Neutrinos in astrophysical systems

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Dedicated to Professor Jan Blomqvist

Some Forewords

- Jan Blomqvist belongs to a generation of physicist who have developed the very first notions about nuclear structure since Denmark and Sweden become, during the 1960’s, the center of theoretical and experimental nuclear physics.
- Most of the ideas coming from the NBI are still around in fields so diverse as QCD and low energy nuclear phenomena.

Neutron and Proton levels in A=208

observed in the nuclei with $A = 207$ and $A = 209$, with energies appreciably below the energy of the first excited state of ^{208}Pb, are the single-particle and the single-hole states. Above this energy, a rather high density of levels is observed, of which only a few are included in the figure. As an example, the multiplet at about 2.6 MeV in ^{209}Bi is classified as an octupole excitation similar to that observed in ^{208}Pb, superposed on the $h_{9/2}$ ground state of ^{209}Bi. (A further discussion of this assignment will be given in Chapter 6.)

The $T = 45/2$ states of ^{209}Bi, which are observed as resonances in elastic and inelastic proton scattering on ^{208}Pb, have total widths of 2–300 keV.

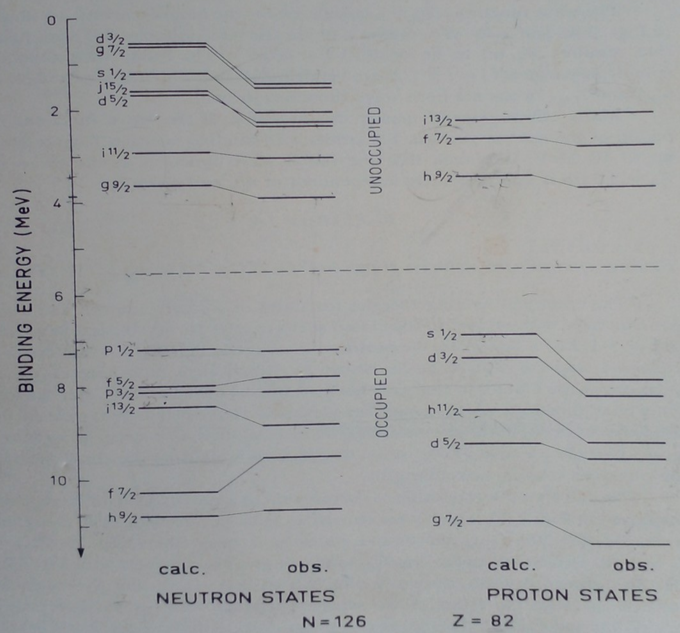


Figure 3-3 The empirical value for the binding energies of single nucleons with respect to ^{208}Pb are taken from the data shown in Fig. 3-2f. The calculated values are taken from J. Blomqvist and S. Wahlborn, *Arkiv Fysik* **16**, 545 (1960).

Radial Wave Functions (A=208)

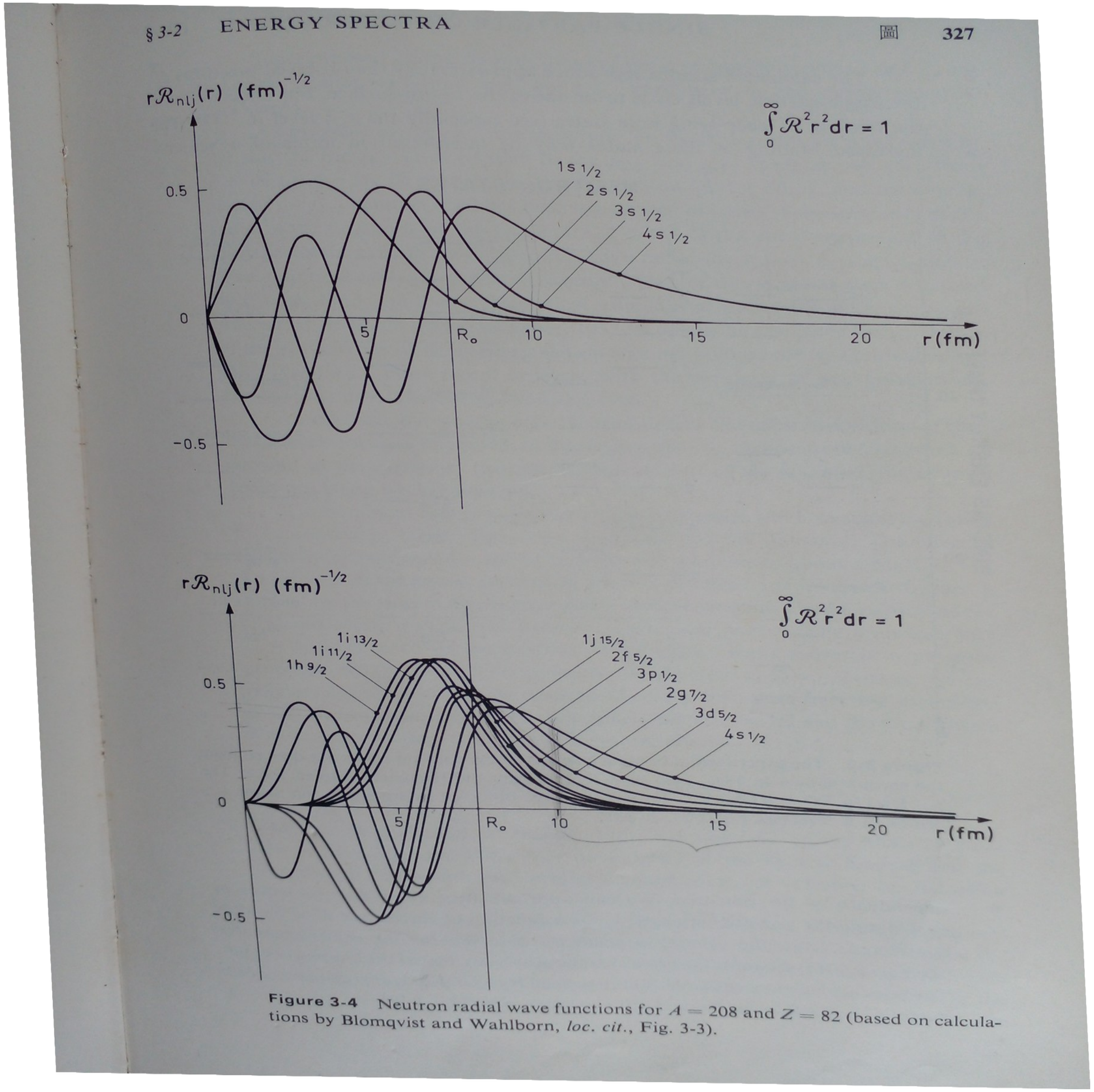

§ 3-2 ENERGY SPECTRA 327

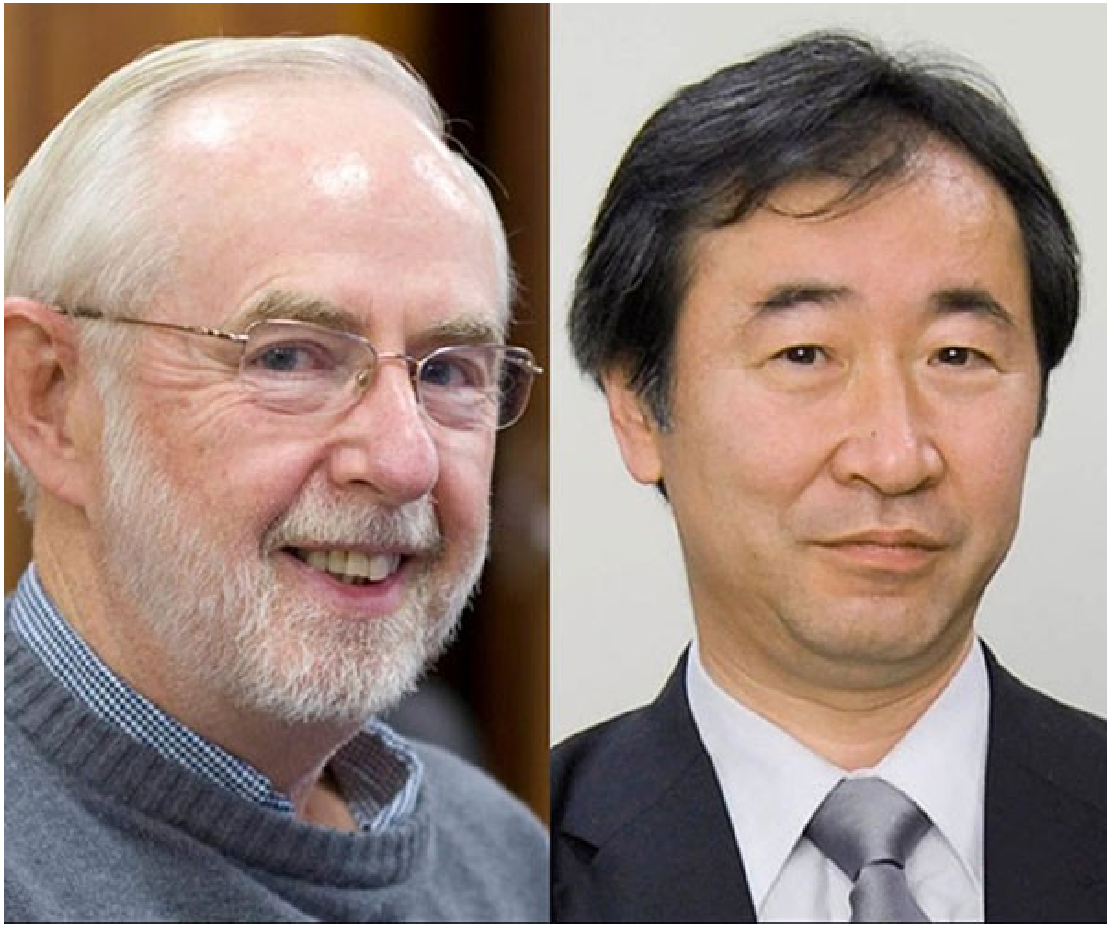
Figure 3-4 Neutron radial wave functions for $A = 208$ and $Z = 82$ (based on calculations by Blomqvist and Wahlborn, *loc. cit.*, Fig. 3-3).

Neutrinos in astrophysics

- Flavors and masses
- Sterile neutrinos
- Interactions between neutrinos
- Neutrinos and dark matter
- Axions, neutrinos and double beta decay.
- Conclusions.

Ettore Majorana

McDonald-Kajita (Nobel 2015)



Basic notions

- 3 flavors (electron, muon, tau)
- 3 mass eigenstates (m1,m2,m3)
- 3 ordering of the masses:

  (normal, inverted, degenerate)
- Maximal breaking of symmetry

  (left handed doublets (charged leptons+antineutrinos)

  (right handed singlets (charged leptons)

Still discussing about neutrinos

Mixing parameters (active neutrinos)

Parameter	Normal hierarchy	Inverse hierarchy
$\sin^2(\theta_{12})$	0.307	0.307
Δm^2_{21}	$7.53 \times 10^{-5}\,\mathrm{eV}^2$	$7.53 \times 10^{-5}\,\mathrm{eV}^2$
$\sin^2(\theta_{23})$	0.545	0.547
Δm^2_{32}	$2.46 \times 10^{-3}\,\mathrm{eV}^2$	$-2.53 \times 10^{-3}\,\mathrm{eV}^2$
$\sin^2(\theta_{13})$	0.0218	0.0218

Supernovae neutrinos

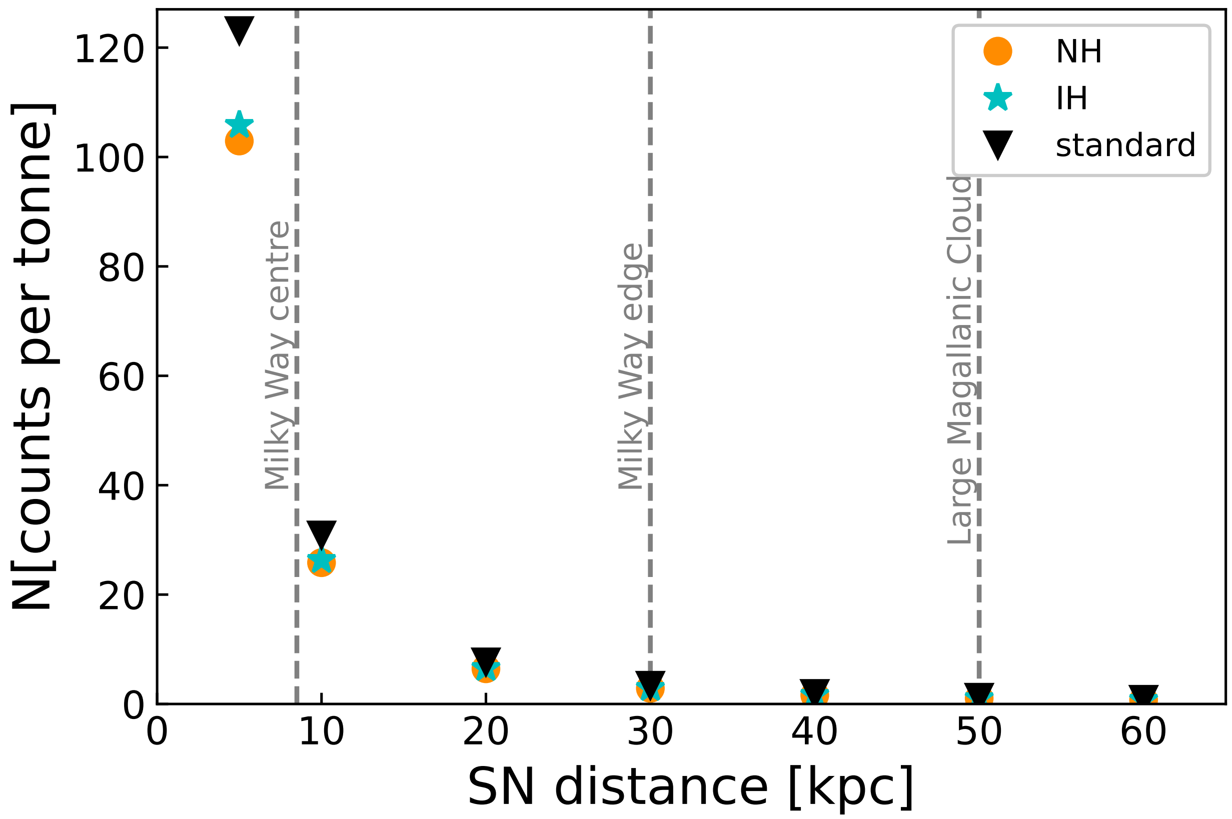
- Core collapse supernovae (stars with masses larger than 8 solar masses)
- 99% of the energy is transported by neutrinos (energies of the order of several MeV)
- Some reactions involving neutrinos

electron+positron→ neutrino+antineutrino

bremsstrahlung

(n+n->n+n+neutrino+antineutrino

Supernovae neutrinos



SN1987A

- E=3x10**53 erg
- Luminosity and spectral flux for each neutrino flavor
- Energy distribution (Fermi, power law) for each neutrino flavor
- Mikheyev-Smirnov-Wolfenstein resonances in flavor convertion at high and low densities.

Luminosity

$$L_{\nu_\beta}(t) = \frac{E_\nu^{tot}}{18} e^{-t/3} \quad .$$

Flux (SN)

$$F^0_{\nu_\beta}(E,\,t) = \frac{L_{\nu_\beta}(t)}{4\pi D^2}\,\frac{f_{\nu_\beta}(E,\eta)}{\langle E_{\nu_\beta}\rangle}$$

(Fermi-Dirac)

$$f_{\nu_\beta}(E,\, \eta_{\nu_\beta}) = \frac{1}{1 + exp[E/T_{\nu_\beta} - \eta_{\nu_\beta}]}$$

Power law

$$f_{\nu_\beta}(E) = \frac{(\alpha+1)^{(\alpha+1)}}{\Gamma(\alpha+1)\,\langle E\rangle}\left(\frac{E}{\langle E\rangle}\right)^{\alpha} e^{-(\alpha+1)E/\langle E\rangle}$$

Flux for each flavor(3 species)

$$F_{\nu_e} = P_e F^0_{\nu_e} + (1 - P_e) F^0_{\nu_x} \quad ,$$
$$F_{\bar{\nu}_e} = \bar{P}_e F^0_{\bar{\nu}_e} + (1 - \bar{P}_e) F^0_{\bar{\nu}_x} \quad ,$$
$$F_{\nu_x} = (1 - P_e) F^0_{\nu_e} + (1 + P_e) F^0_{\nu_x}$$
$$F_{\bar{\nu}_x} = (1 - \bar{P}_e) F^0_{\bar{\nu}_e} + (1 + \bar{P}_e) F^0_{\bar{\nu}_x}$$

Fluxes (3+1)

$$
\begin{aligned}
F_{\nu_e} &= \Theta_e^e F_{\nu_e}^0 + \Theta_e^x F_{\nu_x}^0 + \Theta_e^s F_{\nu_s}^0 \quad , \\
F_{\bar{\nu}_e} &= \Xi_e^e F_{\bar{\nu}_e}^0 + \Xi_e^x F_{\bar{\nu}_x}^0 + \Xi_e^s F_{\bar{\nu}_s}^0 \quad , \\
F_{\nu_x} &= \left(\Theta_\mu^e + \Theta_\tau^e\right) F_{\nu_e}^0 + \left(\Theta_\mu^x + \Theta_\tau^x\right) F_{\nu_x}^0 \\
&\quad + \left(\Theta_\mu^s + \Theta_\tau^s\right) F_{\nu_s}^0 \quad , \\
F_{\bar{\nu}_x} &= \left(\Xi_\mu^e + \Xi_\tau^e\right) F_{\bar{\nu}_e}^0 + \left(\Xi_\mu^s + \Xi_\tau^s\right) F_{\bar{\nu}_x}^0 \\
&\quad + \left(\Xi_\mu^s + \Xi_\tau^s\right) F_{\bar{\nu}_s}^0 \quad , \\
F_{\nu_s} &= \Theta_s^e F_{\nu_e}^0 + \Theta_s^x F_{\nu_x}^0 + \Theta_s^s F_{\nu_s}^0 \quad , \\
F_{\bar{\nu}_s} &= \Xi_s^e F_{\bar{\nu}_e}^0 + \Xi_s^x F_{\bar{\nu}_x}^0 + \Xi_s^s F_{\bar{\nu}_s}^0 \quad ,
\end{aligned}
$$

The mixing factors (3+1,normal)

$$
\begin{aligned}
\Theta_\alpha^e &= |U_{\alpha 1}|^2 P_H P_L (1 - P_S) + |U_{\alpha 3}|^2 P_S \\
&\quad + |U_{\alpha 2}|^2 P_H (1 - P_L)(1 - P_S) \\
&\quad + |U_{\alpha 4}|^2 (1 - P_S)(1 - P_H) \ , \\
\Theta_\alpha^x &= |U_{\alpha 1}|^2 (1 - P_H P_L) + |U_{\alpha 2}|^2 (1 - P_H + P_H P_L) \\
&\quad + |U_{\alpha 4}|^2 P_H , \\
\Theta_\alpha^s &= |U_{\alpha 1}|^2 P_S P_H P_L + |U_{\alpha 2}|^2 P_S P_H (1 - P_L) \ , \\
&\quad + |U_{\alpha 3}|^2 (1 - P_S) + |U_{\alpha 4}|^2 P_S (1 - P_H) \ , \\
\Xi_\alpha^e &= |U_{\alpha 1}|^2 \ , \\
\Xi_\alpha^x &= |U_{\alpha 2}|^2 + |U_{\alpha 3}|^2 \ , \\
\Xi_\alpha^s &= |U_{\alpha 4}|^2 \ .
\end{aligned}
$$

Mixing factors (3+1 inverse)

$$
\begin{aligned}
\Theta_\alpha^e &= |U_{\alpha 1}|^2 P_L (1 - P_S) + |U_{\alpha 2}|^2 P_S \\
&\quad + |U_{\alpha 4}|^2 (1 - P_S)(1 - P_L) \ , \\
\Theta_\alpha^x &= |U_{\alpha 1}|^2 (1 - P_L) + |U_{\alpha 3}|^2 + |U_{\alpha 4}|^2 P_L \ , \\
\Theta_\alpha^s &= |U_{\alpha 1}|^2 P_S P_L + |U_{\alpha 2}|^2 (1 - P_S) \\
&\quad + |U_{\alpha 4}|^2 P_S (1 - P_L) \ , \\
\Xi_\alpha^e &= |U_{\alpha 2}|^2 \bar{P}_H + |U_{\alpha 3}|^2 (1 - \bar{P}_H) \ , \\
\Xi_\alpha^x &= |U_{\alpha 1}|^2 + |U_{\alpha 2}|^2 (1 - \bar{P}_H) + |U_{\alpha 3}|^2 \bar{P}_H \ , \\
\Xi_\alpha^s &= |U_{\alpha 4}|^2 \ .
\end{aligned}
$$

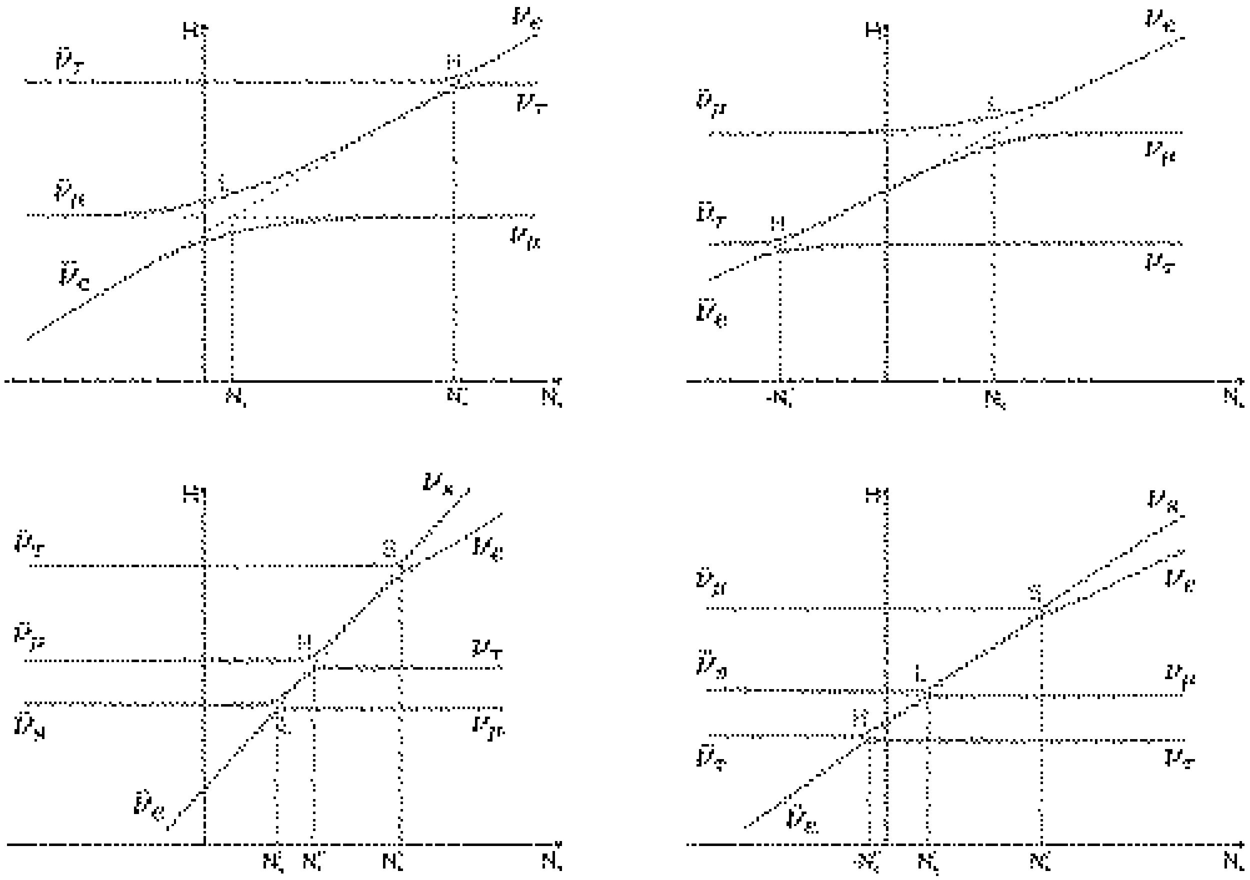
Resonances MSW

normal

inverse

active

steriles



antineutrinos

neutrinos

Some comments about MSW

- The avoided crossing points are strongly dependent on both the hierarchy and the inclusion of sterile neutrinos.
- Neutrino resonances are more sensitive to sterile neutrinos than the resonances for antineutrinos
- The inverse hierarchy is more sensible to the inclusion of sterile neutrinos.

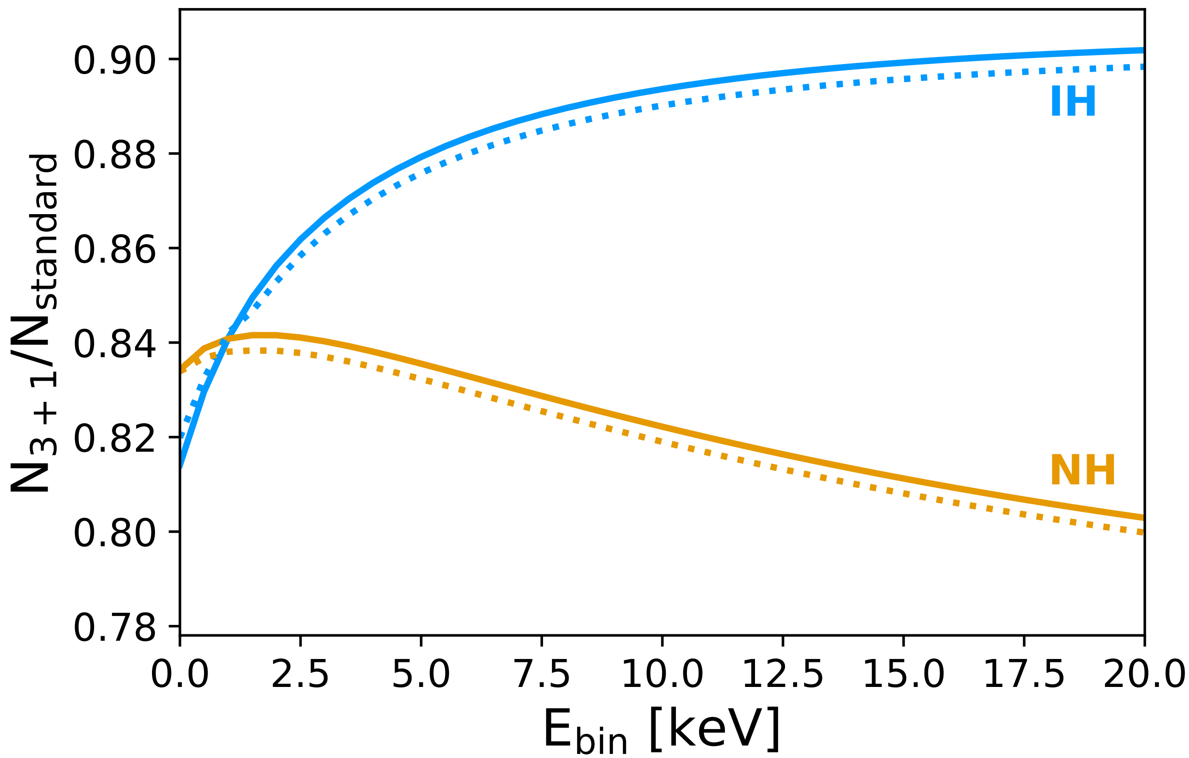
Counts at the mean value of E

Distribution function	no/osc.	NH	IH
PL	760	803	901
FD0	786	830	930
FD1	920	930	952
FD2	856	886	952

Best fit (theta14)

Hierarchy	$F^0_{\nu_s}$	$\langle E_{\nu_s} \rangle$	$\theta_{14} \pm \sigma$	$\frac{\Delta\chi^2}{N-1}$
NH	0	–	0.044 ± 0.021	1.32
	$\neq 0$	10 MeV	0.032 ± 0.016	1.32
		12 MeV	0.033 ± 0.015	1.32
		17 MeV	0.044 ± 0.025	1.30
IH	0	–	0.016 ± 0.009	1.32
	$\neq 0$	10 MeV	0.016 ± 0.009	1.37
		12 MeV	0.016 ± 0.009	1.32
		17 MeV	0.016 ± 0.010	1.37

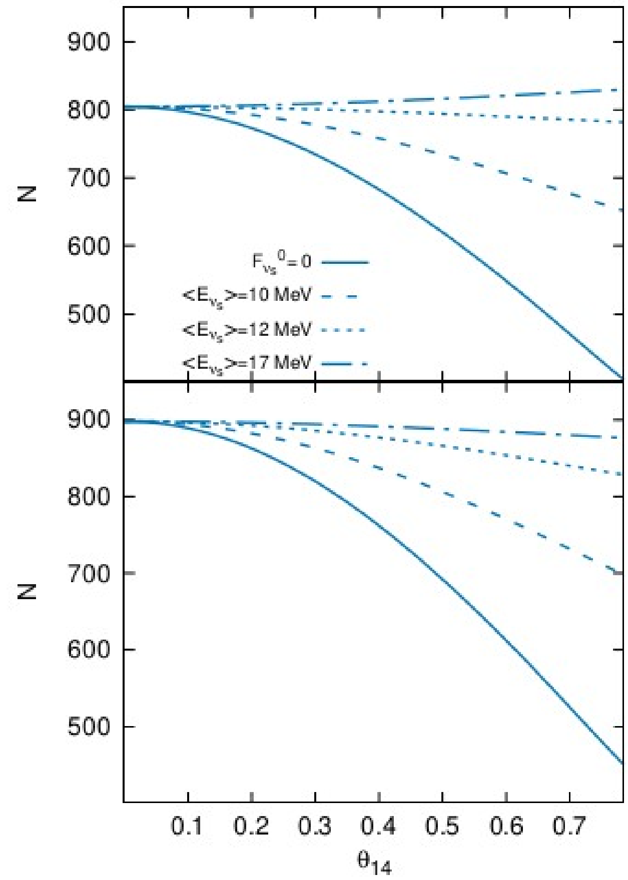
Number of events



(solid line)(ideal efficiency

(dashed line) Efficiency for Xenon1T

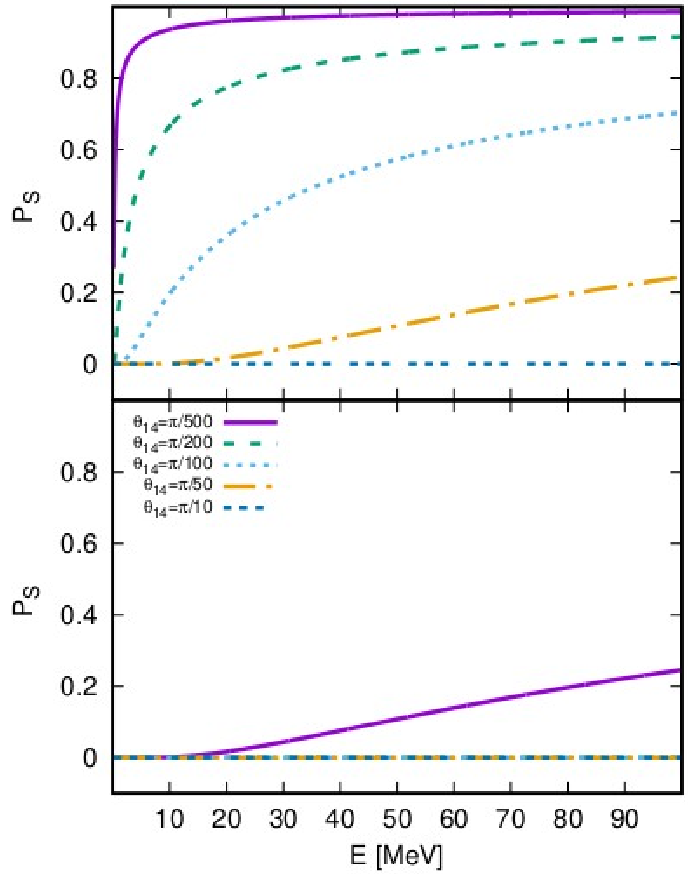
Number of events (+ sterile)



normal

invertida

S resonance (as function of θ14)



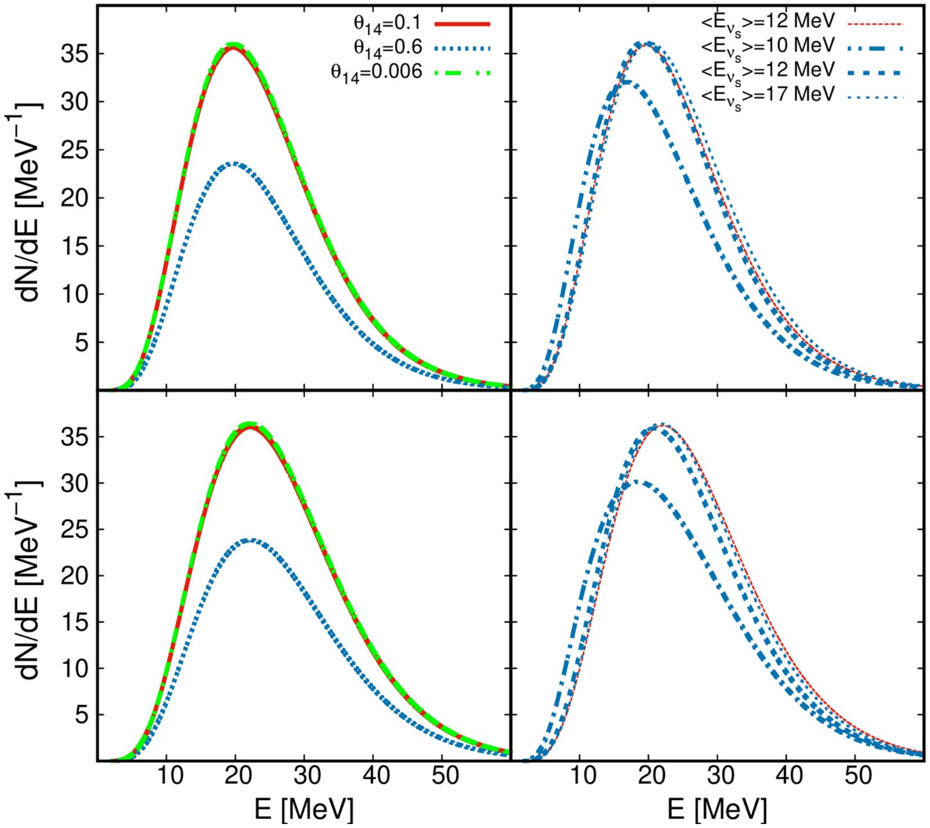
m14**2=10**(-3)eV**2

m14**2=1ev**2

Number of events

Without sterile neutrinos in the SN

With sterile neutrinos in the SN

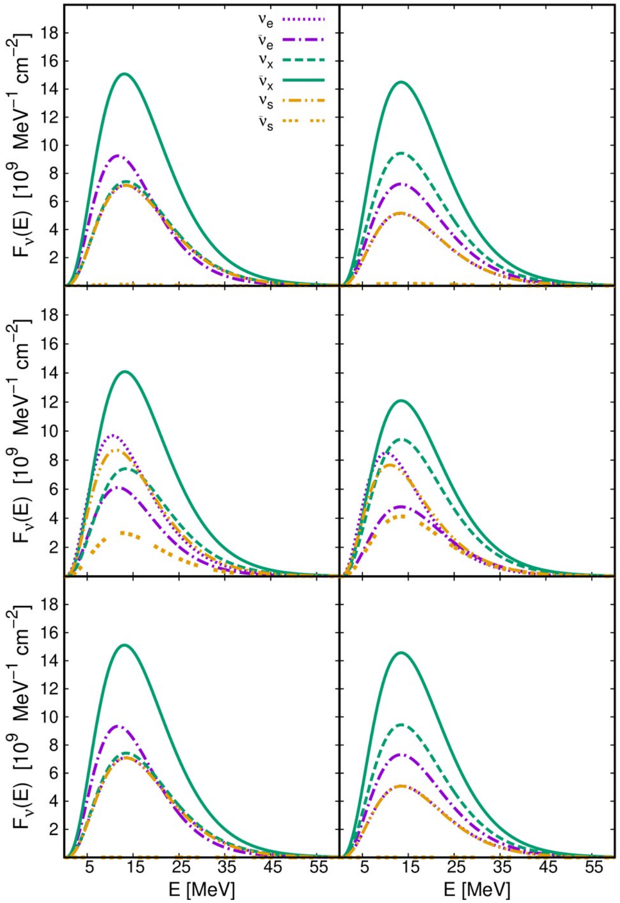


inverse

Events at the detector

normal inverse

No esteriles in SN



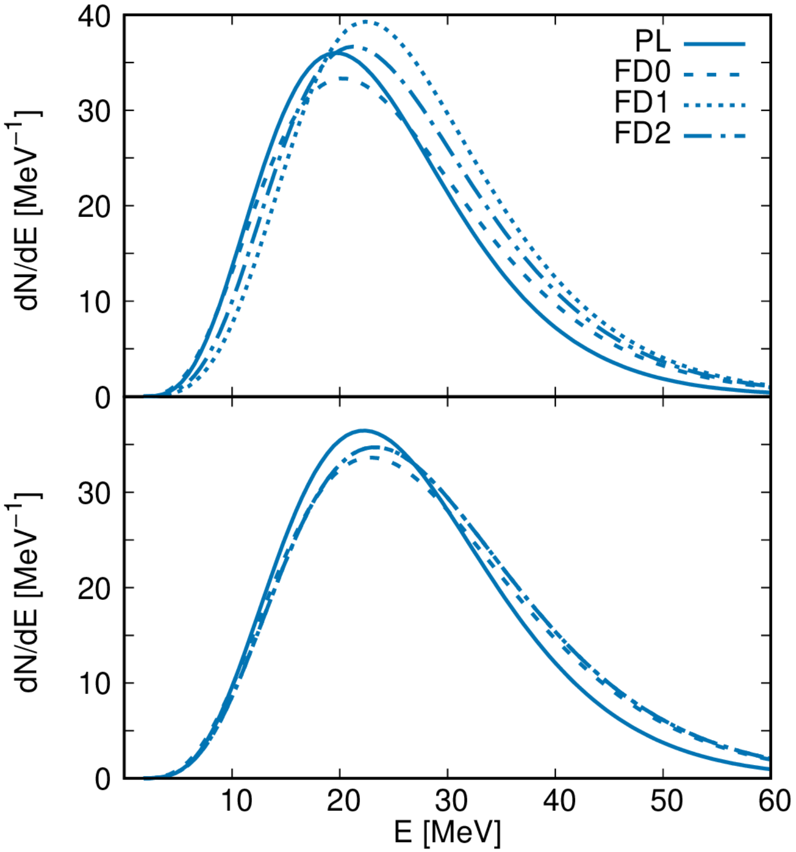
Theta14=0.1

Theta14=0.6

Theta14=0.006

Energy distributions

Active neutrinos only



normal

inverse

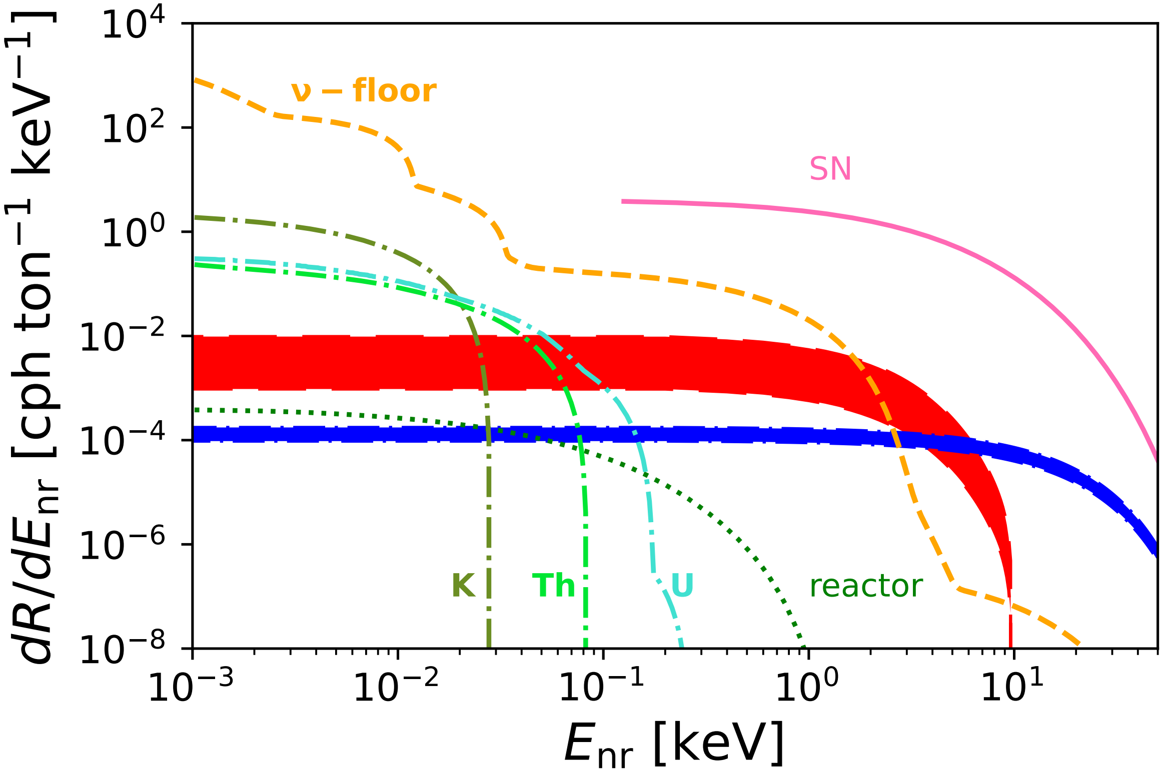
Some comments (up to now)

- Detectors like Gallex,Sage,SuperKamiokande,MiniBooNE, Kamland,Borexino,LSND may show evidences about new neutrino species
- Neutrino fluxes from SuperNovae are sensitive to sterile neutrino species.
- For values of (Δm14**2) of the order of 1 eV**2 the probabilities ceased to be adiabatic..

Propagation of neutrinos in DM

- Present evidences about DM : (acceleration of the expansion of the Universe, no-newtonian behavior of the rotational curves of galaxies) are consistent with 5% of visible matter, 25% of dark matter and 70% of dark energy.
- DM candidates: fermionic (neutral y and cold) wimps...
- The study of the interactions with neutrinos may be a source of information about DM.

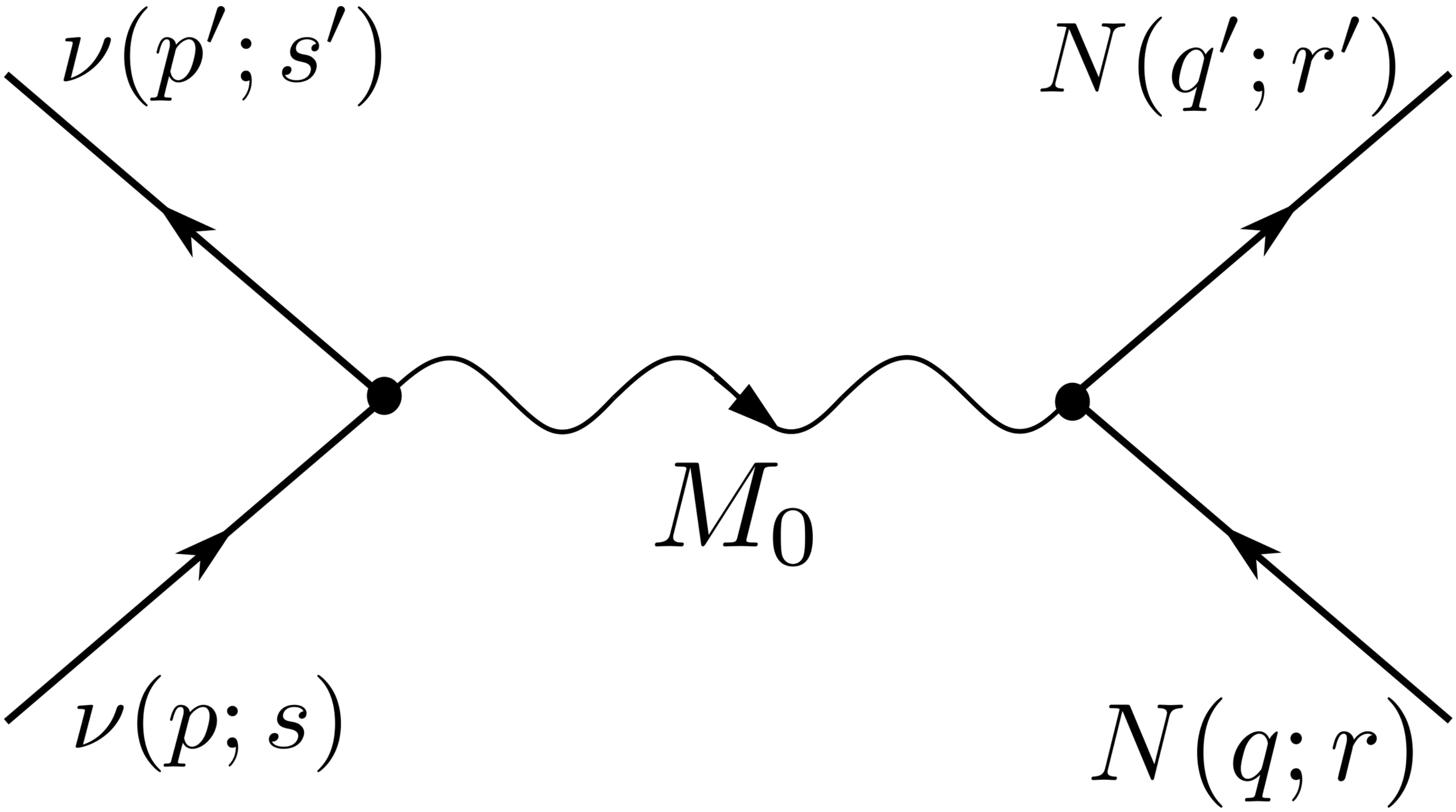
Neutrino sources



Some typical values

- DM mass (200 GeV)
- Intermediate bosons (1TeV)
- Neutrino sources (SuperNovae,GRBs)
- Neutrino energies (up to 150 MeV)
- Detectors: like Xenon1Ton

Basic diagram



Propagator

$$\frac{-g^{\mu\nu} + k^{\mu} k^{\nu} / M_0^2}{k^2 - M_0^2},$$

Lagrangian

$$\mathcal{L} = \mathcal{L}_n + \mathcal{L}_{DM} + \mathcal{L}_{int}$$

Neutrinos (Dirac)

$$\mathcal{L}_{n,Dirac} = \bar{\nu}(i\gamma^{\mu}\partial_{\mu} - m)\nu$$

Neutrinos(Majorana)

$$\mathcal{L}_{n,Majorana} = \frac{1}{2}\left[\bar{\nu}^c(i\gamma^\mu\partial_\mu)\nu^c + \bar{\nu}(i\gamma^\mu\partial_\mu)\nu - (\bar{\nu}m\nu^c + \bar{\nu}^c m\nu)\right]$$

DM velocity distributions

Distribution	$f(\mathbf{v})$
SHM	$f(\mathbf{v}) = \begin{cases} \frac{1}{N}\left(\frac{3}{2\pi\sigma_v^2}\right)^{3/2} \exp\left(-\frac{3\mathbf{v}^2}{2\sigma_v^2}\right) & \text{if } \lvert\mathbf{v}\rvert < v_{esc} \\ 0 & \text{if } \lvert\mathbf{v}\rvert > v_{esc} \end{cases}$
Smooth SHM	$f(\mathbf{v}) = \begin{cases} \frac{1}{N}\left(\frac{3}{2\pi\sigma_v^2}\right)^{3/2} \left(\exp\left(-\frac{3\mathbf{v}^2}{2\sigma_v^2}\right) - \exp\left(-\frac{3v_{esc}^2}{2\sigma_v^2}\right)\right) & \text{if } \lvert\mathbf{v}\rvert < v_{esc} \\ 0 & \text{if } \lvert\mathbf{v}\rvert > v_{esc} \end{cases}$
Tsallis	$f(\mathbf{v}) = \frac{1}{N}\left[1 - (1-q_0)\frac{\mathbf{v}^2}{v_0^2}\right]^{q_0/(1-q_0)}$

S matrix

$$\hat{S} = e^{-iHt} = I - i\int d^4x\, \hat{\mathcal{H}}_{int}(x) - \int\int d^4x\, d^4x' \hat{\mathcal{H}}_{int}(x)\hat{\mathcal{H}}_{int}(x') - \ldots$$

Amplitudes

$$\mathcal{A}^{(1)}_{i\to f} = \langle i|\mathrm{T}\left\{(-i)\int d^4x\hat{\mathcal{H}}_{int}(x)\right\}|f\rangle.$$

Amplitudes

$$
\begin{aligned}
\mathcal{A}^{(1)}_{i\to f} &= -ig \int d^4x \,\langle f|(\bar{\nu}\gamma^{\mu}\nu)\left(\frac{g_{\mu\nu}}{M_0^2}\right)(\bar{N}\gamma^{\nu}N)|i\rangle \\
&= \frac{-ig}{M_0^2}\int d^4x \frac{1}{\sqrt{V}}\, e^{iq'^{\nu}x_{\nu}}\,\bar{u}(p',s')\; e^{ip'^{\nu}x_{\nu}}\gamma^{\mu}\frac{1}{\sqrt{V}}\; e^{-iq^{\nu}x_{\nu}}\; u(p,s)\; e^{-ip^{\nu}x_{\nu}} \\
&\quad \frac{1}{\sqrt{V}}\mathcal{N}'\;\bar{U}(q',r')\,\gamma_{\mu}\,\frac{1}{\sqrt{V}}\mathcal{N}\; U(q,r) \\
&= -\frac{ig_{eff}\mathcal{N}\mathcal{N}'}{V^2}\int d^4x\, e^{-i(p+q-p'-q')^{\nu}x_{\nu}} \times \\
&\quad \bar{u}(p',s')\gamma^{\mu}u(p,s)\bar{U}(q',r')\gamma_{\mu}U(q,r)
\end{aligned}
$$

Matrix element ν-DM

$$
\begin{aligned}
|\mathcal{M}|^2 &= [\bar{u}(p',s')\gamma^\nu u(p,s)\bar{U}(q',r')\gamma_\nu U(q,r)]^\dagger [\bar{u}(p',s')\gamma^\mu u(p,s)\bar{U}(q',r')\gamma_\mu U(q,r)] \\
&= \bar{u}(p',s')\gamma^\nu u(p,s)[\bar{u}(p',s')\gamma^\mu u(p,s)]^\dagger \bar{U}(q',r')\gamma_\mu U(q,r)[\bar{U}(q',r')\gamma_\nu U(q,r)]^\dagger \\
&= \bar{u}(p',s')\gamma^\nu u(p,s)\bar{u}(p,s)\gamma^\mu \bar{u}(p',s')\bar{U}(q',r')\gamma_\mu U(q,r)\bar{U}(q,r)\gamma_\nu U(q',r').
\end{aligned}
$$

Separability of the matrix v-DM

$$\sum_{spins} |\mathcal{M}|^2 = \mathrm{Tr}[(\not{p}' + m)\gamma^\nu(\not{p} + m)\gamma^\mu]\,\mathrm{Tr}[(\not{q}' + M)\gamma_\mu(\not{q} + M)\gamma_\nu]$$

$$= \mathrm{Tr}[p'_\alpha\gamma^\alpha\gamma^\nu p_\beta\gamma^\beta\gamma^\mu + m^2\gamma^\nu\gamma^\mu]\,\mathrm{Tr}[q'^\alpha\gamma_\alpha\gamma_\mu q^\beta\gamma_\beta\gamma^\nu + M^2\gamma_\mu\gamma_\nu]$$

Interaction ν.-DM

$$\frac{1}{4}\sum_{spins}|\mathcal{M}|^2 = 8\left[(p'\cdot q')(p\cdot q) + (p'\cdot q)(p\cdot q') - m^2(q\cdot q') - M^2(p'\cdot p) + 2m^2M^2\right]$$

Cross section

$$d\sigma = \frac{1}{|\vec{v}|}\frac{1}{2E_p}\frac{1}{2E_q}\frac{d^3p'}{2E_{p'}(2\pi)^3}\frac{d^3q'}{2E_{q'}(2\pi)^3}\left|\mathcal{A}^{(1)}_{i\to f}\right|^2$$

Cross section

$$
\begin{aligned}
d\sigma = {} & \frac{g_{eff}^2}{8\pi^2}\frac{1}{p}\frac{1}{M}\frac{d^3q'}{E_{q'}}\frac{d^3p'}{p'}\delta^{(4)}\left(p'+q'-p-q\right) \\
& \times\left[(p'\cdot q')(p\cdot q)+(p'\cdot q)(p\cdot q')-M^2(p'\cdot p)\right] \\
= {} & \frac{g_{eff}^2}{8\pi^2}\frac{1}{p}\frac{1}{M}\frac{d^3q'}{E_{q'}}\frac{d^3p'}{p'}\delta^4\left(p'+q'-p-q\right) \\
\times & \left[\left(p'E_{q'}-\mathbf{p}'\cdot\mathbf{q}'\right)pM+p'M\left(pE_q'-\mathbf{p}\cdot\mathbf{q}'\right)-M^2\left(pp'-\mathbf{p}\cdot\mathbf{p}'\right)\right]
\end{aligned}
$$

Dispersion in no-local media

$$\frac{d\sigma}{d\Omega\, dp'} = \frac{g_{eff}^2}{8\pi^2} p'^2 \left[1 - \frac{M - (|\mathbf{p}| - p')}{E_{q'}} \cos\theta \right]$$

Local velocity distribution

$$\frac{d\sigma}{d\Omega dp'} = \frac{g_{eff}^2}{8\pi^2} p'^2 \left[1 - \frac{M - (|\mathbf{p}| - p')}{E_{q'}} \cos\theta\right] \mathcal{N}(v) \exp\left(-\frac{3(|\mathbf{p}|^2 + p'^2 - 2|\mathbf{p}|p' \cos\theta)}{2\sigma_q^2}\right)$$

Truncated local distribution

$$\frac{d\sigma}{d\Omega dp'} = \frac{g_{eff}^2}{8\pi^2} p'^2 \left[1 - \frac{M - (|\mathbf{p}| - p')}{E_{q'}} \cos\theta \right] \mathcal{N}(v)$$

$$\times \left[\exp\left(-\frac{3(|\mathbf{p}|^2 + p'^2 - 2|\mathbf{p}|p' \cos\theta)}{2\sigma_q^2} \right) - \exp\left(-\frac{3q_{esc}^2}{2\sigma_q^2} \right) \right]$$

Tsallis

$$\frac{d\sigma}{d\Omega dp'} = \frac{g_{eff}^2}{8\pi^2}\frac{1}{N}p'^2\left[1 - \frac{M - (|\mathbf{p}| - p')}{E_{q'}}\cos\theta\right]\left[1 - (1 - q_0)\frac{|\mathbf{p} - \mathbf{p}'|^2}{M^2 v_0^2}\right]^{q_0/(1-q_0)}$$

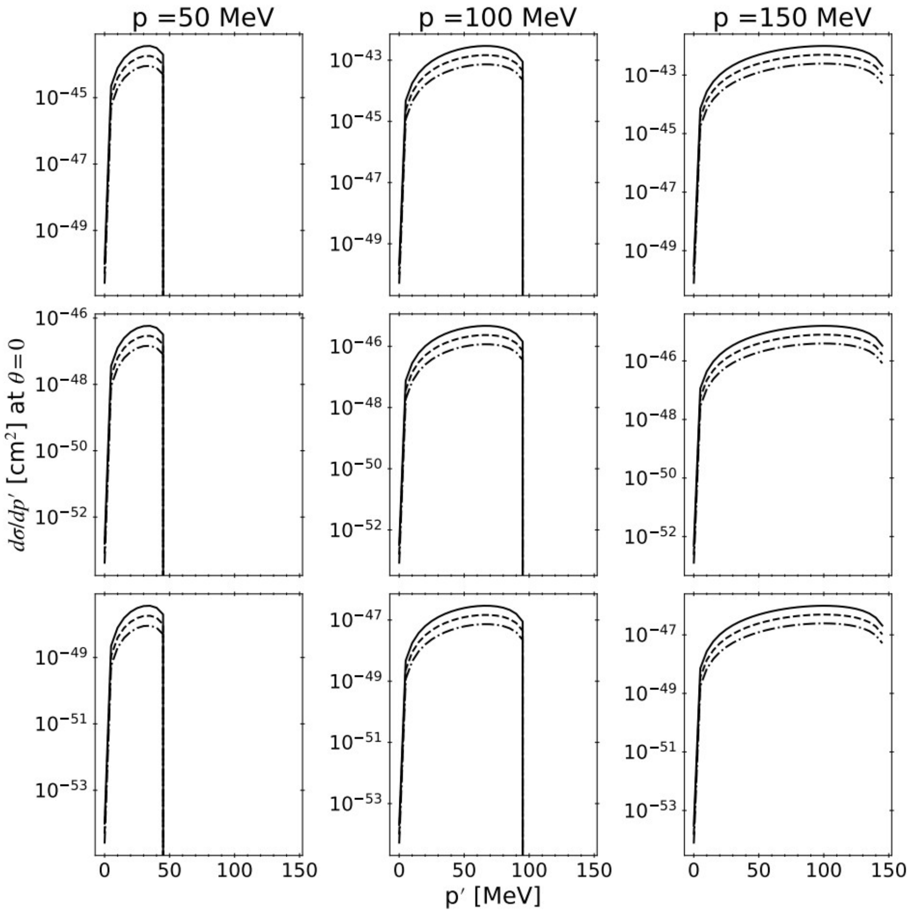
Distribution SHM (Standard halo)

Cross section at 0 degree

M_0=100 GeV

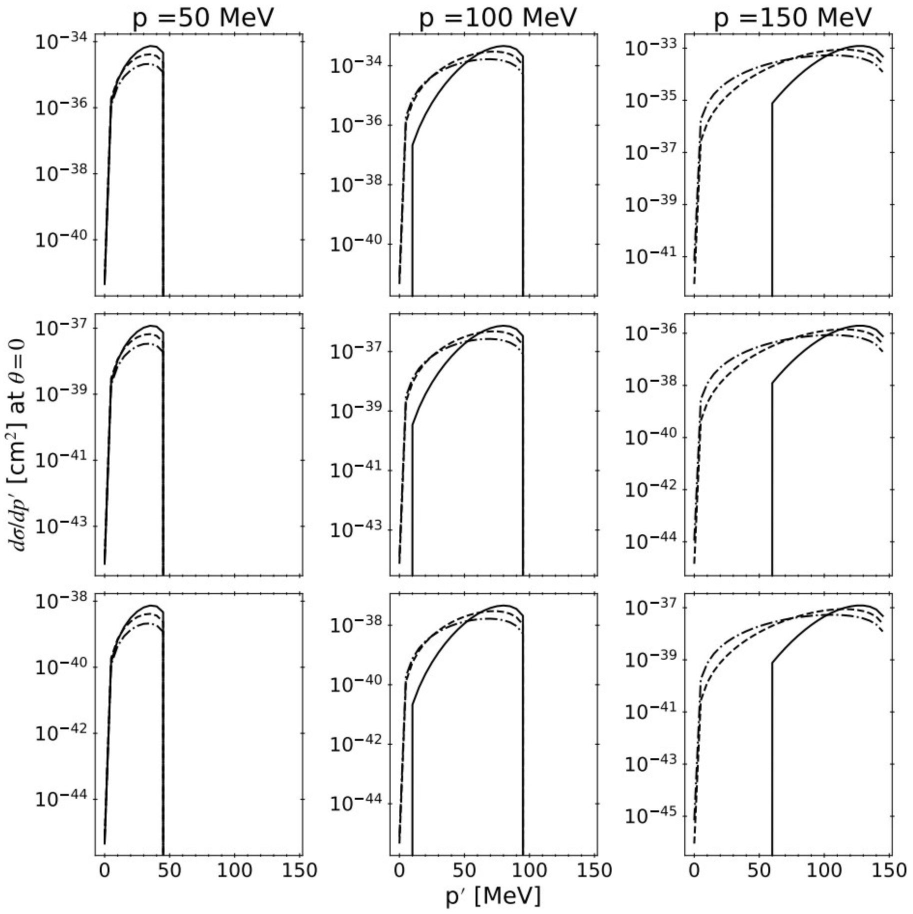
M_0=500 GeV

M_0=1TeV

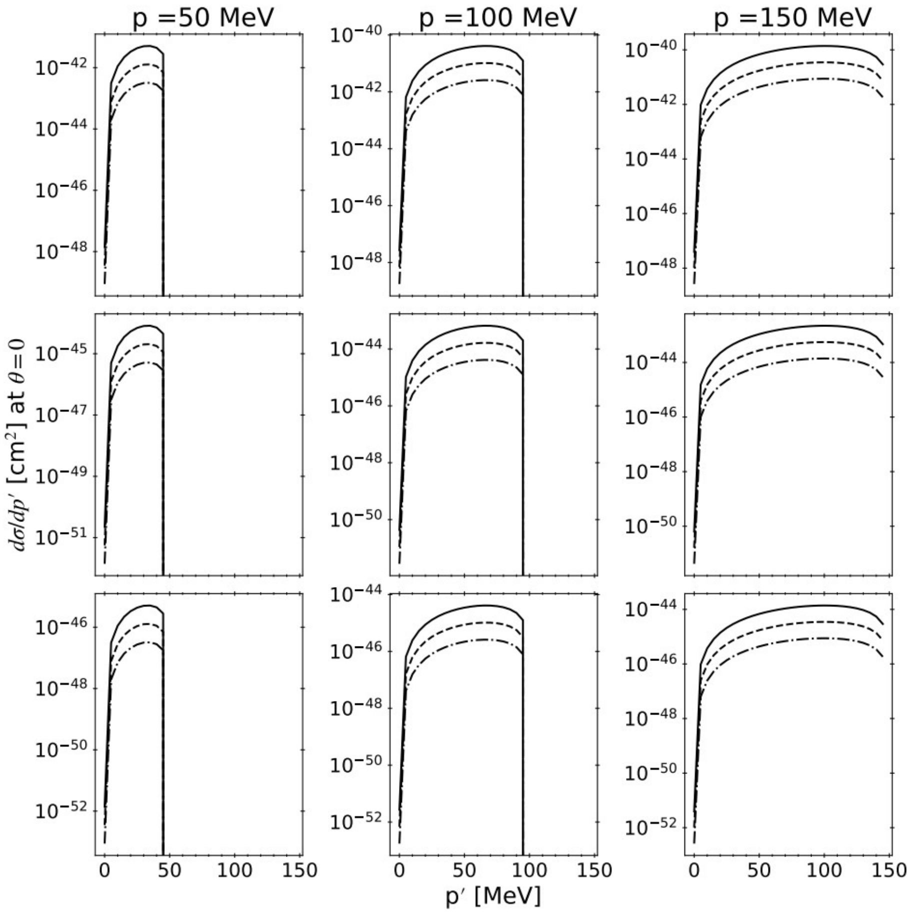


M(DM)=50,100,200 GeV

(SHM truncated)



Tsallis


p =50 MeV
p =100 MeV
p =150 MeV
$d\sigma/dp'$ [cm^2] at θ=0
p′ [MeV]
0
50
100
150

Neutrinos and dark matter

$$\mathcal{L}_{int} = i g_a \bar{\psi}\gamma^{\mu}\gamma^{5}\psi\partial_{\mu}\Phi$$

Peccei y Quinn scalar boson (axion)

Peccei-Quinn

Axion potential

$$V(\Phi) = -\frac{\mu^2}{2}\left(|\Phi|^2 - \frac{1}{f_a^2}|\Phi|^4\right).$$

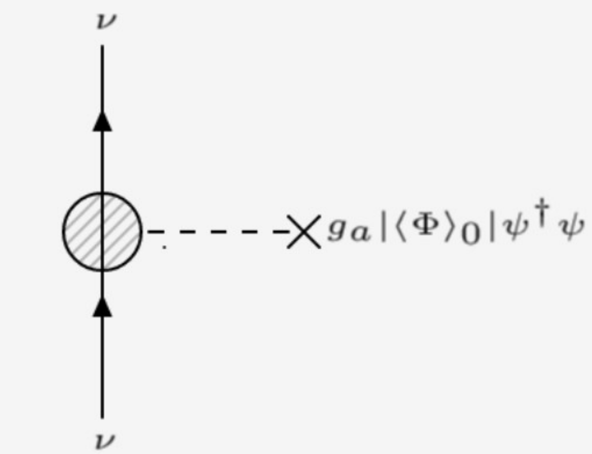
Effective Hamiltonian

$$\mathcal{H}_{int} \approx g_a \left| \langle \Phi \rangle_0 \right| \psi^\dagger \psi + g_a \vec{\nabla} \Phi(\vec{x}, t) . \vec{S}.$$

Neutrino mass

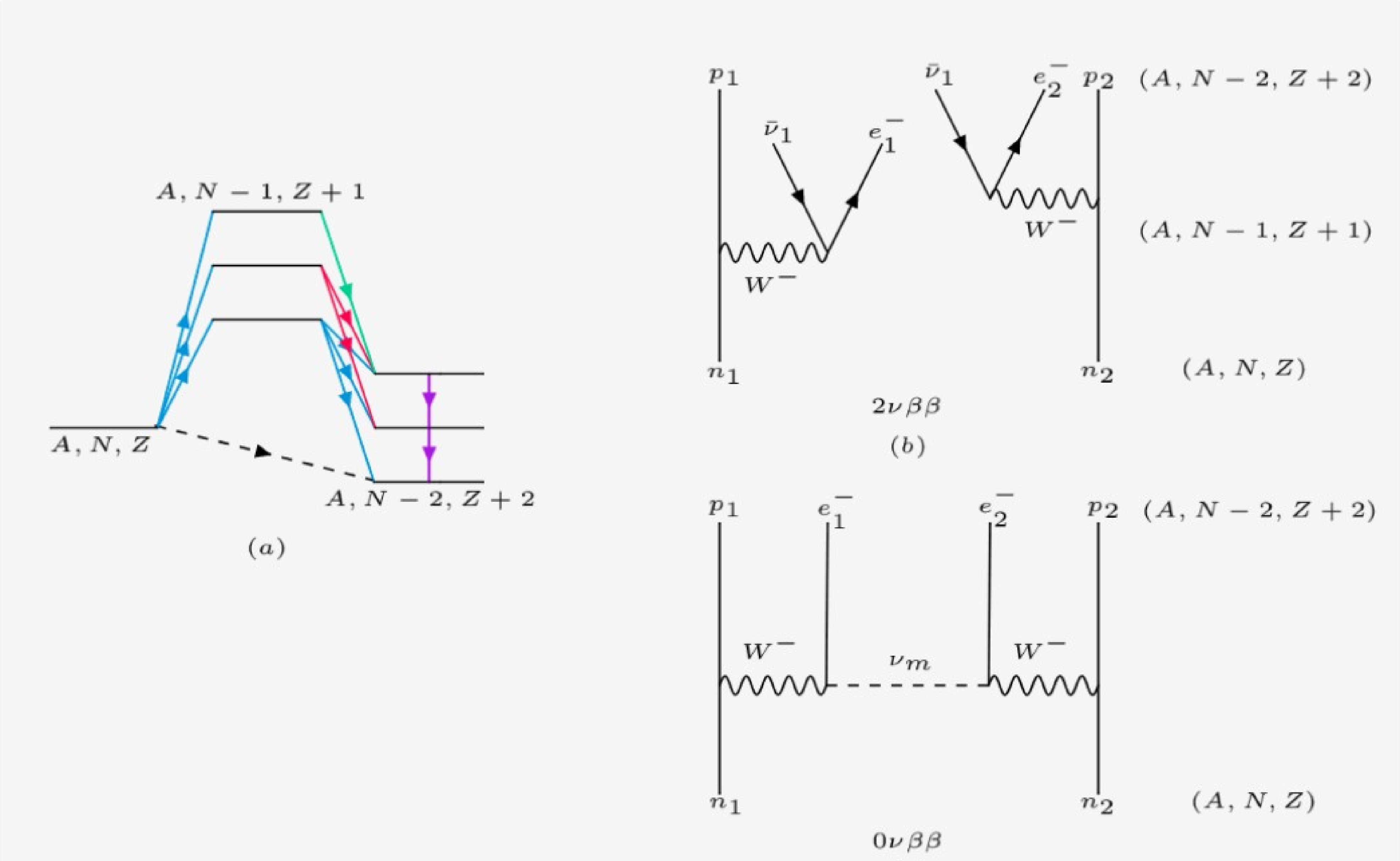
$$m_\nu \to g_a \left| \langle \Phi \rangle_0 \right|$$

Neutrino mass insertion



$$m_\nu \sim g_a|\langle\Phi\rangle_0|$$

About the double beta decay



Half life (0νβ β decay)

$$[t_{1/2}^{(0\nu)}]^{-1} = C_{mm}^{(0)}\left(\frac{\langle m_\nu\rangle}{m_e}\right)^2 + C_{m\lambda}^{(0)}\langle\lambda\rangle\left(\frac{\langle m_\nu\rangle}{m_e}\right) + C_{m\eta}^{(0)}\langle\eta\rangle\left(\frac{\langle m_\nu\rangle}{m_e}\right)$$
$$+ C_{\lambda\lambda}^{(0)}\langle\lambda\rangle^2 + C_{\eta\eta}^{(0)}\langle\eta\rangle^2 + C_{\lambda\eta}^{(0)}\langle\lambda\rangle\langle\eta\rangle,$$

Mass sector

$$\langle m_\nu \rangle = \frac{m_e}{\sqrt{t_{1/2}^{(0\nu)} C_{mm}^{(0)}}}.$$

Mass of the axion

$$m_a \approx \frac{6}{f_a/[10^6 \mathrm{GeV}]} \mathrm{eV}$$

Mass of the neutrino

$$m_{\nu} = g_a \frac{f_a}{\sqrt{2}},$$

mass(axion)/mass(neutrino)

		$g_a/\sqrt{2}$	
$m_a/6$ [eV]	f_a[GeV]	$\langle m_\nu \rangle$=0.1 eV	$\langle m_\nu \rangle$=0.01 eV
10^{-10}	10^{16}	10^{-26}	10^{-27}
10^{-9}	10^{15}	10^{-25}	10^{-26}
10^{-8}	10^{14}	10^{-24}	10^{-25}
10^{-7}	10^{13}	10^{-23}	10^{-24}
10^{-6}	10^{12}	10^{-22}	10^{-23}
10^{-5}	10^{11}	10^{-21}	10^{-22}
10^{-4}	10^{10}	10^{-20}	10^{-21}
10^{-3}	10^{9}	10^{-19}	10^{-20}
10^{-2}	10^{8}	10^{-18}	10^{-19}
10^{-1}	10^{7}	10^{-17}	10^{-18}

Conclusions

- Neutrinos are a key component in the description of phenomena in a wide range of energies.
- More than 3 species may be needed to explain astrophysical systems and reactions.
- The interaction of neutrinos with dark matter may reveal significant information about the composition and distribution of it.

Conclusiones

- Peccei y Quinn postulate, related to the axion mass, could be applied to the generation of the neutrino mass.
- Majorana postulate about neutrinos may be confirmed from the relation existing between double beta decay and axions.
- Modelling axions may change the current view about the existence and composition of dark matter.

Some references

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Finally (thanks God!)

- Muchas gracias!!
- Tak so mycket!
- Kiitos palios!
- Mange tak !
- Bol’shoye spasibo!