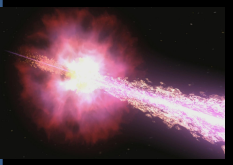
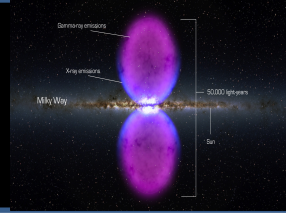




« Neutrinos »

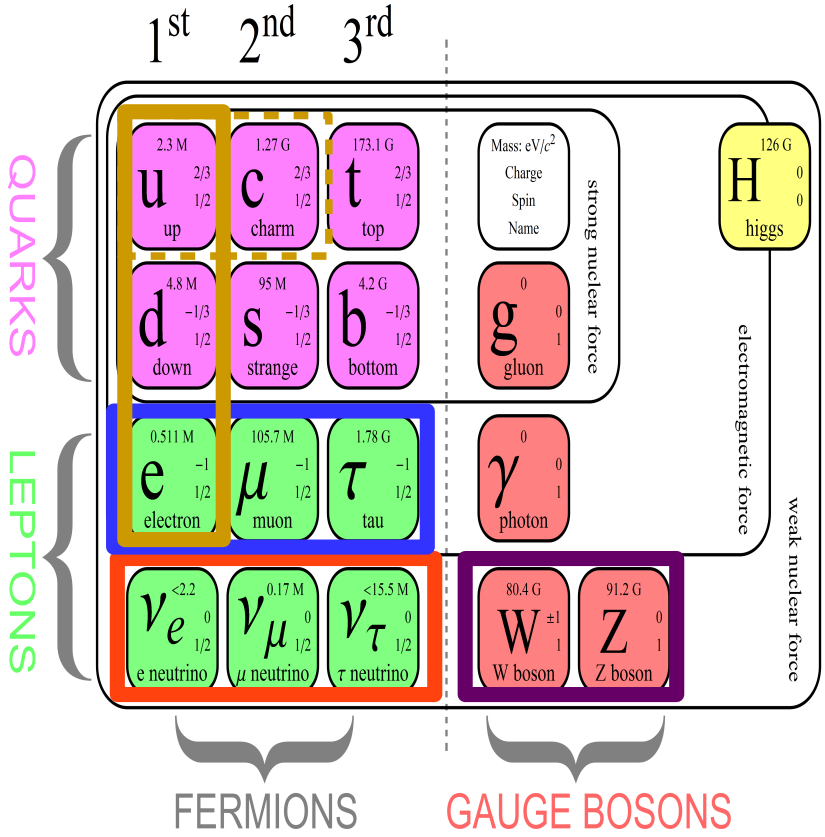
Bruny Baret
Astroparticule & Cosmologie, Paris

Les neutrinos

sources & détection

Ce qu'on voit

Messagers



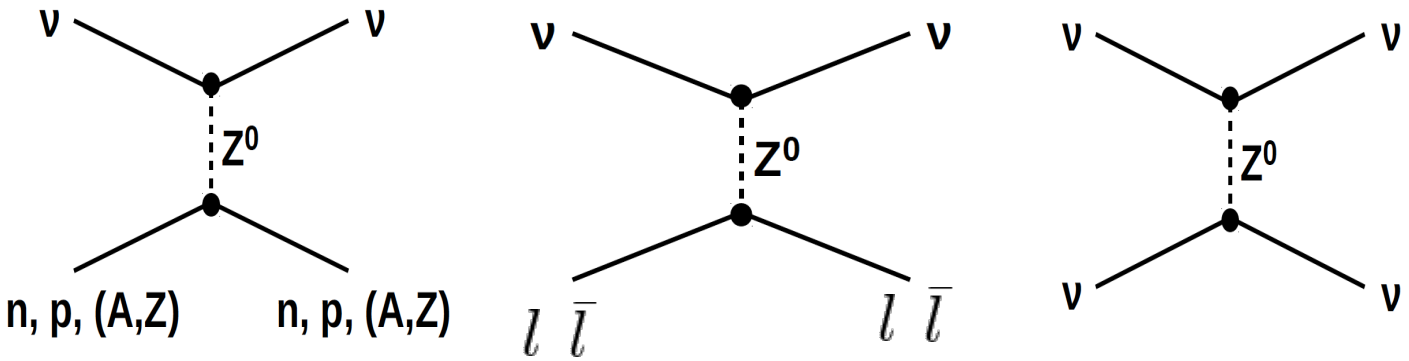
Voyagent :
sans absorption
en ligne droite

mais flux en $1/D^2$

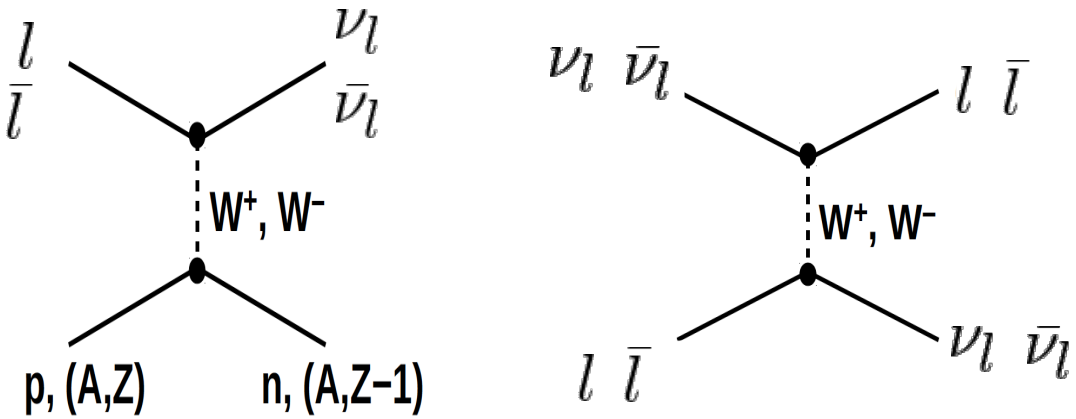
Interaction

Interactions

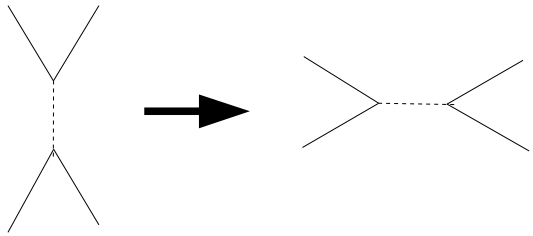
Courant neutre

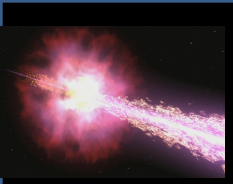


Courant Chargé

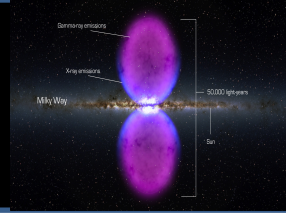


Et tous les symetriques s-t :





Canaux de production



Desintegration beta (Soleil)

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

$${}^{3}\mathrm{He} + p \rightarrow {}^{4}\mathrm{He} + e^{+} + \boldsymbol{\nu_e}$$

$${}^{8}\mathrm{B} \rightarrow {}^{8}\mathrm{Be}^{*} + e^{+} + \boldsymbol{\nu_e}$$

etc..

Capture electronique (Supernovae et Soleil)

$$e^{-} + \mathcal{N}(Z, A) \rightarrow \mathcal{N}(Z-1, A) + \nu_e$$

$$e^{-} + p \rightarrow n + \nu_e \quad \Big| \quad e^{+} + n \rightarrow p + \bar{\nu}_e$$

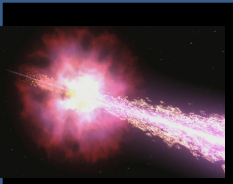
Création de paires (Supernovae):

$$e^{\pm} + N \rightarrow e^{\pm} + N + \nu + \bar{\nu} \quad \Big| \quad N + N \rightarrow N + N + \nu + \bar{\nu} \quad \Big| \quad \gamma + e^{\pm} \rightarrow e^{\pm} + \nu + \bar{\nu}$$

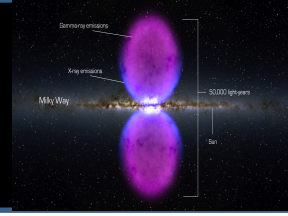
$$\gamma \rightarrow \nu + \bar{\nu}$$

Désintégration de muons et hadrons chargés (chocs astrophysiques)

$$\mu^{+} \rightarrow e^{+} + \bar{\nu}_e + \nu_\mu \quad \Big| \quad n \rightarrow p + e^{-} + \bar{\nu}_e \quad \Big| \quad \pi^{+} \rightarrow \mu^{+} + \nu_\mu \quad \Big| \quad K^{+} \rightarrow \mu^{+} + \nu_\mu$$



3 saveurs + masse → Oscillations



« Simplification » à 2 saveurs :

$$P_{\overline{\nu}_\alpha \to \overline{\nu}_\beta} = \delta_{\alpha\beta} - 4\sum_{k>j} \mathrm{Re}\left(J_{\alpha\beta jk}\right) \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right) \pm 2\sum_{k>j} \mathrm{Im}\left(J_{\alpha\beta jk}\right) \sin\left(\frac{\Delta m^2_{kj} L}{2E}\right)$$

$$L_{osc.}[km] \sim \frac{E}{\Delta m^2}[GeV\,eV^{-2}] \qquad \Delta m^2 \sim 10^{-3} - 10^{-4}$$

Basse énergie (~10MeV): ~100 km

↓

Oscillations dans la source
Effets de matière (MSW) important et pas simple

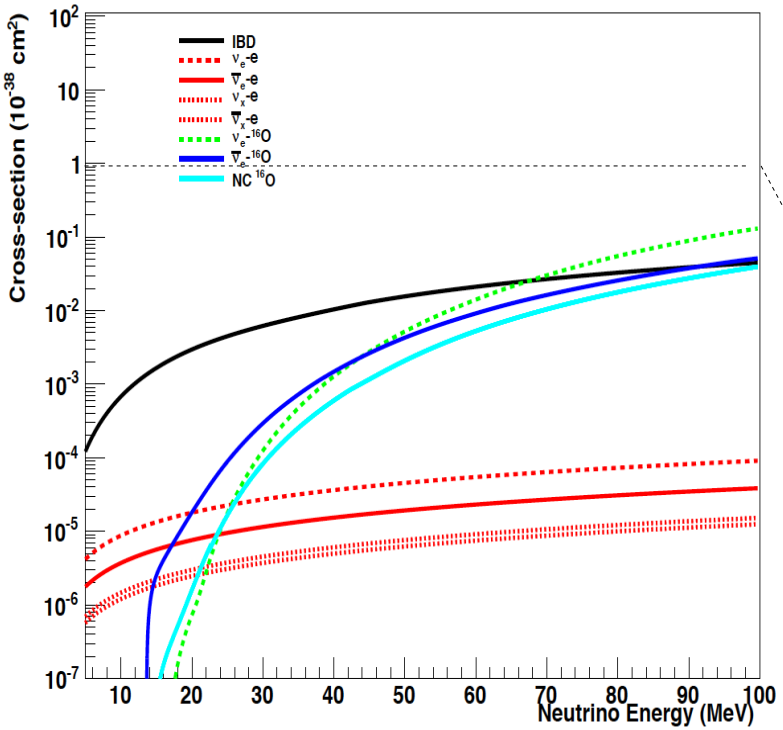
Haute énergie (TeV-PeV) x 10^6 < < Distance source

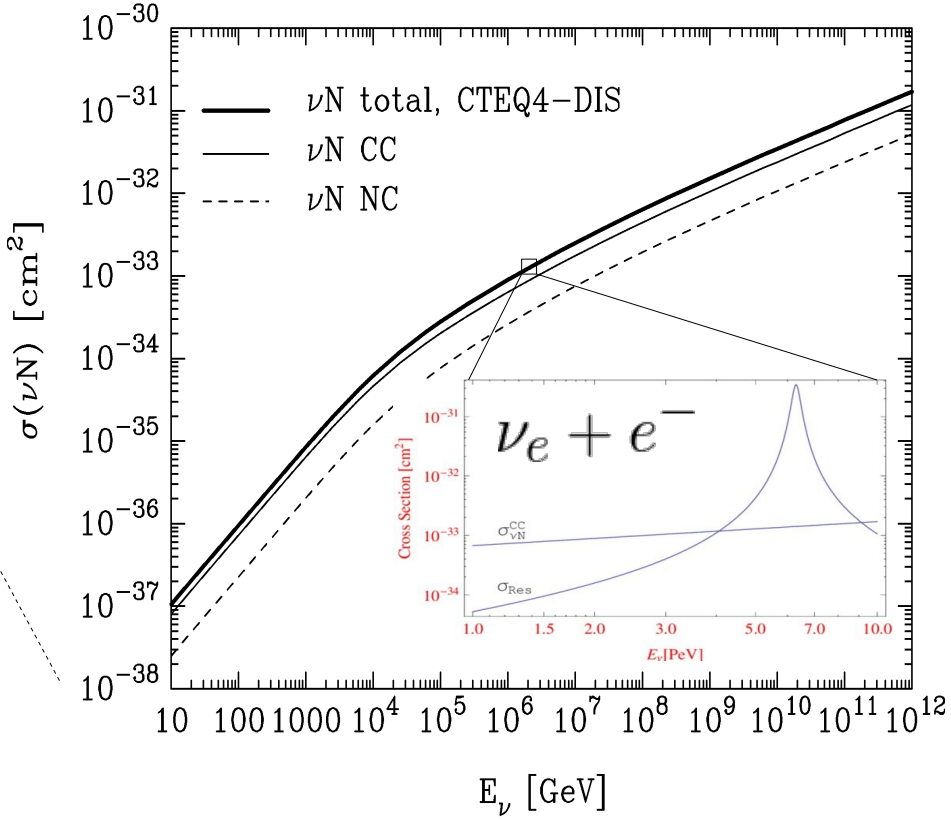
↓

équipartion de saveur simple

Sections efficaces → détection

$\sigma \propto E^2$ $\sigma \propto E$ $\sigma \propto E^{0.4}$

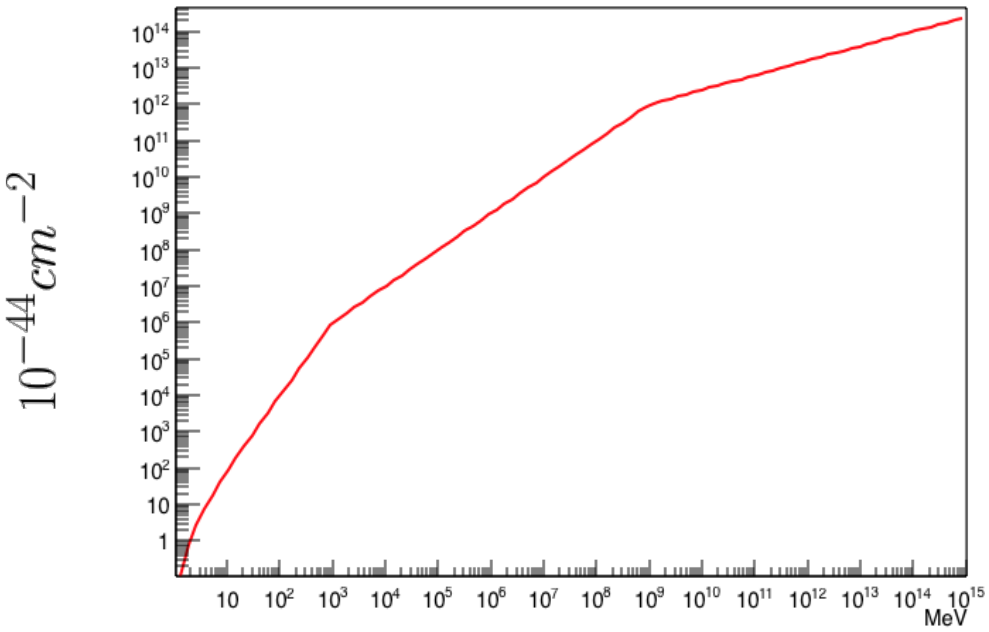


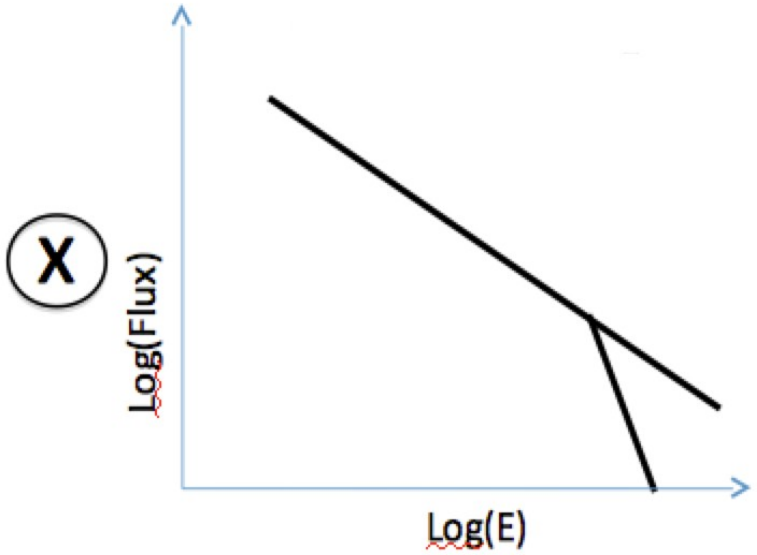


Sections efficaces → détection

E^{α}

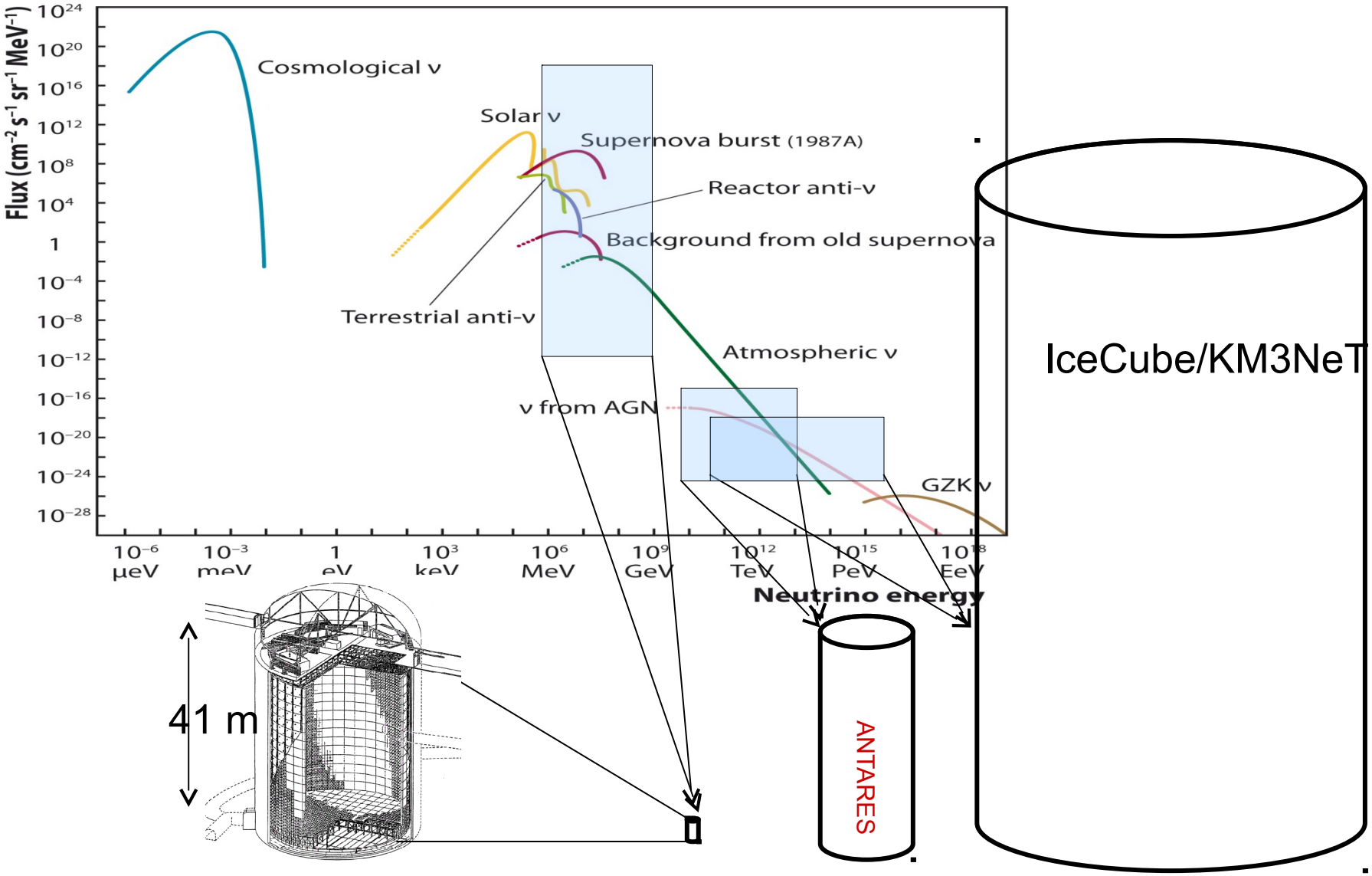
$E^{-\gamma}$





$\alpha < 1$ & $\gamma \gtrsim 1.5 - 2 \Rightarrow$ La taille des détecteurs croit presque linéairement avec E

de très gros détecteurs



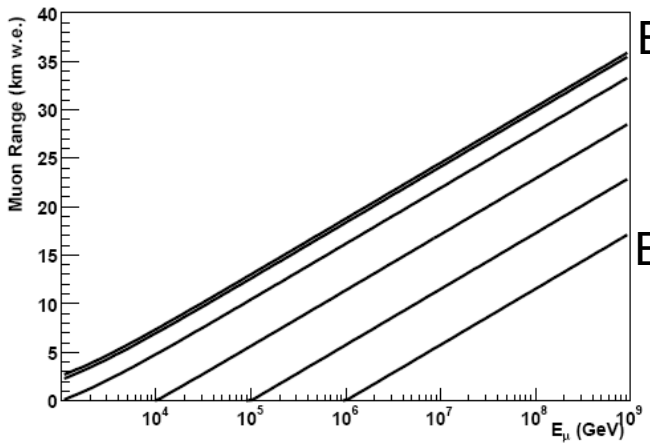
Detection – qq détails

Pertes d'énergie du muon:

$$dE_\mu/dx = \alpha(E_\mu) + \beta(E_\mu) \cdot E_\mu$$

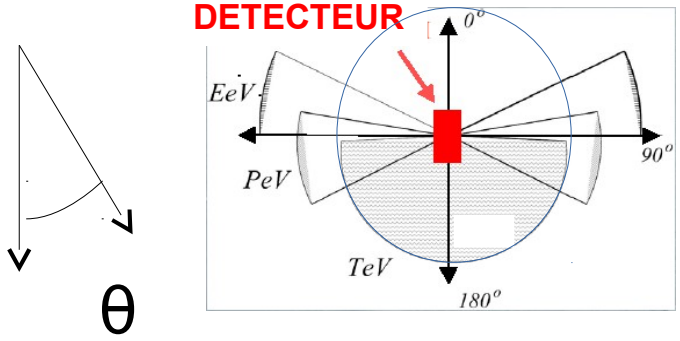
« Portée » du muon:

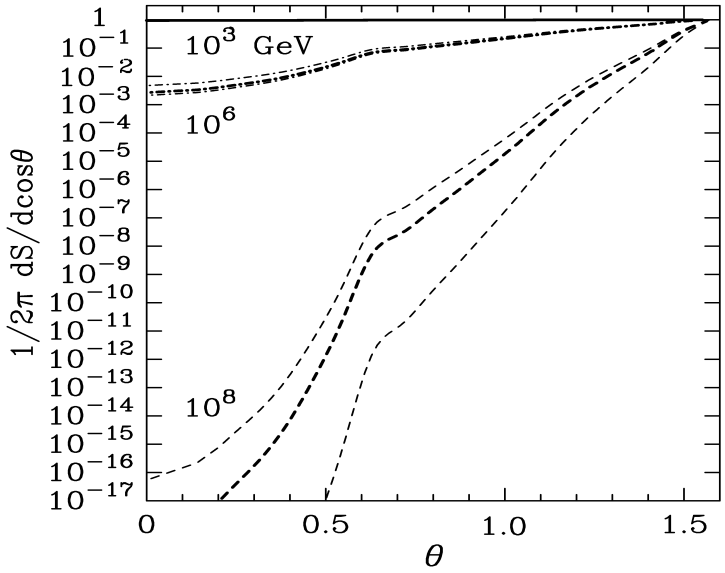
$$R_\mu(E_\mu, E_{thr}) = \int_{E_{thr}}^{E_\mu} \frac{1}{dE_\mu/dx} dE \approx \frac{1}{\beta} ln \frac{(\alpha/\beta) + E_\mu}{(\alpha/\beta) + E_{thr}}$$



E_{thr}=1 GeV

E_{thr}=10^6 GeV

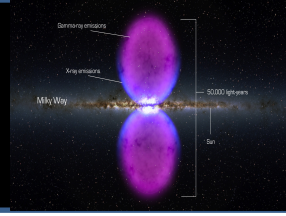




Traces de muons

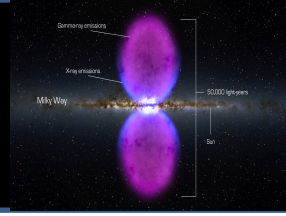
Volume effectif >> Volume instrumenté

Spectre neutrino astrophysiques



Galactique			Extra galactique	
Source astrophysique				
Soleil	Supernova (exp.	acc.) Binaires	AGN/GRB	UHECR diff
Energie 0.1-10 MeV		Tev-PeV		>PeV
Processus de production				
desint. beta	capture elec.	Interactions hadroniques		(top-down ?)

Spectre neutrino astrophysiques



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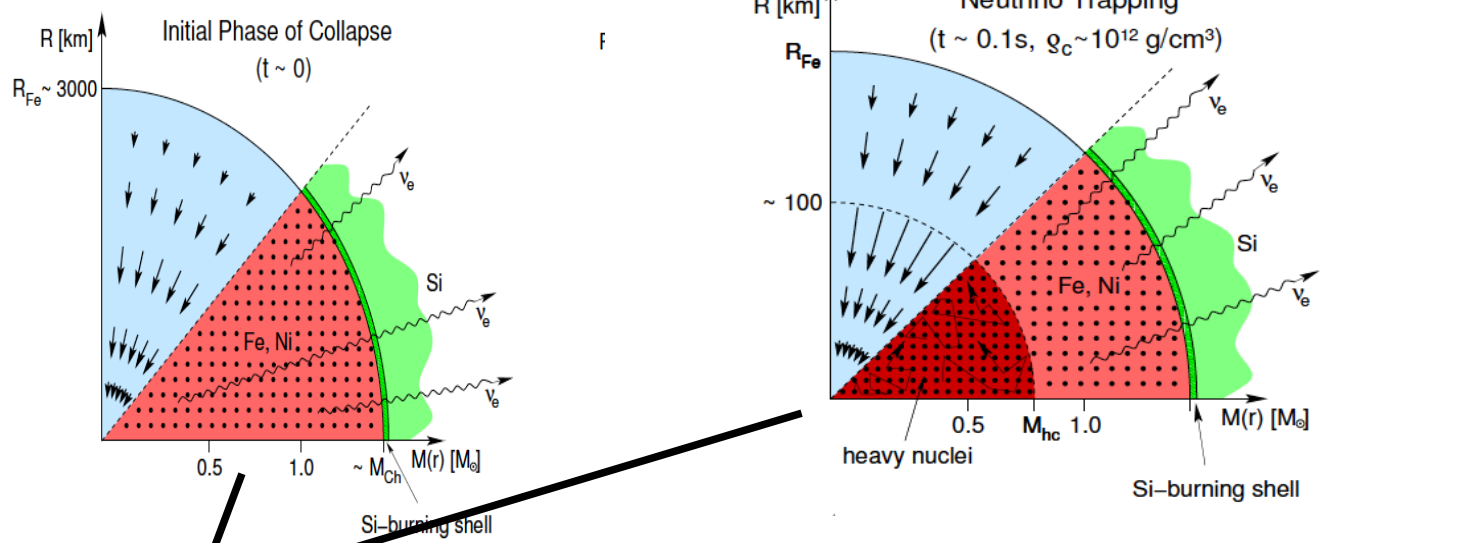
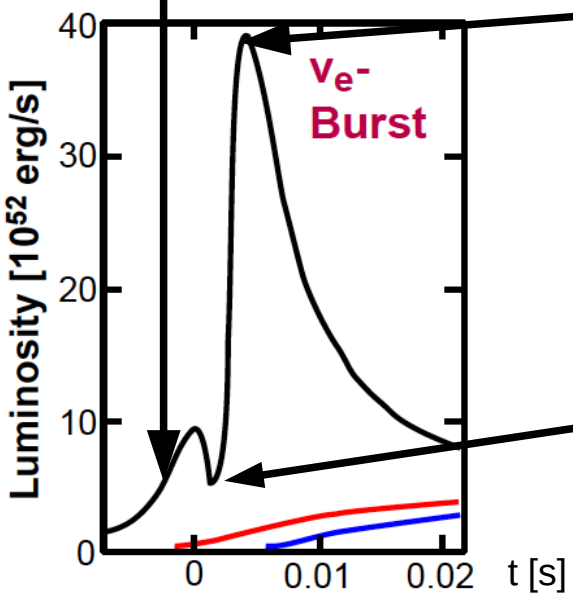
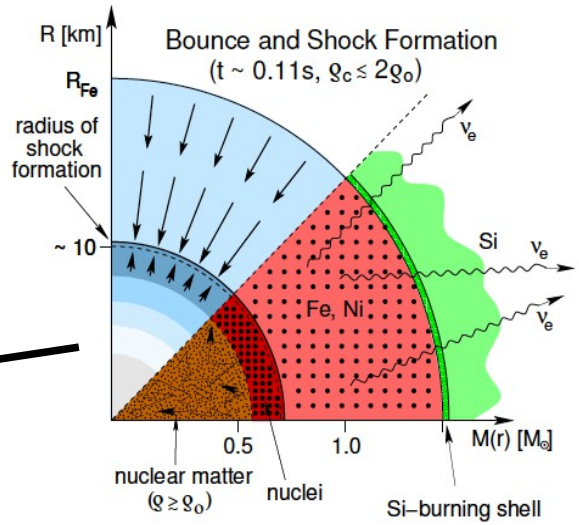
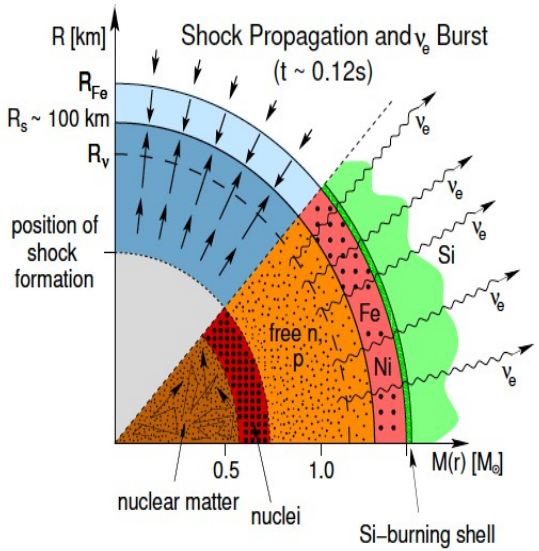
Energie 0.1-10 MeV		Tev-PeV		>PeV
Processus de production				
desint. beta	capture elec.	Interactions hadroniques		(top-down ?)

Supernovae - Phase I



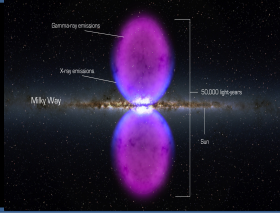


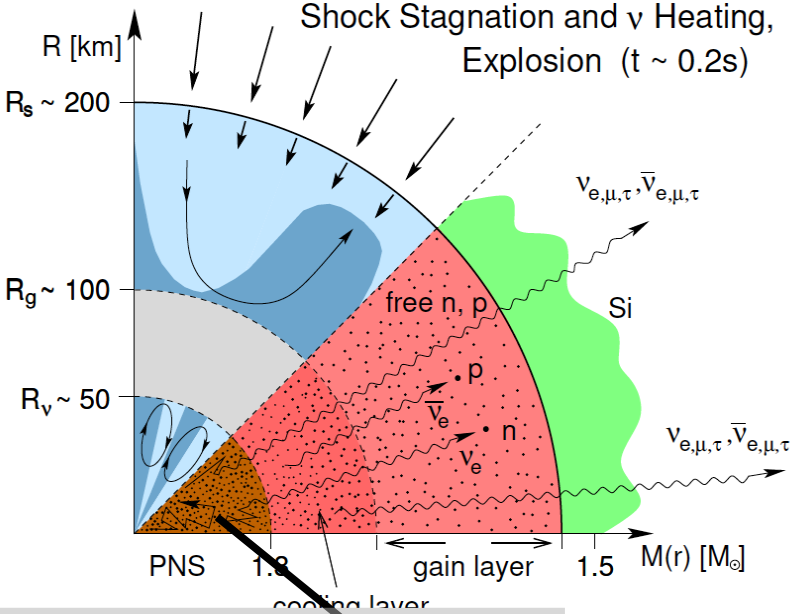


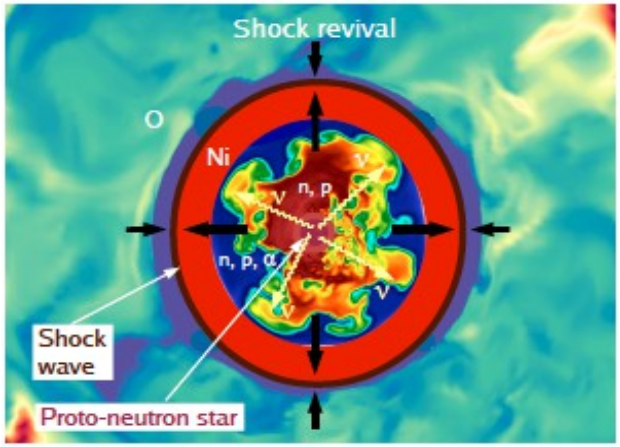


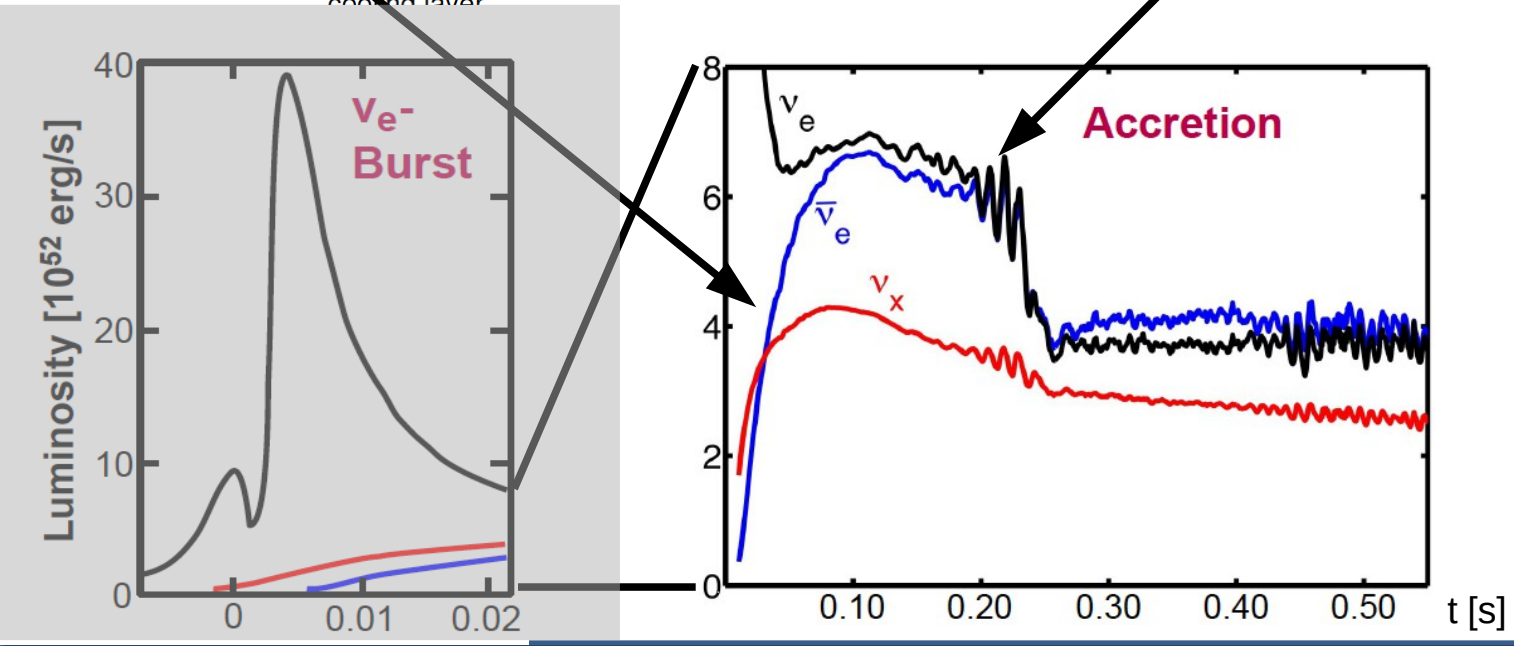
H. Janka

Supernovae – Phase II



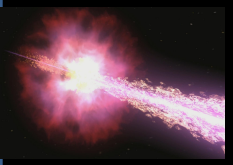




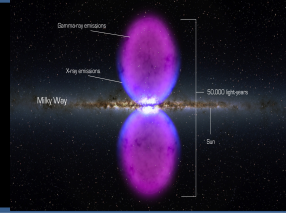


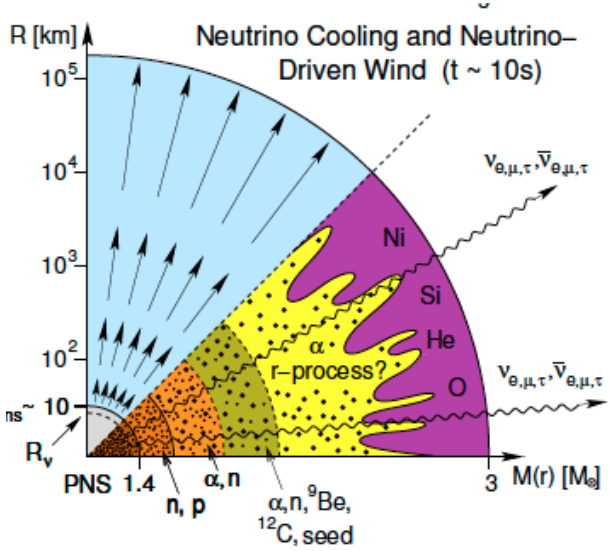
+ autres canaux

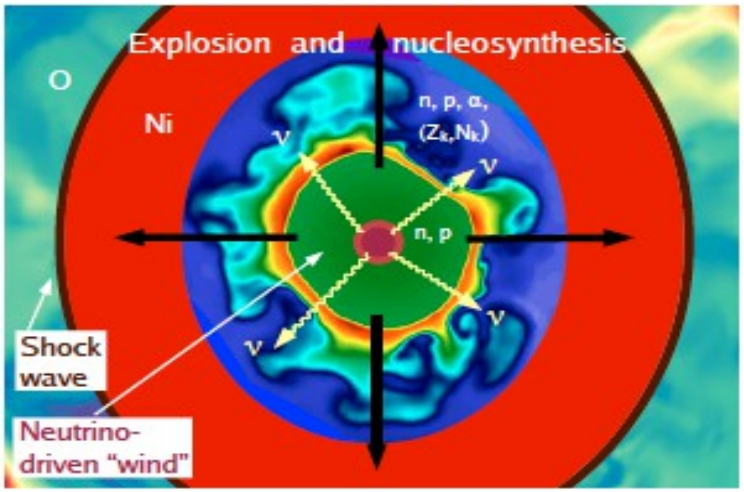
H. Janka

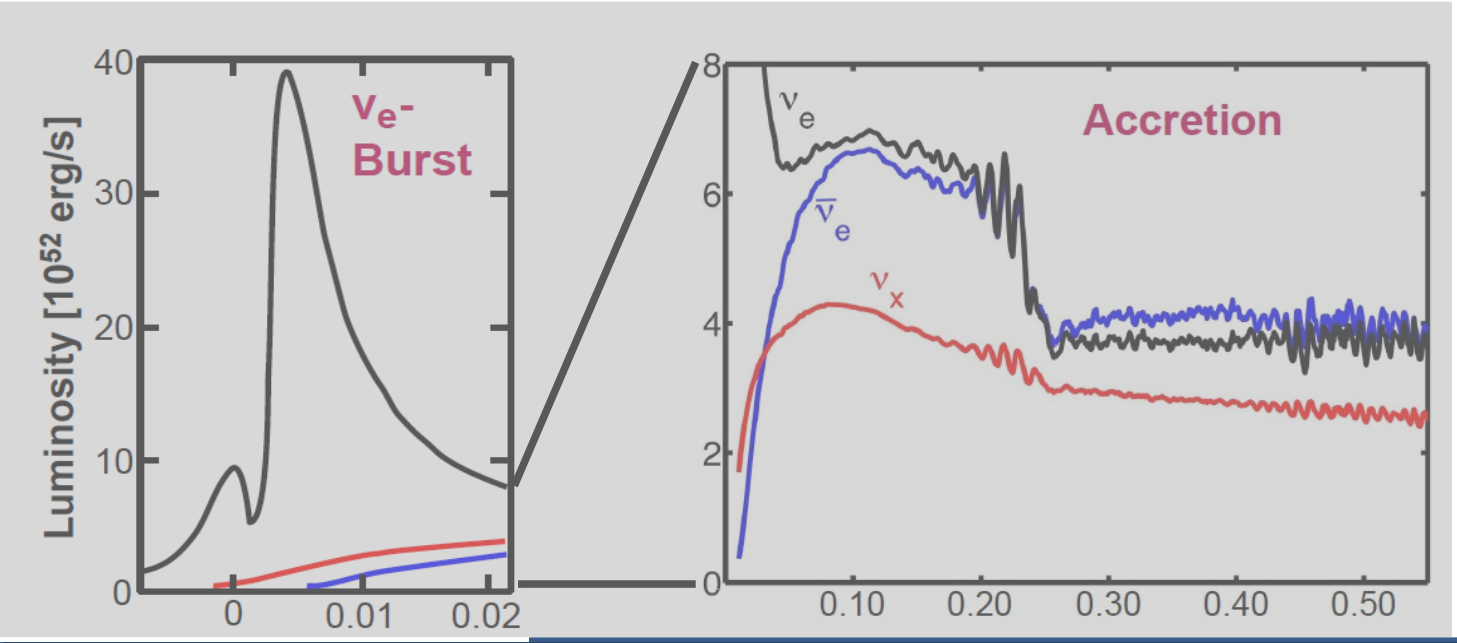


Supernovae – Phase III

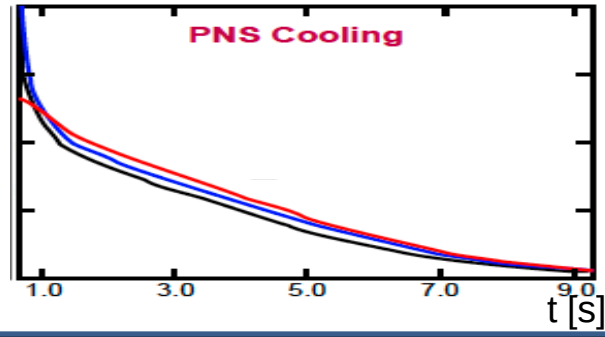


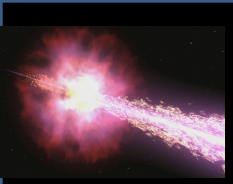




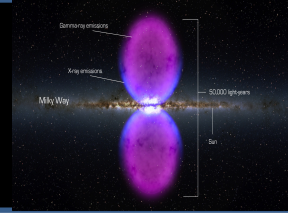


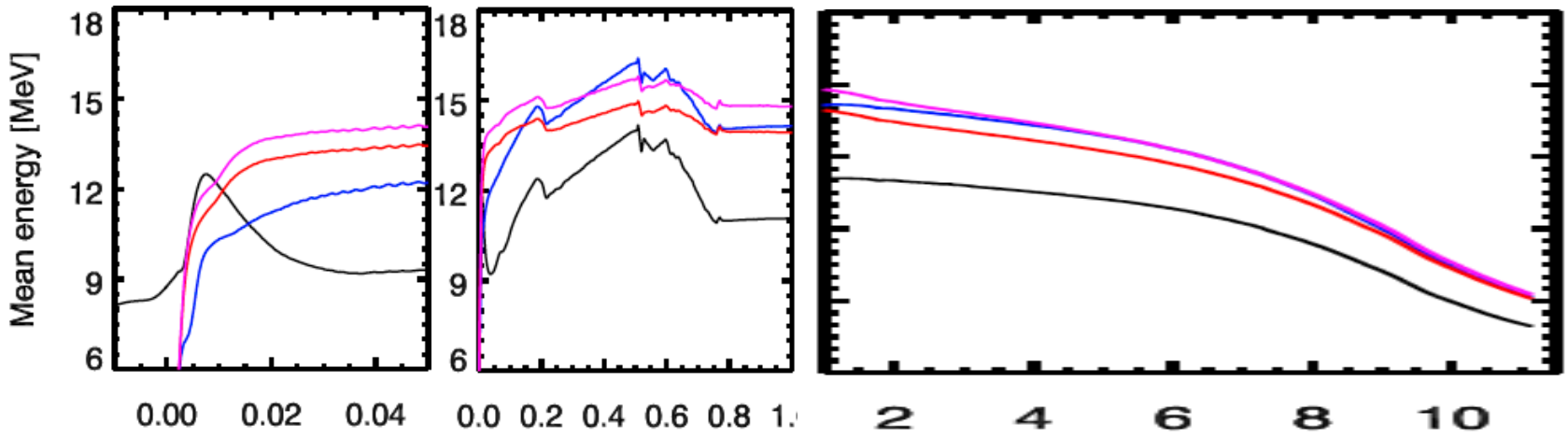
autres canaux

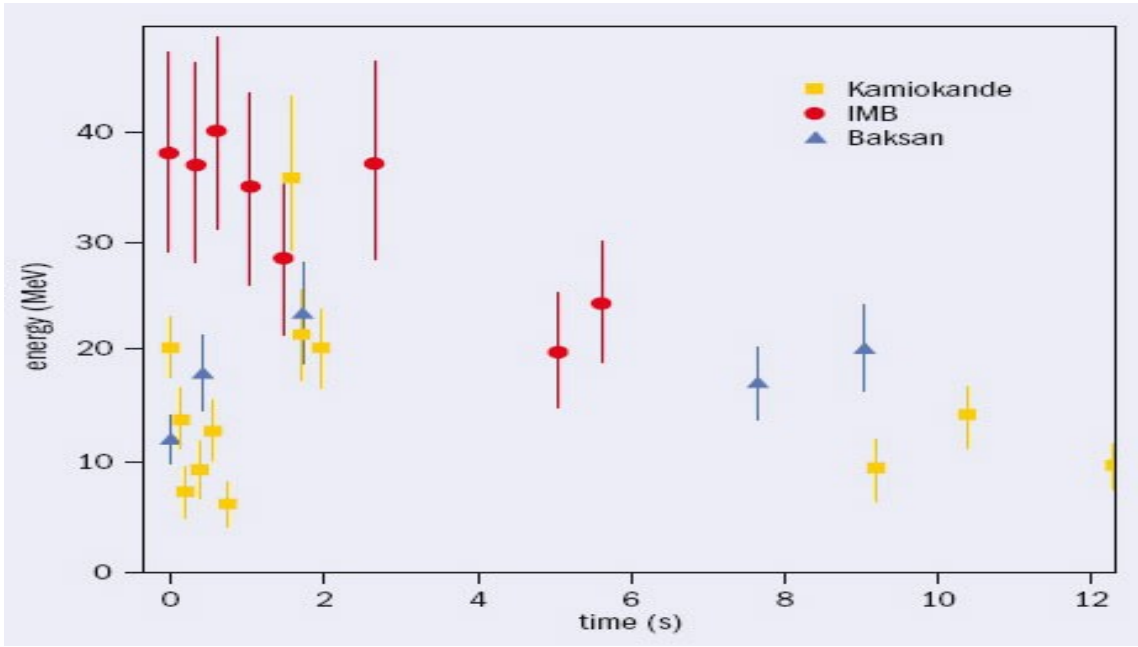




1987 A

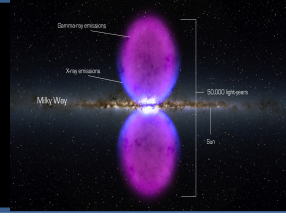






NB : synchronisation
a posteriori

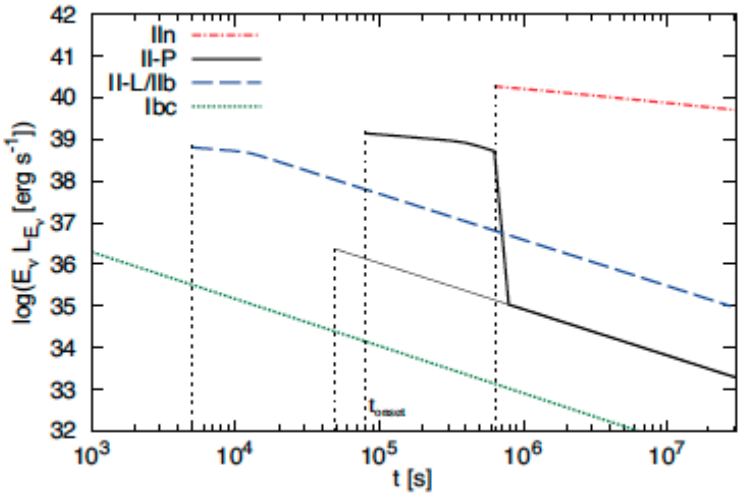
Spectre neutrino astrophysiques

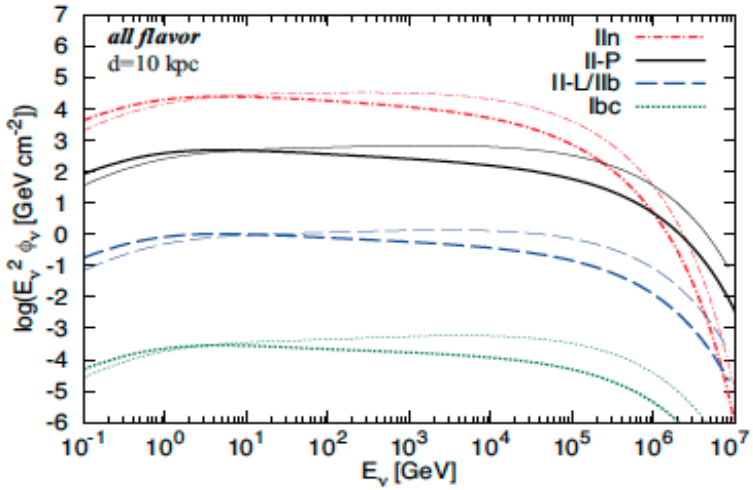


Galactique			Extra galactique	
Source astrophysique				
Soleil	Supernova (exp. acc.)	Binaires	AGN/GRB	UHECR diff
Energie				
0.1-10 MeV	Tev-PeV			>PeV
Processus de production				
desint. beta	capture elec.	Interactions hadroniques		(top-down ?)

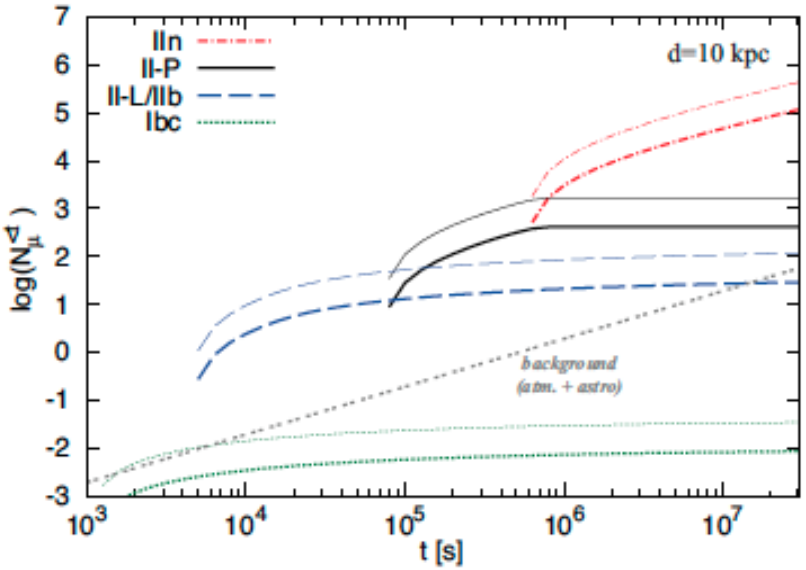
Supernovae – Hautes énergies

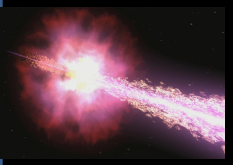
Murase 2017 : SN Type II à 10kpc, interaction pp (CR+ CSM)



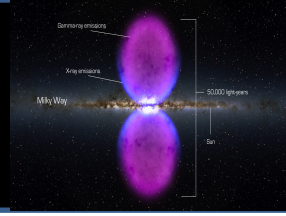


evt pour :
IceCube/KM3NeT





Spectre neutrino astrophysiques



Galactique | Extra galactique

Source astrophysique

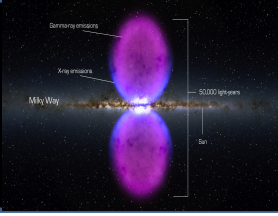
Soleil | Supernova (exp. acc.) | Binaires | + Gal CR diff. | AGN/GRB | UHECR diff

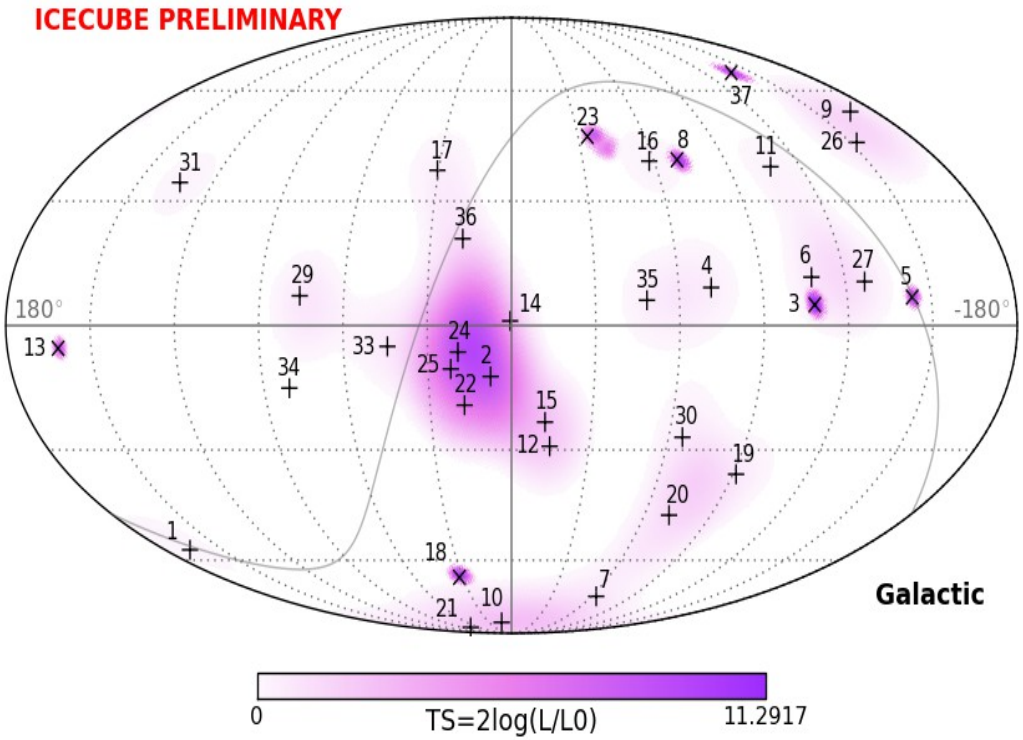
Energie
0.1-10 MeV | Tev-PeV | >PeV

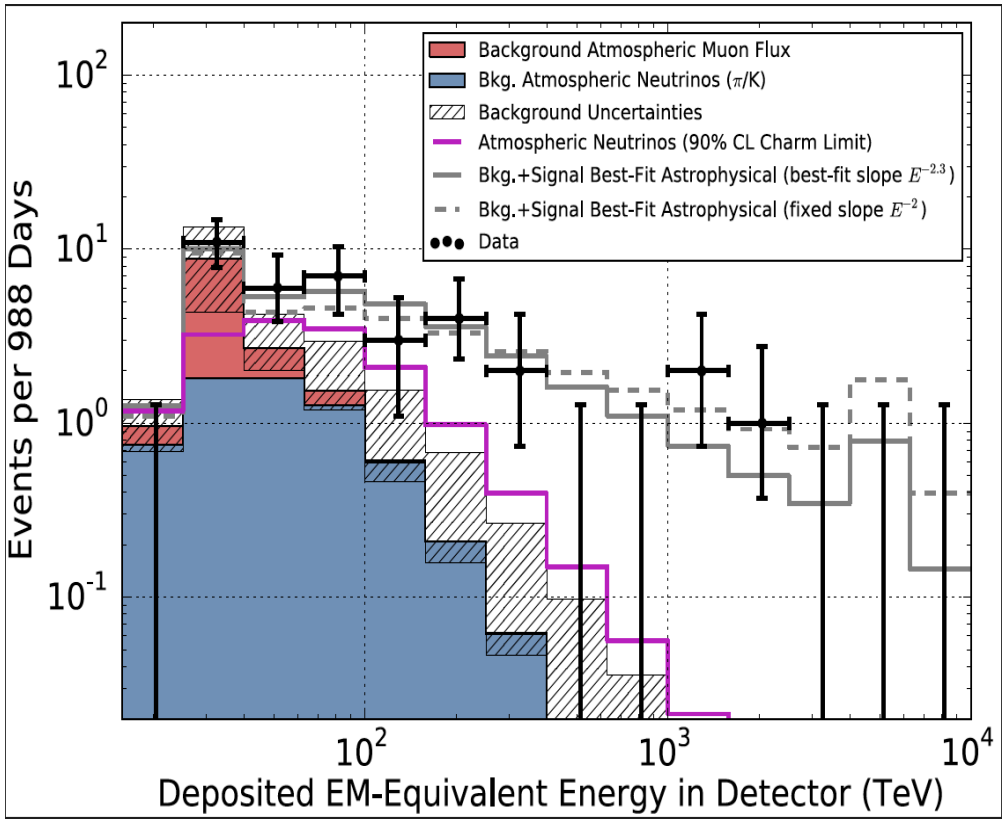
Processus de production

desint. beta | capture elec. | Interactions hadroniques | (+top-down ?)

Le ciel neutrino haute énergie aujourd'hui

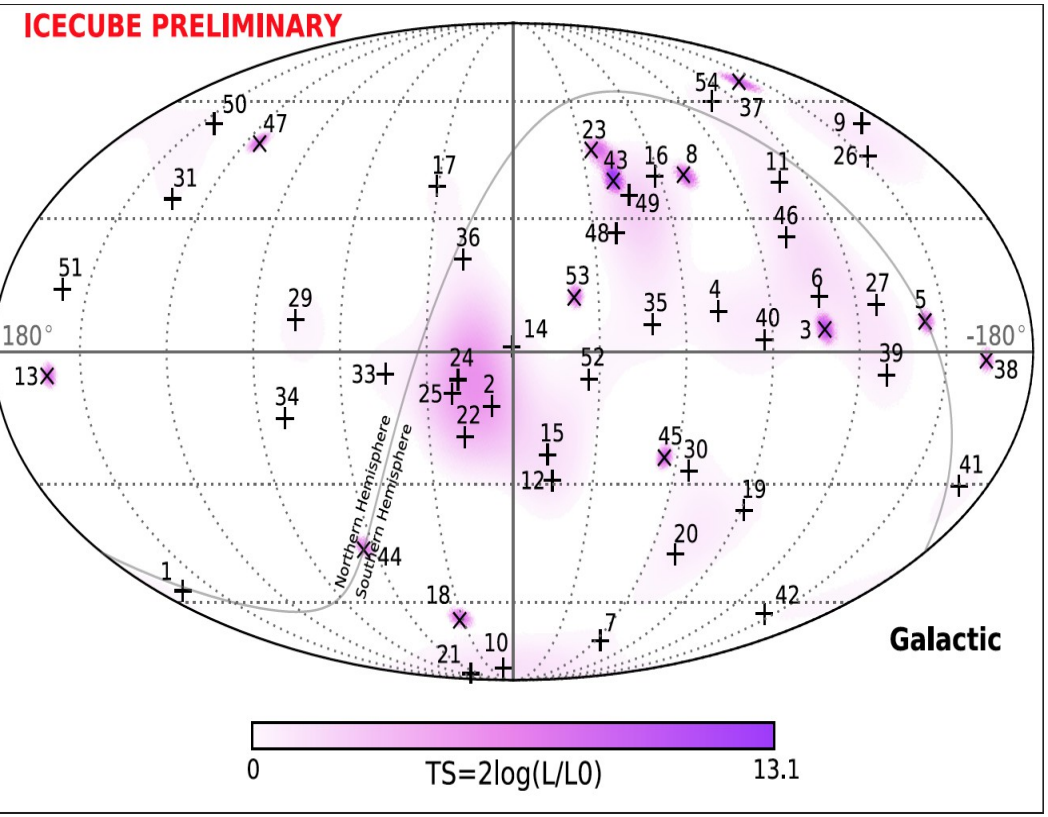


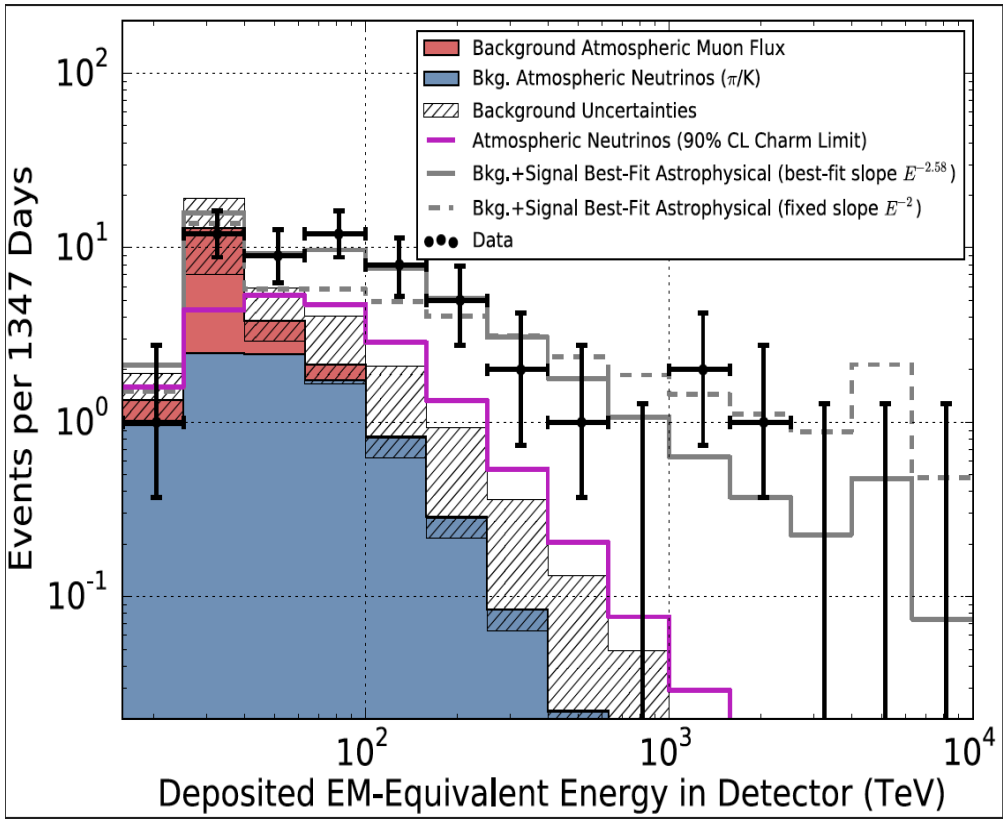




IceCube, *PRL* **111**, 021103 (2013)
IceCube, *Science* **342**, 1242856 (2013)
IceCube, *PRL* **113**, 101101 (2014)

Le ciel neutrino aujourd'hui





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IceCube, *Science* **342**, 1242856 (2013)
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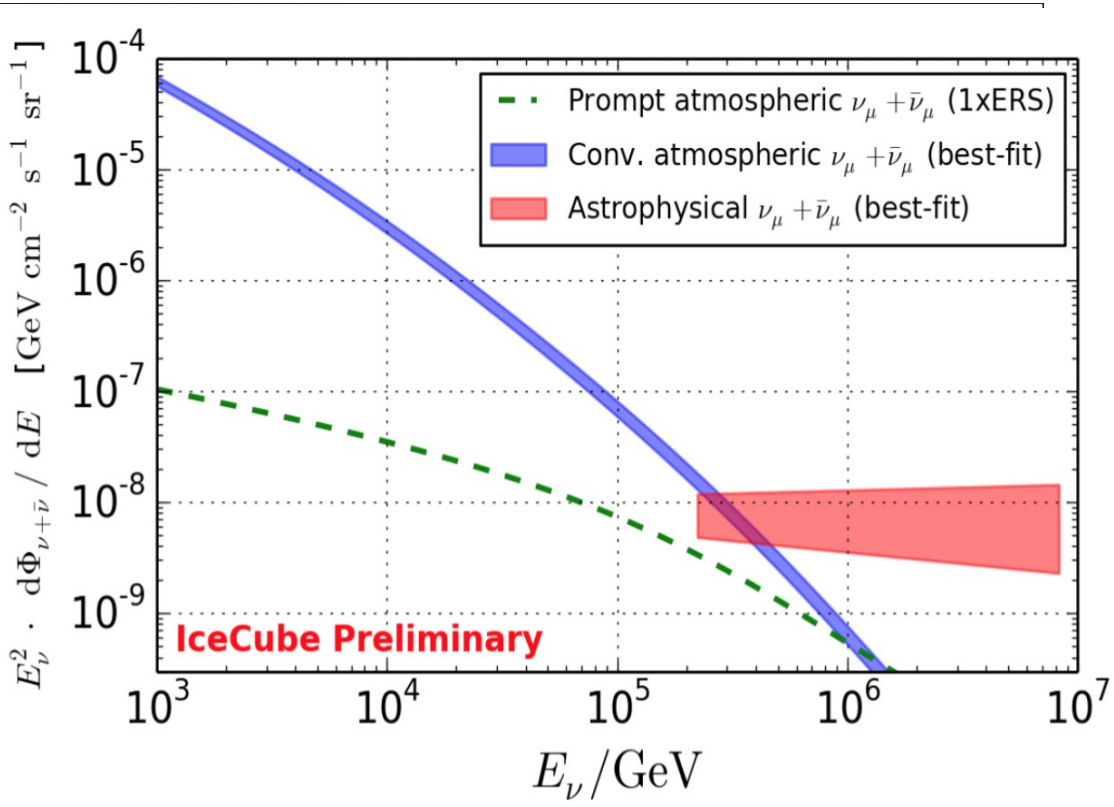
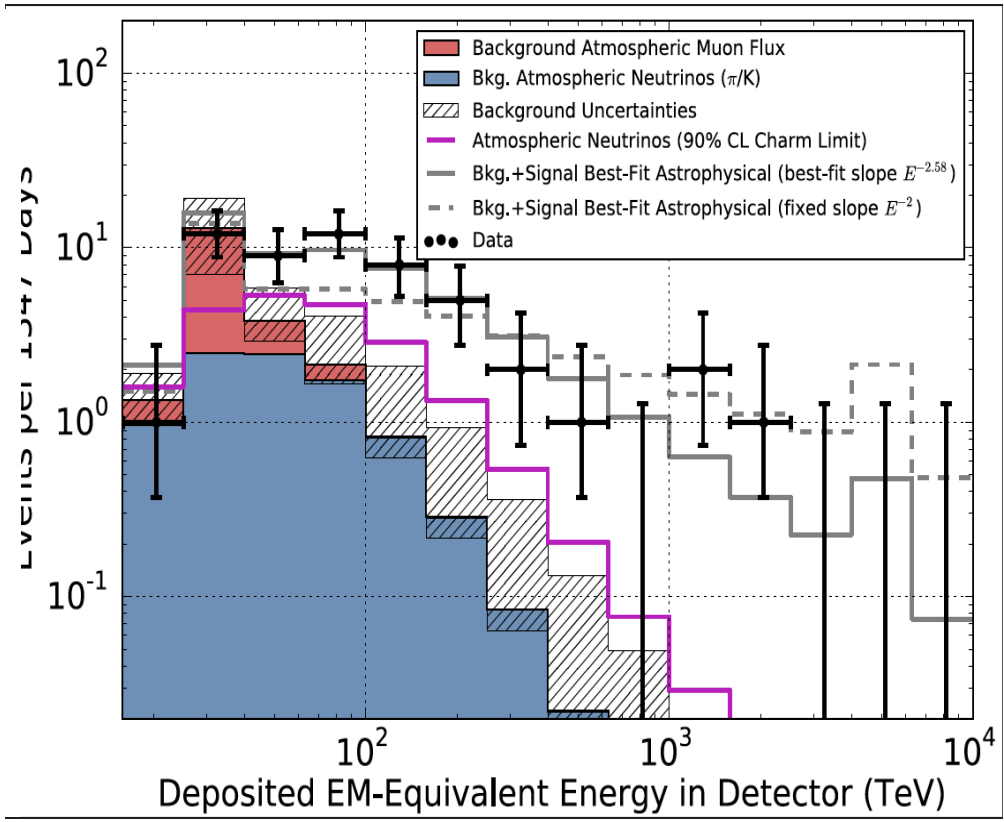
Le ciel neutrino aujourd'hui

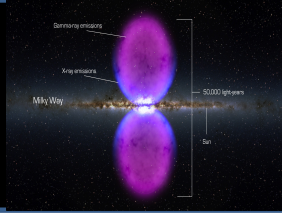
diffus hemisphere nord

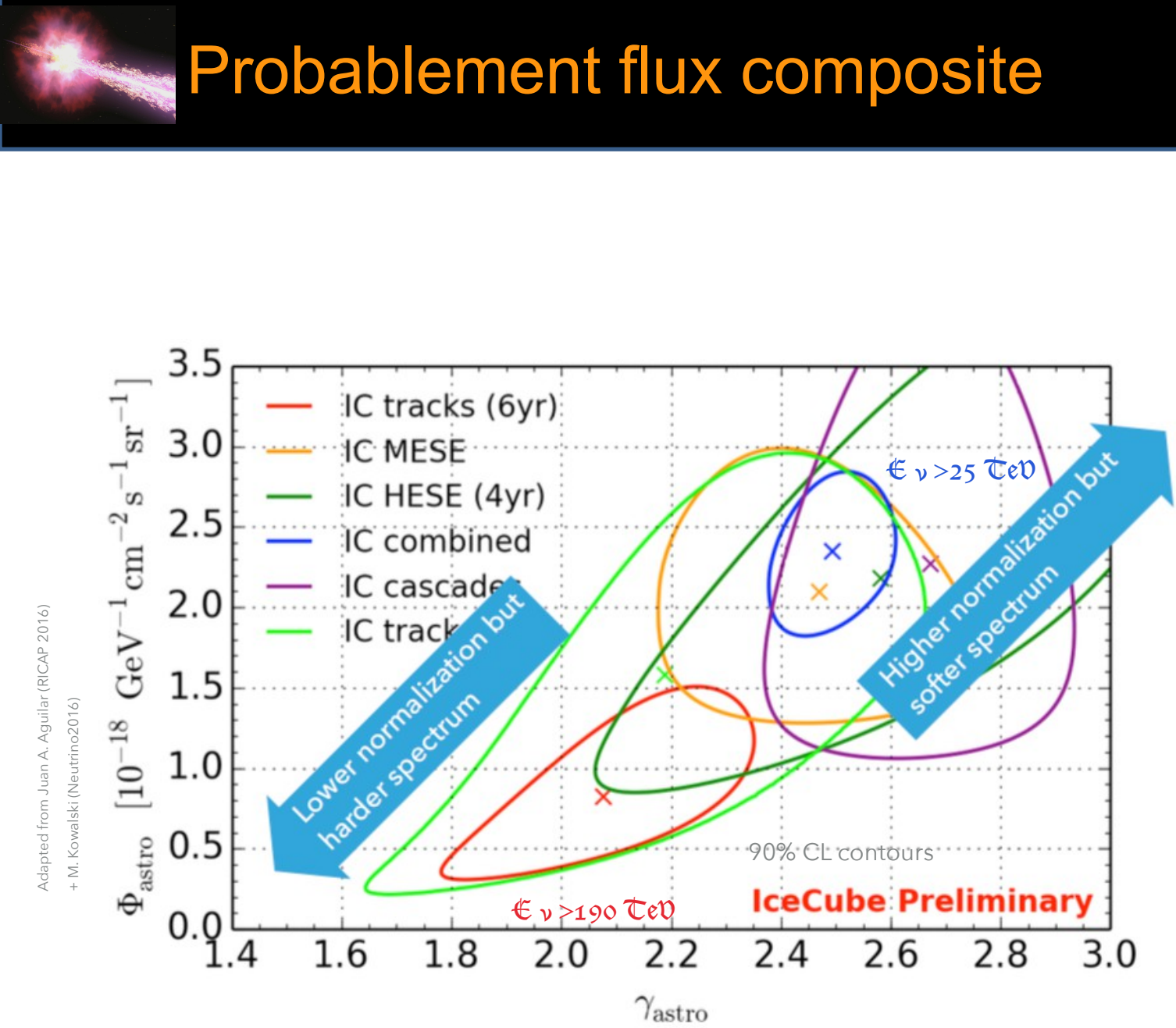




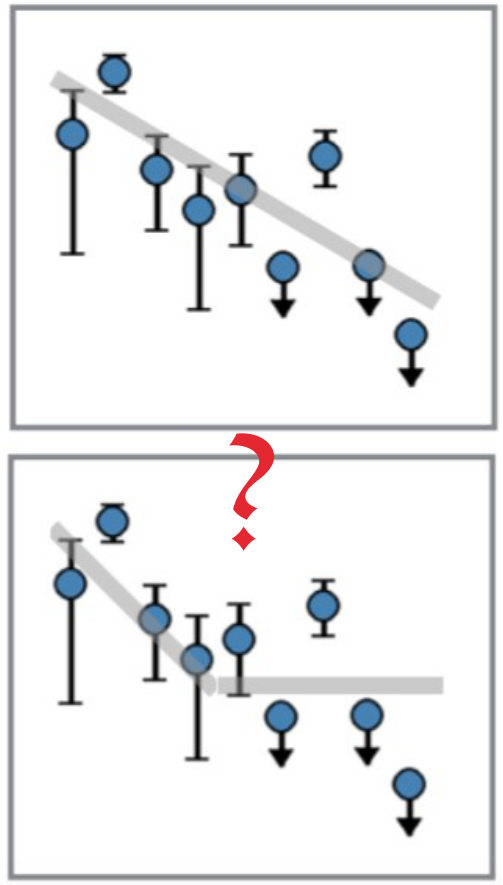
IceCube, *PRL* **111**, 021103 (2013)
IceCube, *Science* **342**, 1242856 (2013)
IceCube, *PRL* **113**, 101101 (2014)

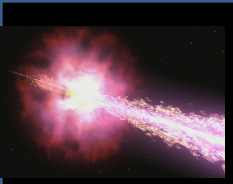
Probablement flux composite



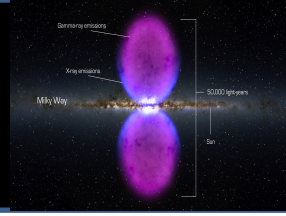


Adapted from Juan A. Aguilar (RICAP 2016)
+ M. Kowalski (Neutrino2016)



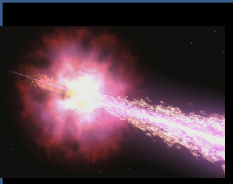


Source potentielles

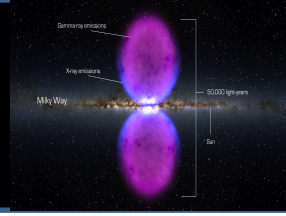


- **Galactic:** (full or partial contribution)
  - diffuse Galactic γ-ray emission [MA & Murase'13; Joshi J C, Winter W and Gupta'13] [Kachelriess and Ostapchenko'14; Neronov, Semikoz & Tchernin'13] [Neronov & Semikoz'14; Guo, Hu & Tian'14; Gaggero, Grasso, Marinelli, Urbano & Valli'15]
  - unidentified Galactic γ-ray emission [Fox, Kashiyama & Meszaros'13] [Gonzalez-Garcia, Halzen & Niro'14]
  - supernova remnants [Mandelartz & Tjus'14]
  - pulsars [Padovani & Resconi'14]
  - microquasars [Anchordoqui, Goldberg, Paul, da Silva & Vlcek'14]
  - Sagitarius A* [Bai, Barger, Barger, Lu, Peterson & Salvado'14; Fujita, Kimura & Murase'15]
  - *Fermi Bubbles* [MA & Murase'13; Razzaque'13] [Lunardini, Razzaque, Theodoseau & Yang'13; Lunardini, Razzaque & Yang'15]
  - Galactic Halo [Taylor, Gabici & Aharonian'14]
  - heavy dark matter decay [Feldstein, Kusenko, Matsumoto & Yanagida'13] [Esmaili & Serpico '13; Bai, Lu & Salvado'13; Cherry, Friedland & Shoemaker'14]

from M. Ahlers



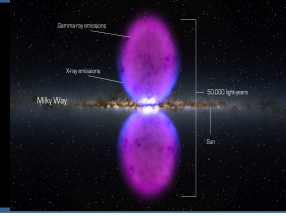
Sources potentielles - suite



- **Extragalactic:**
  - association with sources of UHE CRs [Kistler, Stanev & Yuksel'13]
    [Katz, Waxman, Thompson & Loeb'13; Fang, Fujii, Linden & Olinto'14]
  - association with diffuse γ-ray background [Murase, MA & Lacki'13]
    [Chang & Wang'14; Ando, Tamborra & Zandanel'15]
  - active galactic nuclei (AGN) [Stecker'13;Kalashev, Kusenko & Essey'13]
    [Murase, Inoue & Dermer'14; Kimura, Murase & Toma'14; Kalashev, Semikoz & Tkachev'14]
    [Padovani & Resconi'14; Petropoulou, Dimitrakoudis, Padovani, Mastichiadis & Resconi'15]
  - gamma-ray bursts (GRB) [Murase & Ioka'13; Dado & Dar'14; Tamborra & Ando'15]
  - galaxies with intense star-formation
    [He, Wang, Fan, Liu & Wei'13; Yoast-Hull, Gallagher, Zweibel & Everett'13]
    [Murase, MA & Lacki'13; Anchordoqui, Paul, da Silva, Torres& Vlcek'14]
    [Tamborra, Ando & Murase'14; Chang & Wang'14; Liu, Wang, Inoue, Crocker& Aharonian'14]
    [Senno, Meszaros, Murase, Baerwald & Rees'15; Chakraborty & Izaguirre'15]
  - galaxy clusters/groups [Murase, MA & Lacki'13; Zandanel, Tamborra, Gabici & Ando'14]
  - ...

from M. Ahlers

Spectre neutrino astrophysiques



Galactique | Extra galactique

Source astrophysique

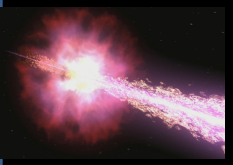
+ Gal CR diff.

Soleil | Supernova (exp. acc.) | Binaires | AGN/GRB | UHECR diff

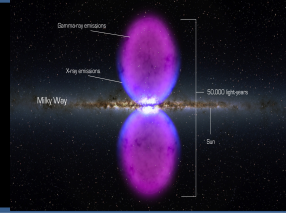
Energie
0.1-10 MeV | Tev-PeV | >PeV

Processus de production

desint. beta | capture elec. | Interactions hadroniques | (+top-down ?)

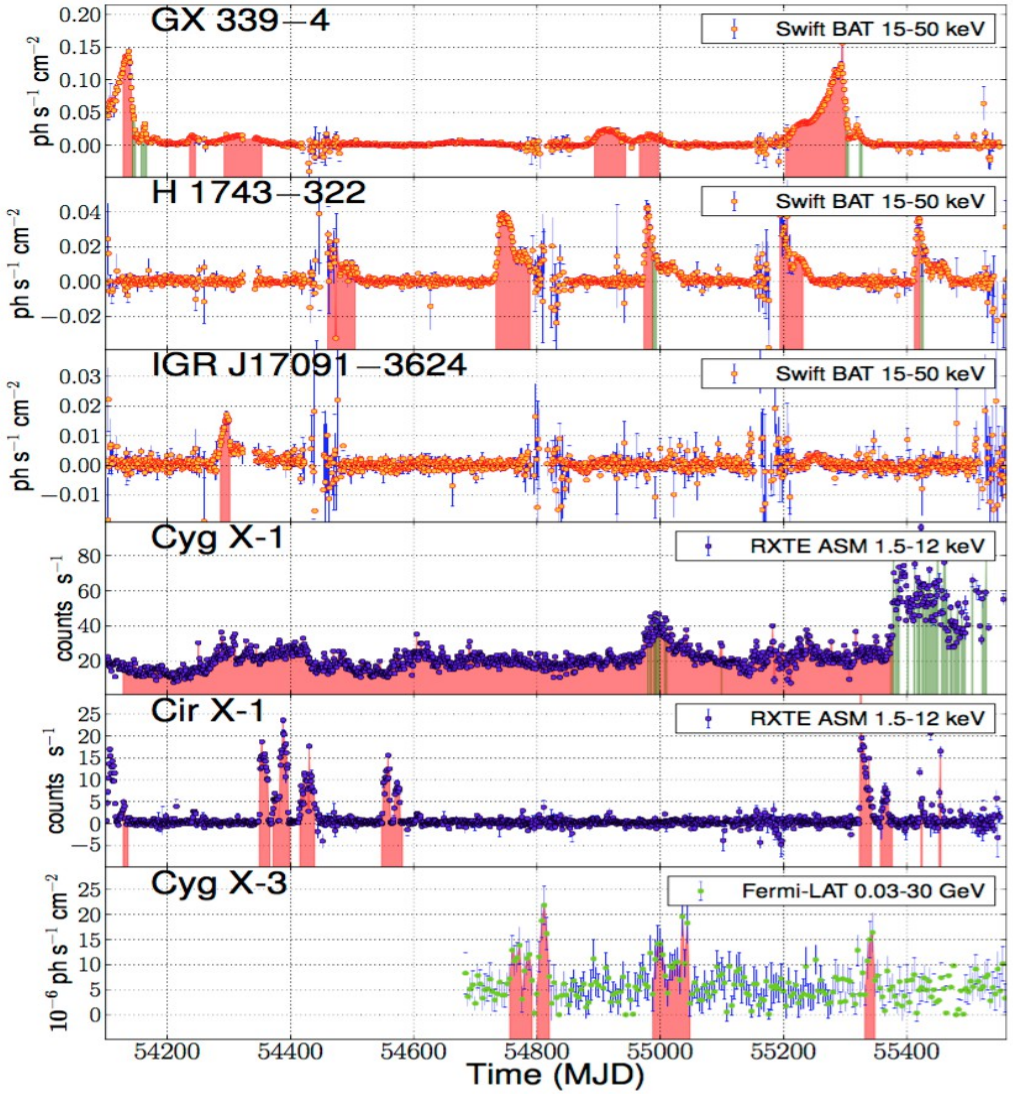


Binaires -X

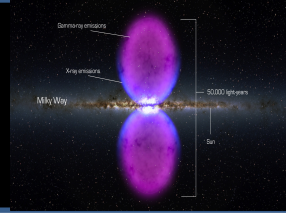


ex : Cir X-1, GX 339−4, H1743−322, IGR J17091−3624, CygX-1 and CygX-3

pp pendant les éruptions (jet)



Spectre neutrino astrophysiques



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Lepto /hadro

Hadronic interaction in relativistic jets:

$$P+(A/\gamma) \rightarrow \pi^0 + \pi^+ + \pi^- + N + \ldots$$

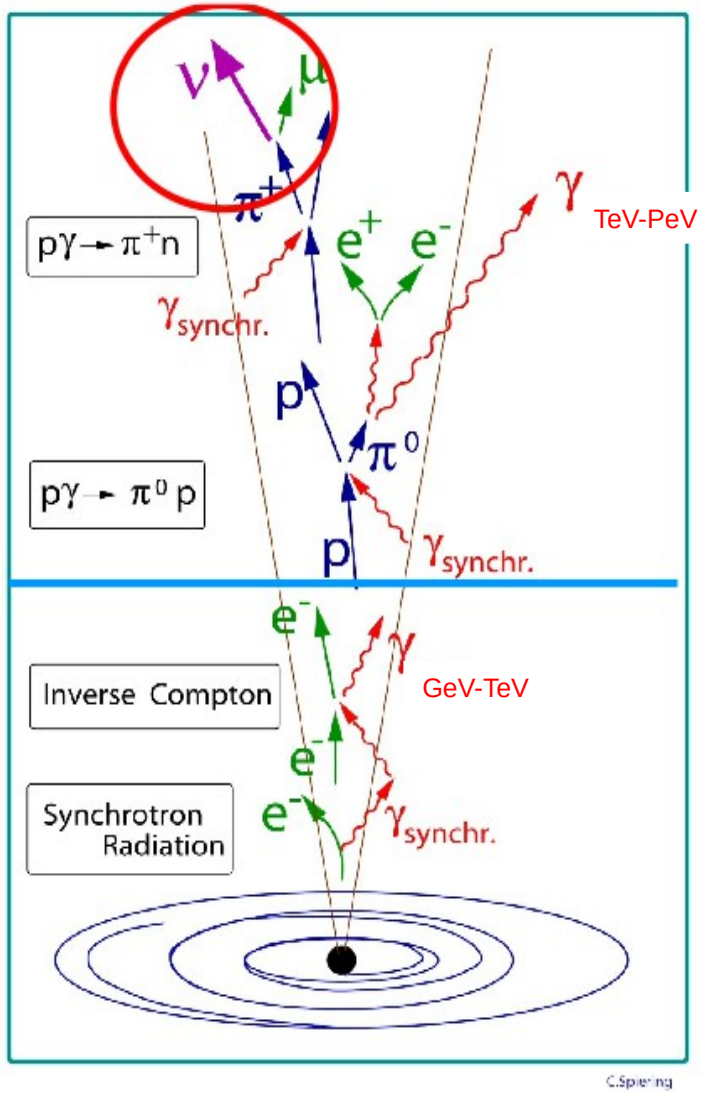
$$\pi^0 \rightarrow \gamma + \gamma$$

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

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$$p + \gamma \rightarrow K^+ + \Lambda / \Sigma$$

$$K^+ \rightarrow \mu^+ + \nu_\mu$$

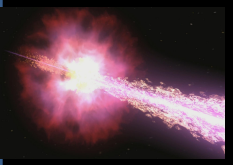


Production de γ H.E.:

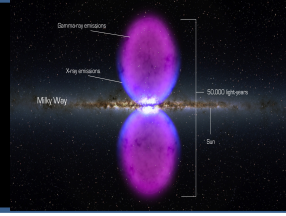
- Hadronique → neutrinos
- leptonique (S.I.C.) → ~~neutrinos~~

$$E_\nu \simeq 0.05 E_p$$

$\nu_e:\nu_\mu:\nu_\tau = 1:2:0$ source => $\nu_e:\nu_\mu:\nu_\tau = 1:1:1$ Terre



Spectre neutrino astrophysiques



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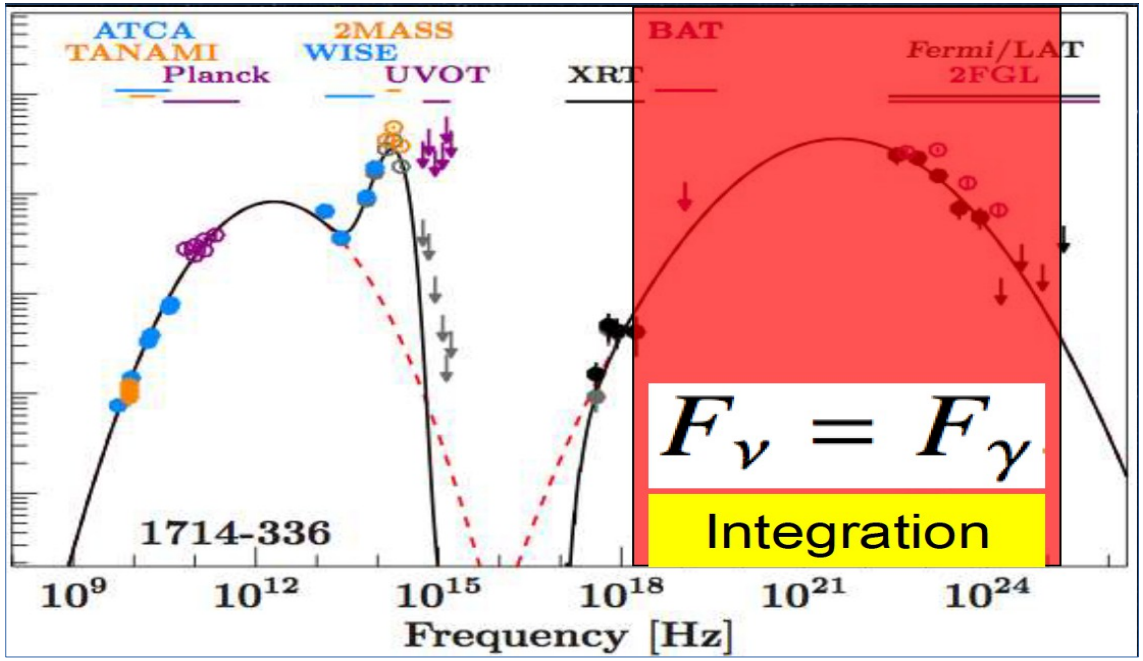
AGN example

Photo-pion production on UV hump -> PeV peaked neutrinos

Krauß et al. 2014, A&A 566, L7

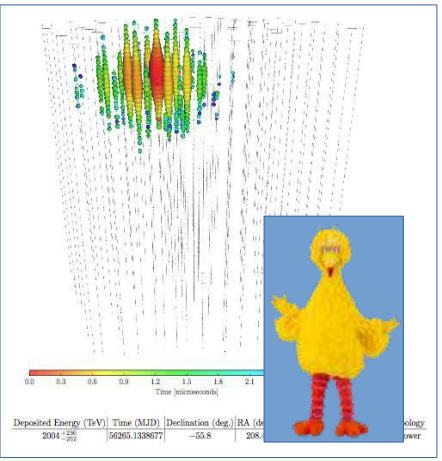


Flavor
Blazar class
Spectrum

$$N_{\nu,\mathrm{obs,PeV}} = f \cdot N_{\nu,\mathrm{max,PeV}}$$

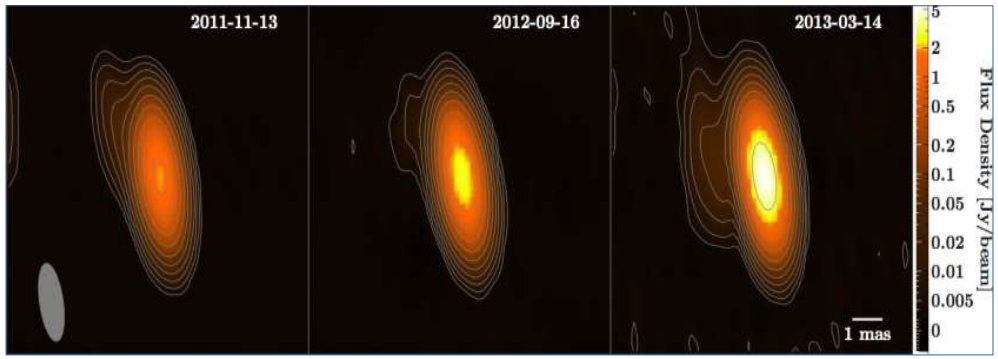
$$N^{\mathrm{max}}_{\nu,\mathrm{PeV}}(\Omega) = A_{\mathrm{eff},\nu_e} \cdot \left(\frac{F_\gamma}{E_\nu}\right) \cdot \Delta t$$

Big Bird ?

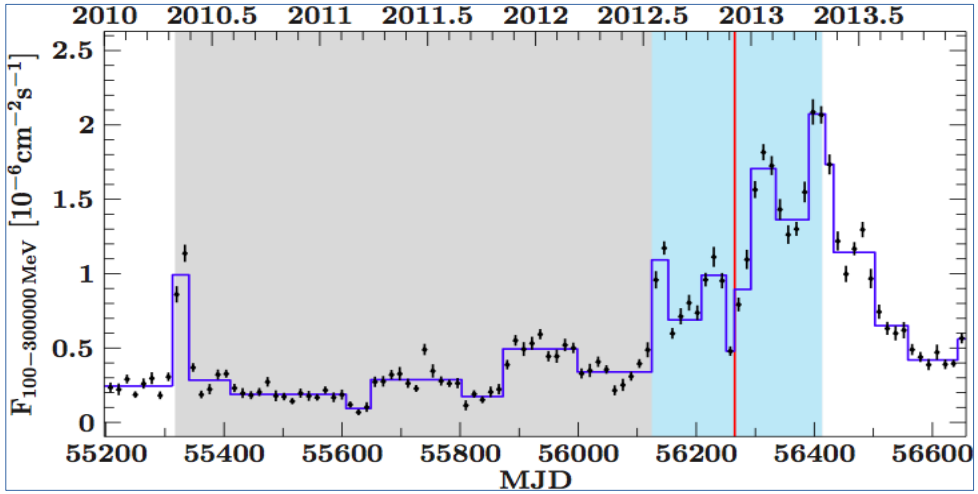


Compatible with 17 Blazars but one dominating the calorimetric output:
PKS B1424-418

BigBird during outburst



$$N_{\nu,\mathrm{max,PeV}}(\mathrm{PKS\ B1424-418}) = 5.8$$
$$N_{\nu,\mathrm{Exp,PeV}}(\mathrm{PKS\ B1424-418}) = 0.16$$

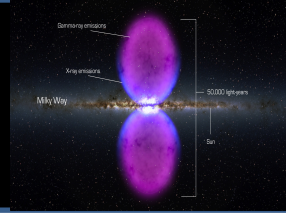


ANTARES Flux limit:
4.2×10^{-8} GeV $cm^{-2}s^{-1}$

Chance proba: 5% (a posteriori)

Conclusion:
« Compatible » as source
Flat or Peaked spectrum

Spectre neutrino astrophysiques



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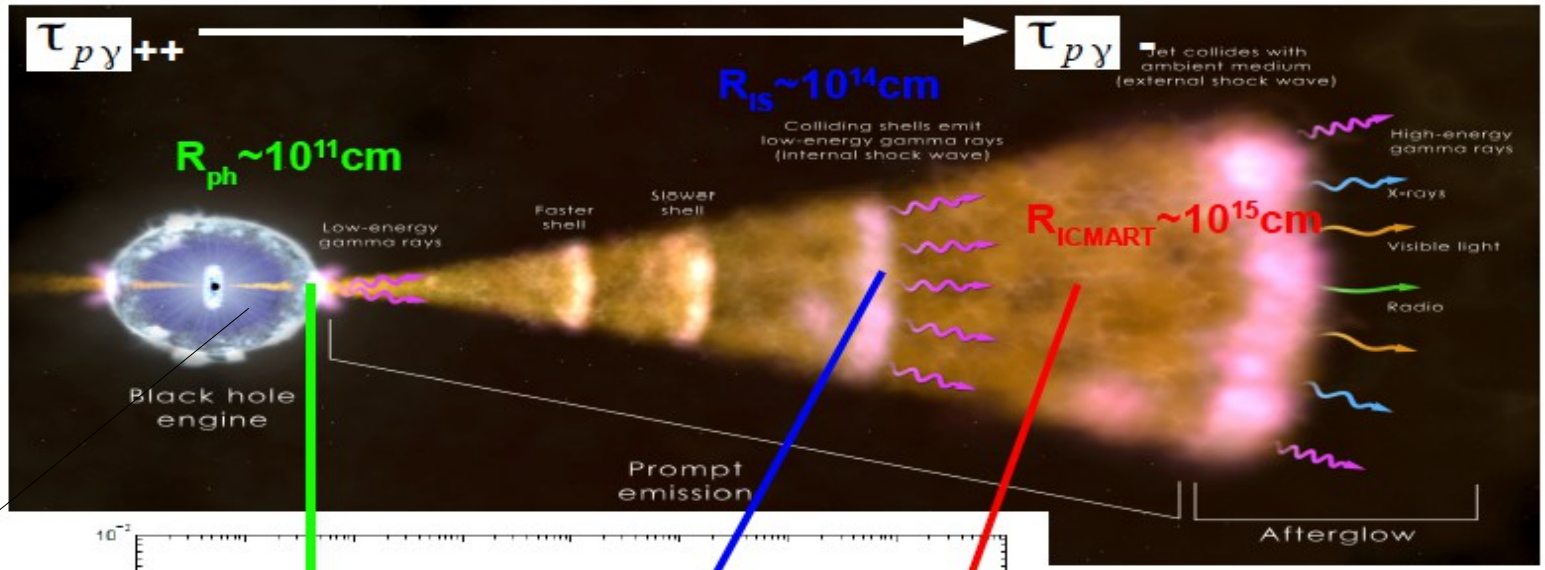
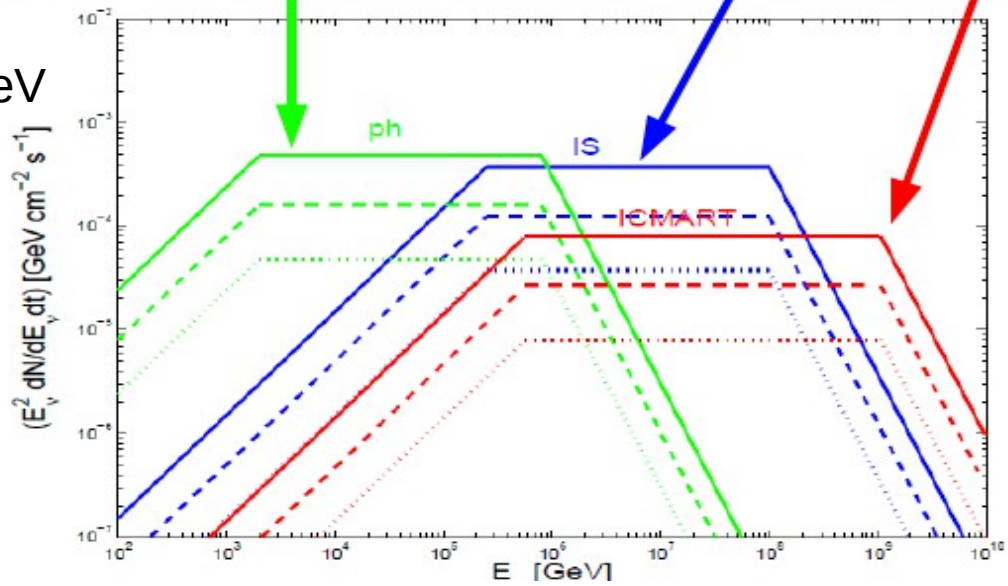
GRBs

Contraindre la charge baryonique ?



pp->10-100GeV
echappement
des n



MAIS :
propagation du choc
accélération effective des p
n importants
cascades
champ B ?
Dégénerescence de parametres

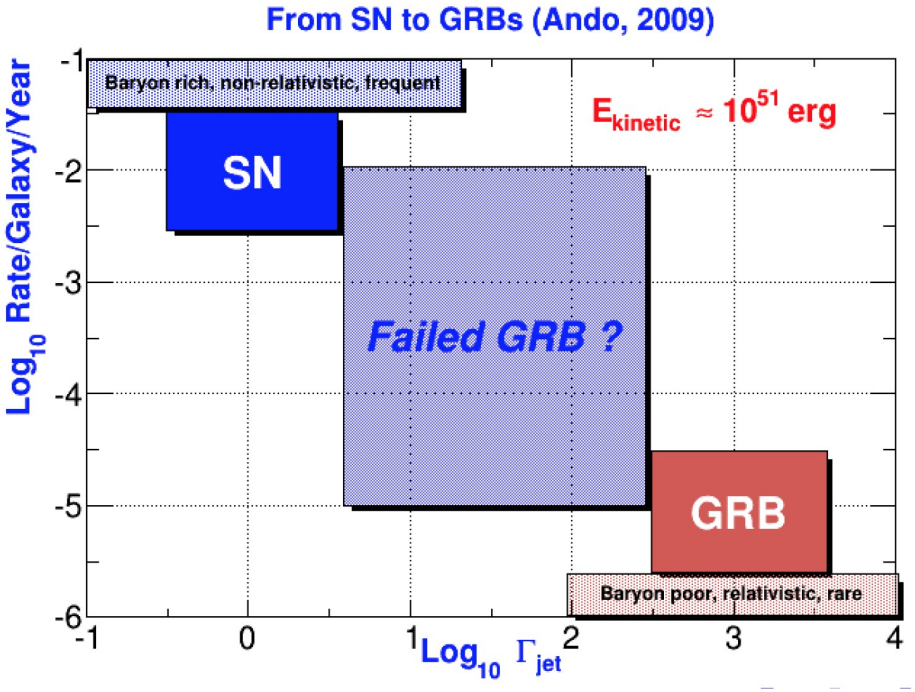
From Zhang&Kumar 2013

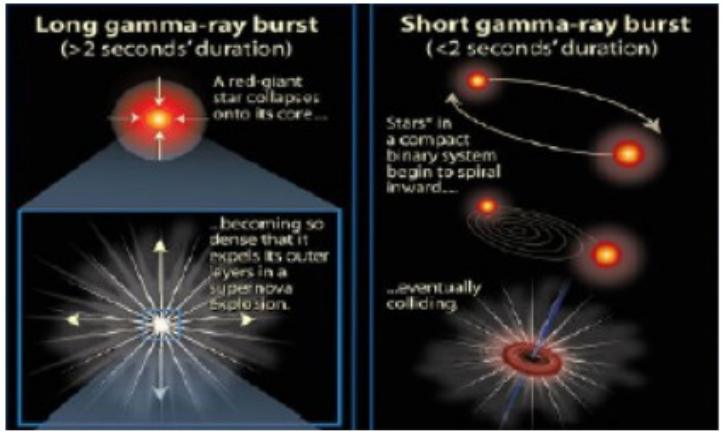
Neutrinos & GW

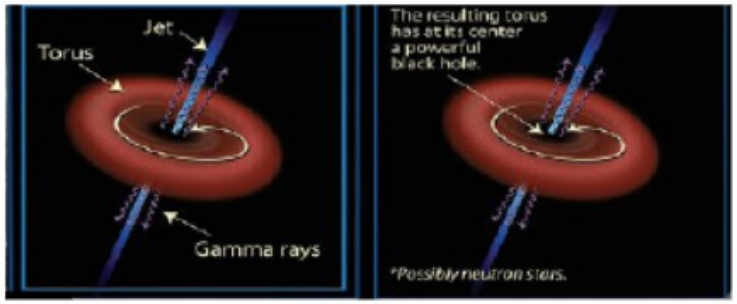
Asymetrical collapse → GW

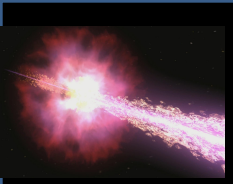
Baryon loaded jets -> HEN

- Dark electromagnetic sources

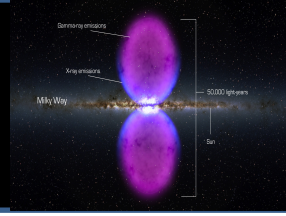








En somme



- Basse énergies (10 MeV):

  Supernovae locale | Modélisation ~maitrisée

  → attendre la prochaine

- Hautes énergies (TeV-Pev):

  Partout ou des p sont accélérés

  Modelisation complexe très incertaine |
  - dans de la matière (binaires, TDE, Novae, SN, pevatrons) Galactique
  - sur le rayonnement (AGN, GRB), extragal.

  → rester le plus modèle indépendant possible

  diffus vu → viser tout ce qui bouge (le plus court le mieux)

  → Raffiner les modèles !