Low energy (100 MeV) neutrino scattering: from fundamental interaction studies to astrophysics

ν

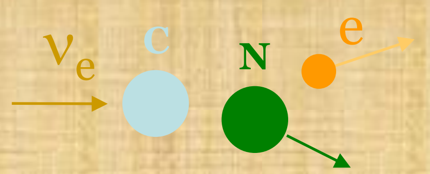
Cristina VOLPE

(Institut de Physique Nucléaire Orsay, France)

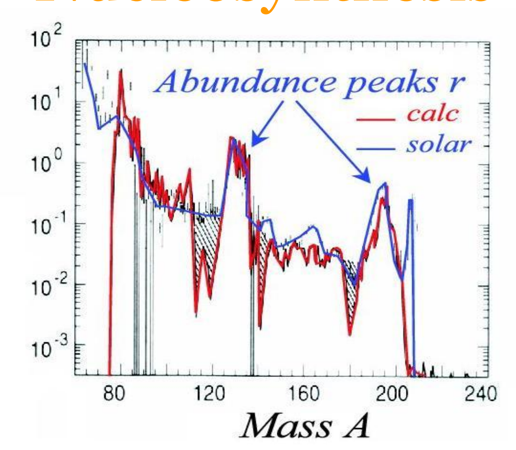
Low energy neutrino scattering

- A topic of current great interest for various domains of physics.

NUCLEAR PHYSICS



Supernovae, Nucleosynthesis



ASTROPHYSICS

Neutrino physics

$$\nu \stackrel{?}{=} \bar{\nu}$$

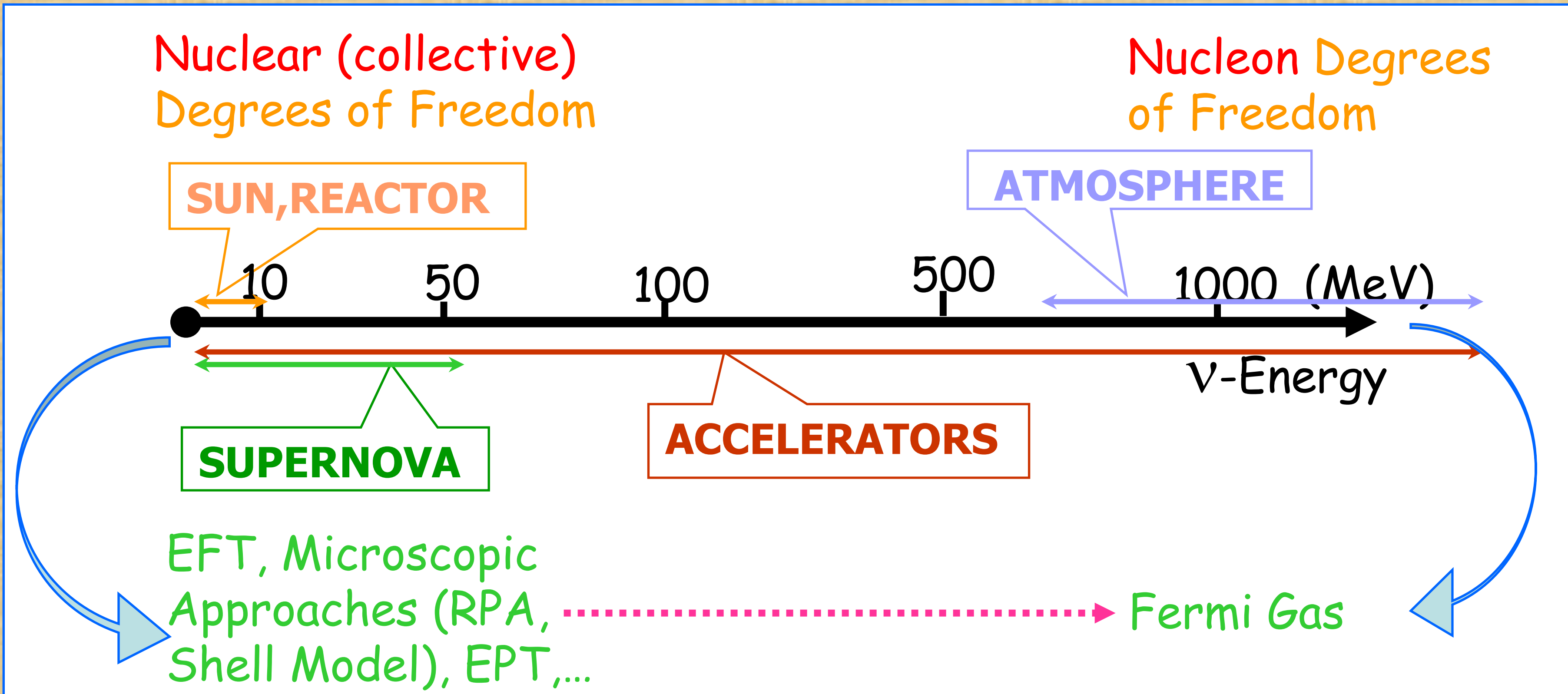
Majorana particle ?

STANDARD MODEL and BEYOND

OUTLINE

- Present status and theoretical aspects
  - Two applications:
    SNII neutrinos and double-beta decay
    - Low energy beta-beams and
      ν-nucleus interactions
  - Conclusions and Pespectives

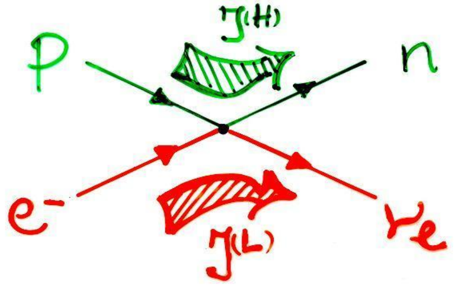
I. ν-Nucleus interactions: PRESENT STATUS

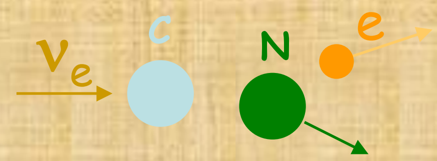


Experimental data are very scarce (d and ^{56}F, ^{12}C).
Theoretical predictions are absolutely necessary.
Many calculations exist based on various models.

THEORETICAL ASPECTS

- The effective V-A interaction Hamiltonian :





(1934) FERMI

$$\hat{H}_{INT} = G \, J^{+(H)\mu} \cdot J^{(L)}_{\mu}$$

$J^{(H)}$ - courant hadronique

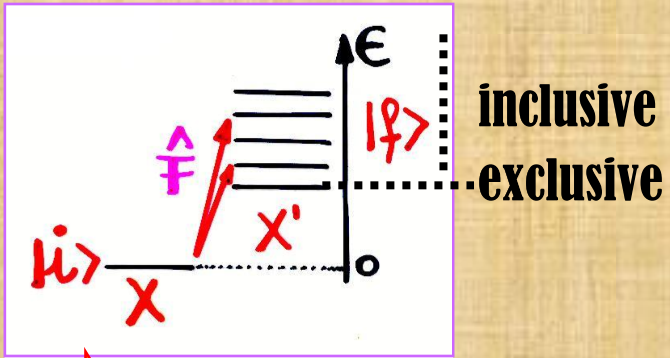
$J^{(L)}$ - courant leptonique

- Using perturbation theory :

$$\sigma(\epsilon_\nu) = \frac{G^2}{2\pi} \cos^2\theta_c \sum_f \left[\int (d\cos\theta) M_f \right] p_e \epsilon_e$$

$$M_f \Rightarrow |\langle f | \hat{F} | i \rangle|^2$$

- The nuclear transition probabilities are the key quantities :



M_f:

$$|\langle f | \sum_k j_\ell(qr_k) Y_\ell(\hat{r}_k) t_\pm(k) | i \rangle|^2$$

FERMI (ISOSPIN) TYPE TRANSITIONS

$$|\langle f | \sum_k j_\ell(qr_k) [Y_\ell(\hat{r}_k) \times \sigma]^{(K)} t_\pm(k) | i \rangle|^2$$

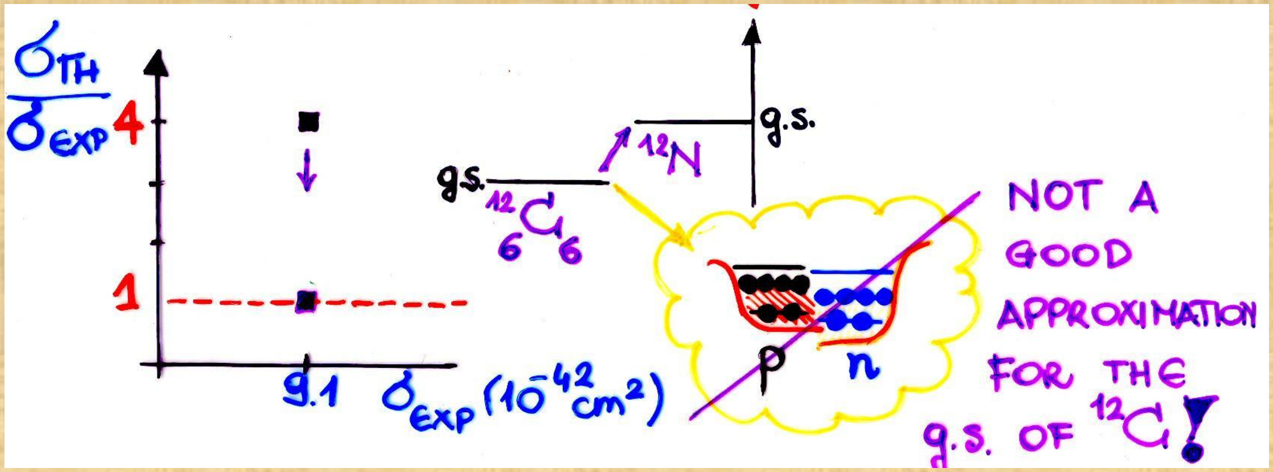
GAMOW-TELLER (SPIN-ISOSPIN) TRANSITIONS

⇒ **ISOSPIN AND SPIN-ISOSPIN collective EXCITATIONS**

Having accurate theoretical values of the ν-nucleus reaction cross sections is a challenging task…

An example

Reactions of neutrinos on carbon (important for the LSND and KARMEN experiment) have been the object of intensive studies to understand the origin of a discrepancies between experiment and theory by a factor of 2-4.



Hayes and Towner, PRC61(2000)044603.
Volpe, et al. PRC62(2000)015501.

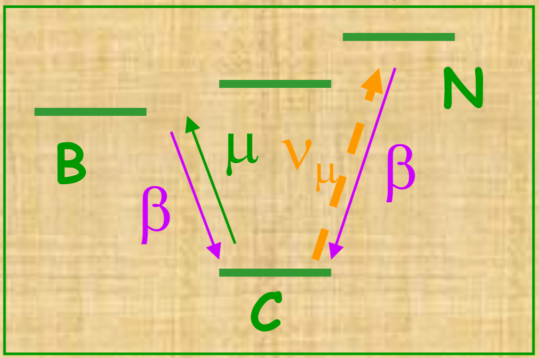
the inclusive cross sections not yet understood…

Possible constraints to the predictions

- From other weak processes :

  Very low momentum transfer (a few MeVs) ⟵ β-decay

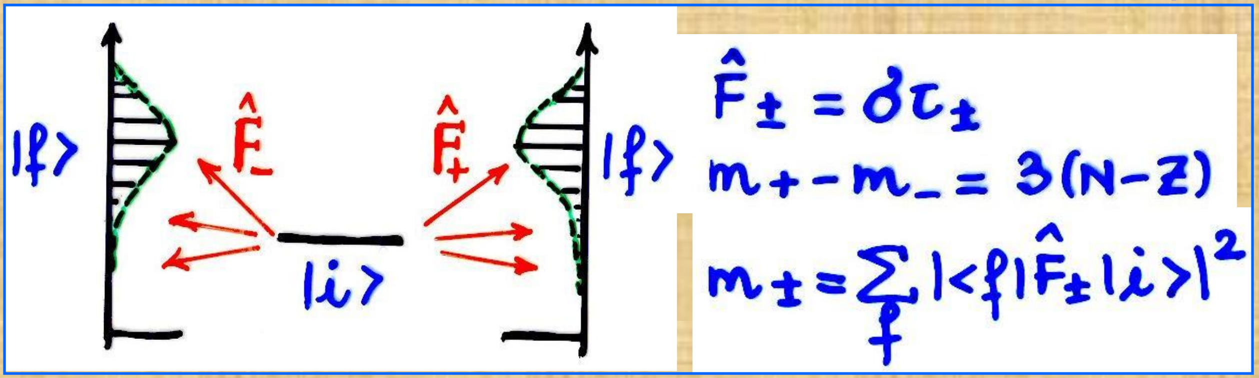
  Low momentum transfer (about 100 MeV) ⟵ μ-capture



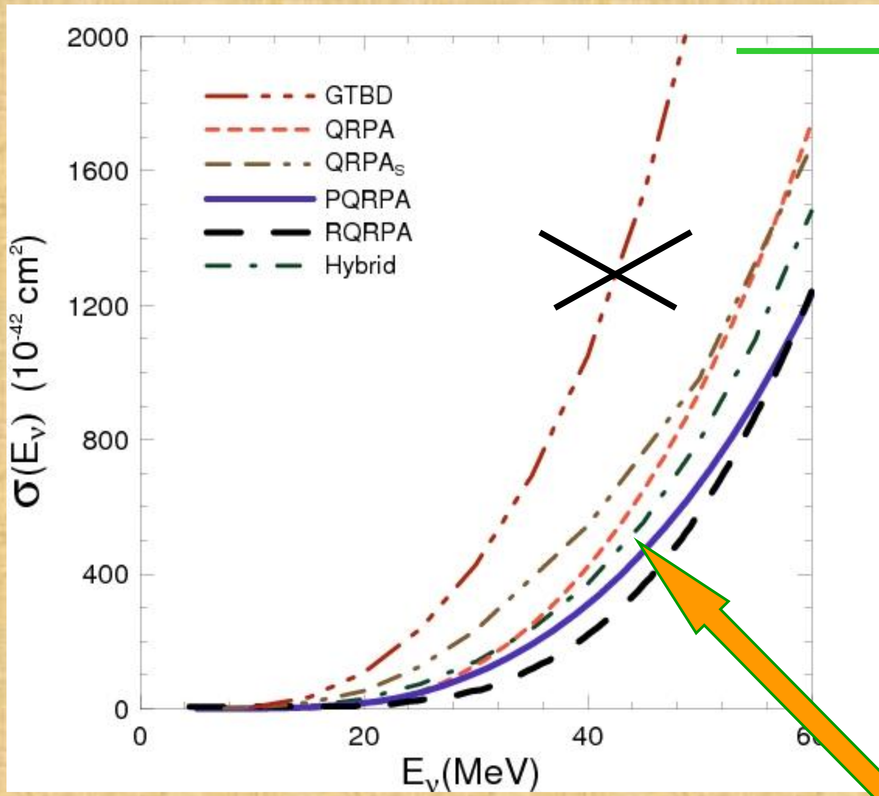
EXAMPLE

- From model-independent sum-rules, for some states.

IKEDA sum rule : example



An example of current uncertainties



Allowed approximation
($qr \rightarrow 0$)

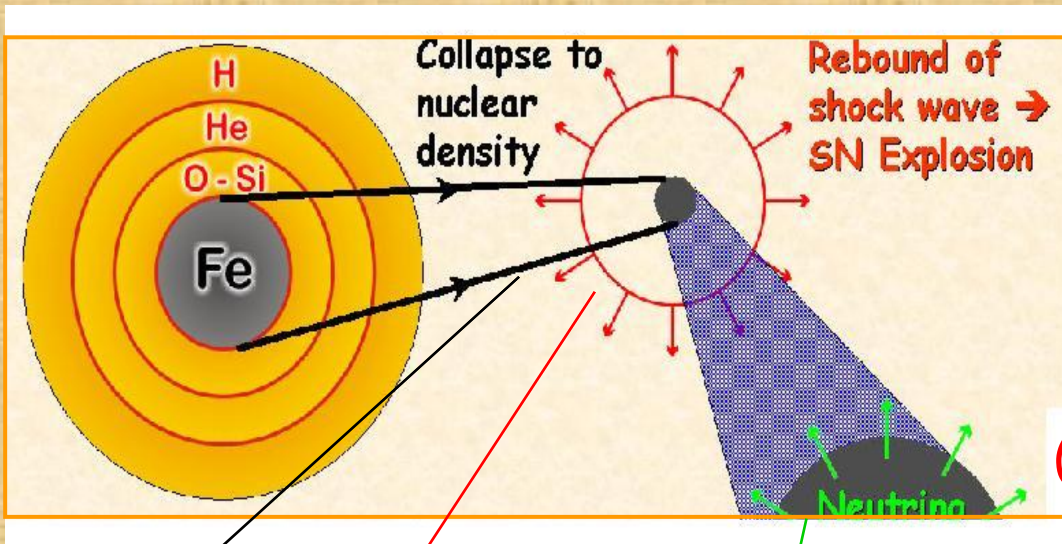
Comparison of different theoretical predictions for the neutrino-iron cross section.

Bertulani and Samana,
PRC78 (2008)
arXiv:0802.1553

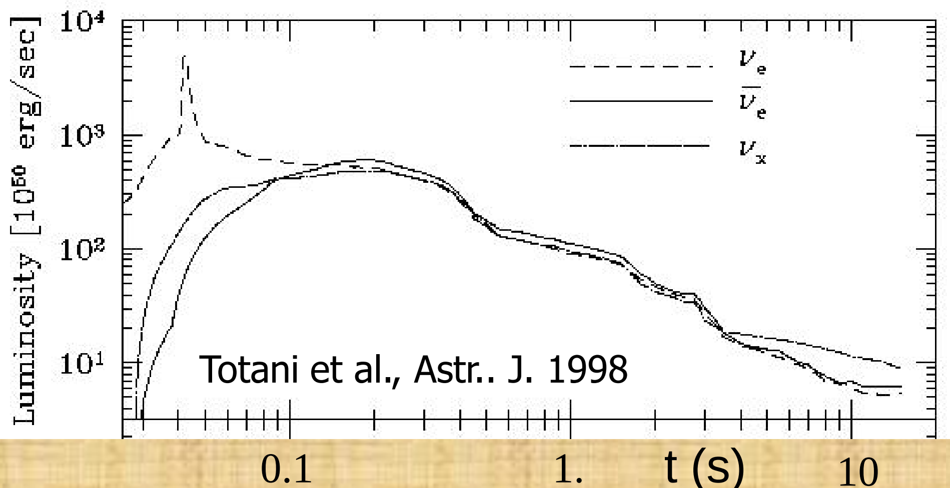
all calculations compatible with the KARMEN measurement...

NEED FOR NEW MEASUREMENTS !

II. Core-collapse SUPERNOVA NEUTRINOS



collapse ν_e burst cooling



Neutrino-nucleus interactions are important :

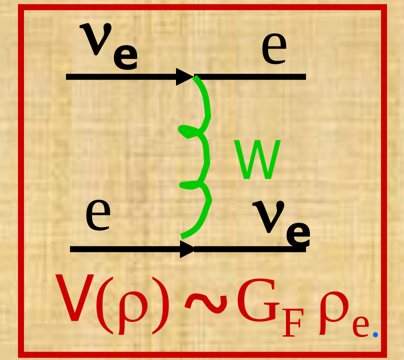
- to understand nucleosynthesis
- to determine the response of supernovae observatories

(ex. LENA, GLACIER, MEMPHYS)

^{12}C ^{40}Ar ^{16}O

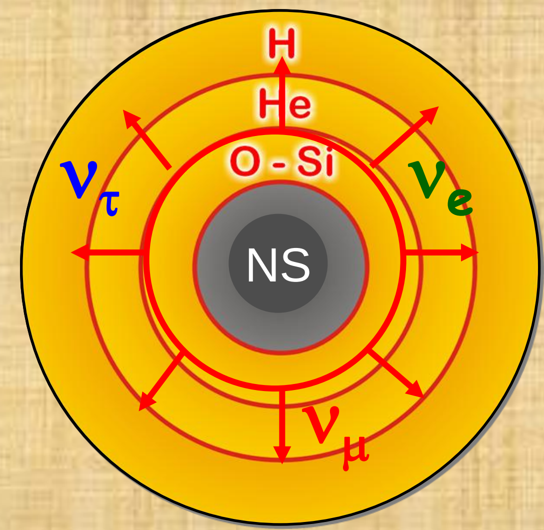
THEIR OBSERVATION WOULD BRING CRUCIAL INFORMATION ON THE EXPLOSION AND ON NEUTRINO PROPERTIES.

Neutrino propagation in dense media



The Mikheev-Smirnov-Wolfenstein (MSW) effect ('78, '86) : neutrino coupling with matter induces a resonant flavour conversion.

the beautiful explanation of the « solar neutrino deficit » problem !



Neutrino-neutrino interaction is important.
a more complex problem :
the neutrino evolution equations are non-linear.

There are also shock wave effects…

IMPRESSIVE PROGRESS IN THE LAST TWO YEARS !

The philosophy…

« To use stars and the primordial Universe for the study of fundamental properties. »

Neutrinos

- mixing angle θ_{13} ?
- mass hierarchy ?
- CP violation ?
- neutrino nature (Majorana or Dirac) ?
- …

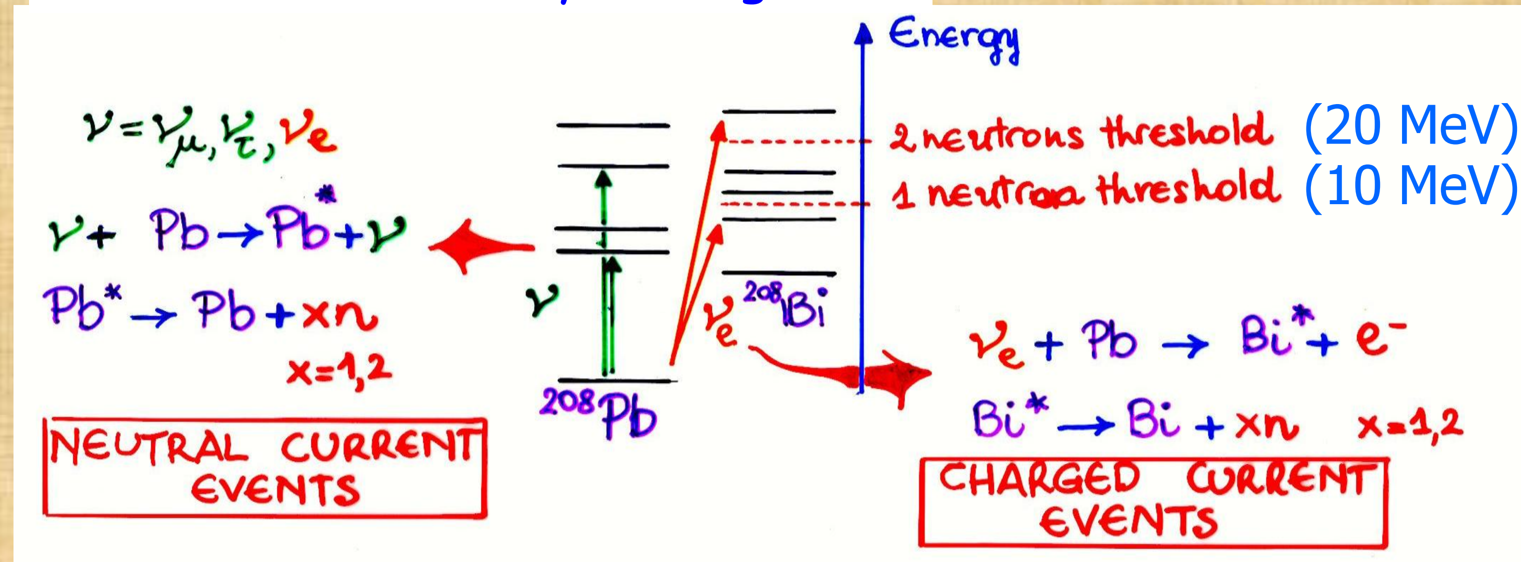
Core-collapse supernovae

- direct effects on the ν-spectra and time distributions
- indirect effects on SN dynamics : explosion, r-process, …
- …

SN neutrinos and ν-properties : θ_{13}

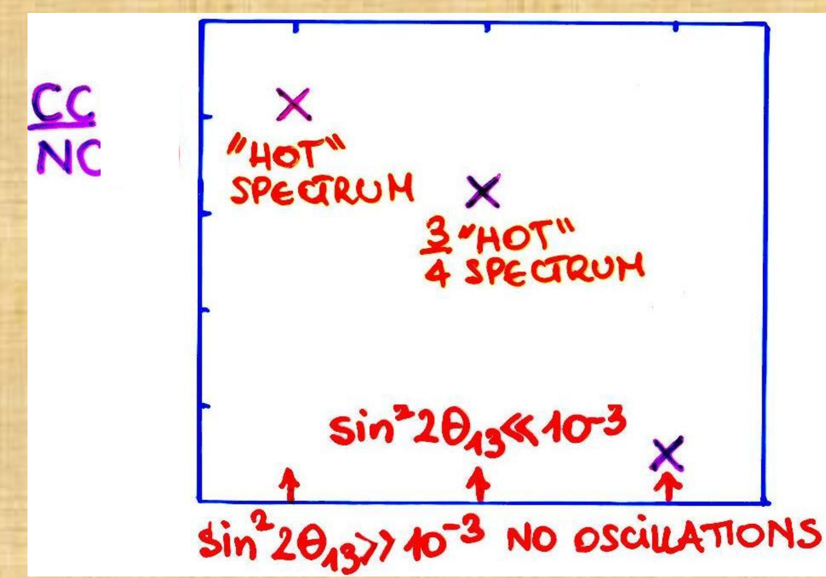
Present limit : $\sin^2 2\theta_{13} < 0.1$ (CHOOZ)

In a lead observatory the signal is:



CC + 2n events depend on the ν_e average energy and therefore on the value of the third neutrino mixing angle.

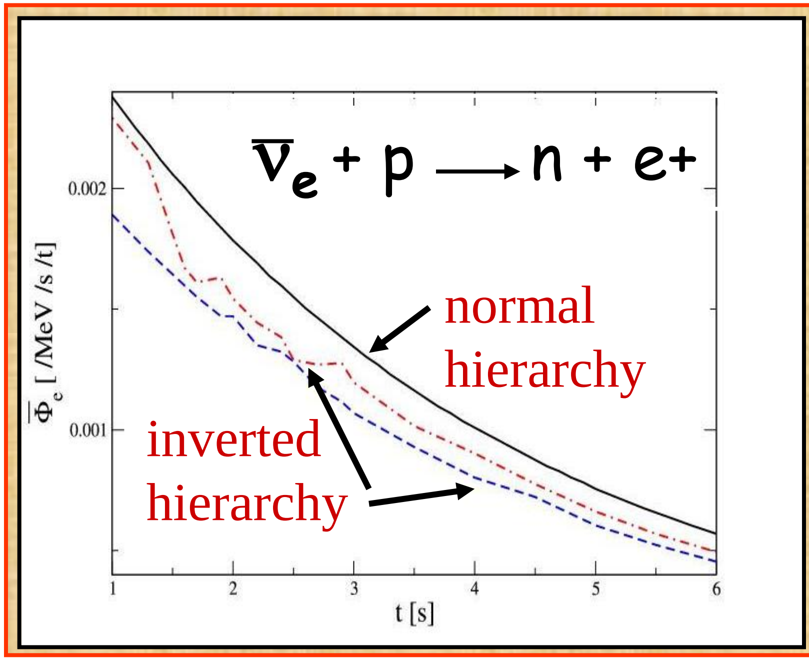
Engel, McLaughlin, Volpe, PRD67(2003)



HALO PROJECT planned AT SNOLAB.

FUTURE LARGE SIZE DETECTORS

I. To measure the neutrino luminosity curve from a future (extra)galactic explosion (ex. 10^5 events in MEMPHYS).



Very first calculation including neutrino-neutrino interaction and shock wave effects.

From the time signal we can learn if $\sin^2 2\theta_{13} > 10^{-5}$!

Gava, Kneller, Volpe, McLaughlin, arXiv:0902.0317

II. To measure the relic neutrino background from past explosions.

Important to have information on relic electron neutrinos as well, using carbon (LENA) and oxygen (MEMPHYS).

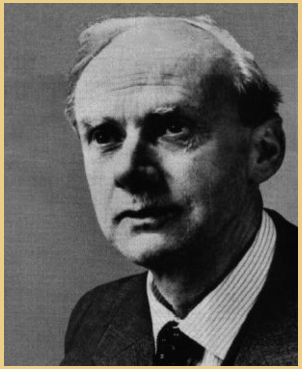
Volpe and Welzel, arXiv:0711.3237

LAGUNA Design Study (FP7) en 2008-2012.

The neutrino nature

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

Dirac particle



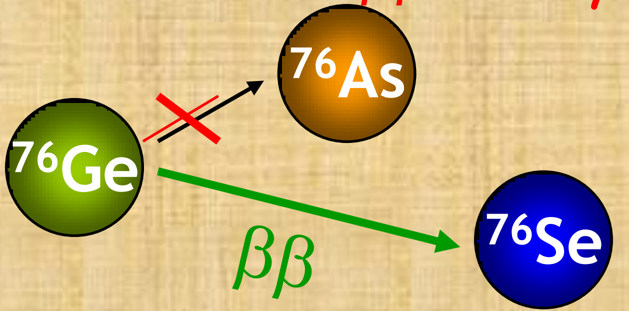
?

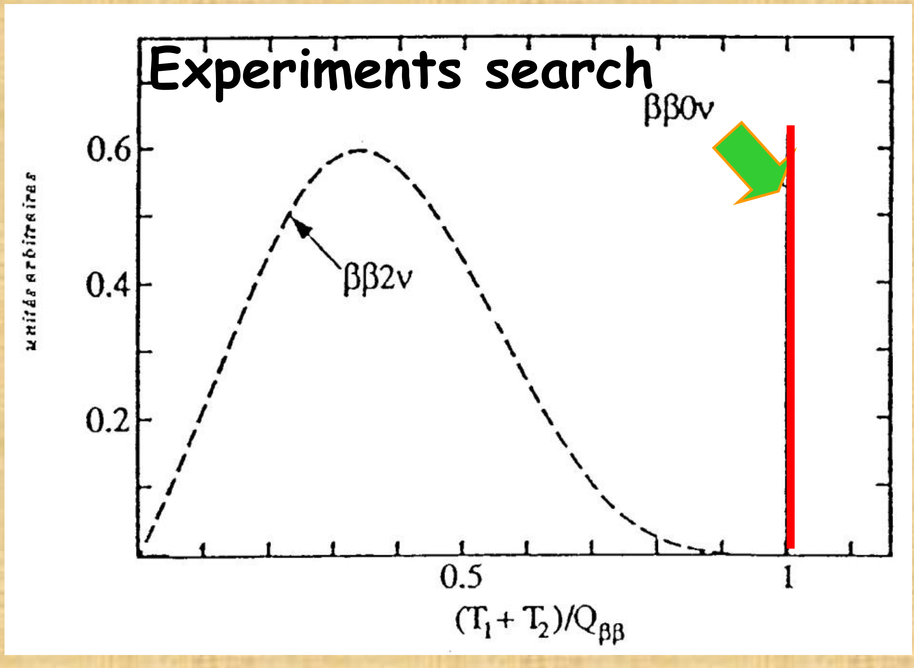
$\nu = \bar{\nu}$

Majorana p.

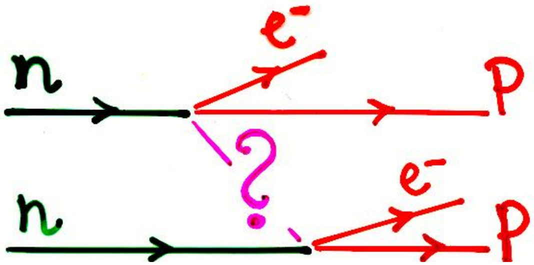
The search for the nature

neutrinoless ββ decay



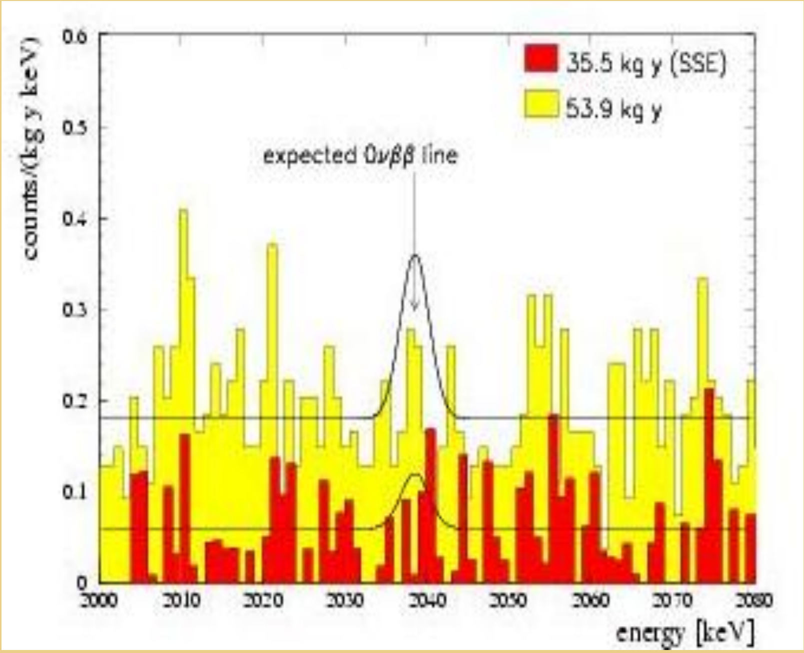


ββ : $2n \rightarrow 2p + 2e^-$



Lepton-violating process

due to Majorana neutrino exchange, physics beyond the Standard Model.



$< m_\nu > < 0.3 - 1.0$ eV
The best present upper limit.

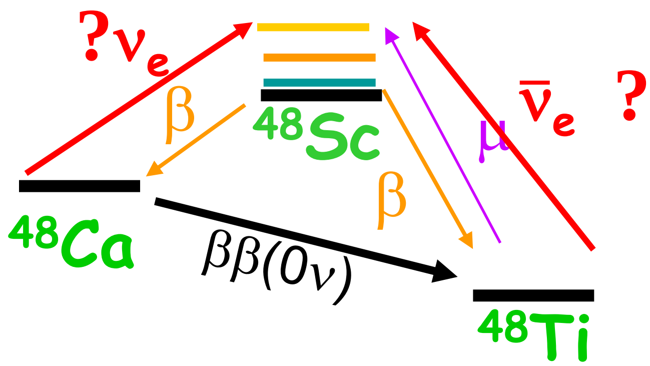
A (debated) claim for evidence.

CUORE and GERDA will confirm/refute it and reach the 50 meV sensitivity.

THE ββ-DECAY observation :
A MAJOR DISCOVERY.

THE PREDICTIONS ARE AFFECTED BY SIGNIFICANT DISCREPANCIES !

« Calibrating » calculations with related observables?



$\beta+/\beta-$: only a few energy levels

Muto,Bender,Klapdor, Z.Phys.A 1989; Aunola, Suhonen, 1996; ...

μ capture : states up to 100 MeV, only one branch

Kortelainen and Suhonen, Europhys. Lett. 2002; Phys. Atom. 2004.

charge-exchange reactions : a very good tool, high resolution

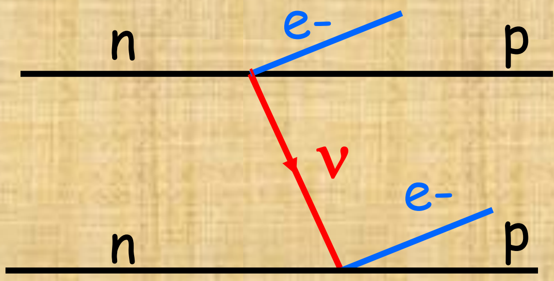
Bernabeu et al., 1988; Akimune et al., 1997; Ejiri, Phys. Rep.; ...

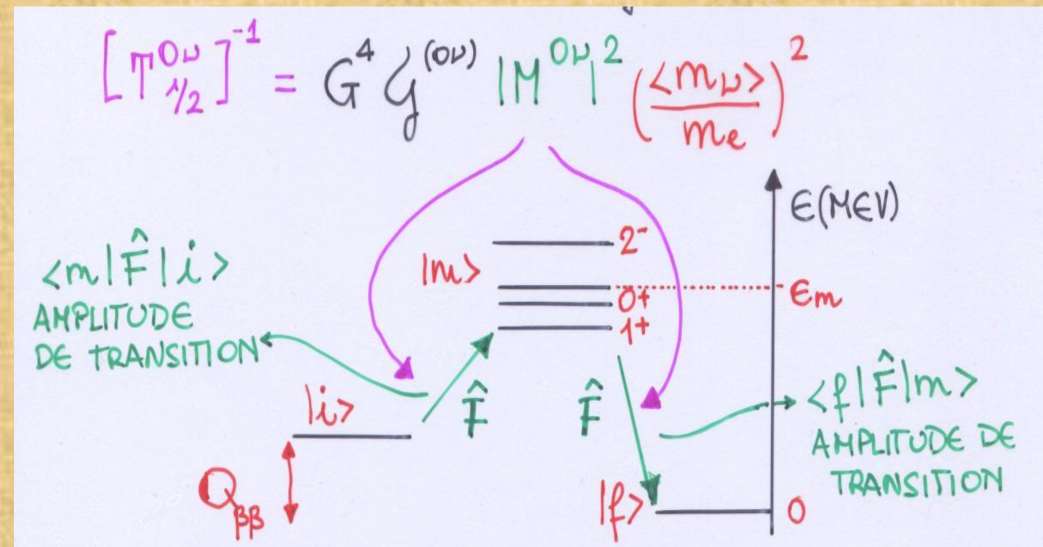
$2\beta(2\nu)$: only 1^+ (GT) states

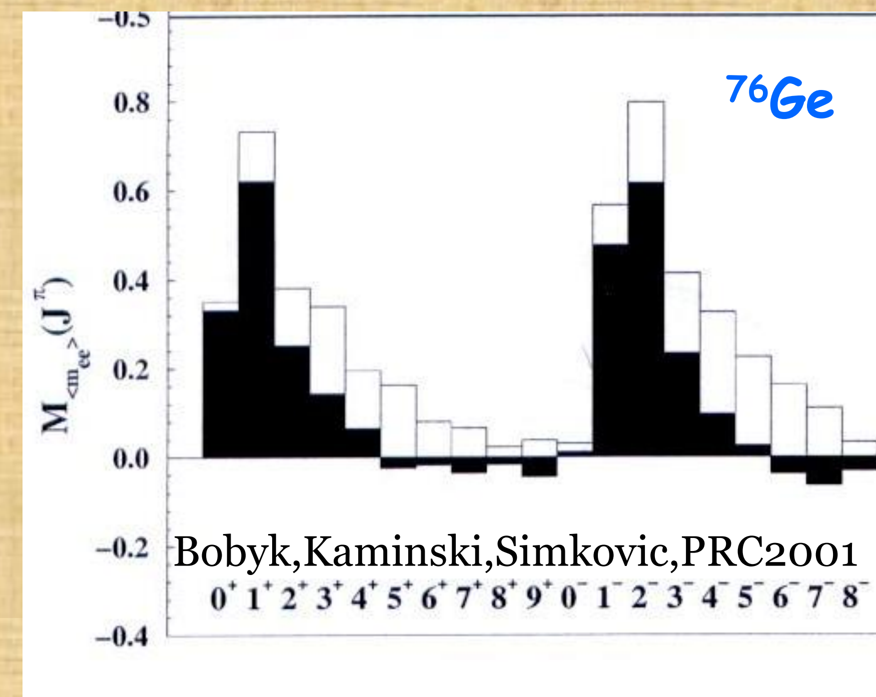
Muto, Bender, Klapdof, 1993; Faessler et al., 1987; Rodin et al. PRC 2001; ...

The 2β(0ν) half-life

2β(0ν): 2n → 2p + $2e^-$





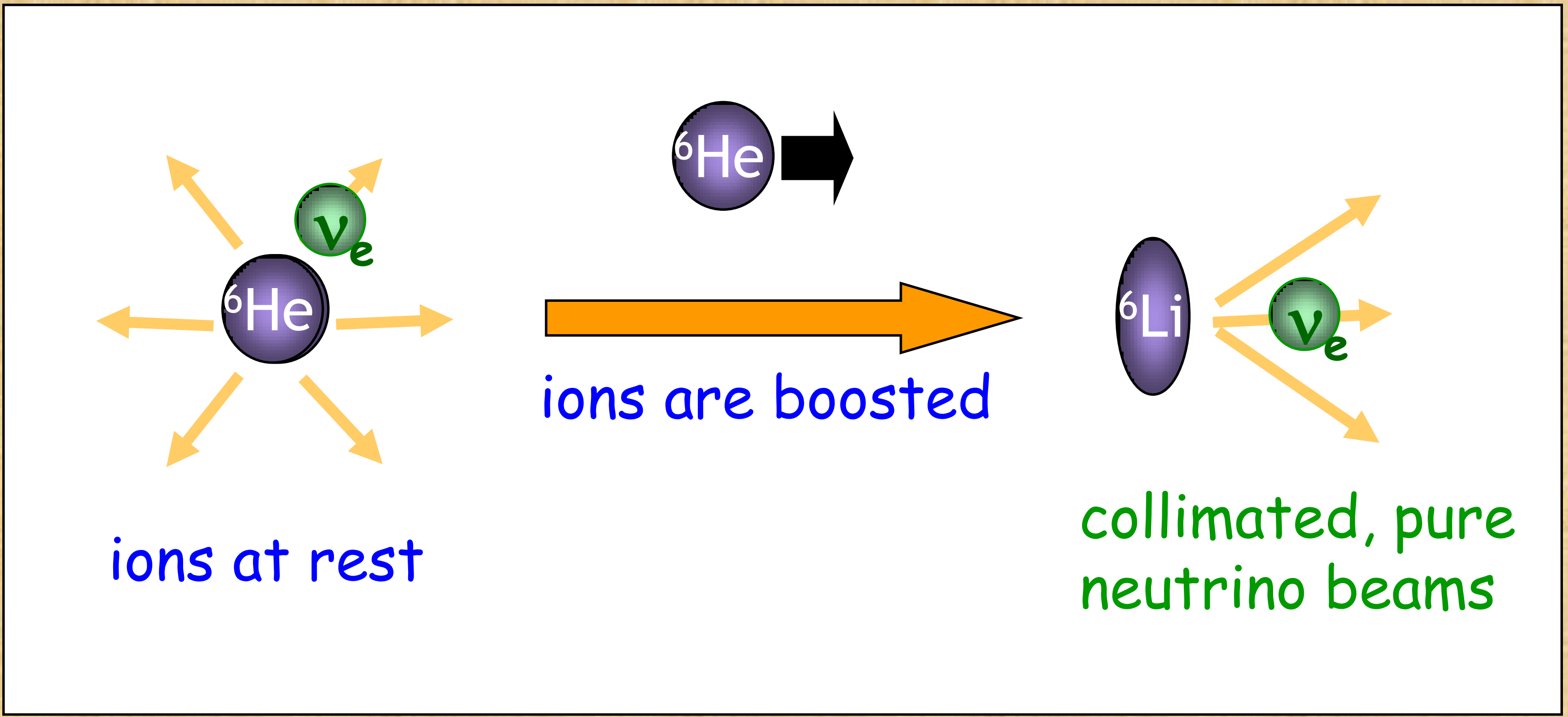


One can show that the states involved in neutrinoless double-beta decay due to the exchange a massive Majorana neutrino are the same states as those excited in neutrino-nucleus interactions.

Volpe, hep-ph/0501233, J. Phys.G.31(2005)

A NEW CONSTRAIN FOR
THE HALF-LIFE CALCULATIONS.

The beta -beam concept



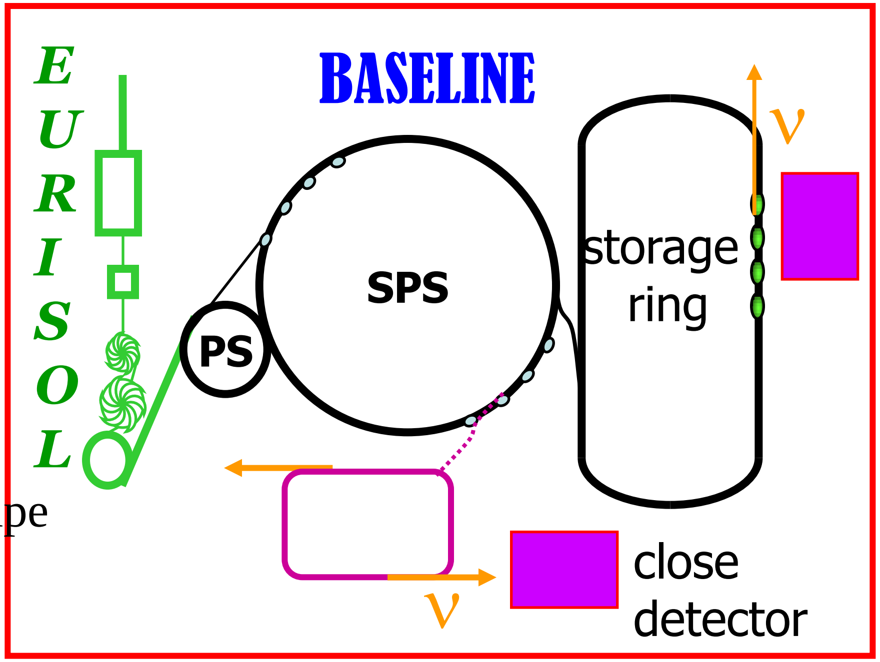
Why don't we use the decay of boosted radioactive ions to produce neutrino beams?

Zucchelli, PLB 2003

LOW ENERGY BETA-BEAMS

C.Volpe, J Phys G 30 (2004) L1.

A proposal to establish a facility for the production of intense and pure low energy neutrino beams (10-100 MeV).



Lazauskas et al, PRD 76 (2007)

Serreau and Volpe PRC 70 (2004)

NEW AXIS for EURISOL, FEASIBILITY STUDY ongoing (FP6)

Physics potential of low energy beta-beams

- 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 PRD 2007
….

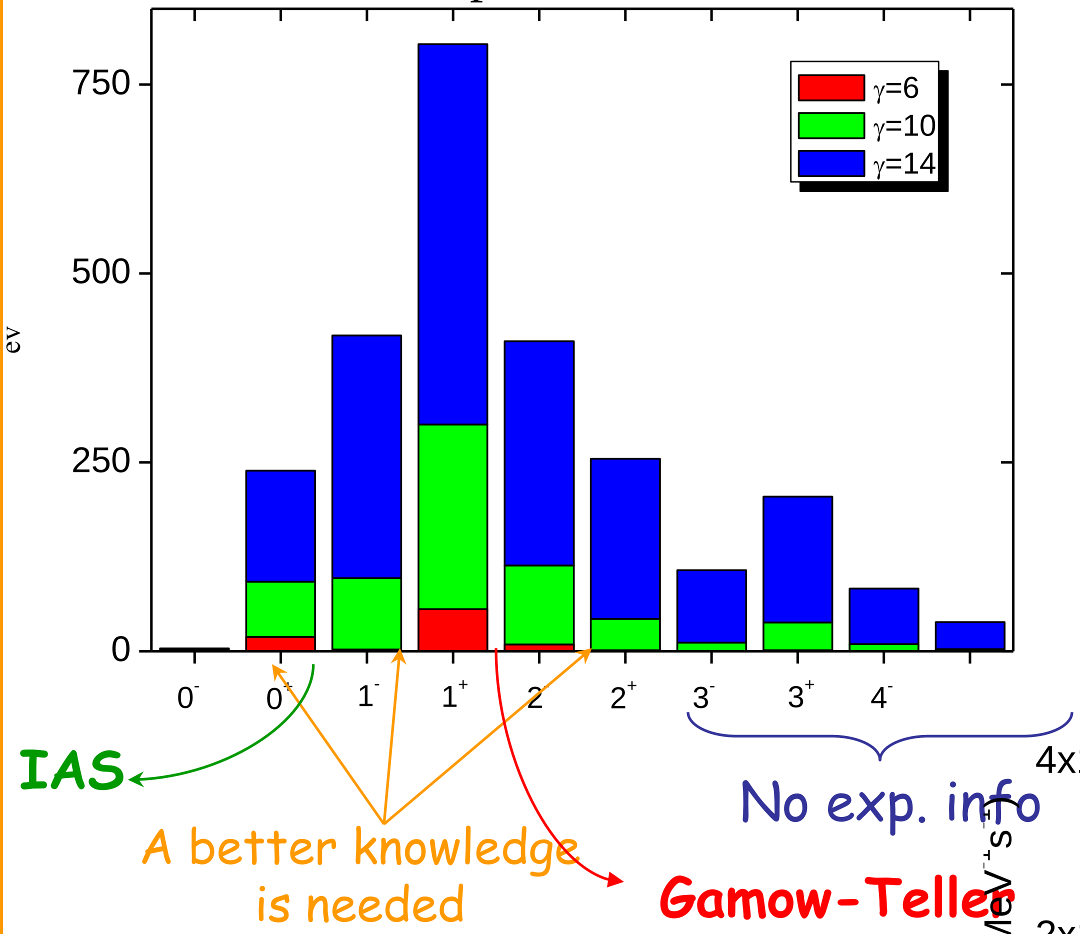
Off-axis options :

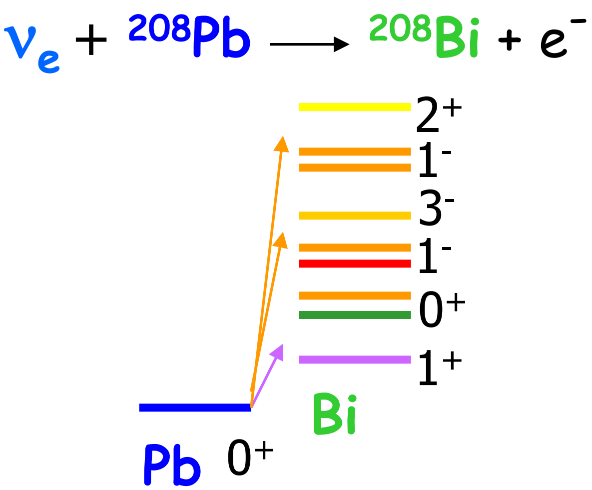
Lazauskas et al PRD 2007, Amanik et al PRC 2007 .

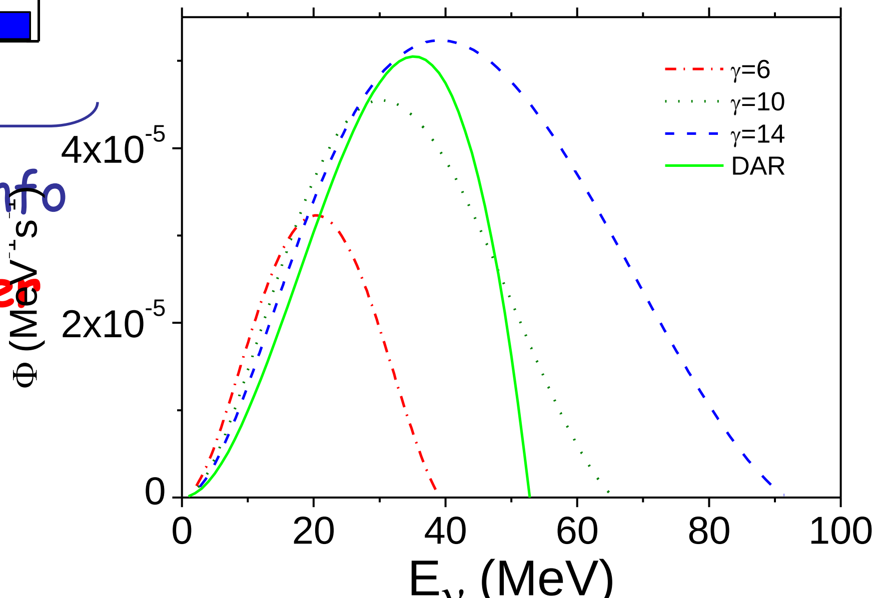
C.Volpe, Review on “Beta-beams”, J. Phys. G34, R1 (2007), hep-ph/0605033

NEUTRINO-NUCLEUS MEASUREMENTS

Lazauskas and Volpe, NPA 2007

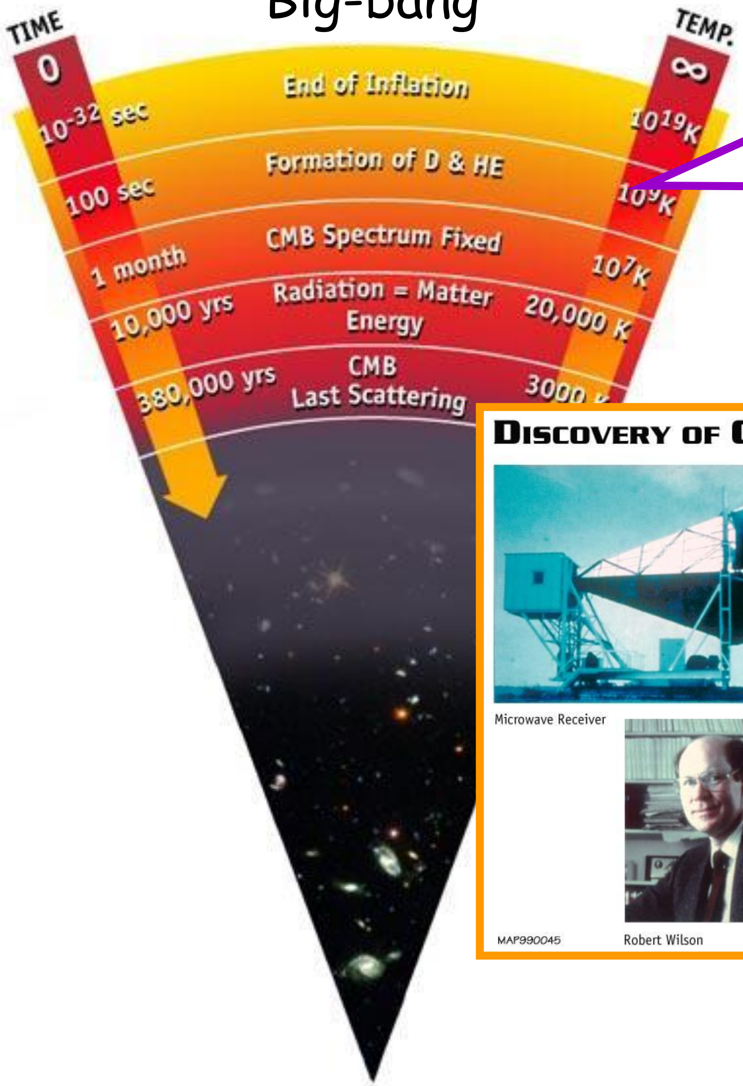






Low energy beta-beams:
A TOOL TO STUDY
SPIN-ISOSPIN EXCITATIONS.

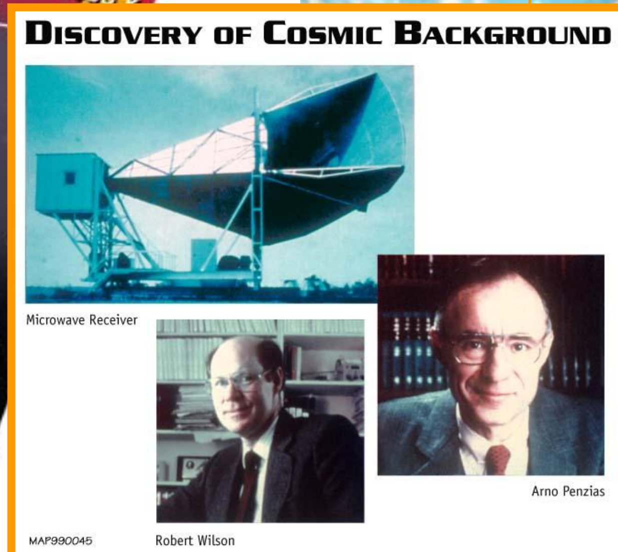
Big-bang



Today
13.7 billion years
after the Big-bang

neutrinos from early Universe
a picture of the Universe
1 second after the Big-Bang !

Cosmological neutrinos
density= 330 cm^{-3}
temperature = 1.9 K

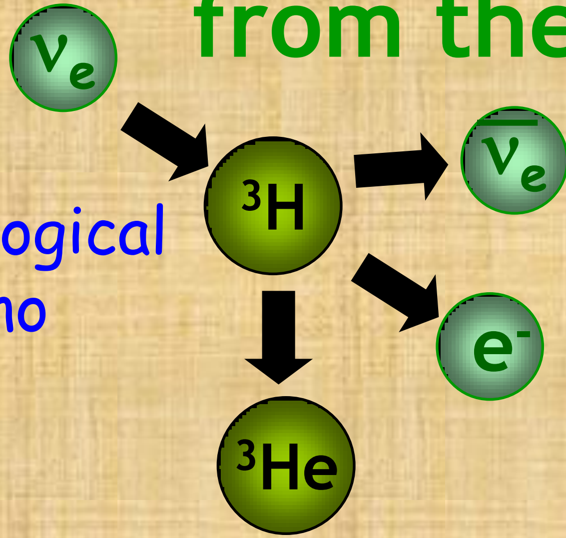


icrowave Background
density = 422 cm^{-3}
temperature = 2.75 K

Penzias and Wilson
Nobel Prize in 1978

The *dream* of detecting neutrinos from the early Universe

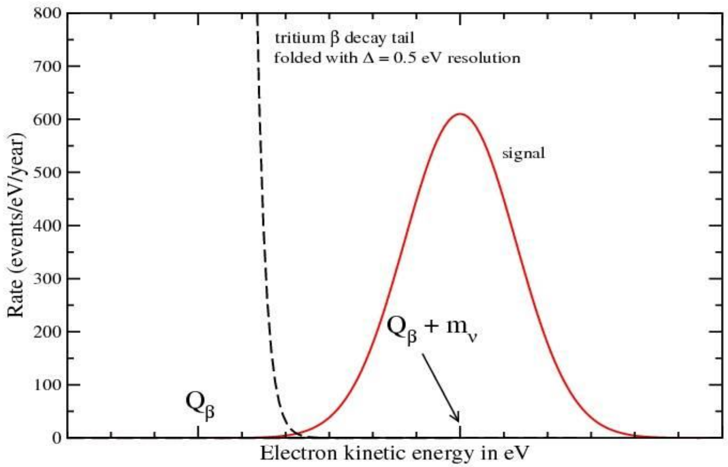
cosmological neutrino



Weinberg, Phys. Rev. 1962

USING RADIOACTIVE NUCLEI ?

The neutrino capture on a radioactive nucleus is a process with no threshold.



Lazauskas,Vogel,Volpe J.Phys.G 2008

Cocco, Mangano, Messina, JCAP 2007

The cross section is enhanced (today at least one neutrino is non-relativistic.)

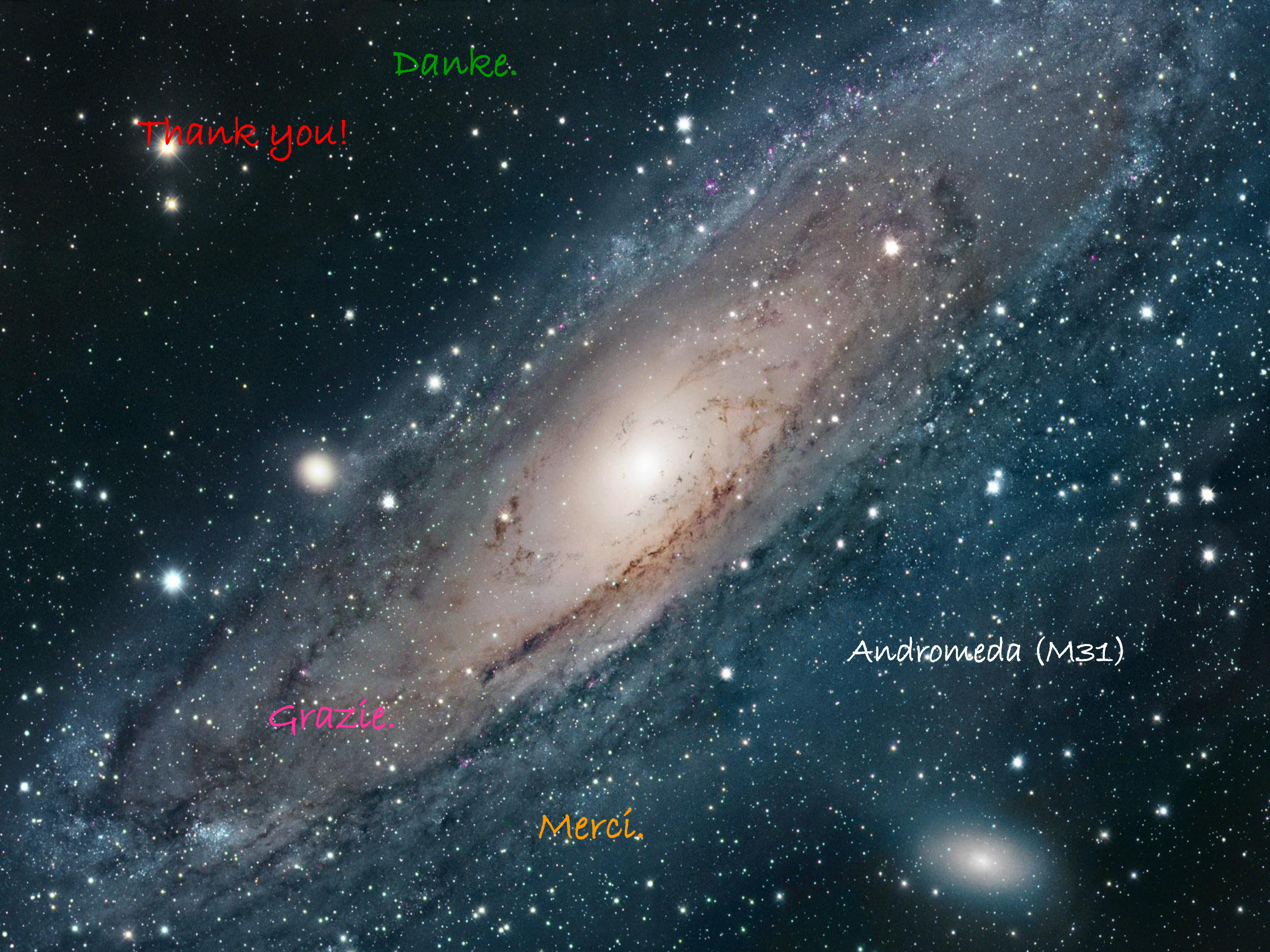
Example : 100 grams of tritium
10 events/year.

Conclusions

- Neutrino scattering at low energy plays a key role on important open issues in astrophysics and for the study of fundamental interactions.

- Need for further measurements with future facilities based on conventional sources (nuSNS) and/or low energy beta-beams.

exciting discoveries might be close...


Danke.
Thank you!
Andromeda (M31)
Grazie.
Merci.

FRONTIERS IN THEORETICAL NEUTRINO PHYSICS

16-19 March 2009 APC, Paris

TOPICS INCLUDE :

neutrino properties,
core-collapse supernova neutrinos,
cosmological ν and their detection,
neutrinos from Gamma-Ray-Bursts,
Ultra-High-Energy ν

Contact : Cristina Volpe, organizer, volpe@ipno.in2p3.fr
Aurelia Guet, secretary, aurelia@apc.univ-paris7.fr

http://ipnweb.in2p3.fr/frontiers