Astroparticles

José I. Illana

1. What?
2. Cosmic rays
3. Neutrinos

What?

Broad and fashionable topic: cosmic rays, neutrinos, gamma rays, dark matter, . . .

The field started with a discovery by Victor Hess (balloon flights, 1911)

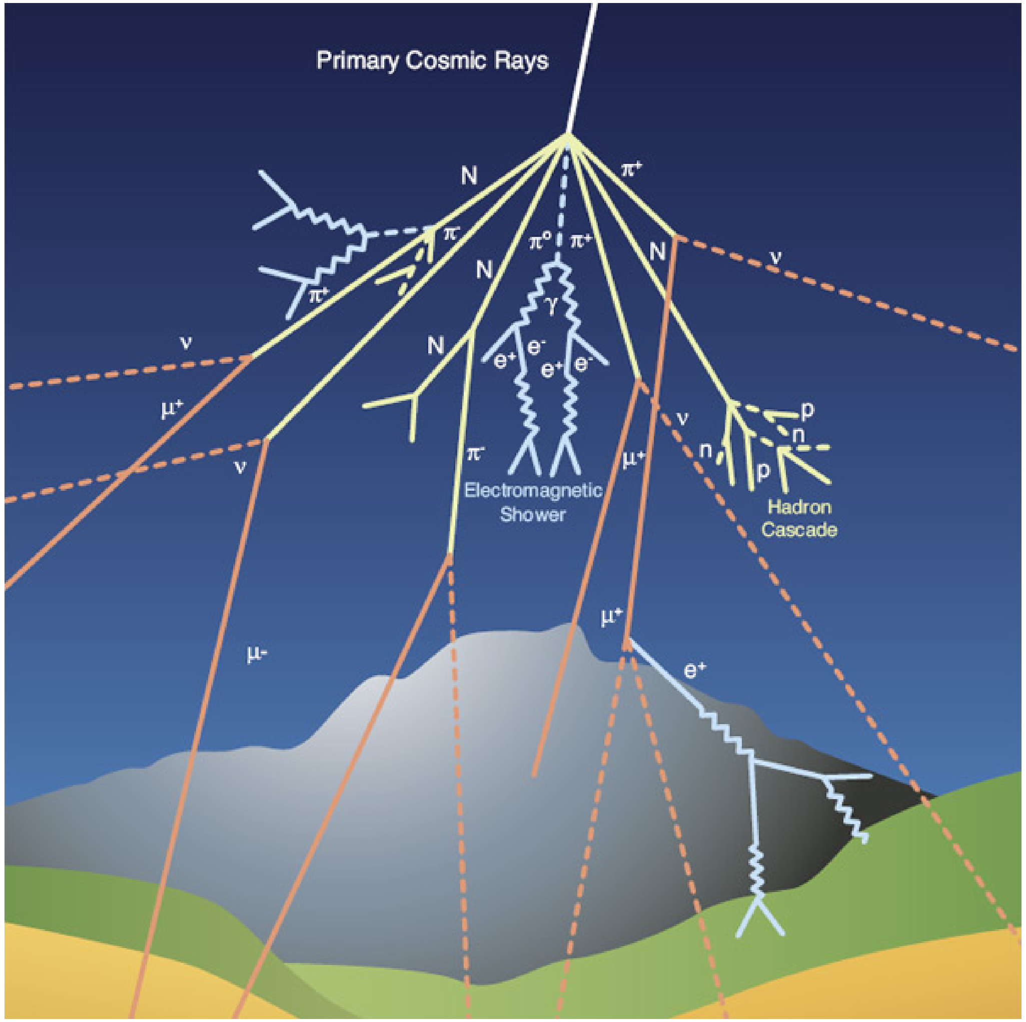
> *A radiation of high penetrating power entering the atmosphere from above, which can't be caused by radioactive emanations*

Physics Nobel Prize 1936 shared by
V. Hess
for his discovery of cosmic radiation &
C.A. Anderson
for his discovery of the positron
in cosmic rays!

[muon, pion, kaon, . . . followed]

Cosmic rays

"Massive particles striking the Earth"



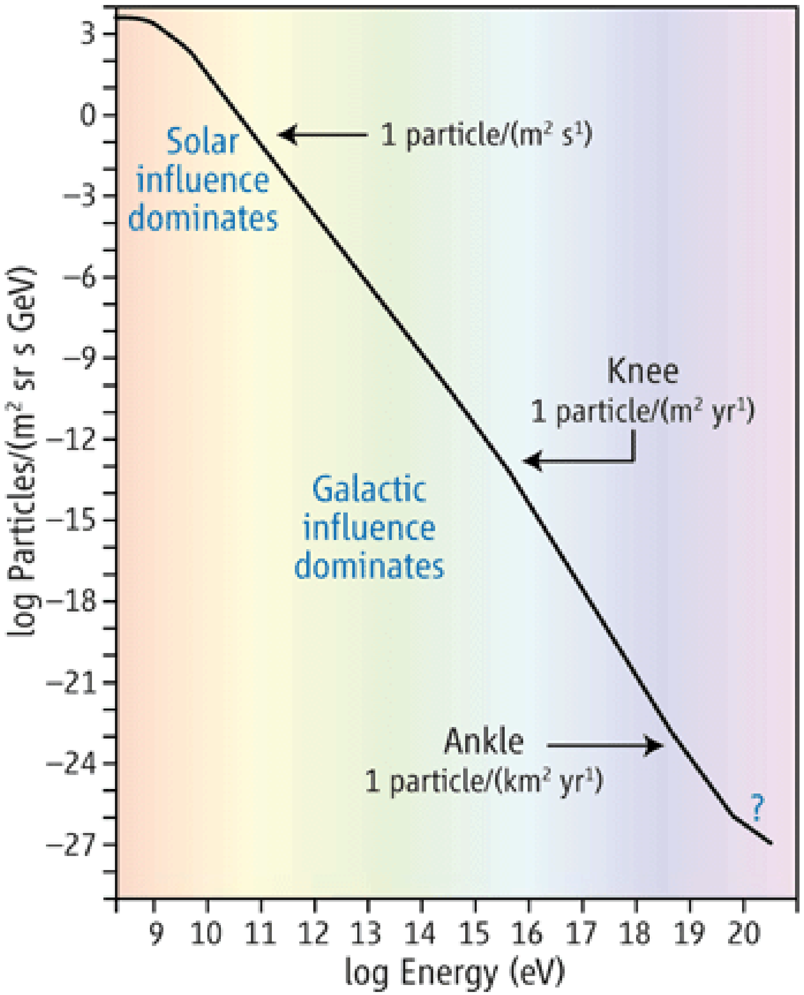
Primary cosmic ray
entering the upper atmosphere
[p, n, nuclei, e, γ, . . .]

Secondary cosmic rays
from subsequent interactions in atm

Cosmic rays | Flux

Primary spectrum

From $10^4\ \mathrm{m}^{-2}\,\mathrm{s}^{-1}$ @ 1 GeV to $1\ \mathrm{km}^{-2}\,\mathrm{yr}^{-1}$ @ 10^{10} GeV and even more !!!



Origin

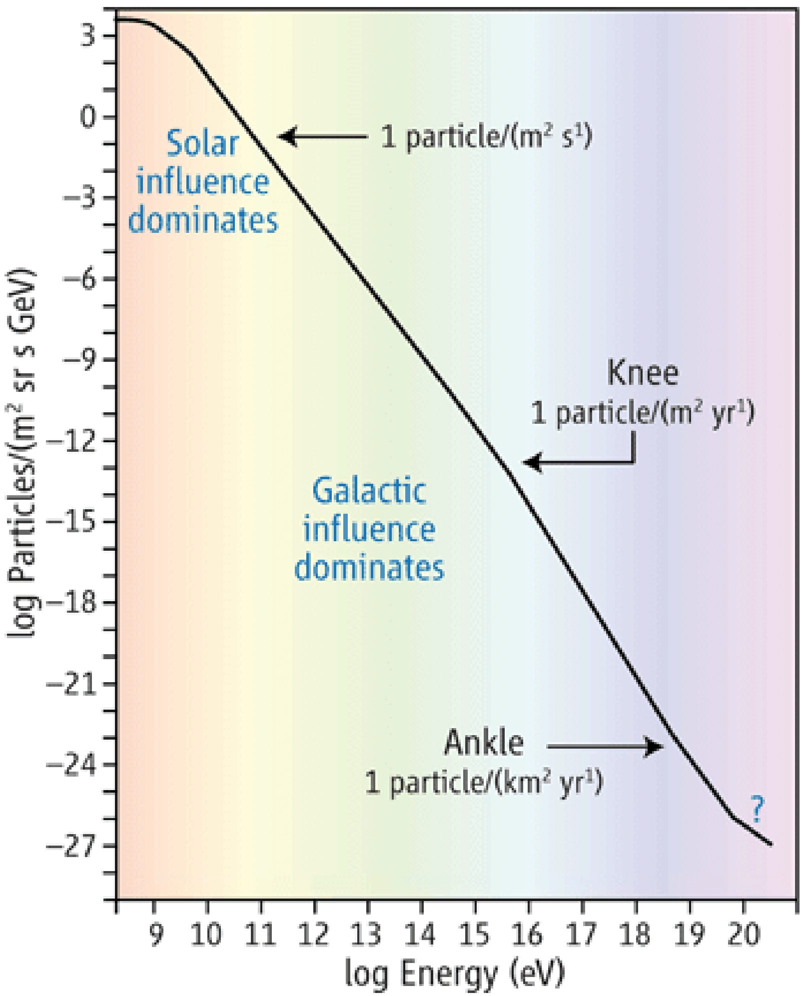
galactic

$\sim 10^6$ GeV **Knee**
max E of some galactic accelerators reached

$\sim 10^{10}$ GeV **Ankle**
extragalactic component starts to dominate

Cosmic rays | Flux

Types of experiments: size matters!

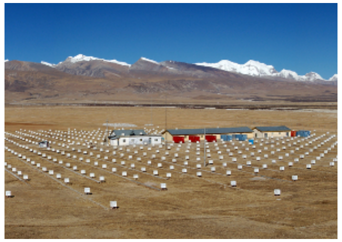


Direct detection:

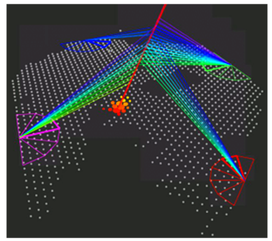
AMS, ...

ANITA, ...

Air showers:



Tibet, ...



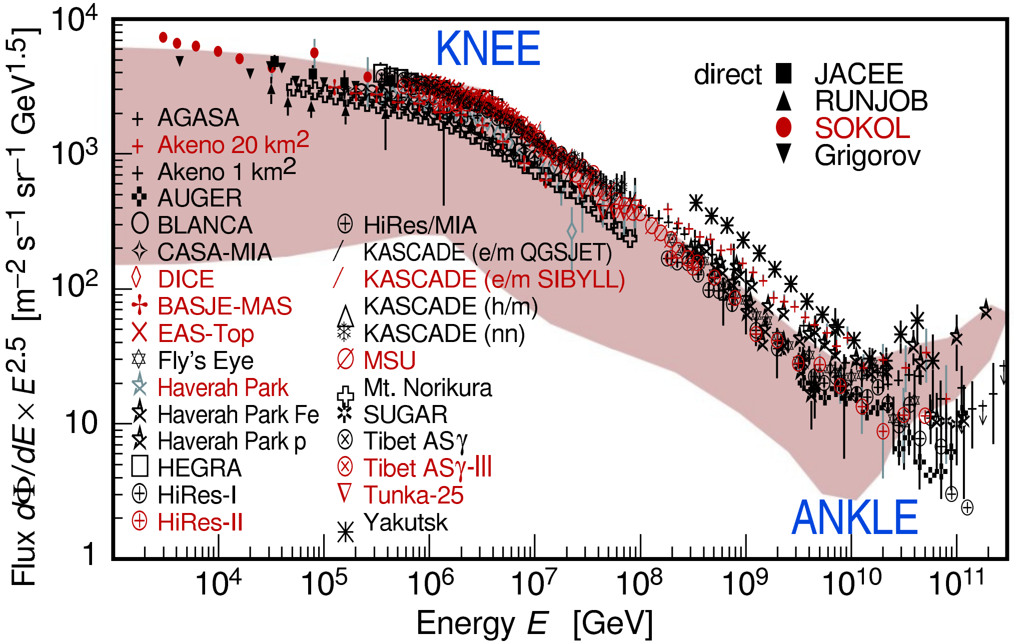
Pierre Auger

...JEM-EUSO ...LUNASKA ...

Cosmic rays | Flux

The "cosmic ray leg"
(broken power law spectrum)

$$\frac{d\Phi}{dE} \propto E^{-\alpha}$$

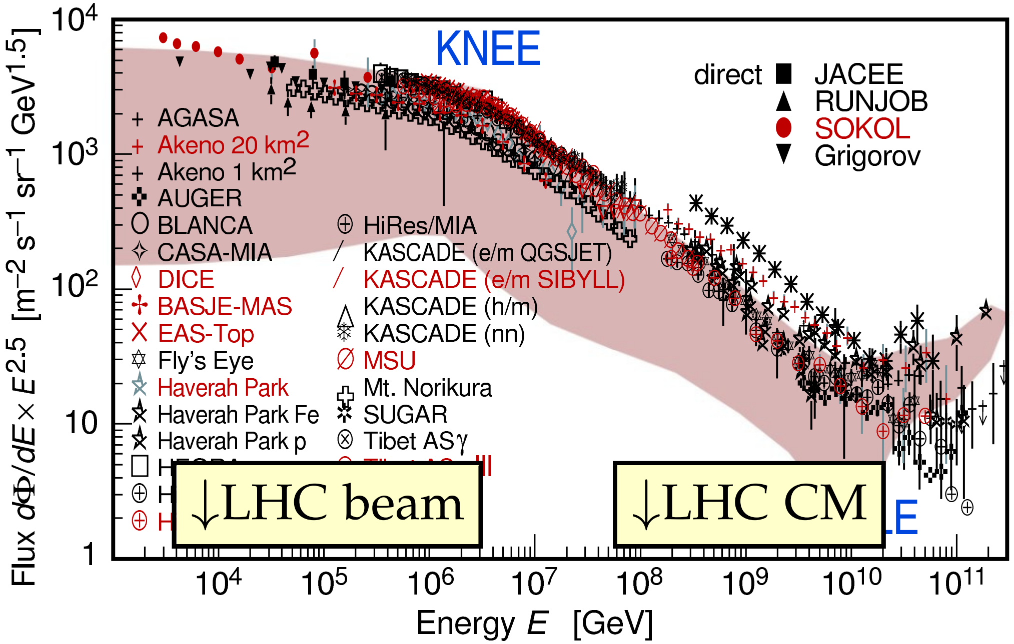


$\alpha = 2.7$ | $\alpha = 3.0$ | $\alpha = 2.7$

Cosmic rays | Flux

Beam energy up to 7 orders of magnitude > in man-made accelerators, and
CM energy up to 3 orders of magnitude > in a collision with a nucleon at rest

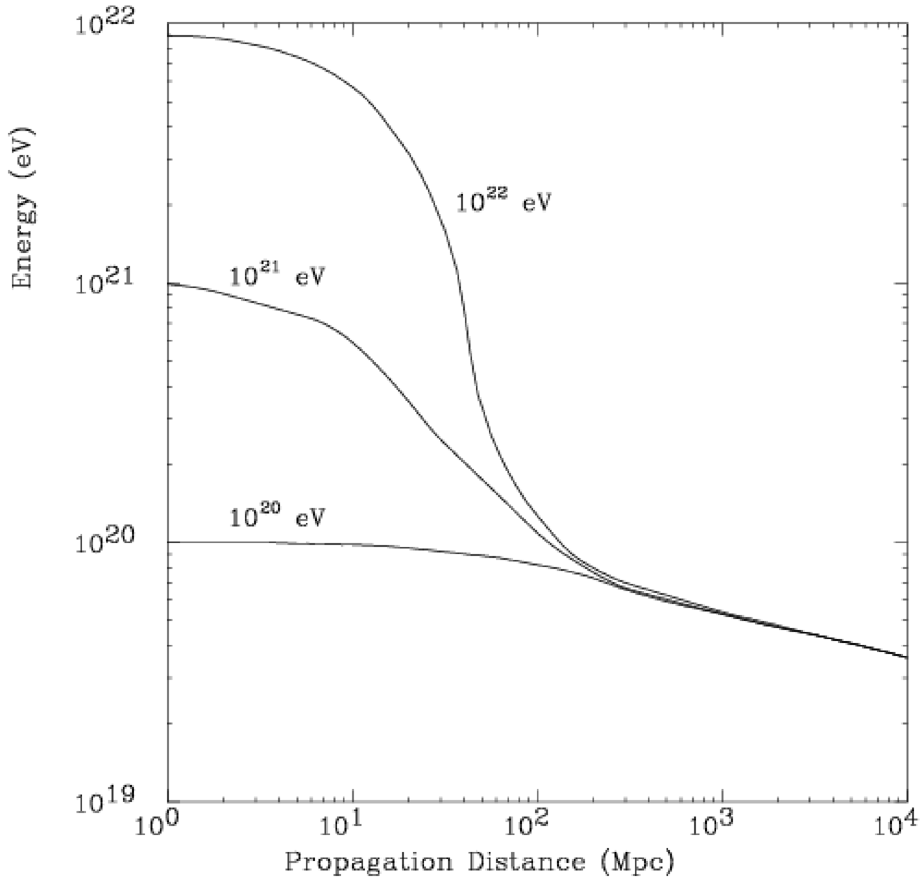
$$\sqrt{s} = \sqrt{2 m_N E}$$



Does this spectrum have an end?

Cosmic rays | GZK suppression

- Photons have an absorption length ~ 10 Mpc, producing e^+e^- with CMB and IRB
- Electrons lose energy very rapidly via synchrotron radiation
- Protons and neutrons lose 20% of their E every 6 Mpc above $E_{\rm GZK} \approx 5 \times 10^{19}$ eV by scattering off CMB: $p + \gamma_{2.7\rm K} \to \Delta^+ \to p + \pi^0 \; (n + \pi^+)$ [Greisen; Zatsepin, Kuzmin '66]

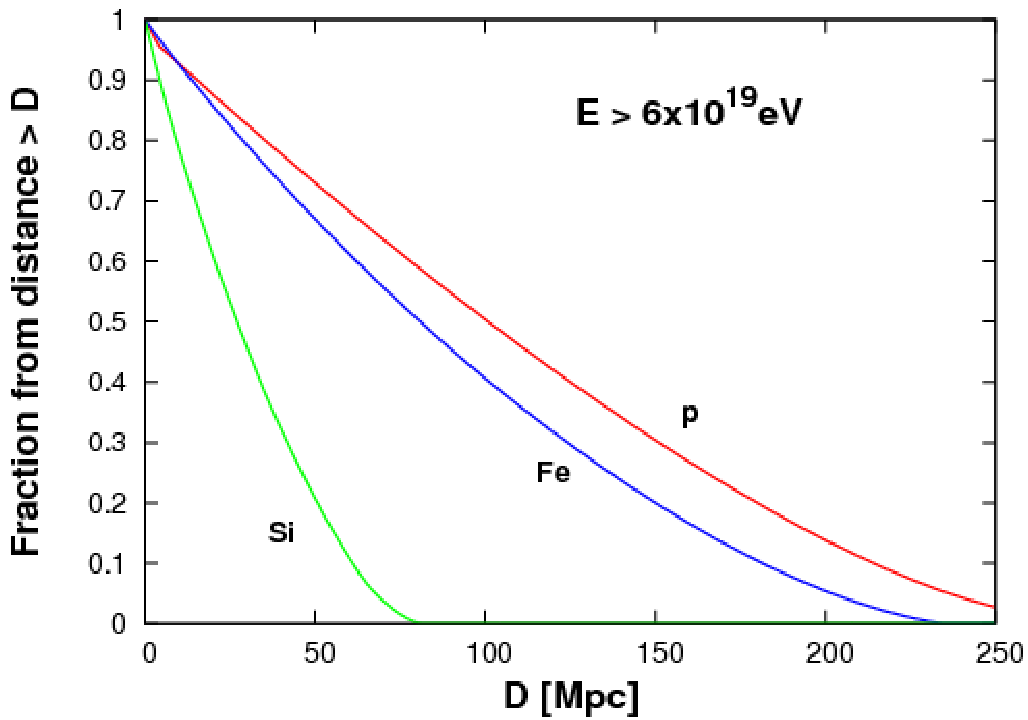


$\Rightarrow D_{\rm GZK} \approx 100$ Mpc, "pile-up" structure

Cosmic rays | GZK suppression

- Nuclei undergo photodisintegration in CMB: $A + \gamma_{2.7\text{K}} \to (A-1) + N$ for $E \gtrsim 5\times10^{19}$ eV

  The fraction of surviving cosmic rays from a distance $> D$ [1406.1117]



  Since there are not (many) powerful sources nearby, the UHECR must experience a suppression above E_{GZK}

Cosmic rays | Acceleration mechanisms?

- "Bottom-Up" scenarios:
  - Direct acceleration by high electric fields, within or near very compact objects. But no power-law spectrum
  - **Fermi mechanism**:
    stochastic schock-wave acceleration in magnetized clouds. It predicts a power-law spectrum but too inefficient to account for the observed UHECRs?
- Exotic:
  - "Top-Down" scenarios:
    decay or annihilation of super-heavy particles or cosmological relics, like topological defects or magnetic monopoles.
    But almost no pairing and flatter spectrum
  - New Physics:
    Breakdown of Lorentz invariance or General Relativity? Too speculative …

Cosmic rays | Where are the sources?

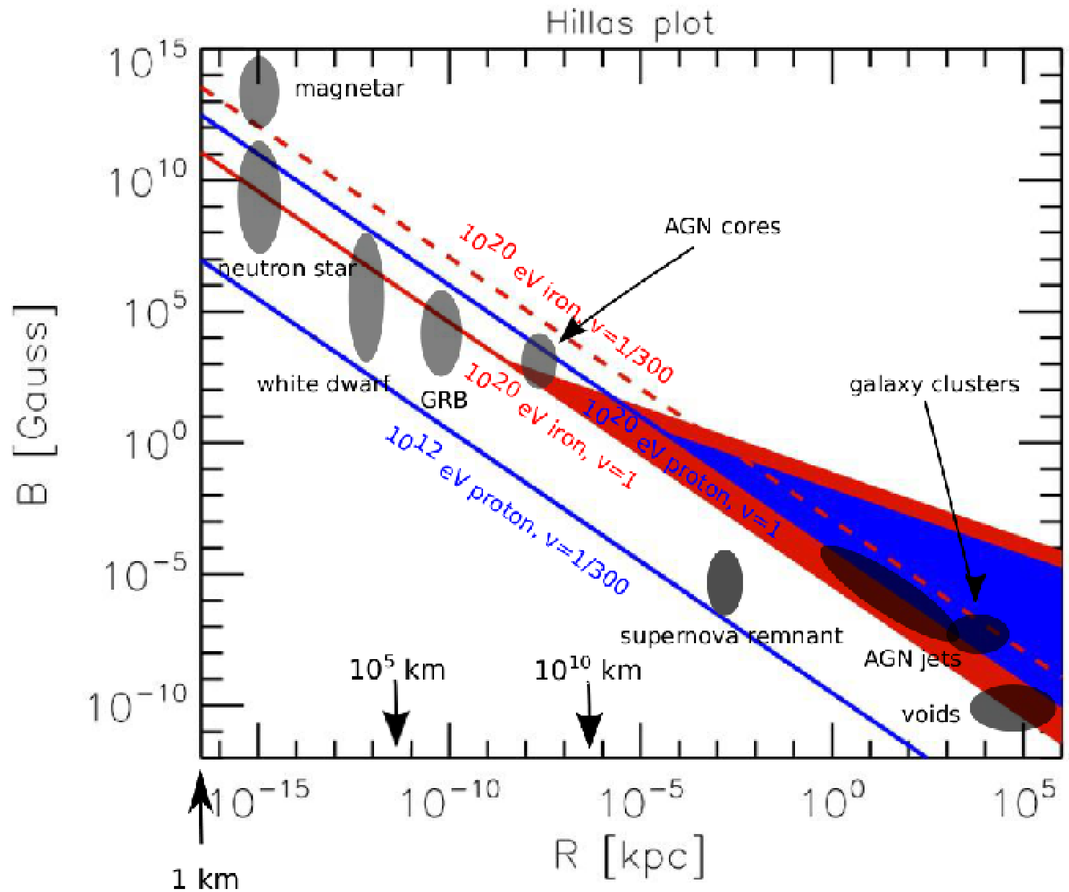
The maximum energy of a charge Ze particle, within a site of size R (Larmor radius) is

$$E_{\rm max} \approx \beta Z \left(\frac{B}{1\ \mu{\rm G}}\right)\left(\frac{R}{1\ {\rm kpc}}\right) 10^{18}\ {\rm eV}$$

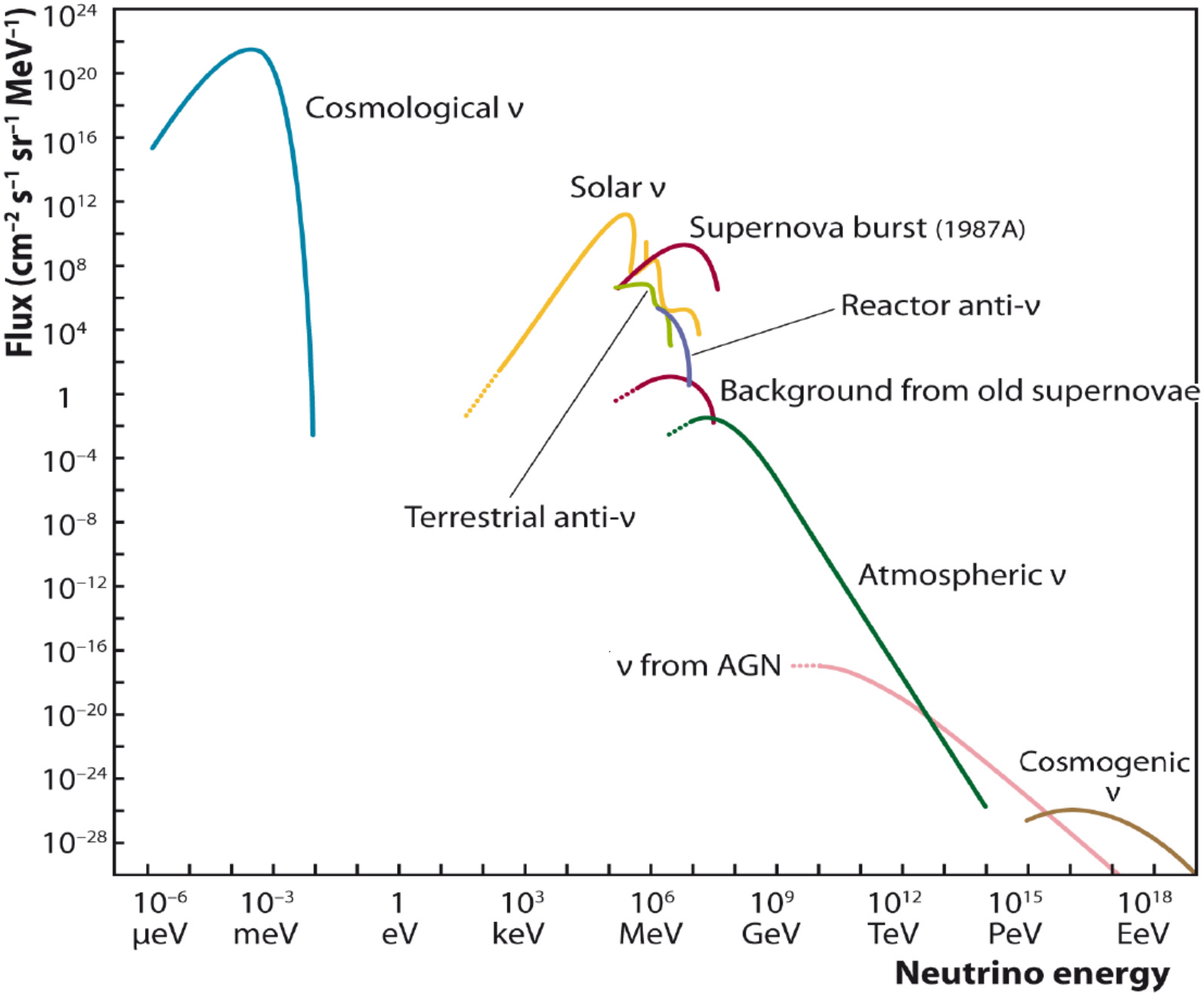
with B the magnetic field inside the acceleration volume, β the shock wave velocity

Then, candidates line up in the Hillas plot (conventional accel scenario) that can be refined [1202.0466]

e.g. AGN and galaxy clusters can accelerate protons and iron to 10^{20} eV but supernova remnants cannot accelerate protons above 10^{15} eV (the position of the CR knee!)



Neutrinos (terrestrial and reactor are not astroparticles)



⇓ Let me focus here (background to ET ν in neutrino telescopes)

⇐ GZK process!

Neutrinos | **Atmospheric neutrinos**

- **The atmospheric neutrino problem**
  - Cosmic rays produce π in the atmosphere that should give a flux of ν_e and ν_μ in (1:2)

$$\pi \to \bar{\nu}_\mu \mu \to \bar{\nu}_\mu \nu_\mu \bar{\nu}_e \, e$$

  - The observed flux of ν_μ is largely reduced

  $\Rightarrow$ Explained by oscillations $\nu_\mu \to \nu_\tau$

- **BUT** this is only true for low energy muons ($E \lesssim 10$ GeV), since otherwise they will typically reach the ground before decaying!

$$\gamma\tau = \frac{E}{m}\tau < h_0 \quad \text{(height of the atmosphere)}$$

  The lifetime is $\tau = 600$ m. Taking $h_0 \sim 10$ km, one gets $E \lesssim 10$ GeV

- On the other hand, π are not the only source of atmospheric neutrinos ...

Neutrinos | Atmospheric neutrinos (at high energy)

- Components of atmospheric lepton (μ, ν_e, ν_μ, ν_τ) fluxes according to parent j:

$$\gamma c\tau_j = \lambda_{\rm dec}^{(j)} = h_0 \quad \Rightarrow \quad \boxed{\text{Critical energy}} \quad \varepsilon_j = \frac{m_j}{\tau_j} h_0$$

Source	j + antipart.		$c\tau_j$	ε_j [GeV]	BR to leptons
✓ Standard	π^+	$\to \mu^+\nu_\mu$	8 m	115	100%
	K_L	$\to \{\mu^\pm\nu_\mu, e^\pm\nu_e\}\pi^\mp$	15 m	210	67%
	K^+	$\to \{\mu^+\nu_\mu, e^\pm\nu_e\}$	4 m	850	69%
✓ Charmed	D^+	$\to \{\mu^+\nu_\mu, e^+\nu_e\}\overline{K}^0$	310 μm	0.38×10^8	18%
	D^0	$\to \{\mu^+\nu_\mu, e^+\nu_e\}K^-$	125 μm	0.96×10^8	7%
	D_s^+	$\to \tau^+\nu_\tau$	150 μm	0.85×10^8	6%
	Λ_c^+	$\to \{\mu^+\nu_\mu, e^+\nu_e\}\Lambda^+$	60 μm	2.40×10^8	4%
! Unflavored	η, η'	$\to \mu^+\mu^-\gamma$	$\lesssim$ Å	—	$\sim 10^{-4}$
	ρ, ω, ϕ	$\to \mu^+\mu^-(\pi^0)$			

Neutrinos **Atmospheric neutrinos** (at high energy)

- Components of atmospheric lepton ($\mu, \nu_e, \nu_\mu, \nu_\tau$) fluxes according to parent j:

$$\phi_\ell(E,\theta) = \sum_j \phi_\ell^{(j)}(E,\theta)$$

$$\begin{aligned} \phi_{\nu_\alpha}(E,\theta) &= \phi_{\nu_\alpha}^{\text{stand}}(E,\theta) + \phi_{\nu_\alpha}^{\text{charm}}(E) \\ \phi_\mu(E,\theta) &= \phi_\mu^{\text{stand}}(E,\theta) + \phi_\mu^{\text{charm}}(E) + \phi_\mu^{\text{unflav}}(E) \end{aligned}$$

at ground level

- Applying an integro differential equation that takes into account sink and source terms in the particle propagation in the atmosphere (Z-moment method) we obtain the fluxes of the different components at ground level from a given profile of the primary nucleons in the top

$$\phi_N = KE^{-\alpha}$$

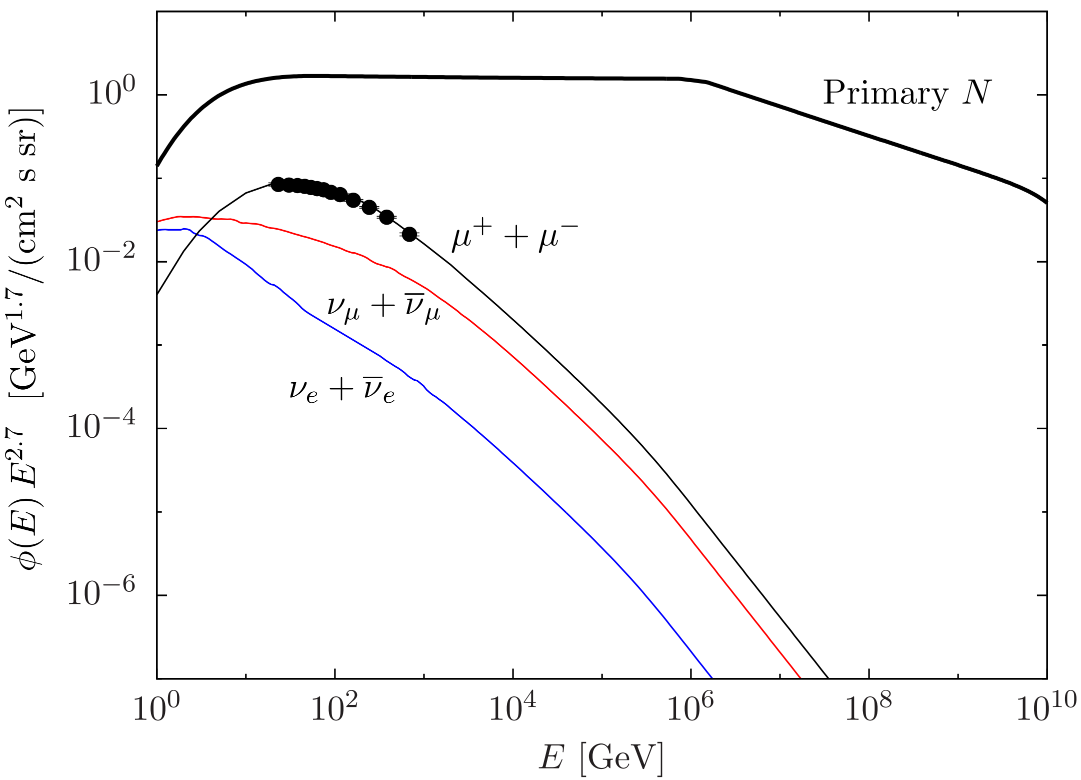
Neutrinos | Atmospheric neutrinos (at high energy)

- The results are [1010.5084]

$$\phi_\ell^{\text{stand}}(E,\theta) \simeq \frac{\mathbf{E}_\ell(\alpha)}{\cos\theta} K E^{-(\alpha+1)}\,, \quad E \gtrsim 10 \text{ TeV} \qquad \text{(far above critical)}$$

$$\phi_\ell^{\text{charm}}(E) \simeq C_\ell^{\text{charm}}(\alpha) K E^{-\alpha}\,, \quad E \lesssim 10^7 \text{ GeV} \quad \text{(below critical)}$$

More accurate results valid also for $E \lesssim 10$ GeV (just standard flux)



$(\nu_e : \nu_\mu) = (1:2)$ at low E

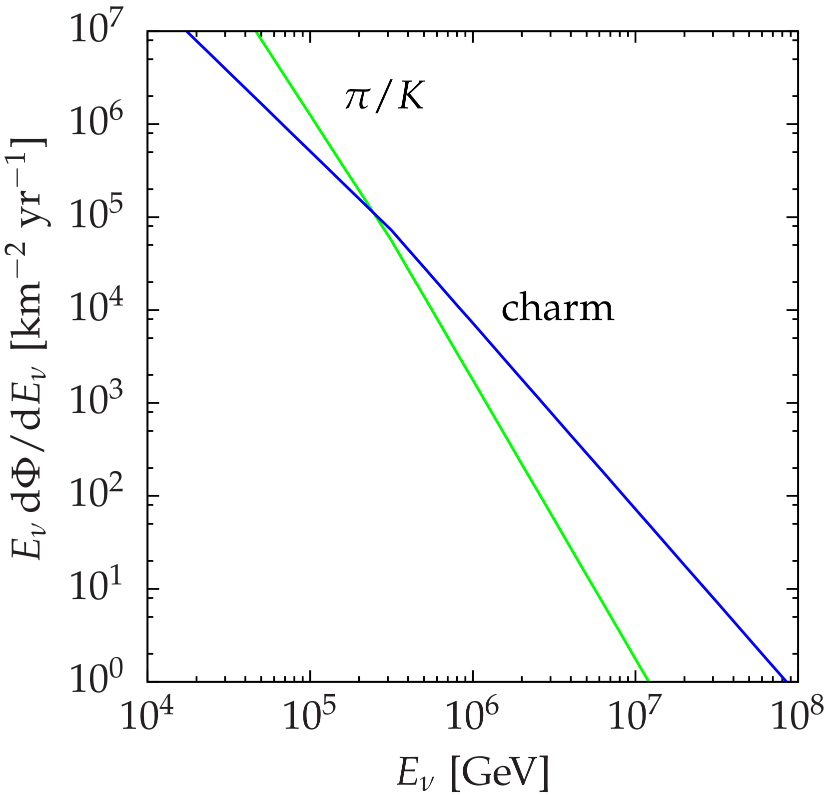
$(\nu_e : \nu_\mu) = (1:17)$ at high E

Neutrinos **Atmospheric neutrinos** (at high energy)

- The results are

$$\phi_\ell^{\text{stand}}(E,\theta) \simeq \frac{\mathbf{E}_\ell(\alpha)}{\cos\theta} K E^{-(\alpha+1)}\,, \quad E \gtrsim 10\ \text{TeV} \quad \text{(far above critical)}$$
$$\phi_\ell^{\text{charm}}(E) \simeq C_\ell^{\text{charm}}(\alpha) K E^{-\alpha}\,, \quad E \lesssim 10^7\ \text{GeV} \quad \text{(below critical)}$$

And comparing standard (π/K) and charm components above 10 TeV



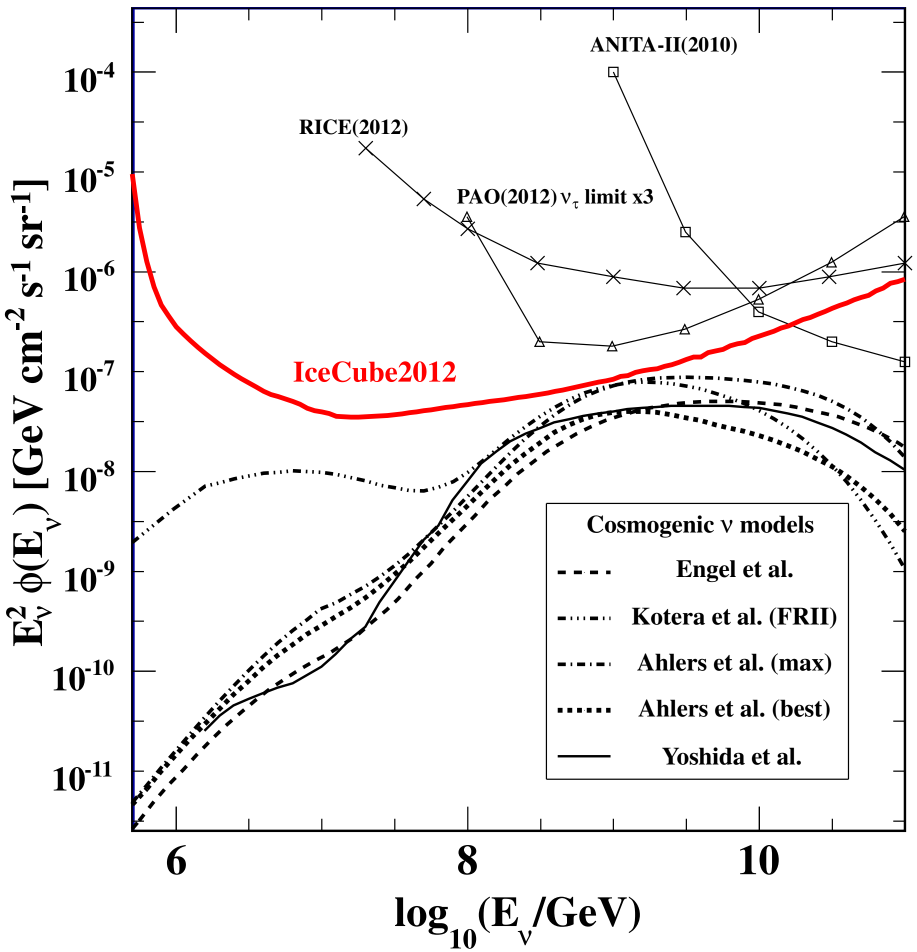
$E_\times \approx 3 \times 10^5$ GeV

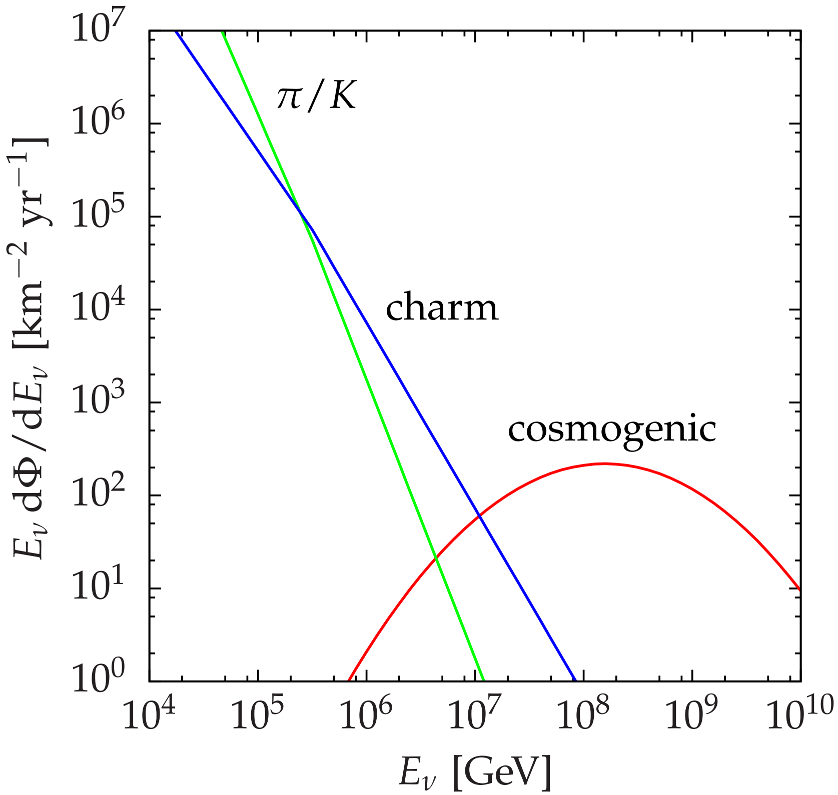
charm

$(\nu_e : \nu_\mu : \nu_\tau) = (48 : 48 : 2)$

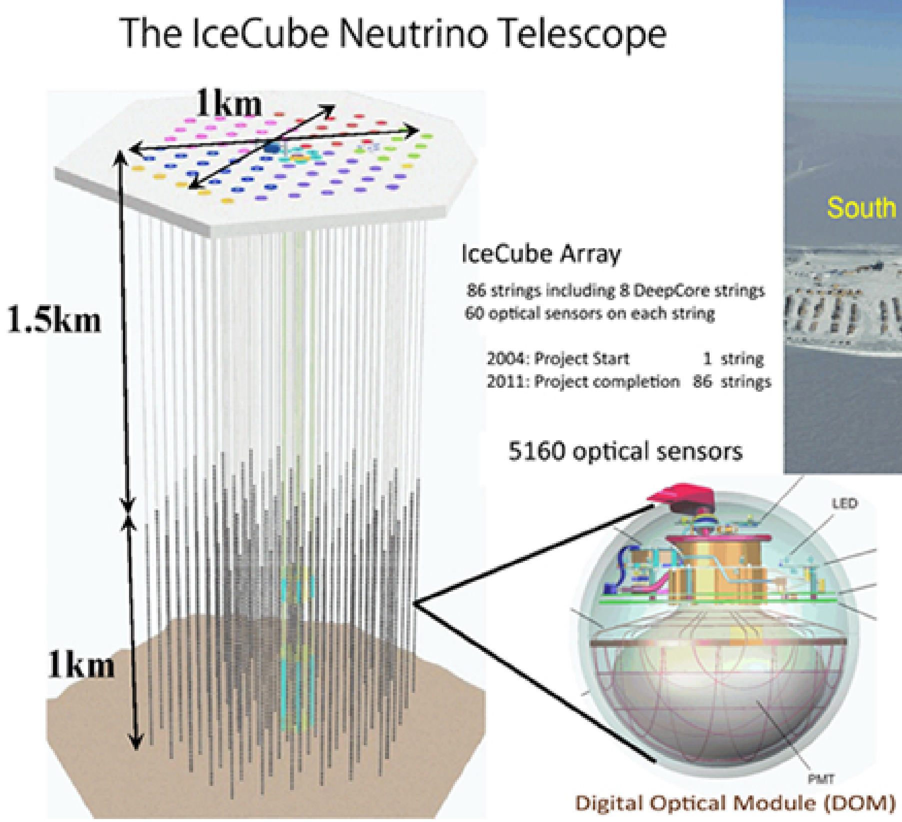
Neutrinos Cosmogenic (at ultrahigh energy)

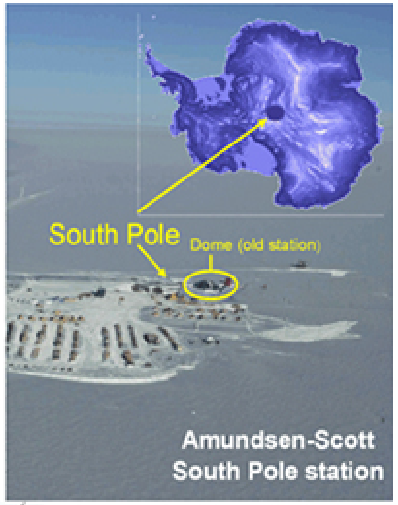
- We fit a cosmogenic flux to an average of several models compatible with the experiments in [1310.5477] and show it together with atmospheric fluxes below

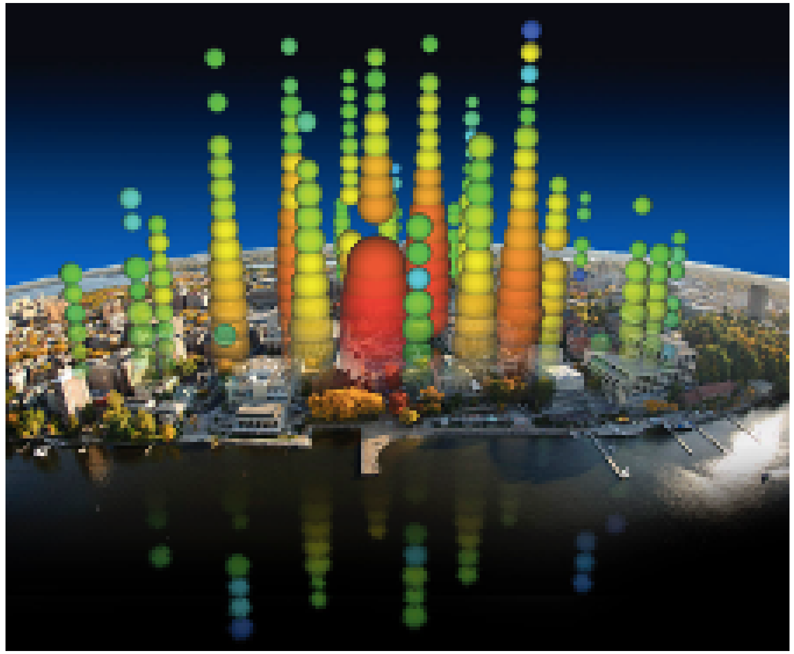




Neutrino Telescopes





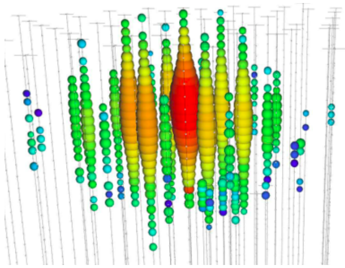


- The event rate is neutrino flavor (ν) and interaction (int) dependent:

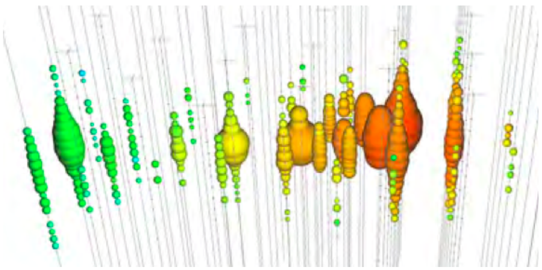
$$N_{\nu,\mathrm{int}} = T N_A \int \mathrm{d}\Omega \int_{E_{\mathrm{thres}}} \mathrm{d}E_\nu \, M_{\mathrm{eff}}^{\nu,\mathrm{int}}(E_\nu) \frac{\mathrm{d}\phi_\nu}{\mathrm{d}\Omega \mathrm{d}E_\nu} P_{\mathrm{surv}}^{\nu}(\theta_z, E_\nu) \int_{y_{\mathrm{min}}}^{y_{\mathrm{max}}} \mathrm{d}y \frac{\mathrm{d}\sigma_{\mathrm{int}}}{\mathrm{d}y}$$

$$\mathrm{d}\Omega = 2\pi \, \mathrm{d}\cos\theta_z \qquad\qquad y = 1 - E'/E_\nu \ \text{(inelasticity)}$$

- Two types of energy deposition



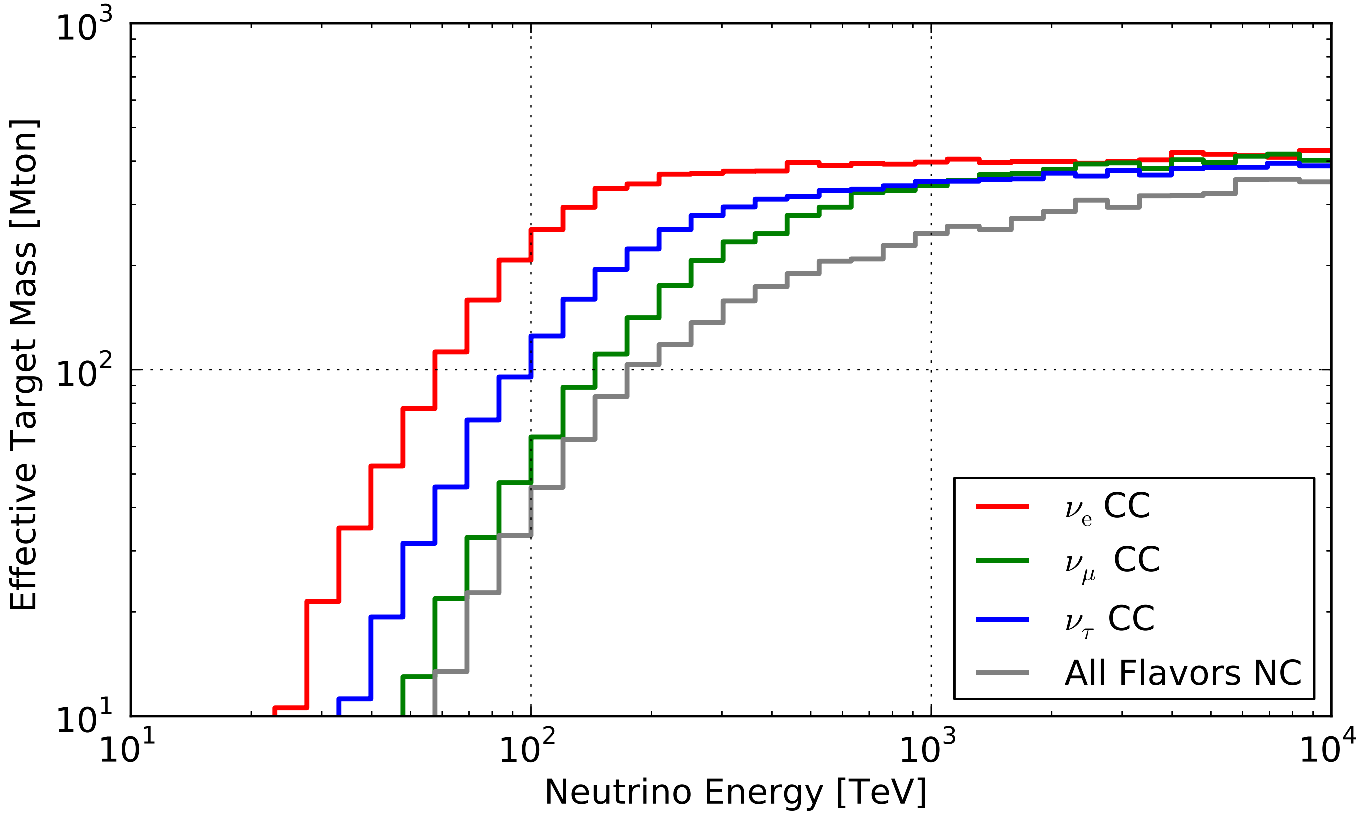
Showers (by electrons and hadrons)	
$N_{\nu_i,\text{NC}}$	$E_{\text{sh}} = yE_\nu$
$N_{\nu_e,\text{CC}}$	$E_{\text{sh}} = E_\nu$
$N_{\nu_\tau,\text{CC}-\text{had}}$	
$N_{\nu_\tau,\text{CC}-\text{electrons}}$	



Tracks (by muons)	
$N_{\nu_\mu,\text{CC}}$	$E_{\text{tr}} = yE_\nu$
$N_{\nu_\tau,\text{CC}-\text{muons}}$	

Neutrino | Telescopes | Effective IceCube mass

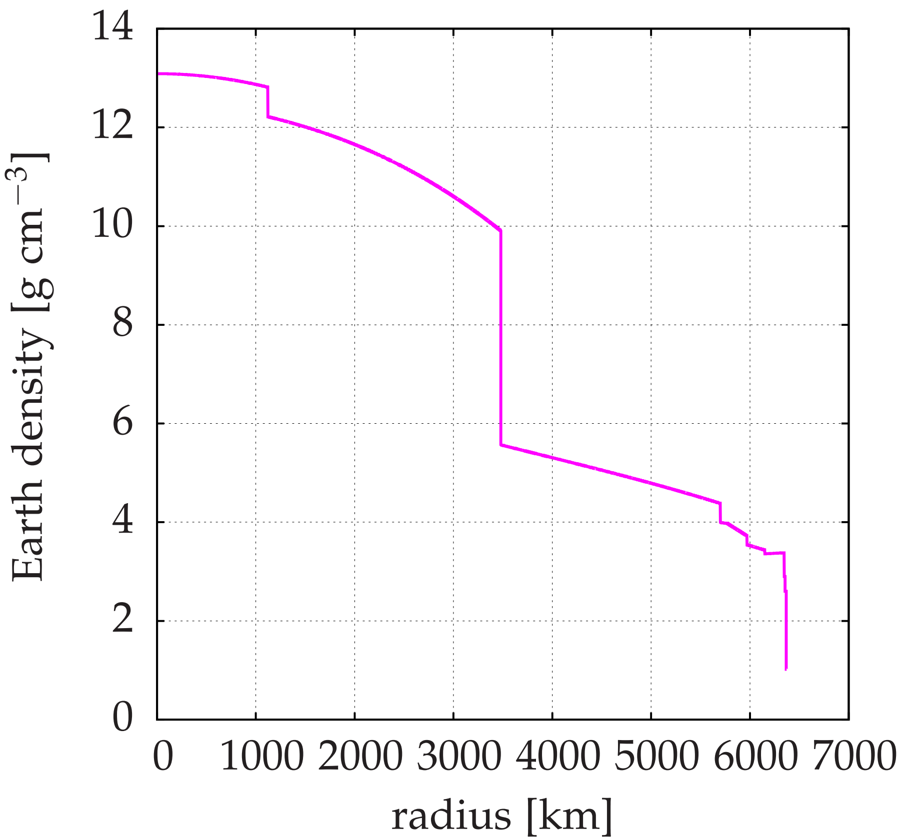
- The effective mass is interaction, flavor and energy dependent: [IceCube '14]

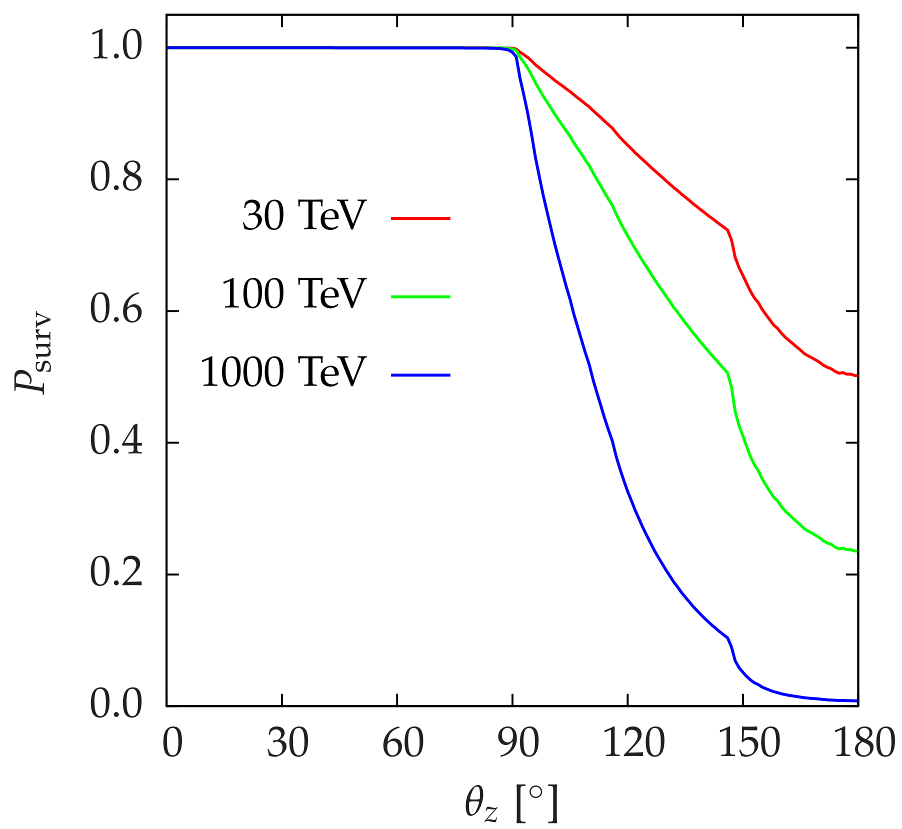


$\Rightarrow$ About 500 Mton, that is 0.5 km^3 of ice, at ultrahigh energy

- Neutrinos *stopped* by CC interactions

$$P^{\nu}_{\text{surv}}(\theta_z, E_\nu) = \exp\left\{-N_A\sigma(E_\nu)\int \rho_\oplus(\theta_z)\text{d}\ell\right\}\ , \quad \sigma = \sigma^{\text{CC}}_{\nu N}$$





Cosmic rays and neutrinos | Take home messages

- Cosmic ray interactions reach several orders of magnitude beyond the largest energies available at (even future) man made accelerators

- Neutrinos point back at their sources (neutrino astronomy!) whereas cosmic rays are bent by (inter)galactic magnetic fields

- Both are ideal laboratories to explore new physics at UHE

- Furthermore, standard neutrino interactions are weak so any new physics effect does not compete with the SM physics (TeV gravity, for instance), in contrast with the large hadronic cross sections of cosmic ray interactions

Take home messages

- Astroparticles are cool !!