CRPA cross-sections for Supernova-Neutrino detection on ^{208}Pb

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Overview

- Supernova-neutrino detection
- Neutrino-nucleus scattering
- The Continuum Random Phase Approximation
- Cross-section results $^{208}Pb(\nu,\nu')^{208}Pb^*$
- Influence of the neutrino energy-distribution

Supernova-neutrino detection

Future galactic supernova

Terrestrial detection of neutrinos :

- escaping from the center of the star
- carrying away largest part of the energy

OMNIS, LAND

^{56}Fe, ^{208}Pb

- neutrino-nucleus cross sections
- nucleon knock-out : low thresholds

Supernova neutrinos : What can be learned ?

Energy information

- ^{56}Fe $\leftrightarrow$ ^{208}Pb cross section : thresholds differences
- 1 neutron $\leftrightarrow$ 2 neutron knock-out

Flavour information

- charge-changing $\leftrightarrow$ neutral-current reactions

Time information

- Black-hole formation
- neutrino masses

The weak interaction hamiltonian

$$\widehat{H}_W = \frac{G}{\sqrt{2}} \int d\vec{x}\ \hat{\jmath}_{\mu,leptonic}(\vec{x})\ \widehat{J}^{\mu,hadronic}(\vec{x})\,, \quad G = 1.16639\ \ 10^{-11} \quad MeV^{-2}$$

lepton current $\quad \hat{\jmath}^0_\mu(x) = \Sigma_{i=e,\mu,\tau}\ \overline{\Psi}_{\nu_i}(x)\,\gamma_\mu\,(1-\gamma_5)\,\Psi_{\nu_i}(x)$

neutral current

nucleon current $\quad \widehat{J}_\mu = \overline{\Psi}_N \left(G_1^V \gamma_\mu + G_2^V \frac{1}{2M} \sigma_{\mu\nu} q^\nu + G^A \gamma_\mu \gamma_5\right) \Psi_N$

The scattering cross section

Golden rule : $\frac{d^2\sigma}{d\Omega\, d\omega} = (2\pi)^4\, k_f \varepsilon_f \sum_{s_f,s_i} \frac{1}{2J_i+1} \sum_{M_f,M_i} \left| \left\langle f \left| \widehat{H}_W \right| i \right\rangle \right|^2$

Neutral current scattering cross section:

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

Response

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

Transverse

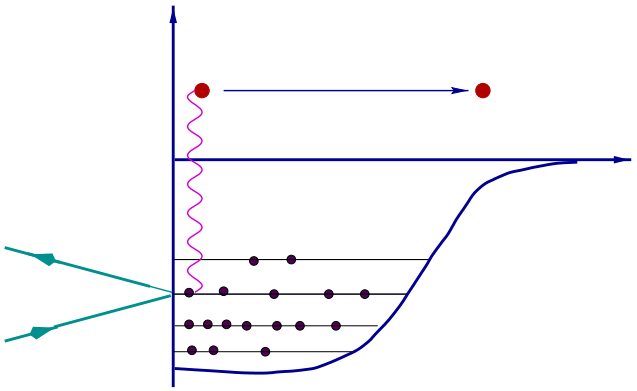
$$\sigma_T^J = \left(-\frac{q_\mu^2}{2|\vec{q}|^2} + \tan^2\left(\frac{\theta}{2}\right)\right) \left[\left| \left\langle J_f \left|\left| \widehat{\mathcal{T}}_J^{mag}(\kappa) \right|\right| J_i \right\rangle \right|^2 + \left| \left\langle J_f \left|\left| \widehat{\mathcal{T}}_J^{el}(\kappa) \right|\right|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

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

The continuum random phase approximation

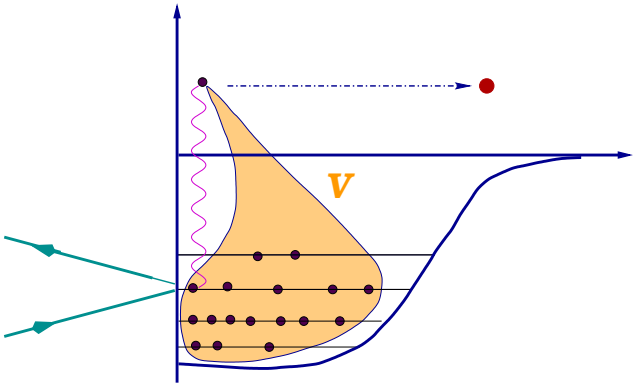
Mean field

- Hartree-Fock
- Woods-Saxon



Mean field + residual interaction

- Skyrme
- Landau-Migdal

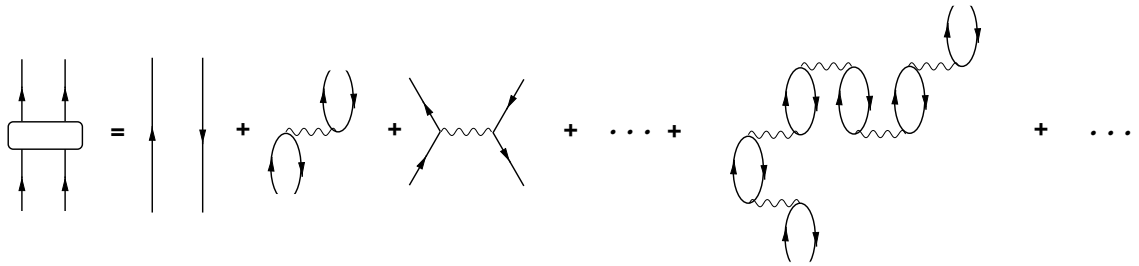


CRPA-excitations :

$$|\Psi_{RPA}\rangle \quad = \quad \sum_{c} \left\{ X_{(\Psi,C)} \left| ph^{-1} \right\rangle \; - \; Y_{(\Psi,C)} \left| hp^{-1} \right\rangle \right\}.$$

CRPA : Green's function approach

Polarization propagator



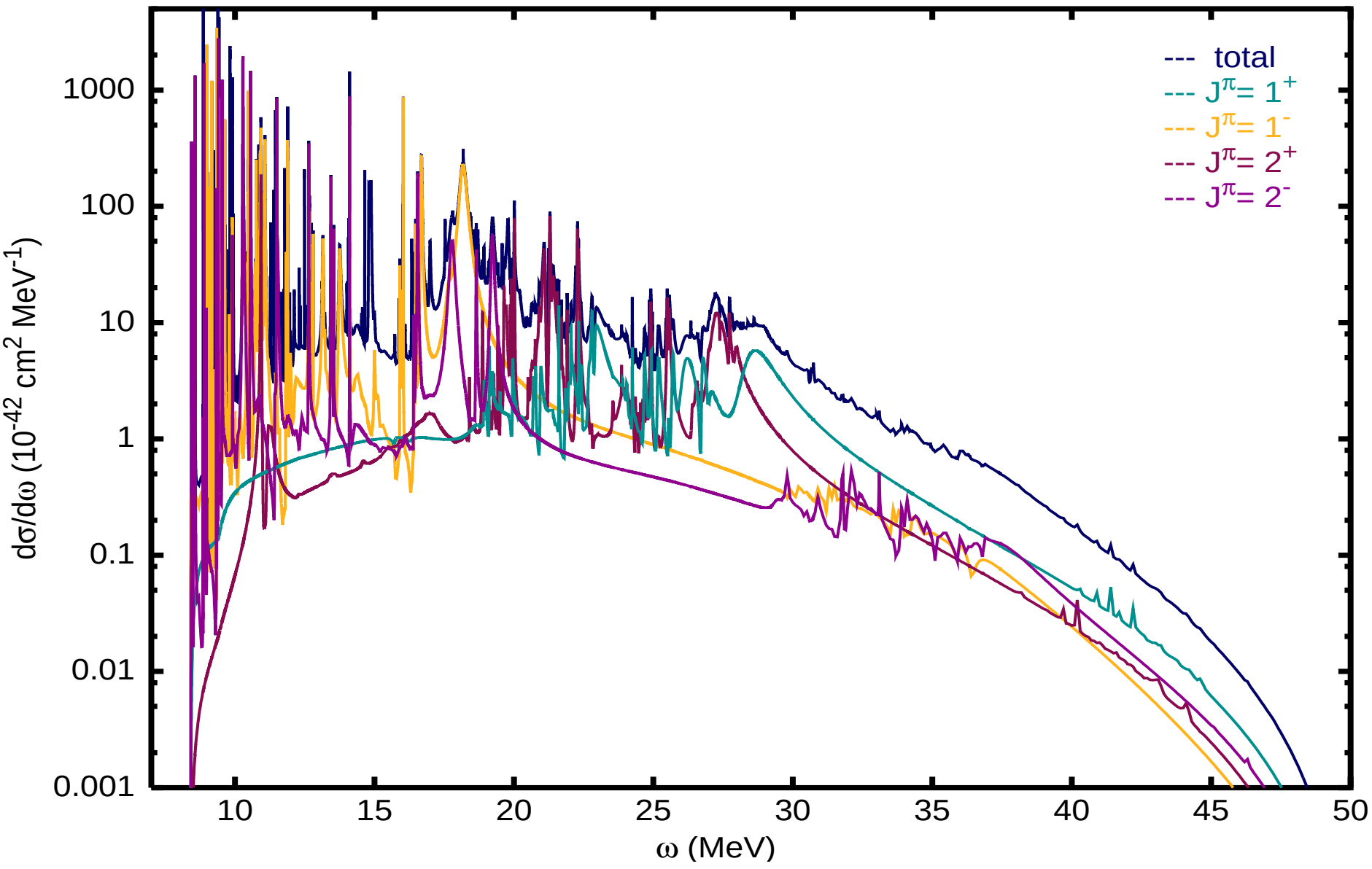
Transition densities

$$\langle \Psi_0 || X_{\eta J} || \Psi_C(J;E) \rangle_r = -\langle h || X_{\eta J} || p(\varepsilon_{ph}) \rangle_r + \sum_{\mu,\nu} \int dr_1 \int dr_2 U^J_{\mu\nu}(r_1,r_2) \mathcal{R} \left(R^{(0)}_{\eta\mu;J}(r,r_1;E) \right) \langle \Psi_0 || X_{\nu J} || \Psi_C(J;E) \rangle_{r_2}$$

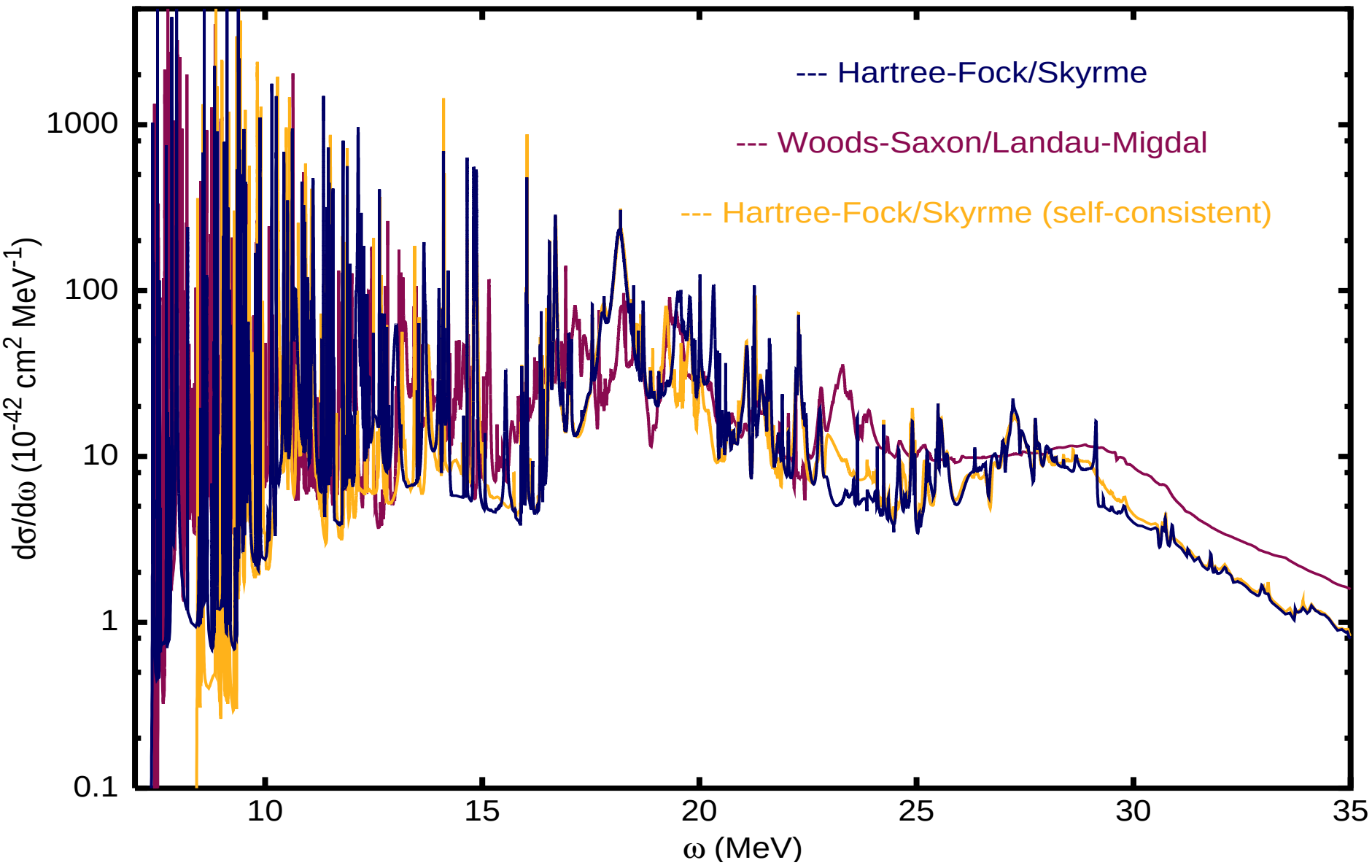
Advantages

- single-particle continuum treated exactly
  - no upper limit to the energy
  - no energy discretization
- self-consistent calculations

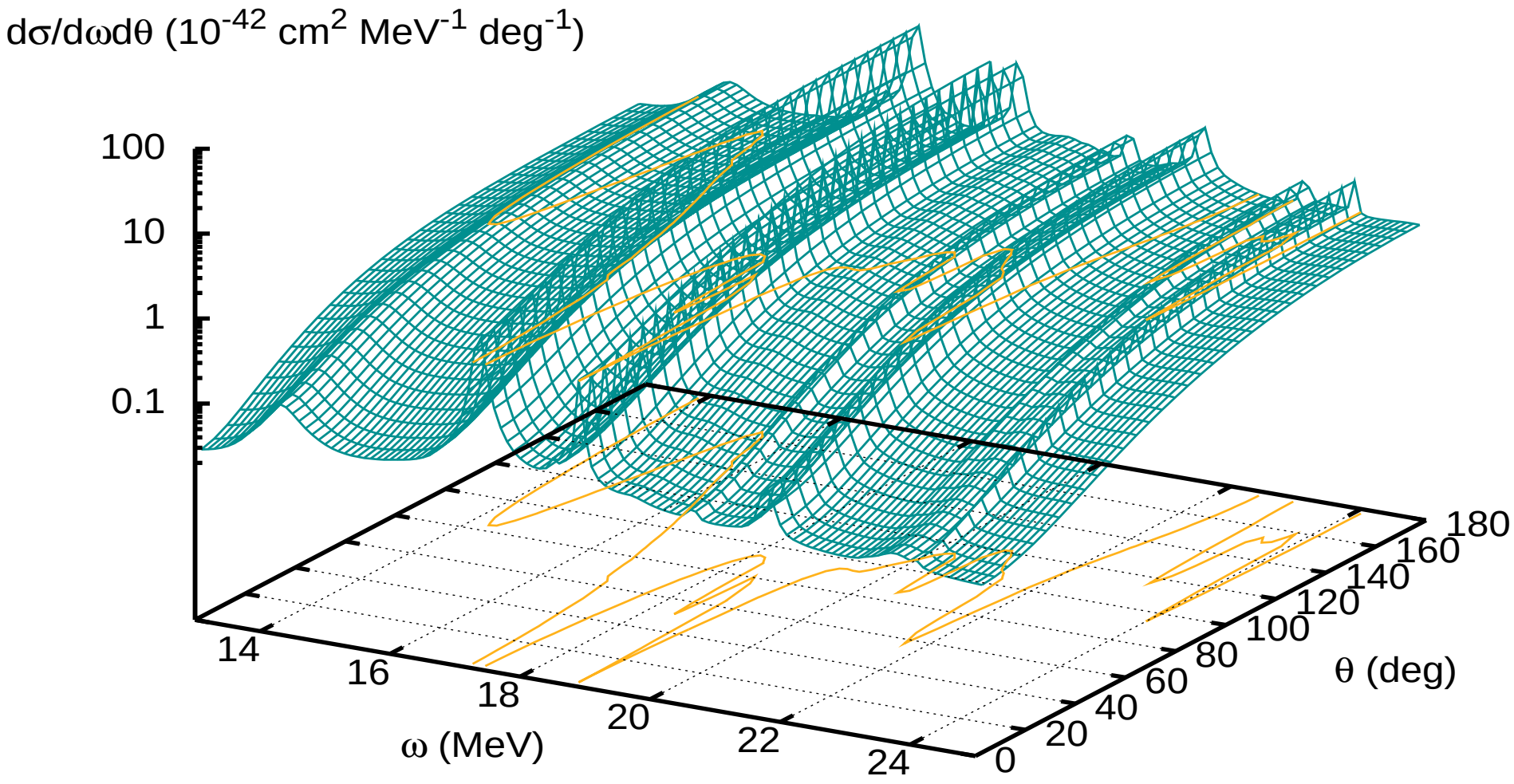
Cross section : Multipole analysis



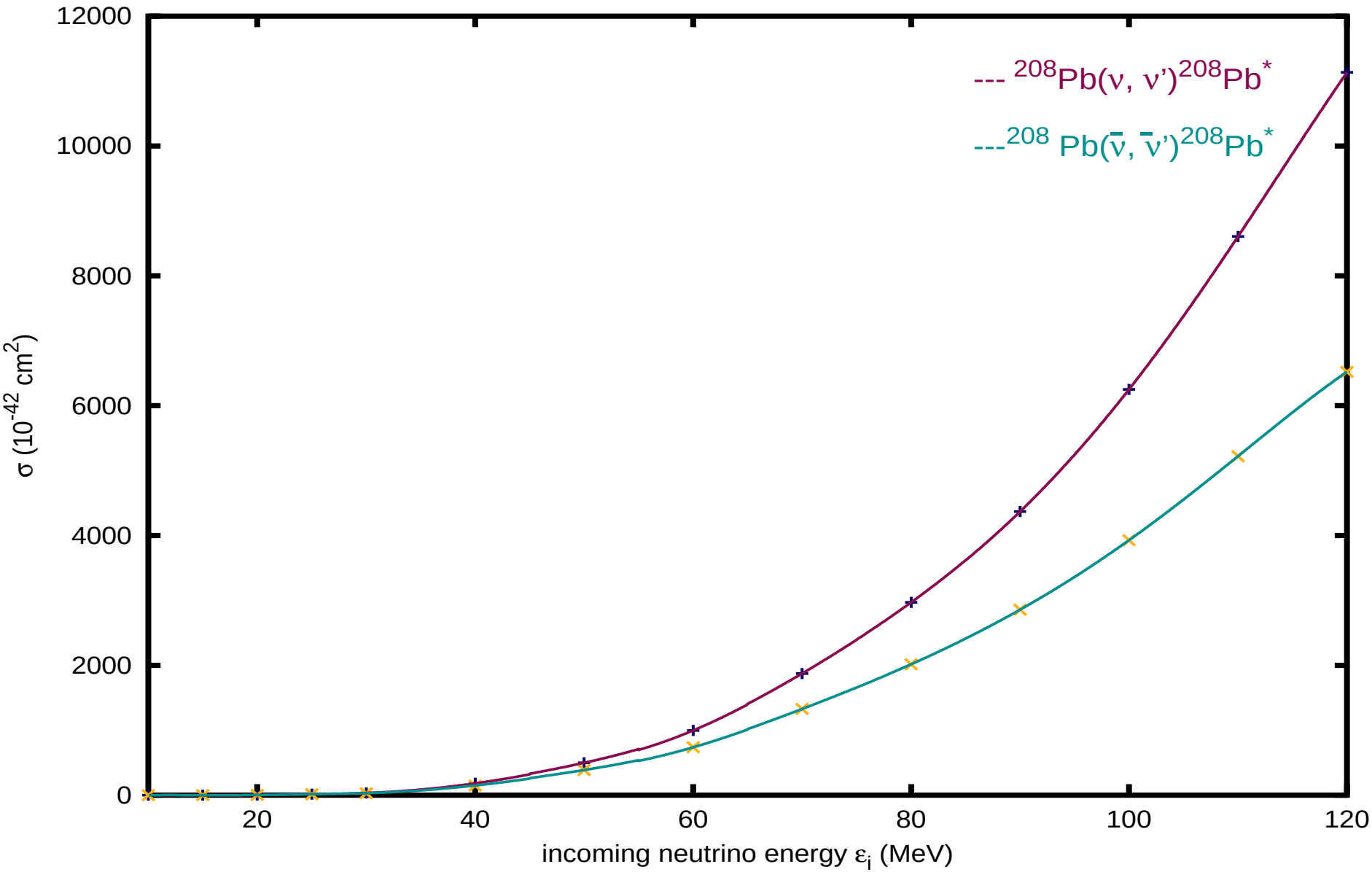
Influence single-particle wave-functions - residual interaction



Angular dependence

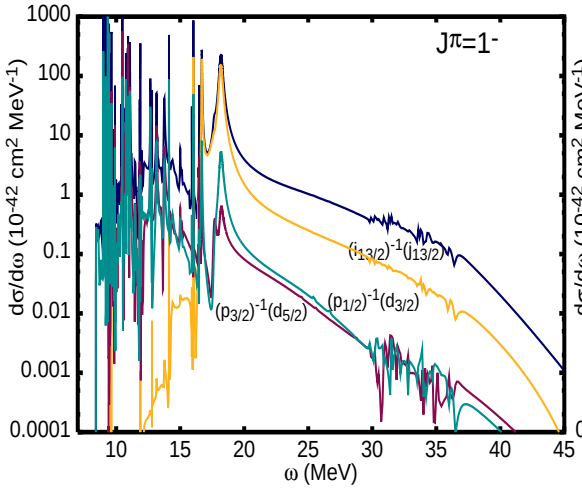


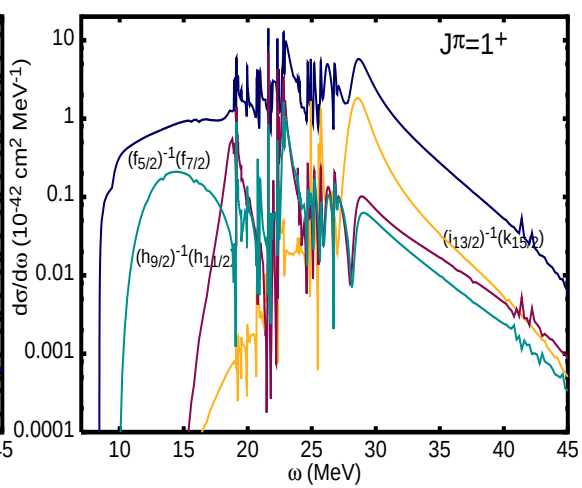
Neutrino - antineutrino cross section

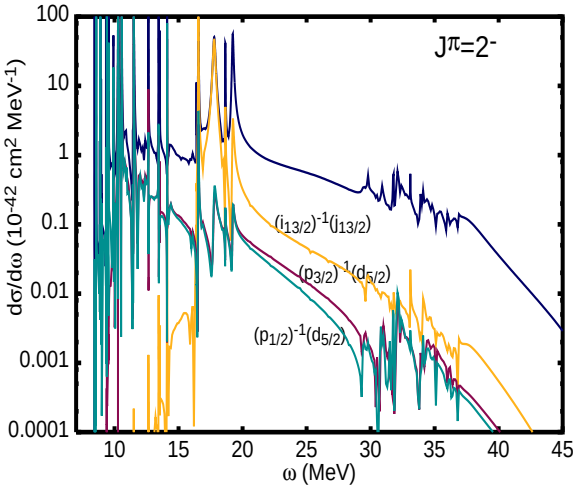


Single-particle channels

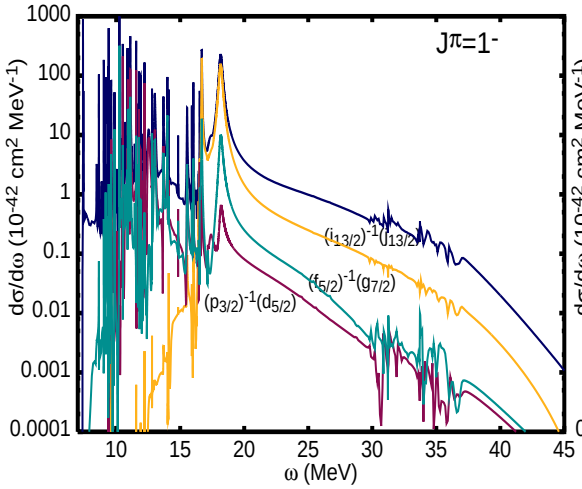
self consistent

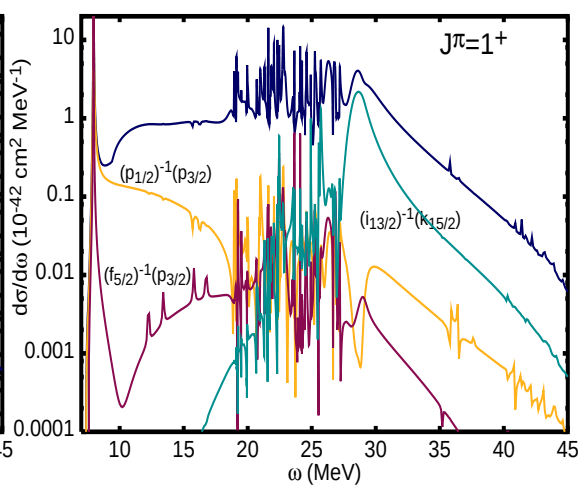


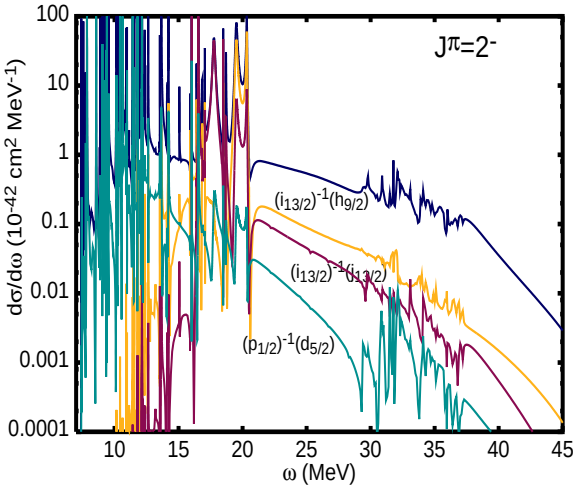




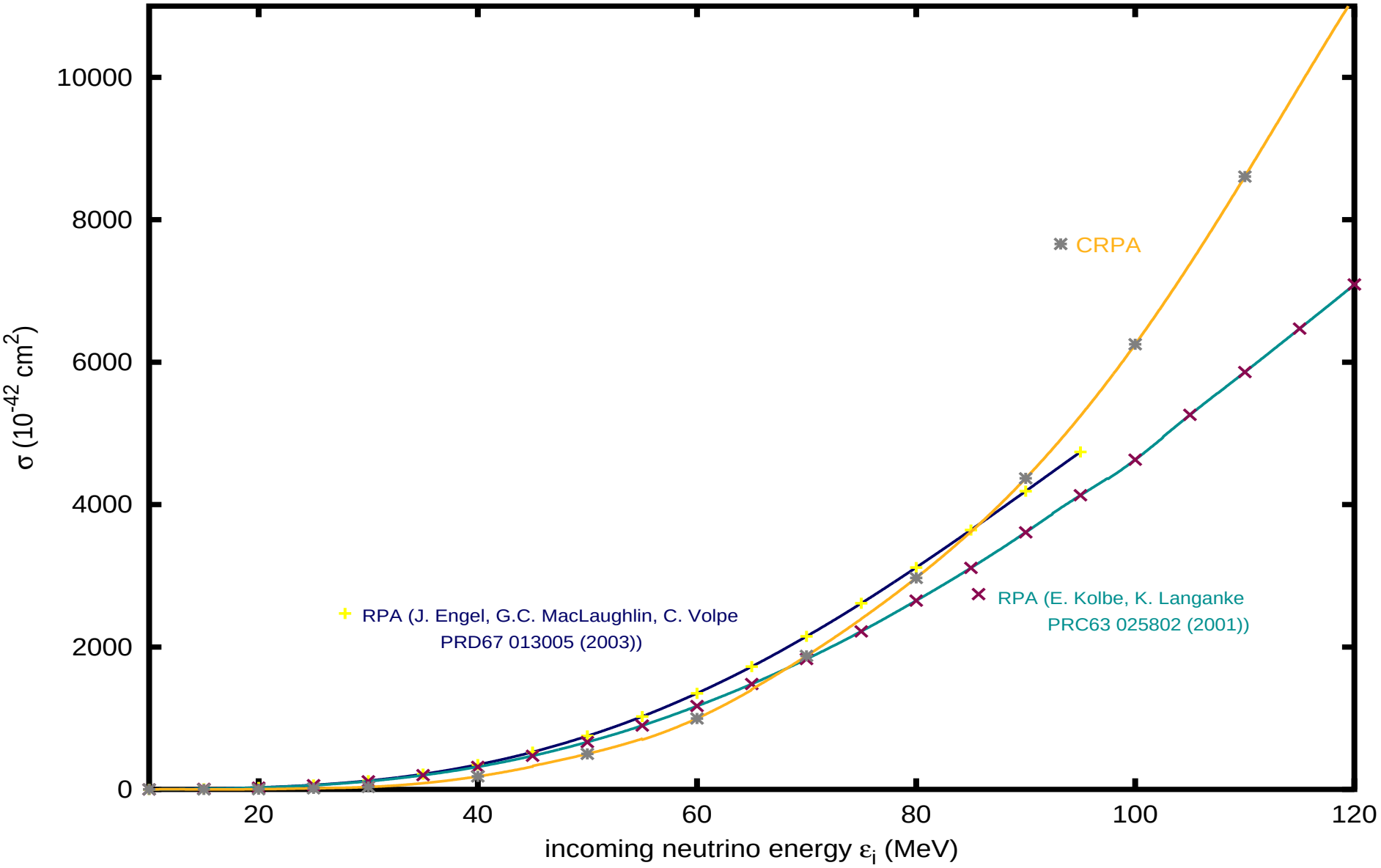
experiment



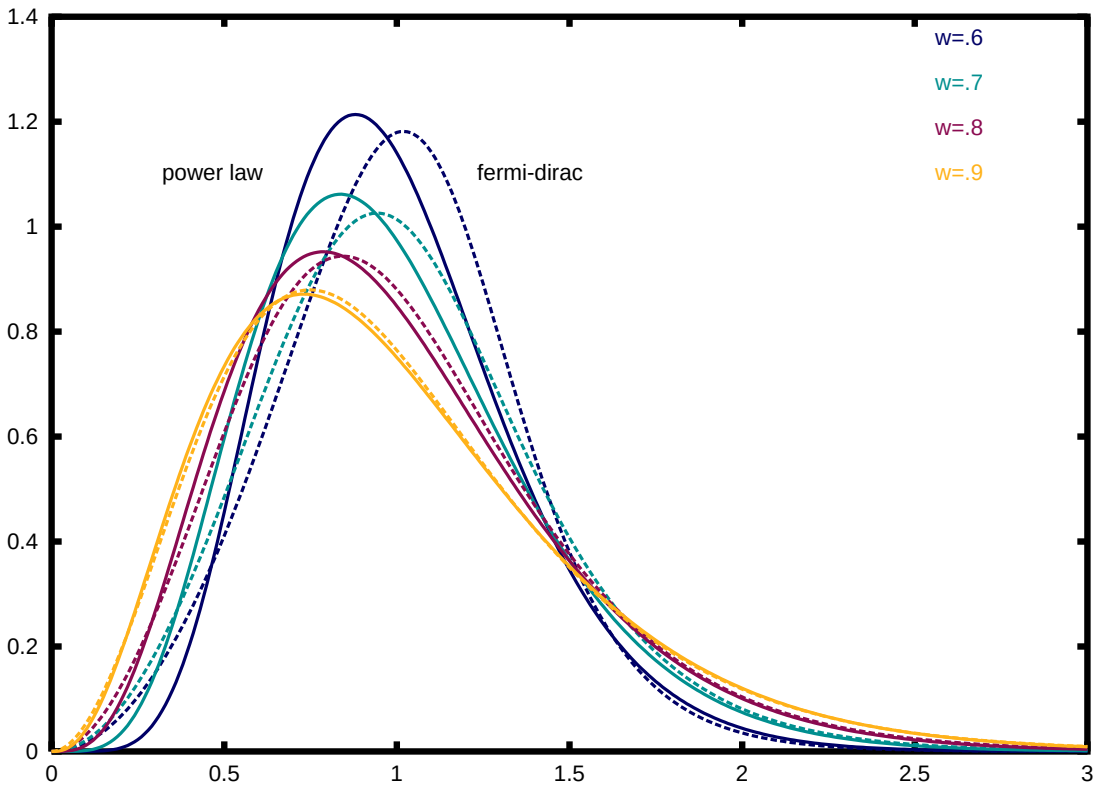




Comparison


10000
8000
6000
4000
2000
0
20
40
60
80
100
120
σ (10^-42 cm^2)
incoming neutrino energy ε_i (MeV)
CRPA
RPA (J. Engel, G.C. MacLaughlin, C. Volpe
PRD67 013005 (2003))
RPA (E. Kolbe, K. Langanke
PRC63 025802 (2001))

Supernova-neutrino energy-distribution



fermi-dirac :

$$n_{FD[T,\eta]}(E) = \frac{N_\eta}{T^3}\frac{E^2}{1+\exp^{(\frac{E}{T}-\eta)}}$$

$T \sim 3-8MeV$

power law :

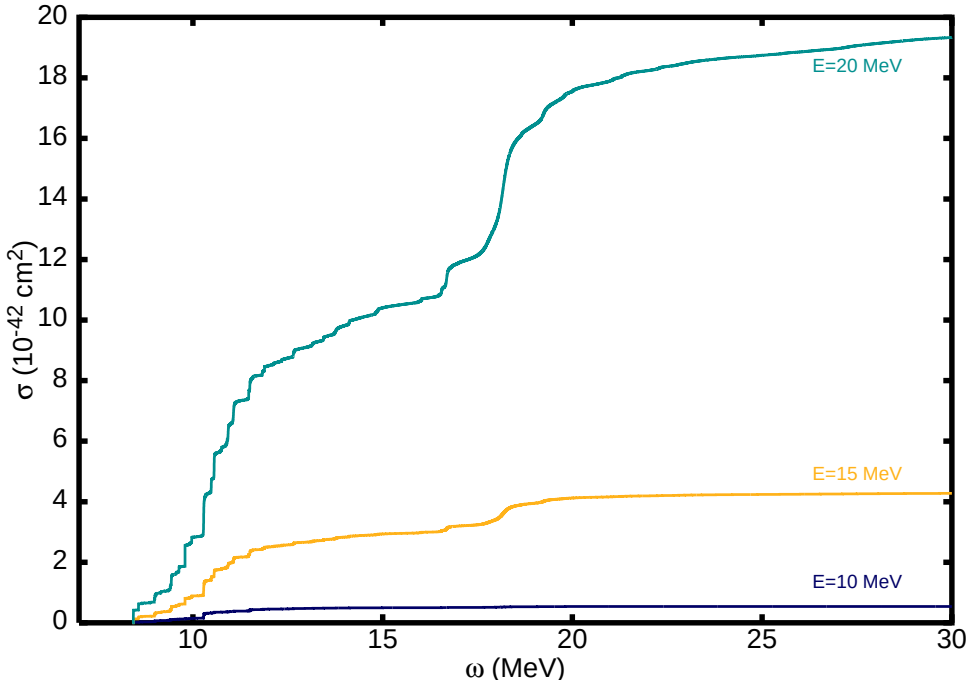
$$n_{PL[<E>,\alpha]}(E) = \left(\frac{E}{<E>}\right)^{\alpha} e^{-(\alpha+1)\frac{E}{<E>}}$$

$<E> \sim 12-20MeV$

Ref : M. Keil, G. Raffelt, H.-T. Janka, astro-ph/0208035

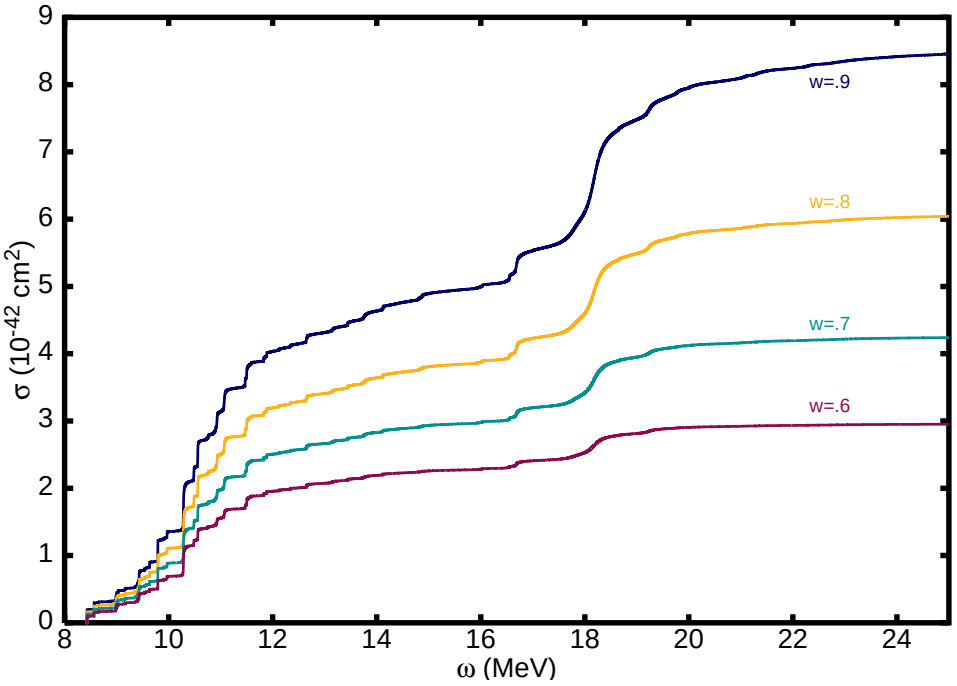
Average energy

	E	σ_{tot}	1n	2n
fermi-dirac	10MeV	0.63	0.56	0.07
power law	10MeV	0.54	0.49	0.05
fermi-dirac	15MeV	4.89	3.17	1.72
power law	15MeV	4.28	2.84	1.44
fermi-dirac	20MeV	22.19	10.99	11.20
power law	20MeV	19.51	9.86	9.65



Spectrum width

	w	σ_{tot}	1n	2n
fermi-dirac	.9	9.06	4.72	4.34
power law	.9	8.80	4.65	4.15
fermi-dirac	.8	6.82	3.92	2.90
power law	.8	6.17	3.65	2.52
fermi-dirac	.7	4.89	3.17	1.72
power law	.7	4.28	2.84	1.44
fermi-dirac	.6	2.82	2.15	0.67
power law	.6	2.96	2.20	0.76



Conclusions

- CRPA Cross-section results $^{208}Pb(\nu,\nu')^{208}Pb^*$
- Deviations from other calculations
- Response very sensitive to energy spectrum
- Measurement ?