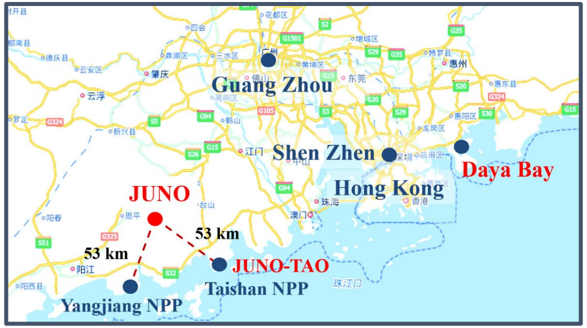
Calibration strategy for the JUNO experiment

Dr. Davide Basilico on behalf of the JUNO collaboration
University of Milan & INFN Milan

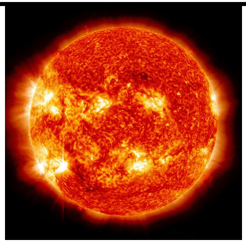
NuFact 2022 - 2022 August 05 - Snowbird

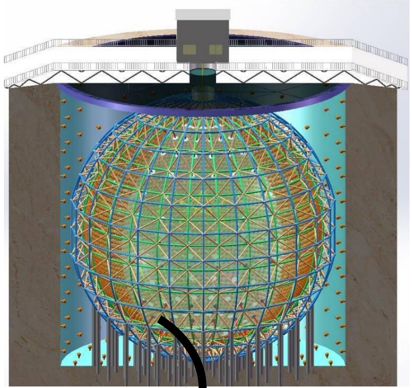
Jiangmen Underground Neutrino Observatory

A large, radiopure, multi-purpose **liquid-scintillator** detector
for **neutrino mass ordering** determination as main physics goal
with **reactor anti-ν_e (medium baseline)**, located in Southern China

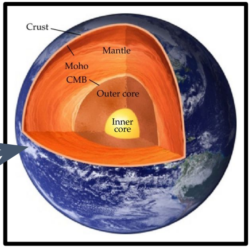


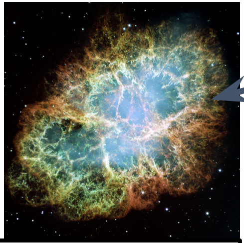
Solar ν (~10-10^3/day)





Geo ν (1-2/day)



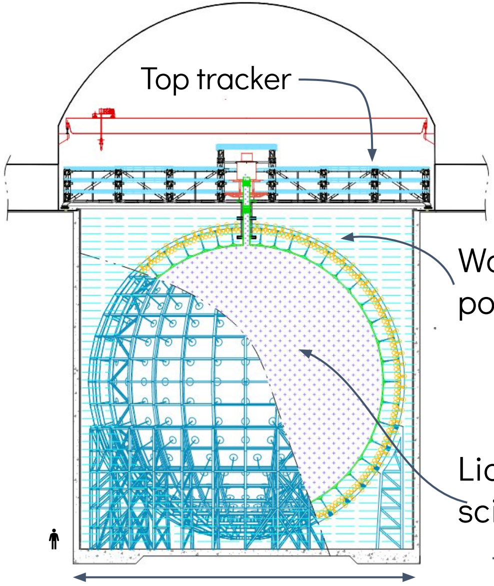


Supernova ν (~5·10^3 in ~10 s)

Reactor ν (~60/day)

Atmosph. ν (10-20/day)

Detector design



Largest ever liquid scintillator (20 kt), equipped with **~43600 PMTs** (25600 small PMTs and ~18000 large PMTs) to collect scintillation light

Underground (1900 m.w.e) + passive shielding layers → external backgrounds suppression

Key requirements:

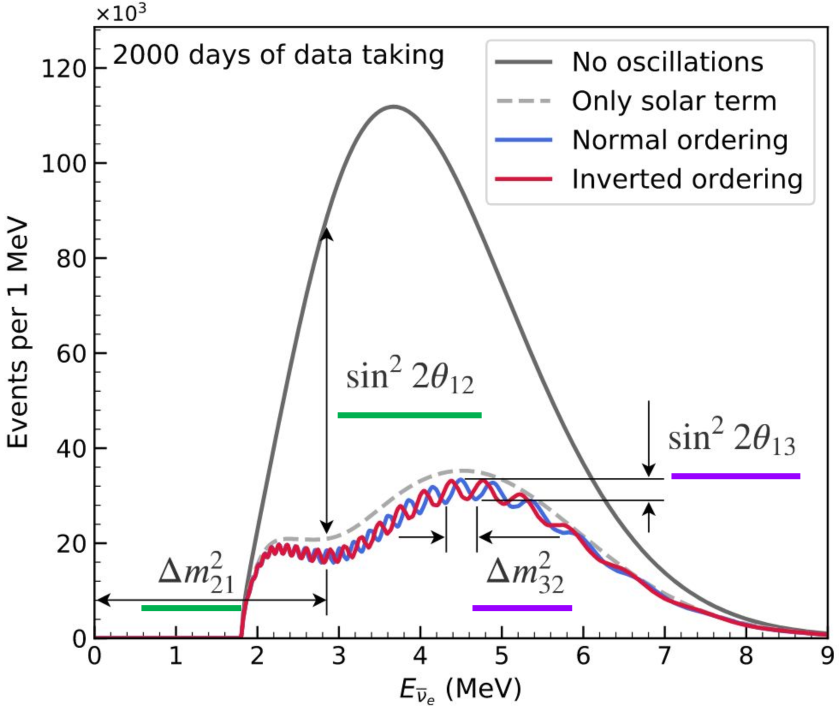
1. **Large mass**: 20kt of ultrapure liquid scintillator
2. **Low background levels**:
   internal radiopurity + passive shielding
3. **High energy resolution**:
   Scintillator light yield (~10^4 phot/MeV) + PMTs coverage (75%) and Quantum Efficiency (~35%)

Experiment	Daya Bay	Borexino	KamLAND	JUNO
Target mass [t]	160	~300	~1000	**~20000**
Photo electrons / MeV	~160	~500	~250	**1345**
Energy resolution @MeV	~8.5%	~5%	~6%	**~3%**
Photocathode coverage	12%	34%	34%	**75.2%**
Energy cal. Uncert.	0.5%	1.0%	2.0%	**<1%**

Plenary talk (Aug 05): "Challenges in the construction of large neutrino detectors: the JUNO case", M. Montuschi

Neutrino mass ordering analysis

Expected spectrum, 6y



10^5 events, W/o bkgs, σ_E/E = 3%√E[MeV]

Osc. par. JHEP 01 (2019) 106

Slow oscillation ("solar par."): $\sin^2\theta_{12}$, Δm^2_{21}

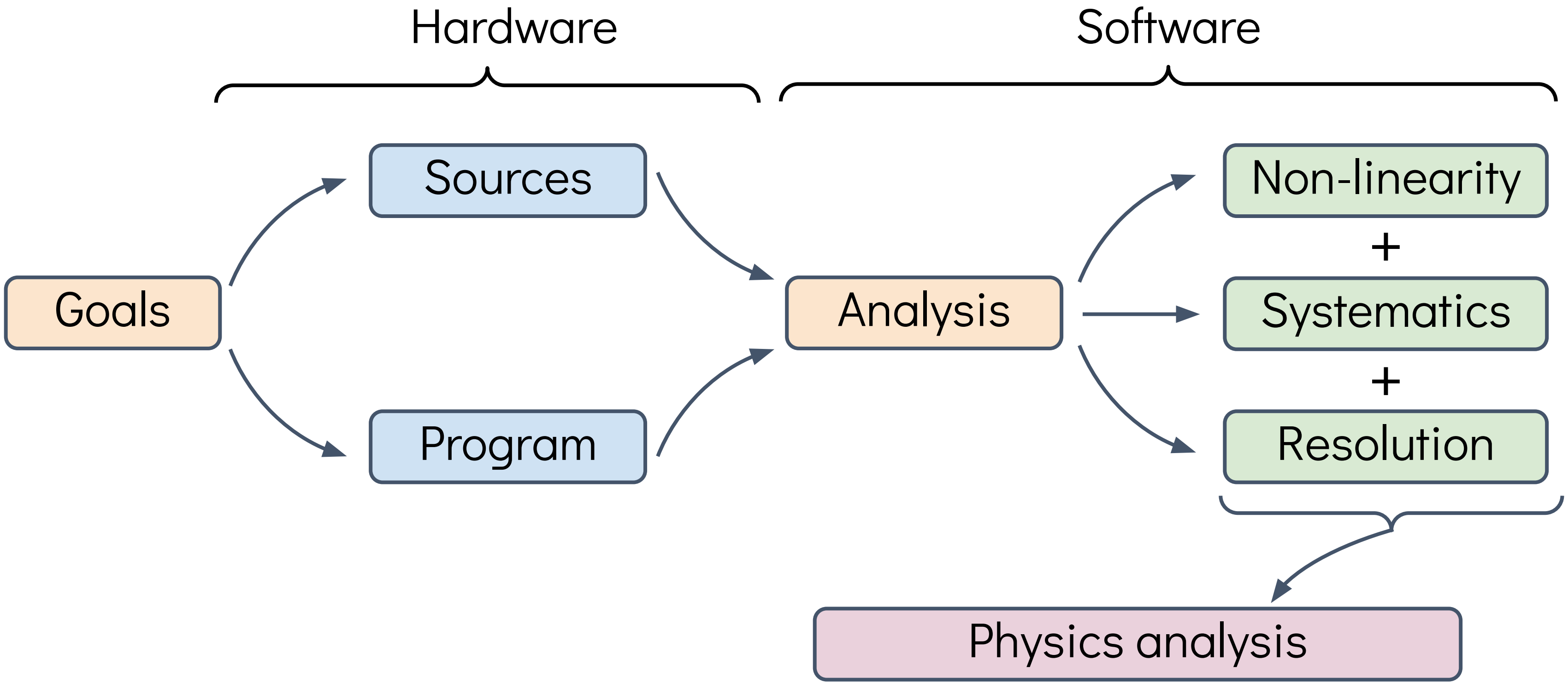
Fast oscillation ("atm. par.) : $\sin^2\theta_{13}$, $|\Delta m^2_{31}|$

JUNO is the first experiment optimized for disentangling "fast" and "slow" oscillation pattern
→ **due to Δm^2_{21} / Δm^2_{31} "interference" effects → depends on NMO**

Key requirements: <1% energy linearity and <3% effective energy resolution

Plenary talk: "Status of JUNO" (L. Ludhova, Aug 01)
WG1 talk: "Oscillation Physics Potential of JUNO" (J. Zhang, Aug 05)

Calibration strategy



Calibration strategy

Calibration of non-linearity

1) physics non-linearity → radioactive sources + cosmogenic isotope ^{12}B

2) instrum. non-linearity → laser source

Systematics understanding and control

→ rad. sources syst (shadowing, non uniformity)

→ PMTs syst. (dark noise, non linearity, ...)

Optimization and calibration of energy resolution

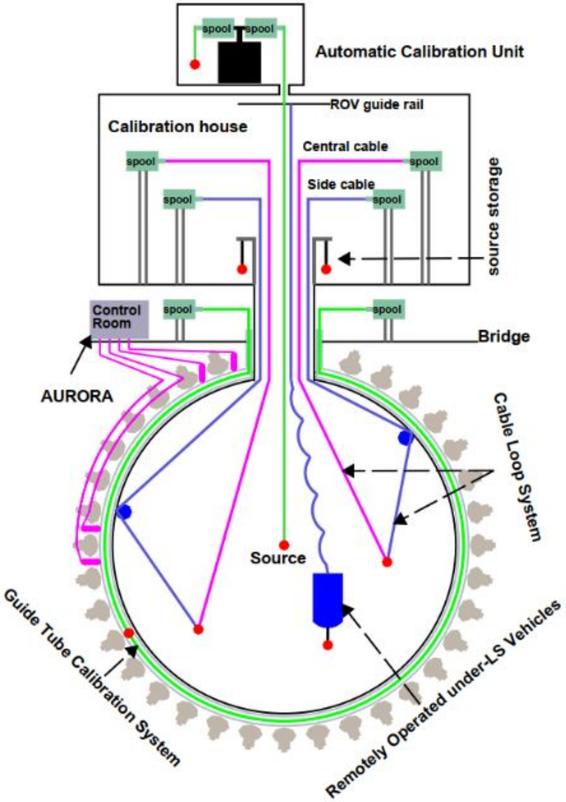
→ position non-uniformity: source in multiple positions

Non-linearity

Systematics

Resolution

Hardware & sources



- 1D: Automatic Calibration Unit (ACU)
- 2D: Cable Loop System (CLS)
- 3D: Remotely Operated under-LS Vehicles (ROV)
- Boundary: Guide Tube Calibration System (GTCS)

Calibration sources:

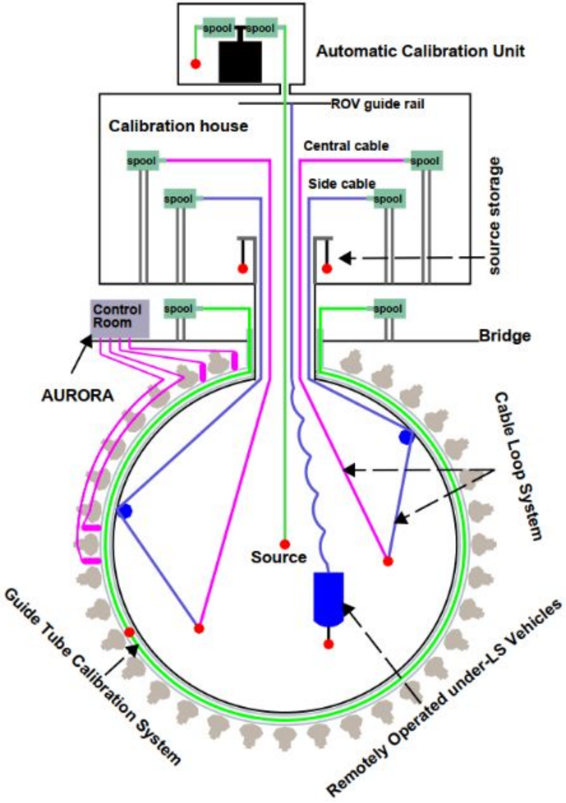
1. Radioactive sources (F. Zhang et al 2021 JINST 16 T08007)
2. Laser source (Y. Zhang et al 2019 JINST 14 P01009)

Radioactive sources:

- γ, e+, n
- E_{min} = 0.662 MeV

Sources/Processes	Type	Radiation
^{137}Cs	γ	0.662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	1.173 + 1.333 MeV
^{40}K	γ	1.461 MeV
^{68}Ge	e^+	annihilation 0.511 + 0.511 MeV
^{241}Am-Be	n, γ	neutron + 4.43 MeV (^{12}C*)
^{241}Am-^{13}C	n, γ	neutron + 6.13 MeV (^{16}O*)
(n,γ)p	γ	2.22 MeV
(n,γ)^{12}C	γ	4.94 MeV or 3.68 + 1.26 MeV

Hardware & sources



- 1D: Automatic Calibration Unit (ACU)
- 2D: Cable Loop System (CLS)
- 3D: Remotely Operated under-LS Vehicles (ROV)

Optimization of energy resolution

$$\frac{\sigma_{E_{\rm vis}^{\rm prompt}}}{E_{\rm vis}^{\rm prompt}} = \sqrt{\left(\frac{a}{\sqrt{E_{\rm vis}^{\rm prompt}}}\right)^2 + b^2 + \left(\frac{c}{E_{\rm vis}^{\rm prompt}}\right)^2}$$

Effective parametrization for energy resolution
→ each terms cover multiple effects, but mainly:

- “a” term → Poisson statistical fluctuations (~2.6%)
- “b” term → energy non-uniformity (~0.8%)
- “c” term → background noise term (~1%)

enabling non-ideal effects ↓

Assumptions	a	b	c	$\tilde{a} = \sqrt{a^2 + (1.6b)^2 + (\frac{c}{1.6})^2}$
Central IBDs	2.62(2)	0.73(1)	1.38(4)	2.99(1)
Ideal correction	2.57(2)	0.73(1)	1.25(4)	2.93(1)
Azimuthal symmetry	2.57(2)	0.78(1)	1.26(4)	2.96(1)
Single gamma source	2.57(2)	0.80(1)	1.24(4)	2.98(1)
Finite calibration points	2.57(2)	0.81(1)	1.23(4)	2.98(1)
Vertex smearing(8 cm/$\sqrt{E(\rm MeV)}$)	2.60(2)	0.82(1)	1.27(4)	3.01(1)
PMT QE random variations	2.61(2)	0.82(1)	1.23(4)	3.02(1)

Non-uniformity is corrected by calibrations with radioactive sources located in multiple positions
→ radial-angular function to correct reconstructed energy

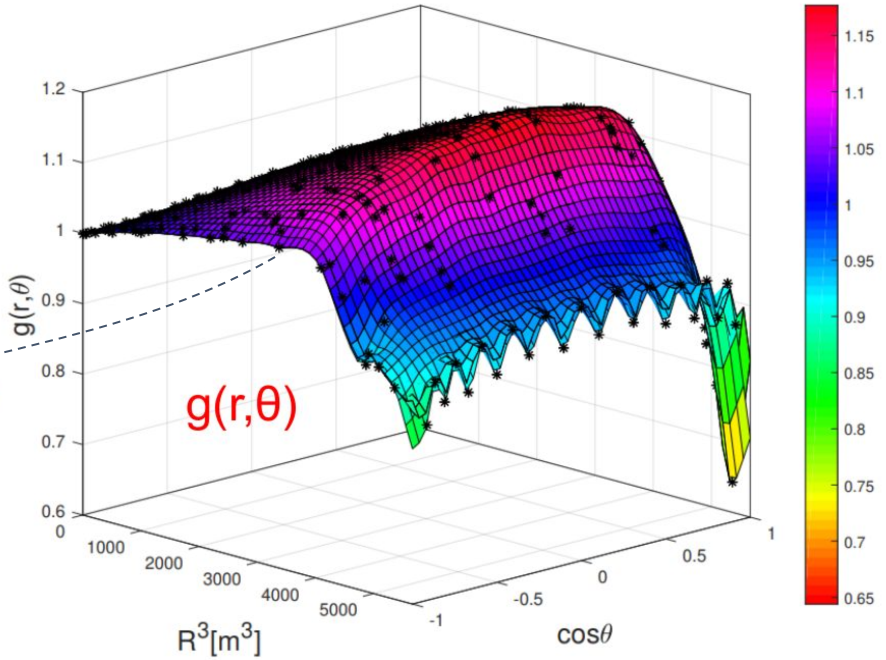
(“*optimizing energy resolution*”)

Optimization of energy resolution

$$\frac{\sigma_{E_{\rm vis}^{\rm prompt}}}{E_{\rm vis}^{\rm prompt}} = \sqrt{\left(\frac{a}{\sqrt{E_{\rm vis}^{\rm prompt}}}\right)^2 + b^2 + \left(\frac{c}{E_{\rm vis}^{\rm prompt}}\right)^2}$$

Non-uniformity is corrected by calibrations with radioactive sources located in multiple positions
→ radial-angular function g(r,θ) to correct reconstructed energy

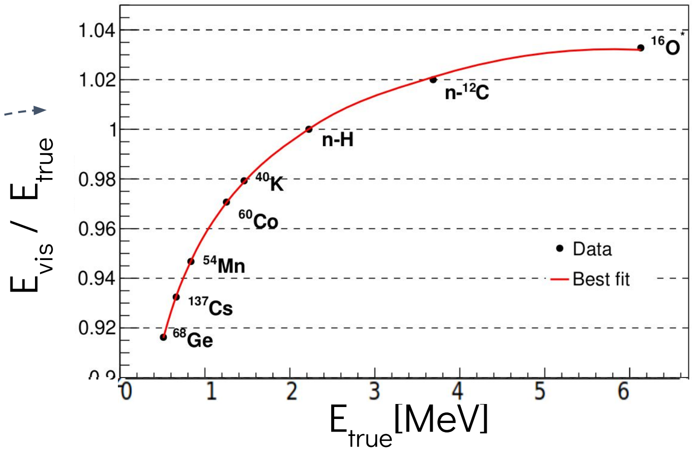
ϕ-symmetry is assumed



* marks calibration points

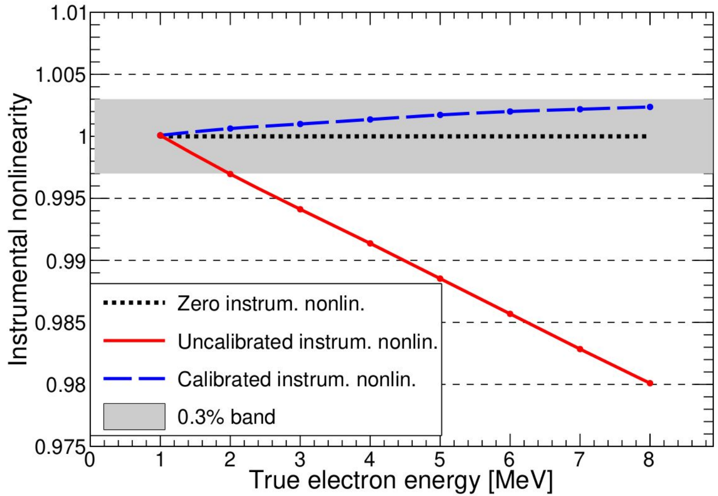
Non-linearity optimization

- **Physics nonlinearity** = non-linearity between particle energy and scintillating/Cherenkov photon
  - LS property, position independent
  - γ calibration sources + ^{12}B cosmogenic isotope



- **Instrumental nonlinearity** = nonlinearity between photon and charge for each channel.
  - PMT instrumentation property
  - Position dependent
  - Laser calib. source

  → dual calorimetry technique → compare LPMTs and sPMTS response



Goal: determination of e+ non-linearity at <1% level

Calibration program

Program structured following three time periods

1) Comprehensive calibrations

- basic understanding of the CD performance
- At the beginning of data-taking
- > 250 points, ~48h

Source	Energy [MeV]	Points
Neutron (Am-C)	2.22	250
Neutron (Am-Be)	4.4	1
Laser	/	10
^{68}Ge	0.511×2	1
^{137}Cs	0.662	1
^{54}Mn	0.835	1
^{60}Co	1.17+1.33	1
^{40}K	1.461	1
Total	/	/

2) Monthly calibrations

- Monitor non-uniformity
- ~100 points, ~11h

System	Source	Points
ACU	Neutron (Am-C)	27
ACU	Laser	27
CLS	Neutron (Am-C)	40
GT	Neutron (Am-C)	23
Total	/	/

3) Weekly calibrations

- track major changes of the detector → variations in the light yield of the LS, PMT gains, and electronics
- central axis, 0.1% precision on gamma peaks

Source	Energy [MeV]	Points
Neutron (Am-C)	2.22	5
Laser	/	10
Total	/	/

Summary

- **JUNO calibration paper**:
  "Calibration strategy of the JUNO experiment". *J. High Energ. Phys.* **2021,** 4 (2021)

- Detailed and precise calibrations are essential to achieve each of the JUNO physics goal

- A multi-dimensional **calibration system** for Central Detector has been created
  $\rightarrow$ employed sources: γ, neutron, UV laser
  $\rightarrow$ program structured in three different time periods (comprehensive, monthly, weekly)

- **Goals**: determination of e+ non-linearity at <1% level + optimization of energy resolution at <3% level, within the IBD energy range of interest

Thank you!

Thank you!

JUNO NuFact 2022 talks:

"Status of JUNO" , L. Ludhova, plenary, Aug 01
"Challenges in the construction of large neutrino detectors: the JUNO case", M. Montuschi, plenary, Aug 05
"Oscillation Physics Potential of JUNO", J. Zhang, WG1, Aug 05

"Calibration strategy of the JUNO experiment". *J. High Energ. Phys.* **2021,** 4 (2021)

Backup

Optimization and calib. of energy resolution

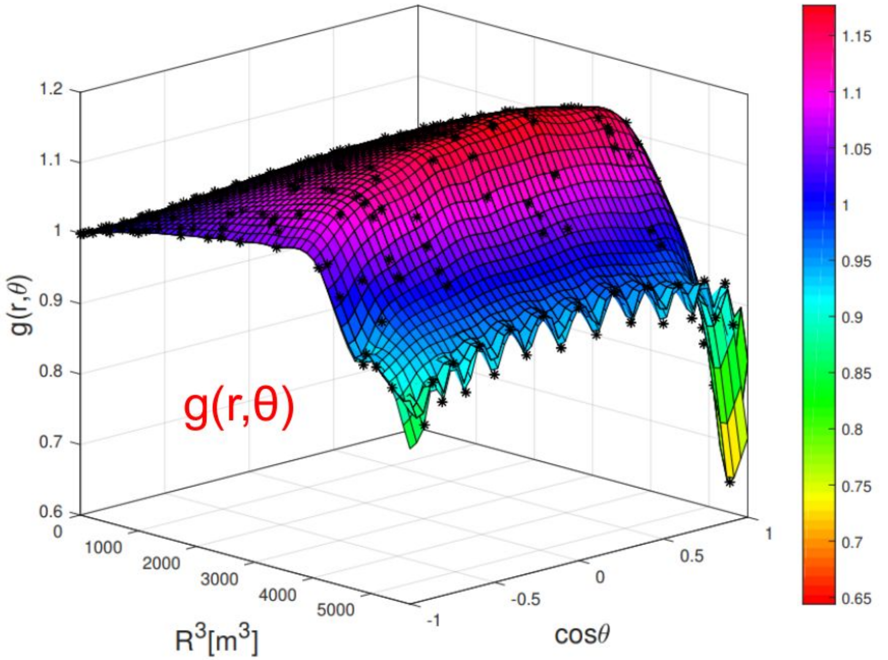
$$\frac{\sigma_{E_{\rm vis}^{\rm prompt}}}{E_{\rm vis}^{\rm prompt}} = \sqrt{\left(\frac{a}{\sqrt{E_{\rm vis}^{\rm prompt}}}\right)^2 + b^2 + \left(\frac{c}{E_{\rm vis}^{\rm prompt}}\right)^2}$$

Non-uniformity is corrected by calibrations with radioactive sources located in multiple positions → g(r,θ) function

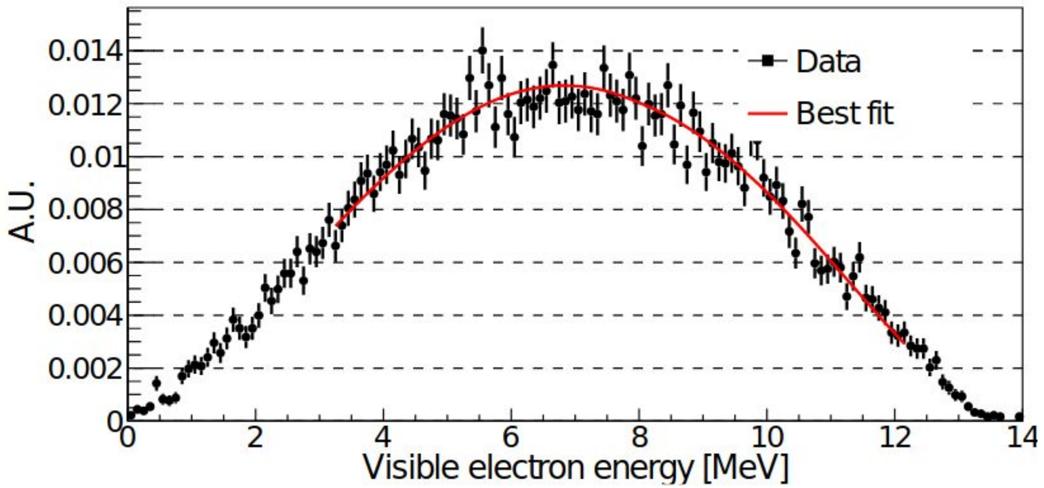
- g(r,θ): radial-angular correction function = light yield in a given position relative to that at the center.
- ΔQ_{DR} = charge bias induced by dark rate = 185 p.e.

$$E_{\rm vis}^{\rm prompt}(r,\theta,\phi) = ({\rm PE_{tot}} - \Delta Q_{\rm DR})/Y_0/g(r,\theta,\phi)$$

ϕ-symmetry is assumed



Cosmogenic isotope 12B



12B decays via β-emissions with a Q value of 13.4 MeV and a lifetime of 29 ms, with more than 98% into the ground state of 12C. Therefore it offers complementary constraints to $f_{nonlin}(E_e)$ at the high energy end. 12B events can be cleanly identified by looking for delayed high energy β event after an energetic muon