Le Soleil
et
la masse des neutrinos

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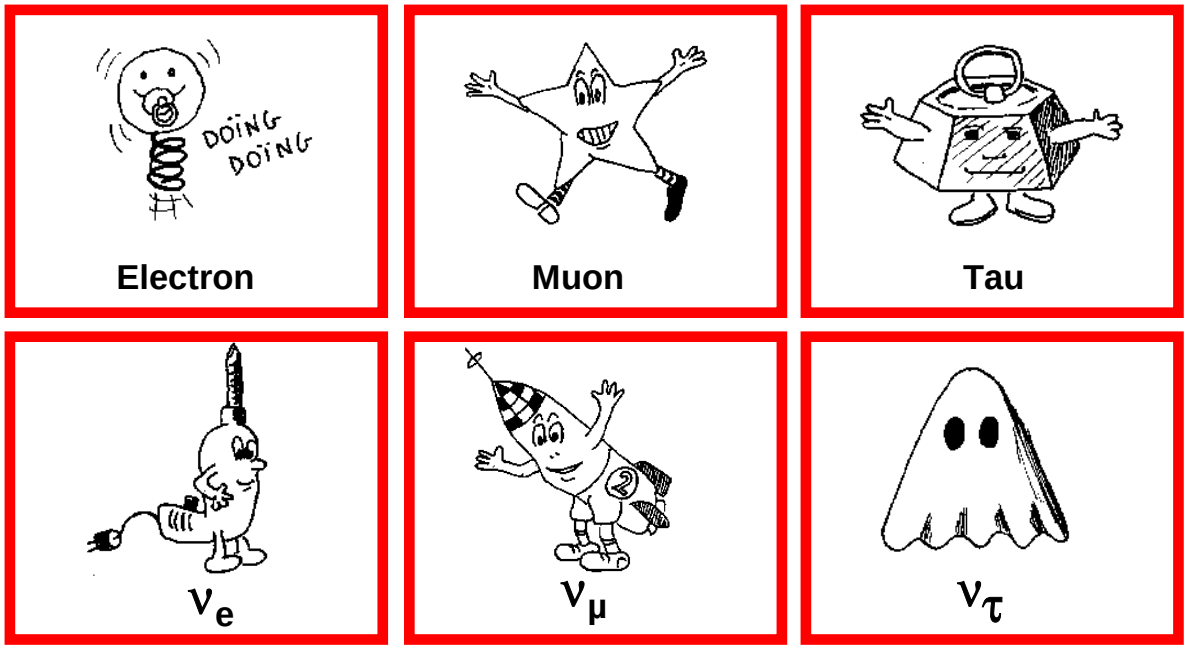
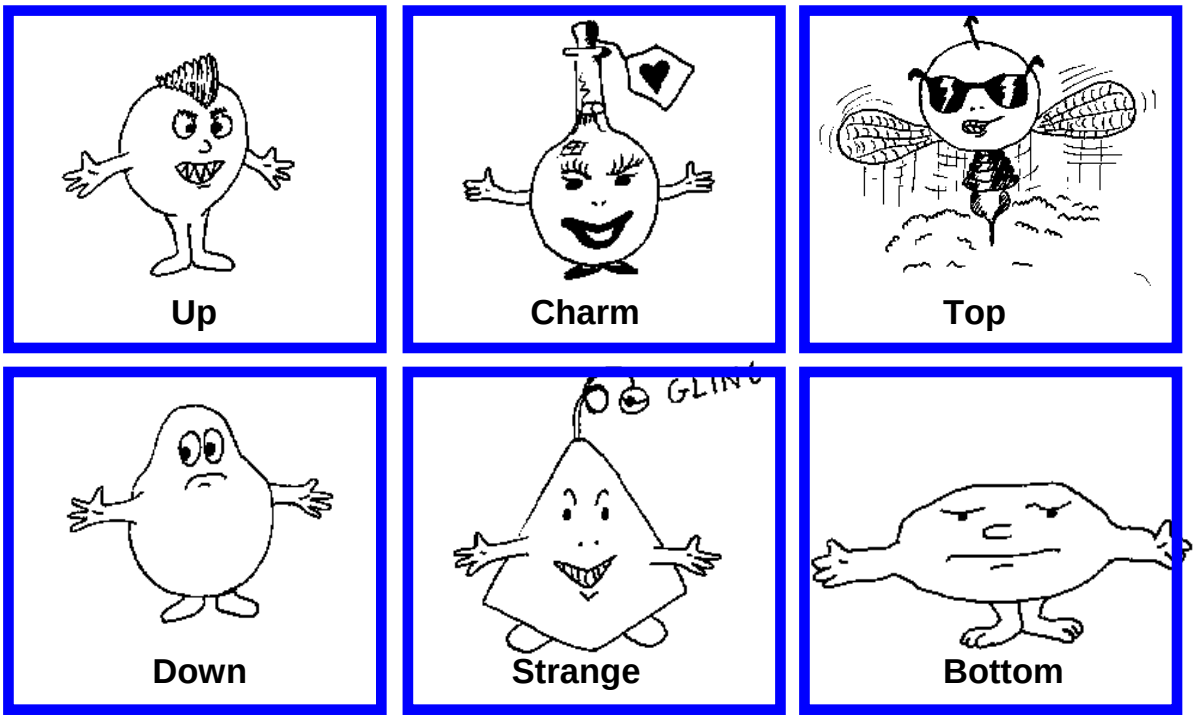
Le modèle standard

Leptons



$M\nu_e < 5$ eV $M\nu_\mu < 170$ keV $M\nu_\tau < 25$ MeV

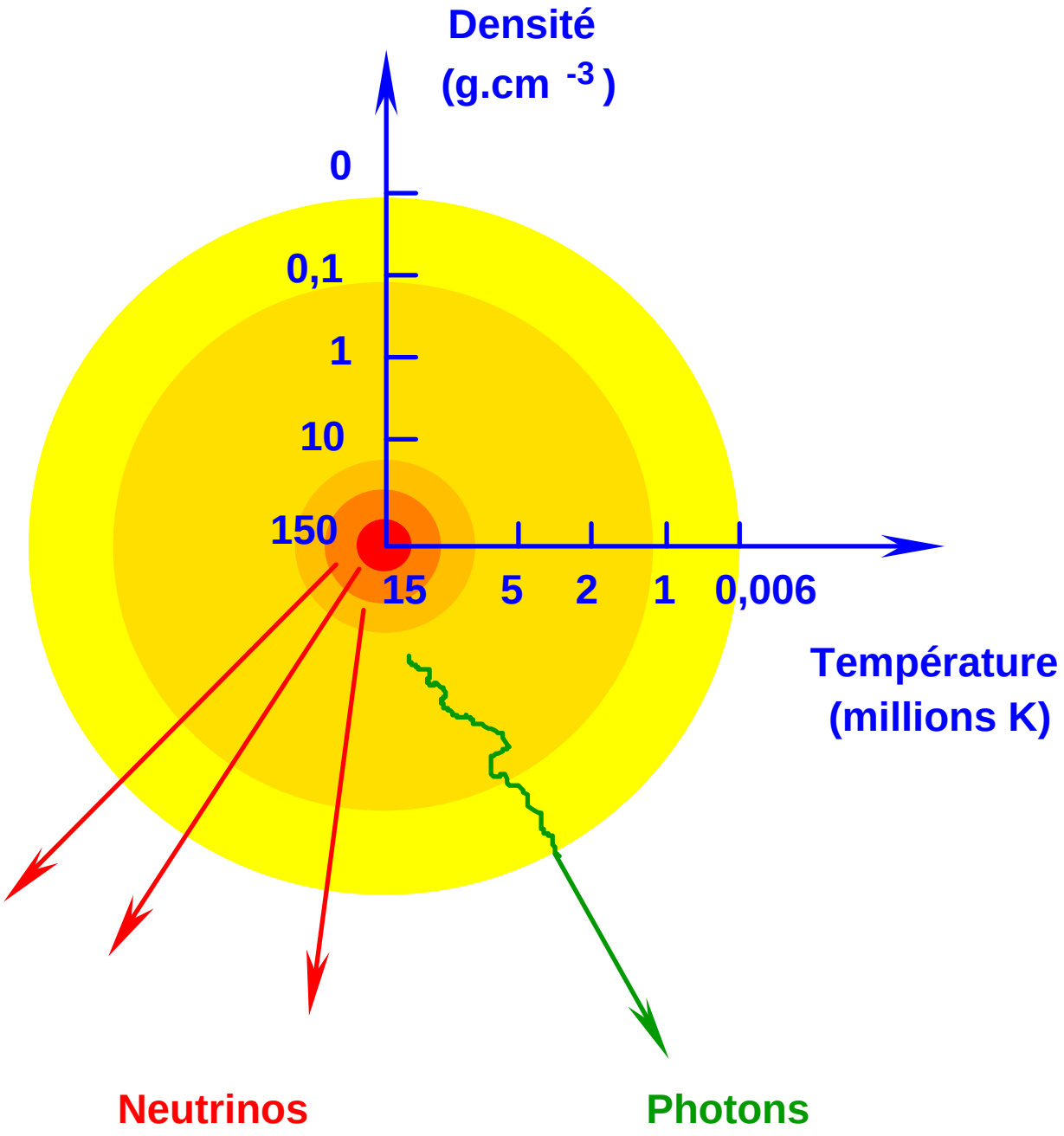
Quarks



Hiérarchie des masses (≈ quarks):

$$M\nu_e \ll M\nu_\mu \ll M\nu_\tau$$

Les neutrinos du Soleil



$$4p \rightarrow {}^{4}He + 2\nu_e + \text{“26,7 MeV -}E_\nu\text{”}$$

Sur Terre : $\phi_\nu = 65.10^9\ cm^{-2}.s^{-1}$

Réactions nucléaires dans le Soleil

⊙ $p + p \rightarrow {}^{2}H + e^{+} + \nu_e$

- ➔ **Réaction primordiale**
- ➔ ϕ/ϕ_{tot} = 91%
- ➔ 0 < E < 0,420 MeV

⊙ ${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$

- ➔ ϕ/ϕ_{tot} =7,1%
- ➔ E = 0,861 MeV ou 0,383 MeV

⊙ ${}^{8}B \rightarrow {}^{8}Be + e^{+} + \nu_e$

- ➔ ϕ/ϕ_{tot} =0,009%
- ➔ 0 < E < 15 MeV

L'énigme des neutrinos solaires

⊙ **Davis, 68 →**

$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

Seuil = 814 keV ⇒ ^8B, ^7Be

(27 ± 2) %

⊙ **Kamiokande 87 → 95**

$\nu_x + e^- \rightarrow \nu_x + e^-$

Seuil = 7,5 MeV ⇒ ^8B

(42 ± 6) %

⊙ **GALLEX, SAGE ≈ 90 →**

$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$

seuil = 233 keV ⇒ ^8B, ^7Be et ν_{pp} !

(51± 5) %

⊙ **SuperKamiokande 96 →**

seuil = 7 MeV ⇒ ^8B

(40 ± 3)%

Où est la solution ?

⊙Erreur expérimentale ?

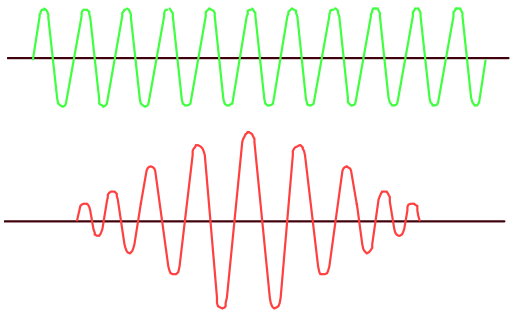
- ➔Chlore : 25 ans de mesure
- ➔SuperKamiokande = Kamiokande
- ➔GALLEX (= SAGE) : 2 sources de ^{51}Cr

		Théorie		
Observé / Théorie		pp	Be	B
Gallium	*0,5*	54%	26%	11%
Chlore	*0,3*		14%	77%
Kamioka	*0,4*			100%

⊙ La physique des particules

- ➔ Oscillations des neutrinos

  ⇒ ***Diminution de B et Be possible***



Les oscillations de neutrinos

⊙ Etats d'interaction ν_e, ν_μ, ν_τ

° Etats de propagation ν_1, ν_2, ν_3

$$\begin{cases} |\nu_e\rangle = \cos\theta_V |\nu_1\rangle - \sin\theta_V |\nu_2\rangle \\ |\nu_\mu\rangle = \sin\theta_V |\nu_1\rangle + \cos\theta_V |\nu_2\rangle \end{cases}$$

➔ Equation de Schrödinger

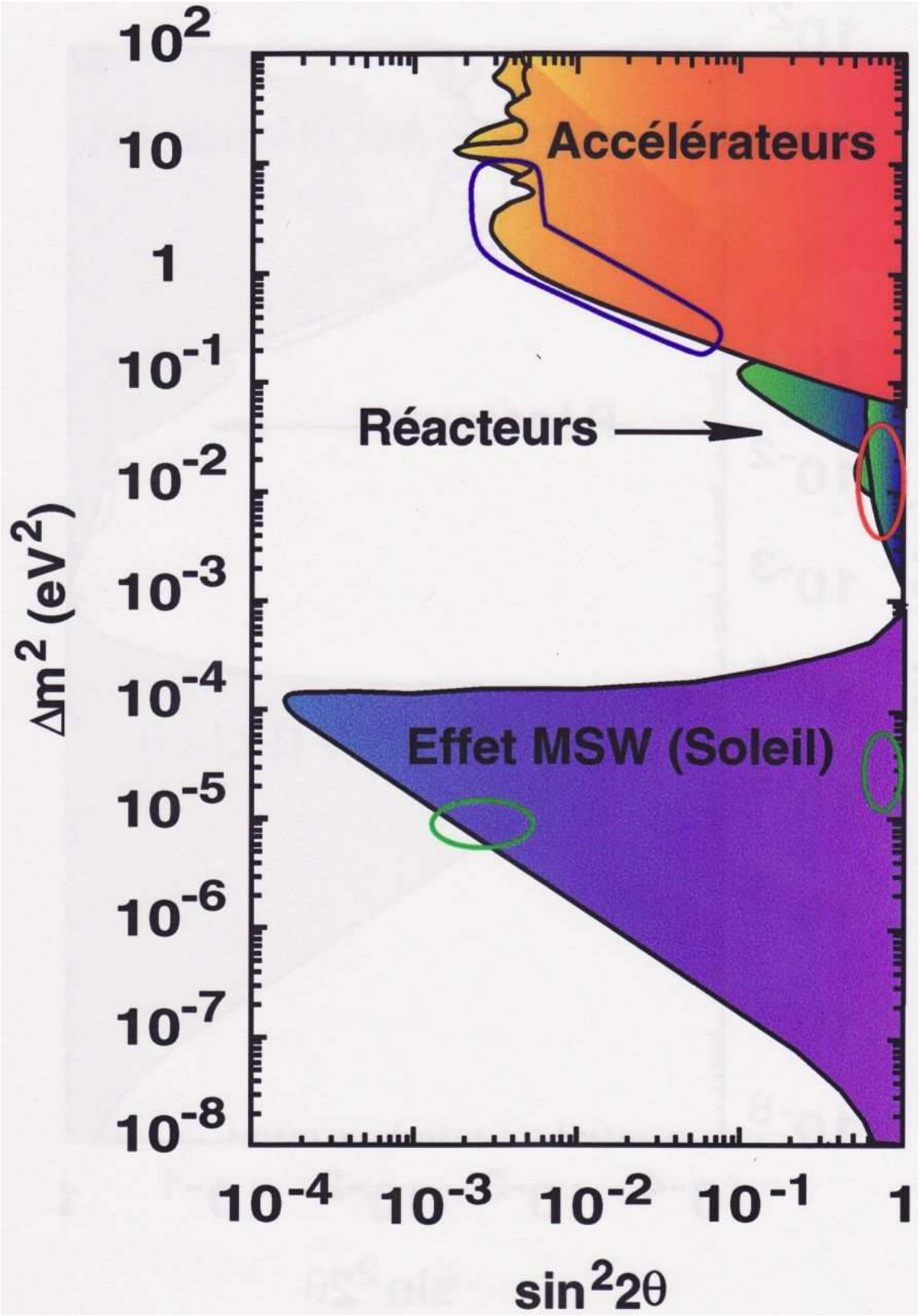
$$|\nu(t)\rangle = \cos\theta_V \bullet e^{-iE_1 t} |\nu_1\rangle + \sin\theta_V \bullet e^{-iE_2 t} |\nu_2\rangle$$

➔ $P(\nu_e \to \nu_e) = |\langle \nu(t) | \nu_e \rangle|^2$

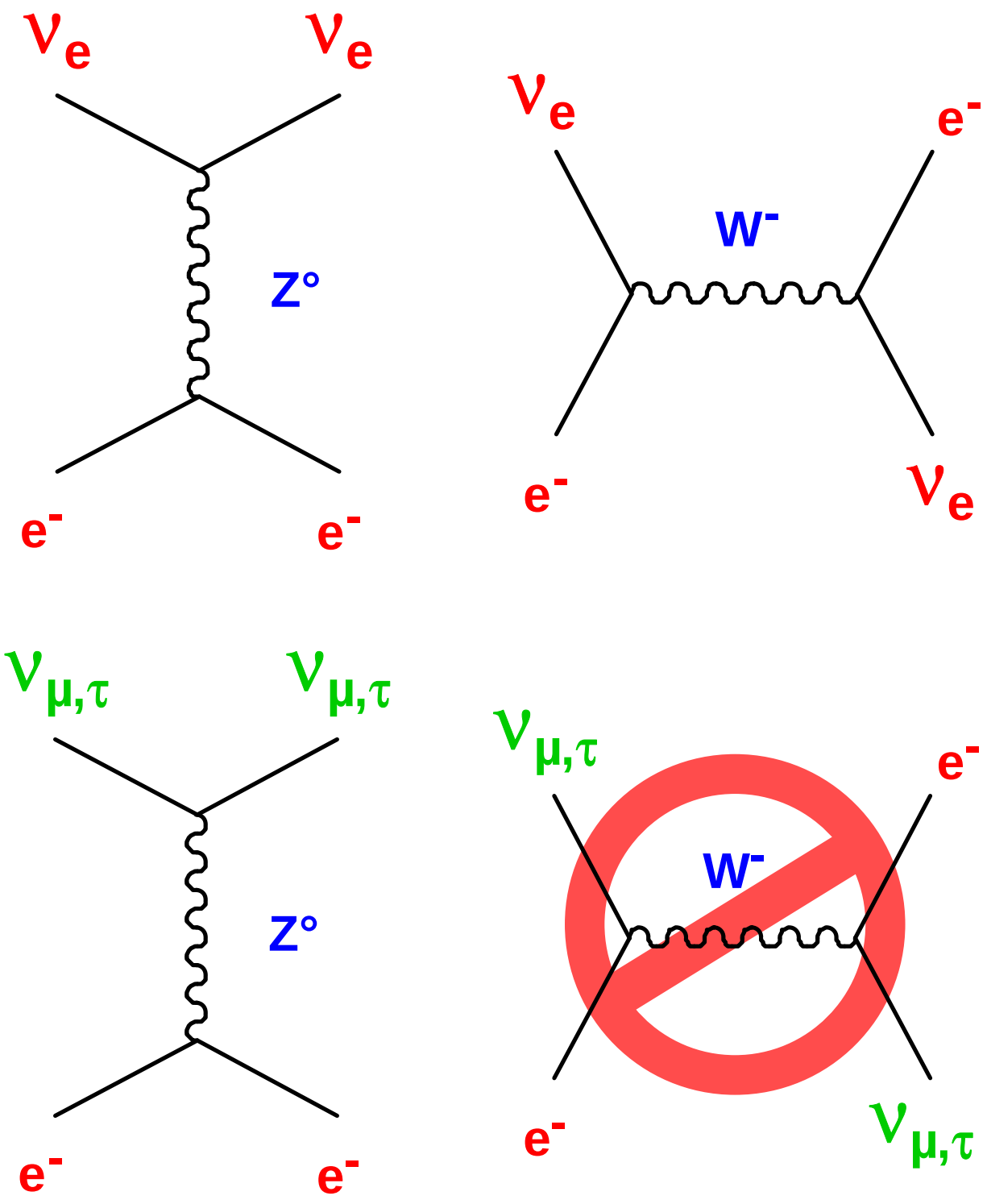
$$\begin{cases} P = 1 - \sin^2 2\theta_V \bullet \sin^2 \pi \dfrac{L}{L_\nu} \\ L_\nu = 2{,}48(m) \bullet \dfrac{E(MeV)}{\Delta m^2 (eV^2)} \end{cases}$$

$$\Delta m^2 = |m_2^2 - m_1^2|$$

Paramètres d'oscillation



Interaction ν-e



Effet MSW

Mikheyev, Smirnov, Wolfenstein
(1978, 1985)

- **Matière = électrons** ~~(muons, tau)~~

Hamiltonien total : $H_m = H_V + W$

$$H_V = \begin{pmatrix} E_1 & 0 \\ 0 & E_2 \end{pmatrix} \quad \rightarrow \quad (\nu_1, \nu_2)$$

$$W = \begin{pmatrix} C + \sqrt{2} \cdot G \cdot \rho_e & 0 \\ 0 & C \end{pmatrix} \quad \rightarrow \quad (\nu_e, \nu_\mu)$$

$$H_m = \begin{pmatrix} \sqrt{2} \cdot G \cdot \rho_e & \frac{E_1 - E_2}{2} \cdot \sin 2\theta_V \\ \frac{E_1 - E_2}{2} \cdot \sin 2\theta_V & (E_2 - E_1) \cdot \cos 2\theta_V \end{pmatrix}$$

$$(\nu_e, \nu_\mu)$$

Les oscillations (suite...)

$$\rho_e = 0 \quad \Rightarrow \quad H_m = H_v \Rightarrow \nu_\alpha = \nu_1, \nu_2$$

$$\rho_e \to \infty$$

$$\Rightarrow H_m = \begin{pmatrix} \sqrt{2} \cdot G \cdot \rho_e & 0 \\ 0 & 0 \end{pmatrix} \Rightarrow \nu_\alpha = \nu_e, \nu_\mu$$

Dans le Soleil, $\rho(R) \approx \rho_c e^{-R/R_0}$

R_0 = 70000 km

$\rho_c = 6\ 10^{25}\ e^-\ \ cm^{-3}$

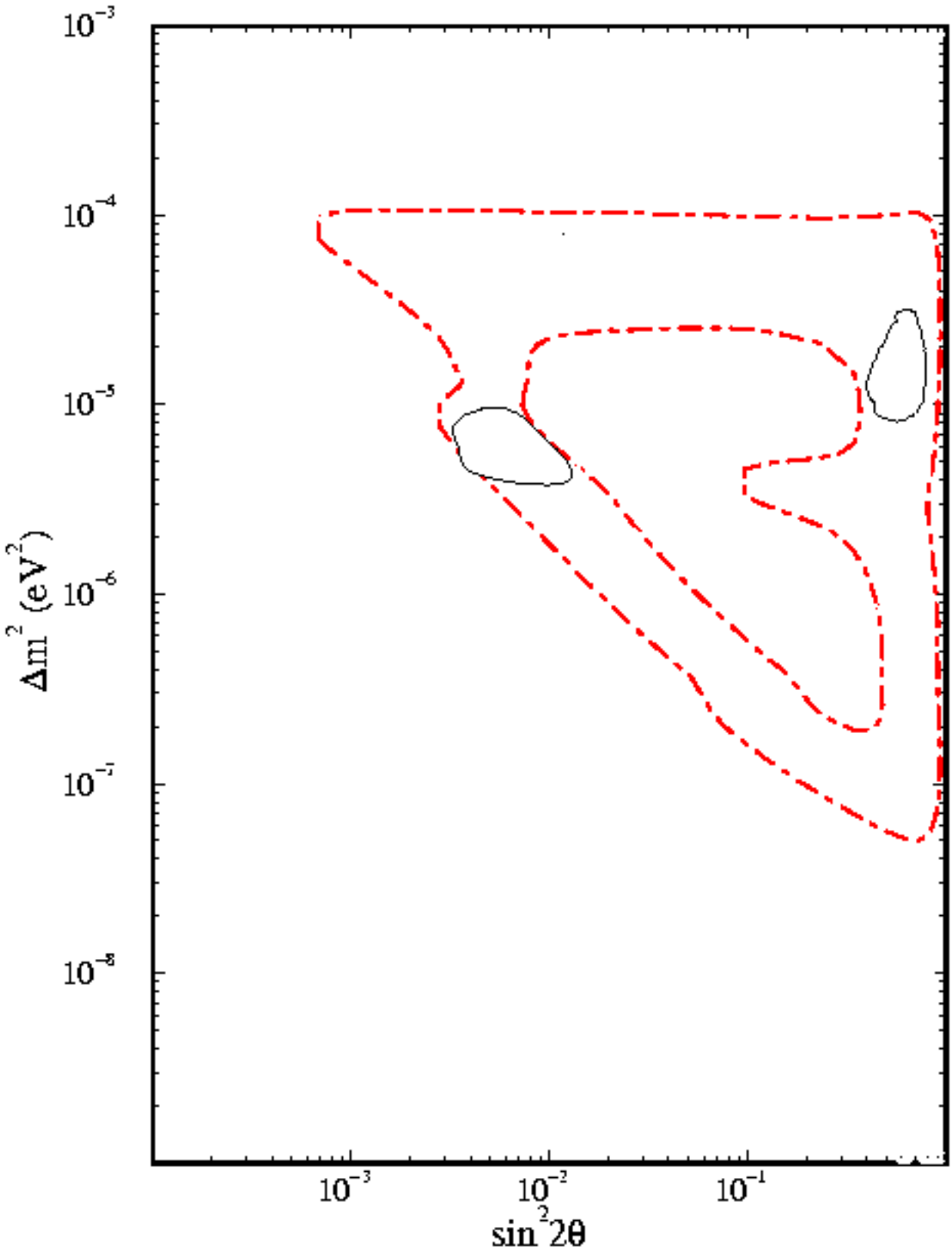
<u>Cœur du Soleil</u> :

$$\nu_e = \nu_1 \cos\theta_V - \nu_2 \sin\theta_V$$

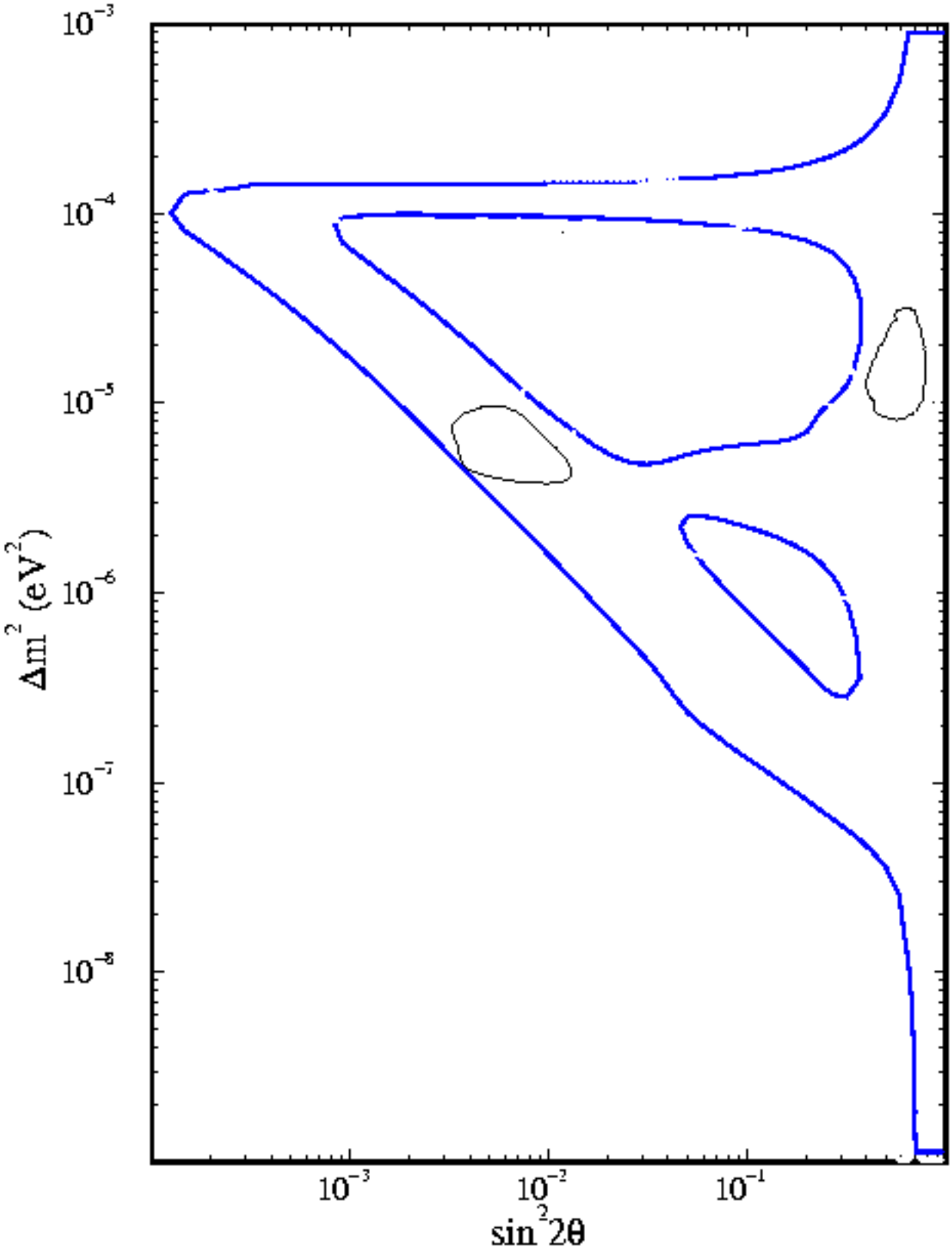
<u>Surface du Soleil</u> :

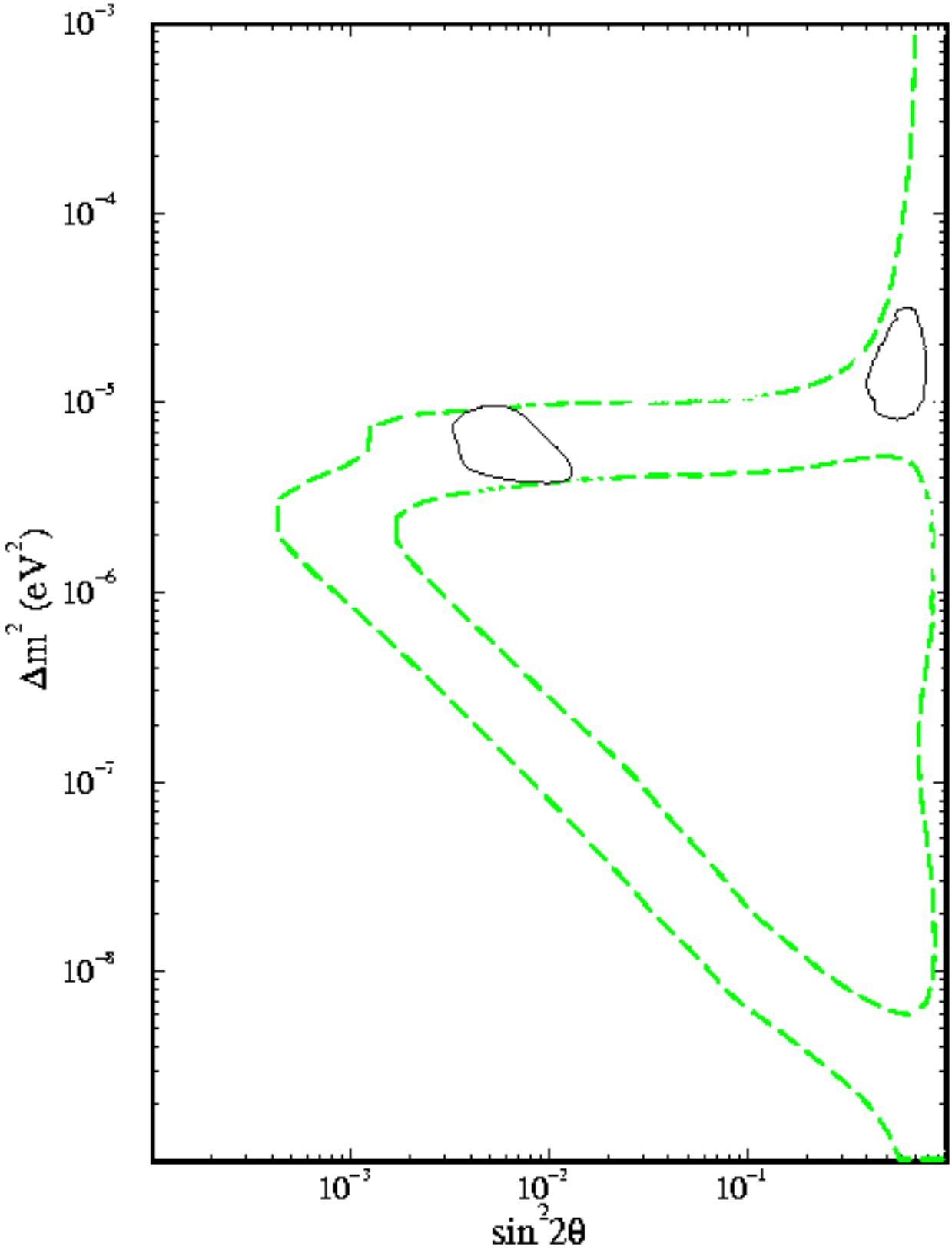
$$\nu_2 = \nu_e \sin\theta_V + \nu_\mu \cos\theta_V \approx \nu_\mu$$

Chlore

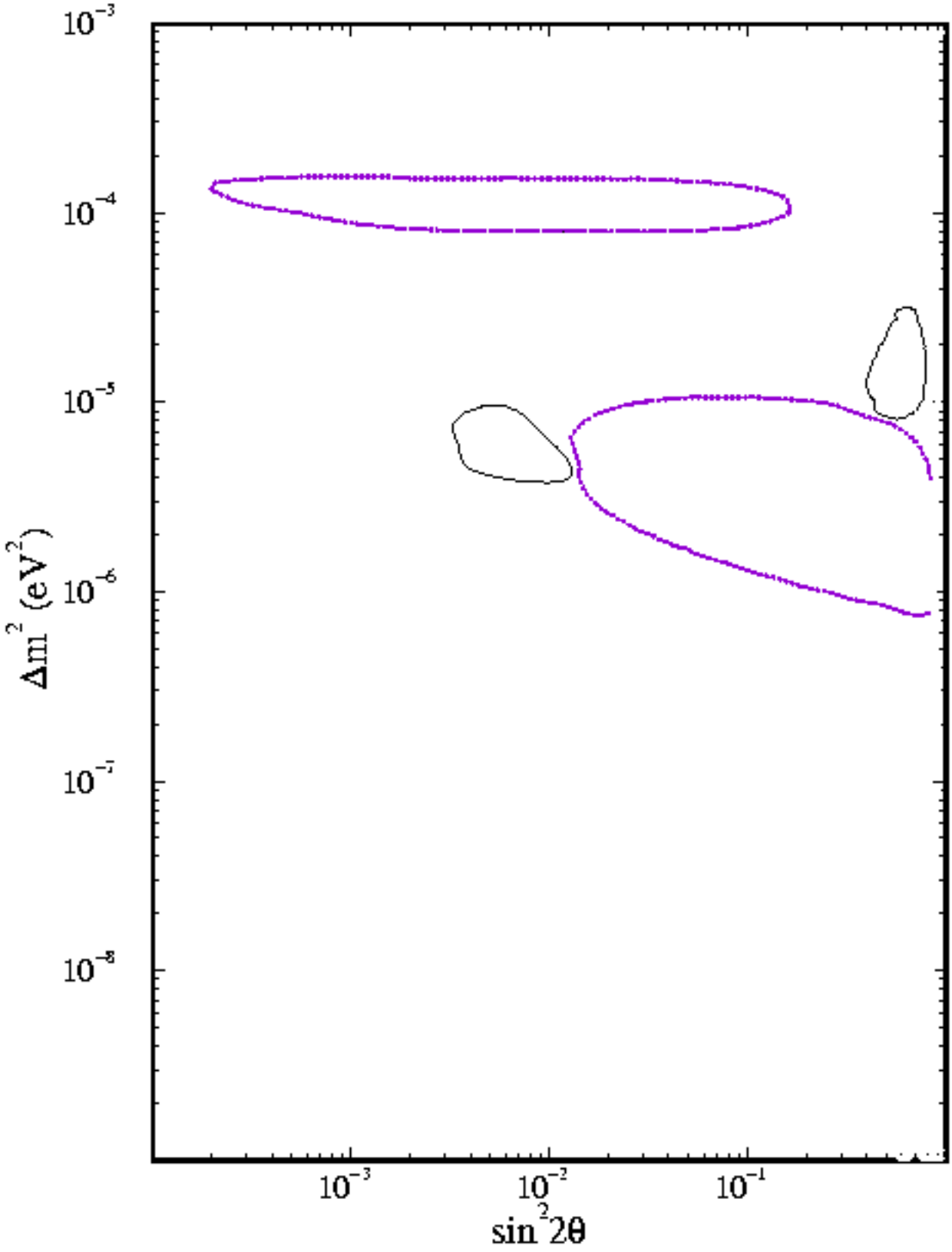


Kamioka + SK

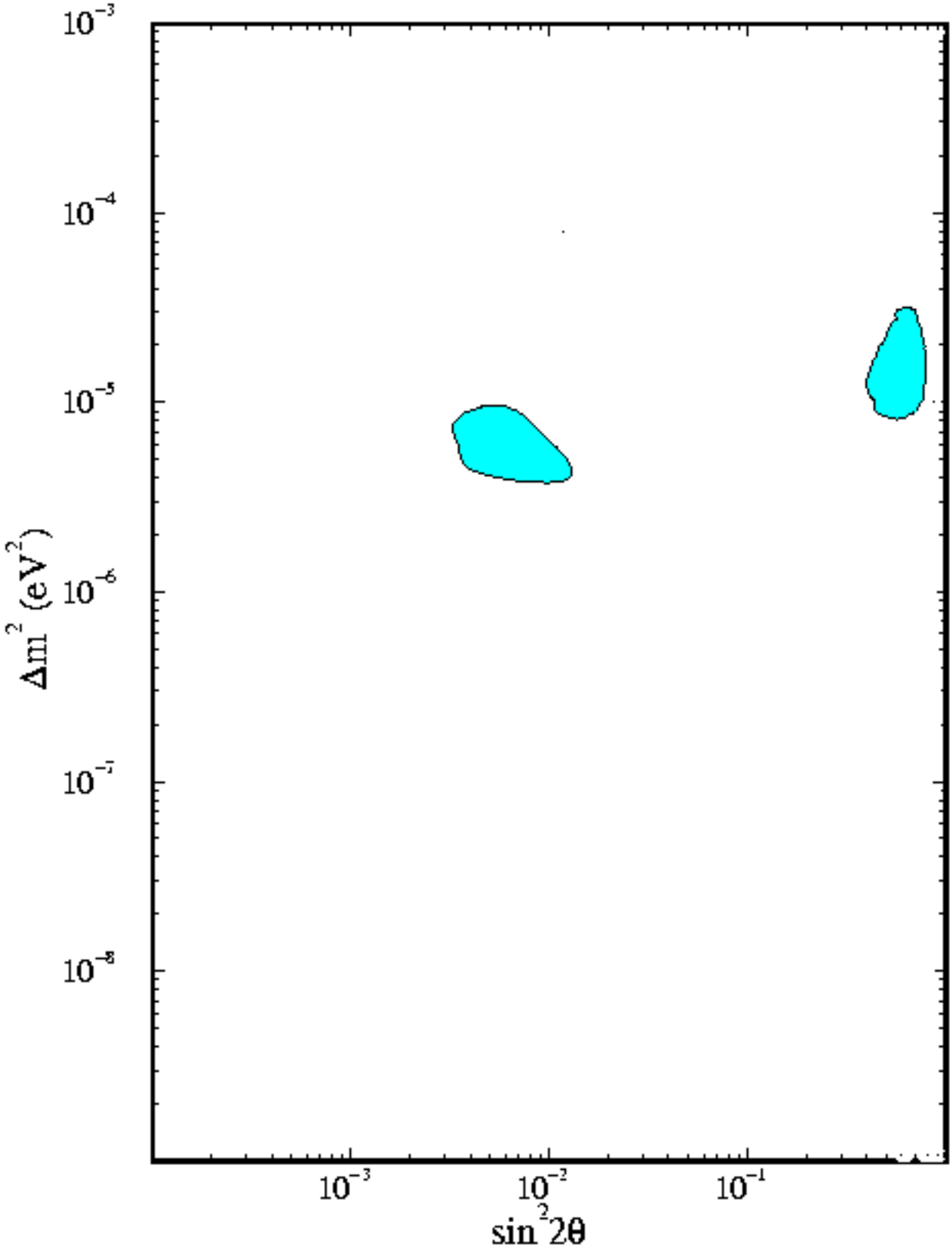




Gallium



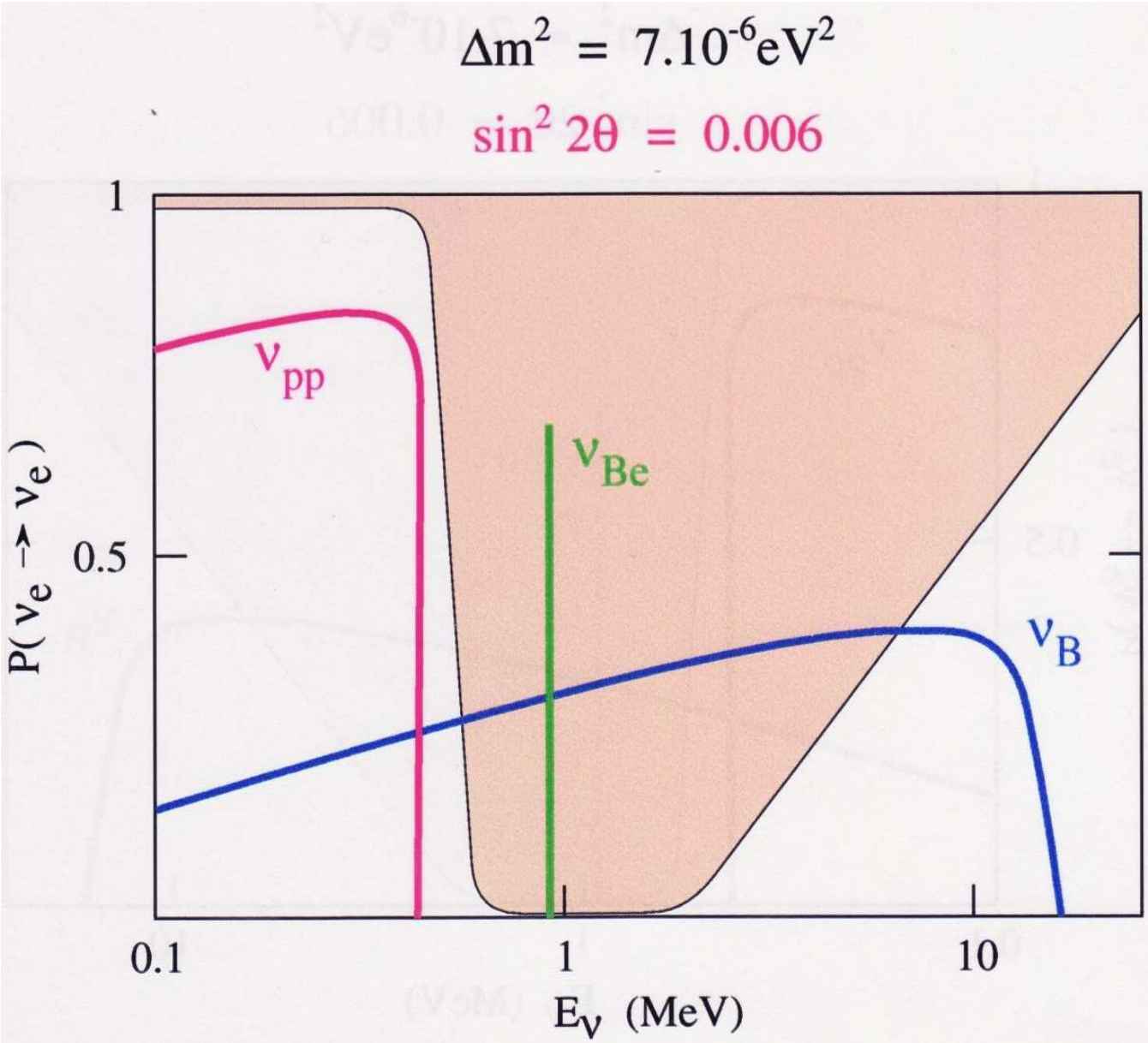
Spectre
Jour-nuit



Autorisé

Modification du spectre

Solution à petit angle



M.Cribier & D.Vignaud

Aller plus loin...

⊙ GNO (11/97→)

- ➔ 30 t. → 100 t. Ga
- ➔ 1 cycle solaire, stabilité du flux
- ➔ seul détecteur sensible aux ν_{pp}

⊙ SNO (98→)

- ➔ 1000 t. D_2O / 7500 t. H_2O

  ⇒ Toutes les saveurs

  $\nu_x + D \rightarrow p + n + \nu_x$
- ➔ Seuil = 7 MeV (^8B)

⊙ Borexino (99→)

- ➔ 300 tonnes de liquide scintillant
- ➔ Seuil = 400 keV ⇒ ^7Be

⊙ Hellaz ?

- ➔ 2000 m^3 He, TPC à 5 bars, 77 K
- ➔ Mesure totale du spectre

  (si seuil < 300 keV)