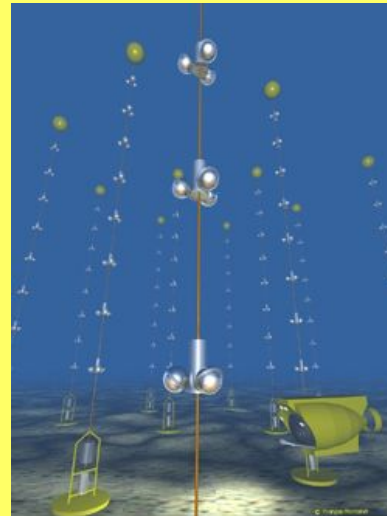


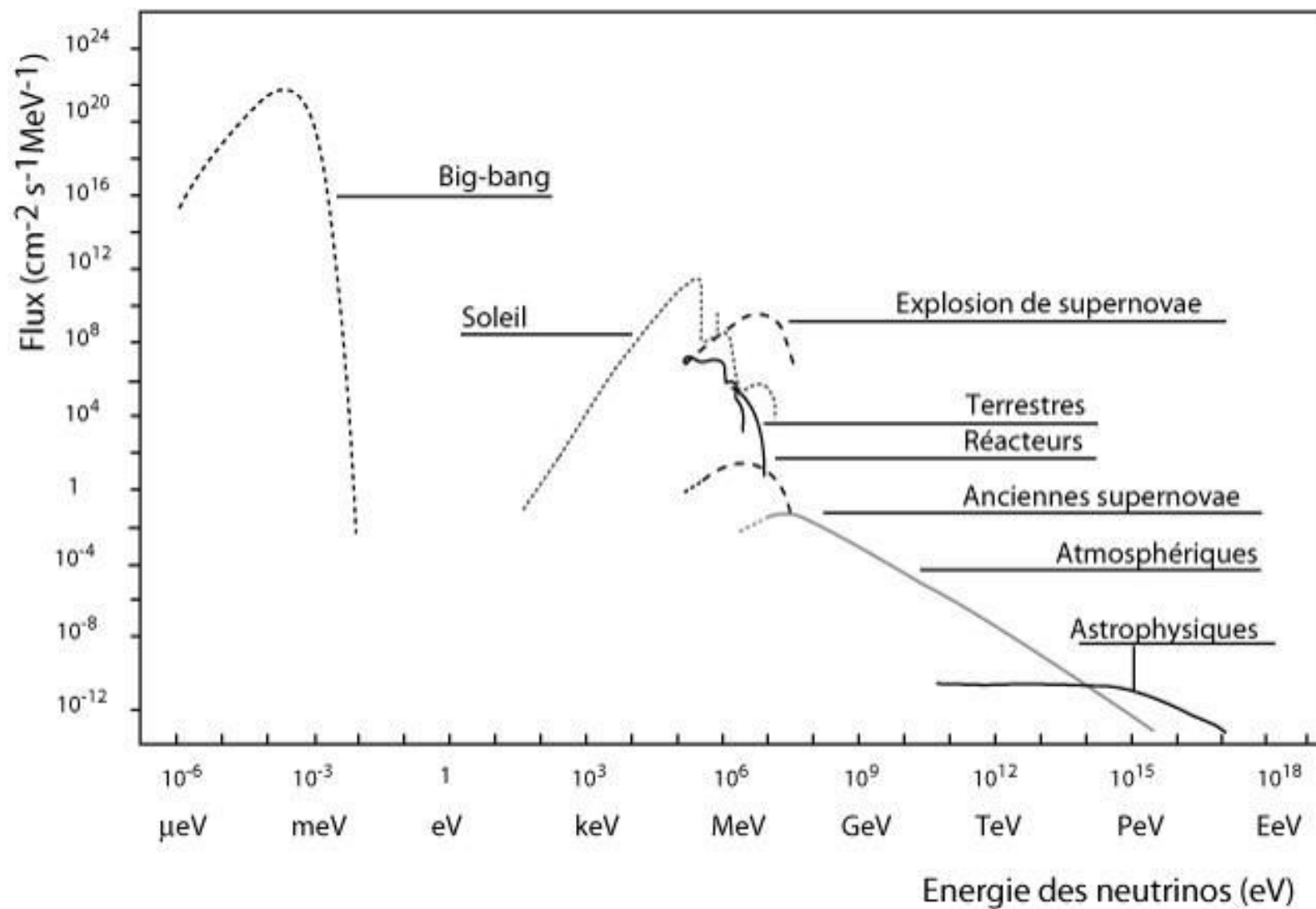
Astro - Neutrinos



Jose Busto
Centre de physique des particules de Marseille
Université Aix - Marseille II

OHP
11 / 09 / 2009

Flux de neutrinos cosmiques



Propriétés physiques du neutrinos

=> excellent vecteur de l'Univers lointain et profond

Neutrino - Electron

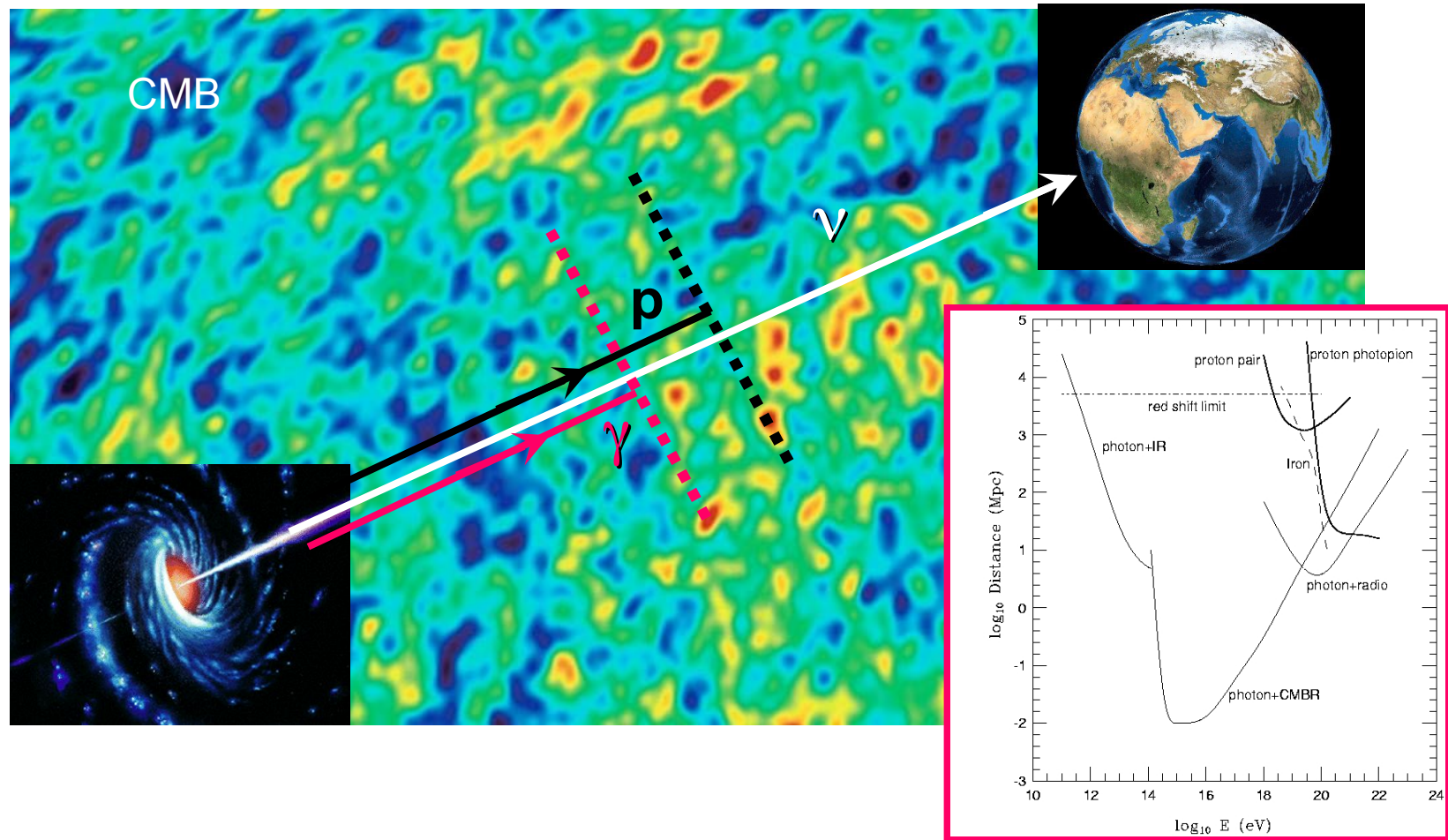
$$\sigma_{\nu_e e^- \rightarrow \nu_e e^-} \approx 9.5 \cdot 10^{-49} \text{ m}^2 \left(\frac{E_\nu}{1 \text{ MeV}} \right)$$

Neutrino – Nucleon < 1 GeV

$$\sigma_{\nu_e n \rightarrow e^- p} = 9.3 \cdot 10^{-48} \text{ m}^2 \left(\frac{E_\nu}{1 \text{ MeV}} \right)^2$$

Neutrino – Nucleon 50 GeV < E < 250 GeV

$$\sigma_{\nu_e N \rightarrow e^- X} \approx 6.7 \cdot 10^{-43} \left(\frac{E}{\text{GeV}} \right) \text{ m}^2$$



Absorption (GZK effect)

γ -rays: $\gamma + \gamma_{2.7k} \rightarrow$

proton: $p + \gamma_{2.7k} \rightarrow \pi^0 + X$

neutrinos: $\nu + \nu_{1.95K} \rightarrow Z+X$

cut-off

$>10^{14}\text{eV}$

$>5 \cdot 10^{19}\text{eV}$

$>4 \cdot 10^{22}\text{eV}$

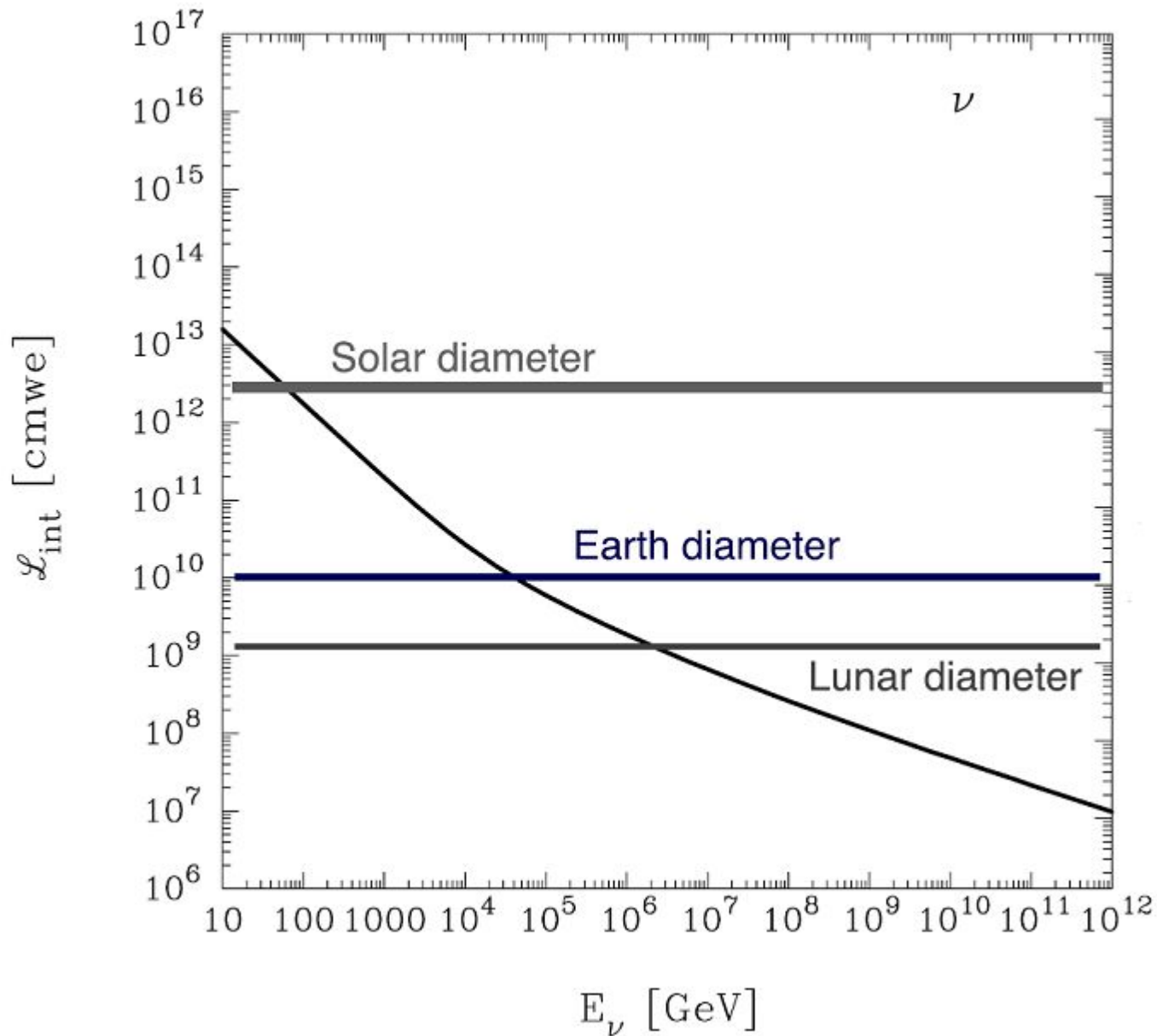
mean free path

10 Mpc

50 Mpc

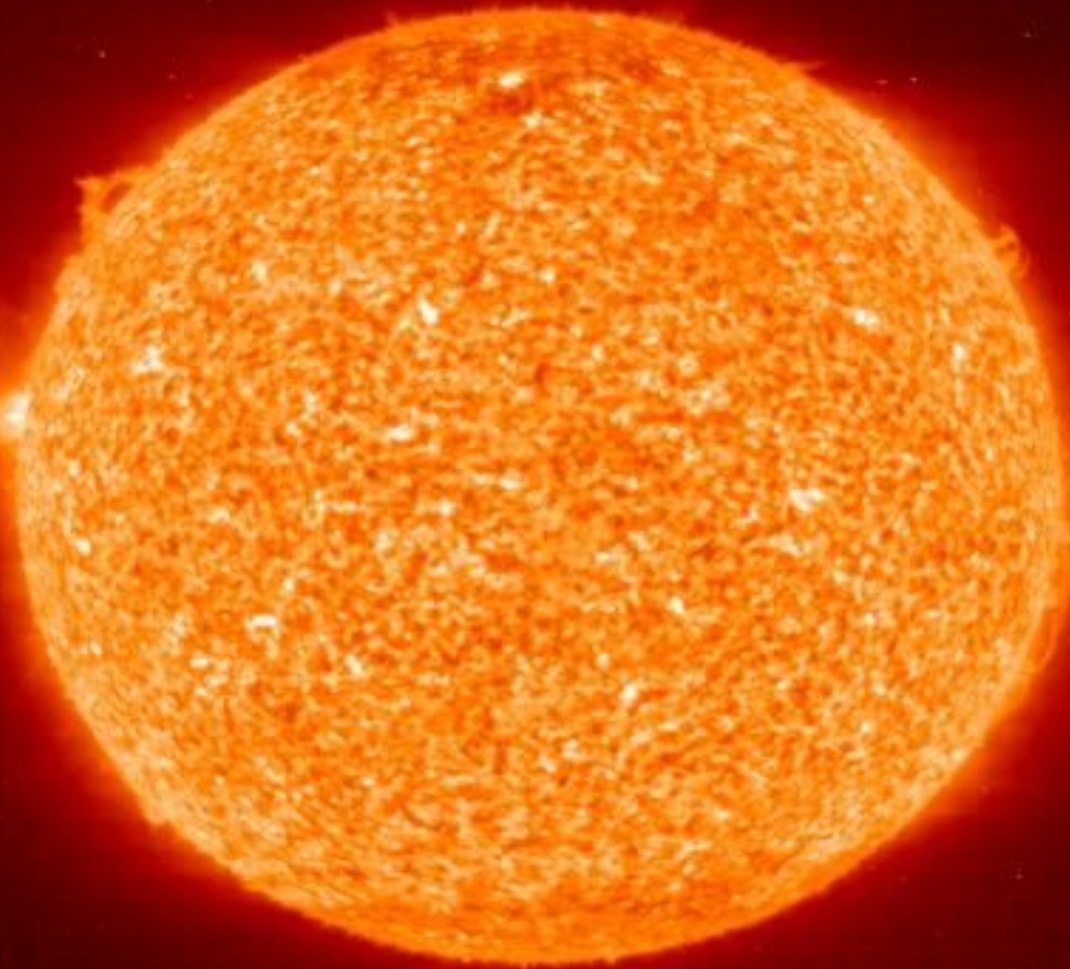
(40 Gpc)

Opacités vis-à-vis des neutrinos



$$\lambda_{\text{int}} = \frac{1}{N_A \sigma_{\text{tot}}^\nu N}$$

Neutrinos Solaires



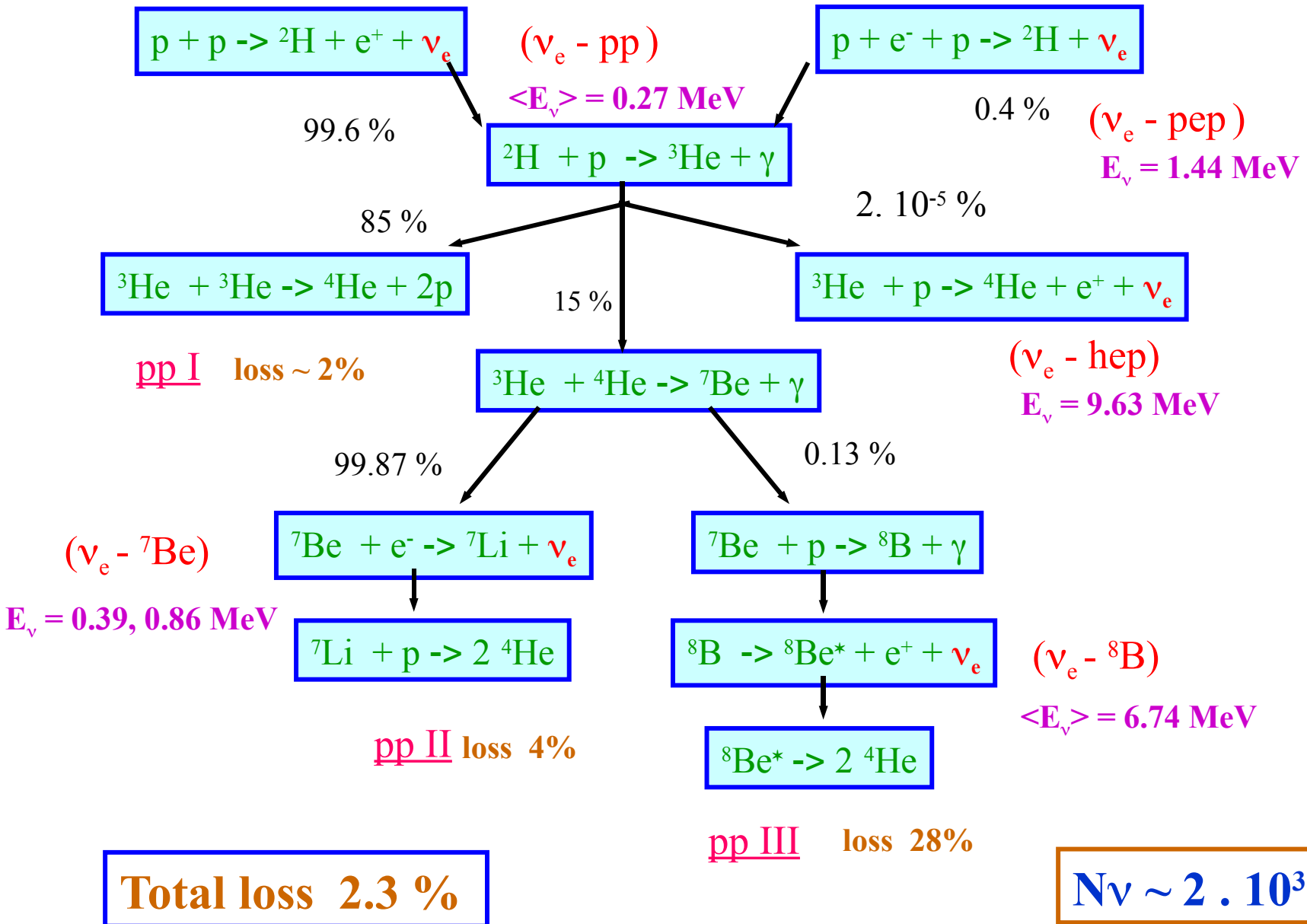
Neutrinos Solaires



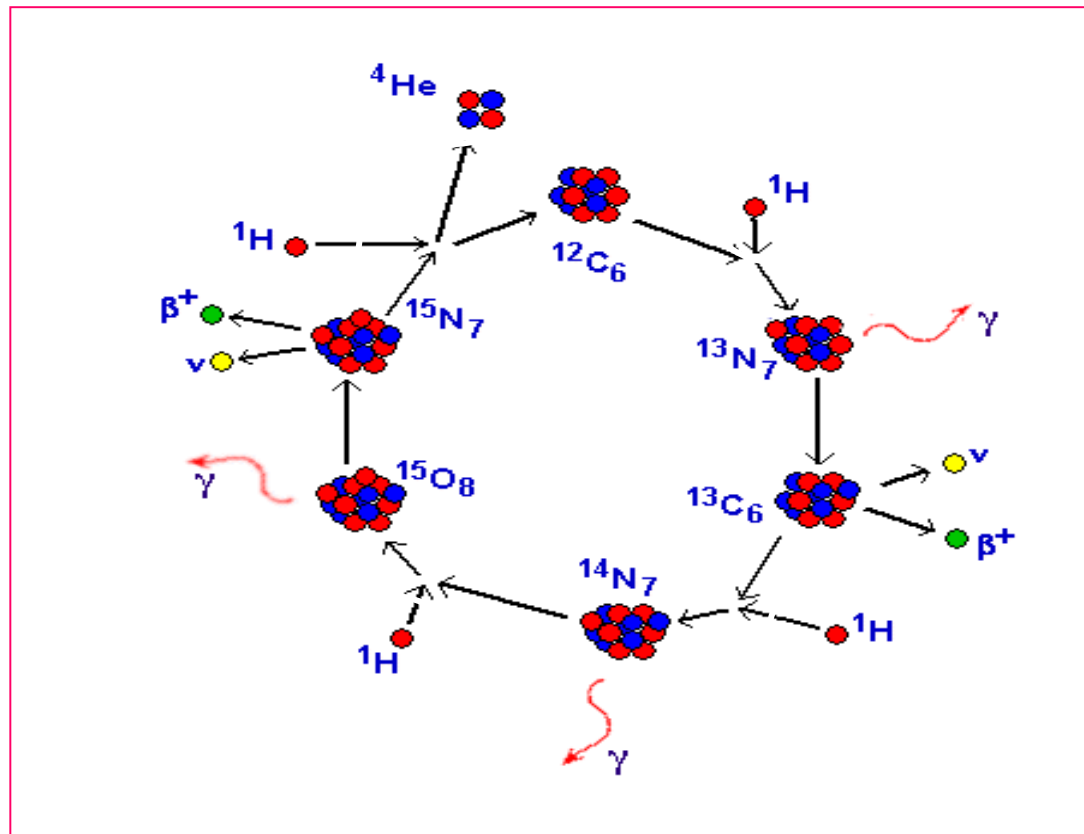
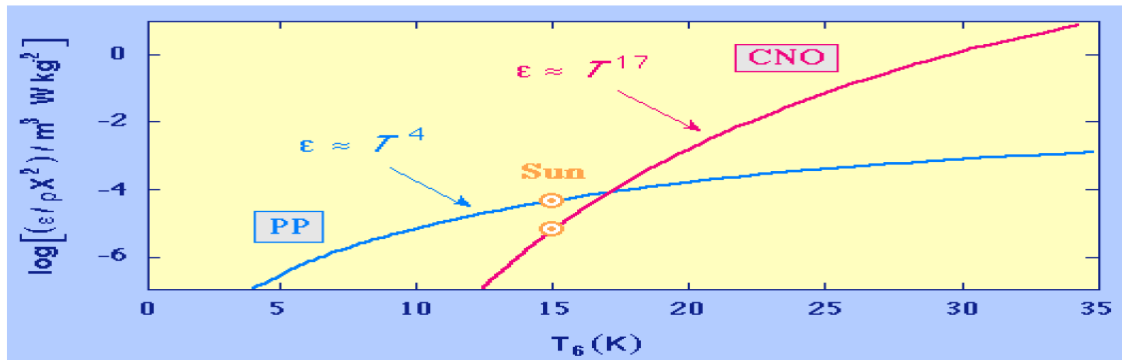
$$N_\nu \sim 2 \cdot 10^{38} \text{ s}^{-1}$$

Total loss 2.3 %

Solar neutrinos



Temperature dependence of pp-chain and CNO-cycle



Le Modèle Solaire SSM

H. Bethe, C. Weizsäcker, . . . , J. Bahcall, S. Turk-Chieze

*Description de l'équilibre hydrostatique des étoiles de la série principale
avec les données en température, densité, composition, . . . , du Soleil*

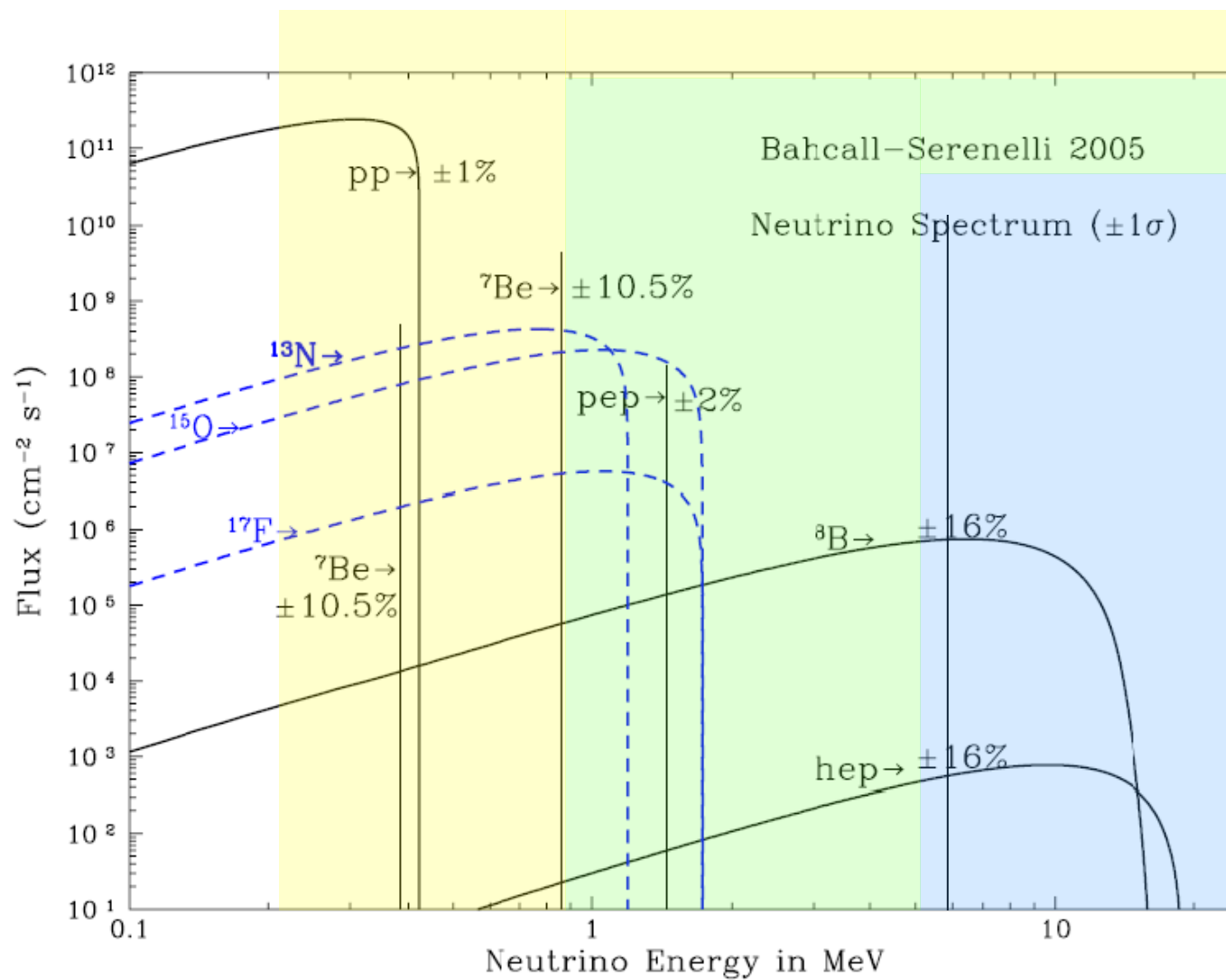
- Fusion H en He comme source d'énergie
- Sections efficaces fortement extrapolées : $E_p \sim 10 \text{ keV}$
- Forte dépendance des paramètres : $\Phi(\nu_{^8\text{B}}) \sim (T_c)^{25}$
-
-

Neutrinos Solaires => bonne connaissance de la machine « Soleil »

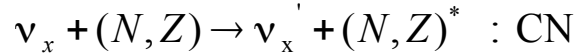
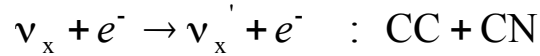
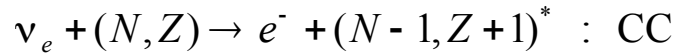
$$\Rightarrow T_c = 15.7 (1 \pm 1 \%) 10^6 \text{ K}$$

| Source | E_{ν}^{max} (MeV) | BS05(ASG,OP) ($\text{cm}^{-2} \text{ s}^{-1}$) | BTCM98 ($\text{cm}^{-2} \text{ s}^{-1}$) |
|---|--------------------------|---|---|
| $p + p \rightarrow {}^2\text{H} + e^+ + \nu$ | 0.42 | 6.06×10^{10} | 5.98×10^{10} |
| ${}^{13}\text{N} \rightarrow {}^{13}\text{C} + e^+ + \nu$ | 1.20 | 2.01×10^8 | 4.66×10^8 |
| ${}^{15}\text{O} \rightarrow {}^{15}\text{N} + e^+ + \nu$ | 1.73 | 1.45×10^8 | 3.97×10^8 |
| ${}^{17}\text{F} \rightarrow {}^{17}\text{O} + e^+ + \nu$ | 1.74 | 3.25×10^6 | |
| ${}^8\text{B} \rightarrow {}^8\text{Be} + e^+ + \nu$ | ~ 15 | 4.51×10^6 | 4.82×10^6 |
| ${}^3\text{He} + p \rightarrow {}^4\text{He} + e^+ + \nu$ | 18.77 | 8.25×10^3 | |
| ${}^7\text{Be} + e^- \rightarrow {}^7\text{Li} + \nu$ | 0.86 (90%) 0.38 (10%) | 4.34×10^9 | 4.70×10^9 |
| $p + e^- + p \rightarrow {}^2\text{H} + \nu$ | 1.44 | 1.45×10^8 | 1.41×10^8 |

Spectre neutrinos dans le SSM



Evolution expérimentale



Détection indirecte Radiochimie

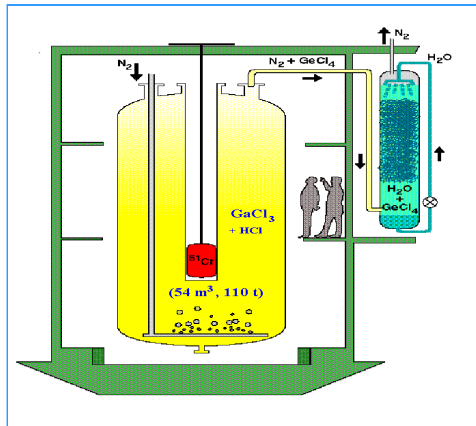
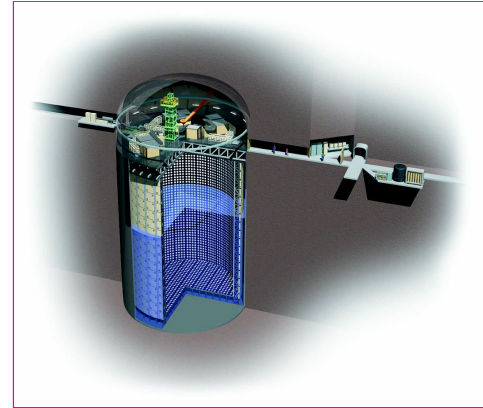


Davis ~ 1970 / (^{37}Cl)
~ 850 keV / $\Phi_\nu = 34\%$

Kamiokande (87) / Cerenkov(H_2O)

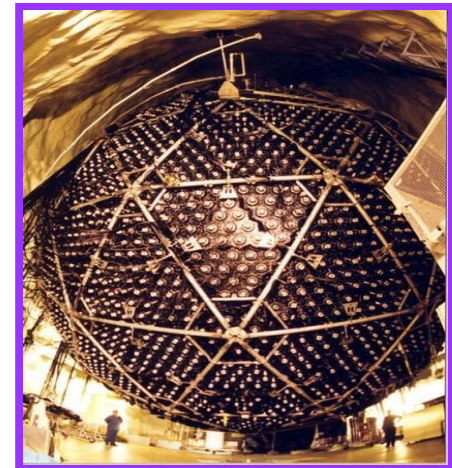
Super-K (~90) ~ 5 MeV / $\Phi_\nu = 46\%$

Détection directe Cerenkov

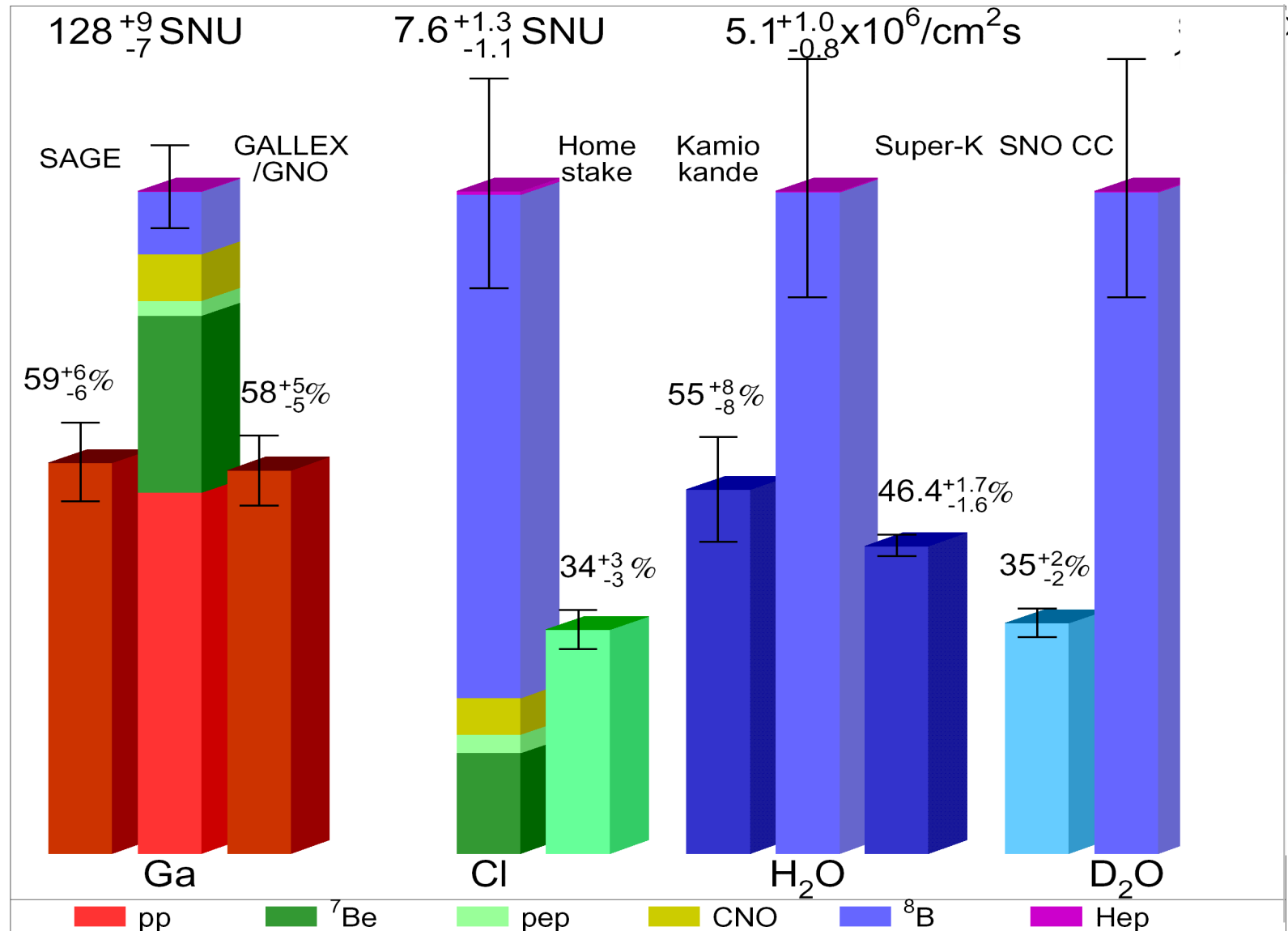


SNO ~ 1990 / Cerenkov (D_2O)
~ 2 - 8 MeV / $\Phi_\nu = 35\% \text{ et } 100\%$

GALEX – SAGE ~ 1990 / (^{71}Ga)
~ 230 keV / $\Phi_\nu = 59\%$



Solar ν Problem



Smaller than expected in wide range of neutrino energy

Détecteur SNO

2092 m to Surface

18 m Diameter
Support Structure
for 9500 PMTs,
60% coverage

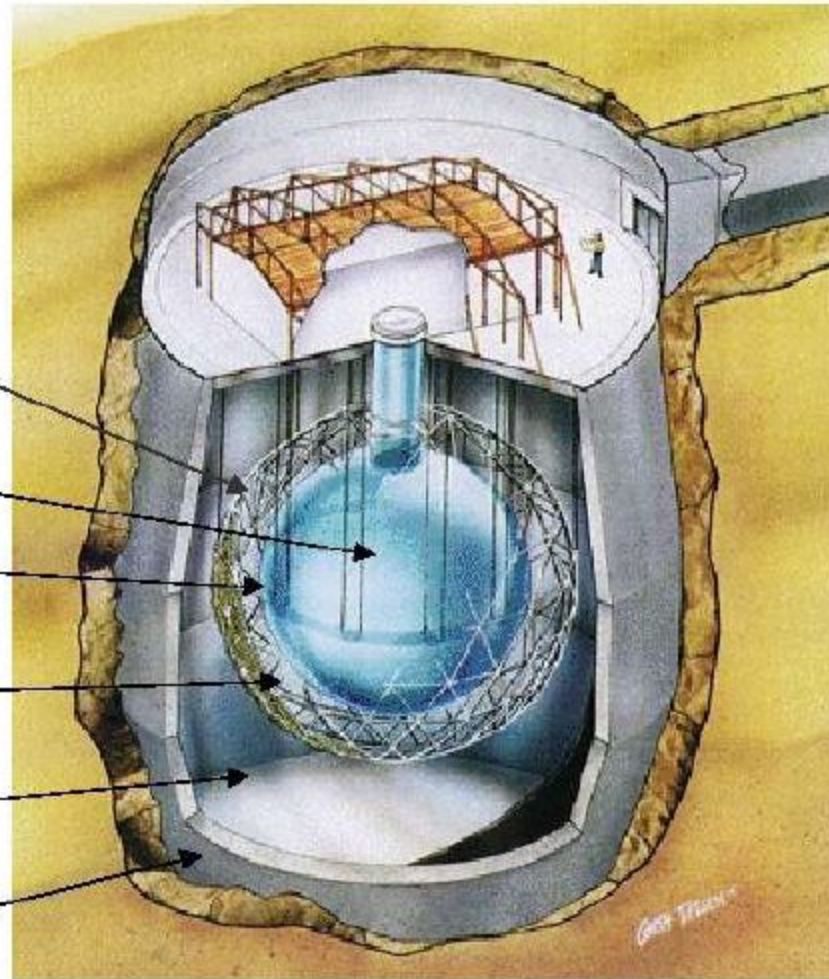
1000 Tonnes D_2O

12 m Diameter
Acrylic Vessel

1700 Tonnes Inner
Shielding H_2O

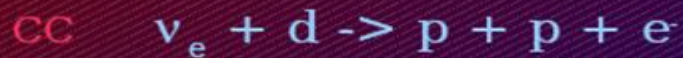
5300 Tonnes Outer
Shield H_2O

Urylon Liner and
Radon Seal



Départ 1999

Oser ICHEP 2002



Sensible uniquement à ν_e

Faible sensibilité à la direction

$$E_{\text{seuil}}(\text{CC}) \sim 8.2 \text{ MeV}$$

$$\phi_{\text{CC}} = \phi_{\nu_e}$$



Sensible aux 3 saveurs

Mesure du flux total du ^8B

$$E_{\text{seuil}}(\text{NC}) \sim 2.2 \text{ MeV}$$

$$\phi_{\text{NC}} = \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}$$



Sensible surtout à ν_e

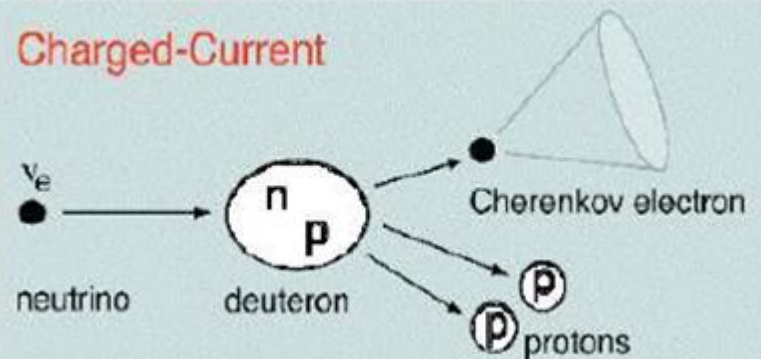
Directionnalité

$$E_{\text{seuil}}(\text{ES}) \sim 7.0 \text{ MeV}$$

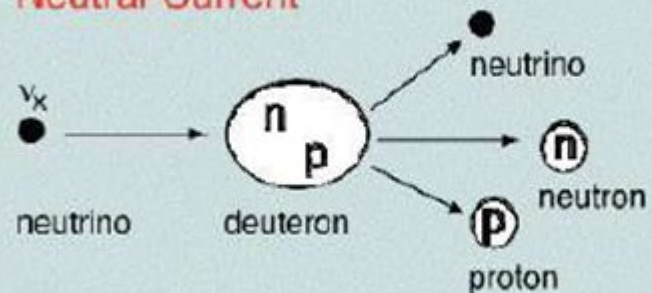
$$\phi_{\text{ES}} = \phi_{\nu_e} + 0.154(\phi_{\nu_\mu} + \phi_{\nu_\tau})$$

Neutrino Reactions on Deuterium

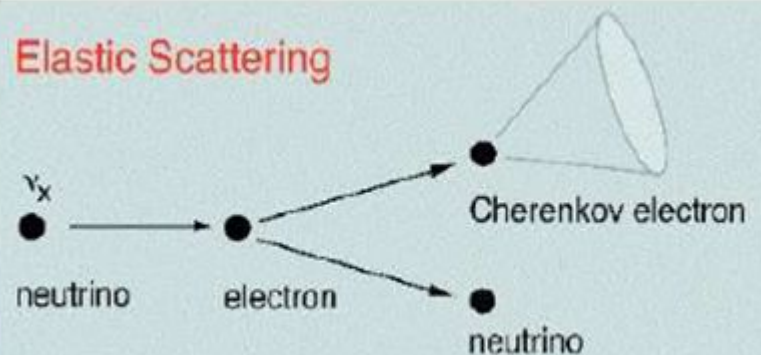
Charged-Current



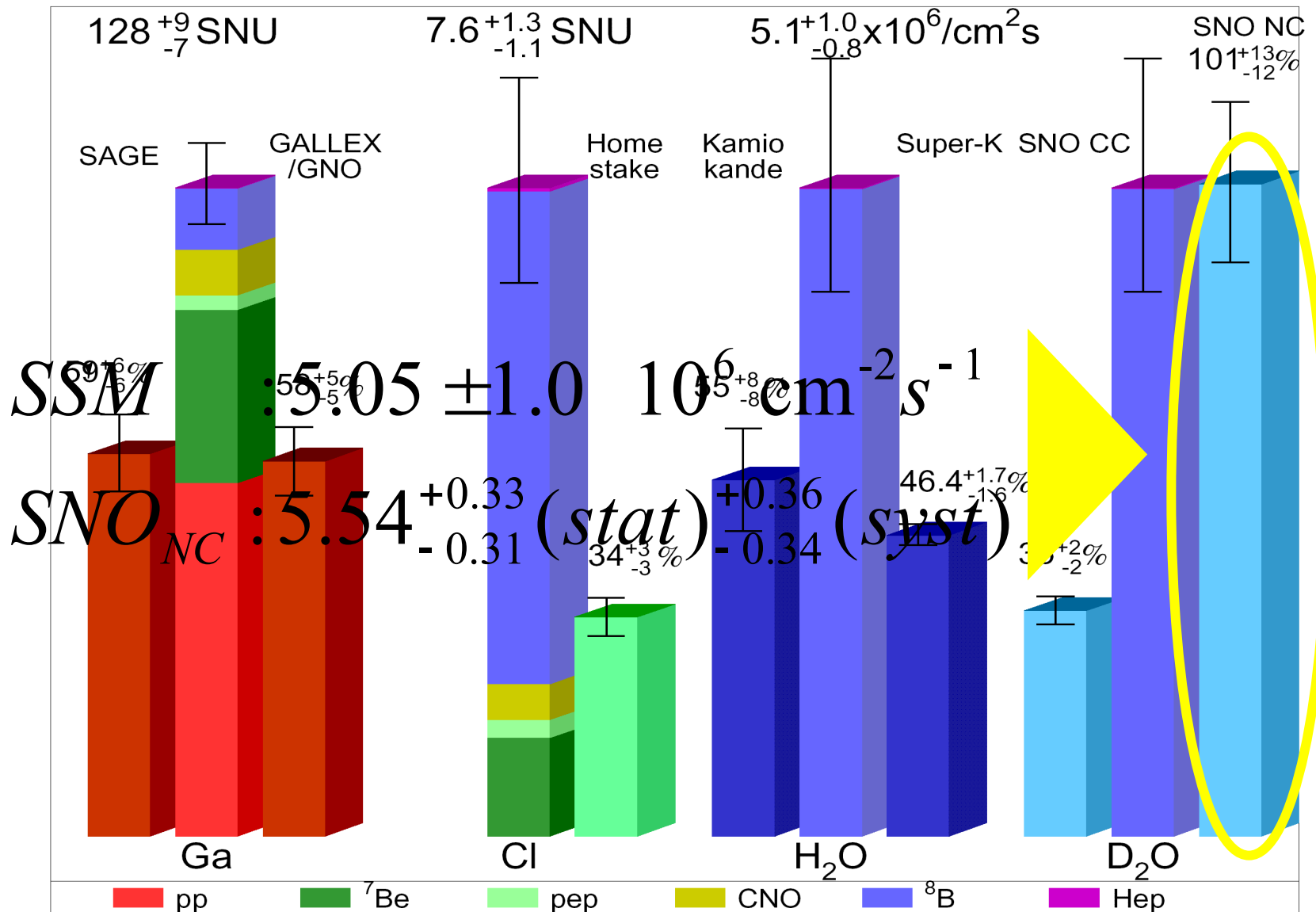
Neutral-Current



Elastic Scattering

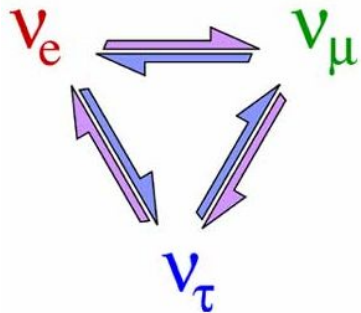


Solar ν Problem



Smaller then expected in wide range of neutrino energy

Oscillations des Neutrinos

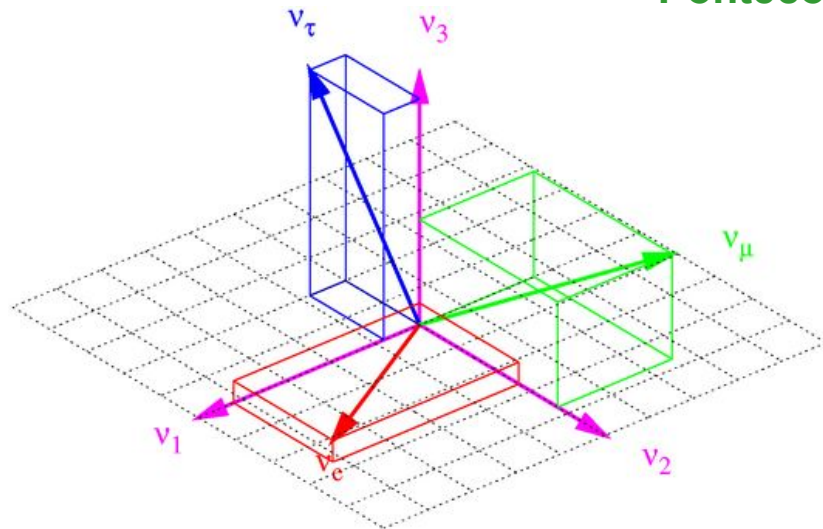


$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad \left. \begin{aligned} \nu_\ell &= \sum_{k=1,2,3} U_{\ell k} \nu_k \\ \sum_{k=1,2,3} |U_{\ell k}|^2 &= 1 \end{aligned} \right\} \ell = e, \mu, \tau$$

Etats propres
de saveur

Etats propres
de masse

Pontecorvo-Maki-Nakagawa-Sakata

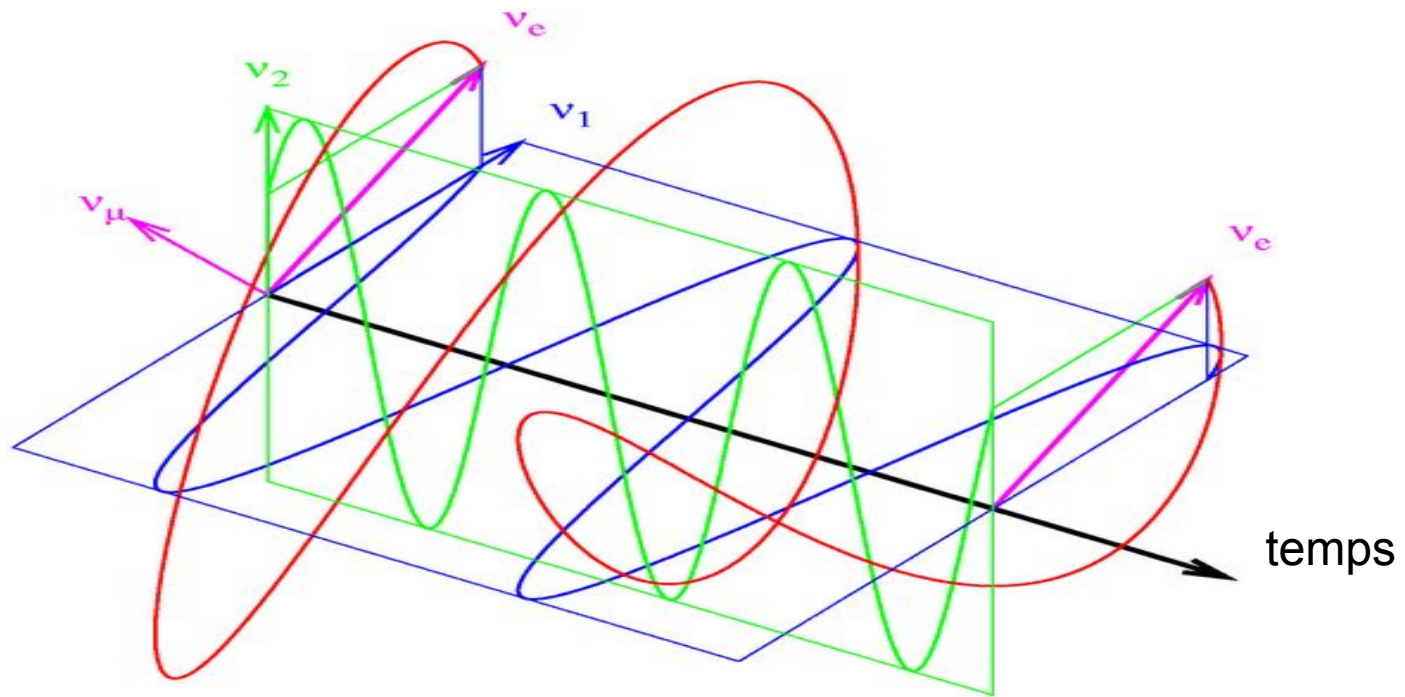


Probabilité d'oscillation
(cas simple)

$$\begin{aligned} P(\nu_l \rightarrow \nu_{l' \neq l}) &= \sin^2 2\theta_{ll'} \sin^2(1.27 \Delta m^2 L / E) \\ P(\nu_l \rightarrow \nu_l) &= 1 - P(\nu_l \rightarrow \nu_{l' \neq l}) \\ \begin{pmatrix} \nu_l \\ \nu_{l'} \end{pmatrix} &= \begin{pmatrix} \cos \theta_{ll'} & \sin \theta_{ll'} \\ -\sin \theta_{ll'} & \cos \theta_{ll'} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \end{aligned}$$



$$m_\nu \neq 0$$



CP

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\vartheta_{23} \simeq \vartheta_{\text{ATM}}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix}}_{\vartheta_{13} \simeq \vartheta_{\text{CHOOZ}}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\vartheta_{12} \simeq \vartheta_{\text{SOL}}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}}_{\beta\beta_{0\nu}}$$

Pontecorvo-Maki-Nakagawa-Sakata

Propagation des neutrinos dans la matière => potentiel d'interaction

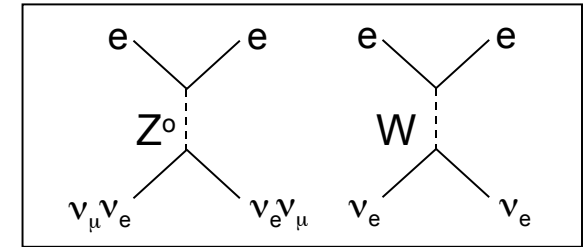
$$n = 1 + V/p$$

$$V_\mu = V_\tau = V_{NC} \text{ et } V_e = V_{NC} + V_{CC}$$

V : potentiel effectif d'interaction

n : indice de réfraction

$$H_m^\alpha = H^\alpha + \frac{1}{2p} \begin{pmatrix} A & 0 \\ 0 & 0 \end{pmatrix} \quad A = 2\sqrt{2}G_F N_e p$$



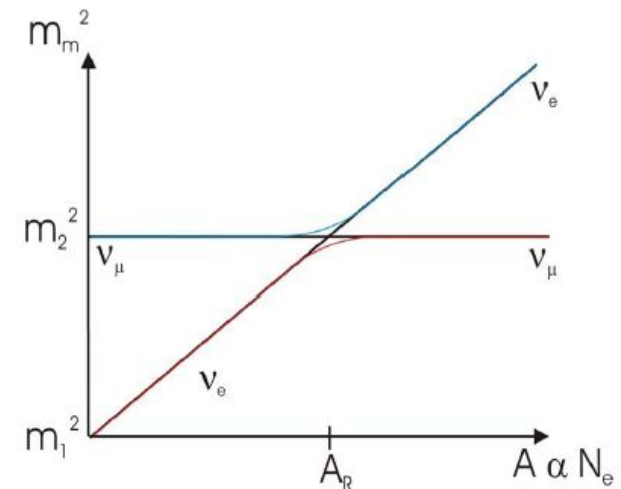
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_m & \sin\theta_m \\ -\sin\theta_m & \cos\theta_m \end{pmatrix} \begin{pmatrix} \nu_{1m} \\ \nu_{2m} \end{pmatrix} \quad \sin^2 2\theta_m = \frac{\sin^2 2\theta}{\left(\frac{A}{\Delta m^2} - \cos 2\theta\right)^2 + \sin^2 2\theta}$$

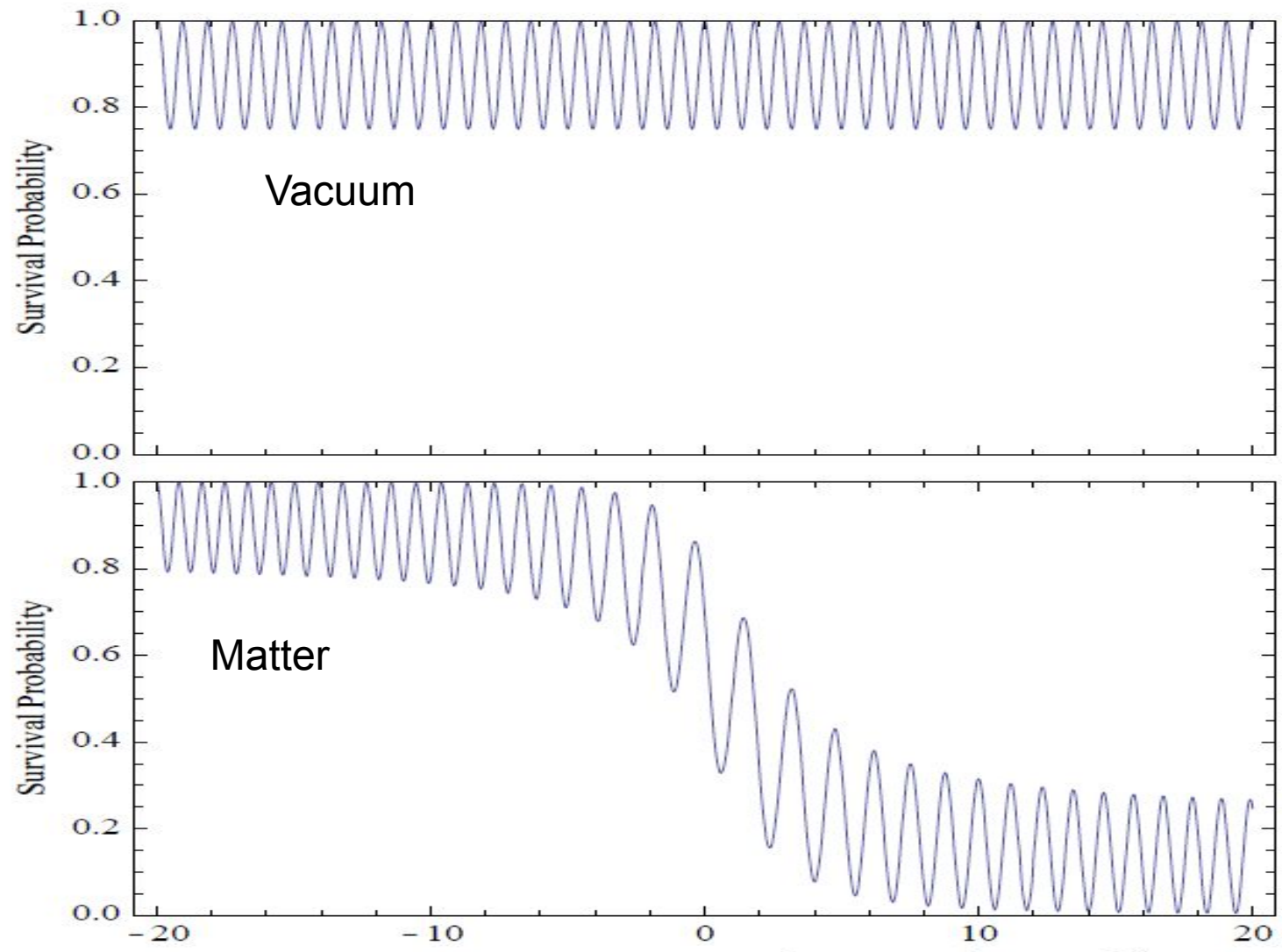
$$\longrightarrow P(\nu_e \rightarrow \nu_\mu) \propto \sin^2 2\theta_m$$

➤ $\frac{A}{\Delta m^2} \approx 0 \Rightarrow \text{Oscillations dans le vide}$

➤ $\frac{A}{\Delta m^2} \gg 1 \Rightarrow \text{Pas d'oscillations}$

➤ $\frac{A}{\Delta m^2} \approx \cos^2 \theta \Rightarrow P \sim 1 \text{ (indépendant de } \theta \text{)}$

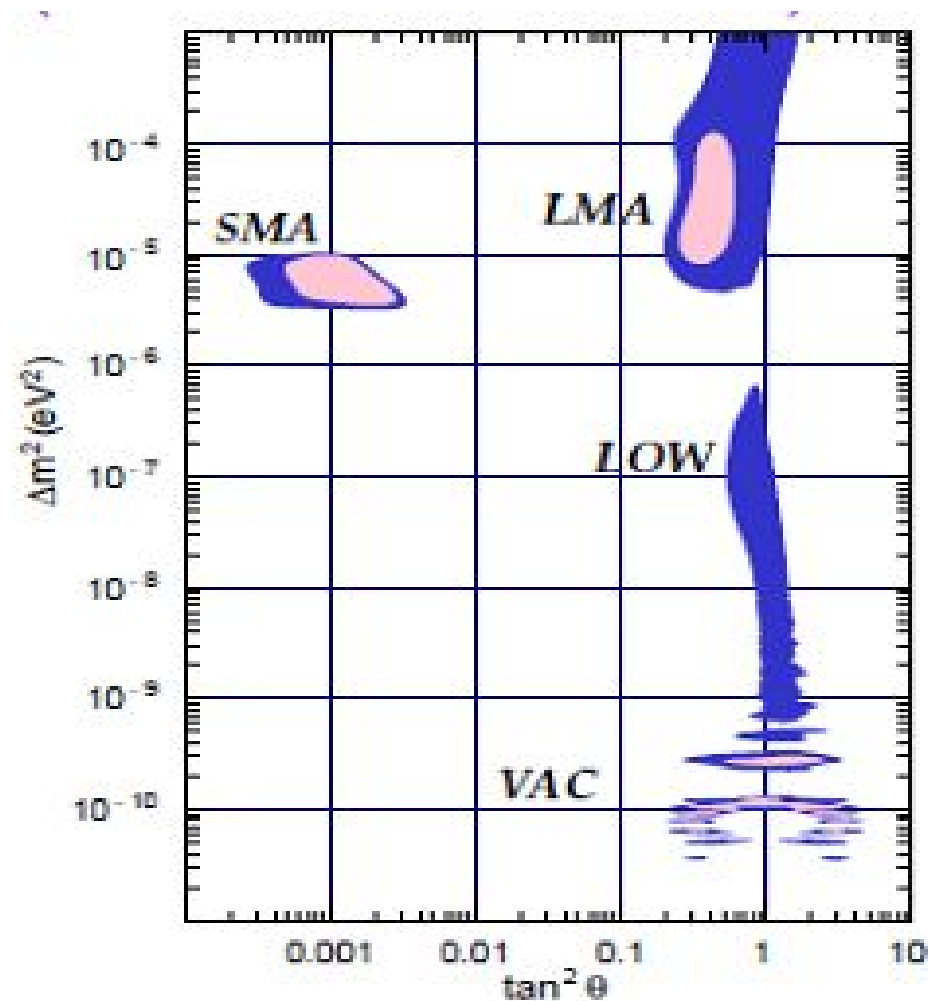




$$R \left[4E \cos 2\theta / (\Delta m^2 \sin^2 2\theta) \right]$$

Solutions possibles à l'aube du 21ème siècle

$$\nu_e \rightarrow \nu_\mu$$



[de Gouvea, Friedland, Murayama, PLB 490 (2000) 125]

Aujourd'hui



$\Delta m_{21}^2 \text{ (eV}^2\text{)}$

10^{-4}

KamLAND

95% C.L.

99% C.L.

99.73% C.L.

• best fit

Solar

95% C.L.

99% C.L.

99.73% C.L.

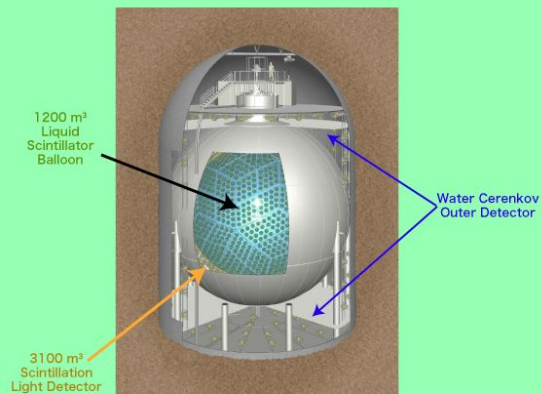
* best fit

10^{-1}

1

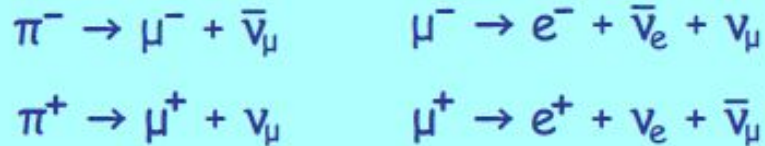
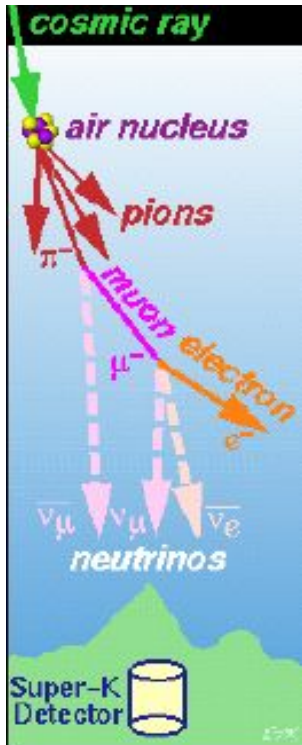
$\tan^2 \theta_{12}$

[KamLAND, PRL 100 (2008) 221803]



Neutrinos atmosphériques

Interaction des Rayons Cosmiques dans la haute atmosphère :



$$2 \nu_\mu \quad 2 \bar{\nu}_\mu \quad 1 \nu_e \quad 1 \bar{\nu}_e$$

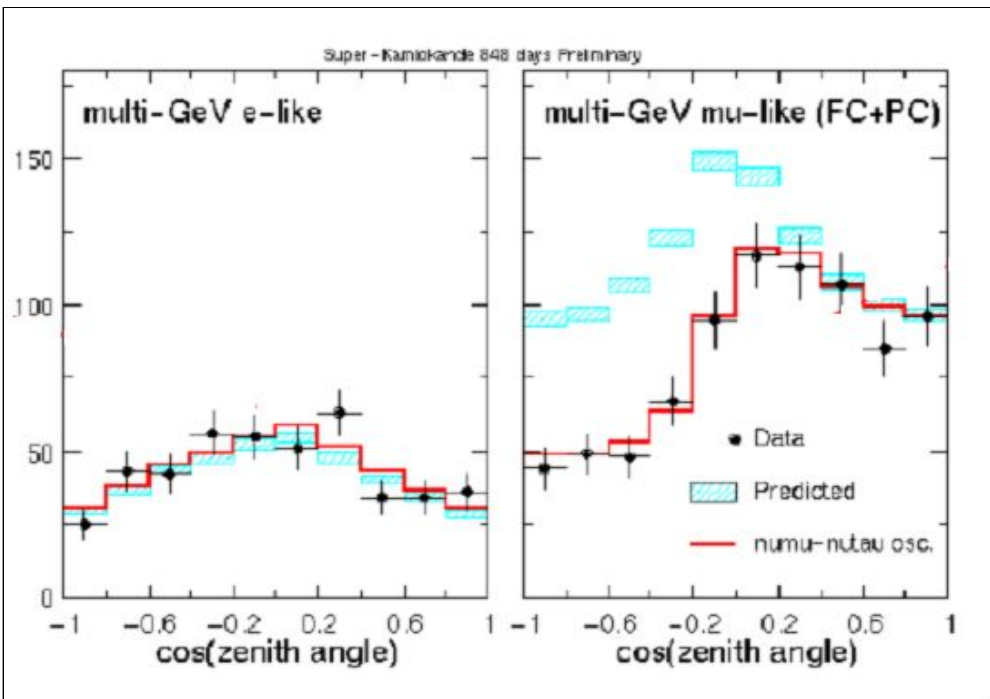
Résultat

$$\nu_\mu / \nu_e \sim 1.36 \pm 0.08$$

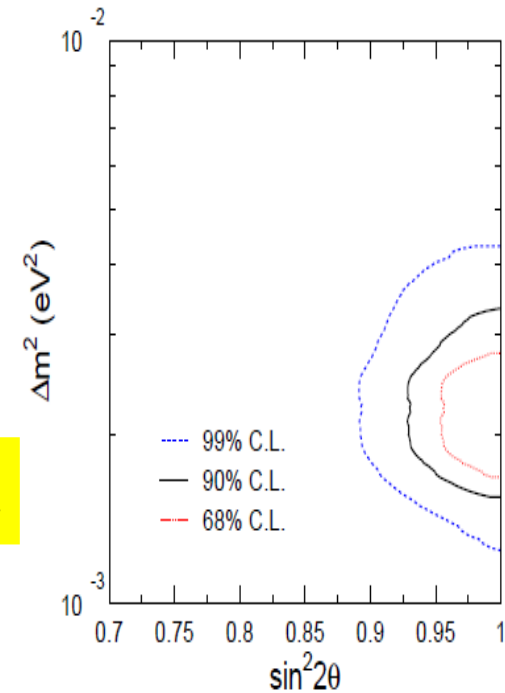
au lieu de **2**

$$\left. \begin{array}{l} \nu_\mu \dashrightarrow \nu_e \\ \text{ou} \\ \nu_\mu \dashrightarrow \nu_\tau \end{array} \right\} \text{ dans l'atmosphère}$$

Neutrinos atmosphériques



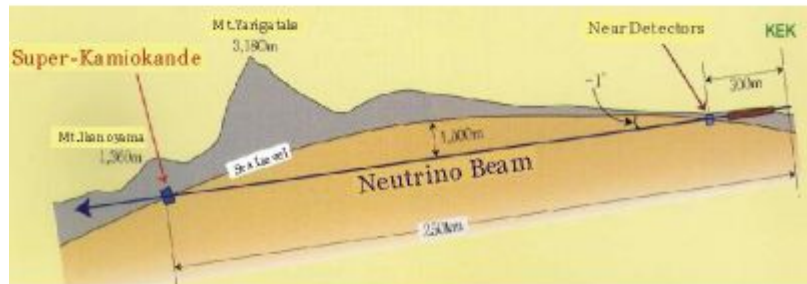
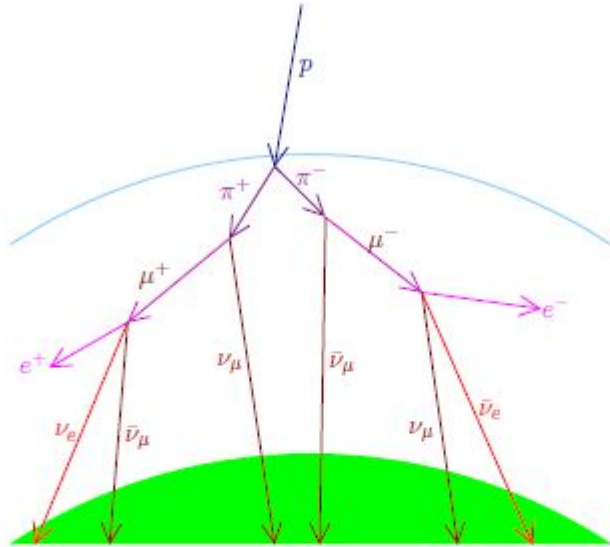
$$\nu_{\mu} \rightarrow \nu_{\tau}$$



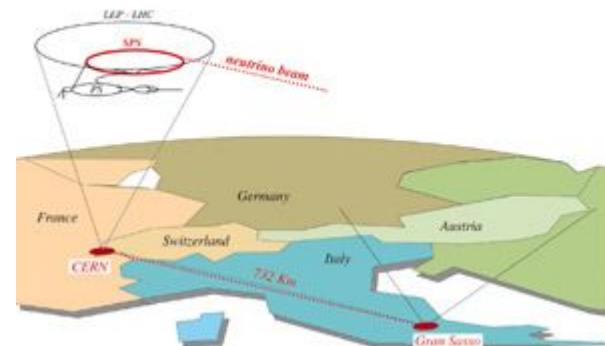
Très faible dépendance avec θ
=> pas d'oscillation

Forte dépendance avec θ
=> d'oscillation

Neutrinos Atmosphériques et LBL



CERN to Gran Sasso Neutrino Beam



Solar
 $\nu_e \rightarrow \nu_\mu, \nu_\tau$

Reactor
 $\bar{\nu}_e$ disappearance

Homestake
 Kamiokande
 GALLEX/GNO & SAGE
 Super-Kamiokande
 SNO
 BOREXino
 (KamLAND)

$\Delta m_{\text{SOL}}^2 \simeq (7.6 \pm 0.2) \times 10^{-5} \text{ eV}^2$
 $\tan^2 \vartheta_{\text{SOL}} \simeq 0.47 \pm 0.06$

Atmospheric
 $\nu_\mu \rightarrow \nu_\tau$

Accelerator
 ν_μ disappearance

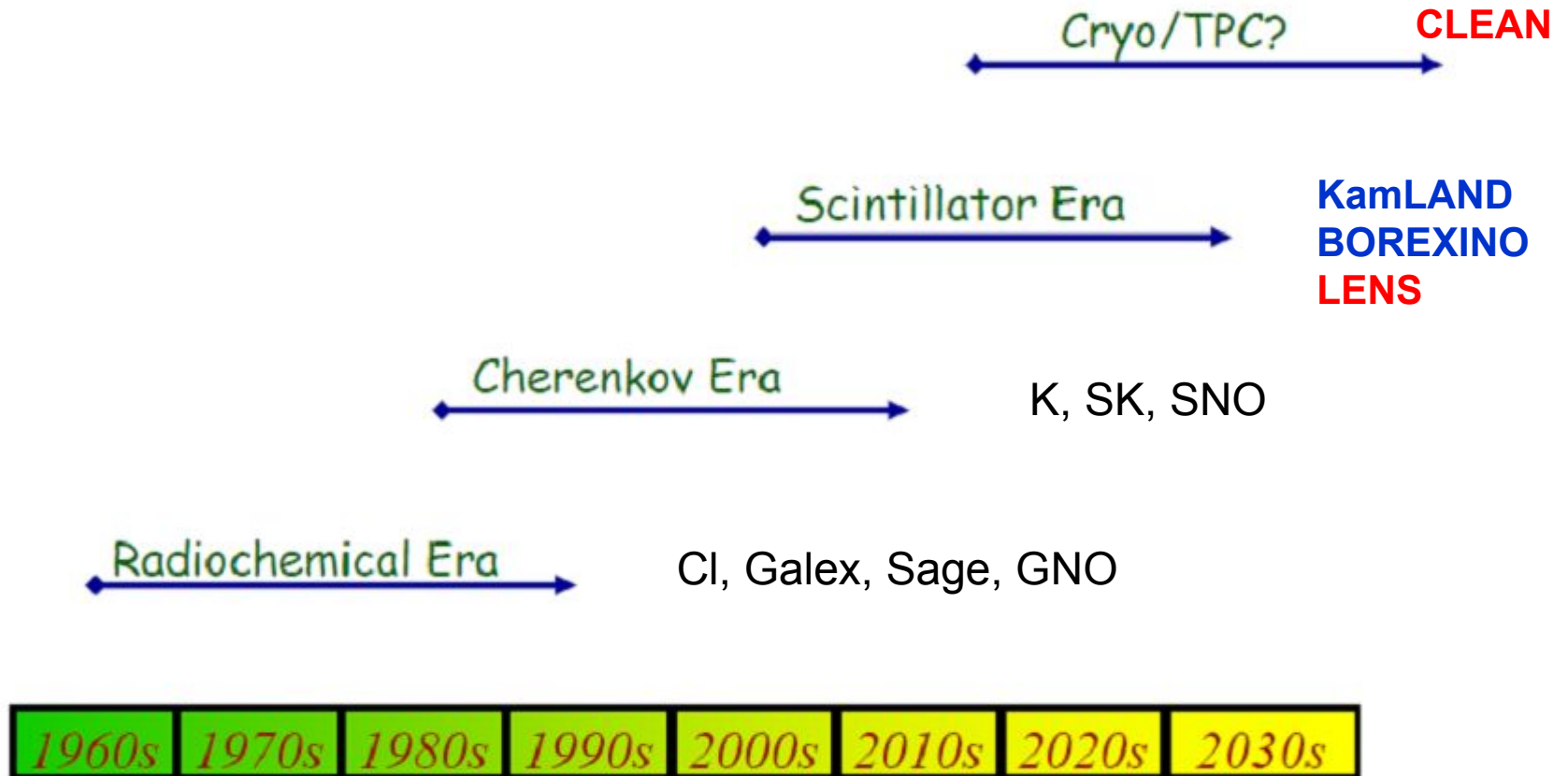
Kamiokande
 IMB
 Super-Kamiokande
 MACRO
 Soudan-2
 (K2K & MINOS)

$\Delta m_{\text{ATM}}^2 \simeq (2.4 \pm 0.1) \times 10^{-3} \text{ eV}^2$
 $\sin^2 \vartheta_{\text{ATM}} \simeq 0.50 \pm 0.07$

Two scales of Δm^2 : $\Delta m_{\text{ATM}}^2 \simeq 30 \Delta m_{\text{SOL}}^2$

Large mixings: $\vartheta_{\text{ATM}} \simeq 45^\circ$, $\vartheta_{\text{SOL}} \simeq 34^\circ$

Nouvelle Génération

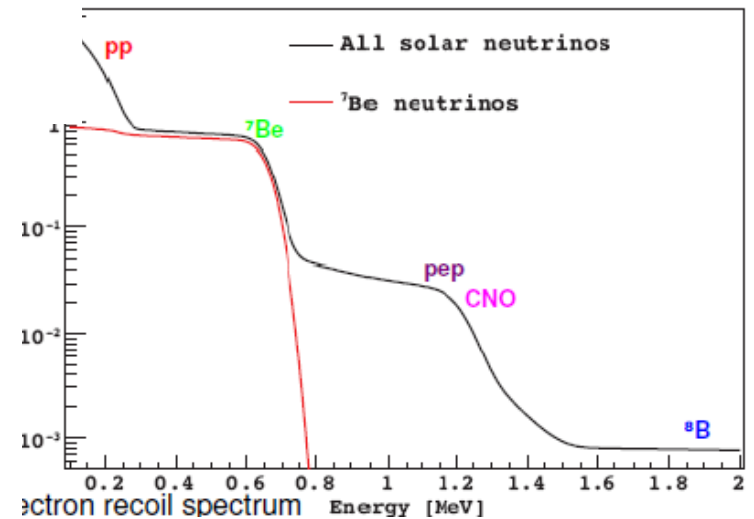
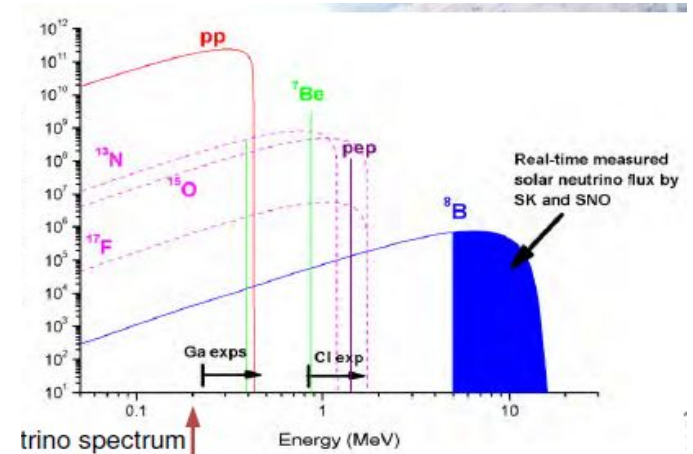
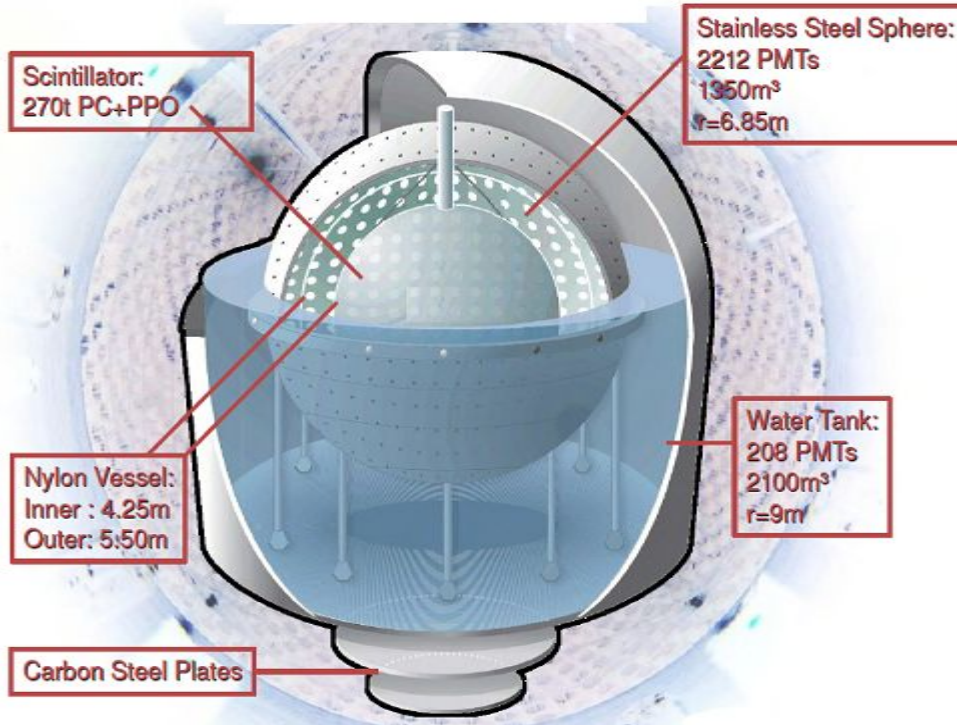


| Experiment | Detection Reaction | Targeted Solar vs | Technology | Other Physics | Status |
|----------------------------|---|----------------------------|---------------------------------|-------------------------------|--------------------------------|
| KamLAND | $\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$ | ${}^7\text{Be}$, CNO, pep | Liq. scintillator | Reactor vs, geo-vs | Purification underway |
| LENS | $\nu_e + {}^{115}\text{In} \rightarrow e^- + 2\gamma + {}^{115}\text{Sn}$ | pp, ${}^7\text{Be}$, pep | In-doped liq. scintillator | ----- | Prototype bkd studies |
| XMASS | $\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$ | pp | Scintillation in cryogenic Xe | dark matter, $0\nu\beta\beta$ | 800 kg stage in design |
| CLEAN | $\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$ | pp | Scintillation in cryogenic Ne | dark matter (DEAP/CLEAN) | 0.1 and 1 ton engineering |
| MOON | $\nu_e + {}^{100}\text{Mo} \rightarrow e^- + {}^{100}\text{Tc}$ | pp, ${}^7\text{Be}$, pep | Scintillator/ Fiber sandwich | $0\nu\beta\beta$ | Prototype for $0\nu\beta\beta$ |
| HERON | $\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$ | pp | Scintillation in cryogenic He | ----- | R&D complete Proposal ended |
| XAX | $\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$ | pp | Scintillation in cryo. Xe+Ar | dark matter, $0\nu\beta\beta$ | Design and simulation |
| Mega-H₂O | $\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$ | ${}^8\text{B}$, hep | H ₂ O Cerenkov | P-dk, LBL vs | Design, sim. |

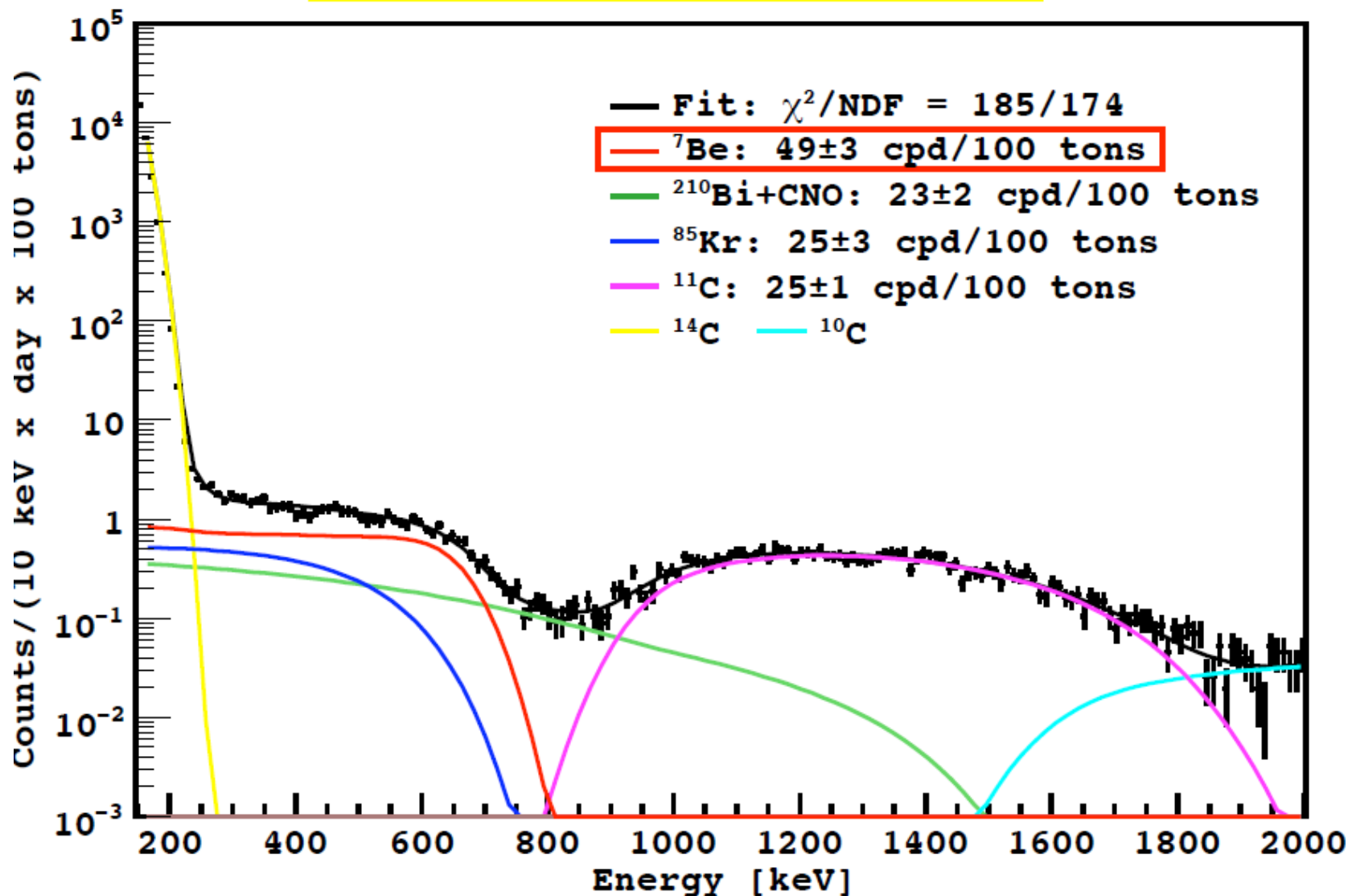
« Ce qui reste à faire »

- Mesures du spectre de neutrinos tout entier (pp, pep, 7Be, CNO)
 - > mesures directes (^8B , $E > 4.5 \text{ MeV}$) $\sim 10^{-3} \%$ du total
- Etudier le « Patern » d'oscillation de manière précise
 - > Oscillations MSW dominant @ $E > 3 \text{ MeV}$
 - > Oscillations vide dominant @ $E < 0.5 \text{ MeV}$
- Mesures précises des sections efficaces
- Controverse métallicite ($A > 4$) => mesure du CNO
 - > Heliosismologie (1998) accord avec SSM @ 0.5%
 - > Heliosismologie (2006) facteur 2 de différence
- Nouvelle physique cachée à basse énergie (MaVaN, μ_ν , ...)

BOREXINO



New Results: 192 Days



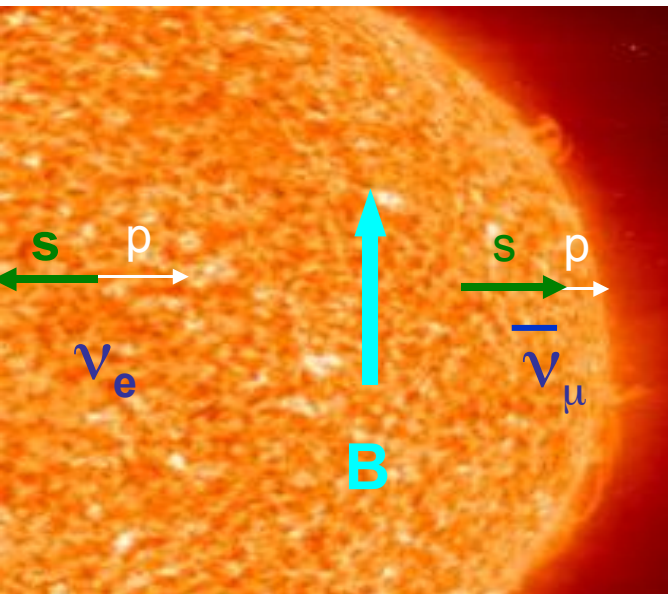
Solutions non standard

Moment magnétique

$$m_\nu \neq 0 \Rightarrow \frac{\mu_\nu}{\mu_B} \approx 3 \times 10^{-19} \frac{m_e}{1eV}$$

Spin-flavor precession

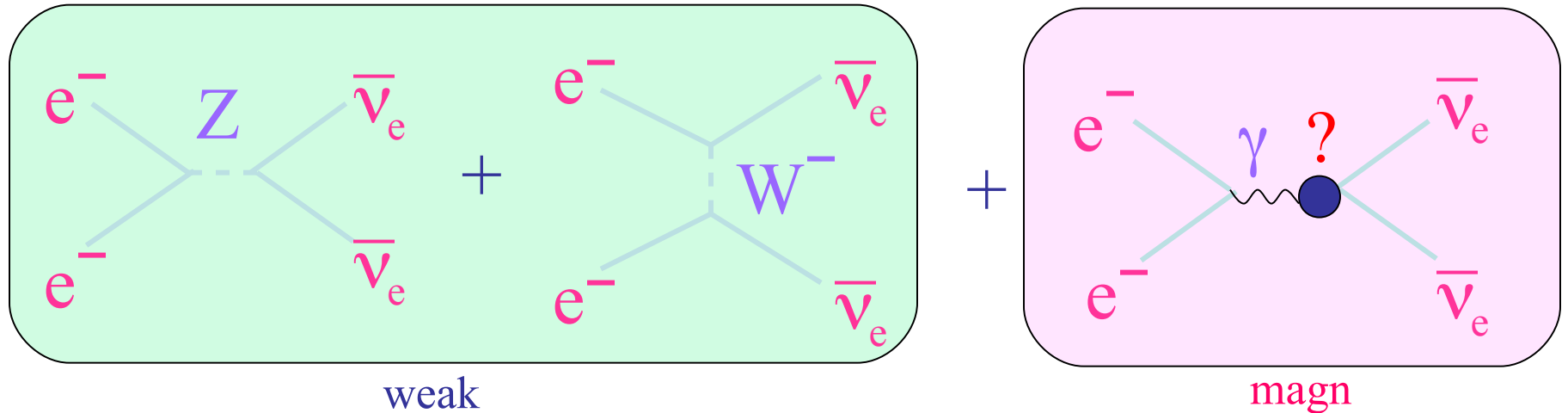
$$i \frac{d}{dt} \begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{eR} \\ \nu_{\mu R} \end{pmatrix} = \begin{pmatrix} H_L & BM^\dagger \\ BM & H_R \end{pmatrix} \begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{eR} \\ \nu_{\mu R} \end{pmatrix}$$



$$H_L = \begin{pmatrix} \frac{\Delta m^2}{2E} \sin^2 \theta + a_e & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & \frac{\Delta m^2}{2E} \cos^2 \theta + a_\mu \end{pmatrix} \quad M = \begin{pmatrix} \mu_{ee} & \mu_{e\mu} \\ \mu_{\mu e} & \mu_{\mu\mu} \end{pmatrix}$$

Marciano, Lim and Akhmedov

Diffusion $\nu - e^-$

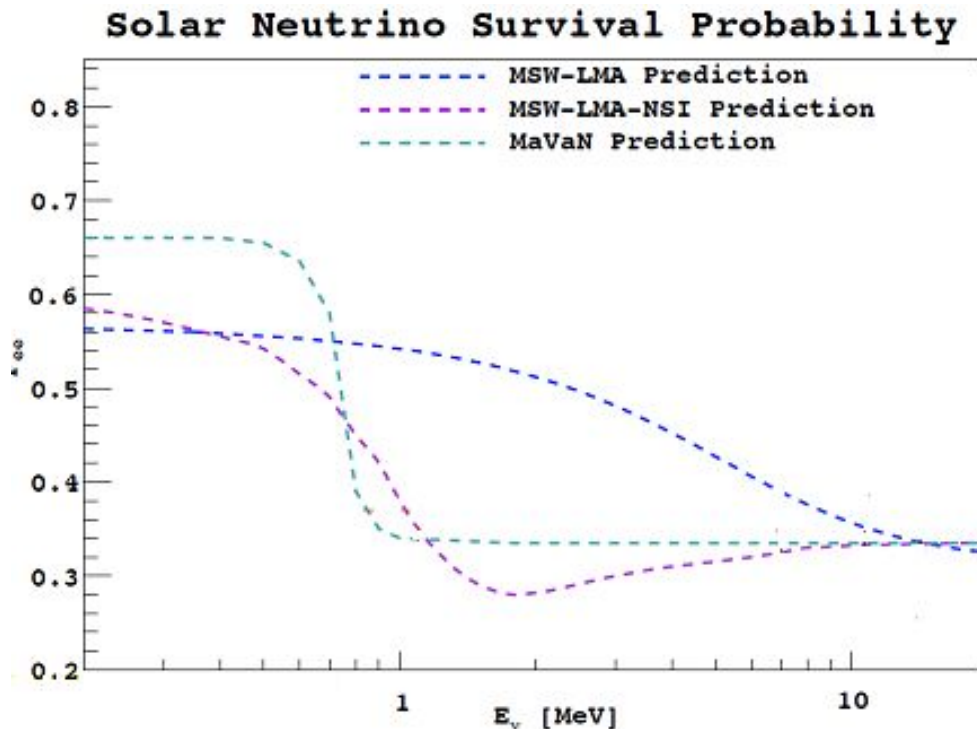
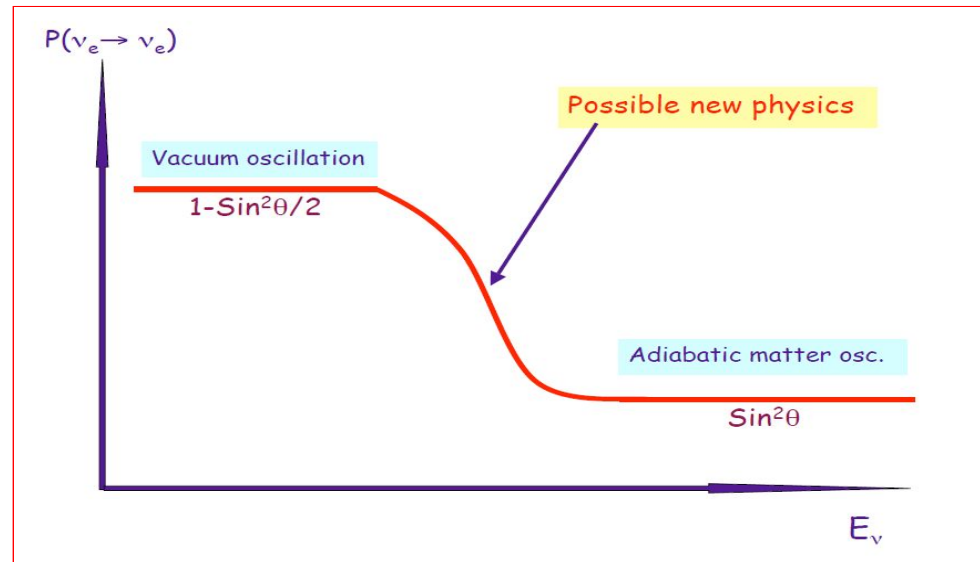


$$\frac{d\sigma}{dT_e} = \underbrace{\frac{G_F^2 m_e}{2\pi E_\nu^2} \left[E_\nu^2 (g_v - g_a)^2 + (g_v + g_a)^2 (E_\nu - T_e)^2 + m_e T_e (g_a^2 - g_v^2) \right]}_{\text{weak}} + \underbrace{\frac{(\pi \alpha^2 \mu_\nu^2)}{m_e^2} \frac{(1 - T_e/E_\nu)}{T_e}}_{\text{magn}}$$

Borexino $|\mu_\nu| < 0.84 \times 10^{-10} \mu_B$

Non Standard Interaction & MaVaN

$$i\hbar \frac{\partial}{\partial x} \begin{bmatrix} \Psi_e(x) \\ \Psi_x(x) \end{bmatrix} = \begin{bmatrix} \varphi(x) & \sqrt{\Lambda} \\ \sqrt{\Lambda} & -\varphi(x) \end{bmatrix} \begin{bmatrix} \Psi_e(x) \\ \Psi_x(x) \end{bmatrix}$$



NSI : Non Standard Neutrino Interactions

[Friedland et al. hep-ph/0402266](#)

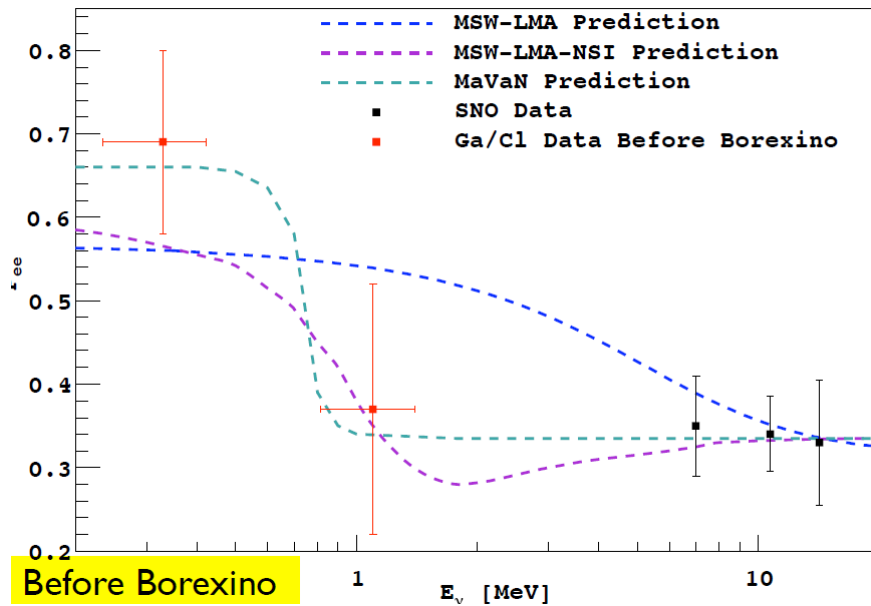
[Miranda et al. hep-ph/0406280](#)

MaVaN : Mass Varying Neutrinos

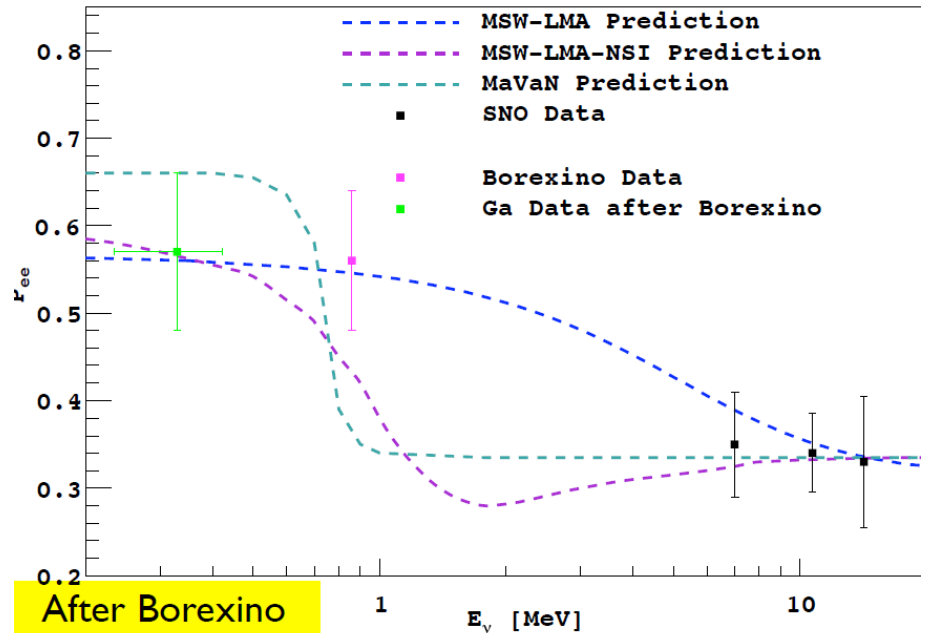
[Fardon et al. astro-ph/0309800](#)

[Barger et al. hep-ph/0502196](#)

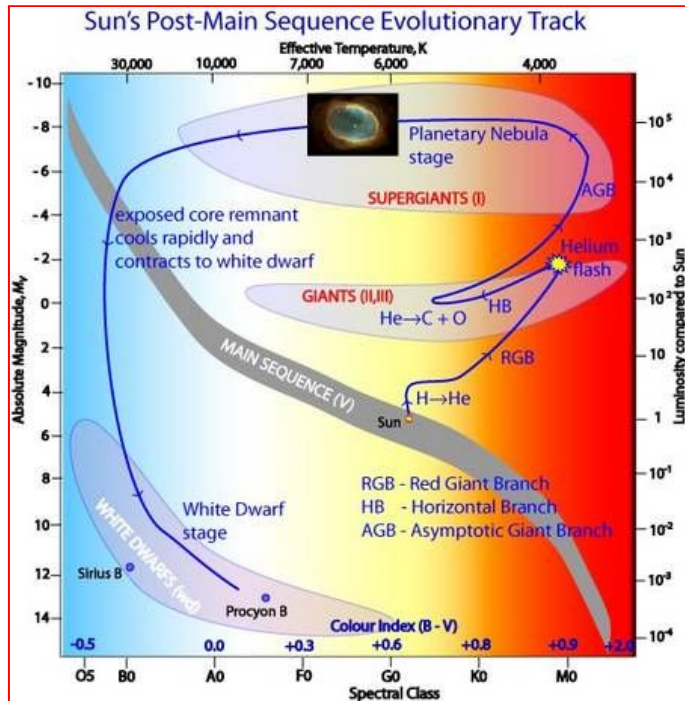
Solar Neutrino Survival Probability



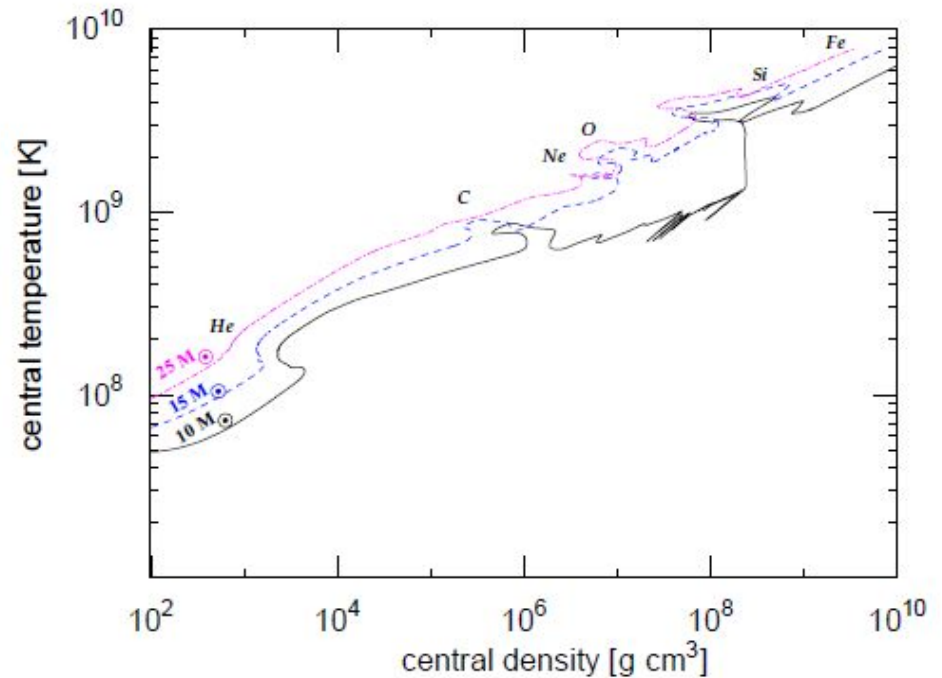
Solar Neutrino Survival Probability



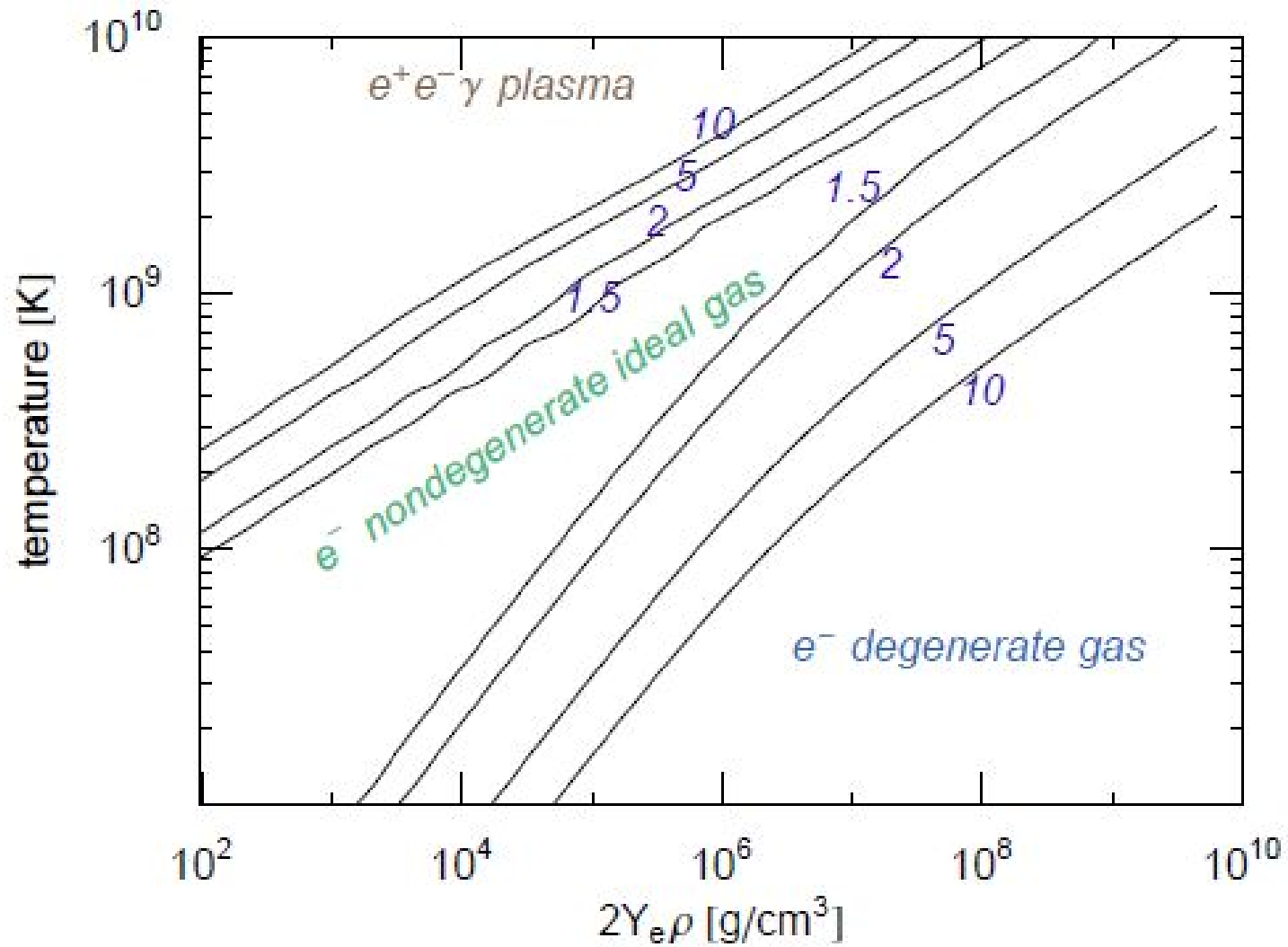
Au-delà de la séquence principale



Etoiles massives

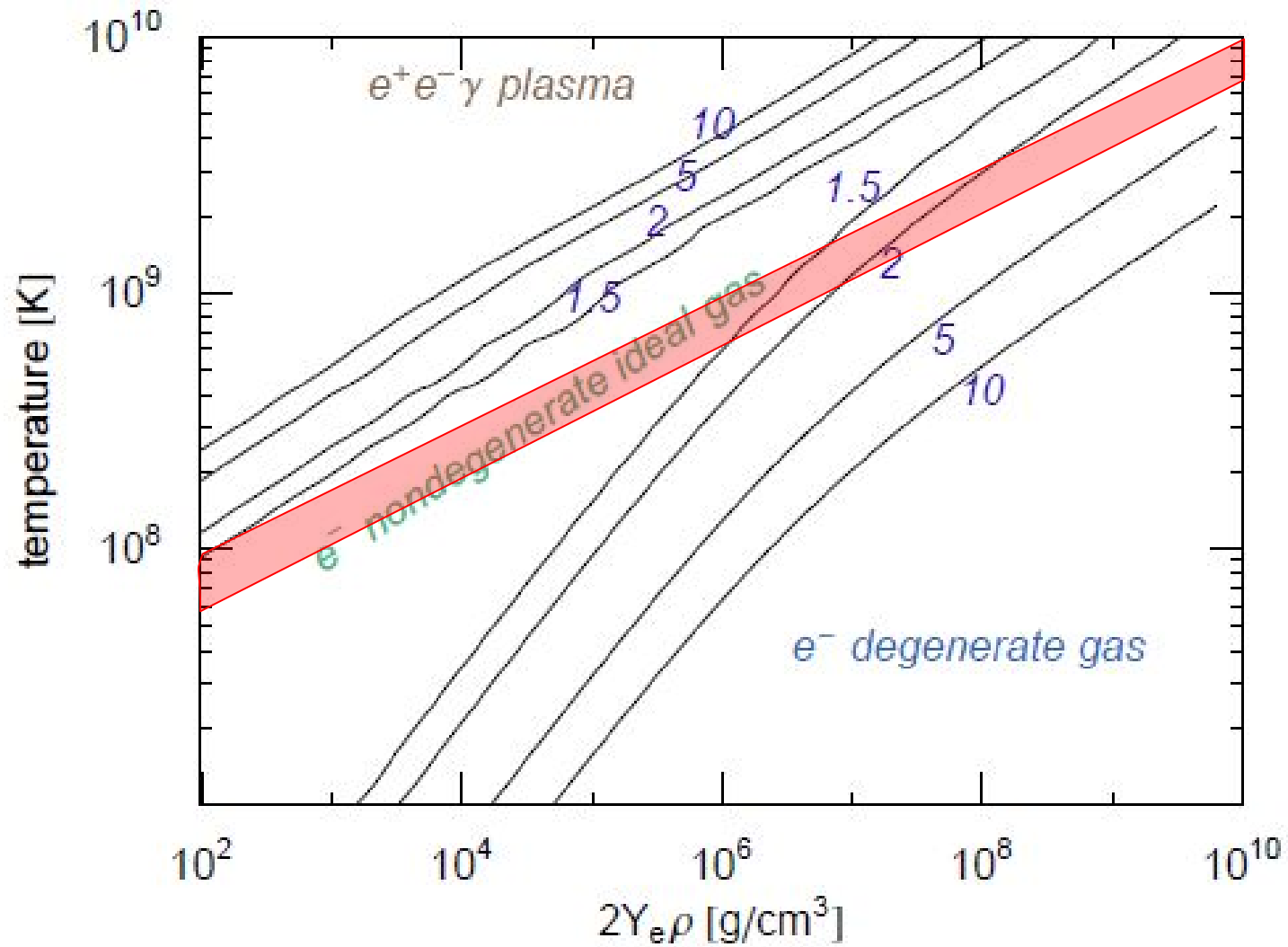


Type de « gaz »



Contours $P_{e+\gamma} / P_{e.g.i.}$

Type de « gaz »



Refroidissement de l'étoile

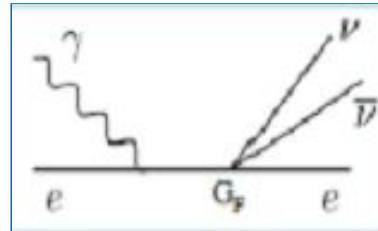
Refroidissement par photons : important dans la zone non dégénérée en dessous de 10^5 erg / g / s/

Refroidissement classique par neutrinos :

Classique (SM)

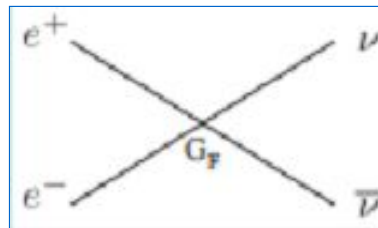
Photoproduction

$$\gamma e^- \rightarrow e \nu \bar{\nu}$$



Création de paires

$$e^+ e^- \rightarrow \nu \bar{\nu}$$



Décroissance de plasmon

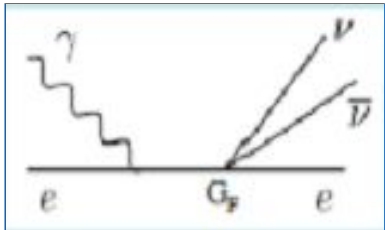

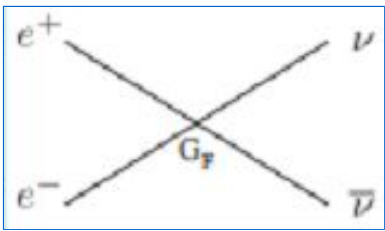
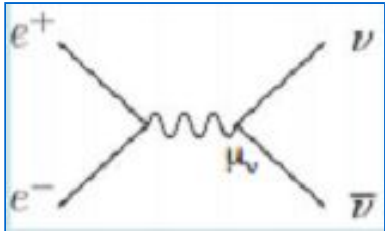
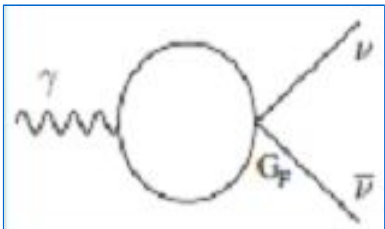
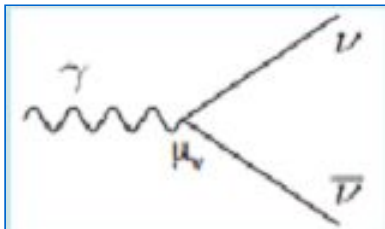
$$\gamma \rightarrow \nu \bar{\nu}$$



Refroidissement de l'étoile

Refroidissement par photons : important dans la zone non dégénérée en dessous de 10^5 erg / g / s

Refroidissement classique par neutrinos et avec moment magnétique :

| | | <u>Classique (SM)</u> | <u>Electromagnétiquement induit</u> |
|-------------------------|--|--|---|
| Photoproduction | $\gamma e^- \rightarrow e \nu \bar{\nu}$ |  |  |
| Création de paires | $e^+ e^- \rightarrow \nu \bar{\nu}$ |  |  |
| Décroissance de plasmon | $\gamma \rightarrow \nu \bar{\nu}$ |  |  |

$$\mu_\nu = 0$$

Non-degenerate
plasma

Pair Production

$$e^+ e^- \rightarrow \nu \bar{\nu}$$

temperature [K]

Photoproduction

$$\gamma e^- \rightarrow e \nu \bar{\nu}$$

Plasmon decay

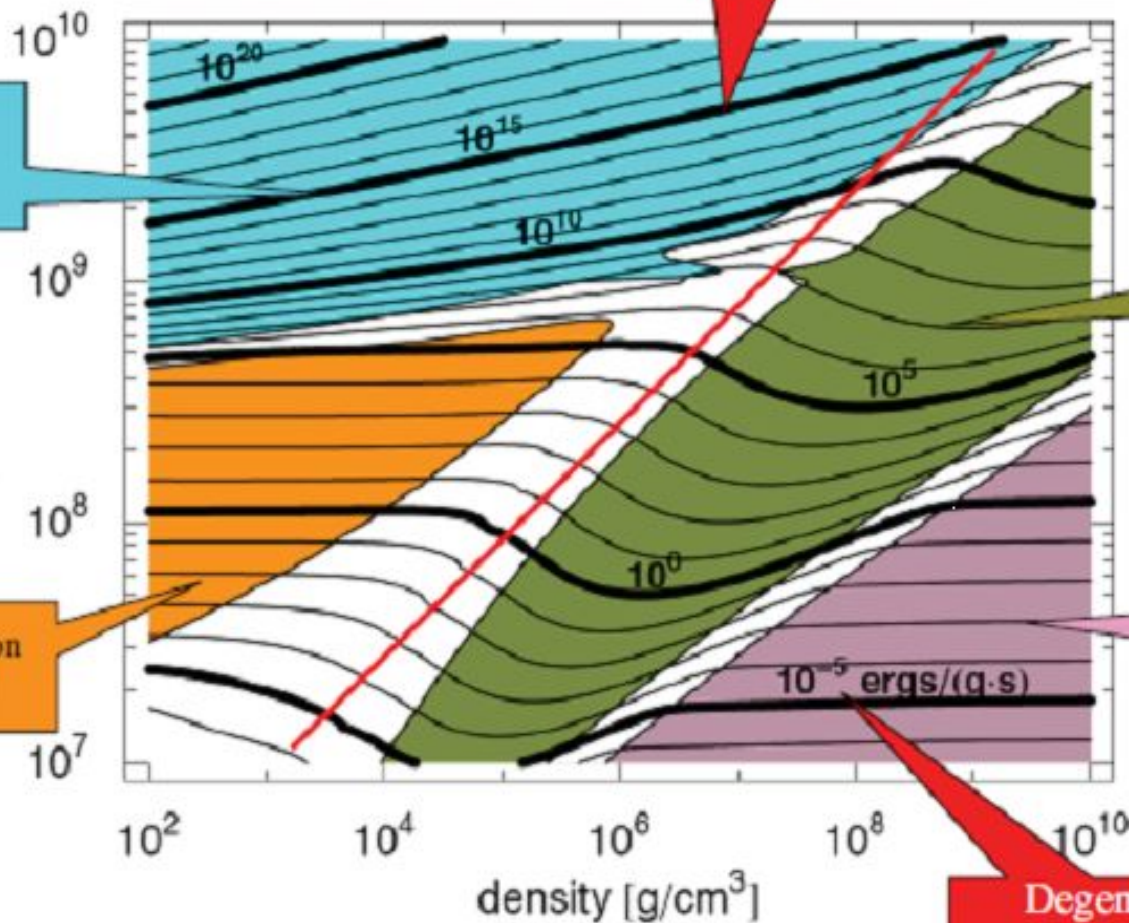
$$\gamma \rightarrow \nu \bar{\nu}$$

Bremsstrahlung

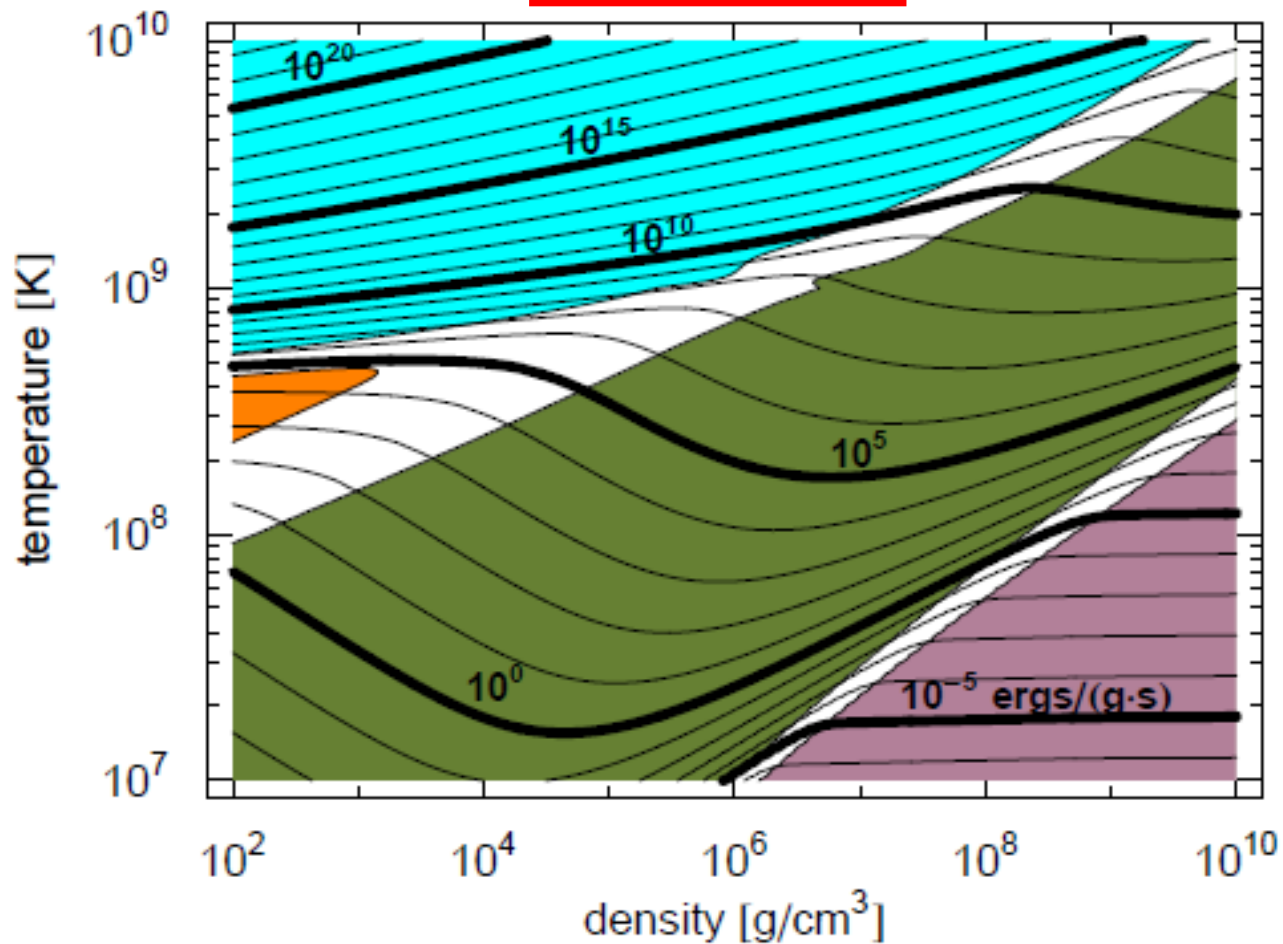
$$e^-(Ze) \rightarrow (Ze)e^- \nu \bar{\nu}$$

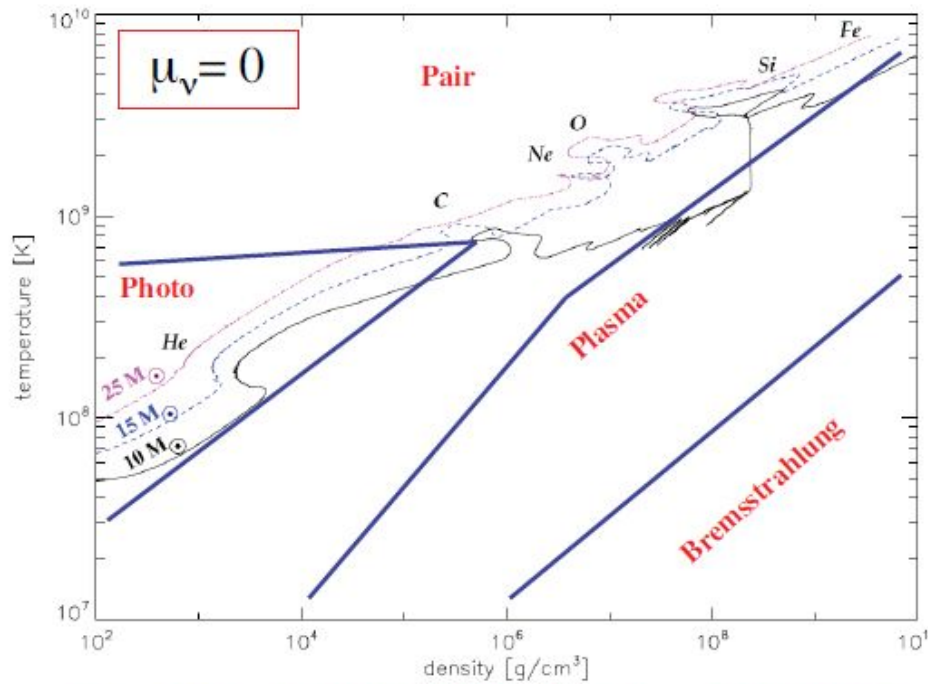
10^{-5} ergs/(g.s)

Degenerate
plasma

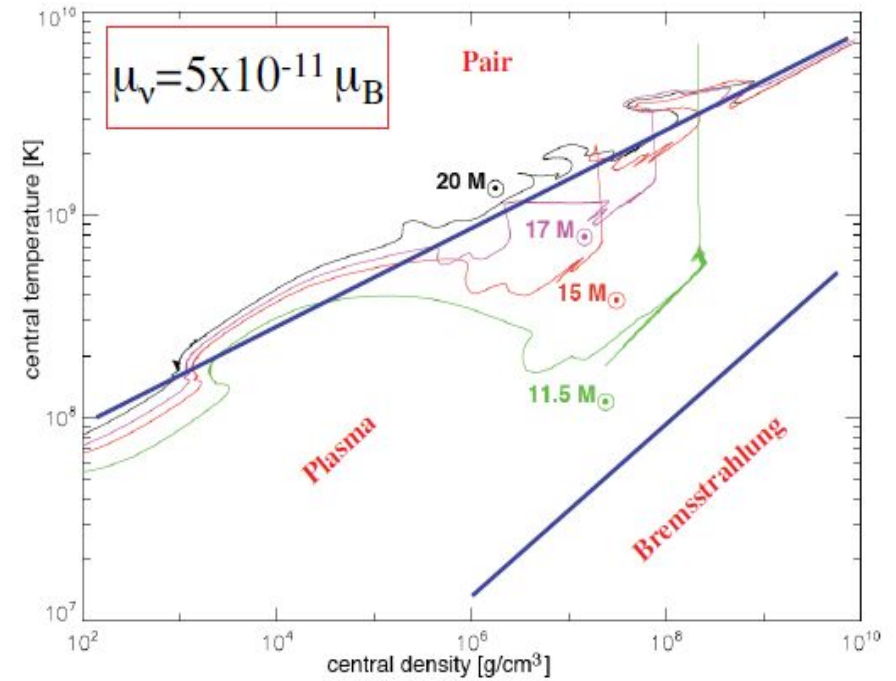


$$\mu_v = 5 \times 10^{-11} \mu_B$$





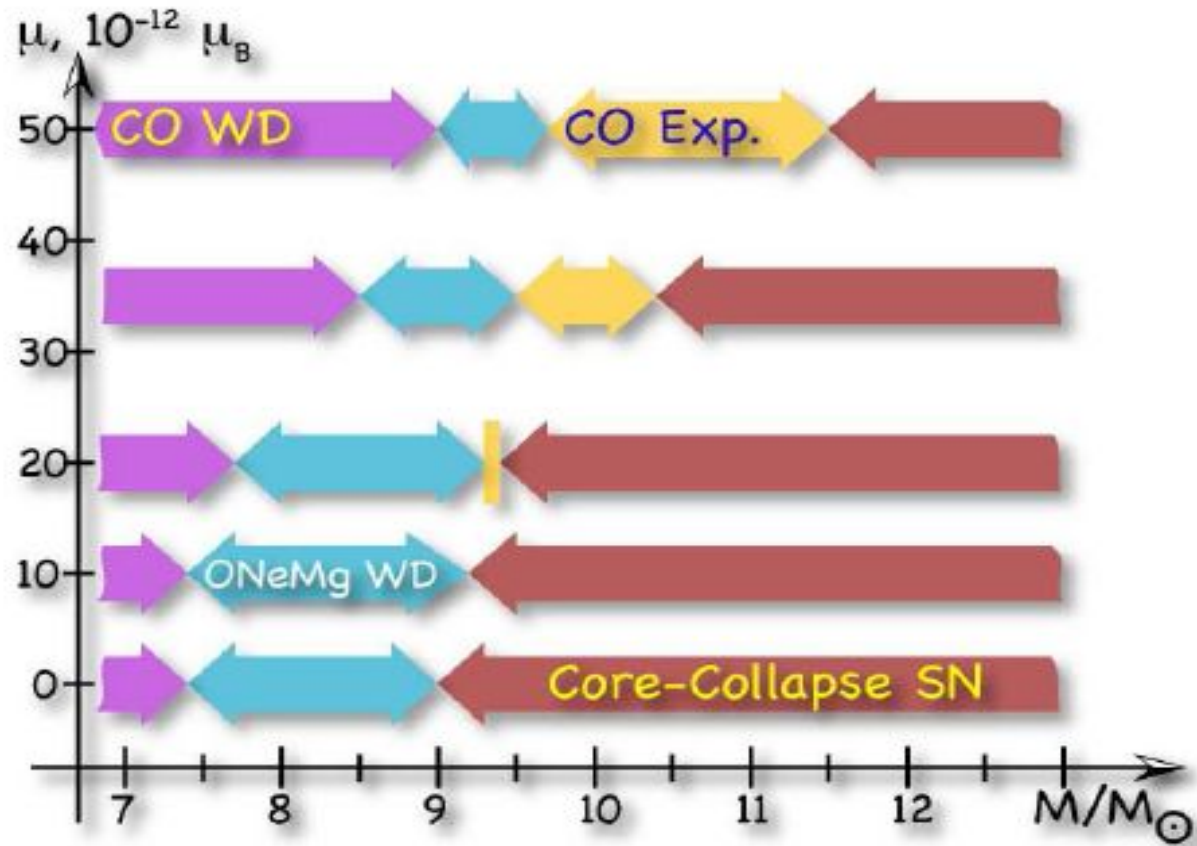
From A.Heger, A.Friedland, M.G., V.Cirigliano APJ:696 (2009)



From A.Heger, A.Friedland, M.G., V.Cirigliano APJ:696 (2009)

Conséquences μ_ν « grand »

1) A. Friedland et al. astro-ph/08094703



2)

Dirac neutrinos

{ Barbieri & G. Fiorentini (1988)
Bell et al. (2005)

$$\frac{\mu_\nu}{\mu_B} \lesssim \underline{3 \times 10^{-15}} \times \left(\frac{\delta m_\nu}{1 \text{ eV}} \right) \left(\frac{1 \text{ TeV}}{\Lambda} \right)^2$$

Nouvelle physique

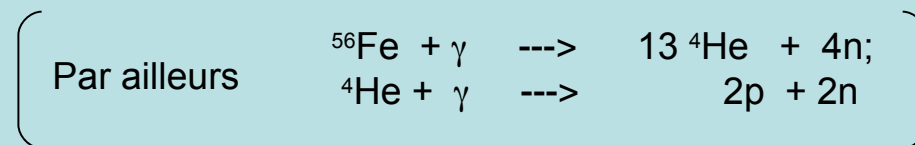
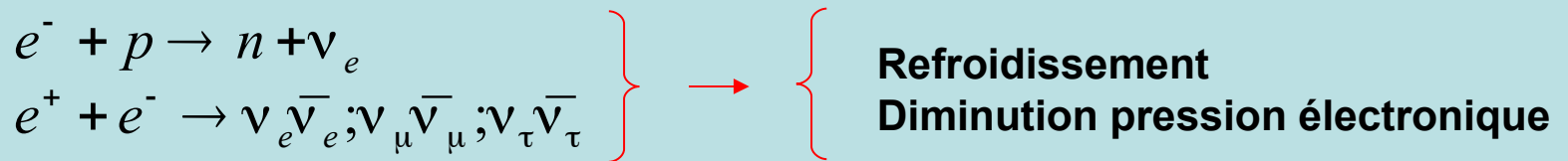
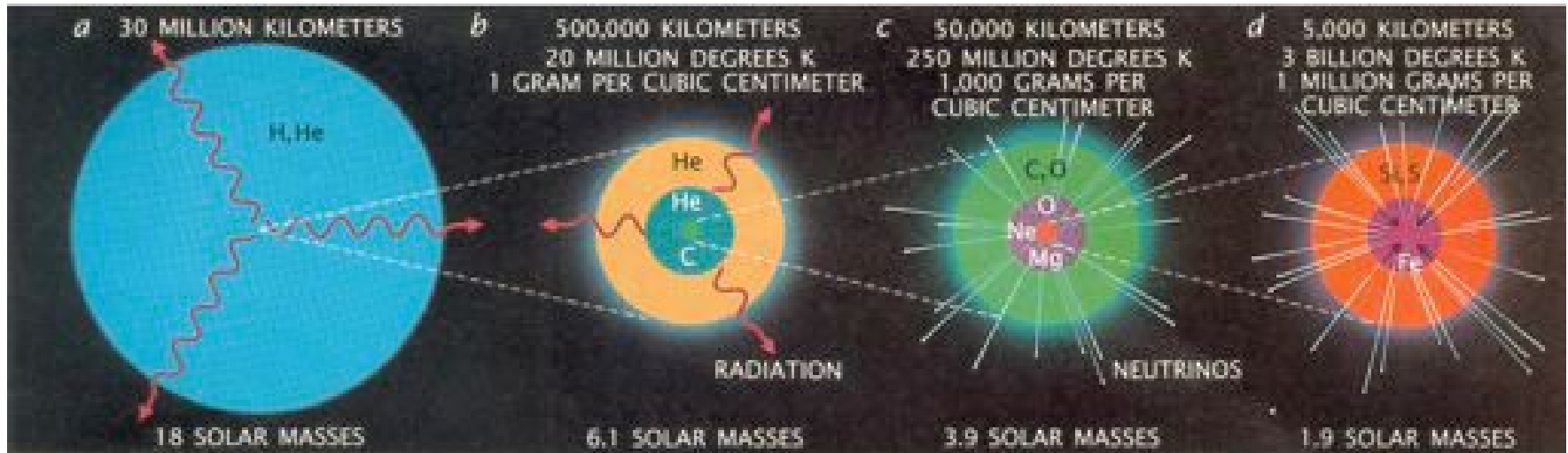
Majorana neutrinos

{ Bell et al. (2006)
Davidson et al. (2005):

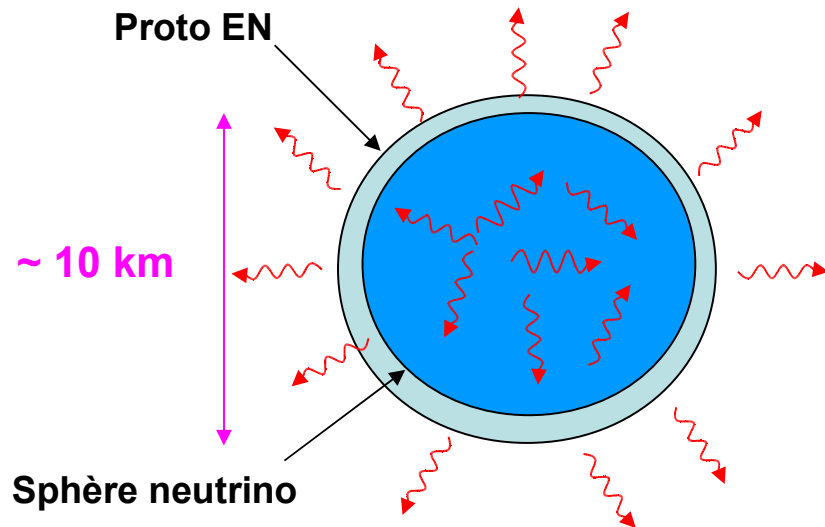
$$\frac{\mu_\nu^{\alpha\beta}}{\mu_B} \lesssim \underline{4 \times 10^{-9}} \left(\frac{[\delta m_\nu]_{\alpha\beta}}{1 \text{ eV}} \right) \left(\frac{1 \text{ TeV}}{\Lambda} \right)^2 \left| \frac{m_\tau^2}{m_\alpha^2 - m_\beta^2} \right|$$

Neutrinos des Supernovae

Au delà de 8 -10 M_{\odot} → noyau de Fe => collapse gravitationnel



$$\rho \sim 10^{14} \text{ g/ cm}^3$$



Diffusion cohérente des ν

$$\lambda_{\nu} \sim 1/\rho\sigma \sim 300 \text{ cm}$$

Temps de diffusion $\tau_{\nu} \sim 1 \text{ s}$

Temps d'effondrement : $\sim 0.1 \text{ s}$

Piégeage dynamique des neutrinos

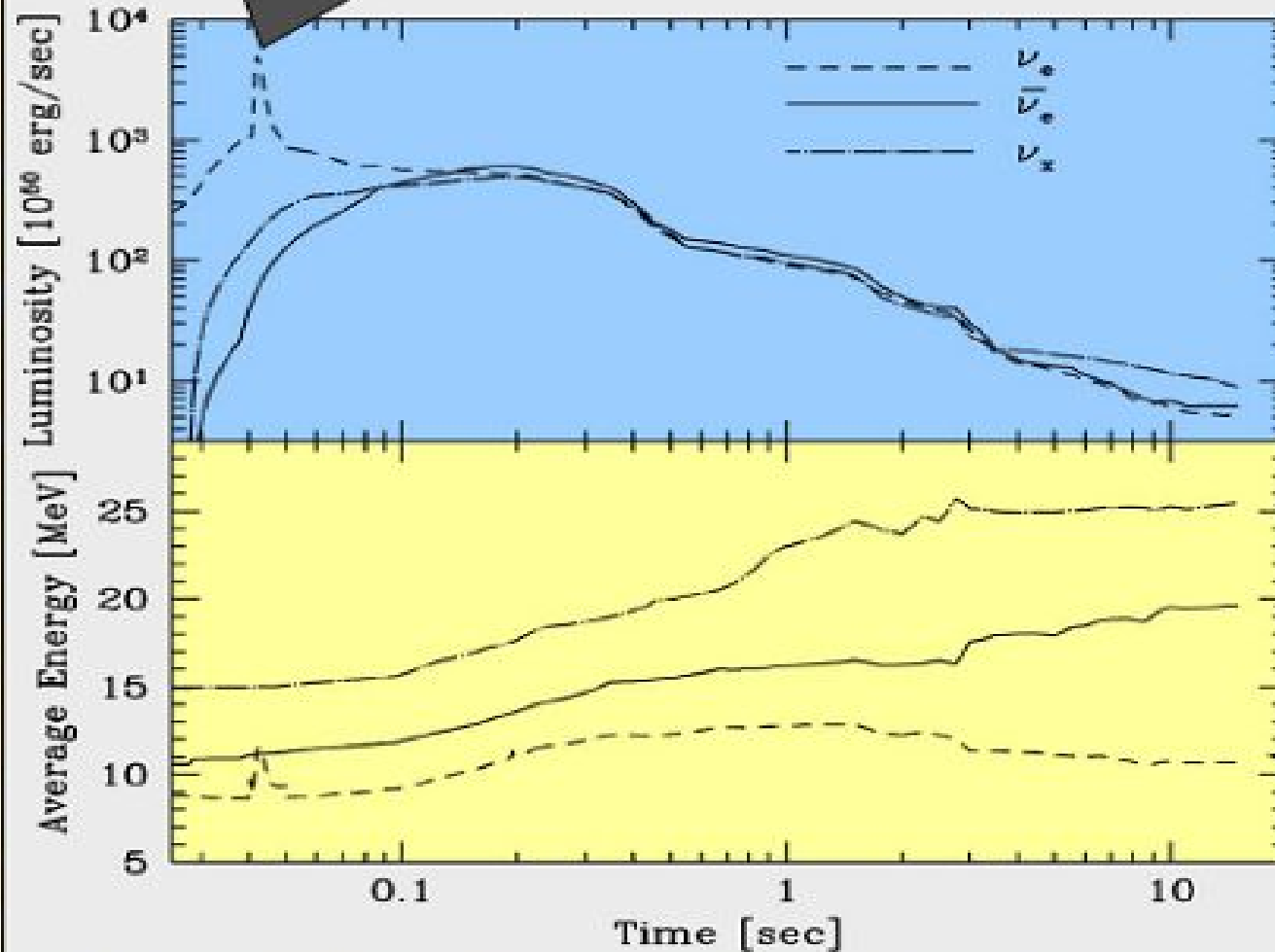
=> Sphère de neutrinos

Burst de neutrino lors de « l'explosion »

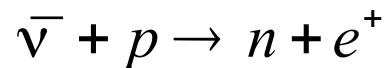
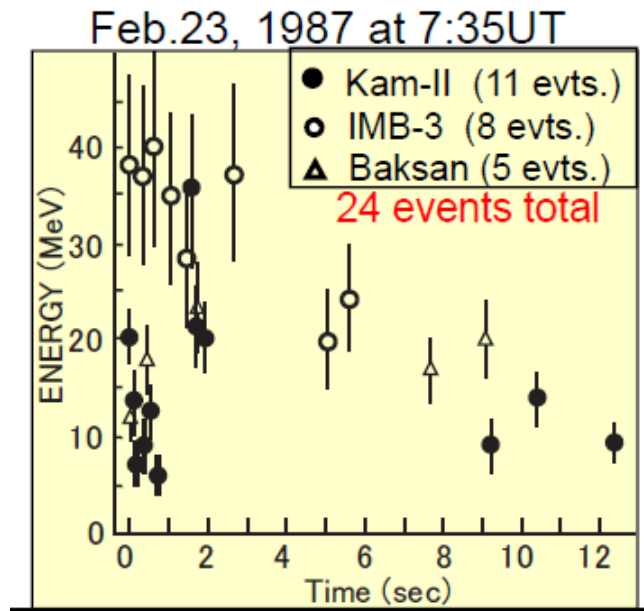
Précurseur optique => alerte

Distribution en temps et en énergie

Prompt ν_e
deleptonization
burst



Supernova 1987A



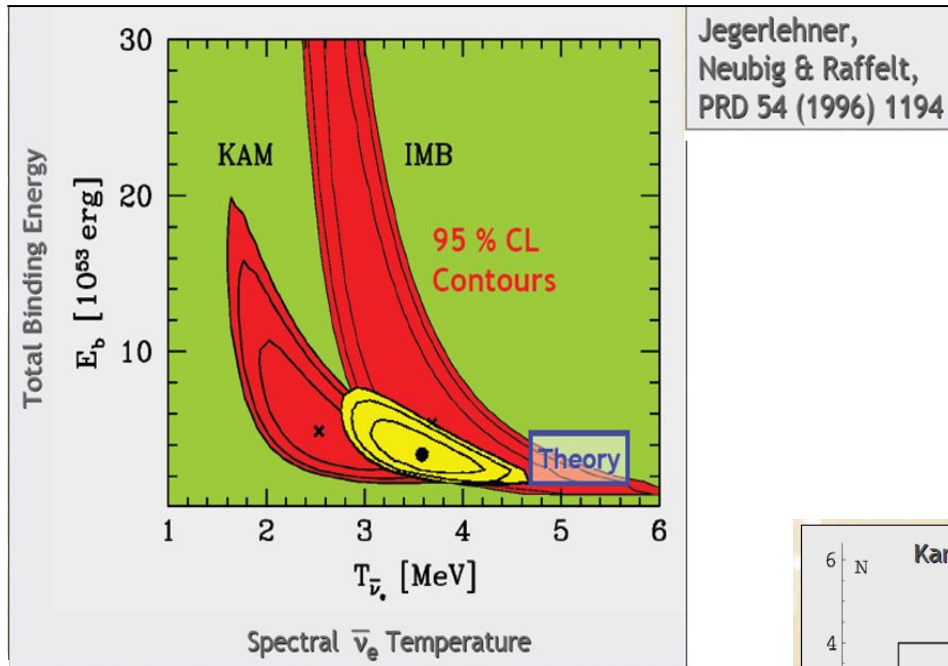
Neutrino



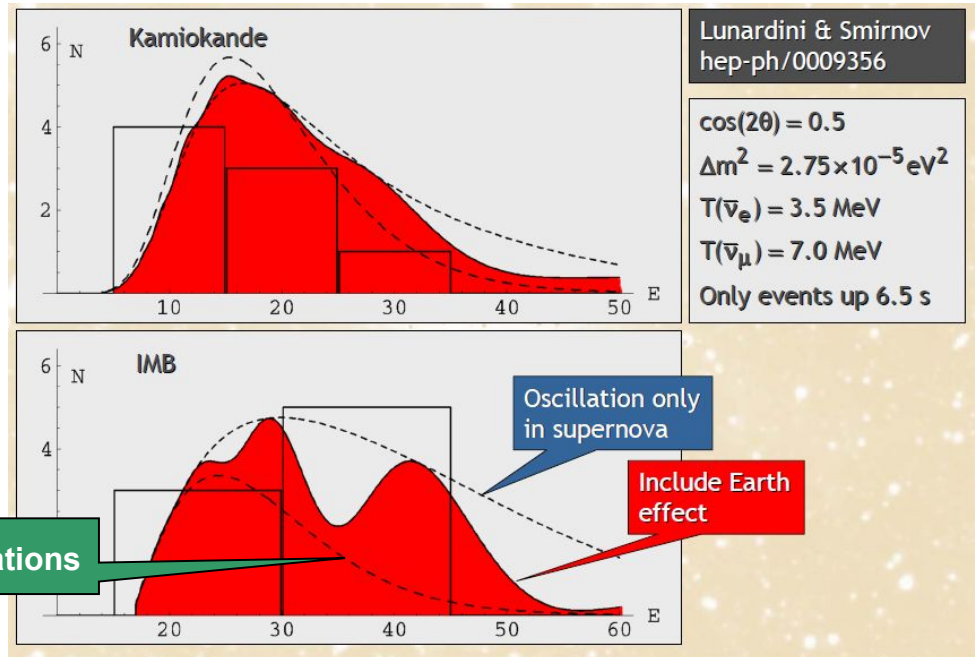
Visible

- Confirmation du mécanisme des SN ; 10^{53} erg (99% neutrinos, $\langle E_{\nu} \rangle \sim 10$ MeV, précurseur optique, ...)
- Limites sur la physique du neutrino : m_{ν} , μ_{ν} , τ_{ν} ,
- Limites sur l'existence d'axions, ν_R , Majorons, ...
- Confirmation de l'effet Shapiro,

- Oscillations des neutrinos dans SN1987A



IMB : 8583 km
K - II : 4363 km



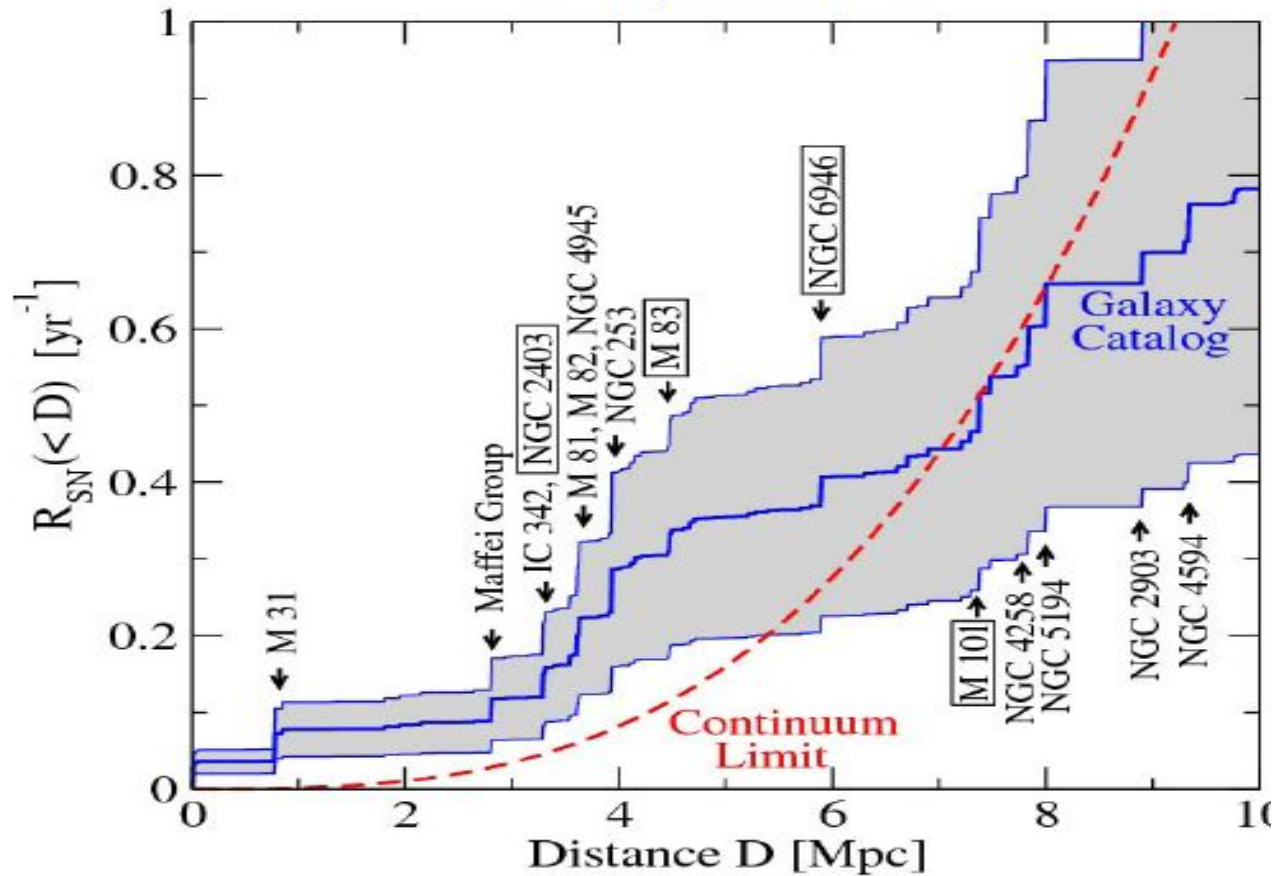
Supernova abundance

Table 1. Estimated rate of galactic core-collapse SNe per century.

| Method | Rate | Authors | Refs. |
|--|------------------|--------------------------------|----------|
| Scaling from external galaxies | 2.5 ± 0.9 | van den Bergh & McClure (1994) | [14, 17] |
| | 1.8 ± 1.2 | Cappellaro & Turatto (2000) | [15, 16] |
| Gamma-rays from galactic ^{26}Al | 1.9 ± 1.1 | Diehl et al. (2006) | [17] |
| Historical galactic SNe (all types) | 5.7 ± 1.7 | Strom (1994) | [18] |
| | 3.9 ± 1.7 | Tammann et al. (1994) | [19] |
| No neutrino burst in 25 years ^a | < 9.2 (90% CL) | Alekseev & Alekseeva (2002) | [20] |

^aWe have scaled the limit of Ref. [20] to 25 years of neutrino sky coverage.

*S. Ando, J. F. Beacom and H. Yuksel,
astro-ph/0503321*



Exceptions :

M83 (SN 1923A, 1945B, 1950B, 1957D, 1968L, 1983N)

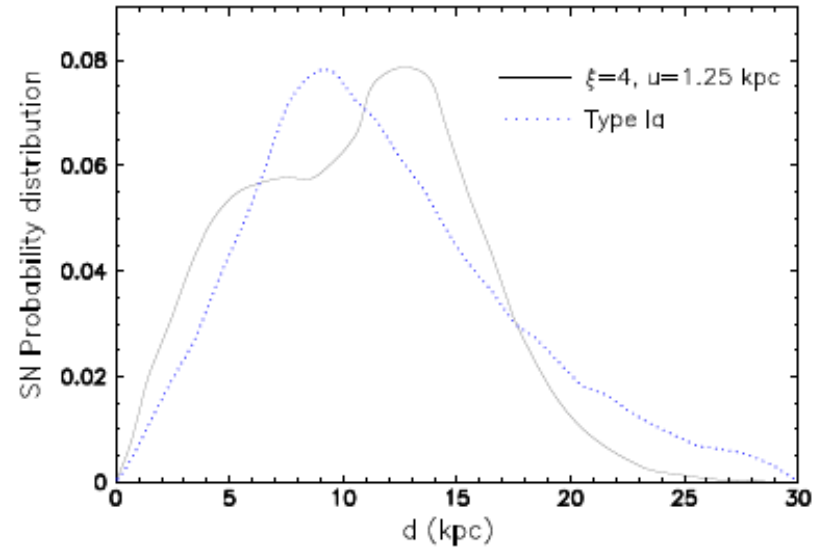
NGC6946 (SN 1917A, 1939C, 1948B, 1968D, 1969P, 1980K, 2002hh, 2004et)

- Localisation galactique

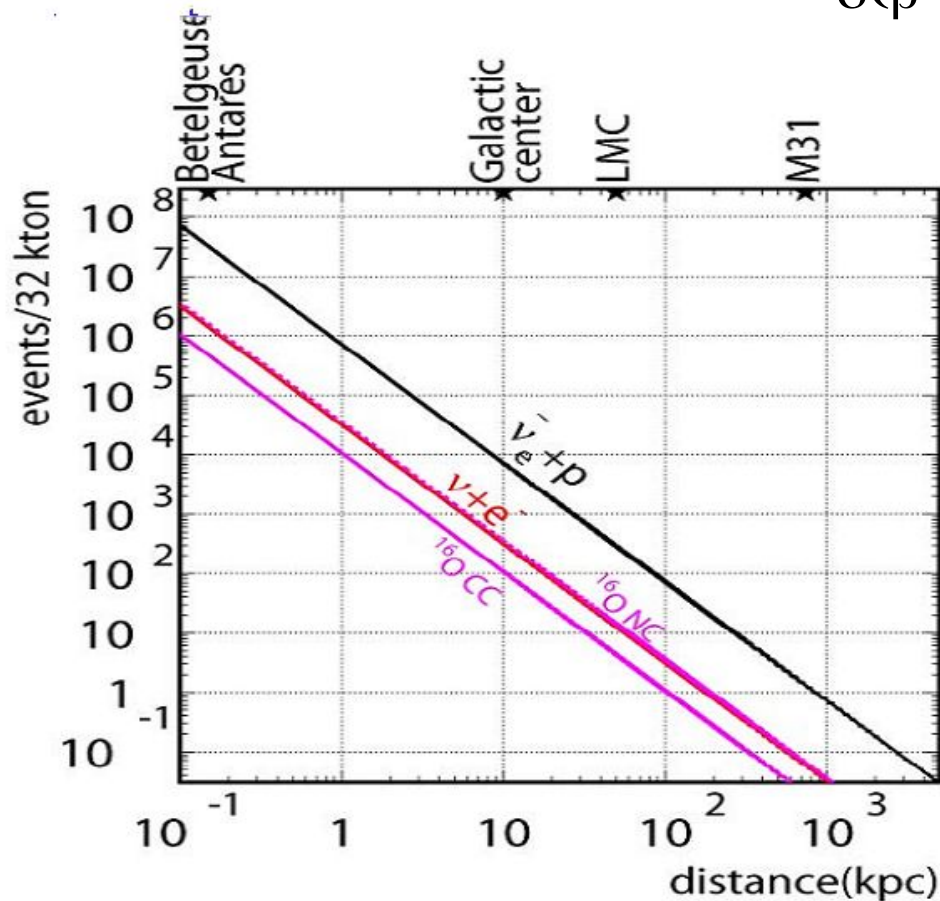
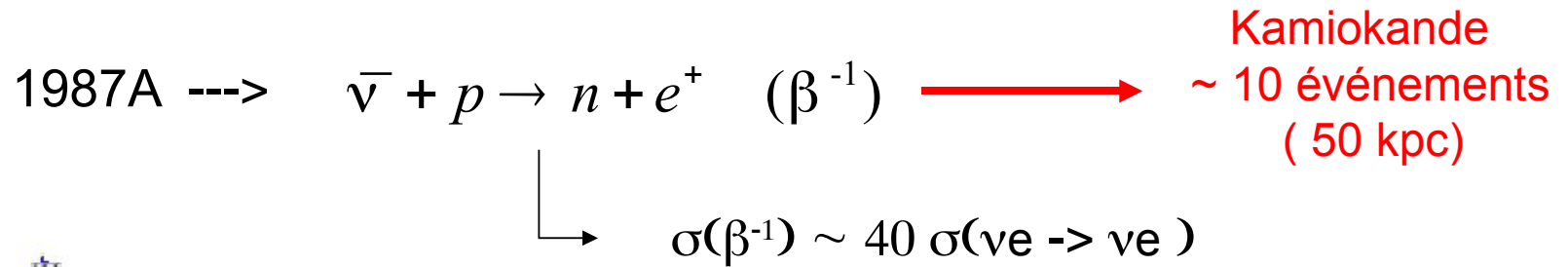
Etude des pulsars, SNR, zone de formation étoiles,...

=>

=> ~ 10kpc du centre galactique.



Détection des neutrinos des SN



H₂O Cerenkov

~7,300 $\bar{\nu}_e + p$ events
 ~300 $\nu + e$ events
 ~360 $^{16}\text{O NC } \gamma$ events
 ~100 $^{16}\text{O CC}$ events
 (with 5MeV thr.)
 for 10 kpc supernova

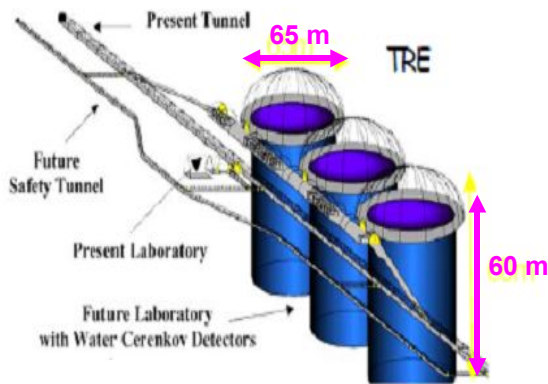
- **Scintillateur liquide :**
(1000 t)

- Inverse beta($\bar{\nu}_e + p \rightarrow e^+ + n$) : ~300 events
Spectrum measurement with good energy resolution, e.g. for spectrum distortion of earth matter effect.
- CC on ^{12}C ($\nu_e + ^{12}\text{C} \rightarrow e + ^{12}\text{N}(^{12}\text{B})$) : ~30 events
Tagged by $^{12}\text{N}(^{12}\text{B})$ beta decay
- Electron scattering ($\nu + e^- \rightarrow \nu + e^-$) : ~20 events
- NC γ from ^{12}C ($\nu + ^{12}\text{C} \rightarrow \nu + ^{12}\text{C} + \gamma$) : ~60 events
Total neutrino flux, 15.11MeV mono-energetic gamma
- $\nu + p$ scattering($\nu + p \rightarrow \nu + p$) : ~300 events
Spectrum measurement of higher energy component.
Independent from neutrino oscillation.

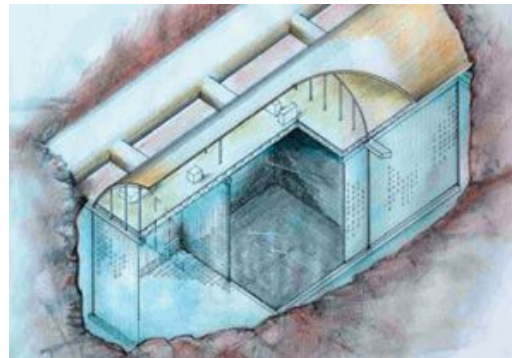
SN @ ~ 10 kpc

Projets d'avenir

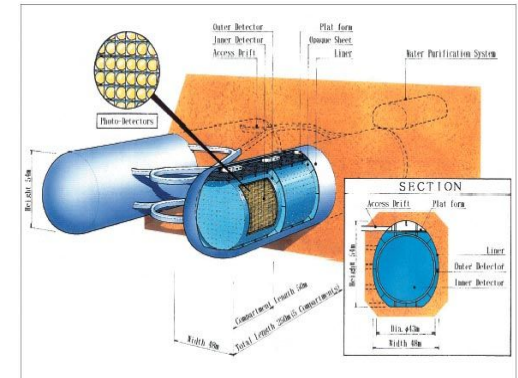
H₂O Čerenkov (0.5 -> 1 Mton)



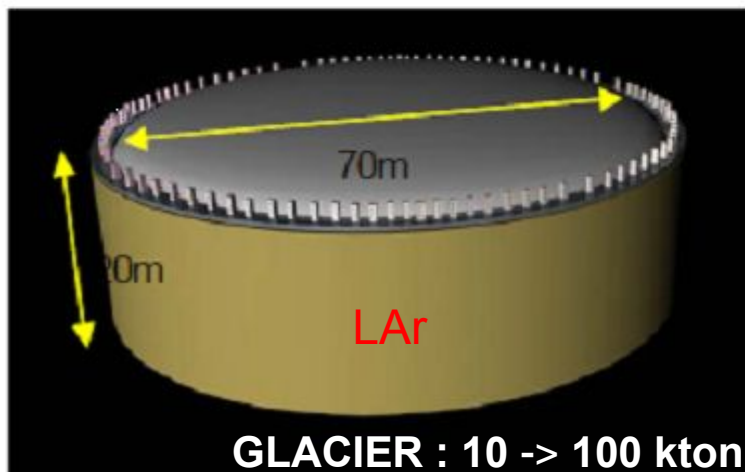
MEMPHYS



UNO



Hyper - K



Liquid scintillator

-> 50 kton

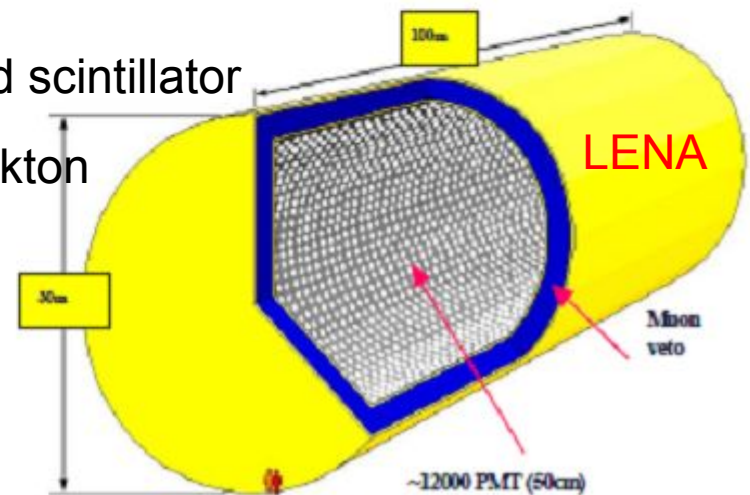


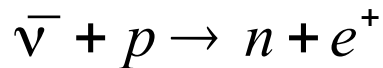
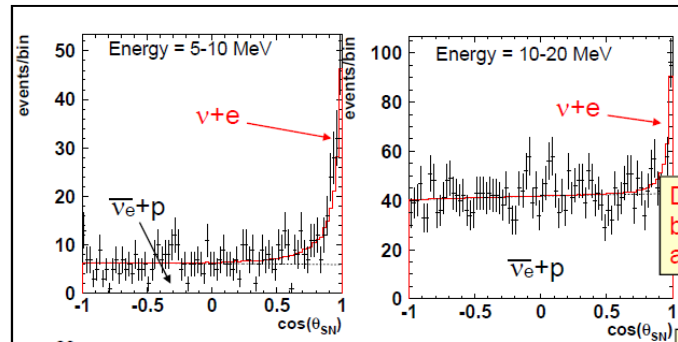
Table 1. Summary of current and proposed detectors.

| Detector | Type | Mass (kton) | Location | Events at 8.5 kpc | Status |
|------------------------|--------------------------------|--|---------------|-------------------|---------------------------|
| Super-K[22] | H ₂ O | 32 | Japan | 7000 | Running |
| SNO[41] | D ₂ O | 1 (D ₂ O) 1.4 (H ₂ O) | Canada | 400 450 | Running until end 2006 |
| LVD[17] | C _n H _{2n} | 1 | Italy | 200 | Running |
| KamLAND[18] | C _n H _{2n} | 1 | Japan | 300 | Running |
| Borexino[20] | C _n H _{2n} | 0.3 | Italy | 100 | 200x |
| Baksan[15] | C _n H _{2n} | 0.33 | Russia | 50 | Running |
| Mini-BooNE[12] | C _n H _{2n} | 0.7 | USA | 200 | Running |
| AMANDA/ IceCube[28] | Long string | 0.4/PMT | South Pole | N/A | Running Running |
| ANTARES | Long string | | Mediterranean | | |
| SAGE[42] | Ga | Russia | 0.06 | few | Running |
| Icarus[31] | LAr | 2.4 | Italy | 200 | 200x |
| Daya Bay[43] | C _n H _{2n} | 0.3 | China | 100 | Proposed |
| SNO+[44] | C _n H _{2n} | 1 | Canada | 300 | Proposed |
| CLEAN[40] | Ne,Ar | 0.01 | Canada/USA? | 30 | Proposed |
| HALO[37] | Pb | 0.1 | Canada | 40 | Proposed |
| MOON[45] | ¹⁰⁰ Mo | 0.03 | ? | 20 | Proposed |
| NO ν A[46] | C _n H _{2n} | 20 | USA | 4000 | Proposed |
| OMNIS[29] | Pb | 2-3 | USA? | >1000 | Proposed |
| LANNDD[32] | LAr | 70 | USA? | 6000 | Proposed |
| MEMPHYS[49] | H ₂ O | 440 | Europe | >100,000 | Proposed |
| UNO[48] | H ₂ O | 500 | USA | >100,000 | Proposed |
| Hyper-K[47] | H ₂ O | 500 | Japan | >100,000 | Proposed |
| LENA[50] | C _n H _{2n} | 60 | Europe | 18,000 | Proposed |
| HSD[51] | C _n H _{2n} | 100 | USA | 30,000 | Proposed |

- **Positionnement angulaire**

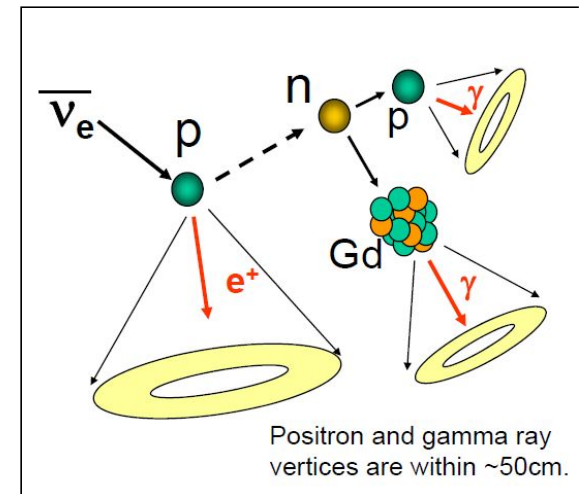
Détection diffusion élastique :

$$\nu + e^- \rightarrow \nu + e^- \quad \Rightarrow \text{cône Cerenkov} \quad \text{----> SK : } 8^\circ$$

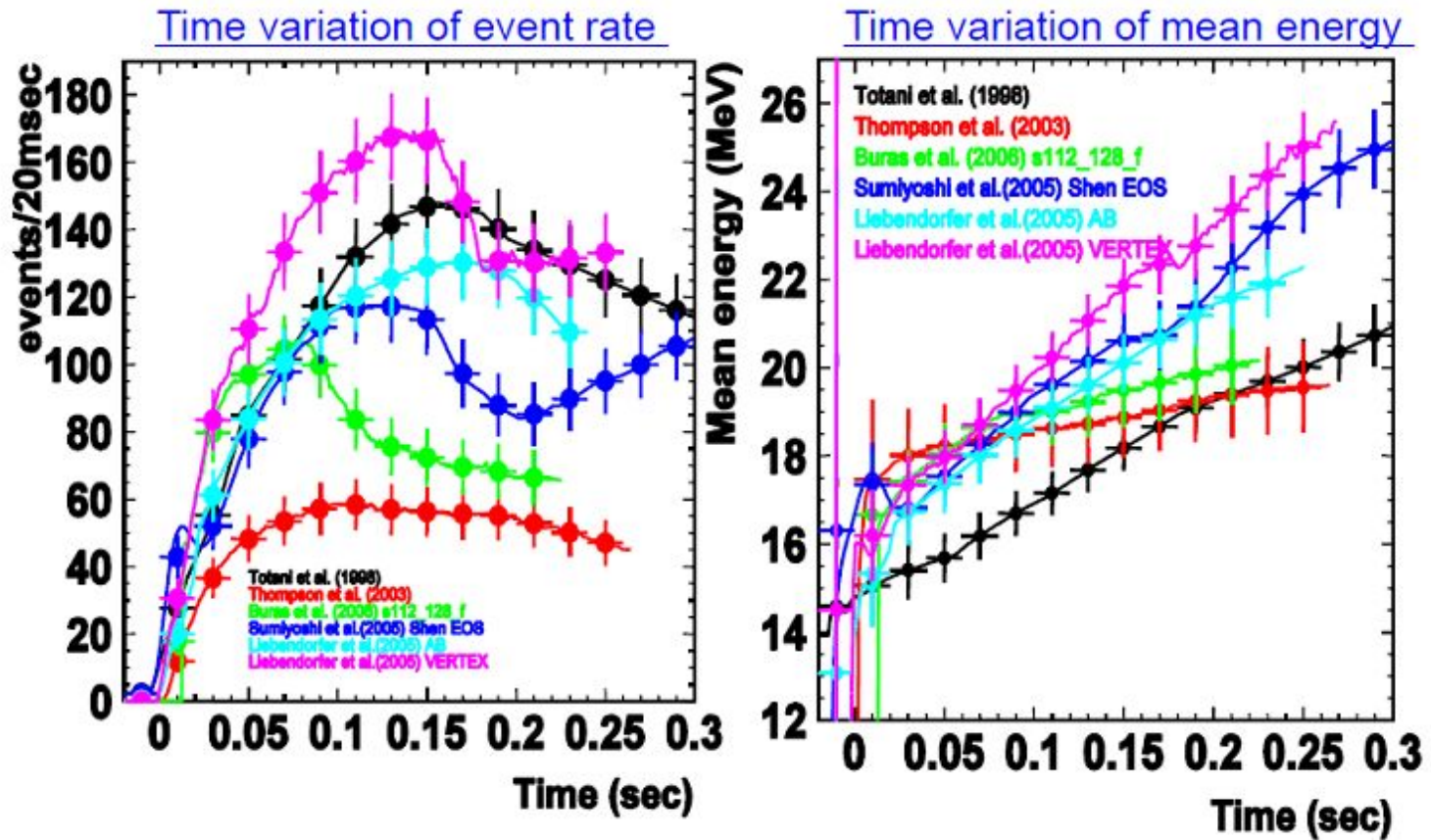


Avec tagging GADZOOKS 0.2% GdCl₃ in H₂O → 3° dans SK

addition Gd dans H₂O

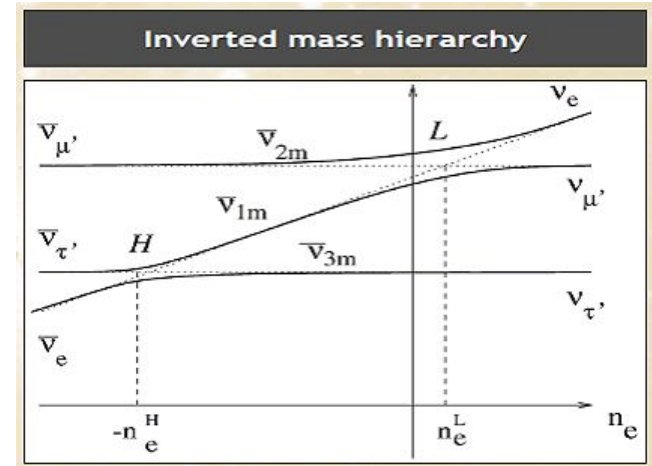
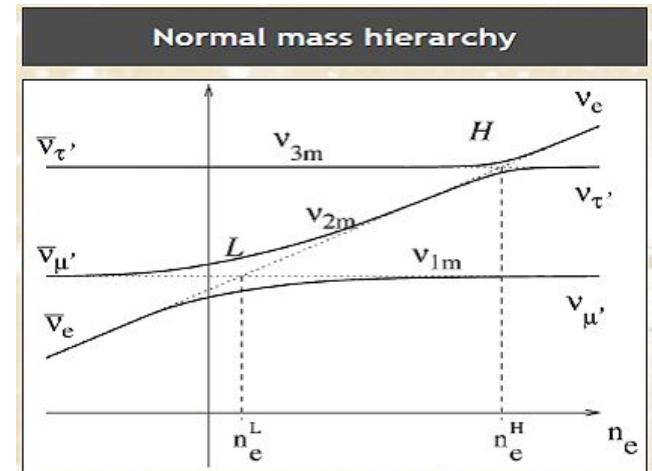
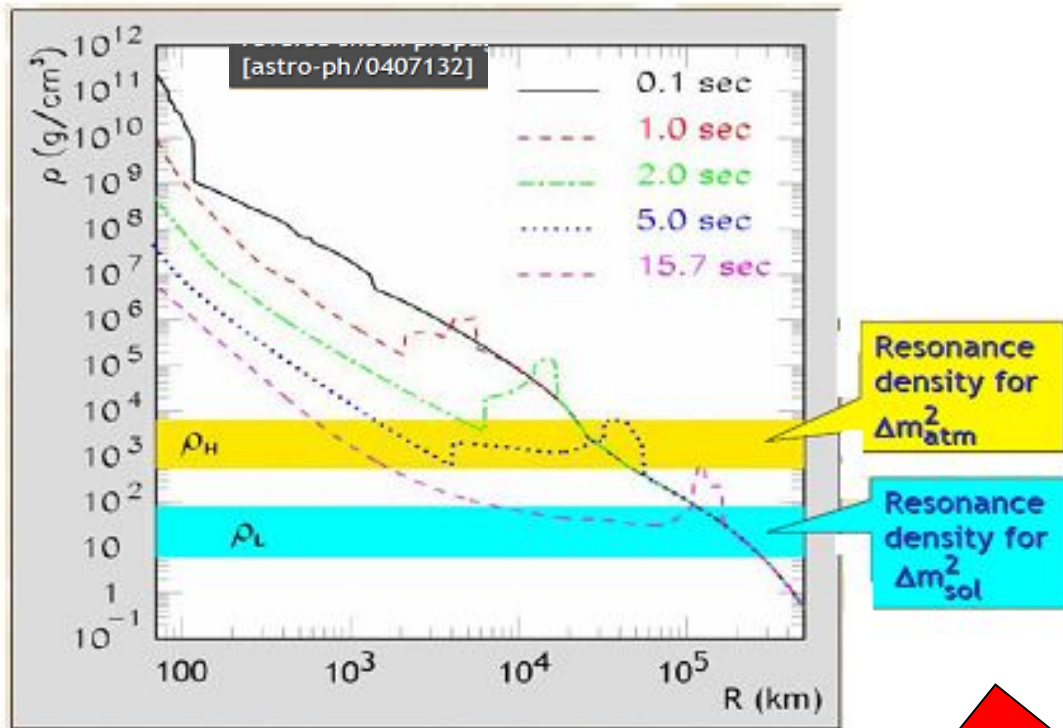


- H_2O , SK (\rightarrow extrapolable pour Megatonne)



Sensibilité à différents modèles
de SN

Résonances H et L pour l'effet MSW



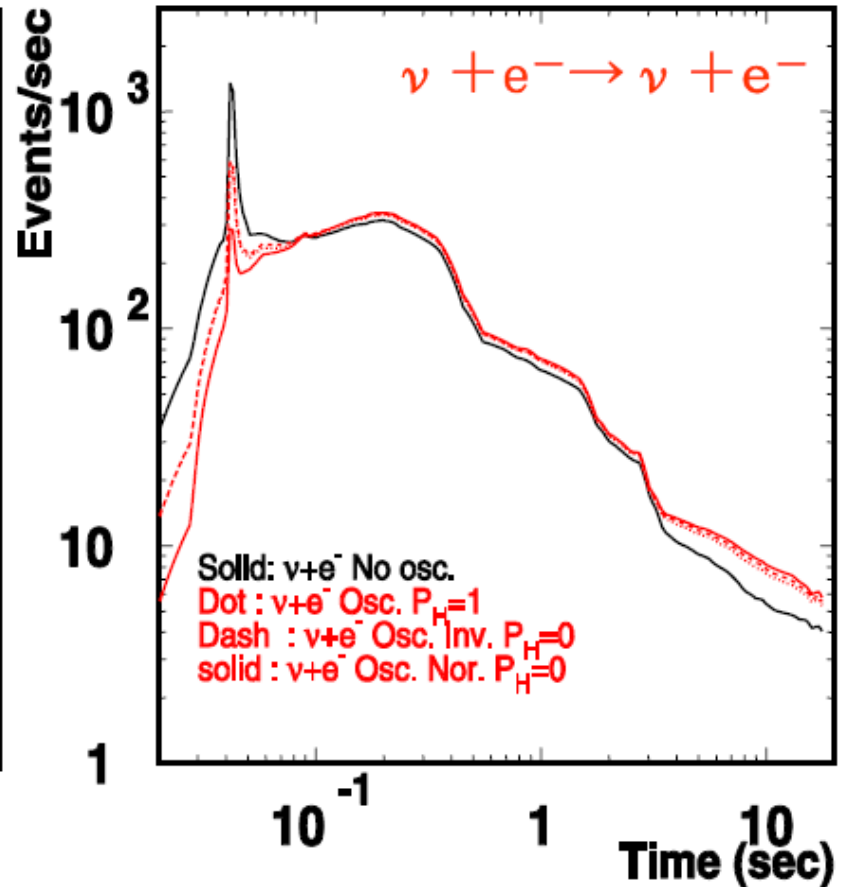
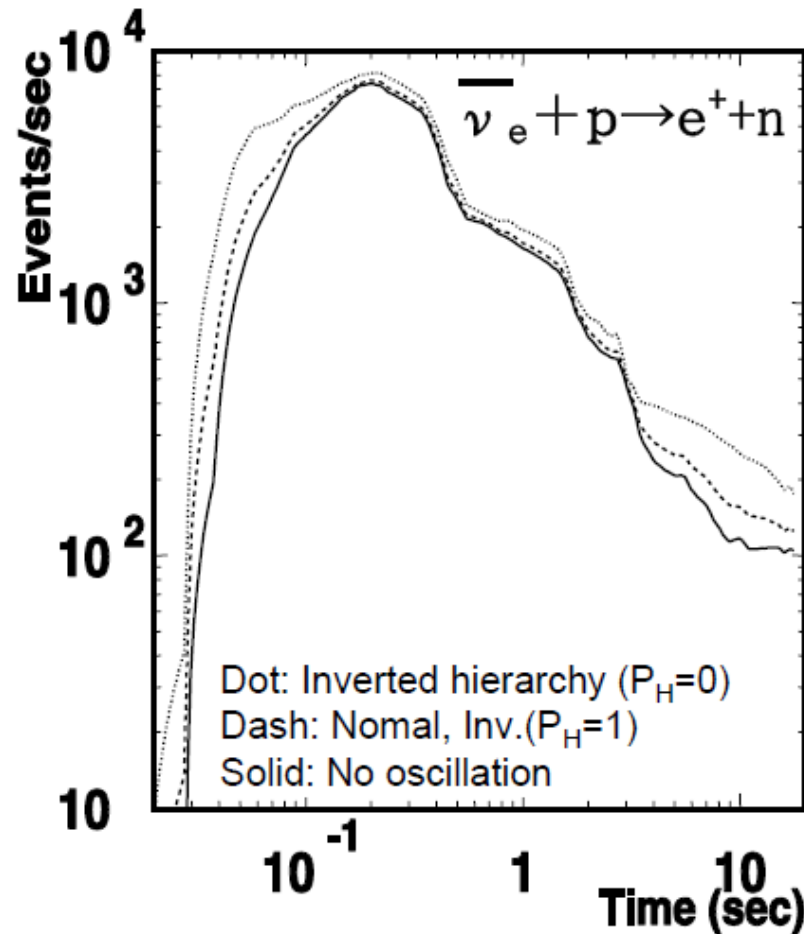
| Case | Mass ordering | $\sin^2(2\Theta_{13})$ | Survival probability | |
|------|---------------|------------------------|-----------------------------------|-----------------------------------|
| | | | p (for ν_e) | \bar{p} (for $\bar{\nu}_e$) |
| A | Normal | $\gtrsim 10^{-3}$ | 0 | $\cos^2(\Theta_{12}) \approx 0.7$ |
| B | Inverted | | $\sin^2(\Theta_{12}) \approx 0.3$ | 0 |
| C | Any | $\lesssim 10^{-5}$ | $\sin^2(\Theta_{12}) \approx 0.3$ | $\cos^2(\Theta_{12}) \approx 0.7$ |

Effect of neutrino oscillations

SN at 10kpc

Time profile

Neutrino flux and spectrum from Livermore simulation



P_H : crossing probability at H resonance
 ($P_H=0$: adiabatic)

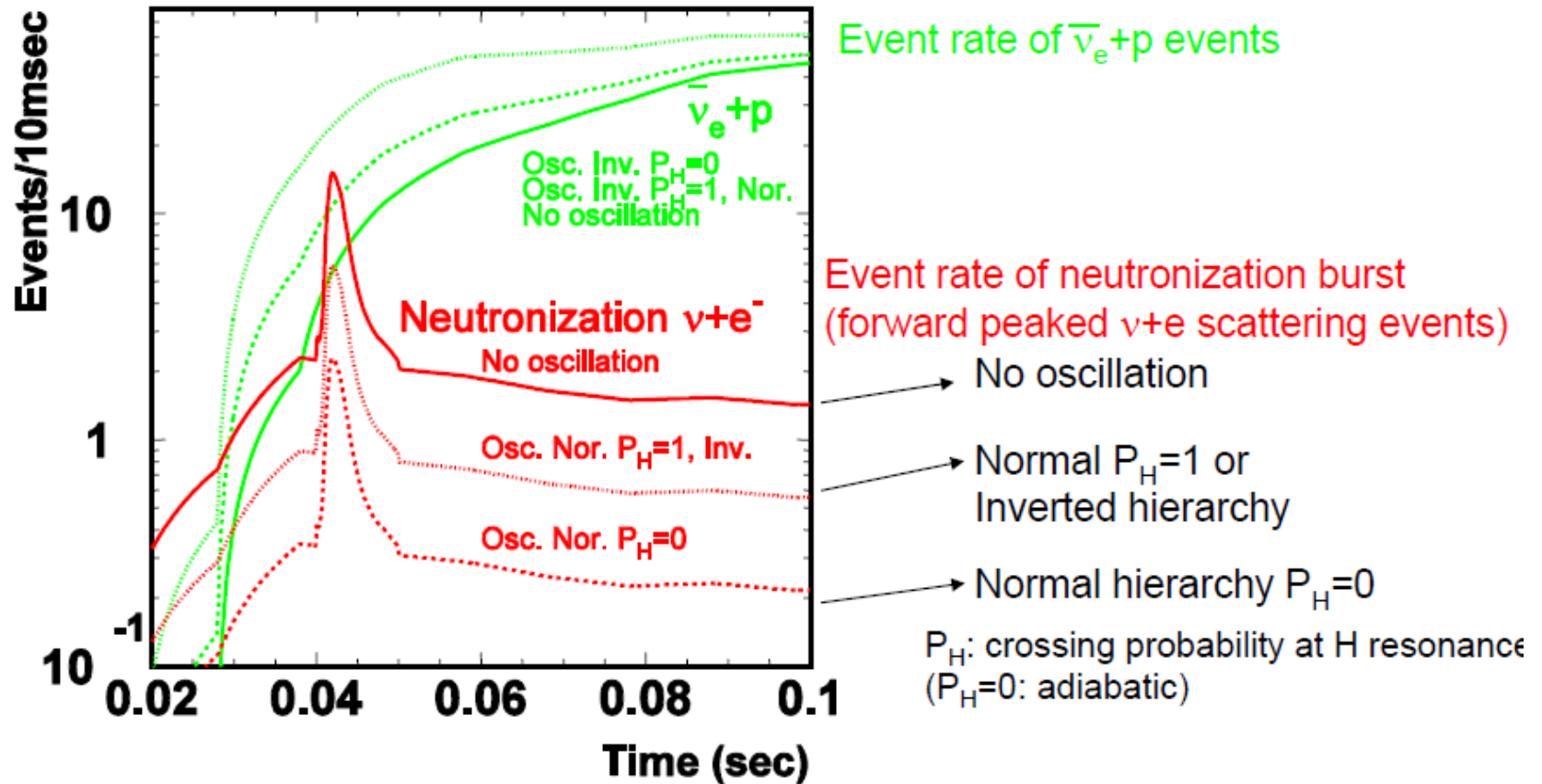
Neutrino oscillation increase number of events
 by 10~30 %.

Neutronization burst ($e^-+p \rightarrow n+\bar{\nu}_e$)

Number of events from 20msec to 0.1 sec

SN at 10kpc

Neutrino flux and spectrum from Livermore simulation



Number of events from neutronization burst is 0.7~5 event for SN@10kpc.

$\bar{\nu}_e + p$ events during this 10msec is about 5 - 20 events

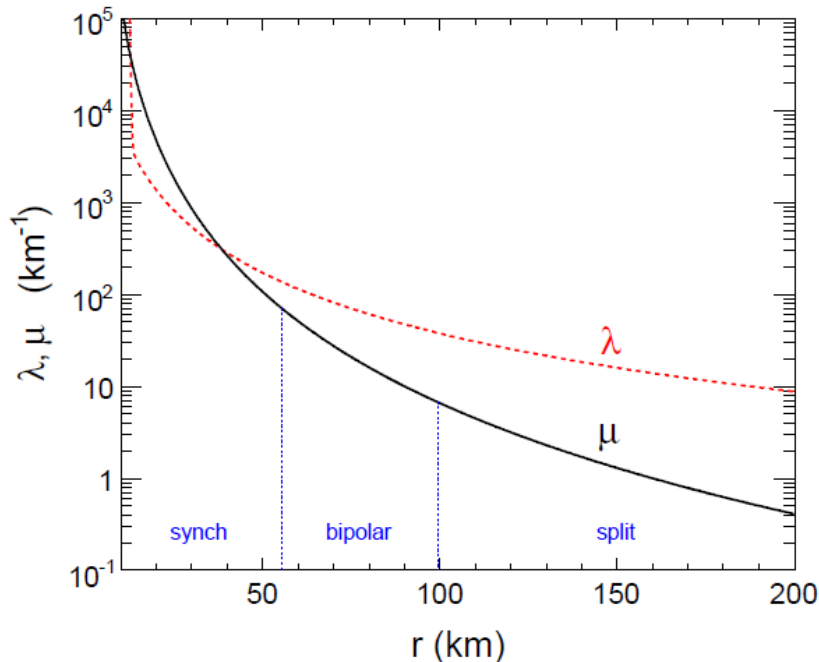
Oscillations collectives de neutrinos

Près de la sphère de neutrinos ($\sim 10^{35} \text{ cm}^{-3}$)
=> interaction neutrino – neutrino importante
=> effet de matière entre neutrinos

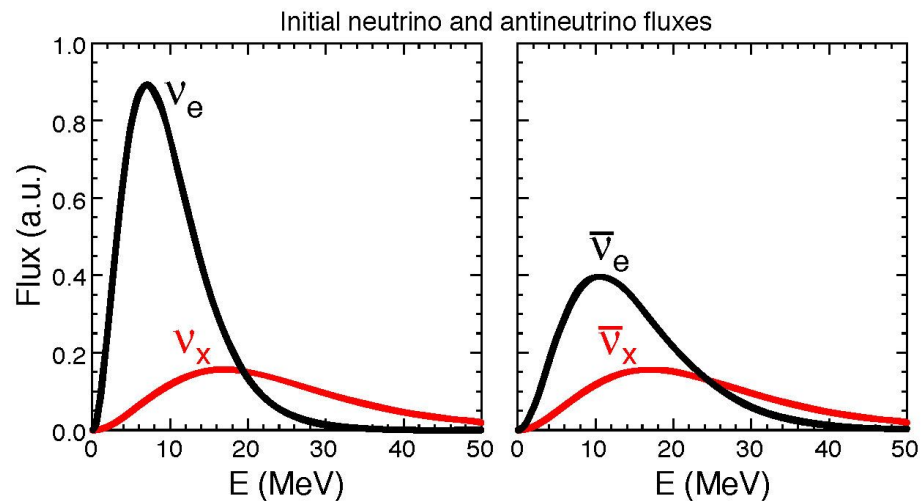
Oscillations dans le vide => $\omega = \Delta m^2 / 2E$

Oscillations dans la matière => $\lambda \geq \omega$

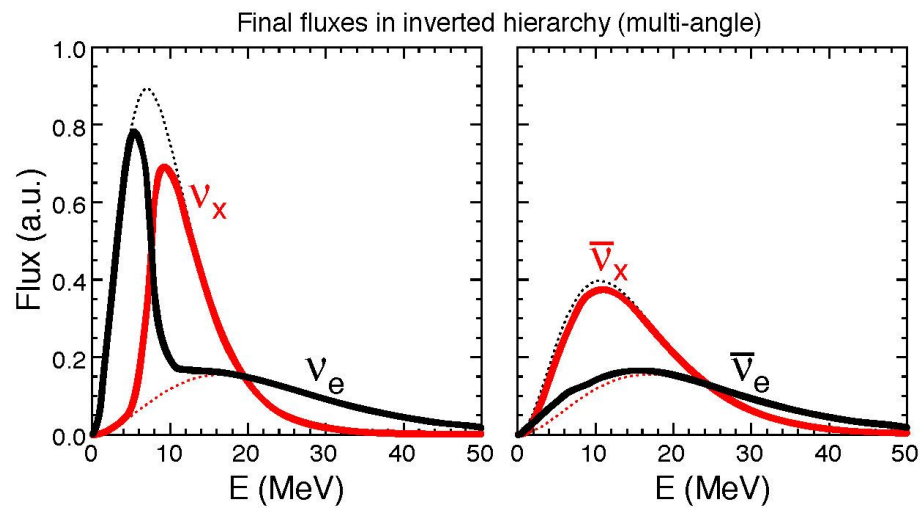
Oscillations entre neutrinos => $\mu \geq \lambda$



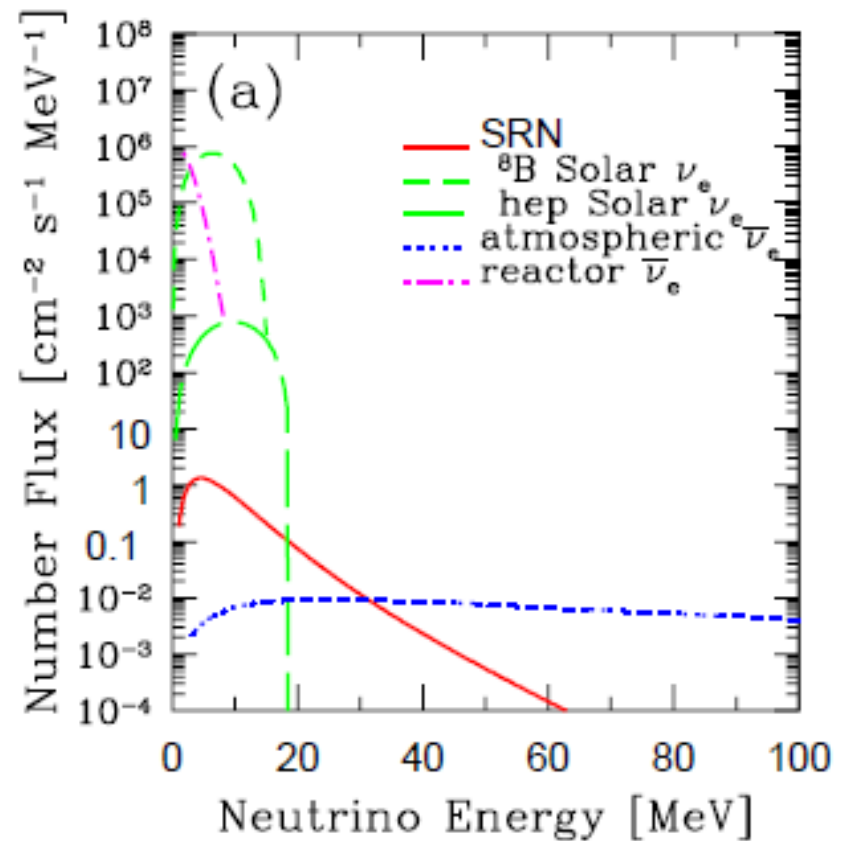
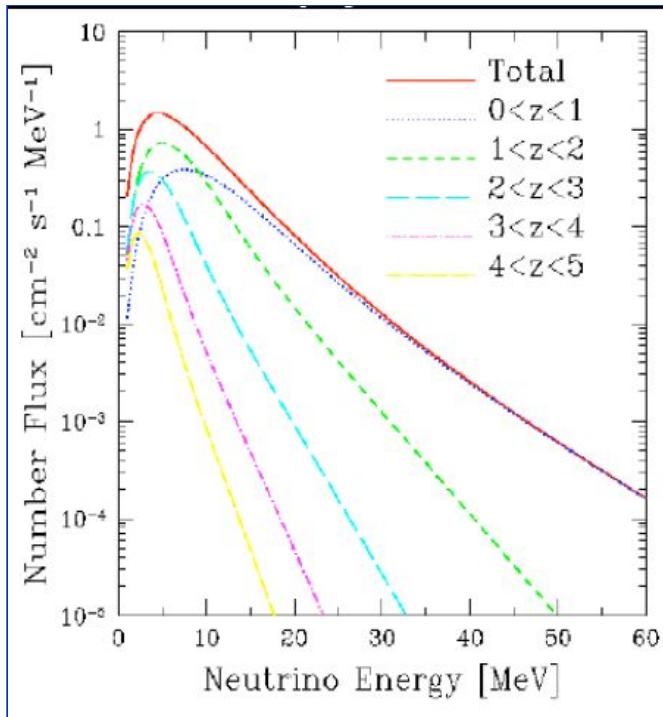
$$\lambda(r) = \sqrt{2} G_F n_e(r)$$
$$\mu(r) = \sqrt{2} G_F \left[N_{\nu_e + \bar{\nu}_x}(r) + \bar{N}_{\nu_e + \bar{\nu}_x}(r) \right]$$



- Hiérarchie inverse
- $\theta_{13} \rightarrow 0$



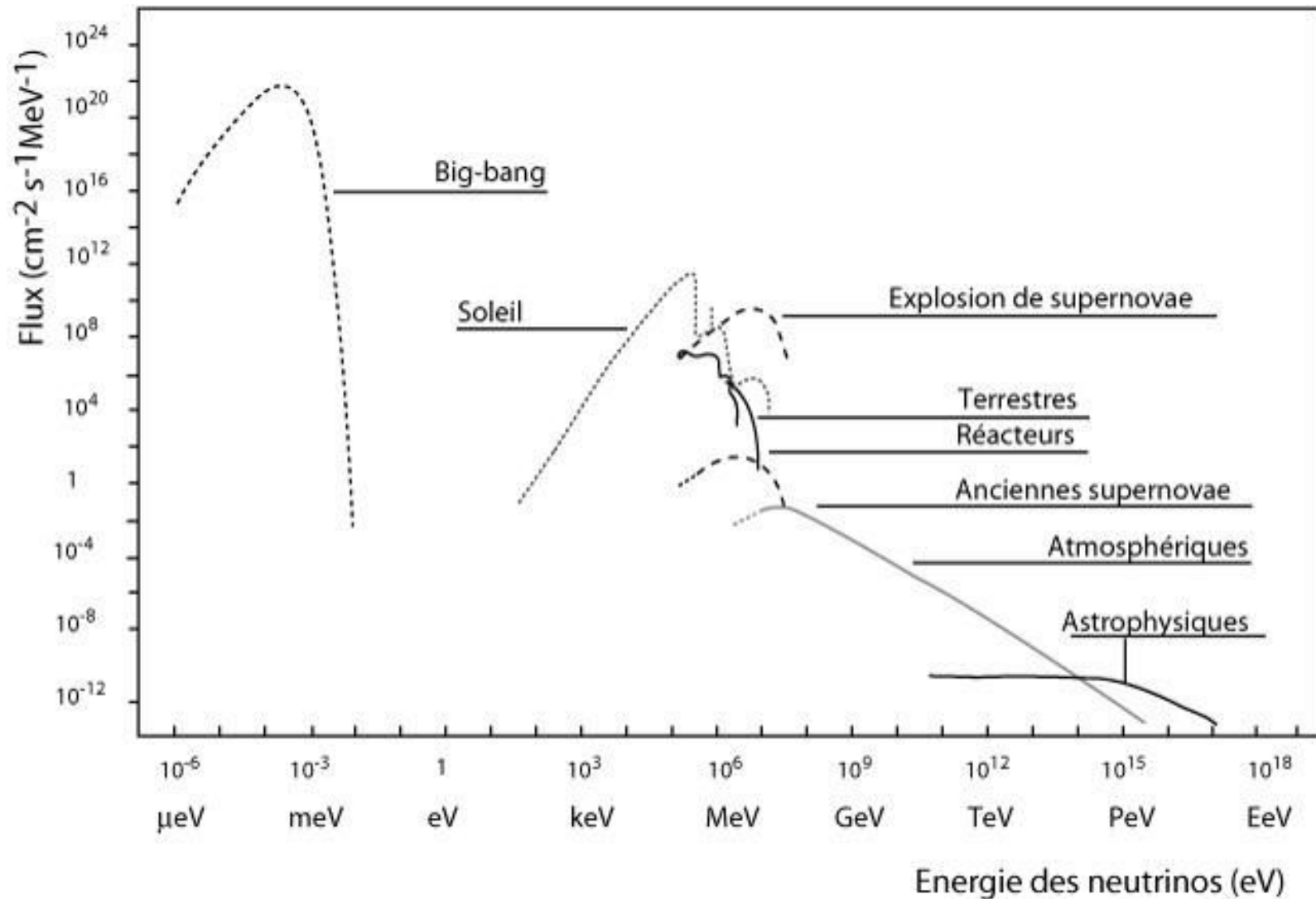
Fond neutrino des SN « déjà explosées »

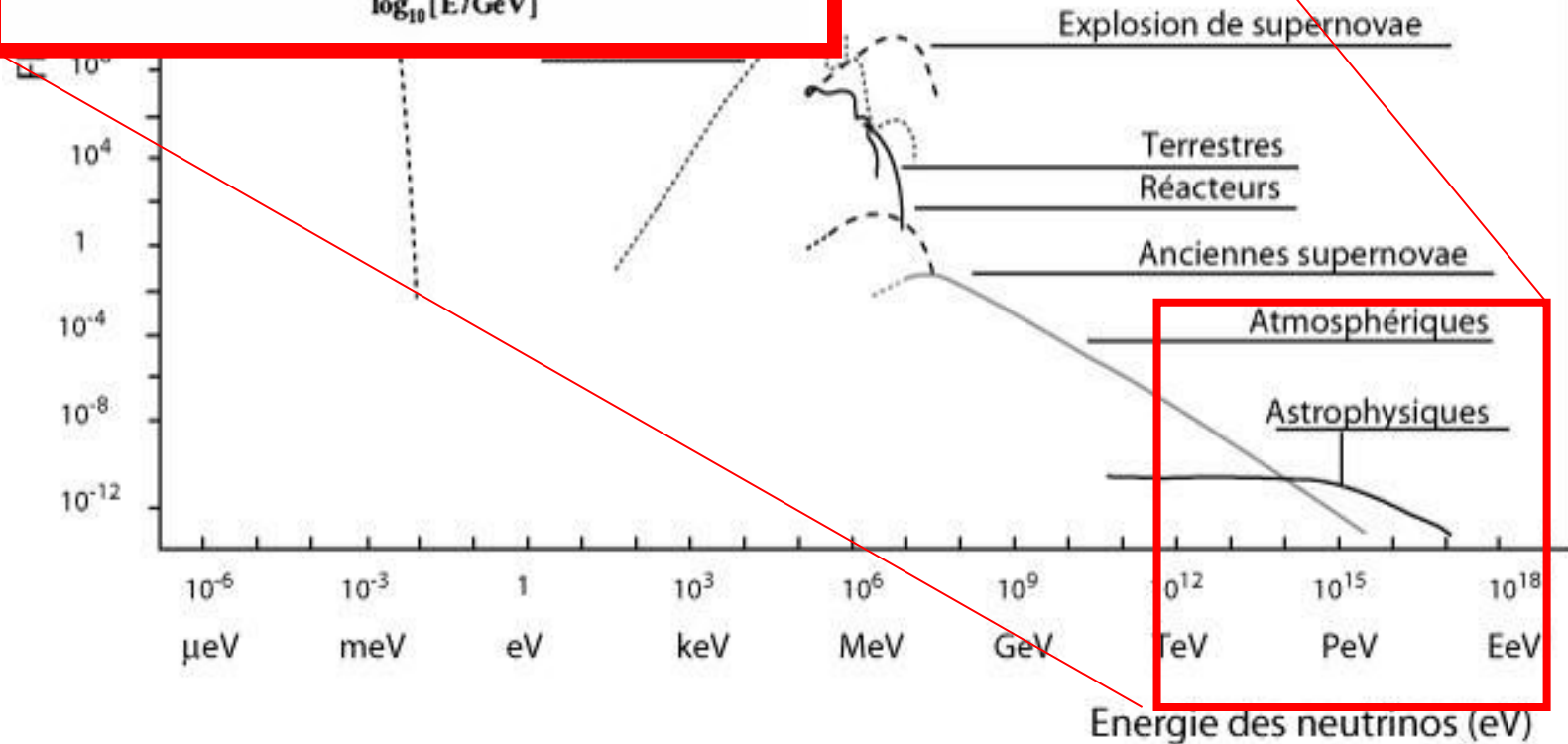
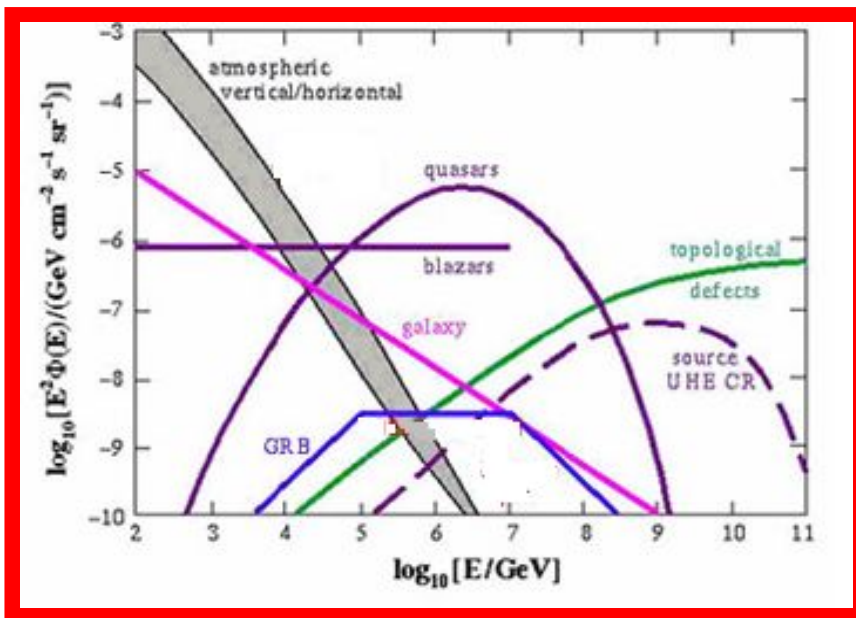


$$\text{SK} : \Phi_{\nu_e}(E > 19.3 \text{ MeV}) < 1.2 \text{ cm}^{-2} \text{s}^{-1}$$

==> Taux d'explosion dans la galaxie

Astrophysique avec des Neutrinos de Très Haute Energie

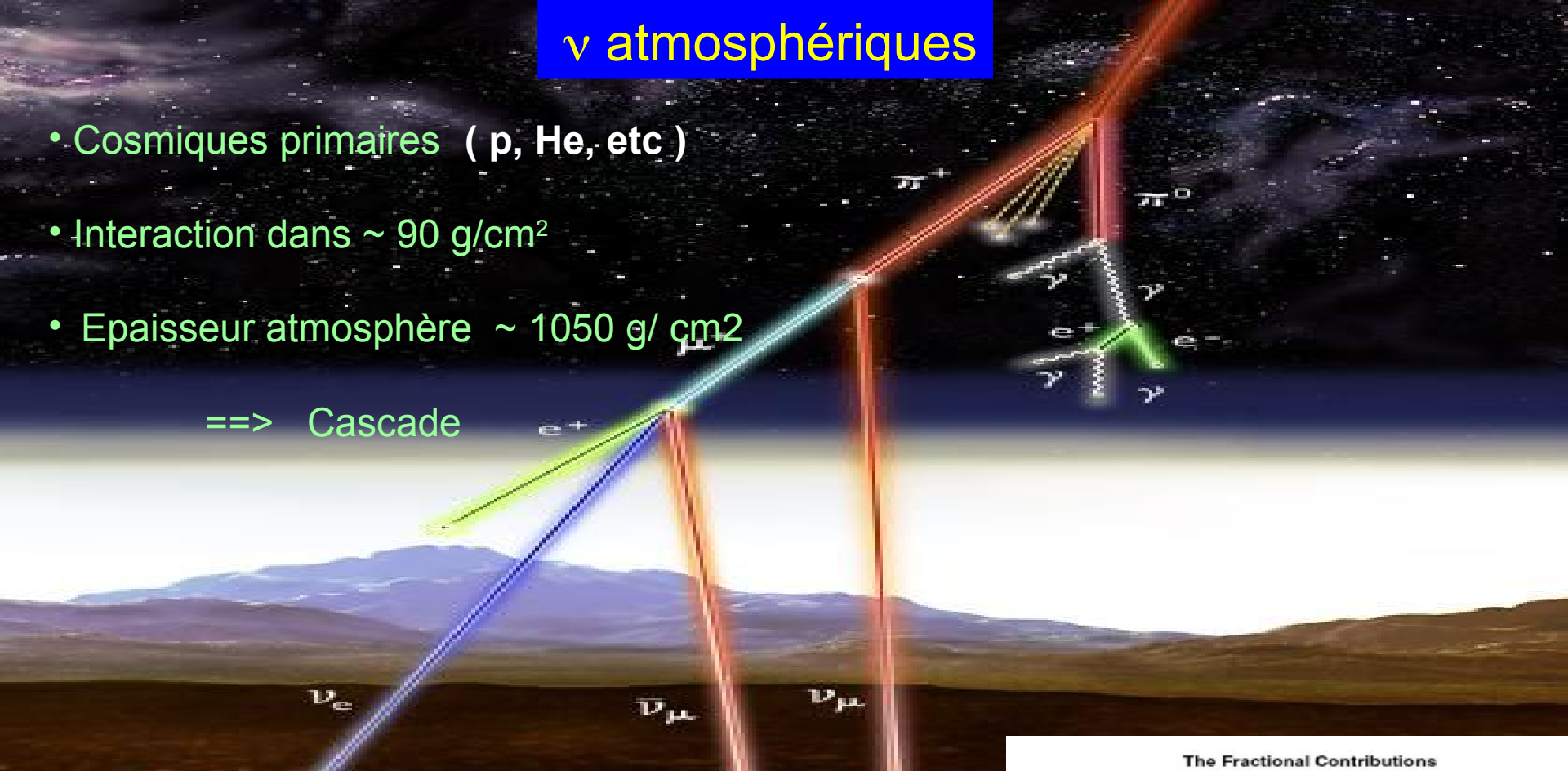




ν atmosphériques

- Cosmiques primaires (p, He, etc)
- Interaction dans $\sim 90 \text{ g/cm}^2$
- Epaisseur atmosphère $\sim 1050 \text{ g/cm}^2$

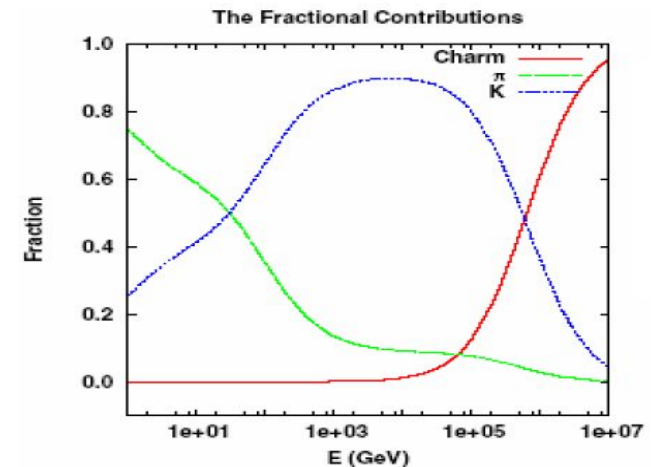
\Rightarrow Cascade



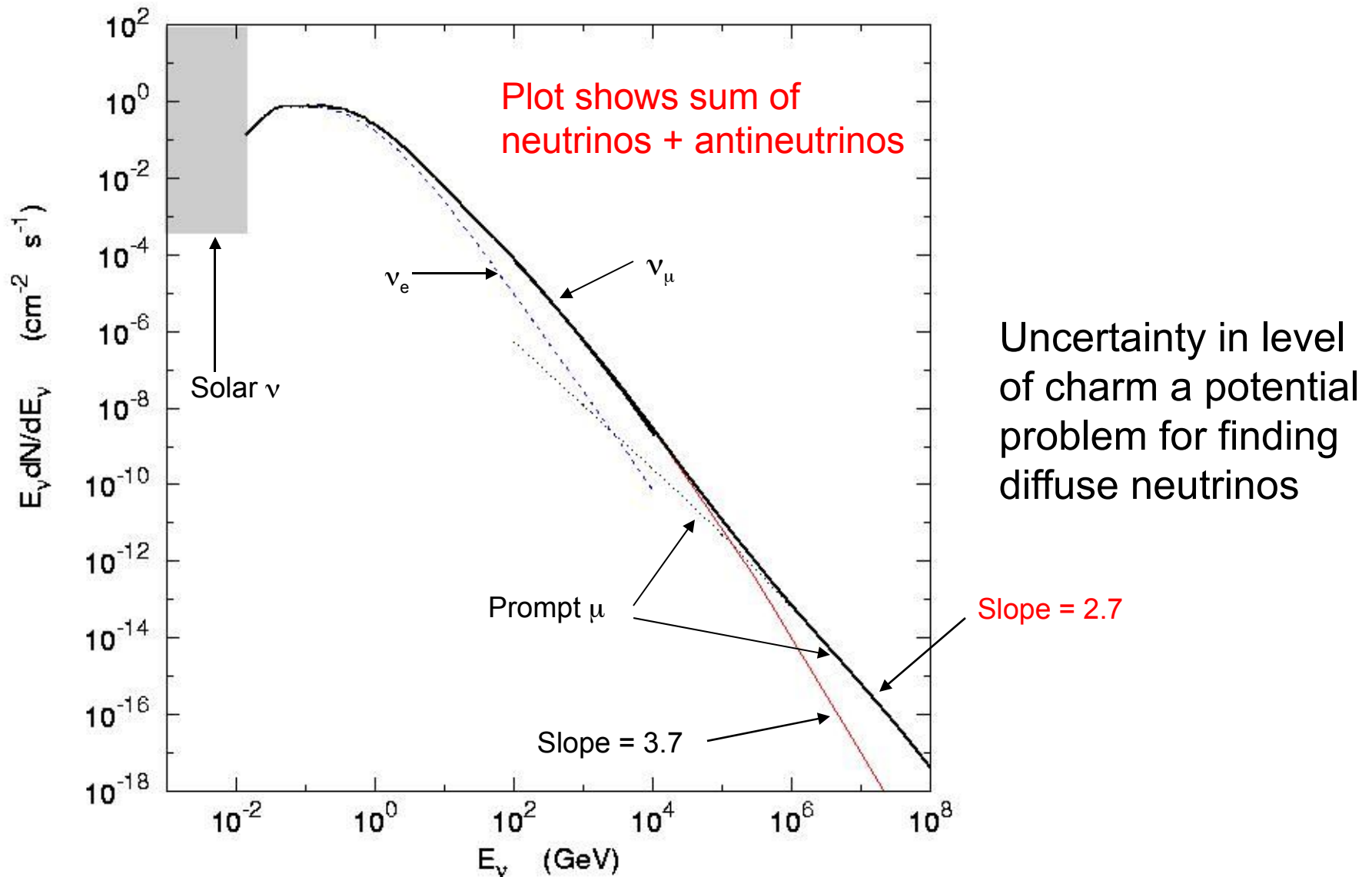
$$K^+ \rightarrow \begin{cases} \mu^+ \nu_\mu \\ \pi^+ \pi^0 \\ \pi^+ \pi^+ \pi^- \\ \pi^+ \pi^0 \pi^0 \\ \pi^0 e^+ \nu_e \end{cases}$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

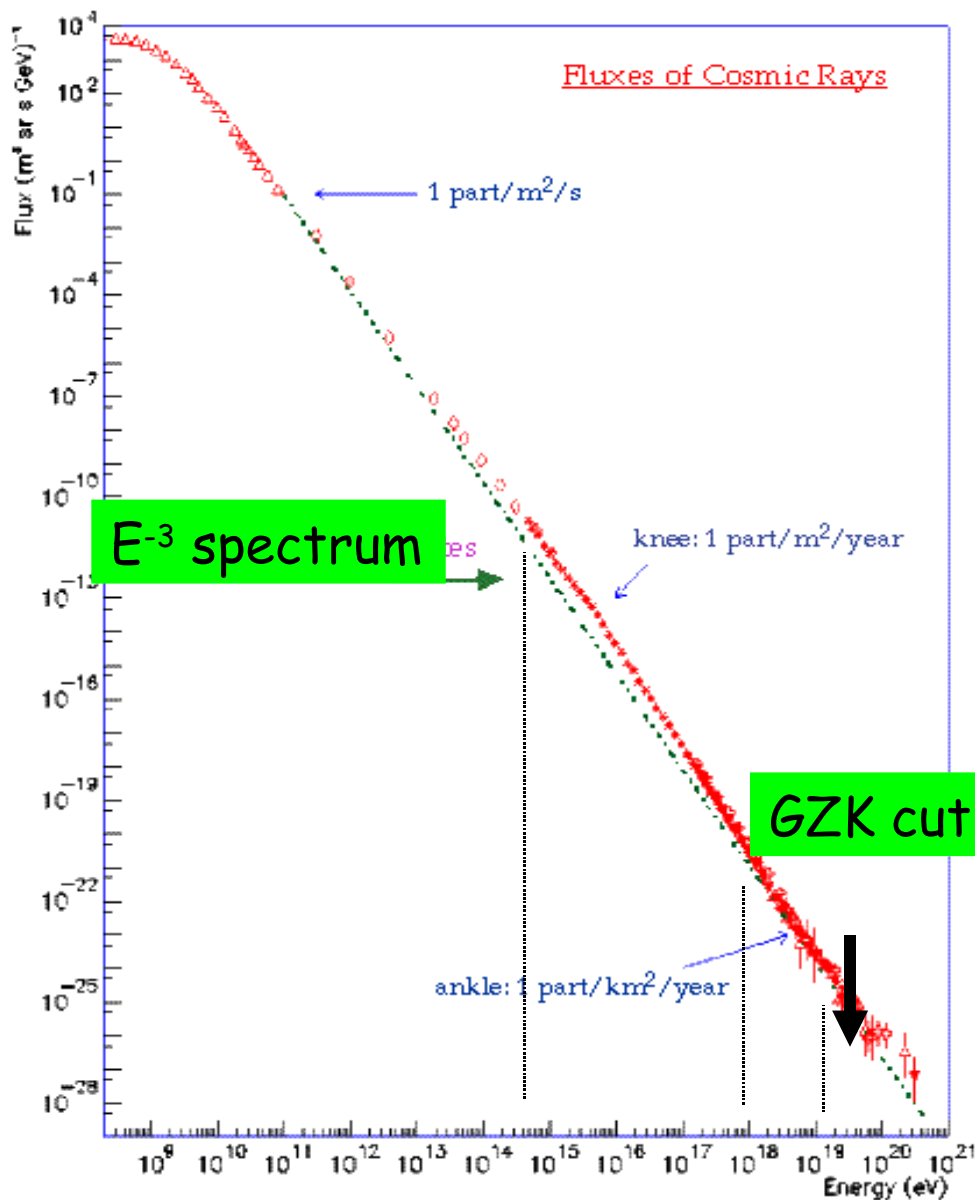
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$



Global view of atmospheric ν spectrum



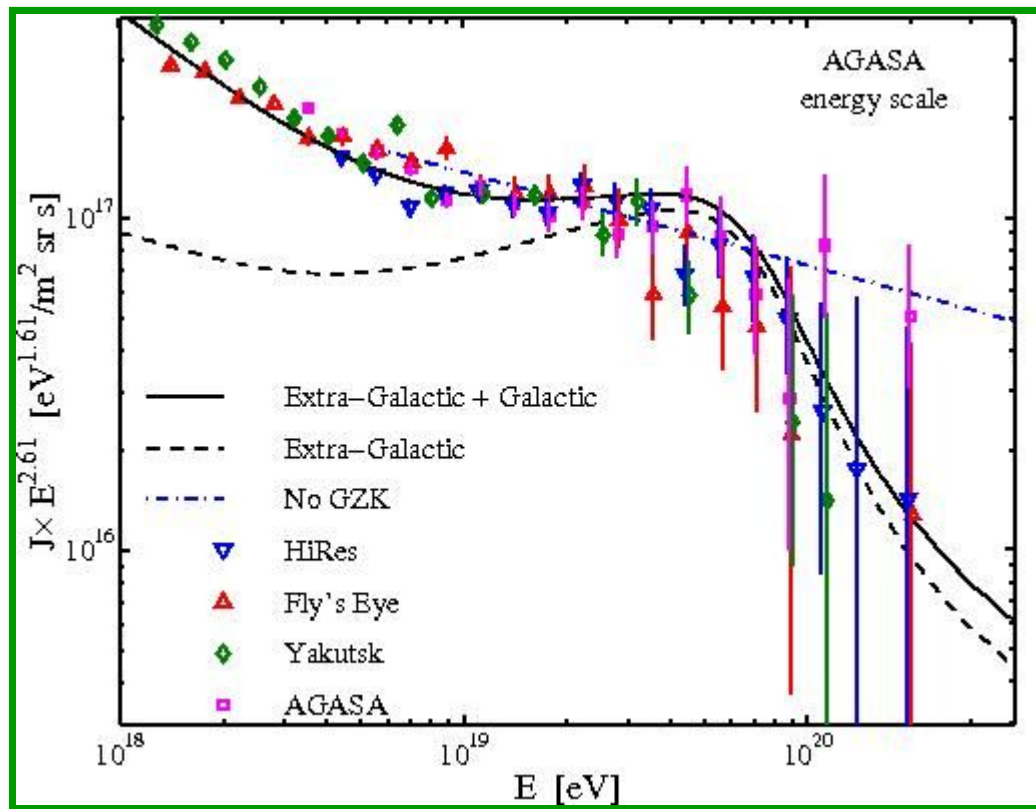
Spectre RC primaire



$E < 10^{15}$ eV
Galactic

$10^{15} < E < 10^{18}$ eV
galactic ?

$E \geq 5 \cdot 10^{19}$ eV
Extra-Galactic?
Unexpected?

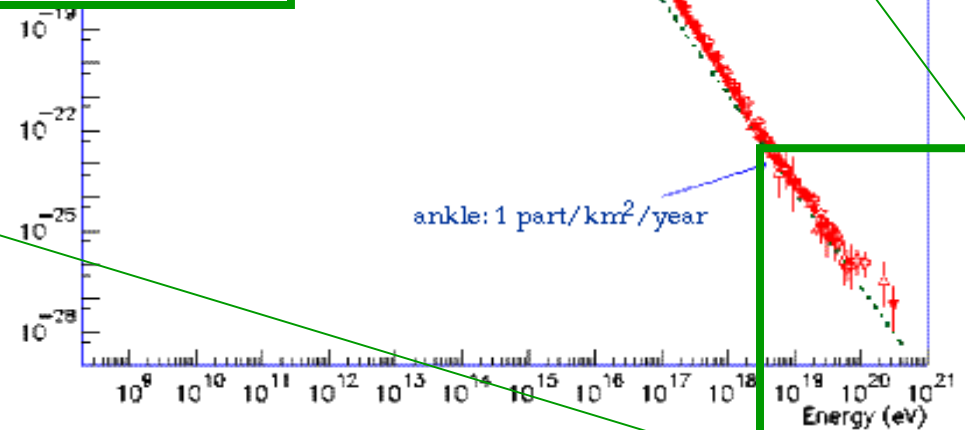


Effet GZK

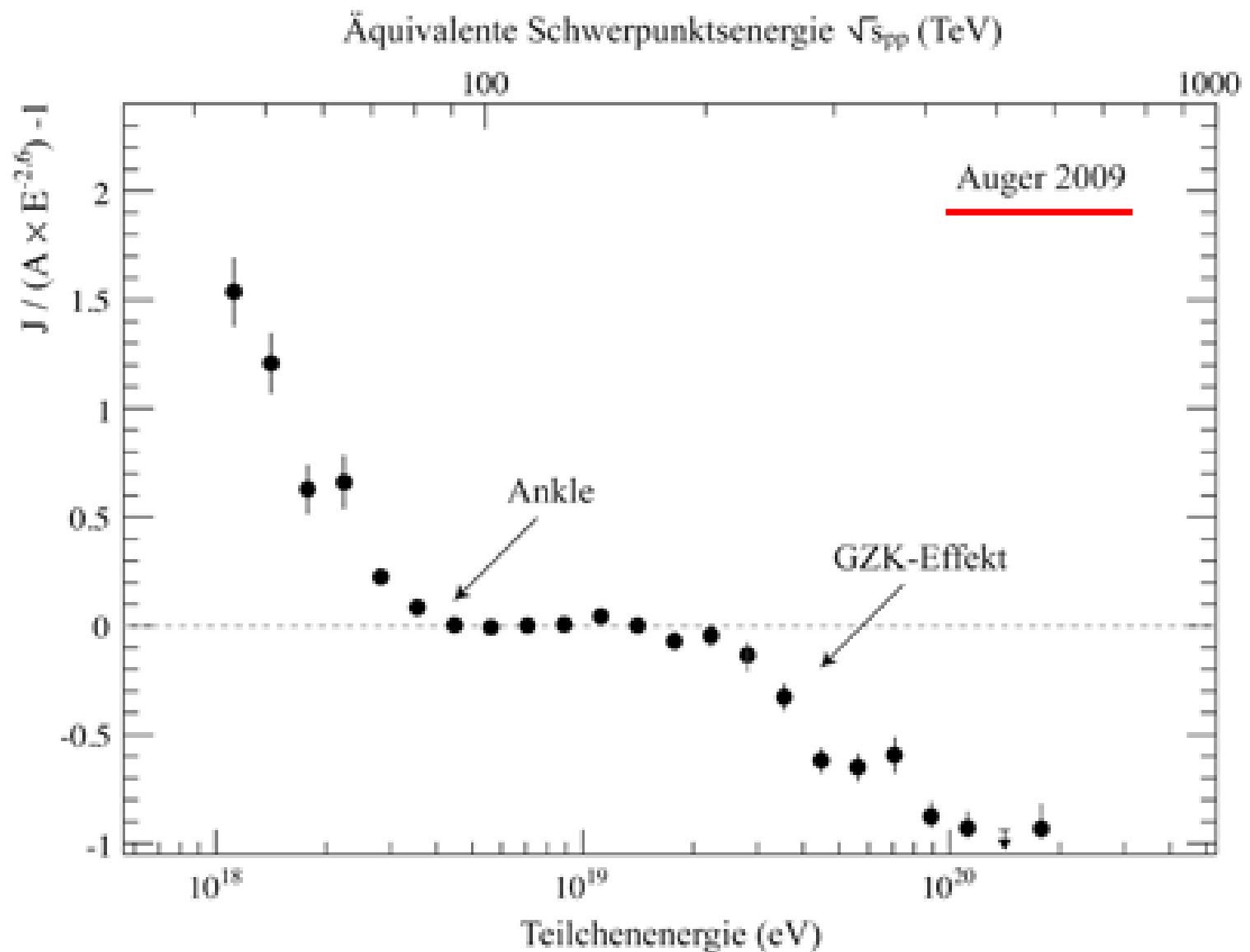
1 part/ m^2/s

or satellites

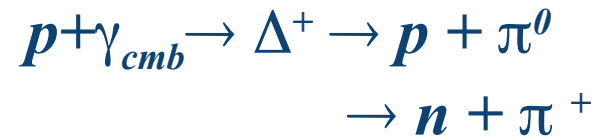
knee: 1 part/ m^2/year



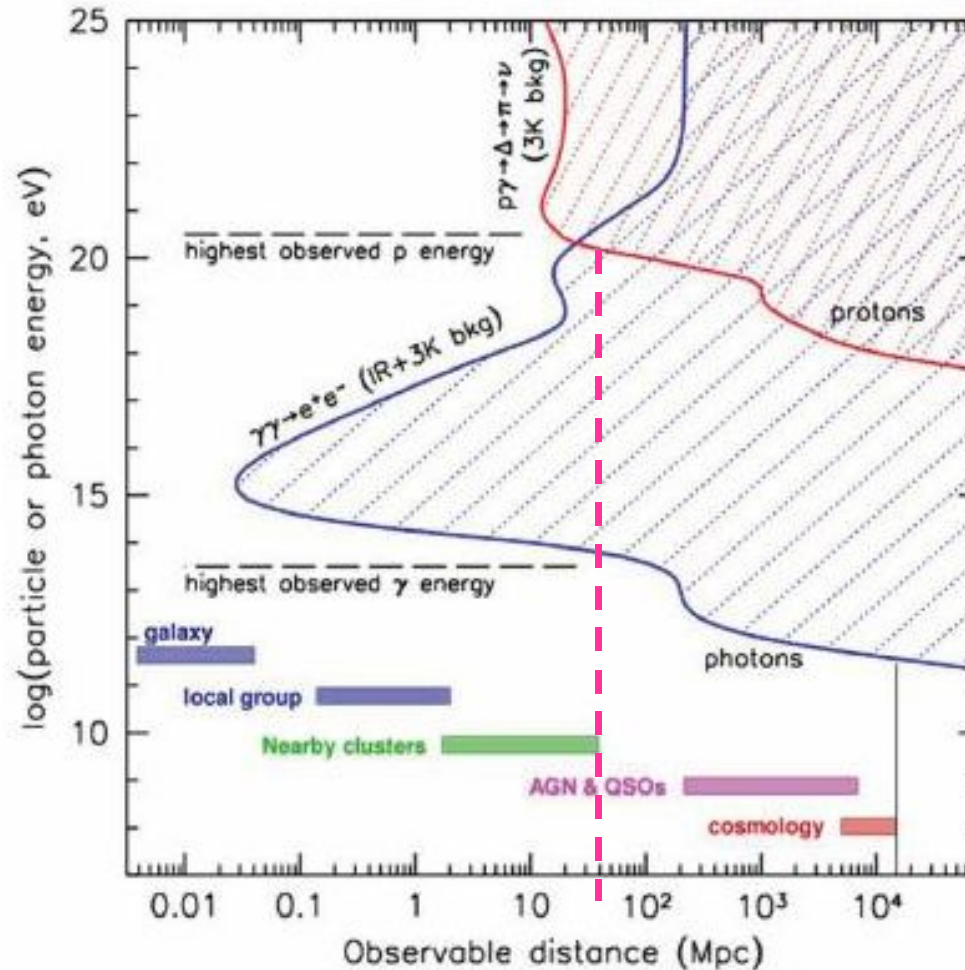
Effet GZK



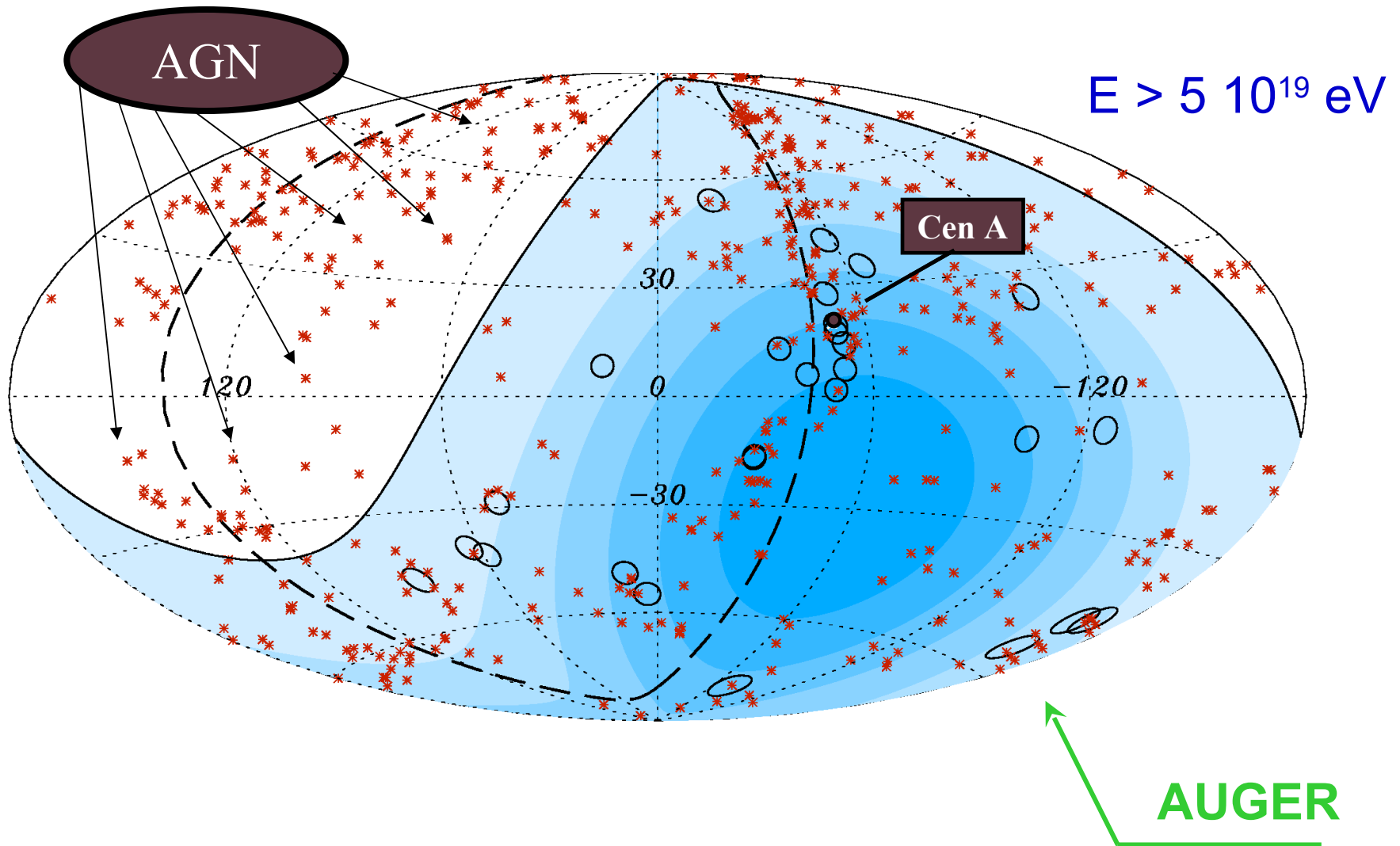
Effet GZK



Faible déflexion
magnétique a haute
énergie



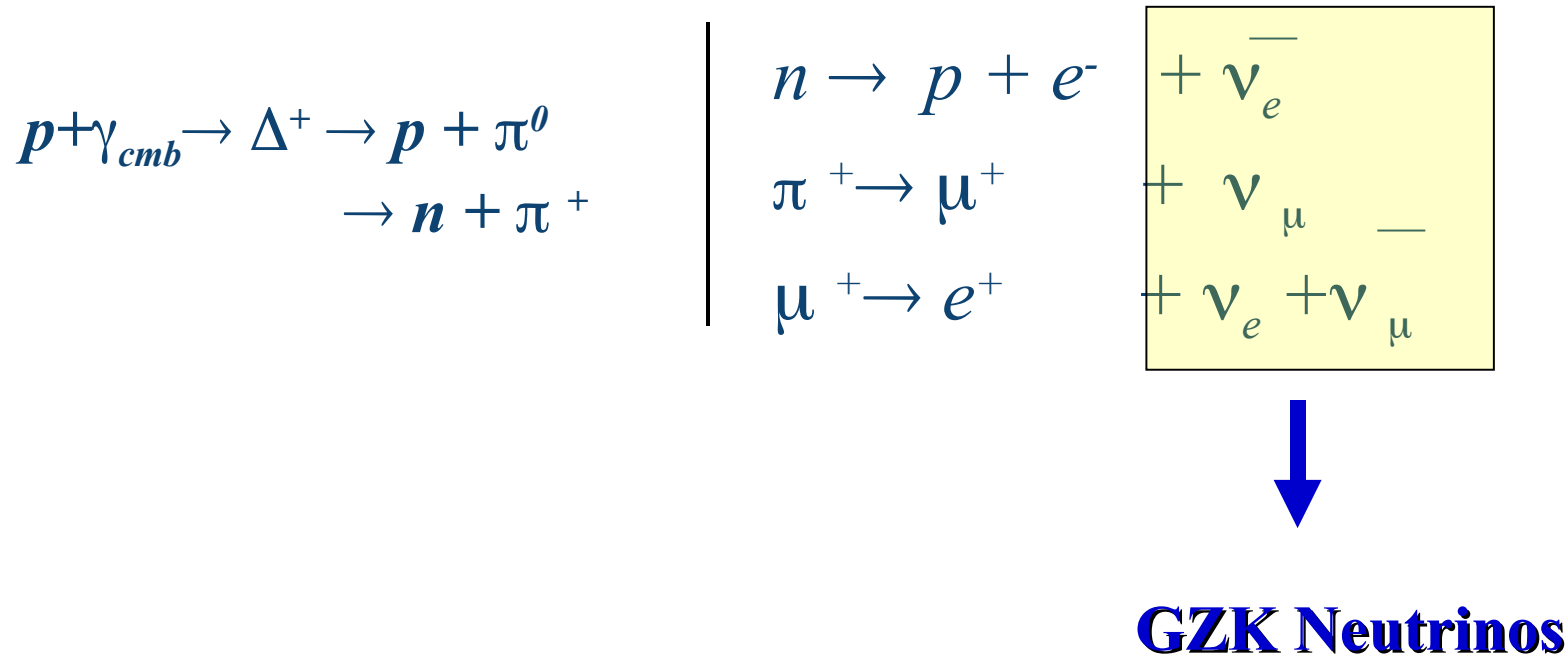
The UHECR Sky is anisotropic



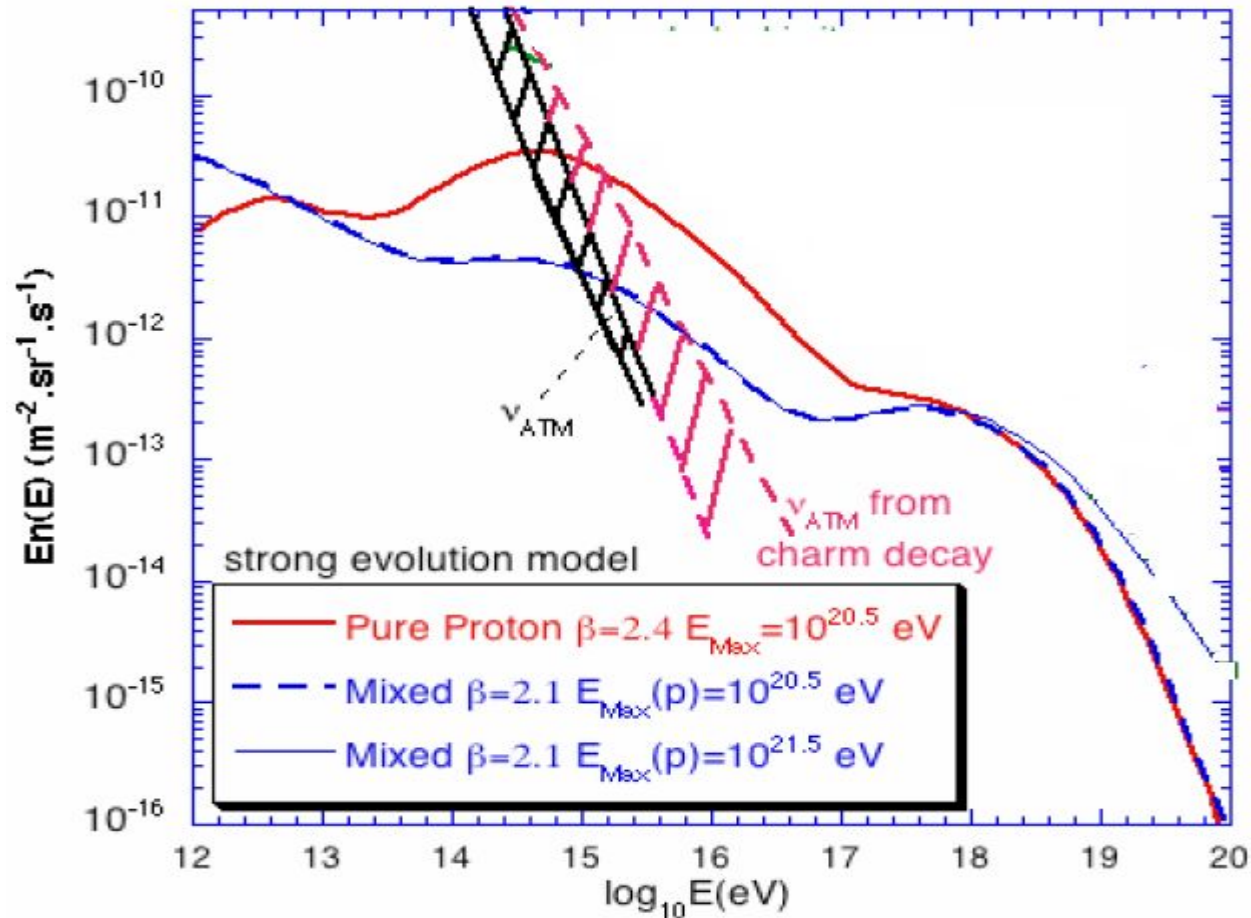
Veron – Cetty catalogue

Implications pour l'Astronomie Neutrino

- Observation de la coupure GZK
 \Rightarrow existence obligée de neutrinos cosmique UHE

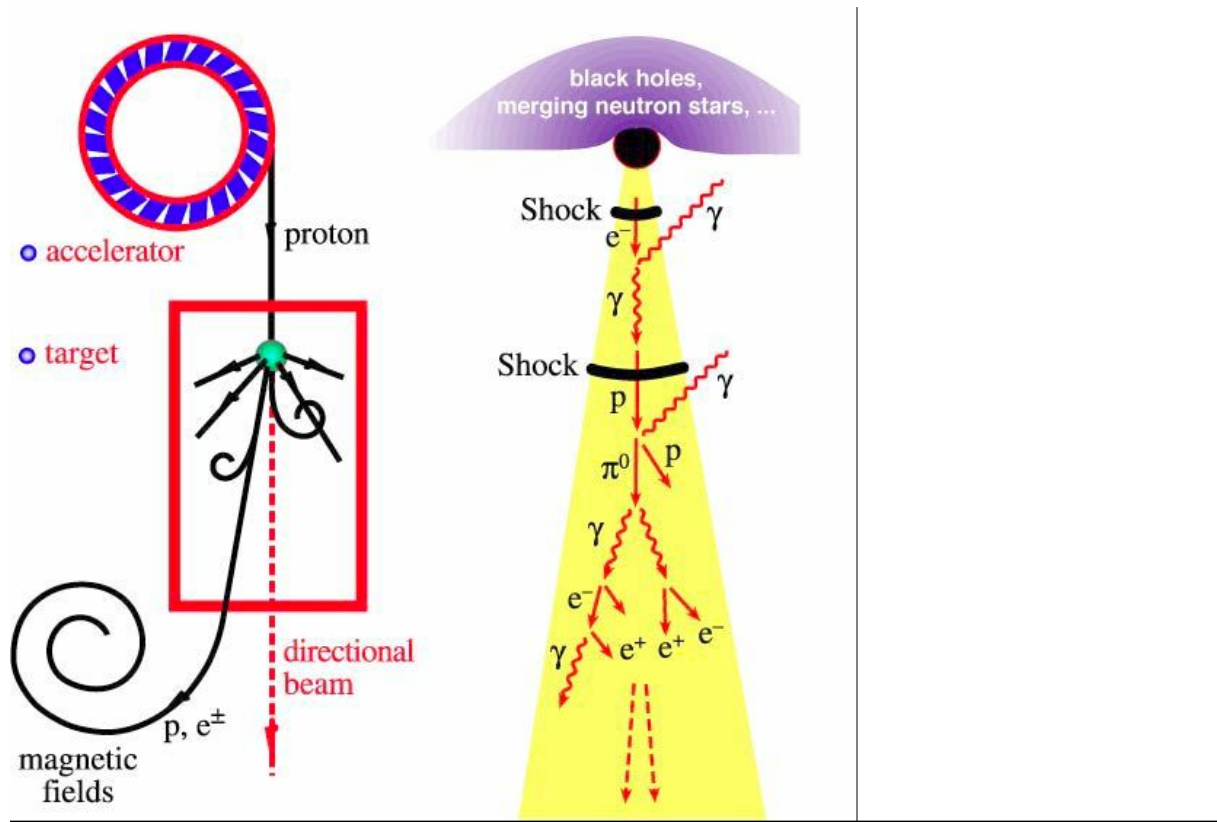


GZK neutrinos garantis mais modèle dépendant

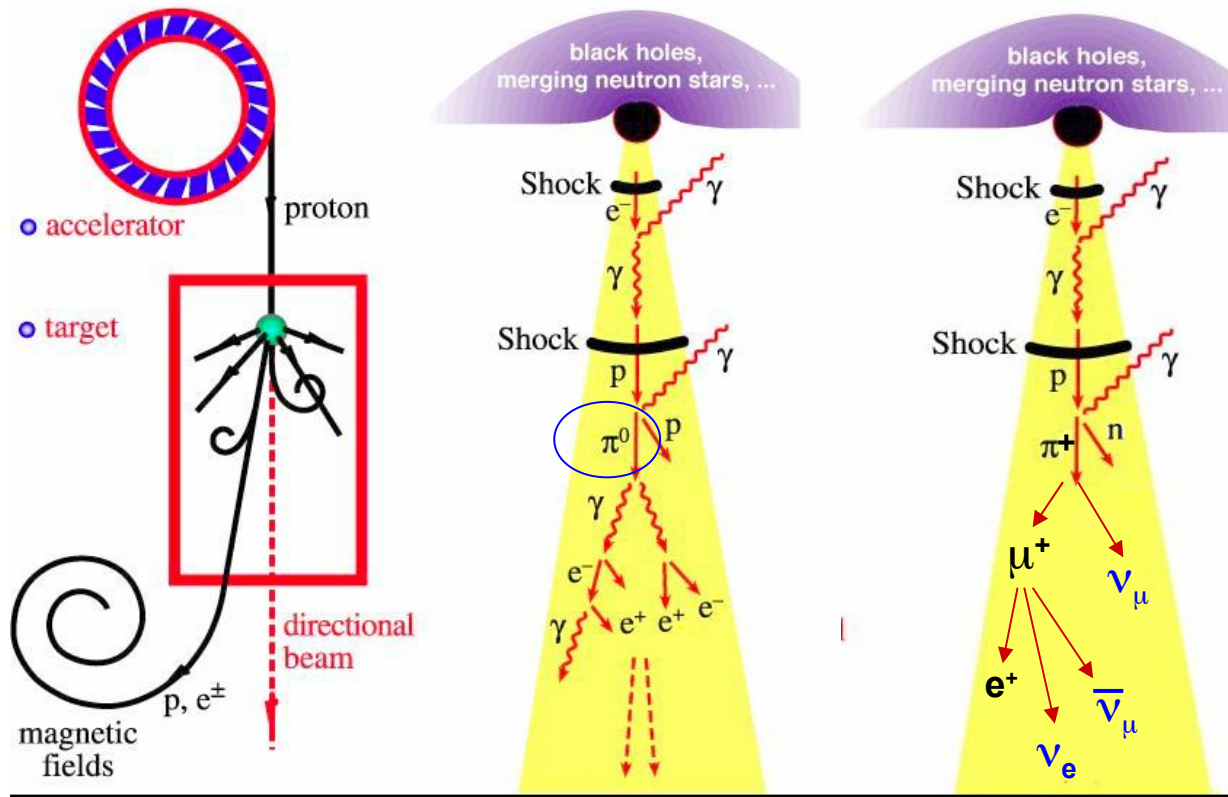


Allard, Ave et al, JCAP 0609 (2006)

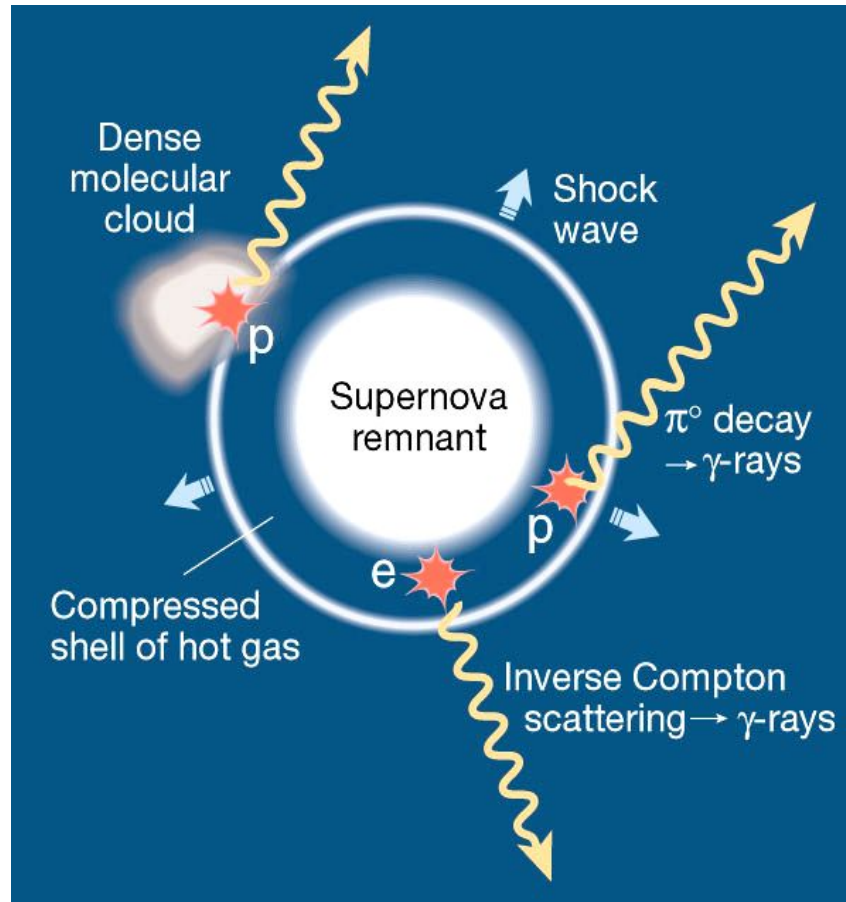
Astronomie gamma et neutrino intimement lies si processus hadronique



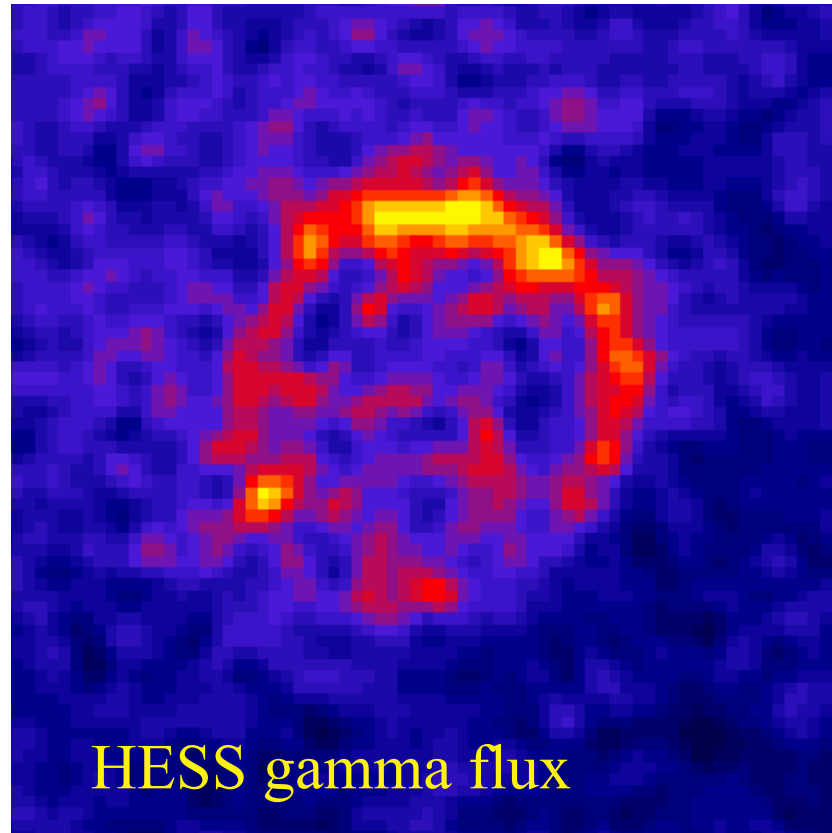
Astronomie gamma et neutrino intimement liées si processus hadronique



Sources γ

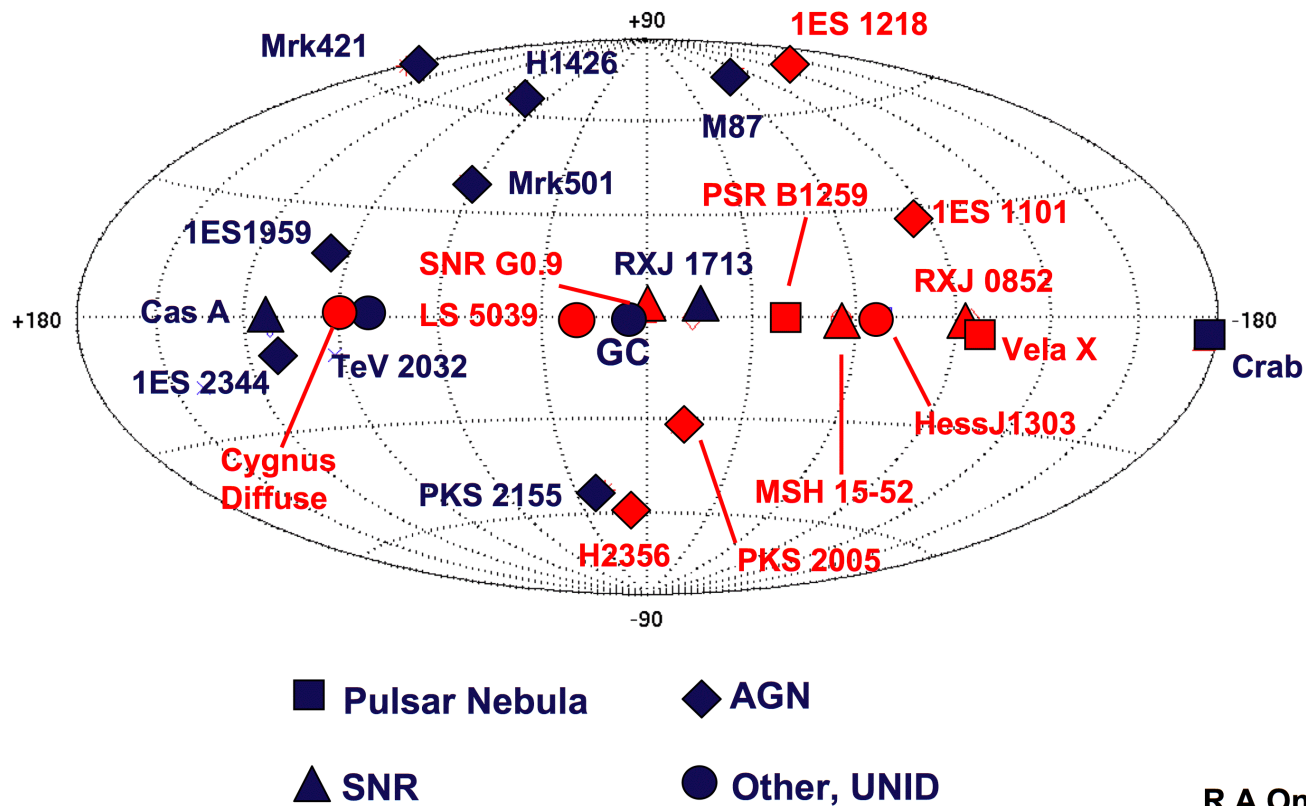


Sources γ

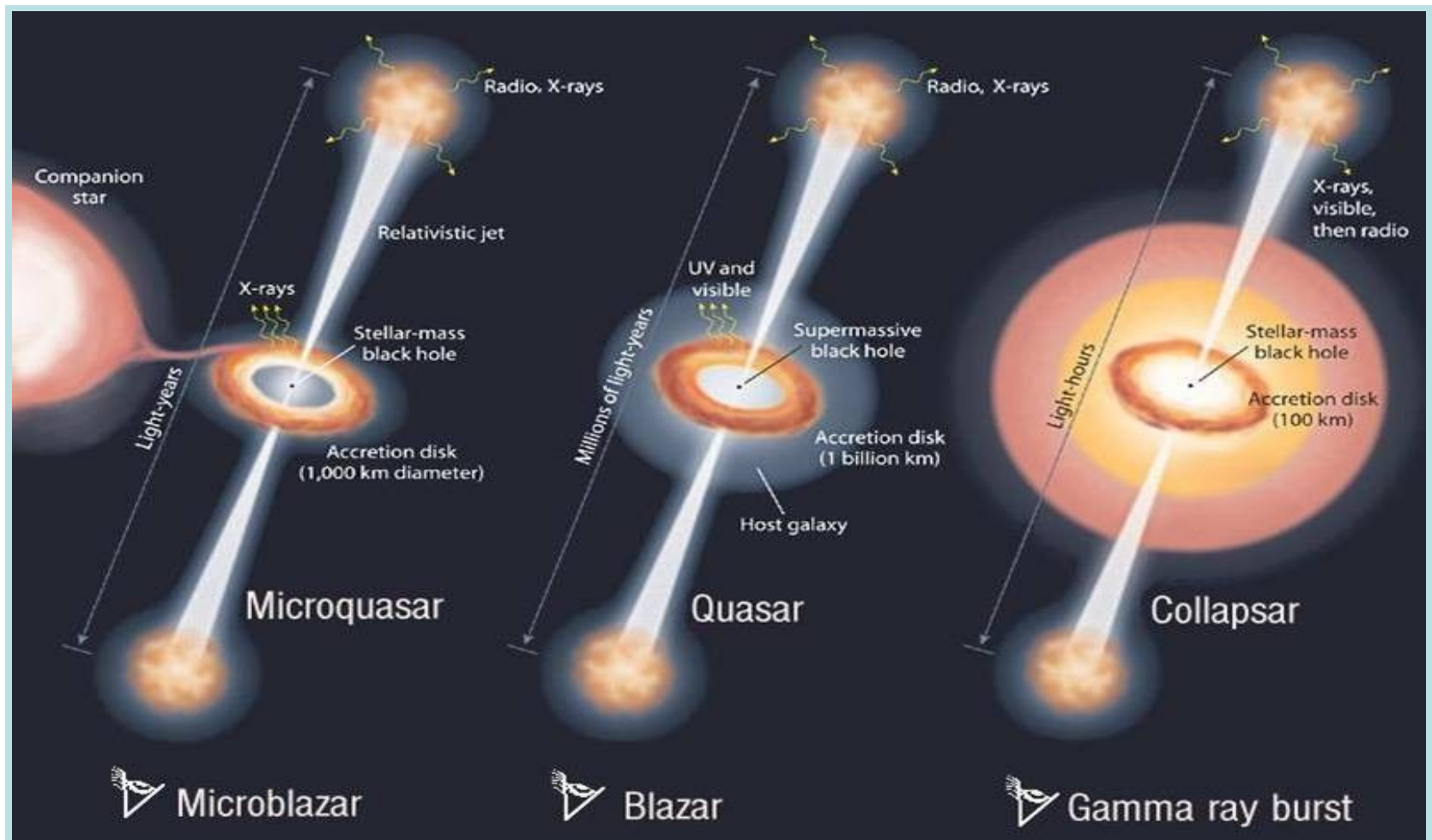


Very High Energy Gamma sources

+ 8-15 add. sources
in galactic plane.



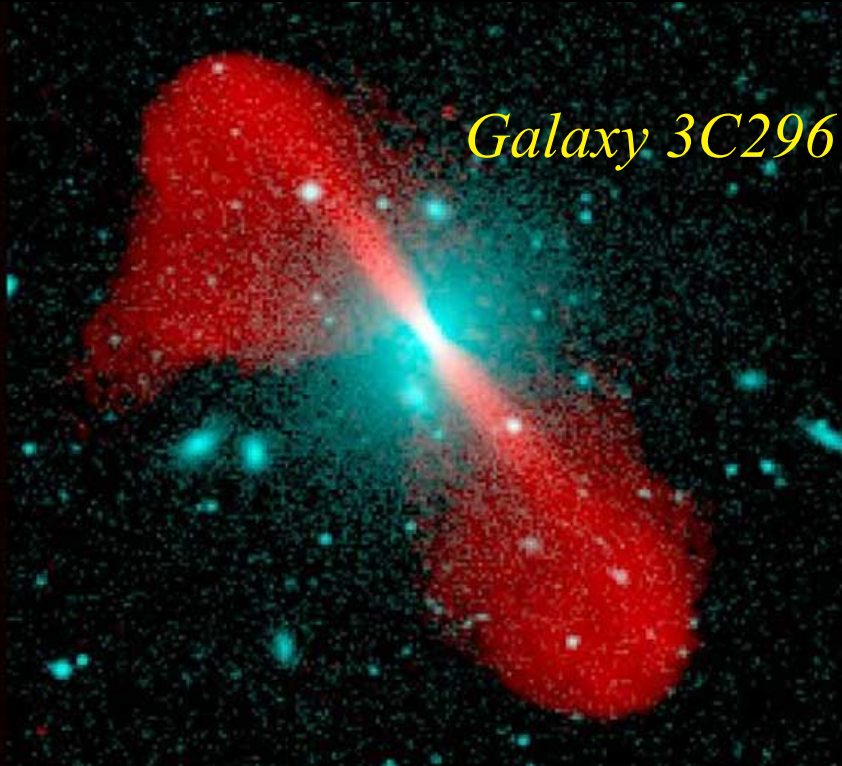
Sources à Jets cosmiques



| | | | | |
|------|--------------------------|--|---|------------------------|
| GRB: | $10^{20} L_{\text{Sun}}$ | $M_{\text{BH}} \sim 1 M_{\text{Sun}}$ | $M \sim 1 M_{\text{Sun}}/\text{s}$ | $\Gamma \sim 10^{2.5}$ |
| AGN: | $10^{14} L_{\text{Sun}}$ | $M_{\text{BH}} \sim 10^9 M_{\text{Sun}}$ | $M \sim 1 M_{\text{Sun}}/\text{yr}$ | $\Gamma \sim 10^1$ |
| MQ: | $10^5 L_{\text{Sun}}$ | $M_{\text{BH}} \sim 1 M_{\text{Sun}}$ | $M \sim 10^{-8} M_{\text{Sun}}/\text{yr}$ | $\Gamma \sim 10^{0.5}$ |

Active galaxies

Galaxy 3C296

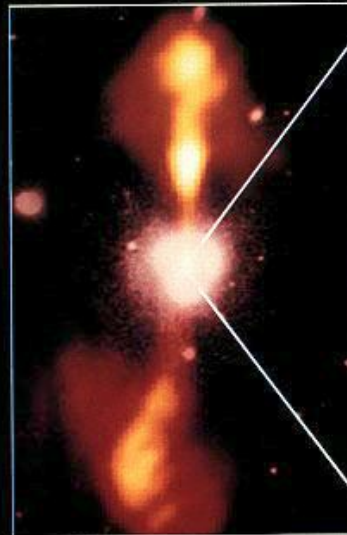


Core of Galaxy NGC4261

Hubble Space Telescope

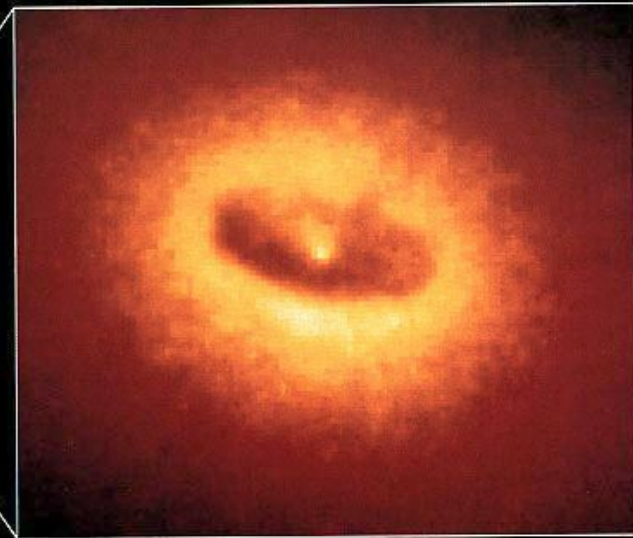
Wide Field/Planetary Camera

Ground-Based Optical/Radio Image



380 Arc Seconds
88,000 LIGHT-YEARS

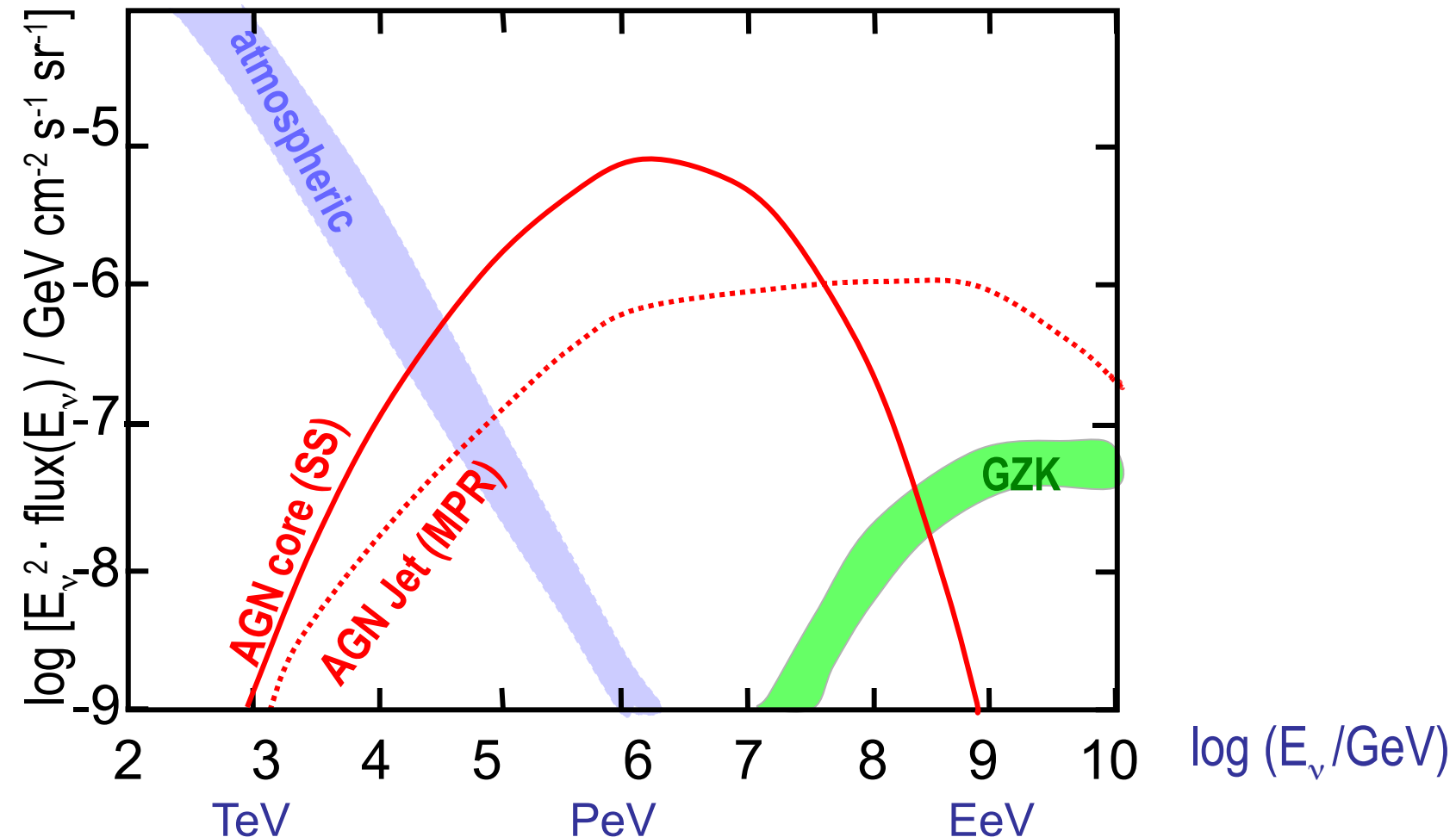
HST Image of a Gas and Dust Disk



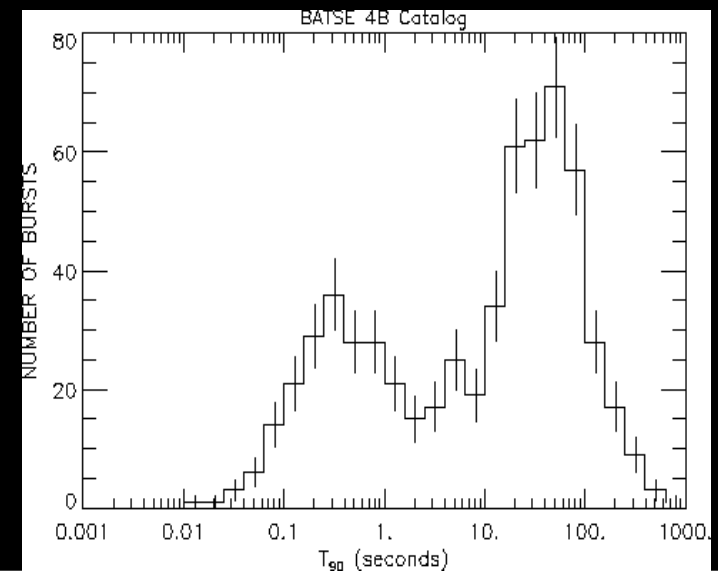
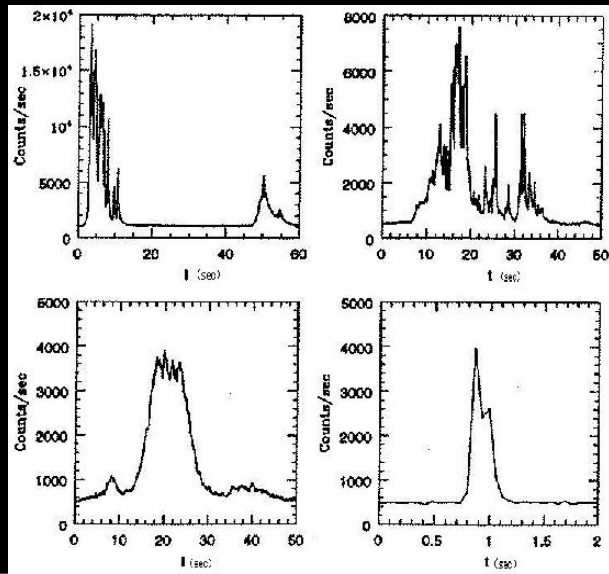
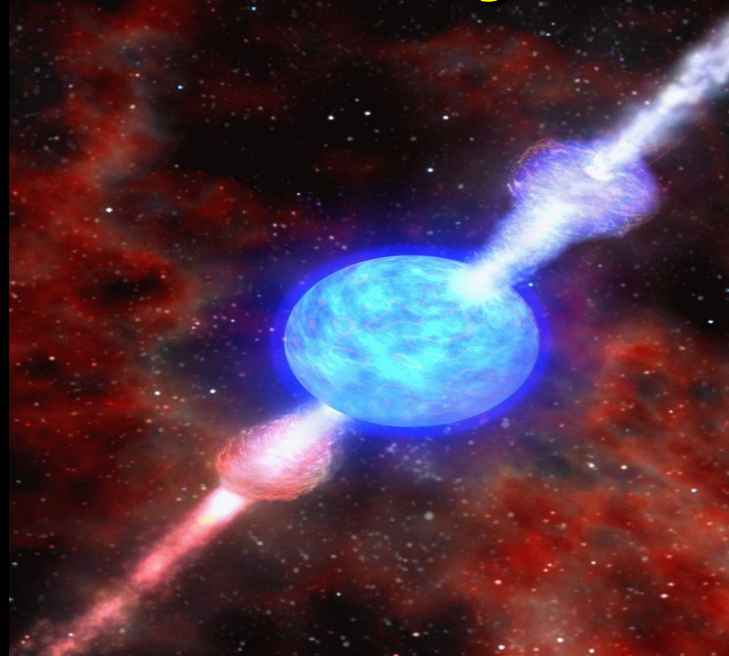
17 Arc Seconds
400 LIGHT-YEARS

Quelques prédictions

... pour la découverte de neutrinos extraterrestres

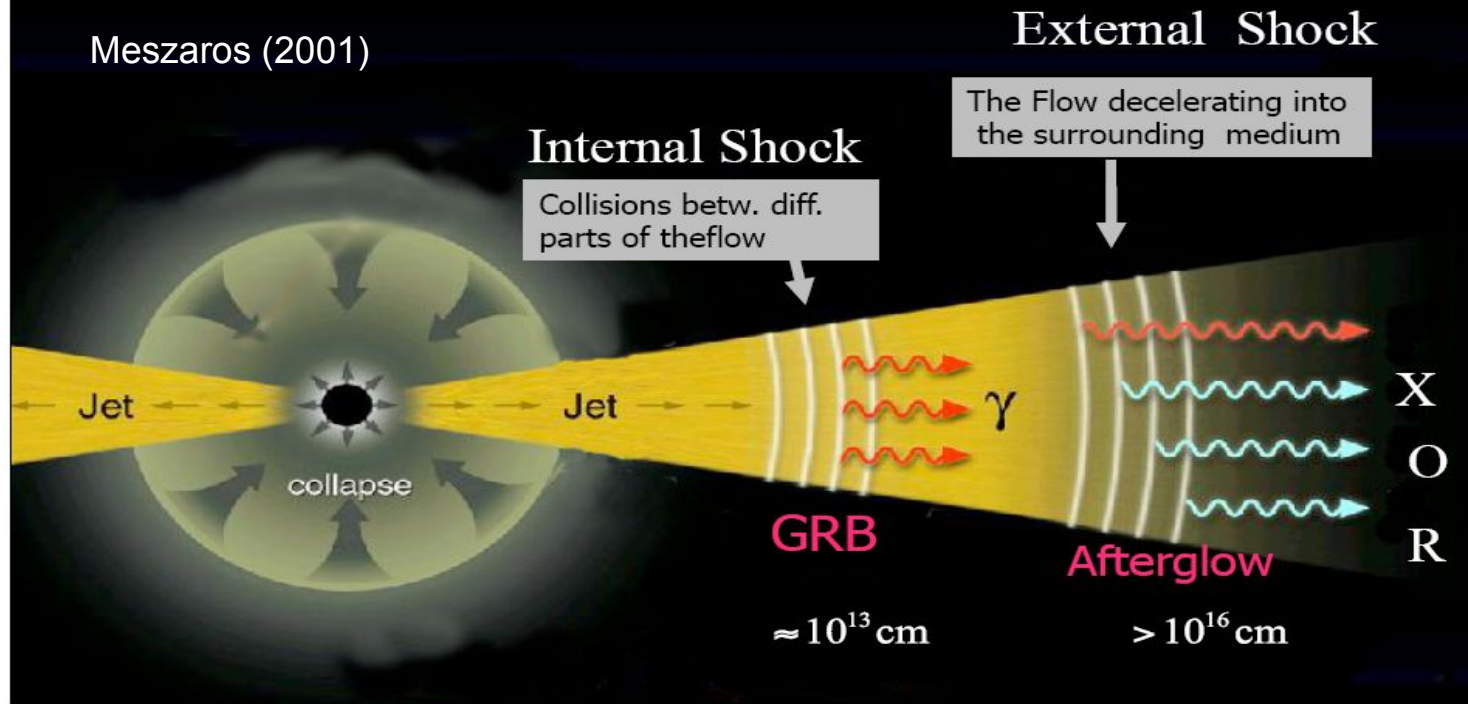


Gamma Ray Burst

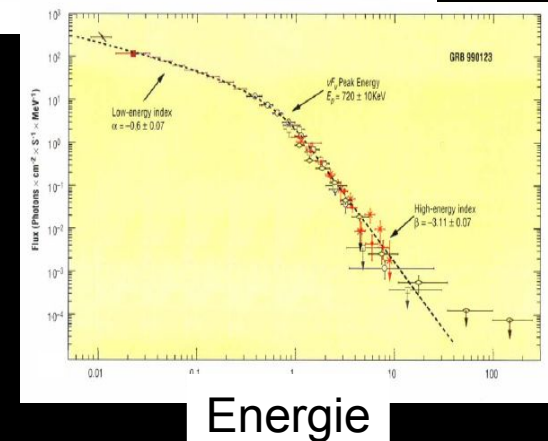
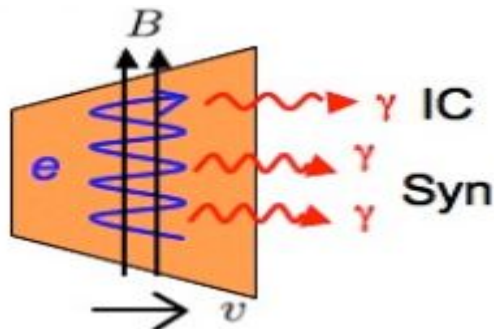


Fireball Model: long GRBs

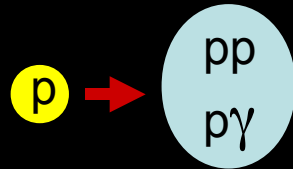
Meszaros (2001)



Production de γ



Production de ν

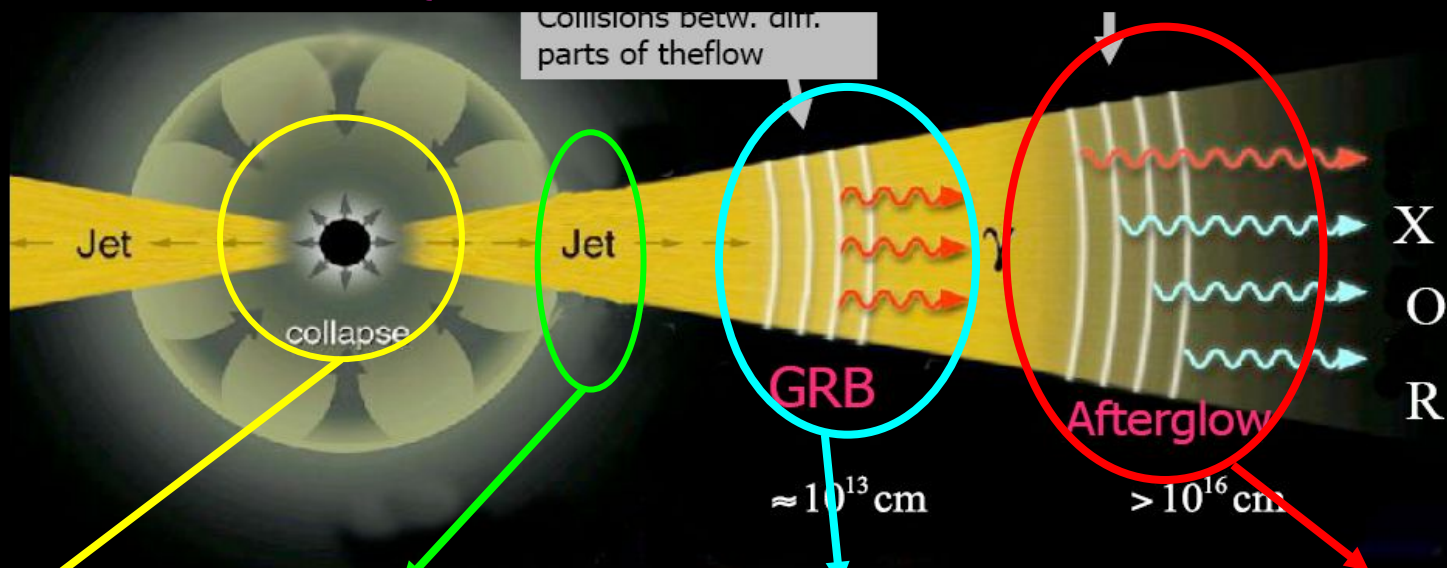


- **Photonuclear** $p\gamma \rightarrow \Delta^+ \rightarrow n\pi^+ / p\pi^0$

- **Nucleon-nucleon** $pp/pn \rightarrow \pi^\pm / K^\pm$

ν **production channels**

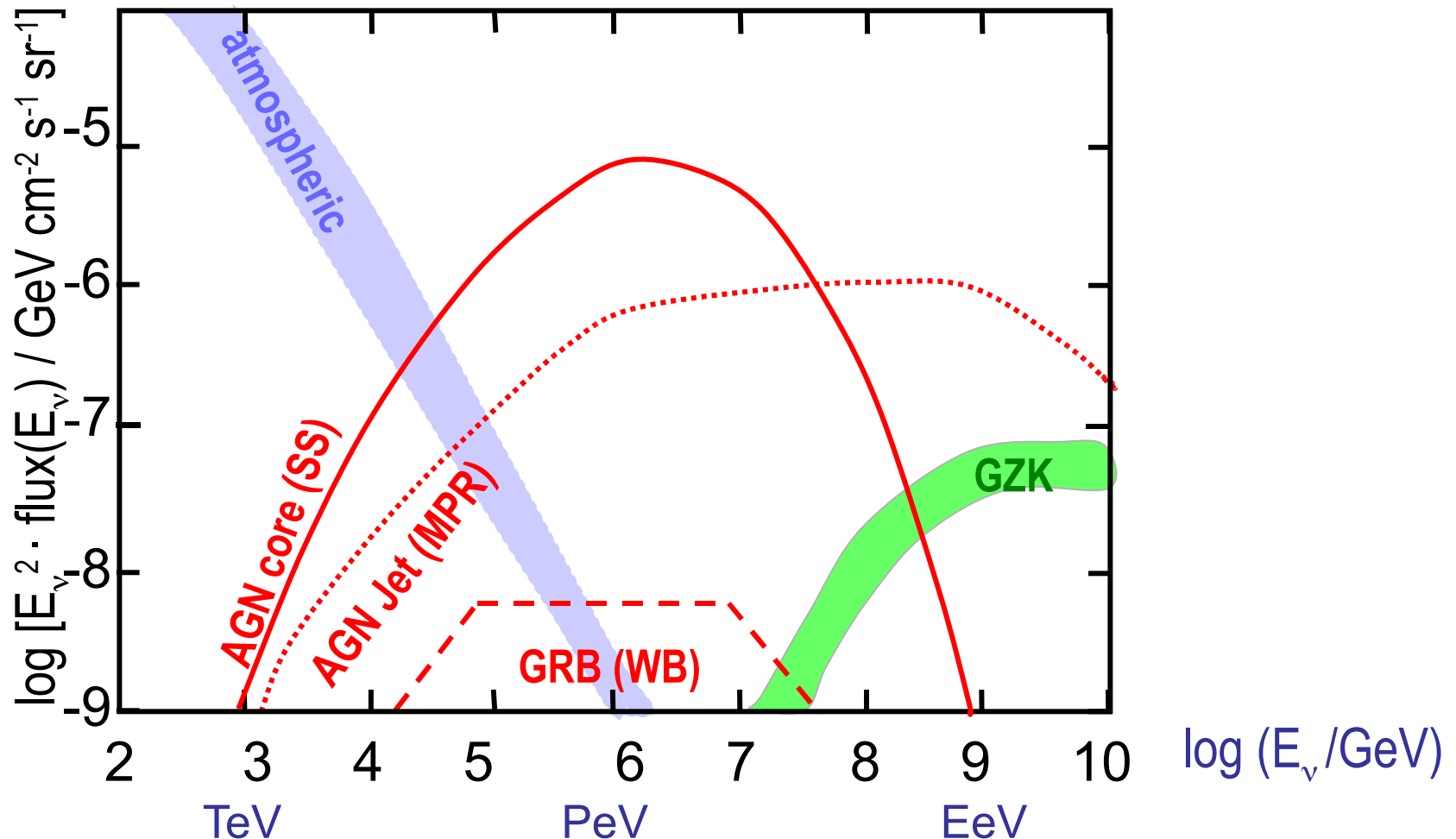
$\pi^+ / K^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu$



| MeV neutrinos | TeV neutrinos | PeV neutrinos | EeV neutrinos |
|--------------------------|------------------------|----------------------|-------------------------|
| at collapse | from inside the star | from internal shocks | from external shocks |
| (Meszaros & Waxman 2001) | (Schneider et al. 02) | HL GRBs | (Waxman & Bahcall 2000) |
| | (Razzaque et al. 2003) | LL GRBs | (Dermer 2002) |
| | (Fabio, KM, et al. 07) | (KM et al. 2006) | (KM 2007) |
| | | Gupta & Zhang 2006 | |

Quelques prédictions

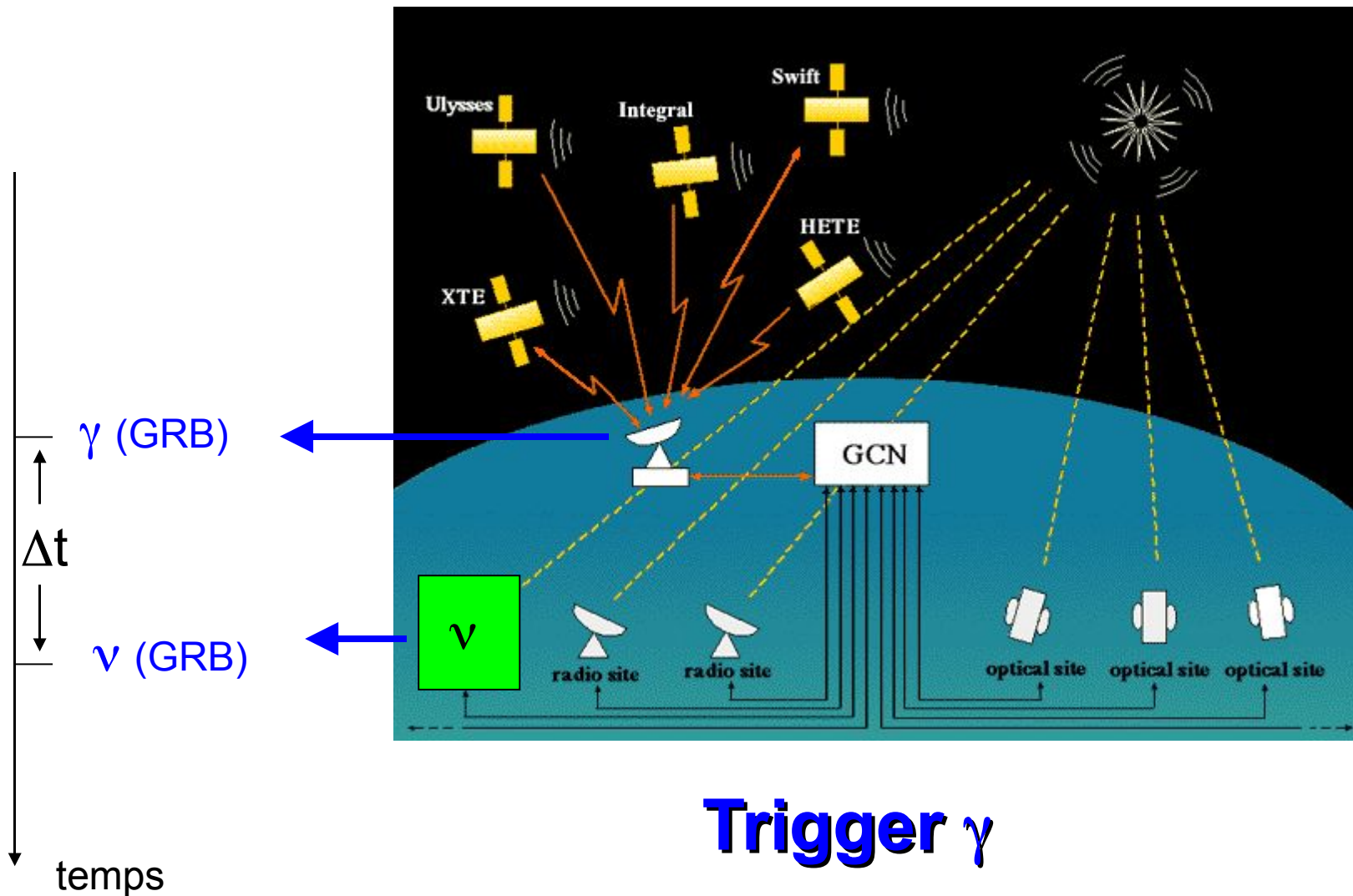
... pour la découverte de neutrinos extraterrestres



Détection en coïncidence

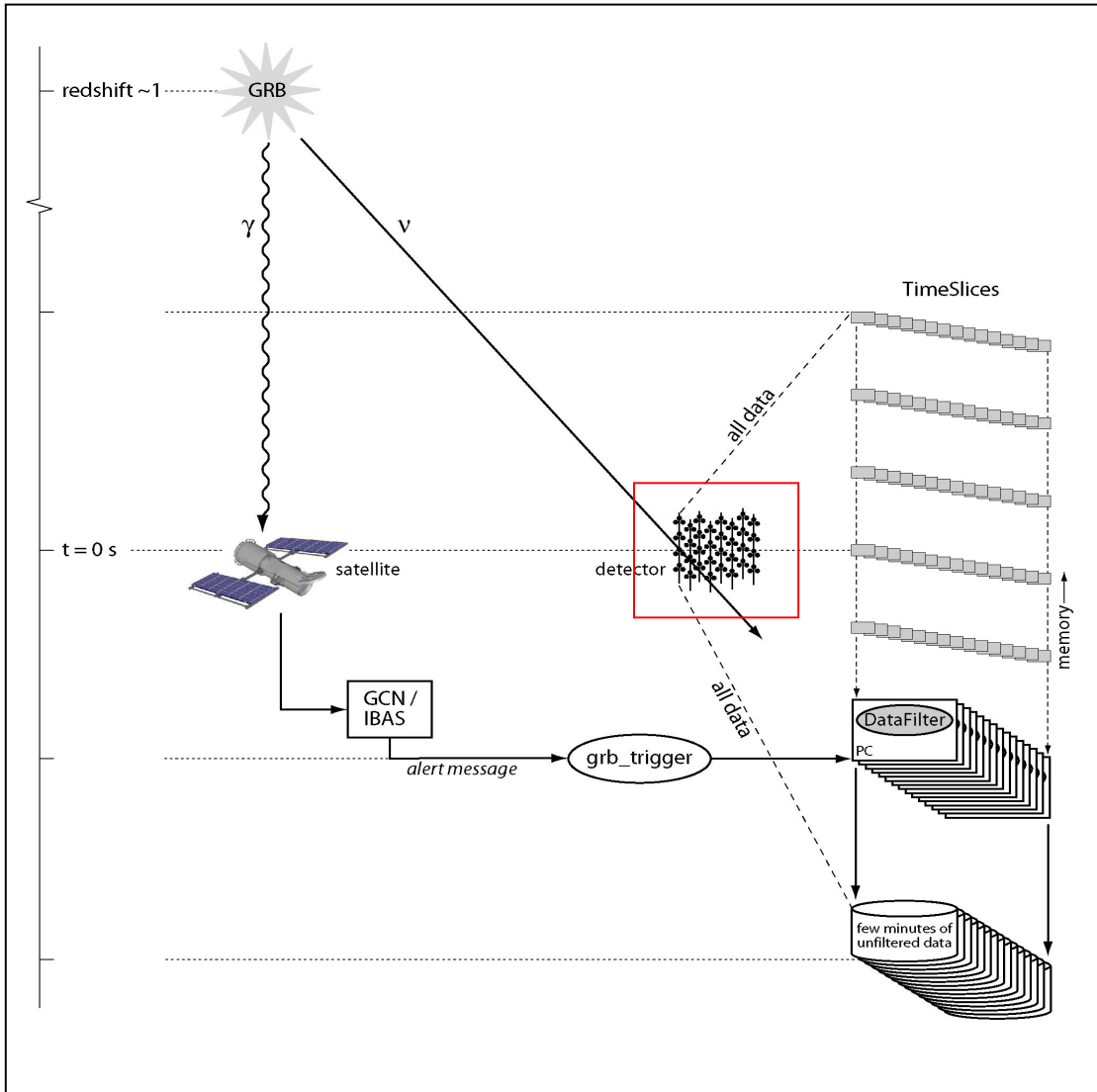
Coïncidence dans l'espace et dans le temps

= > BdF ~ 0



Trigger γ

SWIFT, INTEGRAL, Fermi alerts reception



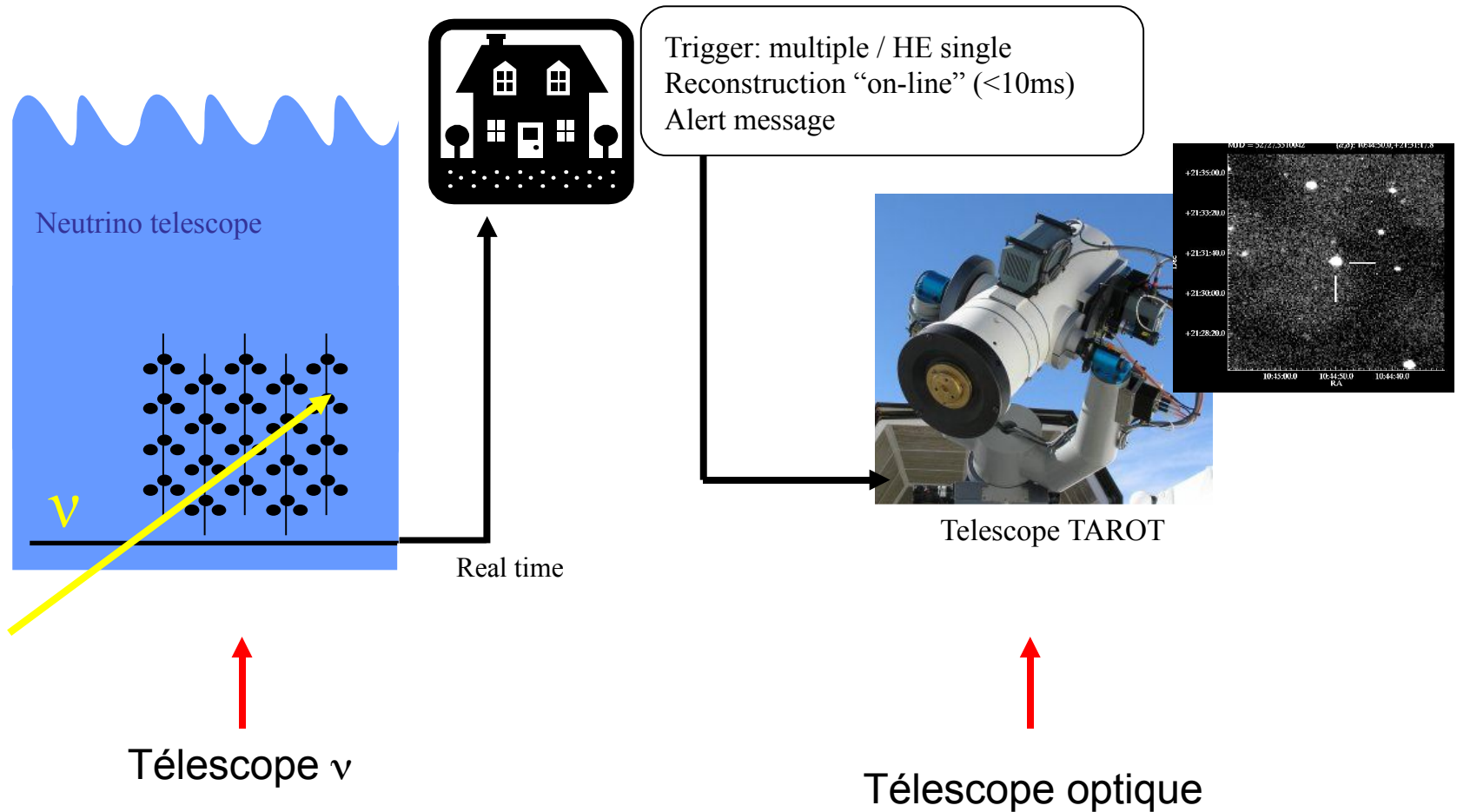
Ex : ANTARES

Continuous data
acquisition

+

GRB data storage
during 2 minutes
without filtering

Trigger ν

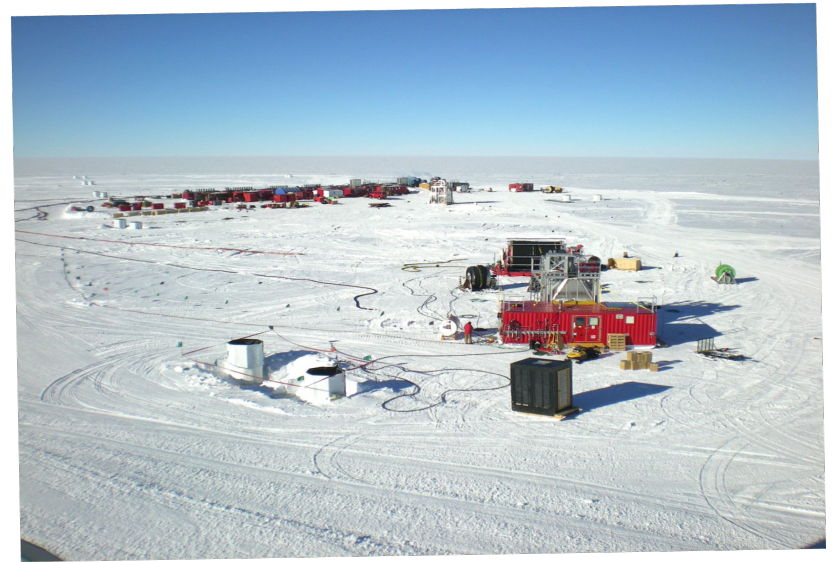


Détection de neutrinos haute énergie

Flux très faibles => très grand volumes => milieu naturel

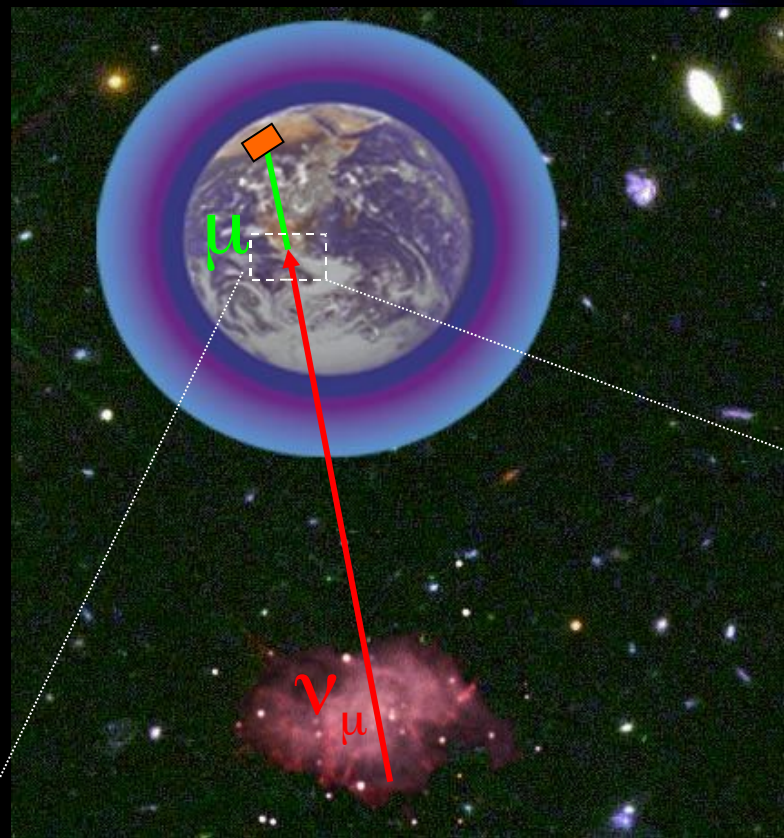


Mer



Glace

Principe de detection



3D PMT
array

Cherenkov
light from μ

$\gamma_{\check{c}}$

2500 m
depth

43°

Measurement :
Time & position
of hits

interaction

$$\theta \leq \frac{1.5 \text{ deg.}}{\sqrt{E_\nu / \text{TeV}}}$$

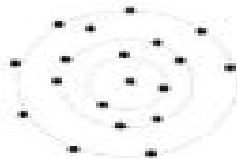


$\mu (\sim \nu)$ trajectory



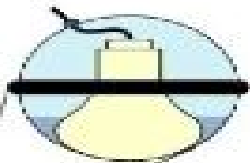
AMANDA-II

Depth



Top view

200 m



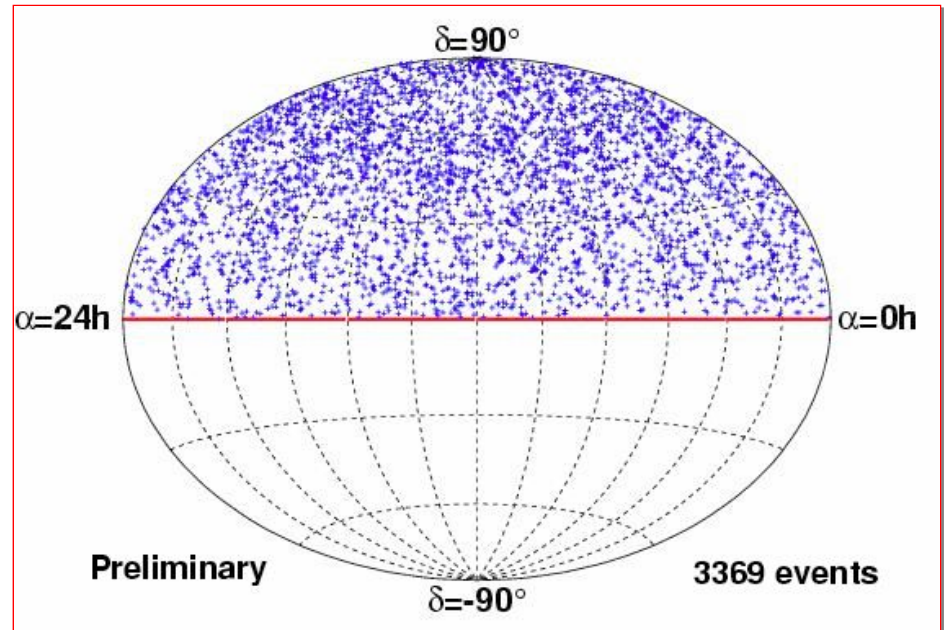
1500 m

2000 m

2500 m

AMANDA

Pole sud



ANTARES

Méditerranée

2500m

buoy

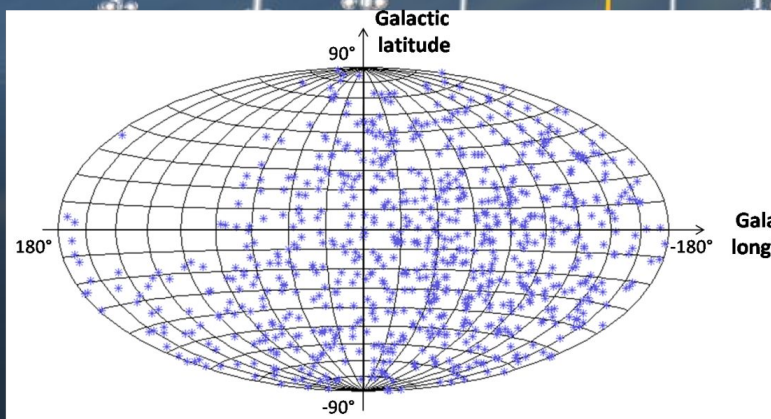
12 lines
900 PMTs
25 storeys / line
3 PMTs / storey

450 m

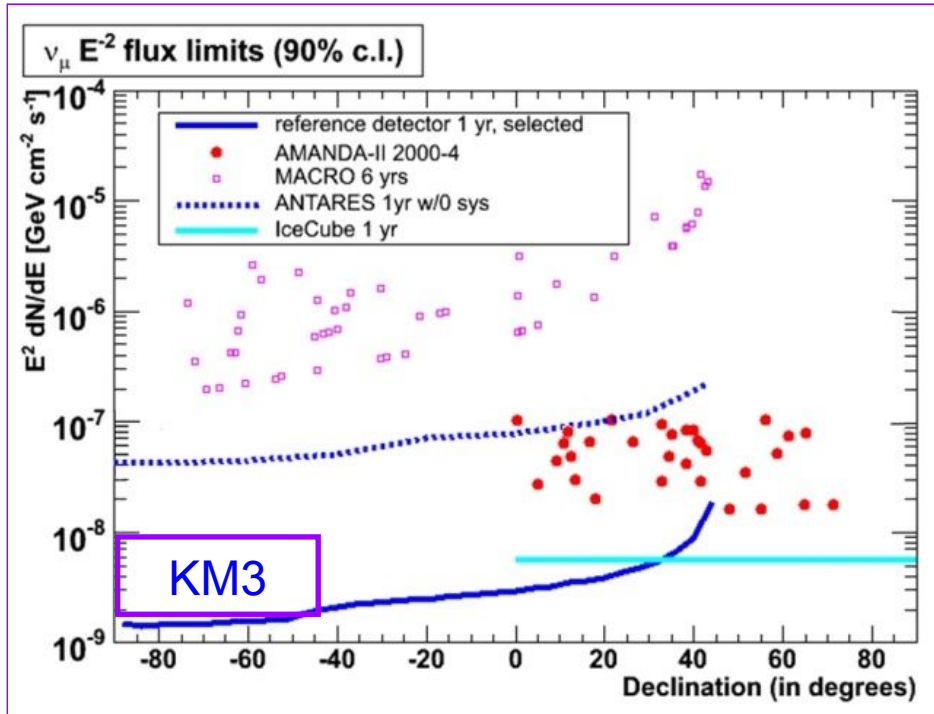
40 km to
shore

Junction
Box

Interlink cables

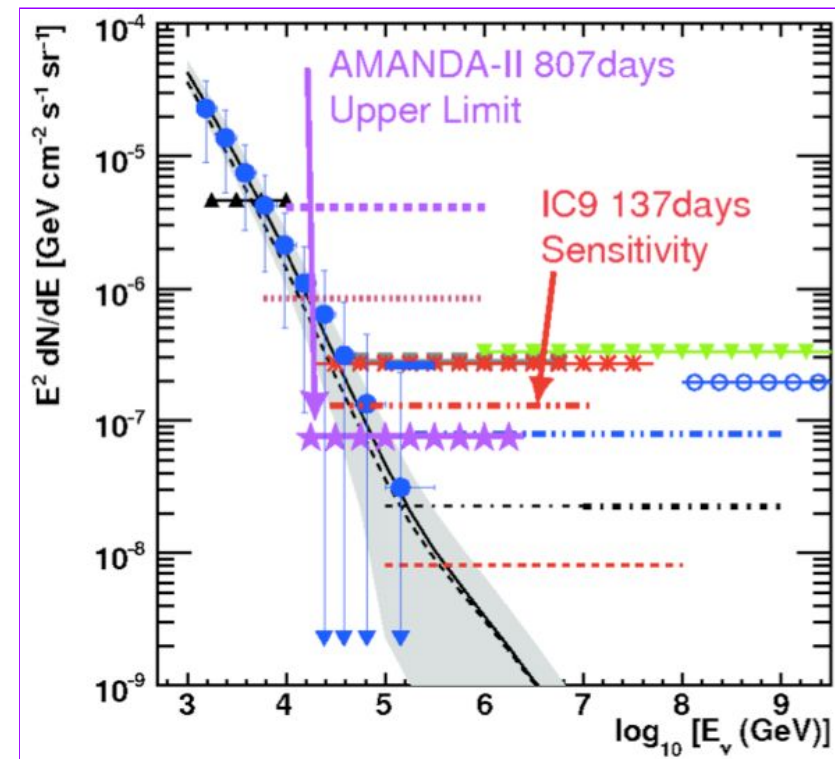


Quelques résultats

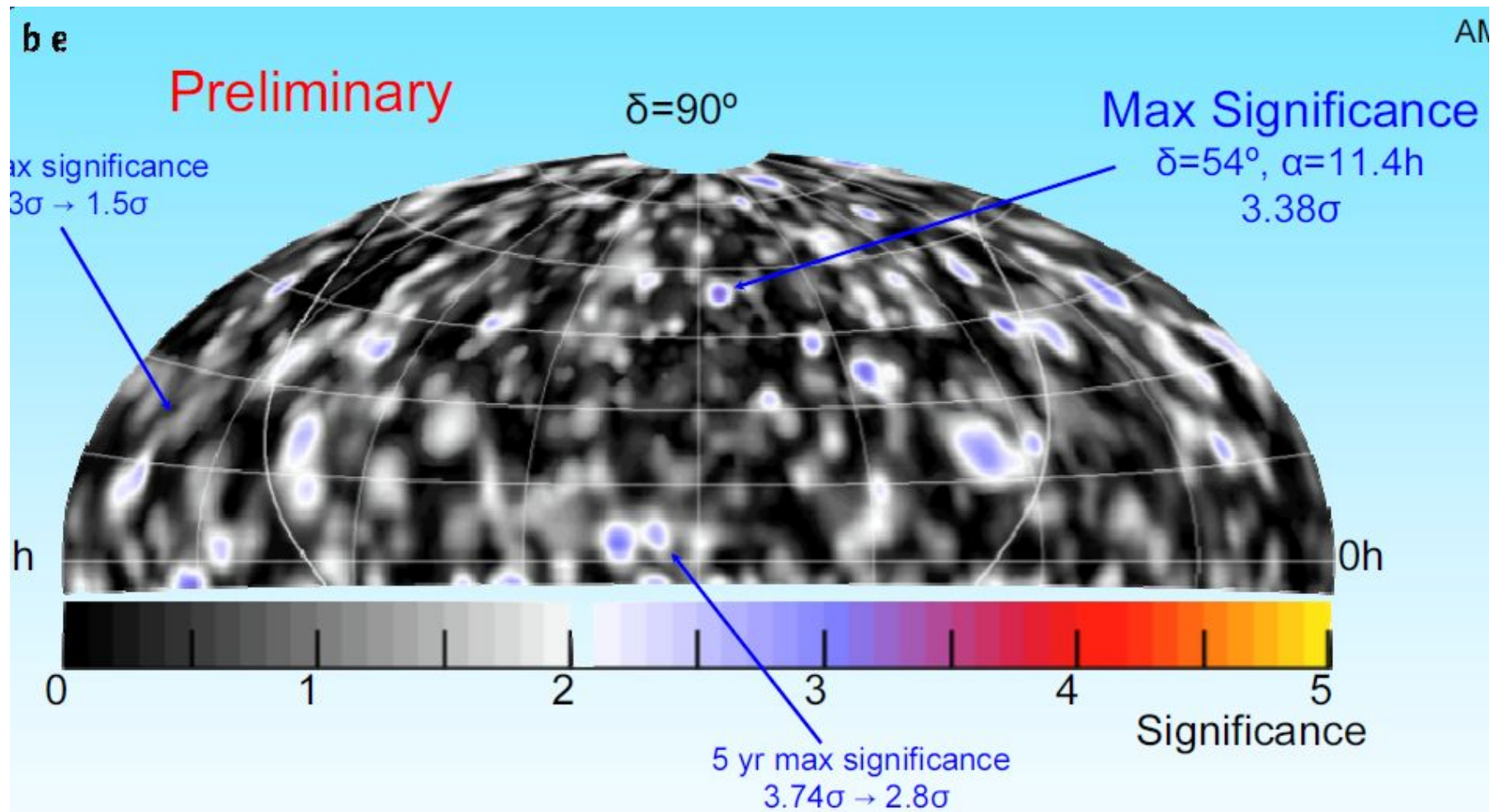


Sources ponctuelles

Flux diffus

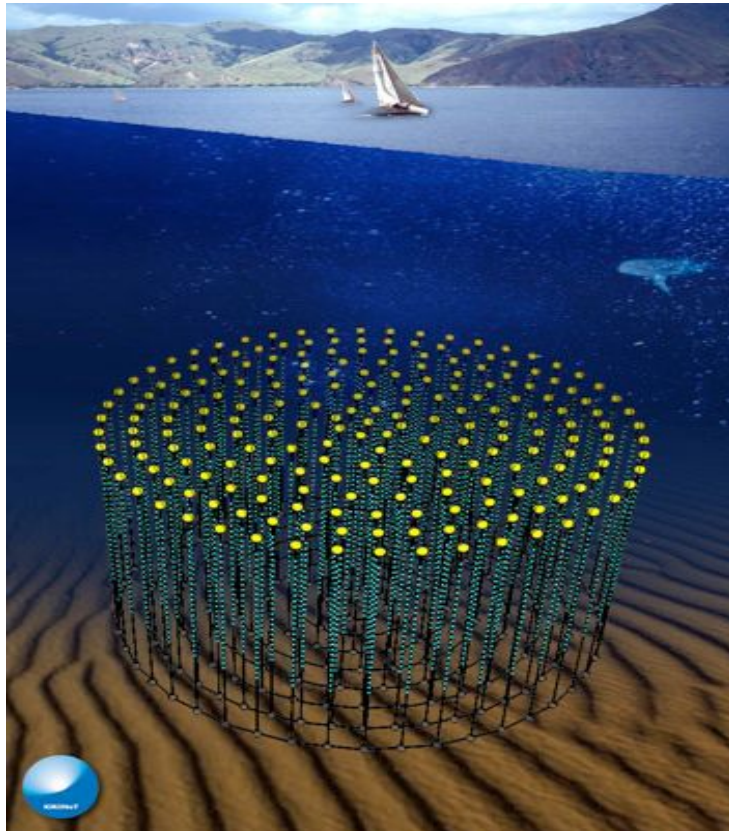


AMANDA + ICE CUBE



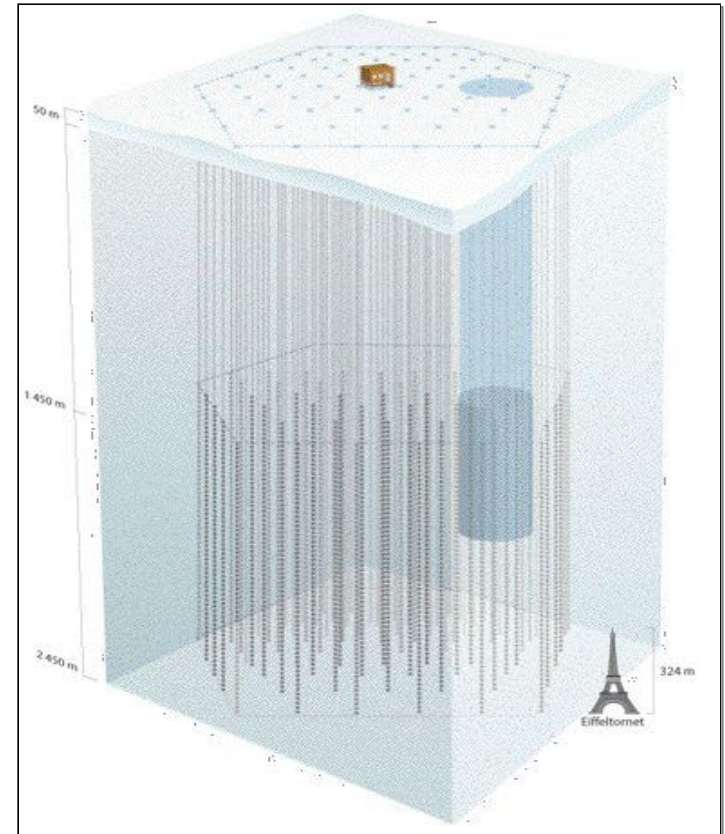
Avenir : détecteur kilométrique

Km3



En préparation

IceCube



En construction

Conclusion

- Le neutrino : extraordinaire vecteur pour étudier l'Univers lointain, profond, violent
- L'Univers : extraordinaire source pour étudier les propriétés du neutrino, des particules et des interaction fondamentales

ASTRO ↔ PARTICULES

FIN!

Distribution en temps et en énergie

