Dark Matter scenarios @ IceCube

Stefano Morisi

in collaboration with

Boucenna, Chianese, Mangano, Miele, Pisanti, Vitagliano

Exploring the Energy Ladder of the Universe

Mainz, 8th June

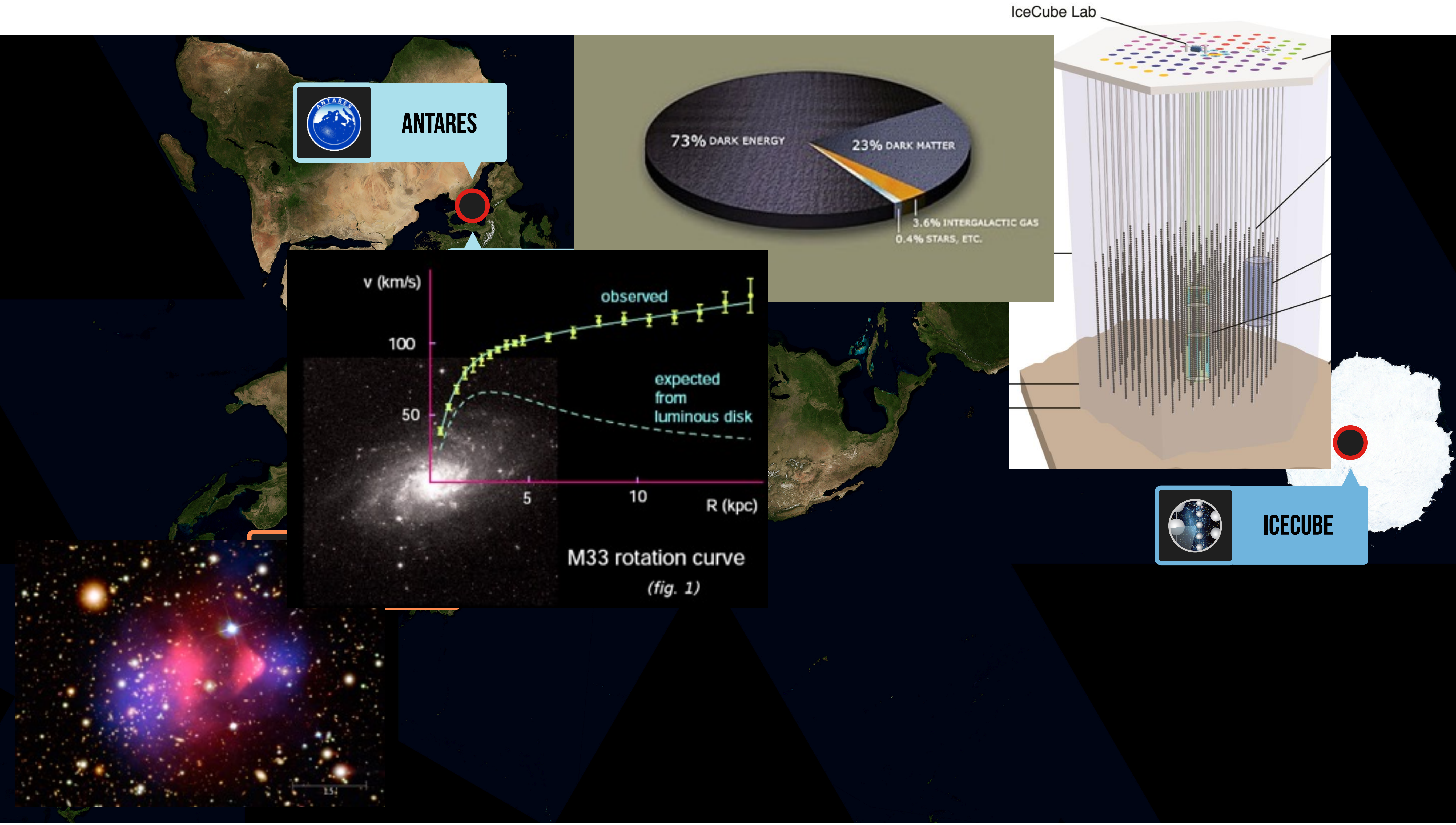
INFN Istituto Nazionale di Fisica Nucleare

Università degli Studi di Napoli Federico II

Neutrino telescopes

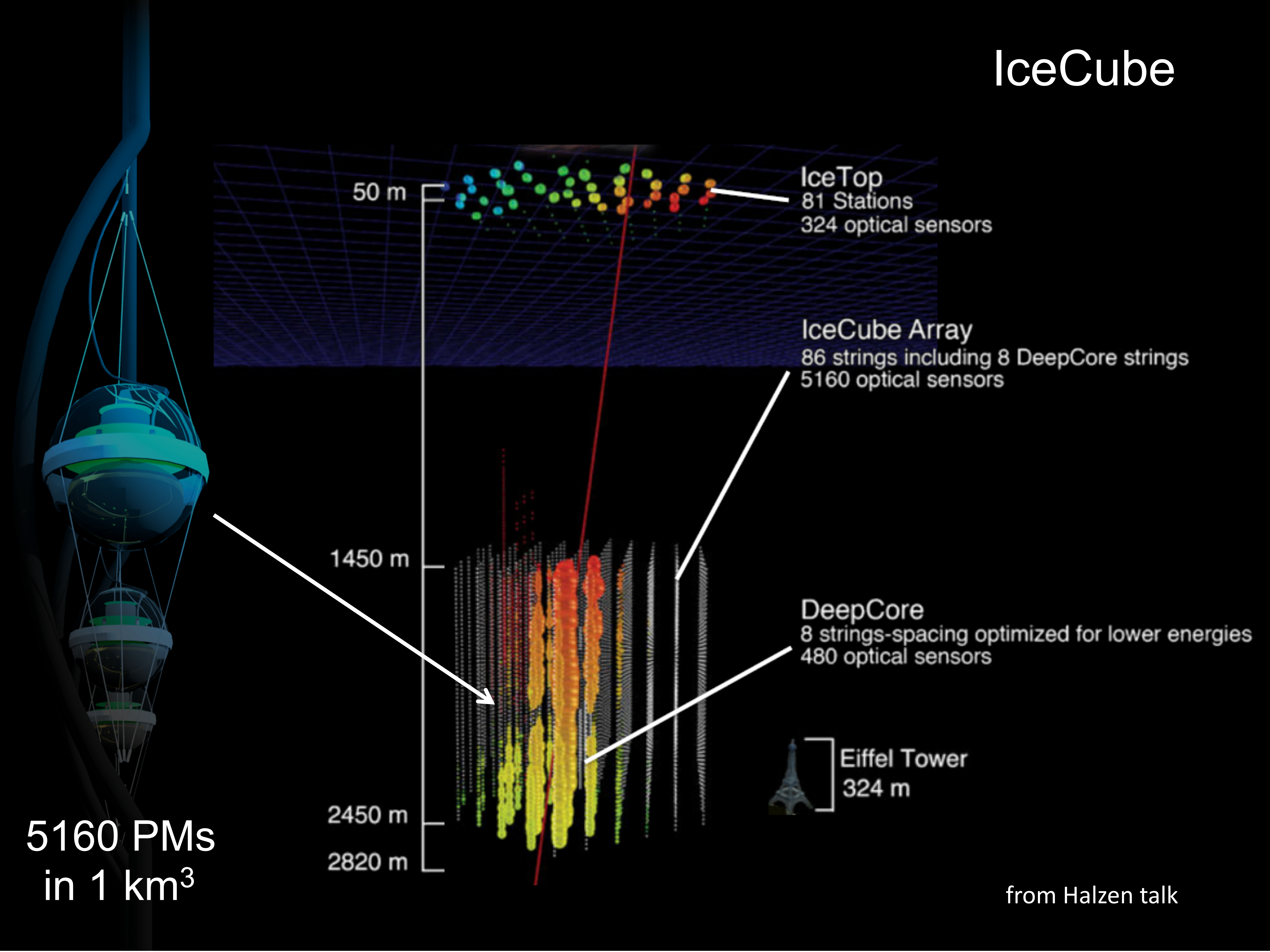
from C.Kopper talk

Neutrino telescopes



from C.Kopper talk

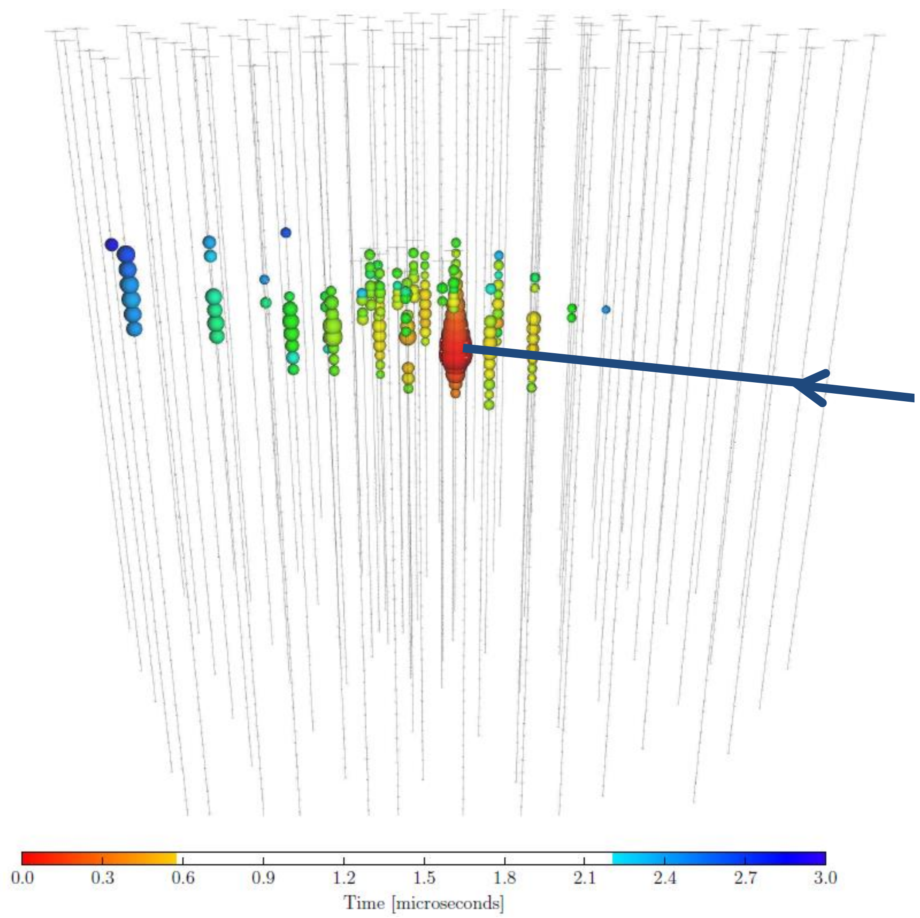
IceCube



5160 PMs in 1 km^3

from Halzen talk

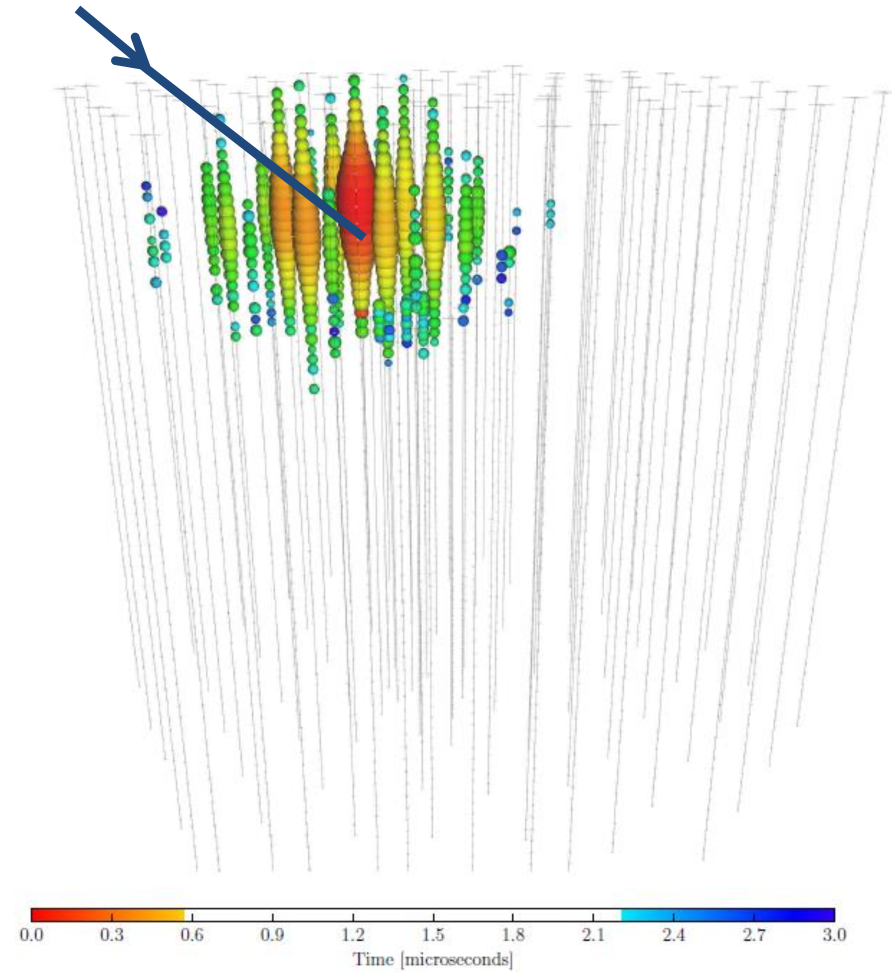
track



- CC interactions
- Mostly ν_μ
- Angular resolution ~1° at 50% CL

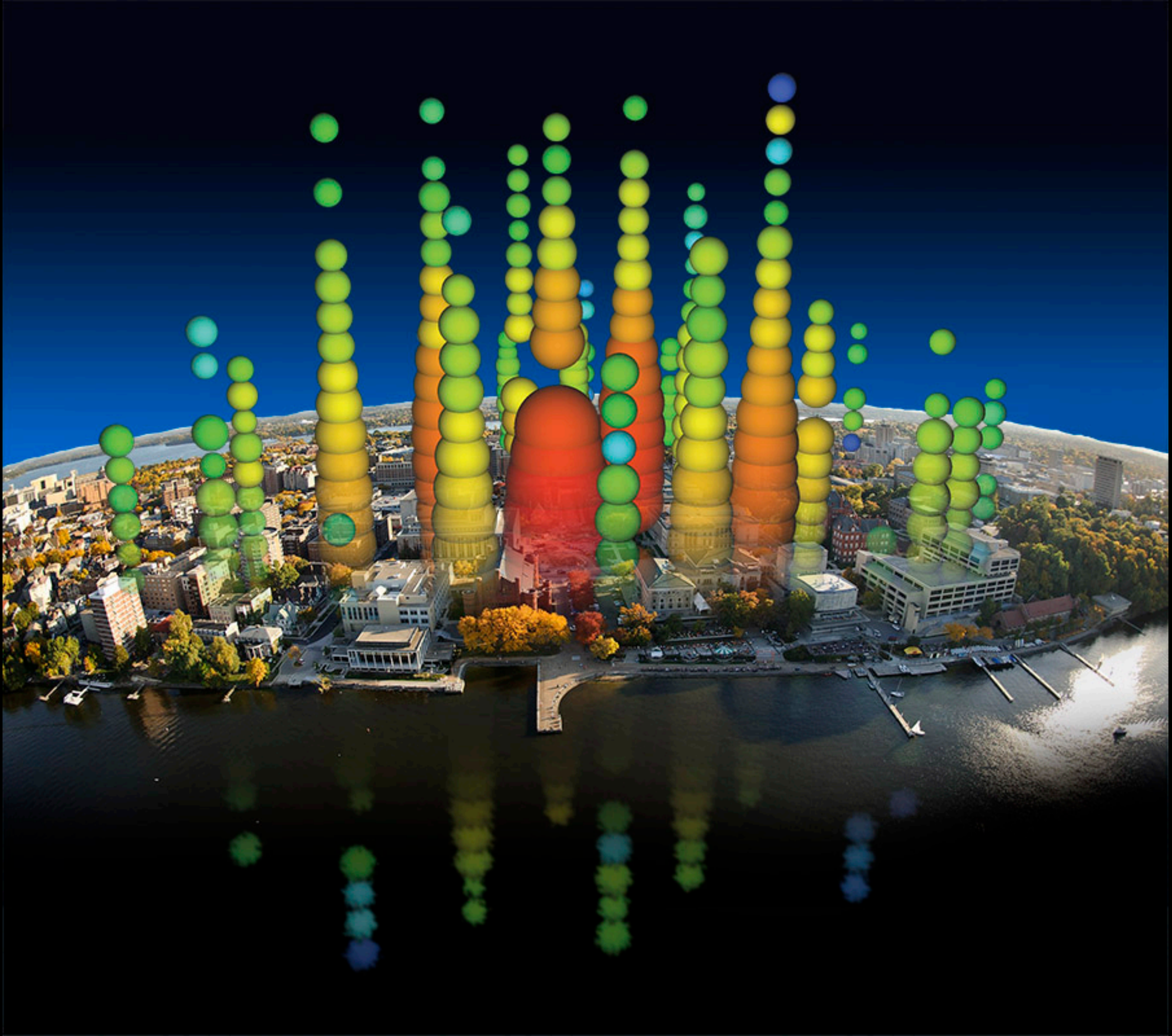
$$\nu_\mu + N \rightarrow \mu + X$$

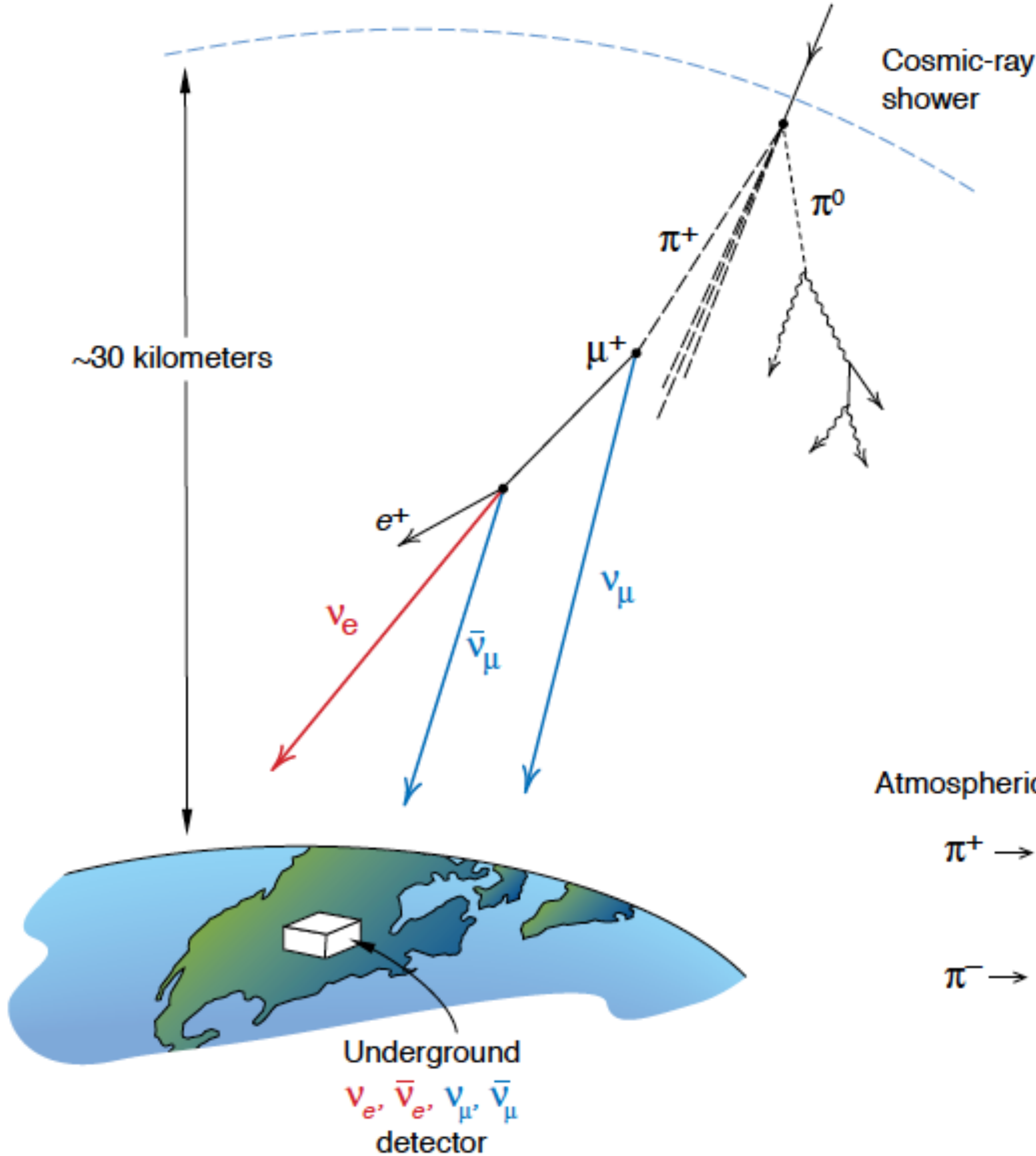
shower



- CC and NC interactions
- Mostly ν_e and ν_τ
- Angular resolution ~15° at 50% CL

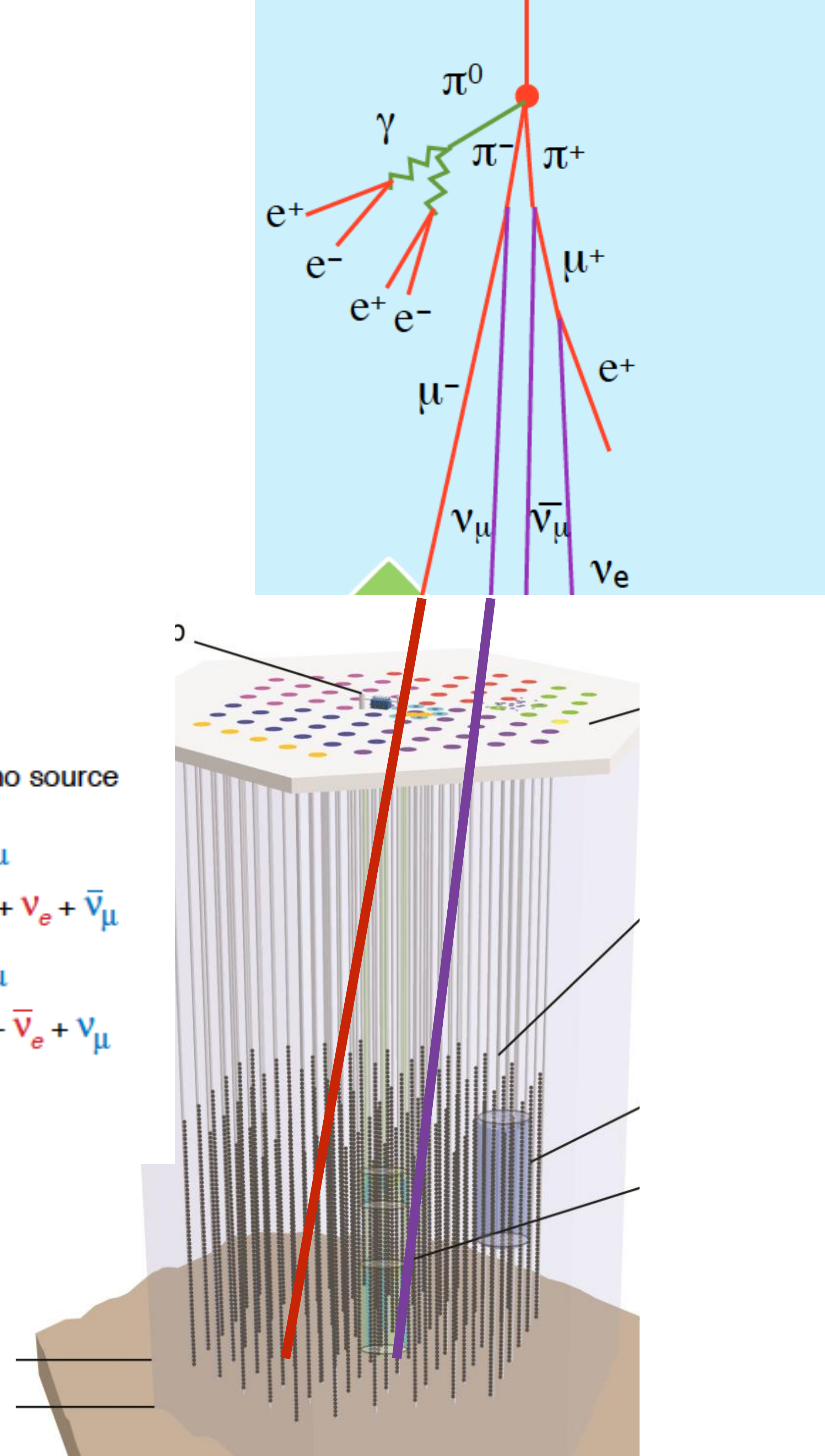
$$\nu_e + N \rightarrow e + X$$
$$\nu_x + N \rightarrow \nu_x + X$$





Atmospheric neutrino source

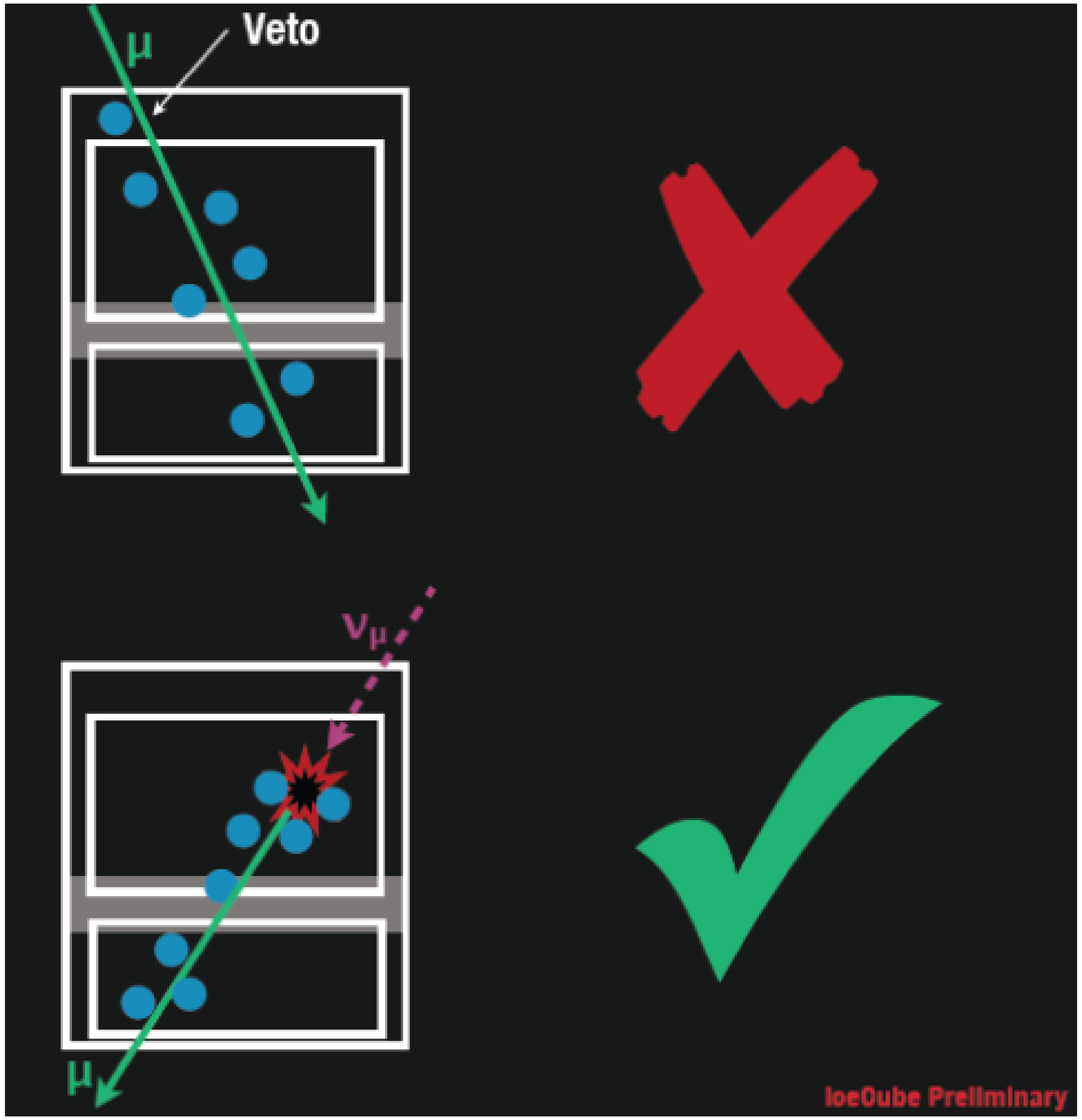
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\quad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\pi^- \to \mu^- + \bar{\nu}_\mu$$
$$\quad \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$



accompanying muon
from the same cosmic-ray cascade

High-Energy Events > 30 TeV (HESE)

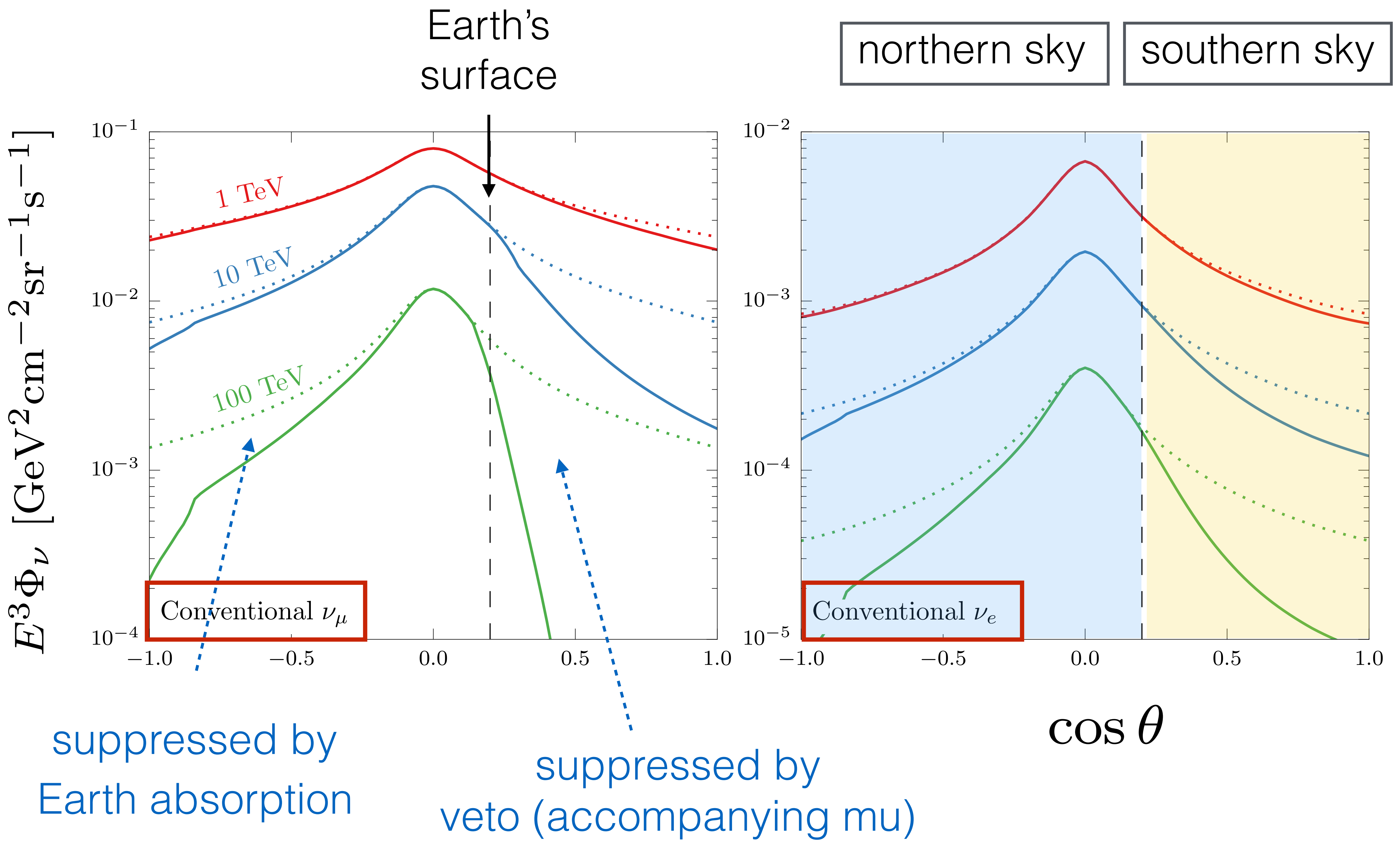
IceCube PRL 113 (2014)



veto:

muons or shower with vertex
inside the fiducial volume
are discarded
if
accompanied by a muon
producing light in the
veto region

Background suppression



Medium-Energy Events > 1 TeV (MESE)

Incoming-track veto

At low energy the number of background muon increase
and
the average rate of energy loss decrease

↓

A single layer of detector (like in HESE)
can not reject incoming penetrating muons

Medium-Energy Events > 1 TeV (MESE)

Incoming-track veto

So in MESE data it is removed the requirement that
veto photons are detected on the external layer of the detector

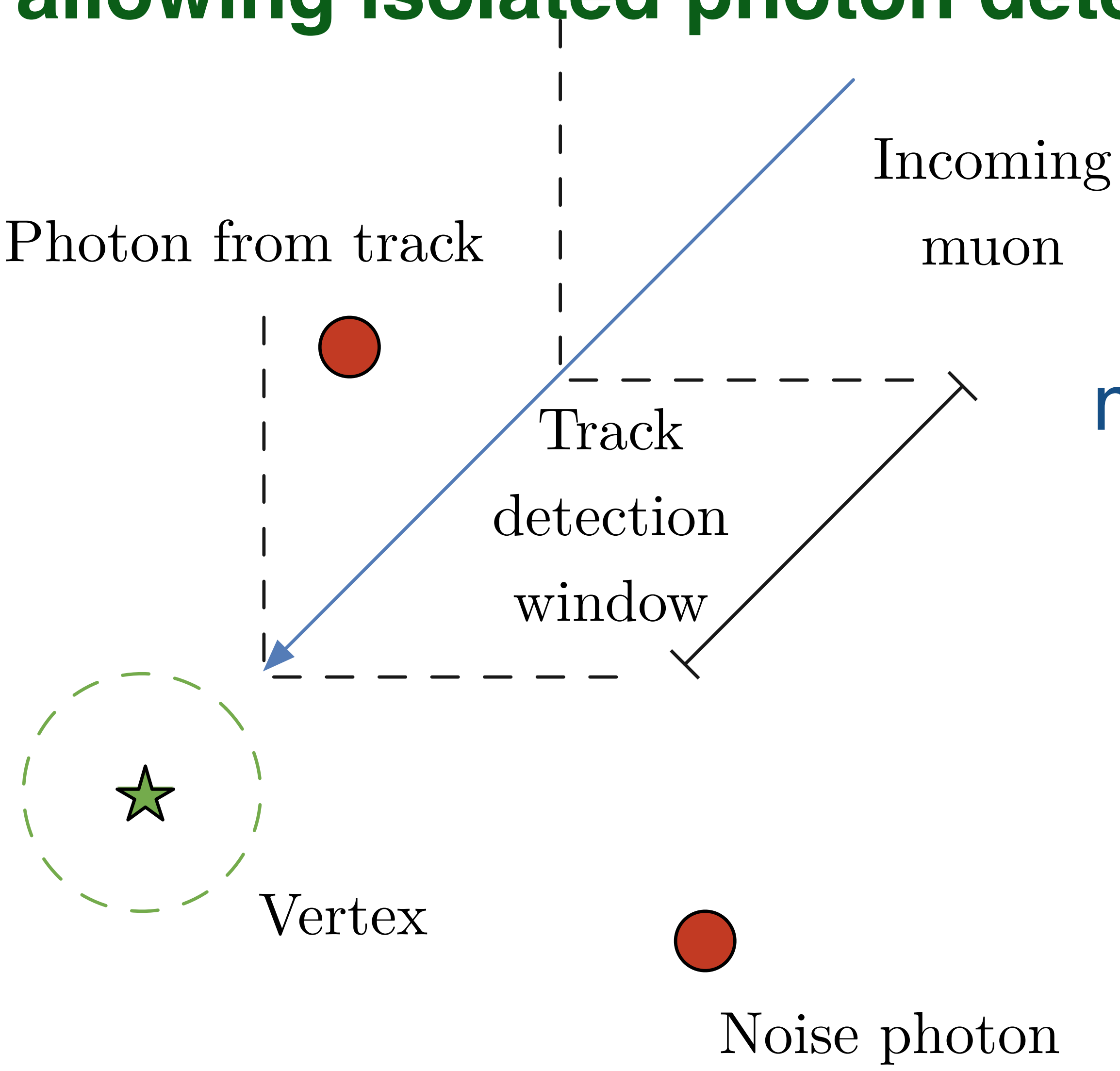
allowing isolated photon detection anywhere in the detector

Medium-Energy Events > 1 TeV (MESE)

Incoming-track veto

So in MESE data it is removed the requirement that
veto photons are detected on the external layer of the detector

allowing isolated photon detection anywhere in the detector

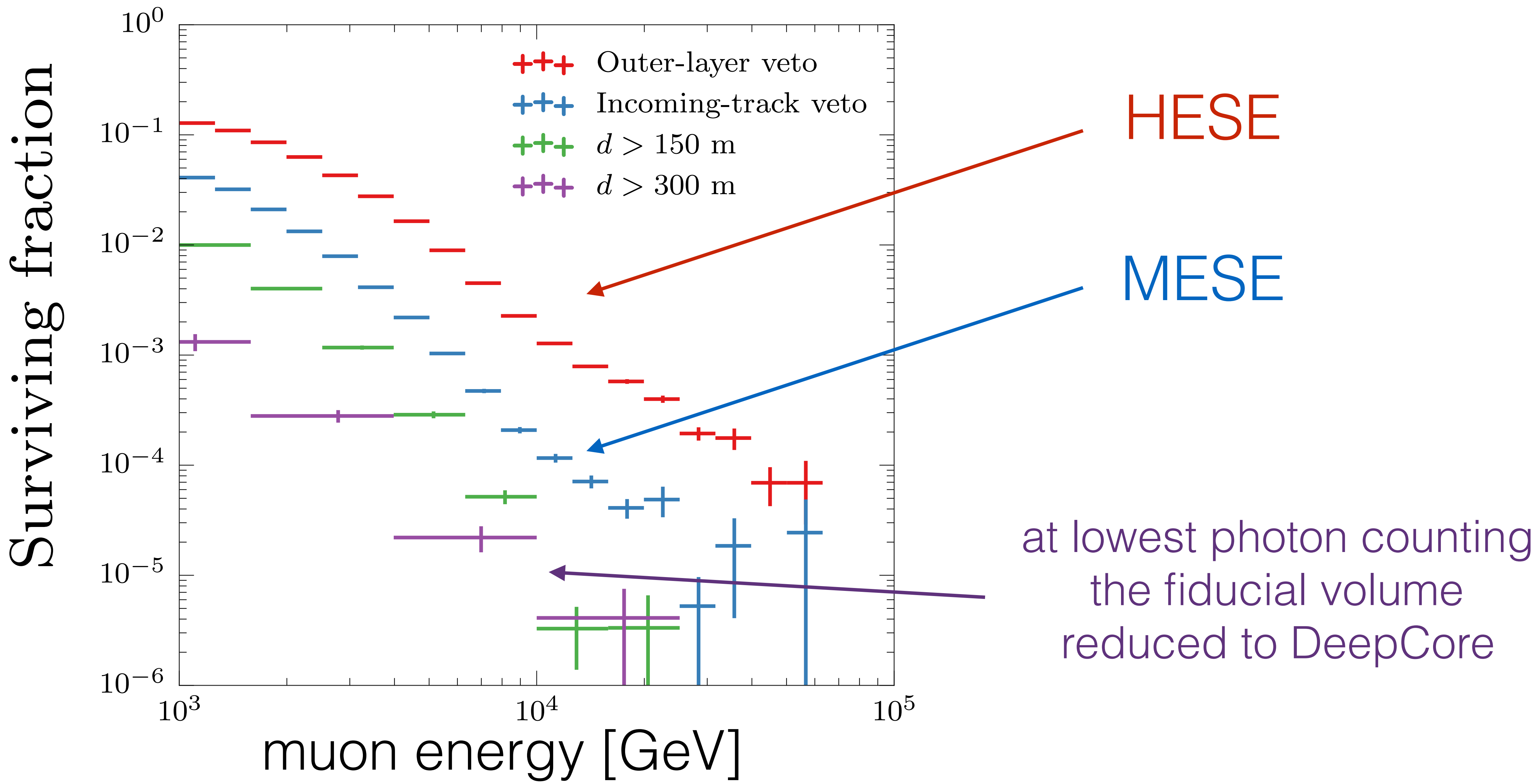


moreover photons are considered in the veto if are consistent with incoming tracks **but** inconsistent with the vertex of neutrino

Medium-Energy Events > 1 TeV (MESE)

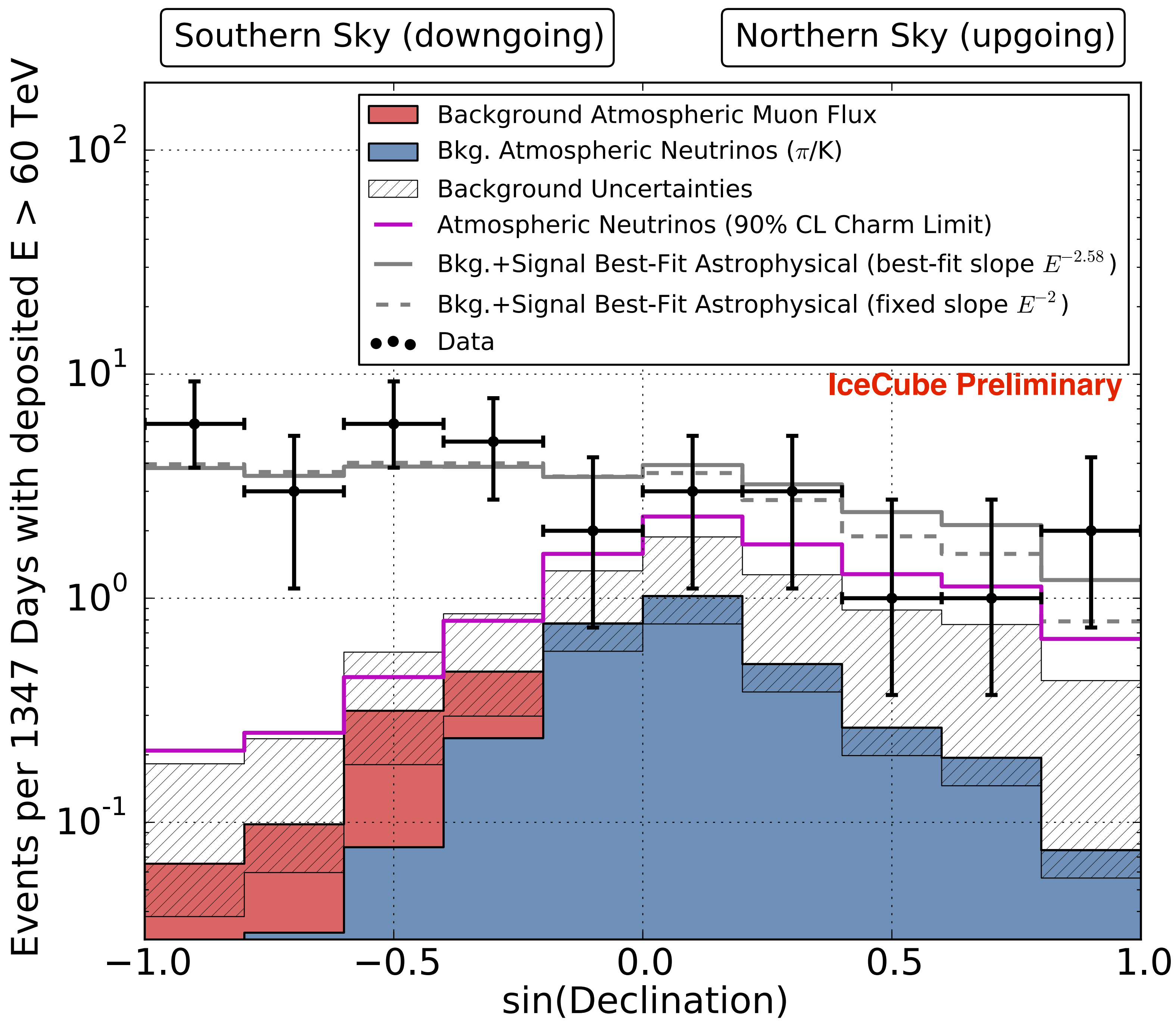
Incoming-track veto

the effectiveness of the veto, is proportional to the probability of detecting at least 2 photons from incoming muons



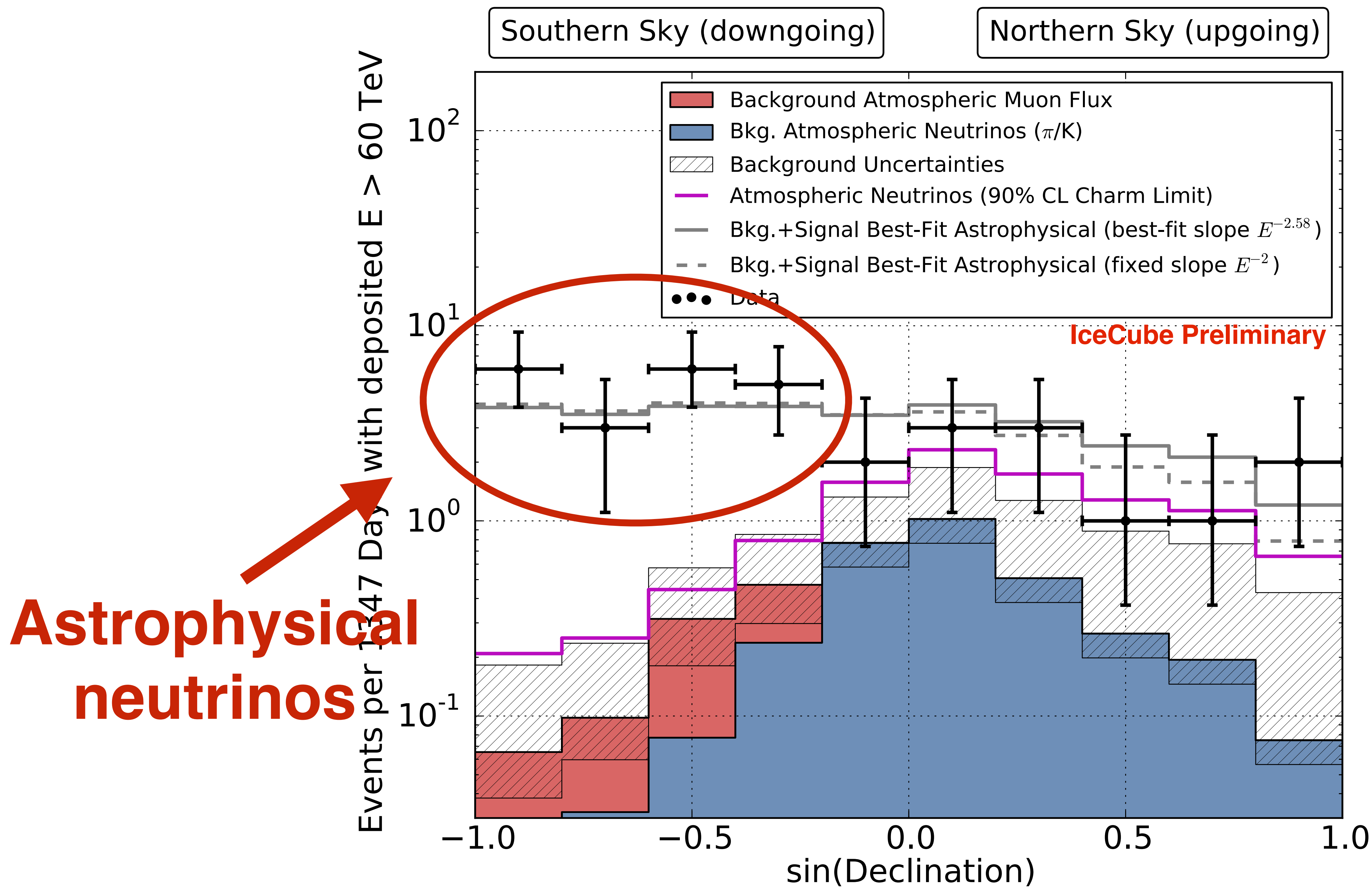
in this talk we concentrate
on HESE data
and we give some comment
at the end about MESE

4 years HESE data: 54 events



from Observation of Astrophysical Neutrinos in Four Years of IceCube Data
(released 21 Oct 2015)   1510.05223

4 years HESE data: 54 events



from Observation of Astrophysical Neutrinos in Four Years of IceCube Data
(released 21 Oct 2015)   1510.05223

Origin of Astrophysical neutrinos

unknown, there are many candidates

- **Galactic:** (full or partial contribution)
  - diffuse Galactic γ-ray emission [MA & Murase'13; Joshi J C, Winter W and Gupta'13] [Kachelriess and Ostapchenko'14; Neronov, Semikoz & Tchernin'13] [Neronov & Semikoz'14,'16; Guo, Hu & Tian'14; Gaggero, Grasso, Marinelli, Urbano & Valli'15]
  - unidentified Galactic γ-ray emission [Fox, Kashiyama & Meszaros'13] [Gonzalez-Garcia, Halzen & Niro'14]
  - *Fermi Bubbles* [MA & Murase'13; Razzaque'13] [Lunardini, Razzaque, Theodoseau & Yang'13; Lunardini, Razzaque & Yang'15]
  - supernova remnants [Mandelartz & Tjus'14]
  - pulsars [Padovani & Resconi'14]
  - microquasars [Anchordoqui, Goldberg, Paul, da Silva & Vlcek'14]
  - Sagitarius A* [Bai, Barger, Barger, Lu, Peterson & Salvado'14; Fujita, Kimura & Murase'15,'16]
  - Galactic Halo [Taylor, Gabici & Aharonian'14]
  - heavy dark matter decay [Feldstein, Kusenko, Matsumoto & Yanagida'13] [Esmaili & Serpico '13; Bai, Lu & Salvado'13; Cherry, Friedland & Shoemaker'14] [Murase, Laha, Ando, MA'15; Boucenna *et al.*'15 ; Chianese, Miele, Morisi & Vitagliano'16]

From Ahlers talk at ICTP

Origin of Astrophysical neutrinos

unknown, there are many candidates

- **Extragalactic:**
  - association with sources of UHE CRs [Kistler, Stanev & Yuksel'13]
    [Katz, Waxman, Thompson & Loeb'13; Fang, Fujii, Linden & Olinto'14;Moharana & Razzaque'15]
  - association with diffuse γ-ray background [Murase, MA & Lacki'13]
    [Chang & Wang'14; Ando, Tamborra & Zandanel'15]
  - active galactic nuclei (AGN) [Stecker'13;Kalashev, Kusenko & Essey'13]
    [Murase, Inoue & Dermer'14; Kimura, Murase & Toma'14; Kalashev, Semikoz & Tkachev'14]
    [Padovani & Resconi'14; Petropoulou *et al.*'15; Padovani *et al.*'16; Kadler *et al.*'16]
  - gamma-ray bursts (GRB) [Murase & Ioka'13; Dado & Dar'14; Tamborra & Ando'15]
    [Senno, Murase & Meszaros'16]
  - galaxies with intense star-formation
    [He, Wang, Fan, Liu & Wei'13; Yoast-Hull, Gallagher, Zweibel & Everett'13; Murase, MA & Lacki'13]
    [Anchordoqui, Paul, da Silva, Torres& Vlcek'14; Tamborra, Ando & Murase'14; Chang & Wang'14]
    [Liu, Wang, Inoue, Crocker & Aharonian'14; Senno, Meszaros, Murase, Baerwald & Rees'15]
    [Chakraborty & Izaguirre'15; Emig, Lunardini & Windhorst'15; Bechtol *et al.*'15]
  - galaxy clusters/groups [Murase, MA & Lacki'13; Zandanel, Tamborra, Gabici & Ando'14]

From Ahlers talk at ICTP

Origin of Astrophysical neutrinos

Fermi shock acceleration

power law spectrum $E^{-\gamma}$

At first order: $\gamma \simeq 2$

Gaisser 1990

At second order: $\gamma \gtrsim 2.3$

photohadronic
p-gamma interactions

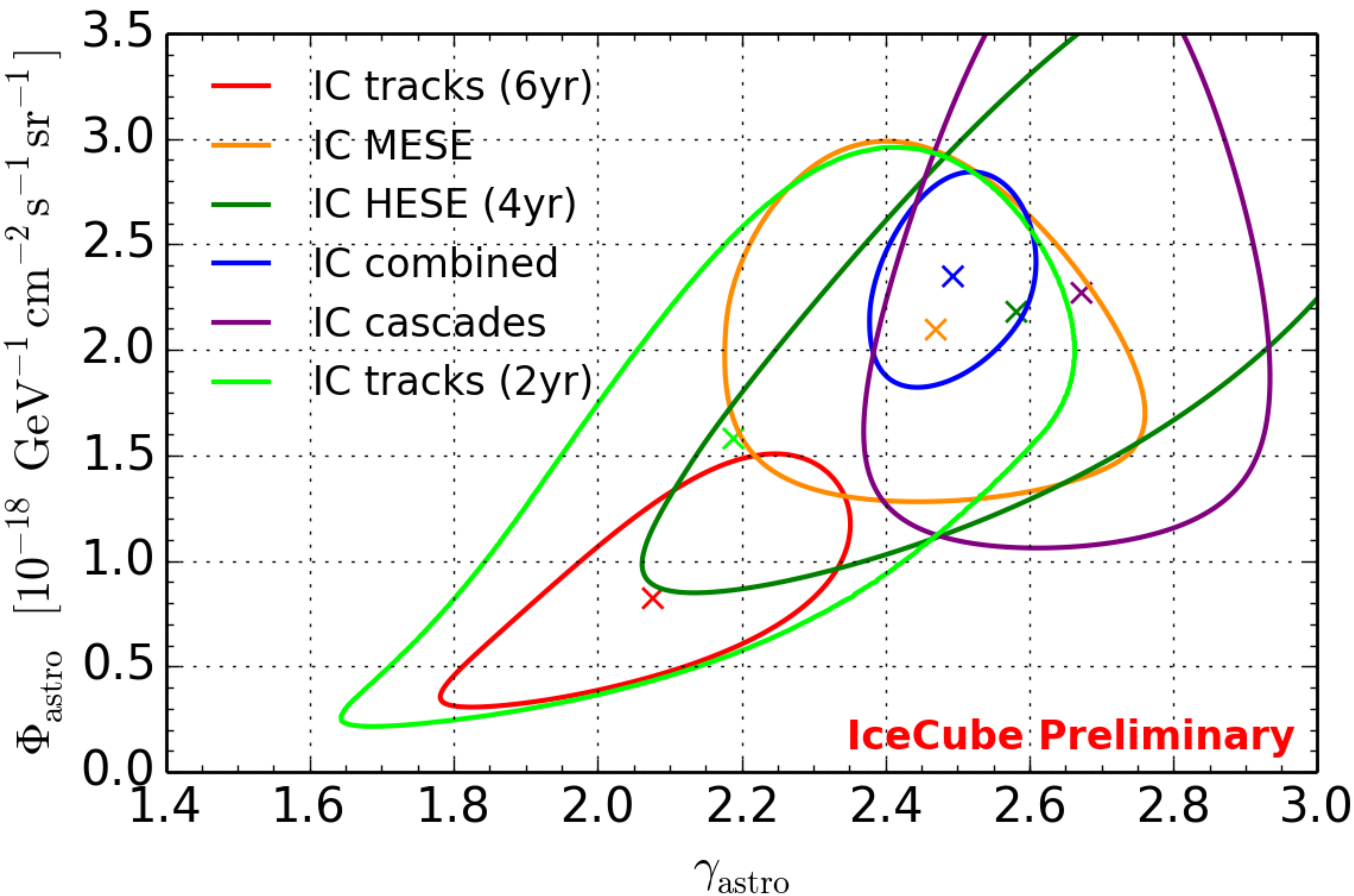
Winter 2013

$\gamma \lesssim 2.1 - 2.2$

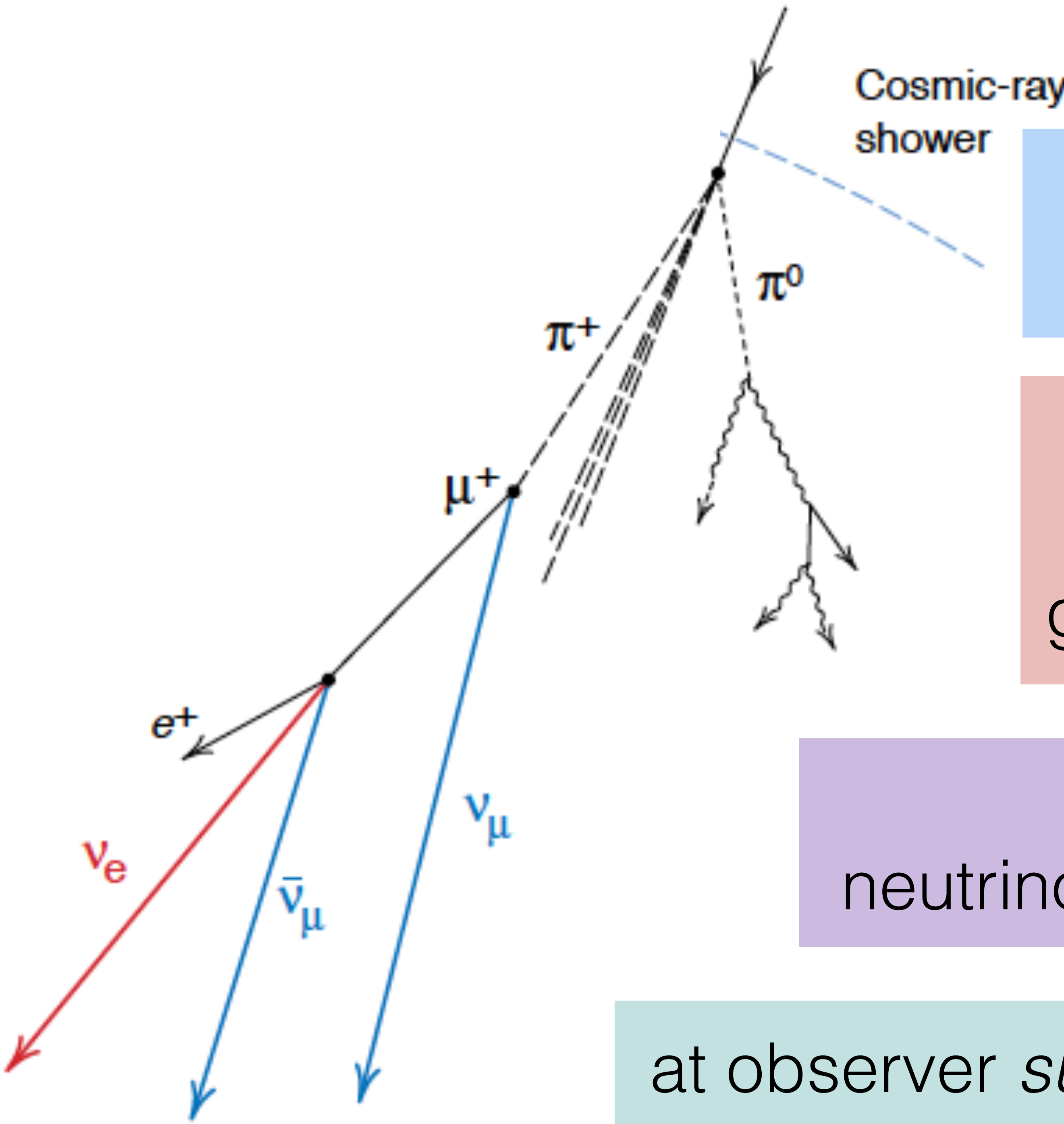
hadronuclear
p-p interactions

Murase et al. 2013

best fit power law spectrum



Gamma Constraints



Interactions producing neutrino also produce gamma-rays

Interactions of cosmic-rays with inter-stellar/galactic matter generate pions that create gamma

at source

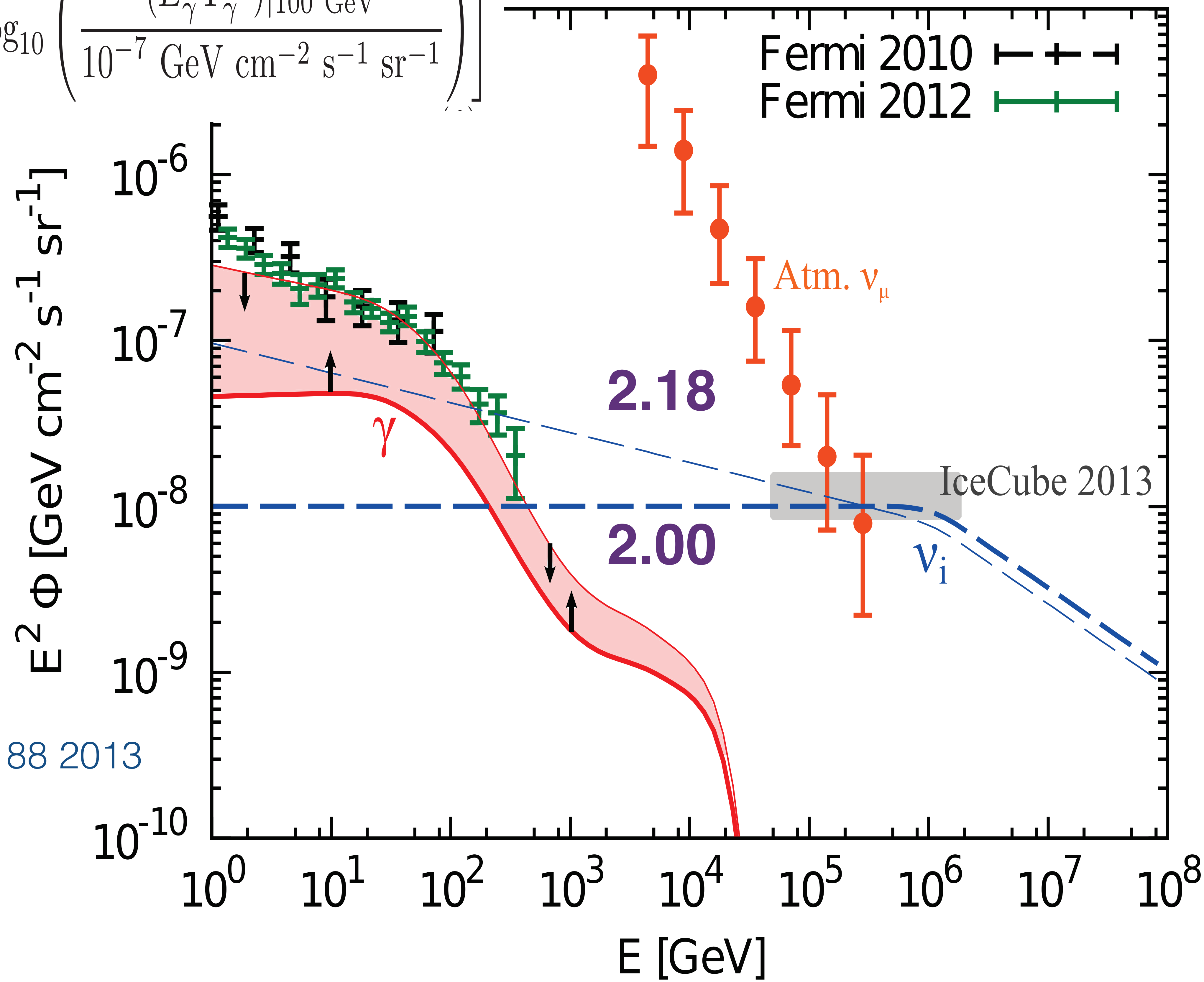
neutrino flux ⟷ gamma flux

at observer *super-TeV gamma* ⟶ *sub-TeV*

- Pair production via scattering with CMB
- inverse Compton

hadronuclear reaction: multi-messenger studies

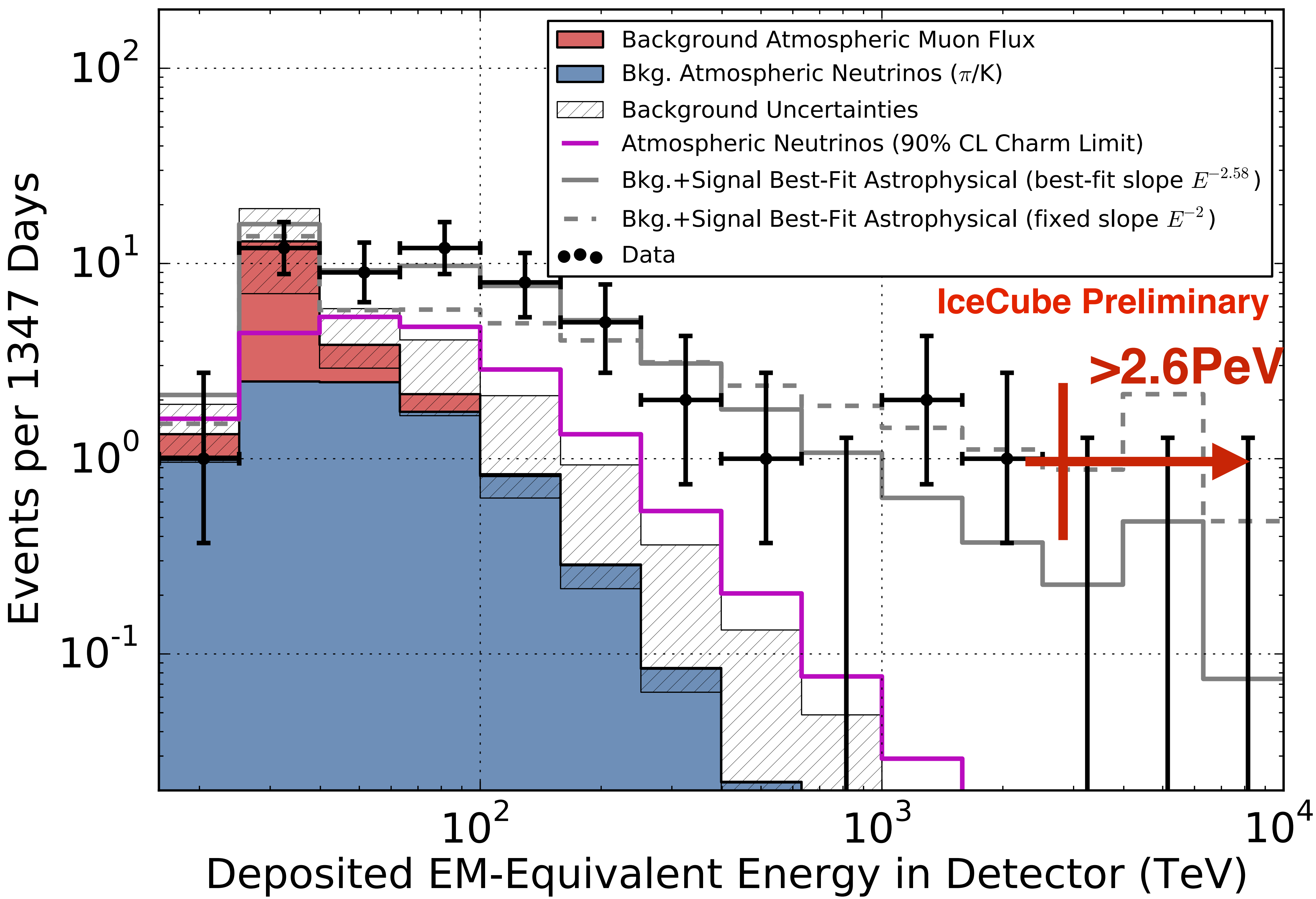
$$\Gamma \lesssim 2.185 \left[1 + 0.265 \log_{10}\left(\frac{(E_\gamma^2 \Phi_\gamma^{\rm up})|_{100\ \rm GeV}}{10^{-7}\ \rm GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}\right)\right]$$



Murase et al, PRD 88 2013

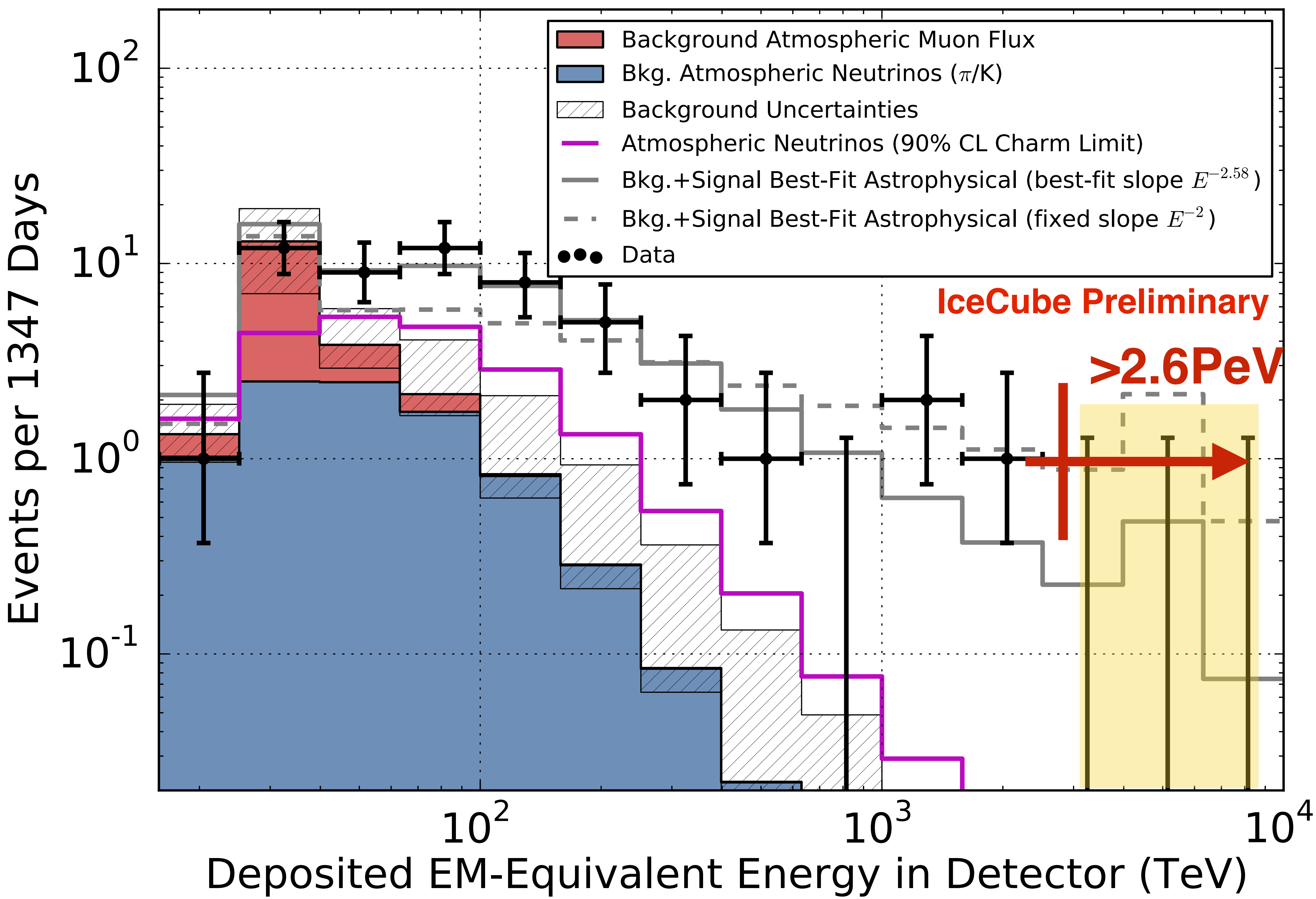
What the Dark Matter tell us about the spectral index?

4 years HESE data: 54 events



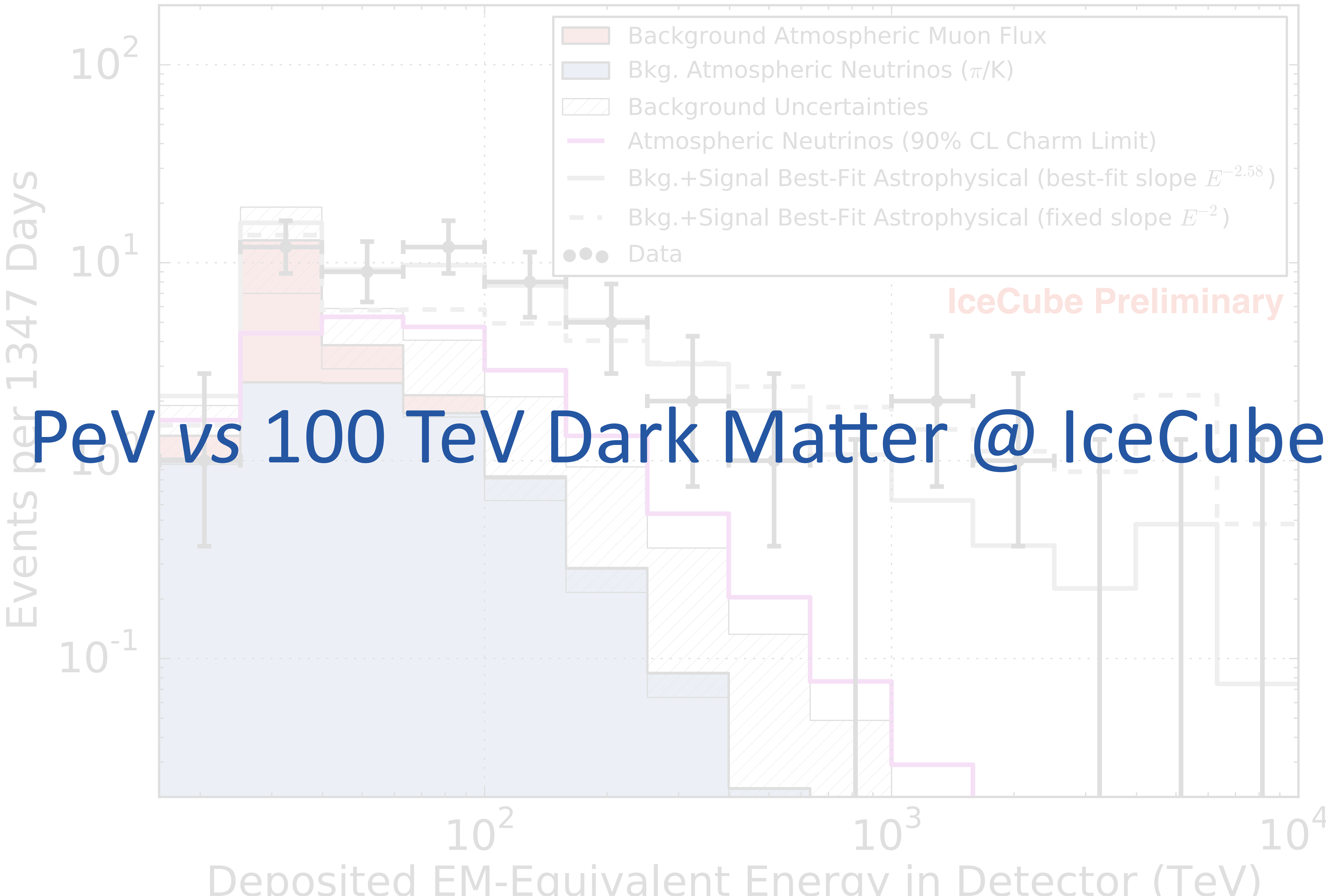
from Observation of Astrophysical Neutrinos in Four Years of IceCube Data
(released 21 Oct 2015)   1510.05223

4 years HESE data: 54 events

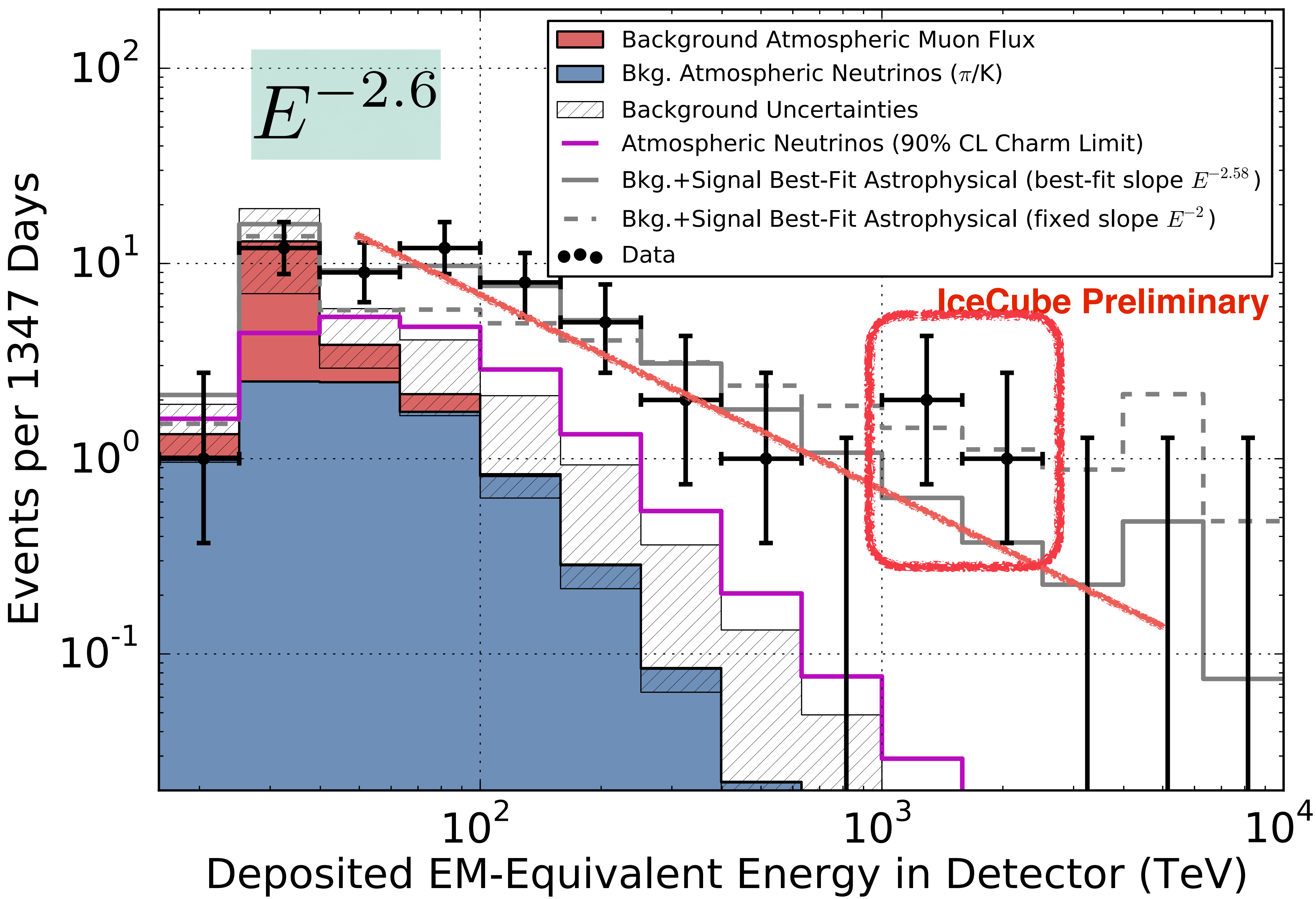


from Observation of Astrophysical Neutrinos in Four Years of IceCube Data
(released 21 Oct 2015) 1510.05223

PeV *vs* 100 TeV Dark Matter @ IceCube

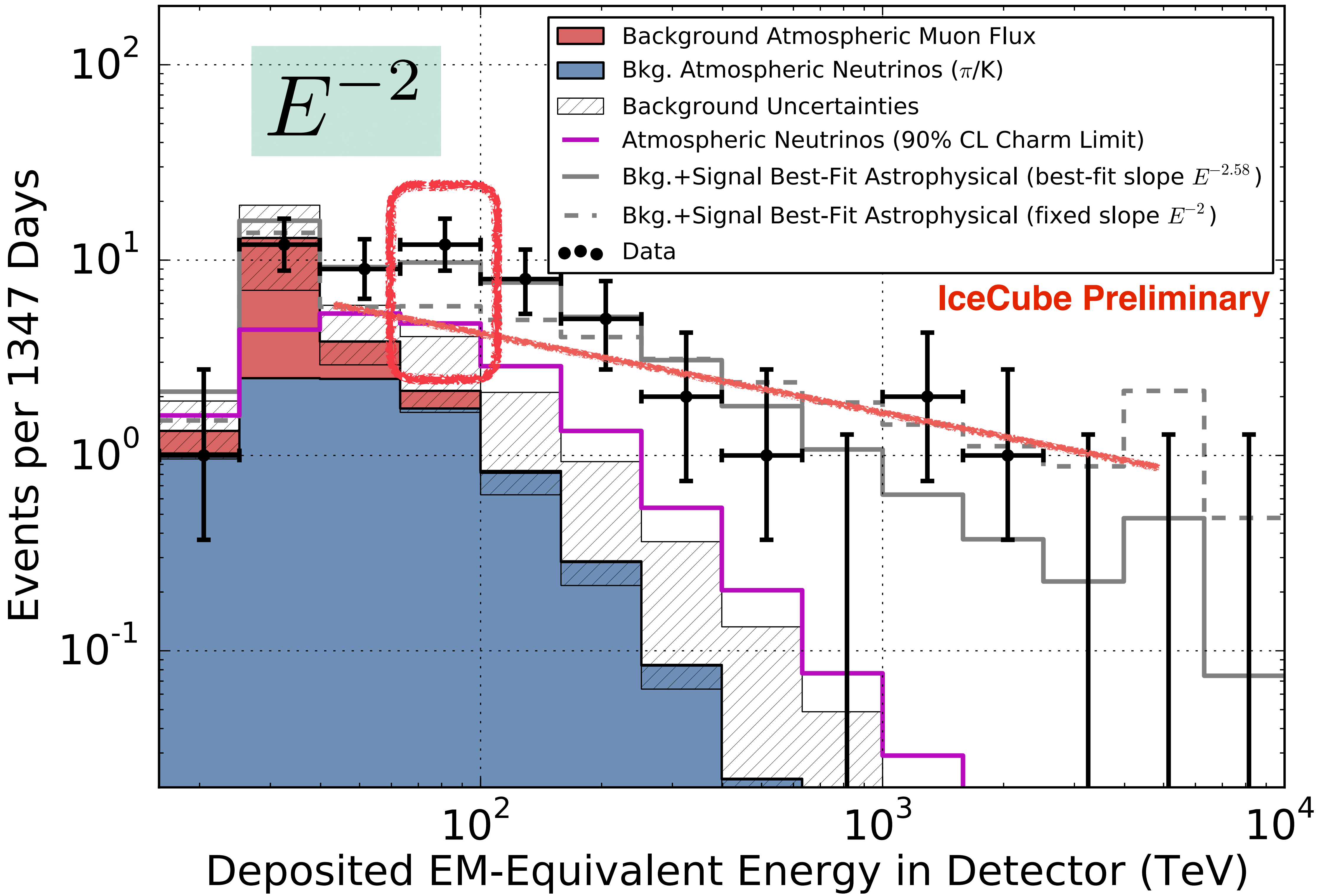


PeV excess

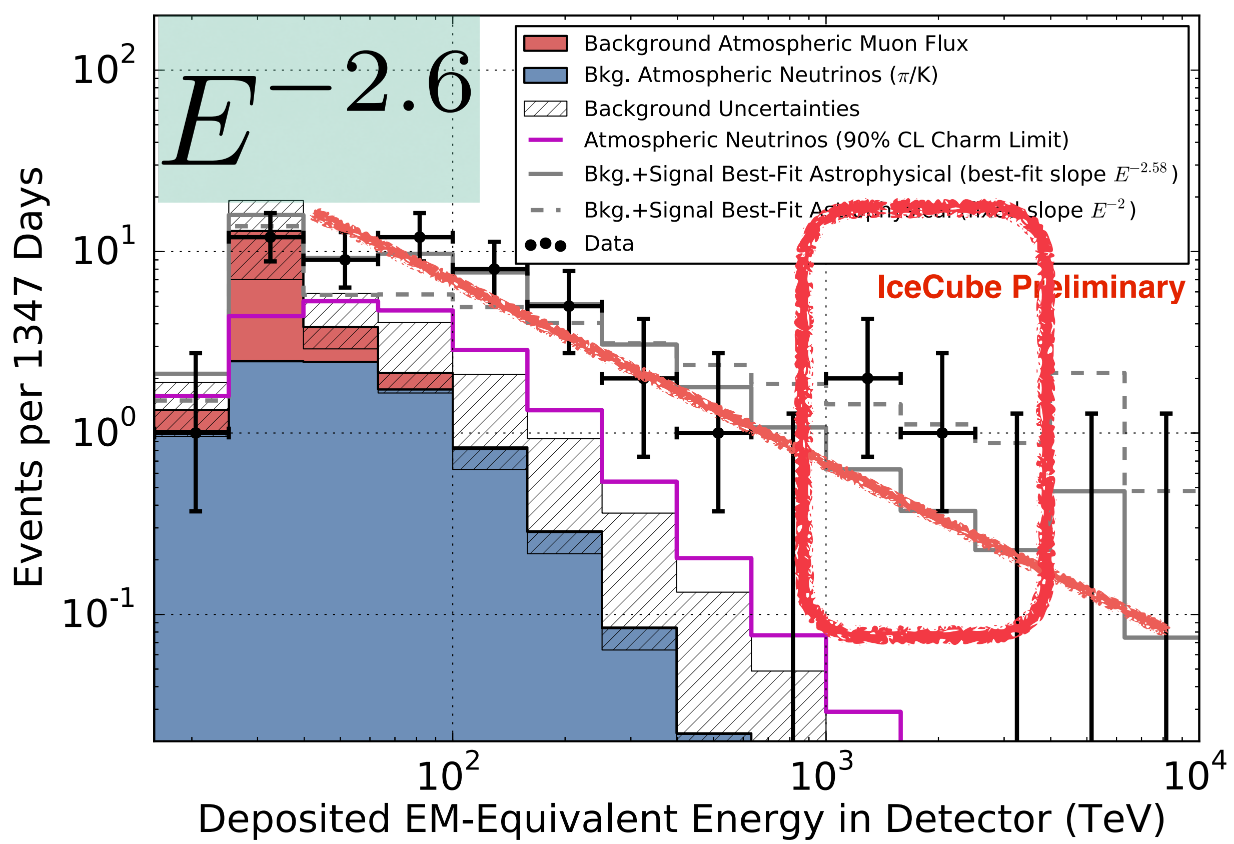


from Observation of Astrophysical Neutrinos in Four Years of IceCube Data
(released 21 Oct 2015) 1510.05223

low-energy O(100) TeV excess



from Observation of Astrophysical Neutrinos in Four Years of IceCube Data
(released 21 Oct 2015) 1510.05223

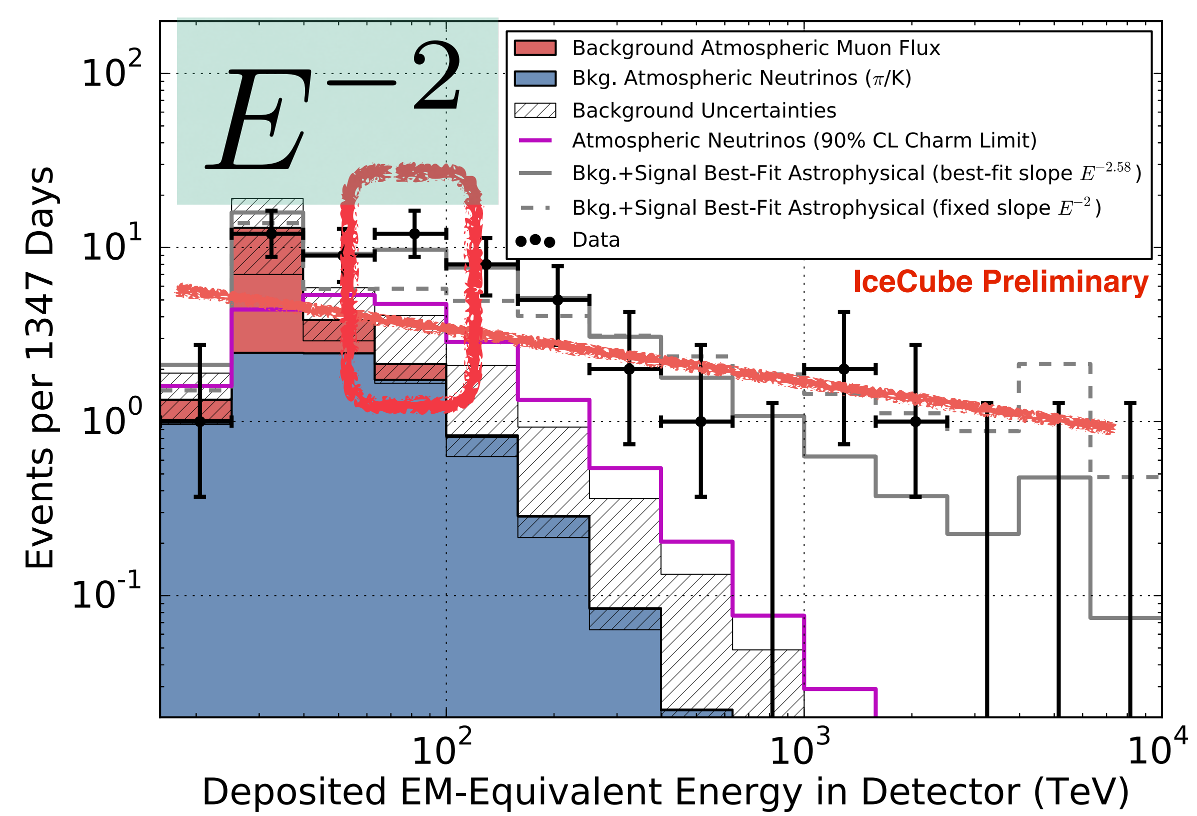


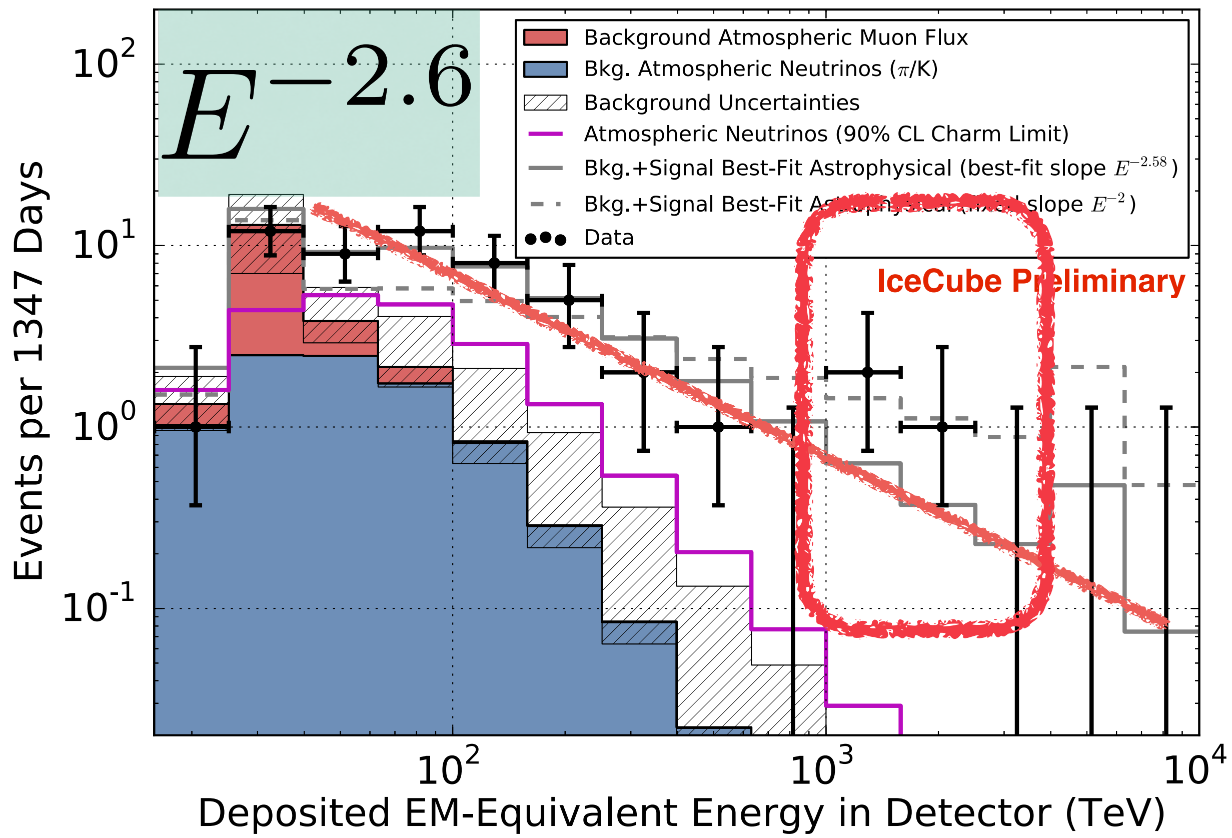
1st case

PeV excess

2nd case

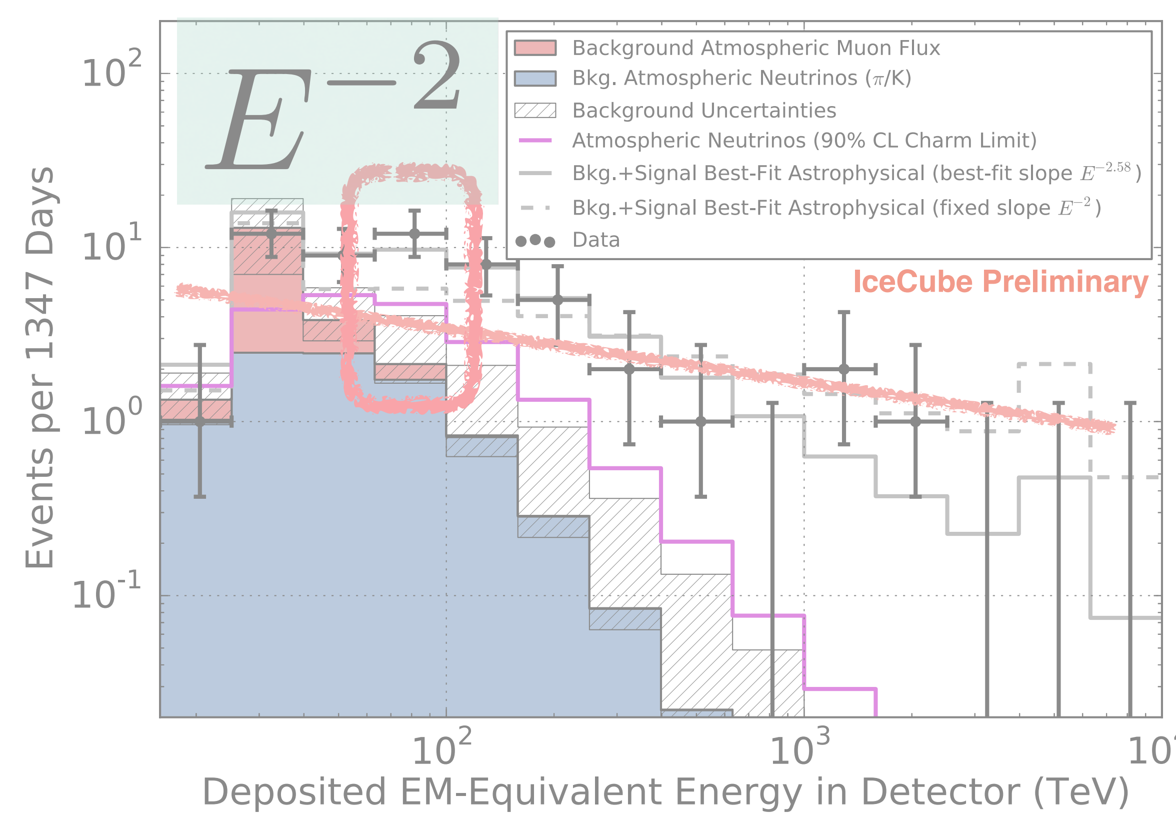
O(100) TeV excess



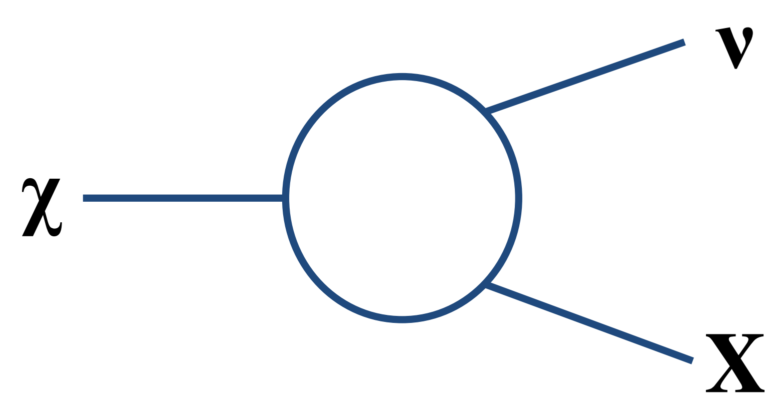


1st case
PeV excess

2nd case
O(100) TeV excess



PeV decaying Dark Matter



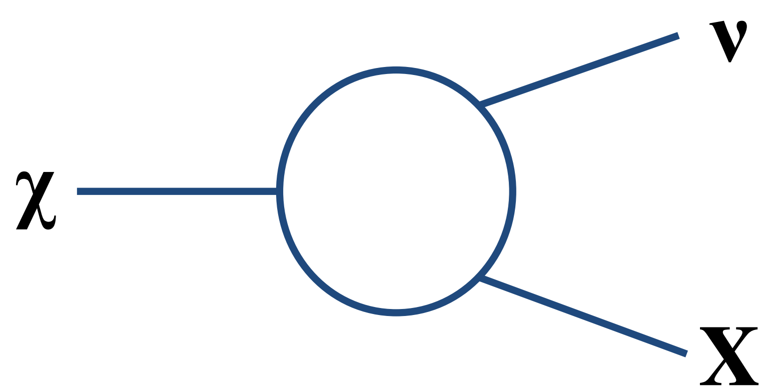
Decaying DM

Feldstein et al., PR D88 (2013)
Esmaili, Serpico, JCAP 1311
Bai et al., arXiv:1311.5864
Ema et al., PL B733 (2014)
Bhattacharya et al., JHEP 1406
Higaki et al., JHEP 1407
Ema et al., JHEP 1410

Rott et al., PR D92 (2015)
Esmaili et al., JCAP 1412
Fong et al., JHEP 1502
Dudas et al., PR D91 (2015)
Murase et al., PRL 115 (2015)
Ko, Tang, PL B751 (2015)
Aisati et al., arXiv:1510.05008

annihilating DM negligible
unless
enhancing DM density or boosted DM

PeV decaying Dark Matter



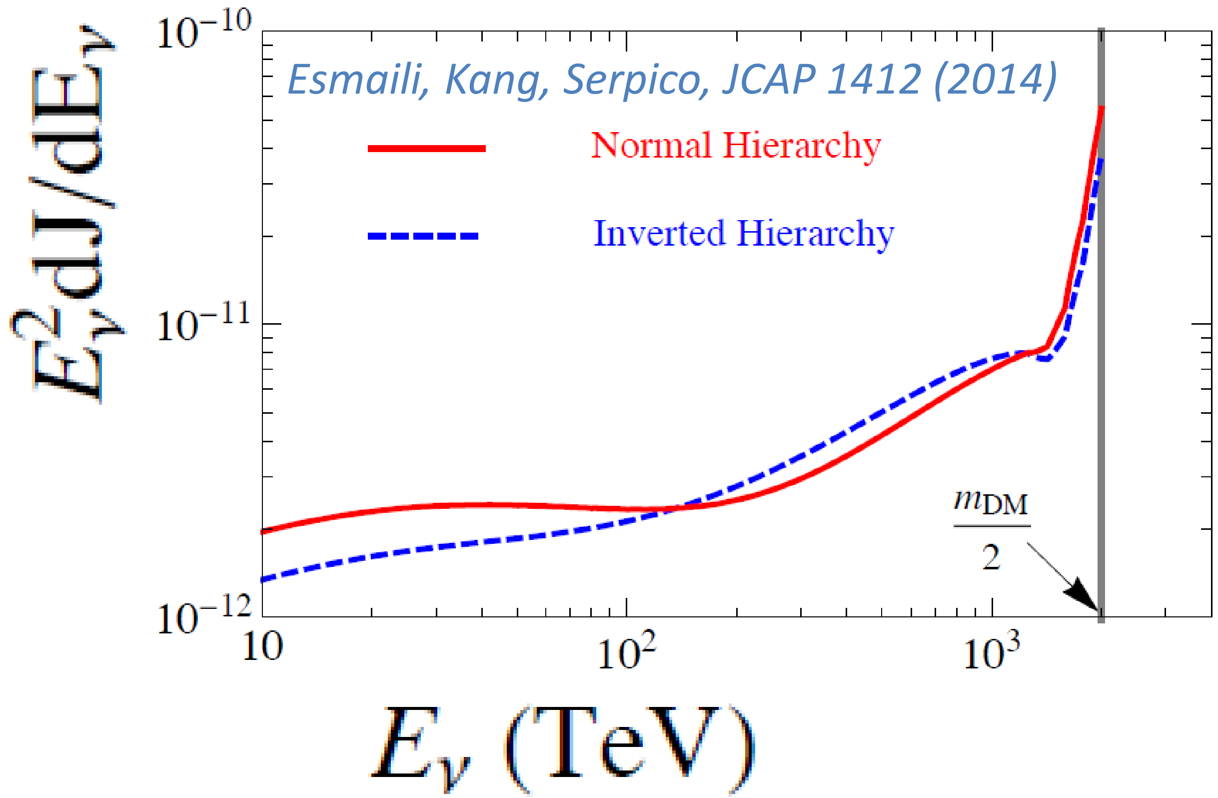
Decaying DM

Feldstein et al., PR D88 (2013)
Esmaili, Serpico, JCAP 1311
Bai et al., arXiv:1311.5864
Ema et al., PL B733 (2014)
Bhattacharya et al., JHEP 1406
Higaki et al., JHEP 1407
Ema et al., JHEP 1410
Rott et al., PR D92 (2015)
Esmaili et al., JCAP 1412
Fong et al., JHEP 1502
Dudas et al., PR D91 (2015)
Murase et al., PRL 115 (2015)
Ko, Tang, PL B751 (2015)
Aisati et al., arXiv:1510.05008

2-bodies decay

3-bodies decay

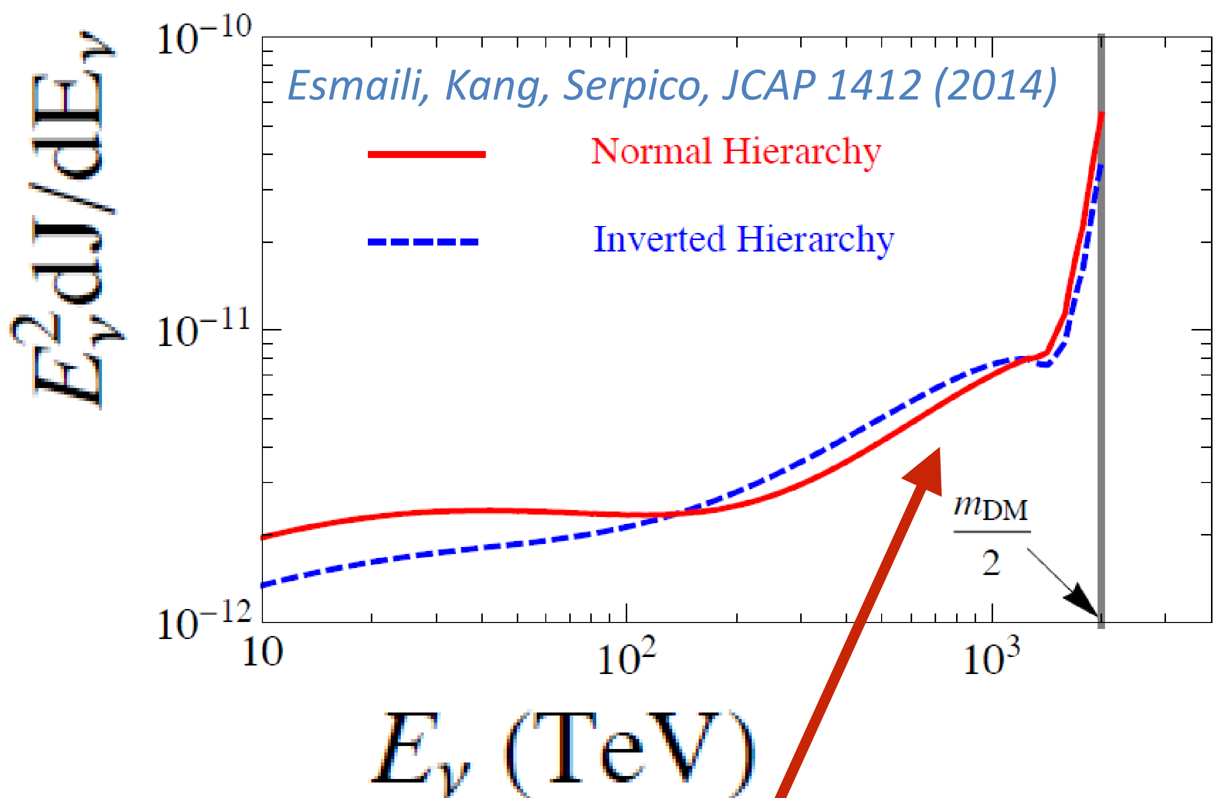
PeV decaying Dark Matter



2-bodies decay

$$\mathcal{L} \supset g\,\overline{L} H^c \chi$$

PeV decaying Dark Matter

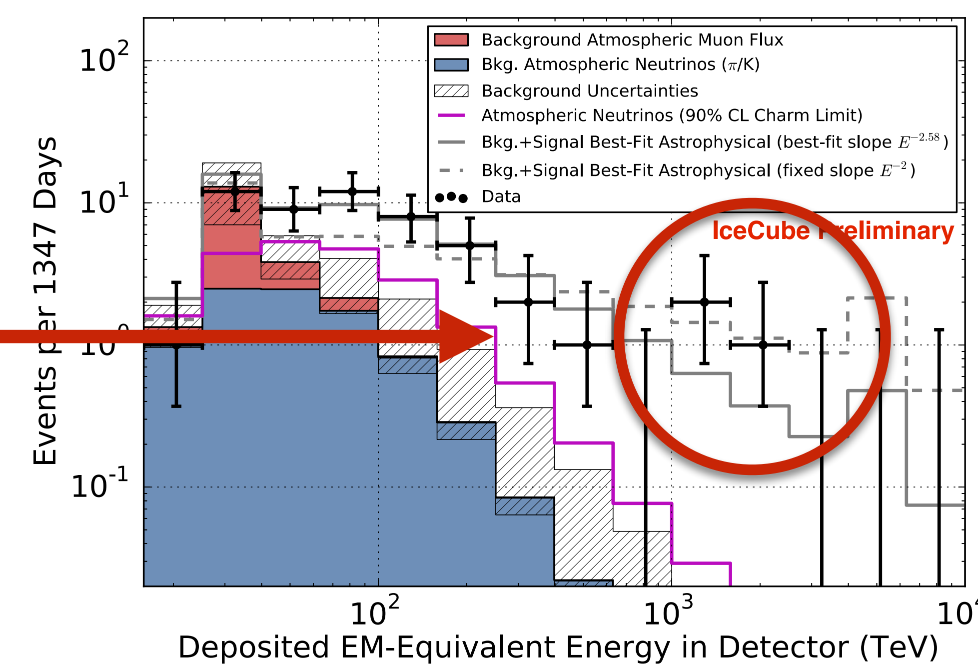


2-bodies decay

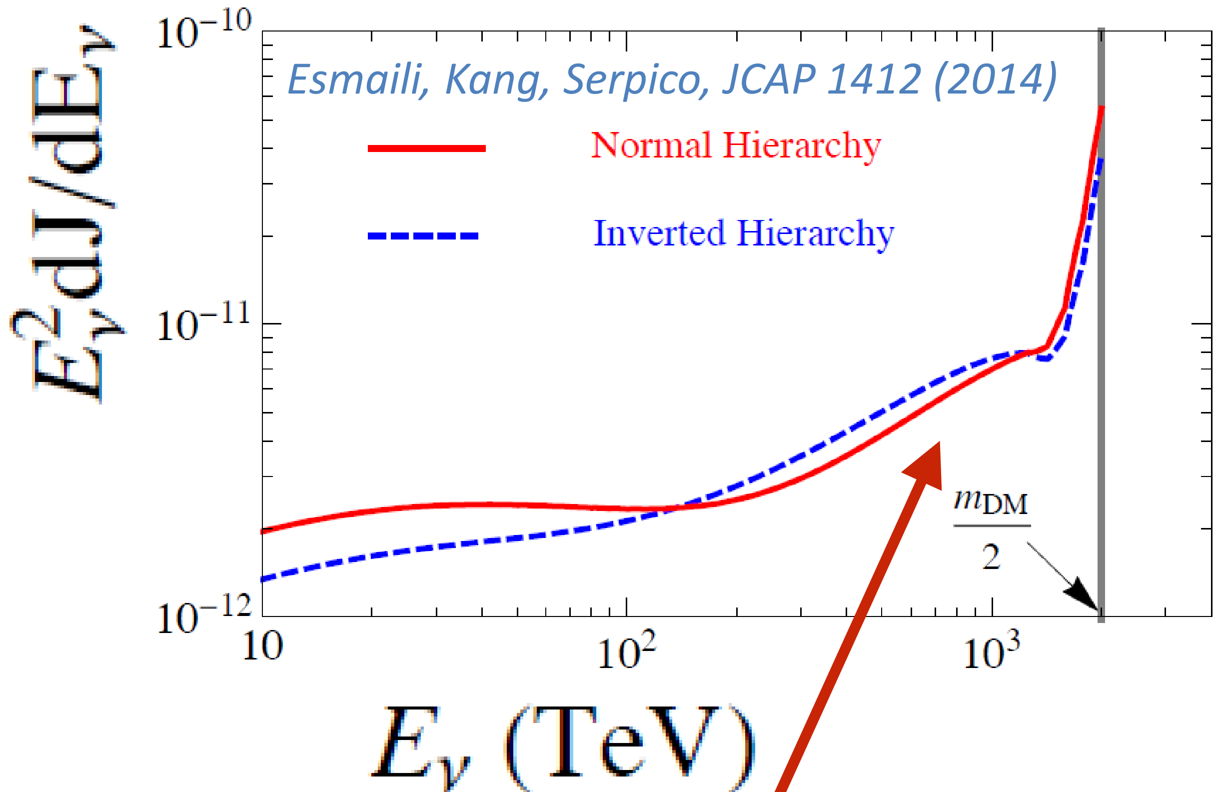
$$\mathcal{L} \supset g\,\overline{L} H^c \chi$$

sharp pick!

in contrast with data



PeV decaying Dark Matter



sharp pick!

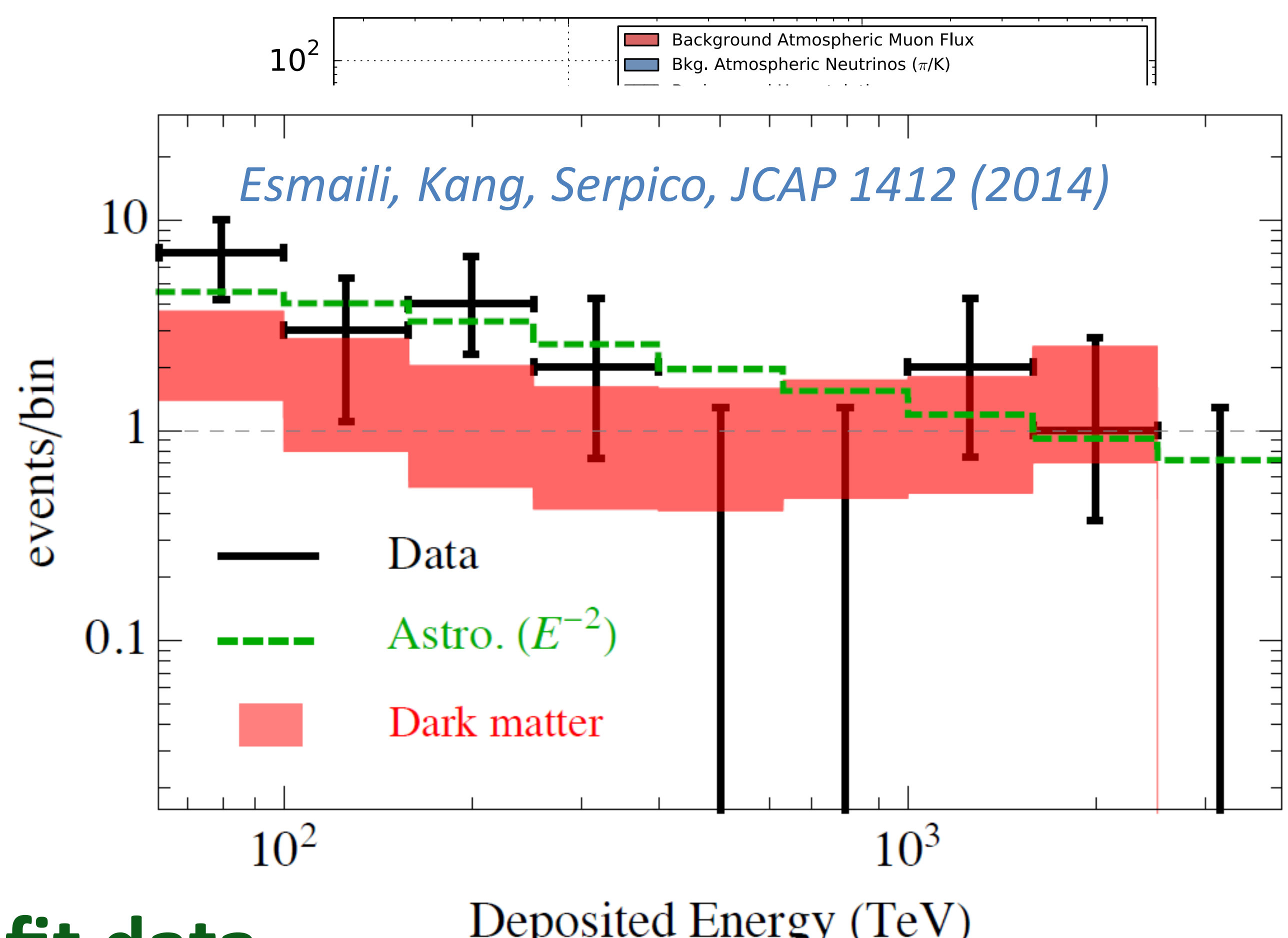
in contrast with data

2-bodies decay

$$\mathcal{L} \supset g\,\overline{L}H^c\chi$$

$\chi \to l^\pm W^\mp$
$\chi \to \nu_l Z$
$\chi \to \nu_l h$

→ **quarks**

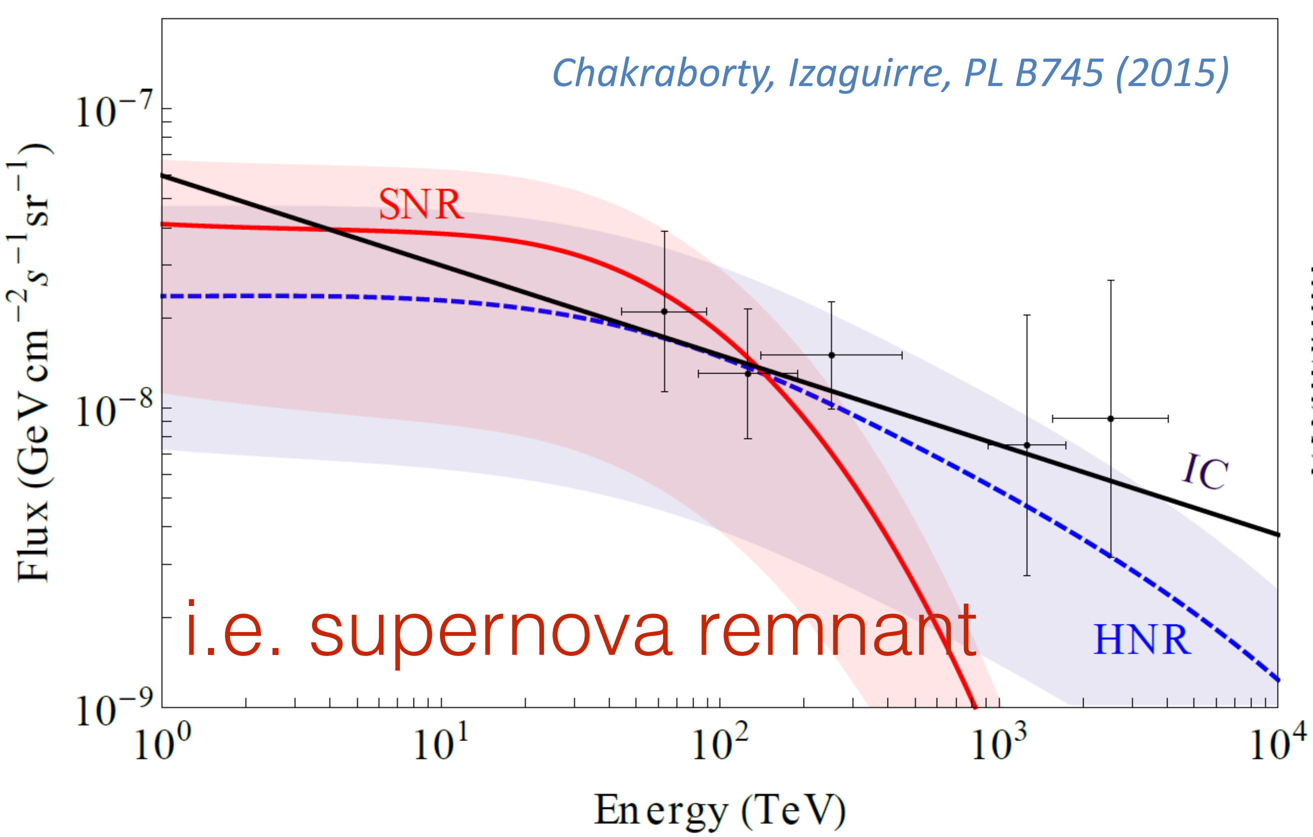


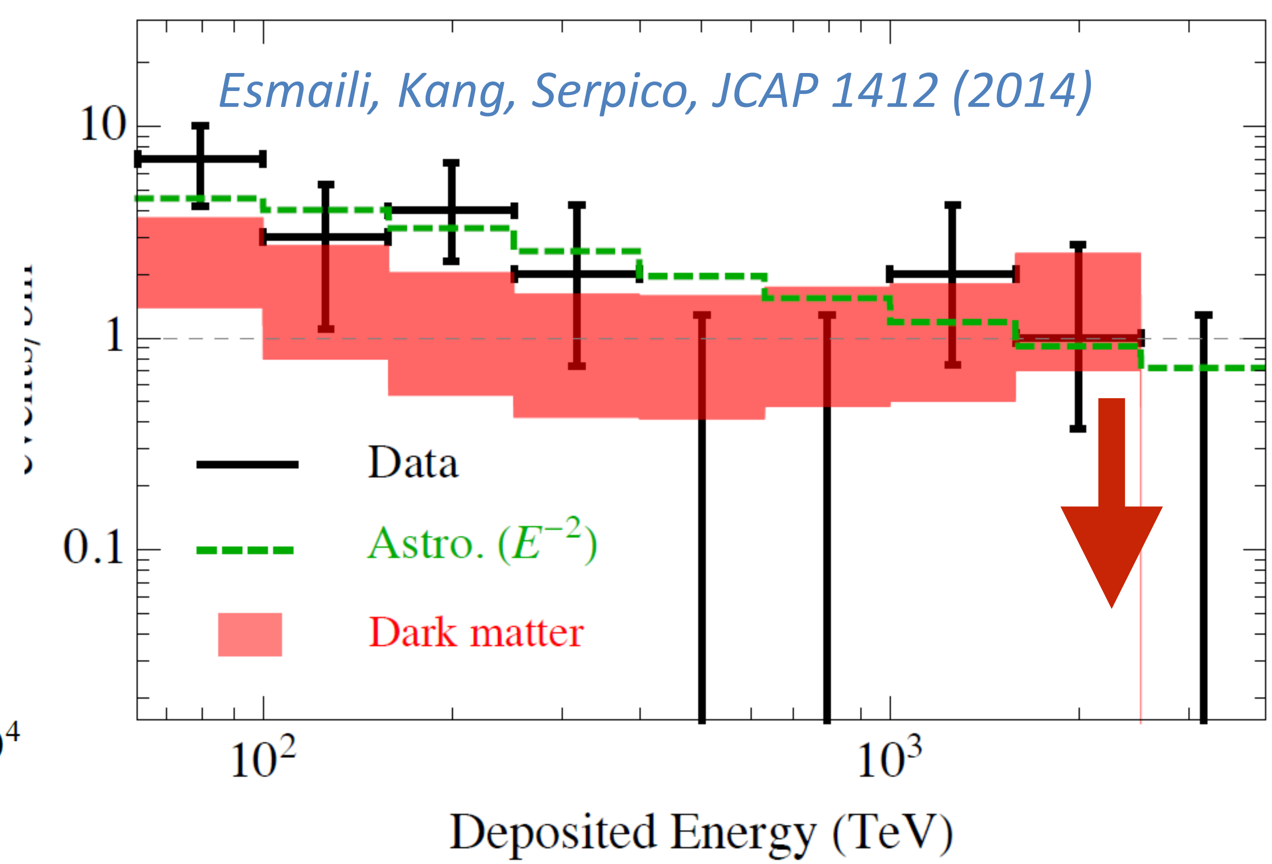
secondary neutrinos produced by quarks allow to fit data

PeV decaying Dark Matter

if at low energy (10-100 TeV) it is
present some astrophysical source

2-bodies decay models
could overshot data and there could be some **tension**





PeV decaying Dark Matter

Boucenna et al, JCAP 1502

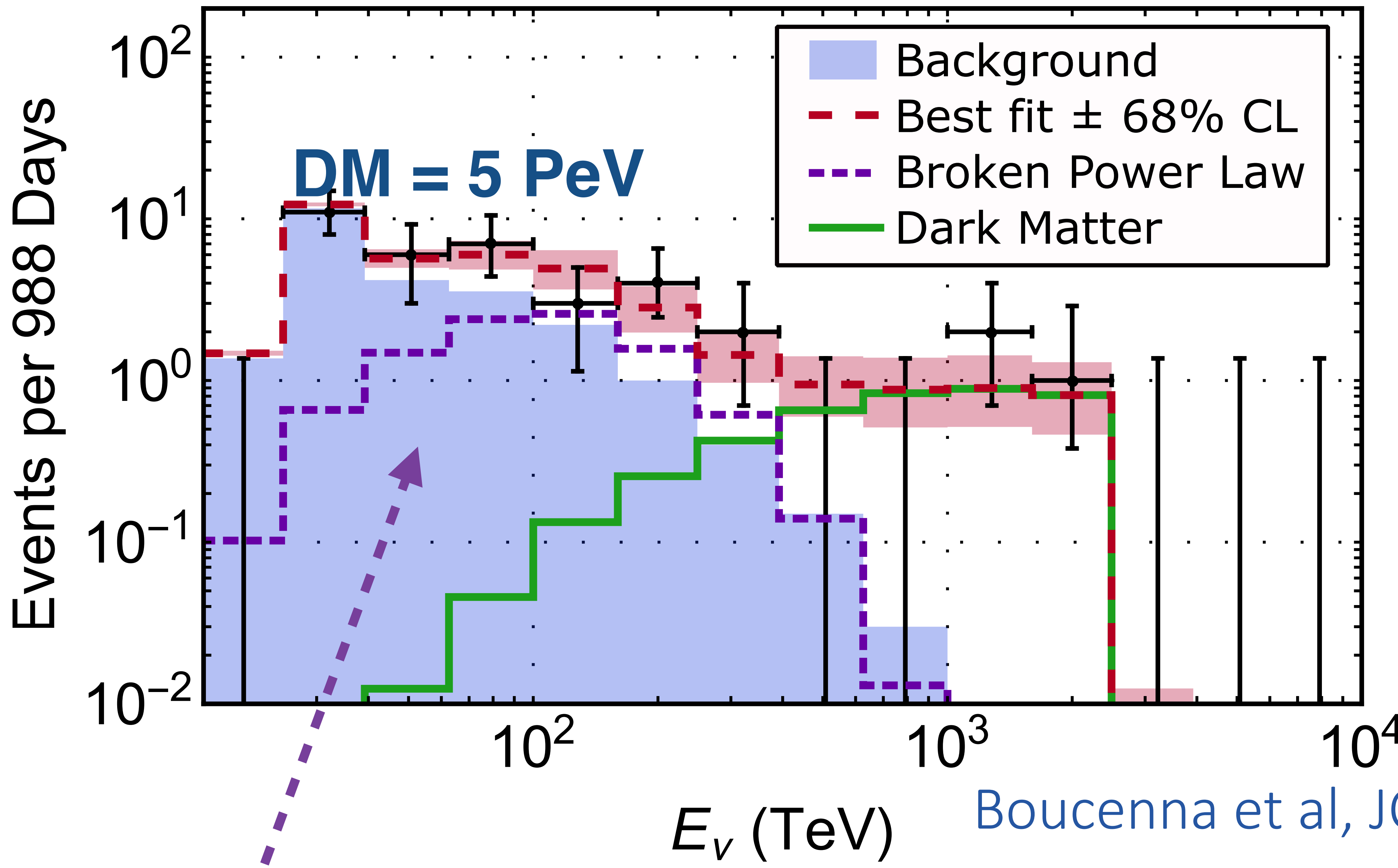
leptophillic	3-bodies decay
↓	↓
no many secondary neutrinos from quarks	easily fit the 1 PeV+2 Pev events

the only possible operator is (in the Standard Model)

$$\chi \, \overline{L} \, \overline{L} \, e_R$$

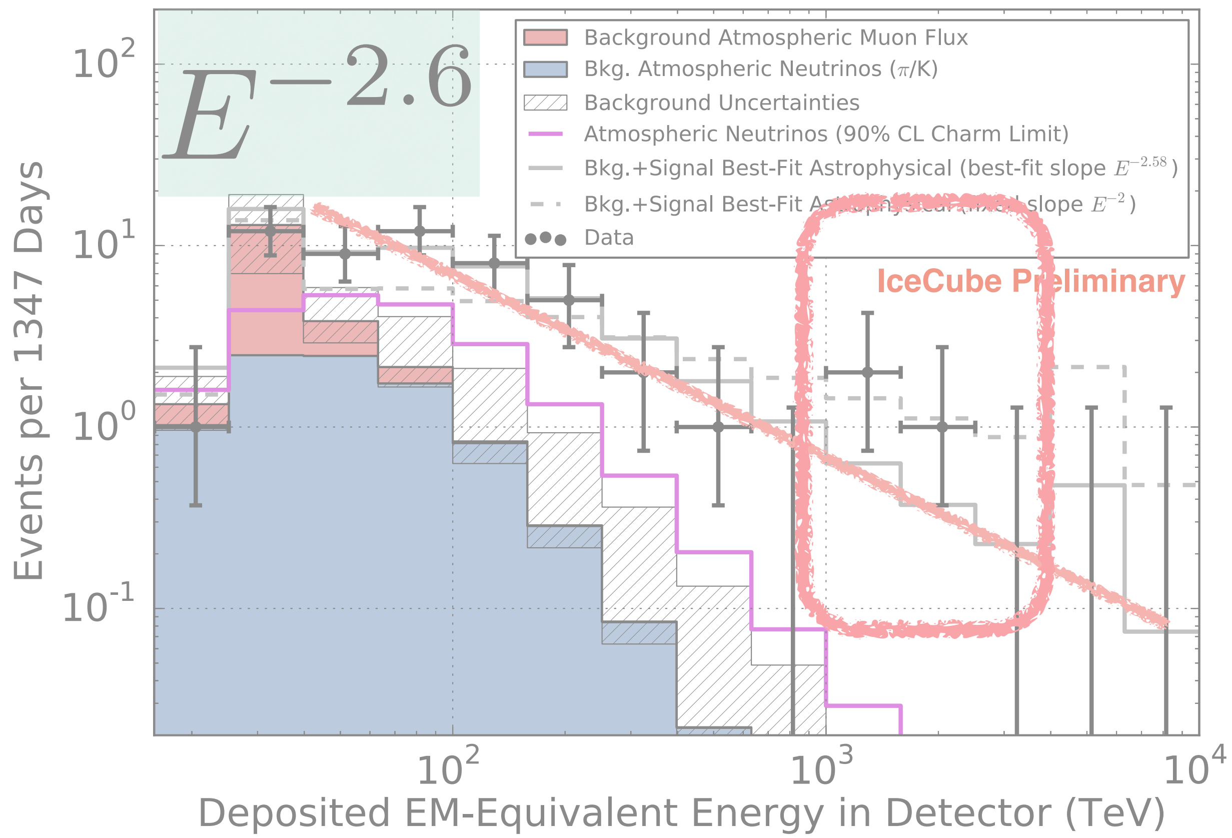
can have flavor symmetry origin, Haba et al, PLB695 2011

PeV Dark Matter: leptophillic 3-bodies decay



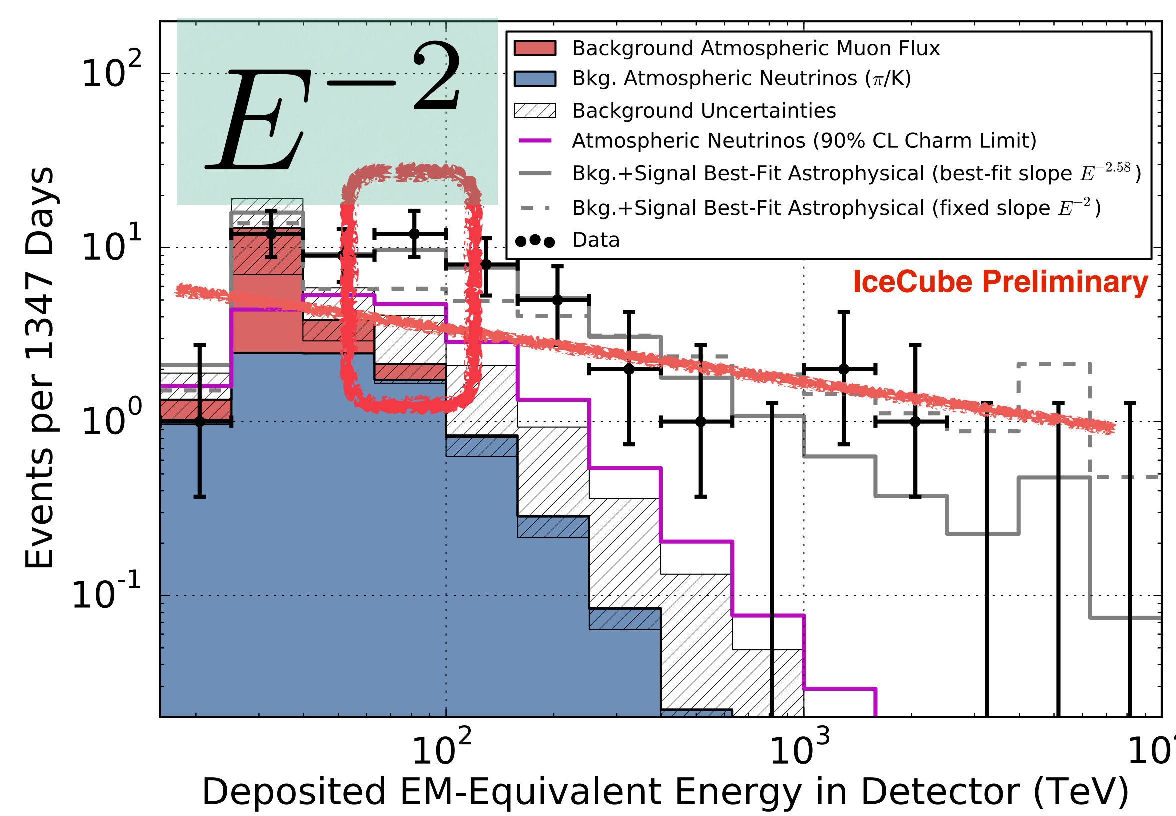
Boucenna et al, JCAP 1502

Broken power-law with spectral index 2

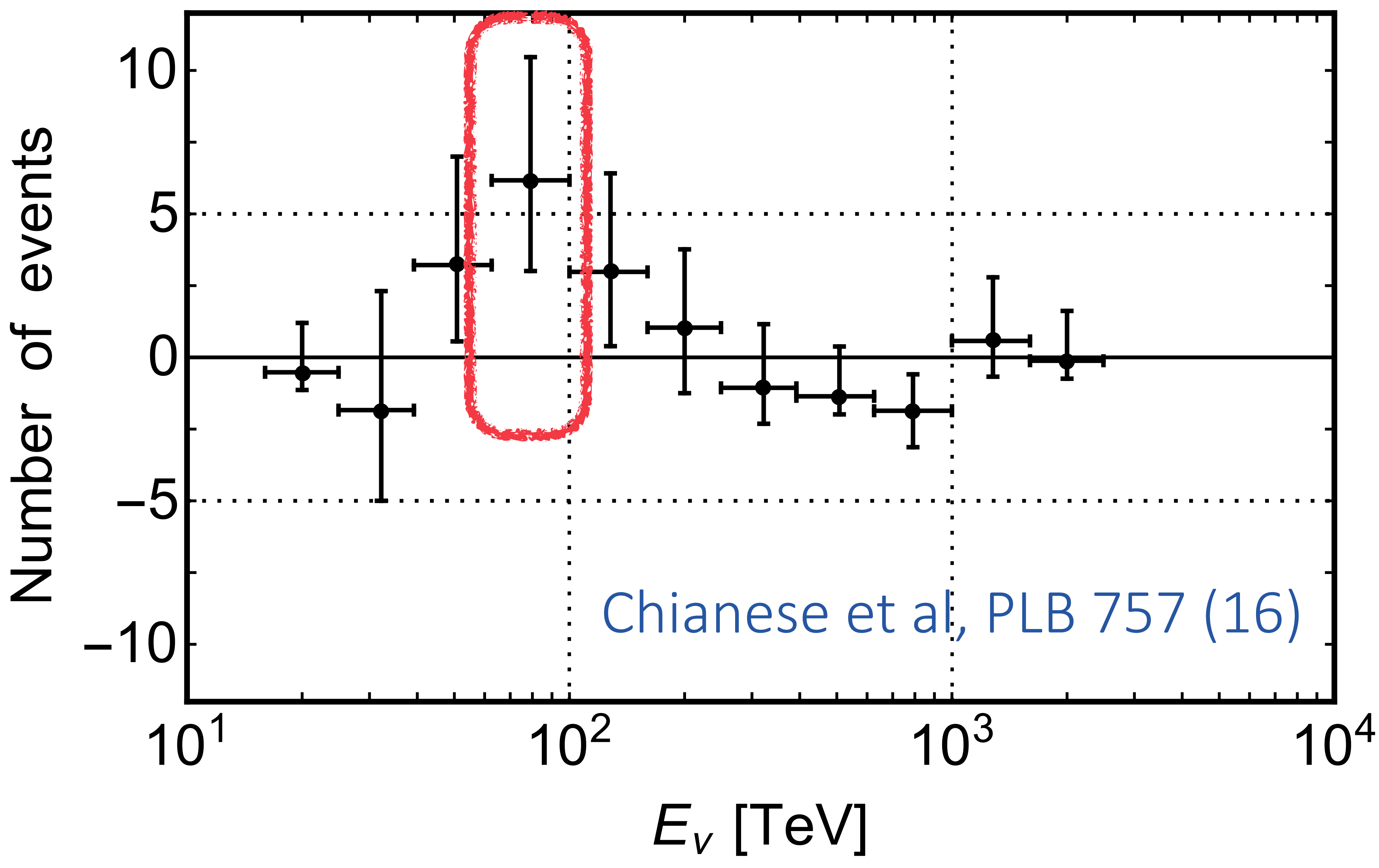


1st case
PeV excess

2nd case
O(100) TeV excess



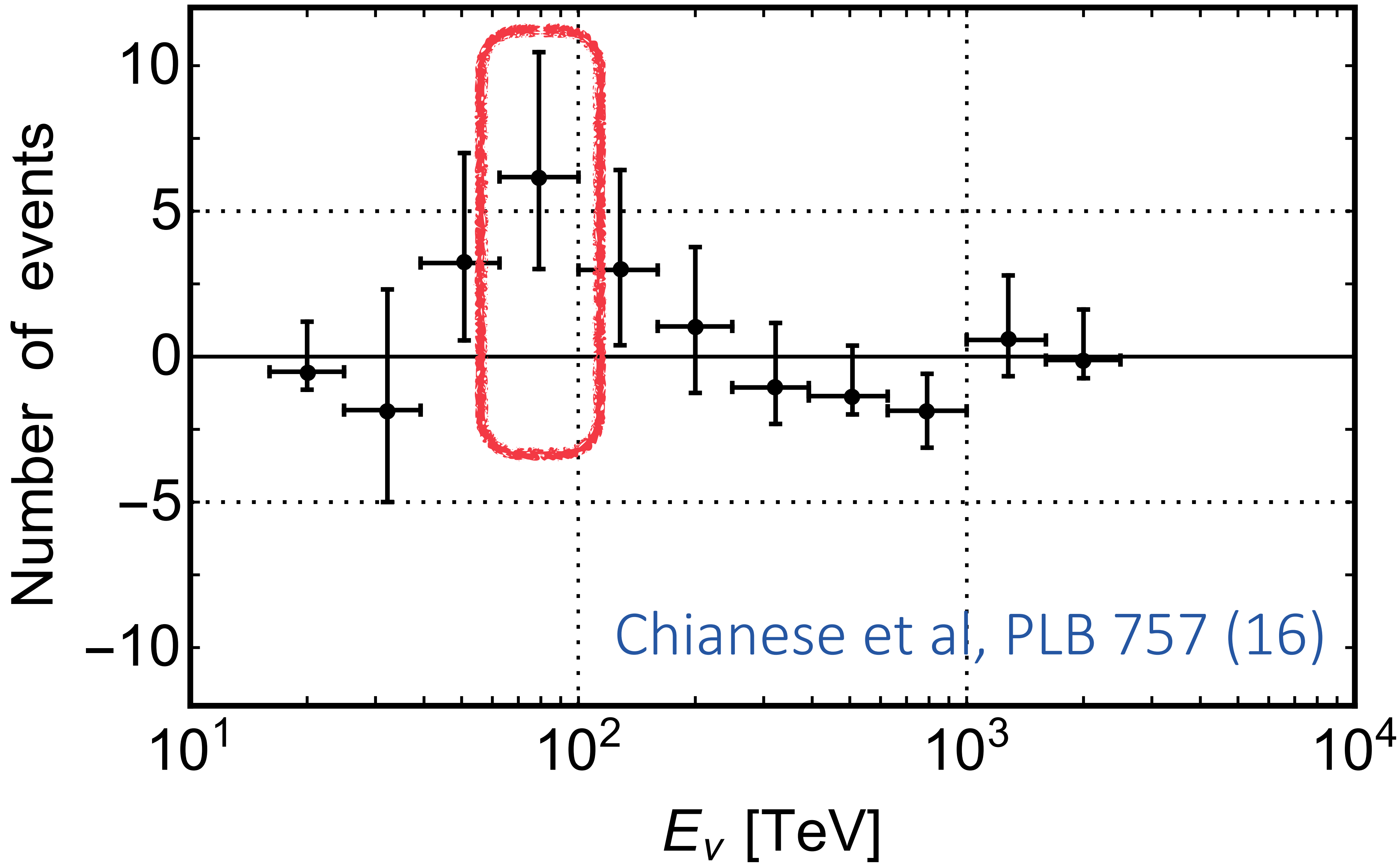
low-energy O(100) TeV excess



about 2-sigma excess with respect the sum of:

- background (atmospheric neutrino and muons)
- astrophysical component with **spectral index -2**

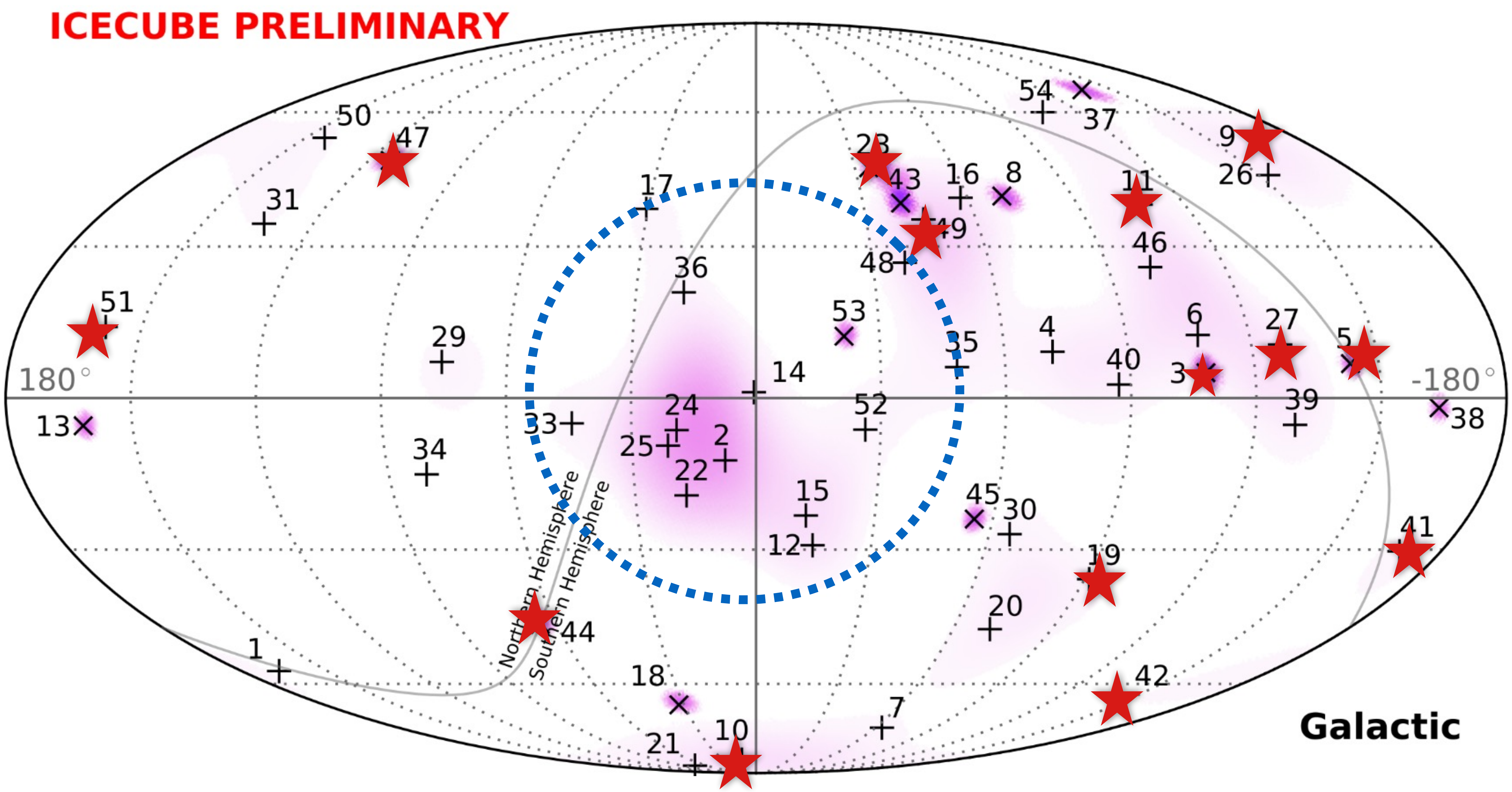
low-energy O(100) TeV excess



- we focus on the events in the energy range 60-100 TeV

- we analyze the angular distribution of these events

Where are the events in the energy range 60-100 TeV?



Statistical tests

Scenario		KS	AD
Astrophysics	Gal. plane		
	Iso. dist.		
DM decay	NFW		
	Isoth.		
DM annih. $\Delta_0^2 = 10^4$	NFW		
	Isoth.		
DM annih. $\Delta_0^2 = 10^6$	NFW		
	Isoth.		
DM annih. $\Delta_0^2 = 10^8$	NFW		
	Isoth.		

We perform two *one-dimensional* statistical tests:

- Kolmogorov Smirnov (KS)
- Anderson Darling (AD)

Astrophysical & DM scenarios

Scenario		KS	AD
Astrophysics	Gal. plane		
	Iso. dist.		
DM decay	NFW		
	Isoth.		
DM annih. $\Delta_0^2 = 10^4$	NFW		
	Isoth.		
DM annih. $\Delta_0^2 = 10^6$	NFW		
	Isoth.		
DM annih. $\Delta_0^2 = 10^8$	NFW		
	Isoth.		

galactic source: galactic plane

extra-galactic source:
isotropic distribution

Astrophysical & DM scenarios

Scenario		KS	AD
Astrophysics	Gal. plane		
	Iso. dist.		
DM decay	NFW		
	Isoth.		
DM annih. $\Delta_0^2 = 10^4$	NFW		
	Isoth.		
DM annih. $\Delta_0^2 = 10^6$	NFW		
	Isoth.		
DM annih. $\Delta_0^2 = 10^8$	NFW		
	Isoth.		

decaying DM

annihilating DM

Δ_0^2 clumpiness factor (range 10^4 to 10^8)

$$p^{\rm ann}(\cos\theta) \propto \int_0^\infty \rho_h^2[r(s,\cos\theta)]\mathrm{d}s + (\Omega_{\rm DM}\rho_c)^2\,\Delta_0^2\beta_\alpha$$

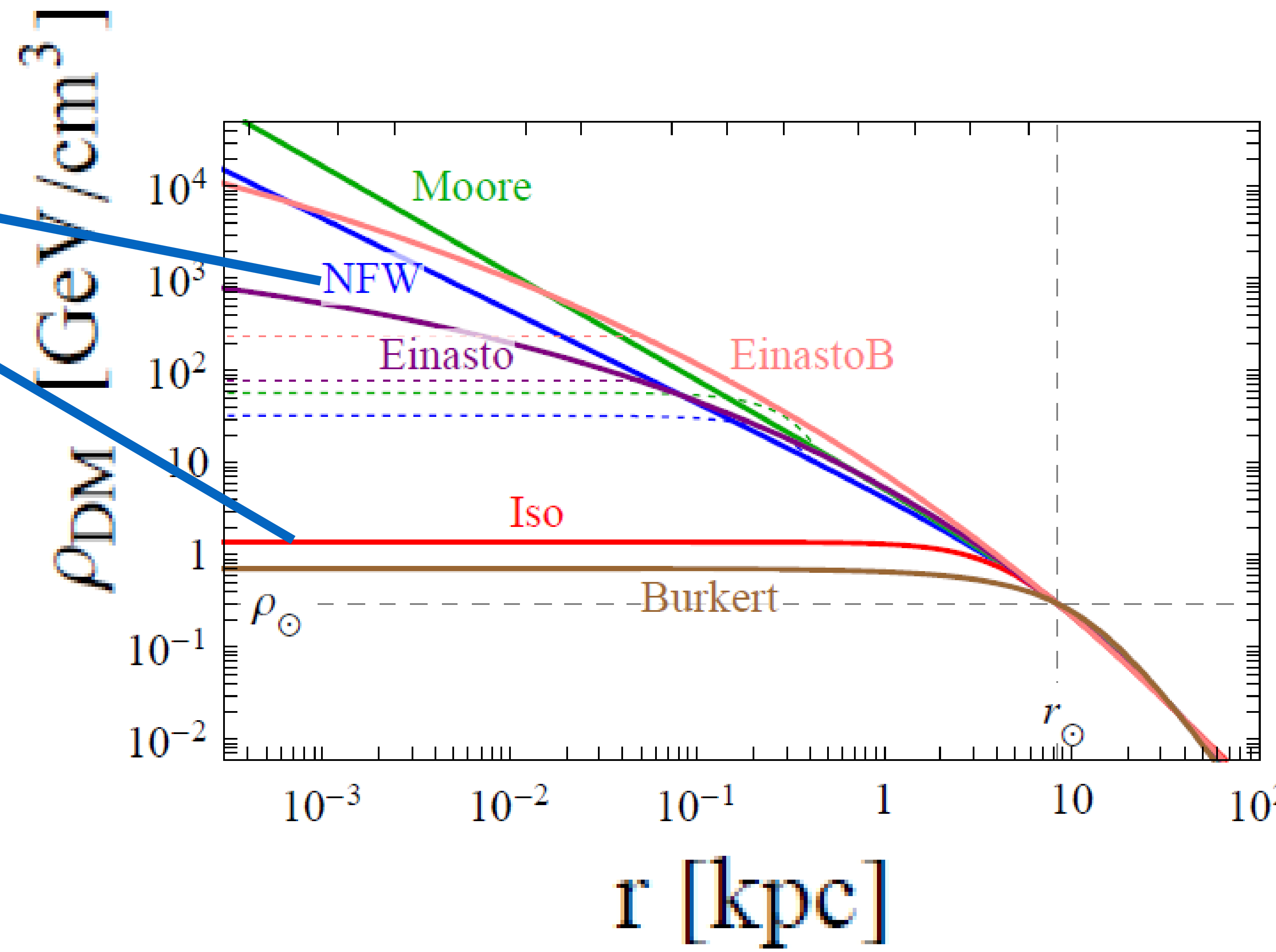
Hooper, Serpico, JCAP 0706

Cirelli et al, JCAP 1103

....

Astrophysical & DM scenarios

Scenario		KS	AD
Astrophysics	Gal. plane		
	Iso. dist.		
DM decay	NFW		
	Isoth.		
DM annih. $\Delta_0^2 = 10^4$	NFW		
	Isoth.		
DM annih. $\Delta_0^2 = 10^6$	NFW		
	Isoth.		
DM annih. $\Delta_0^2 = 10^8$	NFW		
	Isoth.		



Cirelli et al., JCAP 1103 (2011)

Results: p-values

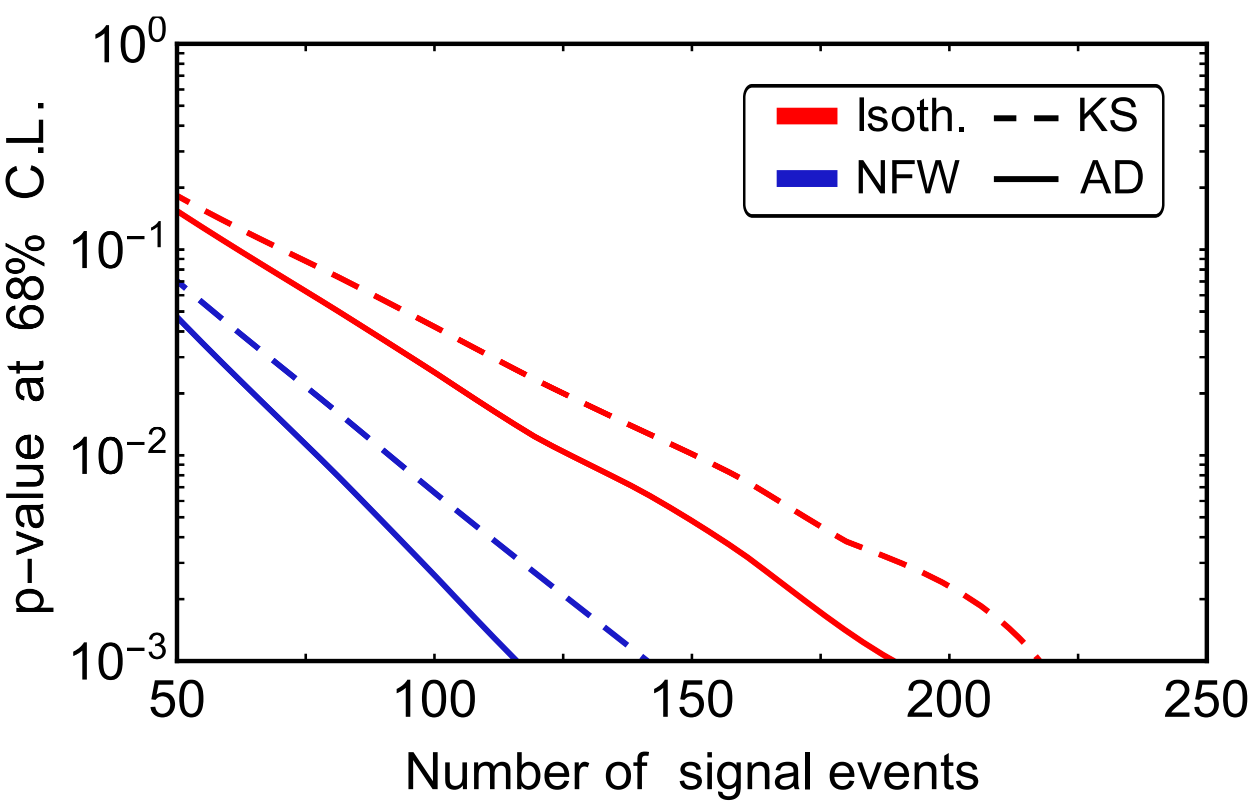
Scenario		KS	AD
Astrophysics	Gal. plane	0.007 - 0.008	not defined
	Iso. dist.	0.20 - 0.55	0.17 - 0.54
DM decay	NFW	0.06 - 0.16	0.03 - 0.14
	Isoth.	0.08 - 0.22	0.05 - 0.19
DM annih. $\Delta_0^2 = 10^4$	NFW	$(0.3 - 0.9) \times 10^{-4}$	$(0.3 - 3.8) \times 10^{-4}$
	Isoth.	$(0.9 - 2.8) \times 10^{-3}$	$(1.0 - 5.0) \times 10^{-3}$
DM annih. $\Delta_0^2 = 10^6$	NFW	0.02 - 0.05	0.02 - 0.07
	Isoth.	0.10 - 0.28	0.08 - 0.29
DM annih. $\Delta_0^2 = 10^8$	NFW	0.19 - 0.54	0.17 - 0.53
	Isoth.	0.20 - 0.55	0.17 - 0.54

- **Disfavor** the correlation with the galactic plane
- Annihilating DM **excluded** for small clumpiness factor in both cases, NFW and Isothermal DM distributions

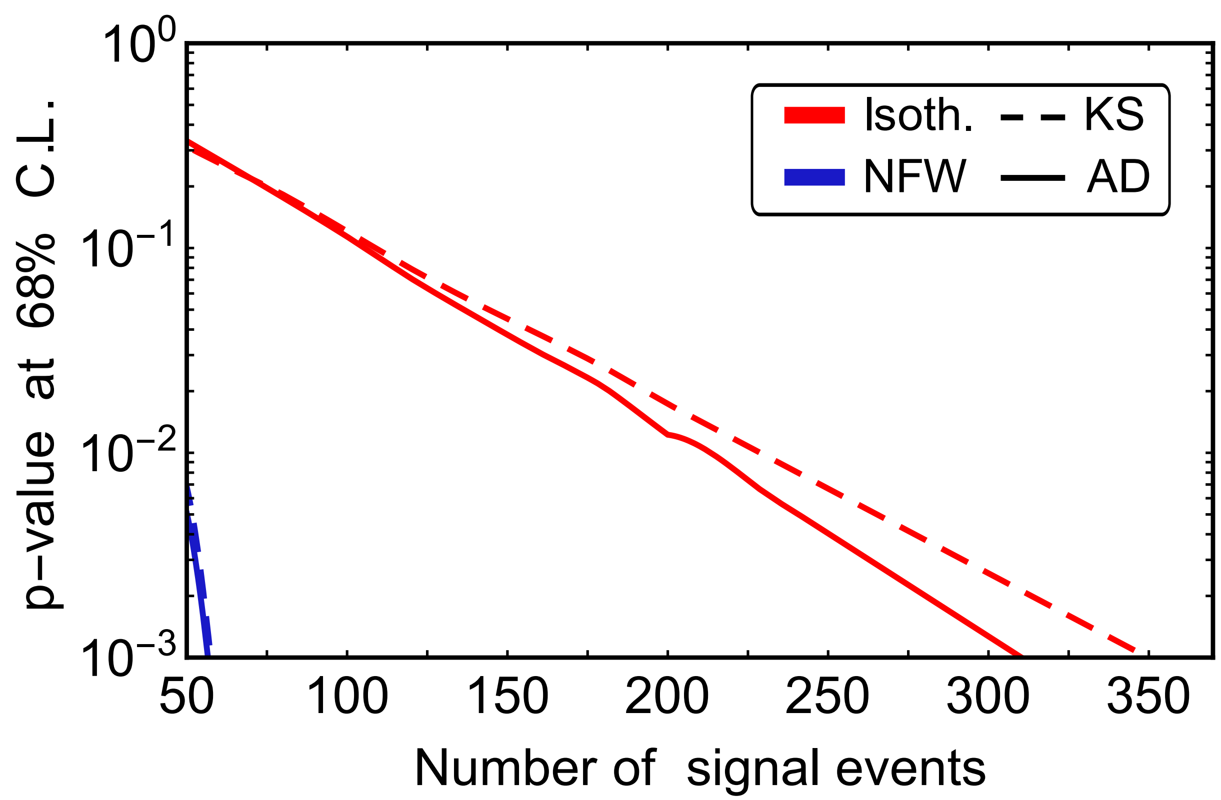
Forecast

We generate 10^5 sets of data according to the isotropic distribution

Then we perform the statistical tests under decaying or annihilating DM null hypothesis

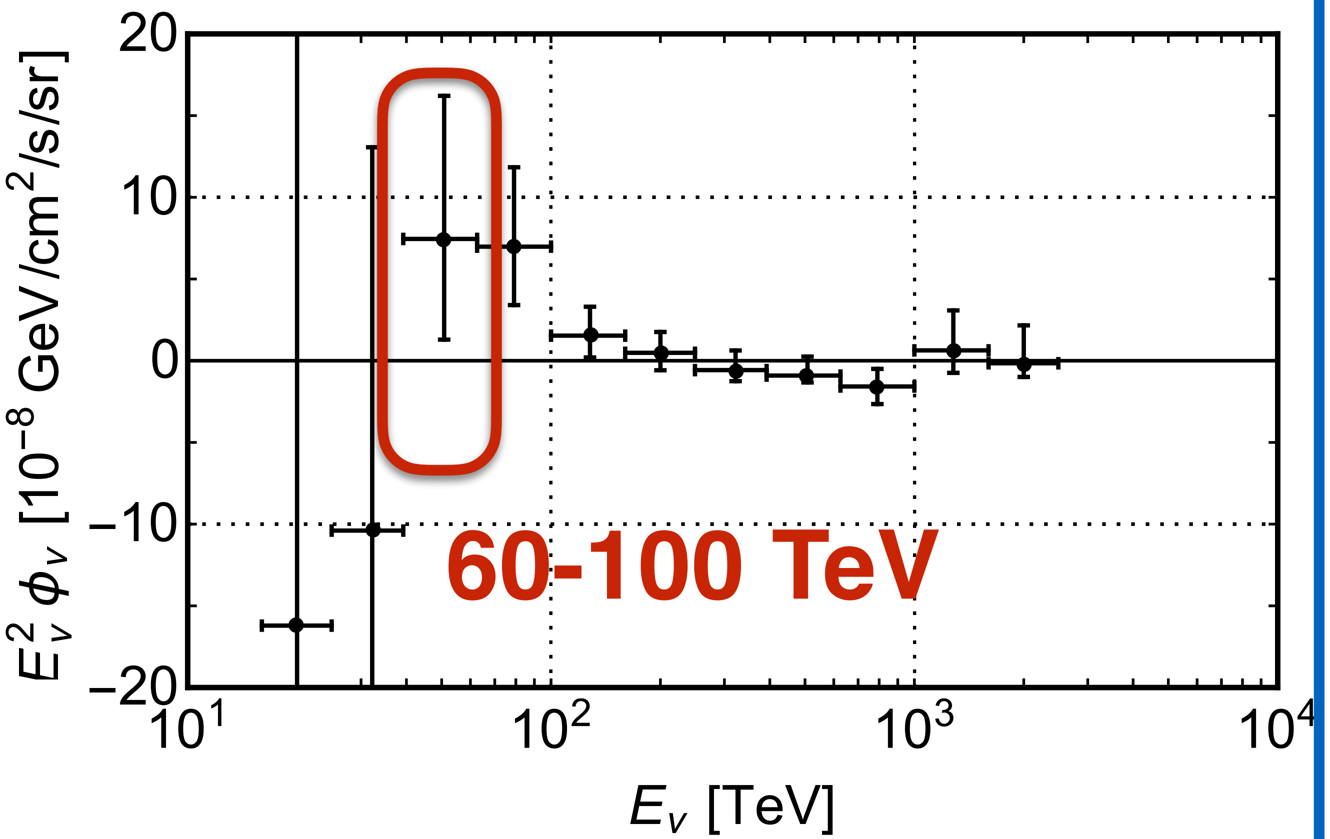


decaying DM



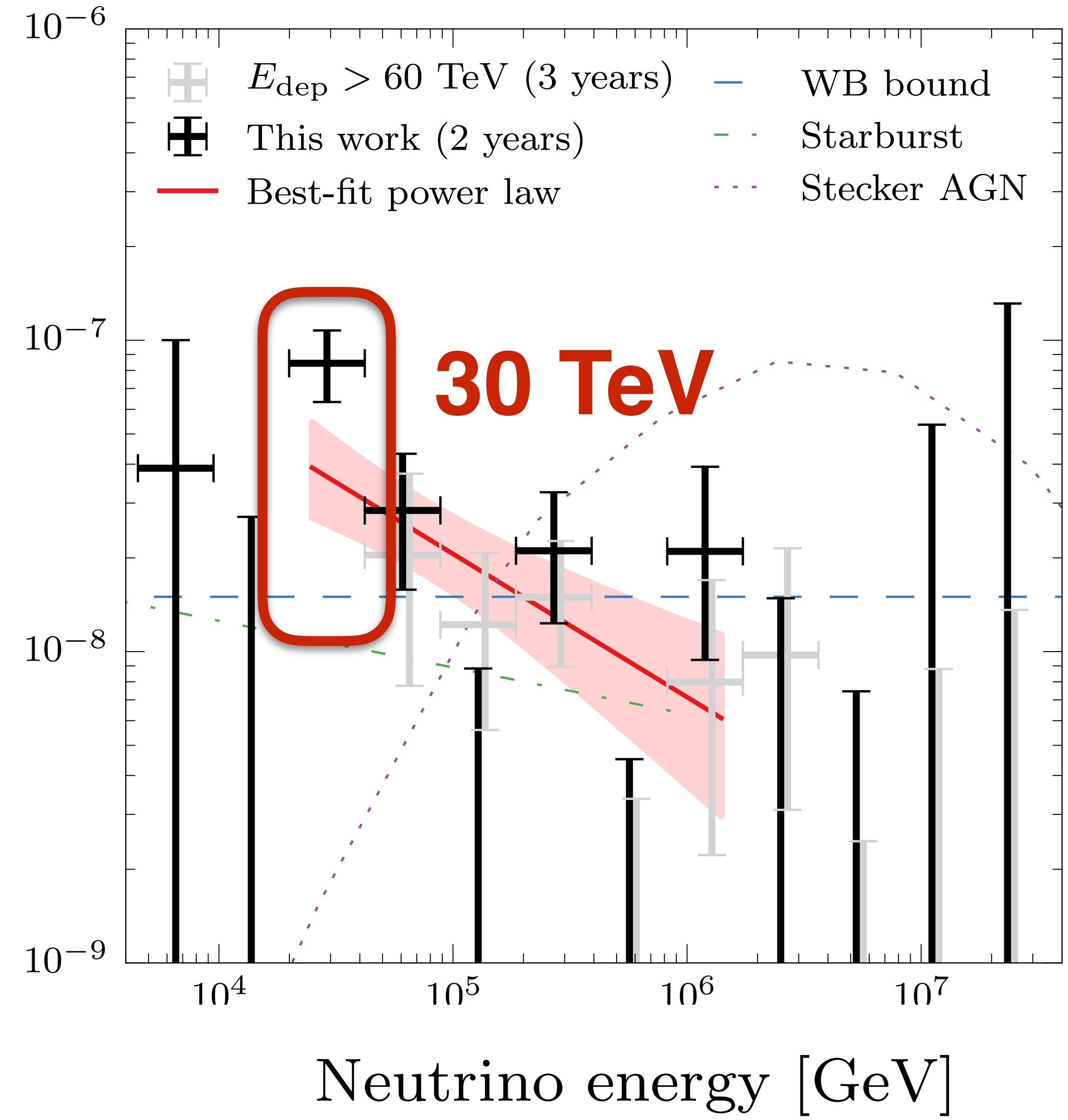
annihilating DM

HESE



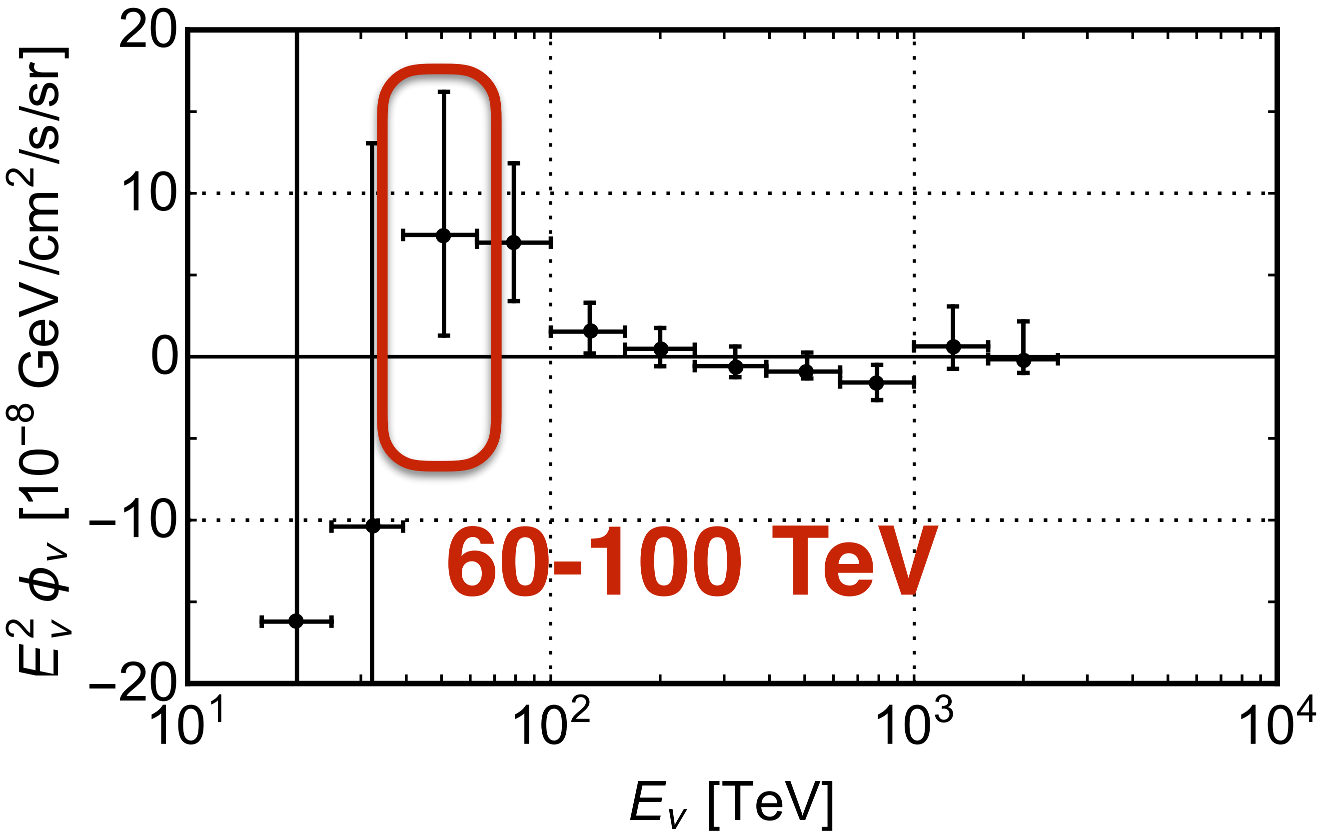
Chianese et al, PLB 757 (16)

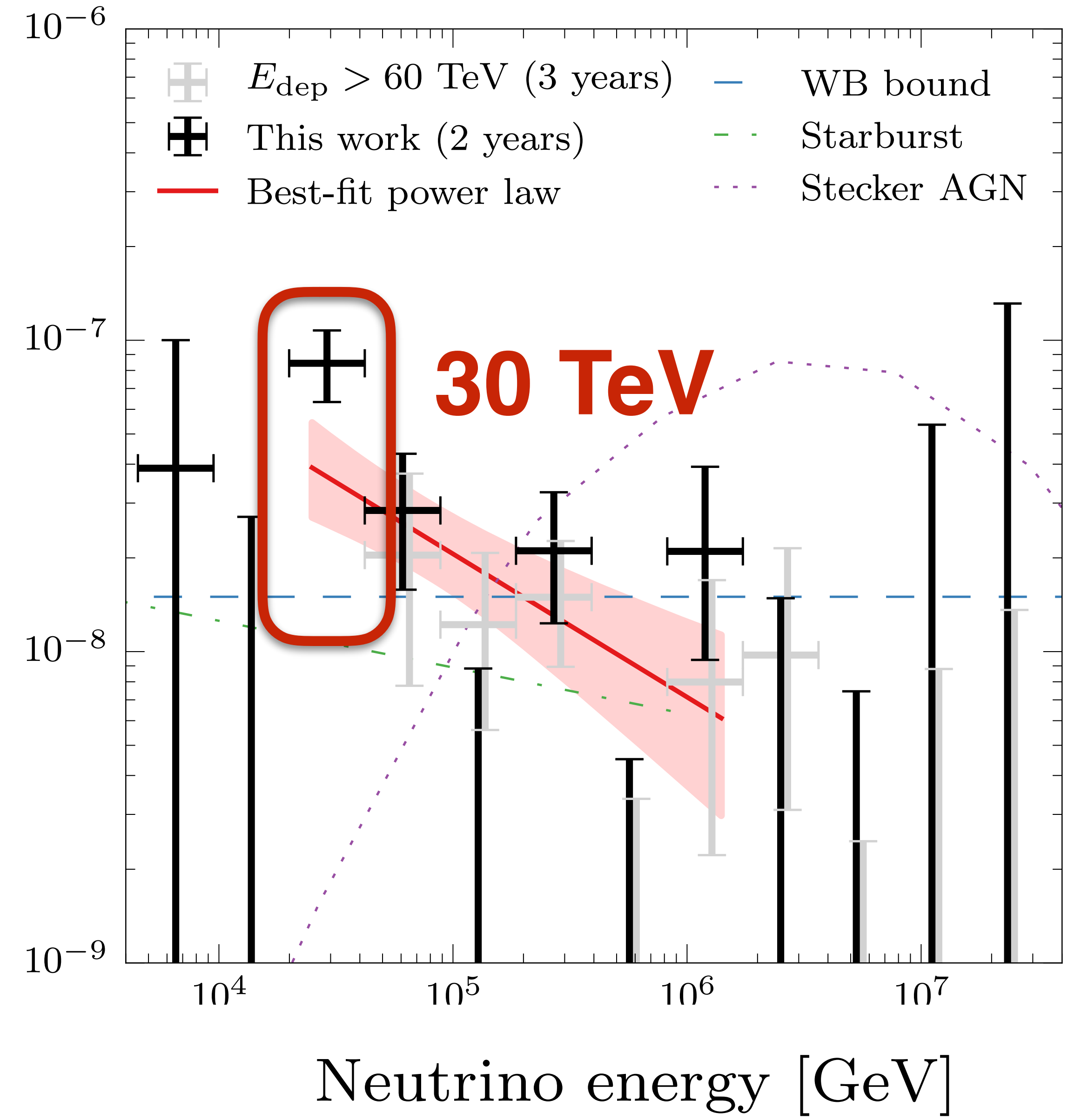
MESE



IceCube 1410.1749

HESE **combining** MESE





work in progress!

Conclusions

depending on the astrophysical power law spectral index we can have some hints of high-energy (PeV) or low-energy (30-100 TeV) excess in IceCube data

in particular if IceCube events have p-p hadronuclear origin
we expect a spectral index of order 2 - 2.2
(not far from Fermi acceleration mechanism)

in this case it exists an excess at low energy in IceCube data
(that could be also a statistical fluctuation)

and hopefully could be some signal of Dark Matter

in any case, Dark Matter could play an important rule
in undestanding neutrino telescope data

Conclusions

depending on the astrophysical power law spectral index we can have some hints of high-energy (PeV) or low-energy (30-100 TeV) excess in IceCube data

in particular if IceCube events have p-p hadronuclear origin
we expect a spectral index of order 2 - 2.2
(not far from Fermi acceleration mechanism)

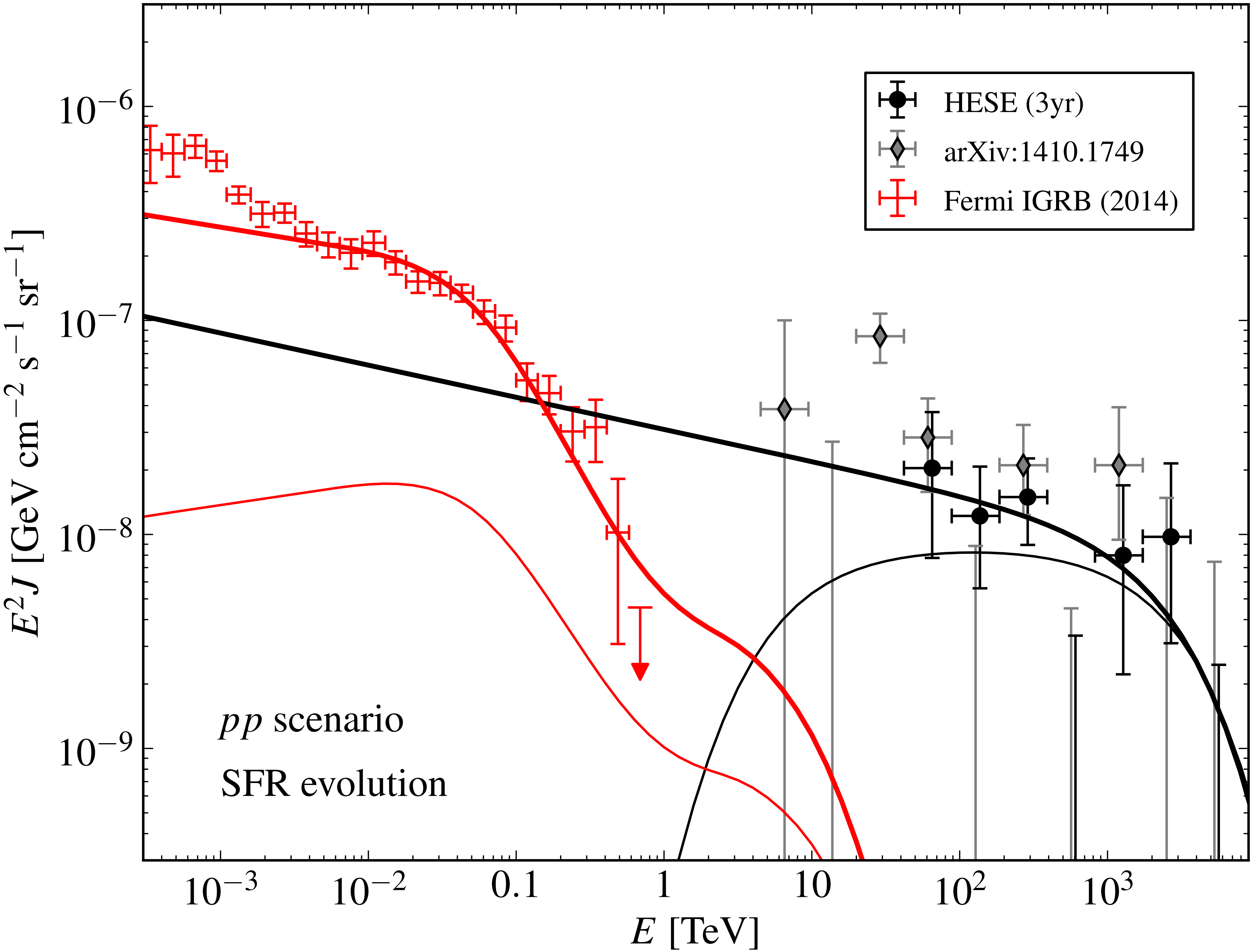
in this case it exists an excess at low energy in IceCube data
(that could be also a statistical fluctuation)

and hopefully could be some signal of Dark Matter

in any case, Dark Matter could play an important rule
in undestanding neutrino telescope data

thanks

backup slides



HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3
E [TeV]
pp scenario
SFR evolution

MESE: comment on North-South model and Dark Matter

Best-Fit Parameter Values for the North-South Model.

Parameter	Best fit	68% C.L.	90% C.L.
ϕ_N	2.1	$0.5 - 5.0$	$0.1 - 7.3$
γ_N	2.0	$1.6 - 2.3$	$1.2 - 2.5$
ϕ_S	6.8	$5.3 - 8.4$	$4.4 - 9.5$
γ_S	2.56	$2.44 - 2.67$	$2.36 - 2.75$

IC collaboration 1507.0399