Kepler Center for Astro and Particle Physics
Eberhard Karls Universitat Tubingen, Germany

# Kepler Kolloquium

# "Low-Energy Neutrino Detection through Neutrino-Nucleus Interaction Probes"

**T.S. Kosmas**

Division of Theoretical Physics, University of Ioannina, GR-45110, Greece

- Low-energy Neutrino production Sources
- Neutrino Detection
- Neutrino-Nucleus Interactions
  - Coherent Neutrino-Nucleus Scattering
  - Inelastic Neutrino-Nucleus Scattering

# Collaborating Groups:

| | |
|---|---|
| University of Ioannina, Greece : | V. Tsikoudi, J. Sinatkas, V. Stavrou K. Balasi, V. Tsakstara, G. Karathanou, P. Giannaka, J. Kardaras |
| Hellenic Army Academy, Greece: | P.C. Divari, Th. Liolios |

| | |
|---|---|
| Univ. of Tuebingen, Germany : | Group of A. Faessler |
| T. Univ. of Darmstadt, Germany : | Group of J. Wambach |
| Univ. of Jyvaskyla, Finland : | Group of J. Suhonen |
| Univ. of Valencia, Spain : | Group of J.W.F. Valle |
| RCNP, Univ. of Osaka, Japan : | H. Ejiri (MOON-experiment) |
| T.Univ Dresden, Germany : | K. Zuber (COBRA-experiment) |

# Important neutrino *production* sources

## *1) Laboratory Neutrino Sources*

i. Reactor neutrinos (Low-Energy neutrino beams)

- Slow – pion and muon decay (E < 52.8 MeV)
- Beta decay (E < 10 MeV)

ii. Accelerator neutrinos (High-Energy neutrino beams)

- Boosted beta-beam neutrinos (E < 100 MeV and more)
- Long (short) baseline neutrinos

## *2) Astrophysical Neutrino Sources*

i. Solar Neutrinos (E < 20 MeV)

ii. Supernova Neutrinos (E < 60 - 80 MeV)

iii. Atmospheric Neutrinos (E < a few GeV)

iv. Gamma-Ray-burst neutrinos, Cosmological Neutrinos, etc.

# *Reactor neutrino sources*

Reactor neutrino beams used to study low-energy neutrino interactions and neutrino oscillations (KARMEN, LSND, BooNE, etc. ):

slow-pion decay

$$\pi^+ \to \mu^+ + \nu_\mu$$

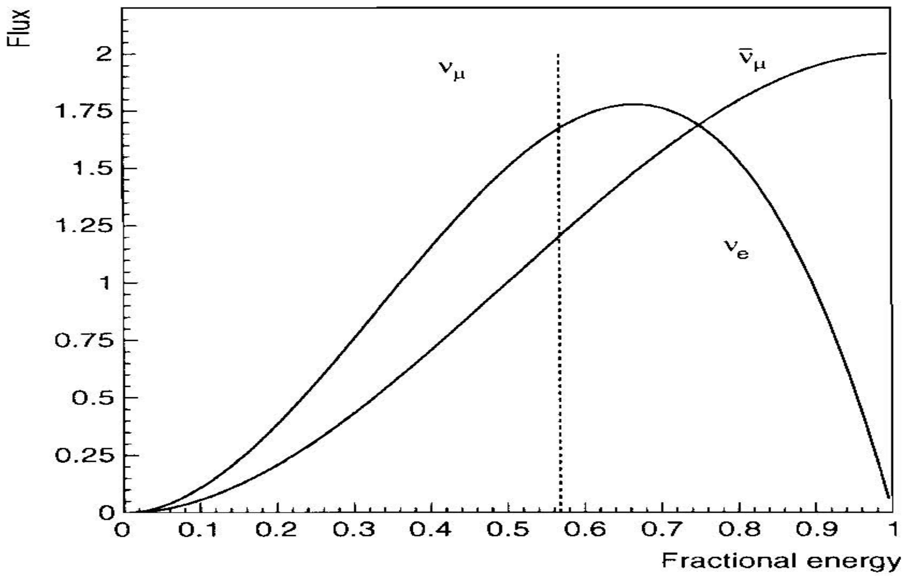
$$\pi^- \to \mu^- + \bar{\nu}_\mu$$

μ-decay (at rest)

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

W.C. Louis / Progress in Particle and Nuclear Physics 63 (2009) 51–73




he neutrino energy spectra from $\pi^+$ and $\mu^+$ DAR. The vertical scale is arbitrary.

## ***Neutrino distributions***

$$n_{\nu_e}(\varepsilon_{\nu_e}) = \frac{96\varepsilon_{\nu_e}^2}{m_\mu^4}(m_\mu - 2\varepsilon_{\nu_e})$$

$$n_{\bar{\nu}_\mu}(\varepsilon_{\bar{\nu}_\mu}) = \frac{32\varepsilon_{\bar{\nu}_\mu}^2}{m_\mu^4}(\frac{3}{2}m_\mu - 2\varepsilon_{\bar{\nu}_\mu})$$

# Reactor Neutrinos for low-energy interactions and neutrino oscillations

The LSND (Liquid Scintillator Reactor Neutrino Detector) was designed to search for the oscillation

$$\tilde{\nu}_\mu \rightarrow \tilde{\nu}_e$$

and obtained evidence for flavor change at the scale $\Delta m^2 \sim 0.2\,\mathrm{eV}^2$

Although KARMEN did not confirm the LSND results, a combined analysis of the two experiments defines compatible regions:

W.C. Louis, Prog.Part. Nucl.Phys. 63 (09)51.

Both experiments used a high-intensity 800 MeV proton beam to produce a large number of $\pi^+$ pions which almost all decay ($\pi^-$ and the produced $\mu^-$ are captured).

The BooNE neutrino detector (FNAL) is now also used for core collapse SN searches : [astro-ph/09103182v1]

# Low-energy *Beta-beam neutrinos*

Recently, the use of *boosted β-decay radioactive nuclei* was proposed* to produce neutrino-beams of low energy (beta-beam neutrinos).

With this facility we obtain an intense, collimated and pure neutrino-beam for searching Neutrino–Nucleus Interactions.

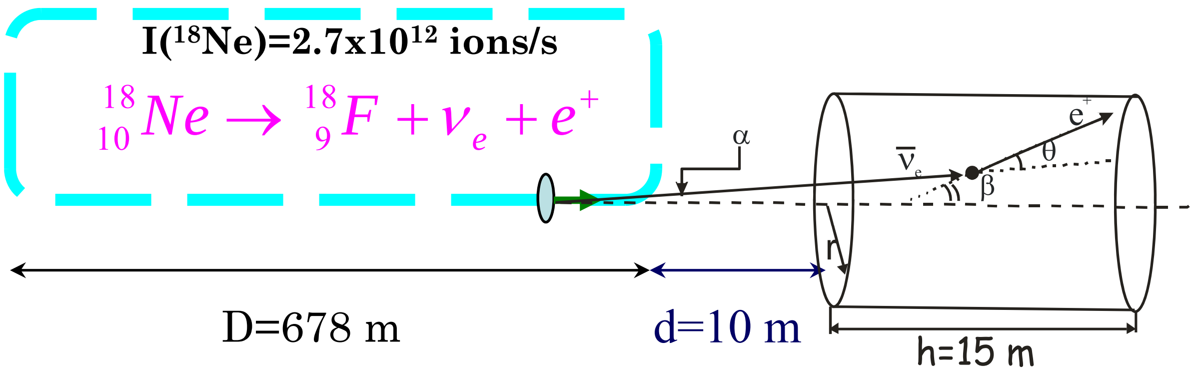
Such studies are important for various open issues in nuclear, particle physics, and astrophysics.

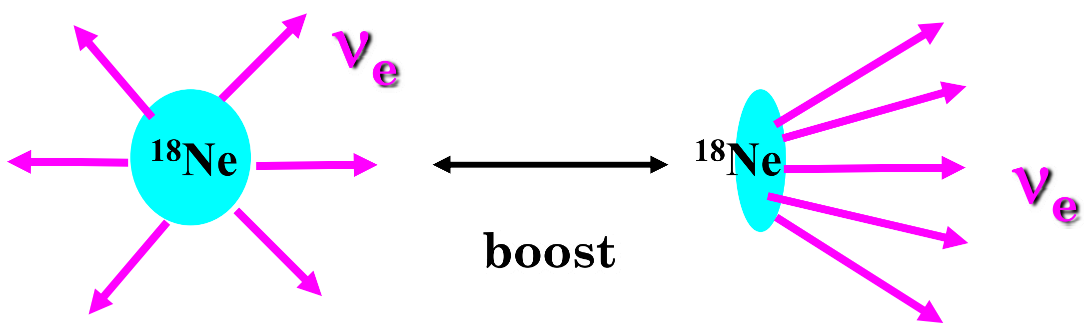
Low-energy Beta-beam neutrinos are useful for the interpretation of SN'v signals.

* C. Volpe, J. Phys. G, 30 (2004) L1–L6

# *Beta-beam neutrinos (radioactive sources)*

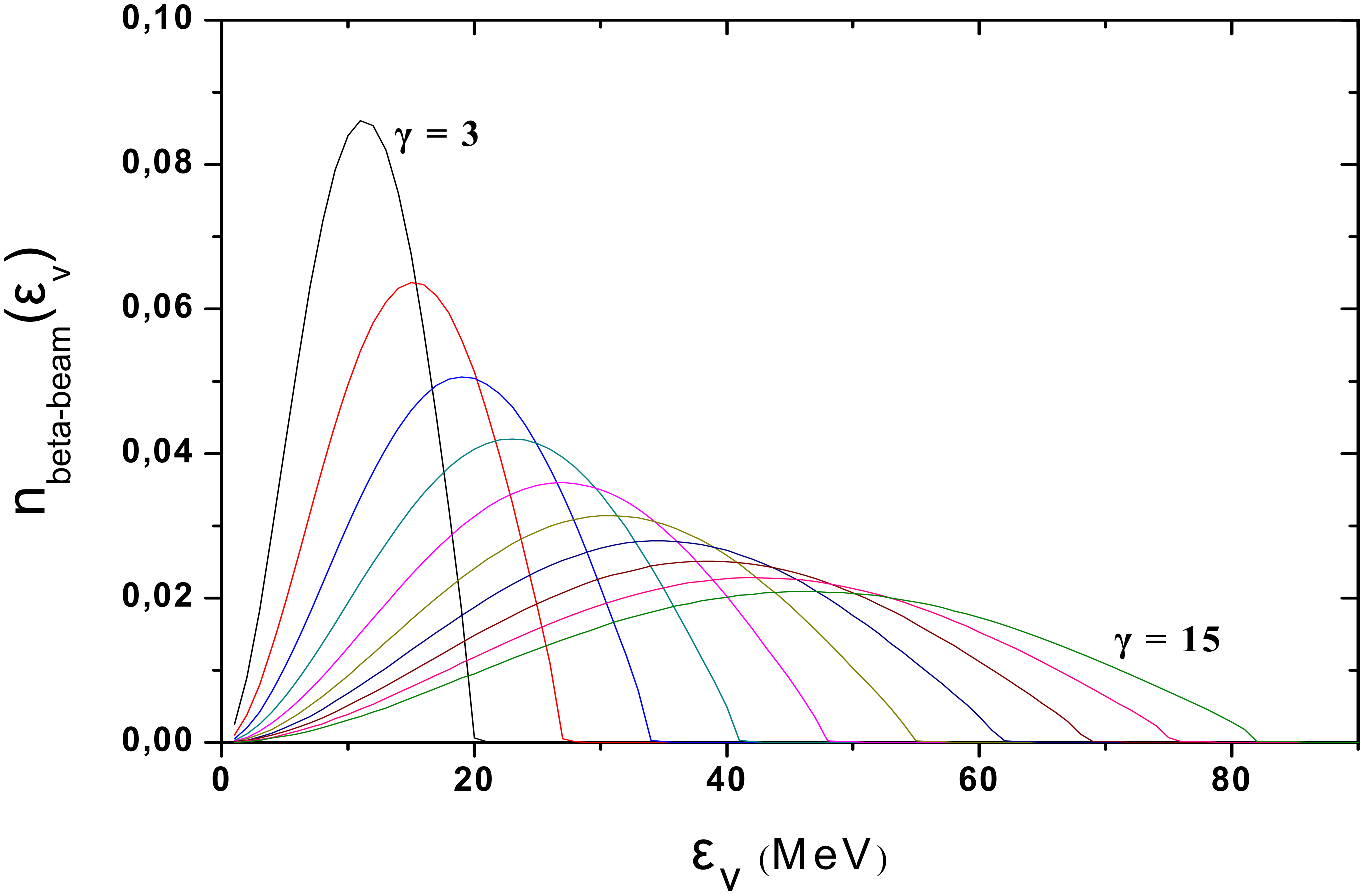
## Small Storage ring-detector



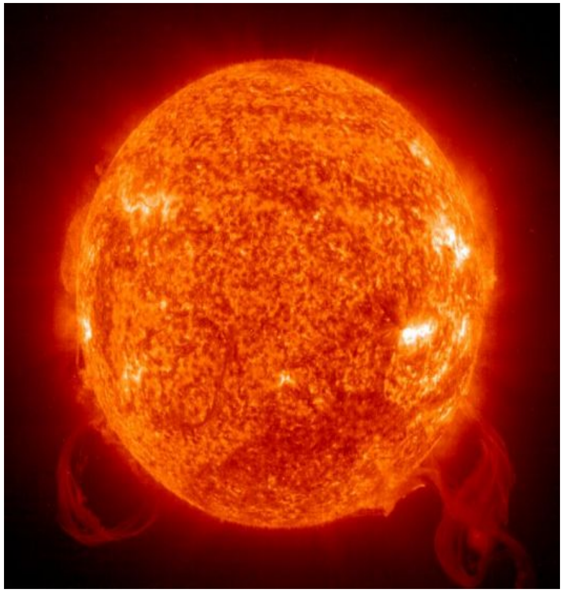

***J. Serreau, C. Volpe: Phys.Rev. C70 (2004) 055502***

# *Energy-spectra of Boosted beta-beam neutrinos*




For the interpretation of low-energy interactions (SN neutrinos, etc.) $\gamma < 15$

The distributions refer to $^{18}$Ne but there are similar for $^{6}$He too.



# Solar Neutrinos

Neutrinos produced by the thermonuclear reactions in the Sun

Underground Neutrino detection Experimen. (Homestake, GALLEX, SAGE, SK, SNO, etc.)

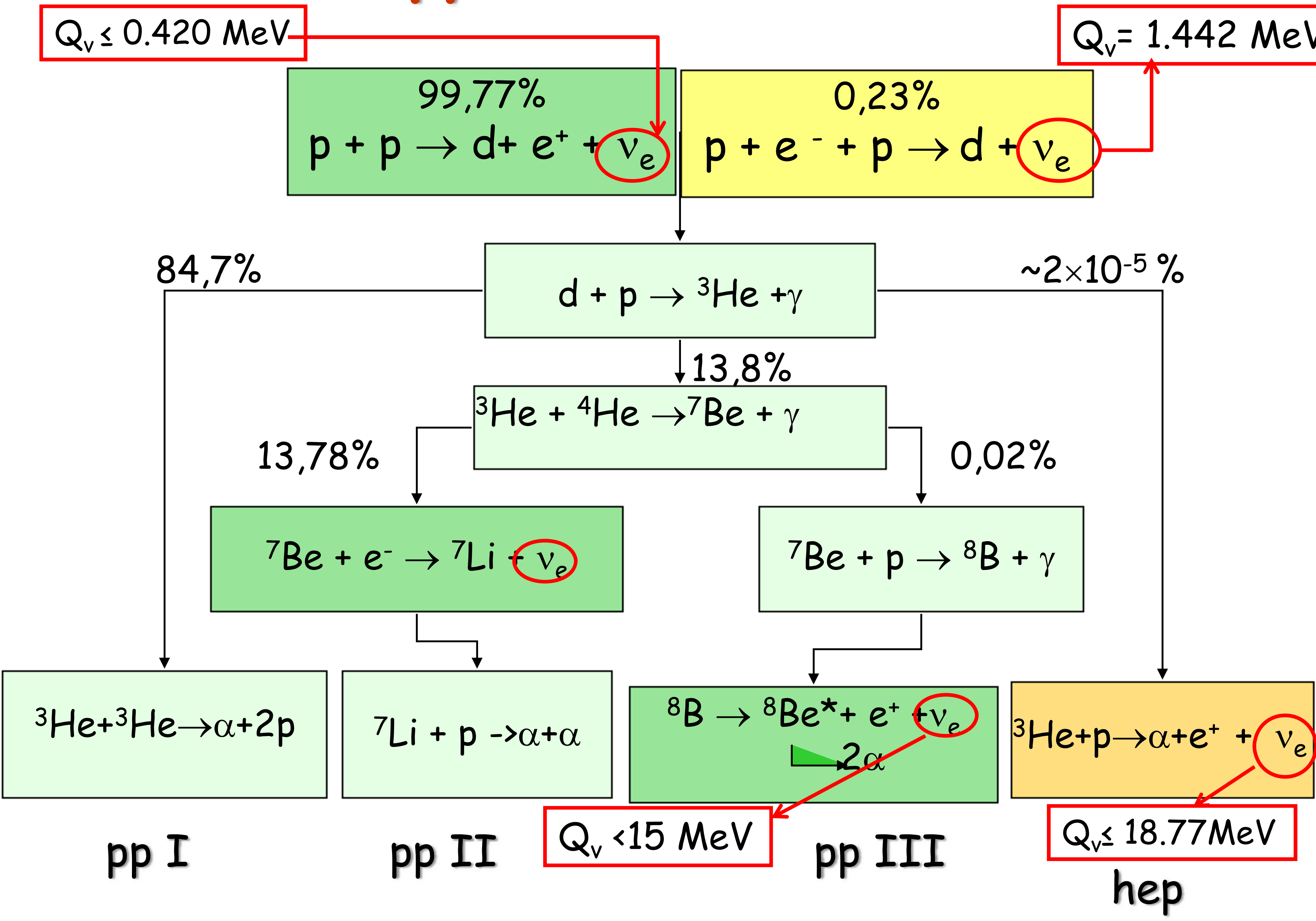
Measurements of solar neutrinos (KAMLAND, Borexino, etc. ) used to test the standard solar model (SSM).

Recent probes, SNO+ experiment, aim to measure low-flux solar neutrinos (pep, CNO-cycle neutrinos) to check the abundances of solar core and clarify if the metallicity in the Sun is homogeneous

[K. Zuber, Inv. Talk, medex09].

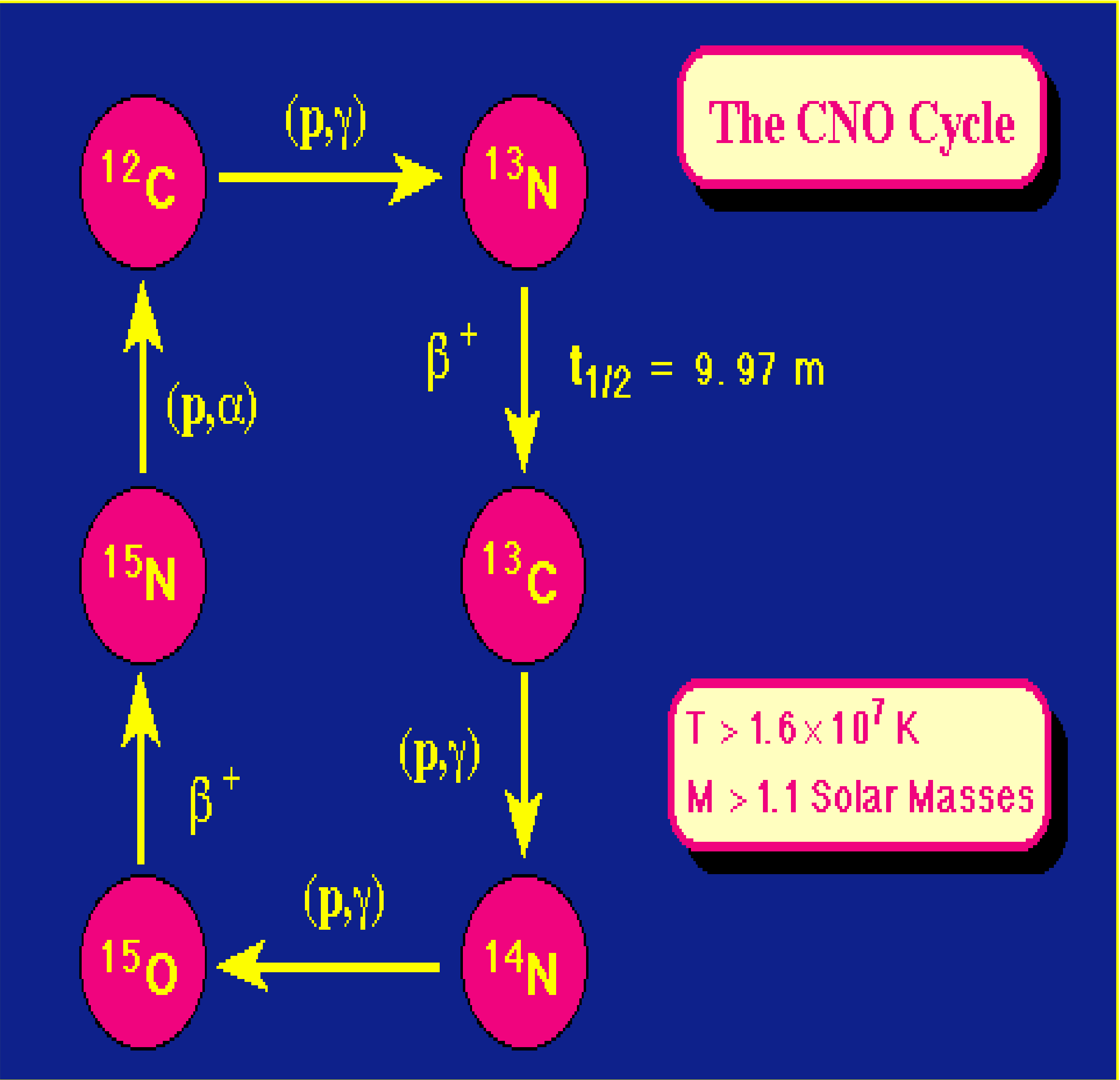
The liquid scintillator detector of SNO+ experiment will be able to study low-energy solar neutrinos, geo-neutrinos, reactor neutrinos, supernova neutrino

# pp-chain reactions



# The CNO cycle

$2^{nd}$ and $3^{rd}$ generation stars like our Sun contain heavier elements (C,N,O,etc) (formed after the explosion, matter ejection of older stars)




$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu_e$$

( ≤ 1.199 MeV)

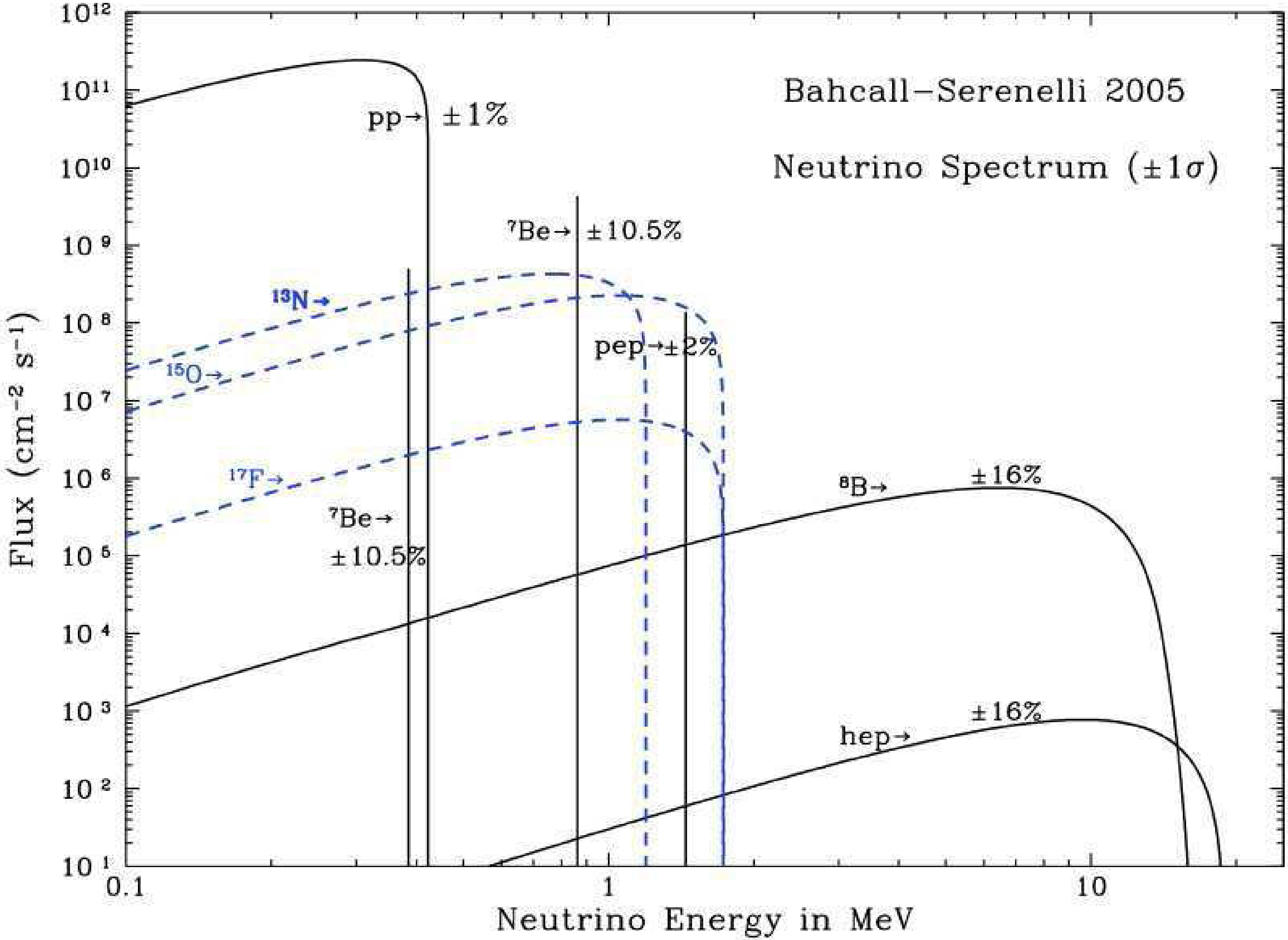
$$^{15}O \rightarrow {}^{15}N + e^{+} + \nu_e$$

(≤ 1.732 MeV)

$$^{17}F \rightarrow {}^{17}O + e^{+} + \nu_e$$

(≤ 1.739 MeV)

# Solar Neutrino fluxes (SSM)



# Core-collapse Supernova Neutrinos

**The energy-spectra of neutrinos emitted in a core collapse SN can be approximated as**

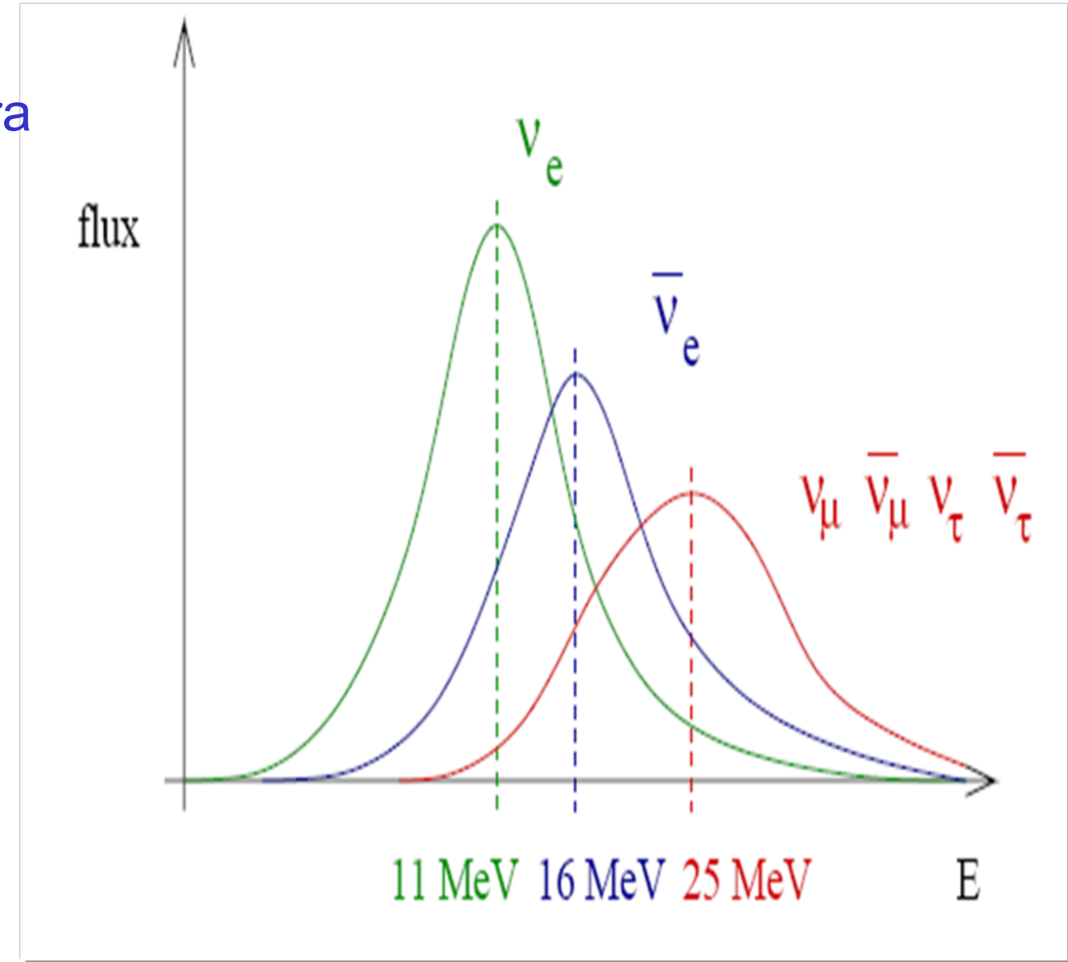
The Mean Energy of the SN spectra reflect the Temperature of the burning shell from where they escaped

$$\langle E_{\nu_e} \rangle \approx 11\, MeV$$

$$\langle E_{\bar{\nu}_e} \rangle \approx 16\, MeV$$

$$\langle E_{\nu_{\mu\tau}} \rangle \approx 25\, MeV$$

SN Energy spectra



# Parameterization of SN-ν energy-spectra

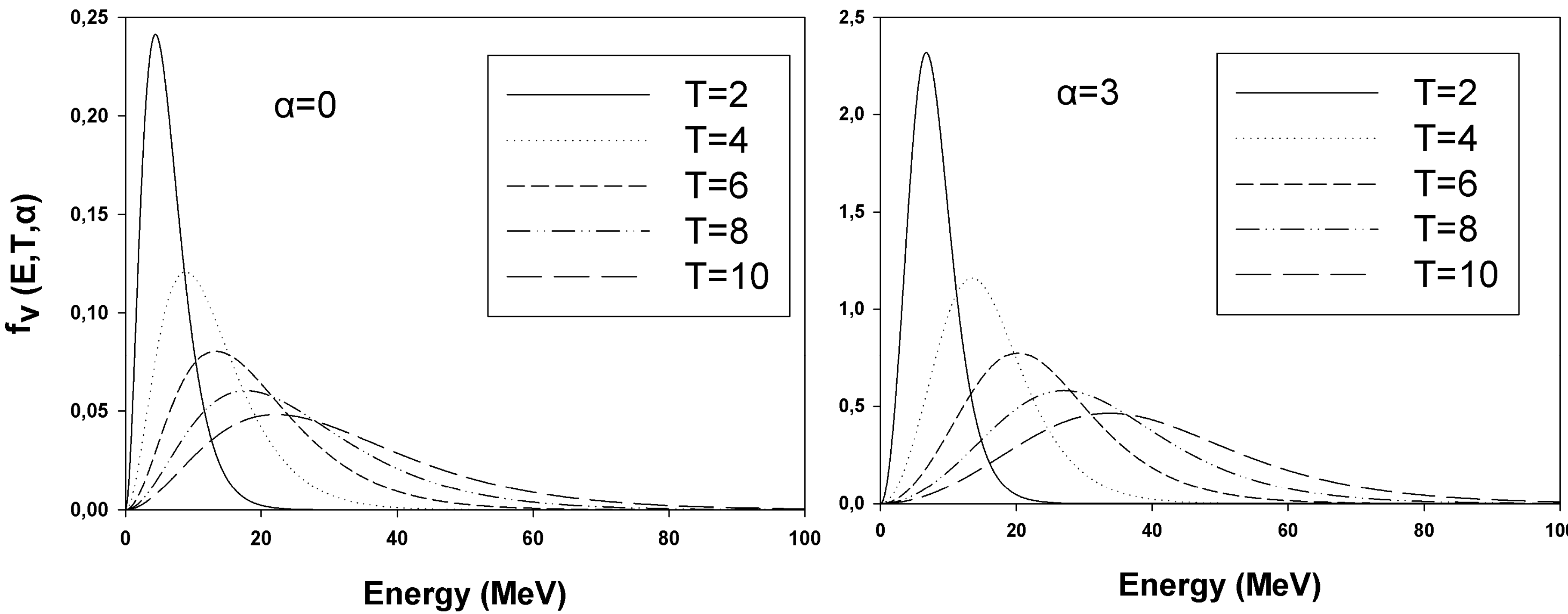
In modeling core-collapse SN and studies of nuclear response to SN-ν, various parametrizations are used :

$$f(E_\nu) = \frac{1}{F_2(\alpha)T^3}\frac{E_\nu^2}{exp[(E_\nu/T)-\alpha]+1}$$

Fermi-Dirac distribution

T = Neutrino Temperature α = Chemical Potential

Supernova neutrino spectra



# Power-Law distribution for SN-ν

The SN-ν energy-spectra can be accurately parameterized with a power- law distribution of the form

$$PL\left(\langle\varepsilon_\nu\rangle,\varepsilon_\nu,\alpha\right)=\left(\frac{\varepsilon_\nu}{\langle\varepsilon_\nu\rangle}\right)^{\alpha} e^{-(a+1)\frac{\varepsilon_\nu}{\langle\varepsilon_\nu\rangle}}$$

$<\varepsilon_\nu>$ = the average neutrino energy

$\alpha$ = spectral pinching parameter

These parameters allow to adjust the width w

$$w=\sqrt{\langle\varepsilon_\nu^2\rangle-\langle\varepsilon_\nu\rangle^2}$$

# Beta-beam neutrino Energy-spectra for SN-ν

The low–energy beta-beam neutrinos can be exploited to interpret a SN–ν signal

Linear combinations of normalized beta-beam spectra are used

$$n_{N_\gamma}(\varepsilon_\nu) = \sum_{i=1}^{N} \alpha_i n_{\gamma_i}(\varepsilon_\nu)$$

The fitting of coefficients $\alpha_i$ and boost factors $\gamma_i$ to a SN-neutrino spectrum is achieved by minimizing the integral

$$\int_{\varepsilon_\nu} d\varepsilon_\nu \left| n_{N_\gamma}(\varepsilon_\nu) - n_{SN}(\varepsilon_\nu) \right|$$

# Neutrino-nucleus interactions

During the last decades, neutrino-nucleus interactions, β-decay modes, nuclear μ-capture, etc., have deepen our knowledge on :

1) the fundamental electro-weak interactions
2) our understanding on nuclear structure

Such precious information inspired significant probes within and beyond the SM and provided valuable interpretations to experiments looking for:

1) neutrino detection probes
2) Neutrino oscillation probes
3) neutrino masses …….

Neutrino–nucleus reactions play important role in astrophysical processes (SN nucleo-synthesis, etc.).

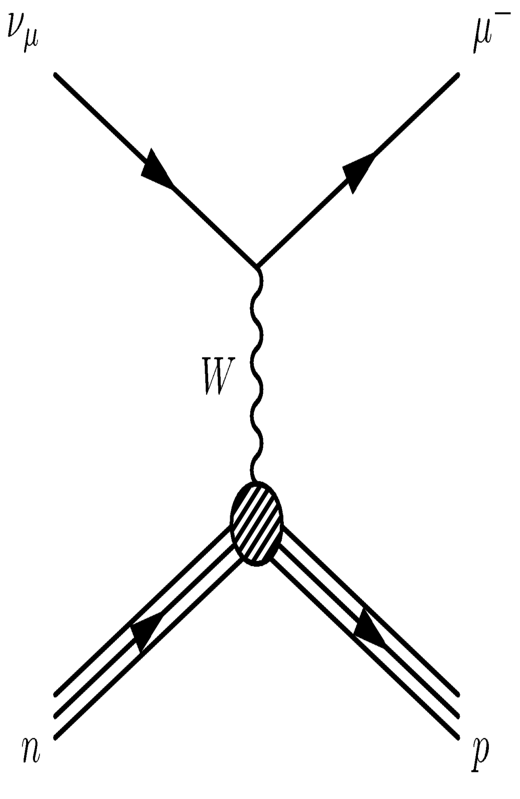
Uncertainties on astrophysical interactions of neutrinos raised numerous questions, still unanswered.

Our knowledge is limited by the understanding of neutrino-nucleus cross sections based on reliable interaction Hamiltonians and w-f.

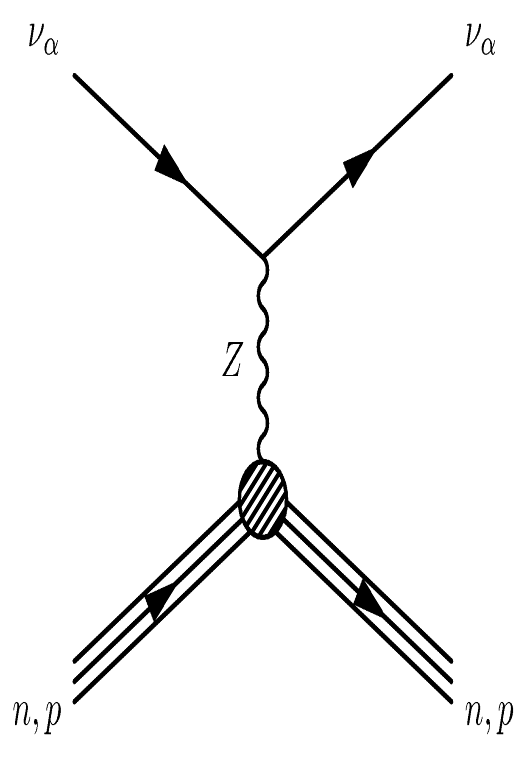
# Theory of Neutrino-nucleus interactions

NC: Neutral current interaction (mediated by the Z-bozon)
CC: Charged-currents interaction (mediated by $W^+$ or $W^-$ bozon)

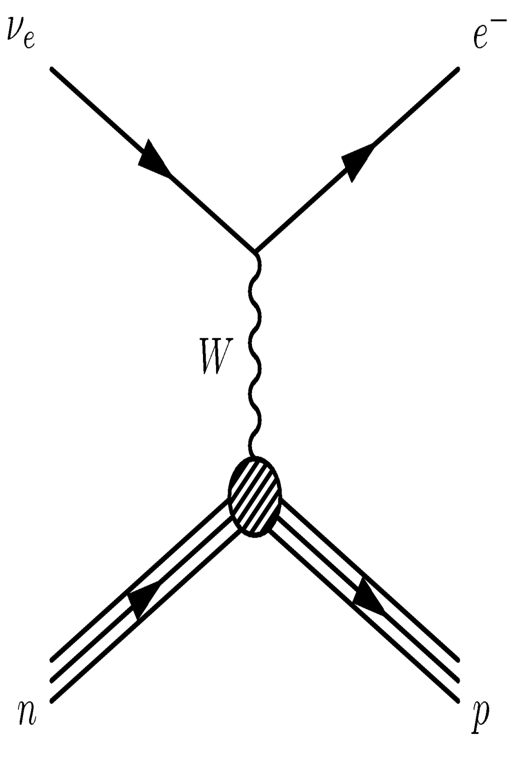
**$\nu_\mu$ CC Event**




**NC Event**




**$\nu_e$ CC Event**



# Neutrino-Nucleus reactions

There are four types of ν-nucleus reactions for ν-detection

- Charged-current reactions (l= e, μ, τ)

$$\nu_l + {}_Z A_N \longrightarrow {}_{Z+1}A^*_{N-1} + l^-$$

$$\overline{\nu}_l + {}_Z A_N \longrightarrow {}_{Z-1}A^*_{N+1} + l^+ \,.$$

- Neutral-current reactions (Coherent Channel Possible)

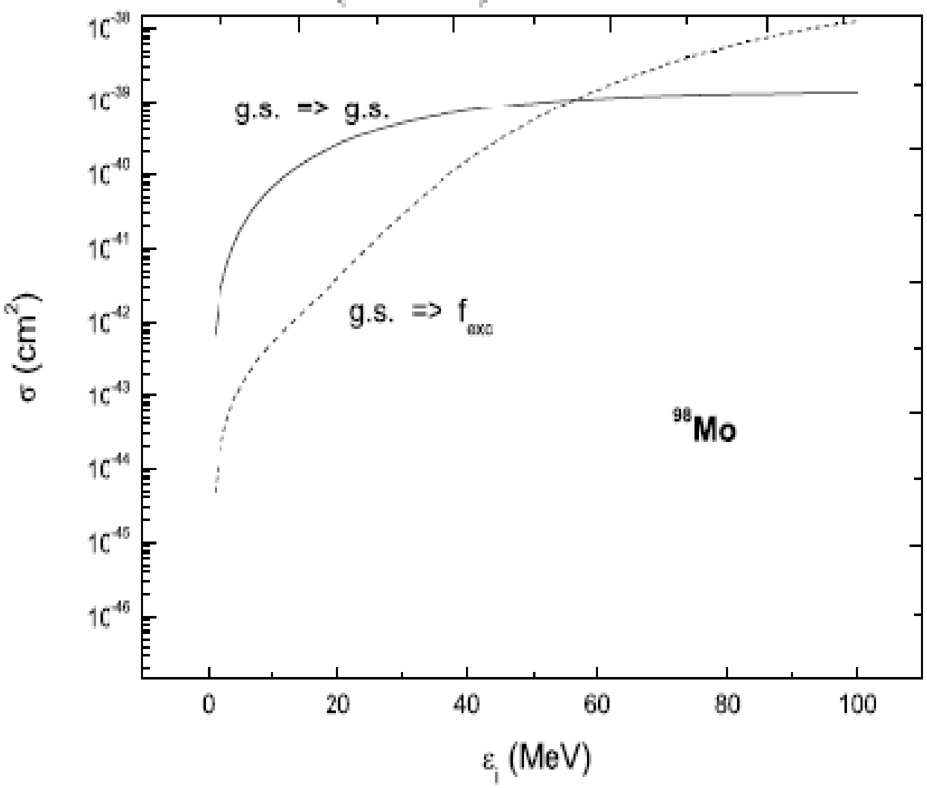
$$\nu + {}_Z A_N \longrightarrow {}_Z A^*_N + \nu'$$

$$\overline{\nu} + {}_Z A_N \longrightarrow {}_Z A^*_N + \overline{\nu}'$$

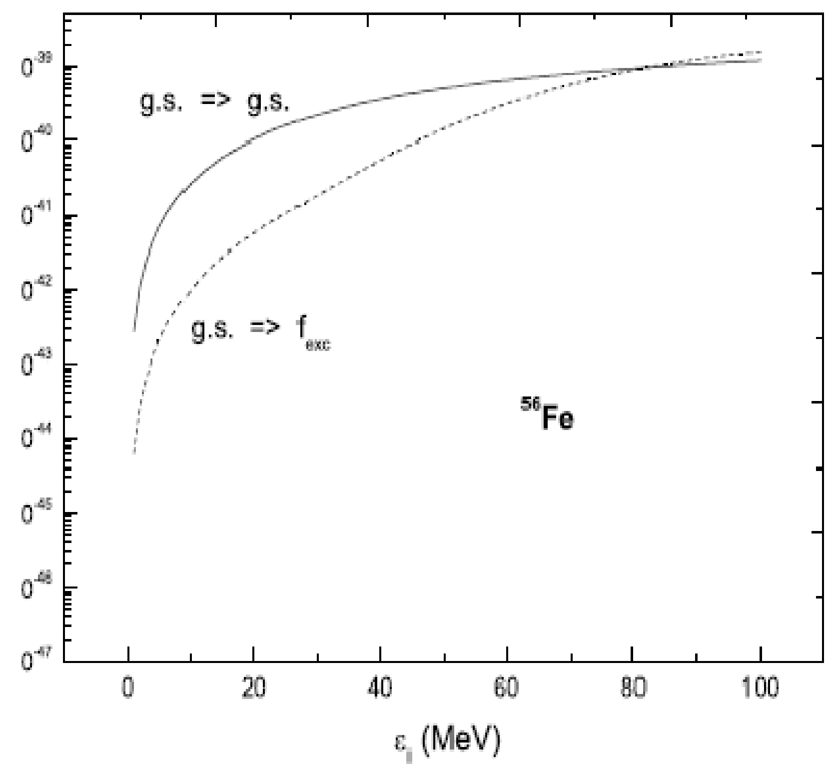
# Coherent ν–**Nucleus** processes

For low-energy neutrinos (solar neutrinos), the coherent channel dominates the total cross section (tsk, et al., NPA, submitted).

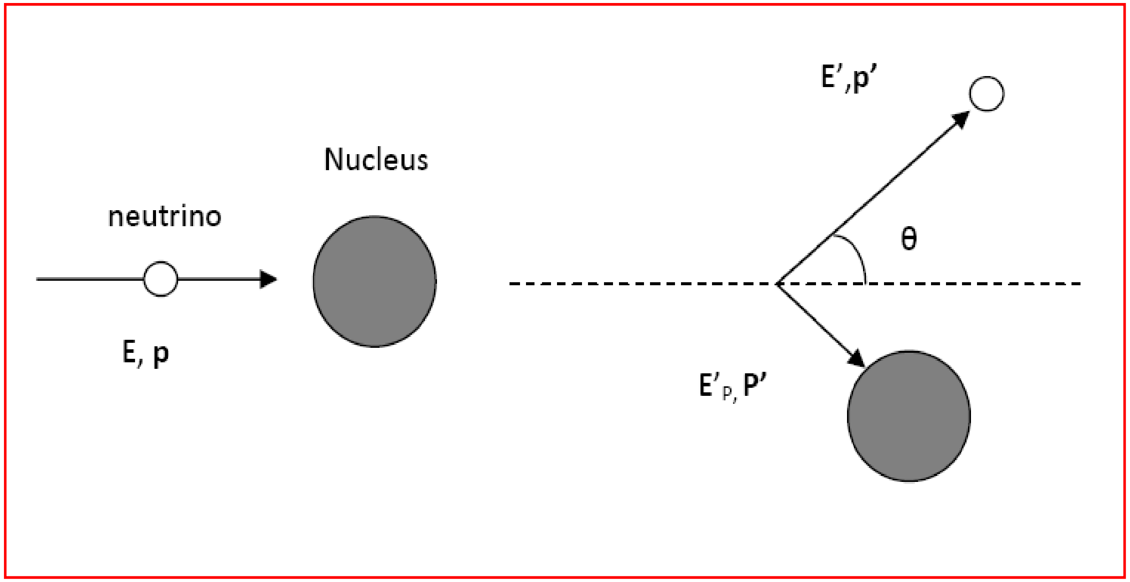
$$^{98}Mo(\bar{\nu},\bar{\nu}')^{98}Mo^*$$




$$^{56}Fe(\nu,\nu')^{56}Fe^*$$



# Coherent ν–Nucleus scattering (Neutral-Currents)




- The **Coherent** differential cross section reads

$$\frac{d\sigma}{d(\cos\Phi)} = G^2 \frac{\sin^2\theta_W}{2\pi} A^2 E_\nu^2 (1+\cos\Phi)$$

$\Phi$ = scattering angle, $\theta_W$ =Weinberg angle, $E\nu$ = incoming-neutrino energy

- Nucleons contribute coherently (coherent process dominates)

# Nuclear recoil

**In experimental studies of Coherent neutrino-nucleus scattering, the only observable is the average recoil energy**

$$\langle E_N \rangle = \frac{2}{3A}\left(\frac{E_\nu}{1MeV}\right)^2 keV$$

(i) **Proportional to $E_\nu^2$, inversely proportional to A (mass number)**

(ii) **Including other experimental criteria, $^{28}Si$, $^{32}S$ best choices**

**The calculations start from the quantity $d\sigma/dT_A$**

$$\left(\frac{d\sigma}{dT_A}\right)_{weak} = \frac{G_F^2 A m_N}{2\pi}(N^2/4)F_{coh}(T_A, E_\nu)$$

$$F_{coh}(T_A, E_\nu) = F^2(q^2)(1 + (1 - \frac{T_A}{E_\nu})^2 - \frac{A m_N T_A}{E_\nu^2}$$

$$q^2 = T_A^2 + 2 A m_N T_A$$

# Coherent neutrino-nucleus scattering

**with**

$$F(Q^2) = \frac{1}{Q_w}[NF_n(Q^2) - Z(1 - 4\sin^2\theta_w)F_p(Q^2)]$$

**The quantity $Q_w$ is**

$$Q_w = N - Z(1 - 4\sin^2\theta_w)$$

**Finally one needs the neutron density of the target**

$$F(Q^2) = \frac{1}{Q_w}\int[\varrho_n(r) - (1 - 4\sin^2\theta_w)\varrho_p(r)]\frac{\sin(Qr)}{Qr}r^2 dr$$

# Coherent neutrino-Nucleus Scattering probes

| Absorber | $E_{Thesh}$ (eV) | Rate $(Kg^{-1}d^{-1})$ |
|---|---|---|
| $S1$ | 100 | 40 |
| | 300 | 22 |
| | 500 | 14 |
| $Al_2O_3$ | 100 | 36 |
| | 300 | 22 |
| | 500 | 14 |
| $Ge$ | 100 | 85 |
| | 300 | 24 |
| | 500 | 8 |
| $Pb$ | 50 | 201 |
| | 100 | 83 |
| | 300 | 4 |
| | 500 | $< 1$ |

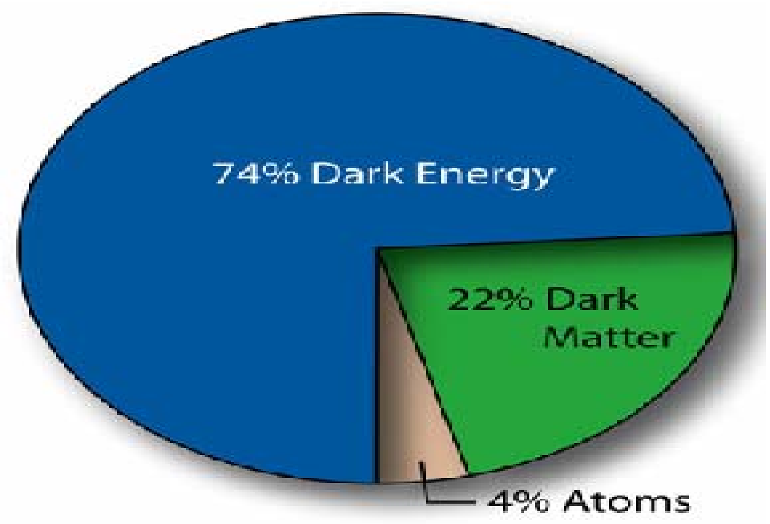
$$X + \nu \Rightarrow \nu + X$$

**Such studies could be done in conjunction with direct detection of Cold Cark Matter**

**(cryogenic detectors).**

Counting rates for Coherent Neutrino-Nucleus Scattering.
The Reactor-Neutrino flux is $10^{13}\ \text{cm}^{-2}\ \text{sec}^{-1}$

# Direct CDM detection: CDM-particle Scattering off nuclei




The Content of the universe:

Dark Energy $\approx$ 73%, Atoms $\approx$ 4%

Cold Dark Matter $\approx$ 23%

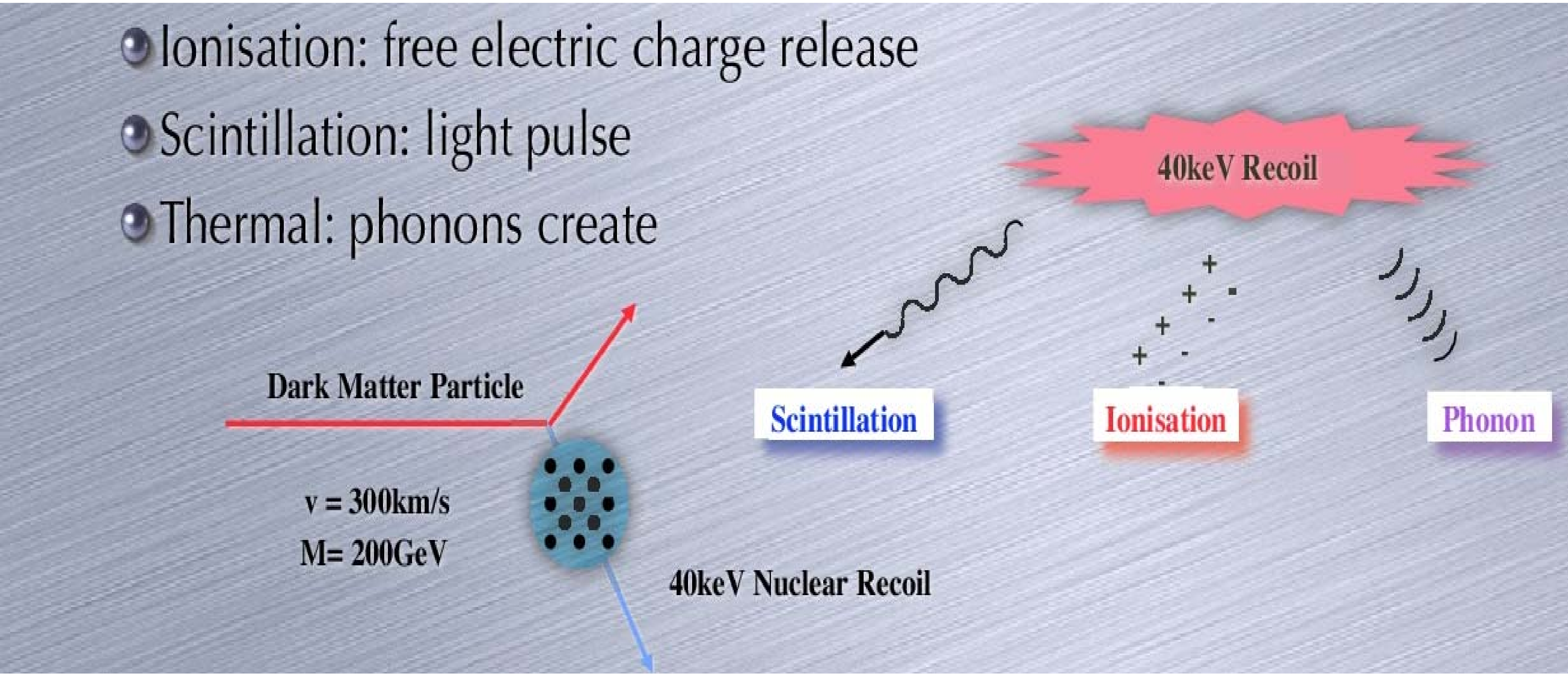
LSP-nucleus scattering ⇨ $\chi + (A, Z) \Longrightarrow \chi' + (A,Z)^*$

A) Coherent process is possible : Vector & Axial-Vector Currents

B) Dominance of Axial-Vector contributions

(Odd-A nuclear targets : $^{73}$Ge, $^{127}$I, $^{115}$In, $^{129,131}$Xe)

# Signals of CNN scattering and direct detection of WIMPs




The energy transfer is very low (30-40 keV)

# Inelastic ν–Nucleus scattering (Cross section)

In Walecka-Donnely method [PRC 6 (1972)719, NPA 201(1973)81]

$$\frac{d^2\sigma_{i\to f}}{d\Omega d\omega} = \frac{G^2}{\pi}\frac{\varepsilon_f^2}{(2J_i+1)}\left(\sum_{J=0}^{\infty}\sigma_{CL}^J+\sum_{J=1}^{\infty}\sigma_T^J\right)$$

where

$$\omega = \varepsilon_i - \varepsilon_f \qquad q = |\mathbf{q}| = \left[\omega^2 + 2\varepsilon_i\varepsilon_f(1-\cos\Phi)\right]^{\frac{1}{2}}$$

1st sum = Coulomb-Longitudinal contr. 2nd sum = Transverse contr.

One of the goals is: To investigate the Response as low-energy neutrino detectors of :

i) Te, Cd, Zn –isotopes (COBRA ββ-decay experiment)
ii) Mo-isotopes (MOON ββ-decay experiment)

i) K.Zuber, Phys. Lett. B 571(03)148, talk at MEDEX-09, June 15-19, 2009, Prague.
ii) H. Ejiri, Phys. Rep. 338 (2000)265; H. Ejiri et a., Phys.Lett. B 530 (02)265;

# Compact expressions for the 7-basic reduced ME

For H.O. basis, all basic reduced ME take analytic compact forms

$$\langle j_1 || T^J || j_2 \rangle = e^{-y} y^{\beta/2} \prod(y) = e^{-y} y^{\beta/2} \sum_{\mu=0}^{n_{max}} \mathcal{P}_\mu^J \, y^\mu ;$$

The Polynomials of even terms in q have constant coefficients as

$$\prod(y) = \sum_{\mu=0}^{n_{max}} \mathcal{P}_\mu^J \, y^\mu, \quad y = \frac{q^2 b^2}{4}$$

$$n_{max} = (N_1 + N_2 - \beta)/2 \, .$$

V.Chasioti, TSK, Czech. J. Phys. 52 (2002)467; Nucl. Phys. A, 829 (2009) 234

Advantages of the above formalism (FORTRAN Code) :

(i) The coefficients $P^J$ are calculated once (reduction of computer time)
(ii) They can be used for phenomenological description of ME
(iii) They are useful for other bases sets (expansion in HO wave-functions)

# Neutrino-nucleus cross sections

A). On the basis of the original calculations we could study:

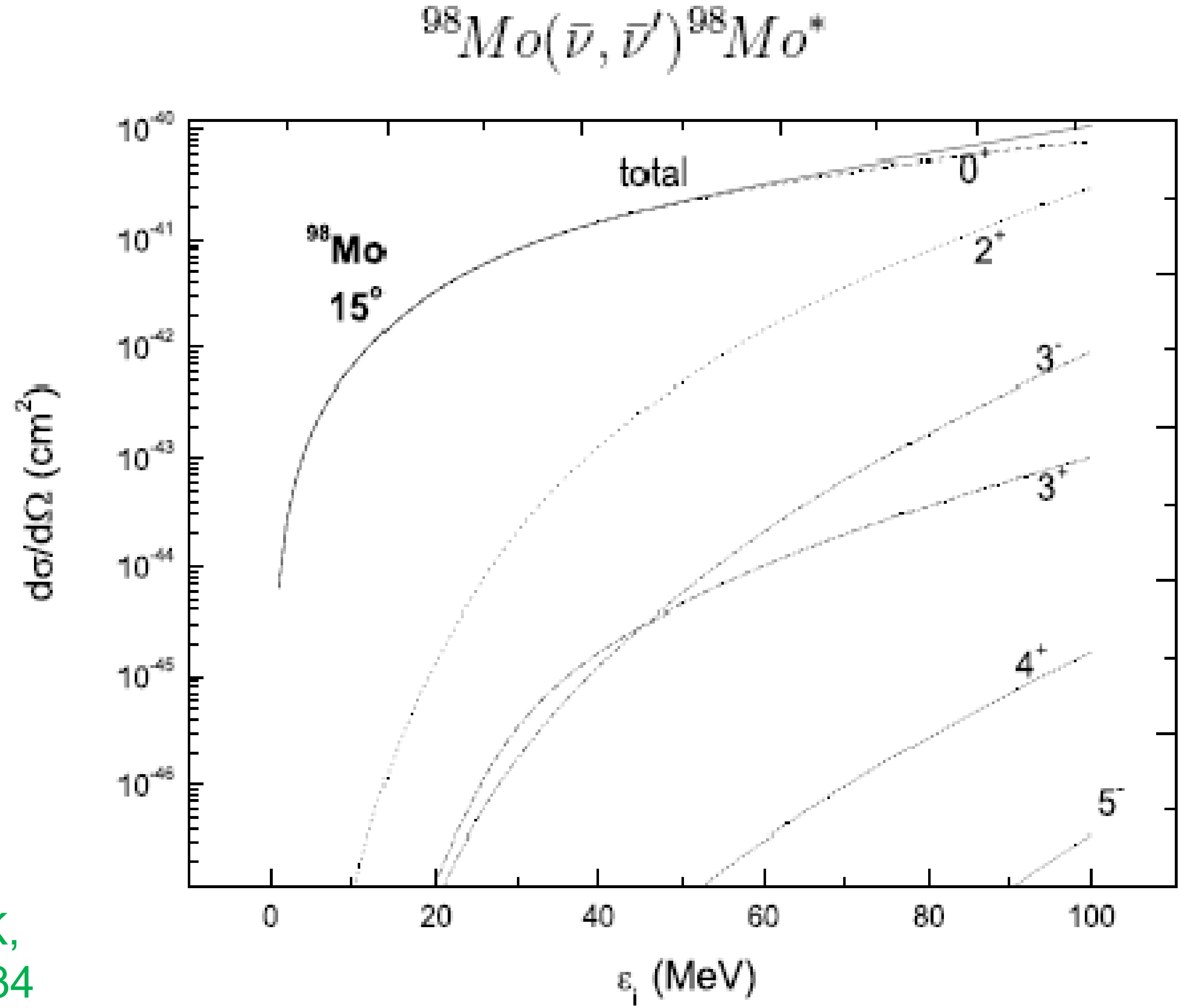
- i) State-by-state calculations of $d\sigma/d\Omega$
- ii) The contribution of the individual multipolarities
- iii) Dominance of Axial-Vector contributions in $\sigma$

B). Nuclear detector response to ν-sources:

- i) solar neutrino spectra
- ii) SN neutrino spectra
- iii) reactor neutrino spectra

# State-by-state calculations of dσ/dΩ

$^{98}$Mo

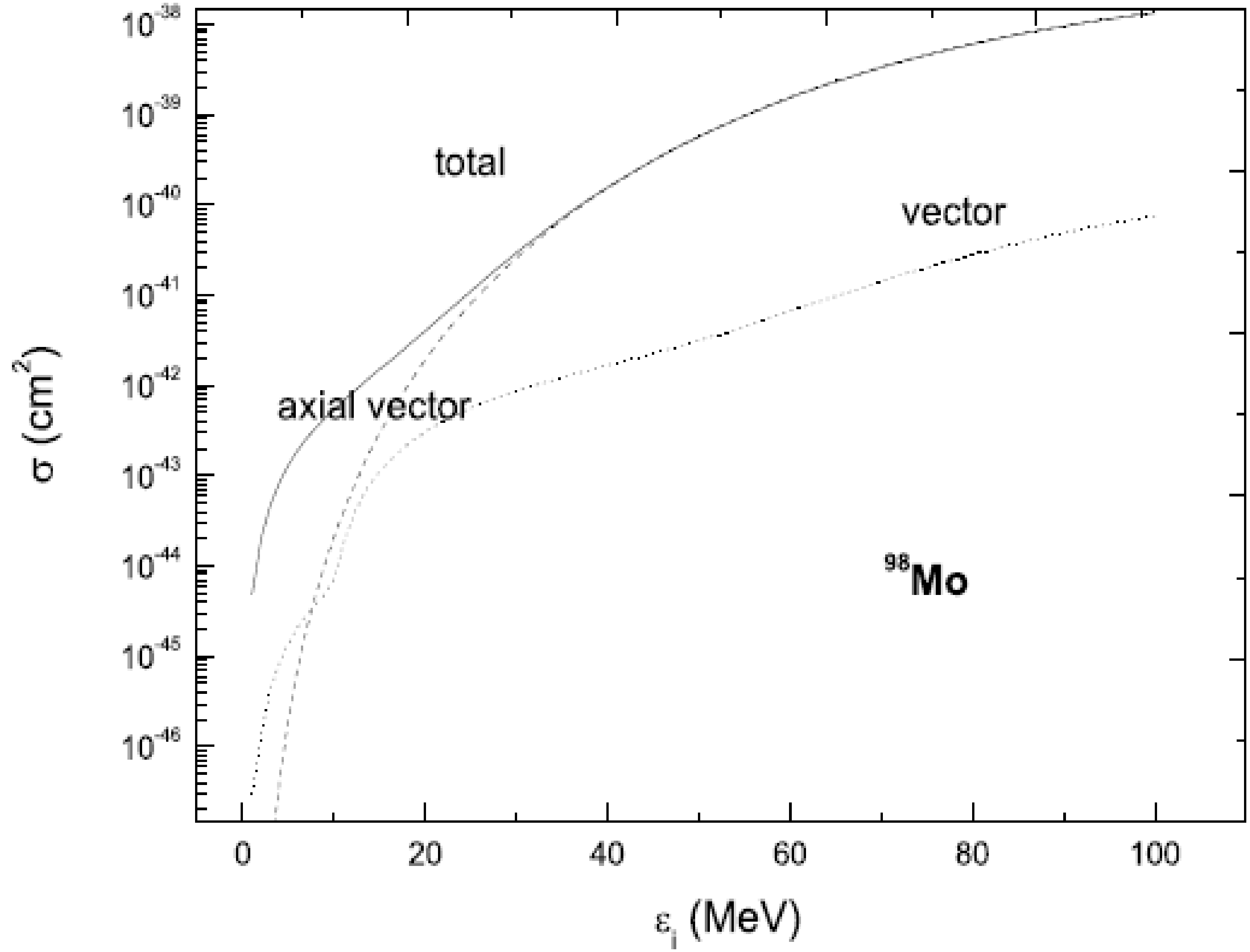



V.Chasioti, TSK, NPA 829 (09) 234

# Dominance of Axial-Vector contributions in σ

$$^{98}Mo(\bar{\nu},\bar{\nu}')^{98}Mo^{*}$$

$^{98}$Mo



# Summary and Outlook

## (i) Low-energy neutrinos searches

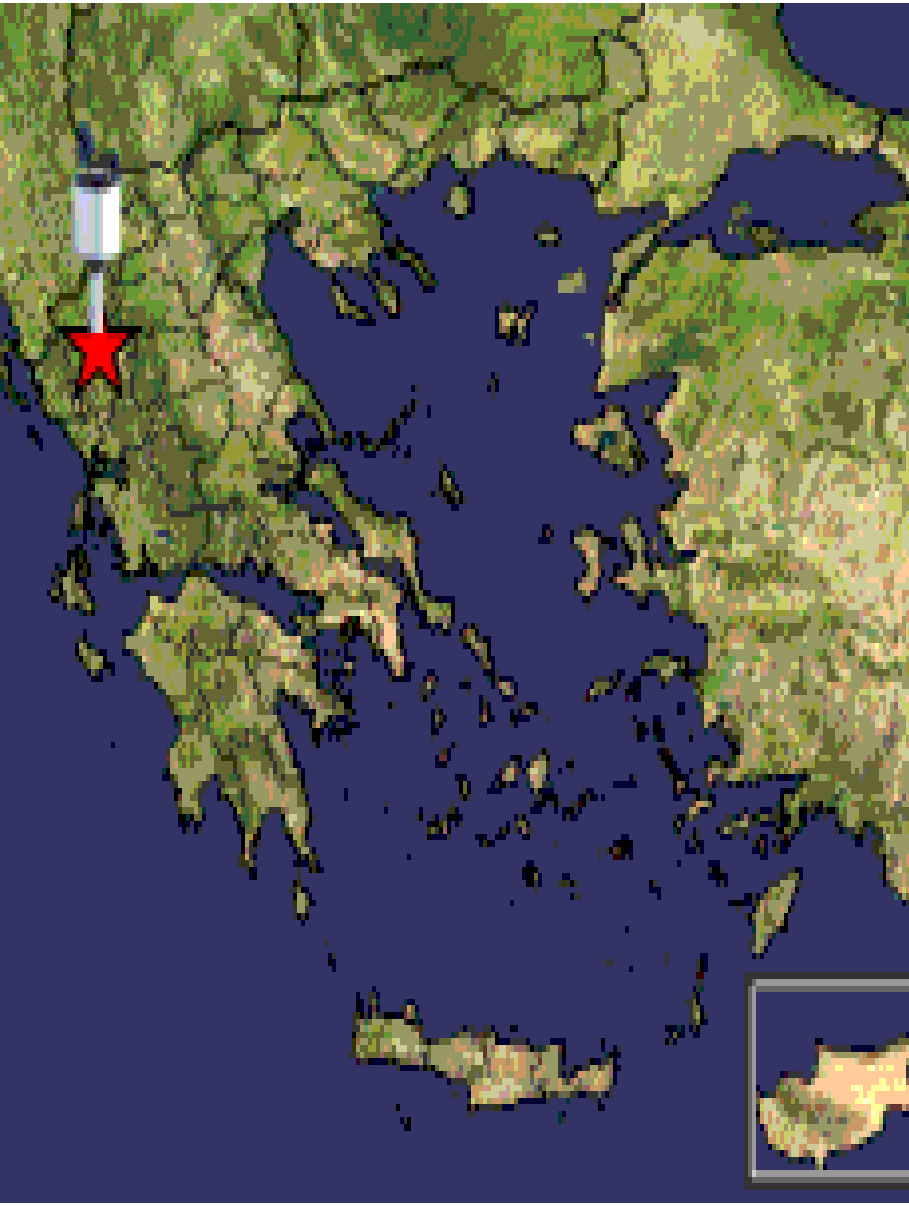
- i. Solar, SN neutrinos
- ii. Reactor and Beta-beam neutrino

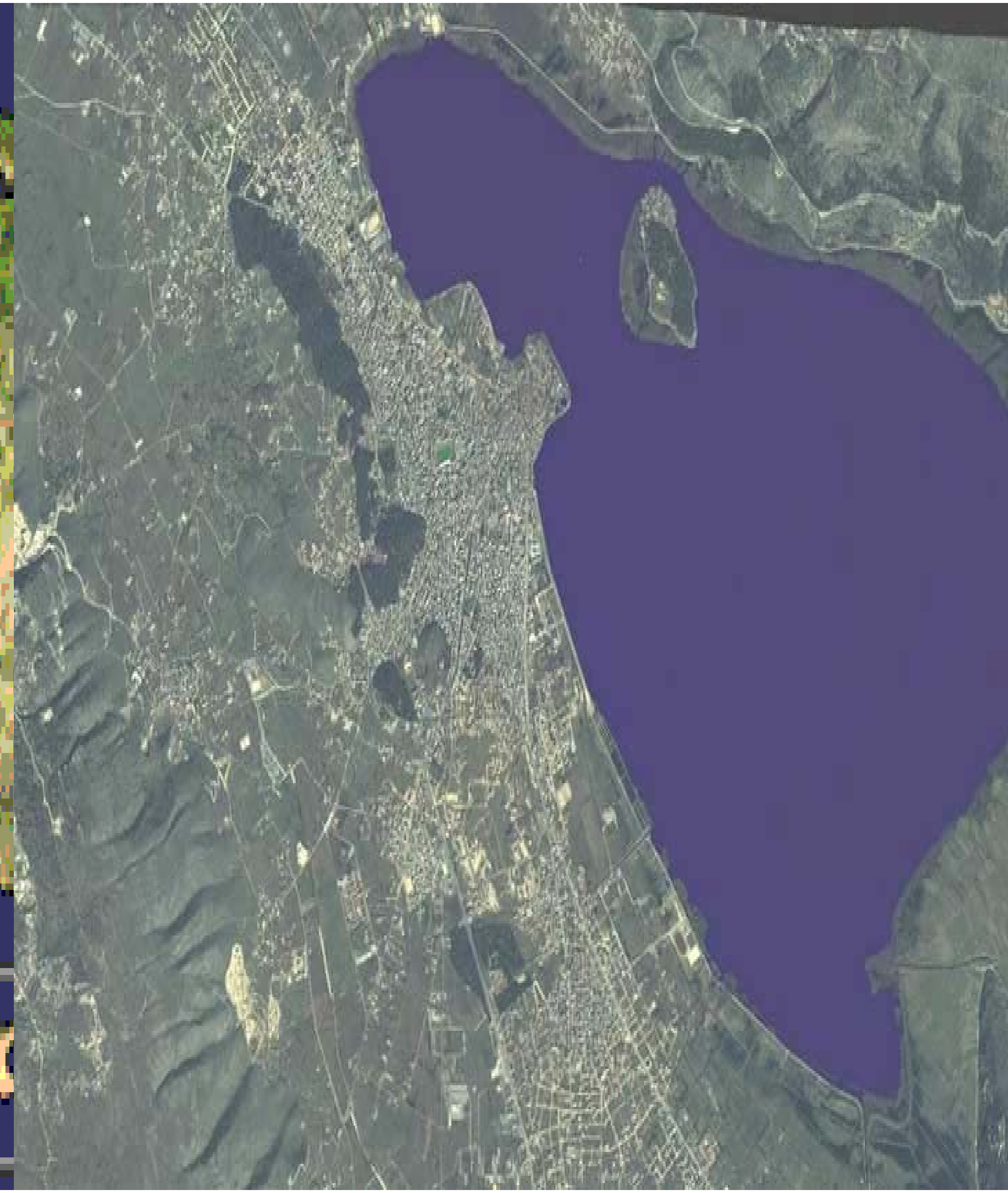
Require: *a). Reliable* neutrino-nucleus reaction cross sections and

*b). The Response Nuclear ν-detectors to various ν-spectra*

**(ii) Recent and future nuclear-recoil experiments, with very low-threshold energy, could measure Coherent Neutrino-Nucleus Scattering in conjunction with experiments of Direct detection of CDM particles and 0ν-double-beta-decay.**

# Ioannina, the city of Silver and Gold





**Thank you for your attention**