Probing dark matter with AGN jets

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Outline

1. The idea
   - AGN candidates
   - Improvements from previous work
2. The ingredients
   - DM distribution
   - Electrons in the jet
   - Differential cross section
3. Results
   - for electron jets
   - for proton jets
4. Conclusions

The idea

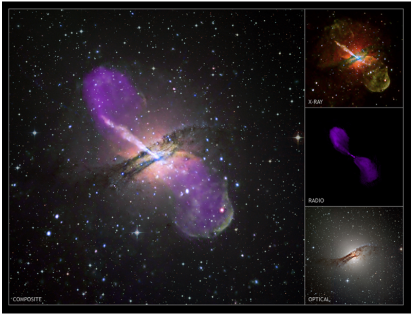
- Original idea by Bloom & Wells (98).
- Active Galactic Nuclei live in the densest regions of the largest dark matter halos and are sources of powerful and collimated jets containing ultra relativistic electrons and protons.
- Study the scattering of those high energy particles off of the dark matter present in the AGN halo with photons in the final state.
- If dark matter is heavy, the photons will be isotropically distributed, and if they have a distinct spectral feature we can hope to detect a signal.
- Fermi has potential for such a detection.

AGN candidates

Requisites for the AGN (if we hope to detect a signal)

- Close by
- Jet at an angle with the line of sight

Centaurus A and **M87** seem to be the best candidates.



Why we can do better than 13 years ago

Improvements on the results of Bloom and Wells (98):

- A complete and detailed calculation of the relevant cross section for the process, which leads to a distinctive spectral feature, physically associated with a resonance
- Models for the dark matter distribution in the inner regions of the AGN
- Observationally motivated jet models
- A comparison with recent Fermi and HESS data
- A novel discussion on proton jets and proton-dark matter scattering

Photon flux

We are interested in the flux of photons

$$\frac{d\Phi_\gamma}{dE_\gamma} = \int \underbrace{\delta_{\rm DM}}_{1} \underbrace{\left(\frac{1}{d^2_{\rm AGN}} \frac{d\Phi^{\rm AGN}_{e[p]}}{dE_{e[p]}} \right)}_{2} \underbrace{\left(\frac{1}{M} \frac{d^2\sigma_{e[p]+\chi\to\gamma+\ldots}}{d\Omega dE_\gamma} \right)_{\cos\theta_0}}_{3} dE_{e[p]}.$$

Three factors in the integrand

1. $\delta_{\rm DM} = \int_{r_{min}}^{r_0} \rho_{\rm DM}(r) dr$, which involves the DM profile;
2. Electron (proton) energy distribution in the jet;
3. Differential cross section (depends on the DM particle model).

Dark matter profile

We consider two theoretically motivated profiles for the inner region of the AGN

- [Gondolo & Silk 99]

$$\rho_{\rm DM}(r) = \frac{\rho'(r)\rho_{\rm core}}{\rho'(r) + \rho_{\rm core}} \propto r^{-2.2} \quad \text{where} \quad \rho_{\rm core} \simeq M_\chi/(\langle \sigma v\rangle_0 t_{BH})$$

- [Gnedin & Primack 04]

$$\rho_{\rm DM}(r) = \rho_0 \left(\frac{a}{r}\right)^{3/2} \quad \text{with} \quad a = 10^5 R_S$$

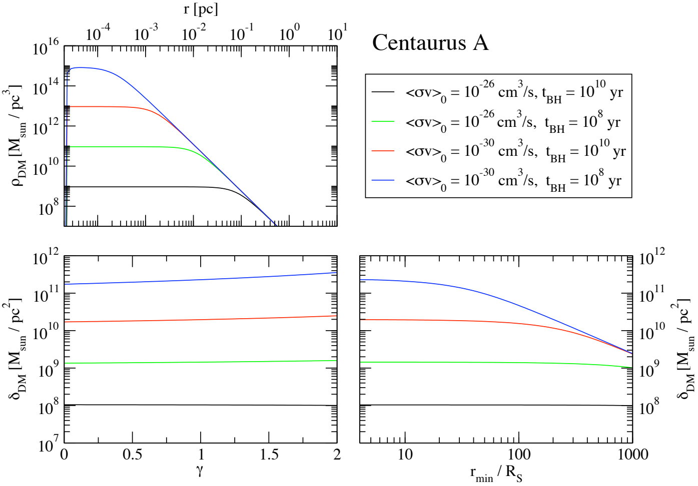
Dark matter profile - Normalization

We require that the dark matter enclosed in $10^5\ R_S$ does not exceed the uncertainty over the black hole mass.

- For CenA $M_{BH} = (5.5 \pm 3.0) \times 10^7\ \mathrm{M}_\odot$ [Neumayer, arXiv:1002.0965]

$$\int_{r_{low}}^{10^5 R_S} dr 4\pi r^2 \rho_{\mathrm{DM}} \leq 3 \times 10^7\ \mathrm{M}_\odot$$

Dark matter profile



Electron energy distribution

Blob geometry: the electrons move isotropically in the blob frame with a power law energy distribution, and the blob itself moves with respect to the central black hole with a moderate bulk Lorentz factor.

Broken power law in the blob frame

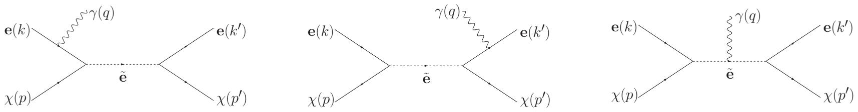
$$\frac{d\Phi_e^{\mathrm{AGN}}}{d\gamma'}(\gamma') = \frac{1}{2} k_e \gamma'^{-s_1} \left[1 + \left(\frac{\gamma'}{\gamma'_{\mathrm{br}}} \right)^{s_2 - s_1} \right]^{-1} \quad \text{for} \quad \gamma'_{\min} \leq \gamma' \leq \gamma'_{\max},$$

where the normalization k_e is obtained from the kinetic power of the jet, L_e.

Values for CenA:
$s_1 = 1.8$, $s_2 = 3.5$, $\gamma'_{\min} = 8 \times 10^2$, $\gamma'_{\mathrm{br}} = 4 \times 10^5$, $\gamma'_{\max} = 10^8$,
$L_e = 3 \times 10^{43}$ erg/s.

Differential cross section - Enhancements

Assume MSSM $\rightarrow$ neutralino is the dark matter particle candidate

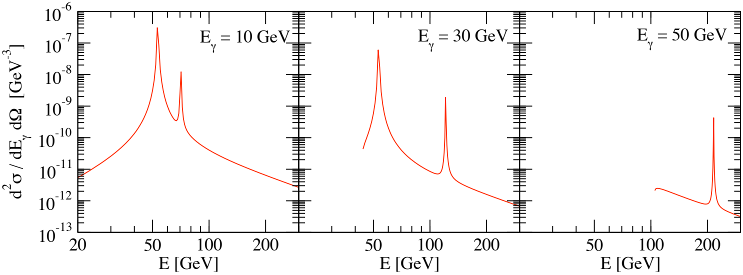


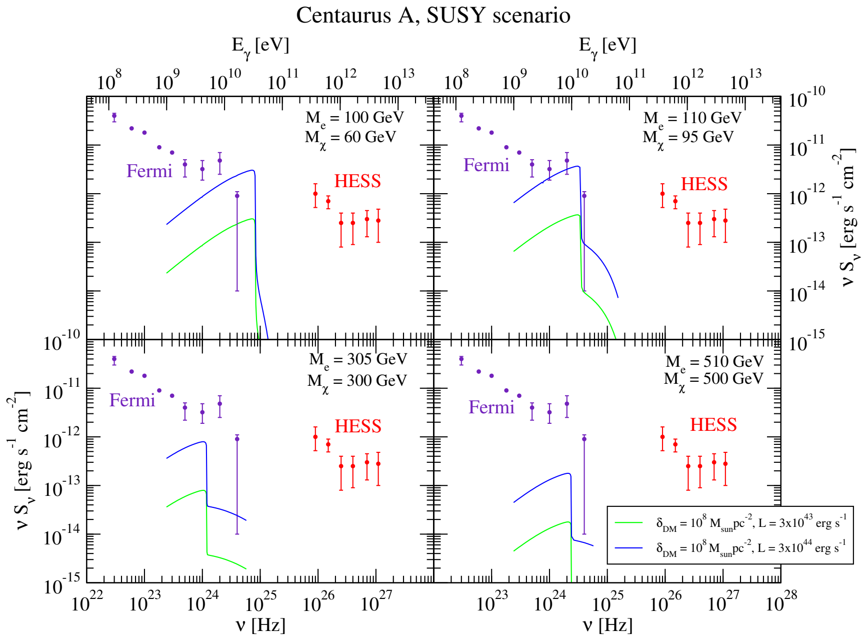
Two enhancements for the cross section

1. Resonance when the exchanged selectron goes on shell;
2. Log enhancement when the photon is collinear with the final electron.

Differential cross section - The resonances

$$M_{\tilde{e}} = 100 \text{ GeV}, M_\chi = 60 \text{ GeV}$$





[Abdo et al. (Fermi-LAT Collaboration) arXiv:1006.5463]

[Aharonian et al. (HESS Collaboration) arXiv:0903.1582]

Protons in the Jet

Study the scattering of protons off of dark matter at the parton level

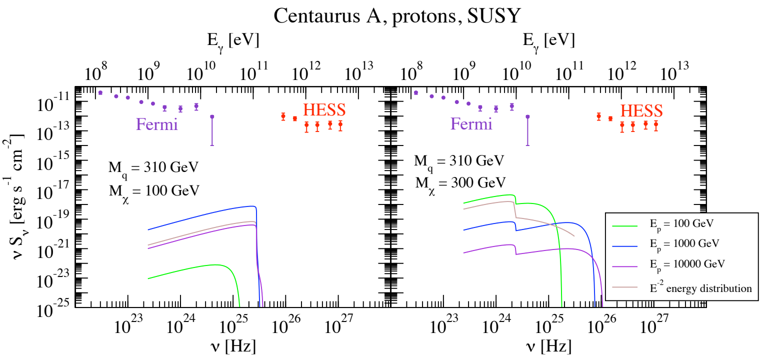
$$\frac{d\Phi_\gamma}{dE_\gamma} = \int dE \int_{x_{min}}^{1} dx \sum_{i=u,d} f_i(x) \left(\frac{1}{M_\chi} \frac{d^2\sigma_{p+\chi\to\gamma+\ldots}}{d\Omega dE_\gamma} \right)_{\cos\theta_0} \left(\frac{1}{d_{\mathrm{AGN}}^2} \frac{d\Phi_p^{\mathrm{AGN}}}{dE} \right) \delta_{\mathrm{DM}}$$

Normalizing the proton energy distribution

$$\frac{d\Phi_p^{\mathrm{AGN}}}{dE} = k_2 \left(\frac{m_p}{E} \right)^2 \quad \to \quad k_2 = \frac{L_p}{m_p^2 \ln\left(\frac{E_{max}}{E_{min}} \right)}$$

we lose by a factor of m_e^2/m_p^2 with respect to the electrons!

Protons - Compare to data



Conclusions

- Given the very characteristic spectral feature shown in the plots, the detection of this effect is possible in principle.
- In 1998 Bloom and Wells concluded that there was no hope to detect such a signal. After 13 years and a more in-depth analysis we have a different conclusion: there is hope!
- It is crucial to collect more data in the ”gap”: higher energy for Fermi, lower energy for atmospheric cherenkov telescopes.
- There are still large astrophysical uncertainties associated with jet geometry and composition, particle spectrum and dark matter distribution.