Neutrino Directionality measurement with the Double Chooz experiment

Journée IRFU - Présentation de 2ème année de thèse

Vincent Fischer

CEA/IRFU/SPP

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Outline

Introduction slide - 1

Nom: Vincent FISCHER

Cursus:

- Magistère de Physique Fondamentale d'Orsay
- Master 2 Noyaux, Particules, Astroparticules et Cosmologie

Thèse: Contact par la foire aux thèses du CEA puis en personne.

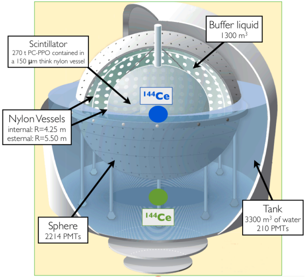
Motivations: Intêret pour la physique du neutrino et la physique expérimentale.

Introduction slide - 2

Sujet: Etude du mélange des antineutrinos électroniques émis par désintégrations beta

Explication:

- Désintégration beta → $E_\nu \sim$ MeV
- Détermination de l'angle de mélange θ_{13} avec Double Chooz.
- Travail sur une analyse parallèle → A voir dans cette présentation.
- Etude d'une oscillation en neutrino stérile en utilisant un réacteur ou une source radioactive.



Introduction slide - 2

Glossaire:

- Gd ou H (Gadolinium ou Hydrogène): Noyau servant de cible à la capture du neutron dans Double Chooz.
- Liquide scintillant: Liquide émettant de la lumière au passage d'une particule chargée (voir Backup).
- Supernova (SN) de type II: Supernova (explosion d'étoile massive en fin de vie) avec effondrement du coeur.

Outline

The neutrino

- First infered by Pauli in 1930 to explain β decay missing energy.
- Discovered in 1956 (reactor neutrinos).
- Weakly interacting particles $\rightarrow$ Very low interaction cross-section ($\sim 10^{-43} cm^2$) $\rightarrow$ Hard to detect

Open questions: Leptonic CP violation, mass, mass hierarchy, Dirac or Majorana, sterile neutrinos...?

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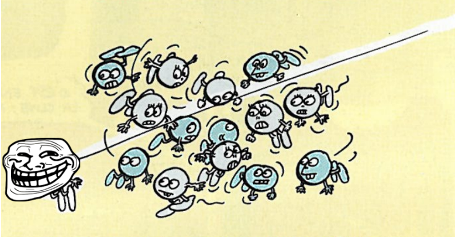

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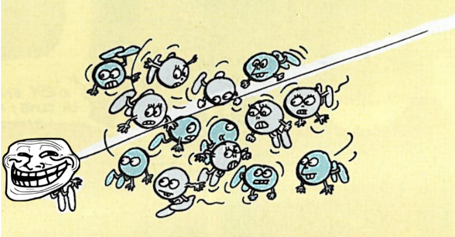


Open questions: Leptonic CP violation, mass, mass hierarchy, Dirac or Majorana, sterile neutrinos...?

Neutrino oscillations

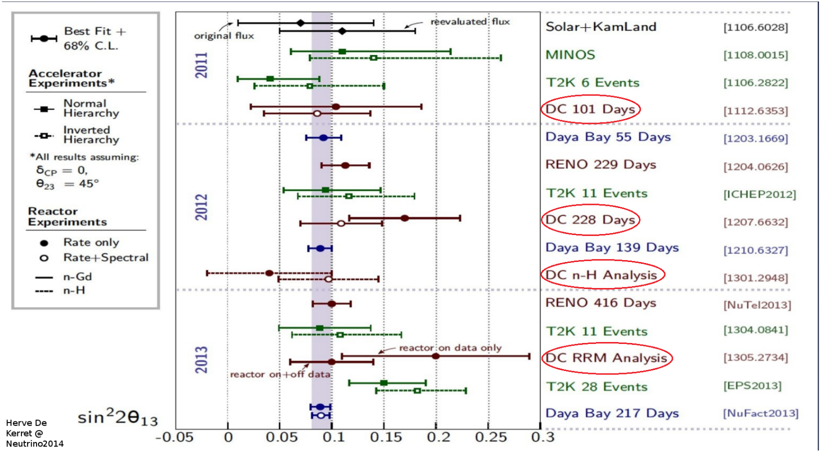
- Infered in 1957 by Pontecorvo and discovered in 1998 by Super-Kamiokande (atmospheric ν's).
- Neutrinos have mass and oscillate between 3 flavors ν_e, ν_μ, ν_τ via the PMNS matrix.

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

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

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

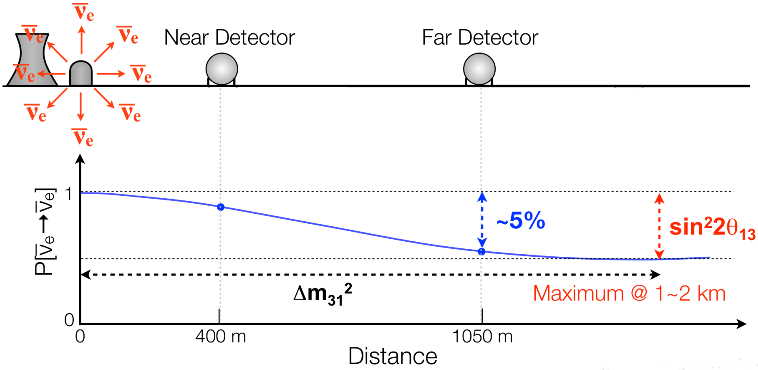
History of θ_{13} measurement



Complementary measurement given by reactor and accelerator experiments.

Measuring θ_{13} with a reactor

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



Outline

The Double Chooz collaboration

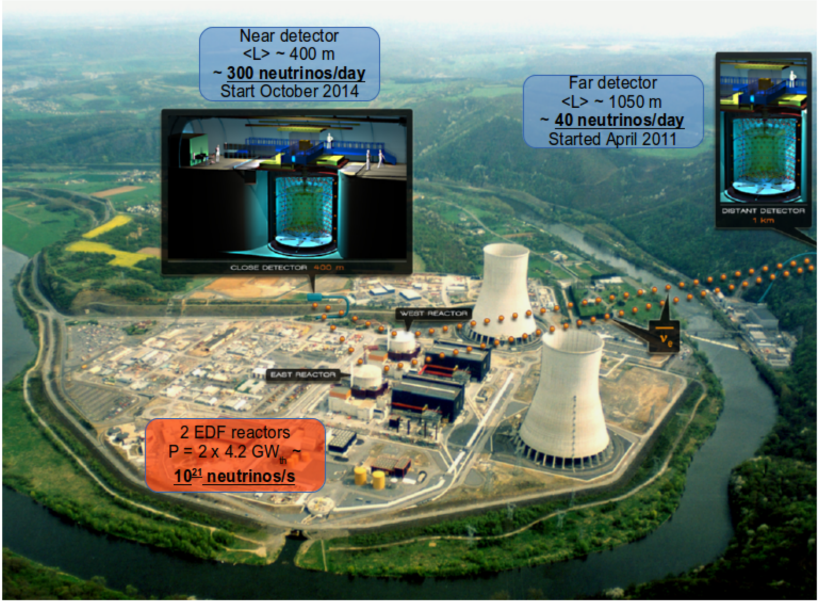
BRAZIL	FRANCE	GERMANY	JAPAN	RUSSIA	SPAIN	USA
CBPF UNICAMP UFABC	APC CEA/DSM/IRFU: SPP, SPhN, SEDI, SIS, SENAC. CNRS/IN2P3: Subatech, IPHC.	EKU Tübingen MPIK Heidelberg RWTH Aachen TU München U. Hamburg	Tohoku U. Tokyo Inst. Tech. Tokyo Metro. U. Niigata U. Kobe U. Tohoku Gakuin U. Hiroshima Inst. Tech.	INR RAS IPC RAS RRC Kurchatov	CIEMAT-Madrid	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

- Glovebox -
For calibration sources deployment

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

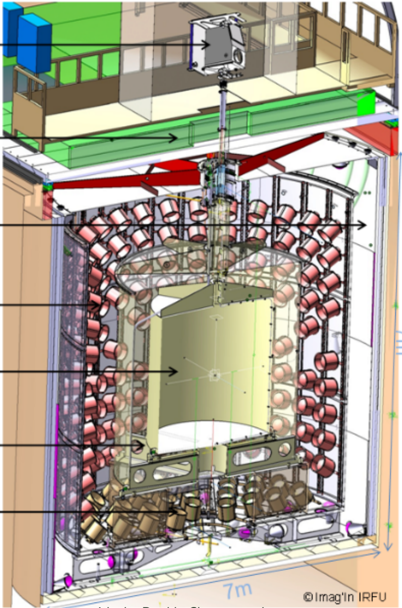
- Inner Veto -
90 m^3 of scintillating oil for muon tagging

390 photomultiplier tubes

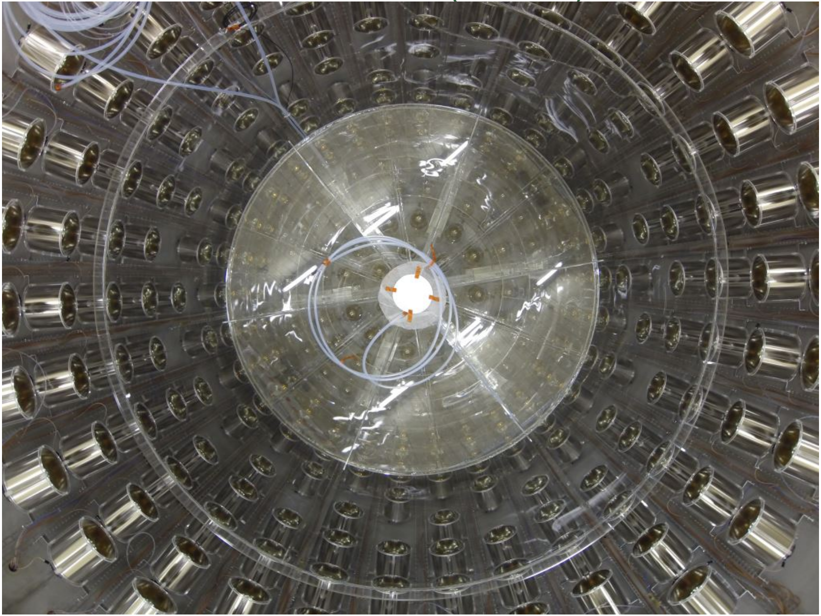
- Target -
10 m^3 of scintillating mineral oil doped with Gadolinium

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

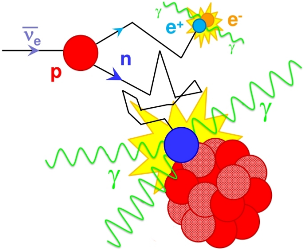
- Buffer -
110 m^3 of non-scintillating mineral oil



The detector (for real)

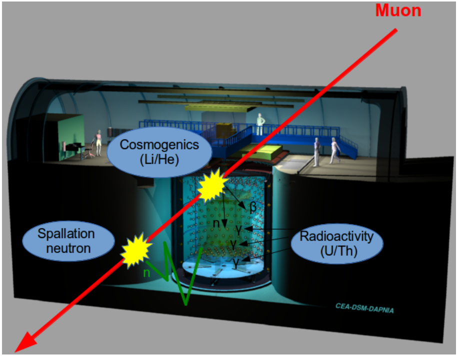


How to detect neutrinos ?



- 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, [6.0-12.0] MeV or [1.5-3.0] MeV for delayed), time and space coincidence $\rightarrow$ Huge background reduction !

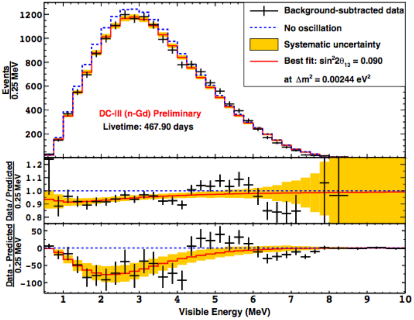
How about backgrounds ?



- 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).

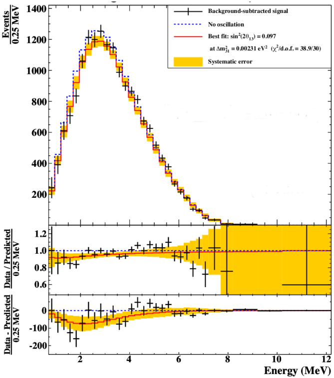
Latest results

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**

Outline

What and why ?

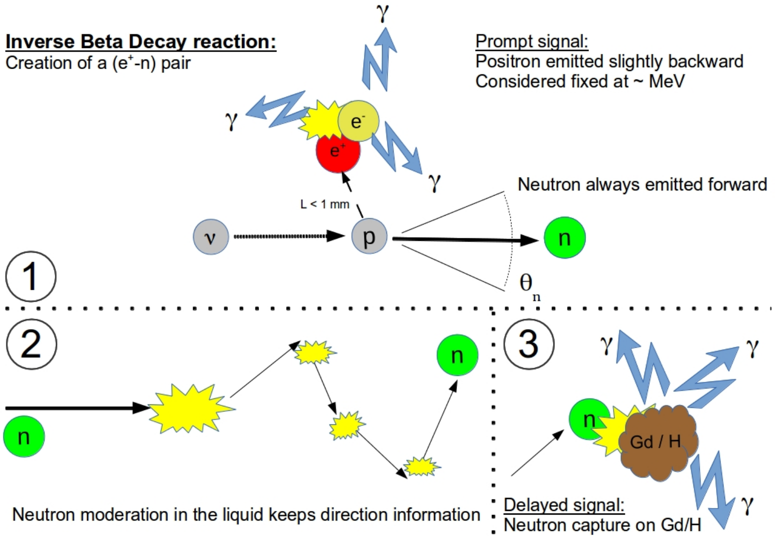
What is it ?

- Neutrino directionality consists of retrieving the direction of a neutrino flux.
- Used to locate neutrino sources.

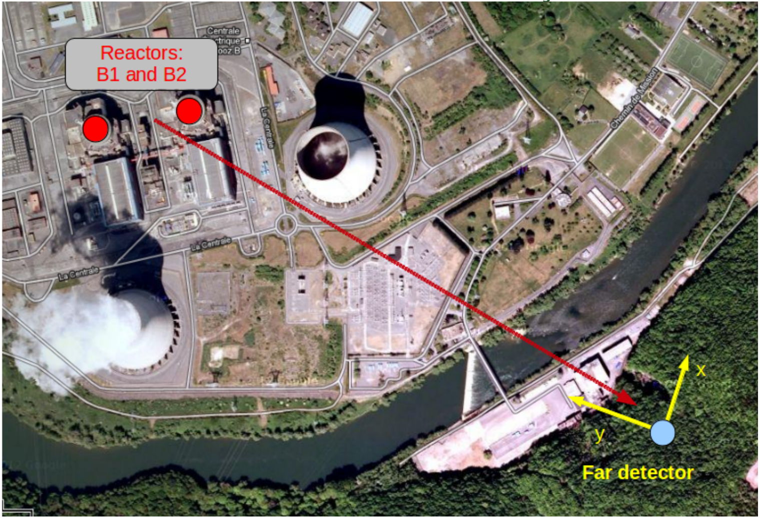
Applications

- Locating supernovas especially if non-visible optically.
- Studying geo-neutrinos from the Earth's crust and mantle.
- Detecting and monitoring nuclear reactors.

Directionality with IBD



The Double Chooz layout



From the detector, the reactors are 3° apart → Localized neutrino source

Simple layout → Ideal for directionality studies

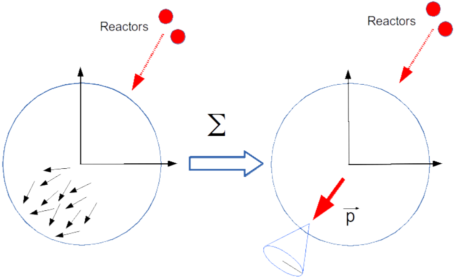
Direction reconstruction

Neutrino direction

Each event is composed of a prompt and a delayed vertex.
This gives a direction vector

$$\overrightarrow{X_{evt}} = \overrightarrow{X_{delayed}} - \overrightarrow{X_{prompt}}$$

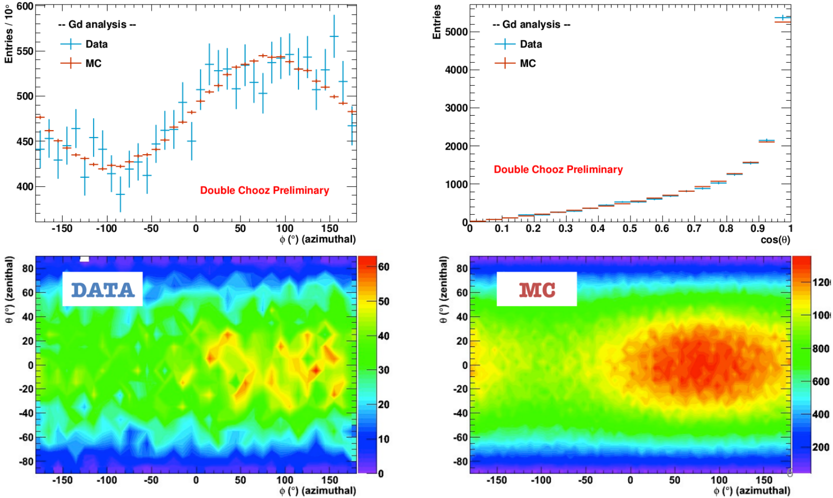
Neutrino wind: $\overrightarrow{p} = \sum_{1}^{N} \frac{1}{N} \frac{\overrightarrow{X_{evt}^i}}{|\overrightarrow{X_{evt}^i}|}$



Angles

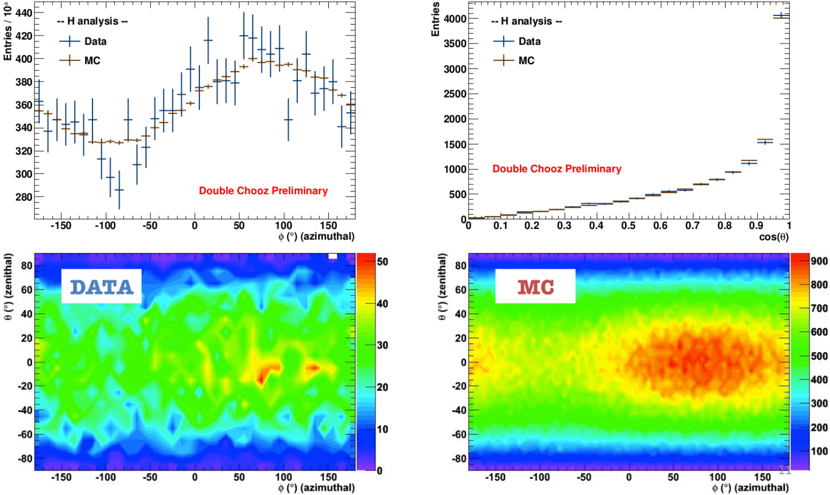
The neutrino wind components gives the azimuthal (θ) and zenithal (ϕ) reconstruction angles with $\theta = \arctan \frac{p_z}{\sqrt{p_x^2+p_y^2}}$ and $\phi = \arctan \frac{p_y}{p_x}$

Gd analysis



Reconstructed angles: $\phi = 85.2 \pm 5.1°$ and $\theta = 11.6 \pm 5.2°$

H analysis



Reconstructed angles: $\phi = 74.6 \pm 4.8^\circ$ and $\theta = 4.5 \pm 4.8^\circ$

Summary

	ϕ (azimuthal)	θ (zenithal)
Real (geometry)	$84.6 \pm 3.0°$	$1.96 \pm 0.11°$
Gd analysis	$85.2 \pm 5.1°$	$11.6 \pm 5.2°$
H analysis	$74.6 \pm 4.8°$	$4.5 \pm 4.8°$

First measurement ever using H ! $\rightarrow$ Proves directionality will be possible in the large scale scintillator detectors.

Larger prospect

Supernova detection

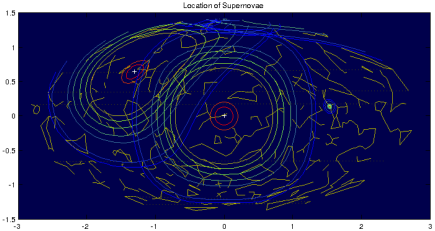
Type II (core-collapse) supernova emits $\sim 10^{53}$ neutrinos.
Current detectors will detect thousands of IBD events for a galactic supernovae.
$\rightarrow$ Possibility to perform a directionality measurement

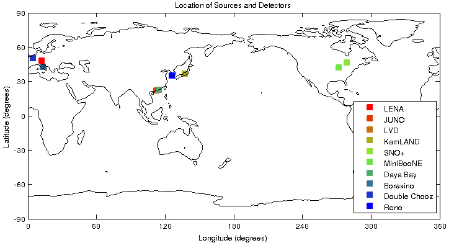
Interest

Provides information even if visible light is absorbed by galactic disk.
During a core-collapse SN, neutrinos arrive several hours before visible light.
$\rightarrow$ Early pointing of the region of interest over the sky

First results

- Development of a toyMC for the IBD reaction
- All large scintillator detector worldwide taken into account
- On this figure: 2 SN @ 10kpc and Betelgeuse @ 0.2 kpc





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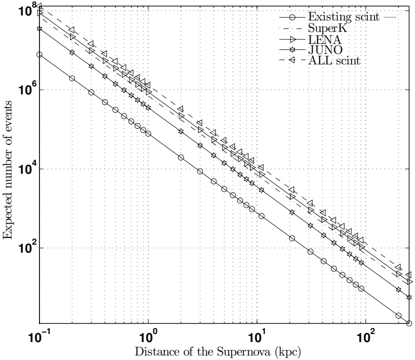
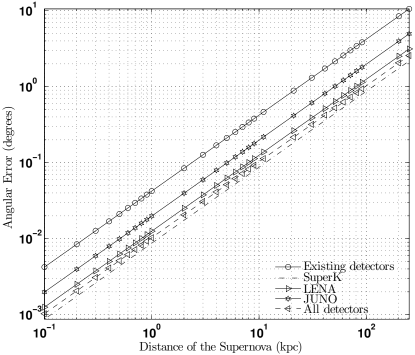




- 8 existing detectors: Reactor detectors, KamLAND, etc...
- 3 future detectors: JUNO, LENA, Super-Kamiokande (with IBD)
- Basic method to compute angular error
- $\rightarrow$ Precise directionality fit incoming

Towards a network of SN telescopes ?

The SNEWS network

SNEWS (SuperNova Early Warning System): Network of neutrino detectors dedicated to give warnings of SN signals.
Idea: Send the astronomical community an alert if several detectors detected a burst of neutrinos simutaneously.
For now → Able to detect a SN signal but without localization.

Upgrades to SNEWS

Adding more detectors to SNEWS → Better confidence on the SN alerts (less false alarms).
Combine all liquid scintillator detectors → Provides directionality information

Outline

Conclusion

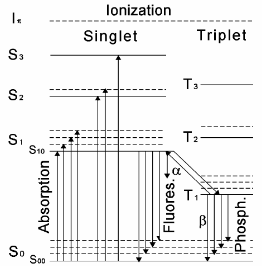
- Directionality is possible with Double Chooz using Gd AND H !
- We decreased the reconstruction uncertainty from 18° (CHOOZ results) to 7° !
- Direct application to larger detectors for geoneutrinos and supernova detection.
- Possibility to detect supernovas before actually seeing them thus transforming neutrino detectors into neutrino 'telescopes'.

Thanks

Thank you for your attention !

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 → Excites molecules that de-excites emitting light
- This light is detected using photomultiplier tubes (PMT's) that amplifies it into a detectable current



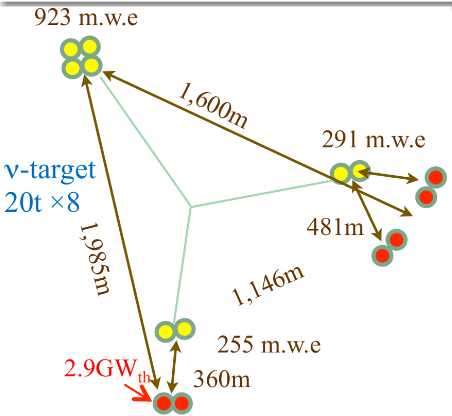
Other reactor experiments

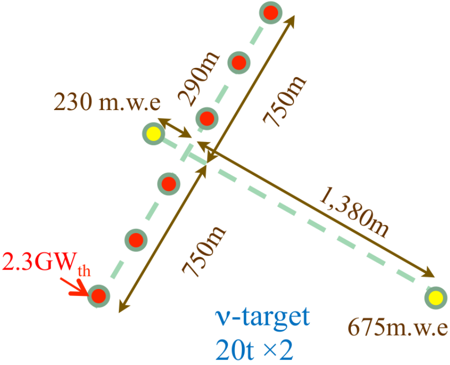
Daya Bay

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

RENO

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

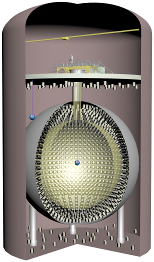




Large Scale Scintillator Detectors

KamLAND, Borexino, SNO+

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



LVD and MiniBoone

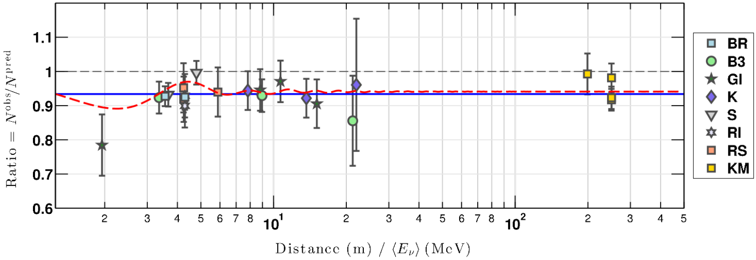
LVD: 1000 t of scintillator, deep underground, main goal: supernova detection
MiniBoone: 680 t at sea level

The future: JUNO and LENA

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

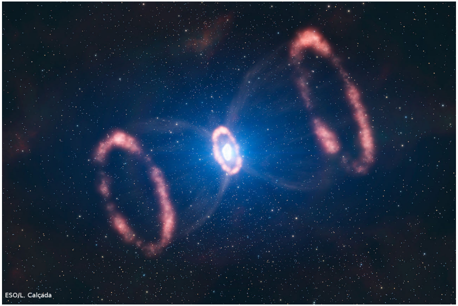
The reactor antineutrino anomaly (RAA)

- Revised calculation of the $\bar{\nu_e}$ rate from nuclear reactors $\rightarrow$ 3.5 % $\bar{\nu_e}$ deficit
- New $\bar{\nu_e}$ cross-sections $\rightarrow$ 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 $(1.4 M_{\odot})$
- 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