Macro Detection using Fluorescence Detectors

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Introduction

Renewed attention has been given to macroscopic composite objects aka macros as dark matter candidates[1]. Macroscopic objects made of baryons may be stable with sufficient strangeness, and may have been formed prior to nucleosynthesis evading the main constraint on baryonic dark matter [2, 3, 4].

The existing constraints on macros mean that any attempt to use detectors to look for macros on human timescales requires a target of very large area. In this work we explore the possibility that fluorescence detectors (FD) for ultra-high energy cosmic rays might detect the nitrogen fluorescence caused by a macro's passage through the atmosphere.

Taking macros to interact through their geometric cross section, the expected number of events in a target of area A_{target} over a time $t_{observe}$ is given by

$$\begin{aligned} N_{events} &= \frac{\rho_{DM}}{M_x} A_{target} t v_x \\ &= 5.5 \times 10^{-6} \frac{g}{M_x} \frac{A_{target}}{m^2} \frac{t_{observe}}{yr} \end{aligned}$$

where ρ is the local dark matter density 7 x 10^{-25} gcm^{-3}[3], and M_x is the mass of the macro. We assume a macro velocity v_x = 250 kms^{-1}.

We consider the particular examples of the FDs of the Pierre Auger Observatory (Auger) and the Extreme Universe Space Observatory onboard the Japanese Experiment Module (JEM-EUSO). Auger includes 24 FD telescopes each composed of 22x20 pixels covering a 30x30 angular view of the sky out to a range of 20km. JEM-EUSO is a space-science mission that will watch the dark side of the Earth and detect UV photons emitted from extensive air showers caused by High Energy Cosmic rays. JEM-EUSO will have the ability to operate in tilt mode, where it is not looking straight down on the surface of the Earth but at an angle to the nadir, which will increase the target area.

Fluorescence Signal

Along the tracjetory of a macro through the atmosphere, it will dissociate the molecules, and ionize and excite atoms first by direct impacts and more importantly through the secondary collisions among atoms.

Following the work of Cyncynates et. al.[5], we propagate the initial energy deposition by the macro radially away from its essentially straight trajectory. Thecross sectional are of the ionized region evolves as

$$\pi r_I(t)^2 = ln(\frac{\sigma_x v_x^2}{4\pi\alpha c_p T_I t})4t\alpha\pi$$

where α ≅ 0.08 m^2s^{-1} is the thermal diffusivity of the air, c_p ≈ 25 kJ $kg^{-1}K^{-1}$is the specific heat of the air. As the electrons and ions recombine, the plasma will radiate photons that can be detected by the FDs.

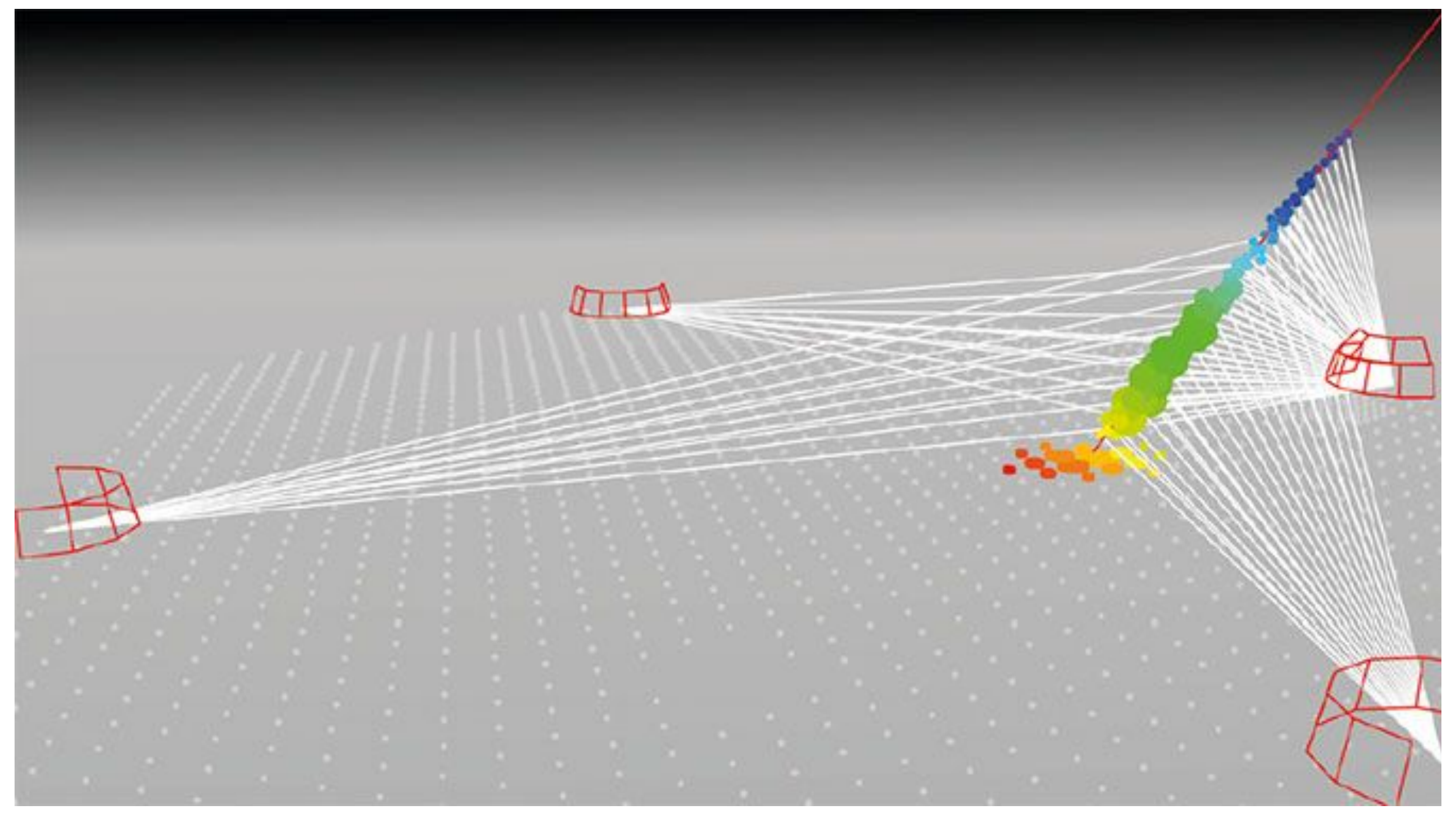

Figure 1:Stereoscopic reconstruction of an air shower. For macros, the reconstruction would be of the trajectory through the atmosphere.
http://cerncourier.com/cws/article/cern/65035

For r_I small enough ($\sigma_x \leq 10^{-7} cm^2$) the plasma will be optically thin.. Taking proper account of the relative rates of radiative recombination rates to the 3-body recombination rates through the factor B_I and the ratio of the recombination time to the cooling time we find that the number of photons that reach the detector s given by

$$N_\gamma^{thin} \simeq 7 \times 10^{22} \min\left(\frac{\tau_{bin}}{t_{I0}}, 1\right) \frac{A_{detector} \sin\theta}{D\ cm} \left(\frac{\sigma_x}{cm^2}\right)^2$$

where η is the fraction of recombinations that yield a photon in our filter range of 350 - 400 nm, $A_{detector}$ is the area of the mirror or the lens that collects or focuses the light, θ is the angle subtended by a pixel and D is the height of the macro above the pixel.

For $\sigma_x \geq 10^{-7} cm^2$, the plasma wil be opticallty thick and radiate as a blackbody. The number of photons that reach the pixel is given by

$$\begin{aligned} N_\gamma^{thick} \simeq 3 \times 10^{19} \frac{A_{detector} \sin\theta}{D\ cm} \times \\ \times \min\left(64 \left(\frac{\sigma_x}{cm^2}\right)^{3/2}, 1\right) \min\left(\frac{\tau_{bin}}{t_{I0}}, 1\right) \end{aligned}$$

These signals are compared against the expected background noise using the signal-to-noise ratio

$$\mathrm{SNR} = \frac{Q\ N_\gamma}{N_{noise}}$$

where $N_{noise} = (Q N_\gamma + Q N_{background})^{1/2}$, Q is the quantum efficiency factor for the photomultiplier tubes and $N_{background}$ is the background number of photons incident on a pixel during one time bin.

Using a signal-to-noise ratio of 5, to see what ranges of σ_x we can probe. The results of this analysis are presented in Figure 2.

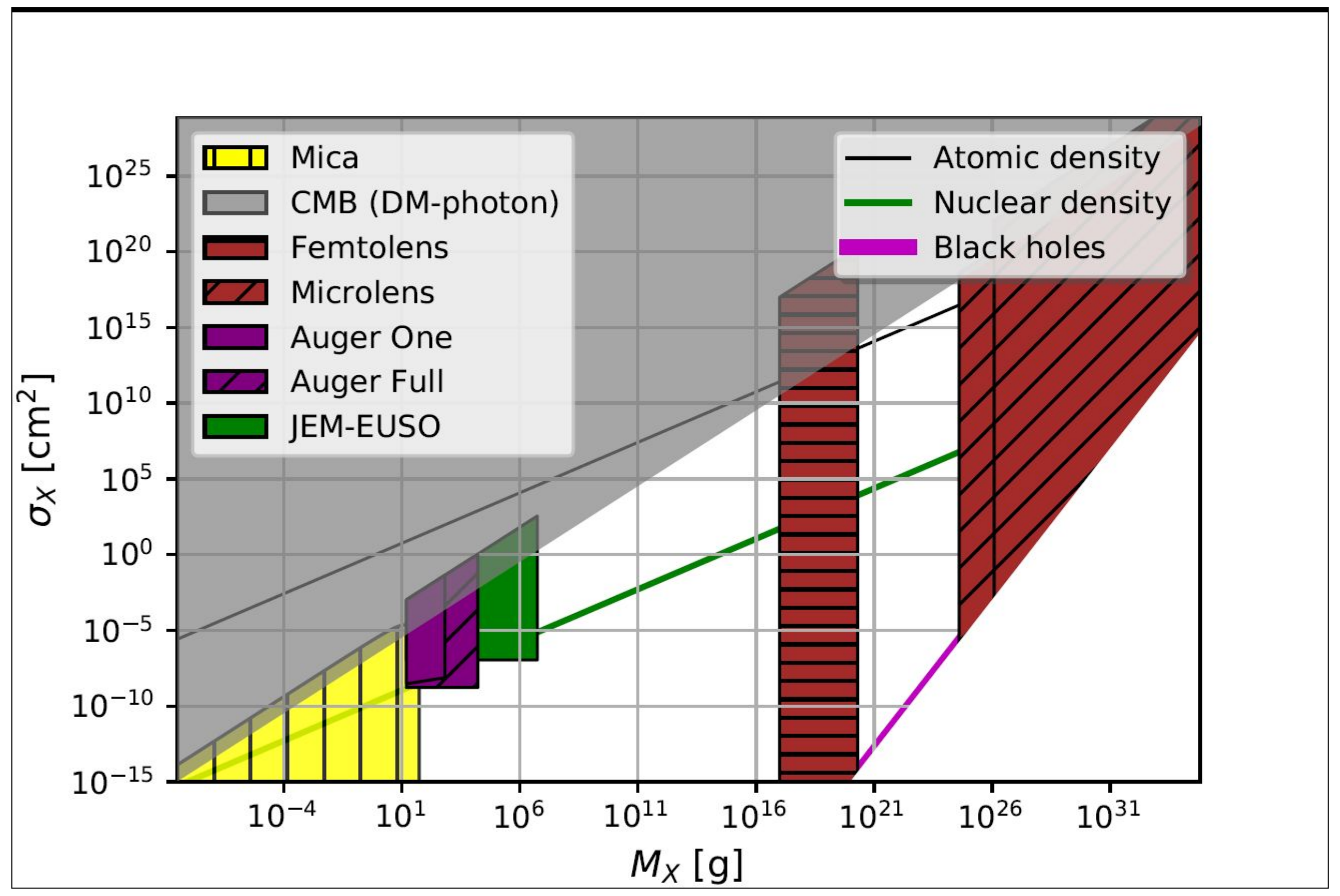

Figure 2: Results of the various regions that can be probed using Auger(for just one FD telescope in purple and the entire array in purple with diagonal hatching) and JEM-EUSO(in green)[5]

Conclusion

We have calculated the luminosity produced by a macro as a function of its physical cross section. A general detection scheme for measuring the fluorescence caused by a macro that is applicable to any FD telescope, whether ground or space based was developed. The parameter space that could be probed by the Pierre Auger and JEM-EUSO experiments was also obtained as specific examples of this scheme. In particular, we will be able to probe the nuclear density line in our parameter space upto a mass of 1.6 x 10^4g with Auger and 5.5 x 10^6g with JEM-EUSO.

Bibliography

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