Fermilab

TeV and PeV neutrinos in km^3 telescopes, a new probe of studying high energy astrophysical phenomena

Work done with Dan Hooper (FNAL)
(arXiv:1211:1974) and arXiv:1206:1607

Ilias Cholis (FNAL)

HEP 2013

ΠΑΝΕΠΙΣΤΗΜΙΟ ΑΙΓΑΙΟΥ

26/04/2013

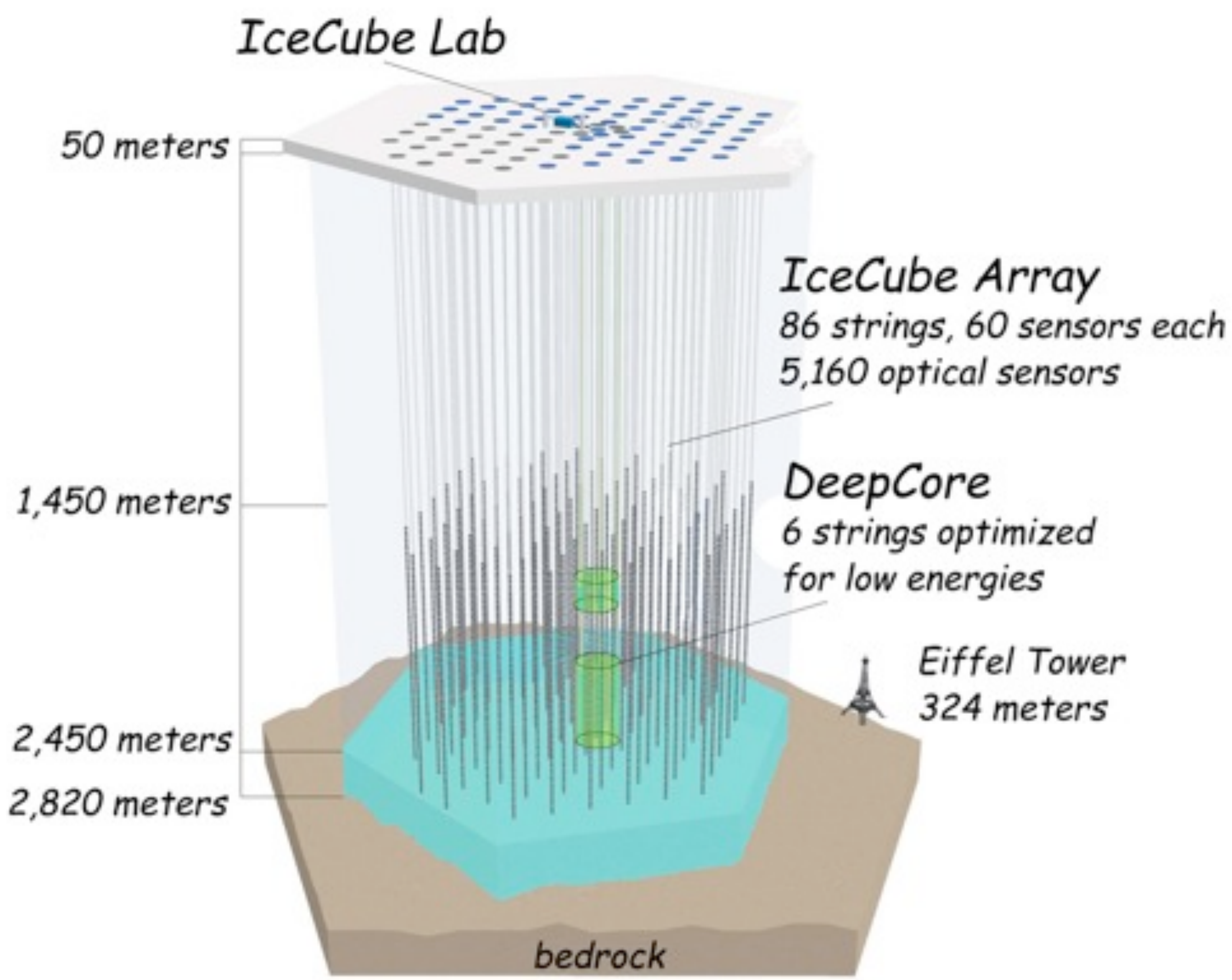
Conference on Recent Developments in High Energy Physics and Cosmology

Outline

- km^3 Experiments (IceCube, KM3NeT)
- Discovery of PeV neutrino events at IceCube
- Astrophysical sources for PeV neutrinos, Gamma Ray Bursts
- A gamma-ray signal that can(or can not) be seen at neutrinos (Fermi Bubbles)
- TeV neutrinos from the Gamma-ray bubbles / DM annihilation
- Conclusions

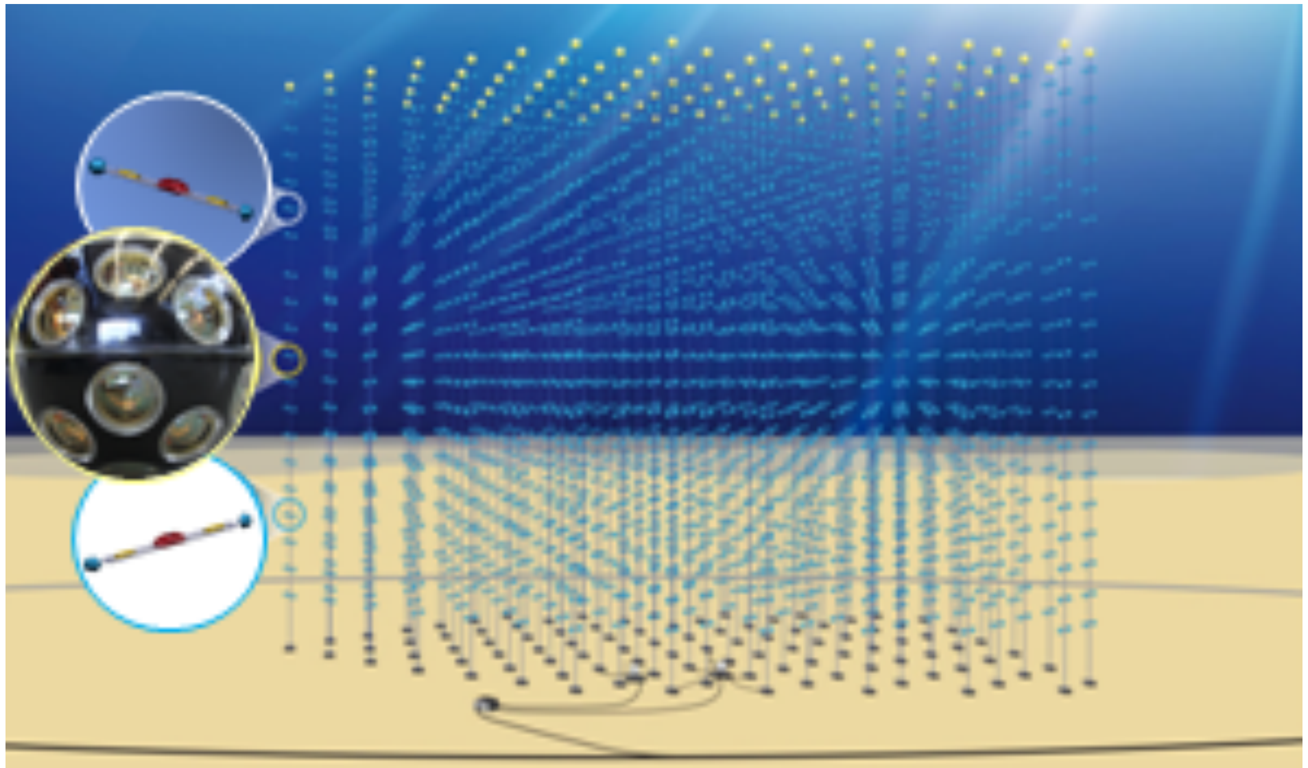
km^3 neutrino telescopes

IceCude Detector



South Pole (completed in 2011)

KM3NeT (proposed)



Mediterranean Sea

cover different portions of the galactic sky

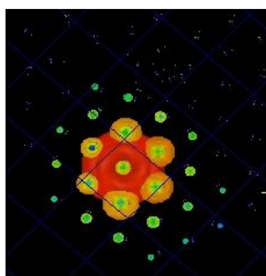
Detection of 2 ~PeV neutrino events

From AyaIshihara's talk at Neutrino 2012 conf. Kyoto (June 8)

Two events passed the selection criteria

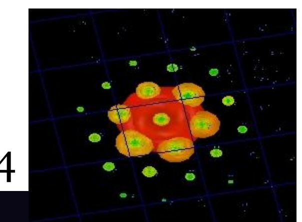
2 events / 672.7 days - background (atm. μ + conventional atm. ν) expectation 0.14 events

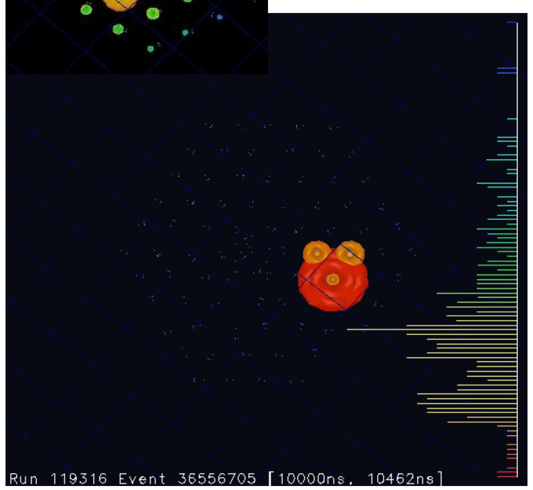
preliminary p-value: 0.0094 (2.36σ)



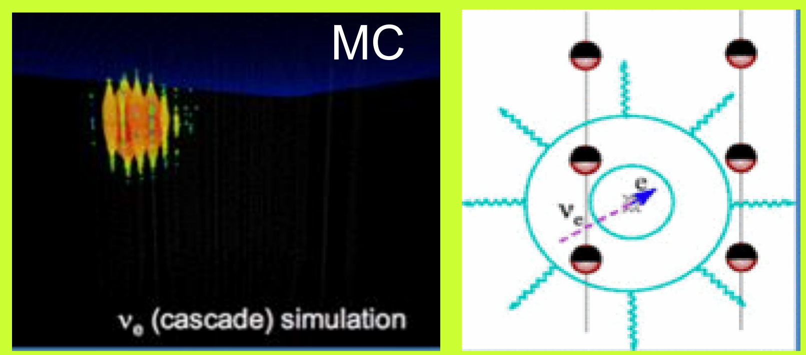
Run119316-Event36556705
Jan 3rd 2012
NPE 9.628×10^4
Number of Optical Sensors 312

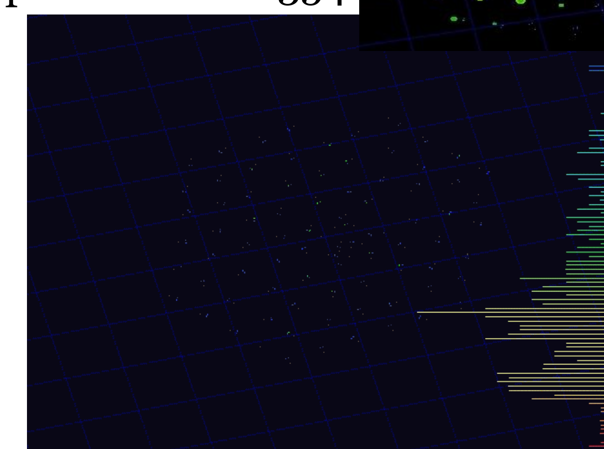
Run118545-Event63733662
August 9th 2011
NPE 6.9928×10^4
Number of Optical Sensors 354

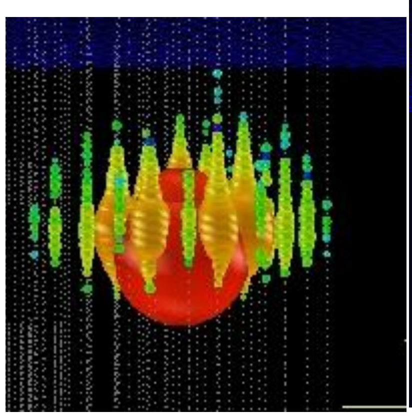


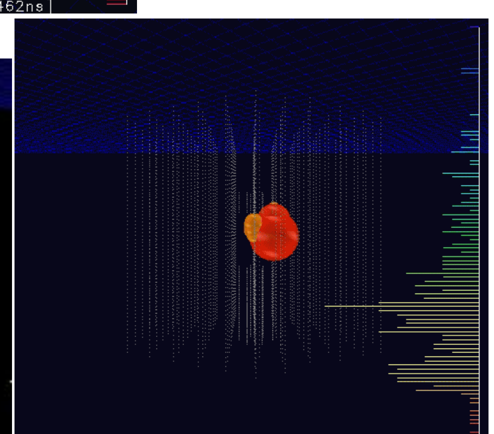


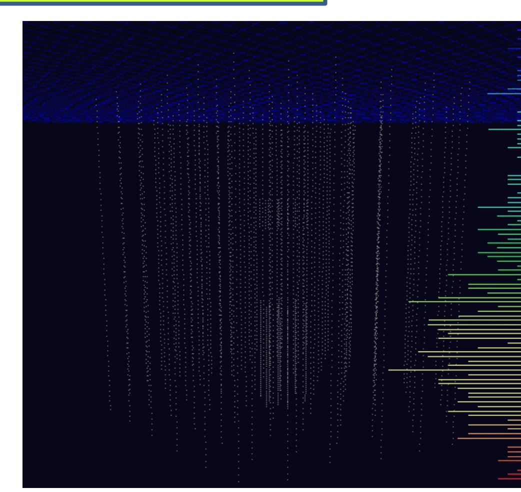
CC/NC interactions in the detector

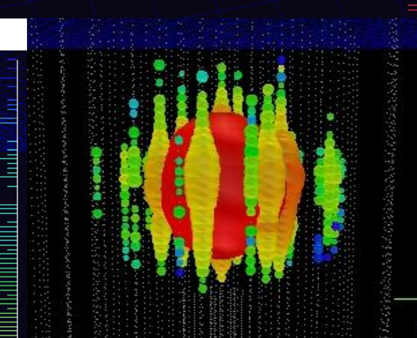




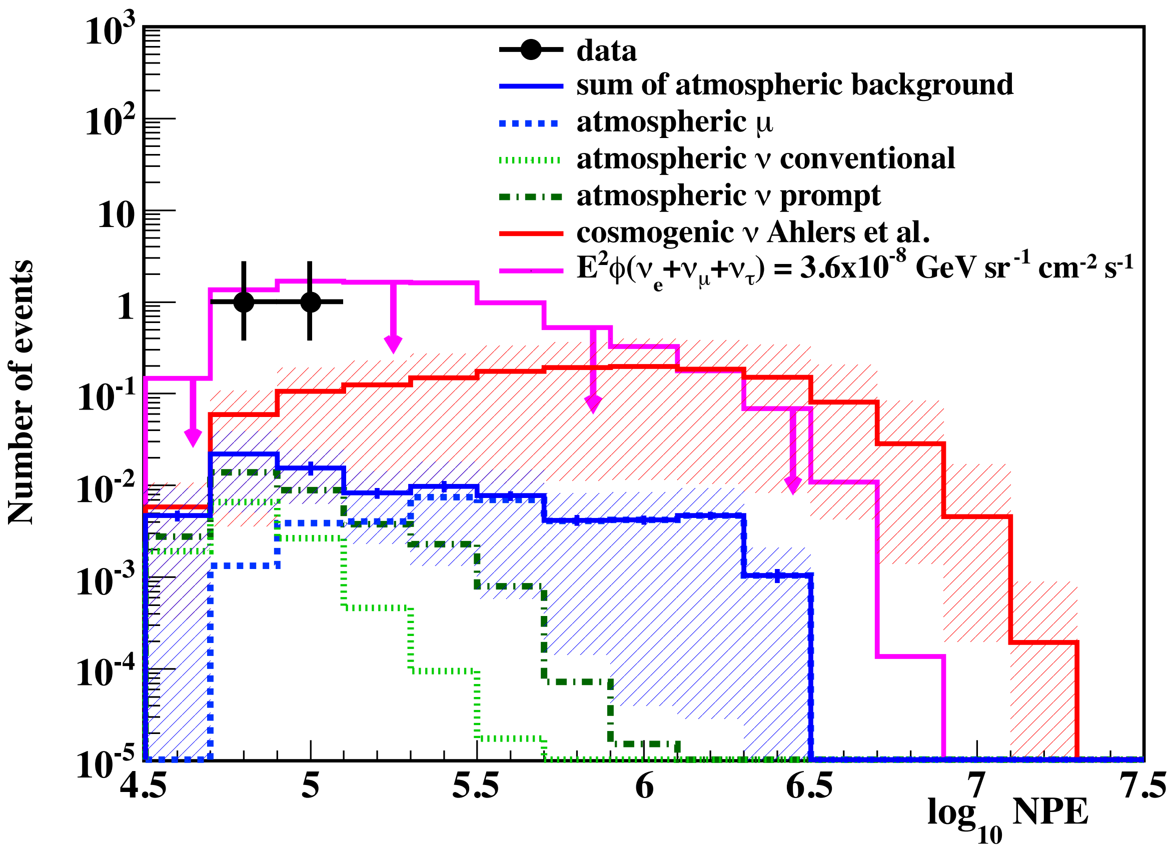








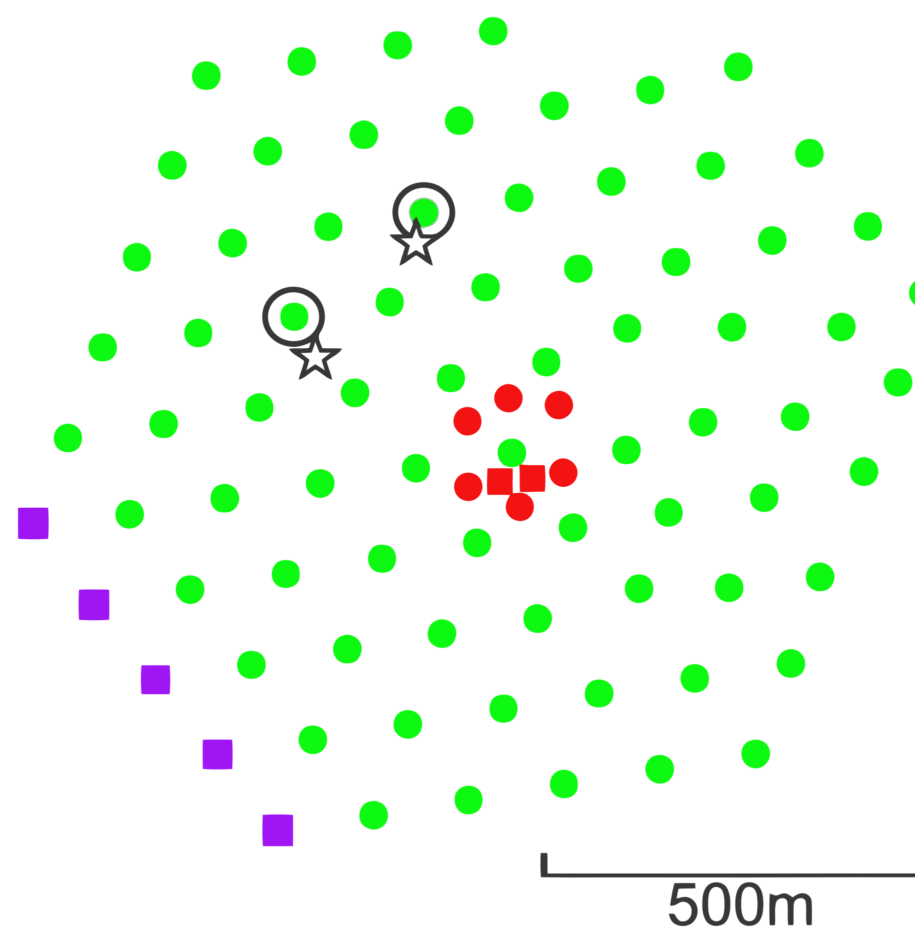
Energy of approximately 1-2 PeV. Both showers are fully contained within the volume of the detector. No indications of any instrumental problems, or of any connection with atmospheric muons.



events	"Bert"	"Ernie"
date (GMT)	August 8, 2011	January 3, 2012
NPE	7.0×10^4	9.6×10^4
number of recorded DOMs	312	354
reconstructed deposited energy (PeV)	1.04 ± 0.16	1.14 ± 0.17
reconstructed z vertex (m)	122 ± 5	25 ± 5

TABLE I. List of characteristics of the two observed events. The vertex z positions are with respect to the center of the IceCube detector at a depth of 1948 m.

arXiv:1304.5356



A few facts on high energy neutrinos

- up-going events: traveling through the Earth.
- down-going events below 10 TeV are dominated by the atmospherically produced neutrinos (CR cascades in the atmosphere). Spectrum is well understood and measured (power-law spectrum with an index of approximately 3.7).
- For neutrino energies above PeV Earth is opaque (typical mean free path of ~100 km).
- For shower events as are the 2 PeV neutrino events in IceCube directionality information is poor.
- PeV neutrino events must be either down-going or near the horizontal direction.
- Hadronic showers can be generated through the neutral current interactions of all neutrino flavors, with a typical shower energy that is about a quarter of that possessed by the initial neutrino.

- Charged-current interactions of electron neutrinos and anti-neutrinos produce a superposition of electromagnetic and hadronic showers which collectively contain the entire energy of the incoming neutrino.
- Difficult to distinguish at those energies.

The IceCube collaboration expects 0.14 background events (including those from conventional atmospheric neutrinos and from misidentified atmospheric muons) over the time period covered by their analysis. The observation of two events with an expected background of 0.14 constitutes a P-value of 0.0094, corresponding to a significance of 2.36 sigma (2.8 sigma).

Astrophysical Production of PeV neutrinos

PeV-scale astrophysical neutrinos can be produced through three primary processes:

- proton photon collisions with energetic photons, generating charged pions (photo-meson production), which yield neutrinos in their decays. In order to exceed the threshold for pion production, we have to consider circumstances in which the target radiation is fairly energetic (10's of eV or above).

- p-p (or p-n in nuclei) collisions between CR p's and gas. This mechanism is dominant at lower neutrino energies. In sources of UHE protons (that can yield PeV neutrinos), the number density of energetic photon targets is typically much larger than that of nucleon targets.

- PeV electron anti-neutrinos from decays of ultra high-energy neutrons. A small fraction of a neutron's energy goes into its neutrino decay product. Neutron decay anti-neutrinos can not be produced in sufficient numbers to account for the two IceCube events.

- We expect cosmic ray collisions with energetic photons to be the dominant mechanism behind IceCube's two reported events (assuming they are astrophysical in nature)

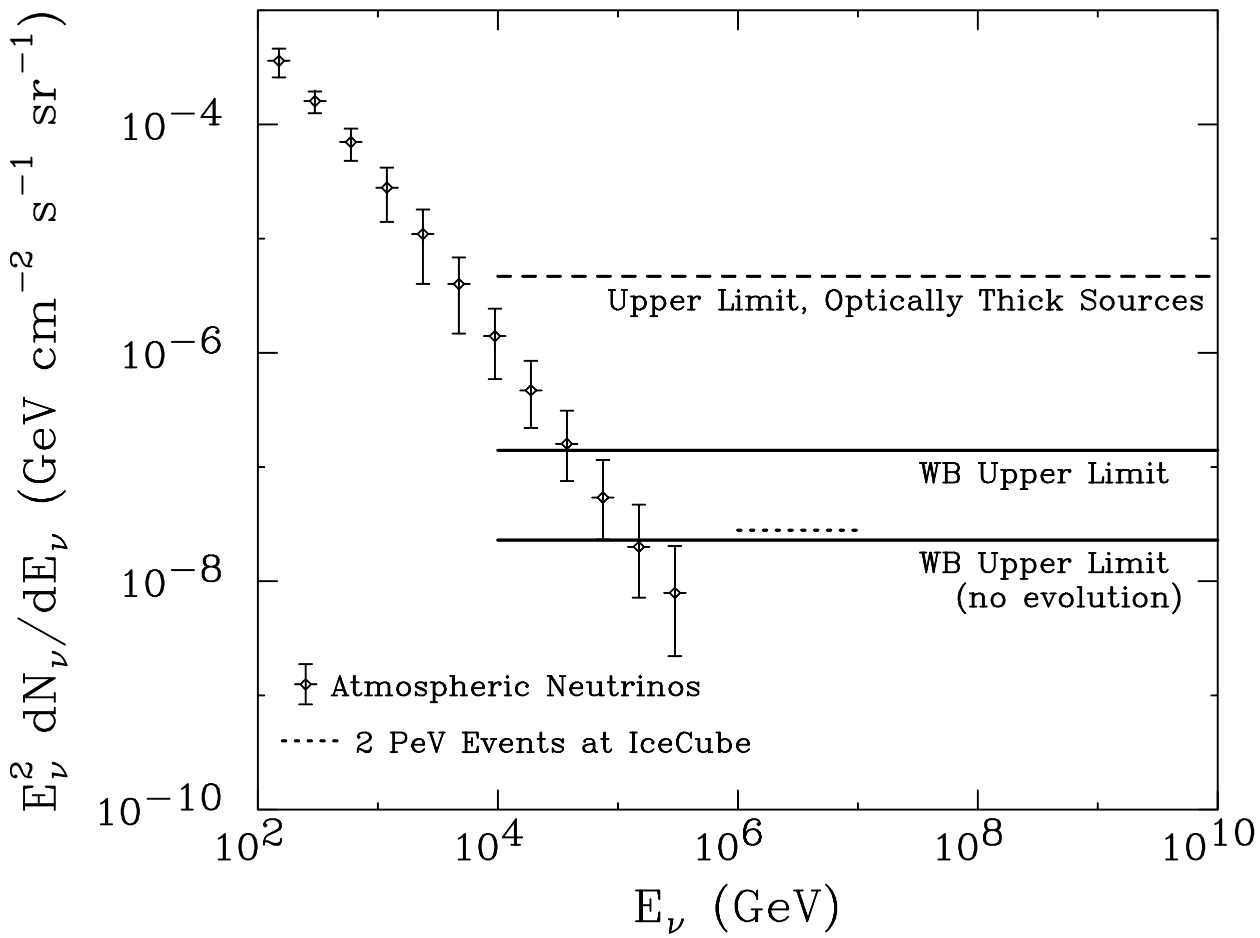
- Each of the three production mechanisms demands very high-energy cosmic rays. This provides us with a direct connection between the observation of high-energy neutrinos and the observed cosmic ray spectrum.

The energy density of neutrinos produced through the photo-meson interactions of these protons can be directly tied to the injection rate of cosmic rays (Waxman-Bahcall):

$$E_\nu^2 \frac{dN_\nu}{dE_\nu} \approx \frac{3}{8} \epsilon_\pi \, t_{\rm H} \, E_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{dE_{\rm CR}}$$

Taking into account the information from the UHECR spectrum one gets an upper limit for the neutrino flux:

$$[E_\nu^2 \Phi_\nu]_{\rm WB} \approx 2.3 \times 10^{-8} \, \epsilon_\pi \, \xi_Z \, {\rm GeV \, cm^{-2} \, s^{-1} \, sr^{-1}}$$

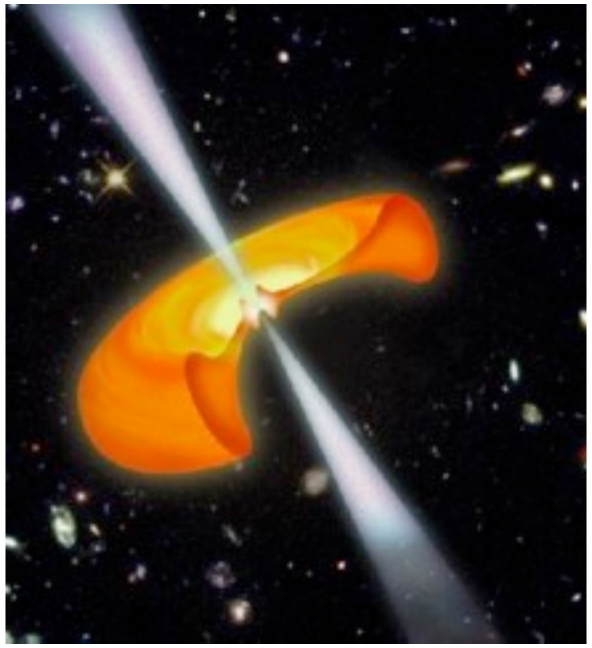


At production we have no tau neutrinos, taking into account oscillations, we have roughly equal mixture of muon and tau flavors. We must also take into account neutrino absorption in the Earth. About half of neutrinos with an inclined trajectory of 10 degrees below the horizon will undergo one or more interactions in the Earth.

Absorption of downward-going neutrinos in the PeV energy range is negligible.

The two reported shower events are entirely contained within the volume of the experiment, IceCube should be capable of detecting partially contained showers as well. For fully included events the effective volume is ~0.1 km^3. IceCube should observe ~13 shower events per year.

Gamma-Ray Bursts as PeV neutrino sources



Intense flashes of gamma-rays associated with supernovae explosions. Jet is along our line of sight.

GRBs constitute one of the most promising sources of high and ultra-high energy cosmic rays. May be capable of accelerating protons to energies as high as 10^20 eV. Contain high densities of gamma-rays, enabling for the efficient production of neutrinos via the photo-meson interactions with high energy ps.

GRBs exhibit a broken power-law spectrum of the form:

$$dN_\gamma/dE_\gamma \propto E_\gamma^{-2} \text{ for } E_\gamma \gtrsim 0.1 - 1 \text{ MeV}$$

$$dN_\gamma/dE_\gamma \propto E_\gamma^{-1} \text{ at lower energies}$$

To exceed the threshold for pion production, the proton must have an energy:

$$E_p \gtrsim 40\,\text{PeV} \left(\frac{\Gamma}{300}\right)^2 \left(\frac{0.3\,\text{MeV}}{E_\gamma}\right) \left(\frac{1}{1+z}\right)^2$$

After taking into account partition of energy we get that ~1/20 (~1/5 of the proton's energy goes to the charged pion) of the proton's energy goes to each neutrino. This leads to neutrinos with characteristic energy:

$$E_\nu \sim 2\,\mathrm{PeV} \left(\frac{\Gamma}{300}\right)^2 \left(\frac{0.3\,\mathrm{MeV}}{E_\gamma}\right) \left(\frac{1}{1+z}\right)^2$$

The resulting neutrinos will have energies near that of the two events reported by IceCube. The neutrino flux at energies below this value will be suppressed by the lack of sufficiently high energy target photons in the fireball. For this reason, the PeV energy scale is where one roughly expects to observe the first GRB neutrinos.

There are known distributions of GRBs

$$\Phi(L) = \Phi_0 \left[\left(\frac{L}{L_b}\right)^{\alpha_1} + \left(\frac{L}{L_b}\right)^{\alpha_2}\right]^{-1}$$

$$L_b = (1.2 \pm 0.6) \times 10^{52}\ \mathrm{erg/s} \quad \alpha_1 = 0.65 \pm 0.15 \quad \alpha_2 = 2.3 \pm 0.3$$

(characteristic values for their luminosity distribution)

The diffuse neutrino flux at Earth is given by:

$$\frac{dN^{\rm obs}}{dE^{\rm obs}_{\nu,\bar{\nu},ph}} = \int_0^{z_{\rm max}} dz \int_{L_{\rm min}}^{L_{\rm max}} dL\ \Phi(L) \frac{R_{\rm GRB}(z)}{1+z} \frac{4\pi D(z)^2}{(1+z)^2} \frac{c}{H_0\sqrt{\Omega_\Lambda + \Omega_M (1+z)^3}} \frac{dN^{\rm obs}}{dE^{\rm obs}}$$

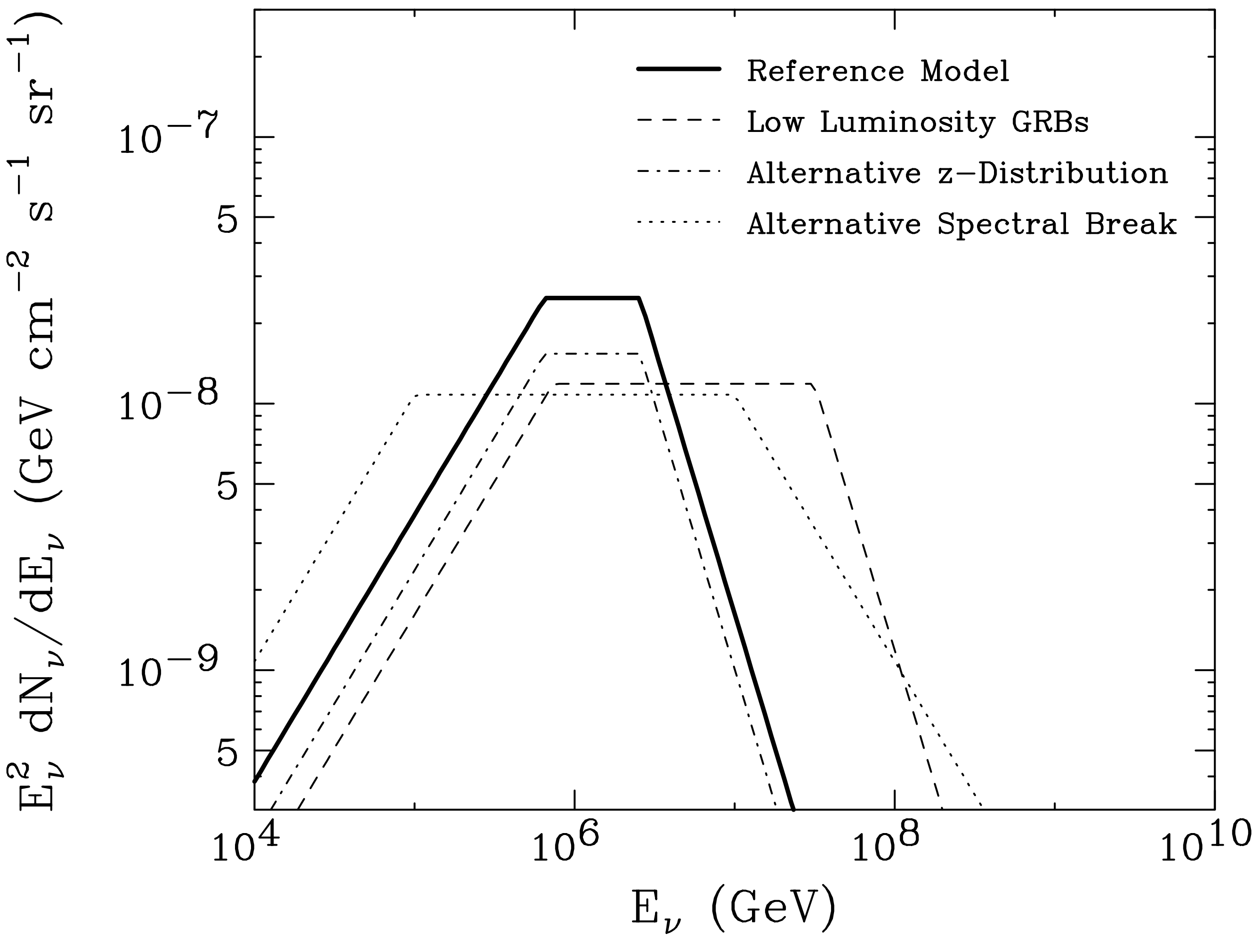
with:

$$D(z) = \int_0^z \frac{c}{H_0} \frac{dz'}{\sqrt{\Omega_\Lambda + \Omega_M (1+z')^3}}$$

$$\frac{dN^{\rm obs}}{dE^{\rm obs}} = \frac{dN^{\rm inj}}{dE^{\rm inj}} \frac{1+z}{4\pi D(z)^2}$$

The injection spectrum of neutrinos approximated as:

$$\frac{dN^{\rm inj}_\nu}{dE^{\rm inj}_\nu} \propto \begin{cases} \left(\frac{E_\nu}{E_1}\right)^{-1} \text{ for } E_\nu \leq E_1 \\ \left(\frac{E_\nu}{E_1}\right)^{-2} \text{ for } E_1 \leq E_\nu \leq E_2 \\ \left(\frac{E_2}{E_1}\right)^{-2} \times \left(\frac{E_\nu}{E_2}\right)^{-3} \text{ for } E_\nu \geq E_2 \end{cases}$$

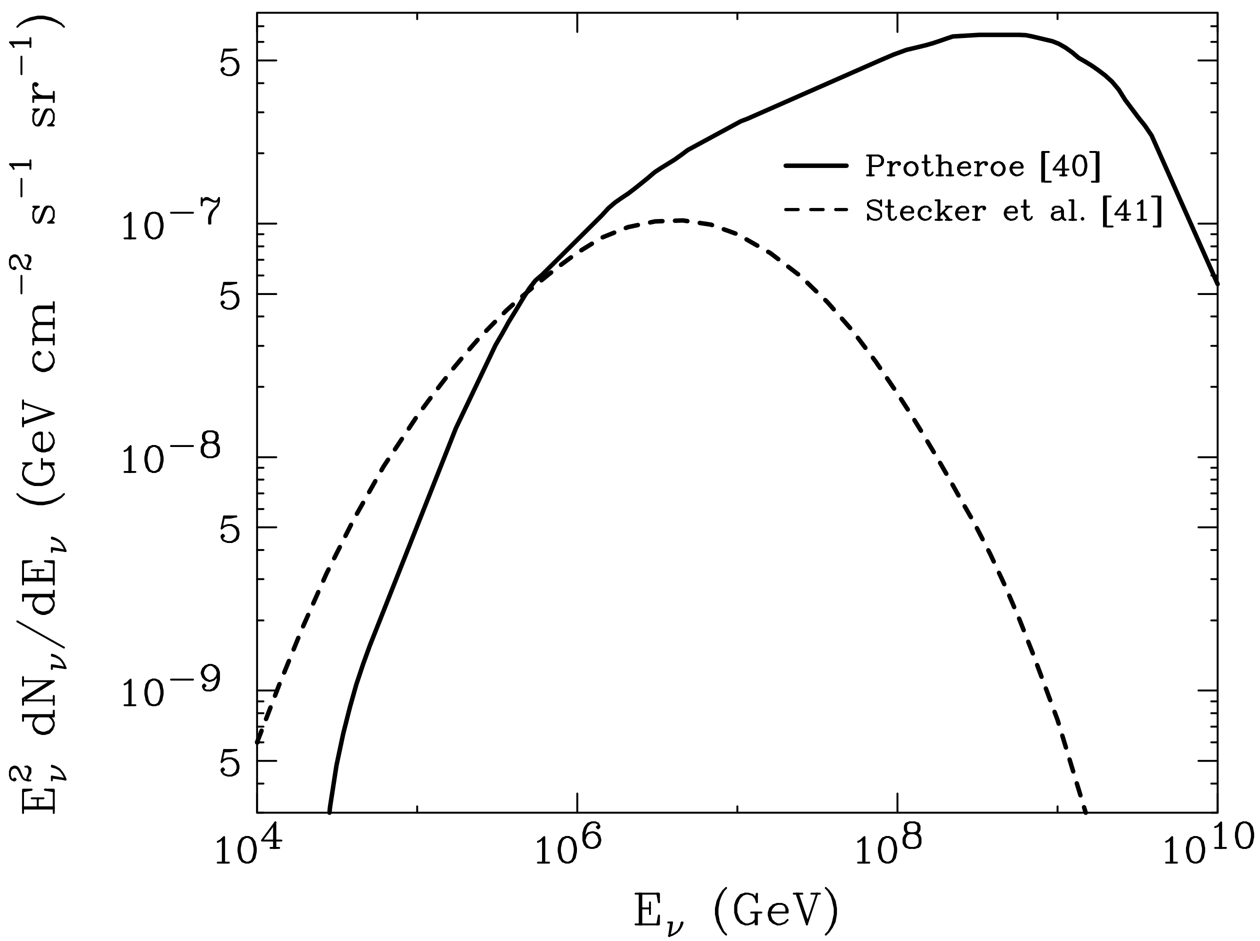


A wide range of assumptions, GRBs are expected to generate fluxes of PeV neutrinos that are similar to that implied by IceCube's two events. We expect a rate of 4-7 showers with energies above 1 PeV per cubic kilometer, per year. For an estimate of ~0.1 km^3 of the effective volume for fully contained showers this gives the observed rate (within a factor of 2).

By restricting an analysis to events which correlate in time and/or direction to known GRBs, it is possible to conduct a nearly background free search for neutrinos originating from GRBs. Some of the non-fully contained events should correlate in time with known GRBs.

Active Galactic Nuclei (AGN)

AGNs have a spectral break at UV ~10 eV. The neutrino spectrum peaks at EeV energies, much higher than that from GRBs. Yet, considerable degree of model dependence due to large uncertainties in the spectrum of the target radiation fields.



For the spectral shape of Protheroe, most showers initiated within IceCube's volume will be of energy 20 PeV or greater. If IceCube's existing data does not contain at least a few enormous (non-contained) showers of this energy, this AGN model will not be able to account for the two reported PeV events.

Alternative possibilities

- Starburst Galaxies: Galaxies undergoing periods of rapid star-formation. Significant fluxes of TeV neutrinos from pp collisions.
- Cosmogenic neutrinos: from 10^17 eV protons. The universe is transparent to 10^17 eV protons; thus cosmogenic neutrinos are unlikely to be the source of the two events reported by IceCube.
- Large scale intergalactic shock waves: Due to structure formation. May be capable of accelerating both electrons and protons to Lorentz factors as high as 10^7. Are constrained by gamma-ray observations above 50 GeV (unless only protons are accelerated).

Searching for multi-TeV neutrino galactic signal "inspired by gamma-rays"

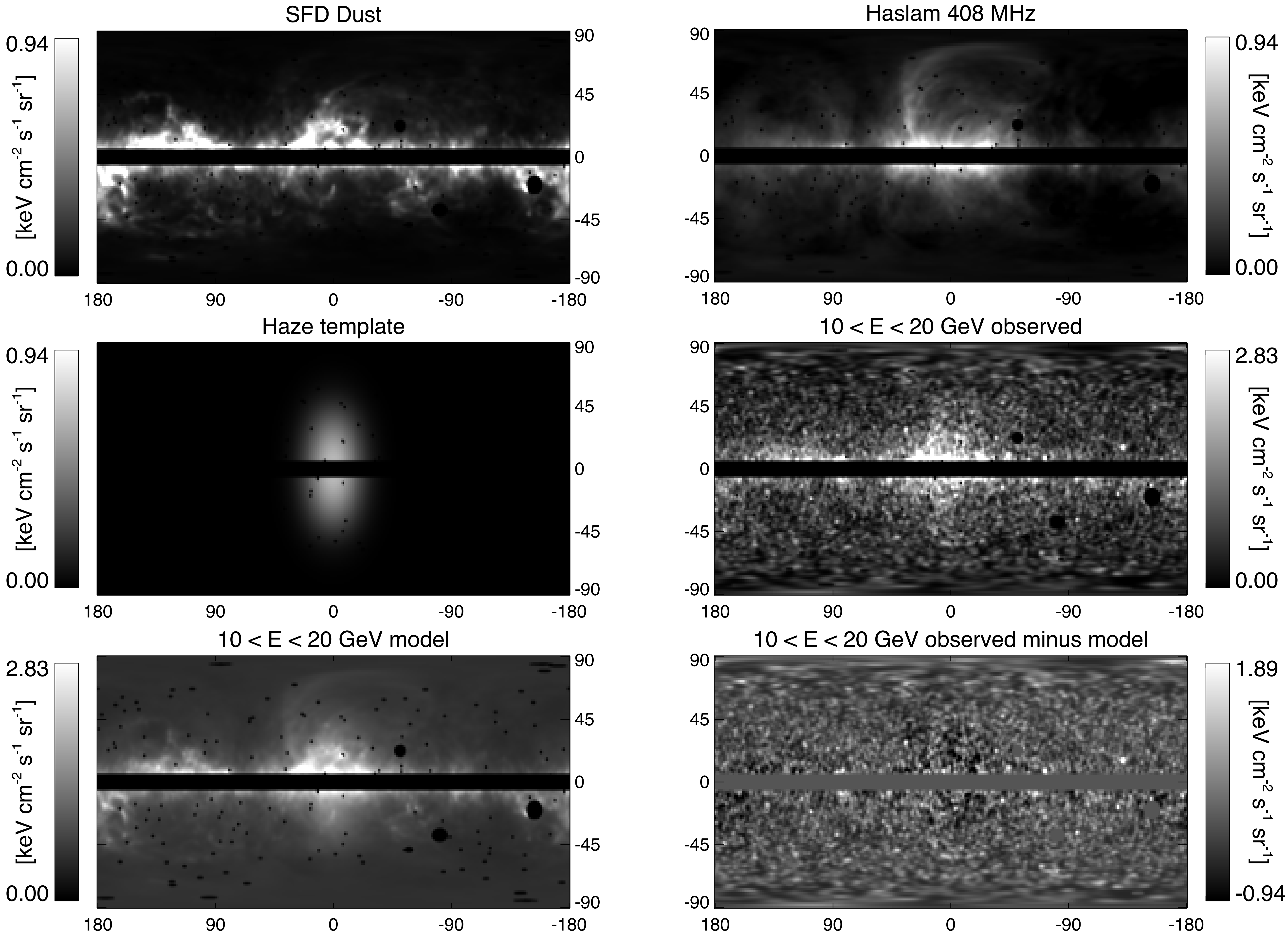
What is the Fermi (gamma-ray) bubbles/Fermi haze?

Since 2004 Finkbeiner has proposed the WMAP (microwave) haze, which suggests the existence of a population of electrons with a spectrum harder than the SNe accelerated electrons, of roughly spherical shape and extending out to at lest 2kpc (~10 kpc considering Fermi data).

Such a population of hard electrons should also give an ICS signal as well which indeed we found. The Fermi haze could be the gamma-ray counterpart of the microwave haze...

We need to model the background.Background gammas come from:
decaying pi0s (and other mesons) produced at inelastic pp collisions,
bremsstrahlung from the softer (SNe) electrons,
Inverse Compton scattering (ICS) i.e. up-scattering of CMB, IR and starlight photons from CR electrons to gamma-ray energies,
point sources and isotropic gammas (ExtraGalactic Background and CRs that mimic gammas in the detector)
For all these we use all-sky templates

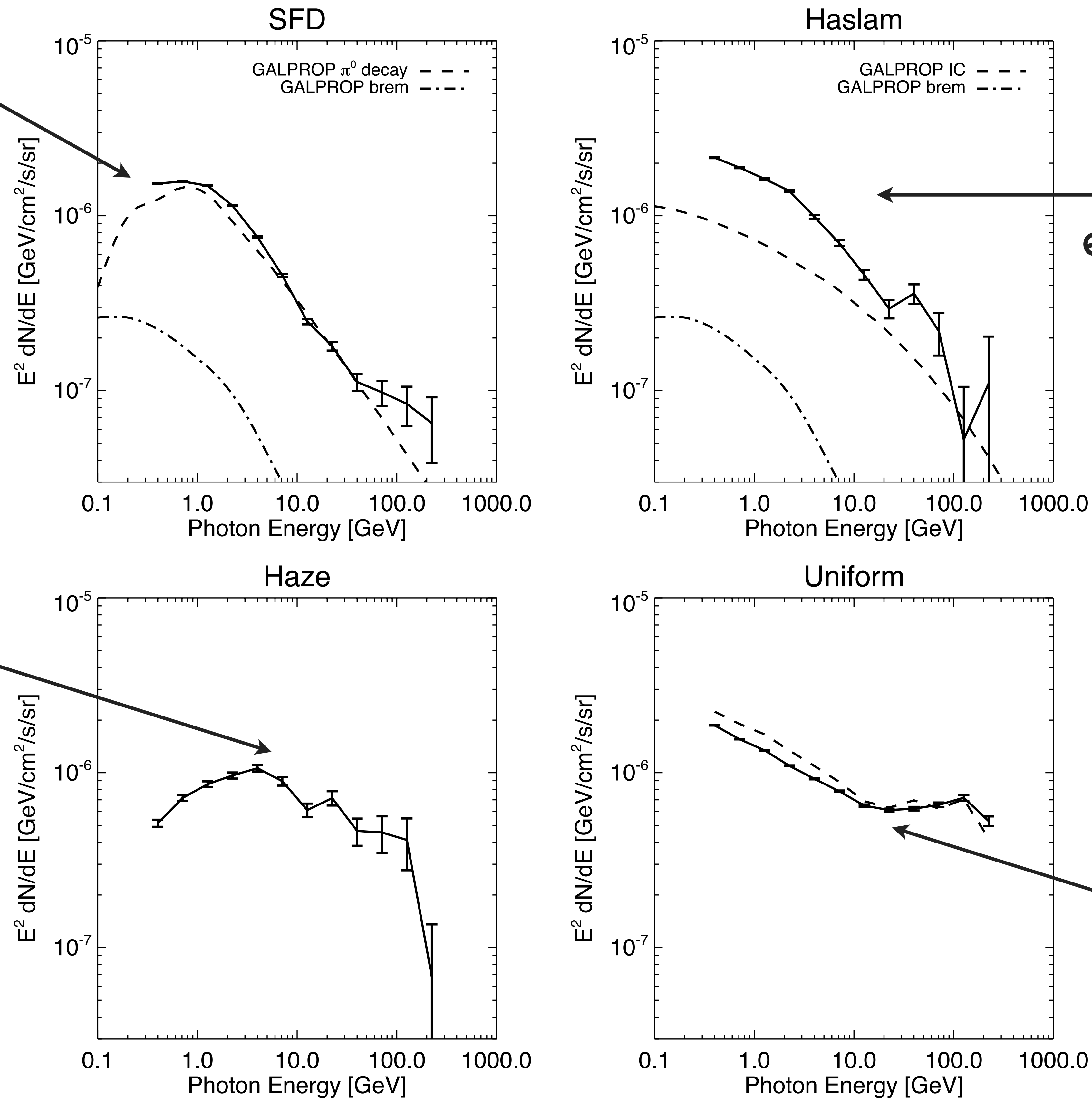
The first Fermi haze template Dobler et al. ApJ 717,825,(2010)



Spectra

Good agreement with the expected pi0+bremss

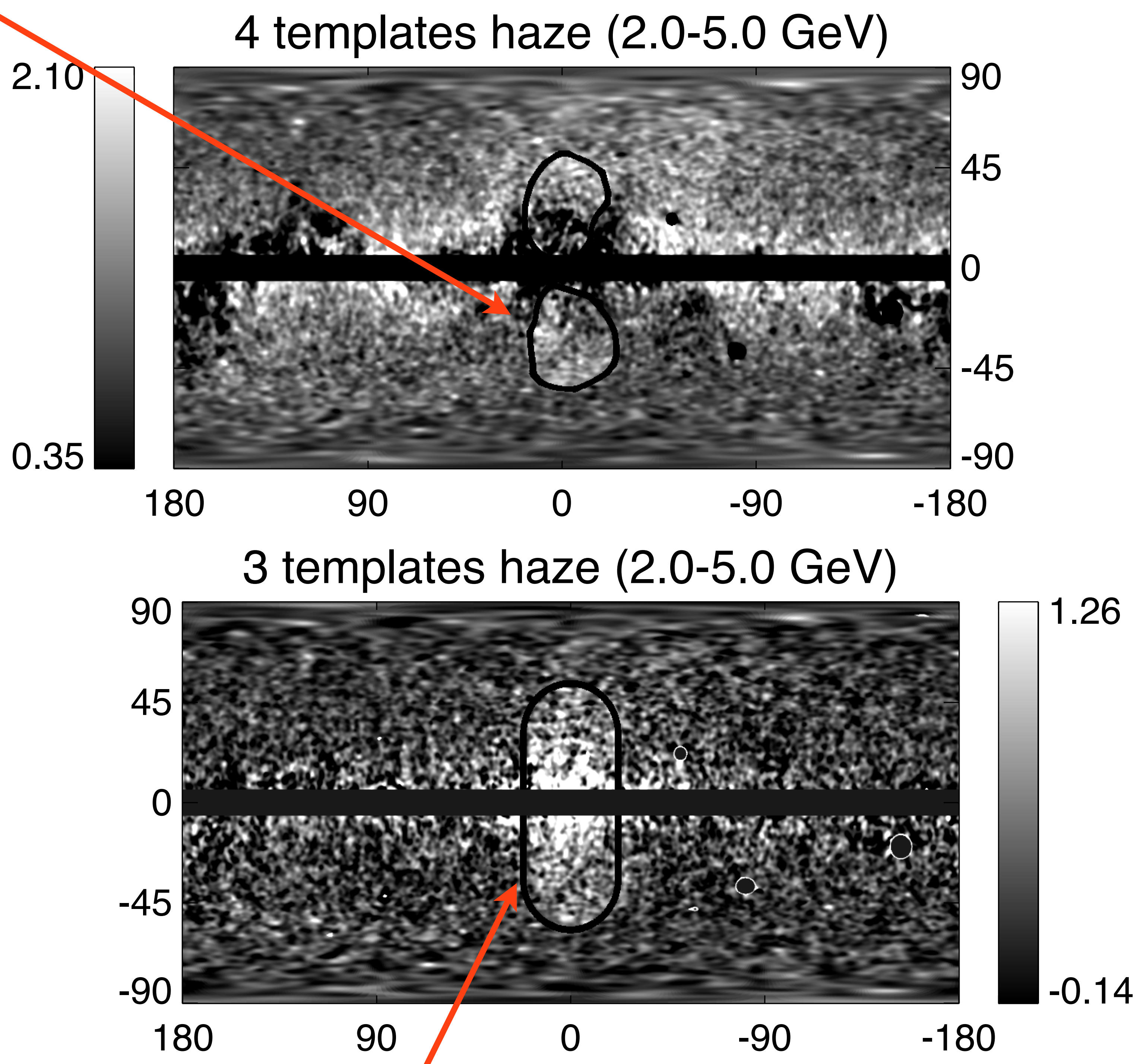
Better at high energies, this template has been varied



Excess: Harder spectrum than typical galactic

Slightly harder than known EGBR (includes CRs)

Fermi Bubbles (Su, Slatyer, Finkbeiner) (SFD+disk+uniform+bubbles)
ApJ 724,1044 (2010)



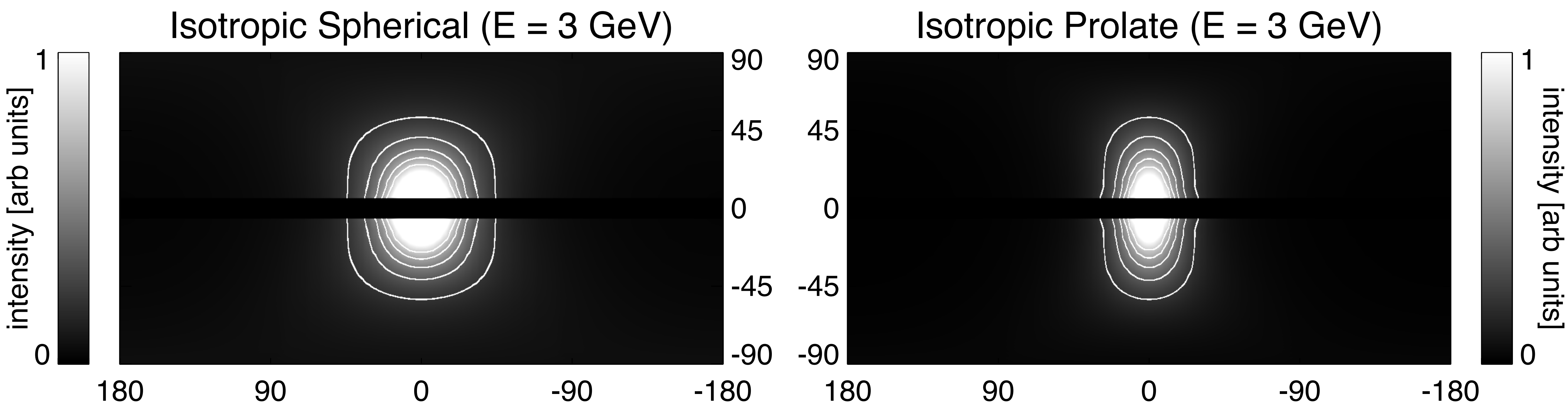
(Updated) Fermi haze (G. Dobler, IC, N.Weiner) ApJ 741,25 (2011)

We used the gamma-ray map from Fermi between 0.5-1 GeV as our background galactic template+uniform + haze(modeled by GALPROP Dark Matter IC signal)

Case of Dark Matter

The DM smooth halo has an approximately Spherical distribution, a possible candidate.

DM can explain the haze signal (WMAP + Fermi) based on solely energetic/spectral arguments, for cases where DM annihilates predominantly to leptons at an enhanced rate.

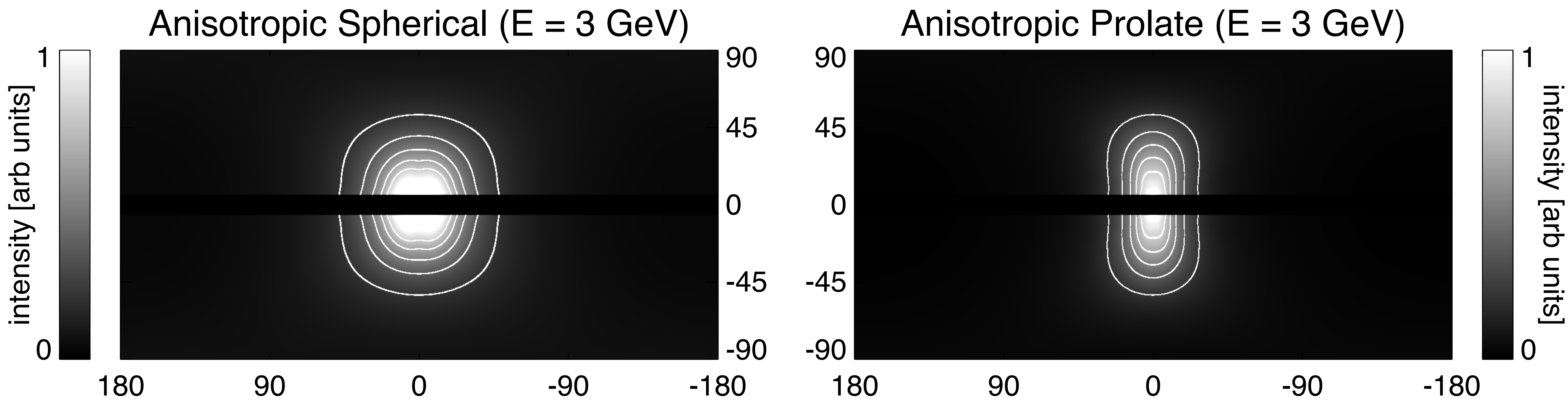


Too spherical

Better but still the emission is too peaked towards the center

Models that annihilate to a significant BR to taus or have large BRs to hadrons can not explain the angular morphology of the signal.

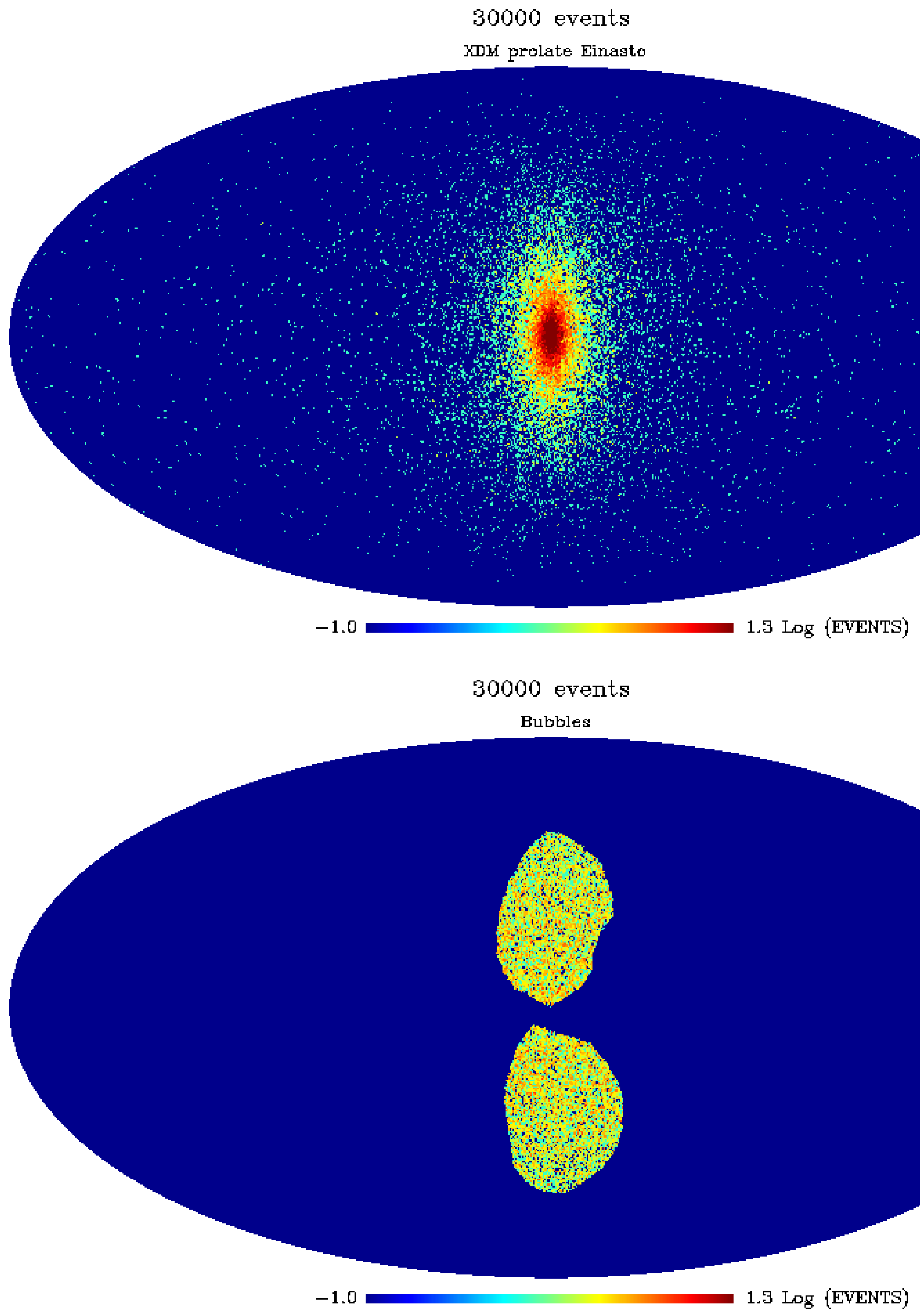
Thus one can get:



So with annihilating DM and specific assumptions on anisotropic and in-homogeneous diffusion we CAN fit the Fermi haze morphology spectrum and amplitude (ApJ 741,25 (2011))

Other explanations include: strong AGN activity may be in order(Guo & Mathews arXiv:1103.0055), strong Galactic wind (Crocker&Aharonian PRL 106:101102,2011), 2nd order Fermi acc. (Mertsch&Sarkar arXiv: 1104.3585 (PRL)).

We can use TeV neutrinos to separate the DM from the galactic wind scenarios.



KM3NeT?

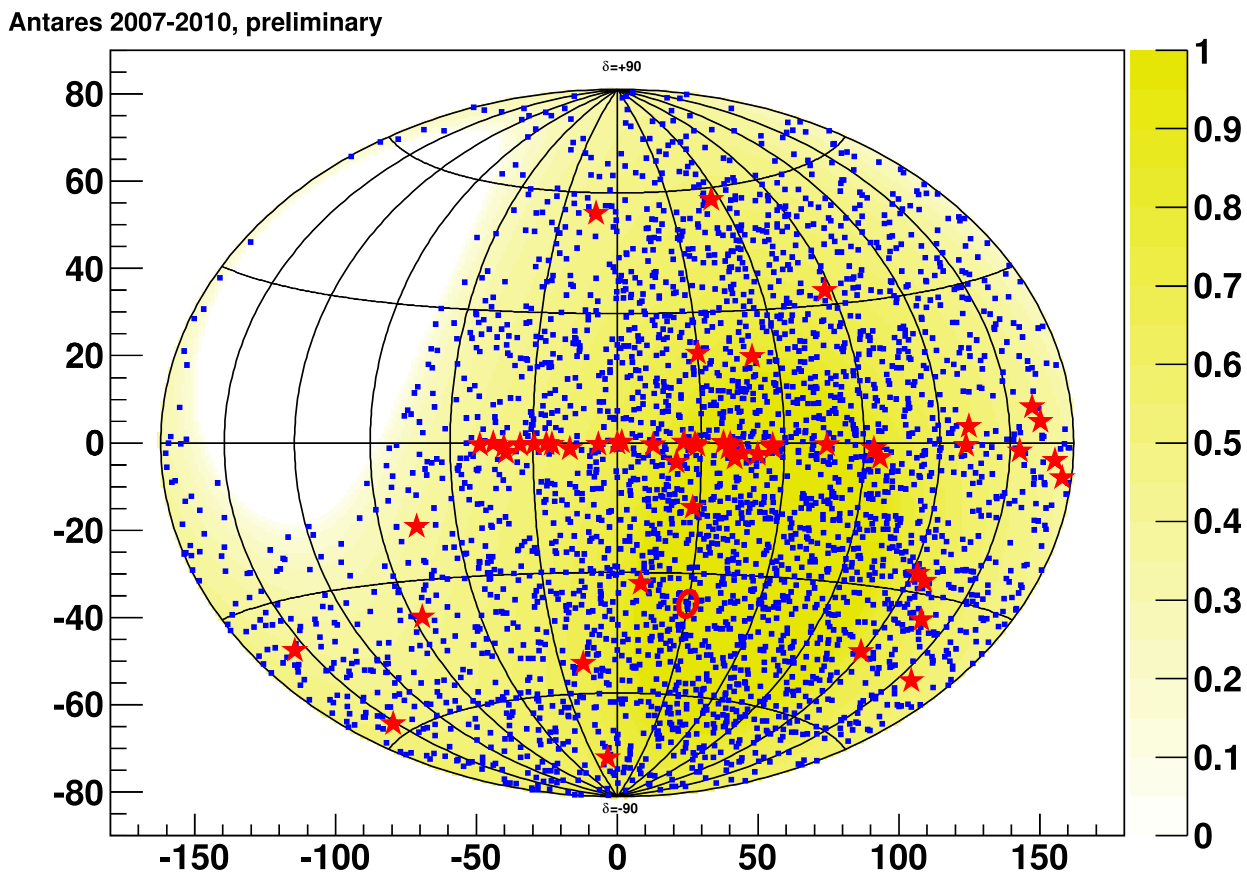
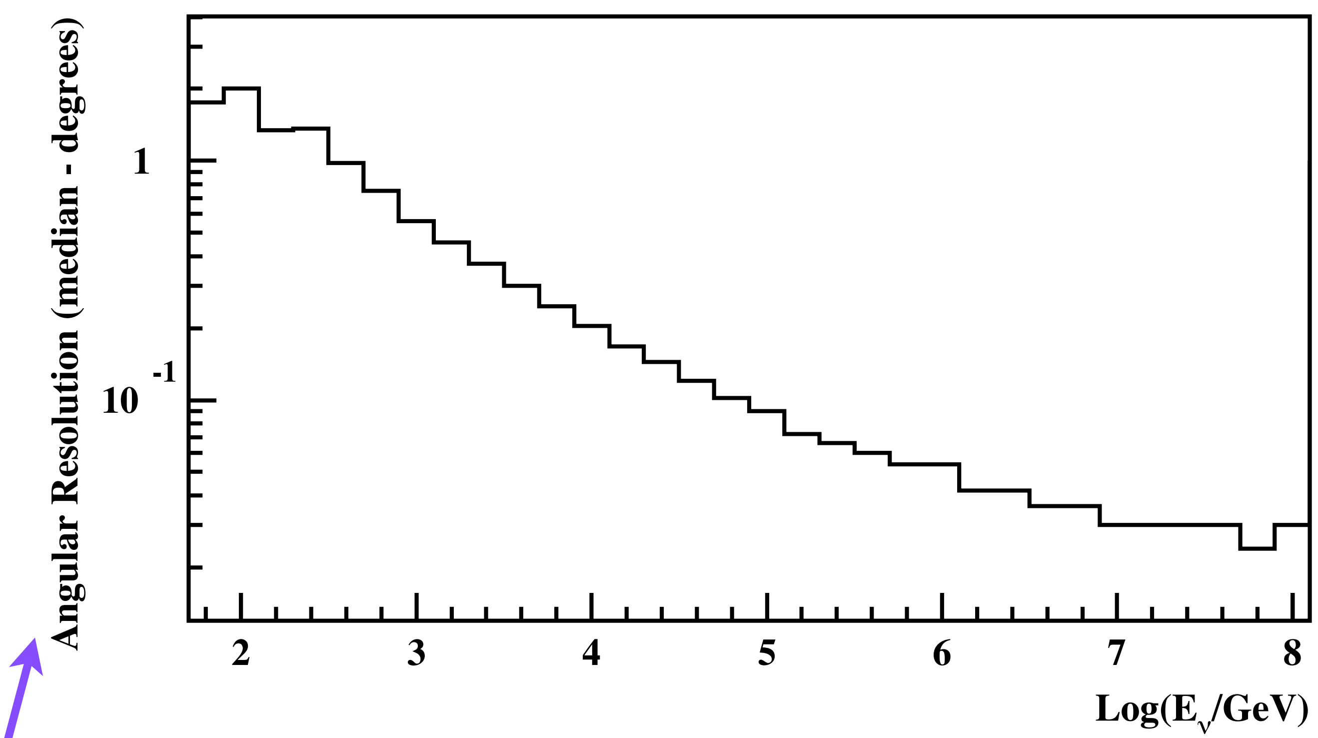
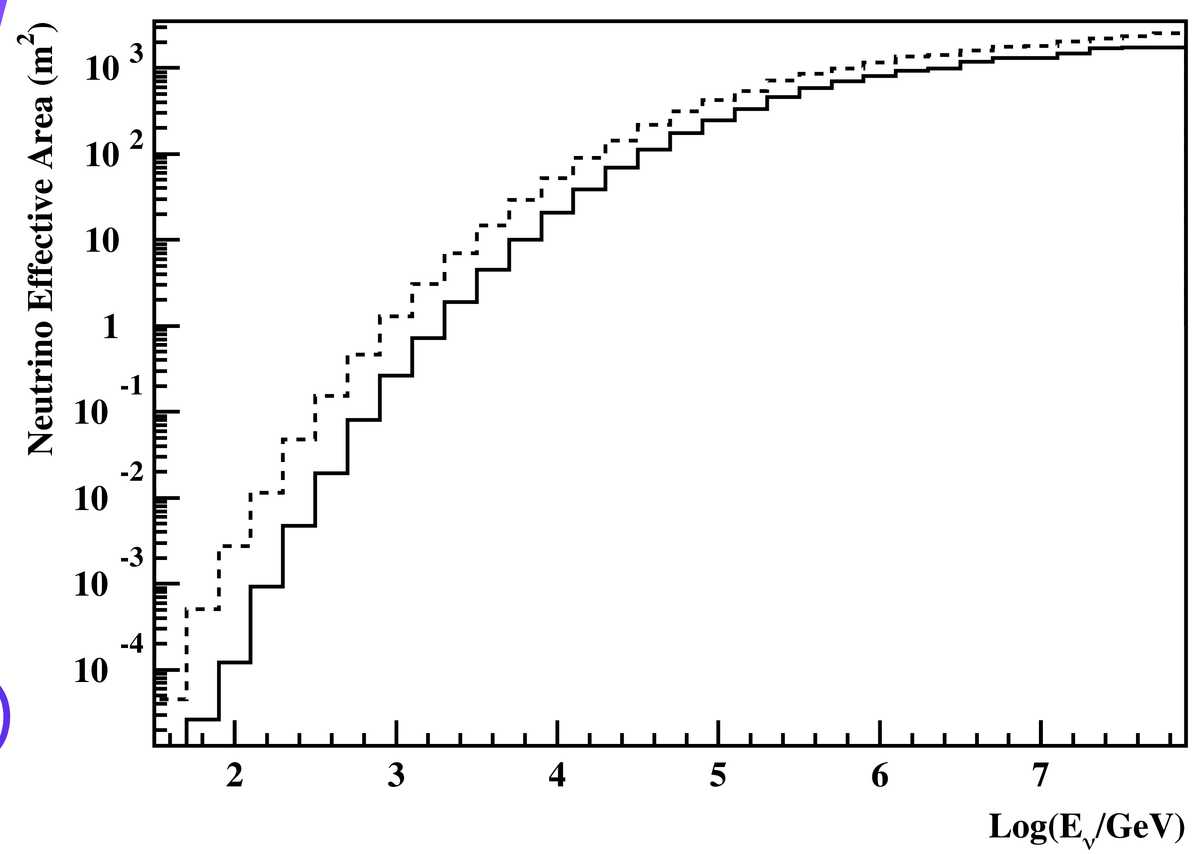


Fig. 5: Galactic skymap showing the 3058 data events. The position of the most signal-like cluster is indicated by the circle. The stars denote the position of the 51 candidate sources.





From HOURS simulation (special thanks to A. Tsirigotis)

Fermi Bubbles, CR protons (hadronic case)

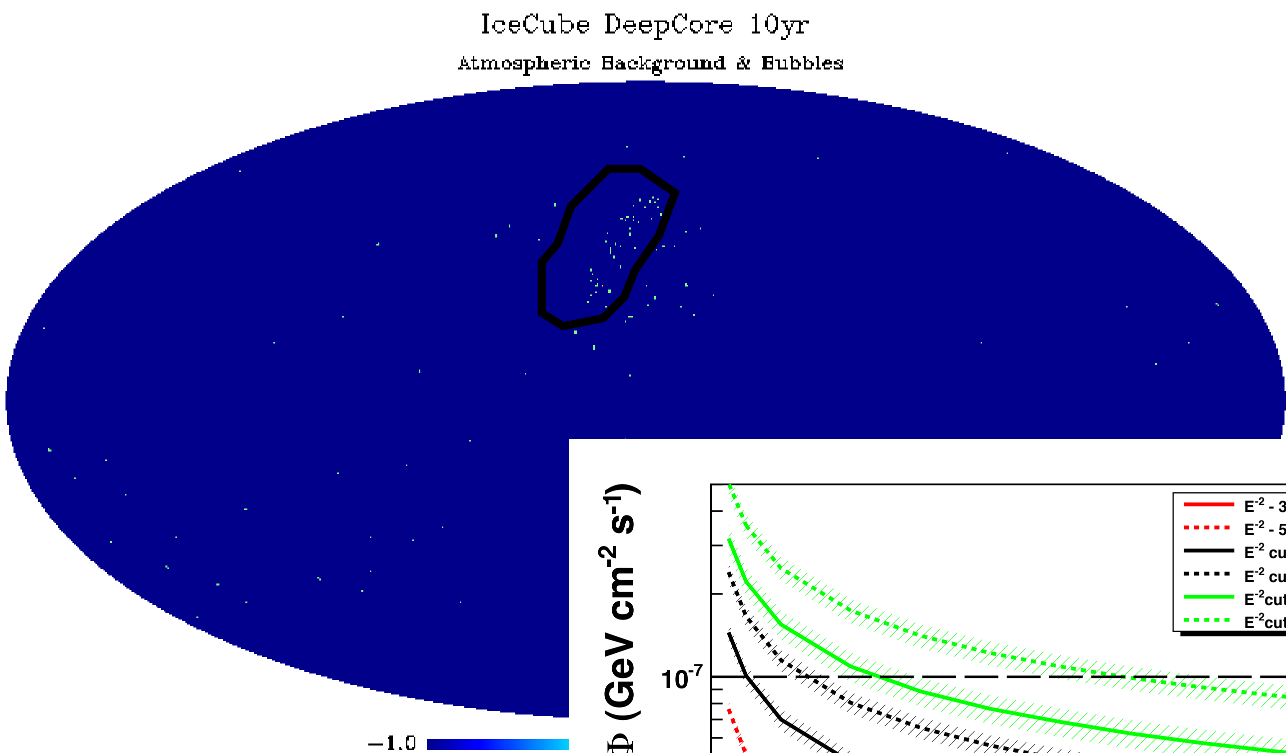
The CR protons responsible for the Bubbles that have a spectrum described by:

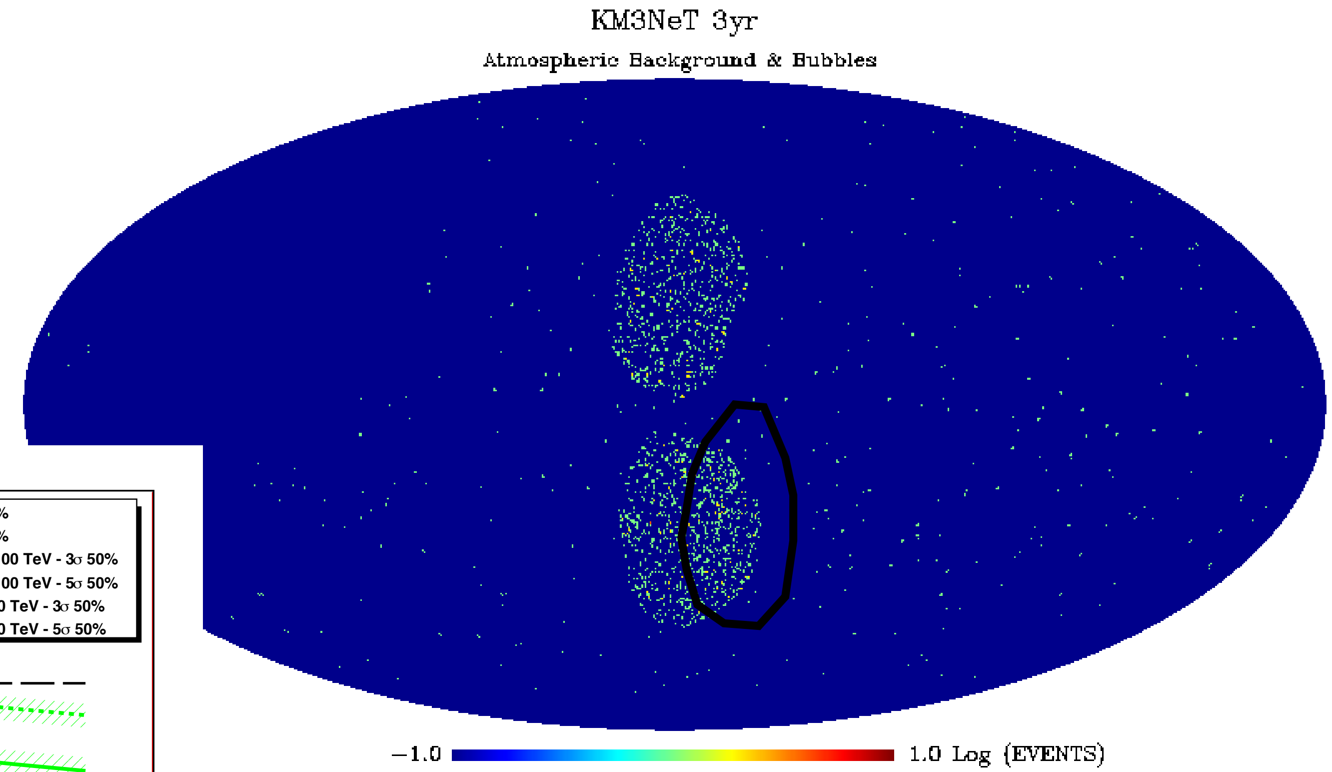
$$\frac{dN_p}{dE_p}dE = N_0 E_p^{-2.1} exp\left[-E_p/E_{p_0}\right]$$

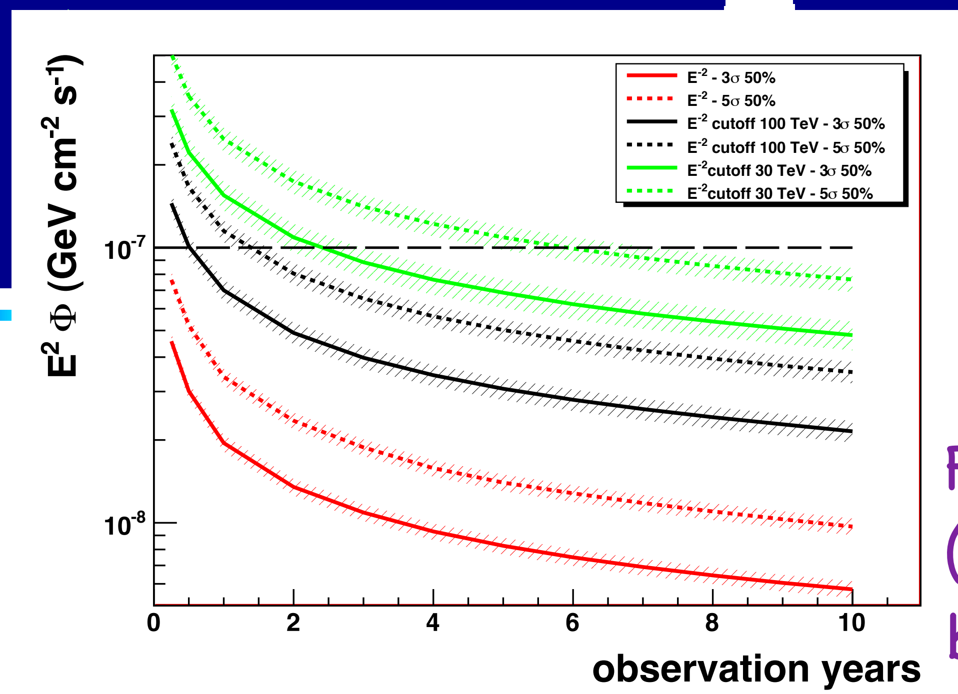
The neutrinos coming from the Bubbles will have the same morphology as the gamma-rays, which is relatively flat in longitude and latitude with clear edges. The total energy stored in the CR protons in the Bubbles is estimated to be ~ 10^56 erg due to an estimated averaged 10^39erg/s of injected power to hard CR protons transferred from the GC via galactic winds in the Fermi Bubbles regions. This process is estimated to have been ongoing for a timescale of multi Gyrs.

The power to neutrinos is ~10^38 erg/s.

The distance of the Bubbles to us is ~8-10 kpc.

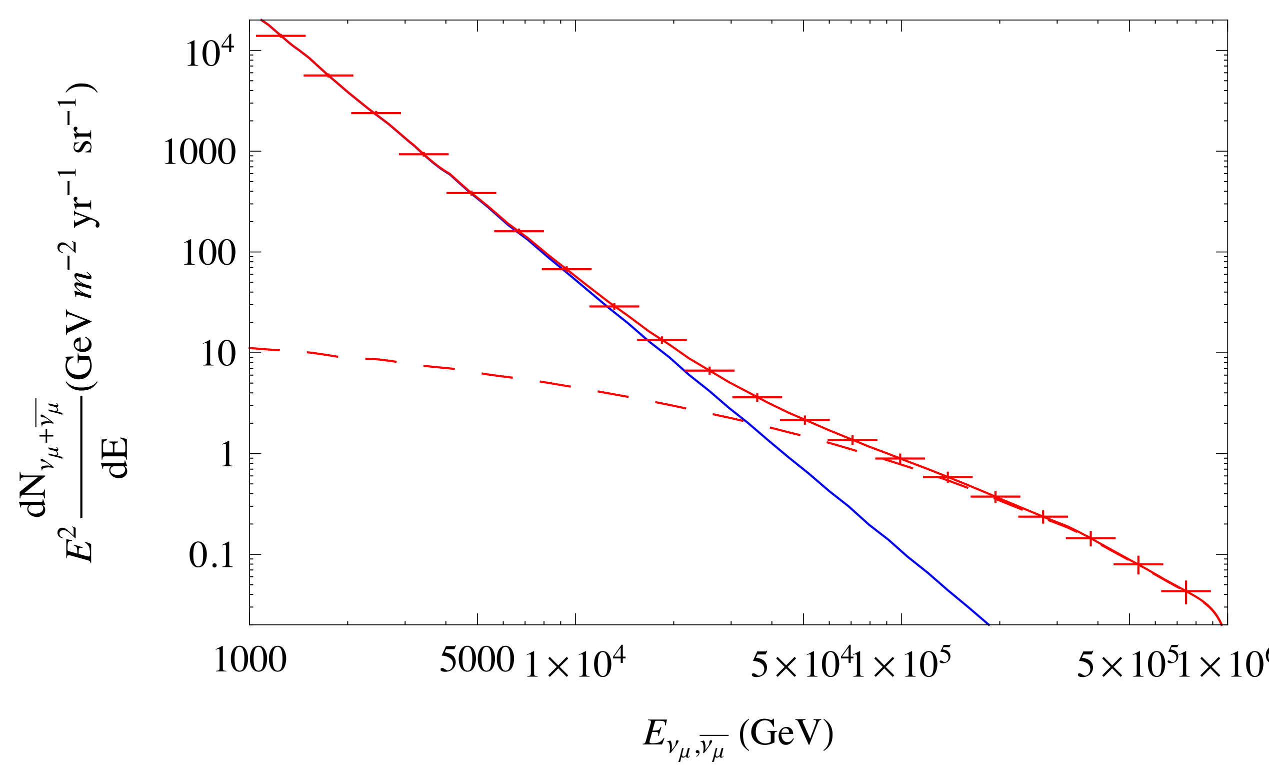






Full-sky simulated above 100TeV (2.7x10^3 DM events) 5x10^2 atm. backg. events

At few years IceCube should have an indication of the Fermi Bubbles for the hadronic scenario. KM3NeT can have a clear observation of the morphology and provide an alternative estimation of the Bubbles energy (for the hadronic case). Alternatively, lack of detection of the Bubbles at ~100 TeV neutrinos will exclude the galactic winds (hadronic)model for the Bubbles.

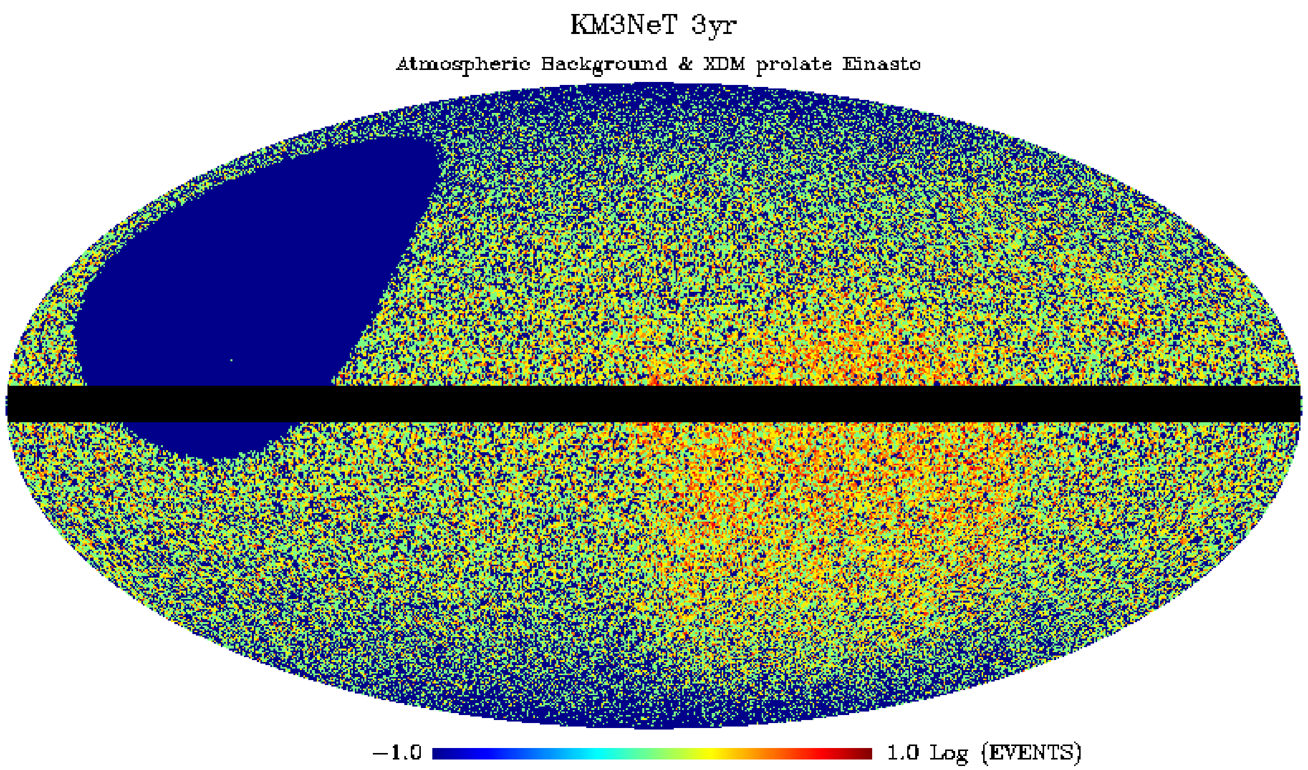


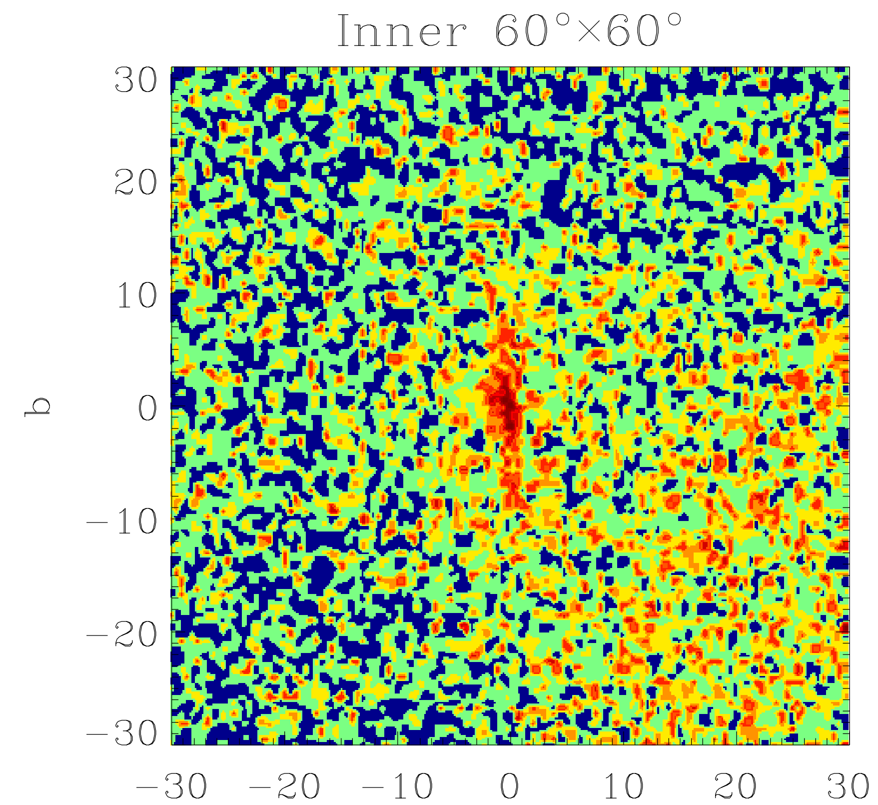
Dark Matter annihilation case

The DM annihilation in the halo contribution is:

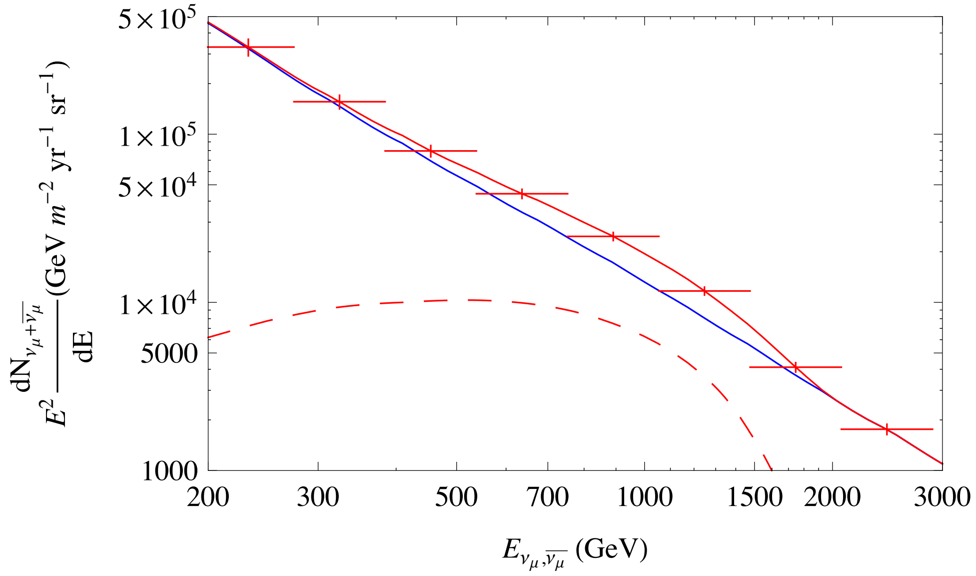
$$\frac{d\phi^0_{\nu^i}}{dE_{\nu^i}} = \int d\Omega \int_{l.o.s.} d\ell(\theta) \frac{\rho^2_{DM} \langle \sigma v \rangle (\ell, \theta)}{8\pi m_\chi^2} \frac{dN_{\nu^i}}{dE_{\nu^i}}$$

The atmospheric background flux is isotropic after averaging for the many different directions of the neutrino telescopes axis within long timescales. While the morphology of the DM signal is much different than that of the atmospheric background, one can expect to see a signal increase of events towards the GC.





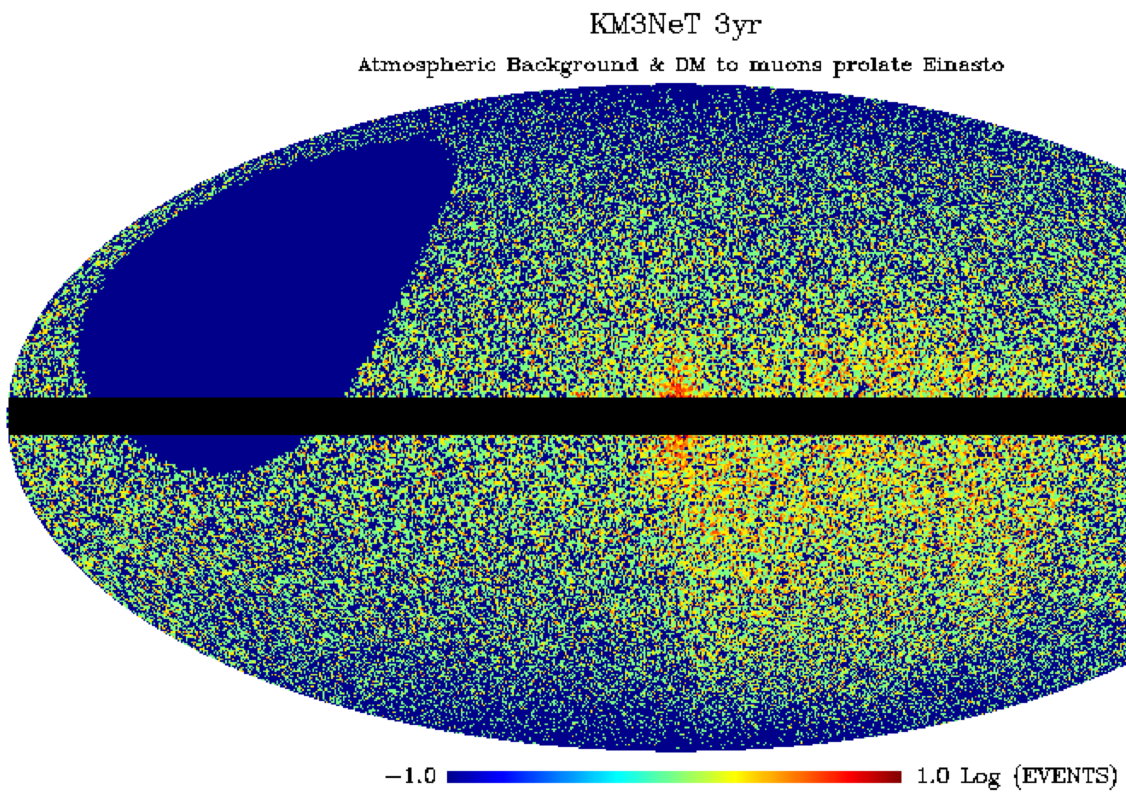
Full-sky simulated between 0.4 TeV and 2.2 TeV (2.4x10^3 DM events)
2.1x10^5 atm. background events

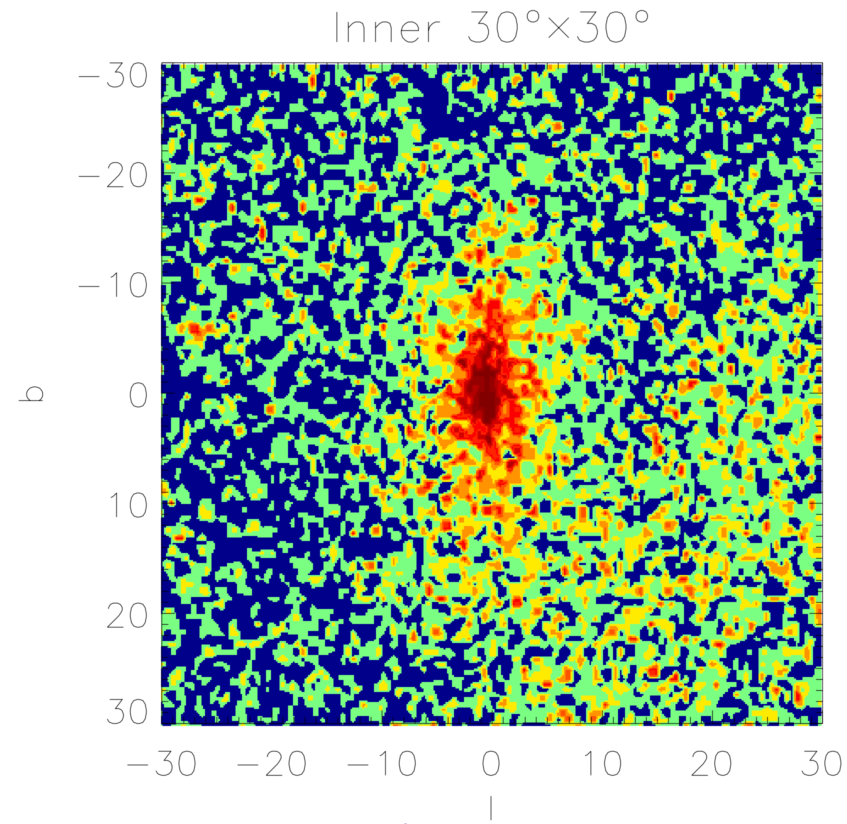


A gradual hardening of the total events spectra decreasing from high galactic latitudes towards the galactic disk (excluding the disk), will be an indication of a signal from DM annihilation in the main halo.

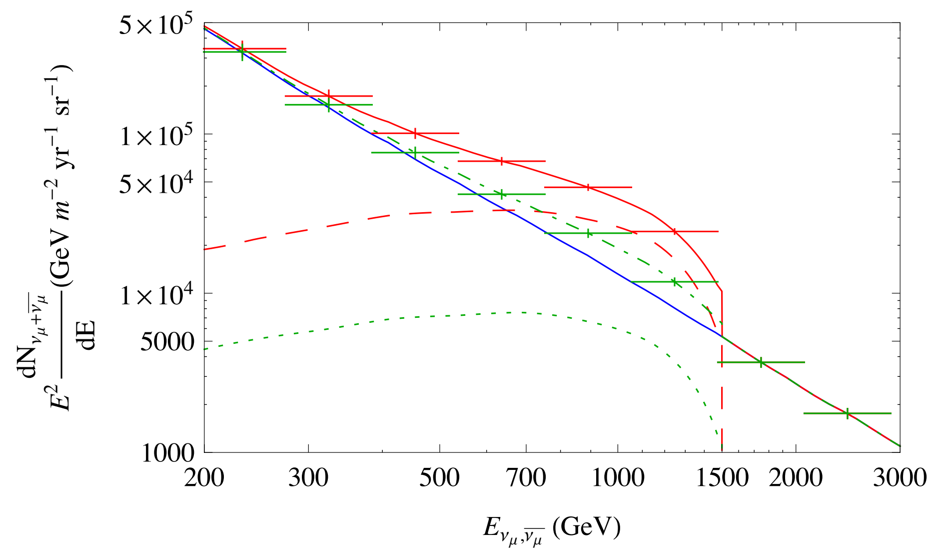
The IceCube DeepCore the sensitivity towards the GC is still too low and the angular resolution, too large (>5 degrees) to provide a robust signal for that DM model.

A more optimistic case for neutrino signal by DM annih.:





Full-sky simulated between 0.5 TeV and 1.5 TeV (6.5x10^3 DM events)
1.4x10^5 atm. background events



Current limits (from dwarf spheroidal galaxies at gamma-ray data)on the muon channel can not exclude such a signal.
Neutrinos can provide an alternative search channel for DM annihilating to muons with an enhanced cross-section.

Conclusions

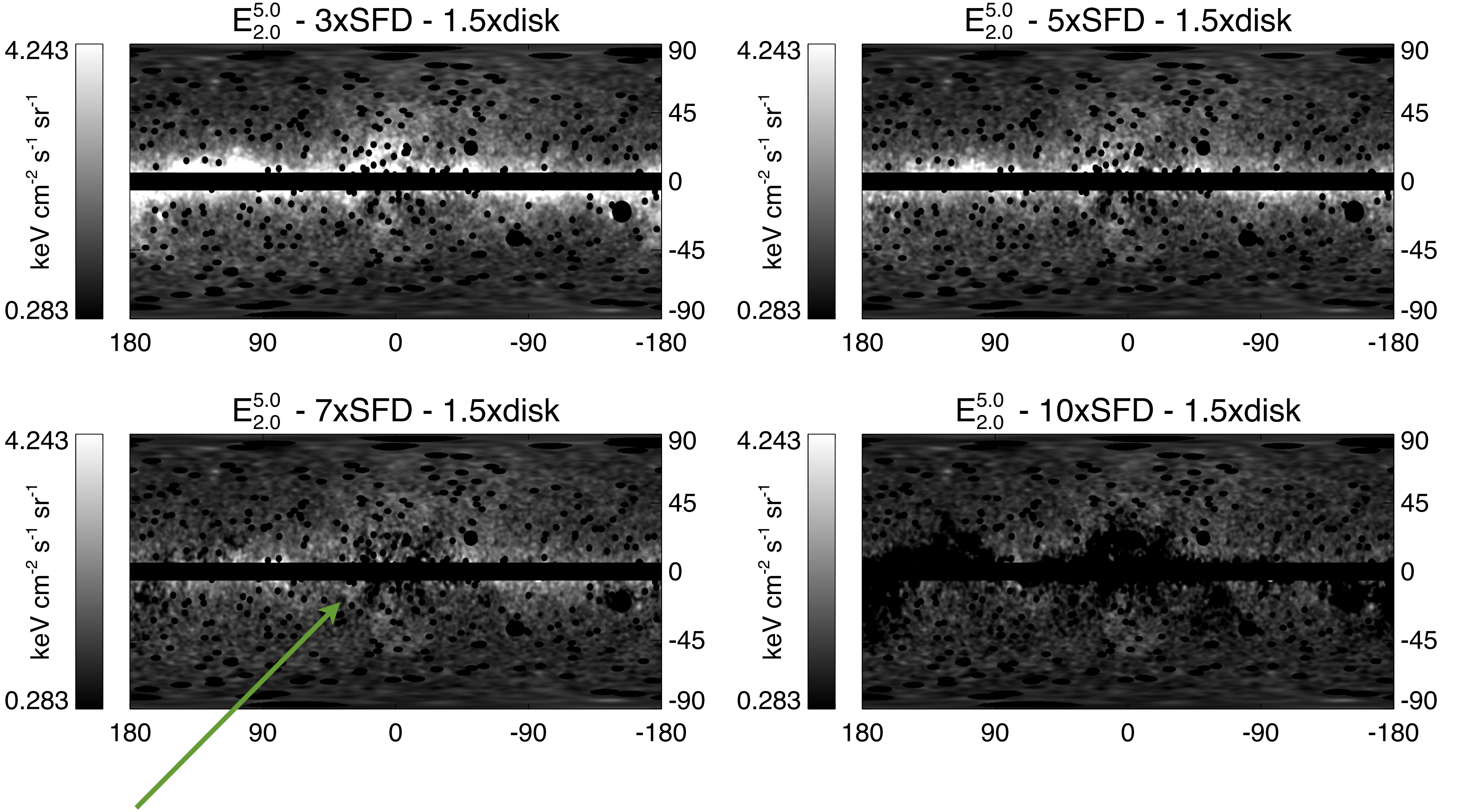
- With the observation of two showers with energies at ~1 PeV at IceCube, we may be witnessing the first light in the field of high-energy neutrino astronomy.
- Photo-meson interactions of ~10-100 PeV protons to be the most promising possibility. Could be realized by a variety of astrophysical sources: GRBs, AGNs and starburst galaxies.
- GRBs can naturally explain the two observed events. A neutrino flux comparable to that implied by the IceCube events is predicted for a wide range of assumptions regarding the redshift distribution, luminosity function, and other physical characteristics.
- AGN models peak at much lower energies. Neutrino spectra are predicted which peak at energies well above those of PeV energies. Searching for even higher energy showers in IceCube data set may be capable of excluding some AGN models.

- The 2 fully contained shower events should be accompanied by tens of PeV muon tracks and partially contained showers.
- Need to further analyze the IceCude existing high energy data.
- IceCube can not observe any signal from DM annihilation at the TeV energies but could observe some ~100 TeV neutrino events towards the northern edge of the bubbles for the hadronic case (strong galactic winds).
- A KM3NeT-like experiment will be able to either exclude the hadronic scenario or confirm the bubbles morphology and measure the spectrum and injected energy.
- Leptonic DM annihilation can be probed by a KM3NeT like experiment at ~3 yrs of observations more efficiently than other indirect channels of search. Hadronic DM annihilation has been already better probed by CR observations.

Thank you

Additional slides

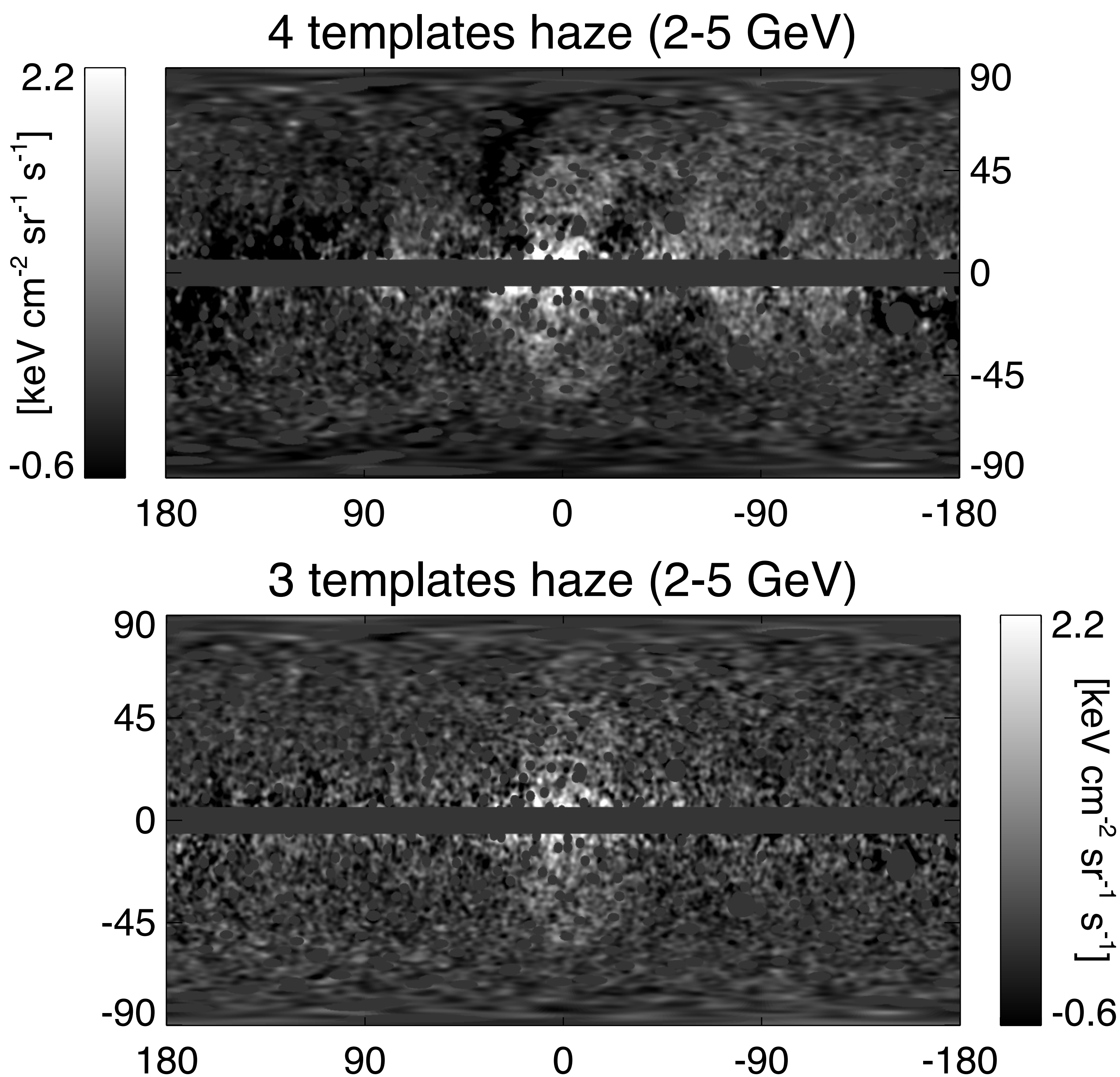
SFD template used as a pi0 tracer may be the root of difference



The X-shape could indicate an over-subtraction (of pi0 gamma-rays) in the SFD template scheme. The pi0 to dust column ratio is not always constant. At the high latitudes the signal is clear (some edge at high latitudes is confirmed with the latest data) BUT at lower latitudes the template selection is important.

Bubbles or haze?

One needs to be very careful for small (but significant when discussing the interpretation) caveats from templates.



The AMS-02 experiment on ISS

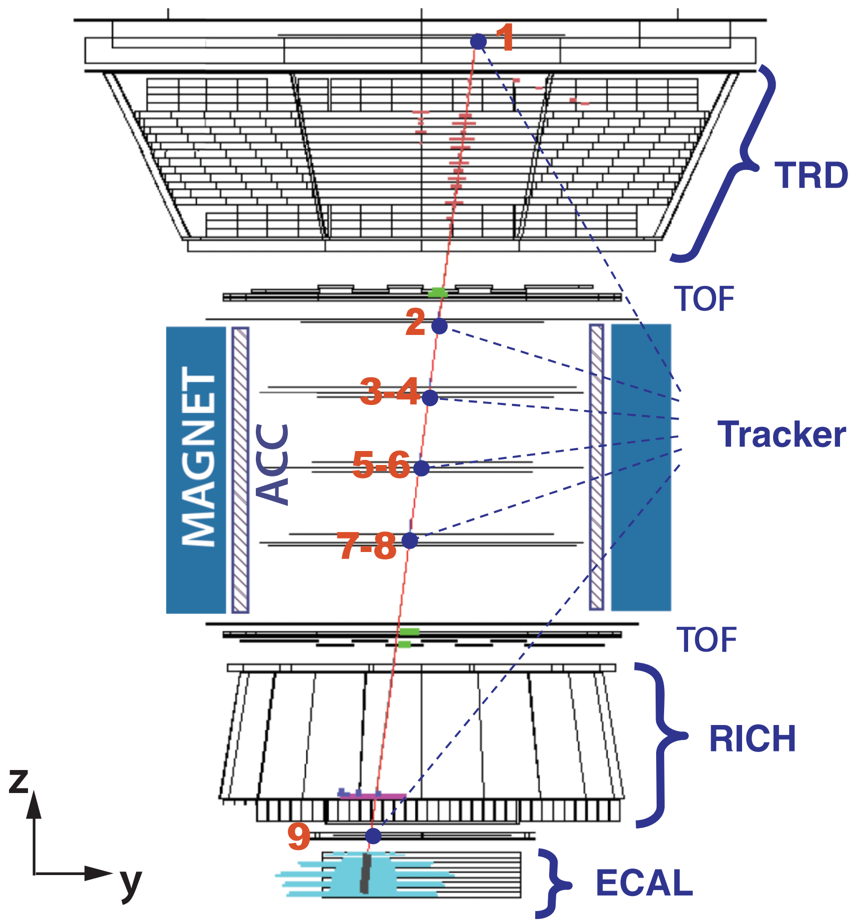
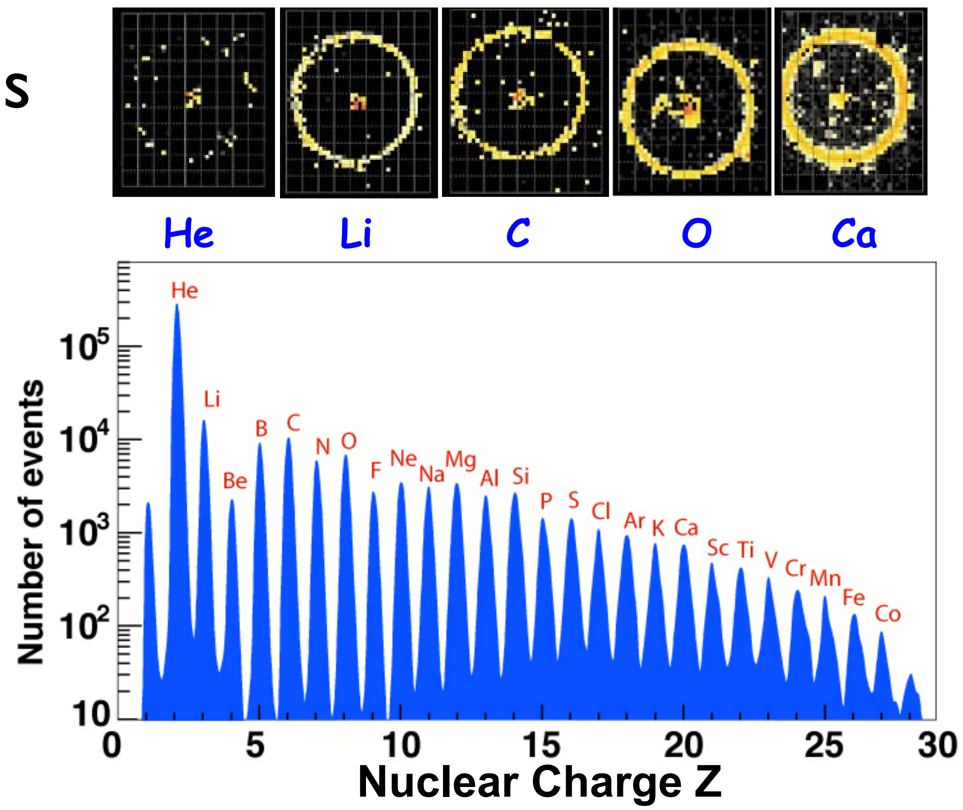
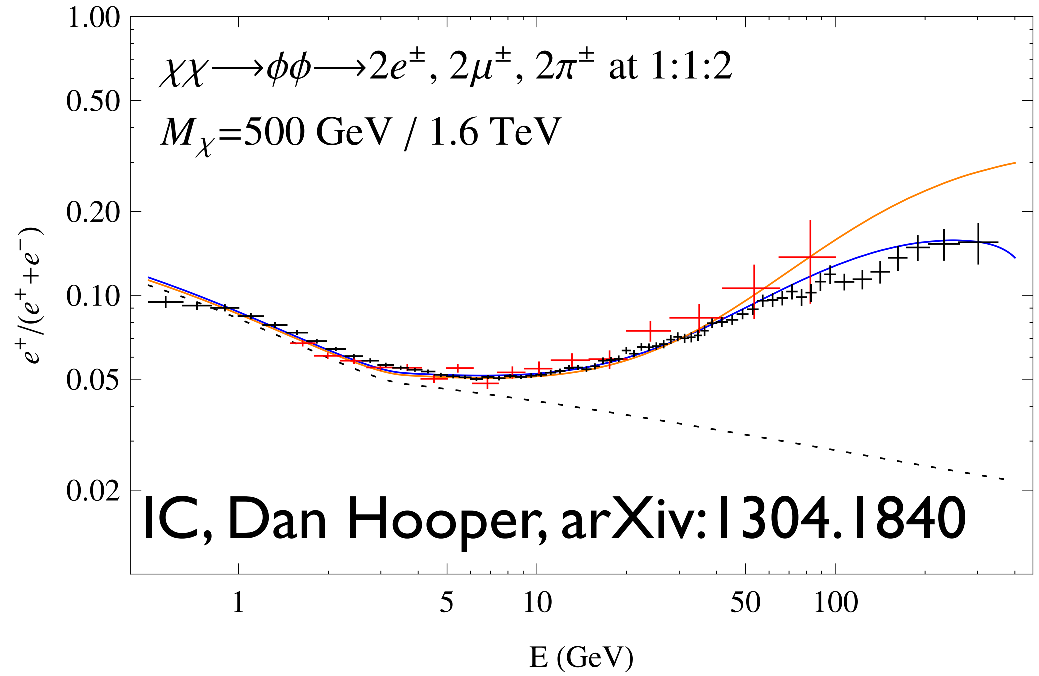


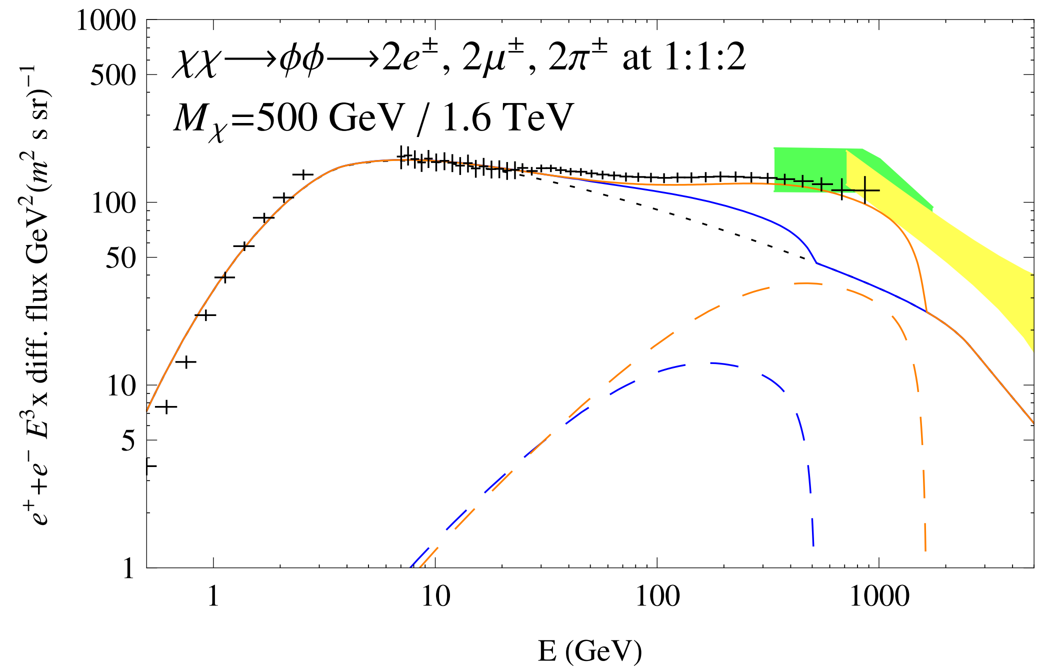
FIG. 1 (color). A 1.03 TeV electron event as measured by the AMS detector on the ISS in the bending (y-z) plane. Tracker planes 1–9 measure the particle charge and momentum. The TRD identifies the particle as an electron. The TOF measures the charge and ensures that the particle is downward-going. The RICH independently measures the charge and velocity. The ECAL measures the 3D shower profile, independently identifies the particle as an electron, and measures its energy. An electron is identified by (i) an electron signal in the TRD, (ii) an electron signal in the ECAL, and (iii) the matching of the ECAL shower energy and the momentum measured with the tracker and magnet.

Lunched on May 16th, will collect data for 20 yrs.
Will measure all CR nuclei species up to Ni.

positron fraction,
positrons,electrons spectra,
antiproton/proton
B/C, Be10/Be9

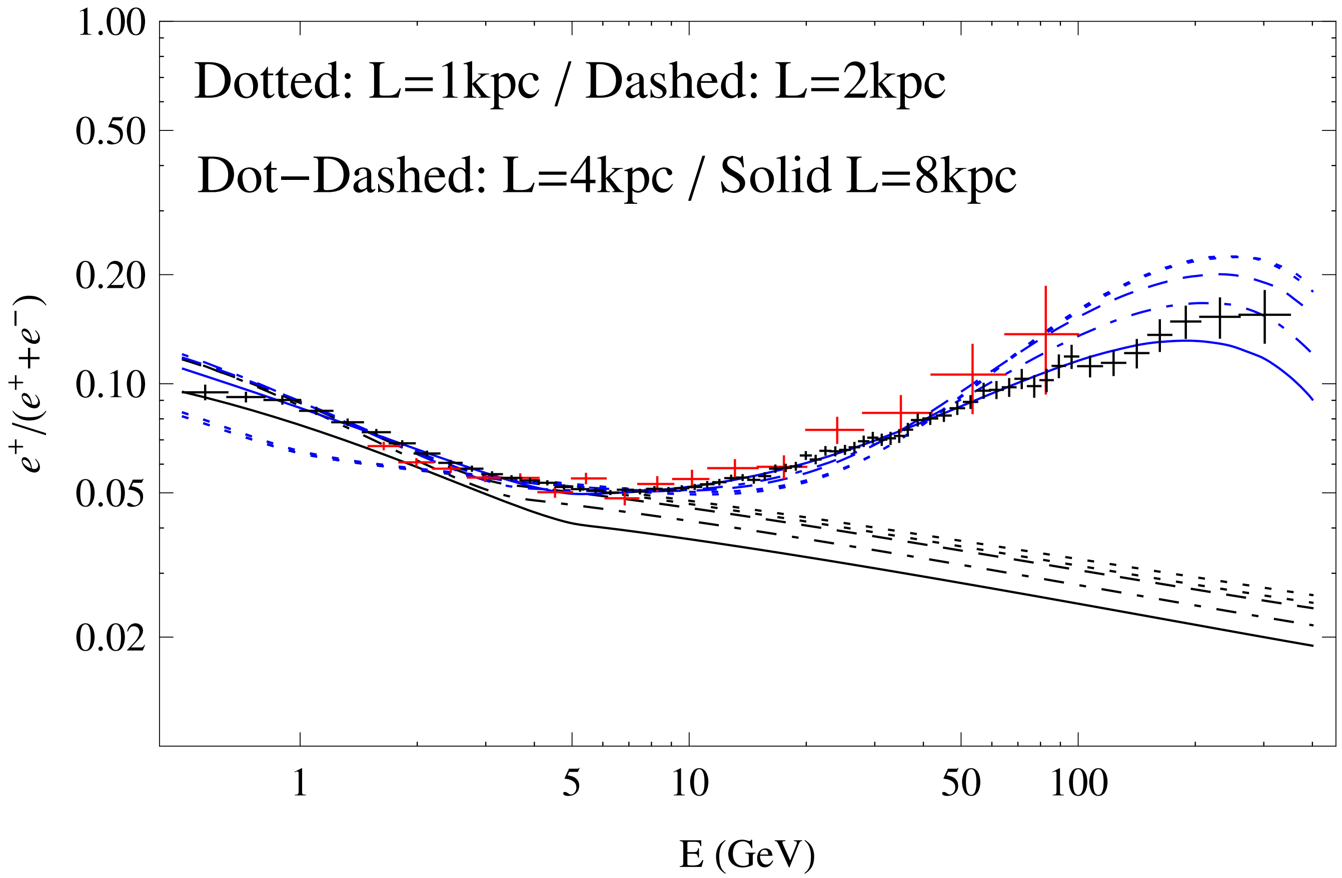






Softer annihilation spectra are preferred from the combined CR lepton spectra

Also thinner diffusion halos demand even softer annihilation spectra. Thicker diffusion halos are somewhat preferred in agreement with indications from gamma-rays.



Still some degeneracy between propagation properties and DM annihilation products. With AMS to release heavier nuclei CR spectra, these degeneracies will strongly we reduced.

Physical models that work with all data (leptons/ antiprotons/ gamma-rays/ microwaves)

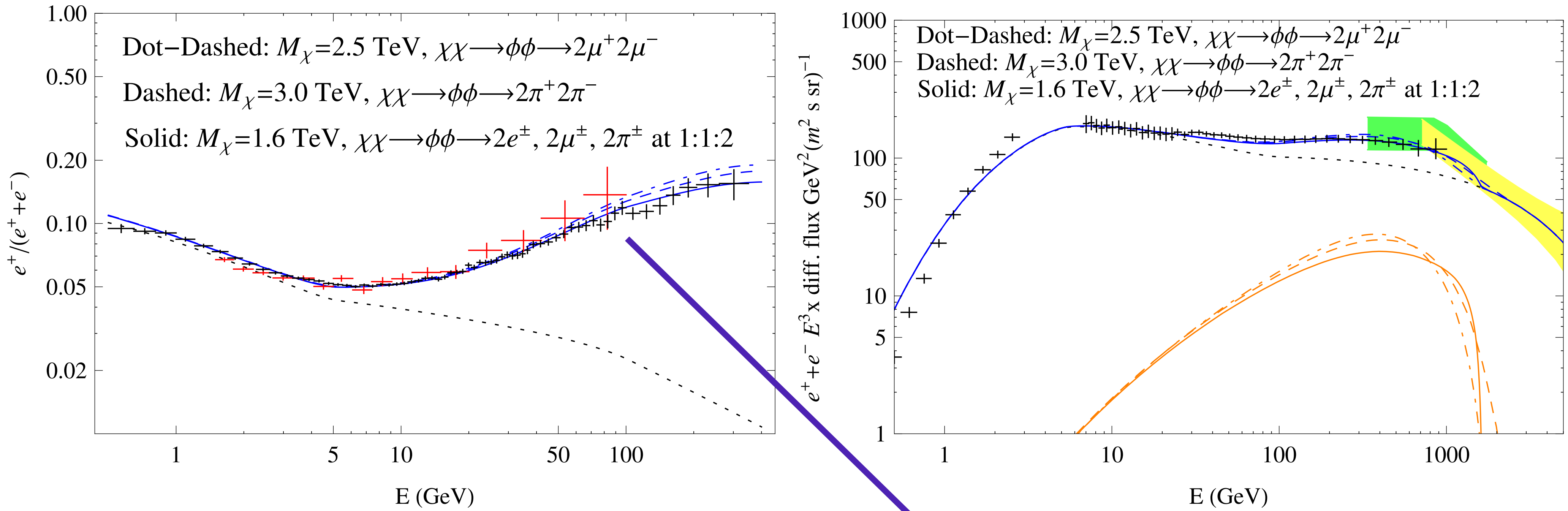
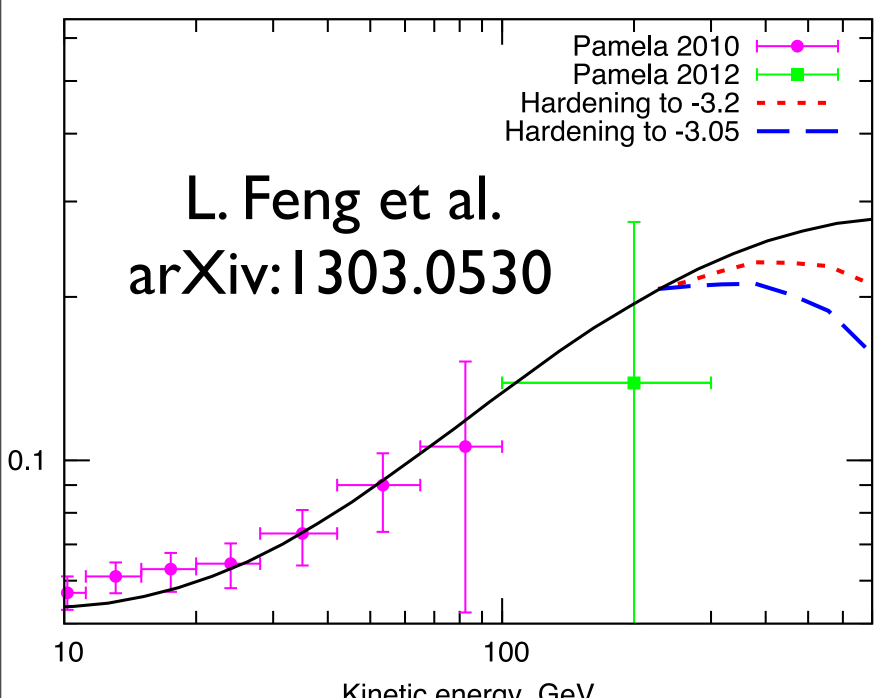
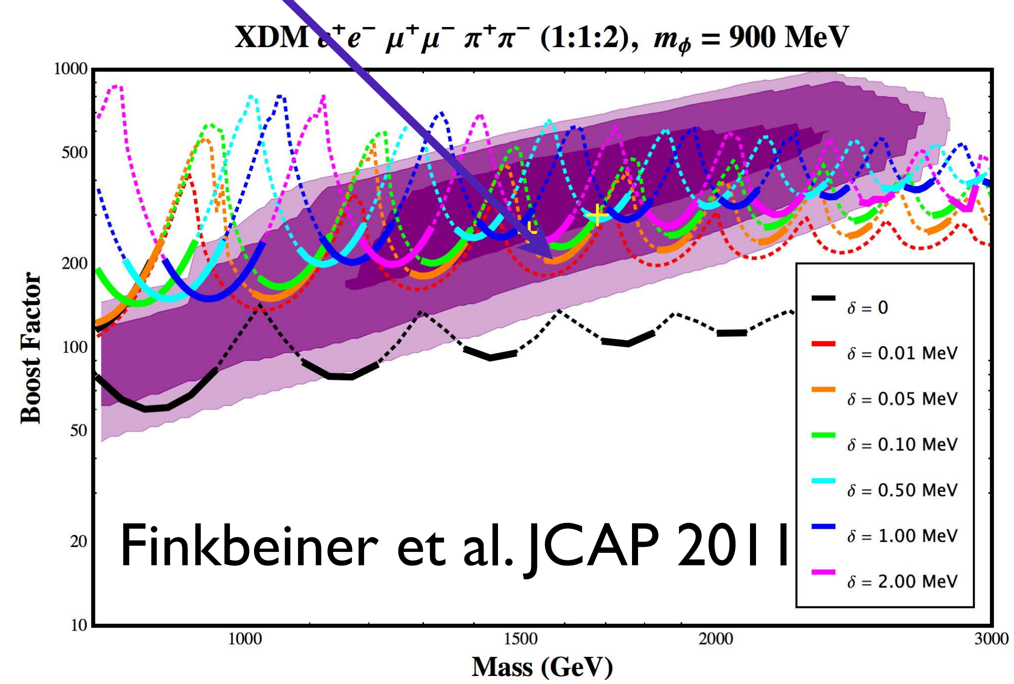


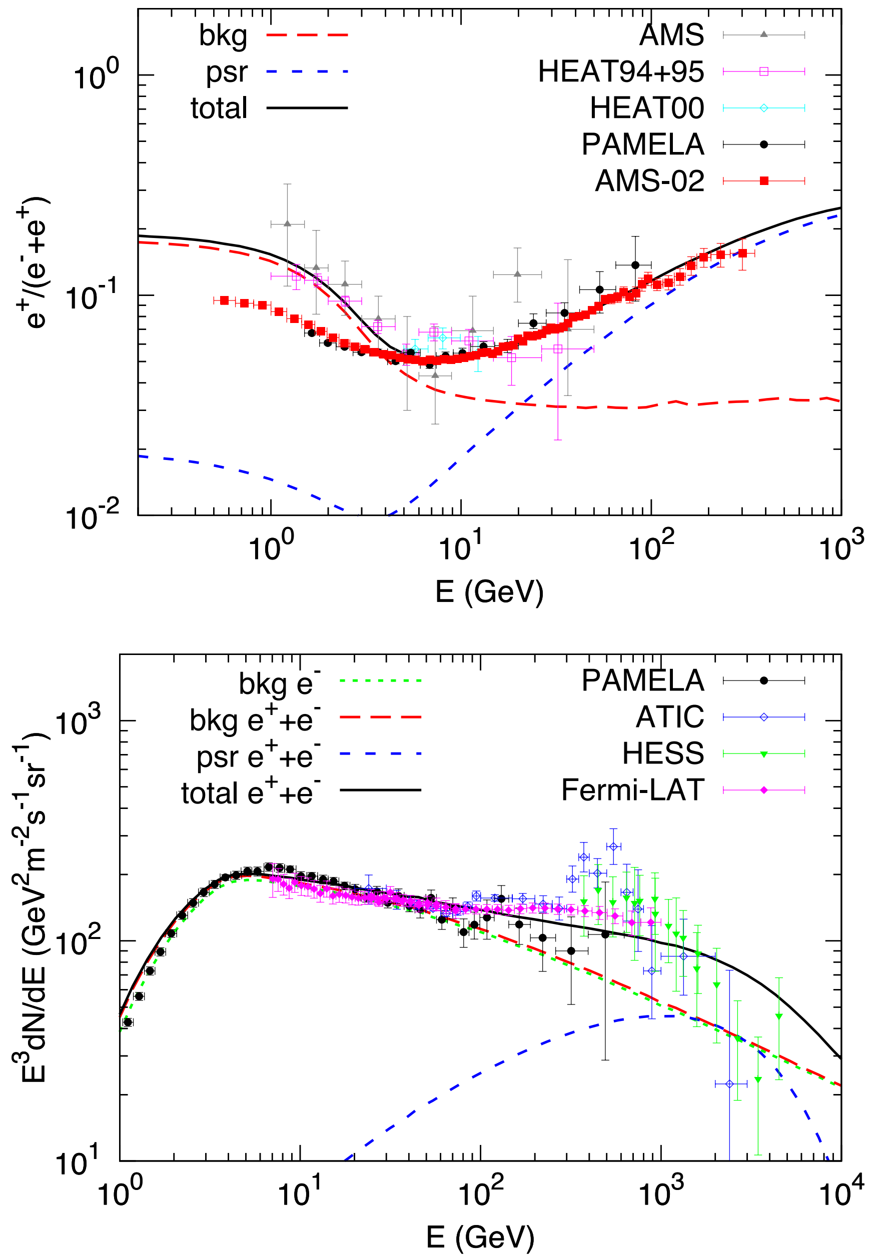
FIG. 6: The same as in Figs. 1, 2, 4 and 5 but for a diffusion zone half-width of $L = 8$ kpc, and for broken power-law spectrum of electrons injected from cosmic ray sources ($dN_{e^-}/dE_{e^-} \propto E_e^{-2.65}$ below 100 GeV and $dN_{e^-}/dE_{e^-} \propto E_e^{-2.3}$ above 100 GeV). The cross sections are the same as given in the caption of Fig. 5. With this cosmic ray background, the dark matter models shown can simultaneously accommodate the measurements of the cosmic ray positron fraction and the overall leptonic spectrum.



(See also Hooper, Zurek PRD 2009)

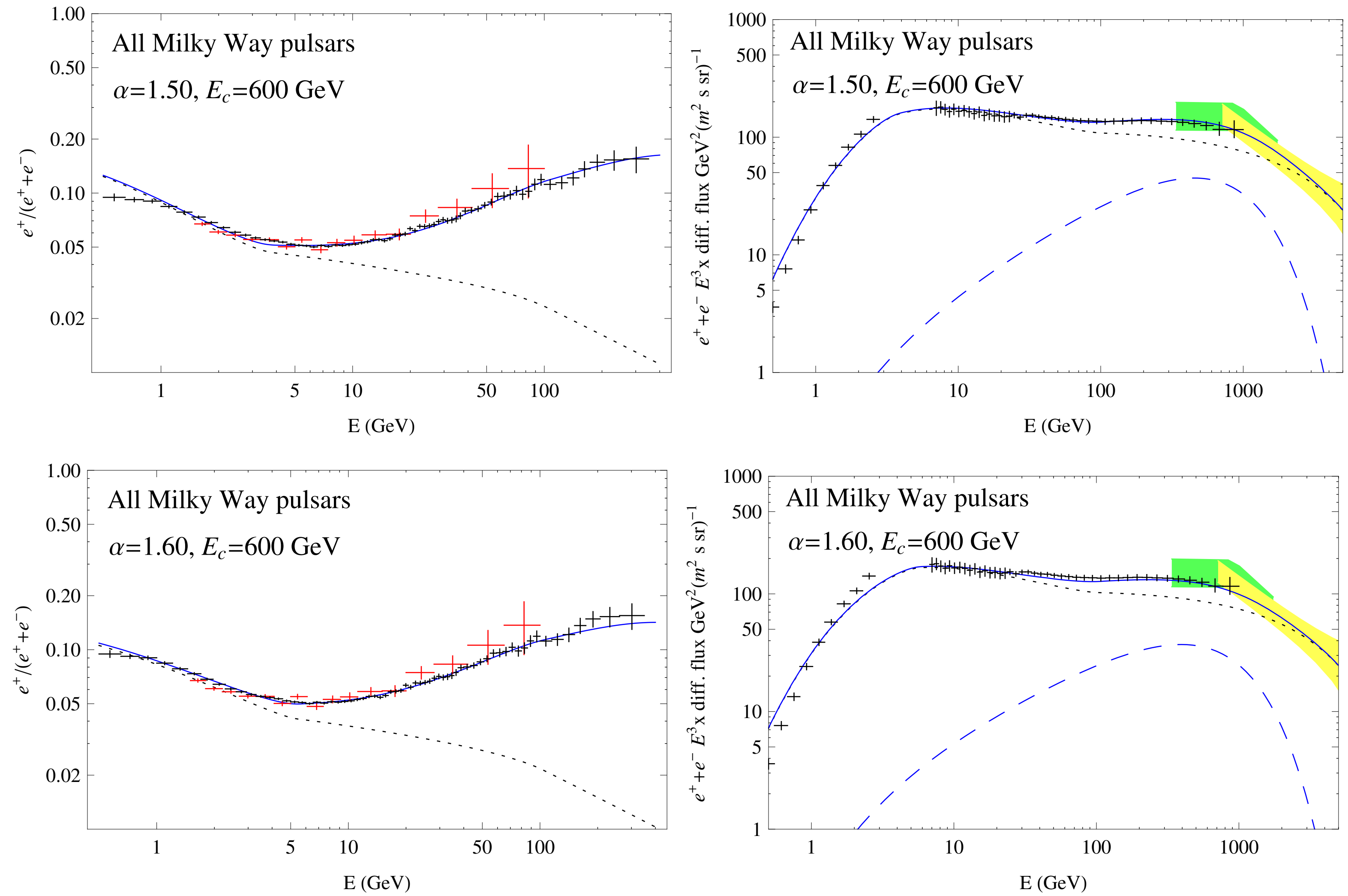


With AMS



Yuan et al arXiv:1304.1482

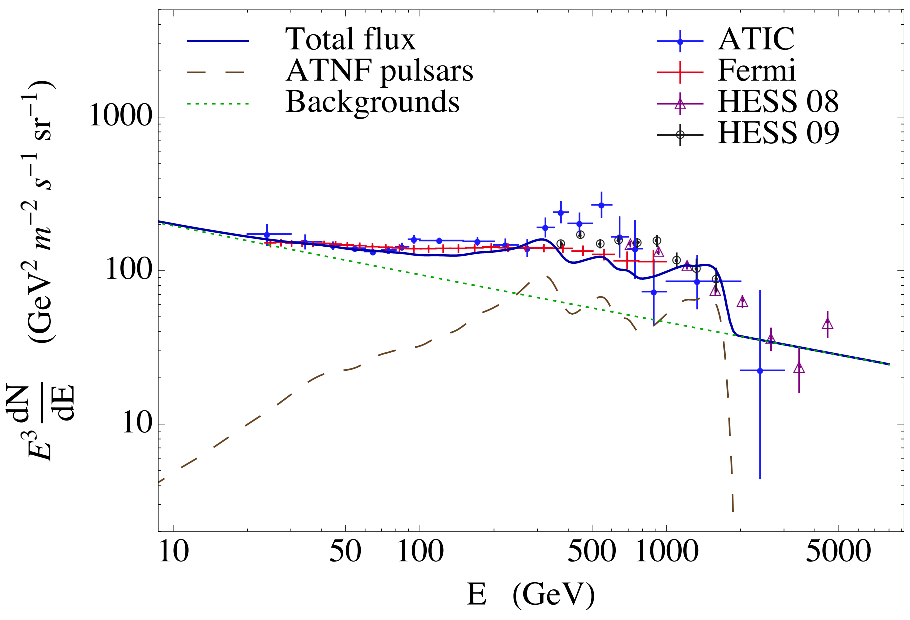
From galactic pulsars (within few kpc)

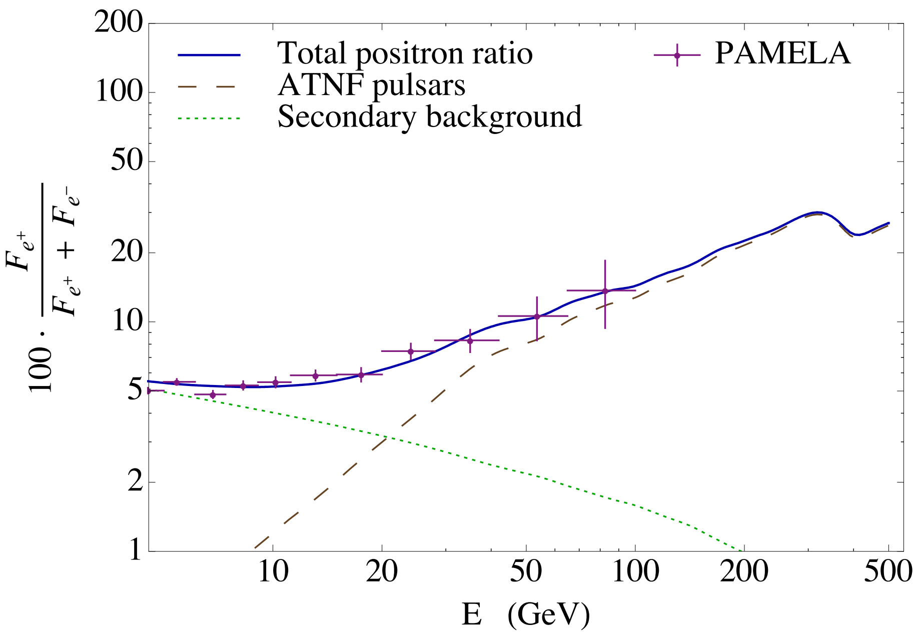


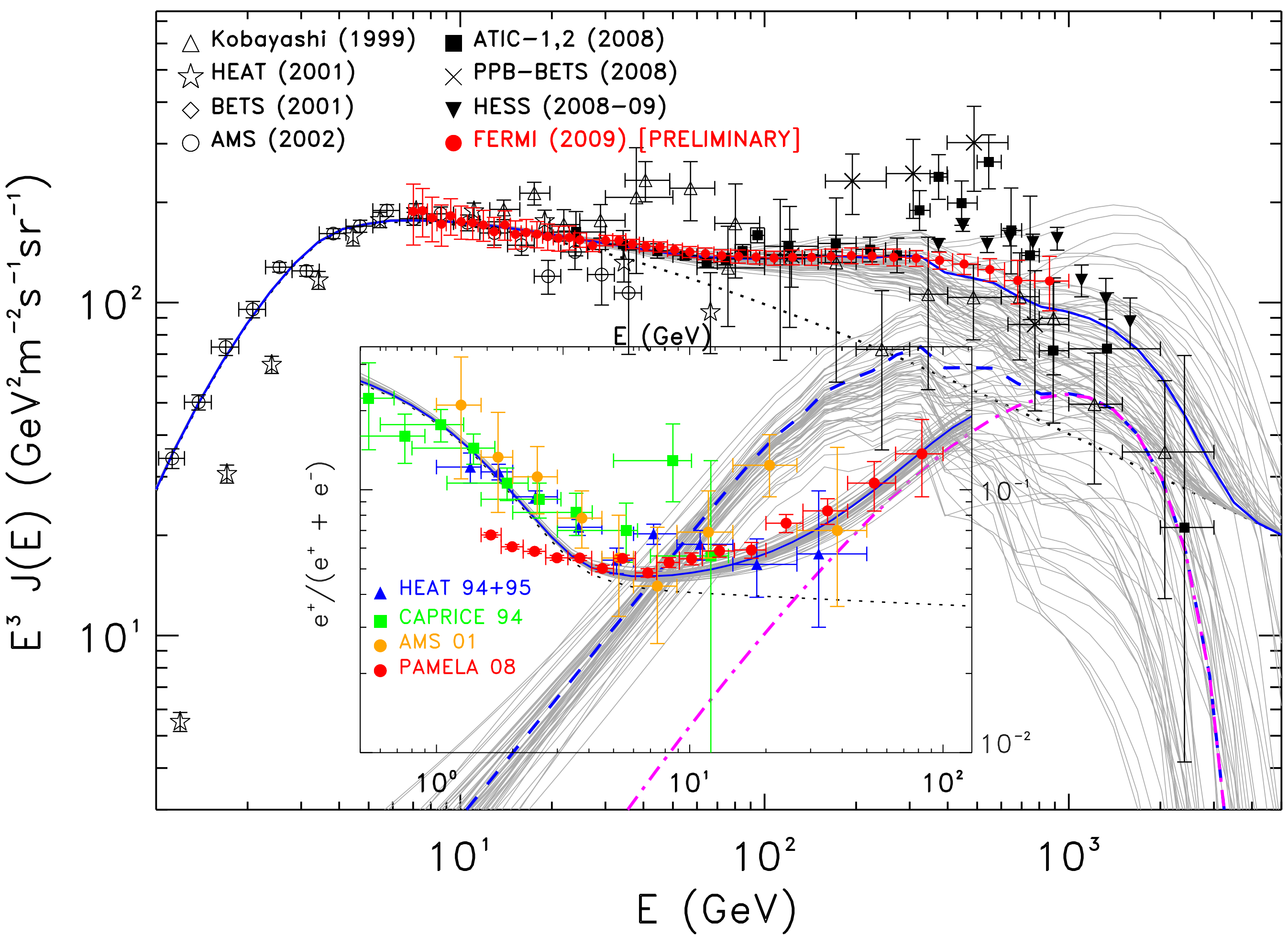
IC, Dan Hooper, arXiv:1304.1840

Prospects for the near future (~2013)

- See positive/negative bumps at higher energy electrons +positrons. One bump/cut-off: DM, Many:pulsars







Fermi Coll, 2009

Malyshev, Cholis, Gelfand, PRD 2009