Derive eq 1 from article Eberling, B. and Ringwald, A., *Relic Neutrino Absorption Spectroscopy*, 2004. Also see appendix A1, of Lunardini, c., Sabancilar. E., Yang. L., *Ultra High Energy Neutrinos: Absorption, Thermal Effects and Signatures*, 2013.

There are different channels contributing to the process $\nu + \overline{\nu} \to$ anything However, the one of main interest is the resonant neutrino-antineutrino annihilation ($\nu\overline{\nu} \to Z^0 \to f\overline{f}$) occurring in the s-channel [10]. From its Mandelstam variable $s = (q^\mu + p^\mu)^2$, the resonance energy can be derived using the four momenta of UHE neutrino (q^μ), and background neutrinos (p^μ):

$$q^\mu = \begin{pmatrix} E' \\ \mathbf{q} \end{pmatrix}, \qquad p^\mu = \begin{pmatrix} \sqrt{\mathbf{p}^2 + m_j^2} \\ \mathbf{p} \end{pmatrix}$$

For UHE neutrinos $|\mathbf{q}| >> m_{\nu_j}$, therefore $E' = \sqrt{\mathbf{q}^2 + m^2} \approx |\mathbf{q}| \equiv q$, resulting in:

$$q^\mu = E' \begin{pmatrix} 1 \\ \hat{\mathbf{q}} \end{pmatrix}$$

So the Mandelstam variable, s, in the comoving frame is:

$$s = \{|\mathbf{p}|^2 + m_j^2 - |\mathbf{p}|^2\} + \{E'^2 - E'^2|\hat{\mathbf{q}}|^2\} + \{2\left(E'\sqrt{\mathbf{p}^2 + m_j^2} - E'|\hat{\mathbf{q}}||\mathbf{p}|\ cos(\theta)\right)\}$$

$$s = \{m_j^2\} + \{0\} + \{2E'\left(\sqrt{\mathbf{p}^2 + m_j^2} - p\ cos(\theta)\right)\}$$

$$s \approx 2E'\left(\sqrt{\mathbf{p}^2 + m_j^2} - p\ cos(\theta)\right) \tag{2}$$

Because te Lorentz-invariant quantity $\sqrt{s}$ can be identified as the total energy available in the center-of-mass frame, the resonance occurs at $\sqrt{s} = M_Z$, with $M_Z = 91.1876$GeV being the Z^0 boson mass. The resonance Energy can be found by solving $\sqrt{s} = M_Z$, and assuming that the background neutrinos are at rest.

$$2E'_{res}\left(\sqrt{p^2 + m_j^2} - pcos(\theta)\right) = M_Z^2$$

$$E'_{res} = \frac{M_z^2}{2\left(\sqrt{\mathbf{p}^2 + m_j^2} - pcos(\theta)\right)}$$

$$E'_{res} = \frac{M_z^2}{2m_j} \tag{3}$$