Exp. Methods in Astroparticle Physics (SS 2020) - Problem sheet 3

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Indirect detection: Dark matter annihilation, decay and search for antideuterons

3.1 Imaging Air Cherenkov Telescopes (IACTs) *4 Points*

In this exercise, we try to estimate the gamma ray flux due to annihilation of dark matter particles. Consider a typical annihilation process of a dark matter particle χ into a photon γ $(\chi\chi \to \gamma\gamma)$. If we want to detect the γ-ray flux from dark matter annihilation, we can look for instance in the galactic center of the Milky Way. In this case, the flux can be computed with

$$\phi \propto \frac{N_\gamma \langle \sigma v \rangle}{M_\chi^2} \int_{\text{line of sight}} \rho^2 (l) \, \mathrm{d}l \, (\hat{n}) \, , \tag{1}$$

or, in a more convenient form

$$\phi \approx \left(1.87 \times 10^{-11} \, \mathrm{cm}^{-2} \, \mathrm{s}^{-1} \, \mathrm{sr}^{-1}\right) \times \left(\frac{N_\gamma \sigma_{\gamma\gamma} v}{10^{-29} \, \mathrm{cm}^3 \, \mathrm{s}^{-1}}\right) \left(\frac{10 \, \mathrm{GeV}}{M_\chi}\right)^2 J \, (\hat{n}) \, , \tag{2}$$

where σv is approximately the thermally averaged annihilation cross section $\langle \sigma v \rangle$, M_χ the dark matter mass and ρ the dark matter density distribution in the halo as a function of the line of sight l and the observation angle ψ. The parameter N_γ is the number of photons generated by each annihilation. In general, the integral over the squared density distribution is called the J-factor

$$J \, (\hat{n}) = \int_{\text{line of sight}} \rho^2 (l) \, \mathrm{d}l \, (\hat{n}) \, . \tag{3}$$

Dimensionless J-factor values for different detector solid angles $\Delta\Omega$ can be found in Figure 1.

a) A typical solid angle of a IACT is in the order of $\Delta\Omega = 10^{-3}\,\mathrm{sr}$. Which value for the J-factor do you read from Figure 1 if you assume a NFW profile at a radius $R = 8.5\,\mathrm{kpc}$ (estimate the mean value). Why is the value larger than the two other coreless density profiles Ka and Kb?

b) Calculate the number of signal events for a typical IACT. Use: for the effective detection area $A_{\text{eff}} = 10^5\,\mathrm{m}^2$, an observation angle of $\Delta\Omega = 10^{-3}\,\mathrm{sr}$ and a measurement duration of $t \approx 100\,\mathrm{h}$. Assume that the dark matter particle is a neutralino with $\sigma_{\gamma\gamma} v = 10^{-31}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ with a mass of $M_\chi = 250\,\mathrm{GeV}$.

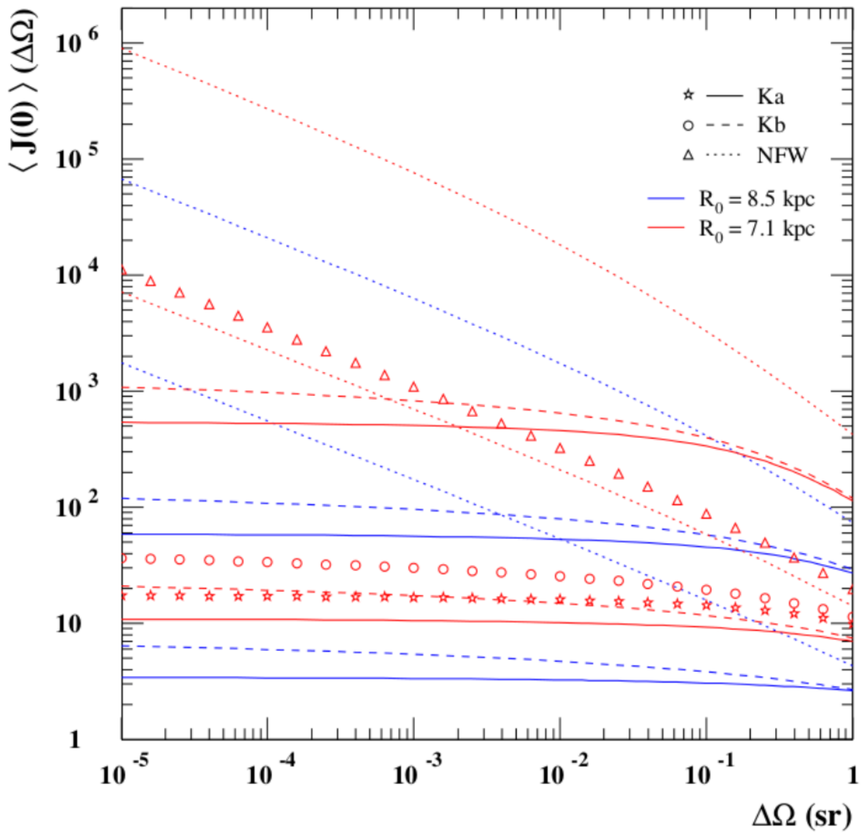

Figure 1: J-factor as a function of $\Delta\Omega$ for different halo profiles (Bergström 1997). Ka and Kb denote acore less density profile, whereas NFW is the Navarro, Frenk and White profile. The dashed lines represent extremal conditions on the dark matter halo, whereas the symbols denote the standard values of the halo parameters.

3.2 Decaying Dark Matter *2 Points*

Let us consider dark matter particles with a mass of $1\,\mathrm{TeV}$ in the Milky Way halo. Suppose these dark matter particles decay with a lifetime of $\tau = 10^{26}\,\mathrm{s}$ (remember, the age of the Universe is $10^{10}\,\mathrm{y}$) into Standard Model particles.

a) How many $1\,\mathrm{TeV}$ dark matter particles are present in a sphere with a radius of $1\,\mathrm{kpc}$ around the Earth?

b) How many events due to the Standard Model particles produced in the dark matter decay would be seen by a detector with a detecting area of $1\,\mathrm{m}^2$ if we are sensitive to particles in a sphere of radius $1\,\mathrm{kpc}$ around the Earth? Use a dark matter density of $\rho = 0.4\,\mathrm{GeV\,cm^{-3}}$.

3.3 The GAPS experiment for the Search of the Anti-Deuteron *4 Points*

The General Antiparticle Spectrometer (GAPS) is designed to search for antideuterons as a signature of dark matter annihilation. The GAPS experiment is based on the idea that antideuterons, when passing through matter, release energy until they are captured by an atom, substituting one of the electrons to form 'exotic atoms'. This allows for a clear signature of antideuteron detection. Read the paper "Antideuteron Sensitivity for the GAPS Experiment", T. Aramaki et al., Astroparticle Physics 74 page 6-13, which you can access on arXiv: https://arxiv.org/abs/1506.02513.

a) Describe the concept of the GAPS experiment.

b) Knowing that the energy density of cosmic rays in the Milky Way is $\epsilon_{\mathrm{CR}} \simeq 1\,\mathrm{eV\,cm^{-3}}$, estimate the energy density in cosmic rays due to dark matter annihilation in the galaxy for the following case: $m_\chi = 100\,\mathrm{GeV}$, $\rho = 0.4\,\mathrm{GeV\,cm^{-3}}$. Utilize that $\langle\sigma v\rangle = 3 \times 10^{-26}\,\mathrm{cm}^3$, $t_{\mathrm{MW}} = 10^{10}\,\mathrm{y}$.

c) Estimate the threshold energy for the production of CR deuterons in the reaction $\mathrm{p} + \mathrm{p} \to \mathrm{p} + \mathrm{p} + \overline{\mathrm{p}} + \mathrm{p} + \mathrm{n} + \overline{\mathrm{n}}$.

d) Calculate the energy spectrum of a hydrogen atom in which the electron has been substituted by an antideuteron. Compare the binding energy with the one corresponding to a captured antiproton.

e) How can the antiproton background be discriminated?