« Beta-beams »

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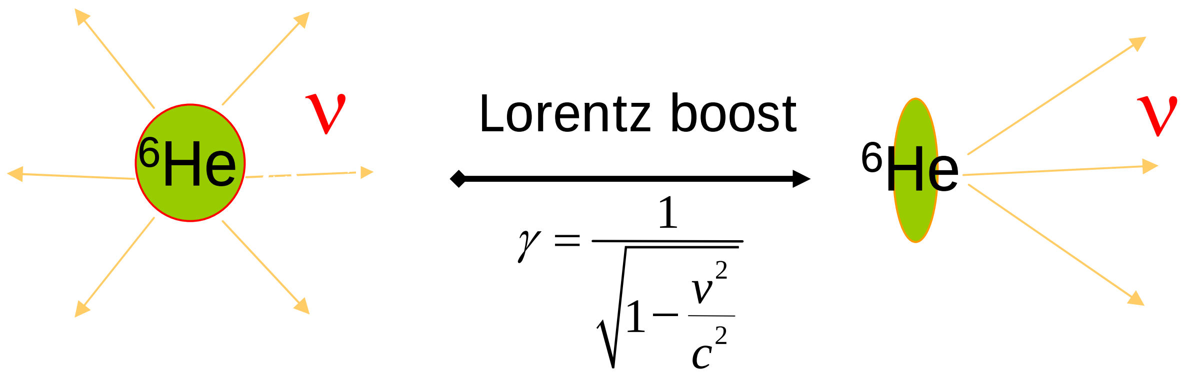
Zucchelli, PLB 2002

Why don't we use the decay of boosted radioactive ions to produce ν-beams?



$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

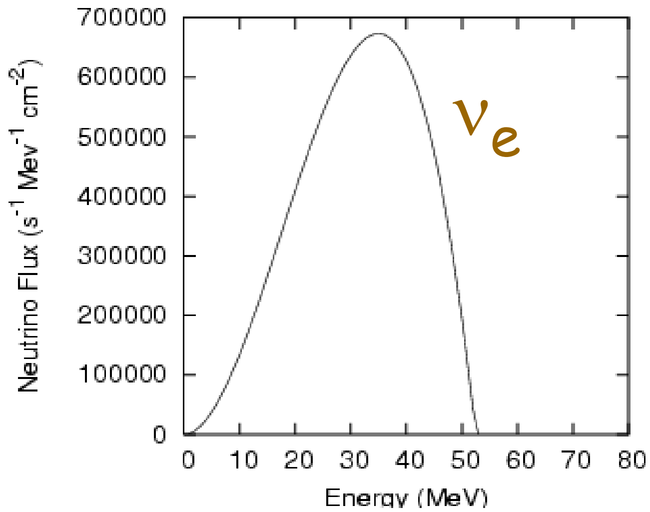
The beta -beam concept

INTENSE ν-BEAMS

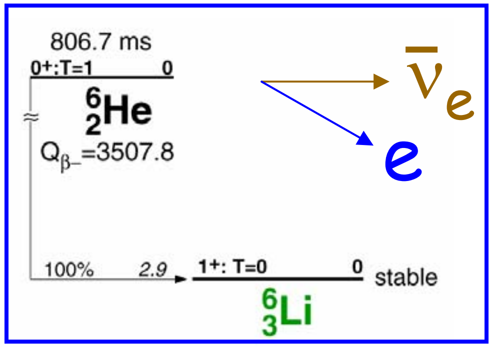
CONVENTIONAL SOURCES

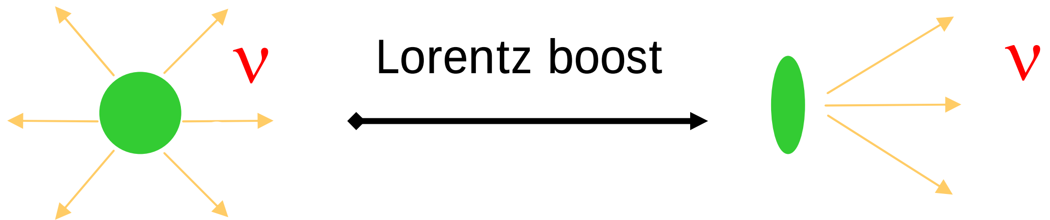
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \quad (0.026\ \mu s)$$

$$\mu^+ \longrightarrow e + \bar{\nu}_\mu + \nu_e \quad (2.2\ \mu s)$$



BETA-BEAMS





Advantages : - pure in flavour
- collimated
- well known fluxes

Zucchelli, PLB 2002

TWO POSSIBLE METHODS.

Proposed scenarios

Low-energy Beta-beams

γ = 5 -14

C. Volpe, Journ. Phys. G. 30 (2004), hep-ph/0303222.
G.C. McLaughlin and C. Volpe, Phys. Lett. B 591 (2004), .
J. Serreau and C. Volpe, PRC70 (2004), hep-ph/0403293.
McLaughlin, Phys. Rev. C70, 045804 (2004), nucl-th/0404002.
....

Original or "standard" Beta-beams

γ = 100

Autin et al., J. Phys. G 29, 1785 (2003), physics/0306106.
M. Mezzetto, J. Phys. G29, 1771 (2003) hep-ex/0302007.
J. Bouchez, M. Lindroos, M. Mezzetto, AIP Conf.Proc.721, 37 (2004).
M. Mezzetto, Nucl. Phys. Proc. Suppl.143, 309-316 (2005).
A. Donini et al., Nucl. Phys. B710, 402 (2005), hep-ph/0406132.
J. Bernabeu, J. Burguet-Castell, C. Espinoza, M. Lindroos, hep-ph/0505054.
electron-capture
P. Huber, M. Lindner, M. Rolinec, W. Winter, hep-ph/0506237.
....

High-energy Beta-beams

γ >> 100

J. Burguet-Castell, D. Casper, JJ Gomez-Cadenas, P. Hernandez,
F. Sanchez, Nucl. Phys. B695, 217 (2004), hep-ph/0312068.
F. Terranova et al, Eur. Phys. J. C38, (2004), hep-ph/0405081.
....

See http://beta-beam.web.cern.ch/beta-beam/.

Volpe, Topical Review, J. Phys. G34, R1 (2007)

OUTLINE

- The original beta-beam project :
  CP violation in the lepton sector

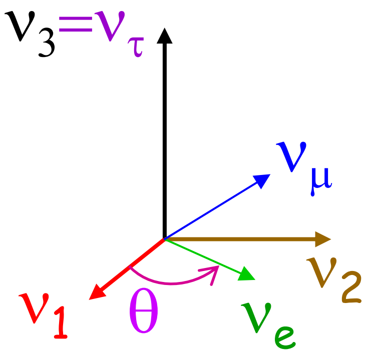
- Low energy beta-beams :
  nuclear, fundamental and
  astrophysics studies

- Conclusions and Pespectives

I. And if neutrinos oscillate ??

Pontecorvo, 1957

- There are two neutrino basis, the mass (or propagation) basis and the interaction (or flavour) basis :

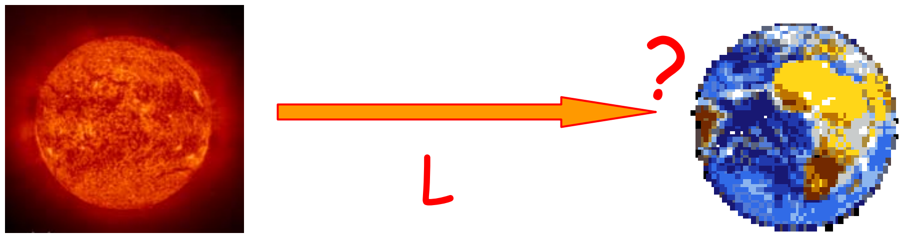


$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

flavour basis — mixing angle — mass basis

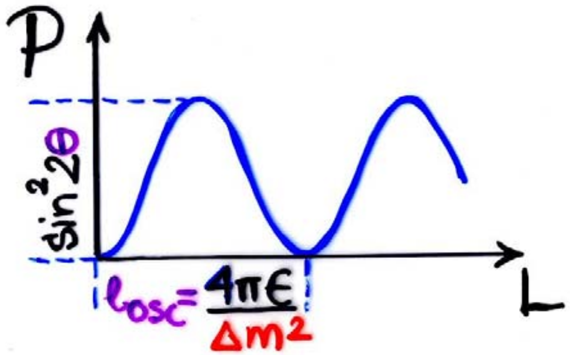
- If we start with a neutrino source of one flavour, the time evolution is given by

$$|\nu\rangle(0) = |\nu_e\rangle$$



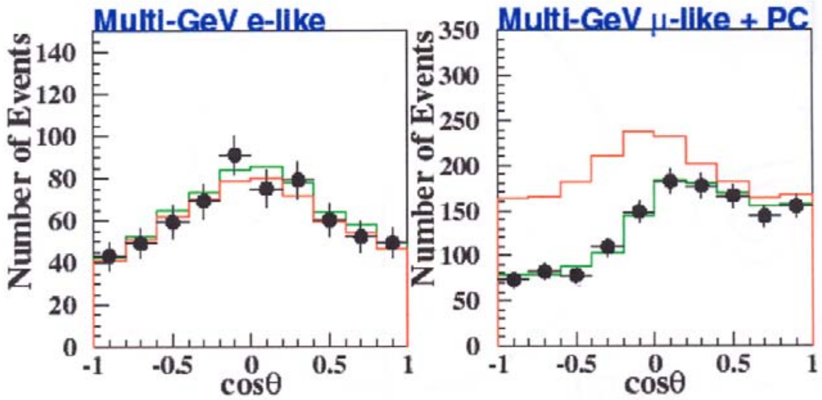
$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \, \sin^2\left(\frac{L}{4E}\Delta m^2\right)$$

probability for neutrino oscillations



The observation of neutrino oscillations

SK (1998) The discovery



NEUTRINOS HAVE MASSES !!!

SK Coll., PRL81, 1998.

K2K (2001)

ACCELERATOR

Confirms Super-K.

K2K Coll., PRL90, 2003.

- $\Delta m^2_{12} \sim 10^{-5}$
  $\sin^2 2\theta_{12} \simeq 0.8$
- $\Delta m^2_{23} \sim 10^{-3}$
  $\sin^2 2\theta_{23} \sim 1.$
- $\sin^2 2\theta_{13} < 0.1$
  (CHOOZ)

SNO (2000) SUN

ν_e as well as ν_μ and ν_τ. fluxes : compatible with predictions.

SNO Coll., PRL87, 2001.

KAMLAND (2002)

REACTOR

Confirms SNO.

KAM. Coll., PRL90, 2003.

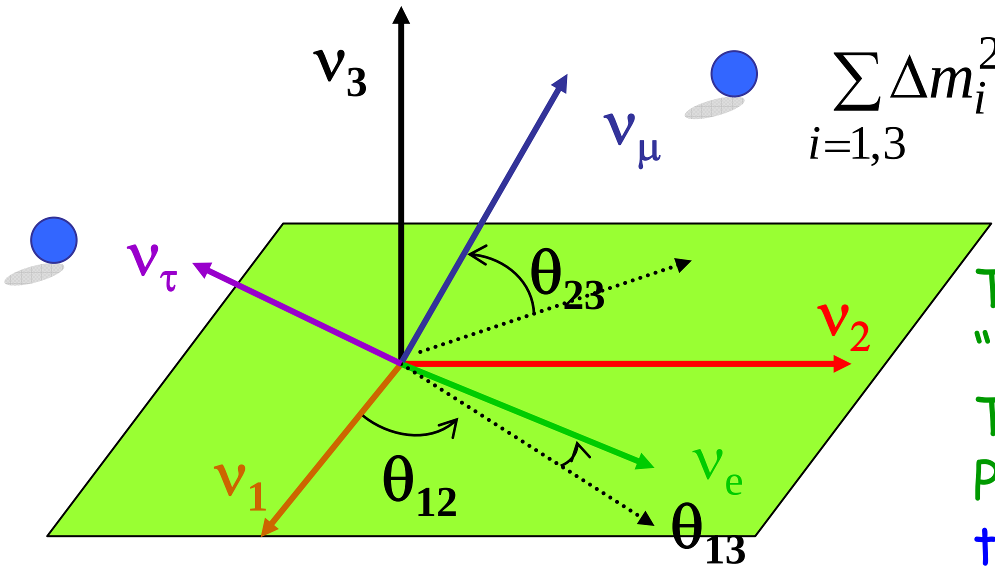
THE OSCILLATION PARAMETERS

- In the case of three families, there are three mass eigenstates (ν_1, ν_2, ν_3) and three flavour eigenstates $(\nu_e, \nu_\mu, \nu_\tau)$.

- Δm_{21}^2, Δm_{32}^2

$$\sum_{i=1,3} \Delta m_i^2 = m_2^2 - m_1^2 + m_3^2 - m_2^2 + m_1^2 - m_3^2$$

Only two Δm^2 are independent.



- The two basis are related by a "rotation" (unitary) matrix, called The Maki-Nakagawa-Sakata-Pontecorvo (MNSP) matrix, which is the analog of the Cabibbo-Kobayashi-Maskawa (CKM) matrix for quarks.

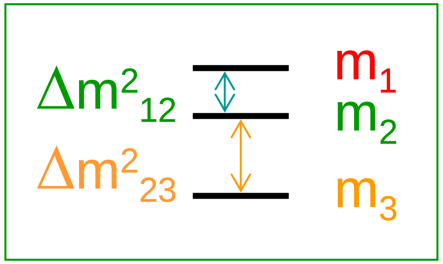
$$c_{ij} = \cos\theta_{ij} \quad s_{ij} = \sin\theta_{ij}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

θ_{23} θ_{13} θ_{12}

THE δ PHASE INTRODUCES A DIFFERENCE BETWEEN ν AND $\bar{\nu}$.

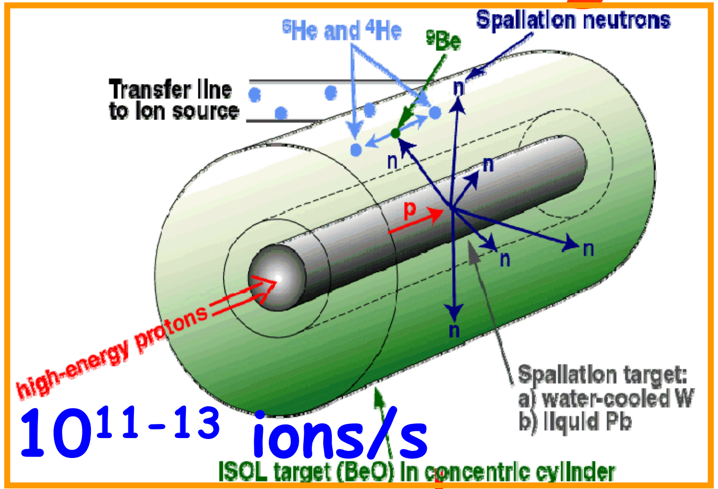
ν Neutrinos still have many mysteries…



- What is the absolute mass scale and the mass hierarchy ?
- What is the value of the angle θ_{13} ?
- Are neutrinos Majorana or Dirac particles ? $\nu \stackrel{?}{=} \bar{\nu}$
- Is there CP violation in the lepton sector ?
- What is the value of the magnetic moment ?
- Are there sterile neutrinos ?
- ….

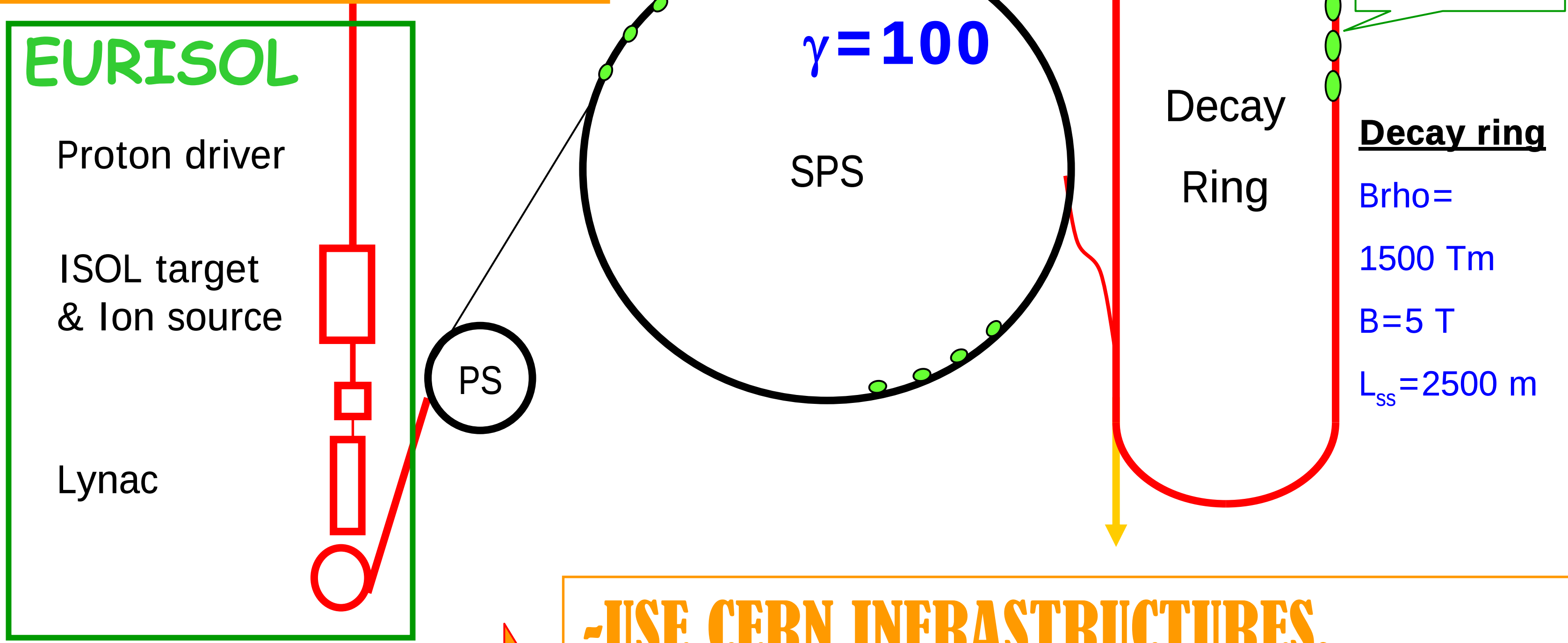
Many projects will tell us more in the near future….

THE original β-BEAM PROJECT



Zucchelli, PLB 2002

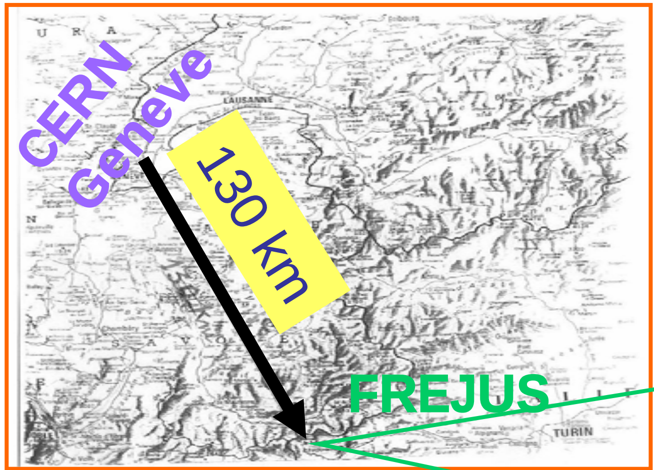
Autin et al., J. Phys. G 29, 2003



-USE CERN INFRASTRUCTURES,

-ION PROD. (EURISOL) & DECAY RING.

CERN-to-FREJUS ν-BEAMS



Frejus Underground Laboratory

MEMPHYS

400 kTon
Water
Cerenkov
Detector

De Bellefon et al. , hep-ex/0607026

Neutrino experiments :

Study of CP and T violation, by comparing the following oscillation probabilities :

$\nu_e \rightarrow \nu_\mu$ (β+)

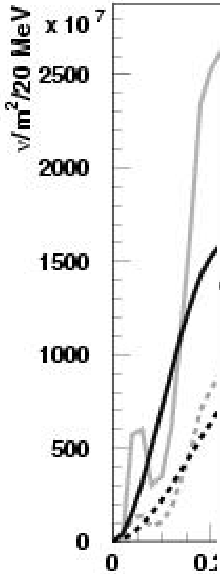
(with Beta-beams) (ms)

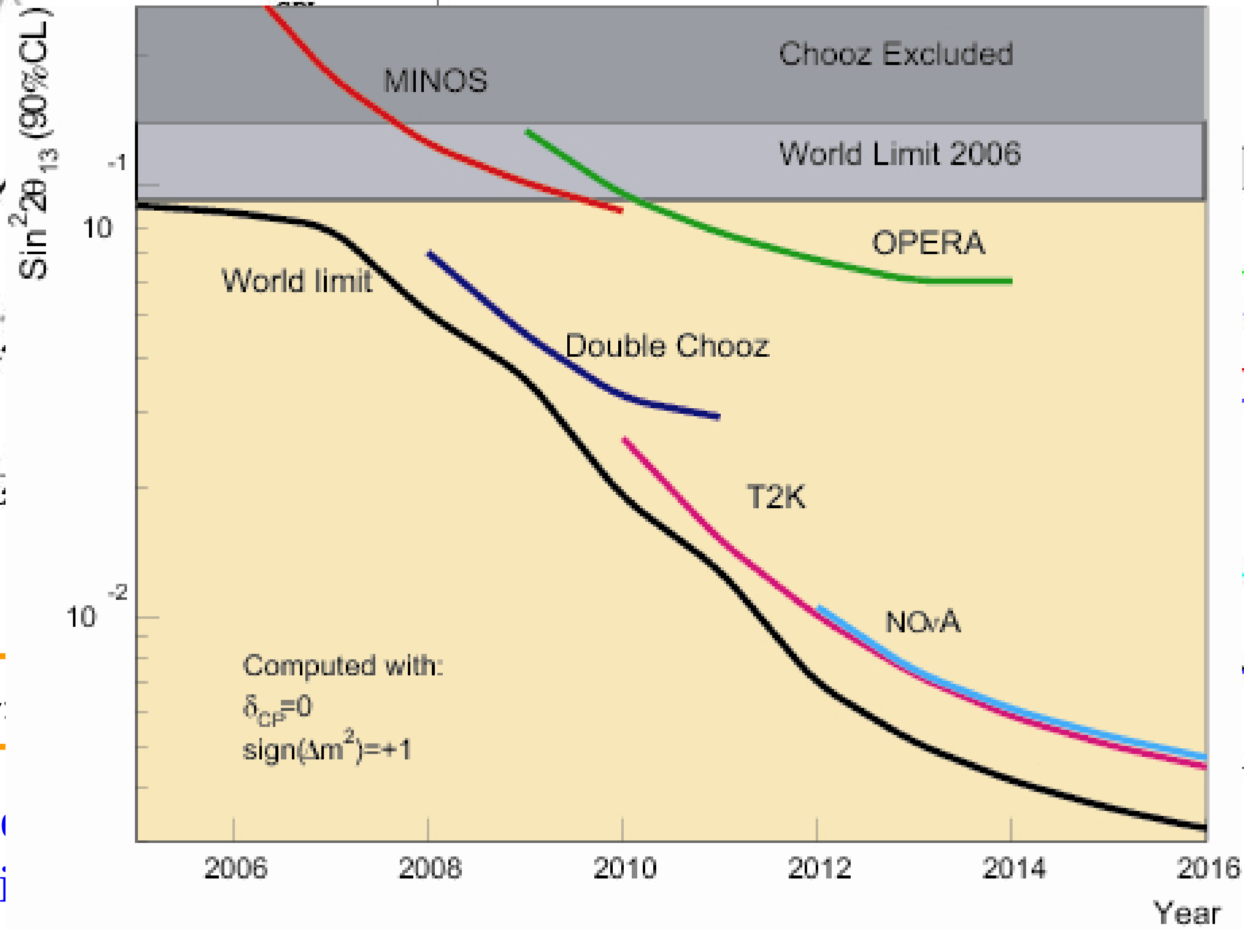
Besides :

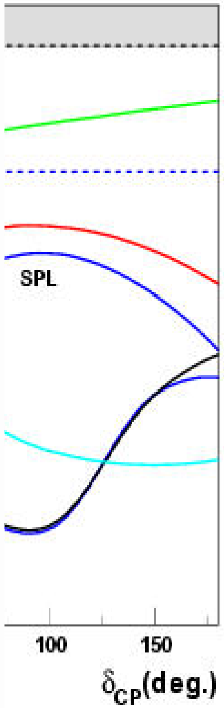
- Astrophysics studies
  Supernova neutrinos
- Proton decay

…a rich physics program!

Sensitivity to theta$_{13}$







γ

CC (

Osci

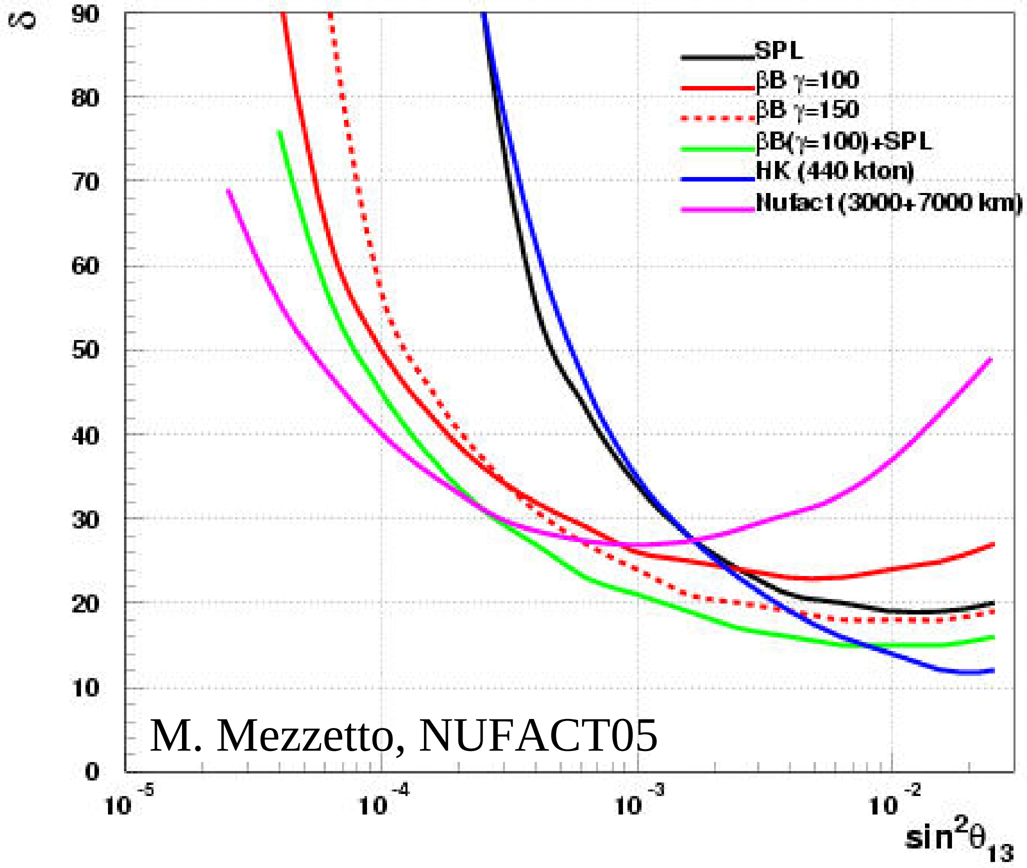
Beam back. 0

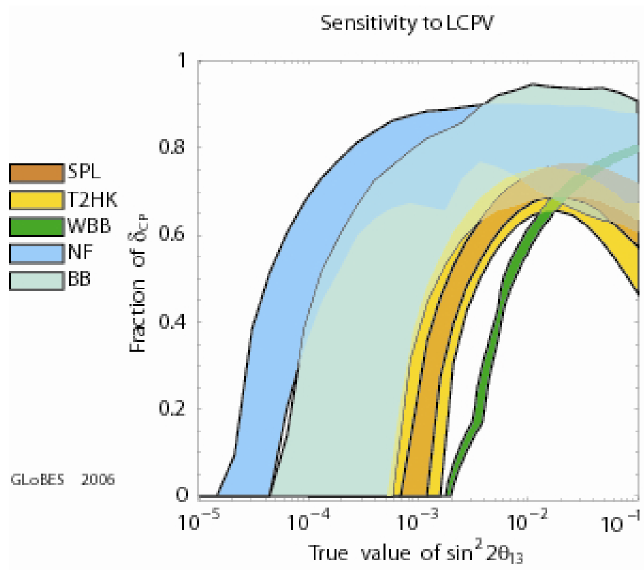
Detector back. 397

Guglielmi et al. 2005

Mezzetto, Nucl. Phys. 143, (2005).

Comparison of the beta-beam sensitivity with other "third generation" projects





ISS study, to appear.

ONE CAN EXPLORE θ_{13} values as small as 1 degree and δ VALUES AS LOW AS 20 degrees.

Electron capture option $\gamma = 100$

- The neutrinos are monoenergetic.
- The candidate beta decaying nuclei (ex. ^{148}Dy) are difficult to produce.

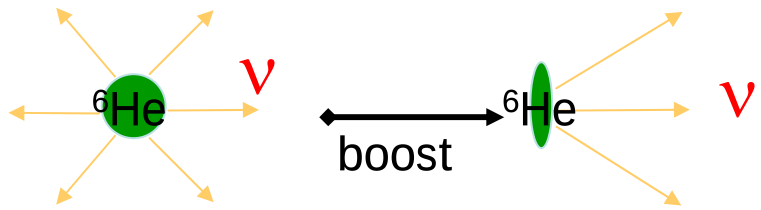
J. Bernabeu et al., JHEP 2005; J. Sato PRL 2005.

High energy beta-beams $\gamma >> 100$

- They benefit from the increased number of events and require smaller detectors.
- They require major modifications of the original baseline.

J. Burguet-Castell et al., Nucl. Phys. B 2004; …and very many others..

...Beta-beams

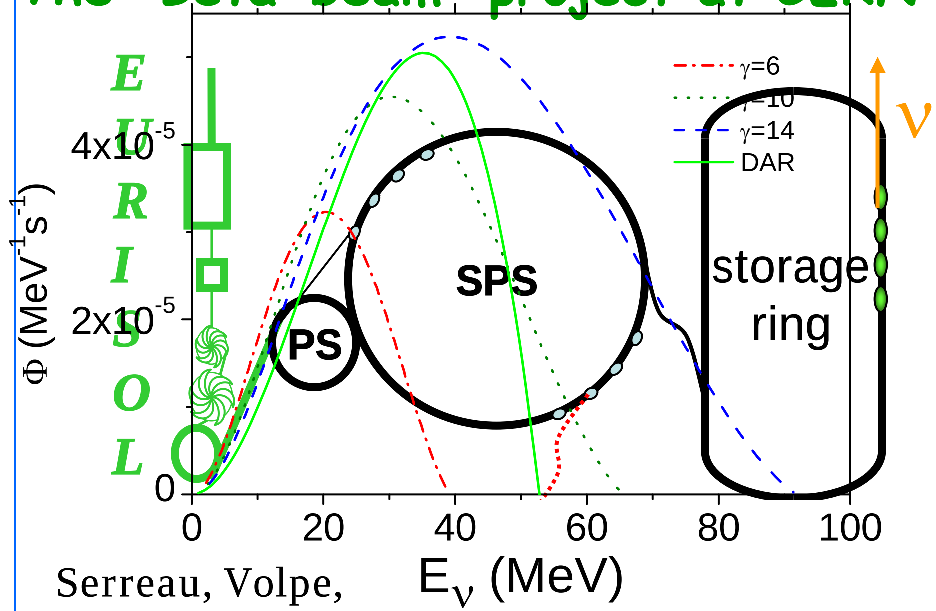


II. Low energy..

Volpe, J Phys G 30 (2004).

To use the novel beta-beam concept produce pure and intense low energy neutrino beams (10-100 MeV, i.e. γ = 5-14).

The "Beta-beam" project at CERN



Serreau, Volpe, PRC2004

Physics potential

- neutrino-nucleus interaction

  Volpe J Phys G 2004
  Serreau and Volpe PRC 2004
  McLaughlin PRC 2004
  Lazauskas and Volpe NPA 2007
  ....

- fundamental interaction studies (Weinberg angle, CVC test, μ_ν, etc…):

  McLaughlin and Volpe, PLB 2004,
  Balantekin et al PLB 2006
  Balantekin et al PRD 2006
  Bueno et al PRC 2006
  Barranco et al 2006
  Amanik et al PRD 2007
  ....

- nuclear astrophysics applications

  Volpe J Phys G 2004
  Jachowicz and McLaughlin PRL 2006
  Jachowicz et al in preparation 2007
  ....

Off-axis options : Lazauskas et al PRD 2007, Amanik et al PRC 2007 .

ν-Nucleus Interactions: Present status

- The study of such reactions is of interest for:
  - a better understanding of the nuclear excitations involved,
  - neutrino experiments (e.g. knowledge of detector response),
  - nuclear astrophysics (nucleosynthesis of heavy elements).

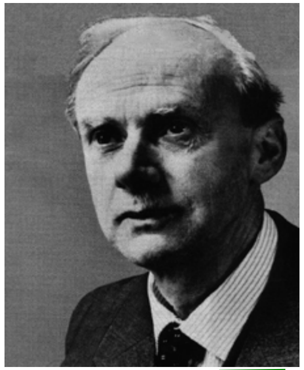
- Experimental data are very scarce (D and ^{56}F, ^{12}C).
  Theoretical predictions are absolutely necessary.
  Many calculations exist (based on Shell Model, RPA, Effective Field Theory, Elementary Particle Model) :
  see eg. Brown, Hayes, Kolbe, Fuller, Haxton, Jachowitz, Kubodera, Langanke, Martinez-Pinedo, Mintz, McLaughlin, Oset, Pourkaviani, Vogel, Volpe, Singh, Towner, etc..

- Getting precise predictions in the low-energy range (20-100 MeV) is a challenging task.
  See the examples of the discrepancies (exp/th) for ν-^{12}C and (between calculations) for ν-^{208}Pb.

NEED for MORE MEASUREMENTS !

Neutrinoless Double-beta Decay

ν Dirac

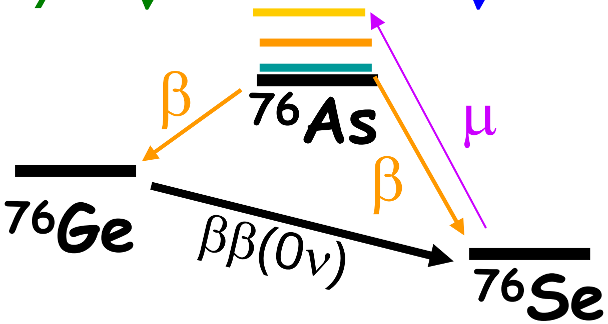


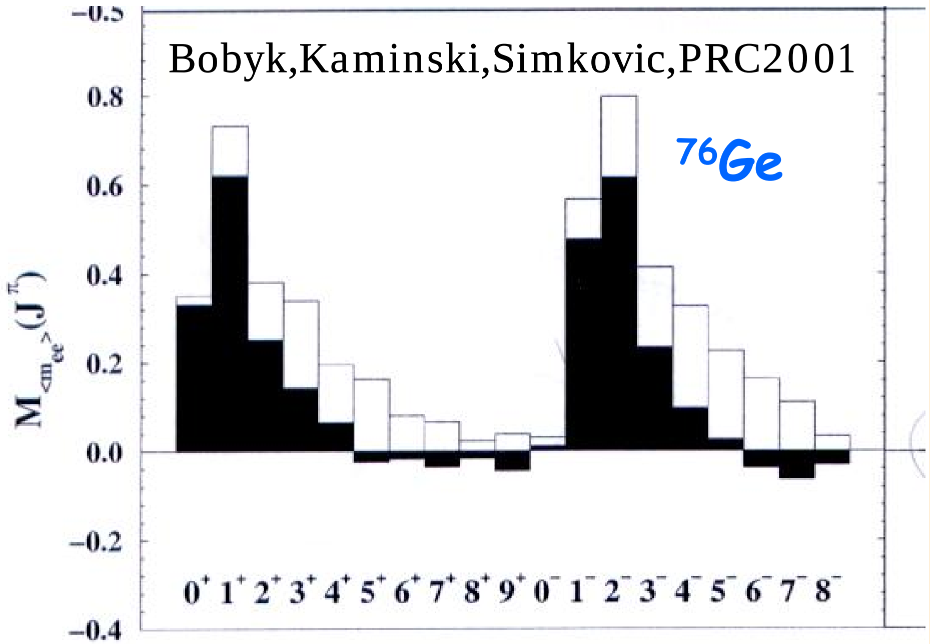
$\nu \neq \bar{\nu}$

ν Majorana

$\nu = \bar{\nu}$

?

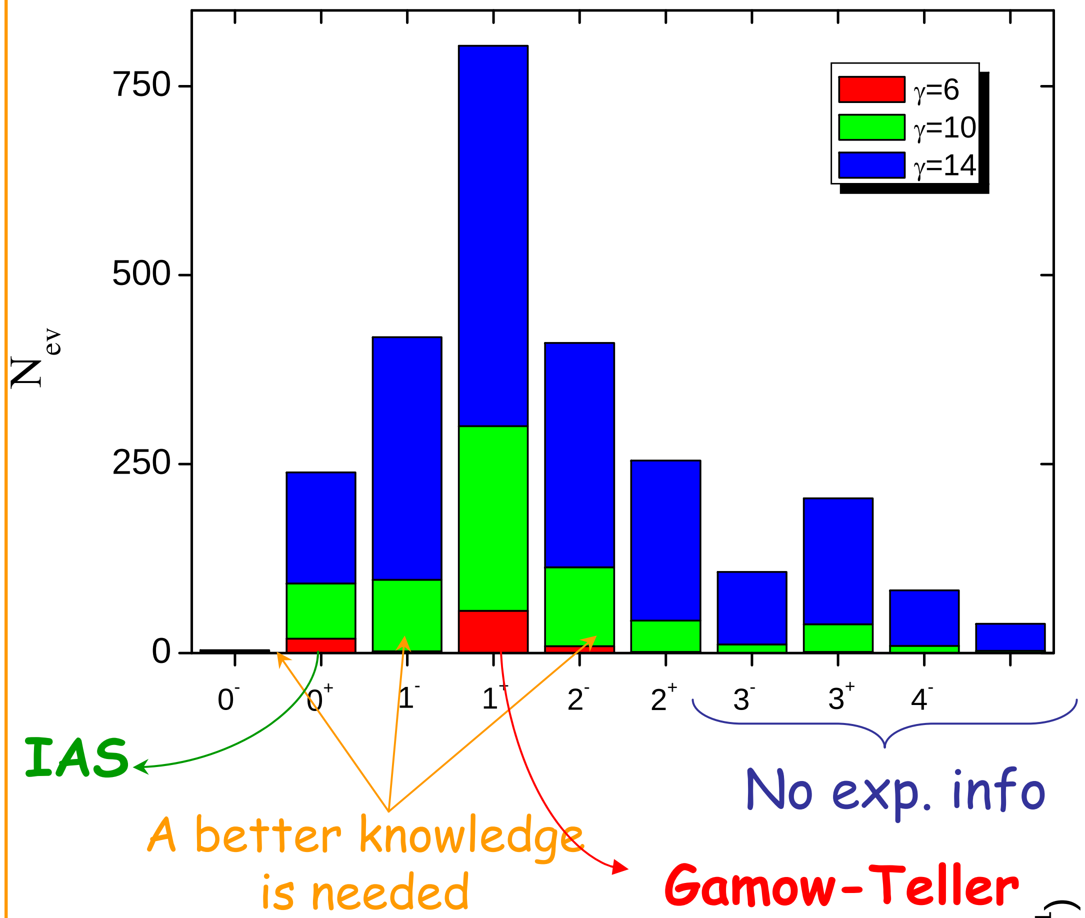




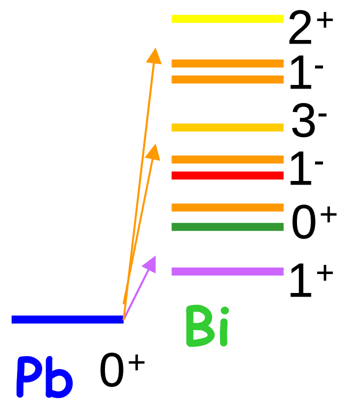
- Several processes have been considered to constrain the nuclear matrix elements, in particular beta-decay, muon capture, 2β(2ν), charge-exchange reactions.

One can show that the states involved in neutrinoless double beta decay due to the exchange of a massive Majorana neutrino are the same states as those excited in neutrino-nucleus interactions. C.Volpe, hep-ph/0501233, J. Phys. G. 31 (2005) 903

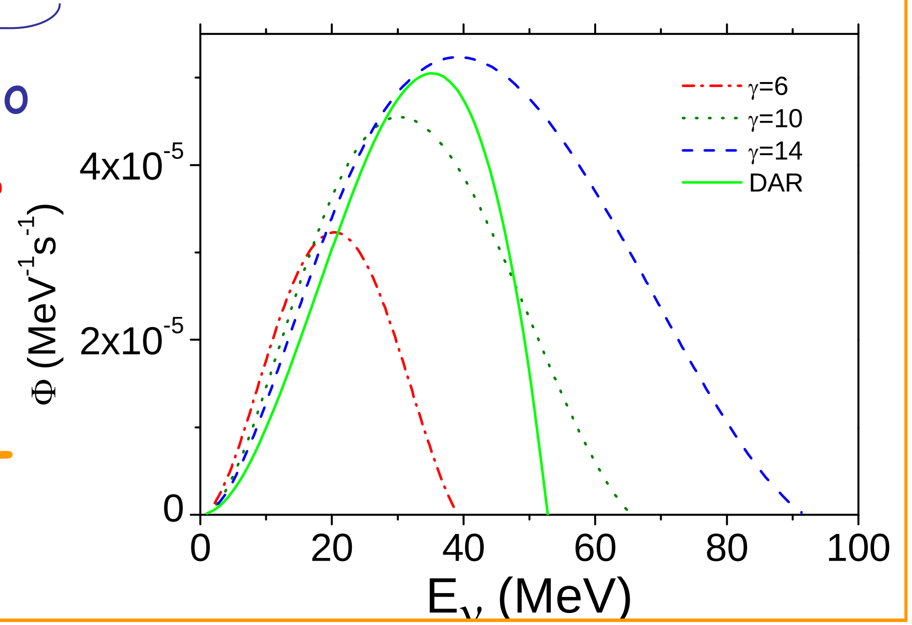
NEUTRINOS AS a PROBE of NUCLEAR STRUCTURE



$\nu_e + {}^{208}Pb \longrightarrow {}^{208}Bi + e^-$



Lazauskas and Volpe, NPA 2007
McLaughlin, PRC 2004
Volpe, J. Phys. G 2004



LOW ENERGY BETA-BEAMS AS A TOOL TO STUDY SPIN-ISOSPIN EXCITATIONS.

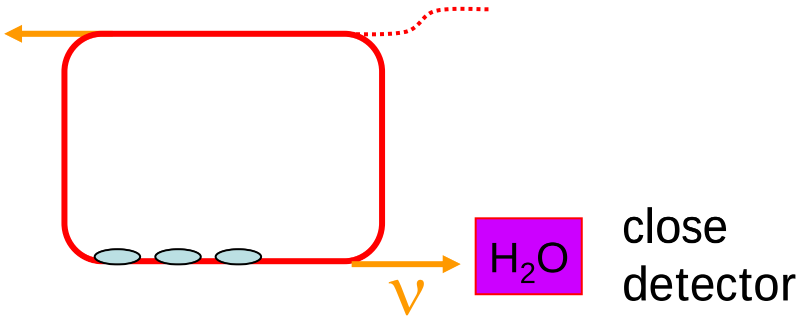
FUNDAMENTAL INTERACTION STUDIES :
θ_W at low Q^2

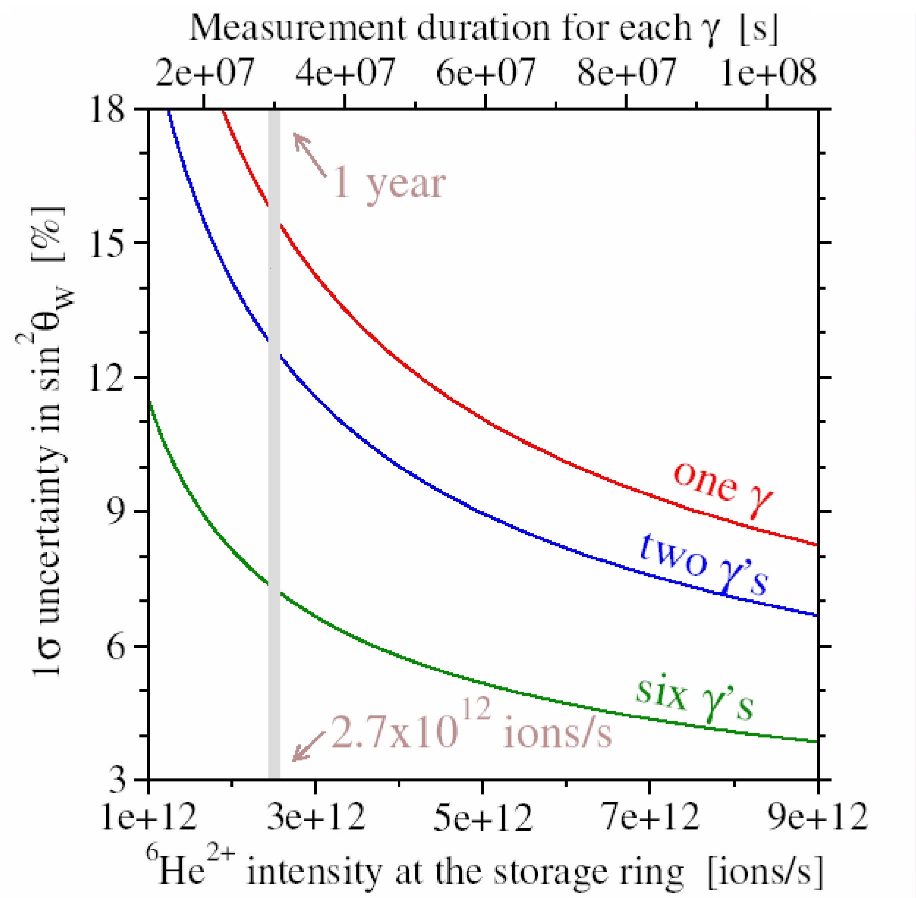
(NuTEV anomaly)

Pure leptonic scattering can be used to measure $\sin^2\theta_W$ at low momentum transfer (t' Hooft 71)

$$\nu + e \longrightarrow \nu + e$$

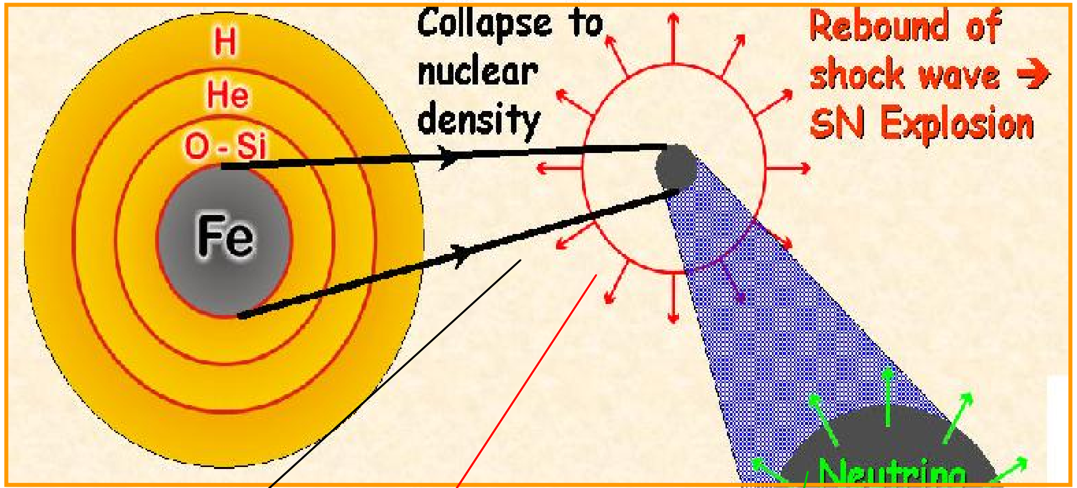
Balantekin et al, PLB 634 2006





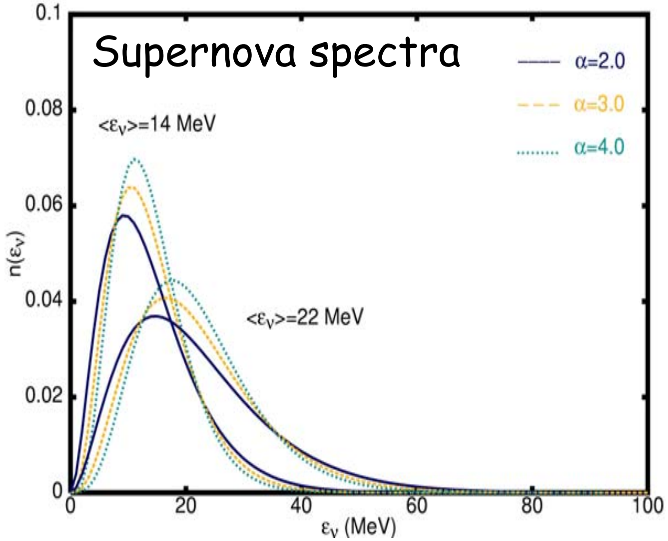
A MEASUREMENT AT 10% LEVEL.

NUCLEAR ASTROPHYSICS : core-collapse Supernovae



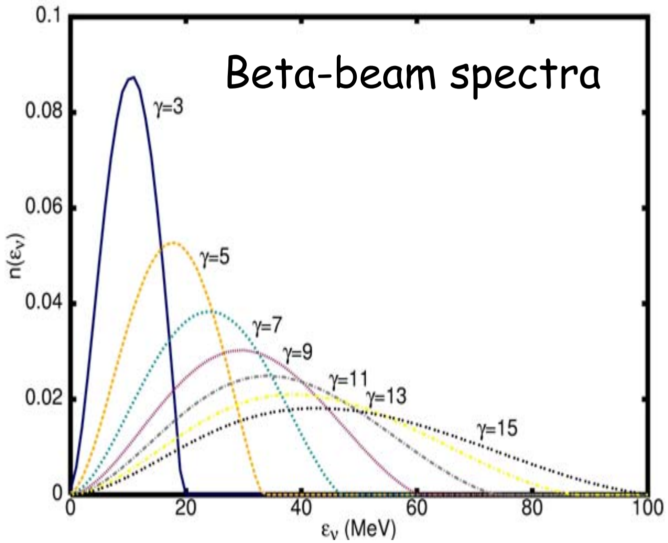
The explosion mechanism: not understood yet.

collapse ν_e burst cooling



Jachowicz and McLaughlin: PRL 96, 2006

A procedure to use low energy beta-beams in order **to obtain information** about the **supernova neutrino spectrum, without the cross section uncertainties.**



Observing the neutrinos from a Supernova explosion will tell us a lot about the processes going on in the center of the star and the dynamics of the explosion.

Conclusions and Perspectives

- Neutrino physics is traversing an exciting phase. Many important questions will be addressed in the near future.

- Beta-beams is a novel idea for the production of neutrino beams. The main goal of the beta-beam project is to address the issue of CP violation in the lepton sector.

  Low-energy beta-beams: Neutrino interaction studies represent a very promising axis of research for such a facility. They require a small devoted storage ring or off-axis detectors.

  CERN appears as a unique site.

- The feasibility study is ongoing, financed by the European Community, within the EURISOL Design Study (2005-2009). The new request has been highly ranked.


Andromeda
Thank you !