Detection of Neutrinos from Micro-Quasars

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Introduction

- Micro-quasars are capable of accelerating particles to very high energy, and they are a source of high-energy neutrinos
- The detection of neutrinos from micro-quasar is important to investigate the composition of the jet (the jet should have relativistic hadrons and radiation or matter fields that provide target protons)
- The impact of neutrino oscillations on highly energetic neutrinos (1-200 TeV neutrinos) is very important

Neutrino detection

The neutrino signal in a km-scale detector like IceCube can be written as [1]

$$S_{\nu_\mu} = \frac{T_{obs} A_{eff}}{4\pi d^2} \int_{10^3\mathrm{GeV}}^{E_\nu^{max}} I_{\nu_\mu}(E_\nu) P(E_\nu) \mathrm{d}E_\nu$$

where T_{obs} is the time observational period, $A_{eff} = 10^6\,\mathrm{m}^2$ is the effective area of the detector, d is the distance to the source, I_{ν_μ} is the neutrino intensity, E_ν^{max} is the maximum value of the neutrino-energy, and $P(E_\nu)$ is the probability that a neutrino of energy E_ν between $1 - 10^3$ TeV, on a trajectory in the detector, produces a muon [2]

$$P(E_\nu) = 1.3 \times 10^{-6} \left(\frac{E_\nu}{10^3\mathrm{GeV}} \right)^{0.8}$$

Neutrino detection

The noise above 1 TeV is [1]

$$R = \sqrt{T_{obs} A_{eff} \Delta\Omega \int_{10^3\,\mathrm{GeV}}^{E_\nu^{max}} F_B(E_\nu) P(E_\nu) \mathrm{d}E_\nu}$$

where $\Delta\Omega = 3 \times 10^{-4}\,\mathrm{sr}$ is the solid angle of the search bin and $F_B(E_\nu)$ is the flux of atmospheric neutrinos [3]

$$F_B(E_\nu) = 2 \left(\frac{E_\nu}{\mathrm{GeV}} \right)^{-3.21} \mathrm{MeV}^{-1}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

The signal-to-noise ratio is

$$\Omega = S_\nu / R = T_{obs}^{1/2}\,\Omega(T = 1\,\mathrm{year})$$

Neutrino detection

We performed the calculations using three models for the neutrino intensity [4]

$$\frac{I_{\nu_\gamma}(E_\nu)}{\mathrm{GeV}^{-1}\mathrm{s}^{-1}} = a_\gamma \left(\frac{E_\nu}{\mathrm{GeV}}\right)^{-\Gamma} e^{-E_\nu/E_\nu^{max}}$$

where a_γ is a constant and Γ is the index of the power-law of the proton spectrum,

$$\frac{I_{\nu_\gamma}(E_\nu)}{\mathrm{GeV}^{-1}\mathrm{s}^{-1}} = b_\gamma \left(\frac{E_\nu}{\mathrm{GeV}}\right)^{-\Gamma}$$

where b_γ is a constant

Neutrino detection

and [1]

$$I_\nu(E_\nu,\psi,\theta) \quad = \quad 4\int \mathrm{d}V\,\frac{f_p}{m_p}\rho_w(r_w)q_\gamma(\psi,2E_\nu,z,\theta)$$

where $f_p = 0.1$ takes into account particle-rejection from the boundary, $q_\gamma(\psi,E,z,\theta)$ is the gamma-ray emissivity (this quantity takes into account the cross section for pp reactions and the proton flux in the observer frame) and $\rho_w(r_w)$ is the mass density of the wind

$$\rho_w(r_w) \quad = \quad \frac{\dot{M}_\star}{4\pi v_\infty r_w^2}\left(1-\frac{R_\star}{r_w}\right)^{-\beta}$$

where $\dot{M}_\star$ is the mass losing rate, v_∞ is the terminal velocity of the wind and r_w is the radial coordinate from the star
If we consider neutrino oscillations the function I_ν can be written as
$I_\nu = I_{\nu_\mu} P_{\mathrm{osc}}^{\nu_\mu\nu_\mu} + I_{\nu_e} P_{\mathrm{osc}}^{\nu_e\nu_\mu}$

Neutrino oscillations

Light neutrino mass eigenstates: $|\nu_1>$, $|\nu_2>$, $|\nu_3>$
Neutrino flavor states: $|\nu_e>$, $|\nu_\mu>$, $|\nu_\tau>$

$$\begin{pmatrix} |\nu_e> \\ |\nu_\mu> \\ |\nu_\tau> \end{pmatrix} = U \begin{pmatrix} |\nu_1> \\ |\nu_2> \\ |\nu_3> \end{pmatrix}$$

The mixing matrix is written (c_{ij} (s_{ij}) represents $\cos\theta_{ij}$ $(\sin\theta_{ij})$ and θ_{ij} is the mixing angle between the mass eigenstates i and j)

$$U = \begin{pmatrix} c_{13}c_{12} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - s_{23}s_{13}c_{12} & c_{23}c_{12} - s_{23}s_{13}s_{12} & s_{23}c_{13} \\ s_{23}s_{12} - s_{13}c_{23}c_{12} & -s_{23}c_{12} - s_{13}s_{12}c_{23} & c_{23}c_{13} \end{pmatrix}$$

Neutrino oscillations

The oscillation probability $P_{\alpha\beta} = | < \nu_\alpha(t)|\nu_\beta > |^2$ (considering $\theta_{13} = 0$)

$$\begin{aligned}
P_{vac}^{\nu_\mu\nu_\mu}(E_\nu) &= 1 - \sin^2 2\theta_{12}\cos^4\theta_{23}\sin^2\delta_{12} - \sin^2\theta_{12}\sin^2 2\theta_{23}\sin^2\delta_{13} \\
&\quad - \cos^2\theta_{12}\sin^2 2\theta_{23}\sin^2\delta_{23} \\
P_{vac}^{\nu_\mu\nu_e}(E_\nu) &= \cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2\delta_{12} \\
P_{vac}^{\nu_\mu\nu_\tau}(E_\nu) &= -\frac{1}{4}\sin^2 2\theta_{12}\sin^2 2\theta_{23}\sin^2\delta_{12} + \sin^2\theta_{12}\sin^2 2\theta_{23}\sin^2\delta_{13} \\
&\quad + \cos^2\theta_{12}\sin^2 2\theta_{23}\sin^2\delta_{23} \\
P_{vac}^{\nu_\tau\nu_e}(E_\nu) &= \sin^2\theta_{23}\sin^2 2\theta_{12}\sin^2\delta_{12} \\
P_{vac}^{\nu_\tau\nu_\tau}(E_\nu) &= 1 - \sin^2 2\theta_{12}\sin^4\theta_{23}\sin^2\delta_{12} - \sin^2\theta_{12}\sin^2 2\theta_{23}\sin^2\delta_{13} \\
&\quad - \cos^2\theta_{12}\sin^2 2\theta_{23}\sin^2\delta_{23} \\
P_{vac}^{\nu_e\nu_e}(E_\nu) &= 1 - \sin^2 2\theta_{12}\sin^2\delta_{12} \\
\delta_{ij} &= \frac{\Delta m_{ij}^2 c^4 d}{4E_\nu \hbar c} \qquad \Delta m_{ij}^2 = m_i^2 - m_j^2
\end{aligned}$$

Neutrino oscillations

For three flavors we adopt the best fit parameters obtained by the analysis of experimental data [5, 6, 7]

$$\begin{aligned}
\Delta m^2_{12} &= 7.65 \times 10^{-5}\ \mathrm{eV}^2 \\
\sin^2\theta_{12} &= 0.304 \\
\Delta m^2_{31} &\simeq \Delta m^2_{32} = 2.40 \times 10^{-3}\ \mathrm{eV}^2 \\
\sin^2\theta_{23} &= 0.5
\end{aligned}$$

Neutrino oscillations

The evolution equation of the neutrino states [8],

$$\imath \frac{\mathrm{d}\nu_f}{\mathrm{d}t} = \left(\frac{UM^2U^\dagger}{2E} + V \right) \nu_f$$

where $M^2 = \mathrm{diag}\left(0, \Delta m_{12}^2, \Delta m_{13}^2\right)$, $V = \mathrm{diag}\,(V_e, 0, 0)$, $V_e = \sqrt{2} G_F N_e(r)$, G_F is the Fermi constant and $N_e(r)$ is the Earth electron density.

After performing a rotation in θ_{23} (to the base $\widetilde{\nu} = (\nu_e,\, \widetilde{\nu}_2,\, \widetilde{\nu}_3)$), $\widetilde{\nu}_3$-state decouples form the rest of the system and evolves independently [8]

Neutrino oscillations

We parametrized the Earth matter density as [9]

$$N_j(x) = \alpha'_j + \beta'_j x^2 + \gamma'_j x^4$$

where x is the trajectory coordinate and the sub-index j represent the shell

The trajectory coordinate in each shell is written as

$x_j = R_\oplus \sqrt{r_j^2 - \sin^2 \eta}$

Neutrino oscillations

Finally [10],

$$
\begin{aligned}
P_2 &= \frac{4\sin^2 2\theta_{12}}{\omega(L)^2}\left(\frac{\Delta m_{12}^2}{4E_\nu}\right)^2 \\
&\times \left(\sin\psi_L - \omega(L)\sum_{i=1}^{4}\frac{\omega\left(x_i^+\right)-\omega\left(x_i^-\right)}{\omega\left(x_i^-\right)\omega\left(x_i^+\right)}\sin 2\psi_i\right)^2 \\
\psi(x) &= \int_0^x \mathrm{d}y\,\omega(y) \\
\omega(x) &= \sqrt{\left(\frac{V_e(x)}{2}-\frac{\Delta m_{12}^2}{4E_\nu}\cos 2\theta_{12}\right)^2+\left(\frac{\Delta m_{12}^2}{4E_\nu}\right)^2\sin^2 2\theta_{12}}
\end{aligned}
$$

Neutrino oscillations

The survival and conversion probabilities can be calculated by [8]

$$
\begin{aligned}
P_{\oplus}^{\nu_e\nu_e} &= 1 - P_2 \\
P_{\oplus}^{\nu_e\nu_\mu} &= \cos^2\theta_{23} P_2 \\
P_{\oplus}^{\nu_e\nu_\tau} &= \sin^2\theta_{23} P_2 \\
P_{\oplus}^{\nu_\tau\nu_\mu} &= \frac{1}{2}\sin^2 2\theta_{23}\left(1 - \frac{1}{2}P_2 - \sqrt{1-P_2}\cos\phi\right) \\
P_{\oplus}^{\nu_\mu\nu_\mu} &= 1 - \cos^4\theta_{23} P_2 - \frac{1}{2}\sin^2 2\theta_{23}\left(1 - \sqrt{1-P_2}\cos\phi\right)
\end{aligned}
$$

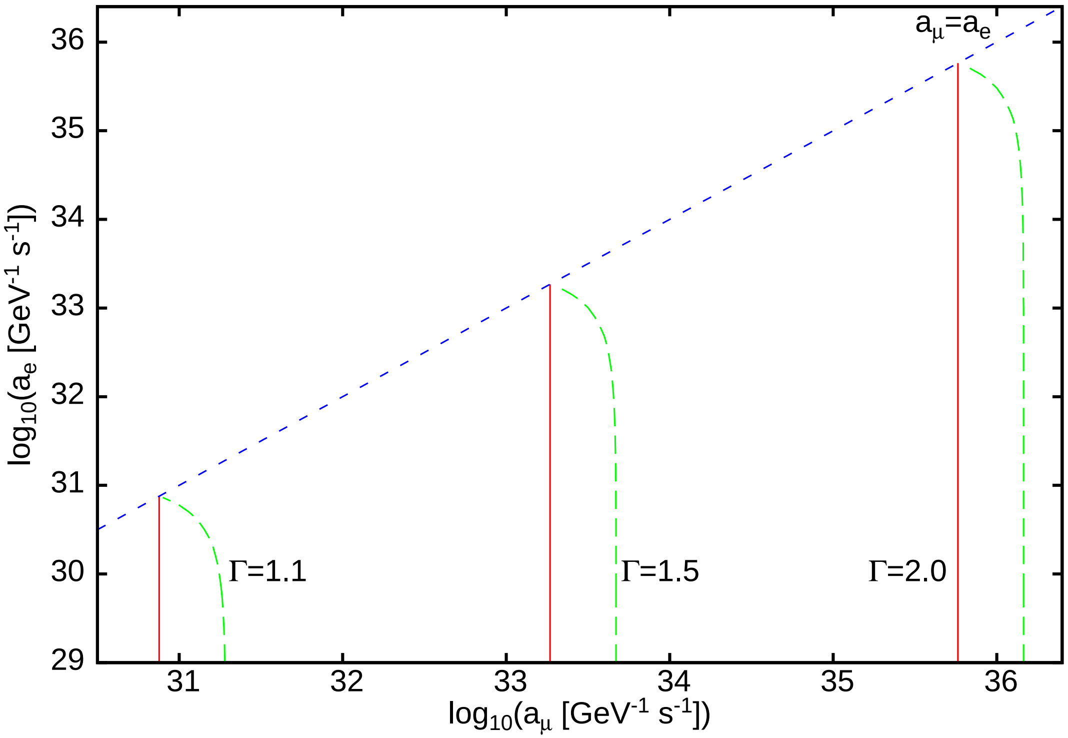
where $\phi = \frac{\Delta m_{13}^2}{2E} L$, $L = 2R_\oplus \cos\eta$ is the total length of the neutrino trajectory inside the Earth

Results obtained using the model given by $I_{\nu_\gamma}(E_\nu) = a_\gamma \left(\frac{E_\nu}{\mathrm{GeV}}\right)^{-\Gamma} e^{-E_\nu/E_\nu^{max}}$

Contours plots of the constants a_μ and a_e (neutrino signal-to-noise ratio of 1).

Red line: without including oscillations

Green line: neutrino oscillations effects incorporated

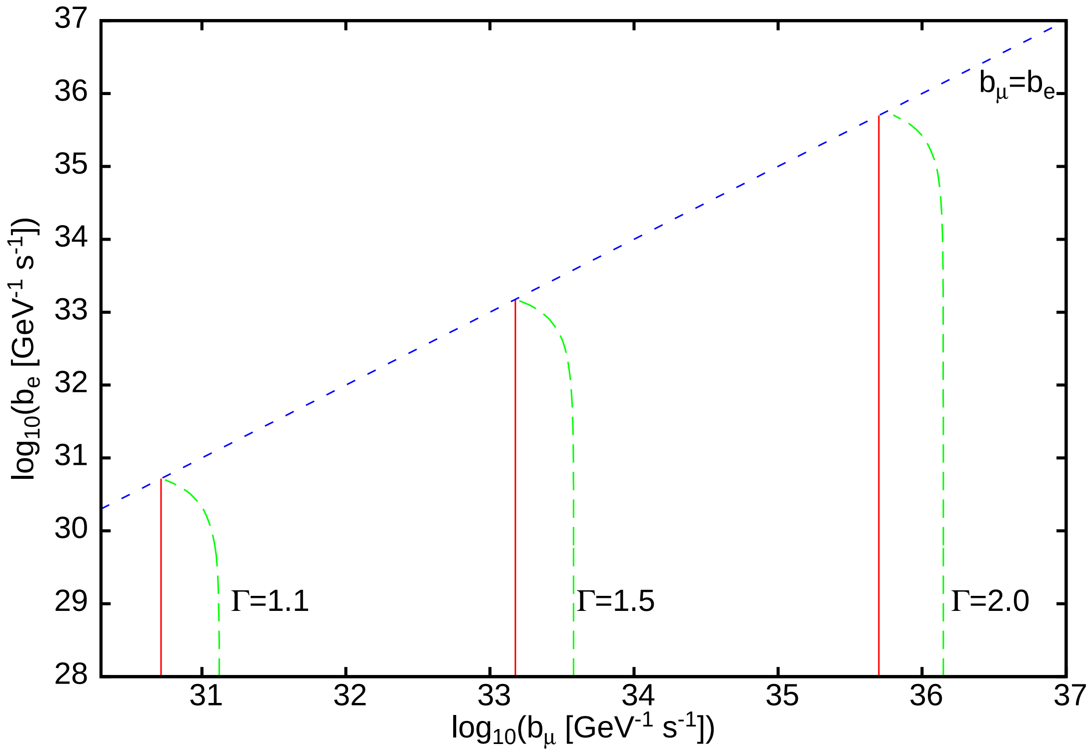


Results obtained using the model given by $I_{\nu_\gamma}(E_\nu) = b_\gamma \left(\frac{E_\nu}{\text{GeV}}\right)^{-\Gamma}$

Contours plots of the constants b_μ and b_e (neutrino signal-to-noise ratio of 1).

Red line: without including oscillations

Green line: neutrino oscillations effects incorporated



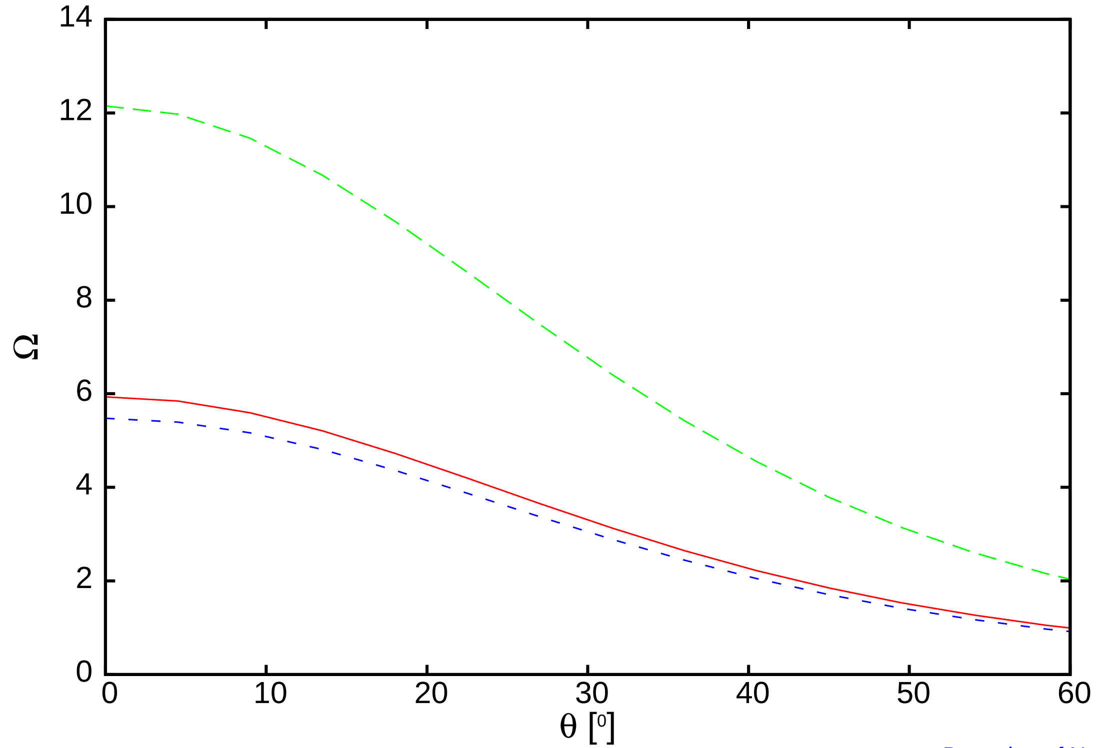
Results obtained using the model given by $I_\nu(E_\nu) = 4\int \mathrm{d}V\, f_p\, m_p^{-1} \rho_w q_\gamma$

Neutrino signal-to-noise ratio as a function of the viewing angle θ and $\eta = 30^0$

Green line: no neutrino oscillations

Red line: only vacuum neutrino oscillation

Blue line: neutrino oscillation (vacuum and matter effects)



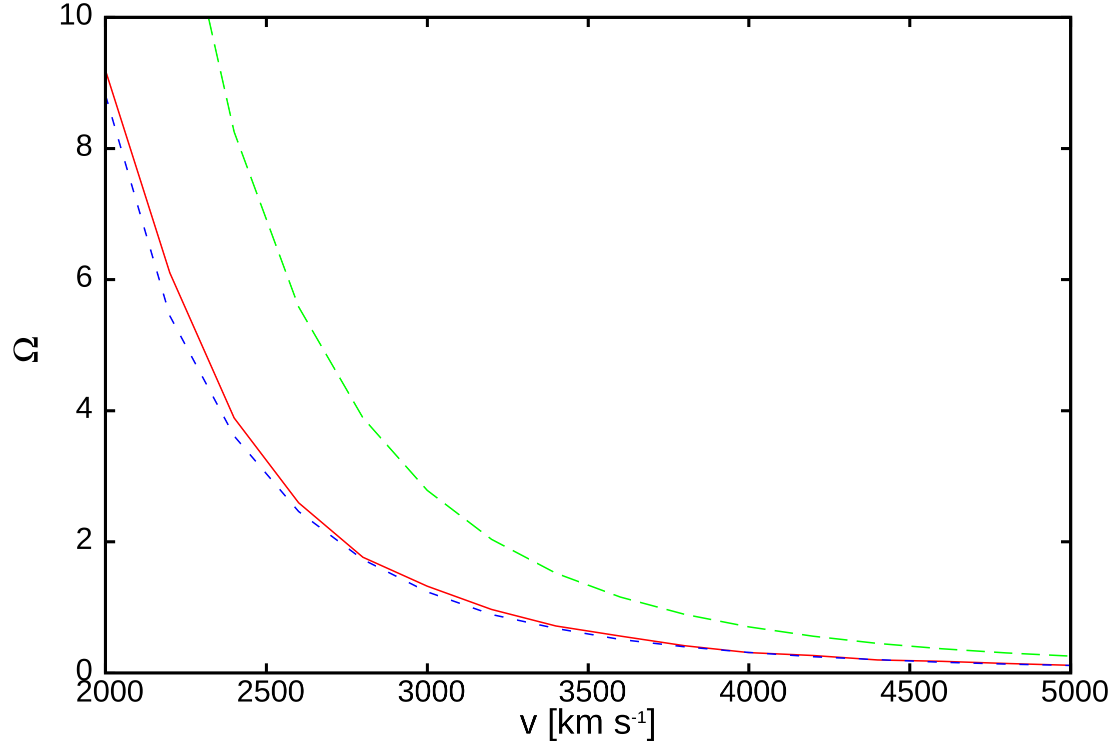
Results obtained using the model given by $I_\nu(E_\nu) = 4\int \mathrm{d}V\, f_p\, m_p^{-1} \rho_w q_\gamma$

Neutrino signal-to-noise ratio as a function of the terminal velocity, $\theta = 30^0$ and $\eta = 30^0$

Green line: no neutrino oscillations

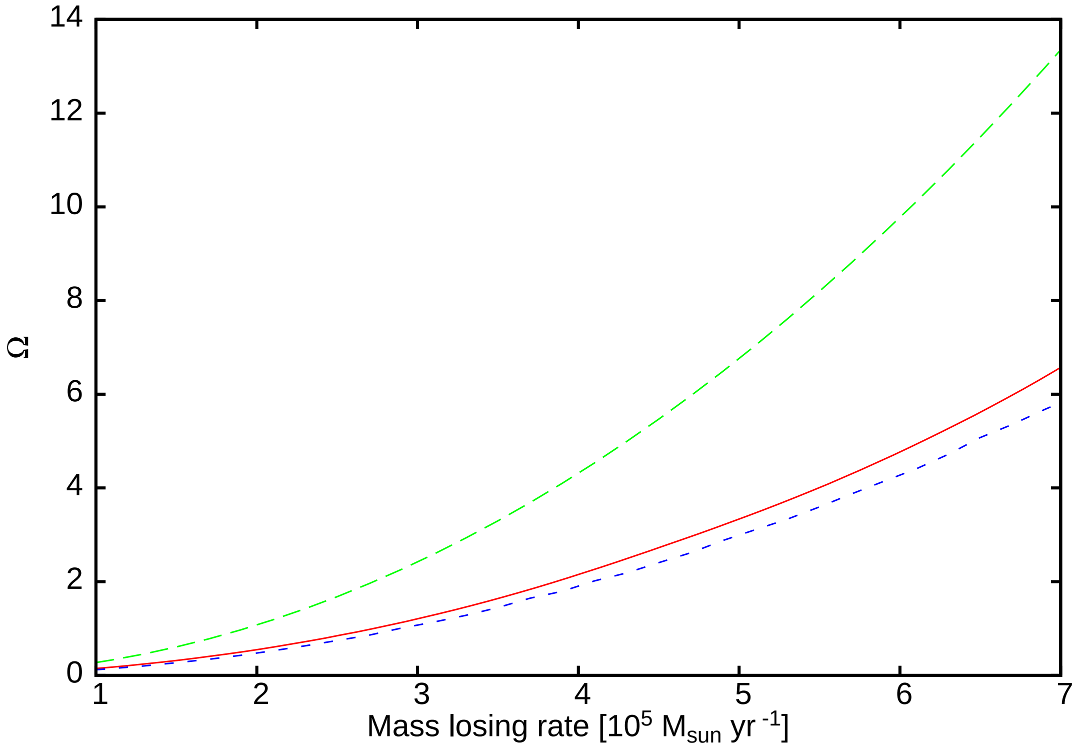
Red line: only vacuum neutrino oscillation

Blue line: neutrino oscillation (vacuum and matter effects)



Results obtained using the model given by $I_\nu(E_\nu) = 4\int \mathrm{d}V\, f_p\, m_p^{-1} \rho_w q_\gamma$

Neutrino signal-to-noise ratio as a function of the mass losing rate,
$\theta = 30^0$ and $\eta = 30^0$
Green line: no neutrino oscillations
Red line: only vacuum neutrino oscillation
Blue line: neutrino oscillation (vacuum and matter effects)



Conclusions

- If neutrino oscillations are included in the calculations, the quantities a_μ and b_μ should be increased by a factor 3, to obtain the same signal to noise ratio
- The signal-to-noise ratio is suppressed by neutrino oscillations
- The inclusion of the neutrino oscillation increases the observable time by a factor of the order of 5
- If these neutrinos are detected, constrains on astrophysical parameters, such as the total jet power, the compact object accretion rate, the terminal wind velocity among others, can be obtained

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