High energy events in IceCube: hints of decaying leptophilic Dark Matter?

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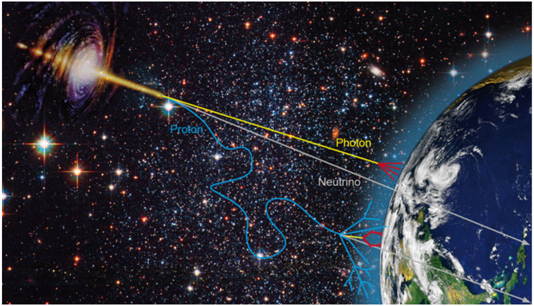
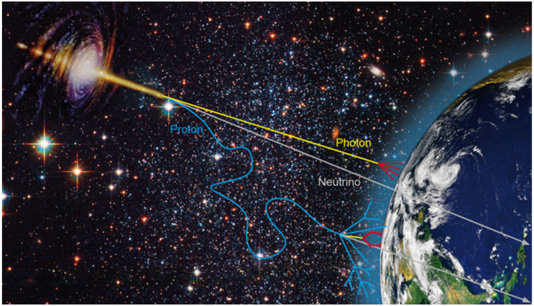
26/10/2015

Messengers from space



Messengers from space



Neutrino astronomy

The questions

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- Where do they come from?
- How are they produced?
  - Bottom-up
  - Top-down
  - Both? $\rightarrow$ arXiv:1507.01000

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Answers from

- Energy spectrum
- Direction
- Flavour composition

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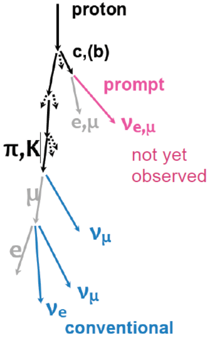
Outline

Background

- The interactions of Cosmic Rays (CR) with the atmophere produce two types of background
- Conventional background: produced by the decays of π and K
- The prompt background corresponds to $\nu_{e(\mu)}$ and $e(\mu)$ coming from the decay of charmed mesons



Analytical spectra

- Dependence on primary flux ($E_\nu \approx 0.05 E_p$)

$$p + p \to X + m\pi$$

$$\pi \to \mu + \nu_\mu$$

$$\mu \to e + \nu_e + \nu_\mu$$

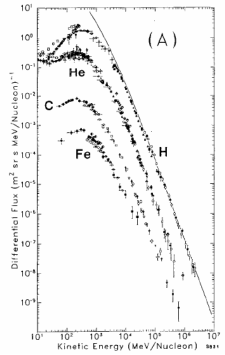
- Spectra are computed through transport equations (decay, interaction, energy losses etc.) or phenomenological models (e.g. Heitler model)
- Transport equations are coupled $\to$ approximations (e.g. no μ decay)

$$\left.\frac{d\phi_\nu}{dE_\nu}\right|_C = \phi_N(E_\nu, X = 0) \frac{A_{C\to\nu}}{1 + \frac{B_{C\to\nu} E_\nu \cos\theta}{\epsilon_C}}$$

Cosmic rays: primary particles

- Mostly protons
- Differential spectrum

$$\frac{d\phi_N}{dE} \propto E^{-(\gamma+1)}$$



Cosmic rays: primary particles

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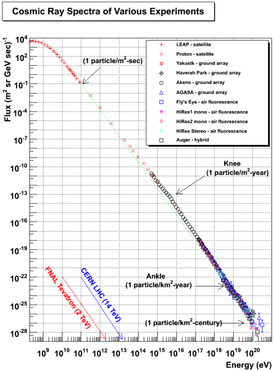
$$\frac{d\phi_N}{dE} \propto E^{-(\gamma+1)}$$

- γ dependent on energy (up to 3 PeV ≈ 1.7, then ≈ 2.0)



Atmospheric fluxes from CORSIKA

- Analytical approximation is not good enough for a comparison with experimental data
- We need to run a Monte Carlo→CORSIKA (COsmic Ray SImulation for KAscade)
- A complete Monte Carlo-used by many collaborations for different experiments-includes: electromagnetic interactions, decays etc.

Atmospheric fluxes from CORSIKA

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C=======================================================================
C
C     000      000     0000       0000    00   0     0       0
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C
C   COSMIC RAY SIMULATION AT KARLSRUHE
C
C
C A PROGRAM TO SIMULATE EXTENSIVE AIR SHOWERS IN ATMOSPHERE
C
C BASED ON A PROGRAM OF P.K.F. GRIEDER, UNIVERSITY BERN
C DUAL PARTON MODEL ACCORDING TO J.N. CAPDEVIELLE, UNIVERSITY BORDEAUX
C EGS4 AND NKG FORMULAS FOR SIMULATION OF ELECTROMAGNETIC PARTICLES
C
C INSTITUT FUER KERNPHYSIK
C KERNFORSCHUNGSZENTRUM AND UNIVERSITY OF KARLSRUHE
C
C VERSION : 1.0
C DATE: 26. OCTOBER 1989
C
C=======================================================================
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Difficulties

General difficulties

- Including the veto of IceCube (reduces the downgoing background)
- Absorption by Earth
- Interaction with the detector

$\rightarrow$Forcing the Monte Carlo

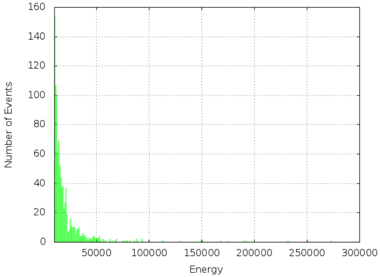
Prompt neutrinos:

- Poor data in the kinematical and energetical range of interest (QCD & non perturbative field theory)

A home-made analysis

- We have realised a simulation of 10000 vertical events with primary energy in the range $[3, 100]$ PeV (relevant to $E_\nu \in [10, 1000]$ TeV)
- Atmospheric fluxes are not appreciable at 1 PeV

- ν flux $\rightarrow$



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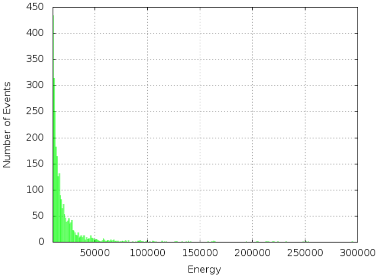
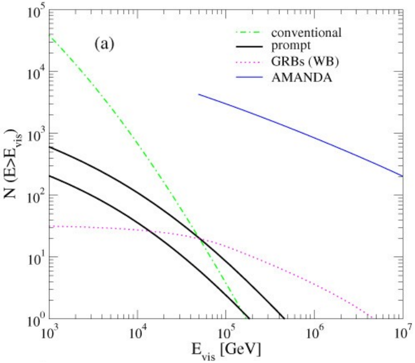


From atmospheric to astrophysical neutrinos



CR propagation

- How can we obain information about astrophysical neutrinos?
- We observe at Earth fluxes which depend on propagation (galactic magnetic fields)
- Propagation is studied through different models. A good approach is via the Ginzburg-Syrovatskii equation, which reduces to the leaky box model assuming large escape time (T.K.Gaisser, *Cosmic Rays and Particle Physics*, Cambridge University Press (1990))

Source flux from observed flux

- From observed to source flux

$$\frac{d\phi}{dE} \propto E^{-(\gamma+1)} \rightarrow \frac{d\phi_S}{dE} \propto E^{-(\gamma+1-\delta)}$$

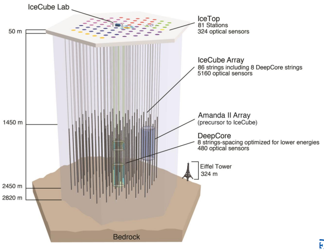
- For example

$$\frac{d\phi}{dE} \propto E^{-2.7} \rightarrow \frac{d\phi_S}{dE} \propto E^{-2}$$

Neutrinos are not trapped by galactic magnetic fields

IceCube: the detector

- What does it search: high energy neutrinos in the range TeV-EeV
- How: Cherenkov detector with 5160 Digital Optical Modules in deep ice, with a large fiducial volume ($\approx$ 1 km^3)+veto
- When: 2010-2013



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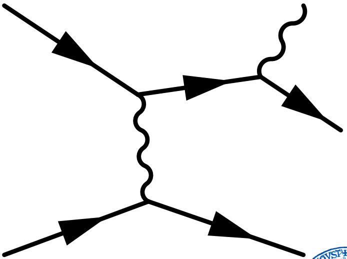

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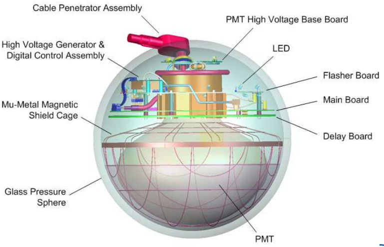
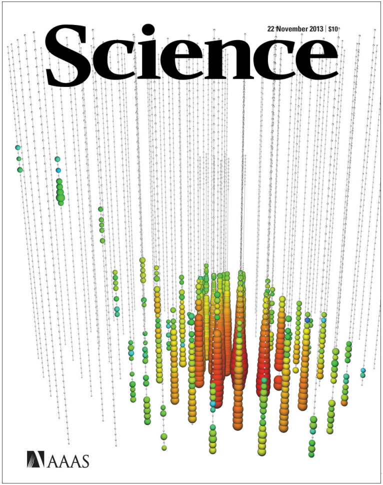


IceCube: events



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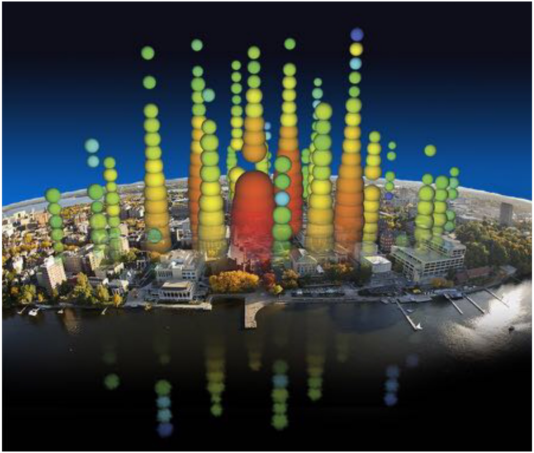


Astrophysical neutrinos: background

- The expected background, given by muons and atmospheric neutrinos from cosmic ray showers is given by

$$N_{\mu^\pm} = 8.4 \pm 4.2$$

and

$$N^{TOT}_{\nu+\bar{\nu}} = 6.6^{+5.9}_{-1.6}$$

- the asymmetric error is due to prompt neutrinos

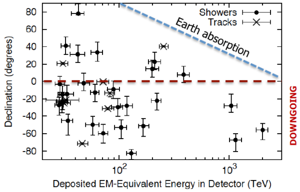
Astrophysical neutrinos: data

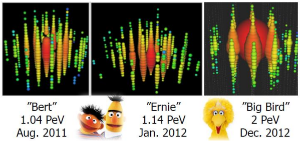
- IceCube has found 37 candidate events with deposited energy from 30 TeV circa to 2 PeV; 2 events with $E_\nu \approx 1$ PeV and one with $E_\nu \approx$2 PeV
- Of all the events 5 could be background

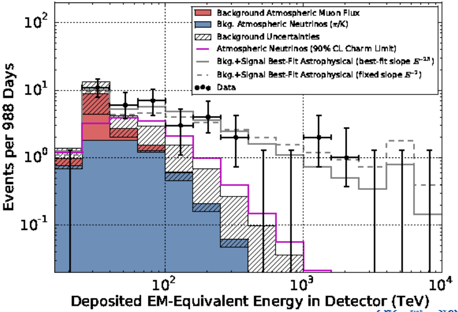
Astrophysical neutrinos detected (5.7 σ)

- IceCube Coll., arXiv:1311.5238, arXiv:1405.5303

Astrophysical neutrinos detected: energy spectrum







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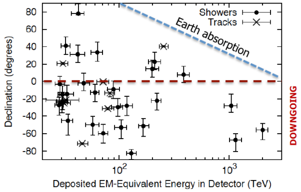

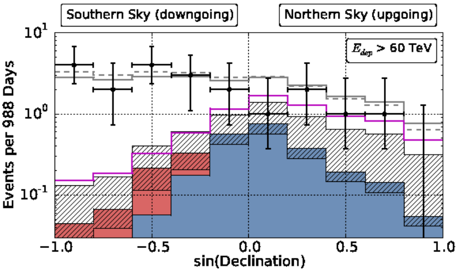

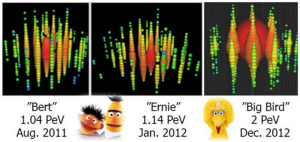

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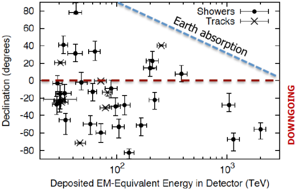
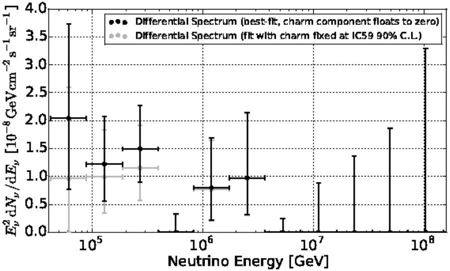
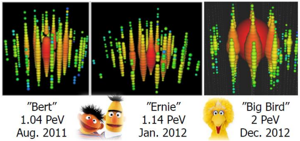






Isotropic $(e : \mu : \tau) = (1 : 1 : 1)$ flux

- Flux in $\text{GeV} \cdot \text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1}$
- A first fit with fixed PL (not fitting well PeV events)

$$E^2 \frac{d\phi_{\nu+\bar{\nu}}}{dE}\bigg|_{flavour} = (0.95 \pm 0.3) \times 10^{-8}$$

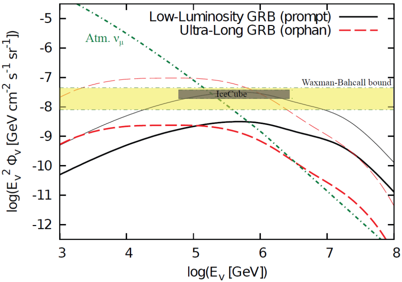
- A second fit

$$E^2 \frac{d\phi_{\nu+\bar{\nu}}}{dE}\bigg|_{flavour} = 1.5 \times 10^{-8} \left(\frac{E}{100 \text{ TeV}}\right)^{-0.3}$$

Can bottom-up accelerators explain all data?

- BU accelerators have difficulties in explaining the data
- GRBs have the right shape profile but an order of magnitude lower normalization

- K. Murase, arXiv:1410.3680
- S. Chakraborty, I. Izaguirre, arXiv:1501.02615



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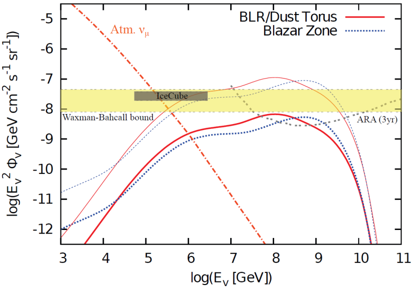

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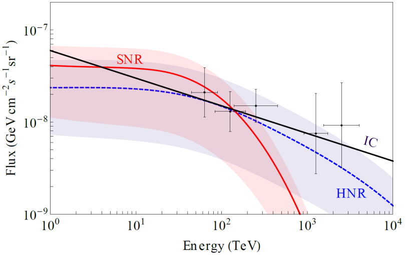
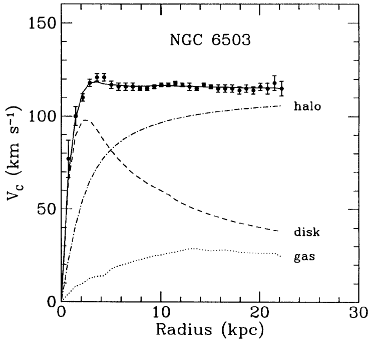
- GRBs have the right shape profile but an order of magnitude lower normalization
- AGN can explain PeV events but are in tension with lower energies data
- SNRs have a cut-off at ≈ 100 TeV (maybe HNRs?)

- K. Murase, arXiv:1410.3680
- S. Chakraborty, I. Izaguirre, arXiv:1501.02615



What is Dark Matter?

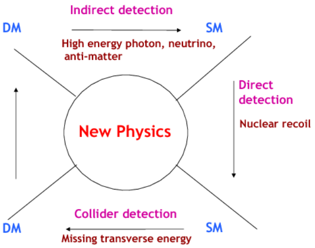
- There are hints of non luminous matter in the universe
- As an example, rotation curves of spiral galaxies can't be fitted by luminous matter only



Icecube from DM: previous approaches

- Different DM scenarios have already been proposed
- Boosted DM: direct detection
- DM coupled to the Higgs
- Tension with data (neutrinos from quark sector vs astrophysical sources at lower energies)

- J. Kopp, J. Liu, X.-P. Wang, arXiv:1503.02669
- A. Esmaili, P.D. Serpico, arXiv:1308.1105



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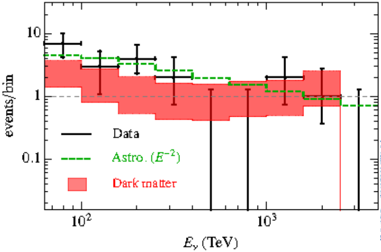
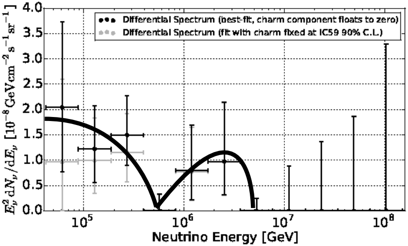


Icecube from DM

We have supposed that the flux is made up of two components astro+DM $\rightarrow$ new particle χ

- fermion
- Dirac mass
- $\mathbf{1}_0$ under $SU(3)_C \times SU(2)_L \times U(1)_Y$



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arXiv.org > hep-ph > arXiv:1507.01000

Search or Article-id

High Energy Physics - Phenomenology

Decaying Leptophilic Dark Matter at IceCube

Sofiane M. Boucenna, Marco Chianese, Gianpiero Mangano, Gennaro Miele, Stefano Morisi, Ofelia Pisanti, Edoardo Vitagliano

(Submitted on 3 Jul 2015)

Icecube from DM

The astrophysical component is parametrized by

- Unbroken Power Law ($E^2 d\phi/dE \propto E^{-\gamma}$)
- Broken Power Law ($E^2 d\phi/dE \propto E^{-\gamma} \exp\{-E/E_0\}$)

The DM component is given by two contributions

- Galactic ($r(s,l,b) = \sqrt{s^2 + R_\odot^2 - 2sR_\odot \cos b \cos l}$)

$$\frac{d\phi_\nu^h}{dE_\nu}(l,b) = \frac{1}{4\pi\, m_\chi\, \tau_\chi} \frac{dn_\nu}{dE_\nu} \int_0^\infty ds \rho_h[r(s,l,b)]$$

- Extra Galactic

$$\frac{d\phi_\nu^{eg}}{dE_\nu} = \frac{\Omega_\chi \rho_c}{4\pi m_\chi \tau_\chi} \int_0^\infty dz \frac{1}{H(z)} \frac{dn_\nu}{dE_\nu} [(1+z)E_\nu]$$

Effective terms (up to dimension 6)

Dimensions	DM decay operators
4	$\bar{L}\tilde{\phi}\chi$
5	—
6	$\bar{L}l\bar{L}\chi$, $\phi^\dagger\phi\bar{L}\tilde{\phi}\chi$, $(\tilde{\phi})^t D_\mu\tilde{\phi}\bar{l}\gamma^\mu\chi$, $\bar{Q}d\bar{L}\chi$, $\bar{u}Q\bar{L}\chi$, $\bar{L}d\bar{Q}\chi$, $\bar{U}\gamma_\mu d\bar{l}\gamma^\mu\chi$, $D^\mu\tilde{\phi}D_\mu\bar{L}\chi$, $D^\mu D_\mu\tilde{\phi}\bar{L}\chi$, $B_{\mu\nu}\bar{L}\sigma^{\mu\nu}\tilde{\phi}\chi$, $W^a_{\mu\nu}\bar{L}\sigma^{\mu\nu}\tau^a\tilde{\phi}\chi$

Decaying DM

We have to compute dn_ν/dE: what are we asking to the new particle χ?

- *naturally* small coupling $\rightarrow$ symmetry
- primary ν $\rightarrow$ direct coupling with neutrino
- spreading ν flux $\rightarrow$ multi body final state
- ...not too much$\rightarrow$ leptophilic

Symmetry

Just an operator with this characteristics

$$\mathcal{L}_{decay} \sim \frac{y_{\alpha\beta\gamma}}{\Lambda^2} \bar{L}_\alpha l_\beta \bar{L}_\gamma \chi + hc$$

How to exclude all the others without unnatural tiny couplings?
Introducing a symmetry like A_4 (or others!)

	L	l	ϕ	χ
A_4	**3**	**3**	**1**	**1**

$$\Gamma_\chi^{total} = 6 \times \Gamma_\chi = \frac{1}{1024} \frac{4y^2}{\Lambda^4} \frac{m_\chi^5}{\pi^3}$$

Analysis

We have conduced a likelihood analysis supposing

$$E_\nu^2 \frac{d\phi_\nu}{dE_\nu}(E_\nu) = E_\nu^2 \frac{d\phi_\nu^\chi}{dE_\nu}(E_\nu) + E_\nu^2 \frac{d\phi_\nu^{Ast}}{dE_\nu}(E_\nu)$$

The two parametrizations for the astro flux are

$$E_\nu^2 \frac{d\phi^{Ast}}{dE_\nu}(E_\nu) = \phi_0 \left(\frac{E_\nu}{100\ \text{TeV}} \right)^{-\gamma}$$

$$E_\nu^2 \frac{d\phi^{Ast}}{dE_\nu}(E_\nu) = \phi_0 \left(\frac{E_\nu}{100\ \text{TeV}} \right)^{-\gamma} \exp\left(-\frac{E_\nu}{125\, TeV} \right)$$

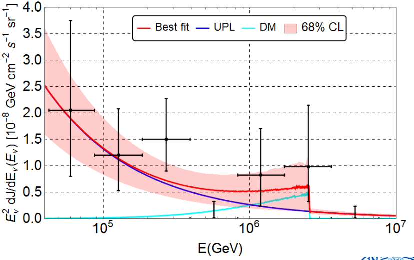
Analysis

- The mass of χ is fixed by the most energetic neutrinos to $m_\chi \approx 5$ PeV, and γ is 0.0 for BPL (spectral index 2.0) and 0.7 for UPL $\rightarrow$ obtained by likelihoods ratios
- MONTE CARLO $\rightarrow$ The best fit for the normalization and the coupling are

Case	y [10^{-5}]	ϕ_0 [10^{-8}]	χ^2/dof
UPL	$0.40^{+0.27}_{-0.40}$	$1.3^{+1.1}_{-1.0}$	1.04
BPL	$0.55^{+0.27}_{-0.48}$	$4.1^{+3.3}_{-2.9}$	0.75

Results: UPL

- The UPL DM coupling is comparable to 0 at 1 σ



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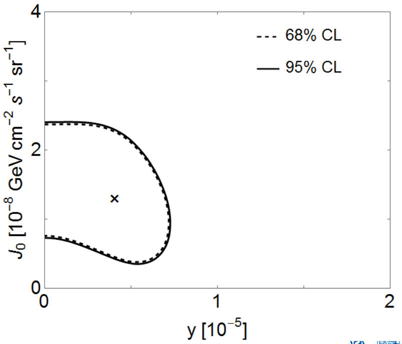
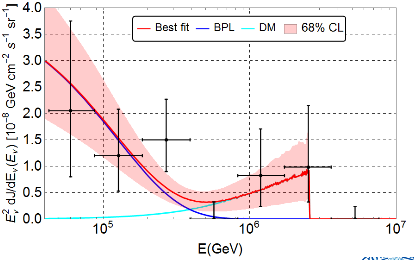


Results: BPL

- There is a (still weak) hint of DM in the BPL case (2 σ compatibility)
- Reduced χ^2 is smaller than in the UPL case



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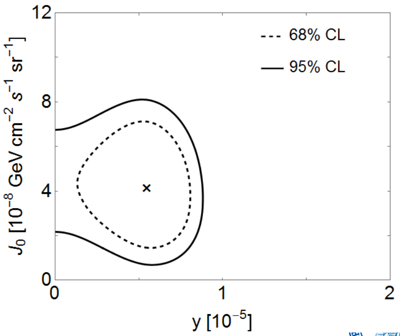

Conclusions

- We have obtained with a hand-made analysis the estimate to the atmospheric background
- We have shown the astrophysical flux we expected
- IceCube, its mechanism, goals and data have been reported
- Given some hints of tension between data and previous models, we have built a double (astro+DM) flux model

Conclusions

- We have found the data to be well explained by a BPL+DM
- The model is falsifiable:
  - dip at 300 TeV/ cut off at 2 PeV
  - anisotropy near the galactic center
- More data (IceCube, KM3NeT and CTA) will shed light

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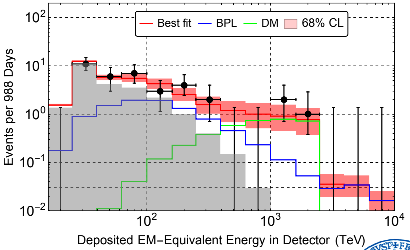
Thank you

New analysis

Case	$y\ [10^{-6}]$	$\phi_0\ [10^{-8}]$	χ^2/dof
UPL	$3.46^{+4.59}_{-2.37}$	$0.83^{+1.31}_{-0.47}$	1.07
BPL	$3.67^{+4.64}_{-2.77}$	$2.43^{+3.74}_{-1.29}$	0.96

Results: UPL

- The UPL DM coupling is not comparable to 0 at 2 σ



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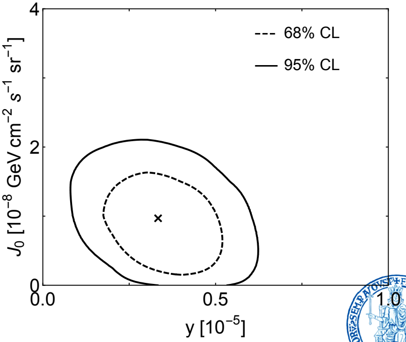
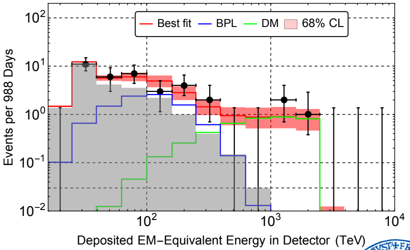


Results: BPL

- There is hint of DM in the BPL case
- Reduced χ^2 is smaller than in the UPL case



Results: BPL

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