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DECAYS OF SUPERNOVA RELIC NEUTRINOS

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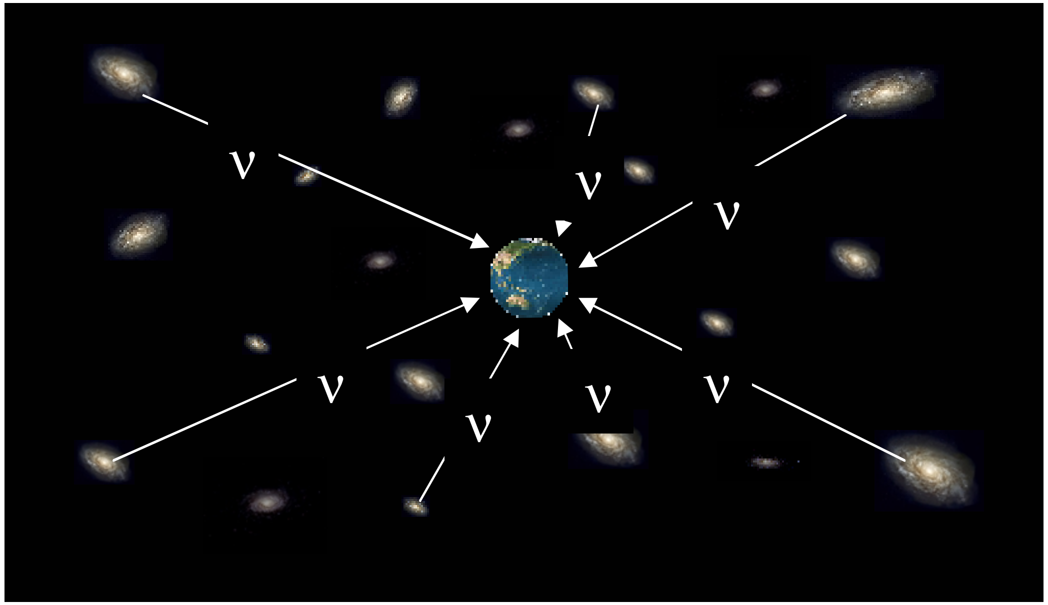
Mainly based on:

[1] G.L.Fogli, E.Lisi, A.M., and D.Montanino, "*Three-generations flavor transitions and decays of supernova relic neutrinos*", accepted by PRD [hep-ph/0401227].

INTRODUCTION

There is a diffuse ν background of O(MeV) energy produced by all the past core-collapse Supernovae in the Universe:

Supernova Relic Neutrinos (SRN)



The detection of SRN flux is the subject of both experimental and theoretical investigations:

By a future detection of SRN we could extract information on supernova physics, neutrino masses and mixing, star formation rate, but also new neutrino properties such as

NEUTRINO DECAY →

In principle, massive neutrinos can not only mix but also decay.

The most stringent and safe limit comes from the non observation of decay effects on solar ν, implying that

$$\frac{\tau}{m} \geq 10^{-4}\ \mathrm{s/eV}$$ (solar ν)

where τ is the lifetime (in the rest frame) for a neutrino of mass *m*.

Constraining SRN we can probe cosmologically interesting ν lifetimes as large as $\tau E/m \sim 1/H_0 \sim 10^{17}$ s, reaching

$$\boxed{\frac{\tau}{m} \sim O\,(10^{11})\ \mathrm{s/eV}}$$ (SRN)

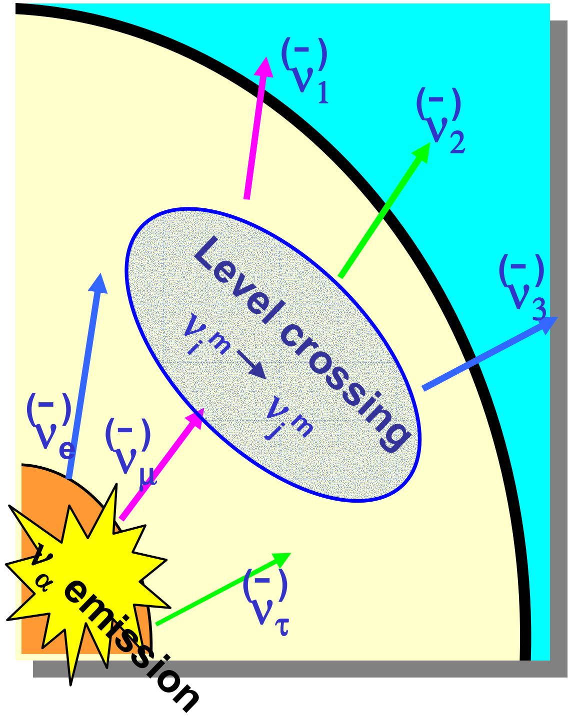
The purpose of this talk is to show how to incorporate the effects of both flavor transitions and decays in observable SRN spectra, by solving the SRN kinetic equations for two-body non-radiative ν decay.

SN NEUTRINO FLAVOR TRANSITION

- For values of τ/m above the solar ν bound, SRN flavor transitions in stellar matter can be taken as decoupled from the subsequent (incoherent) propagation and decay of mass eigenstates in vacuum.

- The fluxes of mass eigenstates ν_i at the surface of the SN can be calculated by taking into account the stellar matter effects on ν propagation.

- These effects are parameterized in term of a level crossing probability P_H among the instantaneous eigenstates ν_i^m ("matter eigenstates") of the Hamiltonian in the medium.



SRN DECAY:THE KINETIC EQUATIONS

At the exit of SN, ν_i mass eigenstates travel independently to the surface of the Earth. In their propagation in vacuum, SRN may be affected by decay.

The Boltzmann equation equation governing $n_{\nu i}(E,t)$ is

$$\boxed{\left(\frac{\partial}{\partial t} - H(t)\,E\,\frac{\partial}{\partial E} - H(t)\right) n_{\nu_i}(E,t) = R_{SN}(t)\,Y_{\nu_i}(E) + \sum_{m_j>m_i} q_{ji}(E,t) - \Gamma_i \frac{m_i}{E}\, n_{\nu_i}(E,t)}$$

where

- $R_{SN}(t)Y_{\nu_i}(E)$ **is the source term from the standard emission for core-collapse SN, R_{SN} is the SN formation rate, Y_ν is the yield (time integrated luminosity)**
- $q_{ji}(E,t) = \int_E^\infty dE'\, n_{\nu_j}(E',t)\, B(\nu_j \to \nu_i)\,\Gamma_j \frac{m_j}{E'}\,\psi_{\nu_j \to \nu_i}$ **is the source from the decay of heavier eigenstates, with decay width $\Gamma_j = 1/\tau_j$, branching ratio B, and normalized decay spectrum ψ**
- $\Gamma_i \frac{m_i}{E} n_{\nu_i}(E,t)$ **is the sink term : the loss of ν_i due to decay to lighter states with total width Γ_i.**

Our result is that these equations can be directly integrated through the substitutions z=z(t) and $\varepsilon=E/(1+z)$.

The solution of the Boltzmann equation is

$$\boxed{\begin{aligned} n_{\nu_i}(E,z) = \frac{1}{1+z}\int_0^\infty \frac{dz'}{H(z')}\left[R_{SN}(z')\, Y_{\nu_i}\!\left(E\,\frac{1+z'}{1+z}\right) + \right.\\ \left.\sum_{\mathrm{m}_j>m_i} q_{ji}\!\left(E\,\frac{1+z'}{1+z}, z'\right)\right] \exp\!\left[-\,\mathrm{m}_i\Gamma_i\big(\xi(z')-\xi(z)\big)\frac{(1+z)}{E}\right] \end{aligned}}$$

with $\xi(z) = \int_0^z \frac{dz'}{H(z')(1+z')^2}$

In practice, these equations can be integrated numerically by following the decay sequence, i.e., starting from the heaviest state ($q_{ji}=0$) and ending to the lightest state ($\Gamma_i=0$).

The $\bar{\nu}_e$ flux at Earth (redshift z=0), relevant for the inverse β decay reaction $\bar{\nu}_e\, p \longrightarrow n\, e^+$ in a Cherenkov detector, is given by

$$\boxed{n_{\bar{\nu}_e}(E) = \cos^2\theta_{12}\, n_{\bar{\nu}_1}(E,0) + \sin^2\theta_{12}\, n_{\bar{\nu}_2}(E,0)}$$

MAJORON DECAY

Among all the possible neutrino decay scenarios, we consider decays into an invisible massless (pseudo)scalar particle X, a "Majoron":

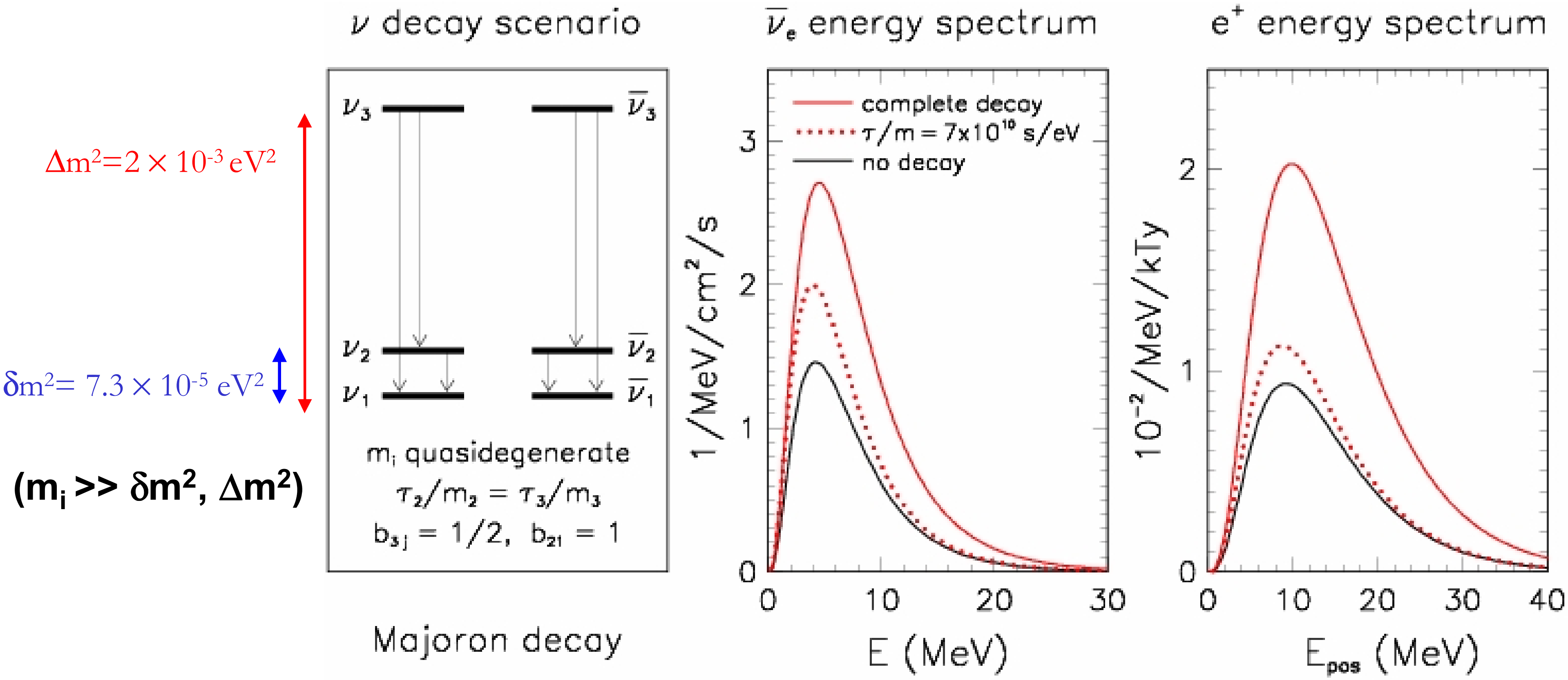
$$\nu_i \longrightarrow \overset{(-)}{\nu}_j \; X \qquad\qquad m_i > m_j$$

For simplicity we consider only two limiting cases: the **nearly degenerate case ($m_i \approx m_j$)**, and the **strongly hierarchical case ($m_i >> m_j \approx 0$)**.

For each of these cases, we evaluate the observable e^+ spectrum generated by inverse beta decay of $\overline{\nu}_e$ assuming

- **no decay** ($\Gamma_i = 0$ in the kinetic equations, i.e. large $\tau/m >> 10^{10}$ s/eV)
- **complete decay** ($\Gamma_i \longrightarrow \infty$ in the kinetic equations, i.e. $\tau/m << 10^{10}$ s/eV). All the states have decayed into the lightest state before detection. The result become independent from the small value of τ/m.
- **incomplete decay** for a specific "intermediate" value of $\tau/m = 7\times 10^{10}$ s/eV.

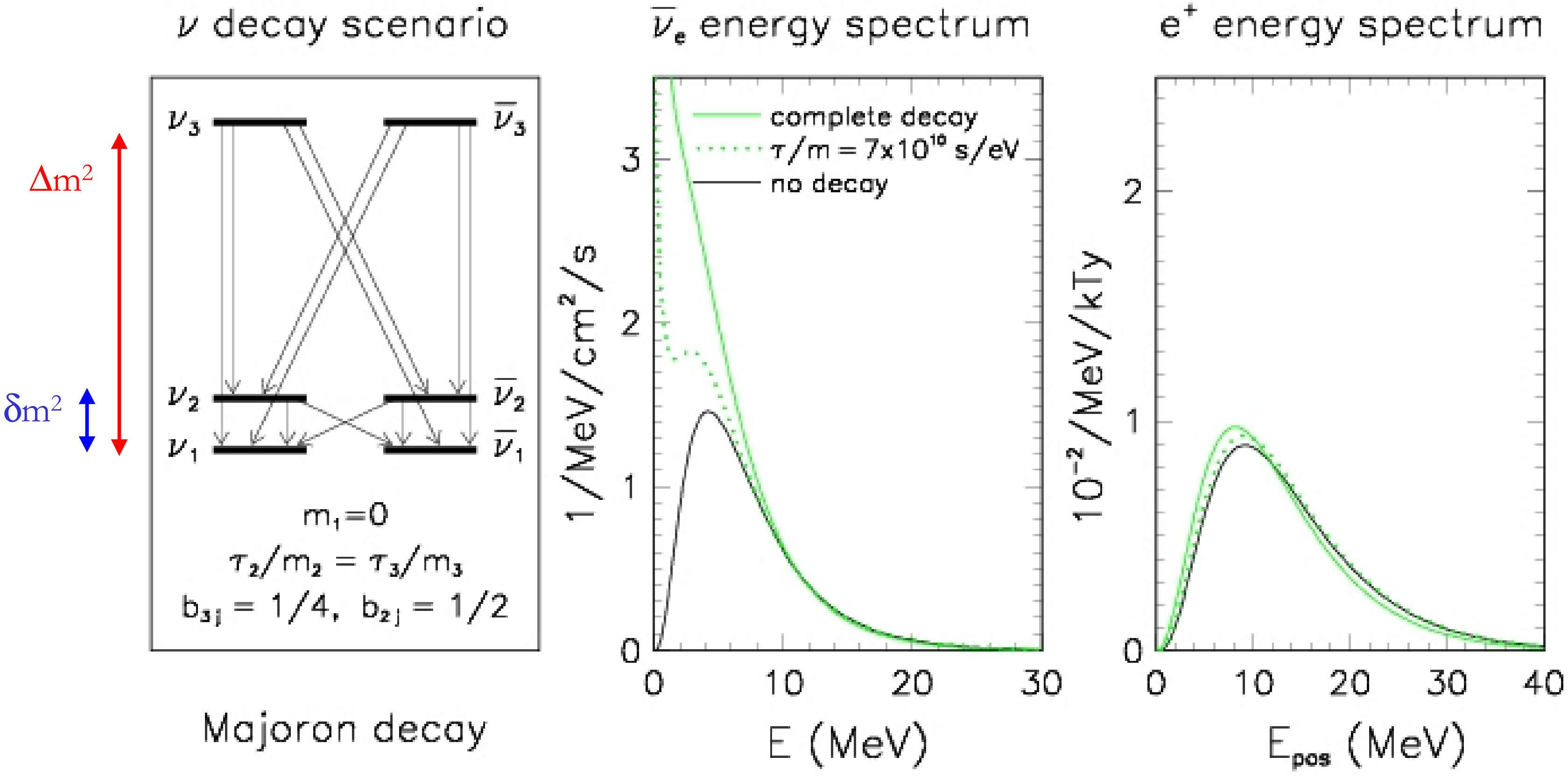
Normal hierarchy, quasidegenerate masses ($m_i \approx m_j$)



($m_i \gg \delta m^2, \Delta m^2$)

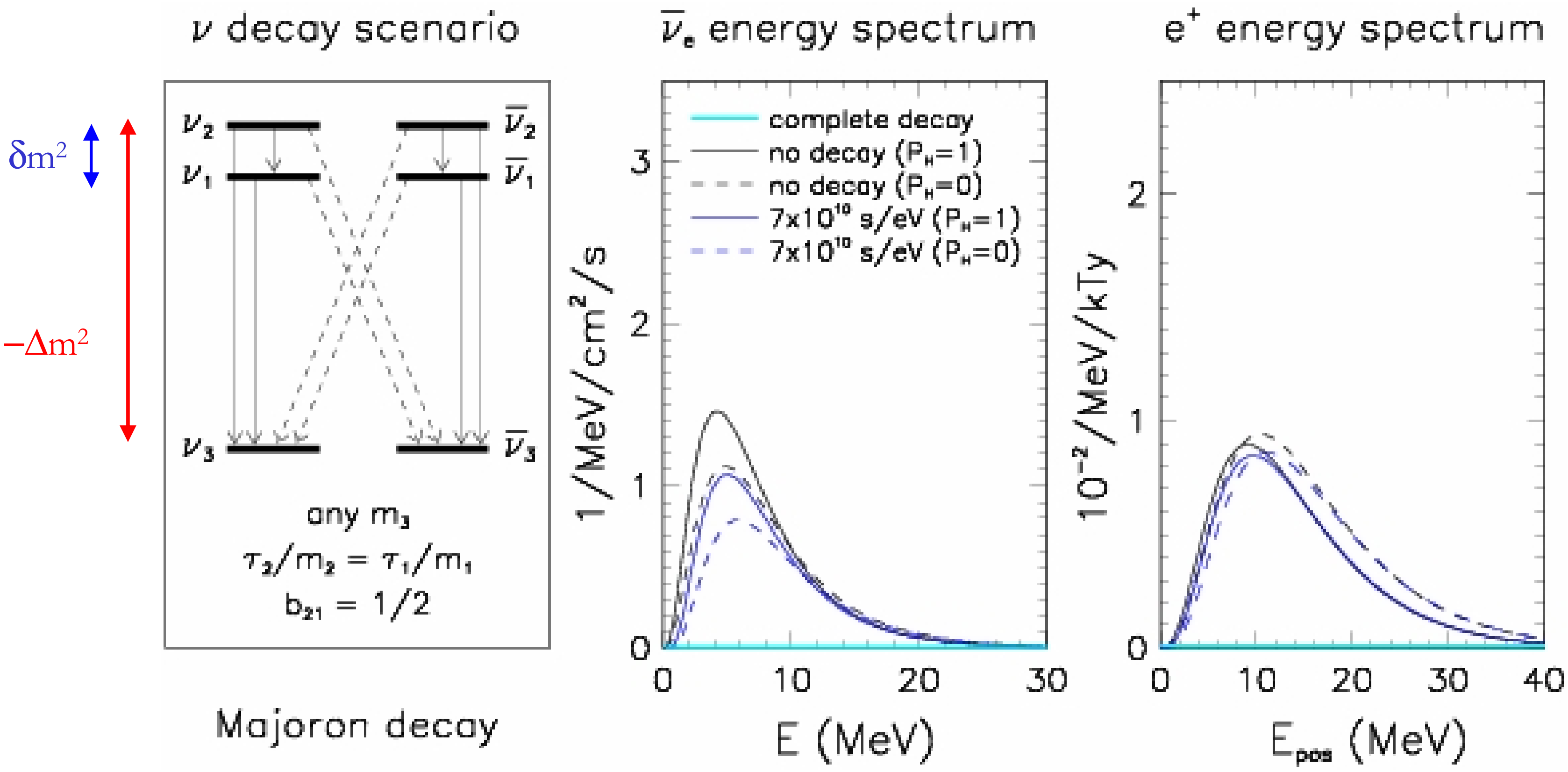
- In this situation $\nu \longrightarrow \bar{\nu}$ decays are forbidden.
- This decay scenario increases the SRN fluxes as compared with no decay.
- Complete decay corresponds to a signal enhancement by a factor ~2.

Normal hierarchy, strongly hierarchical masses (m_1=0)



- All decay channels open.
- Complex decay chain with substancial enhancement of SRN energy spectrum at low energies.
- "Pile-up" of decayed ν with degraded energy w.r.t. the case of no decay.
- e^+ spectrum <u>very similar</u> to the no decay case. Enhancement at low energy suppressed by the ~ E^2 dependence of the cross section.

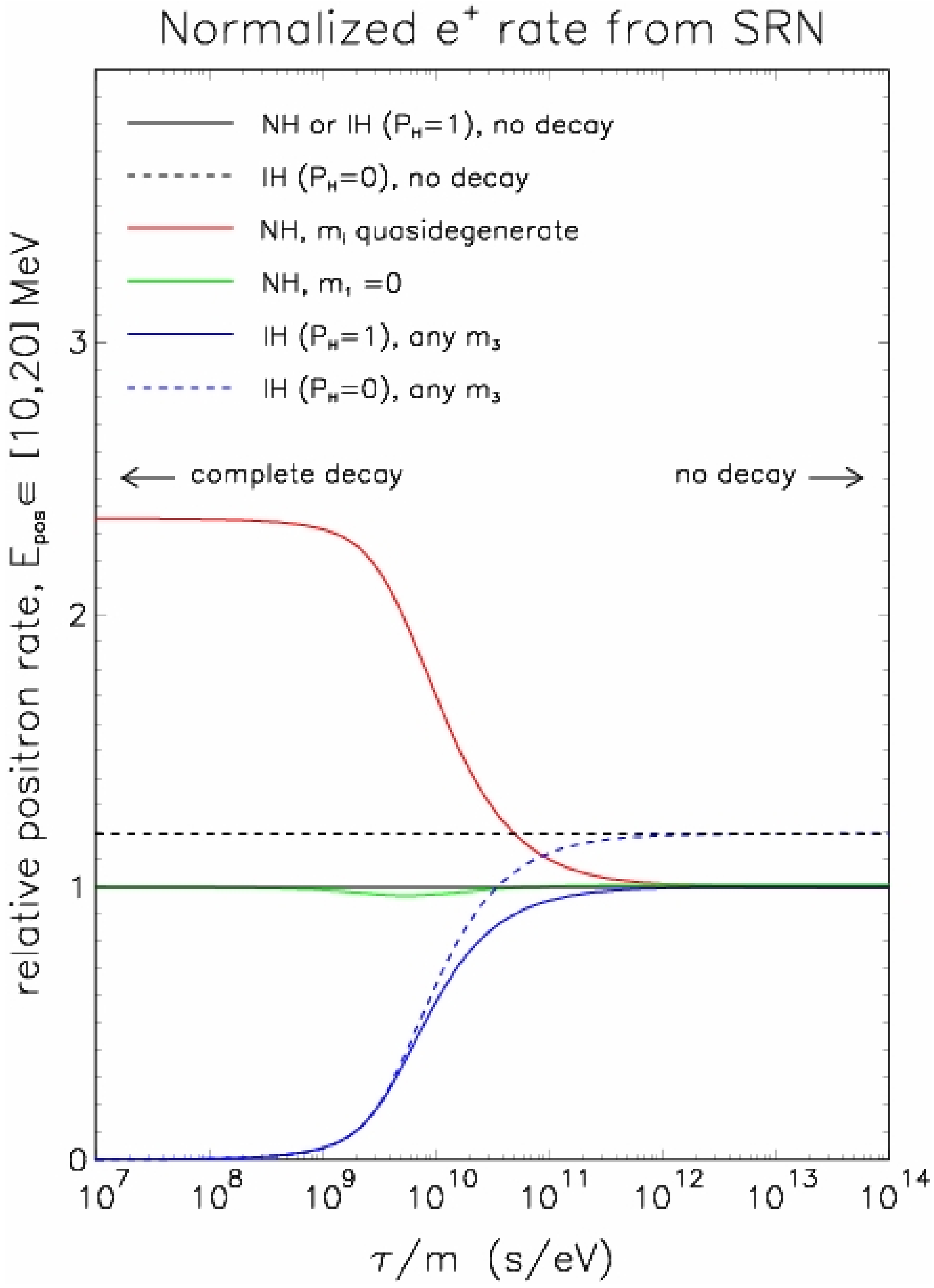
Inverted hierarchy, (I.H.) any m_3



- In I.H., decays to $\bar{\nu}_3$ provide a negligible amount of $\bar{\nu}_e$ ($\propto \sin^2\theta_{13} \lesssim 10^{-2}$), so $m_{1,2} >> m_3$ and $m_{1,2} \approx m_3$ essentially indistinguishable.

- SRN flux generally suppressed w.r.t. to the no decay case.

- In the case of complete decay all states end up as $\overset{(-)}{\nu}_3$ giving an almost complete disappearance of the signal ($\propto \sin^2\theta_{13}$).



We consider the total number events (normalized to the no oscillation case) in the e^+ energy window [10,20] MeV.

Neutrino decay can enlarge the reference no-decay predictions for observable e^+ rates by any factor in the range ~[0,2.3].

Since the current experimental upper bound from SK [M.Malek et al., Phys.Rev.Lett. **90**, 061101 (2003)**] is just a factor ~2-3 above typical no-decay expectations, future observations below this bound could constrain at least some extreme decay cases.**

CONCLUSIONS

Neutrino decays with cosmologically relevant ν lifetimes can, in principle, be probed through the observations of SRN.

- We have shown how to incorporate the effects of both flavor transitions and decays in the calculations of SRN flux, by finding the general solution for the neutrino kinetic equations.

- We have applied this solution to three representative decay scenarios which lead to an observable SRN flux larger, comparable, or smaller than for no decay.

- In the presence of decay, the expected range of SRN rate is significantly enlarged (from zero up to the upper current bound). Future SRN observations might thus constrain at least some extreme decay scenarios, and access a τ/m range which can not be explored by other means.