Cosmic neutrinos

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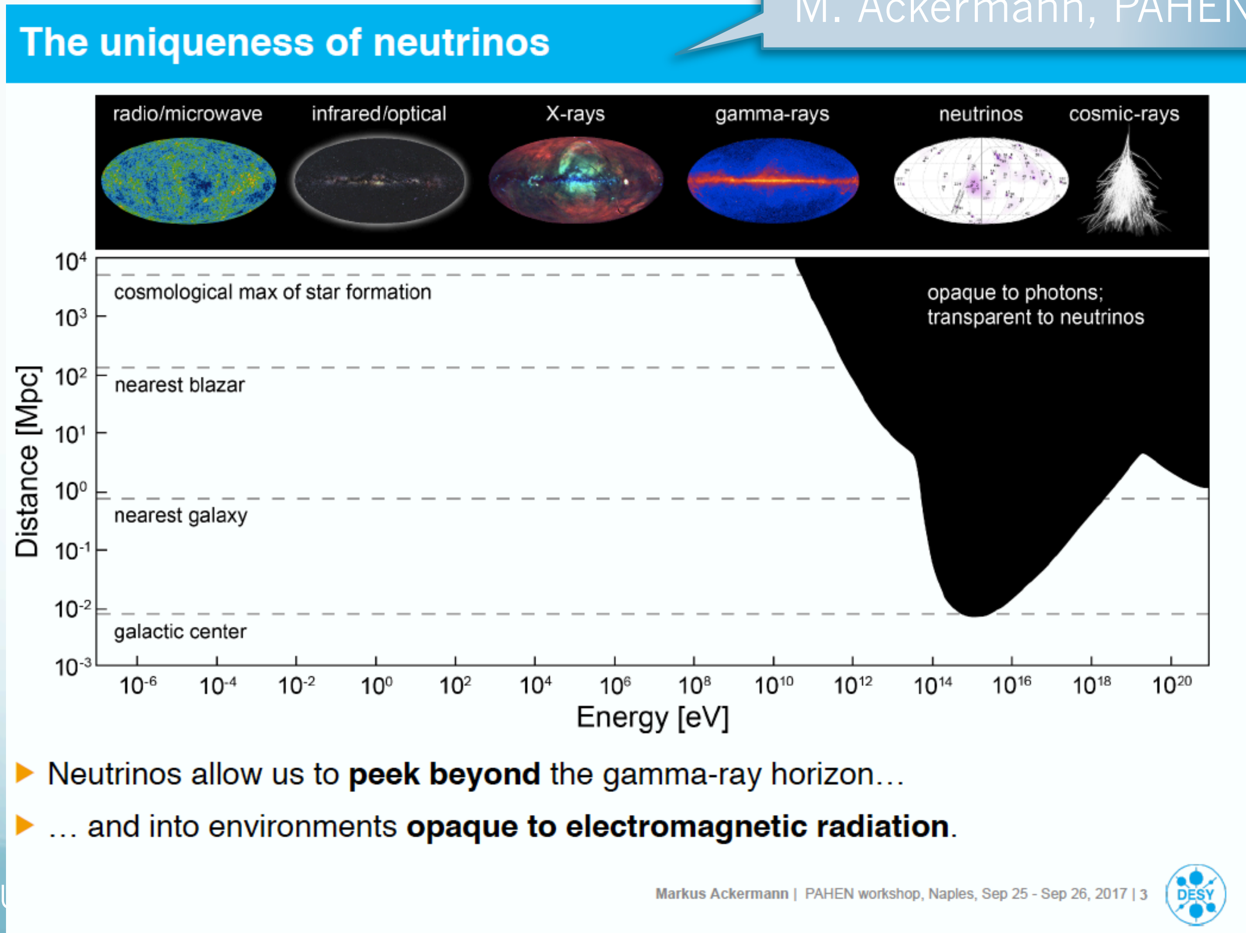
The strong case for ν astronomy

Direct exploration of the extragalactic high-energy Universe above a few tens of TeV has been challenging because CRs are deflected by magnetic fields and confined to a ~50 Mpc horizon, while PeV gamma-rays are highly attenuated by diffuse light sources in the Universe. Neutrinos are, however, undeflected in the galactic or extra-galactic magnetic field and unattenuated in the photon filled Universe.

M. Ackermann, PAHEN2017, Naples



ν from the cosmo?

We expect high energy and ultra-high energy neutrinos produced near the sources of CRs by their interaction with cosmic matter, and also, in the region above ~ PeV, cosmogenic or GZK neutrinos, coming from the interaction of CRs with CMB/EBL.

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Before 2013

ν from the cosmo?

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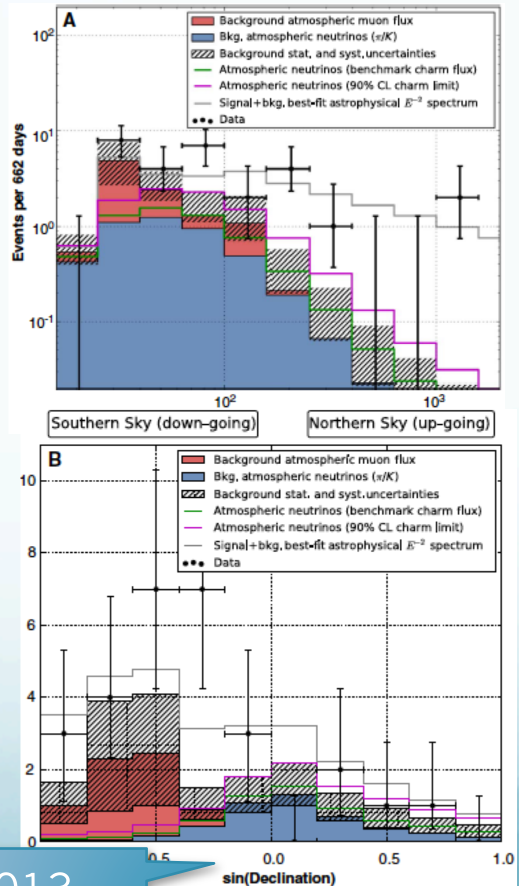
Before 2013

IceCube 2013

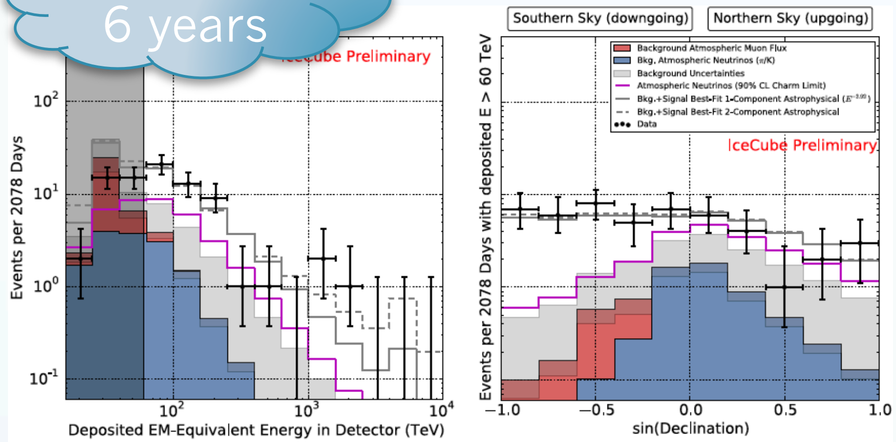


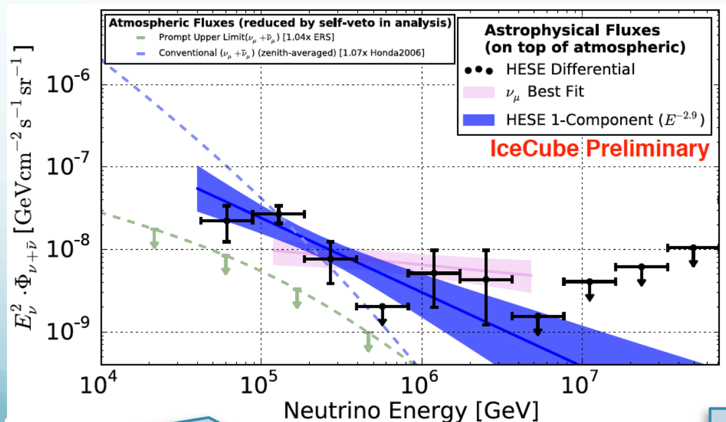
IceCube, Science, 2013

The first HE ν from the cosmo!

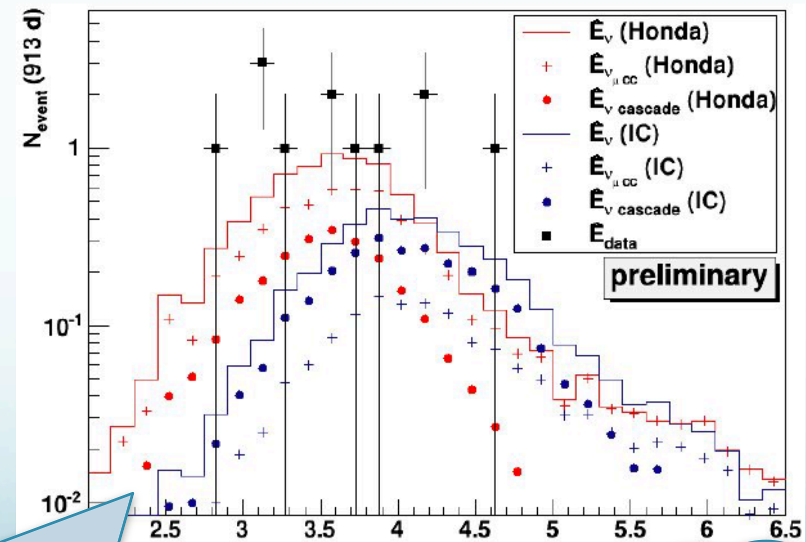
1. Neutrino data sample is obtained with methods that aim to reject the atmospheric muon background.
2. Then, distinction between atmospheric and cosmic ν events is achieved through energy. In fact, the spectrum is a combination of atmospheric (softer), prompt (less softer) and astrophysical (harder) neutrinos. These are estimated by multi-dimensional fits.

IceCube
6 years





IceCube, ICRC Proc., 2017

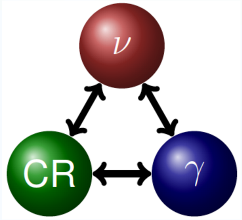


T. Eberl, ICRC Proc., 2017

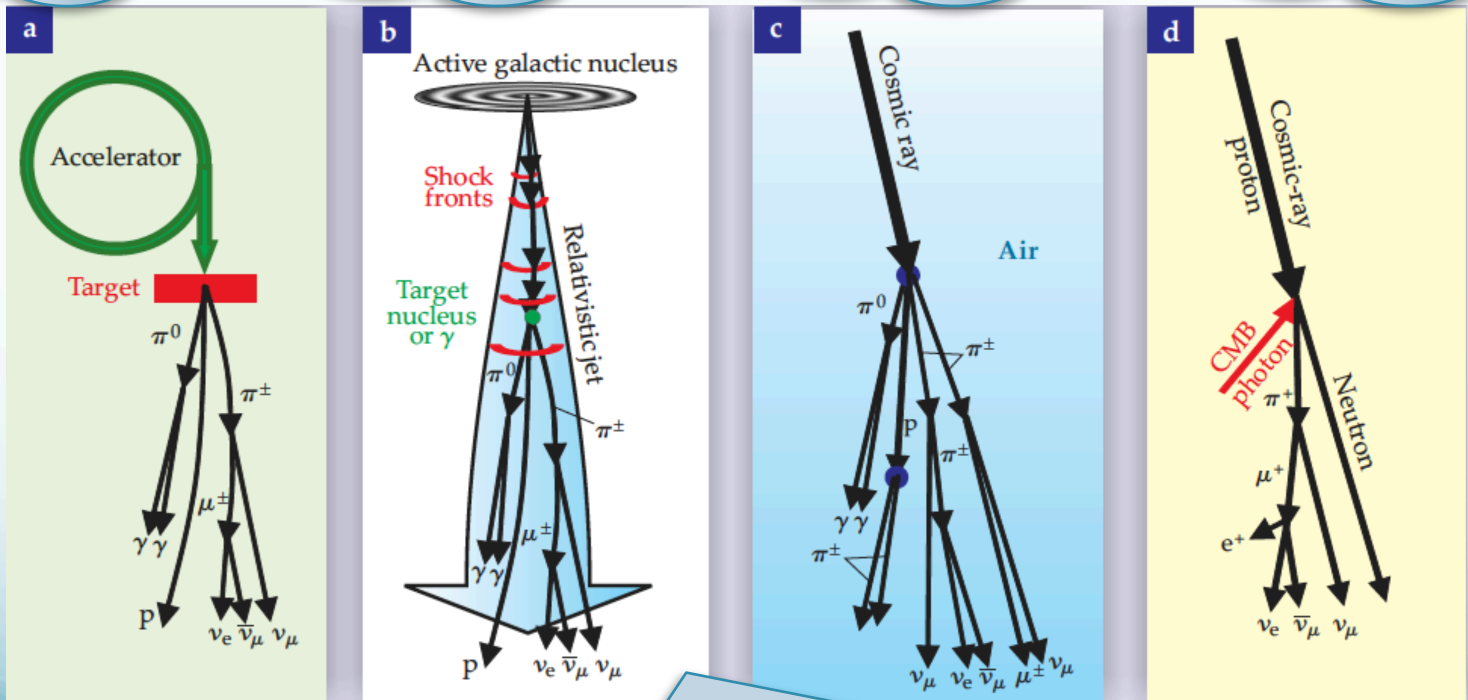
ANTARES
9 years

Multi-messenger character

The particle physics connection:



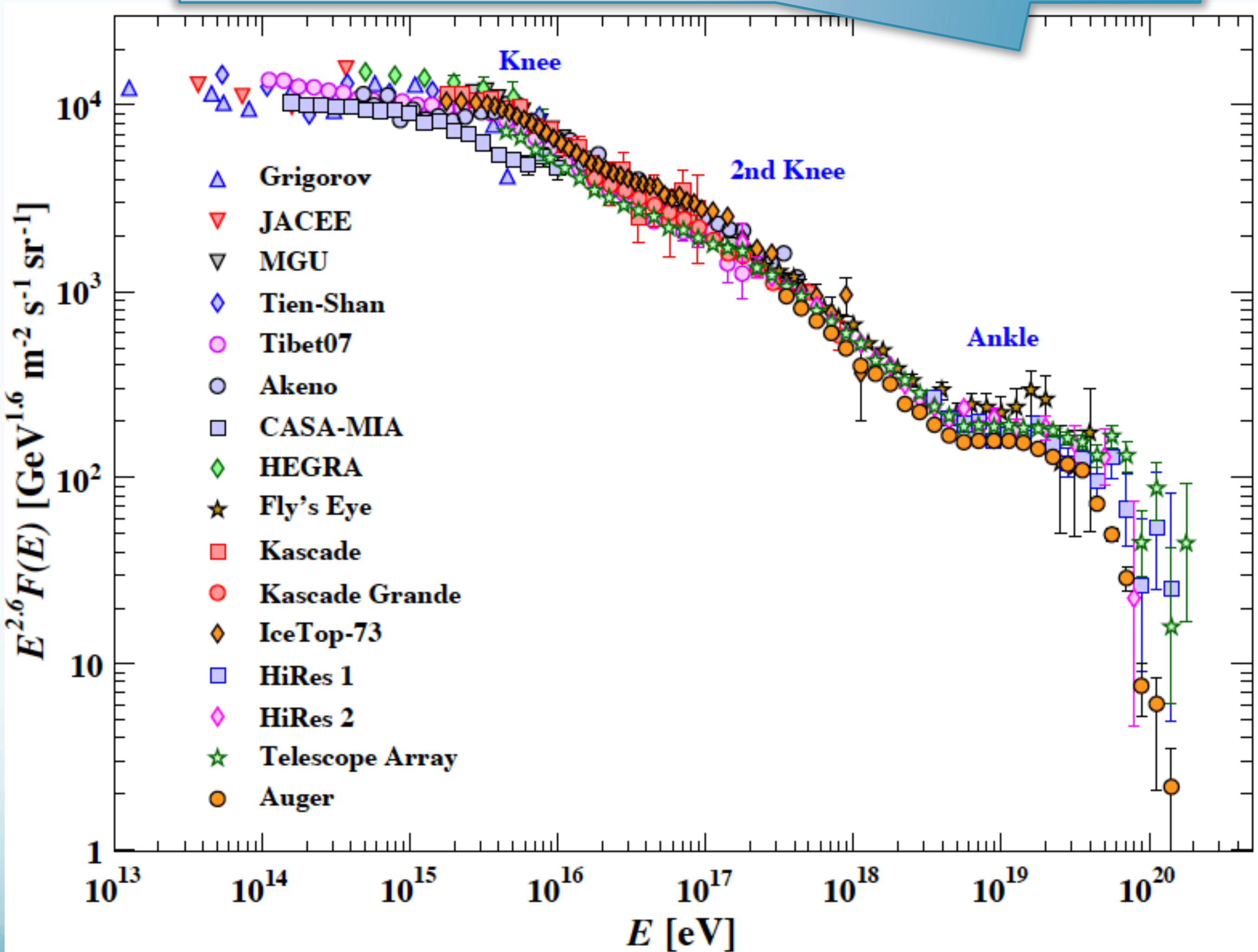
Accelerators | Astrophysical | Atmospheric | Cosmogenic



F. Halzen and S.R. Klein, Physics Today, May 2008

Bottom-up: ν from CRs

Beatty, Matthews, Wakely, Rev. Part. Prop., 2015



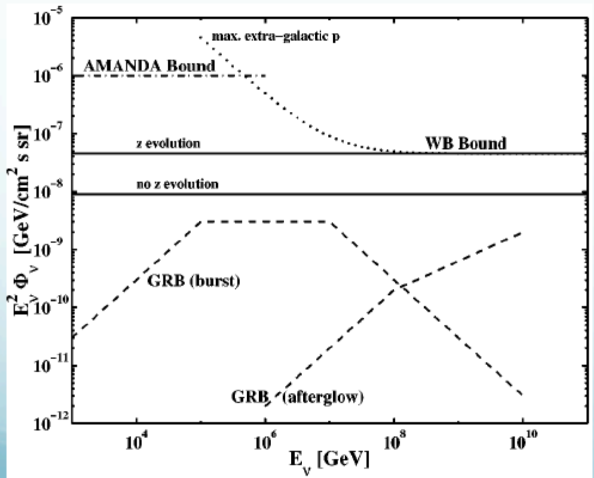
Astrophysical neutrinos

- Connection of ν with CRs production rates is possible only for transparent sources.
- Photo-meson production gives four particles in the final state:

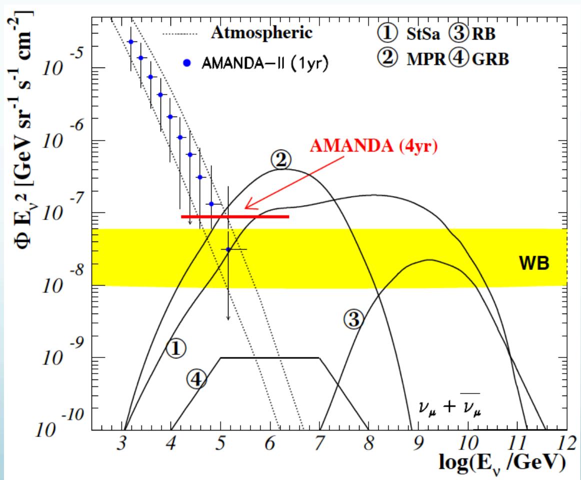
$$\pi^{\pm} \to e\nu_e\nu_\mu\nu_\mu \quad (\pi^{\pm} \to \mu\nu_\mu \qquad \mu \to e\nu_e\nu_\mu)$$

where each ν carry on ~5% of the primary CR energy.

- CR injection rate: $E^2\, dN_p/dEdt \sim 10^{44}$ erg/(Mpc^3 yr), $dN_p/dE \sim E^{-2}$, magnetic field does not change so much the picture ➔ upper bounds on diffuse neutrino flux (WB, MPR).



Waxman&Bahcall, PRD64, 2001

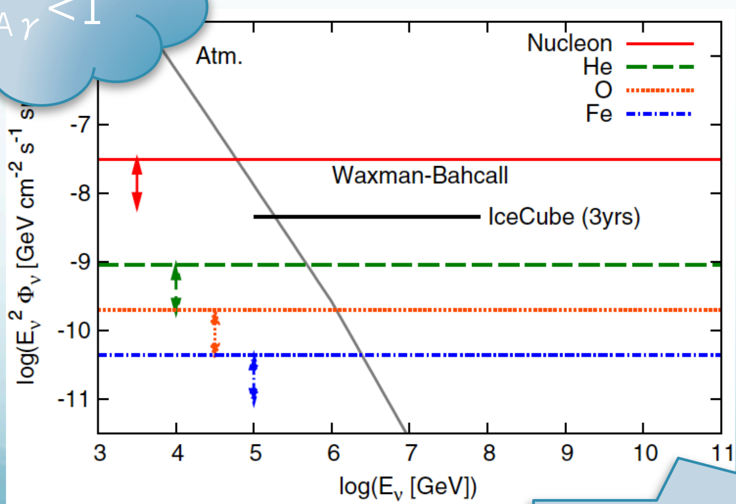


Halzen, Astrophys.Space Sci., 2007

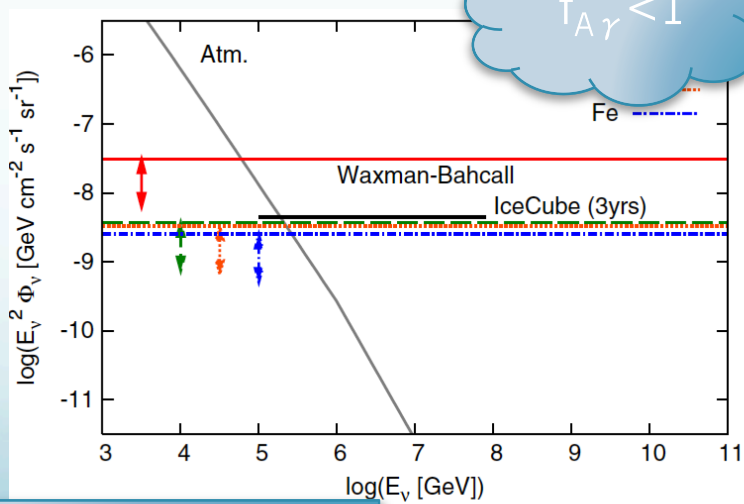
Astrophysical neutrinos

- For nuclei in radiation fields, the photodisintegration process is even more important than the photo-meson process.
- Then, it is claimed that the previous bounds should be lowered: heavy composition of CRs (PAO, Yakutsk) ➔ more nuclei survive photodisintegration ➔ less target photons in the sources ➔ less neutrinos produced.
- Murase&Beacom: injection spectrum like in WB, nuclei escape photo-disintegration in sources (not applicable to cosmogenic ν), photo-disintegration via GDR, different cases for the optical depth.

$\tau_{A\gamma}<1$



$f_{A\gamma}<1$



Murase, Beacom, PRD 2010

Cosmogenic fluxes

Cosmogenic neutrinos arise from CR interaction with extra-galactic background photons (CMB, EBL):

- pair photo-production: $p+\gamma \rightarrow p+e^{+}+e^{-}$
- pion photo-production: $p+\gamma \rightarrow p+\pi^{0}$, $p+\gamma \rightarrow n+\pi^{+}$
- photodisintegration: $(A,Z)+\gamma \rightarrow (A',Z')$+nucleons

As a result, no protons with energies above 1 EeV can originate from z>1 (~50 Mpc) (GZK feature).

Pions/muons decay in ν and γ, which isotropically arrive to Earth ➔ multi-messenger approach can constrain UHECR sources.

Two scenarios:

1. pure proton composition, so called "dip" model (TA)
2. mixed composition (protons at low energy, nuclei at high energy, PAO)

Cosmological evolution:

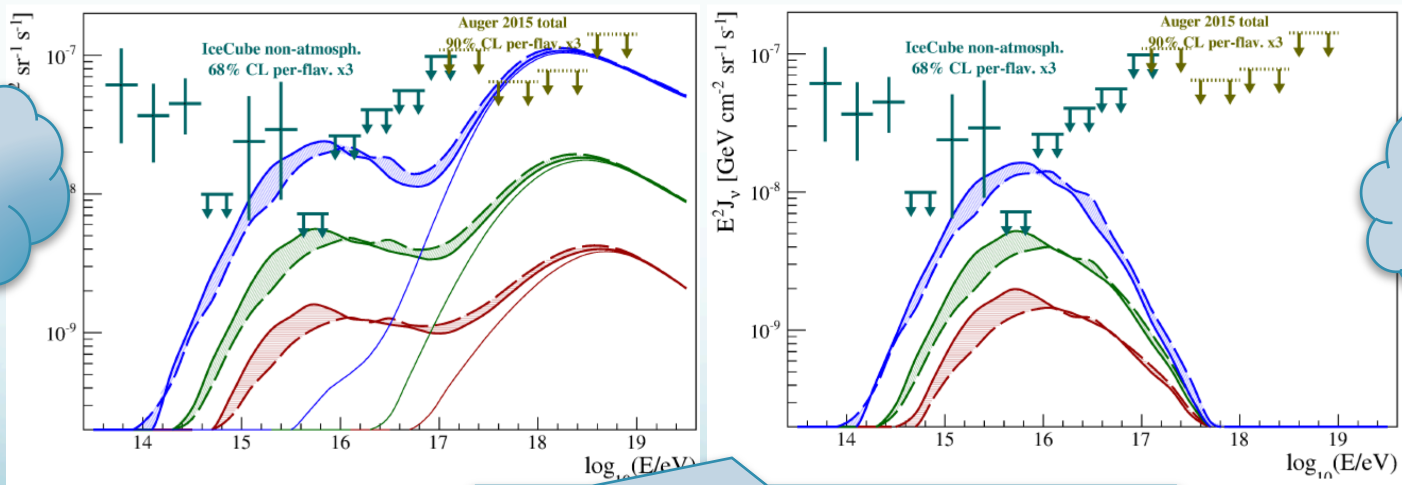
1. no evolution
2. AGN evolution
3. SFR evolution

Cosmogenic fluxes

Propagation codes are typically used to study CRs interaction with cosmic matter in such a way to calculate the flux of cosmogenic ν for comparing with experimental limits.

- SimProp v2r2 with injected spectrum of protons/nuclei.
- Dip model: stronger cosmological evolution than AGN ➔ a total neutrino flux in excess of the PAO and IC limits.
- Mixed composition: extremely low neutrino flux at high energy.
- PAO mass composition ➔ PeV detection at IC, PAO sensitivity insufficient.

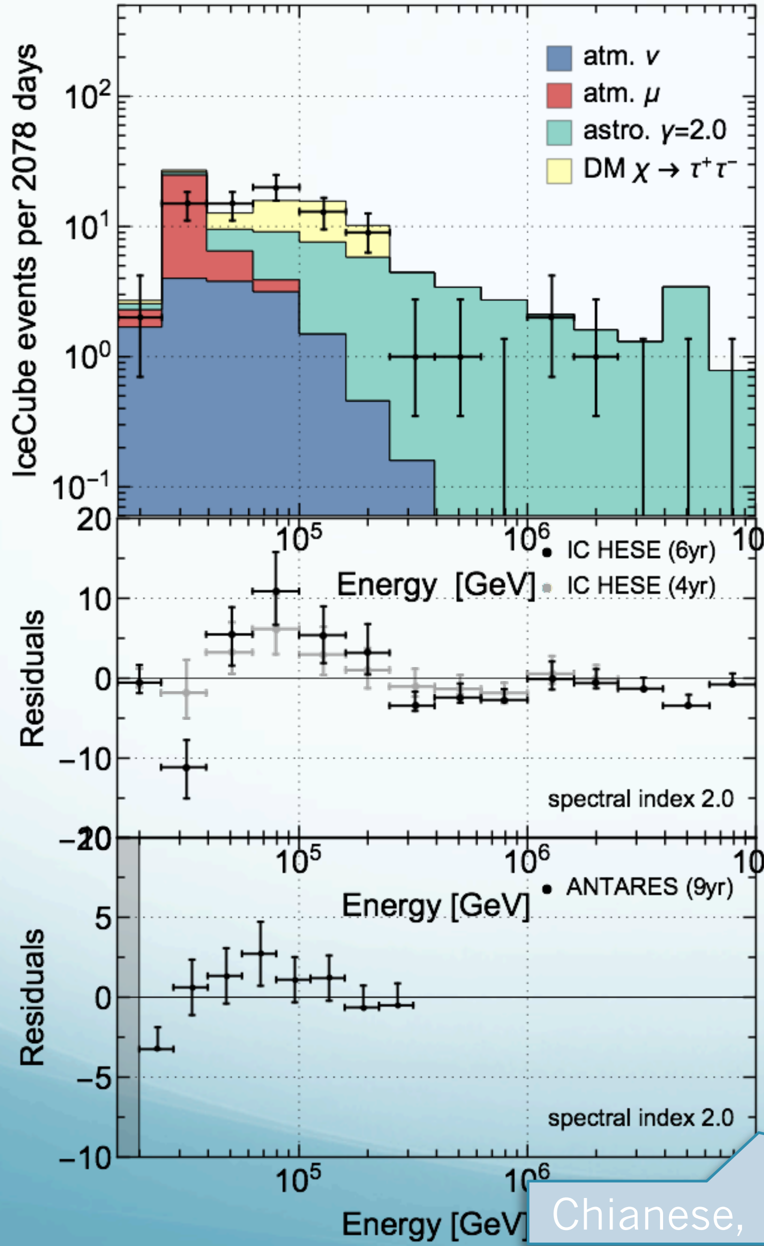
dip model (TA)



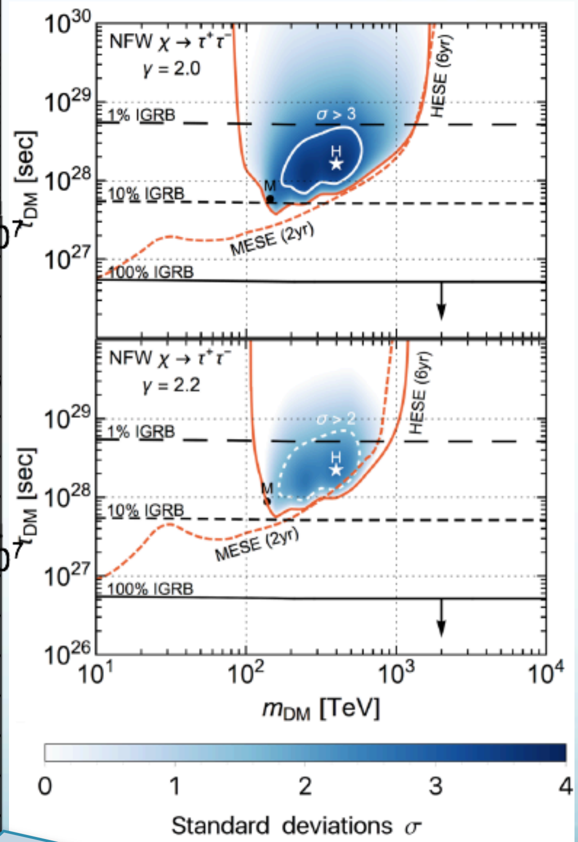
mixed comp. (PAO)

Aloisio et al, JCAP 2015

Top-down example: ν from DM



The slight excess seen by IceCube in the range 40-200 TeV, observed also by the ANTARES telescope, can be interpreted as decaying DM, with a hadronic ($t\text{-}\bar{t}$) and a leptonic channel ($\tau^+\tau^-$).



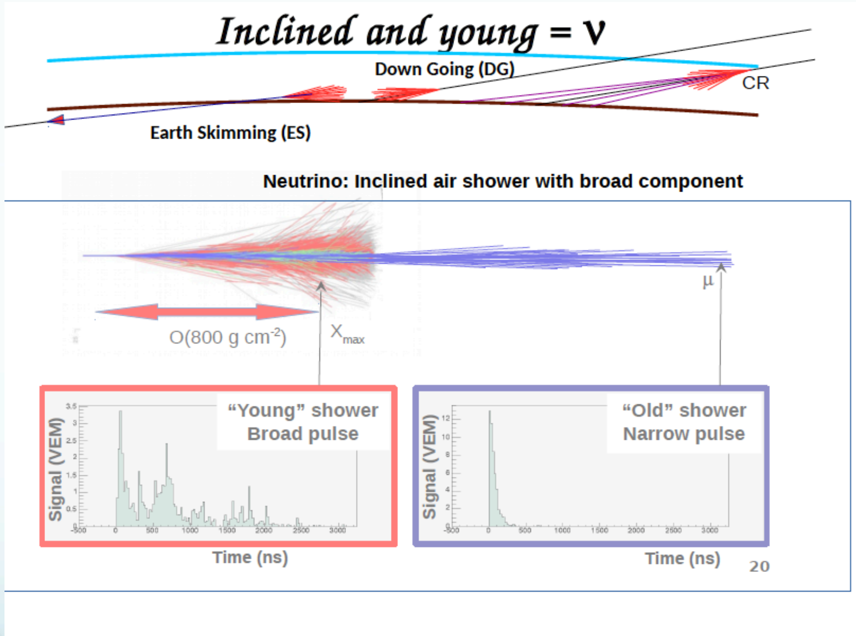
See also:

Feldstein et al., PR D88 (2013); Esmaili and Serpico, JCAP 1311; Boucenna, Chianese, Mangano, Miele, Morisi, **O.P.**, Vitagliano, JCAP 1502.

Chianese, Miele, Morisi, 1707.05168, 1707.05241

Giant air shower arrays

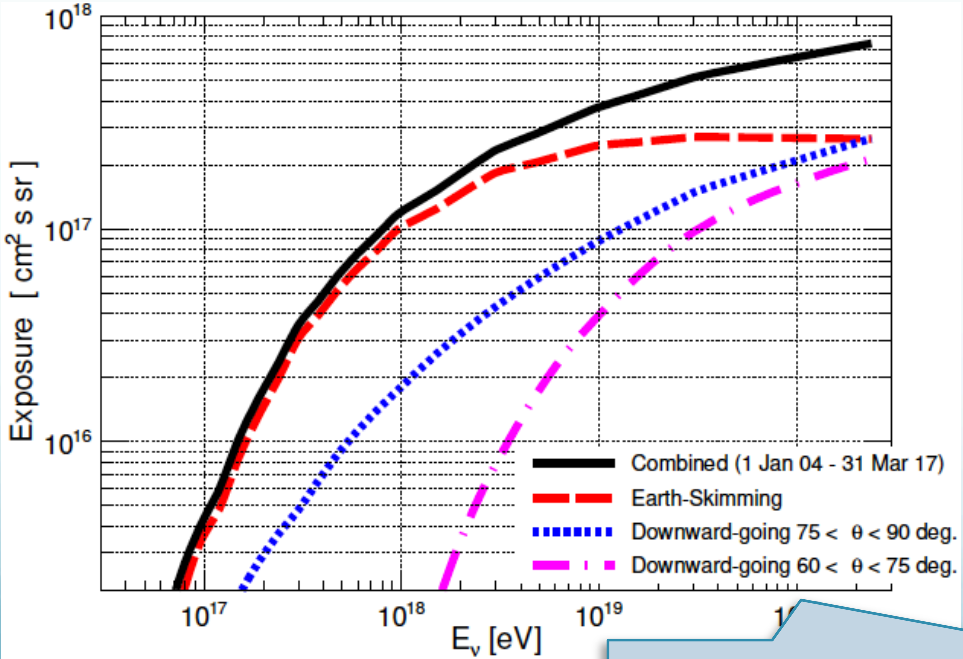
- PAO/TA hybrid experiments (Surface+Fluorescence) sensible to CRs above ~1 EeV.
- Neutrinos detected from inclined showers, ν_τ from Earth-skimming particles with a τ lepton shower (0.1-25 EeV).



Zas, PAHEN2017, Naples

Cosmic ν bounds at PAO

- Exposure = interaction and detection probability integrated over area, direction, time, and distance, as function of neutrino energy.
- Number of events results from convolution of exposure and flux.
- Data from 1 Jan 2004 to 31 Mar 2017 (excluding instability array periods)
- 90% C.L. limit obtained considering the flux producing 2.39 events (Feldman-Cousins, 1998).



Zas, ICRC Proc., 2017

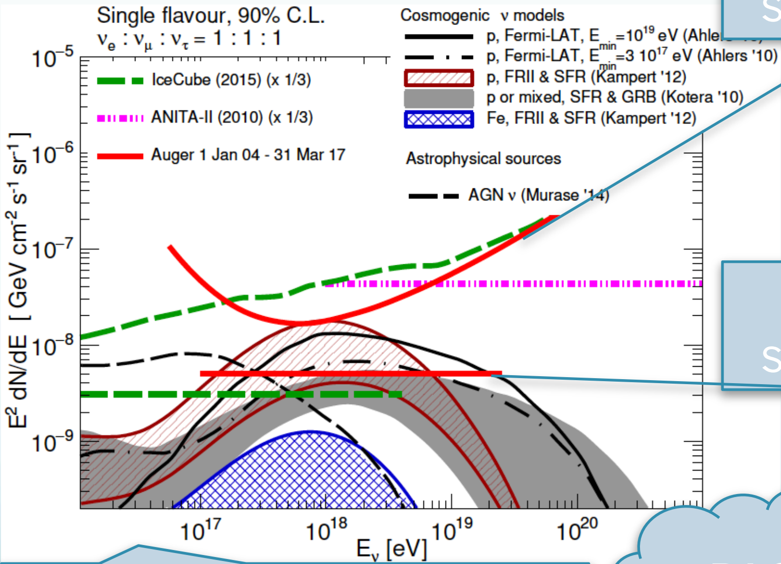
- Earth-skimming neutrinos dominate the exposure in spite of the reduced solid angle to which the detector is sensitive.
- Integral bound by integrating a conventional k E^{-2} spectrum
- Differential bound by integrating over consecutive energy bins.

Bounds on diffuse flux

- PAO: excluded at the 90% C.L. some cosmogenic or astrophysical models.
- TA: no ν candidates in the data set ➔ ν limit

diff. spectrum

integr. spectrum

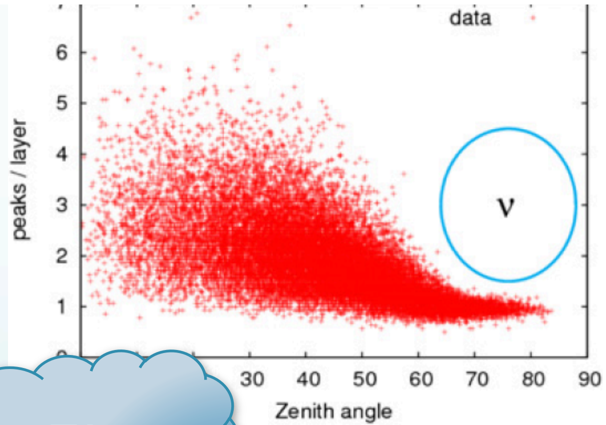


Zas, ICRC Proc., 2017

PAO

Rubtsov, UHECR Proc., 2013

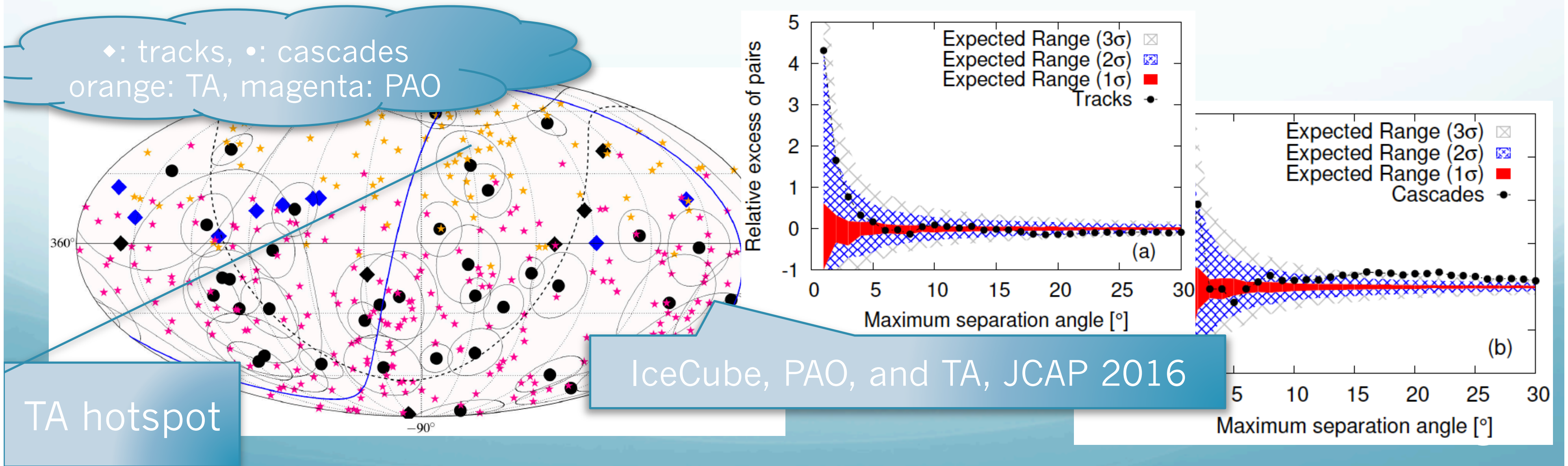
$$E^2 f_\nu < 1.4 \times 10^{-6}\,\mathrm{GeV\,cm^{-2}s^{-1}sr^{-1}} \quad (90\%\ \mathrm{C.L.})$$



TA

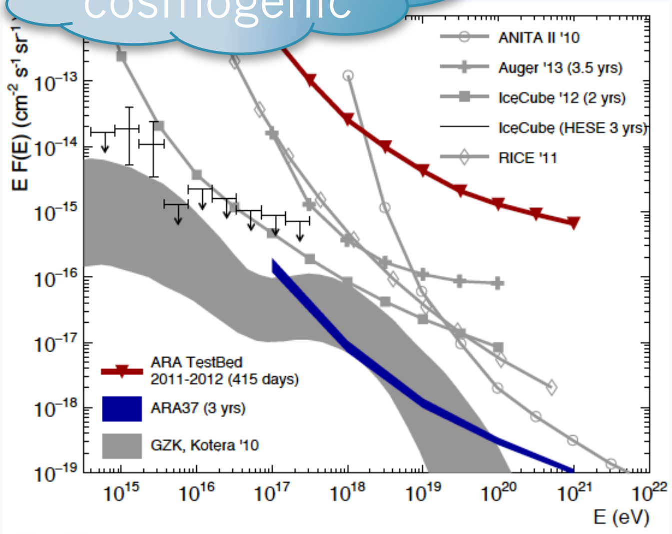
UHECRs—ν correlation

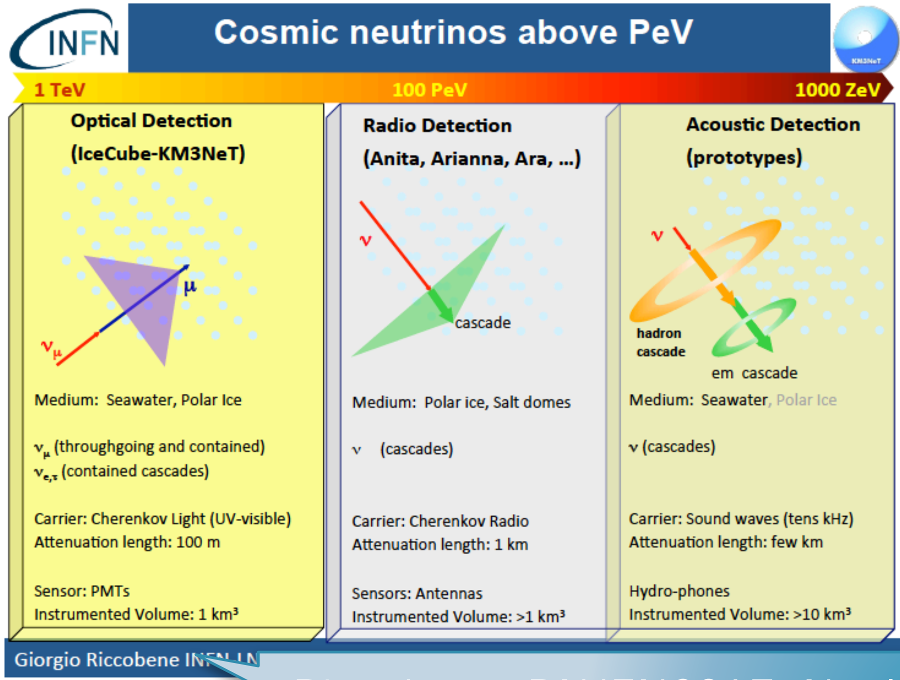
- No statistically significant correlation of UHECRs with sources established until now.
- IceCube neutrino energies much smaller than those of UHECRs.
- IceCube signal isotropy implies extragalactic origin for neutrinos.
- If IceCube ν comes from pp/pγ, it is possible that they point to the same sources of UHECRs.
- Analysis made on IceCube "HE tracks and cascades" and 231 UHECRs.
- Results compatible at 2σ with the ones from an isotropic CR distribution. Small excesses of tracks at small angle separation (1°) and of cascades at intermediate angle (22°), near the region of the TA hotspot.



Radio detection

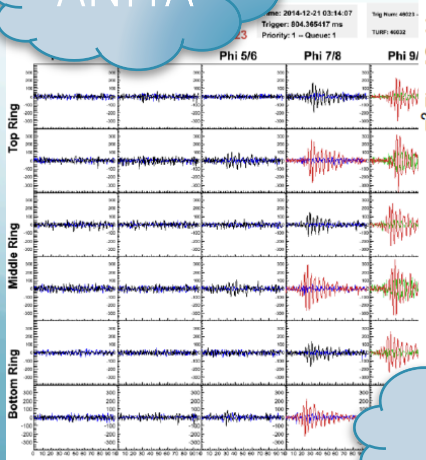
ARA cosmogenic



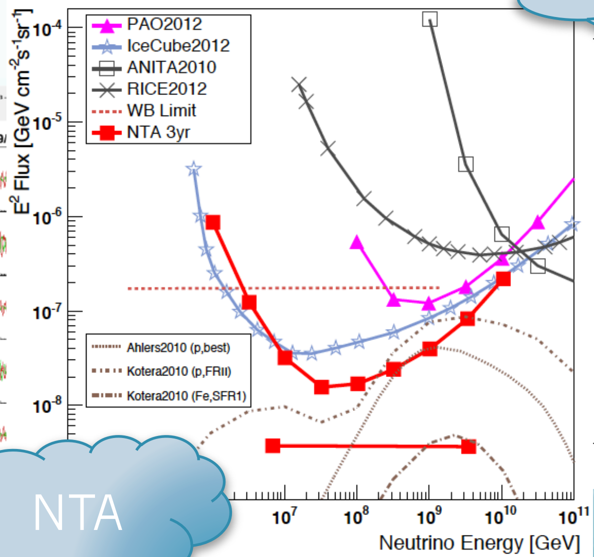


Riccobene, PAHEN2017, Naples

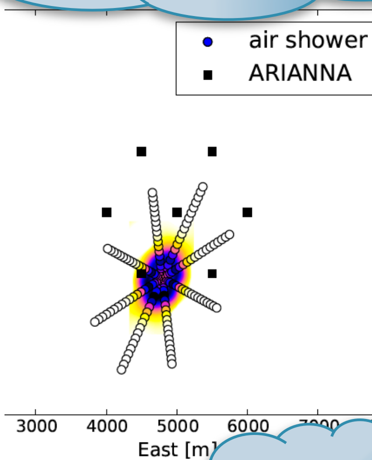
ANITA



NTA

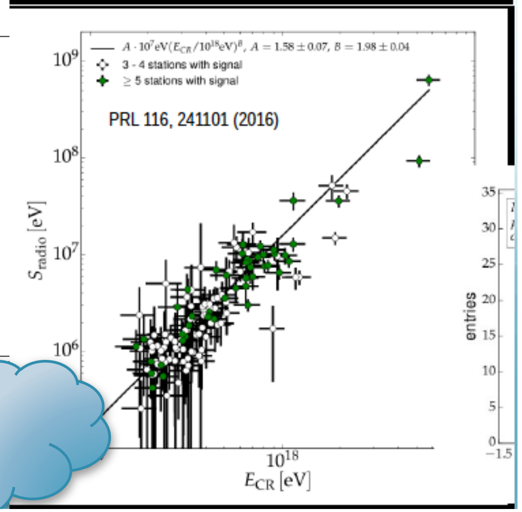


HRA–ARIANNA

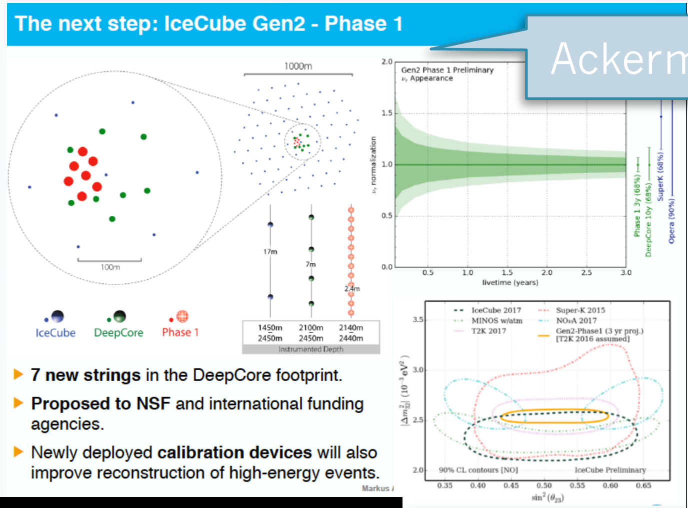


Auger: New energy estimator
Radio energy in 30-80 MHz

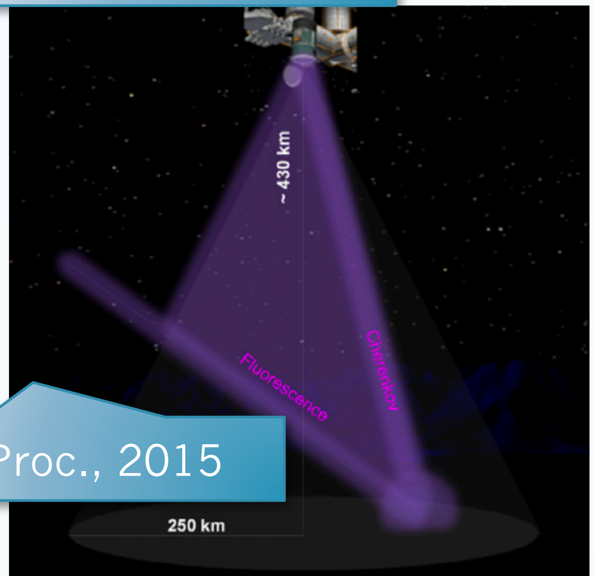
PAO



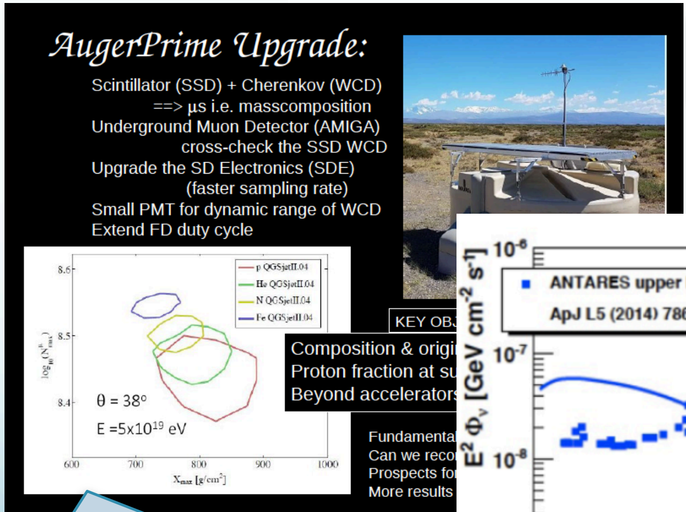
From discovery to astronomy



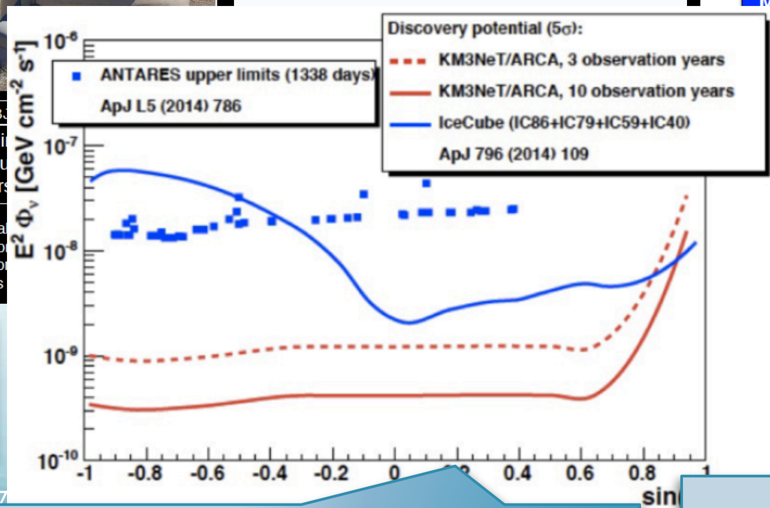
Ackermann, PAHEN2017, Naples



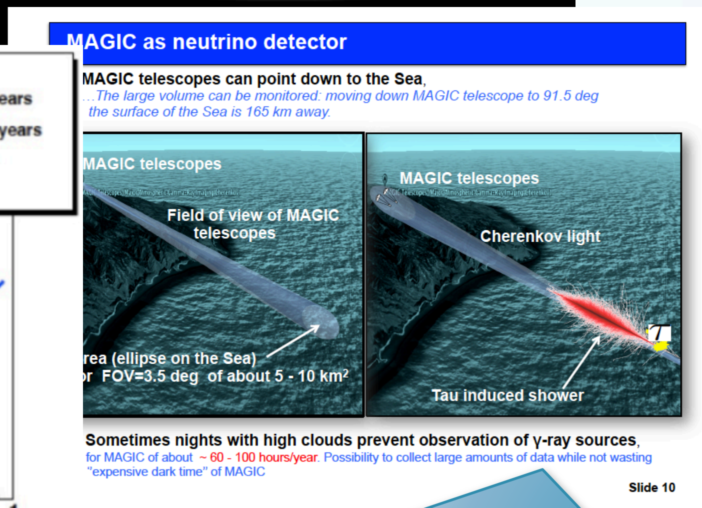
JEM-EUSO, ICRC Proc., 2015



Zas, PAHEN2017, Naples



Margiotta, Nuc.Part.Phys.Proc. 2016



Gora, PAHEN2017, Naples

Conclusions

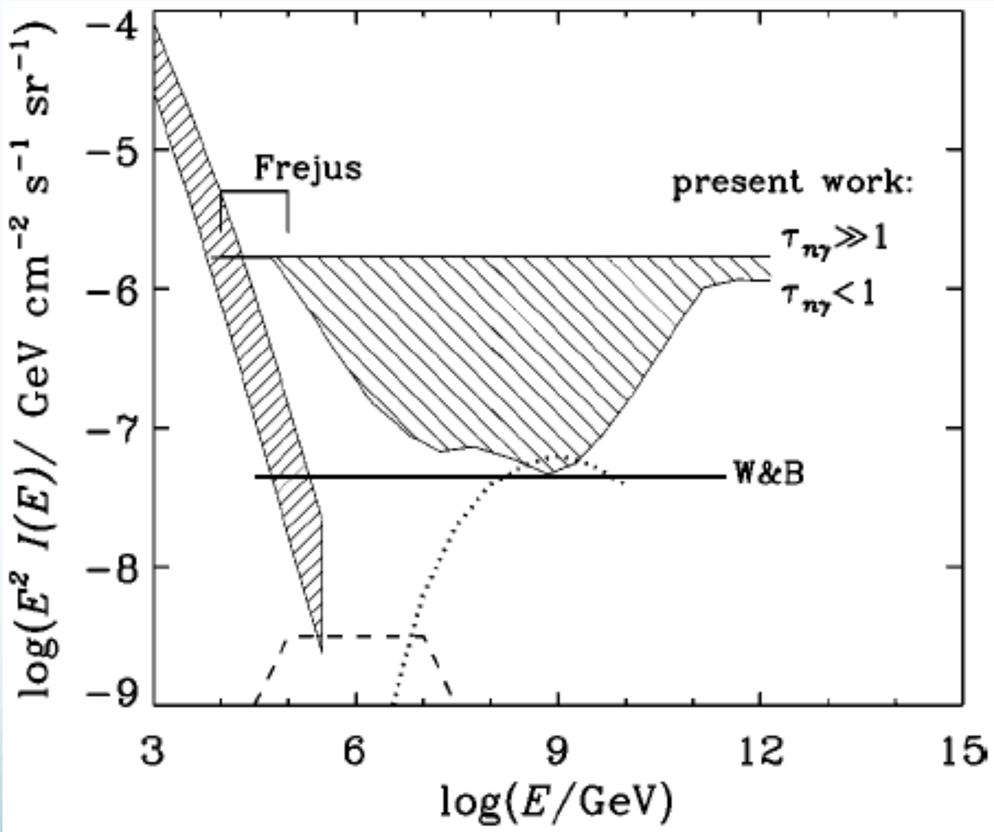
- A diffuse flux of extra-galactic neutrinos has been observed by NT experiments at the level of existing theoretical upper bounds.
- Atmospheric neutrino explanation excluded at more than 5σ (but very welcome studies of the dominant prompt ν background).
- We wait for UHE neutrinos at giant air shower arrays.
- From discovery to astronomy: upgraded/new experiments and new experimental techniques.
- Neutrino astronomy ➔ multi-messenger astronomy.

Thank you!

Backup slides

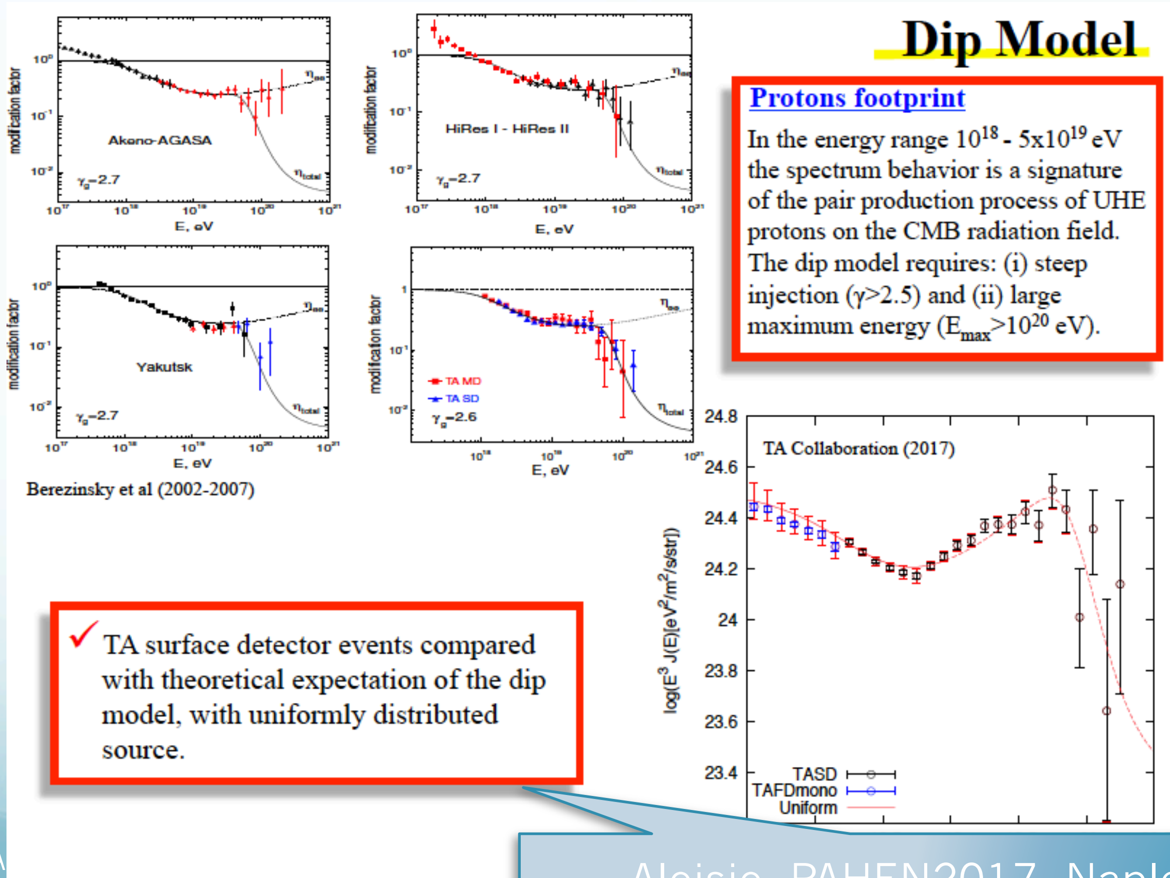
Astrophysical neutrinos

Muon neutrino upper bounds for optically thin pion photo-production sources ($\tau_{n\gamma}$<1) and optically thick pion photo-production sources ($\tau_{n\gamma}$>>1). The WB bound is for evolving sources.



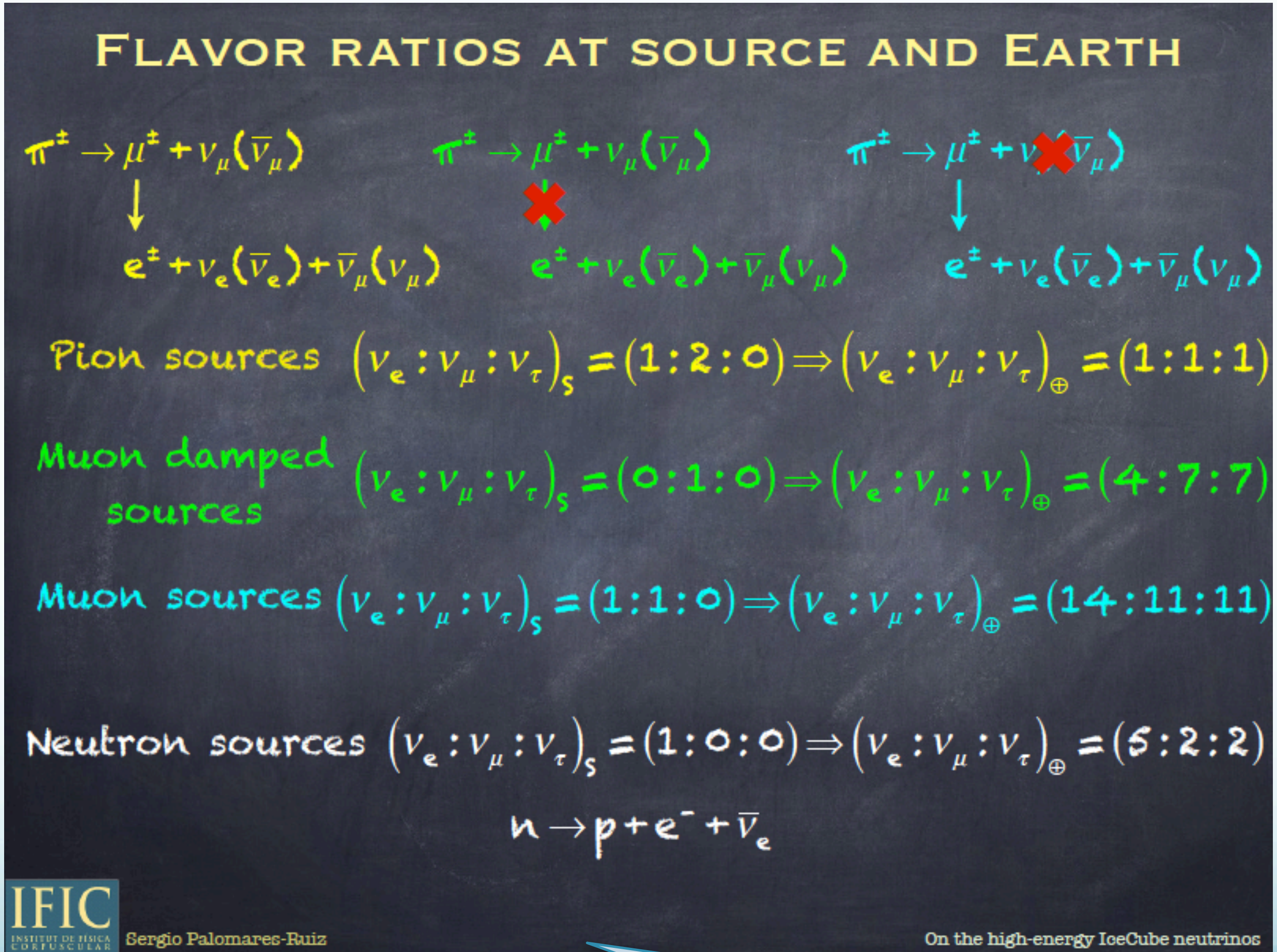
“Dip” model

A pure proton composition is called the “dip” model as a consequence of the peculiar aspect of the spectrum of CRs between 10^{18} and 10^{19} eV, due to the pair production of protons on the CMB. In fact, the pair-production dip is modified strongly when the fraction of nuclei heavier than protons is high at injection.



Aloisio, PAHEN2017, Naples

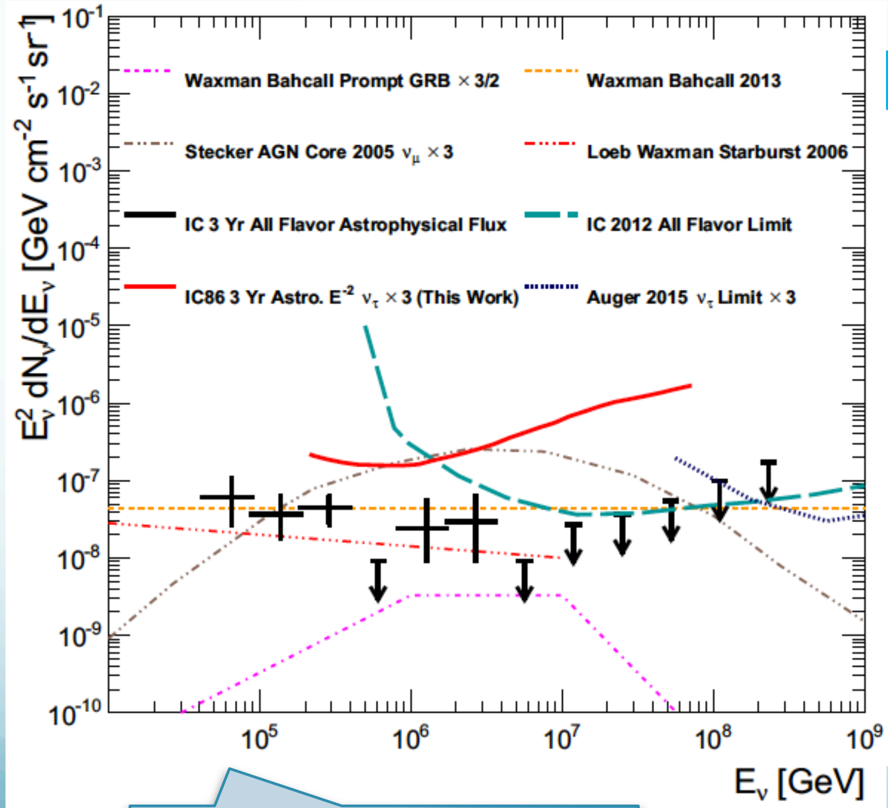
Flavour ratios



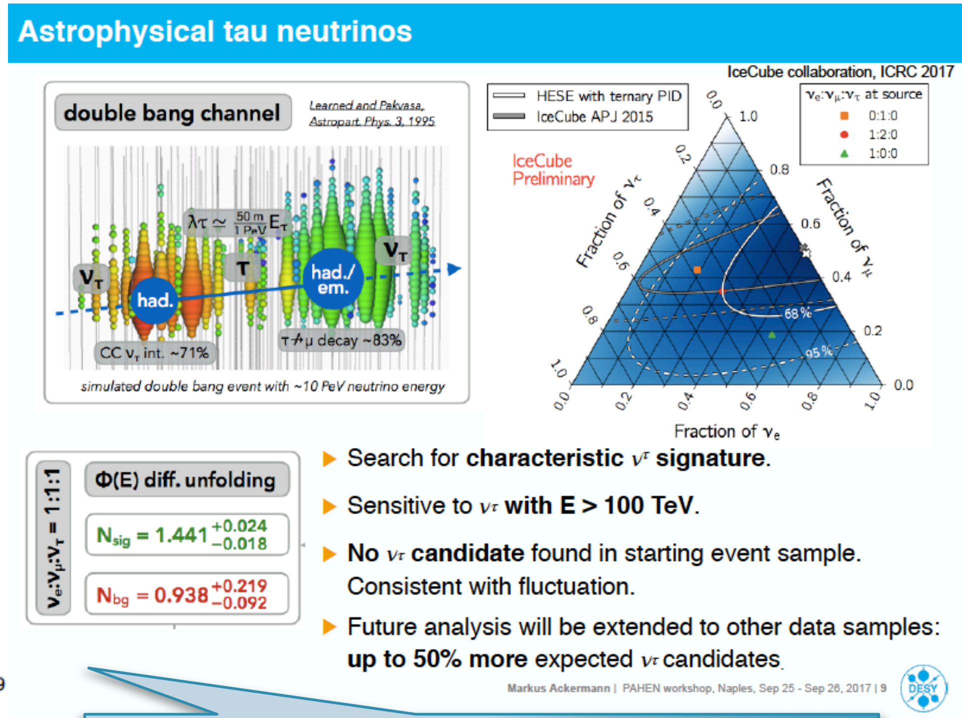
Palomares-Ruìz, PAHEN2017, Naples

Double bang at IceCube

At energies below PeV, the double cascade topology from ν_τ CC interactions is very difficult to distinguish from single cascades. Double bang events are not yet observed and a differential upper limit for astrophysical tau neutrinos was set around the PeV energy region.



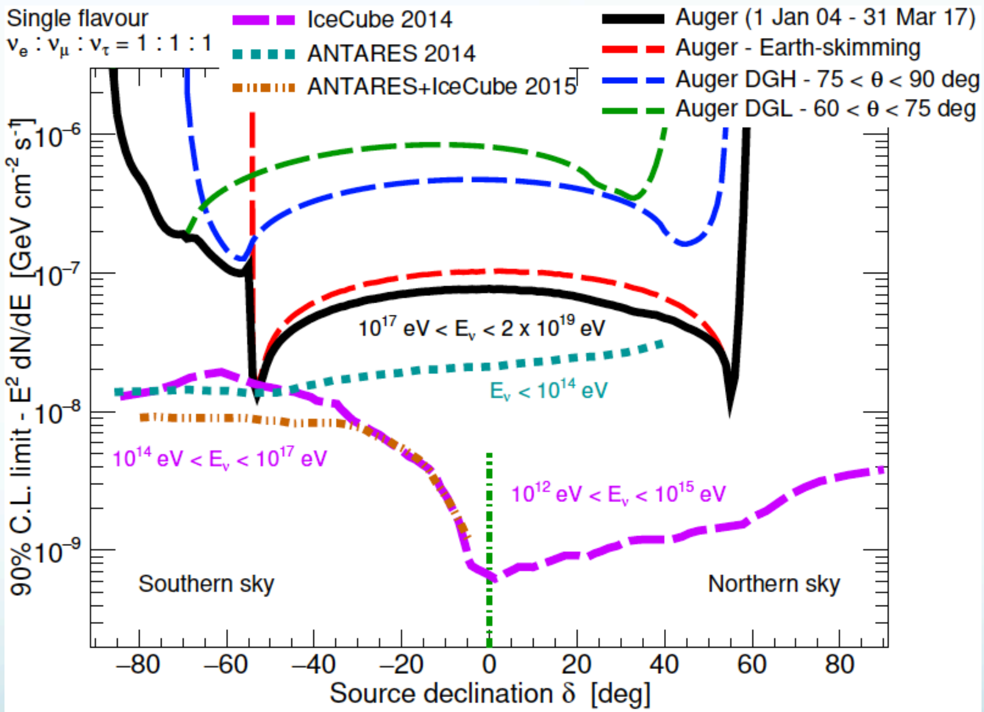
Xu, N&PP Proc., 2017



M. Ackermann, PAHEN2017, Naples

Bounds on point sources

- The experiment exposure can be integrated in right ascension and then converted to an average exposure for a given declination.
- Peaks in the 90% C.L. line are due to Earth-skimming channel, since over 90% of these events have declinations between −54.5° and 59.5°.

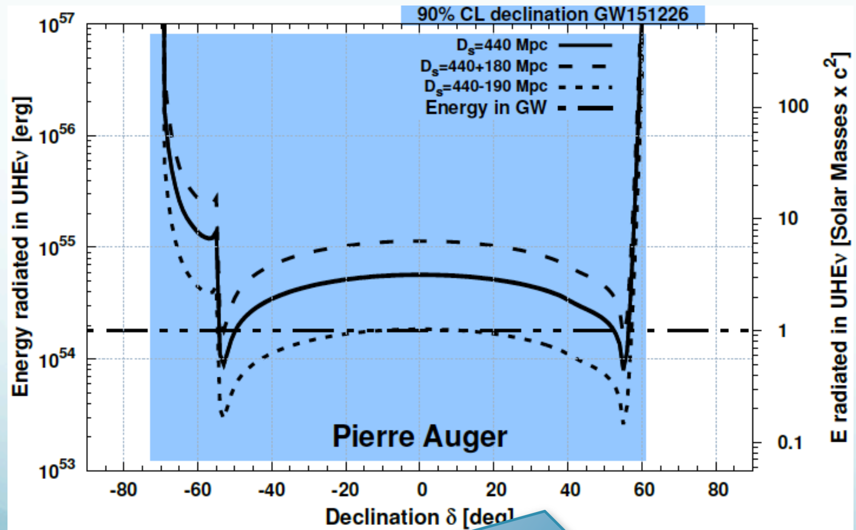


E. Zas, ICRC Proc., 2017

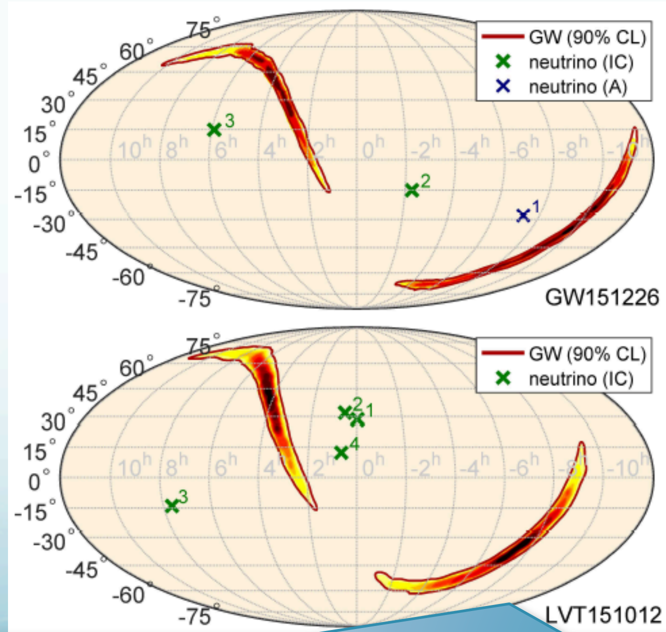
GW– ν correlation

Black Hole mergers, as the one firstly detected by LIGO/Virgo in 2015, could accelerate CRs to the highest energies and produce neutrinos.

- PAO: 1) no inclined showers were observed at all during the ±500 s window around any of the GW events, 2) inclined showers were observed within a day of the detected events but completely consistent with those expected from UHE cosmic rays.
- Antares, IceCube: among the temporally coincident ν events, none were directionally coincident with the GW signals at 90% C.L.

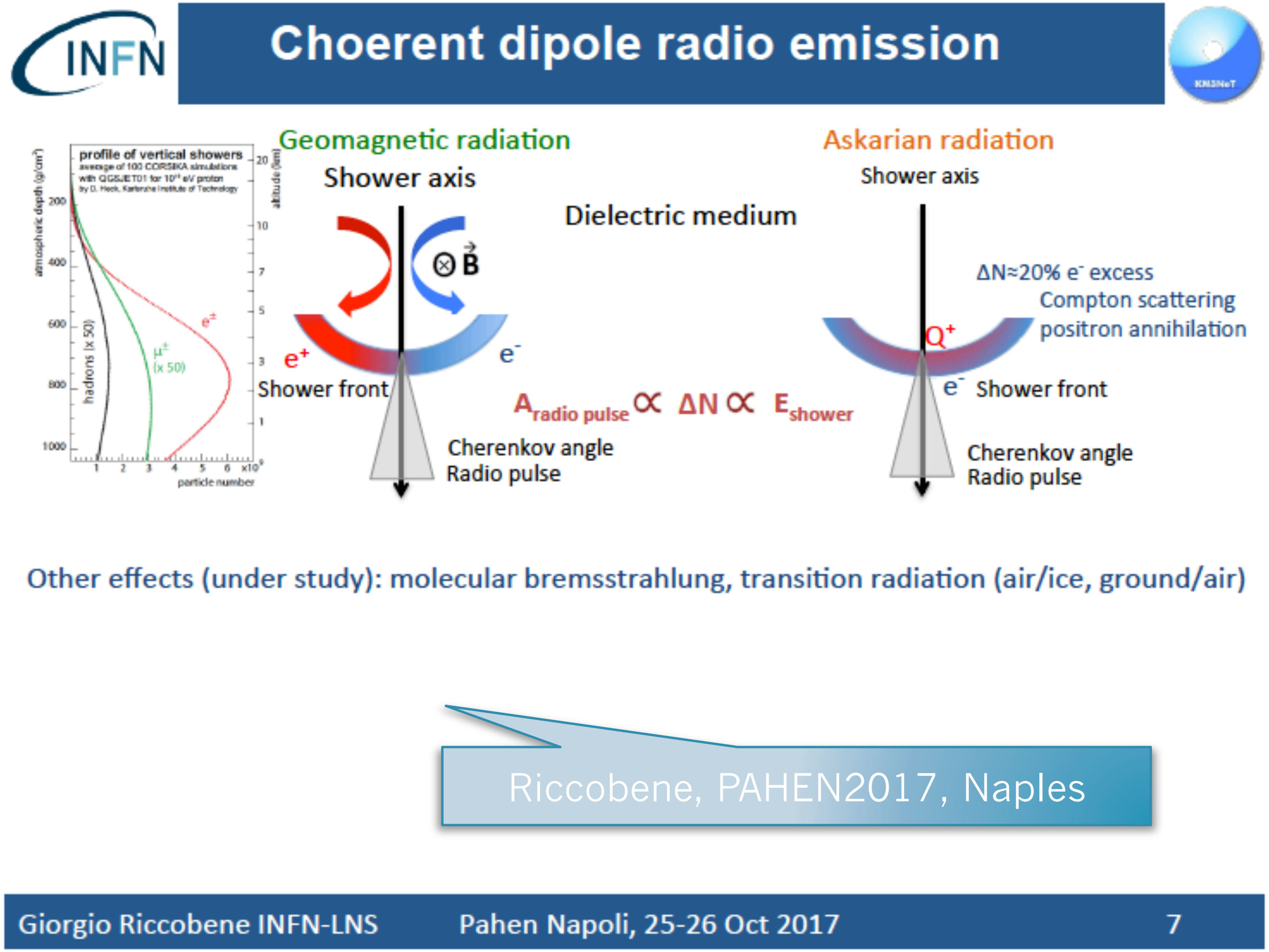


Zas, ICRC Proc., 2017



Antares, IceCube, LIGO, Virgo Phys. Rev., 2017

Radio detection

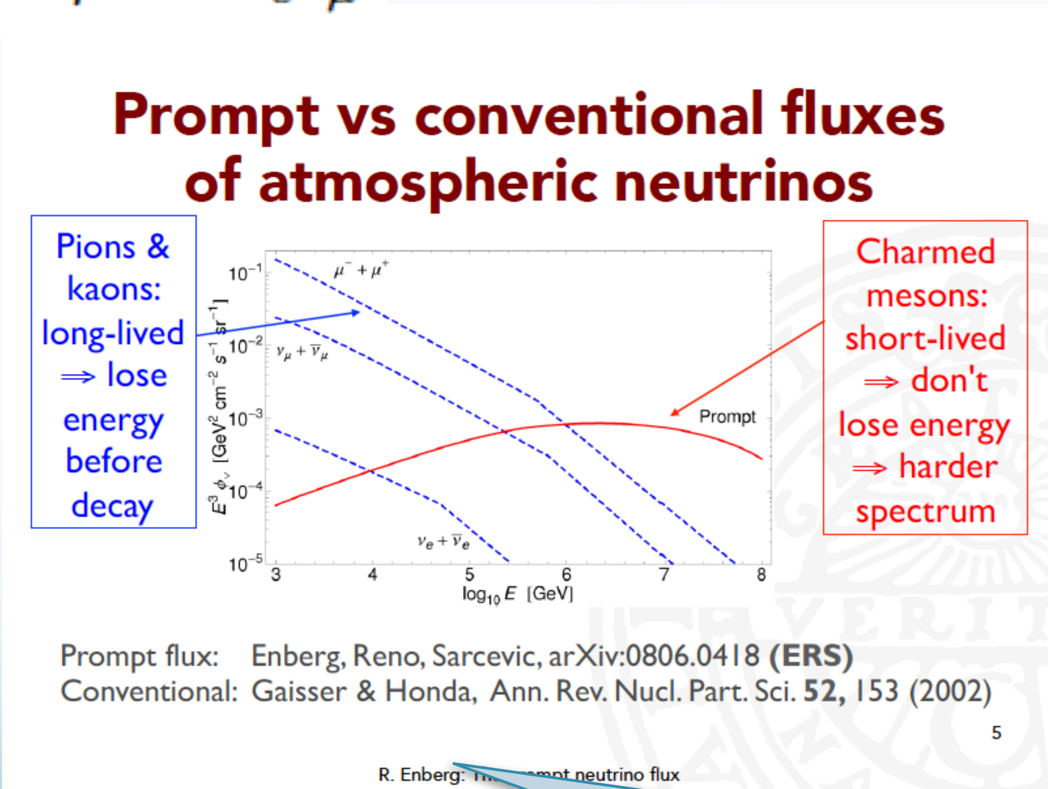


Riccobene, PAHEN2017, Naples

Atmospheric neutrinos

They are the decay product of π and K mesons produced in the interaction of cosmic ray protons with air (and the main background for km3 detectors searching for astrophysical ν).

$$\pi^{\pm} \rightarrow \mu\nu_{\mu} \qquad \mu \rightarrow e\nu_e\nu_{\mu}$$



R. Enberg, PAHEN2017, Naples