Neutrino Directionality measurement with the Double Chooz experiment

Applied Antineutrino Physics 2014 - Paris

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CEA/IRFU/SPP

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Outline

Motivations

- Neutrino directionality consists of retrieving the direction of a neutrino flux.
- Locating supernovas especially if non-visible optically.
- Studying geo-neutrinos from the Earth's crust and mantle.
- Detecting and monitoring nuclear reactors.

Antineutrino sources

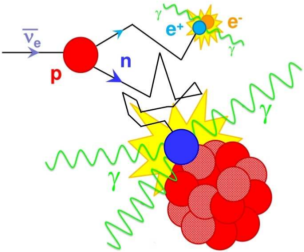
Natural sources

- Core-collapse supernovas:
  - Core collapse of massive stars ($M > 8M_{\odot}$)
  - 99 % of energy emitted as neutrinos (6 flavors) in a 10 s time window $\rightarrow \sim 10^{58}$ neutrinos
- Geo-neutrinos:
  - U and Th chains elements in Earth's crust and mantle
  - Detected by KamLAND and Borexino
  - Provide insight of Earth radiogenic heat and crust/mantle composition

Artificial sources

- Nuclear reactors:
  - Emit $\bar{\nu_e}$ via β-decay of fission products
  - Powerful source of $\bar{\nu_e} \rightarrow \sim\ 10^{20}$ s^{-1}.GW^{-1}

The Inverse Beta Decay process



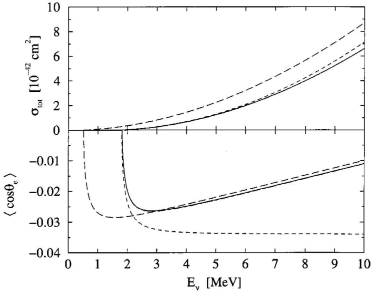
- Inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$
- Higher cross section than other ν interactions $\sigma_{IBD} \sim 10^{-43}$cm^2
- Signature $\rightarrow$ Prompt signal (e^+ energy deposition) followed by delayed signal (neutron capture on Gd or H at 8 or 2.2 MeV).
- Look for: Energy signature ([0.3-20] MeV for prompt, $\sim$8 MeV or 2.2 MeV for delayed), time and space coincidence $\rightarrow$ Huge background reduction !

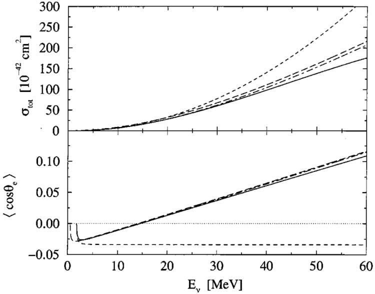
Directionality with IBD

Positron

- Positron energy: $E_e = E_\nu - (M_n - M_p) + \sigma(E_\nu, \cos\theta)$
- Emission angle: $\frac{d\sigma}{d\cos\theta} \sim 1 + V_e a(E_\nu)\cos\theta$
- At low energies $\rightarrow$ Backward emission
- $\rightarrow \bar{\nu_e}$ interaction $\simeq$ Prompt event

From Vogel&Beacom, PRD, VOLUME 60, 053003



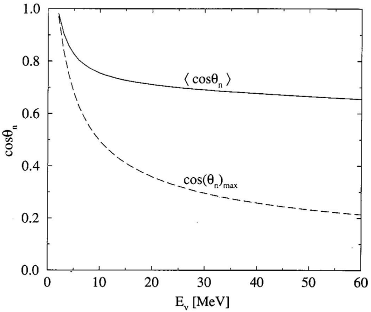


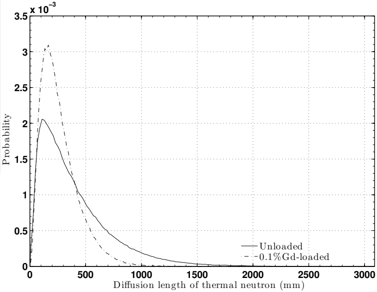
Directionality with IBD

Neutron

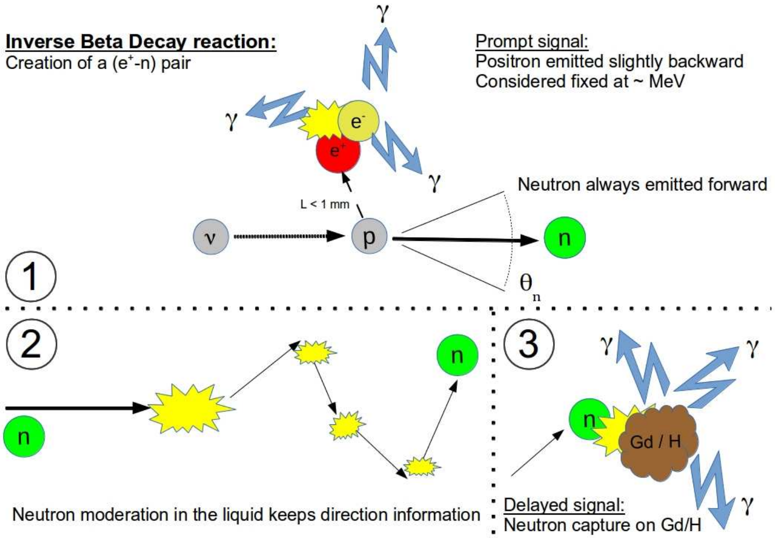
- Neutron kinetic energy:
  $T_n \simeq \frac{E_\nu E_e}{M_n - M_p}\left(1 - V_e \cos\theta\right)$
- Emission angle:
  $\cos\theta_{n,max} = \frac{\sqrt{2E_\nu\Delta - (\Delta^2 - m_e^2)}}{E_\nu}$
- Forward emission but energy-dependant spread
- Moderation + Diffusion + Capture → Delayed event
- Neutron diffusion smears directional information → Statistical-only behavior

From Vogel&Beacom, PRD, VOLUME 60, 053003





Directionality with IBD



Outline

The Double Chooz collaboration

BRAZIL
CBPF
UNICAMP
UFABC

FRANCE
APC
CEA/DSM/IRFU:
SPP, SPhN, SEDI,
SIS, SENAC.
CNRS/IN2P3:
Subatech, IPHC.

GERMANY
EKU Tübingen
MPIK Heidelberg
RWTH Aachen
TU München
U. Hamburg

JAPAN
Tohoku U.
Tokyo Inst. Tech.
Tokyo Metro. U.
Niigata U.
Kobe U.
Tohoku Gakuin U.
Hiroshima Inst. Tech.

RUSSIA
INR RAS
IPC RAS
RRC Kurchatov

SPAIN
CIEMAT-Madrid

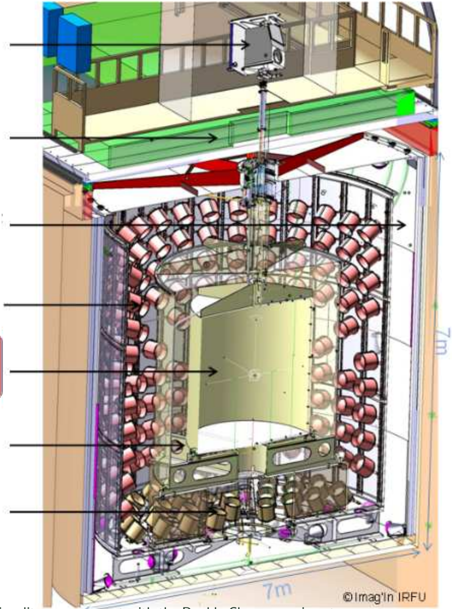
USA
U. Alabama
ANL
U. Chicago
Columbia U.
UC Davis
Drexel U.
U. Hawaii
IIT
KSU
LLNL
MIT
U. Notre Dame
U. Tennessee

150 scientist in 7 countries
spokesman: Hervé de Kerret (CNRS/IN2P3 - APC)
project manager: Christian Veyssière (CEA Saclay)

The experimental site

The detector

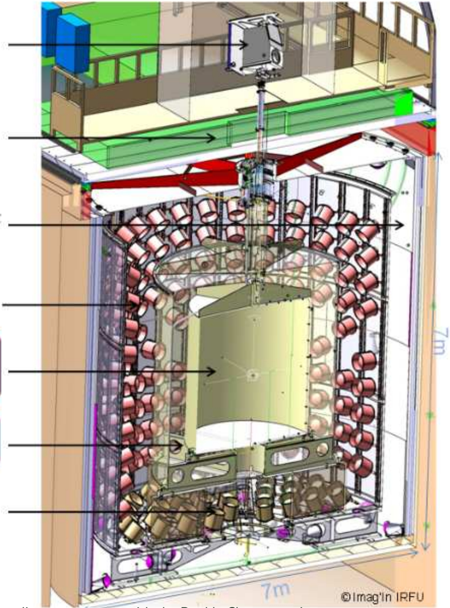
- Target -
10 m³ of scintillating mineral oil doped with Gadolinium



The detector

- Target -
10 m³ of scintillating mineral oil doped with Gadolinium

- Gamma Catcher -
23 m³ of scintillating mineral oil

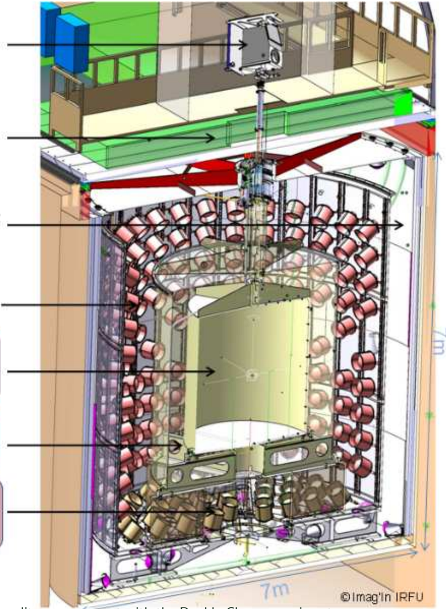


The detector

- Target -
10 m³ of scintillating mineral oil doped with Gadolinium

- Gamma Catcher -
23 m³ of scintillating mineral oil

- Buffer -
110 m³ of non-scintillating mineral oil



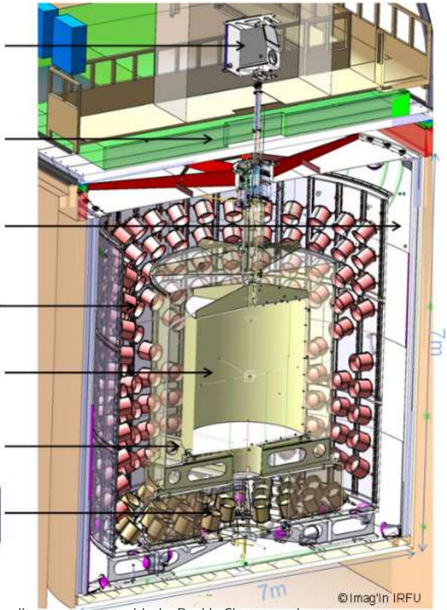
The detector

390 photomultiplier tubes

- Target -
10 m^3 of scintillating mineral oil doped with Gadolinium

- Gamma Catcher -
23 m^3 of scintillating mineral oil

- Buffer -
110 m^3 of non-scintillating mineral oil



The detector

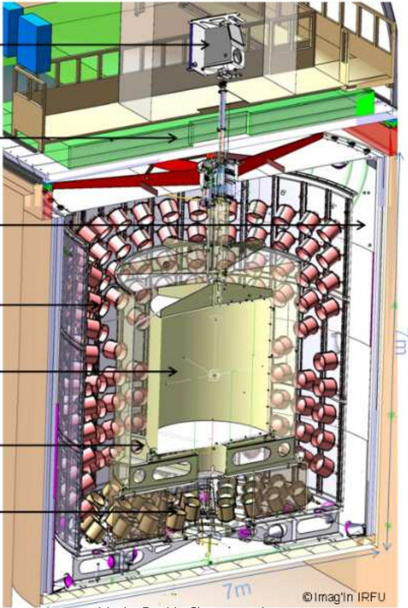
- Inner Veto -
90 m³ of scintillating oil for muon tagging

390 photomultiplier tubes

- Target -
10 m³ of scintillating mineral oil doped with Gadolinium

- Gamma Catcher -
23 m³ of scintillating mineral oil

- Buffer -
110 m³ of non-scintillating mineral oil



The detector

- Outer Veto -
Cover of plastic scintillator strip for muon tagging

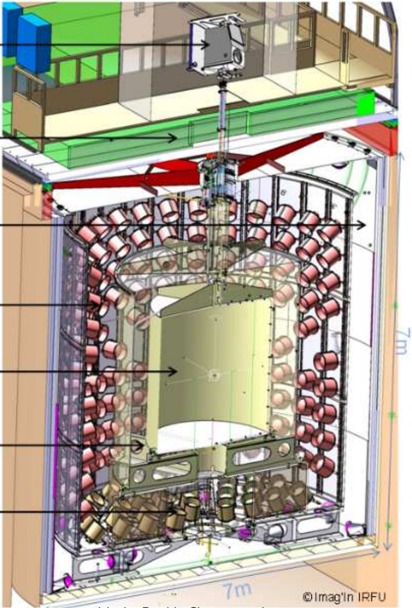
- Inner Veto -
90 m³ of scintillating oil for muon tagging

390 photomultiplier tubes

- Target -
10 m³ of scintillating mineral oil doped with Gadolinium

- Gamma Catcher -
23 m³ of scintillating mineral oil

- Buffer -
110 m³ of non-scintillating mineral oil



The detector

- Glovebox -
For calibration sources deployment

- Outer Veto -
Cover of plastic scintillator strip for muon tagging

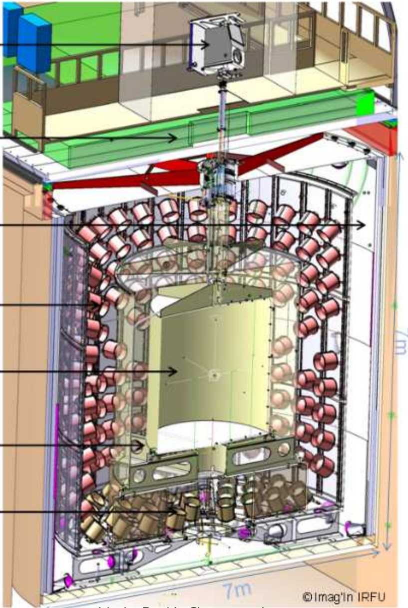
- Inner Veto -
90 m^3 of scintillating oil for muon tagging

390 photomultiplier tubes

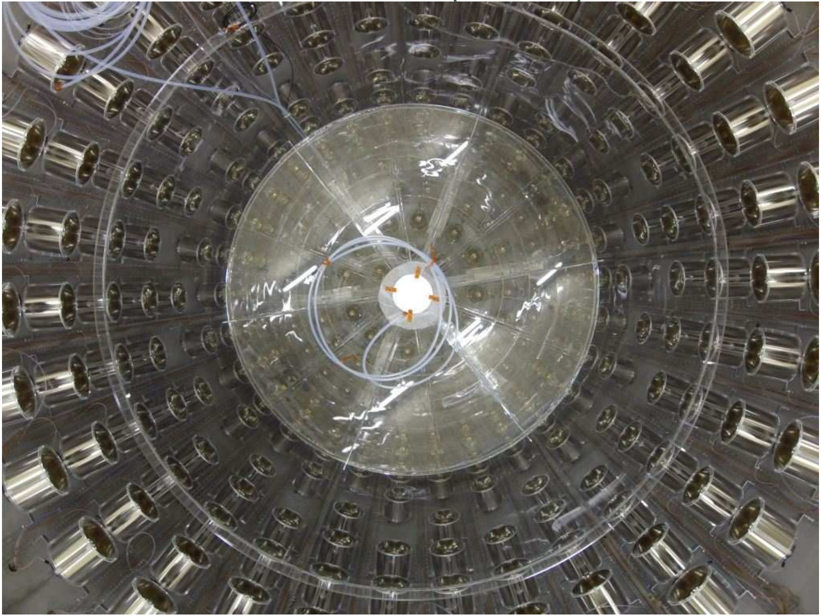
- Target -
10 m^3 of scintillating mineral oil doped with Gadolinium

- Gamma Catcher -
23 m^3 of scintillating mineral oil

- Buffer -
110 m^3 of non-scintillating mineral oil



The detector (for real)

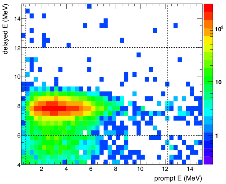


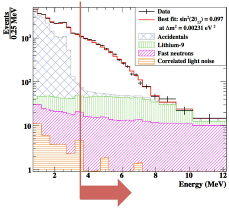
Neutrino candidates

Selection (Gd and H)

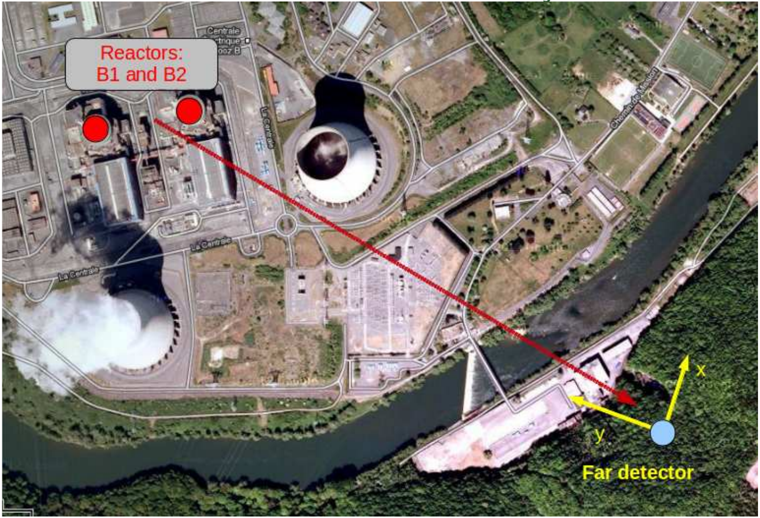
- Prompt event: $0.3 < E < 20\ MeV$, $3.5 < E < 12.2\ MeV$
- Delayed event: $6 < E < 12\ MeV$, $1.5 < E < 3\ MeV$
- Coincidence: $2 < \Delta t < 100\ \mu s$, $10 < \Delta t < 600\ \mu s$, $\Delta R < 900\ mm$
- No muon signal
- Multiplicity cut: No other events in a 500 μs, $1600\ \mu s$ window around prompt event

→ 8246 and 7498 neutrino candidates in Gd and H





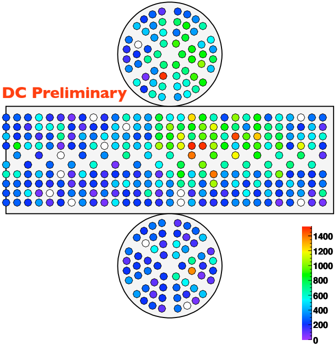
The Double Chooz layout



From the detector, the reactors are 6° apart → Localized neutrino source
Simple layout → Ideal for directionality studies

Position reconstruction

- Maximum likelihood method using charge and time information on PMT's
- Use of calibration sources (light attenuation and angular response) and laser diodes (charge/time likelihoods)
- Resolution : ∼20 cm for a point-like source

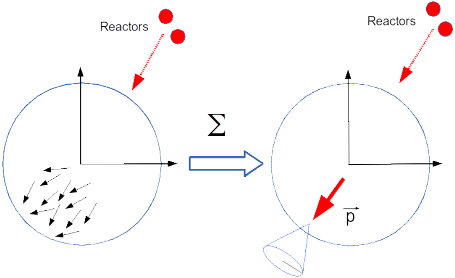


Direction reconstruction

Neutrino direction

Each event is composed of a prompt and a delayed vertex.
This gives a direction vector
$\overrightarrow{X_{evt}} = \overrightarrow{X_{delayed}} - \overrightarrow{X_{prompt}}$

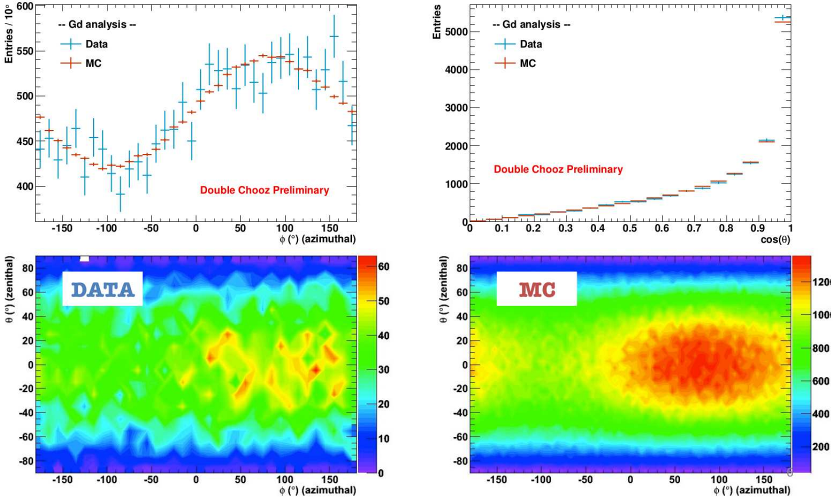
Neutrino wind: $\overrightarrow{p} = \sum_{1}^{N} \frac{1}{N} \frac{\overrightarrow{X^i_{evt}}}{|\overrightarrow{X^i_{evt}}|}$



Angles

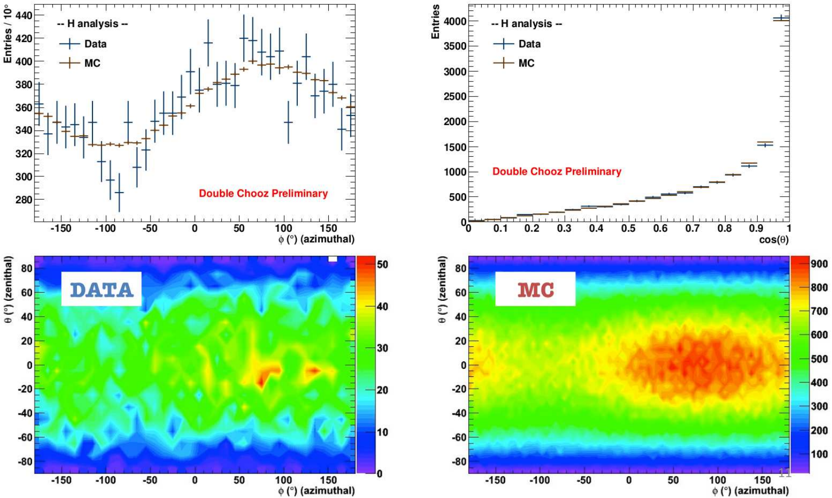
The neutrino wind components gives the azimuthal (θ) and zenithal (ϕ) reconstruction angles with $\theta = \arctan \frac{p_z}{\sqrt{p_x^2+p_y^2}}$ and $\phi = \arctan \frac{p_y}{p_x}$

Gd analysis



Reconstructed angles: $\phi = 84.6 \pm 9.4^\circ$ and $\theta = -4.7 \pm 9.4^\circ$

H analysis


-- H analysis --
Data
MC
Double Chooz Preliminary
Entries / 10°
φ (°) (azimuthal)
Entries
cos(θ)
DATA
MC
θ (°) (zenithal)

Summary

	ϕ (azimuthal)	θ (zenithal)
Real (geometry)	$84.0 \pm 3.0°$	$1.96 \pm 0.11°$
Reconstructed	$84.6 \pm 9.4°$	$-4.7 \pm 9.4°$

First measurement ever using H !

$\rightarrow$ Proves directionality will be possible in the large scale scintillator detectors.

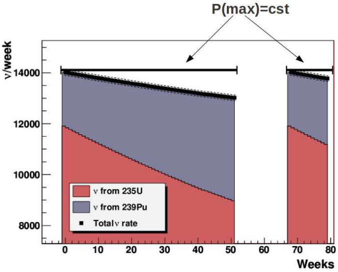
$\rightarrow$ Paves the way for JUNO, LENA or RENO-50

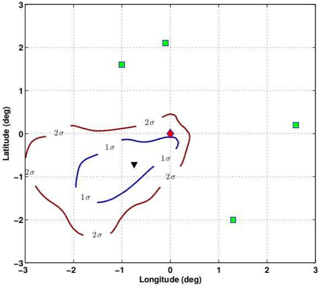
Outline

1. Neutrino directionality
2. Directionality with Double Chooz
3. Application to nuclear non-proliferation
4. Perspectives and conclusion

Non-proliferation

- Application of antineutrinos detection for nuclear safeguards
- Nuclear reactor monitoring → Pu diversion detection via burnup effect
- Rogue reactors detection from unexpected $\bar{\nu}_e$ rate
- Directionality via triangulation would provide useful localization





1^{st} example: Ton scale detector

Detector design

- Size: 1 ton liquid scintillator tank $\rightarrow$ Nucifer-like concept
- Location: 10-25 m away from a 900 MW_{th} reactor

$\rightarrow$ 1500 $\bar{\nu}_e$/d expected @ 25 m

Results

- Strong but hardly useful directional information
- Design incompatible with efficient reconstruction
- High sensitivity to burnup effect

$\rightarrow$ Dedicated to Pu diversion monitoring

2^{nd} example: 10∼100-ton scale detector

Detector design

- Size: 50 tons liquid scintillator tank → Double Chooz-like concept
- Location: 1-5 km away from a 900 MW_{th} reactor

→ 50 $\bar{\nu}_e$/d expected @ 1 km

Results

- Somewhat useful directional information
- Medium sensitivity to burnup effect

→ Dedicated to distant reactor monitoring

3^{rd} example: kt-scale detector

Detector design

- Size: 138 ktons liquid scintillator tank $\rightarrow$ SNIF-like concept (see *arXiV:1011.3850*)
- LAB filled oil tanker $\rightarrow$ Movable detector
- Location: 50-300 km away from a 900 MW_{th} reactor

$\rightarrow \sim 1\ \bar{\nu_e}$/d expected @ 300 km

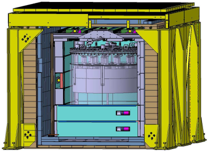
Results

- Low sensitivity to burnup effect
- Not enough statistics for IBD directionality
- Useful however weak directional information via triangulation using 3 locations or more

$\rightarrow$ Dedicated to rogue reactor detection

Results

Nucifer-like case

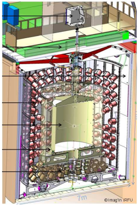


Neutrino rate:

1500 d^{-1} @ 25 m

No directional information

Double Chooz-like case



Neutrino rate:

50 d^{-1} @ 1 km

Limited directional information

SNIF-like case

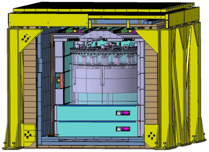
Neutrino rate:

$\sim 1\ \bar{\nu}_e/\text{d}$ expected @ 300 km

Source localization within a 20° cone in a month at 50 km (via IBD)

Results

Nucifer-like case

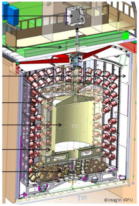


Neutrino rate:

1500 d^{-1} @ 25 m

No directional information

Double Chooz-like case



Neutrino rate:

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Limited directional information

SNIF-like case

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Results

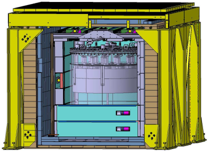
SNIF-like case

Neutrino rate:

$\sim 1\ \bar{\nu}_e$/d expected @ 300 km

Source localization within a 20° cone in a month at 50 km (via IBD)

Nucifer-like case

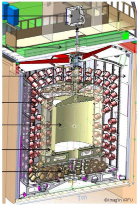


Neutrino rate:

1500 d^{-1} @ 25 m

No directional information

Double Chooz-like case



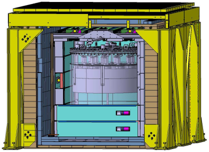
Neutrino rate:

50 d^{-1} @ 1 km

Limited directional information

Results

Nucifer-like case



Neutrino rate:

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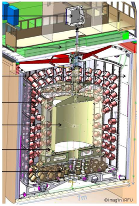
No directional information

Double Chooz-like case



Neutrino rate:

50 d^{-1} @ 1 km

Limited directional information

SNIF-like case

Neutrino rate:

$\sim 1\ \bar{\nu}_e$/d expected @ 300 km

Source localization within a 20° cone in a month at 50 km (via IBD)

Outline

New detector concepts

Segmented detectors

- Existing concept: PROSPECT, NuLat, MiniTimeCube, PANDA, etc...
- Detector divided into several cells
- Huge background reduction
- Very precise position reconstruction → Good directional capabilities

Water-based liquid scintillator detectors

- Advanced Scintillator Detector Concept (ASDC) → see *arXiV:1409.5864*
- Development in future detectors: WATCHMAN, ANNIE, EGADS
- Mixing of scintillating molecules and water
- High light yield (LS) and strong directional capabilities (Čerenkov)
- Enhanced by the use of high-precision photosensors (LAPPD's)

Conclusion

- Directionality measurement is now achieved with Double Chooz using Gd AND H !
- We decreased the reconstruction uncertainty from 18° (CHOOZ results) to 9° !
- $\bar{\nu_e}$ detection via IBD offers statistical directionality
- Application to nuclear non-proliferation is yet hardly achievable but could be strongly enhanced by new detection concepts

Thanks

Thank you for your attention !

Neutrino oscillations

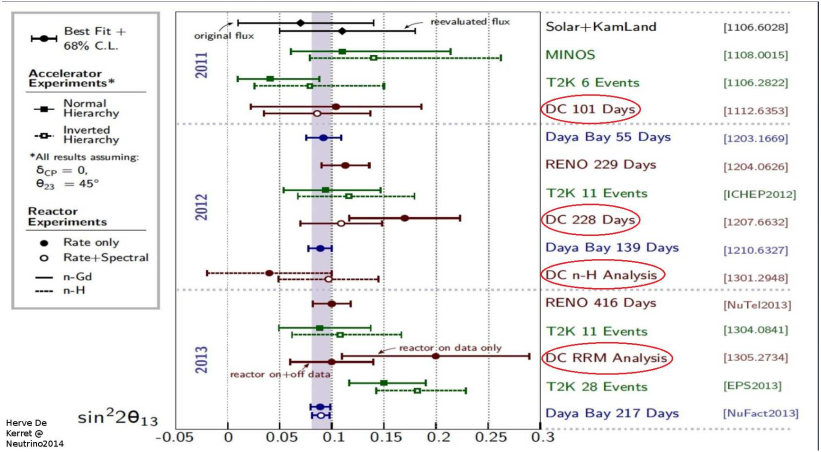
- Infered in 1957 by Pontecorvo and discovered in 1998 by Super-Kamiokande (atmospheric ν's).
- Neutrinos have mass and oscillate between 3 flavors ν_e, ν_μ, ν_τ via the PMNS matrix.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\sin^2 2\theta_{23} \sim 1$	$\sin^2 2\theta_{13} \sim 0.1$	$\sin^2 2\theta_{12} \sim 0.8$
Atmospheric ν's	**Reactor ν's**	Solar ν's

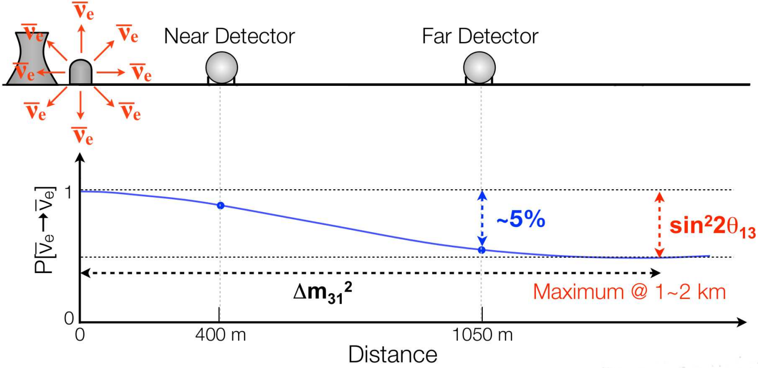
History of θ_{13} measurement



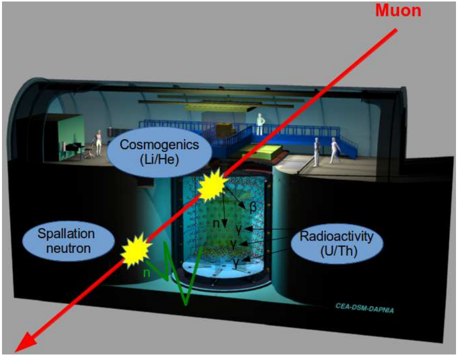
Complementary measurement given by reactor and accelerator experiments.

Measuring θ_{13} with a reactor

- Look for a deficit of $\bar{\nu}_e$
- $P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{13}(eV^2)L(m)}{4E(MeV)}$
- Near detector $\rightarrow$ Reference measurement (no oscillation)
- Far detector $\rightarrow$ Deficit measurement (oscillation)



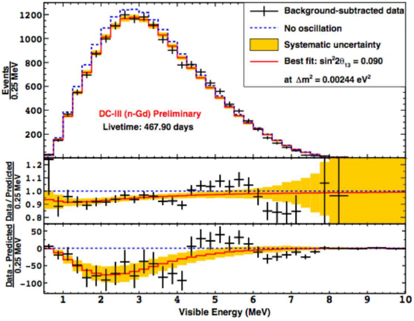
Backgrounds



- Accidental background → Random coincidence created by radioactivity (easily substracted).
- Fast neutron background → Energetic spallation neutron entering the detector (tagged by the vetoes).
- Cosmogenic background → Long-lived isotope created by muon interaction in the detector (main background in DC).

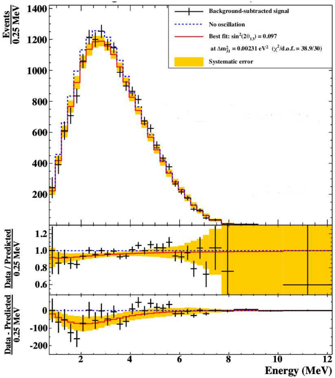
Latest results

Gd analysis (Neutrino2014 @Boston)



$$\sin^2 2\theta_{13} = 0.09 \pm 0.03$$

H analysis (Phys.Lett. B723 (2013) 66-70)



$$\sin^2 2\theta_{13} = 0.097 \pm 0.034(syst.) \pm 0.034(stat.)$$

Next steps and future plans

What happens next ?

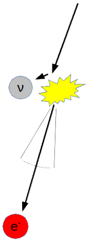
- Near detector ready for fall 2014 !
- Major improvement on systematic errors
- More statistic everyday

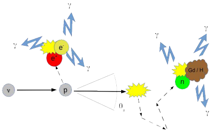
Parallel studies and analysis

- θ_{13} analysis using reactor rate modulation (arXiv:1401.5981 and PLB)
- Pure background measurement with both reactors shut down (Phys.Rev. D87 (2013) 011102)
- Lorentz violation test (Phys.Rev. D86 (2012) 112009)
- **Neutrino directionality**

Directionality methods

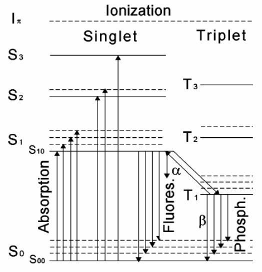
Direction information comes from the detection reaction
2 favorite reactions: Electron scattering ($\nu + e^- \rightarrow \nu + e^-$) and IBD ($\bar{\nu_e} + p \rightarrow e^+ + n$)





Liquid scintillators

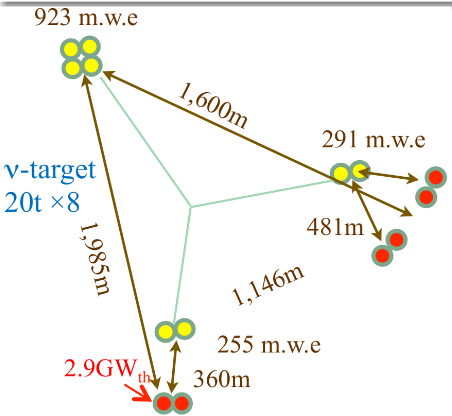
- Scintillation: Process by which ionization produced by charged particles excites a material and light is emitted by fluorescence
- Liquid scintillators: Organic molecules diluted in an optically-inert liquid (mineral oil,..)
- Basically: Charged particle ionizes liquid $\rightarrow$ Excites molecules that de-excites emitting light
- This light is detected using photomultiplier tubes (PMT's) that amplifies it into a detectable current



Other reactor experiments

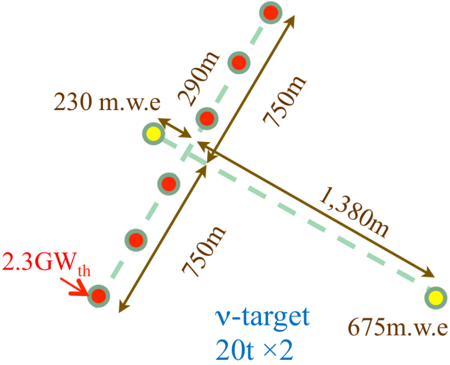
Daya Bay

- 8 detectors, each $2\times$ DC detector
- $6 \times 2.9 GW_{th}$ reactors



RENO

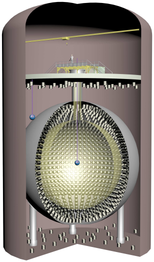
- 2 detectors, each $2\times$ DC detector
- $6 \times 2.3 GW_{th}$ reactors



Large Scale Scintillator Detectors

KamLAND, Borexino, SNO+

Spherical detectors, large size (KamLAND and SNO+: 1000t, Borexino: 300t)
Deep underground, very low background rate



LVD and MiniBoone

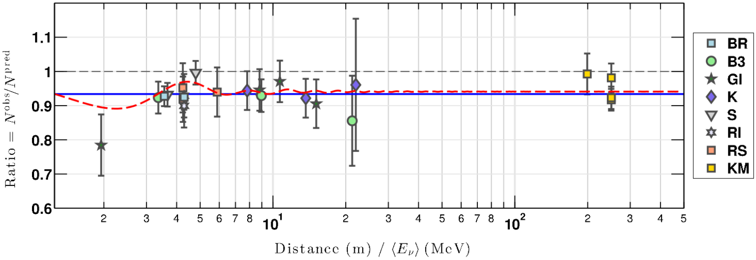
LVD: 1000 t of scintillator, deep underground, main goal: supernova detection
MiniBoone: 680 t at sea level

The future: JUNO and LENA

JUNO: Spherical, 20 kt, construction started
LENA: 50 kt, project ongoing

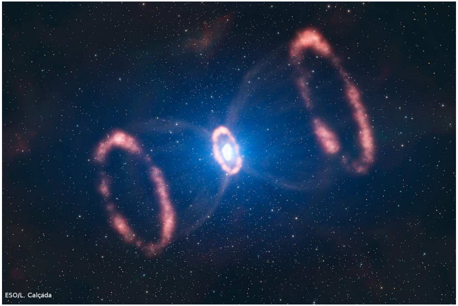
The reactor antineutrino anomaly (RAA)

- Revised calculation of the $\bar{\nu_e}$ rate from nuclear reactors → 3.5 % $\bar{\nu_e}$ deficit
- New $\bar{\nu_e}$ cross-sections → Another 3.5 % $\bar{\nu_e}$ deficit
- This new flux gives a mean $\bar{\nu_e}$ deficit of $R^R = 0.938 \pm 0.011(Detection) \pm 0.023(Prediction)$ $(2.7\ \sigma)$ for 19 previous short range experiments



Type II Supernova

- Core collapse of massive stars ($M > 8M_{\odot}$)
- Chain fusion of H into Fe $\rightarrow$ Core collapse (see slide on SN phases)
- 99 % of energy emitted as neutrinos (6 flavors) in a 10 s time window $\rightarrow \sim 10^{53}$ neutrinos
- Neutrino conversion and oscillation effects $\rightarrow$ Modify amplitude and shape of the energy spectrum



Type II Supernova phases

- Hydrogen burning phase (main phase) withstand gravitation
- After this phase, gravity takes over and the increase of density induces H fusion
- H fuses till the creation of a Fe core
- Density rises till the core reaches the Chandrasekhar mass $(1.4M_\odot)$
- Electron capture on protons giving neutrons and neutrinos $\rightarrow$ Neutron star creation and iron core collapse
- Fall of the outer shells on the core $\rightarrow$ Shockwave and matter ejection