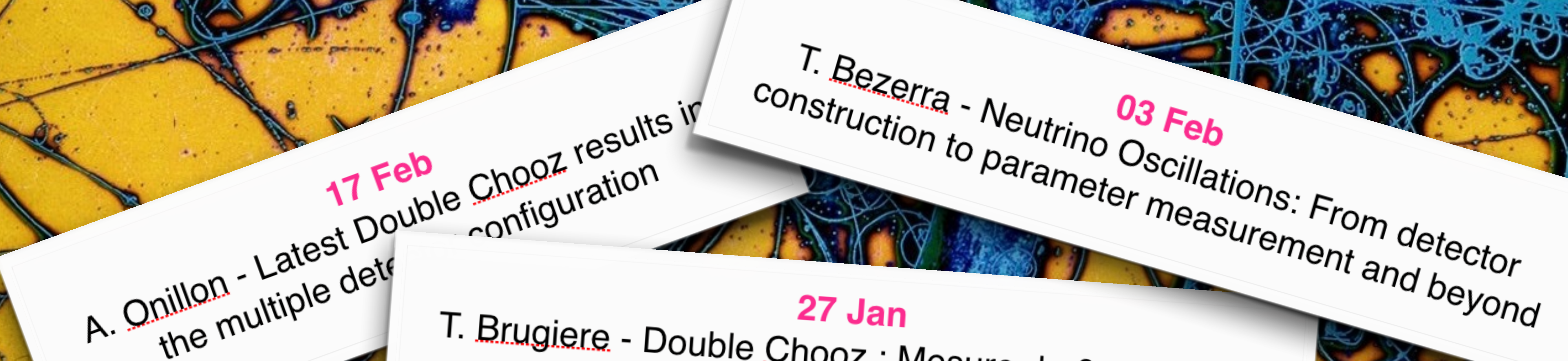
Entering the Era of Precision Neutrino Physics

The role of short- and medium-baseline reactor experiments

Marco Grassi
APC Laboratory - IN2P3



17 Feb
A. Onillon - Latest Double Chooz results i
the multiple dete configuration

03 Feb
T. Bezerra - Neutrino Oscillations: From detector construction to parameter measurement and beyond

27 Jan
T. Brugiere - Double Chooz : Mesure de θ_{13} et étude du spectre en énergie des anti-neutrinos

Entering the Era of Precision Neutrino Physics

The role of ~~short~~- and medium-baseline reactor experiments

JUNO

with some highlights of physics beyond reactors

Marco Grassi
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History of a (slight) Imperfection

1
$$-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$

2
$$M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H -$$
$$\tfrac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} +$$
$$\tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu -$$
$$W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu -$$
$$W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$
$$\tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] -$$
$$gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$
$$igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$
$$\tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j -$$

3
$$\bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] +$$
$$\tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 -$$
$$1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$
$$(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 +$$
$$\gamma^5)u^\lambda_j)] +$$

$$\tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$

4
$$\tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$
$$m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-$$
$$\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) -$$
$$\tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 -$$

5
$$\tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- -$$
$$\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y -$$
$$\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H] +$$
$$\tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] +$$
$$igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

Possibly one of the most
elegant picture of our Universe

As every piece of art,
it contains a slight **imperfection**
(which makes it even more beautiful)

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1

$$-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu$$

2

$$- \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \tfrac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+\phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^-$$

3

$$- \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}_j^\lambda(\gamma\partial + m_u^\lambda)u_j^\lambda - \bar{d}_j^\lambda(\gamma\partial + m_d^\lambda)d_j^\lambda + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}_j^\lambda\gamma^\mu u_j^\lambda) - \tfrac{1}{3}(\bar{d}_j^\lambda\gamma^\mu d_j^\lambda)] + \tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}_j^\lambda\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)u_j^\lambda) + (\bar{d}_j^\lambda\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d_j^\lambda)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}_j^\lambda\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d_j^\kappa)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}_j^\kappa C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u_j^\lambda)] +$$

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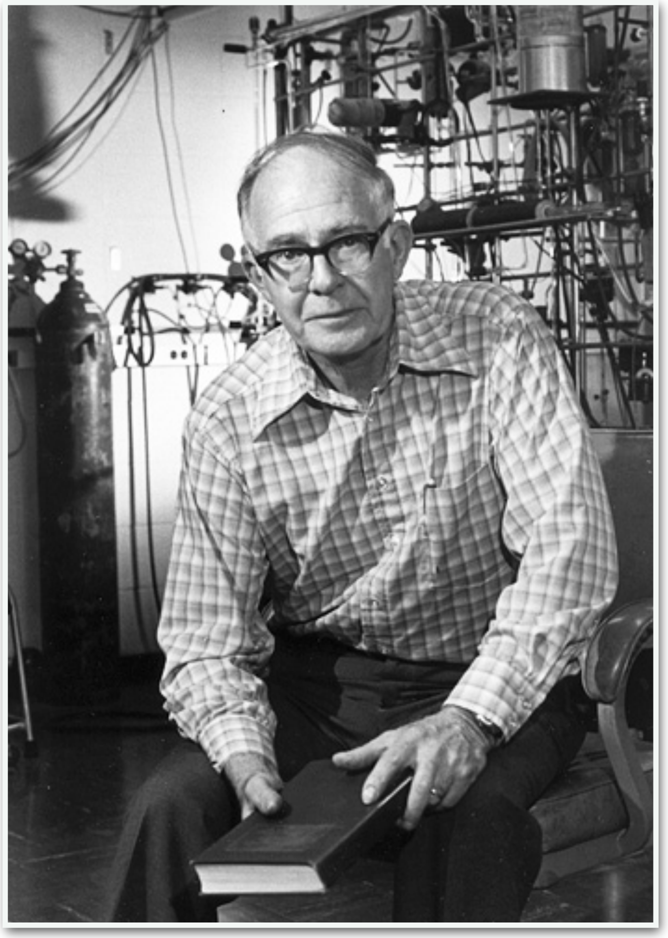
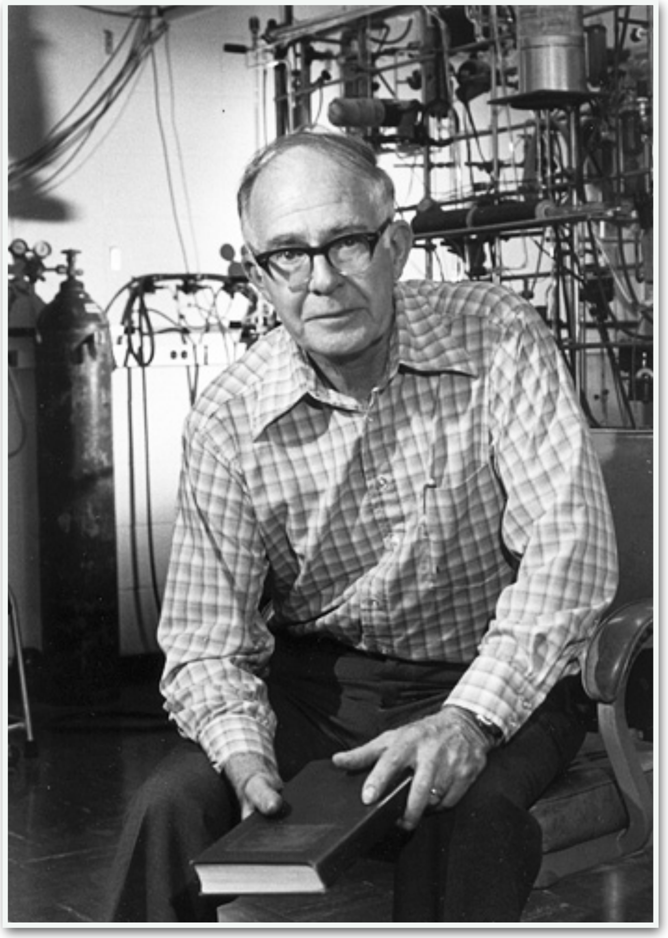
Once upon a time, in the late 60's…



Who knows this guy?

Homestake Experiment ("We miss something")



Raymond Davis
(Nobel Prize 2002)

Homestake Experiment (South Dakota, US):

Raymond Davis and <u>John Bahcall</u> in the late 60s

[**experimental design**] [<u>theoretical calculation</u>]

Count ν_e emitted by nuclear fusion in the Sun

380 m^3 tank of dry-cleaning fluid (C_2Cl_4) deep underground

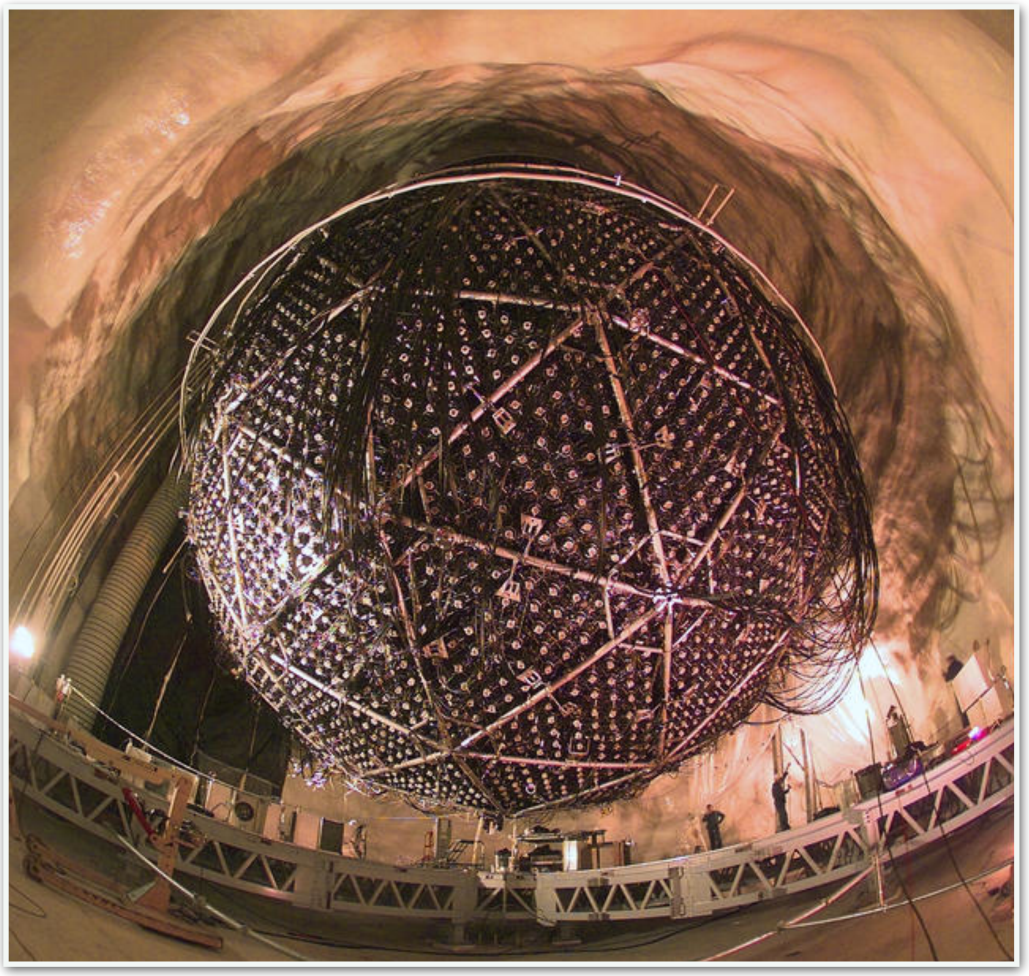
$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

Every week Argon atoms were extracted and counted (^{37}Ar is an unstable isotope)

Davis finds 1/3 of Bahcall's prediction

Solar Neutrino Problem

Sudbury Neutrino Experiment ("We found what we missed!")



Heavy water cherenkov detector

1000 m^3 of D_2O deep underground

Looking at ν_e from the Sun

Exploiting 3 processes:

$$\nu_e + d \rightarrow p + p + e^- \quad \text{(CC)}$$

$$\nu_x + d \rightarrow p + n + \nu_x \quad \text{(NC)}$$

$$\nu_x + e^- \rightarrow \nu_x + e^- \quad \text{(ES)}$$

Measure at the same time

ν_e flux (through the CC process) and

ν total flux (through the ES & NC processes)

PRL 87 (2001) 071301

3.3 σ evidence of a "*non-electron flavor active neutrino component in the solar flux*"

Arthur B. McDonald: Nobel Prize 2015

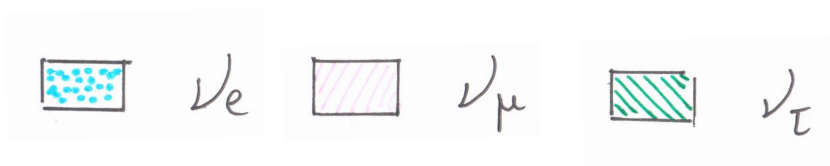
Neutrino Mixing Nowadays

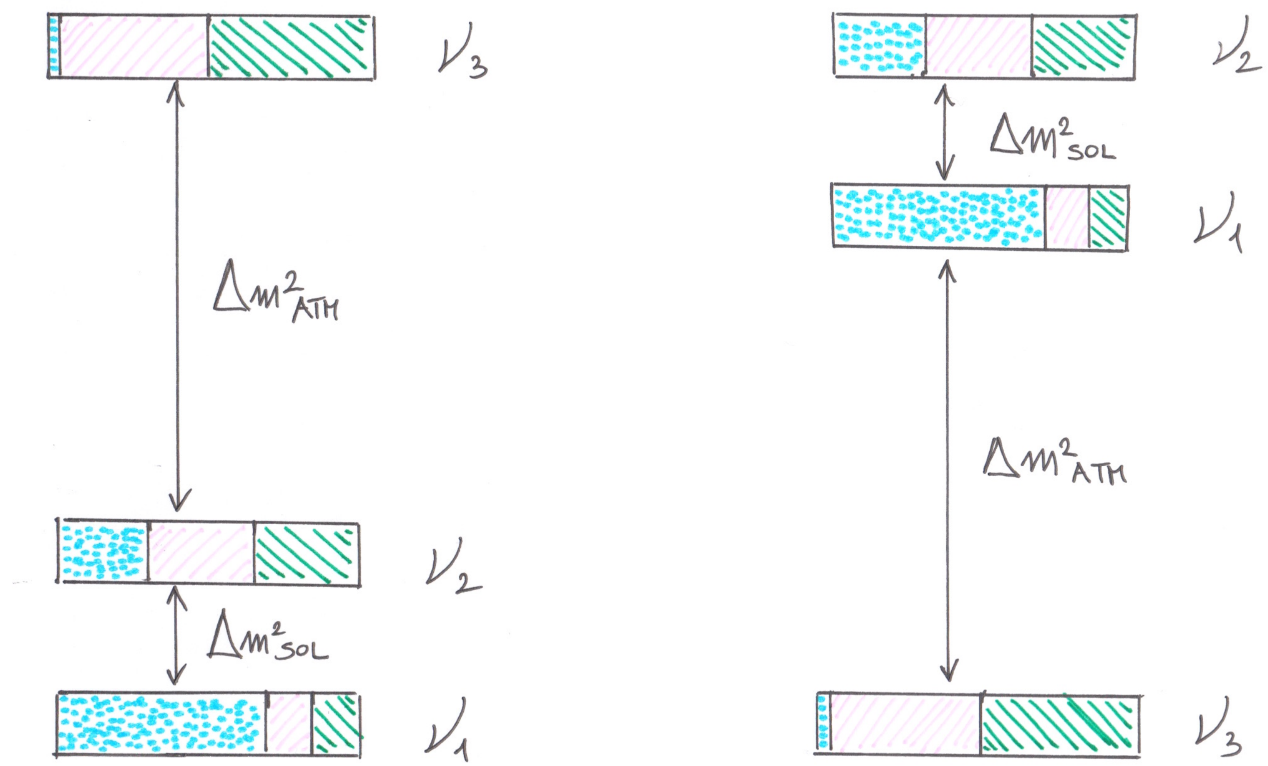
Three Flavor Eigenstates

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

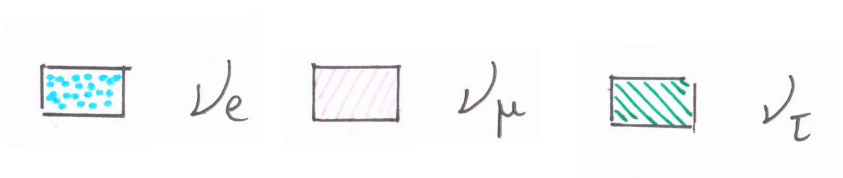
Neutrino Oscillation

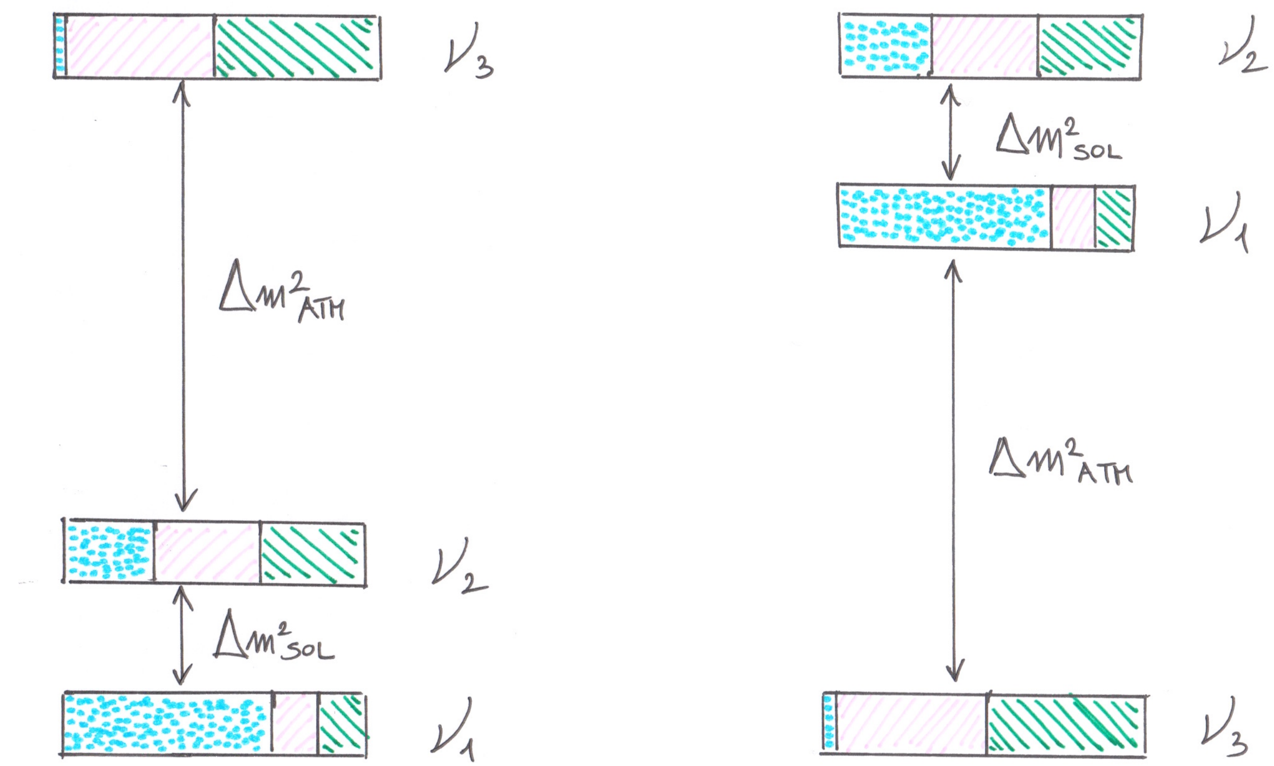
Three Flavor Eigenstates

Three Mass Eigenstates

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

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



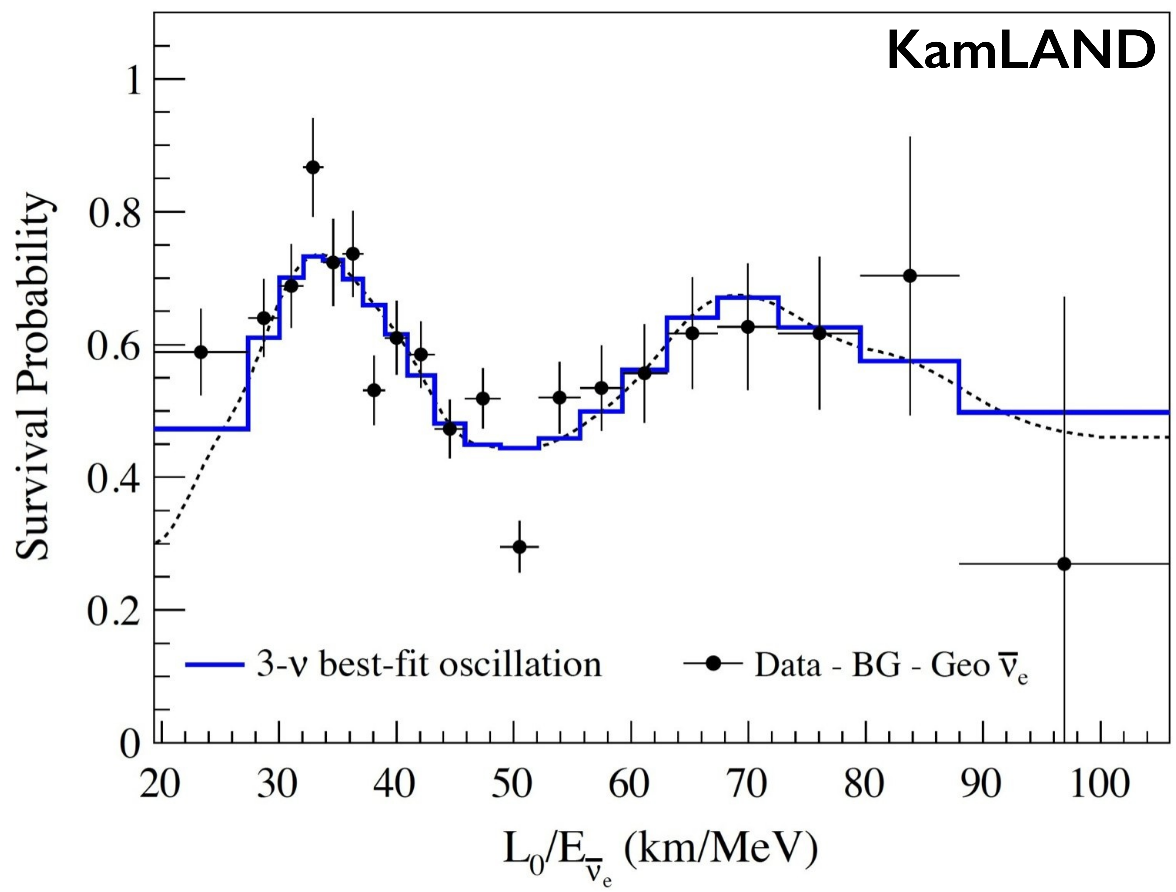


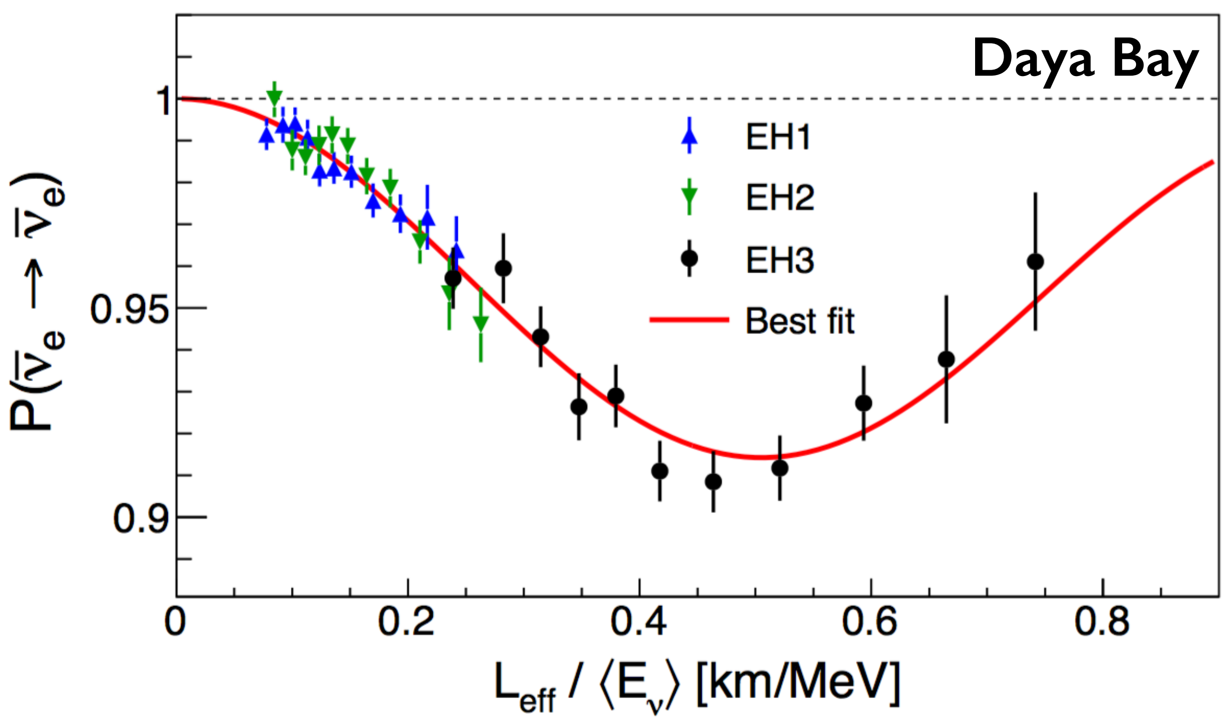
Normal Hierarchy **Inverted Hierarchy**

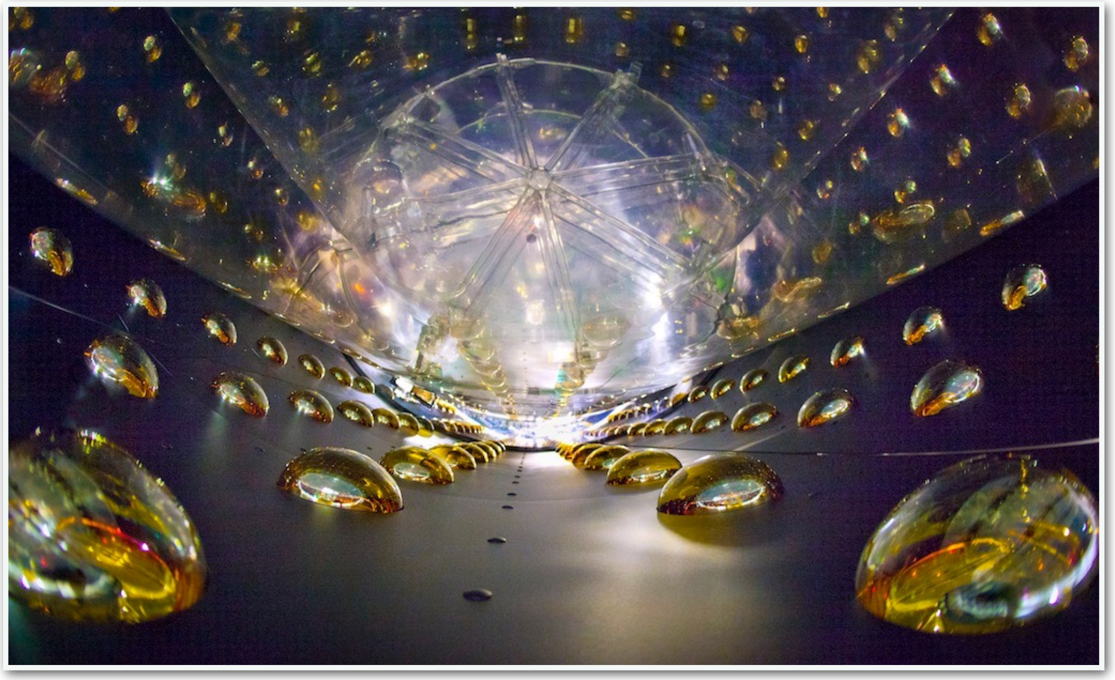
- $|\nu_i\rangle$ propagation described with plane wave solution
- Eigenstates with different mass propagate at different speeds
- Causing interference between flavour components of each mass eigenstates

$$P_{\alpha\beta} \sim \sum [\dots] \sin^2\left(\frac{\Delta m^2 L}{4\,E}\right)$$

Observation of Neutrino Oscillation

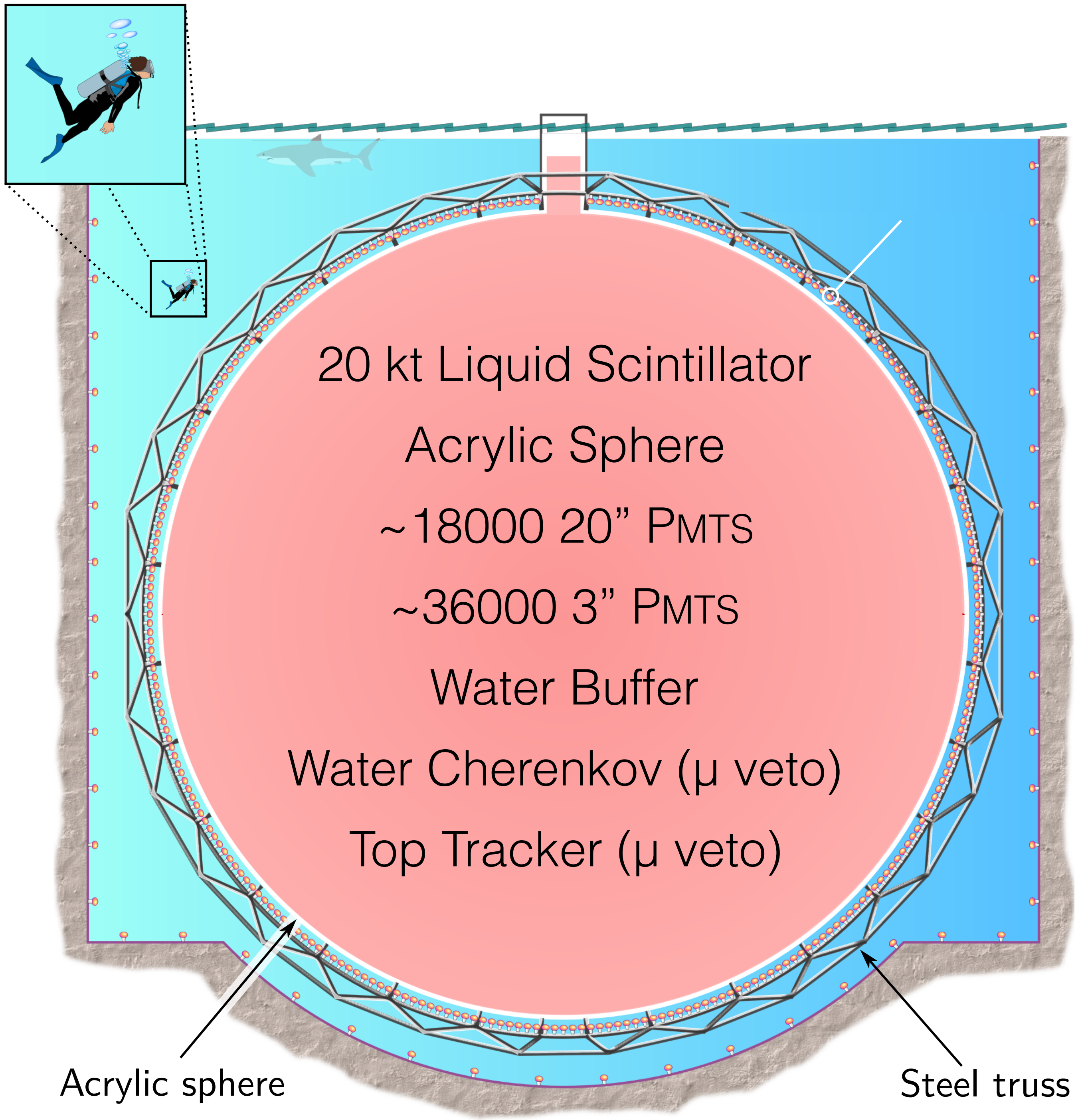






JUNO in the Global Neutrino Landscape

Liquid Scintillator (Anti)neutrino Detector



2 Key parameters:

LARGE & PRECISE

	DETECTOR TARGET MASS	RESOLUTION
KamLAND	1000 t	6%/√E
Double Chooz	8 t	
RENO	16 t	8%/√E
Daya Bay	20 t	
Borexino	300 t	5%/√E
JUNO	**20000 t**	**3%/√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

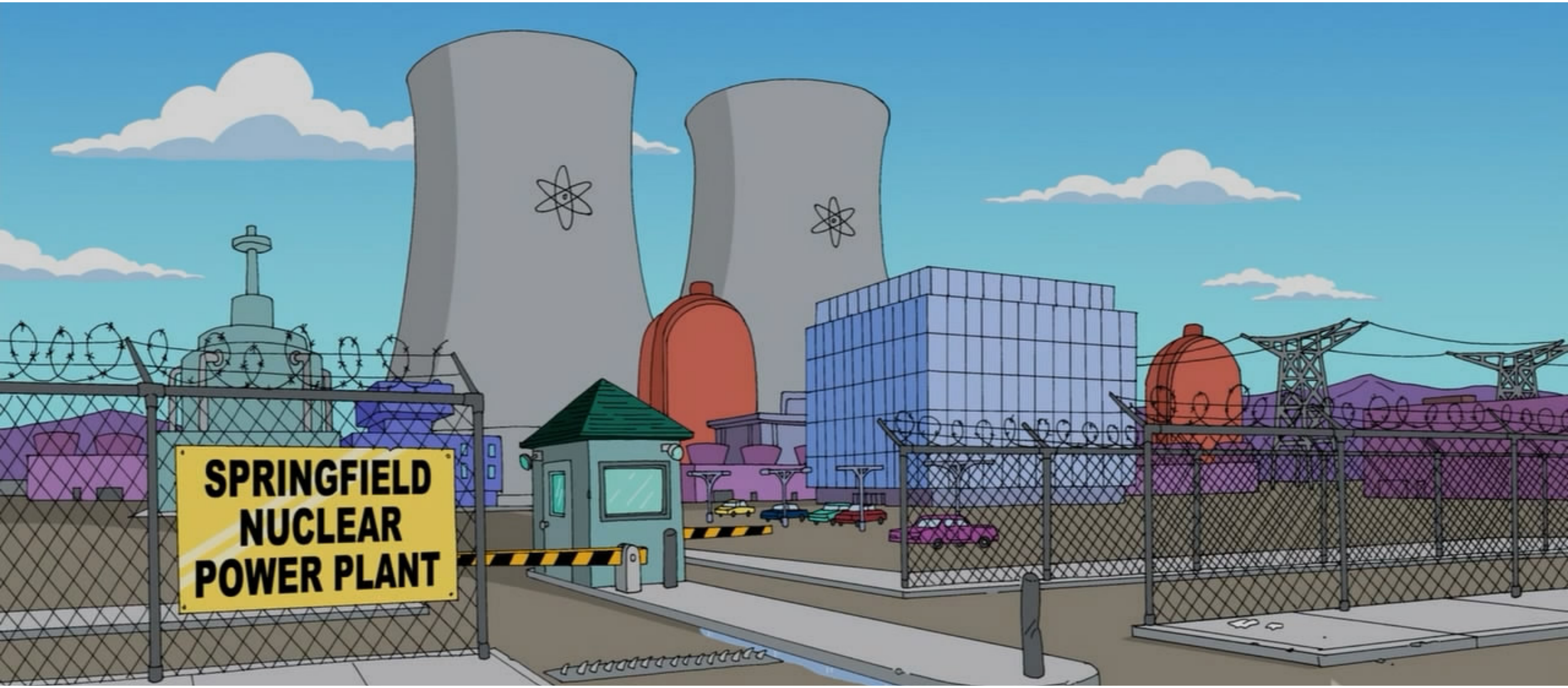
Solar Neutrinos

- 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

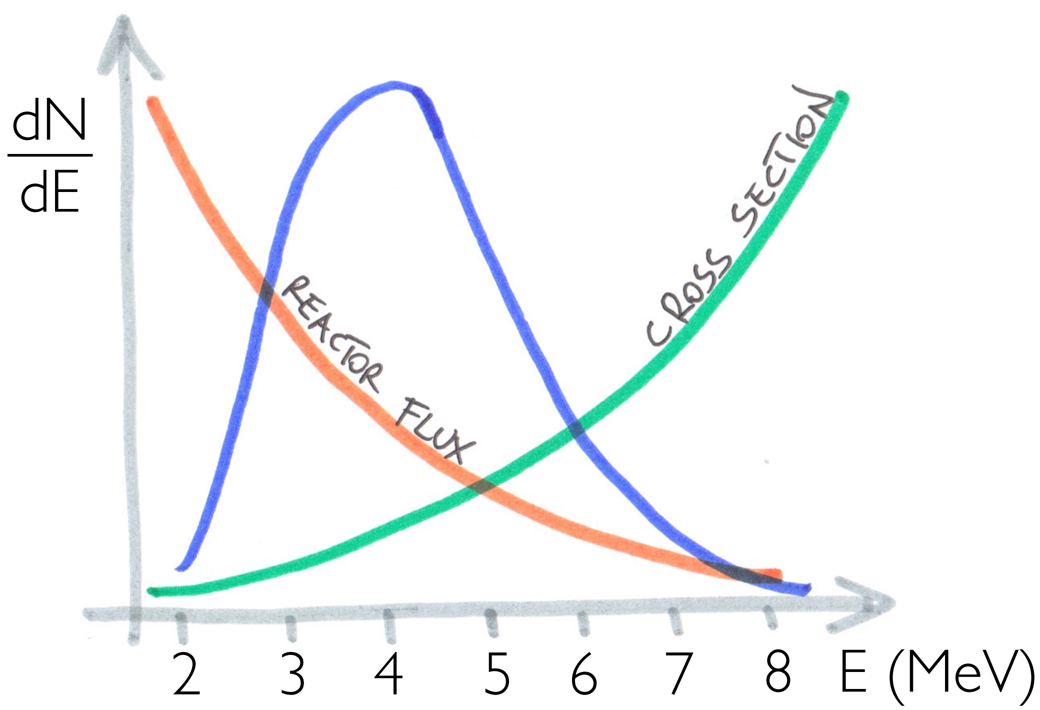
Reactor Neutrino Physics



Antineutrinos from Reactor (Emission)

source

detector



Nuclear Power Plants

Energy by breaking heavy nuclei

Fission fragments are unstable

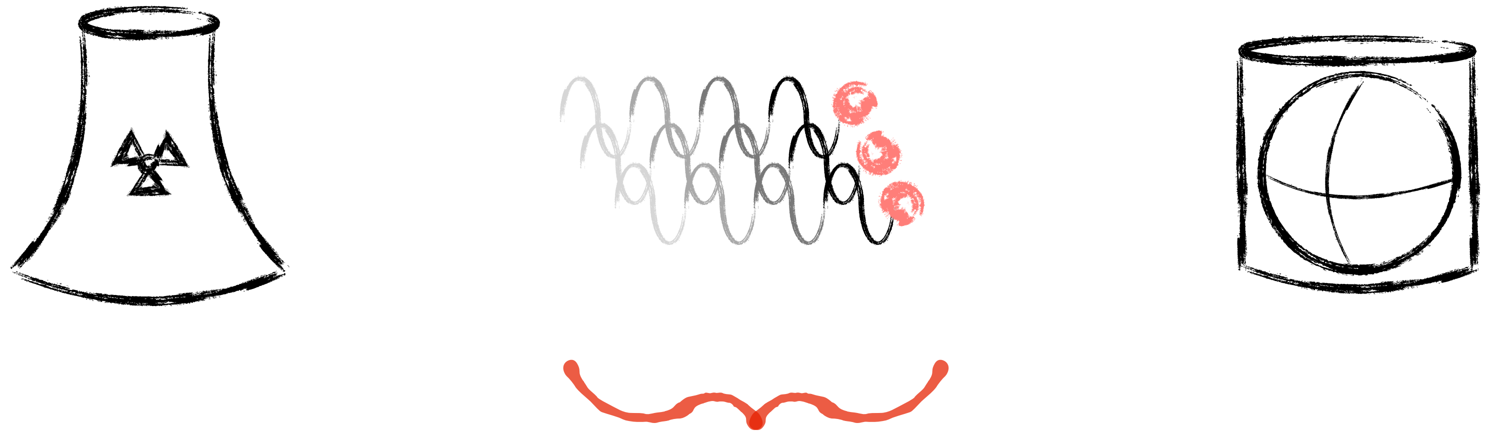
Decaying through a cascade of beta decays

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

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

Antineutrinos from Reactor (Propagation)

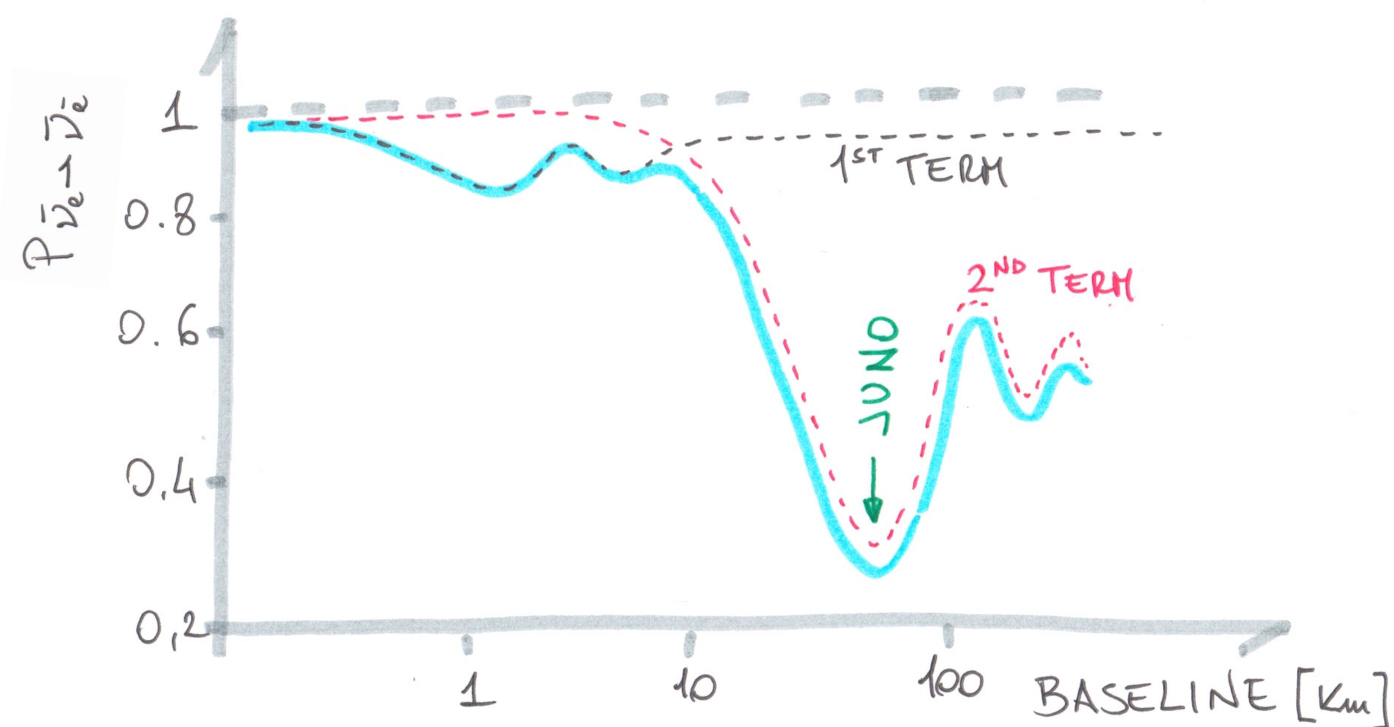
source



detector

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

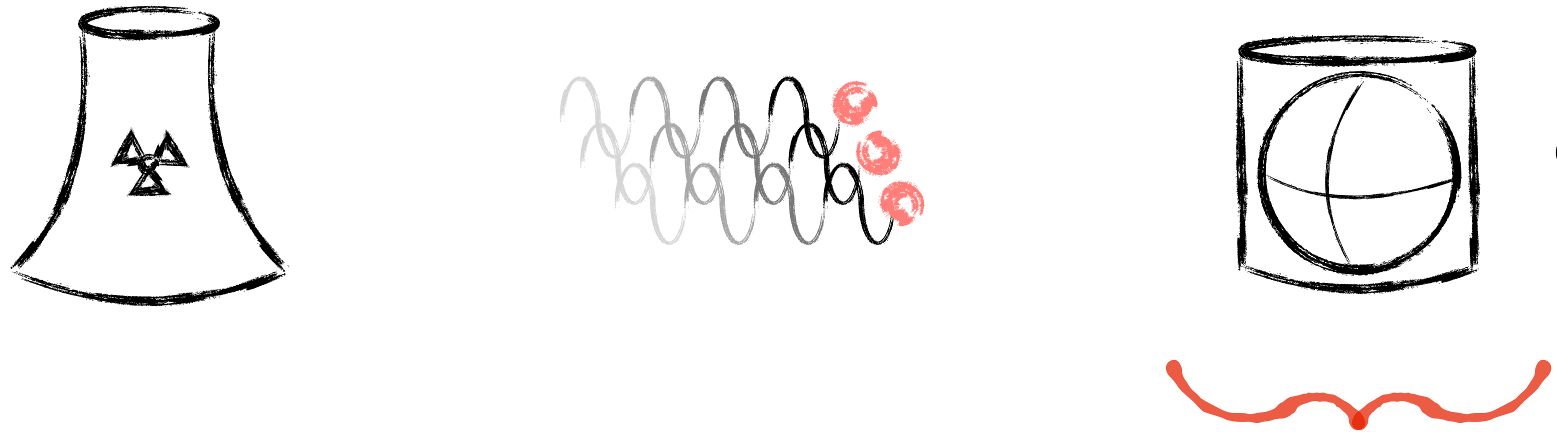
$$- \sin^2 2\vartheta_{12}\,\cos^4\vartheta_{13}\,\sin^2\Delta_{21}$$



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

Antineutrinos from Reactor (Detection)

source



detector

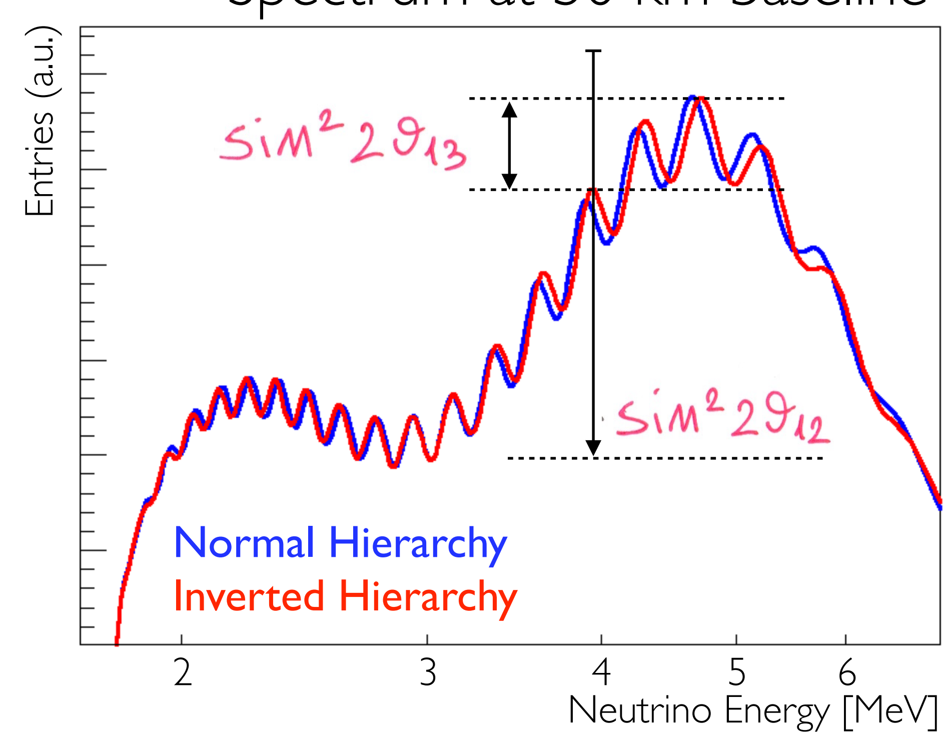
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\vartheta_{13} \cdot \sin^2\left(\cos^2\vartheta_{12}\,\sin^2\Delta_{31} + \sin^2\vartheta_{12}\,\sin^2\Delta_{32}\right) \qquad \text{FAST}$$

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

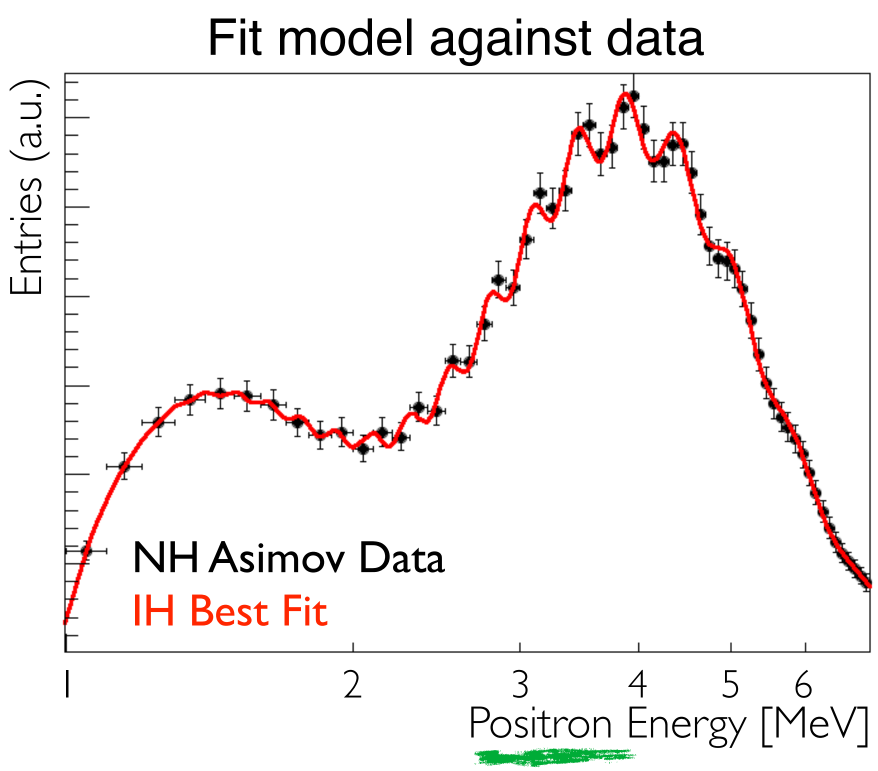
$$\Delta_{ij} = \Delta m^2_{ij}\frac{L}{4E}$$

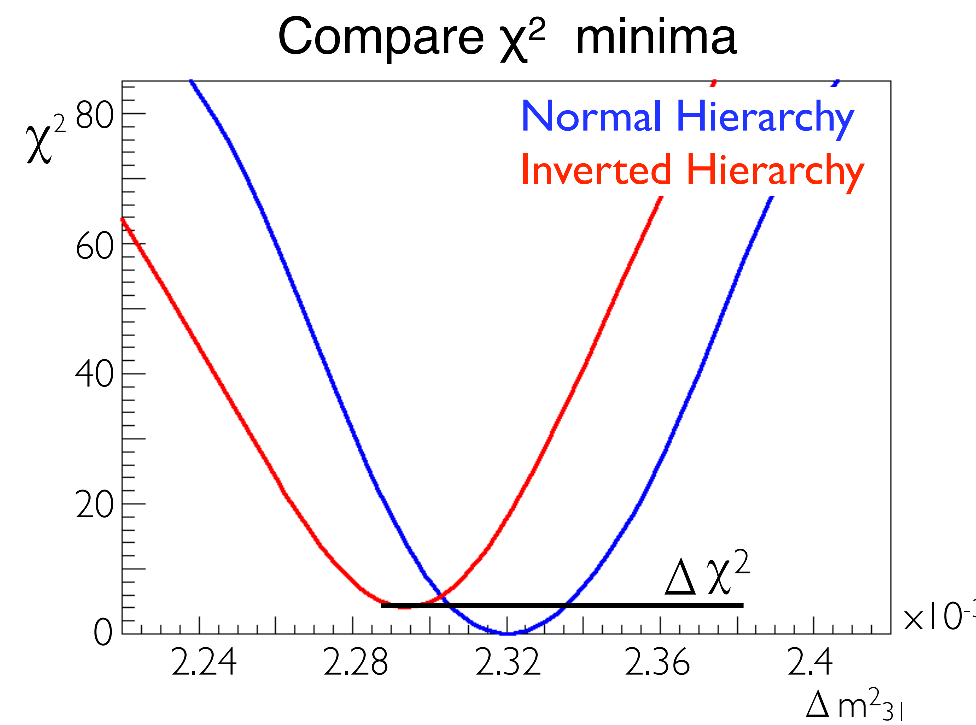
Combined role of Δm^2_{ATM} & Δm^2_{SOL}

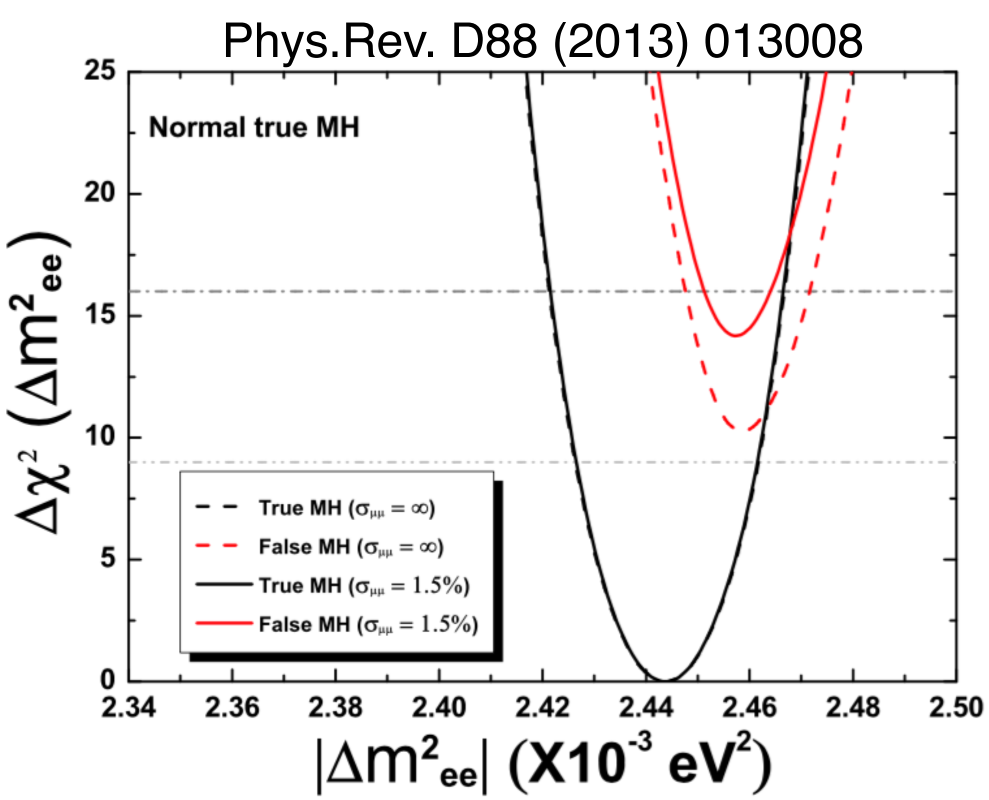
Spectrum at 50 km baseline



Mass Hierarchy Determination







Mass Hierarchy Sensitivity

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

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

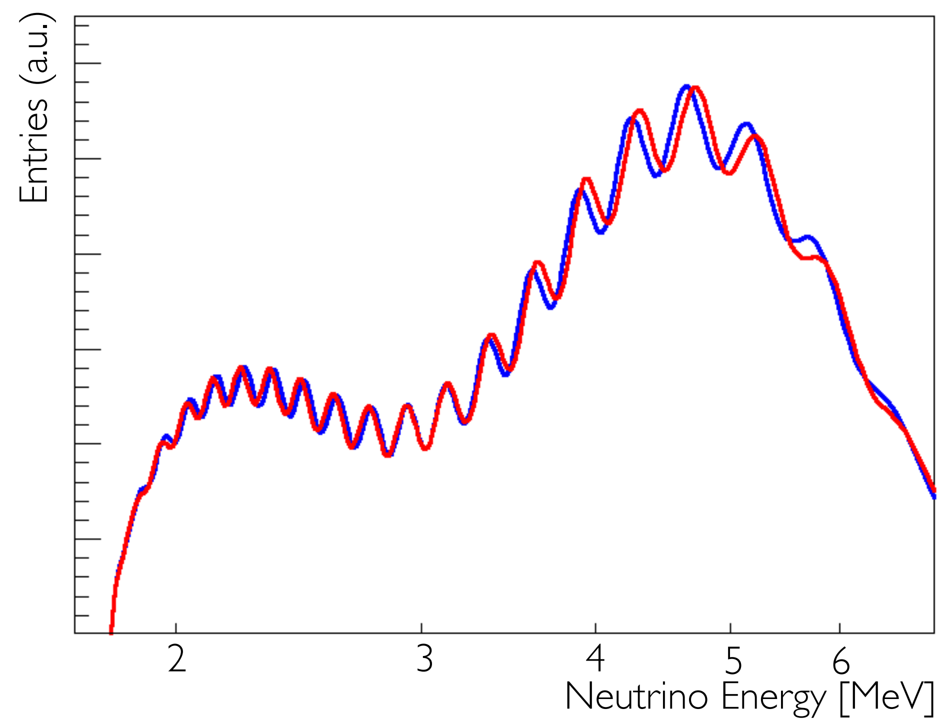
Unconstrained (JUNO only) $\Delta\chi^2 \sim 10$

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



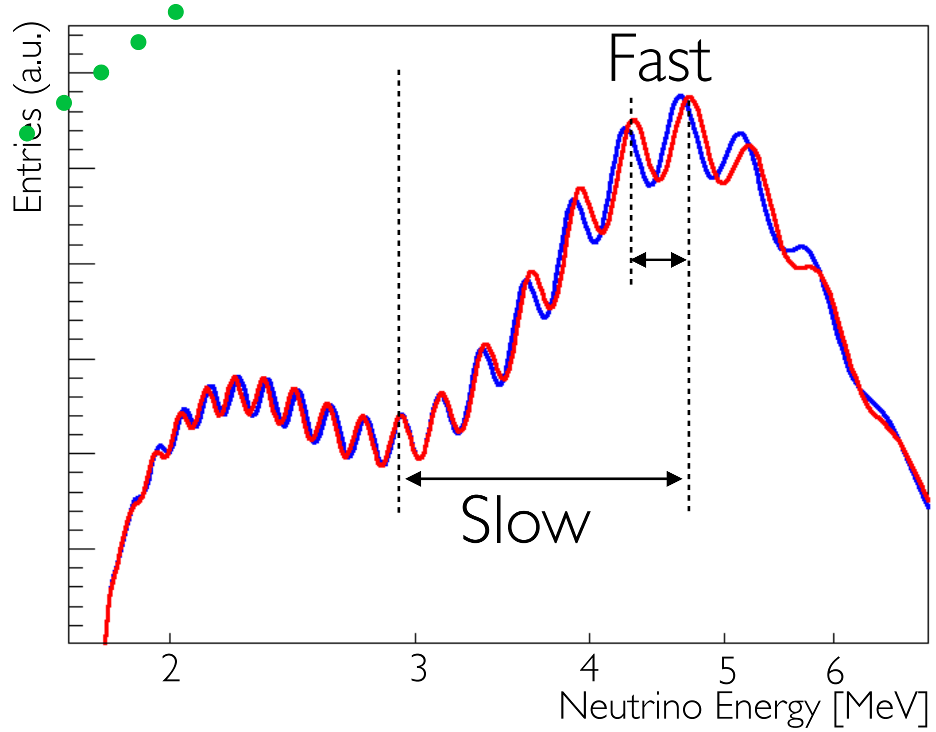
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\vartheta_{13} \cdot \sin^2\left(\cos^2\vartheta_{12}\ \sin^2\Delta_{31} + \sin^2\vartheta_{12}\ \sin^2\Delta_{32}\right) \qquad \text{Fast} \qquad \Delta m^2_{ATM}$$

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

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



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

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

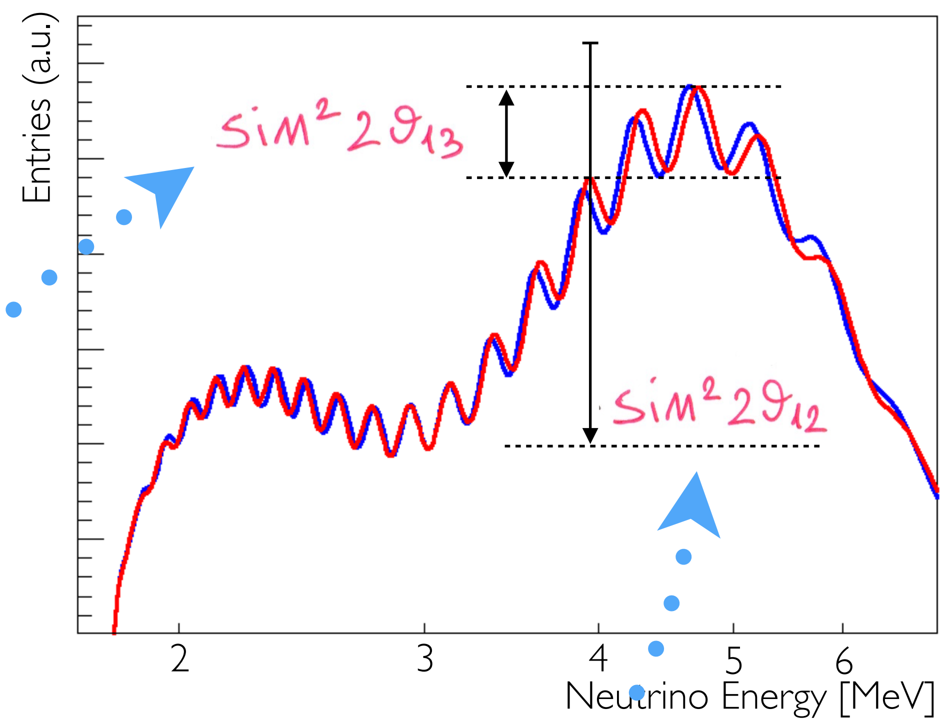
Fast Δm^2_{ATM}

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



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

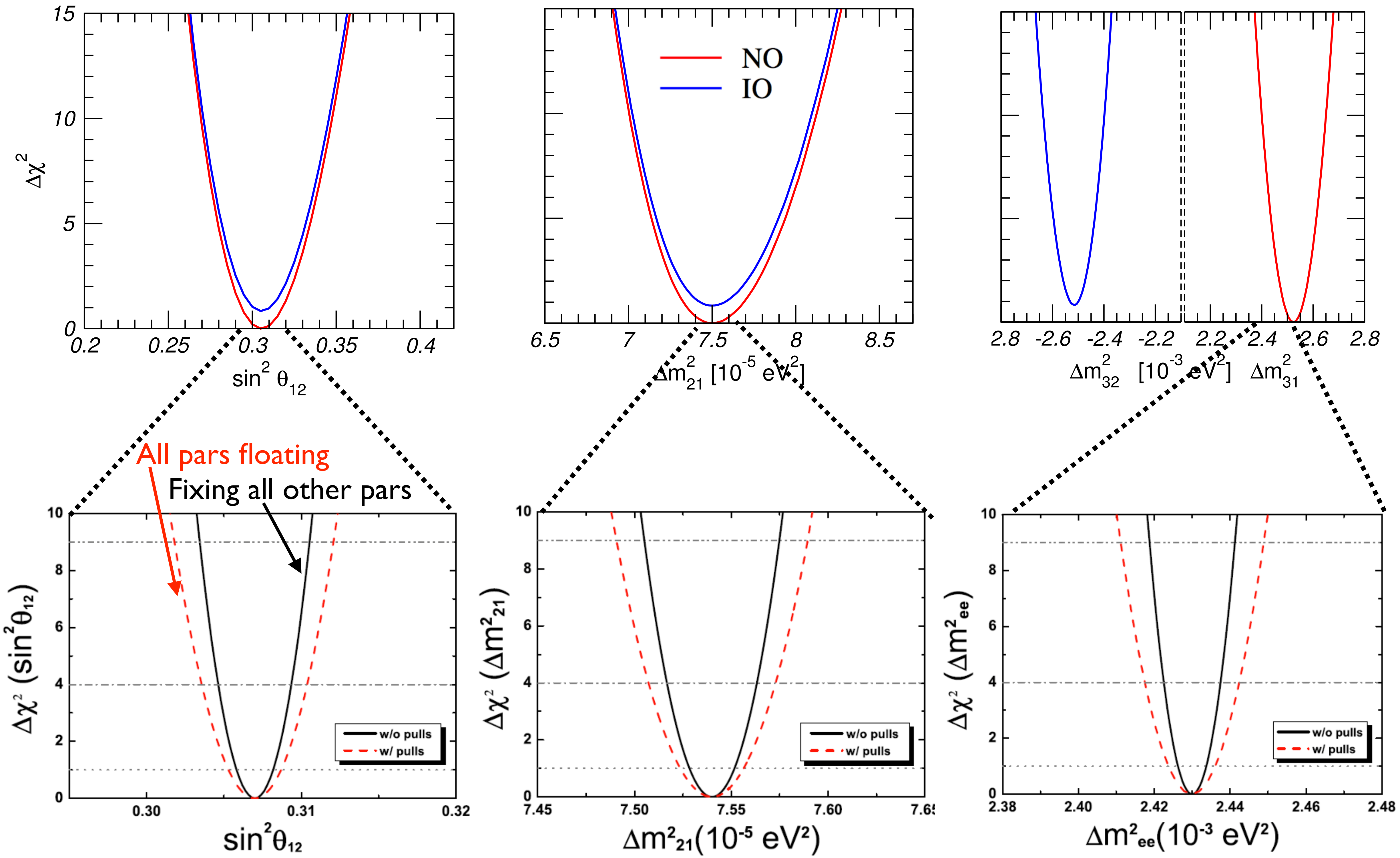
$$- \sin^2 2\vartheta_{12}\,\cos^4\vartheta_{13}\,\sin^2\Delta_{21} \qquad \text{Slow} \qquad \Delta m^2_{SOL}$$

Sensitivity To Oscillation Parameters (Direct Constraints)

Solar Mixing Angle | Solar Mass Splitting | Atmospheric Mass Splitting

NuFit 3.0 (2016)

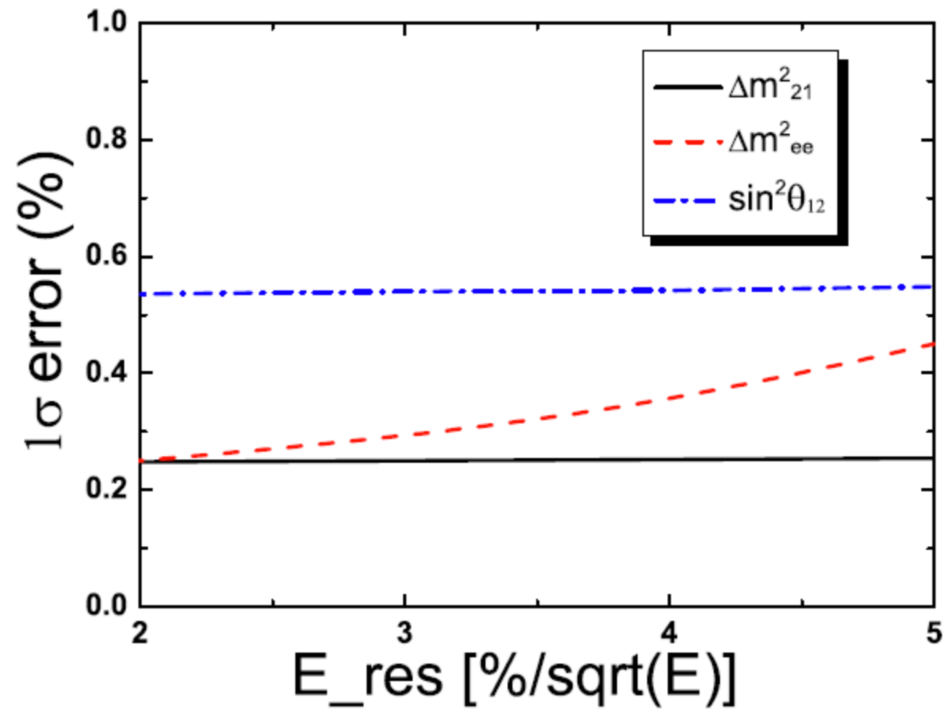
JUNO sensitivity



$\sin^2(\theta_{12})$: 0.54% | Δm^2_{21}: 0.24% | Δm^2_{ee}: 0.27%

Oscillation Parameter Uncertainties

- θ_{21} and Δm^2_{21} precision ensured by **rate + shape** (no second detector)
- Δm^2_{ee} precision due to **multiple oscillation cycles**, each giving independent measurement
- Energy Resolution mostly affects Δm^2_{ee} since measurement relies on resolving **fast oscillation**



Considering background and systematics:

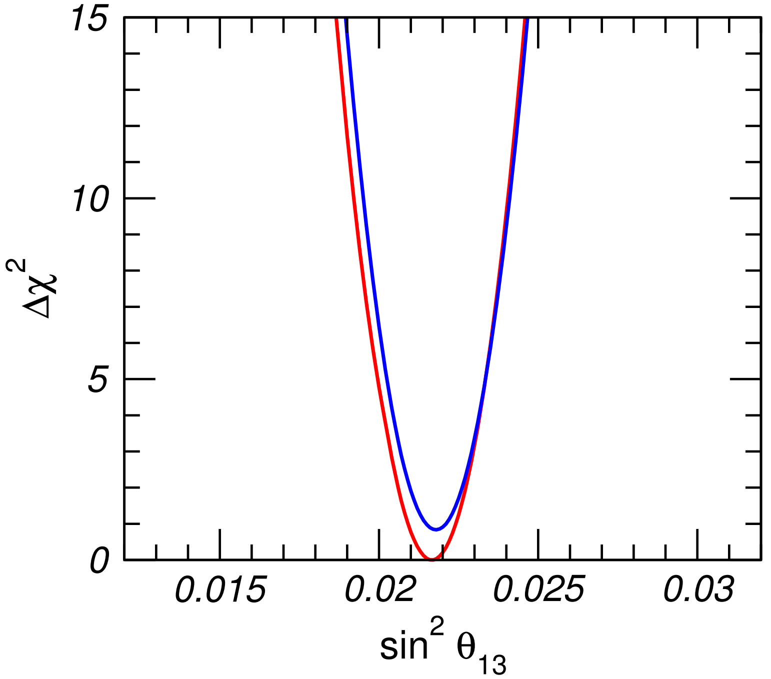
Cosmogenic Bkg (3% Norm + 10% Shape)
Bin-to-bin uncorrelated uncertainty
Energy scale uncertainty
Energy non-linear uncertainty

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

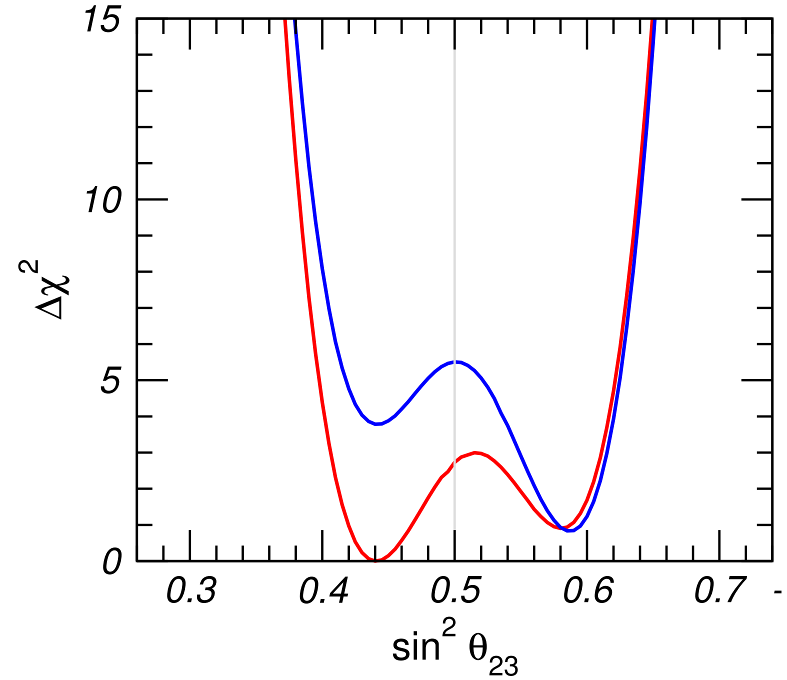
Sensitivity To Oscillation Parameters (Indirect Constraints)

NuFit 3.0 (2016)

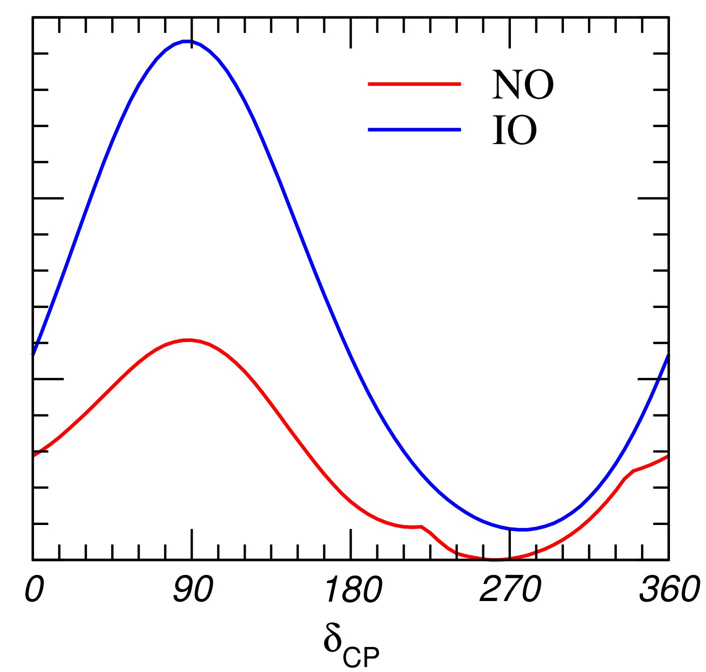
Reactor θ_{13}



θ_{23} octant



CP Phase

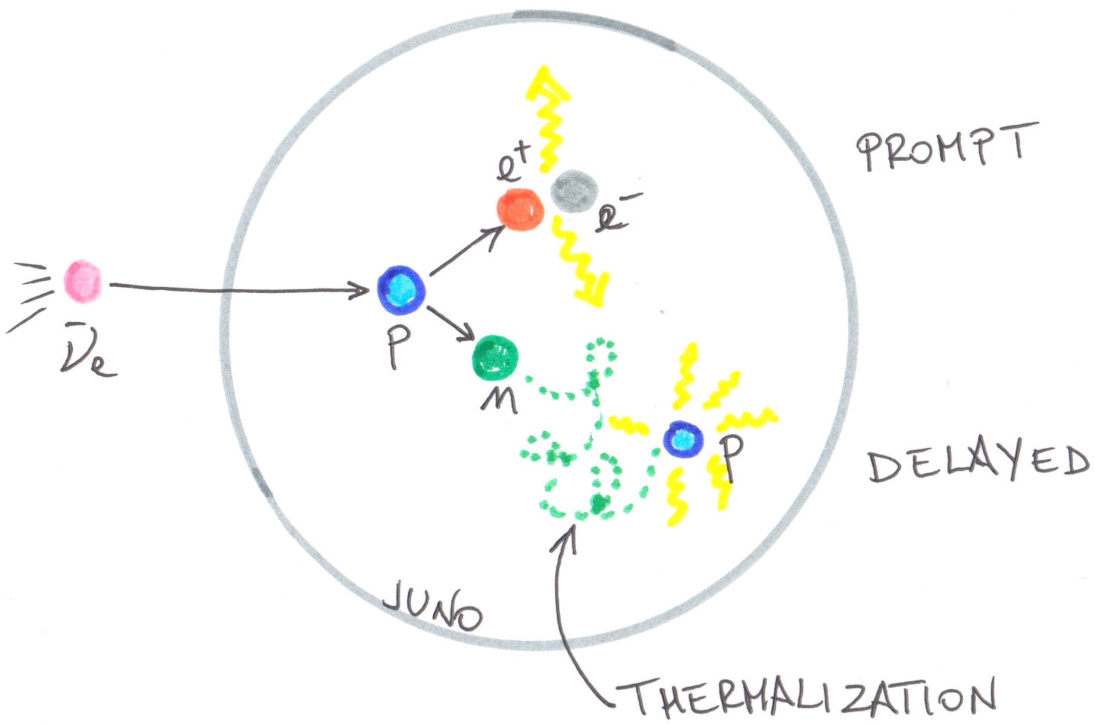


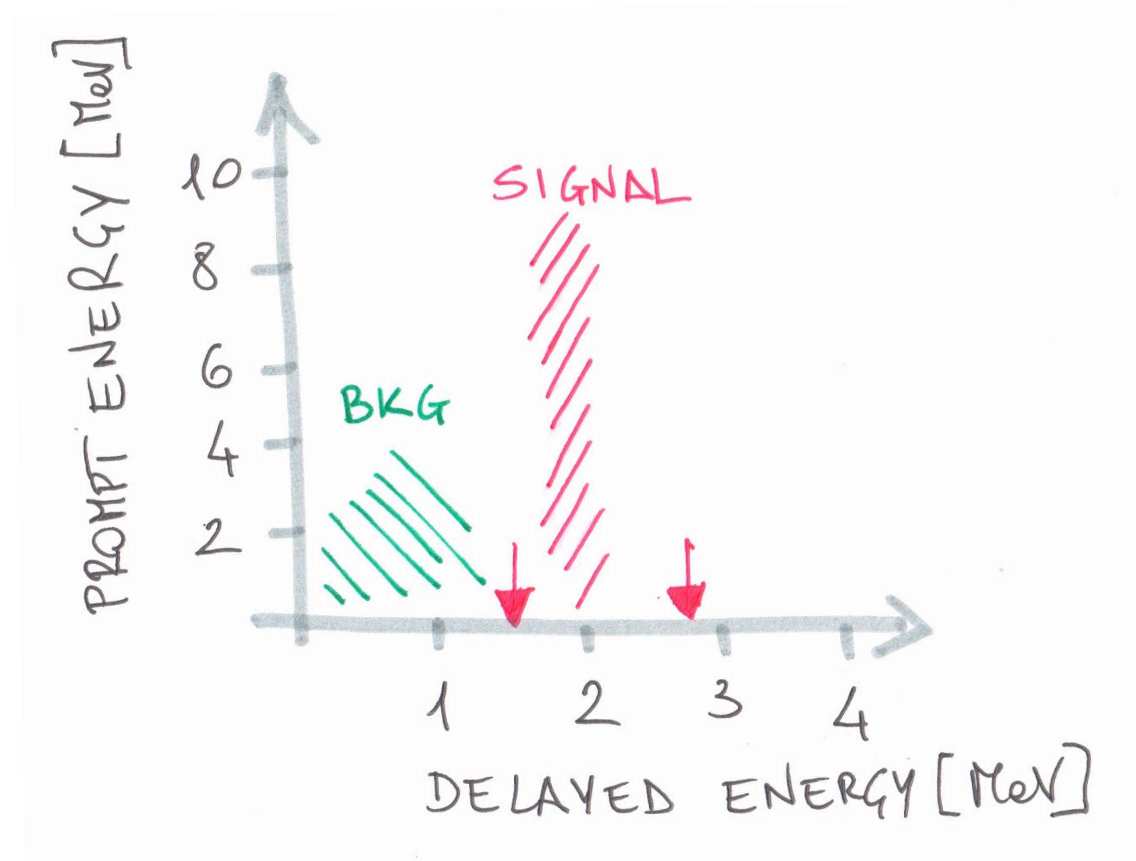
JUNO precision comparable to Double Chooz nowadays (~15 %)

Might be the only experiment to crosscheck θ_{13} accuracy

Both via Mass Hierarchy determination

Signal Events





Inverse Beta Decay (IBD) :

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

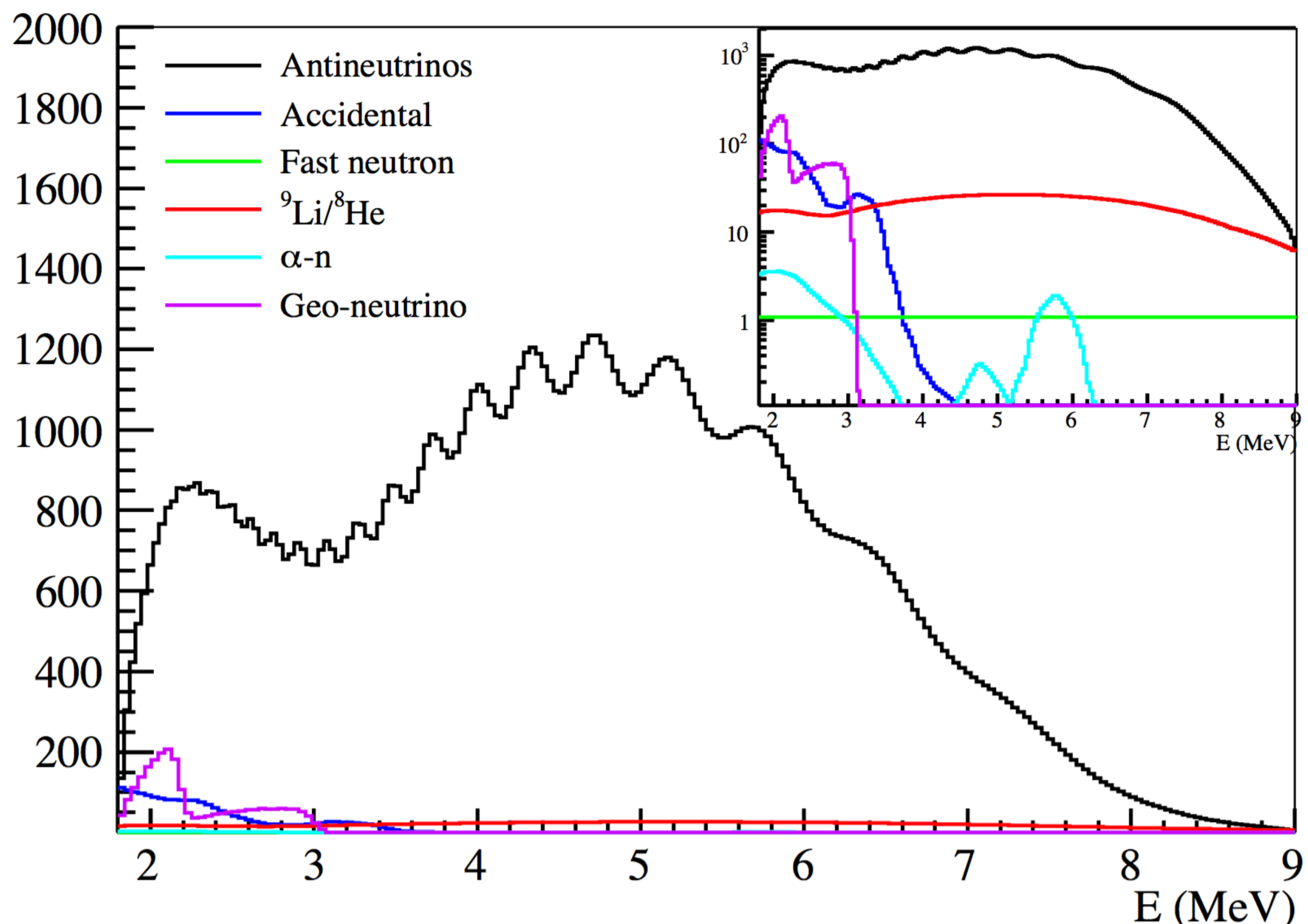
$$n + p \xrightarrow{\tau \sim 200\,\mu s} D + \gamma \ (2.2\ \mathrm{MeV})$$ Delayed

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

BKG Summary after selection



Event Rate per Day

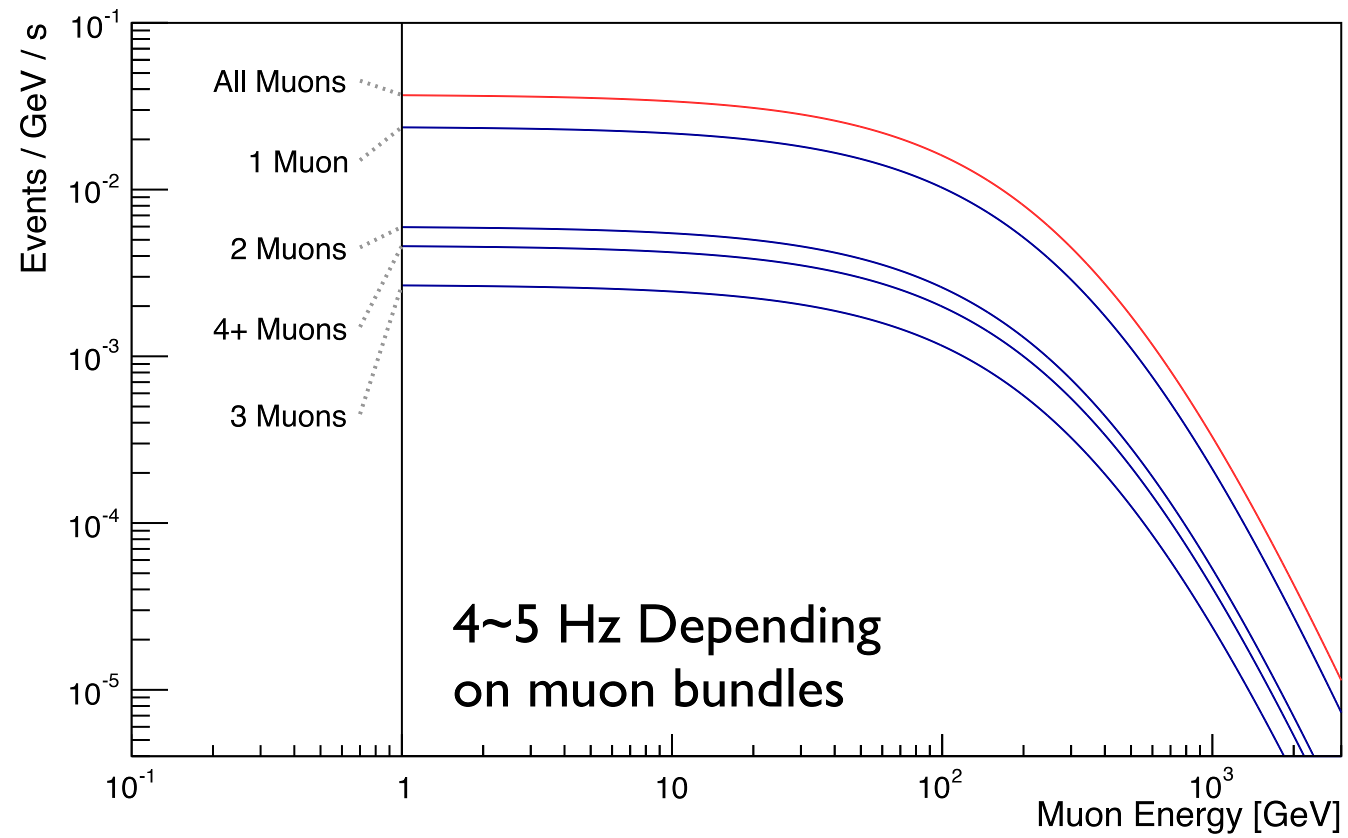
Selection	IBD efficiency	IBD	Geo-νs	Accidental	^{9}Li/^{8}He	Fast n	(α, n)
-	-	83	1.5	$\sim 5.7 \times 10^4$	84	-	-
Fiducial volume	91.8%	76	1.4		77	0.1	0.05
Energy cut	97.8%			410			
Time cut	99.1%	73	1.3		71		
Vertex cut	98.7%			1.1			
Muon veto	83%	60	1.1	0.9	1.6		
Combined	73%	60			3.8		

Cosmogenic Backgrounds

Background associated to cosmic muons surviving the overburden

Average Energy ~200 GeV
Average Track Length ~ 23m

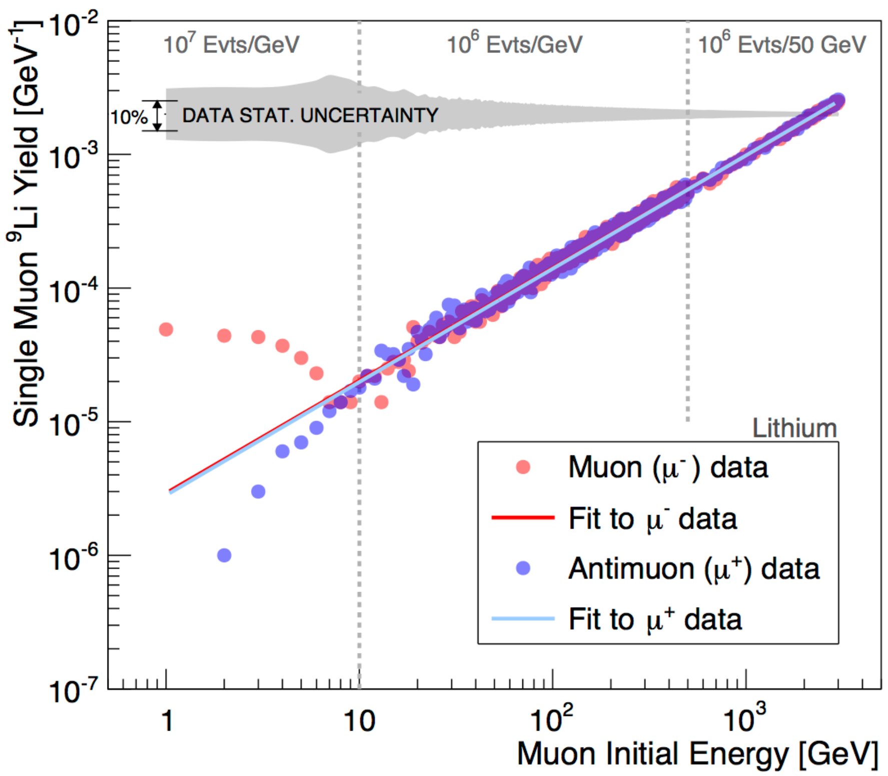
Might arrive in **bundles**:
multiple muons from the same primary cosmic ray

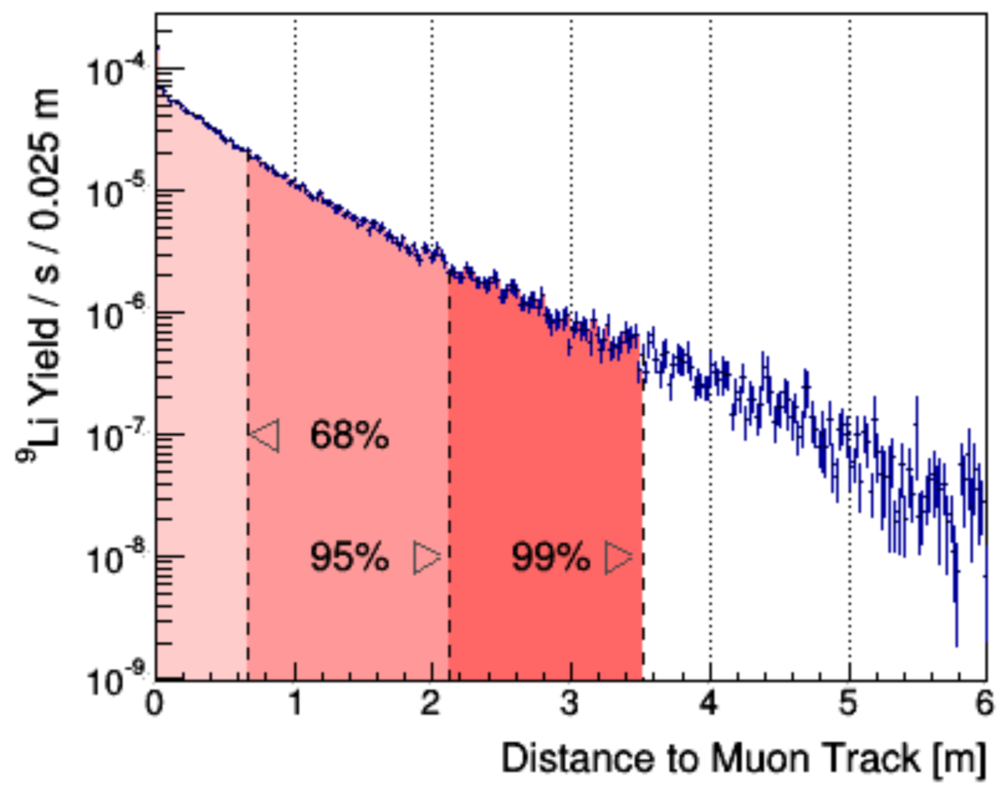


Fast Neutrons:
Interactions between μ and rock
Mainly at the top and at the equator
Strongly suppressed by water buffer

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





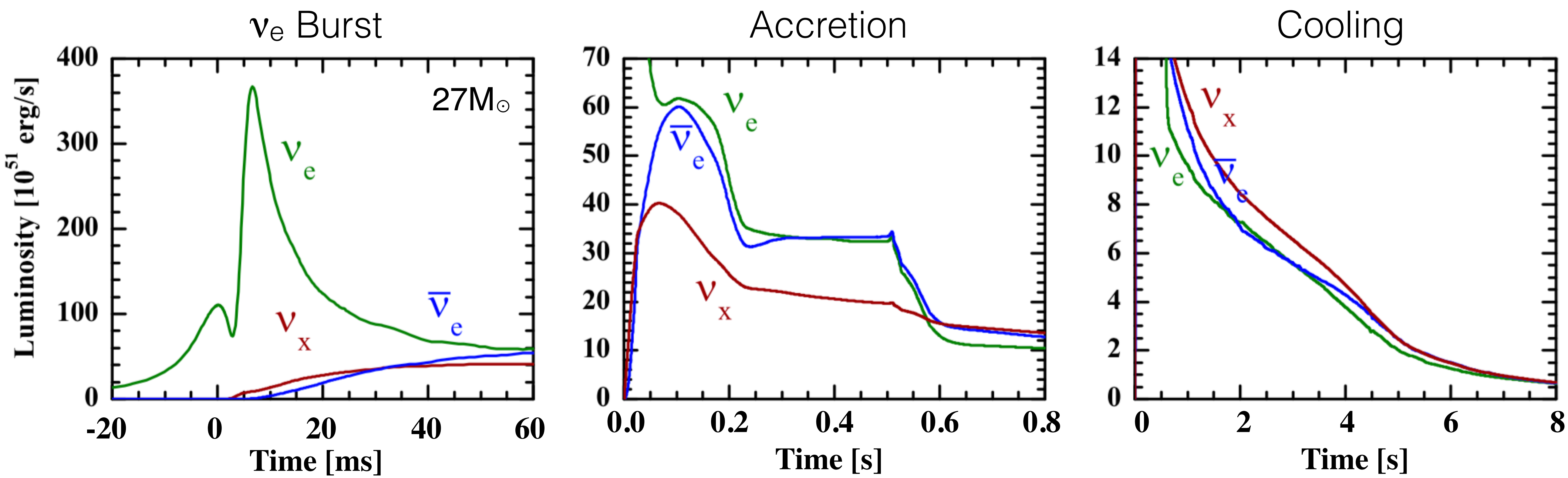
Total yield is ~70 evts/day
In case of **good tracking**, many events could be rejected with a regional veto (eg. 3.5 m, 1.5 s with respect to the muon track)

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 ~ 10%**

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
$\bar{\nu}_e+p \rightarrow e^++n$	CC	5.0×10^3
$\nu+p \rightarrow \nu+p$	NC	1.2×10^3
$\nu+e \rightarrow \nu+e$	ES	3.6×10^2
$\nu+{}^{12}C \rightarrow \nu+{}^{12}C^*$	NC	3.2×10^2
$\nu_e+{}^{12}C \rightarrow e^-+{}^{12}N$	CC	0.9×10^2
$\bar{\nu}_e+{}^{12}C \rightarrow e^++{}^{12}B$	CC	1.1×10^2
NB Other ⟨E_ν⟩ values need to be considered to get complete picture.		

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

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

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

Geoneutrinos

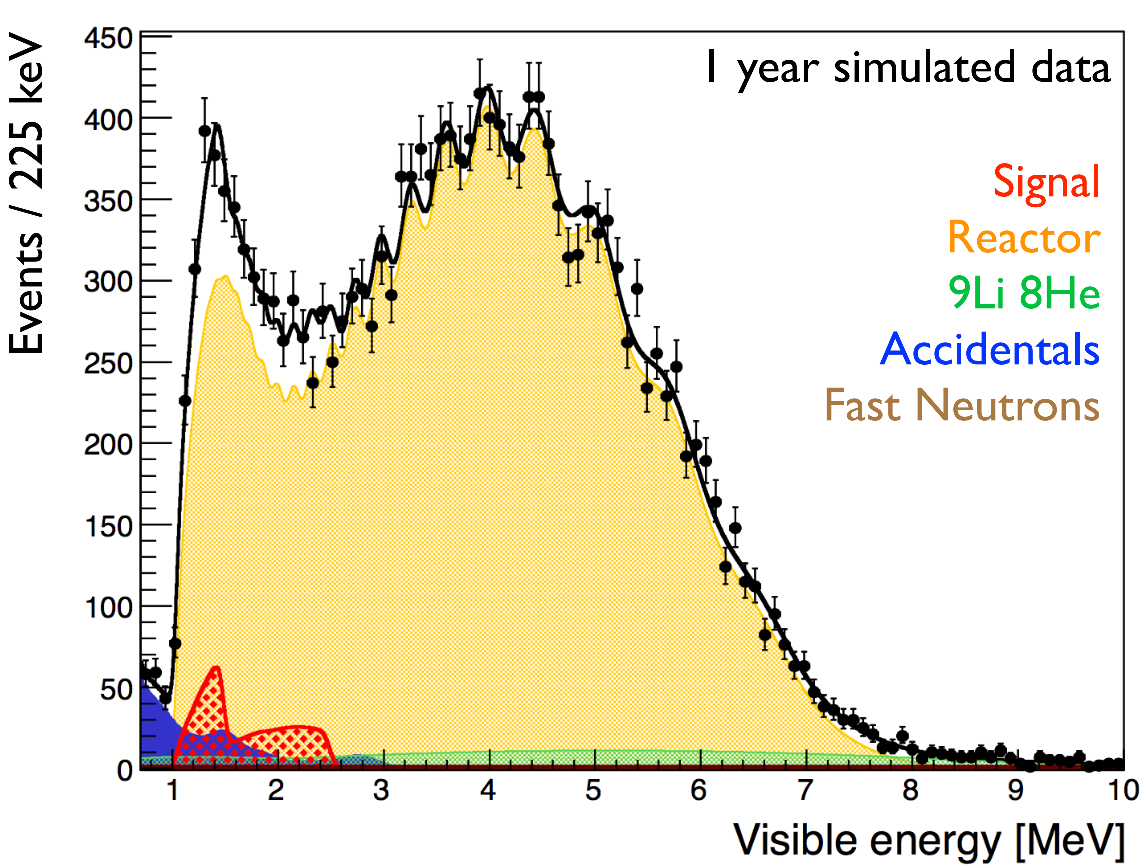
J.Phys. G43 (2016) no.3, 030401

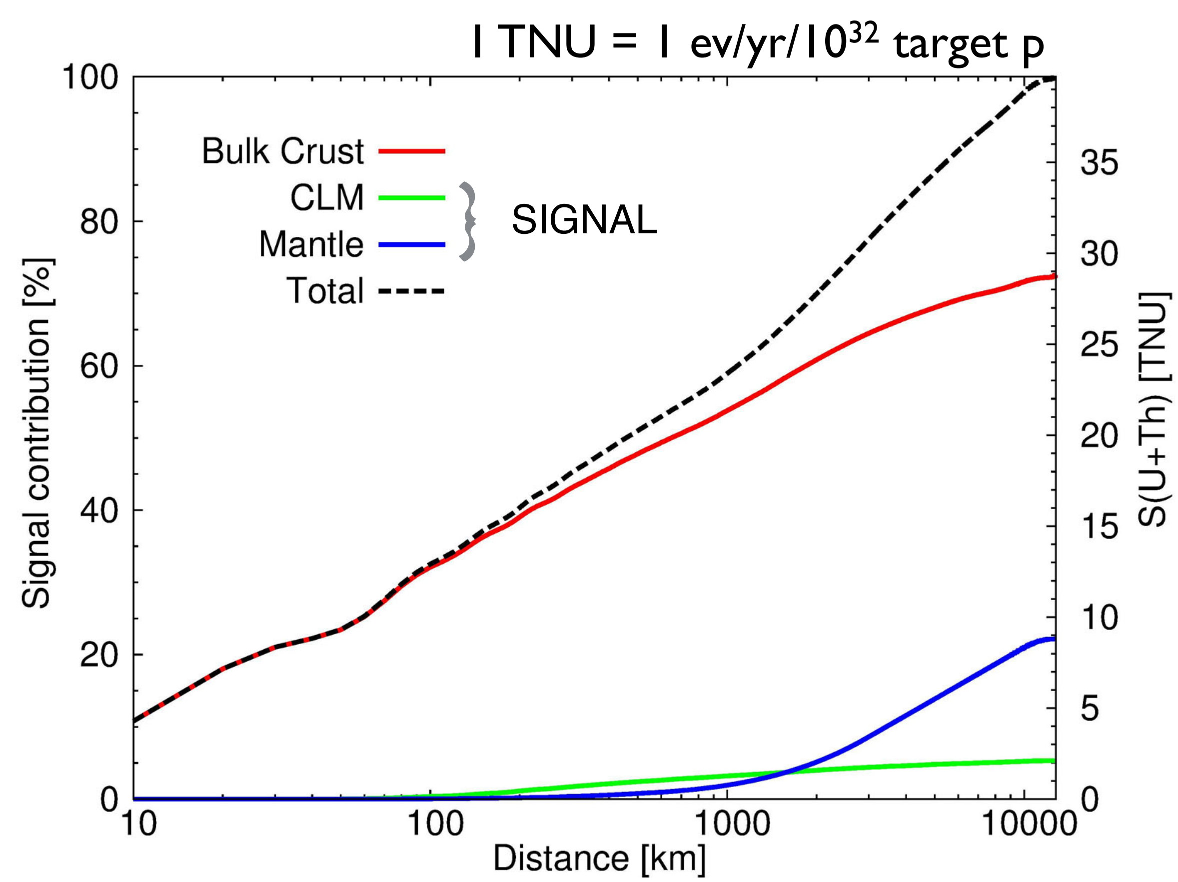
Earth's surface heat flow 46±3 TW. What fraction due to **primordial vs radioactive** sources?

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





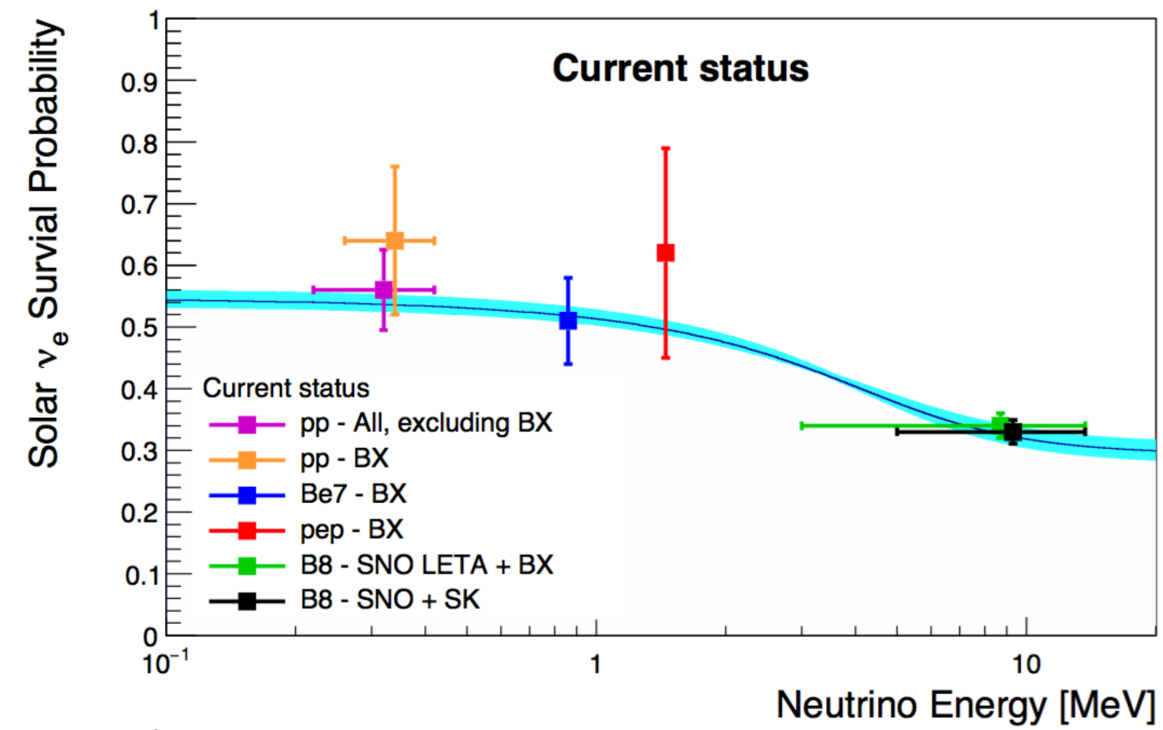
Solar Neutrinos

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

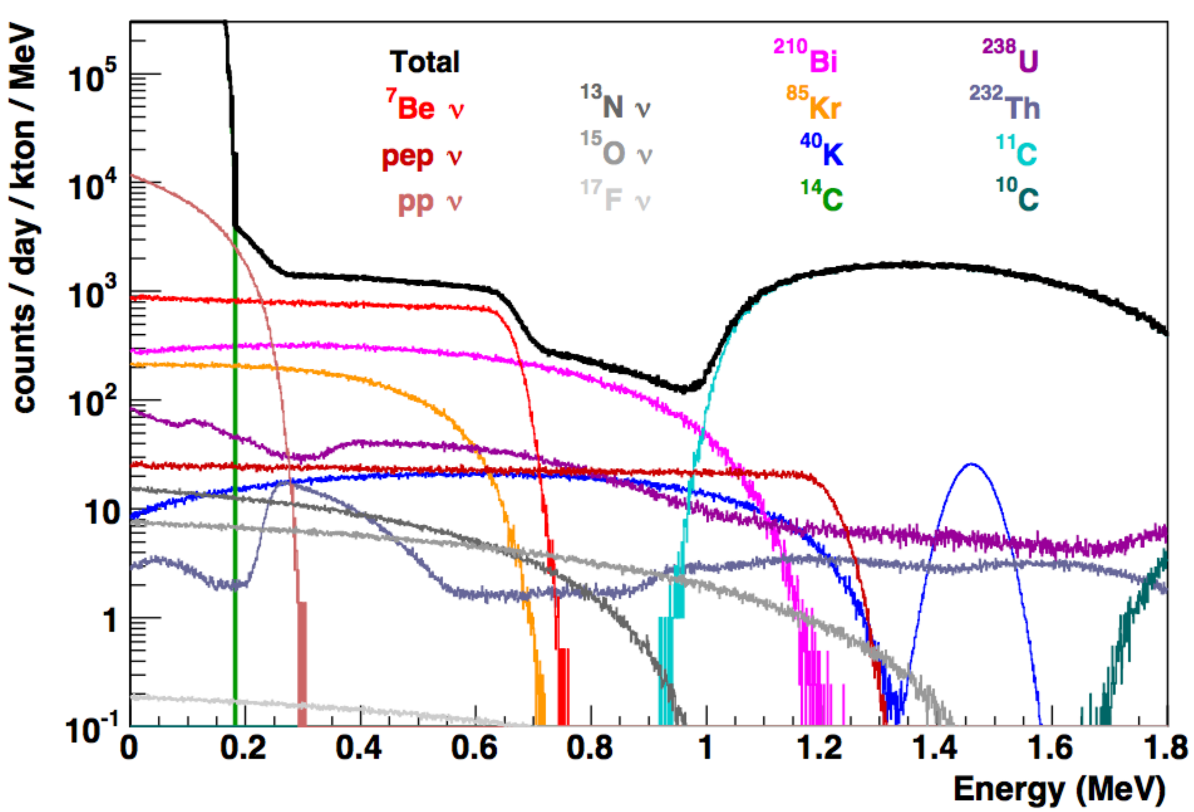
JUNO: neutrinos from **^{7}Be and ^{8}B** chains

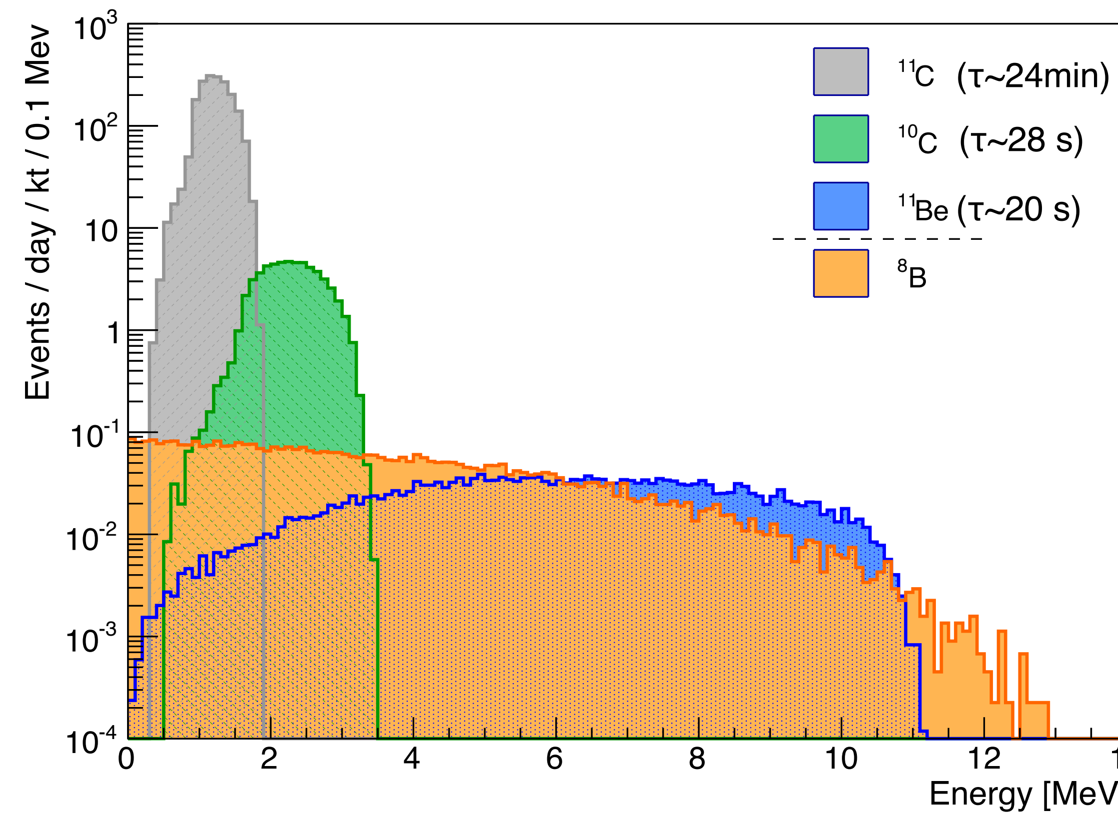
Investigate **MSW effect**: Transition between vacuum and matter dominated regimes

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



arXiv 1602.01733





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

THE DETECTOR

Detector Overview

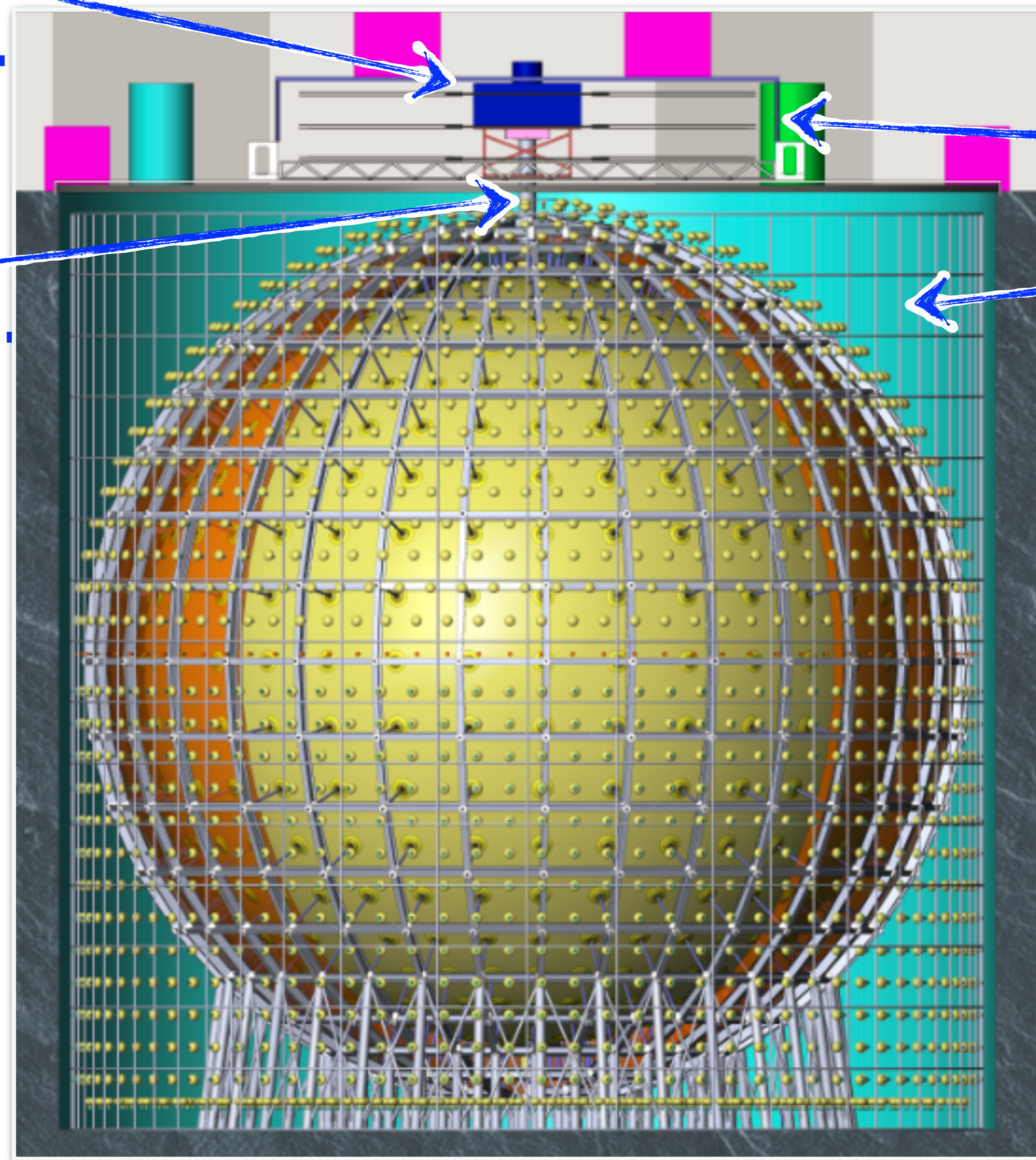
Calibration Room

Muon Veto

Chimney

Top Tracker

Water Pool



Central Detector

Steel Truss

Holding PMTs

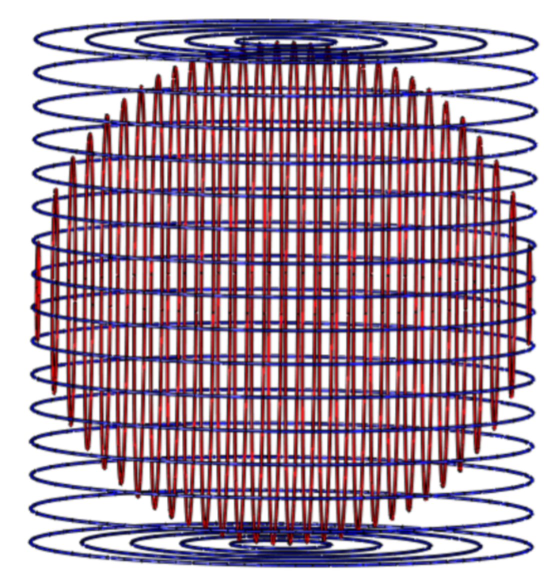
~18000 x 20"

~36000 x 3"

Acrylic Sphere

filled with LS

Magnetic Field Compensating Coil



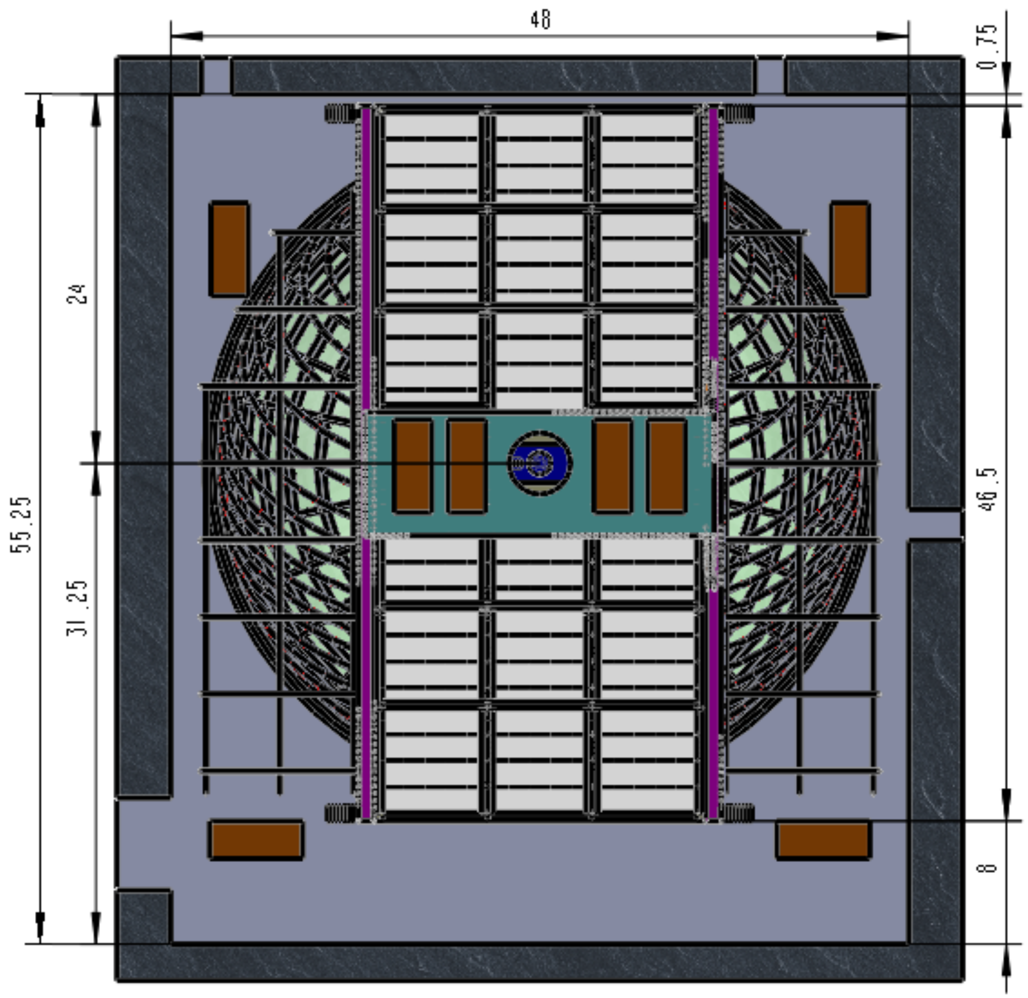
Muon Veto

Muon Veto: critical to reduce backgrounds

Cosmogenic isotopes rejection:
reconstruction of muon tracks and 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

Muon Veto: critical to reduce backgrounds

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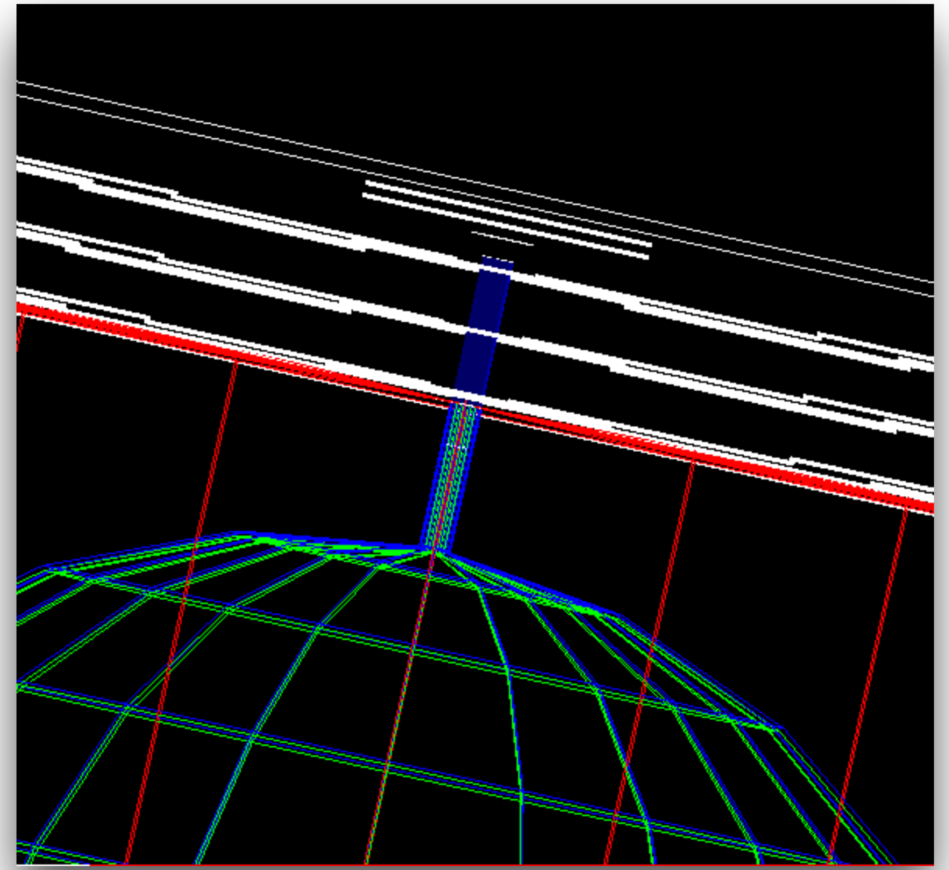
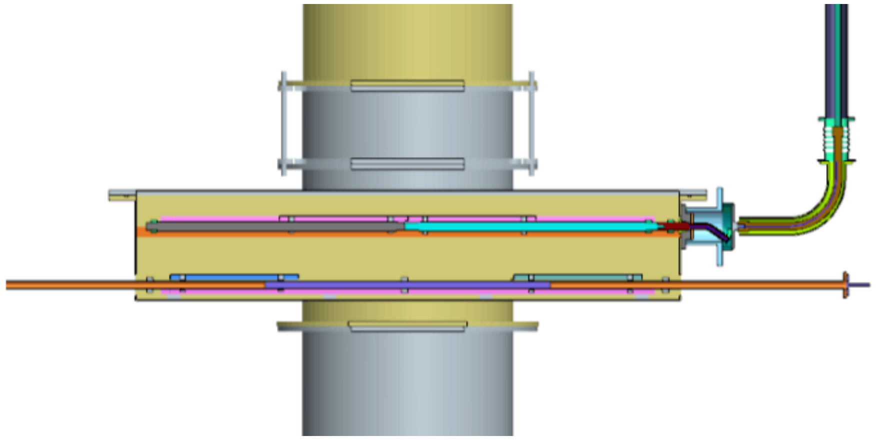


Chimney

Connecting acrylic vessel with external world

Need to be instrumented for **stopping muons**

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



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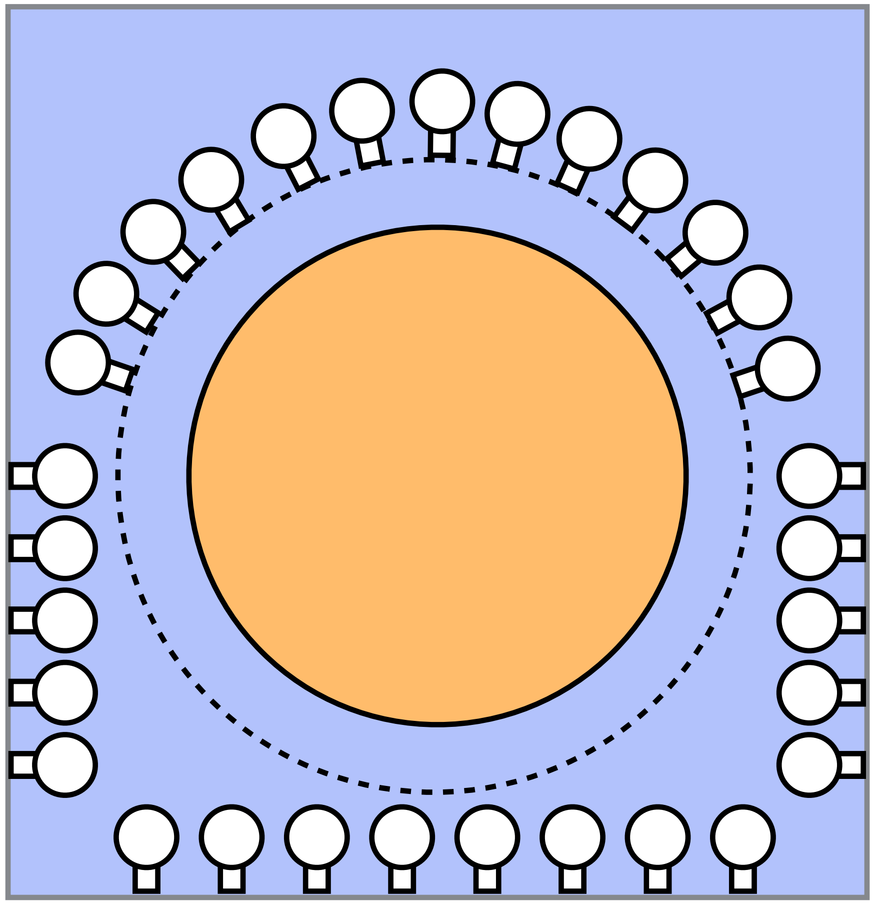


Water Cherenkov

20~30kt ultra-pure water

Water acting as moderator &
pool instrumented to detect Cherenkov light

2000 20'' PMTs located as in the picture

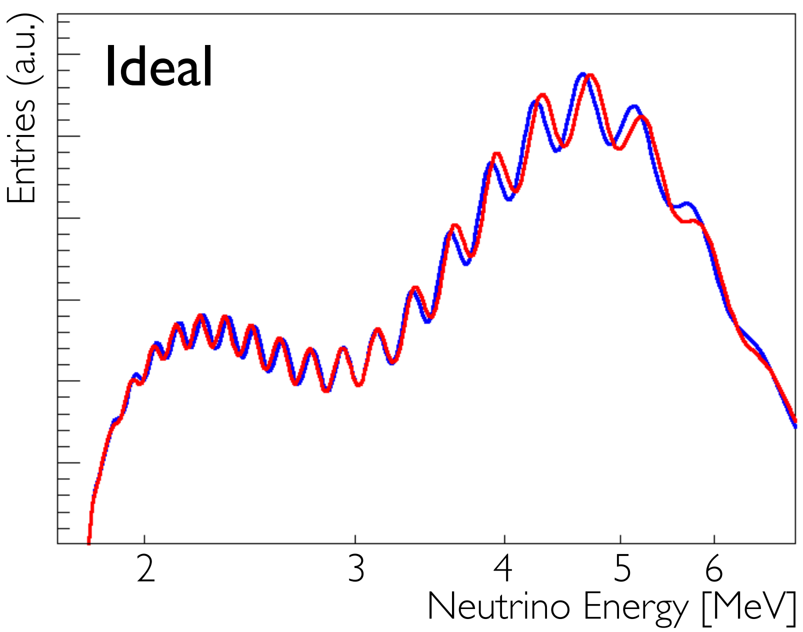
Maximise detection efficiency of Cherenkov light

Central Detector

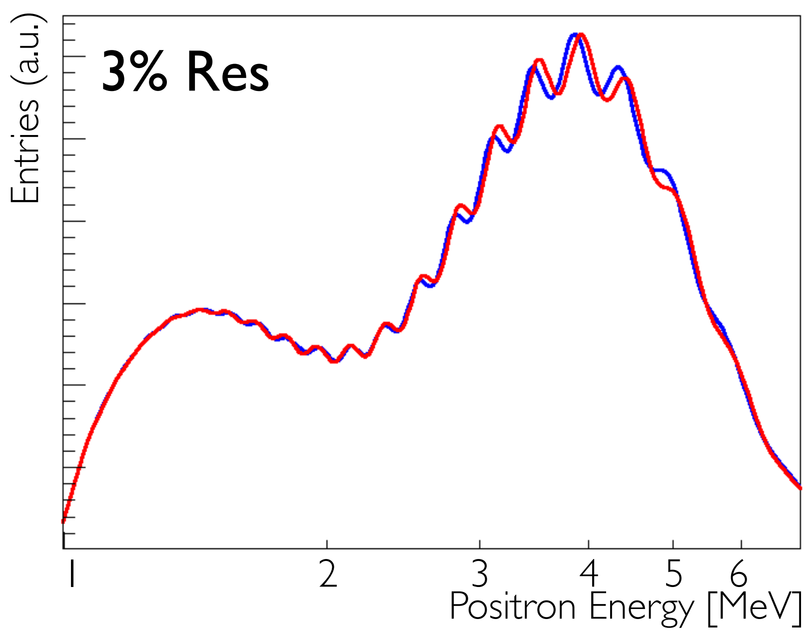
Central Detector design optimised for Mass Hierarchy: "Precise & Large"

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

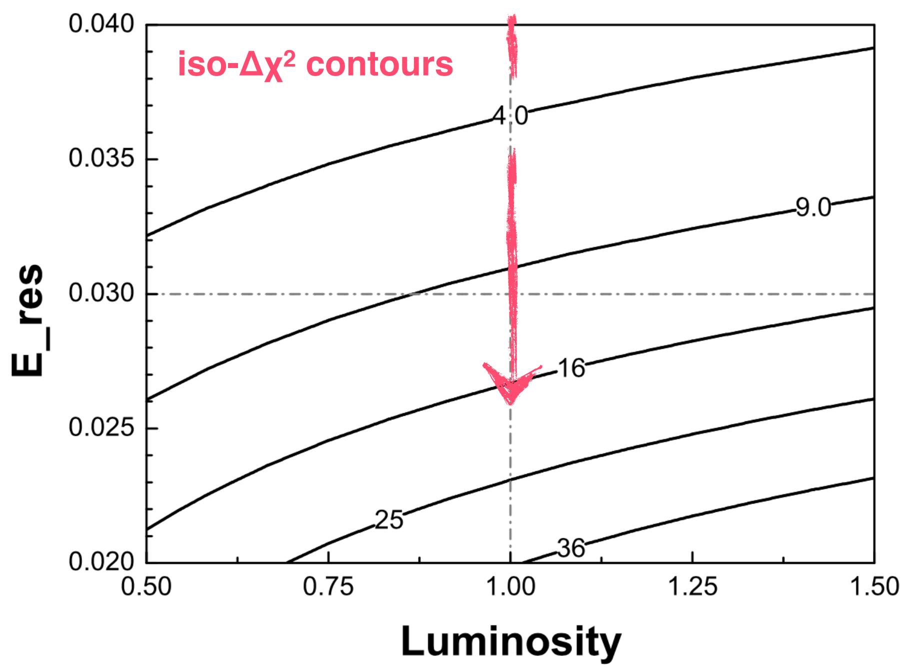
Neutrino Spectrum



Visible Spectrum



MH Sensitivity



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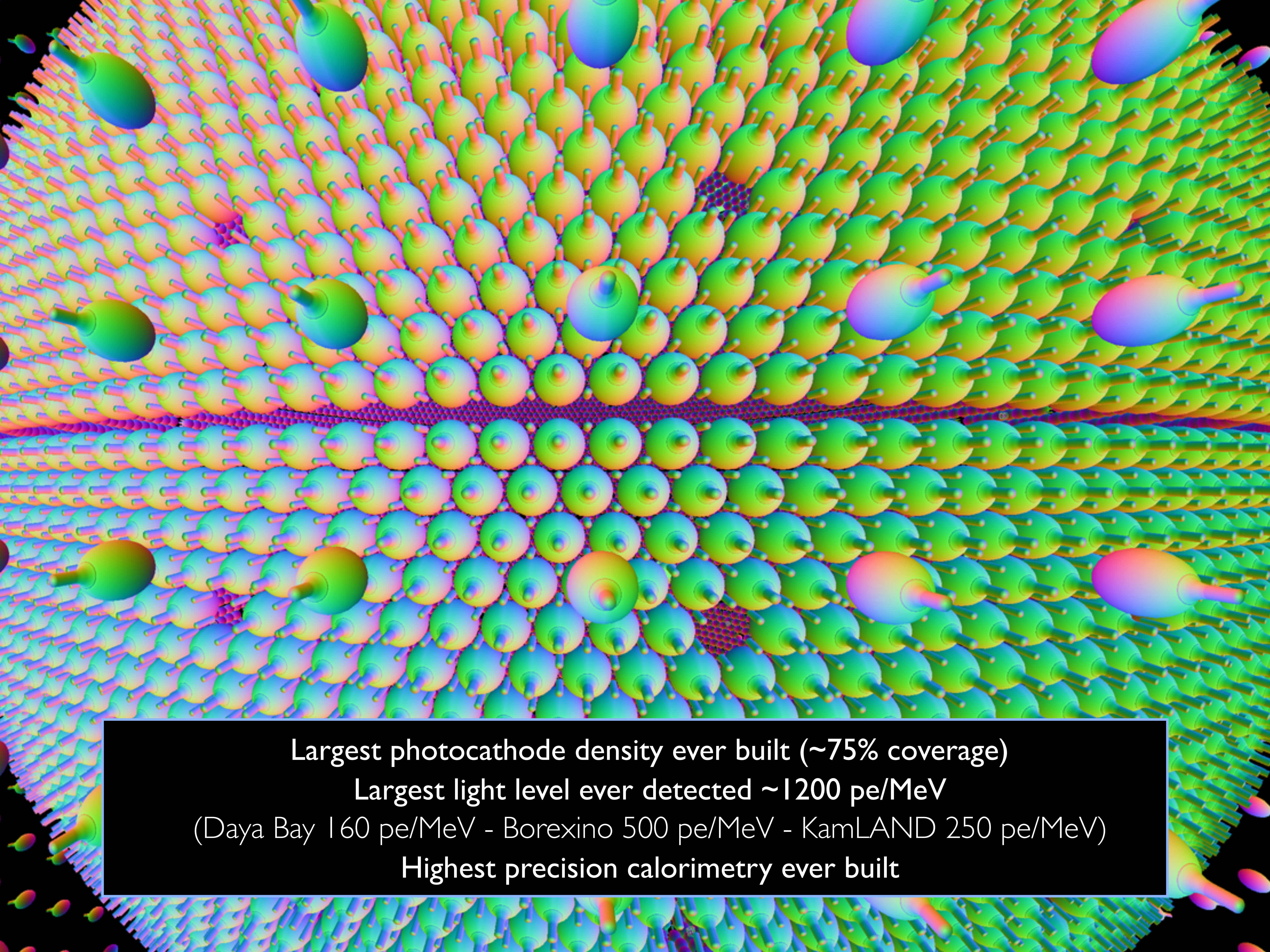
Central Detector design optimised for Mass Hierarchy: "Precise & Large"

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

3% resolution at 1 MeV is pivotal

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

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



Largest photocathode density ever built (~75% 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

Central Detector

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

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

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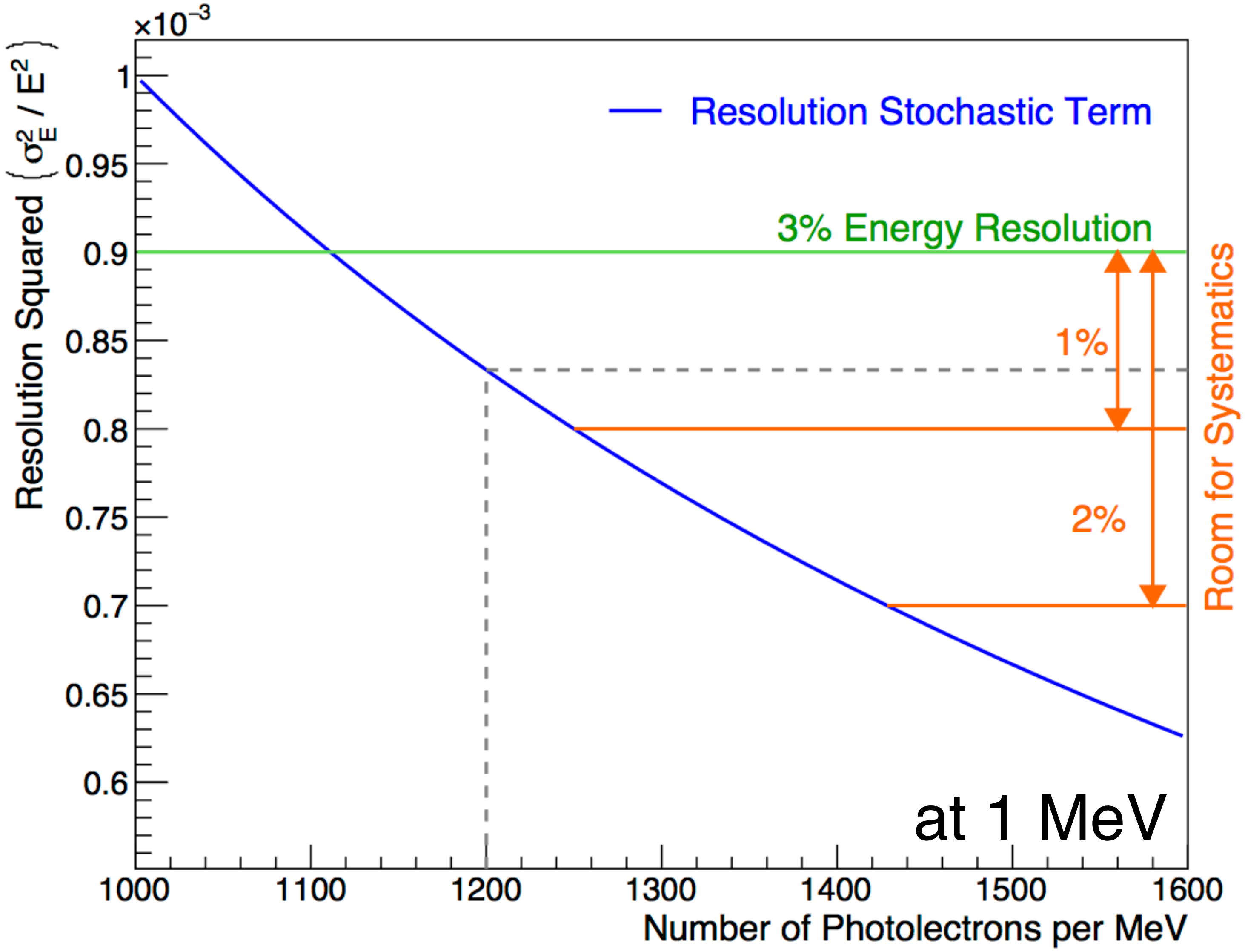


INTERACTION › **LS Quenching** › **Propagation** › **Light collection and digitisation** › **DETECTION**

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 — CAUSES — LS non-linear light yield

Propagation — CAUSES — Response non-uniformity

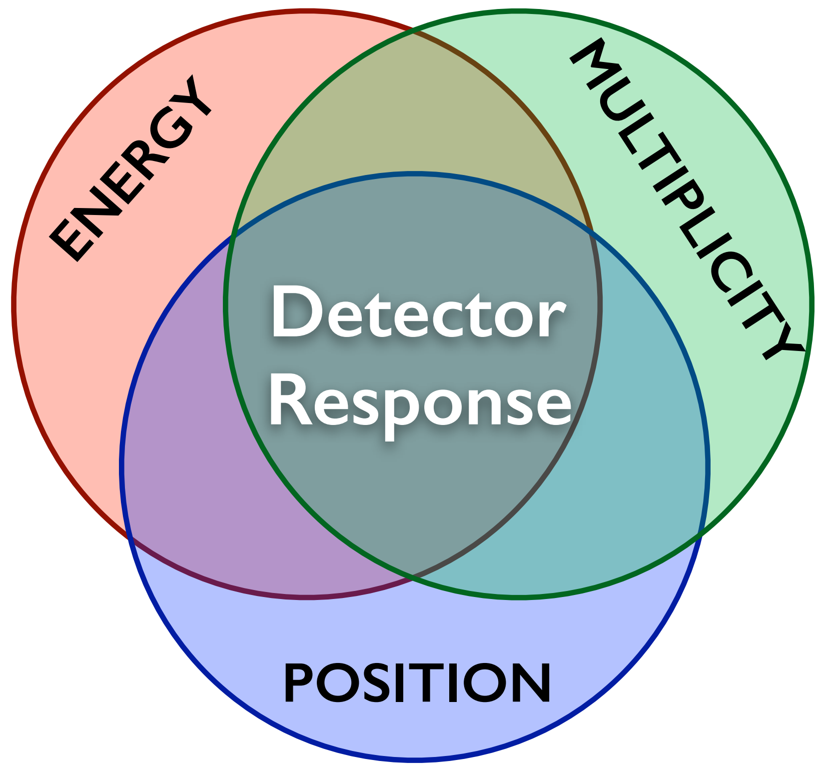
Light collection and digitisation — CAUSES — Single channel bias & non-linearity

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

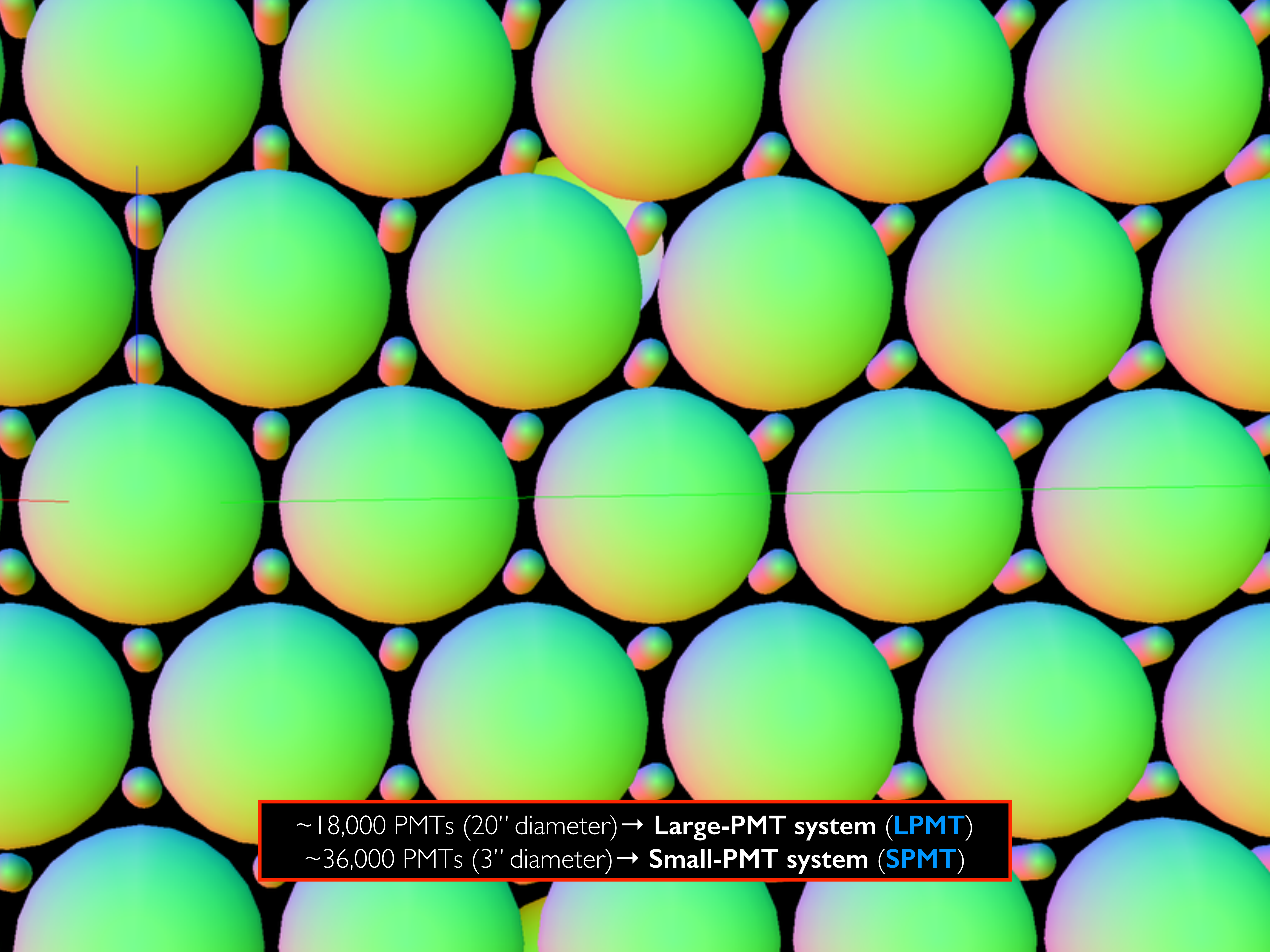
Sources deployed along z axis

Rope system (off-axis)

Remotely Operated Vehicle (off-axis)

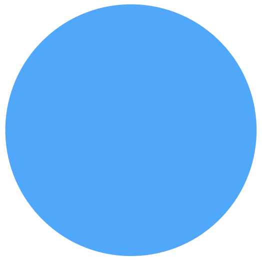
Guide tube surrounding acrylic sphere

Cosmogenic neutrons (unif. distributed)



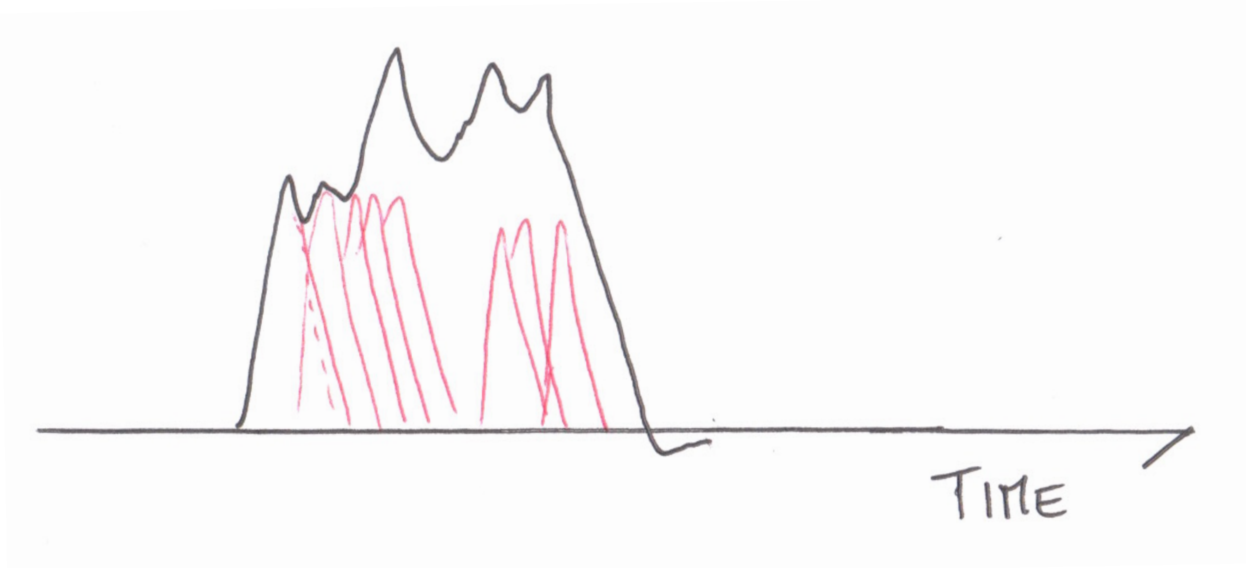
~18,000 PMTs (20" diameter)→ **Large-PMT system** (LPMT)
~36,000 PMTs (3" diameter)→ **Small-PMT system** (SPMT)

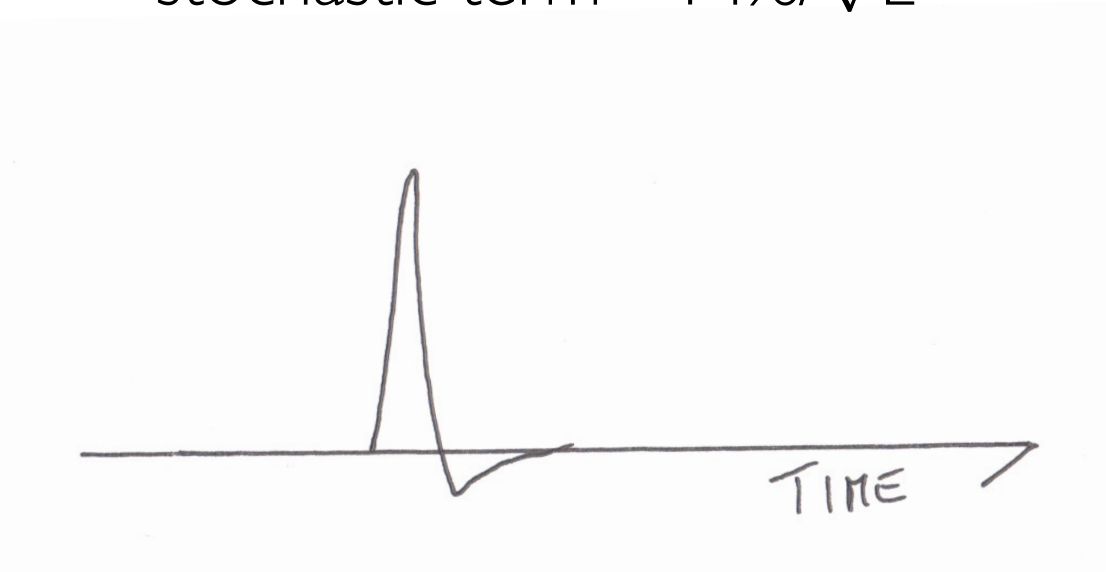
Small PMT



1200 p.e./MeV
75% photo-coverage
stochastic term: 3%/$\sqrt{E}$

~50 p.e. /MeV
4% photocoverage
stochastic term ~14%/$\sqrt{E}$





Large Pmt:

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

Main Calorimetry

Small Pmts

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

Time Reso & sPE identification

Small PMTS as an "aider" to Large PMTS

1. High precision calorimetry

   Improve response systematics within IBD physics

   Aide to achieve ≤3% resolution at 1MeV

2. Physics: Standalone measurement of solar parameters

   Ensure accurate physics results and validate energy scale

3. Improve inner-detector μ-reconstruction resolution

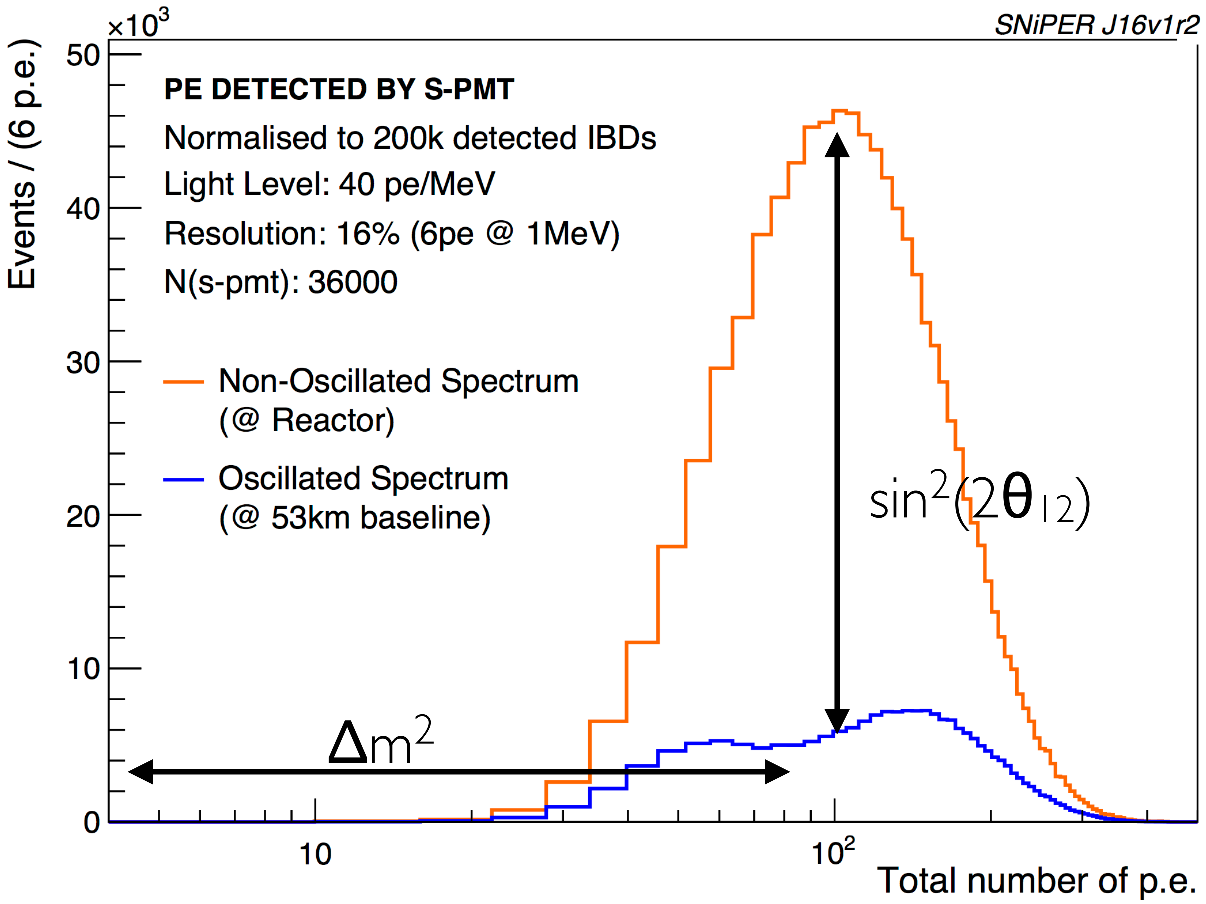
   Aide $^{12}B/^{9}Li/^{8}He$ tagging/vetoing

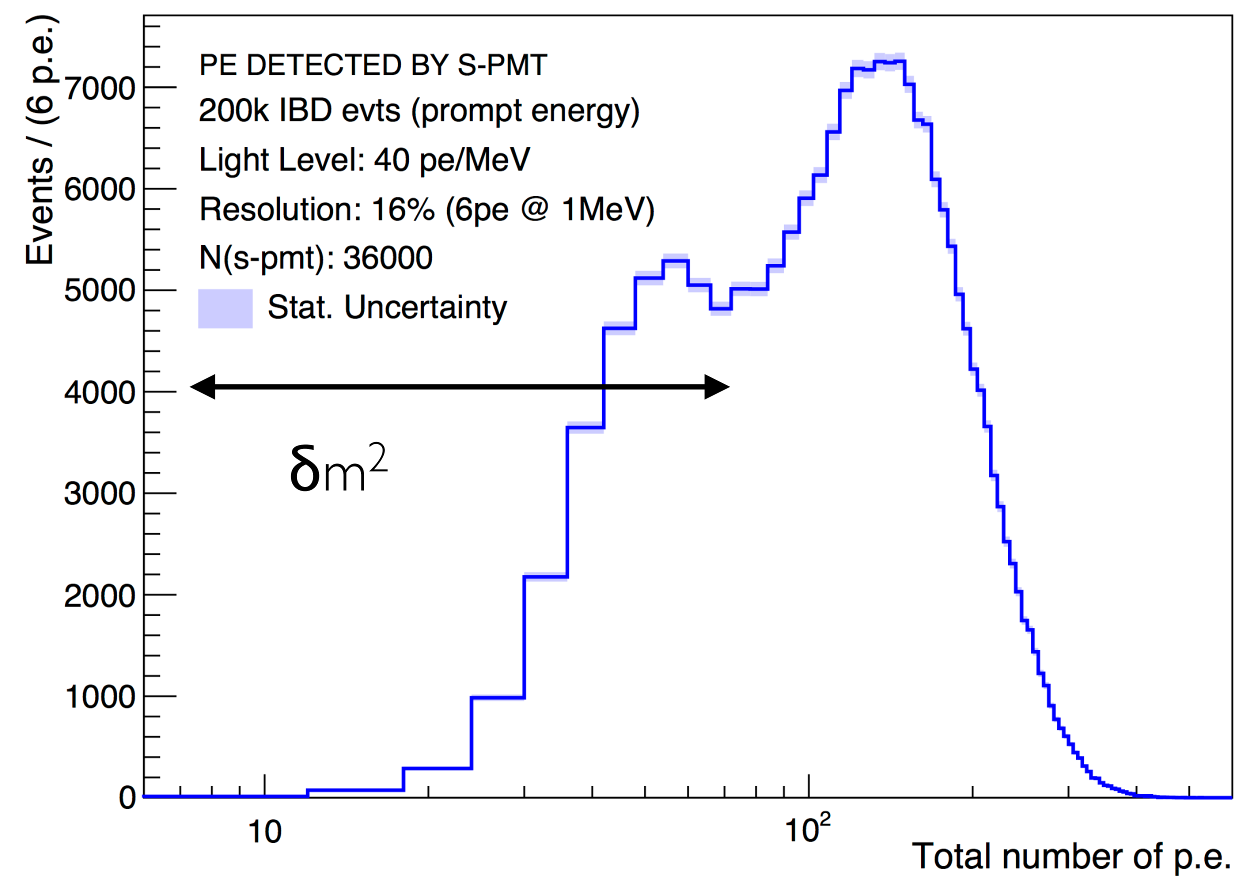
4. High rate SN pile-up (if very near)

   Minimise bias in absolute rate & energy spectrum

5. Complementary readout info: time resolution, dynamic range & trigger

Solar Physics with Small PMTs





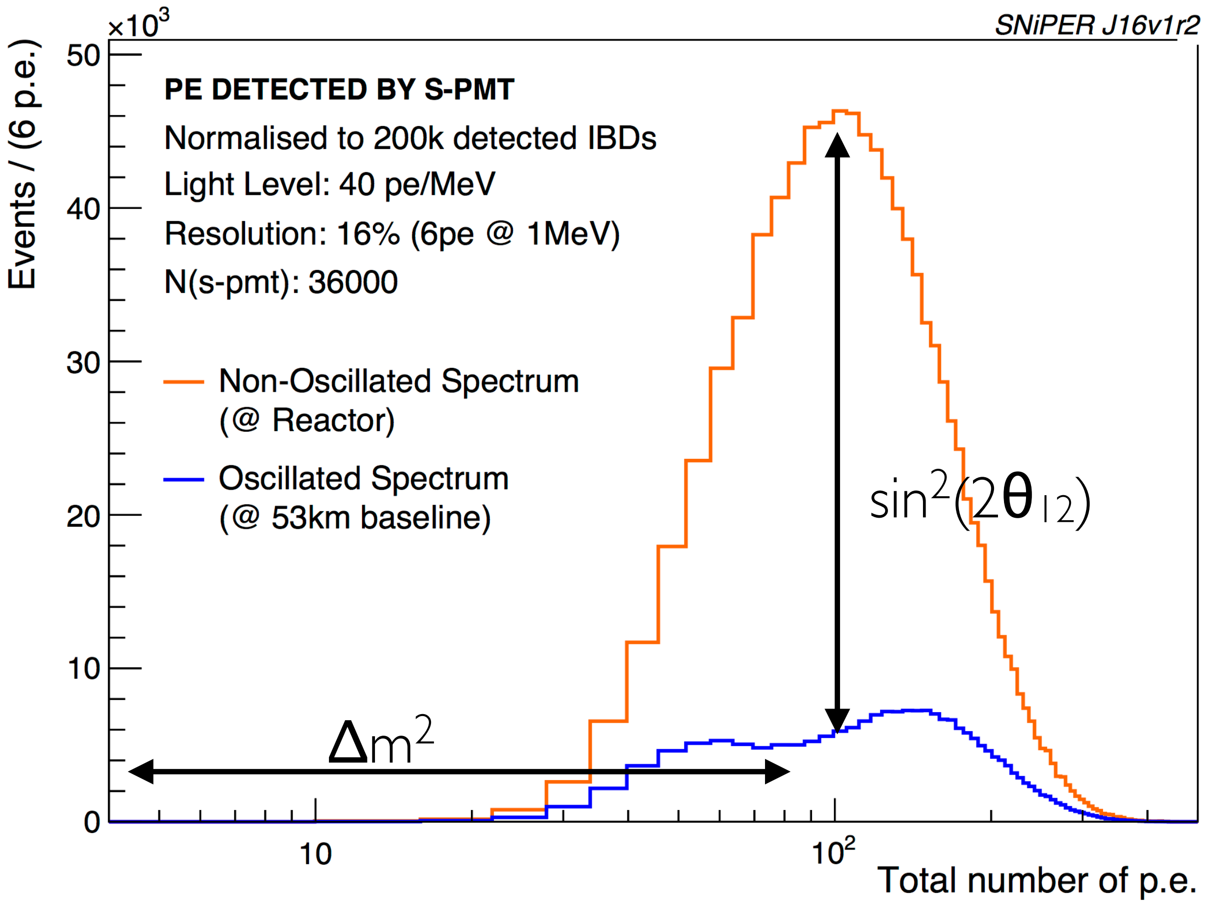
SPMT system alone can measure **solar parameters** $\sin^2(2\theta_{12})$ and Δm^2_{12}

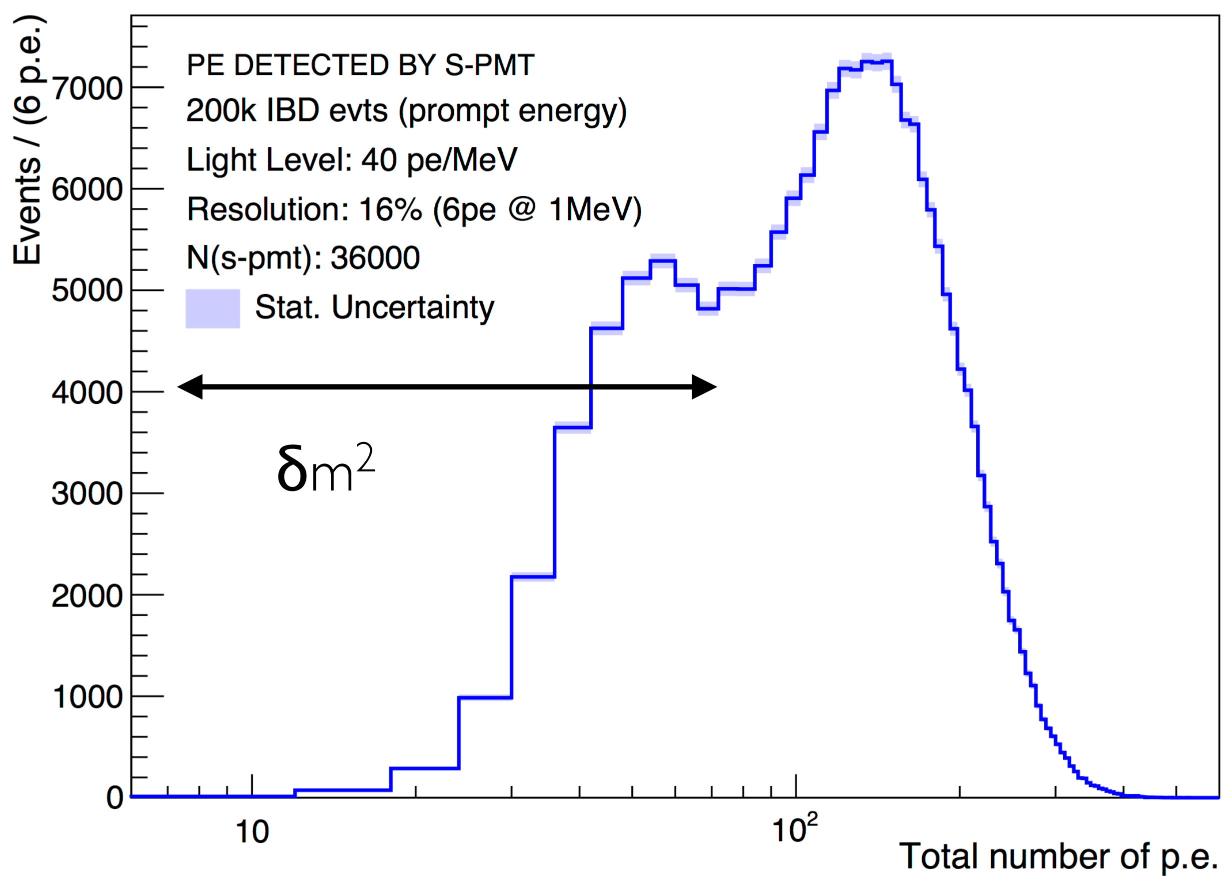
Rate + Slow spectral features (loose constraint on energy resolutions)

JUNO's solar parameters: most precise ever ▸ **Need to ensure accuracy**

Energy scale validation based on physics measurement

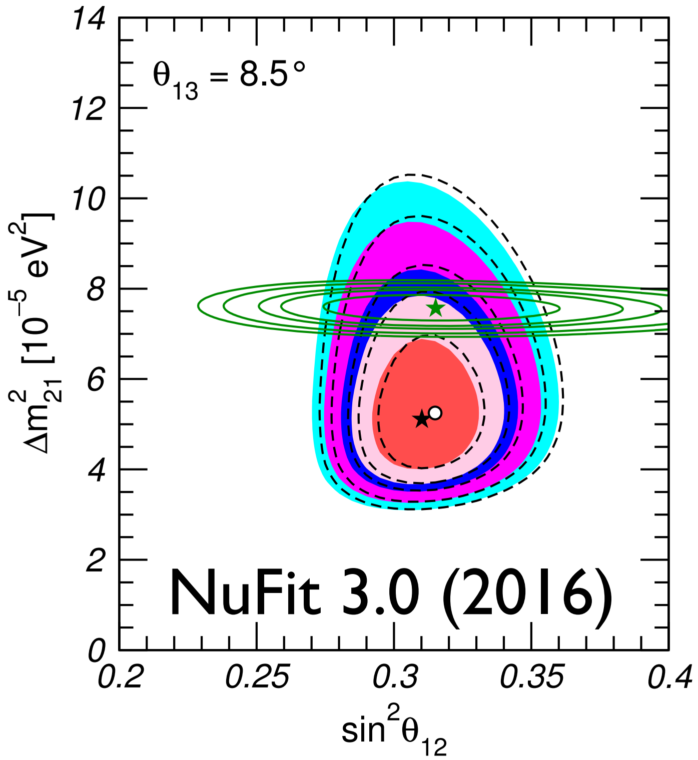
Solar Physics with Small PMTs

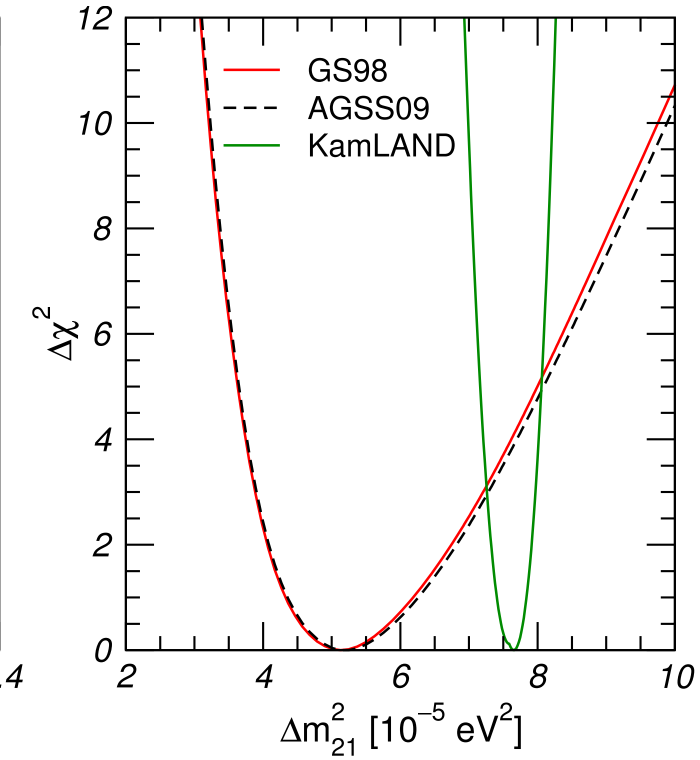




JUNO will play a key role in settling the tension between KamLAND and Solar models

Issue in our understanding of the Sun or reactor physics?





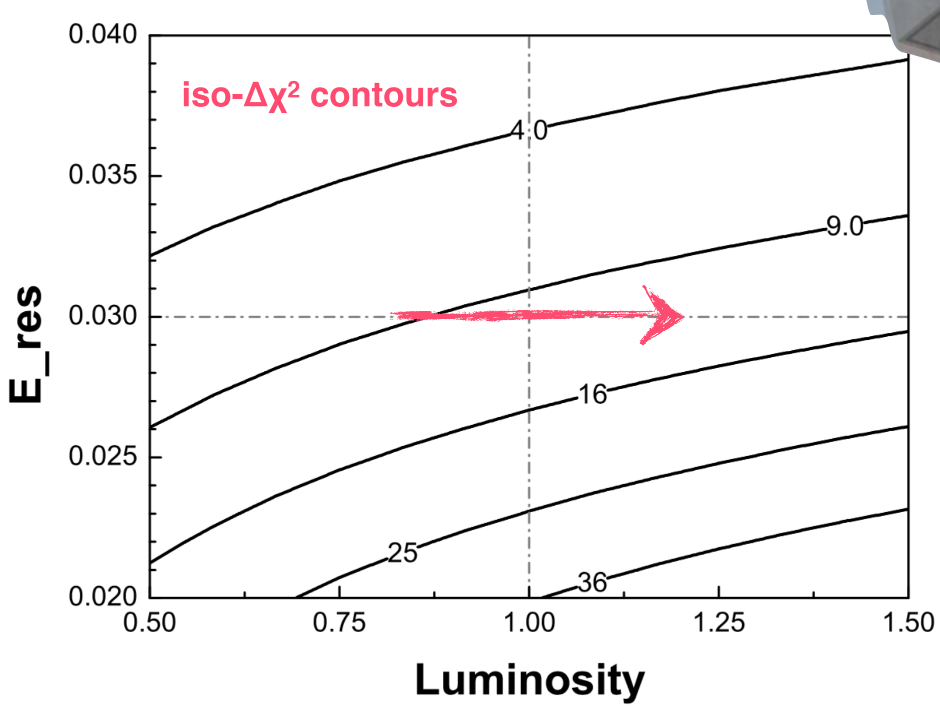
Central Detector

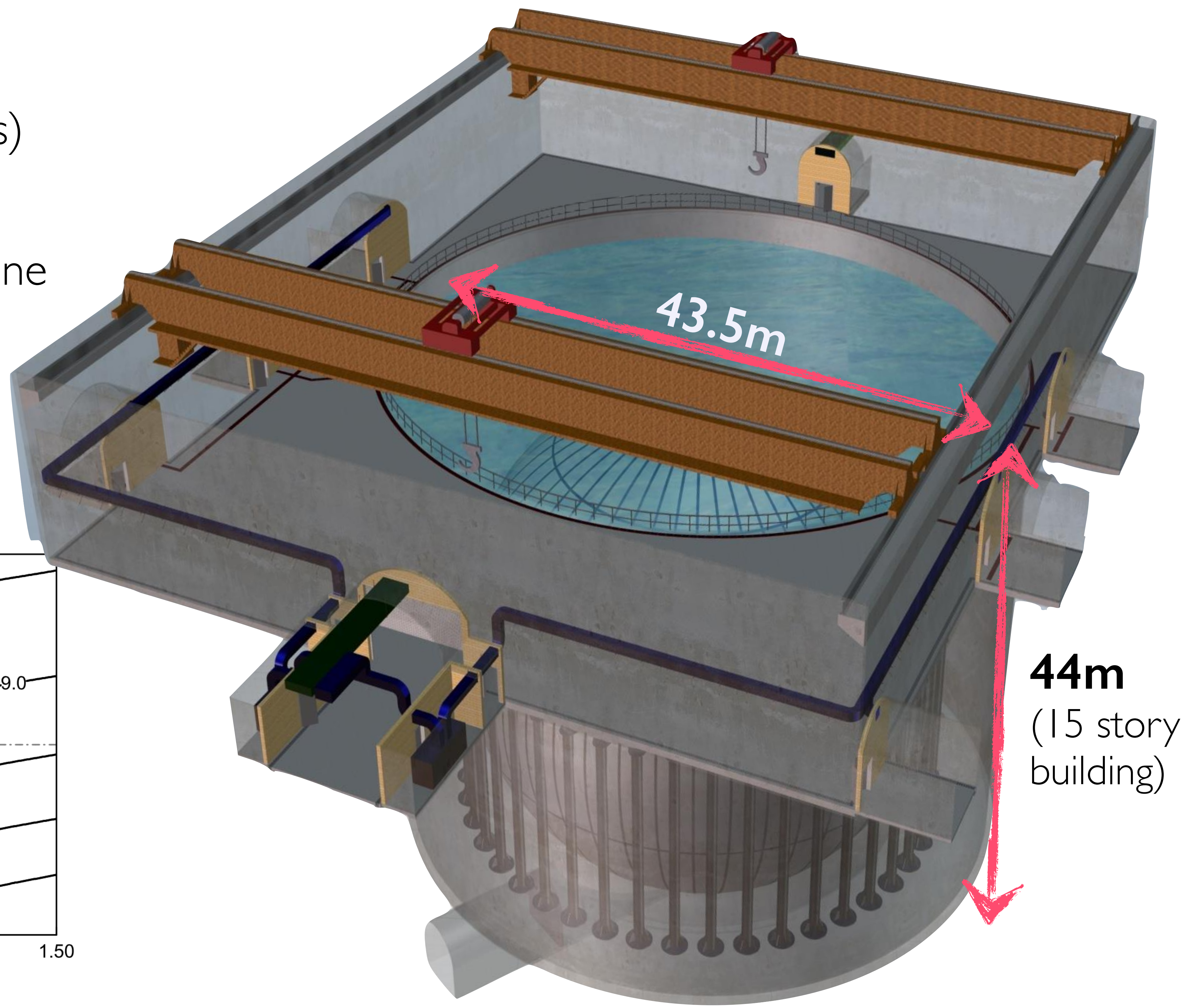
Central Detector design optimised for Mass Hierarchy: “Precise & Large”

Need high statistics
(looking for fine structures)

Need to recover
flux reduction due to baseline

Nominal Luminosity
100k events in 6 years





Schedule

Complete conceptual design. Complete civil design and bidding

PMT production line manufacturing

Complete civil construction. Start detector construction and assembly

Complete detector assembly, installation and LS filling

2013 ▶ 2014 ▶ 2015 ▶ 2016 ▶ 2017 ▶ 2018 ▶ 2019 ▶ 2020

Start civil construction. Complete prototyping (PMT & detector). International collaboration established

Start PMT production. Start detector production

Start LS production

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**