The investigation of liquid scintillator properties, energy and spatial resolution for JUNO reactor neutrino experiment

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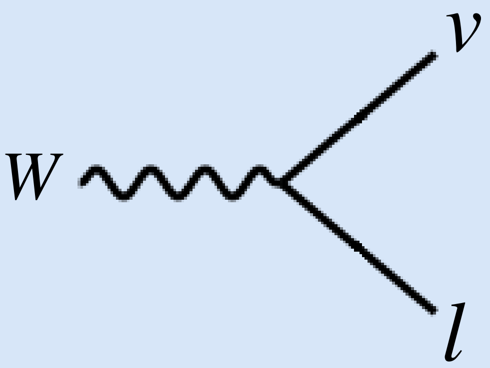
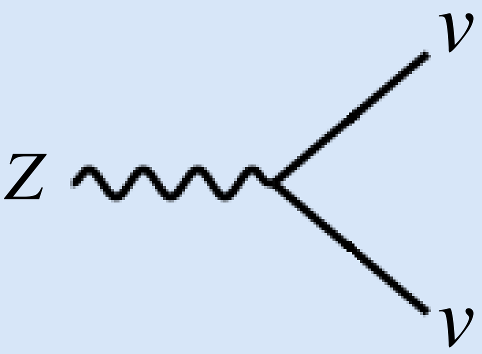
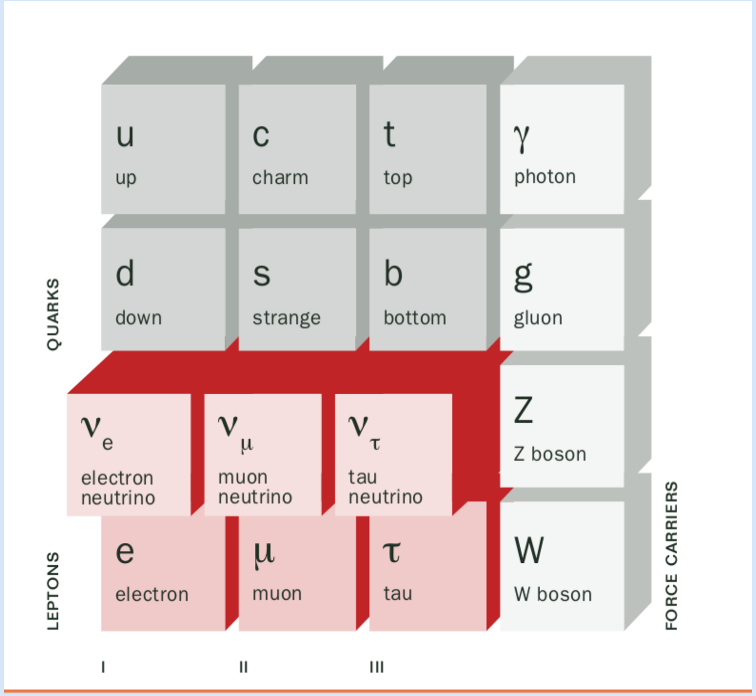
Neutrino

- has no charge
- has a tiny mass
- weakly interacts with matter







	I	II	III	
QUARKS	u up	c charm	t top	γ photon
	d down	s strange	b bottom	g gluon
LEPTONS	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z Z boson
	e electron	μ muon	τ tau	W W boson

FORCE CARRIERS

- three types (flavors) of neutrino
- neutrino can change its flavor due to oscillations

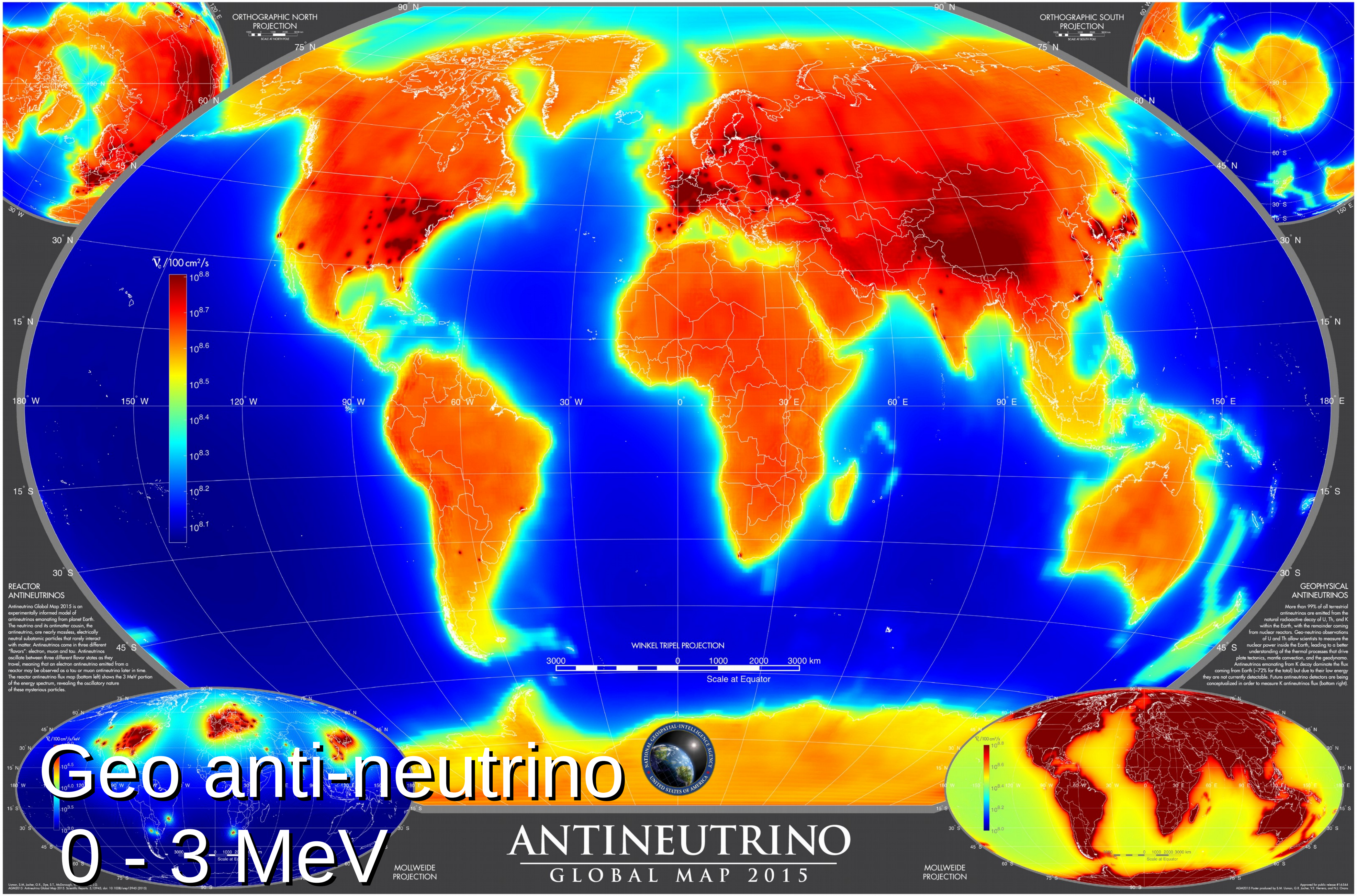
$$\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$$

How to detect?

- **Small cross section → Huge target mass**
- **Cosmic background → Underground laboratory**
- **Surrounded radioactivity → Shielding**
- **Radioactivity of the materials → Purification**

Solar neutrino 0.1 - 10 MeV

Geo anti-neutrino
0 - 3 MeV

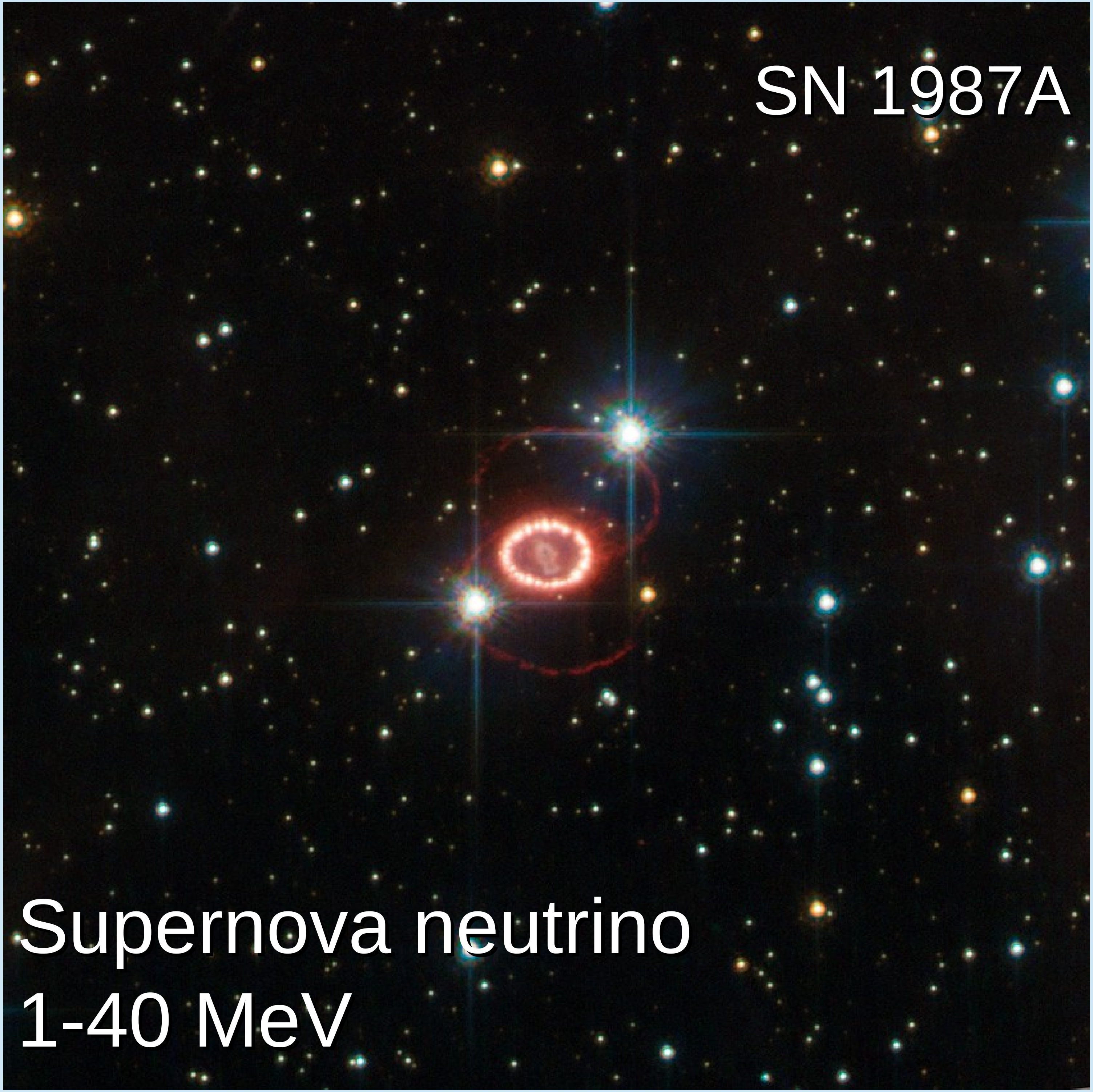


REACTOR
ANTINEUTRINOS

Antineutrino Global Map 2015 is an experimentally informed model of antineutrinos emanating from planet Earth. The neutrino and its antimatter cousin, the antineutrino, are nearly massless, electrically neutral subatomic particles that rarely interact with matter. Antineutrinos come in three different "flavors": electron, muon and tau. Antineutrinos oscillate between three different flavor states as they travel, meaning that an electron antineutrino emitted from a reactor may be observed as a tau or muon antineutrino later in time. The reactor antineutrino flux map (bottom left) shows the 3 MeV portion of the energy spectrum, revealing the oscillatory nature of these mysterious particles.

GEOPHYSICAL
ANTINEUTRINOS

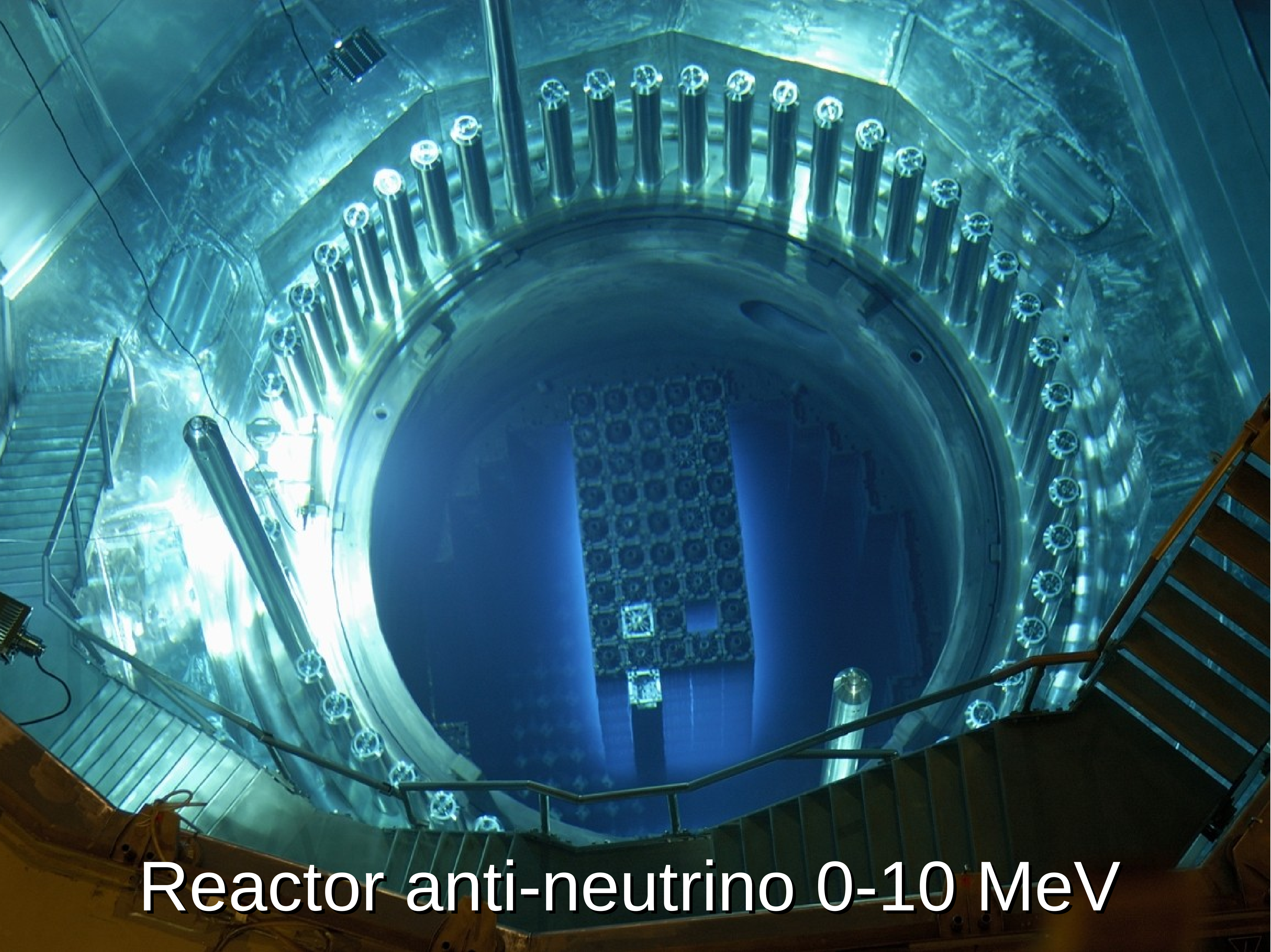
More than 99% of all terrestrial antineutrinos are emitted from the natural radioactive decay of U, Th, and K within the Earth, with the remainder coming from nuclear reactors. Geo-neutrino observations of U and Th allow scientists to measure the nuclear power inside the Earth, leading to a better understanding of the thermal processes that drive plate tectonics, mantle convection, and the geodynamo. Antineutrinos emanating from K decay dominate the flux coming from Earth (~72% for the total) but due to their low energy they are not currently detectable. Future antineutrino detectors are being conceptualized in order to measure K antineutrinos flux (bottom right).



SN 1987A

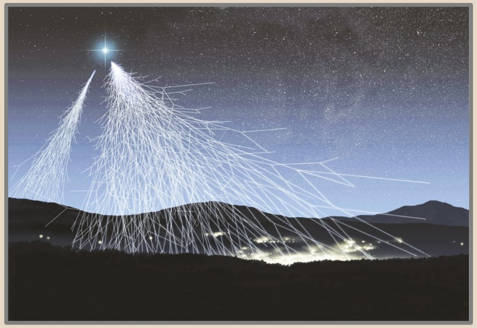
Supernova neutrino
1-40 MeV

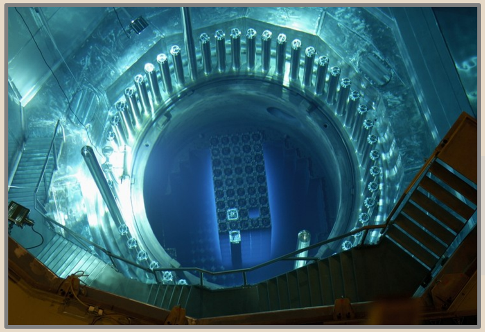
Atmospheric neutrino 0.1 – 1000 GeV

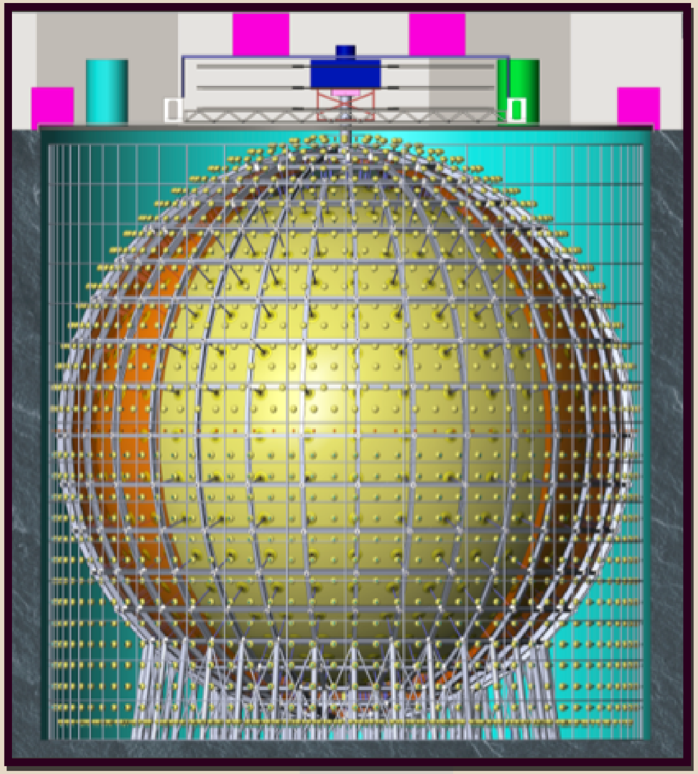


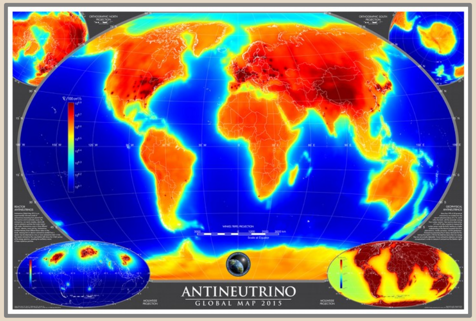
Reactor anti-neutrino 0-10 MeV

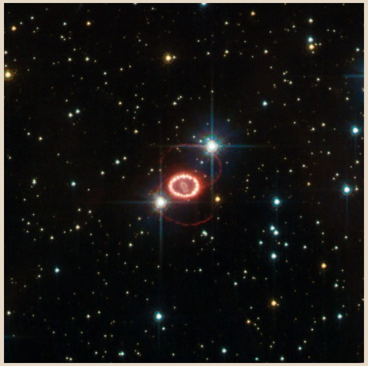
JUNO: multi-purpose experiment











Main purpose:

Neutrino Mass Hierarchy determination

Neutrino Mass Hierarchy determination

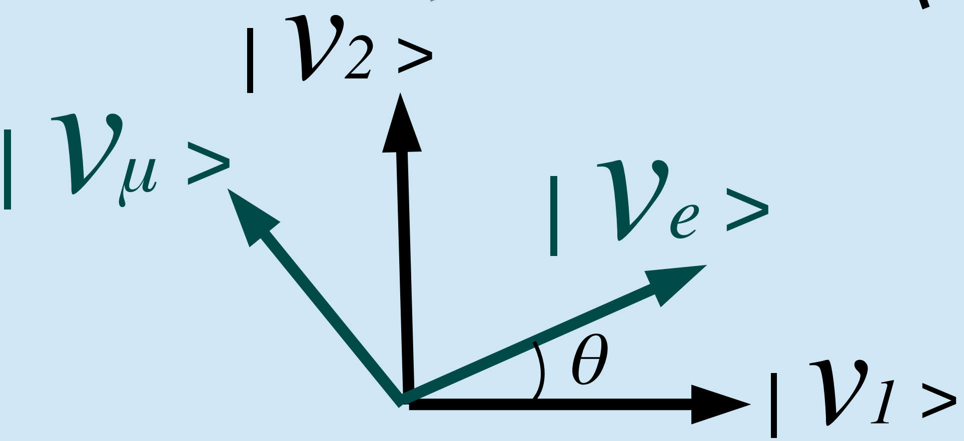
$|\nu_e>$
$|\nu_\mu>$ **Flavor eigenstates**
$|\nu_\tau>$

$|\nu_1>$ m_1
$|\nu_2>$ m_2 **Mass eigenstates**
$|\nu_3>$ m_3

2 flavor case:

$$\begin{pmatrix} |\nu_e> \\ |\nu_\mu> \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |\nu_1> \\ |\nu_2> \end{pmatrix}$$

V_{ij}



In 3 flavor case:
$\theta_1, \theta_2, \theta_3$

Neutrino Mass Hierarchy determination

Absolute masses m_1, m_2, m_3 are unknown.

The oscillation probability

$$P = |\langle\nu_i|\nu_j\rangle|^2$$

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

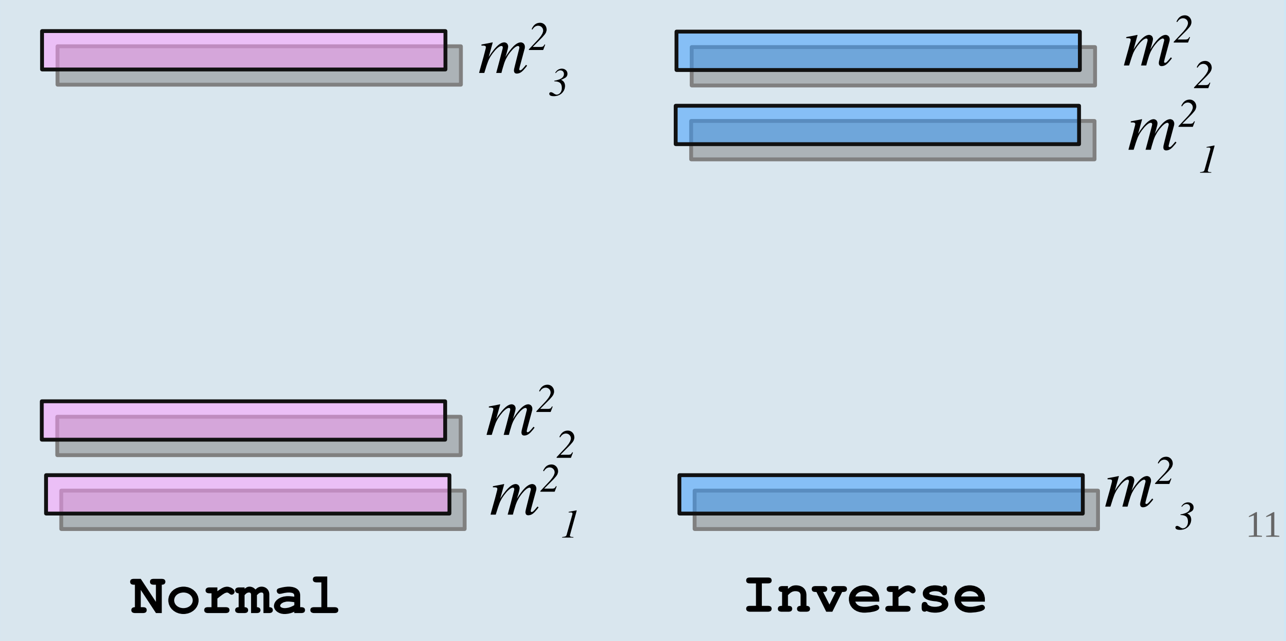
does not depend on the absolute value of masses, but on:

$$\Delta m^2_{ij} = m_i^2 - m_j^2$$

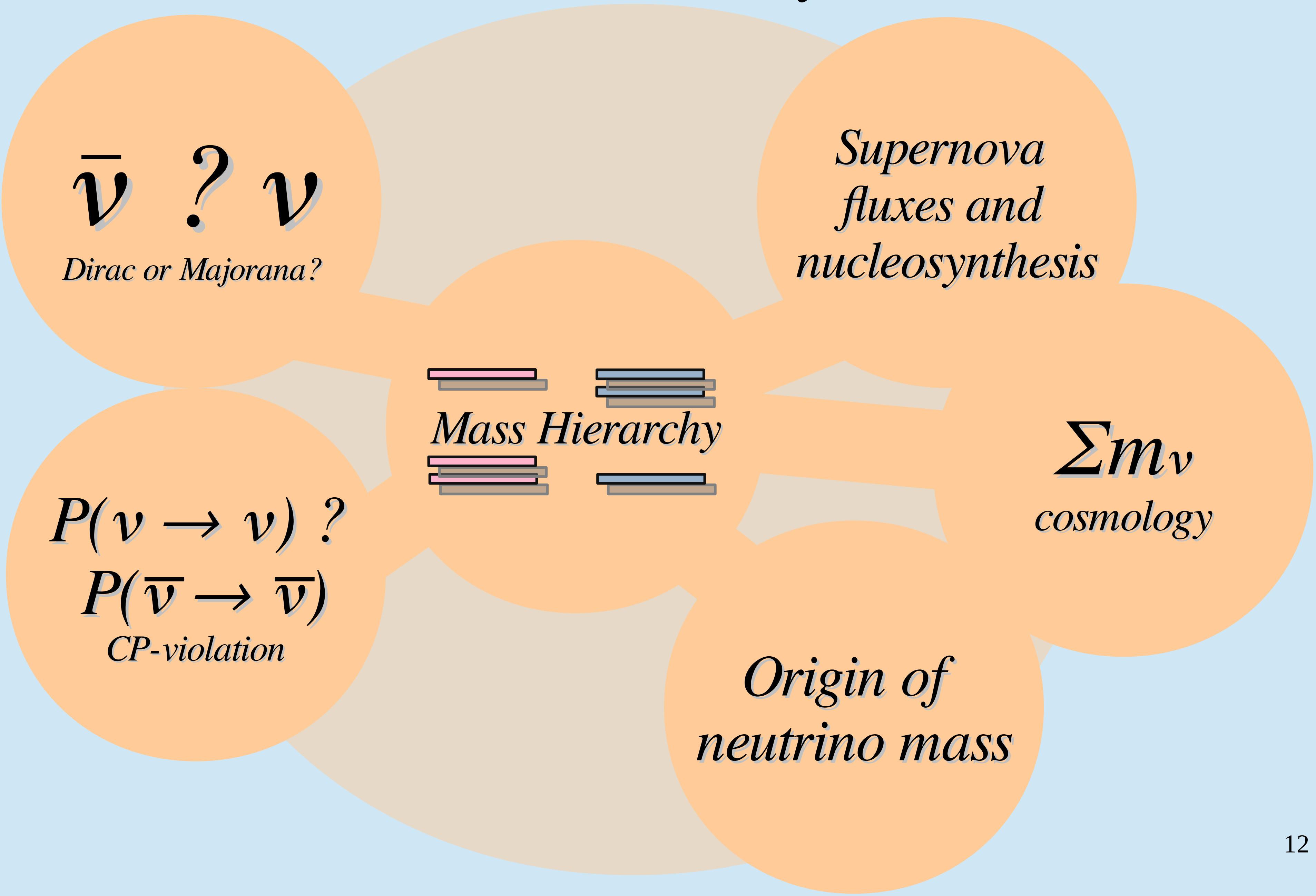
$$\Delta m^2_{21} > 0$$

$$|\Delta m^2_{31}|$$

$$|\Delta m^2_{32}|$$



Neutrino Mass Hierarchy determination



$\bar{\nu}$? ν

Dirac or Majorana?

Supernova fluxes and nucleosynthesis

Mass Hierarchy

Σm_ν

cosmology

$P(\nu \rightarrow \nu)$?

$P(\bar{\nu} \rightarrow \bar{\nu})$

CP-violation

Origin of neutrino mass

JUNO experiment

Ultra pure liquid
scintillator: 20 Ktons

Photomultipliers:
17000 (20 inches)
34000 (3 inches)

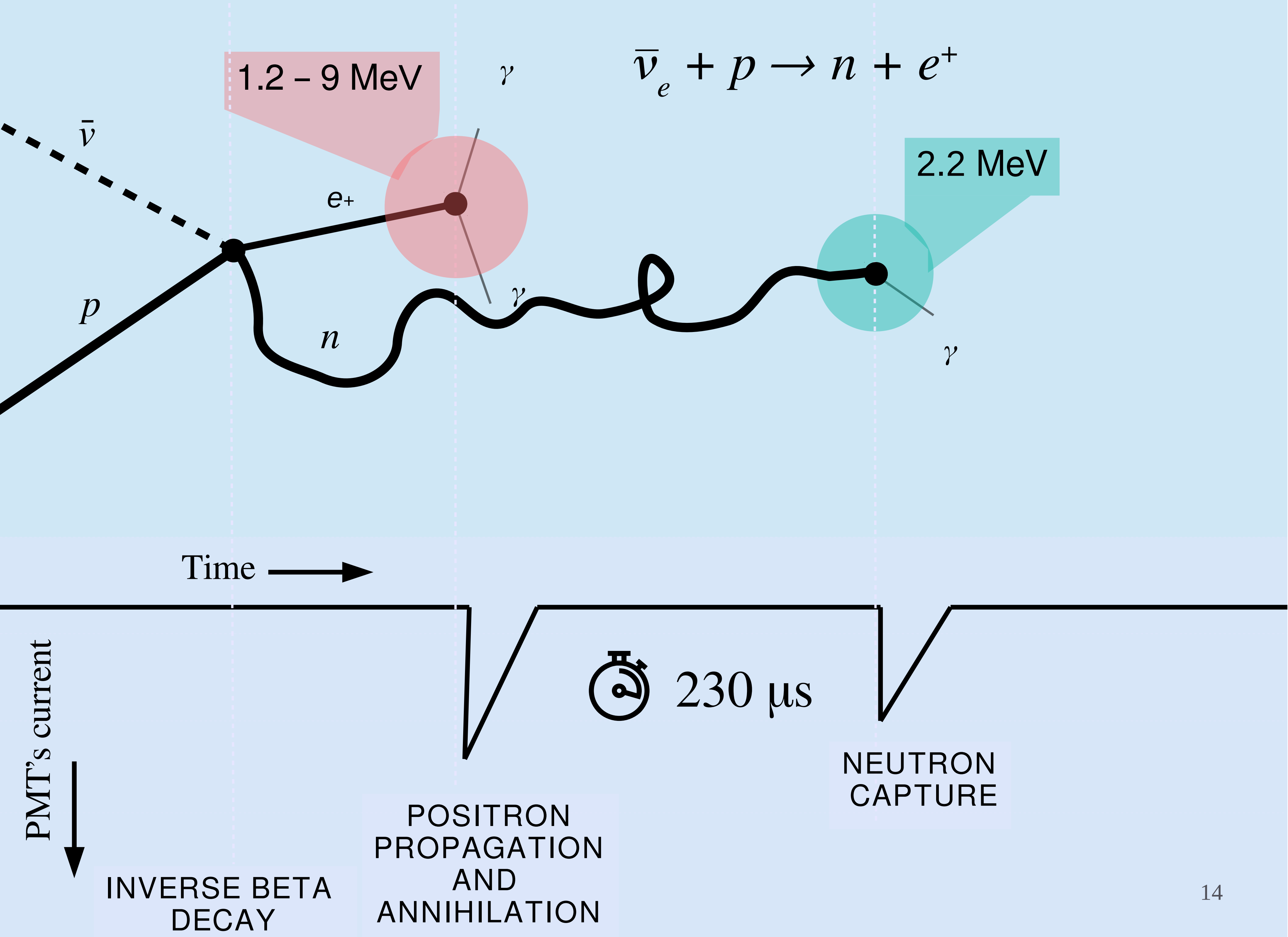
700 m underground

Water Cherenkov pool

53 km from two multi-core
nuclear power plants

Start
in 2020

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



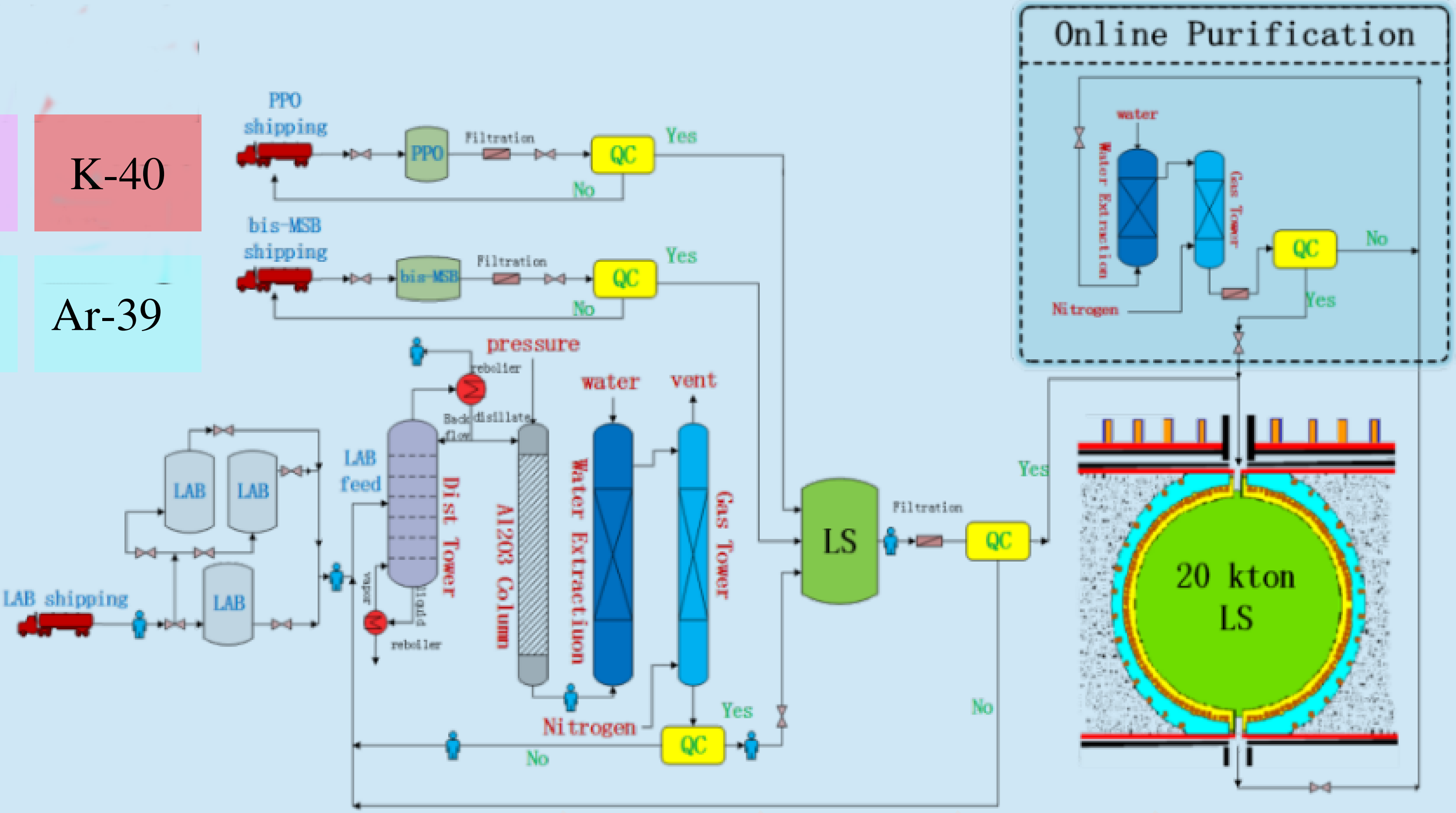
INVERSE BETA DECAY

POSITRON PROPAGATION AND ANNIHILATION

NEUTRON CAPTURE

PURIFICATION

Th-232	U-238	K-40
Rn-222	Kr-85	Ar-39
Pb-210		



Distillation

Al_2O_3 column

Water extraction

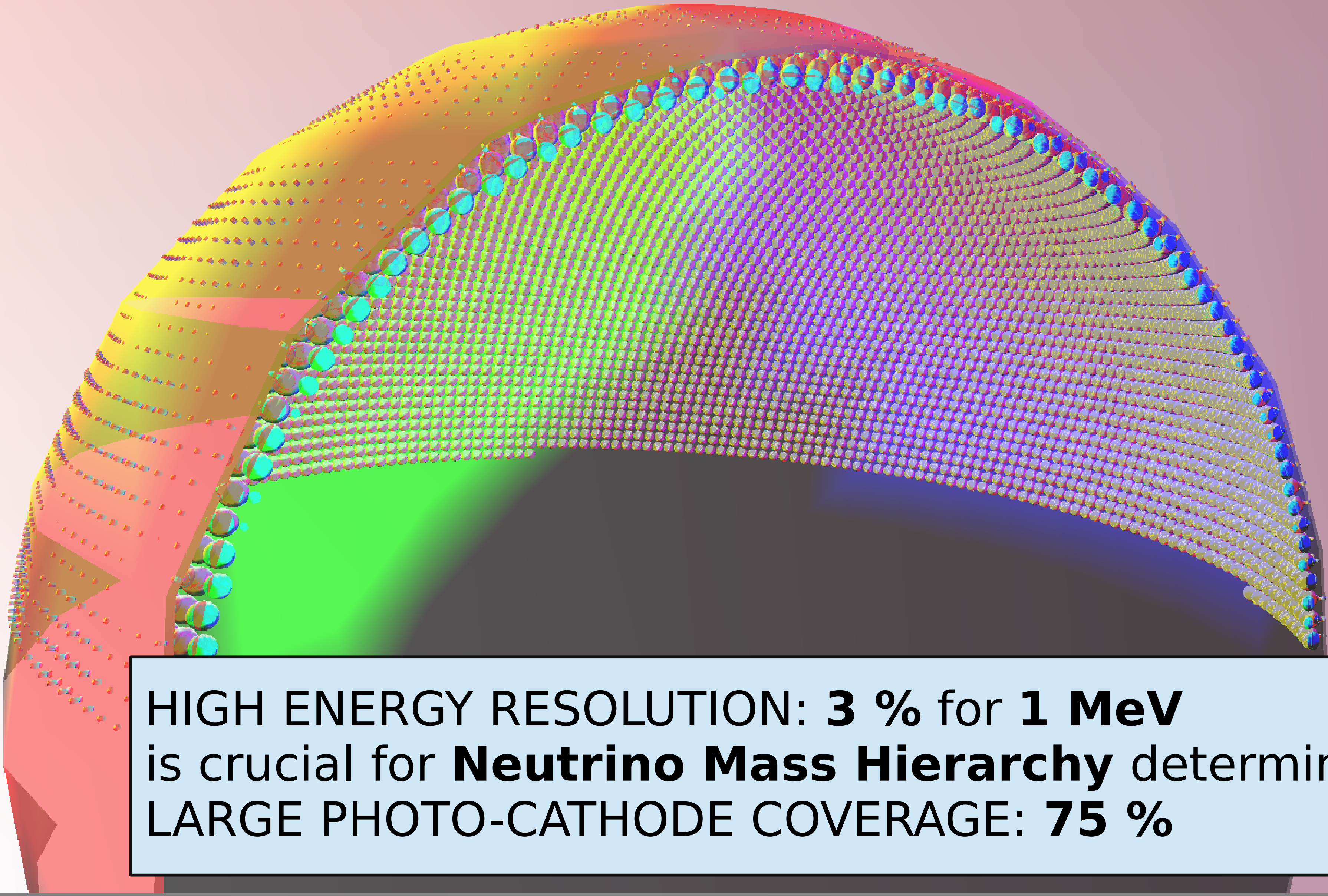
Nitrogen pumping

Filtration

Radioactive purity

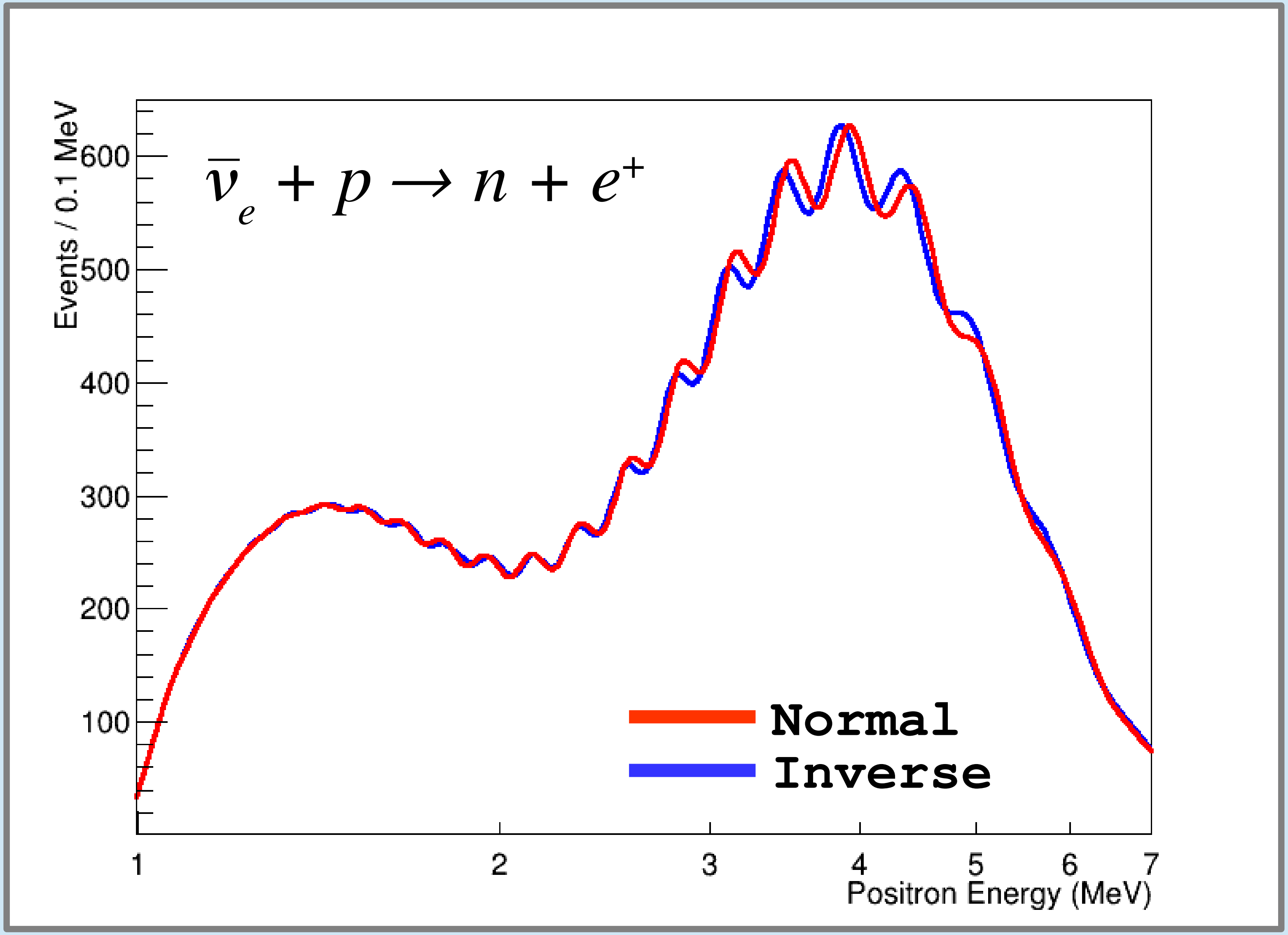
High optical transparency

ENERGY RESOLUTION



HIGH ENERGY RESOLUTION: **3 %** for **1 MeV**
is crucial for **Neutrino Mass Hierarchy** determination
LARGE PHOTO-CATHODE COVERAGE: **75 %**

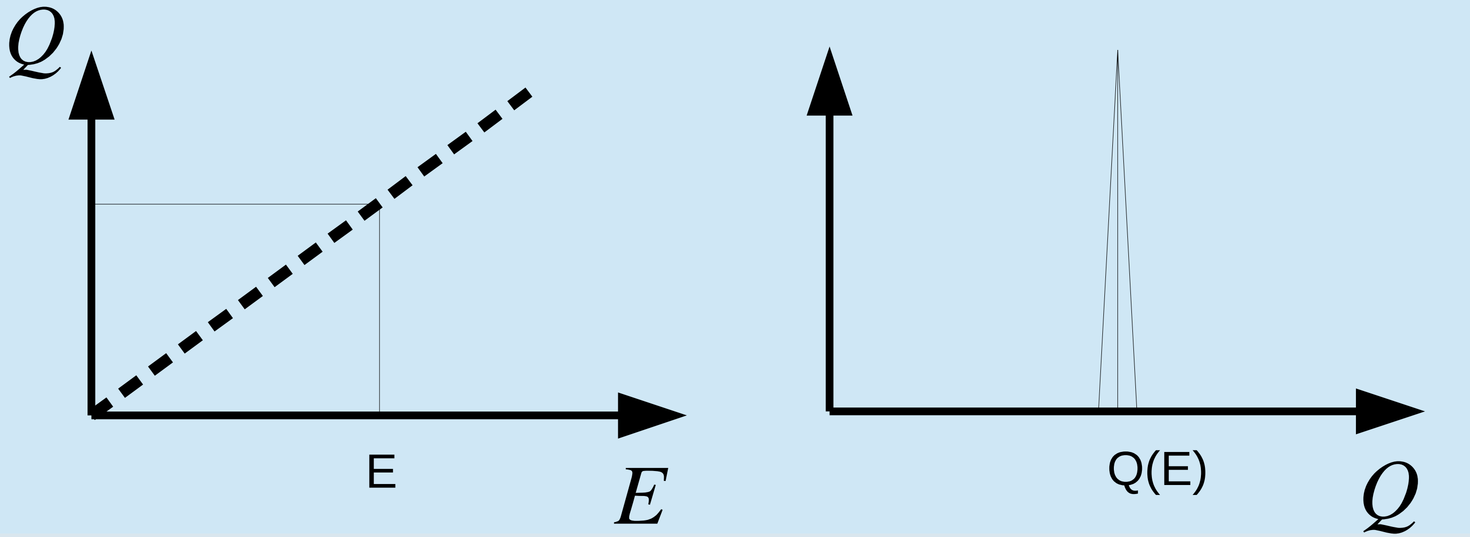
Neutrino Mass Hierarchy determination



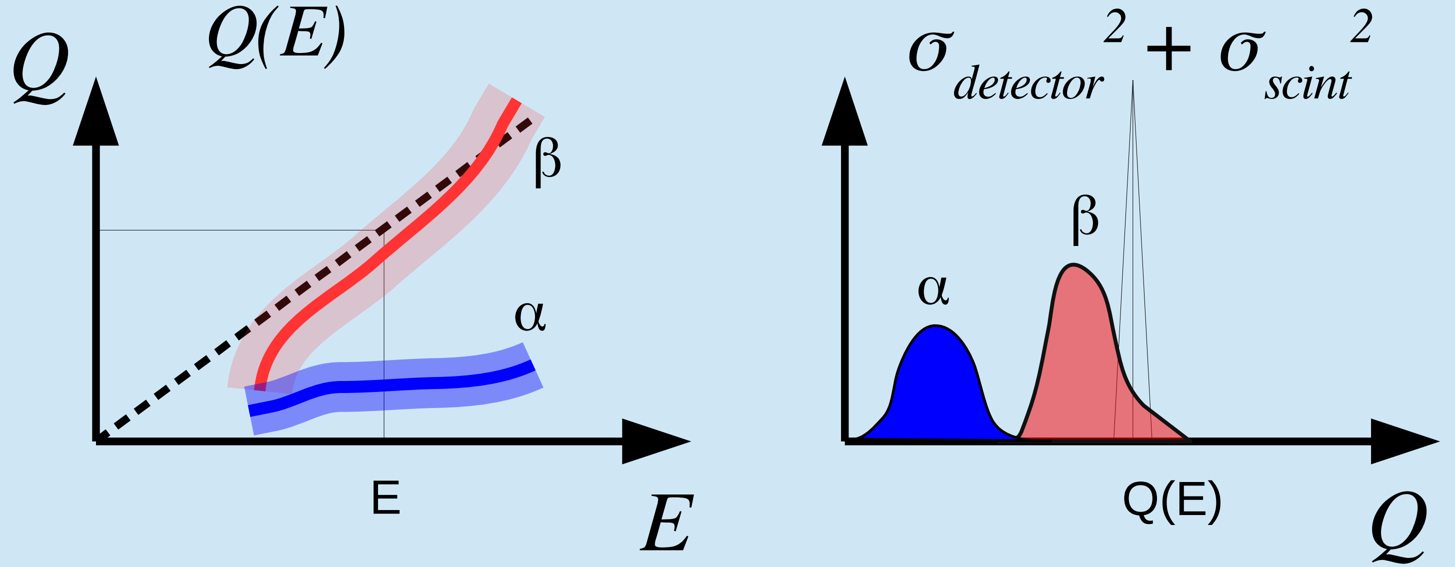
Positron spectrum: 3% energy resolution

SMEARING and SHIFT are DANGEROUS!

Consider our detector is ideal...



Real detector:
non-linearity and energy resolution



Quenching effect

Light yield depends on the type of a particle. The more dE/dX, the less phot.

5 MeV beta: ~50000 photons
5 MeV alpha: ~5000 photons

Light yield is non-linear

Intrinsic degradation of the energy resolution is expected!

Experimental setup

$$E_e = E_\gamma - E'_\gamma$$

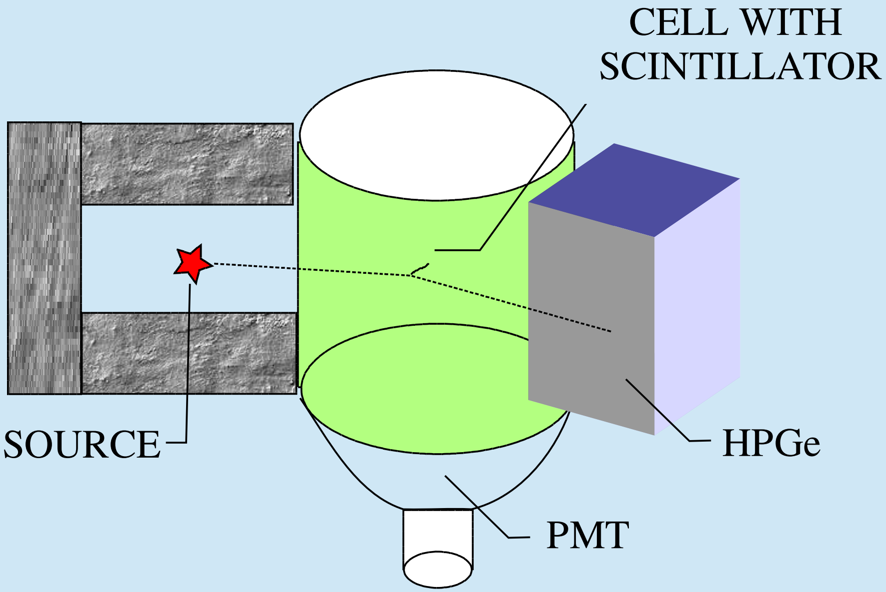
Scintillator

HPGe

$$E_e \text{ vs } Qpmt$$

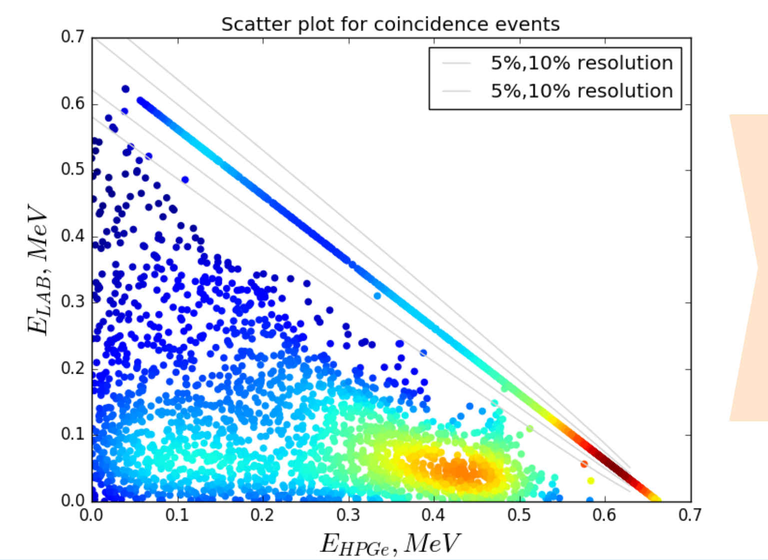
$$\sigma_{setup} \text{ vs } \sigma_{measured}$$

SETUP	JUNO
$Q(E)$	$Q(E)$
$\sigma_{setup}^2 + \sigma_{scint}^2$	$\sigma_{juno}^2 + \sigma_{scint}^2$



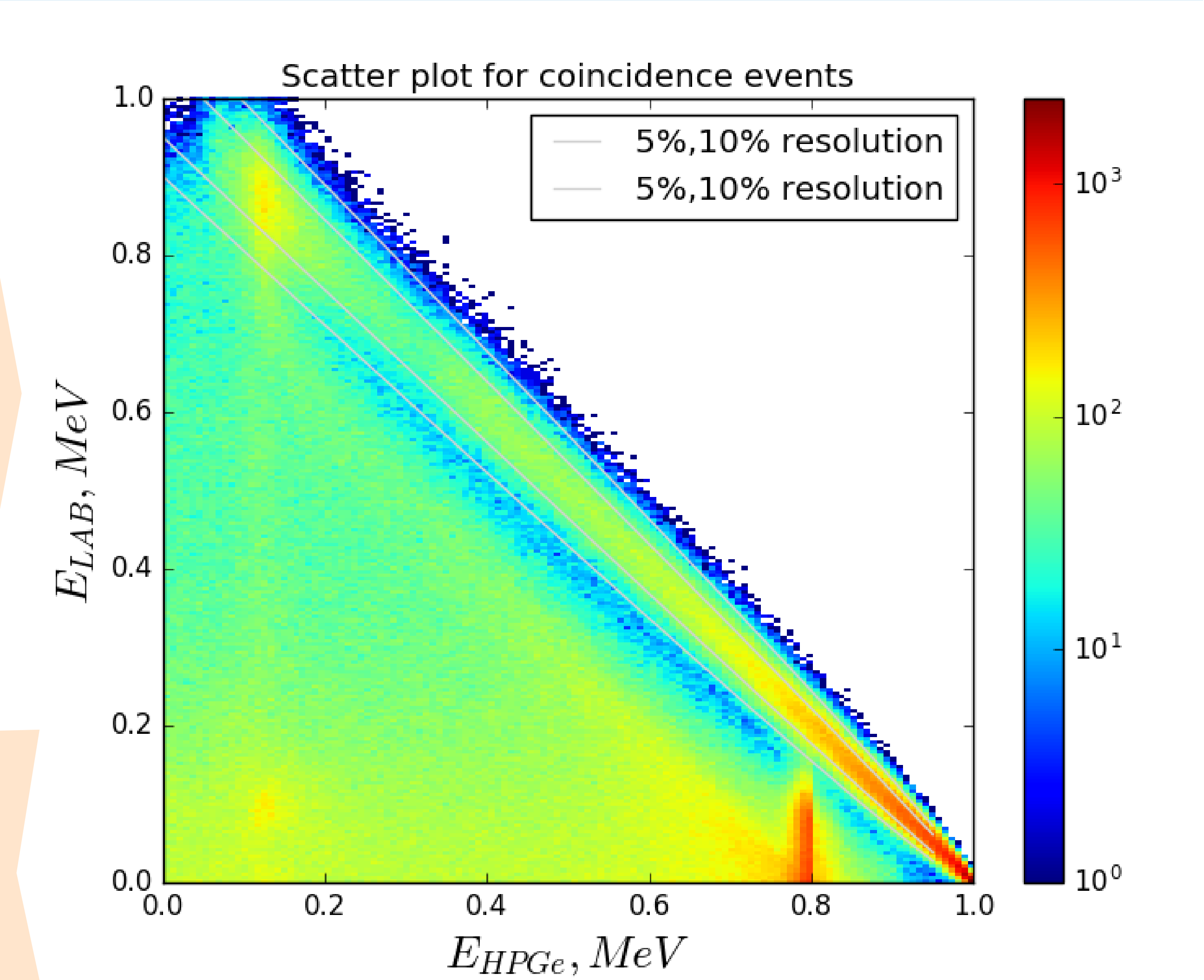
Monte Carlo simulation

Ideal detector



$$Q(E)$$

$$\sigma_{setup}^2 + \sigma_{scint}^2$$



Summary

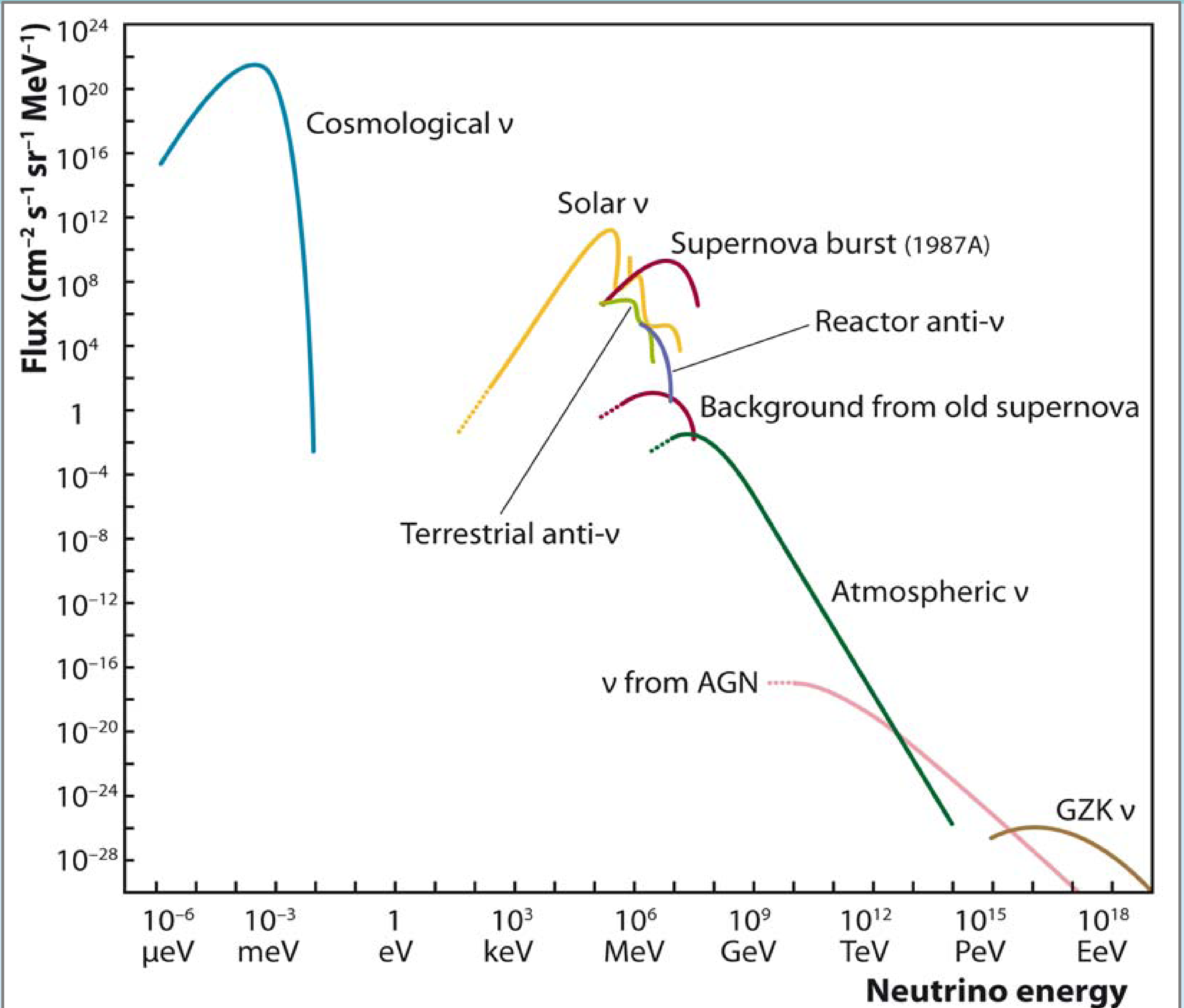
- **JUNO** experiment will have a rich scientific program
- The experiment has technological challenges: **purification, energy resolution** and many others
- Before data-taking, a large amount of research activities should be performed. Non-linear response and energy resolution is necessary to examine in order to determine **Neutrino Mass Hierarchy**

Thank you for your attention!

“So why did we want to detect the free neutrino? Because everybody said, you couldn’t do it”

Clyde Cowan

Backup slides



Some open questions of the neutrino physics

- *Dirac or Majorana*
- *Normal or inverted mass ordering*
- *Mass of the neutrino (MH)*
- *Octant of θ23*
- *CP-violation phase(s) (MH)*
- *Unitarity test, sterile neutrino*
- *and many others...*

Oscillations in case of two generations

$|\nu_e>$

$|\nu_e>$

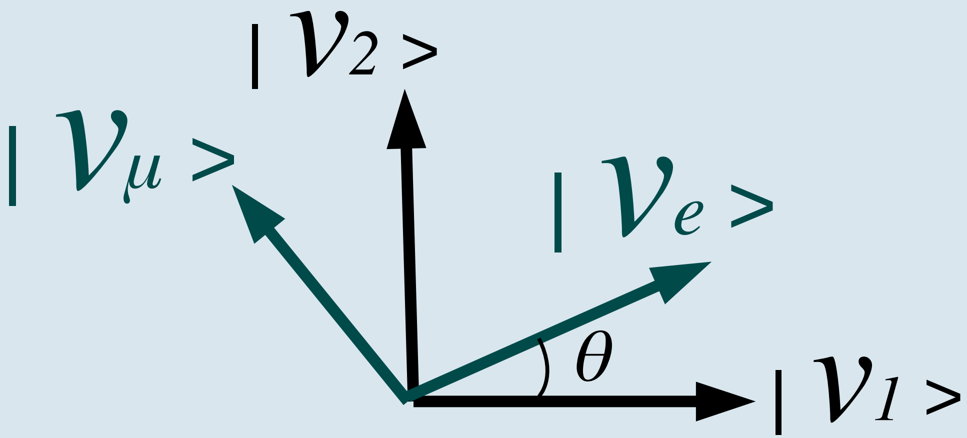
$$A_{ee} = <\nu_e|\nu_e> = 1$$

$$P_{ee} = A_{ee}^2 = 1$$

$$flux \sim 1/r^2$$

Oscillations in case of two generations $\nu_e \leftrightarrow \nu_\mu$

$$\begin{pmatrix} |\nu_e> \\ |\nu_\mu> \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |\nu_1> \\ |\nu_2> \end{pmatrix}$$



Oscillations in case of two generations

$$|\nu_e> = \cos\theta\,|\nu_1> - \sin\theta\,|\nu_2>$$

$$|\nu_e> = \sin\theta\,|\nu_1> + \cos\theta\,|\nu_2>$$

$$A_{ee} = <\nu_e|\,\nu_e> \neq 1 \quad flux \propto 1/r^2$$

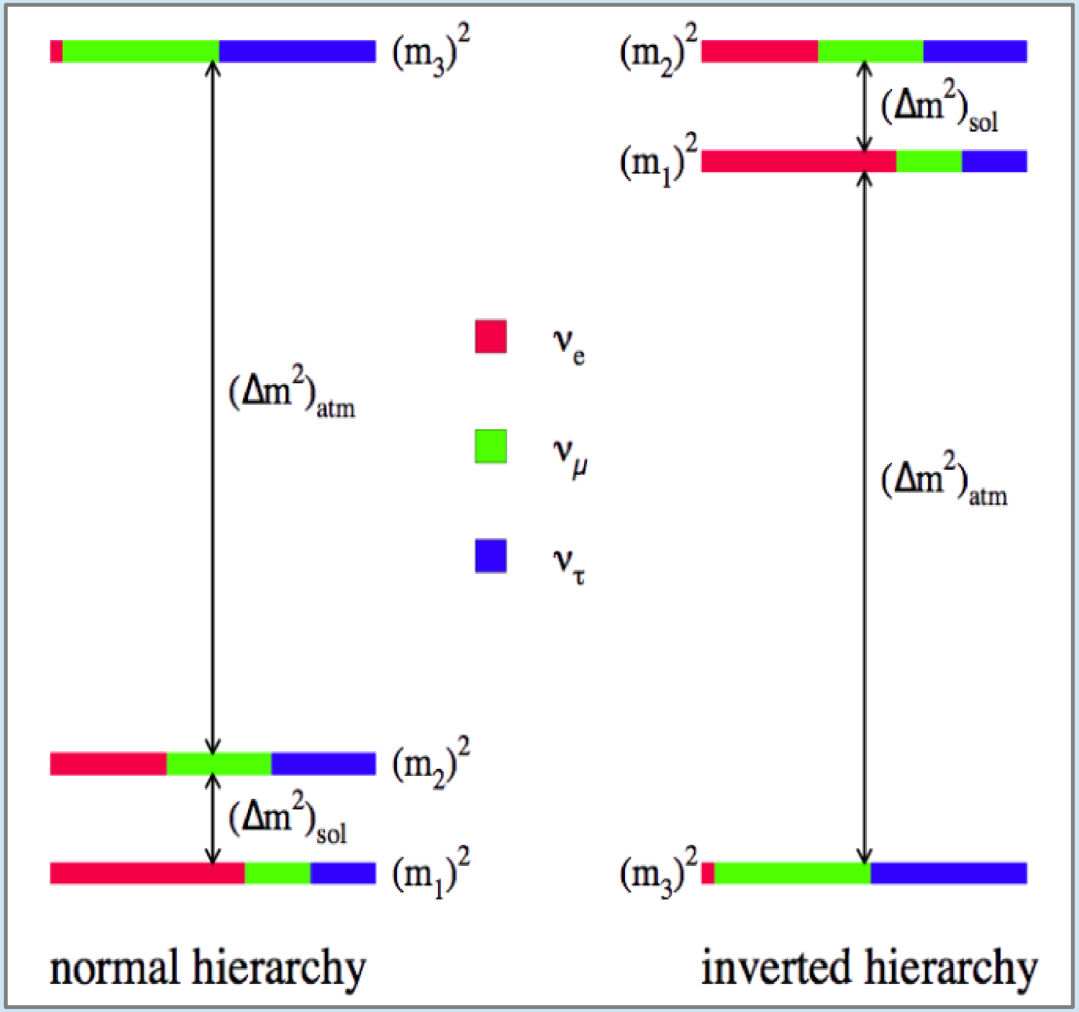
$$P(\nu_e \to \nu_e) = 1 - \frac{1}{2}\sin^2 2\theta\ (1 - \cos\frac{\Delta m^2 L}{2E}) ,$$

Theory and experiment

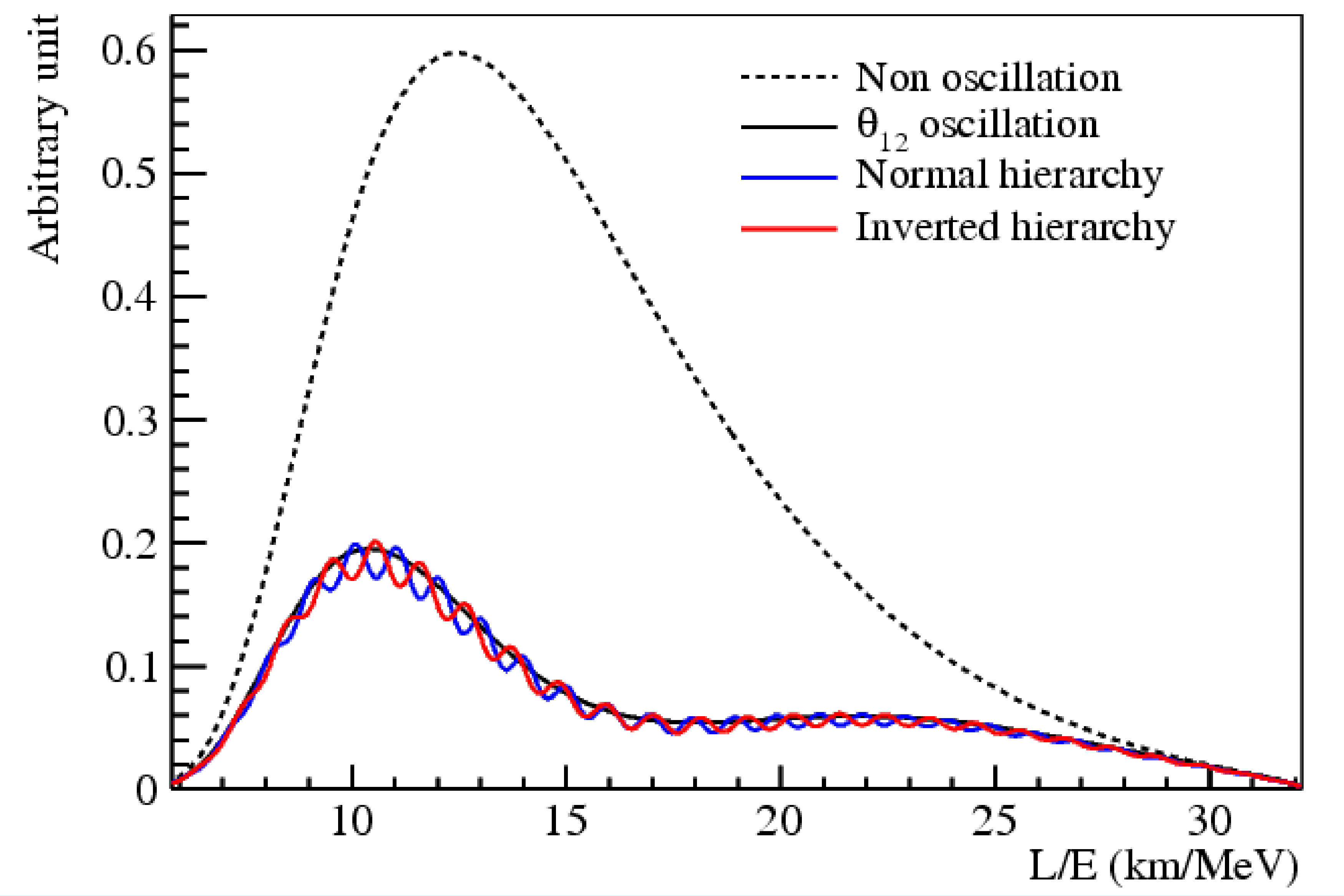
$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} P$$

$$P = \mathrm{diag}\{1, e^{i\alpha_{21}/2}, e^{i\alpha_{31}/2}\}$$

$$\Delta m^2_{21} \quad |\Delta m^2_{32}| \, |\Delta m^2_{31}|$$



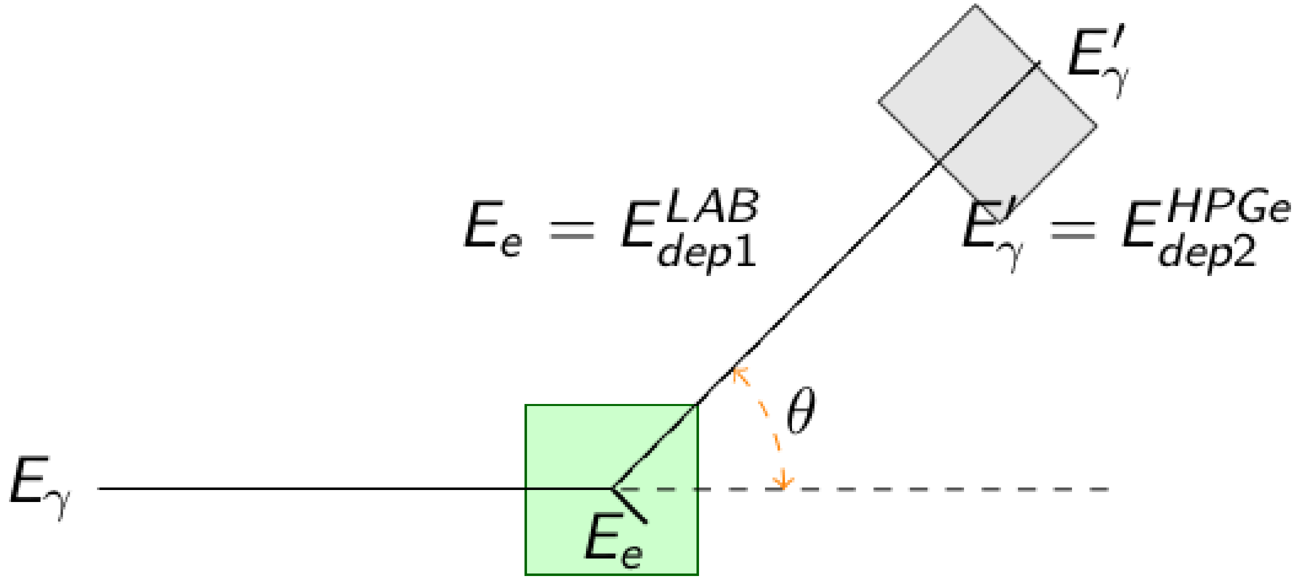
Backup slides

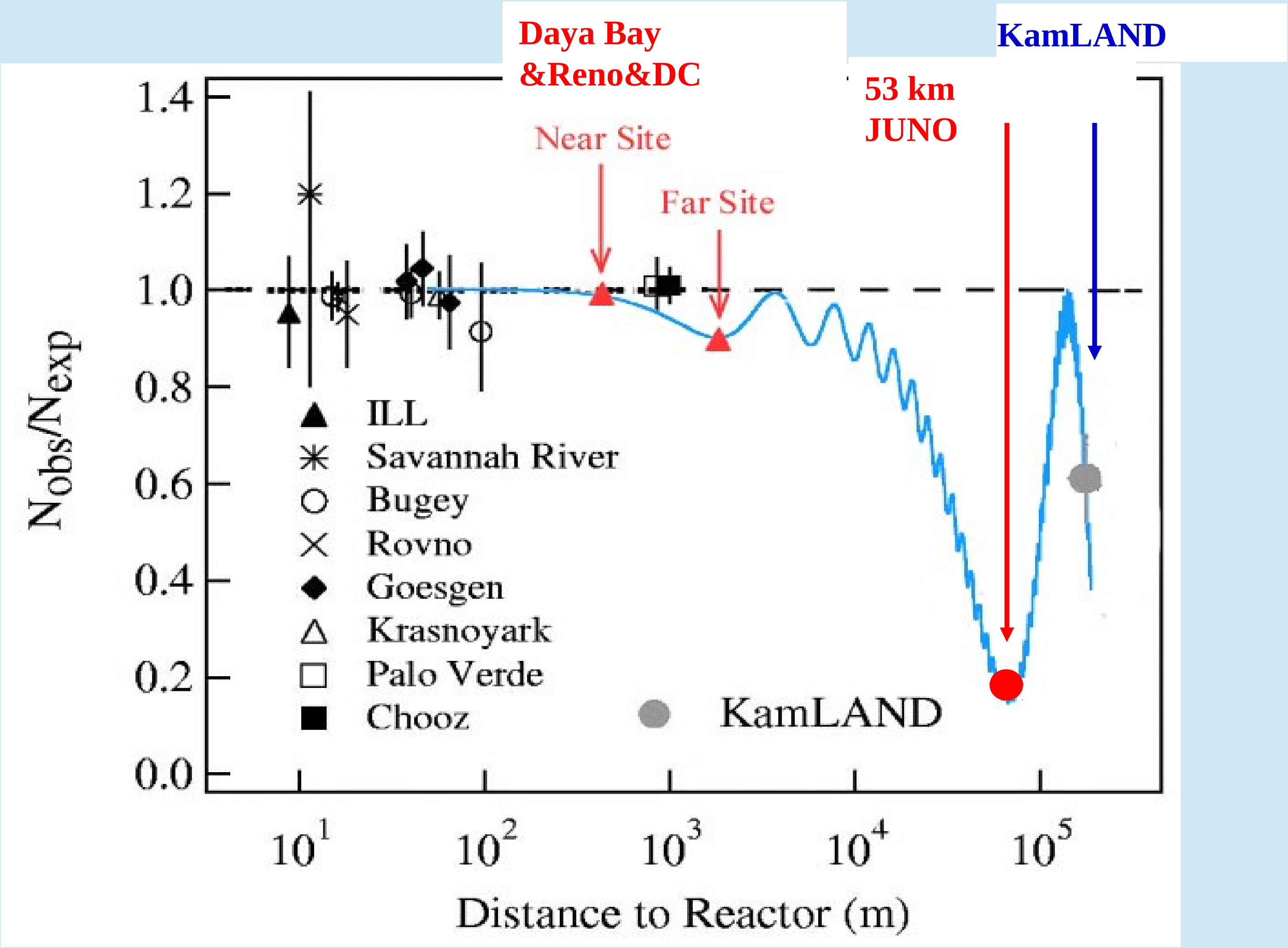


Compton coincidence technique

There is a possibility to measure directly $f(E)$, verify Birk's model and find kB parameter by **Compton coincidence technique** (CC). We will try to measure $f(E)$, using CC-technique with HPGe as a detector of scattered gamma (1%).

$$E'_\gamma = \frac{E_\gamma}{1+\frac{E_\gamma}{m_e}(1-cos\theta)} \qquad E_e = E_\gamma - E'_\gamma = \frac{\frac{E_\gamma^2}{m_e}(1-cos\theta)}{1+\frac{E_\gamma}{m_e}(1-cos\theta)}$$



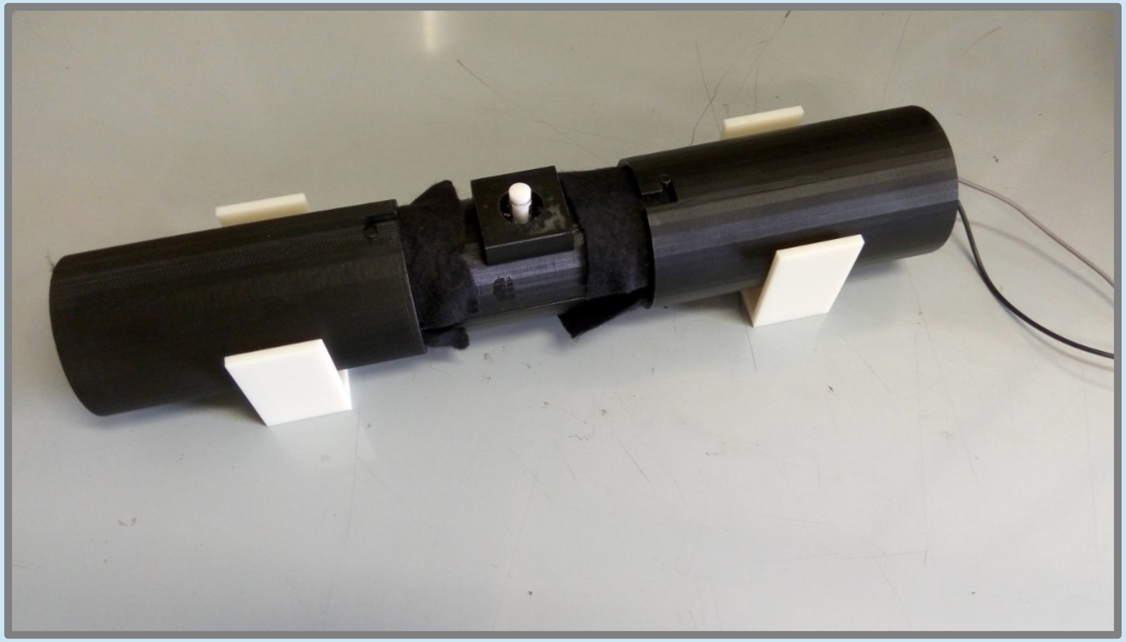


Daya Bay
&Reno&DC

53 km
JUNO

KamLAND

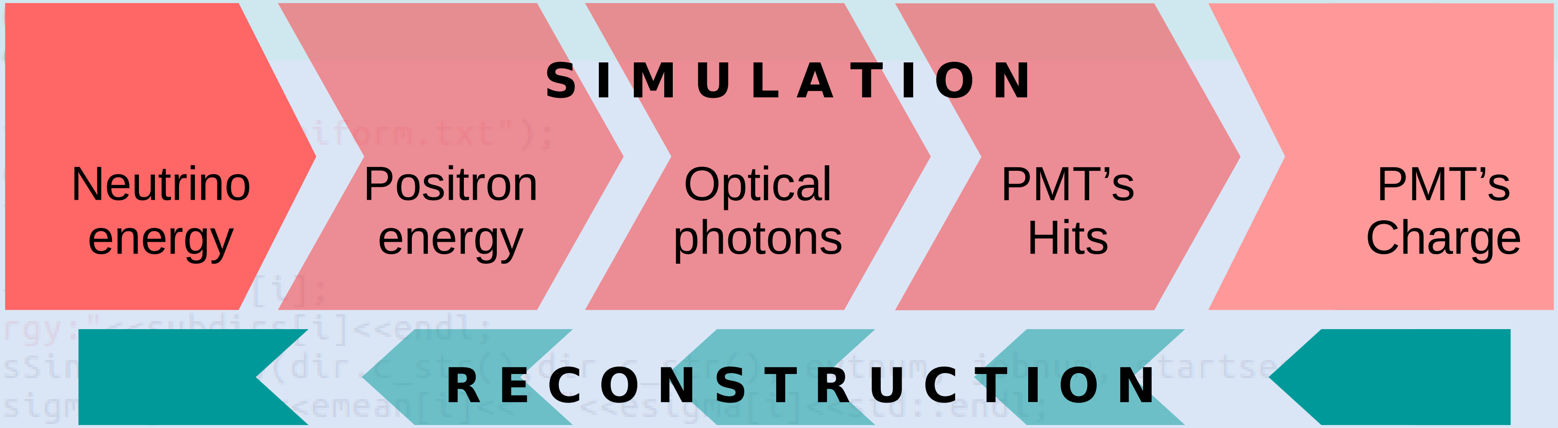
Experimental setup



Strategy

- **Analysis of all published measurements**
- **Performance of the experiment; Monte Carlo simulations.**
- **The development of a phenomenological model.**
- **Simulation and analysis of the JUNO experiment**

SOFTWARE



SIMULATION

Neutrino energy

Positron energy

Optical photons

PMT’s Hits

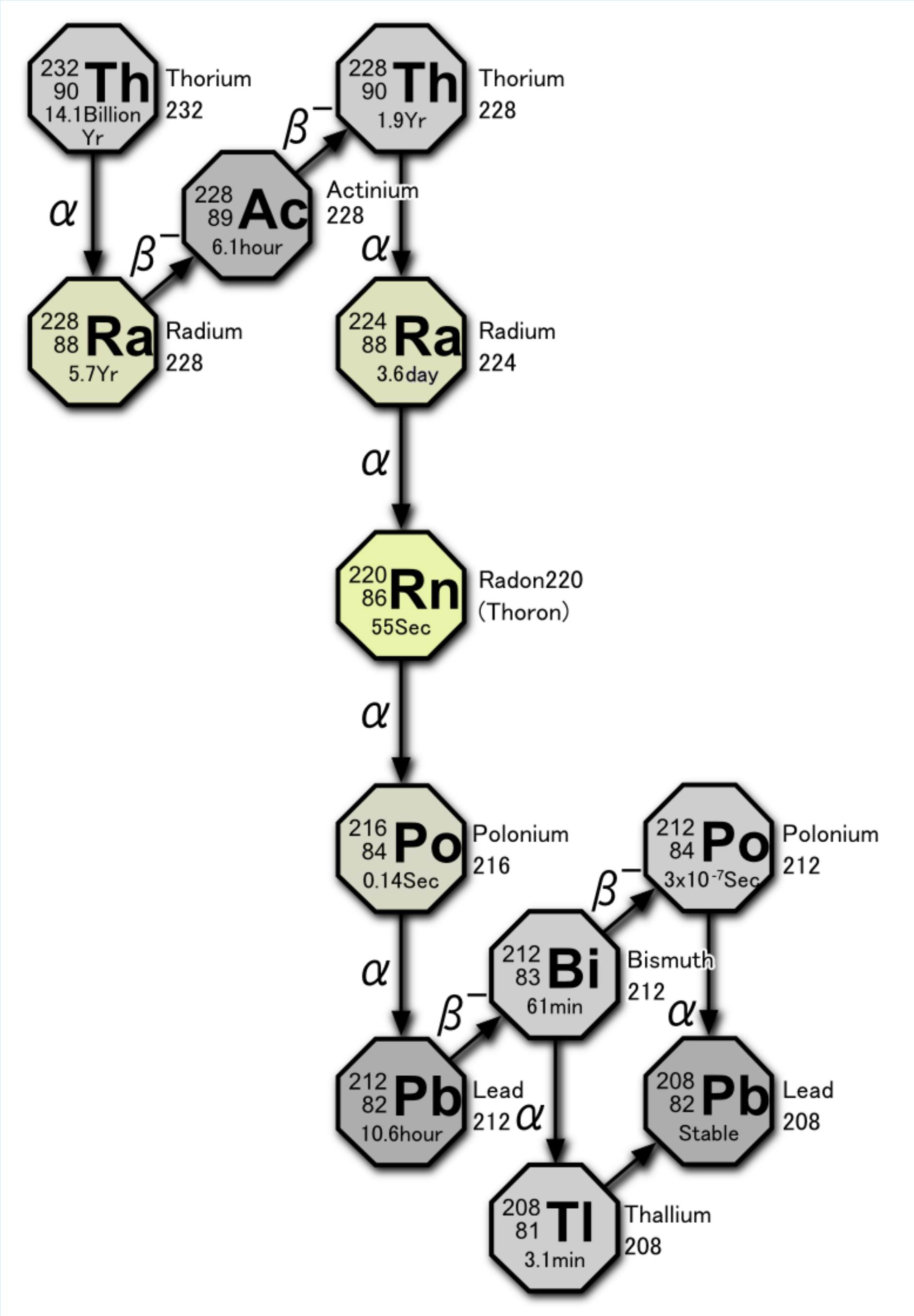
PMT’s Charge

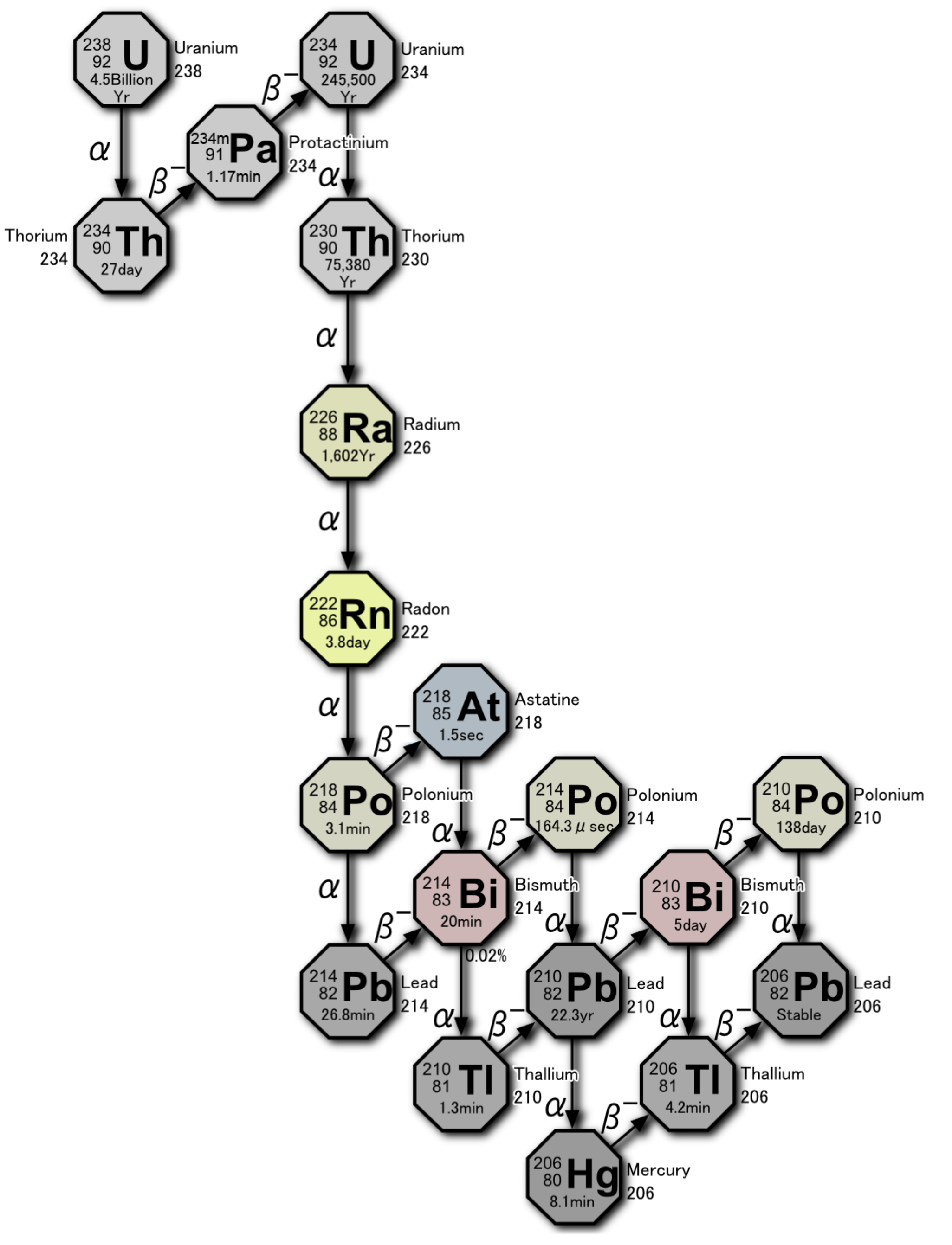
RECONSTRUCTION

“SniPER” is a new framework for large scale neutrino experiments

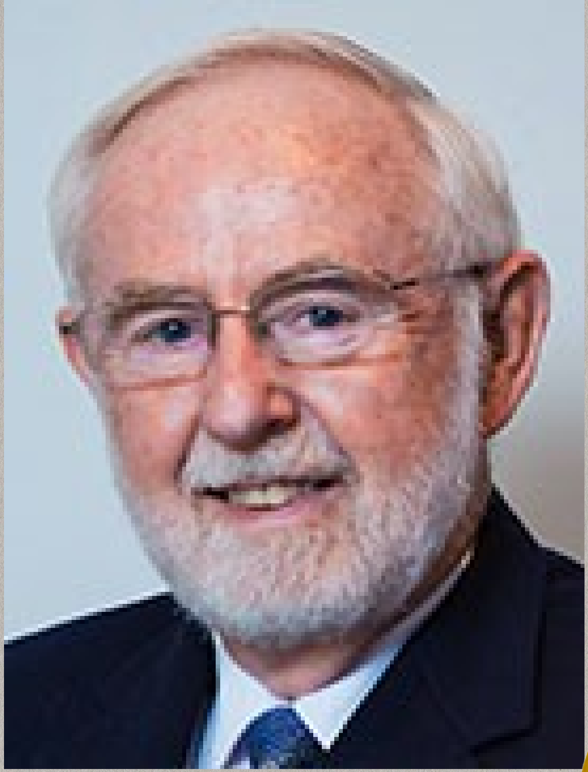
Algorithms, data structures and MC-generators are controlled by a single script

One instrument – for more then 60 collaborators!


232 90 Th 14.1Billion Yr
Thorium 232
α
228 88 Ra 5.7Yr
Radium 228
β⁻
228 89 Ac 6.1hour
Actinium 228
β⁻
228 90 Th 1.9Yr
Thorium 228
α
224 88 Ra 3.6day
Radium 224
α
220 86 Rn 55Sec
Radon220 (Thoron)
α
216 84 Po 0.14Sec
Polonium 216
α
212 82 Pb 10.6hour
Lead 212
β⁻
212 83 Bi 61min
Bismuth 212
β⁻
212 84 Po 3x10⁻⁷Sec
Polonium 212
α
α
208 81 Tl 3.1min
Thallium 208
208 82 Pb Stable
Lead 208


238 92 U 4.5Billion Yr
Uranium 238
α
234 90 Th 27day
Thorium 234
β⁻
234m 91 Pa 1.17min
Protactinium 234
β⁻
234 92 U 245,500 Yr
Uranium 234
α
230 90 Th 75,380 Yr
Thorium 230
α
226 88 Ra 1,602Yr
Radium 226
α
222 86 Rn 3.8day
Radon 222
α
218 84 Po 3.1min
Polonium 218
β⁻
218 85 At 1.5sec
Astatine 218
α
α
214 82 Pb 26.8min
Lead 214
β⁻
214 83 Bi 20min
Bismuth 214
0.02%
β⁻
214 84 Po 164.3 μ sec
Polonium 214
α
α
210 81 Tl 1.3min
Thallium 210
β⁻
210 82 Pb 22.3yr
Lead 210
α
206 80 Hg 8.1min
Mercury 206
β⁻
210 83 Bi 5day
Bismuth 210
β⁻
210 84 Po 138day
Polonium 210
α
α
206 81 Tl 4.2min
Thallium 206
β⁻
206 82 Pb Stable
Lead 206

Super-Kamiokande and SNO

TAKAAKU KAJITA
ARTHUR B. MCDONALD

2015

SNO experiment