Propagation of neutrinos in a background of ultra-light scalar field dark matter

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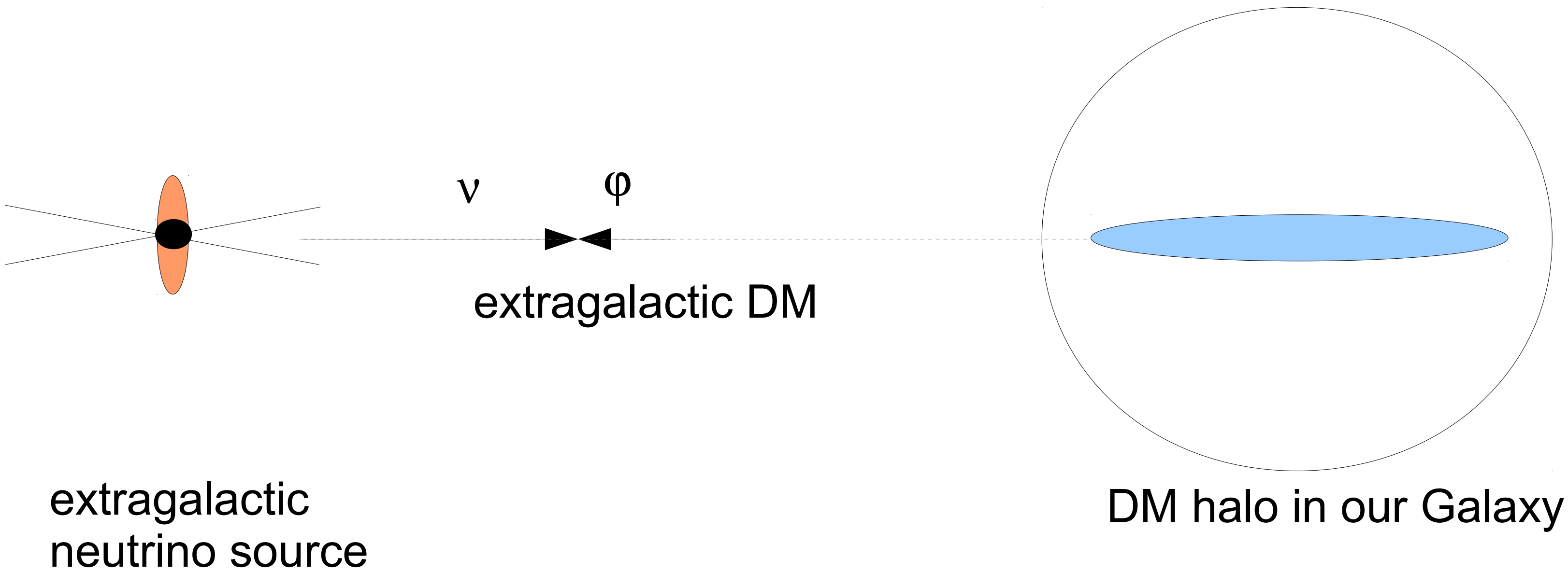
Motivation

- Ultra light scalar field particles
  - really light, m= 10^{-22}-10^{-24}eV (e.g. Hu et al. PRL 2000)
  - As dark matter, could aliviate problems of sharp cusps in galactic halos (e.g. Moore et al. 1999)

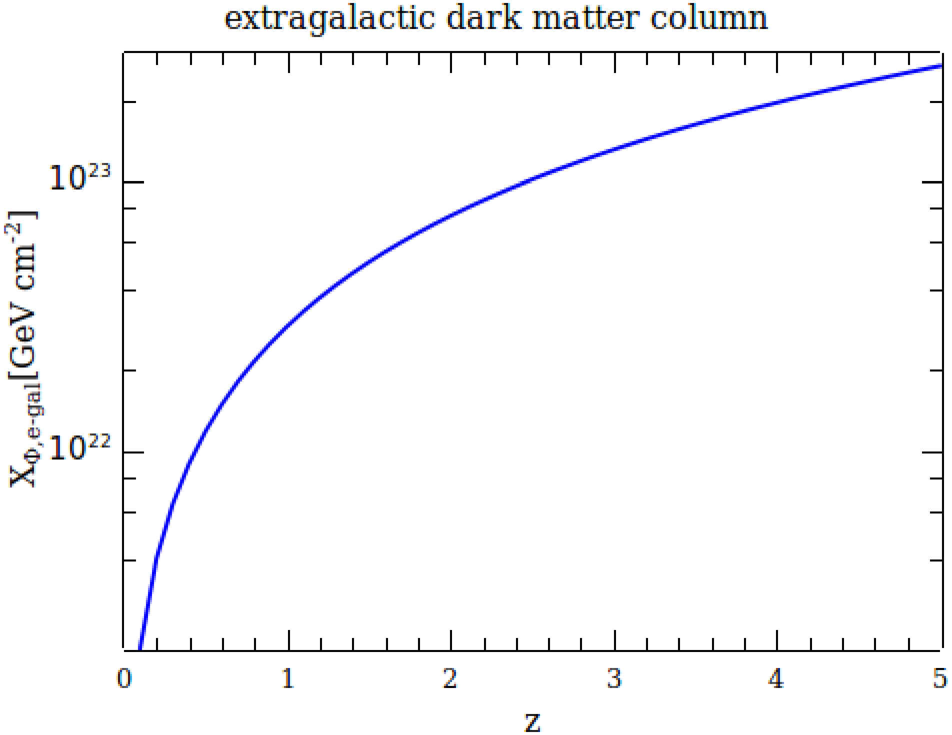
- If coupled to neutrinos (Barranco et al. JCAP 2011), the neutrino flux can be affected.

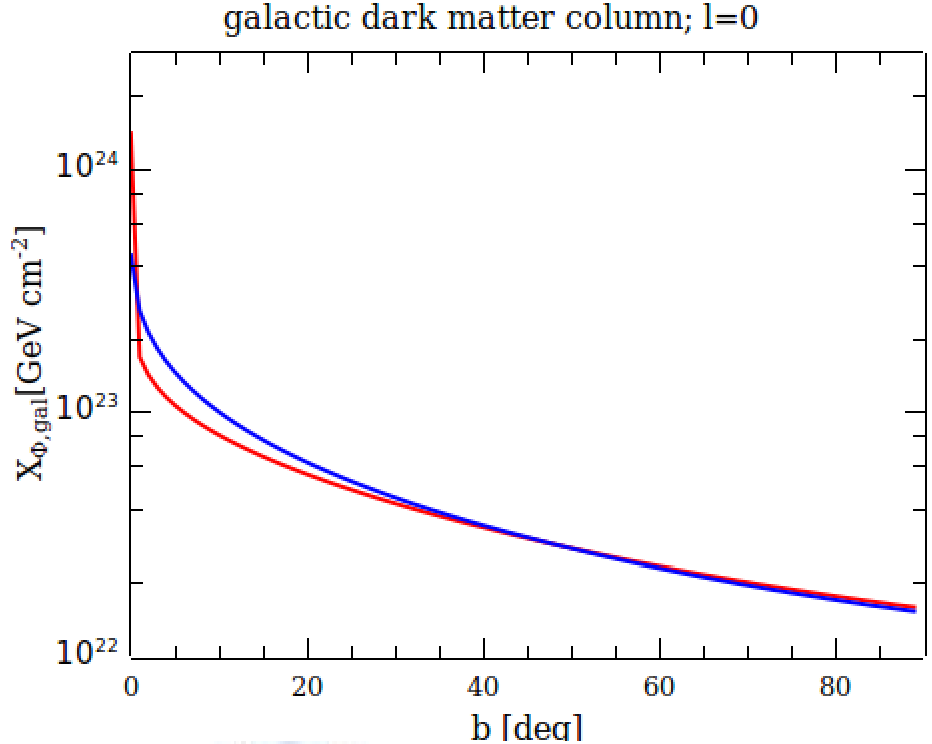
- We perform a more detailed analysis and find that in particular, the flavor ratio can be modified. This is important, considering recent IceCube results.



Galactic and extragalactic DM

As target for high energy neutrinos

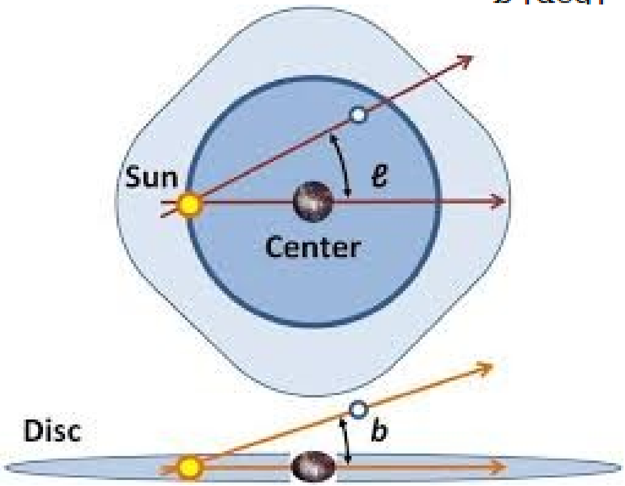




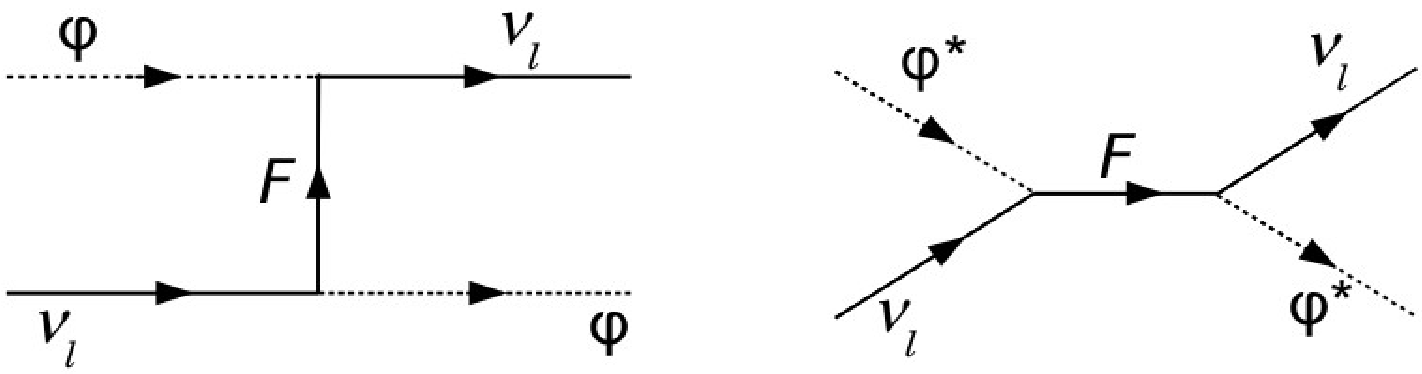
$$X_\varphi = \int dl\ n_\varphi(l)$$

$$n_\varphi^{(\text{eg})}(z) = \left[\frac{3H_0^2}{8\pi G}\right]\frac{\Omega_m}{m_\varphi}(1+z)^3$$

$$n_\varphi^{(\text{g})}(r) = \frac{\rho_0}{\frac{r}{R_0}\left(1+\frac{r}{R_0}\right)^2}$$



The neutrino-scalar particle interaction



Boehm & Fayet (2003)

If $\varphi^* \neq \varphi$, only u channel
If $\varphi^* = \varphi$, both s and u channels

$$\mathcal{M}_u = i\bar{u}_3 g_l^2 (\not{p}_3 - \not{p}_2) \frac{P_L u_1}{u - M_F^2} \qquad \mathcal{M}_s = i\bar{u}_3 g_l^2 (\not{p}_3 + \not{p}_2) \frac{P_L u_1}{s - M_F^2}$$

Coupling constants: $g_l = \{g_e, g_\mu, g_\tau\}$

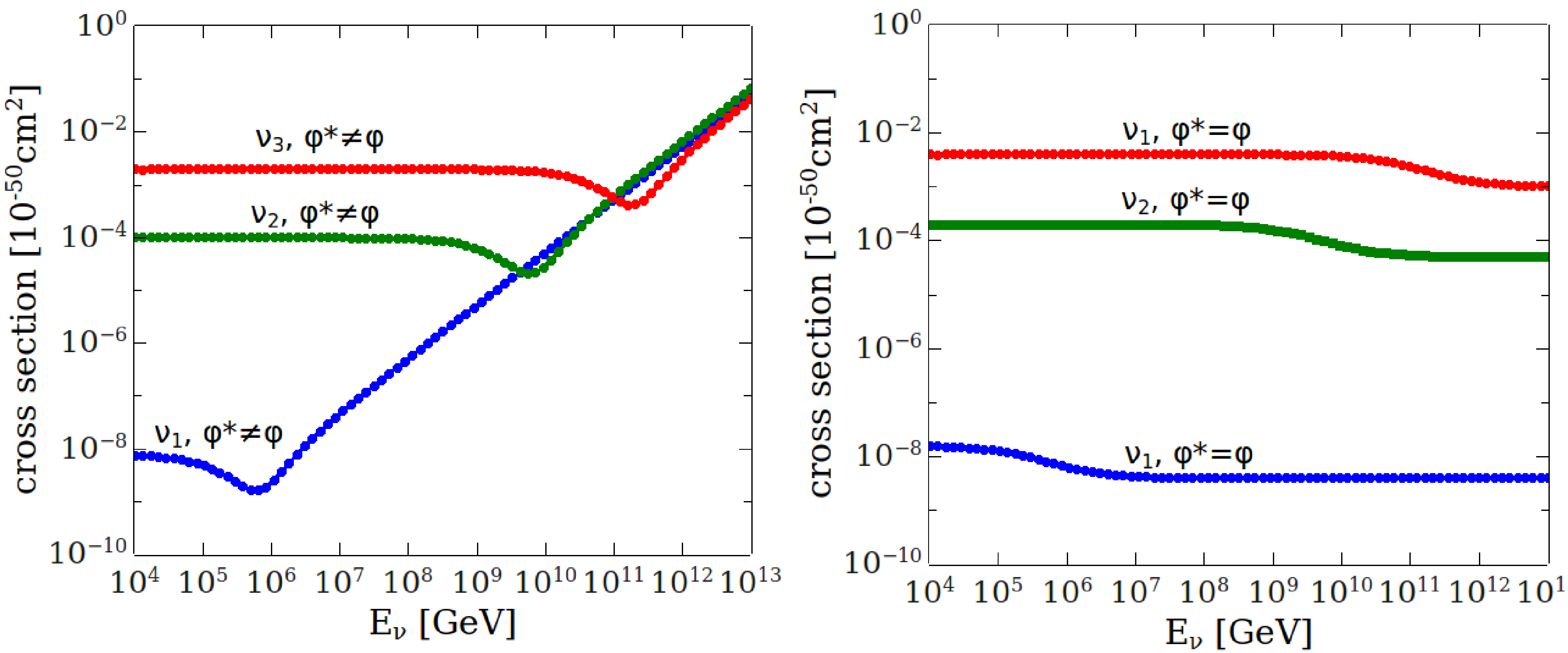
In the mass basis: $g_i = \{g_1, g_2, g_3\} = \sum_l g_l U_{li}$

Current bounds:
(Farzan & Palomarez-Ruiz 2014)

$$|g_e|^2 < 10^{-5}$$
$$|g_\mu|^2 < 10^{-4}$$
$$|g_\tau| \lesssim 1$$

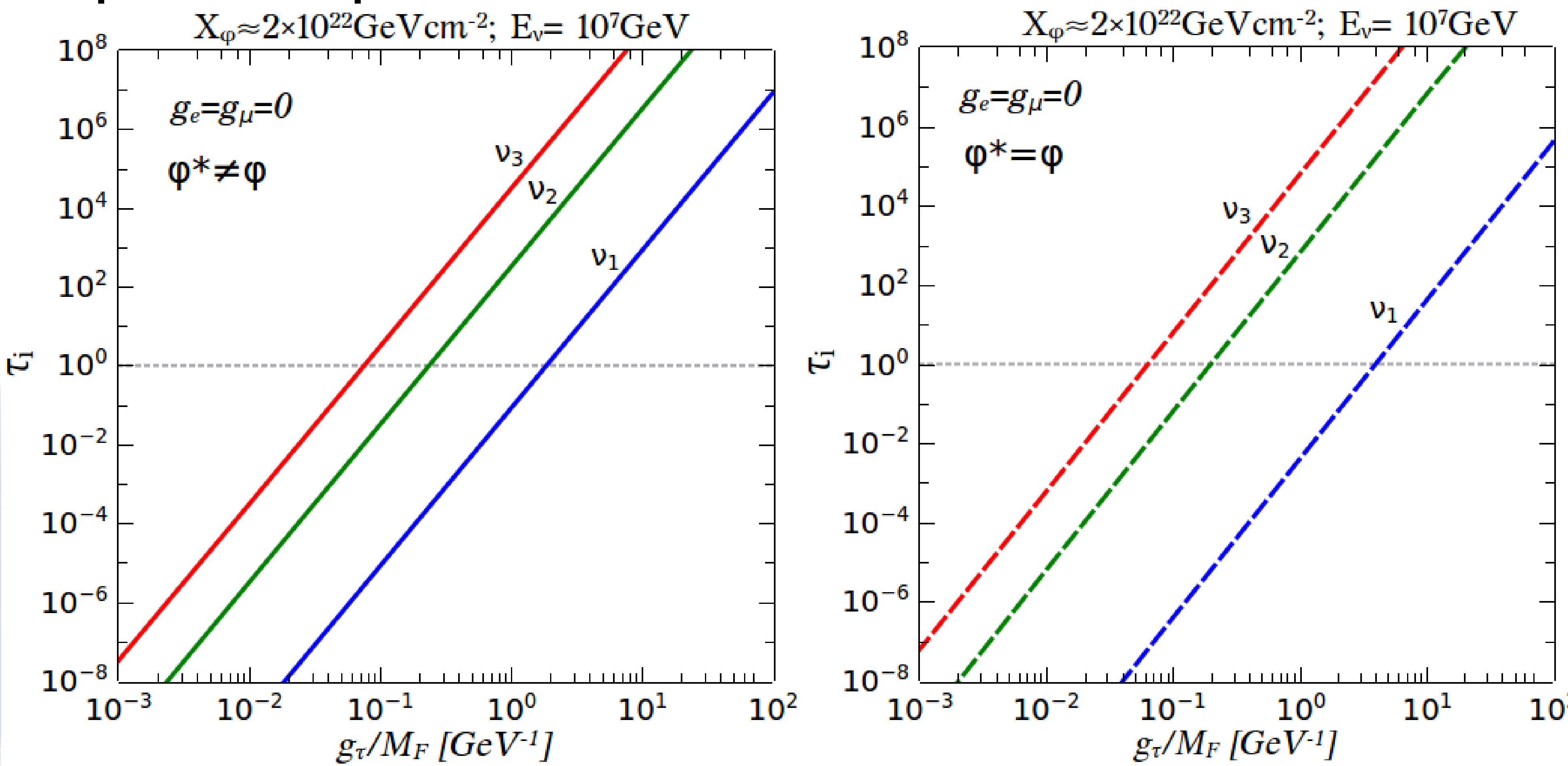
cross section

$g_l/M_F = 0.1\ GeV^{-1}$



Cross sections for depend on $\left(\frac{g_i}{M_F}\right)^4$

optical depth



$$\tau_\nu^{(\mathrm{eg})}(E, z_\mathrm{s}) \;=\; \int dz \frac{dz}{dl} n_\varphi^{(\mathrm{eg})}(z) \sigma_{\nu\varphi}(E(1+z))$$

$$\tau_\nu^{(\mathrm{eg})}(E, l, b) \;=\; X_\varphi(l, b) \sigma_{\nu\varphi}(E)$$

~~$$N_{\nu_i}(E) \;=\; N_{\nu_i}[E(1+z_z), z_\mathrm{s}] \exp\left[-\tau_\nu^{(\mathrm{tot})}\right]$$~~

Not appropriate in this case

Transport equation

$$\frac{\partial N_\nu}{\partial t} = Q_\nu - 3H\,N_\nu + \frac{\partial\,[H\;E\;N_\nu]}{\partial E} - N_\nu \sigma_{\nu\varphi}(E) c n_\varphi + \int_E^\infty dE' \frac{d\sigma(E',E)}{dE} c\; n_\varphi N_\nu(E',t)$$

If E is very close to E', continous loss approximation:

$$\frac{\partial N_\nu(E,t)}{\partial t} = Q(E,t) - 3H(t)N_\nu(E,t) + \frac{\partial\,[H(t)E\;N_\nu(E,t) + b_{\nu\varphi}(E,t)]}{\partial E}$$

$$b_{\nu\varphi}(E,t) = n_\varphi c \int_E^\infty dE' \frac{E^2}{E'} \frac{d\sigma}{dE}$$

(e.g. Berezinsky & Gazizov 2007; Alhers & Anchordoqui 2009; Farzan & Palomares-Ruiz 2014)

In terms of redshift z,

$$\frac{\partial N_{\nu_i}}{\partial z} = -\frac{Q_{\nu_i}}{H(z)(1+z)} + \left[\frac{1}{1+z}\right]\left[2 - \frac{1}{H(z)}\frac{\partial b_{\nu\varphi}}{\partial E}\right] N_{\nu_i} - \left[\frac{E}{1+z} + \frac{b_{\nu\varphi}}{H(z)(1+z)}\right]\frac{\partial N_{\nu_i}}{\partial E}$$

Solution:

$$N_{\nu_i}(z,E) = N_{\nu_i}\left[z_s, E'(z_s)\right] \exp\left[-\int_z^{z_s} dz'' A(z'',E'')\right] + \int_z^{z_s} dz' \frac{Q_{\nu_i}(z',E')}{H(z')(1+z')} \exp\left[-\int_z^{z'} dz'' A(z'',E'')\right]$$

Transport equation

$$\frac{\partial N_{\nu_i}}{\partial z} = -\frac{Q_{\nu_i}}{H(z)(1+z)} + \left[\frac{1}{1+z}\right]\left[2 - \frac{1}{H(z)}\frac{\partial b_{\nu\varphi}}{\partial E}\right] N_{\nu_i} - \left[\frac{E}{1+z} + \frac{b_{\nu\varphi}}{H(z)(1+z)}\right]\frac{\partial N_{\nu_i}}{\partial E}$$

Solution:

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To be observed at z=0:

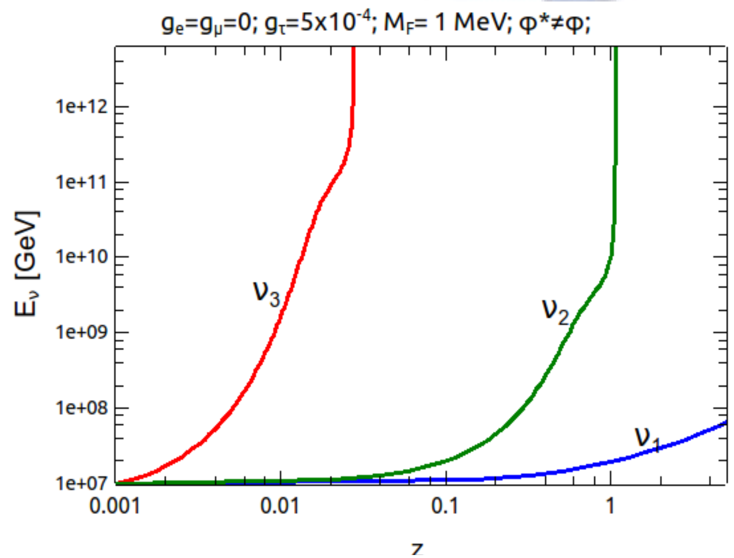
$$N_{\nu_l}(E, z=0) = \sum_{i=1,2,3} |U_{li}|^2 N_{\nu_i}(E, z=0)$$

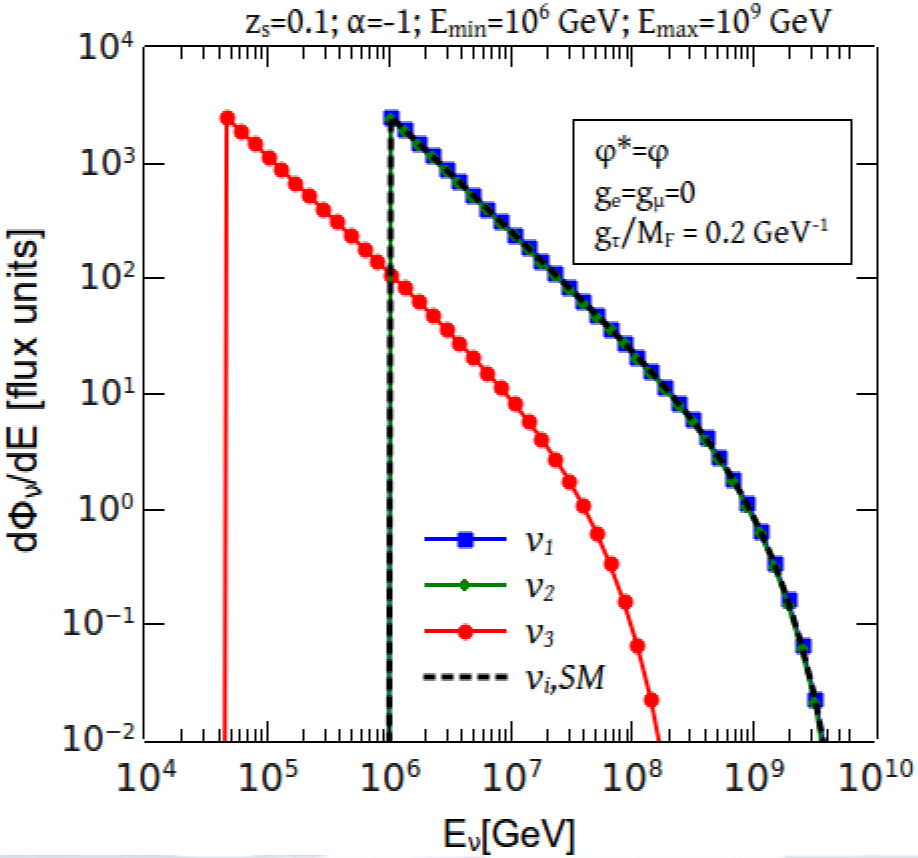
$$J_{\nu_l}(E, z=0) = \frac{d\Phi_{\nu_l}(E, z=0)}{dE} = \frac{c}{4\pi} N_{\nu_l}(E, z=0)$$

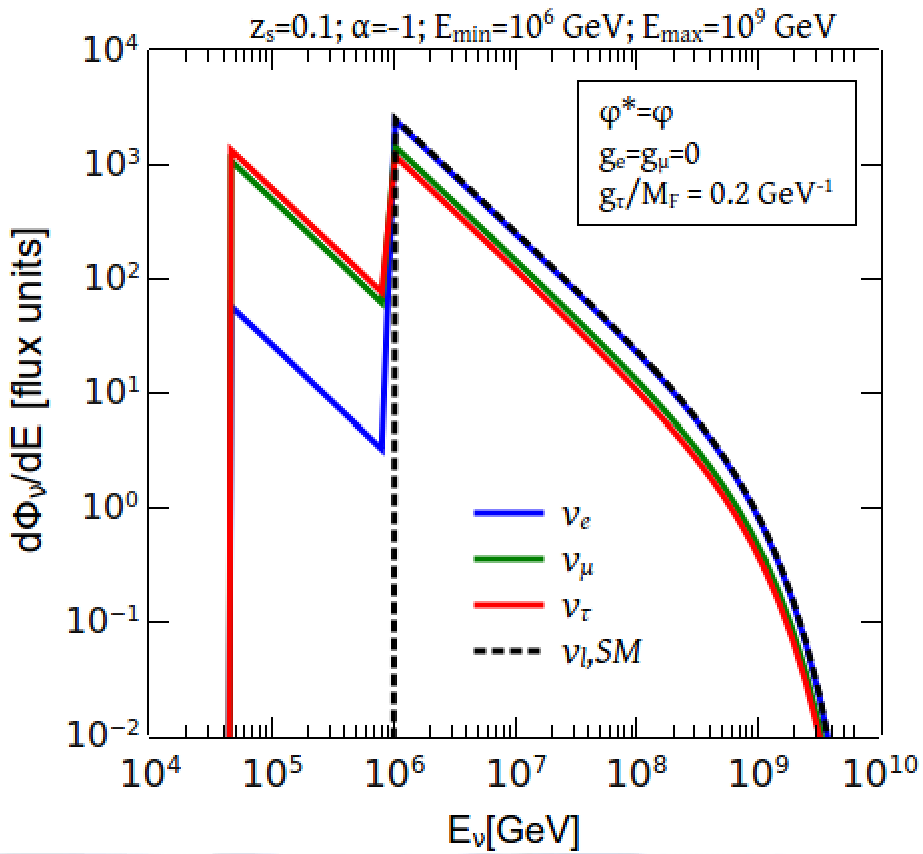
Application to point sources

$$N_\nu(E, z_s) \propto \begin{cases} a\,E & \text{for } E < E_1 = 10^6\ \text{GeV} \\ E^{-2}\exp\left(-\frac{E}{10^8\text{GeV}}\right) & \text{for } E \geq E_1 = 10^6\ \text{GeV} \end{cases}$$

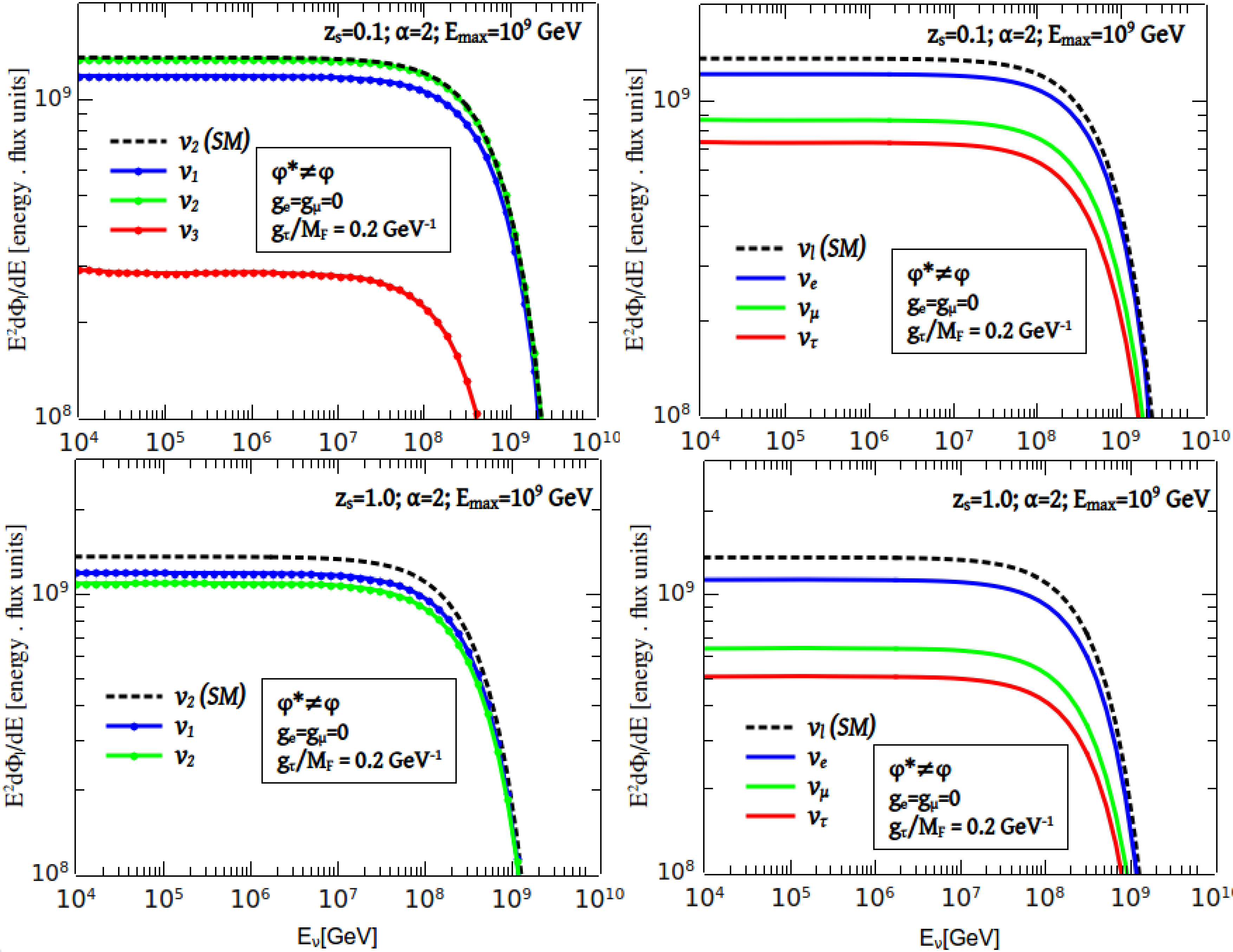
Differential flux: $$\frac{d\Phi_\nu}{dE} = \frac{c}{4\pi} N_\nu$$





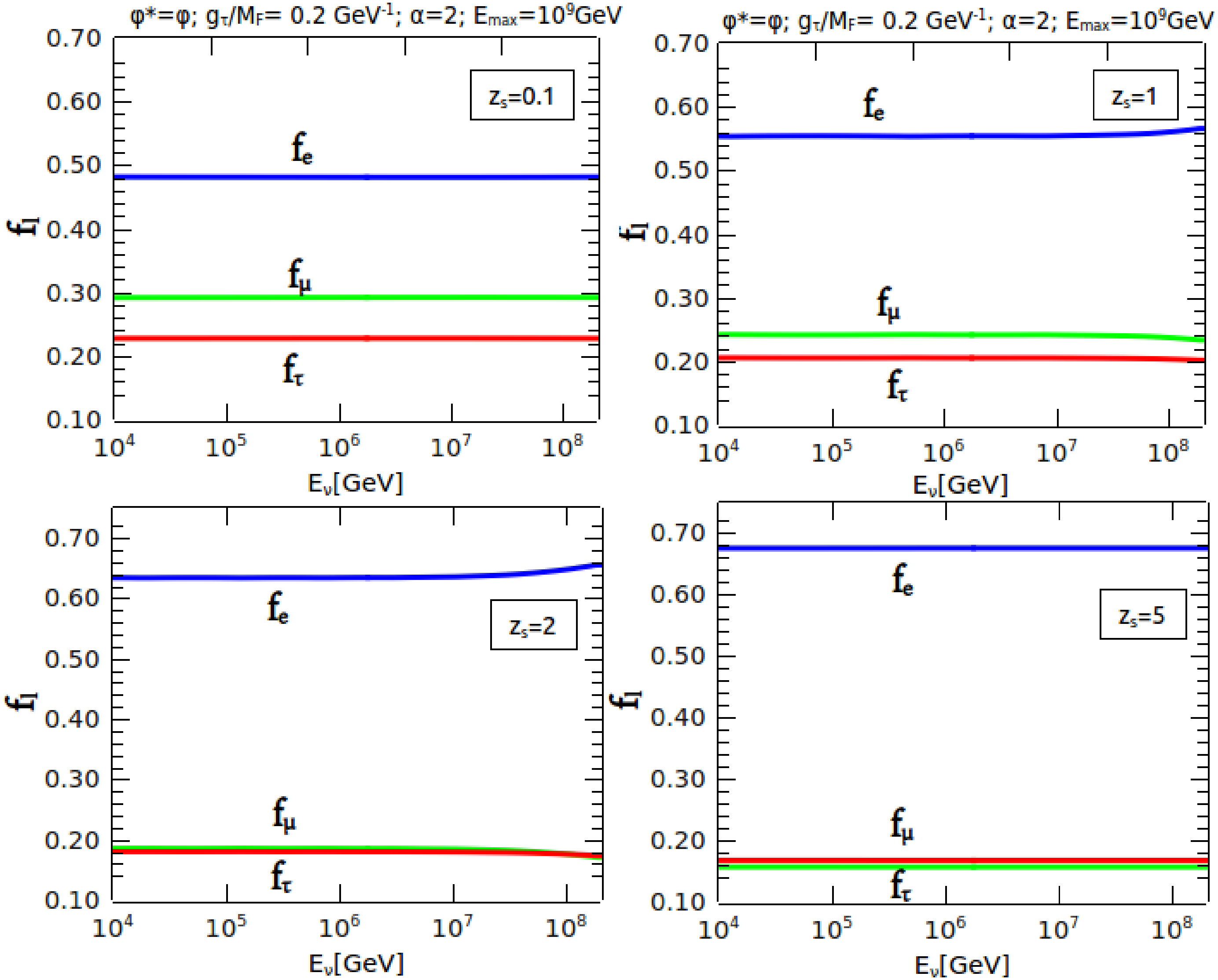


point sources at z=0.1 and z=1, extragalactic propagation

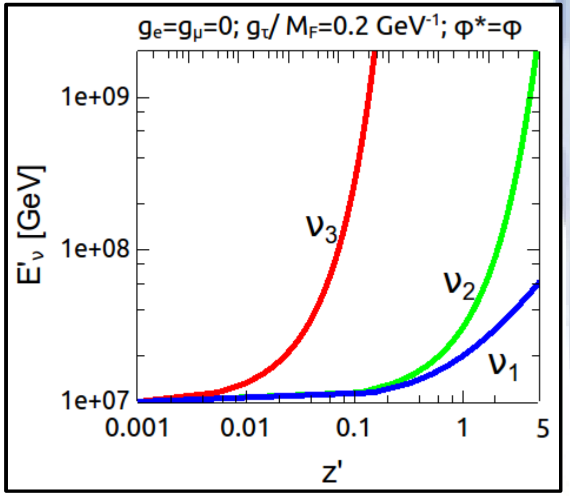


Flavor ratios f_l after extragalactic propagation from a point source

$$f_l = \frac{J_{\nu_l}}{J_{\nu_e} + J_{\nu_\mu} + J_{\nu_\tau}}$$



characteristic curves



$$f_e^{\oplus} \longrightarrow |U_{e1}|^2 \simeq 0.68$$

$$f_\mu^{\oplus} \longrightarrow |U_{\mu 1}|^2 \simeq 0.16$$

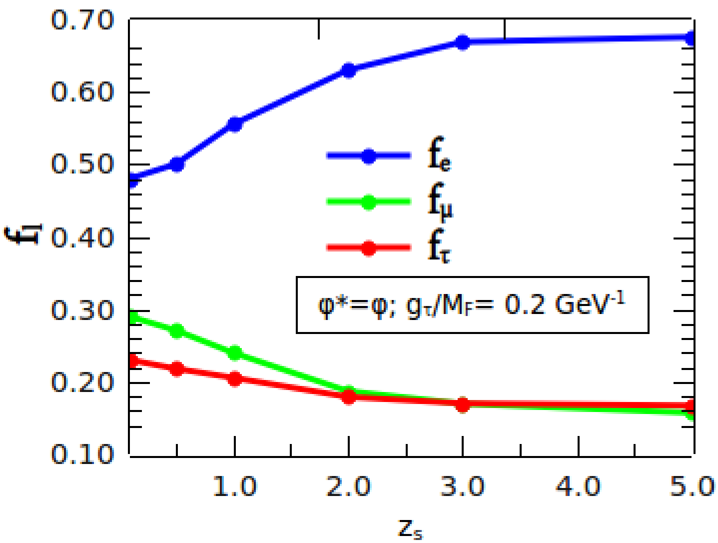
$$f_\tau^{\oplus} \longrightarrow |U_{\tau 1}|^2 \simeq 0.17$$

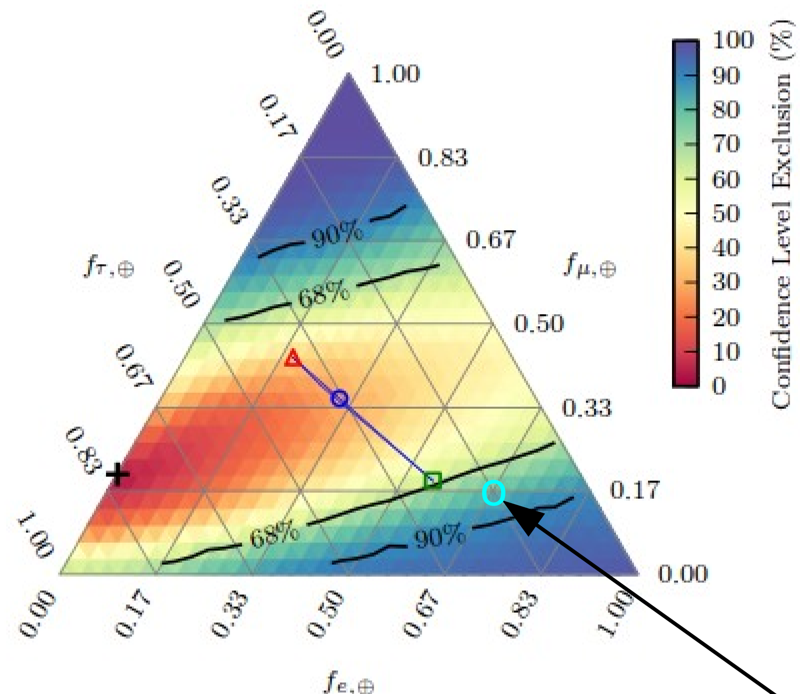
Normal Ordering:

$$m_{\nu_3} = 4.8 \times 10^{-2}\text{eV}$$

$$m_{\nu_1} \ll m_{\nu_2} = 8.6 \times 10^{-3}\text{eV}$$

Flavor ratios f_l vs z_s after extragalactic propagation from a point source

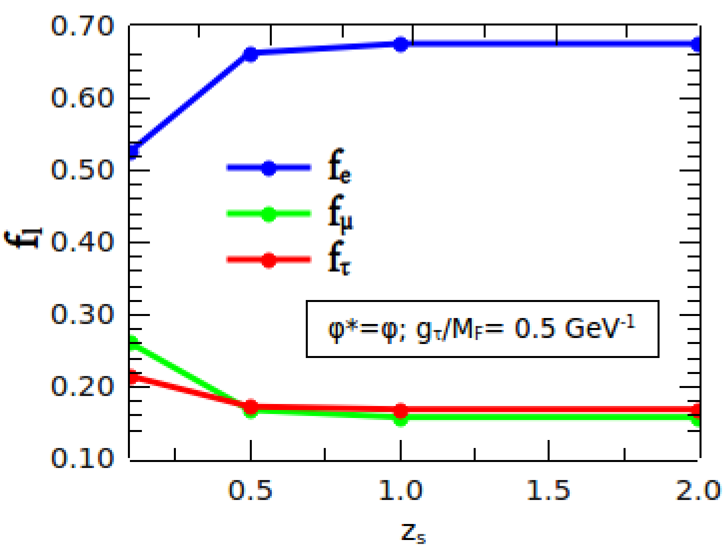


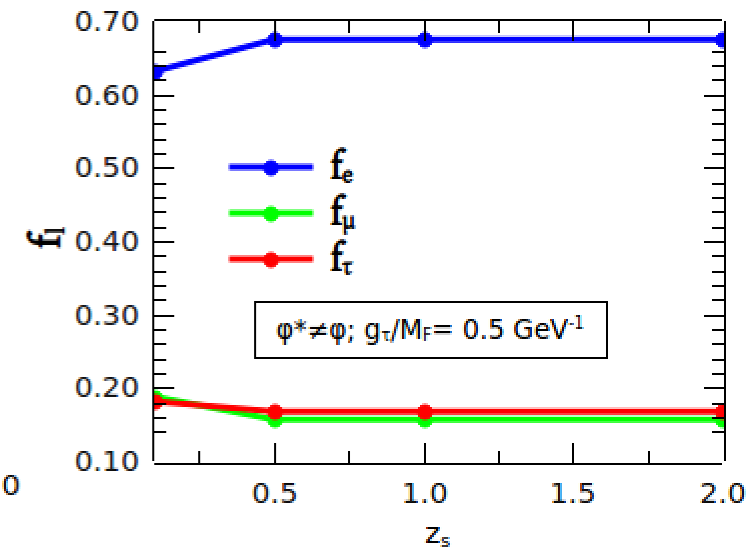


Not favored by IceCube data

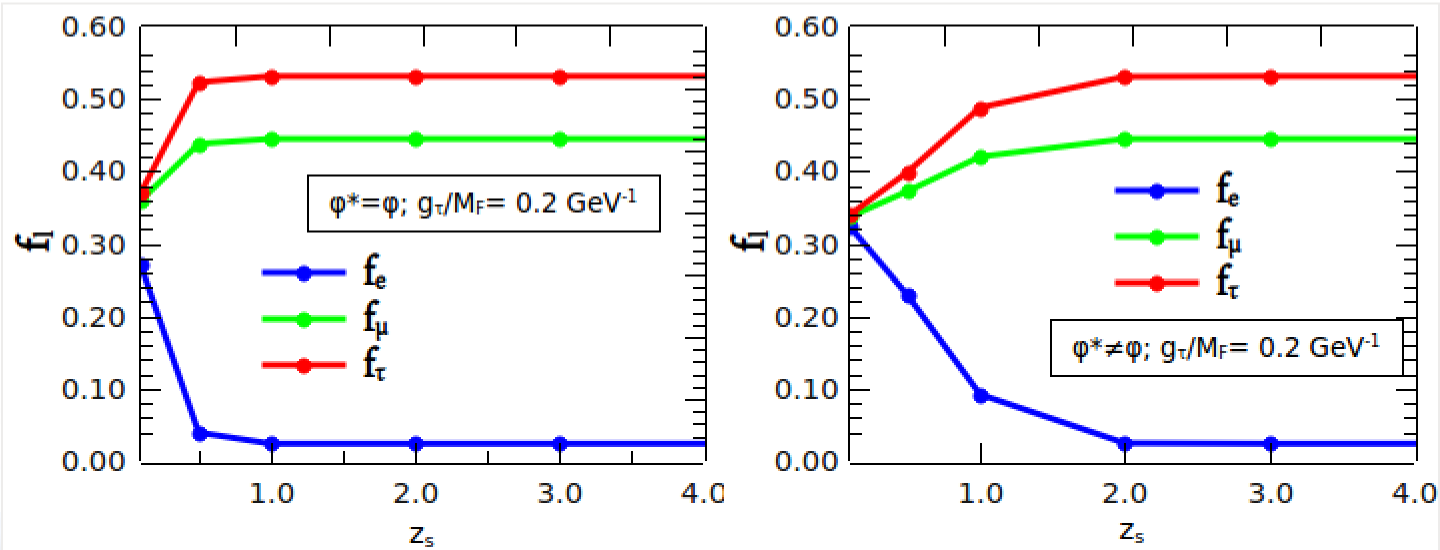
$$f_e^{\oplus} \longrightarrow |U_{e1}|^2 \simeq 0.68$$
$$f_\mu^{\oplus} \longrightarrow |U_{\mu 1}|^2 \simeq 0.16$$
$$f_\tau^{\oplus} \longrightarrow |U_{\tau 1}|^2 \simeq 0.17$$

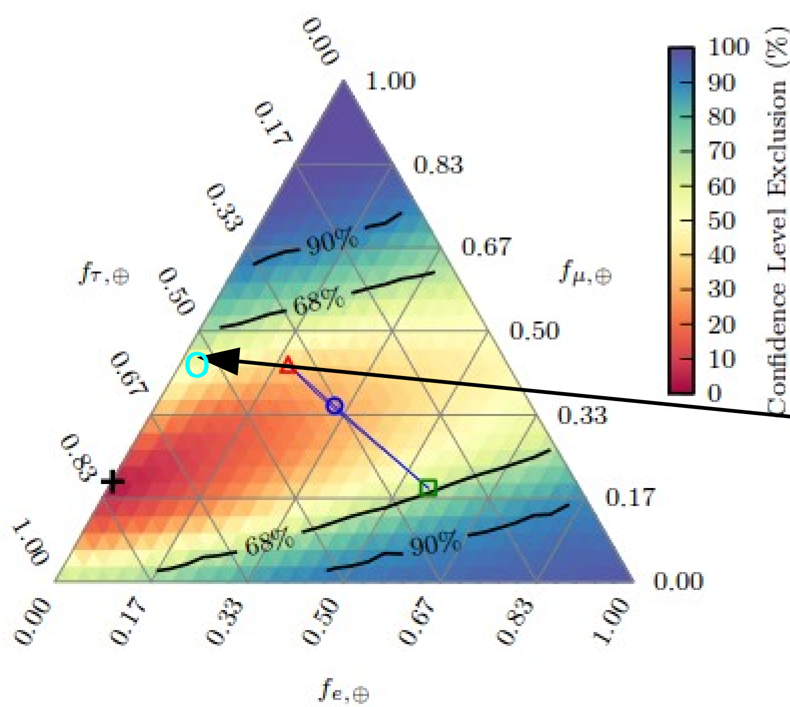
(Normal Ordering)





Flavor ratios f_l vs z_s after extragalactic propagation from a point source





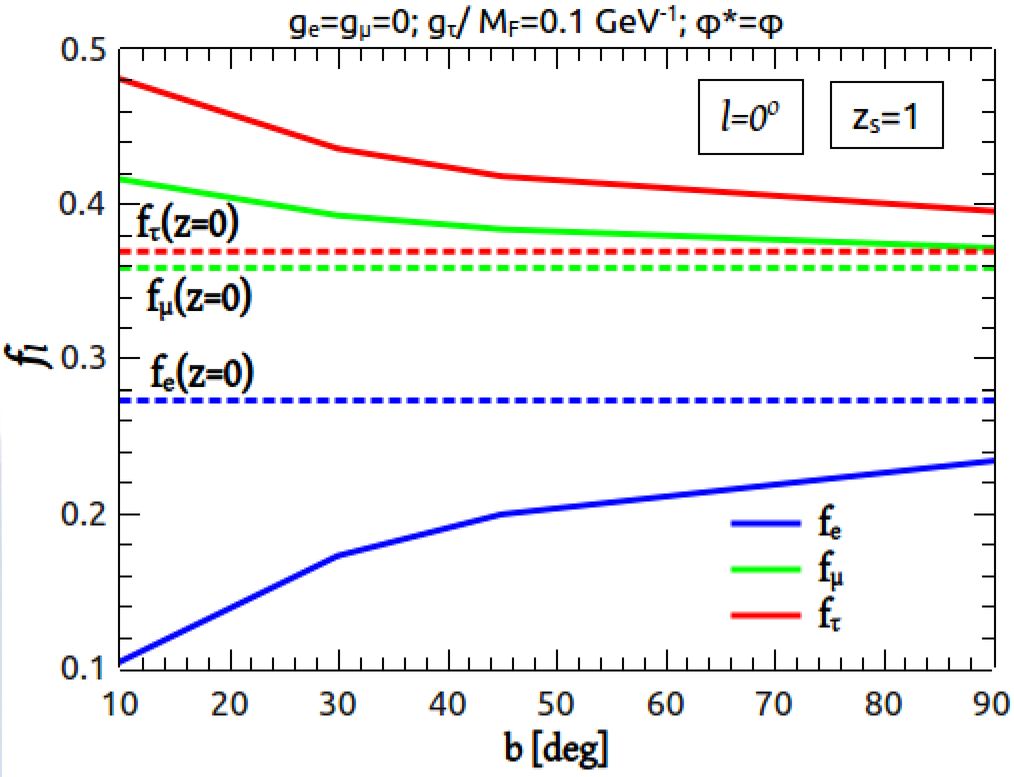
Not so disfavored by IceCube data

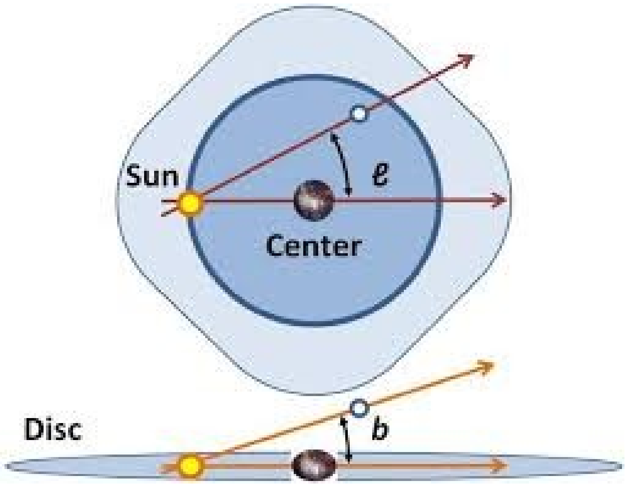
$$f_e^{\oplus} \longrightarrow |U_{e3}|^2 \simeq 0.024$$
$$f_\mu^{\oplus} \longrightarrow |U_{\mu 3}|^2 \simeq 0.44$$
$$f_\tau^{\oplus} \longrightarrow |U_{\tau 3}|^2 \simeq 0.53$$

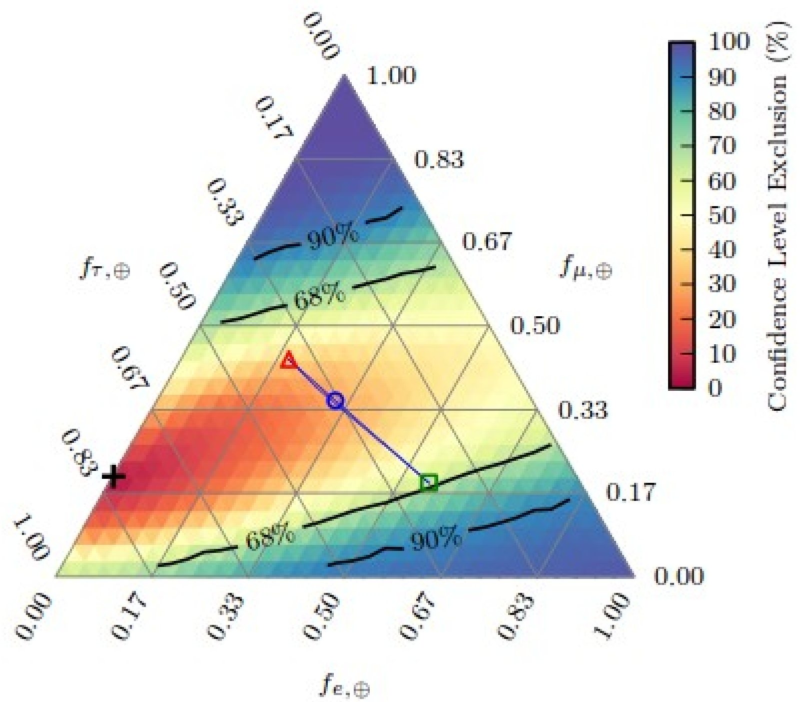
Inverted Order

$$m_{\nu_3} \ll m_{\nu_1} \simeq m_{\nu_2} = 0.48 \times 10^{-2}\text{eV}$$

Point sources: galactic propagation

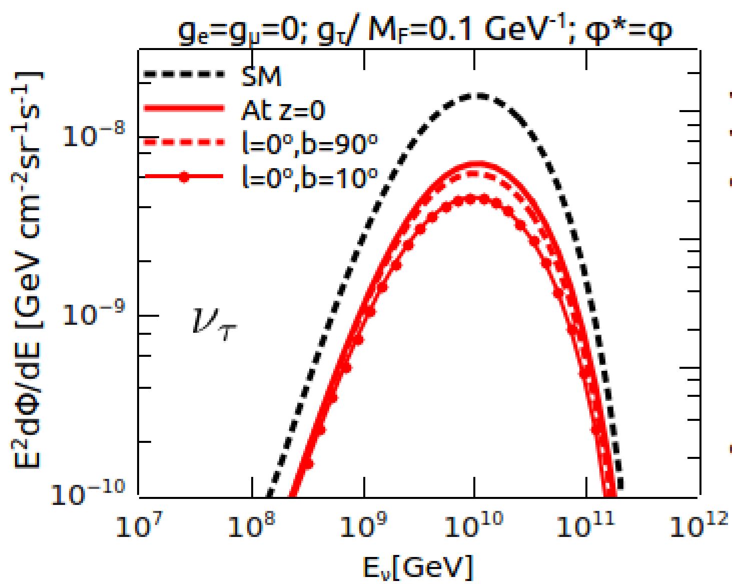


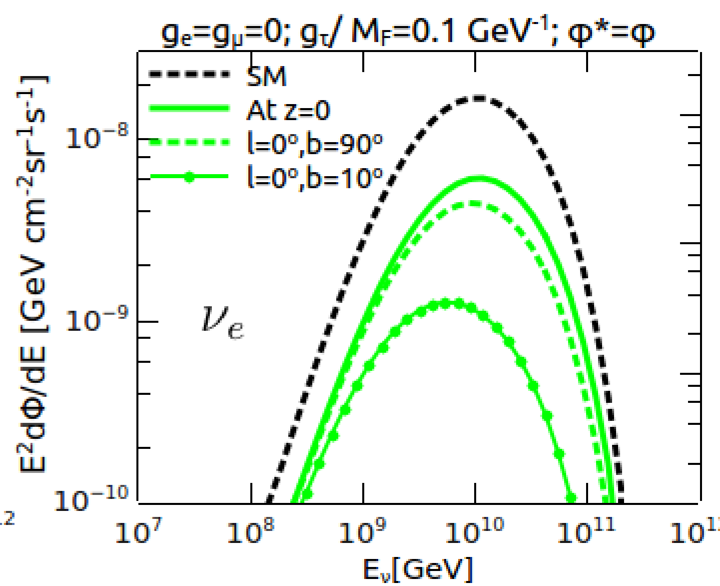




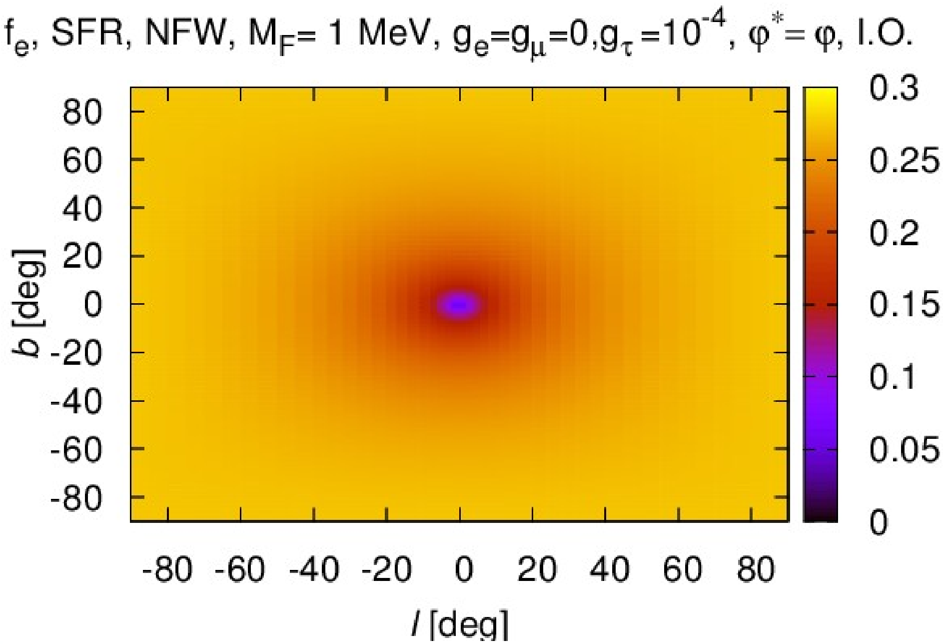
Application to cosmogenic neutrinos....

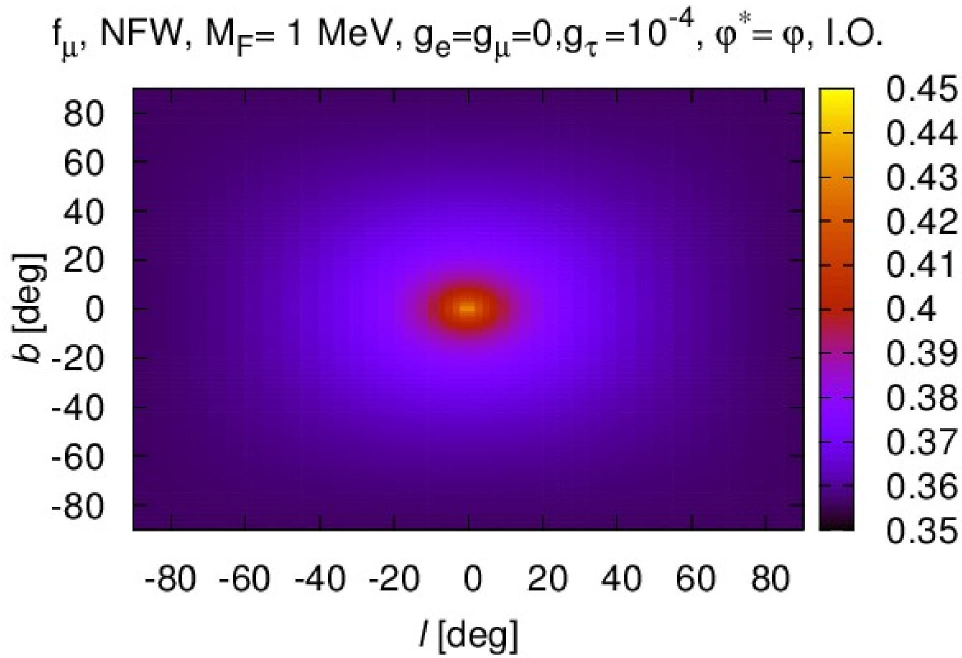
$$N_{\nu_i}(z,E) = N_{\nu_i}\left[z_s, E'(z_s)\right] \exp\left[-\int_z^{z_s} dz'' A(z'', E'')\right]$$
$$+ \int_z^{z_s} dz' \frac{Q_{\nu_i}(z', E')}{H(z')(1+z')} \exp\left[-\int_z^{z'} dz'' A(z'', E'')\right]$$

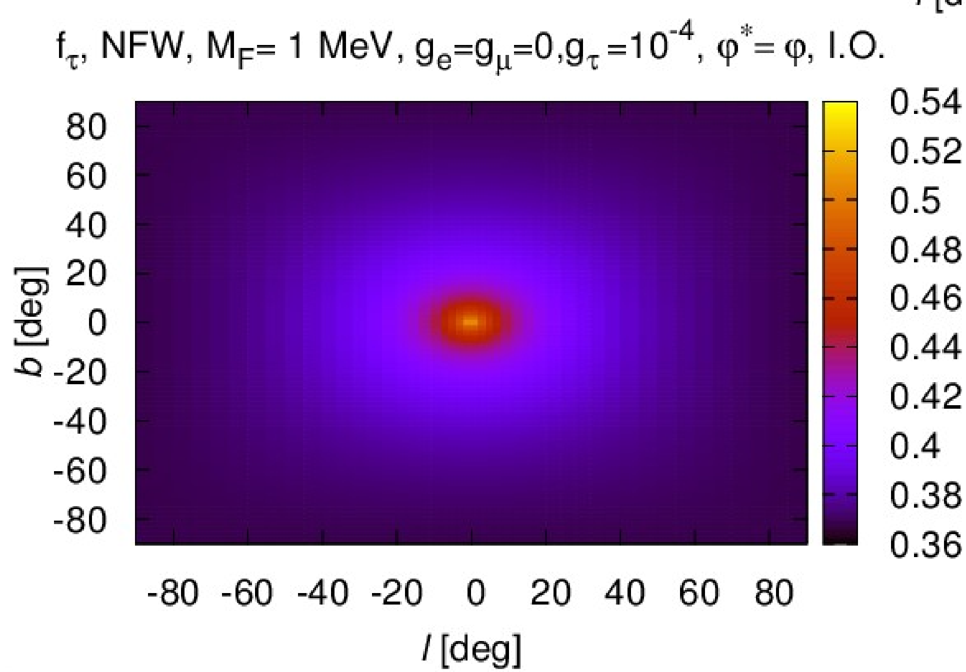




Cosmogenic neutrinos: flavor ratios of integrated fluxes above 10^9 GeV







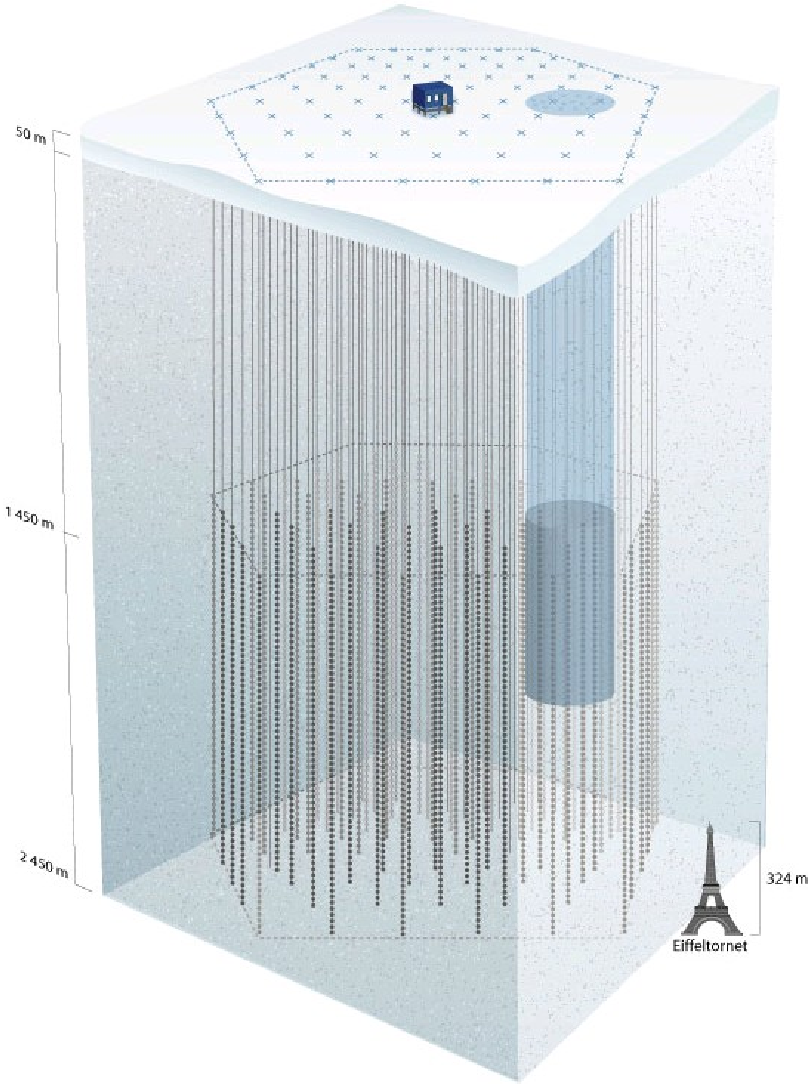
Final comments

.) Interactions of neutrinos and ultra light dark matter scalars can affect the neutrino flavor ratios.

.) For a normal ordering of neutrino masses, the electron neutrino would dominate, while for an inverted ordering, tau neutrino would.

.) The especific flavor ratios to be observed depend on the redshift of the source and on the direction on the sky.

Thanks for your attention!



Some useful references

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