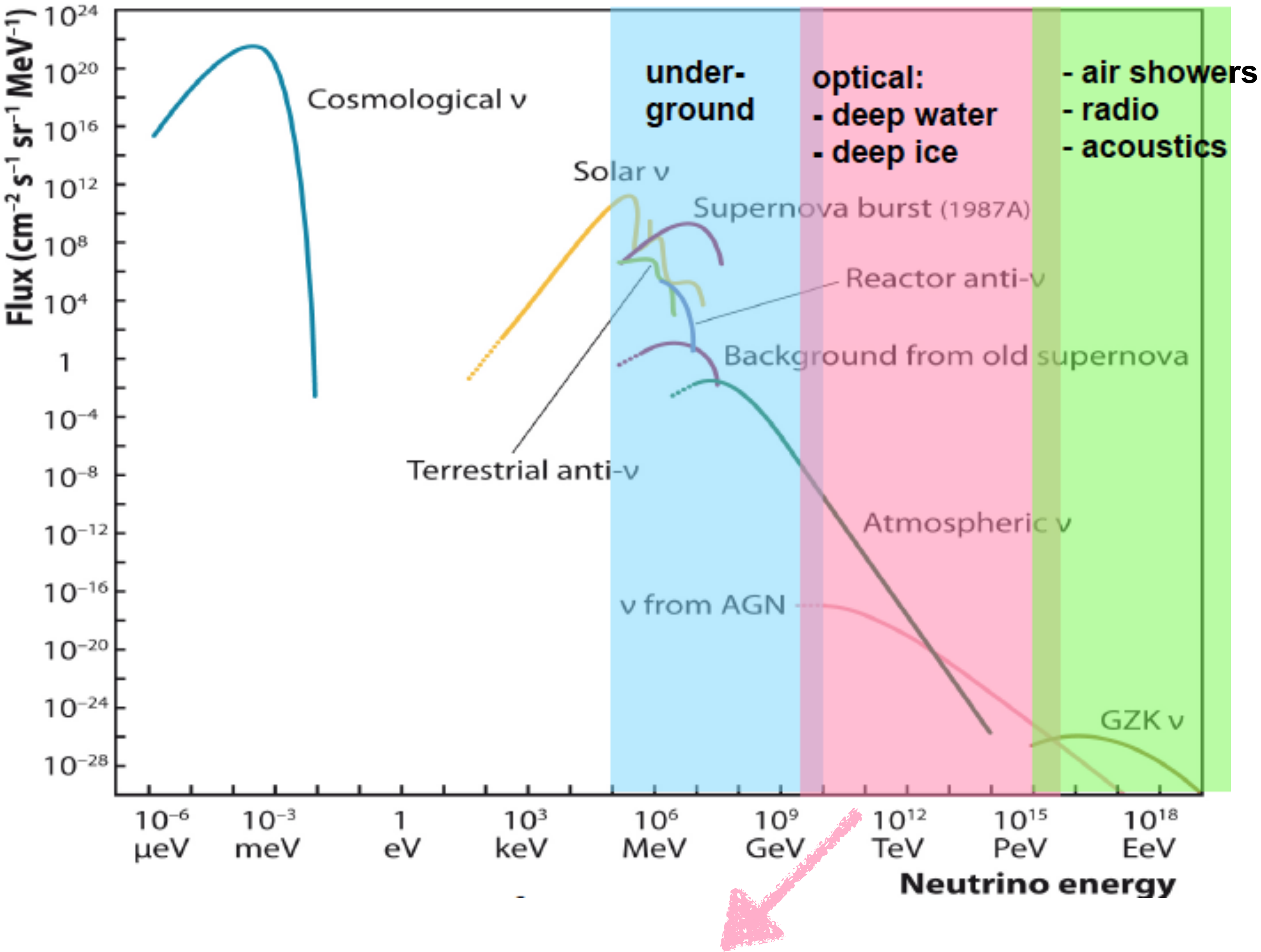
Simposio Latino Americano
de Fisica de Alta Energia
14-18/11/2016

Antonio Marinelli
(University of Pisa & INFN)
In collaboration with Fraija, Gaggero, Grasso, Urbano, Valli

Interpretation of astrophysical neutrinos observed by IceCube

Expected neutrino fluxes and observation methods



This is the region that we will explore in this talk

The idea of a under-ice/water neutrino telescope

ON HIGH ENERGY NEUTRINO PHYSICS

M. A. Markov

Joint Institute for Nuclear Research, Dubna, USSR

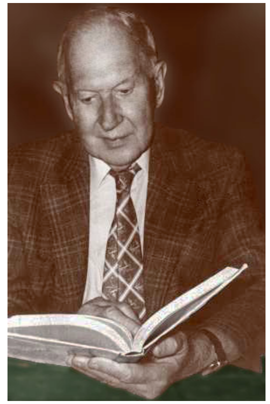
energy spectrum is reconstructed. We propose setting up apparatus in an underground lake or deep in the ocean in order to separate charged particle directions by Čerenkov radiation. We consider μ mesons produced in the ground layers under the apparatus.

Rare events of a frequency of less than one per month are also detectable in cosmic rays. Experiments with cosmic rays are also of interest for their own sake because they may give information on possible high energy neutrinos of cosmic origin.

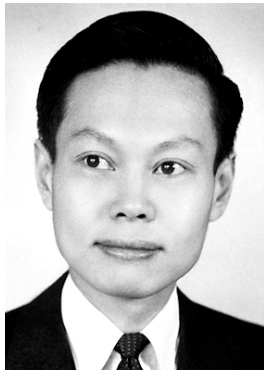
Proceeding of 10th ICHEP 1960
Rochester (pag. 578)

B.Pontecorvo

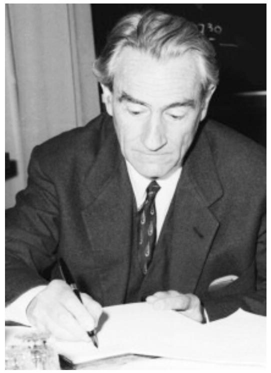
A.Markov



C.N.Yang



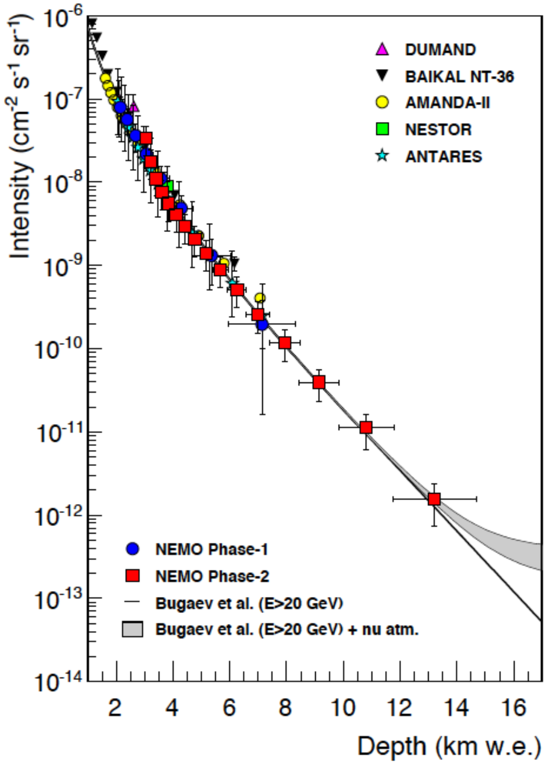
G.Bernardini



M.Schwartz

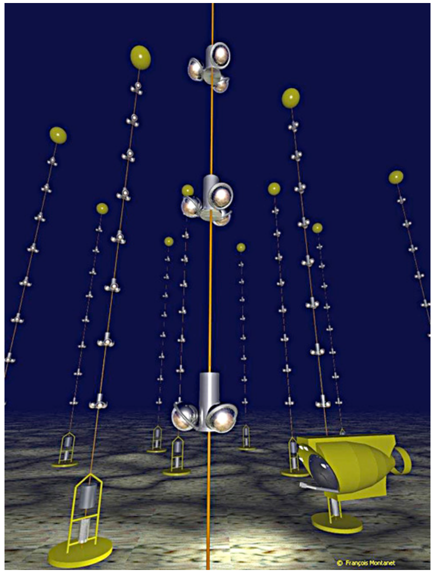
Interesting discussion on that between the 5 physicists

What has been done with Cherenkov Telescopes

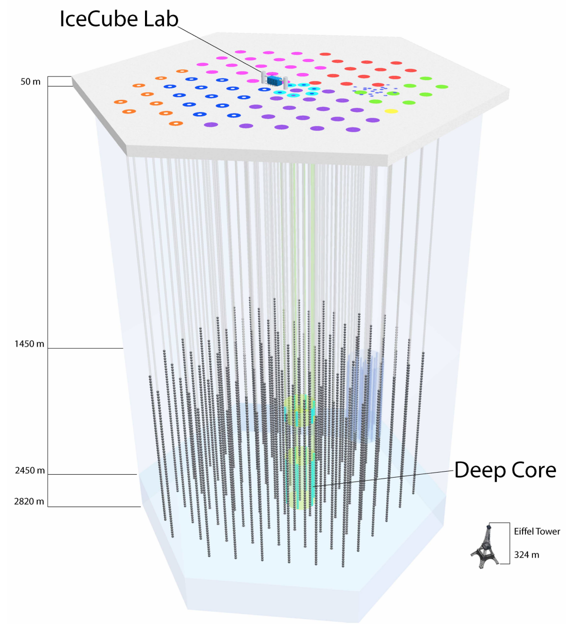


From DUMAND(1975), BAIKAL(1981), NESTOR (90's), AMANDA(1996), NEMO (1998) Mostly:

- Characterization of the sites
- Optimization of the detector geometry
- Measurements of Atmospheric muon flux

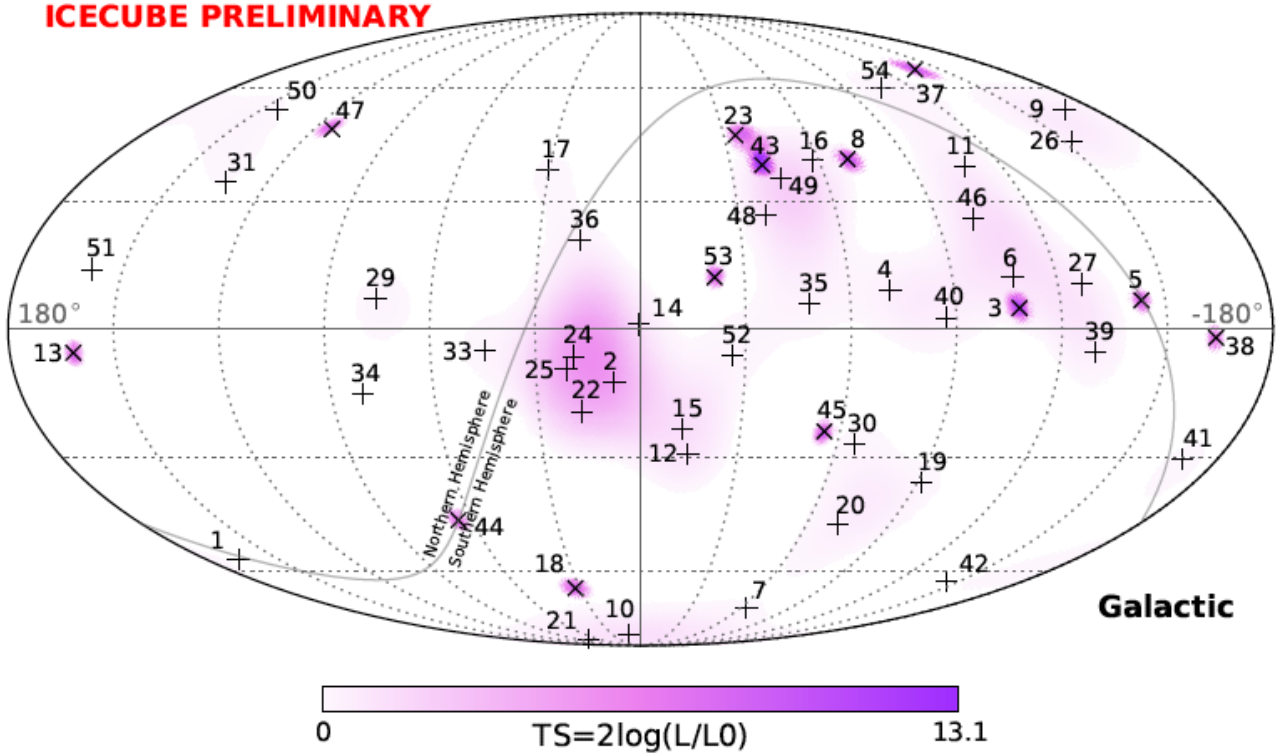


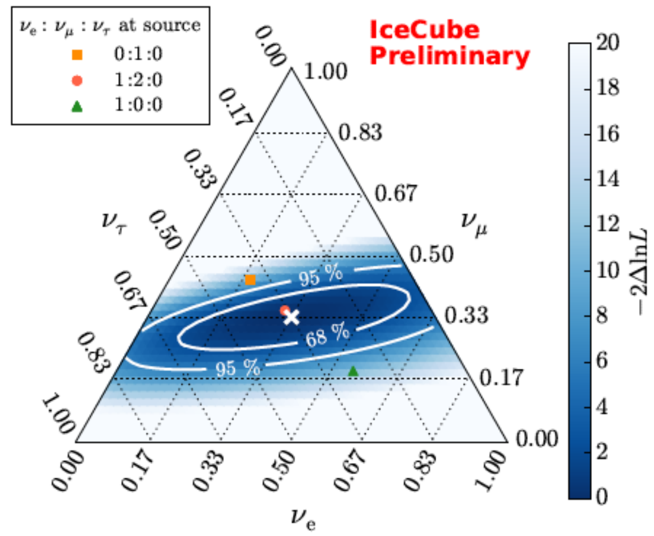
With IceCube and ANTARES : Starting of VHE neutrino astrophysics



IceCube astrophysical neutrinos: where they come from?

arXiv1510.05223v2, ICRC2015 Contribution





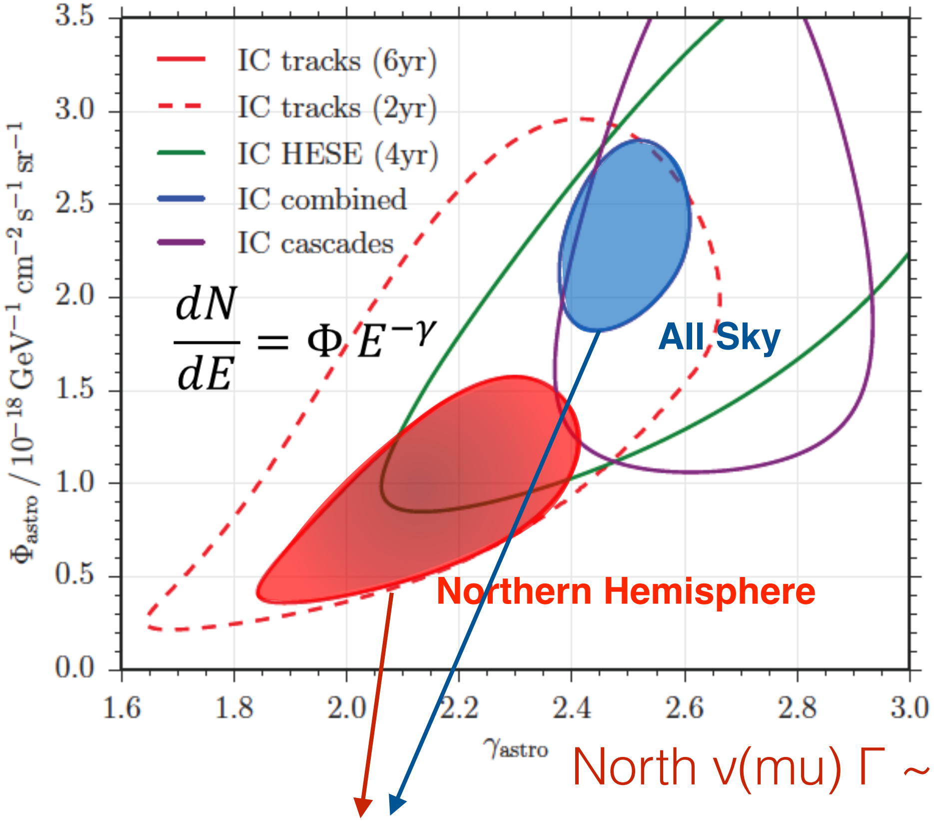
$$\nu_e : \nu_\mu : \nu_\tau = 1:1:1$$

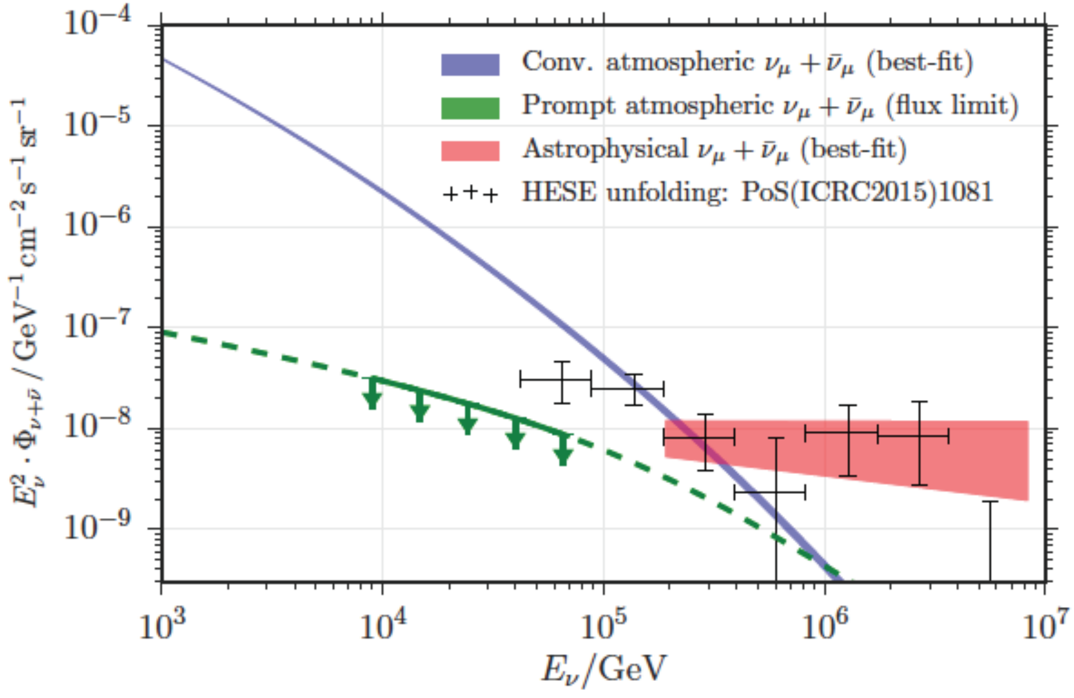
X (track) angular res ~1° + (shower) angular res ~10°-30°

For the full sky analysis of 4 years of HESE data IceCube reconstruct 13 track events and 41 shower events 7σ above the Background. 2016 -> also 6 years of muonic neutrinos from northern hemisphere and MESE analysis

Discrepancy North-South measured neutrino spectra

IceCube coll. arXiv:1607.08006





North v(mu) Γ ~ 2.2 All Sky HESE v Γ ~ 2.5

The (3.2 σ) tension between HESE and muonic v spectral indexes and between normalization factors may be due to:

- Intrinsic energy limit for a dominant class of sources at around 100 TeV
- Presence of a large Galactic component in the South hemisphere

Galactic ν signal considerations

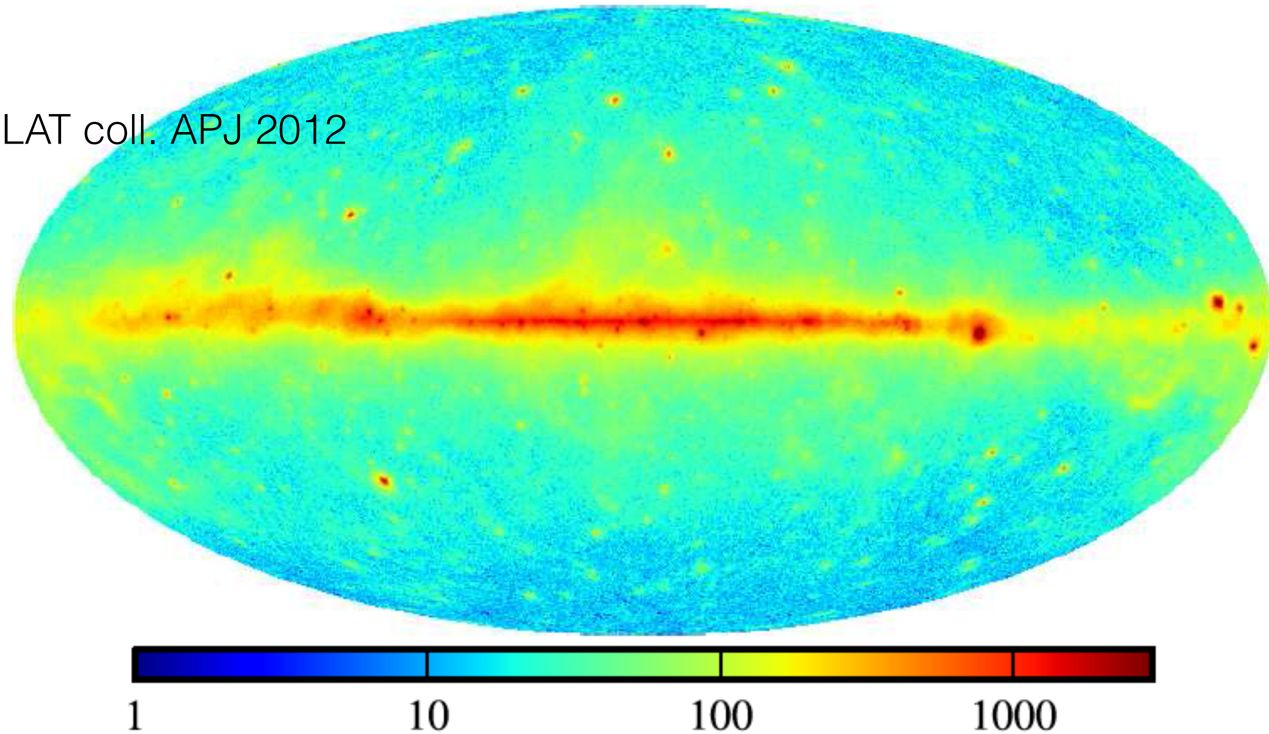
- Galactic diffuse neutrino emission: better understanding of Cosmic-ray transport in our galaxy and connection between CR, diffuse gamma-ray and neutrinos.

- Possibly a subdominat emission from point-like sources since we don't see any significant accumulation of neutrino events.

- supernova remnants [Mandelartz & Tjus'14]
- pulsars [Padovani & Resconi'14]
- microquasars [Anchordoqui, Goldberg, Paul, da Silva & Vlcek'14]
- Sagittarius A* [Bai, Barger, Barger, Lu, Peterson & Salvado'14; Fujita, Kimura & Murase'15]
- Fermi Bubbles [MA & Murase'13; Razzaque'13]
[Lunardini, Razzaque, Theodoseau & Yang'13; Lunardini, Razzaque & Yang'15]
- 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]

Diffuse Galactic Plane gamma-ray emission

Fermi-LAT coll. APJ 2012



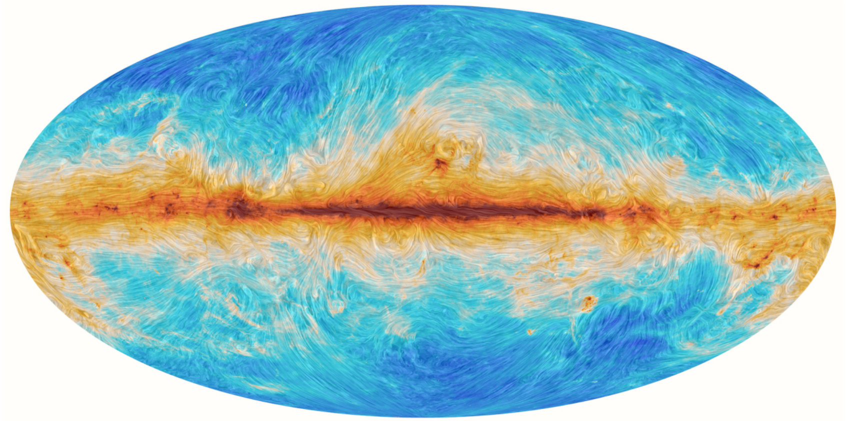
Observed Fermi-LAT counts in the energy range 200 MeV to 100 GeV after point-sources subtraction (log scale = counts/pixel)

The gamma-ray diffuse emission is mainly related:

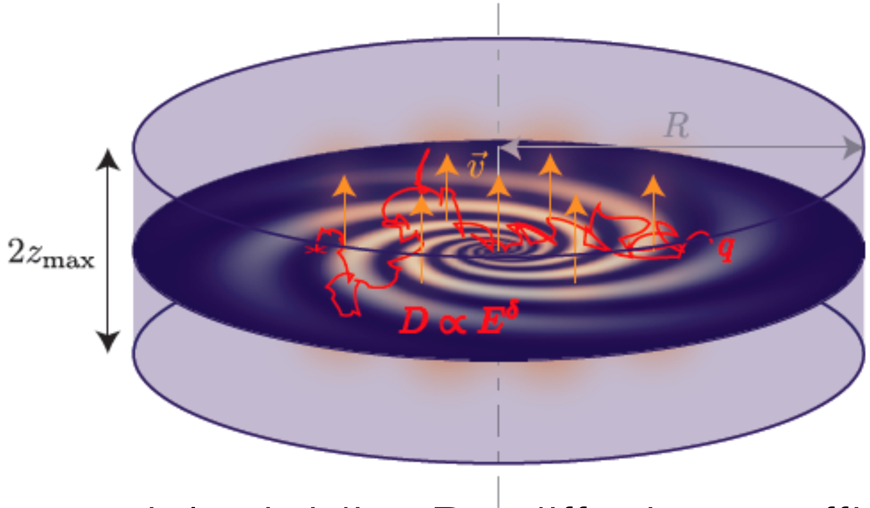
- Photopion production due to the CR/gas collision - Dominant for the inner GP, produce also ν
- Bremsstrahlung of relativistic electrons in gas
- Inverse-Compton of relativistic electrons with ISRF

Novel approach to diffuse Galactic Plane emission: KRAγ

http://www.ias.u-psud.fr/soler/planckhighlights.html



Galactic magnetic fingerprints obtained by Planck



ρ : particle rigidity D : diffusion coefficient

R : distance from galaxy center

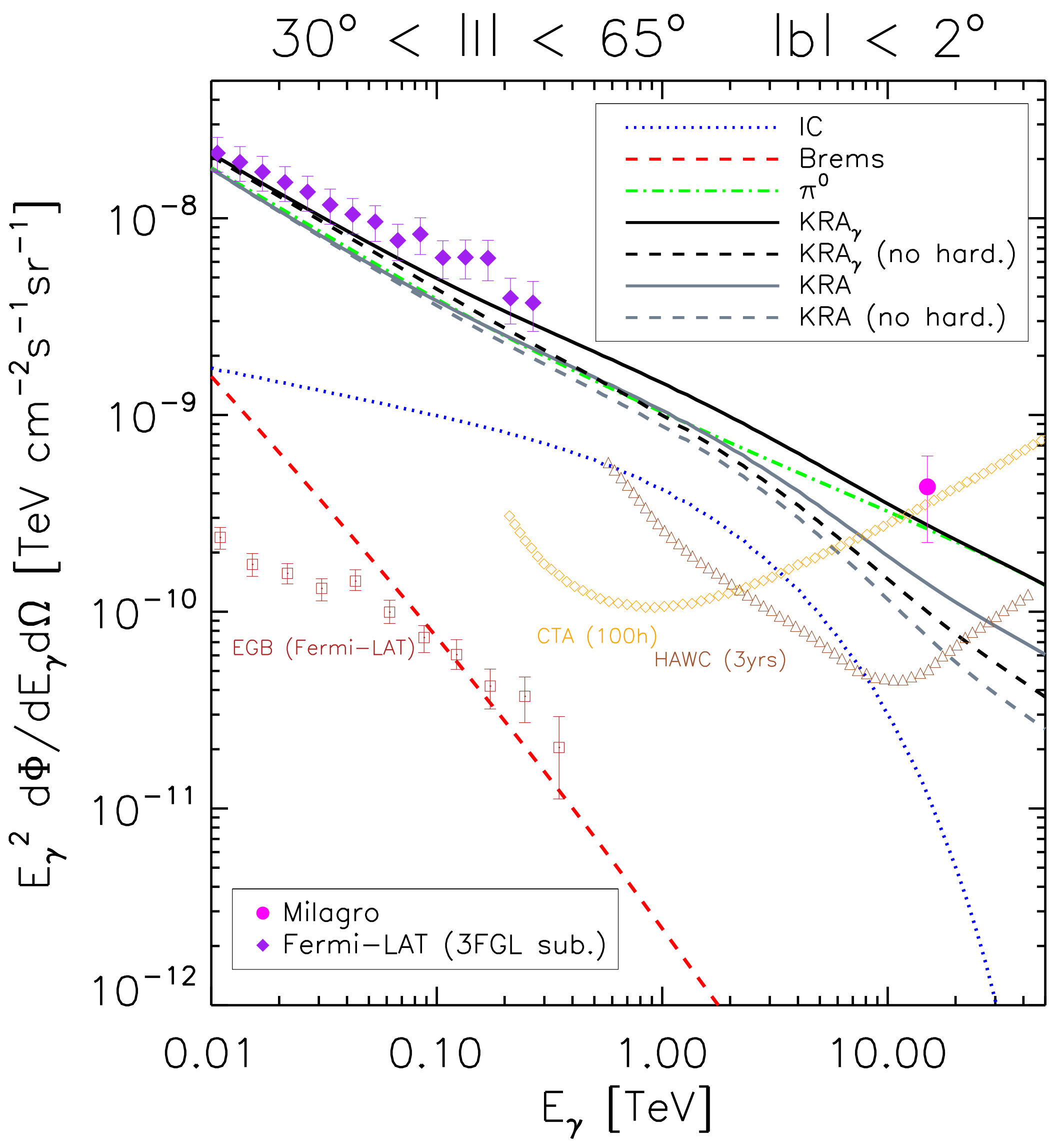
- The diffusion coefficient $D \propto \rho^{\delta}$, in a conventional scenario δ is constant
- Instead the KRAγ model adopts a radial dependent diffusion coefficient (δ(R) = a * R + b) which turns into a spectral hardening toward the GC region. This idea was introduced in *Erlykin and Wolfendale 2013*.

Gaggero, Grasso, Marinelli, Urbano, Valli, APJ Letter arXiv:1504.00227

The KRAγ model solves the Milagro anomaly at 15 TeV

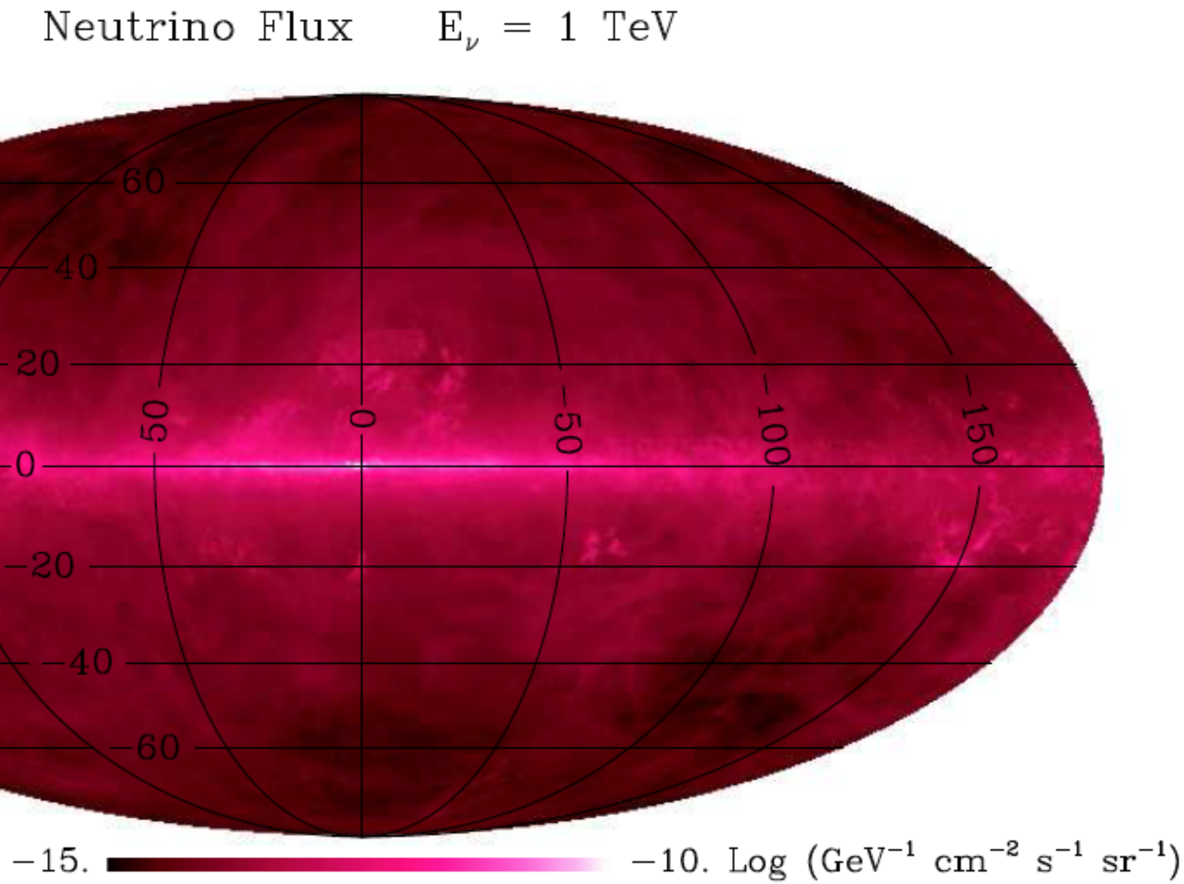
Gaggero, Grasso, Marinelli, Urbano, Valli, APJ Letter, arXiv:1504.00227

- The KRAγ model consistently reproduces Fermi-LAT data (point sources properly subtracted) and Milagro. No extra-tuning required
- Can be used to reproduce also diffuse neutrino emission



Galactic neutrino flux Skymap from the KRAγ model.

Gaggero, Grasso, Marinelli, Urbano, Valli, arXiv:1508.03681, ICRC2015

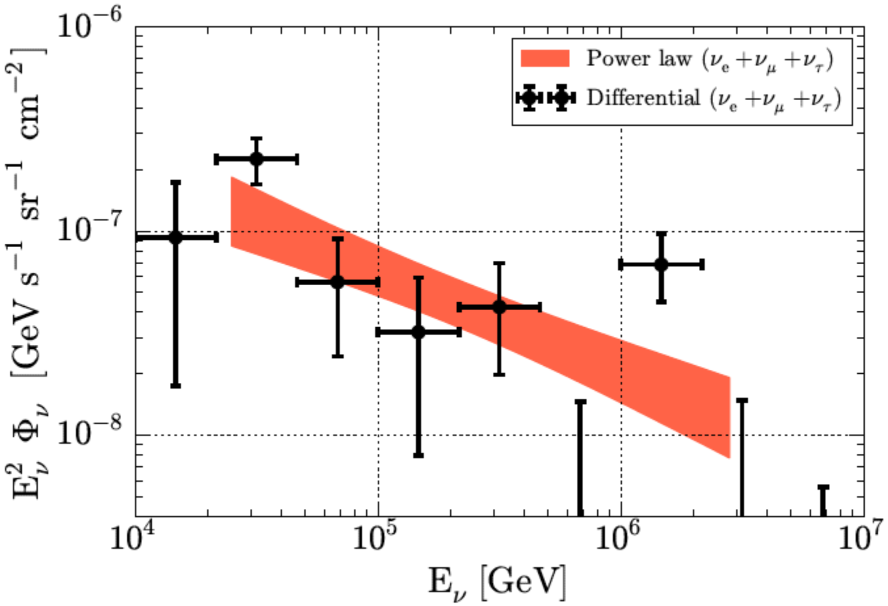


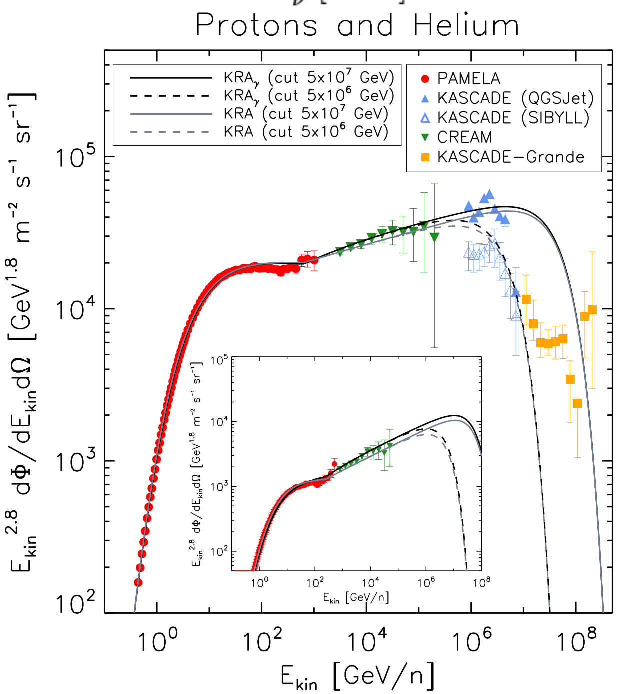
Skymap of neutrino flux produced with KRAγ model.

- The p-nucleon interaction is computed following Kamae et al. 2006
- The target gas distribution is the same used for gamma-ray production (as also used by the Fermi collaboration)

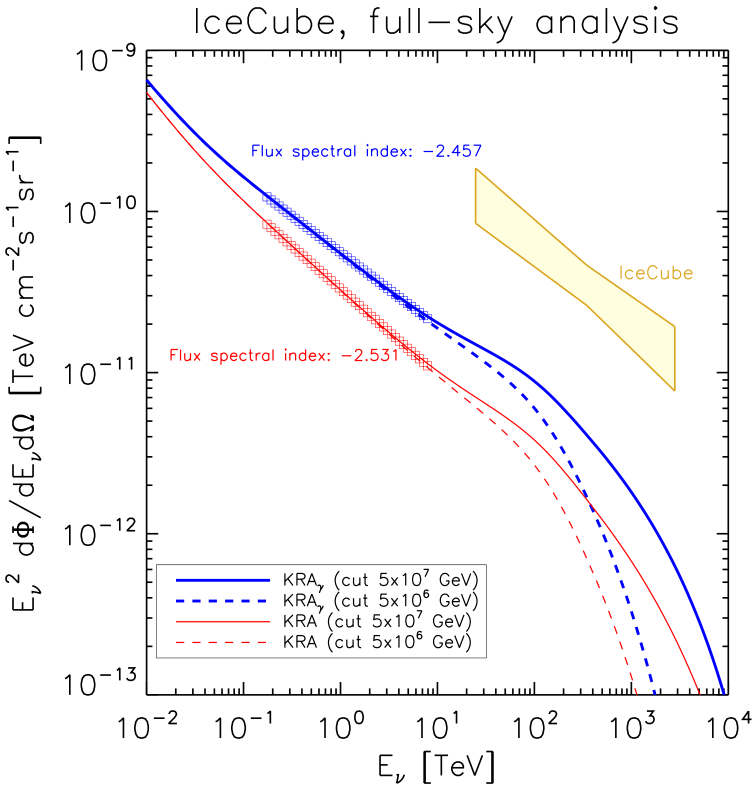
All Sky neutrino from KRA (δ uniform) & KRAγ (δ variable)

IceCube coll. arXiv:1507.03991



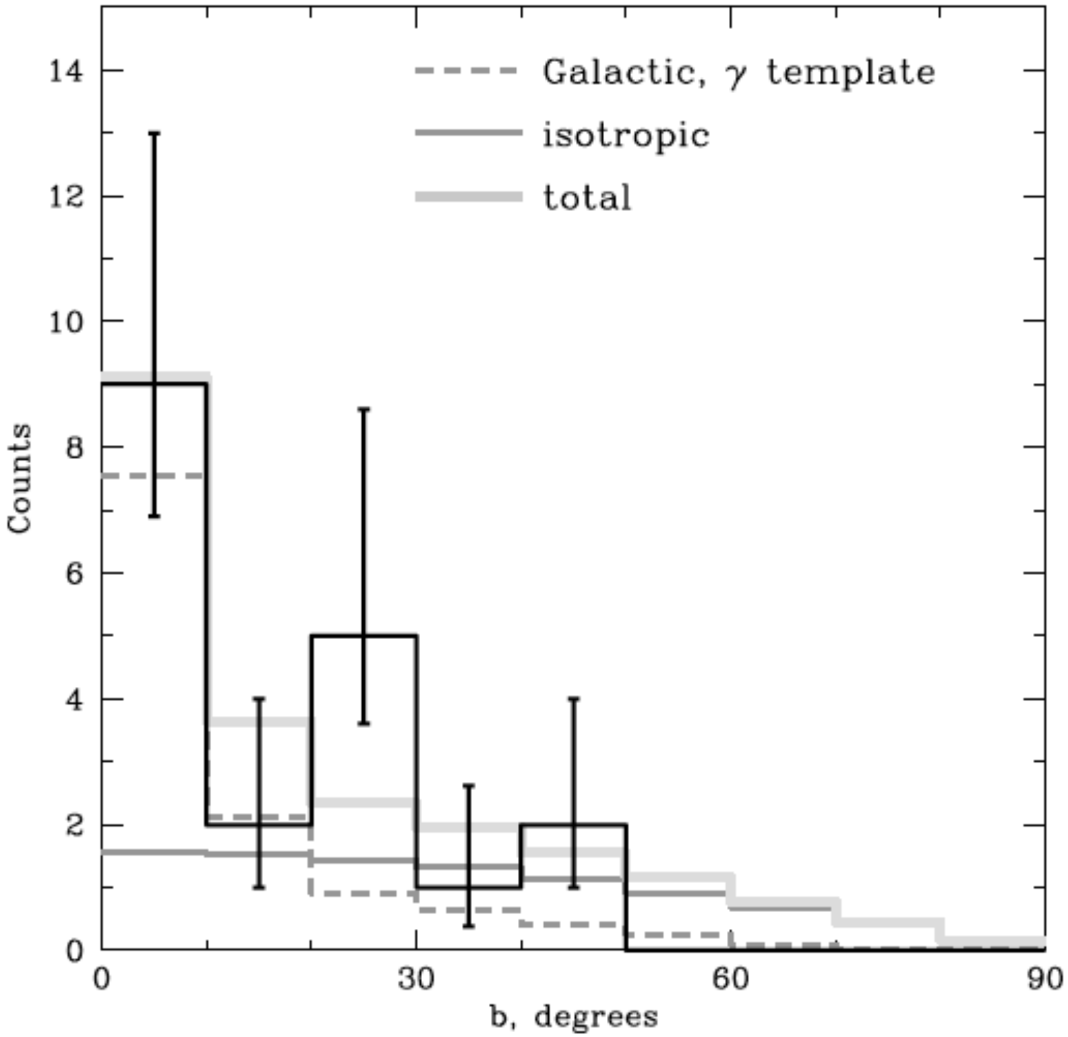


Gaggero, Grasso, Marinelli, Urbano, Valli, arXiv:1507.07796



KRAγ may account between 10% and 20% (depending on CR cut-off) above 60 TeV. More than double of standard scenario.

Galactic diffuse neutrinos obtained from spatial picture



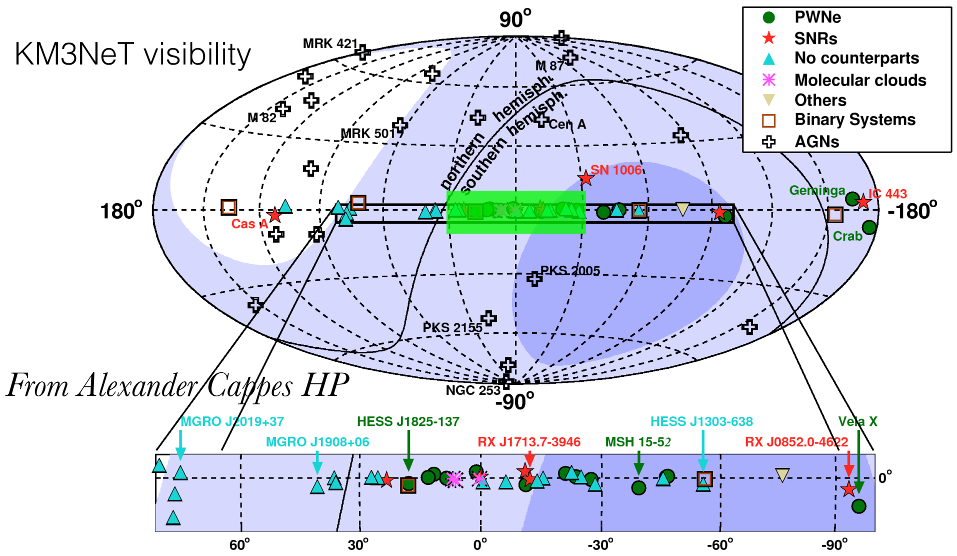
Neronov & Semikoz arXiv:1509.03522

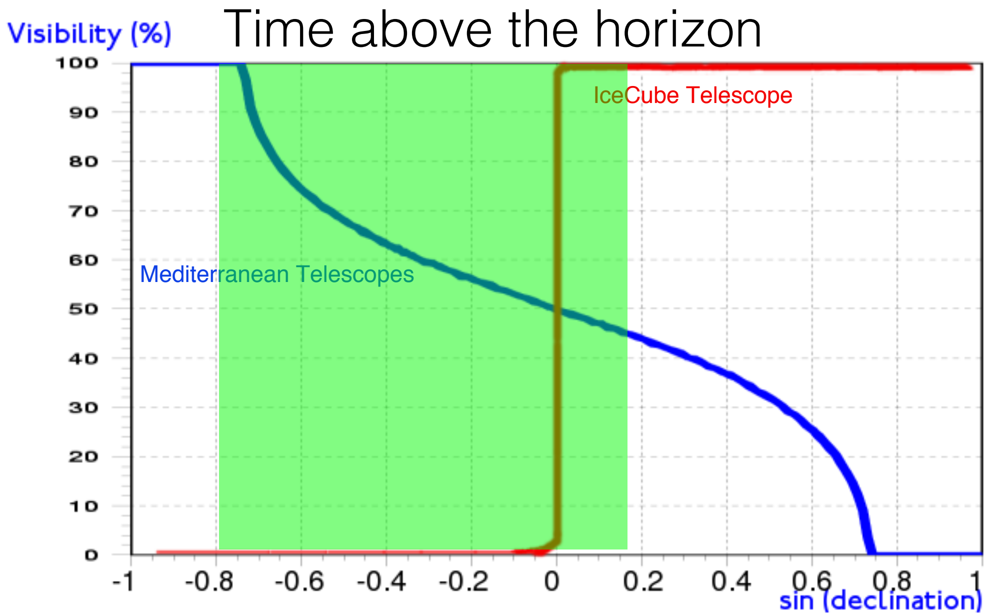
The authors claim
that a isotropy model
have a inconsistency with
data at the level of 3 σ

With the spatial template of IceCube events up to 50% of IceCube events can be explained with Galactic origin

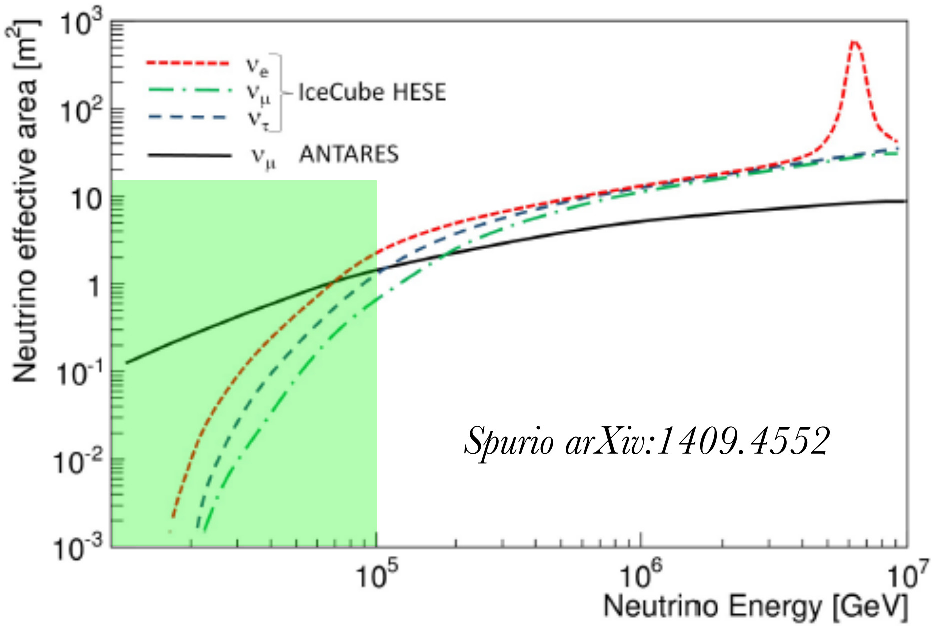
This model predicts more galactic ν respect to KRA$_\gamma$ predictions (up to 20%) and standard diffusion model (up to 8%)

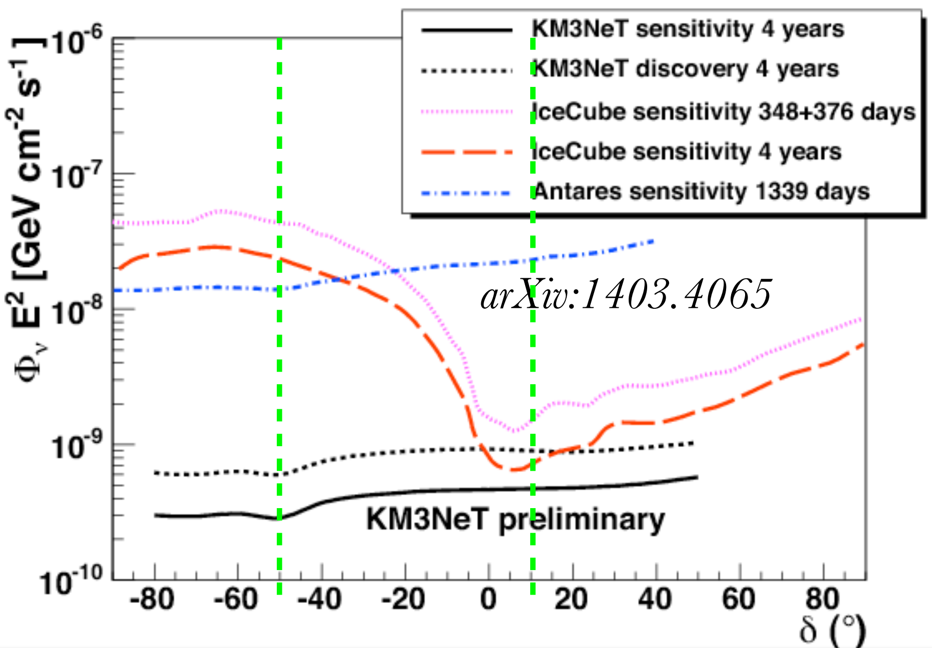
Inner Galactic plane visibility for the Global Neutrino Network





Mediterranean ν telescopes can be more sensitive to this region of the sky

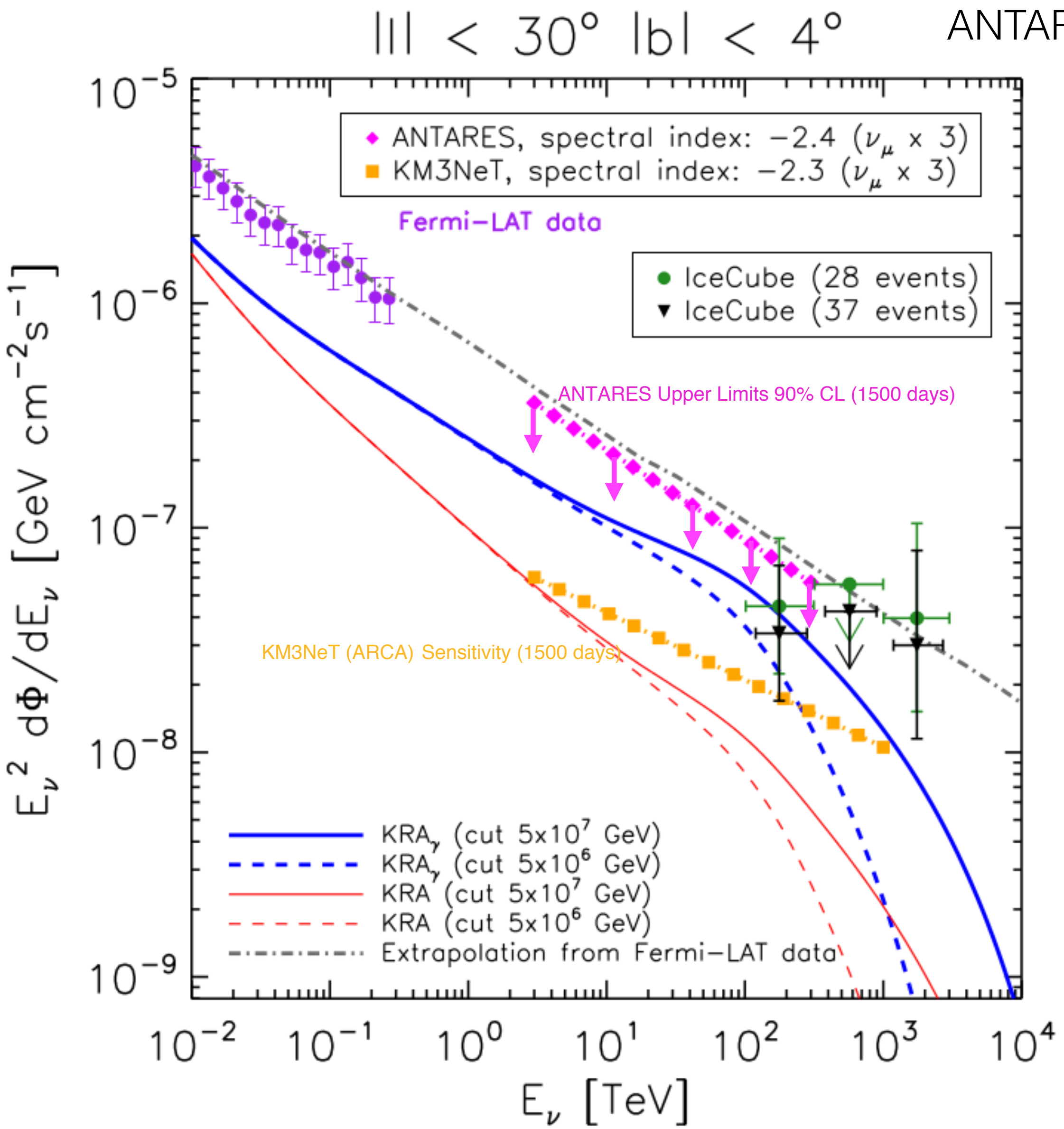




Better constrains to the KRAγ neutrino spectrum of Galactic Ridge introducing Mediterranean telescopes.

Gaggero, Grasso, Marinelli, Urbano, Valli, APJ letter , arXiv 1504.00227

ANTARES coll. Phys Lett B arXiV:1602.03036

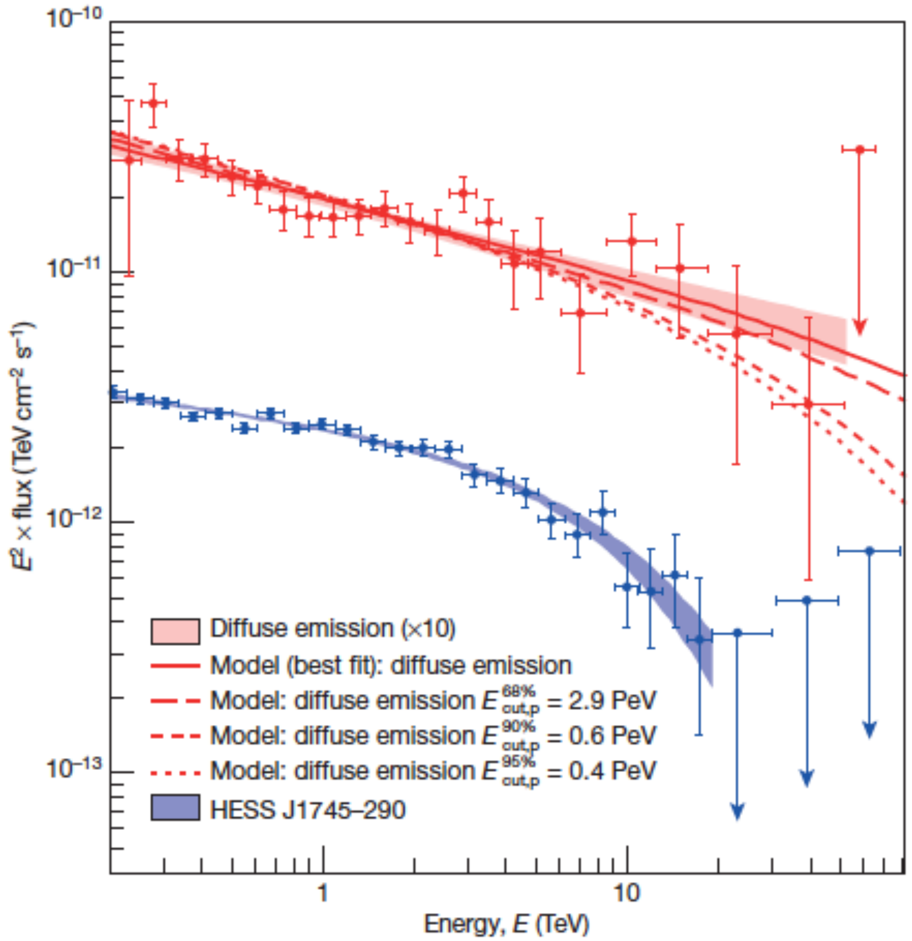


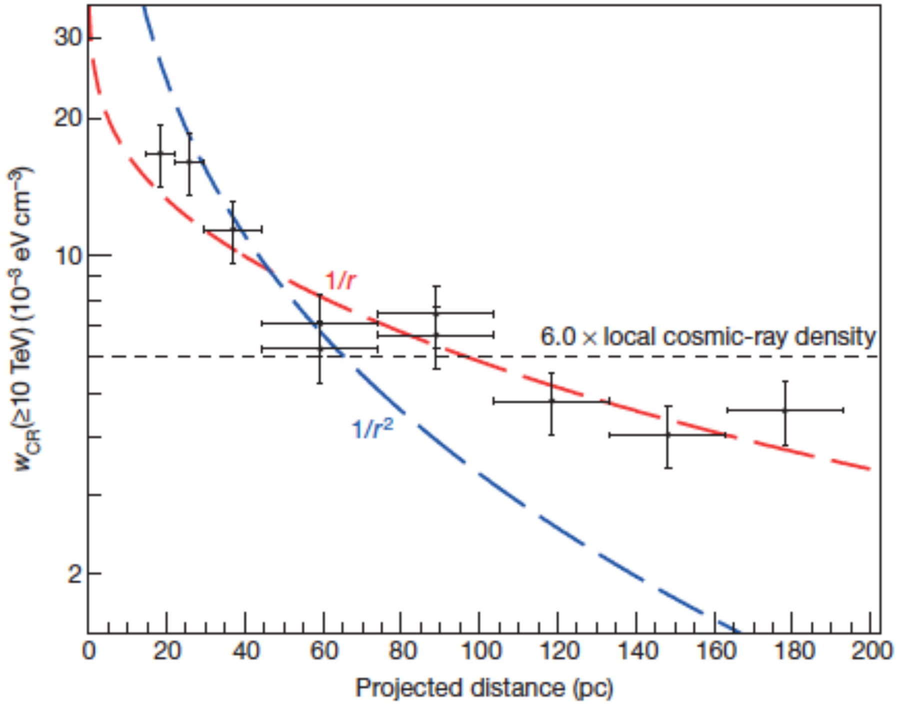
The KRA (δ uniform) and KRAγ (δ variable) produced ν spectra of the inner galactic plane with the CR cut-off at 5 PeV and 50 PeV compared to:

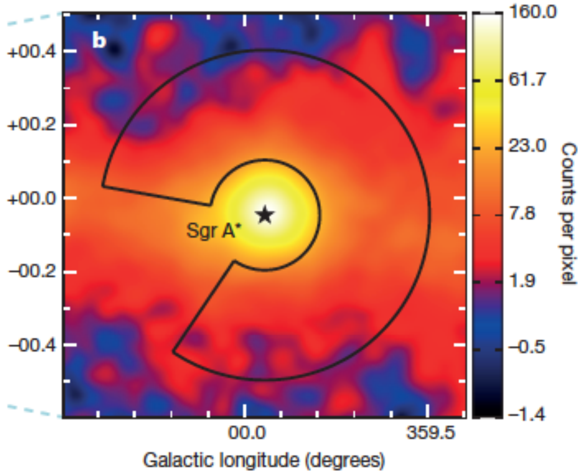
- ANTARES upper limits obtained with ν track events reconstructed in 1500 days of experiment live time.
- IceCube constraints of the flux with observation of 3 ν shower like events in 662 and 998 days of experiment live time.
- Computed KM3NeT sensitivity for this region of the sky with 1500 days of experiment live time.

The case of the Pevatron observed by HESS

doi:10.1038/nature17147 2016 HESS collaboration





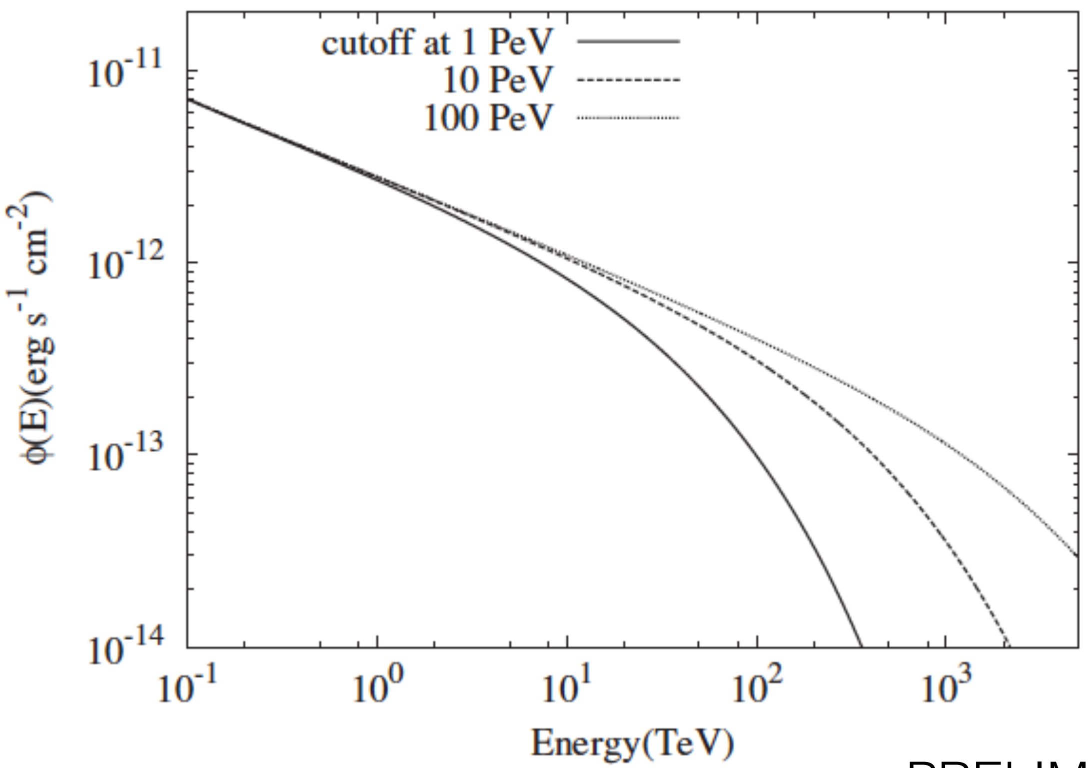


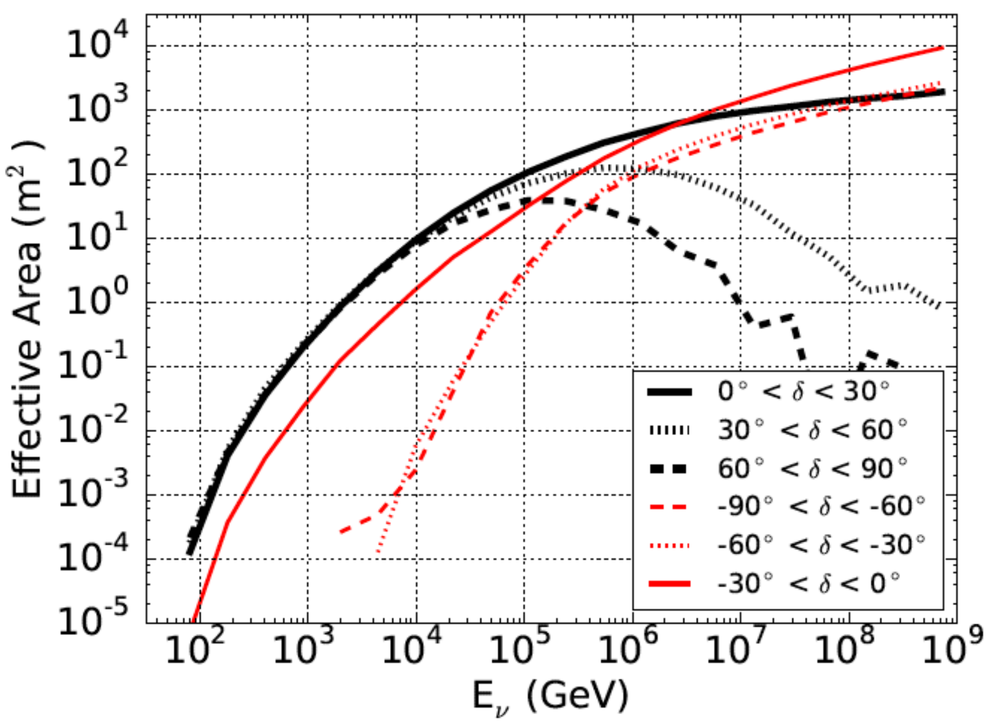
First Pevatron observed in gamma-ray from a diffuse region close to Sagittarius A

Neutrino expected from the Pevatron in IceCube

doi:10.1038/nature17147

IceCube coll. Astr. J. arXiv:1406.6757



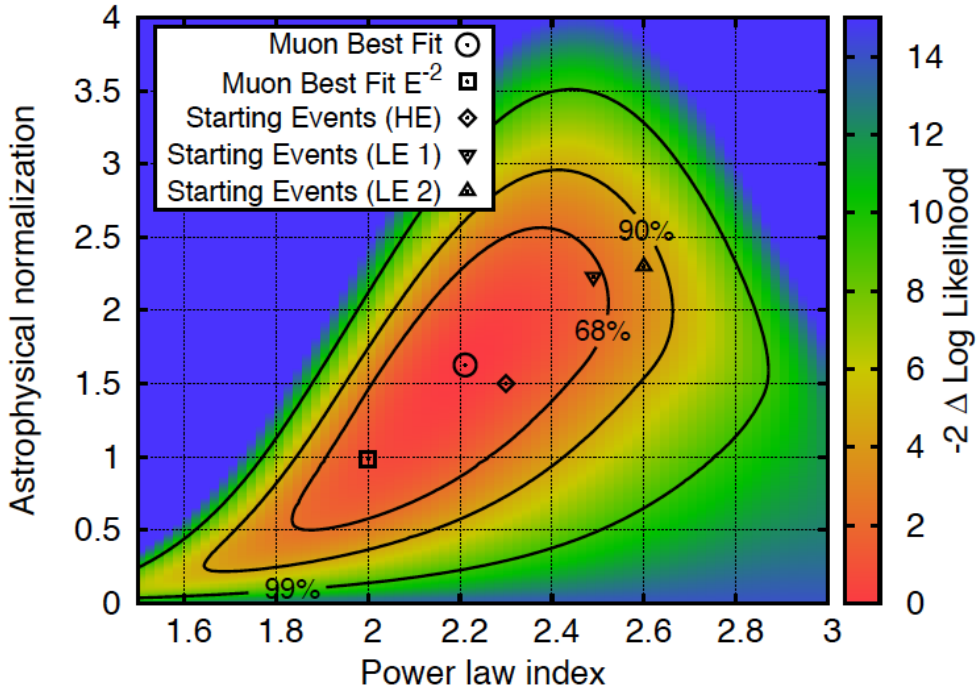


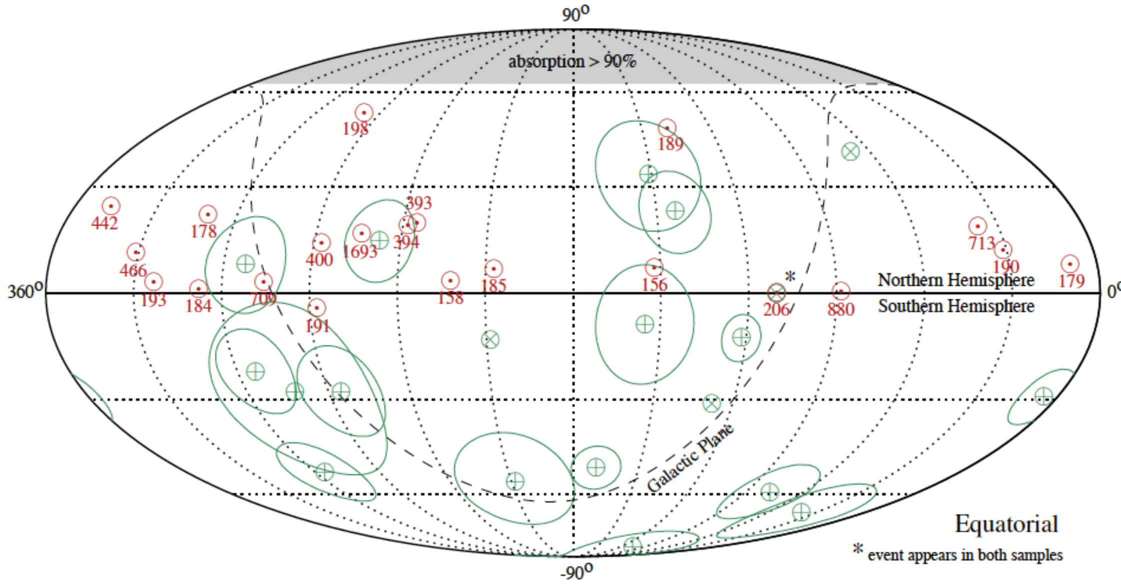
PRELIMINARY

nu evt HESE 4	Cut-off 1 PeV	Cut-off 10 PeV	Cut-off 100 PeV
E > 25 TeV	4 x 10^-2 evt	0,127 evt	0,189 evt
E >10 TeV	9 x 10^-2 evt	0,2 evt	0,27 evt
E > 1 TeV	0,26 evt	0,40 evt	0,47 evt

Estimating the extragalactic contribution from the North hemisphere

IceCube coll., PRL, vol.115, n.8, 2015



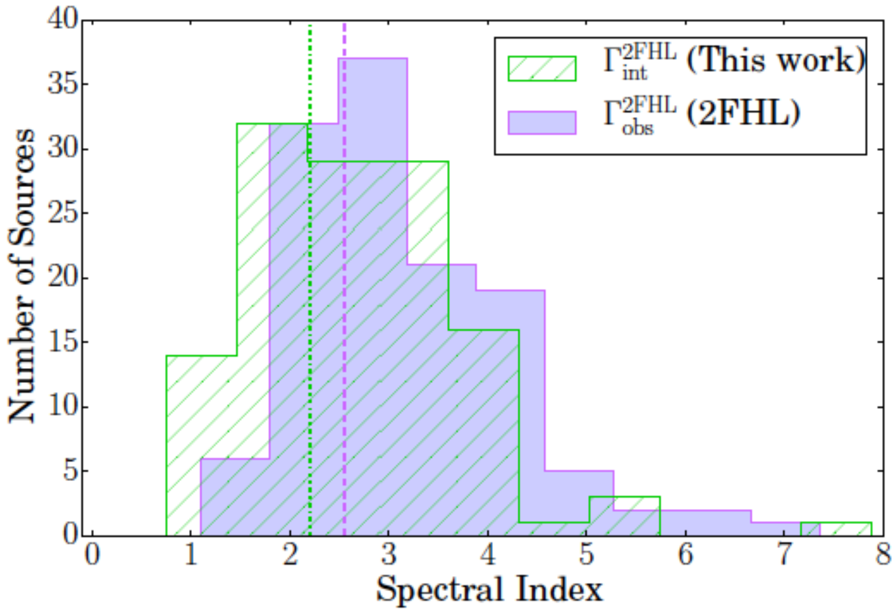


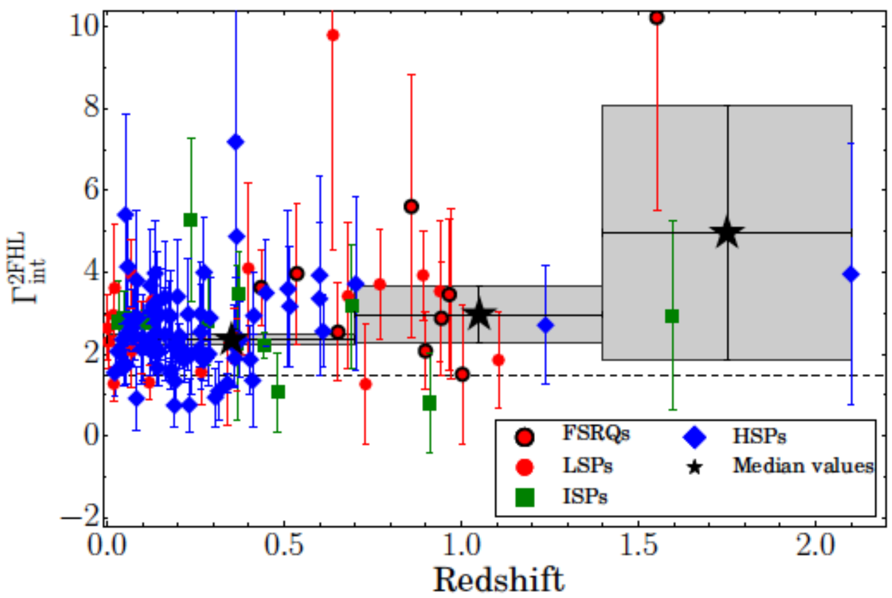
- IceCube collaboration recently published a evidence of astrophysical muon neutrinos from the Northern hemisphere. The neutrinos collected during 659.5 days of live time between May 2010 and May 2012 are inconsistent with the background at the level of 3.7 σ.

- Assuming a modest diffuse galactic contribution from this hemisphere we can consider the observed muon neutrinos as a good bound for the extragalactic neutrino signal. In this case the best-fit analysis gives a Γ ~ 2.2 .

Γ from BL-Lacs & FSRQ survey and IceCube measured Γ

Dominguéz & Ajello, ArXiv:1510.07913





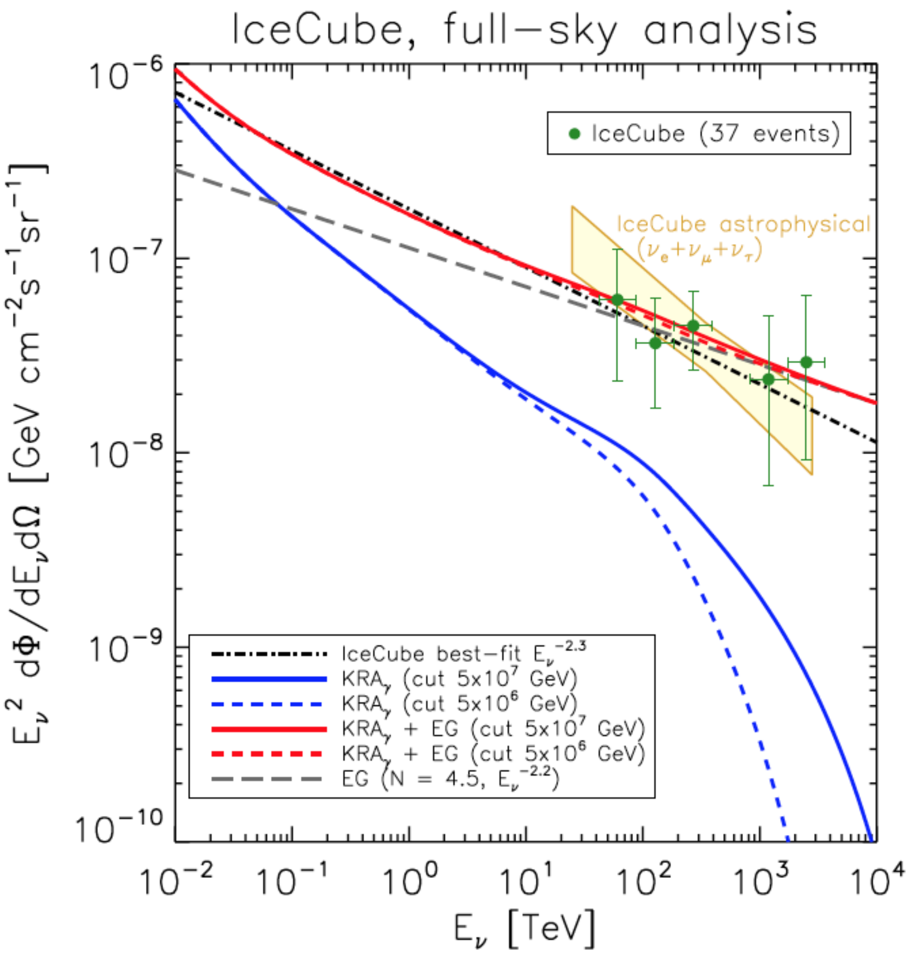
- A analysis of 128 extragalactic sources (mostly Blazars) from the 2FHL (E>50 GeV) catalog set the average intrinsic (unattenuated from the EBL) spectral index at Γ ~ 2.2 versus the measured average Γ ~ 2.5

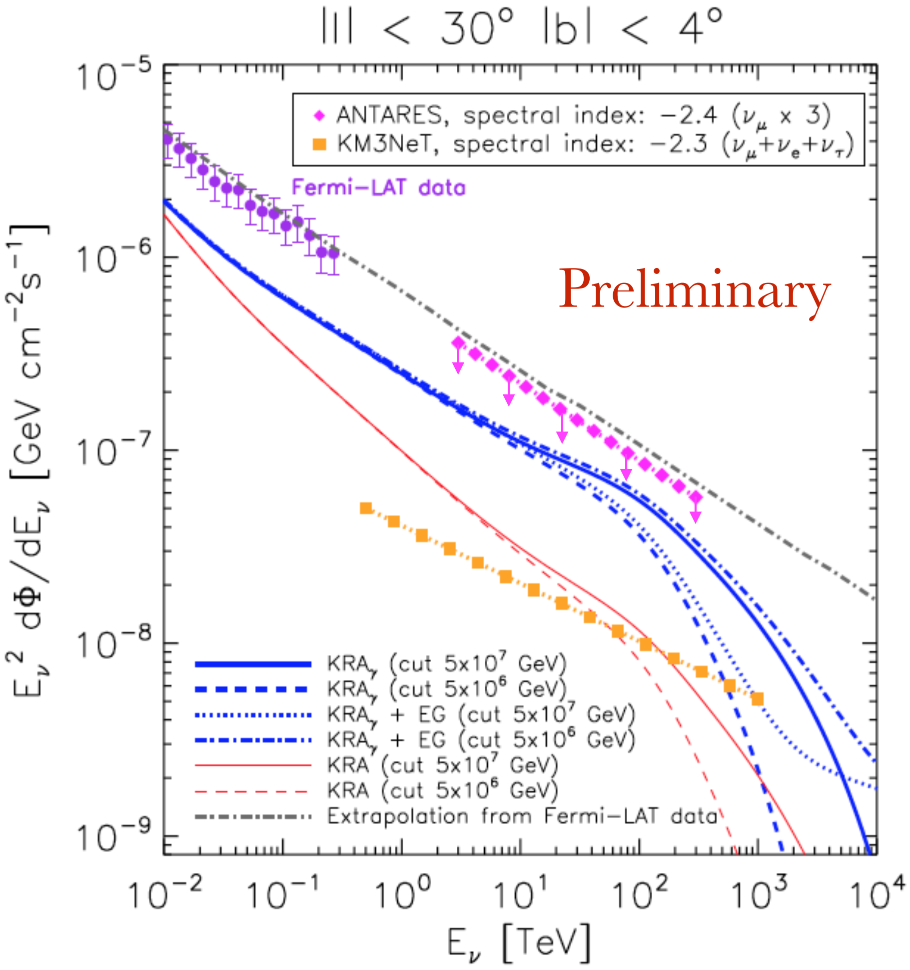
- If the gamma-ray are produced through pion decay we can expect a corresponding neutrino spectrum described by the obtained intrinsic Γ ~ 2.2 .

- This spectrum is well compatible with Northern hemisphere analysis of IceCube (Γ ~ 2.2) but not with the full sky IceCube (4 years HESE) analysis (Γ ~ 2.58)

Galactic+Extragalactic expectations vs Antares upper bounds

Gaggero, Grasso, Marinelli, Urbano, Valli, APJ Letter arXiv:1504.00227

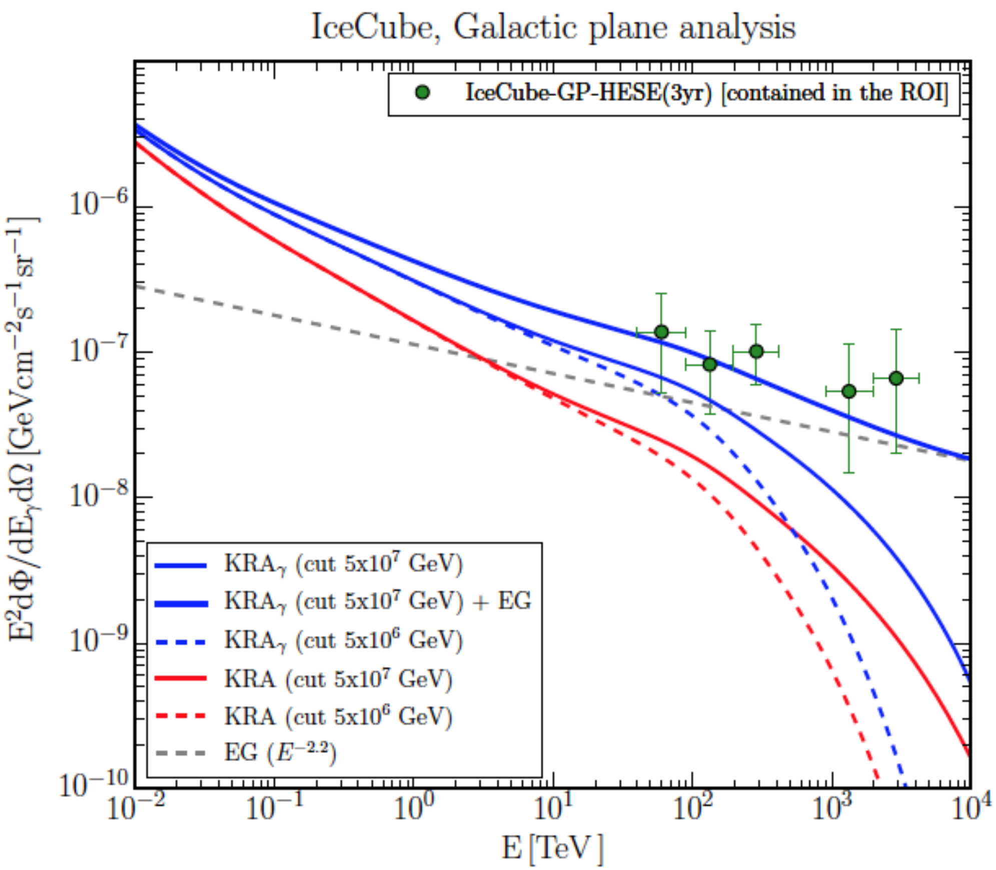




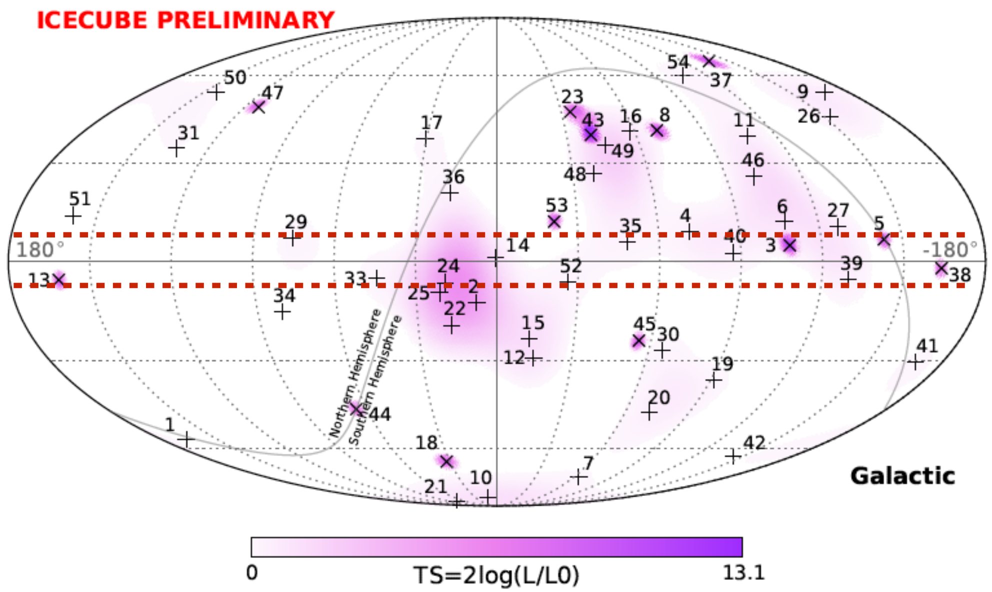
The KRAγ spectrum + extragalactic spectrum (obtained from the muon neutrino analysis of the Northern hemisphere) give a physical meaning to the IceCube full sky measured spectrum and is still consistent, in the ridge region, with the Antares measured upper limits.

G+EG emission in the GP constrained by IceCube

Gaggero, Grasso, Marinelli, Urbano, Valli VLVNT2015



arXiv1510.05223v2, ICRC2015 Contribution

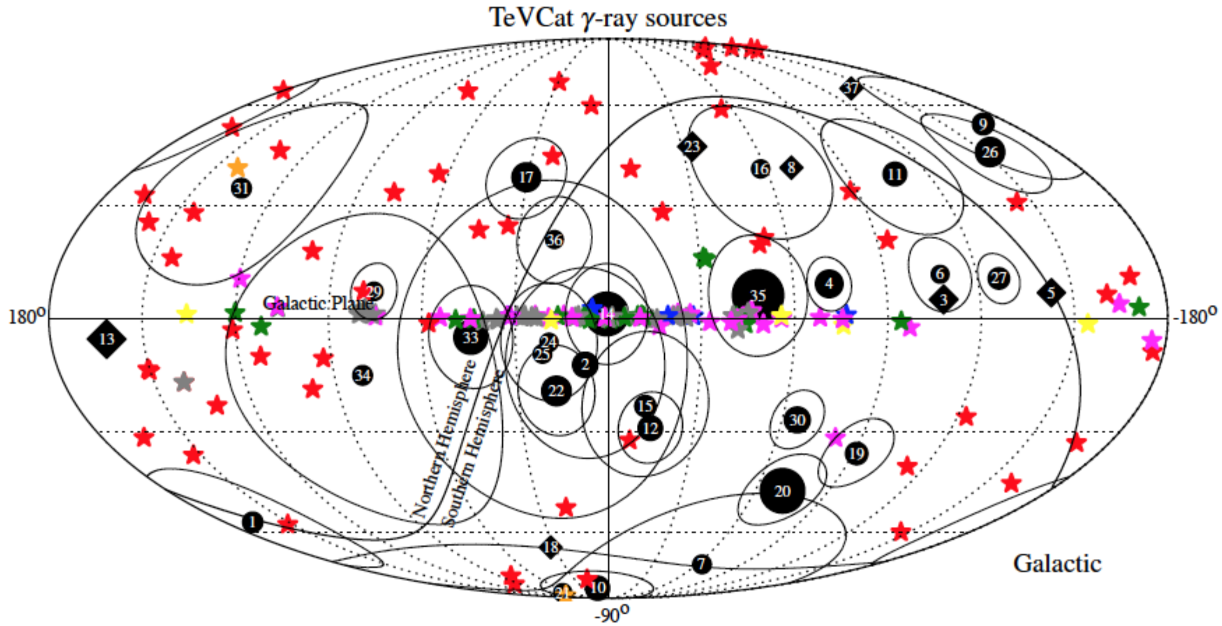


For the whole galactic plane with ϑ<7.5 half of astrophysical flux can be explained with KRA$_\gamma$ and the other half with EG best fit analysis. The Icecube spectrum is obtained considering the contained events for this region

Which sources are responsible of EG emission?

HBL, IBL, LBL, FRI-II, FSRQ,
Star Burst Galaxies

No significant spatial association with known GeV-TeV extragalactic sources.



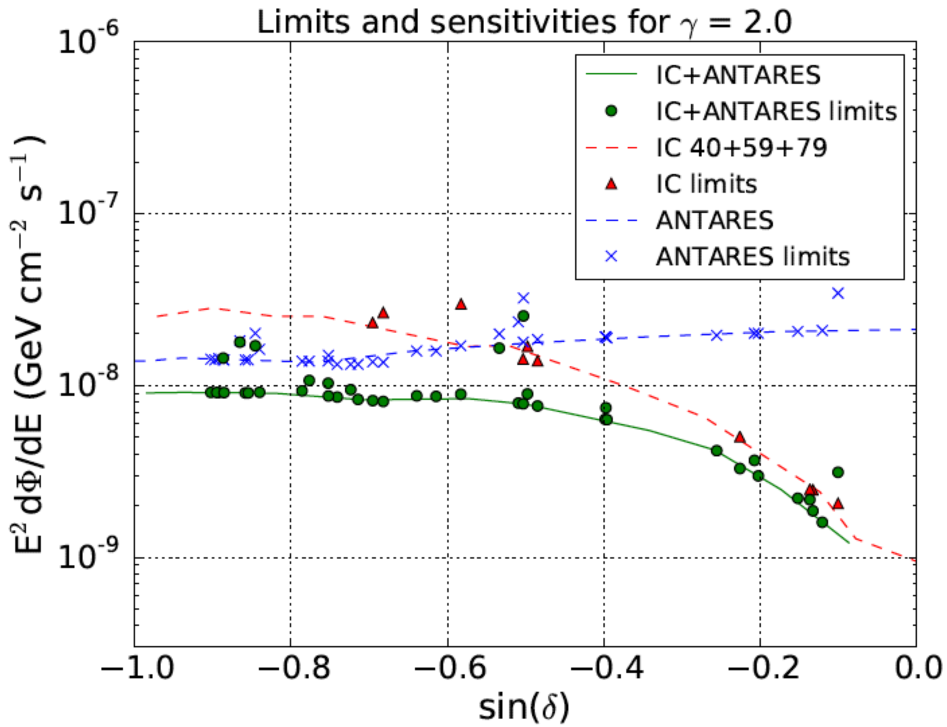
IceCube HESE 3 years

Proposed Source Candidates II

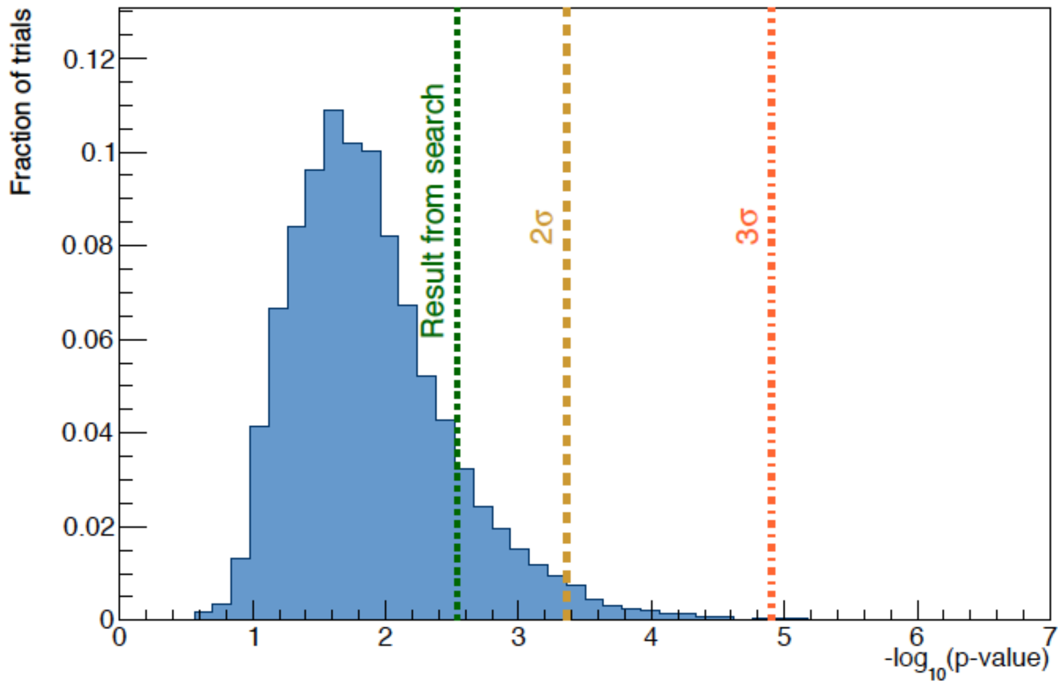
- Extragalactic:
- Association with sources of UHE CRs [Kistler, Stanev & Yuksel'13] [Katz, Waxman, Thompson & Loeb'13; Fang, Fujii, Linden & Olinto'14]
- Association with diffuse gamma-ray background [Murase, MA & Lacki'13] [Chang & Wang'14; Ando, Tamborra & Zandanel'15]
- Active galactic nuclei (AGN) [Stecker'13;Kalashev, Kusenko & Essey'13, Fraija& Marinelli 15, Fraija& Marinelli 16 [Murase, Inoue & Dermer'14; Kimura, Murase & Toma'14; Kalashev, Semikoz & Tkachev'14] [Padovani & Resconi'14; Petropoulou, Dimitrakoudis, Padovani, Mastichiadis & Resconi'15]
- Gamma-ray bursts (GRB) [Murase & Ioka'13; Dado & Dar'14; Tamborra & Ando'15, Fraija 16, Fraija 15]
- 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]
- Galaxy clusters/groups [Murase, MA & Lacki'13; Zandanel, Tamborra, Gabici & Ando'14]
- . . .

The first combined IC-ANTARES analysis for point sources

ANTARES and IceCube coll. arXiv:1508.03681



Upper limits obtained for some TeV cat sources

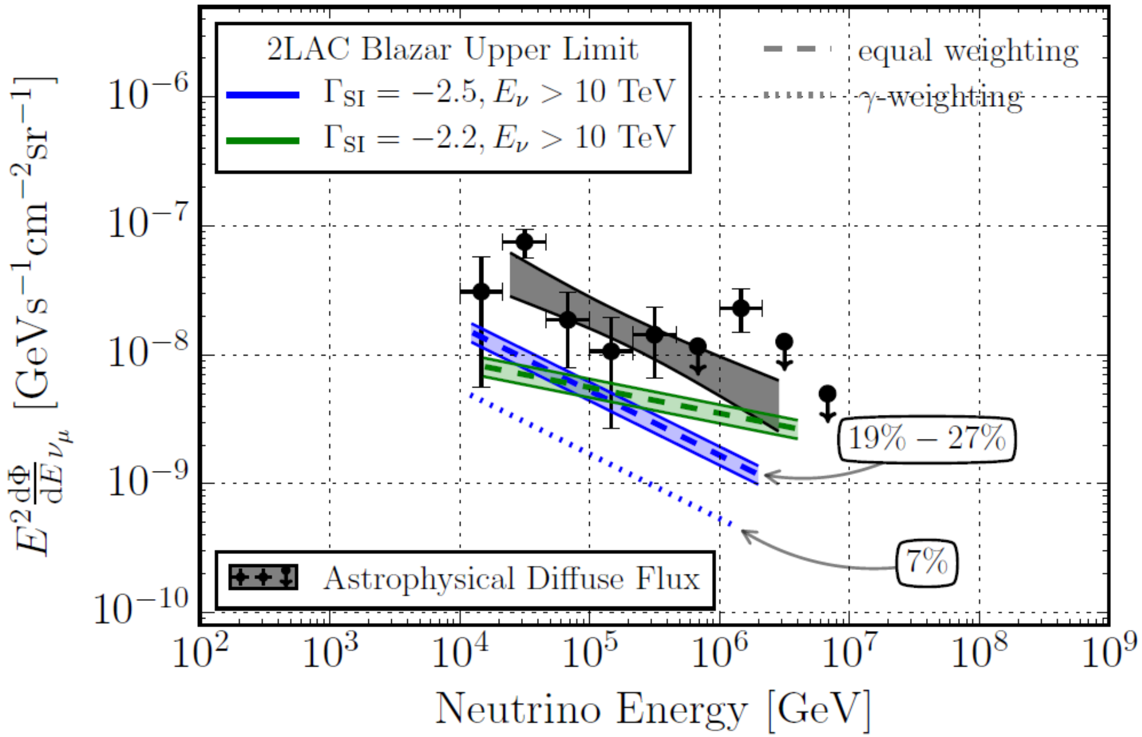


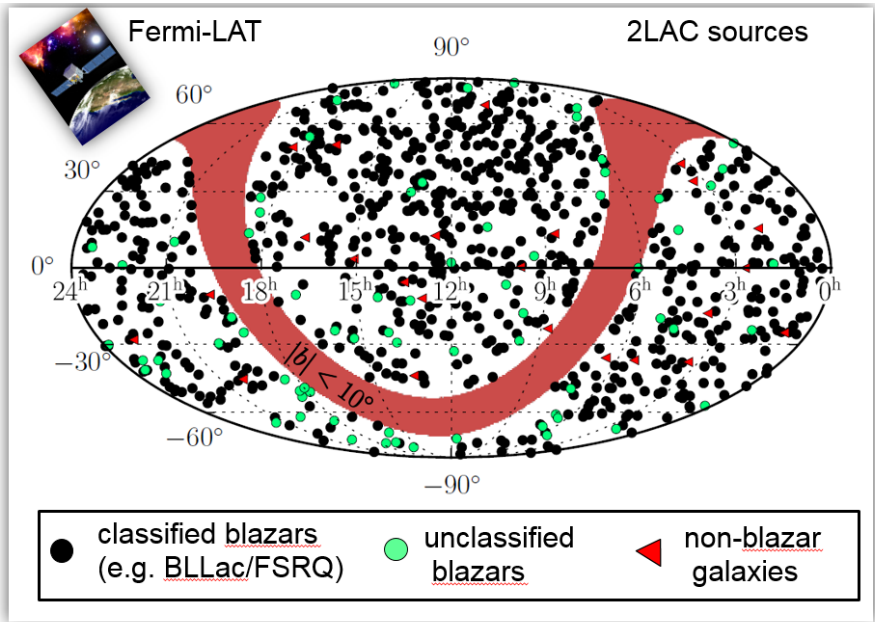
P-Value for the used subsamples of TeV cat sources

New upper limits founded for point-like sources of TeV Catalogue of Southern hemisphere combining ANTARES (2007-2012) and ICeCube (2008-2011) data sets

Upper limits of BL-Lac contribution to IceCube flux

From Glüsenkamp SciNeGhe 2016



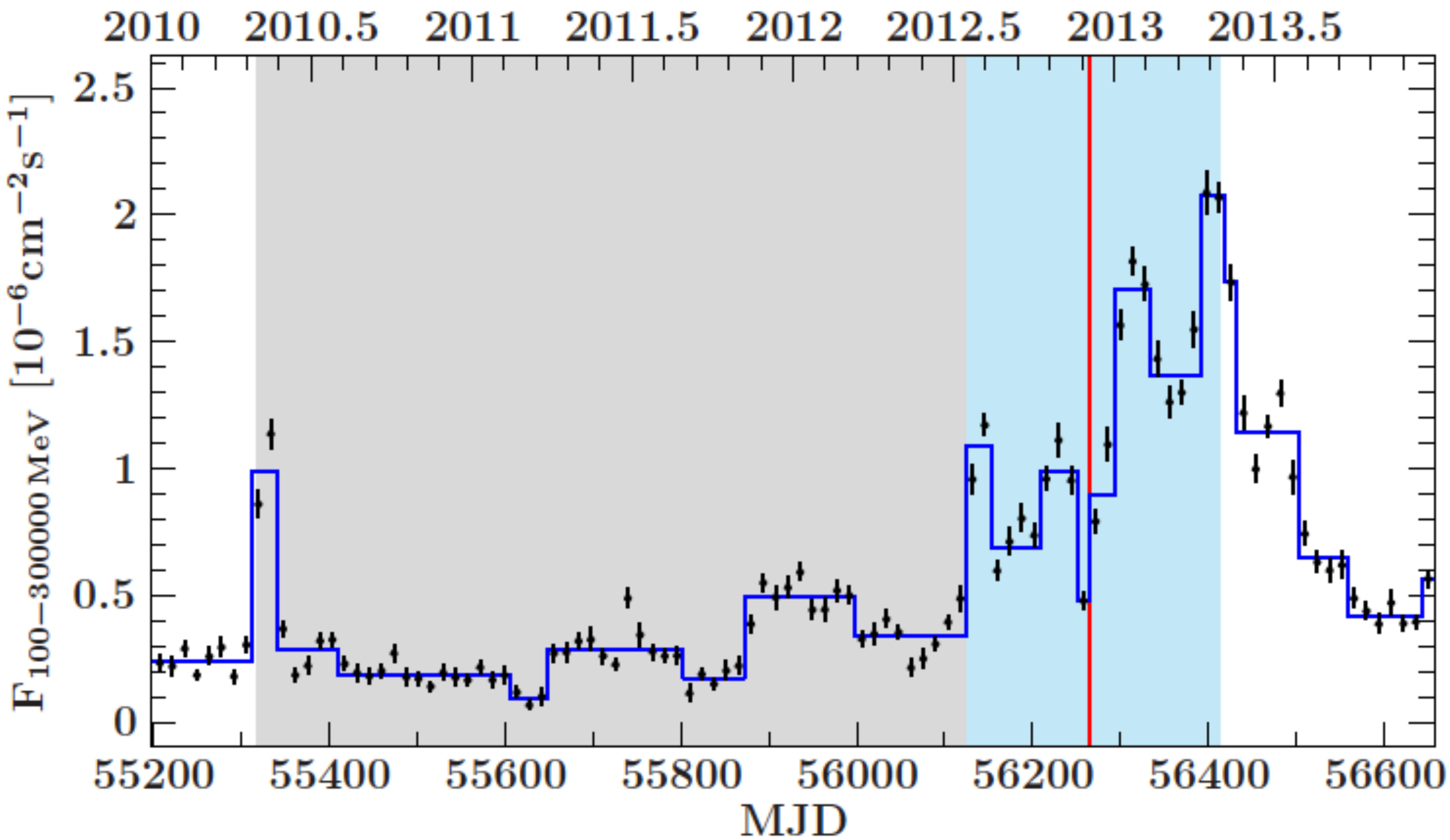


70% flux complete! (Ackermann et al. 2015)

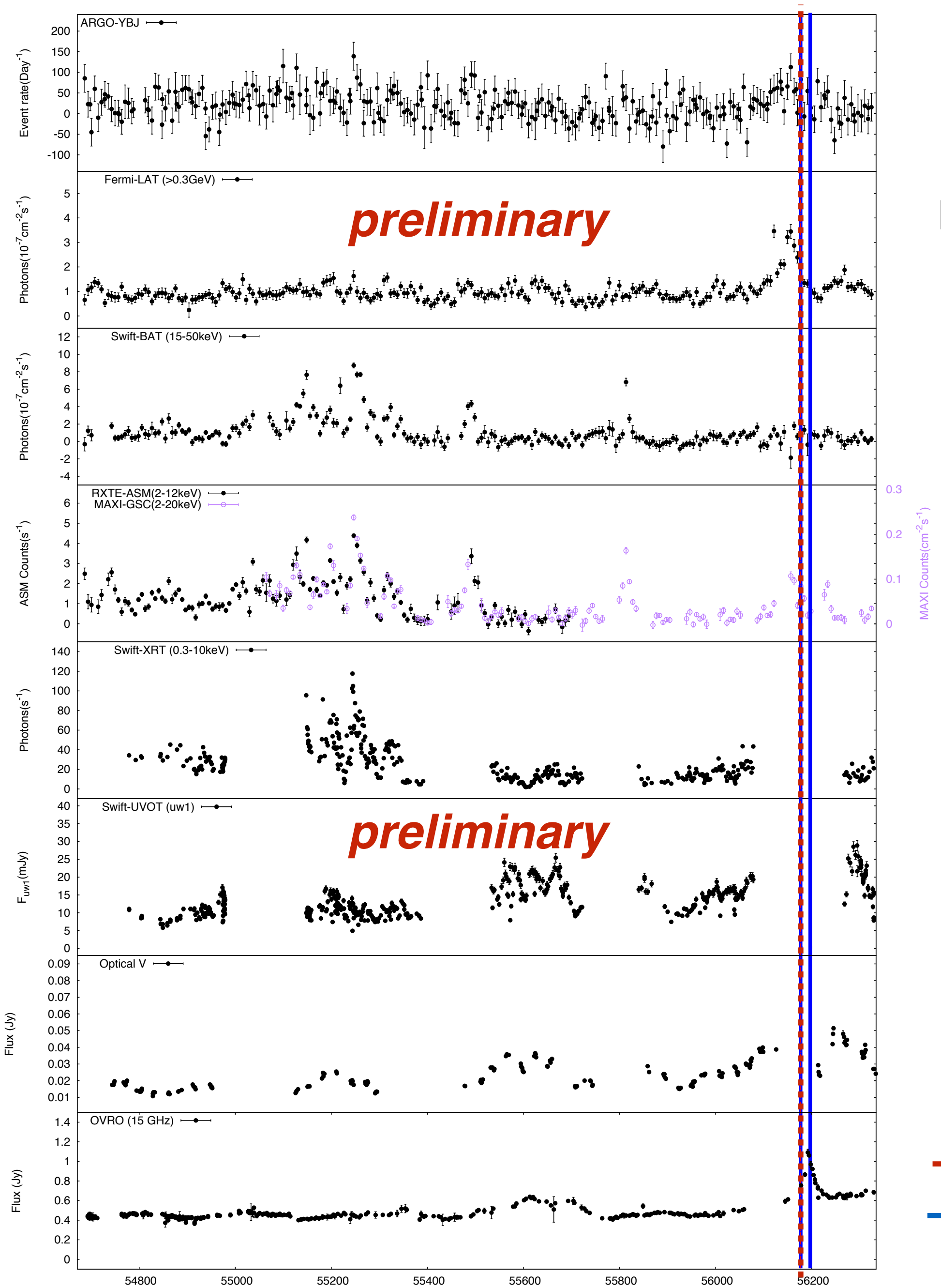
Considering the BL-LAC/FSRQ catalog of Fermi-LAT and assuming these sources also neutrino emitters a limit of max ~ 27% of IceCube measured flux can be explained, still a large room is left for other Extra-Galactic candidates

Time correlation between BL-Lac activity and IceCube event

Kadler et al., ArXiv:1602.02012, Nature



Time correlation (months) between the increasing of gamma-ray activity (blue histogram) of PKS B1424-418 and IceCube PeV event (red line) within 20° from the source position.



In Preparation: Fraija, Marinelli et al.

We found a neutrino event possibly related with the Mrk 421 flare happened in September 2012, Interestingly also two UHECRs observed by TA occurred in a close the time interval (days)

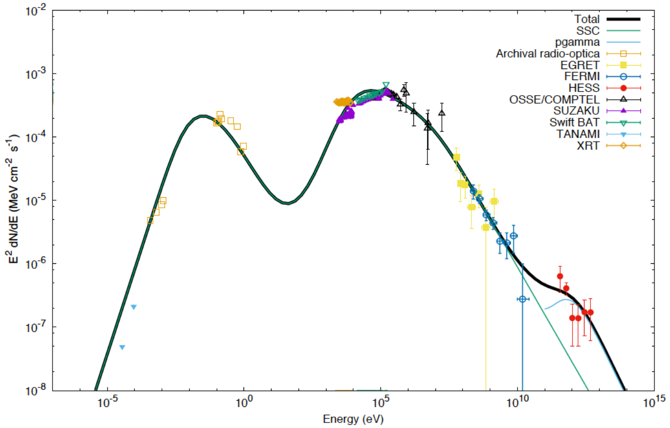
However this neutrino has been measured with an energy of 30 TeV

- - - - neutrino observed by IceCube at 30° from Mrk421

—— UHECRs observed by TA within 10° from Mrk421

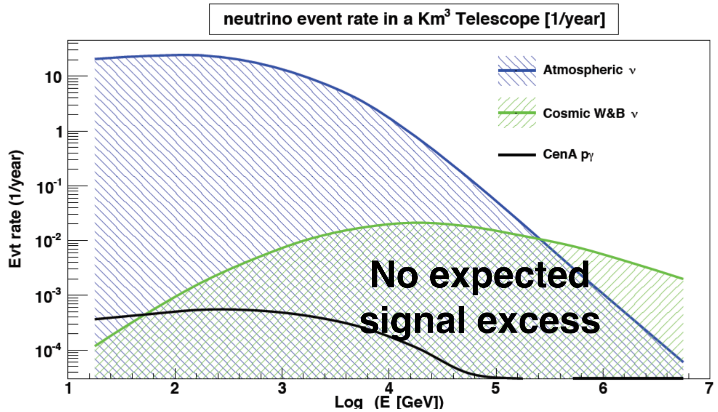
Looking at LLAGN: The cases CenA, M87, NGC1275

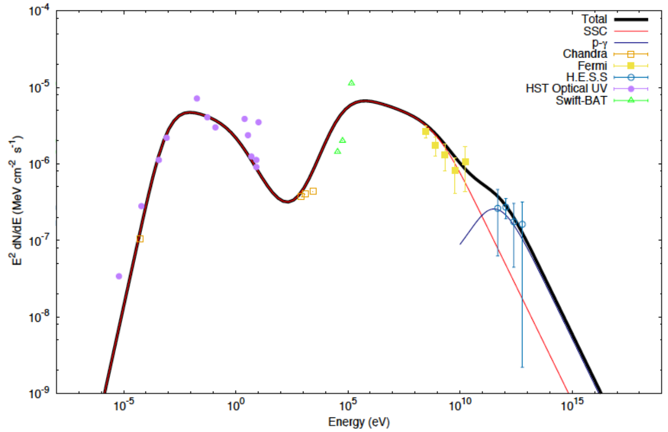
Fraija, Marinelli ApJ 2016



Cen A

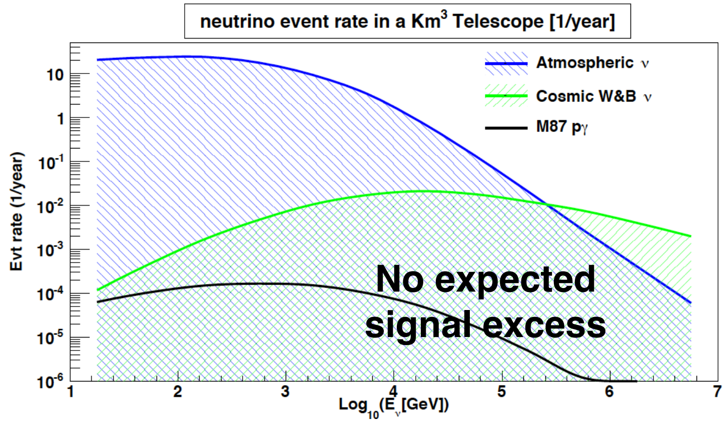
$\gamma \longrightarrow \nu$

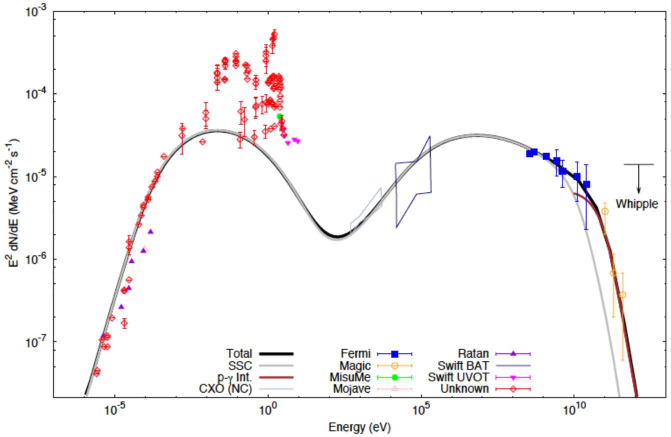




M87

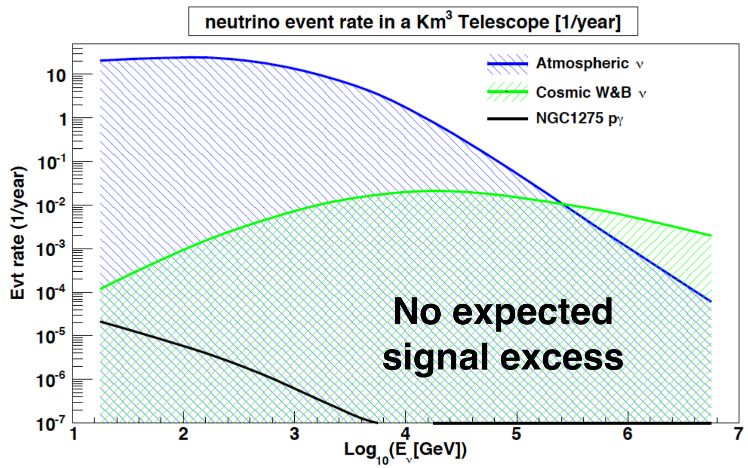
$\gamma \longrightarrow \nu$





NGC1275

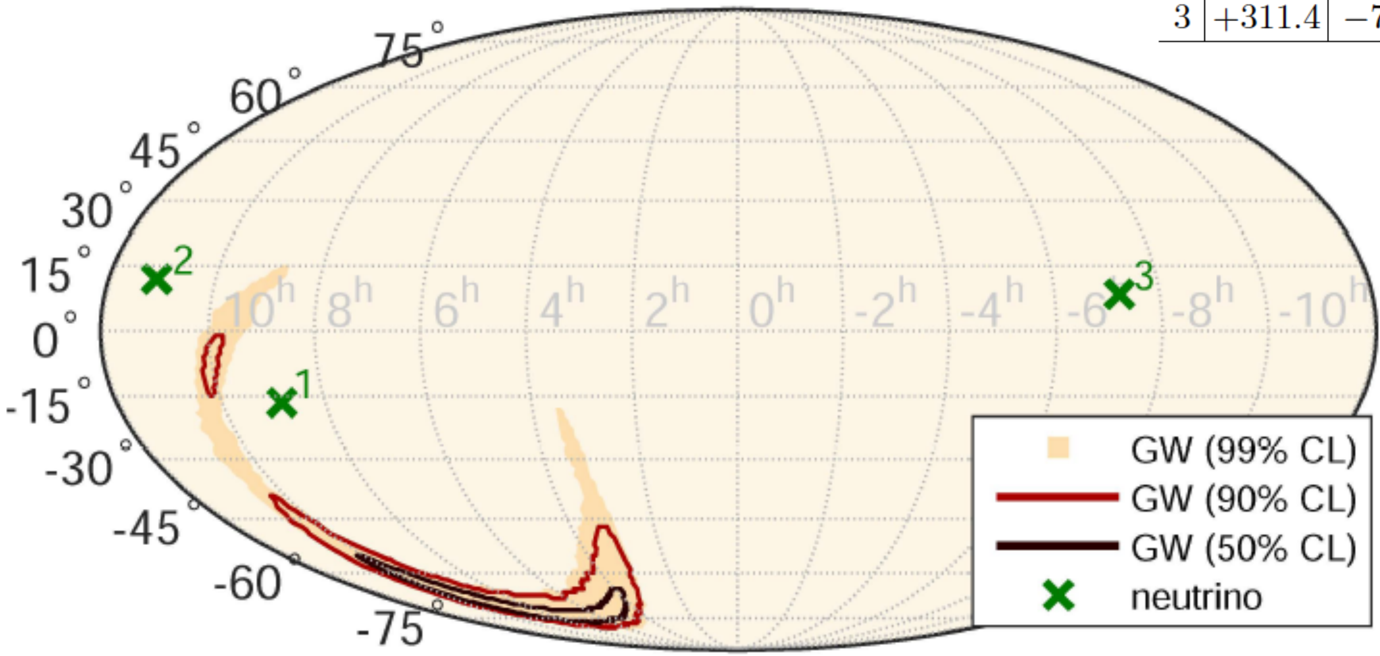
$\gamma \longrightarrow \nu$



Searching for IceCube ν signal associated to GW150914

ANTARES, ICECUBE, LIGO/VIRGO coll arXiv:1602.05411

#	ΔT [s]	RA [h]	Dec [°]	σ_μ^{rec} [°]	E_μ^{rec} [TeV]	fraction
1	+37.2	8.84	−16.6	0.35	175	12.5%
2	+163.2	11.13	12.0	1.95	1.22	26.5%
3	+311.4	−7.23	8.4	0.47	0.33	98.4%



In the time windows of +/- 500 s from the GW event no neutrino events are observed by ANTARES and while 3 neutrino events are detected by IceCube, However no spatial correlation are observed. Considering that IceCube see 1 atm muonic neutrino event every 6 mins the 3 neutrino events are possibly of atmospheric origin.

SUMMARY & CONCLUSIONS

- The era of neutrino astrophysics started with IceCube observations.
- A upper limit of ~20% of IceCube events can be identified as a diffuse galactic neutrinos, ~few % can be identified with galactic point-like sources, ~80% can be extragalactic, which kind of sources?
- For extra-galactic emission small evidences of connection with BL-Lacs and FSRQ, not with LLAGNs, GRBs (less 1%) or GW-BHs, very debated the case of of Starburst Galaxies. DM?
- The Multimessenger approach with other EM, CR component will be crucial to disentangle hadronic emission and to understand the nature of astrophysical accelerators.
- A presence of a Global Neutrino Network (IceCube, Antares, KM3NeT, Baikal) is needed for a homogeneous coverture of the sky.


Thanks for
your
attention!!

BACKUP SLIDES

EXTRAGALACTIC ν SIGNAL CONSIDERATIONS

- The IceCube Northern hemisphere analysis can be a good approximation of expected isotropic neutrino flux of extragalactic origin

- The FR I-II and in general the low luminosity AGNs cannot account for a considerable portion of this flux (only pp scenario can have a compatible Γ)

- BL-Lacs and FSRQ can have a Γ compatible with Northern IceCube analysis but not with full sky (4 years) IceCube spectrum

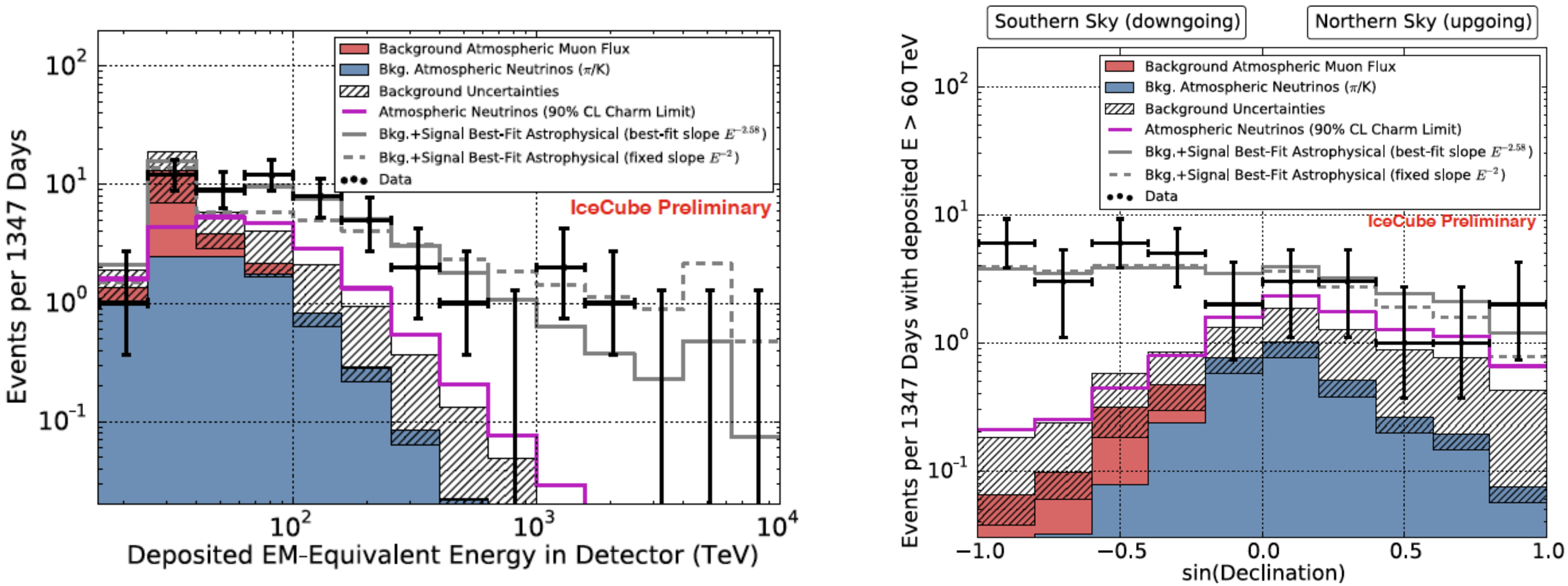
- Contribution of GRBs and Dark matter decay is not discussed here, but no evidences of associated neutrinos for the moment, and Icecube claim that GRBs can contribute for less than 1% to the total measured flux.

- We will procede to estimate the densities of Starburst Galaxies needed to explain the measured IceCube flux taking into account the presented CR transport model used for our galaxy.

IceCube shows that can see astrophysical signal

Analysis of 4 years Icecube data: astrophysical excess 7σ

arXiv1510.05223v2, ICRC2015 Contribution

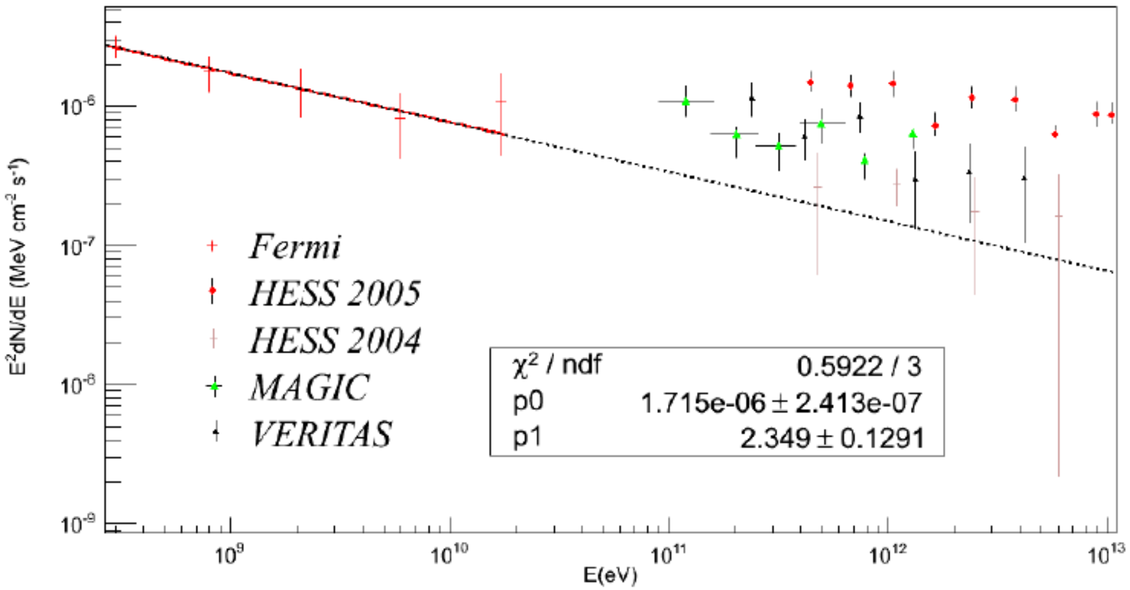


With a best fit analysis giving :

$$E^2\phi(E) = 2.2 \pm 0.7 \times 10^{-8} (E/100\mathrm{TeV})^{-0.58} \mathrm{GeV\,cm^{-2}s^{-1}sr^{-1}}$$

Looking at LLAGN: The case of FR I M87

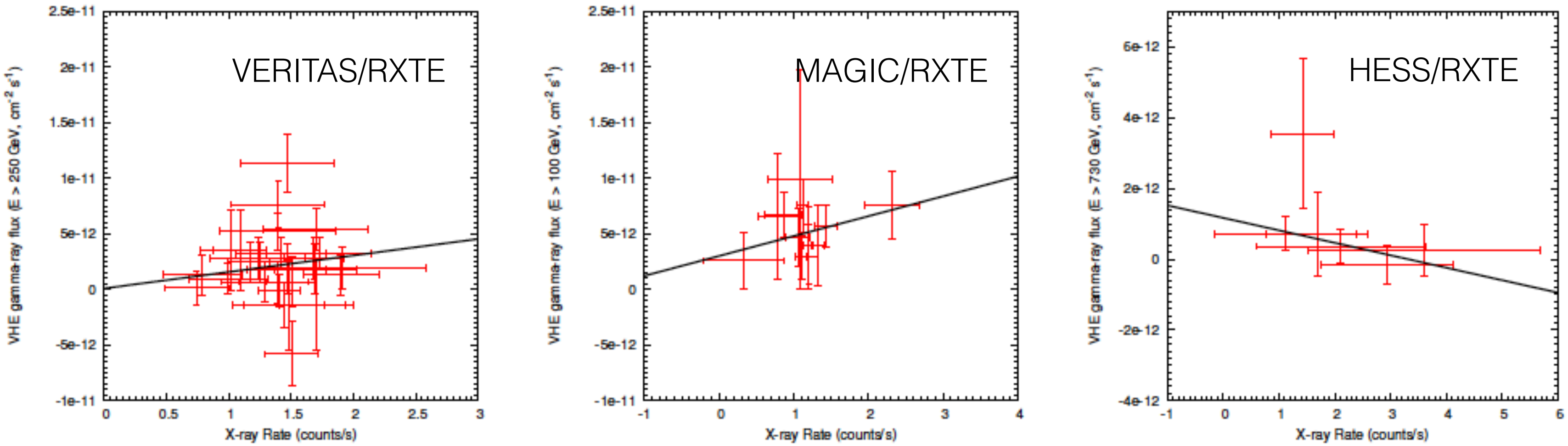
Marinelli, Fraija, Patricelli arXiv:1410.8549



All TeV SEDs cannot be fitted with a single zone emission as did by Fermi-LAT:

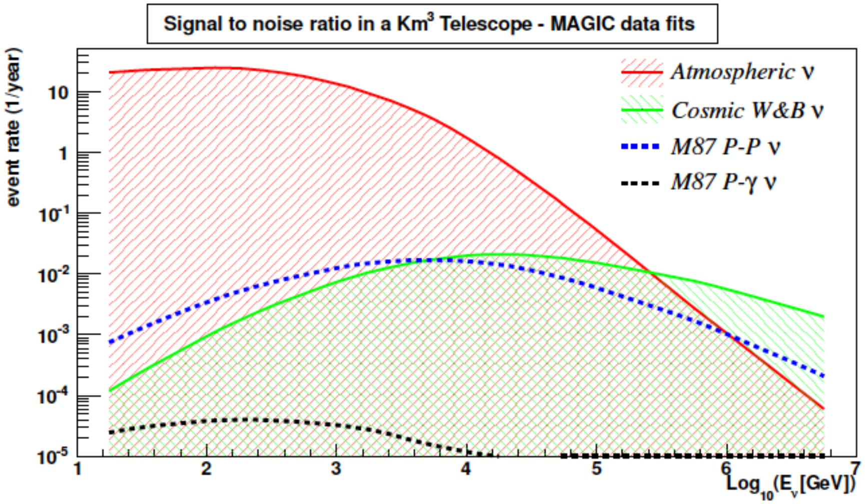
- Different zones of leptonic emission ?
- Different states of the source, not so stable ?
- Hints of Hadronic component in the TeV emission?

Low correlation coefficient between X and gamma rays: Different population of electrons, different emitting regions or Hadronic emission?



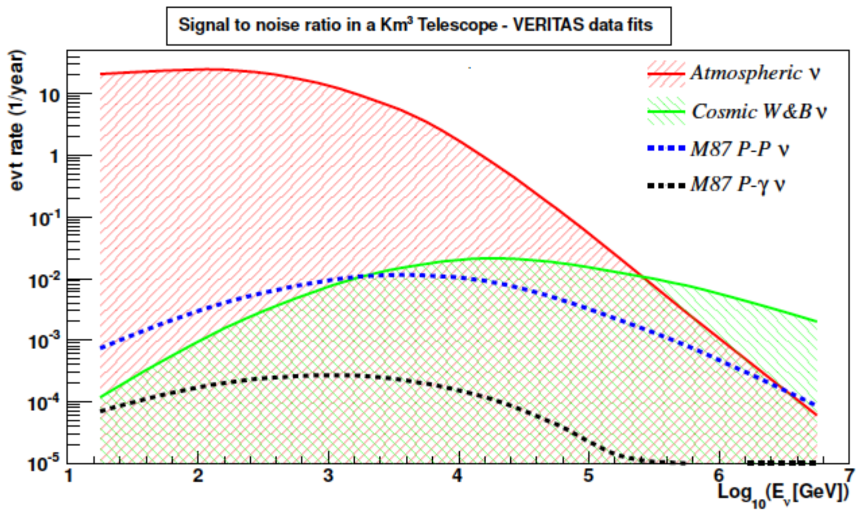
fitting M87 spectra with hadronic emission no ν signal expected

Marinelli, Fraija, Patricelli arXiv:1410.8549



proton-proton interaction

	Parameter	Symbol	H.E.S.S.	MAGIC	VERITAS
$^{a}A_{p\gamma,\gamma}$	[A]	$A_{p\gamma,\gamma}$	13.3 ± 0.096	3.38 ± 0.431	5.39 ± 0.94
Power index	[B]	α	2.28 ± 0.052	2.97 ± 0.121	2.70 ± 0.23



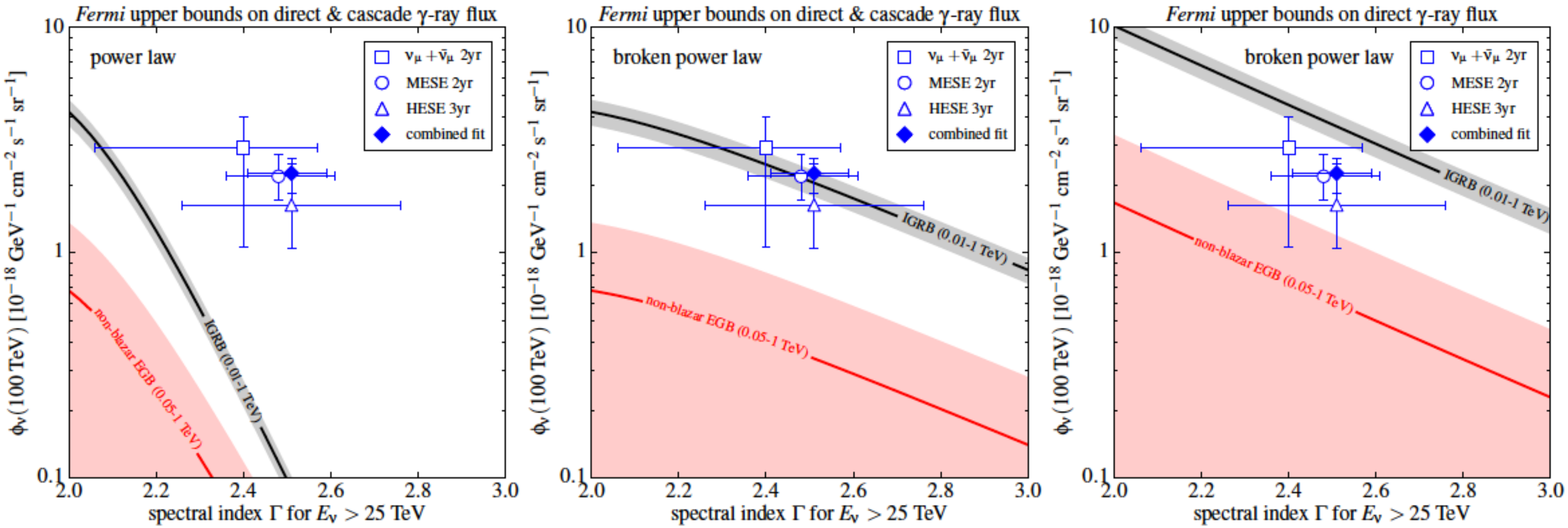
proton-gamma interaction

	Parameter	Symbol	H.E.S.S.	MAGIC	VERITAS
$^{a}A_{pp,\gamma}$	[A]	$A_{pp,\gamma}$	12.0 ± 0.08	4.00 ± 0.43	5.11 ± 0.89
Power index	[B]	α	2.22 ± 0.05	2.33 ± 0.12	2.48 ± 0.20

No signal excess expected for M87 in a few years, proton-gamma interaction produce a spectral index not compatible with IceCube observation!

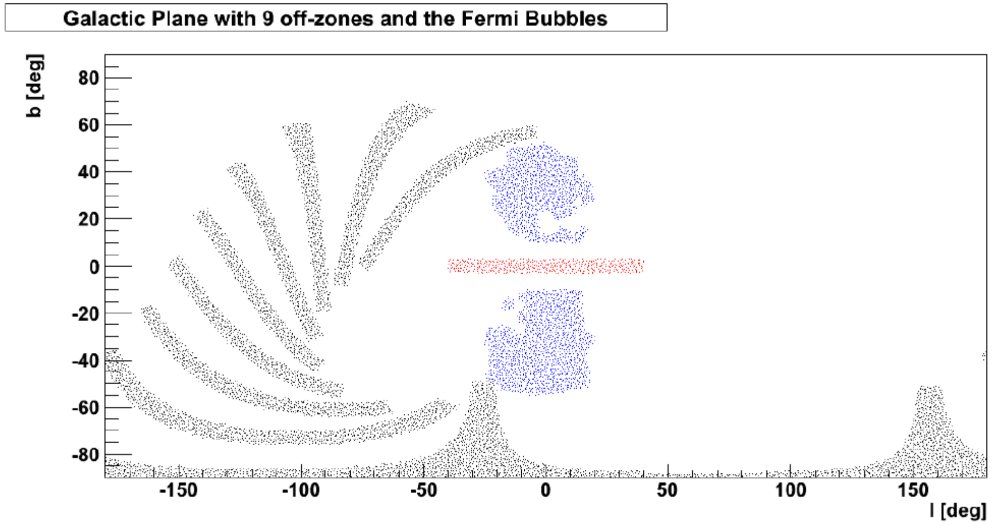
The case of Starburst Galaxies

Bechtol et al. arXiv1511.00688

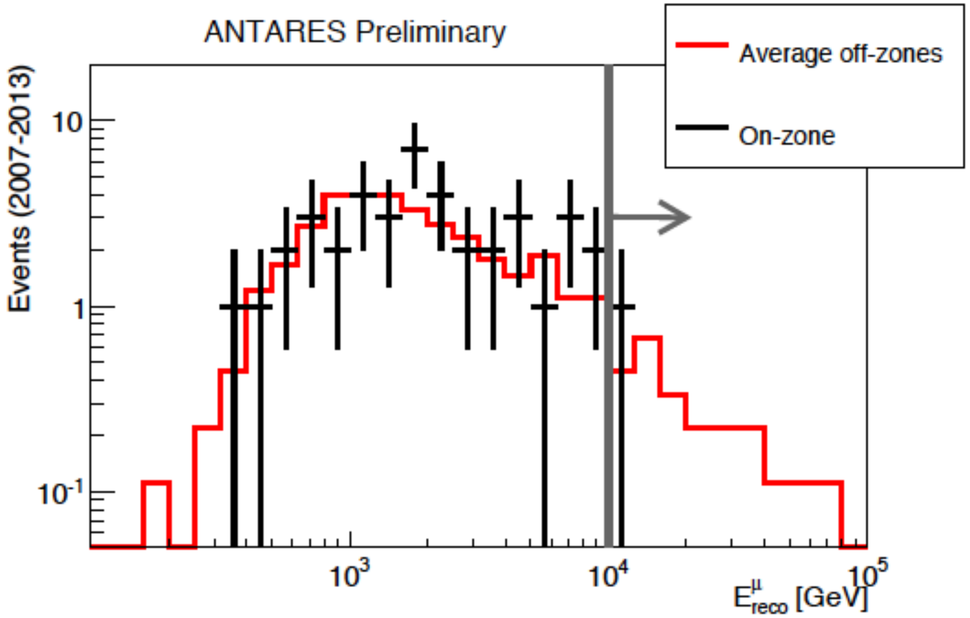


Looking at new Fermi FHL catalog the authors tried to estimate the remaining slot for non BL-lacs sources to explain the astrophysical neutrino fluxes measured by IceCube. This slot sims to be small.

Antares unblinding analysis for the Galactic Ridge



Antares coll., ICRC2015, arXiv:1510.04508



(b) Galactic Plane

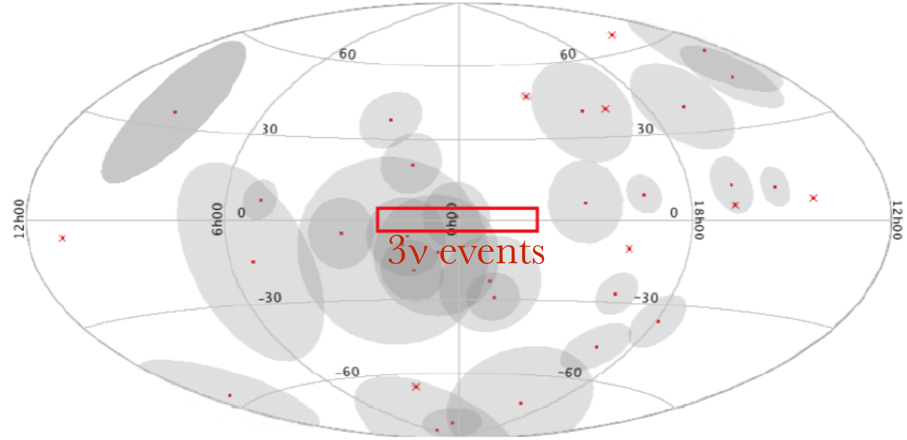
- A unblinded analysis was performed with Antares data collected between 2007 and 2013. No neutrino excess was found in the Galactic ridge region respect to the background expectation obtained considering the nine off-zone regions.

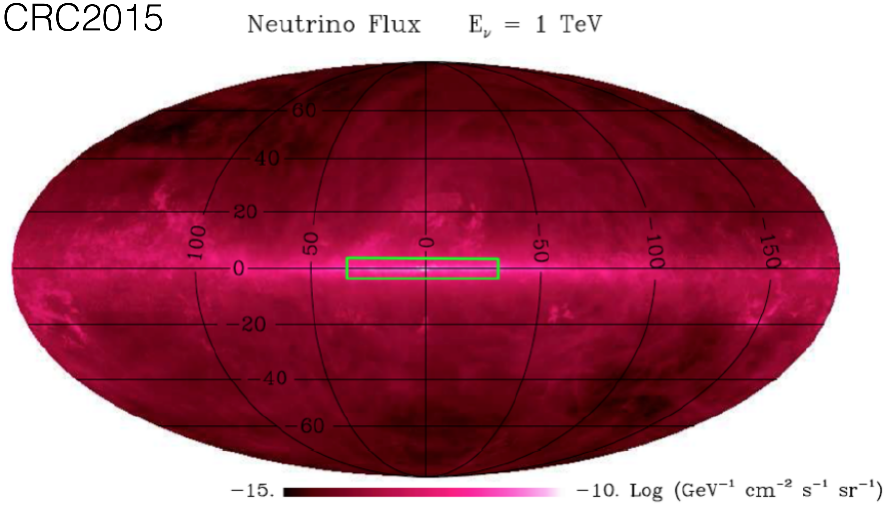
- No high energy neutrino events were observed from the Galactic ridge by considering the Antares data.

- Thanks to this unblinding analysis of the region, upper limits at 90% C.L. where set.

KRA and KRAγ neutrino spectra expected for |b|<4°, |l|<30°

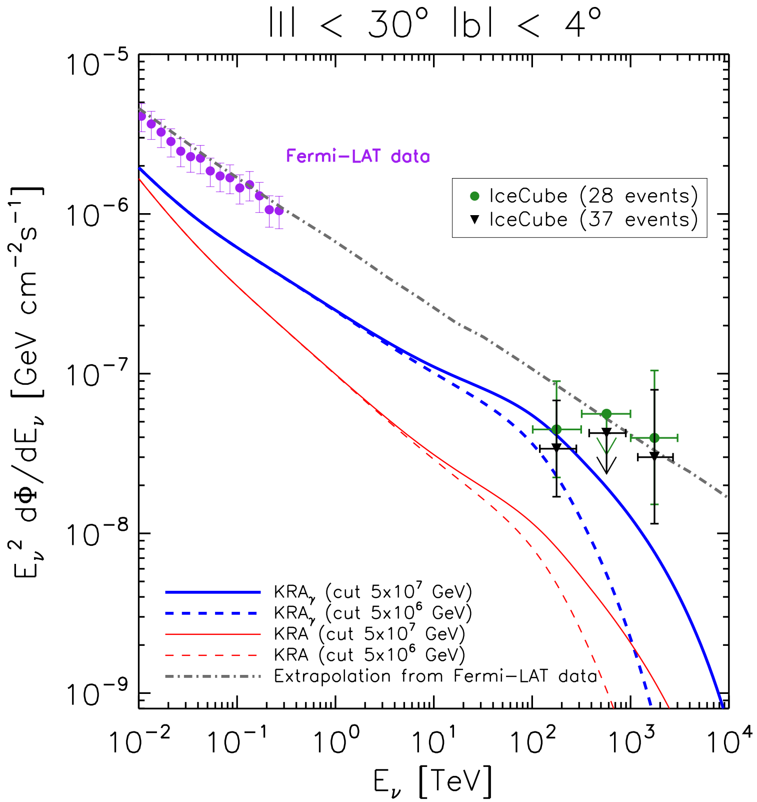
Gaggero, Grasso, Marinelli, Urbano, Valli, arXiv:1508.03681, ICRC2015





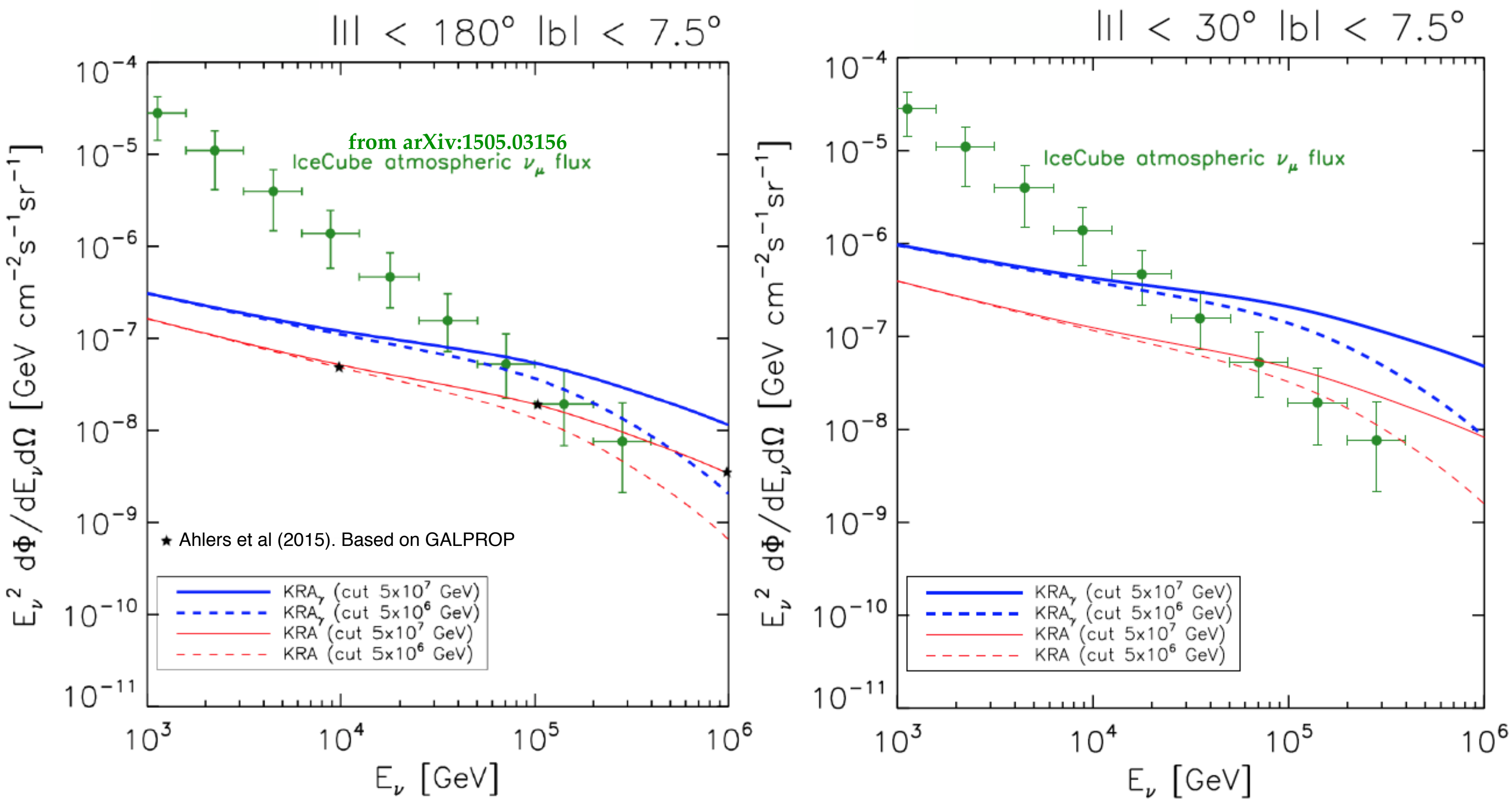
- Skymap with the catalog of IceCube HESE 3 years with 37 events: 29 shower-like and 8 track-like. Only 3 shower-like events are reconstructed in a position of the sky compatible with the |b|<4° and |l|<30°

- From the neutrino spectra obtained with KRA and KRAγ models we can estimate the galactic component of the IceCube observation in this region of the sky.



Galactic Plane neutrino with KRA (δ uniform) & KRAγ (δ variable)

Gaggero, Grasso, Marinelli, Urbano, Valli, arXiv:1508.03681, ICRC2015



Comparison between neutrino spectrum produced with standard KRA model and the new KRAγ model from the entire galactic plane.

The diffuse neutrino spectrum obtained considering the <u>KRAγ model for the inner galactic plane</u>