

Des Particules au Cosmos

Introduction à la Physique des Astroparticules

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Contenu du cours

★ Cours 1 : messagers cosmiques

- Particules cosmiques au niveau du sol, en haute atmosphère
- Provenances et horizons
- Détection

★ Cours 2 : physique des particules *in vivo*

- Matière noire non-baryonique
- Brisure de l'invariance de Lorentz

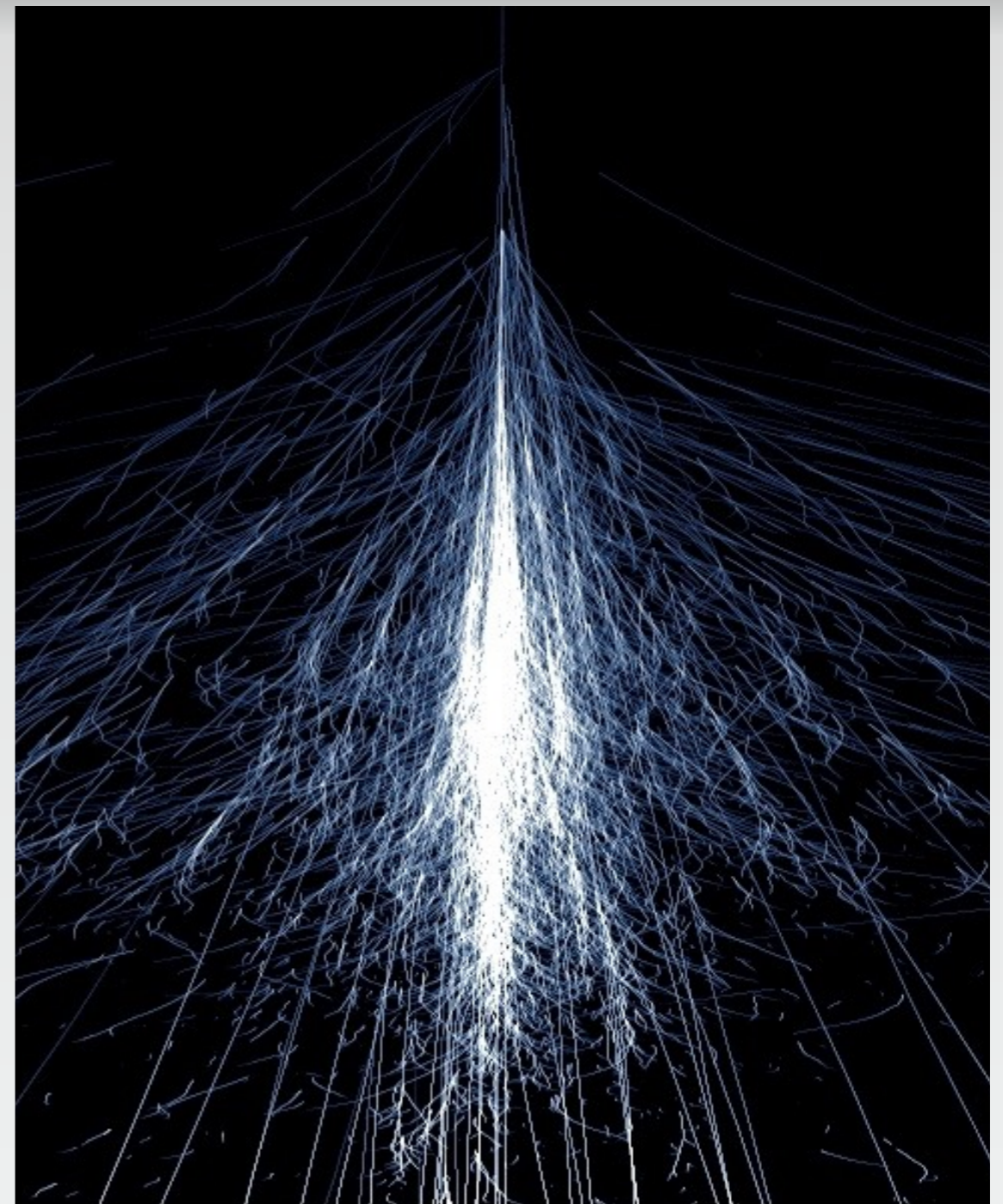
$$E^2 - \vec{p}^2 c^2 = m^2 c^4$$

$$\hbar = c = 1 \quad E^2 - \vec{p}^2 = m^2$$

Cascades atmosphériques

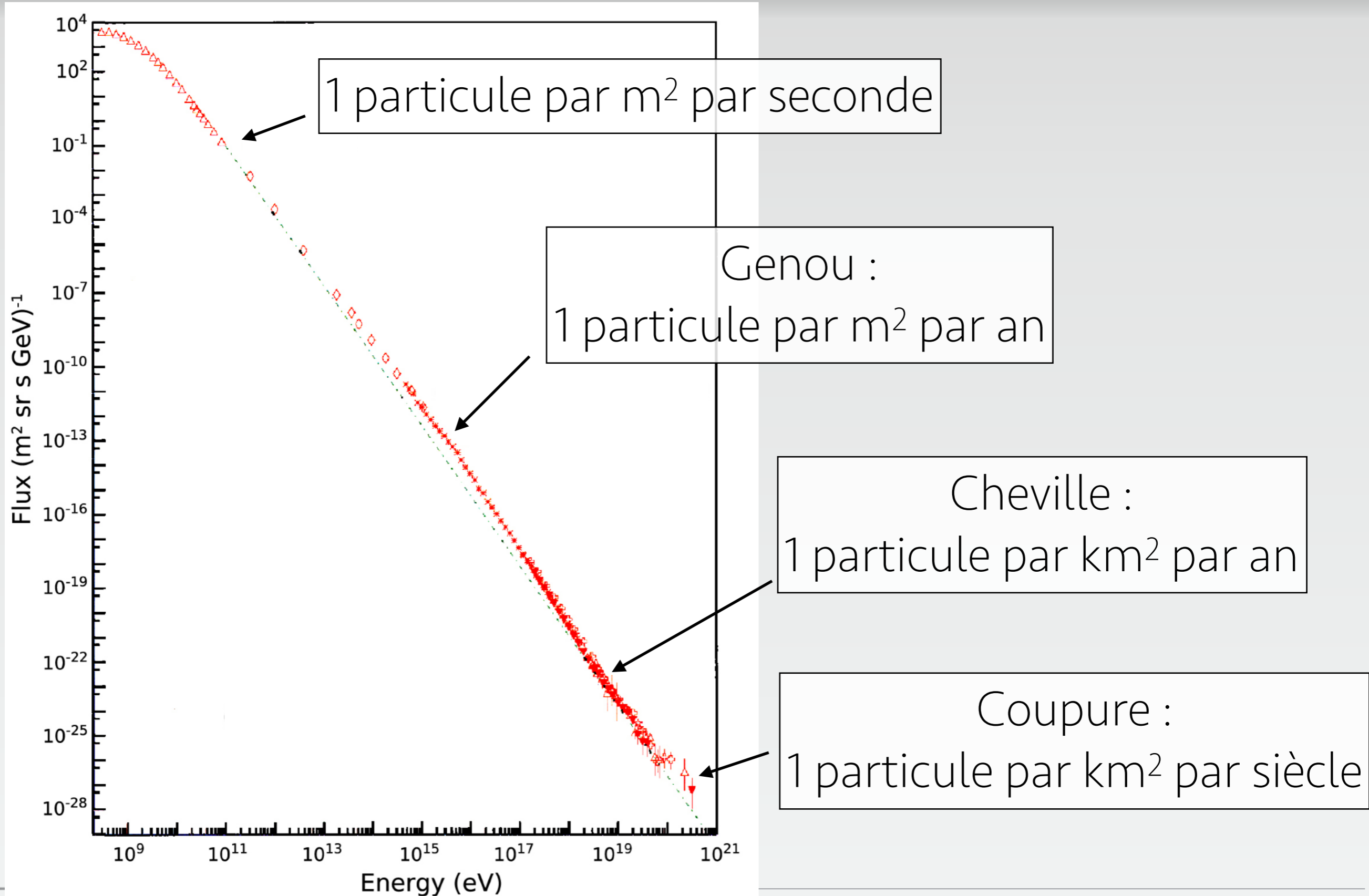


Photon ou électron

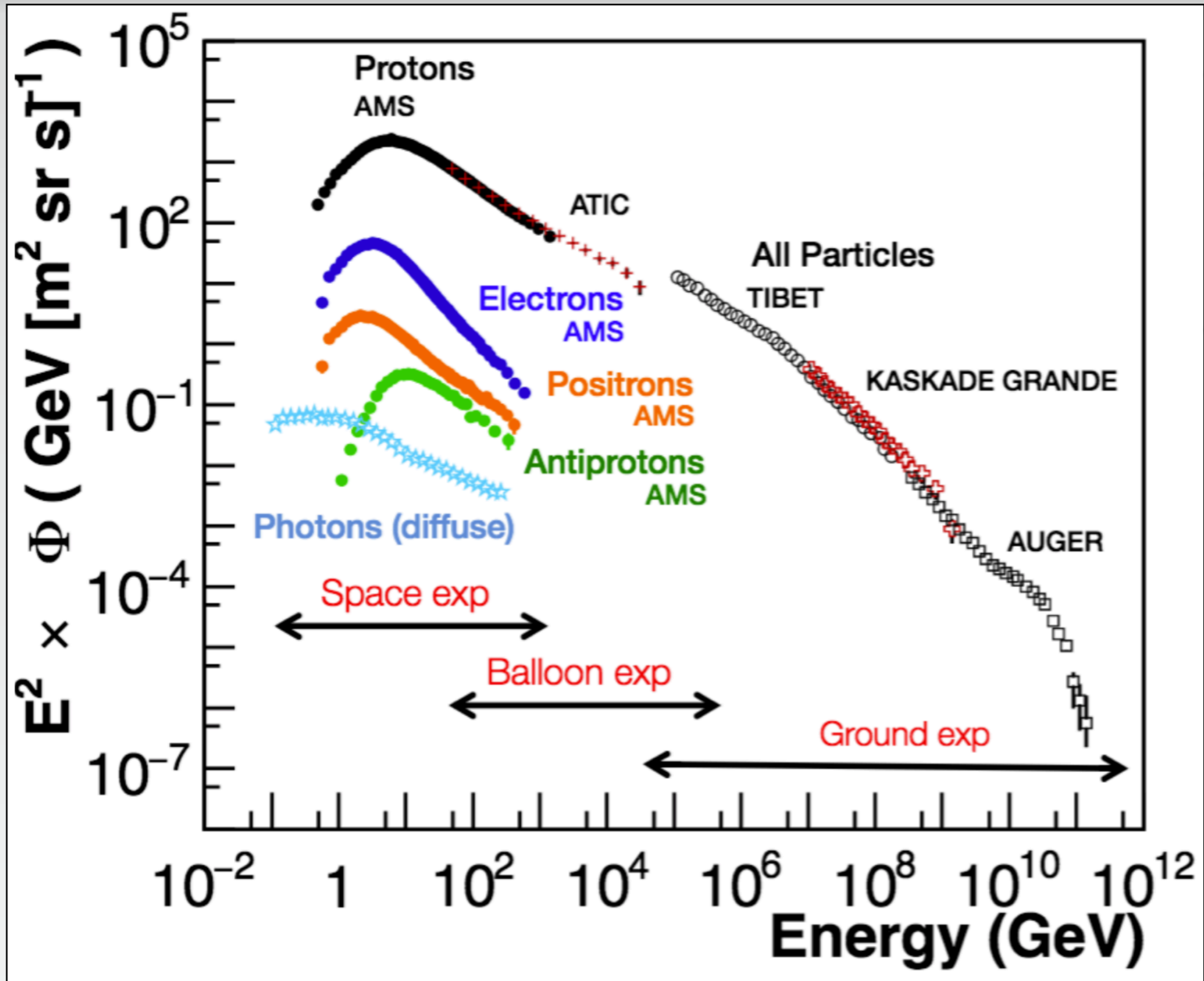


Proton

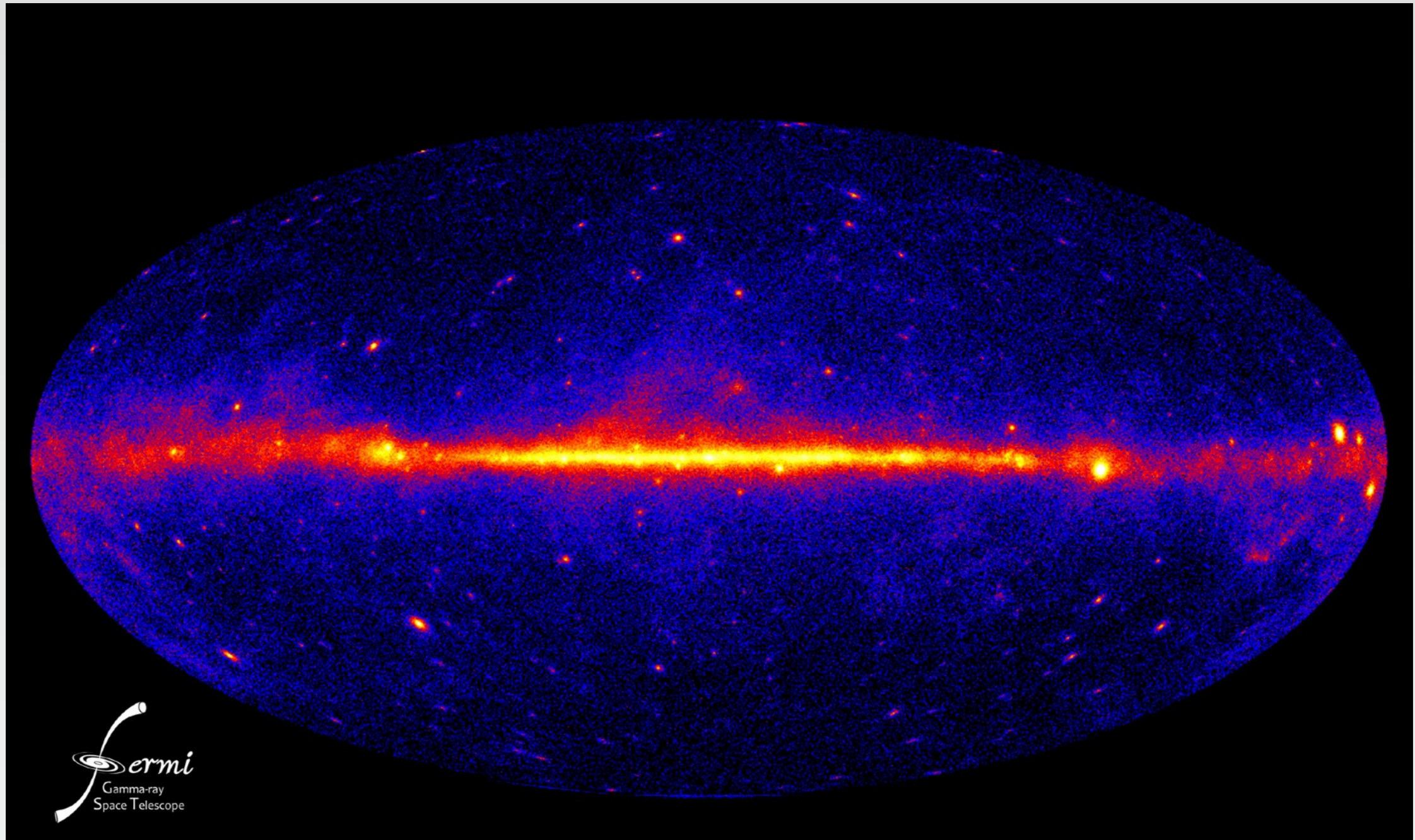
Flux de particules chargées



Composition



Composante neutre



Ciel Gamma vu par Fermi-LAT ($> \text{GeV}$)

Provenance des particules chargées

Protons

Confinement dans la Galaxie :

Rayon de Larmor :

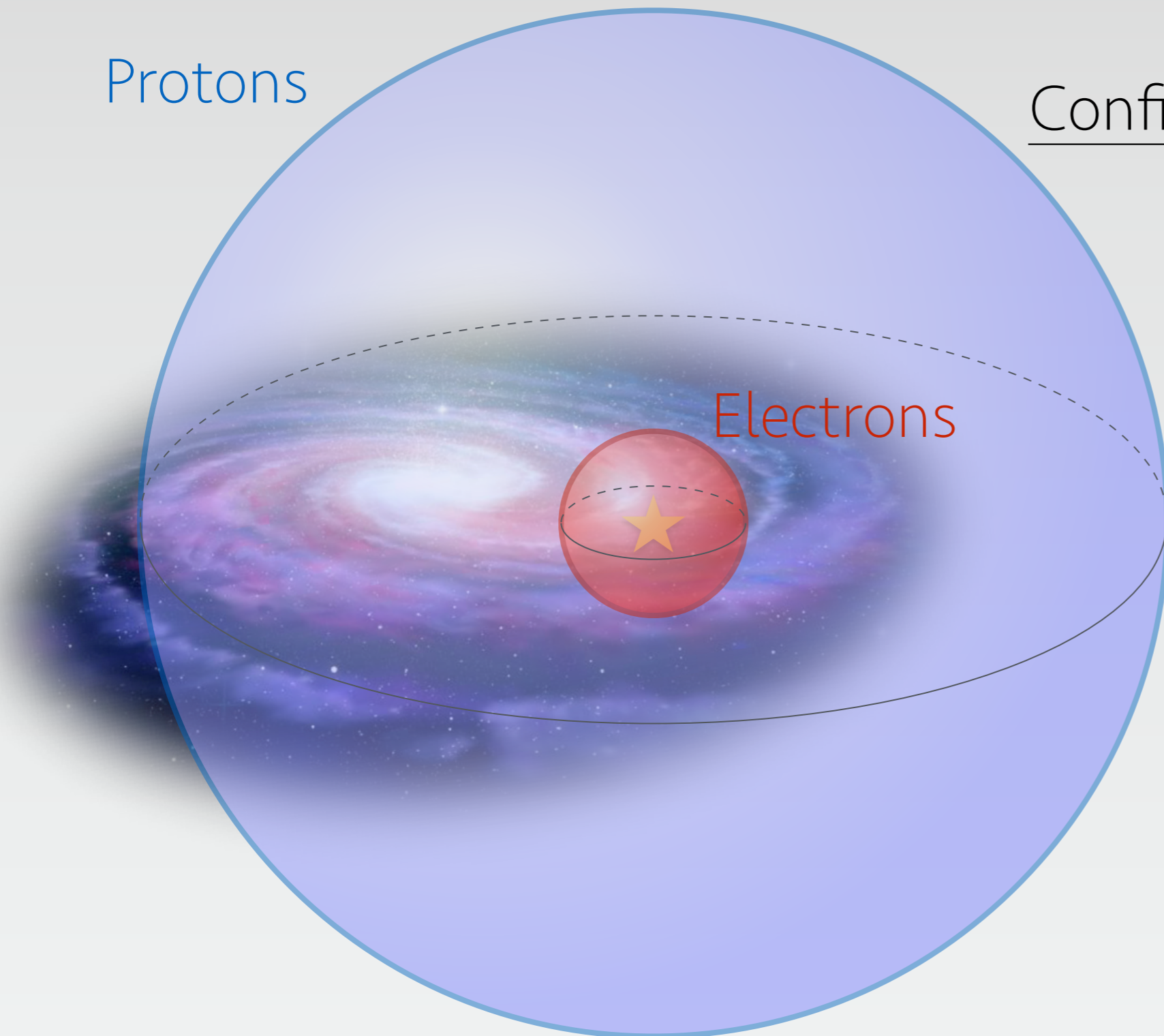
$$R = \frac{mc}{qB} \sqrt{\left(\frac{E}{mc^2}\right)^2 - 1}$$

Limite de confinement

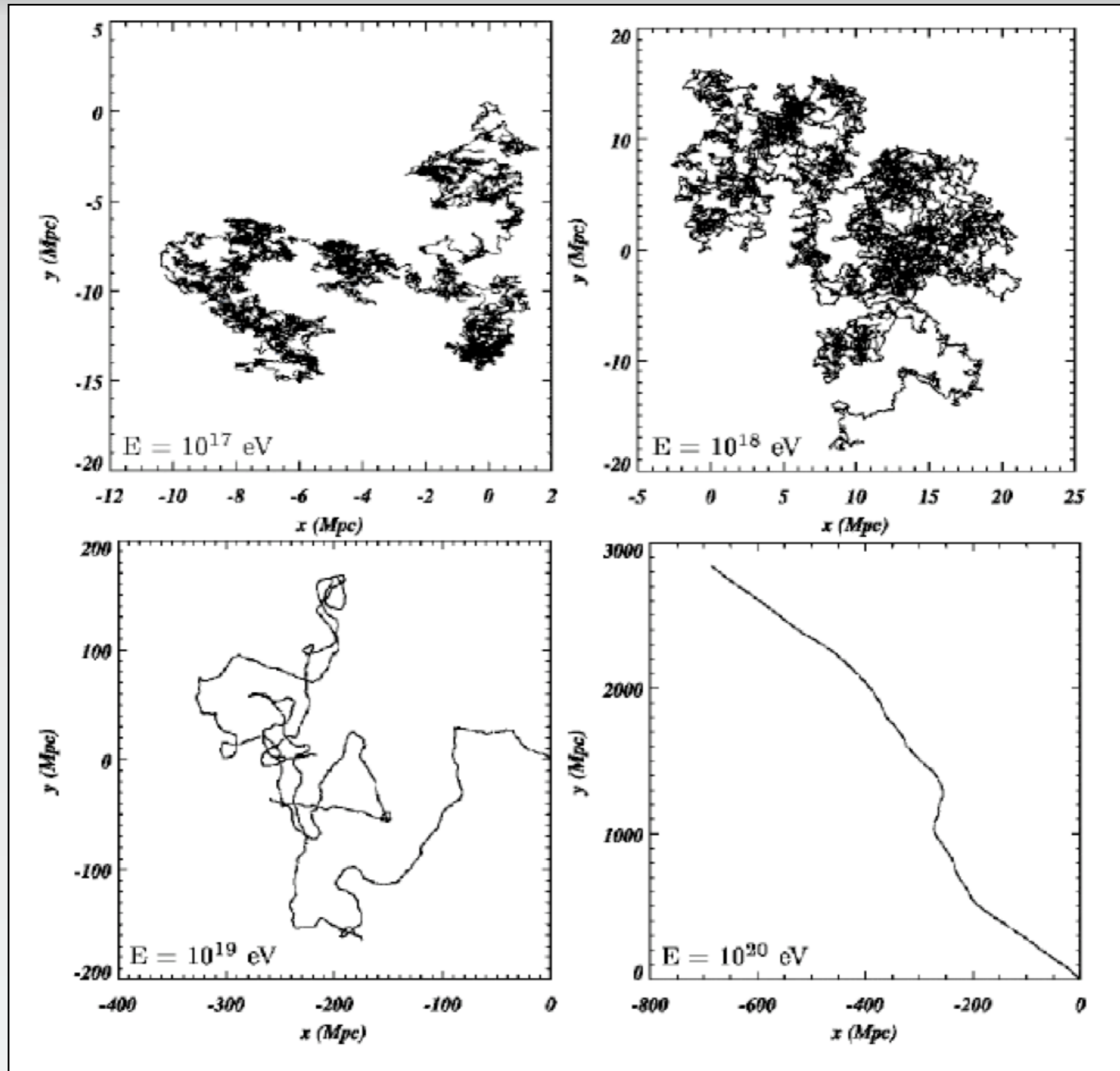
$$E_{lim} \sim D_{mag} q B c$$

μG sur 1 kpc :

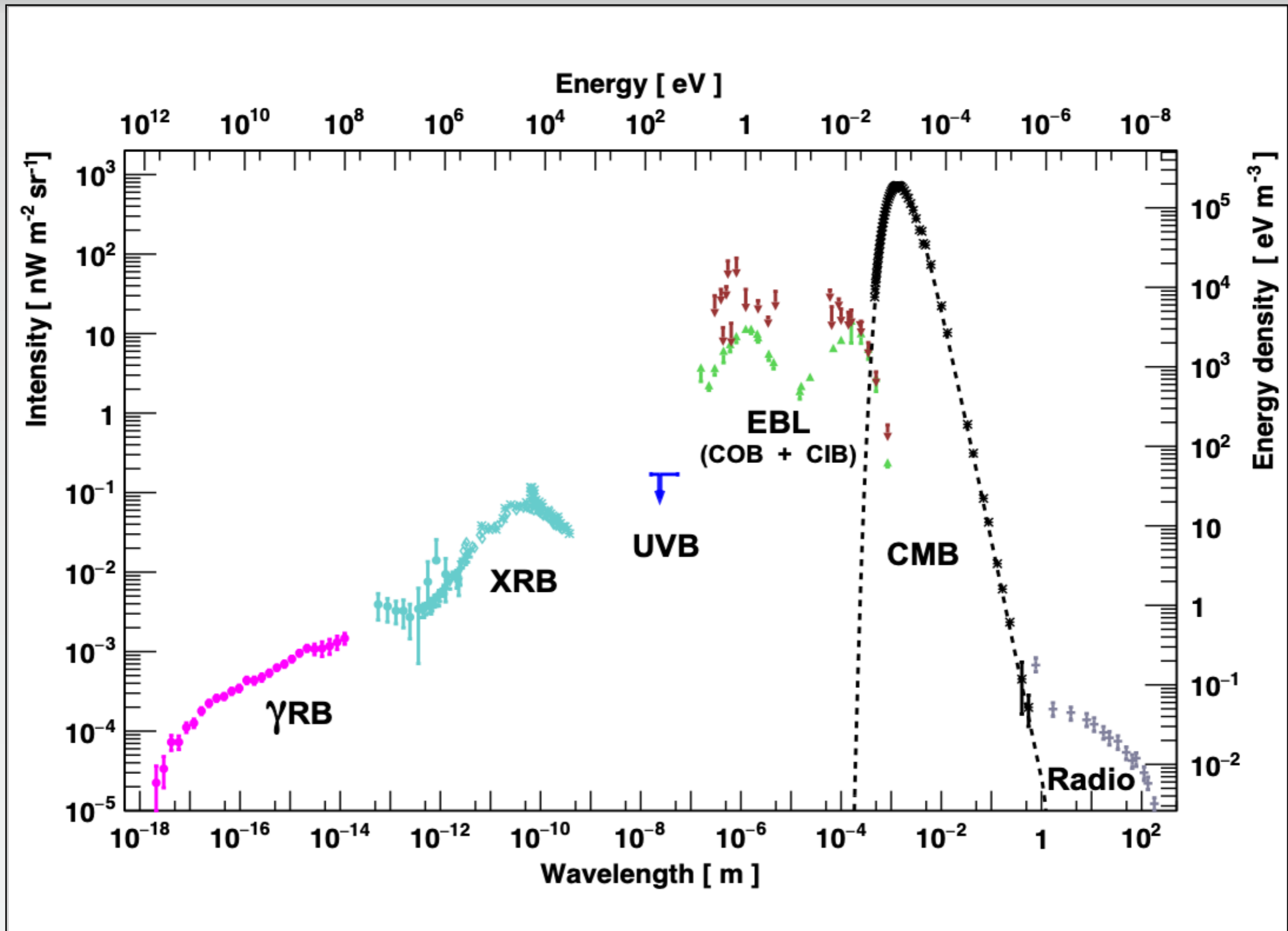
$$E_{lim} \sim 10^{18} \text{ eV}$$



Particules extra-Galactiques



Rayonnements de fond



Seuils de réactions



Energie disponible dans le centre de masse :

$$\sqrt{s} = \sqrt{(P_A + P_{diffus})^2}$$

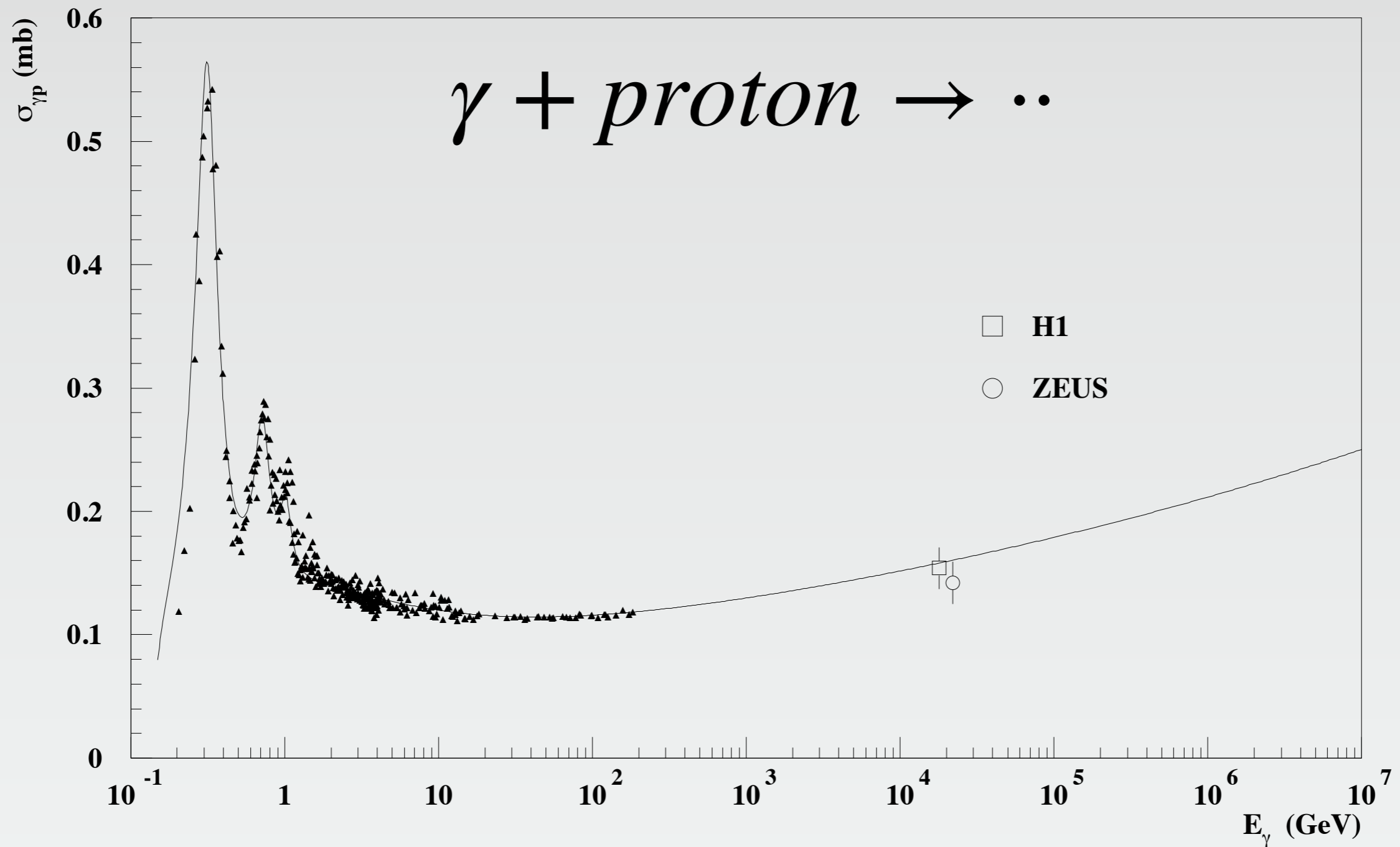
$$s = \underline{E_A^2} + \underline{E_{diffus}^2} + 2E_A E_{diffus} - \underline{\vec{p}_A^2} - \underline{\vec{p}_{diffus}^2} - 2\vec{p}_A \cdot \vec{p}_{diffus}$$

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

$$\left. \begin{array}{l} E_A \gg m_A \\ \cos \theta = -1 \end{array} \right\}$$

$$s = m_A^2 + 4E_{diffus}E_A$$

Production de résonance delta



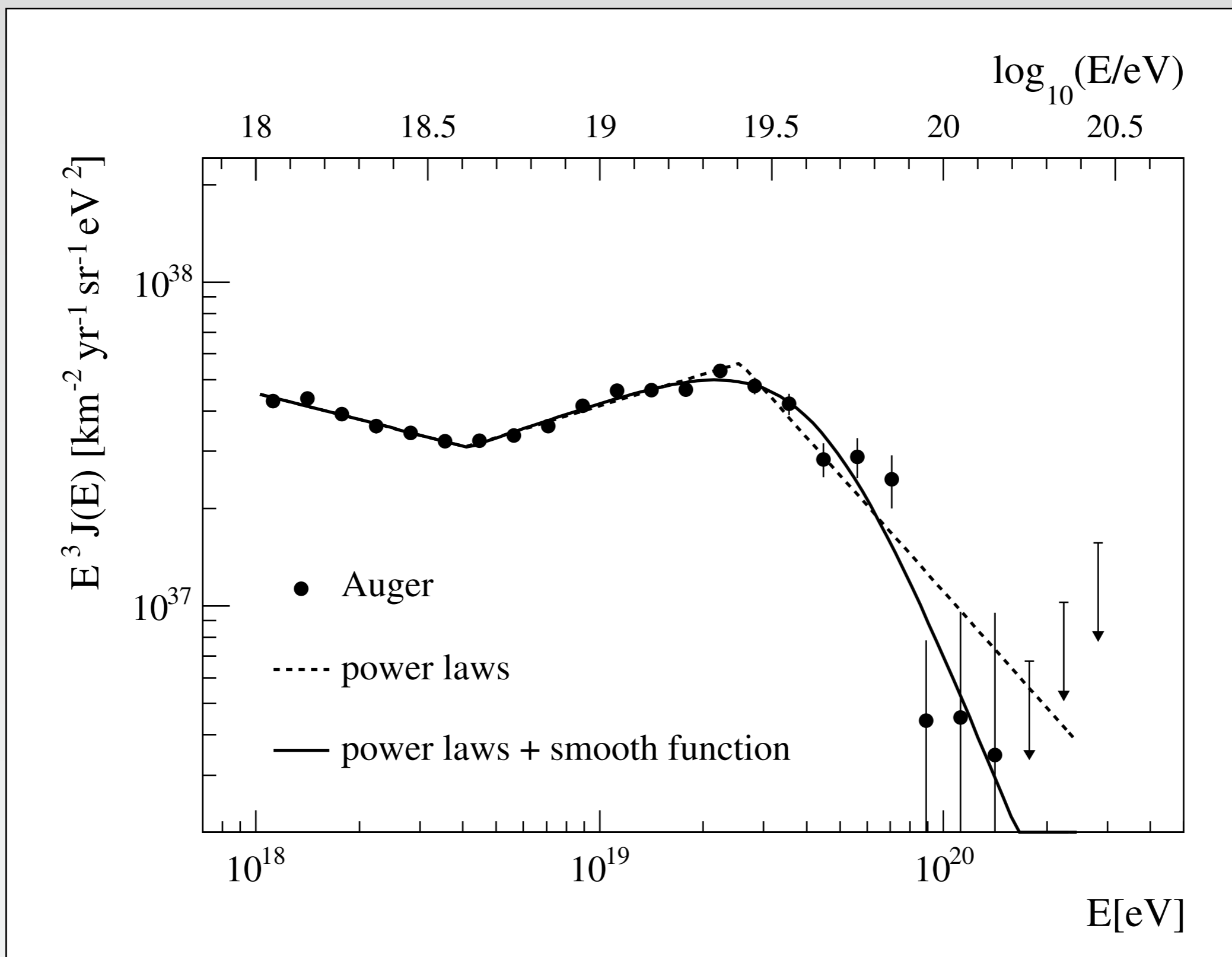
$$\sqrt{s} > m_{\Delta} \quad s = m_p^2 + 4E_{diffus}E_p > m_{\Delta}^2$$

Energie de seuil de production : $E_{seuil} = \frac{m_{\Delta}^2 - m_p^2}{4E_{diffus}}$

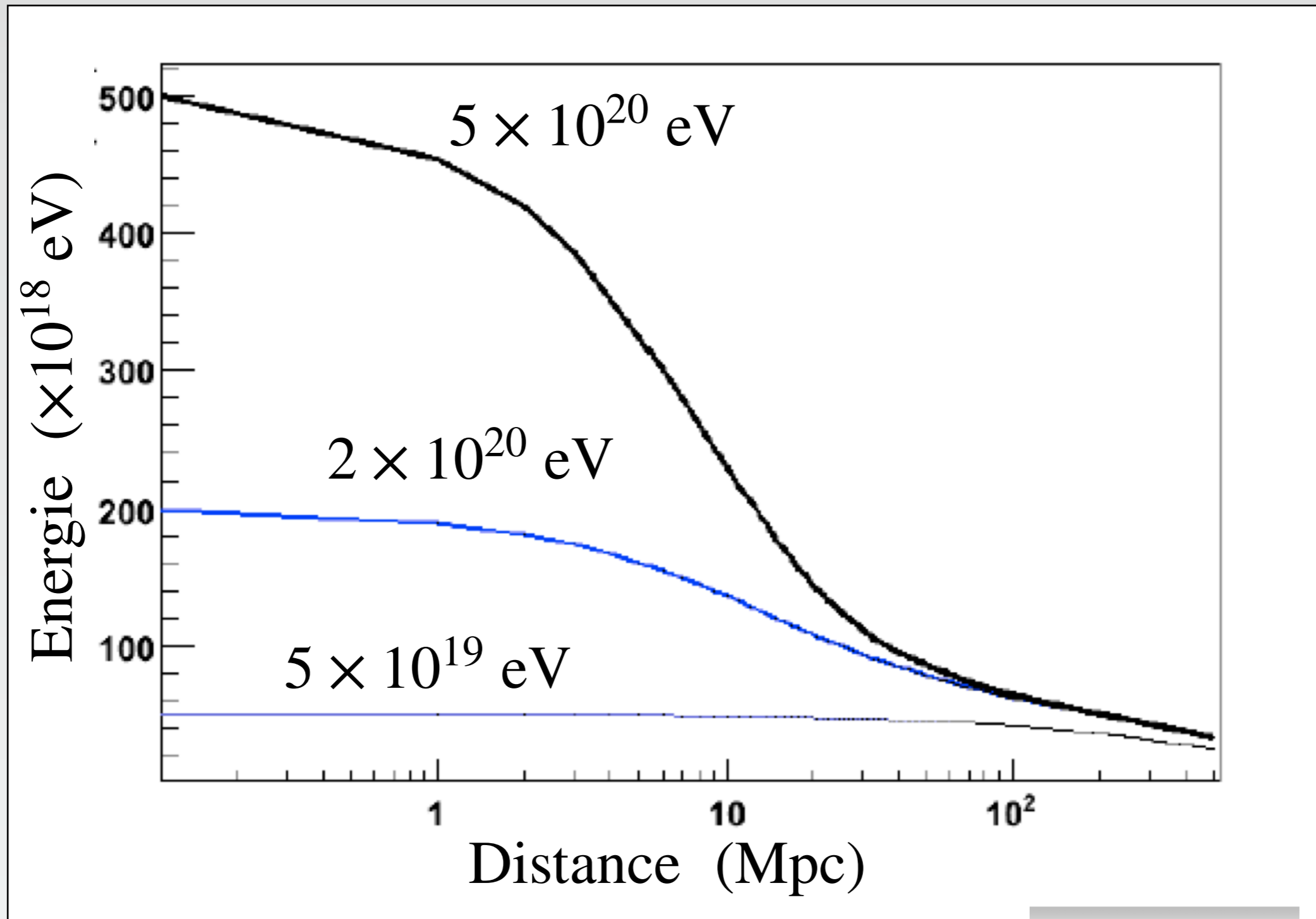
$$E_{CMB} = 10^{-3} \text{ eV} \Rightarrow E_{seuil} = 1.6 \times 10^{20} \text{ eV}$$

↑
Coupure GZK

Observation de la coupure GZK



Horizon pour des protons



Seuils pour les photons

$$\gamma + \gamma_{diffus} \rightarrow e^+ + e^-$$

$$\sqrt{s} > 2m_e \quad s = 4E_{diffus}E_\gamma > 4m_e^2$$

Energie de seuil de production : $E_\gamma > \frac{m_e^2}{E_{diffus}}$

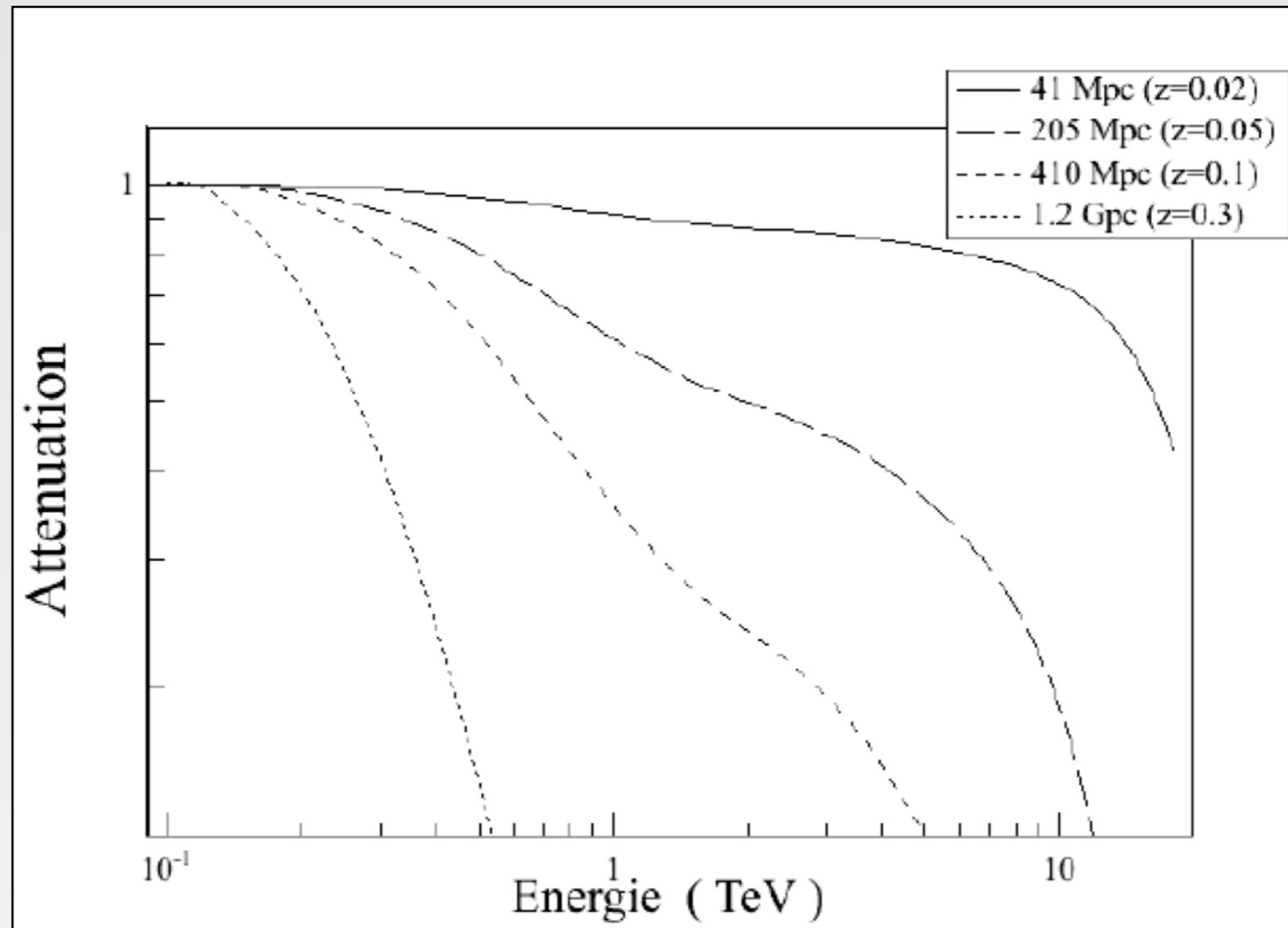
Fond diffus cosmologique : $E_{seuil} = 260 \text{ TeV}$

Fond diffus optique/IR : $E_{seuil} = 2.6 \text{ TeV}$

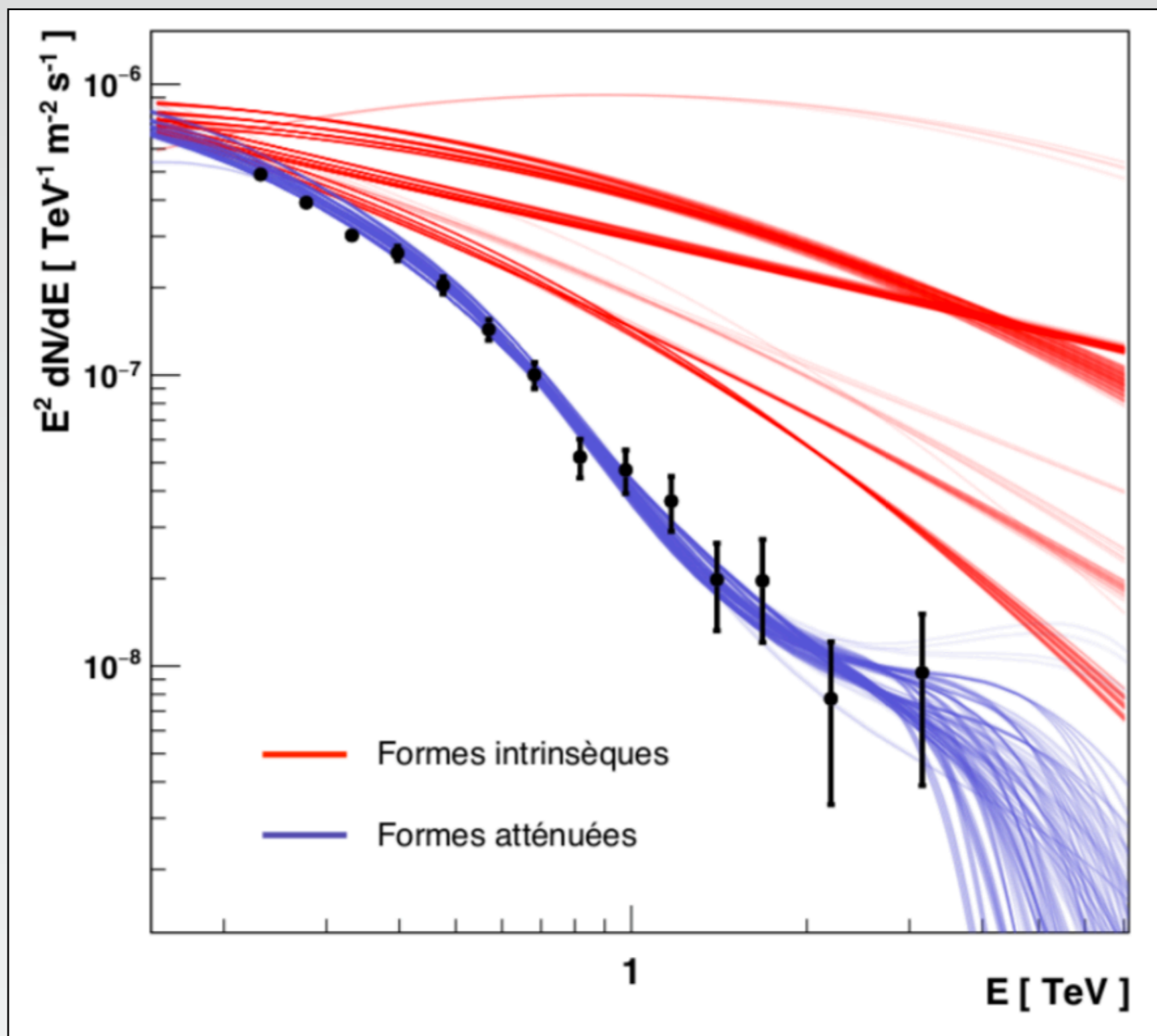
Atténuation des photons gamma

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

$$\tau(E, D) = \int_0^D ds \int_{seuil}^{\infty} d\epsilon \sigma(E, \epsilon) n_{diffus}(\epsilon, s)$$

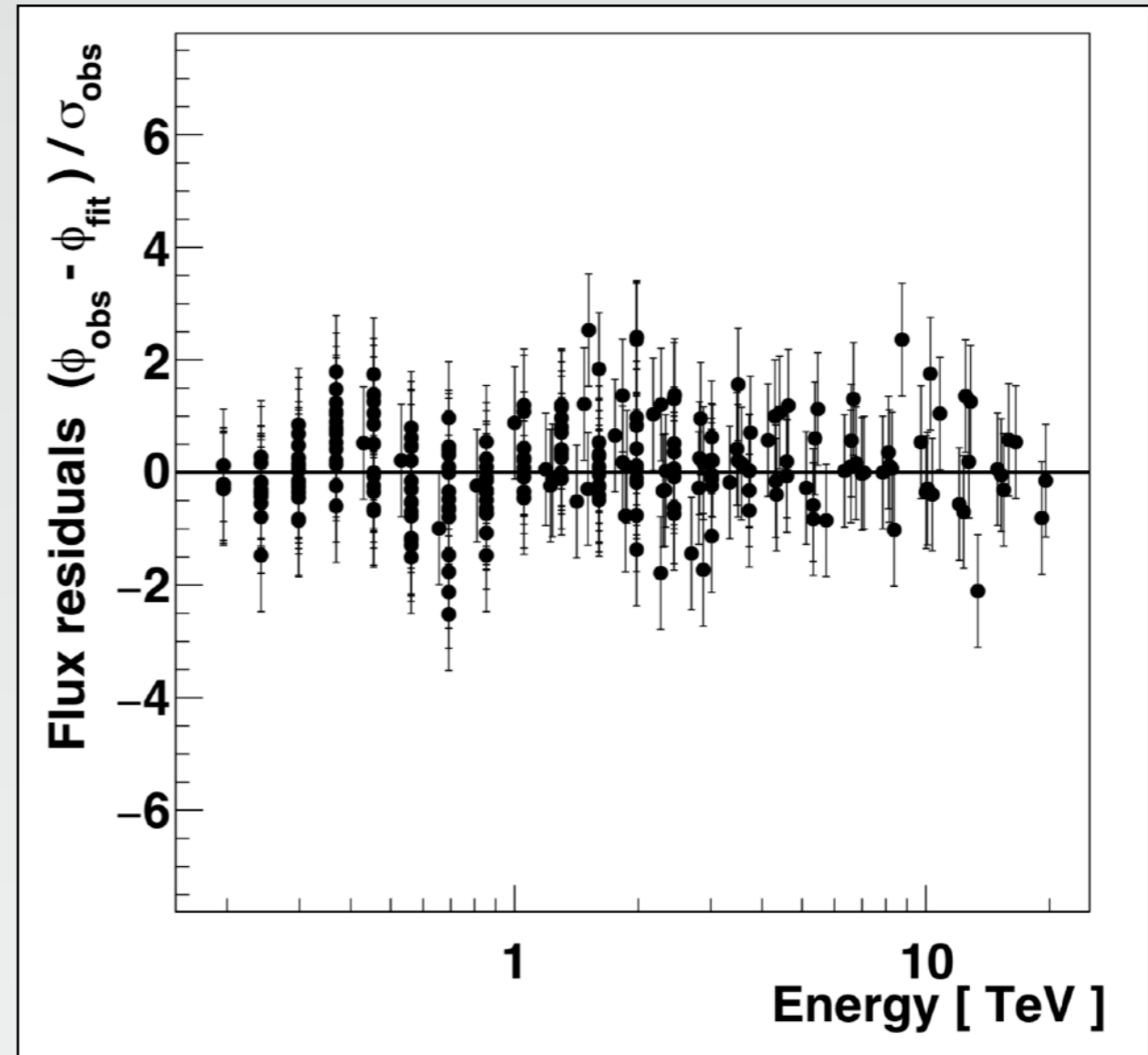
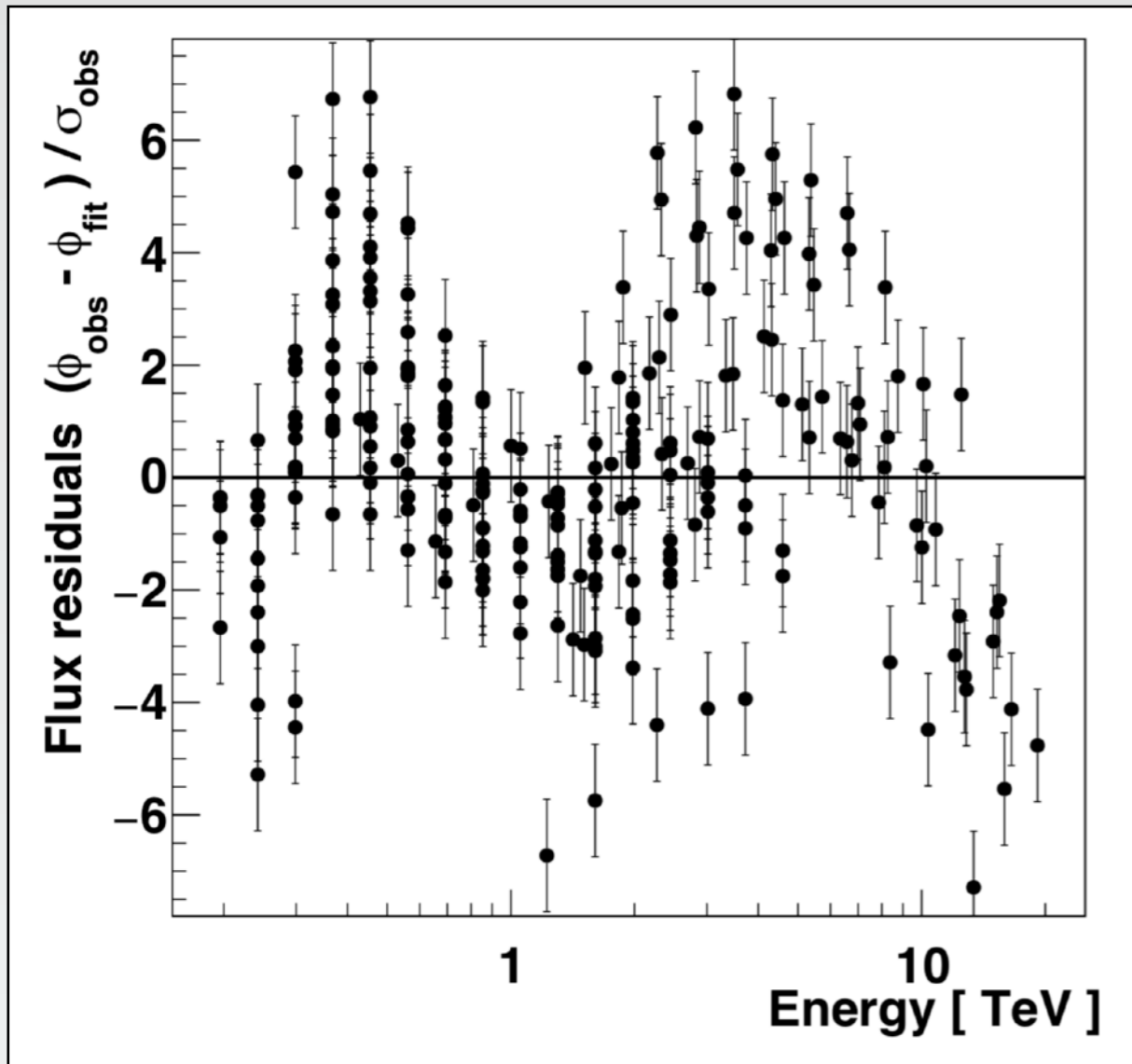


Mesure du fond optique avec les γ



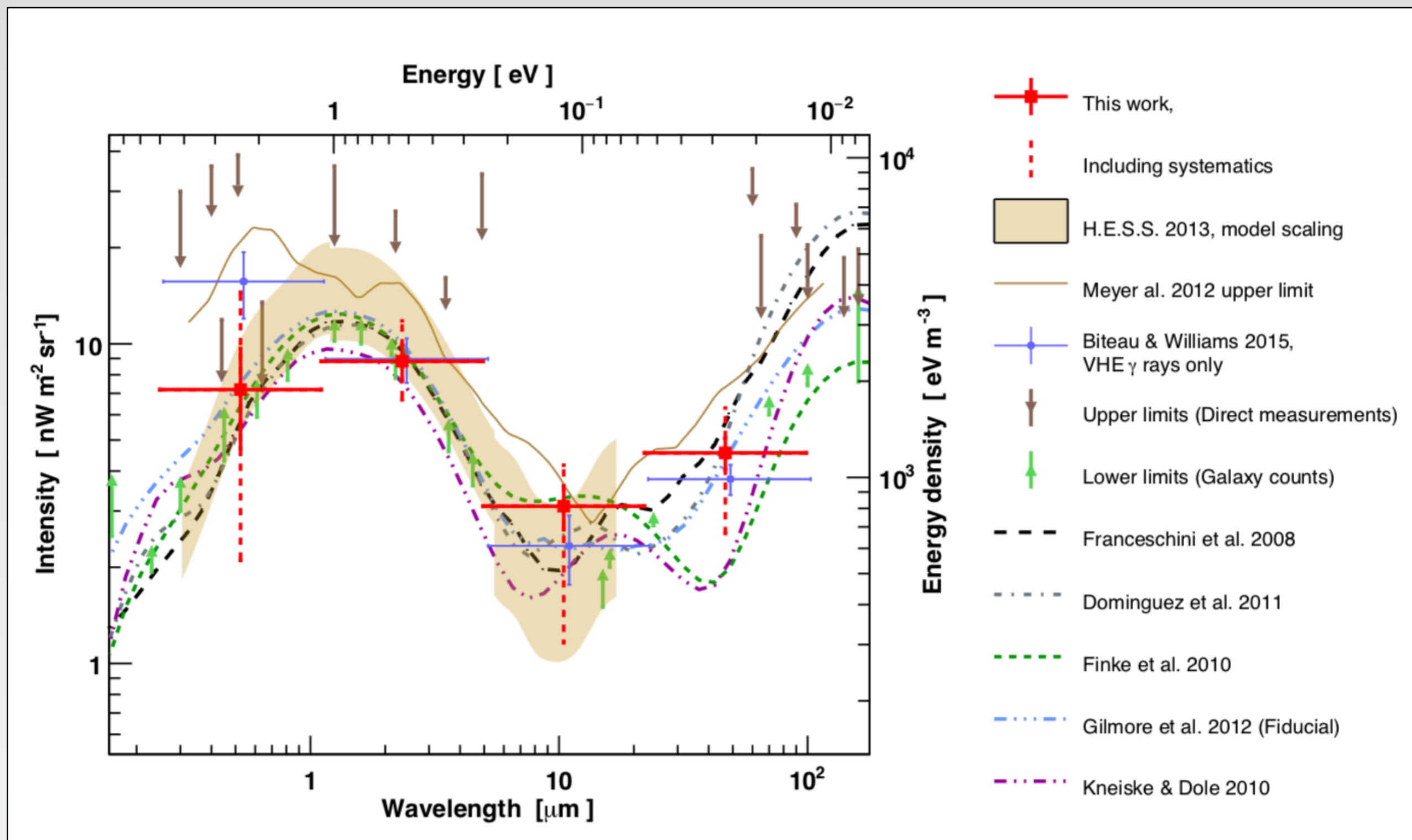
Thèse Matthias Lorentz, H.E.S.S.

Mesure du fond optique avec les γ



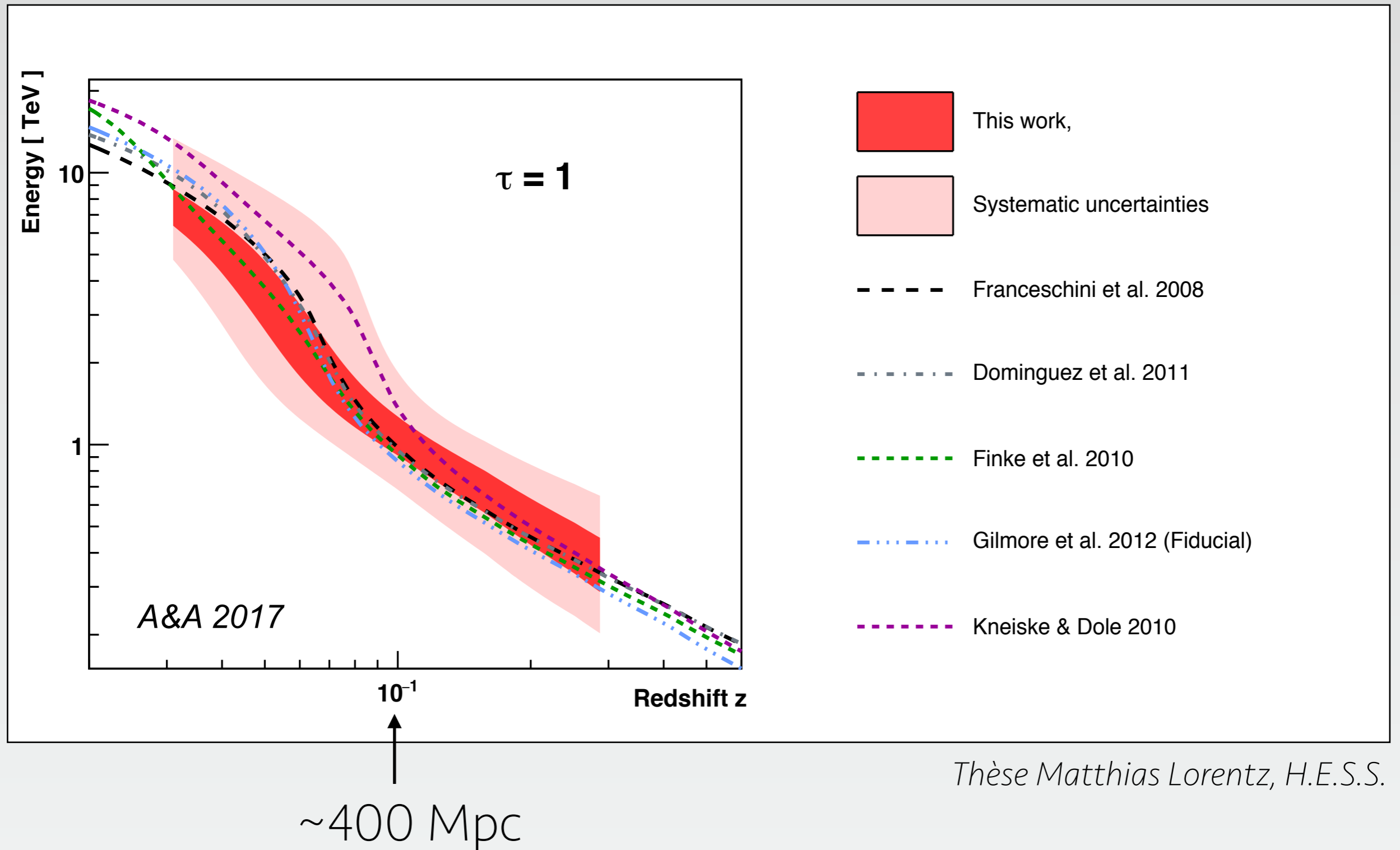
Thèse Matthias Lorentz, H.E.S.S.

Mesure du fond optique avec les γ



Thèse Matthias Lorentz, H.E.S.S.

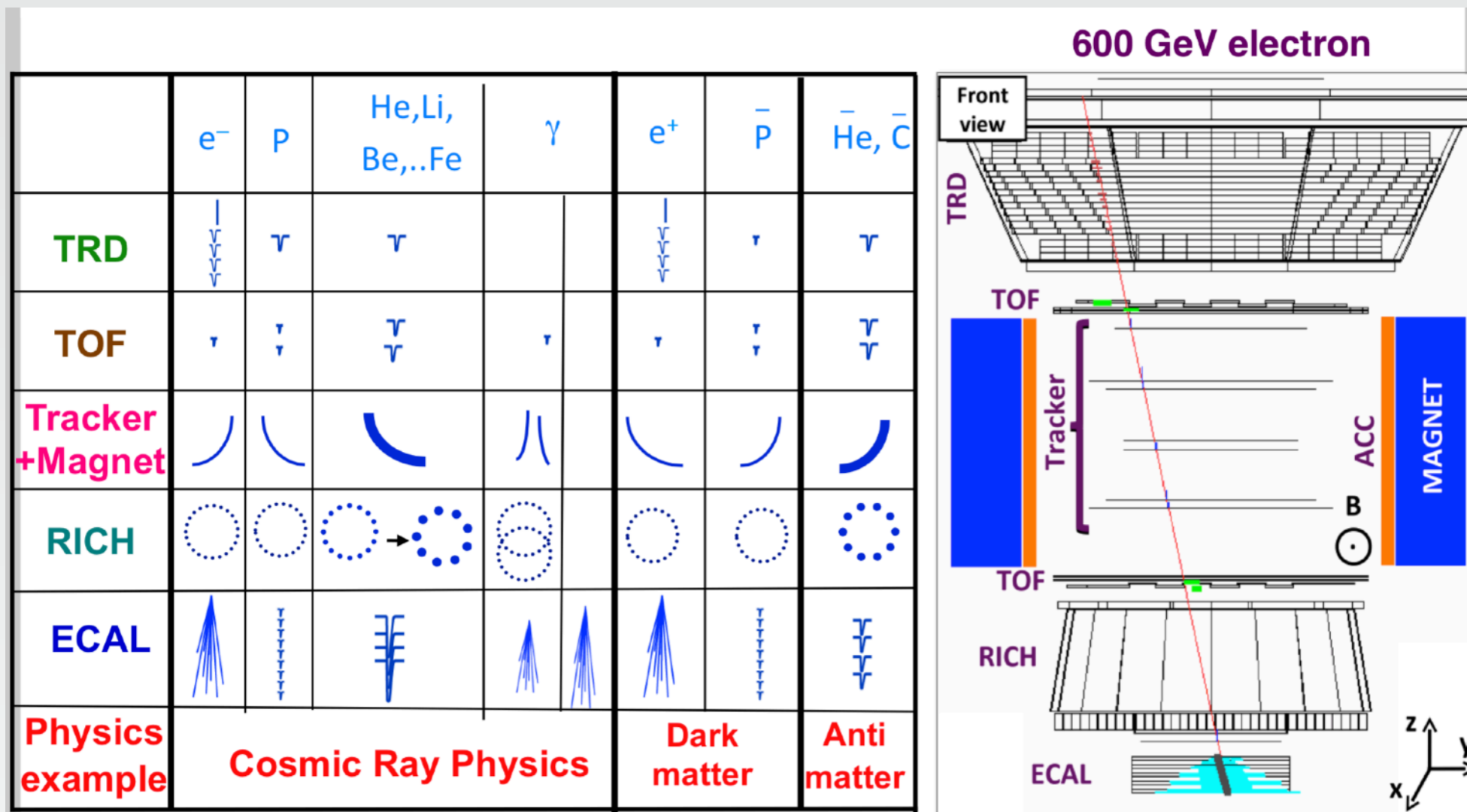
Horizon mesuré pour les γ



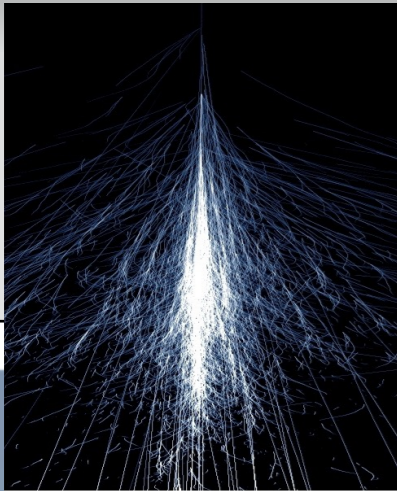
Thèse Matthias Lorentz, H.E.S.S.

Mesures au-dessus de l'atmosphère

AMS



Détection des cascades de hadrons



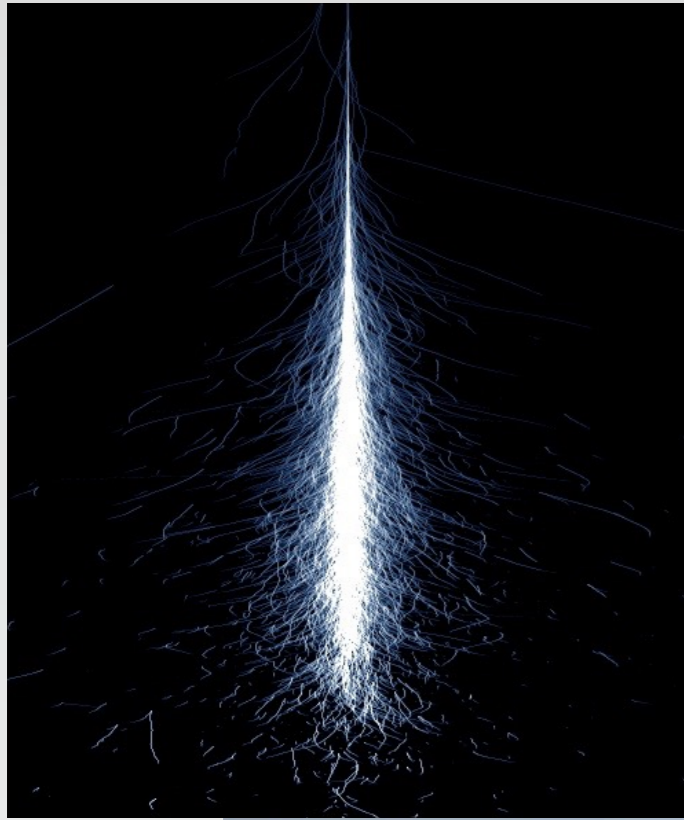
Auger



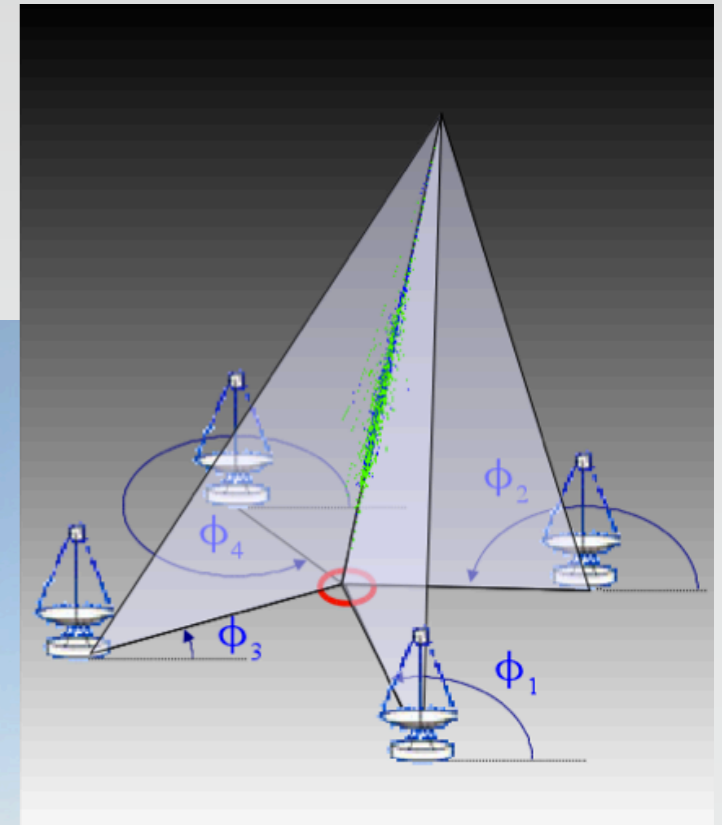
3000 km²

D = 1.5 km

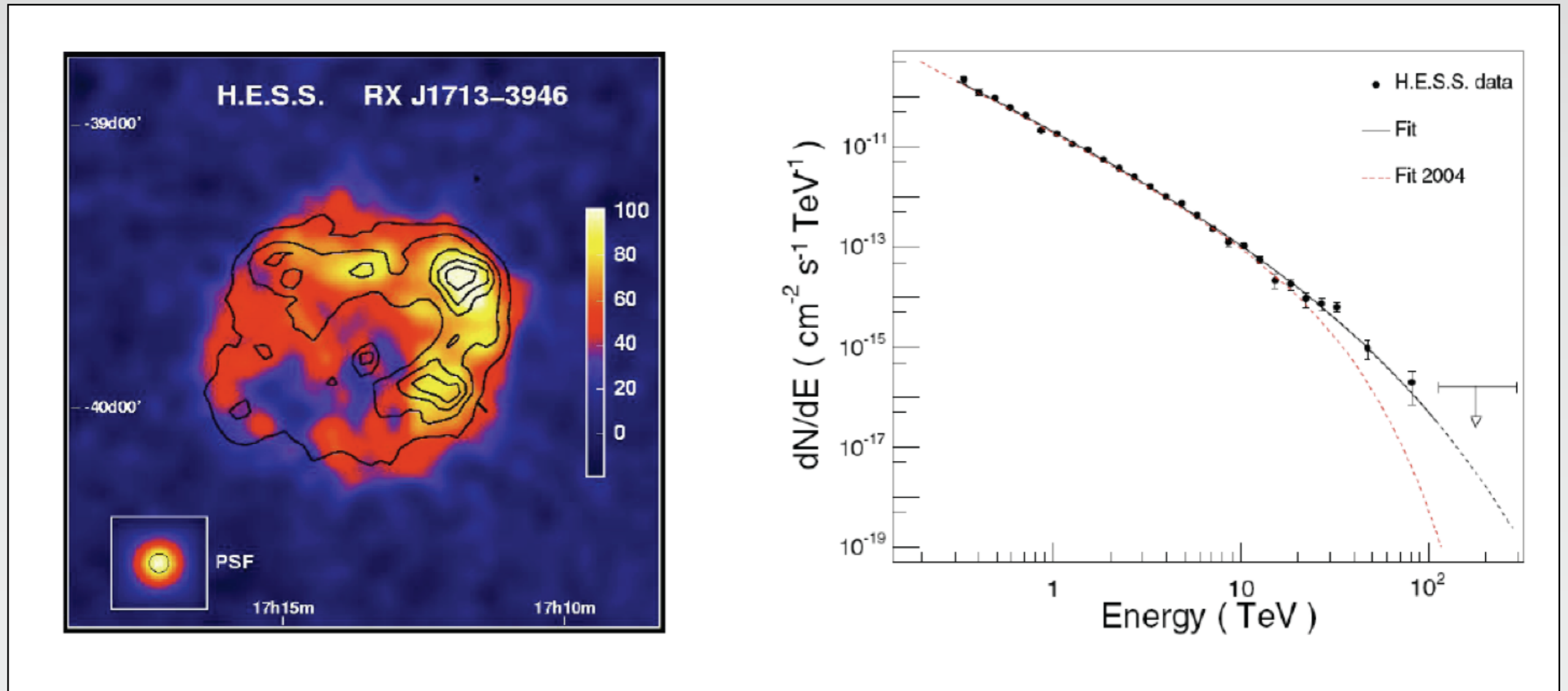
Détection des photons depuis le sol



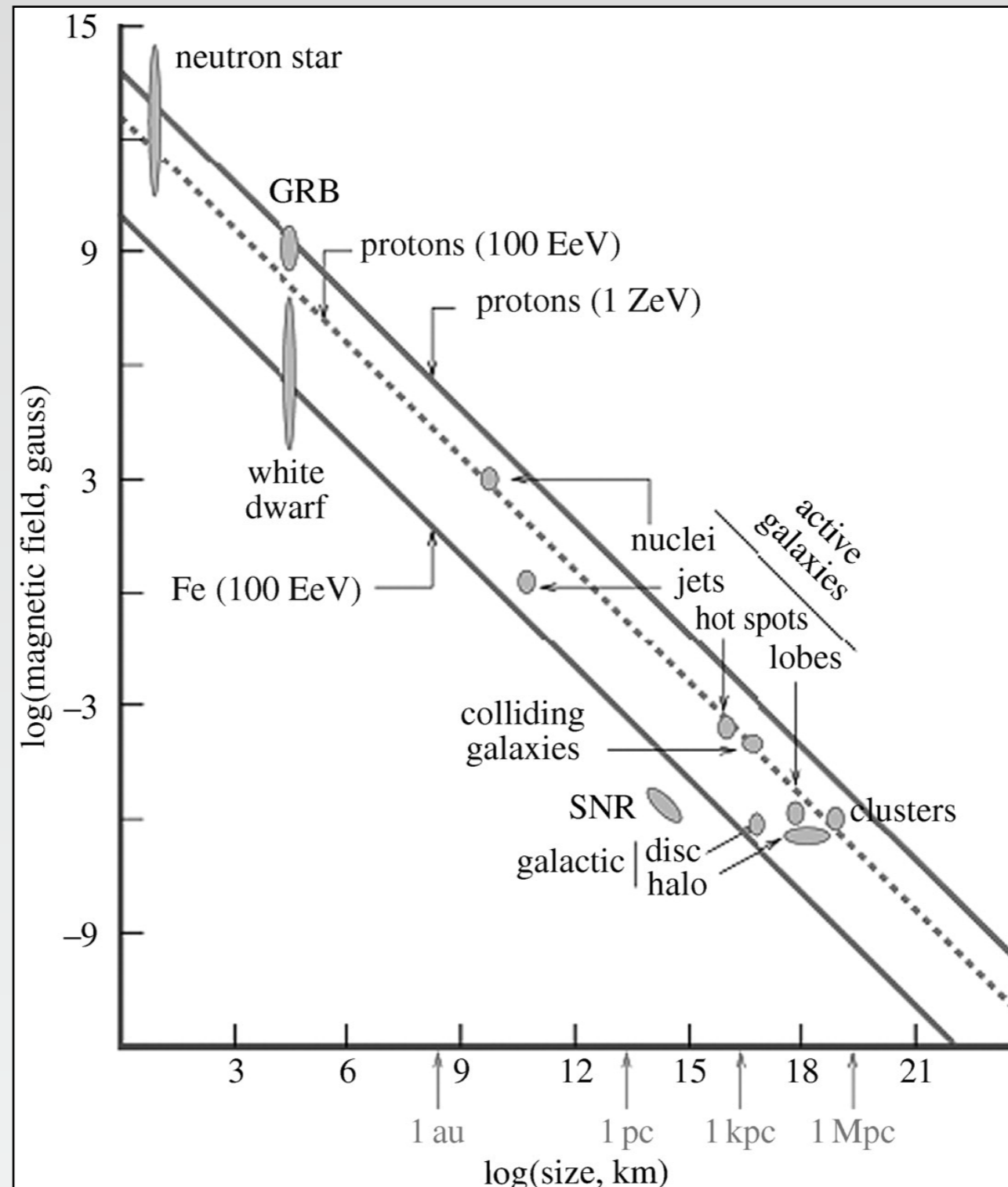
H.E.S.S.



Détection des photons depuis le sol



Sources : critère de Hillas



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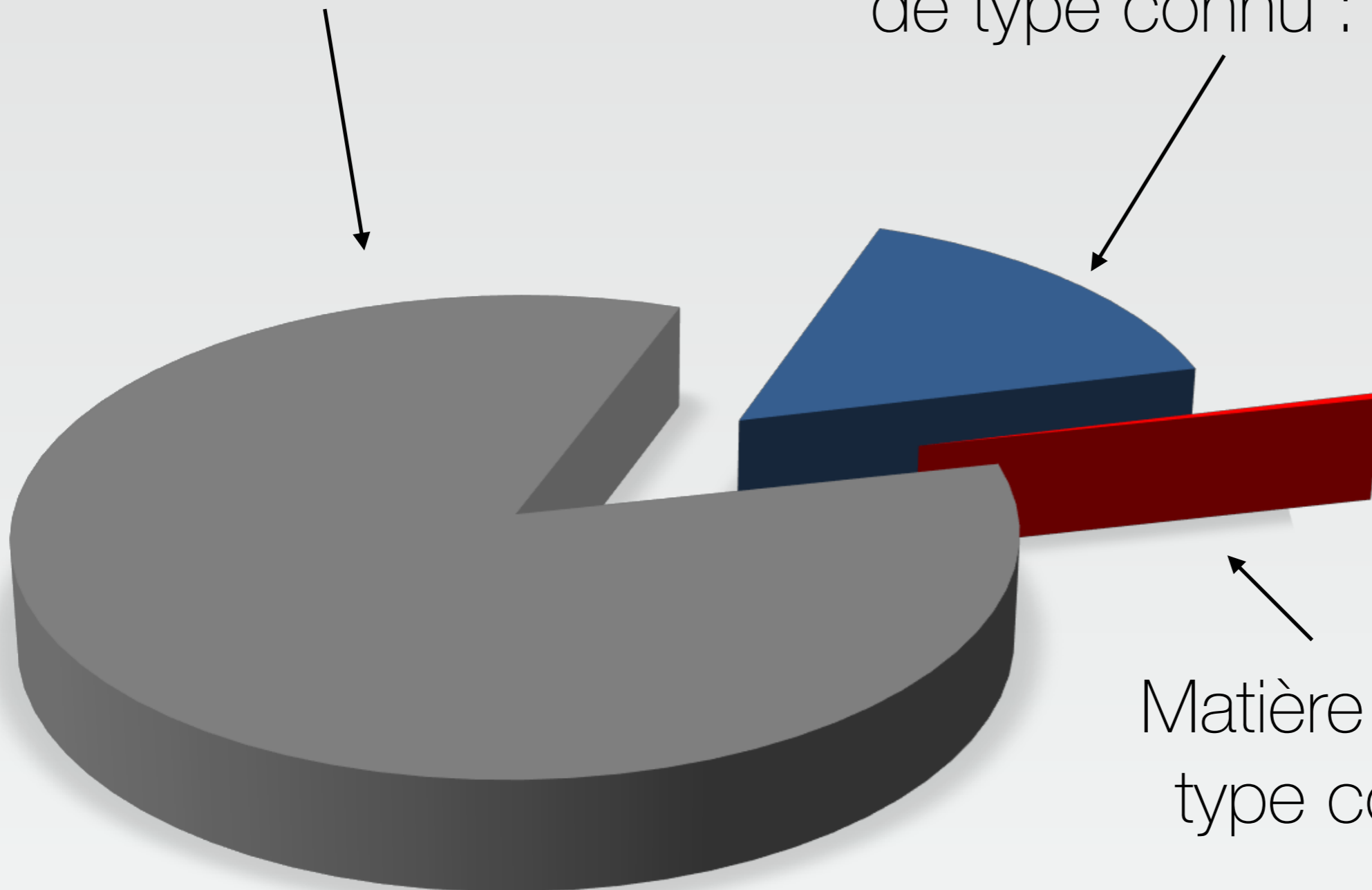
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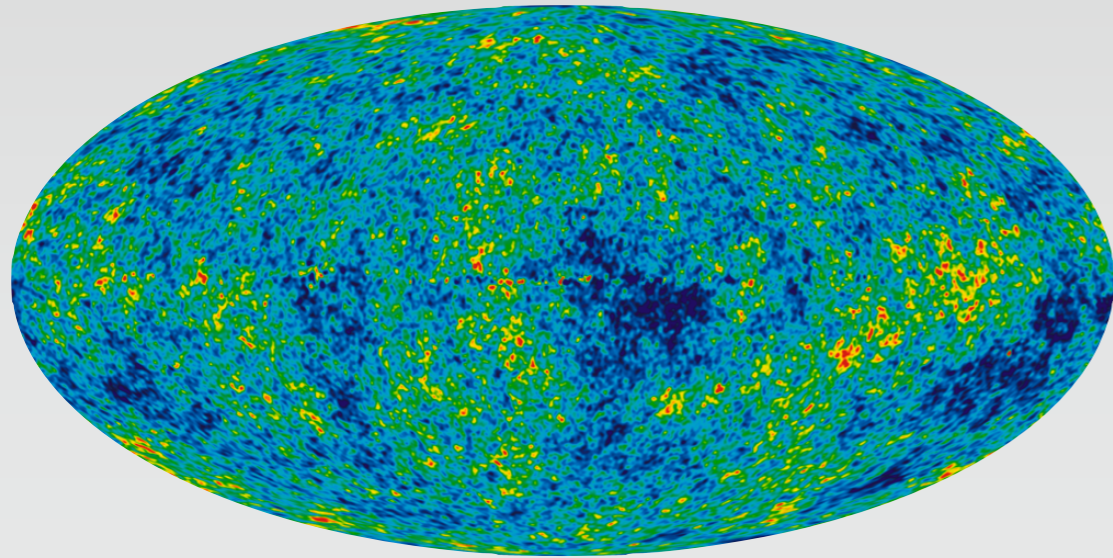
Bilan de la matière

Matière de type
inconnu : 84 %

Matière non lumineuse
de type connu : 15,6 %



Matière lumineuse de
type connu : 0,4 %

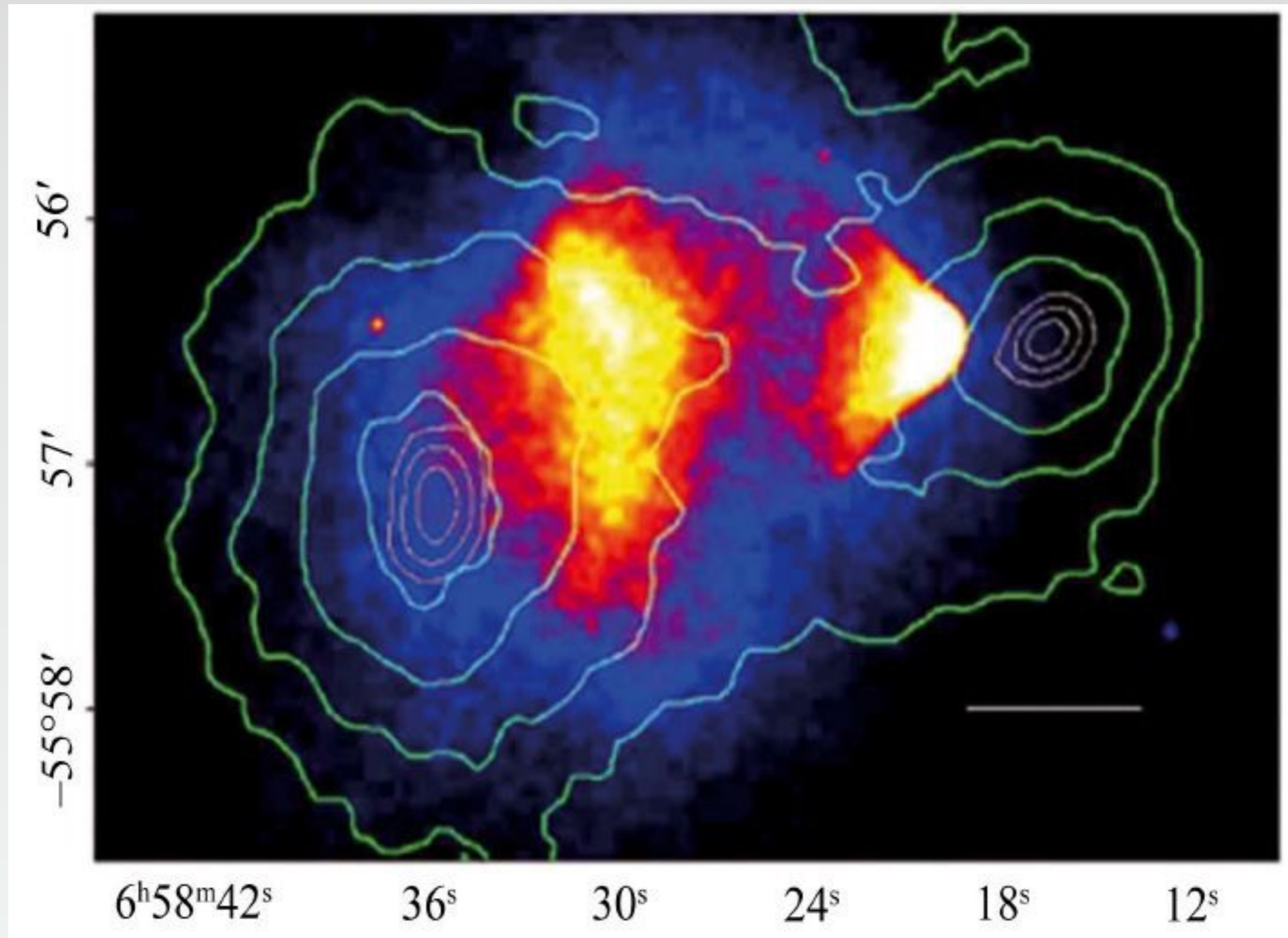


$$\frac{\delta\rho}{\rho} = \frac{\delta T}{T} \simeq 10^{-5}$$

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

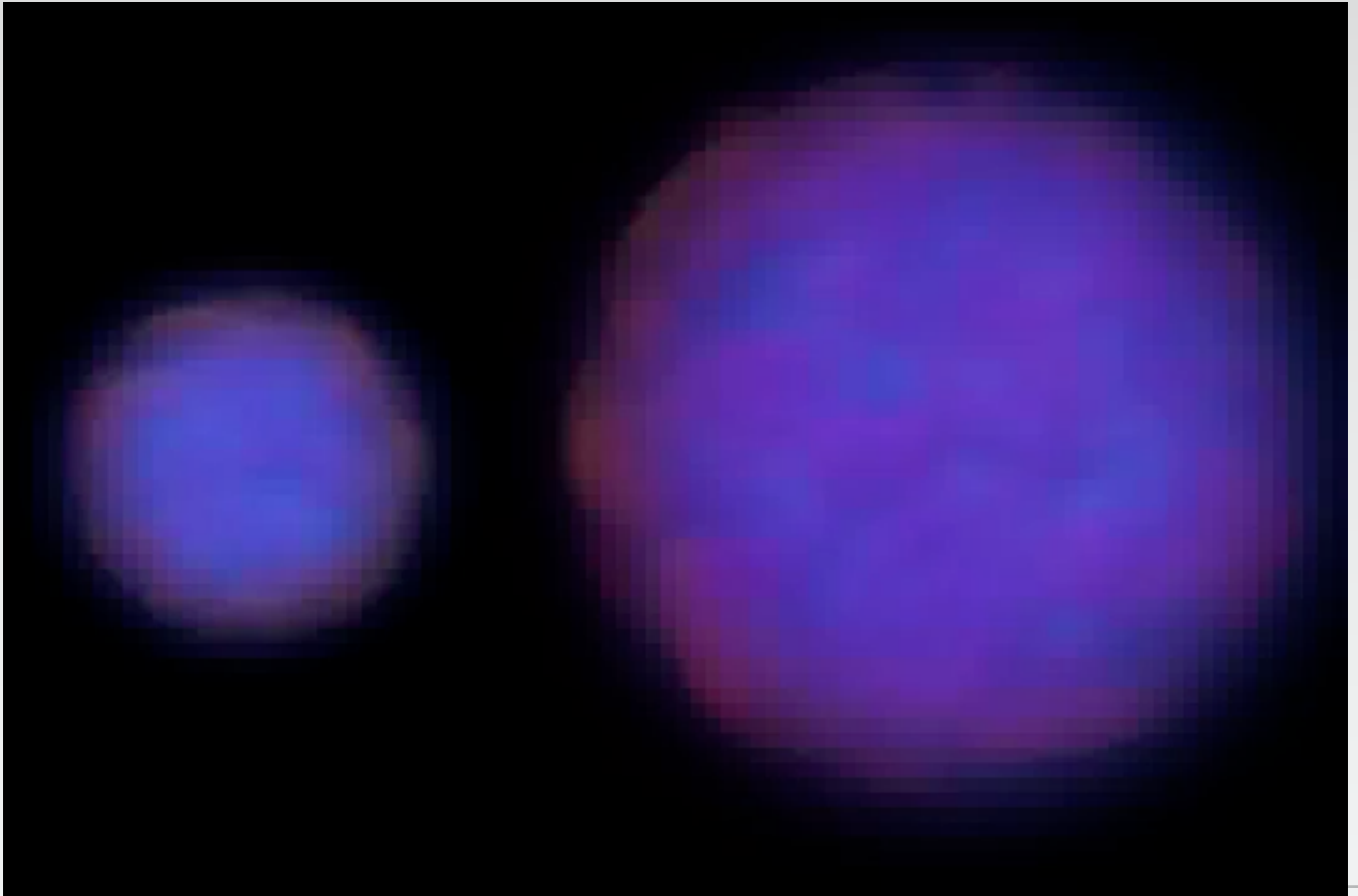


Collisions d'amas

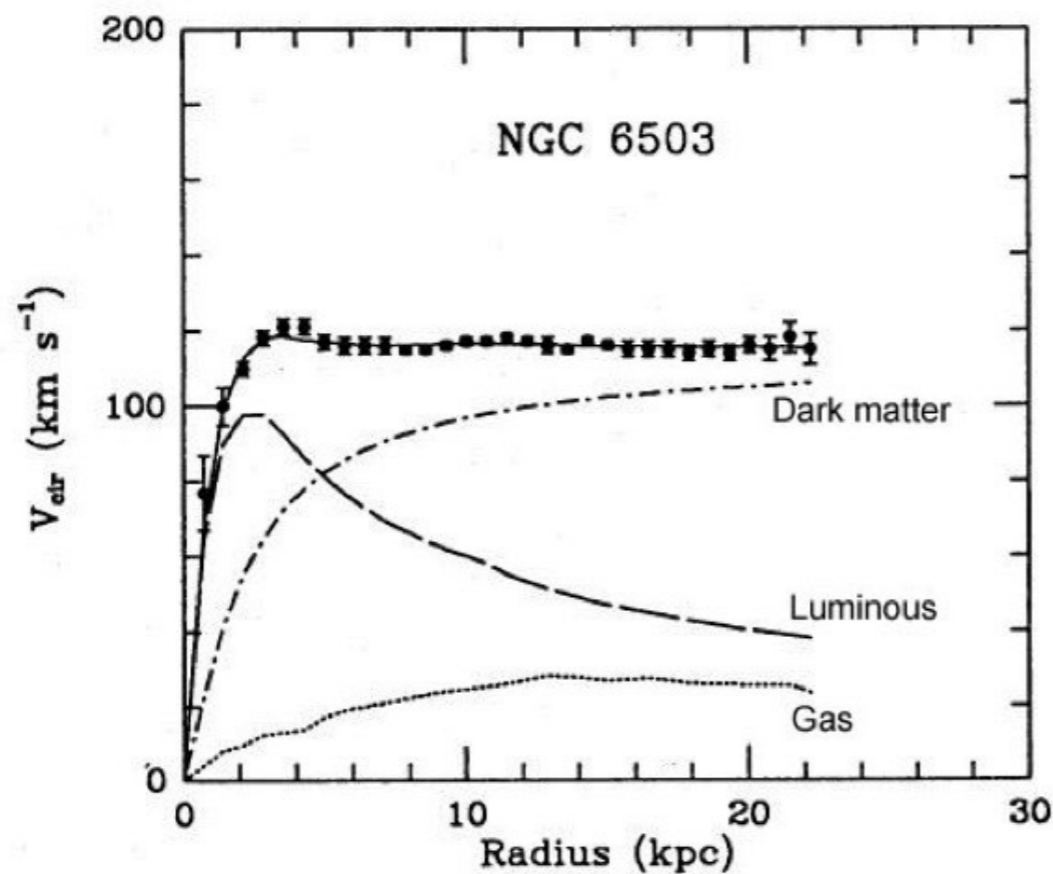
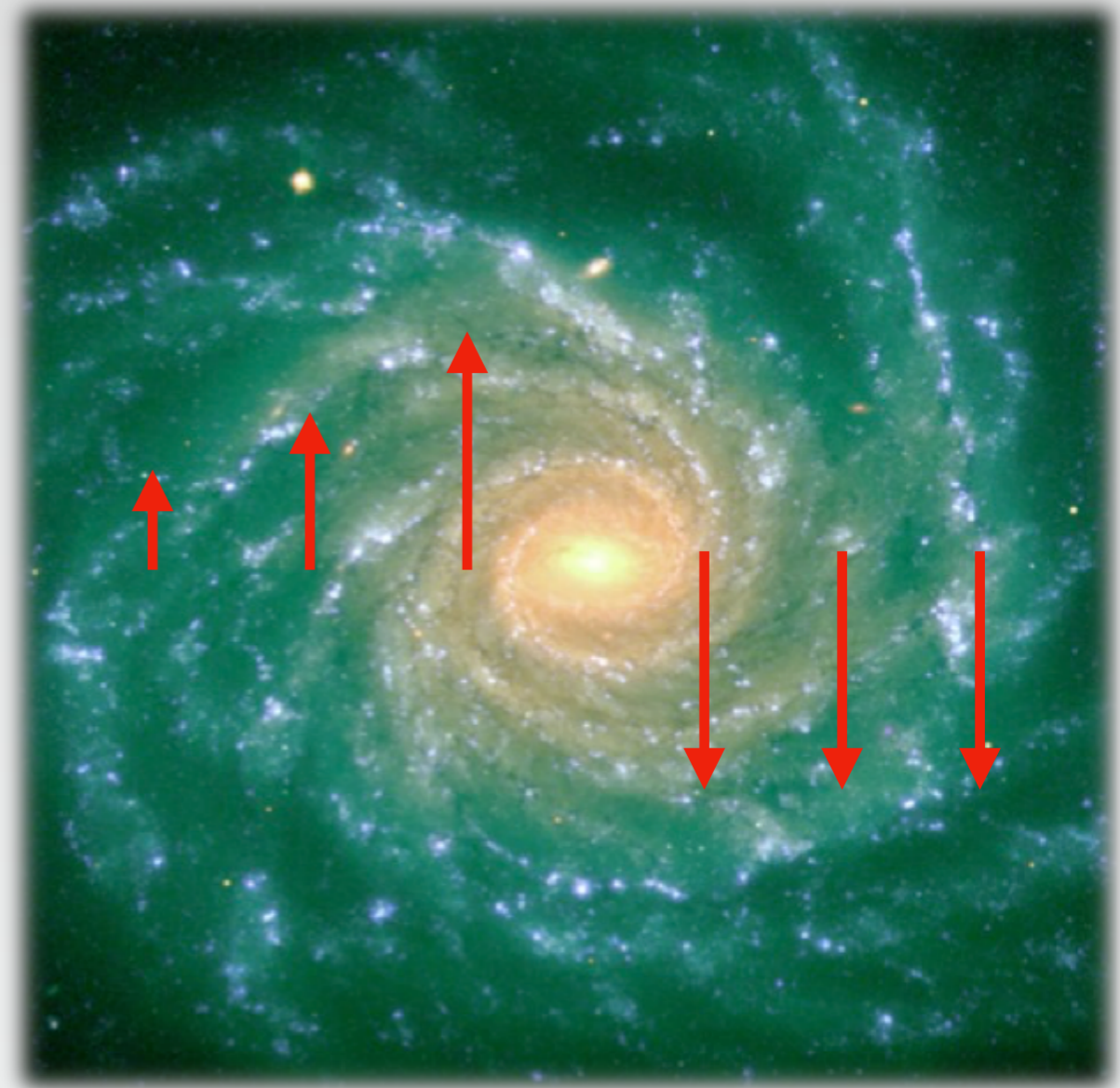




Collisions d'amas



Courbe de rotation des galaxies



1965 : Vera Rubin

K.G. Begeman, A.H. Broels, R.H. Sanders. 1991. Mon.Not.RAS 249, 523.

Succès du modèle standard

Citation: M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

LIGHT UNFLAVORED MESONS ($S = C = B = 0$)

For $l = 1$ (π, ρ, a): $u\bar{d}, (u\bar{u}-d\bar{d})/\sqrt{2}, d\bar{u}$;
for $l = 0$ ($\eta, \eta', h, h', \omega, \phi, f, f'$): $c_1(u\bar{u} + d\bar{d}) + c_2(s\bar{s})$

π^\pm

$J^G(J^P) = 1^-(0^-)$

Mass $m = 139.57061 \pm 0.00024$ MeV ($S = 1.6$)
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s ($S = 1.2$)
 $c\tau = 7.8045$ m

$\pi^\pm \rightarrow \ell^\pm \nu \gamma$ form factors [a]
 $F_V = 0.0254 \pm 0.0017$
 $F_A = 0.0119 \pm 0.0004$
 F_V slope param
 $R = 0.059^{+0.006}_{-0.004}$

π^\pm modes are charge con
For decay limits to particl
Searches for Axions and C

π^0 DECAY MODES

Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
2γ	$(98.823 \pm 0.034) \%$	$S=1.5$	67
$e^+e^-\gamma$	$(1.174 \pm 0.035) \%$	$S=1.5$	67
γ positronium	$(1.82 \pm 0.29) \times 10^{-9}$		67
$e^+e^-e^+e^-$	$(3.34 \pm 0.16) \times 10^{-5}$		67
e^+e^-	$(6.46 \pm 0.33) \times 10^{-8}$		67
4γ	$< 2 \times 10^{-8}$	CL=90%	67
$\nu\bar{\nu}$	$[a] < 2.7 \times 10^{-7}$	CL=90%	67
$\nu_e\bar{\nu}_e$	$< 1.7 \times 10^{-6}$	CL=90%	67
$\nu_\mu\bar{\nu}_\mu$	$< 1.6 \times 10^{-6}$	CL=90%	67
$\nu_\tau\bar{\nu}_\tau$	$< 2.1 \times 10^{-6}$	CL=90%	67
$\gamma\nu\bar{\nu}$	$< 6 \times 10^{-4}$	CL=90%	67

Charge conjugation (C) or Lepton Family number (LF) violating modes

Mode	Fraction	Scale factor/ Confidence level	p (MeV/c)
3γ	$< 3.1 \times 10^{-8}$	CL=90%	67
μ^+e^-	$< 3.8 \times 10^{-10}$	CL=90%	26
μ^-e^+	$< 3.4 \times 10^{-9}$	CL=90%	26
$\mu^+e^- + \mu^-e^+$	$< 3.6 \times 10^{-10}$	CL=90%	26

Lepton Family number (LF) violating modes

Mode	Fraction	Scale factor/ Confidence level	p (MeV/c)
$\mu^+\nu_e$	$< 1.1 \times 10^{-9}$	CL=90%	26
$\mu^+\nu_\mu$	$< 1.1 \times 10^{-9}$	CL=90%	26
$\mu^+\nu_\tau$	$< 1.1 \times 10^{-9}$	CL=90%	26
$\mu^-e^+e^+\nu$	$< 1.1 \times 10^{-9}$	CL=90%	26

Mass $m = 134.97$
 $m_{\pi^\pm} - m_{\pi^0} = 4.1$
Mean life $\tau = (8.1 \pm 0.2) \times 10^{-12}$ s
 $c\tau = 25.5$ nm

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Citation: M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

$\Delta(2200) 7/2^-$

$J^G(J^P) = \frac{7}{2}(1^-)$

Re(pole position) = 2050 to 2150 (≈ 2100) MeV
-2Im(pole position) = 260 to 420 (≈ 340) MeV
Breit-Wigner mass = 2150 to 2250 (≈ 2200) MeV
Breit-Wigner full width = 200 to 500 (≈ 350) MeV

$\Delta(2200)$ DECAY MODES

Mode	Fraction (Γ_i/Γ)
$N\pi$	2-8%
ΣK	1-7%
$\Delta\pi$, D-wave	40-100%
$\Delta\pi$, G-wave	5-25%
$\Delta\eta$, D-wave	seen

$\Delta(2420) 11/2^+$

$J^G(J^P) = \frac{11}{2}(1^+)$

Re(pole position) = 2300 to 2500 (≈ 2400) MeV
-2Im(pole position) = 350 to 550 (≈ 450) MeV
Breit-Wigner mass = 2300 to 2600 (≈ 2450) MeV
Breit-Wigner full width = 300 to 700 (≈ 500) MeV

$\Delta(2420)$ DECAY MODES

Mode	Fraction (Γ_i/Γ)
$N\pi$	5-10%

Λ BARYONS ($S = -1, I = 0$)

$\Lambda^0 = uds$

Λ

$J^G(J^P) = 0(\frac{1}{2}^+)$

Mass $m = 1115.683 \pm 0.006$ MeV
 $(m_\Lambda - m_N) / m_N = (-0.1 \pm 1.1) \times 10^{-5}$ (S)
Mean life $\tau = (2.632 \pm 0.020) \times 10^{-10}$ s (S)
 $(\tau_\Lambda - \tau_{\Sigma^0}) / \tau_\Lambda = -0.001 \pm 0.009$
 $c\tau = 7.89$ cm

Magnetic moment $\mu = -0.613 \pm 0.004 \mu_N$
Electric dipole moment $d < 1.5 \times 10^{-16}$ e cm.

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Citation: M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

Decay parameters

$\rho\pi^-$	$\alpha_- = 0.642 \pm 0.013$
$\bar{\rho}\pi^+$	$\alpha_+ = -0.71 \pm 0.08$
$\rho\pi^0$	$\phi_- = (-6.5 \pm 3.5)^\circ$
"	$\gamma_- = 0.76 [a]$
"	$\Delta_- = (8 \pm 4)^\circ [b]$
$n\pi^0$	$\alpha_0 = 0.65 \pm 0.04$
$\rho e^- \bar{\nu}_e$	$\xi_A/\xi_V = -0.718 \pm 0.015 [f]$

$\Lambda(1405) 1/2^-$

$J^G(J^P) = 0(\frac{1}{2}^-)$

Mass $m = 1405.1^{+1.3}_{-1.0}$ MeV
Full width $\Gamma = 50.5 \pm 2.0$ MeV
Below $\bar{K}N$ threshold

$\Lambda(1405)$ DECAY MODES

Mode	Fraction (Γ_i/Γ)
$\Sigma\pi$	100%

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Citation: M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

η

$J^G(J^PC) = 0^+(0^{-+})$

Mass $m = 547.862 \pm 0.017$ MeV
Full width $\Gamma = 1.31 \pm 0.05$ keV

η DECAY MODES

Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
neutral modes	$(72.12 \pm 0.34) \%$	$S=1.2$	-
2γ	$(39.41 \pm 0.20) \%$	$S=1.1$	274
$3\pi^0$	$(32.68 \pm 0.23) \%$	$S=1.1$	179
$\pi^0 2\gamma$	$(2.56 \pm 0.22) \times 10^{-4}$		257
$2\pi^0 2\gamma$	$< 1.2 \times 10^{-3}$	CL=90%	238
4γ	$< 2.8 \times 10^{-4}$	CL=90%	274
invisible	$< 1.0 \times 10^{-4}$	CL=90%	-
charged modes	$(28.10 \pm 0.34) \%$	$S=1.2$	-
$\pi^+\pi^-\pi^0$	$(22.92 \pm 0.28) \%$	$S=1.2$	174
$\pi^+\pi^-\gamma$	$(4.22 \pm 0.08) \%$	$S=1.1$	236
$e^+e^-\gamma$	$(6.9 \pm 0.4) \times 10^{-3}$	$S=1.3$	274
$\mu^+\mu^-\gamma$	$(3.1 \pm 0.4) \times 10^{-4}$		253
e^+e^-	$< 2.3 \times 10^{-6}$	CL=90%	274
$\mu^+\mu^-$	$(5.8 \pm 0.8) \times 10^{-5}$		253
$2e^+ 2e^-$	$(2.40 \pm 0.22) \times 10^{-5}$		274
$\pi^+\pi^-e^+e^- (\gamma)$	$(2.68 \pm 0.11) \times 10^{-4}$		235
$e^+e^-\mu^+\mu^-$	$< 1.6 \times 10^{-4}$	CL=90%	253
$2\mu^+ 2\mu^-$	$< 3.6 \times 10^{-4}$	CL=90%	161
$\mu^+\mu^-\pi^+\pi^-$	$< 3.6 \times 10^{-4}$	CL=90%	113
$\pi^+e^-\bar{\nu}_e + c.c.$	$< 1.7 \times 10^{-4}$	CL=90%	256
$\pi^+\pi^-\tau^+\tau^-$	$< 2.1 \times 10^{-3}$		236
$\pi^+\pi^-\pi^0\gamma$	$< 5 \times 10^{-4}$	CL=90%	174
$\pi^0\mu^+\mu^-\gamma$	$< 3 \times 10^{-6}$	CL=90%	210

Charge conjugation (C), Parity (P),
Charge conjugation \times Parity (CP), or
Lepton Family number (LF) violating modes

Mode	Fraction	Scale factor/ Confidence level	p (MeV/c)
$\pi^0\gamma$	$< 9 \times 10^{-5}$	CL=90%	257
$\pi^+\pi^-\pi^0$	$< 1.3 \times 10^{-5}$	CL=90%	236
$2\pi^0$	$< 3.5 \times 10^{-4}$	CL=90%	238
$2\pi^0\gamma$	$< 5 \times 10^{-4}$	CL=90%	238
$3\pi^0\gamma$	$< 6 \times 10^{-5}$	CL=90%	179
3γ	$< 1.6 \times 10^{-5}$	CL=90%	274
$4\pi^0$	$< 6.9 \times 10^{-7}$	CL=90%	40
$\pi^0 e^+ e^-$	$[f] < 4 \times 10^{-5}$	CL=90%	257
$\pi^0 \mu^+ \mu^-$	$[f] < 5 \times 10^{-6}$	CL=90%	210
$\mu^+ e^- + \mu^- e^+$	$< 6 \times 10^{-6}$	CL=90%	264

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GAUGE AND HIGGS BOSONS

γ (photon)

$J^G(J^PC) = 0(1^{--})$

Mass $m < 1 \times 10^{-18}$ eV
Charge $q < 1 \times 10^{-35}$ e
Mean life $\tau = \text{Stable}$

g or gluon

$J^G(J^PC) = 0(1^-)$

Mass $m = 0 [a]$
SU(3) color octet

graviton

$J = 2$

Mass $m < 6 \times 10^{-32}$ eV

W

$J = 1$

Charge = ± 1 e
Mass $m = 80.379 \pm 0.012$ GeV
 W/Z mass ratio = 0.88153 ± 0.00017

Mode	Fraction	Scale factor/ Confidence level	p (MeV/c)
$\pi^+\gamma$	$< 7 \times 10^{-6}$	95%	40189
$D_s^+\gamma$	$< 1.3 \times 10^{-3}$	95%	40165
cX	$(33.3 \pm 2.6) \%$		-
$c\bar{s}$	$(31^{+13}_{-11}) \%$		-
invisible	$[c] (1.4 \pm 2.9) \%$		-

W⁻ DECAY MODES

Mode	Fraction	Scale factor/ Confidence level	p (MeV/c)
$\ell^+\nu$			
$e^+\nu$			
$\mu^+\nu$			
$\tau^+\nu$			
hadrons			

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Citation: M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

Z

$J = 1$

Charge = 0
Mass $m = 91.1876 \pm 0.0021$ GeV [d]
Full width $\Gamma = 2.4952 \pm 0.0023$ GeV
 $\Gamma(\ell^+\ell^-) = 83.984 \pm 0.086$ MeV [b]
 $\Gamma(\text{invisible}) = 499.0 \pm 1.5$ MeV [e]
 $\Gamma(\text{hadrons}) = 1744.4 \pm 2.0$ MeV
 $\Gamma(\mu^+\mu^-)/\Gamma(e^+e^-) = 1.0009 \pm 0.0028$
 $\Gamma(\tau^+\tau^-)/\Gamma(e^+e^-) = 1.0019 \pm 0.0032 [f]$

Average charged multiplicity
 $\langle N_{\text{charged}} \rangle = 20.76 \pm 0.16$ ($S = 2.1$)

Couplings to quarks and leptons

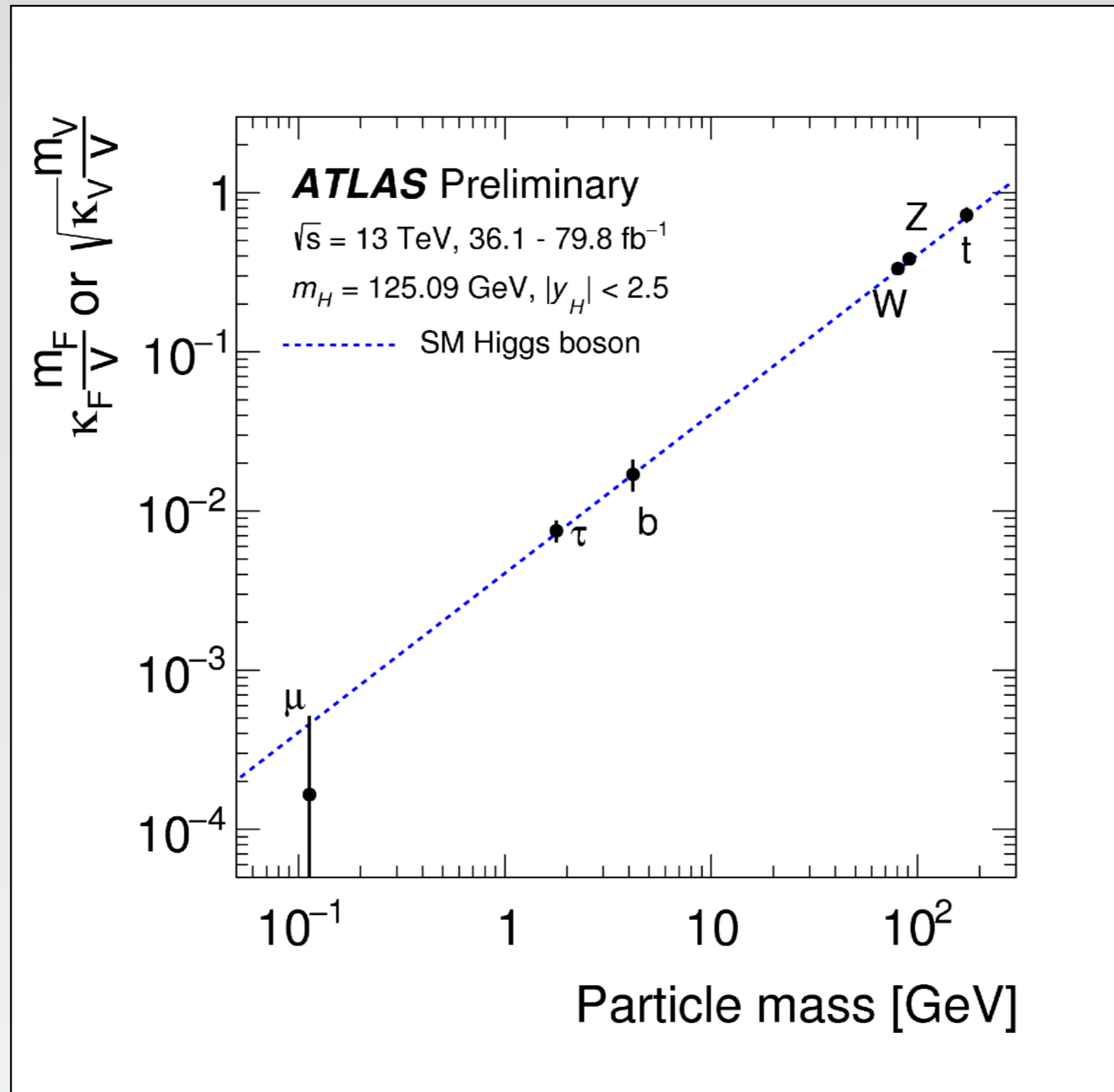
g_V^f	-0.03783 ± 0.00041
g_V^e	0.18 ± 0.05
g_V^ν	$-0.35^{+0.05}_{-0.06}$
g_A^f	-0.50123 ± 0.00026
g_A^e	0.50 ± 0.04
g_A^ν	$-0.514^{+0.050}_{-0.029}$
$g^{f'e}$	0.5008 ± 0.0008
$g^{f'\nu}$	0.53 ± 0.09
$g^{e'\mu}$	0.502 ± 0.017

Asymmetry parameters [a]

A_e	0.1515 ± 0.0019
A_μ	0.142 ± 0.015
A_τ	0.143 ± 0.004
A_b	0.90 ± 0.09
A_c	0.670 ± 0.027
A_b	0.923 ± 0.020

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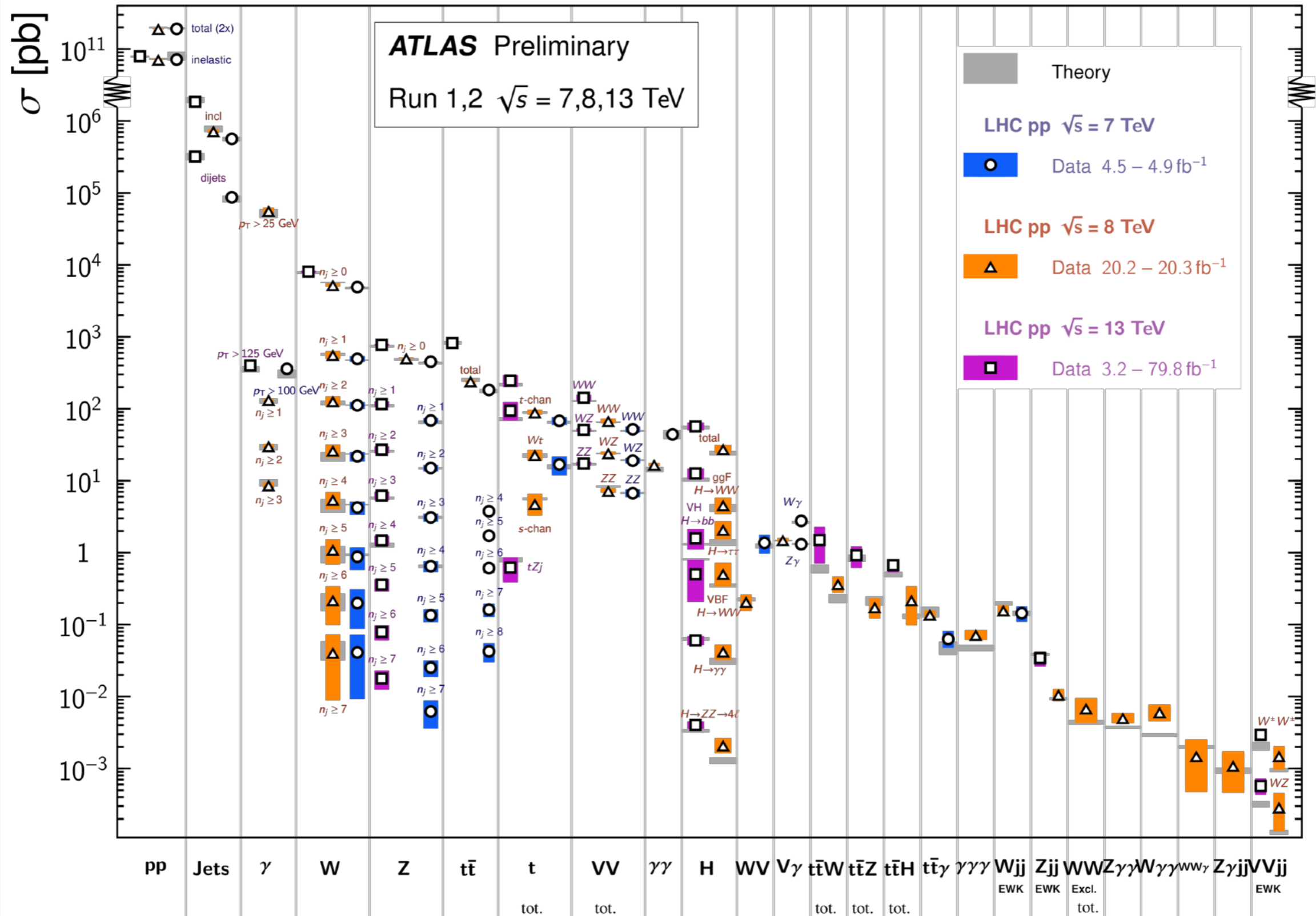
Modèle standard au LHC



Modèle standard au LHC

Standard Model Production Cross Section Measurements

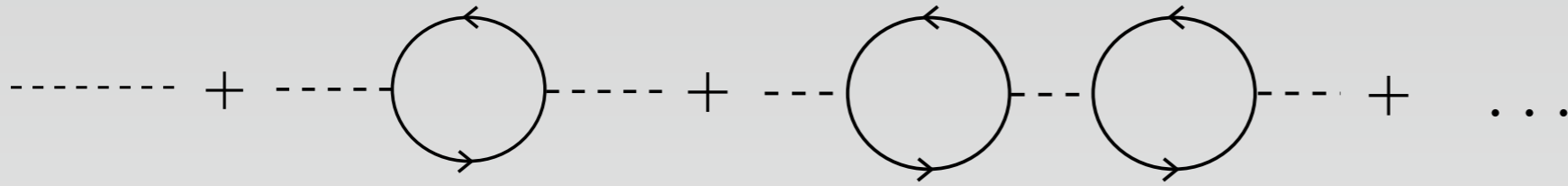
Status: July 2018



Hiérarchie des échelles

$$E_{\text{Planck}} = \sqrt{\frac{\hbar c^5}{G}} = 1.22 \times 10^{19} \text{ GeV}$$

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



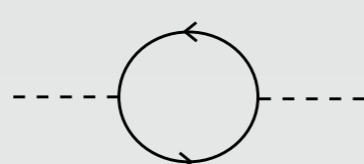
$$\left(\frac{1}{k^2 - m^2} \right)$$

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

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

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

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



A Feynman diagram showing a tadpole loop. It consists of a central circle with two arrows on its circumference, one pointing clockwise and one pointing counter-clockwise. Two dashed lines extend horizontally from the left and right sides of the circle, representing external legs.

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

Electrons : $\xi \propto m^2 \ln \Lambda$

Spin nul (Higgs) : $\xi \propto \Lambda^2$

Solutions au problème de la hiérarchie

- Ajustement très fin des paramètres du modèle standard
- Le boson de Higgs n'est pas élémentaire
- Il existe de nouvelles particules/interactions à l'échelle du TeV
- M_{planck} n'est pas l'échelle fondamentale

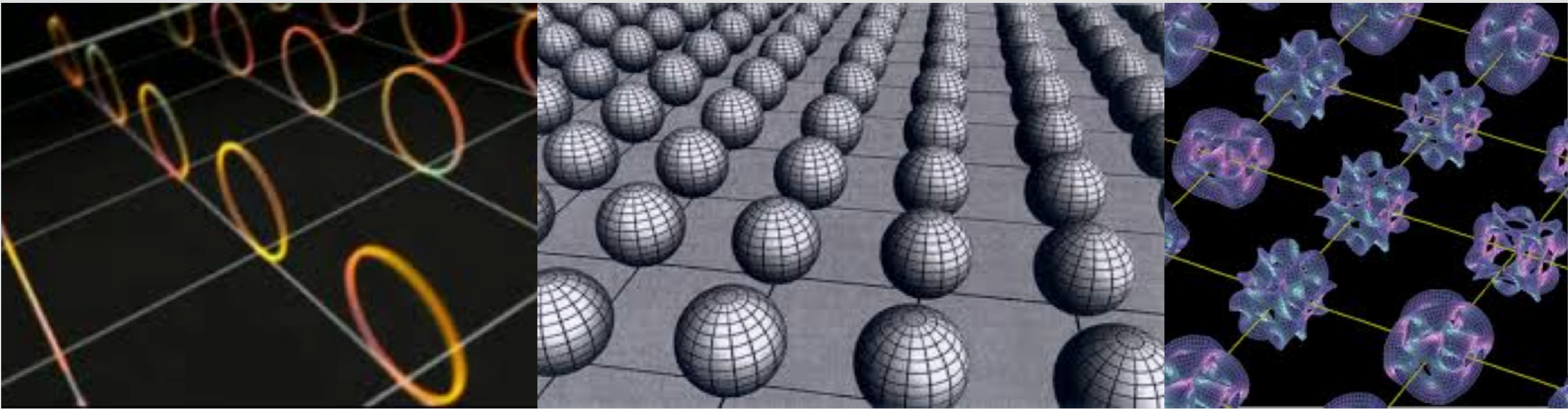
Supersymétrie

Nouvelle symétrie bosons/fermions

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

Nouvelles particules : potentiellement celle de la matière noire

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

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

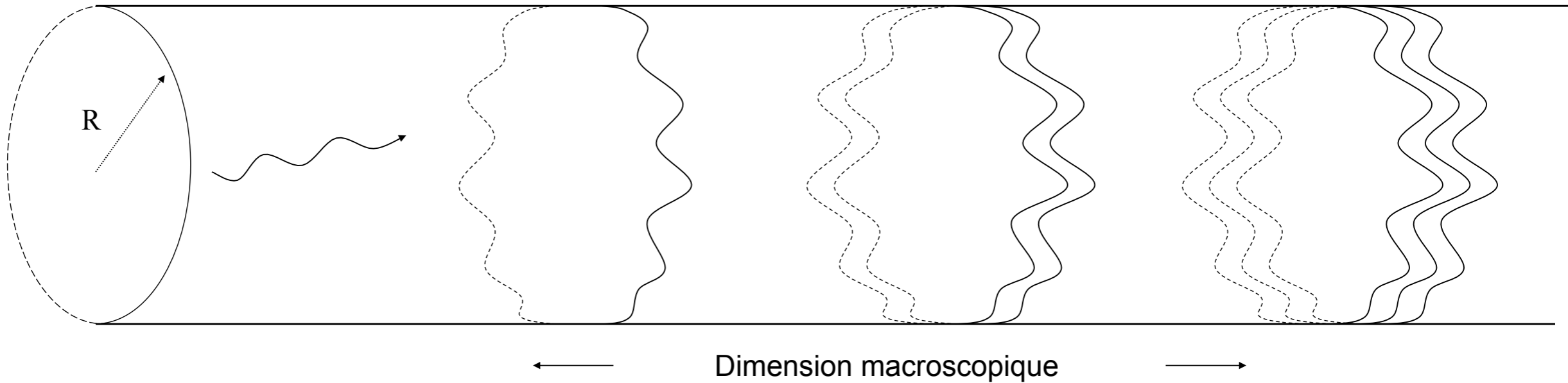
$$\psi(x, t) = \psi_0 e^{-i(Et - px)} \times \exp\left(i \frac{2\pi n}{R} \epsilon\right)$$

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

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

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

Dimension supplémentaire



Densité relique de WIMPs

Equilibre via : $\chi + \bar{\chi} \rightleftharpoons A + \bar{A}$

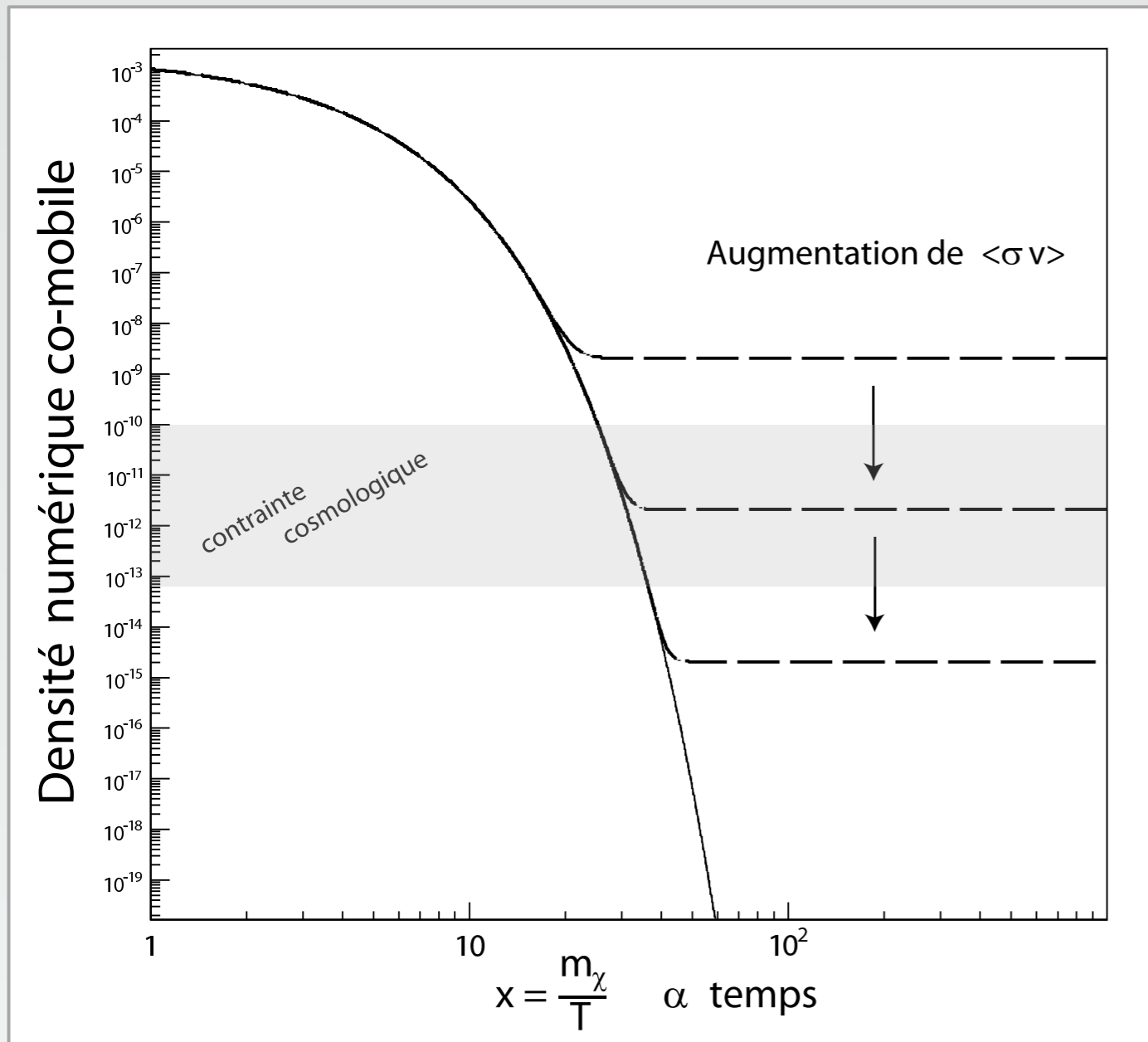
Haute température : $n_{\chi}^{\text{eq}} \propto n_{\gamma} \propto T^4$

Basse température : $n_{\chi}^{\text{eq}} \propto (m_{\chi} T)^{3/2} \times \exp\left(-\frac{m_{\chi} c^2}{kT}\right)$

Départ de l'équilibre thermique : équation de Boltzmann

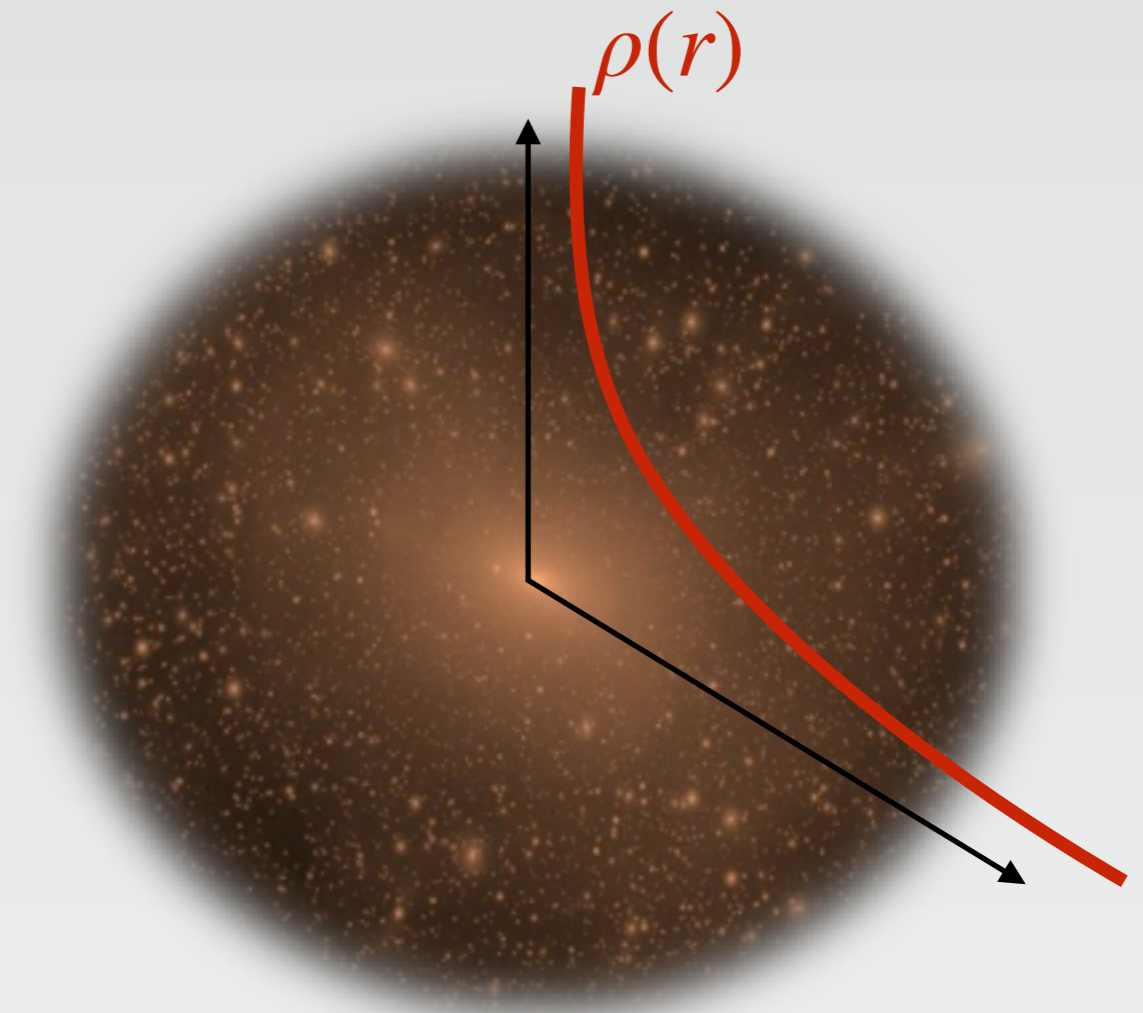
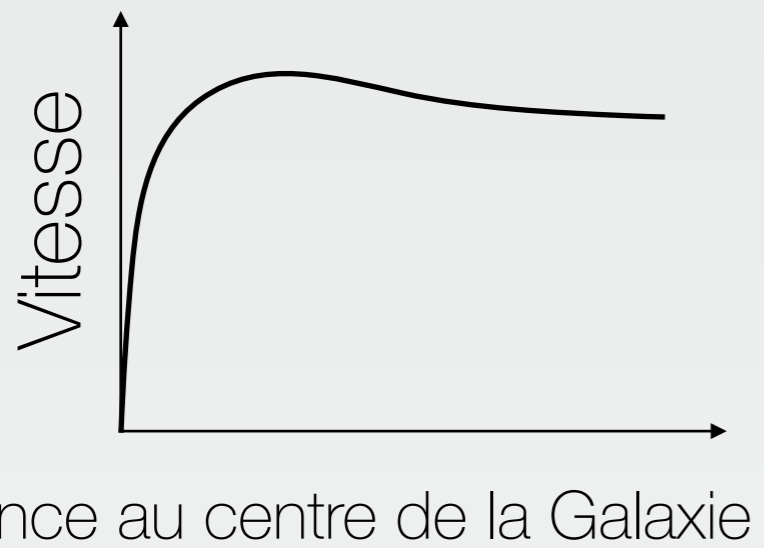
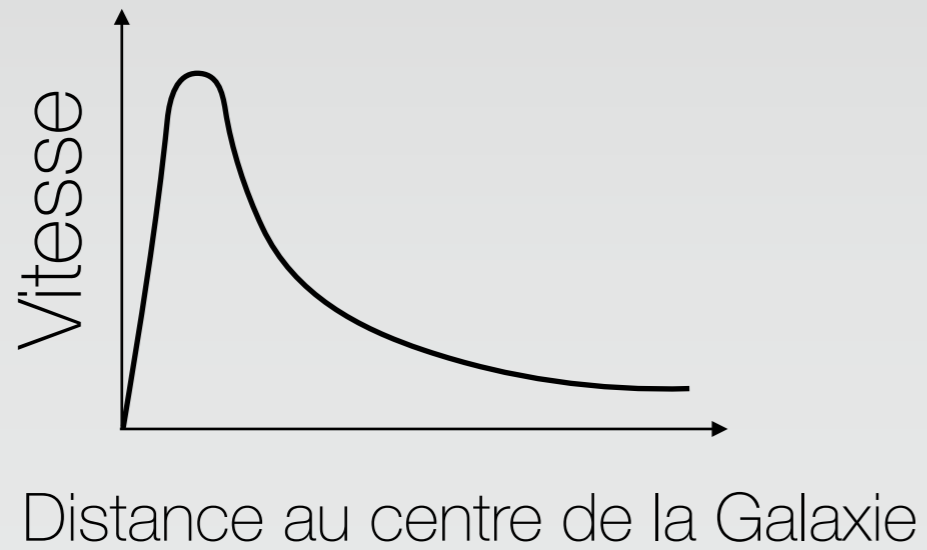
Densité relique de WIMPs

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

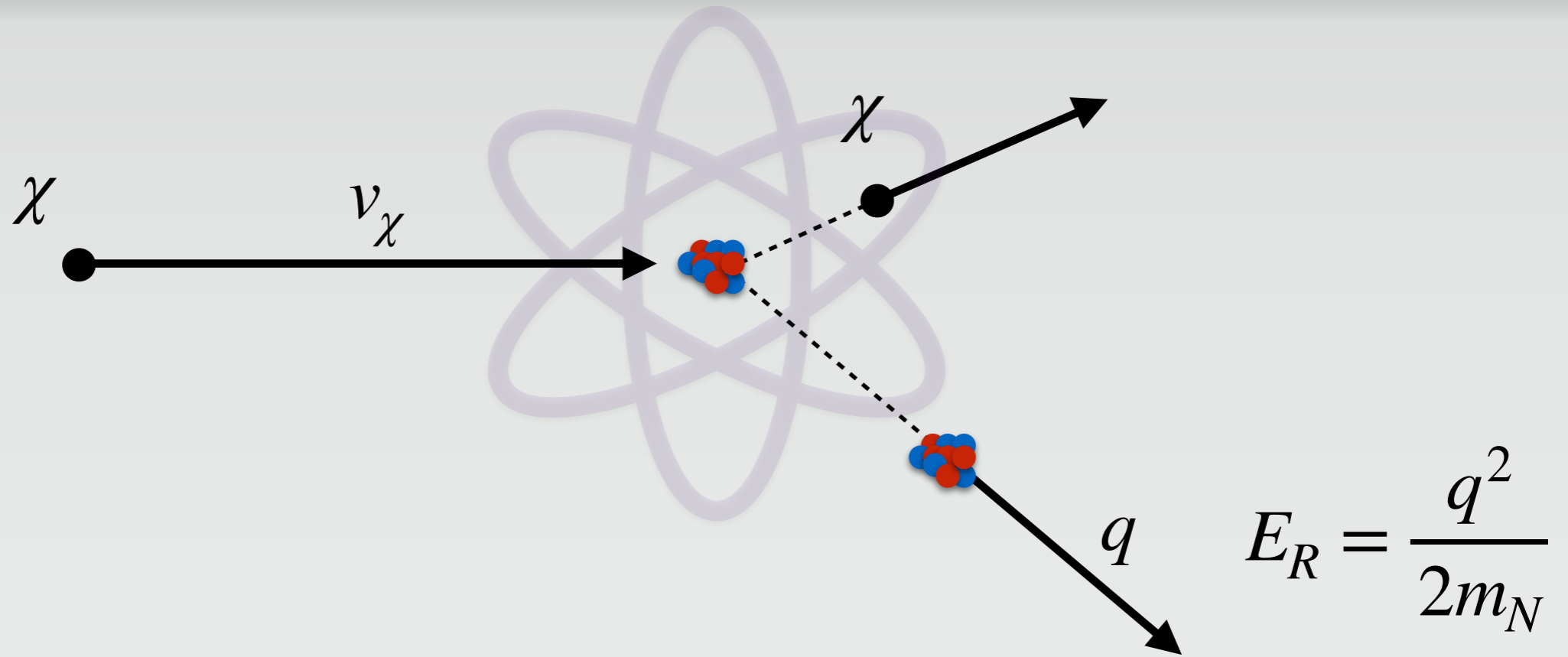


$$\Omega_\chi h^2 = \frac{3 \times 10^{-27} \text{ cm}^3/\text{s}}{\langle \sigma v \rangle}$$

Halo de matière noire



Recherche directe

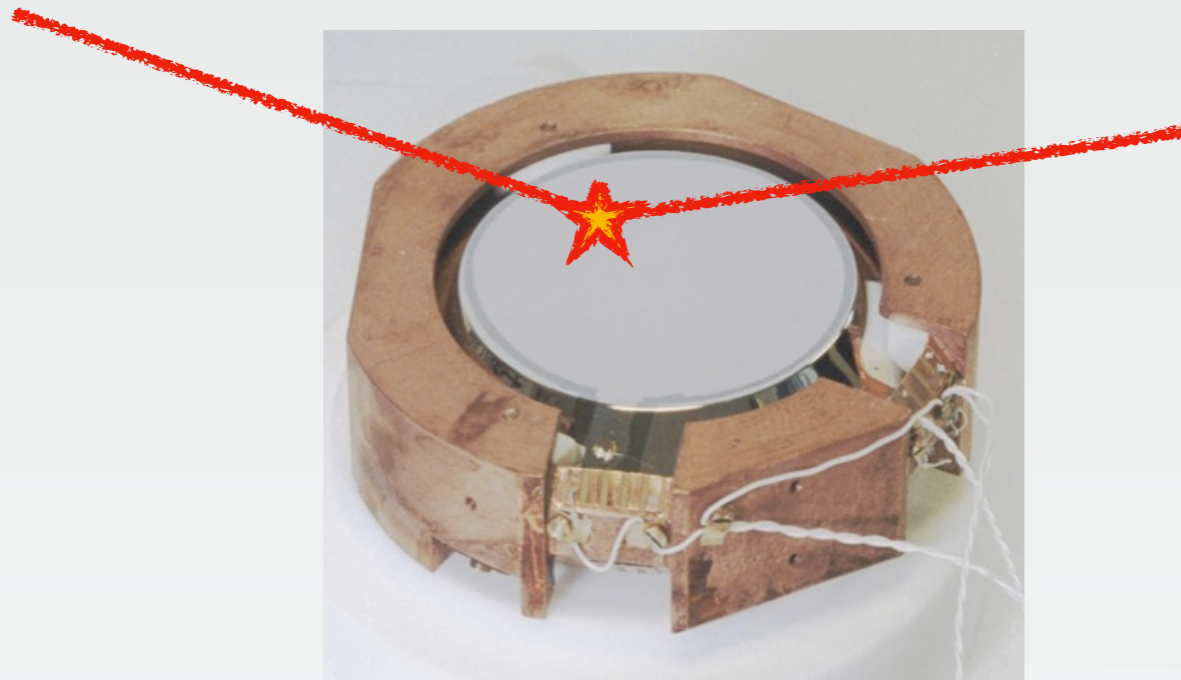
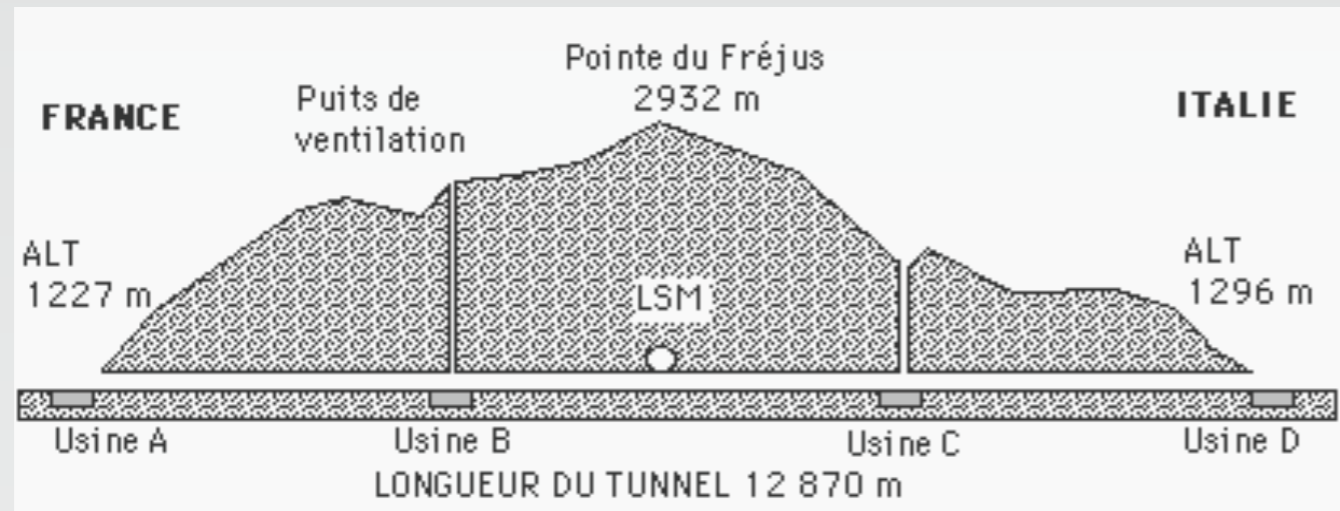


Noyau au repos, centre de masse : $(m_N + m_\chi)v^\star = m_\chi v_\chi$

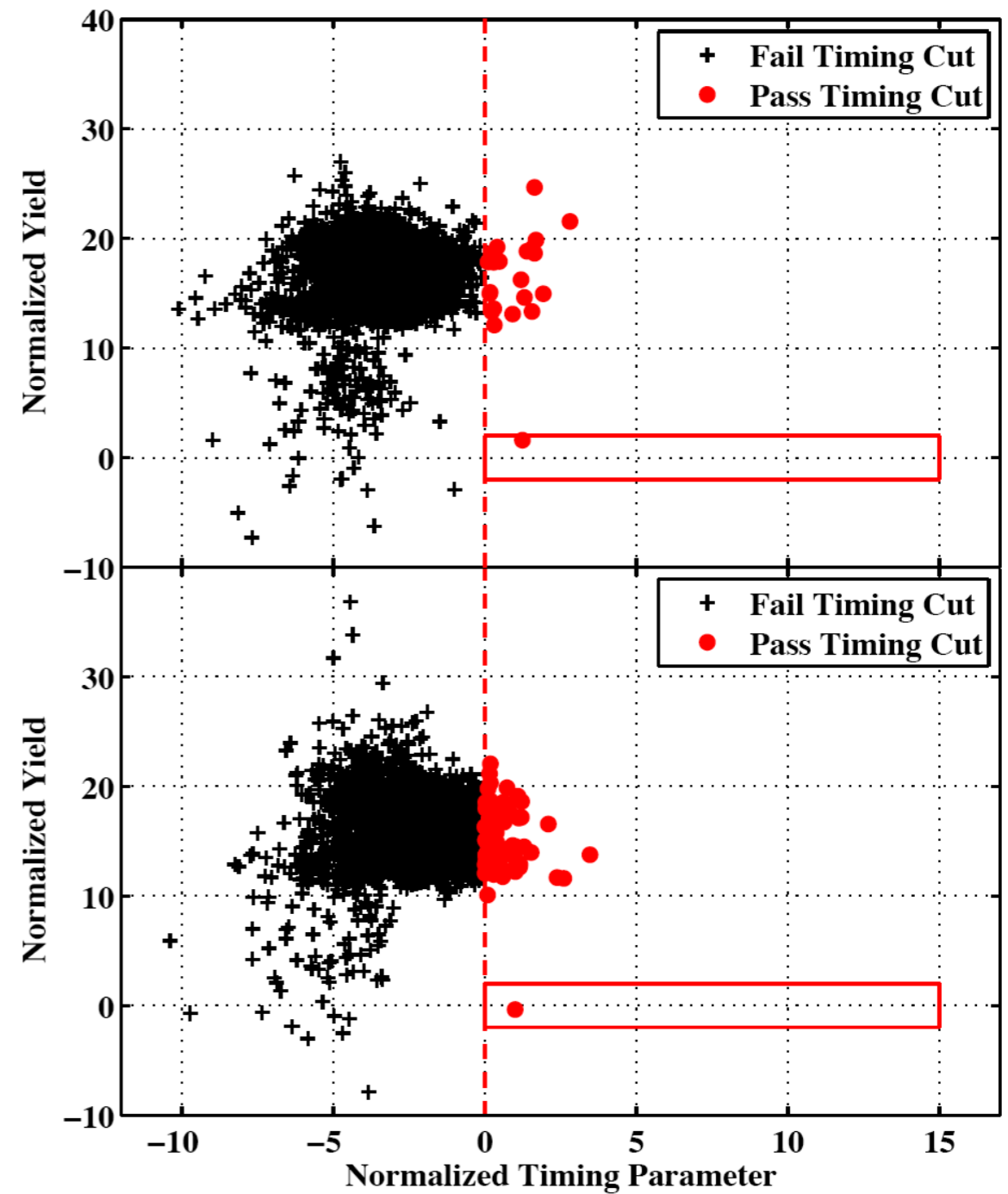
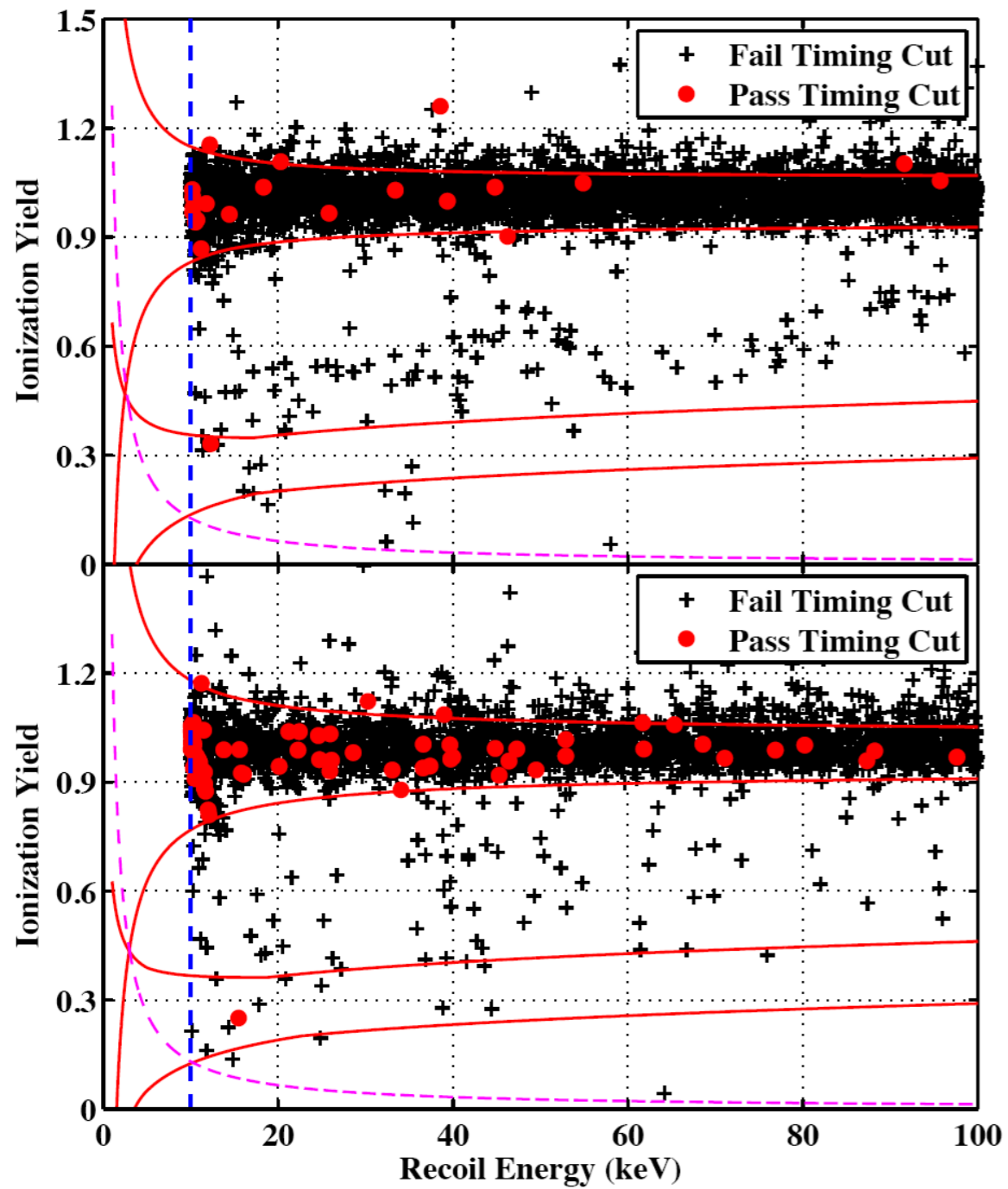
$$\mu = \frac{m_\chi m_N}{m_\chi + m_N} \quad \Rightarrow \quad E_R = \frac{\mu^2 v_\chi^2}{m_N} (1 - \cos \theta^\star)$$

Signal : $m_\chi = m_N = 100 \text{ GeV}$, $v_\chi = 220 \text{ km/s} \Rightarrow E_R^{\text{max}} = 27 \text{ keV}$

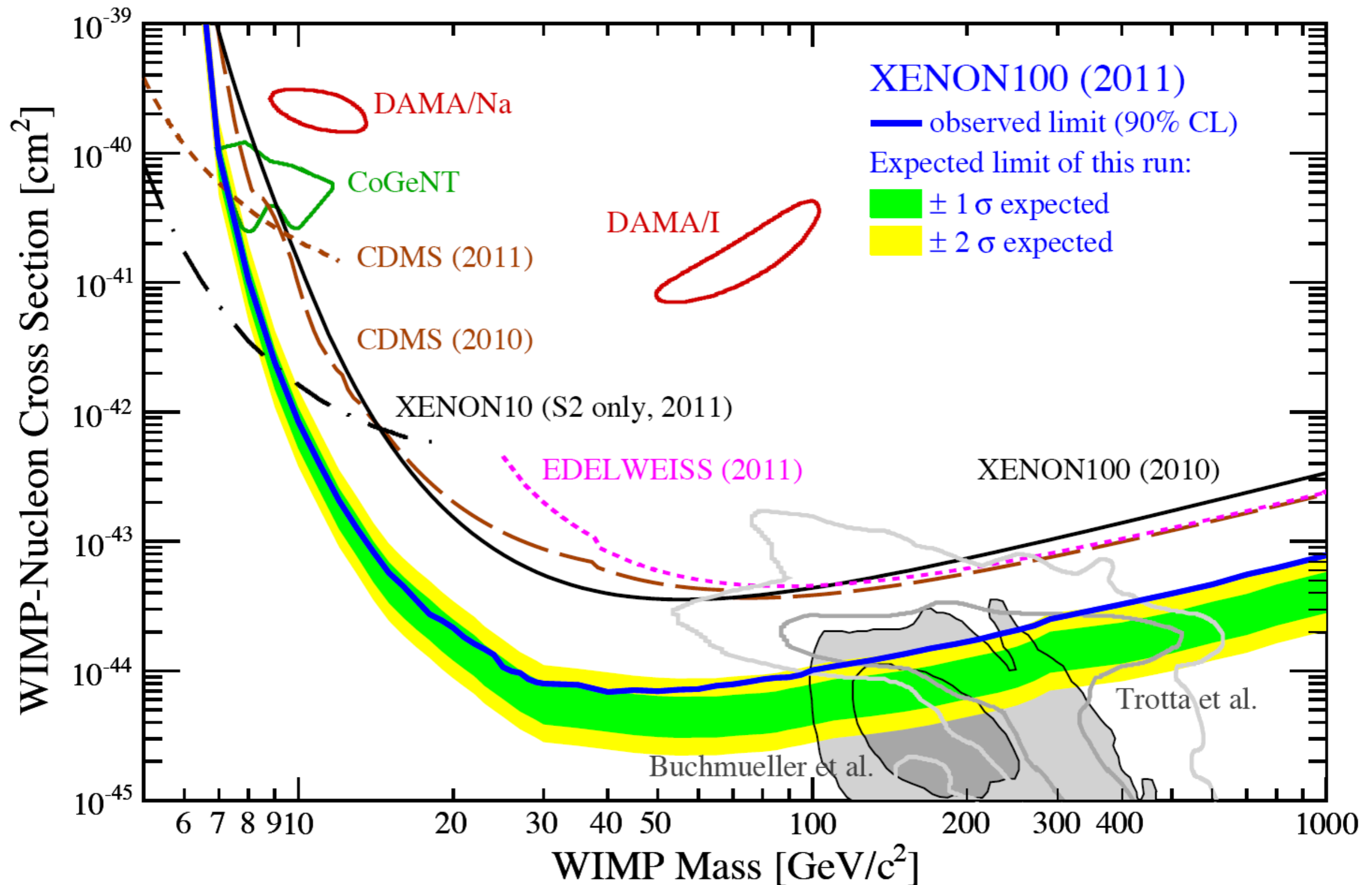
Laboratoires souterrains



Résultats : ionisation

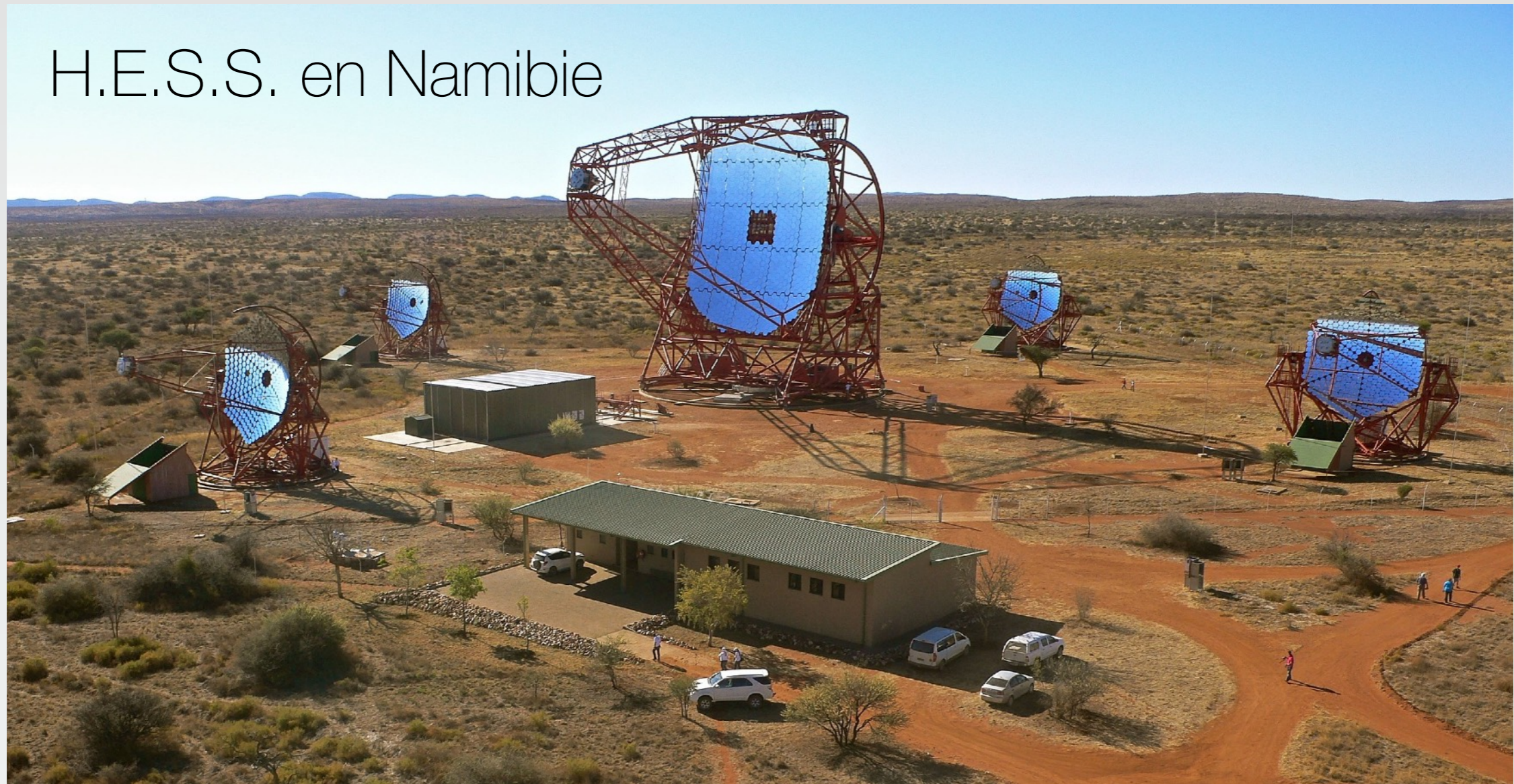


Contraintes sur les WIMPs



Recherche indirecte

H.E.S.S. en Namibie

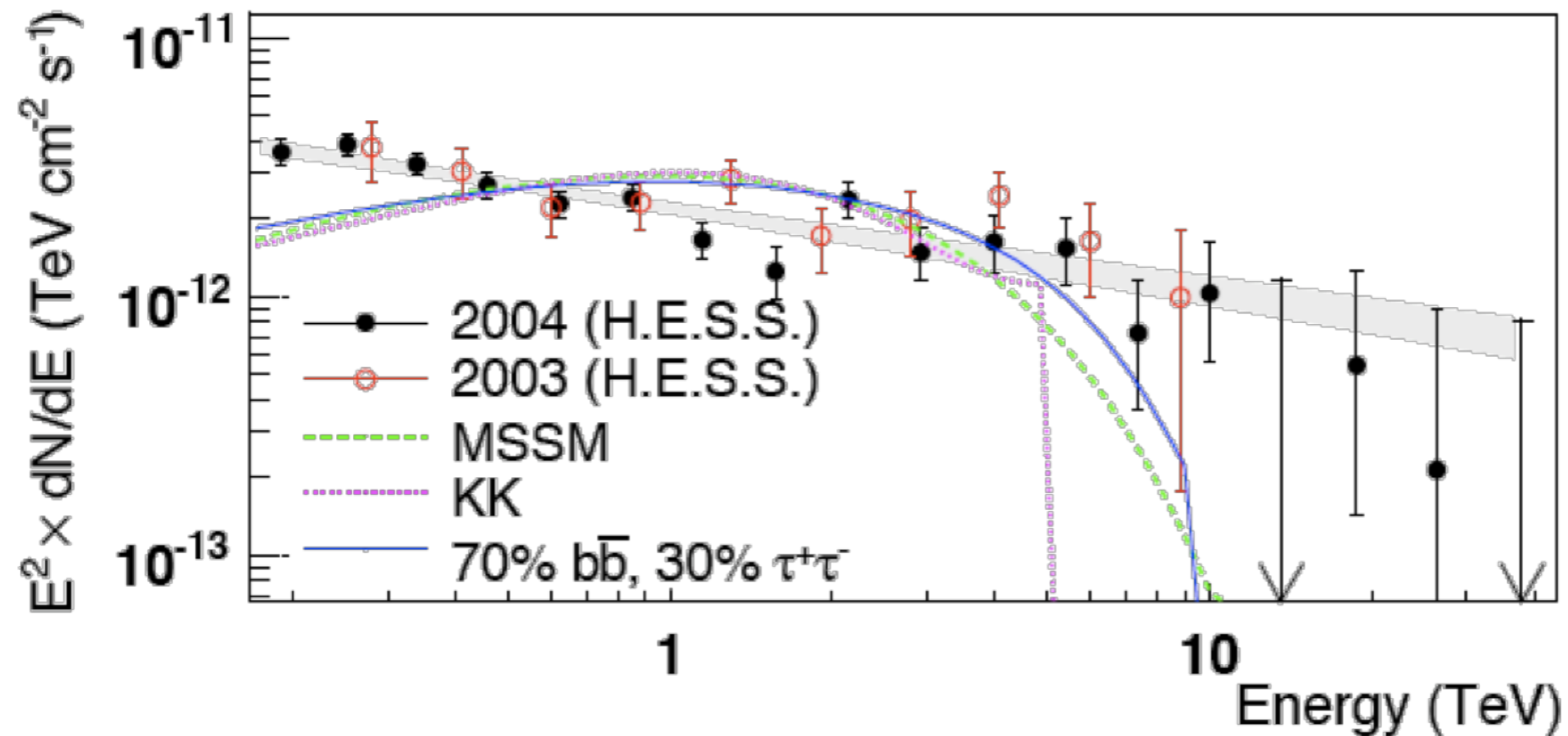


Signal d'annihilation

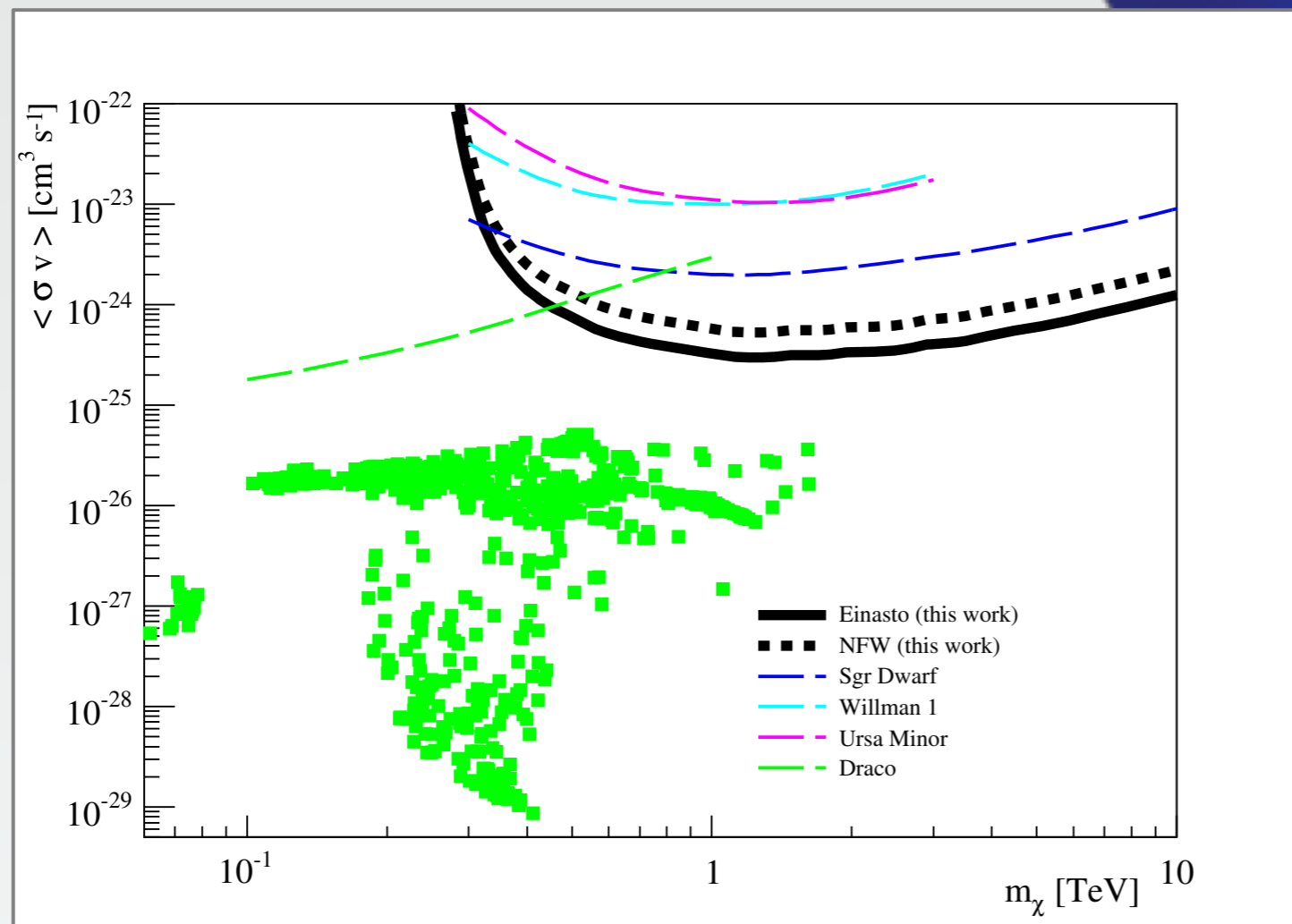
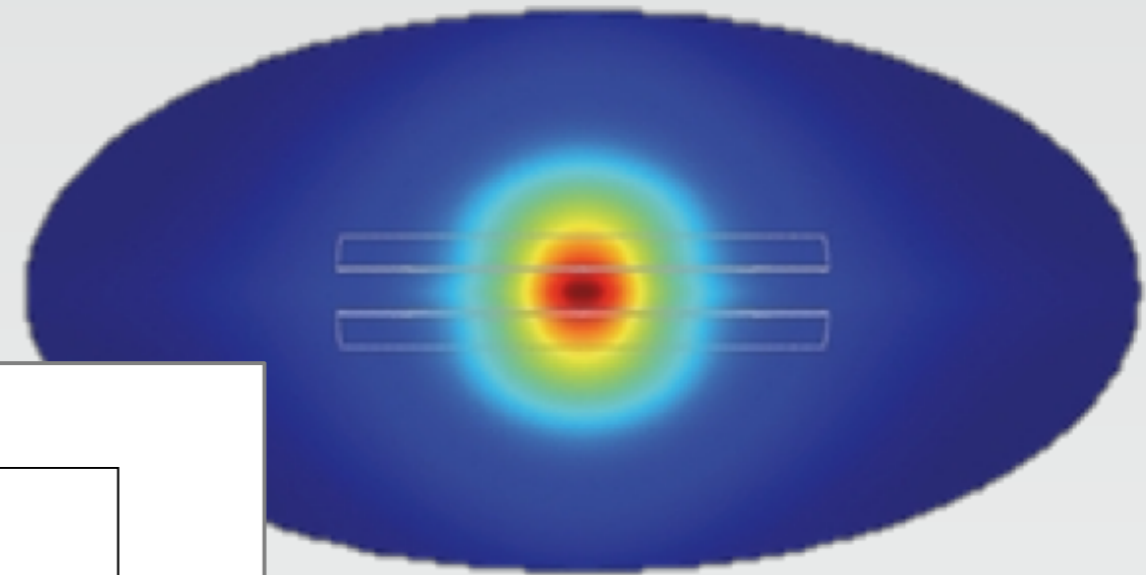
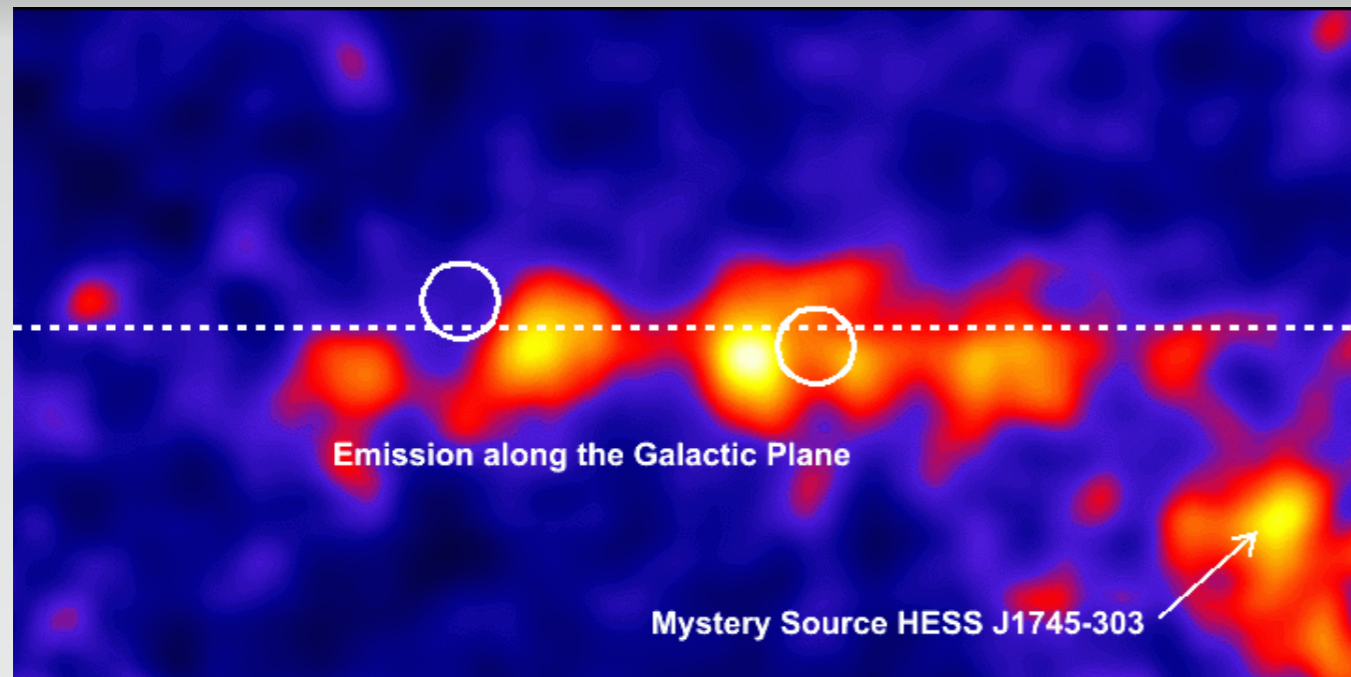
Supernova Remnant G0.9+0.1

HESS J1745-290 (The Galactic Centre)

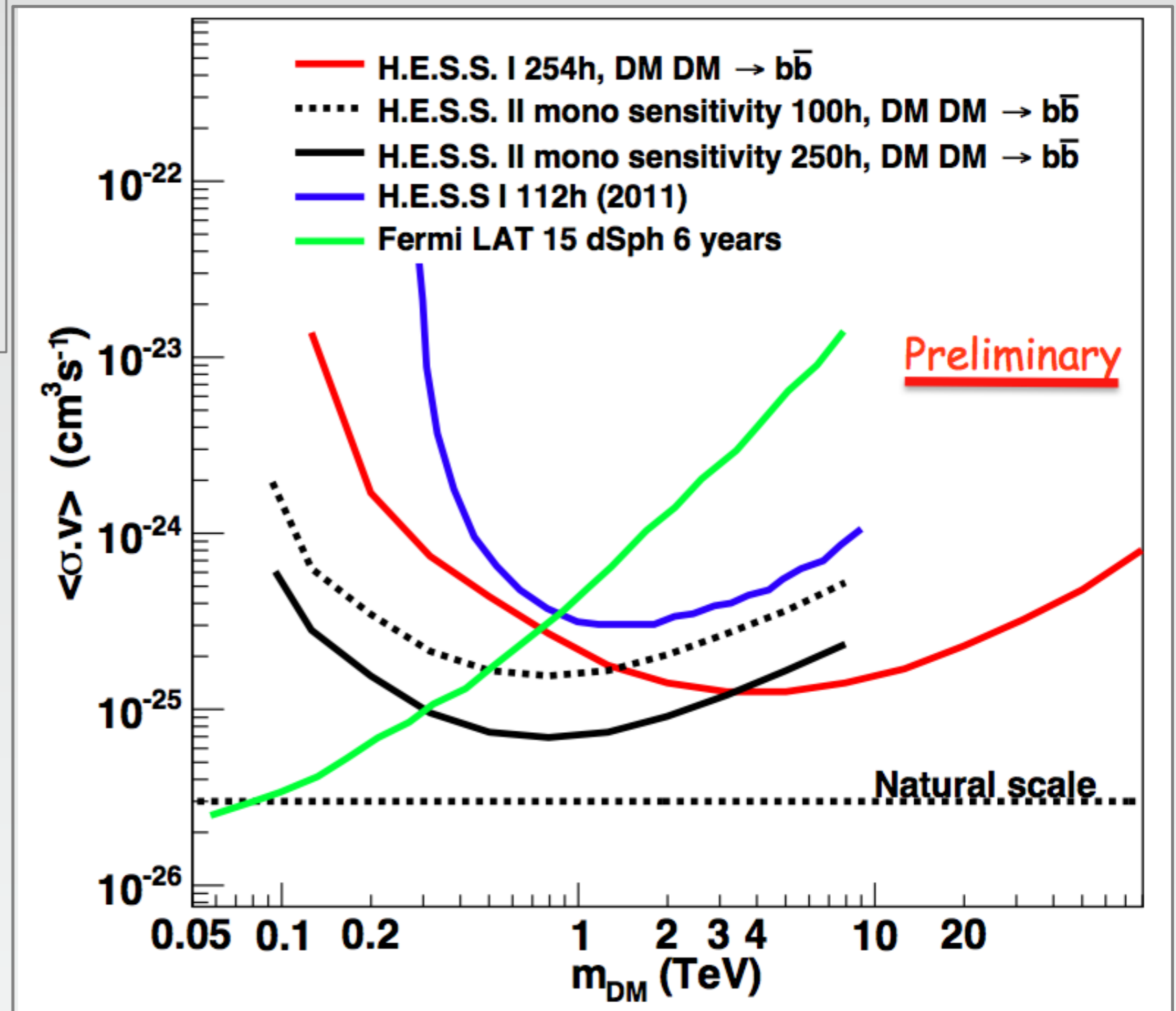
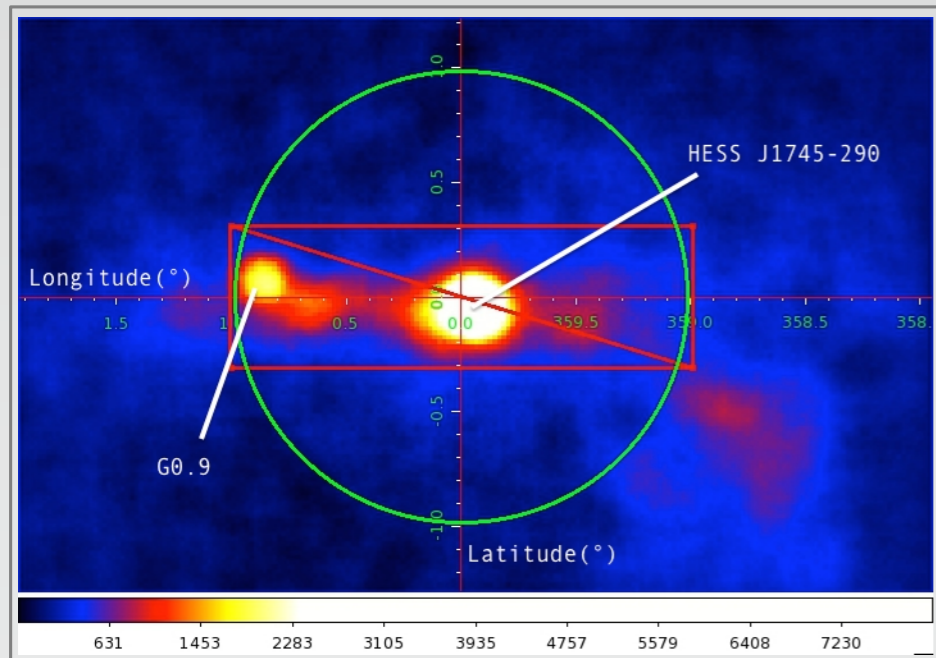
$$\phi = N(E) \frac{\langle \sigma v \rangle}{m^2} \frac{1}{4\pi D^2} \int_V dV \frac{\rho^2}{2}$$



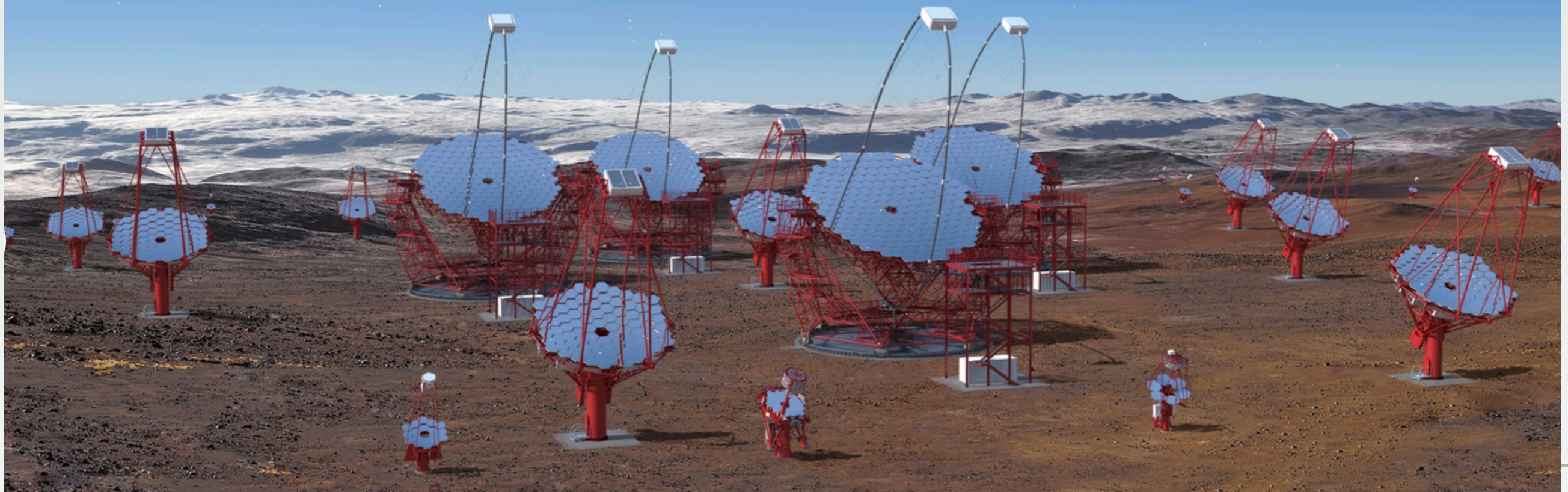
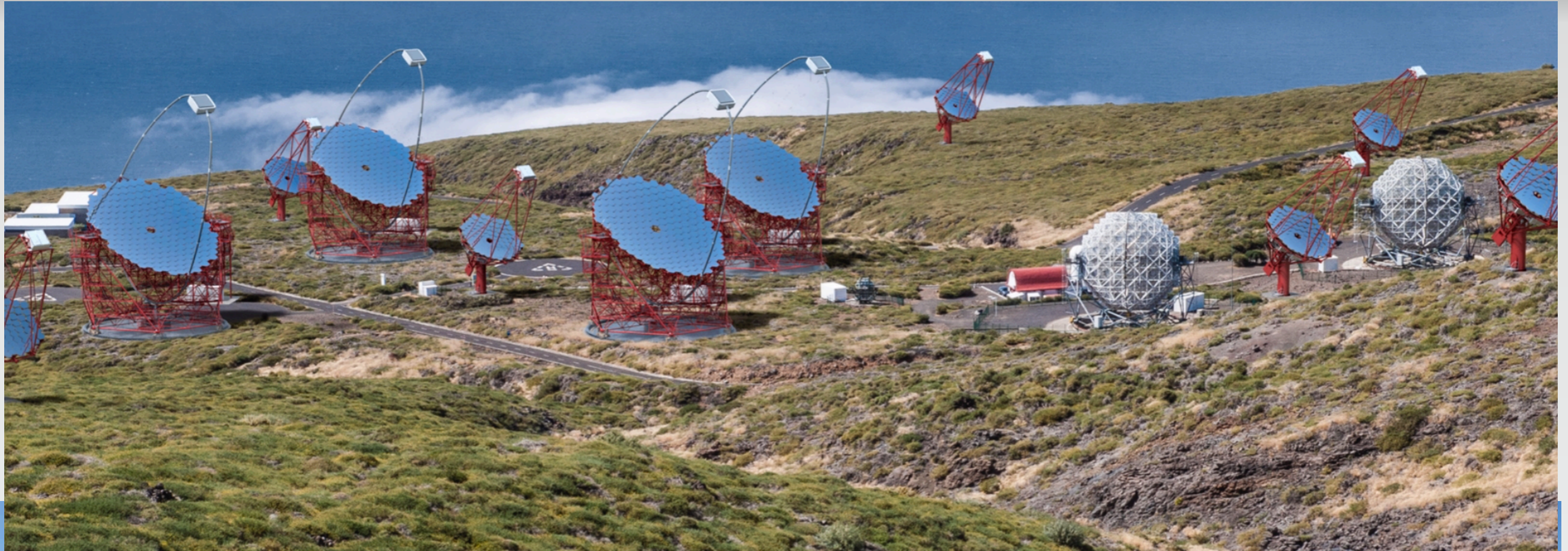
Région du centre galactique



Contraintes sur les WIMPs

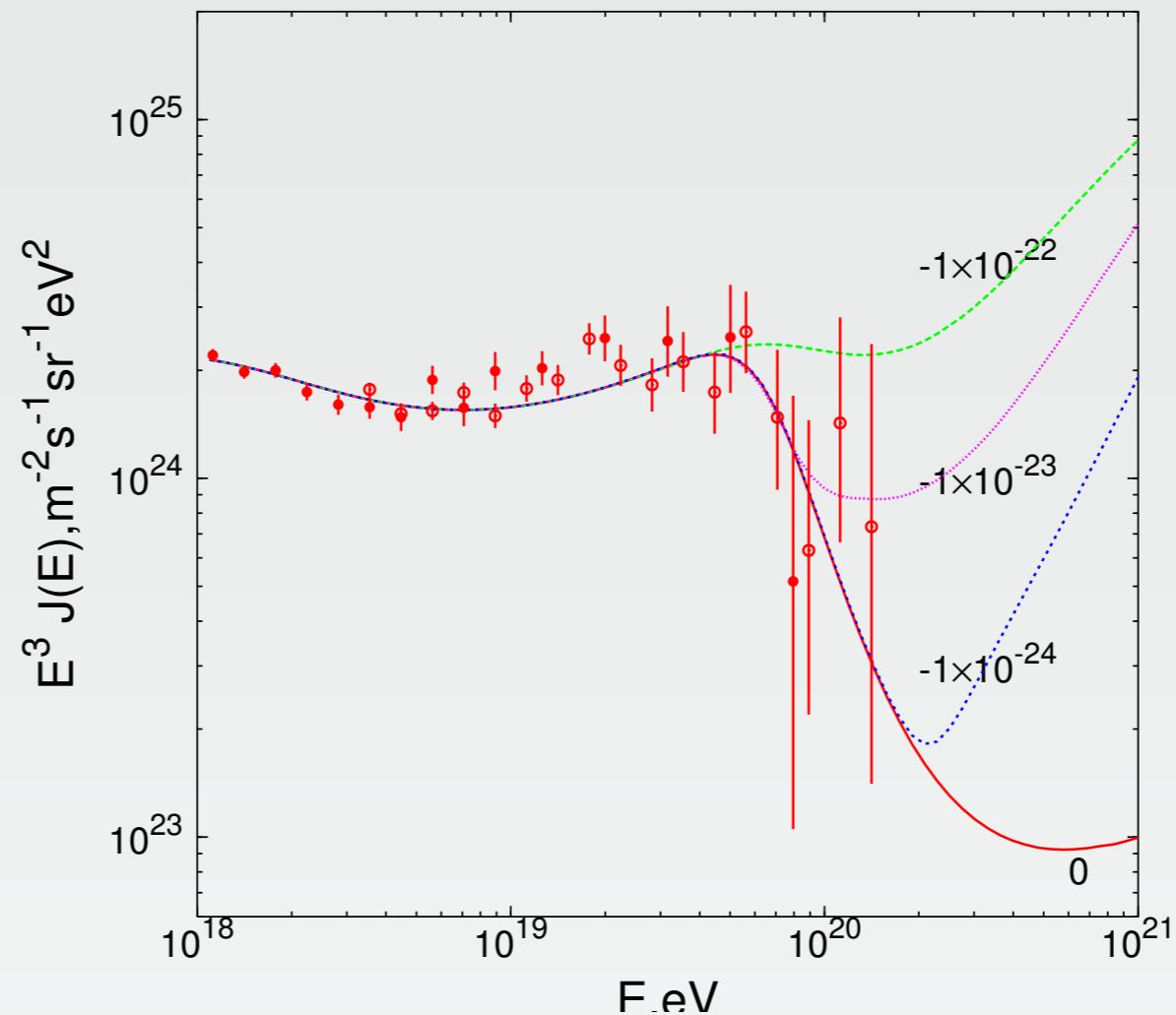


Futur : CTA



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

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



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

$$v = c \times \left(1 \pm \frac{3E}{2\Lambda} \right) \quad \Delta t \propto \frac{\Delta E}{\Lambda} \times \frac{1}{H_0} \int_0^{z_s} dz \frac{1+z}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}}$$

