

Des Particules au Cosmos

Introduction à la Physique des Astroparticules

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Plan des cours 2 et 3

Pierre Brun¹ (Irfu, CEA Saclay)

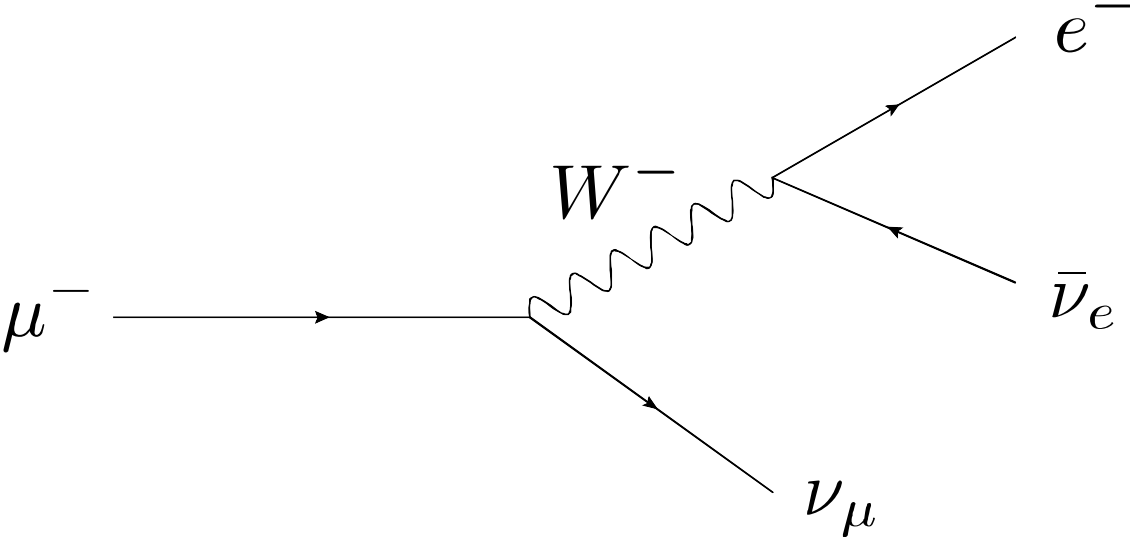
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Plan des cours 2 et 3

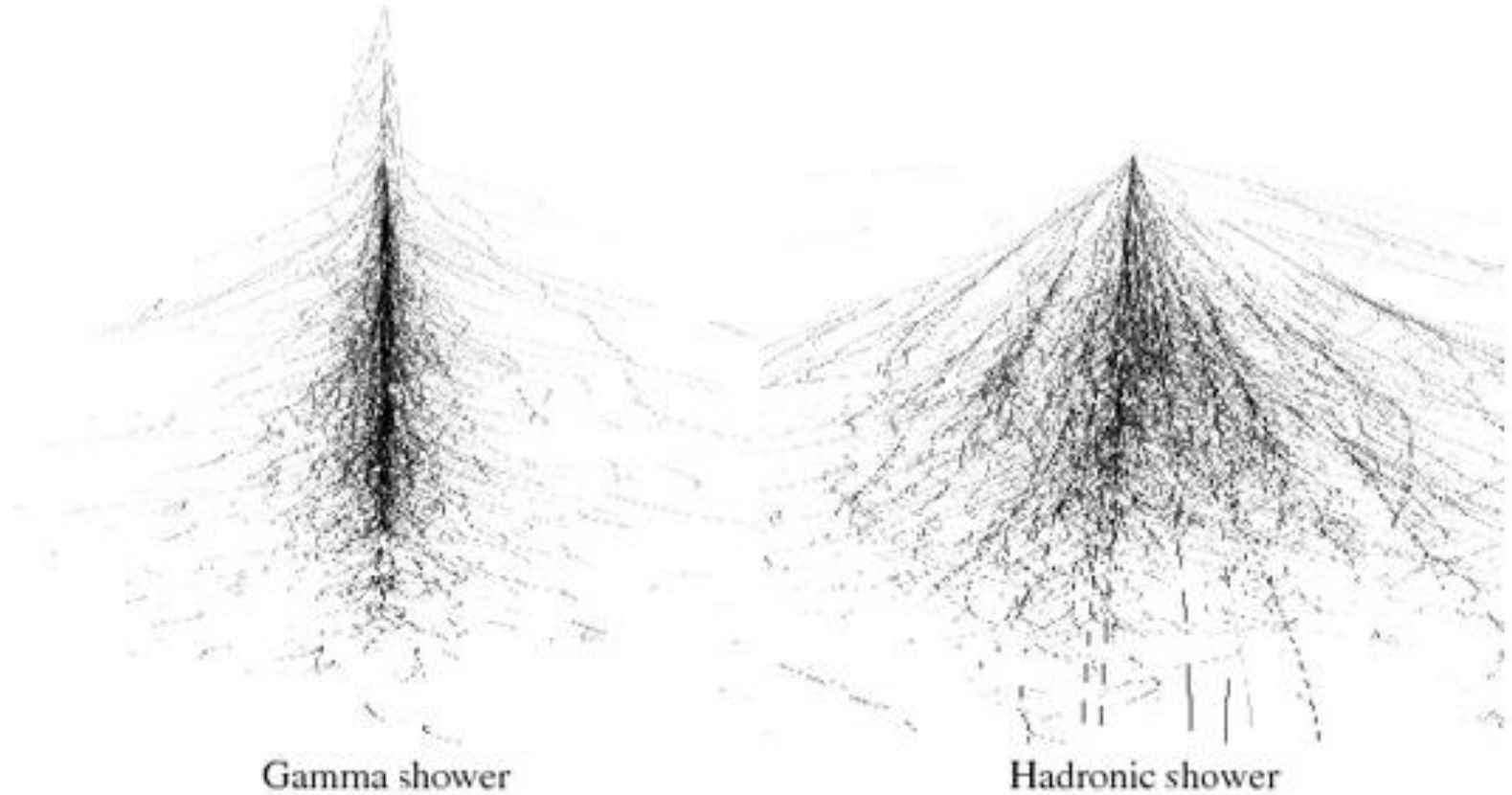
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1.1 Particules cosmiques au niveau du sol

1.2 Une expérience simple d'astroparticules : observation des muons au niveau du sol et dilatation relativiste du temps

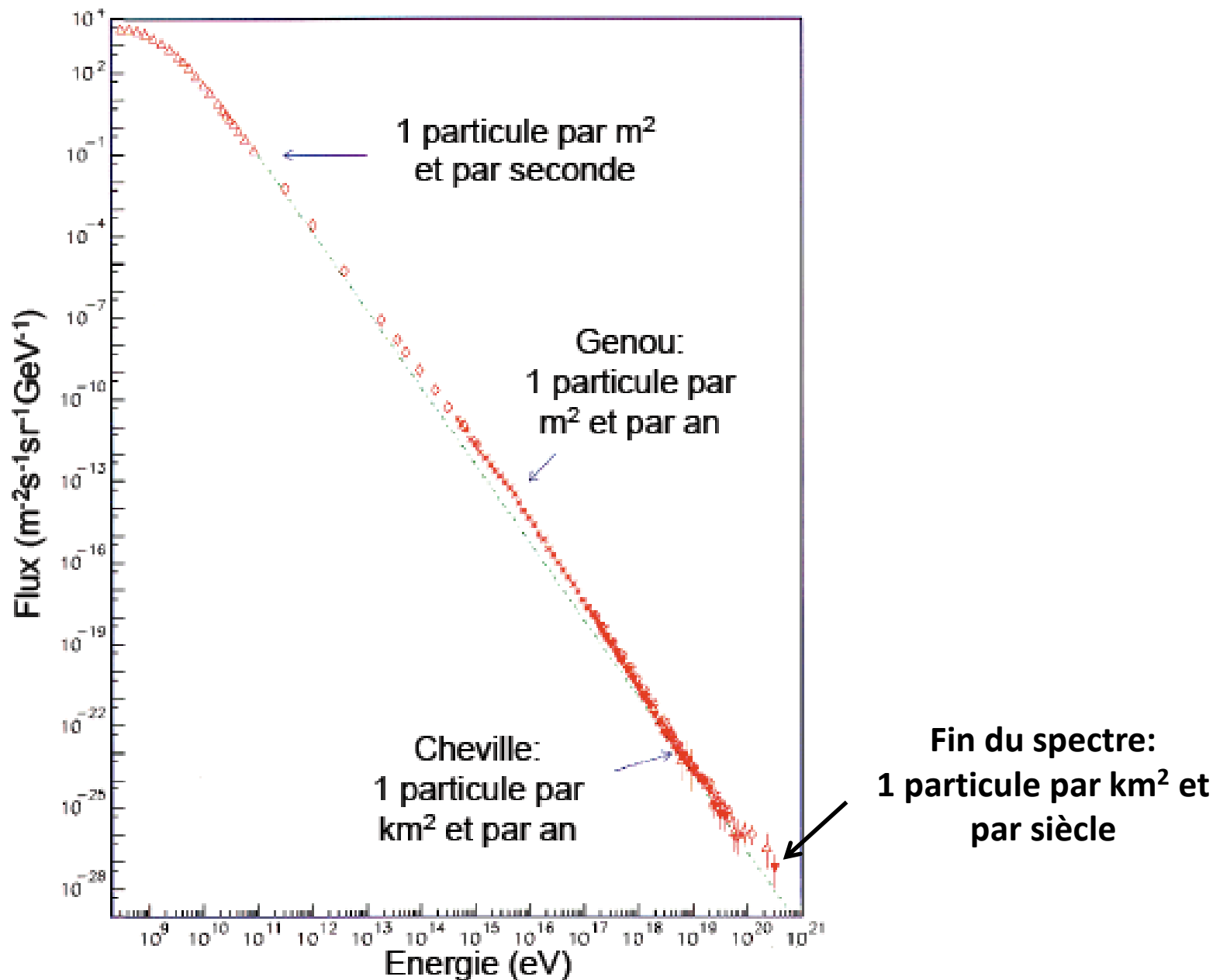


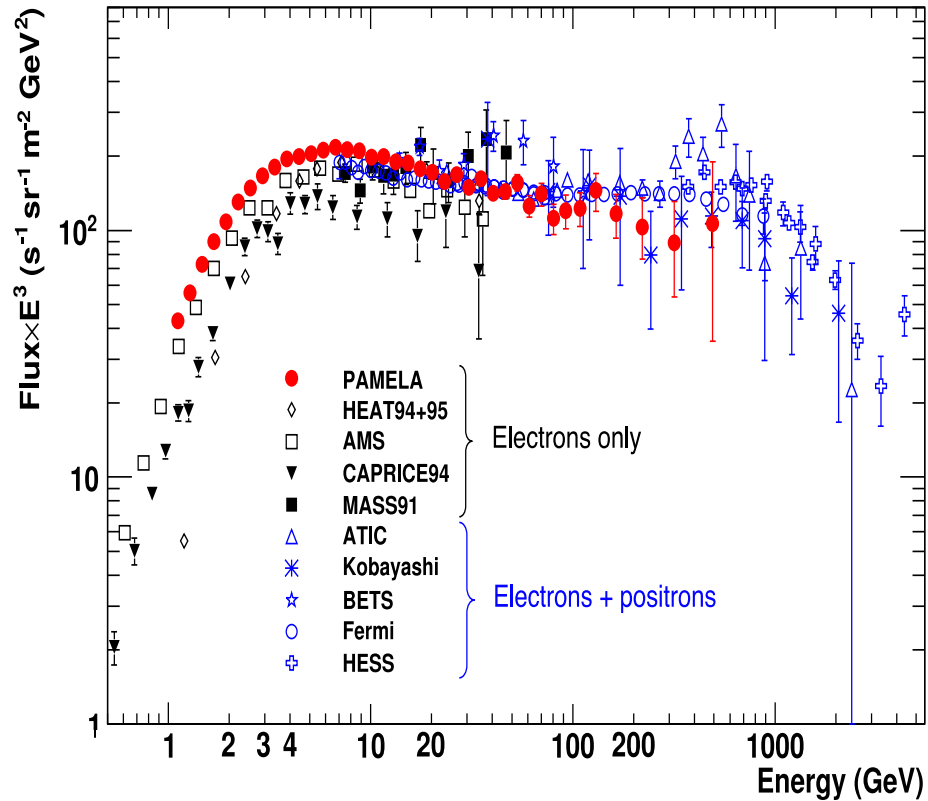
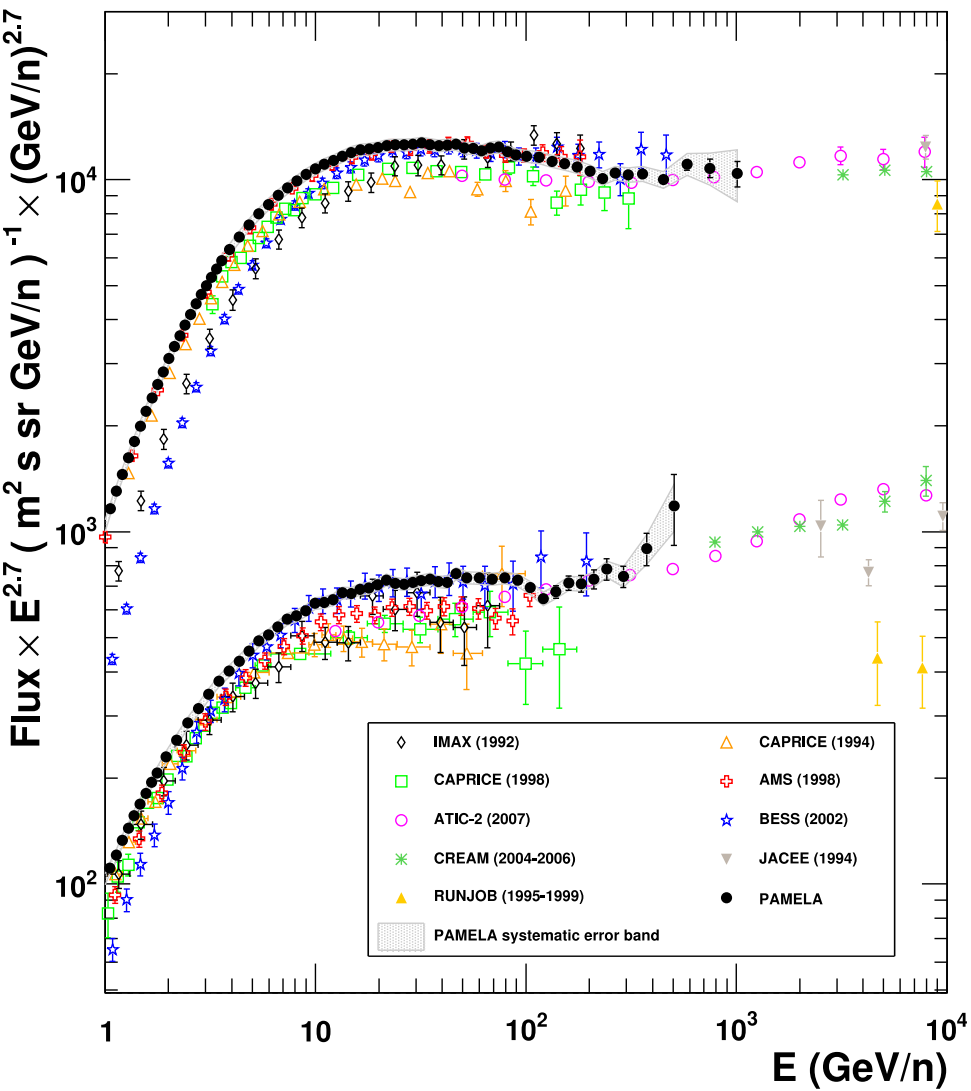
1.3 Cascades atmosphériques

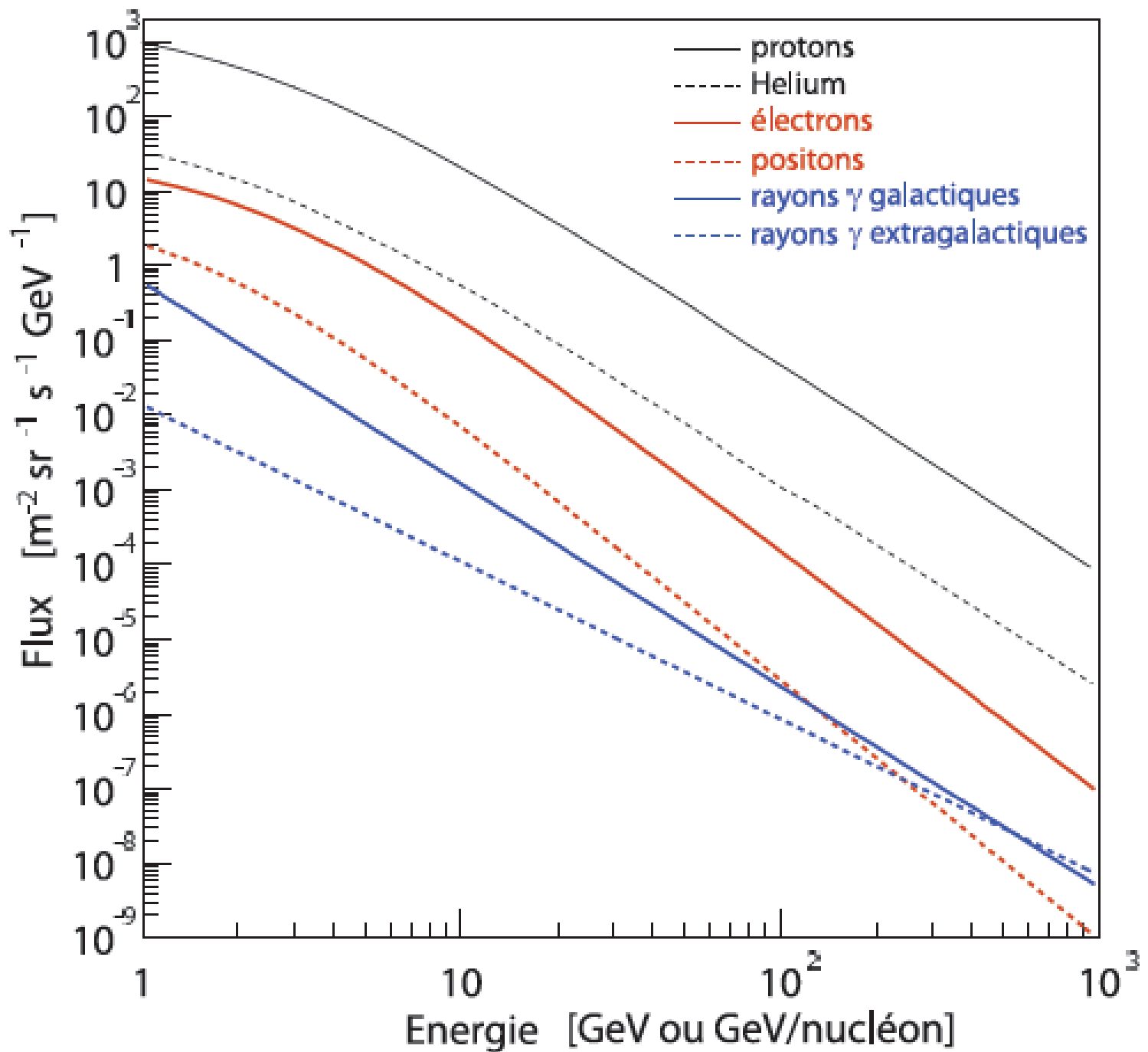


1.4 Particules cosmiques au sommet de l'atmosphère

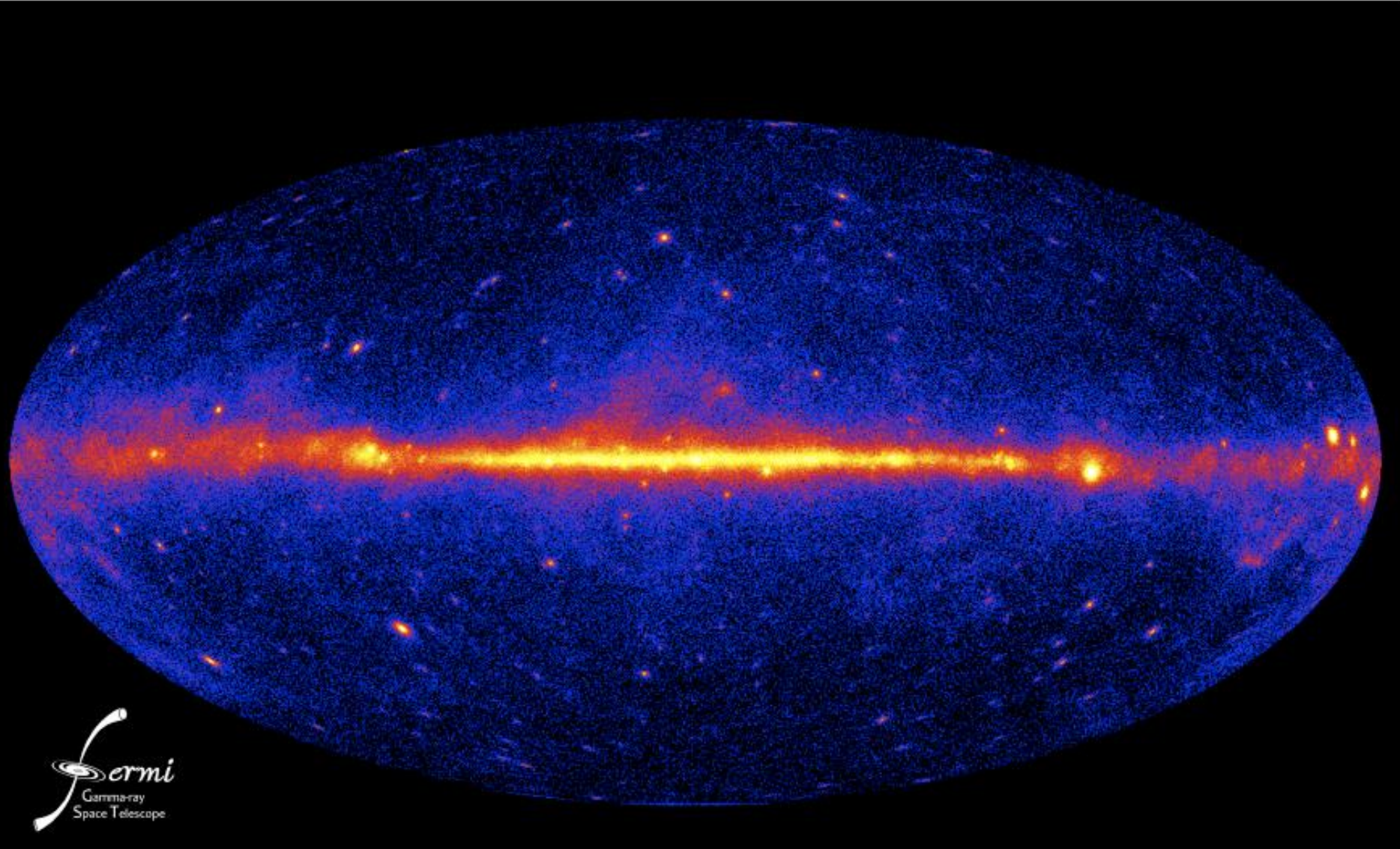
1.4.1 Composante chargée





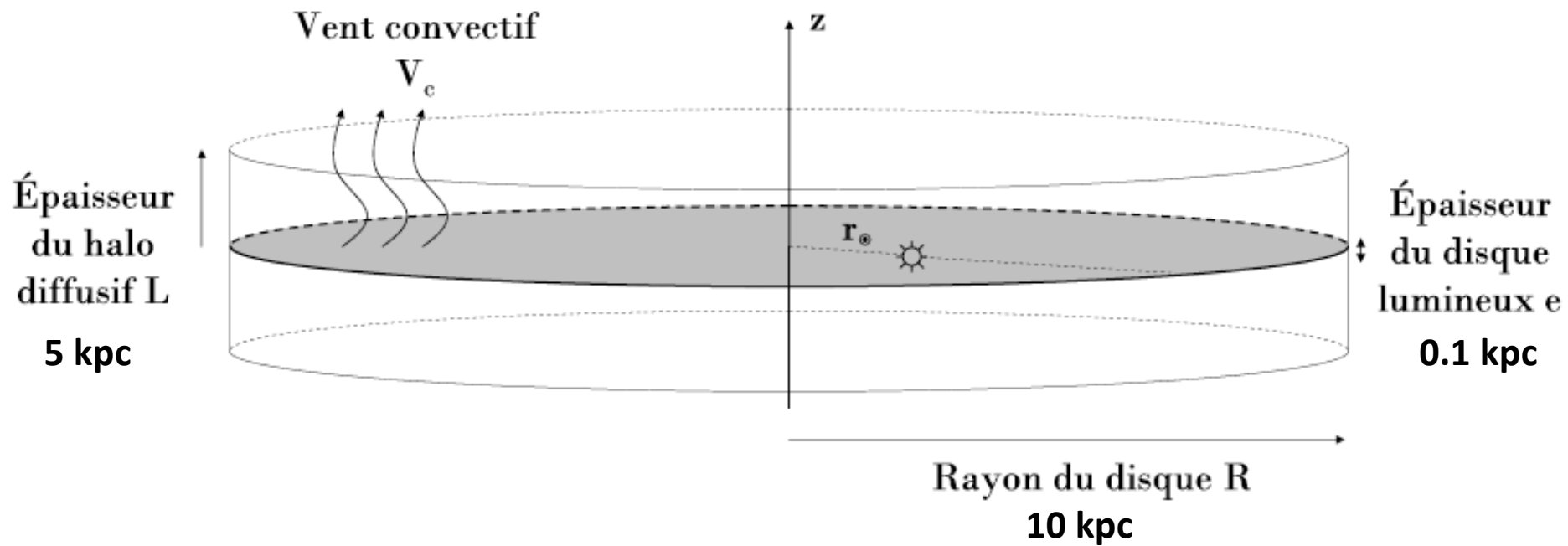


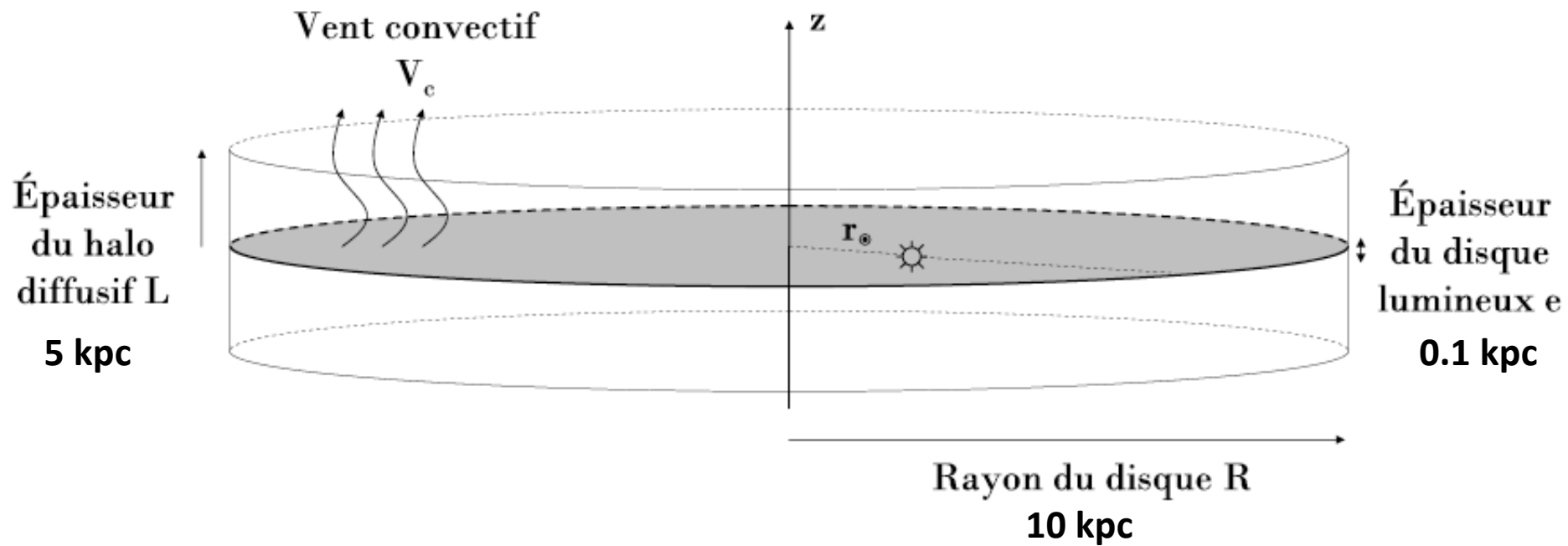
1.4.2 Composante neutre



1.5 Provenance et horizons

1.5.1 Particules chargées



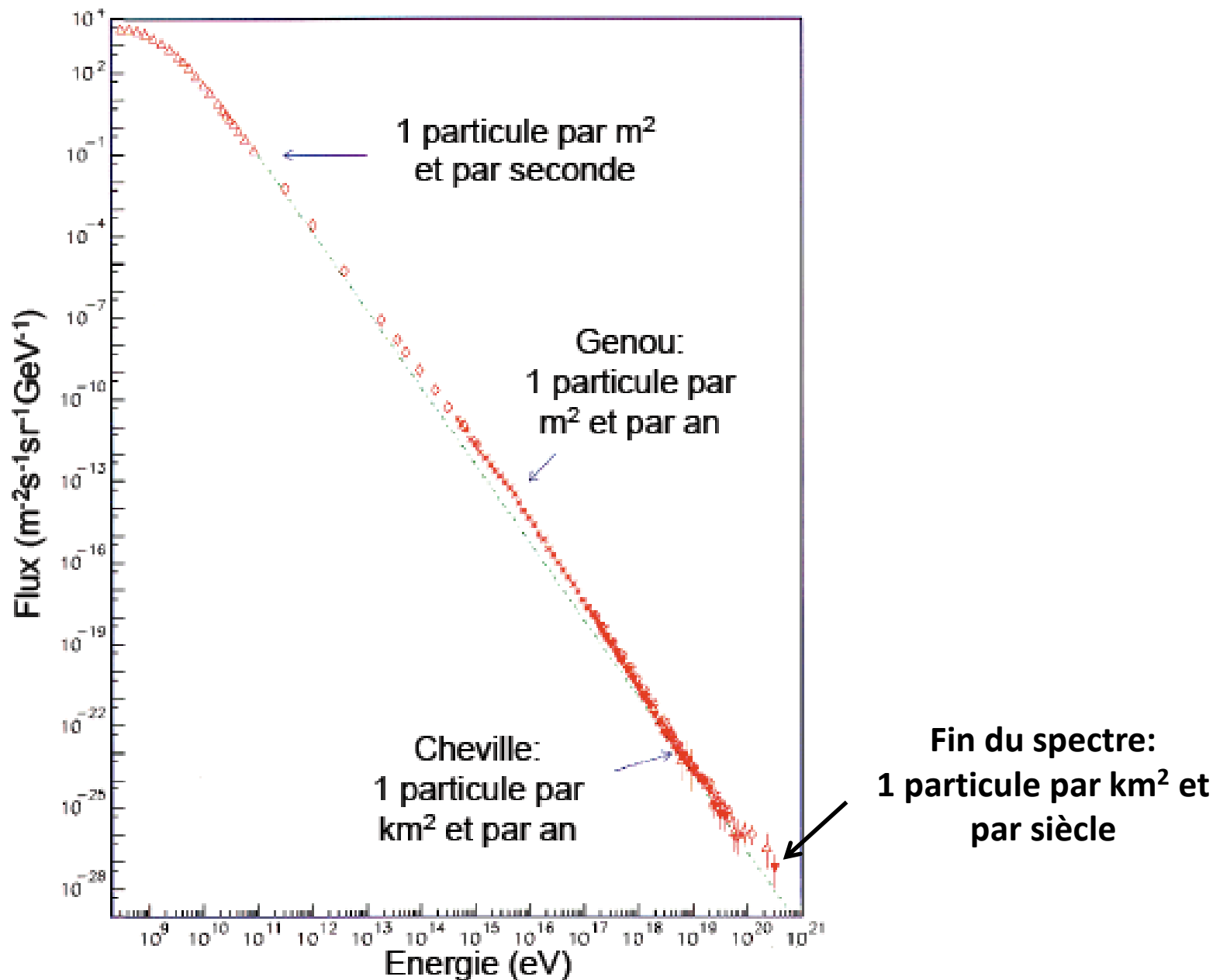


$$\frac{\partial}{\partial z} V_c \psi(\vec{x}, E) - K \Delta \psi(\vec{x}, E) + \frac{\partial}{\partial E} \left(b(E) \psi(\vec{x}, E) - K_{\text{réac}} \frac{\partial \psi(\vec{x}, E)}{\partial E} \right) = Q(\vec{x}, E)$$

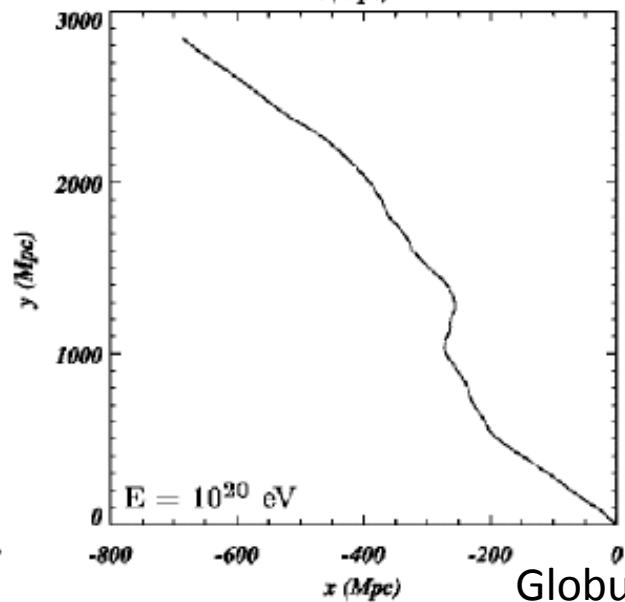
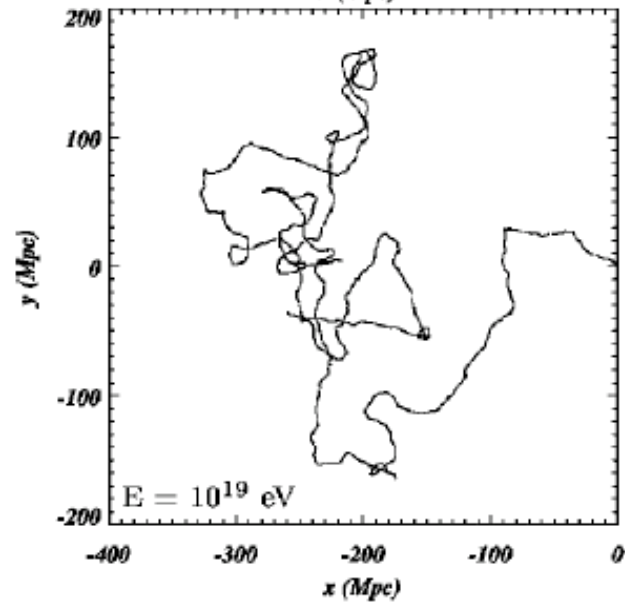
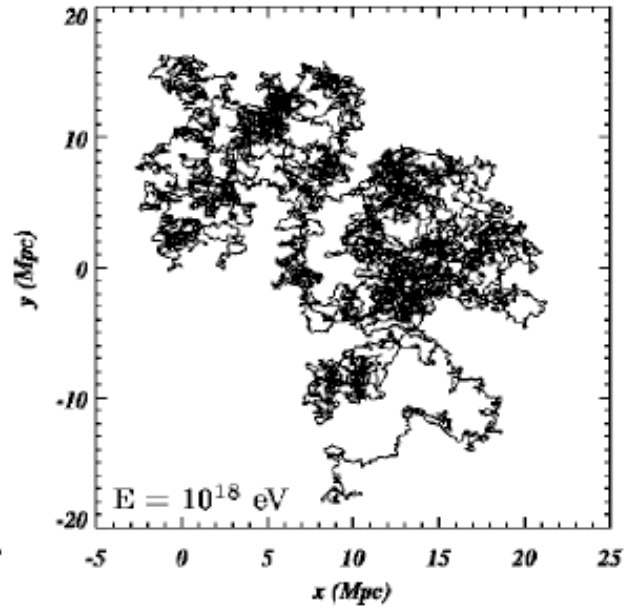
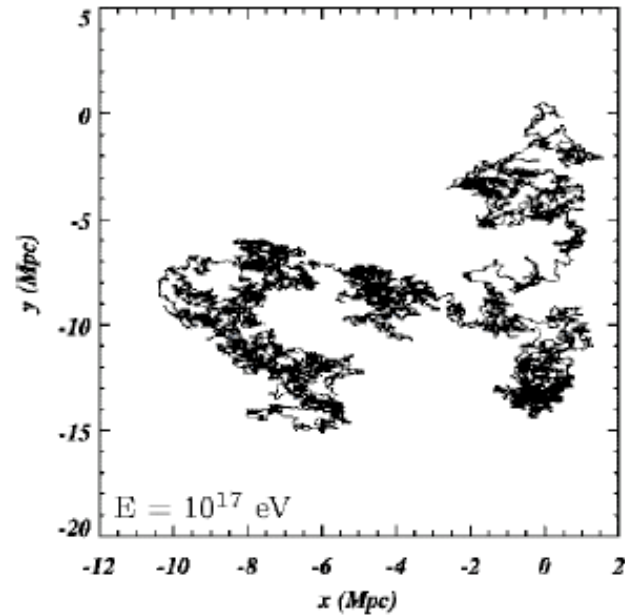
Exemple pour les électrons:

$$E_{emis} = 1 \text{ TeV}$$

$$\lambda \simeq 6.5 \text{ kpc} \sqrt{\left(\frac{E_{det.}}{1 \text{ GeV}}\right)^{-0.3} - 0.12}$$

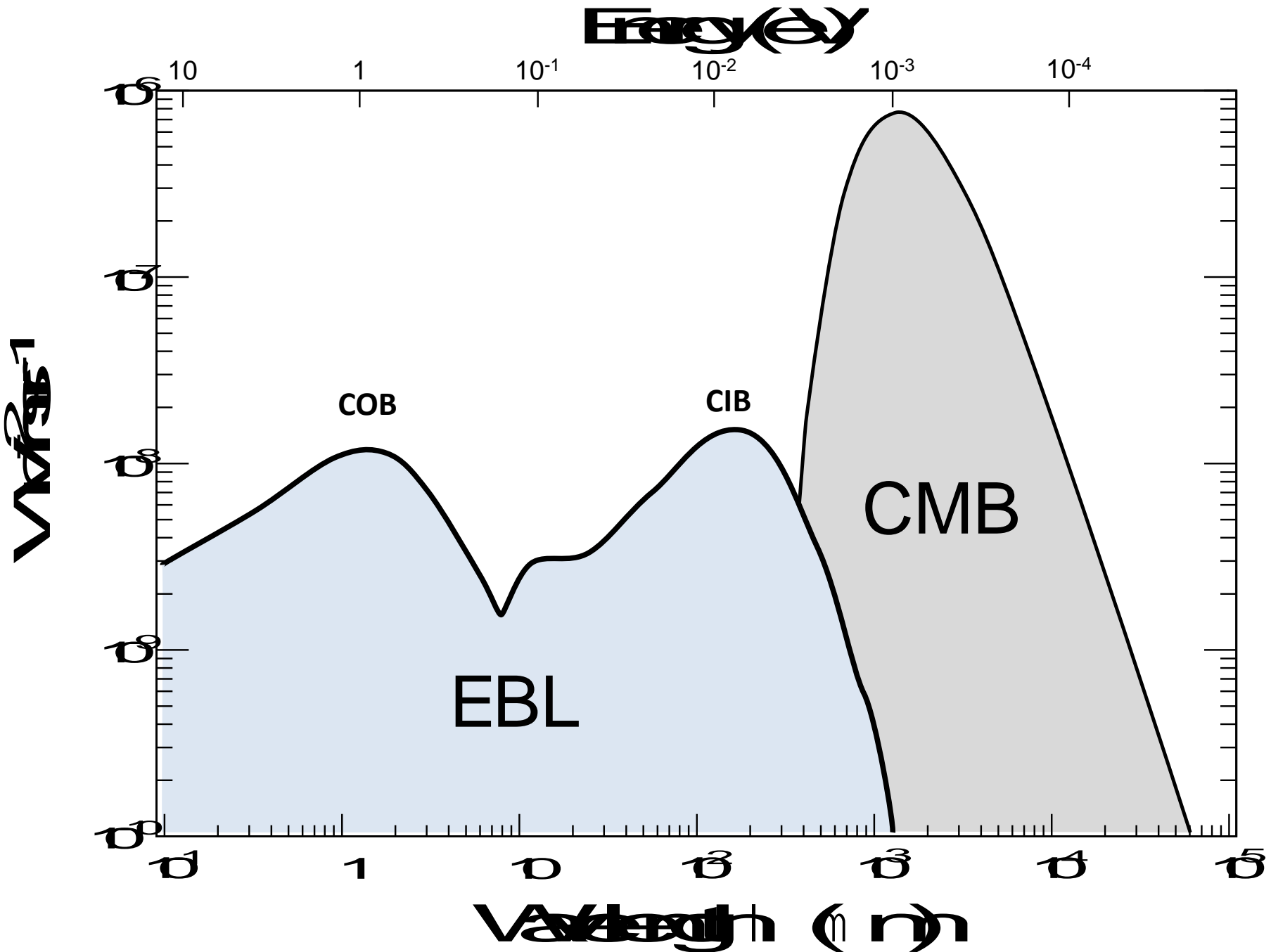


Le cas des particules chargées d'énergie extrême



1.5.2 Horizons pour les particules observées sur Terre

Toile de fond : les rayonnements cosmologiques



$$A + \gamma_{\text{fond}} \rightarrow \dots$$

Energie dans le centre de masse : $\sqrt{s} = \sqrt{(P_A + P_\gamma)^2}$

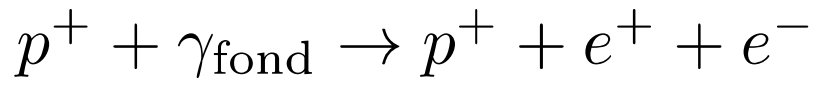
$$P^2 = E^2 - \vec{p}^2$$

$$s = E_A^2 + E_\gamma^2 + 2E_A E_\gamma - \vec{p}_A^2 - \vec{p}_\gamma^2 - 2 \vec{p}_A \cdot \vec{p}_\gamma$$

$$s = m_A^2 + 2E_\gamma (E_A - p_A \cos \theta)$$

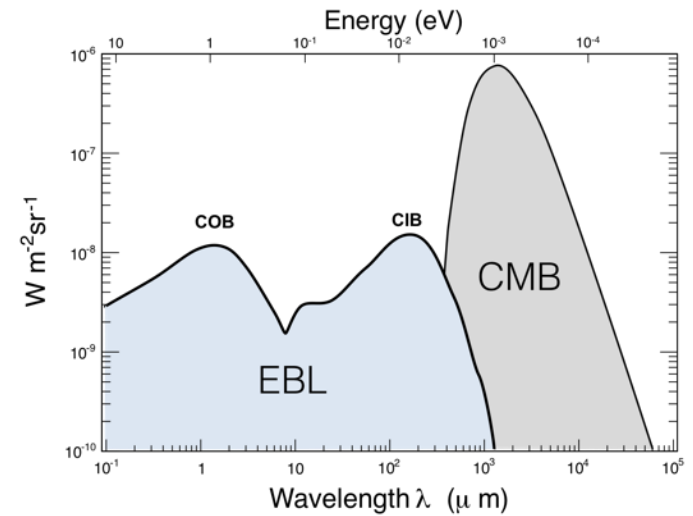
$$E_A \gg m_A$$

$$s = m_A^2 + 2E_\gamma E_A (1 - \cos \theta)$$



$$\sqrt{s} > m_p c^2 + 2m_e c^2$$

$$E_p^{\text{seuil}} = \frac{2 m_e (m_e + m_p) c^4}{E_{\gamma, \text{fond}} (1 - \cos \theta)}$$

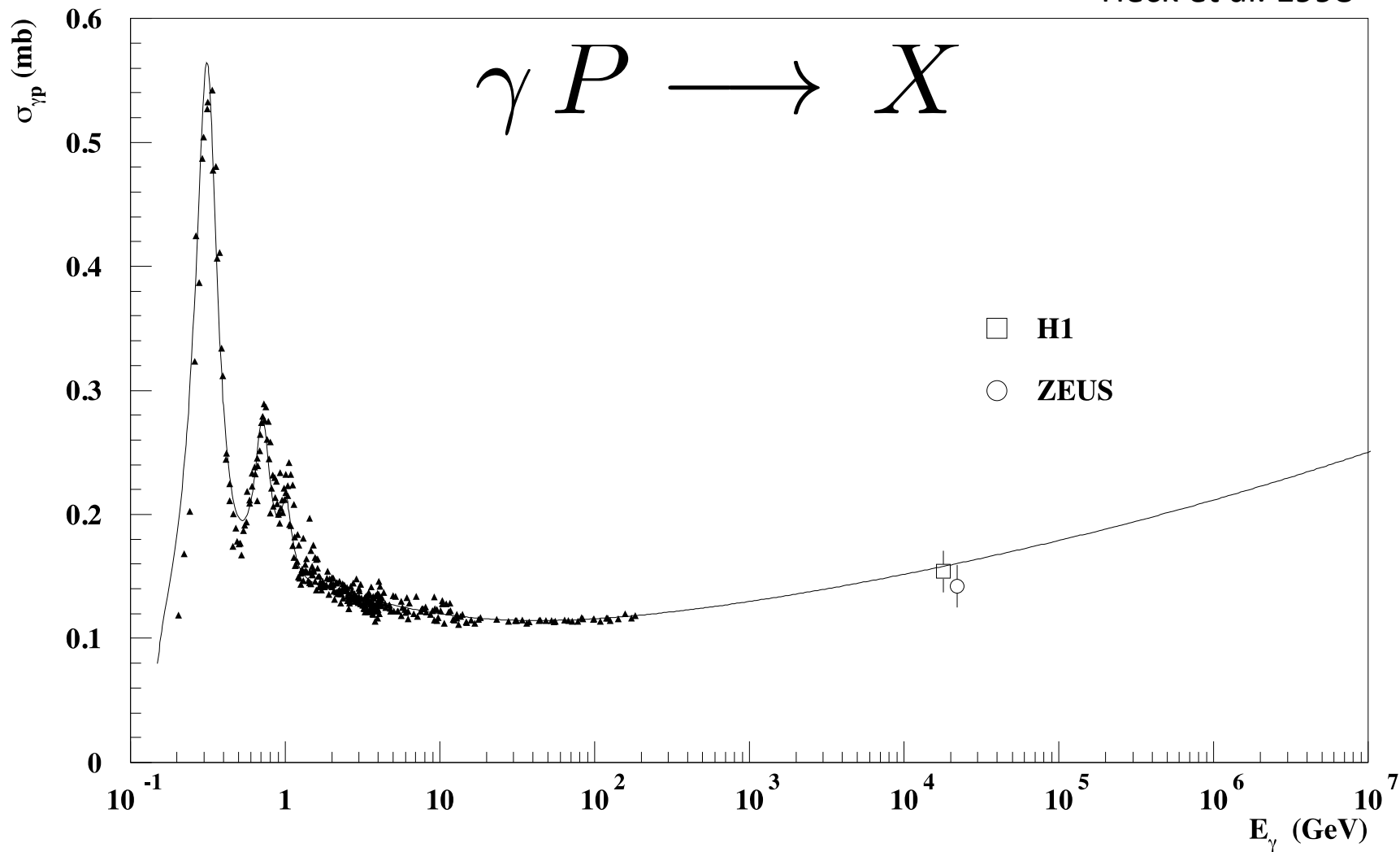


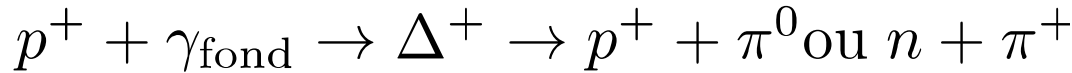
Energie de seuil pour le p^+

$$E_{\text{COB}} = 10 \text{ eV} \quad 5 \times 10^{15} \text{ eV}$$

$$E_{\text{CIB}} = 0.1 \text{ eV} \quad 5 \times 10^{13} \text{ eV}$$

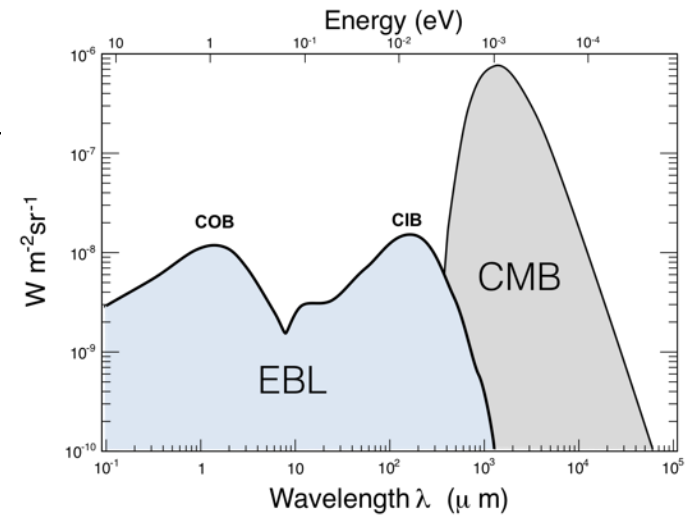
$$E_{\text{CMB}} = 10^{-3} \text{ eV} \quad 5 \times 10^{17} \text{ eV}$$





$$\sqrt{s} = m_{\Delta} c^2$$

$$E_p^{\text{seuil}} = \frac{m_{\Delta}^2 c^4 - m_p^2 c^4}{2E_{\gamma, \text{fond}}(1 - \cos \theta)}$$



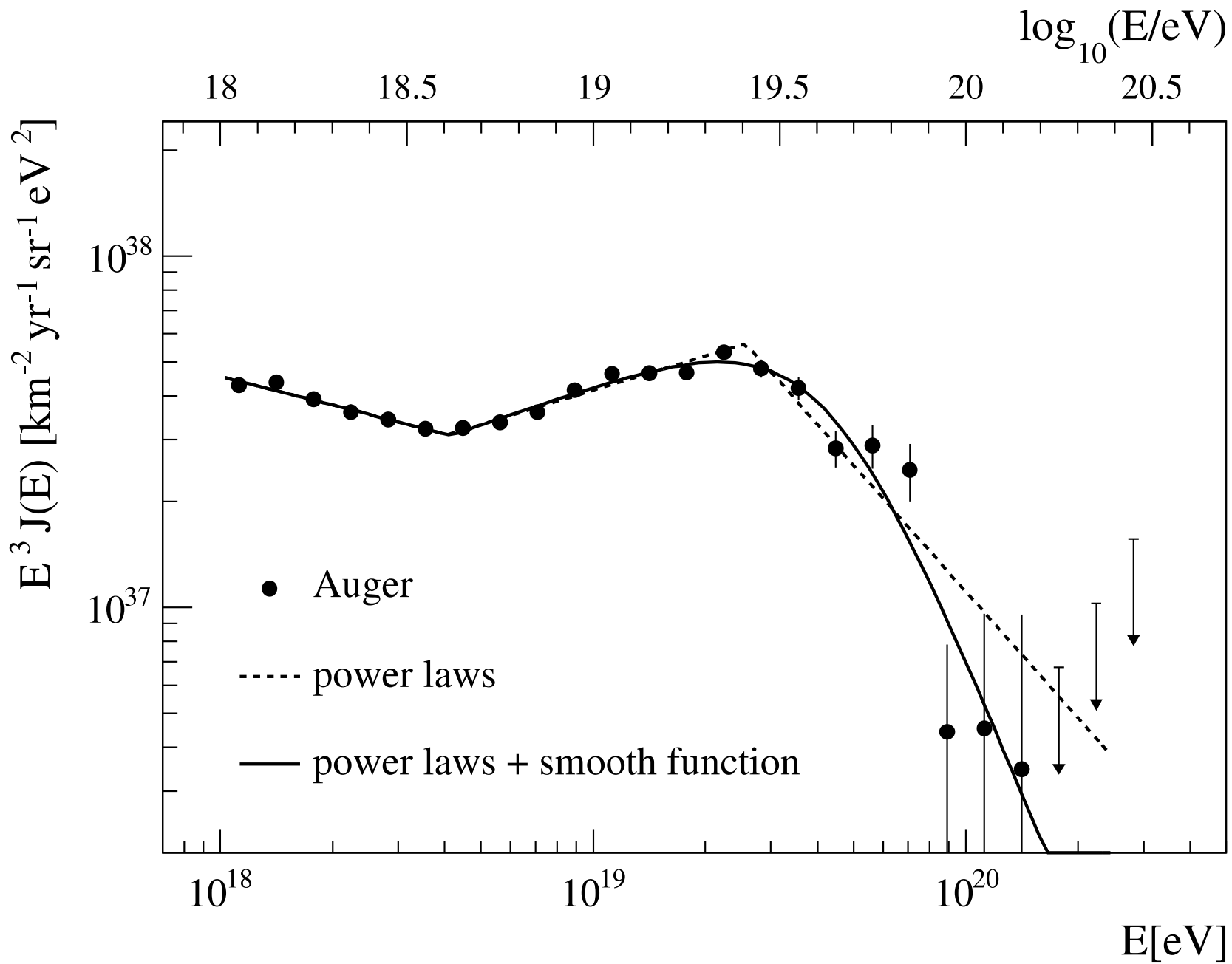
Energie de seuil pour le p^+

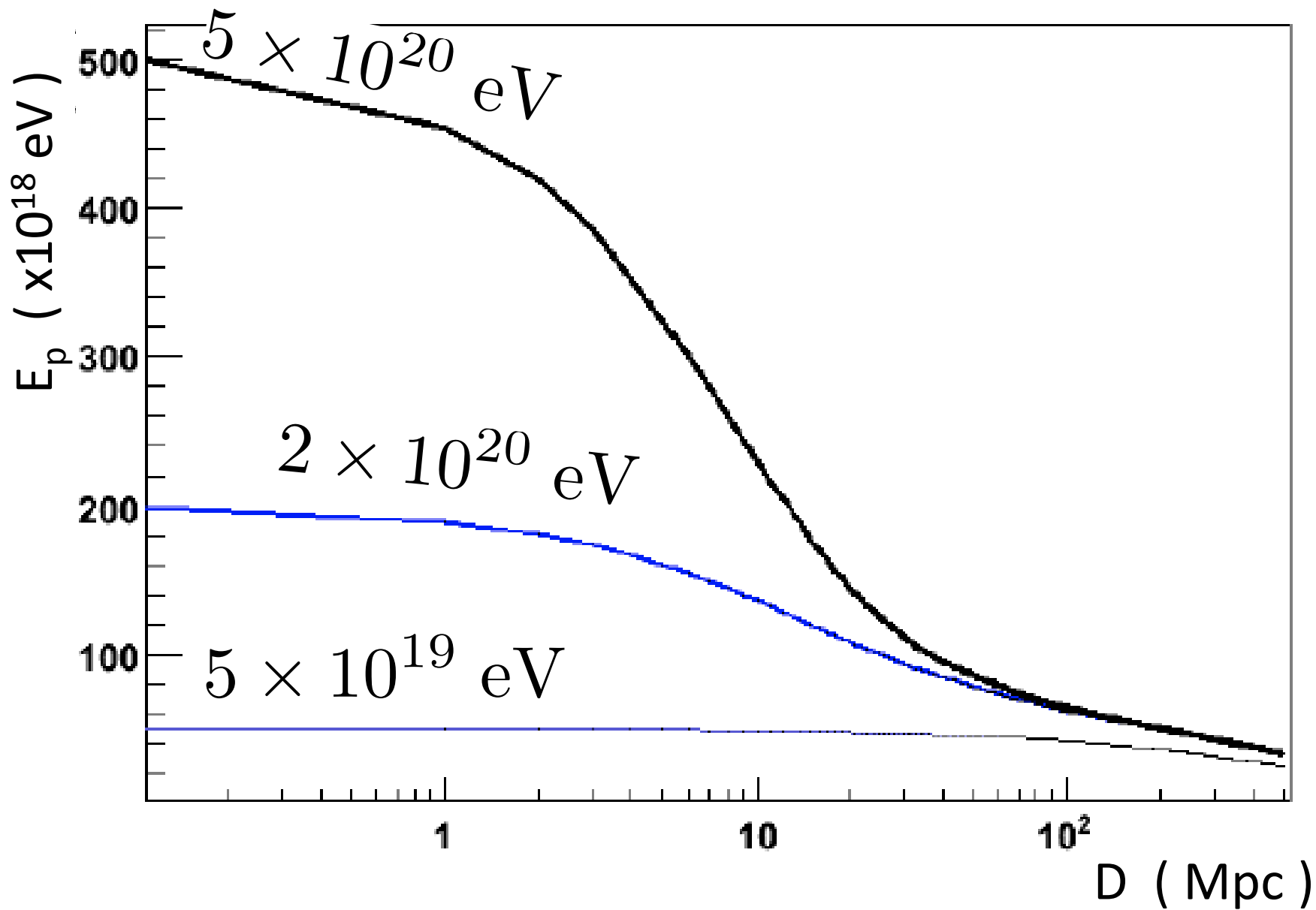
$$E_{\text{COB}} = 10 \text{ eV} \quad 1.6 \times 10^{16} \text{ eV}$$

$$E_{\text{CIB}} = 0.1 \text{ eV} \quad 1.6 \times 10^{18} \text{ eV}$$

$$E_{\text{CMB}} = 10^{-3} \text{ eV} \quad 1.6 \times 10^{20} \text{ eV}$$

Coupure GZK

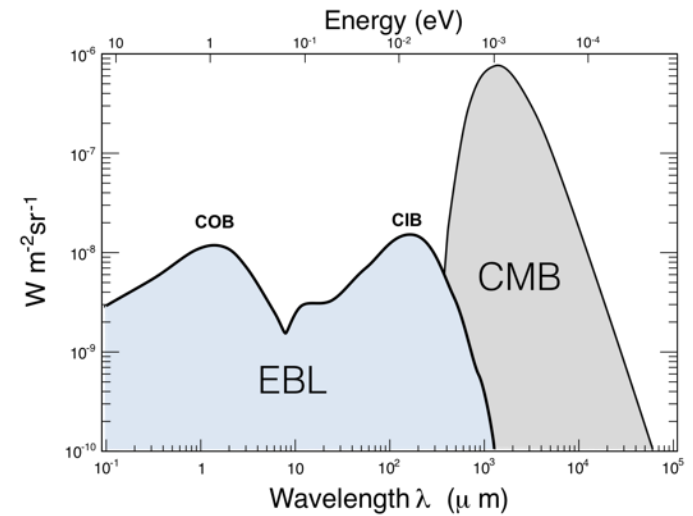




$$\gamma + \gamma_{\text{fond}} \rightarrow e^+ + e^-$$

$$\sqrt{s} > 2m_e c^2$$

$$E_\gamma > \frac{2 m_e^2 c^4}{E_{\gamma, \text{fond}} (1 - \cos \theta)}$$

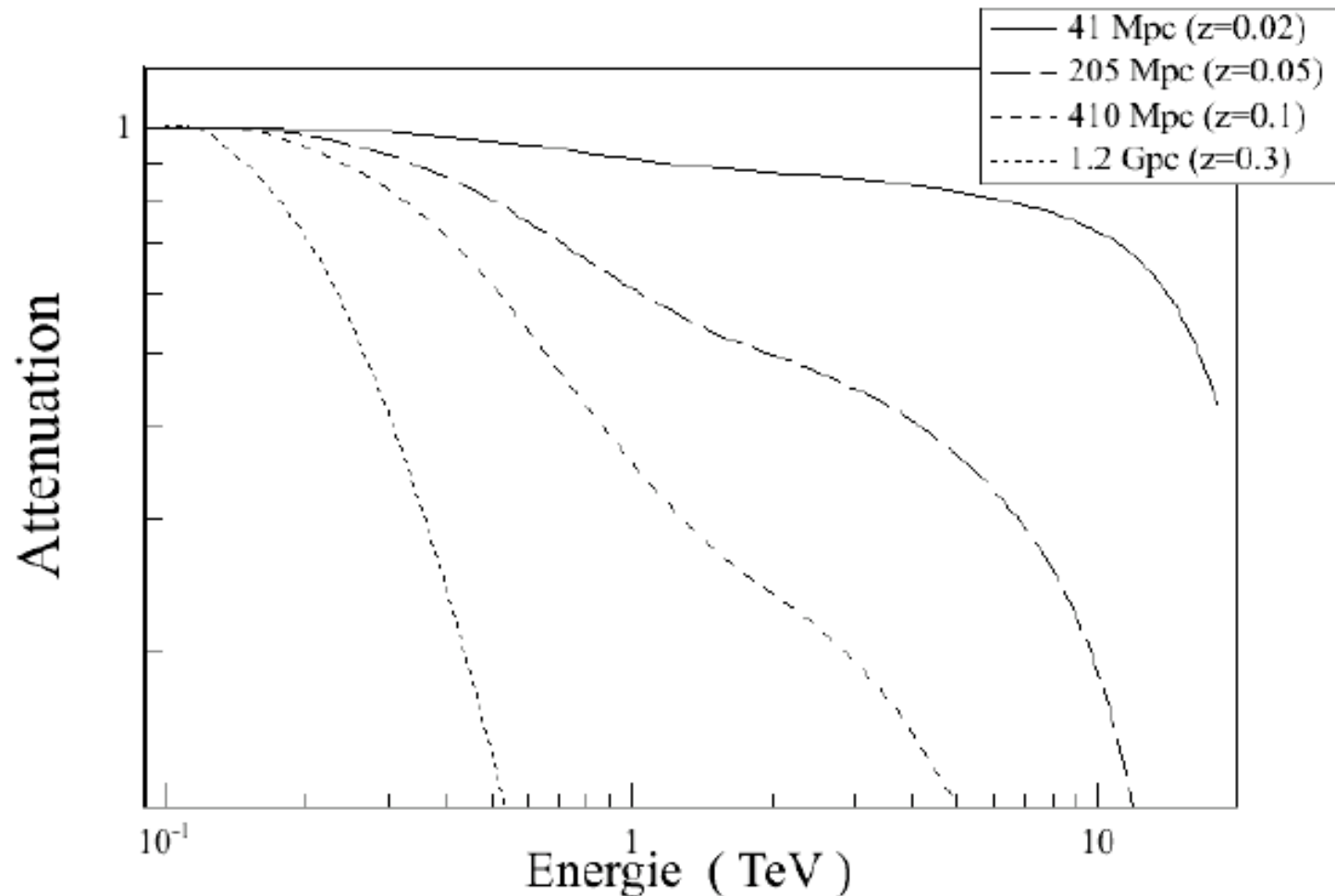


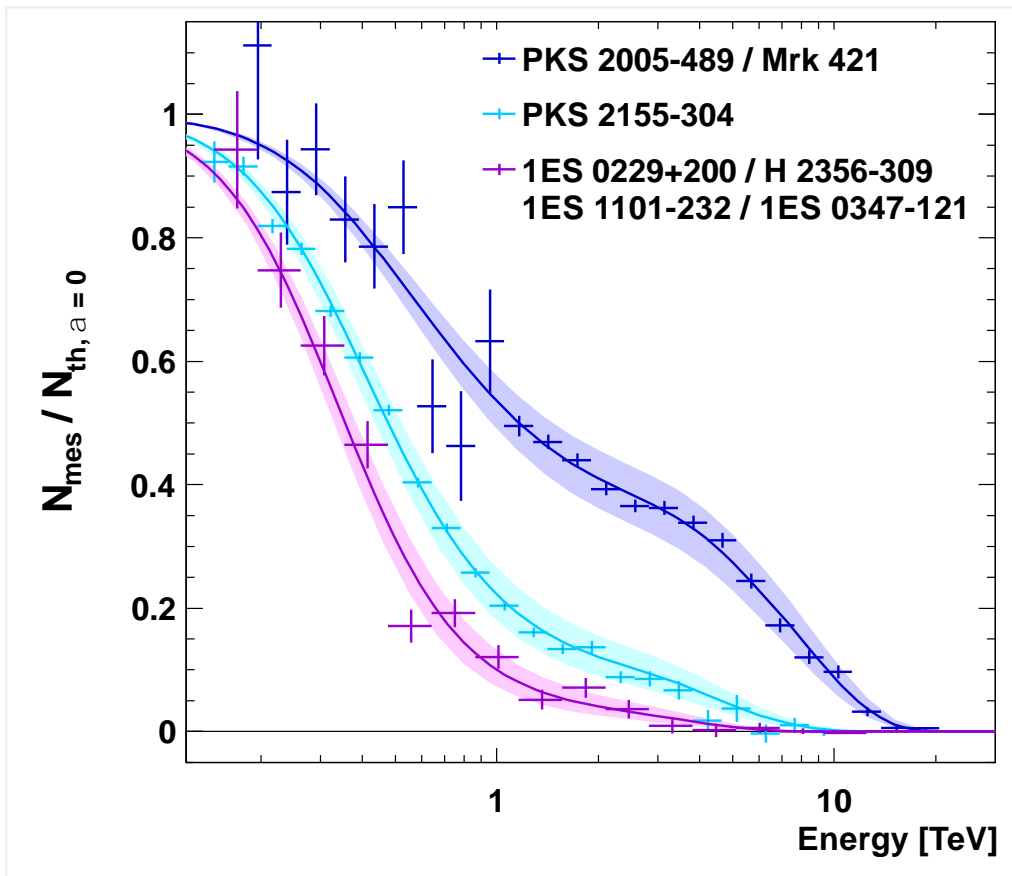
$$E_\gamma^{\text{seuil, CMB}} = \frac{m_e^2 c^4}{E_{\text{CMB}}} = 260 \text{ TeV}$$

$$E_\gamma^{\text{seuil, CIB}} = \frac{m_e^2 c^4}{E_{\text{CIB}}} = 2.6 \text{ TeV}$$

$$\phi_{\text{obs}} = \phi_{\text{source}} \times \exp(-\tau)$$

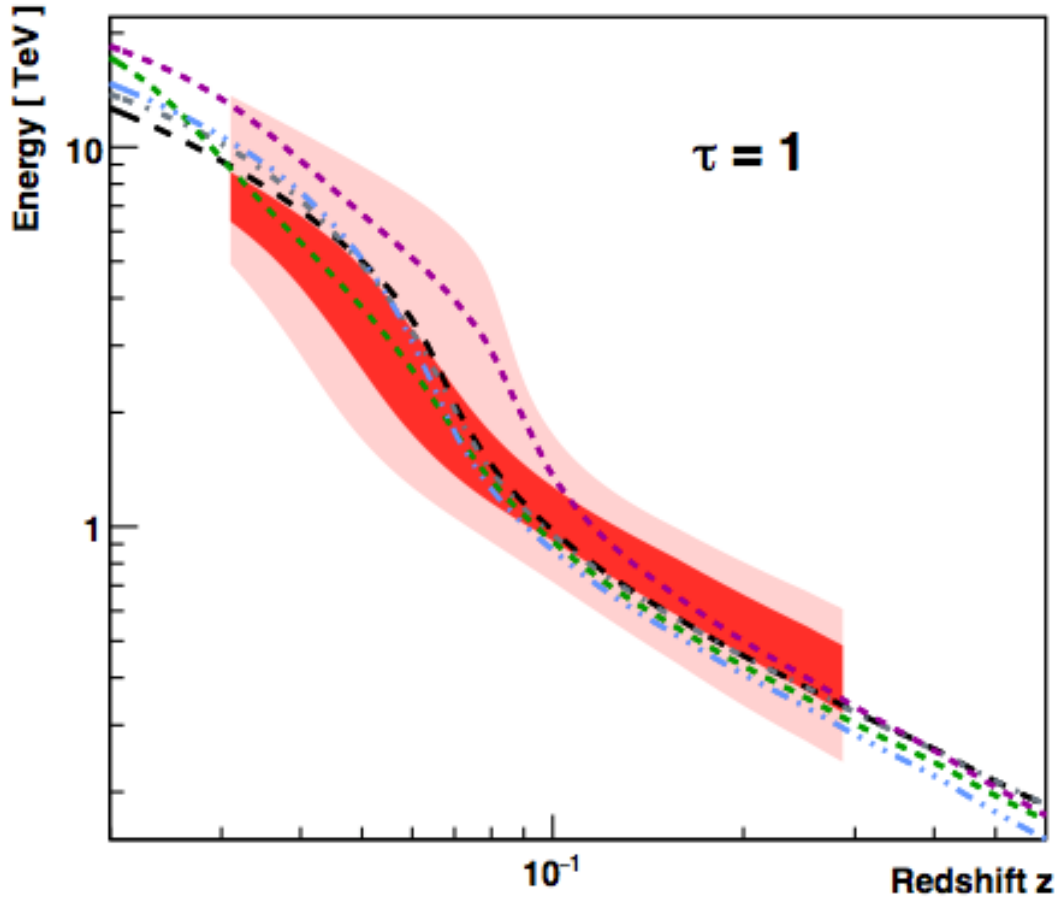
$$\tau(E_\gamma, D) = \int_0^D dl \int_{\epsilon_{\text{seuil}}}^{\infty} d\epsilon \sigma_{\gamma\gamma}(E_\gamma, \epsilon) \times n_{\text{CIB}}(\epsilon, l)$$












H.E.S.S. Collaboration, A&A 2013

HESS 2017



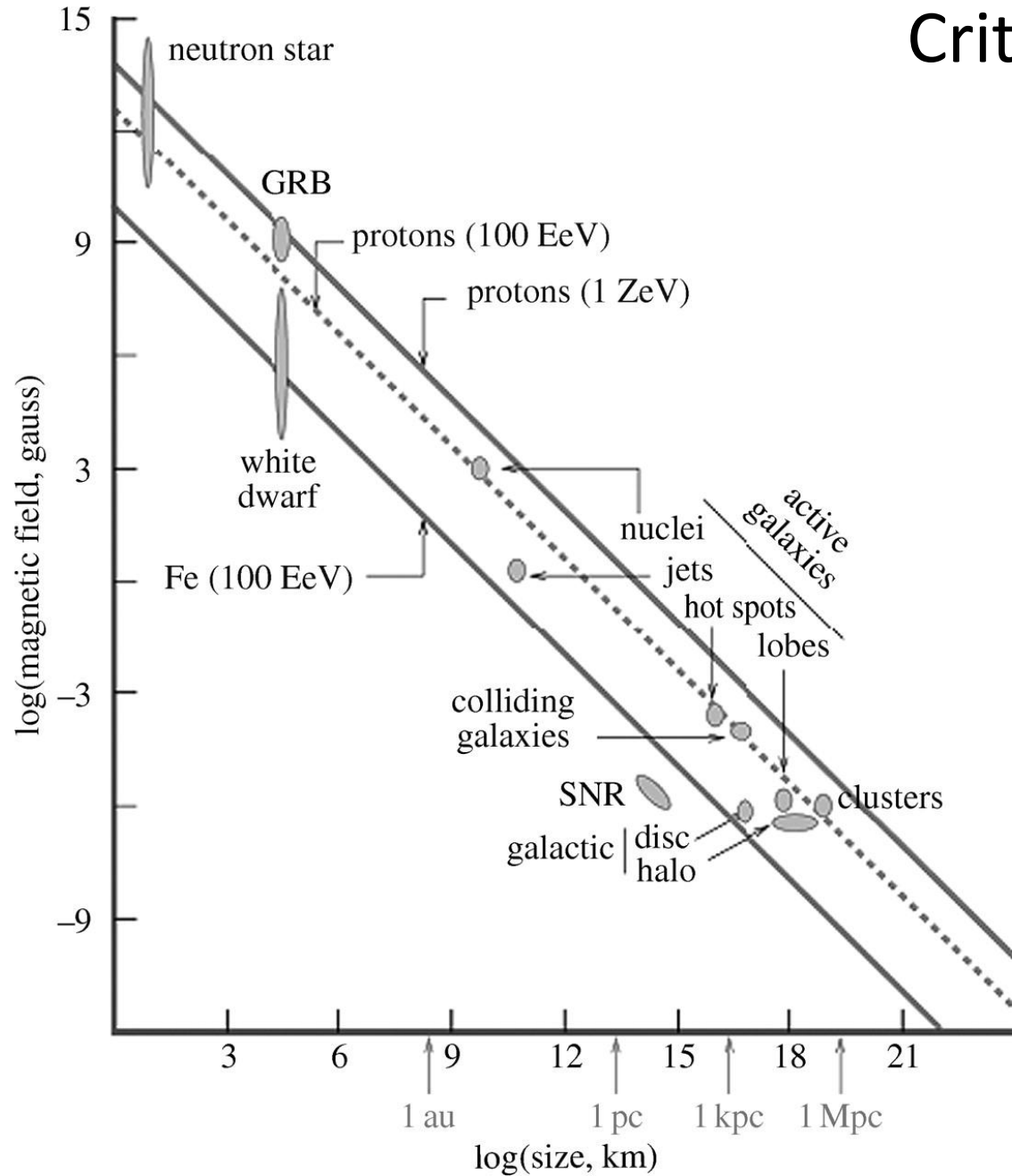
-  This work
-  Including systematics
-  Franceschini et al. 2008
-  Dominguez et al. 2011
-  Finke et al. 2010
-  Gilmore et al. 2012 (Fiducial)
-  Kneiske & Dole 2010

-> neutrinos!

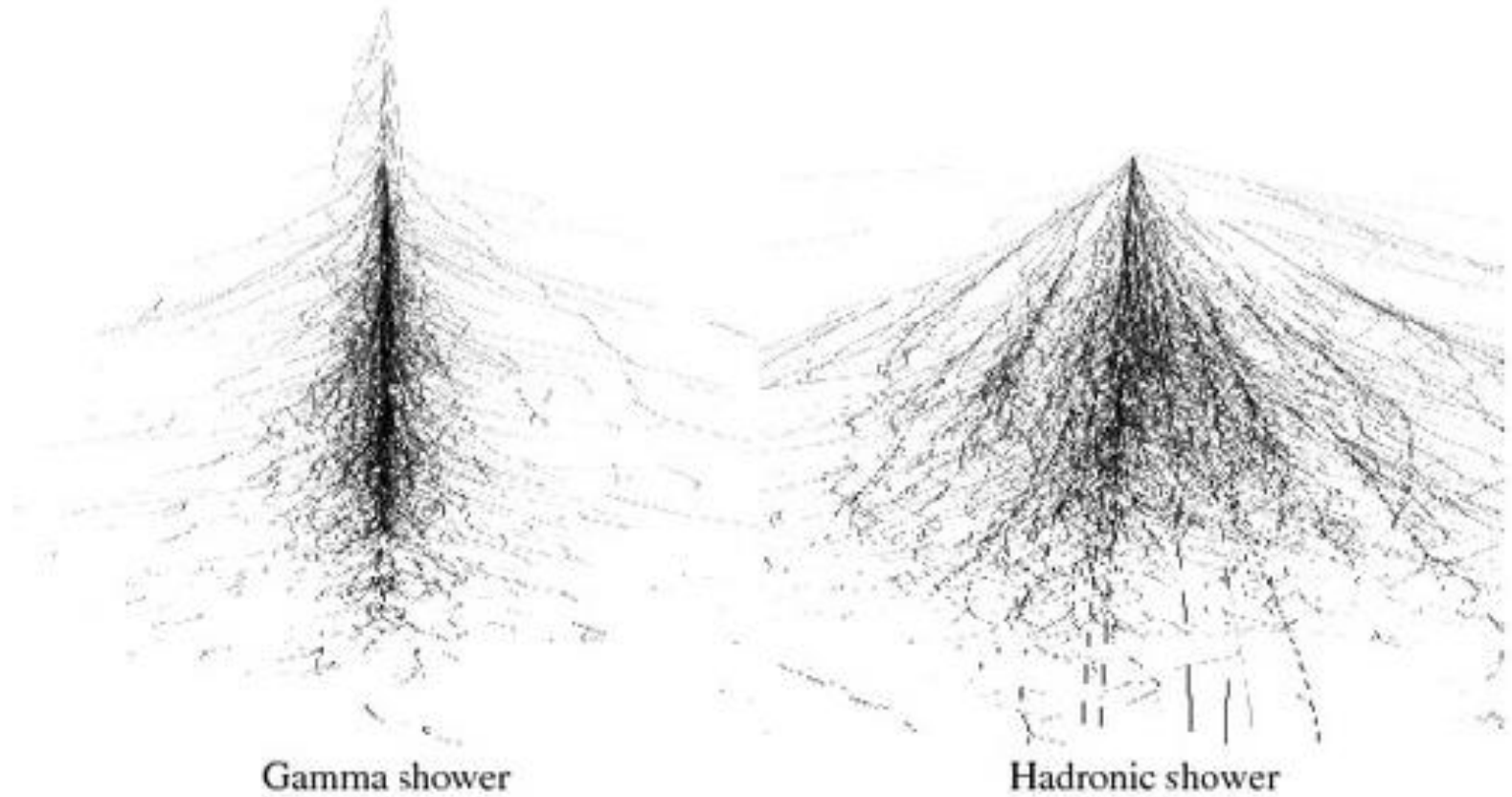
1.6 Les sources de particules cosmiques de haute énergie

1.6.1 Mécanisme d'accélération de Fermi

Critère L x B



1.7 Exemples de méthodes expérimentales au sol et dans l'espace

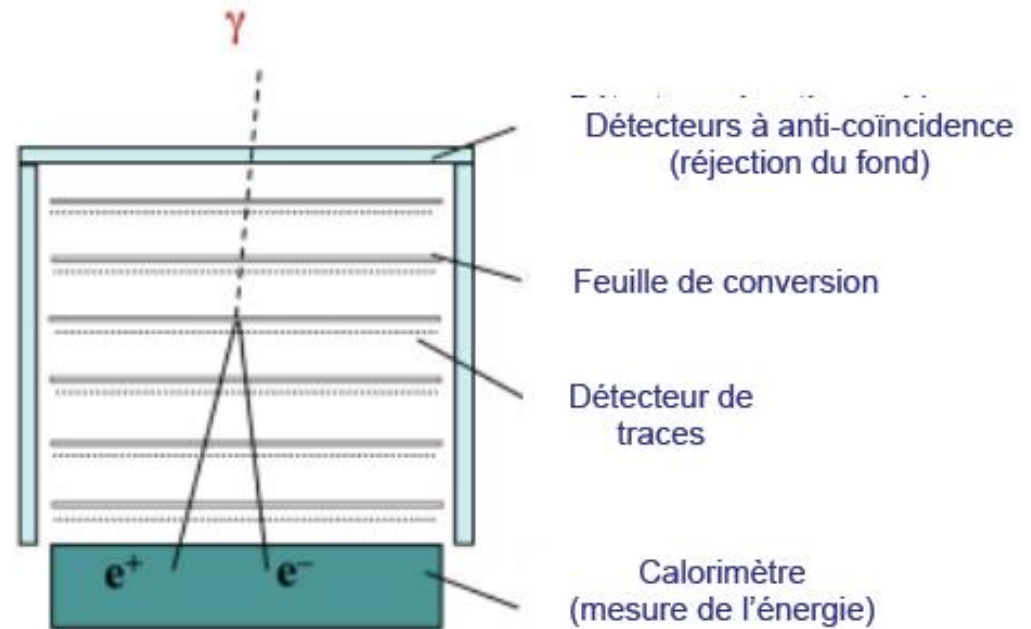
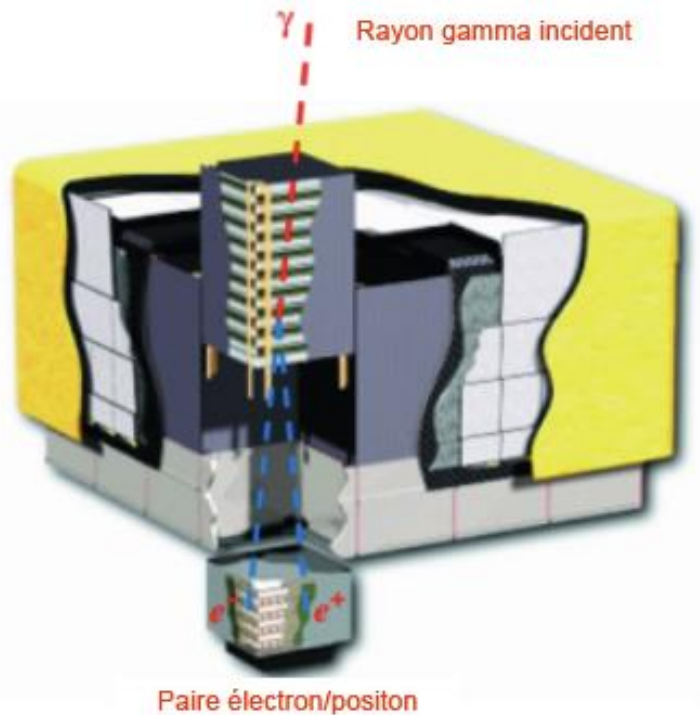


1.7.2 L'observatoire Pierre Auger

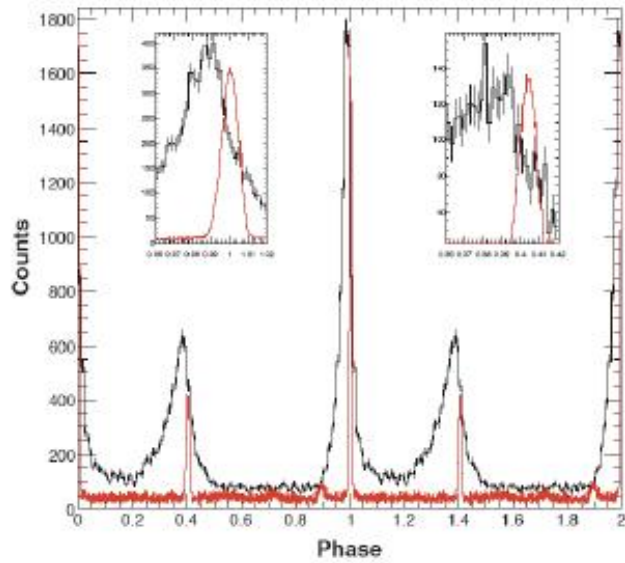


3000 km²
Dcuves = 1.5 km

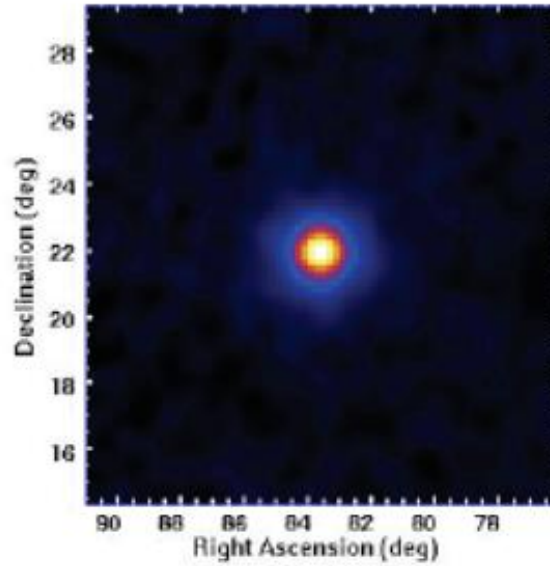
1.7.1 Le télescope spatial Fermi



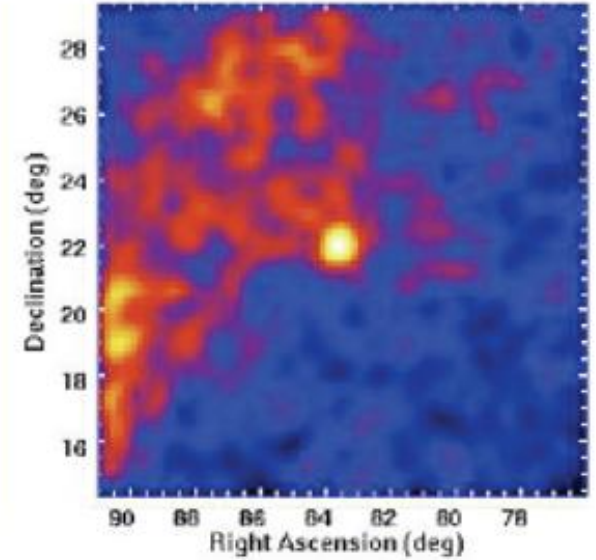
Pulsar du Crabe et sa nébuleuse



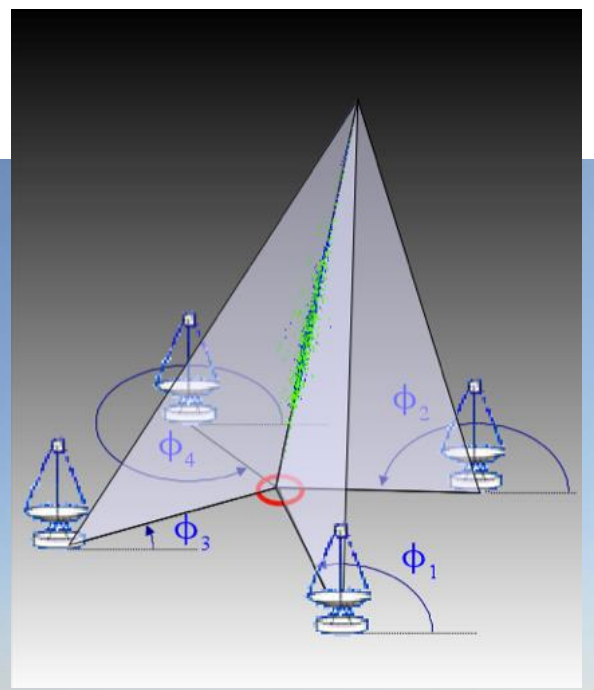
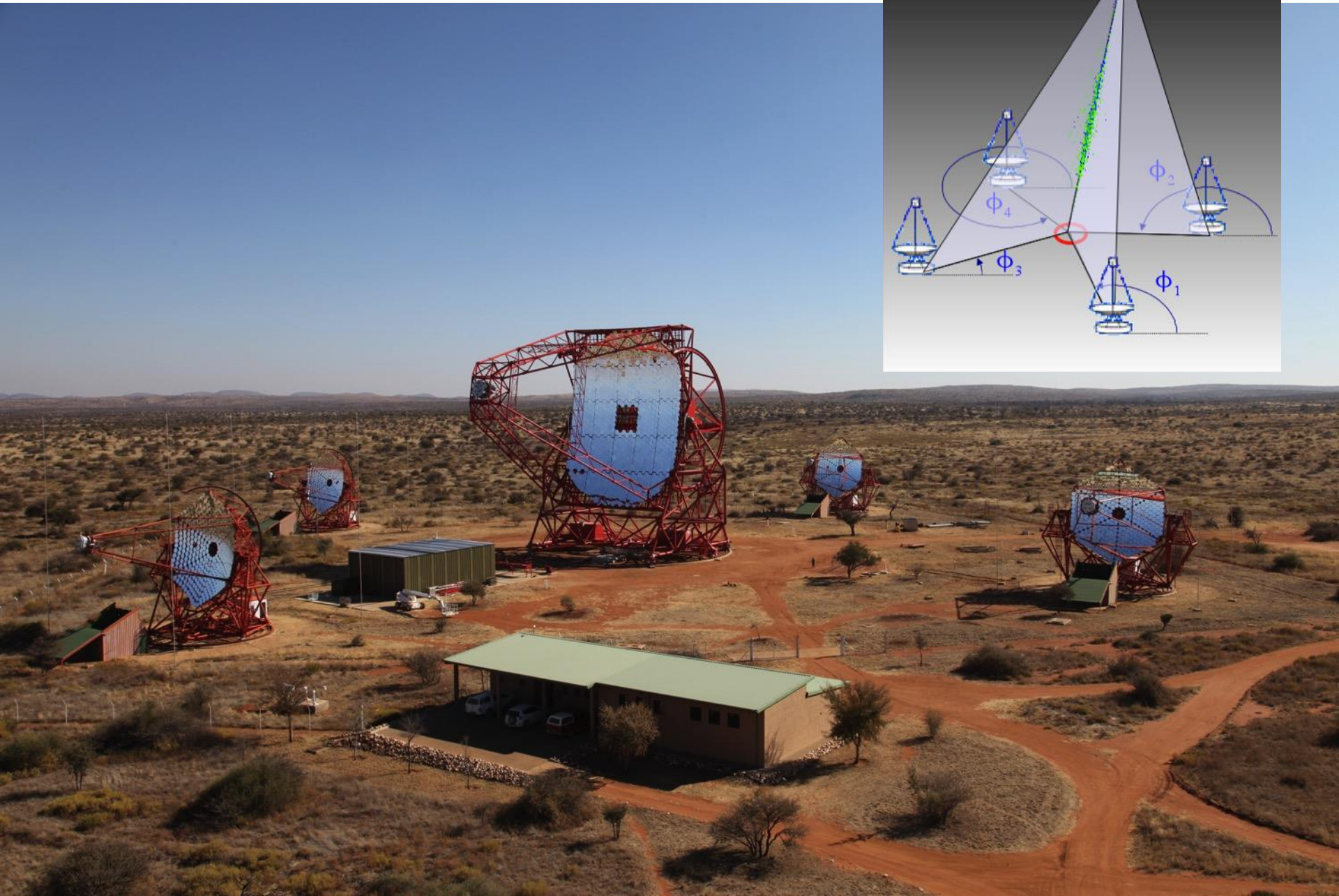
Radio
Fermi > 100 MeV

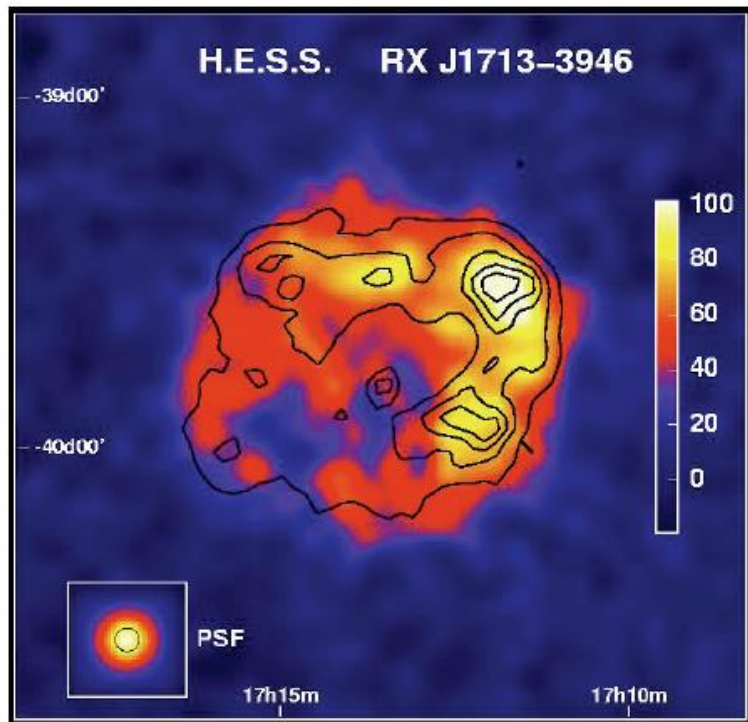


Fermi 300 MeV – 1 GeV
pulsée

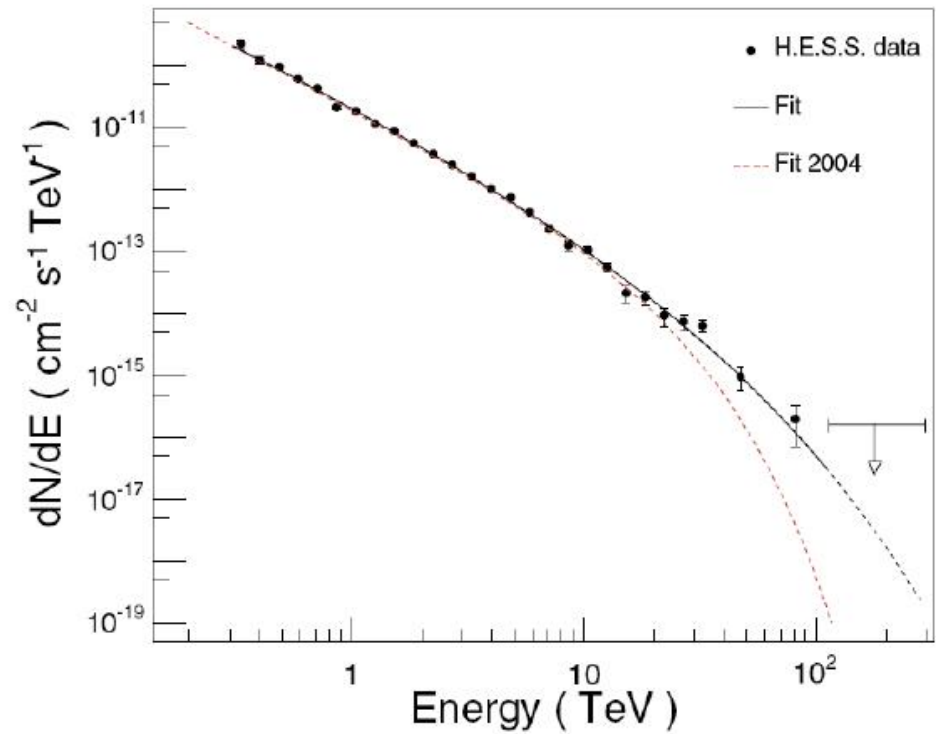


Fermi 300 MeV – 1 GeV
Non pulsée





HESS > 300 GeV



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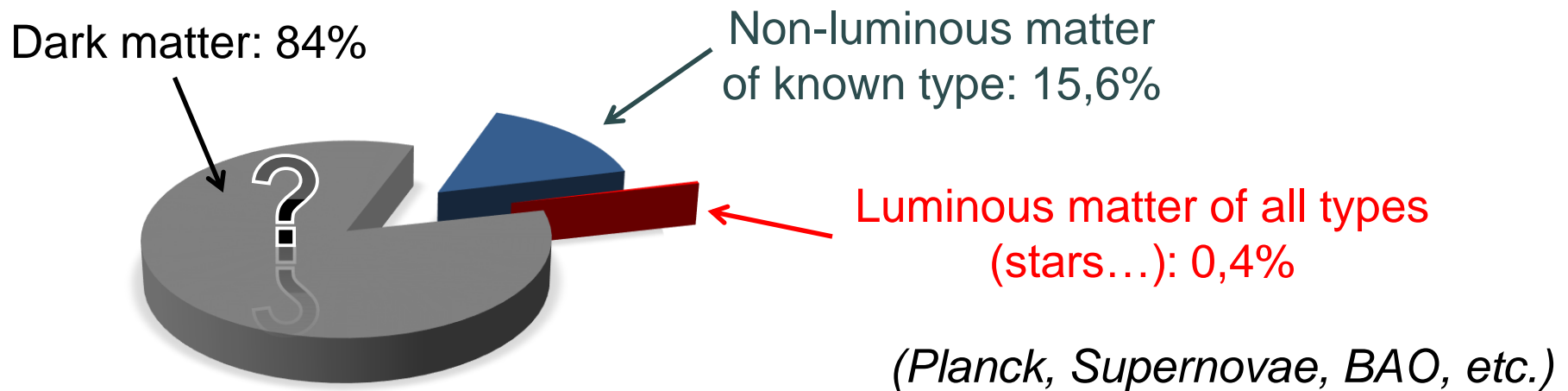
Polycopié disponible à

irfu.cea.fr/pisp/pierre.brun/astroparticules.pdf

2.1 Matière noire non-baryonique

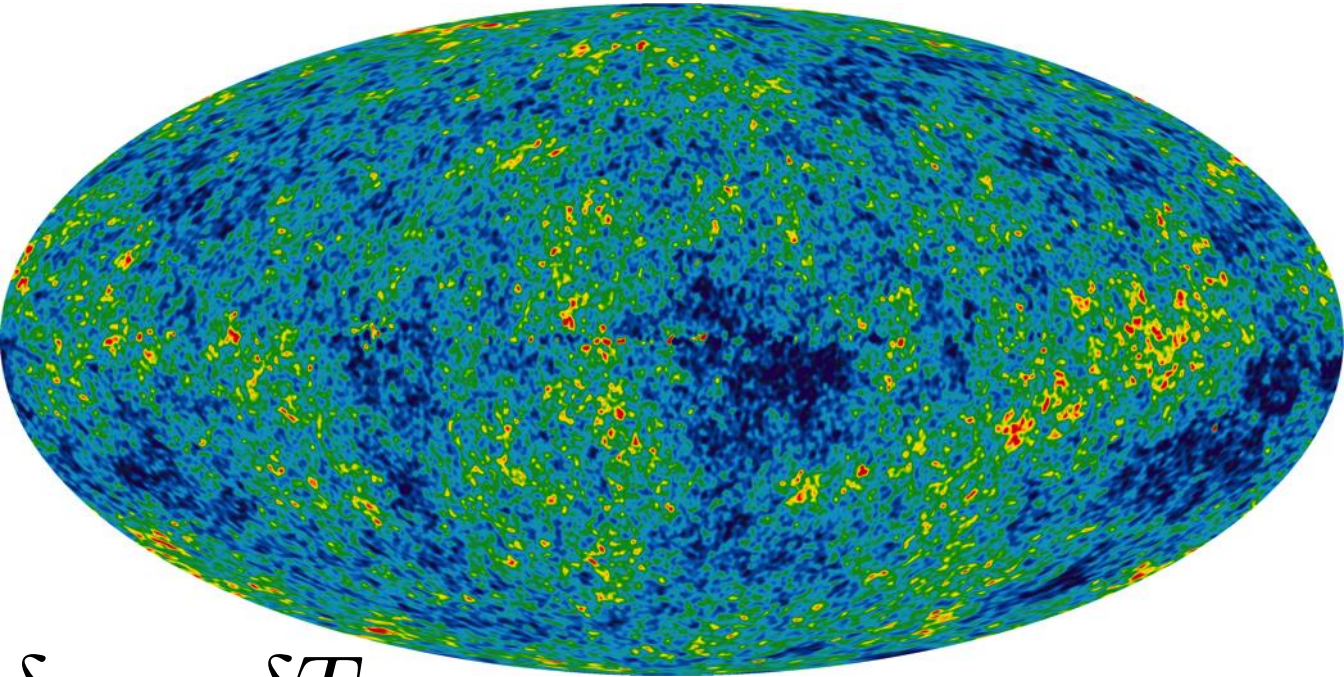
2.1.1 Introduction

84% de la masse de l'univers est de nature inconnue



Indices à toutes les échelles

- CMB : oscillations de densité
- Amas de galaxies: champs de vitesse
- Galaxies : courbes de rotation
- Satellites de la Voie Lactée



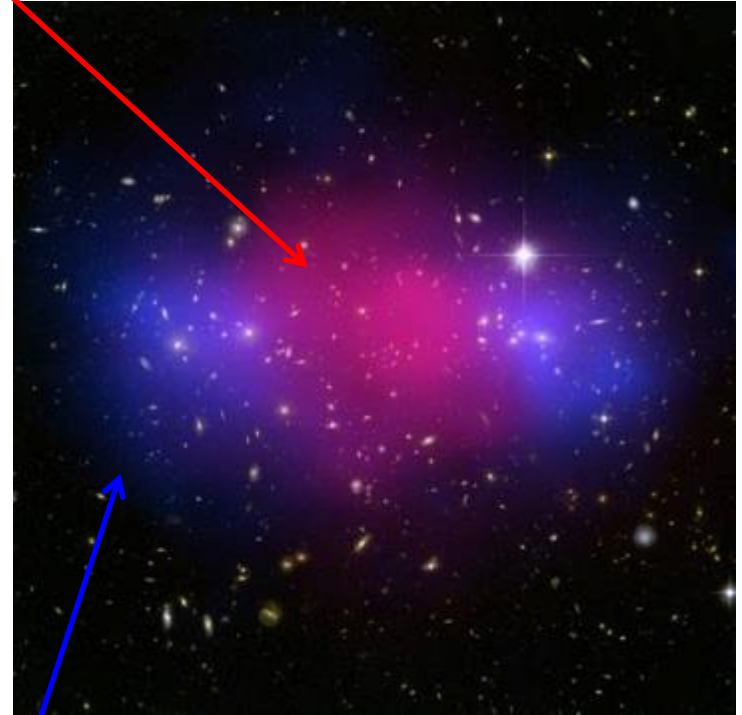
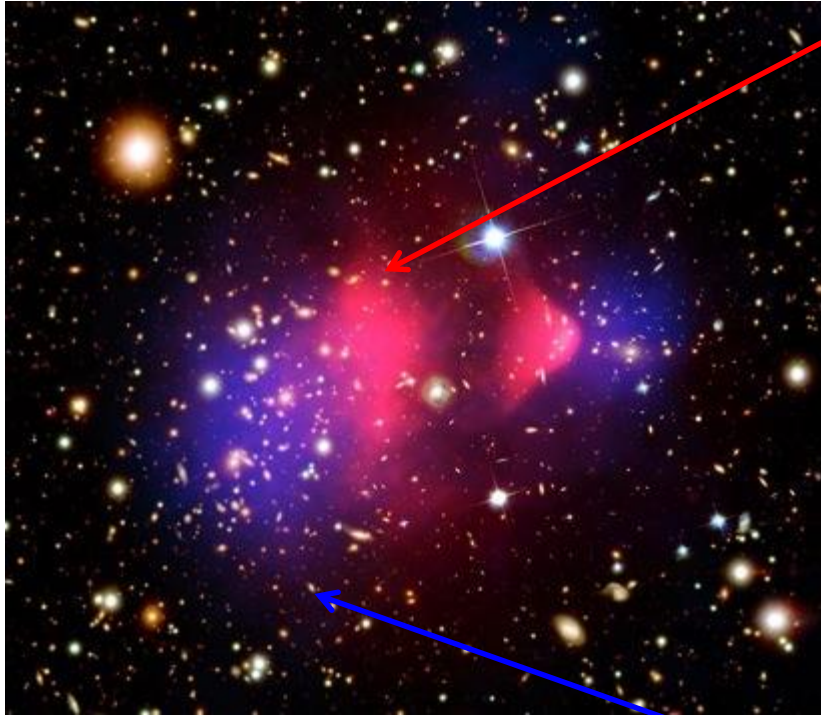
$$\frac{\delta\rho}{\rho} = \frac{\delta T}{T} \simeq 10^{-5}$$

$$\frac{\delta\rho}{\rho} \gg 1$$





Gaz chaud (rayons X)



MACS J0025.4-1222

Masse
(déformation de l'arrière plan)

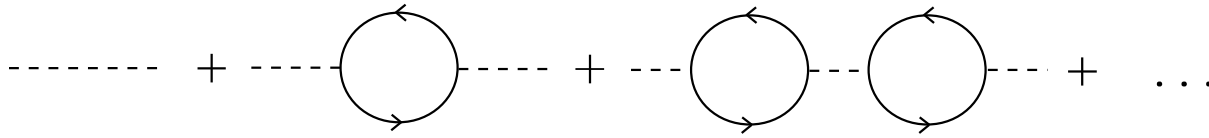
2.1.3 Extensions du modèle standard

Échelle de Planck

Le problème de la hiérarchie des échelles

$$M_{\text{Planck}} = \sqrt{\frac{\hbar c}{g}} = 1.22 \times 10^{19} \text{ GeV}/c^2$$

$$E_{EW} \simeq 100 \text{ GeV}$$



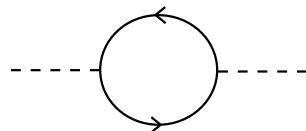
$$\left(\frac{1}{k^2 - m^2} \right)$$

$$\propto \frac{1}{k^2 - m^2} + \frac{1}{k^2 - m^2} \xi \frac{1}{k^2 - m^2} + \frac{1}{k^2 - m^2} \xi \frac{1}{k^2 - m^2} \xi \frac{1}{k^2 - m^2} + \dots$$

$$= \frac{1}{k^2 - m^2} \sum_{n=0}^{\infty} \left(\xi \frac{1}{k^2 - m^2} \right)^n$$

$$= \frac{1}{k^2 - m^2} \frac{1}{1 - \xi \frac{1}{k^2 - m^2}} = \frac{1}{k^2 - m^2 + \xi}$$

$$\left(\frac{1}{k^2 - m^2} \right)_{\text{effectif}} = \frac{1}{k^2 - m^2 + \xi}$$



A Feynman diagram showing a tadpole loop. It consists of a central circle with two arrows indicating a clockwise direction. Two dashed lines extend horizontally from the left and right sides of the circle, representing external legs.

$$\xi \sim \int_0^\Lambda d^4 k f(k)$$

Spin 1 : $\xi \propto \ln \Lambda$

Spin 0 : $\xi \propto \Lambda^2$

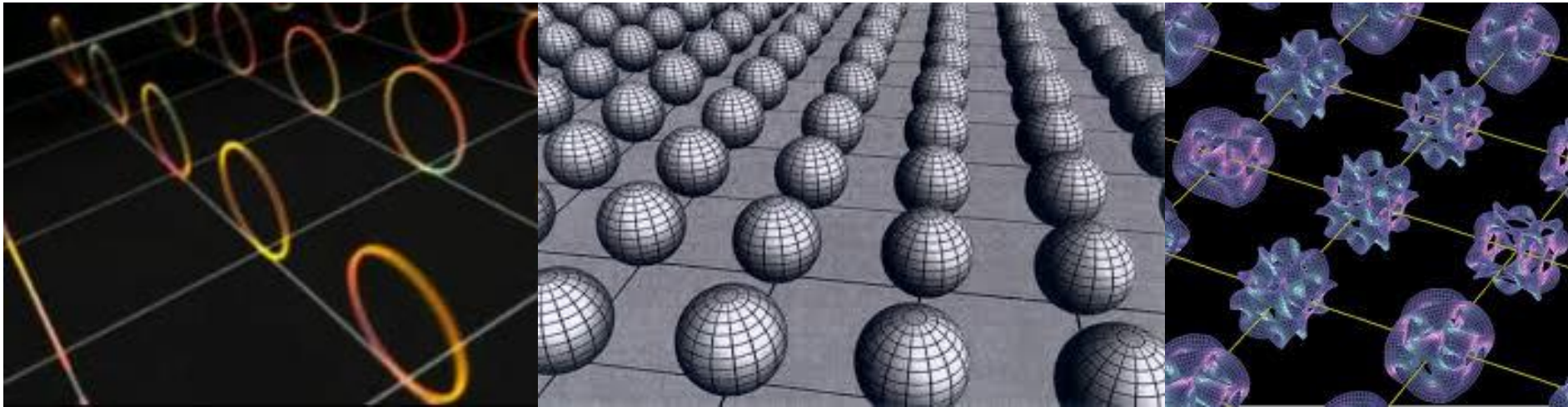
- Ajustement très fin des paramètres MS
- Le boson de Higgs n'est pas scalaire/élémentaire
- Nouvelles particules/interactions au \sim TeV
- Échelle M_{planck} non fondamentale

Supersymétrie : symétrie boson-fermion

$$\delta m_b^2 = -\delta m_f^2$$

Nouvelles particules dont
potentiellement la matière noire

Petites dimensions supplémentaires



$$ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu + h_{ij}(y) dy^i dy^j$$

$$M_{\text{Planck}}^2 = V_\delta M_D^{2+\delta}$$

$$\partial_t^2 \psi - \partial_x^2 \psi + m^2 \psi = 0$$

$$\psi(x, t) = \psi_0 \exp(-i(Et - px))$$

$$\Rightarrow E^2 - \vec{p}^2 = m^2$$

Exemple : Une petite dimension supplémentaire sur un cercle de rayon R

$$\partial_t^2 \psi - \partial_x^2 \psi - \frac{\partial^2 \psi}{\partial \epsilon^2} + m^2 \psi = 0$$

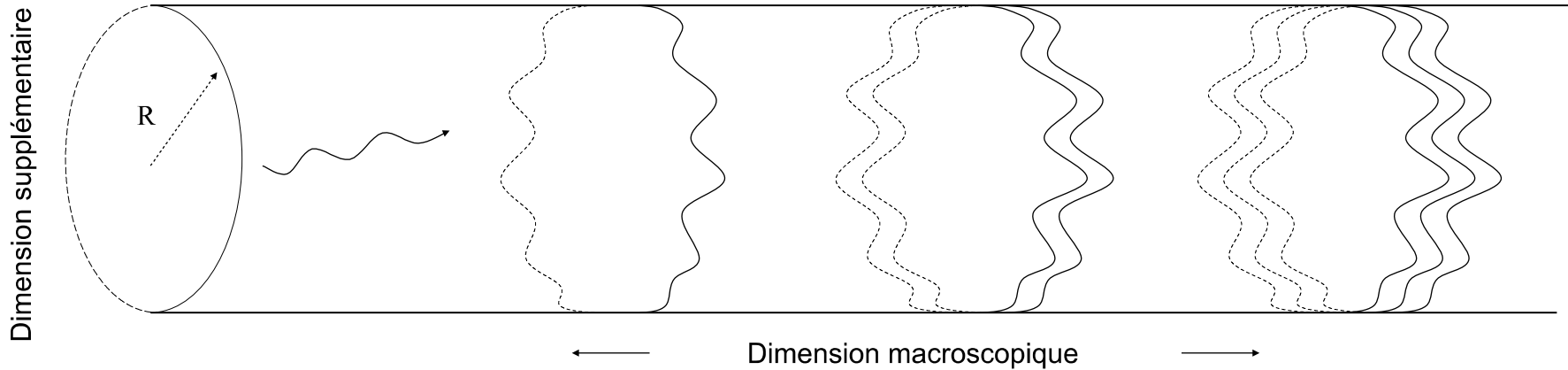
$$\psi(x, t) = \psi_0 e^{-i(Et - px)} \times \exp\left(i \frac{2\pi n}{R} \epsilon\right)$$

$$E^2 - \vec{p}^2 - \left(\frac{2\pi n}{R}\right)^2 = m^2$$

$$E^2 - \vec{p}^2 = m^2 + \left(\frac{2\pi n}{R}\right)^2$$

Dimensions supplémentaires

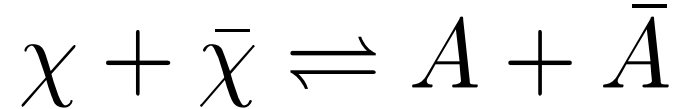
Nombre d'enroulements	$n =$	0	1	2	3
Désignation		B	$B^{(1)}$	$B^{(2)}$	$B^{(3)}$
Masse		m_0	$m_{(1)}^2 = m_0^2 + (R^{-1})^2$	$m_{(2)}^2 = m_0^2 + 4 (R^{-1})^2$	$m_{(3)}^2 = m_0^2 + 9 (R^{-1})^2$



2.1.2 Etablissement de la densité relique dans l'Univers primordial

Densité de particules de matière noire

- Dans le plasma primordial, l'équilibre s'établit par



- A haute température (petit temps)

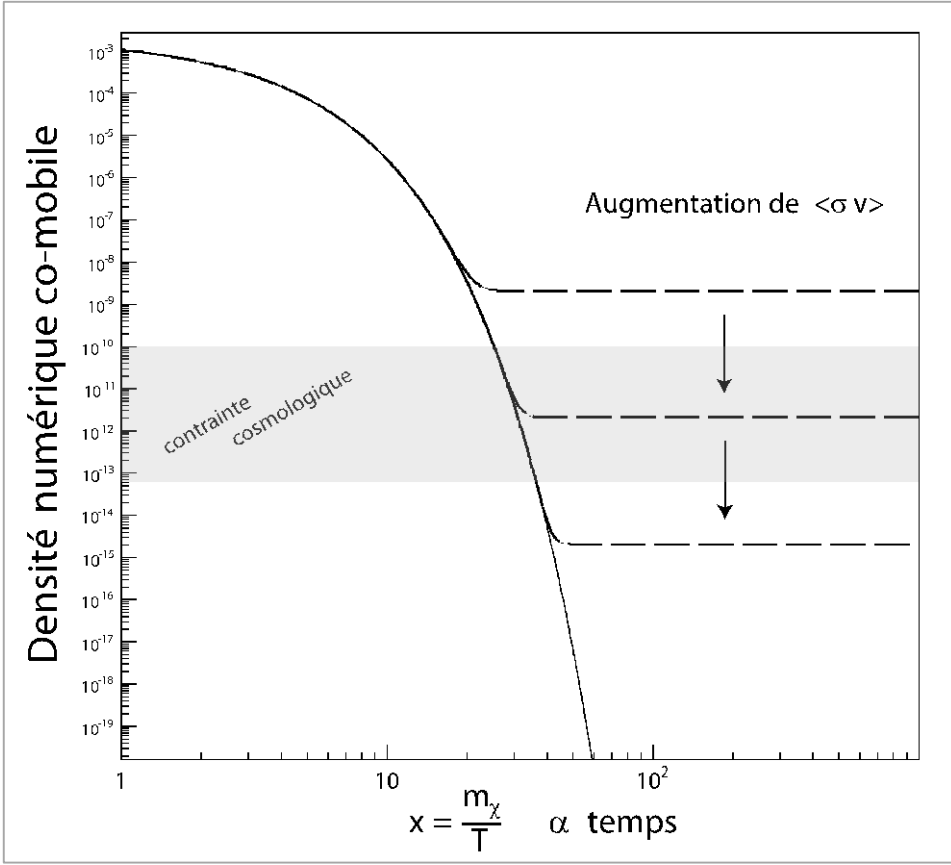
$$n_{\chi}^{\text{eq}} \propto n_{\gamma} \propto T^4$$

- Puis l'expansion dilue tout

$$\chi + \bar{\chi} \rightleftharpoons A + \bar{A} \quad n_{\chi}^{\text{eq}} \propto (m_{\chi} T)^{3/2} \times \exp\left(-\frac{m_{\chi} c^2}{kT}\right)$$

Départ de l'équilibre thermodynamique

$$\frac{dn_\chi}{dt} = -3H n_\chi - \langle \sigma v \rangle \{ (n_\chi)^2 - (n_\chi^{\text{eq}})^2 \}$$



$$\langle \sigma v \rangle h^2 = \frac{3 \rightarrow 10^{-27} \text{ cm}^3/\text{s}}{h^2 v i}$$

Typical weak interaction values:

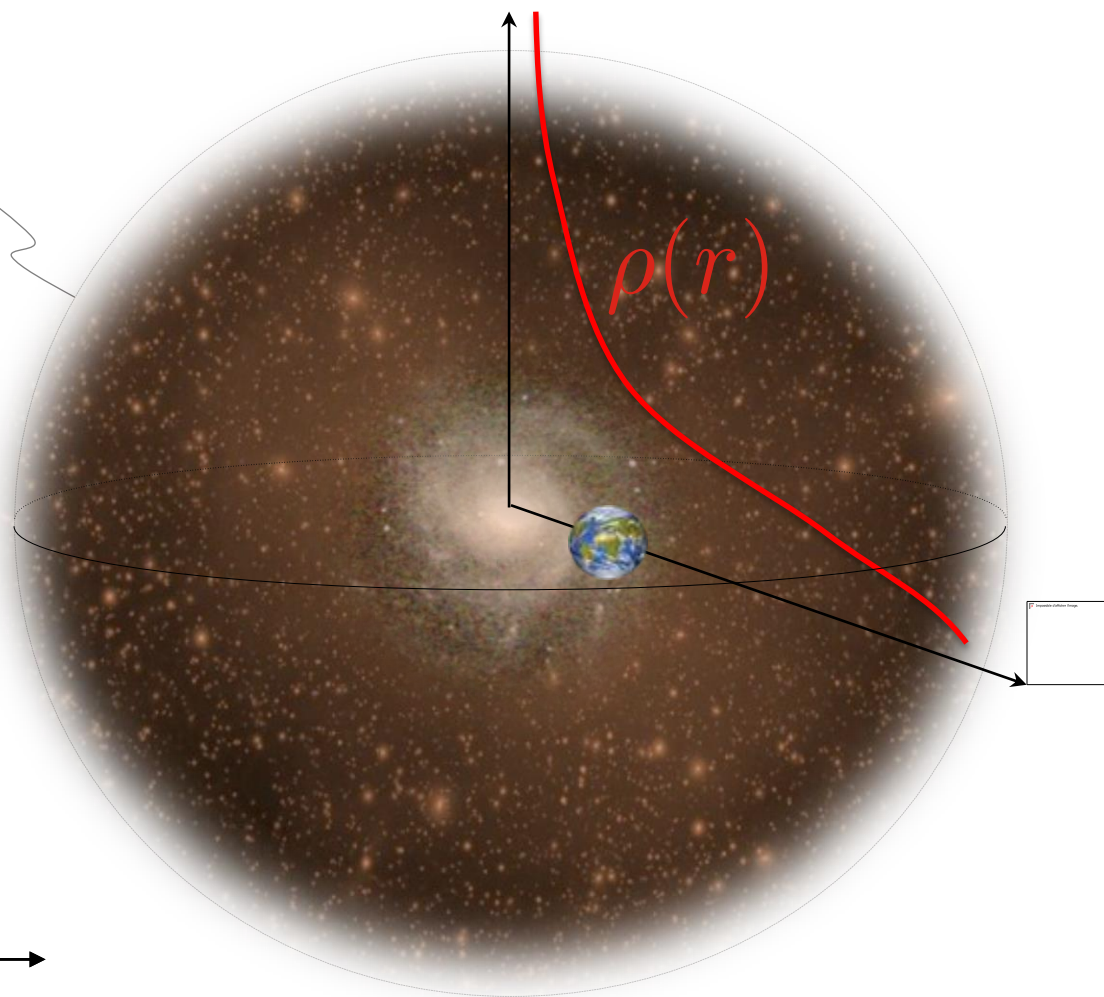
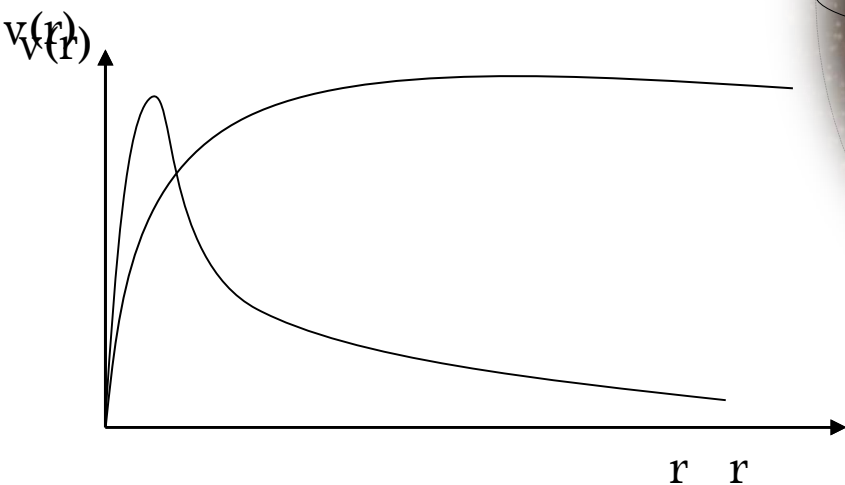
$$h^2 v i \leftarrow \frac{g^2}{(500 \text{ GeV}/c^2)^2} \rightarrow \sim^2/c = 5 \rightarrow 10^{-26} \text{ cm}^{-3}/\text{s}$$

$$\Downarrow$$

$$\langle \sigma v \rangle h^2 \leftarrow 0.0\epsilon$$

Measured: $\langle \sigma v \rangle_{\text{DM}} h^2 = 0.11$
 $= !!!$

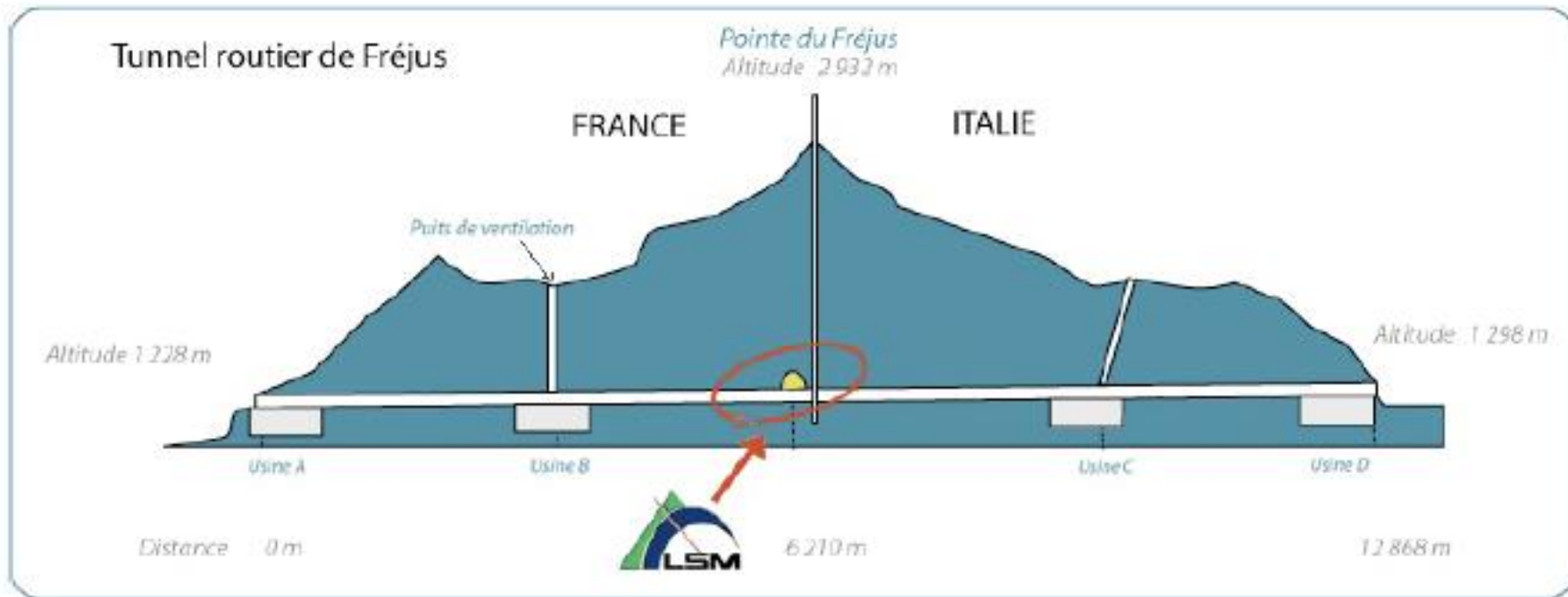
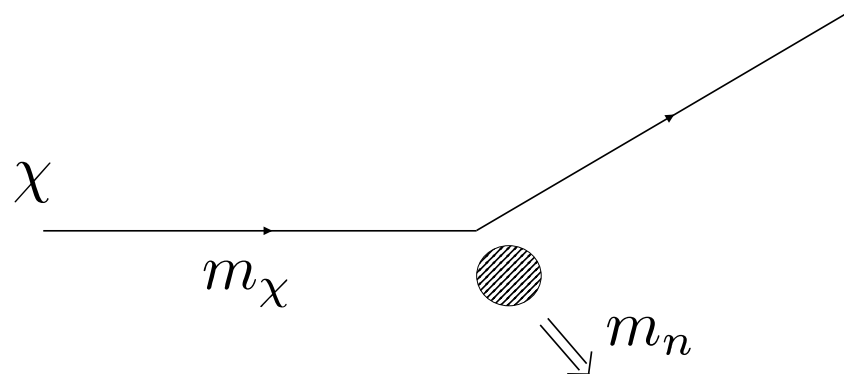
Halo de matière
noire
sphérique
10x plus étendu

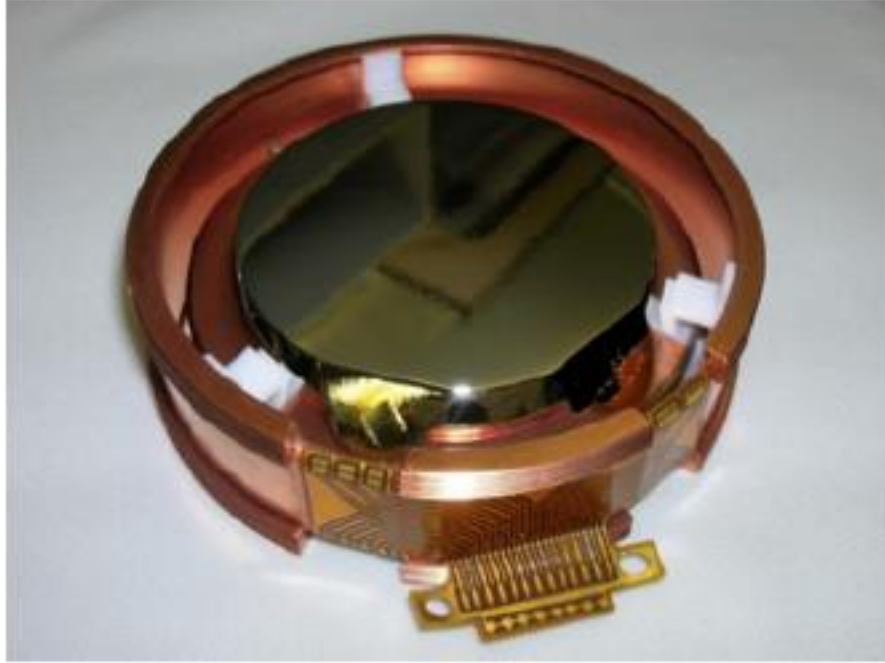


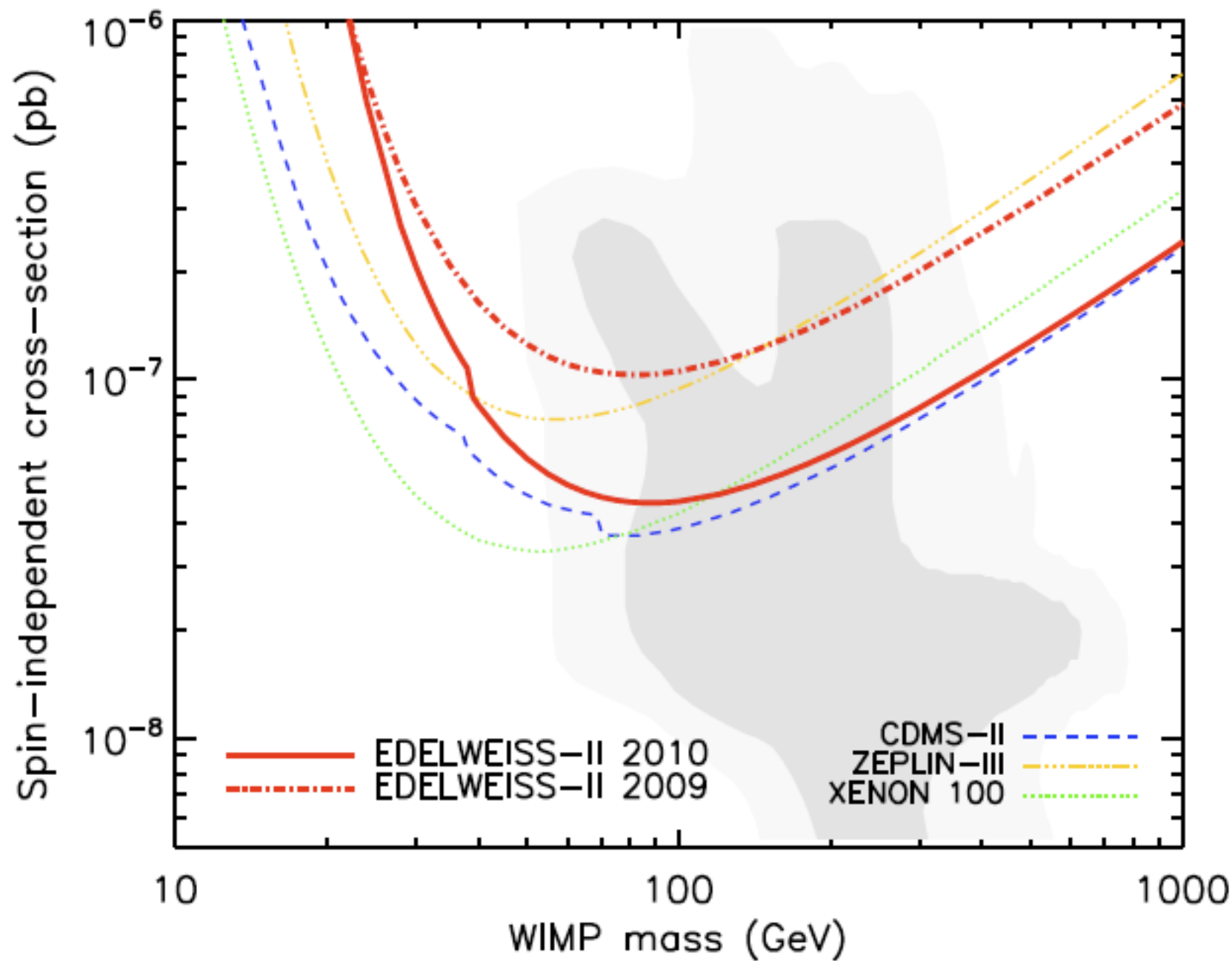
300 kpc

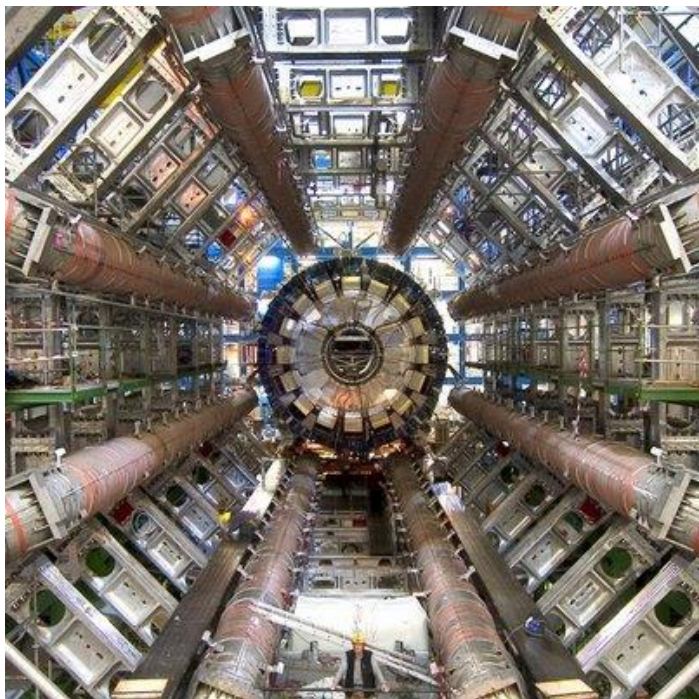
2.1.4 Recherches expérimentales de WIMPs

Recherche directe









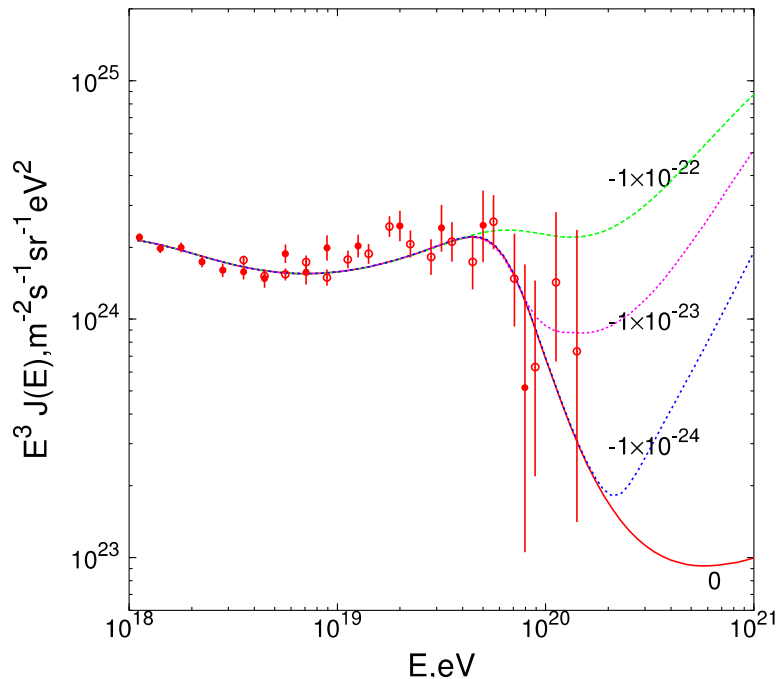
2.2 Recherches de brisures de l'invariance de Lorentz

$$E^2 - p^2 c^2 = m_0^2 c^4 \quad \rightarrow \quad E^2 - p^2 c^2 = m_0^2 c^4 + \xi f(p^2)$$

2.2.1 Modification du seuil GZK

$$E_p > \frac{m_\Delta^2 c^4 - m_p^2 c^4}{4E_\gamma}$$

Protons : $E_p^2 - p^2 c^2 = m_p^2 c^4 + \xi E_p^2$ $E_p > \frac{m_\Delta^2 c^4 - m_p^2 c^4 + \xi E_p^2}{4E_\gamma}$

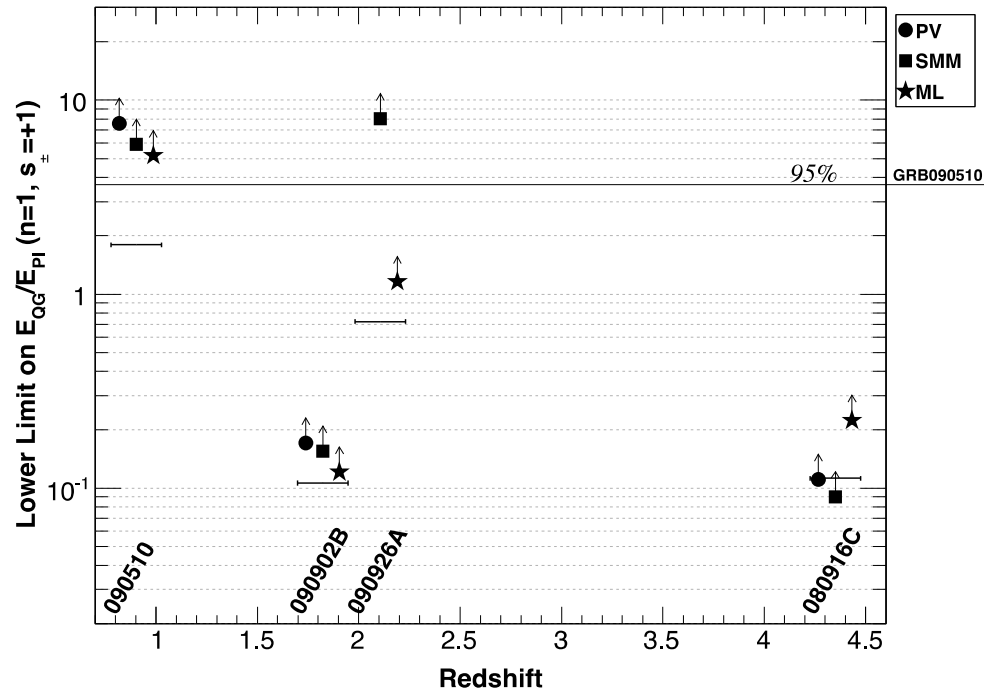


2.2.2 Anomalies temporelles en astronomie gamma

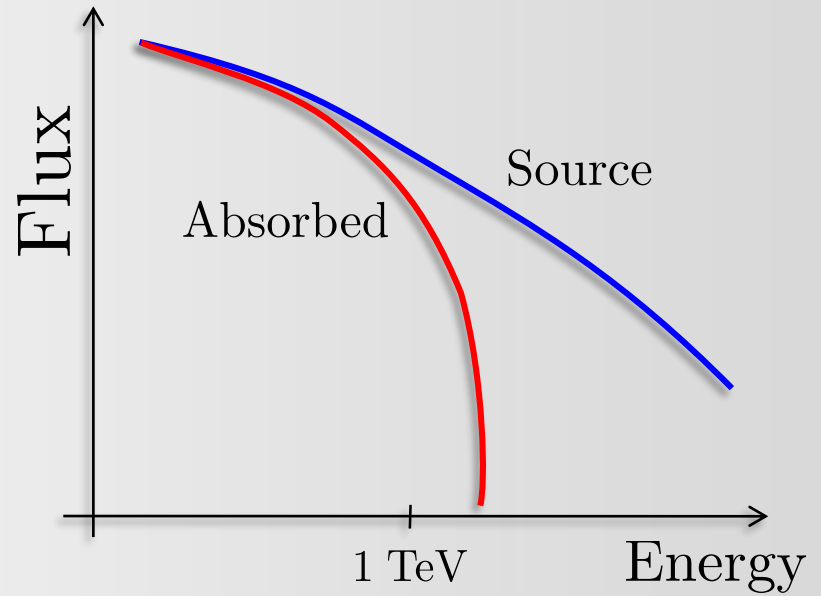
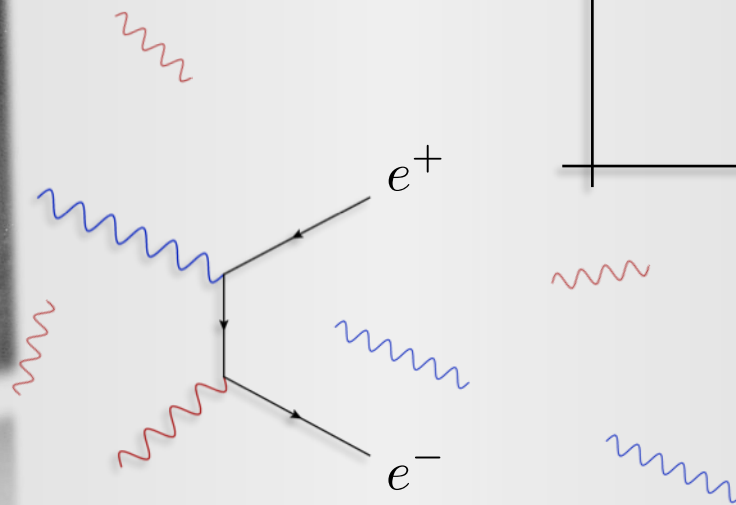
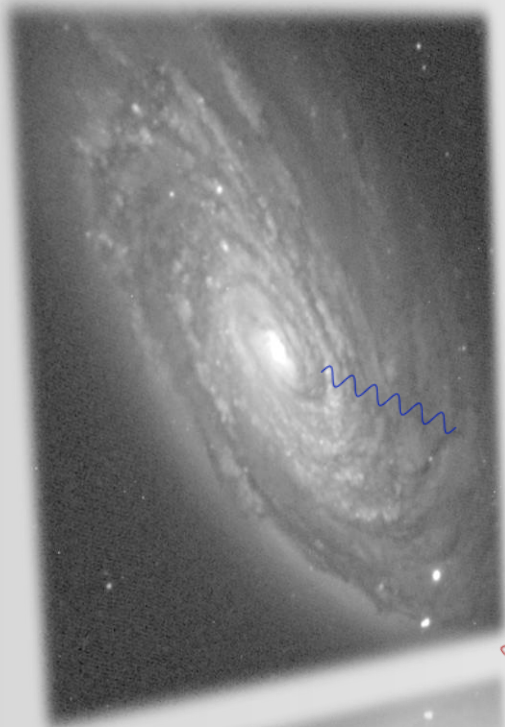
$$E^2 - p^2 c^2 = \pm p^2 c^2 \times \frac{pc}{\Lambda}$$

$$v = c \times \left(1 \pm \frac{3E}{2\Lambda} \right)$$

$$\Delta t \propto \frac{\Delta E}{\Lambda} \times \frac{1}{H_0} \int_0^{z_s} dz \frac{1+z}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}}$$



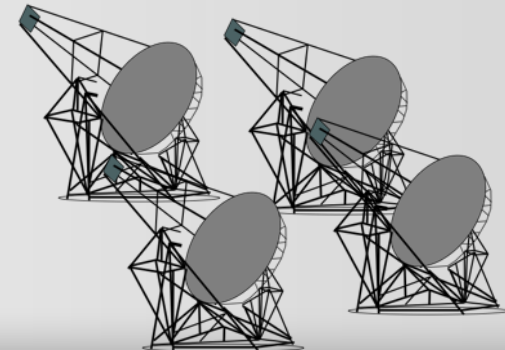
RAYS



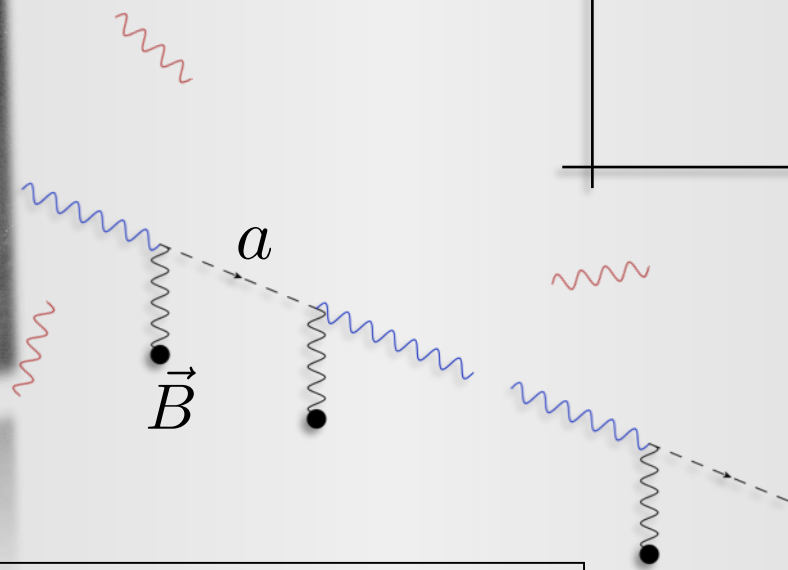
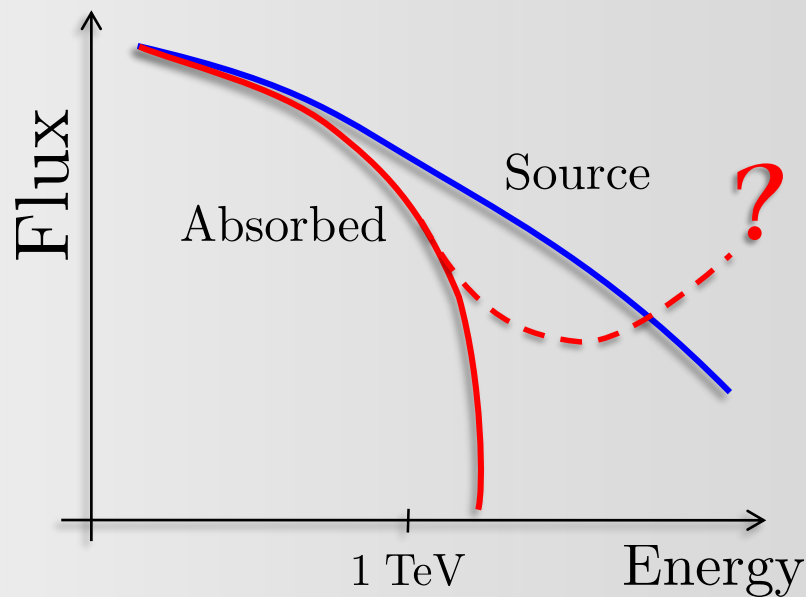
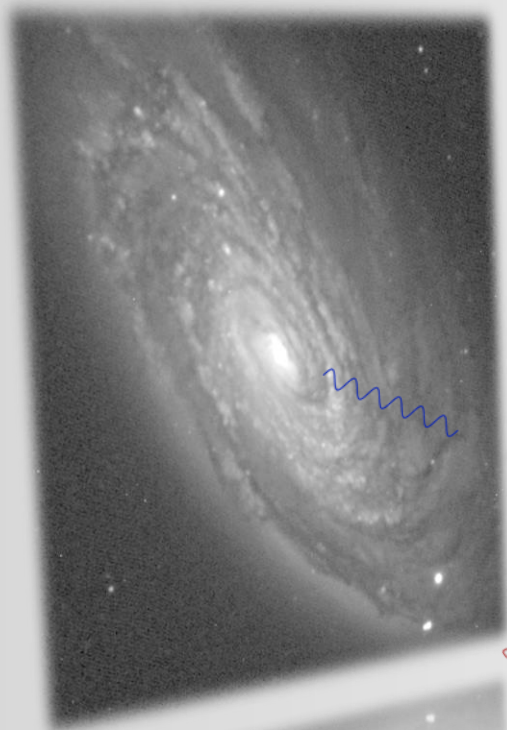
Pair production induce a gamma-ray horizon

$$z \simeq 0.1 \text{ at } E \simeq 1 \text{ TeV}$$

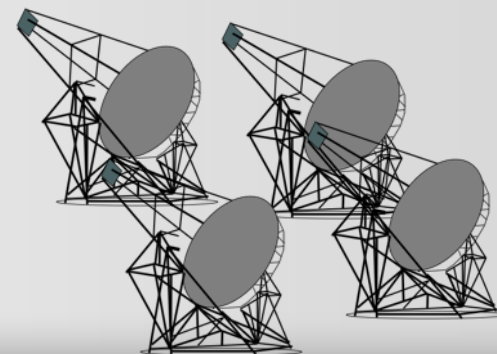
at



RAYS

 γ 

Light ALPs ($m_a \sim \text{neV}$) with $g \sim 10^{-11} \text{ GeV}^{-1}$ could do the job



$$\begin{pmatrix} E - i\partial_z - i\frac{\tau}{2z} & \Delta_B \\ \Delta_B & E - i\partial_z + \Delta_a \end{pmatrix} \begin{pmatrix} A \\ a \end{pmatrix} = 0$$

