Neutrino Physics and Astrophysics

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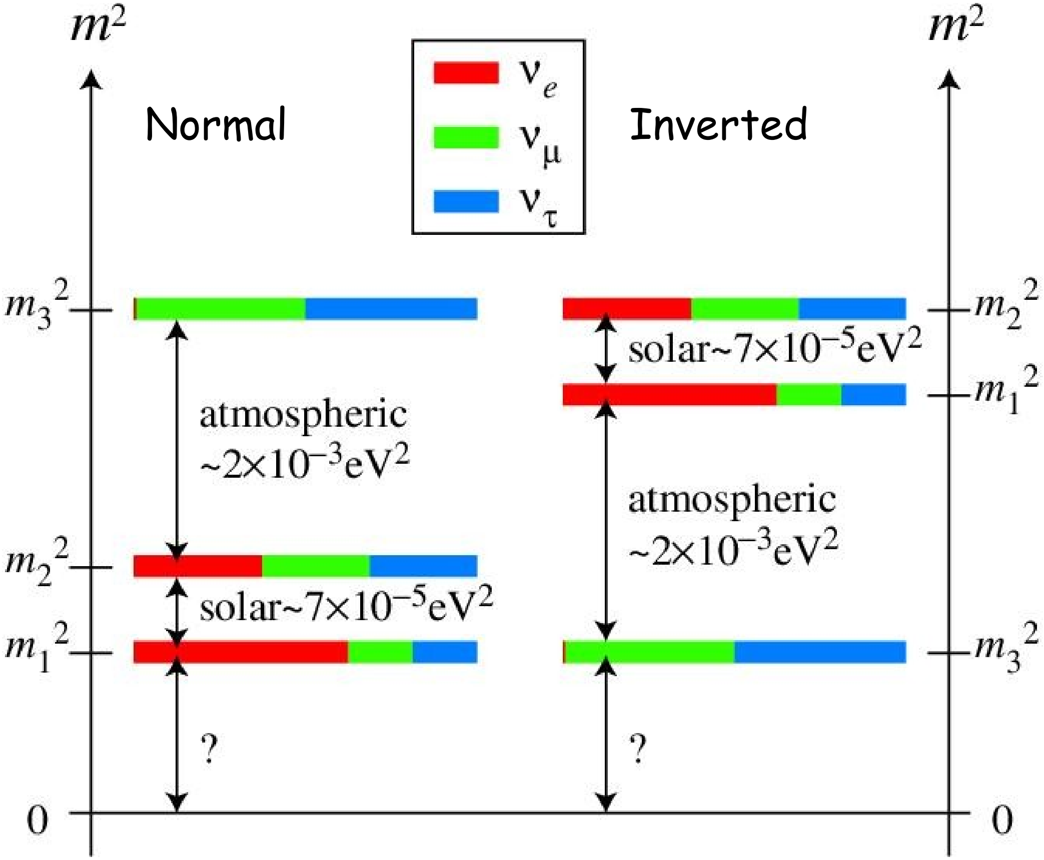
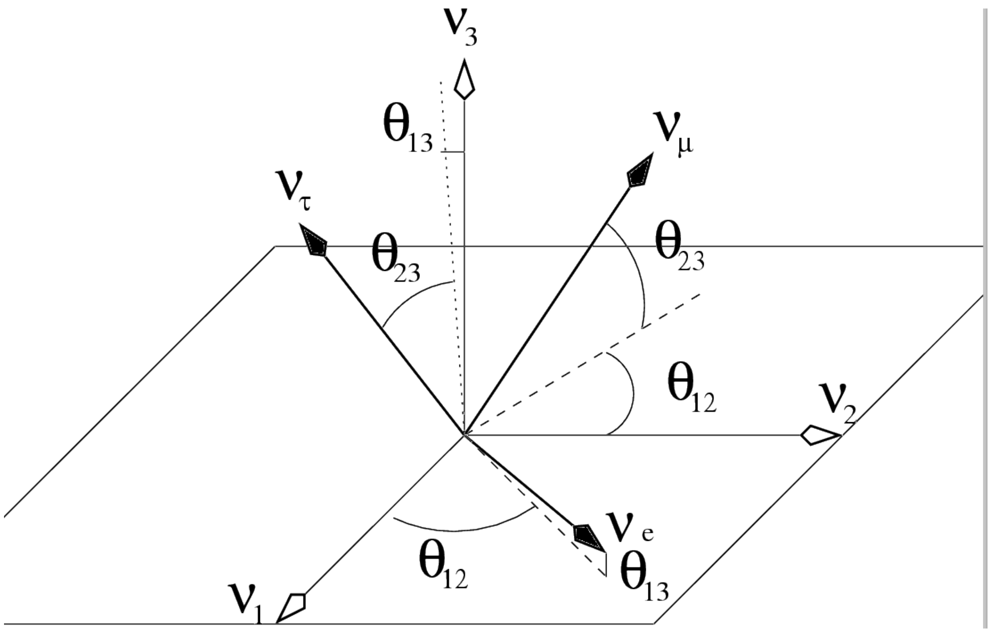
Oscillations revisited

Oscillation parameter		central value	99% CL range
solar mass splitting	$\Delta m^2_{12} =$	$(8.0 \pm 0.3)\, 10^{-5}\, \mathrm{eV}^2$	$(7.2 \div 8.9)\, 10^{-5}\, \mathrm{eV}^2$
atmospheric mass splitting	$\lvert\Delta m^2_{23}\rvert =$	$(2.5 \pm 0.2)\, 10^{-3}\, \mathrm{eV}^2$	$(2.1 \div 3.1)\, 10^{-3}\, \mathrm{eV}^2$
solar mixing angle	$\tan^2\theta_{12} =$	0.45 ± 0.05	$30° < \theta_{12} < 38°$
atmospheric mixing angle	$\sin^2 2\theta_{23} =$	1.02 ± 0.04	$36° < \theta_{23} < 54°$
‘CHOOZ’ mixing angle	$\sin^2 2\theta_{13} =$	0 ± 0.05	$\theta_{13} < 10°$





The neutrino mixing matrix

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

If $\delta \neq 0, \pi, 2\pi$…then weak interactions violate CP symmetry in the lepton sector (as in the quark sector)

atmospheric

CP violation phase

solar

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Links atmospheric & solar sectors

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What more do we want to know?

- Absolute mass scale
- Mass hierarchy
- Measure θ_{13}
- CP violation ?
- Majorana or Dirac neutrinos?
  - Future experiments

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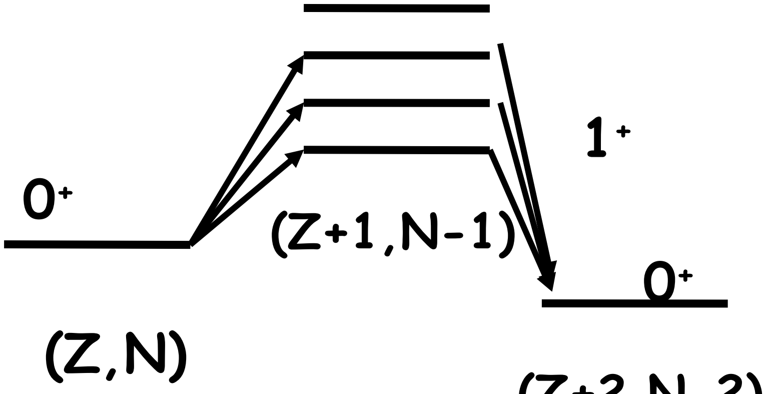
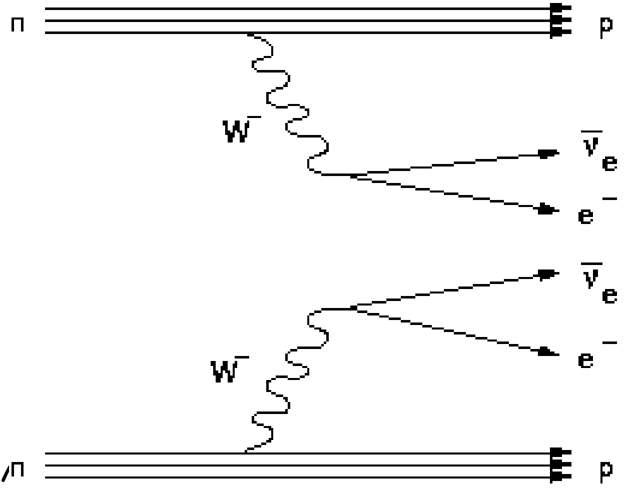
Double β decay

So far→treatment of nuclear beta decay →first order perturbation theory to G

Second-order effects in G →very small in nuclear β decay

Exception →first-order β decay is energetically forbidden





Triplet of isobaric nuclei → daughter decay product is (odd,odd) →unstable. Grand daughter is (even,even), → stable

^{82}Se, ^{76}Ge, ^{100}Mo…

VERY LONG lifetimes...

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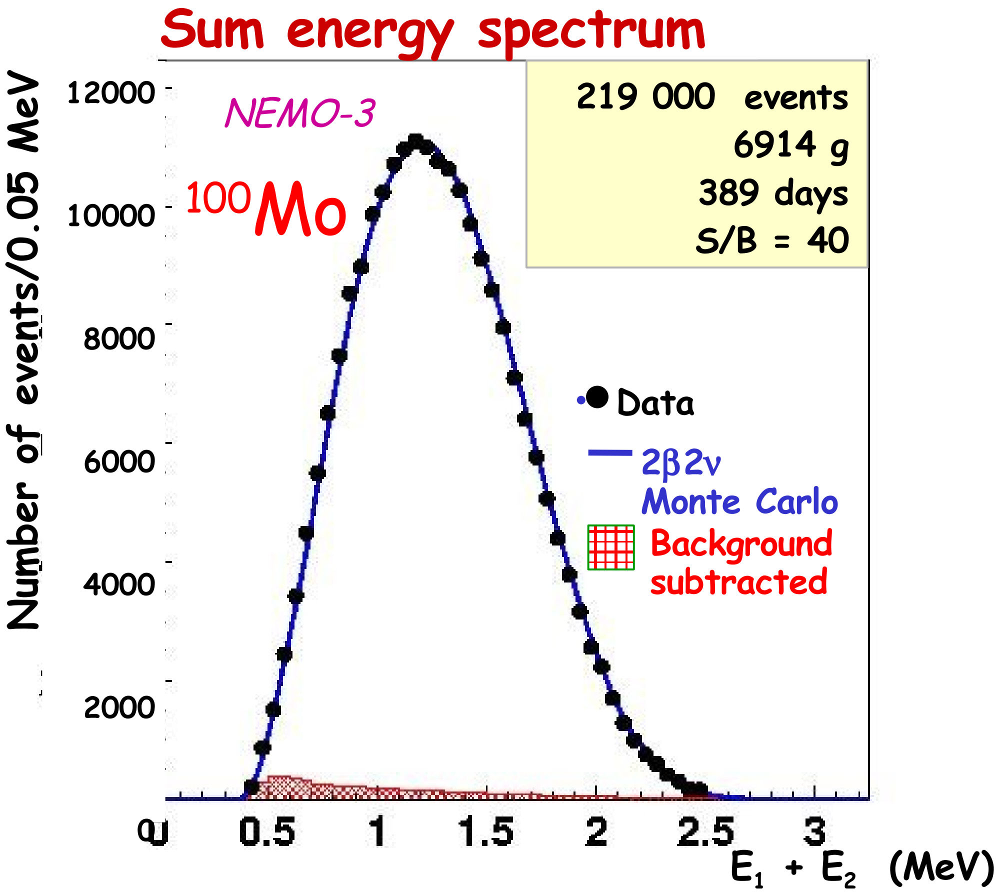
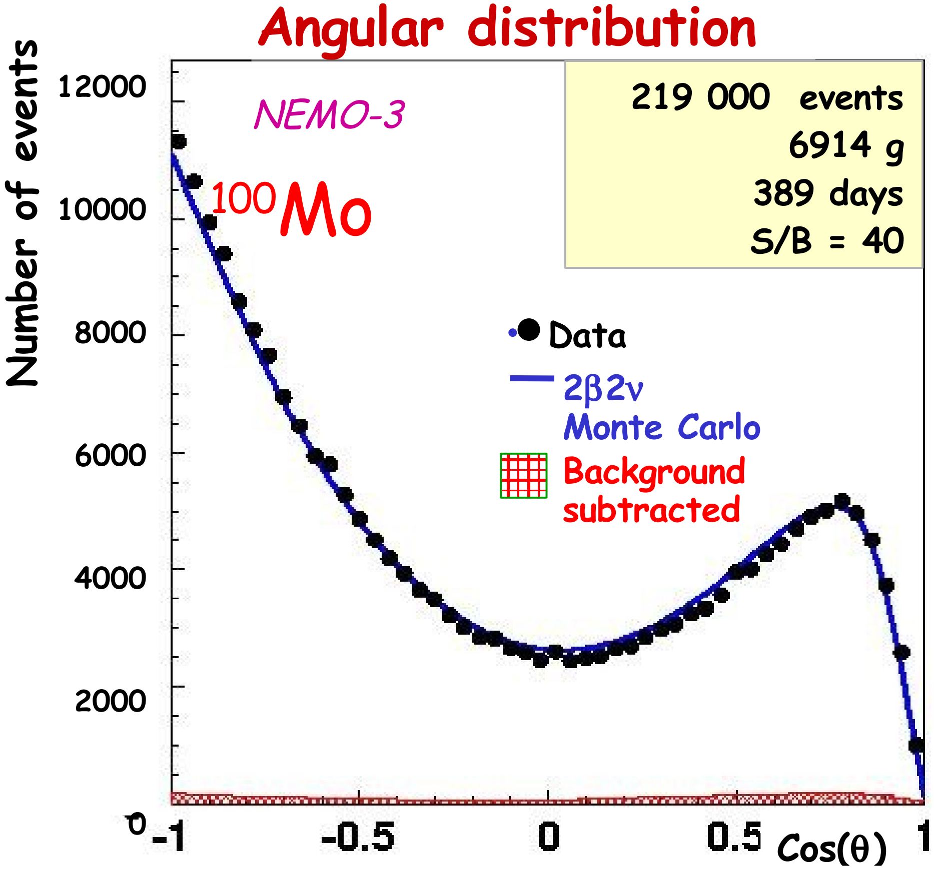
^{100}Mo $\beta\beta2\nu$ Results

Nemo-3 Phase 1 Feb. 2003 – Dec. 2004





$T_{1/2}(\beta\beta2\nu) = 7.11 \pm 0.02\ (\text{stat}) \pm 0.54\ (\text{syst}) \times 10^{18}$ years

Phys. Rev. Lett. 95 182302 (2005)

«ββ factory» → tool for precision test

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Neutrinoless double-β decay

- double-β decay →very small decay rate
  - large suppression of the phase-space factor (the small energy release must be shared by four leptons)

One could ask whether double-β decay would be possible without emission of neutrinos (neutrinoless double beta decay)

Its existence would imply that

- Neutrino and antineutrino are not distinct particles
- Lepton number is not exactly conserved

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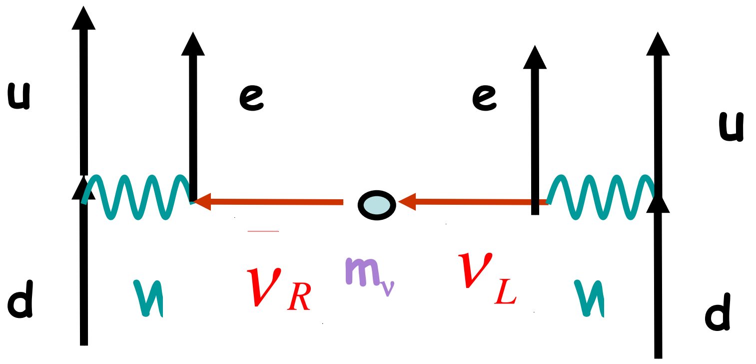
Majorana neutrinos and neutrinoless double β decay

If neutrinos have a small mass and they are Majorana neutrinoless double β decay becomes possible. It requires:

Helicity flip

Change a neutrino into an antineutrino: violate lepton number

L=N(leptons) - N(antileptons)



With respect to normal double β decay the process has

- Larger available phase space
- A helicity supression $O(m_\nu/E_\nu)^2$

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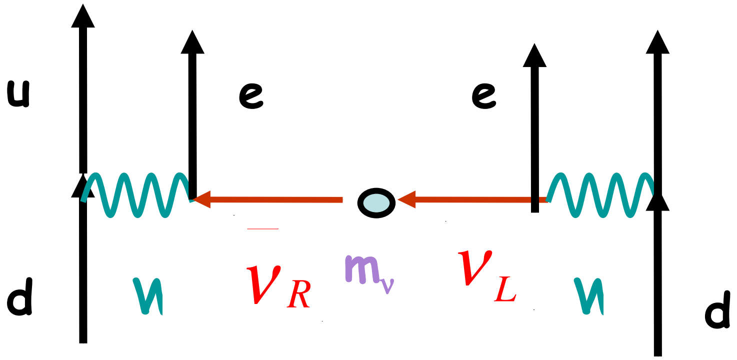
Neutrinoless double β decay and neutrino mass

Neutrinoless double β decay is sensitive to neutrino masses and to the nature of the neutrino (Dirac or Majorana).

Helicity suppression

$$T^{-1}_{2\beta0\nu} : (\frac{\mu_{\nu}}{E})^2 10^9 \, T^{-1}_{2\beta2\nu}$$

Enhanced phase space



The two effects balance each other for m_ν O(eV)

Sensitive to Mass hierarchy

$$|<m>| \equiv | m_1|U_{e1}|^2 + m_2|U_{e2}|^2 e^{i\alpha_{21}} + m_3|U_{e3}|^2 e^{i\alpha_{31}} |$$

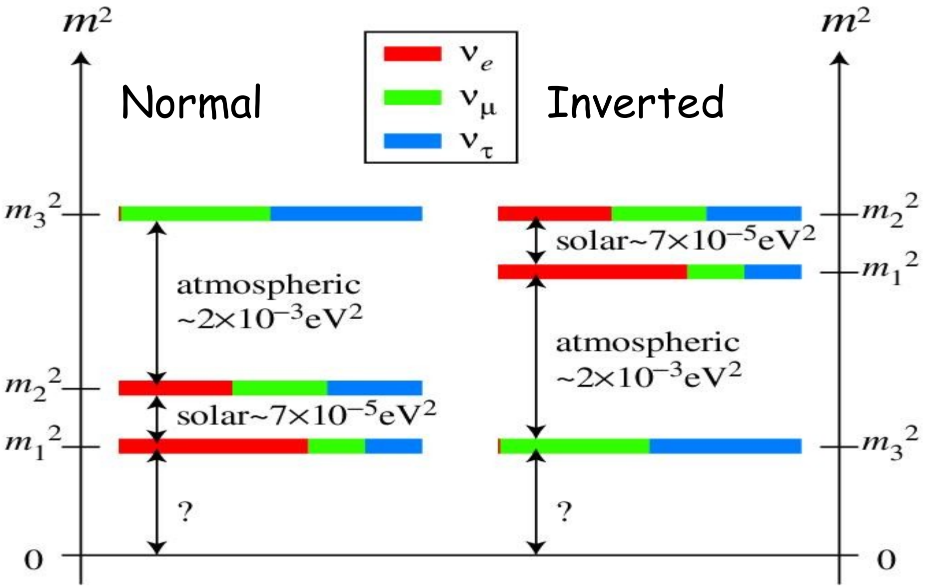
NH: $$|<m>| \simeq \left| \sqrt{\Delta m^2_\odot} \cos^2\theta_{13} \sin^2\theta_\odot + \sqrt{\Delta m^2_{\text{atm}}} \sin^2\theta_{13} e^{i\alpha_{32}} \right|$$

tiny

IH: $$\sqrt{\Delta m^2_{\text{atm}}} \cos 2\theta_\odot \leq |<m>| \simeq \sqrt{\left(1 - \sin^2(2\theta_\odot) \sin^2 \frac{\alpha_{21}}{2}\right) \Delta m^2_{\text{atm}}} \leq \sqrt{\Delta m^2_{\text{atm}}}$$

Accessible to current experiments

QD: $$|<m>| \simeq m_{\bar{\nu}_e} \left| \left(\cos^2\theta_\odot + \sin^2\theta_\odot e^{i\alpha_{21}} \right) \cos^2\theta_{13} + \sin^2\theta_{13} e^{i\alpha_{31}} \right|$$



QD if masses >> Δm^2

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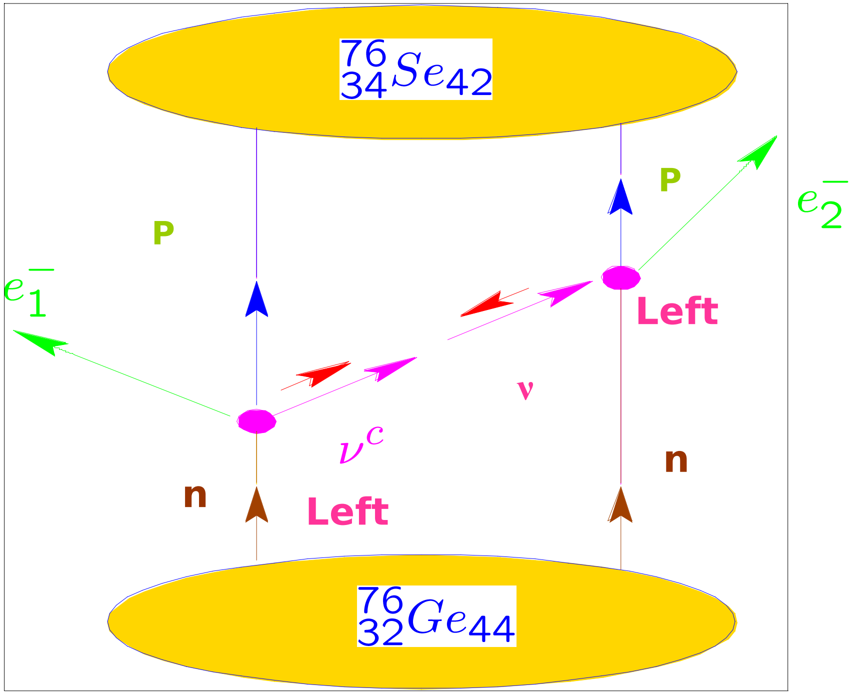
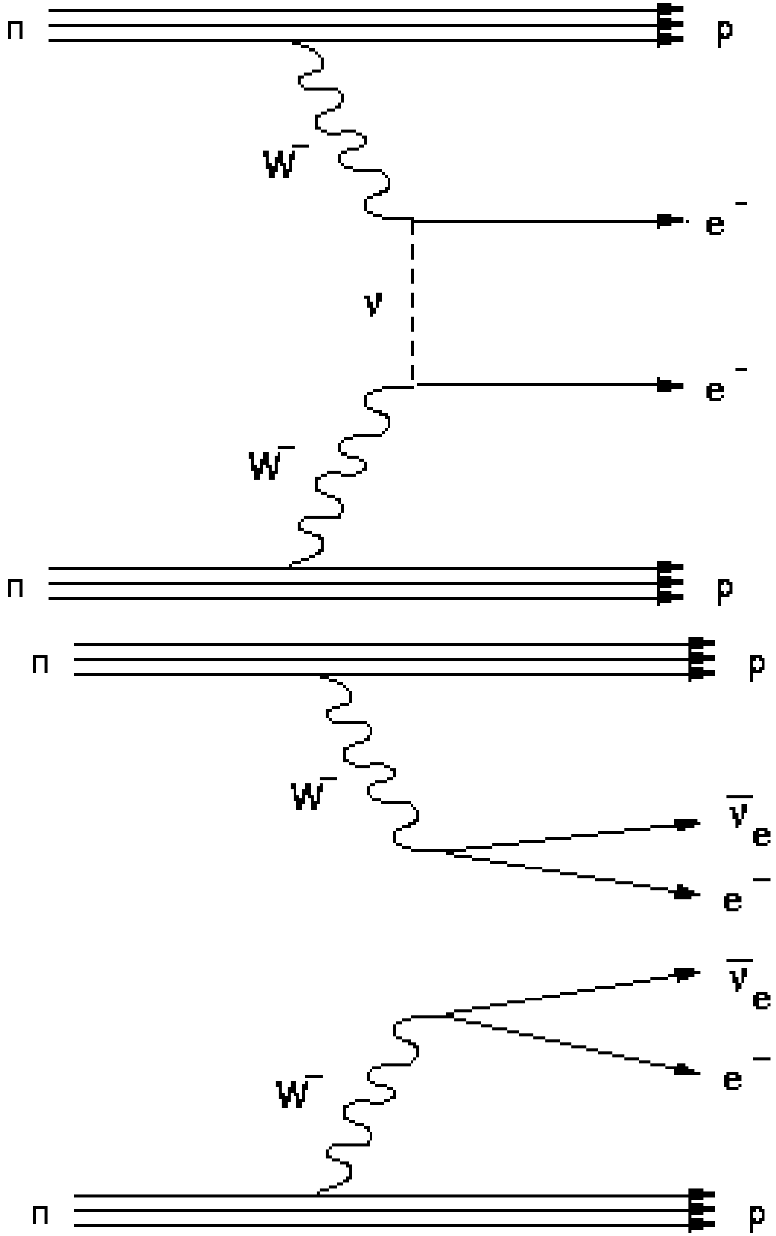
Neutrinoless double beta decay

only for Majorana Neutrinos

$\nu = \nu^c$





Phase Space

$10^6 \times 2\nu\beta\beta$

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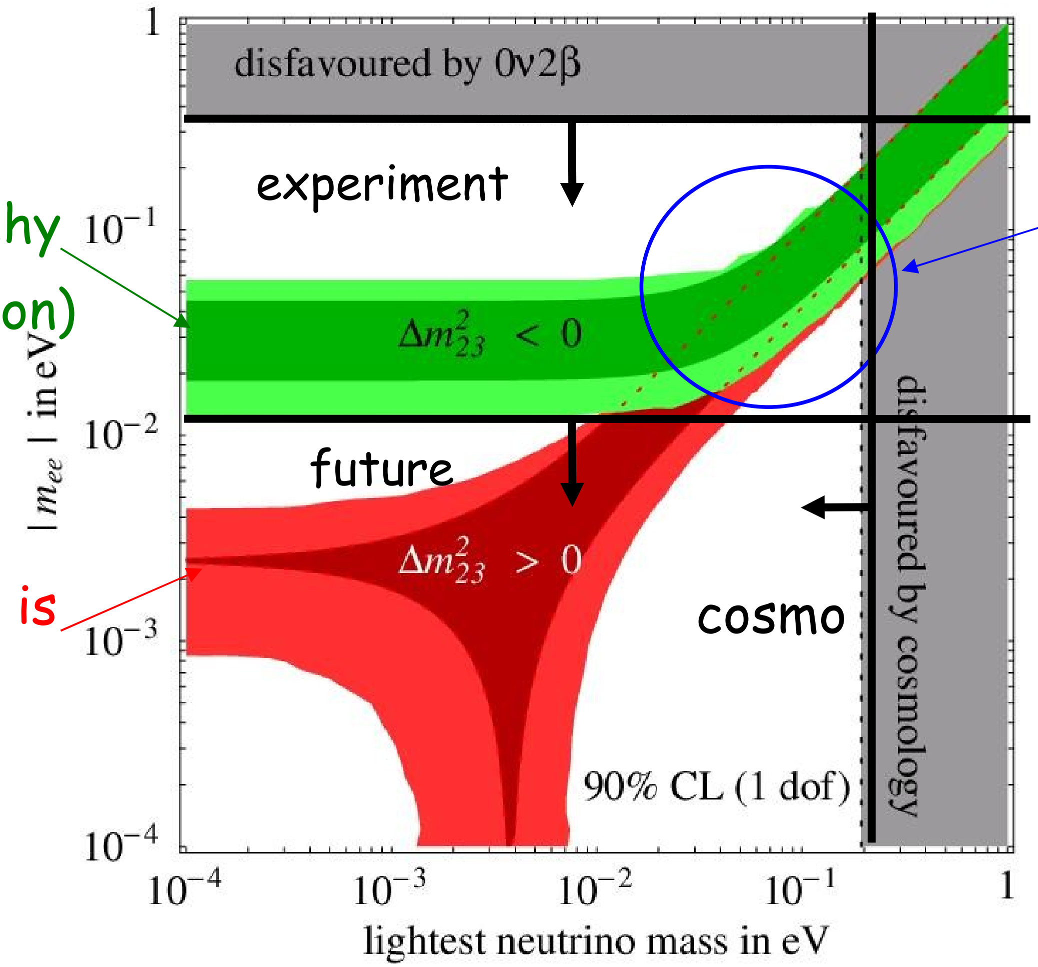
ββ0nu & neutrino masses

Inverted hierarchy is TESTABLE (1ton)

Normal hierarchy is NOT TESTABLE (100ton)



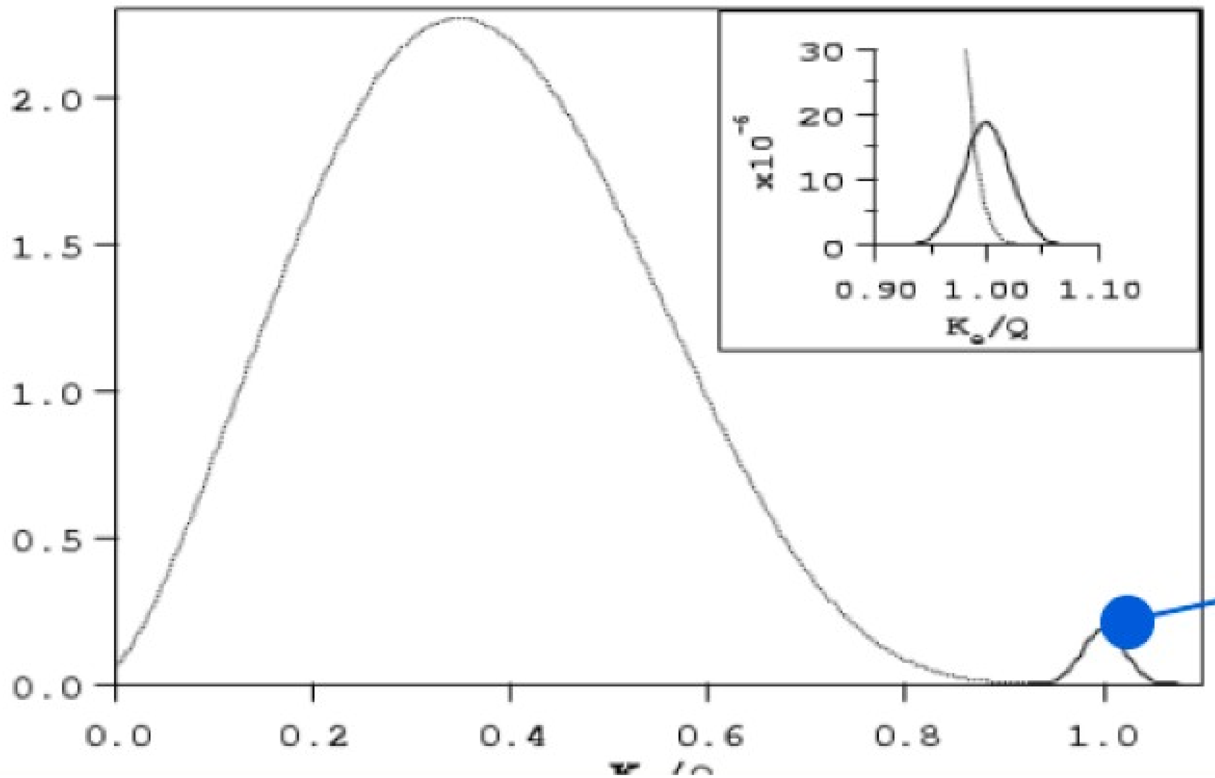
Approx. degeneracy is TESTABLE

$$|m_e| = \sum_i U_{ei}^2 m_i$$

Majorana mass of the electron neutrino

from: F. Feruglio, A. Strumia, F. Vissani ('02)

Experimental signature



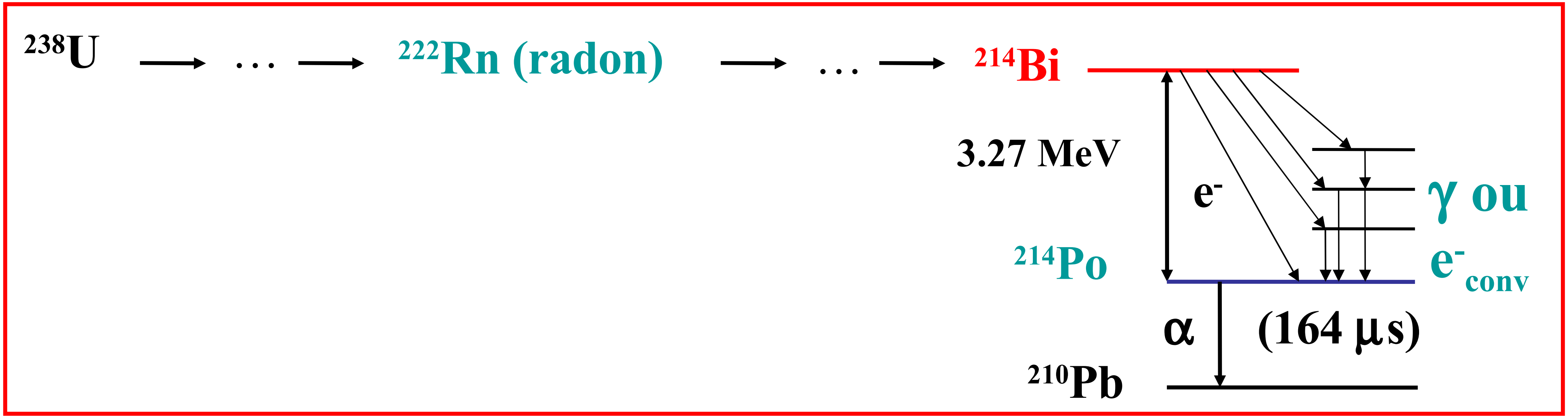
Neutrinoless bb decay

Other background sources: Separation from ββ0nu improved by explicit 2e- signature

ββ0nu: Spike at the end-point of decay nucleus, convoluted with experimental resolution

ββ0nu: Continuous spectrum. Separation from bb0nu depends on detector resolution

Radioactive Natural Chains



$^{238}U \rightarrow \ldots \rightarrow$ ^{222}Rn (radon) $\rightarrow \ldots \rightarrow$ ^{214}Bi

3.27 MeV

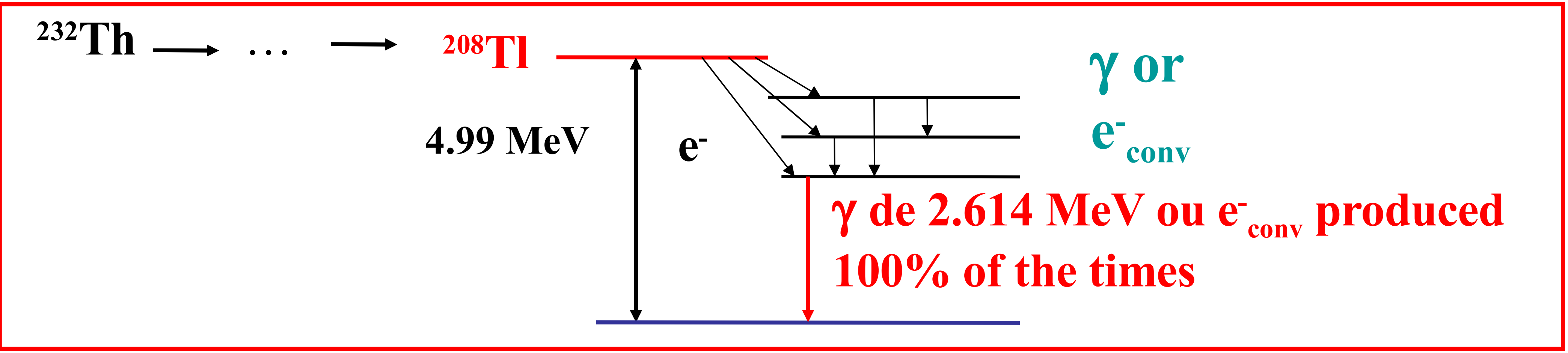
e^-

γ ou e^-_{conv}

^{214}Po

α (164 µs)

^{210}Pb



$^{232}Th \rightarrow \ldots \rightarrow$ ^{208}Tl

4.99 MeV

e^-

γ or e^-_{conv}

γ de 2.614 MeV ou e^-_{conv} produced 100% of the times

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Non ββ2nu backgrounds

If ^{214}Bi et ^{208}Tl are present in the sources

$e^- + \gamma$ **(Compton)** $\longrightarrow e^- + e^-$

$e^- + e^-_{conv}$

e^- **(Möller)** $\longrightarrow e^- + e^-$

"Internal Backgrounds"

If ^{214}Bi et ^{208}Tl are present in the environment

γ interacts with the source $\longrightarrow e^- + e^-$ **(double Compton, or Compton + Möller)**

"External Background"

In addition a neutron produced around the detector can thermalize in a hydrogen-rich material and produce phtons by radioactive capture. Neutrons are dangerous. Produced by fission but also from muon spallation. Muon flux at lab and its influence in neutron background must be well understood.

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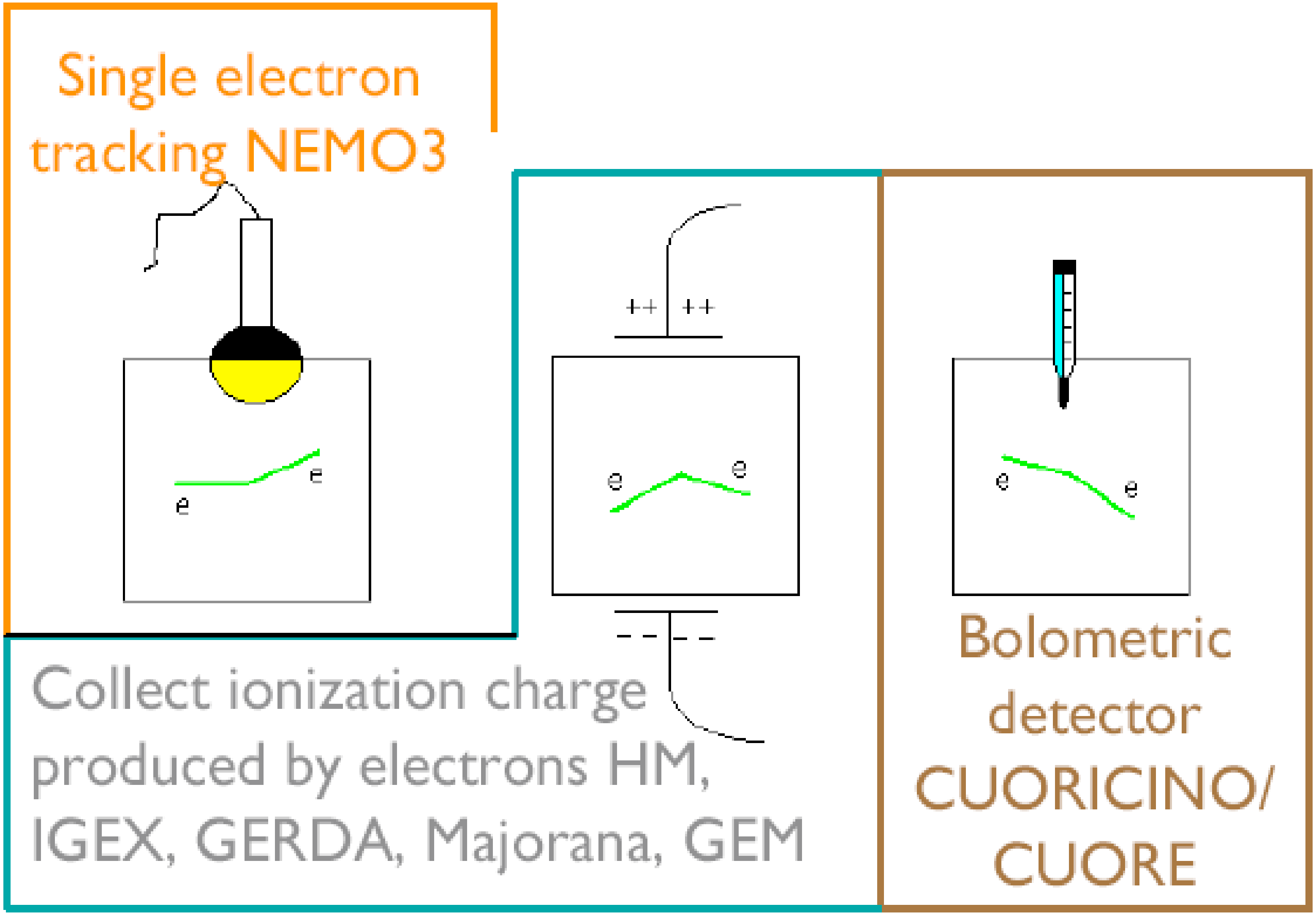
Experiments



Single electron tracking NEMO3

Collect ionization charge produced by electrons HM, IGEX, GERDA, Majorana, GEM

Bolometric detector CUORICINO/ CUORE

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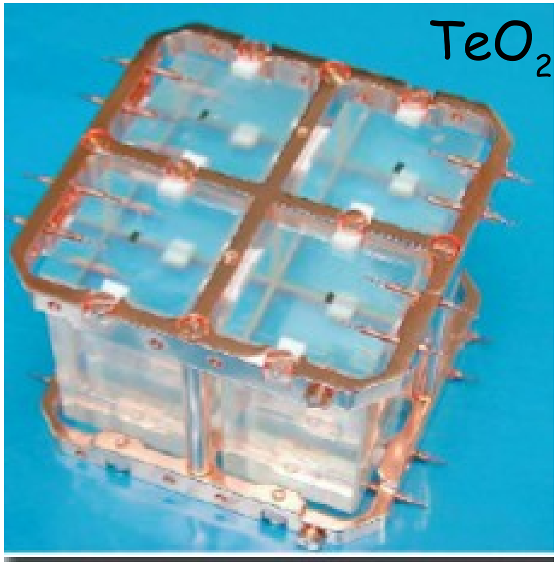
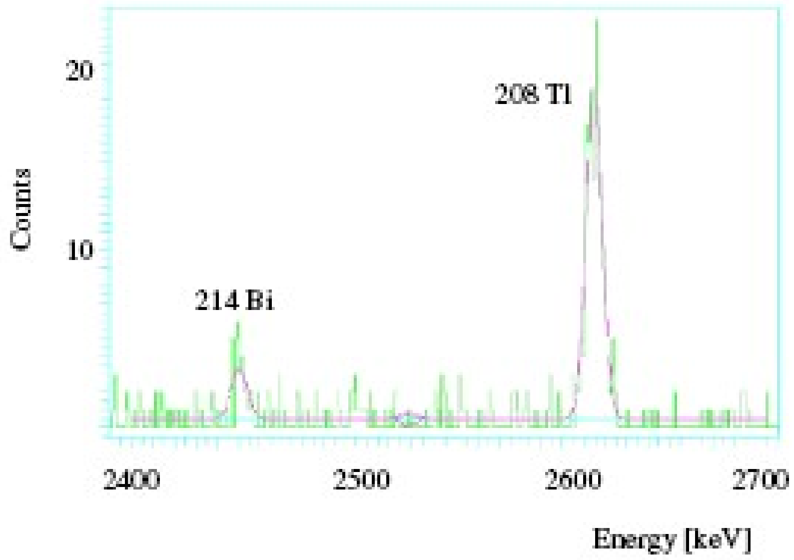
Experimental approaches: Source = Detector (SED)





Bolometers (Cuore, Cuoricino) and the "classical" Ge semiconductor detectors.

Advantages: Excellent energy resolution, excellent efficiency, compact.

Disadvantages: No pattern signature (2e- not observed, but only total energy deposited), difficulty to reject non ββ background, limited to a single isotope per experiment.

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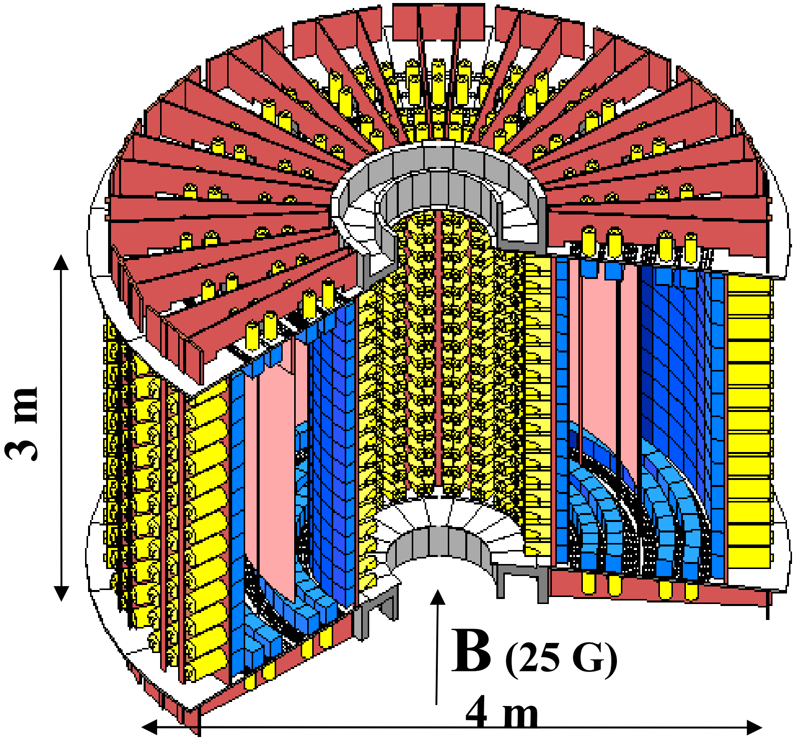
Experimental approaches: Track-Calo (TC)

Source foils + tracker+ calorimeter



First practical example: Nemo detector

Advantages: Pattern signature observed, particle ID allows rejection of external backgrounds, several sources (or optimal source) in the same detector

Disadvantages: Modest energy resolution due to calorimeter resolution and energy losses in source

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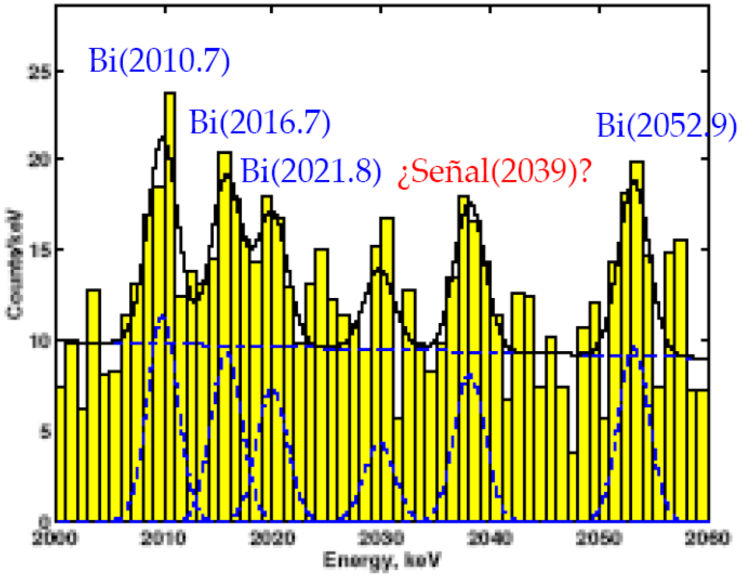
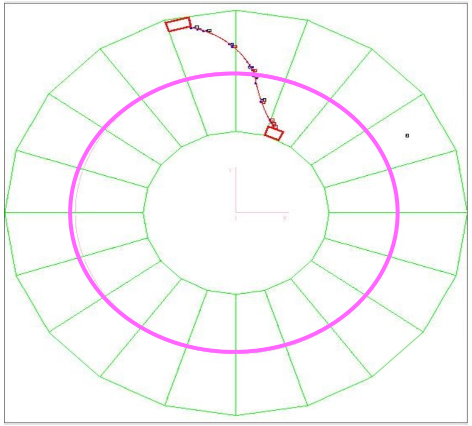
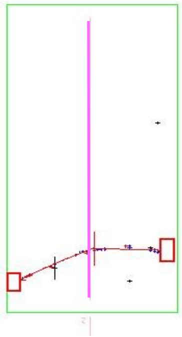
Towards discovery?





Top view



Side view

Both approaches are valid and not really in competition: They are rather complementary approaches to maximize the possibility of discovery.

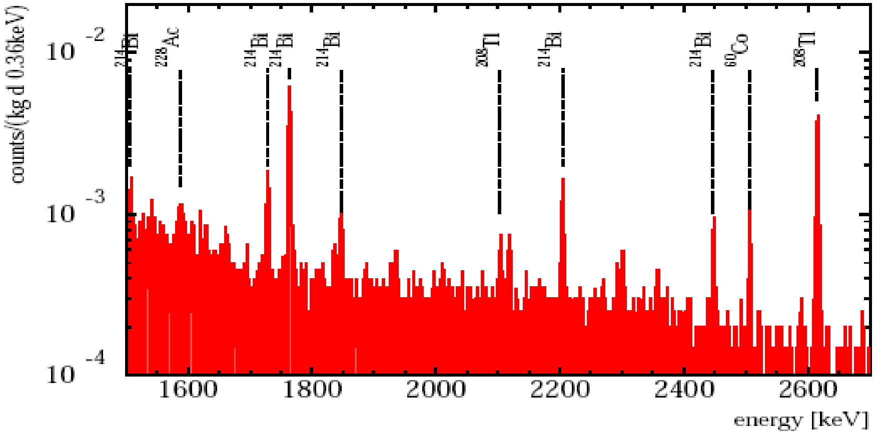
Dominating background for TC is bb2nu while for SED is external backgrounds.

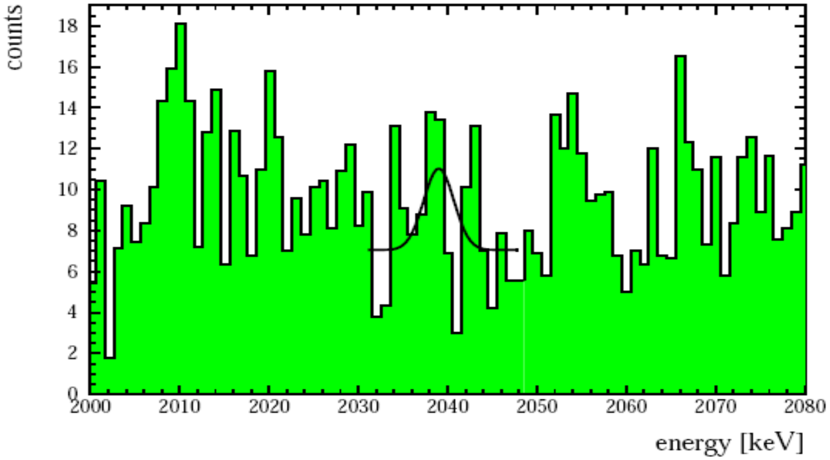
Uncertainties in nuclear matrix elements. One would like no to place all eggs in the same basket.

Think discovery, not exclusion plot!

A very controversial claim

- Heidelberg Moscow experiment on ^{76}Ge
- Part of the collaboration claims m_ν=0.2-0.6eV





IGEX

- Also ^{76}Ge give upper bound on mn between 0.33 and 1.35 eV depending on nuclear matrix element model (partially exclude HM)

$$T_{1/2}(0\nu) > 1.57 \times 10^{25}\ \text{yr (90\% C.L.)}$$

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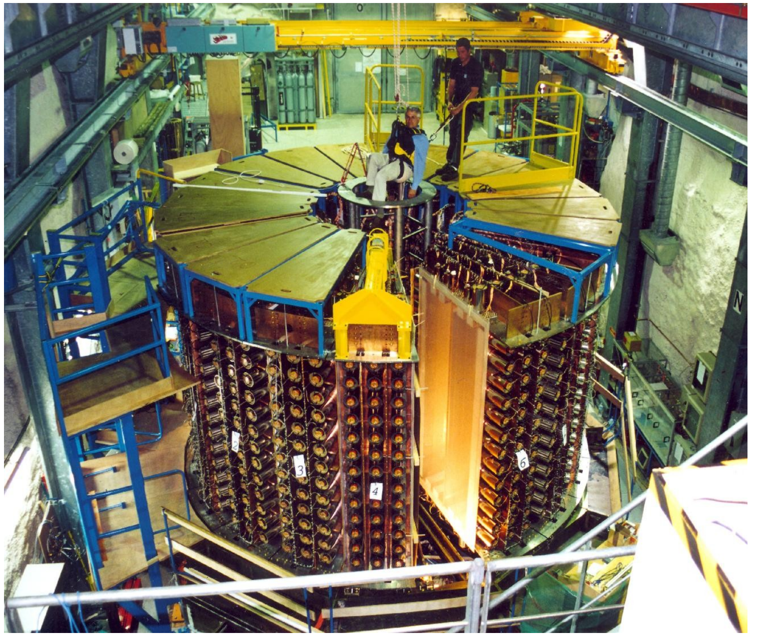
NEMO 3: Neutrino Ettore Majorana Observatory

(France, UK, Spain, Russia, USA, Japan, Czech Republic, Ukraine, Finland)



Tracking detector: drift chamber (6180 Geiger cell)
σ_t = 5 mm, σ_z = 1 cm (vertex)

Calorimeter (1940 plastic scintillators– Low radioactive PMTs)
Energy Resolution FWHM=14% (1 MeV)

Shieldings against gammas and neutrons
Magnetic field for charge identification
High radiopurity materials

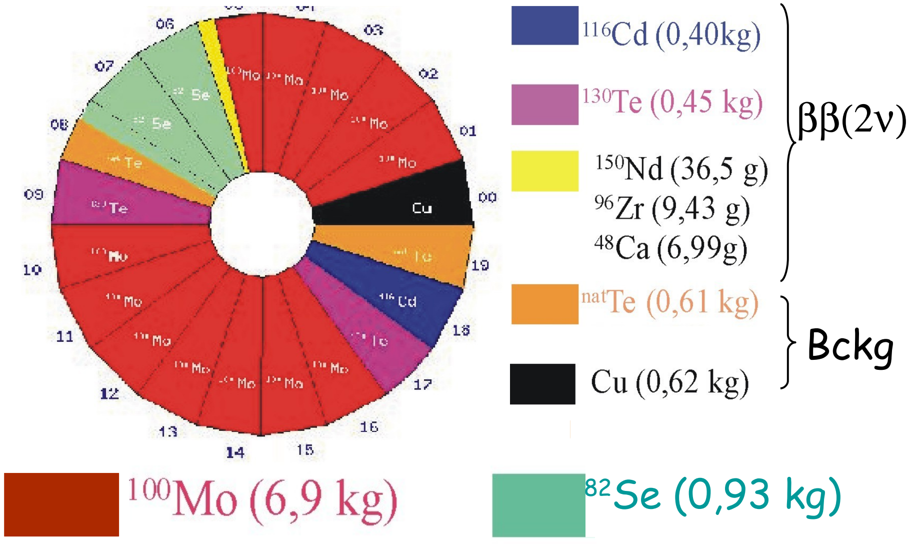
Identification e^-, e^+, γ, α

Efficiency : 8% in the 2.7 – 3.2 windows energy region

Running at Modane underground laboratory since 2003

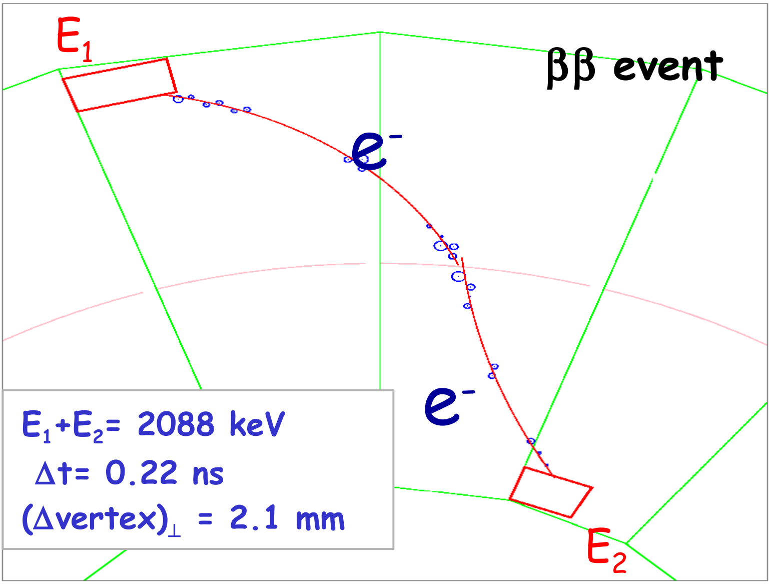
Multi-source detector

ββ sources (thickness ~ 60 mg/cm²)



^{100}Mo (6,9 kg) ^{82}Se (0,93 kg)

Unique feature: measurement of all kinematic parameters: individual energies and angular distribution



E_1+E_2= 2088 keV
Δt= 0.22 ns
$(\Delta\text{vertex})_\perp$ = 2.1 mm

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Nemo results

- m<0.7-2.8eV for ^{100}Mo (7kg)
- m<1.7-4.9eV for ^{82}Se (2kg)
- Proof of principle – does not exclude H-M
- Waiting for super-Nemo

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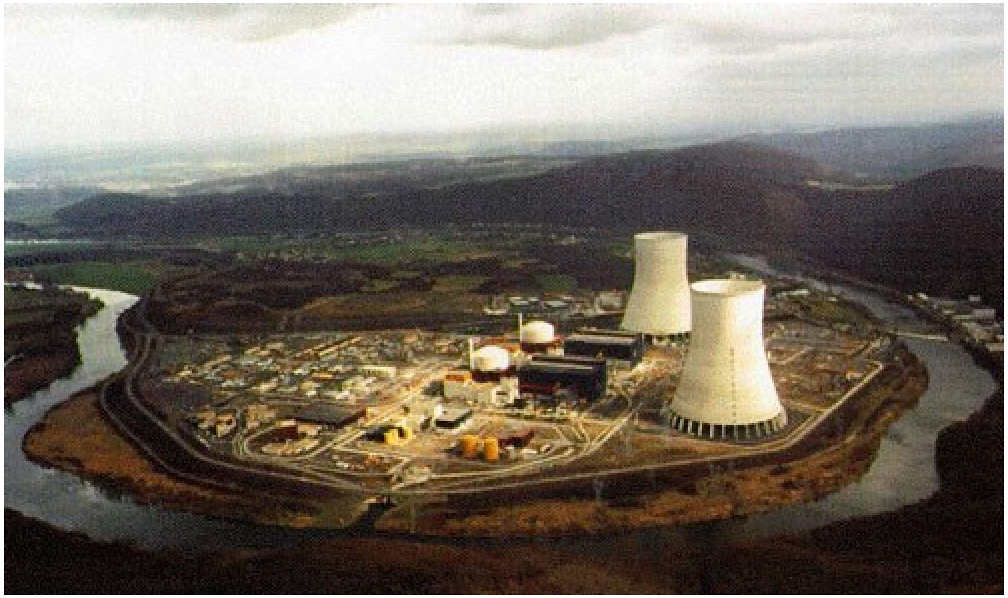
Reactors

- Double CHOOZ: 2 identical detectors near and far to measure θ_{13} with low systematics



$$P(\overline{\nu}_e \text{ Disappearance}) =$$

$$= \sin^2 2\theta_{13} \sin^2[1.27\Delta m^2_{atm}(eV^2)L(km)/E(GeV)]$$

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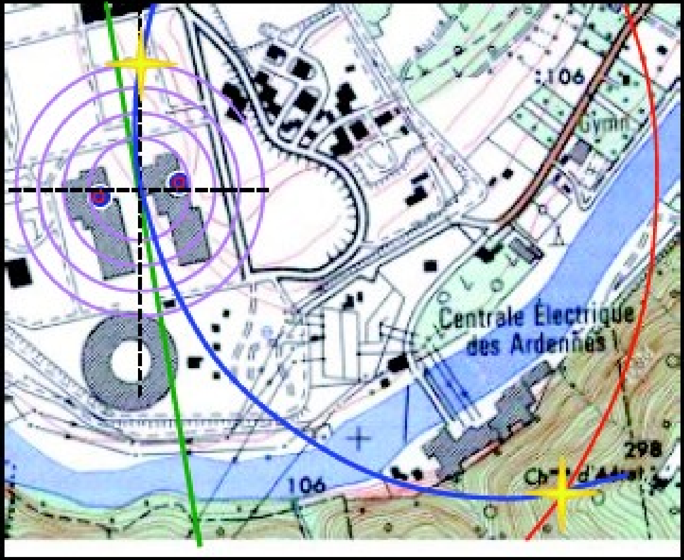
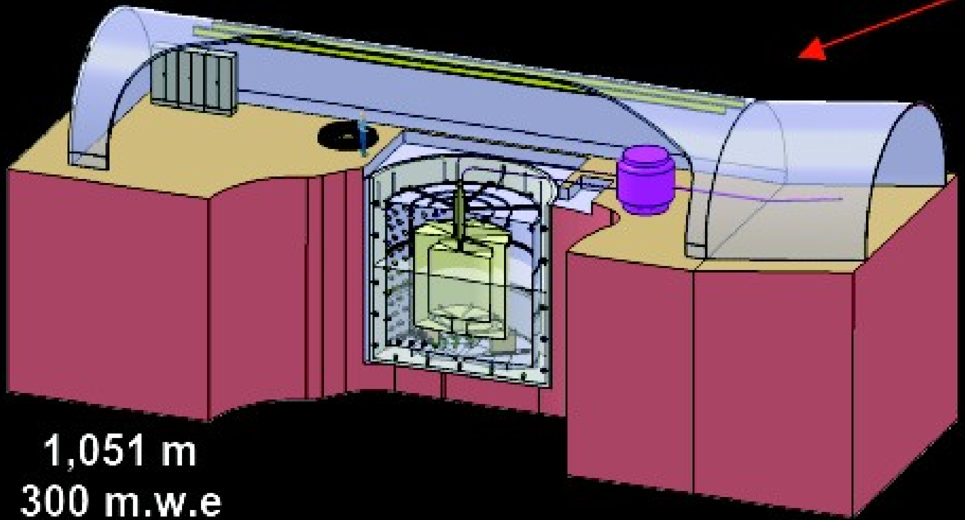
1 km site

274 m site

Integration to start mid-2007

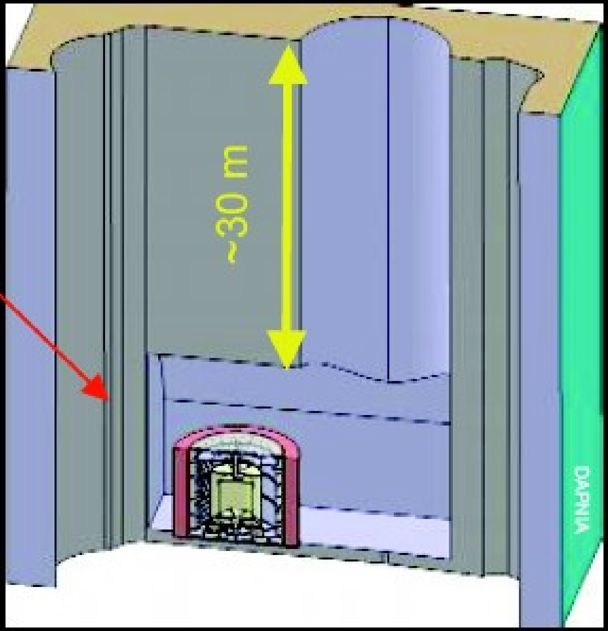


μ flux x ~10



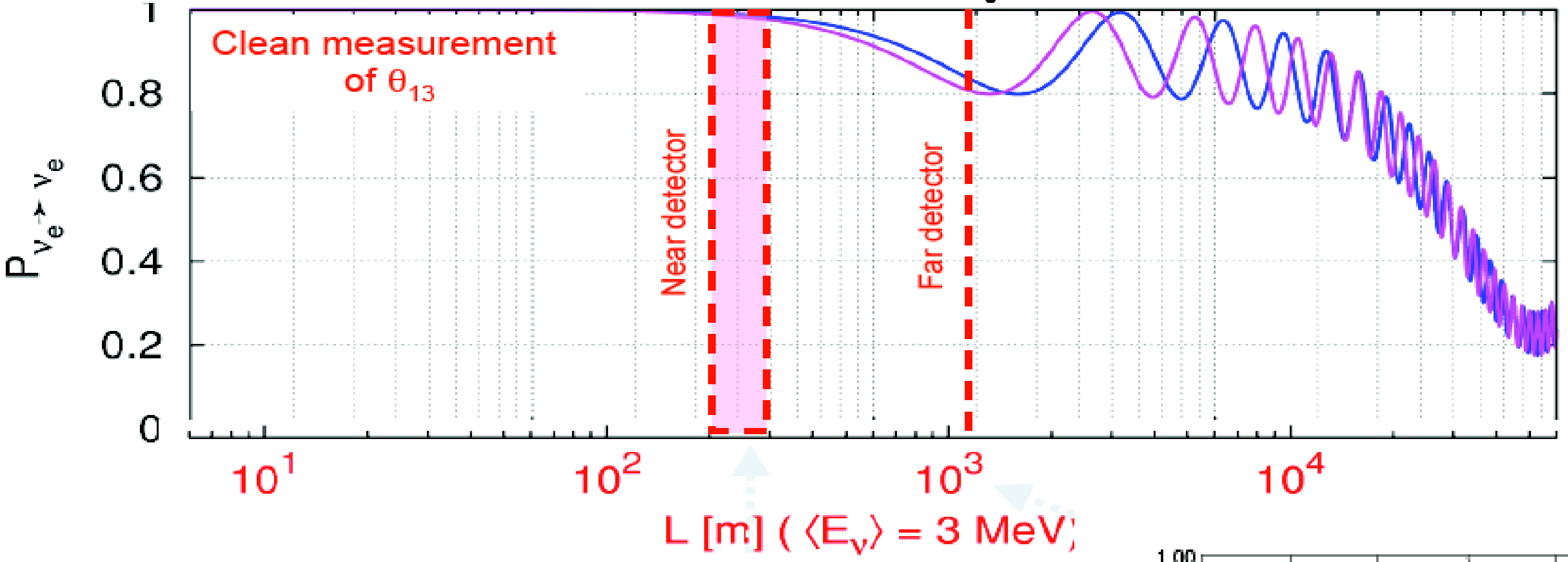
1,051 m
300 m.w.e
15 200 events/y

274 m
80 m.w.e
162 260 events/y



Integration end of 2009

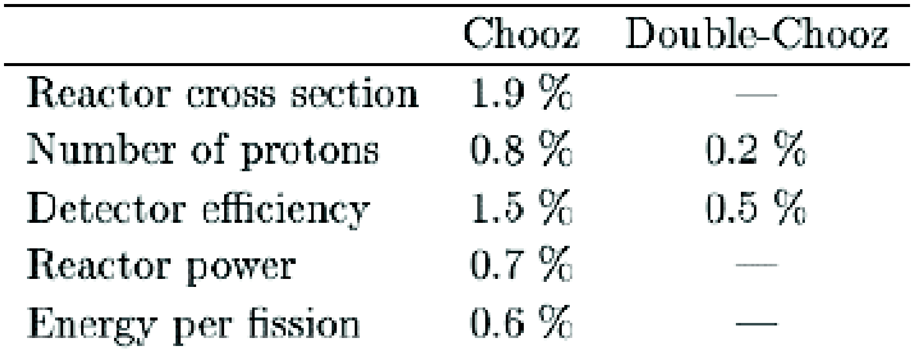
Double Chooz expected sensitivity



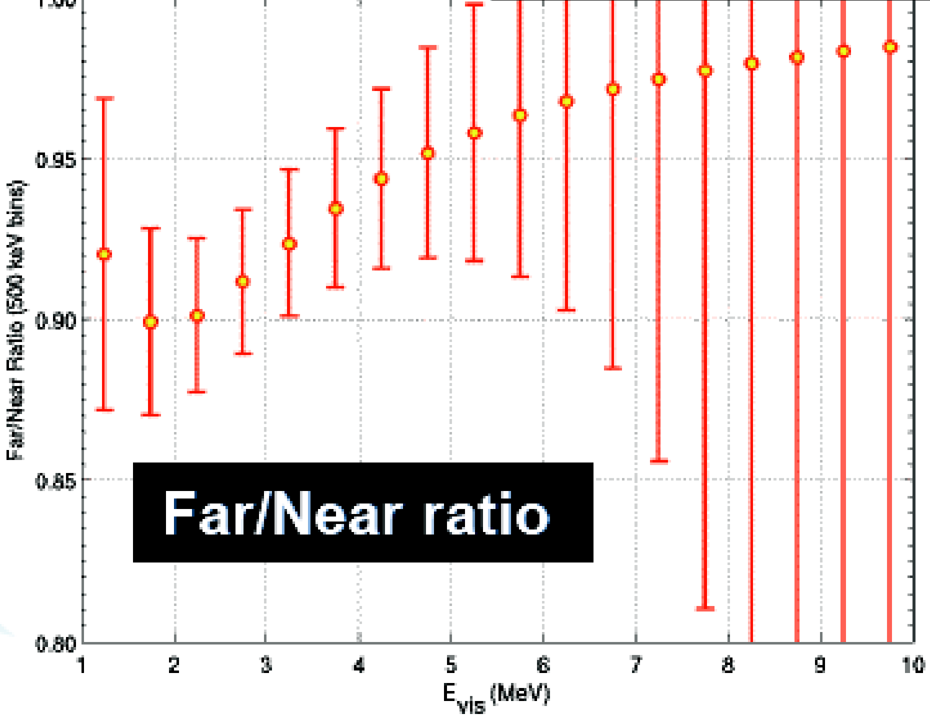
Δm^2_{atm} = 3.0 10^{-3} eV^2

$\sin^2(2\theta_{13})=0.12$

Systematics aim at <0.6%



	Chooz	Double-Chooz
Reactor cross section	1.9 %	—
Number of protons	0.8 %	0.2 %
Detector efficiency	1.5 %	0.5 %
Reactor power	0.7 %	—
Energy per fission	0.6 %	—



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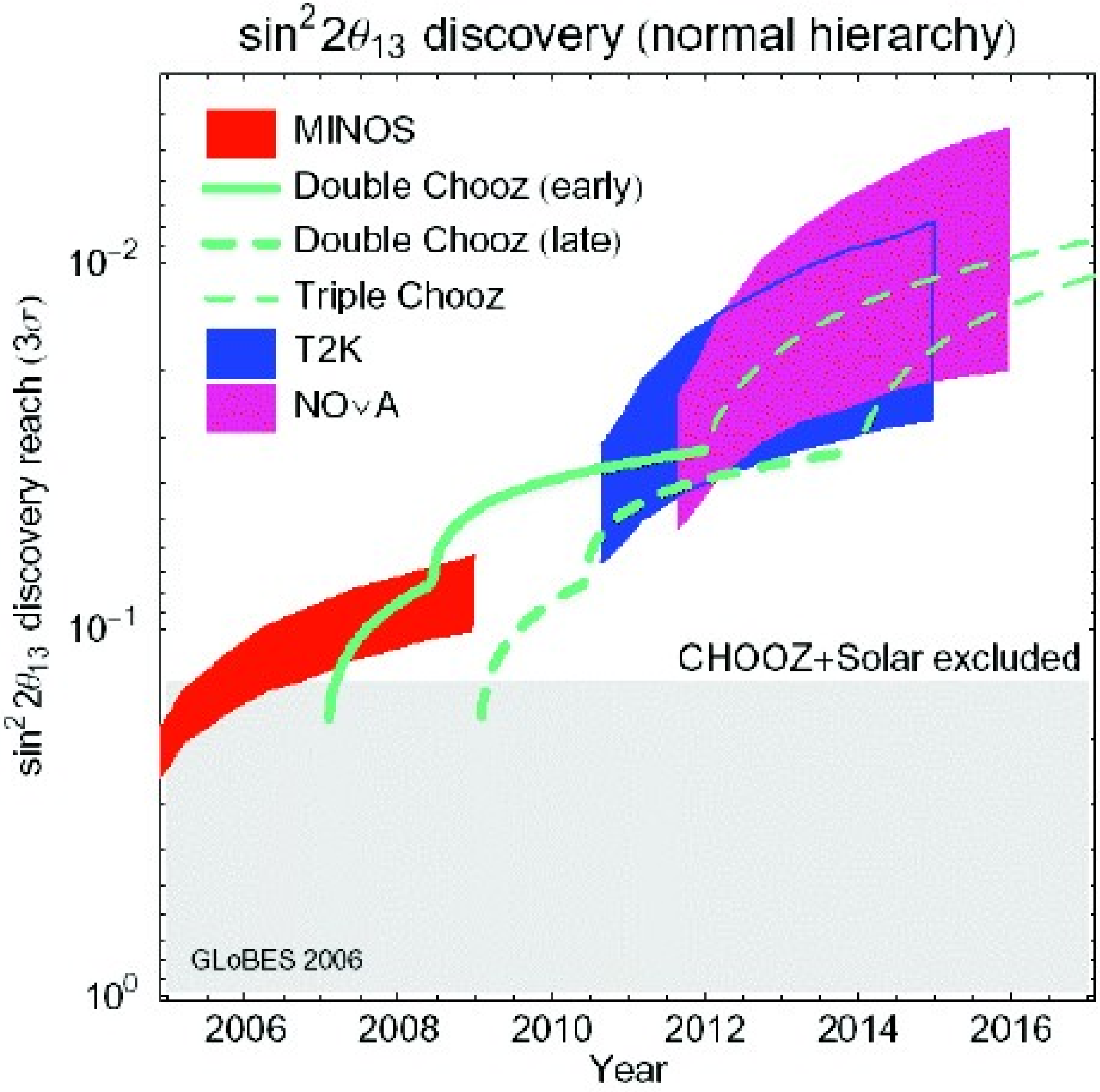
$\mathrm{Sin}^2 2\theta_{13}$ future reach



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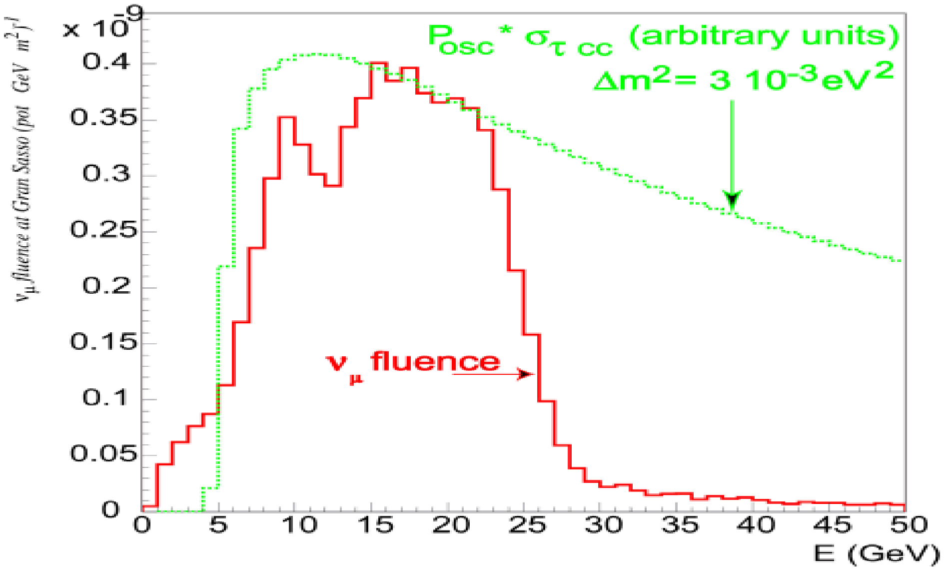
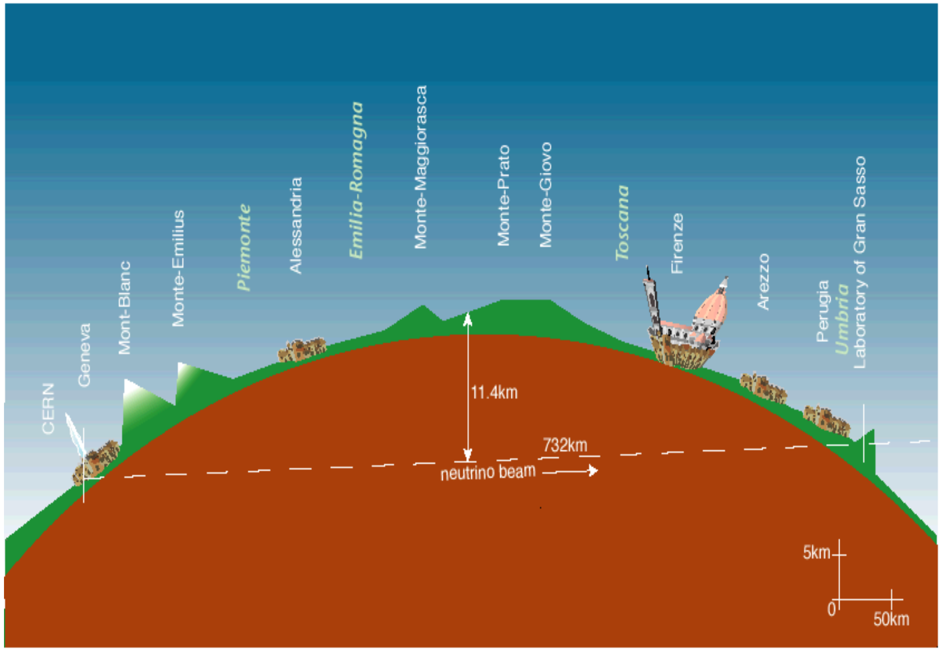
Just Starting

Provide evidence for $\nu_\mu \rightarrow \nu_\tau$ oscillations in the region of atmospheric neutrinos by looking for ν_τ appearance in a pure ν_μ beam





CNGS PROGRAM:

Base line 762km

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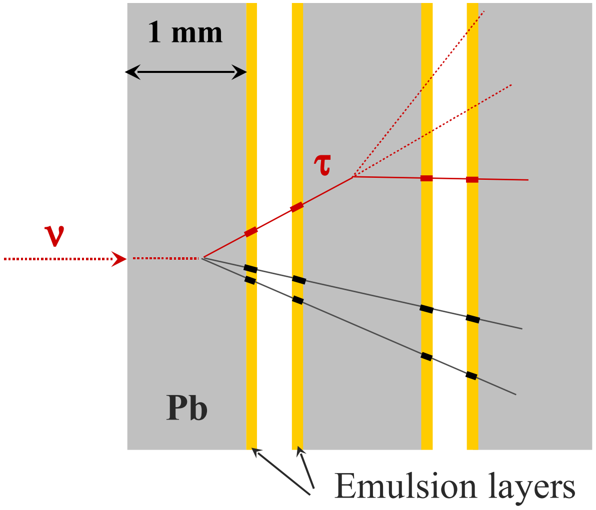
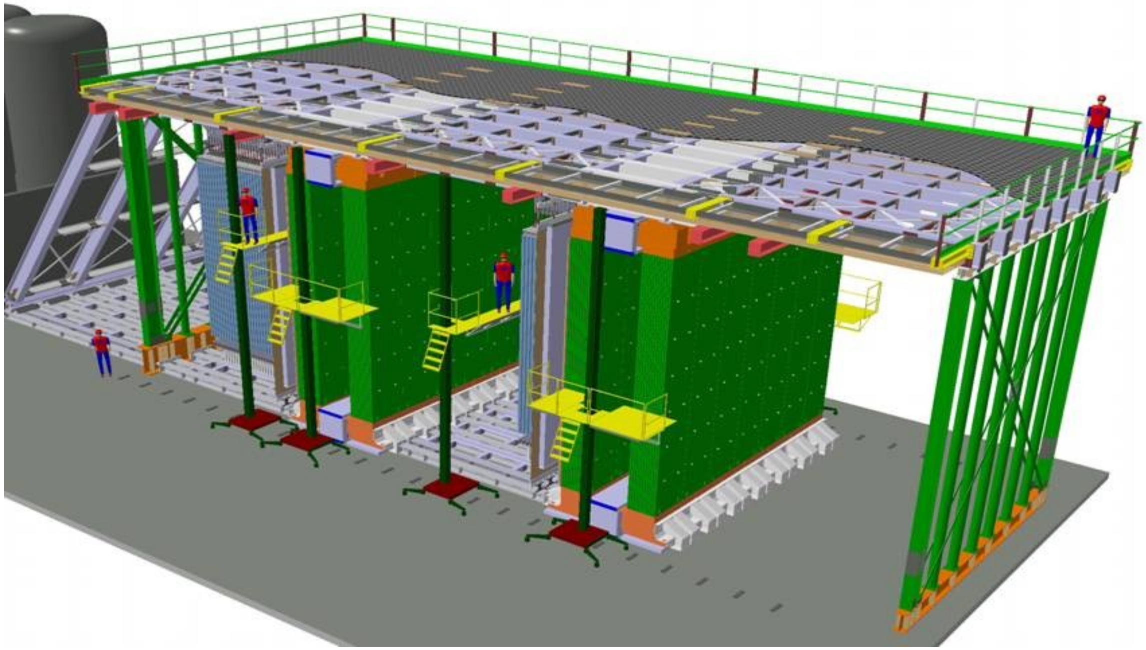
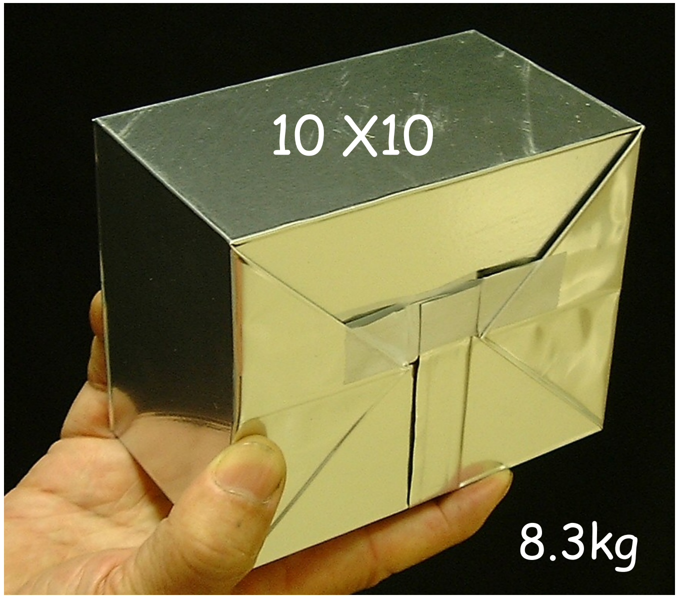
Opera







Expect a few signal events per year, depending on mixing parameters. With negligible backgrounds. A very challenging experiment!

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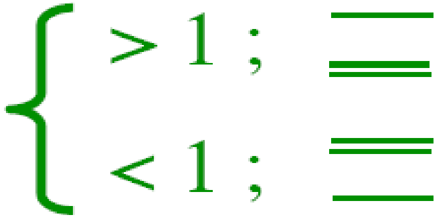
Sensitivity to hierarchy ?

- Matter effects : enhance mixing for ν_e and suppress it for anti-ν_e mass if the hierarchy is normal.
- Assymetry not from CP... but need to resolve ambiguity

Sign[m^2(—) - m^2(═)]

$$\frac{P(\nu_\mu \to \nu_e)}{P(\bar{\nu}_\mu \to \bar{\nu}_e)} \cong \frac{1+S(E/6GeV)}{1-S(E/6GeV)}$$



→ Need long baseline ~3000km and 1GeV beams

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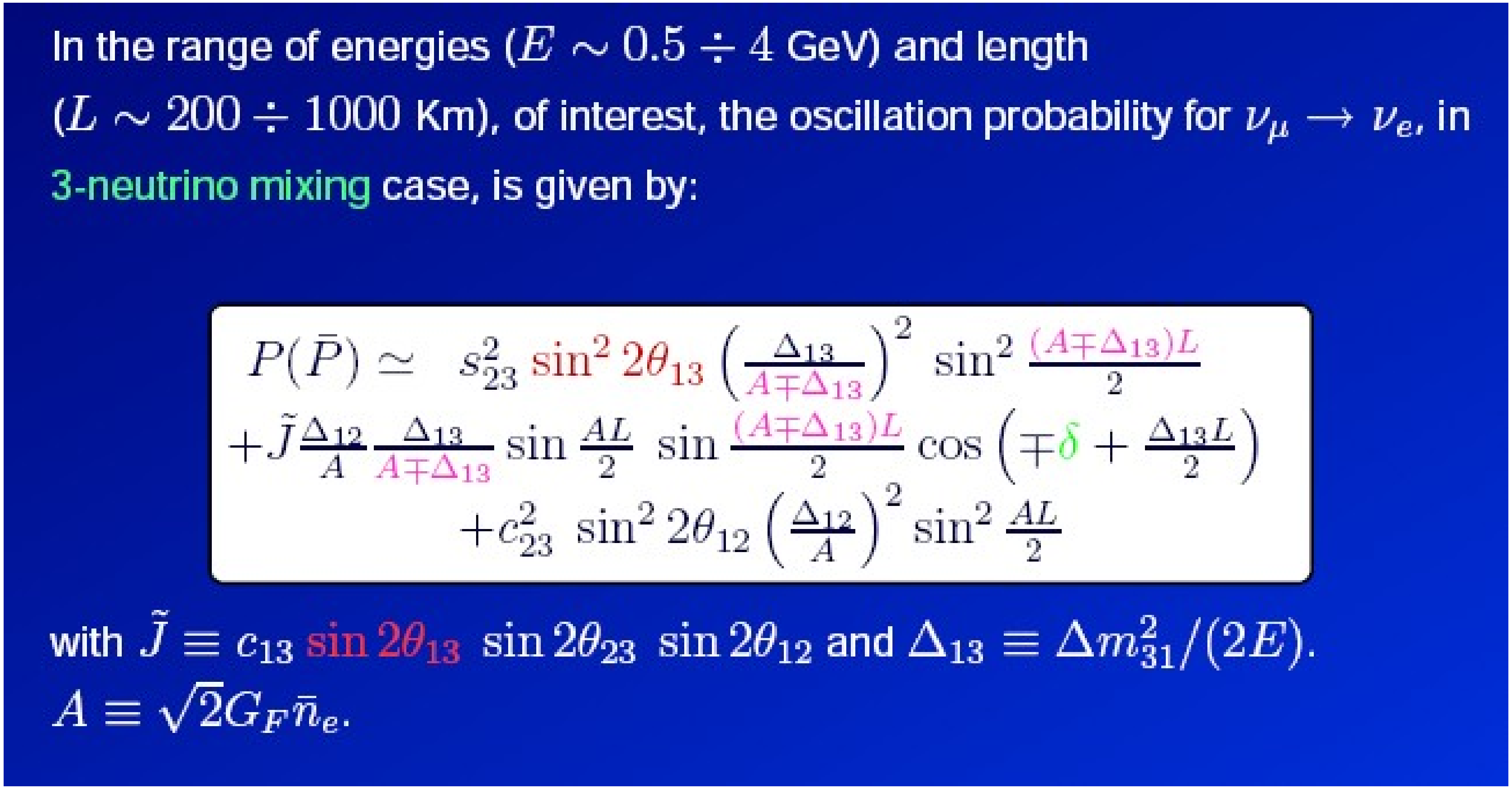
Future Long baselines:



In the range of energies ($E \sim 0.5 \div 4$ GeV) and length ($L \sim 200 \div 1000$ Km), of interest, the oscillation probability for $\nu_\mu \to \nu_e$, in 3-neutrino mixing case, is given by:

$$
\begin{aligned}
P(\bar{P}) \simeq \; & s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{A \mp \Delta_{13}}\right)^2 \sin^2 \frac{(A \mp \Delta_{13})L}{2} \\
& + \tilde{J} \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{A \mp \Delta_{13}} \sin \frac{AL}{2} \sin \frac{(A \mp \Delta_{13})L}{2} \cos\left(\mp\delta + \frac{\Delta_{13} L}{2}\right) \\
& + c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2 \frac{AL}{2}
\end{aligned}
$$

with $\tilde{J} \equiv c_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12}$ and $\Delta_{13} \equiv \Delta m_{31}^2/(2E)$.
$A \equiv \sqrt{2} G_F \bar{n}_e$.

- Measure in nu and anti-nu at different energies and different distances

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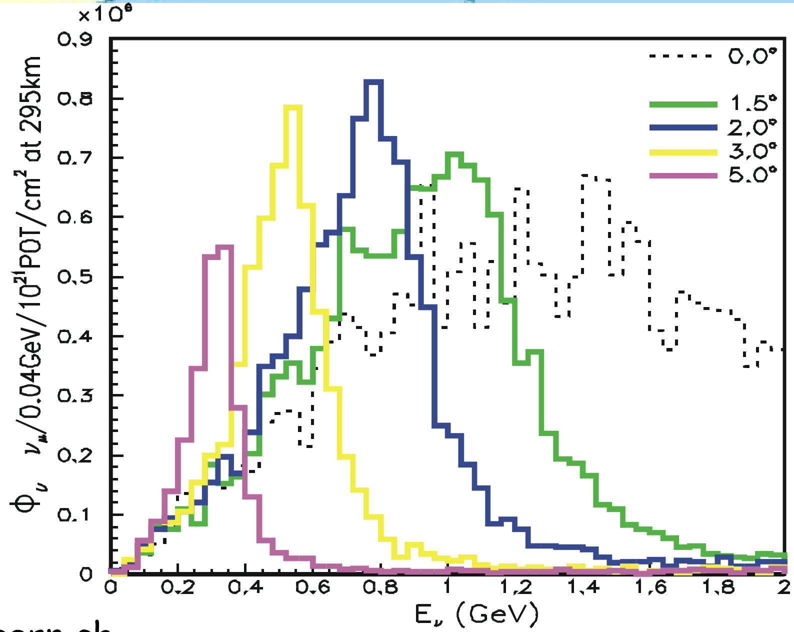
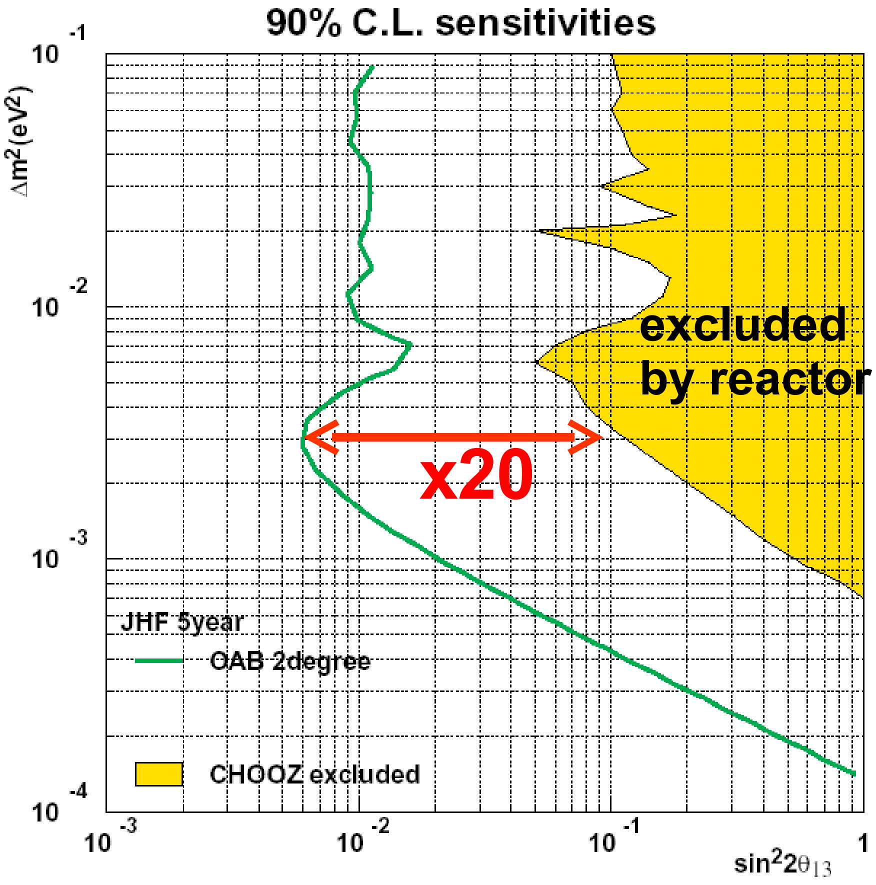
T2K

- Off axis search for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$
- Less ν_e contamination
- Narrow band beam tuned to expected oscillation maximum: 0.8GeV



Sensitivities in first phase(5yrs)

Search for ν_e appearance



$$\sin^2 2\theta_{\mu e} \equiv \sin^2\theta_{23} \cdot \sin^2 2\theta_{13}$$

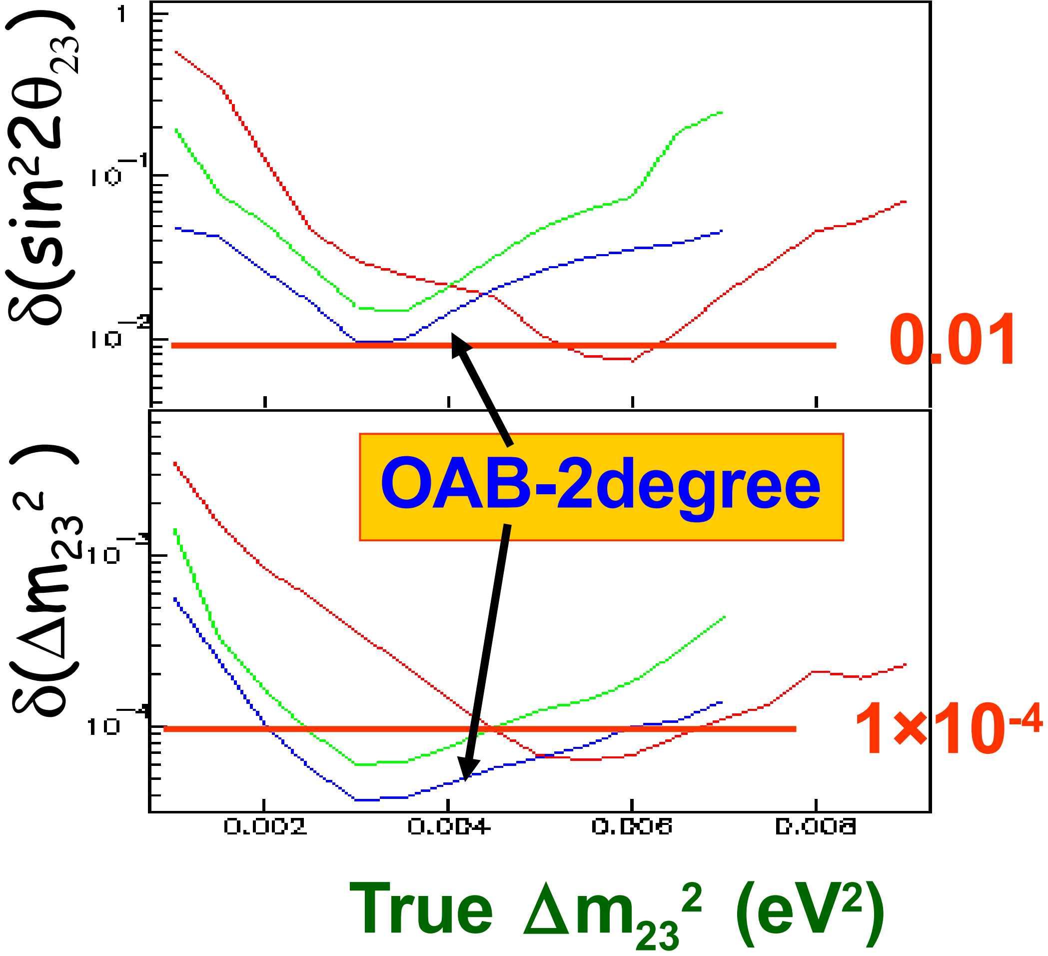
~0.5

Sensitive

$\sin^2 2\theta_{13} > 0.006$ (90%)

$\sin^2 2\theta_{13} > 0.018$ (3σ)

ν_μ disappearance



$\delta(\sin^2 2\theta) \sim 0.01$

$\delta(\Delta m^2)$ ~<1×10^{-4}

w/ beam MC, & full SK det. simulation

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β-beams

- Create pure ν_e or $\bar{\nu}_e$ beams by accelerating radioactive nuclei and letting decay in flight.
- R&D on how to produce such beams going
- No contamination from ν_μ.
- Would allow measurement of δ_{CP} and θ_{13}

^{6}He, ^{6}Li

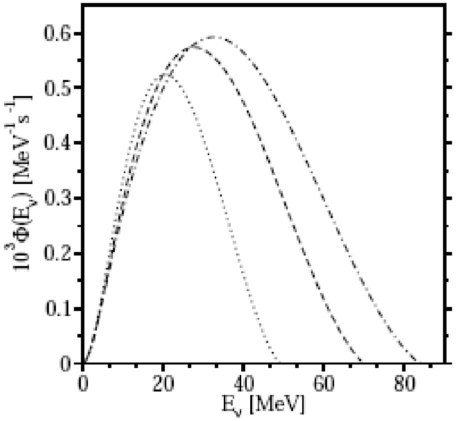

Figure 7. Anti-neutrino fluxes from low energy beta-beams. The curves correspond to $\gamma = 7$ (dotted line), $\gamma = 10$ (broken line) and $\gamma = 12$ (dash-dotted line) for the boosted helium-6 ions. Similar curves are obtained for neutrinos from neon-18 ions. The detector is located at 10 m from a small devoted storage ring (see Section III) (Balantekin *et al* 2006a).

hep-ph/060533

CP and mass hierarchy reach

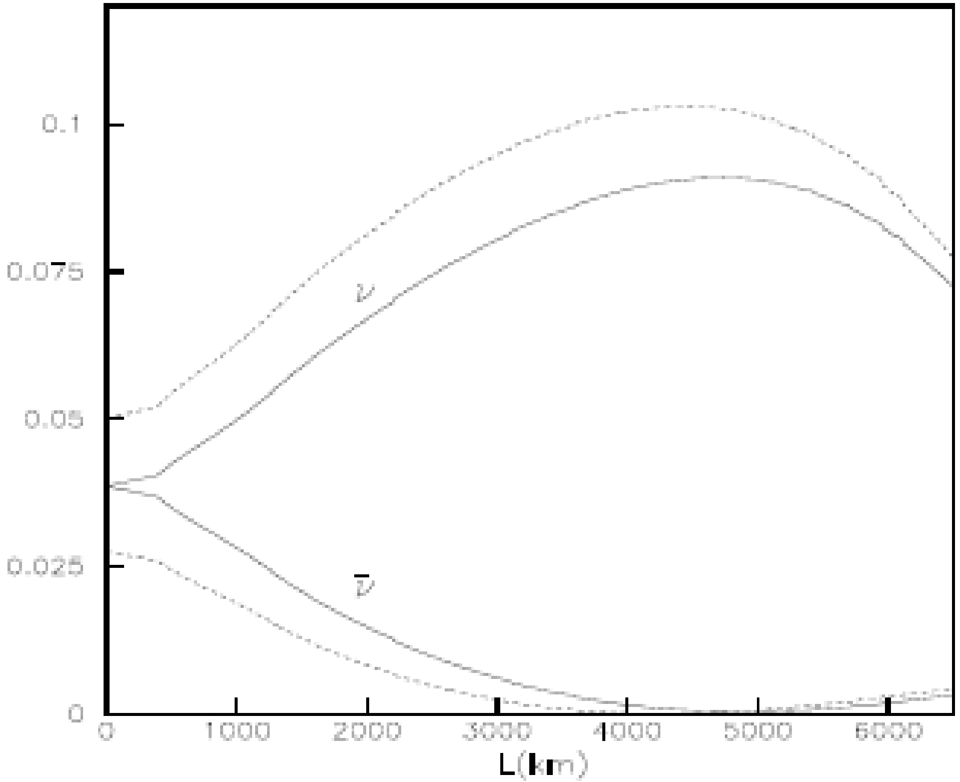

Figure 5. Comparison of the $\nu_e \rightarrow \nu_\mu$ and the $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ appearance oscillation probability, as a function of the baseline distance L between the source and the detector, evaluated at the first atmospheric oscillation maximum $E/L = |\Delta m^2_{23}|/2\pi$. From about $L = O(1000)$ km, matter effects become significant and can be exploited to extract the sign of Δm^2_{23}. The solid and dashed curves show the true CP violation effects for $\delta = 0°$ and $90°$.

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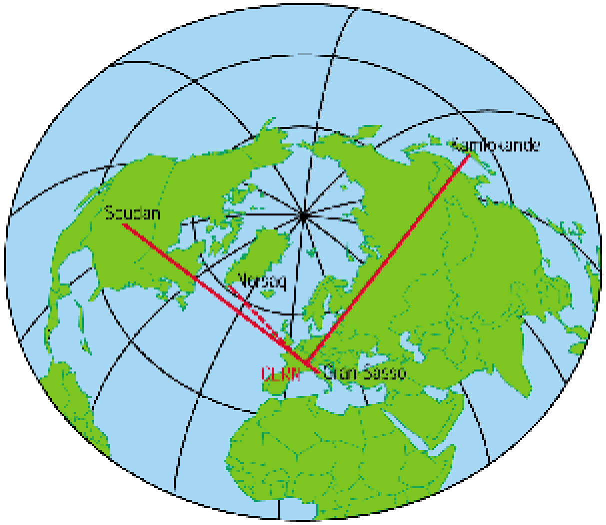
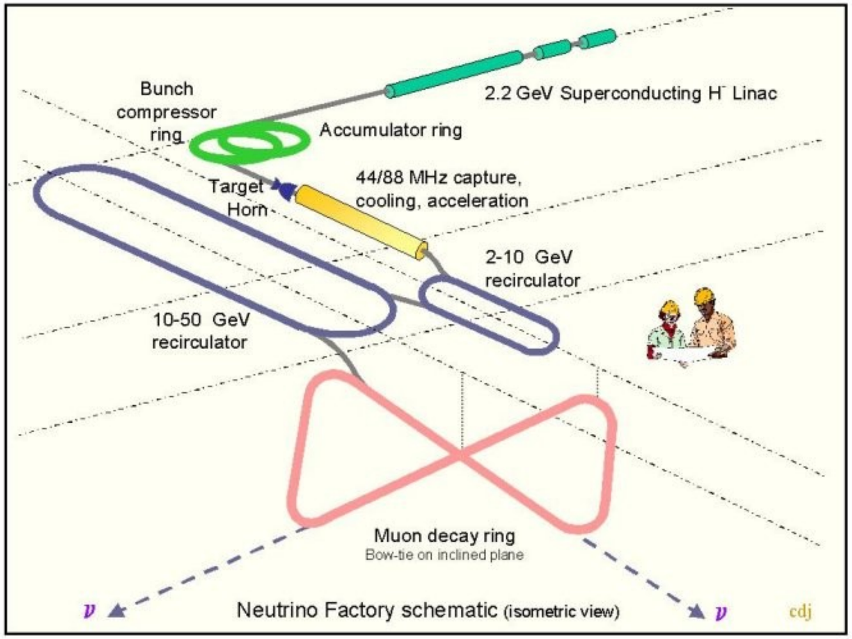
Neutrino Factories



3000km baselines

- ν_μ and anti-ν_e
- XOR anti-ν_μ and ν_e
- Contamination-free for appearance and disappearance experiments.
- Collimated beams



Neutrino Factory schematic (isometric view)

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Neutrino and Astrophysics

- Neutrinos are produced in stars, supernovae explosions
- They interact only weakly, not deflected by magnetic fields (as far as we know)
- Good probe candidate for distant objects

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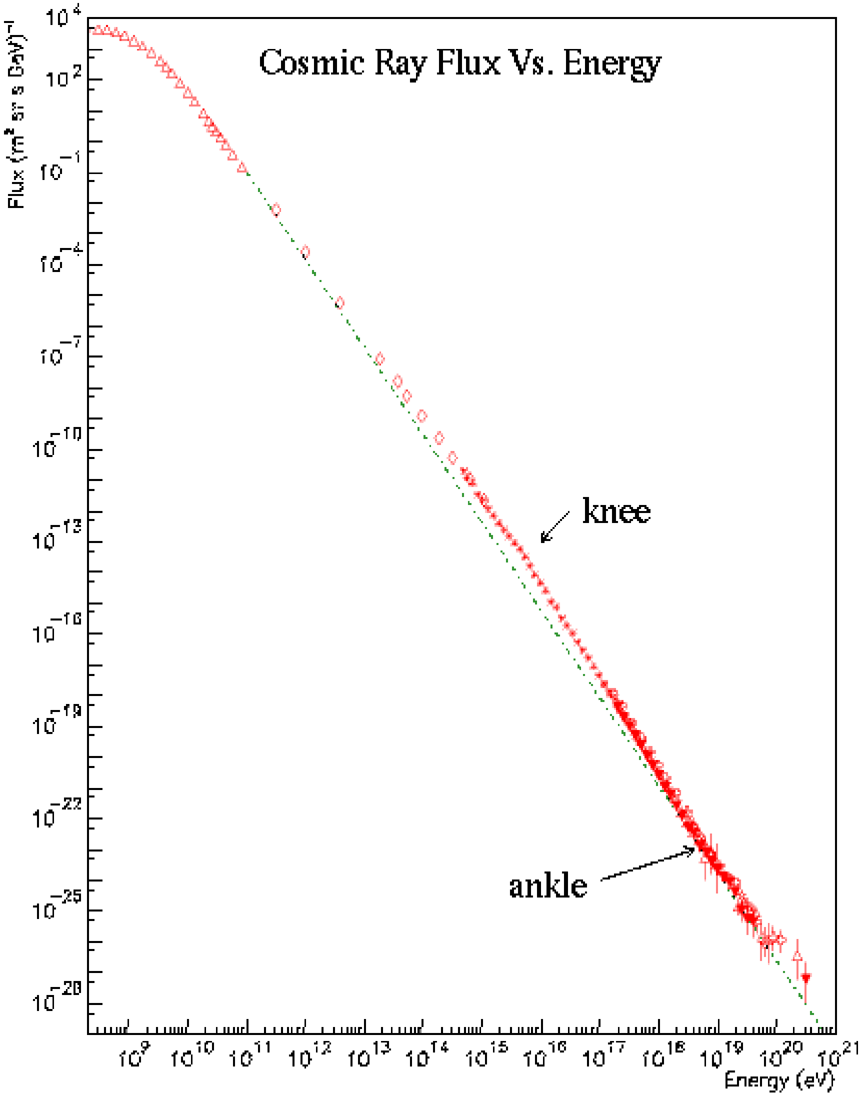
Cosmic Ray Flux



- $dN/dE \propto E^{-2}$
- $E > 10^{18}$eV ?
- Where do they come from?
- Acceleration mechanisms ?
- How do they reach the earth without interacting ?

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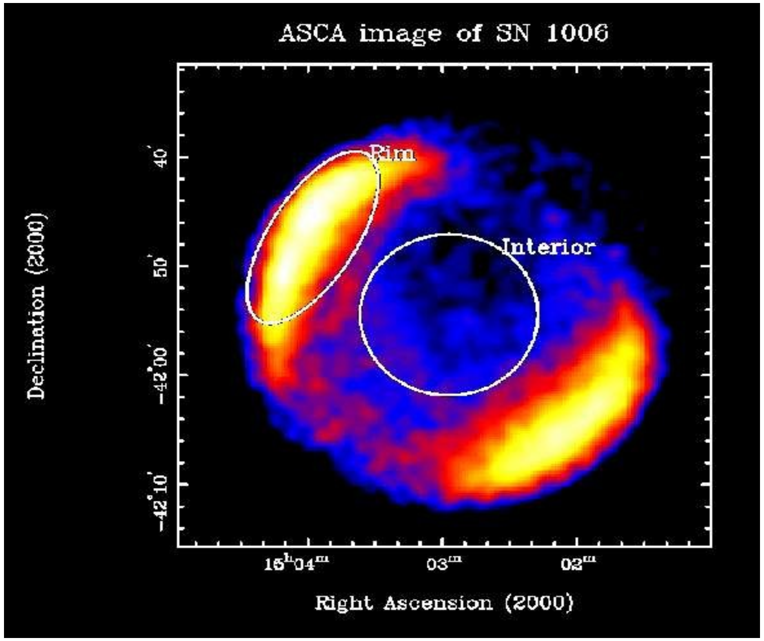
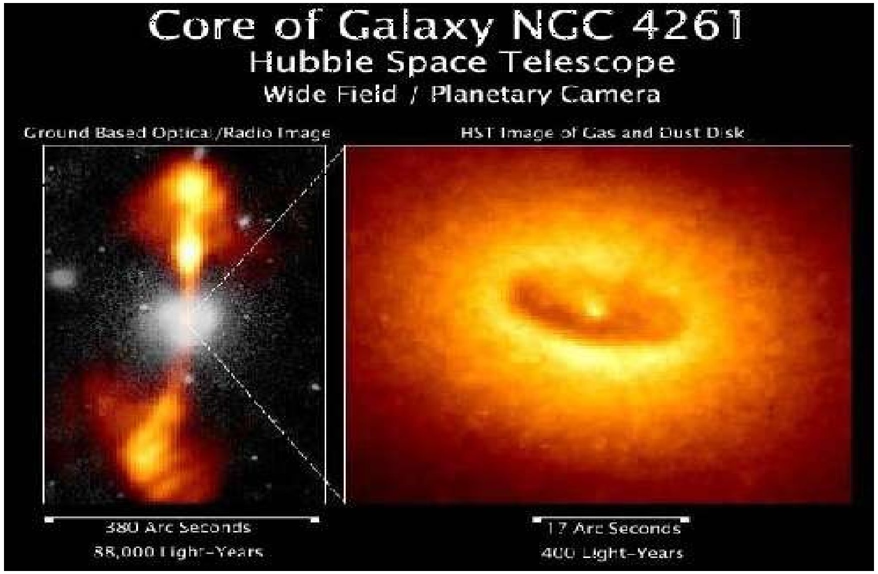
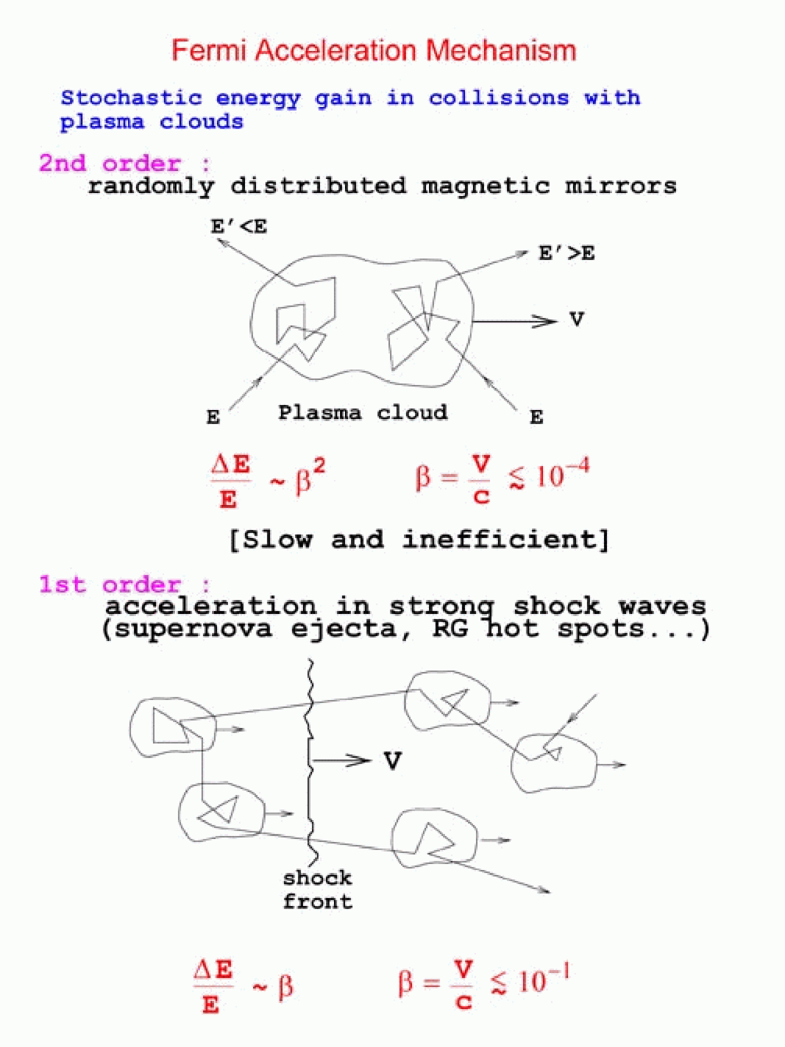
Cosmic Ray Sources





- Supernovae can explain rays up to 10^{15}eV
- Active Galactic Nuclei (AGN) ($M>10^6 M_\odot$ BH in galactic centre) are suspected to produce UHECR

Acceleration Mechanisms



Fermi Acceleration Mechanism

Stochastic energy gain in collisions with plasma clouds

2nd order : randomly distributed magnetic mirrors

$\frac{\Delta E}{E} \sim \beta^2 \qquad \beta = \frac{V}{c} \lesssim 10^{-4}$

[Slow and inefficient]

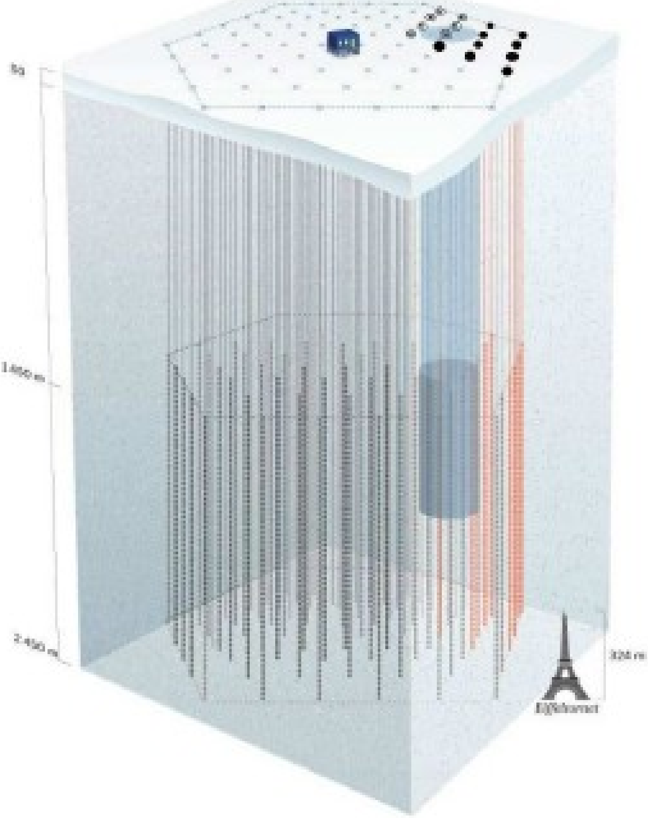
1st order : acceleration in strong shock waves (supernova ejecta, RG hot spots...)

$\frac{\Delta E}{E} \sim \beta \qquad \beta = \frac{V}{c} \lesssim 10^{-1}$

- Fermi Mechanism (1949)
- Particles collide stochastically with magnetic clouds in the interstellar medium. Those particles involved in head-on collisions will gain energy and those involved in tail-end collisions will lose energy. On average, however, head-on collisions are more probable

Predicted Neutrino fluxes

$$dN/dE_\nu \sim 5 \cdot 10^{-8} E_\nu^{-2}\ \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$



- Need large target volumes
- Water/Ice Čerenkov are the only reasonable solution cost-wise
- Aim to instrument km^3 of ice/water
- If CR originate from accelerated hadrons expect $\phi_\gamma \sim \phi_\nu$ otherwise expect no HE neutrinos

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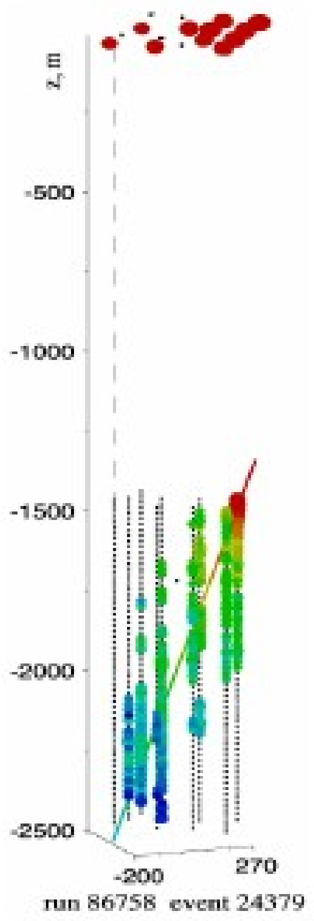
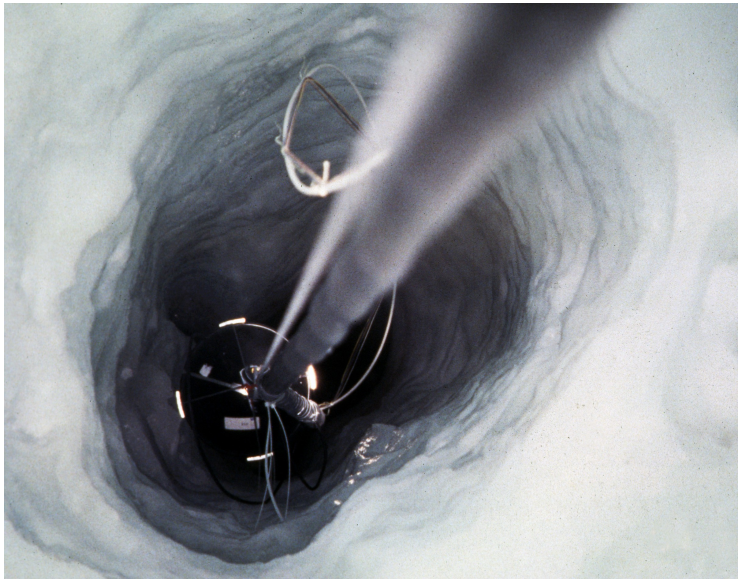
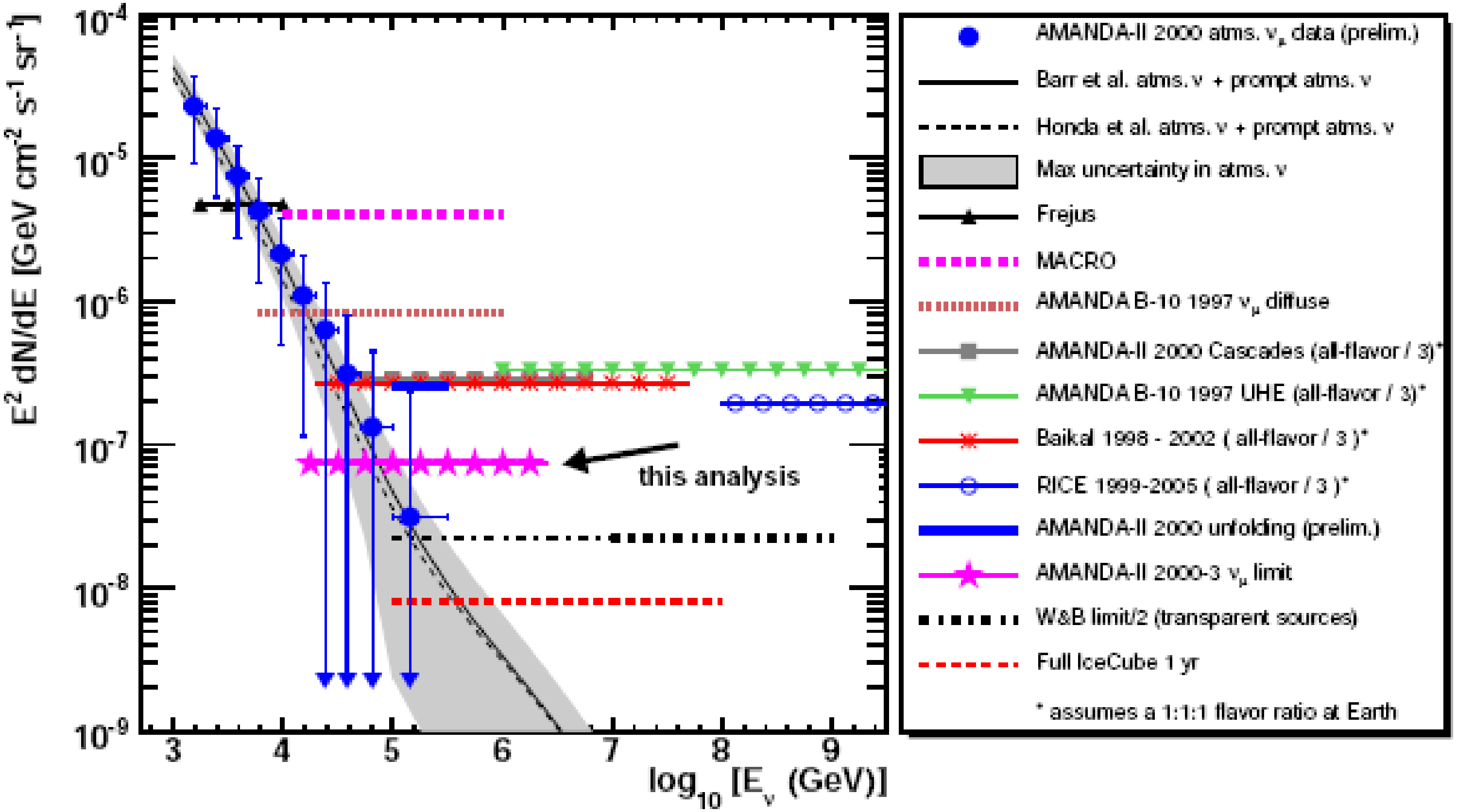
Amanda detector



- South Pole ice cap: 2.5km of clear ice
- 19 photomultiplier strings
- Muon neutrino CC gives Cerenkov cone



Amanda results



- 2000-2003 limit for muon neutrinos for E^{-2} spectrum 7.4×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} for 16 TeV to 2.5 PeV

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Limits and production models

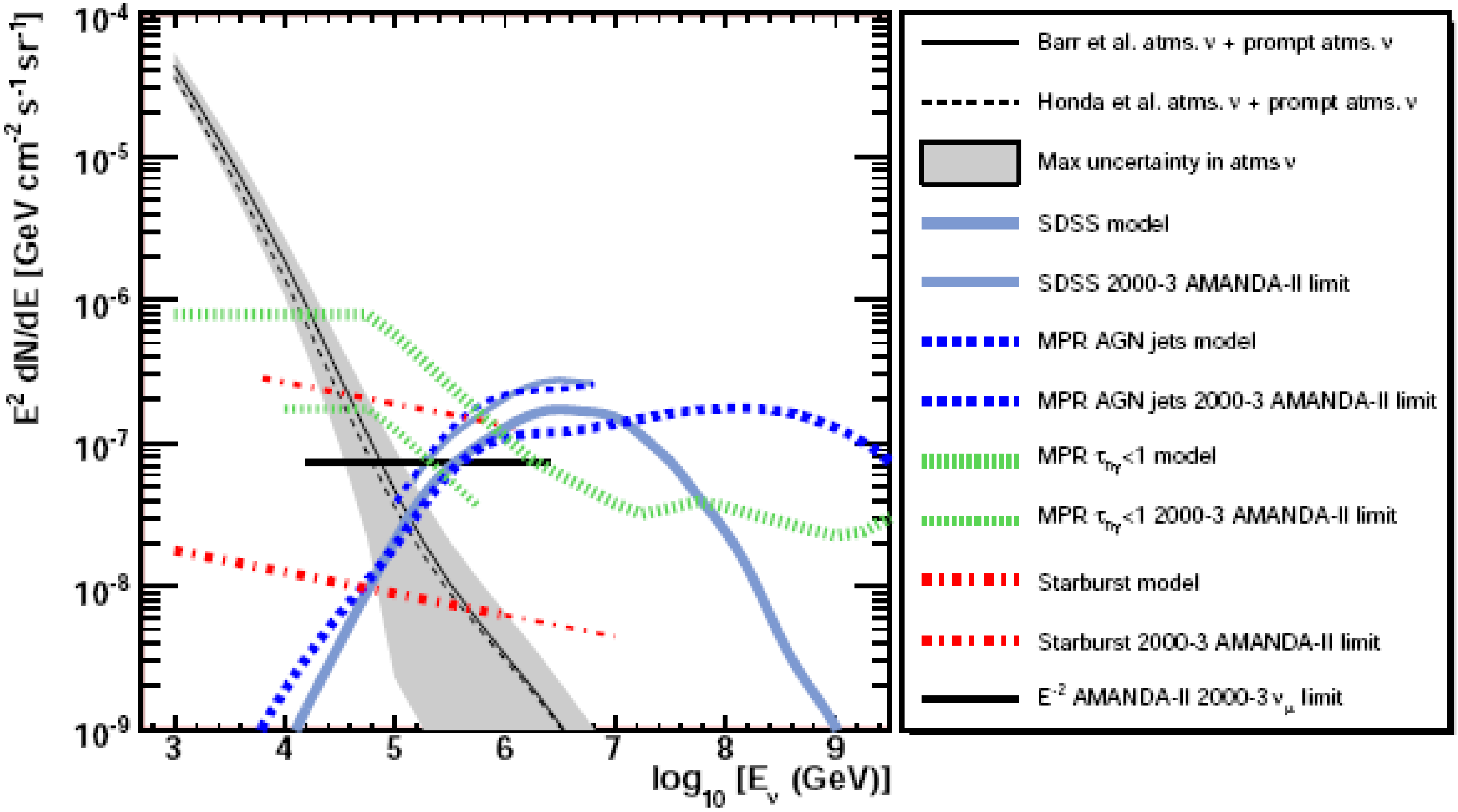

FIG. 9: Astrophysical neutrino models and upper limits established with this analysis. The Barr *et al.* and Honda *et al.* atmospheric neutrino models are shown as thin lines with maximum uncertainties assumed by this analysis represented by the band. Other models that were tested included the SDSS AGN core model [7, 8], the MPR upper bounds for AGN jets and optically thin sources [6], and a starburst galaxy model [9].

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Search for point sources

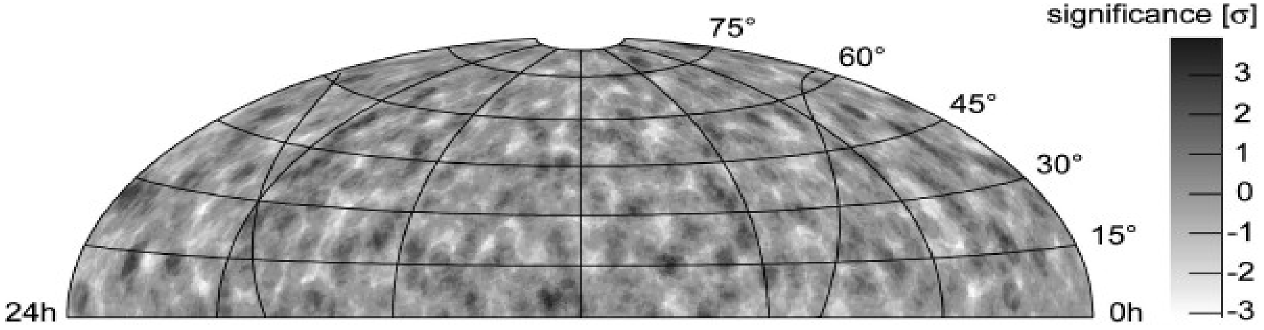
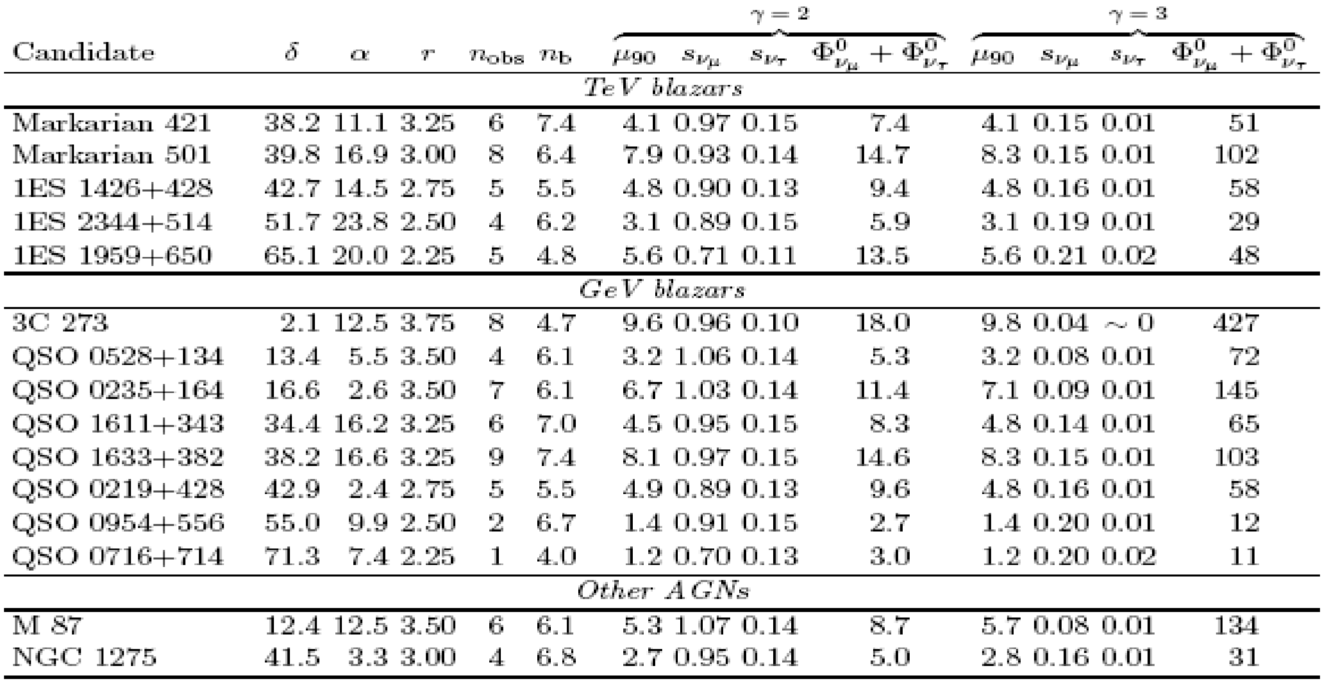


FIG. 6: Sky map of the significance obtained by scanning of the northern sky to search for event clusters. The significance is positive for excesses and negative for deficits of events compared to the expected background.

$$\Phi^0_{\nu_\mu+\bar{\nu}_\mu} = 5.5 \cdot 10^{-11}\,\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

etween 1.6 TeV and 2.5 PeV

No observed point source emitter



						$\gamma = 2$				$\gamma = 3$			
Candidate	δ	α	r	n_{obs}	n_{b}	μ_{90}	s_{ν_μ}	s_{ν_τ}	$\Phi^0_{\nu_\mu} + \Phi^0_{\nu_\tau}$	μ_{90}	s_{ν_μ}	s_{ν_τ}	$\Phi^0_{\nu_\mu} + \Phi^0_{\nu_\tau}$
TeV blazars													
Markarian 421	38.2	11.1	3.25	6	7.4	4.1	0.97	0.15	7.4	4.1	0.15	0.01	51
Markarian 501	39.8	16.9	3.00	8	6.4	7.9	0.93	0.14	14.7	8.3	0.15	0.01	102
1ES 1426+428	42.7	14.5	2.75	5	5.5	4.8	0.90	0.13	9.4	4.8	0.16	0.01	58
1ES 2344+514	51.7	23.8	2.50	4	6.2	3.1	0.89	0.15	5.9	3.1	0.19	0.01	29
1ES 1959+650	65.1	20.0	2.25	5	4.8	5.6	0.71	0.11	13.5	5.6	0.21	0.02	48
GeV blazars													
3C 273	2.1	12.5	3.75	8	4.7	9.6	0.96	0.10	18.0	9.8	0.04	~ 0	427
QSO 0528+134	13.4	5.5	3.50	4	6.1	3.2	1.06	0.14	5.3	3.2	0.08	0.01	72
QSO 0235+164	16.6	2.6	3.50	7	6.1	6.7	1.03	0.14	11.4	7.1	0.09	0.01	145
QSO 1611+343	34.4	16.2	3.25	6	7.0	4.5	0.95	0.15	8.3	4.8	0.14	0.01	65
QSO 1633+382	38.2	16.6	3.25	9	7.4	8.1	0.97	0.15	14.6	8.3	0.15	0.01	103
QSO 0219+428	42.9	2.4	2.75	5	5.5	4.9	0.89	0.13	9.6	4.8	0.16	0.01	58
QSO 0954+556	55.0	9.9	2.50	2	6.7	1.4	0.91	0.15	2.7	1.4	0.20	0.01	12
QSO 0716+714	71.3	7.4	2.25	1	4.0	1.2	0.70	0.13	3.0	1.2	0.20	0.02	11
Other AGNs													
M 87	12.4	12.5	3.50	6	6.1	5.3	1.07	0.14	8.7	5.7	0.08	0.01	134
NGC 1275	41.5	3.3	3.00	4	6.8	2.7	0.95	0.14	5.0	2.8	0.16	0.01	31

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Limits on fluxes from GRB

- Looking for events at the direction and time of satellite detected Gamma-Ray Bursts
- No observed correlation

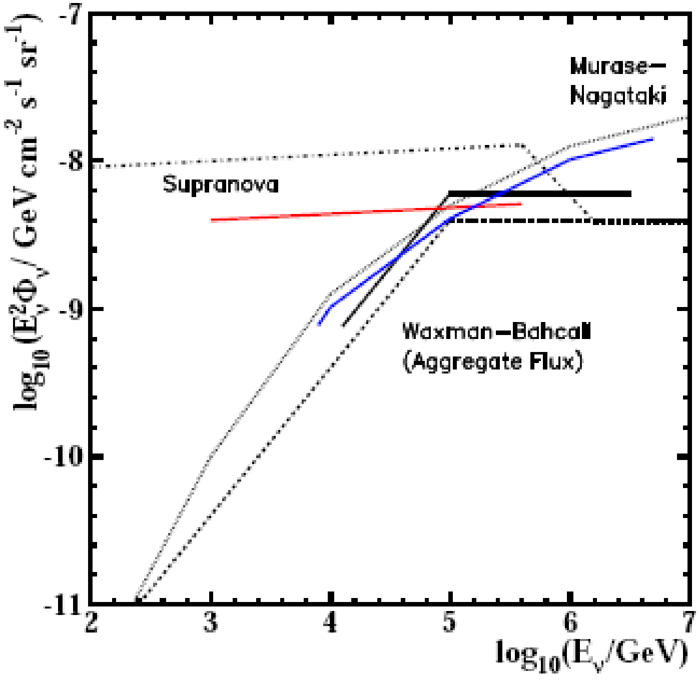

Fig. 9.— AMANDA flux upper limits (solid lines) for muon neutrino energy spectra predicted by the Waxman-Bahcall spectrum (Waxman 2003) (thick dashed line), the Razzaque et al. spectrum (Razzaque et al. 2003a) (dot-dashed line) and the Murase-Nagataki spectrum (Murase & Nagataki 2006a) (thin dotted line). The central 90% of the expected flux for each model is shown. For the Waxman-Bahcall model we include both long- and short-duration bursts; for the other spectra, only long-duration bursts are included. Including short-duration bursts would improve the flux upper limits by approximately 13%. While our analysis was restricted to bursts located in the Northern Hemisphere (2π sr), all flux upper limits are for the entire sky (4π sr).

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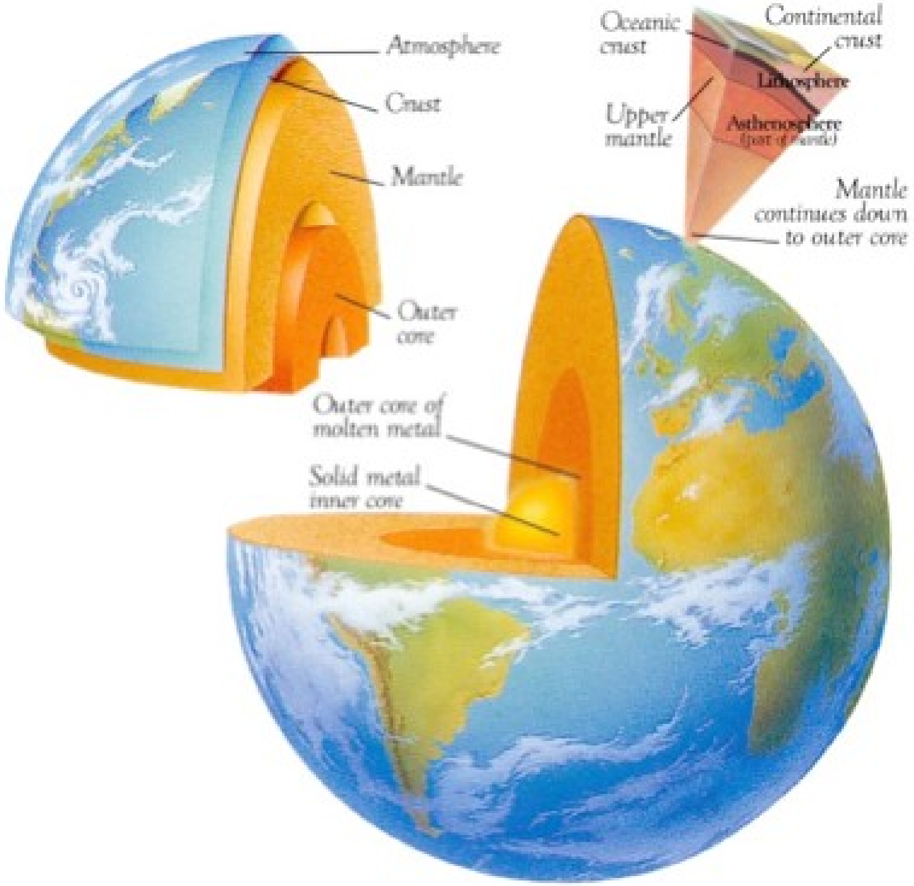
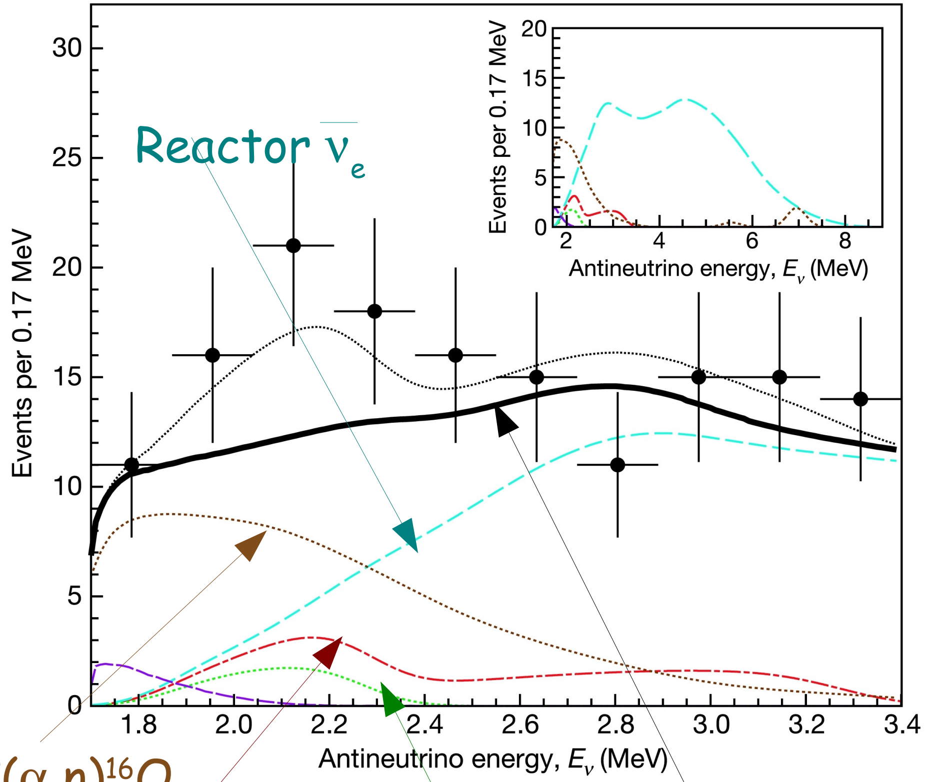
GeoPhysics with neutrinos



- The temperature of the earth increases as we go deeper
- Due to energy release in radioactive decays.
- Studying the neutrinos can help us understand the earth content

Measuring the Earth Power…

T. Araki et al. (KamLAND), Nature 436 (2005) 499-503.



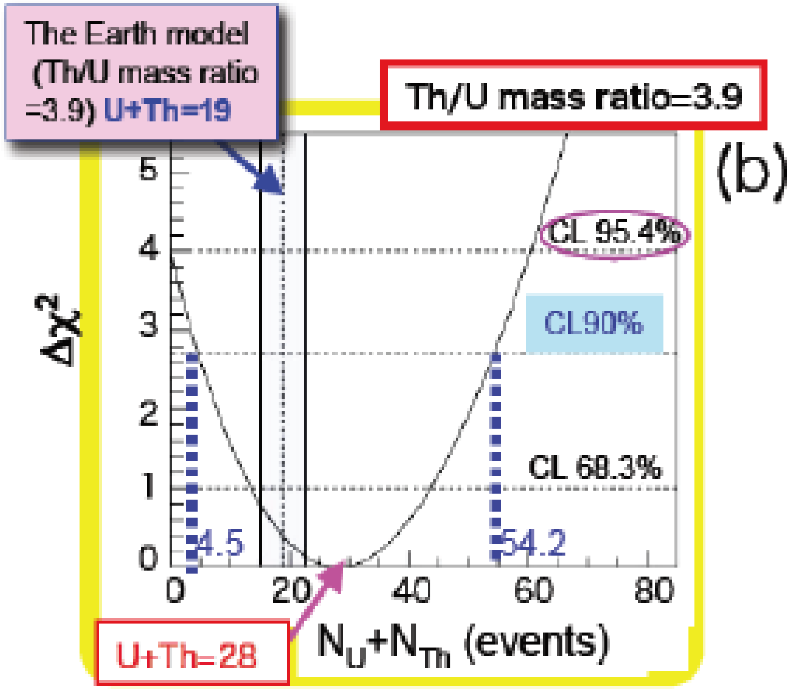
Reactor $\bar{\nu}_e$

$^{13}C(\alpha,n)^{16}O$

^{238}U

^{232}Th

Expected without GeoNeutrinos



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  - Giunti's site : kept up to date references and results of al neutrino experiments http://www.nu.to.infn.it/
  - The Neutrino Oscillation Industry page: http://neutrinooscillation.org/