Neutrino Flavor Ratios Modified by Cosmic Ray Secondary-acceleration

ref.) NK & Ioka 2015, PRD accepted (arXiv:1504.03417)

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High Energy Neutrinos and Cosmic Rays

- IceCube: 54 events in 30 TeV – 2 PeV
- TeV-PeV neutrinos = the probe of high energy CRs
- emitted via interactions between accelerated CR protons and (1) ambient matter or (2) photon field

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

or $$\pi^- \to \mu^- + \bar{\nu}_\mu \to e^- + \bar{\nu}_\mu + \nu_e + \nu_\mu$$

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

roughly speaking ↓

- Cosmic ray accelerator = HE neutrino factory
- flavor ratio at a source… $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

Neutrino Flavor Ratio at the Earth

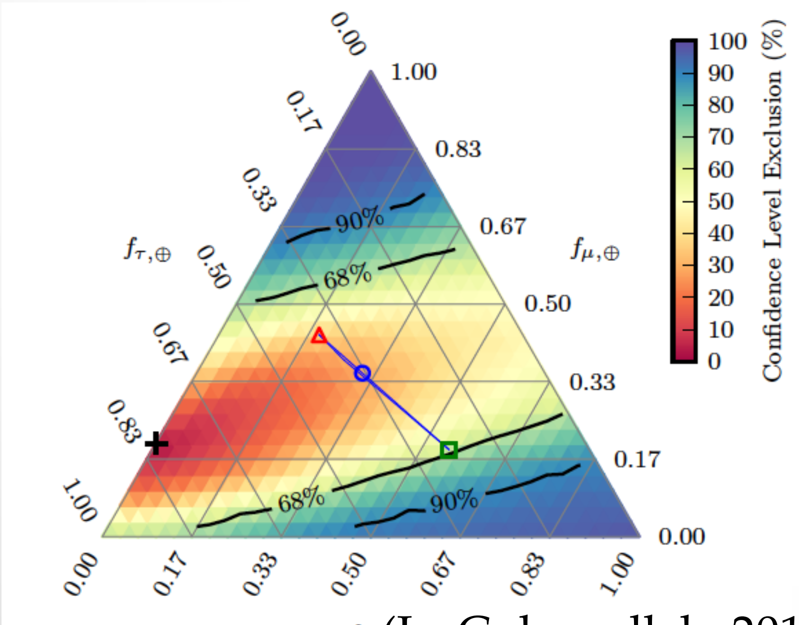
$$\Phi_{\nu_\alpha} = \sum_\beta P_{\alpha\beta}\Phi^0_{\nu_\beta} = \sum_\beta \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2 \Phi^0_{\nu_\beta}$$

observed

intrinsic

mixing matrix

→ For initial flux ratio $\Phi^0_{\nu_e} : \Phi^0_{\nu_\mu} : \Phi^0_{\nu_\tau} = 1:2:0$,
the observed ratio is expected to be $\Phi_{\nu_e} : \Phi_{\nu_\mu} : \Phi_{\nu_\tau} \approx 1:1:1$



(IceCube collab. 2015)

Recent results of IceCube (35 TeV – 2 PeV)
… consistent with
$\Phi_{\nu_e} : \Phi_{\nu_\mu} : \Phi_{\nu_\tau} \approx 1:1:1$

(The best fit value is 0 : 0.2 : 0.8)

Modification of Neutrino Flavor Ratio

1. Synchrotron/IC cooling of π/μ

π/μ would lose their energy before they decay into ν_i
→ The neutrino spectra would be softened, and the flavor ratio is also affected (Kashti & Waxman 2005, etc.)

2. Re-acceleration of π/μ ← this talk

π/μ would be accelerated by shocks and/or turbulence before they decay into ν_i
→ The neutrino spectra and flavor ratio would be modified! (Winter et al. 2014, etc.)

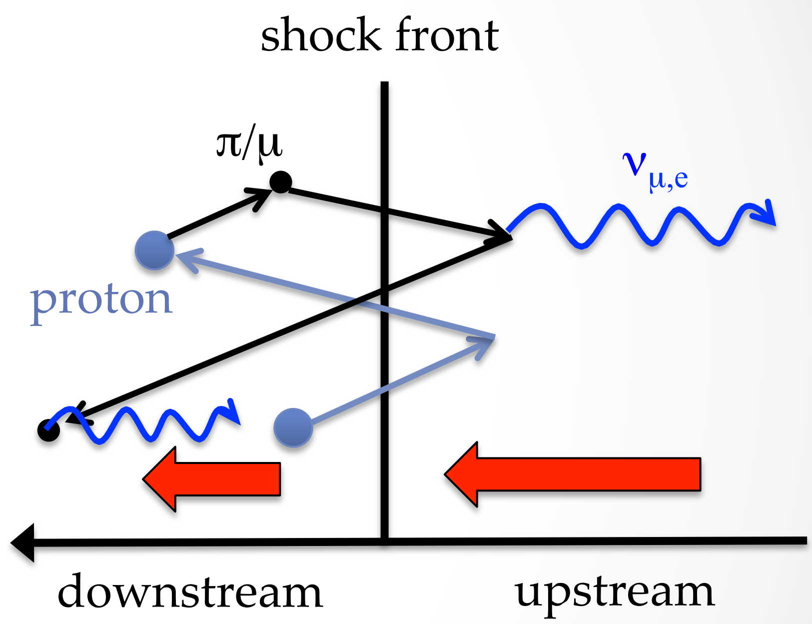
The neutrino spectra and flavor ratio will tell us some important properties of CR accelerators (magnetic field, acceleration process, etc.)

Re-acceleration of Secondary CRs (π/μ)

shock acceleration of primary protons
→ secondary π/μ production

→ π/μ are reaccelerated at the shock before their decay
($\tau_\pi=2.6\times10^{-8}\gamma_\pi$ s, $\tau_\mu=2.2\times10^{-6}\gamma_\mu$ s)

→ The energy spectra of π/μ would be harder than those of their primary particles



Stochastic acceleration is also possible (Murase et al. 2012).

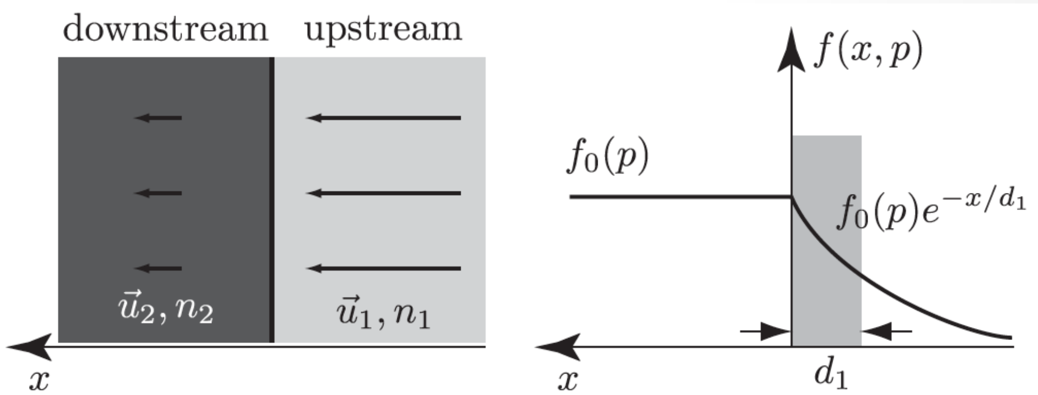
Re-acceleration of secondary π

Convection-Diffusion equation for the distribution function f_π
(one-dimensional, stationary, neglecting synchrotron cooling)

$$u\frac{\partial f_\pi}{\partial x} = \underbrace{\frac{\partial}{\partial x}\left[D(p)\frac{\partial f_\pi}{\partial x}\right]}_{\text{diffusion}} + \frac{p}{3}\frac{du}{dx}\frac{\partial f_\pi}{\partial p} \underbrace{- \frac{f_\pi}{\tau_\pi}}_{\text{decay}} + \underbrace{Q_\pi(x,p)}_{\text{source term}},$$

velocity field:

$$u(x) = \begin{cases} u_1 & (x \le 0), \\ u_2 & (x > 0), \end{cases}$$



source term: proportional to the distribution of primary protons

$$Q_\pi(x,p) = \begin{cases} Q_{\pi,0}(p)\exp\left[xu_1/D(p_{\rm p})\right] & (x \le 0), \\ Q_{\pi,0}(p) & (x > 0), \end{cases}$$

- $p \approx \xi_\pi p_{\rm p}$ $(\xi_\pi \approx 0.2)$

In the following discussion we assume Bohm diffusion ($D(p) \propto p$)

Solve the Transport Equation of π

upstream

$$f_{\pi,-} = \left[f_{\pi,0} - \frac{DQ_{\pi,0}}{D/\tau_\pi + (\xi_\pi - \xi_\pi^2)u_1^2} \right] \exp\left(\frac{\sqrt{u_1^2 + 4D/\tau_\pi} + u_1}{2D} x \right)$$

$$+ \frac{DQ_{\pi,0}}{D/\tau_\pi + (\xi_\pi - \xi_\pi^2)u_1^2} \exp\left(\frac{\xi_\pi u_1}{D} x \right),$$

downstream

$$f_{\pi,+} = (f_{\pi,0} - Q_{\pi,0}\tau_\pi) \exp\left(-\frac{\sqrt{u_2^2 + 4D/\tau_\pi} - u_2}{2D} x \right) + Q_{\pi,0}\tau_\pi.$$

at the shock front:

$$f_{\pi,0}(p) = \gamma B_\pi \int_0^p \frac{dp'}{p'} \left(\frac{p'}{p} \right)^{\gamma A_\pi} \frac{D(p') Q_{\pi,0}(p')}{u_1^2}. \sim \frac{D(p)}{u_1^2} Q_{\pi,0}(p)$$

$\frac{D(p)}{u_1^2} = t_{\rm acc}$

A_π, B_π: p-independent factors

Re-acceleration of secondary μ

Convection-Diffusion equation for the distribution function f_μ

$$u\frac{\partial f_\mu}{\partial x} = \underbrace{\frac{\partial}{\partial x}\left[D(p)\frac{\partial f_\mu}{\partial x}\right]}_{\text{diffusion}} + \frac{p}{3}\frac{du}{dx}\frac{\partial f_\mu}{\partial p} \underbrace{- \frac{f_\mu}{\tau_\mu}}_{\text{decay}} + \underbrace{Q_\mu(x,p)}_{\text{source term}},$$

source term : proportional to the distribution of primary particles, f_π (shown in the last slide):

$$Q_\mu = \frac{1}{\xi_\mu} \cdot \frac{f_\pi(x, p/\xi_\mu)}{\tau_\pi(p/\xi_\mu)}, \quad \xi_\mu \approx 0.75$$

Solve the Transport Equation of μ

upstream & downstream

$$f_{\mu,-} = \left(f_{\mu,0} - \frac{4Dq^-_{\mu,\mathrm{a}}}{(u_1^2+4D/\tau_\mu) - (\xi_\mu\sqrt{u_1^2+4D/\tau_\pi} - (1-\xi_\mu)u_1)^2} - \frac{Dq^-_{\mu,\mathrm{b}}}{D/\tau_\pi + (\xi_\mu\xi_\pi - \xi_\mu^2\xi_\pi^2)u_1^2} \right) \exp\left(\frac{\sqrt{u_1^2+4D/\tau_\mu}+u_1}{2D} x \right)$$
$$+ \frac{4Dq^-_{\mu,\mathrm{a}}}{(u_1^2+4D/\tau_\mu) - (\xi_\mu\sqrt{u_1^2+4D/\tau_\pi} - (1-\xi_\mu)u_1)^2} \exp\left(\frac{\xi_\mu(\sqrt{u_1^2+4D/\tau_\pi}+u_1)}{2D} x \right)$$
$$+ \frac{Dq^-_{\mu,\mathrm{b}}}{D/\tau_\pi + (\xi_\mu\xi_\pi - \xi_\mu^2\xi_\pi^2)u_1^2} \exp\left(\frac{\xi_\mu\xi_\pi u_1}{D} x \right), \qquad \text{(A5)}$$

$$f_{\mu,+} = \left(f_{\mu,0} - \frac{4Dq^+_{\mu,\mathrm{a}}}{(u_2^2+4D/\tau_\mu) - (\xi_\mu\sqrt{u_2^2+4D/\tau_\pi} + (1-\xi_\mu)u_2)^2} - q^+_{\mu,\mathrm{b}}\tau_\mu \right) \exp\left(-\frac{\sqrt{u_2^2+4D/\tau_\mu}-u_2}{2D} x \right)$$
$$+ \frac{4Dq^+_{\mu,\mathrm{a}}}{(u_2^2+4D/\tau_\mu) - (\xi_\mu\sqrt{u_2^2+4D/\tau_\pi} + (1-\xi_\mu)u_2)^2} \exp\left(-\frac{\xi_\mu(\sqrt{u_2^2+4D/\tau_\pi}-u_2)}{2D} x \right) + q^+_{\mu,\mathrm{b}}\tau_\mu . \qquad \text{(A6)}$$

at the shock front:

$$f_{\mu,0}(p) = \gamma \int_0^p \frac{dp'}{p'} \left(\frac{p'}{p}\right)^{\gamma A_\mu} \frac{D(p')}{u_1^2} \left(q^-_{\mu,\mathrm{a}}(p')B^-_{\mu,\mathrm{a}} + q^-_{\mu,\mathrm{b}}(p')B^-_{\mu,\mathrm{b}} + q^+_{\mu,\mathrm{a}}(p')B^+_{\mu,\mathrm{a}} + q^+_{\mu,\mathrm{b}}(p')B^+_{\mu,\mathrm{b}} \right).$$

- $q^{\pm}_{i,\mathrm{a}}, q^{\pm}_{i,\mathrm{b}} \sim Q_\mu$

Neutrino spectra

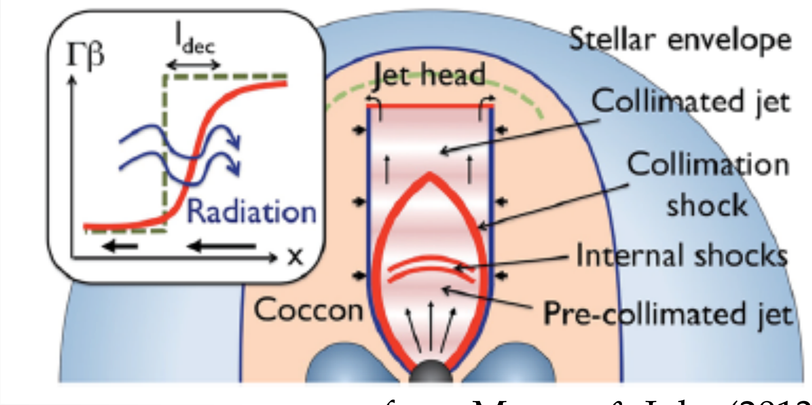
$$\Phi^0_{\nu_\mu}(p) = \int dx^3 \frac{4\pi p^2}{\xi_{\nu_\mu}} \frac{f_\pi(x, p/\xi_{\nu_\mu})}{\tau_\pi(p/\xi_{\nu_\mu})},$$

$$\Phi^0_{\bar{\nu}_\mu}(p) = \int dx^3 \frac{4\pi p^2}{\xi_{\bar{\nu}_\mu}} \frac{f_\mu(x, p/\xi_{\bar{\nu}_\mu})}{\tau_\mu(p/\xi_{\bar{\nu}_\mu})},$$

$$\Phi^0_{\nu_e}(p) = \int dx^3 \frac{4\pi p^2}{\xi_{\nu_e}} \frac{f_\mu(x, p/\xi_{\nu_e})}{\tau_\mu(p/\xi_{\nu_e})},$$

where $\xi_{\nu_\mu} \approx 0.25,\ \xi_{\bar{\nu}_\mu} \approx 0.33,\ \xi_{\nu_e} \approx 0.33$

Application: low-power GRBs



from Murase & Ioka (2013)

- IceCube observations have ruled out typical long GRBs as the main source of HE neutrinos (Abbasi+12; He+ 2012)
- Low-power GRBs (ultra-long GRBs, LLGRBs) are still not strongly constrained.

Consider the internal shocks occurring inside a star

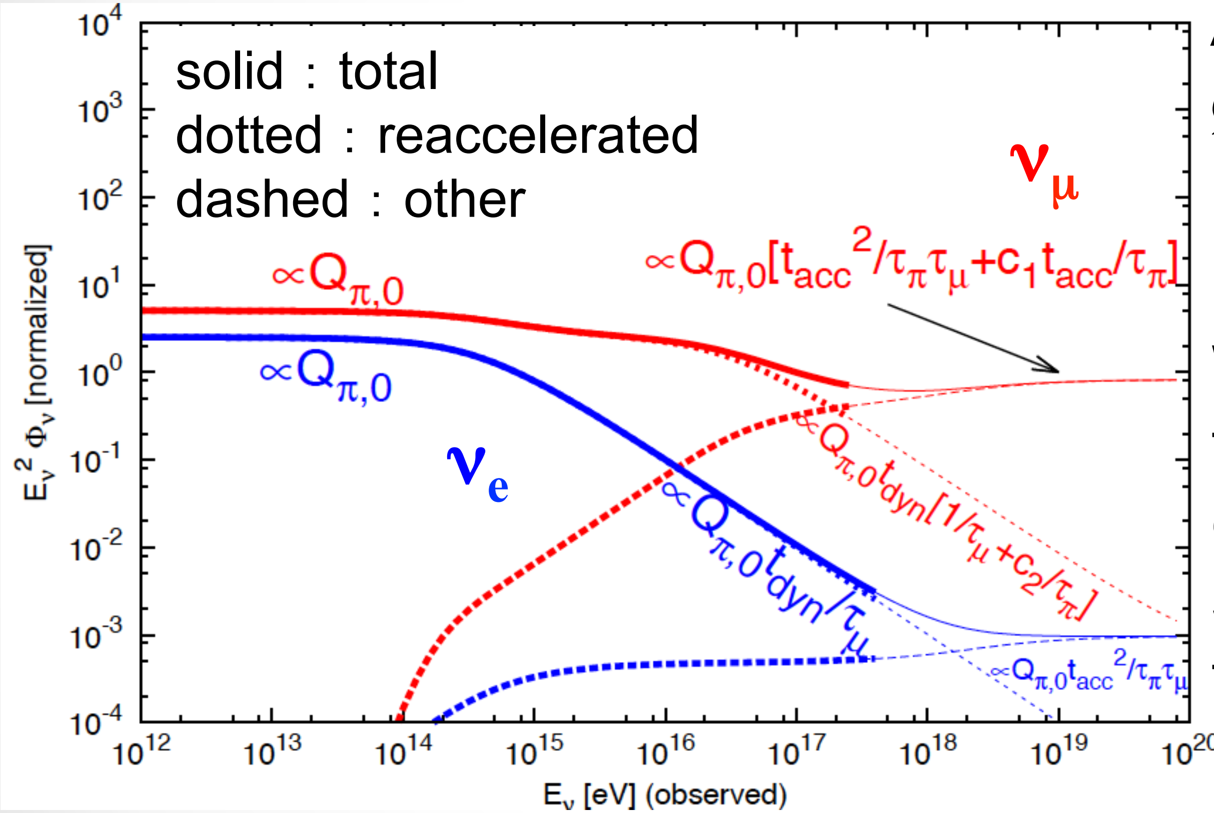
$$t_{\rm acc} = \frac{D(p)}{u_-^2} = \frac{\eta \varepsilon_i}{3ceB\beta_-^2}$$
$$\simeq 4.4 \times 10^{-5}\ {\rm s}\ \frac{\eta \varepsilon_{i,100{\rm TeV}} \Gamma_2^3 \Delta t_{\rm ms}}{L_{B,47}^{1/2} \beta_-^2},$$

$$\tau_\pi = \tau_{\pi,0} \frac{\varepsilon_\pi}{m_\pi c^2} \simeq 1.9 \times 10^{-2} {\rm s}\ \varepsilon_{\pi,100{\rm TeV}},$$
$$\tau_\mu = \tau_{\mu,0} \frac{\varepsilon_\mu}{m_\mu c^2} \simeq 2.1 {\rm s}\ \varepsilon_{\mu,100{\rm TeV}},$$

∴ π/μ can be re-accelerated before their decay

Results: neutrino spectra

(spectra at the source)

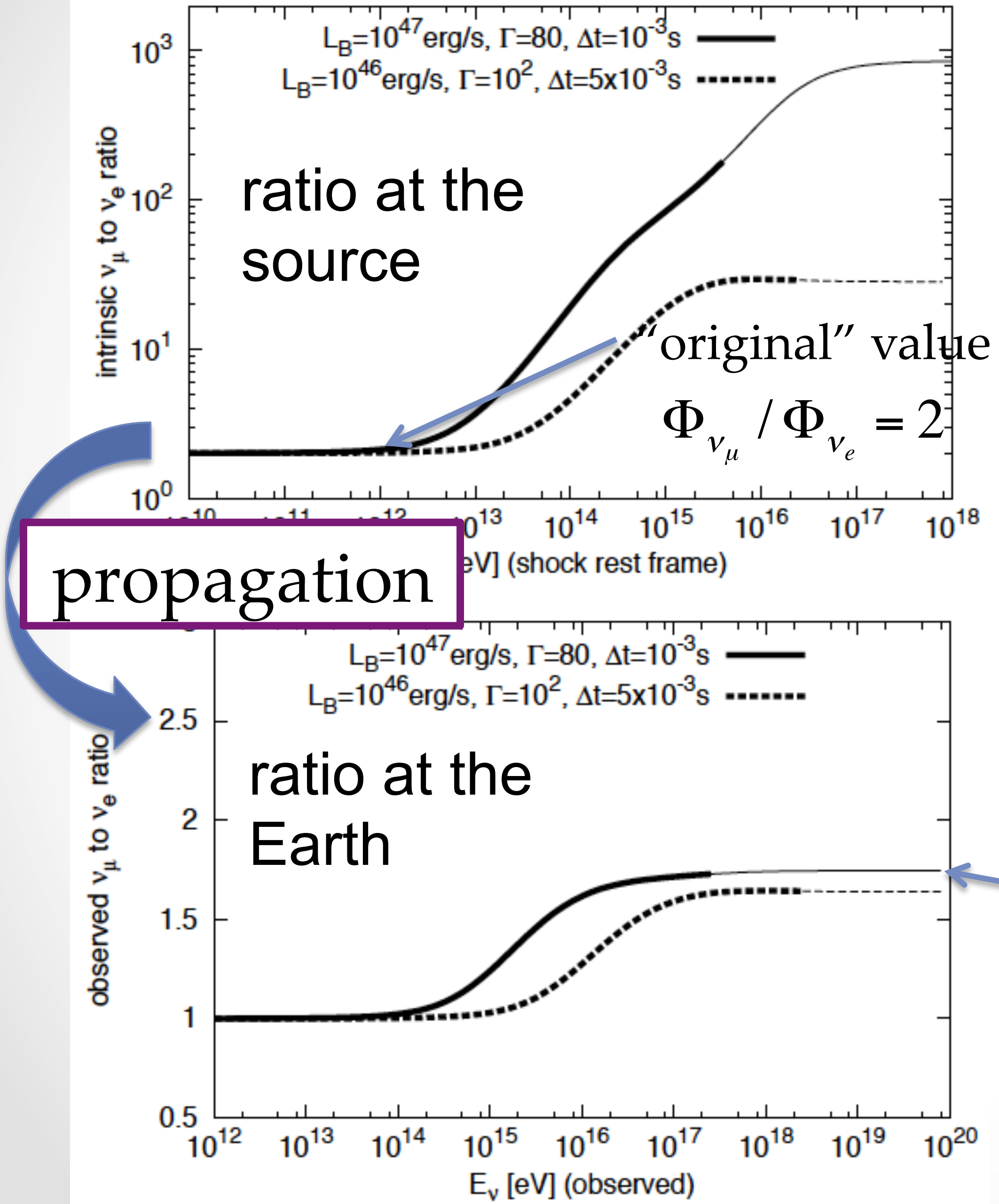


$L_B = 10^{47}$ erg/s, $\Gamma = 80$, $\Delta t = 1$ msec, $\beta_{rel} = 0.5$, $Q_\pi(E) \propto E^{-2}$

When $\tau_{\pi,\mu}$ >~ $t_{dyn} = \Gamma\Delta t$, the reaccelerated component (harder) starts to dominate over the other component → appears as a flat excess at the high energy range

- Note: E_ν >~ a few 10^{17}eV → $t_{i,syn}$ <~ t_{acc} : high energy cutoff due to the cooling of π/μ would appear

Results : flavor ratio (ν_μ:ν_e)



←The asymptotic ratio is determined from the ratio of t_{acc} to τ_μ

$$\because\ f_{\pi,acc}(x,p)/\tau_\pi \sim Q_\pi(x,p)t_{acc}/\tau_\pi$$

$$f_{\mu,acc}(x,p)/\tau_\mu \sim Q_\mu(x,p)t_{acc}/\tau_\mu$$

$$\sim[f_\pi(x,p)/\tau_\pi]\underline{t_{acc}/\tau_\mu}$$

$$\sim[Q_\pi(x,p)t_{acc}/\tau_\pi]\cdot(t_{acc}/\tau_\mu)$$

taking into account the flavor oscillation during propagation

~ 1.8 : 1 (in the limit $t_{acc}/\tau_\mu \to 0$)

→ One can constrain the acceleration timescale at the source!

Summary (for the detail, see arXiv:1504.03417)

- The spectra and flavor ratio of high energy neutrinos would be modified by the shock re-acceleration of secondary π/μ.
- The asymptotic value of the flavor ratio in the high-energy range is determined from the ratio of the acceleration timescale (t_{acc}) to the decay timescale of μ (τ_μ).
- The combination of the neutrino spectra and flavor ratio may tell us some properties of CR accelerators (especially the acceleration timescale).

various timescales

parameters: $L_B = 10^{47}$ erg/s, $\Gamma = 80$, $\Delta t = 1$ msec, $\beta_{rel} = 0.5$ (rel. velocity of colliding shells)

- t_{acc} : acceleration timescale
- $t_{i,syn}$: sync. cooling timescale
- $t_{i,IC}$: IC cooling timescale
- $t_{i,dec}$: lifetime of a particle i
- $t_{p\gamma}$: $p\gamma$ interaction timescale
- t_{dyn} : dynamical timescale

$t_{acc} >> t_{i,syn}$ when $\varepsilon_i >\sim 10^{16}$ eV
→ cooling of π/μ should be taken into account