Low-energy neutrino-nucleus cross sections

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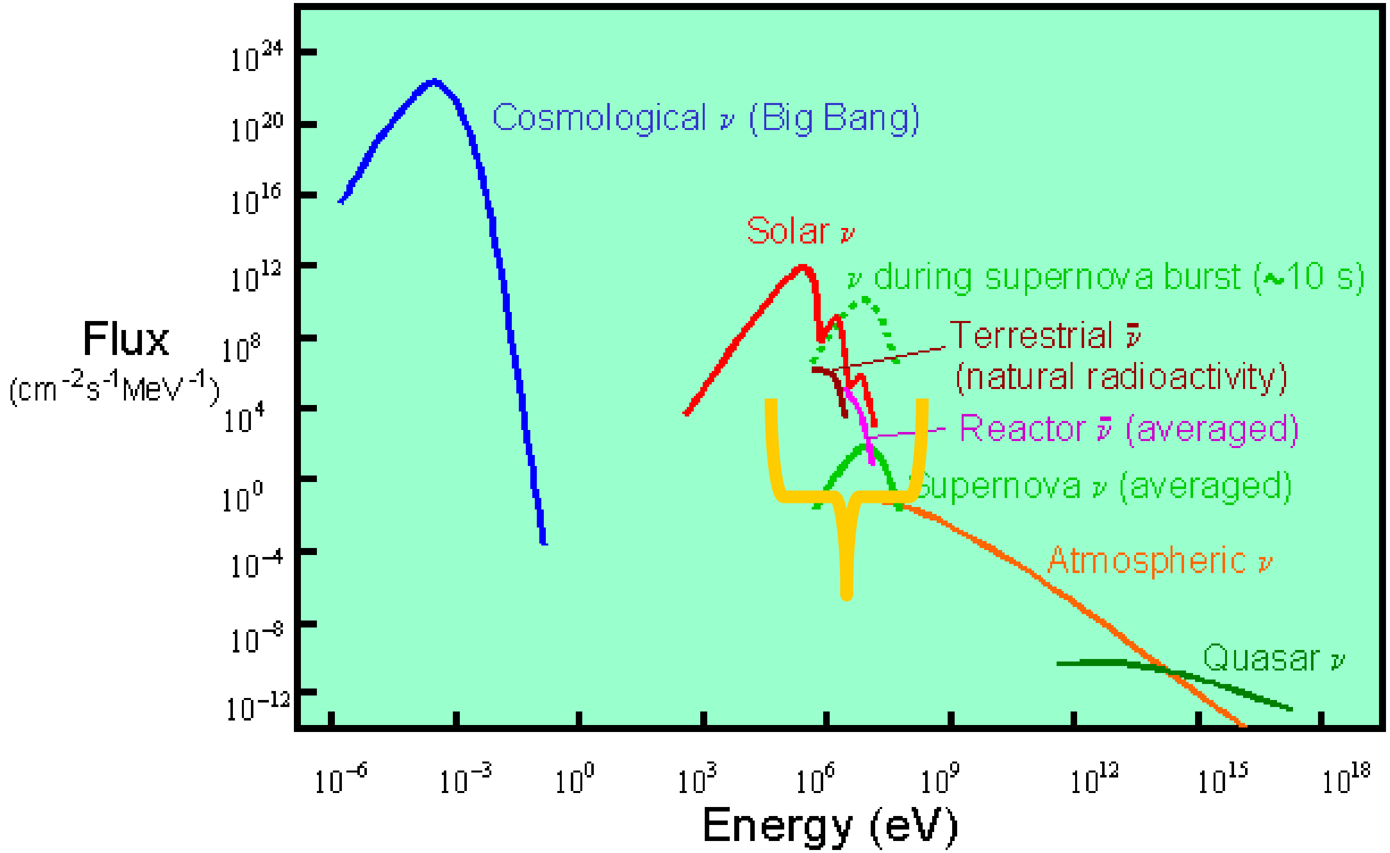
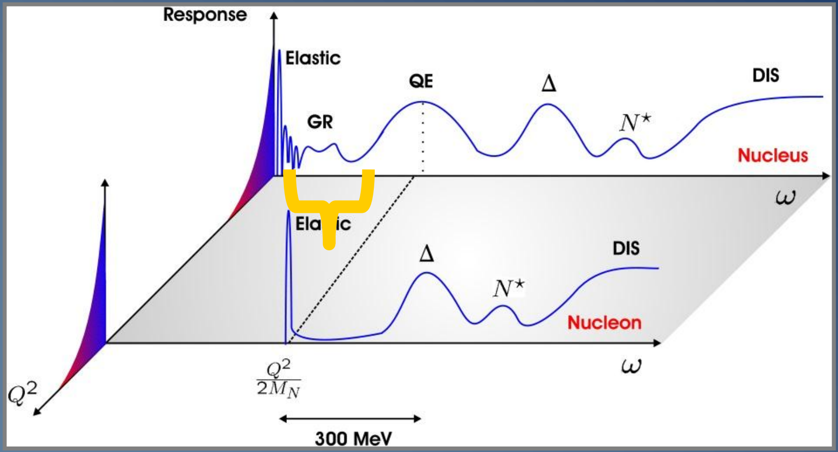
Neutrino energies

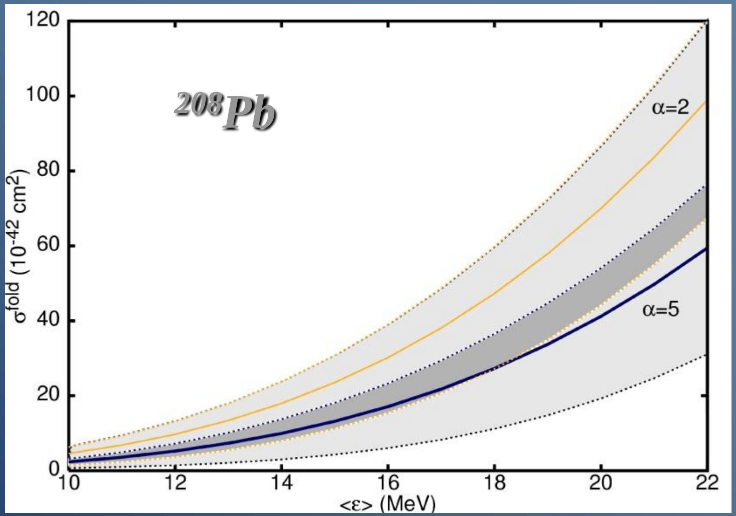


Flux on earth of neutrinos from various sources, in function of energy

Neutrino-hadron scattering



- little experimental data is available
  - small cross sections
  - no monochromatic neutrino beams



Uncertainties :

- one has to rely on theoretical predictions,
- uncertainties induced by model dependence, and more fundamental uncertainties …

N.J. et al, PRC66, 065501 (2002) ;

E. Kolbe et al, PRC63, 025802 (2001) ;

J. Engel et al, PRD67, 013005 (2001)

What can we learn from these neutrinos ?

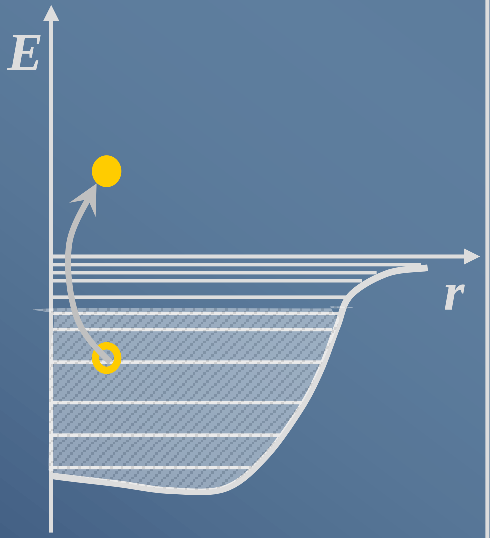
- Electroweak tests
- Nuclear structure information
- Astrophysical neutrinos : a.o. core-collapse supernovae
- Oscillations
- Neutrinonucleosynthesis

How can we learn from these neutrinos ?

- ➢ Detect them
  - Neutrino-electron scattering
  - Neutrino-hadron scattering
- ➢ Study their interactions : theory + experiment

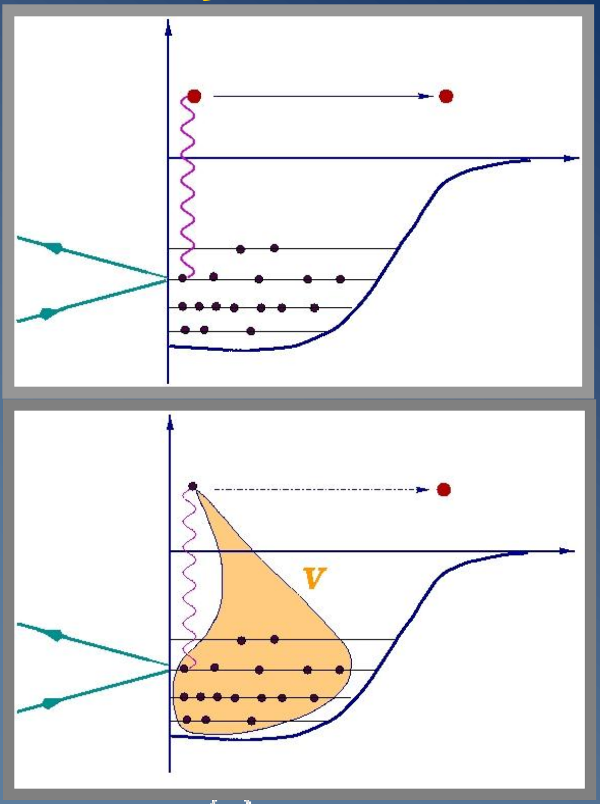
Formalism

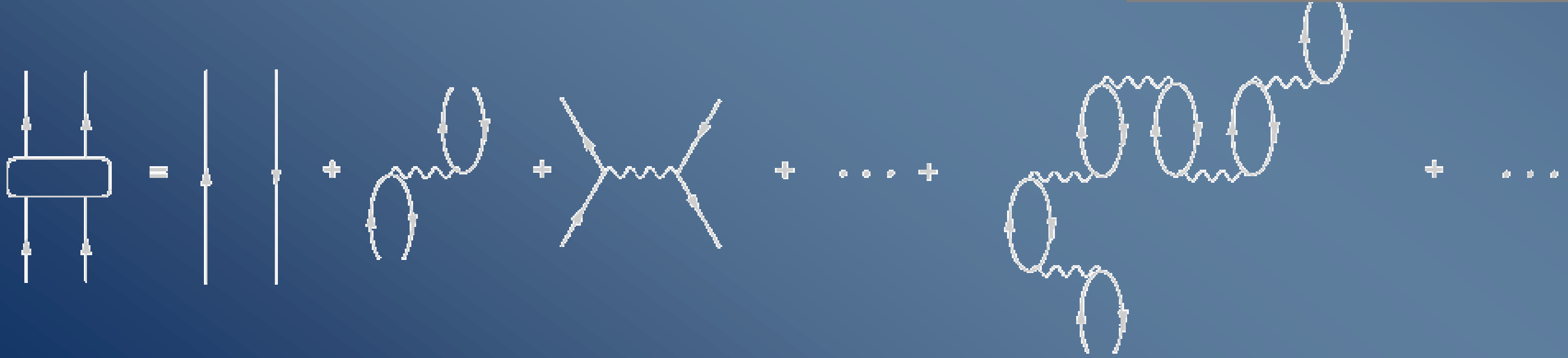
Modeling neutrino-nucleus cross sections @ low energies :



Continuum RPA

- Green's function approach
- Skyrme II residual interaction
- ground state : Hartree-Fock single-particle wave functions (Skyrme)
- non-relativistic





Formalism

Lepton tensor

$$l_{\alpha\beta} \equiv \sum_{s,s'} [\overline{u}_l \gamma_\alpha (1-\gamma_5) u_l]^\dagger [\overline{u}_\nu \gamma_\beta (1-\gamma_5) u_\nu]$$

Hadronic current

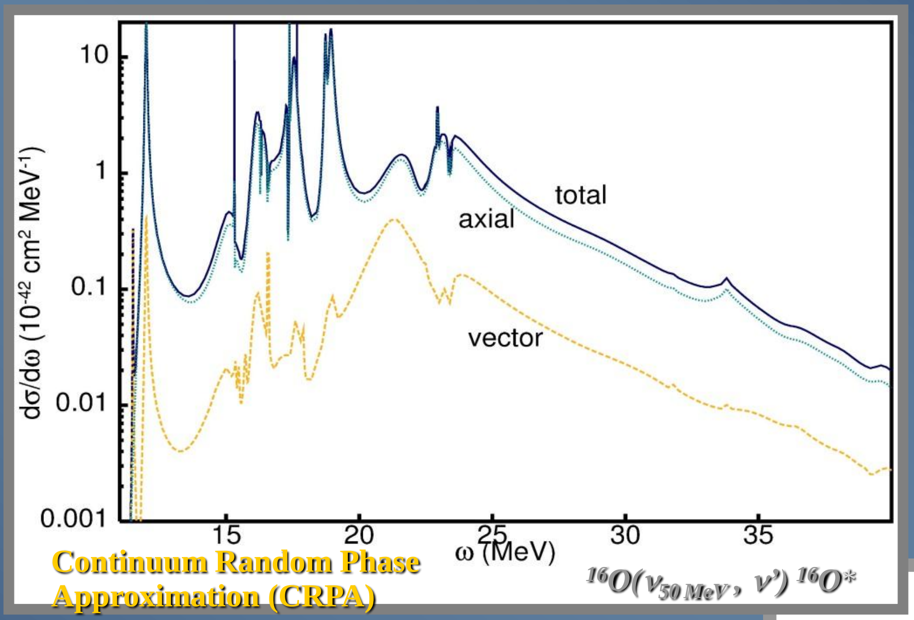
$$J^\mu = F_1(Q^2)\gamma^\mu + i\frac{\kappa}{2M_N}F_2(Q^2)\sigma^{\mu\nu}q_\nu + G_A(Q^2)\gamma^\mu\gamma_5 + \frac{1}{2M_N}G_P(Q^2)q^\mu\gamma_5$$

$$\boxed{\left(\frac{d^2\sigma_{i\to f}}{d\Omega d\omega}\right)_{\frac{\nu}{\overline{\nu}}} = \frac{G^2\varepsilon_f^2}{\pi}\,\frac{2\cos^2\left(\frac{\theta}{2}\right)}{2J_i+1}\left[\sum_{J=0}^{\infty}\sigma_{CL}^J + \sum_{J=1}^{\infty}\sigma_T^J\right]}$$

$$\sigma_{CL}^J = \left|\left\langle J_f \left\| \widehat{\mathcal{M}}_J(\kappa) + \frac{\omega}{|\vec{q}|}\widehat{\mathcal{L}}_J(\kappa) \right\| J_i \right\rangle\right|^2$$

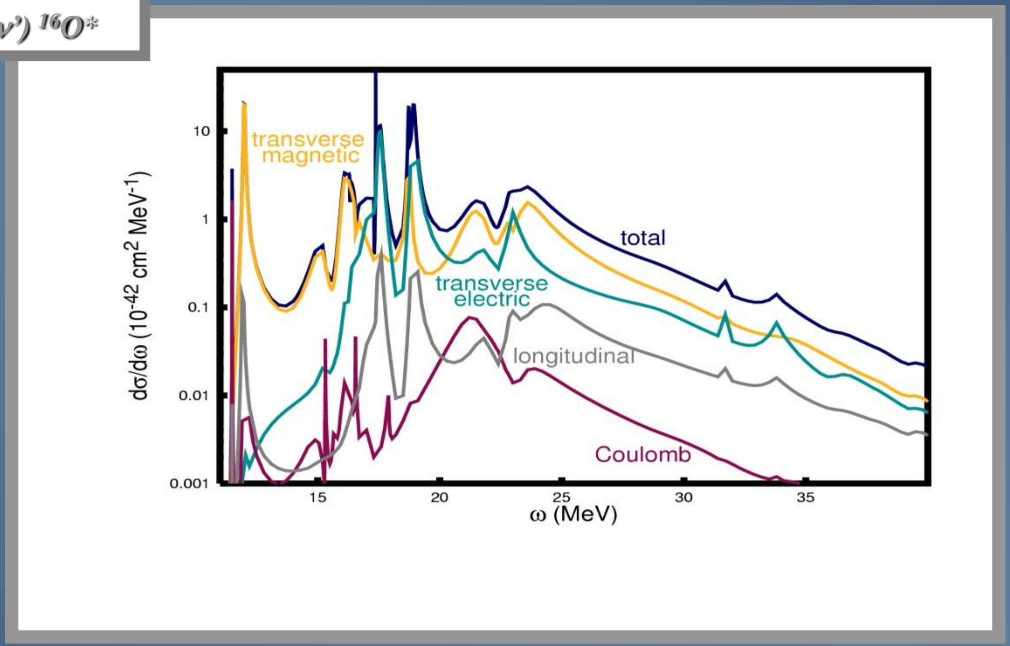
$$\sigma_T^J = \left(-\frac{q_\mu^2}{2|\vec{q}|^2} + \tan^2\left(\frac{\theta}{2}\right)\right)\left[\left|\left\langle J_f \left\| \widehat{\mathcal{J}}_J^{mag}(\kappa) \right\| J_i \right\rangle\right|^2 + \left|\left\langle J_f \left\| \widehat{\mathcal{J}}_J^{el}(\kappa) \right\| J_i \right\rangle\right|^2\right]$$

$$\mp \tan\left(\frac{\theta}{2}\right)\sqrt{-\frac{q_\mu^2}{|\vec{q}|^2} + \tan^2\left(\frac{\theta}{2}\right)}\left[2\Re\left(\left\langle J_f \left\| \widehat{\mathcal{J}}_J^{mag}(\kappa) \right\| J_i \right\rangle \left\langle J_f \left\| \widehat{\mathcal{J}}_J^{el}(\kappa) \right\| J_i \right\rangle^*\right)\right]$$

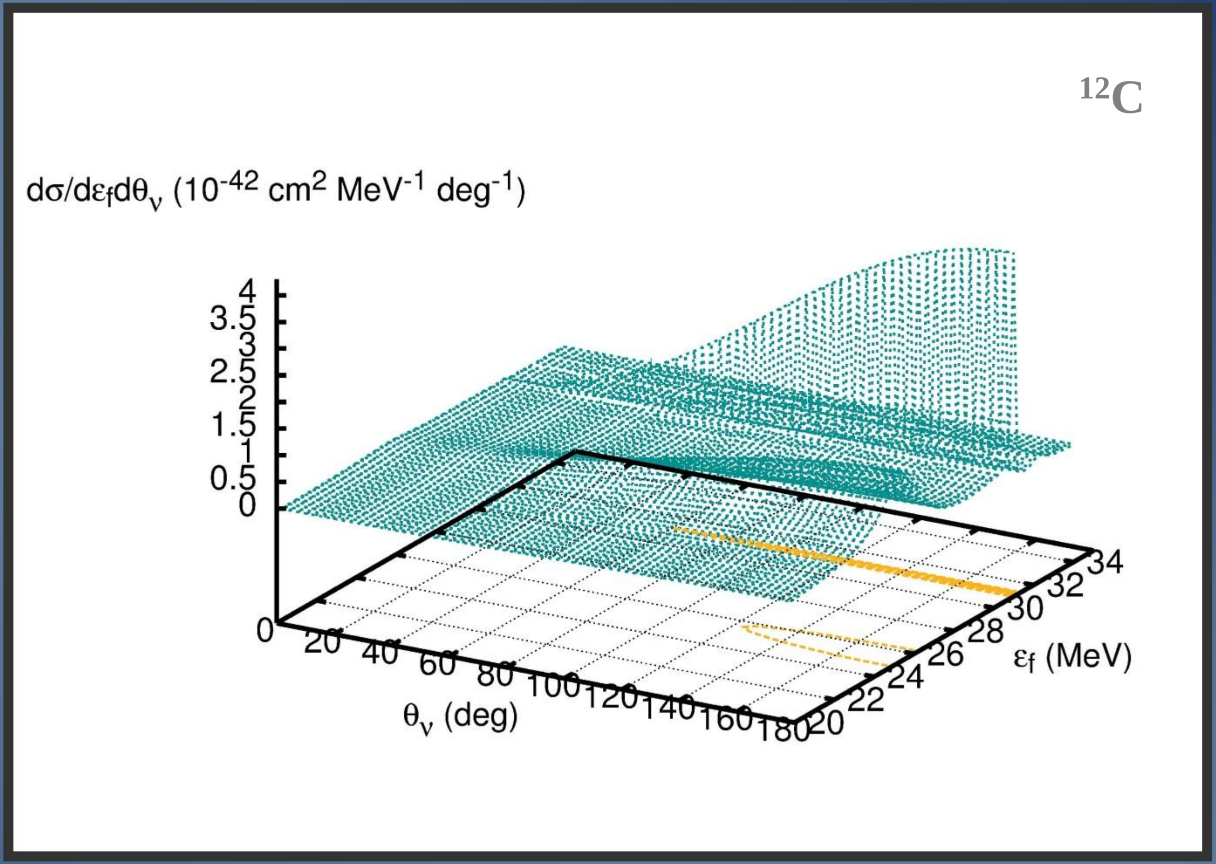


- Axial contribution dominant

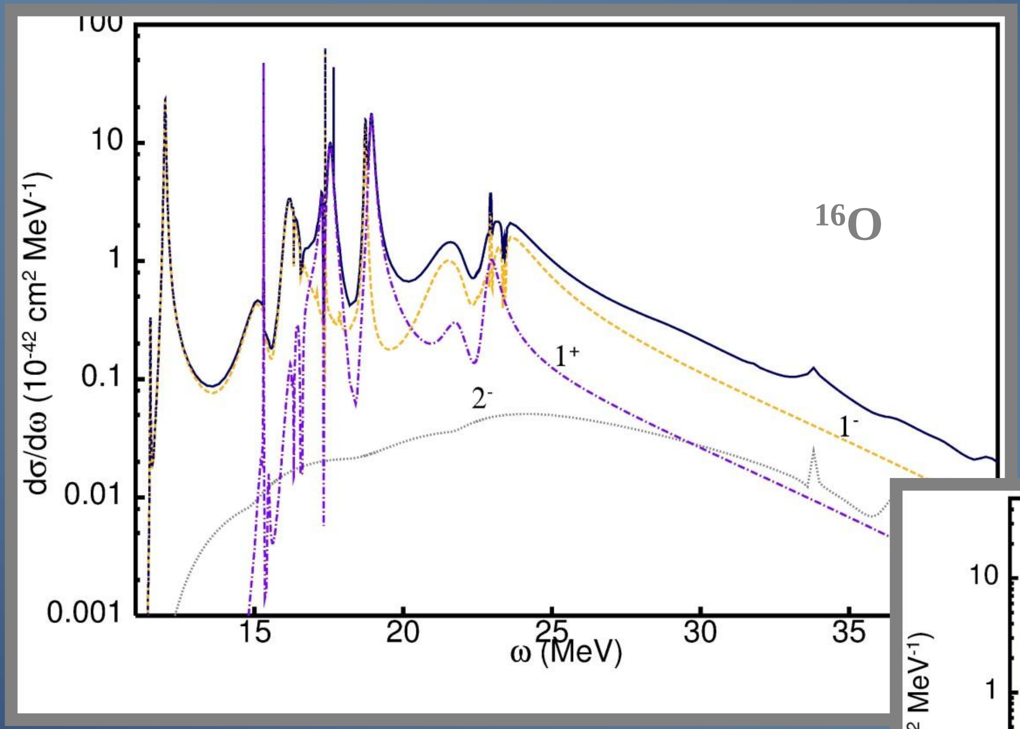
- Transverse contribution dominant

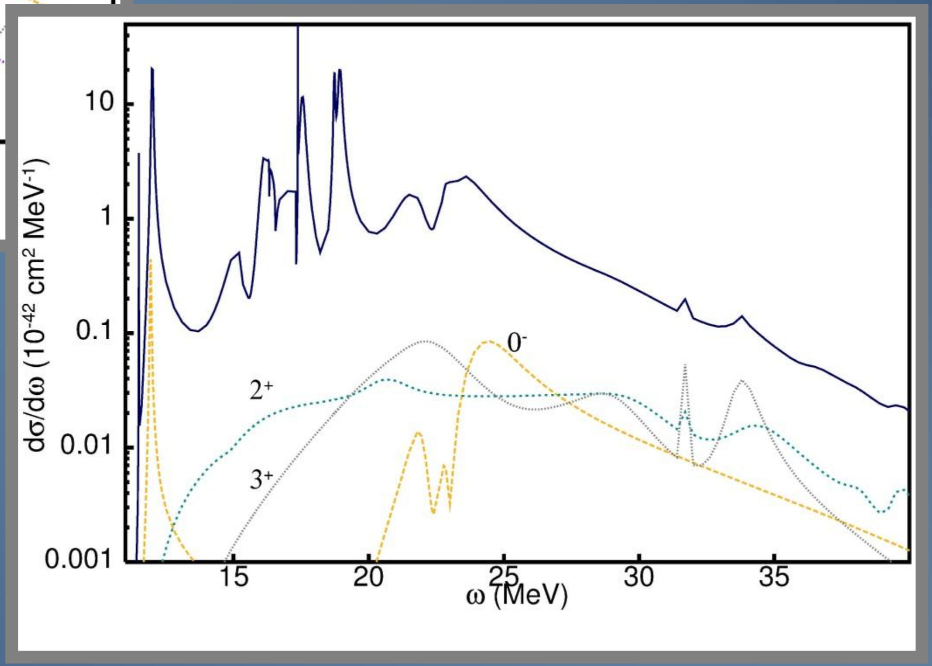


Basic features



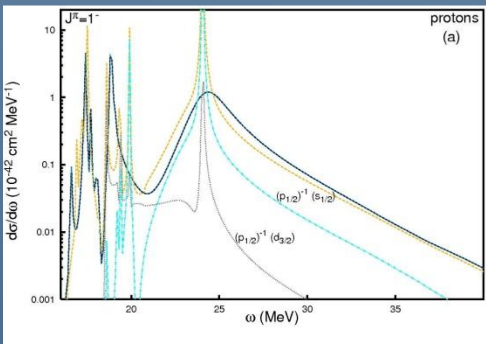
Higher order multipoles important :

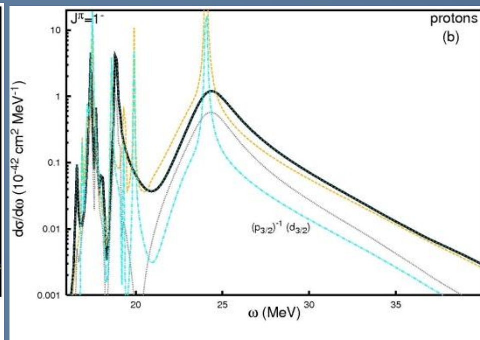


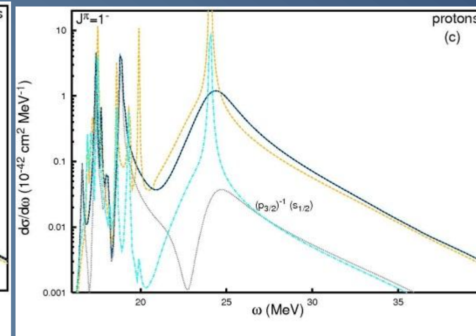


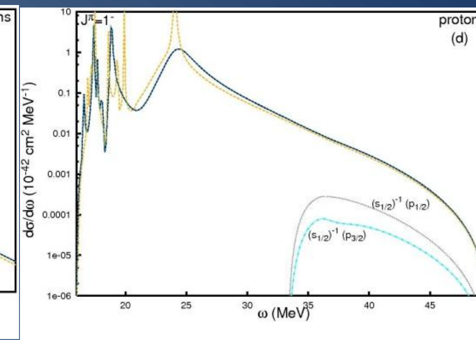
Basic features

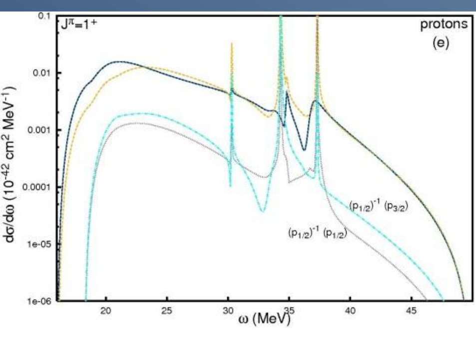
Contribution of different single-particle channels in ^{12}C

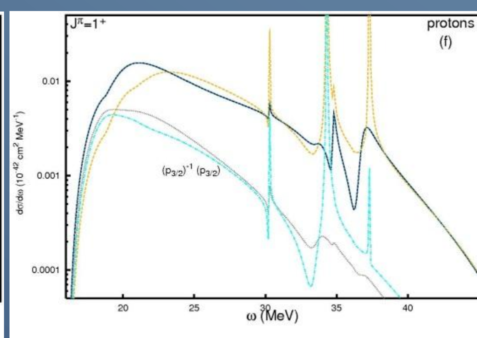


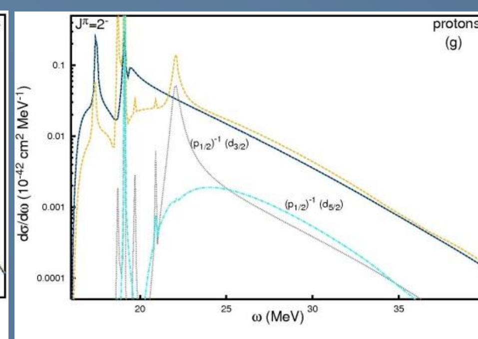


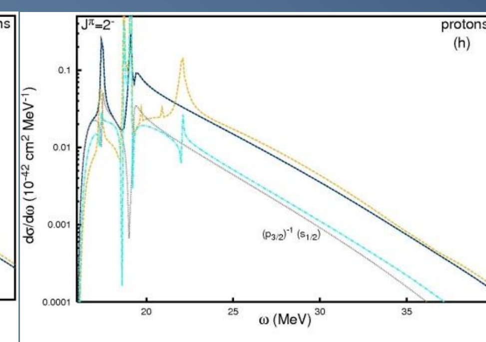




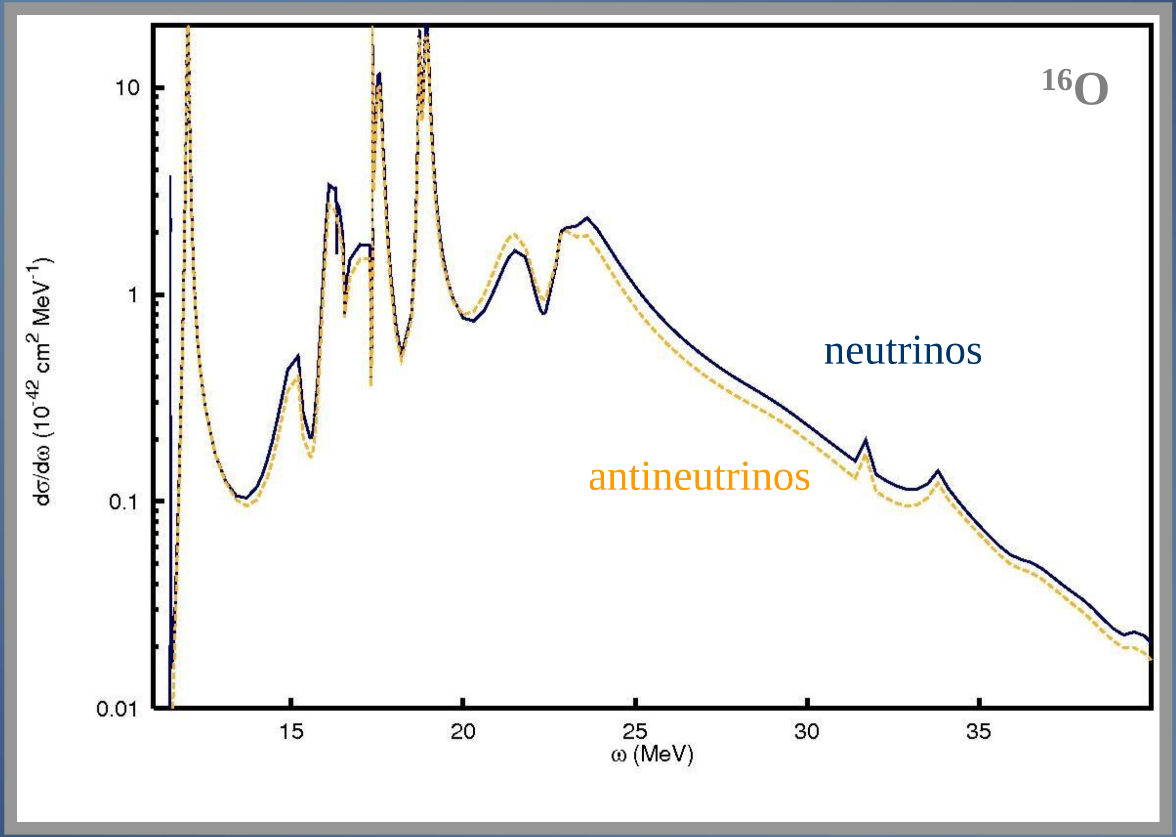






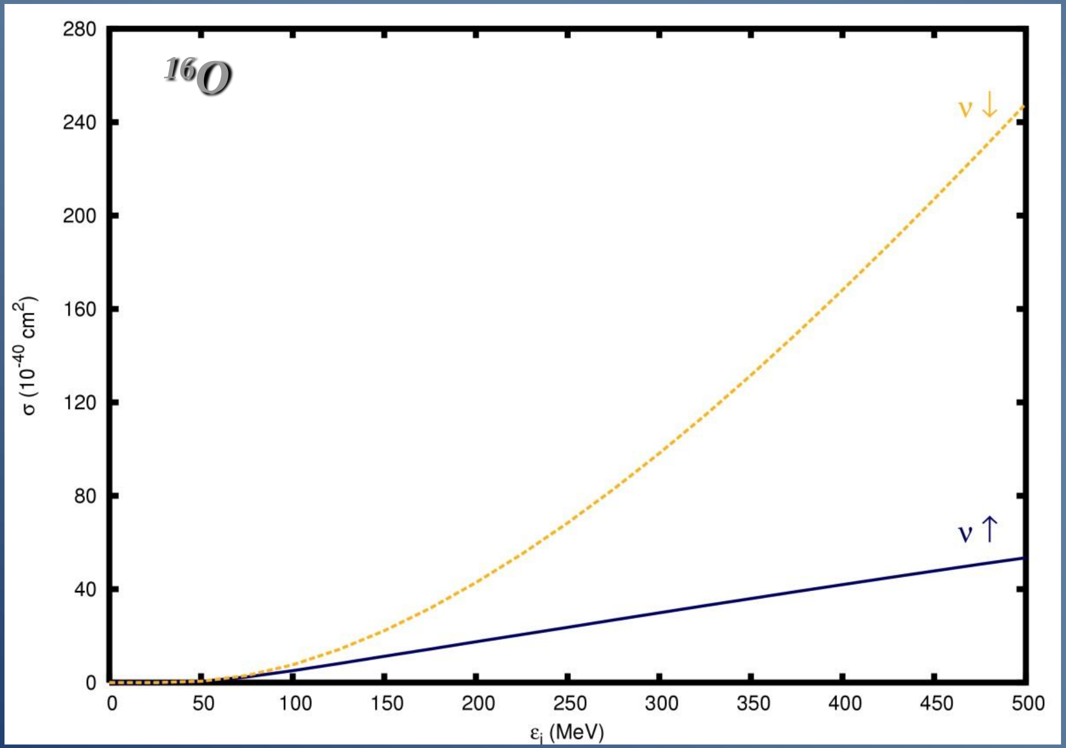


Neutrinos versus antineutrinos



Helicity dependence of the cross section:

$$
\begin{aligned}
& l_- l_-{}^* h_+ h_+{}^* + l_+ l_+{}^* h_- h_-{}^* \\
&\quad = S(h_+ h_+{}^* + h_- h_-{}^*) + hA(h_+ h_+{}^* - h_- h_-{}^*) \\
&\quad = (S + hA) h_+ h_+{}^* + (S - hA) h_- h_-{}^*
\end{aligned}
$$



For neutrinos :

S+hA = *S-A*, is small

S-hA = *S+A*, is large

$h_- h_-{}^*$ dominates

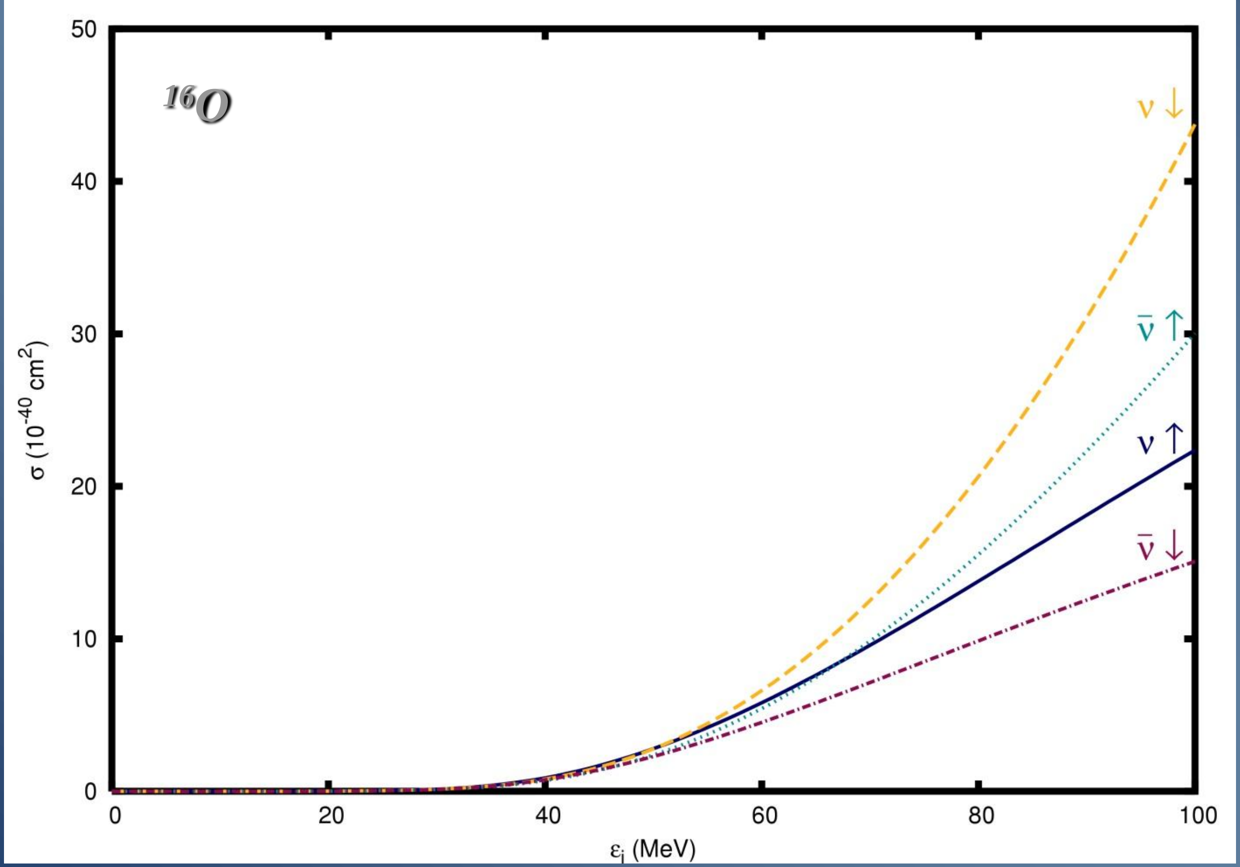
For antineutrinos :

S+hA = *S+A*, is large

S-hA = *S-A*, is small

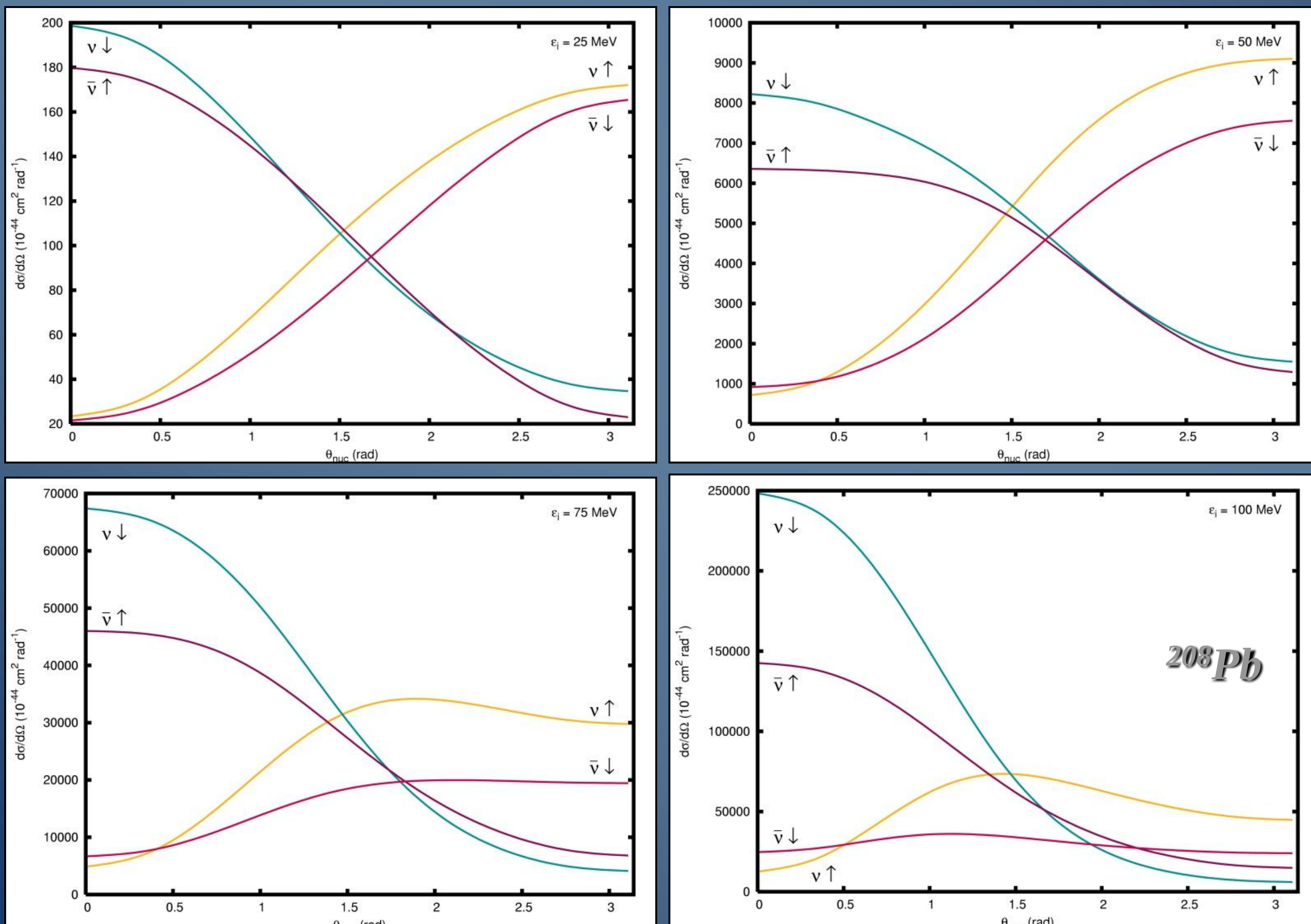
$h_+ h_+{}^*$ dominates

Adding antineutrinos to the picture :



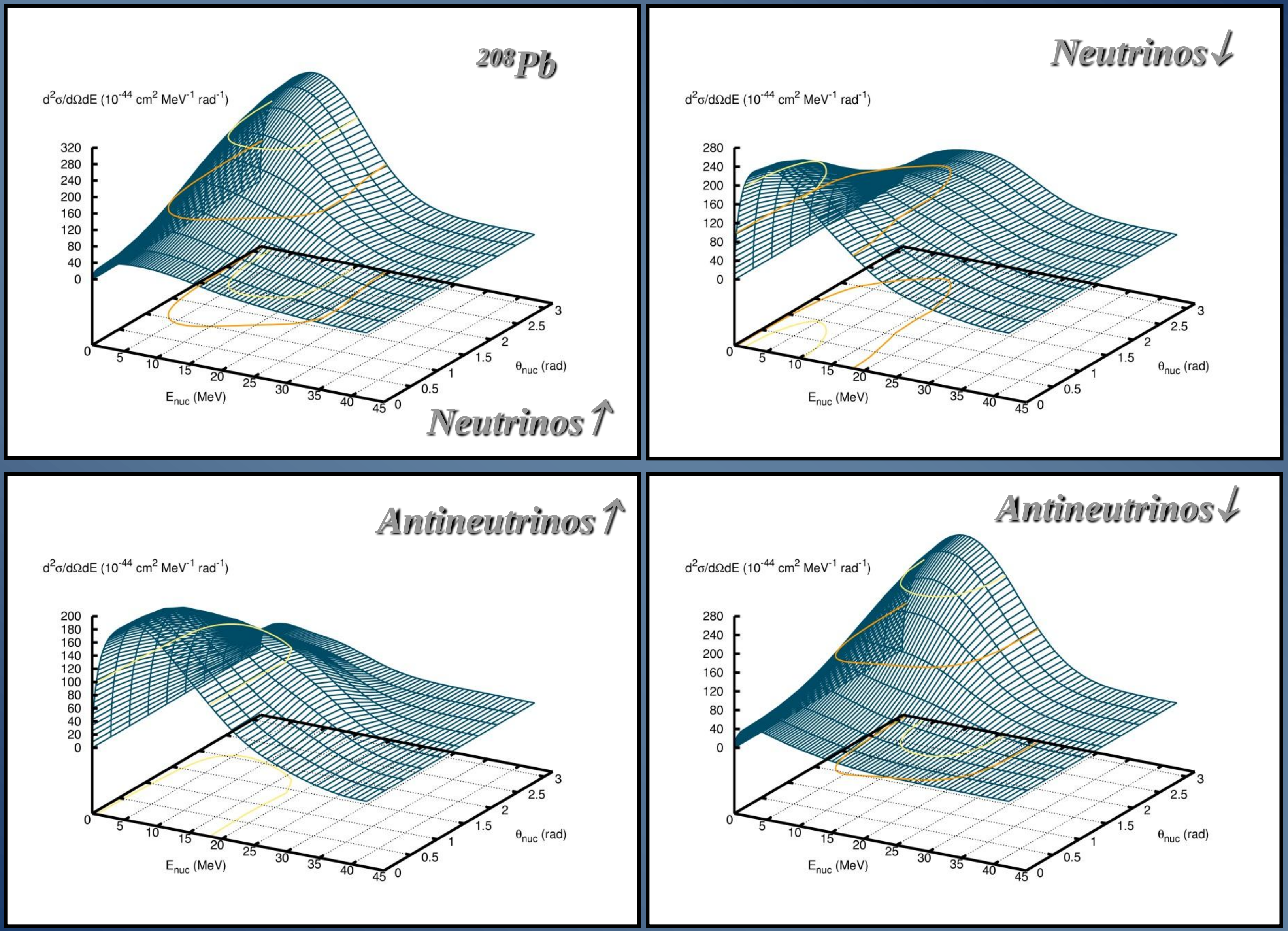
- Neutrinos favor 'spin down' nucleon knockout
- Antineutrinos mainly induce 'spin up' knockout reactions
- Polarization differences increase with incoming neutrino energies

The asymmetry and the dissimilarities between neutrinos and antineutrinos are most clear considering the angular cross section :

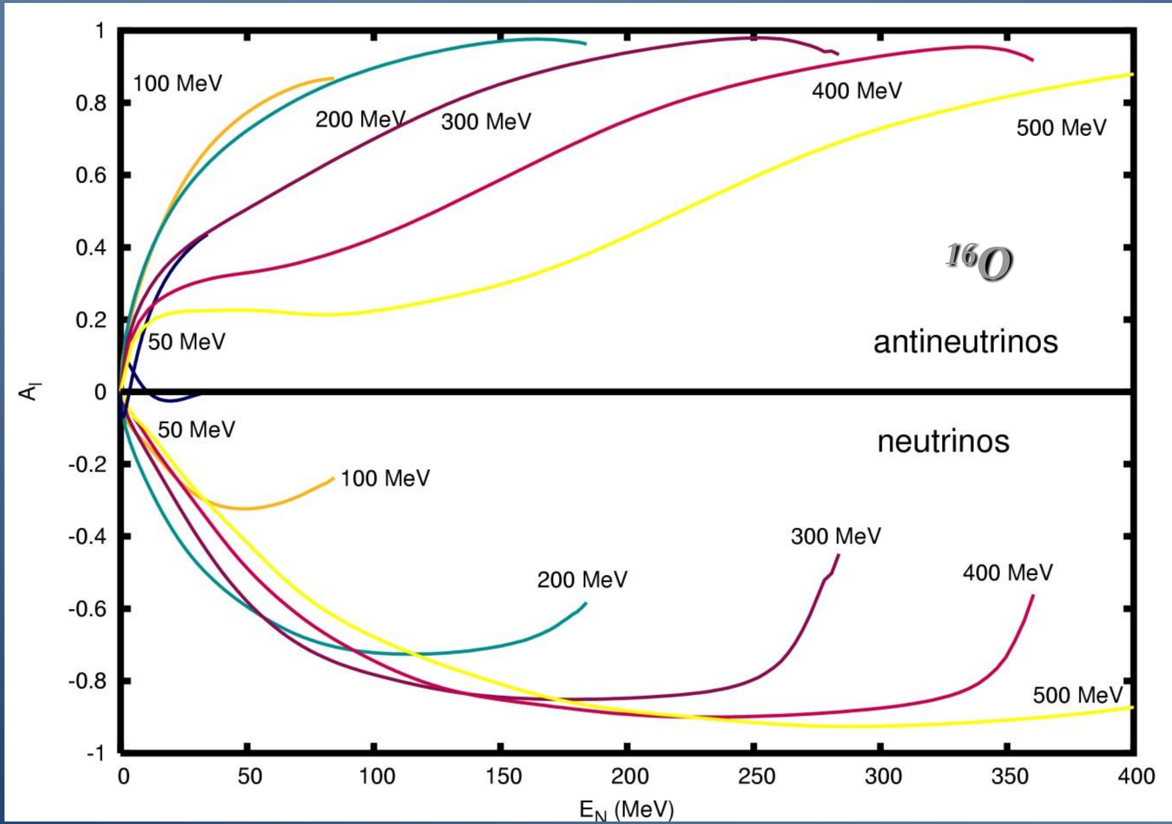


The asymmetry is most prominent for forward nucleon knockout, and remains large over a broad angular range.

For the suppressed backward scattering reactions, the asymmetry is completely reversed ν versus antiν



Longitudinal **polarization asymmetry** : $$A_l = \frac{\sigma(s_N^l = \uparrow) - \sigma(s_N^l = \downarrow)}{\sigma(s_N^l = \uparrow) + \sigma(s_N^l = \downarrow)}$$

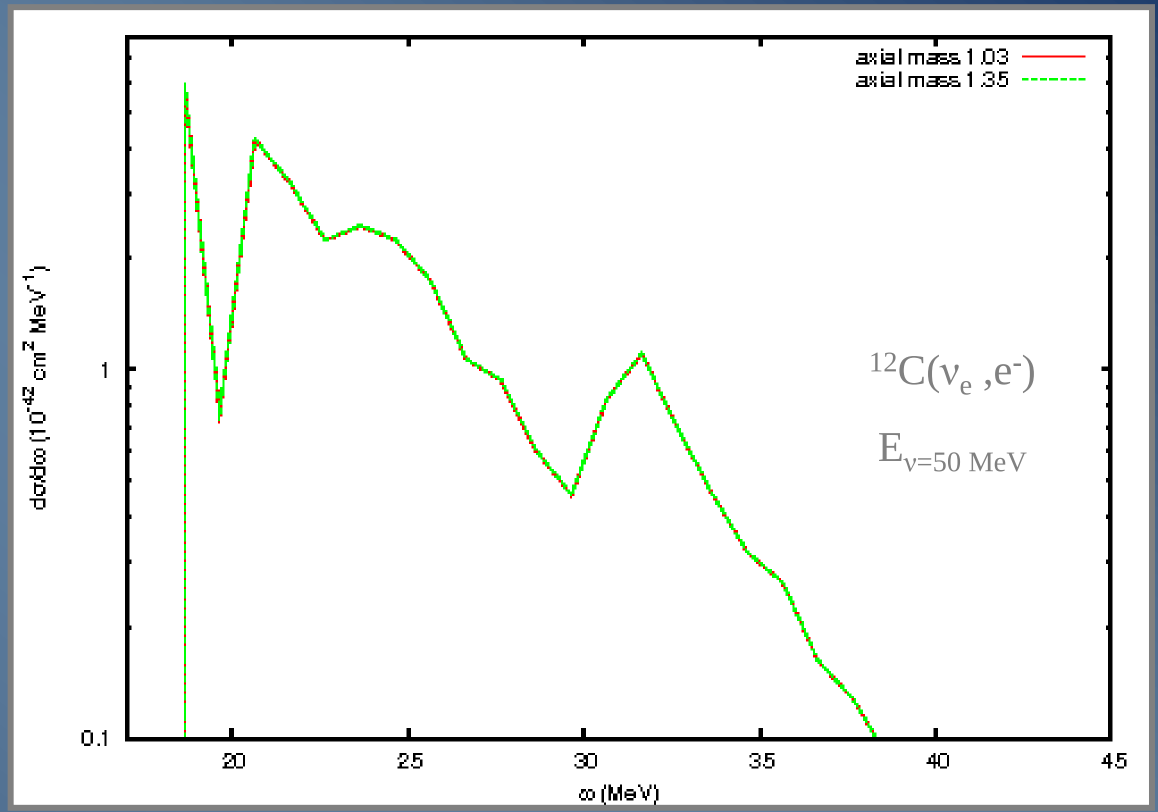


- For antineutrinos, A_l is large and positive
- For neutrinos, A_l is large and negative

N. Jachowicz, K. Vantournhout, J. Ryckebusch, K. Heyde, PRL 93, 082501 (2004) ; N. Jachowicz, K. Vantournhout, J. Ryckebusch, K. Heyde, PRC71, 034604 (2005).

M_A @ low energies

Dependence on M_A is very small at very low neutrino energies …

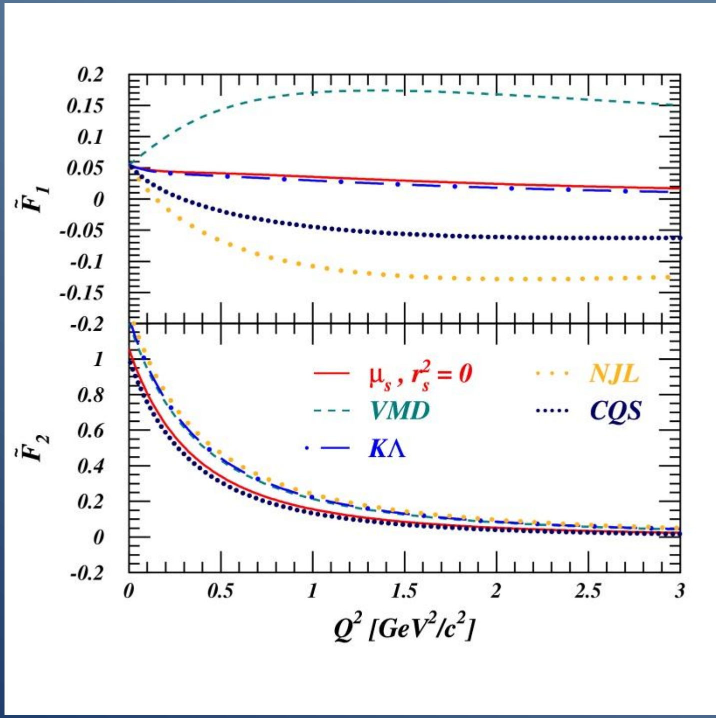


Strangeness in the nucleon

Axial form factor :

$$G_A(Q^2) = -\frac{(\tau_3 g_A - g_A^s)}{2} G(Q^2), \qquad g_A = 1.262$$

$$G(Q^2) = (1 + Q^2/M^2)^{-2}, \qquad M = 1.032$$



Weak vector form factors :

$$F_1^s = \frac{1}{6} \frac{-r_s^2 Q^2}{(1 + Q^2/M_1^2)^2}, \qquad M_1 = 1.3$$

$$F_2^s = \frac{\mu_s}{(1 + Q^2/M_2^2)^2}, \qquad M_2 = 1.26$$

Model	$\mu_s(\mu_N)$	$r_s^2(\mathrm{fm}^2)$
VMD	-0.31	0.16
$K\Lambda$	-0.35	-0.007
NJL	-0.45	-0.17
CQS (K)	0.115	-0.095

Strangeness

Traditionally :

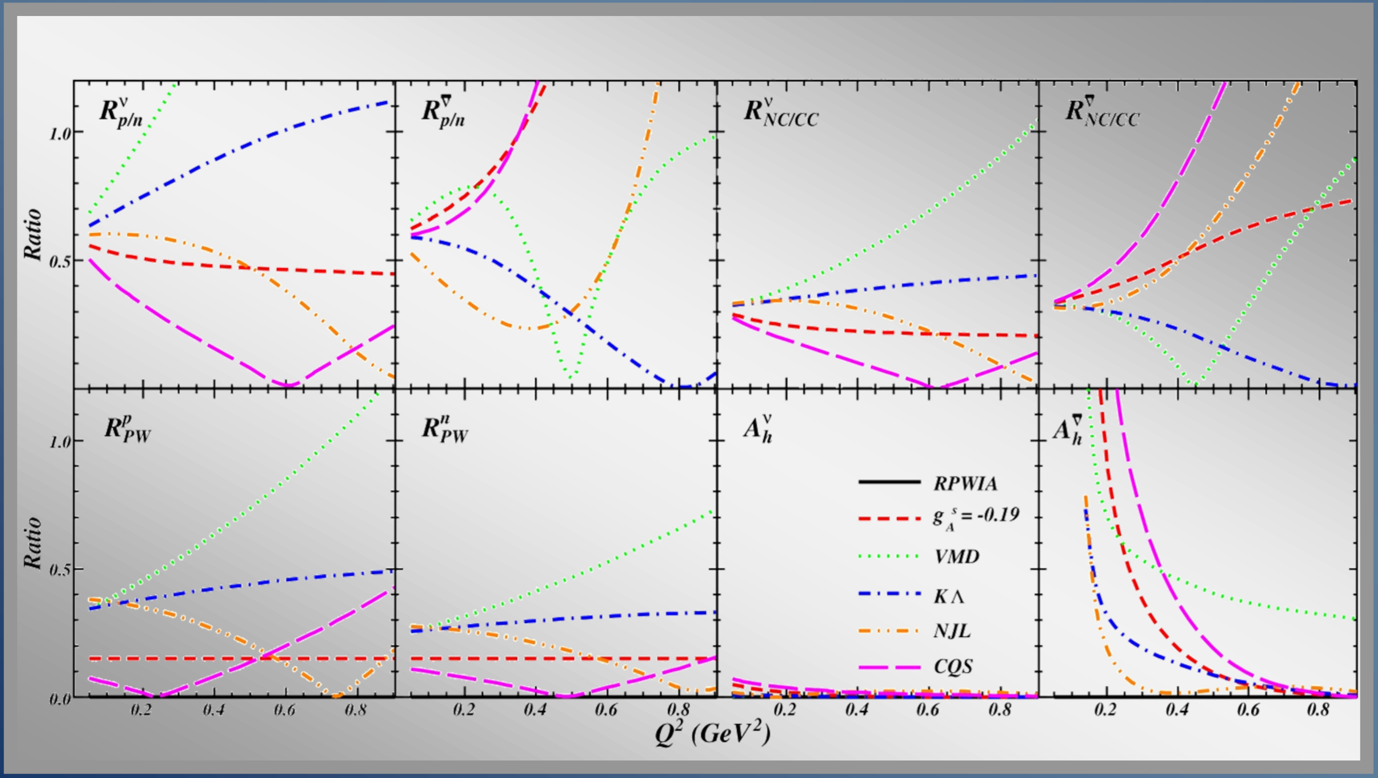
•strangeness contribution to the ***weak vector formfactors*** : Parity Violating Electron Scattering (Sample, Happex, G0, …)

Correlated !

•strangeness contribution to the ***axial current*** : neutrino scattering

-vector current contributions are suppressed

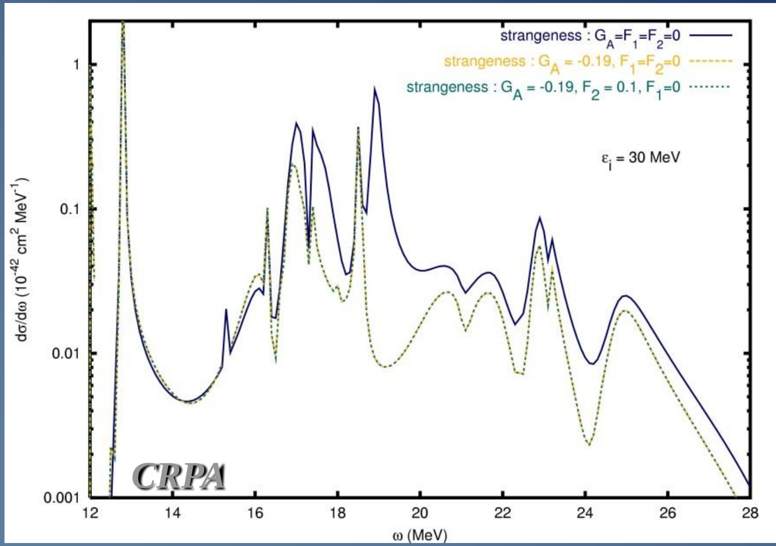
-no radiative corrections

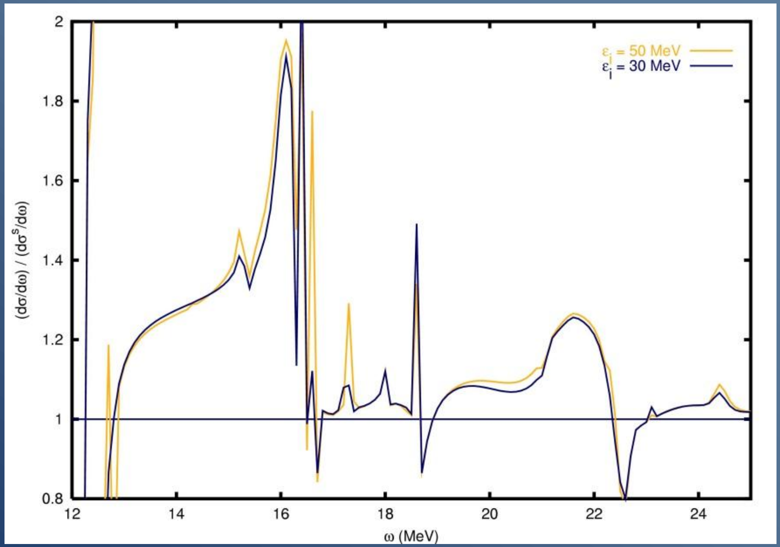


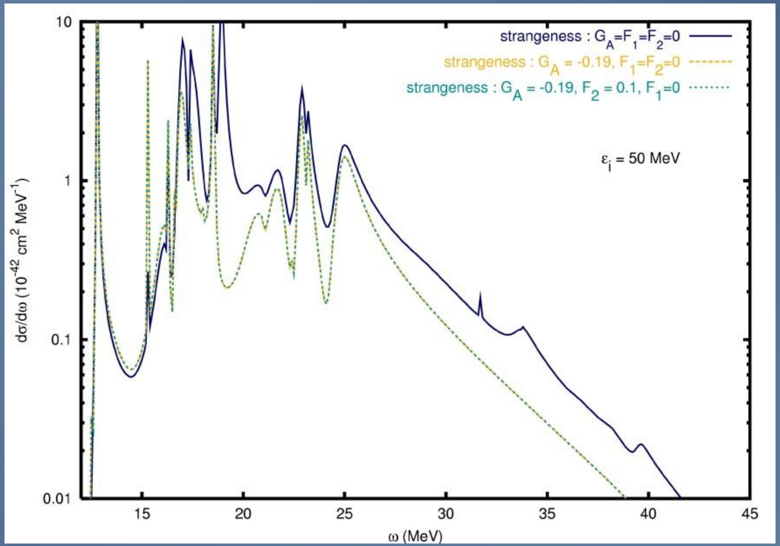
N.J., P. Vancraeyveld, P. Lava, J. Ryckebusch, PRC76, 055501 (2007).

Neutrino cross sections including strangeness

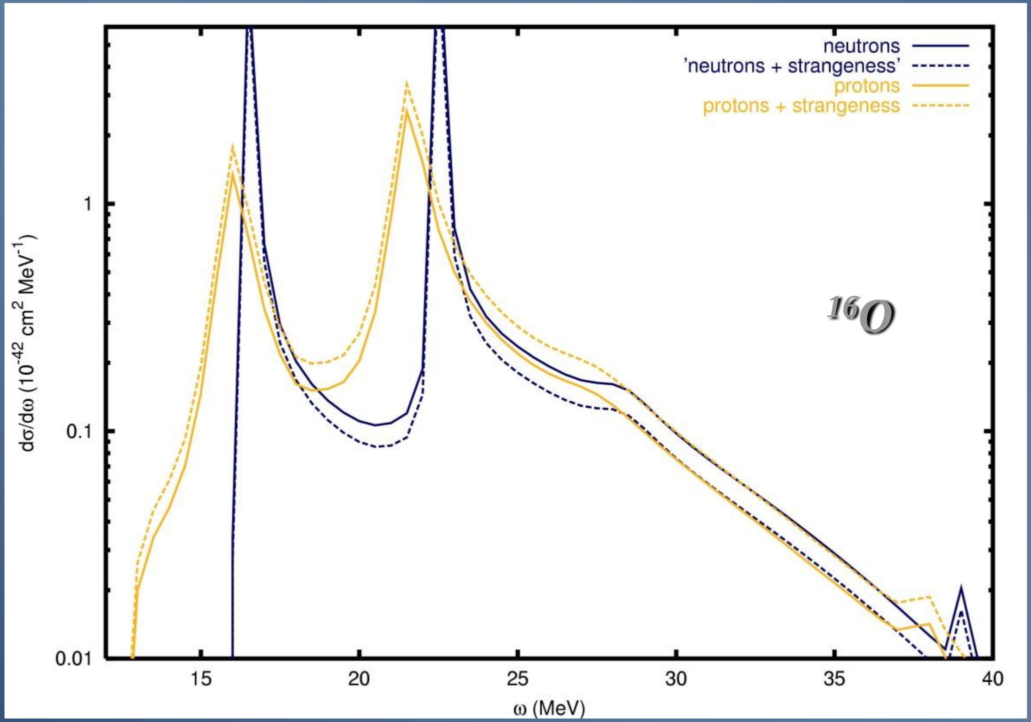
- Generally : net strangeness effect vanishes for isoscalar targets
- close to particle knockout threshold the influence becomes larger due to binding energy differences between protons and neutrons
- differential cross sections differ, energy of reaction products can be very different







proton/neutron cross sections

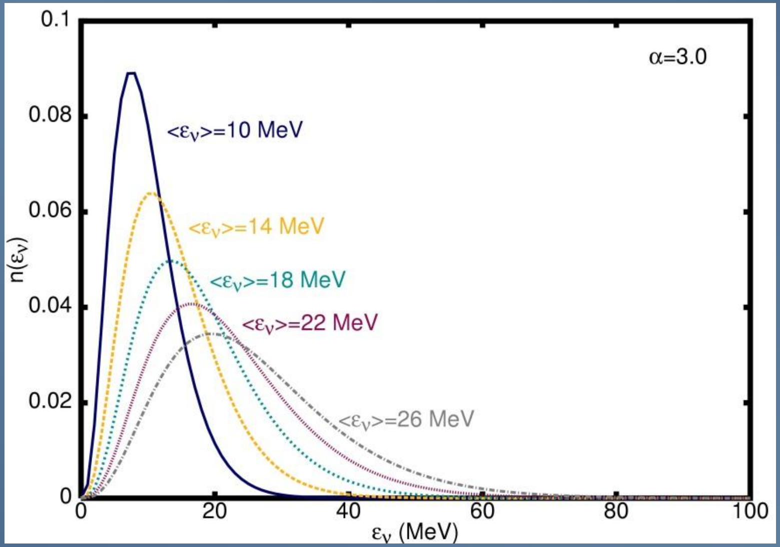


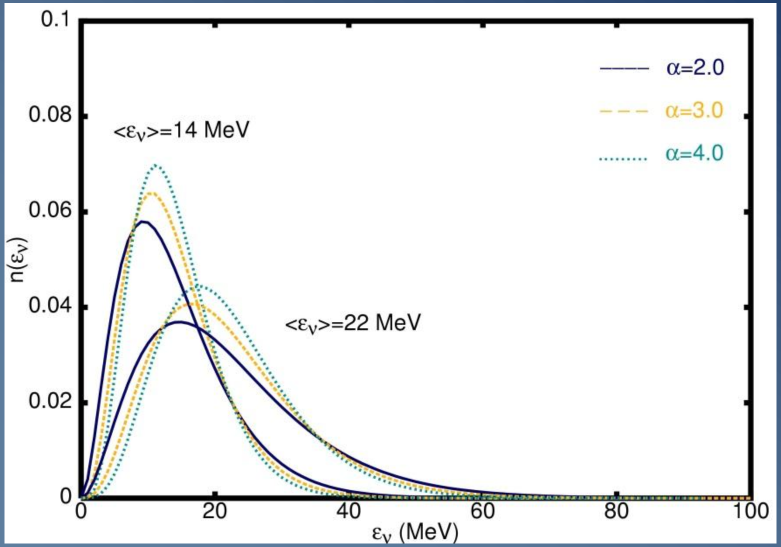
- differences up to 20%
- opposite effect for protons and neutrons

Energy dependence of the cross section

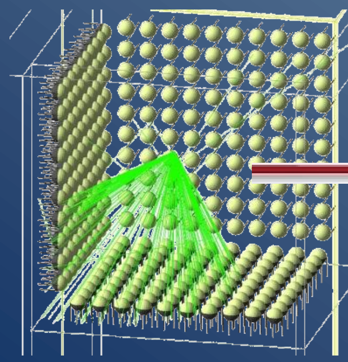
Supernova neutrino spectra :

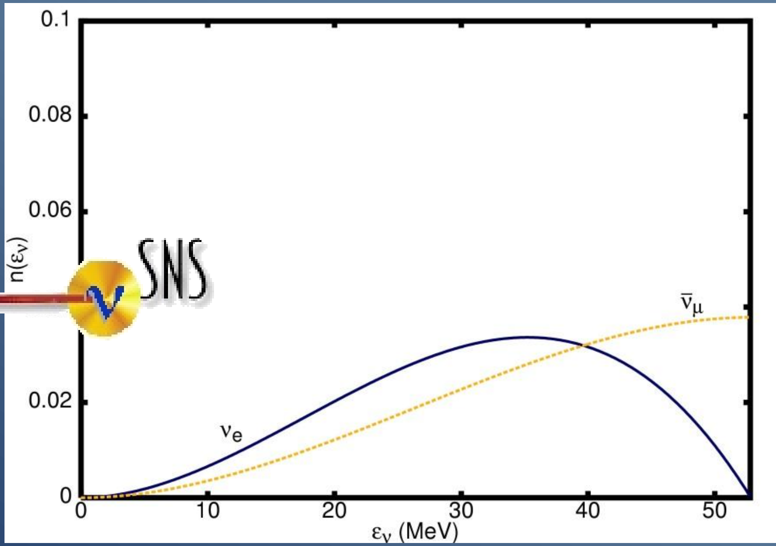
$$n_{SN[\langle\varepsilon\rangle,\alpha]}(\varepsilon) = \left(\frac{\varepsilon}{\langle\varepsilon\rangle}\right)^{\alpha} e^{-(\alpha+1)\frac{\varepsilon}{\langle\varepsilon\rangle}}$$





Experimentally :





Michel spectra :

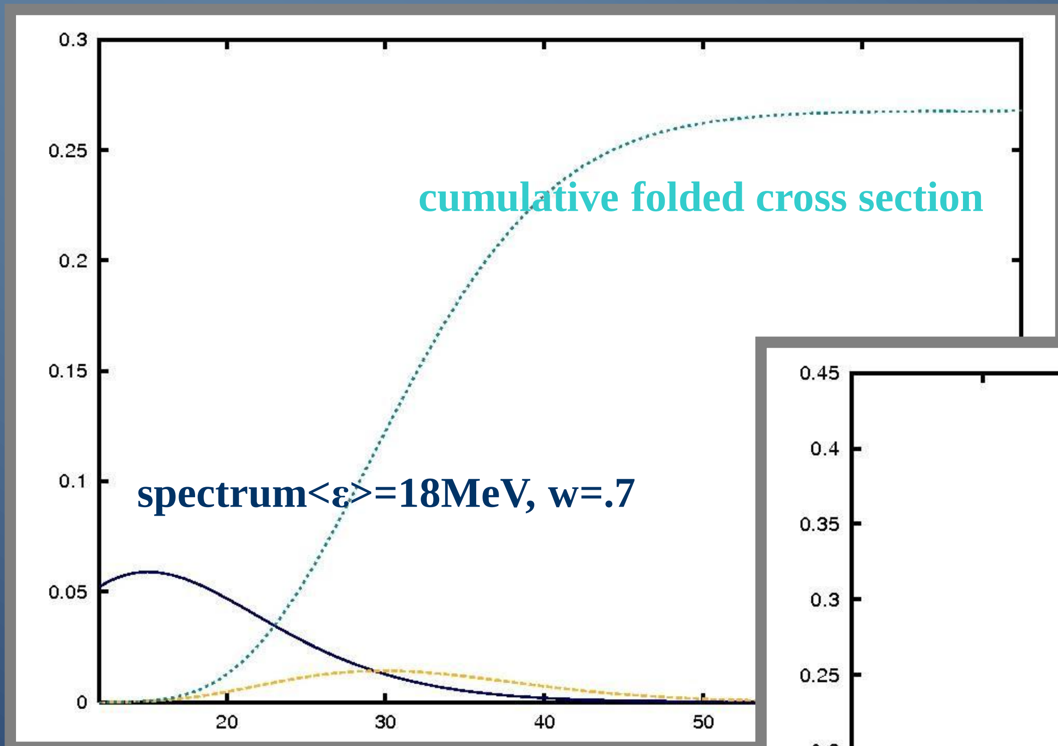
$$n_{\nu_e}(\varepsilon_{\nu_e}) = \frac{96\varepsilon_{\nu_e}^2}{m_\mu^4}(m_\mu - 2\varepsilon_{\nu_e}),$$

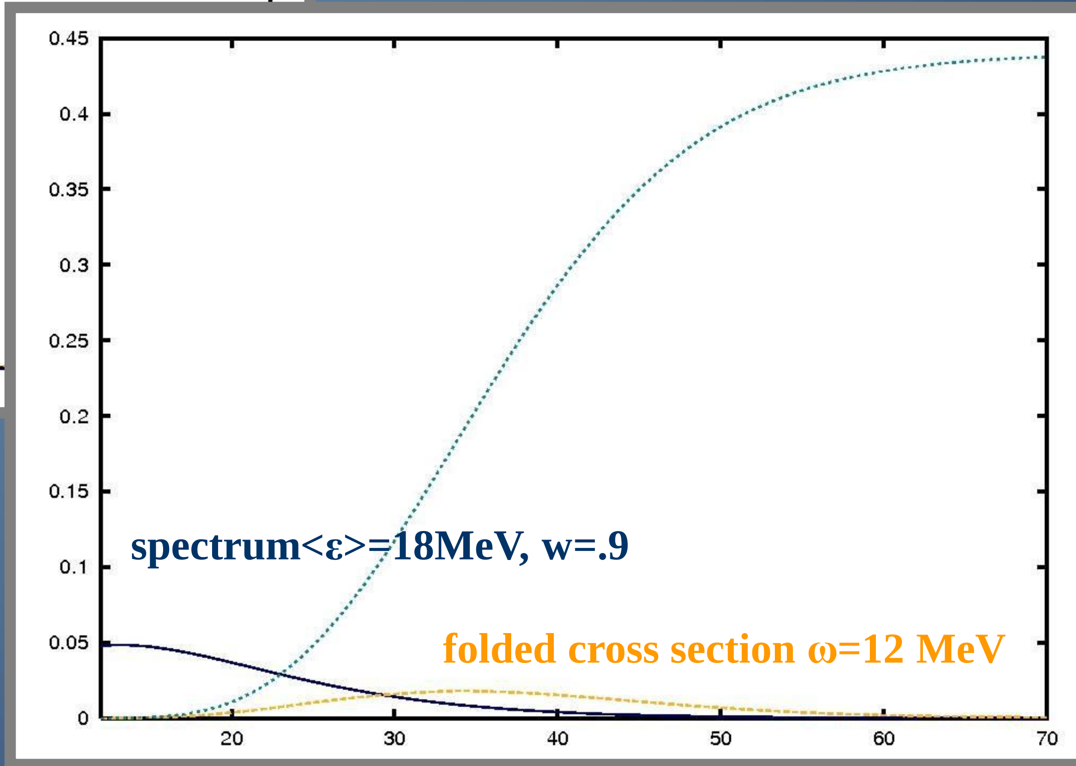
$$n_{\overline{\nu}_\mu}(\varepsilon_{\overline{\nu}_\mu}) = \frac{32\varepsilon_{\overline{\nu}_\mu}^2}{m_\mu^4}(\frac{3}{2}m_\mu - 2\varepsilon_{\overline{\nu}_\mu})$$

Energy dependence of the cross section

Supernova neutrino spectra :

$$n_{SN[\langle\varepsilon\rangle,\alpha]}(\varepsilon) = \left(\frac{\varepsilon}{\langle\varepsilon\rangle}\right)^{\alpha} e^{-(\alpha+1)\frac{\varepsilon}{\langle\varepsilon\rangle}}$$

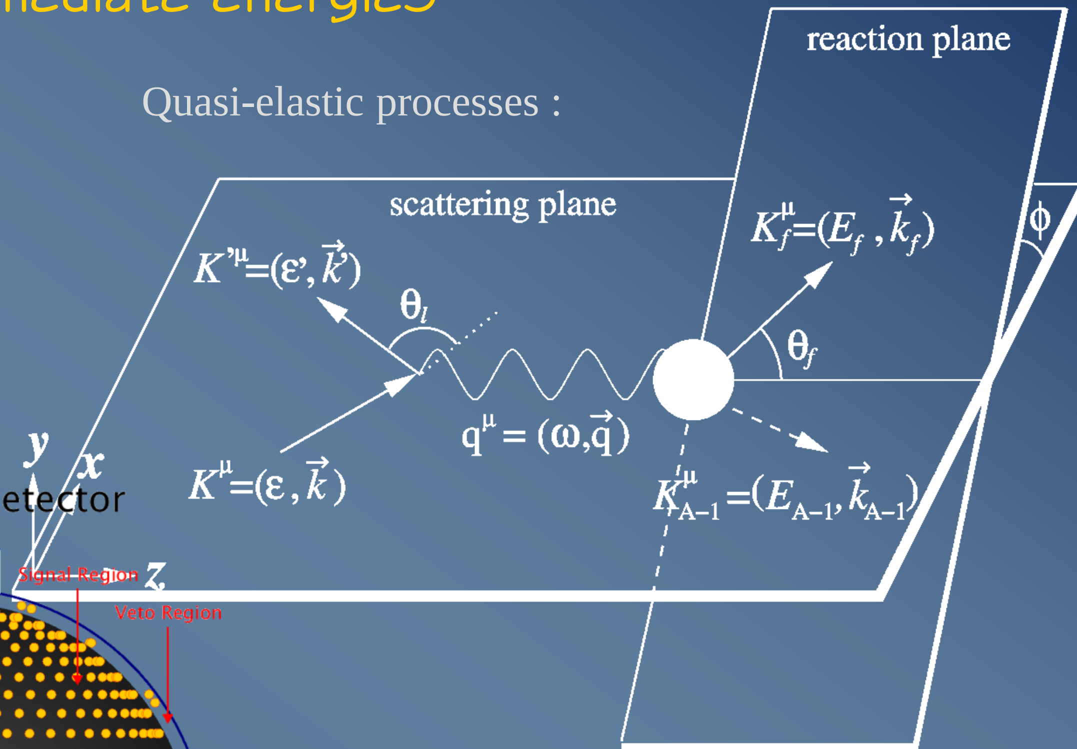


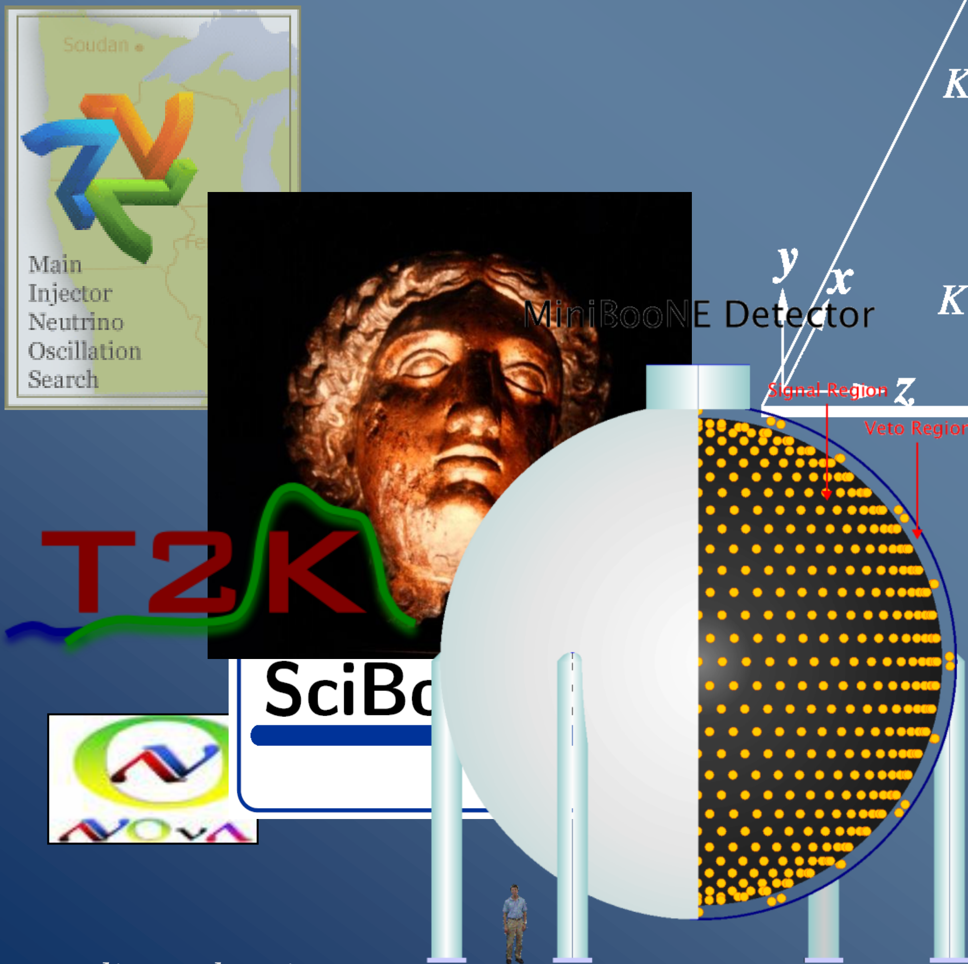


MiniBooNe

Experiments at intermediate energies

Quasi-elastic processes :





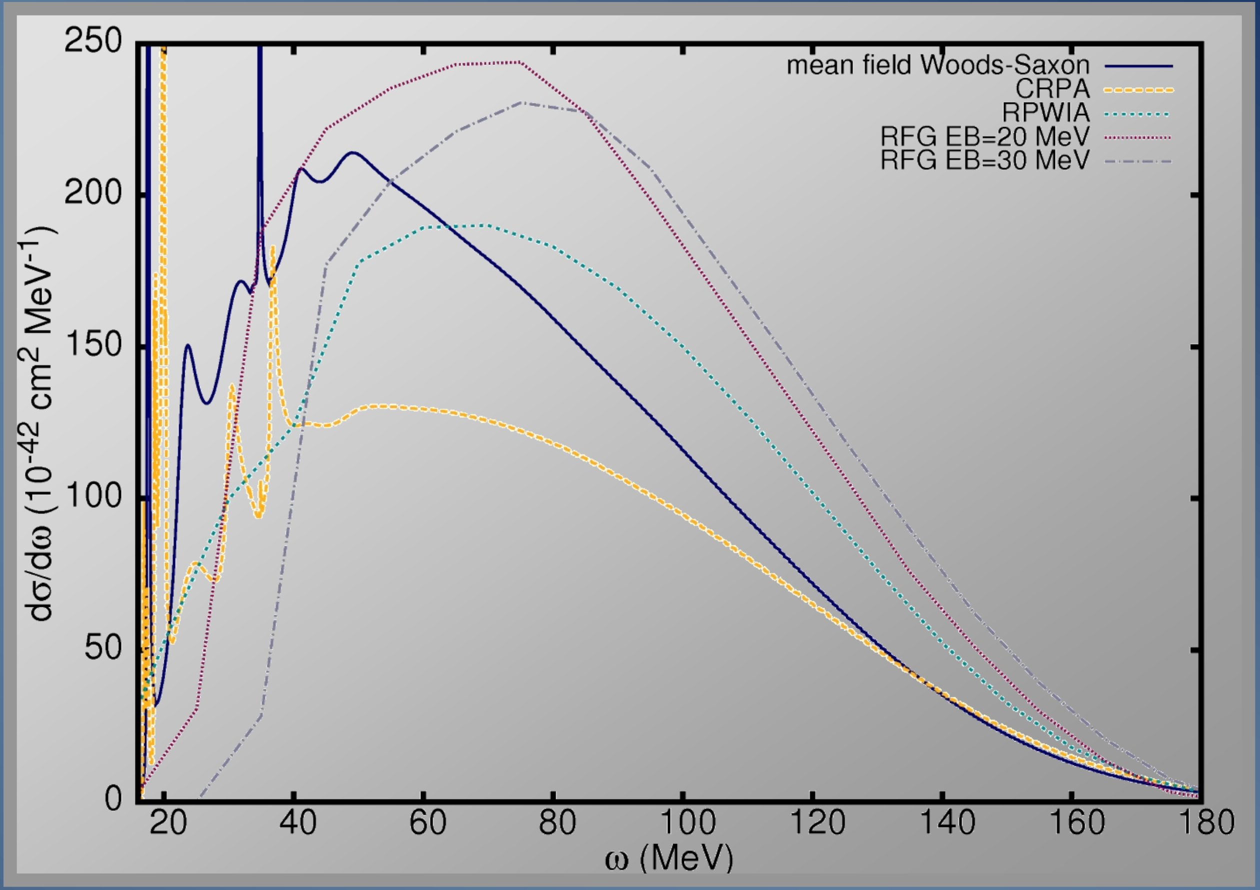
Intermediate energies : 100 MeV - … GeV

Energy distribution !

MiniBooNe

Cross sections at low Q^2

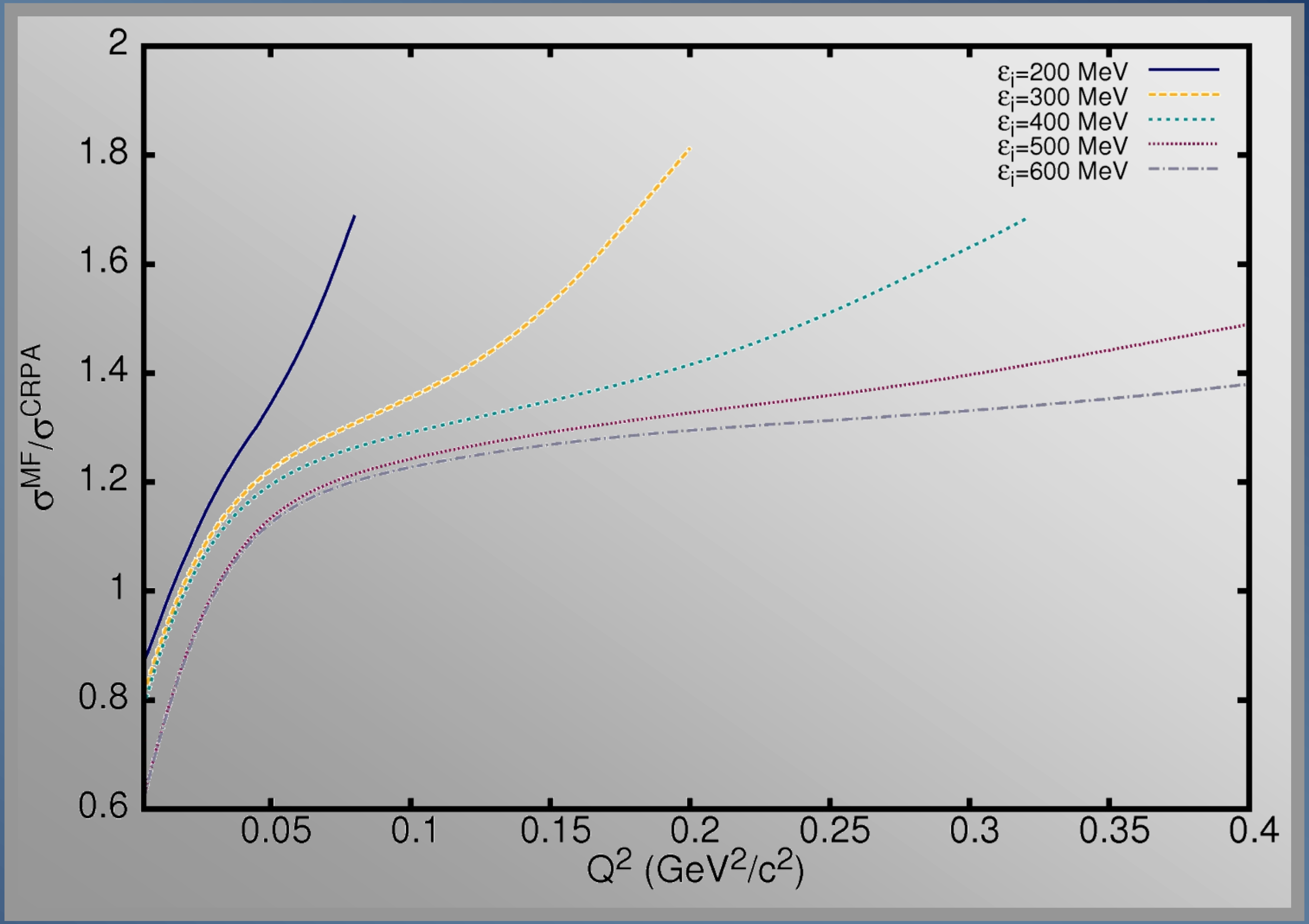
Comparison between inclusive cross sections obtained within a relativistic Fermi gas calculation, a relativistic plane wave impulse approximation (RPWIA) approach, a mean-field calculation, and a calculation including CRPA correlations implemented using a Skyrme parametrization as residual interaction.



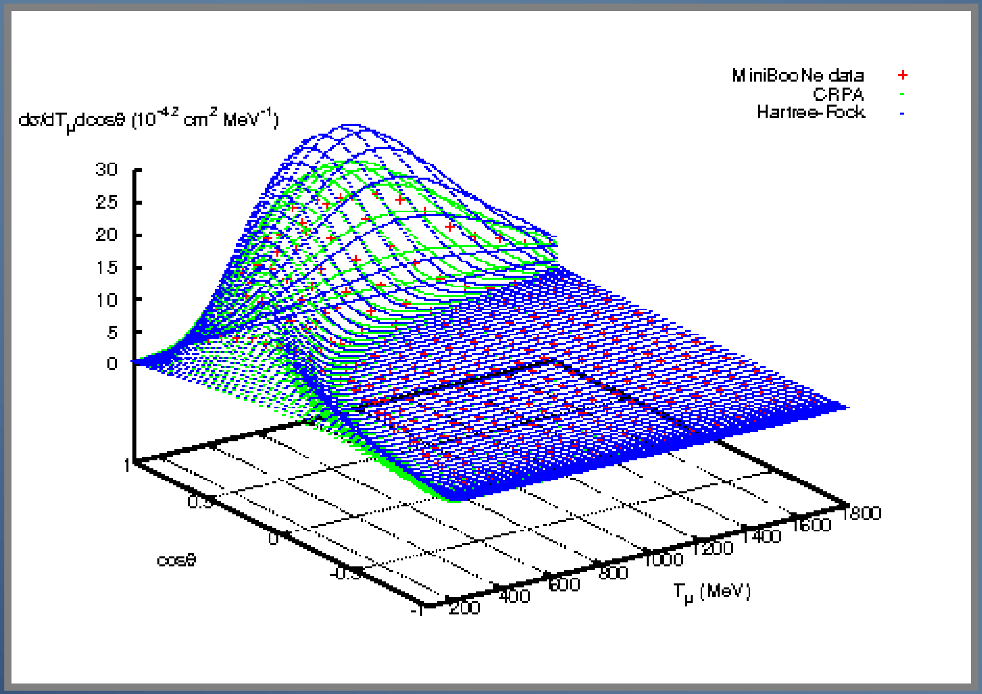
MiniBooNe

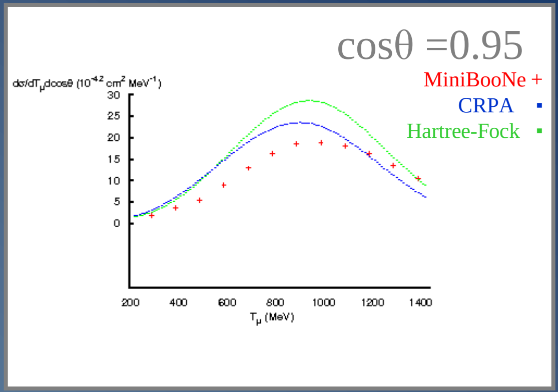
Cross sections at low Q^2

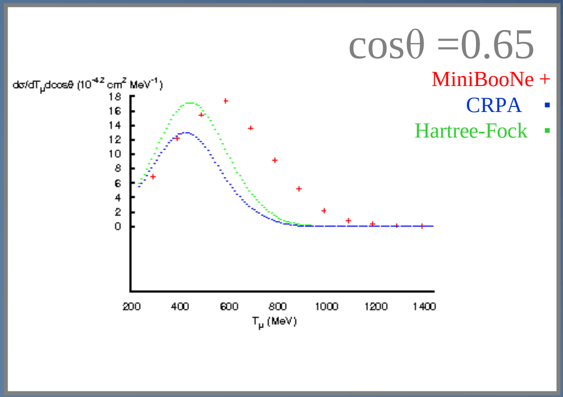
Q^2 dependence as a function of incoming energy

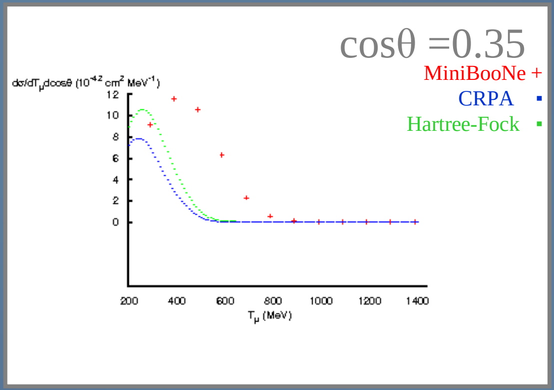


Comparison with MiniBooNe data



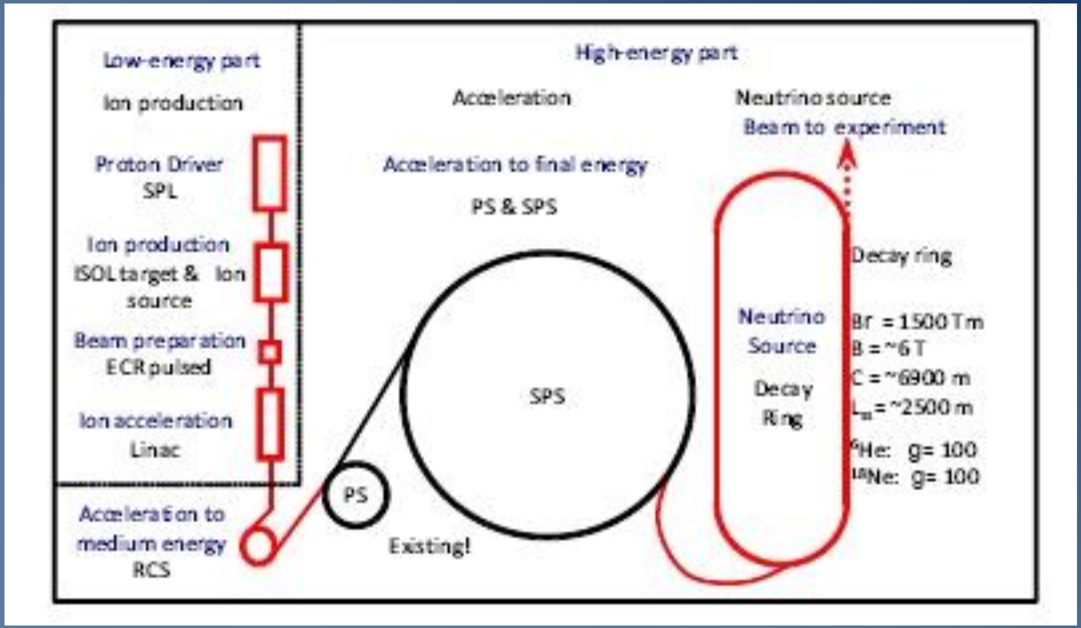






Beta-beam neutrino spectra :

- β-decay of a primary boosted nuclear beam generates intense neutrino beams,
- with average energy and precise shape of the spectrum determined by the boost factor γ of the primary beam

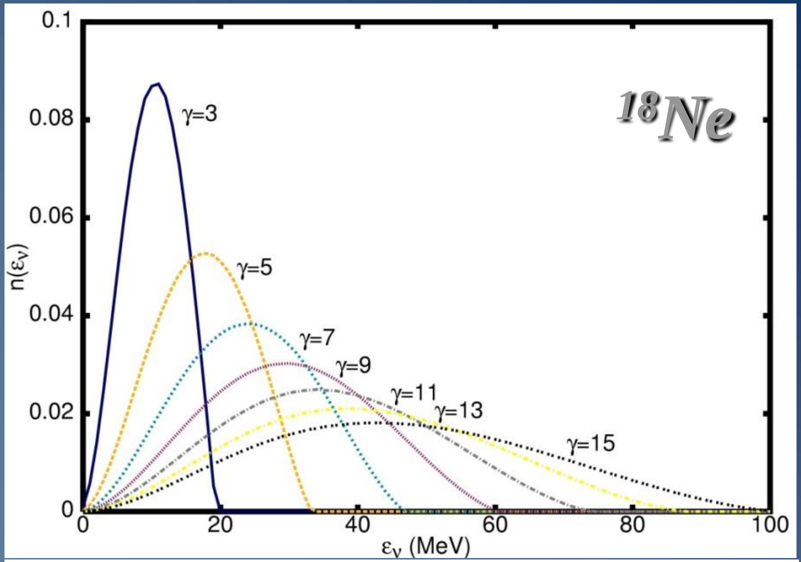


•First proposed to produce high energy neutrinos in oscillation experiments

(P.Zuchelli, Phys.Lett.B 532, 166 (2002).

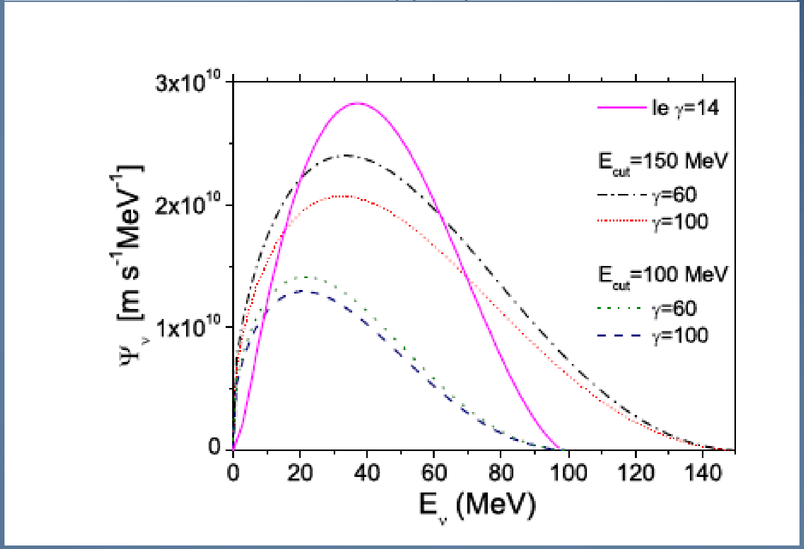
- At lower gamma factor, the neutrino energy becomes very suitable for neutrino-nucleus scattering investigations

(C. Volpe, J.Phys. G30, 1 (2004)).

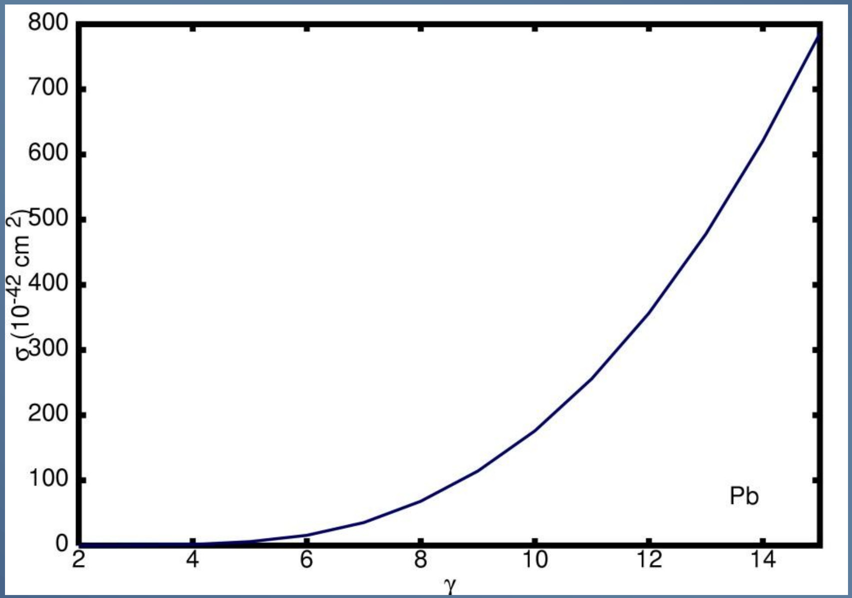


- A detector away form the main axis of the storage ring will detect the least energetic neutrinos

(R.Lazauskas et al. PRD76, 053006)

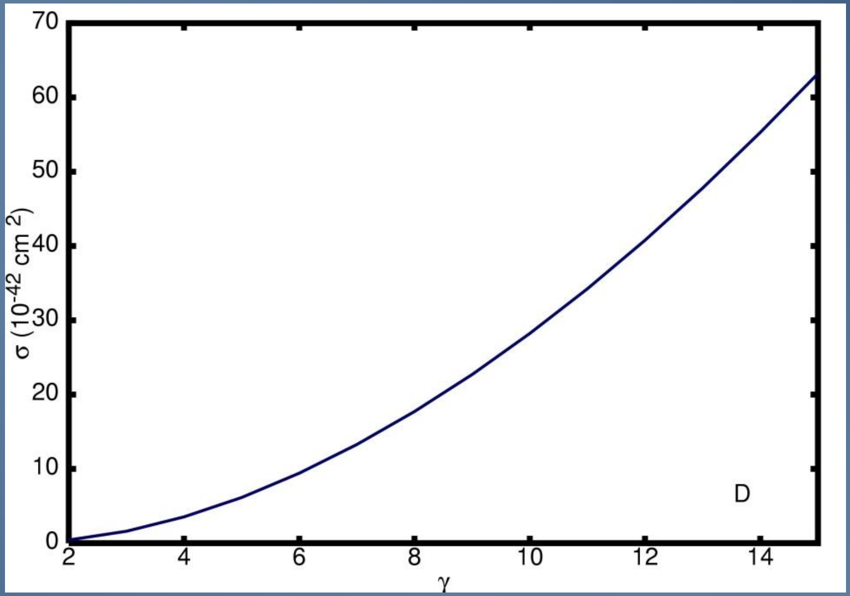


→Suited for nuclear structure studies, studies of supernova neutrino responses …



Cross section as a function of the boost factor γ of the beam

$$\sigma_{\gamma}^{fold} = \int_0^{\infty} d\varepsilon_i \, \sigma(\varepsilon_i) \, n^{\gamma}(\varepsilon_i)$$



Procedure :

• linear combinations of normalized beta-beam spectra :

$$n_{N\gamma}(\varepsilon_i) = \sum_{i=1}^{N} a_i n_{\gamma_i}(\varepsilon_i)$$

$$\int d\varepsilon_i n_{\gamma_i}(\varepsilon_i) = 1 \quad \forall i$$

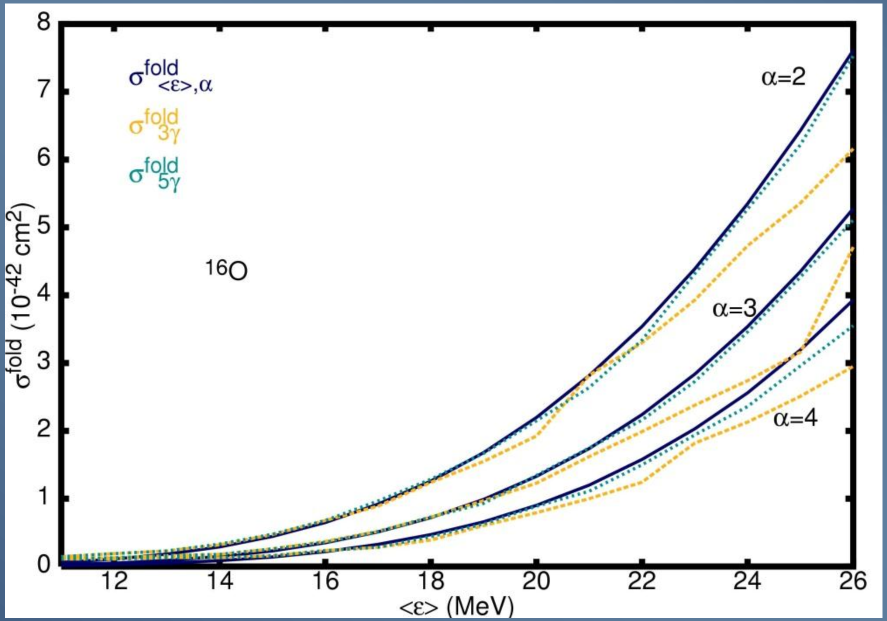
$$\int d\varepsilon_i n_{N\gamma}(\varepsilon_i) = 1$$

• fitting the constructed energy distribution to the supernova-neutrino spectrum by minimizing the expression,

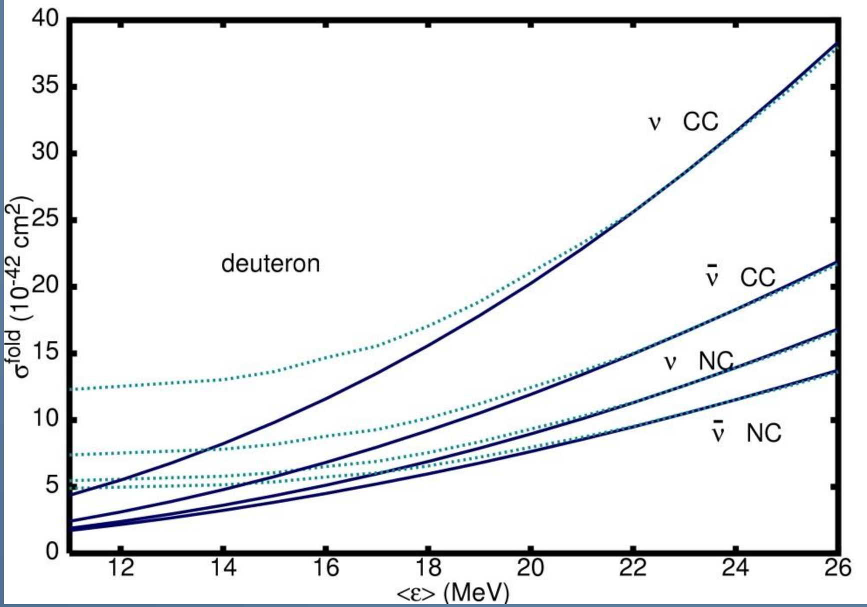
$$\int_{\varepsilon_i} d\varepsilon_i \left| n_{N\gamma}(\varepsilon_i) - n_{SN}(\varepsilon_i) \right|$$

$$n_{SN[\langle\varepsilon\rangle,\alpha]}(\varepsilon) = \left(\frac{\varepsilon}{\langle\varepsilon\rangle}\right)^{\alpha} e^{-(\alpha+1)\frac{\varepsilon}{\langle\varepsilon\rangle}}$$

varying the expansion parameters a_i and the boost factors γ_i



Total folded cross sections :

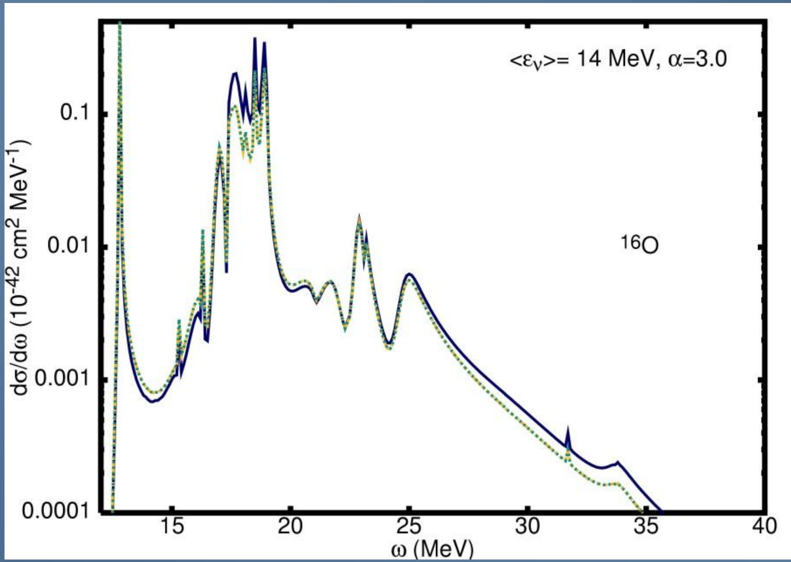


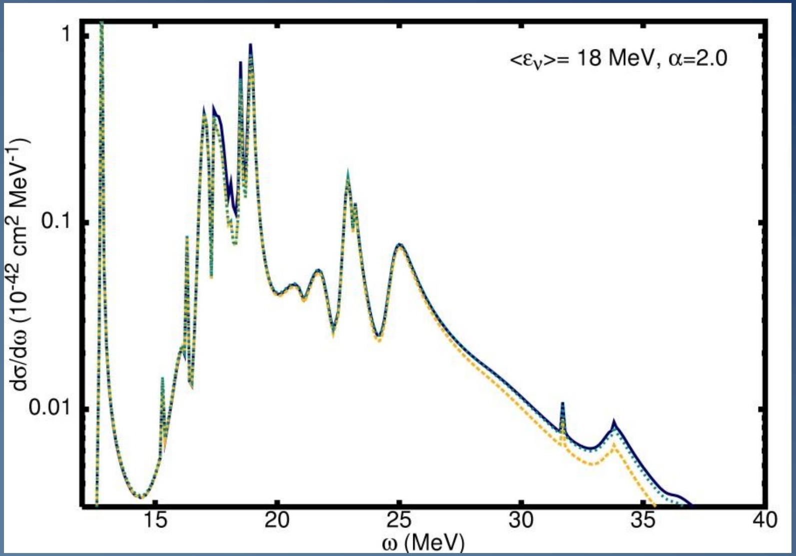
- ^{16}O : CRPA calculation
- deuteron : S. Nakamura, T. Sato, S. Ando et al., Nucl. Phys. A 707 (2002)

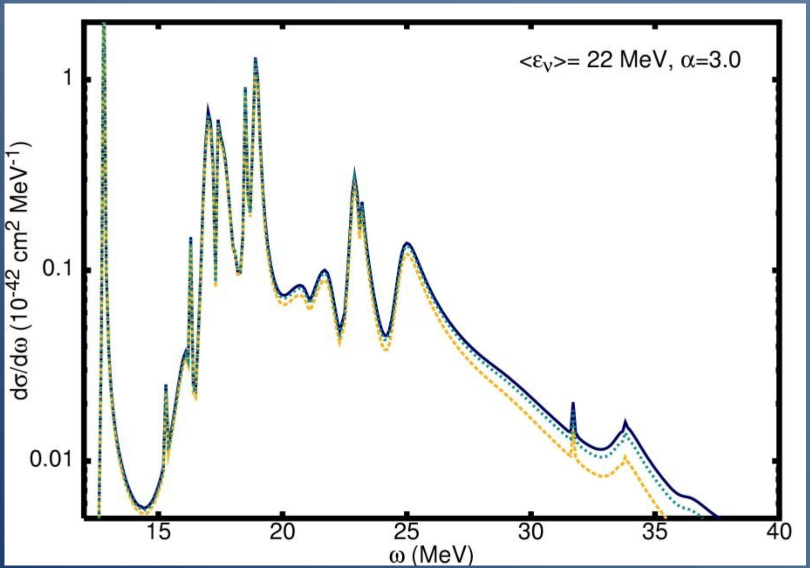
LowE β-beams

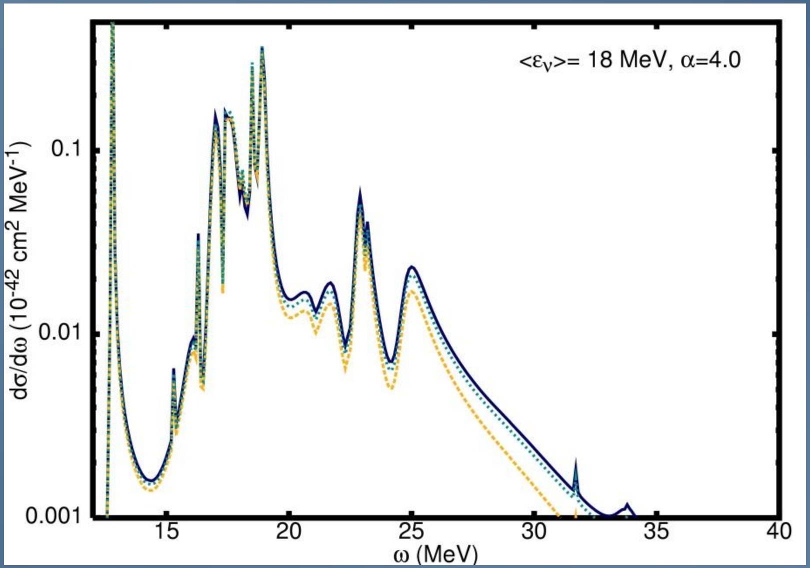
^{16}O

… differential folded cross sections

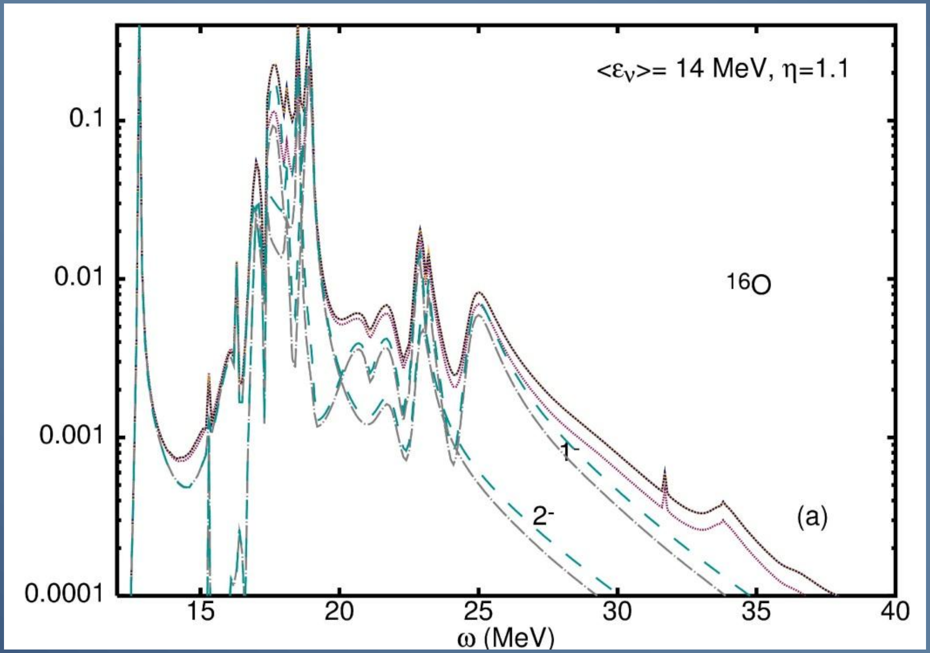


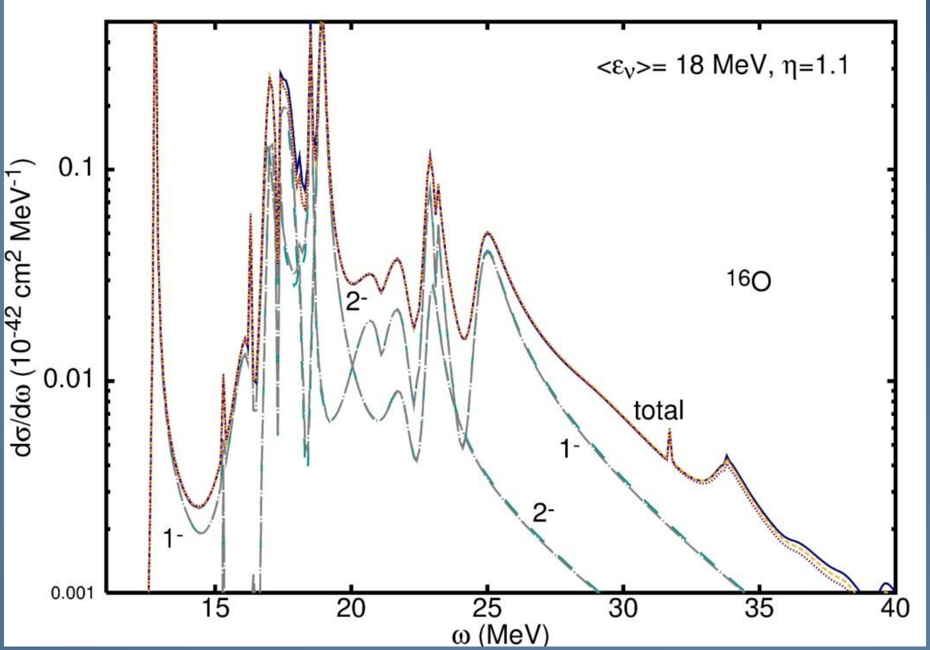






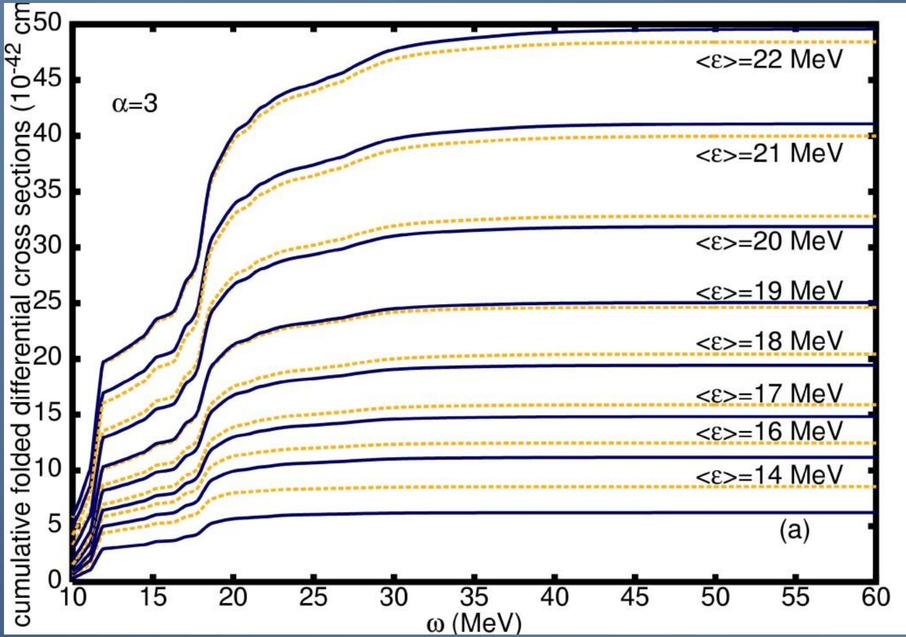
… differential folded cross sections –multipole contributions





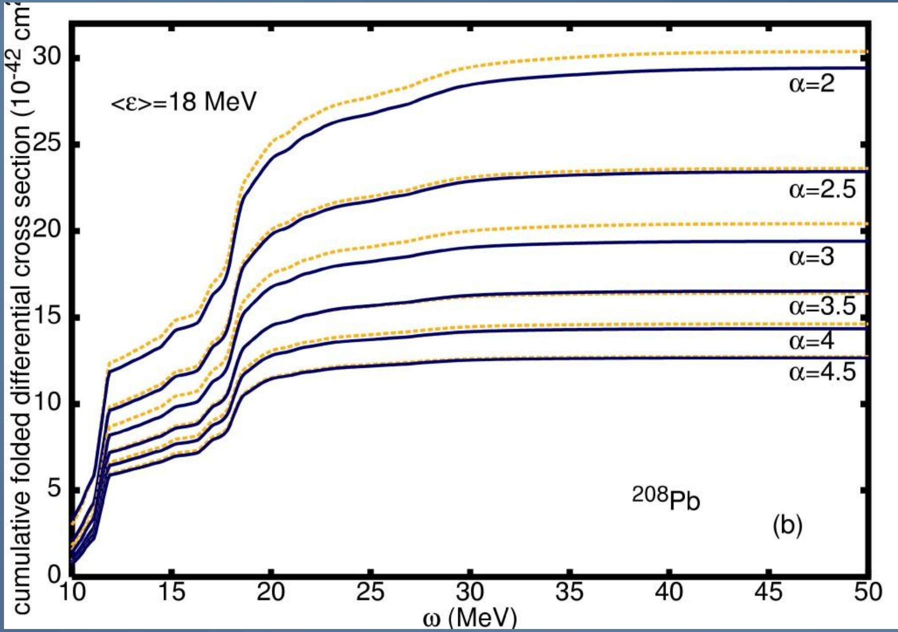
This very satisfying agreement suggests that it is possible to reconstruct supernova-neutrino signal using the results of the beta-beam measurement directly, without going through the intermediate step of using a nuclear structure calculation

- For each set of beta-beam data at a given γ, there will be a measured response in the detector
- Taking appropriate linear combinations of the measured response provides a very accurate picture of the response of the detector to an incoming supernova-neutrino spectrum

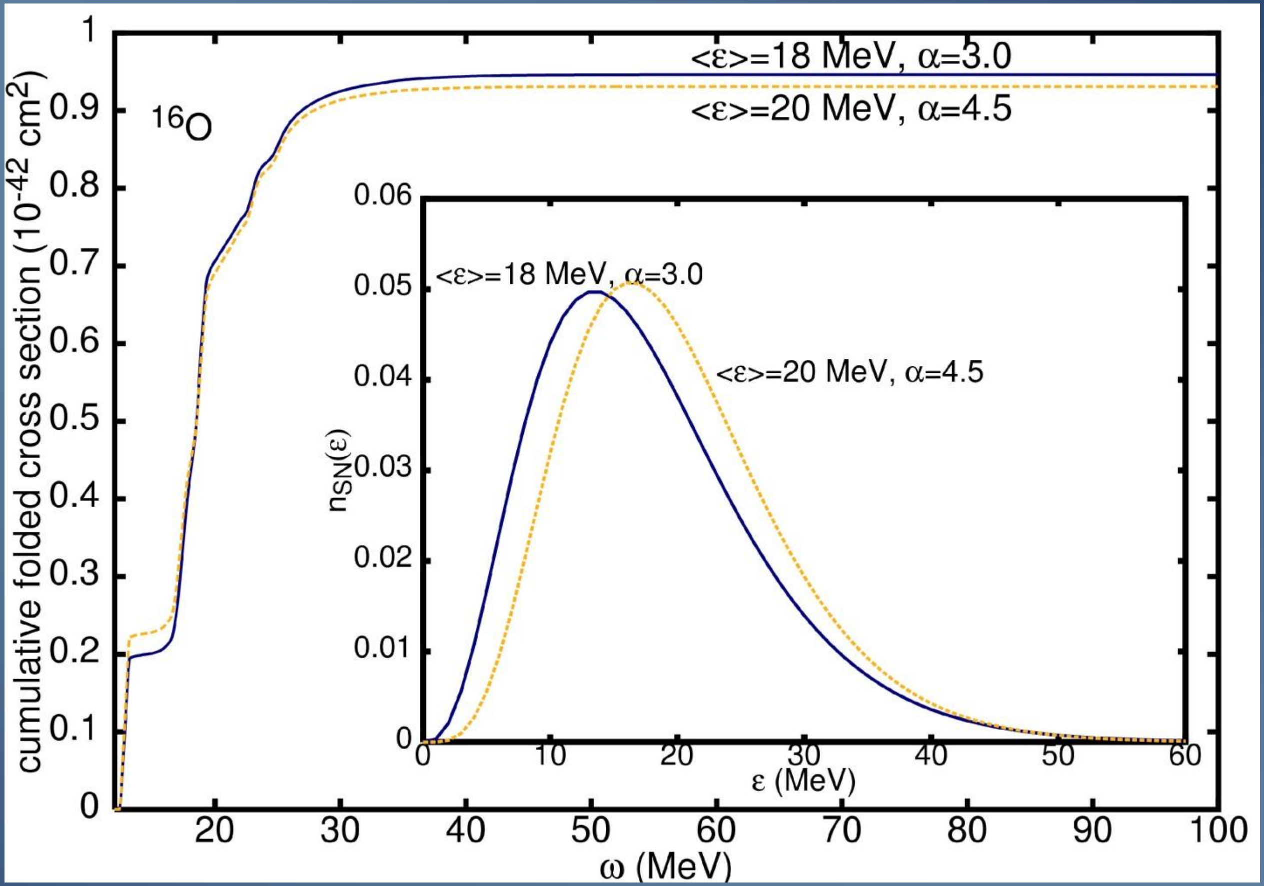


Energy ‘resolution’

Width ‘resolution’



Reconstructing the supernova neutrino spectrum ?



Inversion of the method : reconstructing the supernova neutrino energy spectrum

Supernova neutrino signal in a terrestrial detector

$$\sigma^{fold}_{signal}(\omega) = \int d\varepsilon_\nu \, \sigma(\varepsilon_\nu, \omega) \, n_{SN}(\varepsilon_\nu).$$

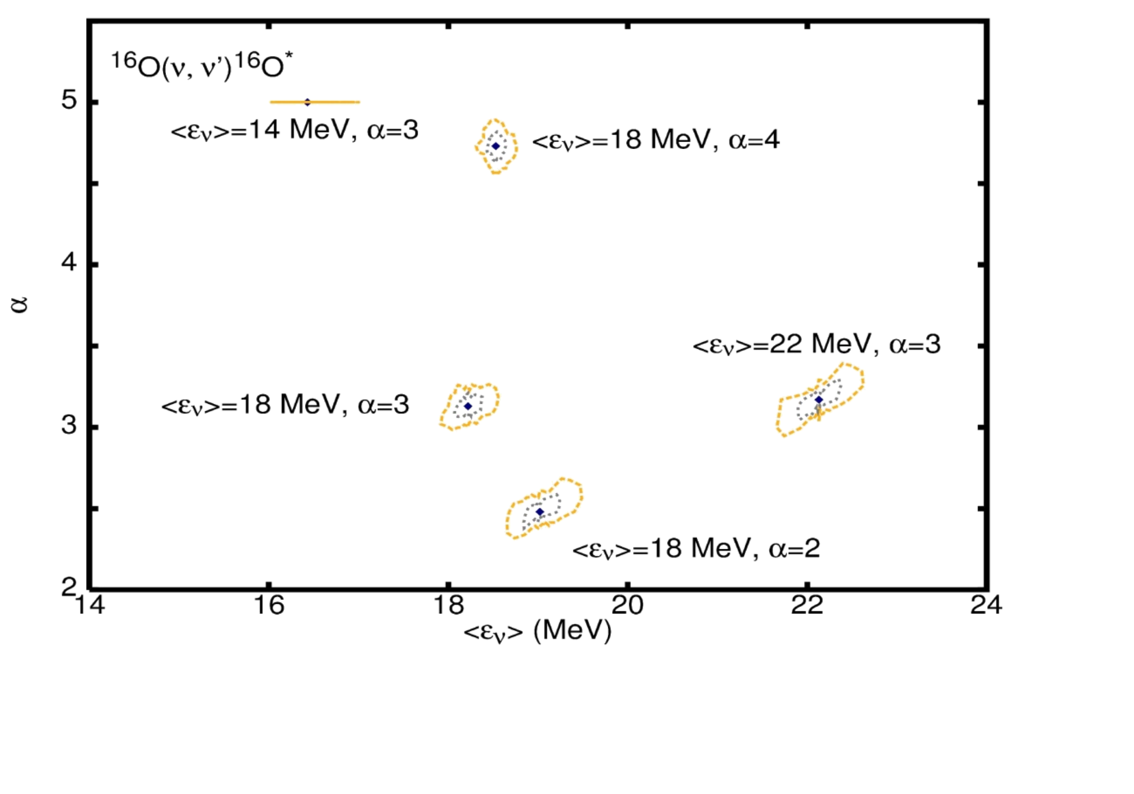
Fit with linear combination of beta beam responses :

$$\sigma^{fold}_{fit}(\omega) = \sum_{i=1}^{N} a^{\gamma_i} \int d\varepsilon_\nu \, \sigma(\varepsilon_\nu, \omega) \, n^{\gamma_i}(\varepsilon_\nu)$$

↓

a^{γ_i}, γ_i ⇒ n_{SN}

Inversion of the method – reconstruction in terms of average energy and width of the spectrum



curves : 90% confidence levels for spectra with

5 and 10 % uncertainty on the expansion parameters

N.J., G. McLauglin, PRL96, 172301 (2006) ; N.J., G. McLaughlin, C. Volpe, PRC77, 055501 (2008)

Summary

Neutrino cross sections in the 10s of MeV energy range

- Nuclear structure effects are important
- Strongly energy dependent
- Dominated by axial, transverse contributions
- Strangeness influence can be important
- Low-energy beta beams would provide an excellent opportunity to study the nuclear response in this energy range, important for e.g. supernovaneutrinos