The Jiangmen Underground Neutrino Observatory

Institute of High Energy Physics
Chinese Academy Of Sciences
中国科学院高能物理研究所

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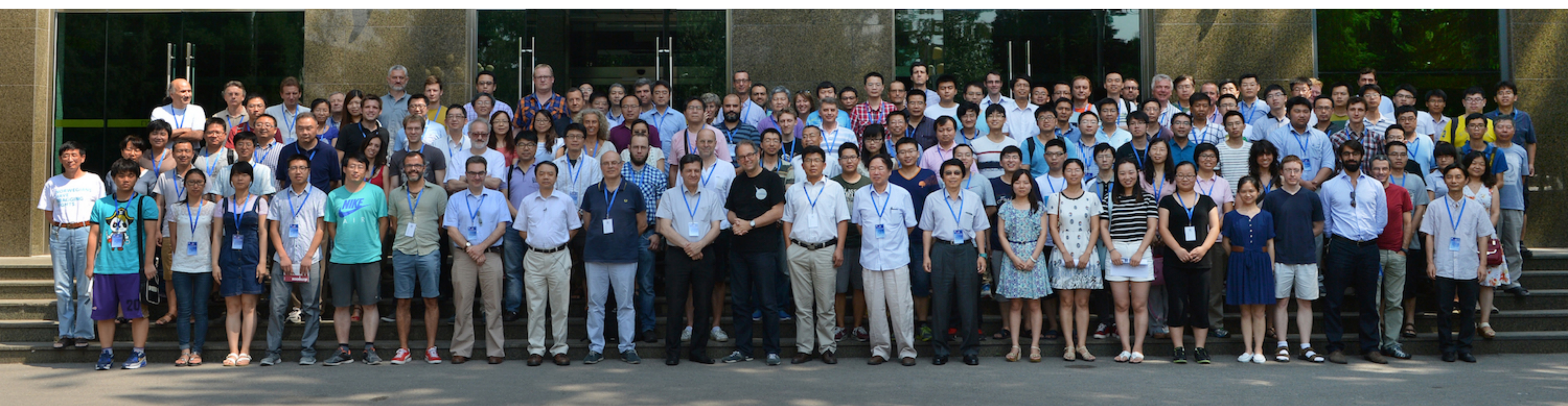
on behalf of the JUNO Collaboration



Outline

JUNO — **Neutrino**

Few slides to give some context

JUNO — **Observatory**

What we want to observe (Physics Programme)

JUNO — **Jiangmen**

Where the detector is located (hint: close to nuclear power plants)

JUNO — **Underground**

Civil engineering

JUNO — **Observatory**

How we observe (the Detector)

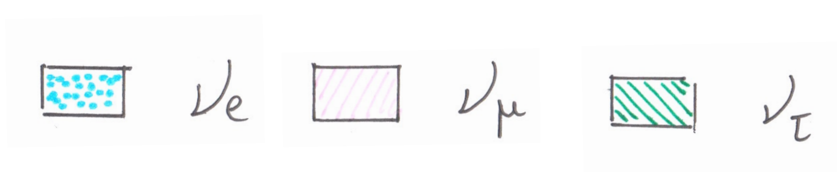
Neutrino Mixing - Theory

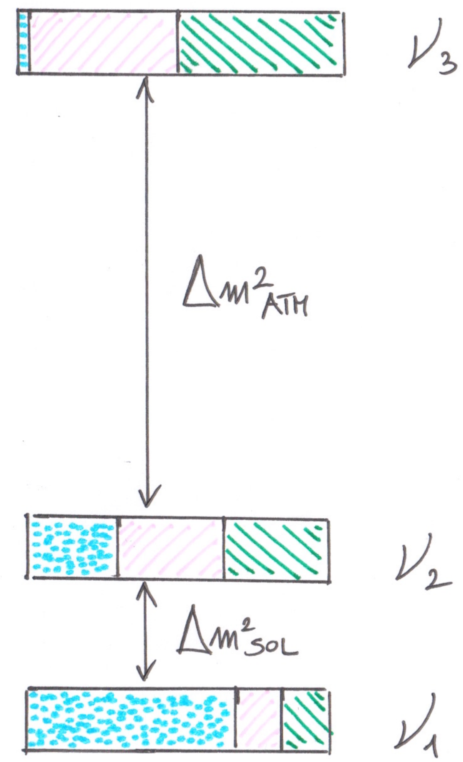
Three Flavor Eigenstates

Three Mass Eigenstates

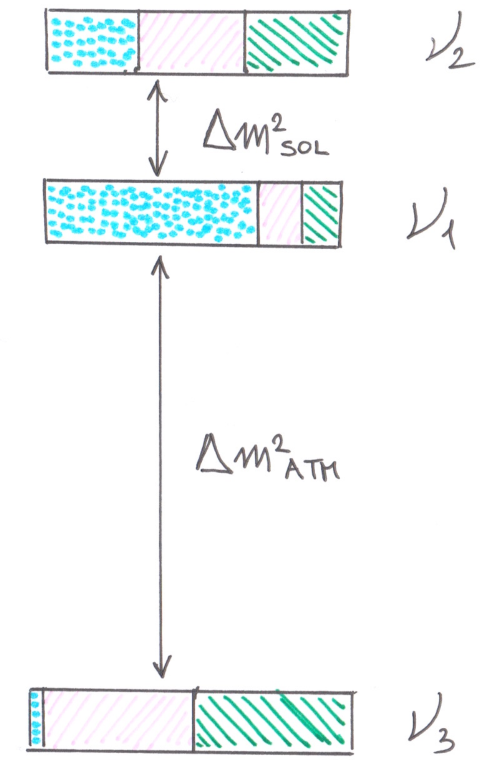
$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha,i}\,|\nu_i\rangle$$

$$\alpha = e, \mu, \tau$$





Normal Hierarchy

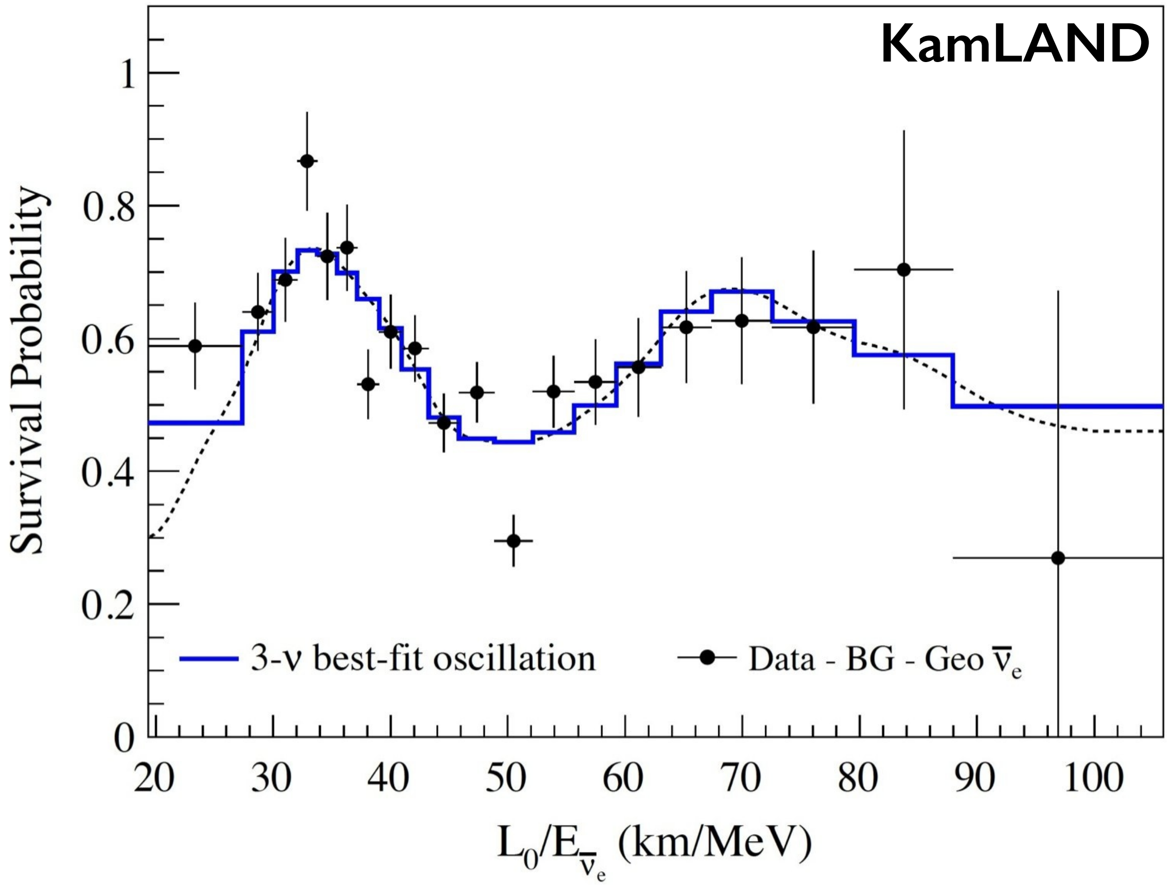


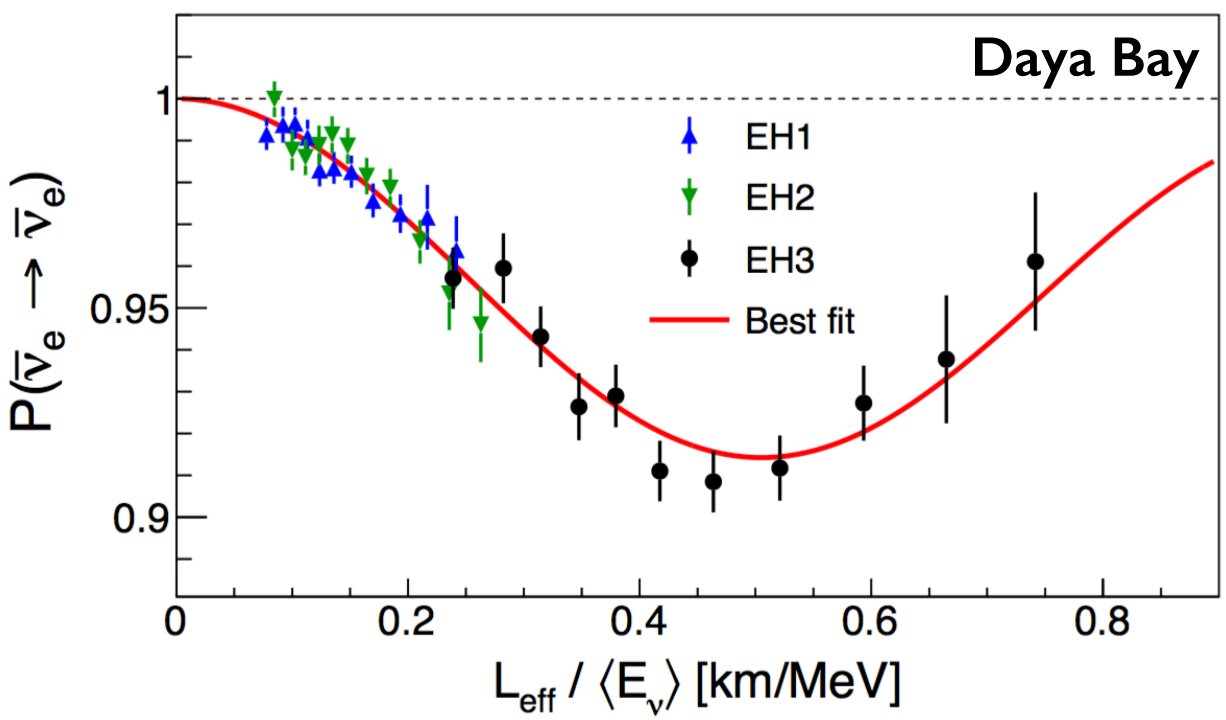
Inverted Hierarchy

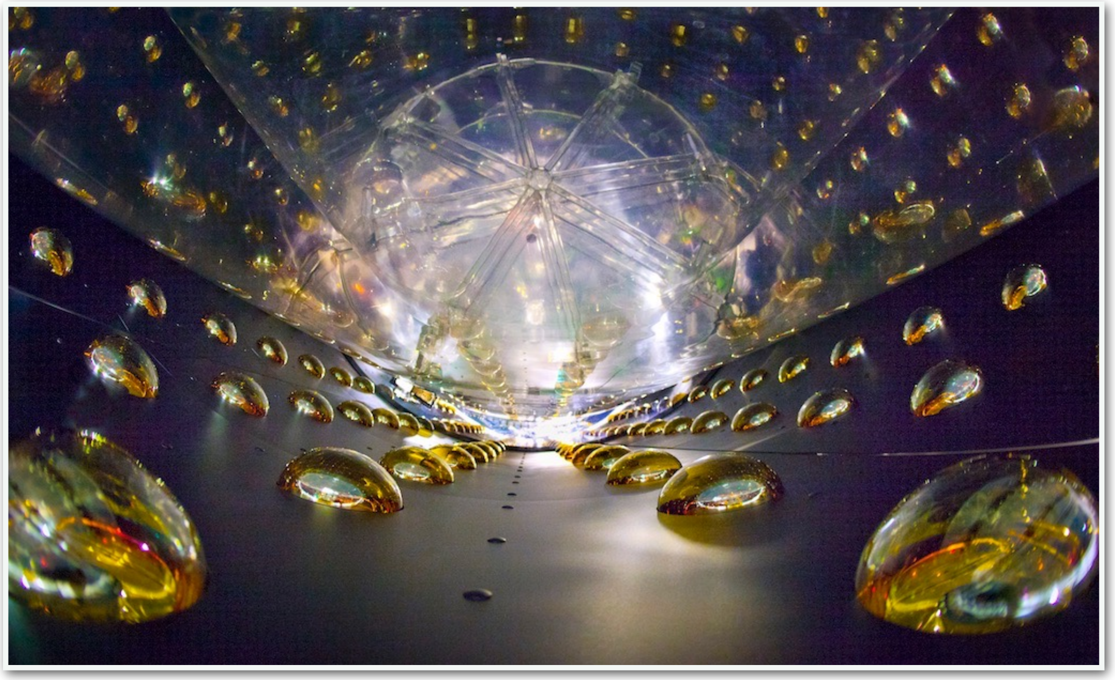
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\vartheta_{23} & \sin\vartheta_{23} \\ 0 & -\sin\vartheta_{23} & \cos\vartheta_{23} \end{pmatrix} \begin{pmatrix} \cos\vartheta_{13} & 0 & \sin\vartheta_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\vartheta_{13}\, e^{i\delta} & 0 & \cos\vartheta_{13} \end{pmatrix} \begin{pmatrix} \cos\vartheta_{12} & \sin\vartheta_{12} & 0 \\ -\sin\vartheta_{12} & \cos\vartheta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric | Reactor (L~1km) | Solar

Neutrino Oscillation - Experimental

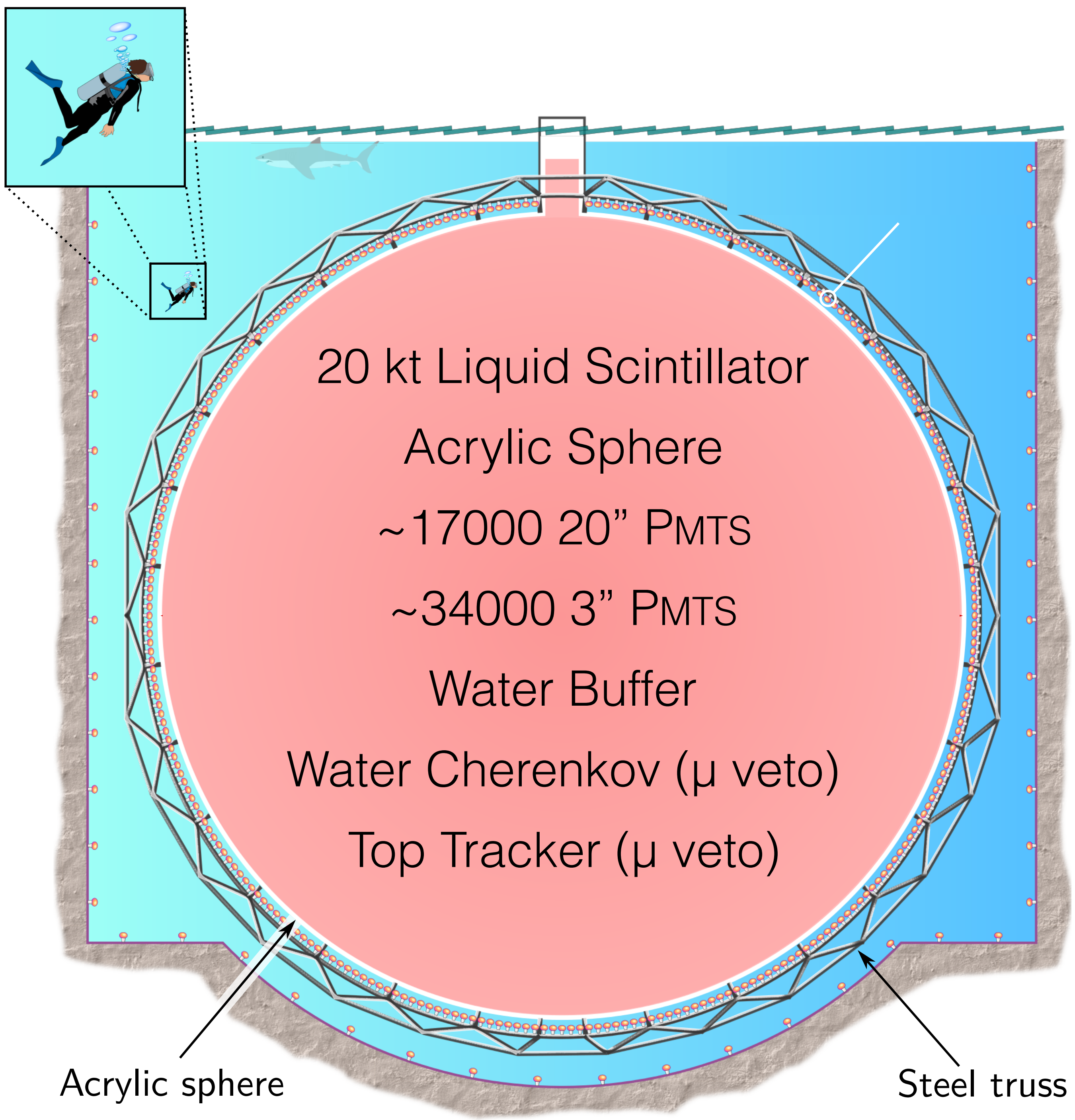






JUNO in the Experimental Neutrino Landscape

Liquid Scintillator (Anti)neutrino Detector



2 Key parameters:

LARGE & PRECISE

	DETECTOR TARGET MASS	RESOLUTION
KamLAND	1000 t	$6\%/\sqrt{E}$
Double Chooz	8 t	$8\%/\sqrt{E}$
RENO	16 t	$8\%/\sqrt{E}$
Daya Bay	20 t	$8\%/\sqrt{E}$
Borexino	300 t	$5\%/\sqrt{E}$
JUNO	20000 t	$3\%/\sqrt{E}$

Physics Programme

Reactor Neutrinos

- First combined observation of solar and atmospheric oscillation
- Mass hierarchy via solar-atmospheric interference
- Vacuum oscillation ▶ Not relying on matter enhancement (and related uncertainties)
- No θ_{23} octant or δ_{cp} ambiguities ▶ Complementary to NOvA, Pingu, DUNE
- Most precise measurement of solar parameters (θ_{12}, Δm^2_{12})

Supernova Neutrinos

- Supernova burst likely to happen in the next 10 years
- Unique opportunity for Particle Physics and Astrophysics

Geoneutrinos

- JUNO alone might detect more geo-ν than all the other world exps together

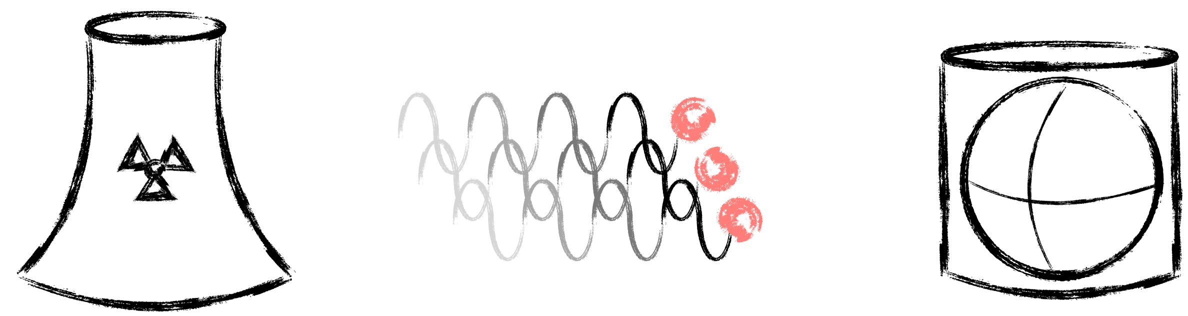
Solar Neutrinos

- Open issues in Solar physics (MSW turn on, Metallicity) could be addressed

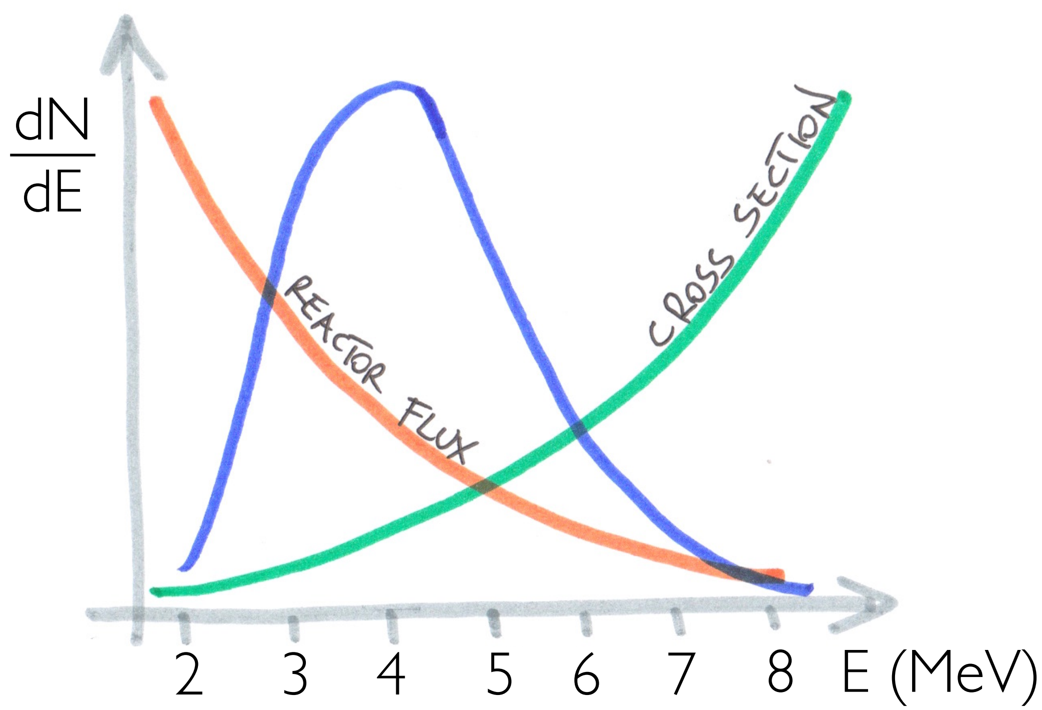
Much More

- Take a look at our Yellow Book: J.Phys. G43 (2016) no.3, 030401

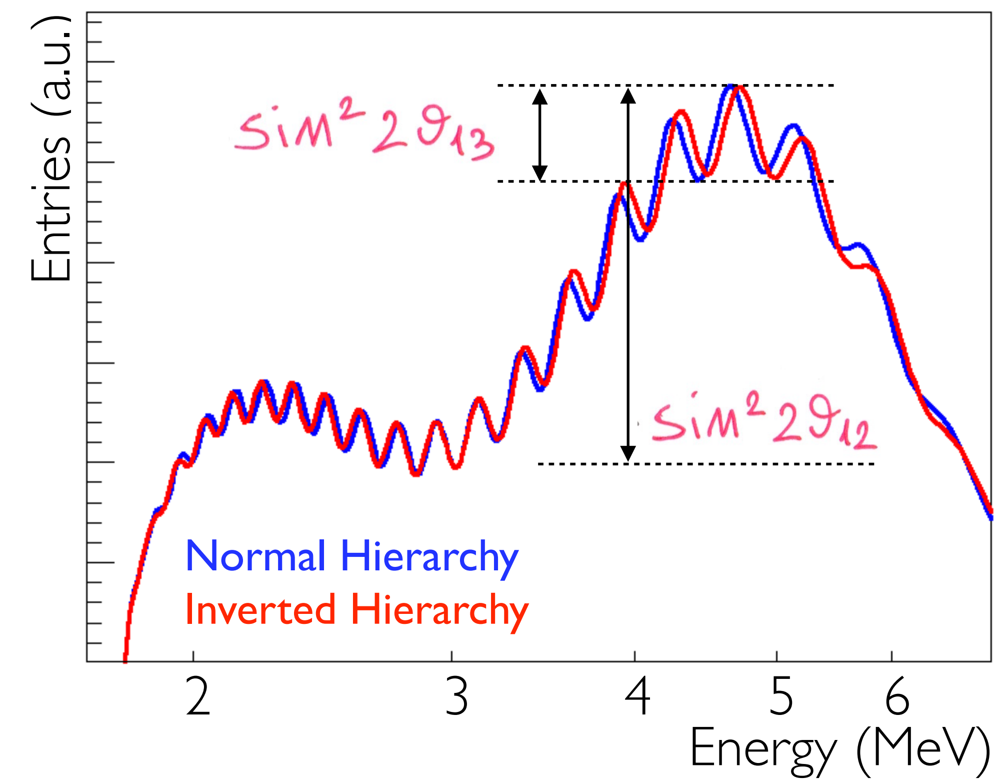
Antineutrinos from Reactor



Spectrum at Emission



Spectrum at 50 Km

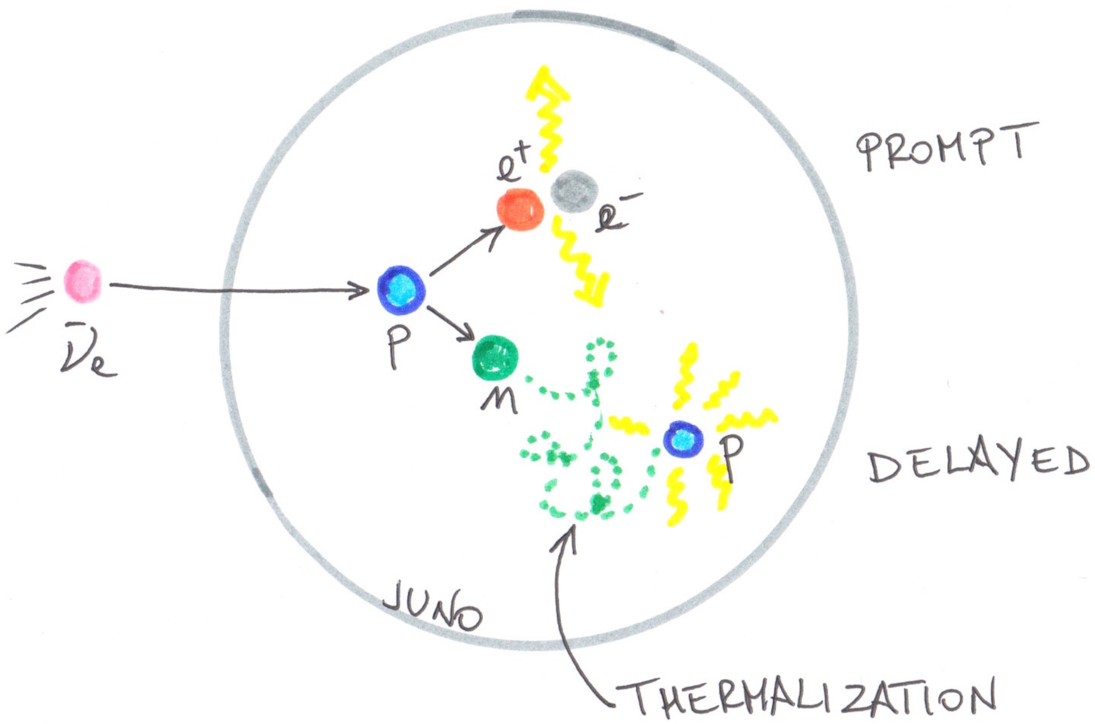


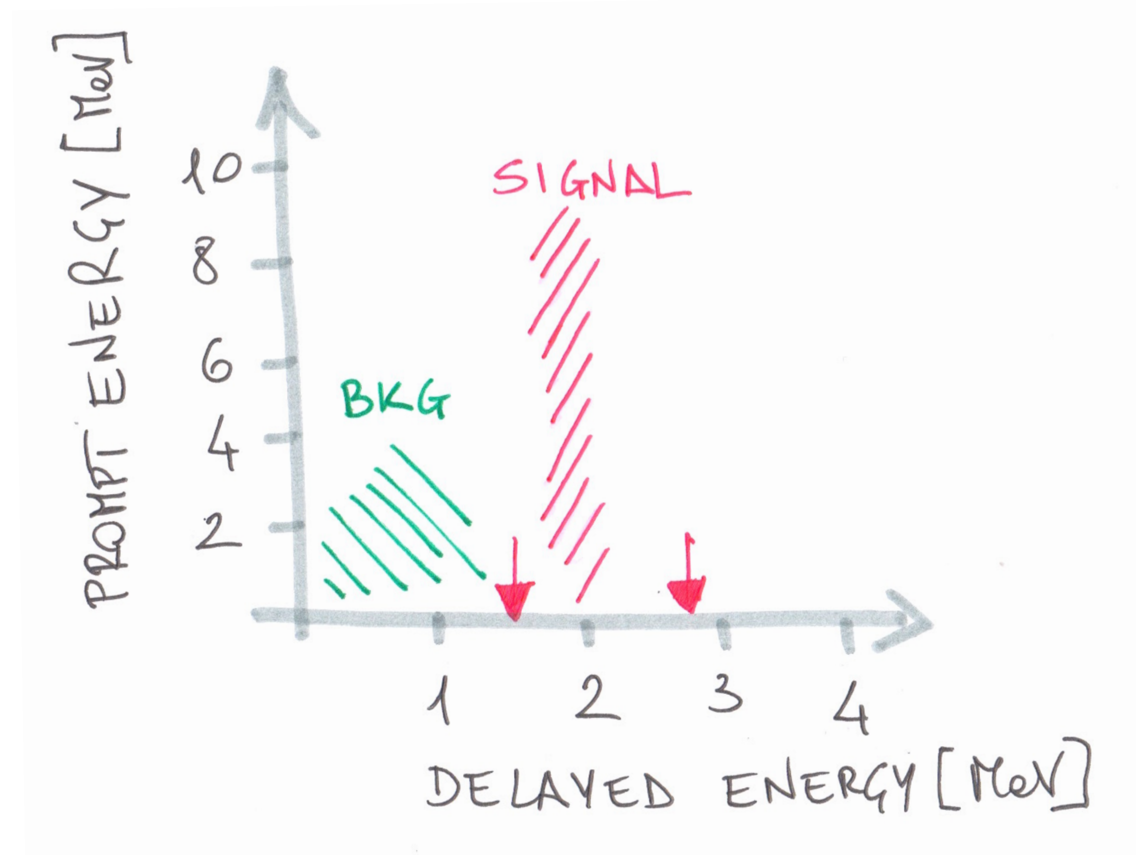
Survival Probability

$$P_{\bar\nu_e\to\bar\nu_e} = 1 - \sin^2 2\theta_{13}\cdot\sin^2\left(\cos^2\theta_{12}\,\sin^2\Delta_{31} + \sin^2\theta_{12}\,\sin^2\Delta_{32}\right) \qquad \text{FAST} \quad \Delta m^2_{ATM}$$

$$- \sin^2 2\theta_{12}\,\cos^4\theta_{13}\,\sin^2\Delta_{21} \qquad \text{SLOW} \quad \Delta m^2_{SOL}$$

Antineutrino Detection - Signal Events





Inverse Beta Decay (IBD) :

$$\bar{\nu}_e + p \longrightarrow e^+ + n$$ Prompt

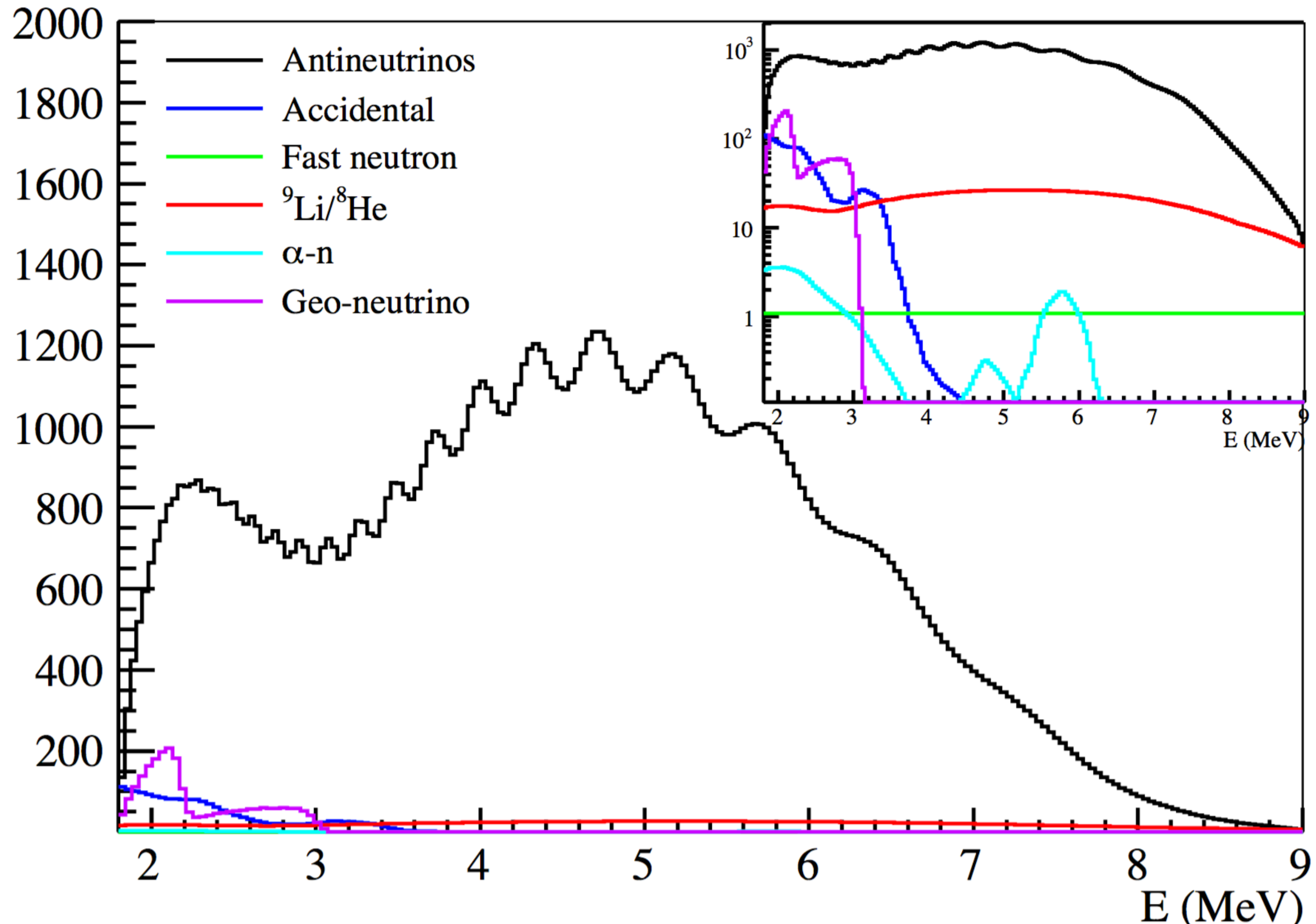
$$n + p \xrightarrow{\tau \sim 200\,\mu s} D + \gamma \;(2.2\ \mathrm{MeV})$$ Delayed

60 IBD/day

$$E(\bar{\nu}_e) = K(e^+) + K(n) - (m(n) - m(p)) + m(e^+) \sim K(e^+) + 1.8\ \mathrm{MeV}$$

Visible Energy

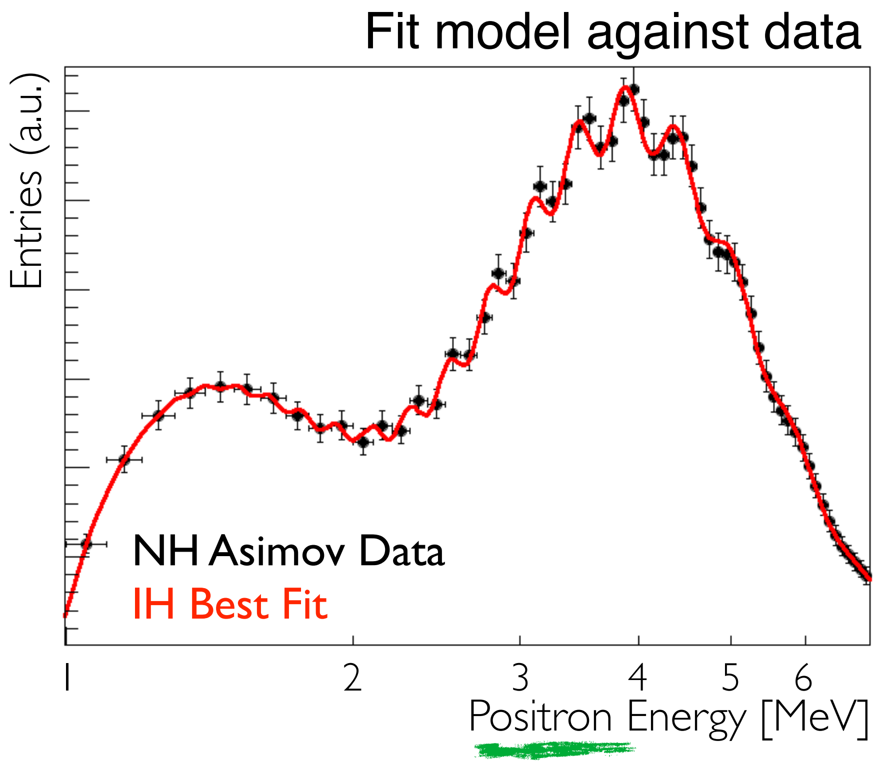
Selection Criteria & Residual Background



Event Rate per Day

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				

Mass Hierarchy Determination



Many Experimental Caveats

Detection Systematics

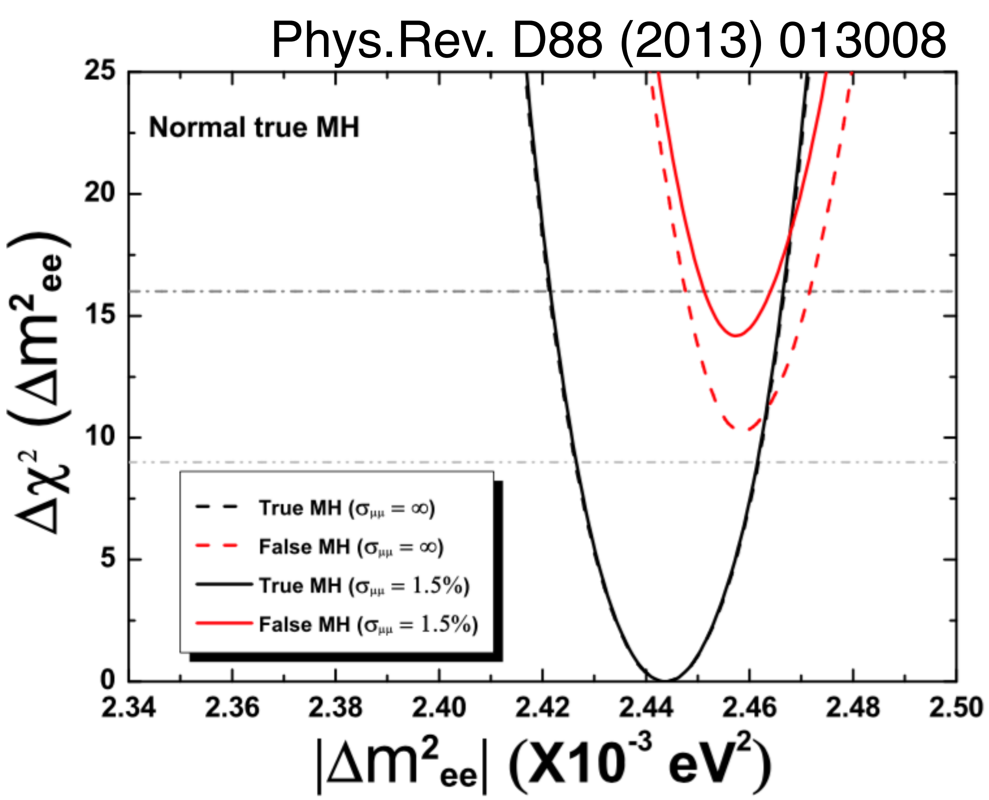
- Energy Resolution

- Energy Linearity

Background-related uncertainties

Spatial distribution of reactor cores

>>> we'll deal with them in a few slides



Mass Hierarchy Sensitivity

100k signal events (20kt x 36GW x 6 years)

$\Delta\chi^2$: Fitting wrong model - Fitting correct one

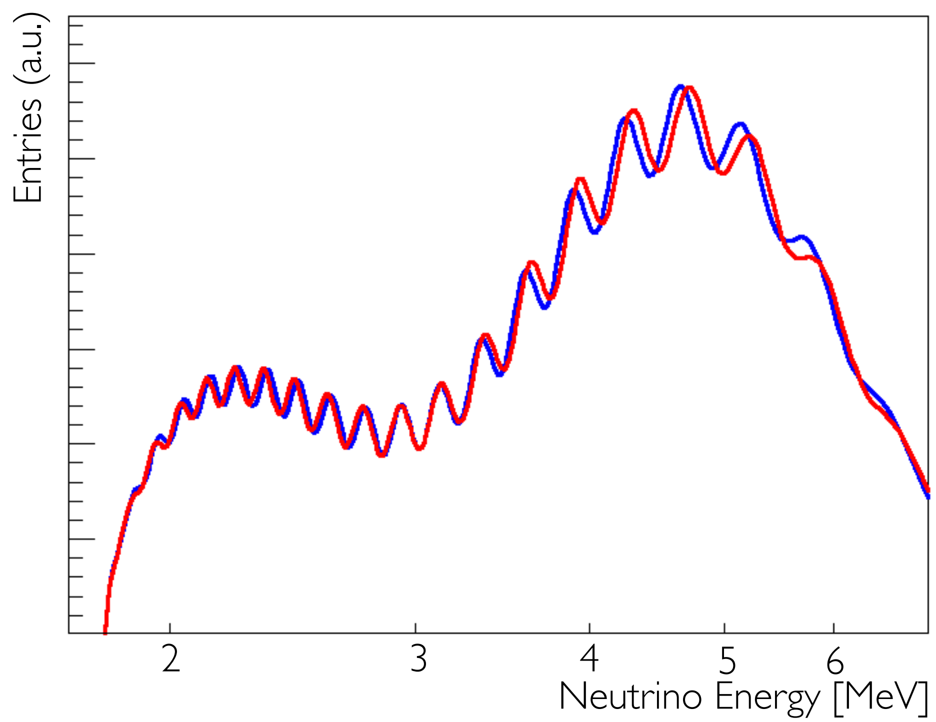
Unconstrained (JUNO only) $\Delta\chi^2 \sim 10$

Using external $\Delta m_{\mu\mu}$ (1.5% precision) from long baseline exps: $\Delta\chi^2 \sim 14$

Oscillation Parameters

Access to four oscillation parameters: θ_{13} , θ_{12} , Δm^2_{21} , $|\Delta m^2_{ee}|$

Measurement of $\sin^2(2\theta_{12})$, Δm^2_{21} , $|\Delta m^2_{ee}|$ with better than 1% precision



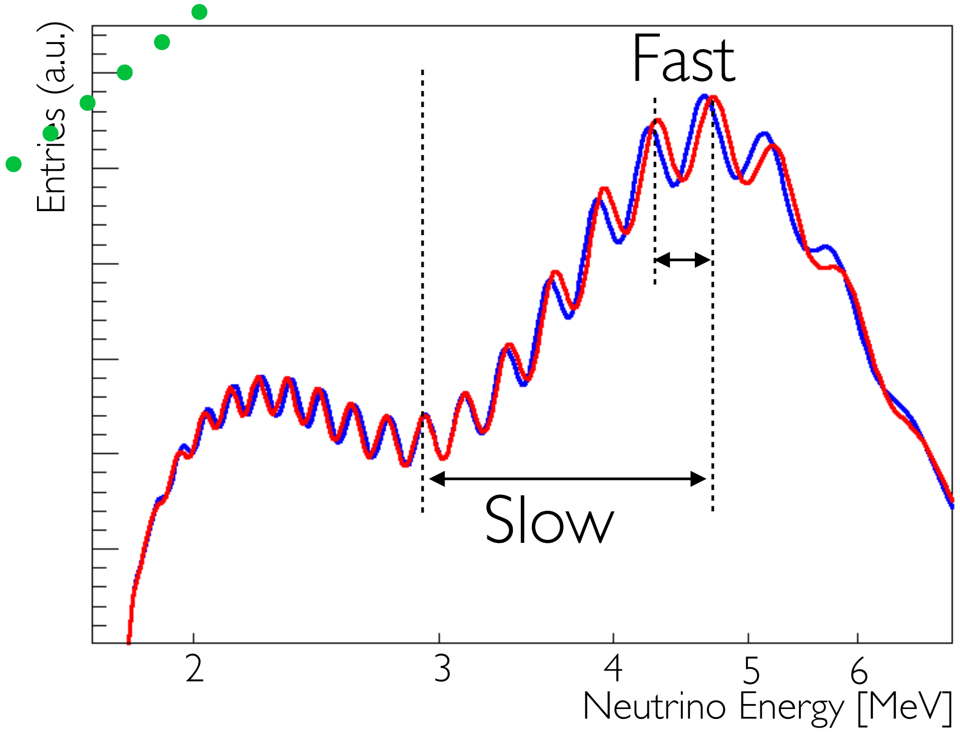
$$P_{\bar\nu_e \to \bar\nu_e} = 1 - \sin^2 2\vartheta_{13} \cdot \sin^2\left(\cos^2\vartheta_{12}\ \sin^2\Delta_{31} + \sin^2\vartheta_{12}\ \sin^2\Delta_{32}\right) \quad \text{Fast} \quad \Delta m^2_{ATM}$$

$$- \sin^2 2\vartheta_{12}\ \cos^4\vartheta_{13}\ \sin^2\Delta_{21} \quad \text{Slow} \quad \Delta m^2_{SOL}$$

Mass Splittings

Access to four oscillation parameters: θ_{13} , θ_{12} , Δm^2_{21} , $|\Delta m^2_{ee}|$

Measurement of $\sin^2(2\theta_{12})$, Δm^2_{21} , $|\Delta m^2_{ee}|$ with better than 1% precision



$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\vartheta_{13} \cdot \sin^2\left(\underbrace{\cos^2\vartheta_{12}\,\sin^2\Delta_{31} + \sin^2\vartheta_{12}\,\sin^2\Delta_{32}}\right)$$

Fast Δm^2_{ATM}

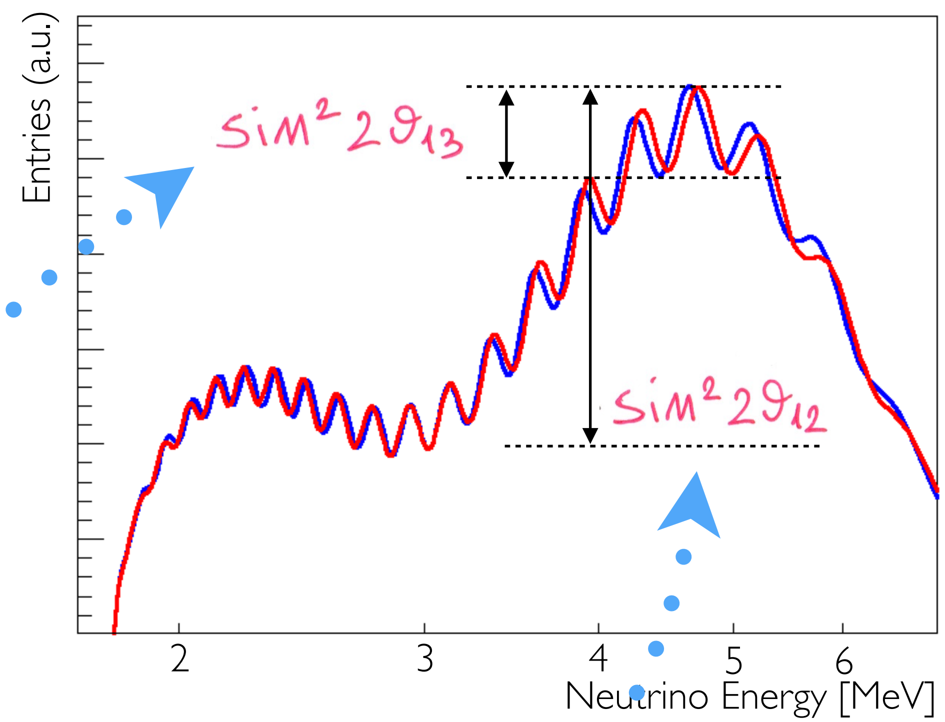
$$- \sin^2 2\vartheta_{12}\,\cos^4\vartheta_{13}\,\sin^2\Delta_{21}$$

Slow Δm^2_{SOL}

Mixing Angles

Access to four oscillation parameters: θ_{13} , θ_{12} , Δm^2_{21} , $|\Delta m^2_{ee}|$

Measurement of $\sin^2(2\theta_{12})$, Δm^2_{21} , $|\Delta m^2_{ee}|$ with better than 1% precision



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Fast Δm^2_{ATM}

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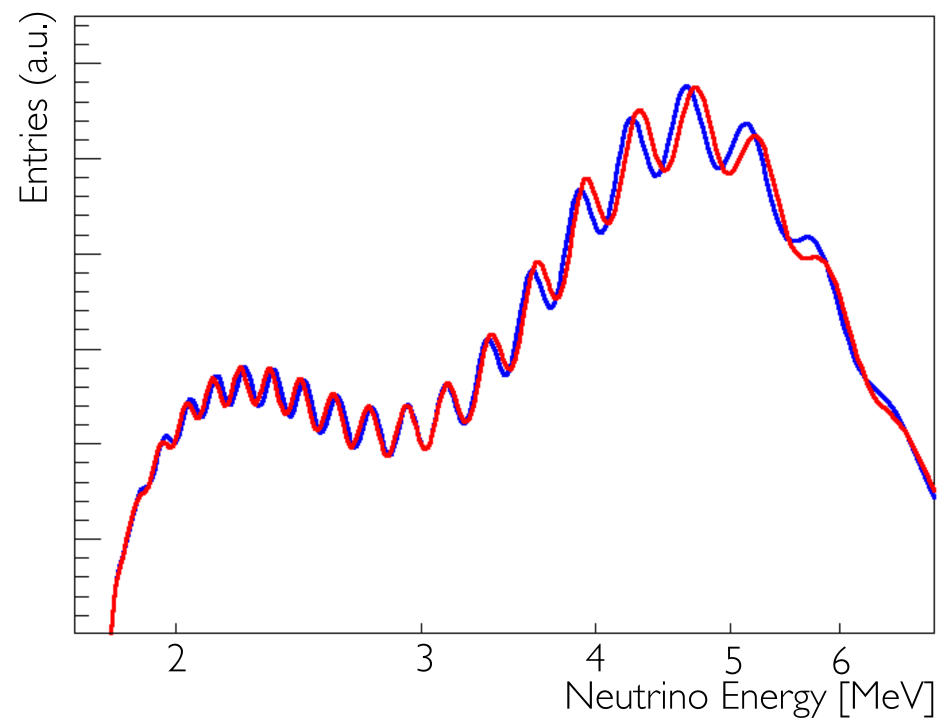
Slow Δm^2_{SOL}

Oscillation Parameters

Access to four oscillation parameters: θ_{13} , θ_{12} , Δm^2_{21} , $|\Delta m^2_{ee}|$

Measurement of $\sin^2(2\theta_{12})$, Δm^2_{21} , $|\Delta m^2_{ee}|$ with better than 1% precision



Cosmogenic Bkg (3% Norm + 10% Shape)

Bin-to-bin uncorrelated uncertainty

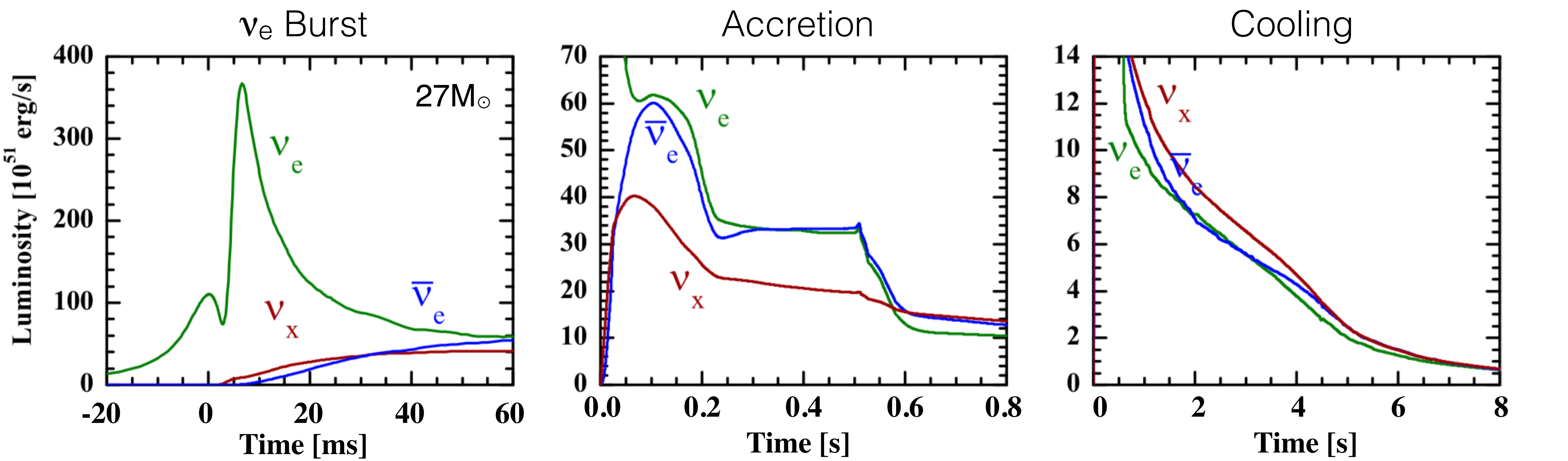
Energy scale uncertainty

Energy non-linear uncertainty

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

Non-Reactor Neutrino Physics

Supernova Neutrinos



- Huge amount of energy (3×10^{53}erg) emitted in neutrinos (~0.2M☉) over **long time range**
- 3 phases equally important ▶ 3 experiments teaching us about astro- and particle-physics

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

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

Geoneutrinos

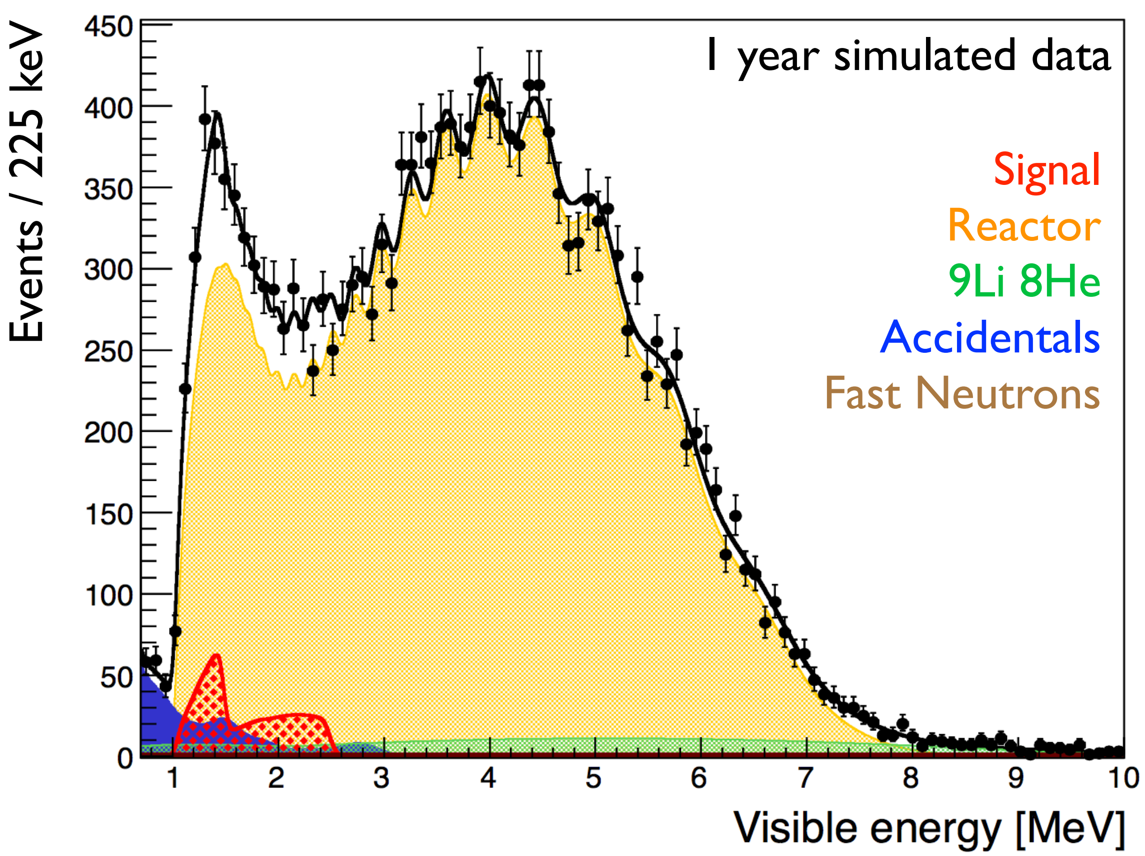
J.Phys. G43 (2016) no.3, 030401

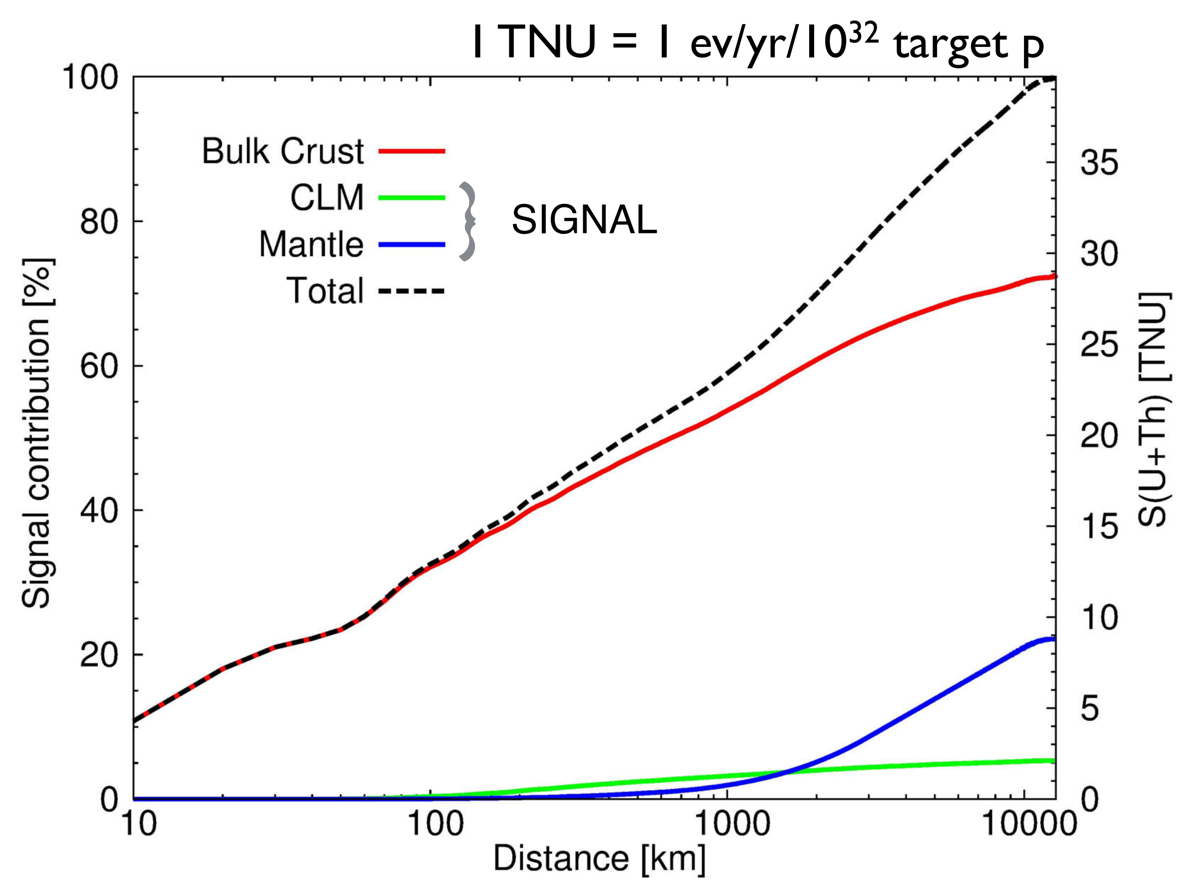
Earth's surface heat flow 46±3 TW. What fraction due to **primordial vs radioactive** sources?

Understanding of:

- **composition** of the Earth (chondritic meteorites that formed our Planet)
- chemical layering in the mantle and the nature of **mantle convection**
- energy needed to drive **plate tectonics**
- power source of the geodynamo, which powers the magnetosphere

Detect **electron antineutrinos from the ^{238}U and ^{232}Th** decay chains





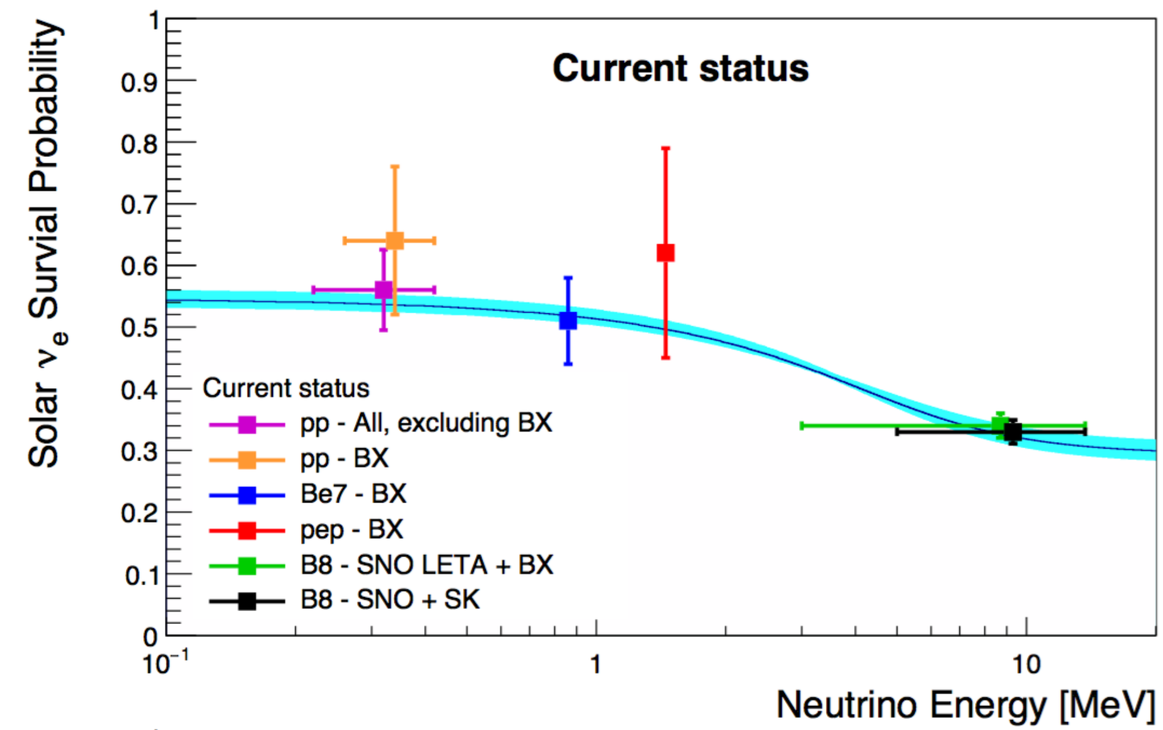
Solar Neutrinos

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

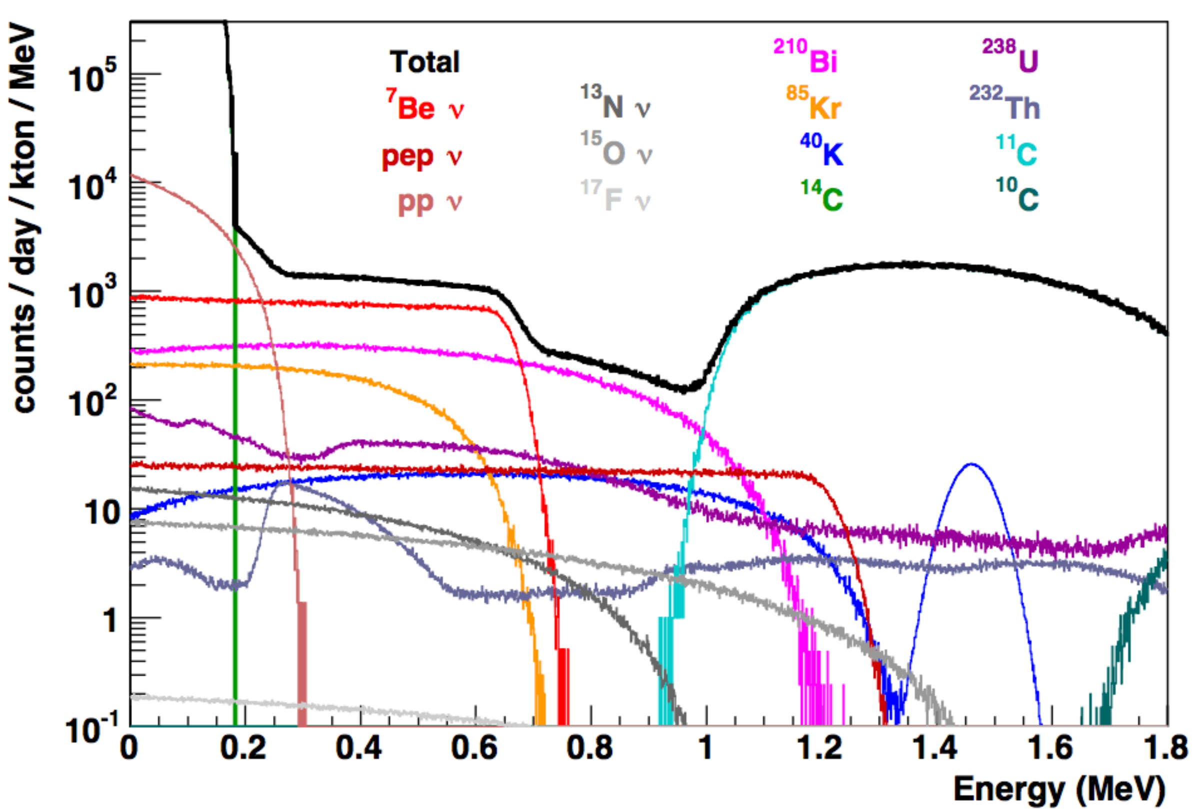
JUNO: neutrinos from **^{7}Be and ^{8}B** chains

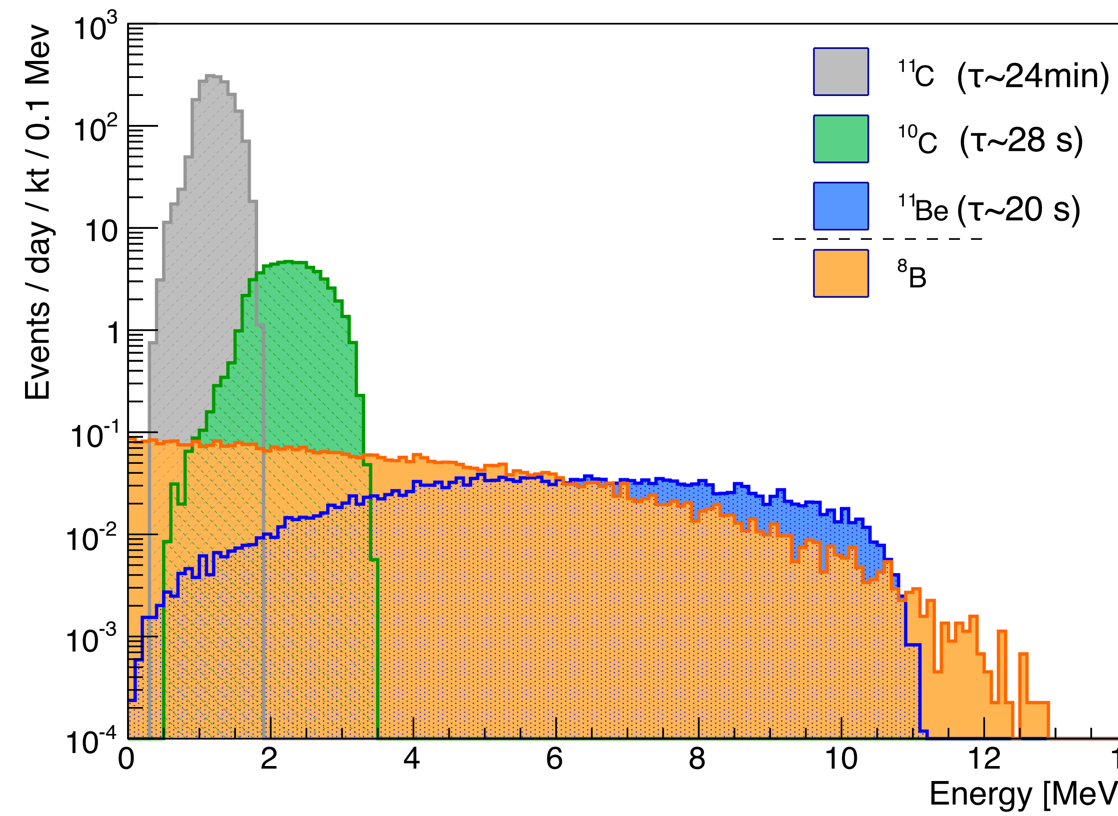
Investigate **MSW effect**: Transition between vacuum and matter dominated regimes

Constrain **Solar Metallicity** Problem: Neutrinos as proxy for Sun composition



arXiv 1602.01733





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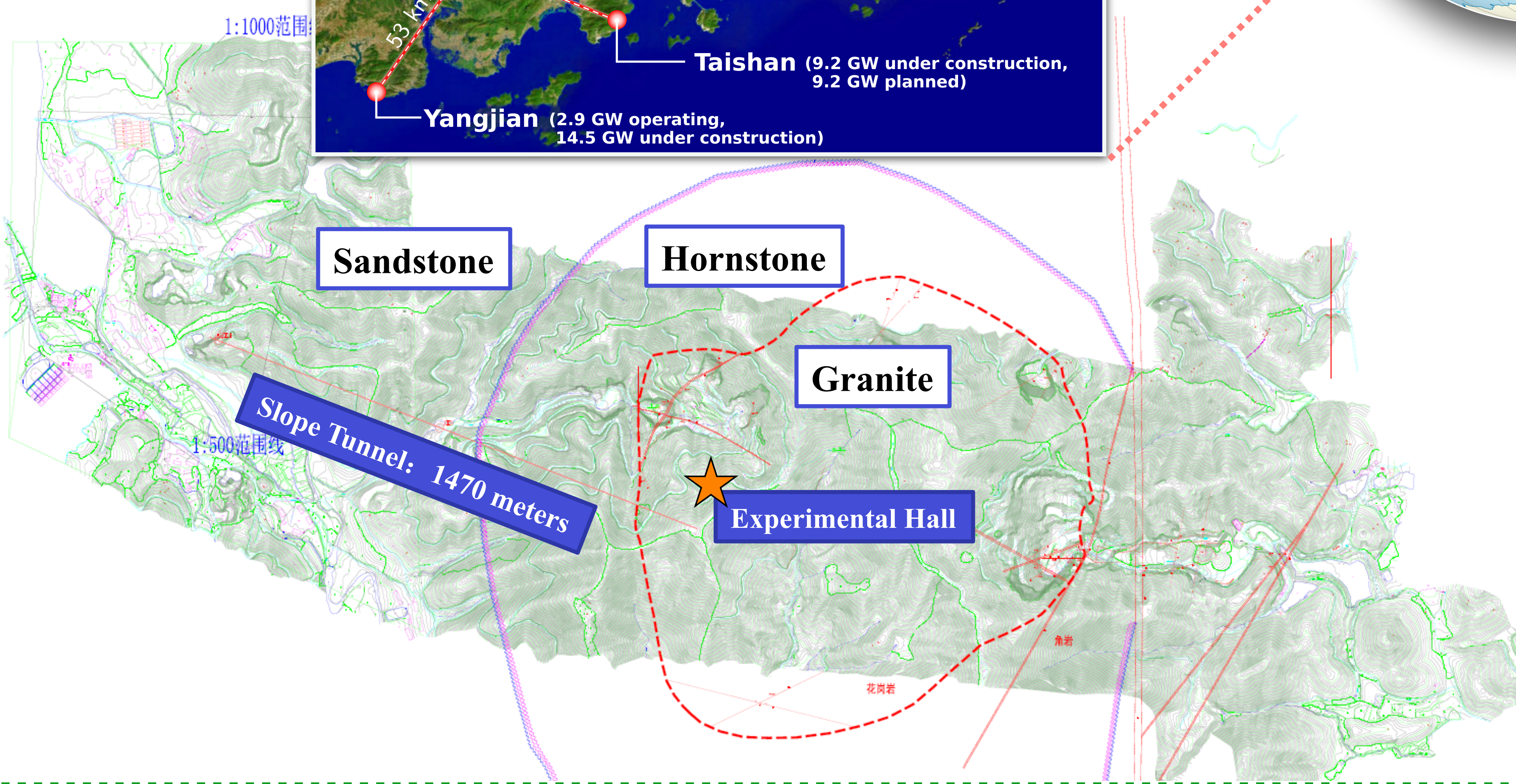
A New Lab in Southern China

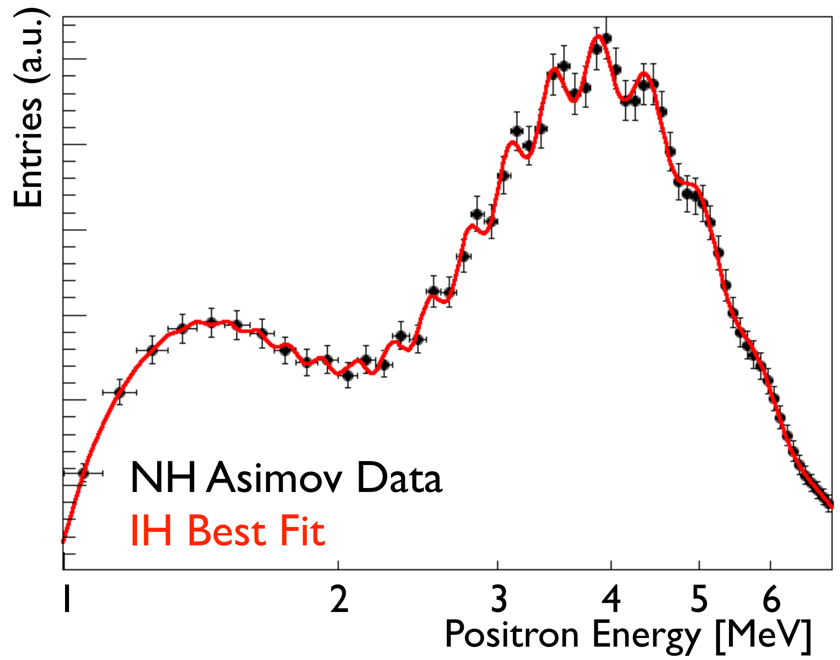


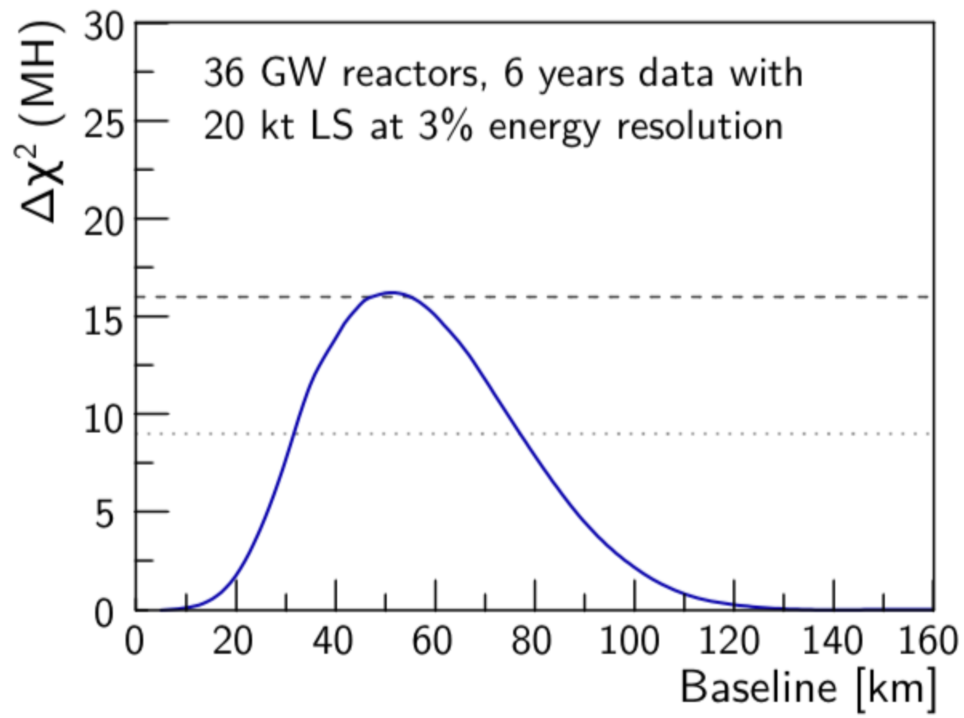
Nice granite structure at right distance from reactors (very lucky!)

Jiangmen City
Guandong province

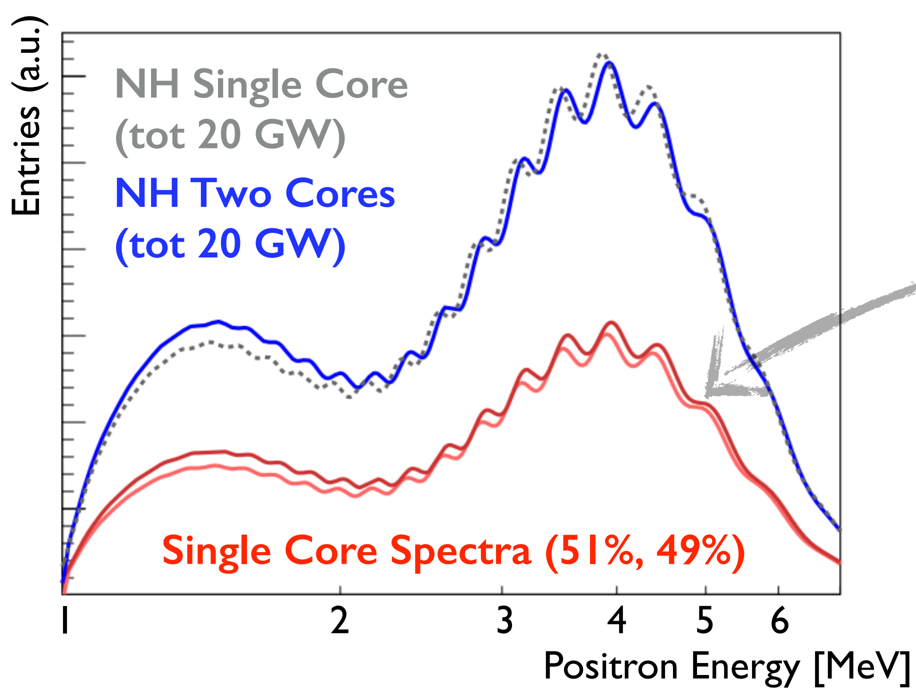
Baseline Optimisation

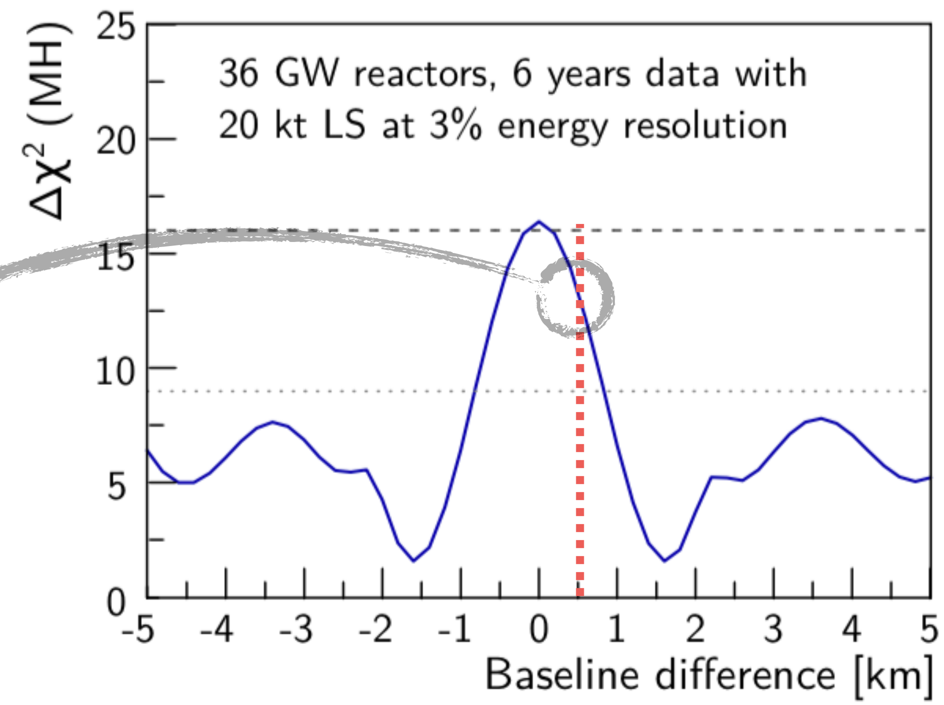
Fitting competitive hypoteses





~50 km optimal baseline for MH





~500m maximum allowed baseline difference

Toy MC

Phys.Rev. D88 (2013) 013008

720 m Rock Overburden (1900 mwe)

1340 m Tunnel (42% slope) - 611 m Vertical Shaft

Detector Overview

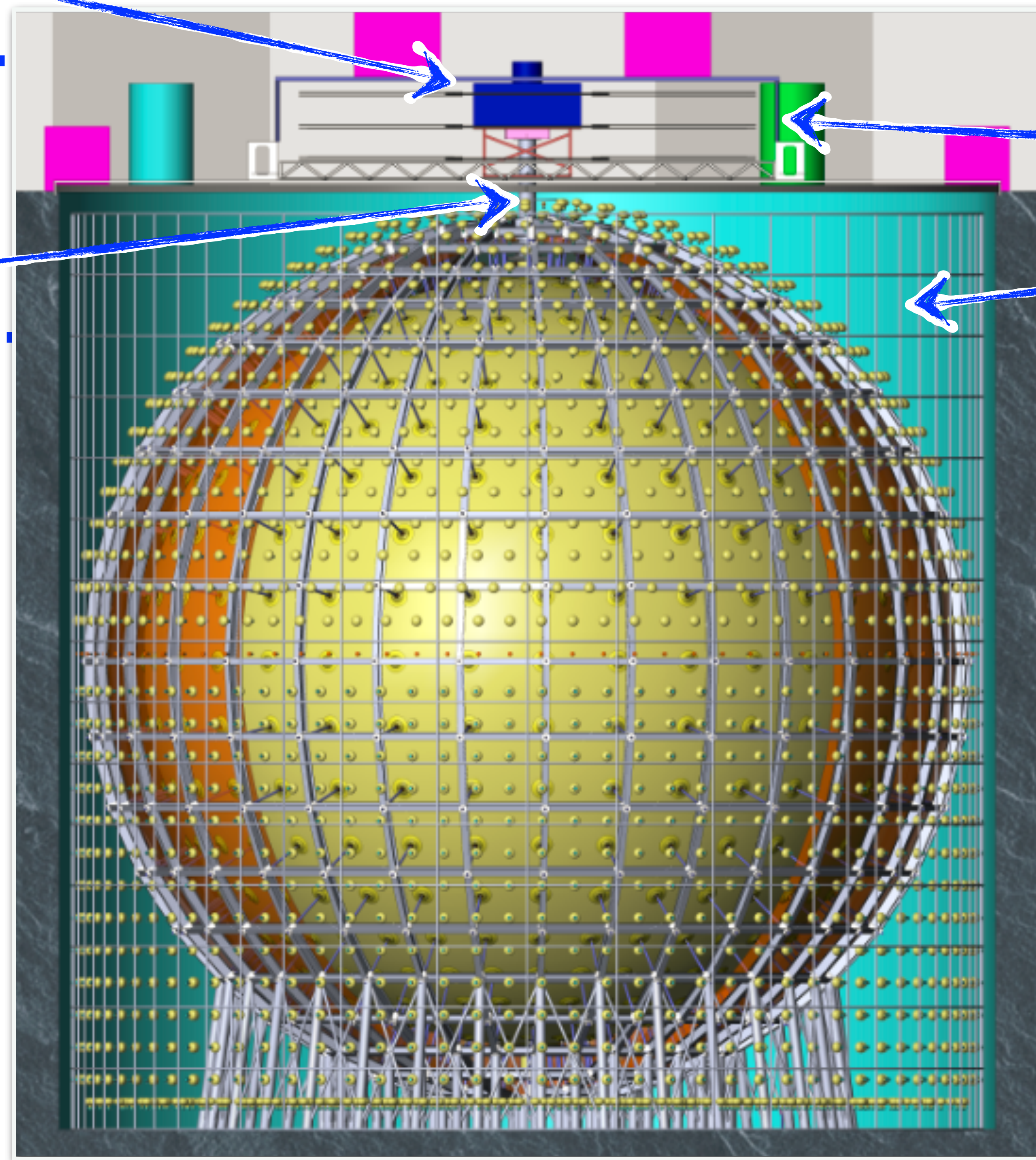
Calibration Room

Muon Veto

Chimney

Top Tracker

Water Pool



Central Detector

Steel Truss

Holding PMTs

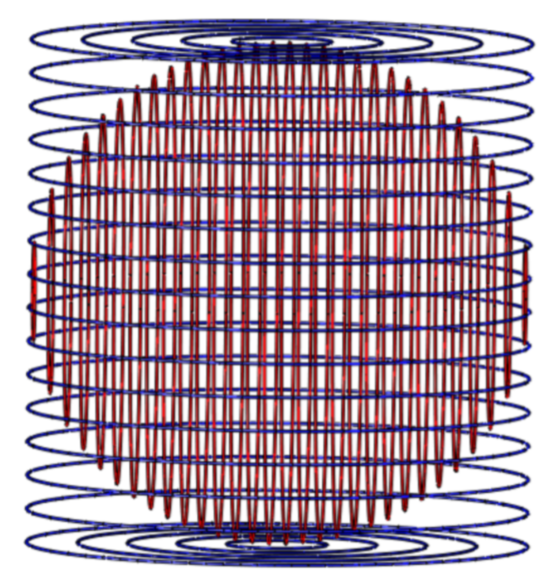
~17000 x 20”

~34000 x 3”

Acrylic Sphere

filled with LS

Magnetic Field
Compensating Coil



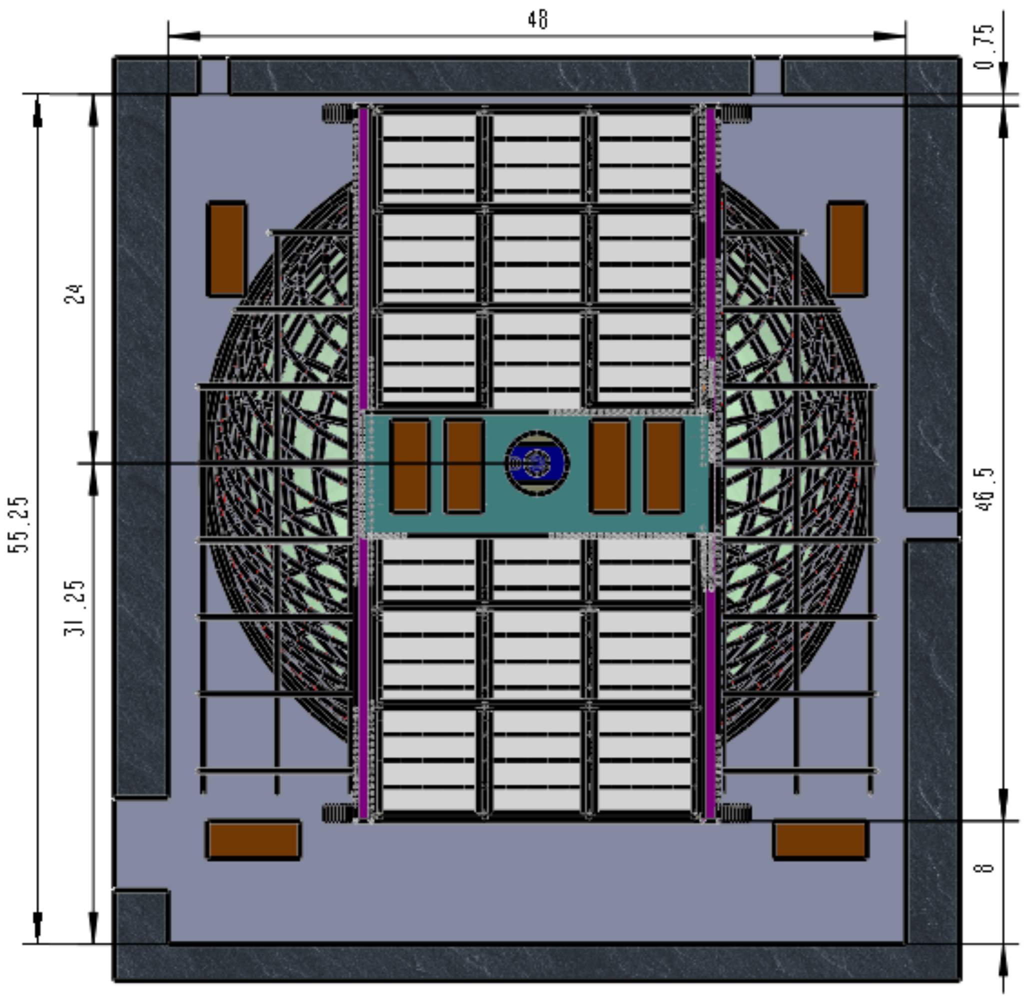
Muon Veto

Muon Veto: critical to reduce backgrounds

Cosmogenic isotopes rejection:
reconstruction of muon tracks + $\mathcal{O}(1s)$ veto surrounding the track

Neutron Rejection:
passive shielding (water) + time coincidence w/ muon + multiple proton recoils

Gamma rejection: passive shielding (water)



Top Tracker

Using **OPERA** plastic scintillator (49m^2/module)

Three layers to ensure good muon tracking

Partial coverage due to available modules

- **Reject ~50% muons**
- Provide tagged muon sample to study reconstruction and background contamination with central detector

Muon Veto

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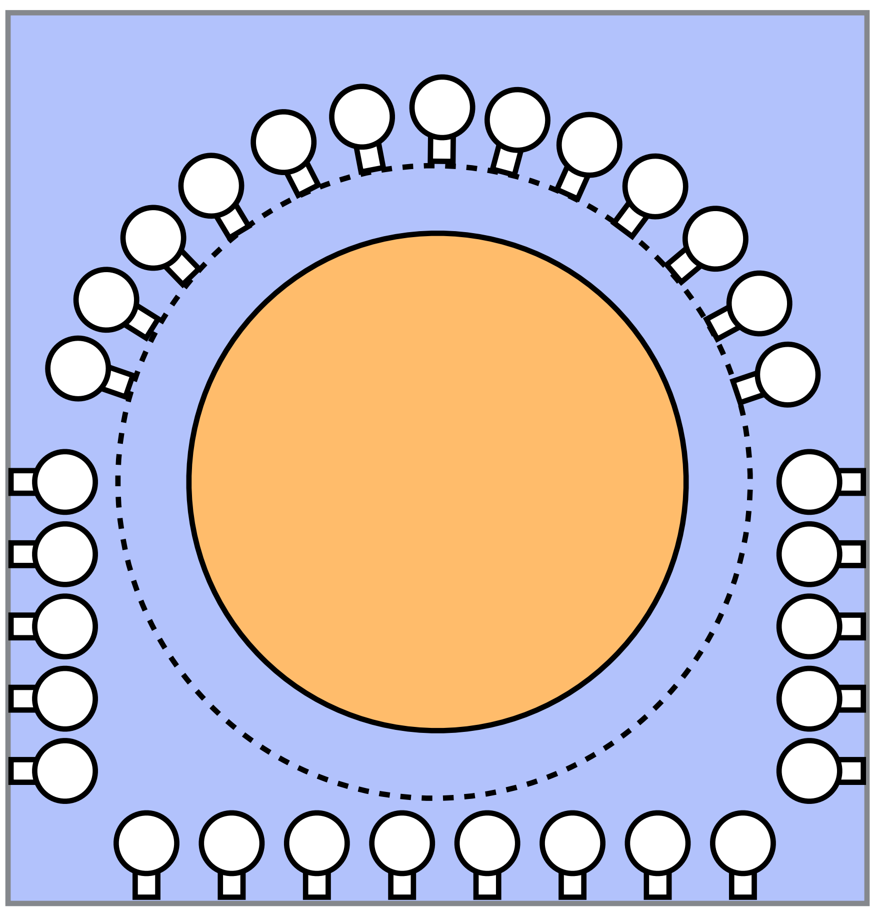


Water Cherenkov

20~30kt ultra-pure water

Water acting as moderator &
pool instrumented to detect Cherenkov light

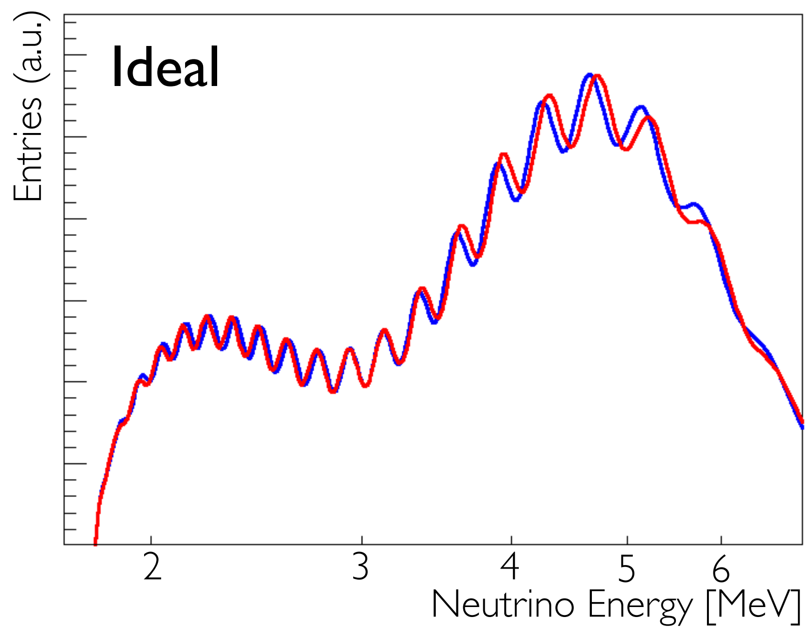
2000 20'' PMTs located as in the picture

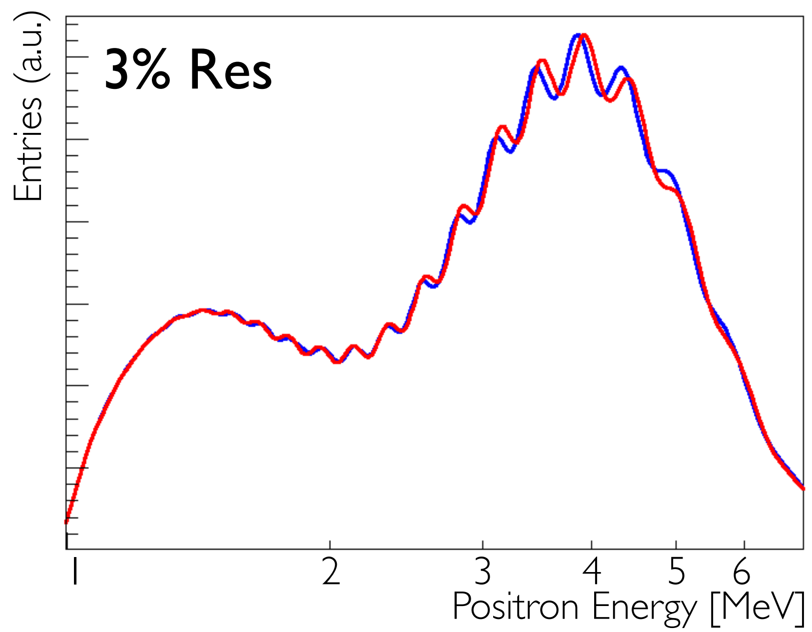
Maximise detection efficiency of Cherenkov light

Central Detector

Central Detector design optimised for Mass Hierarchy: "Precise & Large"

Detector Resolution: $$\frac{\sigma(E)}{E} = \sqrt{\frac{a}{E} \oplus \frac{b}{\sqrt{E}} \oplus c}$$





Central Detector

Central Detector design optimised for Mass Hierarchy: "Precise & Large"

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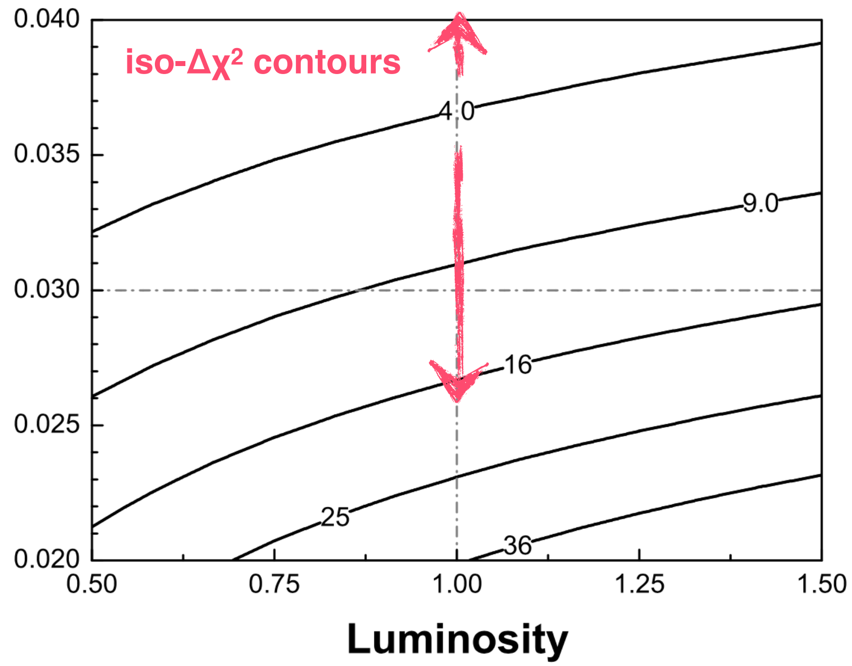

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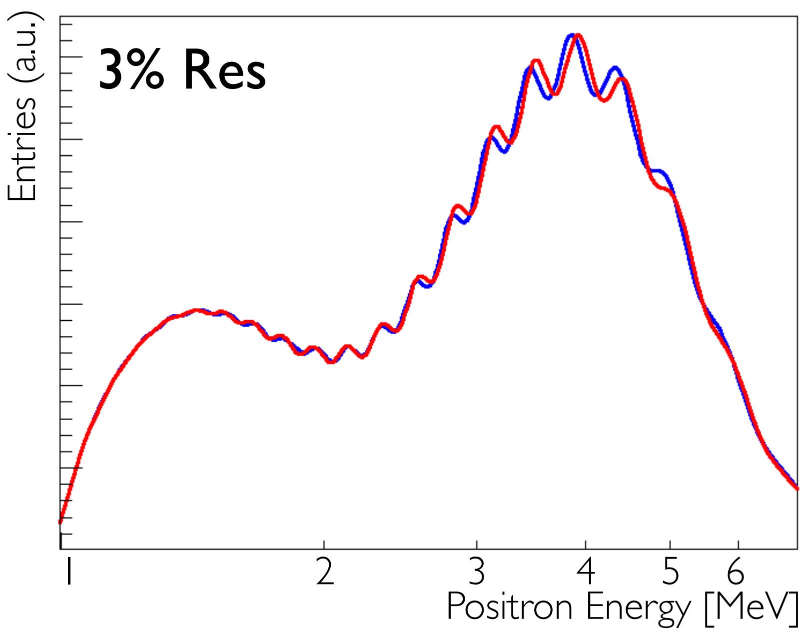
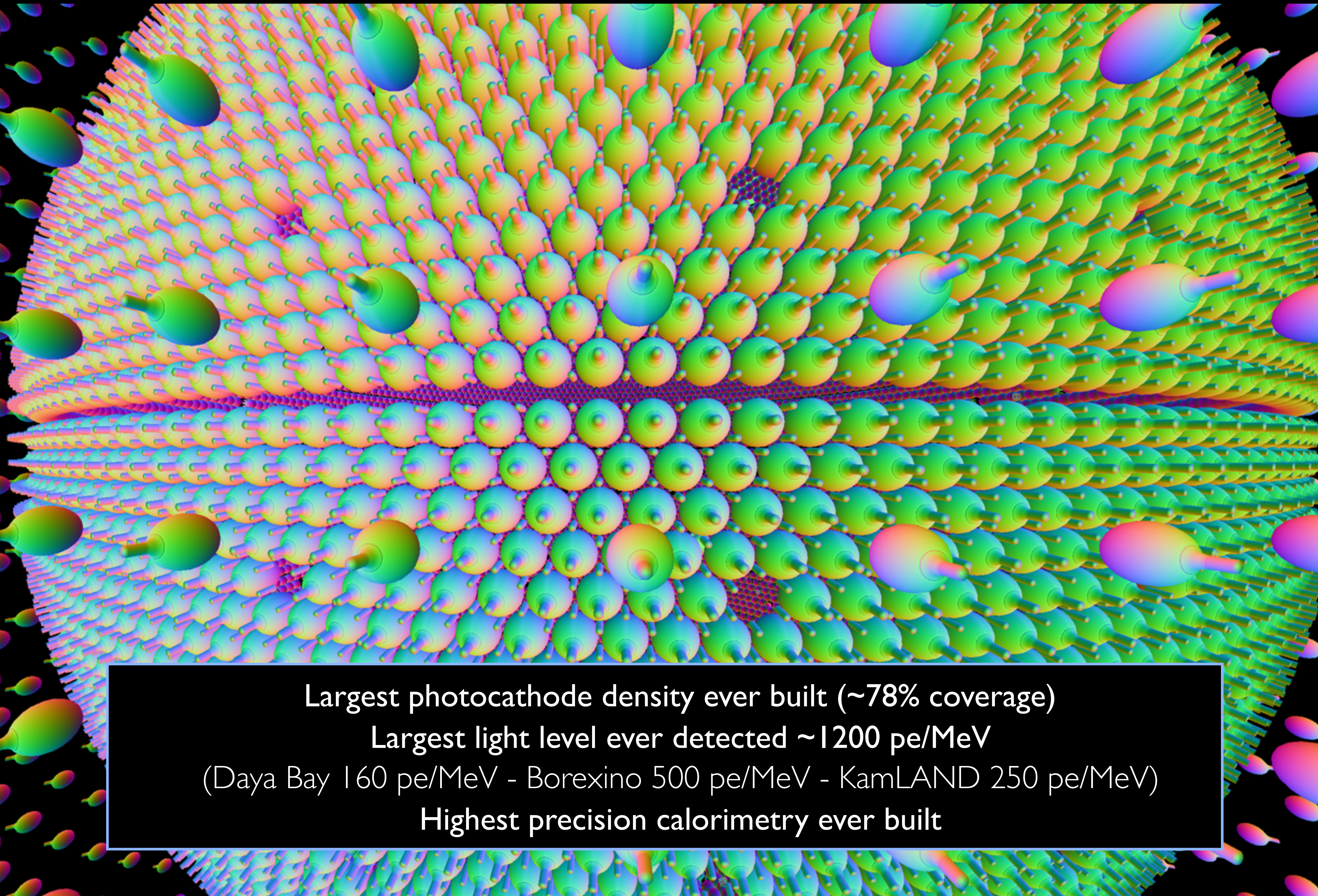


3% resolution at 1MeV is pivotal

b - stochastic term → Maximise detected light → Large photocoverage Transparent Scintillator

c - non-stochastic term → Control systematics → Small (3") PMTs Calibration



Largest photocathode density ever built (~78% coverage)
Largest light level ever detected ~1200 pe/MeV
(Daya Bay 160 pe/MeV - Borexino 500 pe/MeV - KamLAND 250 pe/MeV)
Highest precision calorimetry ever built

Large PMTS

Large PMTs: 20'', 78% coverage - 30% quantum efficiency at 420 nm

Meant for Calorimetry

2 different producers: NNVC (China) 15000 units & Hamamatsu (Japan) 5000 units

Characteristics	unit	MCP PMT (NNCV - IHEP)	R12860 (Hamamatsu)	Note
Electron Multiplier		Micro Channel Plate	Dynode	
Photocathode Mode		Reflection + Transmission	Transmission	
Quantum Efficiency (400nm)	%	26(T), 30 (T+R)	30 (T)	En Resolution
Relative Detection Efficiency	%	110	100	En Resolution
Single Photo-electron P/V		3+	3+	Reconstruction
Transient Time Spread	ns	12	3	Vertex
Rise Time / Fall Time	ns	R~2, F~10	R~7, F~17	
Anode Dark Count	Hz	~30 k	~30 k	Trigger
After Pulse Time Distribution	μs	4.5	4, 17	
After Pulse Rate	%	3	10	
Glass		Low-Potassium Glass	Hario-32	Background

INTERACTION ➤ LS Quenching ➤ Propagation ➤ Light collection and digitisation ➤ DETECTION

LS Quenching	Propagation	Light collection and digitisation
CAUSES	CAUSES	CAUSES
LS non-linear light yield	Response non-uniformity	Single channel bias & non-linearity

Addressing Resolution Non-Stochastic Term

INTERACTION › LS Quenching › Propagation › Light collection and digitisation › DETECTION

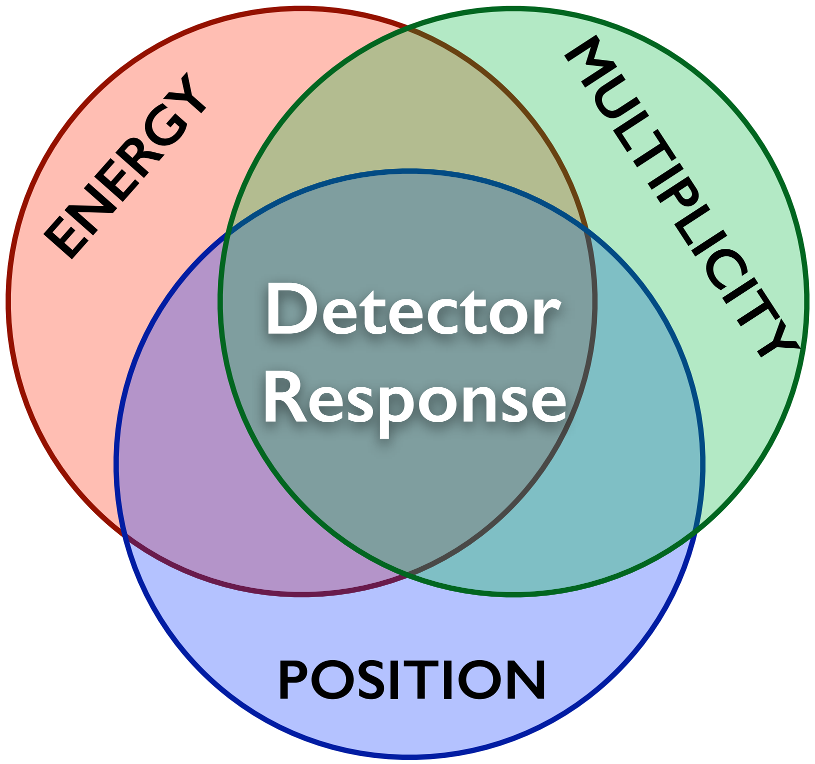
LS Quenching	Propagation	Light collection and digitisation
CAUSES	CAUSES	CAUSES
LS non-linear light yield	Response non-uniformity	Single channel bias & non-linearity

Scintillator Response

In-situ calibration sources (mostly gamma lines)

Bench top measurements (Compton scattering)

Daya Bay: ~1% precision



Single Channel Response

Probe same event with two independent systems

Large-PMT & Small-PMT orthogonal systematics

Break degeneracy

Spatial Response

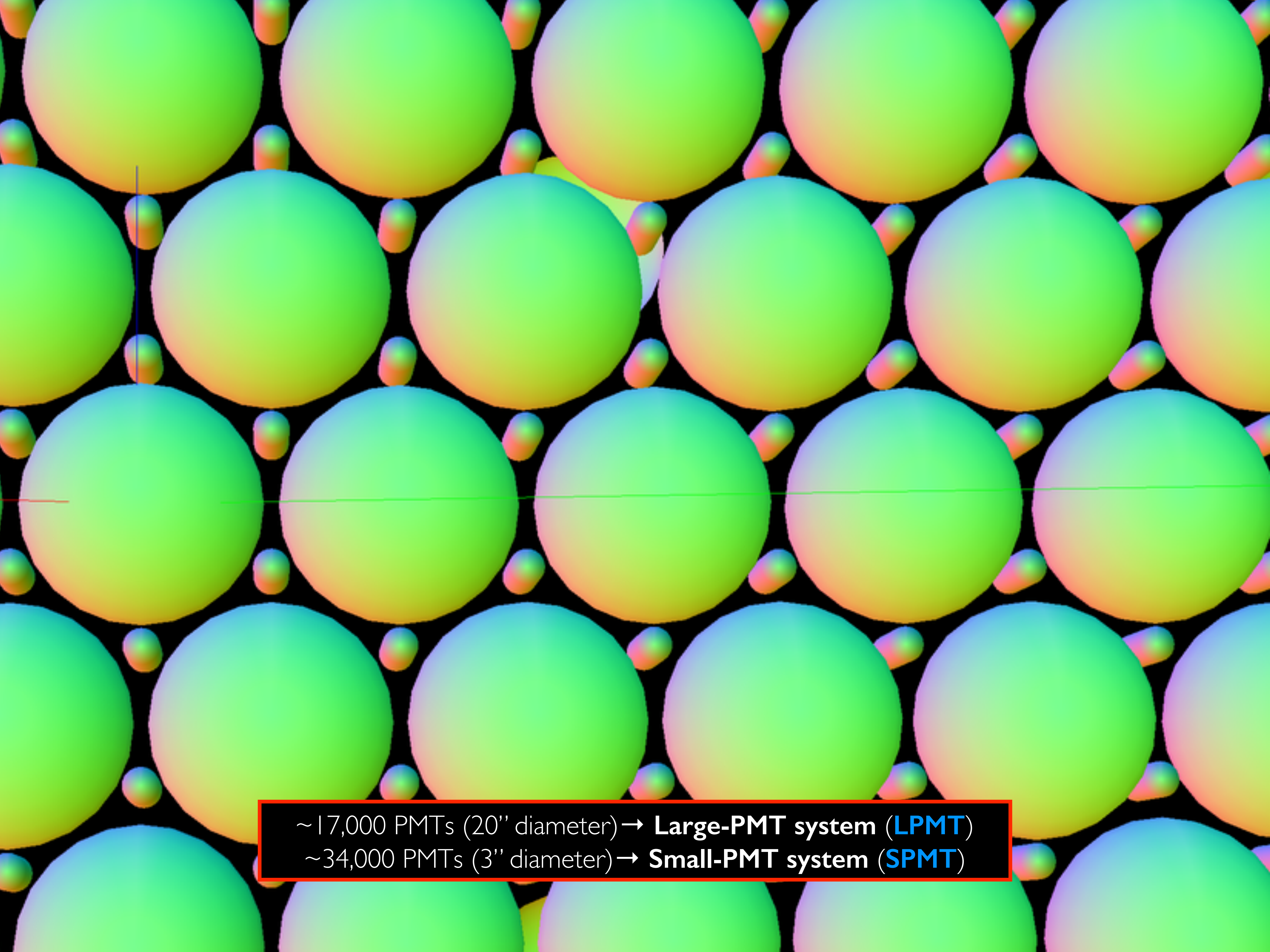
Sources deployed along z axis

Rope system (off-axis)

Remotely Operated Vehicle (off-axis)

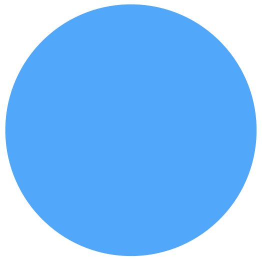
Guide tube surrounding acrylic sphere

Cosmogenic neutrons (unif. distributed)



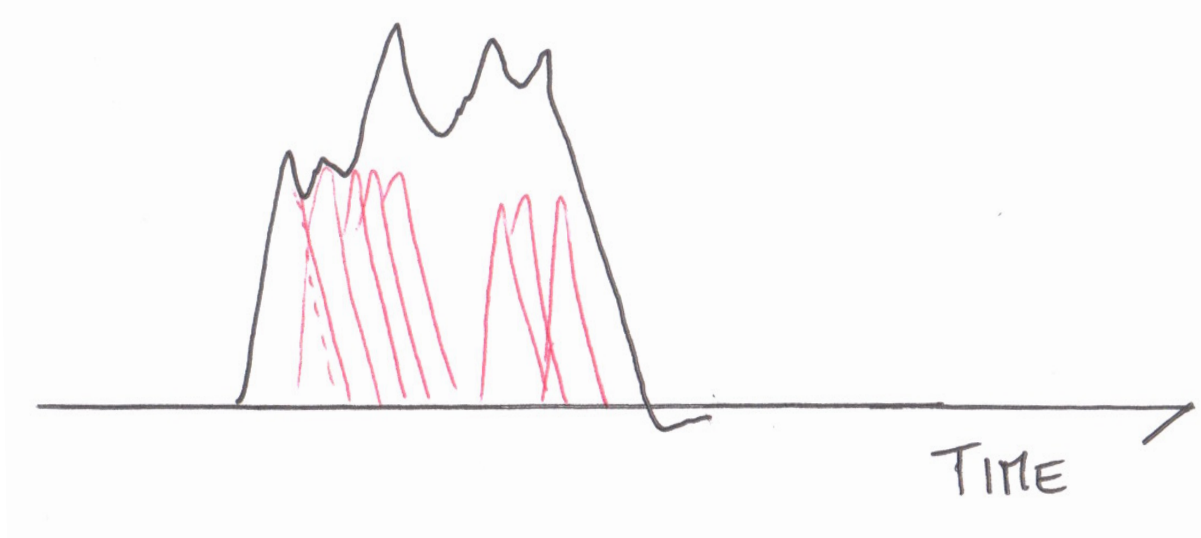
~17,000 PMTs (20" diameter)→ **Large-PMT system** (LPMT)
~34,000 PMTs (3" diameter)→ **Small-PMT system** (SPMT)

Small PMT



1200 p.e./MeV
78% photo-coverage
stochastic term: $3\%/\sqrt{E}$

$\sim$100 p.e. /MeV
10% photocoverage
stochastic term > $10\%/\sqrt{E}$



Large Pmt:
- Typically slower & poorer resolution
- B-field weak
- Large dark noise (huge photocatode)

Main Calorimetry

Small Pmts
- Faster (cf. transit time spread)
- High p.e. resolution
- B-field strong
- High quantum & collection eff.
- Low dark noise

Time Reso & sPE identification

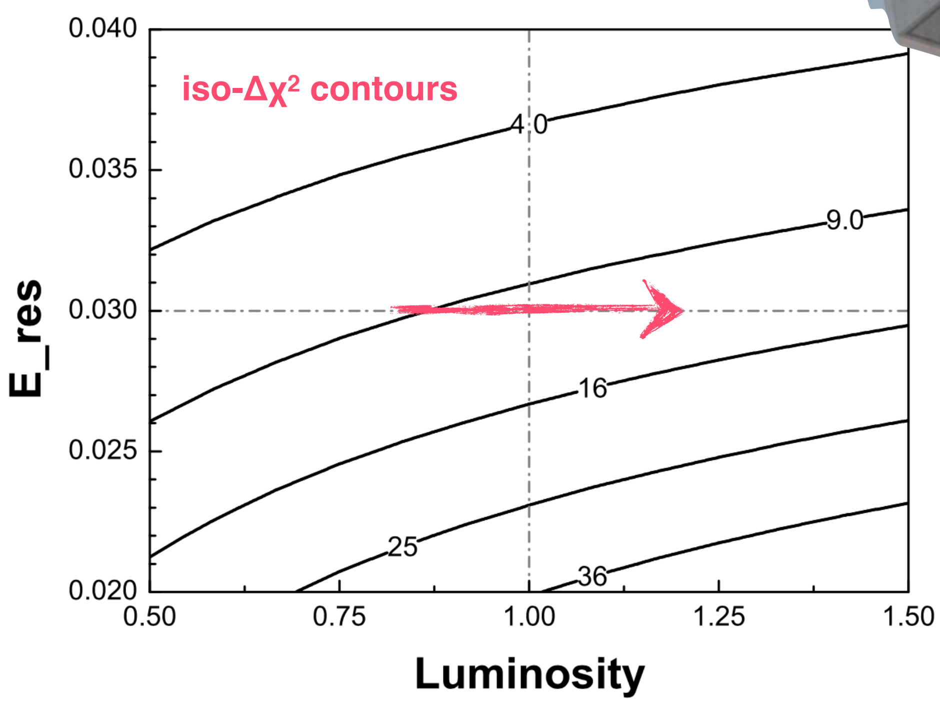
Central Detector

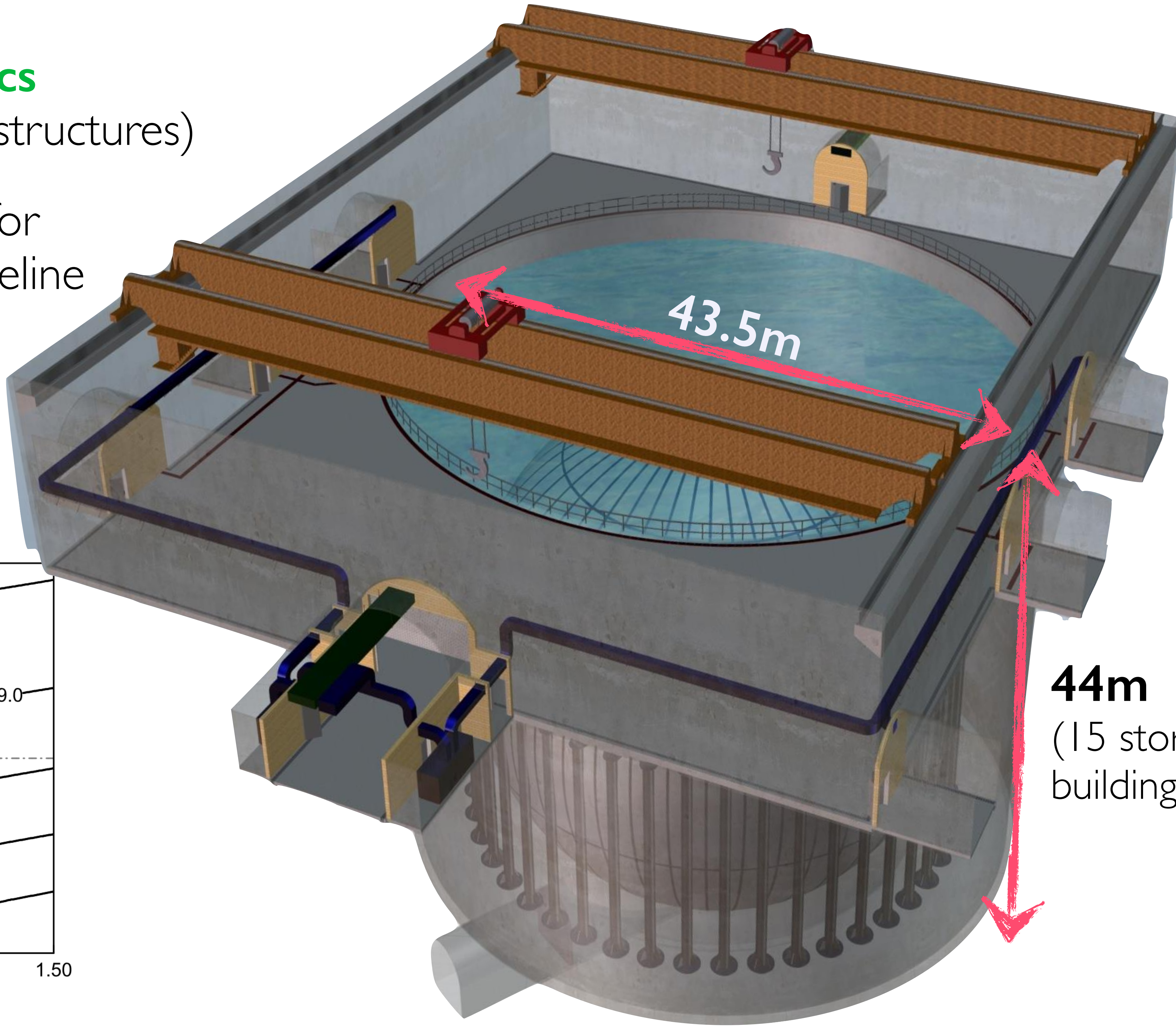
Central Detector design optimised for Mass Hierarchy: "Precise & Large"

Needed for **high statistics**
(looking for spectral fine structures)

Needed to compensate for
flux reduction due to baseline

Nominal Luminosity
100k events in 6 years





44m
(15 story
building)

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

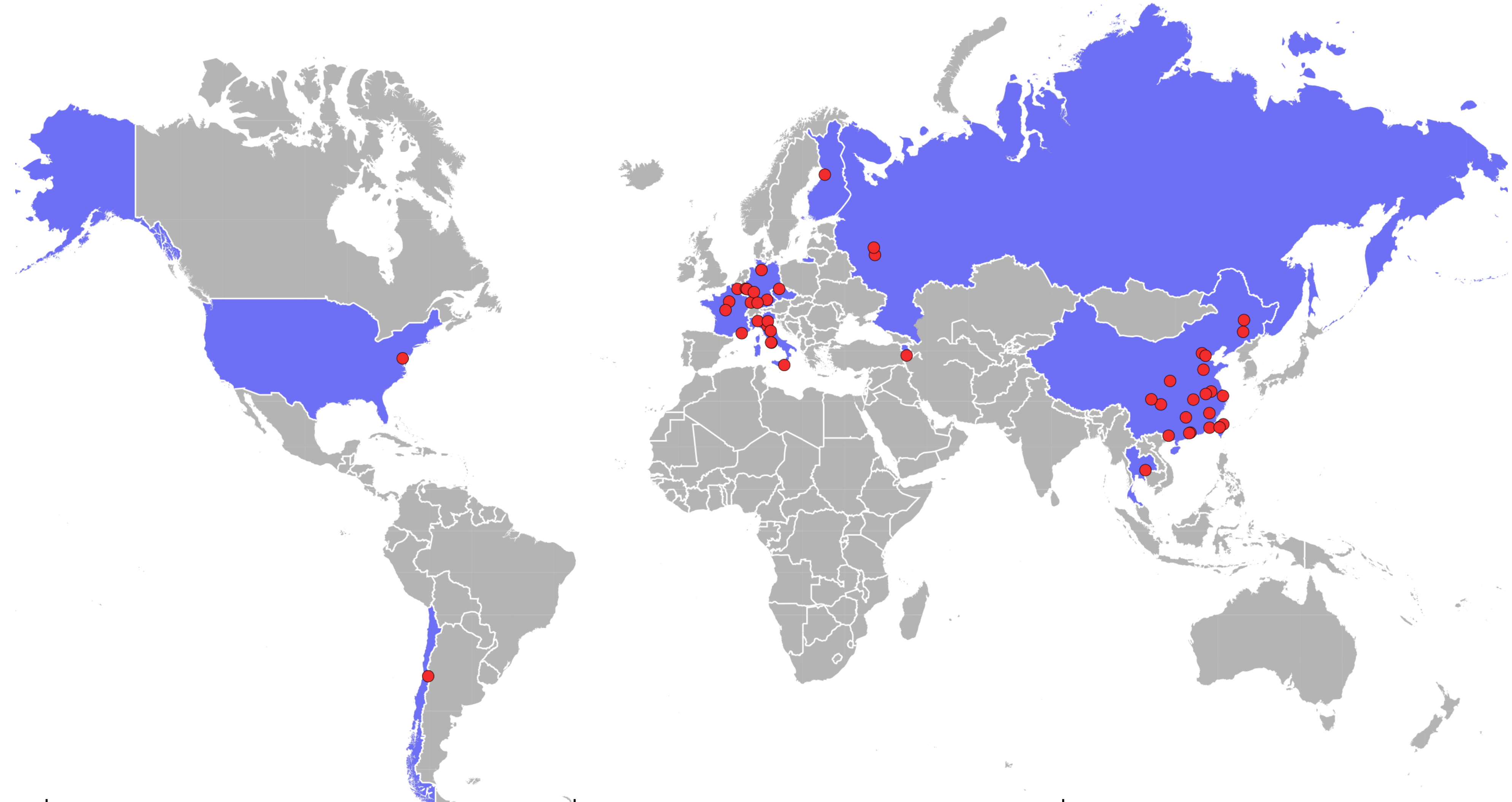
CONCLUSIONS

- JUNO unprecedented **large & high precision calorimetry** liquid scintillator detector
  - Requiring high light level (1200 pe/MeV) to reach **3% energy resolution** at 1MeV
- High precision neutrino oscillation with **reactor-ν**
  - MASS HIERARCHY : **solar/atmospheric interference**
    (almost) insensitive to matter effects
  - SOLAR SECTOR : ≤1% precision in **solar terms**
    Needed for CP-violation

    Complementary to other experiments
  - NON-REACTOR ν : leading physics capabilities (Supernova, Geoneutrinos, Solar neutrinos…)
- JUNO international collaboration established in 2014 & funded ▸ **data taking by ~2020**

BACKUP

International Collaboration



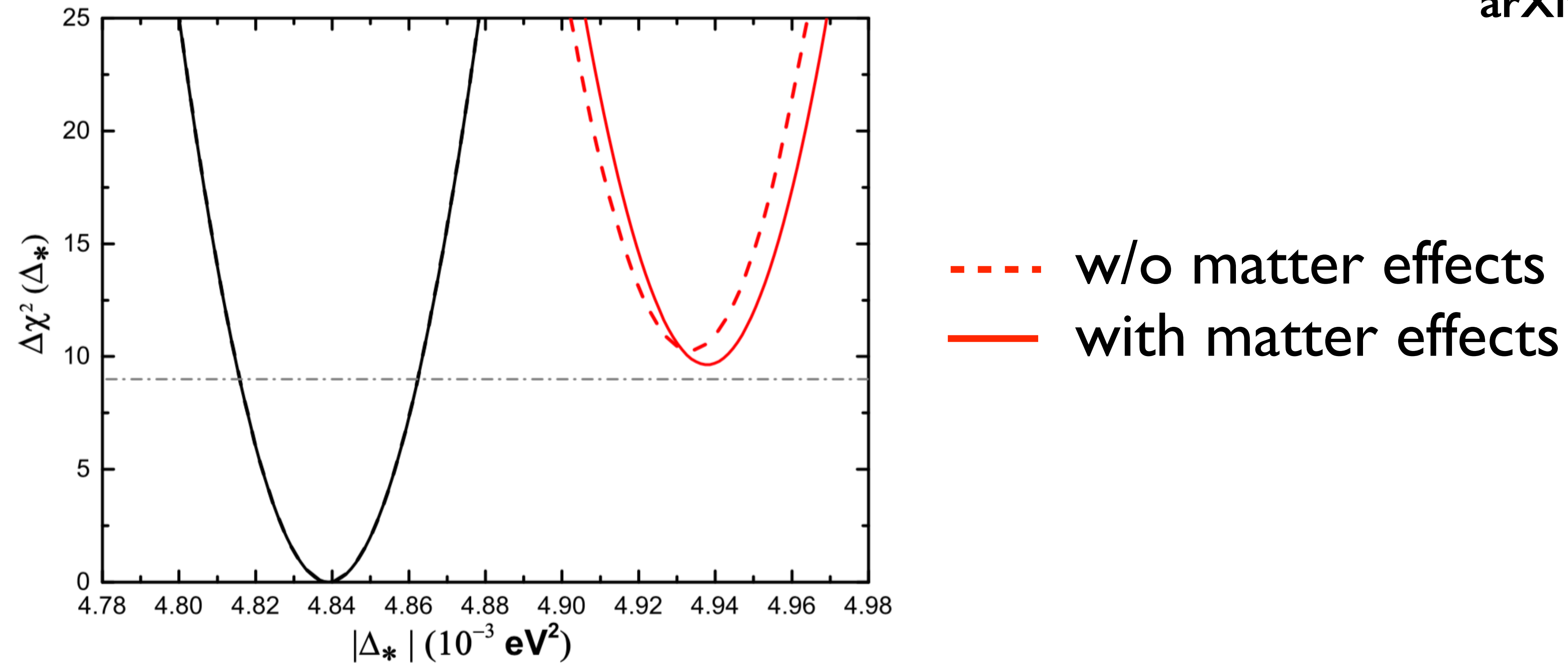
Armenia	Yerevan Physics Institute
Belgium	Université libre de Bruxelles
Chile	PCUC
China	BISEE
China	Beijing Normal U.
China	CAGS
China	ChongQing University
China	CIAE
China	DGUT
China	ECUST
China	Guangxi U.
China	Harbin Institute of Technology
China	IHEP
China	Jilin U.
China	Jinan U.
China	Nanjing U.
China	Nankai U.
China	NCEPU
China	Pekin U.
China	Shandong U.
China	Shanghai JT U.
China	Sichuan 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
Czech	R. Charles U. Prague
Finland	University of Oulu
France	APC Paris
France	CPPM Marseille
France	IPHC Strasbourg
France	LLR Palaiseau
France	Subatech Nantes
Germany	ZEA FZ Julich
Germany	RWTH Aachen U.
Germany	TUM
Germany	U. Hamburg
Germany	IKP FZ Jülich
Germany	U. Mainz
Germany	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
Russia	INR Moscow
Russia	JINR
Russia	MSU
Taiwan	National Chiao-Tung U.
Taiwan	National Taiwan U.
Taiwan	National United U.
Thailand	SUT
USA	UMD1
USA	UMD2

REACTOR PHYSICS

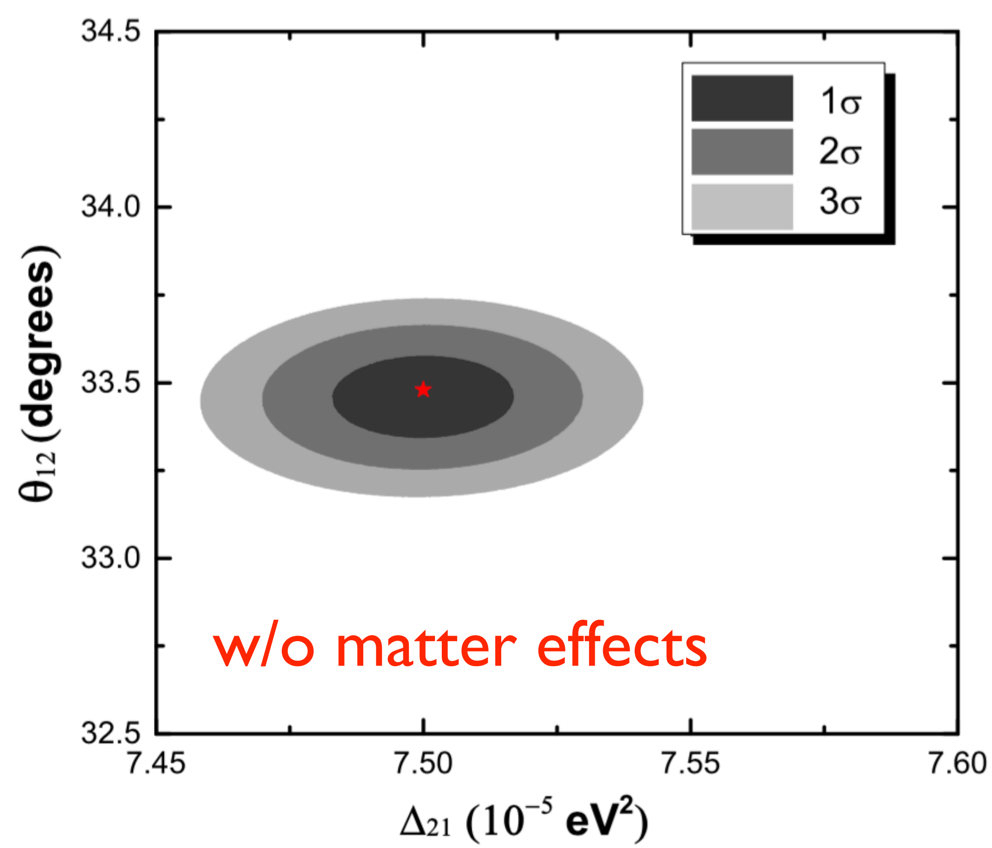
Relevance of Matter Corrections

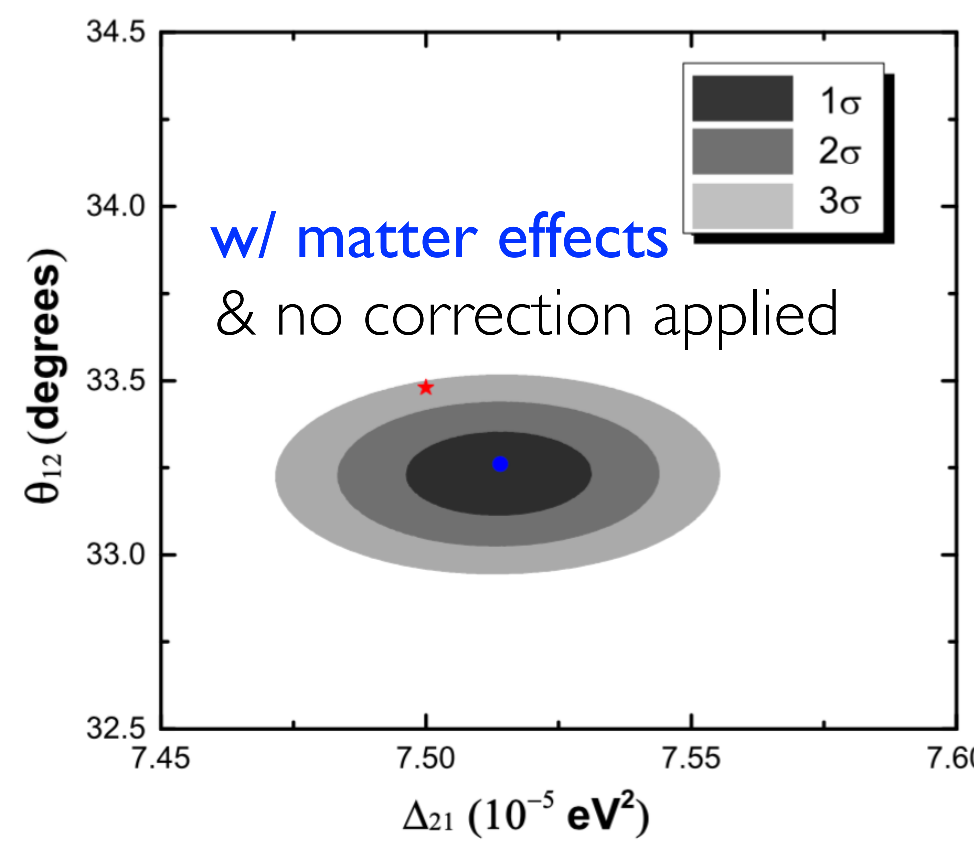
arXiv: 1605.00900

MASS HIERARCHY



SOLAR PARAMETERS





Nuclear Reactors and Baselines

Taishan: 2 cores (4.6 GW each) under construction
2 cores waiting for approval (likely not ready by 2020)

Yangjiang: 3 cores (2.9 GW each) operational
3 cores (2.9 GW each) under construction

Full configuration: 10^5 events in 6 years

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

Background From Natural Radioactivity

Natural **radioactivity** from LS, PMT glass, concrete, rock…

Singles: no prompt-delayed time structure

7.6 Hz from MC simulations

Fraction of neutron like ~8%

Two such events might happen to be close in space and time

Prompt-delayed coincidence within 1ms ~ 410/day

Additionally requiring spacial correlation (within 1.5 m): **1.1/day**

Radioactivity can be precisely measured during data taking

Uncertainty on accidental background rate can be controlled within 1%

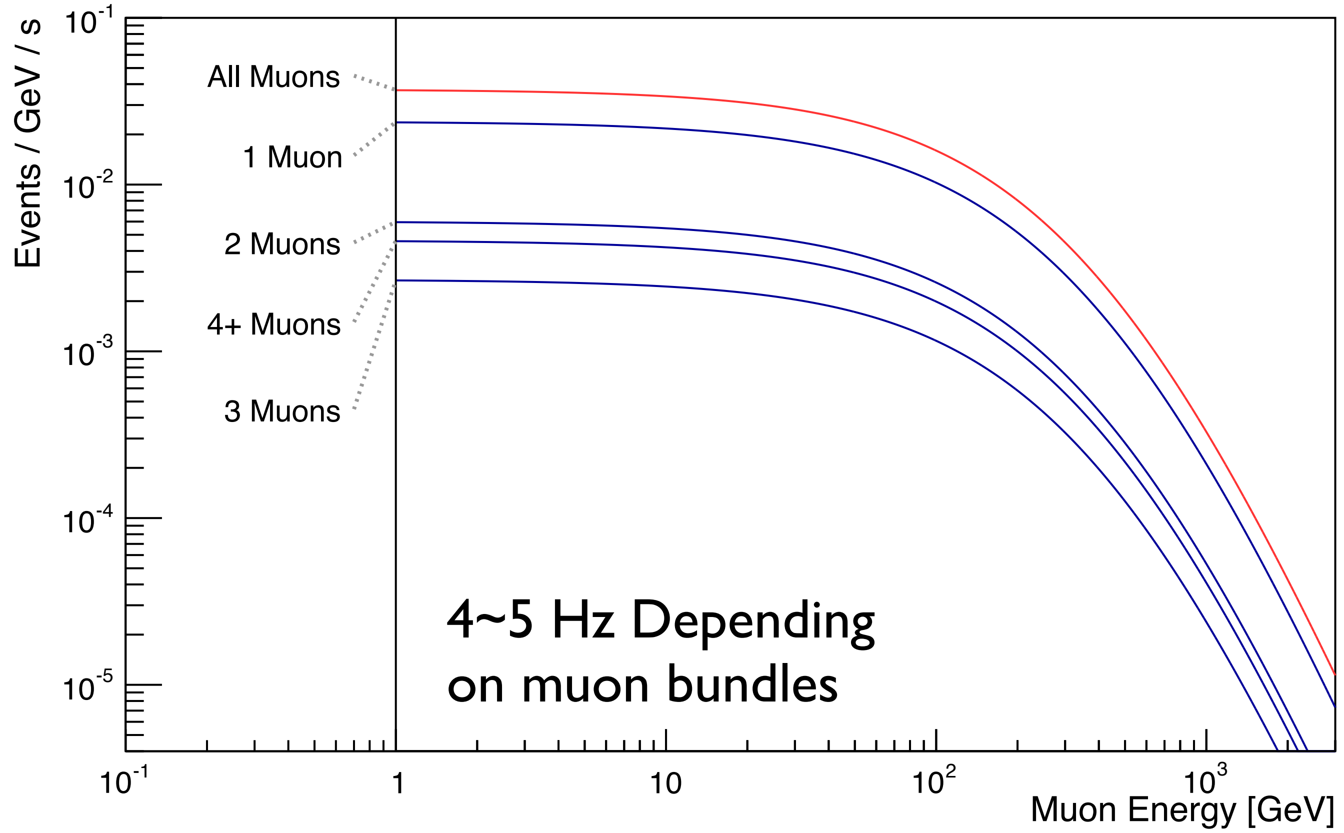
(**negligible shape uncertainty**)

Cosmogenic Backgrounds

Background associated to cosmic muons surviving the overburden

Average Energy ~200 GeV
Average Track Length ~ 23m

Might arrive in bundles: multiple muons from the same primary cosmic ray



Fast Neutrons:

Interactions between μ and rock

Mainly at the top and at the equator

Strongly suppressed by water buffer

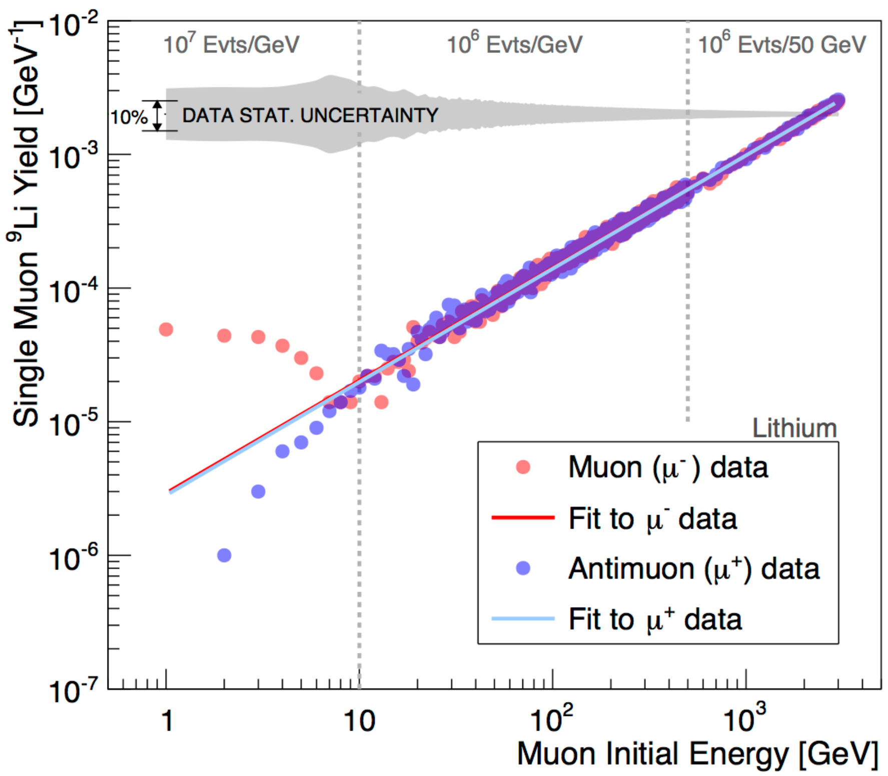
Long-Lived Isotopes (^{8}He ^{9}Li):

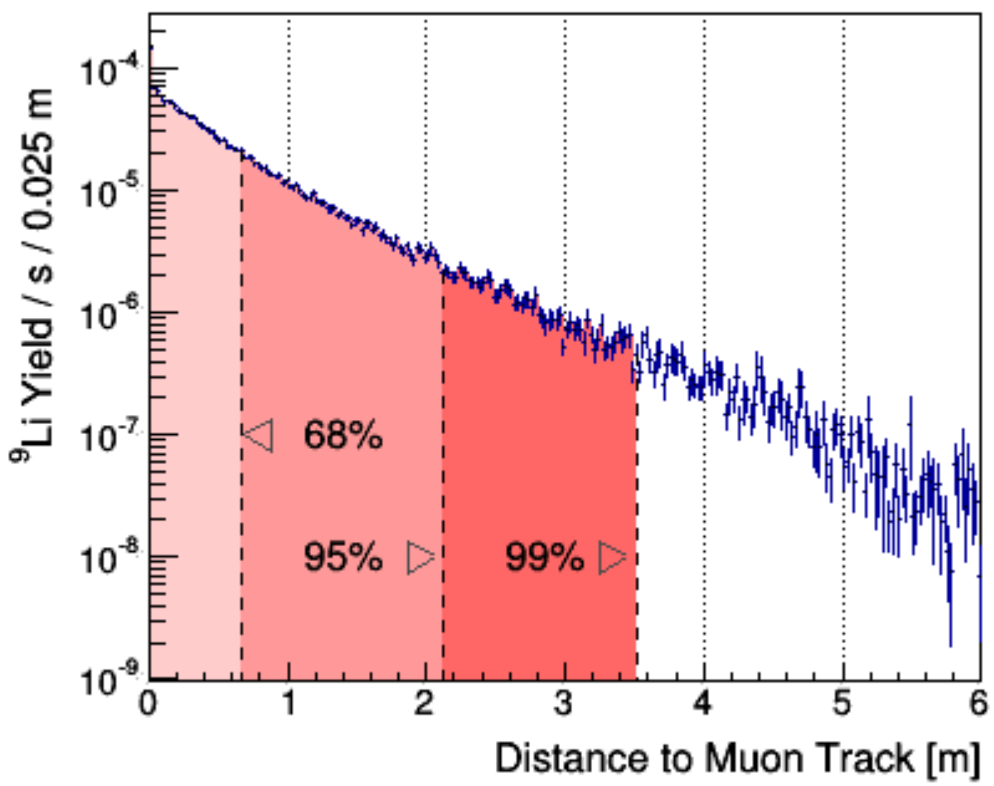
Inelastic scattering on carbon

Large branching ratio of β n decay

IBD-like event: irreducible background

Cosmogenic Isotopes





Total yield is ~70 evts/day
In case of **good tracking**, many events could be rejected with a regional veto (eg. 3.5 m, 1.5 s with respect to the muon track)

Challenging events are when a **muon showers** ($E_{DEP} \gg E_{MIP}$)
Whole detector must be vetoed, introducing large dead time

Current belief is to be able to reach **B/S ~ few %**

Accidental Background

Accidental background The rate of accidental backgrounds can be calculated as $R_{acc} = R_p \cdot R_d \cdot \Delta T$, where R_p and R_d are the rate of prompt and delayed signals, respectively, and ΔT is the time coincidence window. A fiducial volume cut is essential to significantly suppress such background. The accidental background consists of mainly three types of random coincidence: (radioactivity, radioactivity), (radioactivity, cosmogenic isotope) and (radioactivity, spallation neutrons):

- (radioactivity, radioactivity): The singles rate obtained from Monte Carlo simulation is about 7.6 Hz after fiducial volume cut (see Sec. 13.4.4),in which the faction of neutron-like signals is $\sim$8%. Thus the rate of prompt-delayed coincidence within 1.0 ms is $\sim$410/day. In addition, a toy Monte Carlo (MC) study gives a factor of 380 suppression by requiring R_{p-d} <1.5 m, where R_{p-d} is the distance between the prompt-delayed pair, thus the accidental background rate is reduced to 1.1/day.
- (radioactivity, cosmogenic isotope): based on the rates of cosmogenic isotopes in Sec. 13.4.3, the neutron-like singles from cosmogenic isotopes is estimated to be $\sim$340/day. The rate of accidental coincidence between radioactivity and those isotopes is <0.01/day after $\Delta T < 1.0$ ms and R_{p-d} <1.5 m cut.
- (radioactivity, spallation neutrons): Though the total rate of spallation neutrons is 1.8 Hz, after 1.5 ms muon veto the rate is reduced to $\sim$45/day. The coincidence between radioactivity and the residual spallation neutrons is negligible after the time and spatial cut.

Thus the total rate of accidental backgrounds is estimated to be 0.9/day, after taking into account the efficiency of muon veto. During data taking, the rate of radioactivity can be precisely monitored, so can the neutron-like events from muon spallation. So the uncertainty of accidental background rate can be controlled within 1% and the uncertainty of spectrum shape is negligible due to the large statistics of prompt-like singles.

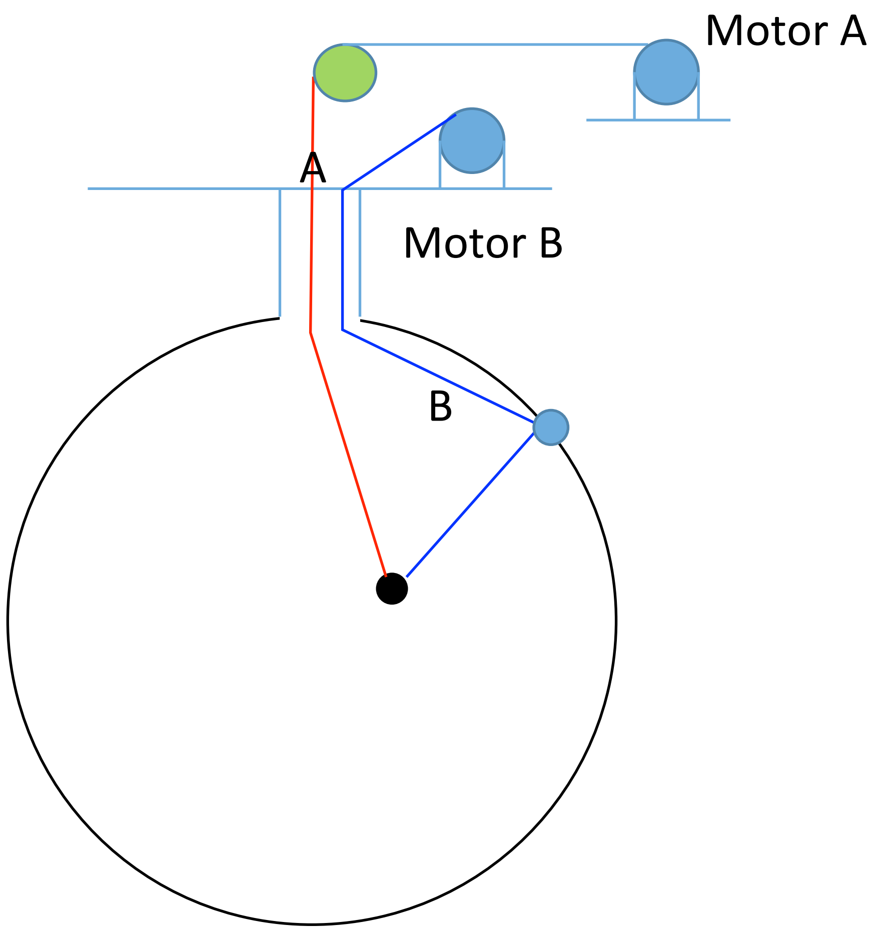
(α,n) Background

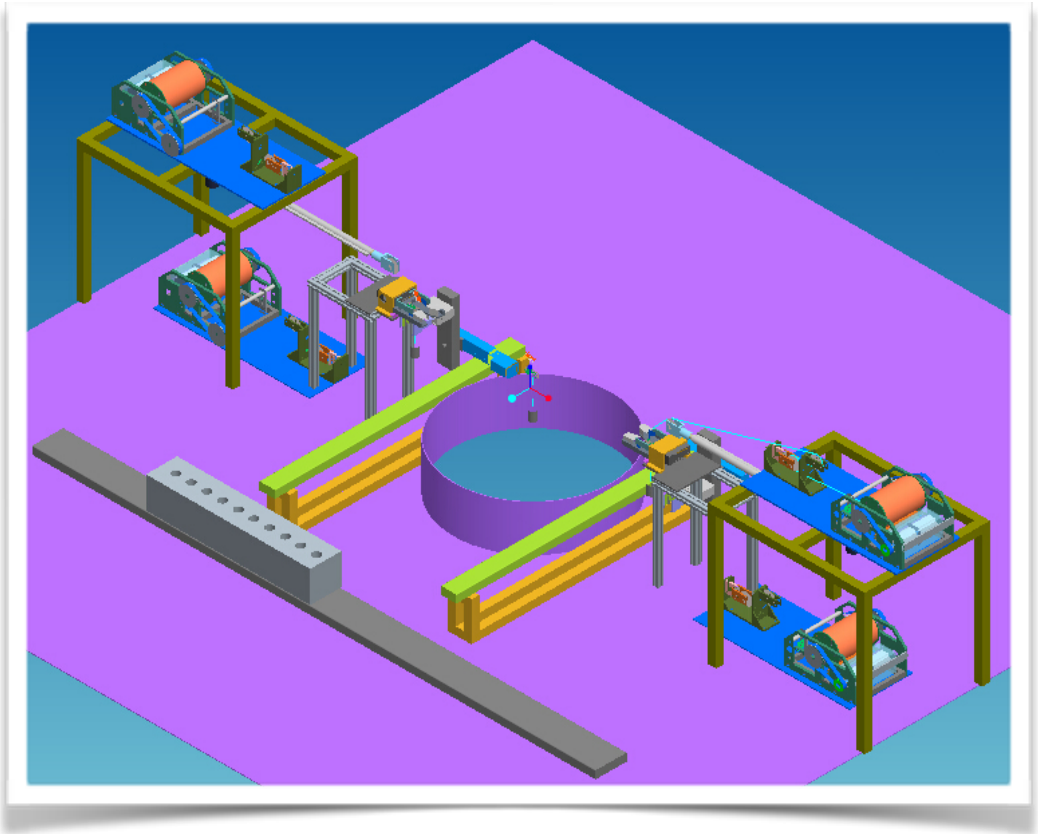
^{13}**C**$(\alpha, n)^{16}$**O background** The alpha particles from the U, Th radioactivities can react with the ^{13}C in LS. The $^{13}C(\alpha, n)^{16}O$ reaction could lead to a correlated background if the neutron is fast enough or there is a gamma from the de-excitation of the ^{16}O excited states. Based on the estimated natural radioactivity concentrations, the (α, n) background rate is estimated to be 0.05/day for the "Acrylic Sphere" option, and 0.01/day for the "Balloon" option due to the lower U/Th concentration. The highest energy of alpha's from U/Th is about 9 MeV, and the cross section of $^{13}C(\alpha, n)^{16}O$ reaction is known with a ~20% uncertainty for an alpha with energy <10 MeV. Thus if the rate of alpha particles is well measured, the (α, n) background can be predicted precisely. In this analysis, a 50% relative uncertainty for both the background rate and the energy spectrum shape is conservatively assumed.

(α,n) interactions: α's emitted by natural radioactivity within the detector could eject neutrons from stable nuclei, with $^{13}C(\alpha,n)^{16}O$ being the most prevalent interaction. Protons scattered by the neutron or $^{16}O^*$ de-excitation γ-rays could mimic a prompt signal, while the eventual neutron capture provided a delayed signal.

DETECTOR

Calibration System





System to deploy calibration sources within the detector

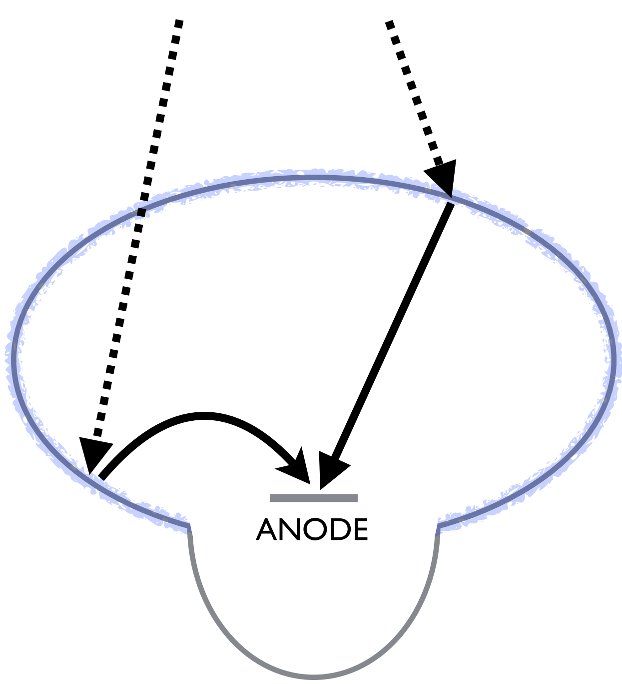
Radioactive elements: need to be securely stored outside the detector

Need to know the **position** with few cm accuracy

Current proposals: **Rope System + Guide Tube + Remote Operated Vehicle**

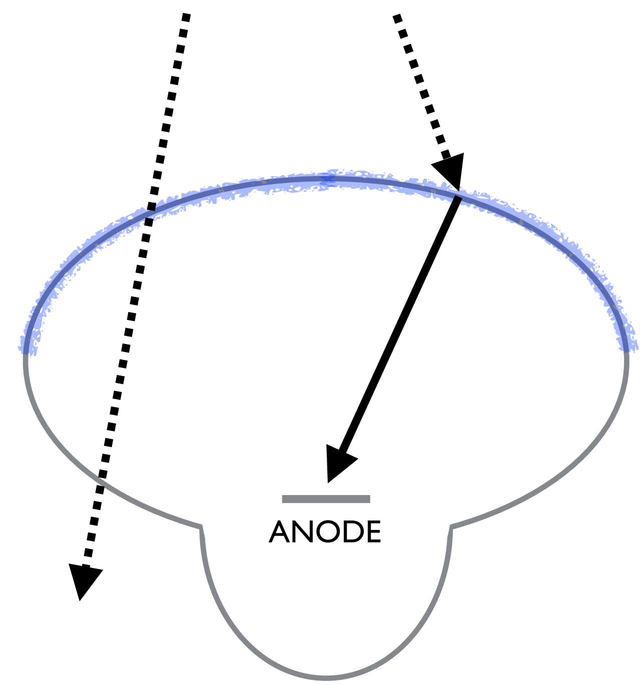
Photocathode

MCP PMT



Transmission
+
Reflection

Hamamatsu

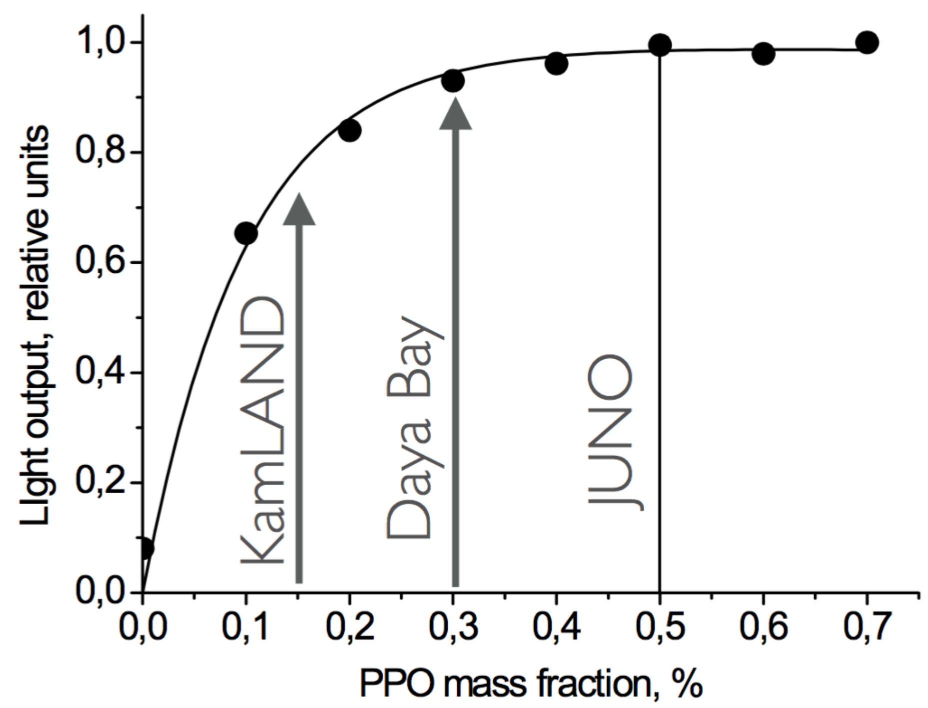


Transmission

Liquid Scintillator

20 kton Liquid Scintillator

- Cocktail: LAB + PPO + bisMSB (no Gd Loading)
- Increase light yield
  - Fluor concentration optimisation ongoing
- Increase transparency
  - Improve the production process of raw solvent (LAB)
  - onsite purification
- Reduce radioactivity
  - no Gd Loading
  - K/U/Th contamination < 10^{-15} g/g



LAB	Attenuation Length [m] at 430nm
RAW	14.2
Vacuum Distillation	19.5
SiO_2 Column	18.6
Al2O3 Column	25

Small PMTS as an "aider" to Large PMTS

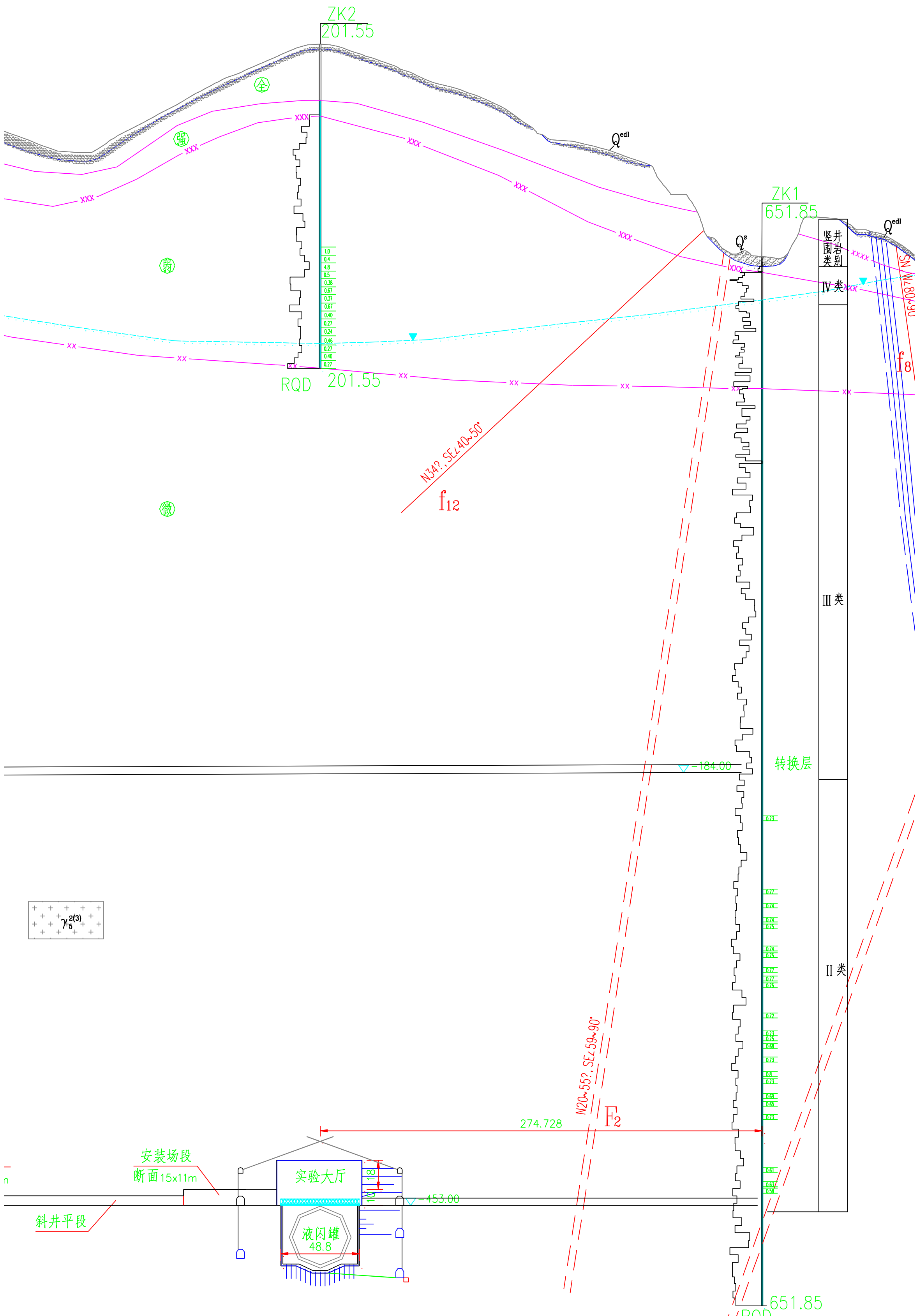
1. **High precision calorimetry**
   Improve response systematics within IBD physics
   Aide to achieve $\leq$3% resolution at 1MeV

2. **Improve inner-detector μ-reconstruction resolution**
   Aide $^{12}B/^{9}Li/^{8}He$ tagging/vetoing

3. **High rate SN pile-up (if very near)**
   Minimise bias in absolute rate & energy spectrum

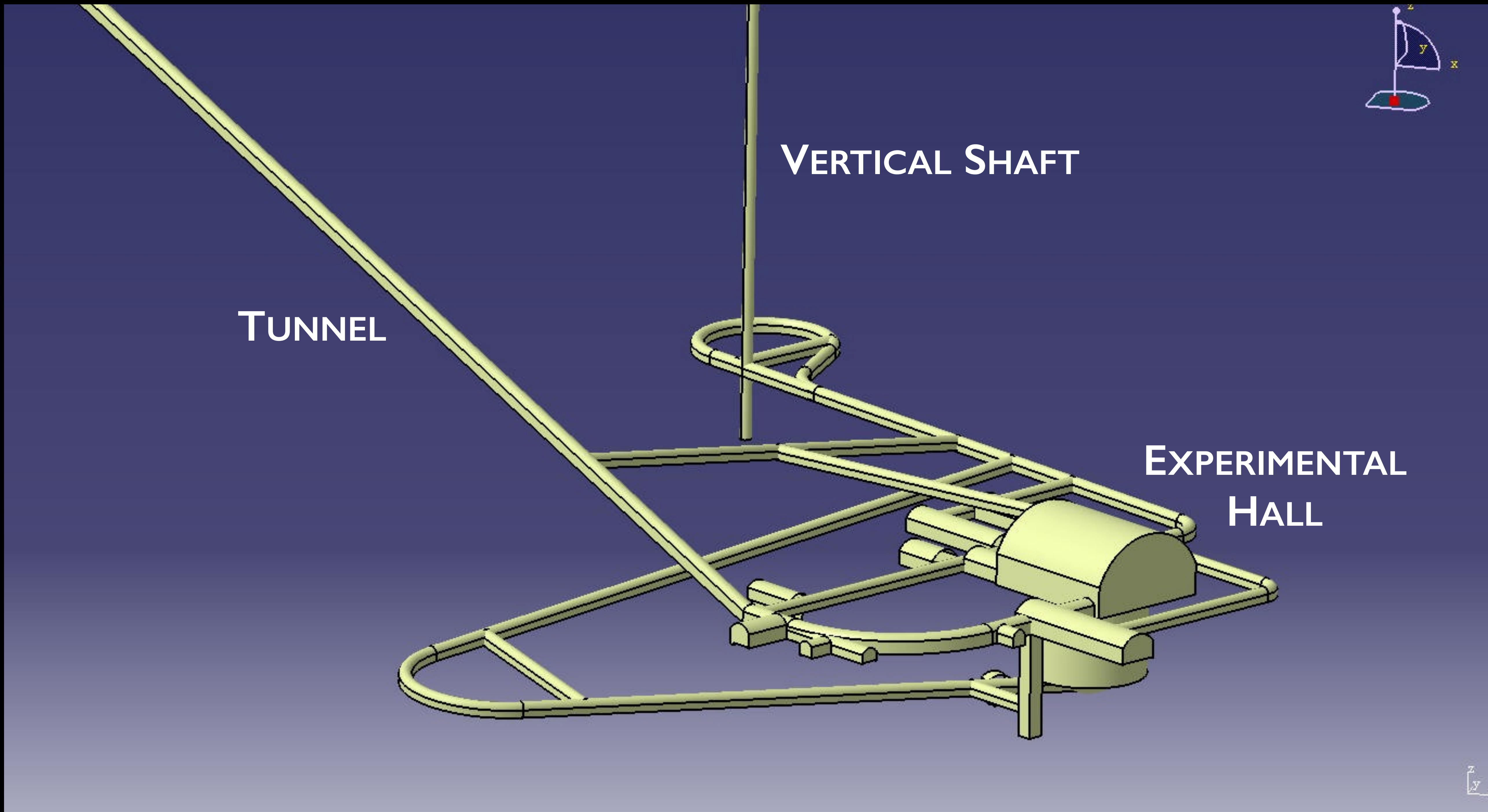
4. **Vital complementarity: time resolution, dynamic range & trigger**
   Articulate additional complementary to LPMT system: better/simple

Overburden



720 m Rock Overburden (1900 mwe)

611 m vertical shaft (digging…)


Vertical Shaft
Tunnel
Experimental
Hall

Top Veto System

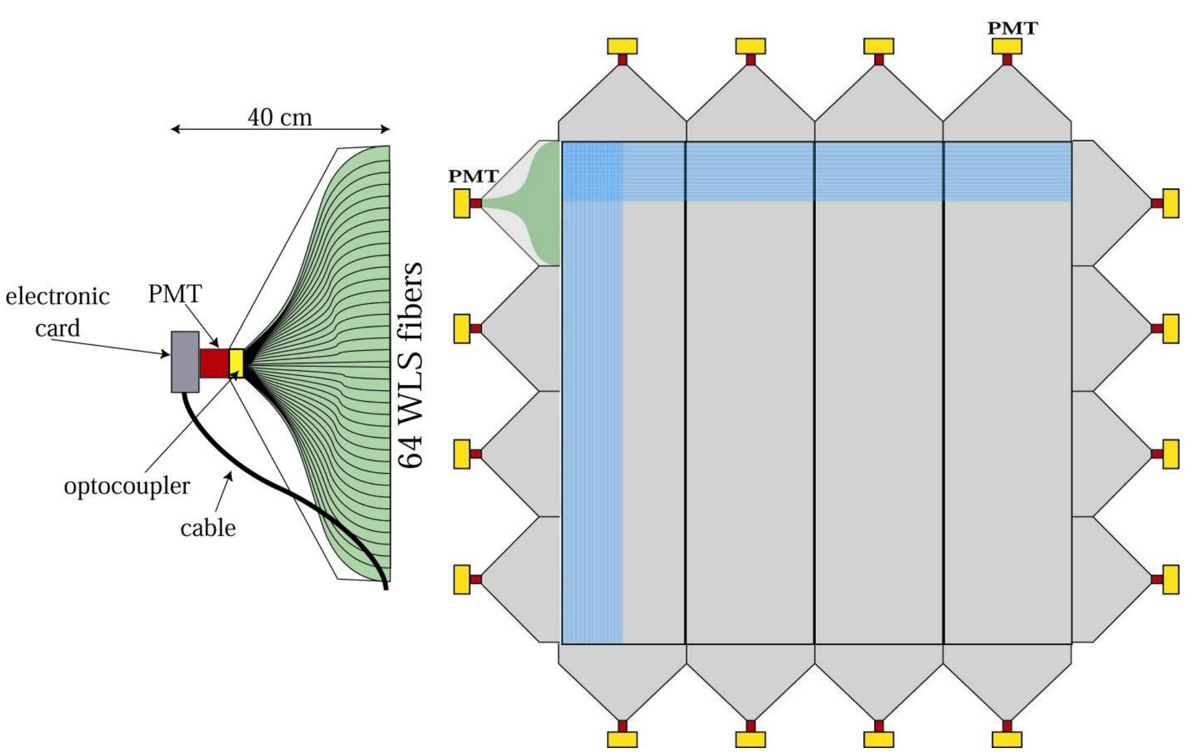
Use plastic scintillator walls from OPERA

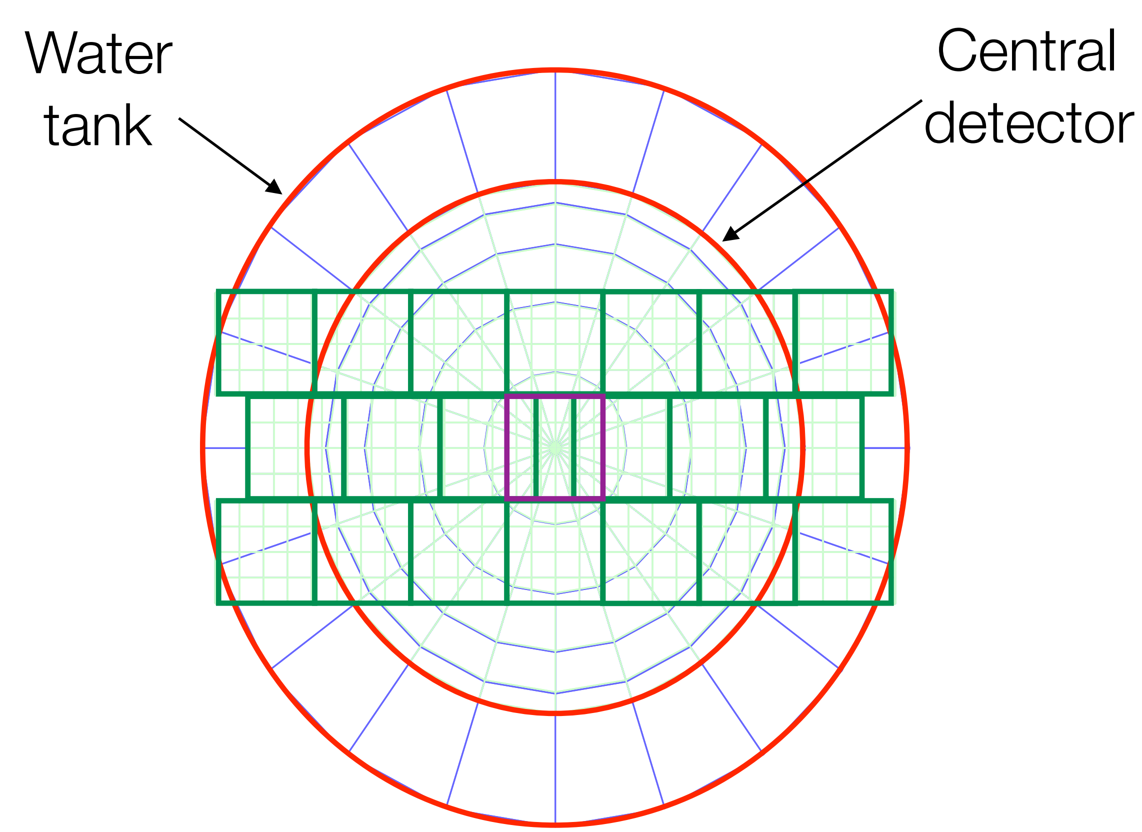
Each module is 7x7 m

Modules are meant to be used vertically, while we use them horizontally

We want several layers: muon tracking ⊕ reject gammas from the rock

OPERA modules are not enough to cover entirely the JUNO surface





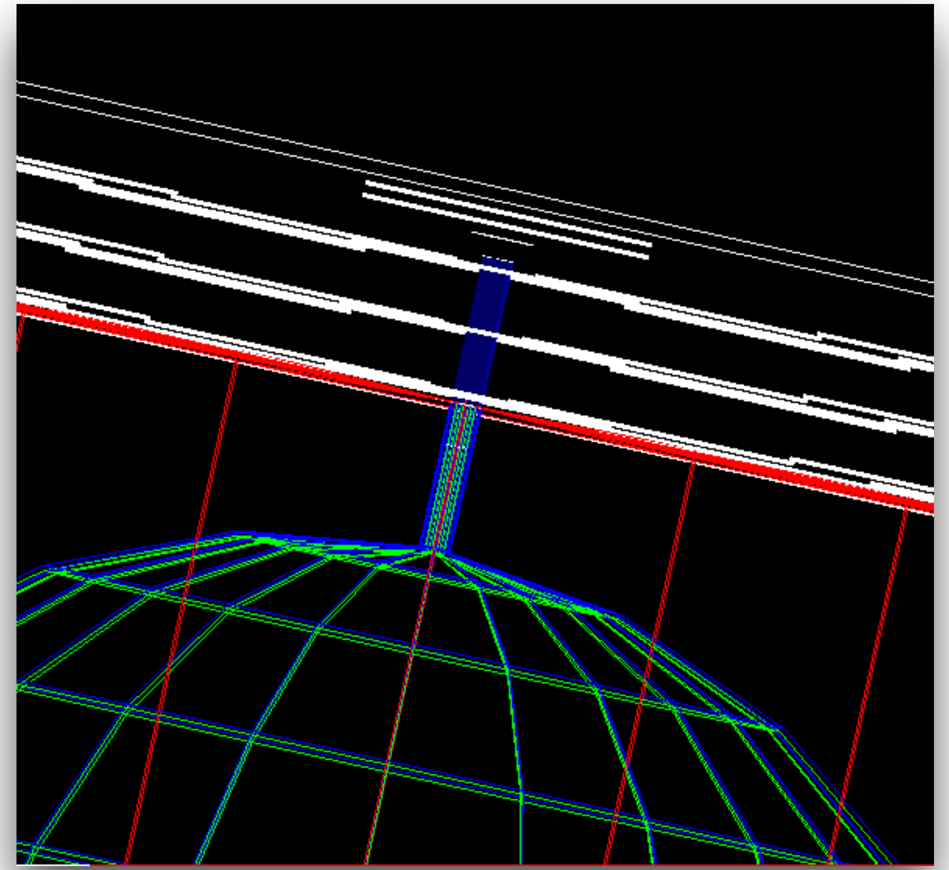
Muon Veto

Muon Veto: critical to reduce backgrounds

Cosmogenic isotopes rejection:
reconstruction of muon tracks and O(1s) veto surrounding the track

Neutron Rejection:
passive shielding (water) + time coincidence w/ muon + multiple proton recoils

Gamma rejection: passive shielding (water)

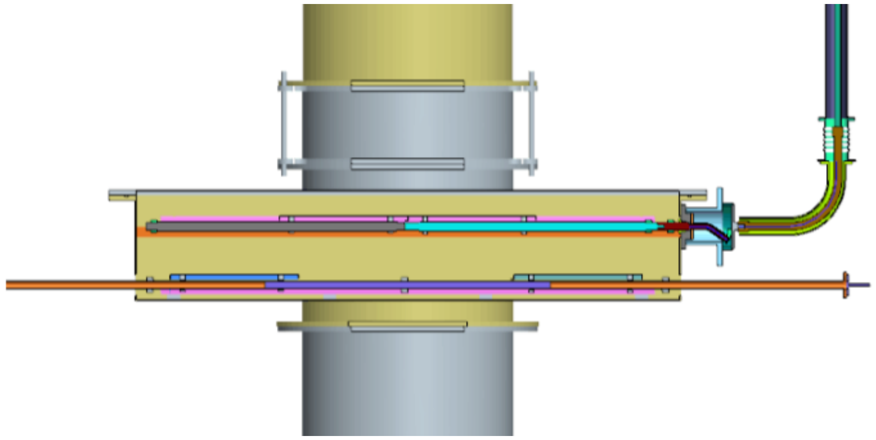


Chimney

Connecting acrylic vessel with external world

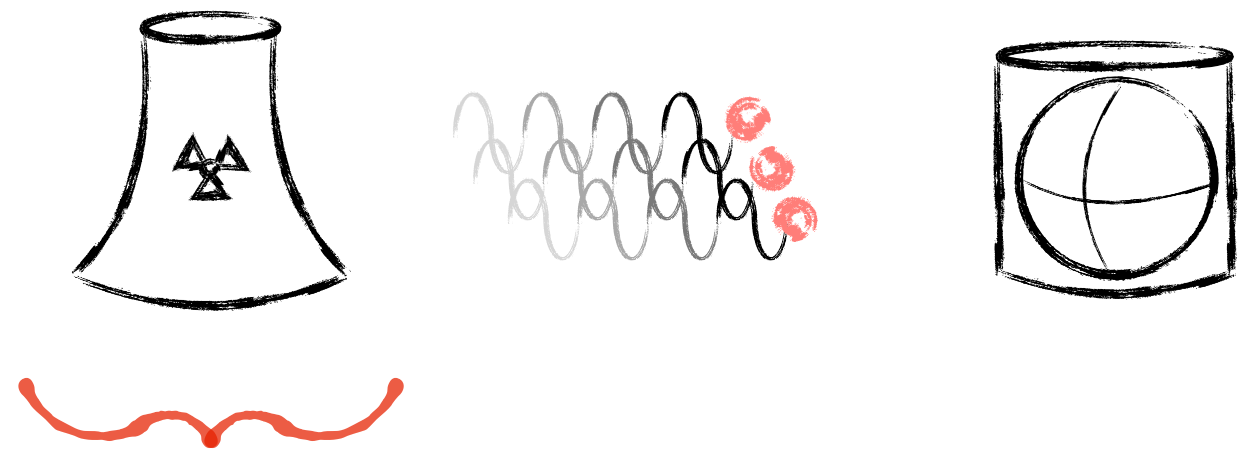
Need to be instrumented for **stopping muons**

Need **shutter** to prevent light contamination in CD

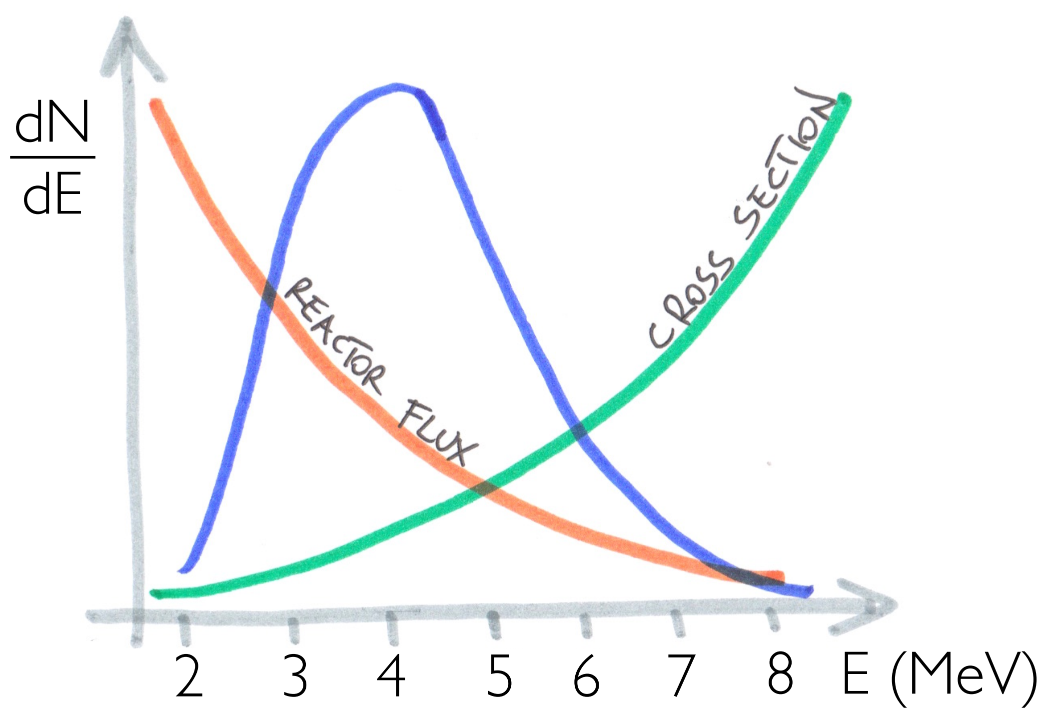


PHYSICS

Antineutrinos from Reactor (Emission)



Spectrum at Emission



Nuclear Power Plants

Energy by breaking heavy nuclei

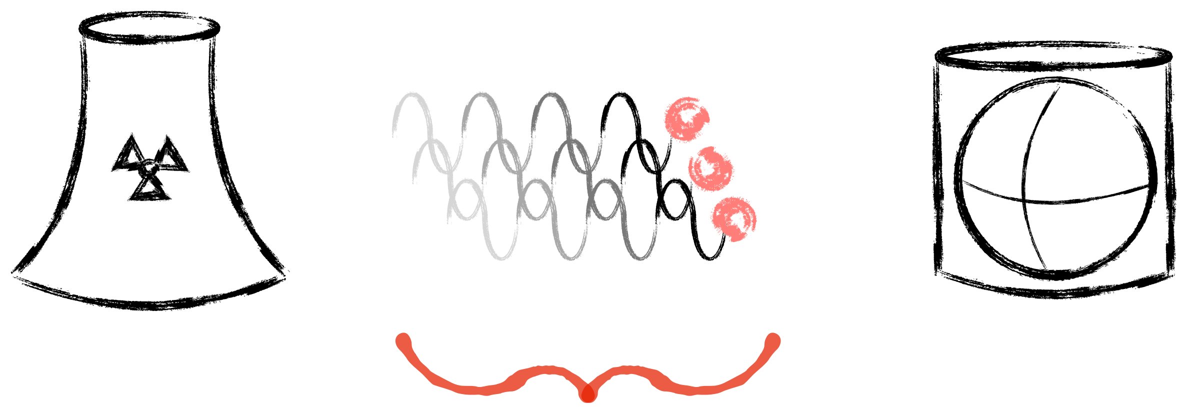
Fission fragments are unstable

Decaying through a cascade of beta decays

($n \blacktriangleright p + e^- + \bar{\nu}_e$)

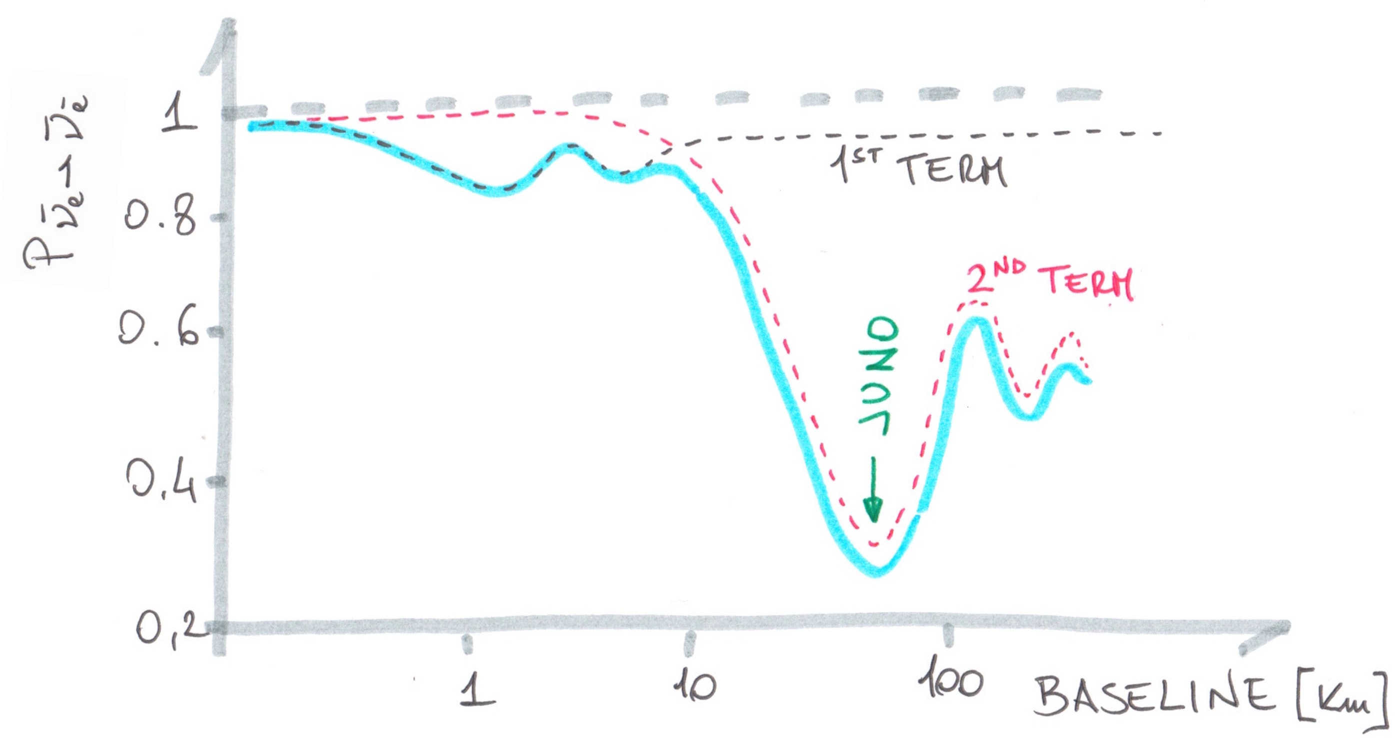
3 GW_{th} reactor : $\sim 10^{20}$ $\bar{\nu}_e$ / s

Antineutrinos from Reactor (Propagation)



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

$$- \sin^2 2\vartheta_{12}\ \cos^4\vartheta_{13}\ \sin^2\Delta_{21}$$

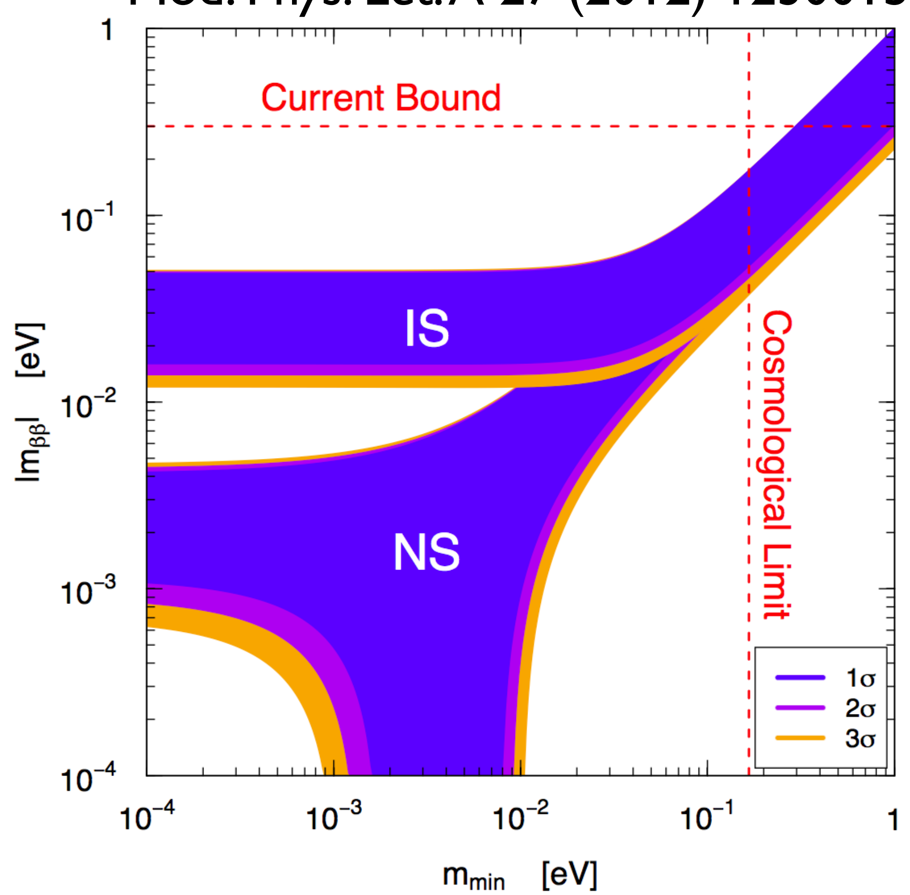


$$\Delta_{ij} = \Delta m^2_{ij} \frac{L}{4E}$$

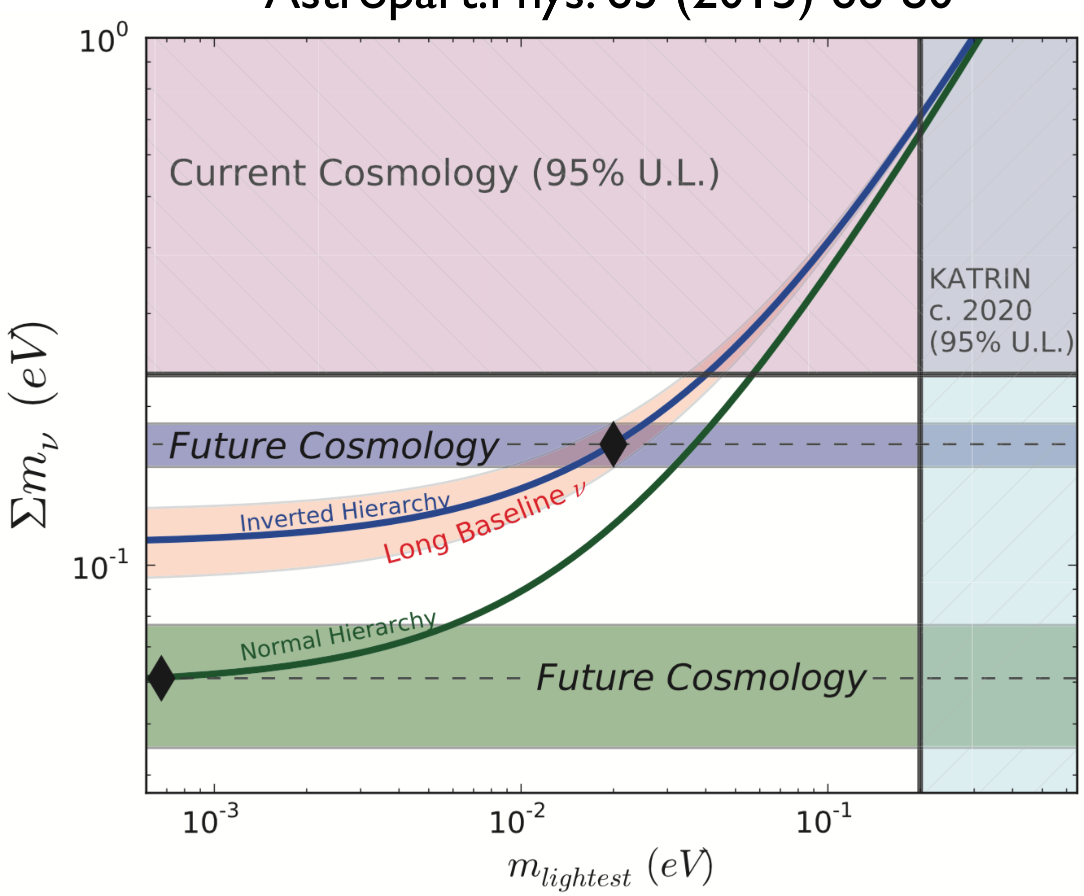
Importance of MH Determination

- **Fundamental parameter** that we did not manage to predict (so far)
- Help to understand what is the true nature of neutrinos (**Dirac** *vs* **Majorana**)
  - Define next generation of neutrino-less double beta decay experiments
- Help to determine **CP-violation** in the leptonic sector
  - Most experiment are degenerate in δ_{CP} and MH
- Help to use **cosmological measurements** to constrain neutrino physics

Mod. Phys. Let. A 27 (2012) 1230015



Astropart.Phys. 63 (2015) 66-80

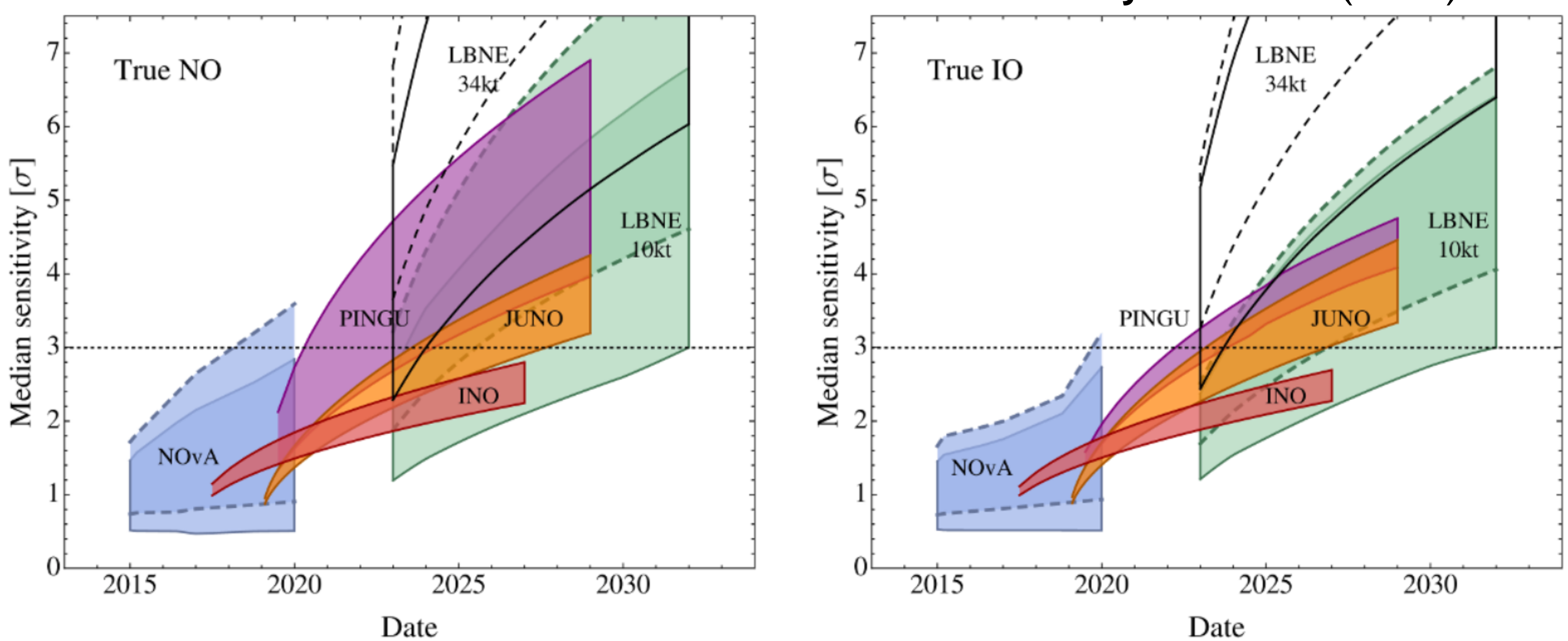


Proposed Experiments Aiming at MH

Large value of θ_{13} allows to resolve MH with different experimental techniques

- Medium baseline (~50km) **reactor** anti-ν_e oscillation experiments (JUNO, RENO50)
- Long baseline **accelerator** (anti-)ν_μ experiments (NOvA, DUNE/LBNE)
- **Atmospheric** (anti-)ν_μ experiments (INO, Pingu, DUNE, Hyper-K)

JHEP 1403 (2014) 028



NOvA LBNE: δ_{CP} variation

Pingu, INO: θ_{23} 40~50°

JUNO 3%~3.5% Resolution

JUNO: no matter effects
no CP dependence

JUNO: "*Competitive in schedule and complementary in physics*"®

Survival Probability (1)

JHEP 1305 (2013) 131

To make the effects of the mass hierarchy clearer, we would like to rewrite eq. (2.4) as,

$$\begin{aligned} P_{ee} = 1 &- \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21}) \\ &- \sin^2 2\theta_{13}\sin^2(|\Delta_{31}|) \\ &- \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{21})\cos(2|\Delta_{31}|) \\ &\pm \frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin(2\Delta_{21})\sin(2|\Delta_{31}|)\,, \end{aligned} \tag{2.6}$$

where only the last term depends on the mass hierarchy, which takes the plus and minus sign, respectively, for normal (NH) and inverted hierarchy (IH),

$$\Delta m^2_{31} \equiv \begin{cases} m_3^2 - m_1^2 > 0 \quad \text{(NH)} & \text{(2.7a)} \\ m_3^2 - m_1^2 < 0 \quad \text{(IH)}. & \text{(2.7b)} \end{cases}$$

Survival Probability (2)

arXiv: 1307.7419

we can observe the oscillation signals driven by both the solar mass-squared splitting (Δm^2_{21}) and the atmospheric mass-squared splitting (Δm^2_{32}) in the antineutrino energy spectrum [11]. The oscillation resulted from the atmospheric mass-squared splitting manifests itself in the energy spectrum as multiple cycles which shift in the opposite directions for inverted hierarchy (IH) and normal hierarchy (NH), as shown in the following formula,

$$\begin{aligned} P_{\bar{\nu}_e\to\bar{\nu}_e} &= 1-\sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31}+\sin^2\theta_{12}\sin^2\Delta_{32})-\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \qquad (1.1)\\ &= 1-2s^2_{13}c^2_{13}-4c^2_{13}s^2_{12}c^2_{12}\sin^2\Delta_{21}+2s^2_{13}c^2_{13}\sqrt{1-4s^2_{12}c^2_{12}\sin^2\Delta_{21}}\cos(2\Delta_{32}\pm\phi), \end{aligned}$$

where $\Delta_{21}\equiv\Delta m^2_{21}L/4E$, $\Delta_{32}\equiv\Delta m^2_{32}L/4E$, in which L is the baseline and E is the antineutrino energy, and

$$\sin\phi=\frac{c^2_{12}\sin 2\Delta_{21}}{\sqrt{1-4s^2_{12}c^2_{12}\sin^2\Delta_{21}}},\ \cos\phi=\frac{c^2_{12}\cos 2\Delta_{21}+s^2_{12}}{\sqrt{1-4s^2_{12}c^2_{12}\sin^2\Delta_{21}}}.$$

Survival Probability (3)

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Using the standard parametrization of the leptonic mixing matrix [7], we get the effective mass-squared differences in Eq. (2) for different channels of neutrino oscillations

$$
\begin{aligned}
\Delta m^2_{ee} &\simeq \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}\,, & (5)\\
\Delta m^2_{\mu\mu} &\simeq \sin^2\theta_{12}\Delta m^2_{31} + \cos^2\theta_{12}\Delta m^2_{32} + \sin 2\theta_{12}\sin\theta_{13}\tan\theta_{23}\cos\delta\Delta m^2_{21}\,, & (6)\\
\Delta m^2_{\tau\tau} &\simeq \sin^2\theta_{12}\Delta m^2_{31} + \cos^2\theta_{12}\Delta m^2_{32} - \sin 2\theta_{12}\sin\theta_{13}\cot\theta_{23}\cos\delta\Delta m^2_{21}\,, & (7)
\end{aligned}
$$

where terms at the order of $\mathcal{O}(\sin^2\theta_{13}\Delta m^2_{21})$ have been neglected for simplicity. We can also calculate the differences of the effective quantities between different flavors as

$$
\begin{aligned}
|\Delta m^2_{ee}| - |\Delta m^2_{\mu\mu}| &= \pm\Delta m^2_{21}(\cos 2\theta_{12} - \sin 2\theta_{12}\sin\theta_{13}\tan\theta_{23}\cos\delta)\,, & (8)\\
|\Delta m^2_{\mu\mu}| - |\Delta m^2_{\tau\tau}| &= \pm 2\Delta m^2_{21}\sin 2\theta_{12}\sin\theta_{13}\csc 2\theta_{23}\cos\delta\,, & (9)
\end{aligned}
$$

where the positive and negative signs correspond to normal and inverted mass hierarchies, respectively. Therefore, comparisons of oscillations between different flavors may distinguish the MH and even tell us possible information on the CP-violating phase.

One must keep in mind that the effective mass-squared differences defined here are only MH-invariant under the condition of $\Delta_{21} \ll 1$. In the reactor neutrino experiment at a medium baseline ($\Delta_{21} \sim 1$), where all the oscillation modes and their interference terms are measurable, the absolute value of Δm^2_{ee} is not invariant by changing the sign of the neutrino MH. However, it is still close to Δm^2_{ee} rather than $\Delta m^2_{\mu\mu}$ and we can get an additional MH sensitivity with the inclusion of a prior $\Delta m^2_{\mu\mu}$ measurement.

Detector Resolution Requirement

parametrization for the detector energy resolution is defined as

$$\frac{\sigma_E}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}\ , \tag{2.12}$$

where the visible energy E is in the unit of MeV.

Based on the numerical calculation of sensitivity studies in terms of $\Delta\chi^2_{\mathrm{MH}}$, we find the approximate relation for the effects of non-stochastic terms (i.e., b, c) using the a term as,

$$\sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2} \simeq \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{1.6\,b}{\sqrt{E}}\right)^2 + \left(\frac{c}{1.6\,\sqrt{E}}\right)^2}\ , \tag{2.13}$$

which demonstrates that the effect of b is 1.6 times larger than the a term, and the non-trivial c term is less significant than a by a factor of 1.6. Therefore, a requirement for the resolution of $a/\sqrt{E}$ better than 3% is equivalent the following requirement,

$$\sqrt{(a)^2 + (1.6 \times b)^2 + \left(\frac{c}{1.6}\right)^2} \leq 3\%\ . \tag{2.14}$$

EXPERIMENTAL CHALLENGES

Experimental Challenges

Keep Constant Resolution Term Below 1% (Energy Calibration)

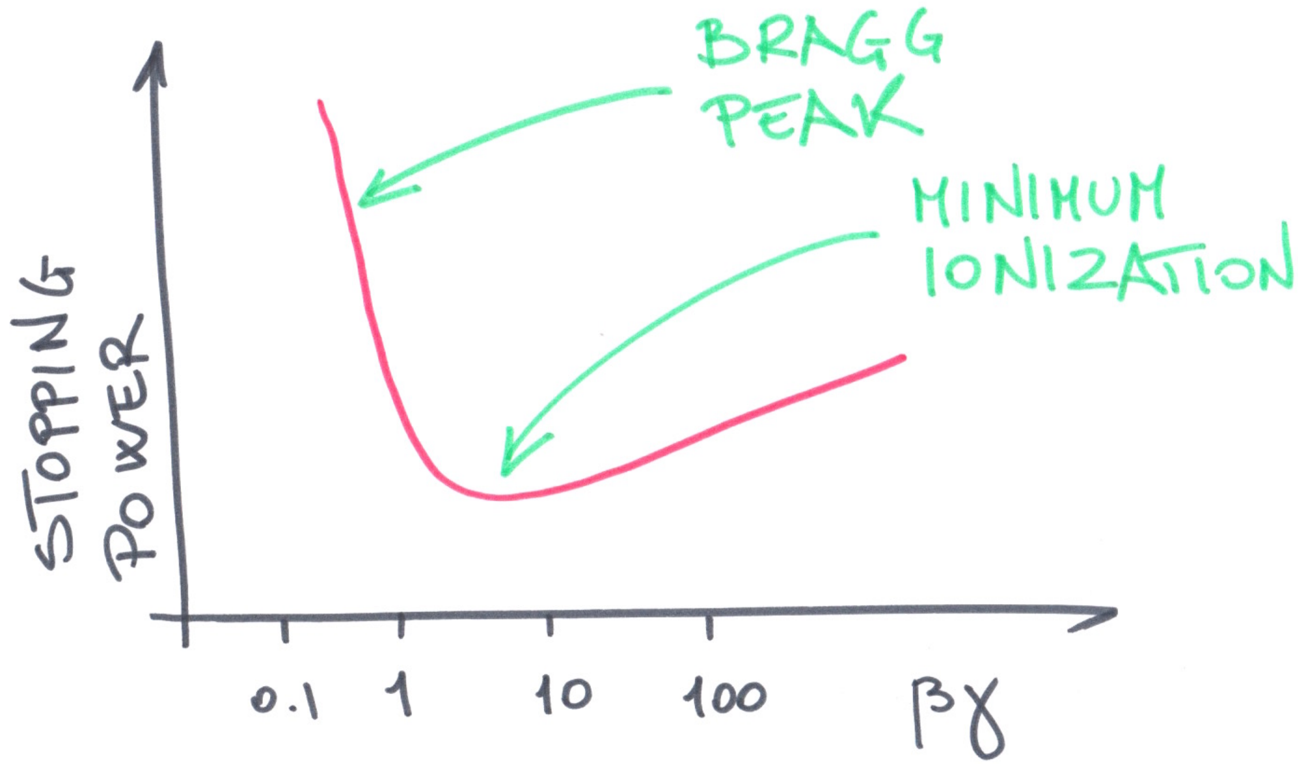
- Energy Non-linearity
  - Due to Liquid Scintillator Response
  - Due to Readout Electronics
- Non-uniformity

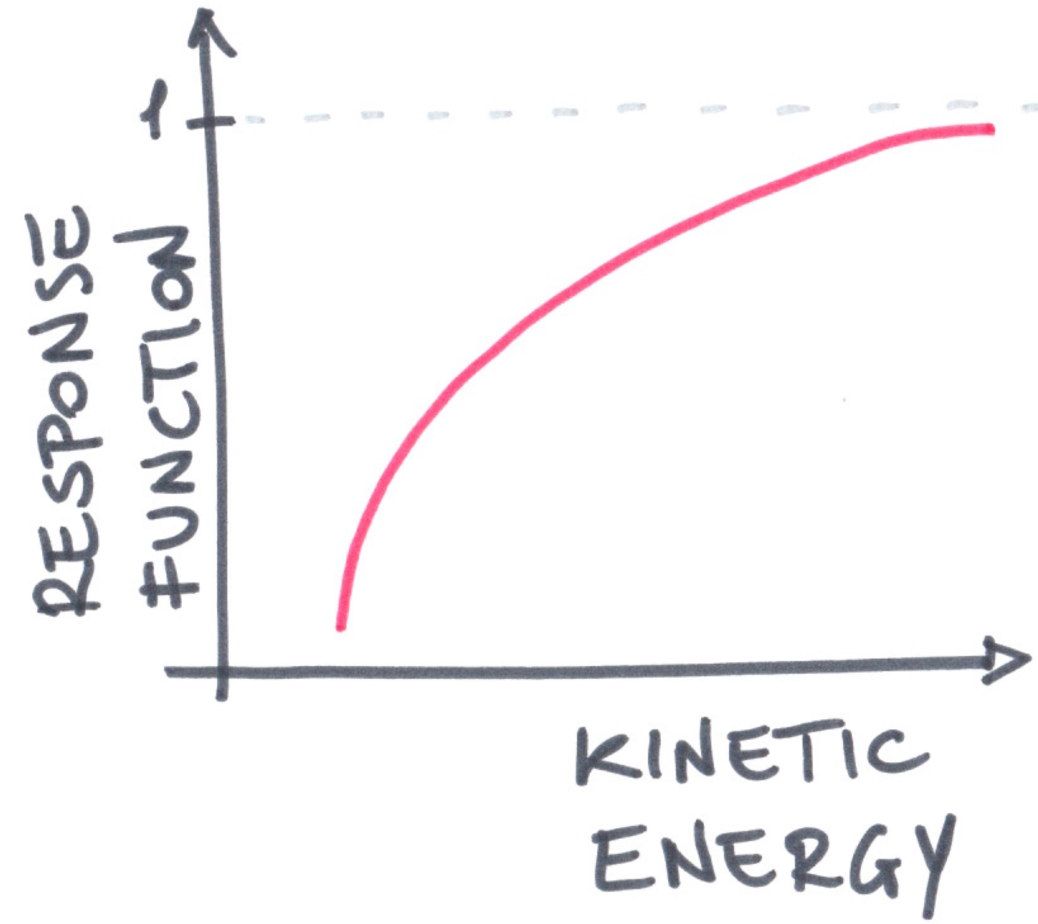
Reduce Natural Radioactivity (Purification)

Reduce Cosmogenic Backgrounds (Muon Tracking)

Maximize Light Collection (PMTS)

Scintillator Non-linearity (Quenching)





Particles with low initial energy ▶ large dE/dx ▶ total light output is quenched.

More energetic particles ▶ most of their energy lost with small dE/dx.

▼

high dE/dx at end of track contributes less to total light yield.

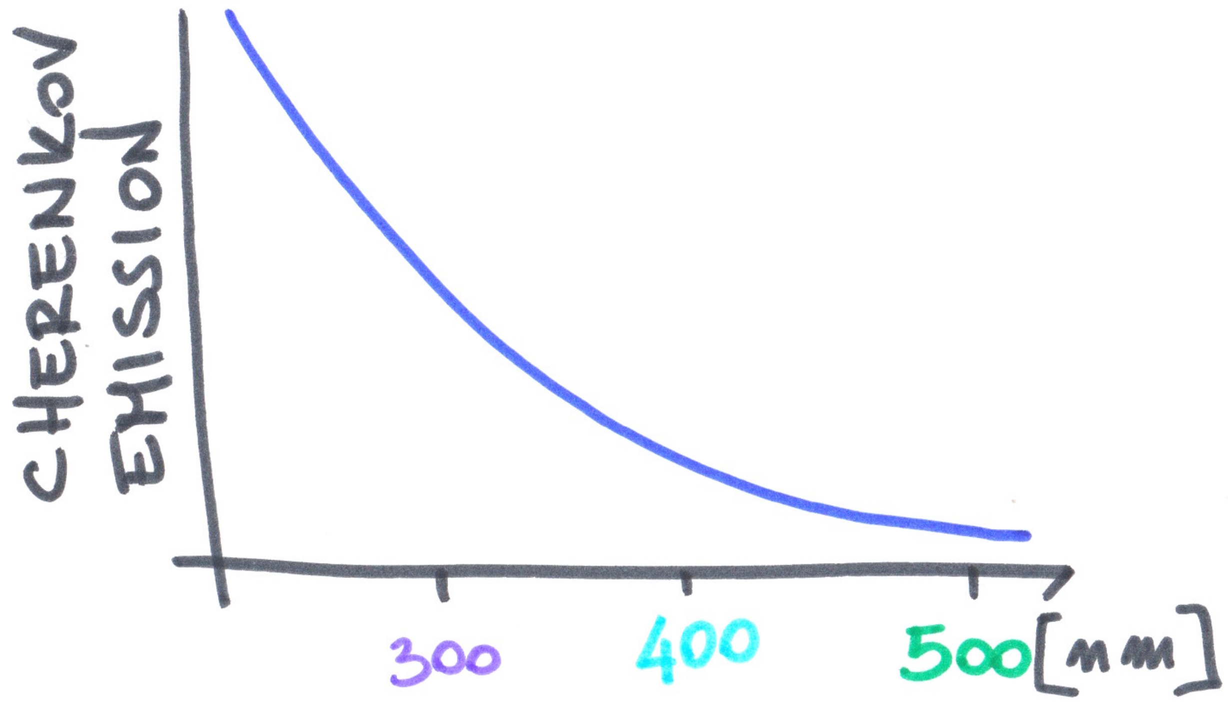
Ionization quenching leads to a non-linear relation between the energy of the ionizing particle and the light produced by the scintillator

Scintillator Non-linearity (Cherenkov)

Charged particles in LS have speed greater than phase velocity of light

Cherenkov light emission (mostly UV)

$$n(LS) = 1.48$$
$$\beta_{MIN} = 1/n = 0.675$$
$$E_{MIN}(e^-) = 0.7\ \text{MeV}$$

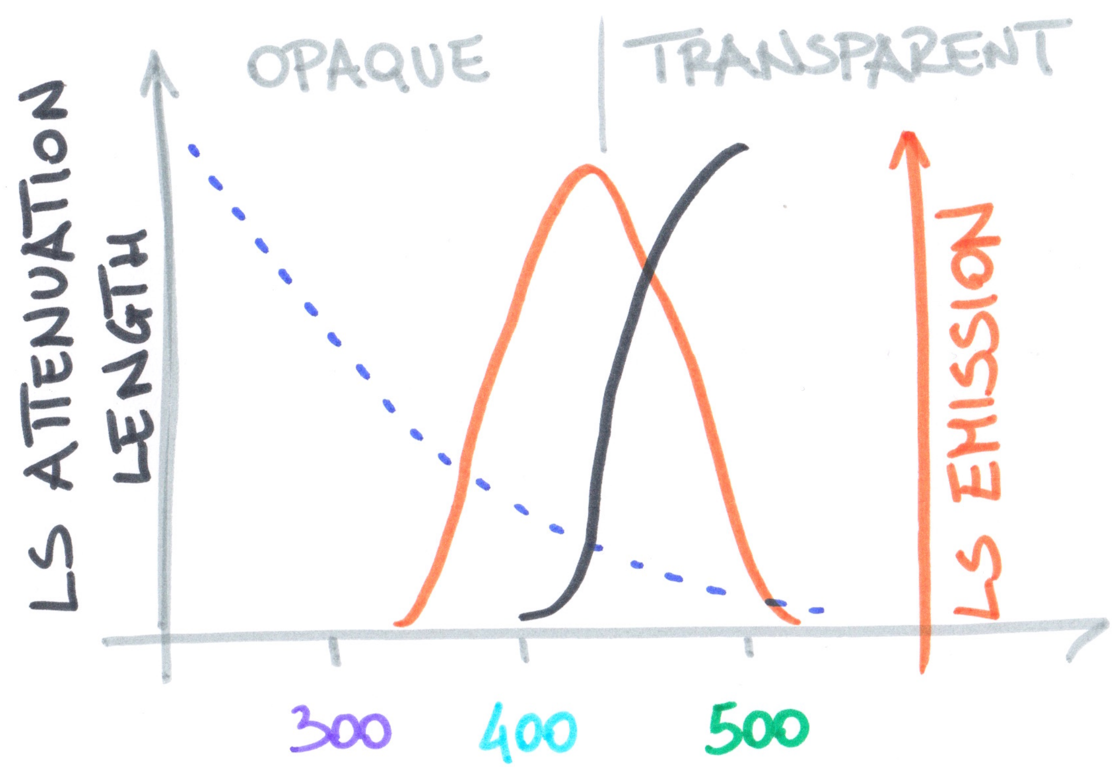


LS is opaque to UV light

Cherenkov light is re-absorbed by LS

Sometimes it is re-emitted as scint. light

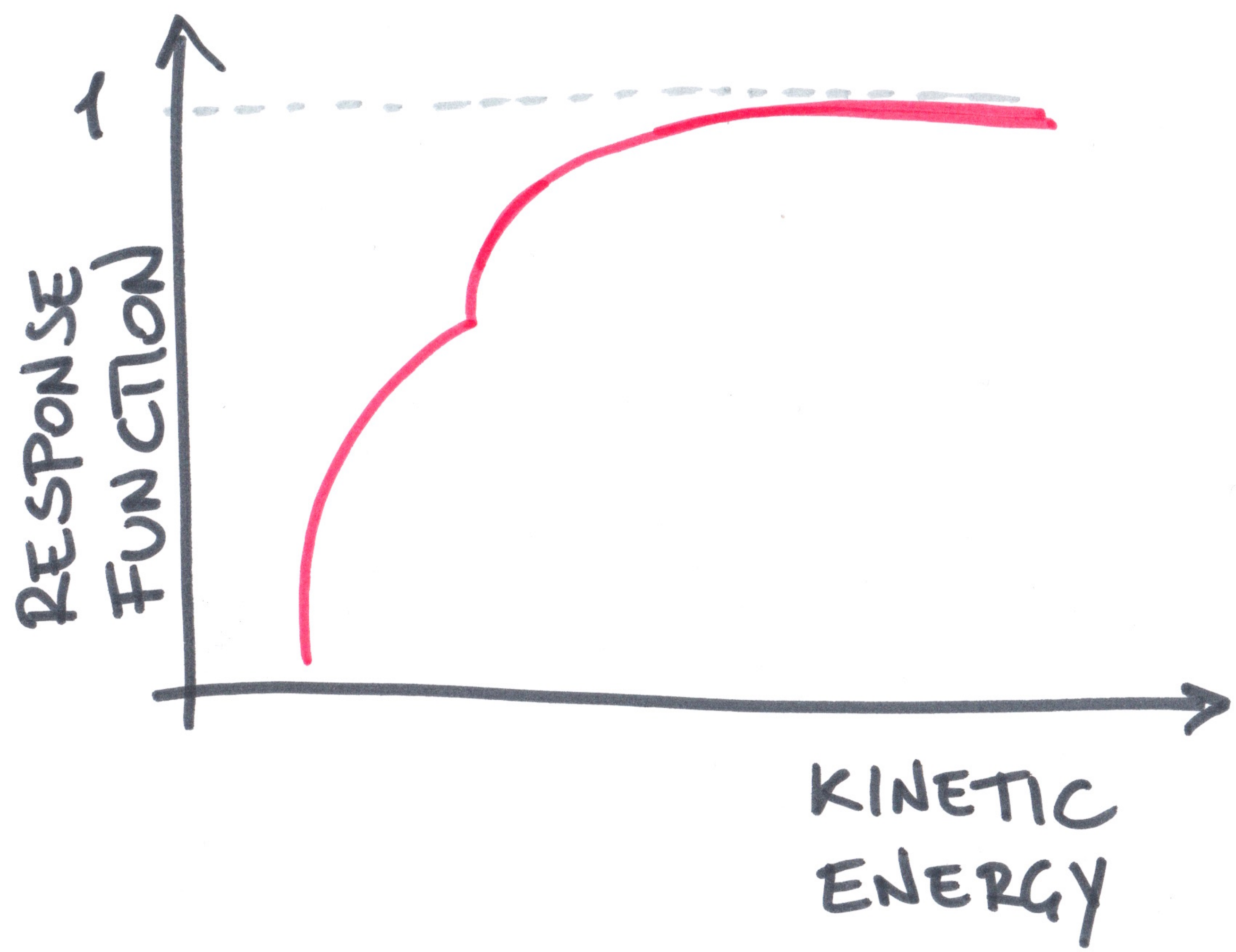
Re-emission prob is poorly known



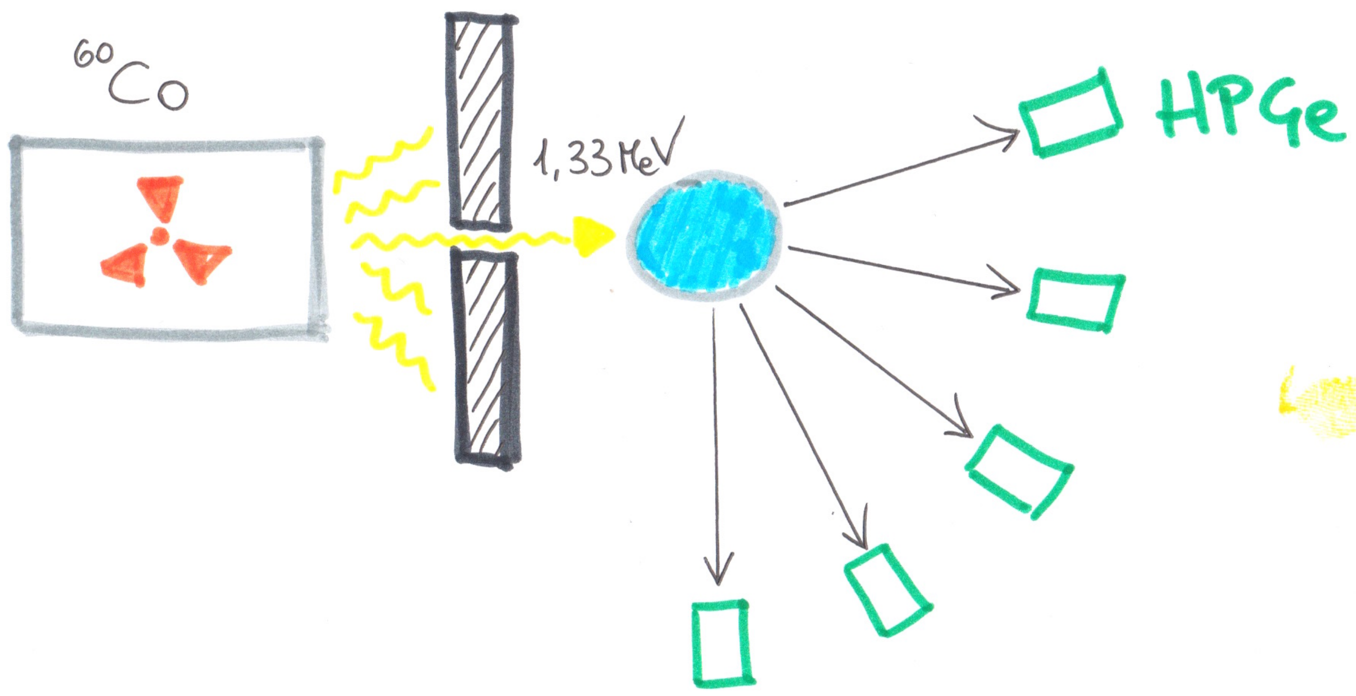
Overall Scintillator Non-linearity

Ionization quenching reduces light at low particle energy
Cherenkov light mildly enhances LS light yield at higher particle energy

Overall non-linear energy dependence of the light output needs to be carefully evaluated



LS Non-linearity Measurement

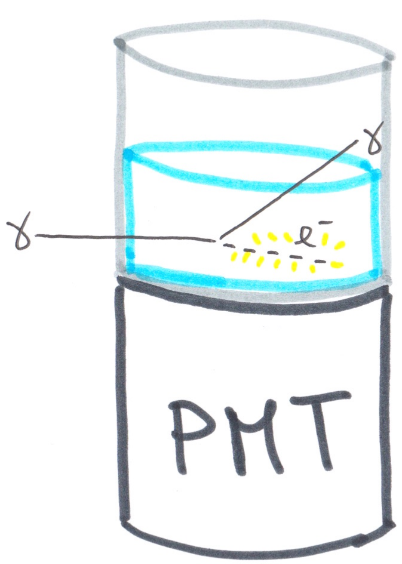


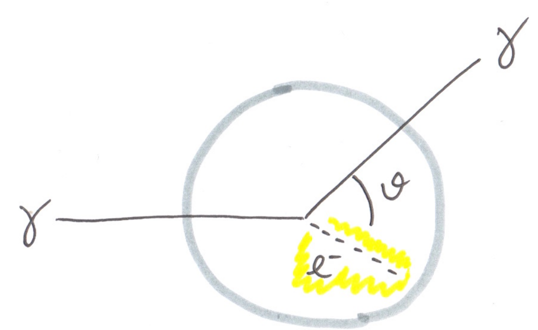
Exploiting Compton scattering from a known gamma

HPGe are basically photo-diodes placed at a fixed angle

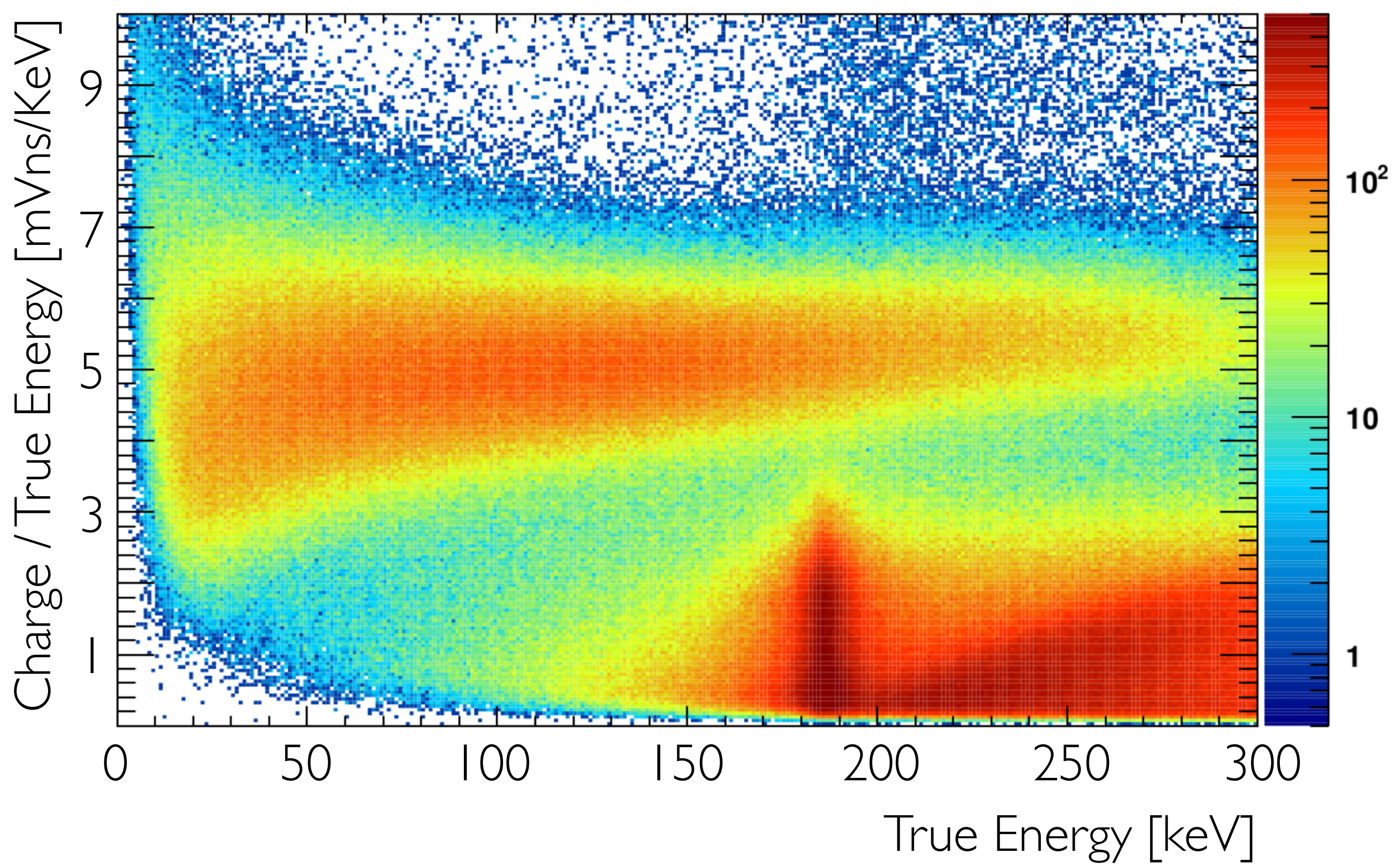
Electron true energy is derived from the gamma angle

Electron excites LS, whose light is collected by a standard pmt





LS Non-linearity Measurement



Exploiting Compton scattering from a known gamma

HPGe are basically photo-diodes placed at a fixed angle

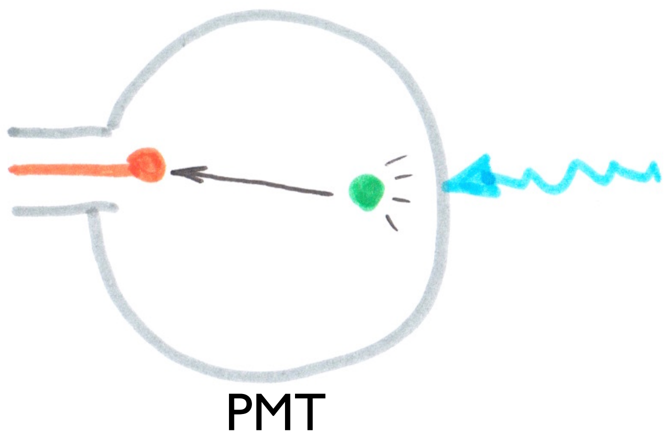
Electron true energy is derived from the gamma angle

Electron excites LS, whose light is collected by a standard pmt

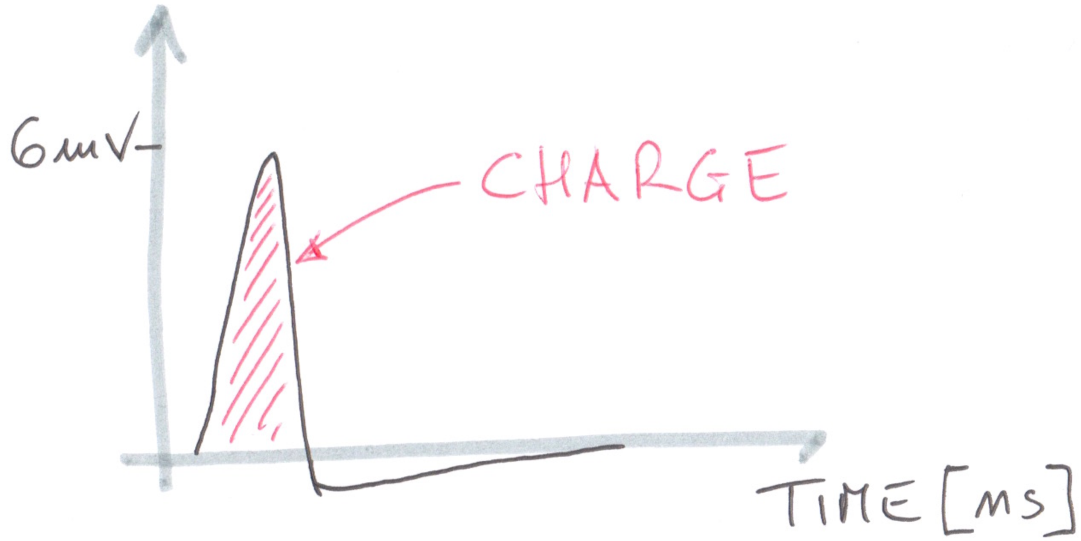
Electron measured energy is quenched and needs to be compared with the true energy

Electronics Non-Linearity

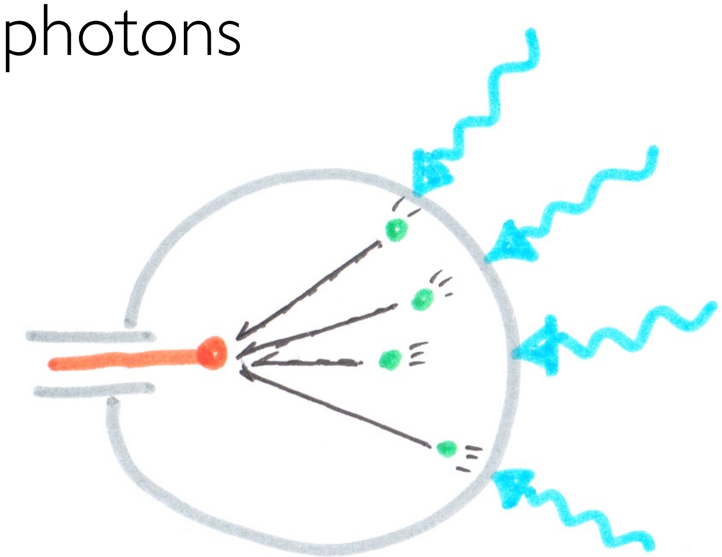
Single photon



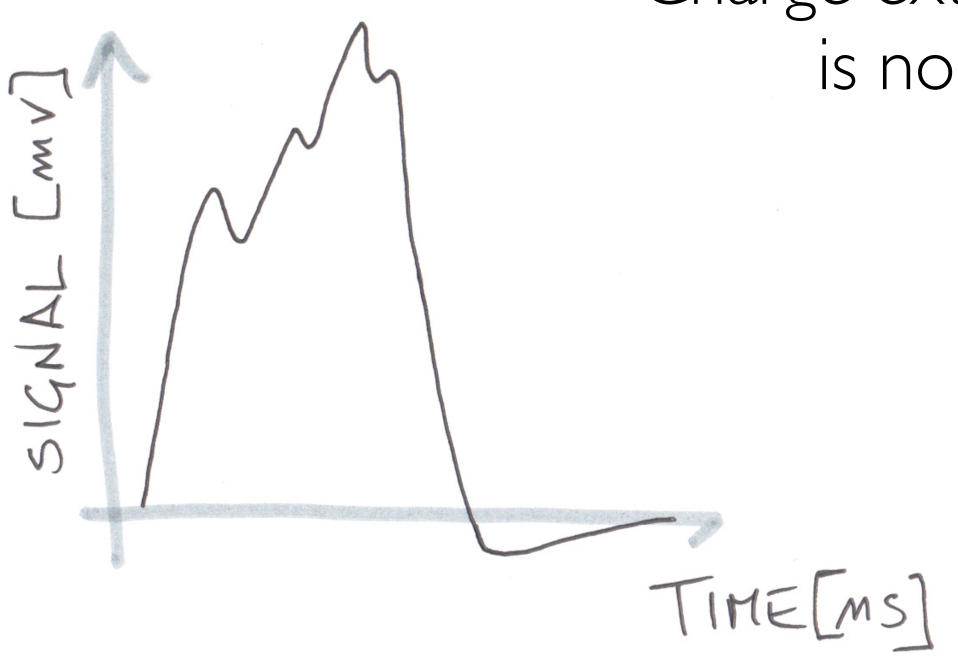
Output signal seen from FADC



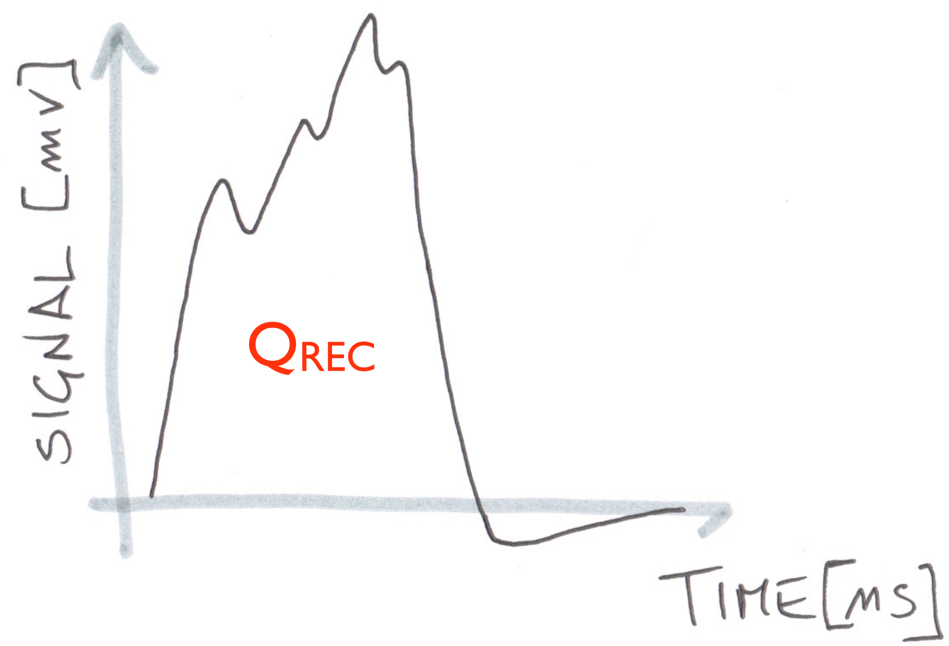
Multiple photons

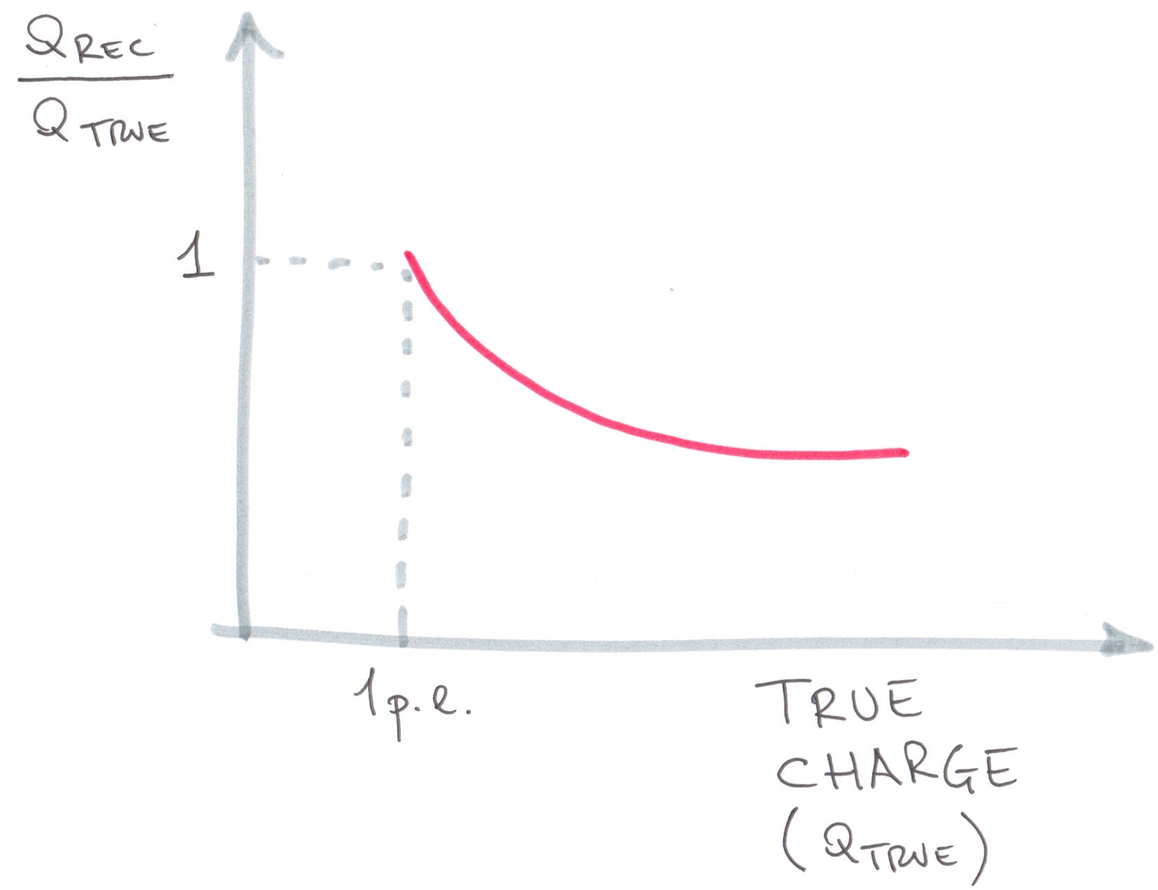


Charge extraction
is non-trivial



Electronics Non-Linearity





Experience (i.e. previous experiments) tells us that **charge** extraction from complex waveforms might be **biased**

Such bias is both energy and position dependent
(it is a function of the number of p.e. collected at the PMT anode)

Ad hoc **correction** might be implemented at single-channel level

Significance with Non-Linearity

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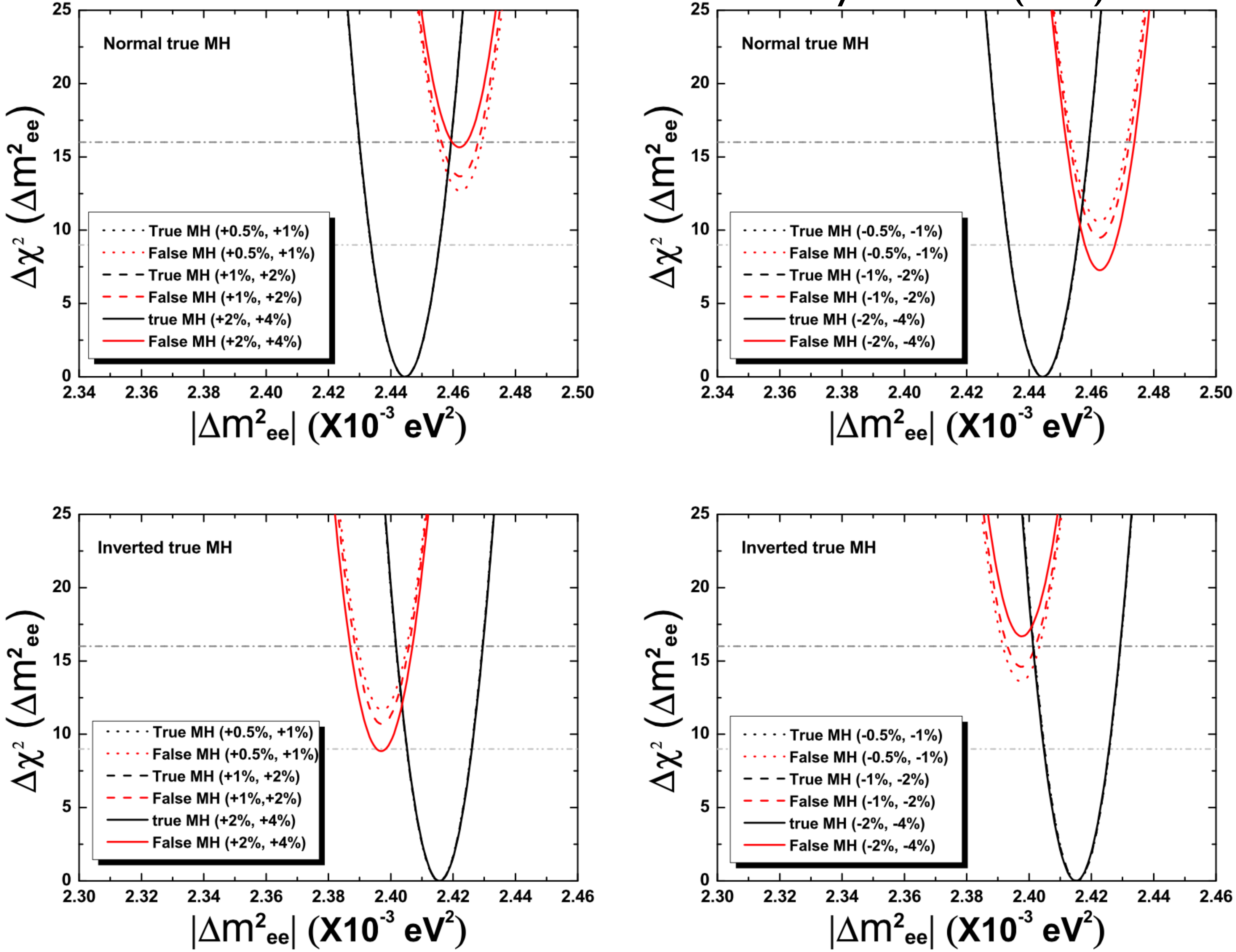
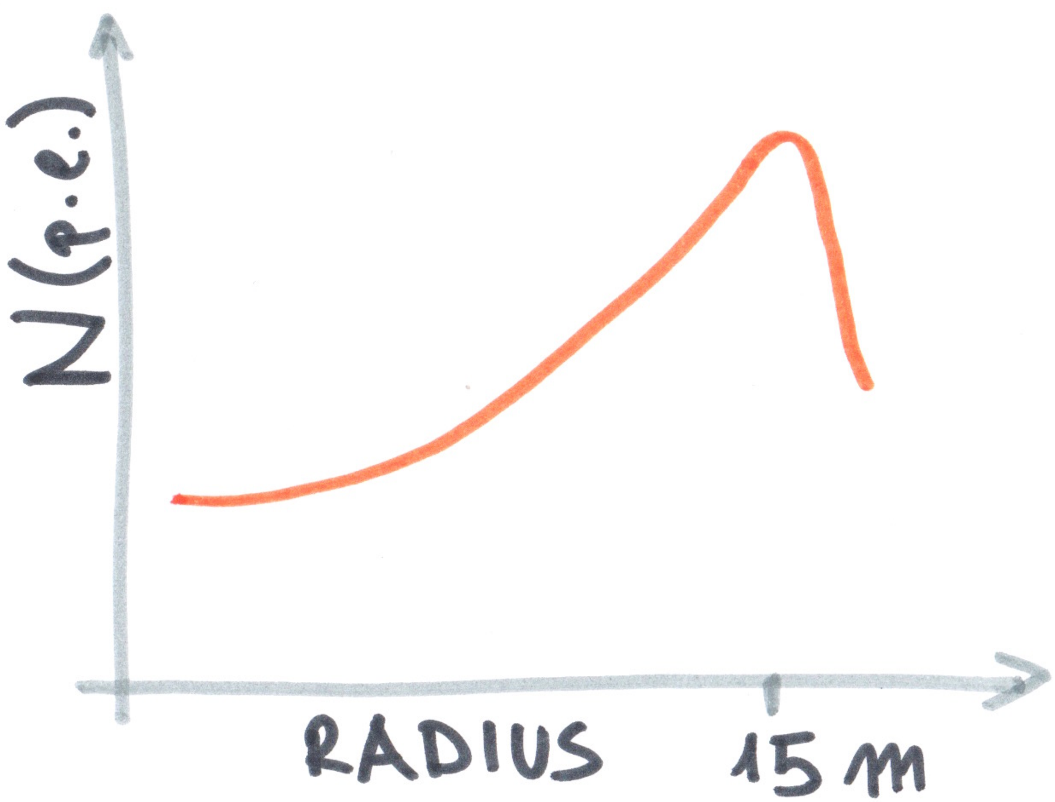
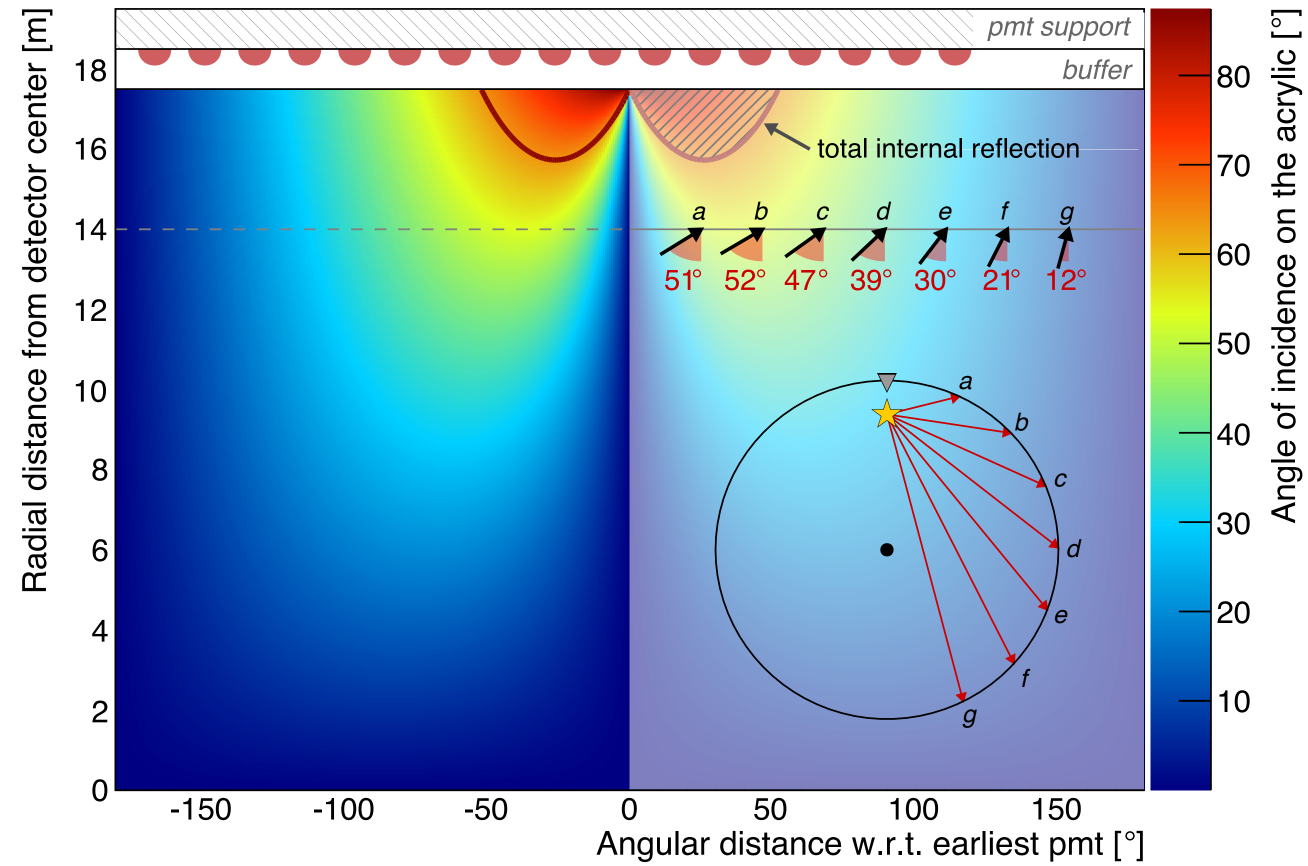


Non-Uniformity





Liquid scintillator **refractive index** is similar to mineral oil: 1.4~1.5

Buffer is made of water: interface is not optically matched

Light emitted close to edge gets more dispersed

In events within 2m from the edge some light undergoes **total internal reflection**