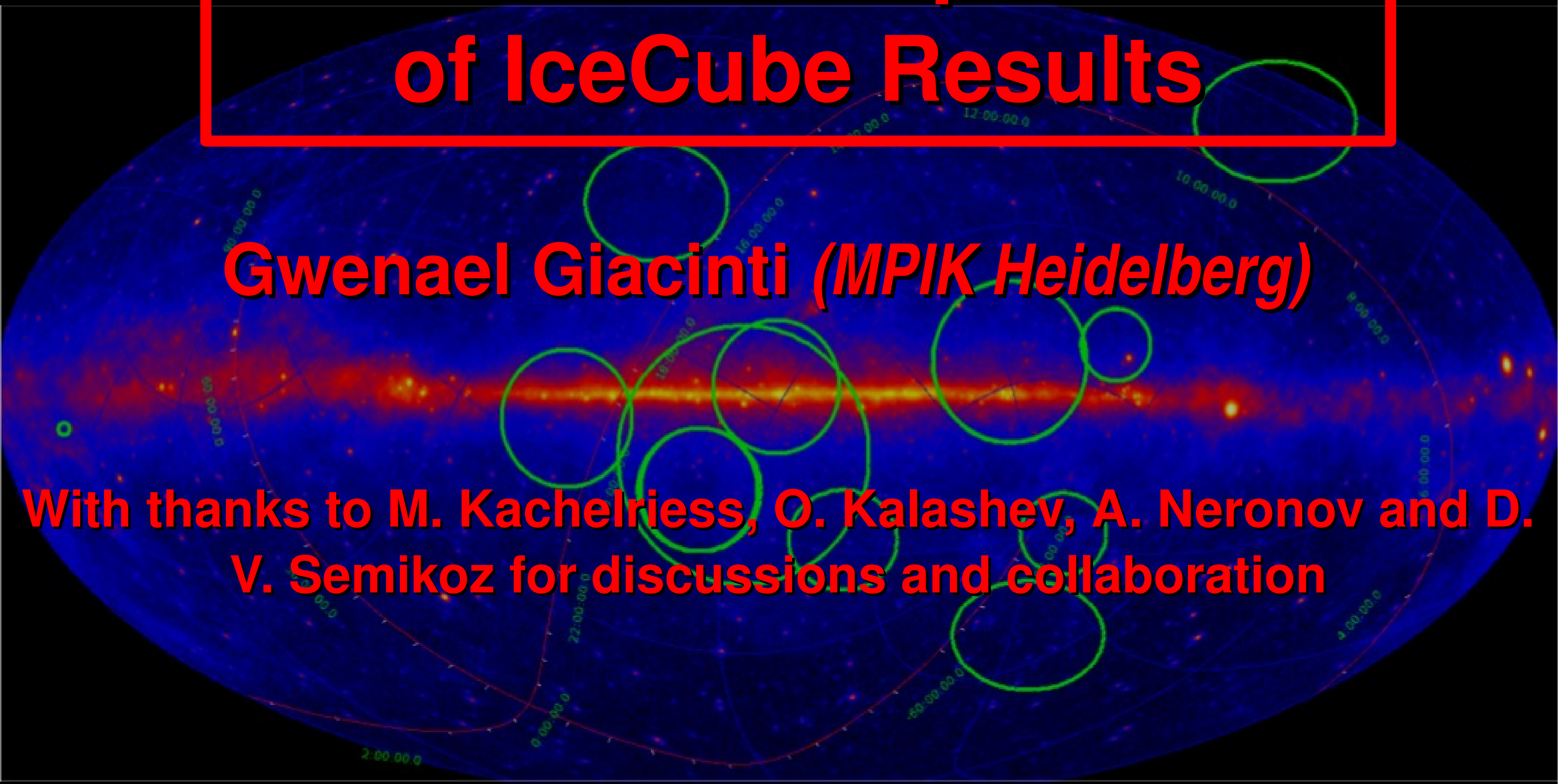
Theoretical Interpretations of IceCube Results



Gwenael Giacinti ***(MPIK Heidelberg)***

With thanks to M. Kachelriess, O. Kalashev, A. Neronov and D. V. Semikoz for discussions and collaboration

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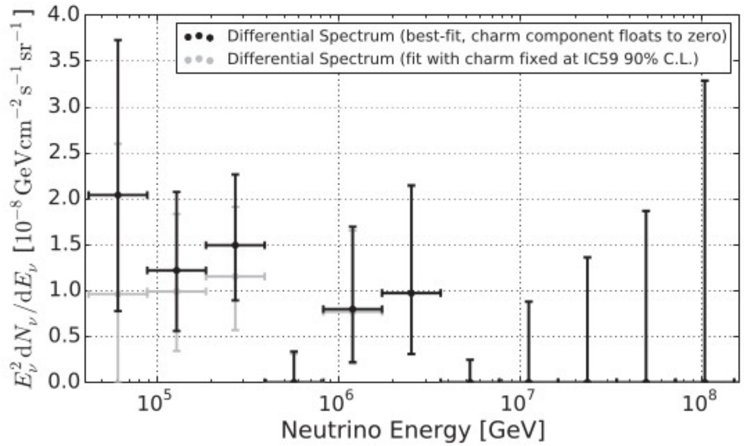
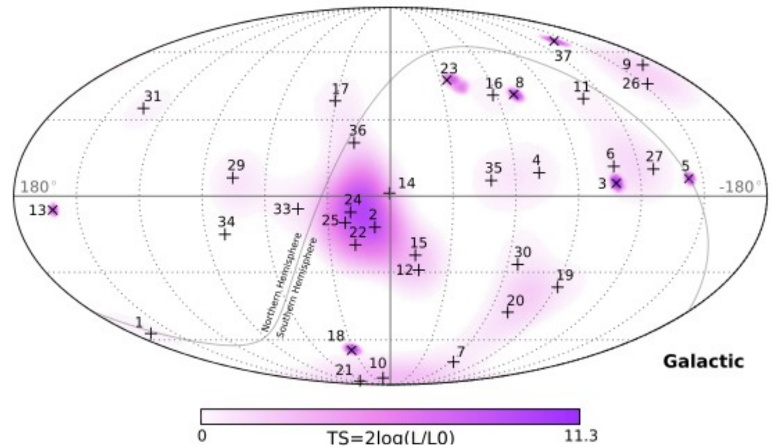
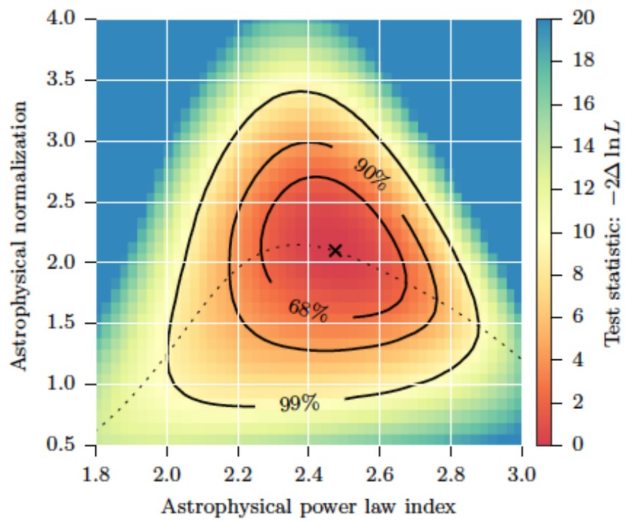
PRL **113,** 101101 (2014) PHYSICAL REVIEW LETTERS week ending 5 SEPTEMBER 2014

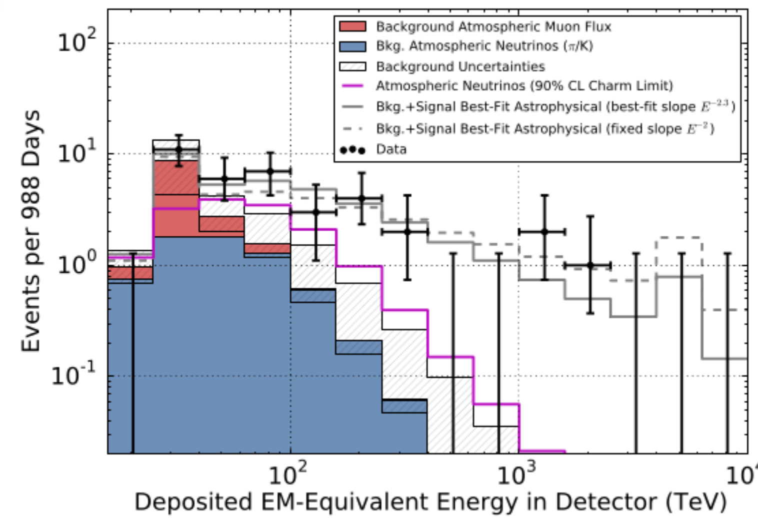






37 events with
E ~ 30 TeV - 2 PeV

IceCube Coll.,
PRL 113 (2014)



Origin ? $\quad$ $\mathbf{p_{CR} + p \rightarrow}$ **charged/neutral** $\boldsymbol{\pi \rightarrow \nu}$ **&** $\boldsymbol{\gamma}$

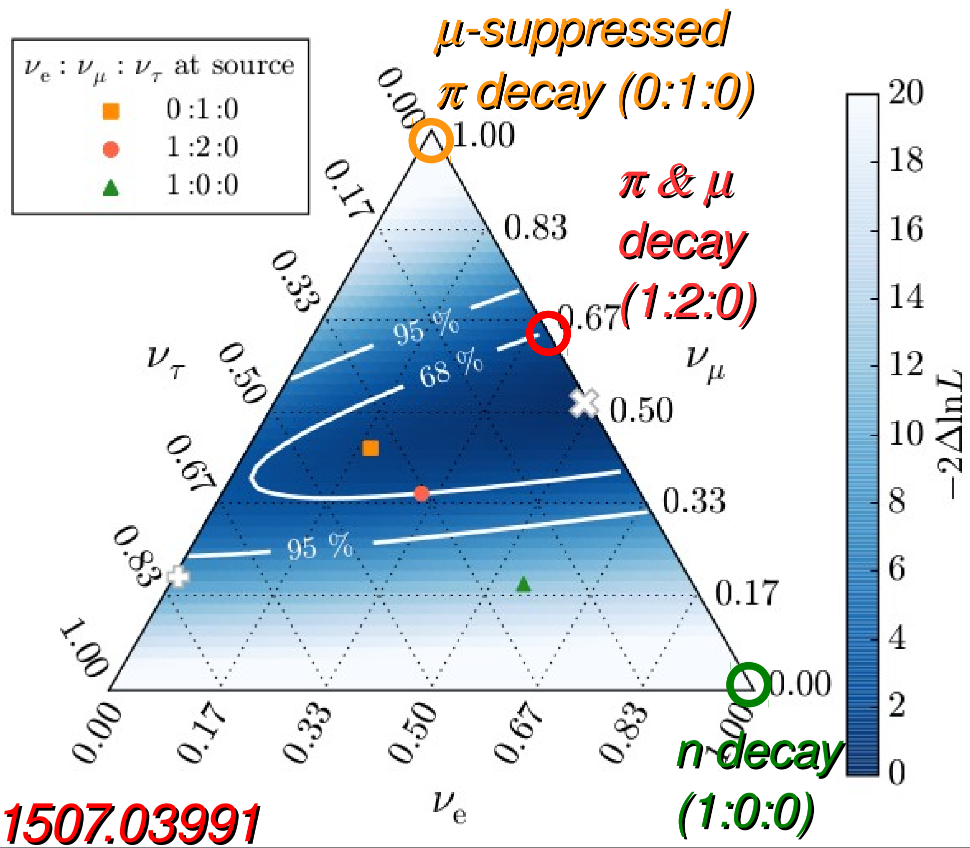
$\mathbf{p_{CR} + \gamma}$

(or decay of PeV dark matter ???)

IC Neutrino flavours

$$p + p \rightarrow \pi^+ + \ldots$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

	$(\nu_e : \nu_\mu : \nu_\tau)$
pion & muon decay	$(1:2:0)$
neutron decay	$(1:0:0)$
muon-suppr'd pion decay	$(0:1:0)$



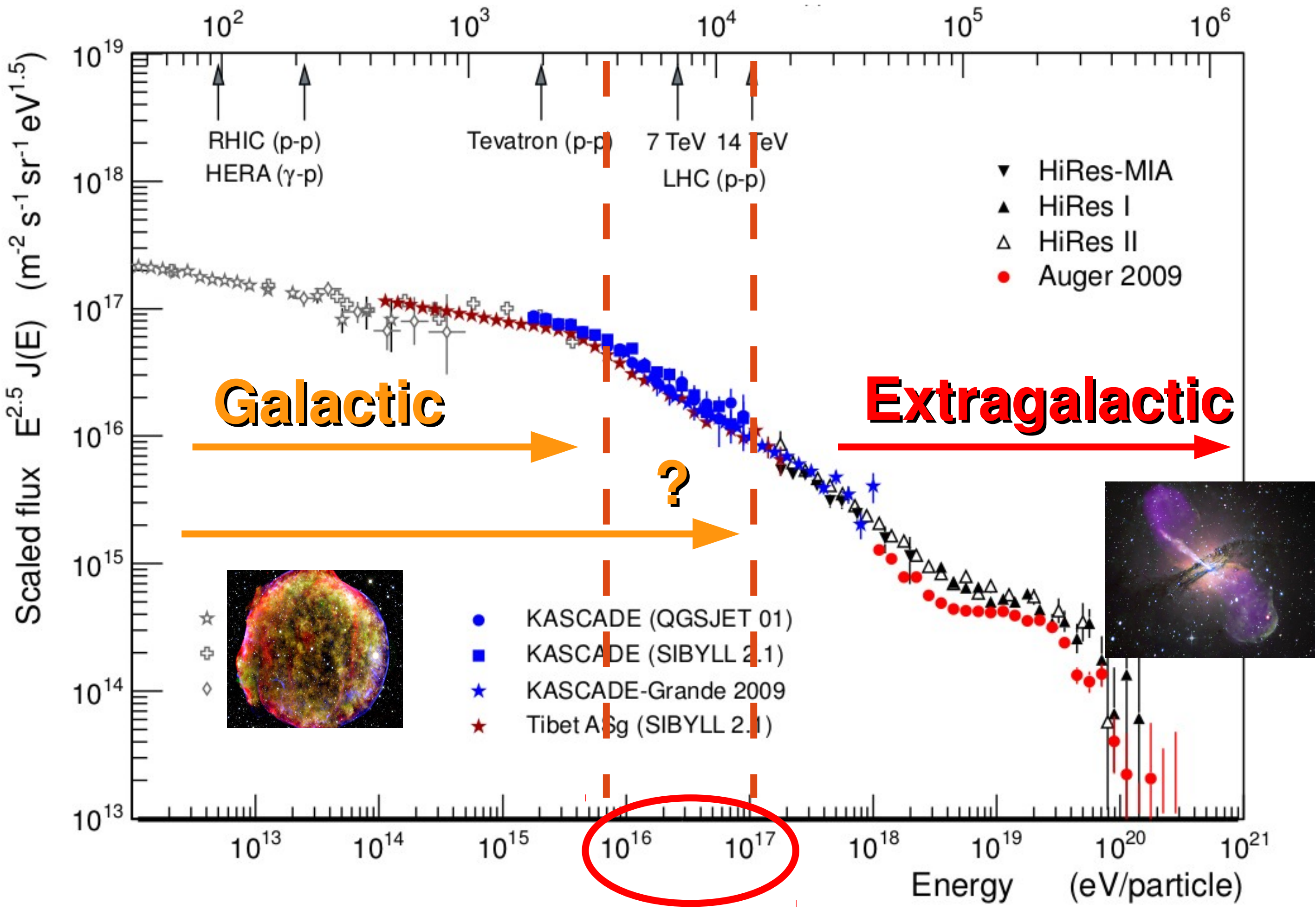
IC Coll, 1507.03991

π produced in CR interactions with gas (pp) or radiation (pγ)

Relating neutrino energy is ~ 5% of CR energy

(Up to) a few PeV neutrinos => From ~ 10^{17} eV CRs !

→ Galactic / extragalactic?
→ Glashow resonance ?
→ "Exact" slope ?
→ Isotropic / point sources?



π produced in CR interactions with gas (pp) or radiation (pγ)

Relating neutrino energy is ~ 5% of CR energy

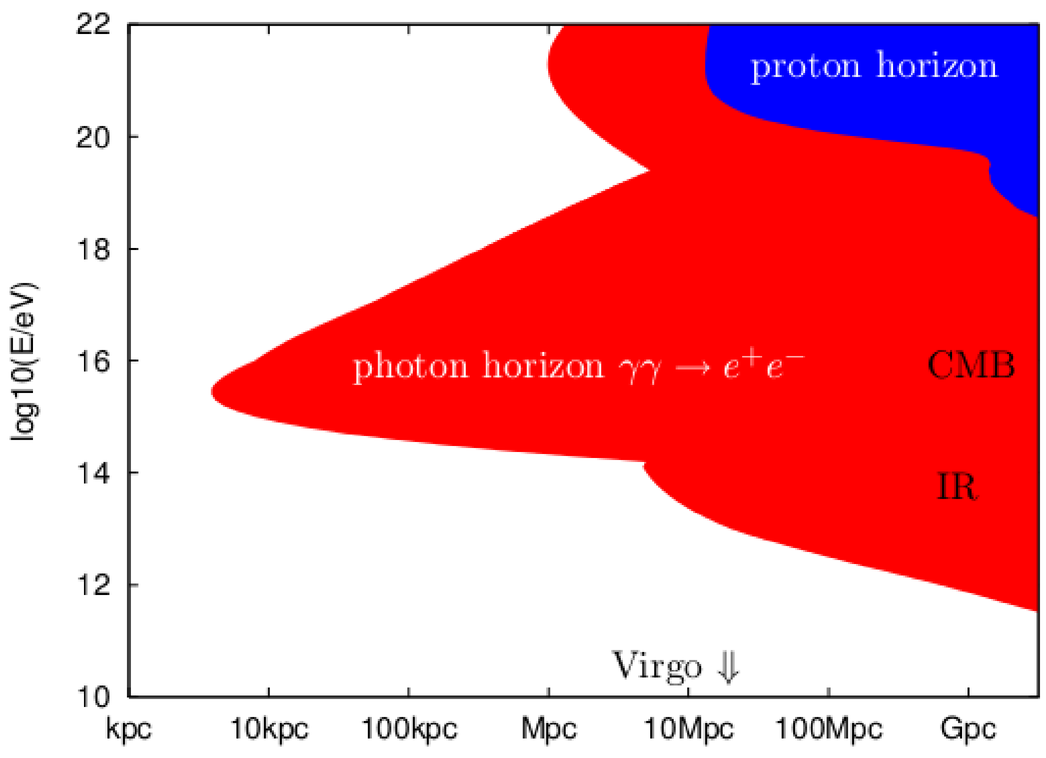
(Up to) a few PeV neutrinos => From ~ 10^{17} eV CRs !

~ PeV γ-rays

Cascade down to ~ multi-GeV energies

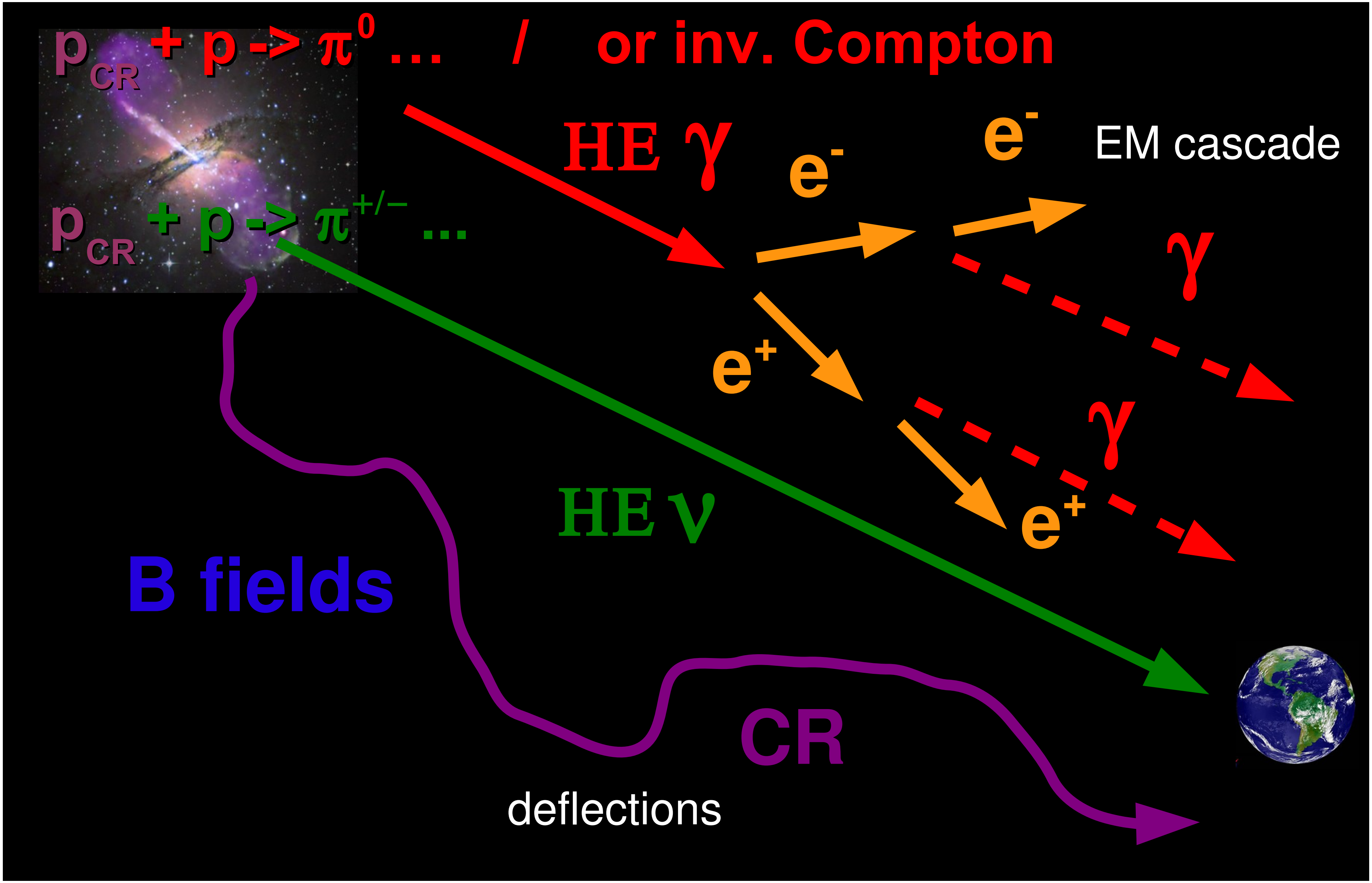
$$\gamma + \gamma_{\rm bkg} \rightarrow e^+ + e^-$$

$$e^\pm + \gamma_{\rm bkg} \rightarrow e^\pm + \gamma$$



From M. Kachelriess

Multi-messenger studies



EGB & Isotropic Diffuse γ-Ray Background versus IC ν's

extragalactic emission : $\alpha < 2.3$ / IceCube analysis : $\alpha = 2.4 - 2.6$

24th European Cosmic Ray Symposium (ECRS2014) IOP Publishing
Journal of Physics: Conference Series **632** (2015) 012037 doi:10.1088/1742-6596/632/1/012037

M. Kachelriess

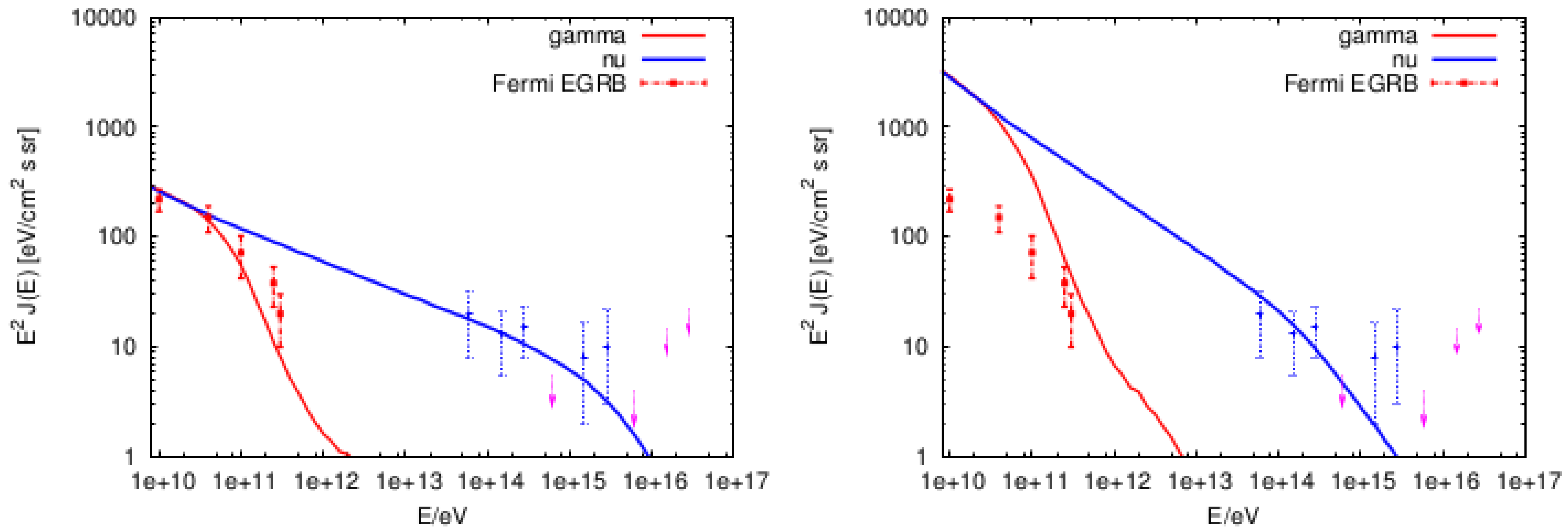
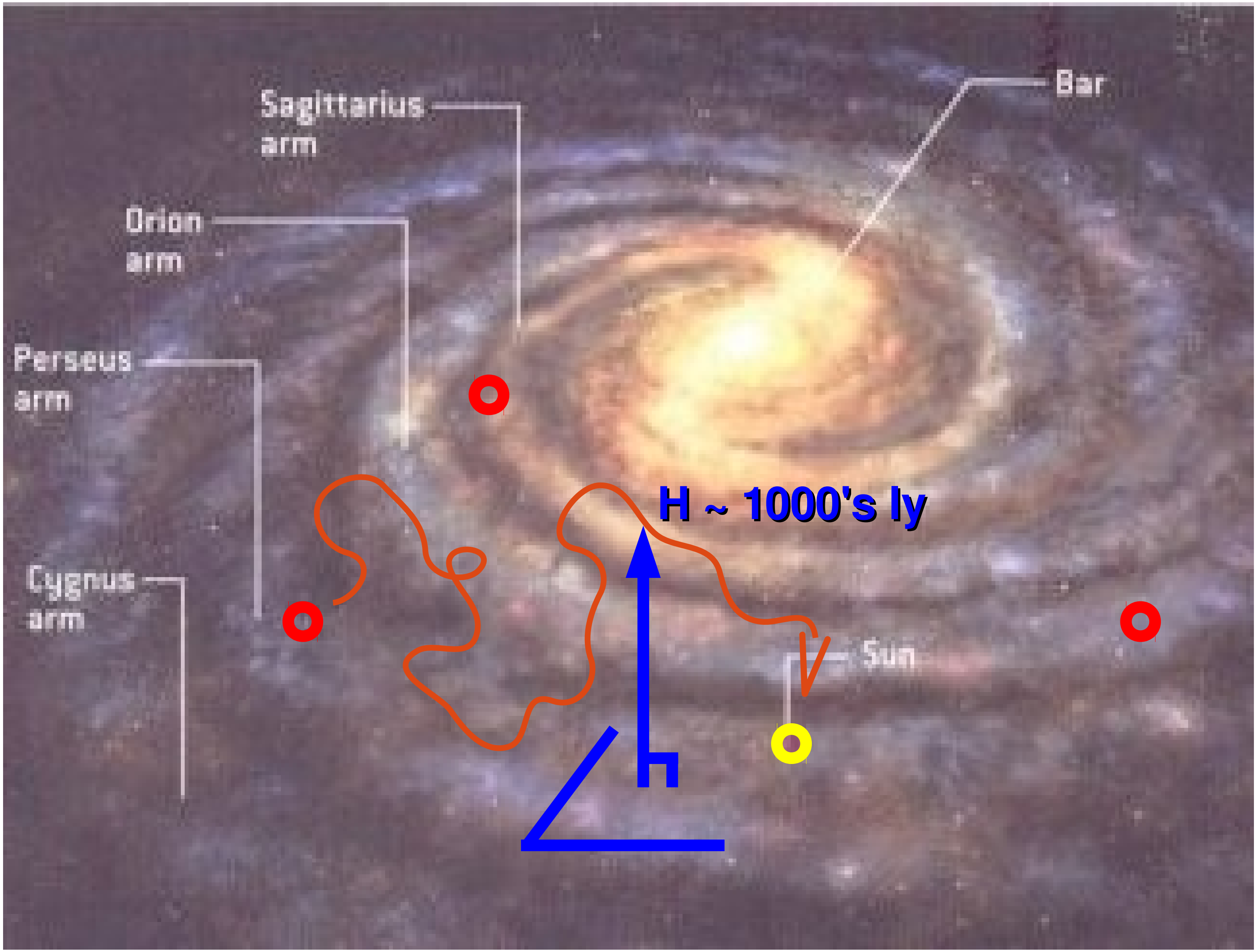


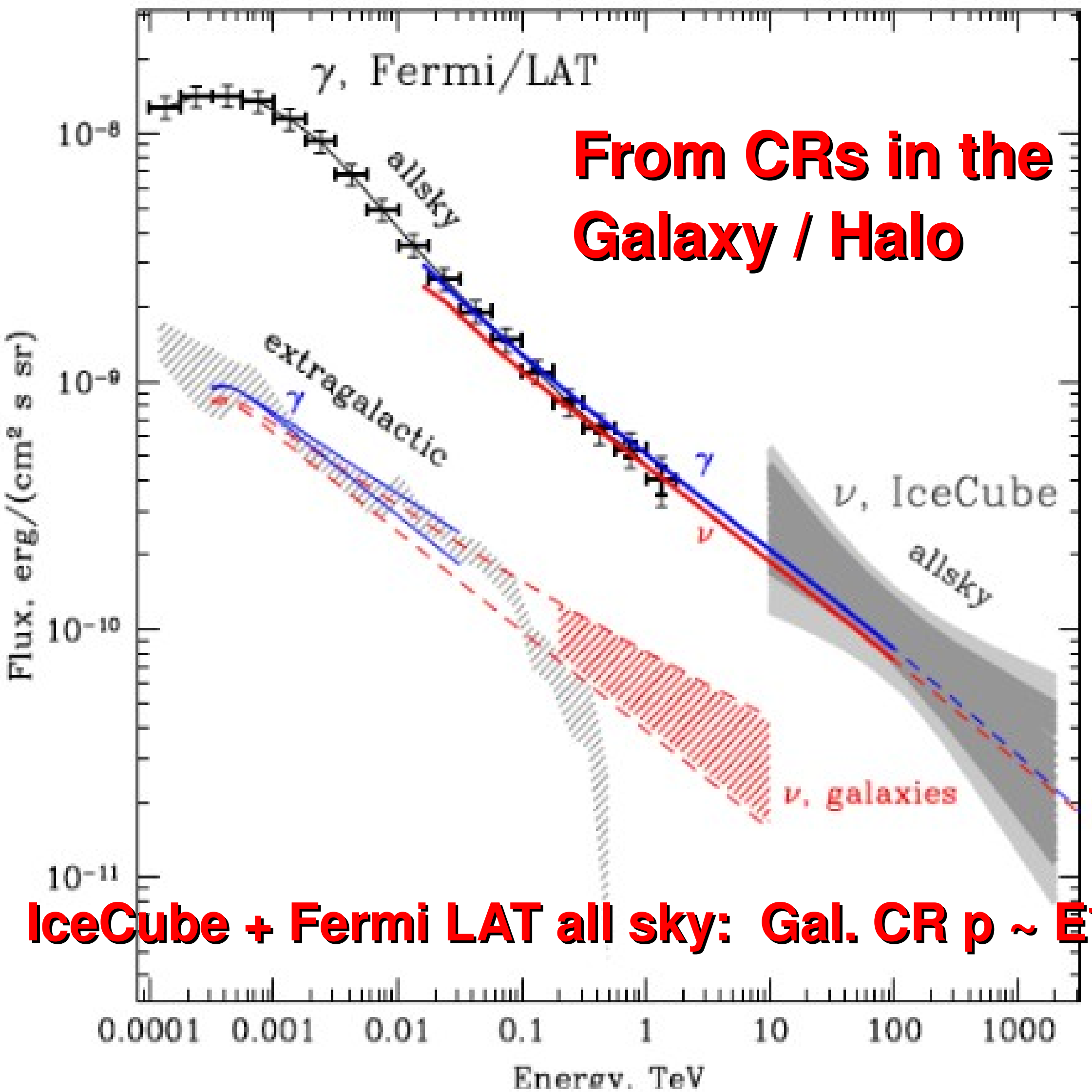
Figure 3. Intensity of the diffuse EGRB and neutrinos arising from *pp* collisions, left $\alpha = 2.3$ and right $\alpha = 2.5$.

Our Milky Way



LARGE neutrino flux

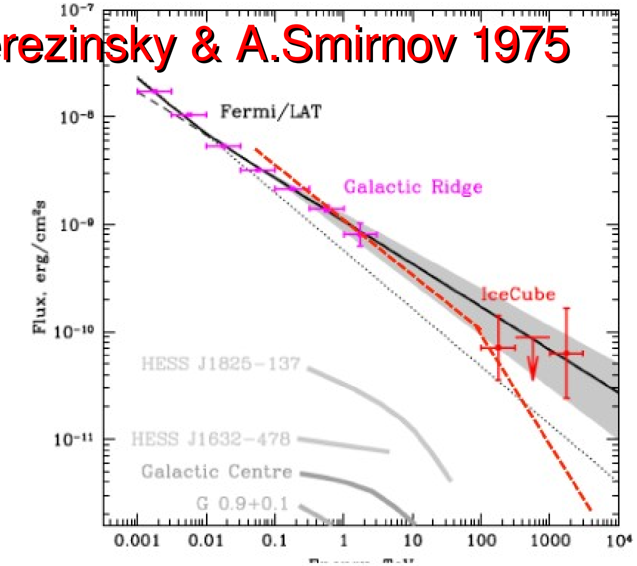
Neronov & Semikoz 2014
arXiv:1412.1690



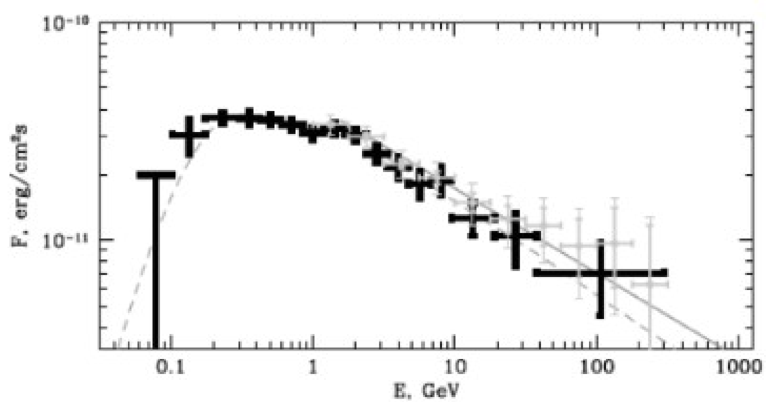
From CRs in the Galaxy / Halo

IceCube + Fermi LAT all sky: Gal. CR p ~ $E^{-2.5}$

V.Berezinsky & A.Smirnov 1975



In the LMC, the avg. CR p spectrum is ~ 2.45



Neronov & Malishev, arXiv: 1505.07601

IceCube neutrinos from Galactic point sources

Kachelriess & Ostapchenko, arxiv:1405.3797

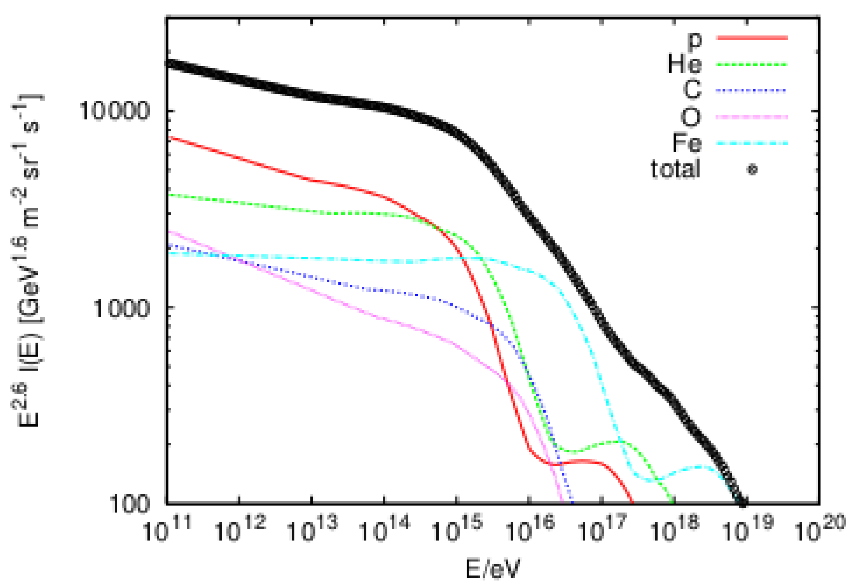


FIG. 5: All particle CR spectrum and individual contribution of five elemental groups in the escape model of Ref. [34].

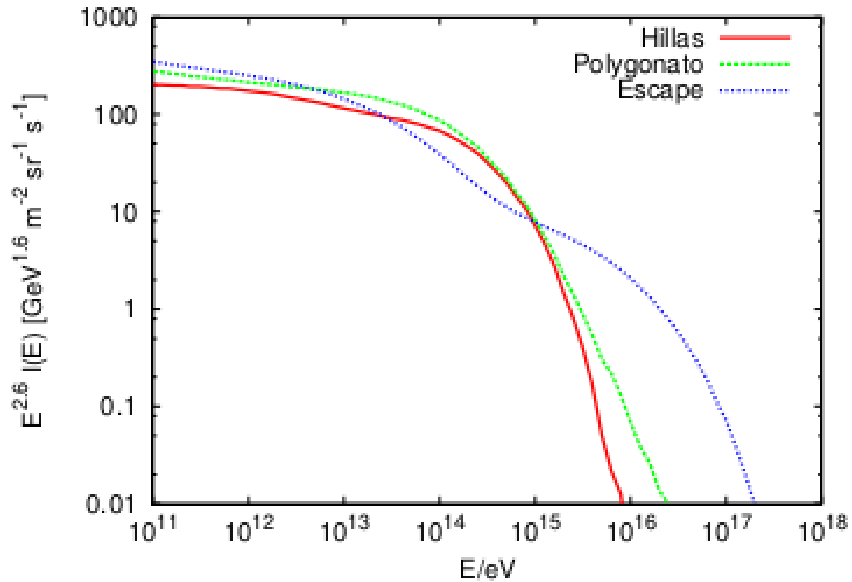


FIG. 7: A comparison of the total neutrino spectra $E^{2.6}I(E)$ predicted by the three CR models.

Giacinti, Kachelrieß, D. V. Semikoz, PRD 90, 041302 (2014)

LOW neutrino flux
Suggest <u>Individual sources</u>

GALACTIC SOURCES - CANDIDATES

→ **CRs IN THE HALO**

- **Link with diffuse Galactic γ-ray emission**

Neronov et al. 2013, Ahlers&Murase 2013, Joshi et al. 2013, Kachelriess & Ostapchenko 2014
Neronov & Semikoz 2014, Guo et al. 2014, Gaggero et al. 2015

- **Galactic CRs in our Halo** *Taylor, Gabici & Aharonian 2014*

→ **Galactic sources that are currently active** *Kachelriess & Ostapchenko 2014*

- **Pulsars ?** *Padovani & Resconi 2014*
- **Microquasars ?** *Anchordoqui et al. 2014*
- **sub-PeV neutrinos from hypernova remnants ?** *Fox et al. 2013*
- **Milagro sources as PeVatrons ?** *Gonzalez-Garcia et al. 2014*
- **Supernova remnants** *… NO !*

→ **CURRENT/PAST ACTIVITY FROM GAL. CENTER OR OUTFLOW**

- **Sagitarius A*** *Bai et al. 2014, Fujita et al. 2015*
- **Fermi Bubbles** *Razzaque 2013, Ahlers & Murase 2013, Lunardini et al. 2013, 2015*

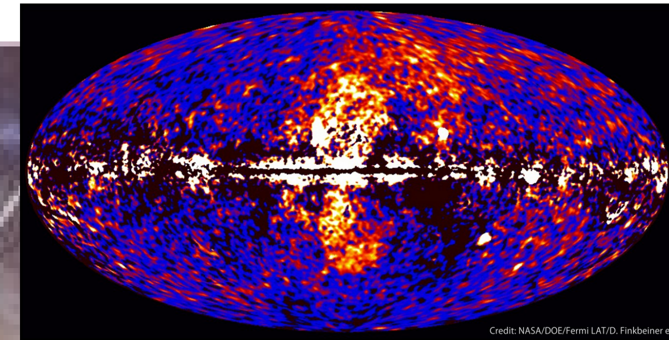
→ **PeV dark matter decay**

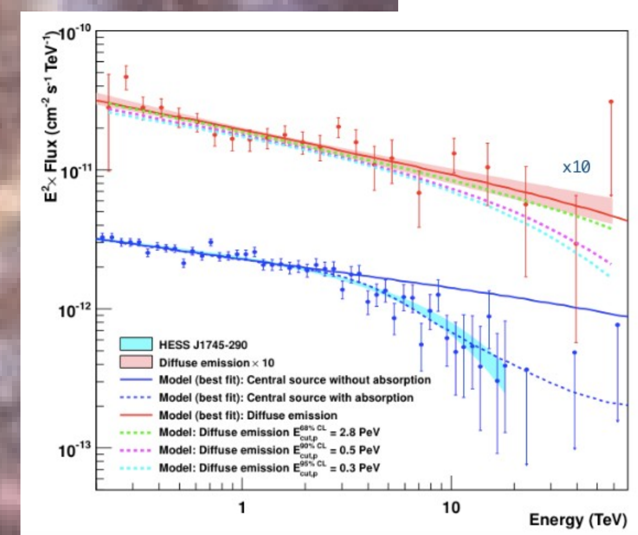
Feldstein et al. 2013, Esmaili & Serpico 2013, Bai et al. 2013,...

→ **… ?**

Central outflow

Fermi bubbles



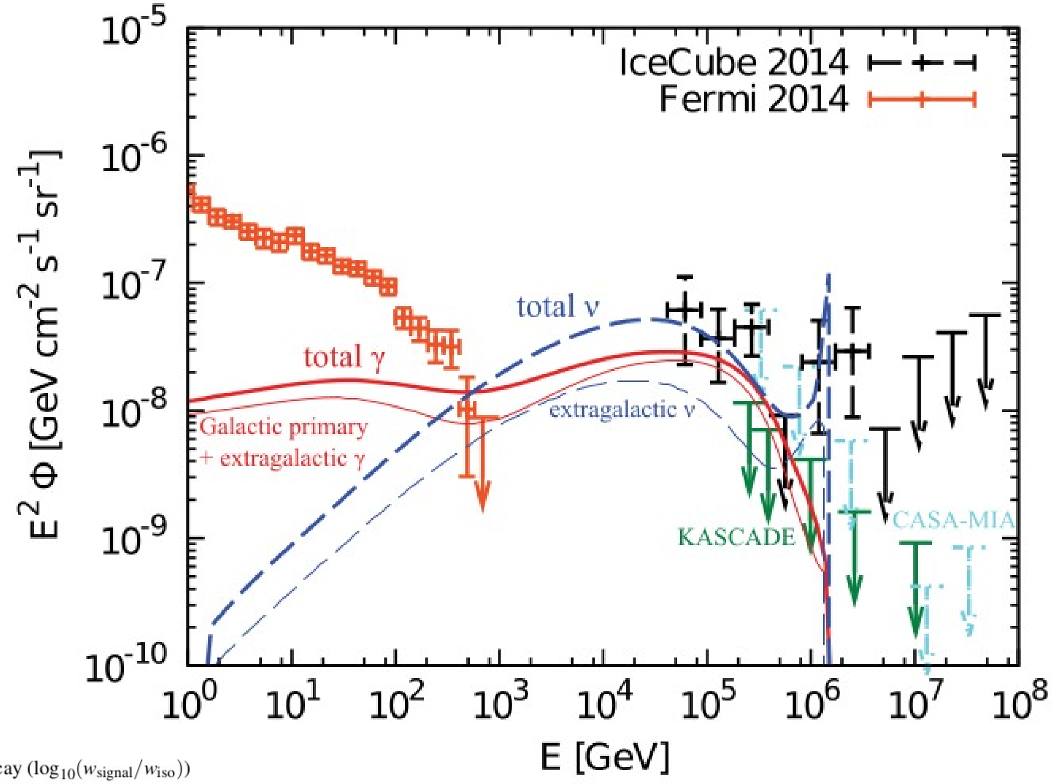


Aharonian ICRC 2015

In any case : Some anisotropy ...

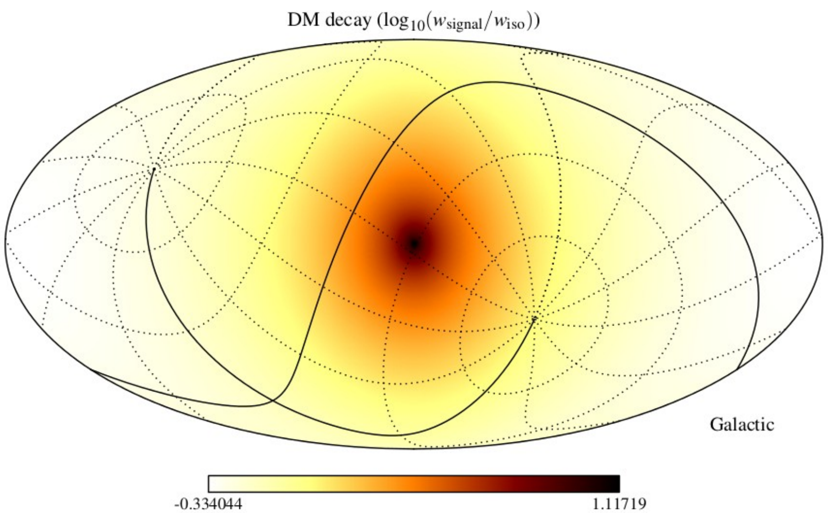
Decay of PeV dark matter ?

Murase et al. 2015
→ **Scenario testable in the future**



→ Spectral shape …

→ Anisotropy →



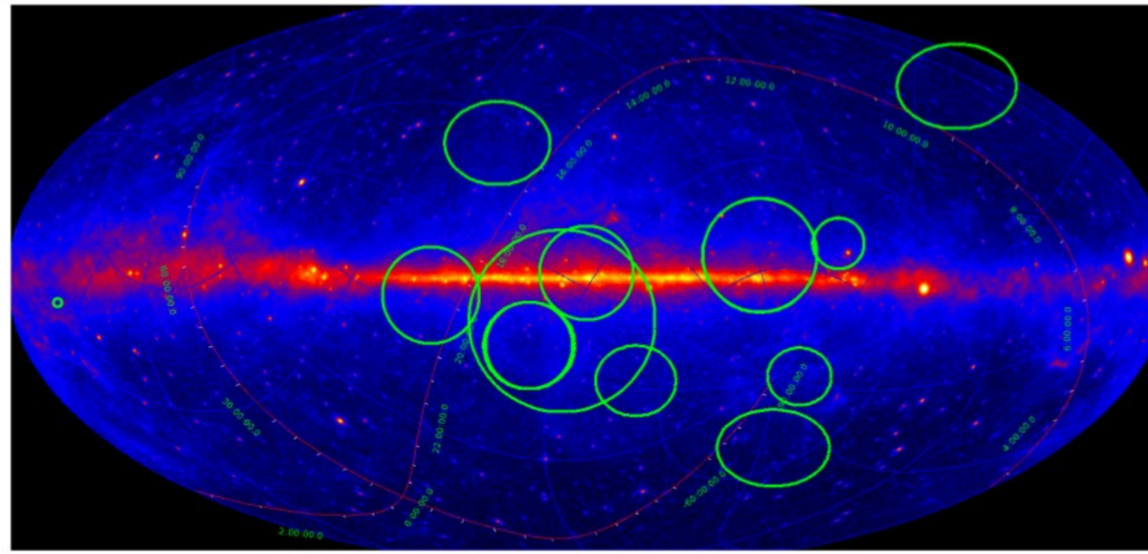
Ahlers et al. 2015

Half of events with energy >100 TeV are in the Galactic plane : Correlation with gamma-rays ?

IC 3 years data

From D. Semikoz

See also Neronov, Semikoz and Tchernin, arXiv:1307.2158



Evidence for the Galactic contribution to the IceCube astrophysical neutrino flux

Andrii Neronov[1], Dmitry Semikoz[2]

[1] ISDC, Astronomy Department, University of Geneva, Ch. d'Ecogia 16, Versoix 1290, Switzerland

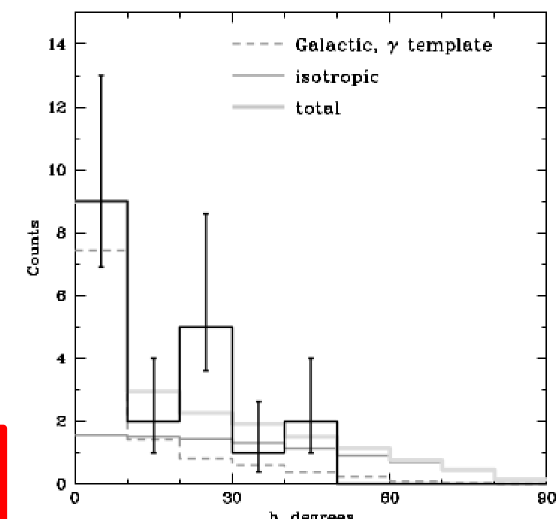
[2] AstroParticle and Cosmology (APC), 10 rue Alice Domon et Léonie Duquet, F-75205 Paris Cedex 13, France

ArXiv:1509.03522

Abstract

We show that the Galactic latitude distribution of IceCube astrophysical neutrino events with energies above 100 TeV is inconsistent with the isotropic model of the astrophysical neutrino flux. Namely, the Galactic latitude distribution of the events shows an excess at low latitudes $|b| < 10°$ and a deficit at high Galactic latitude $|b| \gtrsim 50°$. We use Monte-Carlo simulations to show that the inconsistency of the isotropic signal model with the data is at $> 3\sigma$ level.

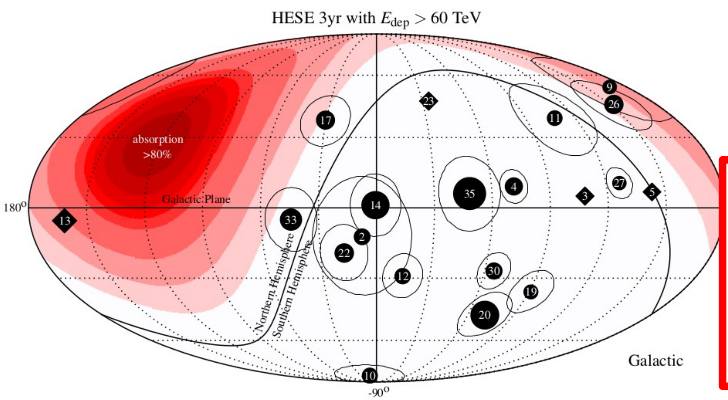
Keywords: multi-messenger astronomy; neutrino astronomy; Milky Way galaxy



gure 1: Galactic latitude profile of the $E > 100$ TeV IceCube utrino signal. Dark grey solid histogram shows the expected profile the isotropic neutrino signal. Dashed dark grey histogram shows the Galactic component profile. Thick light grey solid histogram shows the sum of the Galactic and extragalactic components.

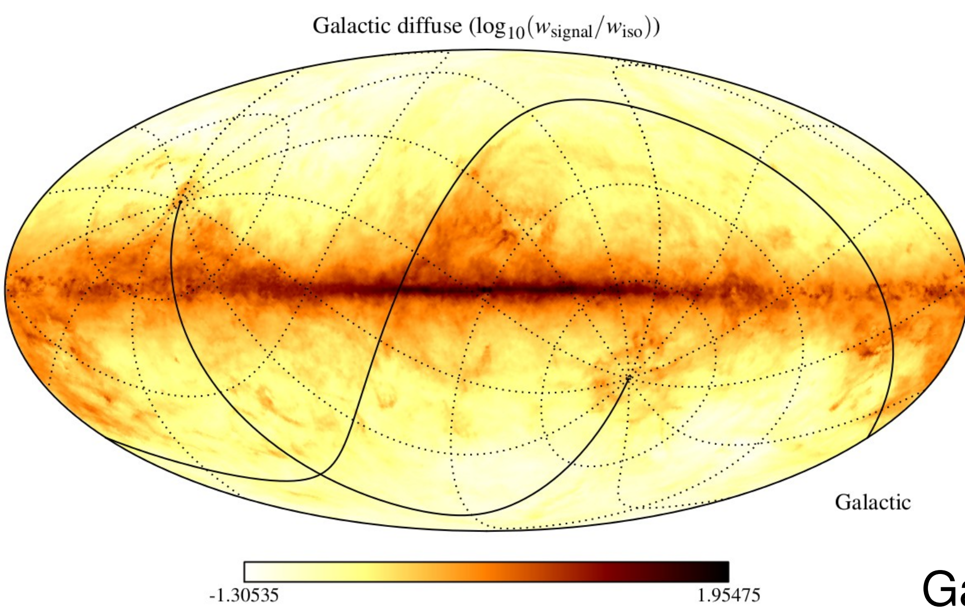
Anisotropy vs Galactic sources

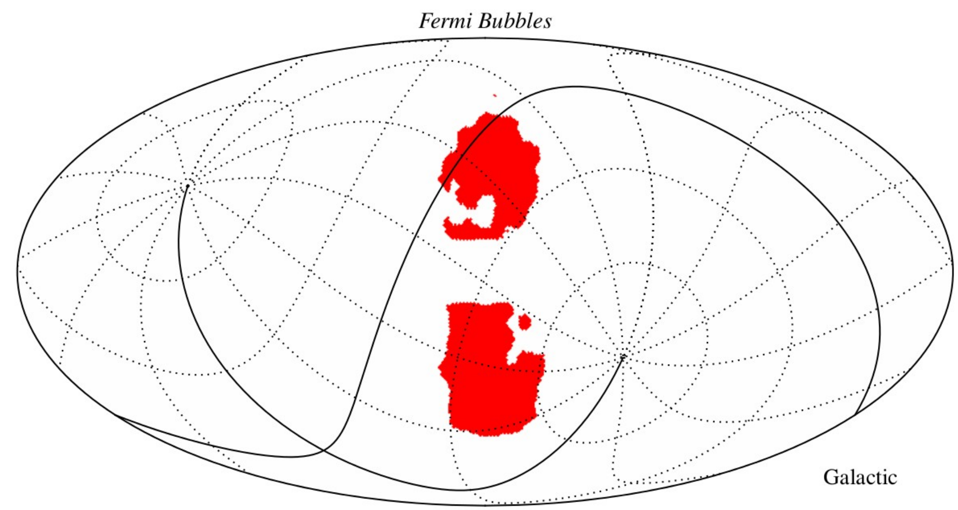
Ahlers et al. 2015



Abstract

We study the contribution of Galactic sources to the flux of astrophysical neutrinos recently observed by the IceCube Collaboration. We show that the Galactic diffuse neutrino emission consistent with γ-ray (*Fermi*-LAT) and cosmic ray data (KASCADE, KASCADE-Grande and CREAM) is expected to account for only 4%−8% of the IceCube flux above 60 TeV. Direct neutrino emission from cosmic ray-gas (pp) interactions in the sources would require an unusually large average opacity above 0.01. On the other hand, we find that the IceCube events already probe Galactic neutrino scenarios via the distribution of event arrival directions. We show that most Galactic scenarios can only have a limited contribution to the astrophysical signal: diffuse Galactic emission ($\lesssim 50\%$), quasi-diffuse emission of neutrino sources ($\lesssim 65\%$), extended diffuse emission from the *Fermi Bubbles* ($\lesssim 25\%$) or unidentified TeV γ-ray sources ($\lesssim 25\%$). Presently, dark matter decay remains unconstrained.





Galactic emission templates used in the analysis

EXTRAGAL. SOURCES - CANDIDATES

<u>* Link with UHECR sources</u>

Kistler et al. 2013, Fang et al. 2014

→ **<u>ACTIVE GALACTIC NUCLEI / ACTIVE GALAXIES (*pp*, *p*γ)</u>**

Stecker et al. 2013, Kalashev et al. 2013, Murase, Inoue & Dermer 2014, Kimura, Murase et al. 2014, Kalashev, Semikoz & Tkachev 2014, Padovani & Resconi 2014, Petropoulou, et al. 2015, Giacinti, Kachelriess, Kalashev, Neronov & Semikoz 2015, …

- Association with diffuse gamma-ray bkg. *Murase et al. 2013, …*

→ **<u>Gamma-ray bursts</u>** *Murase & Ioka 2013, Tamborra & Ando 2015, …*

<u>* Galaxy clusters</u> *Murase et al. 2013, Zandanel et al. 2014, Giacinti et al. 2015, …*

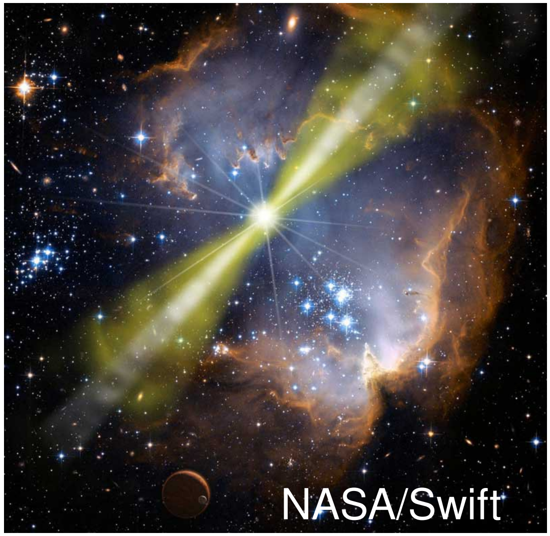
<u>* STARBURST GALAXIES (/ galaxies with intense star-formation)</u>

Loeb & Waxman 2006, Yoast-Hull et al. 2013, Murase, Ahlers & Lacki'13; Anchordoqui et al. 2014, Tamborra et al. 14, Chang & Wang 2014, Liu, Wang, Inoue, Crocker & Aharonian'14, Senno et al. 2015, Chakraborty & Izaguirre 2015, Giacinti, Kachelriess, Kalashev, Neronov & Semikoz 2015, …

<u>* TYPE IIn SUPERNOVAE</u> *Zirakashvili & Ptuskin 2015*

<u>* … ?</u>

Gamma-Ray Bursts



UHECR sources ? (Waxman 1995) $p + \gamma \to \Delta^+ \to n + \pi^+$

Waxman & Bahcall (1997) → Neutrino flux detectable with large detector

Search for Prompt Neutrino Emission from Gamma-Ray Bursts with IceCube

IceCube Collaboration: M. G. Aarts
M. Ahrens[6], D. Altmann[7], T. Ande

arXiv:1412.6510

ABSTRACT

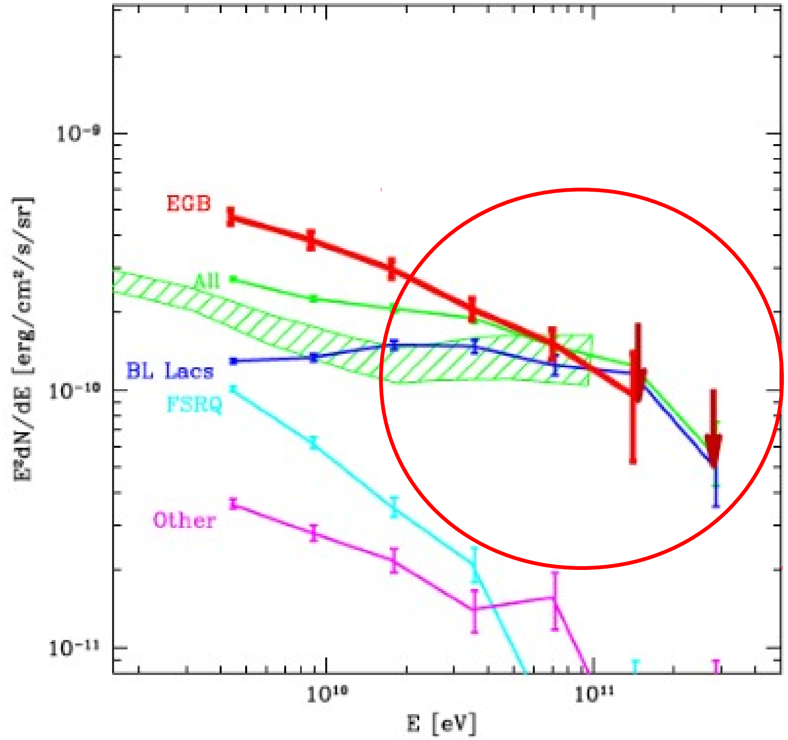
We present constraints derived from a search of four years of IceCube data for a prompt neutrino flux from gamma-ray bursts (GRBs). A single low-significance neutrino, compatible with the atmospheric neutrino background, was found in coincidence with one of the 506 observed bursts. Although GRBs have been proposed as candidate sources for ultra-high energy cosmic rays, our limits on the neutrino flux disfavor much of the parameter space for the latest models. We also find that no more than $\sim 1\%$ of the recently observed astrophysical neutrino flux consists of prompt emission from GRBs that are potentially observable by existing satellites.

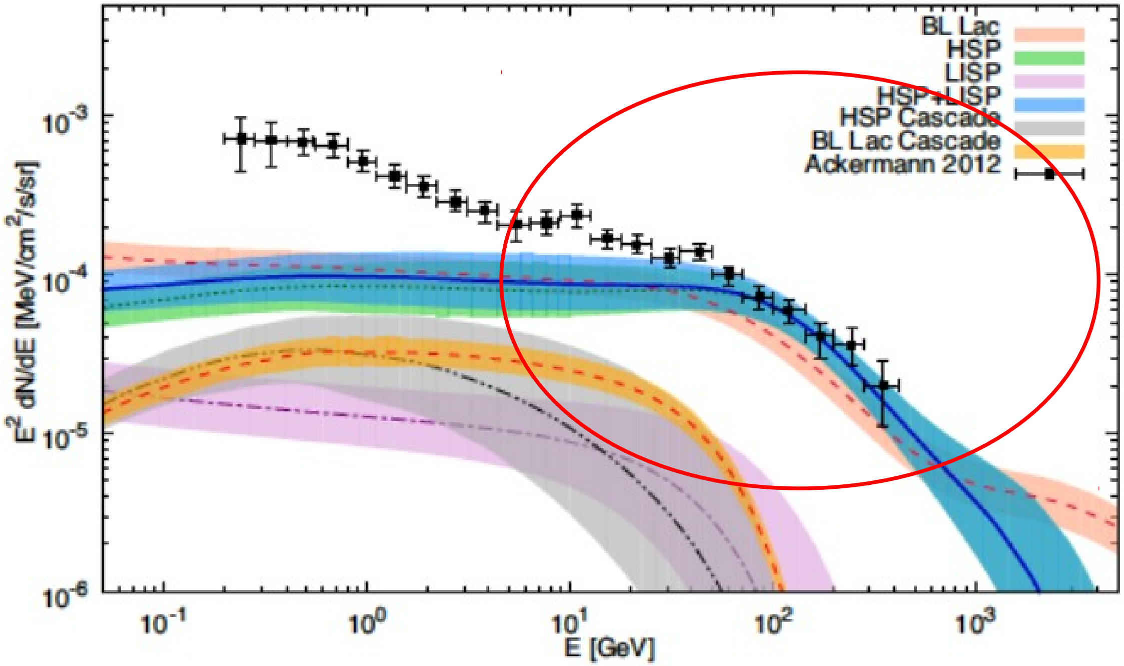
separately. In the absence of an emerging signal in the coming years, IceCube limits will increasingly constrain GRBs as dominant sources of UHECRs.

See also Ahlers & Halzen 2014 THEORY : Reville&Bell 2014

BL Lacs = main contributors to HE part of diffuse extragal. γ-ray flux

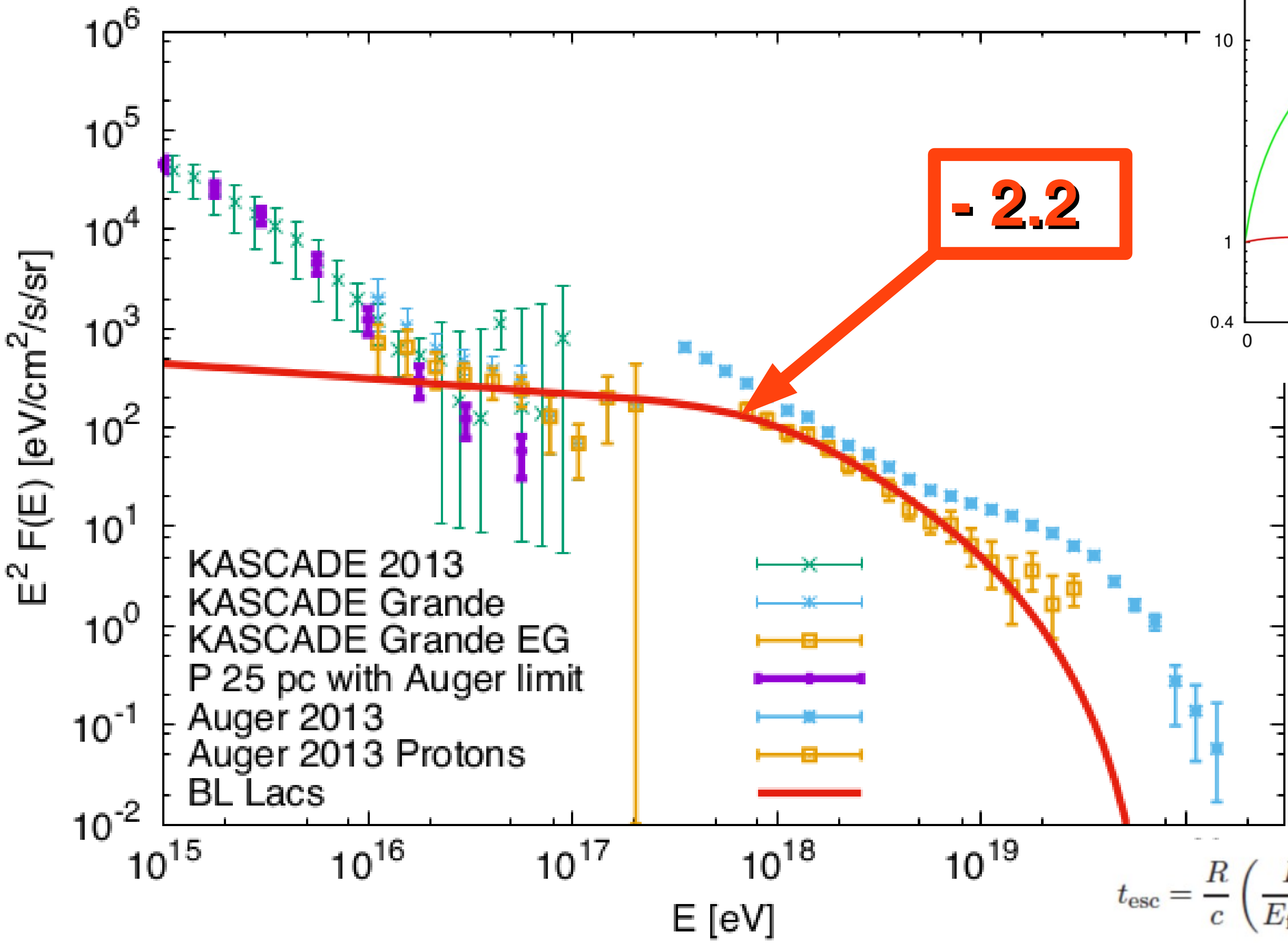
Neronov & Semikoz, arXiv:1103.3484

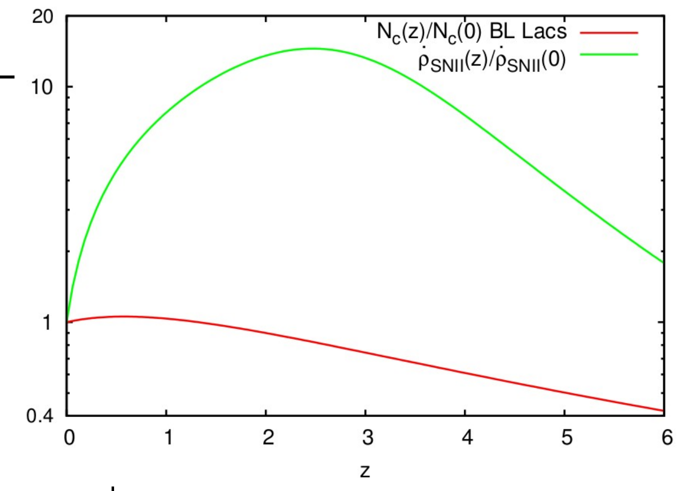




M. Di Mauro et al, arXiv:1311.5708

UHECR proton flux (escape model)





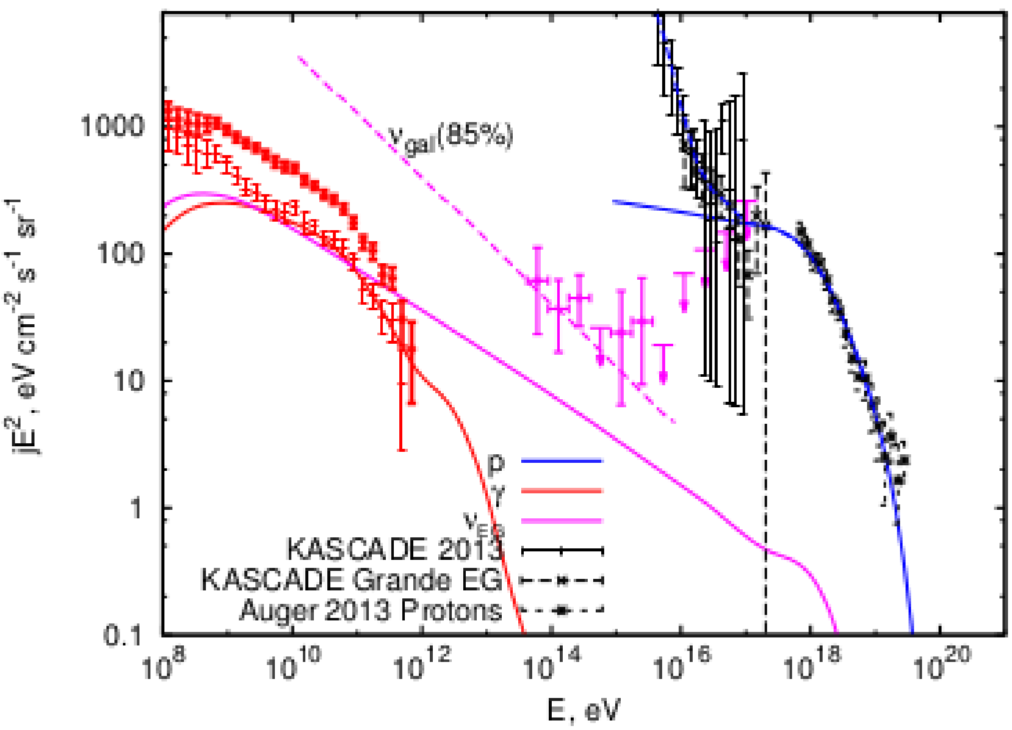
$$t_{\rm esc} = \frac{R}{c}\left(\frac{E}{E_{\rm free}}\right)^{-1/3} \simeq 5\times10^6\ {\rm s}\left[\frac{E}{10^{11}\ {\rm eV}}\right]^{-1/3}$$

$$t_{pp} = \frac{1}{c\kappa\sigma_{pp}n} \simeq 1\times10^6\ {\rm s}\ \left(\frac{n}{10^9\ {\rm cm}^{-3}}\right)^{-1}$$

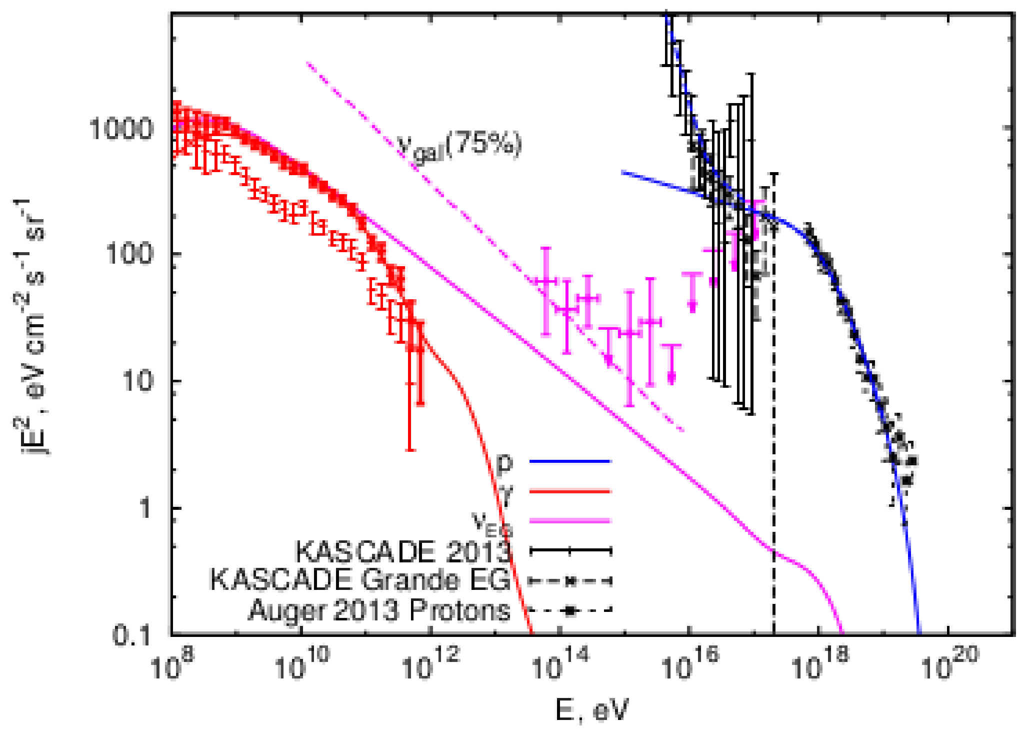
Giacinti, Kachelriess, Kalashev, Neronov & Semikoz, arXiv:1507.07534

Diffuse fluxes from BL Lacs / FR Is

$\alpha = 2.11$
$E_{esc} = 3.10^{11}$eV



$\alpha = 2.17$
$E_{esc} = 3.10^{11}$eV



$R = 10^{14}$ cm $\quad B = 10^4$ G $\quad n = 10^9$ cm^{-3}

Giacinti, Kachelriess, Kalashev, Neronov & Semikoz, arXiv:1507.07534

Diffuse fluxes from BL Lacs / FR Is

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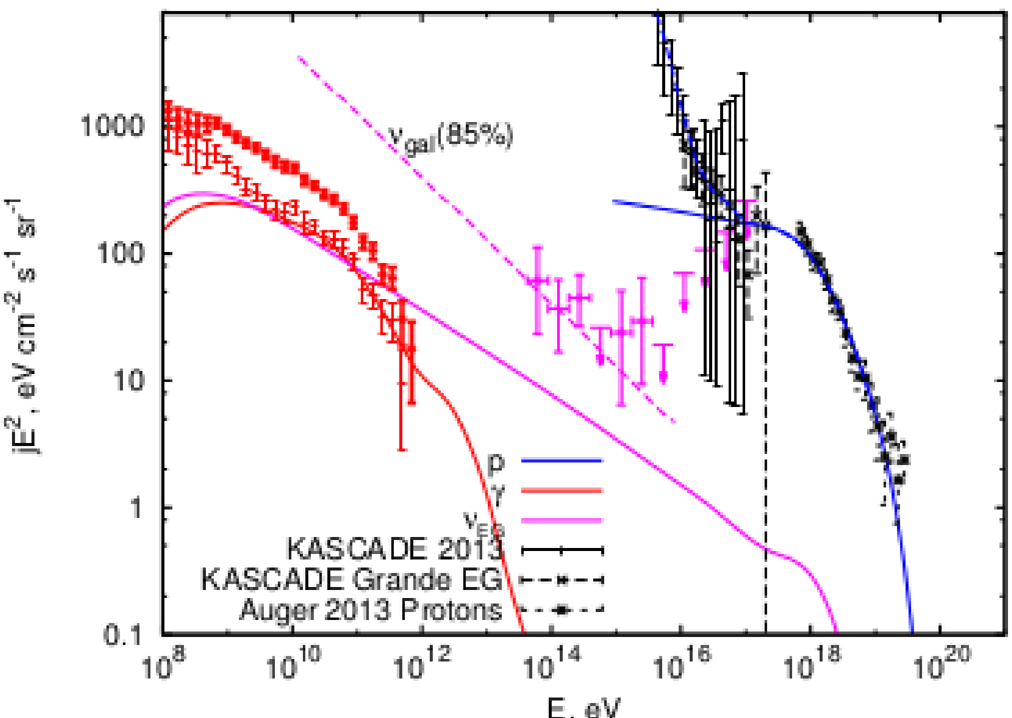

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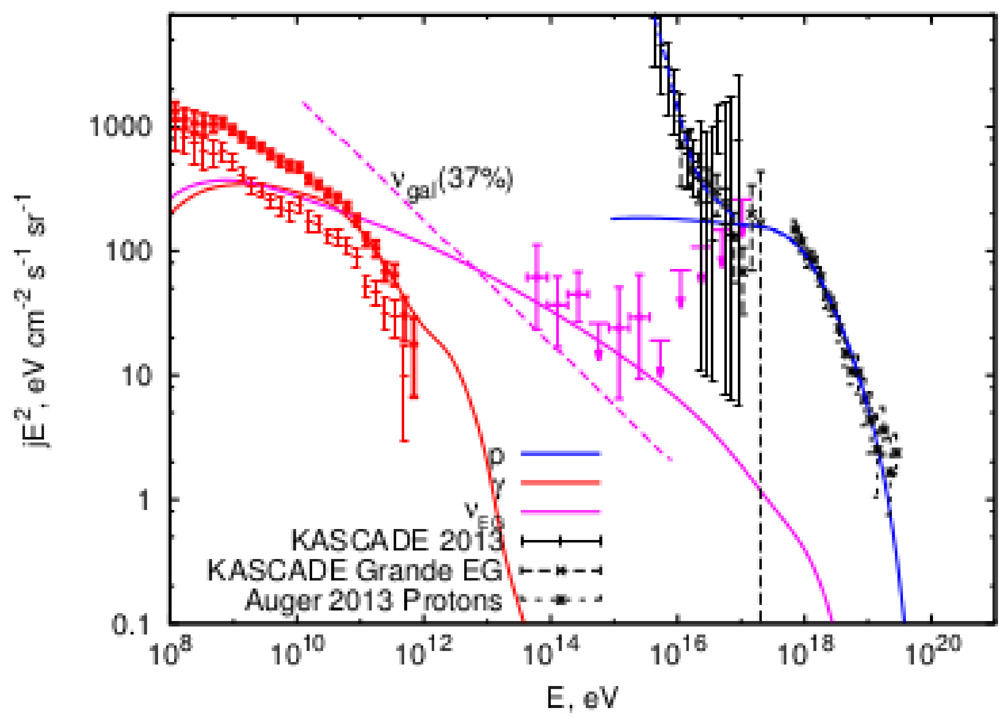
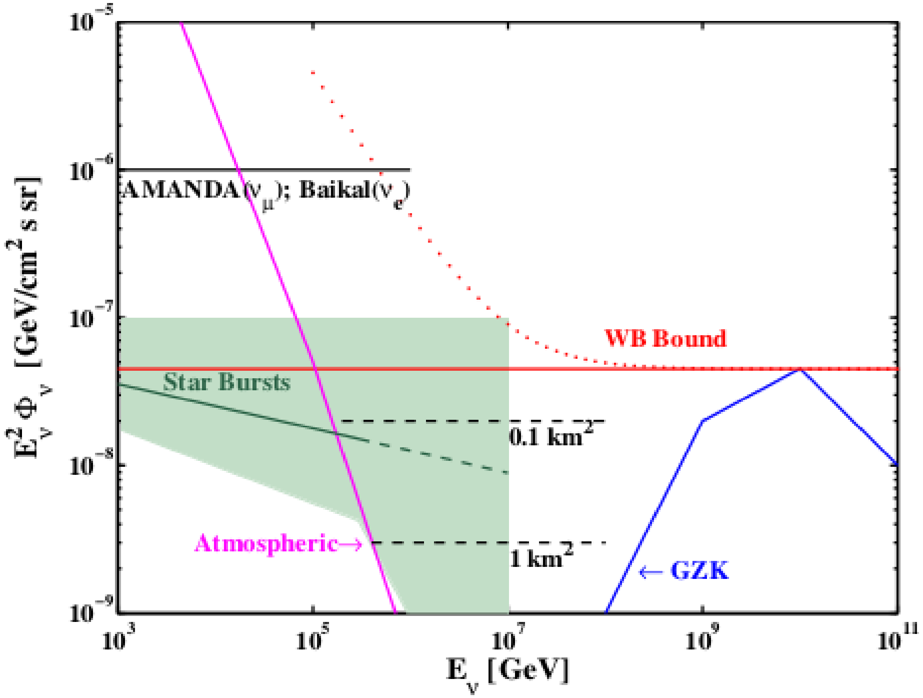


EGB / nu & slope pb : Can be explained by diffusion in the sources at HE

Giacinti, Kachelriess, Kalashev, Neronov & Semikoz, arXiv:1507.07534

Starburst galaxies

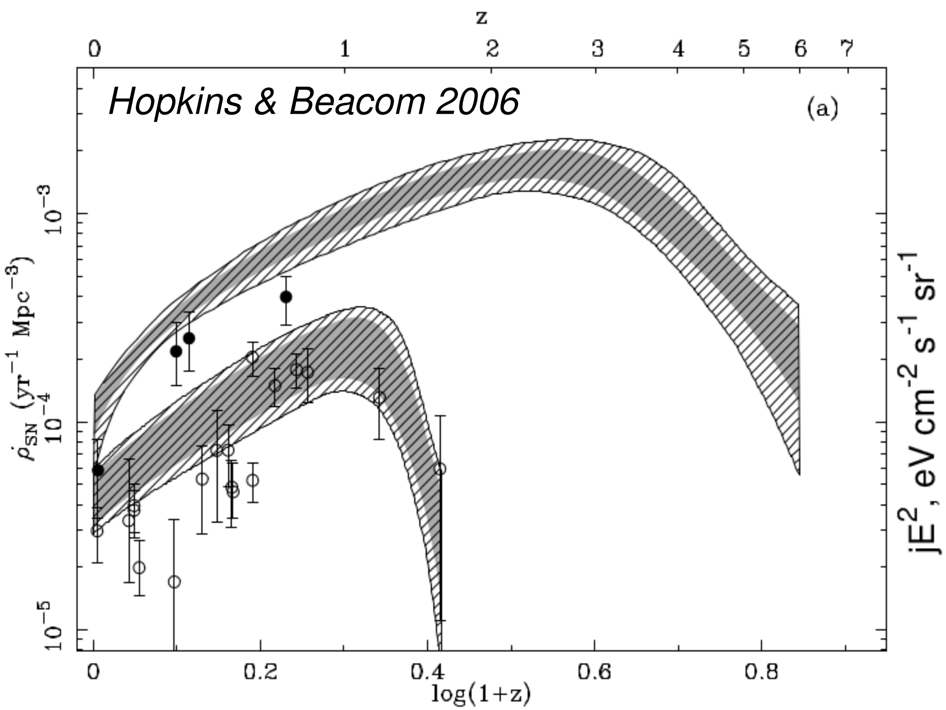


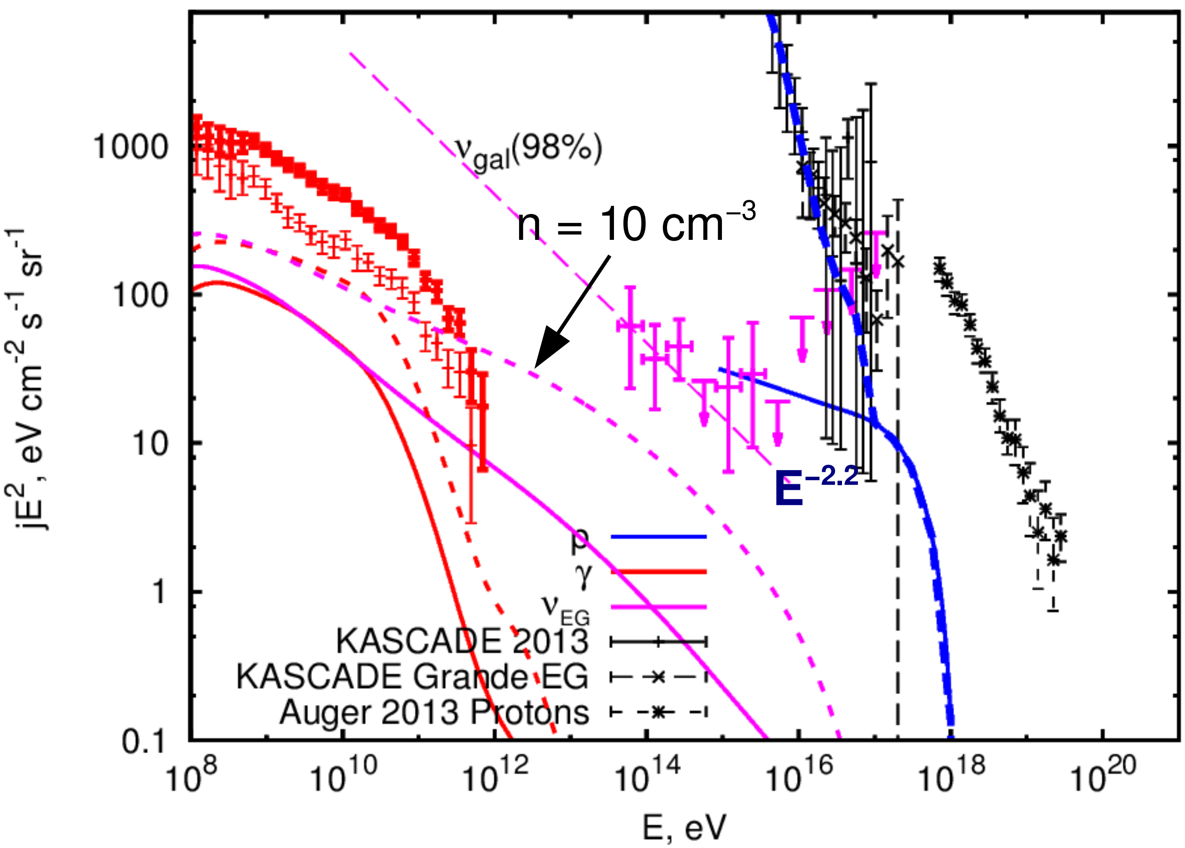
Loeb & Waxman 2006

n = 1 – 100 cm^{-3} , B ~ 100 μG, SFR ~ 10 – 1000 x MW

Starburst galaxies

Giacinti, Kachelriess, Kalashev, Neronov & Semikoz, arXiv:1507.07534





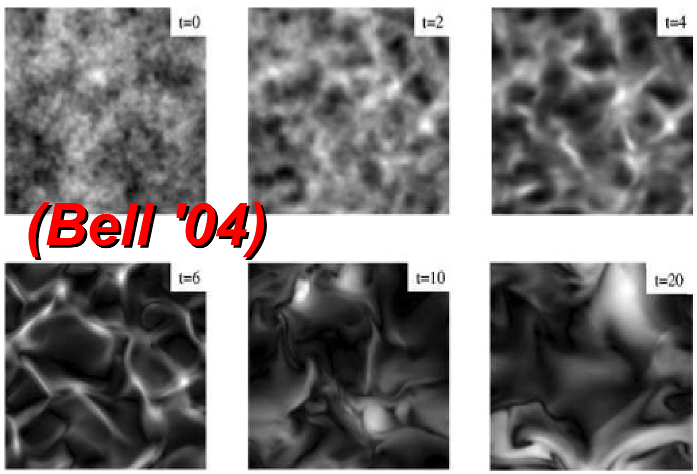
n = 1 cm^{-3}

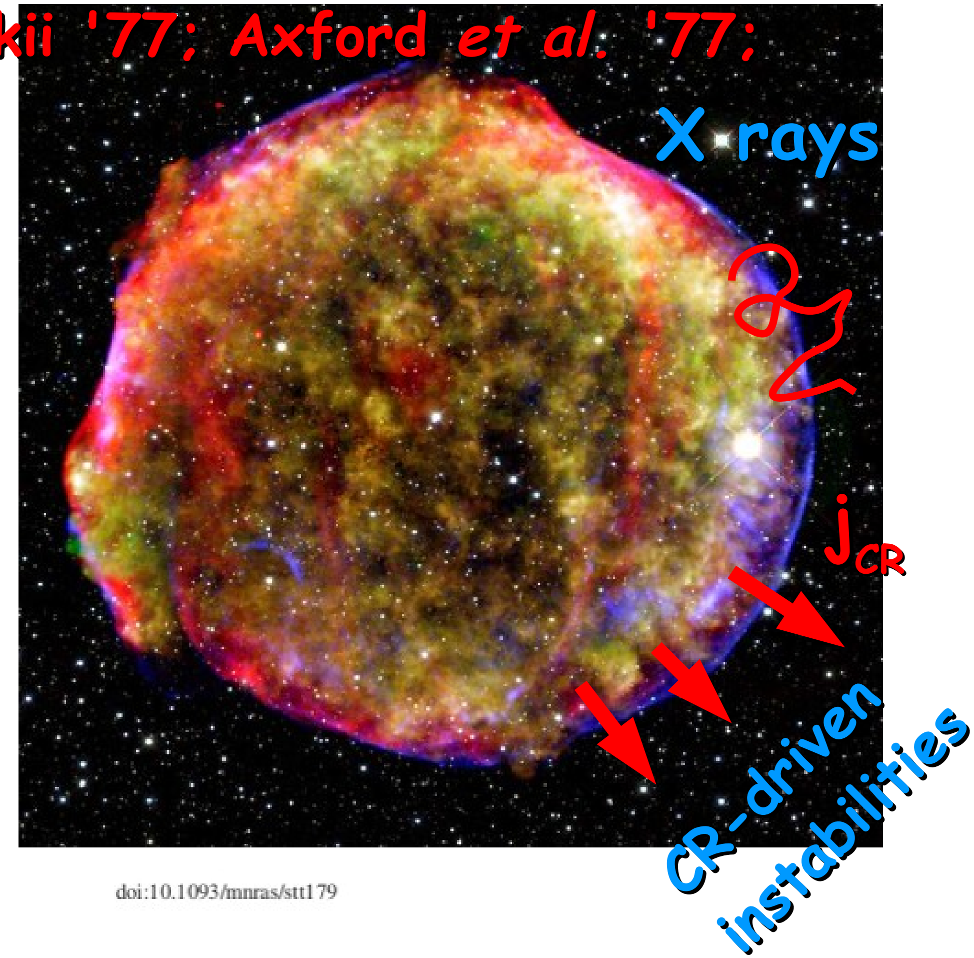
$$I(E) = \frac{c}{4\pi H_0} \int_0^{z_{\max}} \frac{dz}{(1+z)\omega}\, q_{\rm CR}(z, E')\, e^{-\tau(E')},$$

where $\omega = \sqrt{\Omega_\Lambda + \Omega_{\rm m}(1+z)^3}$.

Supernovae in dense winds ?

Diffusive shock acceleration (Krymskii '77; Axford *et al.* '77; Bell '78; Blandford & Ostriker '78)





MNRAS **431**, 415–429 (2013)
Advance Access publication 2013 February 27

doi:10.1093/mnras/stt179

Cosmic-ray acceleration and escape from supernova remnants

A. R. Bell,★ K. M. Schure, B. Reville and G. Giacinti
Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, UK

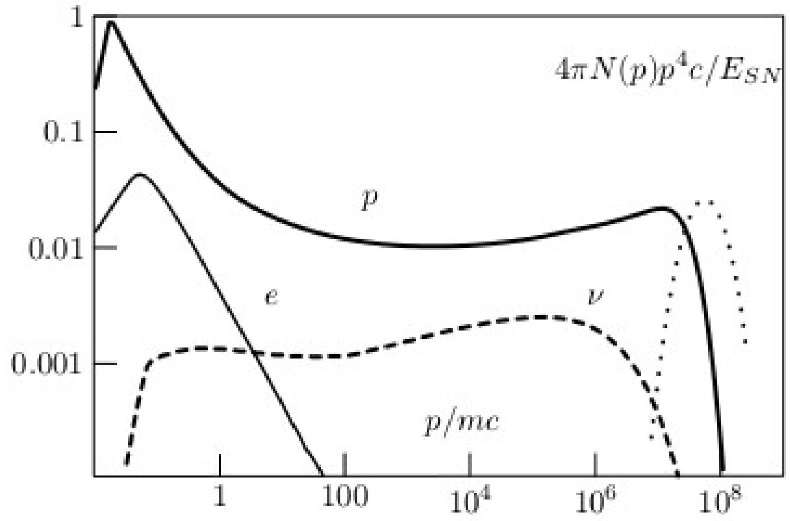
$\rho \propto r^{-2}$ wind

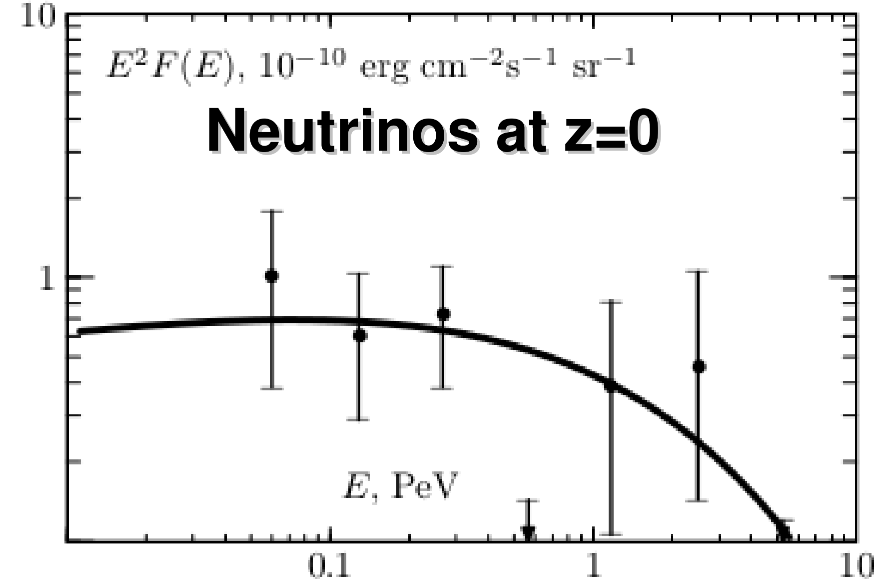
$$T = 760 \eta_{0.03} u_7^2 \sqrt{\frac{\dot{M}_5}{v_4}} \ \mathrm{TeV}$$

Type IIn Supernovae

Zirakashvili & Ptuskin, arXiv:1505.08144

CRs : 30 yr after the explosion





$$f(E_\nu)E_\nu^2 = \frac{3\xi_{CR}K_\nu}{16\pi^2 \ln(E_{\max}/mc^2)} \frac{cV_f^2\sigma_{pp}\dot{M}^2}{mu_w^2R_fD^2} =$$

$$10^{-8}\mathrm{erg\ cm^{-2}s^{-1}t_{yr}^{-1}D_{Mpc}^{-2}}\xi_{CR}\left(\frac{\dot{M}}{10^{-2}\ M_\odot\ yr^{-1}}\right)^2\left(\frac{u_w}{100\ km\ s^{-1}}\right)^{-2}\left(\frac{E_{SN}}{10^{52}\ erg}\right)^{1/2}\left(\frac{M_{ej}}{10\ M_\odot}\right)^{-1/2}$$

Conclusions

- Currently compatible with ~ ½ Galactic, ½ extragalactic
- Galactic contribution can be constrained in the future

- <u>Galactic:</u> CRs in the halo, VHE active Gal. sources or central outflow ? → Possible surprizes ?

- <u>Extragalactic:</u> BL Lacs / FR Is are excellent candidates (Diffuse gamma-ray, neutrino & UHECR fluxes)
→ *EGB / nu & slope pb : Can be explained by diffusion in the sources at HE*
- If diffuse neutrino flux disconnected from the others : starburst galaxies, SNe in dense winds, ... promizing