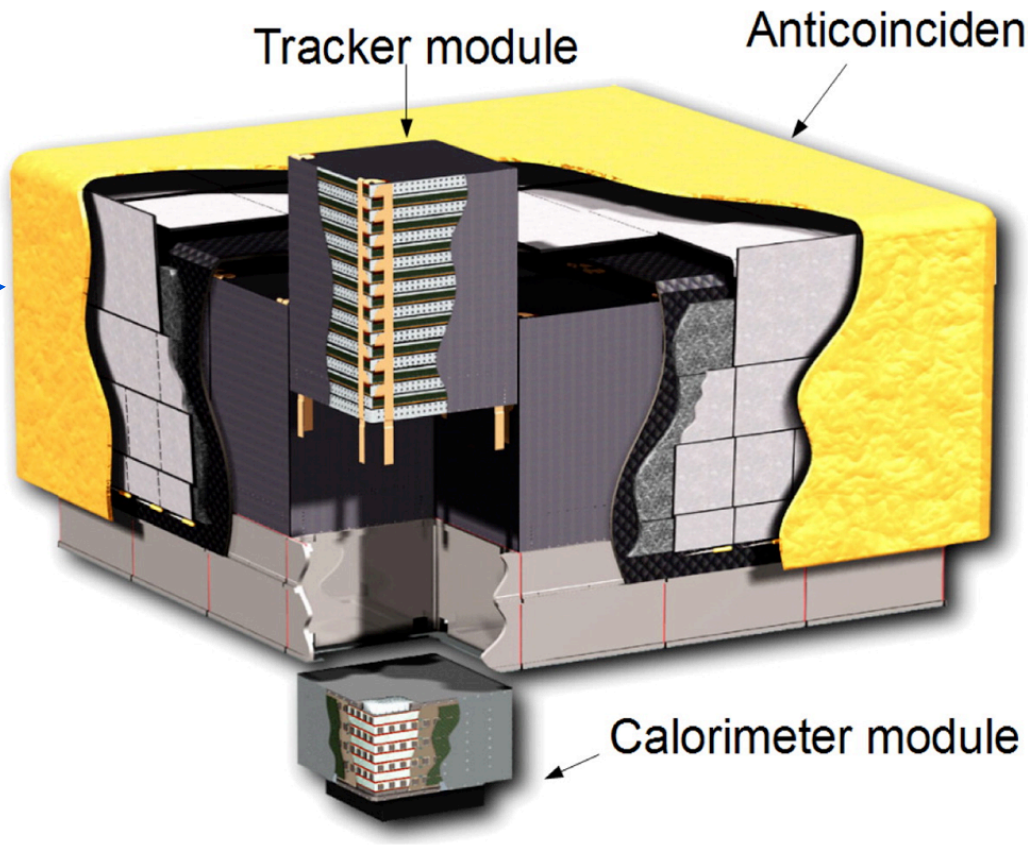
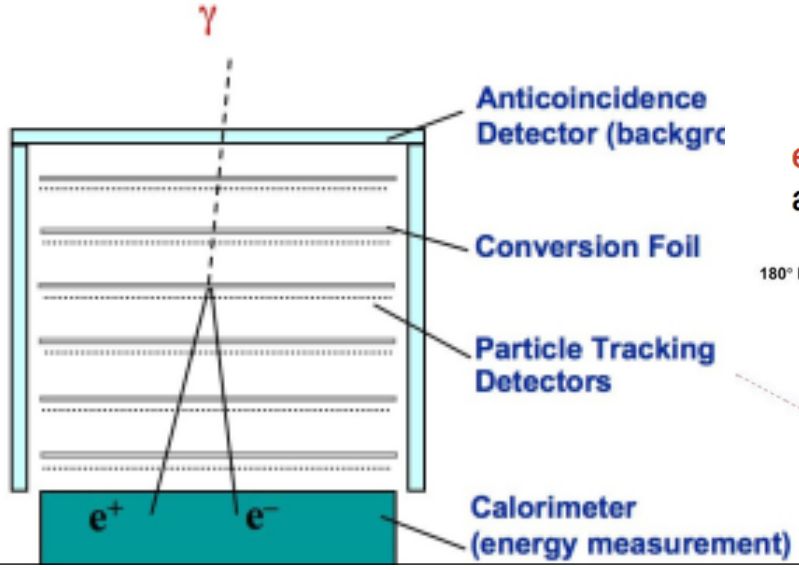
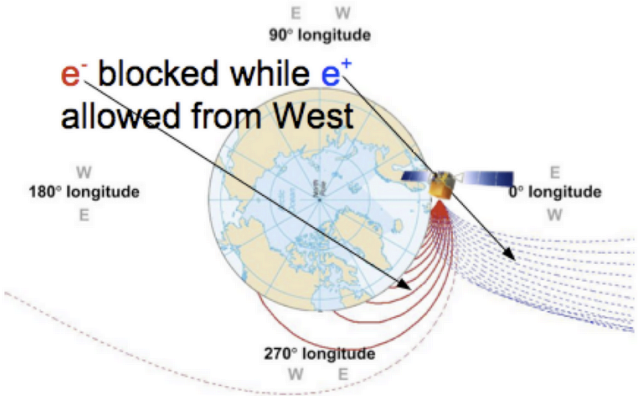
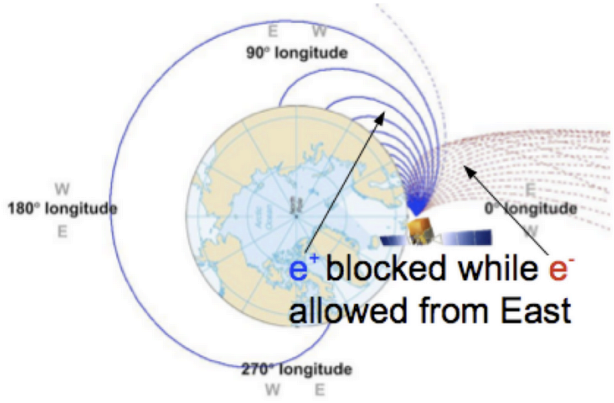
The Gamma Ray Perspective of the Mystery of the Origin of UHECRs

Tonia Venters
Astrophysics Science Division
NASA Goddard Space Flight Center

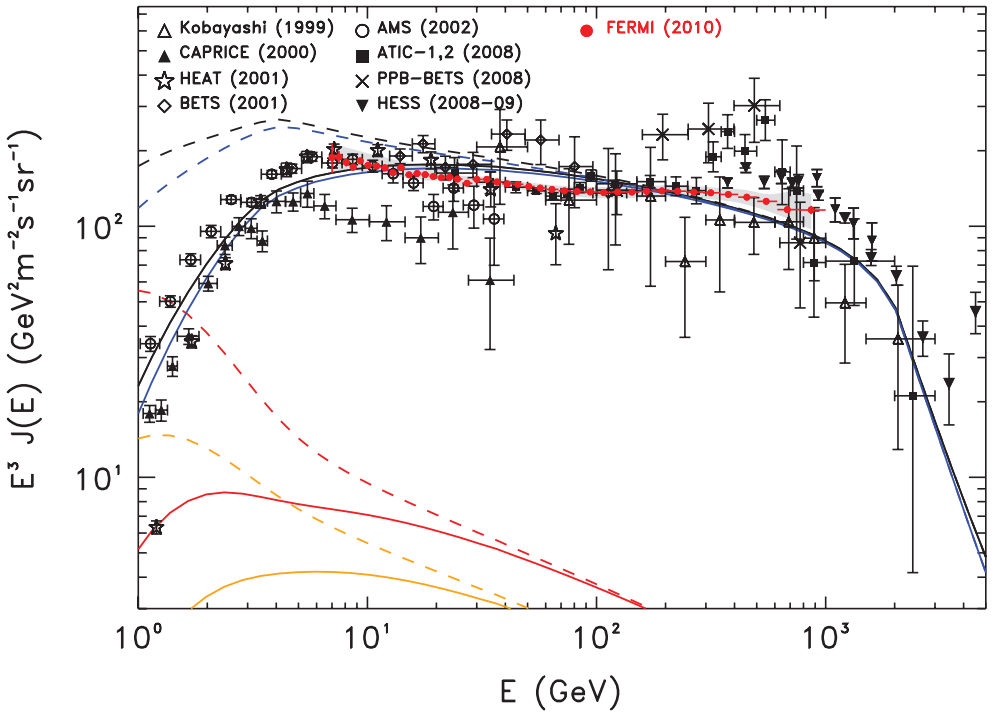

Tracker module
Anticoincidence
Calorimeter module


γ
Anticoincidence
Detector (backgrc
Conversion Foil
Particle Tracking
Detectors
e+
e−
Calorimeter
(energy measurement)

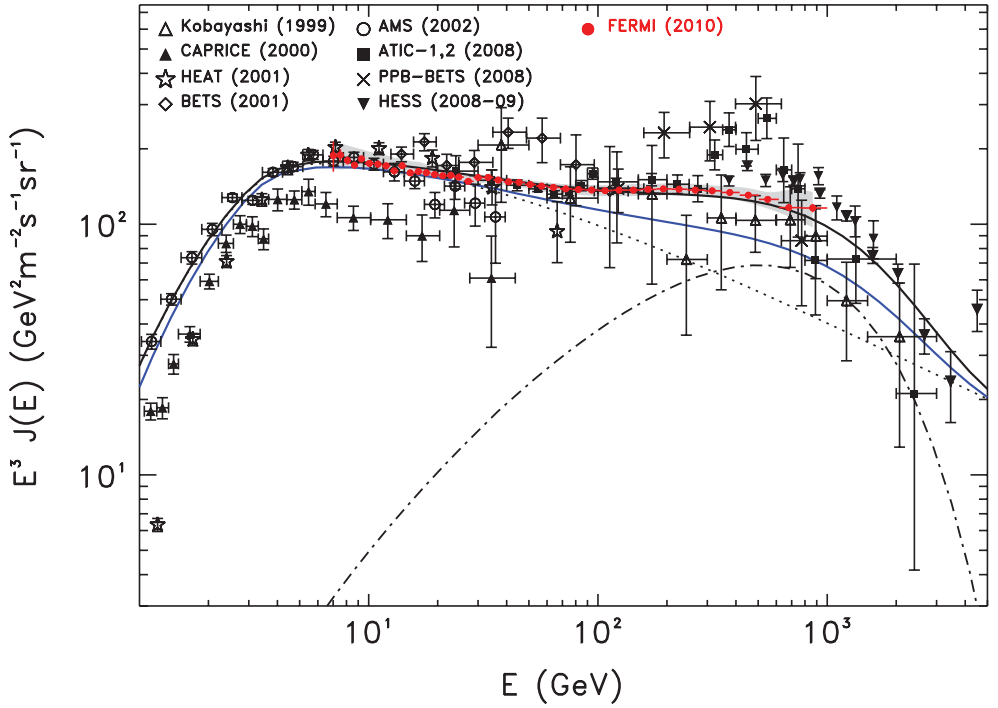

90° longitude
e- blocked while e+
allowed from West
180° longitude
0° longitude
270° longitude

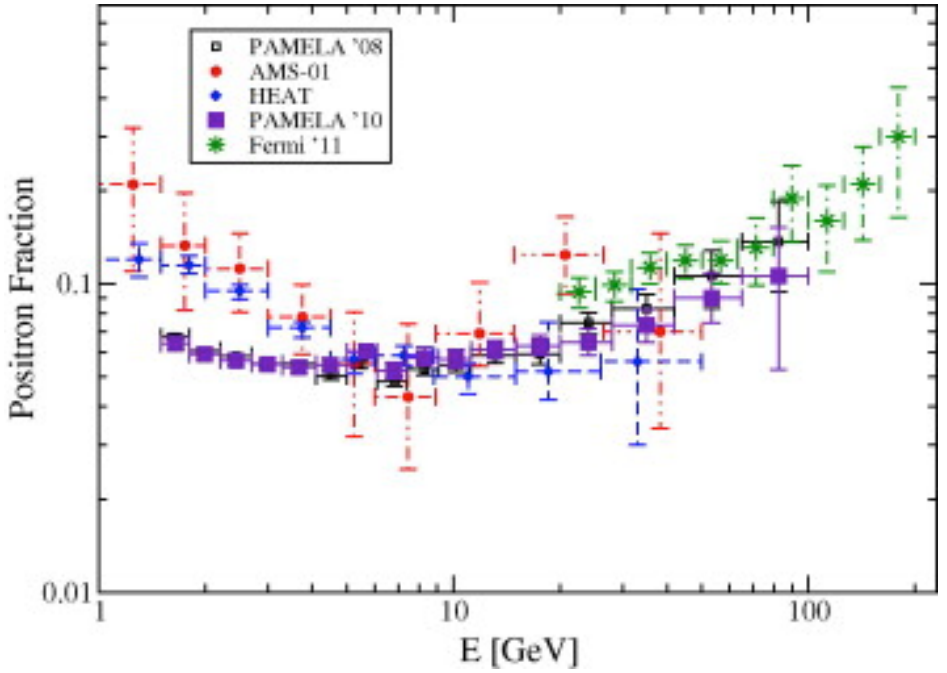

90° longitude
180° longitude
0° longitude
e+ blocked while e-
allowed from East
270° longitude

Fermi CRE Spectrum

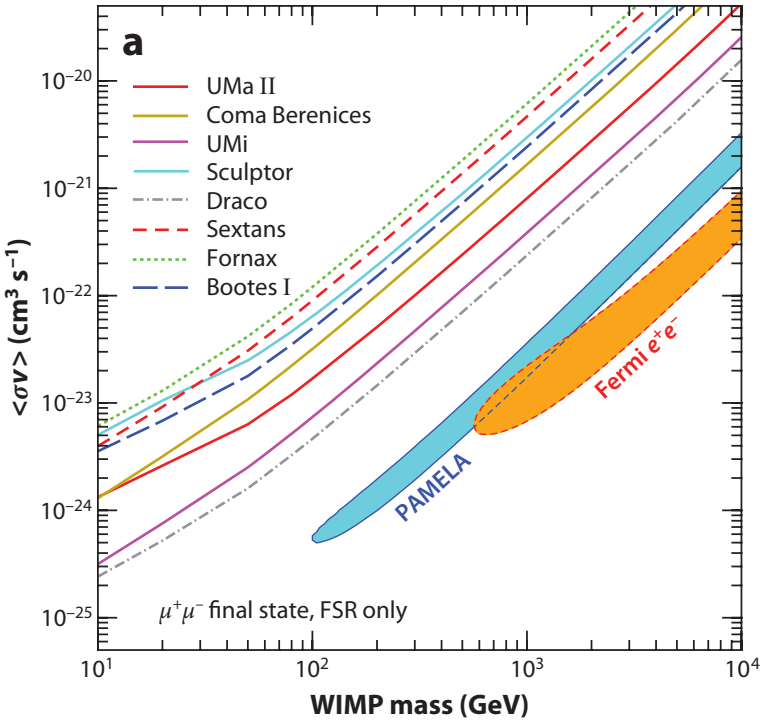


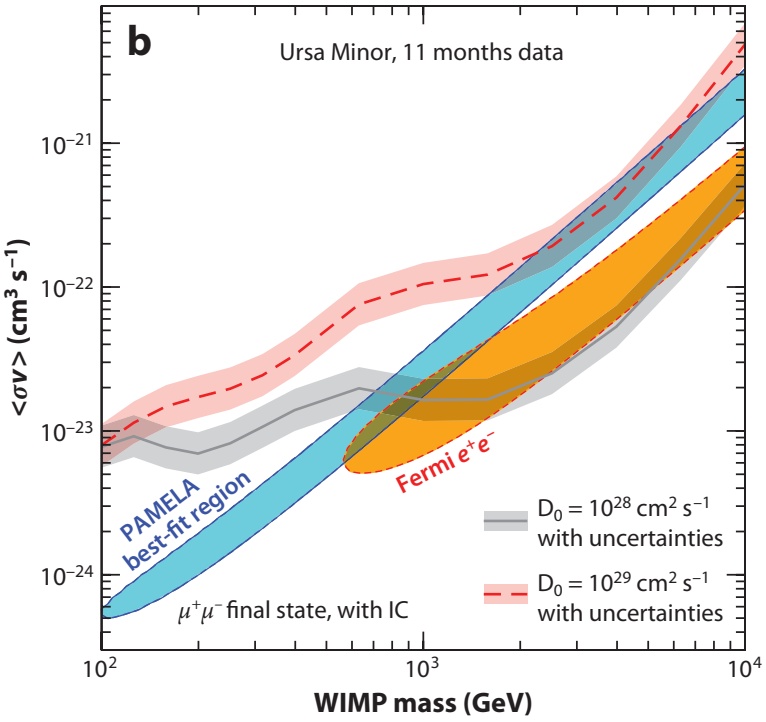
Ackermann et al. 2010

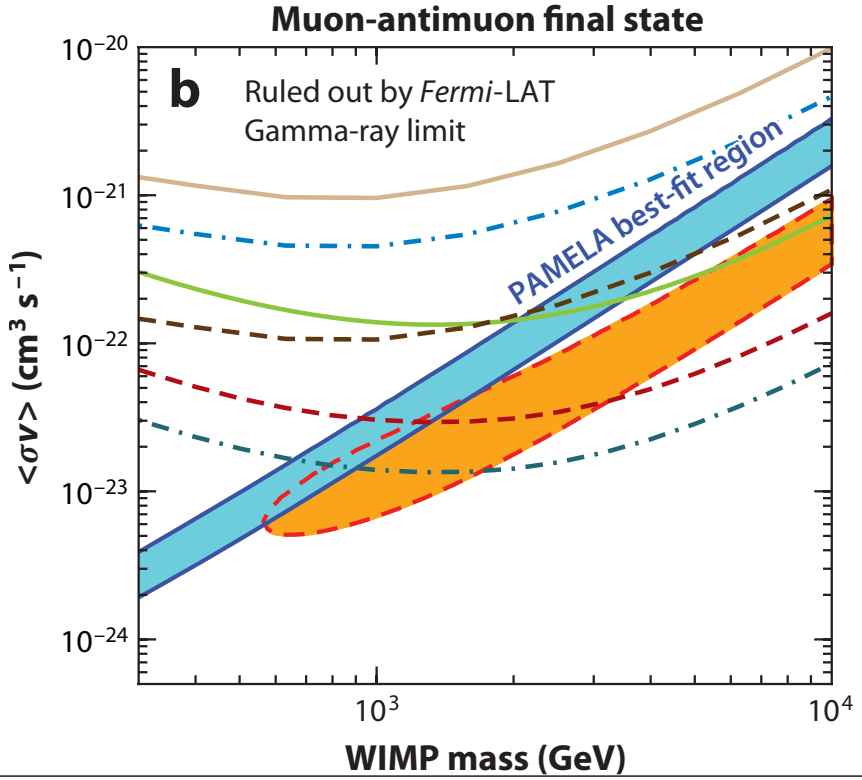




Dwarf Spheroidal Limits



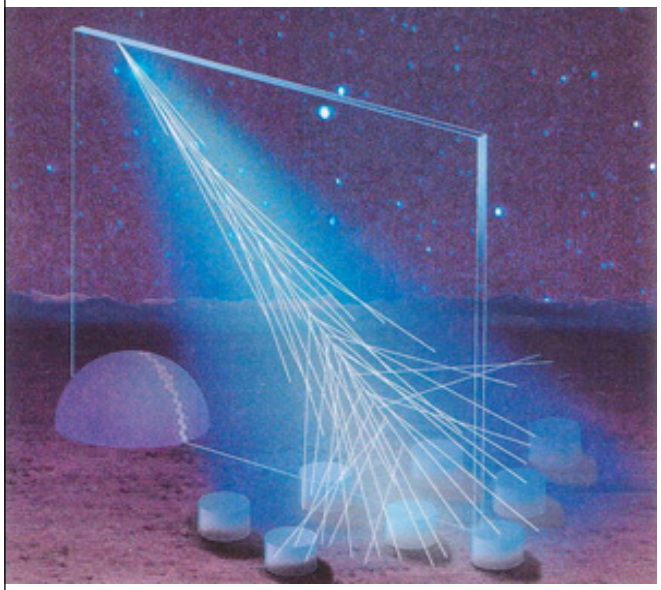




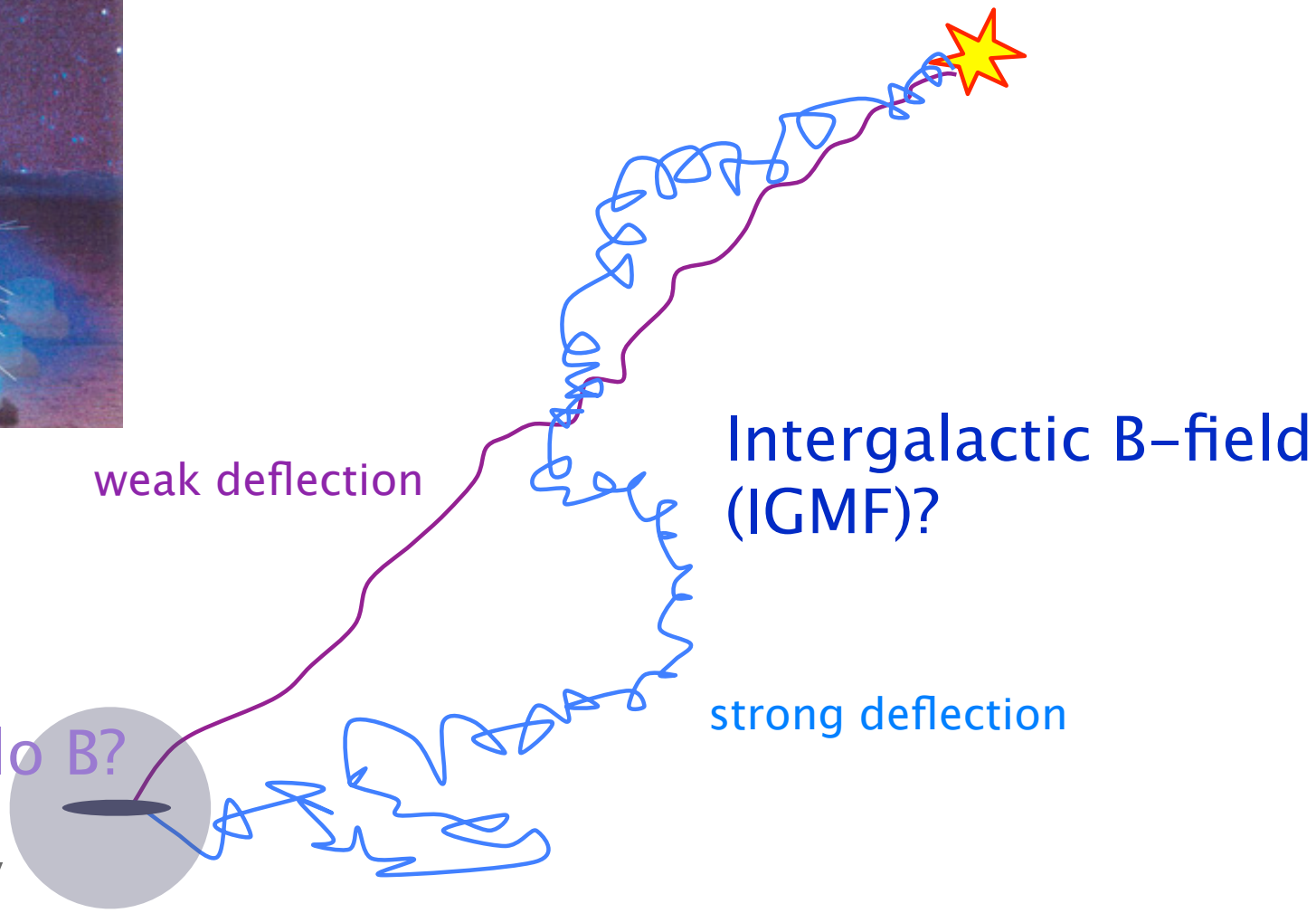
Galaxy Cluster Limits

Porter, Johnson, & Graham 2011

The Problem...



Pierre Auger (concept)



Cosmic-ray propagation

Propagation model

CR sources

>source distribution

>source spectrum

>source composition

astrophysics input

B fields

diffusion coef.

photon background

matter distribution

physics input

cross sections

basic physics

(EM interactions...)

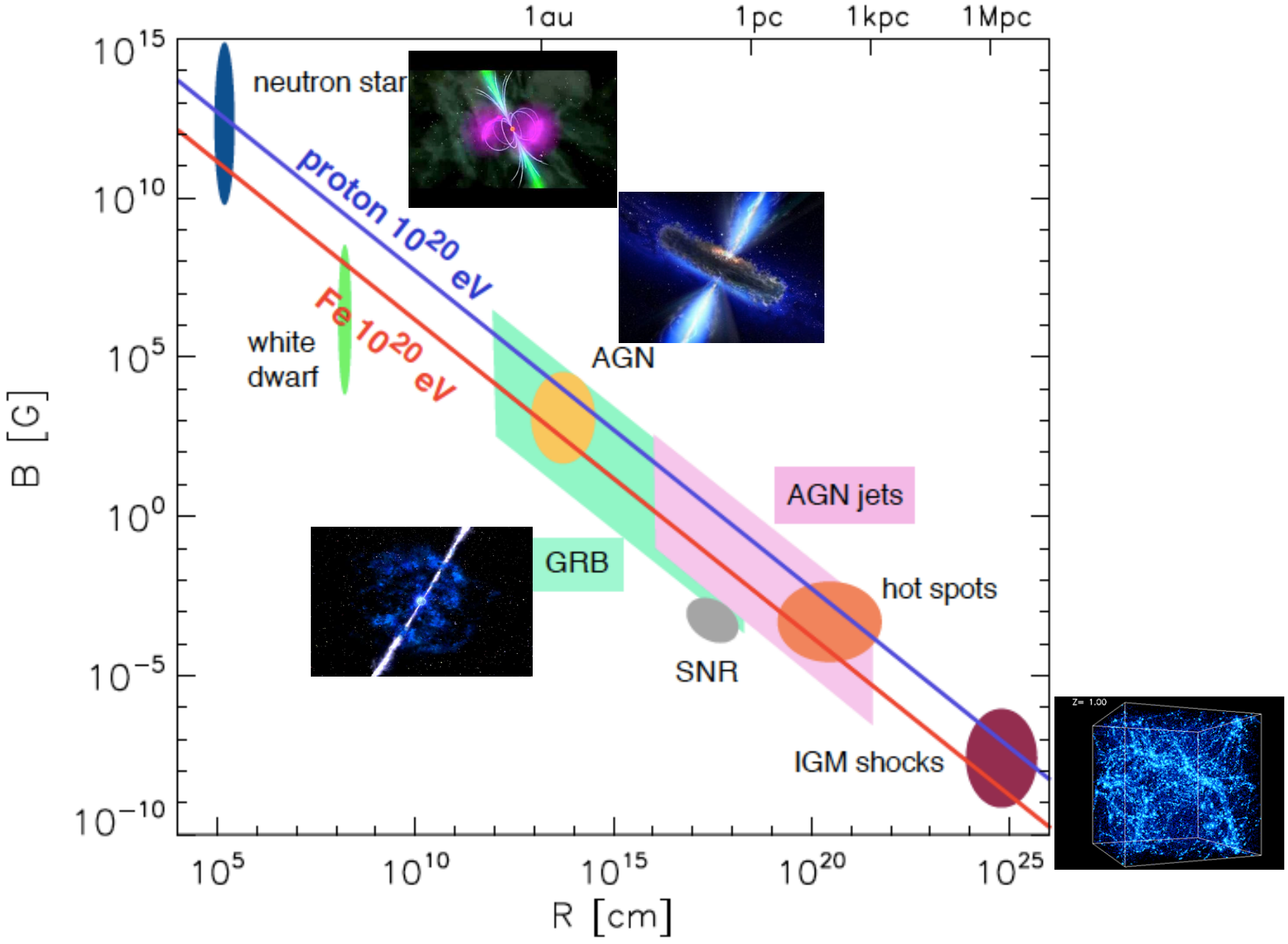
>propagated spectrum

>propagated composition

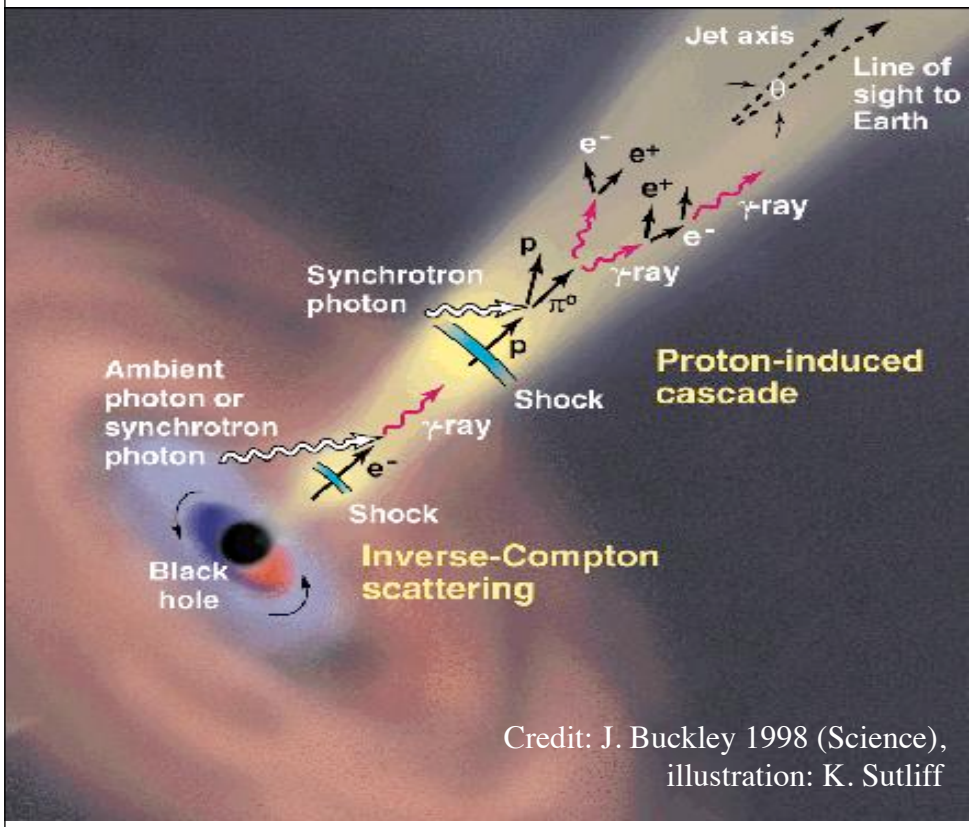
>angular distribution

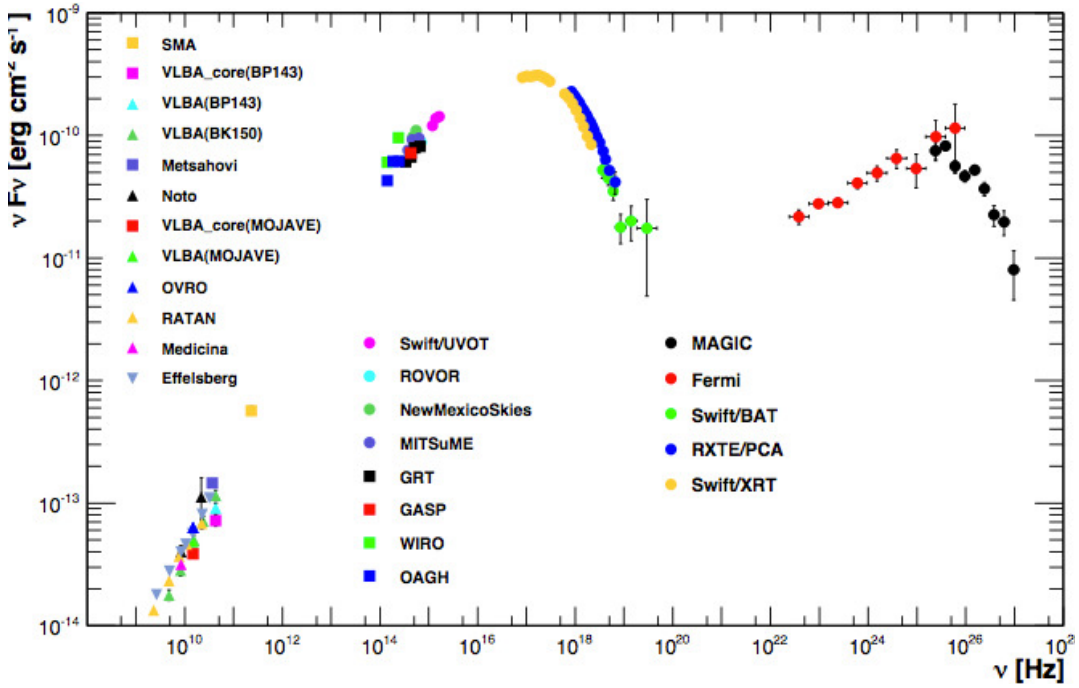
Earth

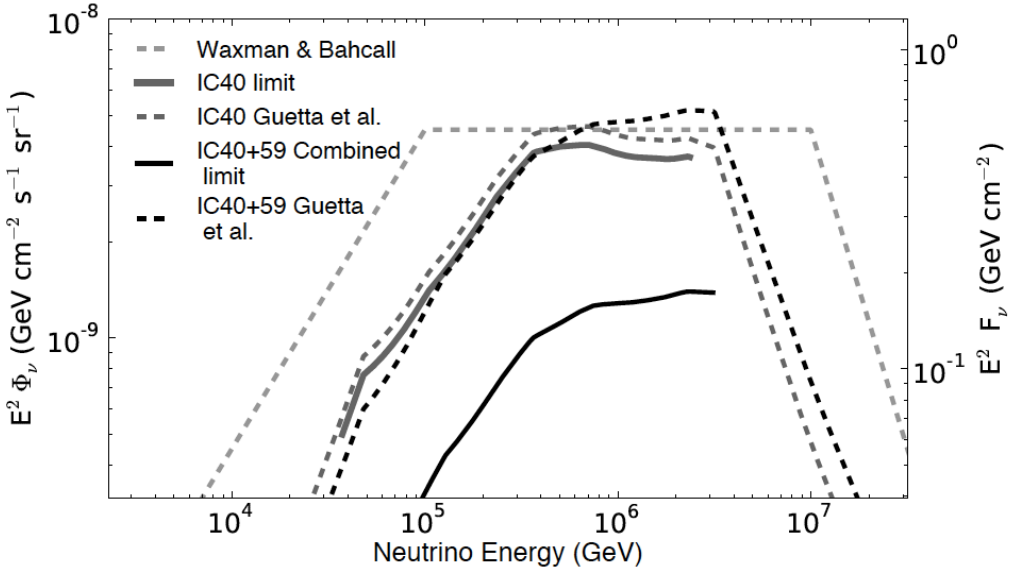
Plausible Sources (officially)

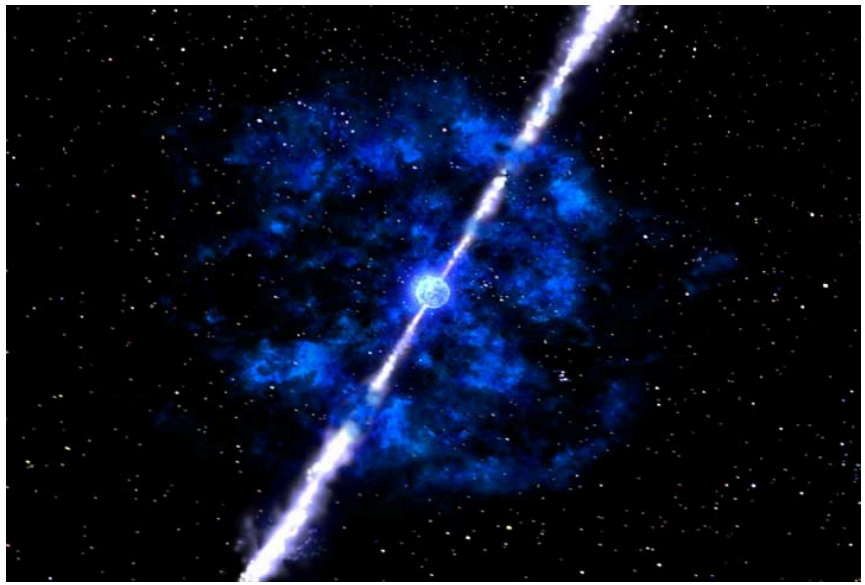


Hadrons in Jets

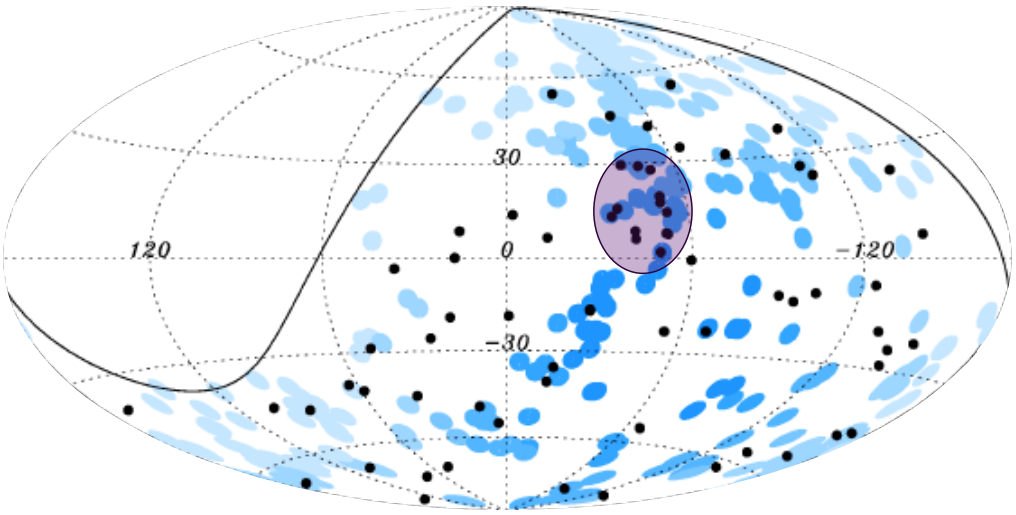


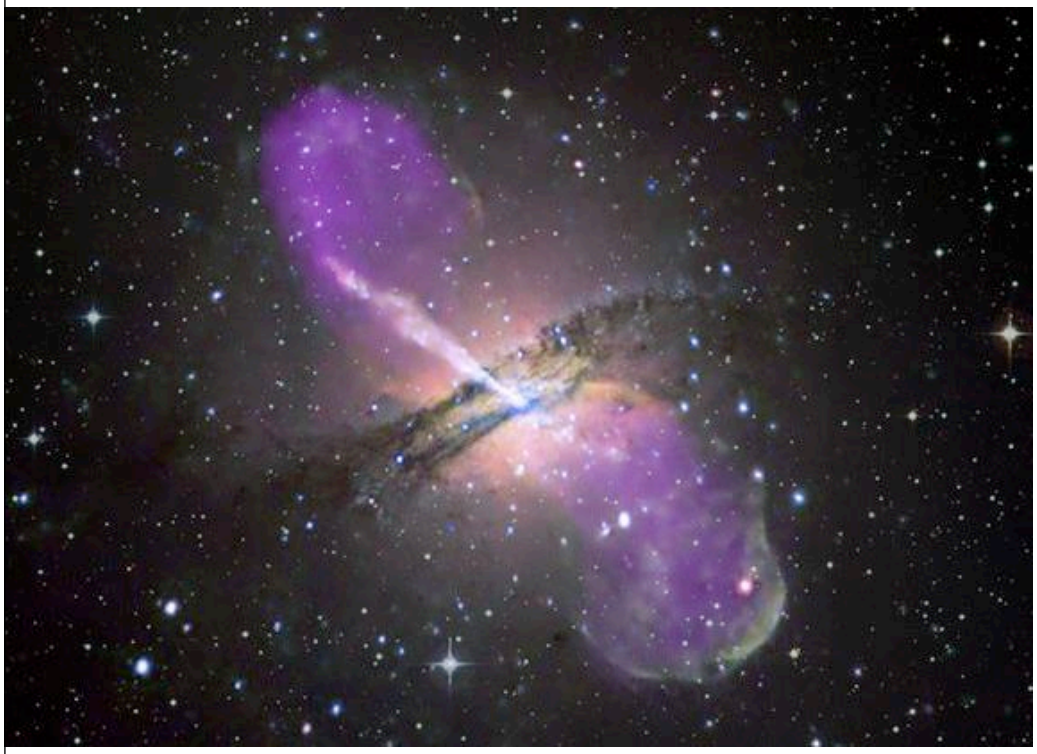


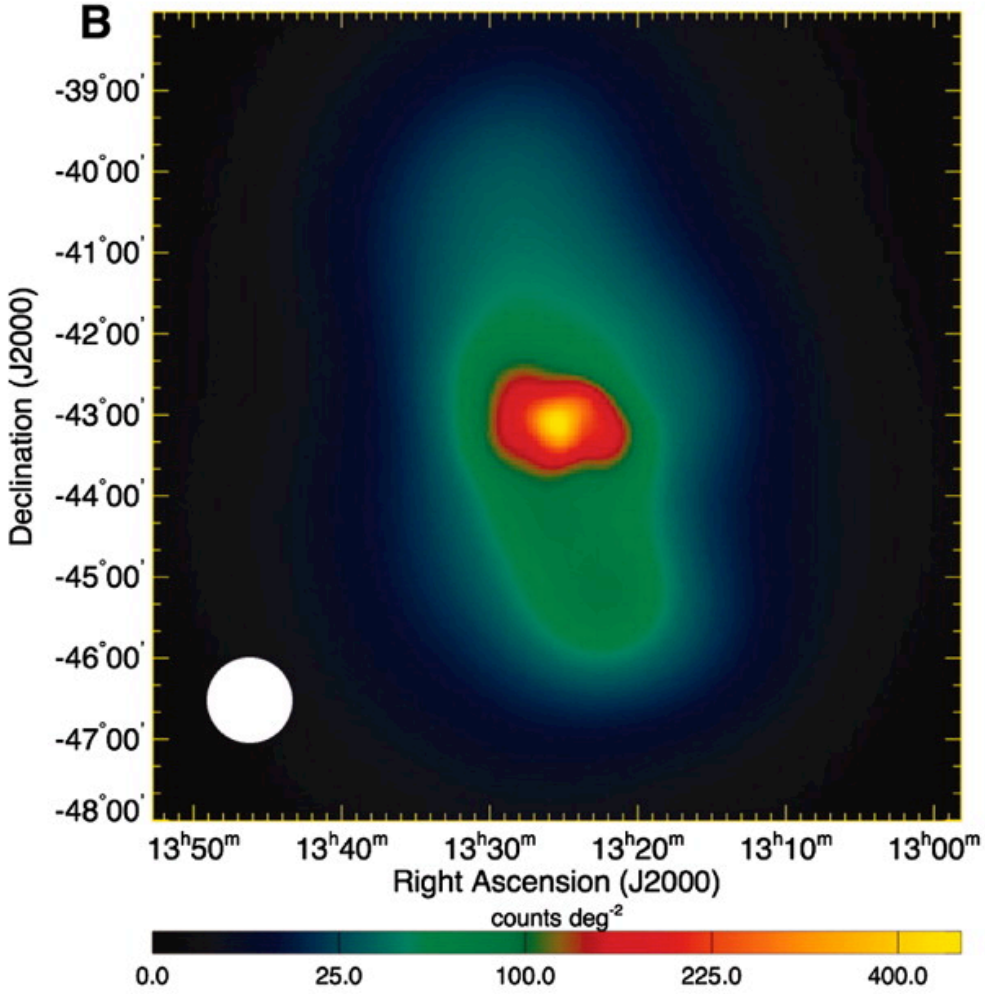




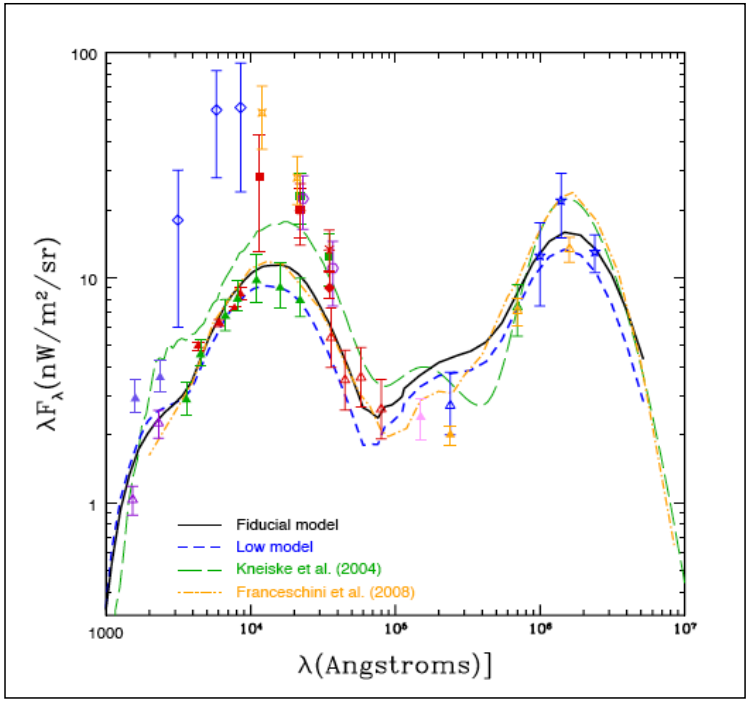
Centaurus A


30
120
0
−120
−30

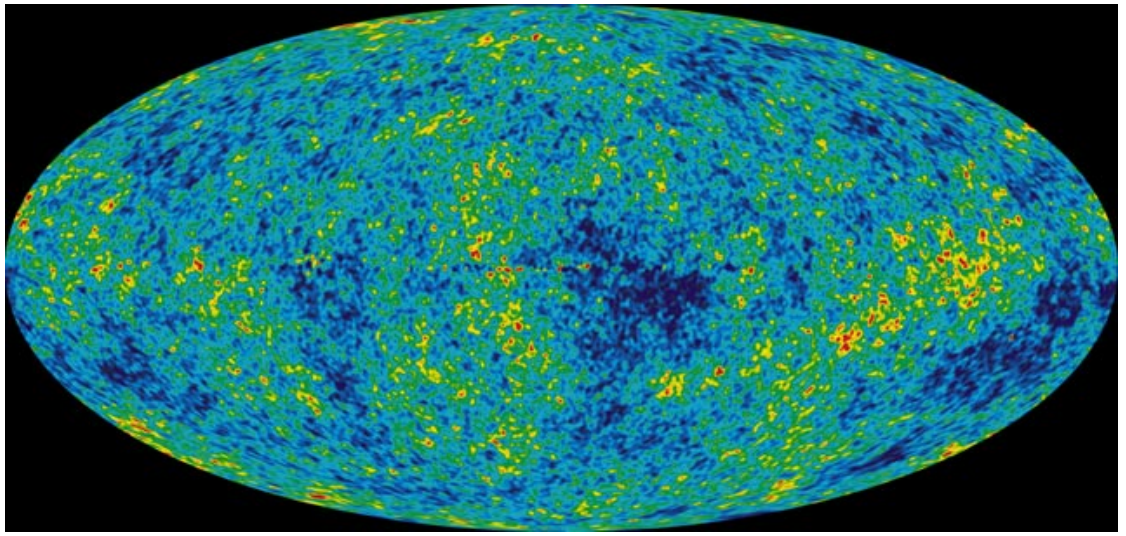



B
-39°00'
-40°00'
-41°00'
-42°00'
-43°00'
-44°00'
-45°00'
-46°00'
-47°00'
-48°00'
Declination (J2000)
13h50m
13h40m
13h30m
13h20m
13h10m
13h00m
Right Ascension (J2000)
counts deg-2
0.0
25.0
100.0
225.0
400.0

Interactions behind Propagation

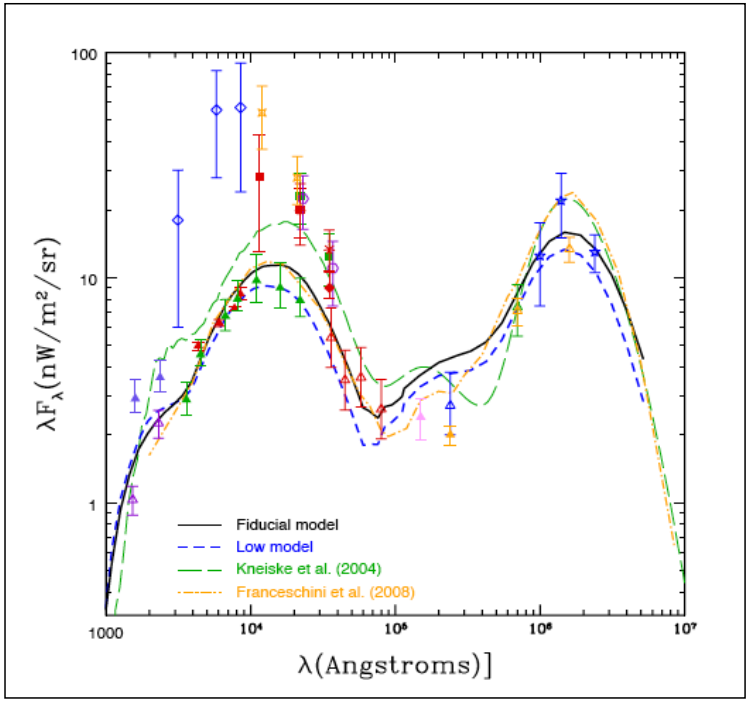


Gilmore et al. 2009

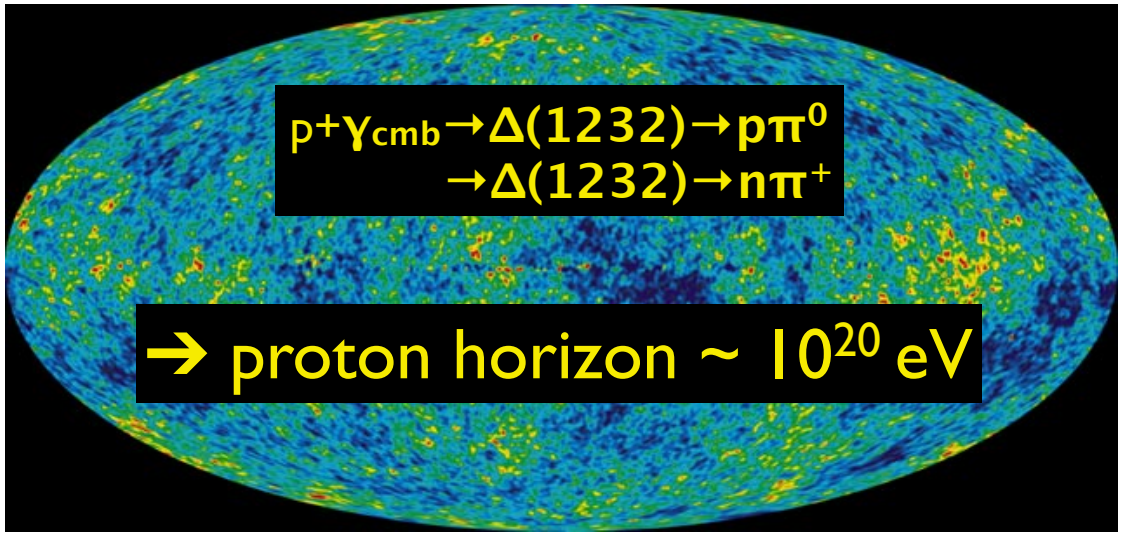


Protons and Nuclei	Bethe-Heitler pair production Photodisintegration (nuclei only) Photomeson Production	*e.g.*, $p^{\pm}\gamma \rightarrow p^{\pm}e^{-}e^{+}$ *e.g.*, ${}_{n}N\gamma \rightarrow {}_{n}N^{*} \rightarrow {}_{n-1}Np$ *e.g.*, $p\gamma \rightarrow \Delta(1232) \rightarrow p\pi^{0}$
Electrons	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.*, $\mu^{\pm} \rightarrow \bar{\nu}_{\mu}\,(\nu_{\mu})\,e^{\pm}\nu_{e}\,(\bar{\nu}_{e})$, $\pi^{0} \rightarrow \gamma\gamma$ $\mu^{\pm}\tilde{\gamma} \rightarrow \mu^{\pm}\gamma$

Interactions behind Propagation



Gilmore et al. 2009



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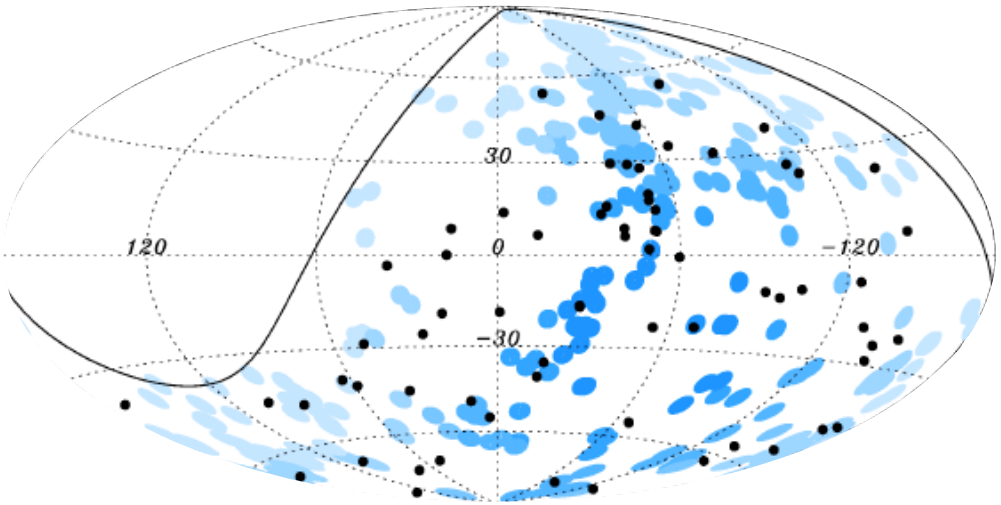
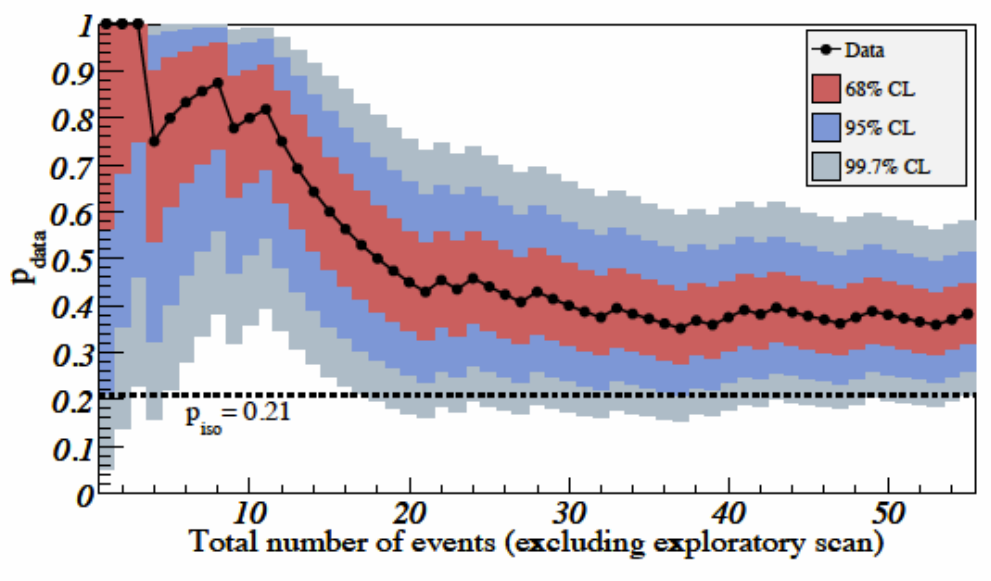
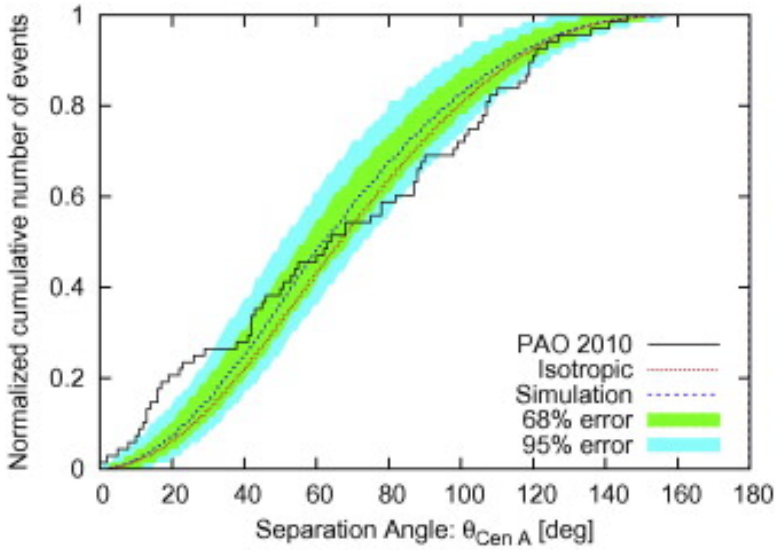
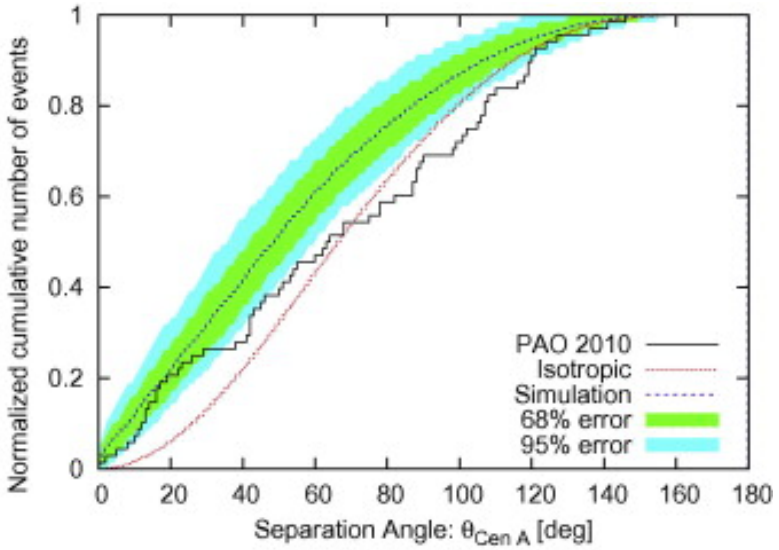
Searching for the Anisotropy...









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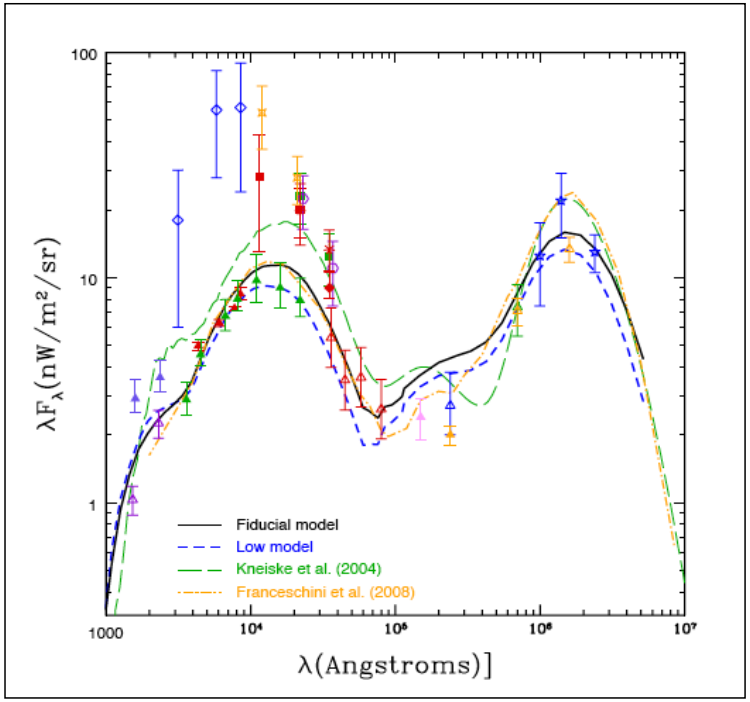
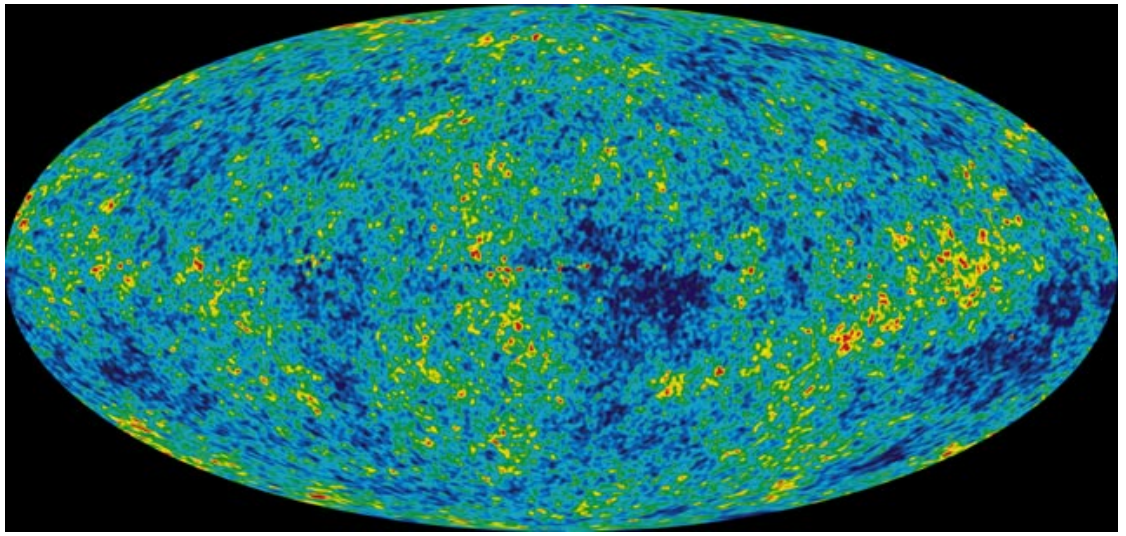


Gilmore et al. 2009



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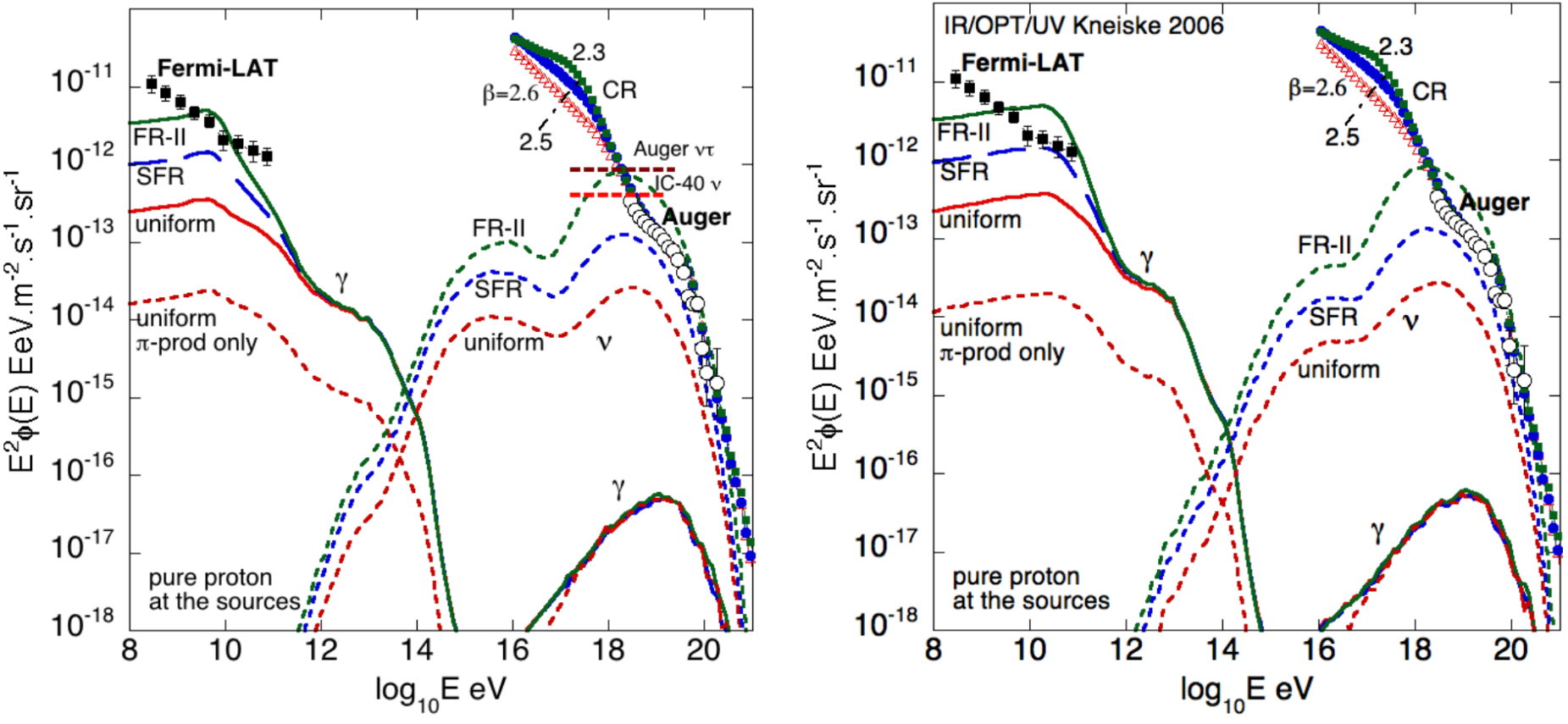
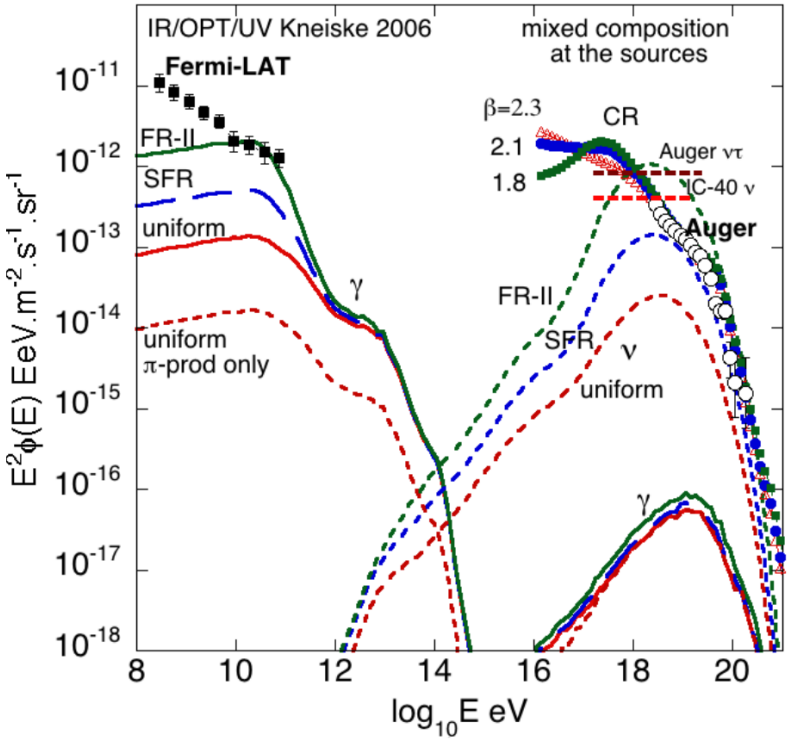
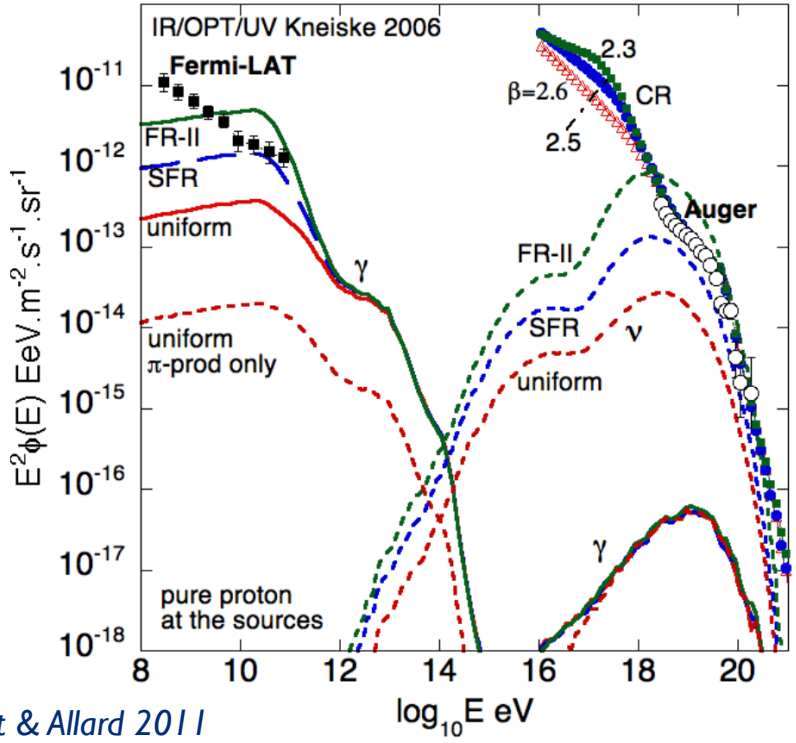
UHECR Propagation in Action

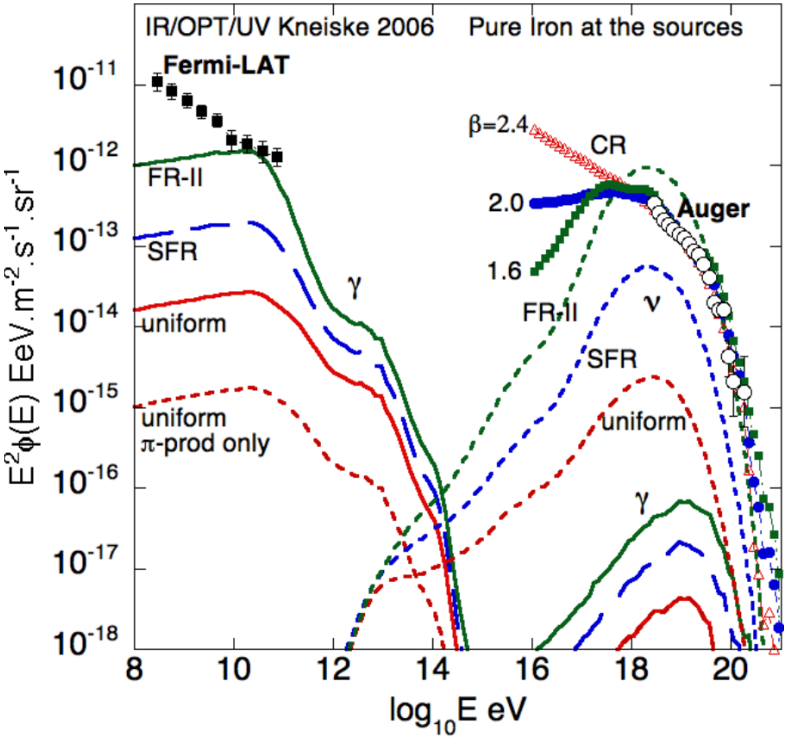


Decerprit & Allard 2011

UHECR Propagation in Action







Decerprit & Allard 2011

Cosmic-ray propagation

Propagation model

CR sources

>source distribution

>source spectrum

>source composition

astrophysics input

B fields

diffusion coef.

photon background

matter distribution

physics input

cross sections

basic physics

(EM interactions...)

>propagated spectrum

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>angular distribution

Earth

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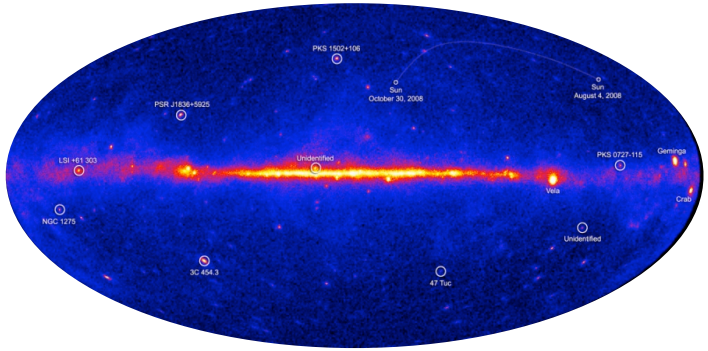
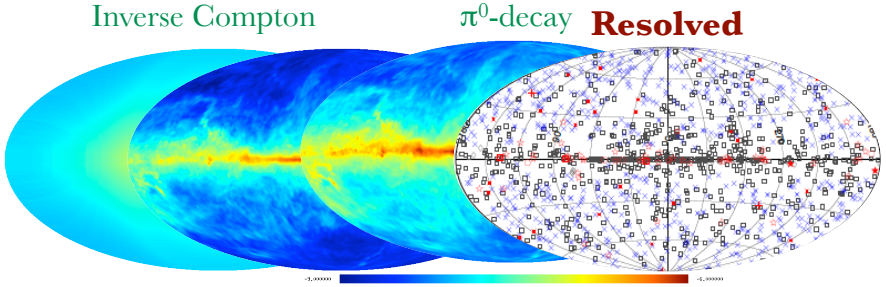
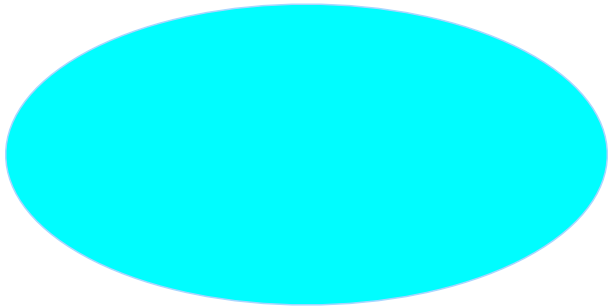
Components of the EGB





Galactic diffuse emission
(CR interactions with the interstellar medium)



Isotropic diffuse emission
(presumably extragalactic)

Known players:

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

Suspected contributors:

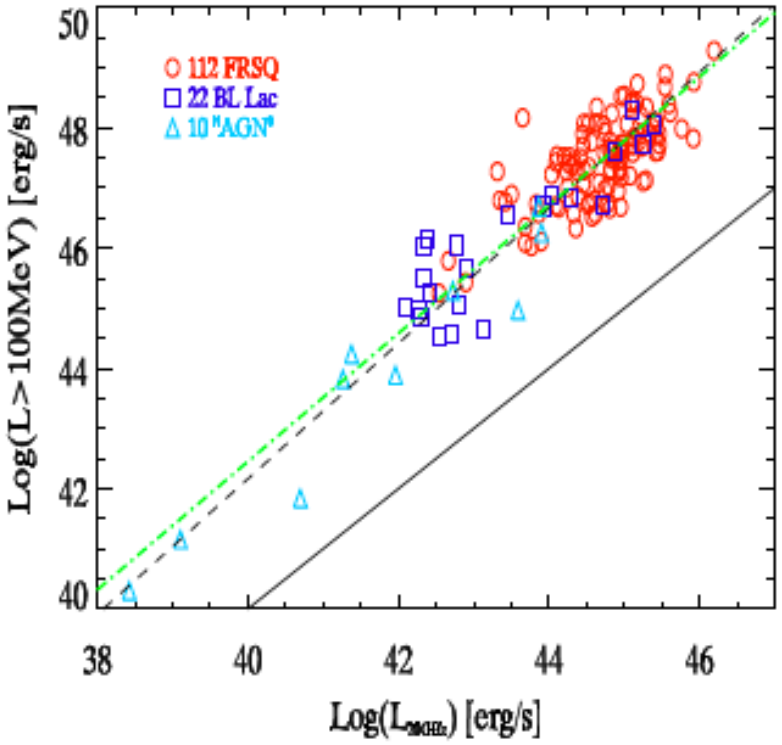
- Truly diffuse emission - gamma rays produced in EM cascades of highly energetic particles

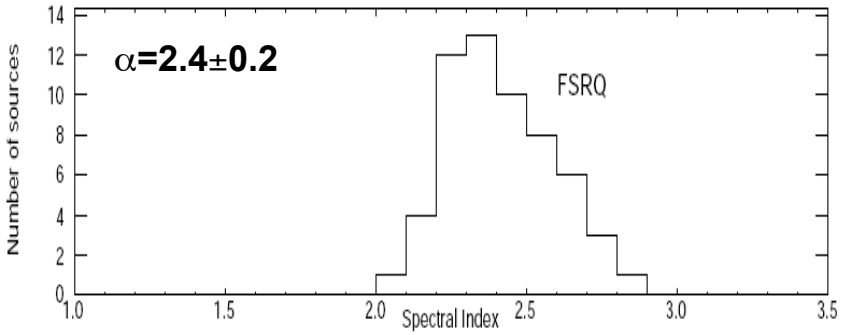
Players about which we like to speculate:

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

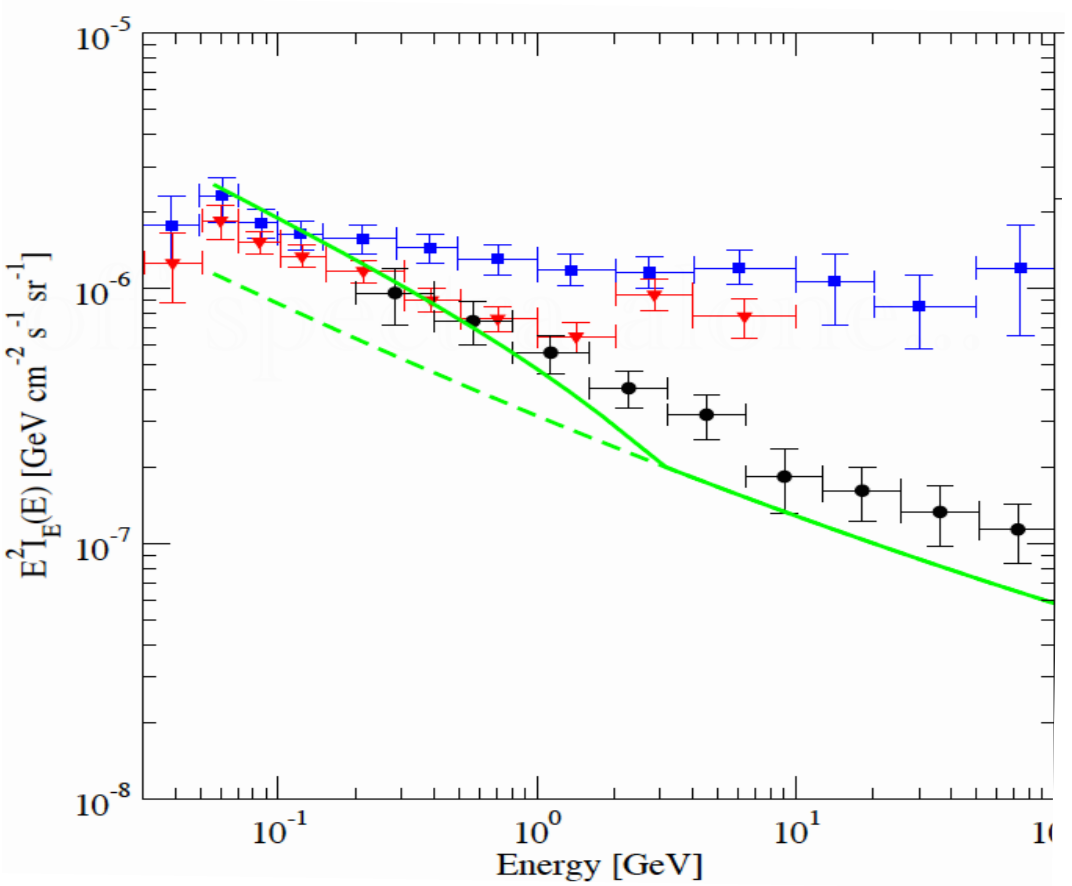
One cannot live off of spectra alone...

Maybe, it's like this...



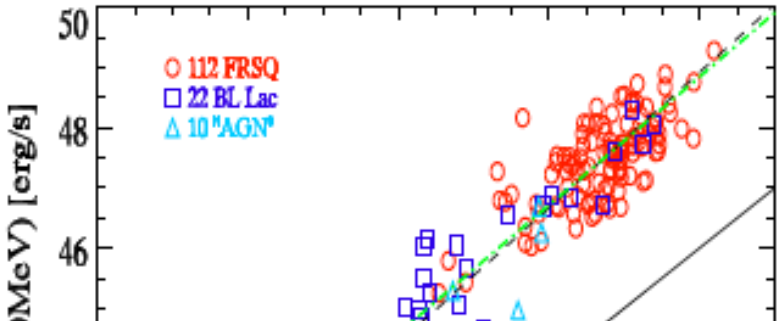


⇏

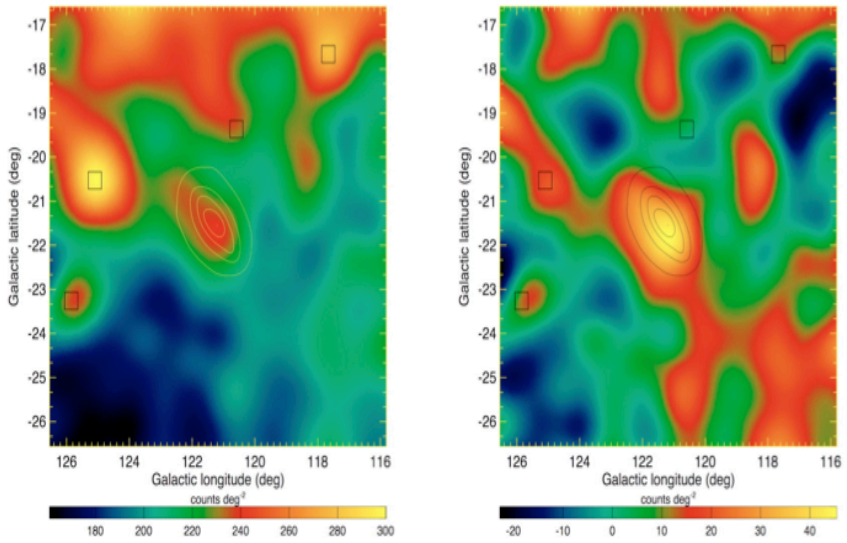


Stecker & Venters 2011

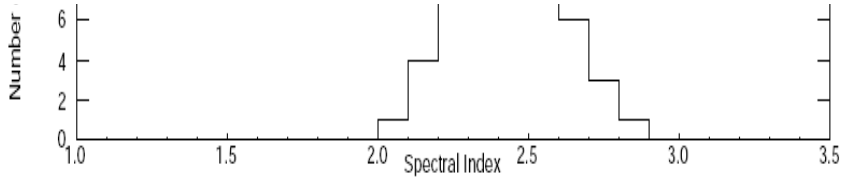
Nah... It's more like this...

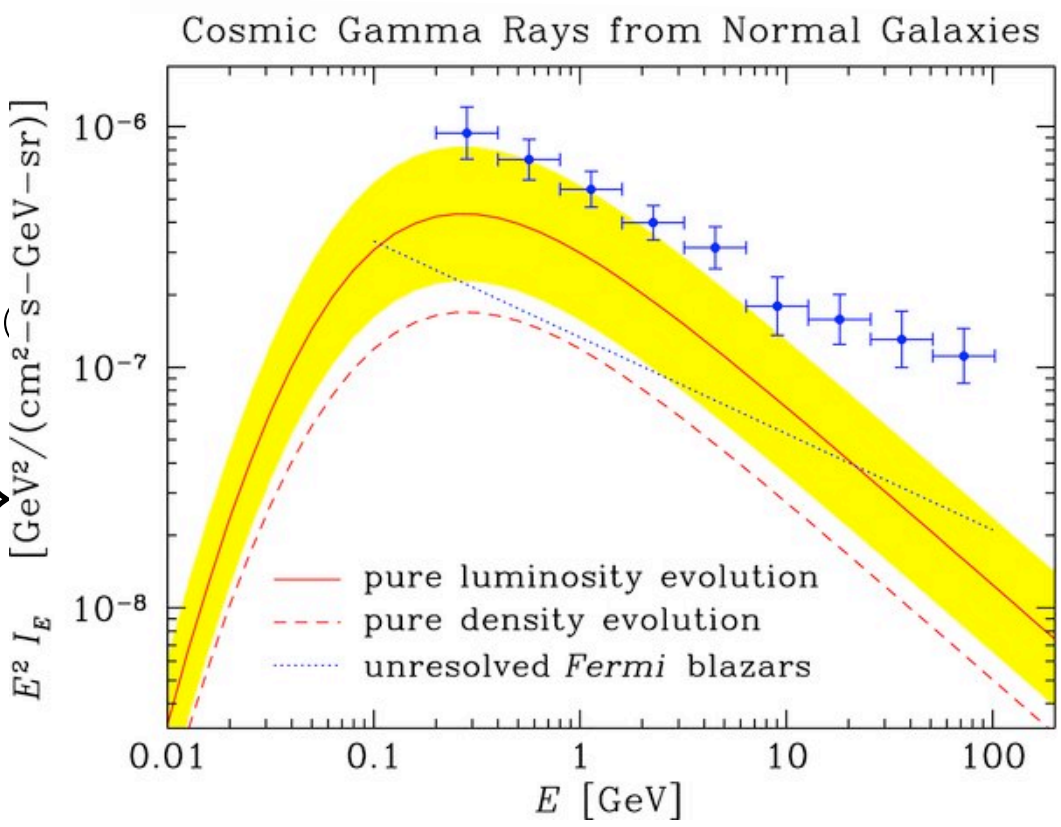


LAT collaboration: *Fermi*/LAT observations of Local Group galaxies: detection of M 31 and search for M 33



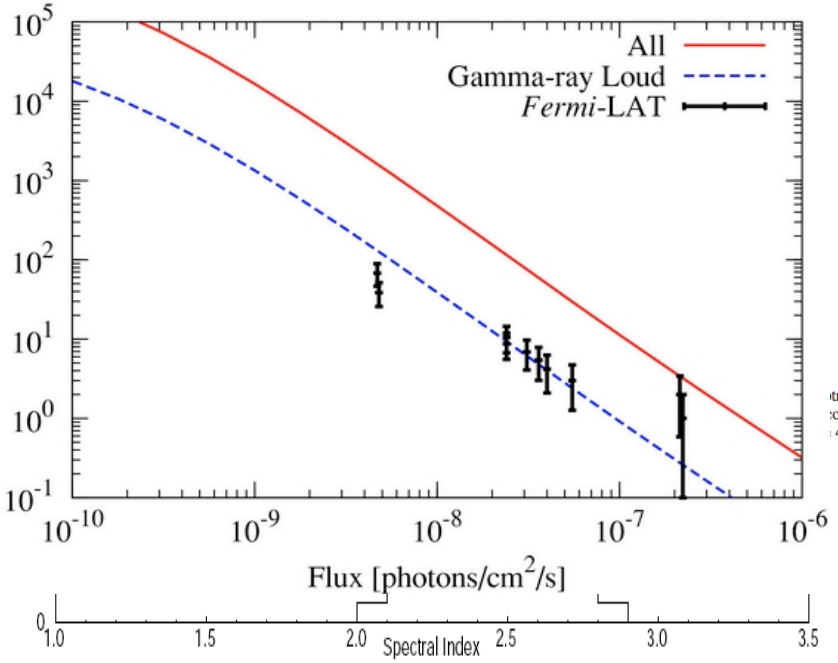
g. 1. Gaussian kernel ($\sigma = 0.5°$) smoothed counts maps of the region of interest (ROI) in a true local projection before (*left*) and after subtraction the background model (*right*) for the energy range 200 MeV–20 GeV and for a pixel size of $0.05° \times 0.05°$. Overlaid are IRIS 100 μm contours M 31 convolved with the LAT point spread function to indicate the extent and shape of the galaxy. The boxes show the locations of the 4 point irces that have been included in the background model.





Fields et al. 2010

Well... Let's not forget these guys...



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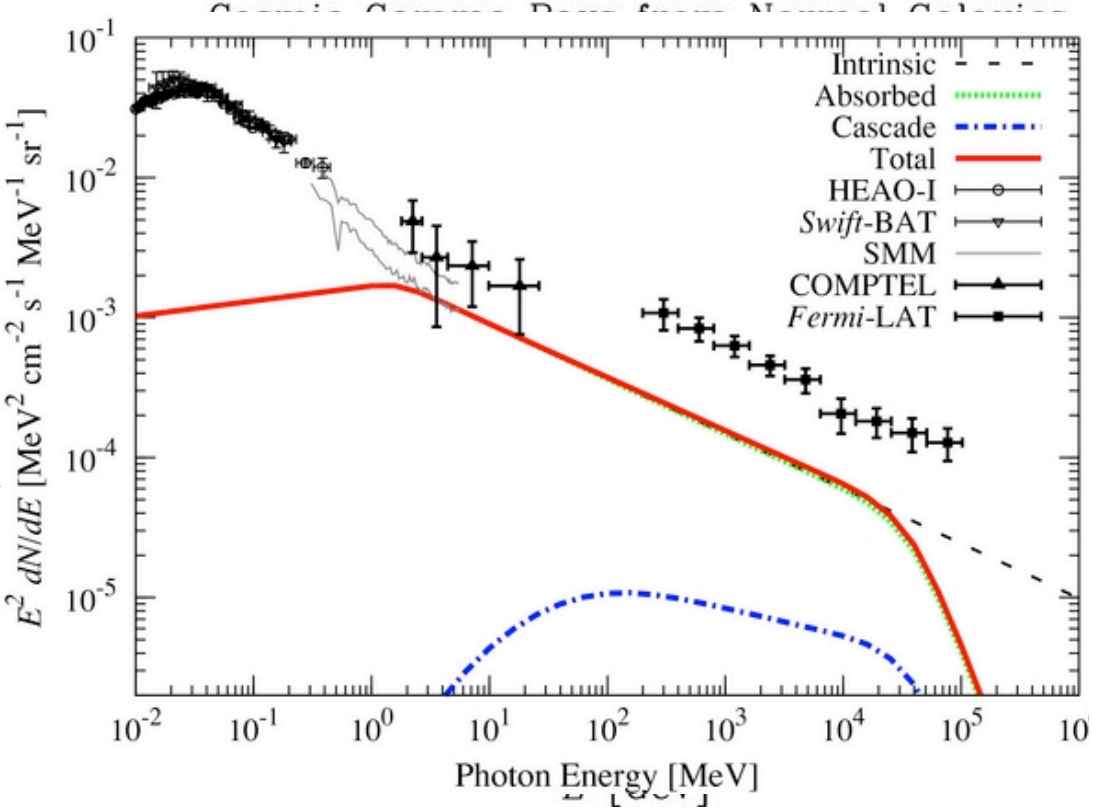
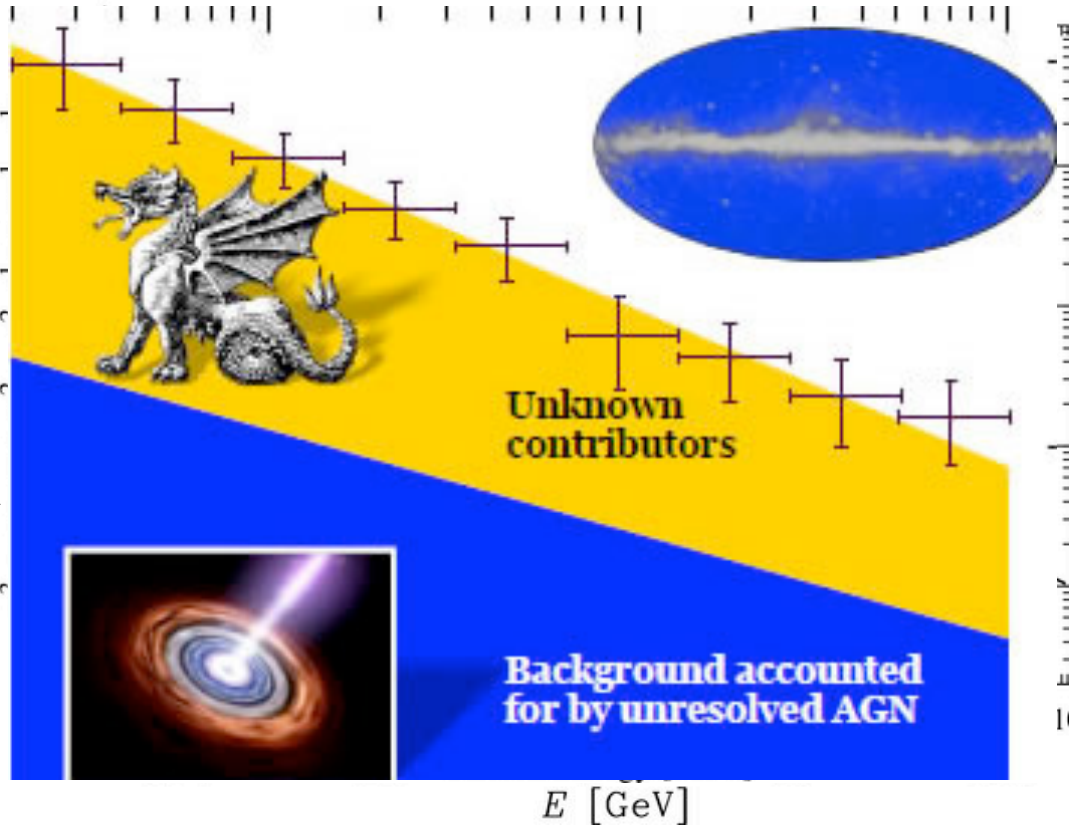


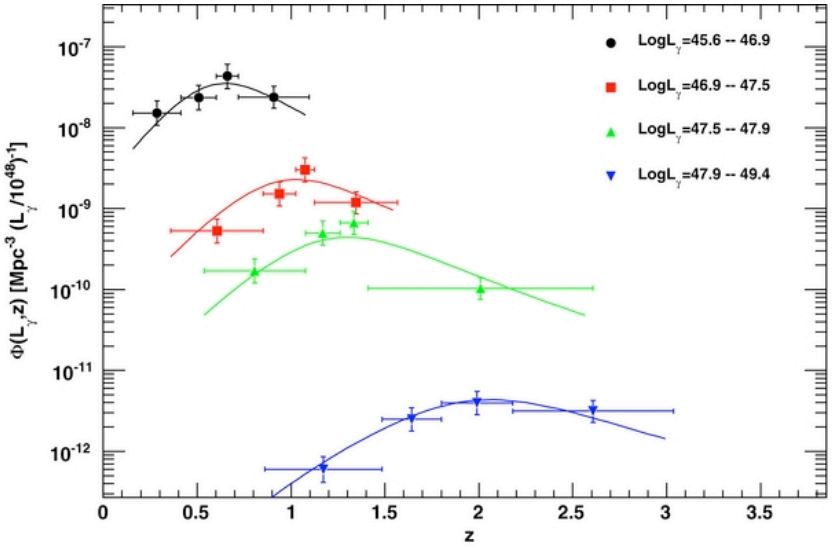
Inoue 2011

I always thought this was cooler...

⇒



Actually... You're all right (wrong)...



C… liv… ⇒

LAT collaboration: *Fermi*/LAT observations of Local Group galaxies: detection of M 31 and search for M 33

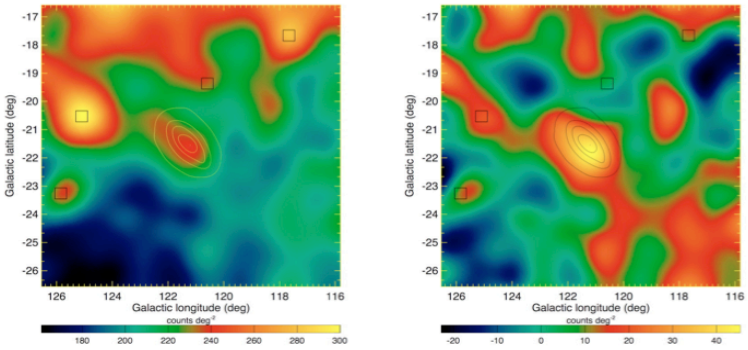
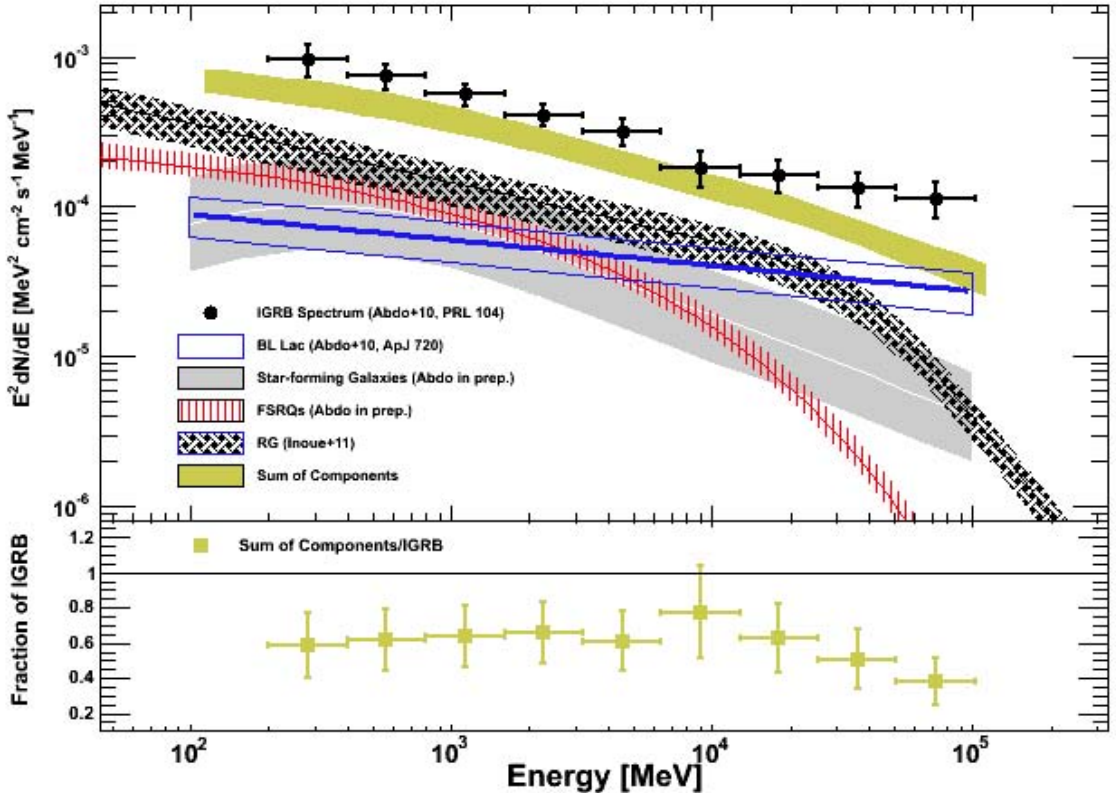
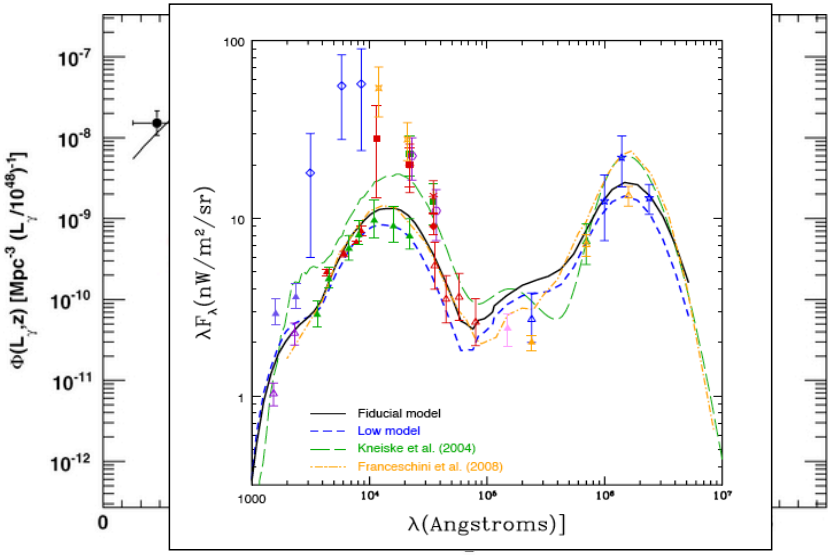
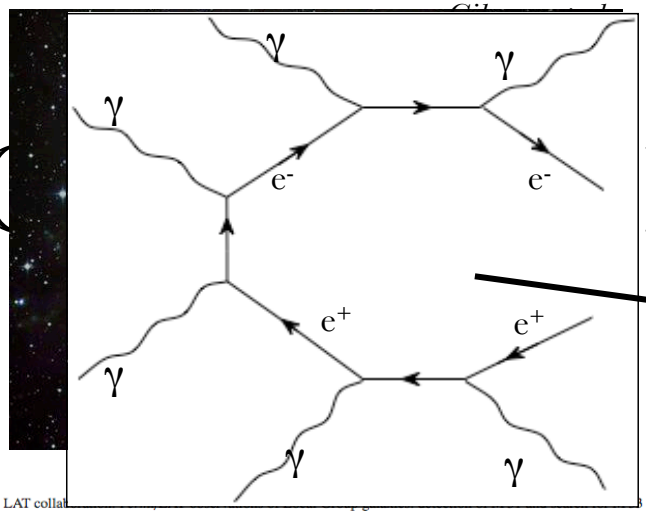


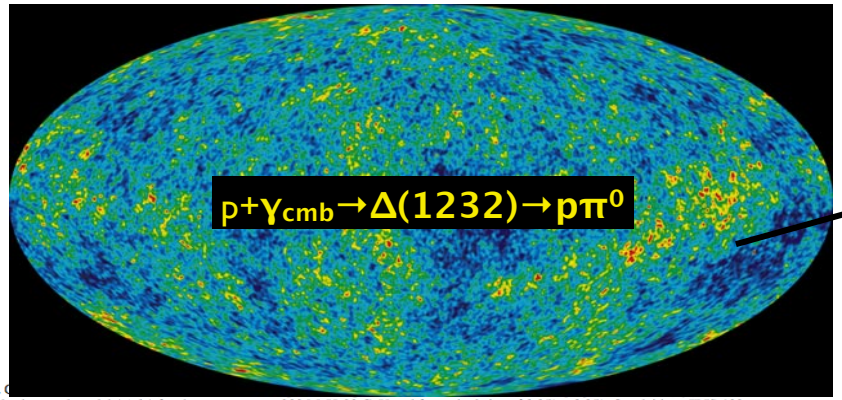
Fig. 1. Gaussian kernel (σ = 0.5°) smoothed counts maps of the region of interest (ROI) in a true local projection before (*left*) and after subtraction of the background model (*right*) for the energy range 200 MeV–20 GeV and for a pixel size of 0.05° × 0.05°. Overlaid are IRIS 100 μm contours of M 31 convolved with the LAT point spread function to indicate the extent and shape of the galaxy. The boxes show the locations of the 4 point sources that have been included in the background model.

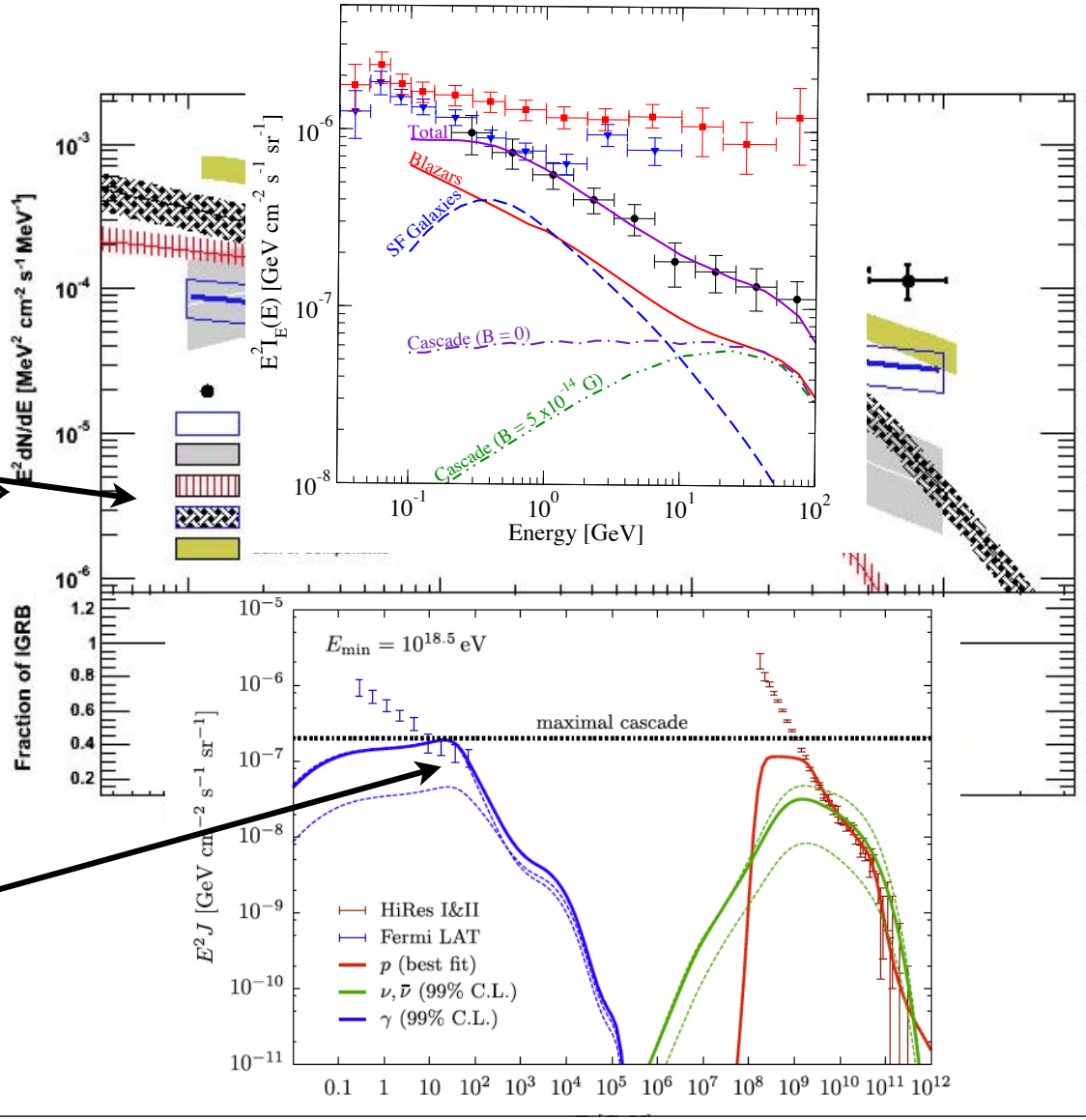


Hey!!! You forgot about this...










STOP

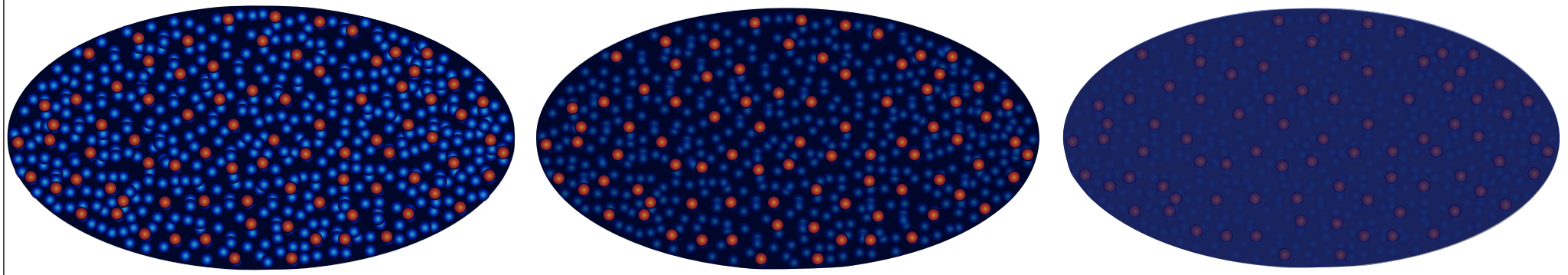
Hey guys... We DO have more than just a spectrum...

Anisotropy of a Multi-component EGB

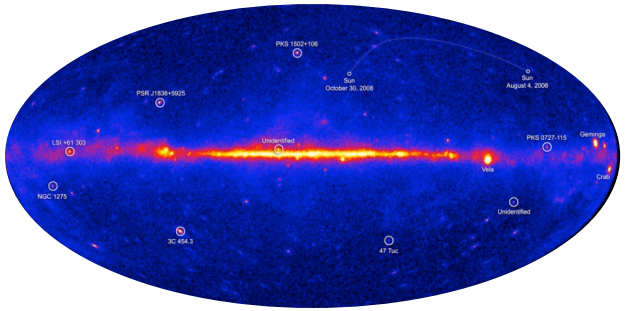
- Determine $C_l(E)$, the angular power of fluctuations in intensity at a given angular scale, l, as a function of energy.
- In a two component background, the anisotropy energy spectrum is given by

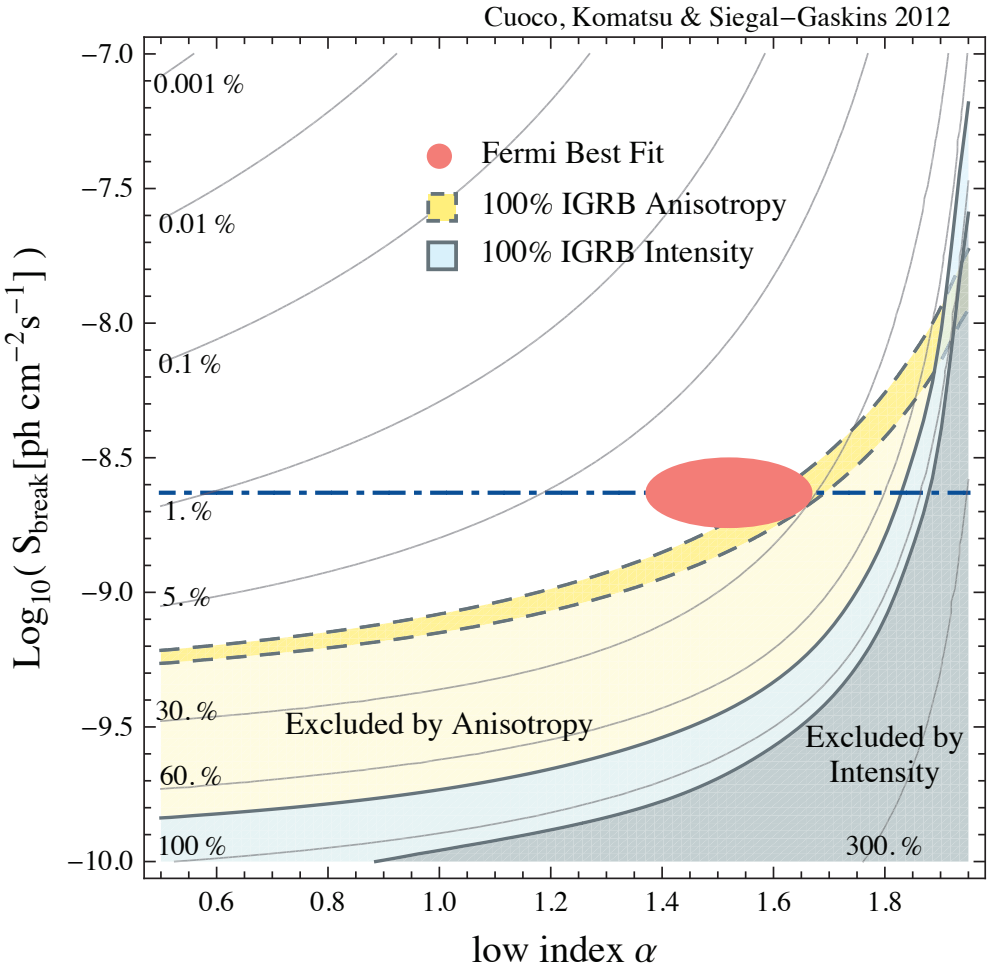
$$C_l^{\mathrm{tot}} = f_1{}^2 C_l^{(1)} + f_2{}^2 C_l^{(2)} + \text{cross terms},$$

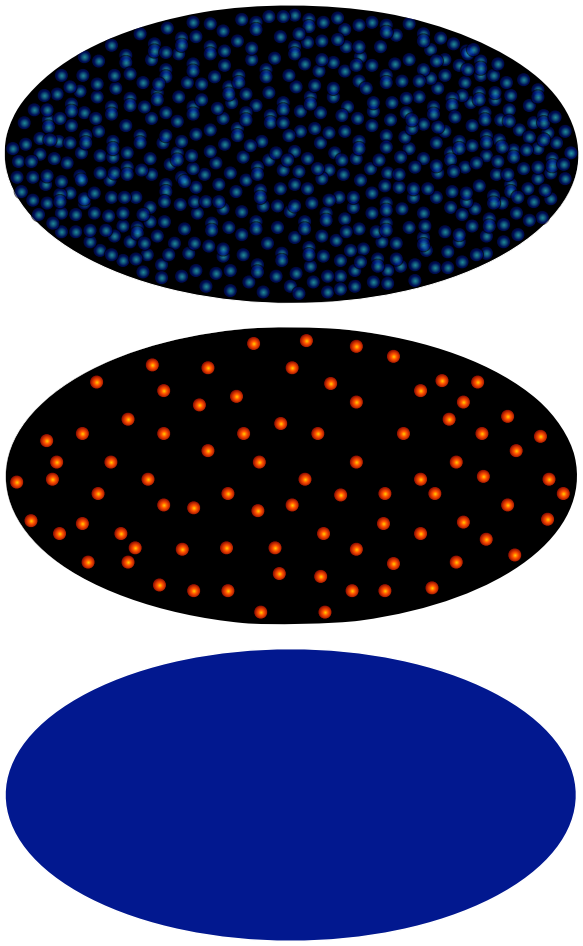
  where f_n is the fractional contribution of component n to the background ($f_\mathrm{n} = I_\mathrm{n}(E)/I_\mathrm{tot}(E)$).
- If the relative contributions of the components of the background change as a function of energy, the result is a *modulation* in the spectrum of the anisotropy as a function of energy.

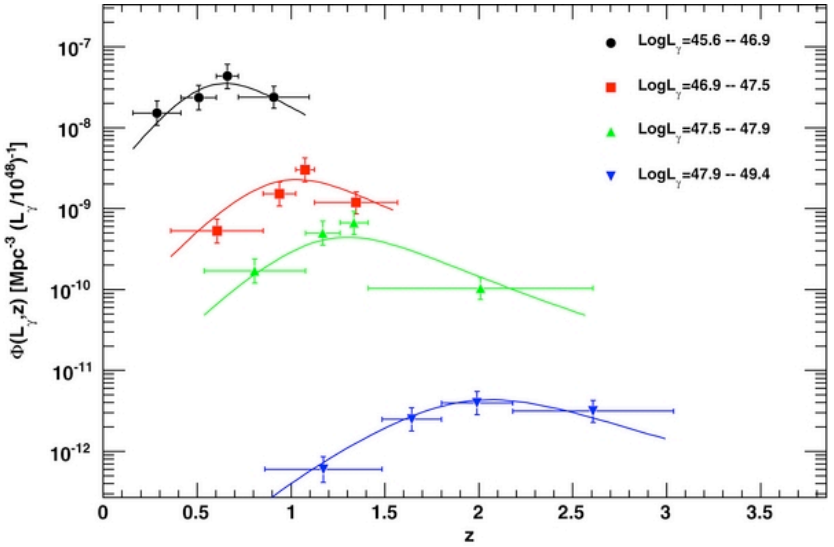


Anisotropy Studies

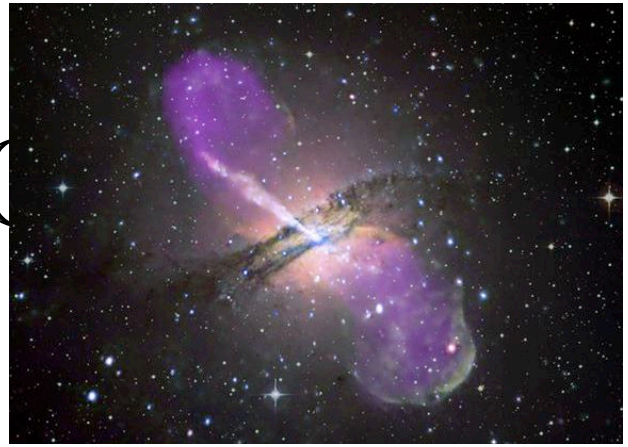








More like this...



LAT collaboration: *Fermi*/LAT observations of Local Group galaxies: detection of M 31 and search for M 33

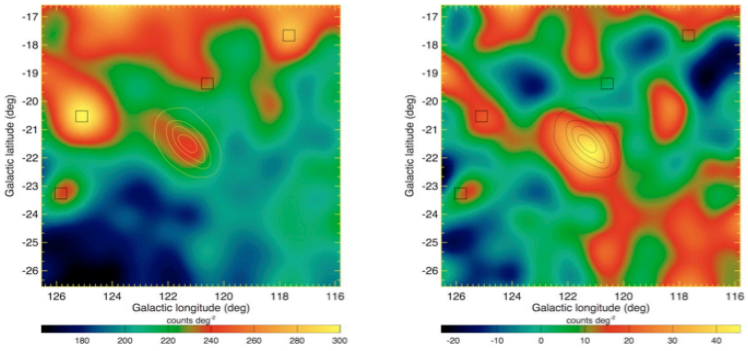
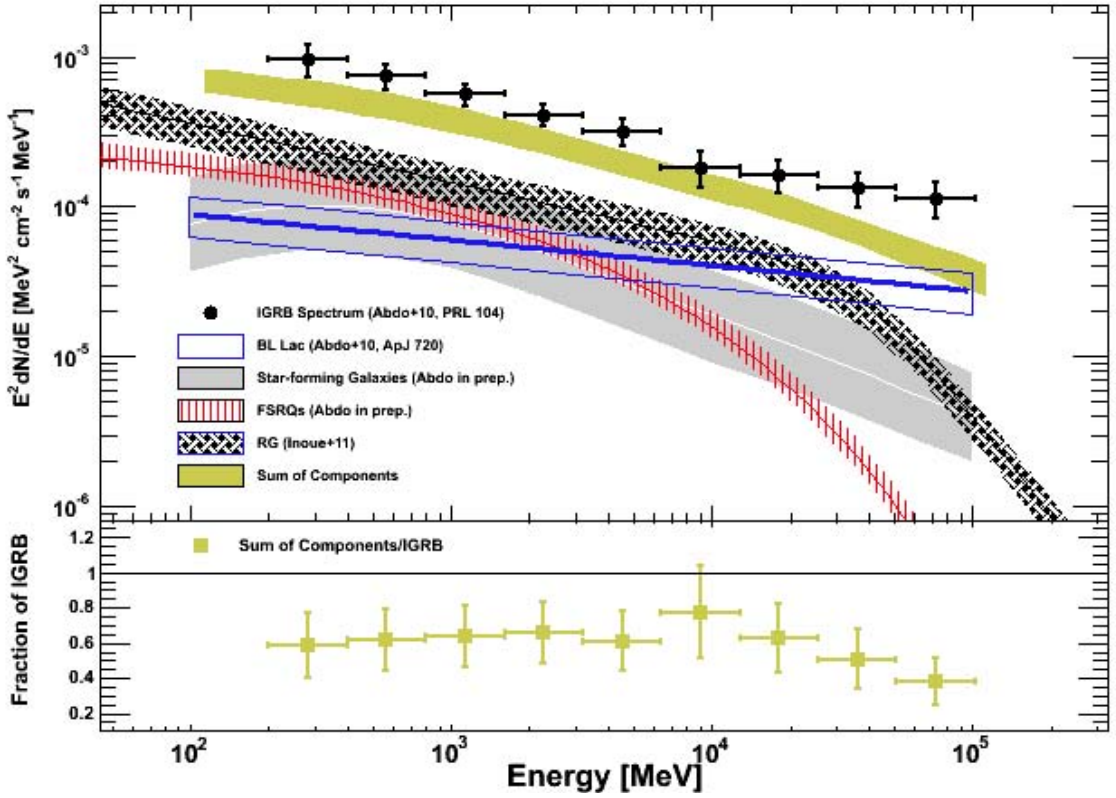
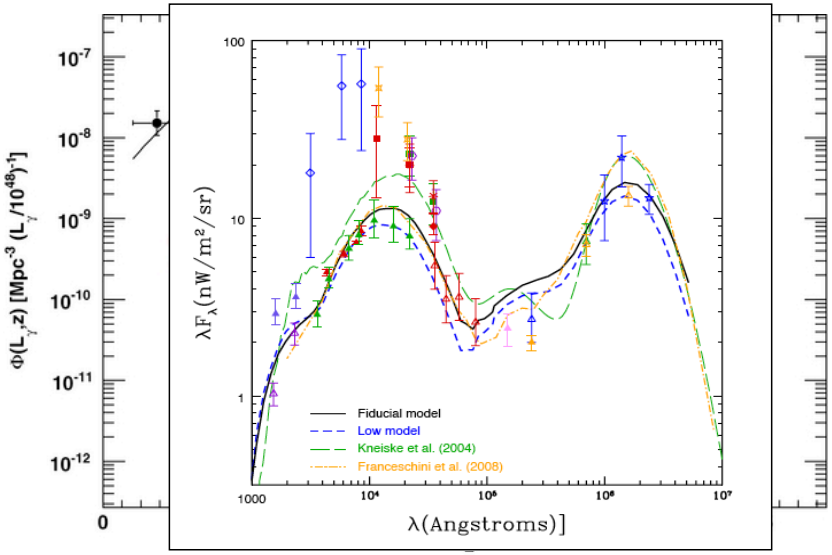
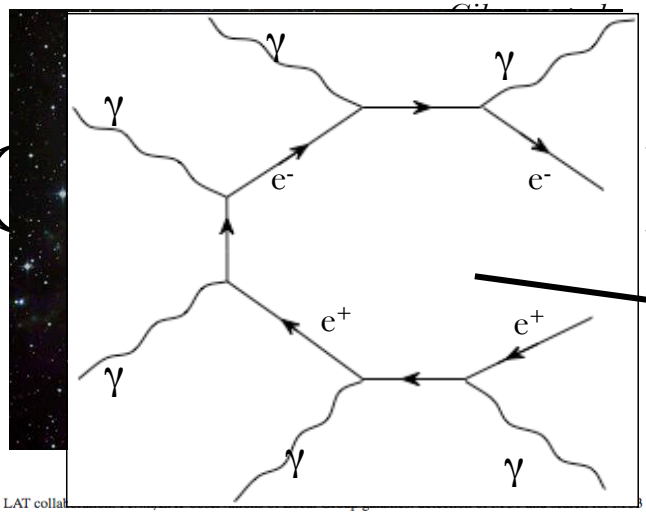


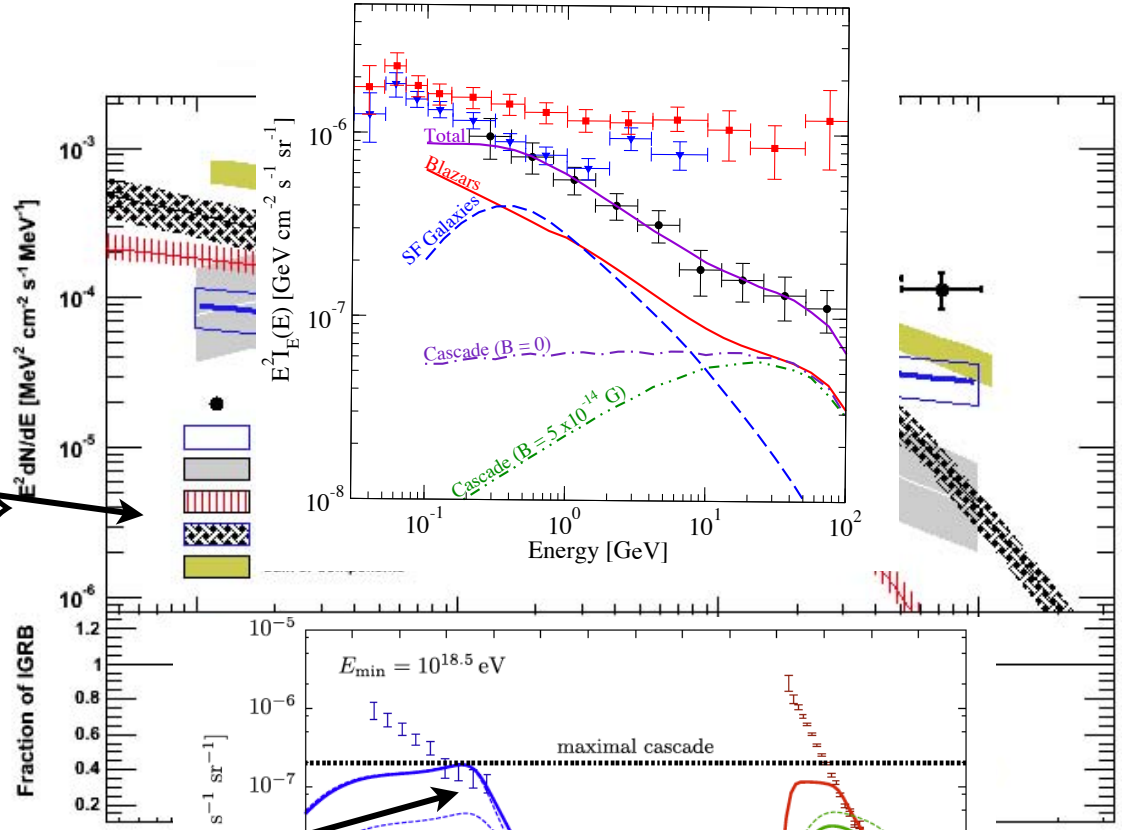
Fig. 1. Gaussian kernel ($\sigma = 0.5°$) smoothed counts maps of the region of interest (ROI) in a true local projection before (*left*) and after subtraction of the background model (*right*) for the energy range 200 MeV–20 GeV and for a pixel size of 0.05° × 0.05°. Overlaid are IRIS 100 μm contours of M 31 convolved with the LAT point spread function to indicate the extent and shape of the galaxy. The boxes show the locations of the 4 point sources that have been included in the background model.

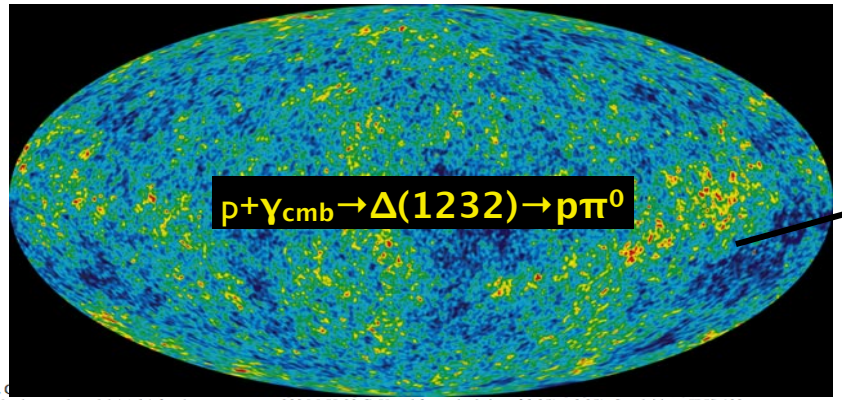


With maybe a little of this...









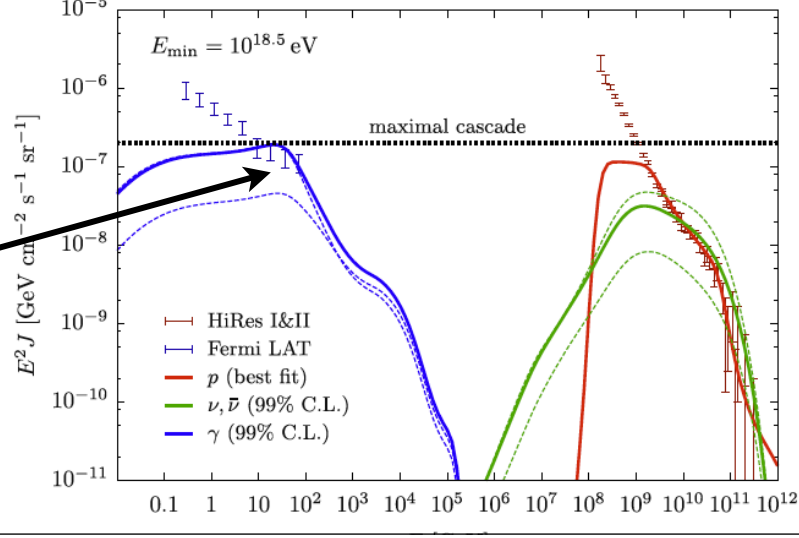
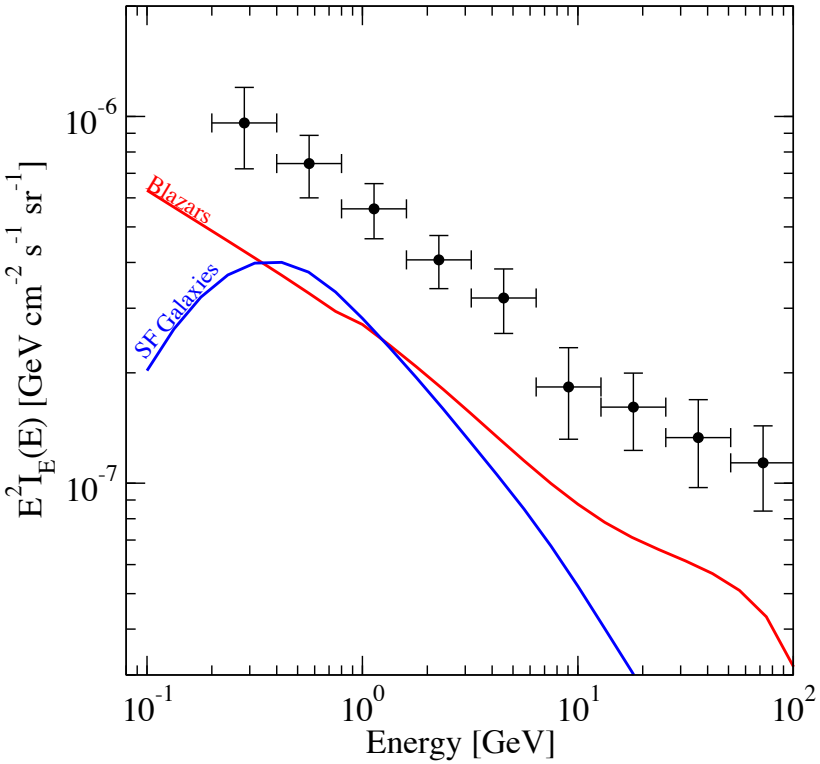
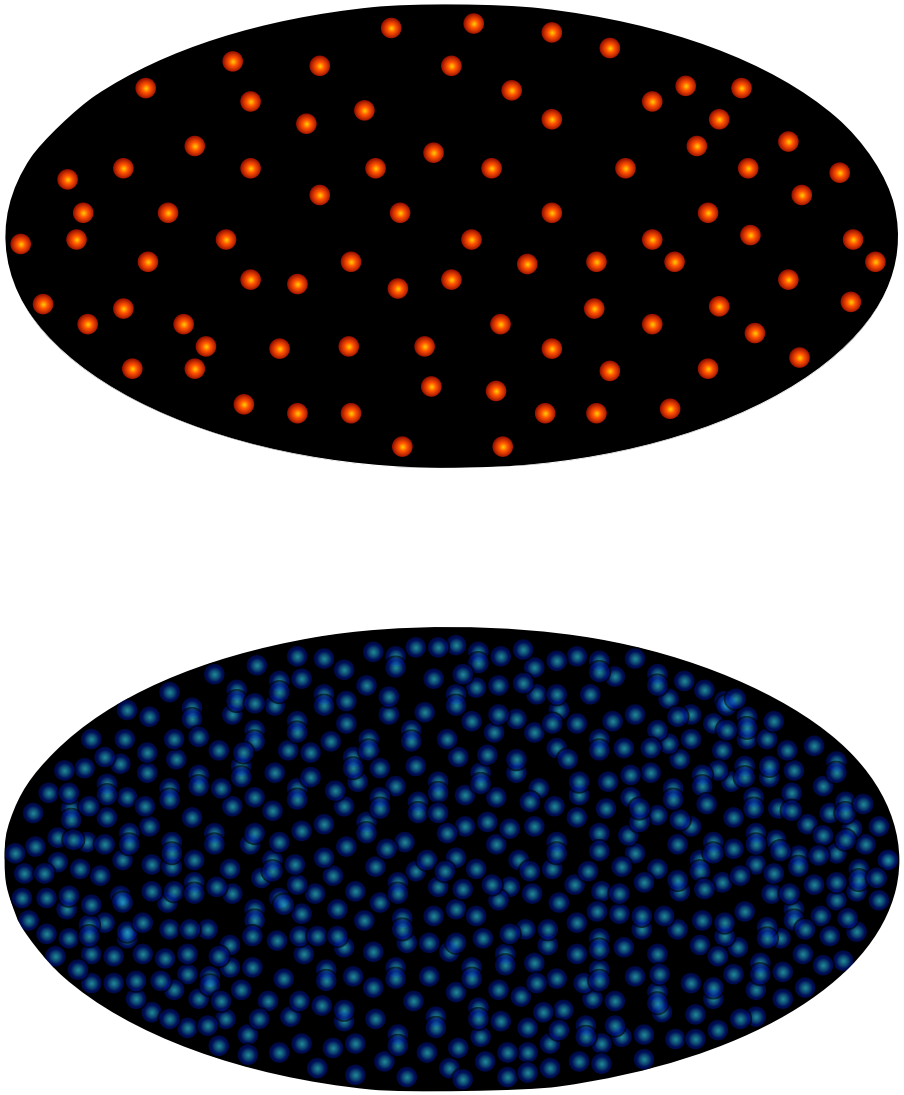


Fig. 1. C
of the background model (*right*) for the energy range 200 MeV–20 GeV and for a pixel size of 0.05° × 0.05°. Overlaid are IRIS 100 μm contours of M 31 convolved with the LAT point spread function to indicate the extent and shape of the galaxy. The boxes show the locations of the 4 point sources that have been included in the background model.

Anisotropy as a Function of Energy





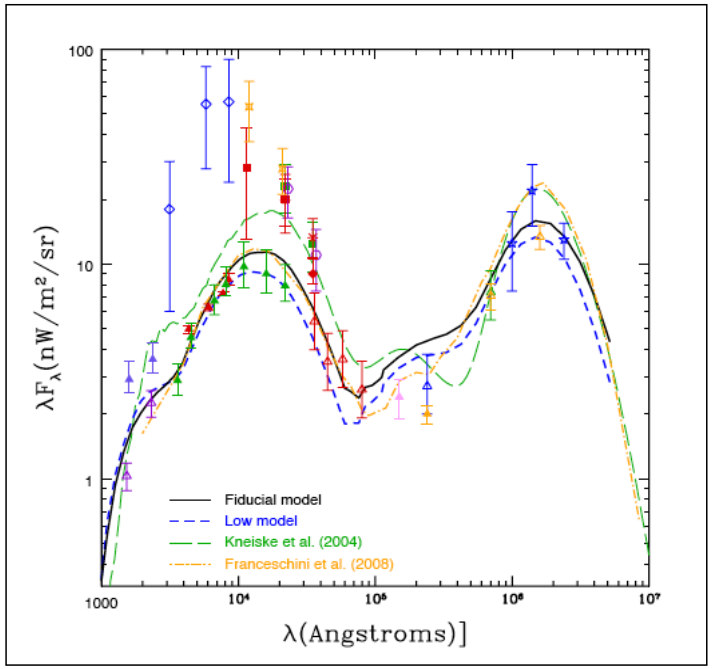
$$C_l^{\rm tot}(E) = f_{\rm bl}{}^2(E) C_l^{\rm bl} + f_{\rm gal}{}^2(E) C_l^{\rm gal}$$

VHE Gamma Rays in the EBL

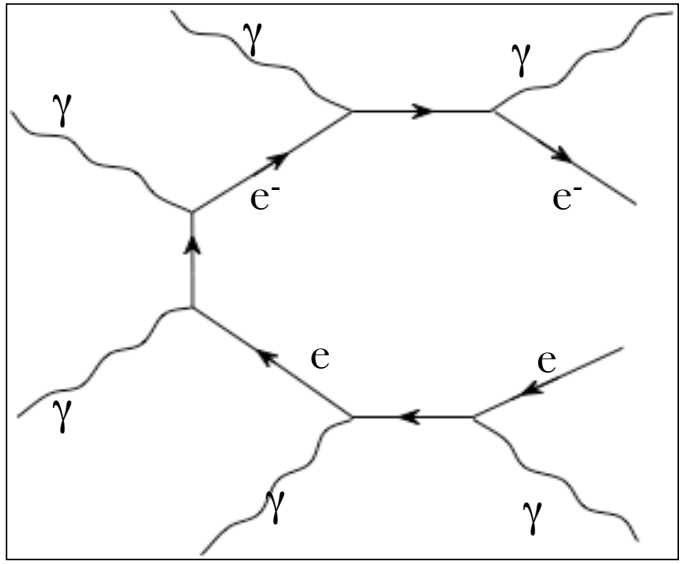
Extragalactic background light (EBL)

consists of:

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



Gilmore et al. 2009



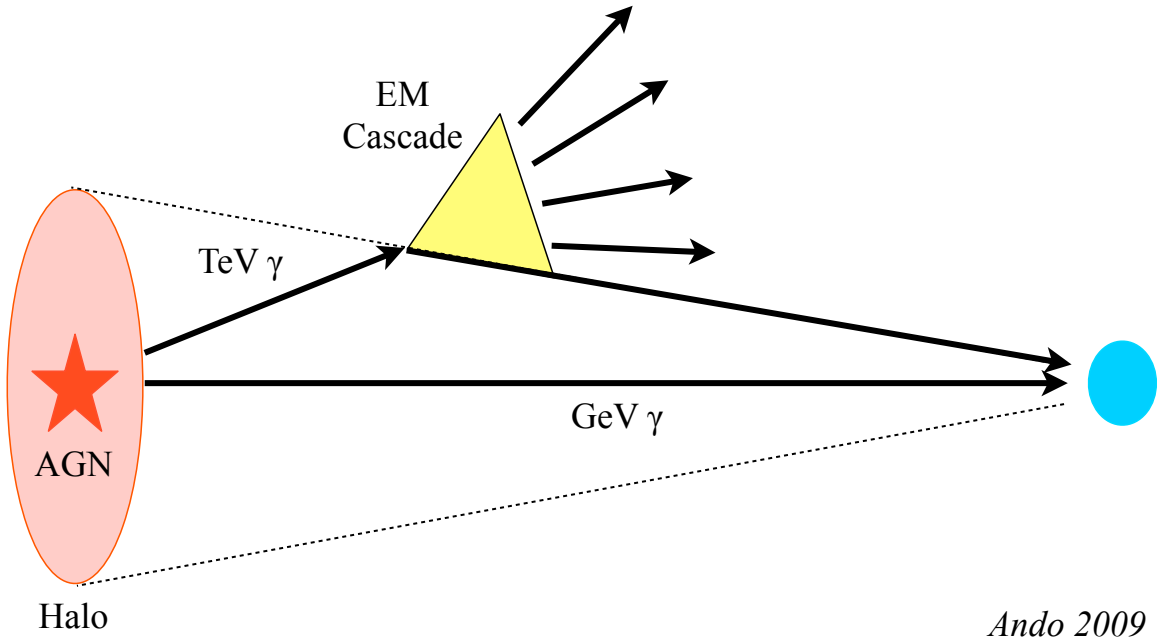
Venters 2009

Cascades -

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

⇒ For a cosmological population - spectrum should exhibit a suppression at the high energy part of the EGRB and an enhancement at the lower energy part resulting from cascades

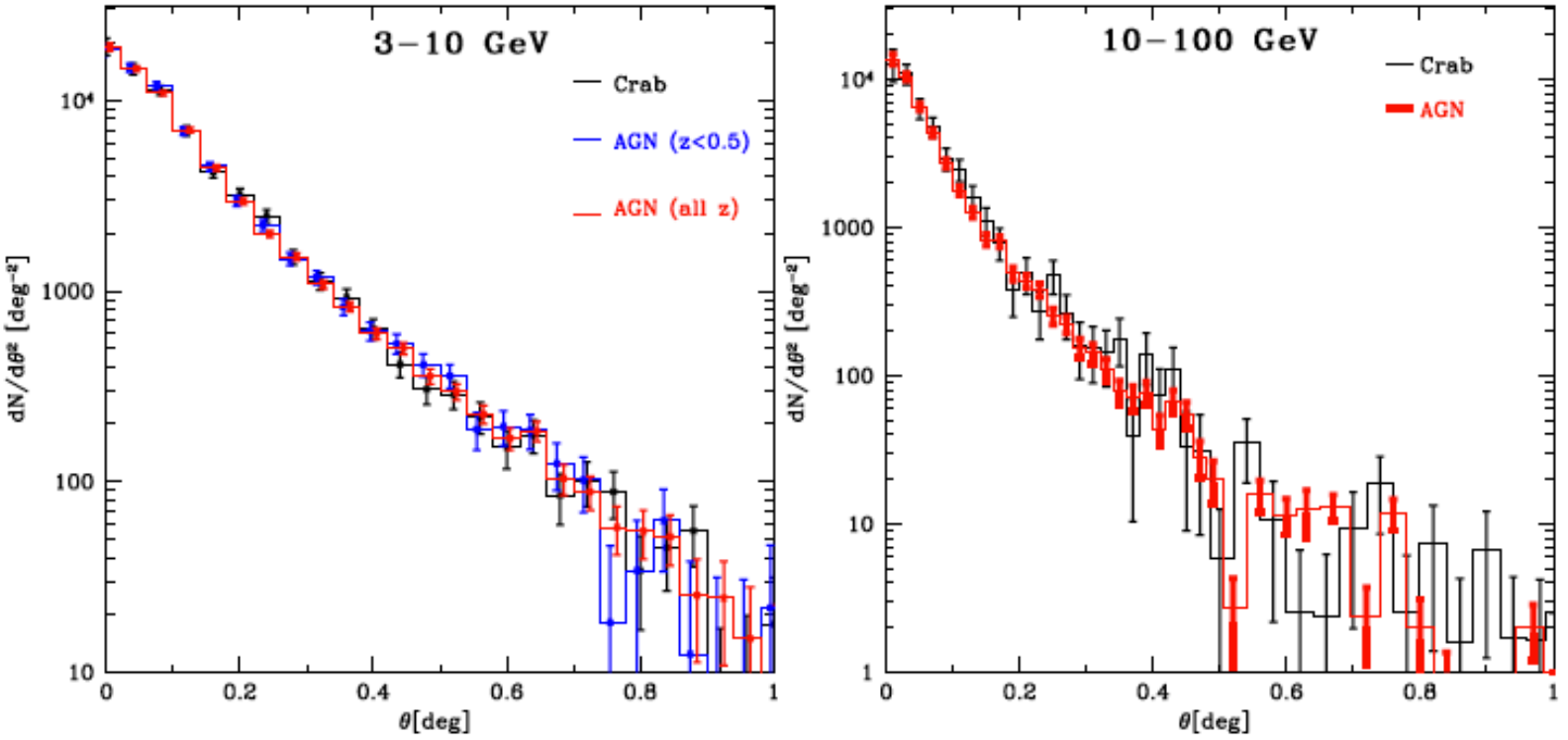
Magnetic Deflection of Cascades



Ando 2009

- Charged particles of cascades deflected by IGMF.
- 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.

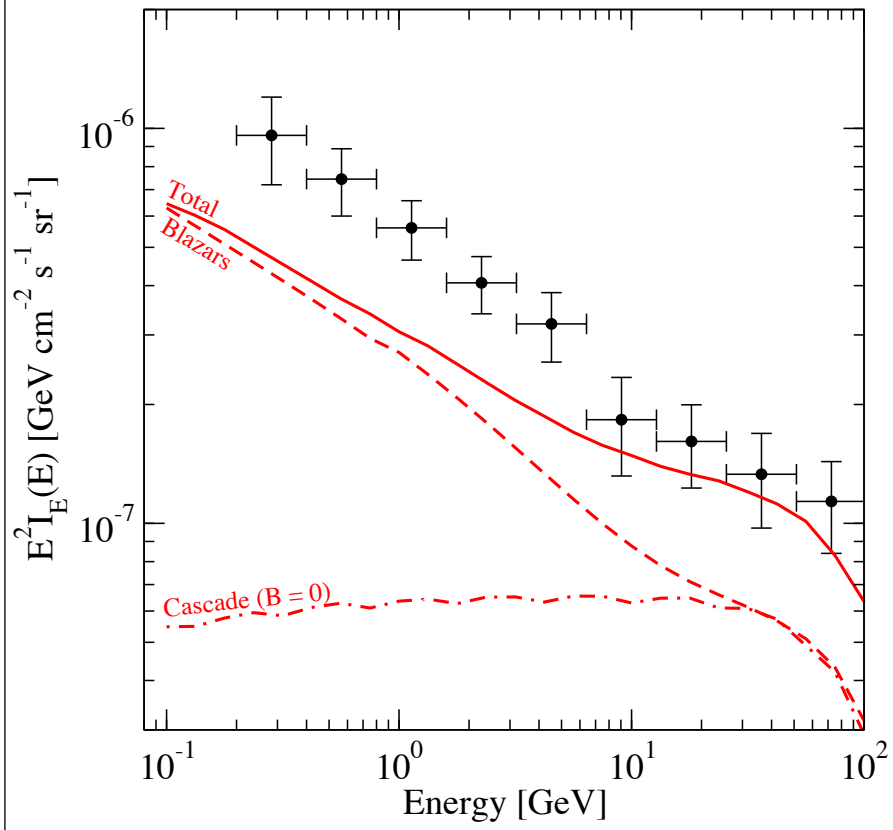
Search for Gamma-ray Halos

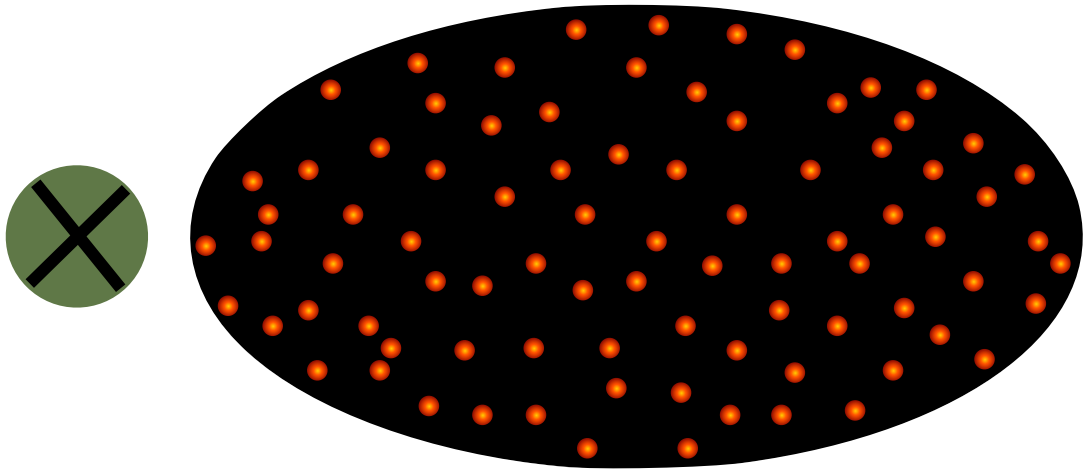


The Impact of Cascades

- Cascades impact the anisotropy energy spectrum of the EGB in three different ways:
  - For a population of emitters of VHE gamma-rays, cascades can comprise a significant fraction of the contribution of the parent population to the EGB ($I_{\rm par}(E)$).
  - Cascade radiation could be a significant contribution to the EGB at higher energies ($I_{\rm tot}(E)$)
  - Gamma-ray halos resulting from cascade development in the IGMF could impact the anisotropy of the parent population ($C_l^{(\rm n)}$).
- For our particular model, we considered IGMF field strengths that result in two limiting cases:
  - "Isotropization" of cascade radiation (strong IGMF - deflection of cascades is large enough that cascades from one source would be confused with another).
  - No magnetic deflection of cascades (zero IGMF).

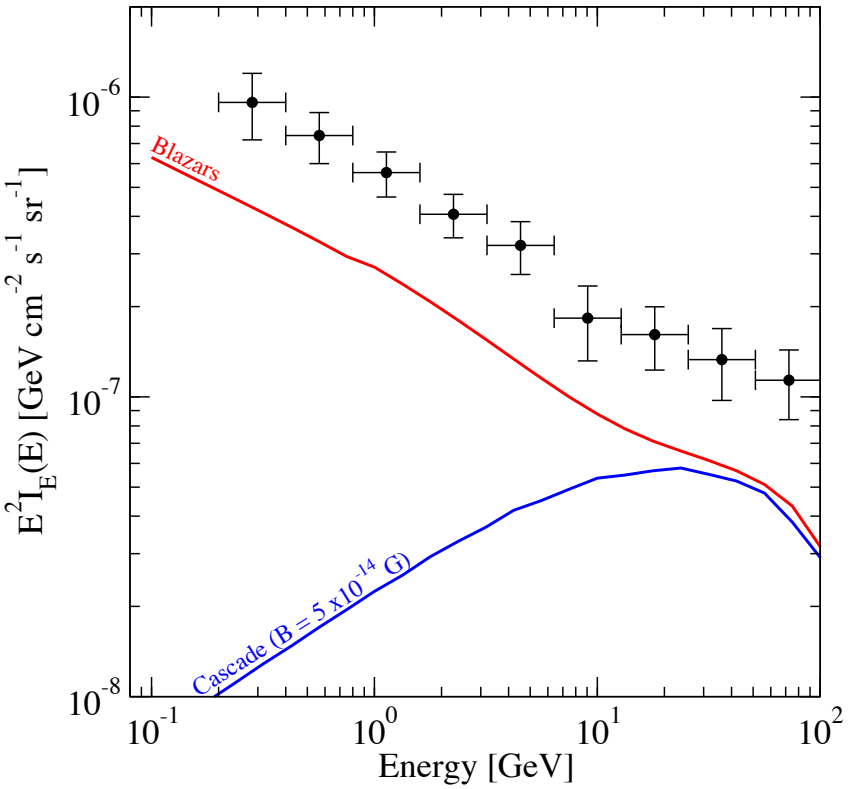
The Impact of Cascades (zero B)

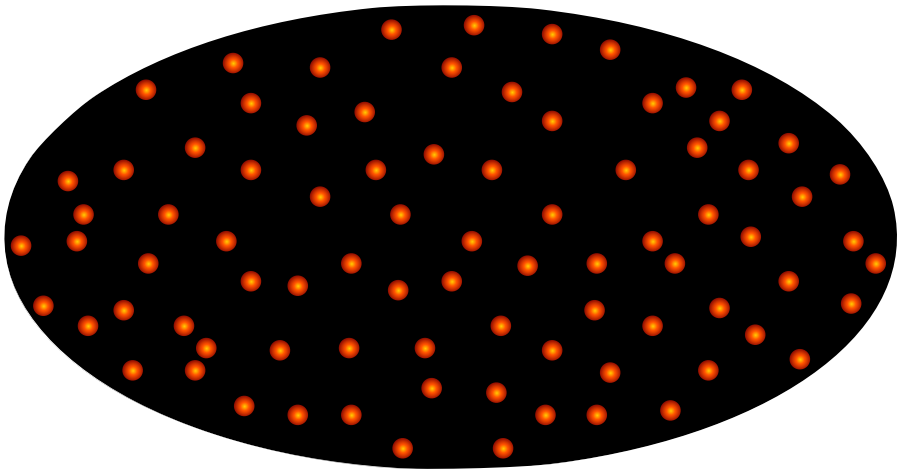


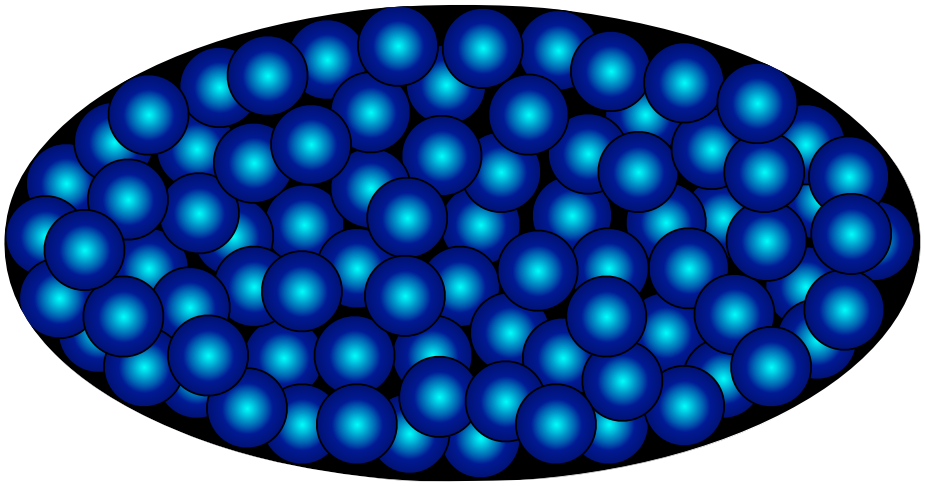


$$C_l^{\rm tot}(E) = (f_{\rm bl}(E) + f_{\rm cas}(E))^2 C_l^{\rm bl}$$

The Impact of Cascades (non-zero B)

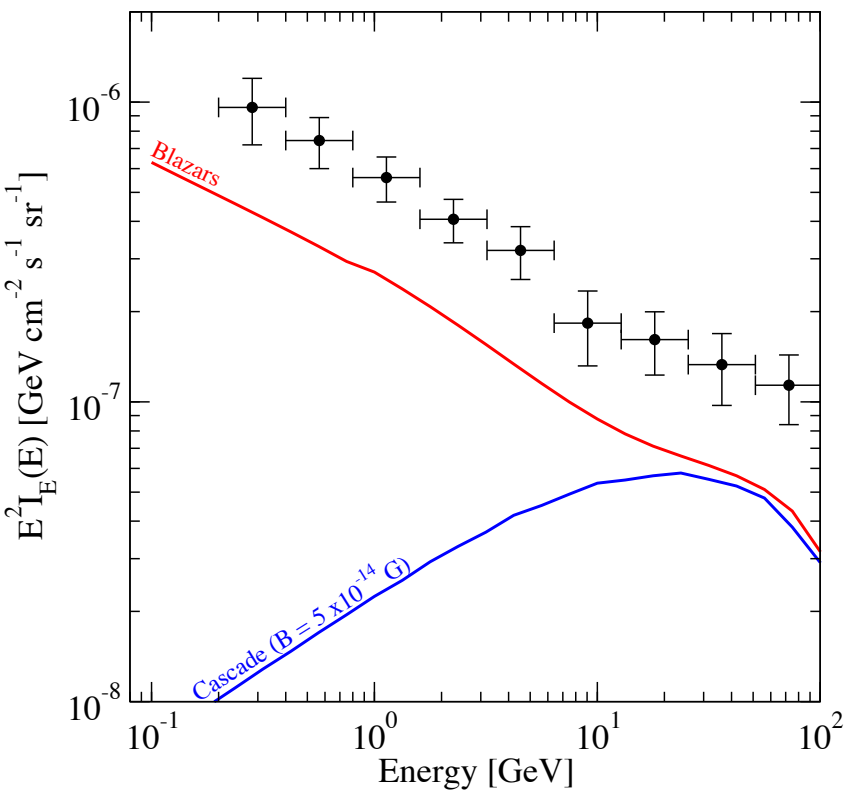


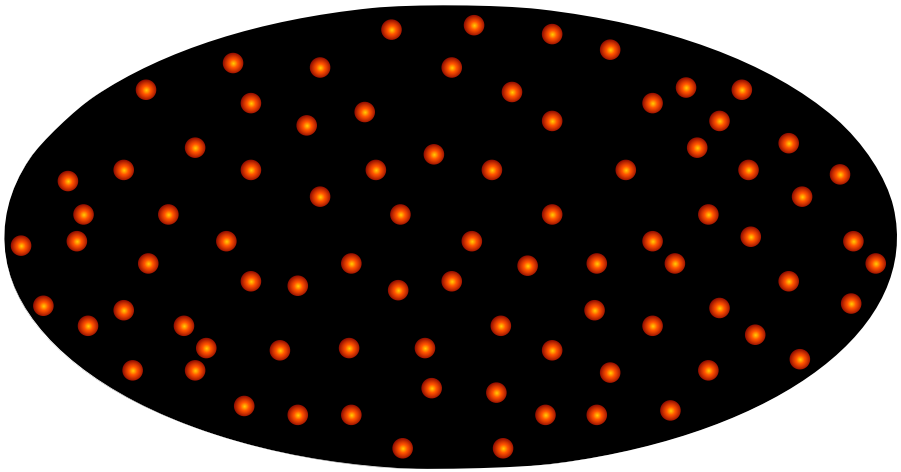


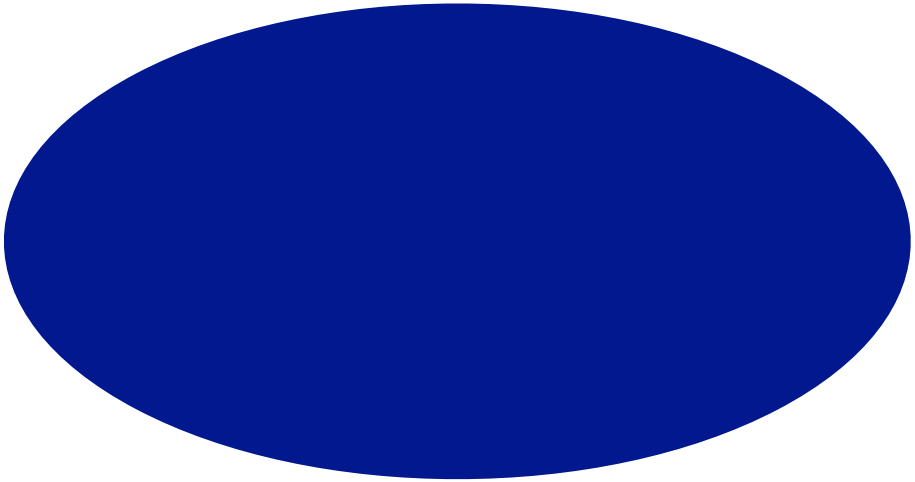


$$C_l^{\mathrm{tot}}(E) = f_{\mathrm{bl}}{}^2(E) C_l^{\mathrm{bl}} + f_{\mathrm{cas}}{}^2(E) C_l^{\mathrm{cas}} + \text{cross terms}$$

The Impact of Cascades (non-zero B)

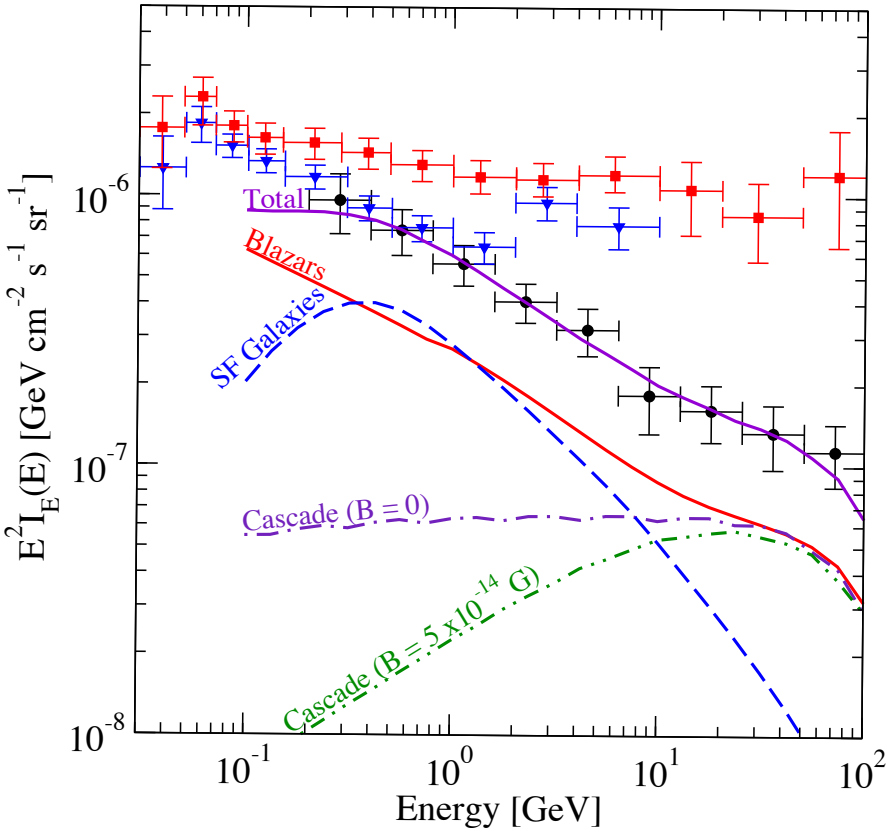


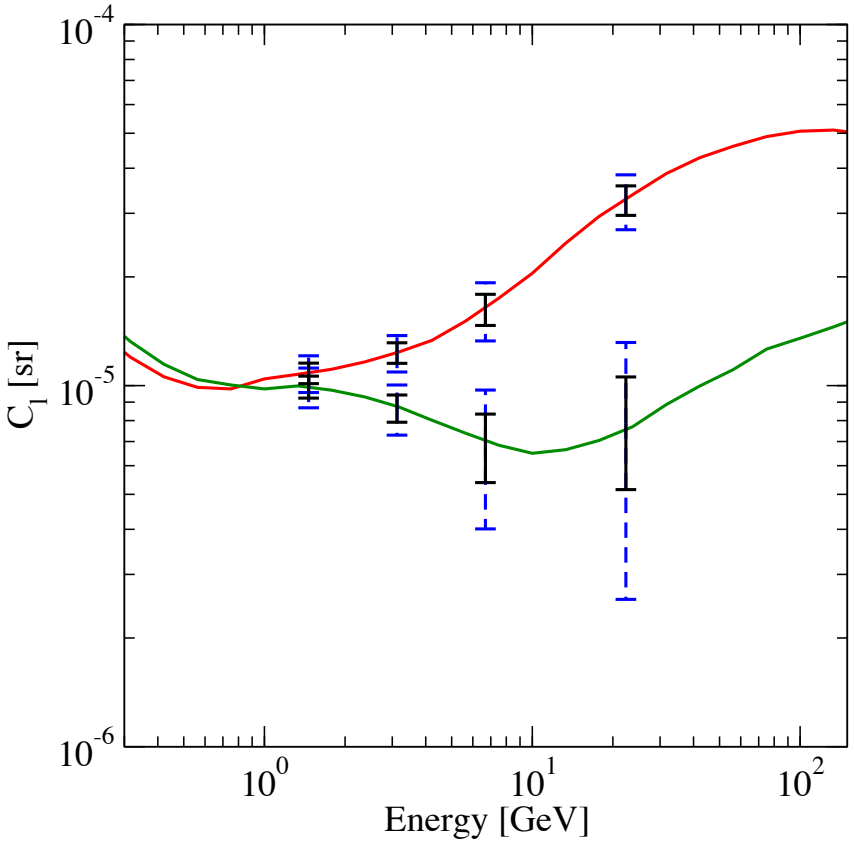


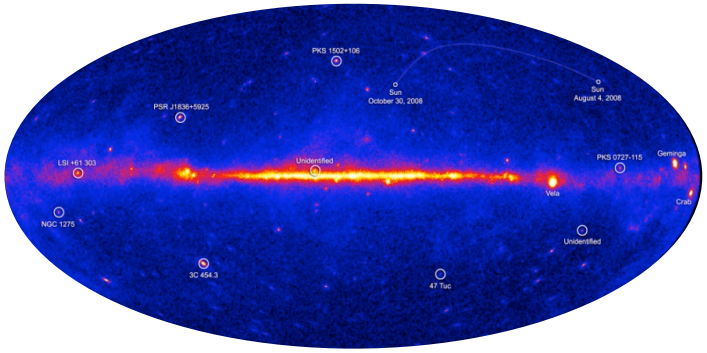


$$C_l^{\rm tot}(E) = f_{\rm bl}{}^2(E) C_l^{\rm bl} + \cancel{f_{\rm cas}{}^2(E) C_l^{\rm cas}} + \cancel{\text{cross terms}}$$

Cascades and EGB Anisotropy



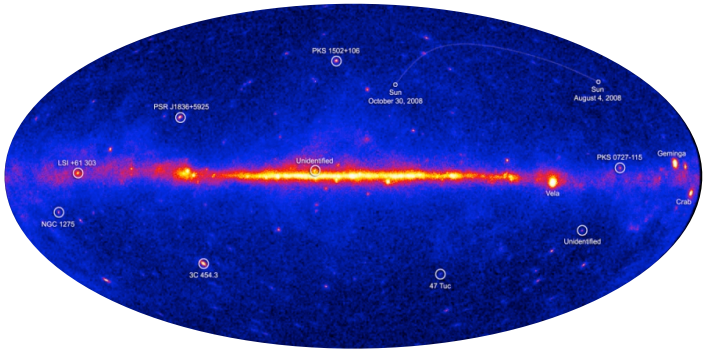




Future Work

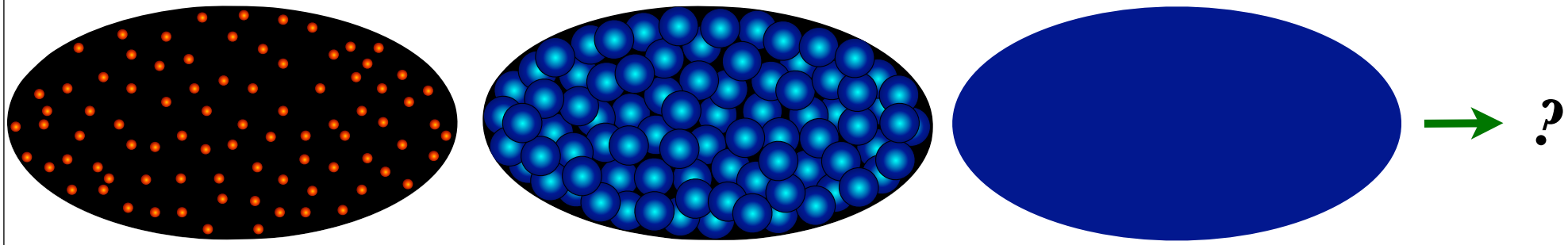
- The cases presented here assume that the *cascades would not have appreciable anisotropy*, either because there are no halos (zero IGMF case) or the density of halos is large compared to the source density. For intermediate field strengths, cascades could have appreciable anisotropy, and their fluctuations would correlate with the parent population.
- To assess the impact of cascades and their corresponding halos on the observed gamma-ray sky, we will explore field configurations that more closely resemble those expected in large scale structure.

Extra Slides

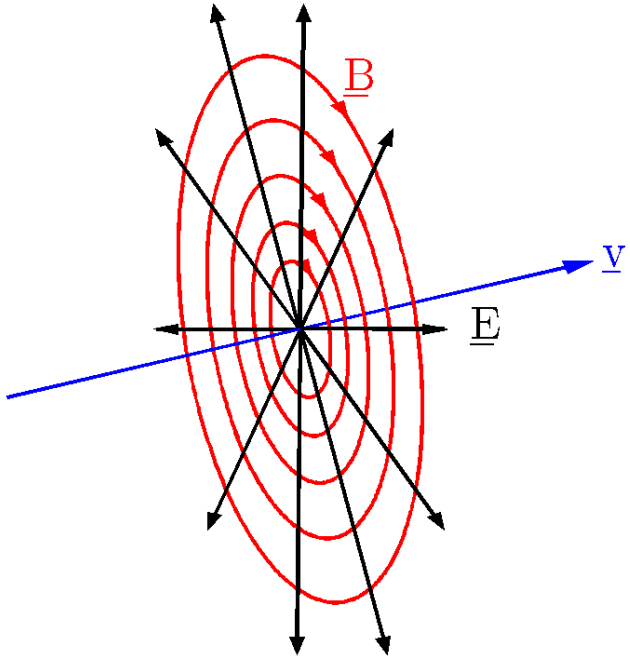


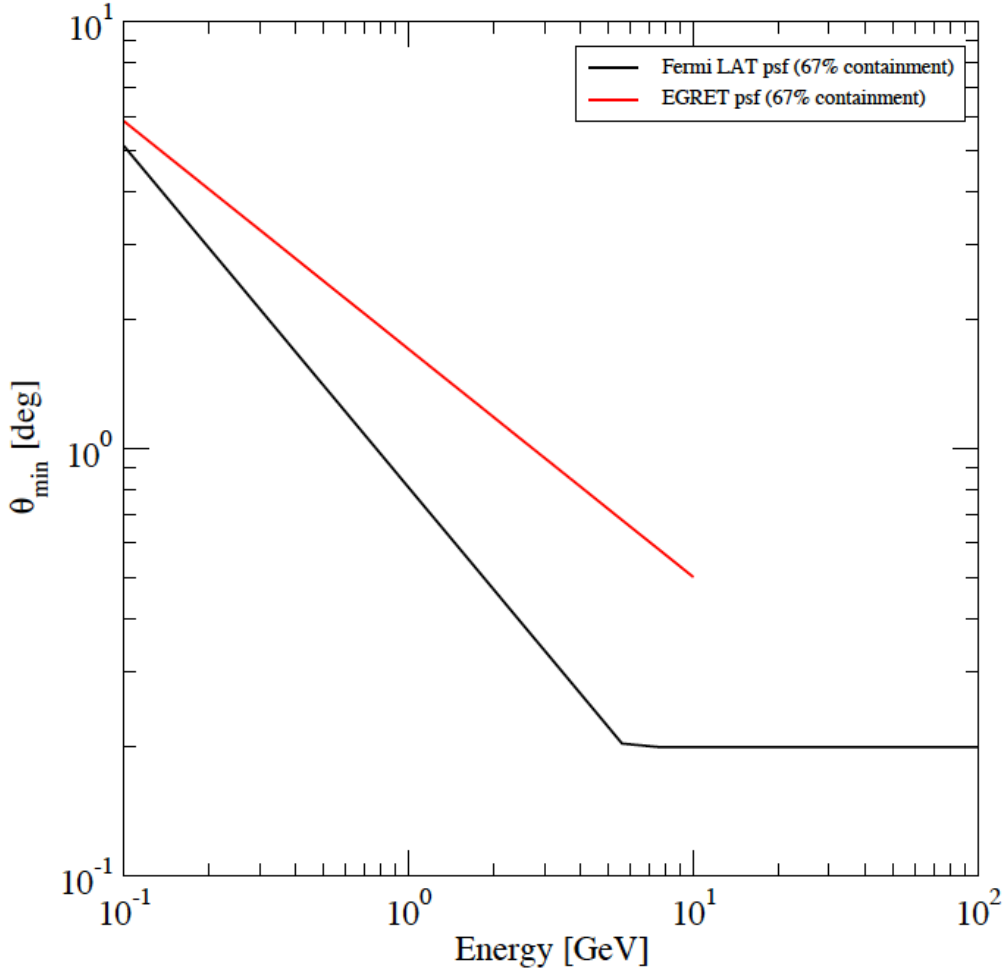
Conclusions

- As TeV gamma rays propagate through the extragalactic background light (EBL) and the CMB, they initiate electromagnetic cascades.
- Charged particles are deflected in the IGMF → halo of lower energy gamma rays around a TeV source → *modulation in the anisotropy in energy bands with significant cascade emission.*
- *Anisotropy studies of the gamma-ray sky could provide insight into the IGMF.*

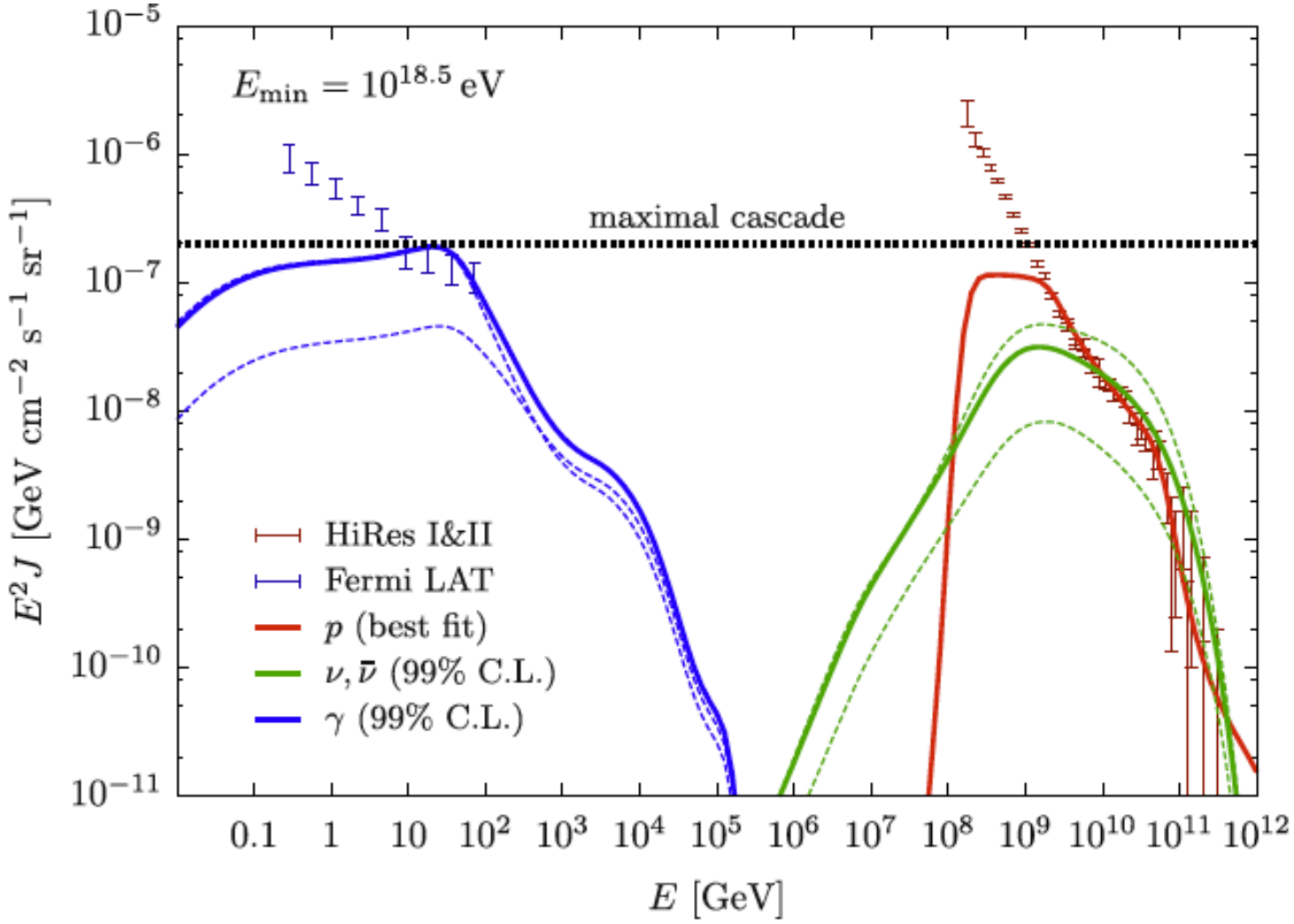


PLASMA BEAM!!!




Fermi LAT psf (67% containment)
EGRET psf (67% containment)
θ_{min} [deg]
Energy [GeV]
10^{1}
10^{0}
10^{-1}
10^{-1}
10^{0}
10^{1}
10^{2}

Maximum Background from EM Cascades due to the GZK Effect



PP Laboratory open questions

- Relativistic jet
- Small angle between jet axis and line-of-sight
- Broadband emission from jet
- Gamma-ray emission: IC of soft photons from energetic electrons
- Very luminous, variable

Connection with Accretion Disk and Black Hole?

Γ~ 5↔50

Population properties? Evolution?

Effect on host galaxy? Galaxy cluster?

Is radio emission produced in the same location as the gamma-ray emission?

Where in the jet?

Synchrotron? Ambient? From disk? From jet?

Are p^+ efficiently accelerated? Is energetic e^- population directly accelerated or is it produced in p^+ induced cascades?

Which soft photons?

Where do the energetic electrons come from?

What is the duty cycle of blazars?

Overlap of bursts? Or continuous emission + variability?