Neutrino Astronomy / Astro-physics

teresa.montaruli@unige.ch

We covered:

- Measured CR spectrum
- Candidate Galactic and extra-galactic sources from energy balance between energy density of sources and injected in CRs
- Non-thermal spectra (power laws): Fermi mechanisms.

$$\gamma \sim \frac{P_{esc}}{\xi} = \frac{1}{\xi} \times \frac{T_{cycle}}{\tau_{esc}} \qquad E_k = E_0(1+\xi)^k \qquad \Delta E = \xi E$$

2 features:

1) The higher the energy of a particle (E_0) the slowest the acceleration process (the smaller is ξ)

2) E_{max} will depend on the maximum number of cycles $k_{max} = T_{shock}/T_{cycle}$: $E_{max} = k_{max} \xi \Delta E$

A shock wave looses its accelerating efficiency when the ejected mass = mass of the swept up in ISM or $\rho_{SN} = \rho_{ISM}$~1p/cm³ => E_{max}~ ZeβB ~ Z x 300 TeV

Then the Sedov phase (adiabatic shock deceleration) starts

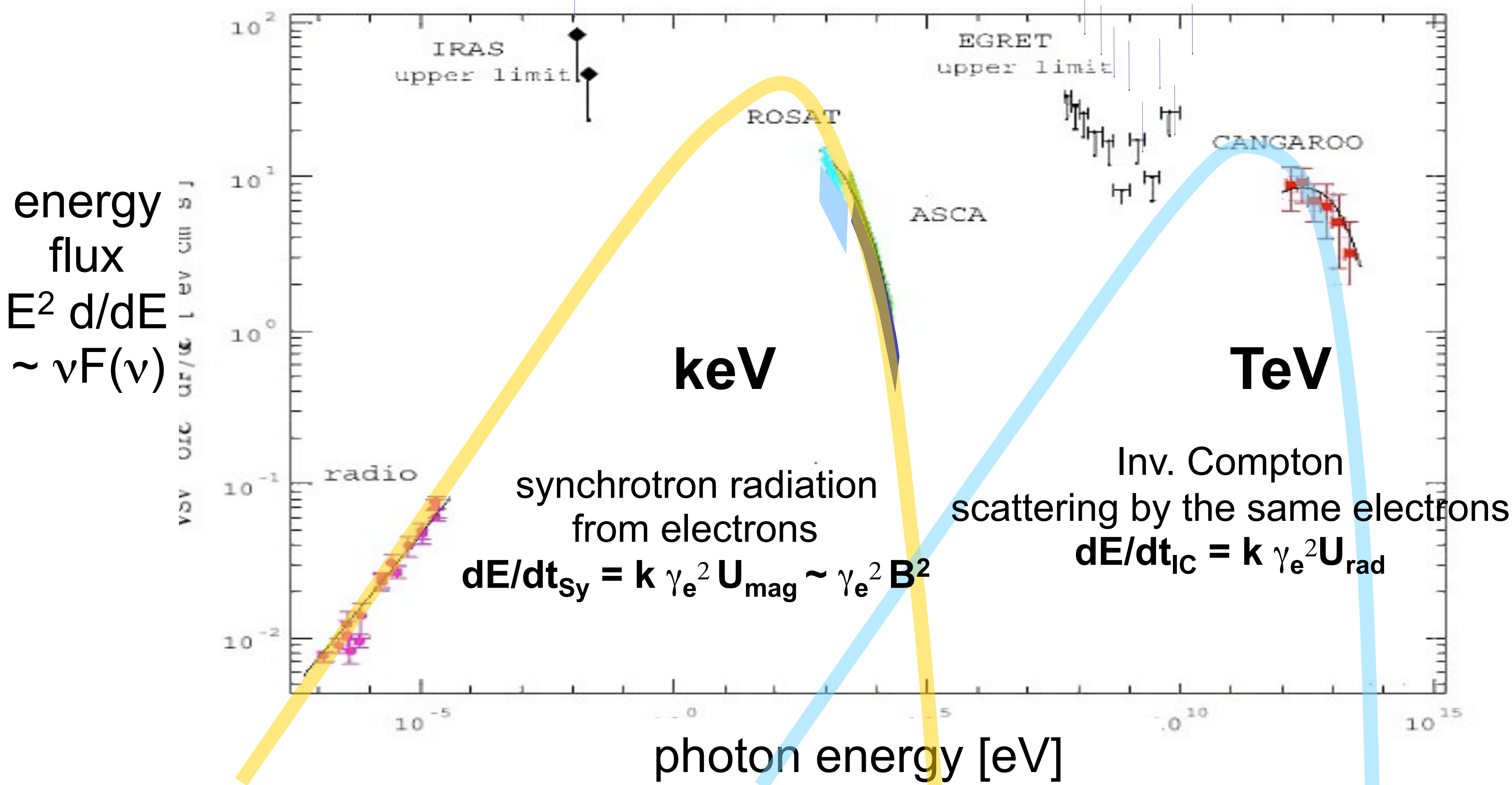
Neutrino Astronomy / Astro-physics

Today

- hadronic/leptonic processes
- Neutrino beam dumps: pp and p-gamma hadronic processes
- Flux of neutrinos and gammas from source injection proton spectrum
- Effective areas

MWL spectral emission distribution RXJ 1713.7-3946

$P_{sync}/P_{IC} = U_{mag}/U_{rad}$
in the Thompson regime



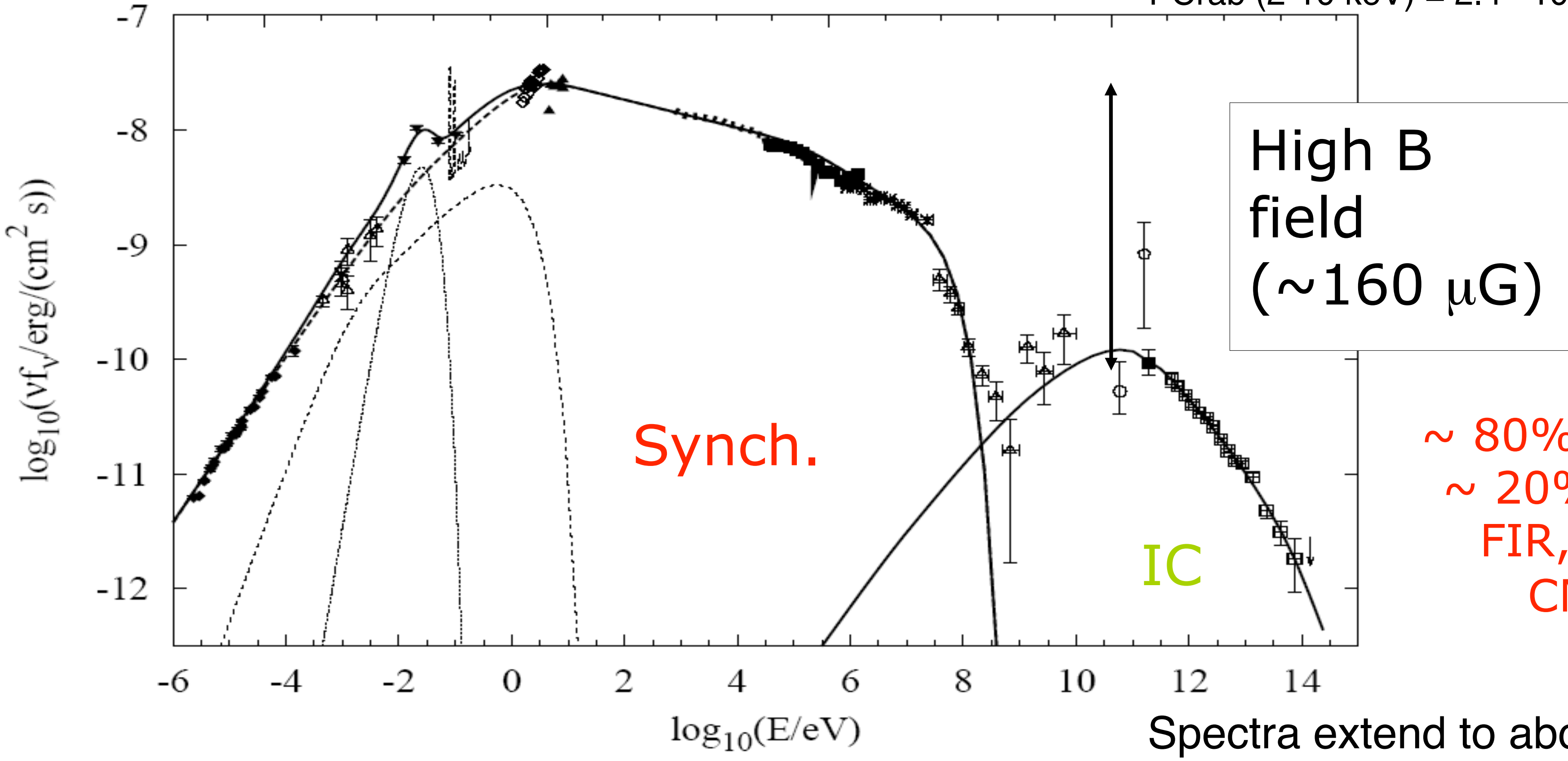
In leptonic processes: the **synchrotron luminosity** is proportional to the **B-field strength** and **Lorentz factor of electrons** radiating. **Inverse Compton:** in the rest frame of an electron the photon energy is boosted by γ_e and after scattering, transforming in the lab again, the photon energy is boosted by γ_e^2. The IC luminosity is also proportional to the energy density of seed photons which can be the synchrotron photons. Synchrotron cooling is faster than IC if B > 3 uG.

In hadronic processes, photons are produced via $\pi^0 \rightarrow \gamma\gamma$.

Crab Nebula multiwavelength spectrum

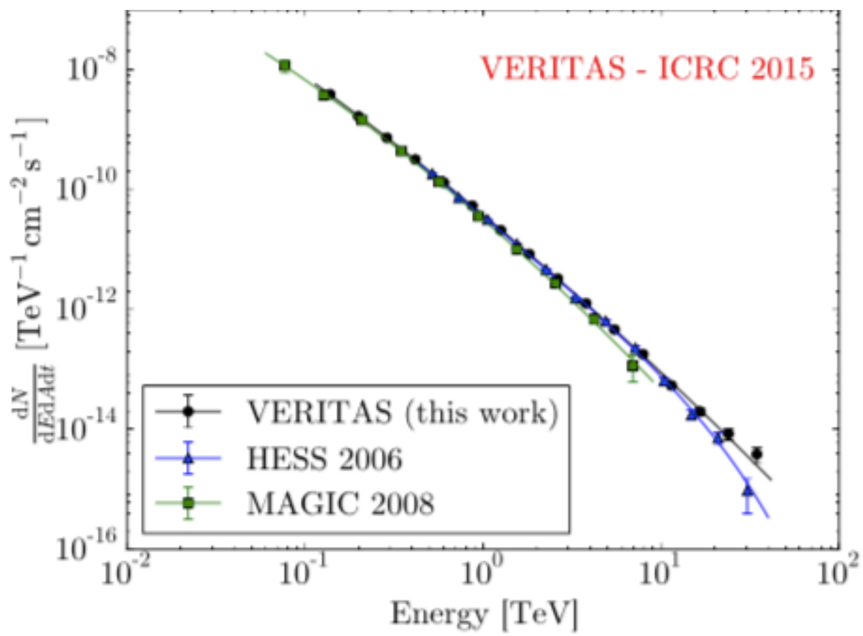
Aharonian et al. 2004

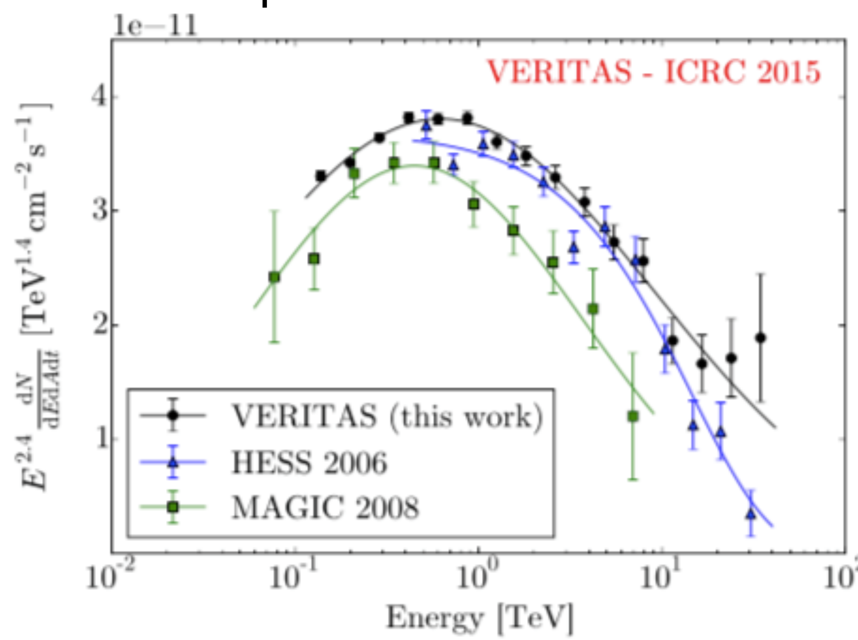
1 Crab (2-10 keV) = $2.4 \cdot 10^{-8}$ erg cm^{-2} s^{-1}



~ 80% SSC
~ 20% IC
FIR,mm,
CMB

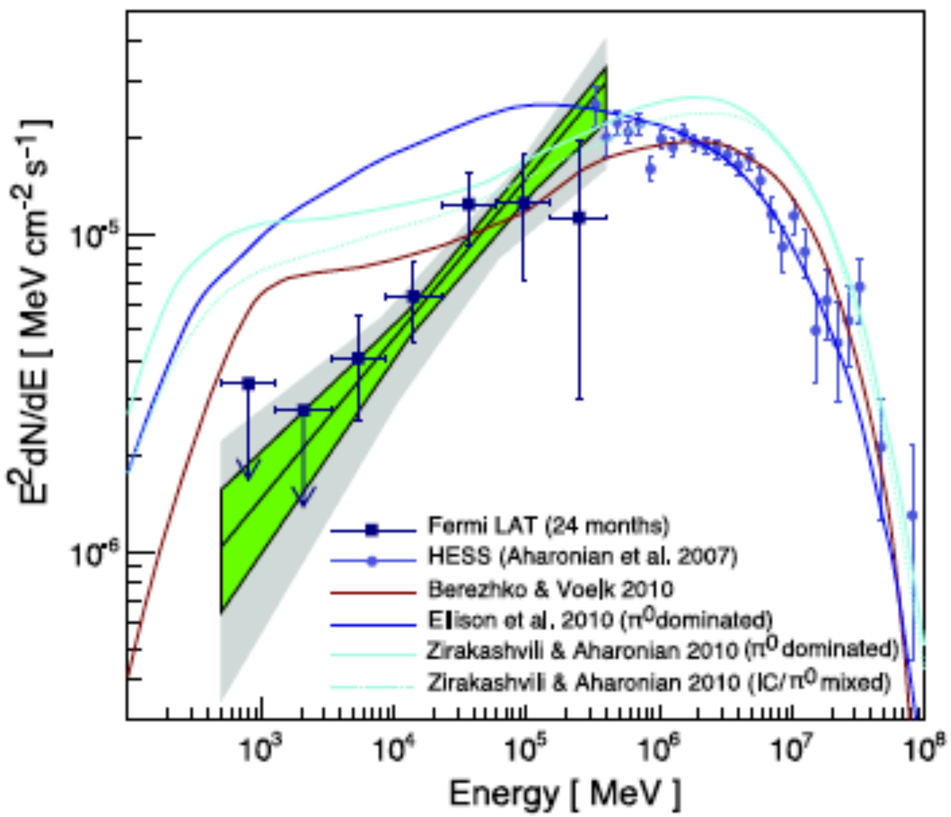
Spectra extend to about 40 TeV

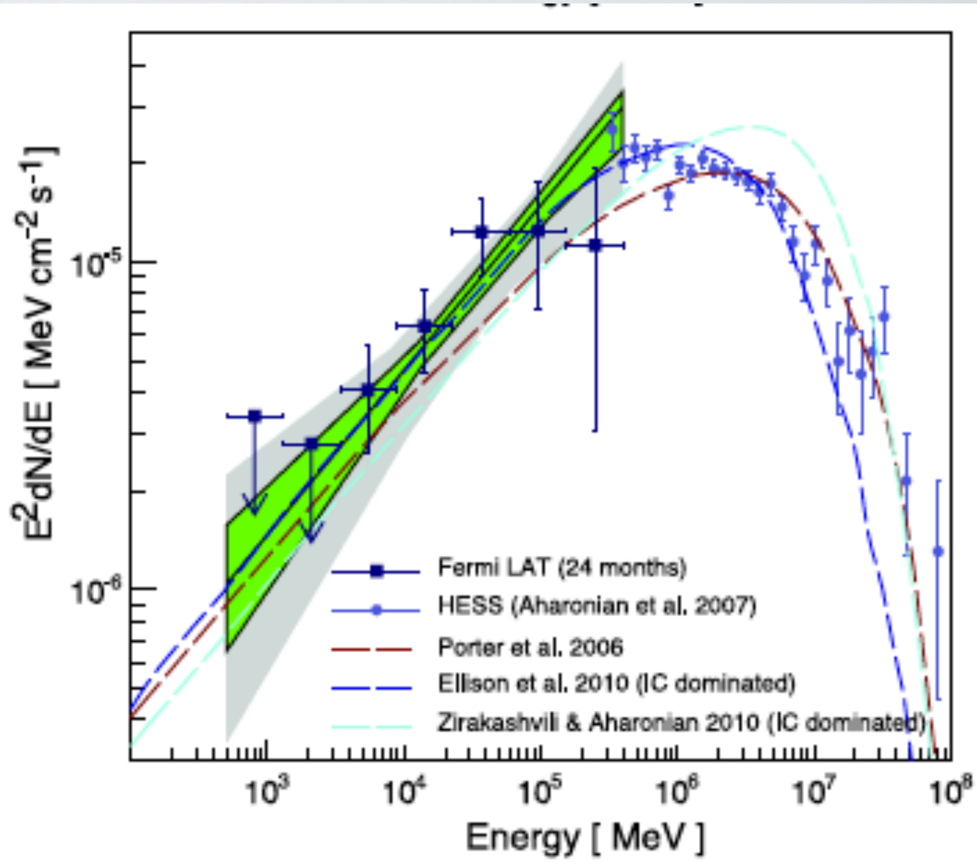




FERMI OBSERVATIONS OF RXJ 1713.7-3946

Aharonian et al., Nature, 432, 75 (2004) ;
Aharonian et al., A&A, 464, 235 (2007)



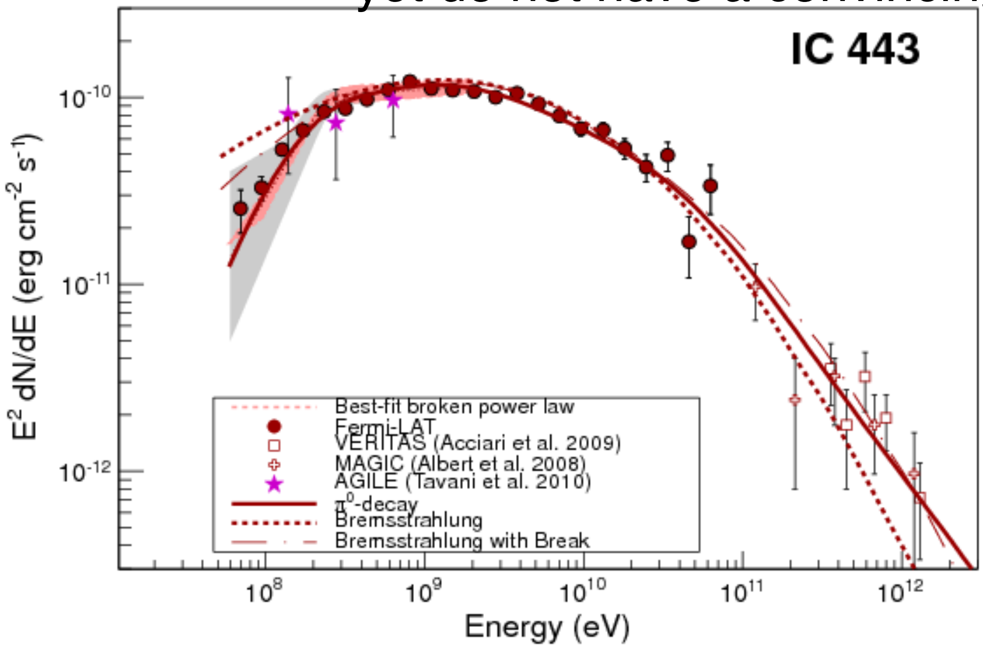


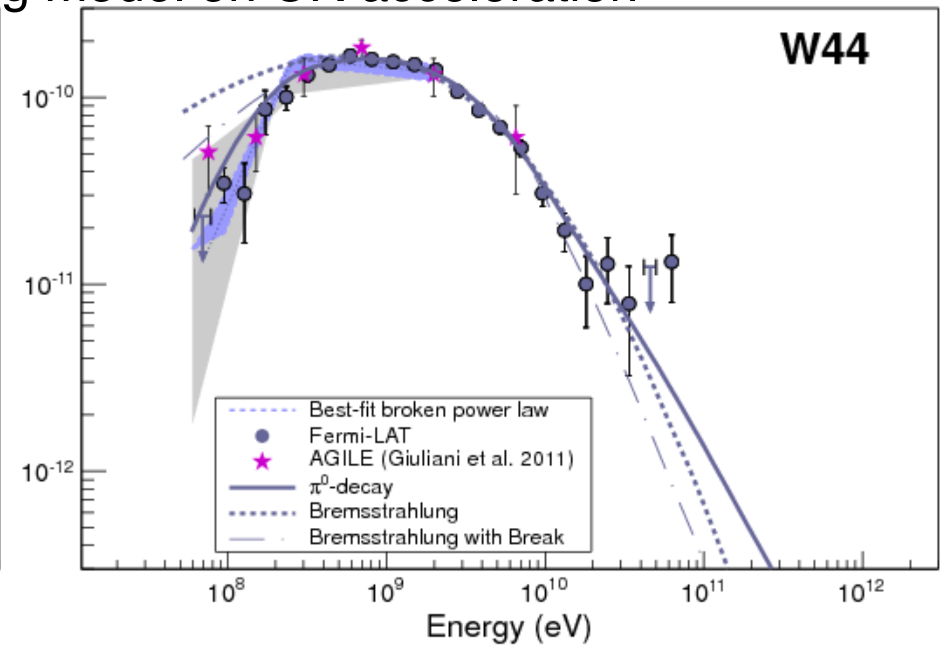
`The dominance of leptonic processes in explaining the gamma-ray emission does not mean that no protons are accelerated in this SNR, but that the ambient density is too low to produce a significant hadronic gamma-ray signal.' (arXiv:1103.5727).

SNR maybe efficient accelerators during short periods when the shock speed is high and they transit from the free expansion (ejecta dominated phase) to the Sedov phase (adiabatic deceleration).
Eg. Bell & Lucek, 2001

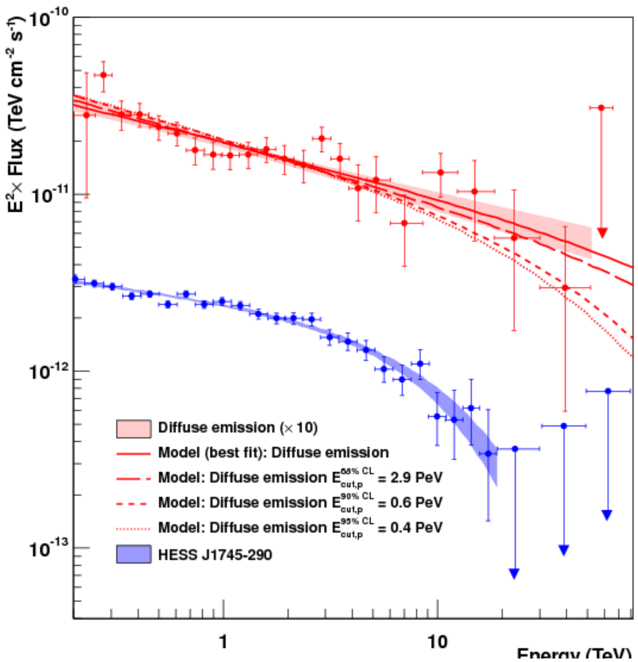
EVIDENCE FOR PION DECAY?

Fermi identified various candidates for pionic gammas but yet did not verify that what we yet do not have a convincing model on CR acceleration





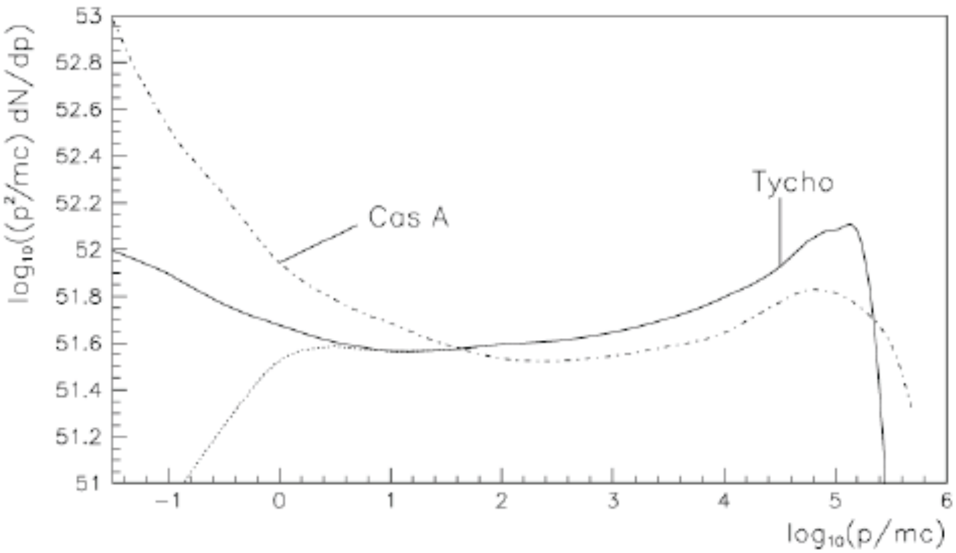
Ackermann et al. (Fermi Collaboration), Science, 339, 807 (2013)



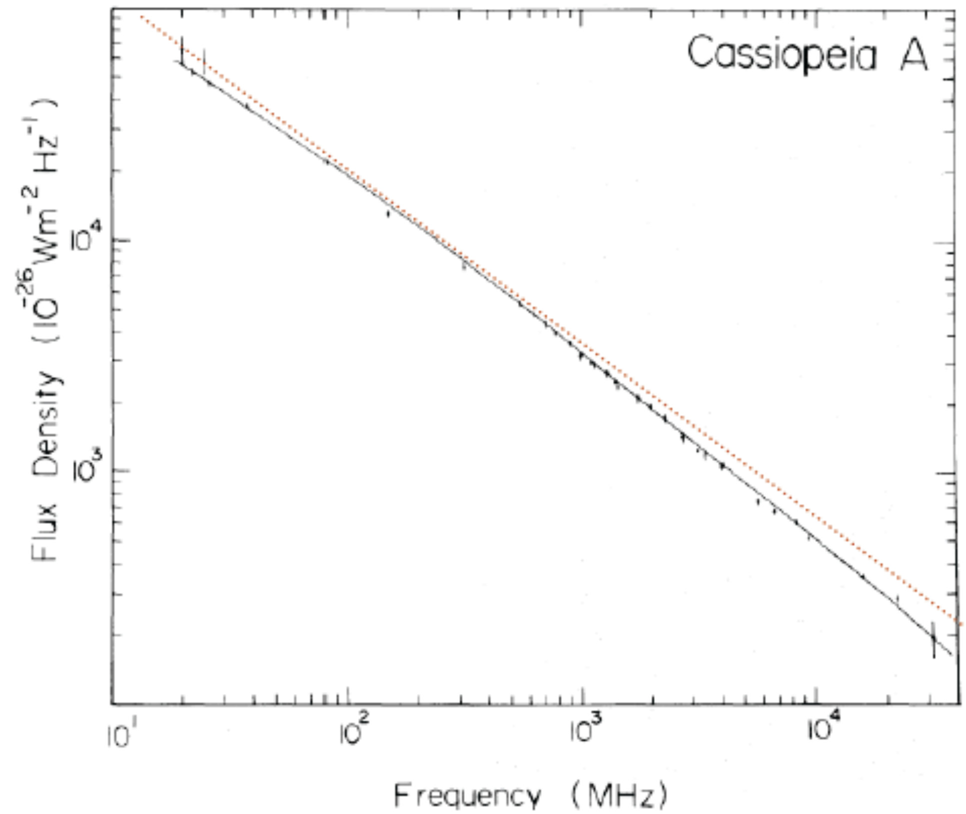
Recent news: the First PeVatron from Galactic Centre with 10 yrs of HESS data

Nature 531 (2016) 476 (https://inspirehep.net/record/1434943)

Efficient diffusive shock acceleration should give a *concave* spectrum (due to feedback on the shock by cosmic ray pressure)



(Voelk *et al*, A&A396:649,2002)



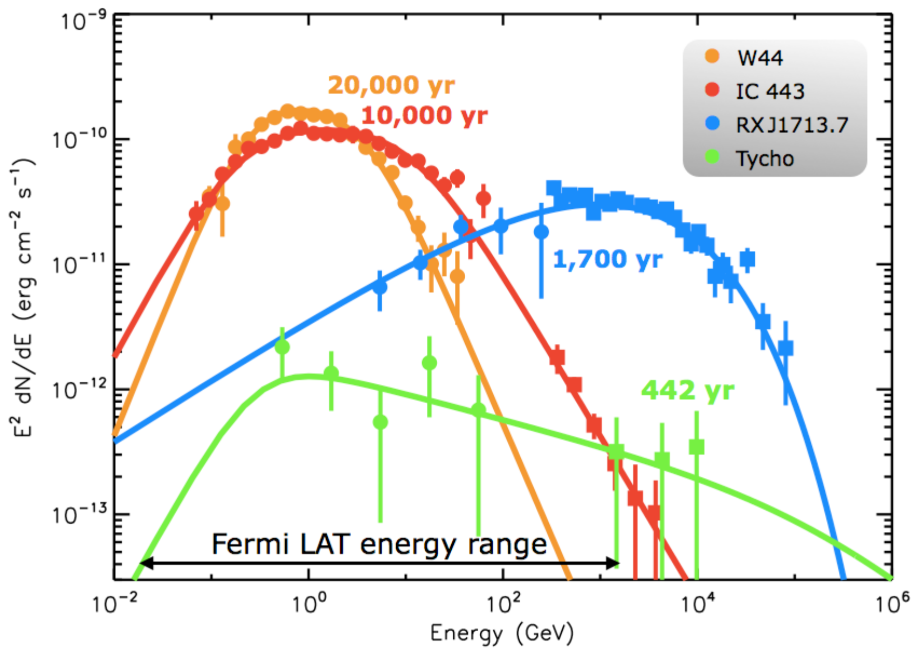
but the synchrotron radio spectrum of this young SNR is a *convex* power-law

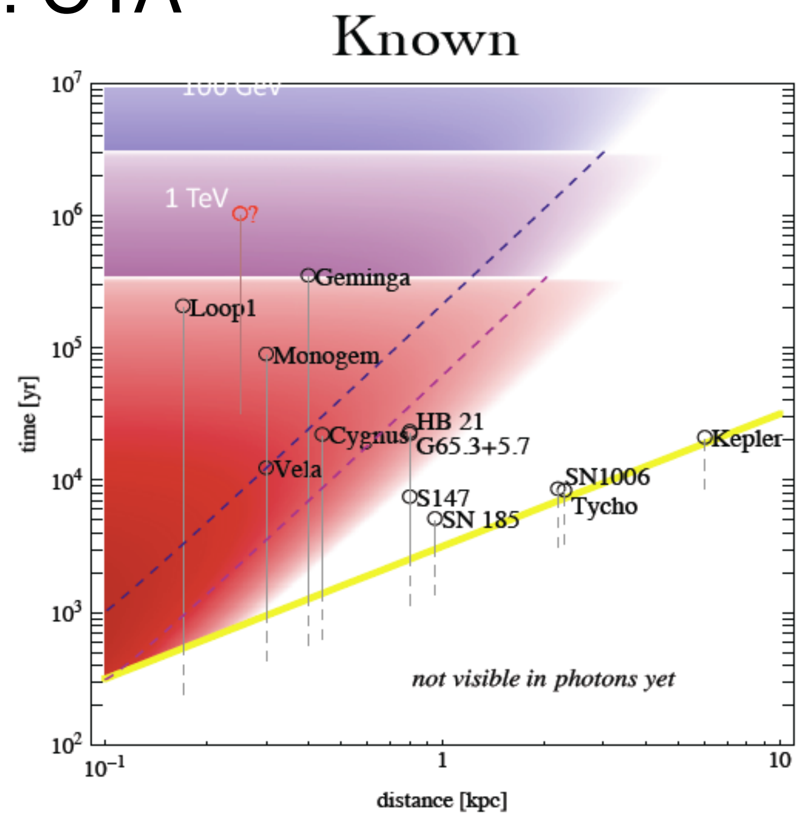
… well-fitted by log-normal spectrum expected from **2nd order** Fermi acceleration by MHD turbulence *behind* the shock wave (Cowsik & Sarkar, MNRAS:207:745,1984)

Evolution of gamma-ray properties with age

Gamma-ray properties evolve with SNR age and when the shock acceleration is very efficient photons may be not visible

We need more source statistics! CTA

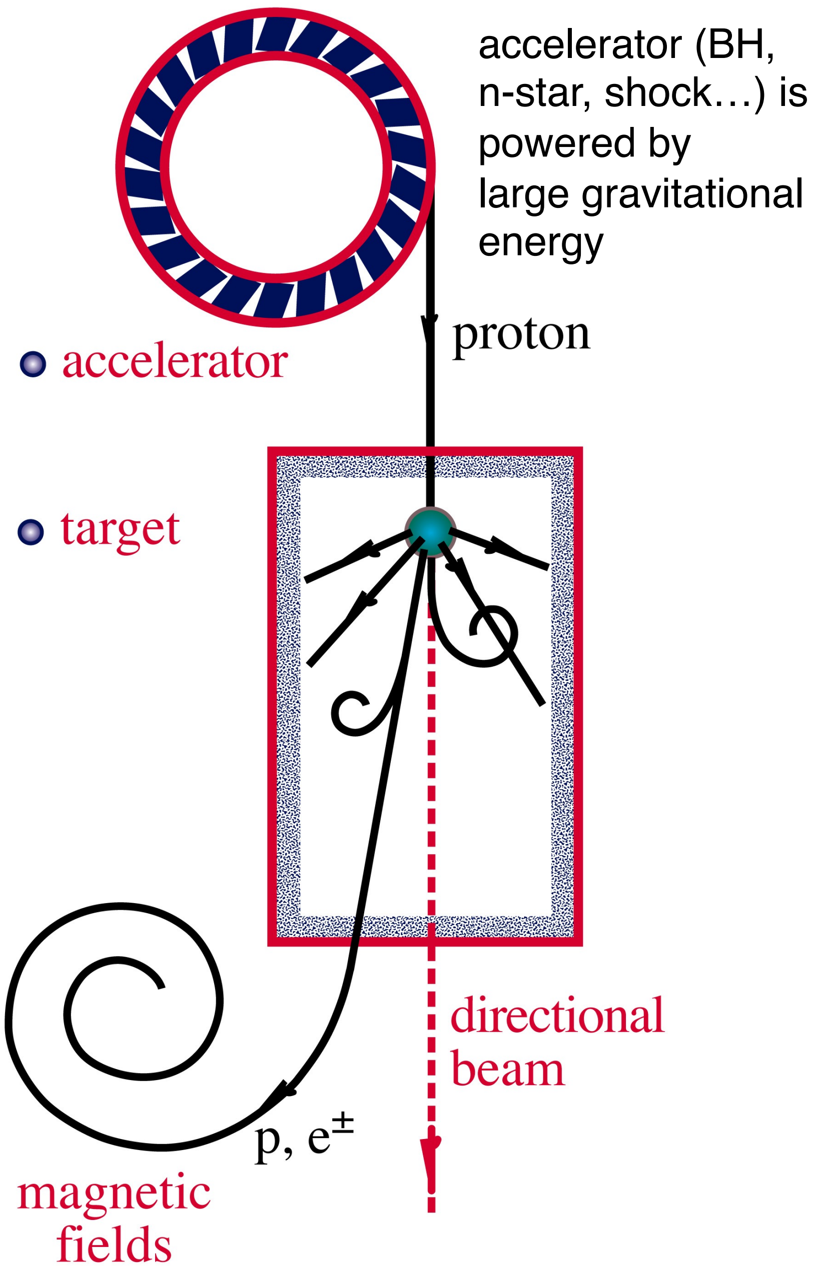




Ahlers, Mertsch & Sarkar,PRD80:123017,2009

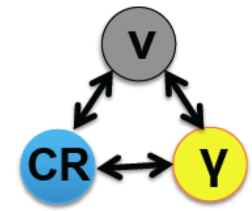
The general model for neutrino - gamma -CR sources

ν and γ beam dumps



Hadronuclear (e.g. star burst galaxies and galaxy clusters)

$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\,\gamma \\ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu \\ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \bar{\nu}_\mu \nu_\mu \end{cases}$$



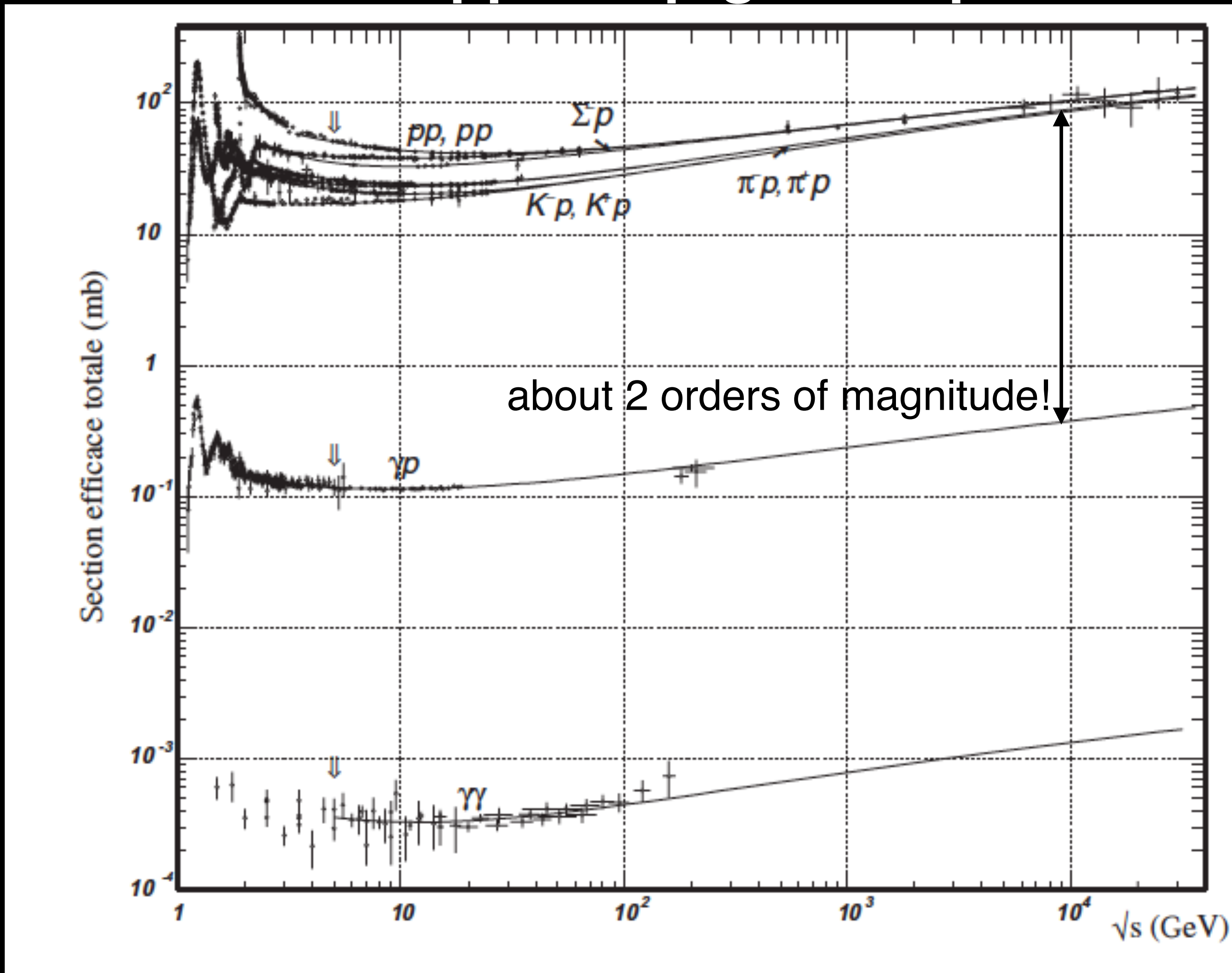
Photohadronic (e.g. gamma-ray bursts, active galactic nuclei)

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\,\pi^0 \rightarrow p\,\gamma\,\gamma \\ n\,\pi^+ \rightarrow n\,\mu^+ \nu_\mu \rightarrow n\,e^+ \nu_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

cosmic ray + gamma

cosmic ray + neutrinos

pp and p-gamma processes



In astrophysical environments, the density of photons is typically much larger than that of protons, unless there are residual masses from explosions (SNRs) or an accelerator with a molecular clouds and large rate of star formation (starbursts). Hence, even if the cross section for pp interaction is about 2 orders of magnitude larger than that of pγ, this last may dominate.

Reminder: Reaction thresholds

m_p, p_p $\longrightarrow$ $\longleftarrow$ m_t, p_t

$s = E_{cm}^2$ $c = 1$

$$t + p \rightarrow M_1 + M_2 + \ldots M_n$$

$$\sqrt{s}_{th} = \sum_f M_f = \sqrt{E_{tot}^2 - |\mathbf{p}_{tot}|^2}$$

The threshold of a reaction corresponds to the energy to produce all final states at rest.

Remember also that from the invariance of total 4-momentum squared in the CM and Lab frame:

total energies in the lab

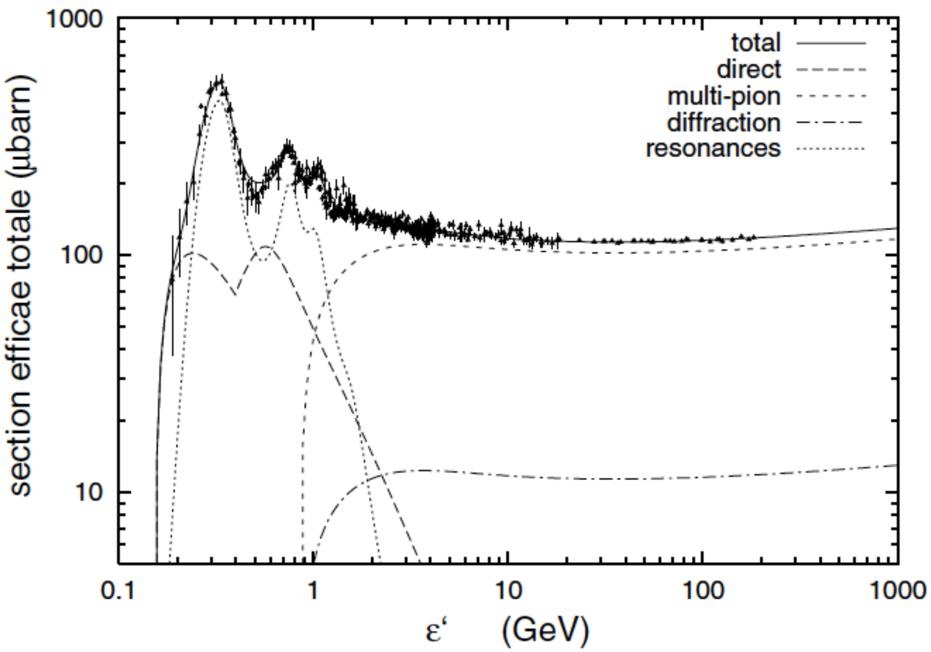
$$\sqrt{s} = \sqrt{(E_p + E_t)^2 - (\vec{p_p} + \vec{p_t})^2} = \sqrt{m_p^2 + m_t^2 + 2E_pE_t(1 - \beta_p\beta_t \cos\theta)}$$

At threshold and in the lab frame (the p rest-frame):

$$\sqrt{s_{th}} = \sqrt{m_p^2 + m_t^2 + 2E_pm_t} = \sum_f M_f \qquad m_p^2 + m_t^2 + 2(E_{k,p} + m_p)m_t = (\sum_f M_f)^2$$

$$E_{k,p} = \frac{(\sum_f M_f)^2 - (m_p + m_t)^2}{2m_p}$$

p-gamma



Direct photo-production of pions:

eg. $p + \gamma \rightarrow p + \pi^0$

$\sqrt{s_{th}} = m_p + m_\pi$ = 1.08 GeV

Energy of the photon in the lab:

$$\epsilon = \frac{m_\pi(m_\pi + 2m_p)}{2m_p} \sim 150\text{MeV}$$

For delta-resonance Δ(1232) it is larger:

$$\epsilon = \frac{m_\Delta^2 - m_p^2}{2m_p} \sim 340\text{MeV}$$

If the proton is at rest ($E_p = m_p$), ϵ= 340 MeV in the lab

Hence in the CM: $E'_p = \gamma_p m_p$ and the photon energy is : $\epsilon' = \gamma_p \frac{m_\Delta^2 - m_p^2}{2m_p} = \gamma_p^2 \frac{m_\Delta^2 - m_p^2}{2E'_p}$

Hence the accelerated proton must have a threshold energy in the CM frame of:

$$E'_p = \gamma_p^2 \frac{m_\Delta^2 - m_p^2}{2\epsilon'} \sim \gamma_p^2 \times 300GeV \times \left(\frac{1\text{MeV}}{\epsilon'}\right)$$

p-p

$$p + p \rightarrow \pi^+ : \pi^- : \pi^0$$

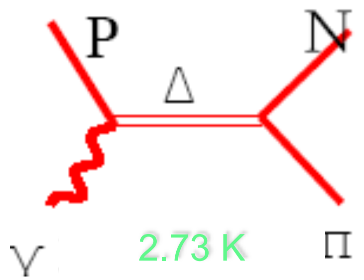
In the lab

$$E_{p,th} = \frac{(2m_p + m_\pi)^2 - 2m_p^2}{2m_p} \sim 1.23 \text{ GeV}$$

In the CM: $E_{p,th}$ = Y x 1.23 GeV

The end of the CR spectrum: GZK cut-off

[Greisen 66; Zatsepin & Kuzmin66]



$$\gamma + p \rightarrow \Delta^+ \rightarrow p + \pi^0$$

$$\gamma + p \rightarrow \Delta^+ \rightarrow n + \pi^+$$

$3k_BT$ effective energy for Planck spectrum of CMB

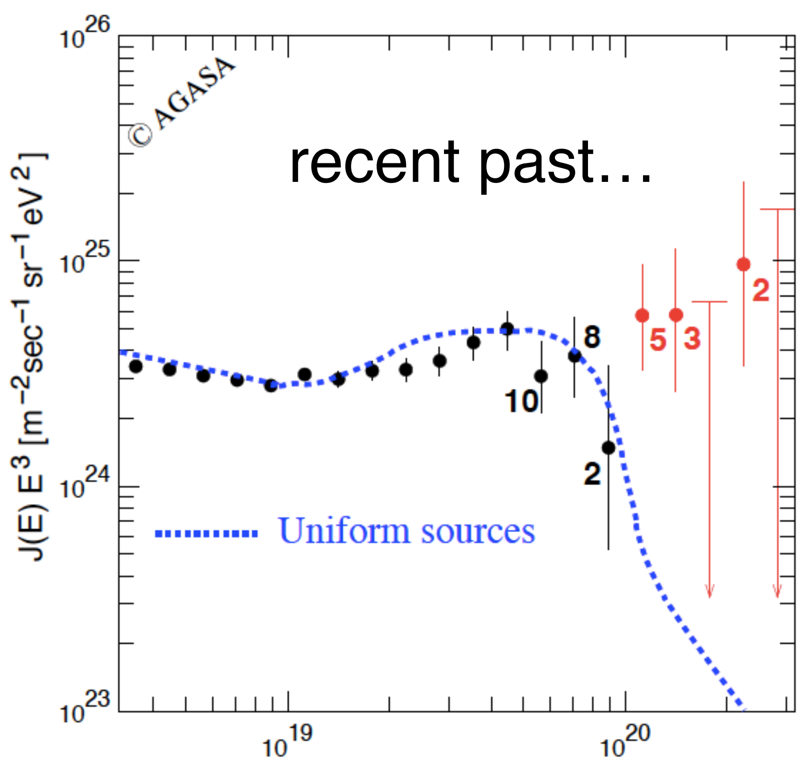
$$\epsilon' = 3k_BT = 4 \times 2.73 \times 8.62 \times 10^{-5} eV$$

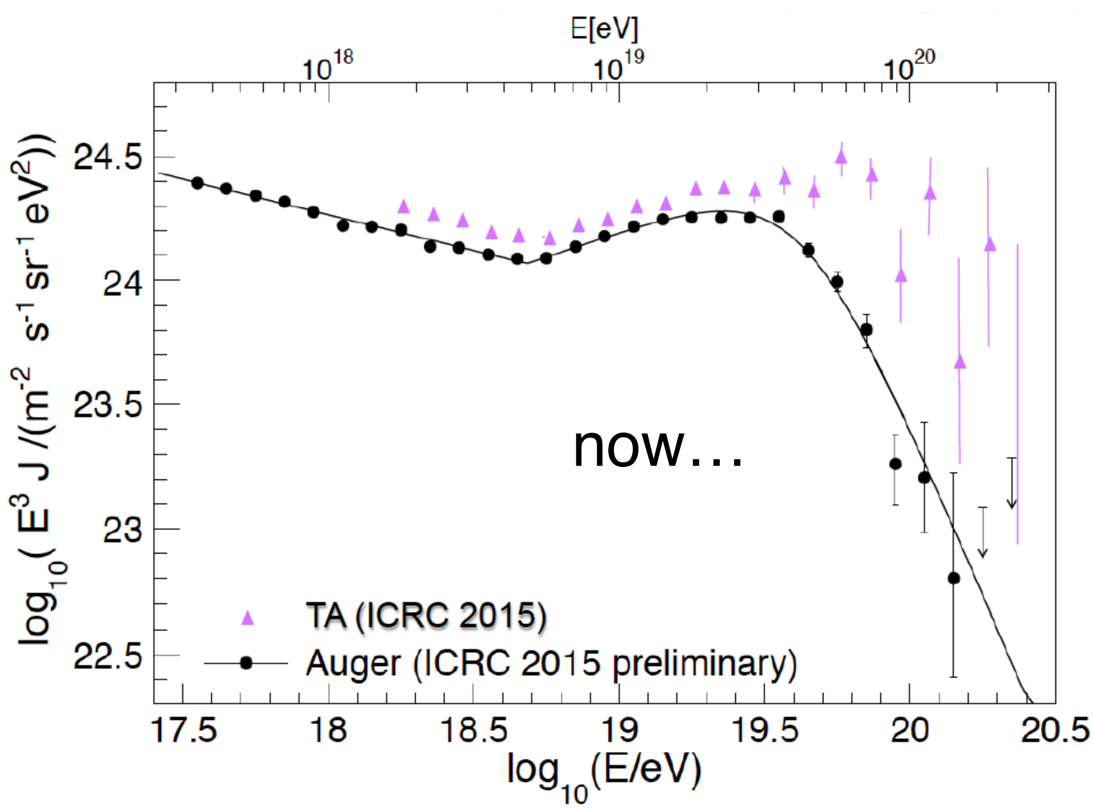
$$\epsilon = \frac{m_\Delta^2 - m_p^2}{2m_p} \sim 340\mathrm{MeV}$$

$$\gamma_p = \frac{\epsilon'}{\epsilon} = 2 \cdot 10^{11}$$

⇒Hence the threshold energy of the proton in the CM is $E'_p \sim \gamma_p\, m_p = 2 \cdot 10^{20}$ eV

Integrating over Planck spectrum $E_{p,th} \sim 5 \cdot 10^{19}$ eV





Assumption on average energy fractions

$$x_\nu = \frac{E_\nu}{E_p} = \frac{1}{4} < x_F > = \frac{1}{20}$$

0.2

$$x_\gamma = \frac{E_\gamma}{E_p} = \frac{1}{2} < x_F > = \frac{1}{10}$$

$$dE_{\nu,\gamma} = x_{\nu,\gamma} dE_p$$

Kelner & Aharonian
http://arxiv.org/pdf/astro-ph/0606058.pdf

https://inspirehep.net/record/718405

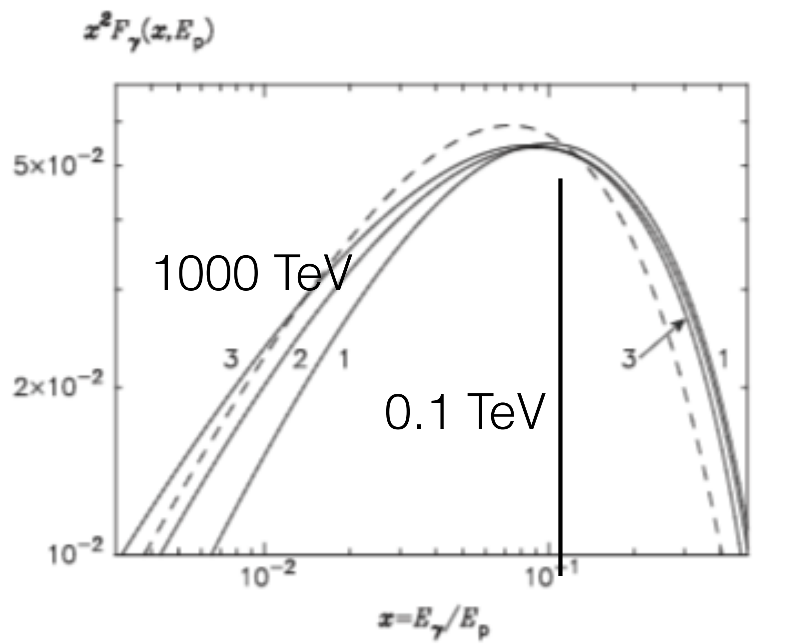


Figure 7: Energy spectra of gamma-rays described by Eq.(58) for three energies of incident protons: 0.1 TeV (curve 1), 100 TeV (curve 2) and 1000 TeV (curve 3). The dashed curve corresponds to the Hillas parameterization of the spectra obtained for proton energies of several tens of TeV.

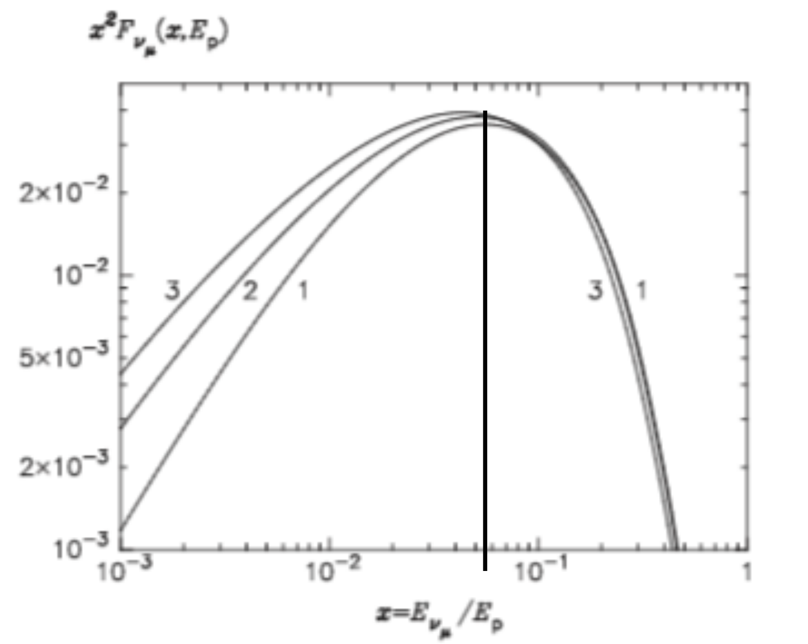


Figure 9: Energy spectra of all muonic neutrinos described by Eq.(62) and (66) for three energies of incident protons: 0.1 TeV (curve 1), 100 TeV (curve 2) and 1000 TeV (curve 3).

Two Body Decay Kinematics

Each neutrino takes about 1/4 of the pion energy (on average)

In the Lab (pion at rest)

"Neutrino massless" means $E_\nu = p_\nu$. Therefore the energy and momentum conservation yield

$$m_\pi = \sqrt{p_\mu^2 + m_\mu^2} + E_\nu, \tag{23}$$

$$0 = \mathbf{p}_\mu + \mathbf{p}_\nu. \tag{24}$$

Through Equation (24), $p_\mu^2 = E_\nu^2$. Isolating the root square in Equation (23) and squaring gives

$$(m_\pi - E_\nu)^2 = E_\nu^2 + m_\mu^2$$
$$\Rightarrow m_\pi^2 + \cancel{E_\nu^2} - 2m_\pi E_\nu = \cancel{E_\nu^2} + m_\mu^2,$$

therefore, with $m_\pi = 139.6$ MeV and $m_\mu = 105.7$ MeV,

$$\Rightarrow E_\nu = p_\nu = p_\mu = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} = 29.7839183 \simeq 29.8 \text{ MeV (in natural units).} \tag{25}$$

Three Body Decay Kinematics

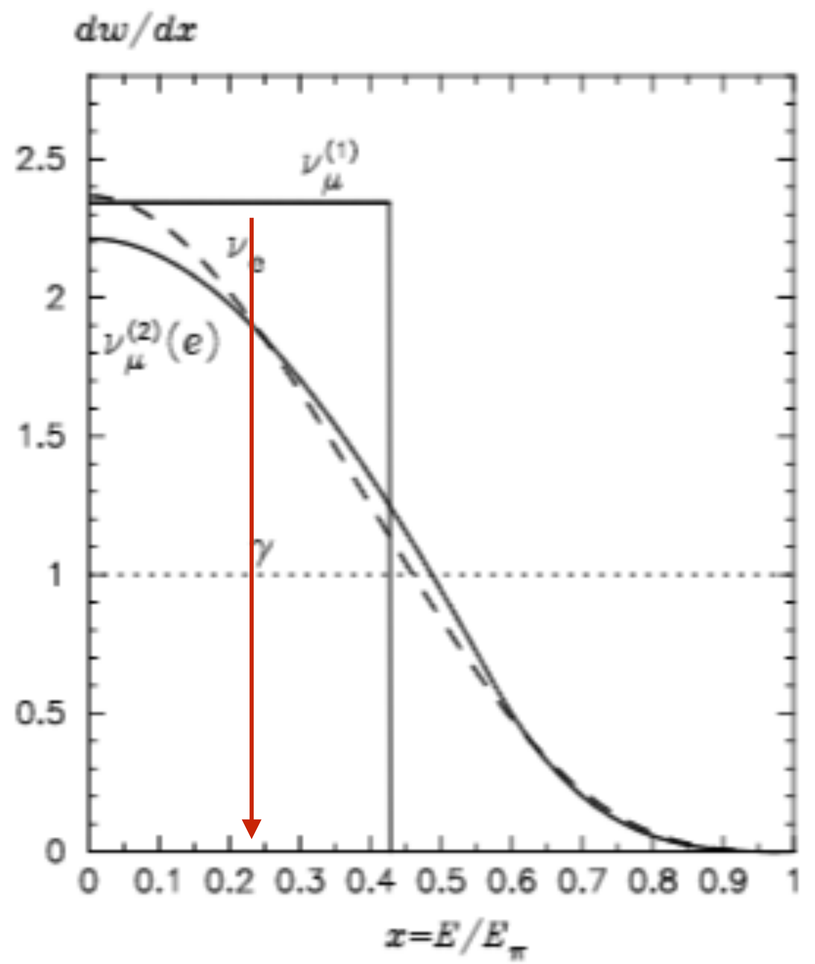


Figure 4: Energy distributions of the secondary products (photons, electrons, muonic and electronic neutrinos) of decays of monoenergetic ultrarelativistic neutral and charged pions. All distributions are normalized, $\int_0^1 dw = 1$.

In the LAB and for $E_\pi >> m_\pi$

(mass of electrons/neutrinos neglected)

$$E_{\nu,\max} = \frac{1}{m_\pi}\left(E_\pi E_\nu^0 + p_\pi p_\nu^0\right) \approx \lambda E_\pi ,$$

where

$$\lambda = 1 - m_\mu^2/m_\pi^2 = 0.427 .$$

p-gamma

On average 1/3 of the p energy goes into pions

$$p + \gamma \to \Delta^+ \to p + \pi^0 \quad 2/3$$

$$p + \gamma \to \Delta^+ \to n + \pi^+ \quad 1/3$$

branching ratios

	$p\pi^+$	$p\pi^0$	$p\pi^-$	$n\pi^+$	$n\pi^0$	$n\pi^-$
Δ^{++}	1					
Δ^+		2/3		1/3		
Δ^0			1/3		2/3	
Δ^-						1

$$\pi^0 \to \gamma + \gamma$$

½ of pion energy goes into each photon

$$\pi^+ \to \mu^+ + \nu_\mu \to (e^+ \nu_e \bar{\nu}_\mu) + \nu_\mu$$

On average 1/4 of the pion energy goes into each neutrino

Assuming : $\frac{dN_p}{dE_p} \propto E_p^{-2}$ => $\frac{dN_p}{dE_p} \propto E_p^{-2} = E_\nu^{-2} x_\nu^2$ and

Since : $\frac{E_\nu}{E_p} = x_\nu \sim \frac{1}{20}$ => $dE_p = x_\nu^{-1} dE_\nu$

multiplicity and BR

$$\frac{dN_\gamma}{dE_\gamma} \propto 2 \times \frac{2}{3} E_\gamma^{-2} \frac{1}{x_\gamma} \frac{dN_p}{dE_p} = 2 \times \frac{2}{3} E_\gamma^{-2} x_\gamma = 2 \times \frac{2}{3} \frac{1}{10} E_\gamma^{-2}$$

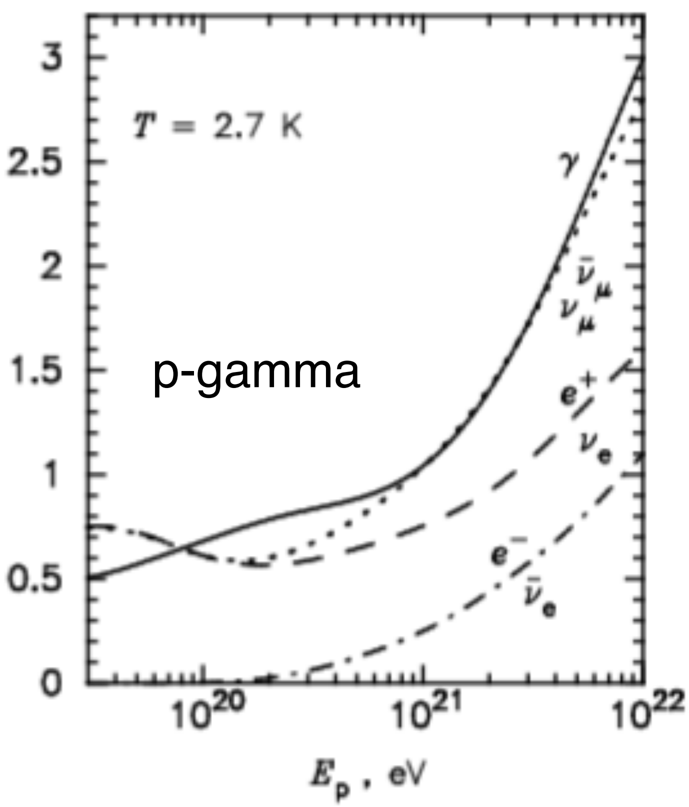
$$\frac{dN_\nu}{dE_\nu} \propto 2 \times \frac{1}{3} E_\nu^{-2} \frac{1}{x_\nu} \frac{dN_p}{dE_p} = 2 \times \frac{1}{3} E_\nu^{-2} x_\nu = 2 \times \frac{1}{3} \frac{1}{20} E_\nu^{-2}$$

=>

$$\frac{dN_\nu}{dE} = \frac{1}{4} \frac{dN_\gamma}{dE}$$

Multiplicities

multiplicities from SOPHIA MC



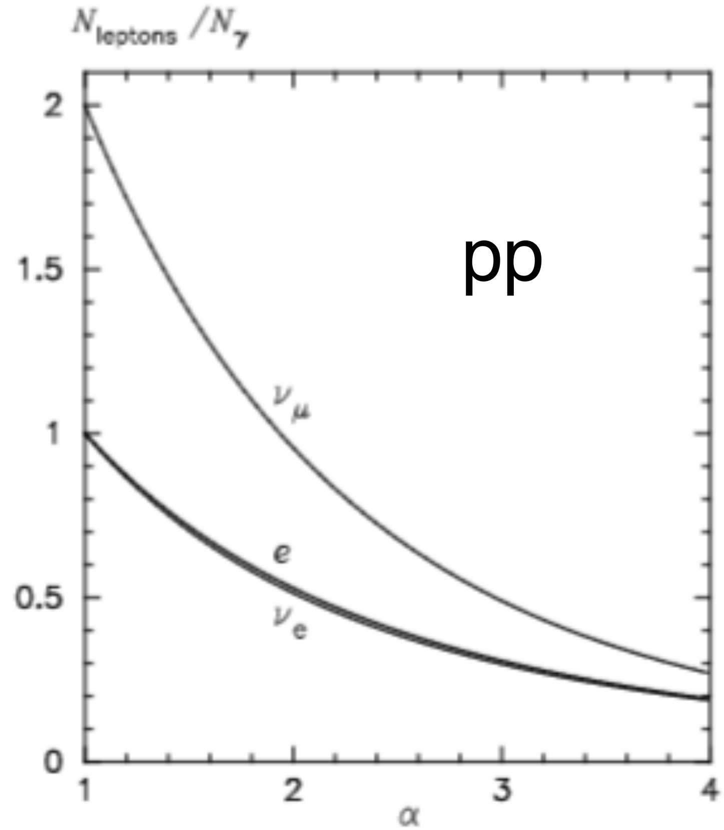


Figure 5: The ratio of the number of leptons to photons of same energy for power-law distributions of pions with spectral index α. It is assumed that π^0, π^+ and π^- have identical distributions.

Kelner & Aharonian

https://inspirehep.net/record/718405

Galactic SNR and pp

In Galactic SN shocks CRs interact with the H in the Galactic disk (pp interactions, lower threshold than p-gamma)

$$p + p \to \pi^+ : \pi^- : \pi^0$$

$$E_{p,th} = \frac{(2m_p + m_\pi)^2 - 2m_p^2}{2m_p} \sim 1.23 \text{ GeV}$$

if all muons decay and for E^{-2} p spectrum:

2 pions x 1/3 of energy to each pion

$$\frac{dN_\nu}{dE} \sim 2 \times \frac{2}{3} \times \frac{1}{20}$$

$$\frac{dN_\gamma}{dE} \sim 2 \times \frac{1}{3} \times \frac{1}{10}$$

Assume always:

$$x_\nu = \frac{E_\nu}{E_p} = \frac{1}{4} < x_F >= \frac{1}{20}$$

0.2

$$x_\gamma = \frac{E_\gamma}{E_p} = \frac{1}{2} < x_F >= \frac{1}{10}$$

Ignoring oscillations there is a factor of about 1 between the gamma and neutrino flux.

For a full calculation see: http://arxiv.org/pdf/astro-ph/0606058for pp

Gamma-neutrino connection at source (before oscillations)

$$\frac{dN_\nu}{dE} = \frac{dN_\gamma}{dE} \,\mathrm{for\, p-p}$$

$$\frac{dN_\nu}{dE} = \frac{1}{4}\frac{dN_\gamma}{dE} \,\mathrm{for\, p}-\gamma$$

What happens during propagation of messengers to us?

Oscillations in 3 families

oscillation probability in 3 families (E. Lisi's lectures)

$$P(\nu_\alpha \to \nu_\beta) = \sum_i |U_{\alpha,i}|^2 |U_{\beta,i}|^2 + 2\sum_{i<j} U_{\alpha,i} U_{\beta,i} U_{\alpha,j} U_{\beta,j} \cos\left(\frac{\Delta m^2_{ij} L}{2E}\right).$$

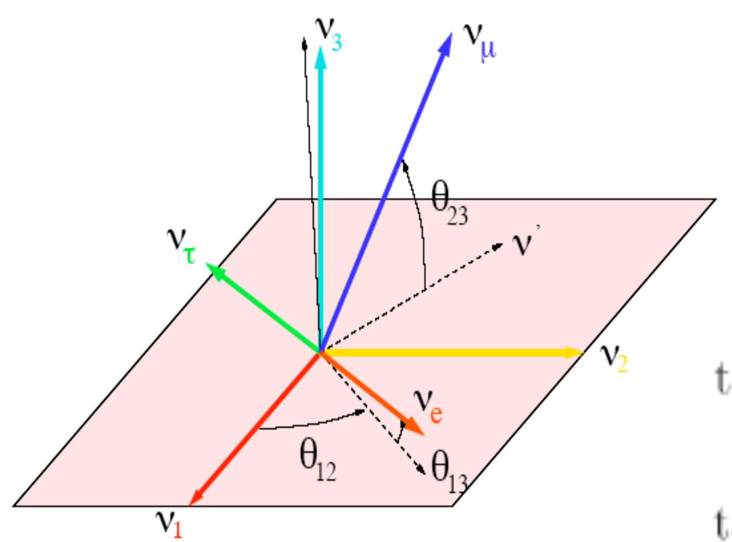
solar U_{e1}, $U_{e2} \leftrightarrow \theta_{12}$ CHOOZ $U_{e3} \leftrightarrow \theta_{13}$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

atmospheric $U_{e3} \leftrightarrow \theta_{13}$ $U_{\mu 3}, U_{\tau 3} \leftrightarrow \theta_{23}$

MNSP matrix

Parameter	best-fit ($\pm 1\sigma$)	3σ
Δm^2_{21} [10^{-5} eV ^{2}]	$7.54^{+0.26}_{-0.22}$	$6.99 - 8.18$
$\|\Delta m^2\|$ [10^{-3} eV ^{2}]	2.43 ± 0.06 (2.38 ± 0.06)	$2.23 - 2.61$ ($2.19 - 2$
$\sin^2\theta_{12}$	0.308 ± 0.017	$0.259 - 0.359$
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	$0.437^{+0.033}_{-0.023}$	$0.374 - 0.628$
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	$0.455^{+0.039}_{-0.031}$,	$0.380 - 0.641$
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	$0.0234^{+0.0020}_{-0.0019}$	$0.0176 - 0.0295$
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	$0.0240^{+0.0019}_{-0.0022}$	$0.0178 - 0.0298$



$$\tan^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2},$$

$$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2},$$

$$\sin^2\theta_{13} \equiv |U_{e3}|^2,$$

Astrophysical neutrino oscillations

$$P(\nu_\alpha \to \nu_\beta) = \sum_i |U_{\alpha,i}|^2 |U_{\beta,i}|^2 + 2\sum_{i<j} U_{\alpha,i}U_{\beta,i}U_{\alpha,j}U_{\beta,j} \cos\left(\frac{\Delta m^2_{ij} L}{2E}\right).$$

We can express the phase in astro units:

$$\varphi \sim 3\cdot 10^8 \left(\frac{\Delta m^2}{8\cdot 10^{-5}\ \mathrm{eV}^2}\right)\left(\frac{D}{1\ \mathrm{kpc}}\right)\left(\frac{10\ \mathrm{TeV}}{E_\nu}\right)$$

For astrophysical source at kpc-distances emitting vs of 10 TeV: COSφ averages to zero since the extension of sources is about 1 pc and their distance is of the order of 1 kpc so the baseline is known with precision 1/1000 not $1/10^8$ hence we use the incoherent term

$$P(\nu_\alpha \to \nu_\beta) = \sum_i |U_{\alpha,i}|^2 |U_{\beta,i}|^2$$

$\nu_\alpha \backslash \nu_\beta$	ν_e	ν_μ	ν_τ
ν_e	60%	20%	20%
ν_μ	20%	40%	40%
ν_τ	20%	40%	40%

$$P(\nu_e \to \nu_e) = \sum_i |U_{ei}|^2 |U_{ei}|^2 = |U_{e1}|^4 + |U_{e2}|^4 + |U_{e3}|^4 = 0.82^4 + 0.57^4 + 0 = 0.56$$

$$P(\nu_e \to \nu_\mu) = \sum_i |U_{ei}|^2 |U_{\mu i}|^2 = |U_{e1}|^2 |U_{\mu 1}|^2 + |U_{e2}|^2 |U_{\mu 2}|^2 + |U_{e3}|^2 |U_{\mu 1}|^2 = 0.82^2\cdot 0.4^2 + 0.57^2 \cdot 0.58^2 + 0 = 0.22$$

$$P(\nu_e \to \nu_\tau) = \sum_i |U_{ei}|^2 |U_{\tau i}|^2 = |U_{e1}|^2 |U_{\tau 1}|^2 + |U_{e2}|^2 |U_{\tau 2}|^2 + |U_{e3}|^2 |U_{\tau 1}|^2 = 0.82^2\cdot 0.4^2 + 0.57^2 \cdot 0.58^2 + 0 = 0.22$$

From source to Earth

At source:

$$\nu_e : \nu_\mu : \nu_\tau \sim 1 : 2 : 0$$

pion-muon decay

$\nu_\alpha \backslash \nu_\beta$	ν_e	ν_μ	ν_τ
ν_e	60%	20%	20%
ν_μ	20%	40%	40%
ν_τ	20%	40%	40%

Maybe not true if charmed meson threshold is overcome: 0:1:0 (Sarcevic et al., arXiv:0808.2807)

At Earth:

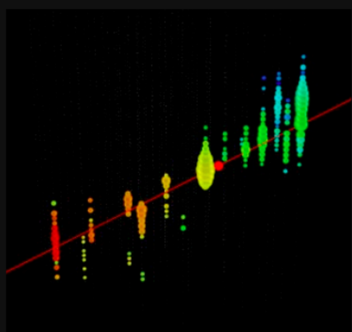
$$\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$$

Maybe not true if muons cannot decay (Kashti & Waxman, PRL 95 (2005) 181101)

60% of ν_e survive and 2x20% come from 2xν_μ = 100%
2x40%=80% of 2xν_μ survive and 20% come from ν_e= 100%
20% of ν_τ come from ν_e and 2 x 40% from ν_μ= 100%

Neutrino events in a neutrino telescope

CC Muon Neutrino

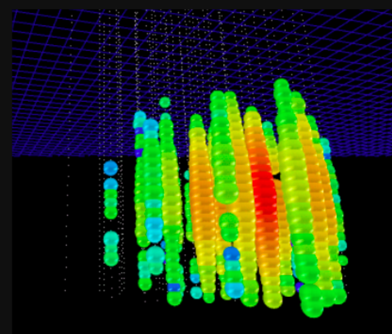


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution

Neutral Current /Electron Neutrino



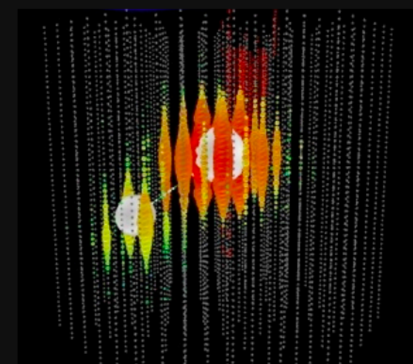
$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies $\gtrsim$ 100 TeV)

CC Tau Neutrino

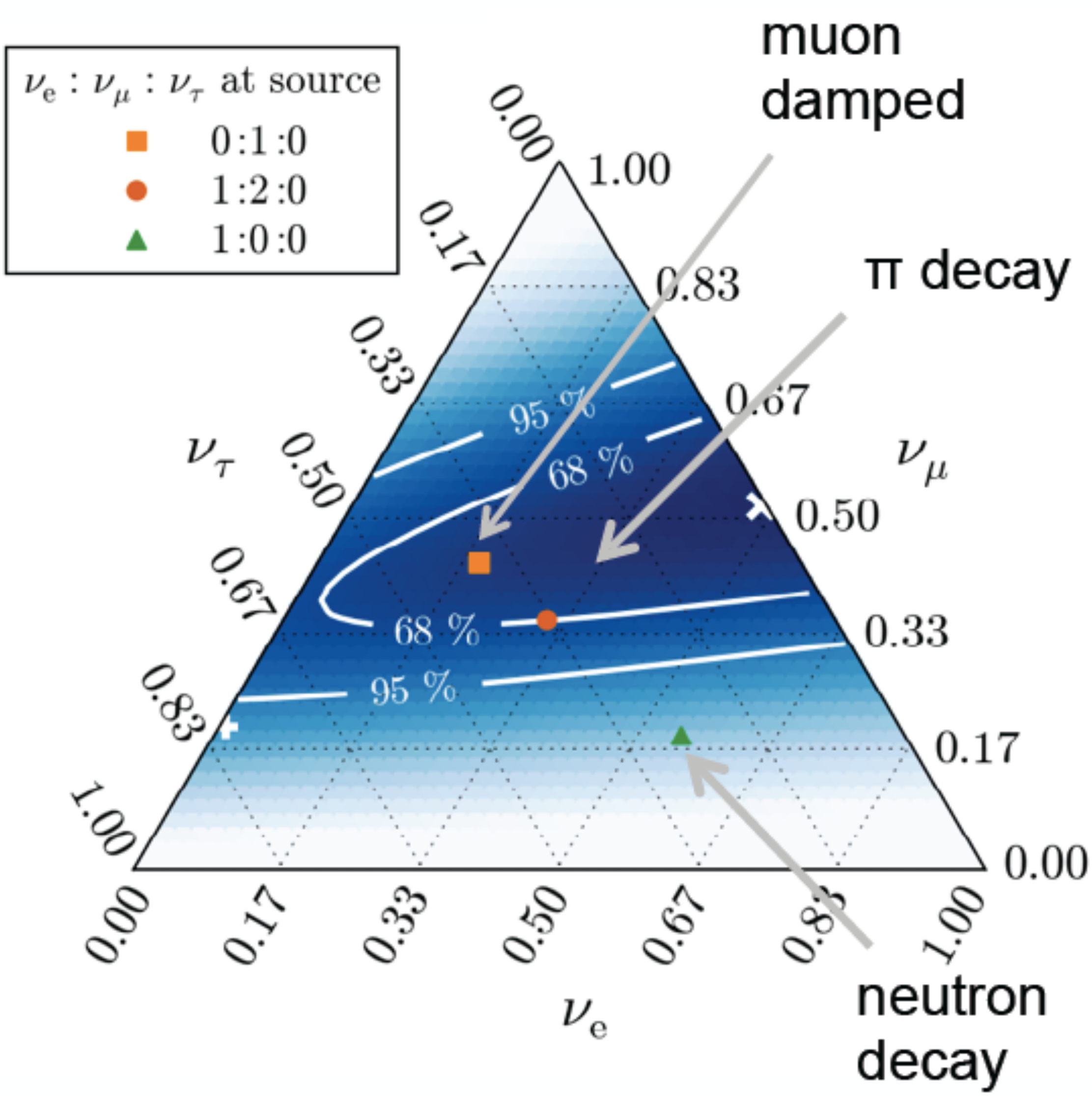


$$\nu_\tau + N \rightarrow \tau + X$$

“double-bang” and other signatures (simulation)

(not observed yet)

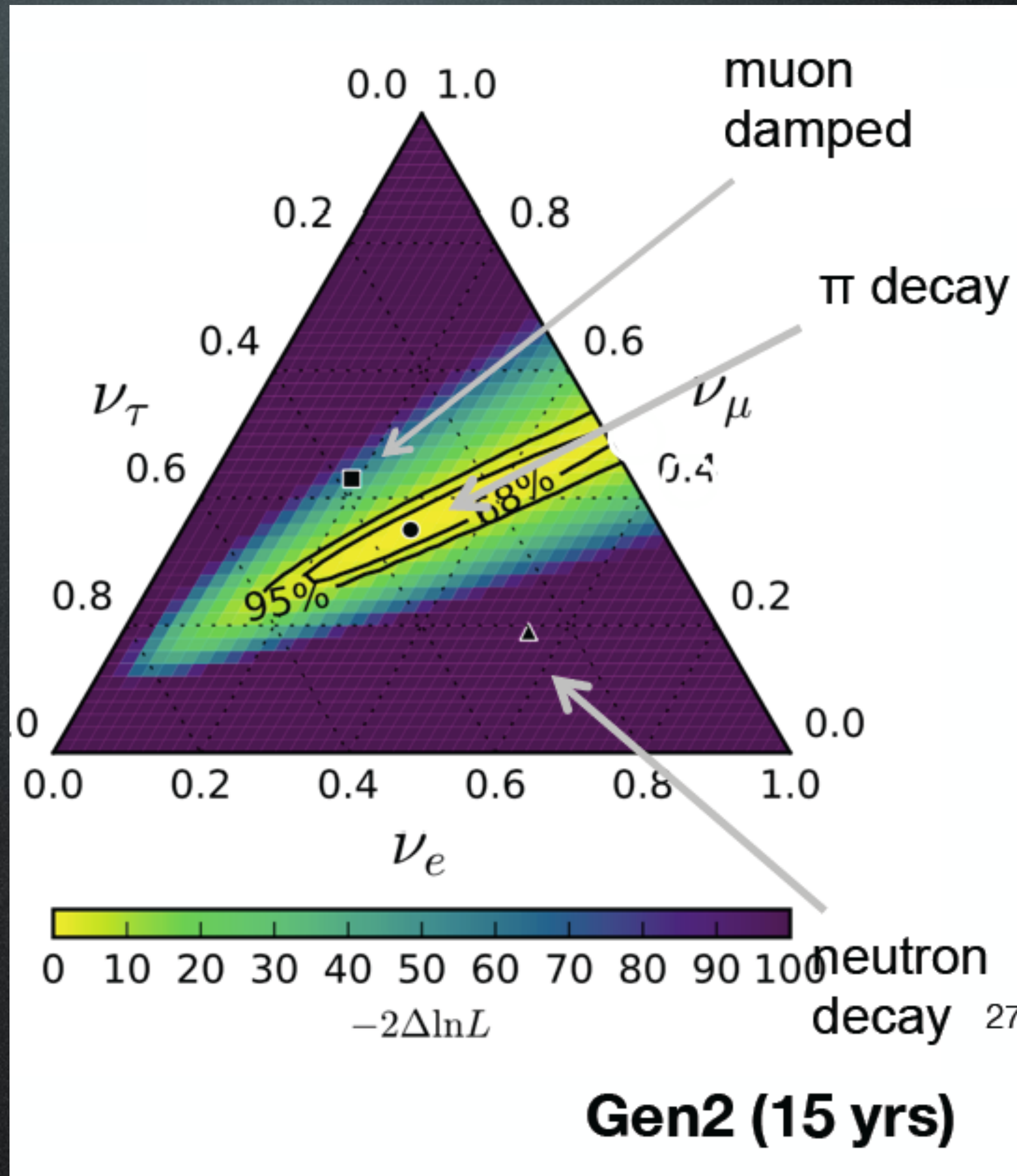
First flavor physics in a Neutrino telescope



IceCube, ApJ 2015, see also PRL2015)

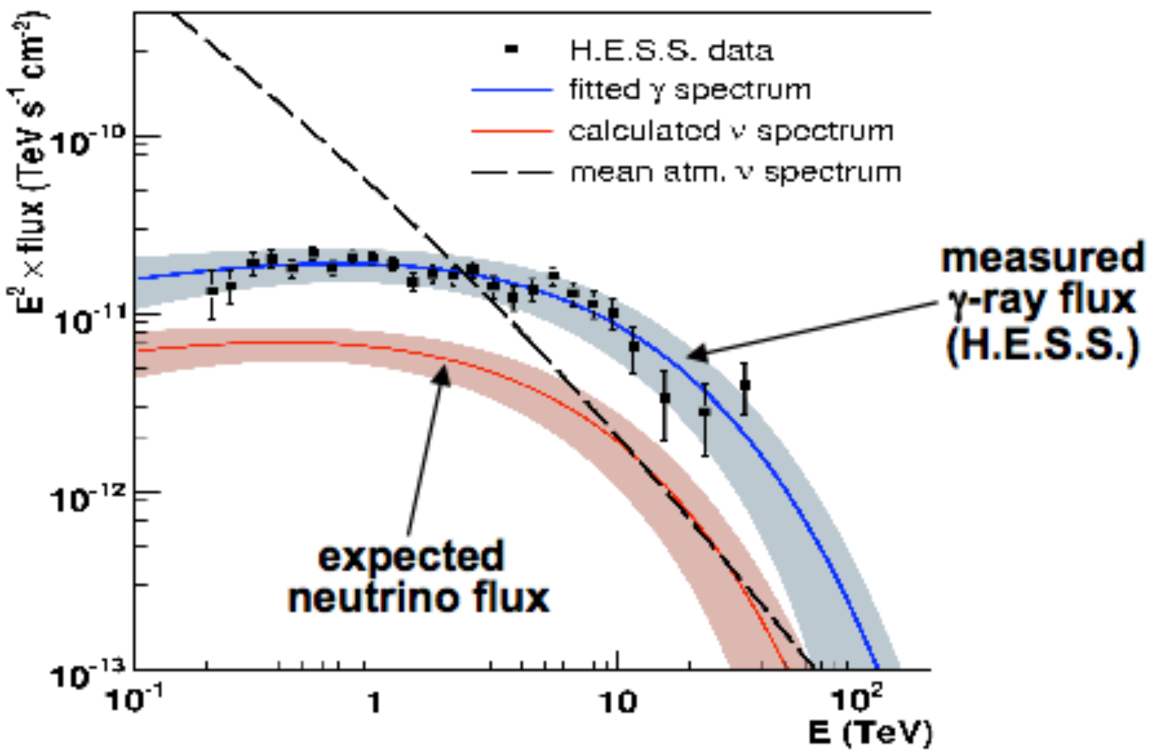
Future:

Flavor ratio constrain the conditions at source
e.g. magnetic fields (muon cooling), charm production, neutron dominated



Neutrino rates (exercise)

Neutrino and γ-Ray Spectra for RX J1713.7-3946 (SNR)

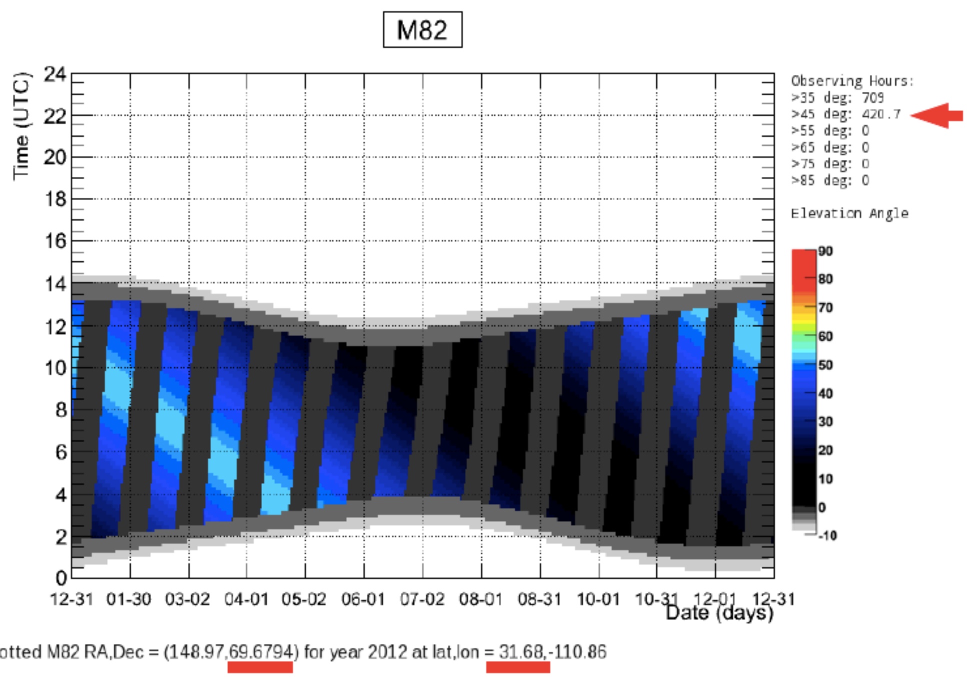


$$N = T \times \int_{E_{min}}^{E_{max}} A_{eff}(E) \times \frac{dN}{dE} dE$$

$$N = T \times \sum_{bins} A_{eff}\left(\frac{dN}{dE}(bin\ center) \times \Delta E_{bin}\right)$$

Source Visibility

IACT gamma-ray telescope



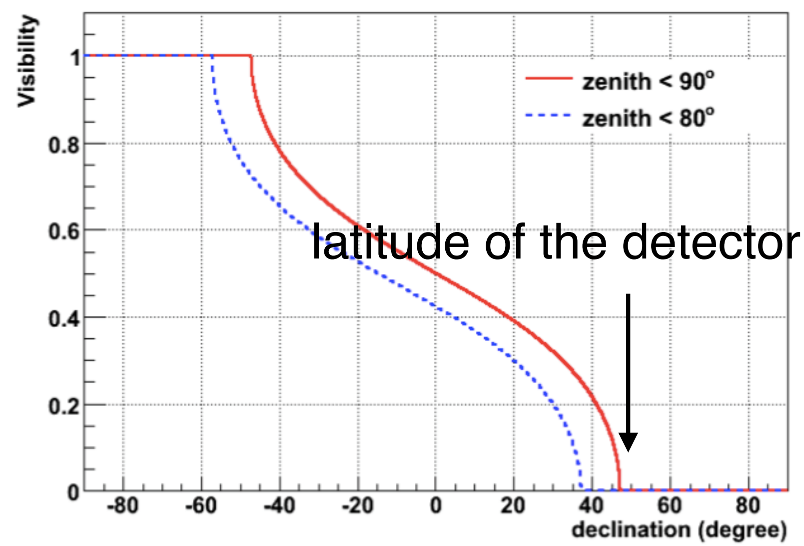
ource culminates at a Zenith angle of 70-32=38 degrees

Visible from December to May

South Pole is a special case…

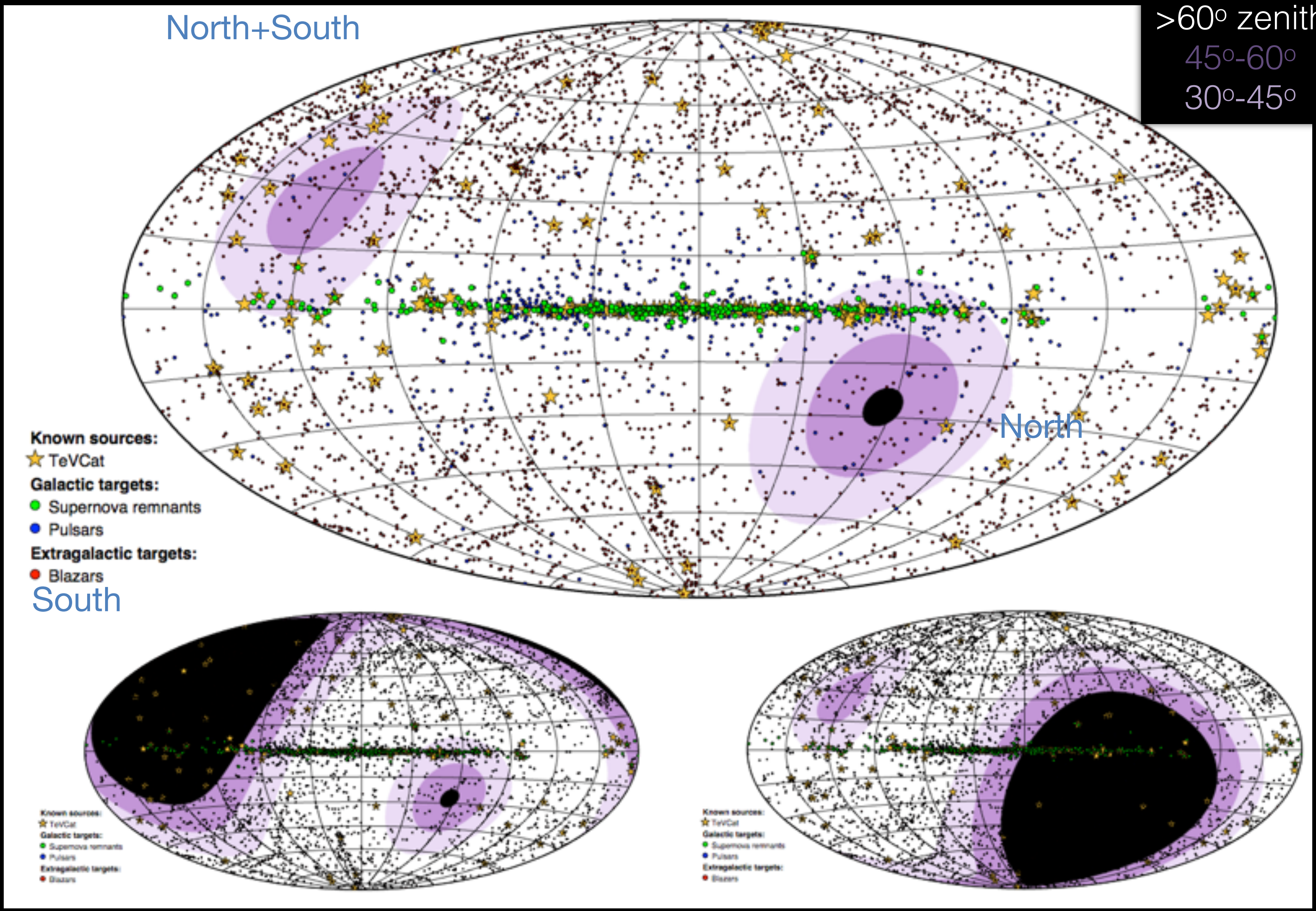
Declination and zenith are complementary angles

$\delta = 90° - \theta \in [0, 180°]$

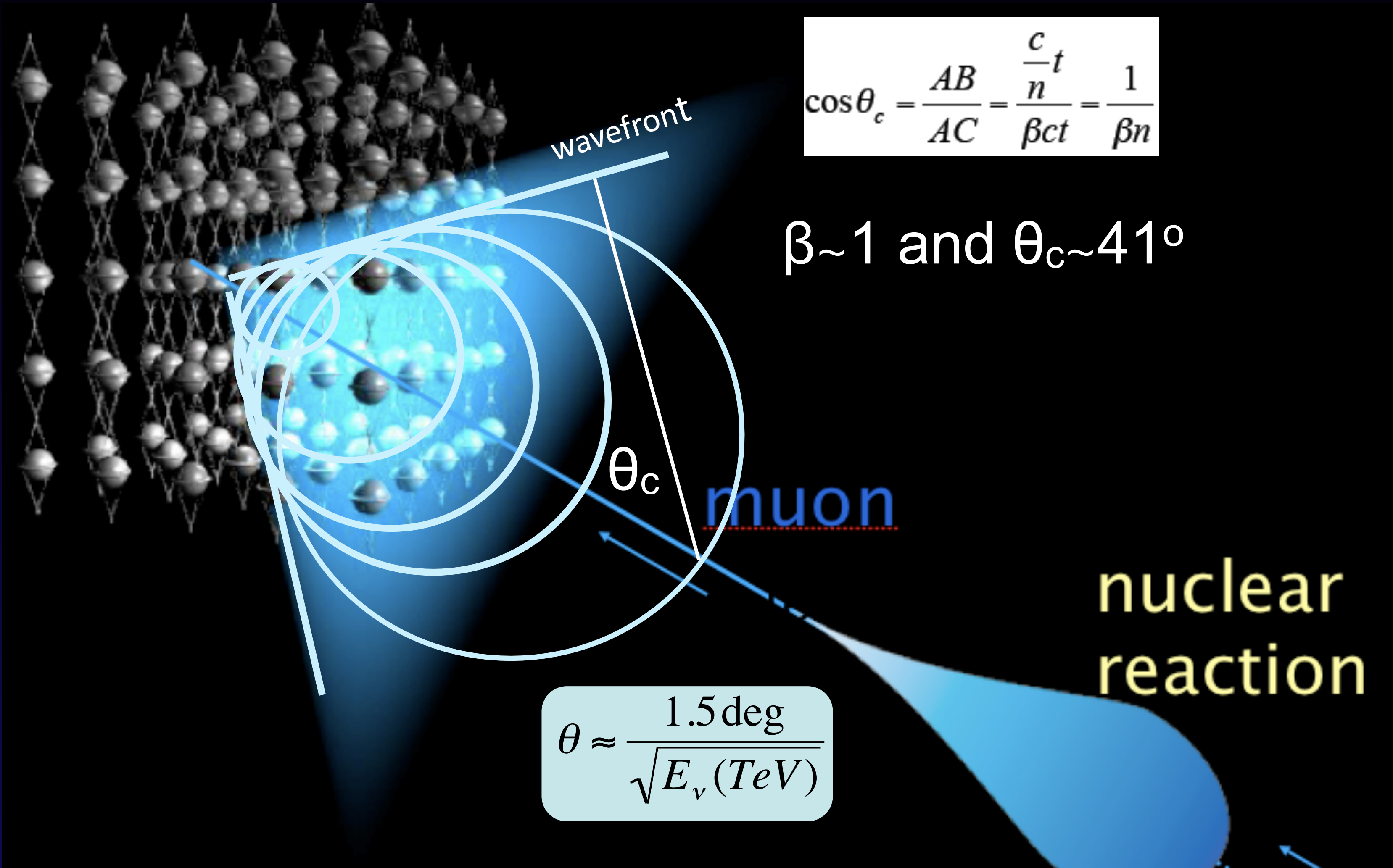


Warning! this plot applies to analyses using up-going atmospheric neutrino dominated tracks but UHE neutrino astronomy has also to be done using down-going atmospheric muon dominated samples

The Sites and sky coverage



Concept of Neutrino Detector



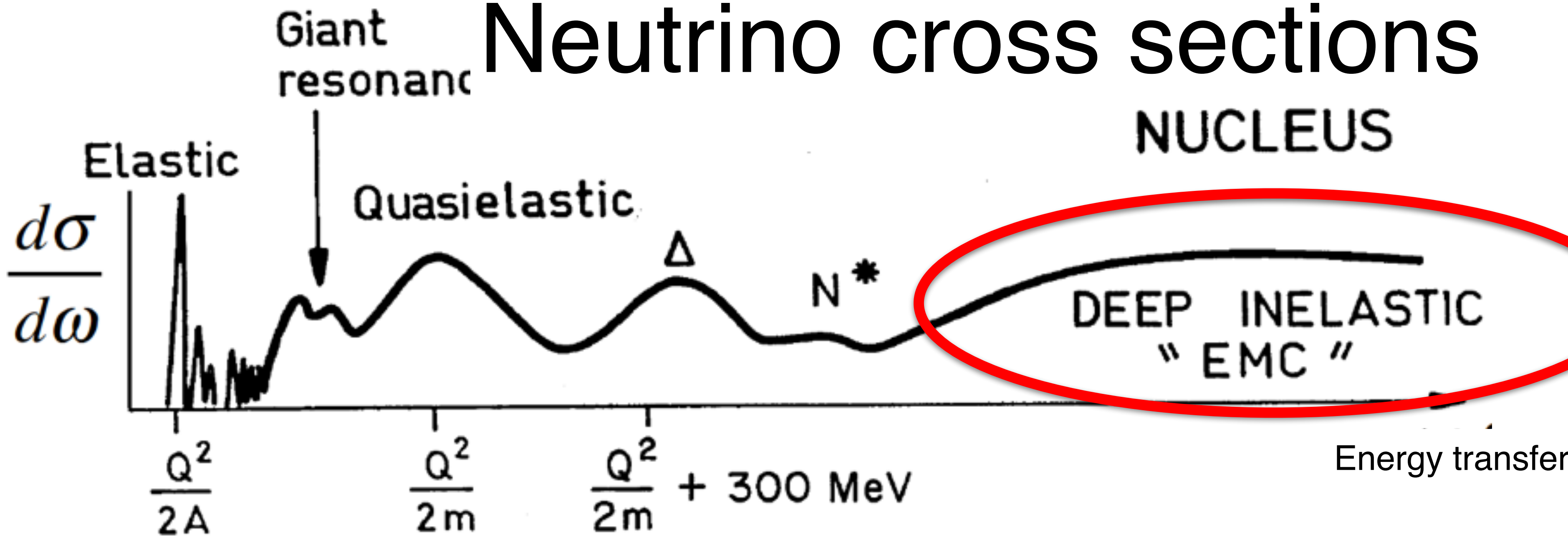
$$\cos\theta_c = \frac{AB}{AC} = \frac{\frac{c}{n}t}{\beta ct} = \frac{1}{\beta n}$$

$\beta \sim 1$ and $\theta_c \sim 41^o$

$$\theta \approx \frac{1.5\,\text{deg}}{\sqrt{E_\nu(TeV)}}$$

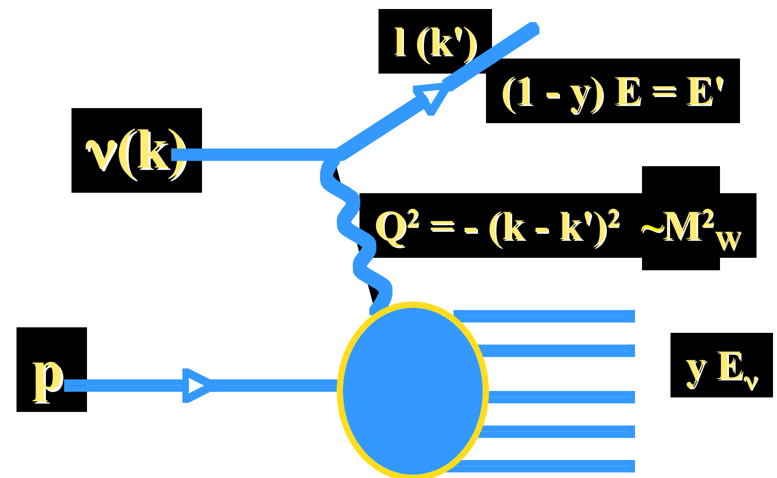
Between 300-600 nm about 3.5 x 10^4 Cherenkov photons/m of a muon track

Neutrino cross sections



P. Mertsch's lecture

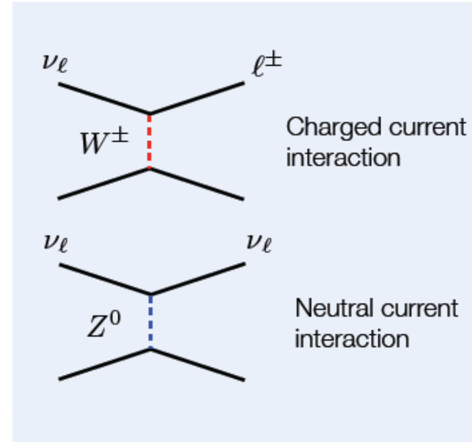
Deep Inelastic Scattering (charged and neutral currents) with very large momentum transfers.



Large target mass due to small x-section

$$\nu_\mu + N \to \mu^- + X \qquad \bar{\nu}_\mu + N \to \mu^+ + X$$

$$\nu_\mu + N \to \nu_\mu + X \qquad \bar{\nu}_\mu + N \to \bar{\nu}_\mu + X$$



$$\frac{d^2\sigma}{dxdy} = \frac{2G_F^2 M E_\nu}{\pi}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2\left[xq(x,Q^2)+x\overline{q}(x,Q^2)(1-y)^2\right]$$

$$Q^2 = 2ME_\nu xy \qquad y = \nu/E_\nu \qquad \nu = E_\nu - E_\mu$$

$$q(x,Q^2) = \frac{u_v(x,Q^2)+d_v(x,Q^2)}{2} + \frac{u_s(x,Q^2)+d_s(x,Q^2)}{2} + s_s(x,Q^2) + b_s(x,Q^2)$$

$$\overline{q}(x,Q^2) = \frac{u_s(x,Q^2)+d_s(x,Q^2)}{2} + c_s(x,Q^2) + t_s(x,Q^2),$$

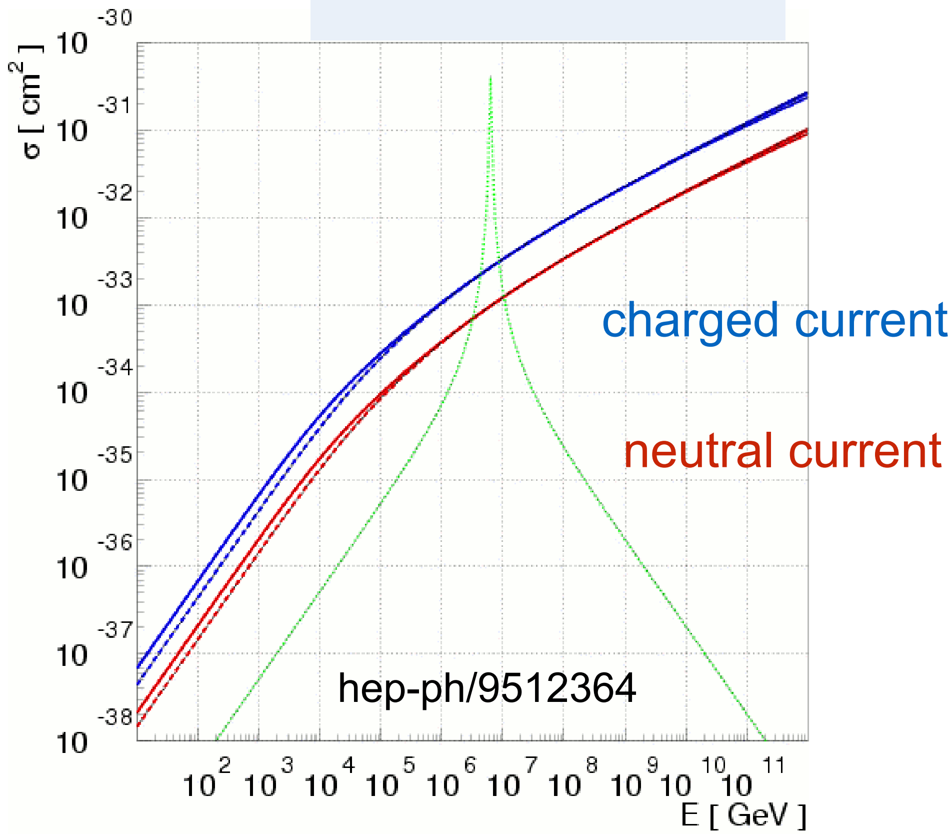


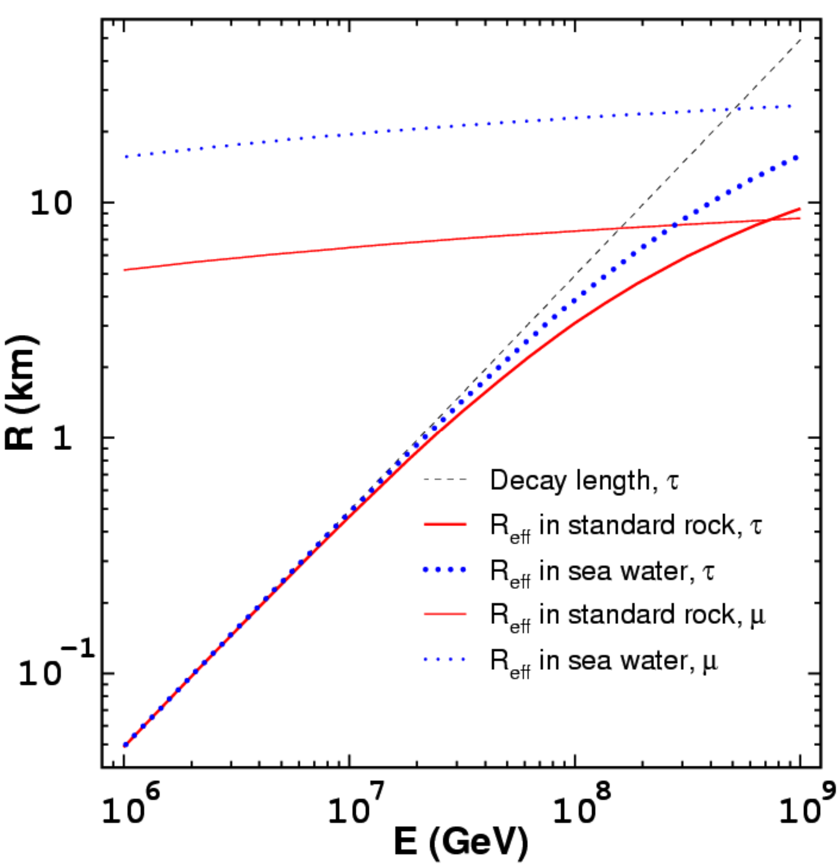
Figure 33: Simulated neutrino cross sections: higher blue curves are CC, lower red curves are NC; solid are ν, dashed are $\bar{\nu}$; green dotted is $\bar{\nu}_e e^- \to W^-$

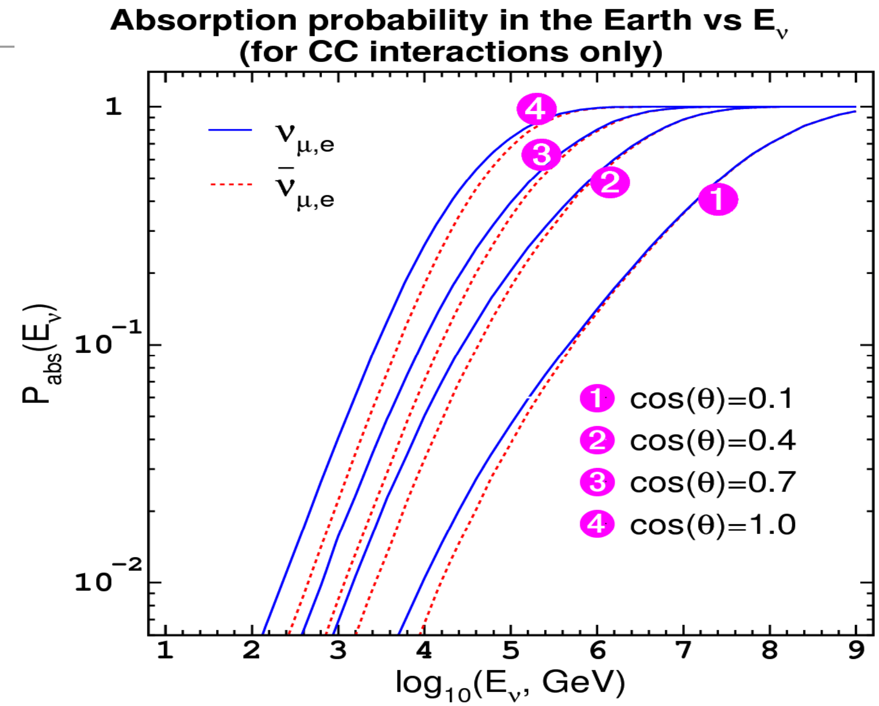
At low energy, neutrino and anti-neutrino cross sections differ because the valence quark dominate

Muon/tau range and absorption/regeneration of neutrinos in the Earth

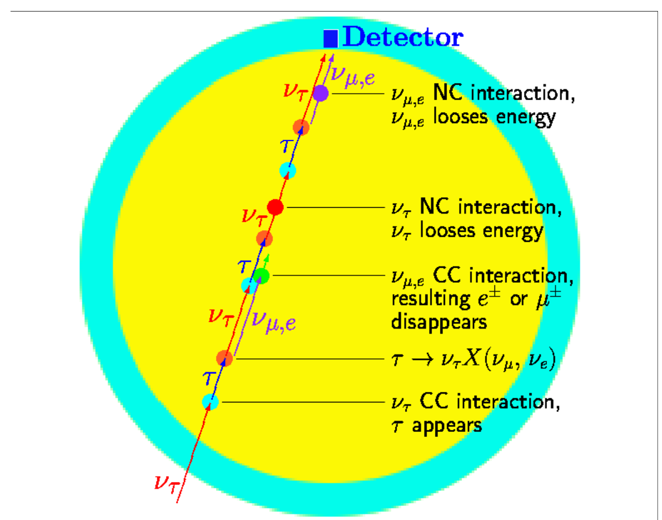
$$P_{surv} = e^{N_A \int dl cos\theta \rho(l) \sigma_\nu(E_\nu)}$$

$$R = \int_0^X \frac{dx}{dE} dE = \int_{E_0}^0 -\frac{dE}{a+bE} = -\frac{1}{a}\int_{E_0}^0 \frac{dE}{1+bE/a} = \frac{1}{b}\ln(1+E_0/E_c)$$





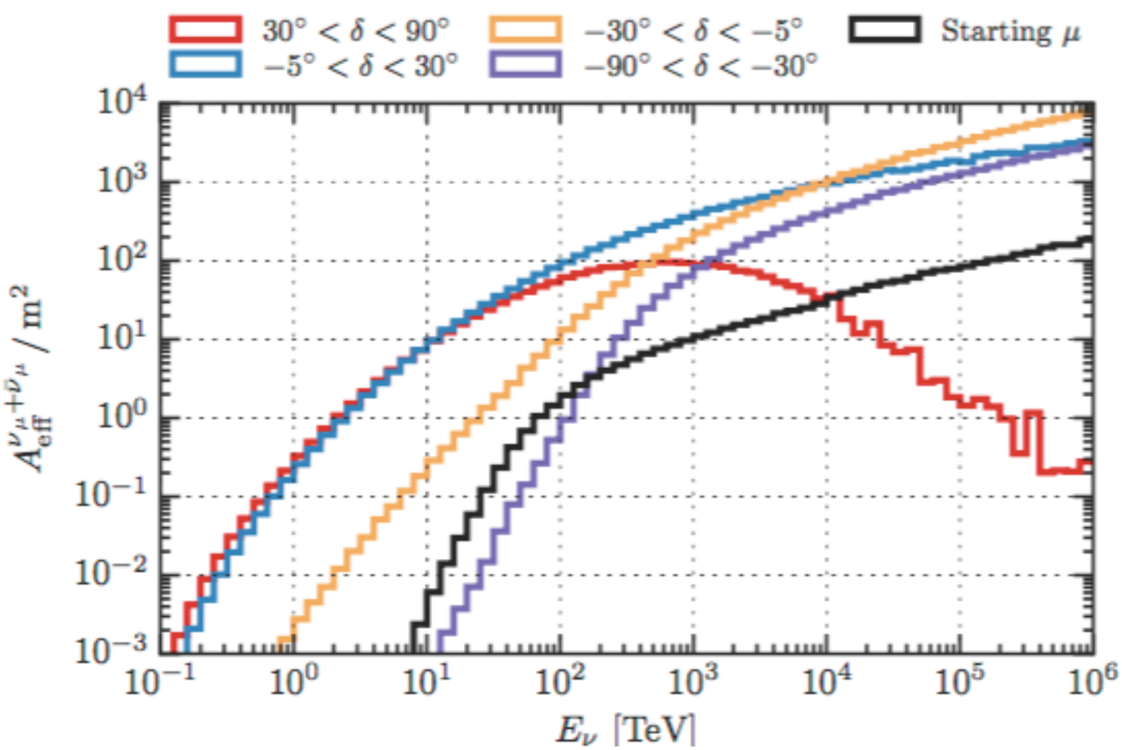
Tau neutrinos never absorbed but loose energy

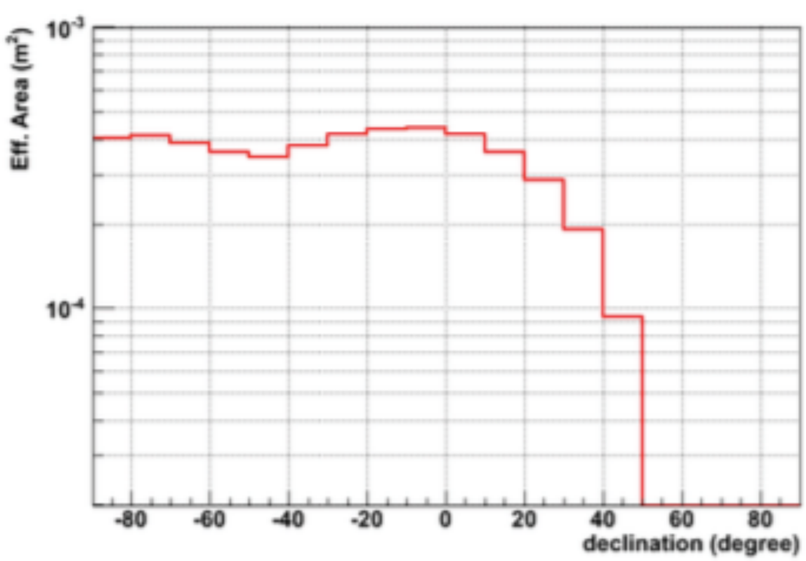


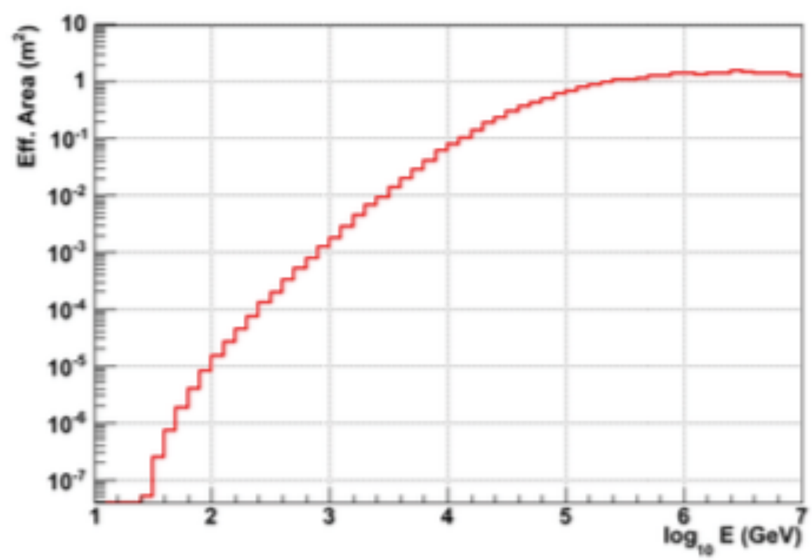
L'Abbate, TM, Sokalski, Astropart.Phys.23:57-63,2005

Bugaev, TM, Shlepin, Sokalski, Astropart.Phys. 21:491-509,2004

Effective Area





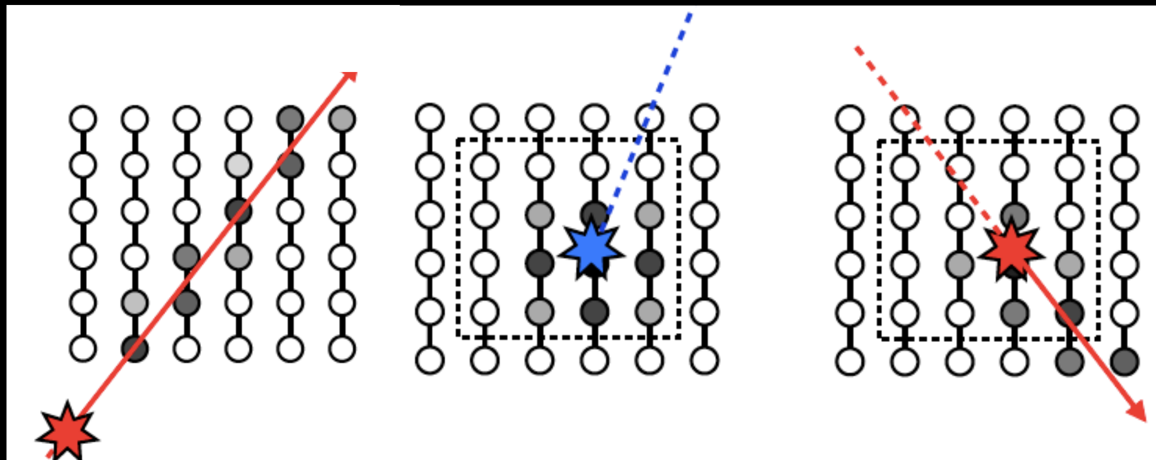


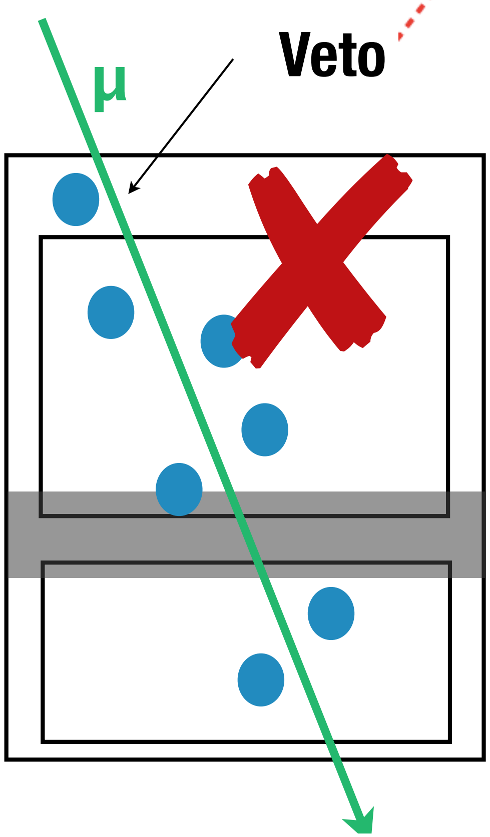
Neutrino selection & background rejection

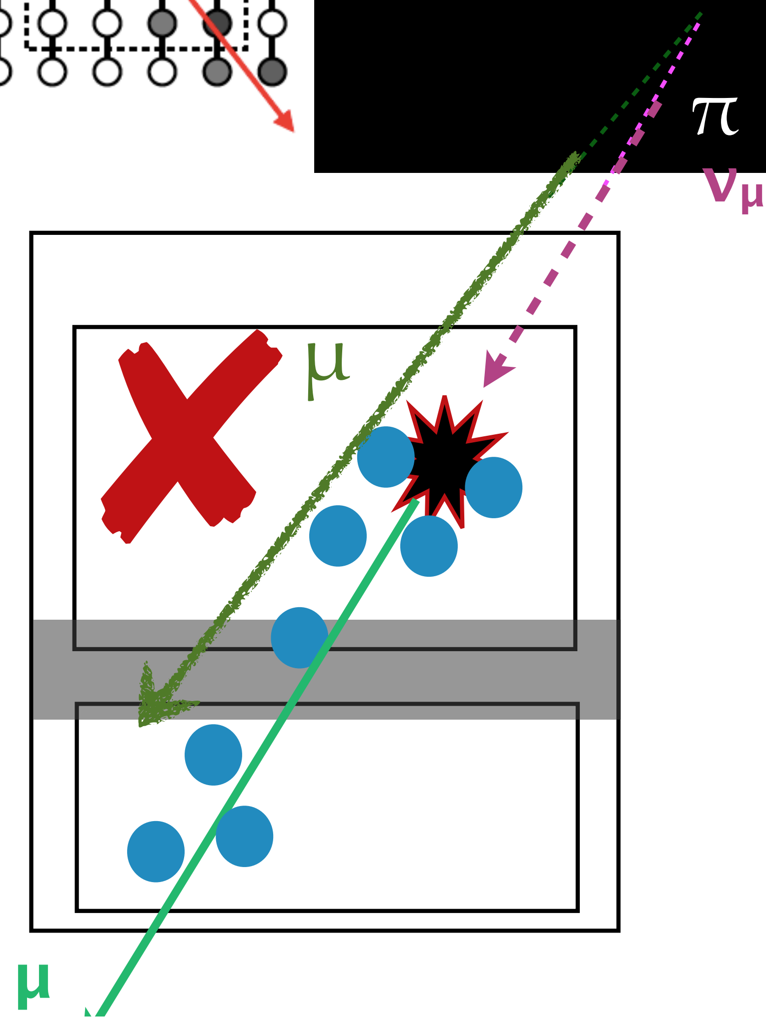
Upgoing thoroughgoing neutrino induced muons - Earth is a filter - or vertex identification of ‘starting events’ (tracks and cascades)

Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

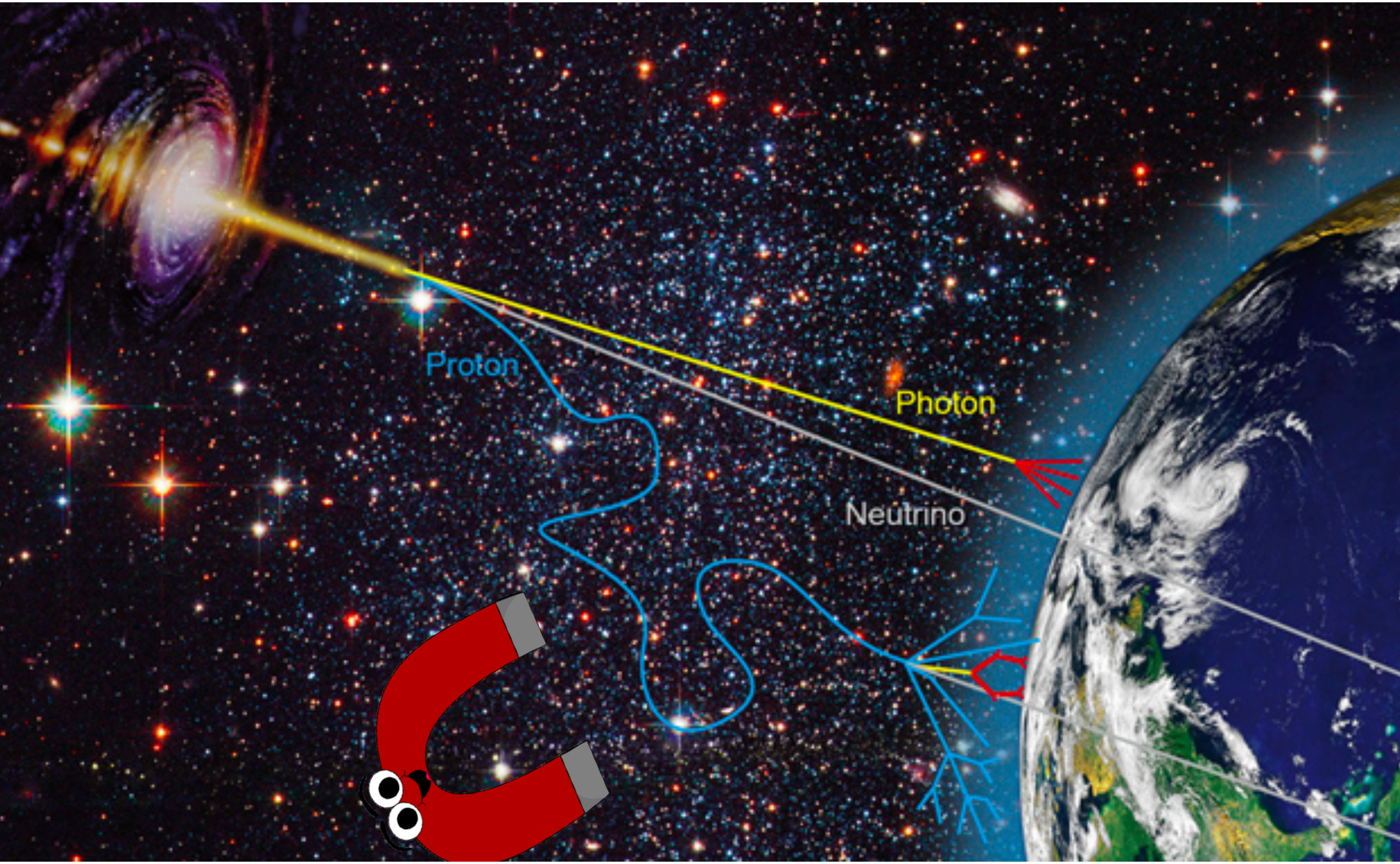
Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)







Multi-messenger astrophysics



Reminder: Mean free path

$$w = \text{interaction prob.} = \text{w} = \text{N}\sigma\text{dx}$$

σ = cross section
N= n. of target particles / volume

P(x) = prob. that a particle does not interact after traveling a distance x
P(x + dx) = prob that a particle has no interaction between x and x+dx = P(x+dx) = P(x) (1-wdx)

$$P(x+dx) = P(x) + \frac{dP}{dx}dx = P(x) - P(x)wdx$$

$$\frac{dP}{P} = -wdx \Rightarrow P(x) = P(0)e^{-wx}$$

P(0) = 1 it is sure that initially the particle did not interacts

$$\lambda = \frac{\int xP(x)dx}{\int P(x)dx} = \frac{1}{w} = \frac{1}{N\sigma}$$

Atomic number

Medium density

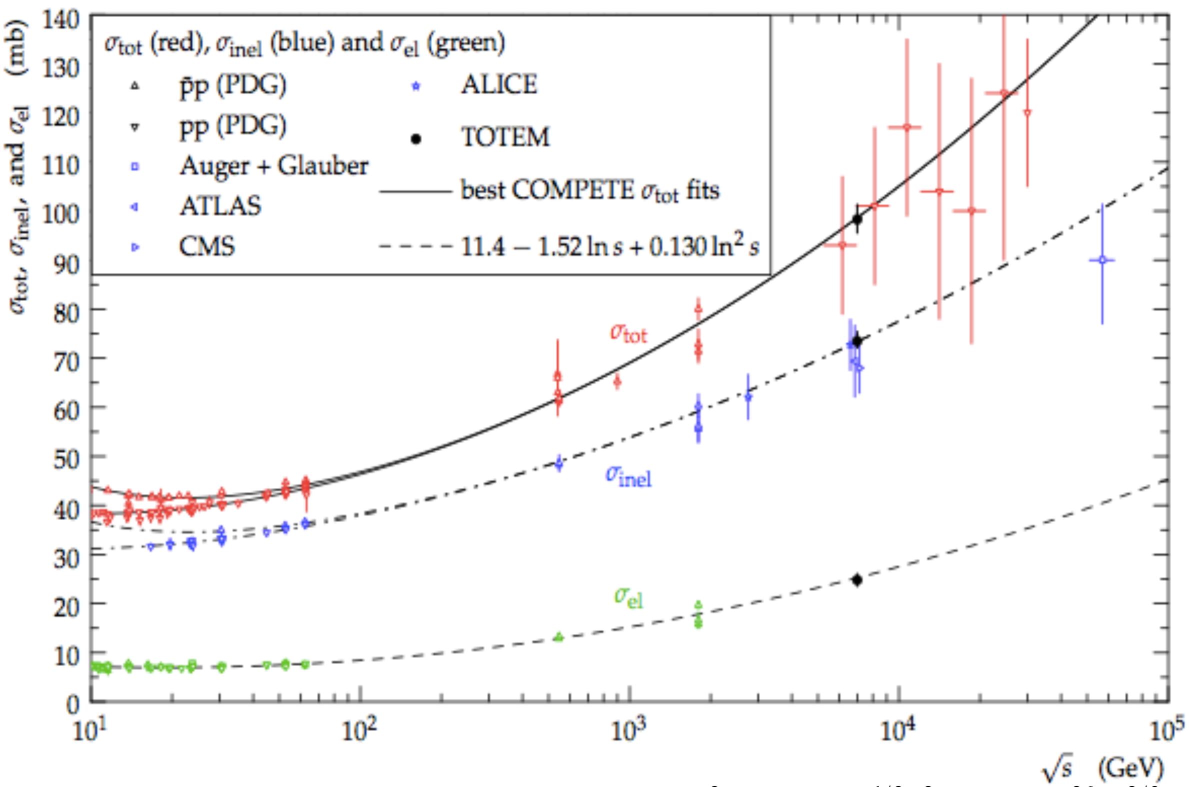
$$\lambda_I = \lambda\rho = \frac{\rho}{N_c\sigma} = \frac{Am_p}{\sigma}$$

in g/cm²

Example: interaction length of CRs in the atmosphere

$$\lambda_I = \lambda\rho = \frac{\rho}{N_c\sigma} = \frac{Am_p}{\sigma}$$ in g/cm^2

Total, inelastic and elastic (anti-)protons on proton cross section



At p∼10GeV/c $\sigma_{pp,inel}$ ∼40 mb

At 1 TeV $\sigma_{pp,inel}$ ~ 50 mb

(1mb = 10^{-27} cm^2)

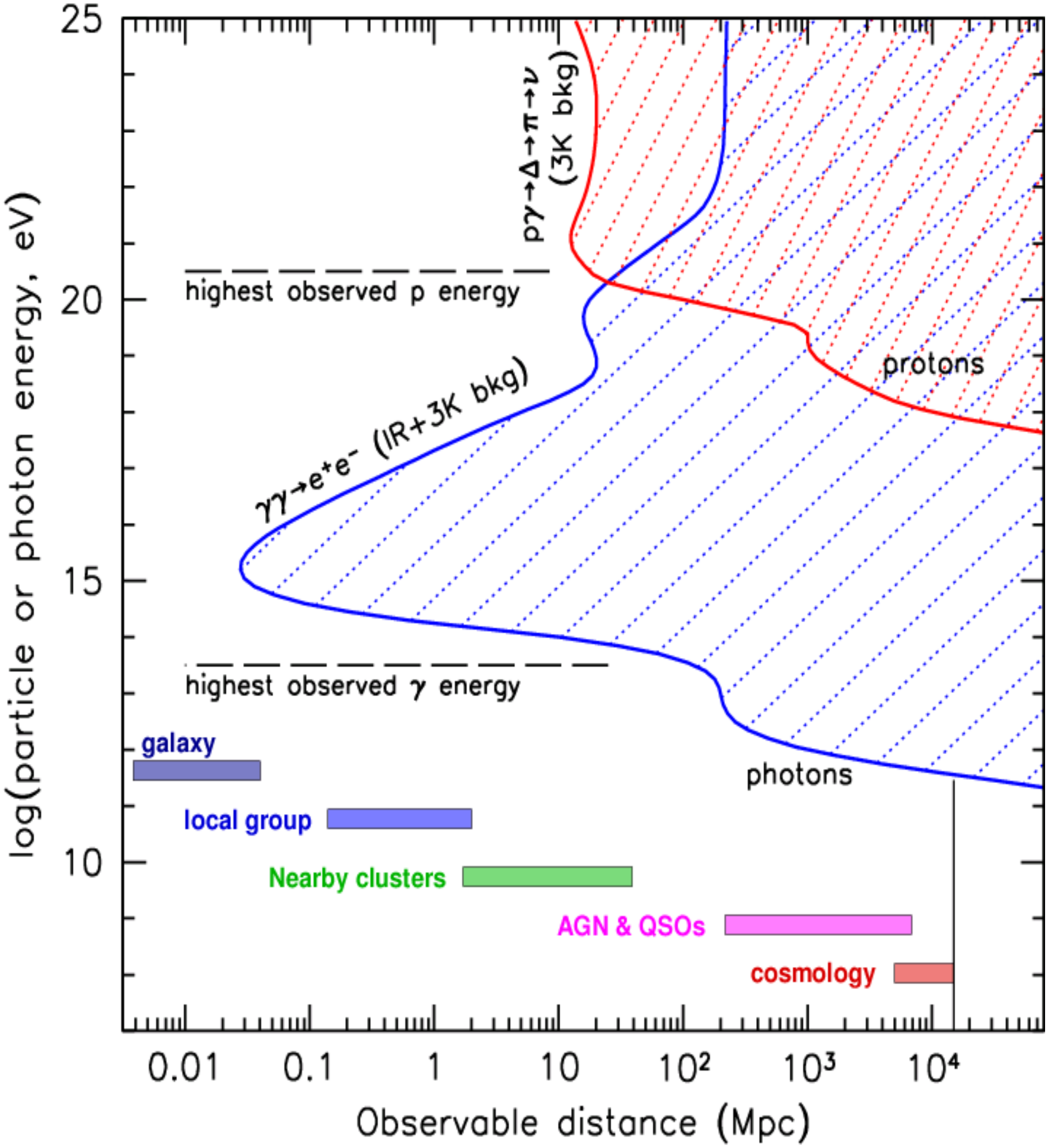
<$A_{atmosphere}$> = 14.5 (dominated by N)

$$\lambda_I = \frac{Am_p}{\sigma_{pAir}}$$

For a beam of A nucleons: $\sigma_{nucl} = \pi \cdot r_N^2 = \pi \cdot (r_o A^{1/3})^2 \cong 5\times10^{-26} A^{2/3} \quad cm^2 = 50 \quad mb$ x $A^{2/3}$

```
For p-AIR: 14.5*1.67 x 10^-27kg /300 x 10^-27 cm^2 = 80 g/cm^2
For Fe-Air: 5 g/cm^2
```

The multi-messenger's horizons



arxiv.org/pdf/0811.1160v2.pdf

Proton horizon (GZK cut-off):

$$p\gamma_{2.7K} \to \Delta^+ \to \pi^+ n$$

$$L_\gamma = \frac{1}{\sigma_{p-\gamma_{CMB}} n_\gamma} \sim \frac{1}{10^{-28}\mathrm{cm}^2 \times 400\mathrm{cm}^{-3}} \sim 10\ \mathrm{Mpc}$$

The neutrino horizon is comparable to t observable universe!

$$\bar{\nu}\nu_{1.95K} \to Z \to X$$

$$E_{res} = \frac{M_Z^2}{2m_\nu} \cong 4\times 10^{21}\left(\frac{1\mathrm{eV}}{m_\nu}\right)\mathrm{eV}$$

$$L_\nu = \frac{1}{\sigma_{res}\times n} = \frac{1}{5\times 10^{31} cm^2 \times 112 cm^{-3}} \approx 6G$$

T. J. Weiler, Phys. Rev. Lett. 49, 234 (1982)

The proton horizon

$$r_{\phi\pi}(E_{20}) \cong \frac{13.7 \exp[4/E_{20}]}{[1+4/E_{20}]} \text{ Mpc}$$

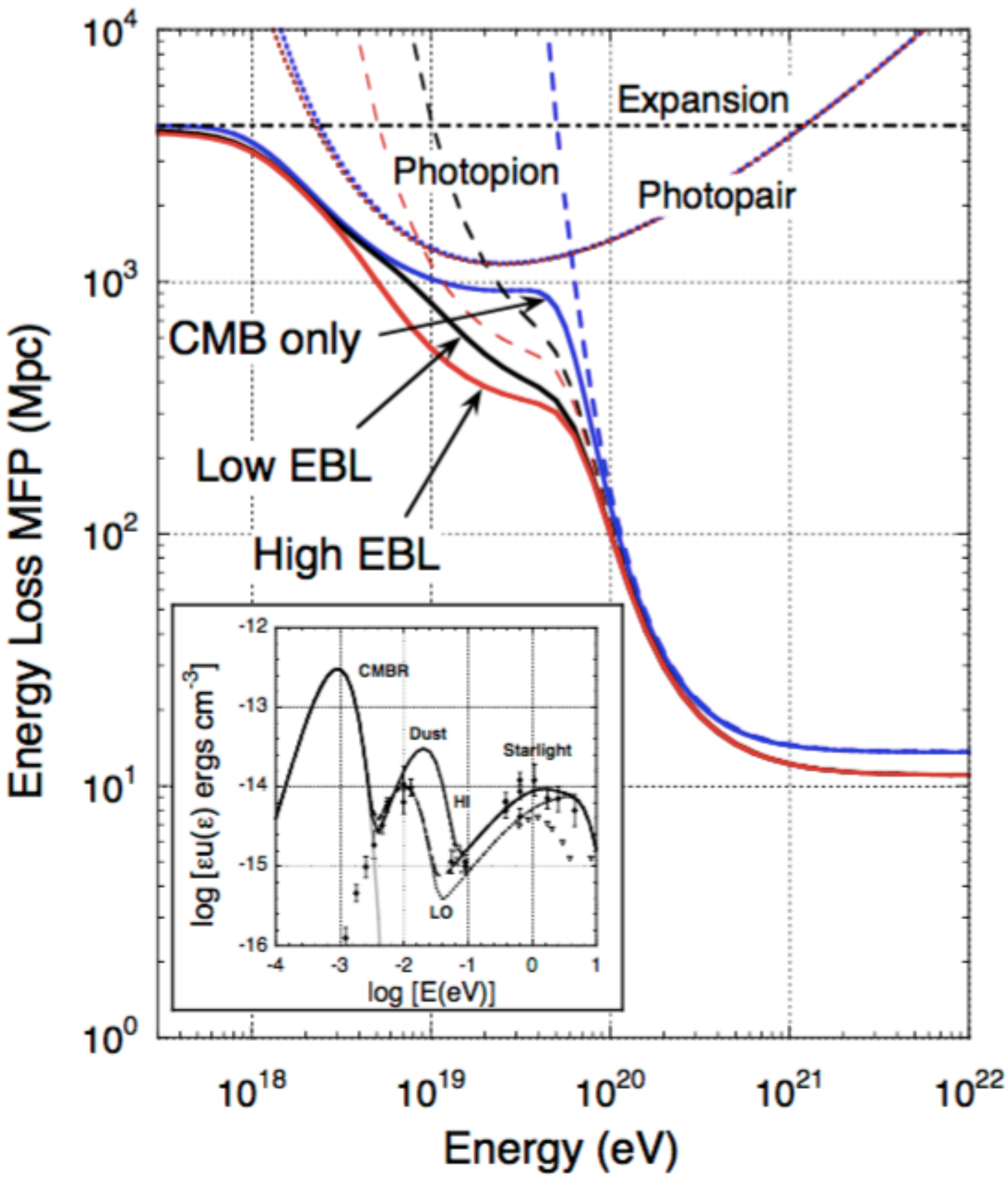
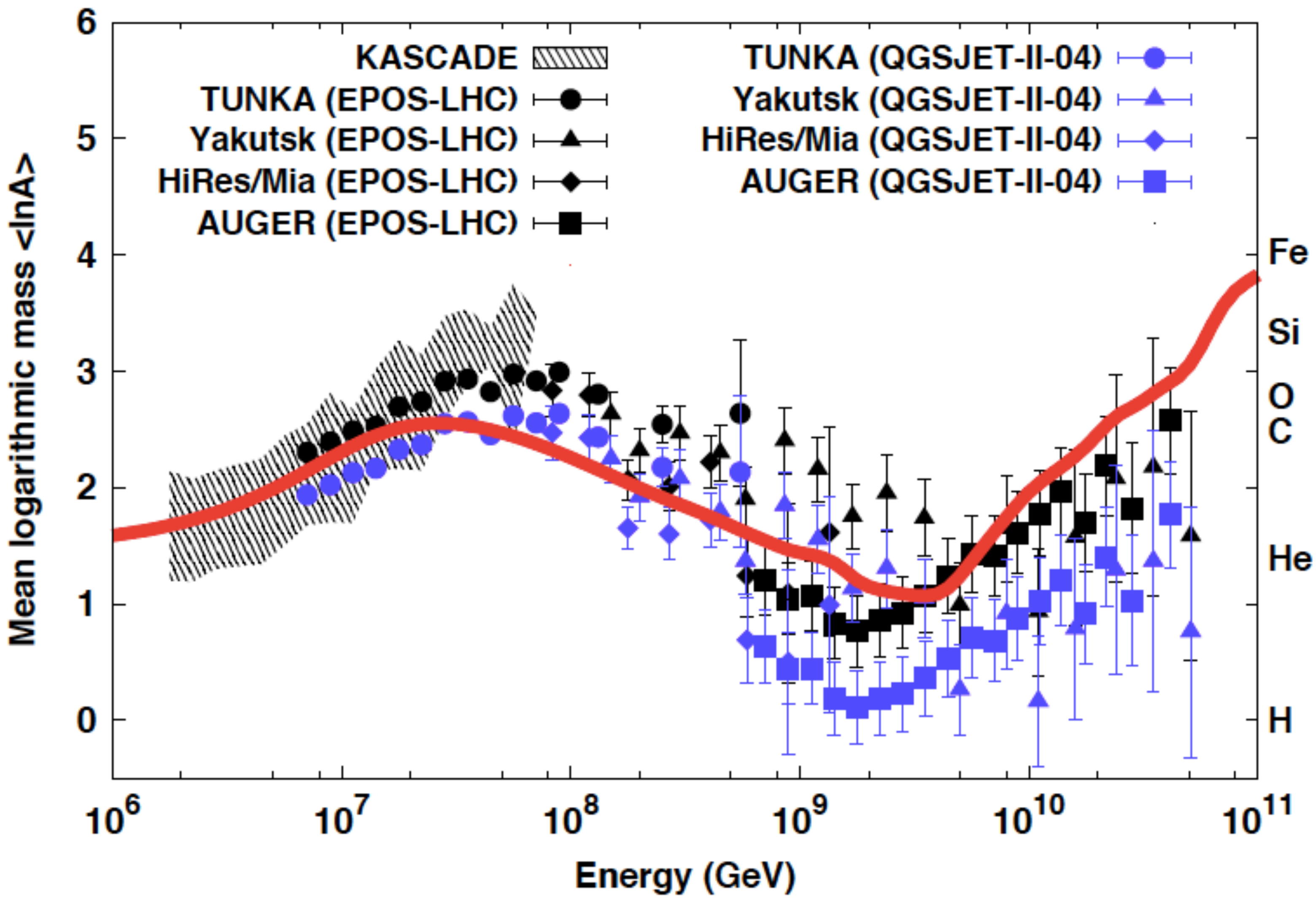


Figure 1. Mean-free paths for energy loss of UHECR protons in different model EBLs are shown by the solid curves, with photopair (dotted) and photopion (dashed) components shown separately. "CMB only" refers to total energy losses with CMB photons only, using eq. (4) for the energy-loss rate of protons due to photopion production. Inset: Measurements of the EBL at optical and infrared frequencies, including phenomenological fits to low-redshift EBL in terms of a superposition of modified blackbodies. A Hubble constant of 72 km s^{-1} Mpc^{-1} is used throughout.

What about neutrons? for a neutron of E = 10^9 GeV = 10^6 TeV $l_{decay} = \Upsilon c\tau$ = E/mc^2x c x 886 s = 10^9 GeV/1GeV x 3×10^8m/s x 886s = 2.66×10^{20} m x 3.24×10^{-20} kpc/m = 8.6 kpc

CR Composition



Deflection of CRs in B-field

$$mv^2 / r = pv / r = ZevB / c$$

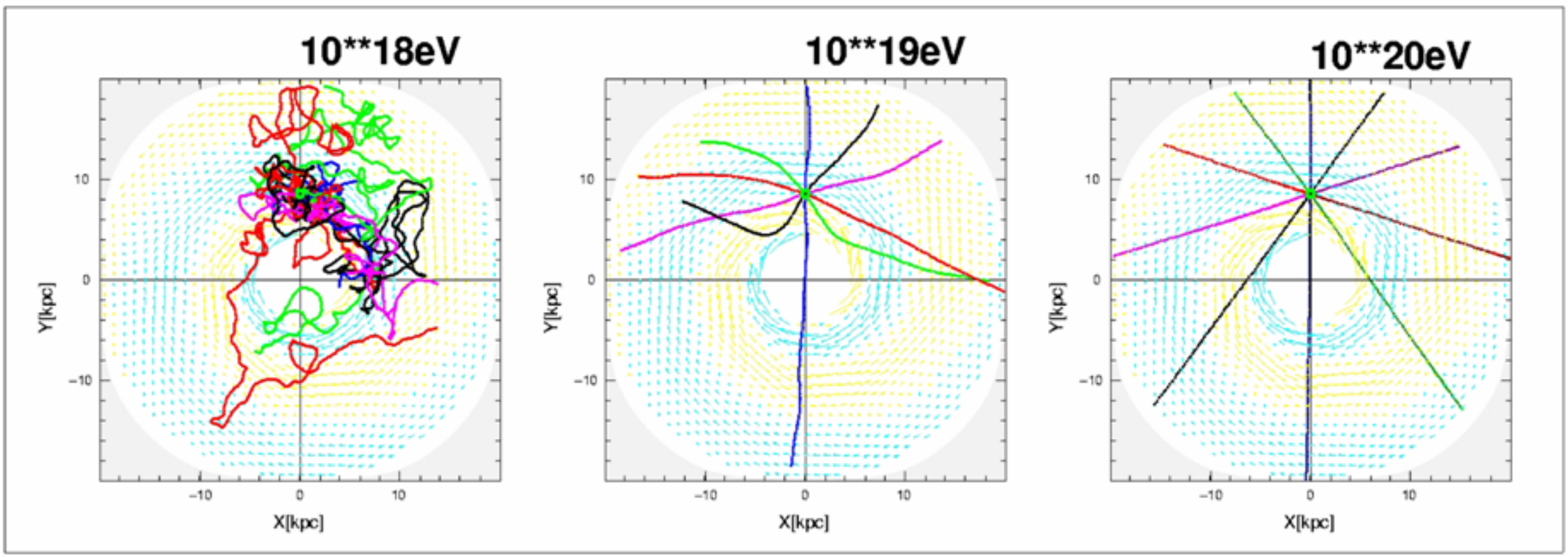
$$r = pc / ZeB$$

$$r(cm) = \frac{1}{300} \frac{E(eV)}{ZB(G)}$$

$$(10^{12} eV) = 10^{15} cm = 3 \times 10^{-4} pc$$

$$r = (10^{15} eV) = 10^{18} cm = 3 \times 10^{-1} pc$$

$$(10^{18} eV) = 10^{21} cm = 300 pc$$



Deflection of CRs in B-field

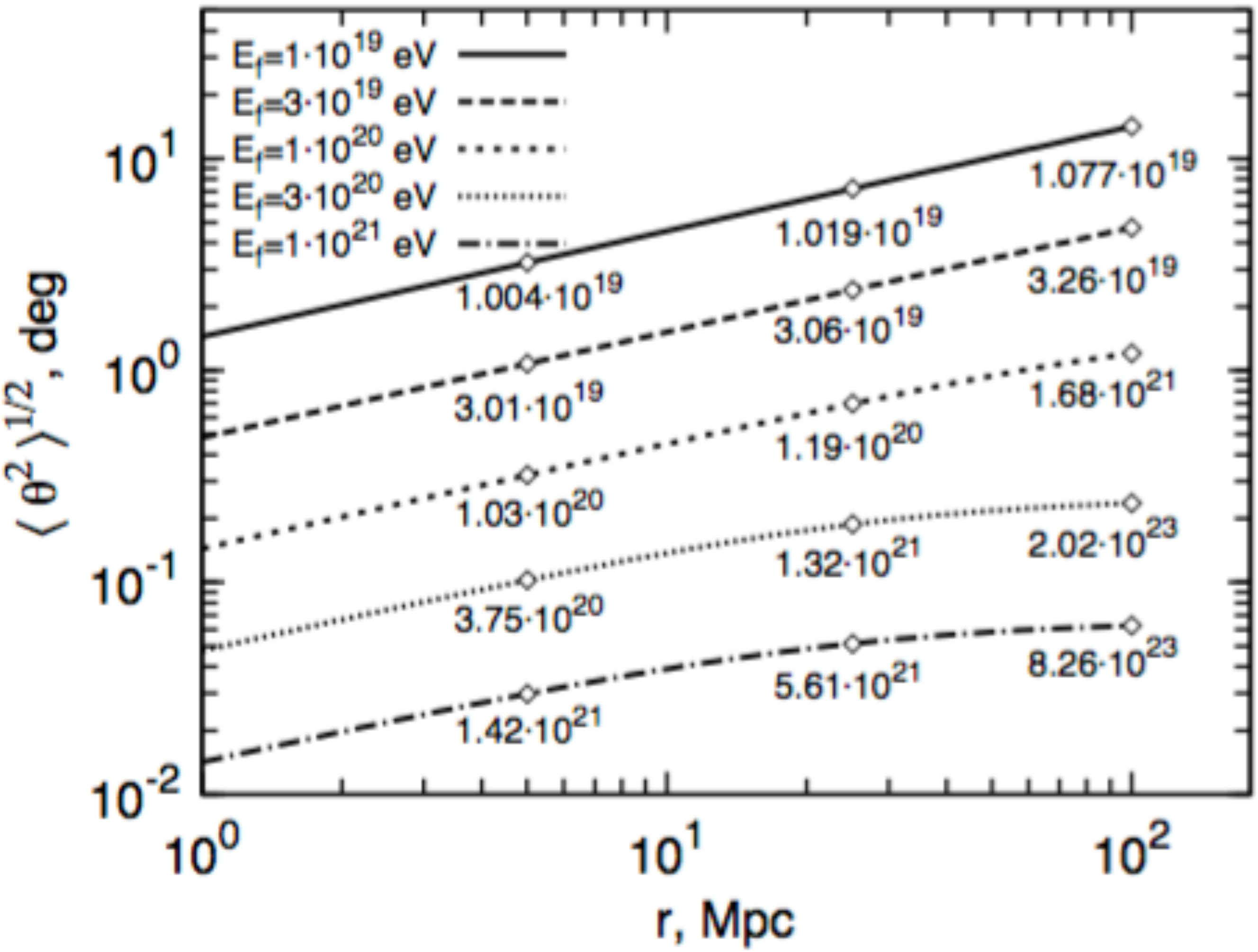


FIG. 2: The mean deflection angle of protons for the fixed *observed* energy E_f over the distance r. The numbers at the curves indicate the energies which proton had at the distance r from the observer.

Kelner, Aharonian, http://arxiv.org/pdf/1006.1045.pdf