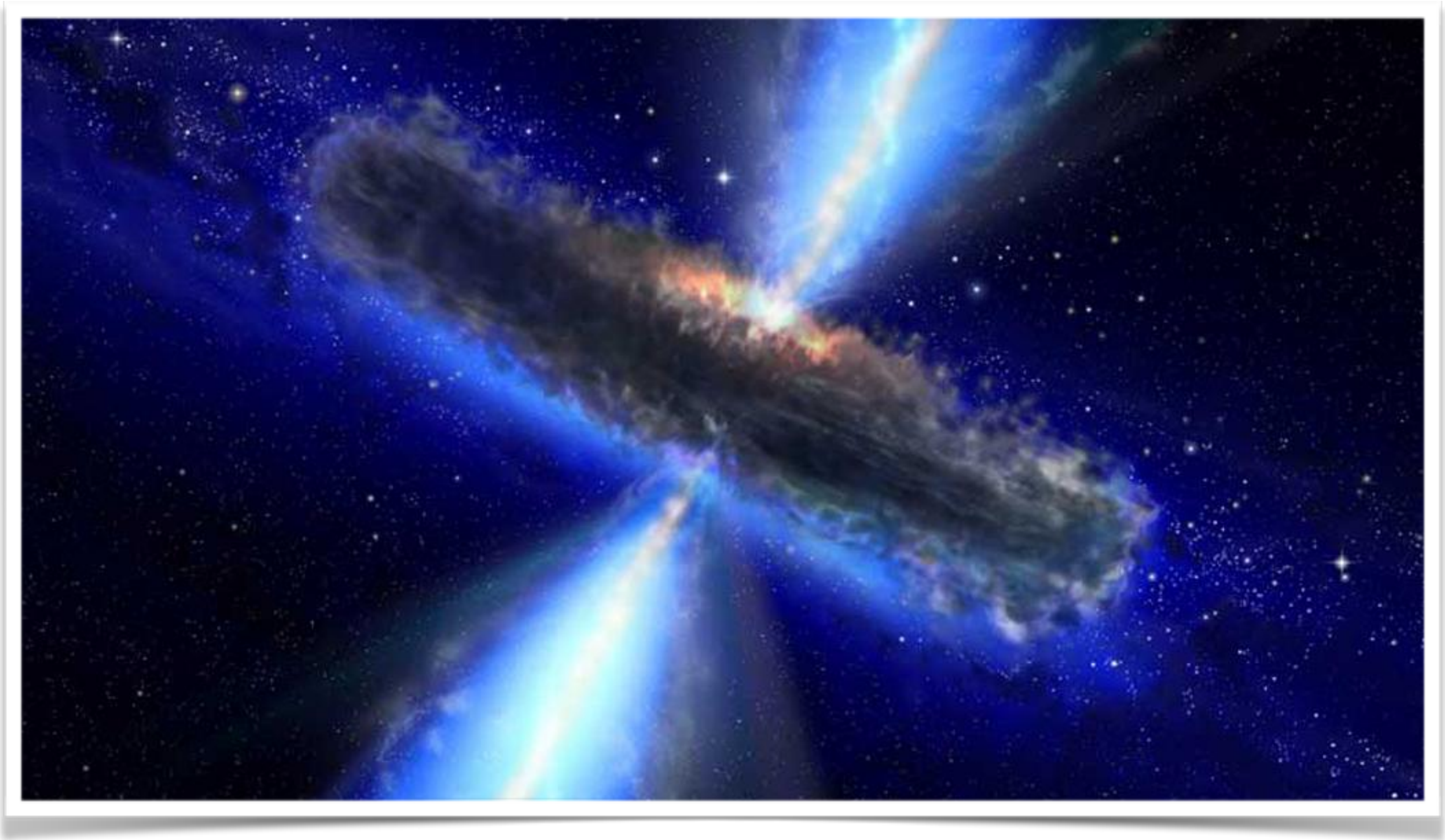
WIMP-induced Gamma Rays from Active Galactic Nuclei



Chris Jackson
Univ. of Texas at Arlington

in collaboration with Miguel Gómez (UTA)
and Gabe Shaughnessy (Wisconsin)

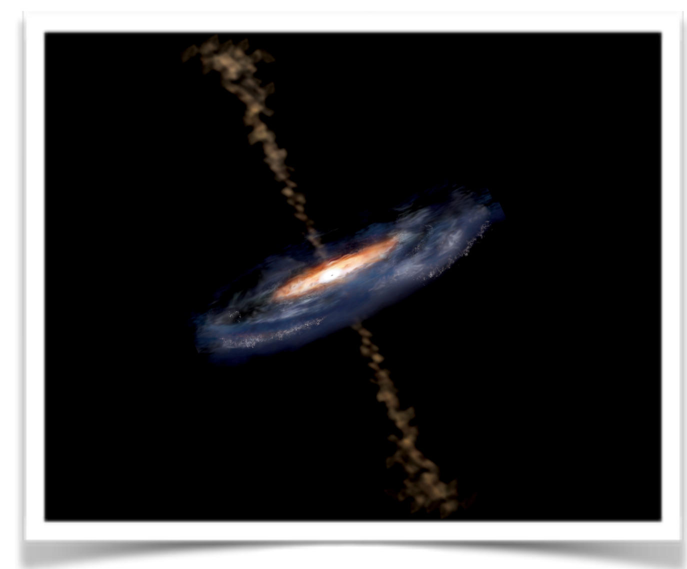
motivation

- "leave no stone unturned" in the search for dark matter (continue to consider exotic scenarios and/or sources)

- one possible interesting "laboratory" to look for and study dark matter are the cores of Active Galactic Nuclei (AGN) [Bloom & Wells '97, Gorchtein et al. '10, Huang et al. '11, Chang et al. '12, Profumo et al. '13, Gómez et al. '13]

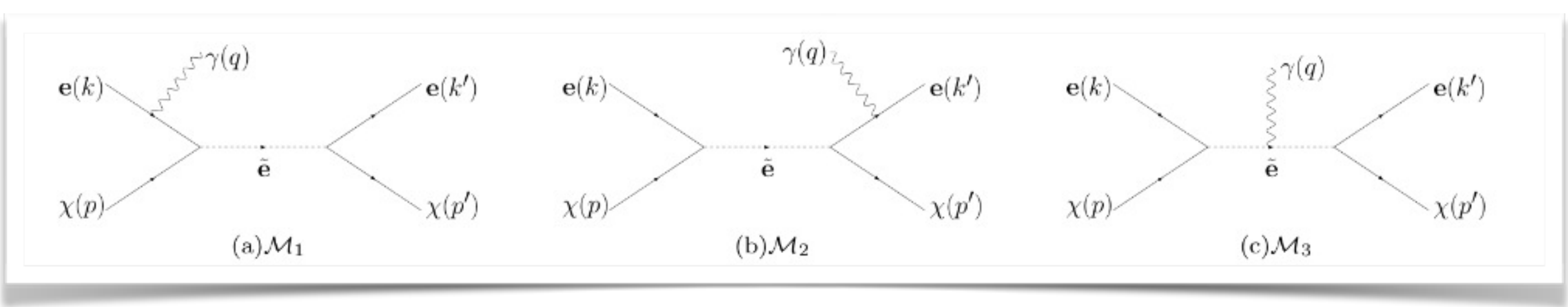
- AGN are the source of extremely energetic "jets" of particles (assumed to be mostly electrons)

- The core of AGN are also believed to house the densest regions of dark matter in the Universe



- "Universe's largest fixed-target experiment": jet particles collide with DM particles and cause them to "up-scatter" to another particle in the dark sector.

- In the process, a gamma ray is emitted...



- Fermi LAT has many observations of AGN gamma ray spectra

gamma rays from jet-halo interactions

- the flux from jet-halo WIMP interactions:

$$\frac{d\Phi_\gamma}{dE_\gamma} = \int \delta_{DM} \times \left(\frac{1}{d^2_{AGN}} \frac{d\Phi_e^{AGN}}{dE_e} \right) \times \left(\frac{1}{M_B} \frac{d^2\sigma_{e+B_H \to \gamma+e+B_H}}{d\Omega dE_\gamma} \bigg|_{\theta=\theta_0} \right) dE_e \, ,$$

DM density profile (cosmology) — dynamics of AGN jet (astrophysics) — jet-halo interaction cross section (particle physics)

- predictions exist for SUSY and 5-d UED.

- we performed the calculation in the 6-d UED (or "chiral square") model and focused on the AGN at Centaurus A.

- WIMP is a scalar (KK excitation of SM hypercharge gauge boson) and couples to electron and 1st KK excitation of electron through:

$$\Delta\mathcal{L} = g_1 \left[\bar{\psi}_E (Y_L P_L + Y_R P_R) \psi_e + \bar{\psi}_e (Y_L P_R + Y_R P_L) \psi_E \right] B_H$$

- this model predicts a very rich and interesting gamma ray spectrum from DM at the center of our galaxy ("the WIMP forest", Bertone et al. '09). could it also for AGNs?

contribution from DM density profile

- first factor = "line of sight" integral of DM density profile:

$$\delta_{DM} \equiv \int_{r_{min}}^{r_0} \rho_{DM}(r)\, dr$$

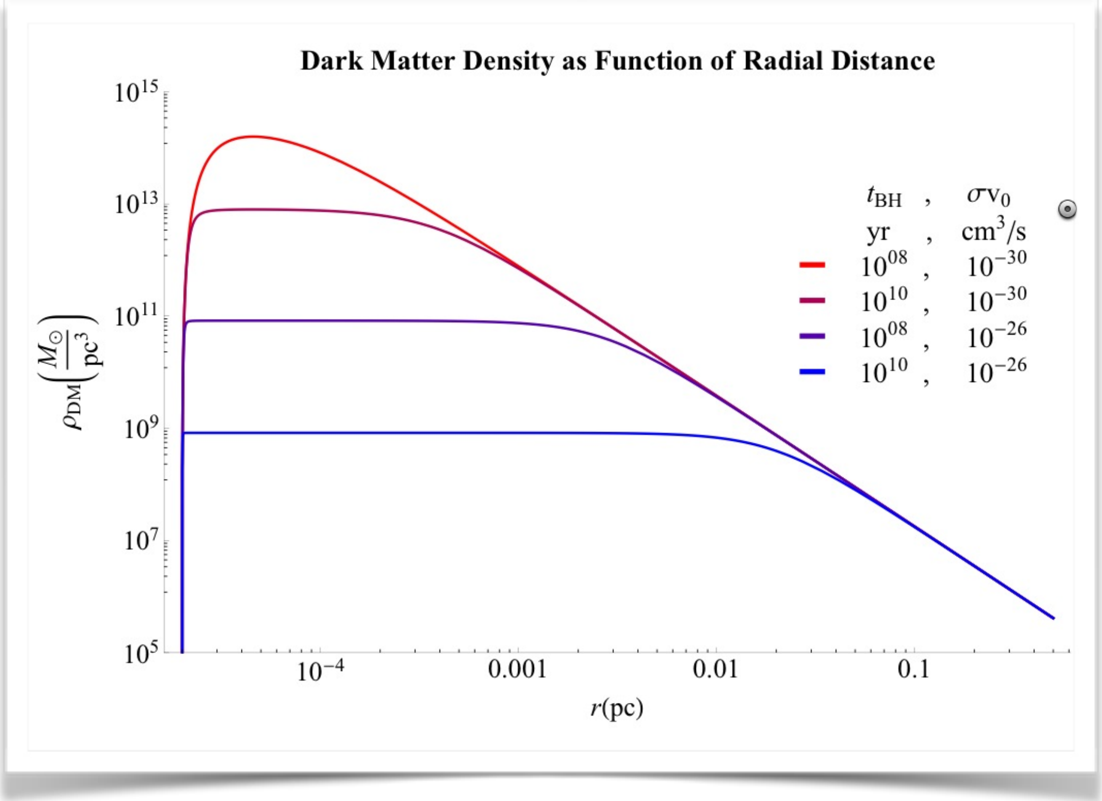
- "r min" is the minimum distance of interest (i.e., the "base" of the jet) and "r0" is the distance at which the AGN jet peters out

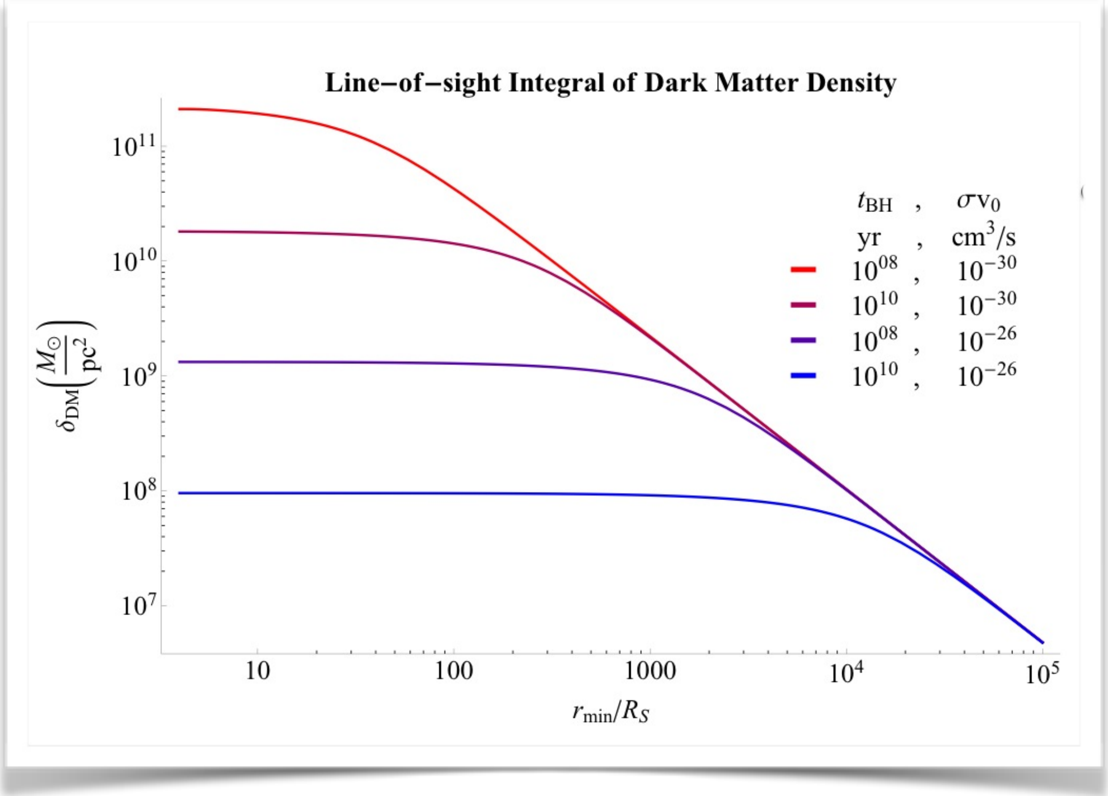
- for the density profile, we chose to work with the Gondolo-Silk profile:

$$\rho(r) = \frac{\rho'(r)\ \rho_{core}}{\rho'(r) + \rho_{core}}$$

$$\rho_{core} \simeq \frac{M_{DM}}{\langle\sigma v\rangle_0 t_{BH}}$$

$$\rho'(r) = \rho_0 \left(\frac{R_{sp}}{r_0}\right)^{-\gamma} \left(1 - \frac{4R_S}{r}\right)^3 \left(\frac{R_{sp}}{r}\right)^{\gamma_{sp}}$$





contribution from AGN jet factor

- luckily, our results do not depend heavily on the geometry of the jet... however, they do depend sensitively on the modeling of the energy distribution.

- based on Fermi LAT observations, we assume the distribution in the electron boost is a *broken power law* (where primed = "blob frame" where e's move isotropically and unprimed = BH frame):

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

$$s_1 = 1.8, \qquad s_2 = 3.5, \qquad \gamma'_{br} = 4 \times 10^5, \qquad \gamma'_{\mathrm{min}} = 8 \times 10^2, \qquad \gamma'_{\mathrm{max}} = 10^8 \; .$$

- the quantities in the two frames are related by the blob velocity and boost (~ 3 for Cen A):

$$\Gamma_B = \frac{1}{\sqrt{1 - \beta_B^2}}$$

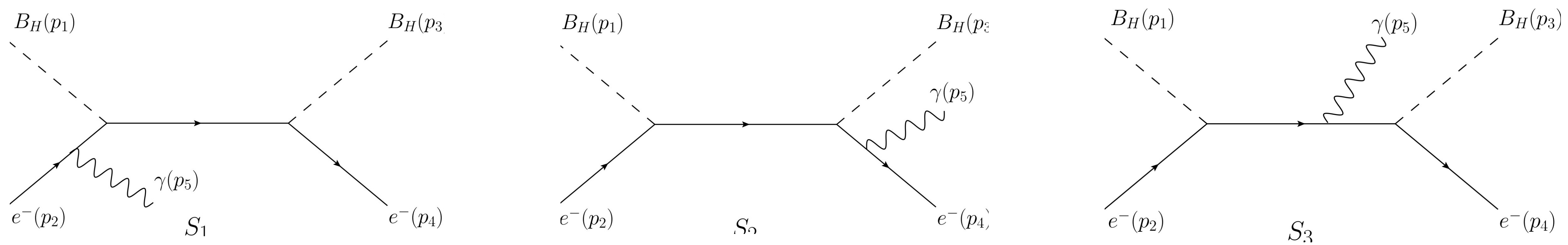
- in the end, the AGN factor in the flux equation takes the form:

$$\frac{1}{d_{AGN}^2} \frac{d\Phi_e^{AGN}}{dE_e} = \frac{1}{d_{AGN}^2 m_e} \int_{\mu_0}^{1} \frac{1}{\Gamma_B (1 - \beta_B \mu)} \frac{d\Phi_e^{AGN}}{d\gamma} (\gamma \Gamma (1 - \beta_B \mu))\, d\mu$$

(where the lower limit is ~ 0.9 in the BH frame)

jet-halo interaction cross section

- the major contribution comes from s-channel diagrams (with a subdominant contribution for u-channel diagrams):

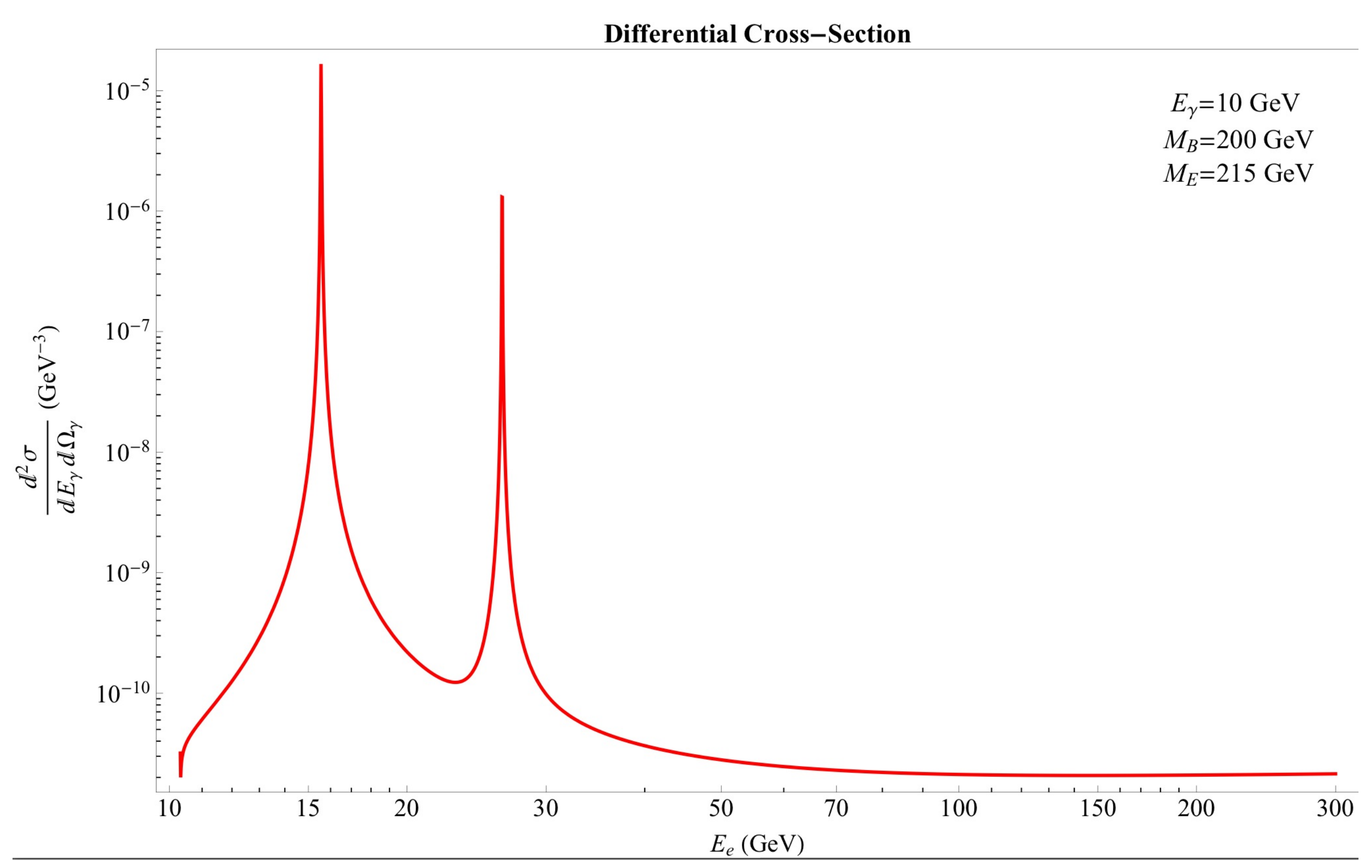


- the cross section from these diagrams contain resonances when the intermediate "heavy electron" goes on-shell

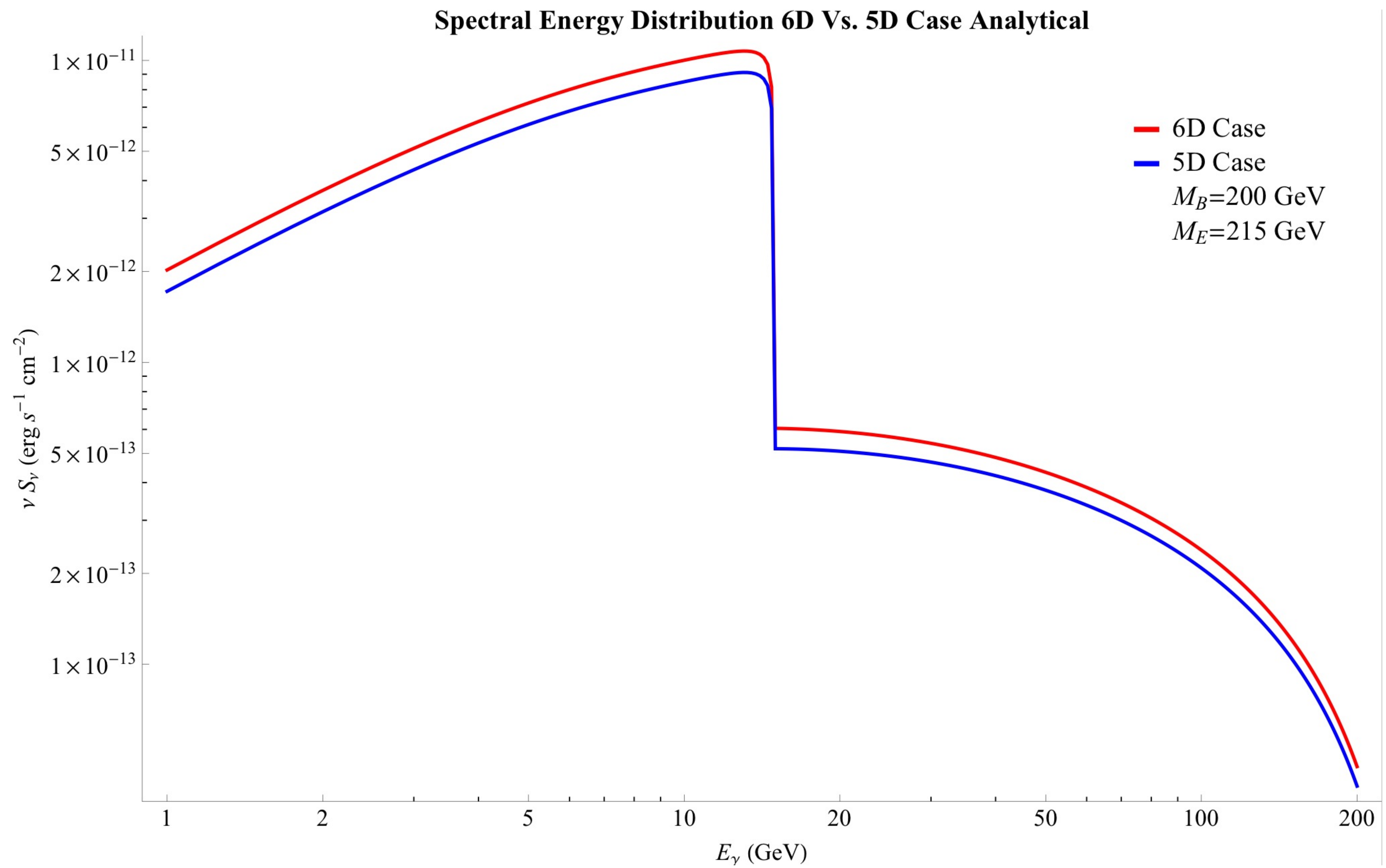
- the cross section also receives logarithmic enhancements from the configurations where the photon is emitted collinear to the outgoing electron:

$$\frac{d^2\sigma}{dE_5 d\Omega_5} = \frac{1}{(2\pi)^5}\frac{1}{32M_B^2E_2}\left[|\mathcal{M}|^2_{log}t_{45}\int d\Omega_4\frac{E_5E_4}{t_{45}} + 4\pi|\mathcal{M}|^2_{no\,log}\right]$$

$$= \frac{\pi}{(2\pi)^5}\frac{1}{32M_B^2E_2}\left[|\mathcal{M}|^2_{log}t_{45}\ln\left(\frac{4E_4^2}{m_e^2}\right) + 4|\mathcal{M}|^2_{no\,log}\right].$$



gamma ray spectrum from AGN jet-halo interactions



5-d spectrum originally computed in Gorchtein et al. '10

gamma rays from annihilation (continuum)

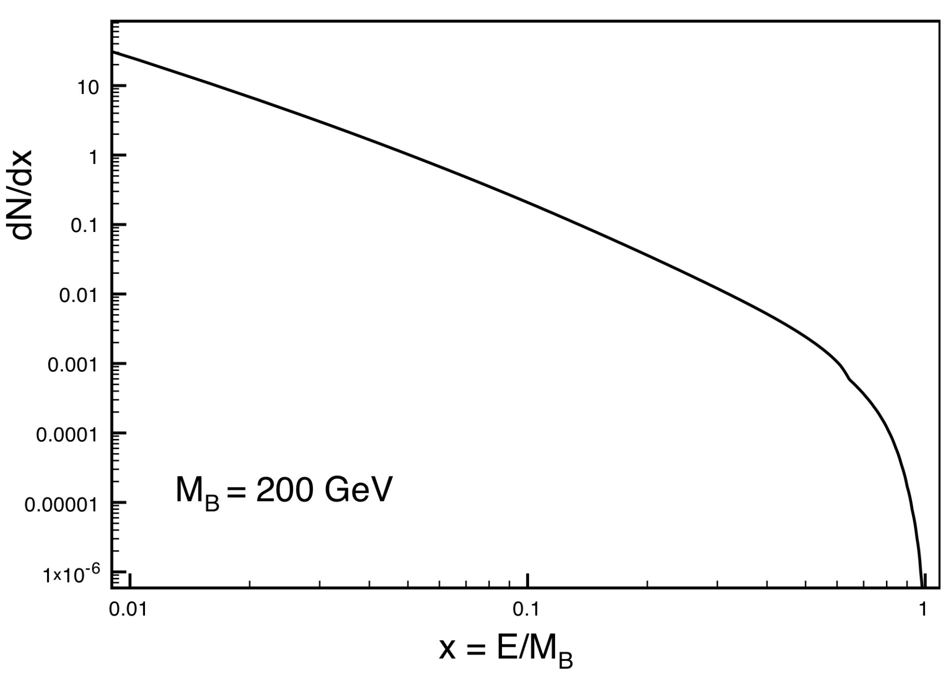
- previous studies of signals of DM from AGNs focused exclusively on the component from jet-halo interactions

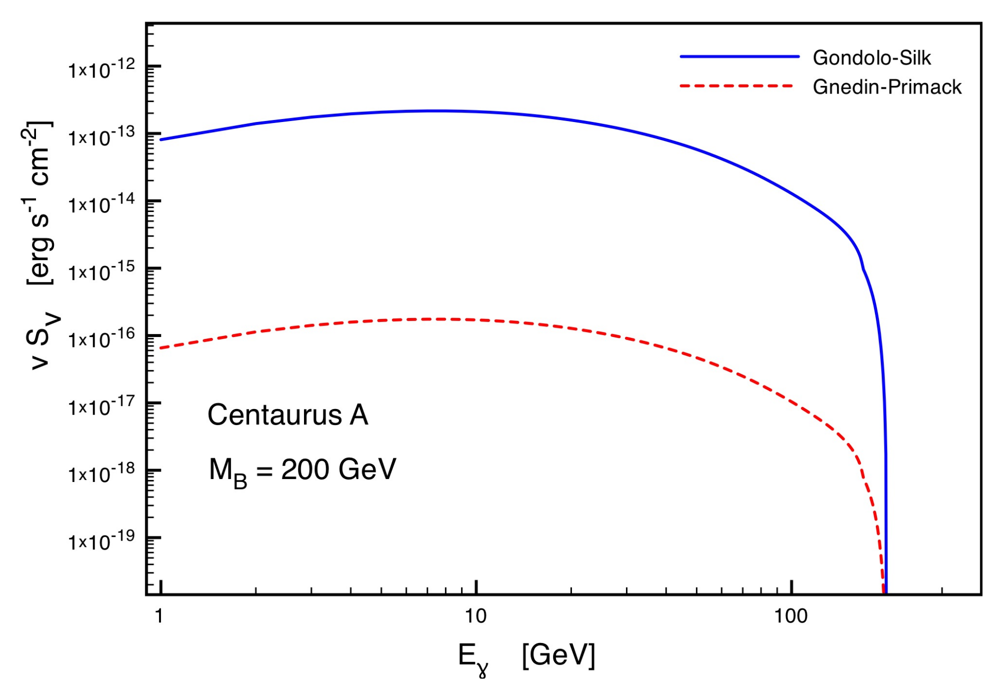
- we wanted to check whether or not WIMP annihilations within the AGN halo could enhance the signal and/or change the shape of the spectra

- the flux of gamma rays from WIMP annihilations in AGN goes as the DM density squared and falls off as the inverse distance squared:

$$\left(\frac{d\Phi}{dE_\gamma}\right)_{ann.} = \frac{dN_\gamma}{dE_\gamma}\frac{\langle\sigma v\rangle_{tot}}{8\pi M_B^2 d_{AGN}^2}\int_{r_{min}}^{r_0} dr 4\pi r^2 \rho_{DM}^2(r)$$

- for continuum annihilations where WIMPs annihilate into light SM states which then radiate and/or hadronize/decay into photons:

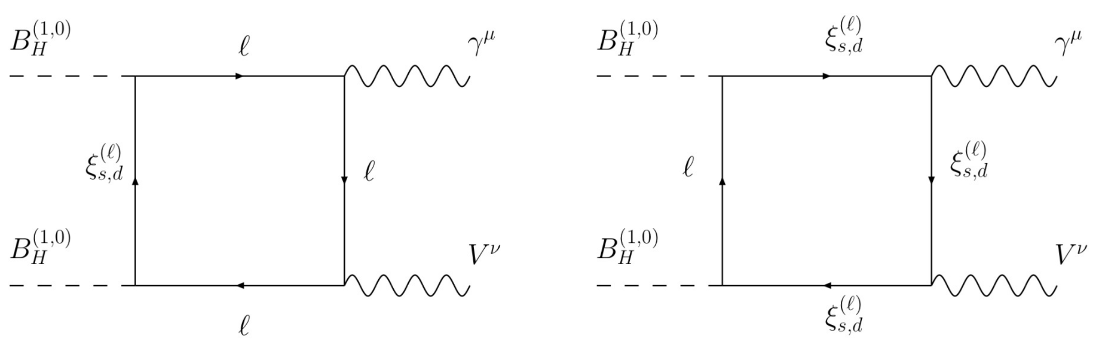




gamma rays from annihilation (line emission)

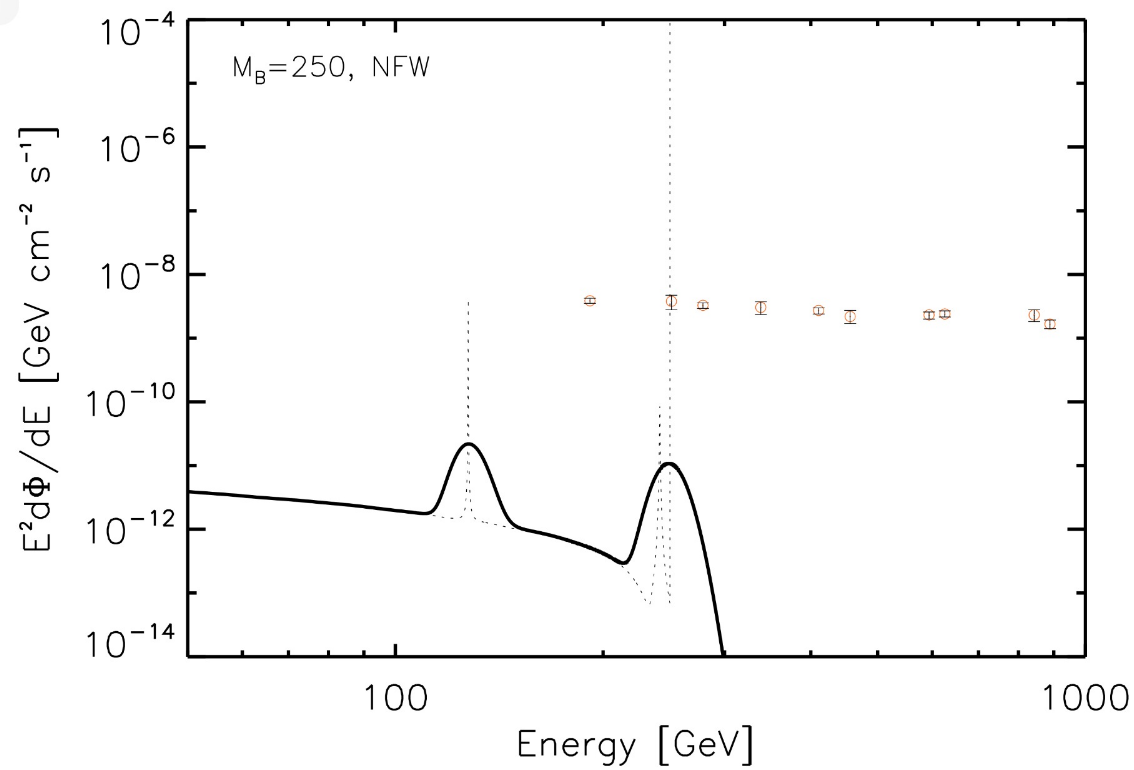
- the "chiral square" model was chosen for this study because of its rich and interesting spectrum from the center of our galaxy ("WIMP forest")

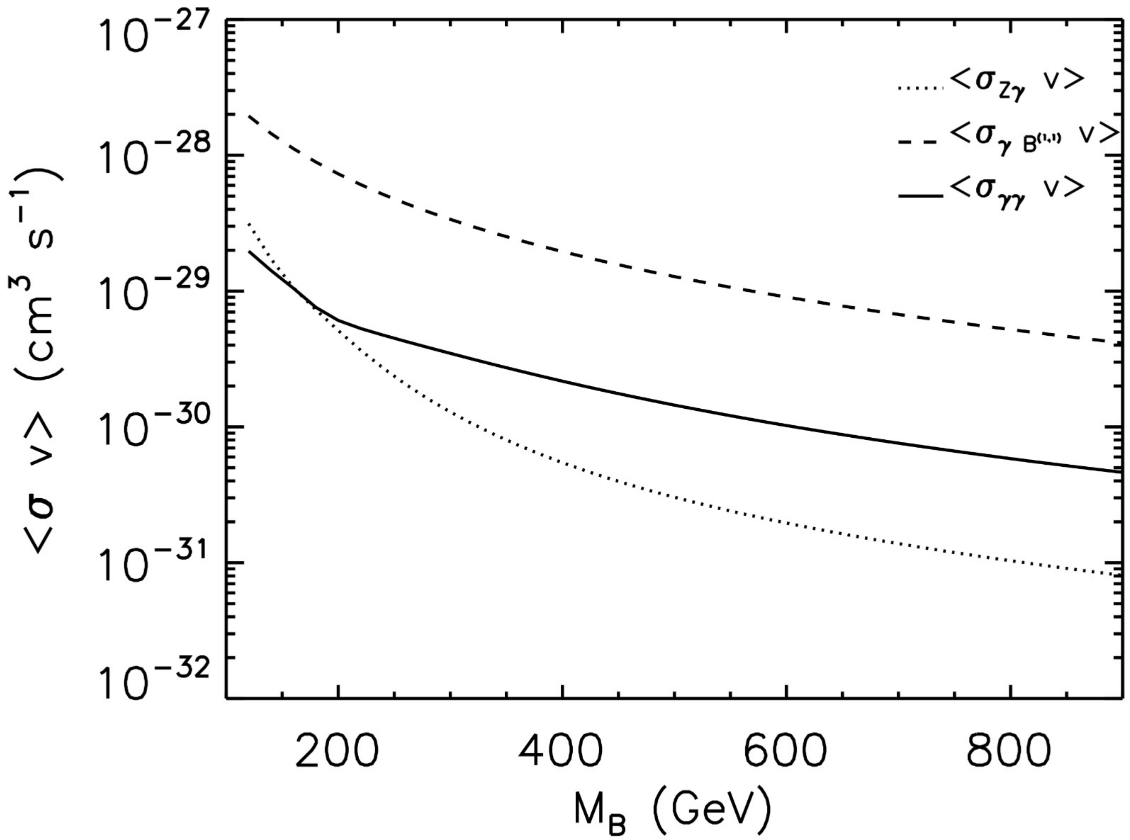
- the lines arise from box diagrams



- continuum is suppressed due to annihilations into mostly "photon-unfriendly" final states

- line cross sections are enhanced via "threshold enhancements"... and, in some cases, reduced internal cancellations amongst Feynman diagrams





total gamma ray spectrum of Cen A

- total spectrum:

$$\frac{d\Phi_{\rm tot}}{dE_\gamma} = G_0(E'_\gamma, E_\gamma)\left(\frac{d\Phi_{\rm bkg}}{dE'_\gamma} + \frac{d\Phi_{\rm cont.}}{dE'_\gamma} + \frac{d\Phi_{\rm line}}{dE'_\gamma} + \lambda_{\rm AGN}\frac{d\Phi_{\rm AGN}}{dE'_\gamma}\right) dE'_\gamma$$

- assume astro. background follows a power law:

$$\frac{d\Phi_{\rm bkg}}{dE_\gamma} = A_{\rm b}\left(\frac{E_\gamma}{\rm GeV}\right)^{\delta_{\rm b}}$$

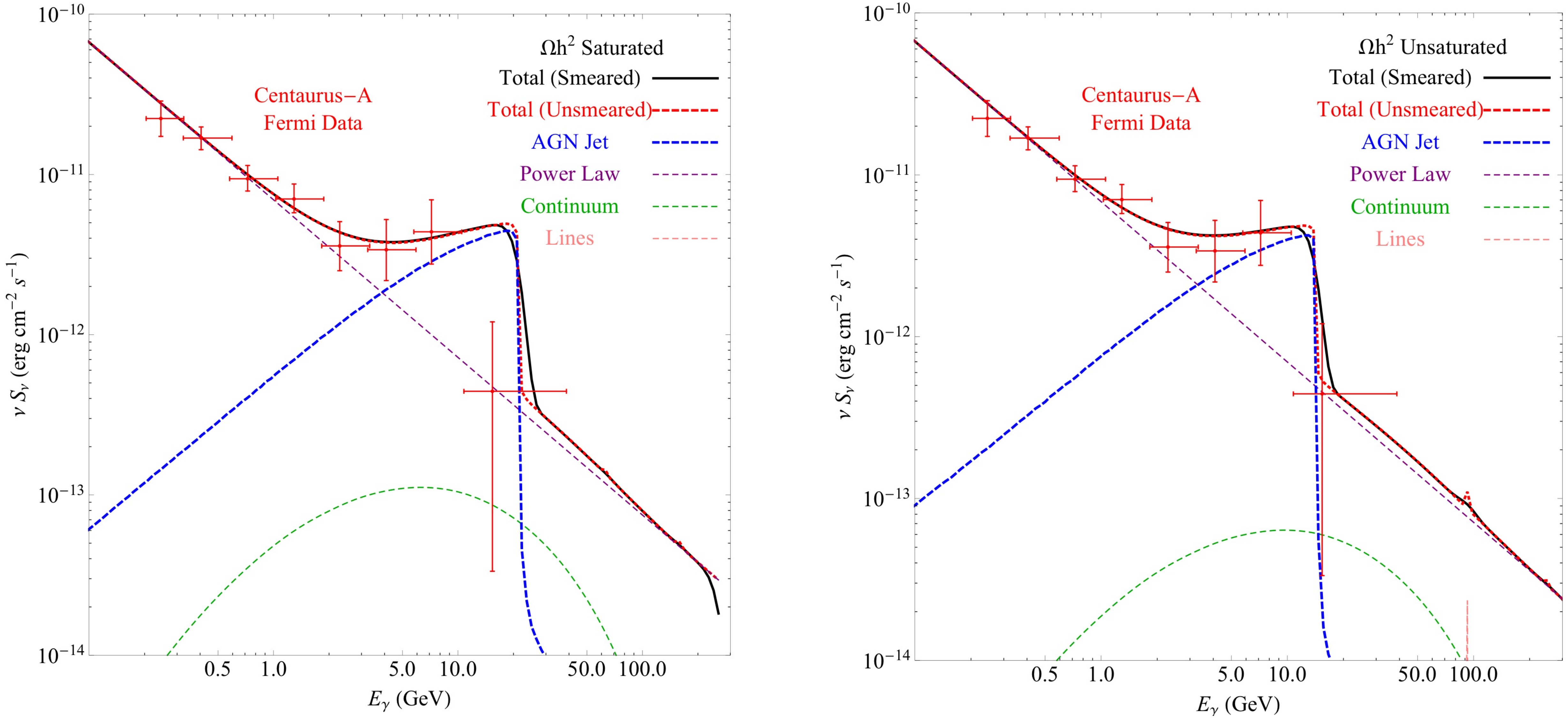
- take into account energy resolution (10% for Fermi LAT)

$$G_0(E'_\gamma, E_\gamma) = \frac{1}{\sqrt{2\pi}\sigma_{exp}} e^{-\frac{(E'_\gamma - E_\gamma)^2}{2\sigma^2_{exp}}}$$

- the coefficient for the AGN piece parameterizes our uncertainty for this piece (we take it to range from 0.5 - 1)

- in the following, we fit the relic density in two ways: 1) we assume that BH accounts for all of dark matter ("saturated") and 2) we assume that BH is one component among others that contribute to the relic density ("unsaturated")

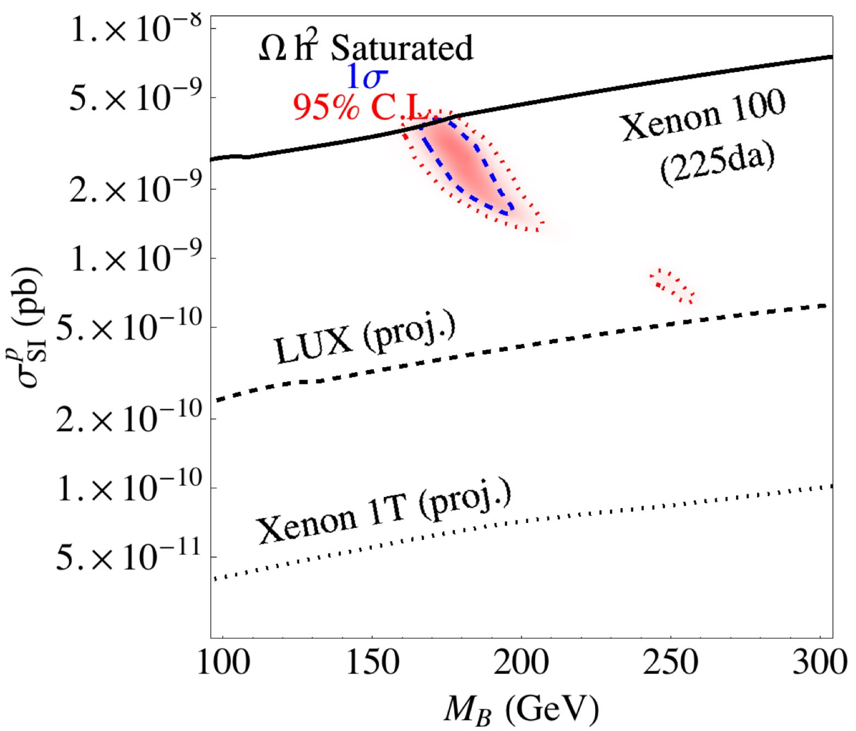
total gamma ray spectrum of Cen A

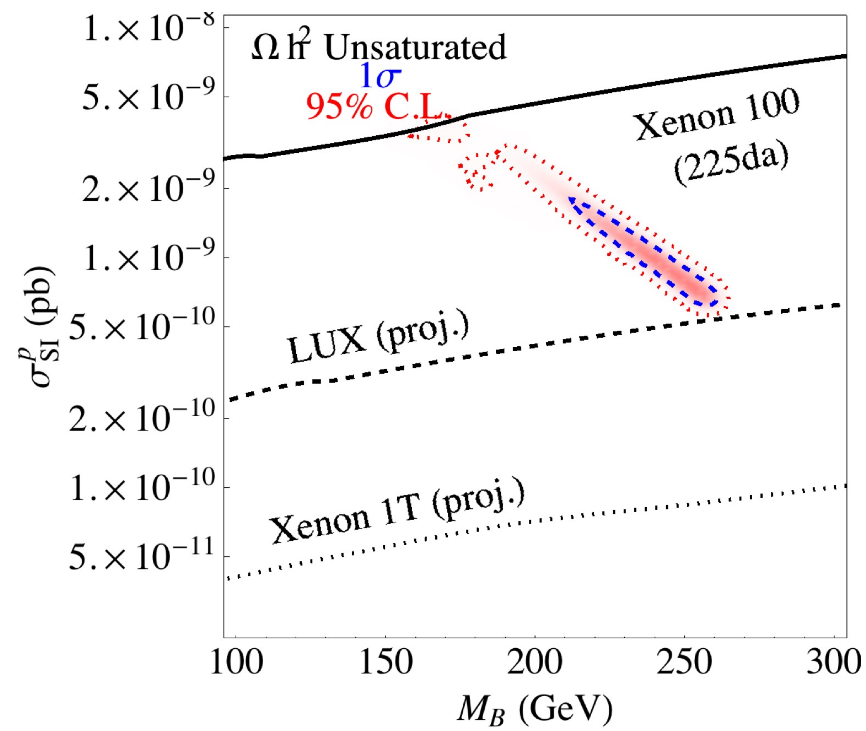


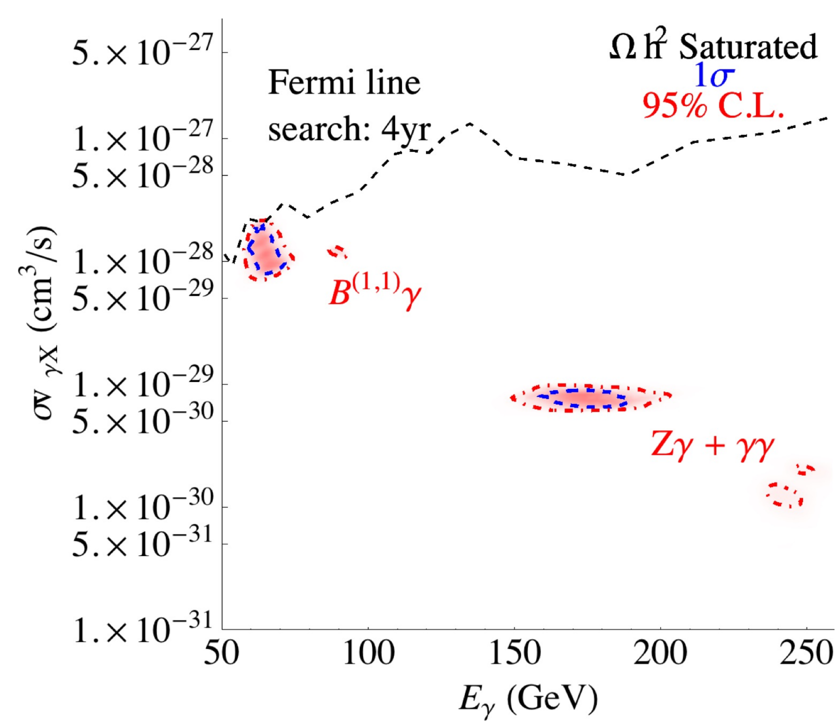
the AGN jet component and astrophysical background completely outshine contributions from continuum and line annihilations.

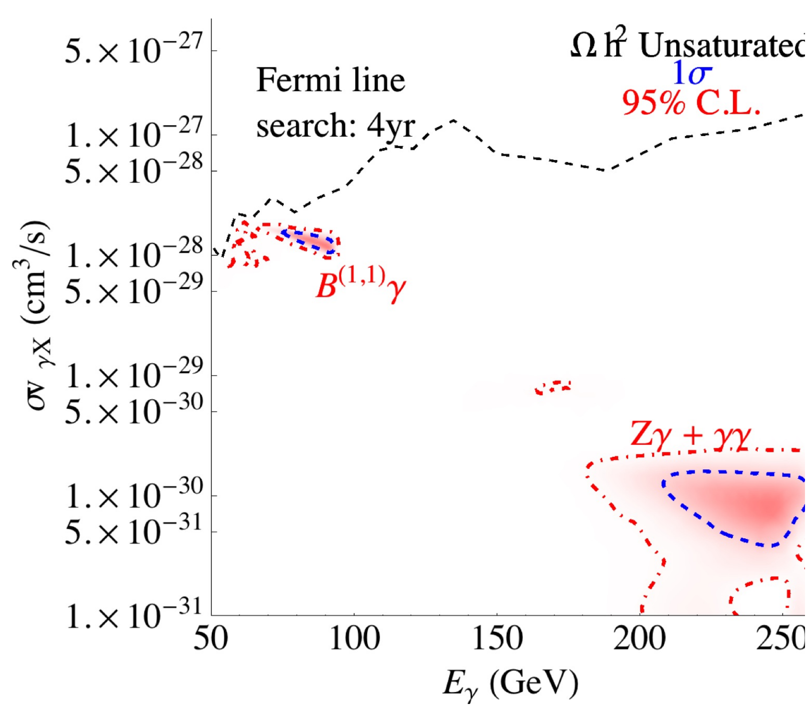
using AGN to bound new physics

- using parameter values extracted from the AGN fit, we can make predictions for other experiments:









summary

- turn over every stone in the search for dark matter!
- AGNs provide an interesting possibility...
  - extremely dense regions of DM around the core
  - highly-energetic jets of charged particles blasting through these regions
  - interactions of these two components can produce gamma ray spectra with very distinctive features
- WIMP annihilations are typically overshadowed by AGN jet component
- Observations of AGN gamma ray spectra can provide important information regarding the parameter spaces of models of new physics.