First Thai-CTA workshop – Chiang Mai, February 2019

Dark matter modeling EXERCISES

Dr. Miguel A. Sánchez-Conde

Feb 2019

PROBLEM 1. From N-body cosmological simulations, the dark matter halo concentration-mass relation is given by [1]:

$$c_{200}(M_{200}, z=0) = \sum_{i=0}^{5} c_i \times \left[\ln\left(\frac{M_{200}}{h^{-1}M_\odot}\right)\right]^i, \tag{1}$$

where $c_i = [37.5153, -1.5093, 1.636\cdot 10^{-2}, 3.66\cdot 10^{-4}, -2.89237\cdot 10^{-5}, 5.32\cdot 10^{-7}]$. Adopt $h = 0.7$.

From the expression above it is possible to obtain the characteristic density, ρ_0, of the corresponding NFW DM density profile as follows:

$$\rho_0 = 2 \times 200 \times \rho_{crit}\ c_{200}/(3\ F(c)), \tag{2}$$

where $F(c) = 2/c \times [ln(1+c) - c/(1+c)]$ and ρ_{crit} is the critical density of the Universe.

i) Compute the *total* J-factor, J_T, i.e. the one integrated for the *whole* object (in units of $\mathrm{GeV}^2\ \mathrm{cm}^{-5}$ and $\mathrm{M}_\odot^2\ \mathrm{kpc}^{-5}$) for the Draco dwarf galaxy, the Andromeda galaxy and the Virgo galaxy cluster, assuming that their dark matter density profiles is well described by NFW in all cases. Rank the objects according to their annihilation fluxes. Take the following values as the masses and distances of these objects:

Target	Distance (kpc)	M_{200} ($\mathrm{M}_\odot$)
Draco	82	$2\cdot 10^{8}$
Andromeda	778	$1.5\cdot 10^{12}$
Virgo	$15.4 \cdot 10^{3}$	$5.4\cdot 10^{14}$

Note: [You can also use either the CLUMPY software or your own code to compute J_T from the general expression of the J-factor that we saw in the lectures.]

ii) In terms of level of annihilation flux of these objects at Earth, how would the ranking be modified by including subhalos in the above computation? Adopt the following parametrization for the substructure boost [2]:

$$\log_{10} B(M) = \sum_{i=0}^{5} b_i \left[\log_{10}\left(\frac{M_{200}}{M_\odot}\right)\right]^i . \tag{3}$$

where b_i =[-0.186, 0.144, $-8.8\cdot 10^{-3}$, $1.13\cdot 10^{-3}$, $-3.7\cdot 10^{-5}$ $-2\cdot 10^{-7}$].

iii) The annihilation flux is $\frac{d\phi_\gamma}{dE} = J_T \times \phi_{PP}$, where $\phi_{PP} = \frac{<\sigma v>}{2m_\chi^2}\frac{dN_\gamma}{dE_\gamma}$ is the particle physics factor. Compute the corresponding DM annihilation fluxes (with and without subhalos) of these objects assuming that the annihilation happens entirely through the $b\bar{b}$ DM annihilation channel. Given the curve of differential CTA sensitivity, should we expect to observe these objects for e.g. 50h of observation?

Hint: Adopt the thermal relic cross section value and use the tables in Ref. [3] for the DM spectrum. Use Fig. 1 for the differential CTA sensitivity.

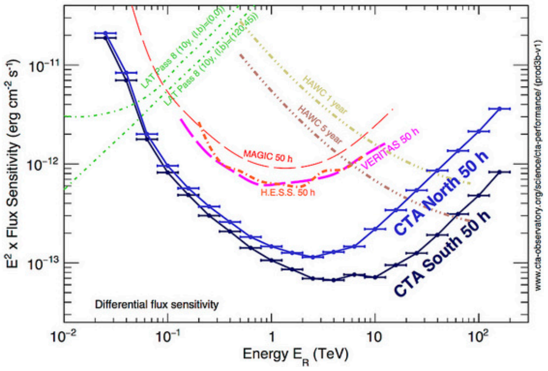

Figure 1: Predicted CTA differential sensitivity.

iv) Calculate the minimum value of the J-factor that would be ideally needed in order to have a detection with CTA. Do it so for a WIMP mass of 1 TeV that annihilates entirely to $b\bar{b}$. Use the following numbers as nominal values for CTA:

Parameter	CTA
Energy range	0.05-100 TeV
Effective area, A_{eff}	$\sim 10^6$ m^2
Observing time, T_{obs}	250 h

PROBLEM 2. The gamma-ray flux corresponding to the Galactic center excess as observed by the Fermi LAT between 1-3 GeV and integrated within the innermost one degree of the Galaxy is $\phi_{GCE} \sim 10^{-10}$ erg cm^{-2} s^{-1}. The spectrum of this excess is compatible with a WIMP mass $m_\chi = 49$ GeV annihilating to b quarks with roughly half of the thermal relic cross section value [4].

i) Calculate the corresponding J-factor necessary to account for the observed excess flux.
Hint: The annihilation flux is $\frac{d\phi_\gamma}{dE} = J \times \phi_{PP}$, where $\phi_{PP} = \frac{<\sigma v>}{2m_\chi^2} \frac{dN_\gamma}{dE_\gamma}$ is the particle physics factor. Use tables in Ref. [3] for the DM spectrum.

ii) Is this value of the J-factor compatible with the one expected from our Galaxy integrated for that same inner region?
Hint: Assume an NFW profile with a normalization at the Solar galactocentric radius $\rho(r = r_\odot = 8\ kpc) = 0.4\ GeV/cm^3 = 1.0477 \times 10^7 M_\odot/kpc^3$ and a scale radius $r_s = 20\ kpc$. As a good approximation, one can use that the J-factor for the GCE region is $J_{GCE} = \frac{1}{4\pi D^2} \int_V \rho_{DM}^2(r)\, dV$, where the volume integral is performed up to the physical radius that corresponds to the GCE region.

iii) One of the most promising dwarf candidates recently discovered by the Dark Energy Survey (DES) is Reticulum II. Assuming a dark matter origin for the GCE (with the properties given above), should we expect to observe a dark matter-induced gamma-ray signal from Reticulum II with the Fermi LAT?
Hint: Assume that this object is located at 32 kpc and its total mass is $M_{200} \sim 10^7\ M_\odot$. Its concentration, significantly boosted due to tidal forces, is probably around $c_{200} \sim 40$ [2]. The Fermi LAT sensitivity at 1 GeV is $F_{min} \sim 10^{-6}\ MeV\ cm^{-2}\ s^{-1}$. As an approximation (the object is a dwarf so NFW is formally not applicable) one can use the following expression for the *total* J-factor, i.e. the one obtained for the *whole* object:

$$J_T = \frac{1}{4\pi D^2}\int_V \rho^2_{DM}(r)\, dV = \frac{1}{4\pi D^2}\frac{M200\, c_{200}(M_{200})^3}{[f(c_{200}(M_{200}))]^2}\frac{200\,\rho_{crit}}{9}\left(1 - \frac{1}{(1+c_{200}(M_{200}))^3}\right), \tag{4}$$

with D the distance from the Earth to the center of the halo, r is the galactocentric distance inside it, $f(x) = \ln(1+x) - x/(1+x)$ and ρ_{crit} is the critical density of the Universe.

References

[1] Sánchez-Conde M. A., Prada F., 2014, MNRAS, 442, 2271

[2] Moliné Á., Sánchez-Conde M. A., Palomares-Ruiz S., Prada F., 2017, MNRAS, 466, 4974

[3] Cirelli M., et al., 2011, Journal of Cosmology and Astro-Particle Physics, 2011, 51

[4] Calore F., Cholis I., McCabe C., Weniger C., 2015, PRD, 91, 063003