CAN COSMIC RAYS SEE ANY DARK MATTER?

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- New Physics at the TeV
- Proton and heavy-nuclei knees
- Could this really work?
- Ultrahigh energy neutrinos

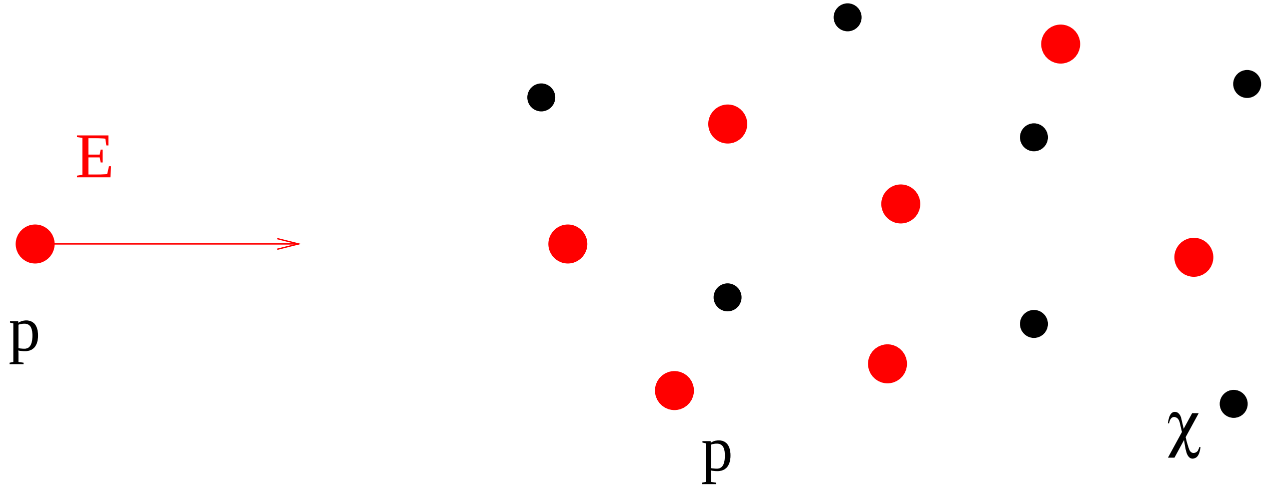
P. Draggiotis, M. Masip, I. Mastromatteo, JCAP **0807** (2008) 014

M. Masip, I. Mastromatteo, JCAP **0812** (2008) 003

R. Barceló, M. Masip, I. Mastromatteo, JCAP **0906** (2009) 027

Madrid, September 2009

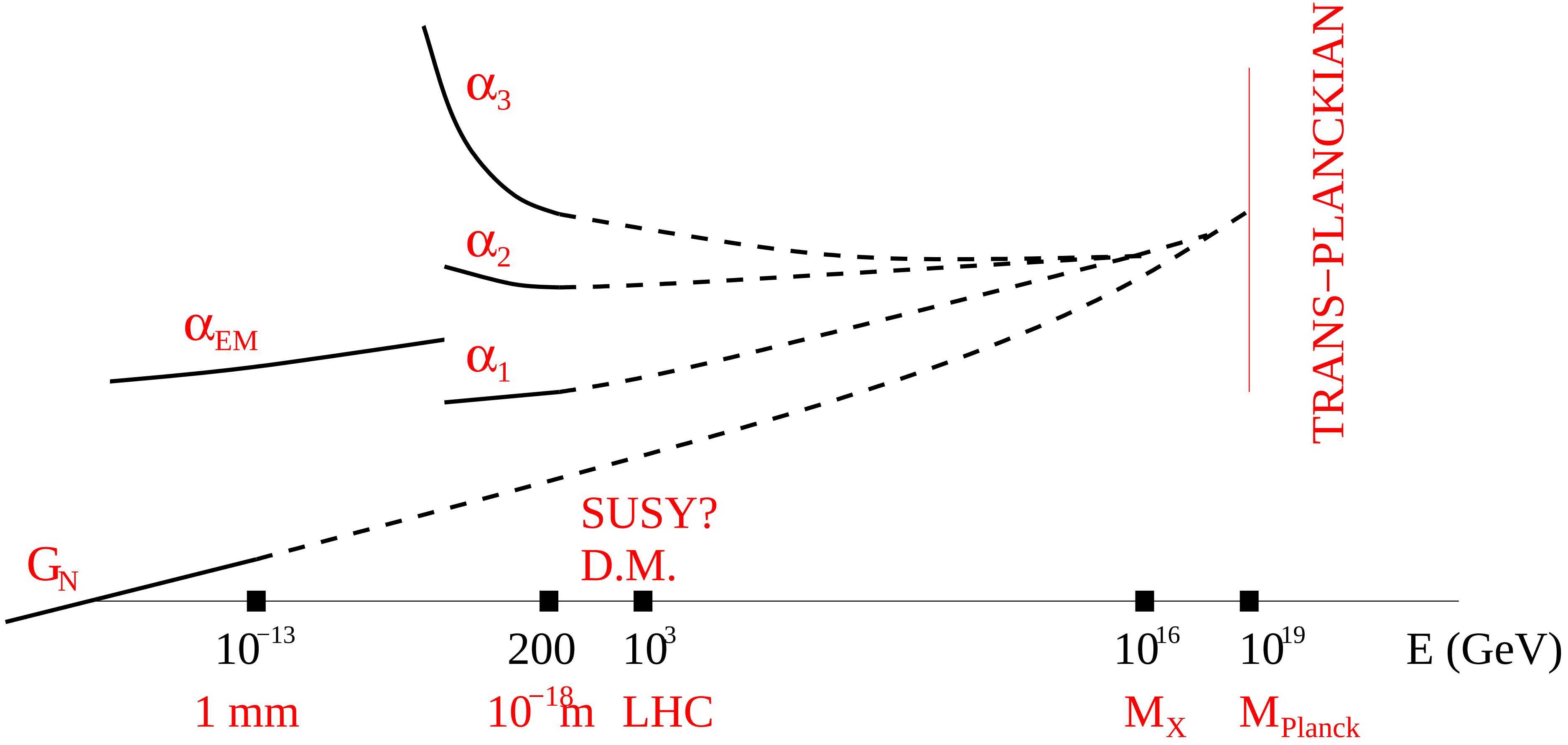
Dark $\equiv$ small cross section...



$\sigma_{pp} \approx 10$ mbarn $\qquad \sigma_{p\chi} \approx 10^{-6}$ mbarn

... but it may depend on the energy

Where is the New Physics? How *different* is it?



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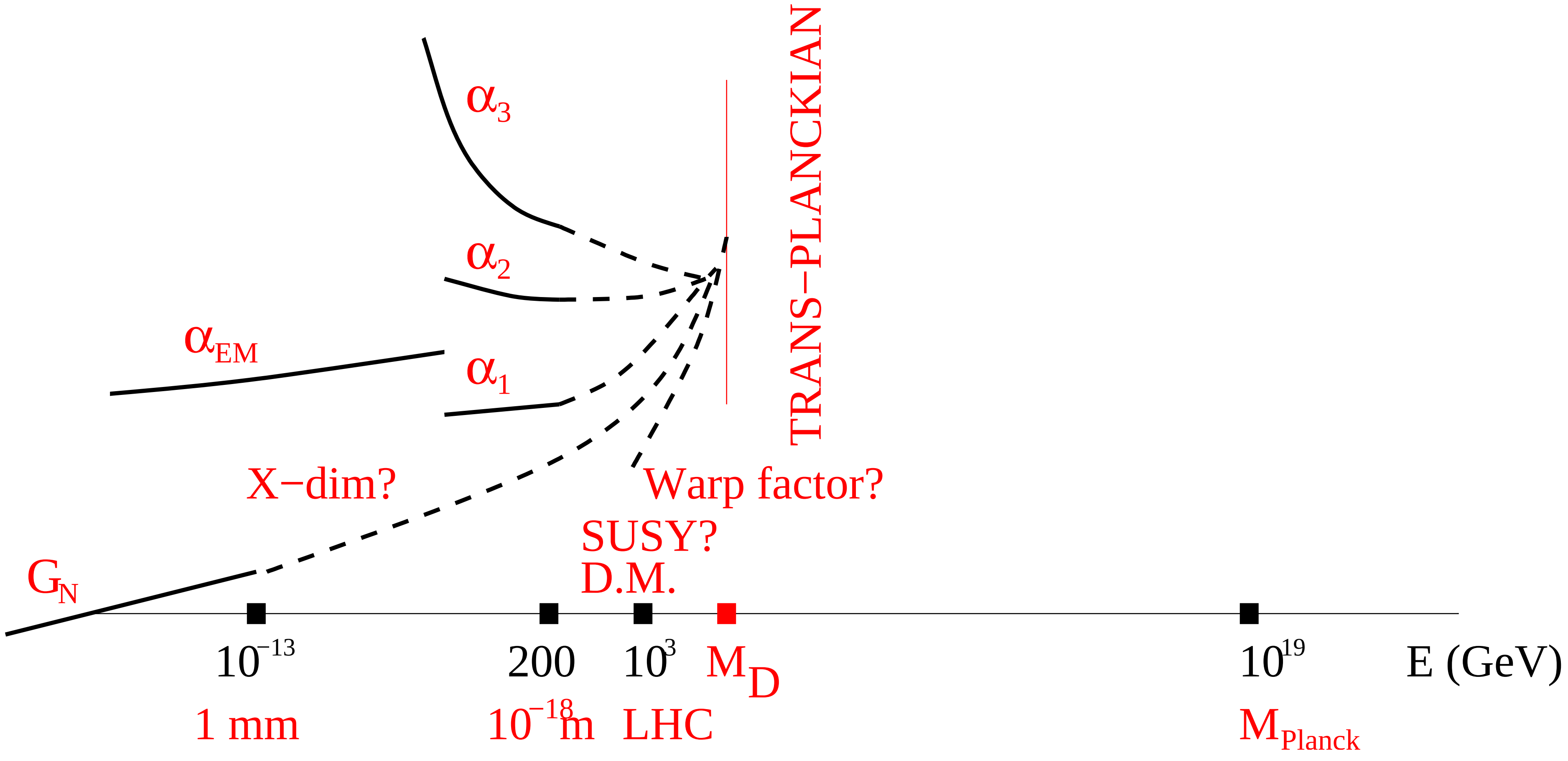
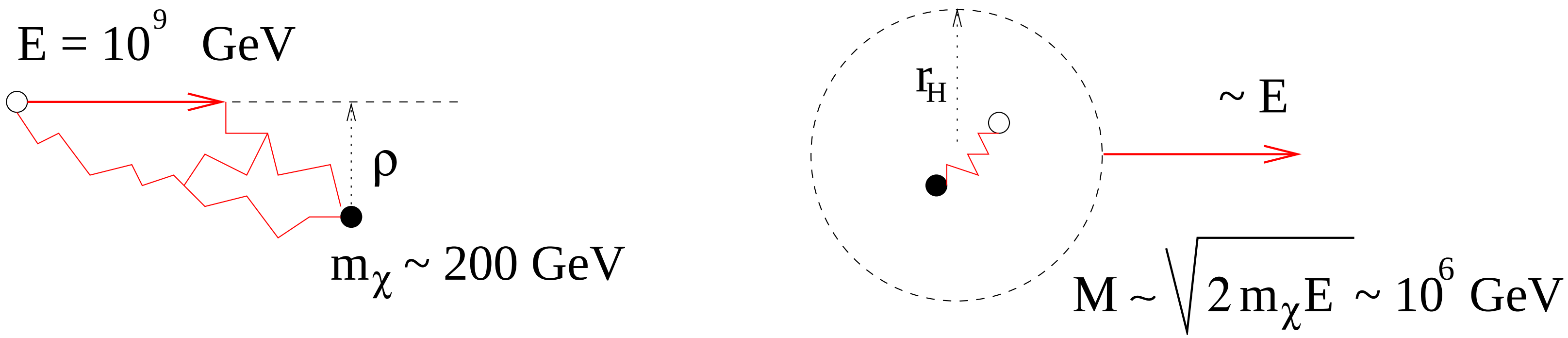


Trans-Planckian collisions

- Black Hole production



- Eikonal process

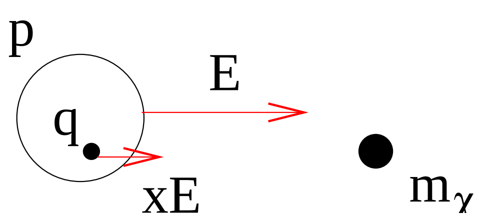
- Both are long distance processes: $r_H, b_c \ll M_D^{-1}$. To *see* quantum gravity, string theory or a Z boson the particle *needs* to go inside the horizon. Described by classical gravity (strongly coupled but no loops).

- Cross sections grow fast in the transplankian regime

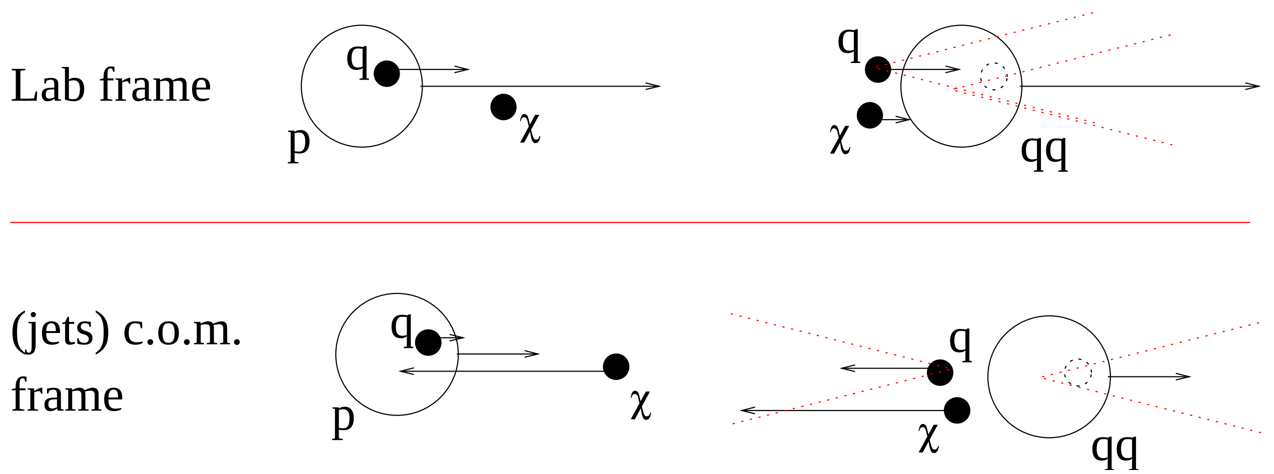
$$\sigma_{BH}^{q\chi} \approx \frac{1}{M_D^2}\left(\frac{s}{M_D^2}\right)^{\frac{1}{n+1}} \qquad \sigma_{eik}^{q\chi} \approx \frac{1}{M_D^2}\left(\frac{s}{M_D^2}\right)^{1+\frac{4}{n}}$$

- The typical distance in the interaction is still $M_D^{-1} < r_H, b_c < 1\ \mathrm{GeV}^{-1}$

χ *sees* the partons inside the proton: $\sum_i \int_{M_D^2/s}^{1} \mathrm{d}x\ f_i(x,\mu)\sigma(xs)$



Eikonal event



• HERWIG: The scattering parton and the proton remnant jets give in their c.o.m. frame a very similar spectrum of stable particles (independent of the nature of the parton), dominated by energies below 1 GeV (for any E_{jet}!).

• HERWIG: The frequency of each species is also independent on E_{jet} and of the nature of the parton

55% ν 20% γ 20% e 5% p

Possible observable effects

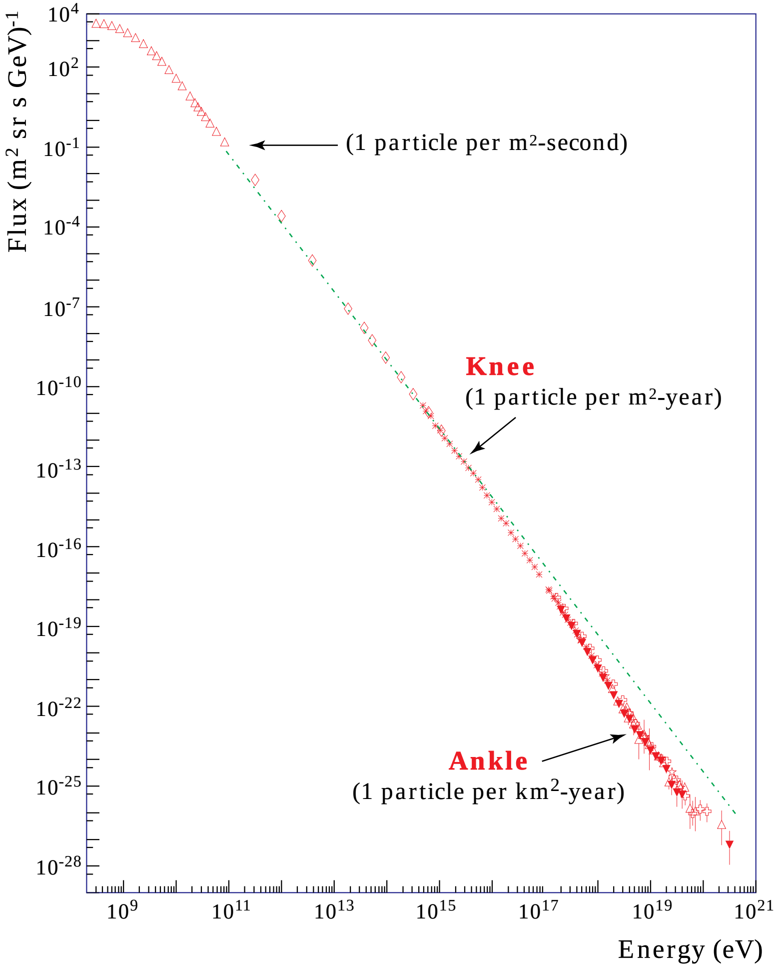
• Cosmic rays of $E \leq 10^8$ GeV are *trapped* by random magnetic fields in our galaxy ($r_L \approx 0.1$ kpc for a 10^8 GeV proton in $B = 1\ \mu$G)

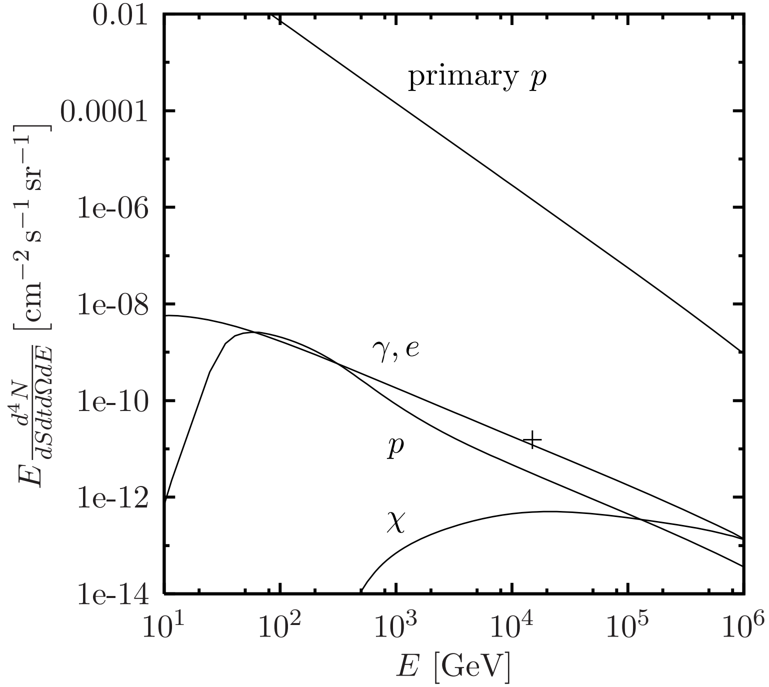
• These cosmic rays diffuse from their source (mostly in the galactic arms) and reach the Earth isotropically. Their trajectory from the production point is not a straight line, but a random walk of length l. The column density of dark matter that they face grows with time, and a fraction of them may interact before reaching the Earth.

$$p_{int} = 1 - e^{\sigma_{p\chi} n_\chi l}$$

• In these models the $\sigma_{p\chi}$ grows fast above $\sqrt{s} = \sqrt{2 m_\chi E} \approx M_D$. There could be an energy threshold where p_{int} becomes order one.

$$E_{thr} = E_{knee}??$$





$$\Phi_N \approx \int_{10^6\ \mathrm{GeV}}^{10^8\ \mathrm{GeV}} \mathrm{d}E\ 1.8\ (E^{-2.7} - 10^{1.8} E^{-3.1})\ \frac{\mathrm{nucleons}}{\mathrm{cm}^2\ \mathrm{s\ sr}}$$

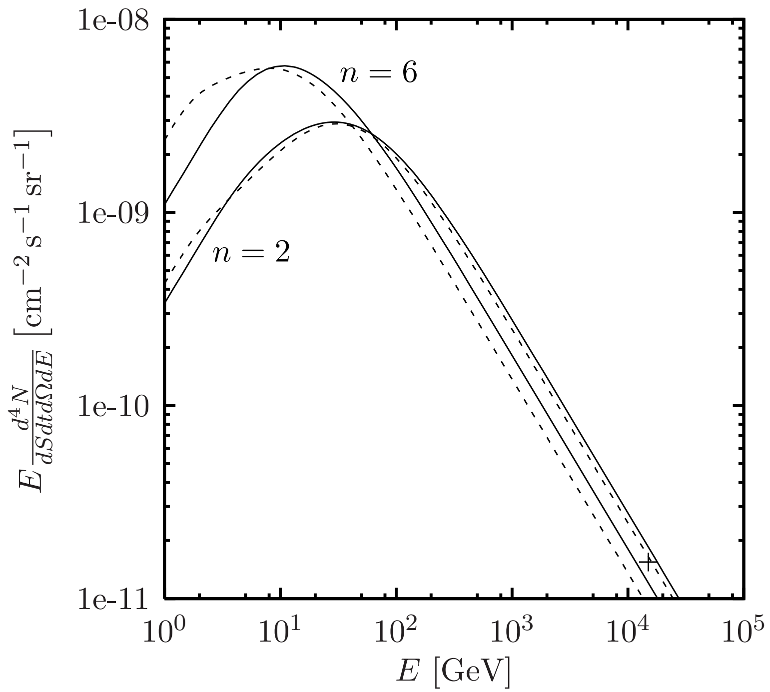
have been *processed* into secondary particles of less energy

γ-ray flux $\quad + $ MILAGRO

$m_\chi = 100$ GeV (500 GeV dashes)

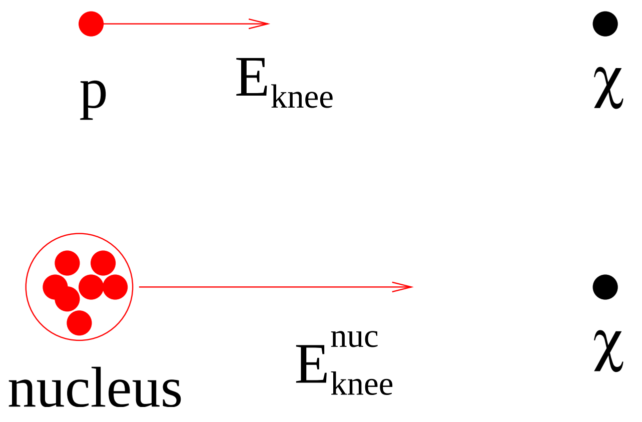
$M_D = 5$ TeV; $m_\chi = 200$ GeV

$n = 2, 6 \qquad \approx E^{-2}$



- New proton-dark matter interactions at the TeV scale could explain the knee in the cosmic ray flux at 10^6 GeV and possible anomalies in the diffuse TeV gamma ray flux.

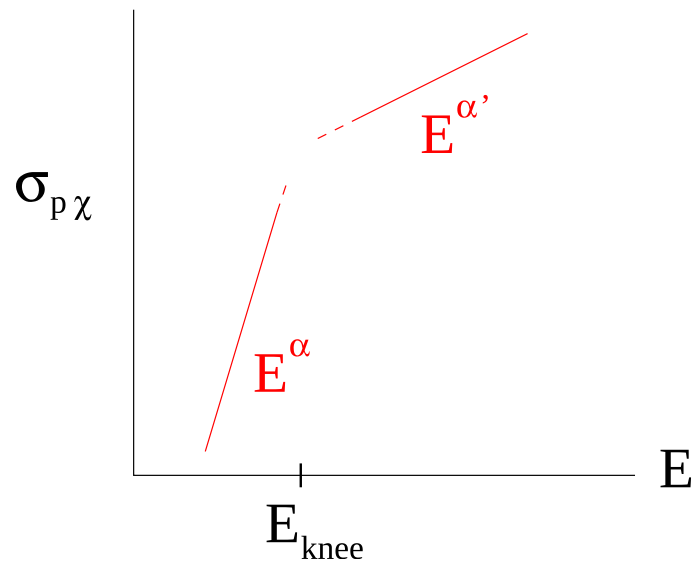
- If protons have a threshold E_{knee} where they interact with dark matter, also heavier nuclei will: He, C, Si, Fe



$$E^{nuc}_{knee} = A \; E_{knee}$$

(for $\sigma_{p\chi}$ a step function)

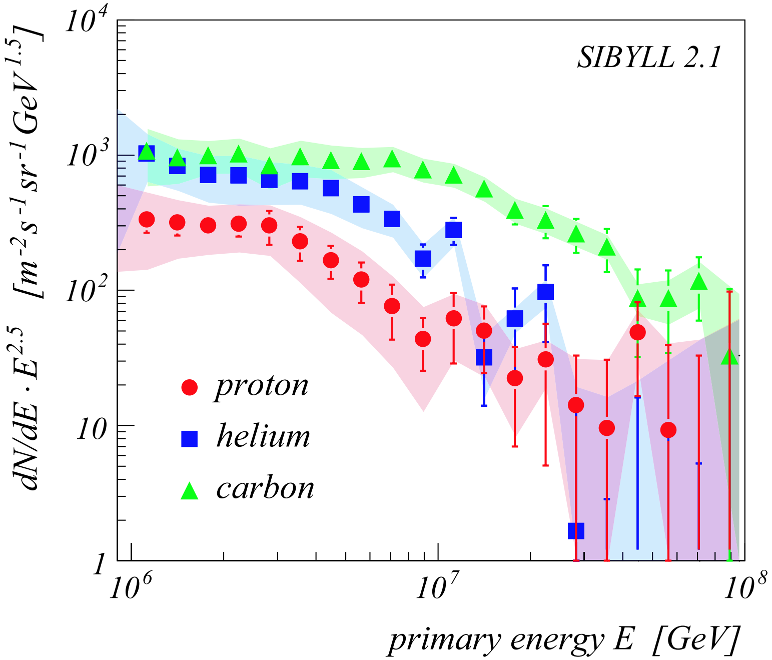
- $\sigma_{p\chi}$ may be better described by a power law; $\sigma_{n\chi}$ scales with the mass number; the length of the trajectory of a nucleus scales with the atomic number



$$\sigma_{nuc\,\chi} \approx A^{2/3} \sigma_{p\chi} \;; \quad \tau \sim (Z/E)^{\beta}$$

$$\Longrightarrow \quad E^{nuc}_{knee} = E_{knee} \; A^{\frac{\alpha-1}{\alpha-\beta}} \; Z^{\frac{-\beta}{\alpha-\beta}}$$

- KASCADE observes knee-like features in the He, C, Si and Fe spectra, with the position of the individual knees shifted to higher energies with increasing atomic number.



- Results depend on the hadronic model used in the simulations.

- We can also explain a *sustained* spectral index of -3.1 above the knee. To obtain a change in the index from -2.7 to -3.1 we need a probability of interaction

$$p_{int}(E > E_{knee}) = 1 - \left(\frac{E_{knee}}{E}\right)^{0.4}$$

- If the length l of a cosmic ray trajectory has an average value L and a probability distribution

$$w(l) = \frac{1}{L} e^{-l/L} \ ,$$

$$p_{int}(E) = \int \mathrm{d}l \ p_{int}(l, E) \ w(l) = 1 - \frac{1}{\sigma_{p\chi} n_\chi L + 1} \approx 1 - \frac{1}{\sigma_{p\chi} n_\chi L}$$

- Since $L \sim E^{-\beta}$ (with β between 0.3 and 0.6), a cross section at $E > E_{knee}$ with $\sigma_{p\chi}(E) \sim E^{\alpha'}$ with $\alpha' = 0.4 + \beta$ would work!

What are the required values of $\sigma_{p\chi}$ and ρ_χ?

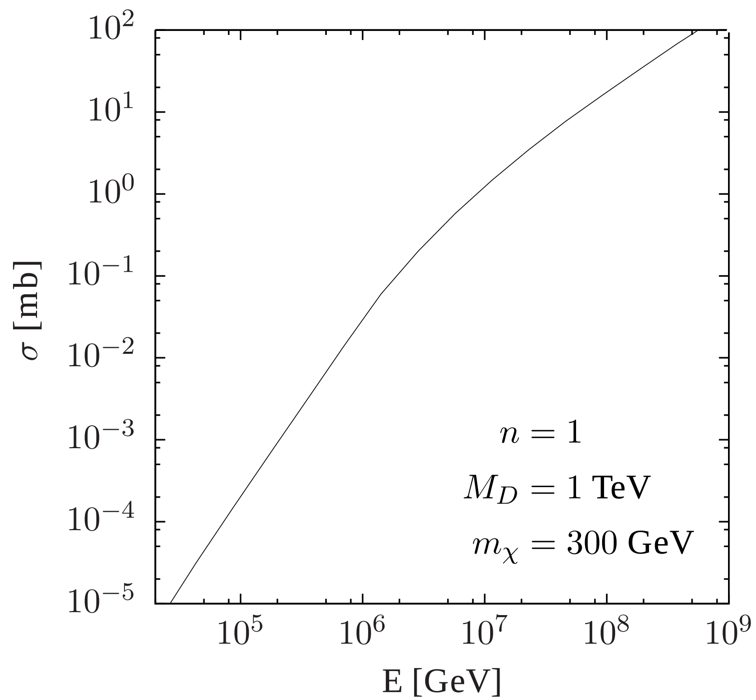
• We can estimate them by comparing with interstellar (baryonic) matter (IM). A significant fraction of cosmic rays interact with IM in their way to the Earth; their cross section is around 10 mb.

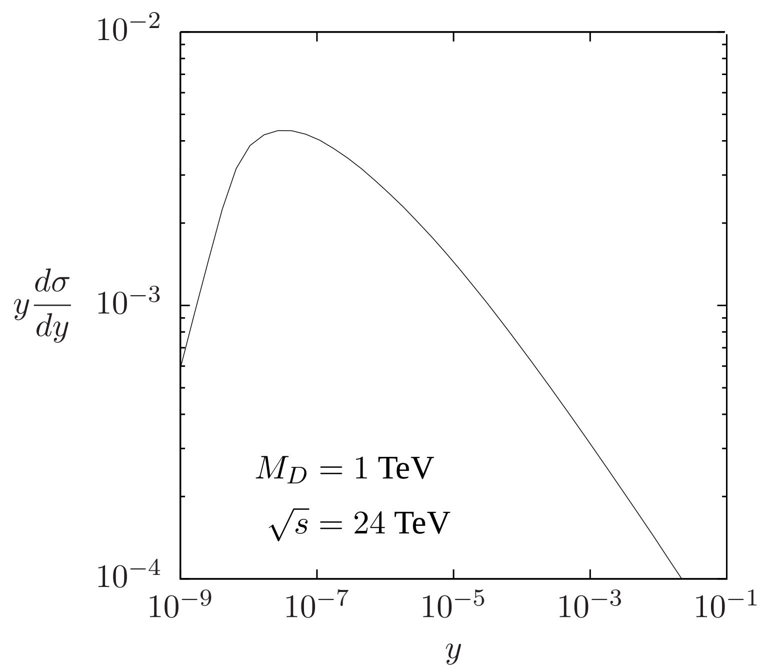
• Therefore, the scenario requires $\sigma_{p\chi}$ of order mbarn and dark-matter densities larger than ρ_{IM}.

• Very large p–χ cross sections can be obtained for $n = 1$ extra dimensions. In ADD the size L of the extra dimensions (the mass $1/L$ of the KK excitations) and the fundamental scale M_D (where the gravitational interaction is unsuppressed) are related

$$L \sim \frac{1}{M_D}\left(\frac{M_P}{M_D}\right)^{2/n}$$

• Macroscopic gravity and supernova observations put bounds on L that imply $M_D > 50$ TeV for $n = 2$ or $M_D > 10^8$ GeV for $n = 1$. To have an acceptable framework with $n = 1$ and $M_D \approx$ TeV there should be a mechanism giving an extra (MeV) mass to the KK excitations of the graviton (Giudicce et al: a warp factor). Very soft interaction, $y = (E - E')/E$:





• Although the total amount of dark matter in our galaxy is larger than the amount of baryonic interstellar matter, the former is distributed within the galactic halo, whereas the latter is concentrated within the galactic disk. If $\rho_\chi \approx 0.3$ GeV/cm^3 (the local density near the solar system), we obtain $x_\chi \approx 0.1\ x_{IM}$, which is insufficient to explain the cosmic ray knee.

• The total amount of dark matter in the galaxy is well stablished, but its distribution is *underconstrained* (rotation curves can be fitted with different distributions).

• Higher DM column densities along the cosmic ray trajectory can be obtained if *(i)* there are higher DM densities near the cosmic ray sources; or *(ii)* cosmic rays spend a significant fraction of time inside local clouds of DM; or *(iii)* the DM distribution is anomalous (non-spherical), flattened towards the galactic plane

Implications in UHE neutrino physics

- If DM interacts strongly above the energy threshold E_{knee}, then neutrinos should do the same.

- The c.o.m. energy at the knee is $\sqrt{s} = \sqrt{2 m_\chi E_{knee}}$. This $\sqrt{s}$ is reached in ν–p collisions at

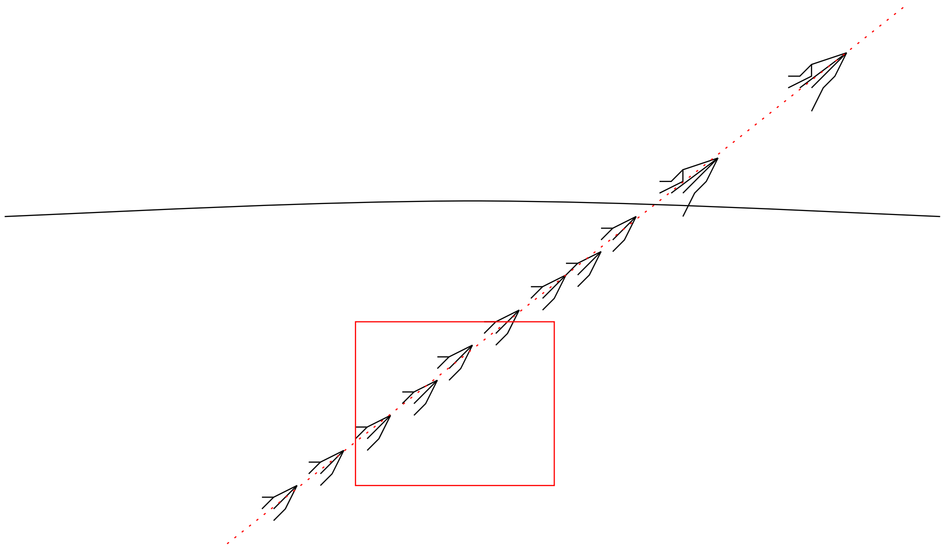
$$E_\nu = \frac{m_\chi}{m_p} E_{knee} \approx 10^8 \text{ GeV}$$

- Therefore, we would not observe (cosmogenic) neutrino events of energy $E \geq 10^8$ GeV at neutrino telescopes (IceCube, Anita)

- What kind of signal should we search in ν telescopes? Why we have not seen these strongly interacting neutrinos in air showers?

The ν–p interaction is very soft

• A 10^9 GeV neutrino would interact 10 times in the atmosphere and then every 1–10 meters of ice, depositing around 1–10 TeV of energy ($y \approx 10^{-6}$) in each interaction.



• The total energy deposited by the neutrino in the atmosphere would be below the $\approx 10^8$ GeV threshold in air-shower experiments.

Summary

- Do cosmic rays see any dark matter?

While IceCube and Anita do not see any standard cosmogenic neutrinos, maybe...

Smoking gun: superposition of a continuous of mini-showers in an inclined event