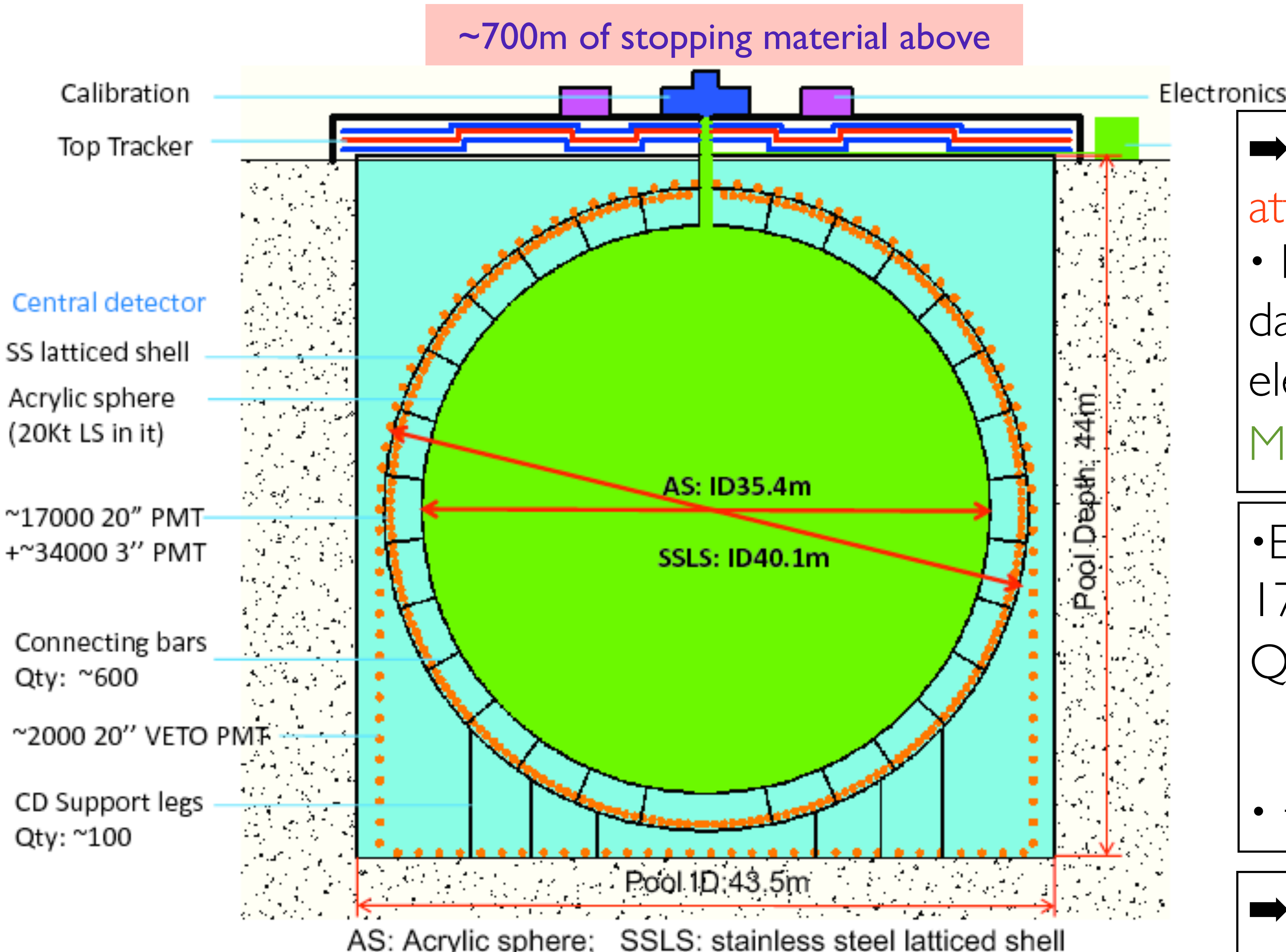
➡minimize cosmic ray bkg + shield against cavern radioactivity

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

JUNO detector



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

➡ 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)

- 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")

➡minimize cosmic ray bkg + shield against cavern radioactivity

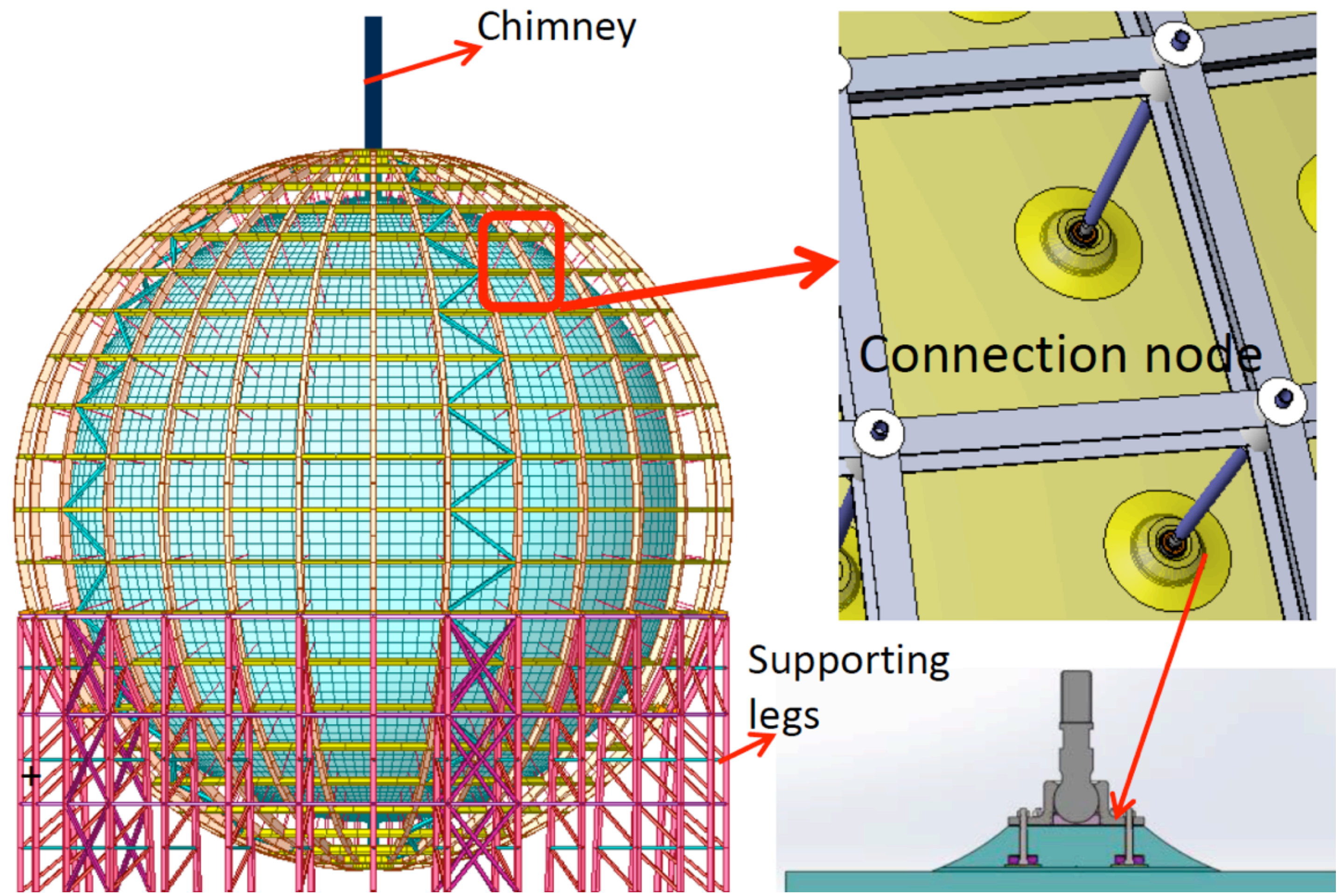
- veto activity from incoming muons and photons by surrounding water buffer (Cherenkov) and top scintillators

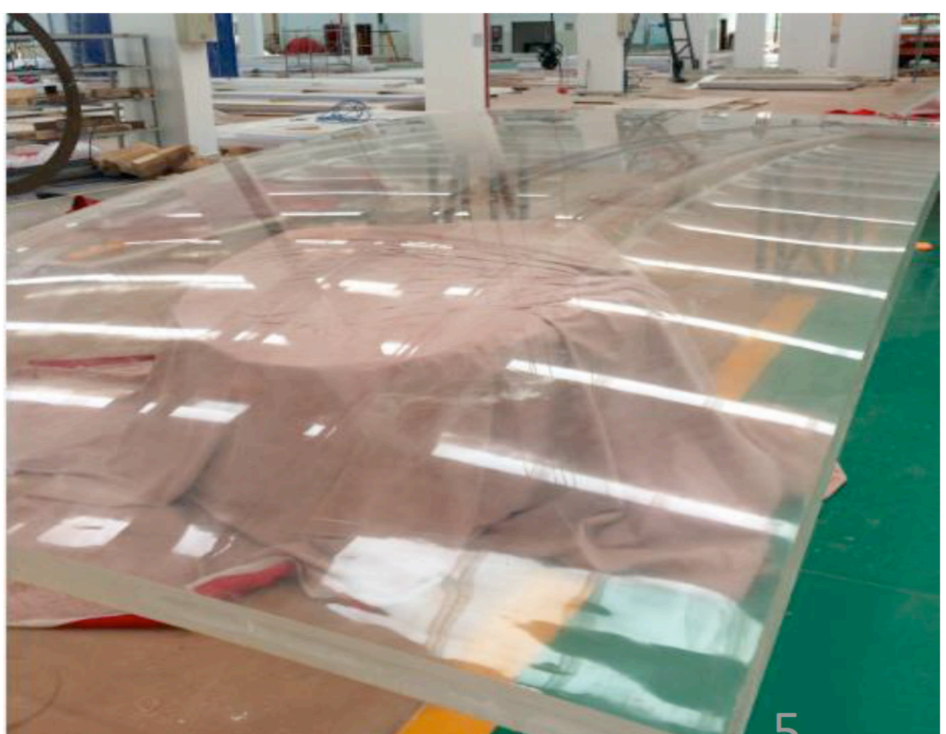
➡front-end electronics under water with challenging design and testing currently under-way for resilience

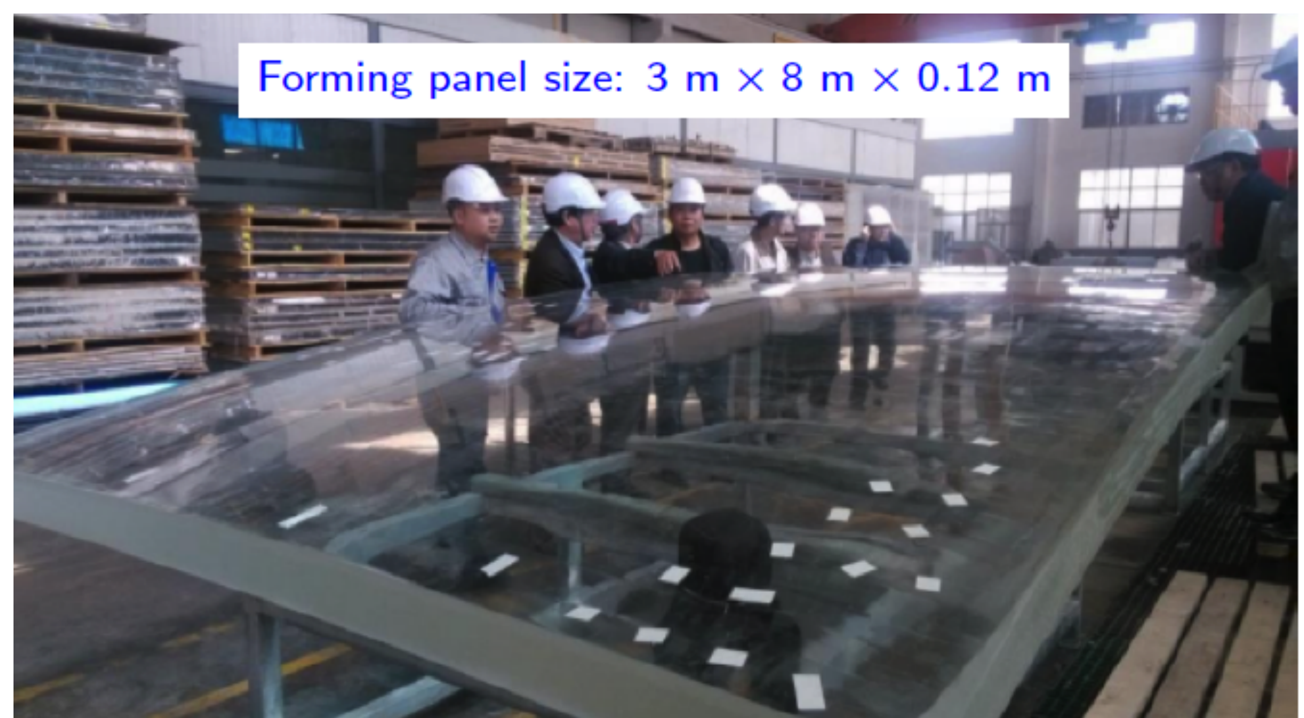
Central detector

- Acrylic Sphere and stainless steel truss immersed in water
- 265 acrylic panels of 3x8 m, with a 12 cm thickness
- Total weight: ~600 t of acrylic and ~600 t of steel

- Design and bidding completed, acrylic being produced, construction will start in 2019

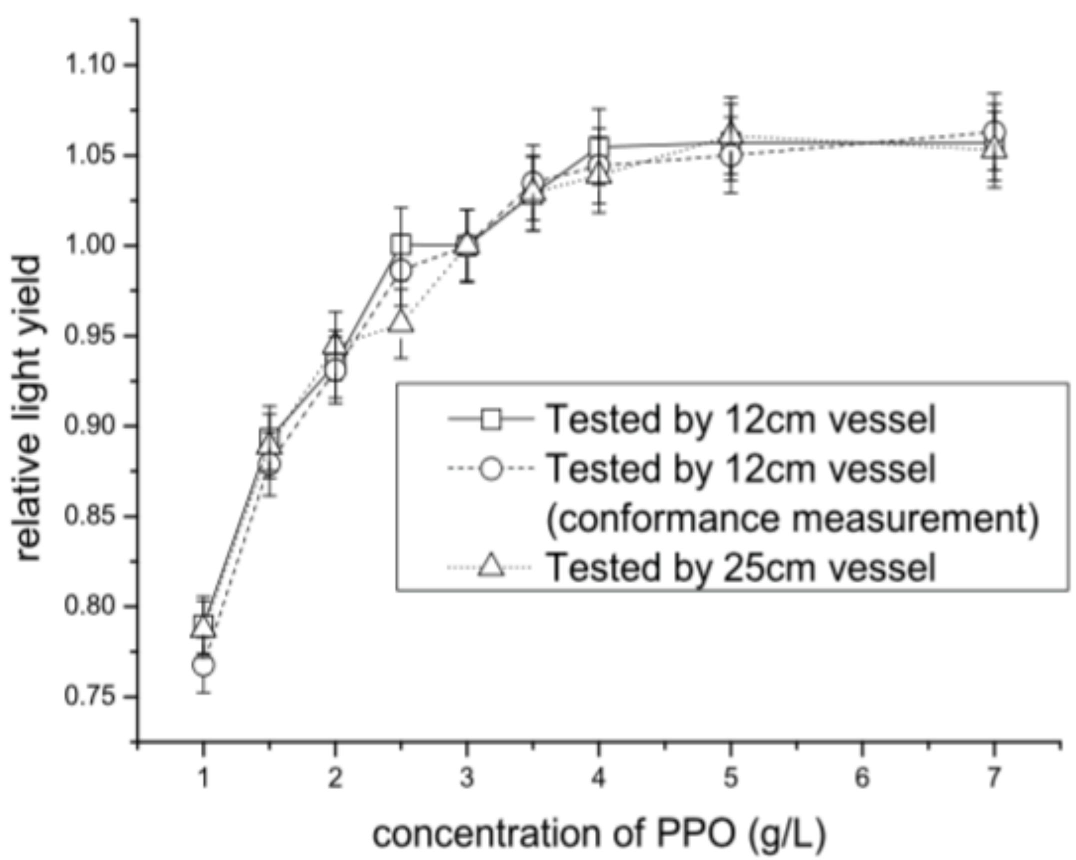




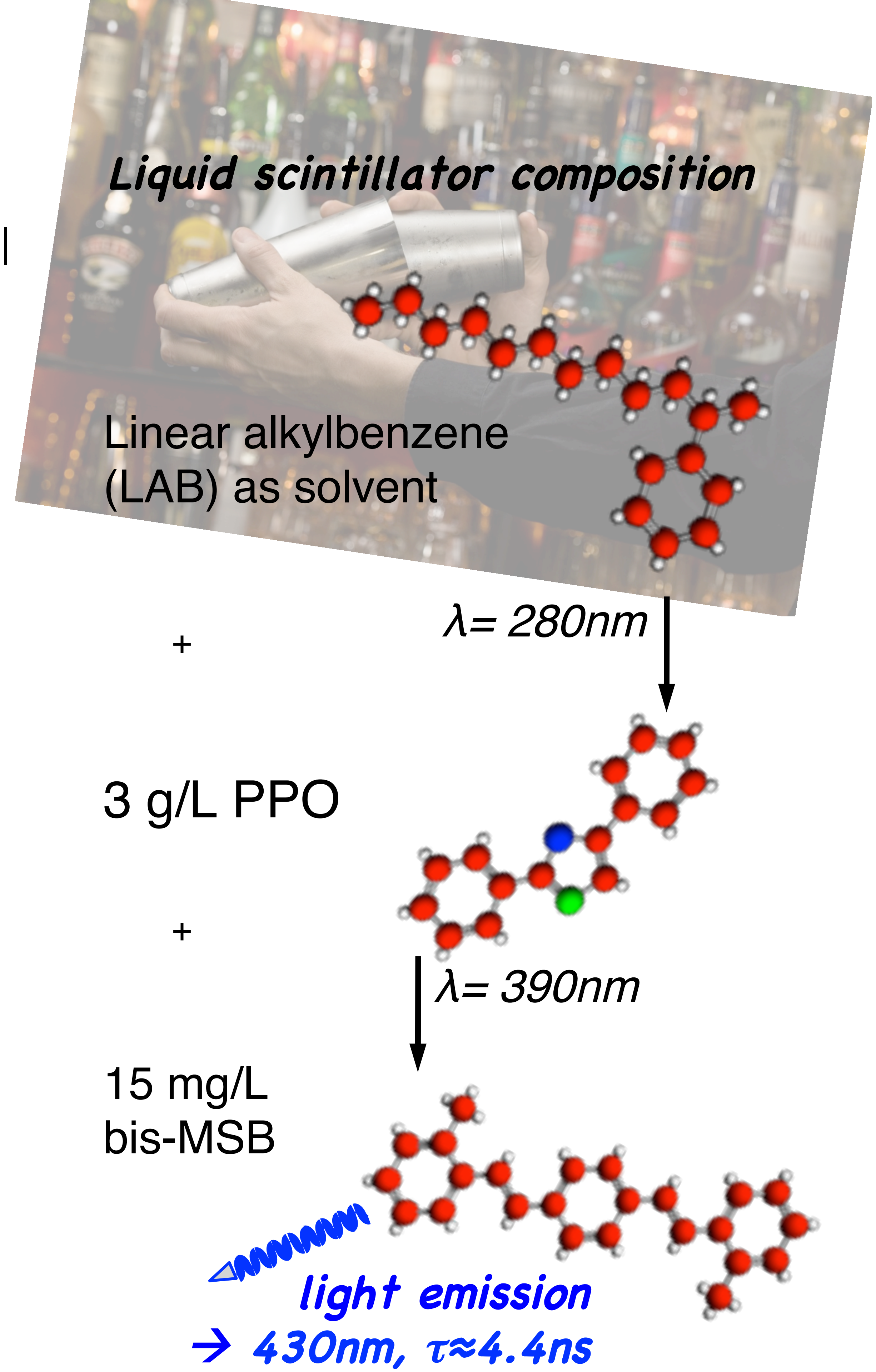


20 kt liquid scintillator

- 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: purification

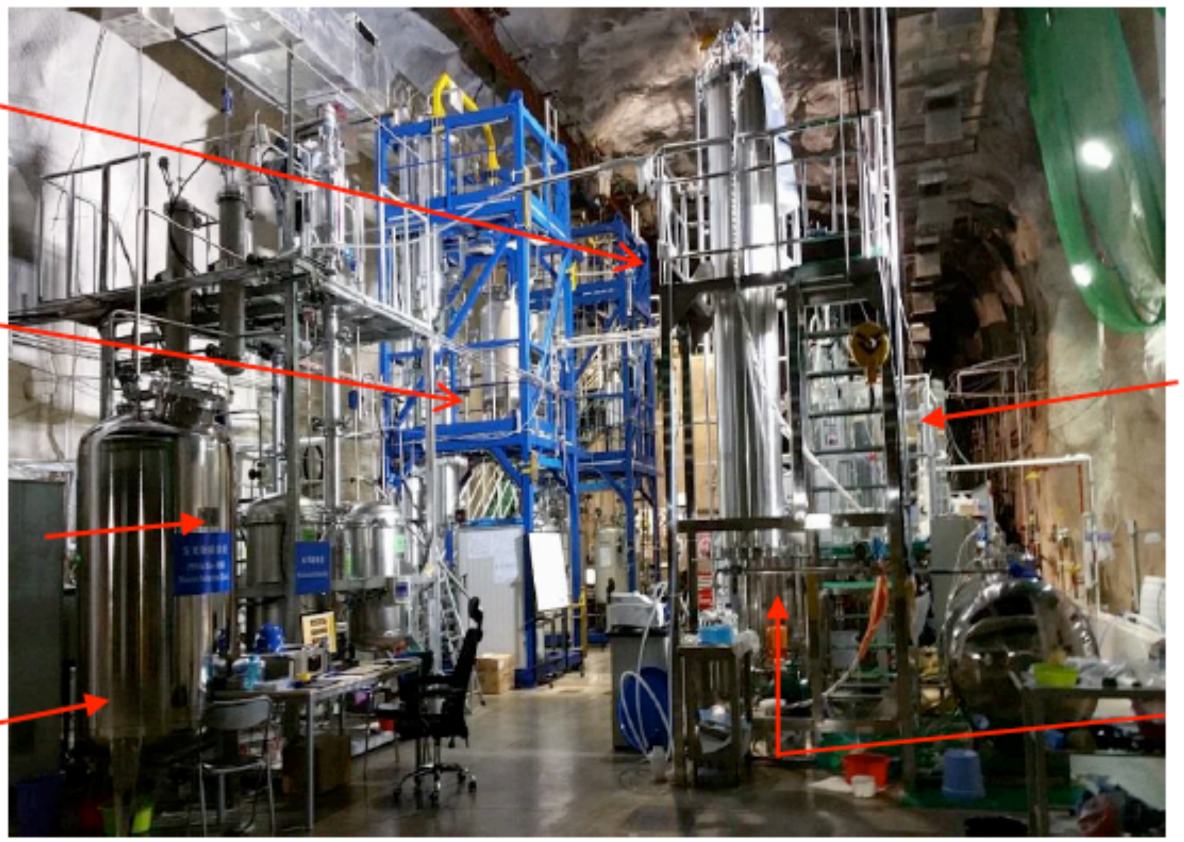
- Two main constraints drive need for thorough LS purification:
  - attenuation length: > 20 m at λ=430 nm (for 3g/L PPO in LAB)
  - radio-purity: 10^{-15} g/g (^{238}U, ^{232}Th) and 10^{-17} g/g (^{40}K)

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 and Rn

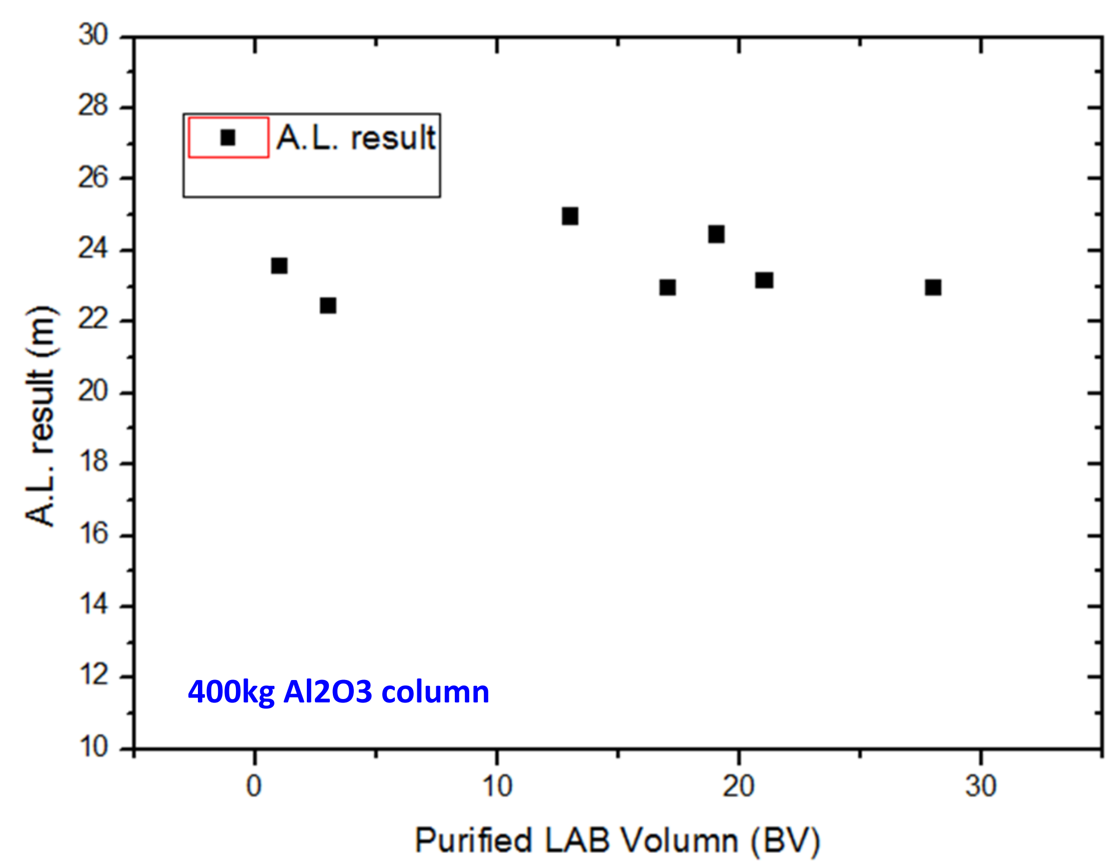
Scintillator purification: tests

- Pilot plant established in the Daya Bay LS hall and has been running in Feb-Mar
  - filled Daya Bay detector with sample LAB and purified with alumina
  - Optimization of fluorescent material to get the final recipe



Sample name	Sampling time	A.L. result（m）
DYB AD1 LS	20170307 0905	14.6
Purified LAB before filling (20170306 11:05)	201703121619	25.1
5#Tank raw LAB	20170227 21:50	20.5
Filled LS(0.5g/l PPO)	201703122311	23.8
DYB AD1 Gd-LS（201703)	20170314-1600取	8.15
DYB AD1 LS	20170314-2320	14.6

goal a.l. attained as result of purification, after "realistic operations"



20" PMT: the "eyes"

- To maximize photo-coverage use large (20") PMT
- Ordered 15k "NNVT" MCP-PMT
- + 5K Hamamatsu R12860 "conventional dynode"


NNVT

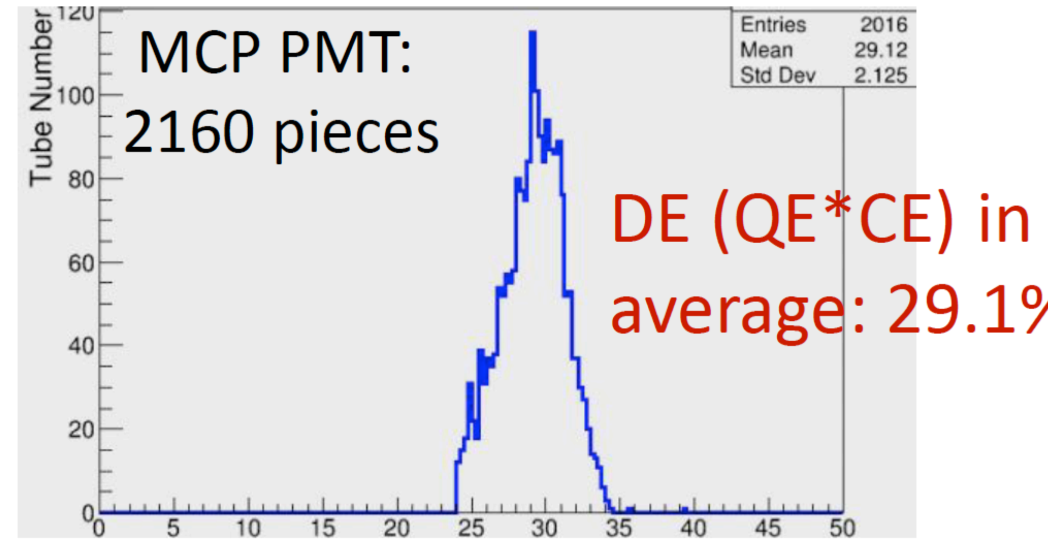

R12860

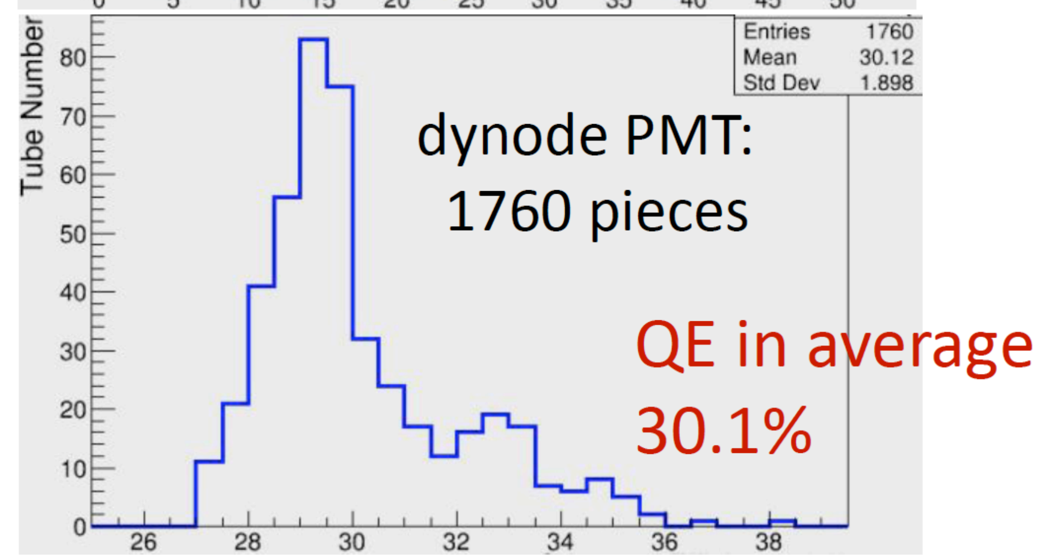
Quantity	Unit	NNVT	R12860	Important for
collection mode		Reflection+Transmission	Transmission	
Quantum efficiency (400 nm)	%	30	30	E resolution
Relative detection efficiency	%	110	100	E resolution
TTS	ns	12	3	Vertex position (against bkgs)
Anode dark current	KHz	20-30	10-50	Need for a trigger
After pulse 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

20" PMT: features and QA

- About 2600 MCP and 1700 dynode produced and delivered to JUNO
- 4500 m^2 station operating near to JUNO site until 2020 for potting to Front-End electronics and Quality Assessment

Measurements from the vendors





20'' PMT: resilience/reliability

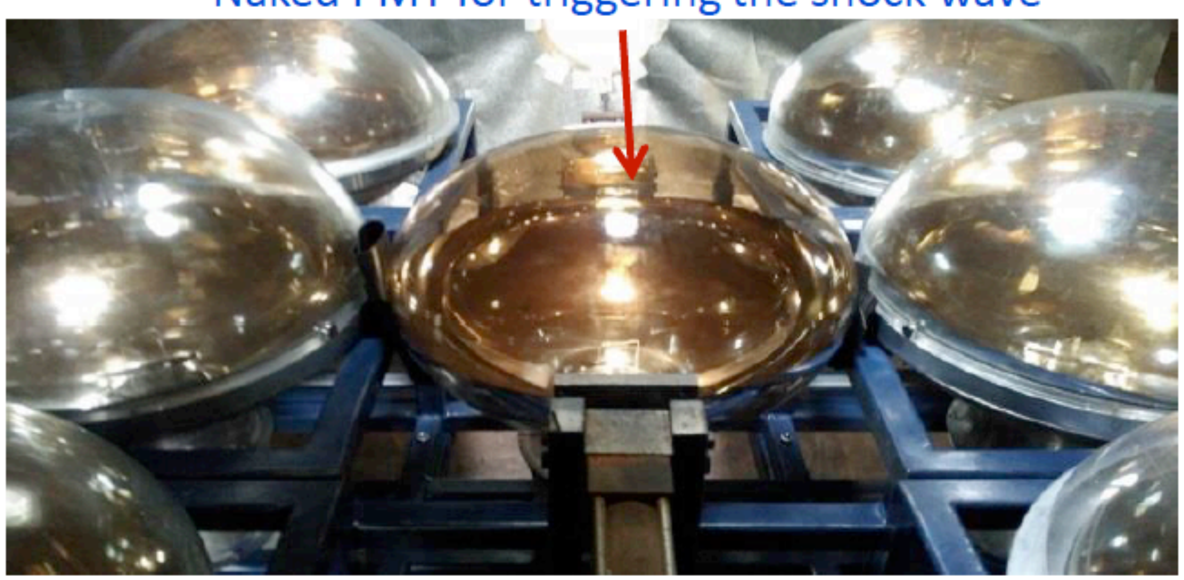
System is under-water: needs to be reliable and resilient

- Waterproof potting: multiple waterproof layers, aim at failure rate < 0.5% in first 6 years
- Shock protection: avoid propagation of waves from implosion of one PMT (from under water pressure) to neighbouring PMTs

✓ studied behaviour of various materials in 50 prototypes by performing several induced shock tests

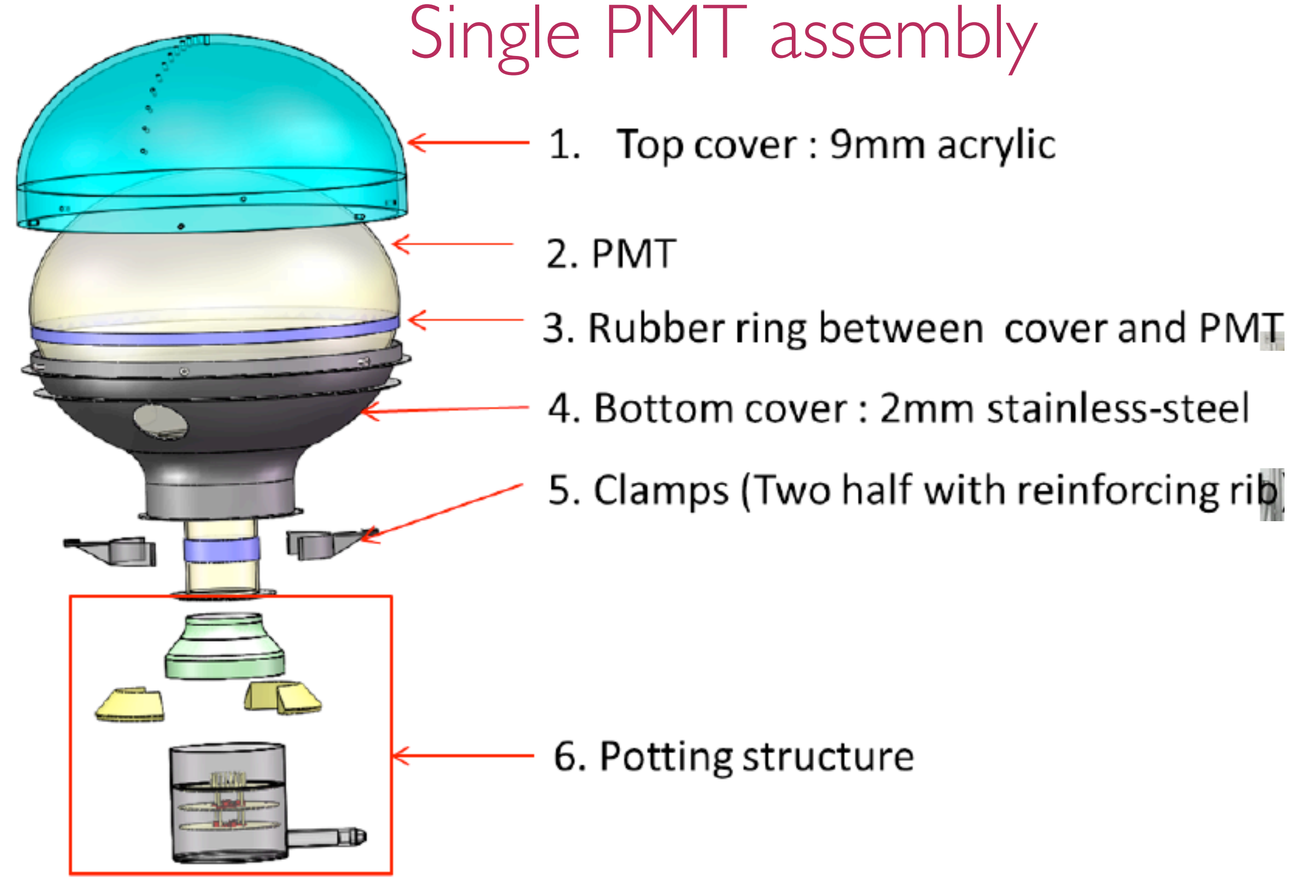
✓ settled for acrylic + stainless steel protection covers, with 9 mm thickness optimized to balance hardness vs transparency to optical photons

Naked PMT for triggering the shock wave

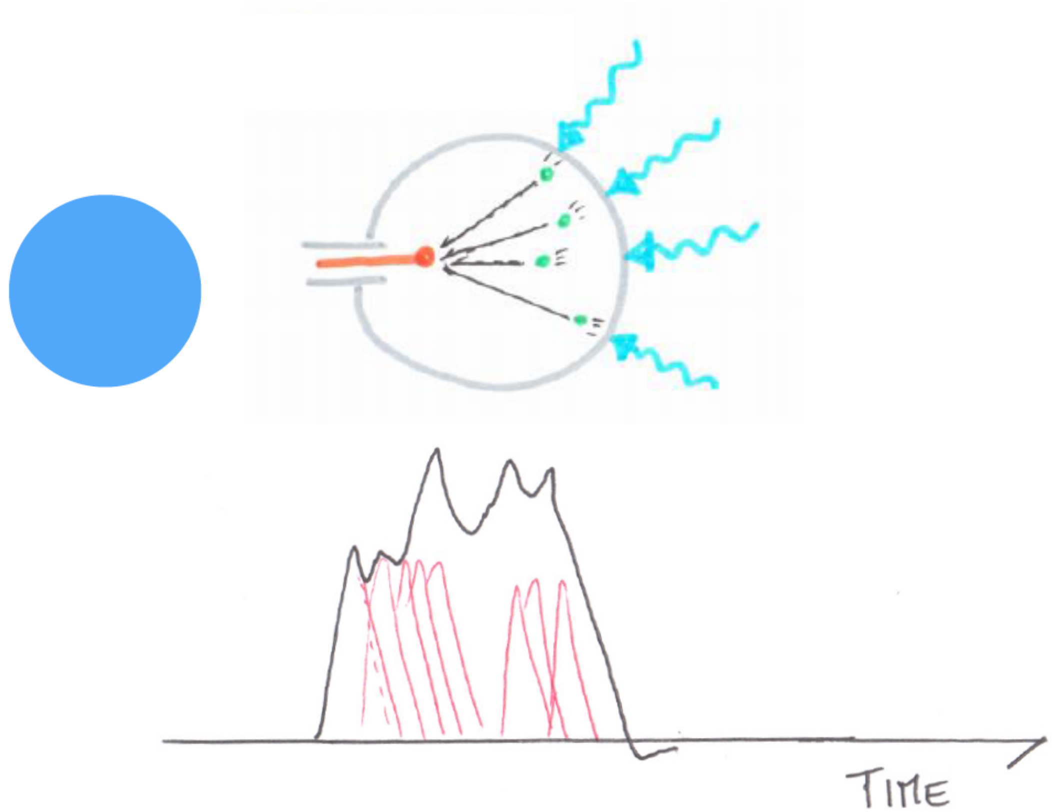


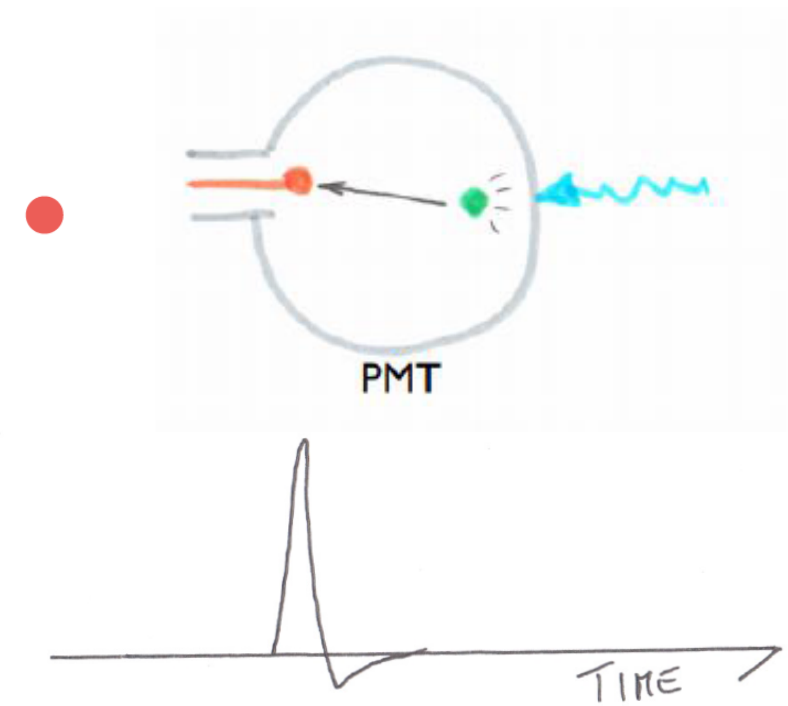
Implosion test

Single PMT assembly



Not only statistics...



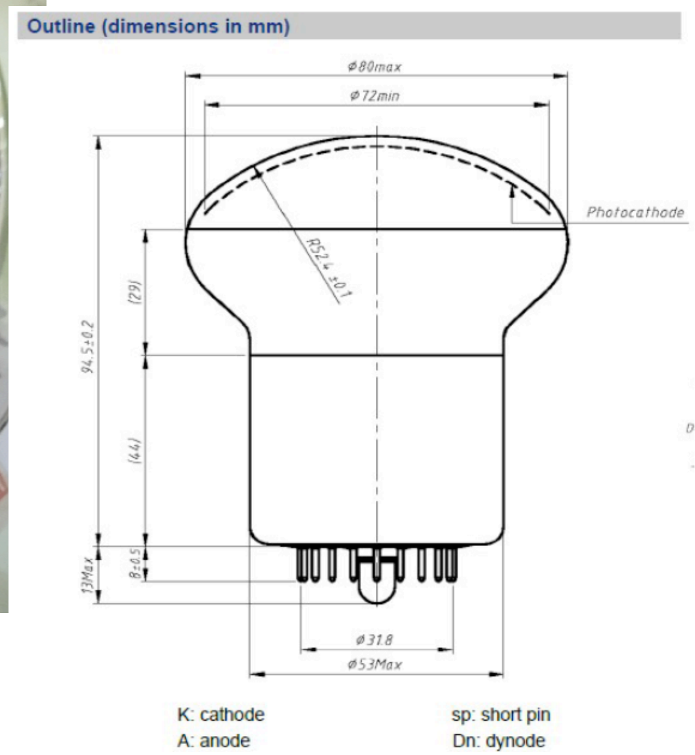


✓ 75% photo-coverage and collects ~1200 p.e./MeV
➡ but depending on event E and position, PMT could be "flooded" by p.e. and waveform saturate → loss of linearity
➡ and large cathode → high dark rate

➡ 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

- *<u>Multi-calorimetric approach</u>* reduces non-stochastic terms ("systematics") in the energy resolution dependence ($\leq$ 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)

3'' PMT: the other pair of eyes



Parameters	HZC's response
QE×CE @ 420 nm	24% (>22%)
TTS(FWHM) of SPE	<5ns
P/V ratio of SPE	3 (>2)
SPE signal width (sigma)	35% (<45%)
Dark rate @ ¼ PE	1kHz (<1.8kHz)
QE uniformity	<30% in Φ60mm
Pre/after pulse ratio	<5%, < 15%
Nonlinearity	<10%@1-100PE
Radioactivity	238U: <400ppb, 232Th: <400ppb, 40K: <200ppb

- 26k PMT ordered from HZC-Photonics
  - custom-made: new development with improved TTS (based on KM3Net design)
- 16 PMTs read-out by a multi-channel connector on a single "underwater box" (cabling configuration matters and is being optimized)
- Bidding *completed* before summer, *start production at beginning of 2018*

3" PMT: preliminary measurements

- Test results of XP72B22 samples

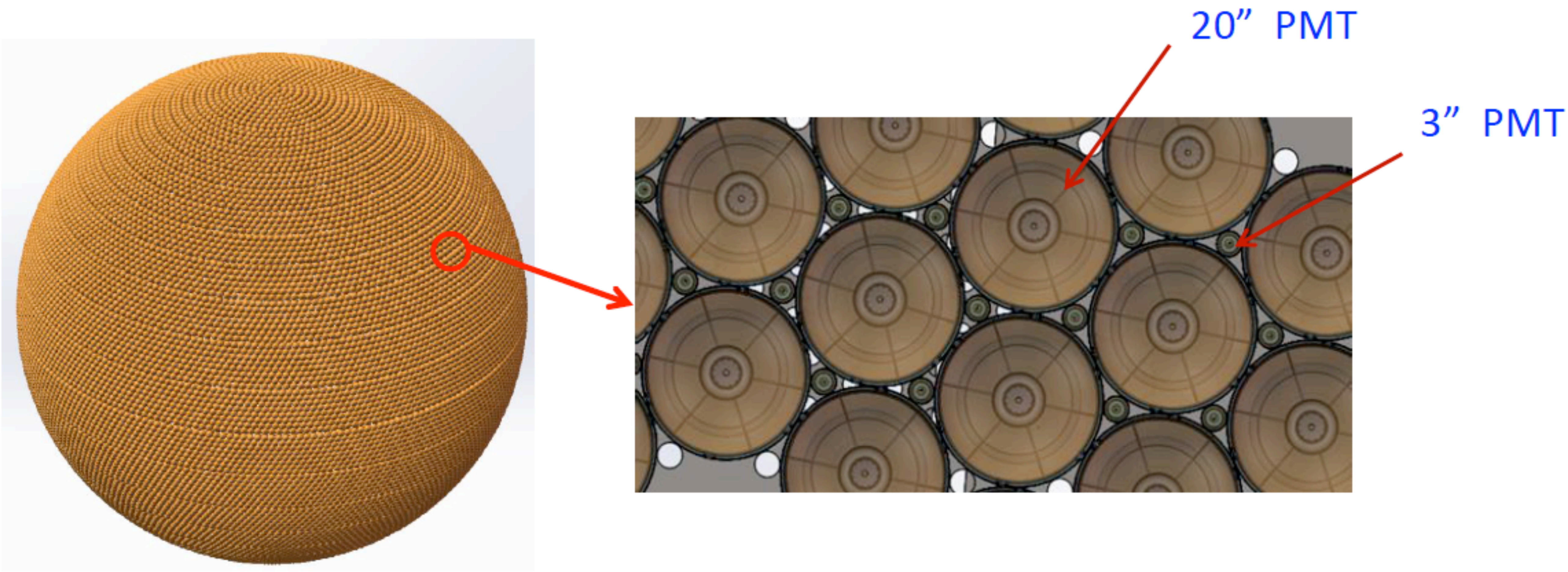
- QE: 23.5% - 26%; P/V: 3;

- SPE resolution: <30%; TTS: 2-5ns

No.	Resolution	P-V Ratio	Gain@1350V	TTS(ns)
70195	0.231	4.889	2.5e+07	2.2
70197	0.276	6.818	2.3e+07	2.3
70215	0.245	2.832	0.4e+07	2.0
70218	0.251	5.239	1.0e+07	2.7
70219	0.279	4.592	0.6e+07	3.2
70222	0.269	6.657	1.5e+07	2.6
70226	0.239	7.800	2.3e+07	5.0
70236	0.249	6.440	2.2e+07	4.4

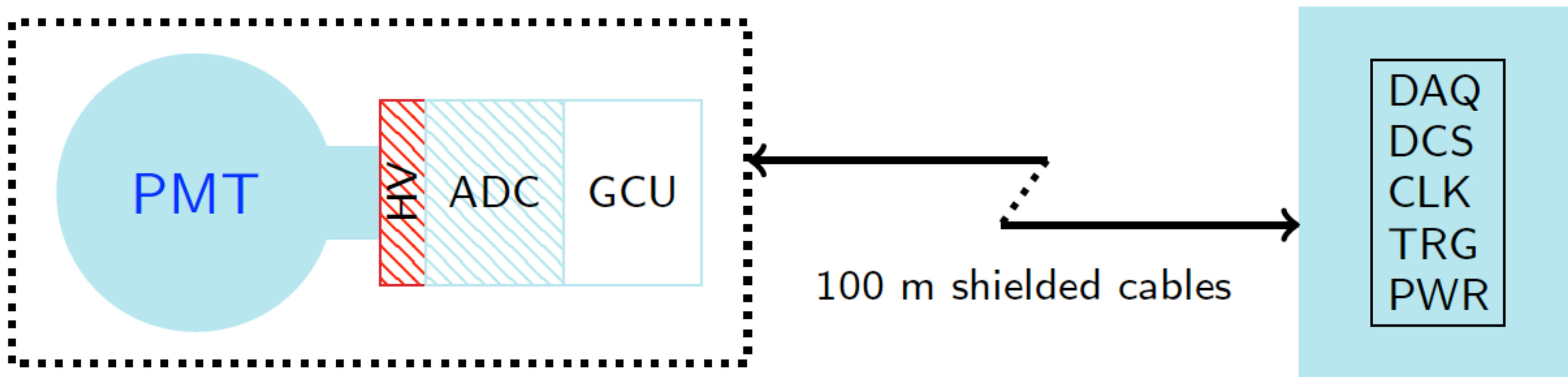
Z.Qin, NNN2017

JUNO PMT system, overall



- optical coverage = ~78%: 18,000 20’’ PMTs (75%) + 25,000 3’’ PMTs (2.5%)
- Several geometrical arrangements probed and relative position of optical surfaces of 20’’ and 3’’ PMT optimized to <u>maximize overall light collection, yet minimize complexity of installation</u>

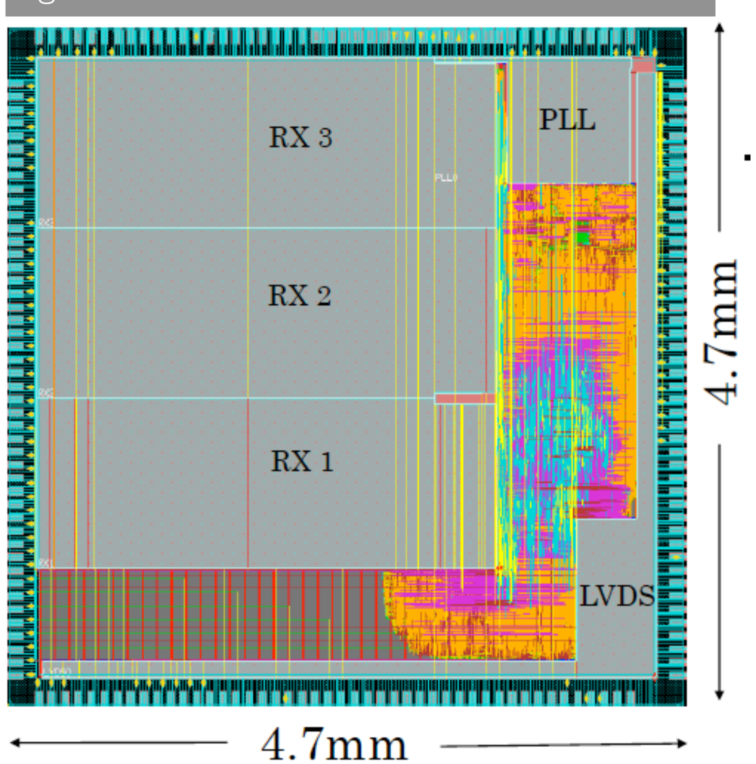
Read-out, HV, DAQ



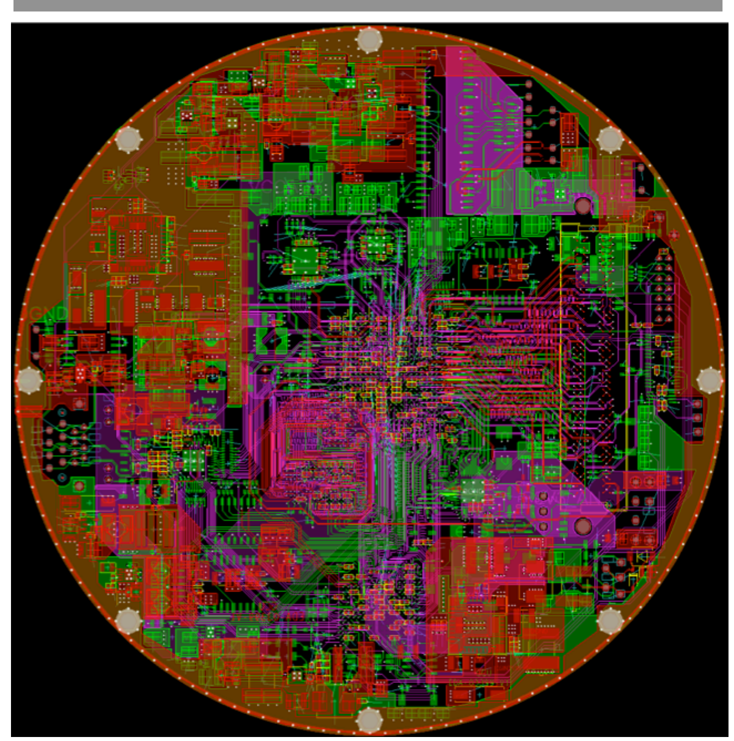
PMT readout electronics will installed underwater, very close to PMT :

- PMT Voltage Divider and High Voltage
- Front-End electronics: analog and digital electronics

Vulcan chip: ASIC capable of fast data sampling and processing, employs three 8-bit ADCs optional compensation for signal overshoot



GCU board: PMT interface to the DAQ and DCS performs the first online digital analysis of the signal



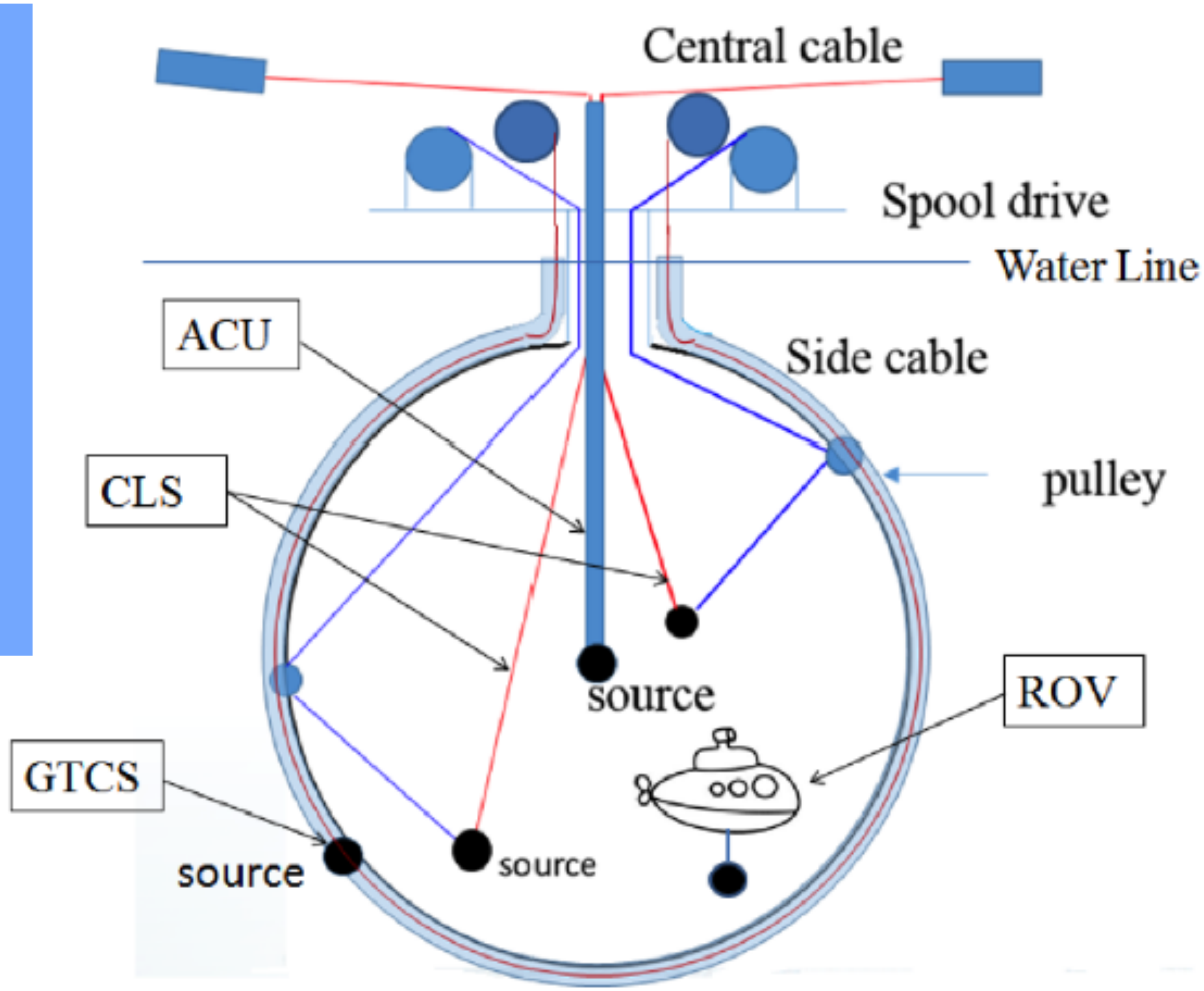
- Design advanced, prototype performances being measured
- particular focus on reliability of UW parts
- 2 alternative HV prototypes also being tested

σ(E): calibremus, calibremus, calibremus...

- Uncertainty on energy scale < 1% crucial for total σ(E)/E~3% at 1 MeV
  - NB: uniformly in the detector
- JUNO envisaged complementary methods for E response determination across detector and for various energy loss processes

- **1D**: Automatic Calibration Unit (ACU) along z axis: *could reach sub-cm positioning*
- **2D**: Cable Loop System (CLS) over vertical planes: *test reaches 10 cm precision*
- **2D**: Guide Tube Calibration System (GTCS) to probe outer CD surface: *full-size tested*
- **3D**: Remotely Operated under-LS Vehicle (ROV), whole detector volume scanned: first version designed and tested

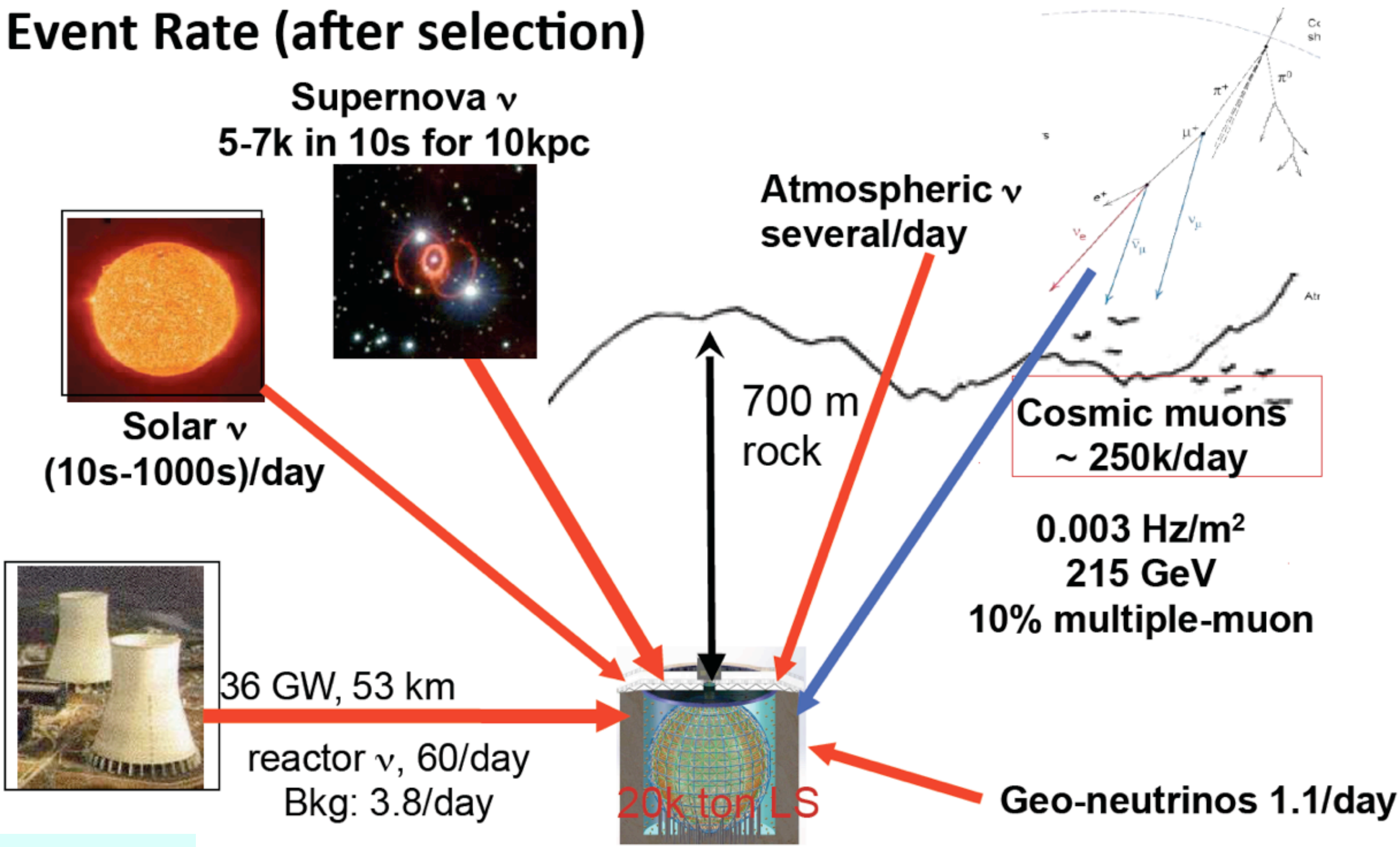
Using known radio-active sources:
- γ ^{40}K, ^{54}Mn, ^{60}Co, ^{137}Cs
- e^+ ^{22}Na, ^{68}Ge
- n ^{241}Am-Be, ^{241}Pu-^{13}C, ^{241}Am-^{13}C



Some other selected topics with JUNO

(full suite at: J. Phys. G 43 (2016) 030401)

Other signals, other measurements...

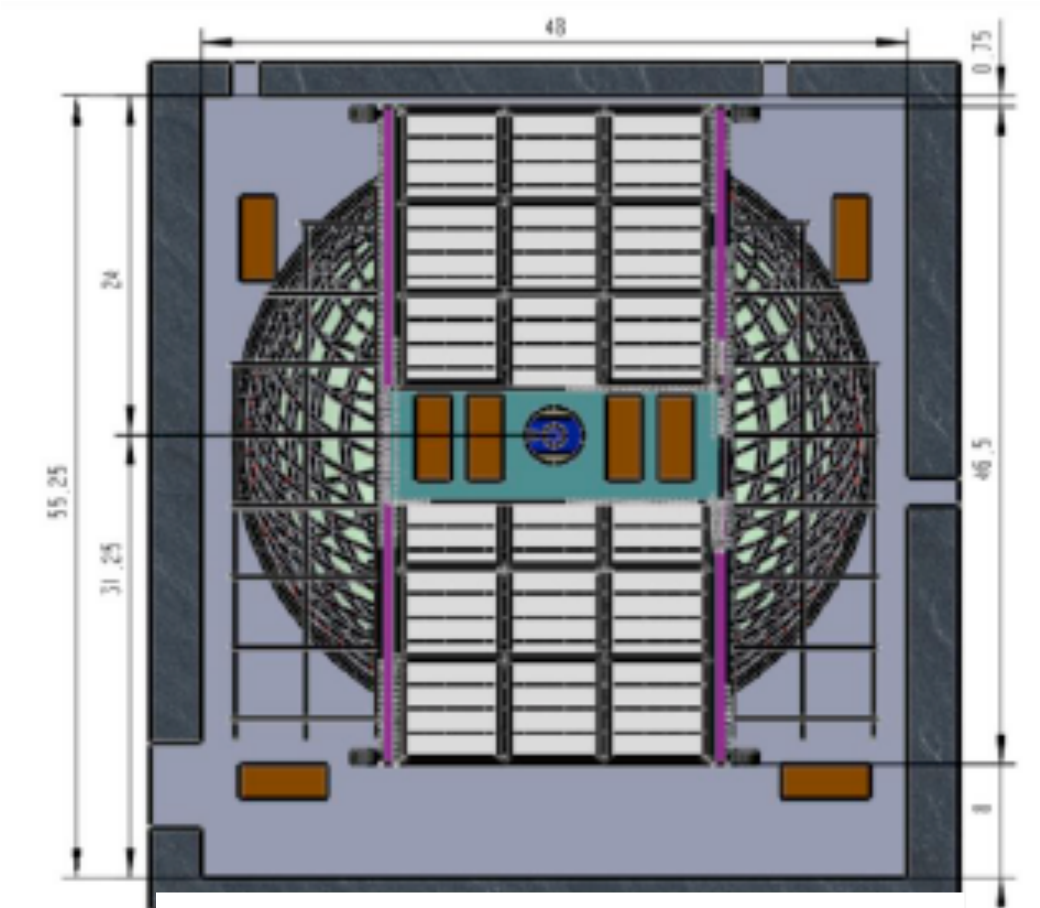


Y. B. Hsiung at NNN16

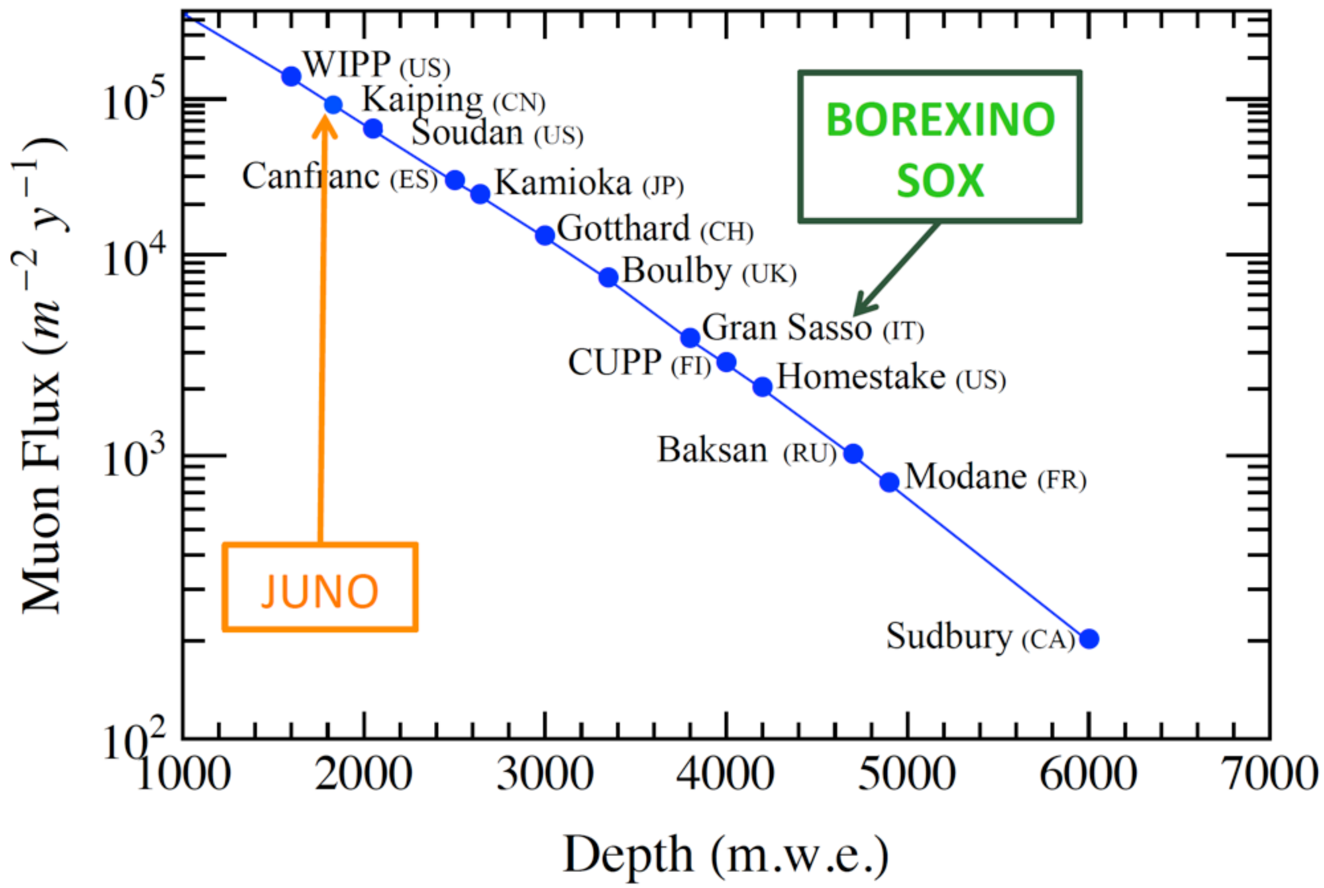
J. Phys. G 43 (2016) 030401

- JUNO's features make it an excellent detector for other physics
  - E.g. detector mass makes it a good target for a lot of physics
  - but need to control the backgrounds

Muon veto



the OPERA Target Tracker

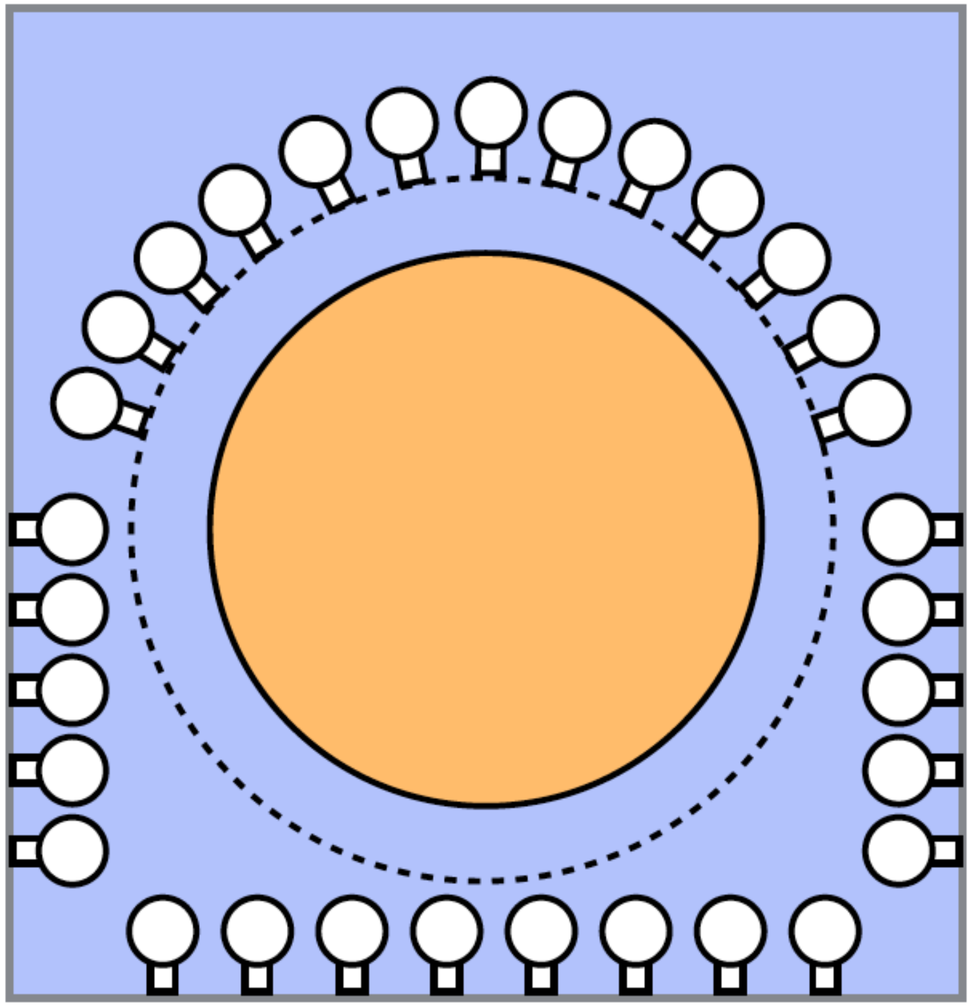


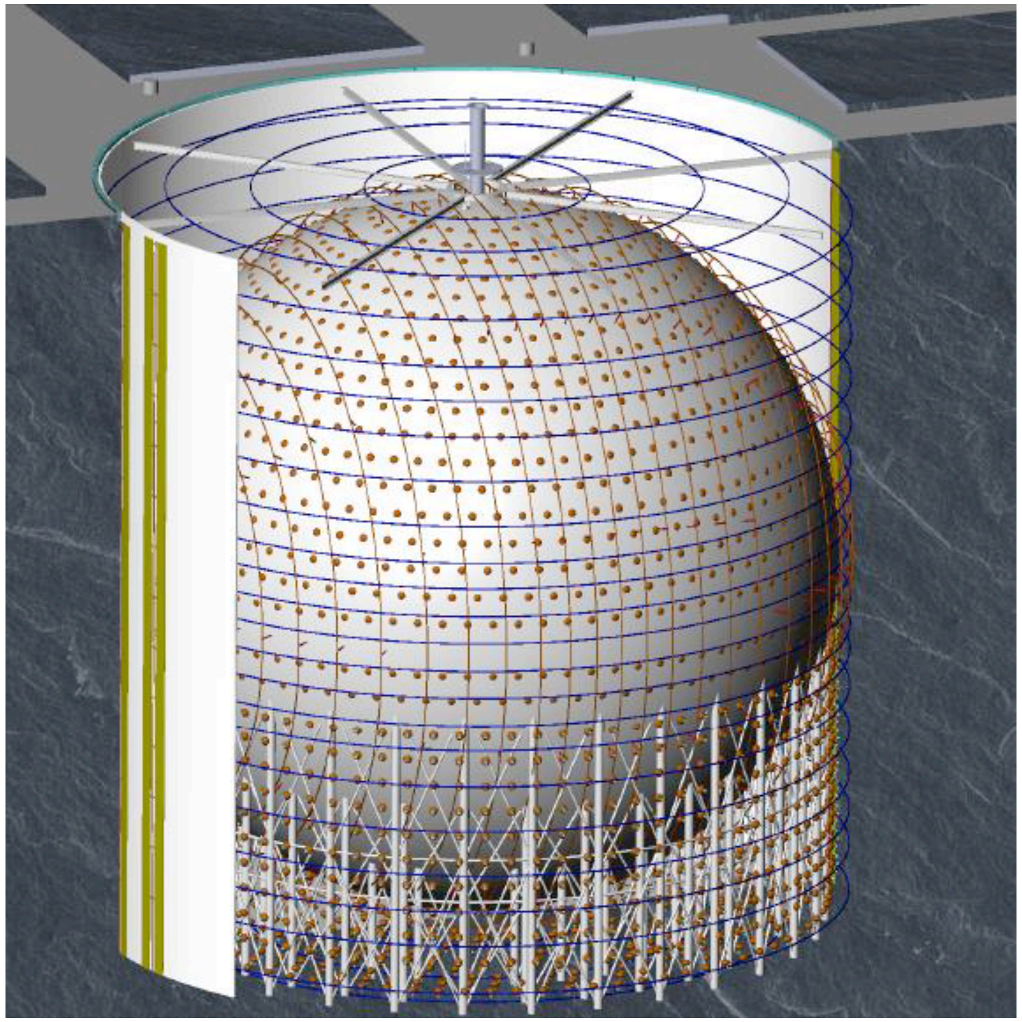
Overburden	Muon flux	$< E_\mu >$	R_μ in CD	R_μ in WP
748 m	0.003 Hz/m^2	215 GeV	3.0 Hz	1.0 Hz

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

- TT has been shipped to near-JUNO site for aging tests

Water pool





- Even if LS is purified, surrounding environment intrinsically radioactive
- Identify "Outside-in" e and *n* from 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%
  - fast neutron background ~0.1/day, Rn activity < 0.2 Bq/m^3

Background processes

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				

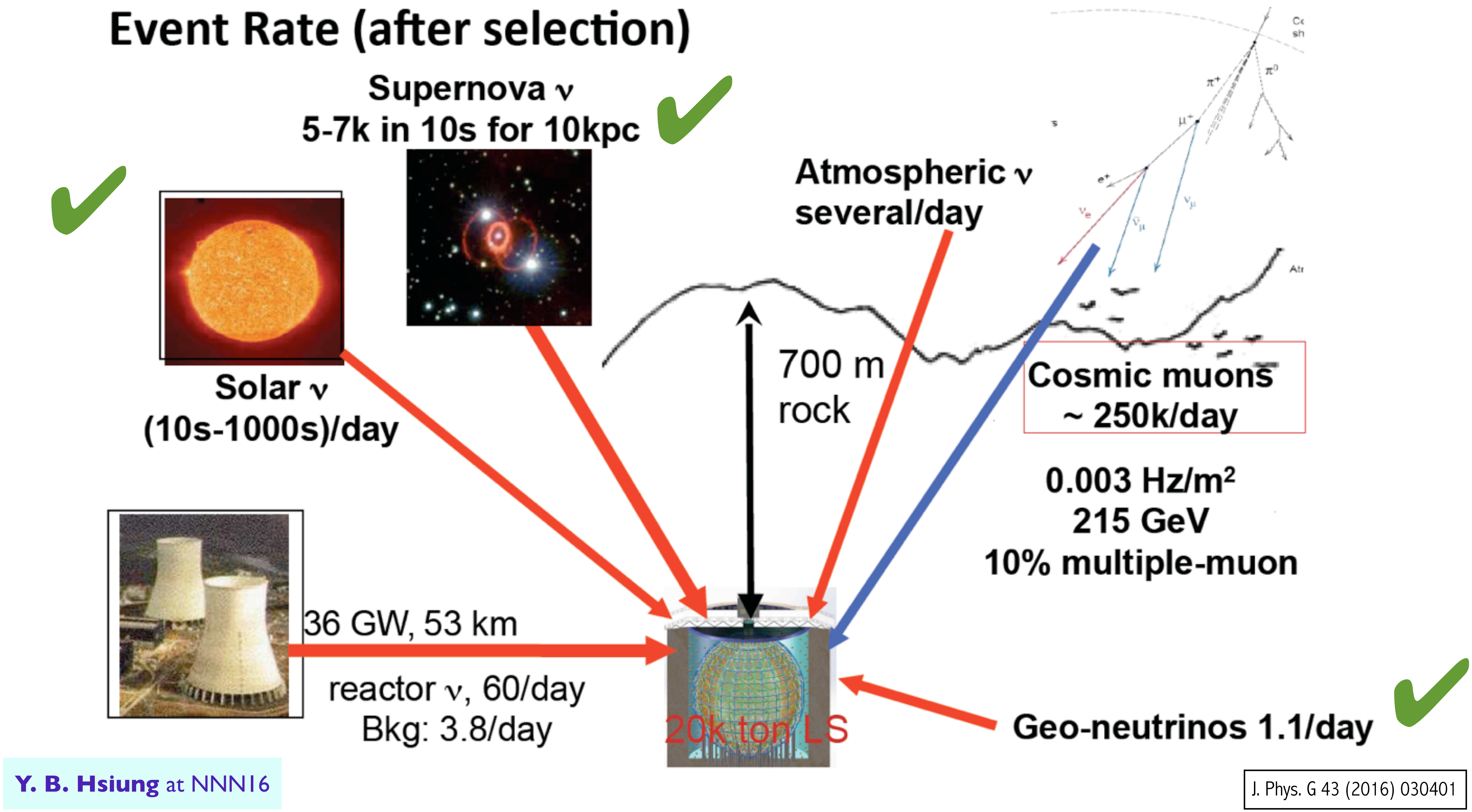
Expected upper limit for each material (Preliminary)

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

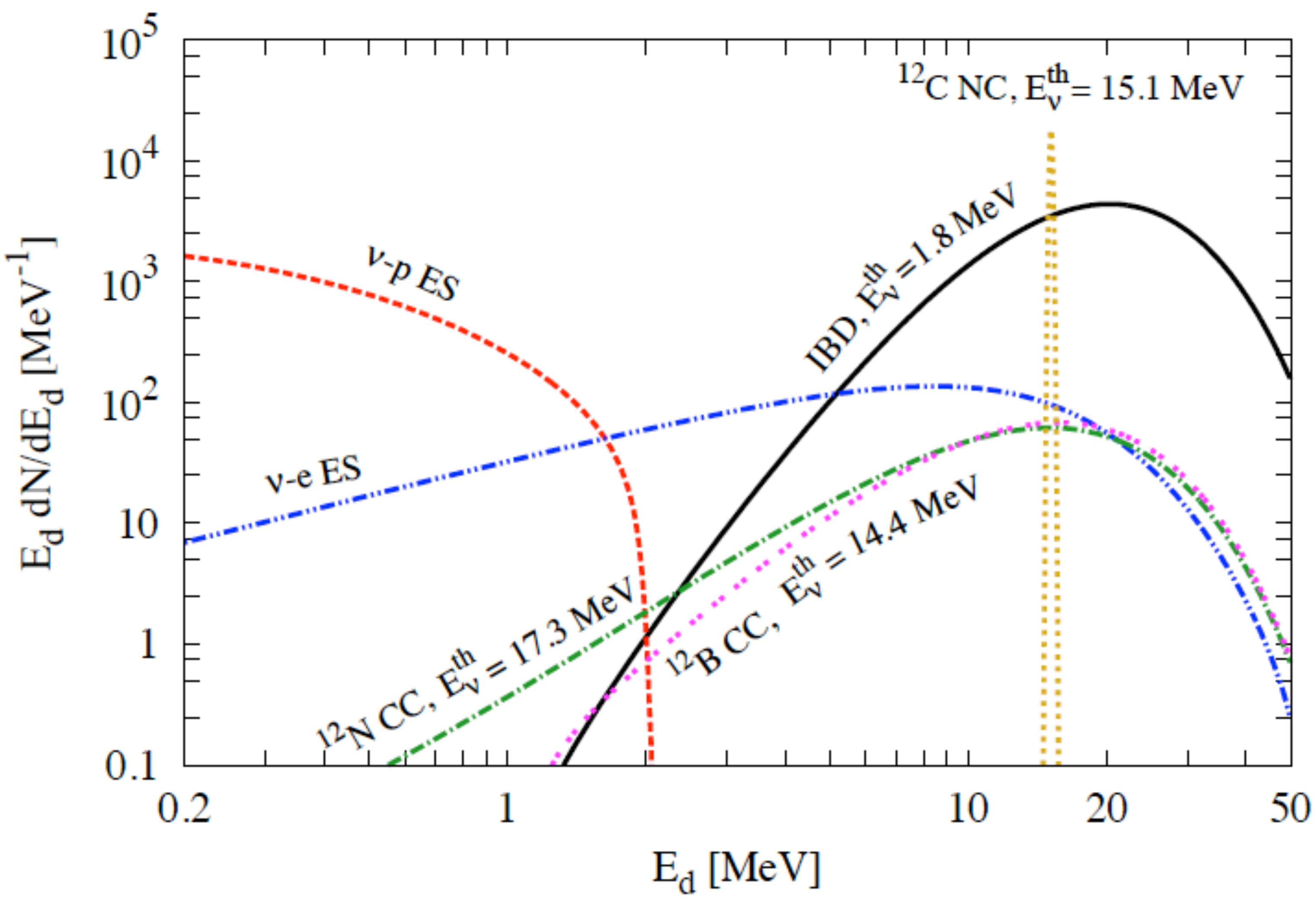
➢ The most critical materials are shown with "stars" in the material column.

Other signals, other measurements...

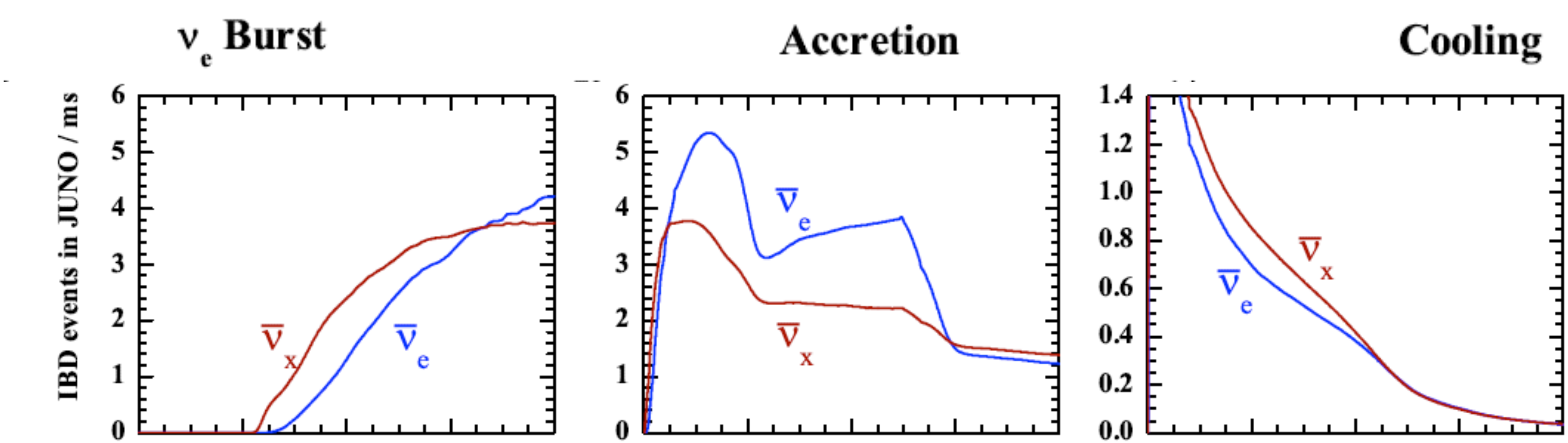


- JUNO's features make it an excellent detector for other physics
  - E.g. detector mass makes it a good target for a lot of physics
  - but also to much intrinsic bkg activity + it's shallow → muons → C, Li, etc

Supernova neutrinos

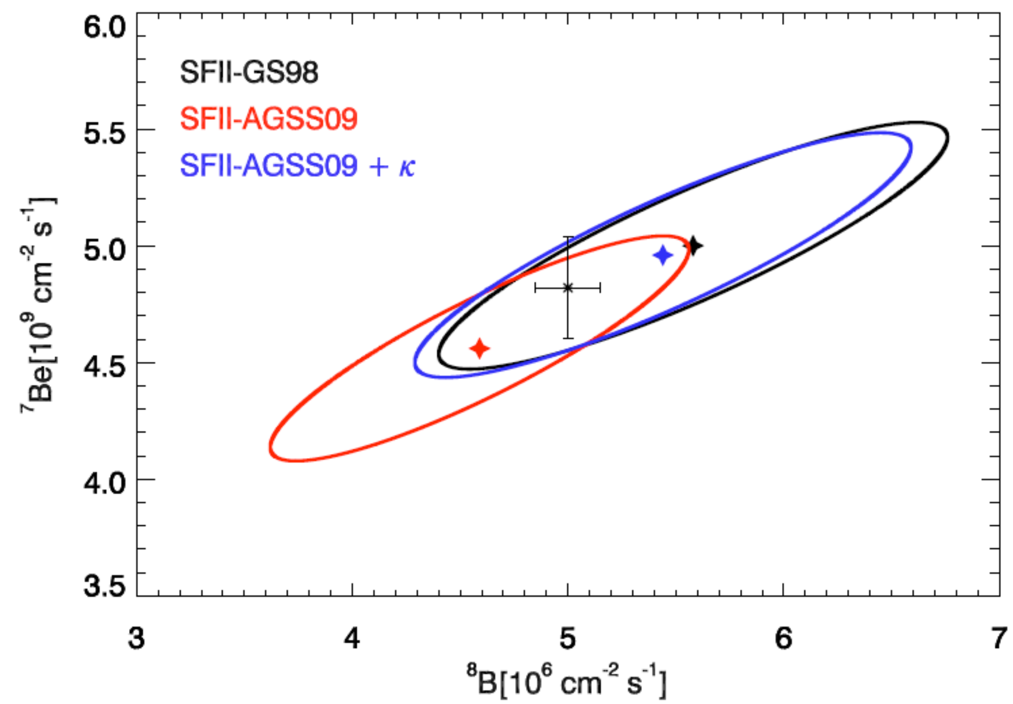


- Galactic SN at a distance of 10 kpc
- ~5000 **ν** events in the IBD channel, 2000 events for elastic neutrino-proton scattering, and 300 events for elastic neutrino-electron scattering in the JUNO detector
- Specialized trigger under study, to cope with concentrated spray of events with characteristic time profile
  - e.g. for Betelgeuse (d ~0.2 kpc): ~10 MHz trigger rate

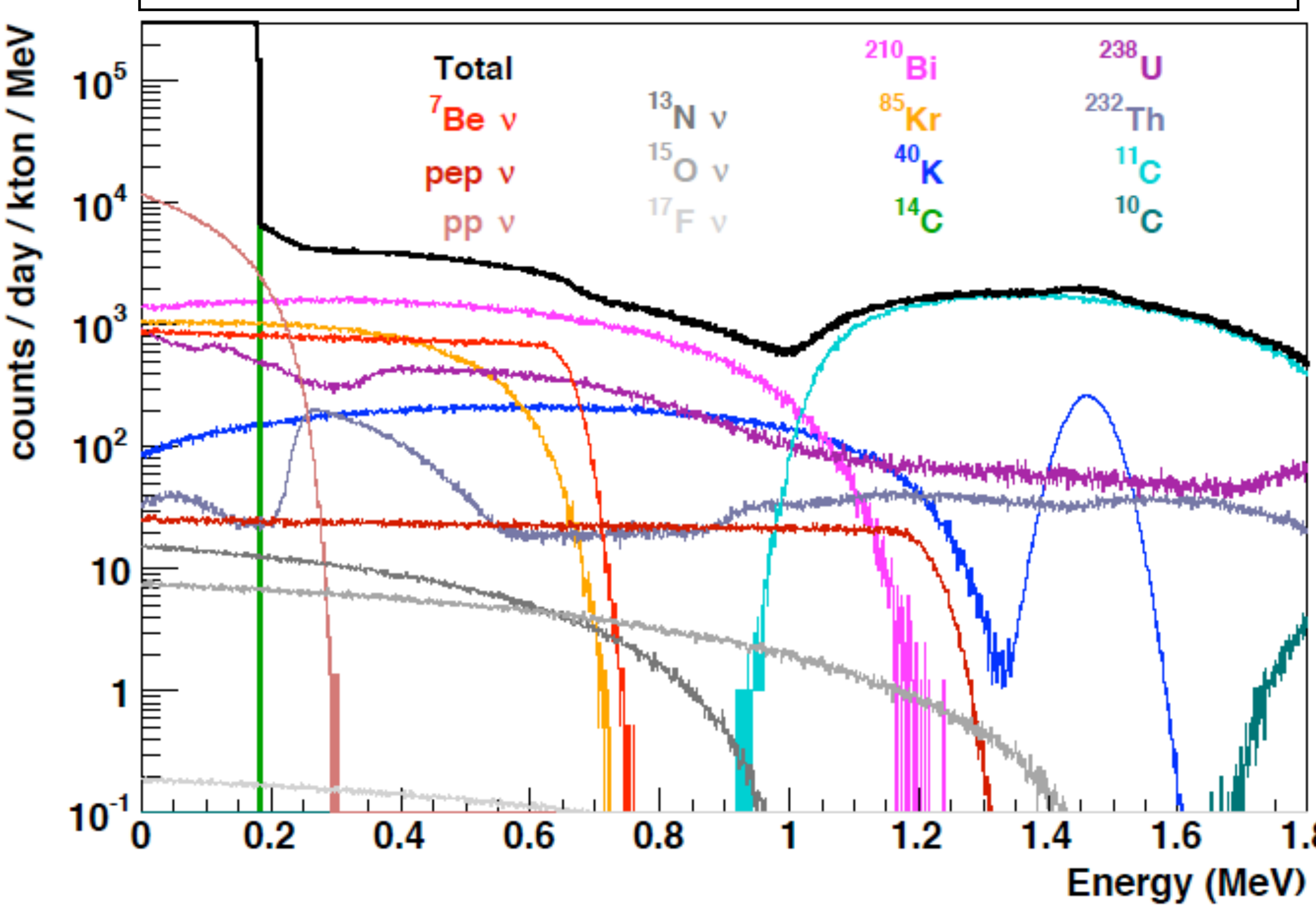


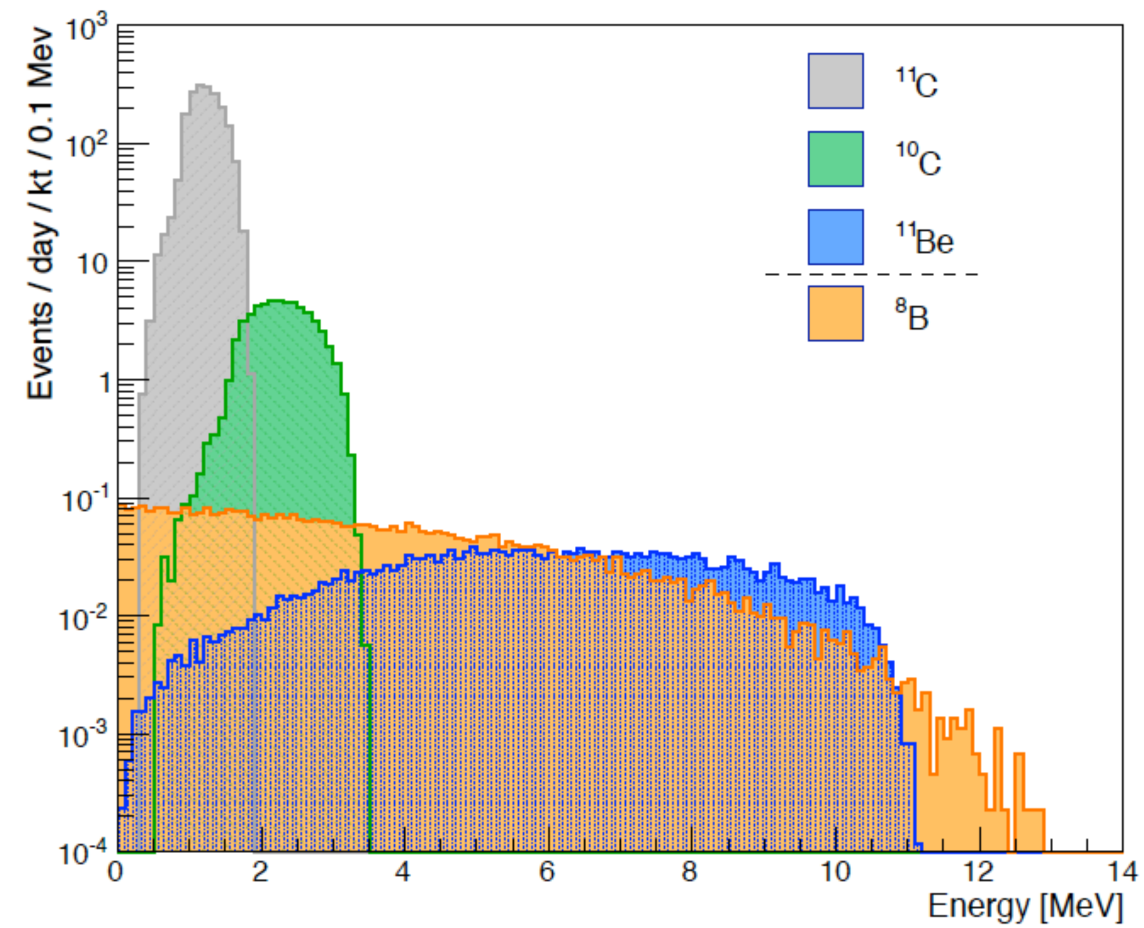
Solar neutrinos: possible?

- Refined measurements of ^{7}**Be** and ^{8}**B** fluxes would constrain metallicity in Sun-like stars better
- JUNO with large exposure ideal to enhance statistics and measure ^{7}Be "shoulder" thx to unprecedented E_{res}
- <u>Radio-purity (for ^{7}Be) and event-by-event cosmogenic veto (^{8}B) capabilities</u> main challenges that remain open
  - also, dedicated triggers and study of ^{14}C-^{14}C overlap might be needed for low E



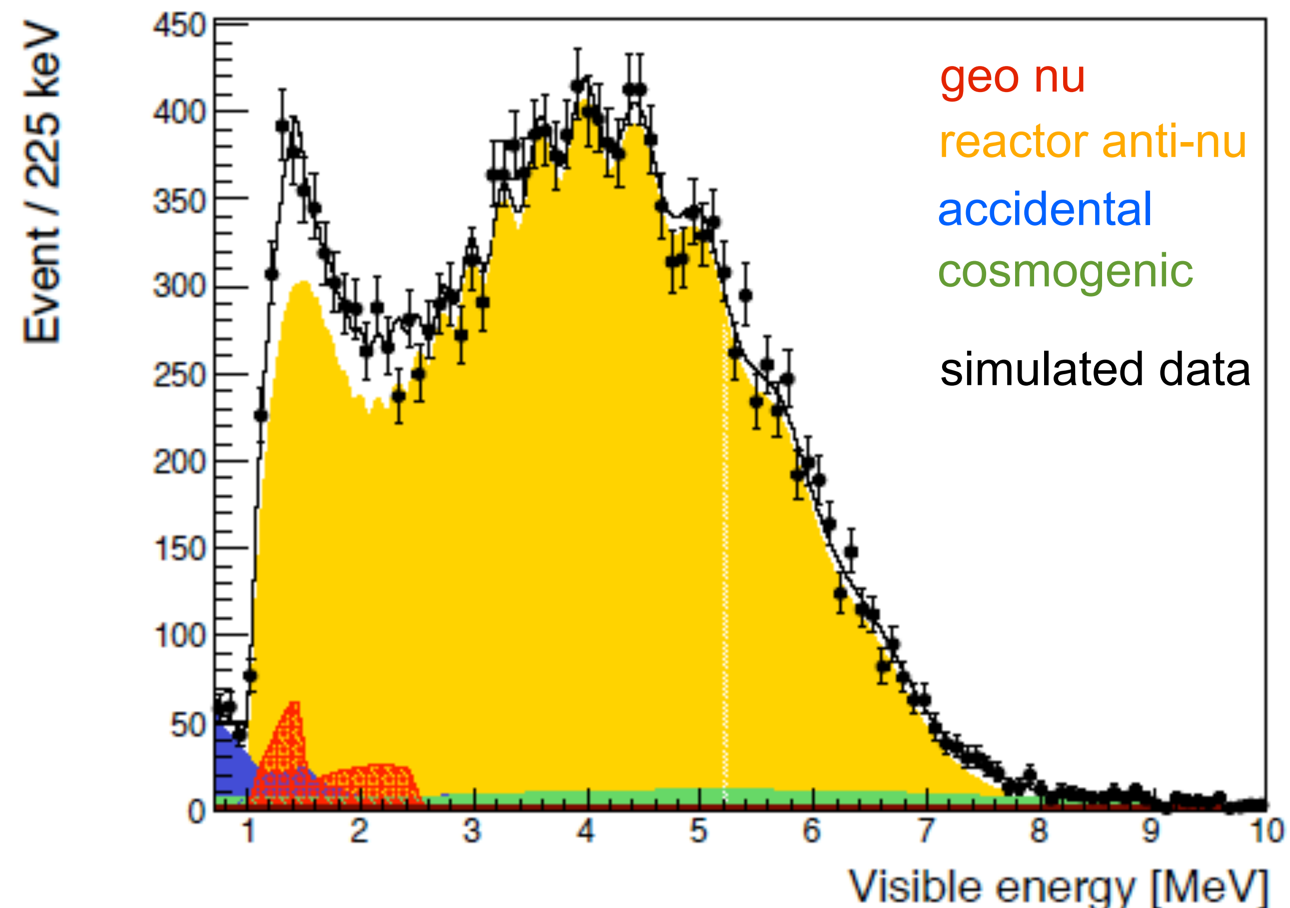
Assumed radio-purity: 10^{-16} g/g (^{238}U, ^{232}Th)





Geo-neutrinos

- Geo-neutrino "observational network" now developed across world
  - current (KamLAND + Borexino) precision on geo-neutrino (U+Th) flux is ~17-25%, SNO+ will join in
- at JUNO same challenges as for solar measurements
  - + here reactor ν large background
- signal can be extracted by template fit
- thanks to its mass, JUNO can reach 17% precision on the (U+Th) flux within the first year and 6% after 10 years
- U vs Th separation achievable with 11%-19% after 10 years



single toy Monte Carlo for 1-year measurement with fixed chondritic Th/U mass ratio

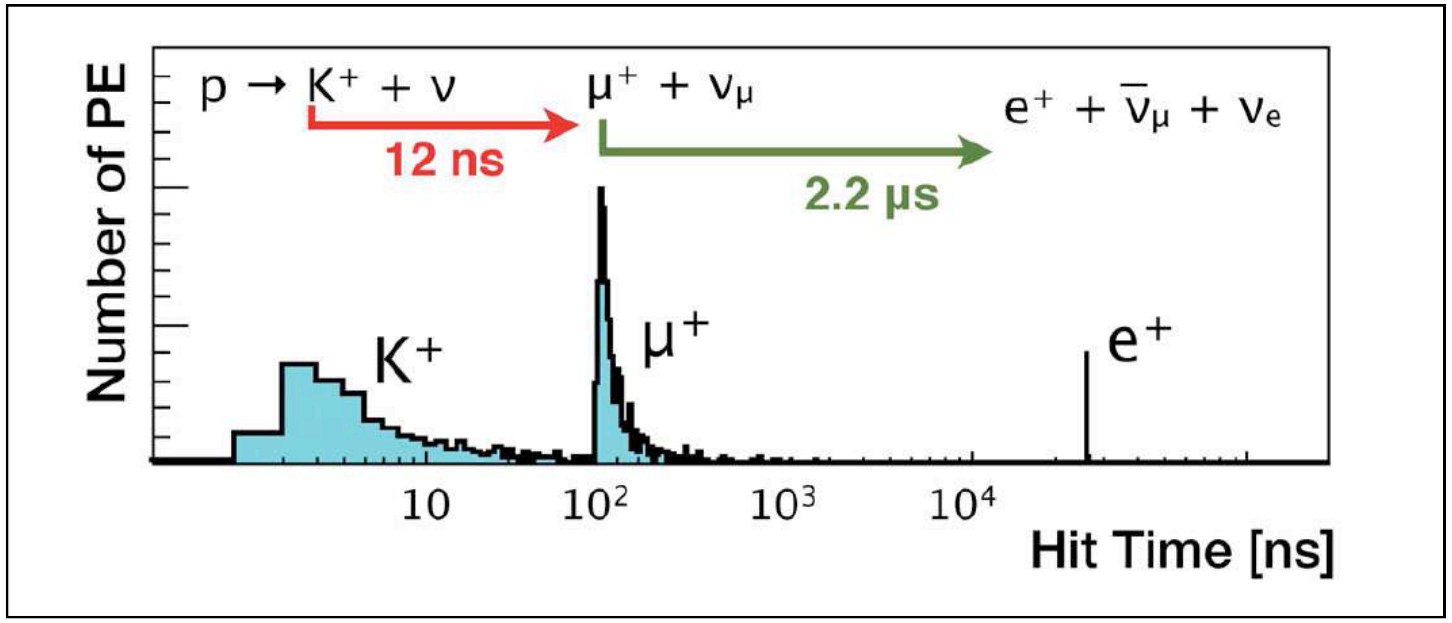
Table 8-4: Signal and backgrounds considered in the geoneutrino sensitivity study: the number of expected events for all components contributing to the IBD spectrum in the 0.7 - 12 MeV energy region of the prompt signal. We have assumed 80% antineutrino detection efficiency and 17.2 m radial cut (18.35 kton of liquid scintillator, 12.85×10^{32} target protons).

Source	Events/year
Geoneutrinos	408 ± 60
U chain	311 ± 55
Th chain	92 ± 37
Reactors	16100 ± 900
Fast neutrons	36.5 ± 36.5
^{9}Li - ^{8}He	657 ± 130
$^{13}C(\alpha, n)^{16}O$	18.2 ± 9.1
Accidental coincidences	401 ± 4

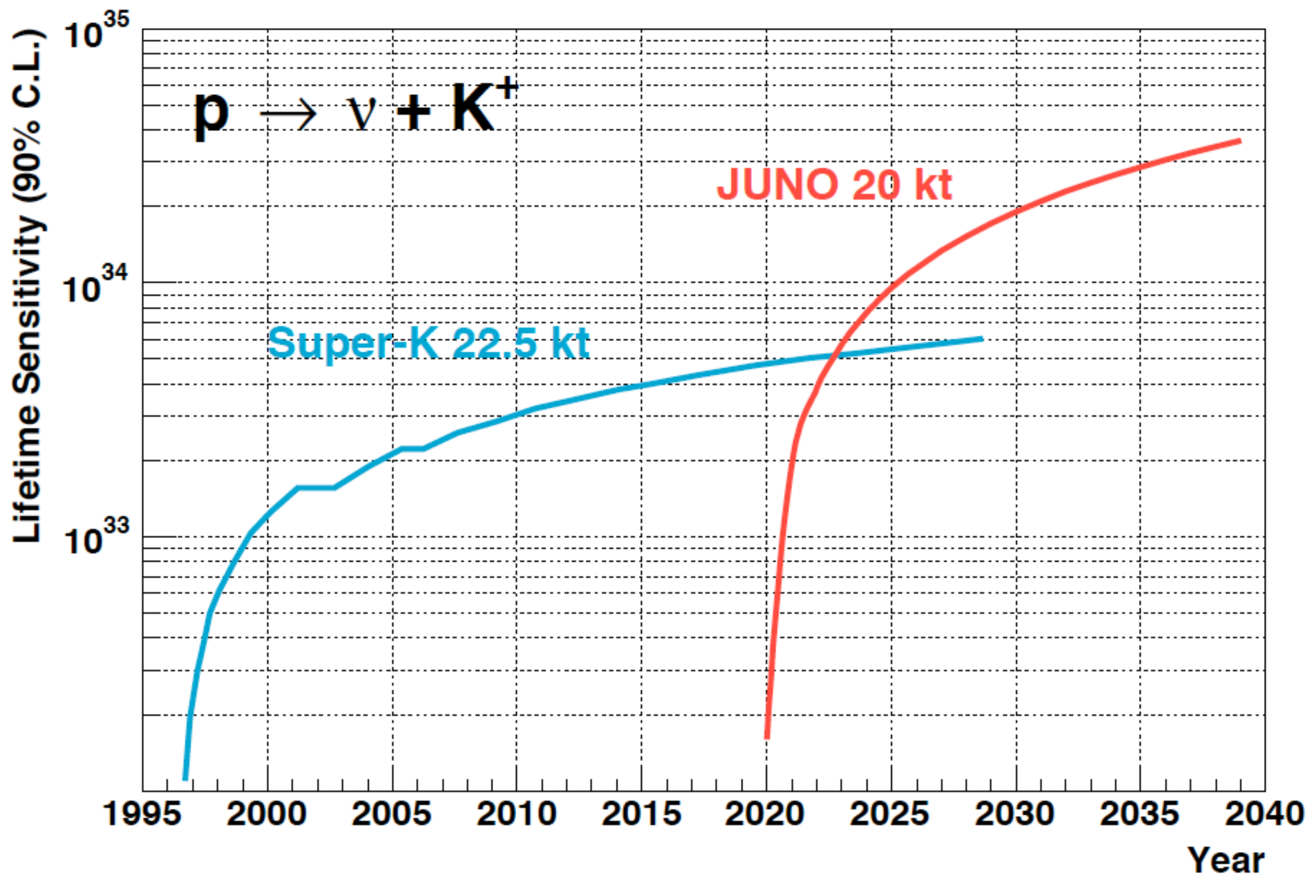
Proton decay

$BR(K^+ \to \mu^+ \nu_\mu) = 63.43\%$

- JUNO complementary to large Cherenkov detectors (e.g. SK, HK) in search for proton decays
- from H, $p \to \nu + K^+ (\to \mu^+ \nu_\mu)$ decay sub-threshold for Cherenkov light in water but $E_{kin}(K^+) \sim 105$ MeV well visible as scintillation light
- Main bkg: muons from atmospheric neutrinos (but different time pattern)



- a cut on the time interval between time where pulse=15% wrt maximum and time where pulse=85% is more effective for signal than atmospheric 1-pulse
- *ΔT(15-85) > 7 ns keeps ~65% signal, rejects >99% bkg*



- expected background is 0.5 events in 10 years
- expected $\tau > 1.9 \; 10^{34}$ yrs *(Feldman-Cousins)*
- example "observed" would be $\tau > 6.8 \; 10^{33}$ yrs if 2 events of bkg fluctuation
- With current projections, JUNO will be competitive (and complementary) soon after switch-on

Schedule

- **2013**: Complete conceptual design. Complete civil design and bidding
- **2014**: Start civil construction. Complete prototyping (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 and assembly
- **2018**: Start LS production
- **2019**: Complete detector assembly, installation and LS filling
- **2020**: Start data taking

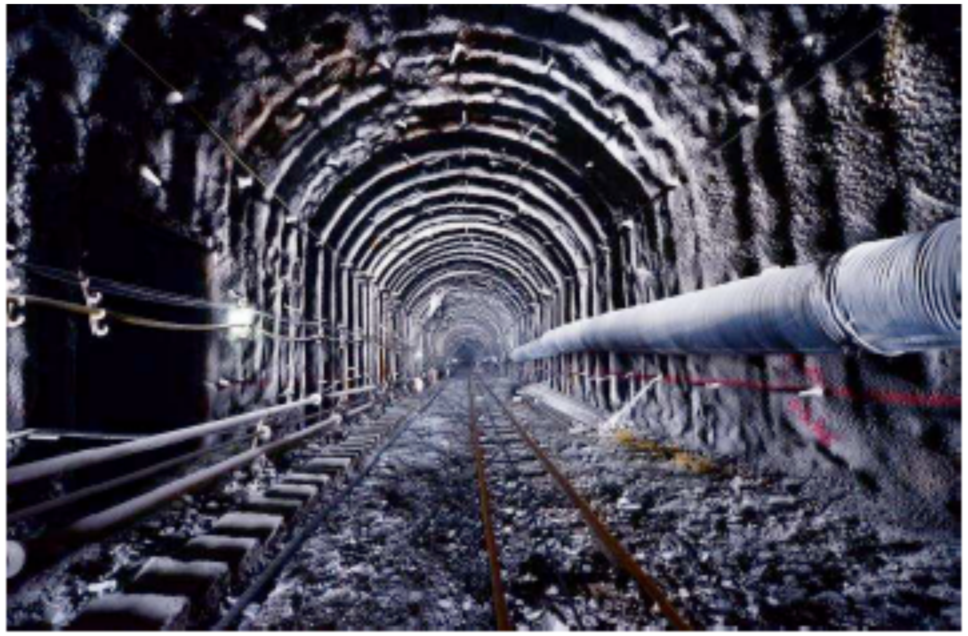
Conclusions

- With its size and unprecedented energy resolution, JUNO will have an impact on many areas of neutrino physics

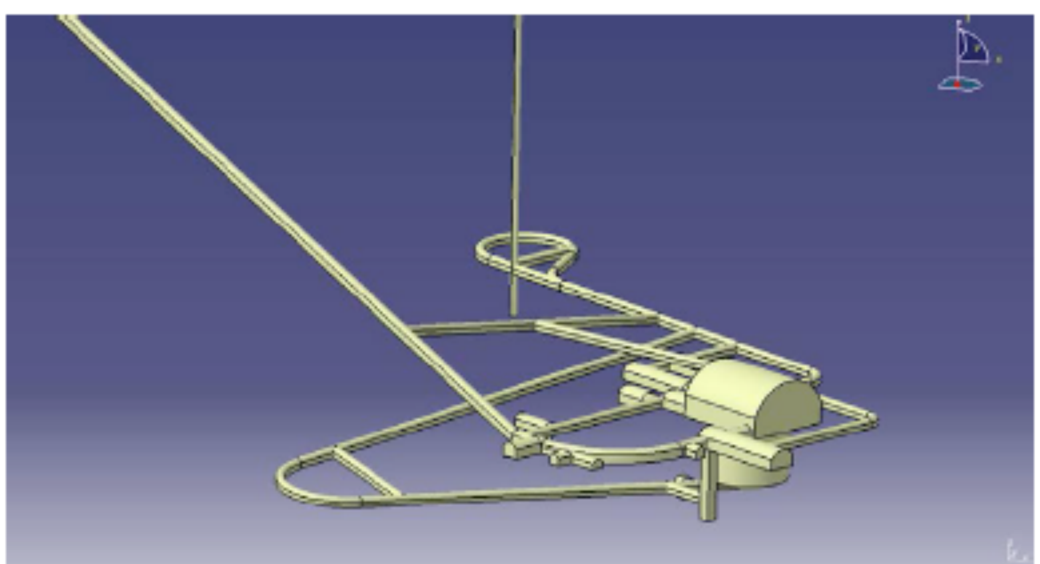
- Demanding specs to meet challenging and multi-faceted physics programme (MH and beyond)
- Hope I gave you an idea of the many technical aspects considered and tests put in place to achieve best possible performance and reliability in detector and electronics design
  - Now it's the time to produce and build...

Additional material

JUNO civil construction



- 1020m slope tunnel excavated out of 1340m (few months ago)
  - initial delays on account of underground water leaks now under control
- ~580 m deep vertical shaft excavated
- Overburden to JUNO: ~700m (~1900 MWE)



Interference term

Survival probability

$$P_{\bar\nu_e\to\bar\nu_e} = 1 - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

Fast oscillations with the two similar mass splittings

slow solar oscillations

$$\Delta_{ij} \equiv \Delta m^2_{ij} L/4E,$$

$$= 1 - \frac{1}{2}\sin^2 2\theta_{13}\left[1 - \sqrt{1 - \sin^2 2\theta_{12}\sin^2\Delta_{21}}\cos\left(2|\Delta_{ee}| \pm \phi\right)\right] - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21},$$

NH: +
IH: -

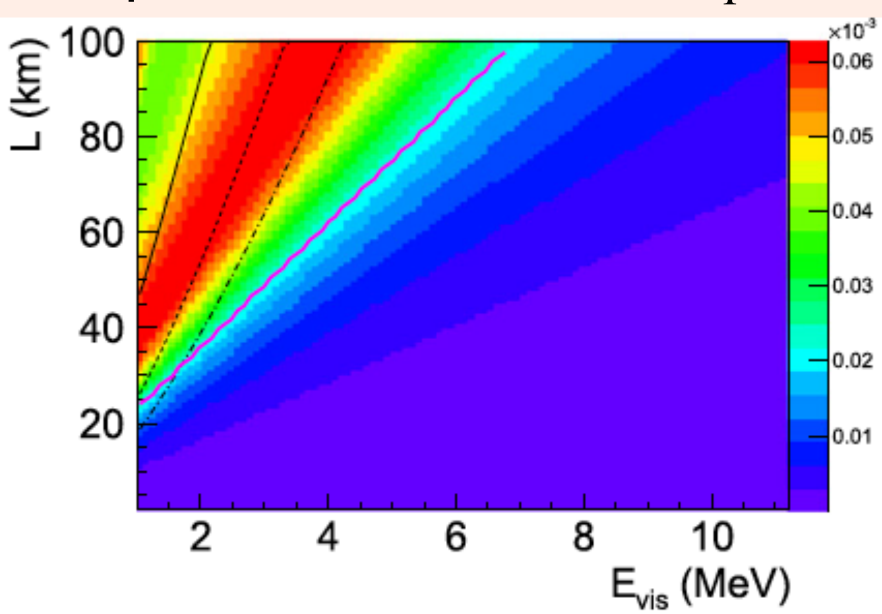
$$\Delta m^2_\phi = 4E\phi/L.$$

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

$$\sin\phi = \frac{c^2_{12}\sin\left(2s^2_{12}\Delta_{21}\right) - s^2_{12}\sin\left(2c^2_{12}\Delta_{21}\right)}{\sqrt{1-\sin^2 2\theta_{12}\sin^2\Delta_{21}}},$$

$$\cos\phi = \frac{c^2_{12}\cos\left(2s^2_{12}\Delta_{21}\right) + s^2_{12}\cos\left(2c^2_{12}\Delta_{21}\right)}{\sqrt{1-\sin^2 2\theta_{12}\sin^2\Delta_{21}}},$$

Can be seen as an extra effective mass-squared difference Δm^2_Φ= f(E,L)

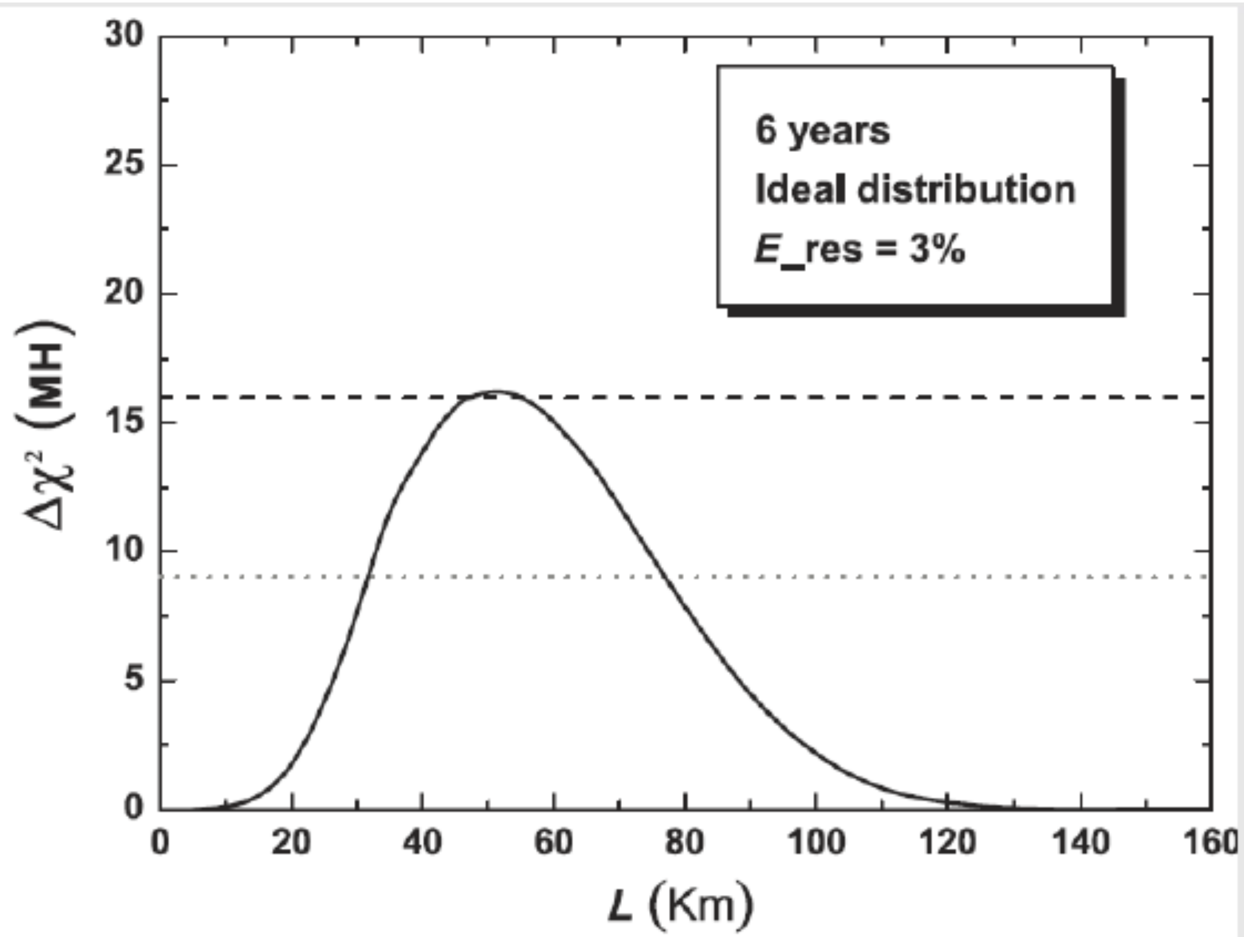


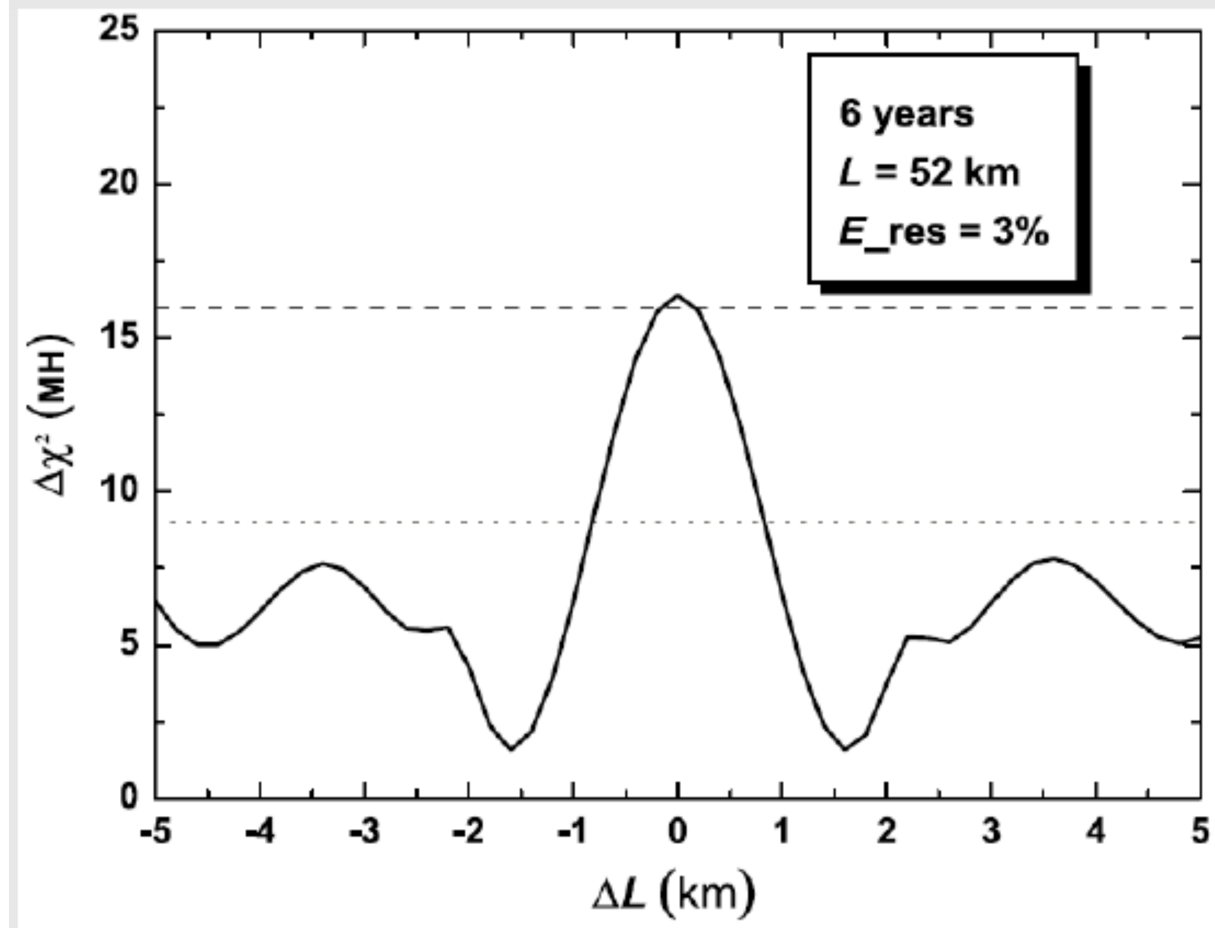
Effective mass-squared difference

NH: $2|\Delta m^2_{ee}| + \Delta m^2_\Phi$ and increases with energy

IH: $2|\Delta m^2_{ee}| - \Delta m^2_\Phi$ and decreases with energy

Baseline optimization





Optimal baseline is at L = 50-60 km, at the oscillation maximum of Δm^2_{12}

In case of multiple reactors, minimize the spread of L

Choice of the experimental site

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

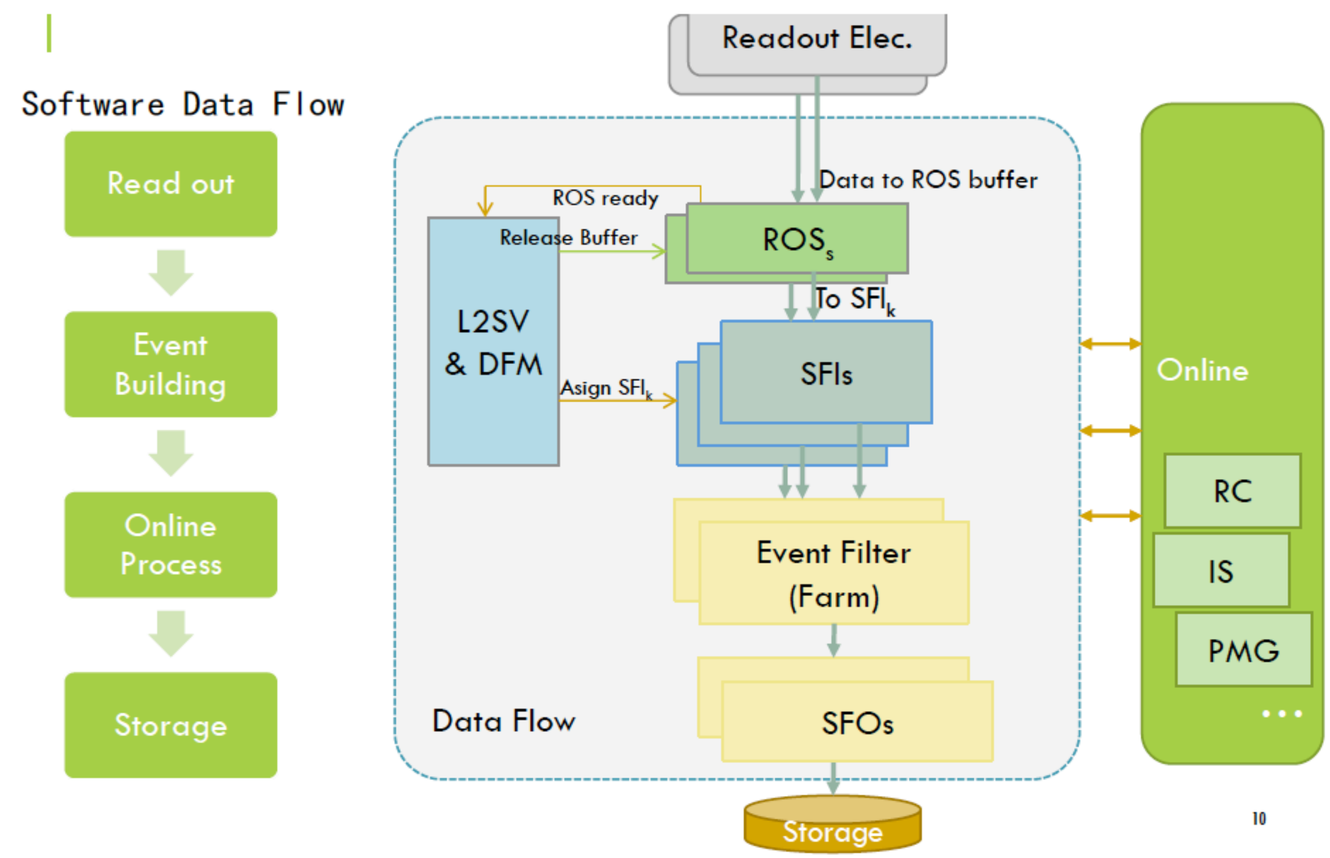
Baseline trigger

Trigger

- all the PMT send out a trigger signal, synchronous with the reference clock
- if a decision by the Global Trigger Electronics (dry), data request sent to the single PMTs. PMT reply by sending the requested waveform data, in a specific time window, through async lines

DAQ

- each 20'' PMT read out one-by-one : 16 Mbit/s (with 1 kHz physics rate)
  - ~2GB/s (CDR)
- 3'' PMT read out in blocks of 128 channels: ≤ 1 Mbit/s



Isotopes	Q (MeV)	$T_{1/2}$	Rate (per day)
^{3}H	0.0186 (β^-)	12.31 year	1.14×10^4
^{6}He	3.508 (β^-)	0.807 s	544
^{7}Be	Q_{EC}=0.862 (10.4% γ, $E_\gamma = 0.478$)	53.22 day	5438
^{8}He	10.66 ($\beta^-\gamma : 84\%$), 8.63 ($\beta^- n : 16\%$)	0.119 s	11
^{8}Li	16.0 (β^-)	0.839 s	938
^{8}B	16.6 (β^+)	0.770 s	225
^{9}Li	13.6 ($\beta^- : 49\%$), 11.94 ($\beta^- n : 51\%$)	0.178 s	94
^{9}C	15.47 ($\beta^+ p : 61.6\%, \beta^+\alpha : 38.4\%$)	0.126 s	31
^{10}Be	0.556 (β^-)	1.51e6 year	1419
^{10}C	2.626 ($\beta^+\gamma$)	19.29 s	482
^{11}Li	20.55 ($\beta^- n : 83\%$, $\beta^- 2n : 4.1\%$)	0.00875 s	0.06
^{11}Be	11.51 ($\beta^-\gamma : 96.9\%$), 2.85 ($\beta^-\alpha : 3.1\%$)	13.76 s	24
^{11}C	0.960 (β^+)	20.36 min	1.62×10^4
^{12}Be	11.708 ($\beta^-\gamma$, $\beta^- n : 0.5\%$)	0.0215 s	0.45
^{12}B	13.37 ($\beta^-\gamma$)	0.0202 s	966
^{12}N	16.316 ($\beta^+\gamma$)	0.0110 s	17
^{13}B	13.437 ($\beta^-\gamma$)	0.0174 s	12
^{13}N	1.198 (β^+)	9.965 min	19
^{14}B	20.644 ($\beta^-\gamma$, $\beta^- n : 6.1\%$)	0.0126 s	0.021
^{14}C	0.156 (β^-)	5730 year	132
^{15}C	9.772 (β^-)	2.449 s	0.6
^{16}C	8.010 ($\beta^- n : 99\%$)	0.747 s	0.012
^{16}N	10.42 ($\beta^-\gamma$)	7.130 s	13
^{17}N	8.680 ($\beta^-\gamma : 5\%$), 4.536 ($\beta^- n : 95\%$)	4.173 s	0.42
^{18}N	13.896 ($\beta^-\gamma : 93\%$), 5.851 ($\beta^- n : 7\%$)	0.620 s	0.009
neutron			155 000

Table 13-9: The estimated rates for cosmogenic isotopes in JUNO LS by FLUKA simulation, in which the oxygen isotopes are neglected. The decay modes and Q values are from TUNL Nuclear Data Group [479].

JUNO can be a telescope