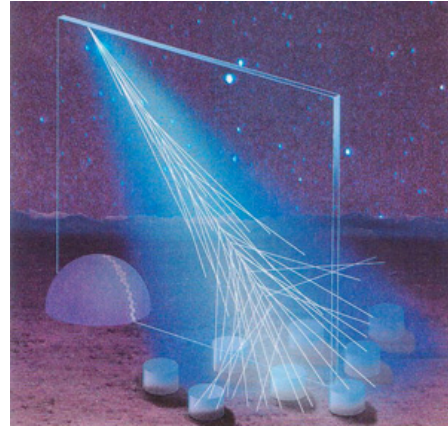


Cascades, Backgrounds, and the Intergalactic Magnetic Field*

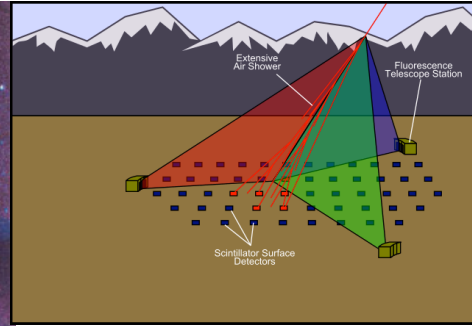
Tonia Venters
NASA Goddard Space Flight Center
June 10, 2014

*based on Venters & Pavlidou 2013, MNRAS, 432, 3485

What's in it for me?

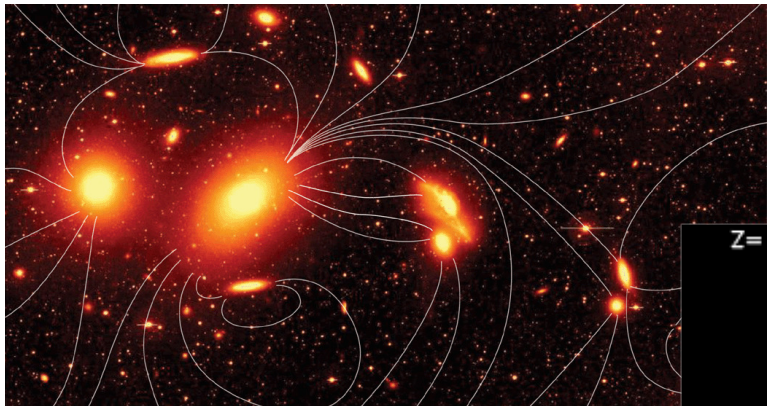
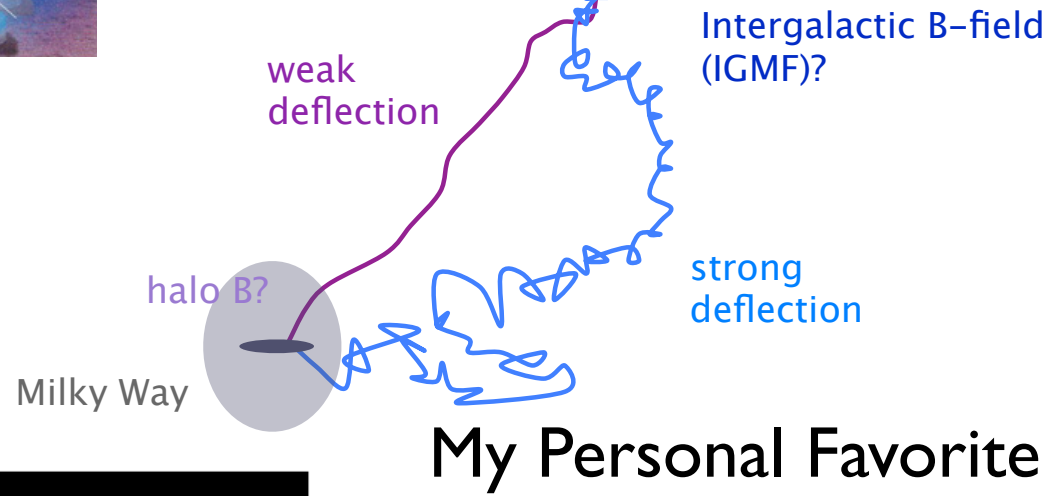


Pierre Auger (concept)

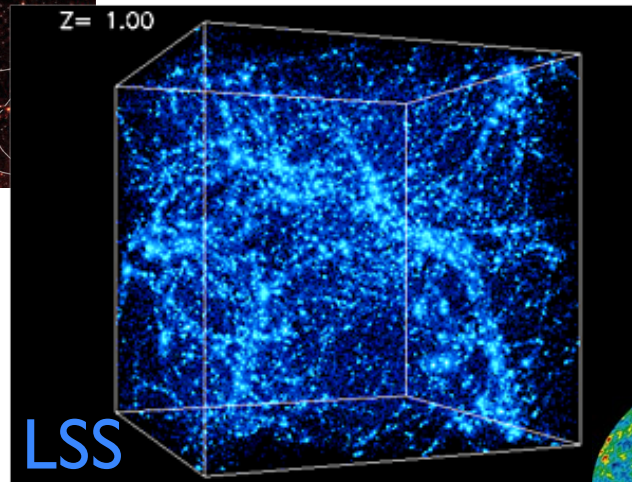


Telescope Array (concept)

UHECR Source

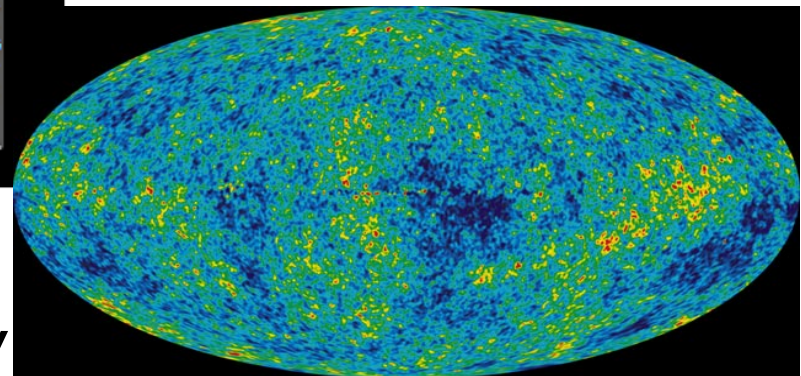


Astrophysical B Fields



LSS

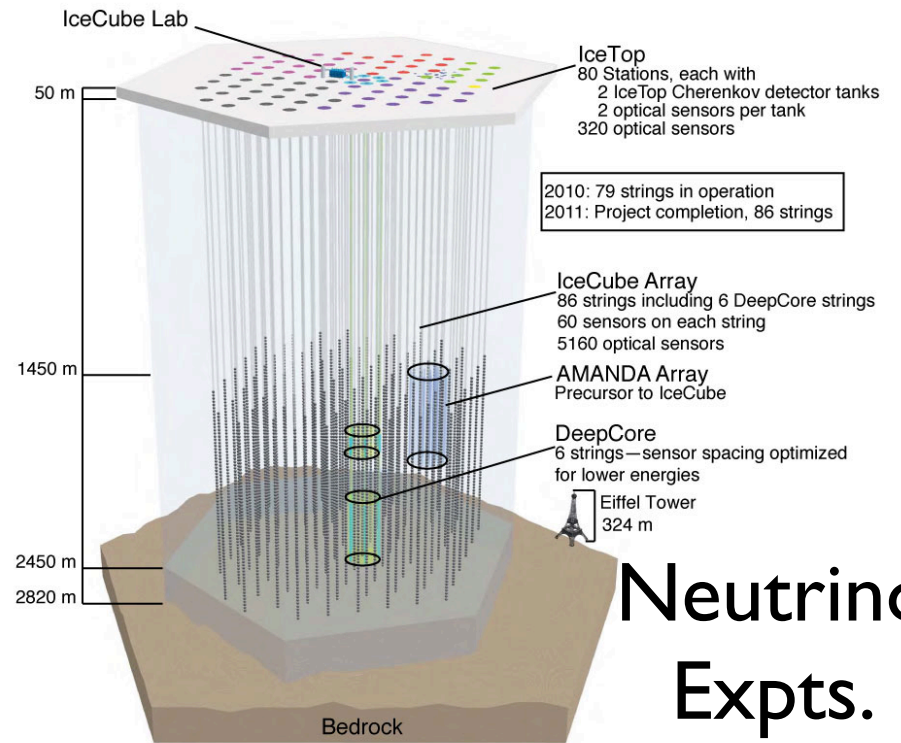
Cosmology



Our Allies



Gamma-ray Satellites



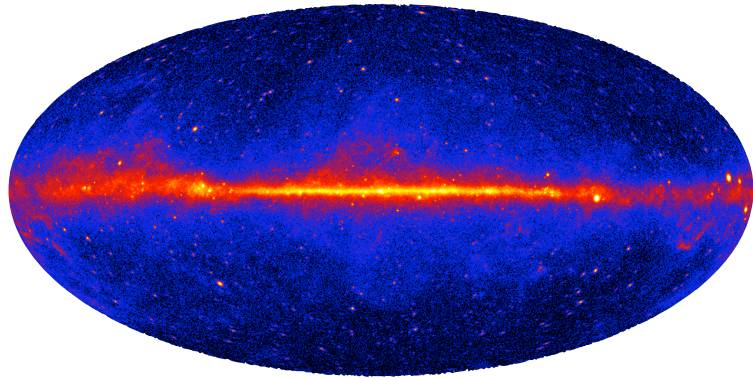
Air Shower Arrays



IACTs



Components of the EGB

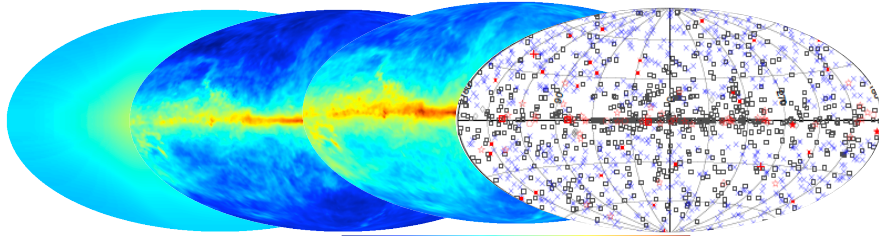


Known players:

- ◆ Star-forming galaxies
- ◆ Active galaxies (blazars, and maybe some from other types of radio galaxies)

Inverse Compton

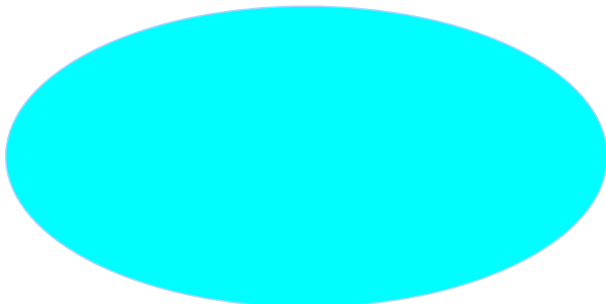
π^0 -decay **Resolved**



Bremsstrahlung

Galactic diffuse emission

(CR interactions with the interstellar medium)



Isotropic diffuse emission

(presumably extragalactic)

Suspected contributors:

- Truly diffuse emission - gamma rays produced in EM cascades of highly energetic particles

Players about which we like to speculate:

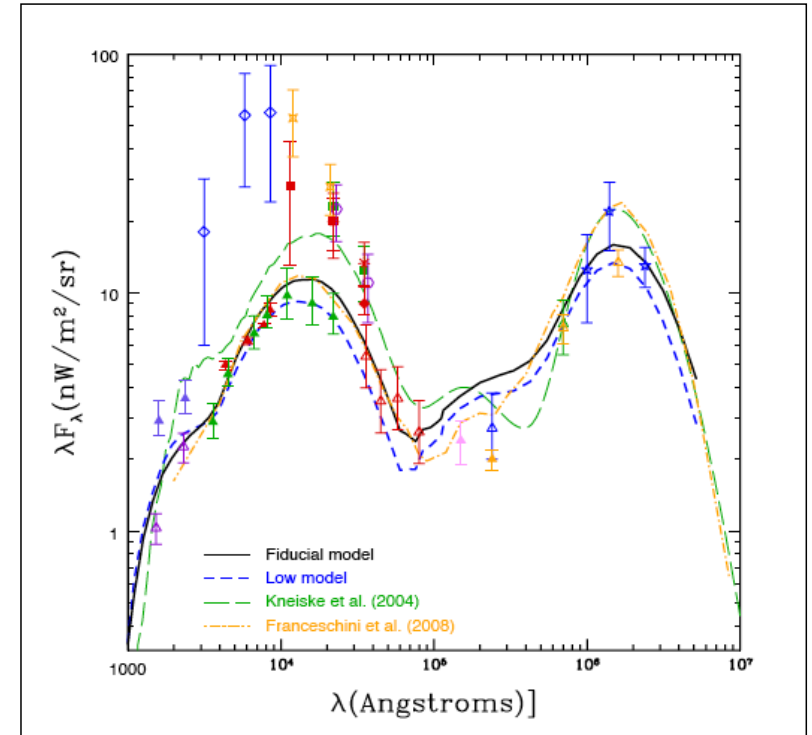
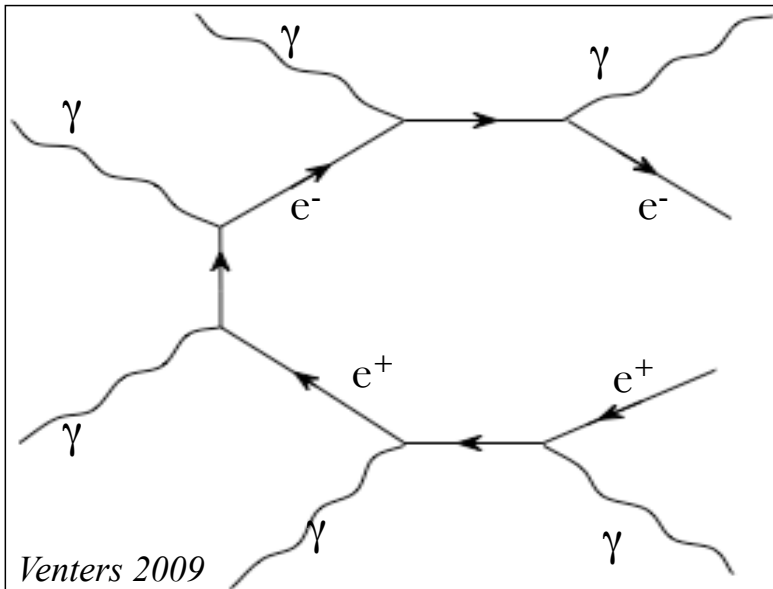
- Exotic physics (e.g., dark matter annihilation?)



VHE Gamma Rays in the EBL

Extragalactic background light (EBL) consists of:

- ◆ Emission from starlight at NIR/Opt./UV wavelengths
- ◆ Reradiated thermal dust emission at FIR wavelengths

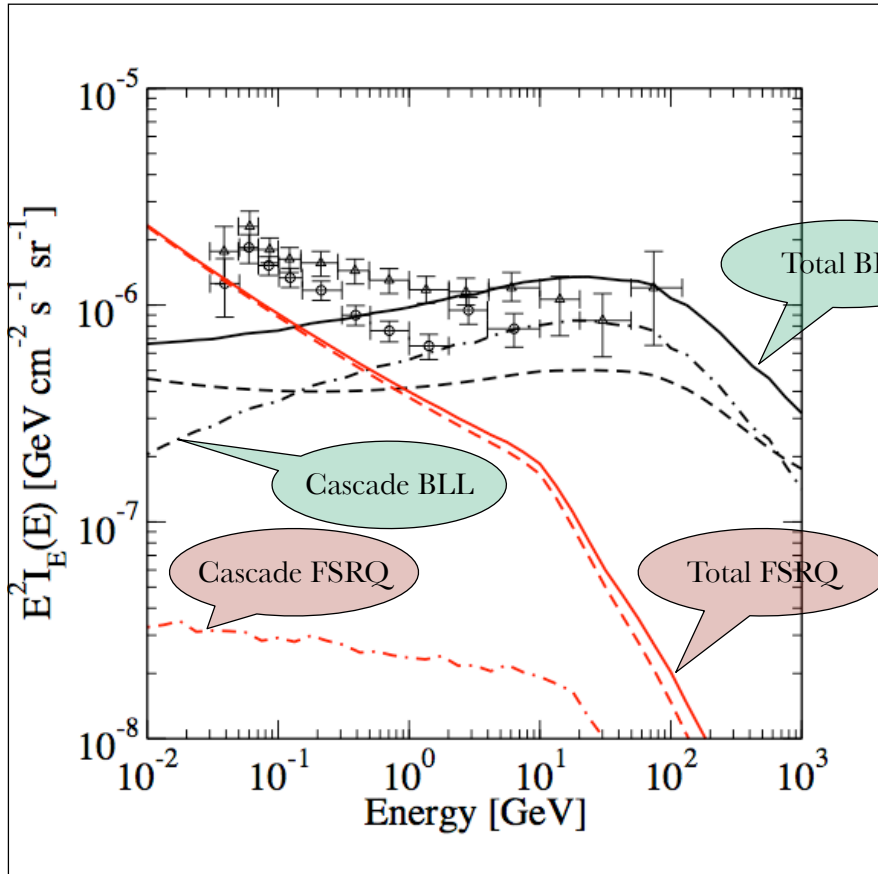


Gilmore et al. 2009

Cascades -

- ◆ e^+e^- pair production
- ◆ inverse Compton scattering of cascade electrons

Cascades and the EGB



Venters 2010

For a cosmological population of VHE γ -ray emitters -- collective spectrum should exhibit a suppression at the high energy part of the EGB and an enhancement at lower energies resulting from cascades

Magnetic Deflection of Cascades

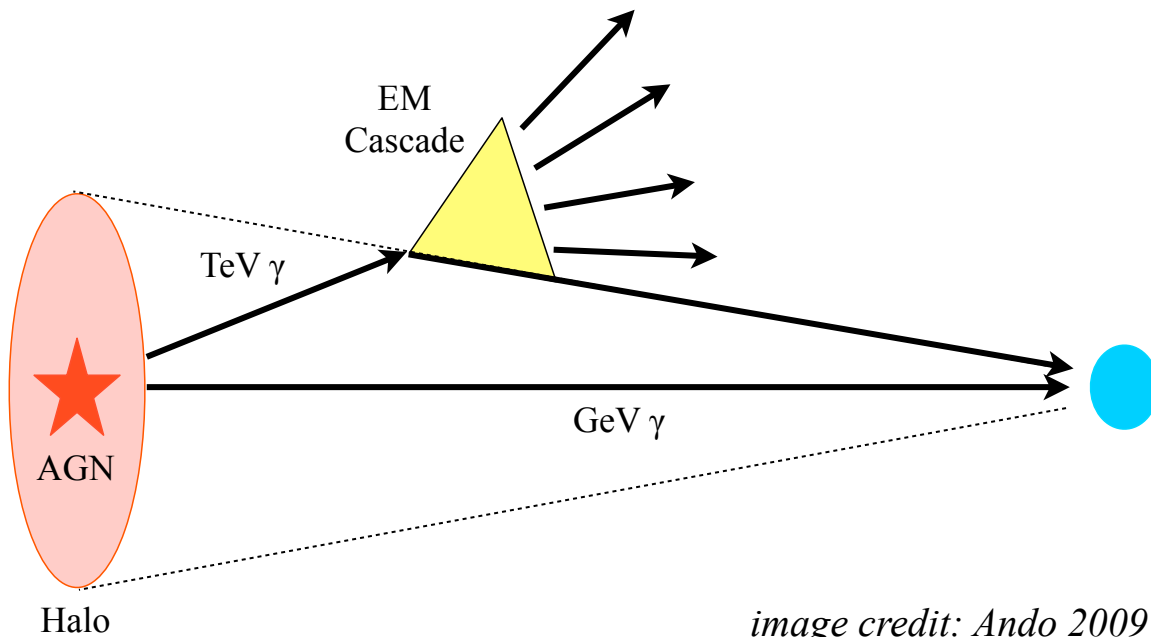


image credit: Ando 2009

- Gamma-rays initially emitted off observer's line-of-sight initiate cascades that are deflected in direction of observer.
- Deflected emission makes a halo around source.

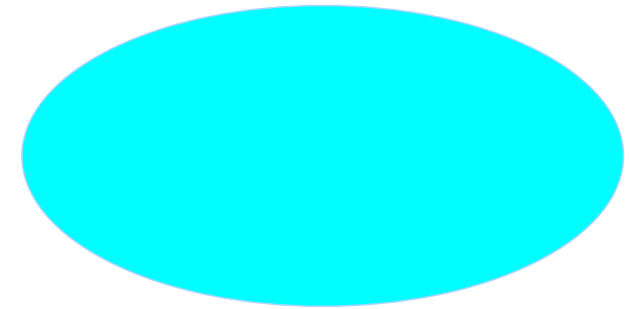
Anisotropy Studies

$$\frac{\partial I}{I} = \sum_{l=1}^{\infty} \sum_{m=-l}^l a_{lm} Y_{lm}$$

$$\langle a_{lm} a_{l'm'}^* \rangle = C_l$$

$$C_l^{\text{tot}}(E) = f_1^2(E) C_l^{(1)} + f_2^2(E) C_l^{(2)} + \text{cross terms,}$$

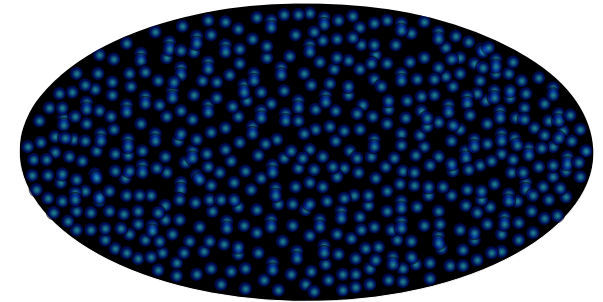
where $f_n(E) = I_n(E) / I_{\text{tot}}(E)$



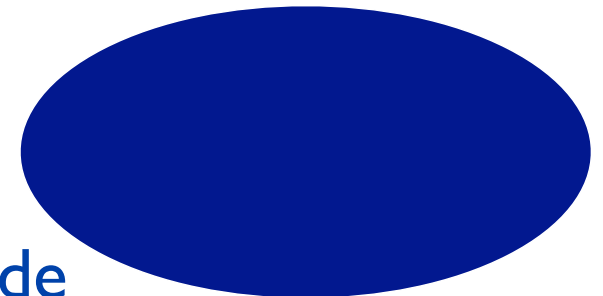
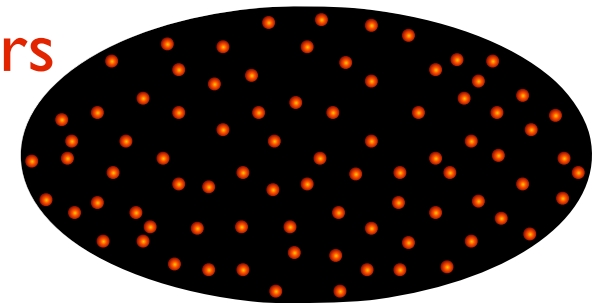
Isotropic diffuse emission
(presumably extragalactic)



Star-forming Galaxies



Blazars



Deflected Cascade

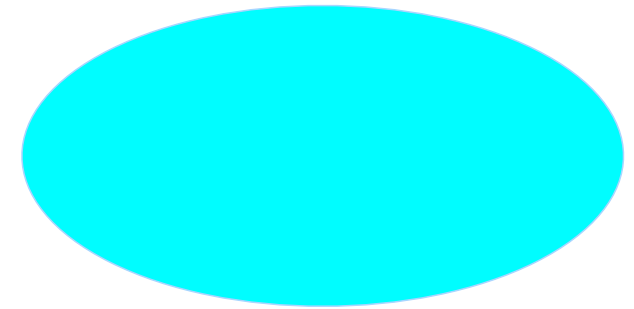
Anisotropy Studies

$$\frac{\partial I}{I} = \sum_{l=1}^{\infty} \sum_{m=-l}^l a_{lm} Y_{lm}$$

$$\langle a_{lm} a_{l'm'}^* \rangle = C_l$$

$$C_l^{\text{tot}}(E) = f_1^2(E) C_l^{(1)} + f_2^2(E) C_l^{(2)} + \text{cross terms,}$$

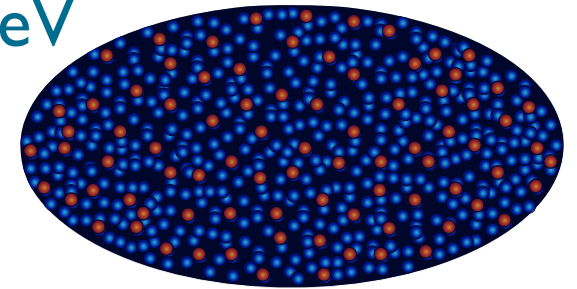
where $f_n(E) = I_n(E) / I_{\text{tot}}(E)$



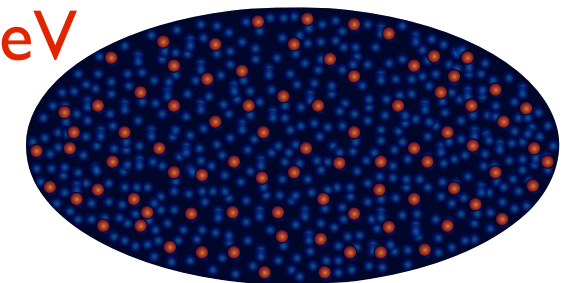
Isotropic diffuse emission
(presumably extragalactic)



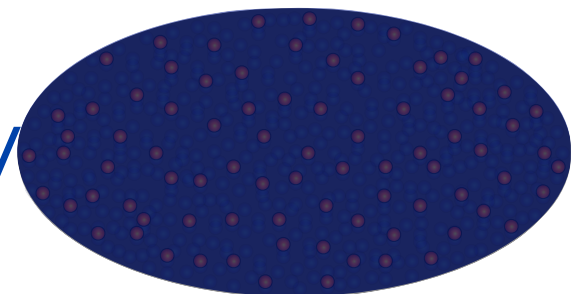
~ 1 GeV



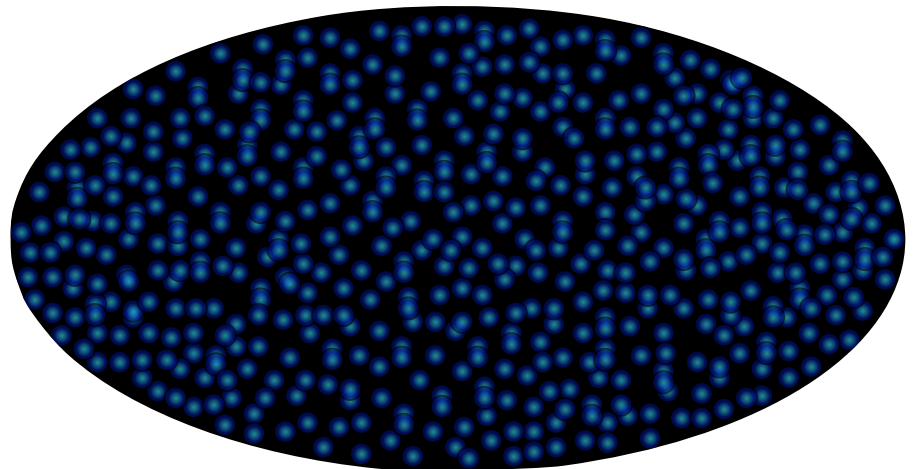
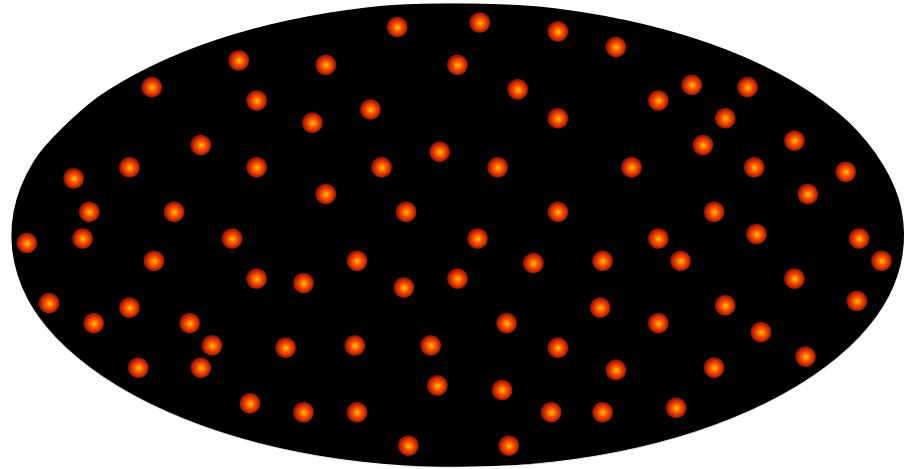
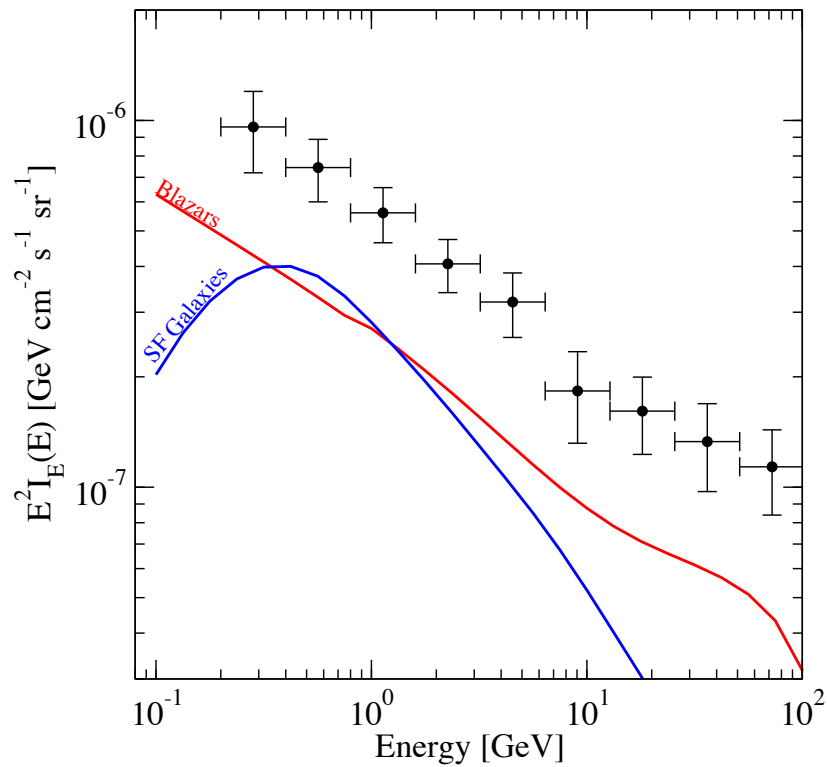
~ 10 GeV



~ 100 GeV



Anisotropy as a Function of Energy



$$C_l^{\text{tot}}(E) = f_{\text{bl}}^2(E) C_l^{\text{bl}} + f_{\text{gal}}^2(E) C_l^{\text{gal}}$$

Impact of Cascades

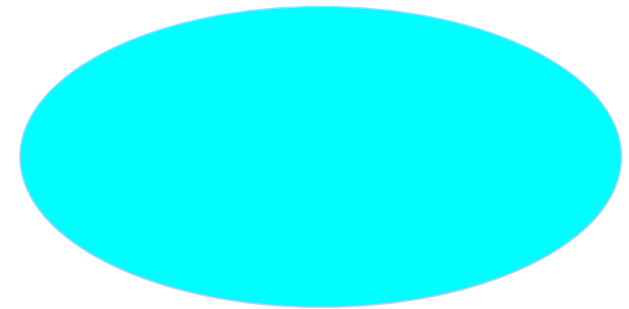
(null B)

$$\frac{\partial I}{I} = \sum_{l=1}^{\infty} \sum_{m=-l}^l a_{lm} Y_{lm}$$

$$\langle a_{lm} a_{l'm'}^* \rangle = C_l$$

$$C_l^{\text{tot}}(E) = f_1^2(E) C_l^{(1)} + f_2^2(E) C_l^{(2)} + \text{cross terms,}$$

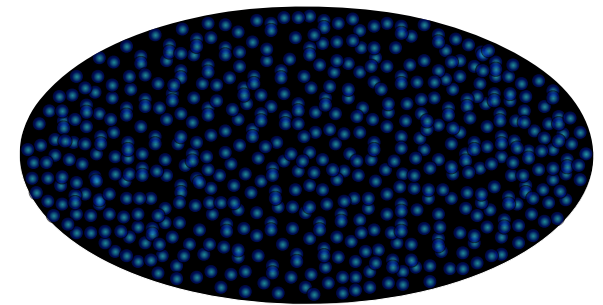
where $f_n(E) = I_n(E) / I_{\text{tot}}(E)$



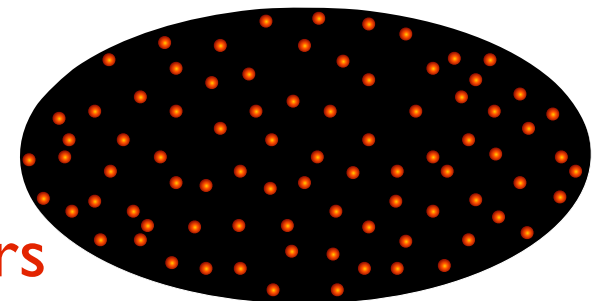
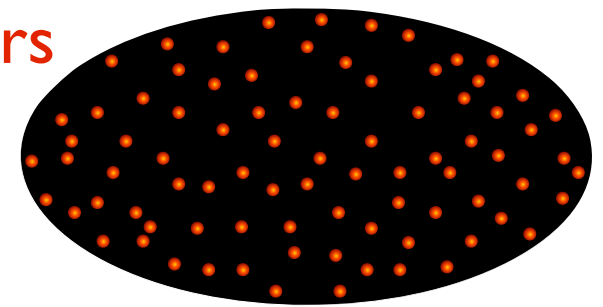
Isotropic diffuse emission
(presumably extragalactic)



Star-forming Galaxies

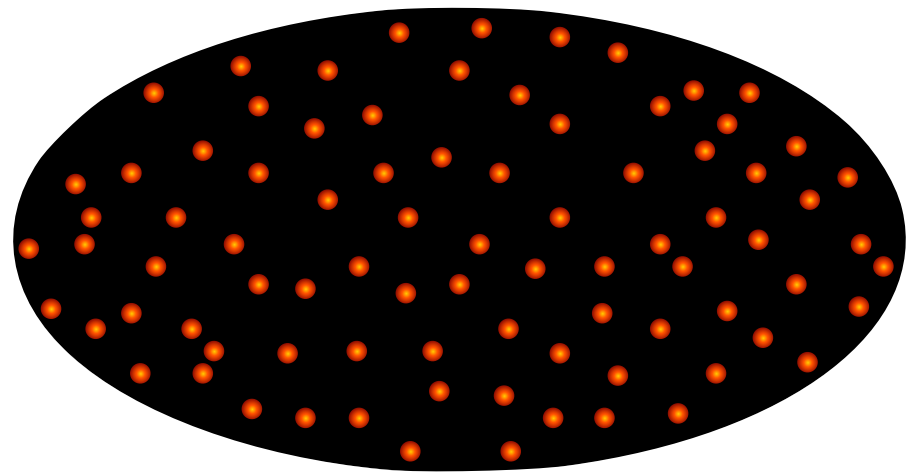
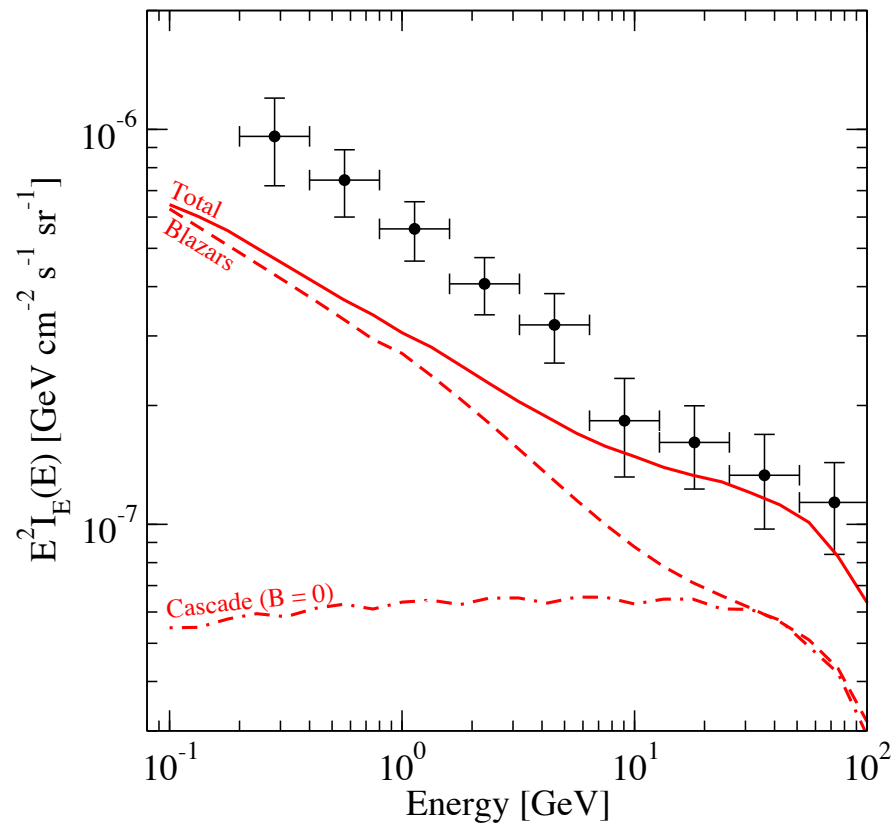


Blazars



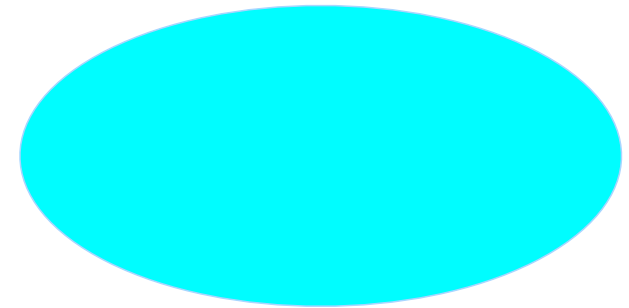
Cascades from Blazars

The Impact of Cascades (zero B)



$$C_l^{\text{tot}}(E) = (f_{\text{bl}}(E) + f_{\text{cas}}(E))^2 C_l^{\text{bl}}$$

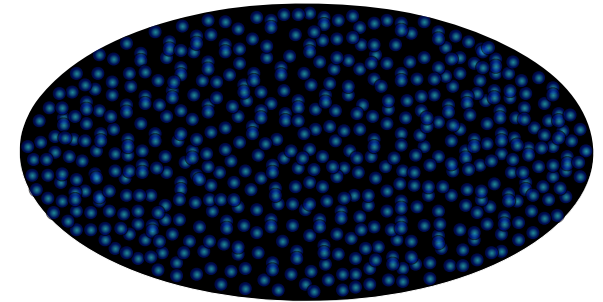
Impact of Cascades (intermediate B)



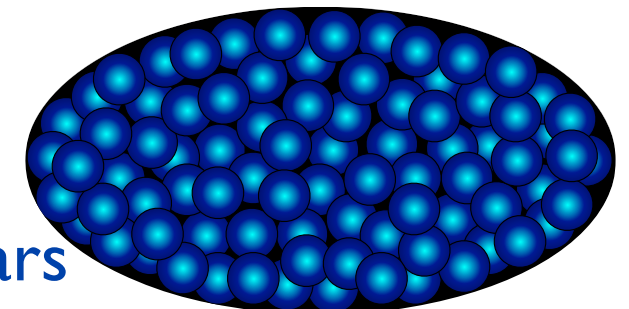
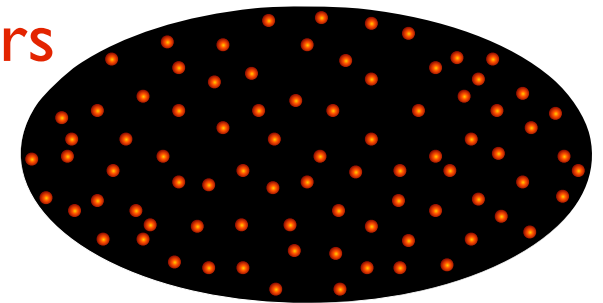
Isotropic diffuse emission
(presumably extragalactic)



Star-forming Galaxies



Blazars



Cascades from Blazars

$$\frac{\partial I}{I} = \sum_{l=1}^{\infty} \sum_{m=-l}^l a_{lm} Y_{lm}$$

$$\langle a_{lm} a_{l'm'}^* \rangle = C_l$$

$$C_l^{\text{tot}}(E) = f_1^2(E) C_l^{(1)} + f_2^2(E) C_l^{(2)} + \text{cross terms,}$$

where $f_n(E) = I_n(E) / I_{\text{tot}}(E)$

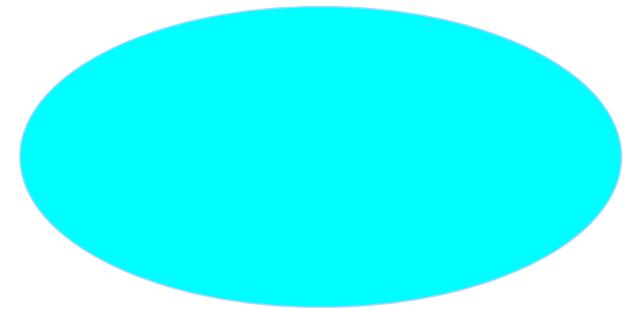
Impact of Cascades (non-zero B)

$$\frac{\partial I}{I} = \sum_{l=1}^{\infty} \sum_{m=-l}^l a_{lm} Y_{lm}$$

$$\langle a_{lm} a_{l'm'}^* \rangle = C_l$$

$$C_l^{\text{tot}}(E) = f_1^2(E) C_l^{(1)} + f_2^2(E) C_l^{(2)} + \text{cross terms,}$$

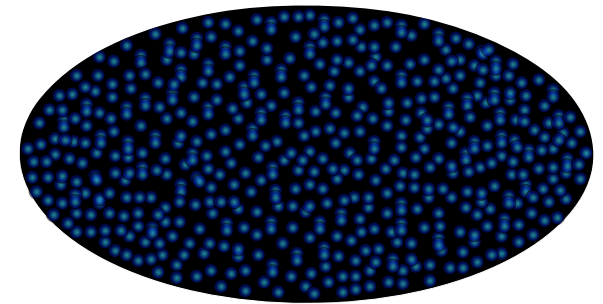
where $f_n(E) = I_n(E) / I_{\text{tot}}(E)$



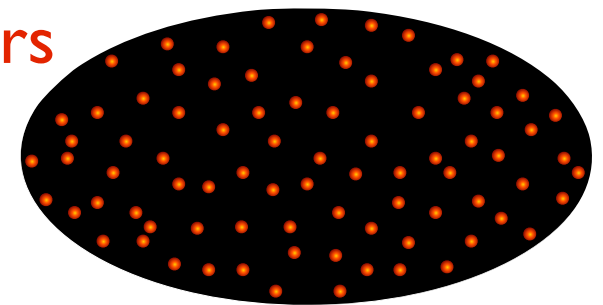
Isotropic diffuse emission
(presumably extragalactic)



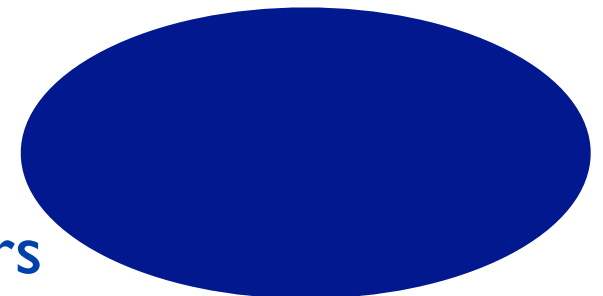
Star-forming Galaxies



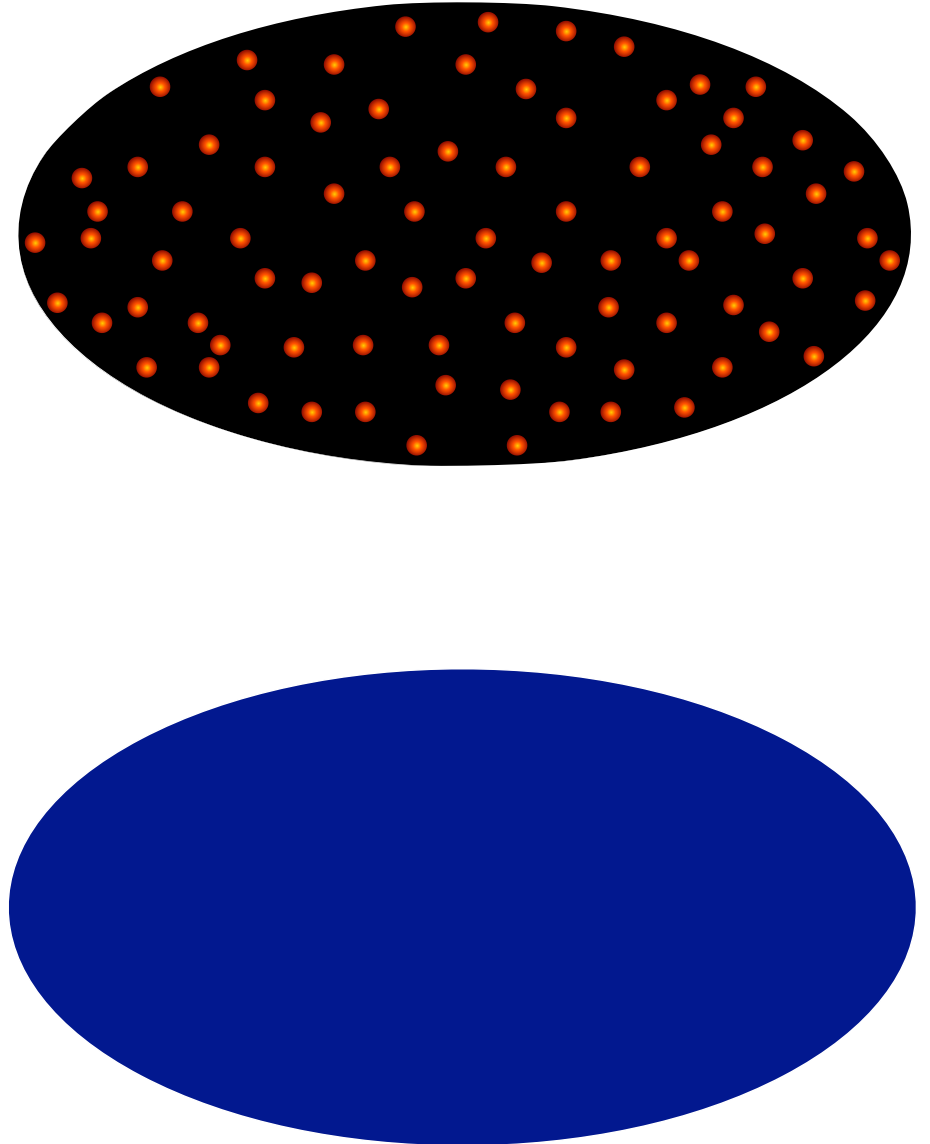
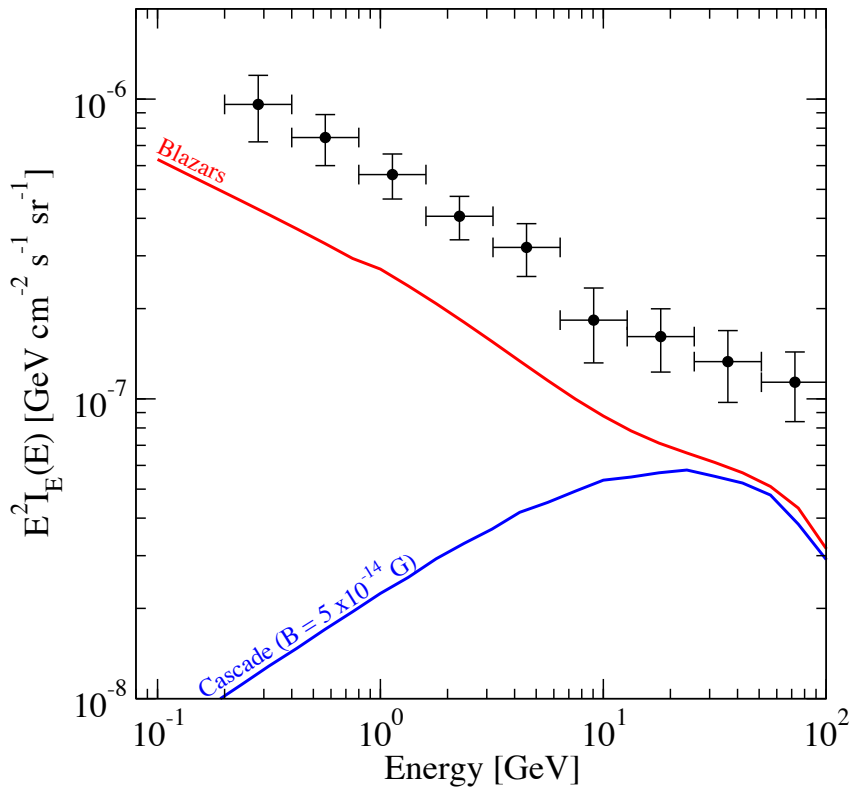
Blazars



Cascades from Blazars

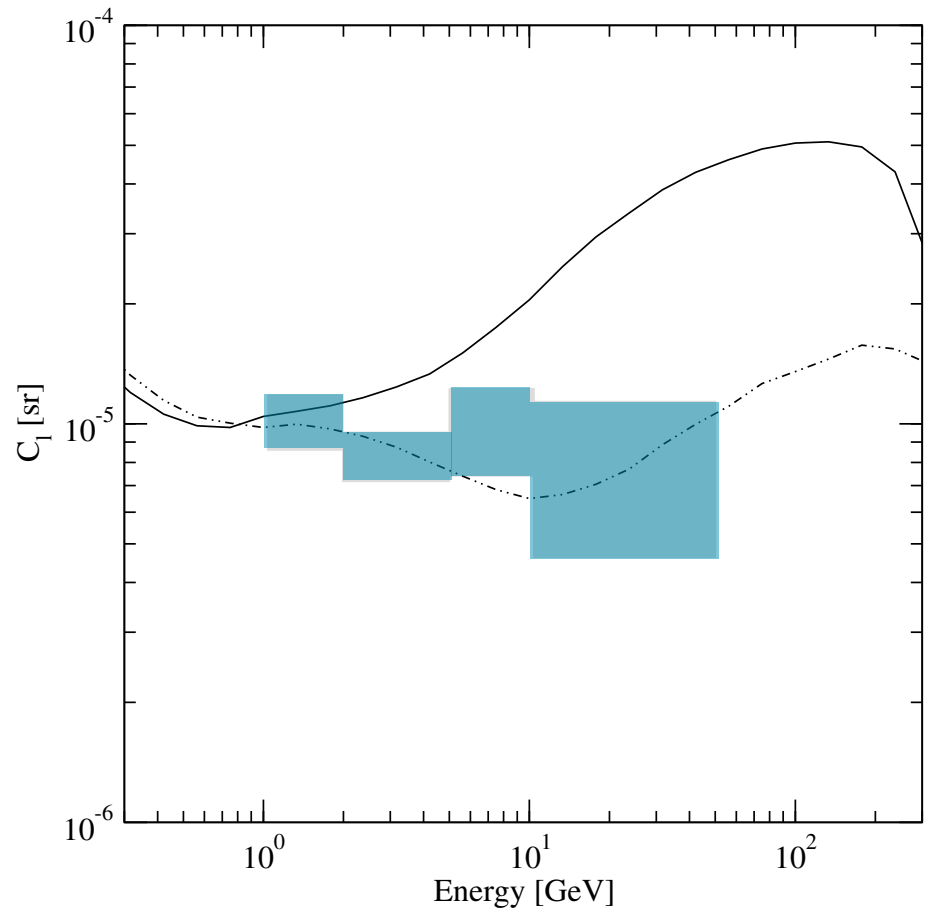
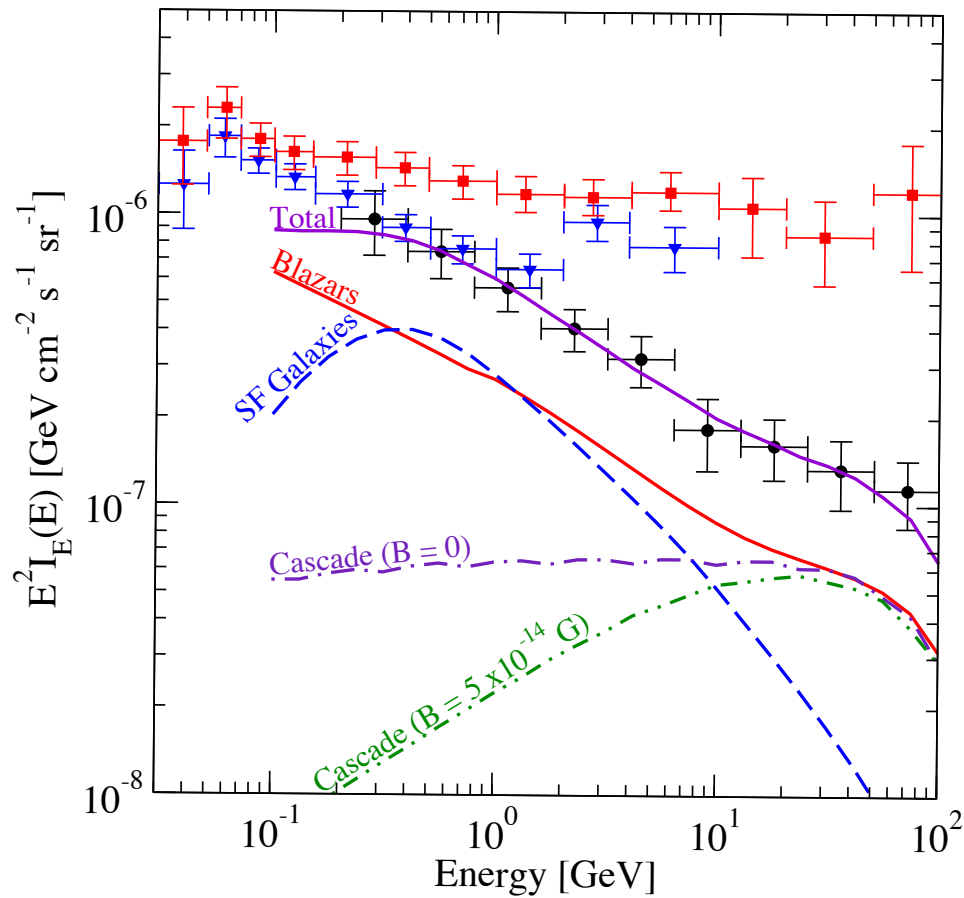


The Impact of Cascades (non-zero B)

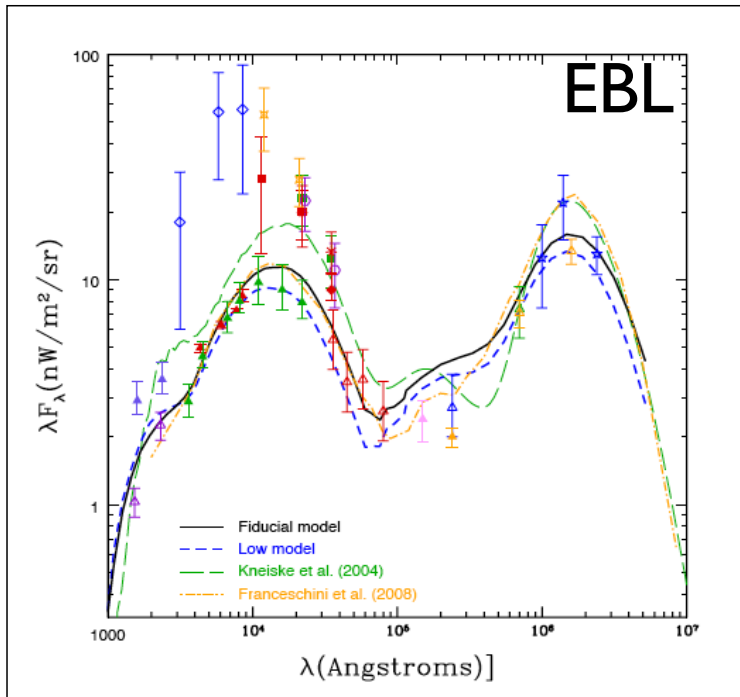


$$C_l^{\text{tot}}(E) = f_{\text{bl}}^2(E) C_l^{\text{bl}} + \cancel{f_{\text{cas}}^2(E) C_l^{\text{cas}}} + \cancel{\text{cross terms}}$$

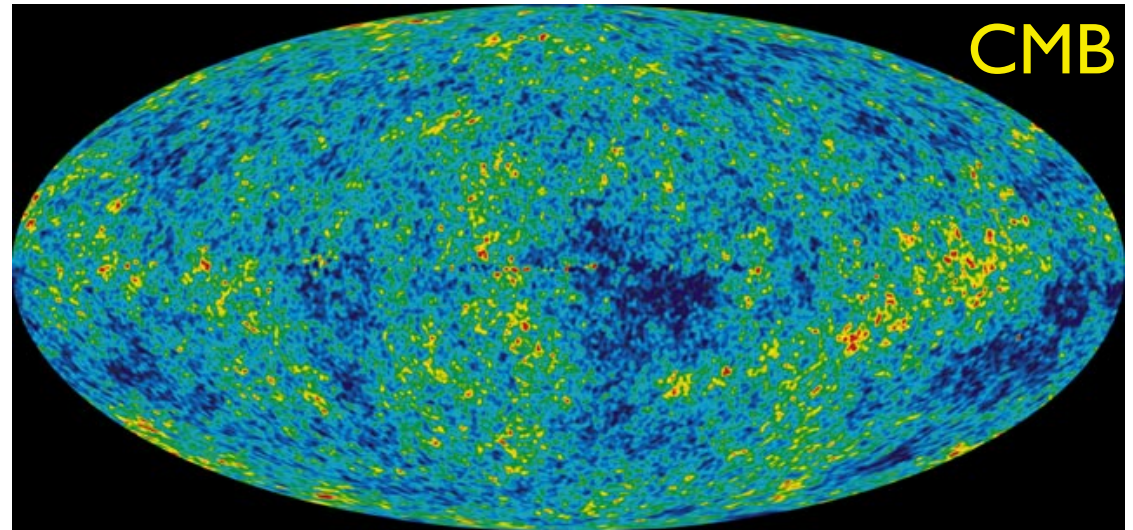
Cascades and EGB Anisotropy



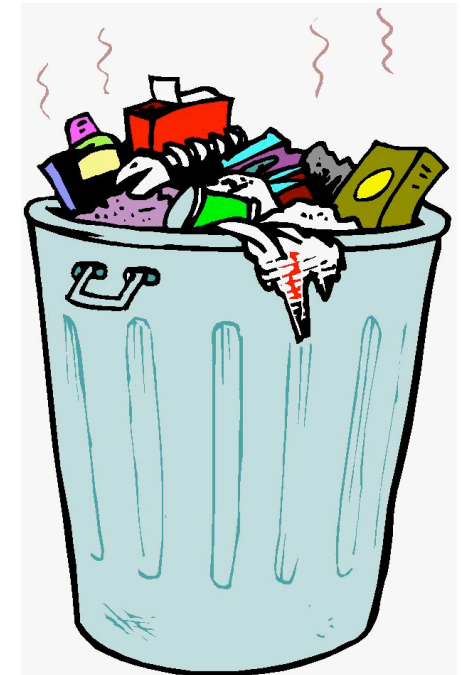
Interactions behind CR Propagation



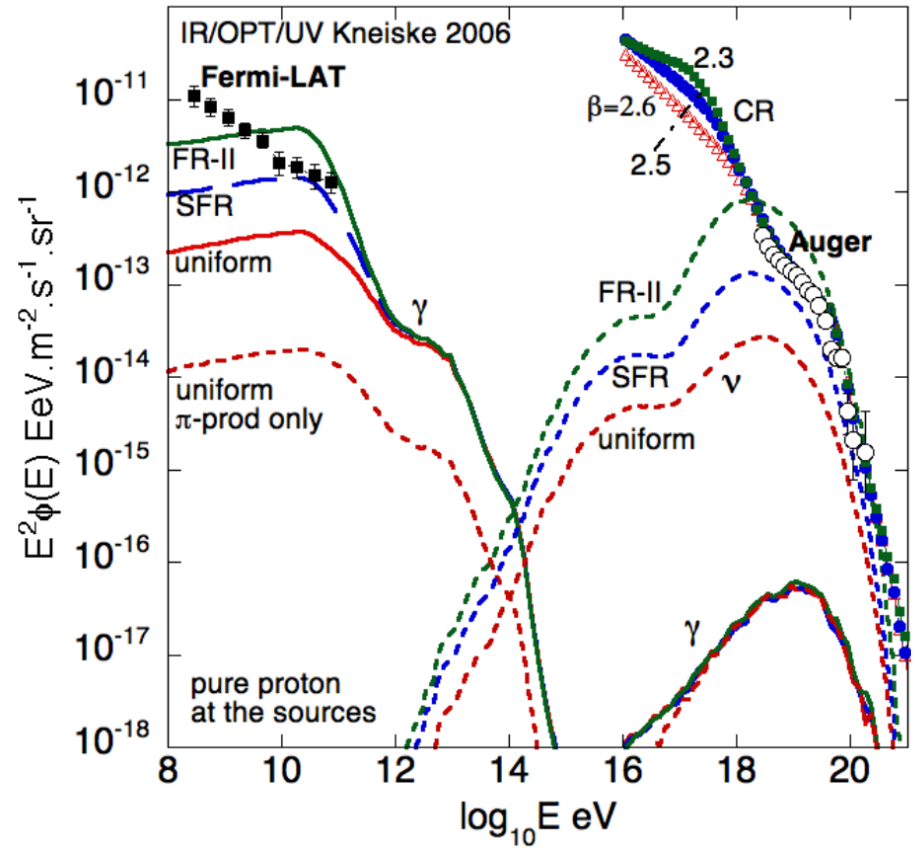
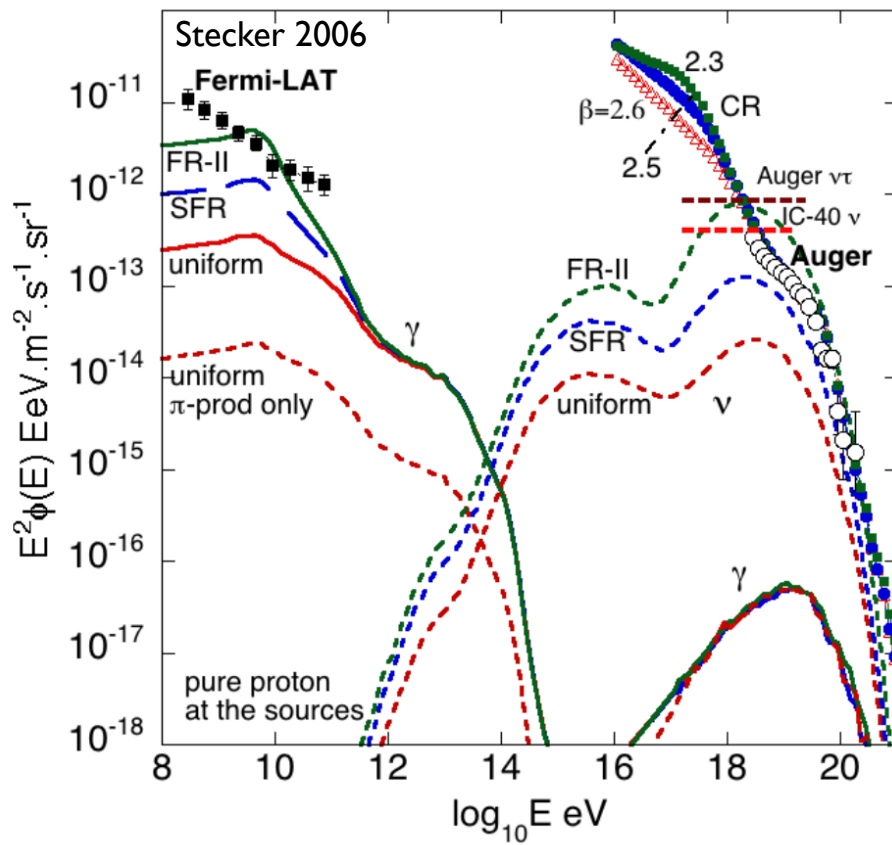
Gilmore et al. 2009



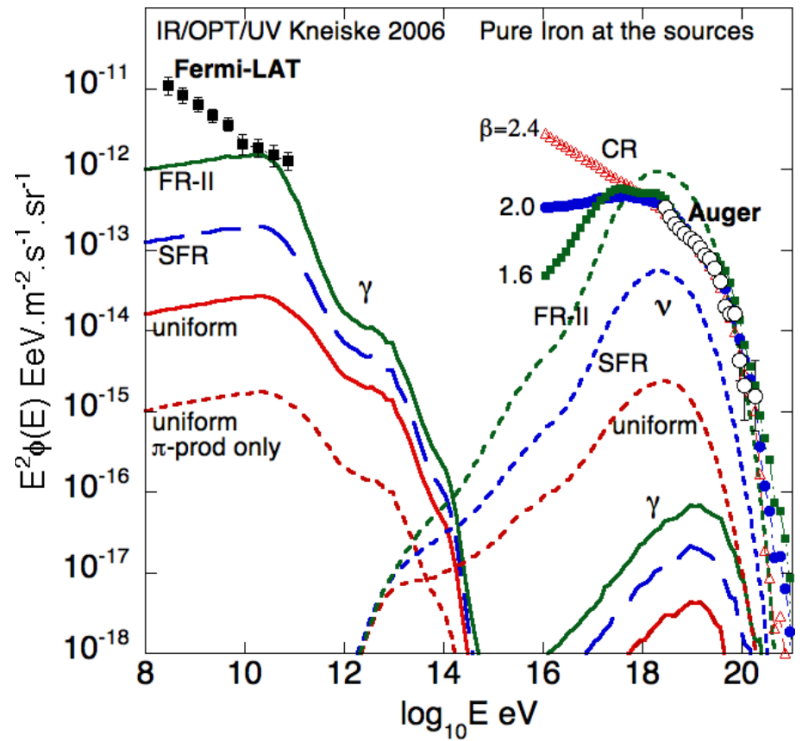
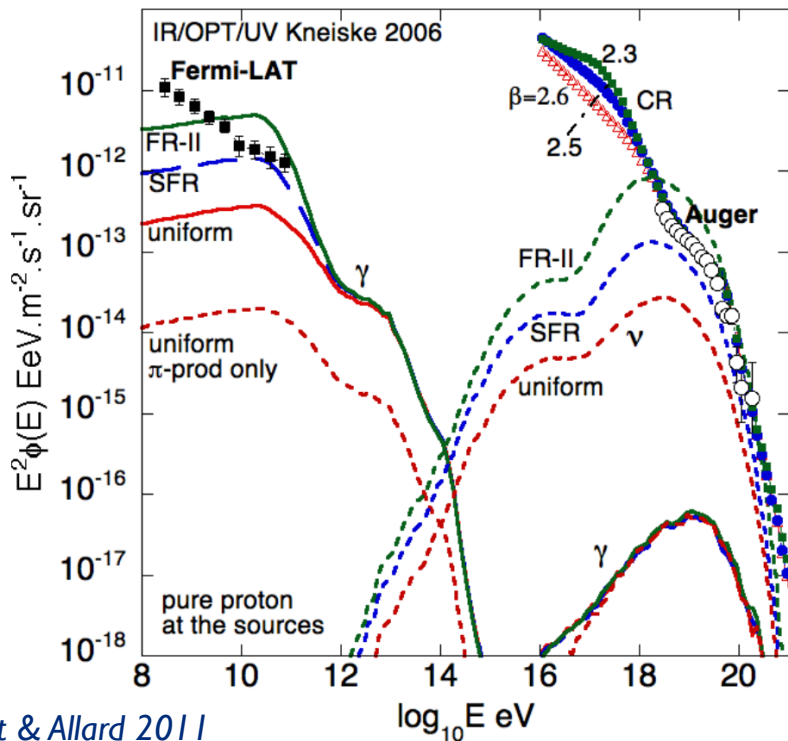
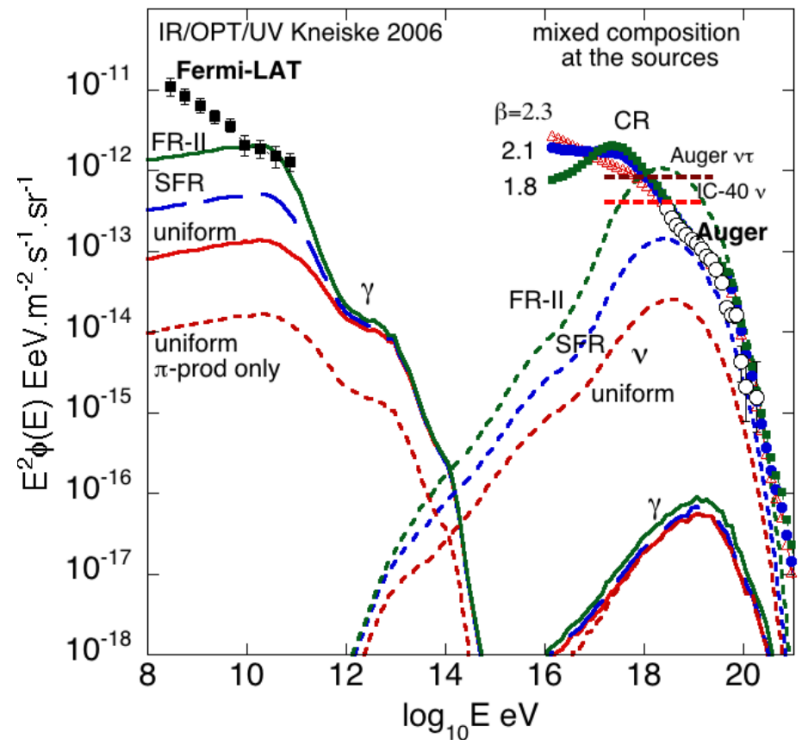
Protons and Nuclei	Bethe-Heitler pair production Photodisintegration (nuclei only) Photomeson Production	$e.g., p^\pm \gamma \rightarrow p^\pm e^- e^+$ $e.g., {}_n N \gamma \rightarrow {}_n N^* \rightarrow {}_{n-1} N p$ $e.g., p \gamma \rightarrow \Delta(1232) \rightarrow p \pi^0$
Electrons	Inverse Compton Triple Pair Production Synchrotron	$e^\pm \gamma \rightarrow e^\pm \gamma$ $e^\pm \gamma \rightarrow e^\pm e^+ e^-$ $e^\pm \tilde{\gamma} \rightarrow e^\pm \gamma$
Photons	Pair Production Double Pair Production	$\gamma \gamma \rightarrow e^+ e^-$ $\gamma \gamma \rightarrow e^+ e^- e^+ e^-$
Mesons & Muons	Decay Synchrotron	$e.g., \mu^\pm \rightarrow \bar{\nu}_\mu (\nu_\mu) e^\pm \nu_e (\bar{\nu}_e), \pi^0 \rightarrow \gamma \gamma$ $\mu^\pm \tilde{\gamma} \rightarrow \mu^\pm \gamma$



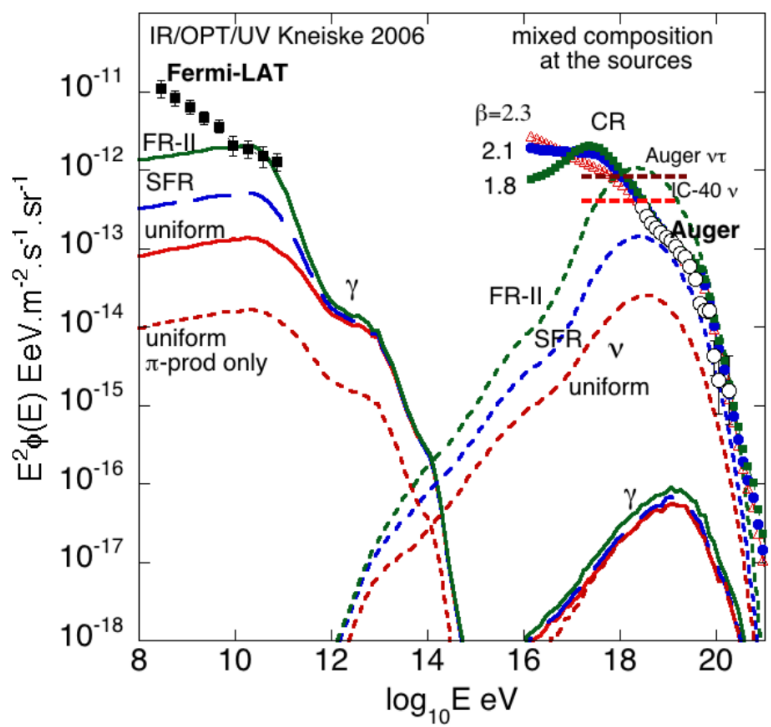
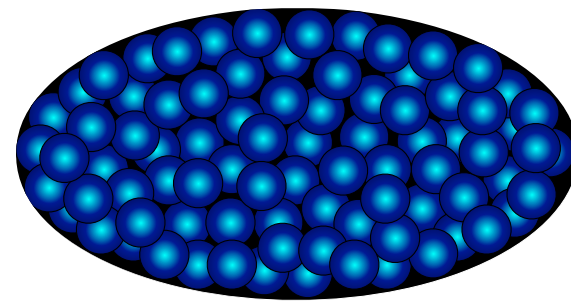
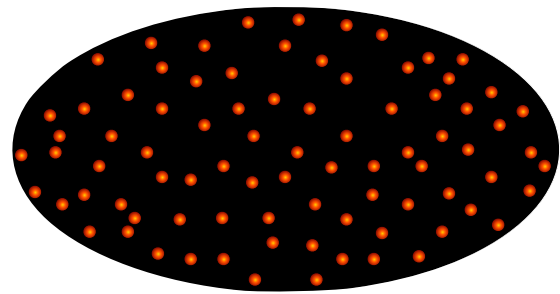
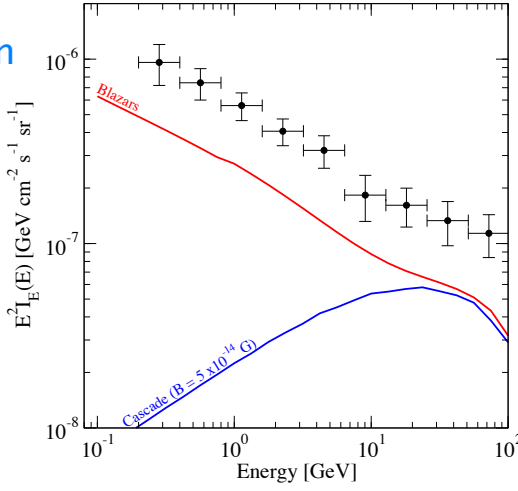
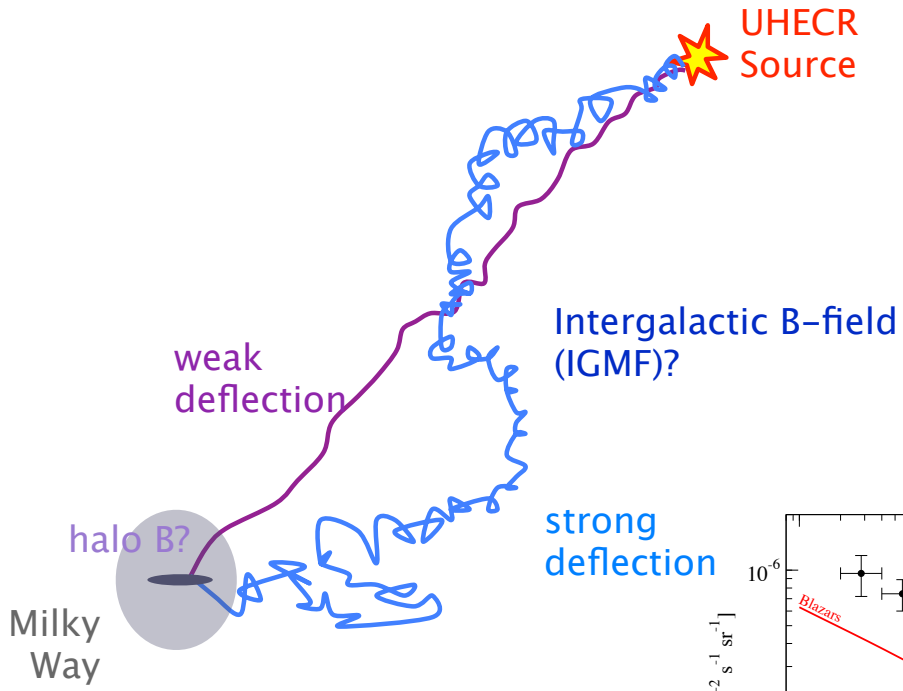
UHECR Propagation in Action



UHECR Propagation in Action



Stay Tuned!



$$C_l^{\text{tot}}(E) = f_{\text{bl}}^2(E) C_l^{\text{bl}} + f_{\text{cas}}^2(E) C_l^{\text{cas}} + \text{cross terms}$$