High energy neutrinos from astrophysical sources: a self-consistent approach

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in collaboration with M. Kachelrieß

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Outline

1 Motivation

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2. Astrophysical sources
   - Optically thick sources as neutrino sources

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   - Neutrino Yield
   - Unnormalized neutrino fluxes
   - Flavor content

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Motivation

Interest of high energy neutrinos (HE ν)

- penetrating power + no deflection $\rightarrow$ neutrino astronomy
  - interior of stars [G. G. Raffelt, 1996, R. C. Schirato and G. M. Fuller, 2002]
  - distant cosmological epochs $\rightarrow$ relic neutrino absorption spectroscopy

    [B. Eberle, A. Ringwald, L. Song and T. Weiler, 2004]
  - origin of UHECRs $\rightarrow$ characterize astrophysical sources

    [L. A. Anchordoqui, H. Goldberg, F. Halzen and T. J. Weiler, 2005, T. Kashti and E. Waxman, 2005,

    M. Ahlers, L. A. Anchordoqui, H. Goldberg, F. Halzen, A. Ringwald, and Th. J. Weiler, 2005]

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- penetrating power + no deflection $\rightarrow$ neutrino astronomy
- ν conversion from the source to the detector $\rightarrow$ ν properties
  - mixing angles [H. Athar, M. Jezabek and O. Yasuda, 2000, P. Bhattacharjee and N. Gupta, 2005, P. D. Serpico and M. Kachelrieß, 2005, M. C. González-García, F. Halzen and M. Maltoni, 2005, P. Serpico, 2005]
  - *CP* phase [P. D. Serpico and M. Kachelrieß, 2005, W. Rodejohann, 2007]
  - ν decay [J. F. Beacom et al, 2002, G. Barenboim and C. Quigg, 2003, D. Meloni and T. Ohlsson, 2006]
  - + terrestrial experiments $\rightarrow$mass hierarchy [W. Winter, 2006]

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- big ν detection volume : ICECUBE, Auger, Anita, ...
  - flavor determination

    [D. Fargion, 1997, S. I. Dutta, M. H. Reno and I. Sarcevic, 2000, J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa and T. J. Weiler, 2003]

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- large HE ν fluxes
  - top-down models:
    - topological defects: disfavoured by EGRET and spectral shape of UHECRs
    - SHDM : disfavoured by the absence of γ at high energies and galactic anisotropy

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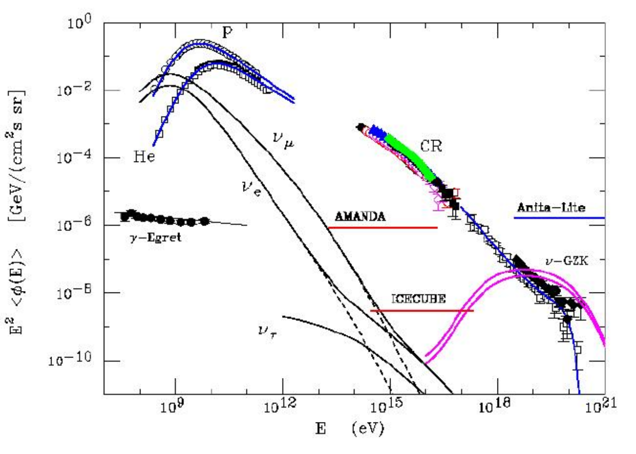
- large HE ν fluxes
  - top-down models:
    - topological defects: disfavoured
    - SHDM : disfavoured
  - bottom-up models $\longrightarrow$ astrophysical sources $\longrightarrow$ optically thick

Astrophysical sources

Limits



[P. Lipari, 2006]

Astrophysical sources

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Waxman-Bahcall upper limit on high energy ν fluxes [E. Waxman and J. N. Bahcall, 1999]
$\longrightarrow E^2\phi_\nu(E) \lesssim 10^{-8}$ GeV/cm^{2}s sr

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only applies to optically thin sources
$\downarrow$

- is it possible to get large HEν fluxes from optically thick sources?
- do they have any special feature?

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  - thick ($\tau \gtrsim 1$) $\rightarrow$ multiple scattering suppresses CR flux

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- strongly energy dependent flavor ratio $\rightarrow$ a bump shows up

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Optically thick sources

- Transparent sources: accelerated protons interact once with the surrounding material $\rightarrow$ relationship $\nu \leftrightarrow$ UHECR $\leftrightarrow \gamma$'s
  optical depth $\tau \equiv L/l_{\rm int} < 1$

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  - cocooned black hole [V. S. Berezinsky and V. L Ginzburg, 1987]
  - cores of AGNs [F. Stecker, C. Done, M. Salamon and P. Sommers, 1991]
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Optically thick sources as neutrino sources

Our Monte Carlo simulation

source: phenomenological characterization

- injected protons $\mathrm{d}N/\mathrm{d}E \propto E^{-\alpha}$ $\longrightarrow$ ($\alpha = 2.2$, $E_{\max} = 10^{24}$ eV)
- slab with
  - −protons
  - −thermal photons $\longrightarrow$
    - – size L
    - – temperature T
    - – magnetic field negligible

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interactions: SOPHIA [A. Mücke *et al.*, 2000] and HERWIG [G. Corcella *et al.*, 2001]

$p + \gamma \rightarrow$ secondary mesons
- $\pi \rightarrow \mu + \nu_\mu \rightarrow e + \nu_e + \nu_\mu + \nu_\mu$
- $K^{\pm} \rightarrow \mu + \nu_\mu \ ,\ \pi^{\pm} + \pi^0 \ ,\ \ldots$
- $K_L^0 \rightarrow \pi + e + \nu_e \ ,\ \pi + \mu + \nu_\mu \ ,\ \ldots$
- charm mesons decay

↓

High Energy Neutrinos

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Neutrino Yield: $Y_\nu = \frac{J_\nu(E)}{\tau J_p(E)}$ [V. S. Berezinsky and V. V. Volynsky, 1979, V. S. Berezinsky and A. Z. Gazizov, 1993]

transparent source $\tau < 1$

$Y_\nu = Y_\nu(x)$, *dimensionless energy* $x \equiv \frac{E\omega}{m_p^2}$, $\omega = 1.6T$

- contribution: mainly from π decays: $\pi \to \mu + \nu_\mu \to e + \nu_e + 2\nu_\mu$

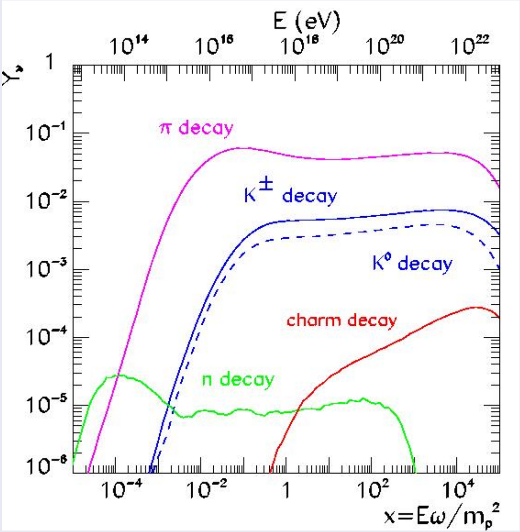
contributions

mainly

- π decay
- neutron decay

(at low energies)

$T = 10^4$ K, $\tau = 0.4$



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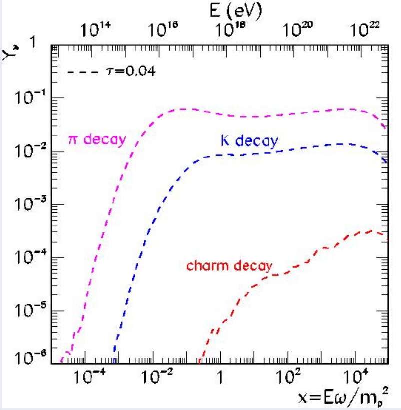
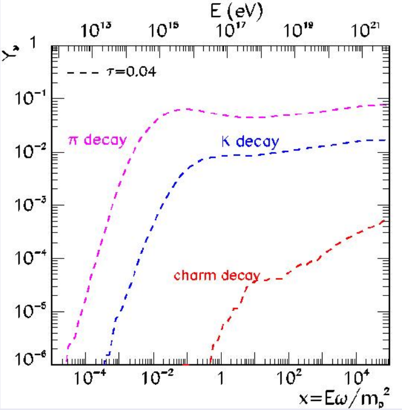


$T = 10^5$ K



independent of T

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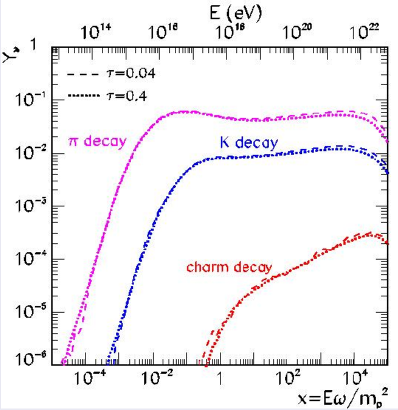

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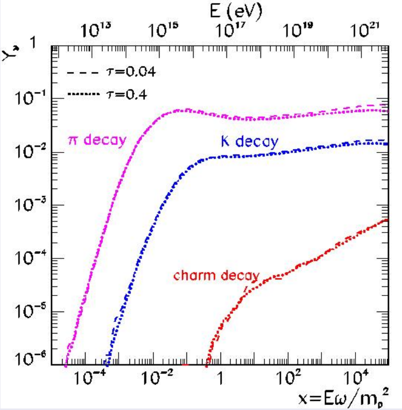

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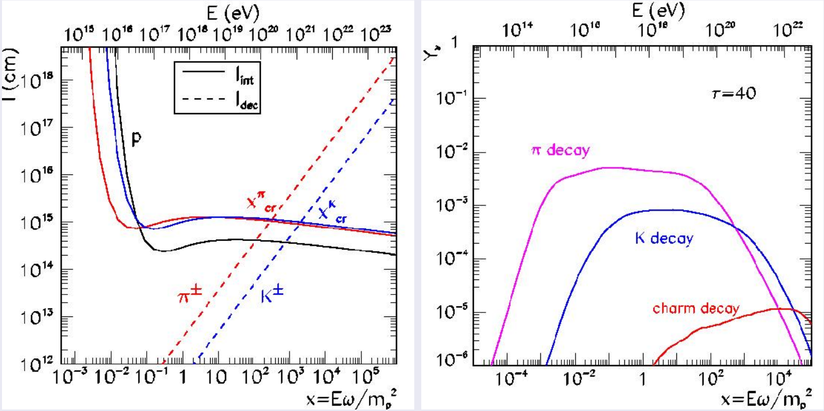
optically thick sources $\tau \gtrsim 1$

multiple scattering important $\to$ critical energy $x_\mathrm{cr}^{\pi,K}(T)$: $l_\mathrm{decay} = l_\mathrm{int}$

- contribution depends on the energy
  - $x < x_\mathrm{cr}^\pi \longrightarrow$ pion decay
  - $x_\mathrm{cr}^\pi \lesssim x \lesssim x_\mathrm{cr}^K \to K$ decay
  - $x_\mathrm{cr}^K < x \longrightarrow$ charm meson decay

$T = 10^4$ K, $\tau = 40$



- $x < x^{\pi}_{\rm cr} \rightarrow$ pion decay dominates
- $x^{\pi}_{\rm cr} \lesssim x \lesssim x^{K}_{\rm cr} \rightarrow \pi$'s scatter before decaying $\Rightarrow$ K decay important
- $x^{K}_{\rm cr} < x \rightarrow K$'s scatter before decaying $\Rightarrow$ charm meson decay dominates

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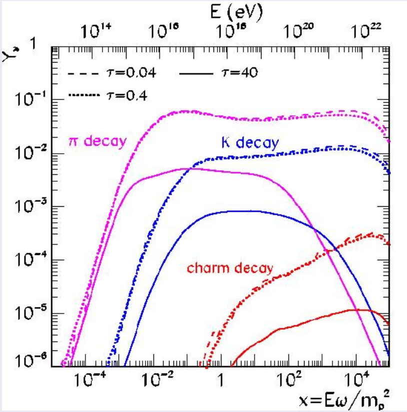
- Y_ν depends on T : $x_{\rm cr}^{\pi} \approx 2 \times 10^{10}/(T/{\rm K})^2$

$T = 10^4$ K



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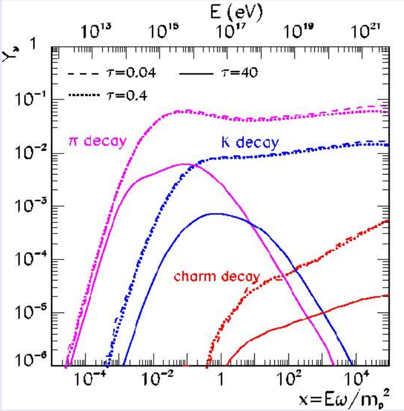

Large HE ν flux if

- opaque sources ($\tau \gtrsim 1 \Rightarrow L \gtrsim l^p_{\rm int}$) to avoid the WB upper limit
- not very high temperature ($E_{\rm cr} \propto 1/T^3$)

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Unnormalized Neutrino Spectra: thickness

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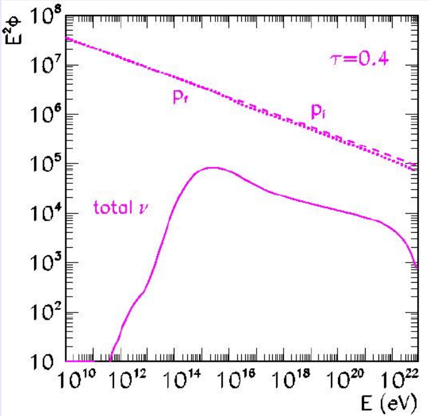

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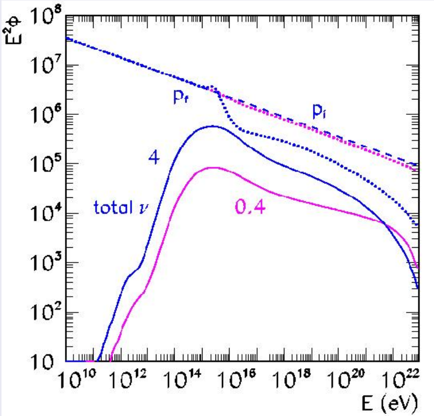

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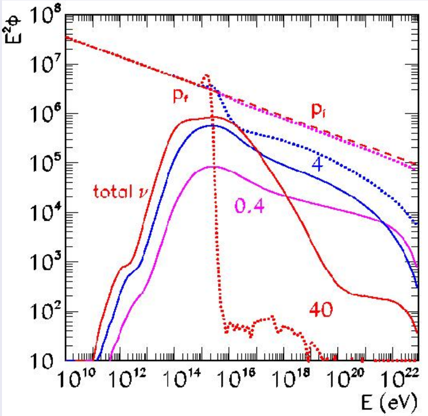

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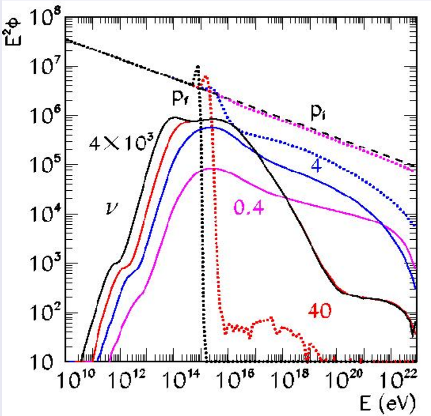

$\tau \gtrsim 1 \Longrightarrow$ cosmic ray suppression

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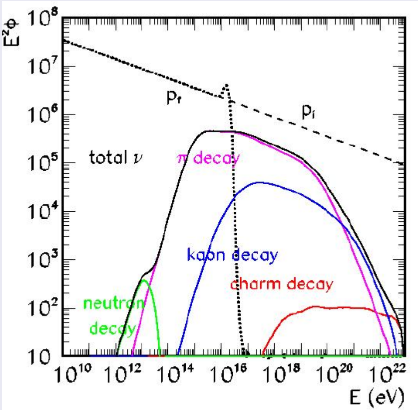
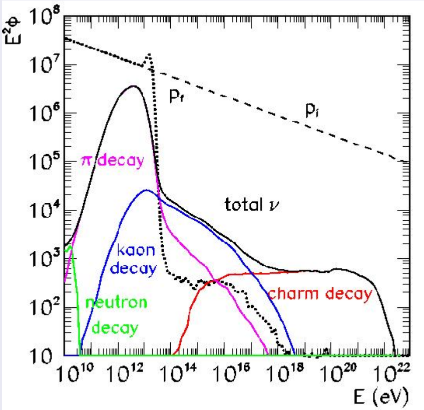


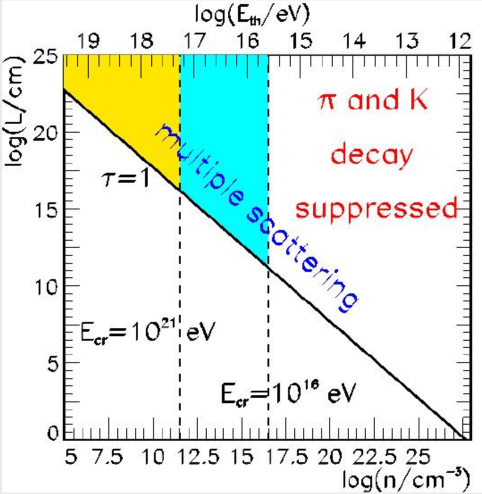
$T = 10^7$ K



high temperature $\Longrightarrow$ high-energy ν flux suppression

Conditions for large HEν fluxes

opaque source ($\tau \gtrsim 1$) and not too dense



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Flavor content $(\phi_{\nu_e}, \phi_{\nu_\mu}, \phi_{\nu_\tau})$

Motivation

- *measurable* in ν telescopes and extensive air shower experiments

  [J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa and T. J. Weiler, 2003, D. Fargion, 1997, S. I. Dutta, M. H. Reno and I. Sarcevic, 2000]

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- interesting applications
  - astrophysical diagnostics: characterize sources

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Example

- pion decay $\rightarrow$ (1,2,0)
- neutron beam source $\rightarrow$ (1,0,0) [L. A. Anchordoqui *et al.*, 2003, P. D. Serpico and M. Kachelrieß, 2005]
- muon-damped ν_μ sources from π decay $\rightarrow$ (0,1,0)

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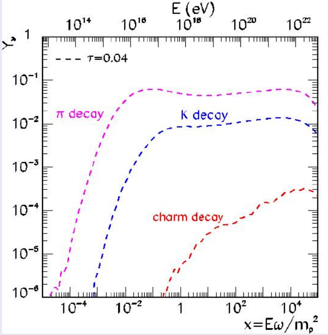
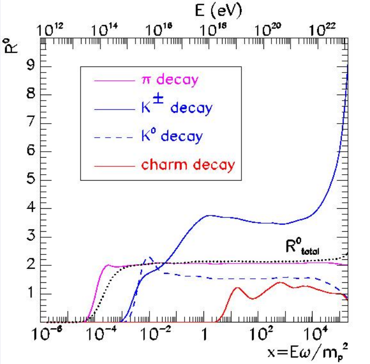
- optically thick sources $\rightarrow (\phi_{\nu_e}, \phi_{\nu_\mu}, \phi_{\nu_\tau})$?

Flavor Content at the source

Flavor ratio: $R^0 = \phi_{\nu_\mu}/(\phi_{\nu_e} + \phi_{\nu_\tau})$

- depends on the reaction → optically thin source: $R^0 = R_\pi \approx 2$





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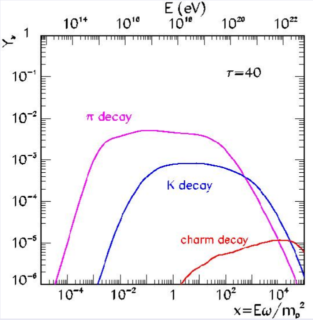
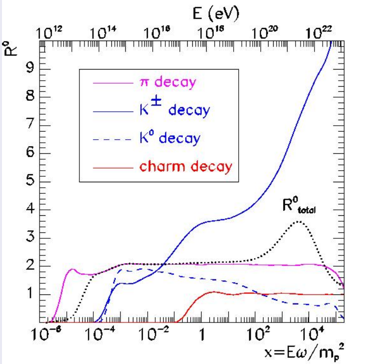
- optically thick sources: strong energy dependence
  - $x < x_{cr}^{\pi} \rightarrow R^0 = R_\pi \approx 2$
  - $x_{cr}^{\pi} \lesssim x \lesssim x_{cr}^{K} \rightarrow R^0 = R_K > 2 \Rightarrow$ bump
  - $x_{cr}^{K} < x \rightarrow R^0 = R_{ch} \approx 1$





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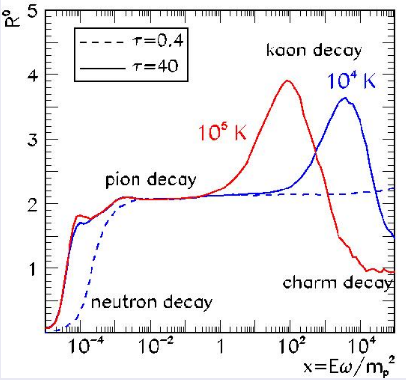
  - $x < x_{\rm cr}^\pi \rightarrow R^0 = R_\pi \approx 2$
  - $x_{\rm cr}^\pi \lesssim x \lesssim x_{\rm cr}^K \rightarrow R^0 = R_K > 2$
  - $x_{\rm cr}^K < x \rightarrow R^0 = R_{\rm ch} \approx 1$

$\Downarrow$

bump at $x \approx x_{\rm cr}^K$

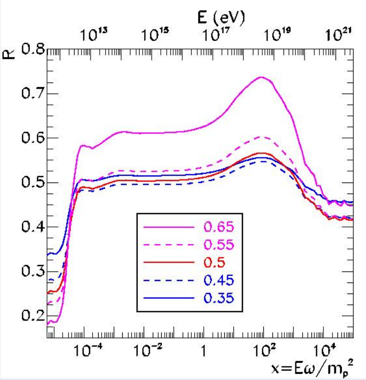


Flavor Content at the Earth

Flavor ratio: $R^0 + \nu$ oscillation $\rightarrow R = \phi^D_{\nu_\mu}/(\phi^D_{\nu_e} + \phi^D_{\nu_\tau})$

$\phi^D_{\nu_\alpha} = \sum_\beta P_{\alpha\beta}\phi_{\nu_\beta} \Rightarrow R$ depends on the ν mixing parameters (θ_{ij}, δ_{CP})

mainly on θ_{23}



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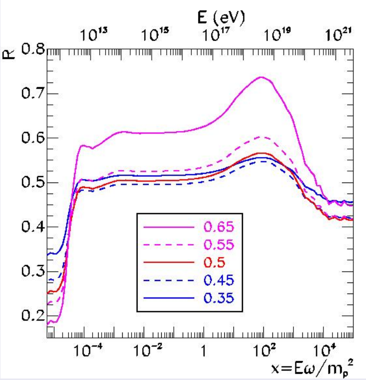
$\Downarrow$

presence of a bump $\rightarrow$ information on

- source: cross-over $\pi - K$ decay
- ν's: sensitivity to the θ_{23} octant



Summary

High Energy Neutrinos

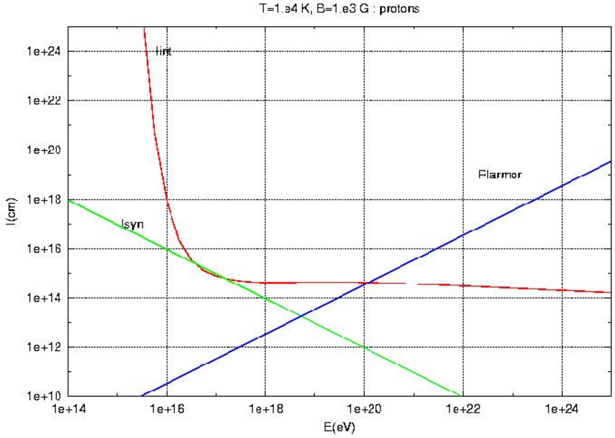
- penetrating power + no deflection $\rightarrow$ ideal astronomical messengers: UHECRs sources, ...
- complementary source of ν's $\rightarrow$ neutrino properties: mixing, *CP*, ...

$\downarrow$

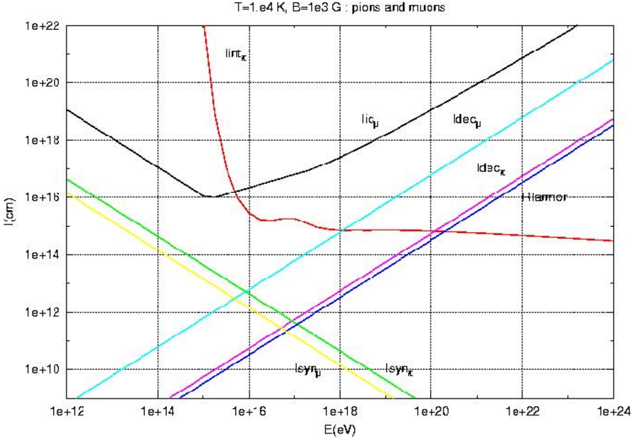
Optically Thick Sources

- Neutrino yield
  - multiple scattering $\Rightarrow$ WB limit avoided
  - if density is too high $\Rightarrow$ HEν's from π and K decay suppressed
- Flavor ratio depends strongly on the energy
  - bump shows up at the cross-over between π and K

Presence of magnetic fields (work in progress ...)



Presence of magnetic fields (work in progress ...)



Neutrino Spectra

Assumptions:

- injected proton spectrum:

$$\mathrm{d}N_\mathrm{p}/\mathrm{d}E \propto E^{-\alpha} \begin{cases} \alpha = 2 & , \; E < 10^{-18}\ \mathrm{eV} \\ \alpha = 2.7 & , \; E > 10^{-18}\ \mathrm{eV} \end{cases}$$

[V. Berezinsky, A. Gazizov and S. Grigorieva, 2004]

- source: homogeneous slab filled with thermal photons

characterized by $\begin{cases} T = 10^4\ \mathrm{K},\ \ldots\ ,\ 10^7\ \mathrm{K} \\ L = 10^{10}\ \mathrm{cm},\ \ldots,,10^{16}\ \mathrm{cm} \end{cases}$

Diffuse neutrino spectra from uniform sources

$$F_\nu(E) = \frac{1}{4\pi} \int_0^\infty \frac{dz}{H(z)} \mathcal{L}_\nu(z, E_g)$$

- $\mathcal{L}_\nu(z, E_g)$: number of ν's emitted per comoving volume, time and energy with generation energy $E_g = E(1+z)$

$$\mathcal{L}_\nu(z, E_g) = \eta(z) J_\nu(Eg)$$

  - $J_\nu(Eg)$: neutrino spectra from a single source
  - $\eta(z)$: number of sources per co-moving volume and per unit of time

- $H(z)$: Hubble parameter, $H(z)^2 = H_0^2[\Omega_m(1+z)^3 + \Omega_\Lambda]$

Constraints

- UHECR spectrum (AGASA) $\Rightarrow$ limits on the proton spectra emitted $\Rightarrow J_\nu(E) \rightarrow$ optically thin sources

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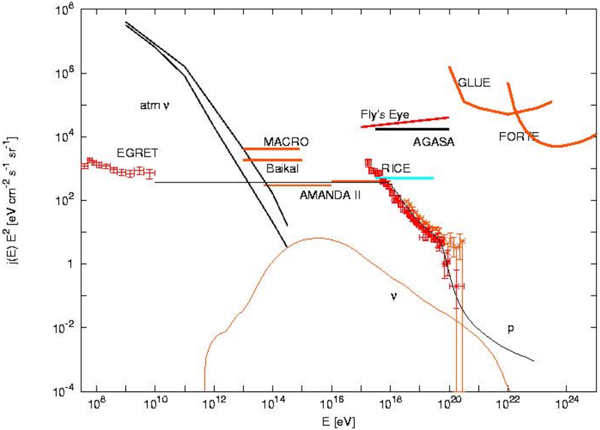
- UHECR spectrum (AGASA) $\Rightarrow$ limits on the proton spectra emitted $\Rightarrow J_\nu(E) \rightarrow$ optically thin sources
- current limits on ν fluxes (AMANDAII) $\rightarrow$ sources with $\tau \gtrsim 1$
- EGRET observations $\Rightarrow$ limits on the electromagnetic cascade produced:

$$\omega_{\rm cas} = f_{\rm em} E_{\rm tot} \int_0^\infty \frac{{\rm d}z}{H(z)} \eta(z) \leq \omega_{\rm obs} = 2 \times 10^{-6}\ {\rm eV/cm^3}$$

[R. Aloisio, V. Berezinsky and M. Kachelrieß, 2004]

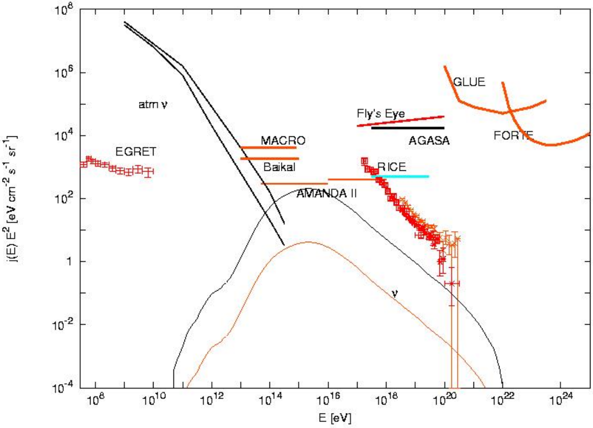
Constraints

$T = 10^5$ k and $\tau << 1$



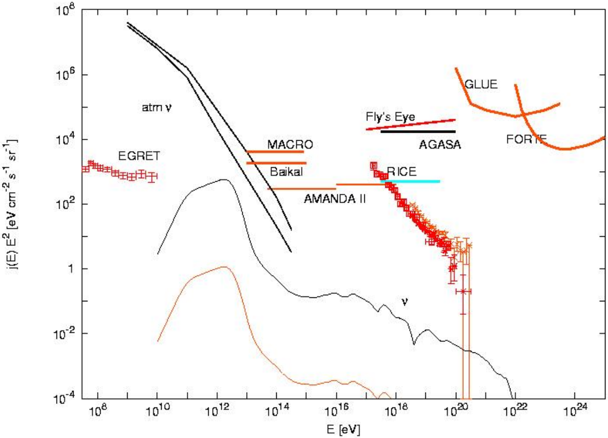
Constraints

$$T = 10^5 \text{ k and } \tau \gtrsim 1$$



Constraints

$$T = 10^7 \text{ k and } \tau \gg 1$$



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