On the capture rate of big-bang neutrinos by nuclei within the Dirac and Majorana hypotheses

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The capture rates of non-relativistic neutrinos on beta decaying nuclei depends on whether their mass is Dirac or Majorana. It is known that for relic neutrinos from the big-bang, and within minimal assumptions, the rate is a factor two larger in the Majorana case. We show that this difference also depends on the value of the lightest neutrino mass and on the type of mass hierarchy. If the lightest neutrino has a mass below the meV, so that it is still relativistic today, its capture rate for the case of Dirac masses becomes equal to that for Majorana masses. As a consequence, for the case of normal neutrino mass hierarchy, for which the total capture rate is dominated by the contribution from the lightest neutrino, if this one is below the meV the distinction between the Dirac and Majorana scenarios can only rely on the detection of the two heavier neutrinos, which is something very challenging.

Based on Roulet & FV, JCAP10(2018)049

mass**less**ness of neutrinos

- Neutrinos massless in standard model (SM)
- Oscillations say that this is wrong – good! - and learned a lot with their study
- But oscillations treat equally neutrinos and antineutrinos, as we study only the case p>>m: Dirac/Majorana masses give the same result
- And lightest neutrino mass is not probed

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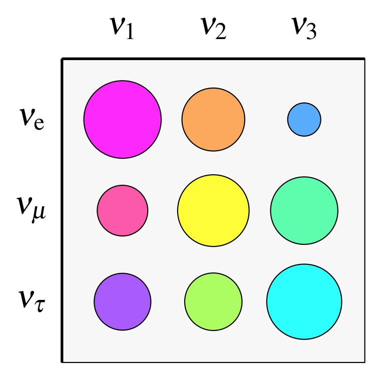
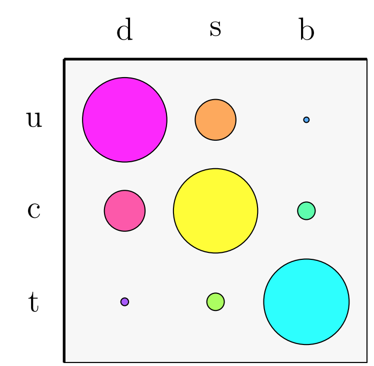
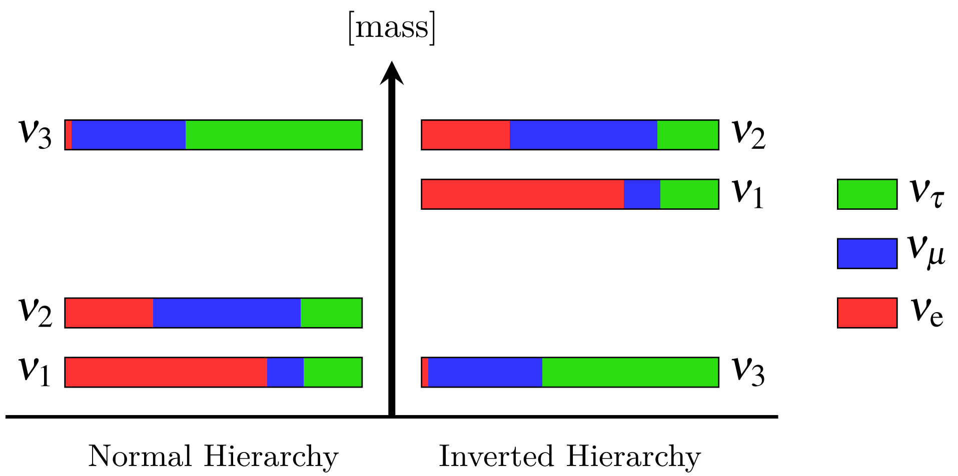
what we learned from oscillations

Fantini, Gallo Rosso et al, 2018







what we did not learn

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a tough road *ahead of us*

Not many clues on lightest or overall neutrino mass from theory

Hard to probe it in lab - β-decay, 0νββ

In plausible SM extensions, we have *typically* Majorana neutrinos.

It is just essential to test this *hypothesis* – only 0νββ is usually considered

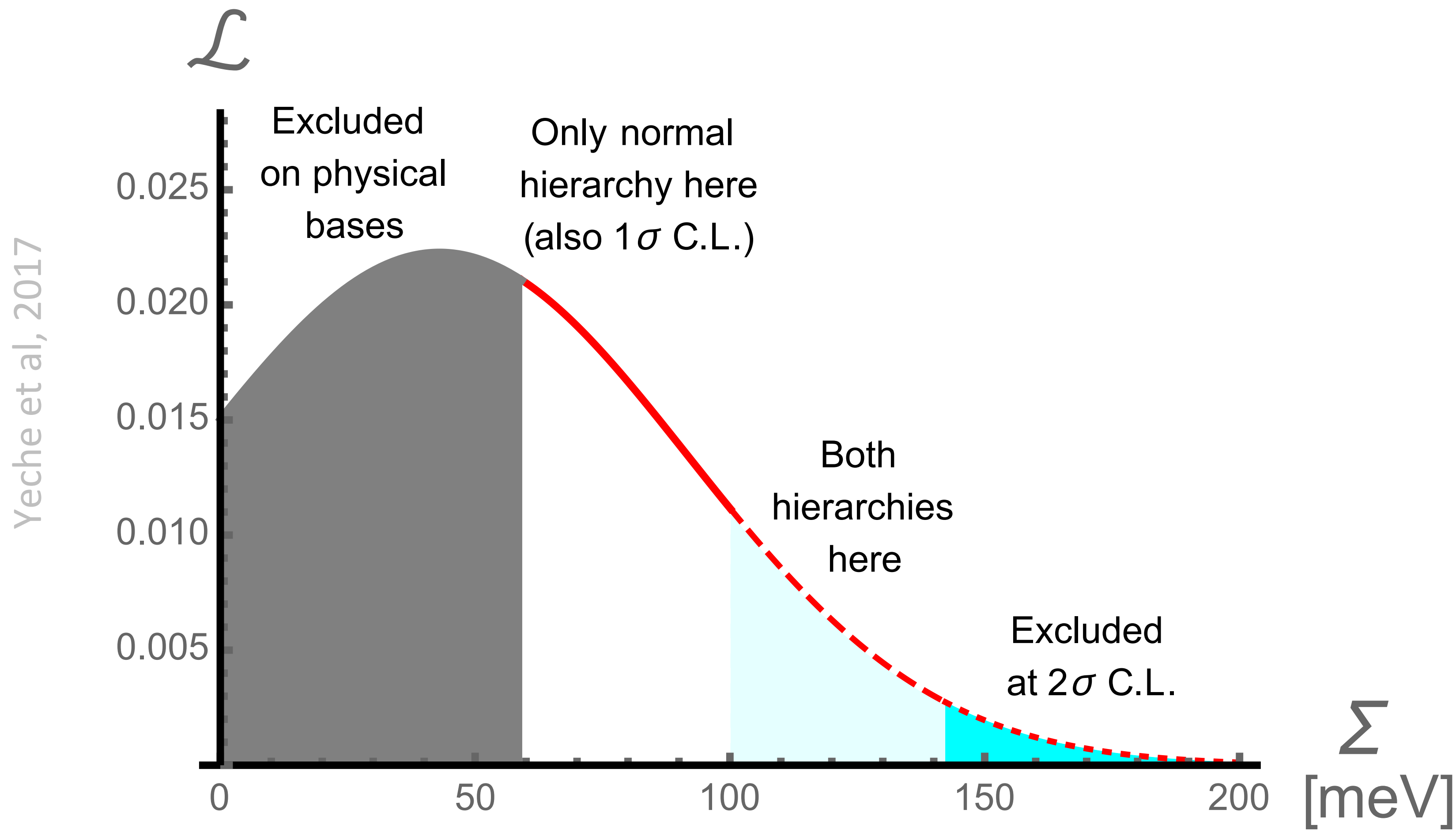
neutrinos from big-bang (CνB)

- recombination temperature ~250 meV
- any imprint of ν masses of this size on CMB?

- today, neutrinos from big-bang have T~0.2 meV
- 2nd heaviest neutrinos is >8 meV; 3rd >50 meV; but what about the lightest? maybe *this* is relativistic

Lesgourgues & Pastor, 2014

CMB sensitive to $\Sigma = m_1 + m_2 + m_3$



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Lesgourgues & Pastor, 2014

can we see CνB directly?

Cocco, Mangano, Messina 2007
Long, Lunardini, Sabancilar 2014
PTOLEMY!

- radioactive nuclei can capture big-bang neutrinos
- this yields lines that occur after ‘endpoint’
- their positions depend upon lightest neutrino mass
- the rate is sensitive to the type of the mass

let us elaborate on the difference of Dirac & Majorana

$\nu_e + T \rightarrow e^- + {}^3He$ [1/2]

Roulet & FV, 2018

Dirac field:

$$\mathbf{\Psi}^{\rm D} = \sum_{\vec{p},\lambda} \mathbf{a}_{\vec{p},\lambda}\, \psi_{\vec{p},\lambda} + \mathbf{b}^\dagger_{\vec{p},\lambda}\, \psi^{\rm C}_{\vec{p},\lambda}$$

Initial states (hot Big-Bang):

$$|\nu^{\rm D}\rangle = \mathbf{a}^\dagger_{\vec{p},-}|0\rangle \text{ and } |\bar{\nu}^{\rm D}\rangle = \mathbf{b}^\dagger_{\vec{p},+}|0\rangle$$

Matrix elements for the transition:

$$\langle 0|P_{\rm L}\mathbf{\Psi}^{\rm D}|\nu^{\rm D}\rangle = P_{\rm L}\psi_{\vec{p},-}$$

and

$$\langle 0|P_{\rm L}\mathbf{\Psi}^{\rm D}|\bar{\nu}^{\rm D}\rangle = 0$$

Majorana field:

$$\mathbf{\Psi}^{\rm M} = \sum_{\vec{p},\lambda} \mathbf{c}_{\vec{p},\lambda}\, \psi_{\vec{p},\lambda} + \mathbf{c}^\dagger_{\vec{p},\lambda}\, \psi^{\rm C}_{\vec{p},\lambda}$$

Initial states (hot Big-Bang):

$$|\nu^{\rm M}\rangle = \mathbf{c}^\dagger_{\vec{p},-}|0\rangle \text{ and } |\bar{\nu}^{\rm M}\rangle = \mathbf{c}^\dagger_{\vec{p},+}|0\rangle$$

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$$\langle 0|P_{\rm L}\mathbf{\Psi}^{\rm M}|\bar{\nu}^{\rm M}\rangle = P_{\rm L}\psi_{\vec{p},+}$$

$\nu_e + T \rightarrow e^- + {}^3He$ [2/2]

Dirac field:

$$\langle 0|P_L \mathbf{\Psi}^D|\nu^D\rangle = P_L \psi_{\vec{p},-}$$

and

$$\langle 0|P_L \mathbf{\Psi}^D|\bar{\nu}^D\rangle = 0$$

Probability:

If $\int d^3x|\psi^2_{\vec{p},\lambda}| = 1$,

then $\int d^3x|P_L\psi^2_{\vec{p},-}| = \frac{1+\beta}{2}$

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and $\int d^3x|P_L\psi^2_{\vec{p},+}| = \frac{1-\beta}{2}$

Dirac mass means less event

Roulet & FV, 2018

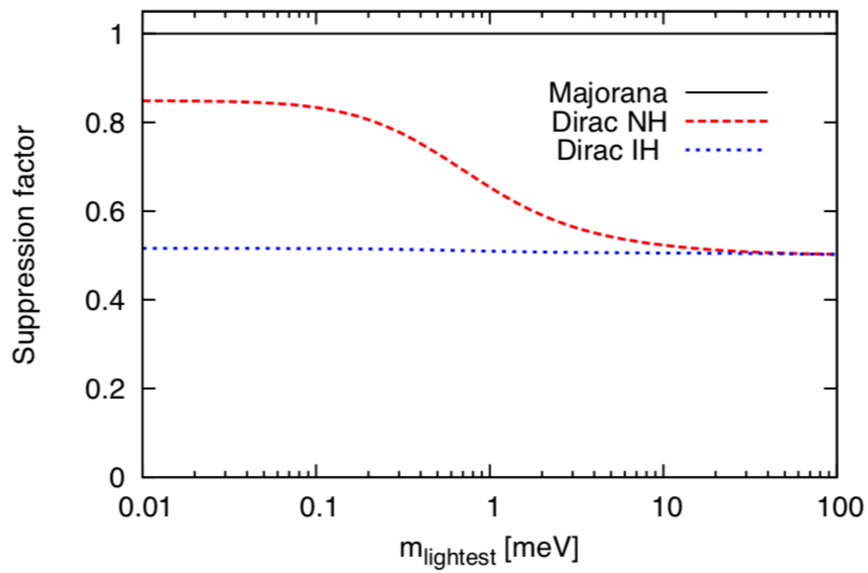


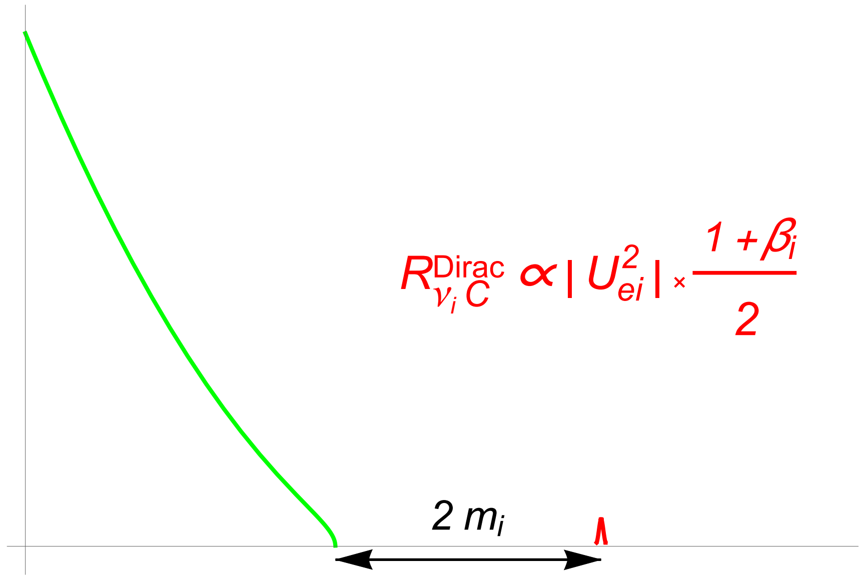
Figure 1: Numerical calculation of the suppression factor for the Dirac neutrino capture process, as a function of the lightest neutrino mass and for the two neutrino mass hierachies (normal and inverted). For comparison, also the case of Majorana neutrinos is shown, for which the suppression is 1 or, in other words, there is no suppression.

Remarks

Three lines: positions depend upon m_i
intensity depends upon $|U_{ei}^2|$

Thus with normal hierarchy the most intense line is due to the lightest neutrino

Issue of energy resolution especially with small m_i and normal hierarchy



Roulet & FV, 2018

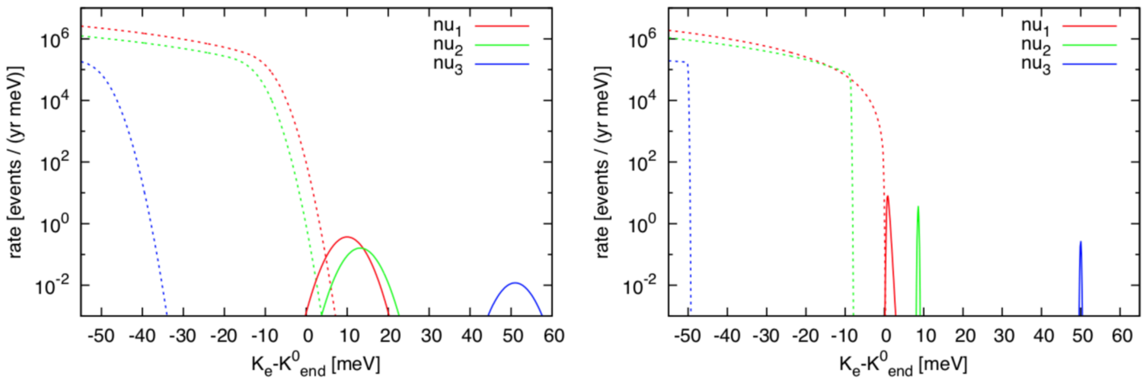


Figure 2: Rate of beta decay (dashed lines) and CνB capture for Dirac neutrinos (solid lines) and for a target with 100 g of tritium. We assume the normal hierarchy and show separately the contributions associated to each of the three neutrino mass eigenstates for two different futuristic scenarios for the detection. The left panel adopts the lightest neutrino mass as $m_1 = 10$ meV and the energy resolution $\Delta = 7$ meV. The right panel has instead $m_1 = 0.3$ meV and $\Delta = 0.3$ meV.

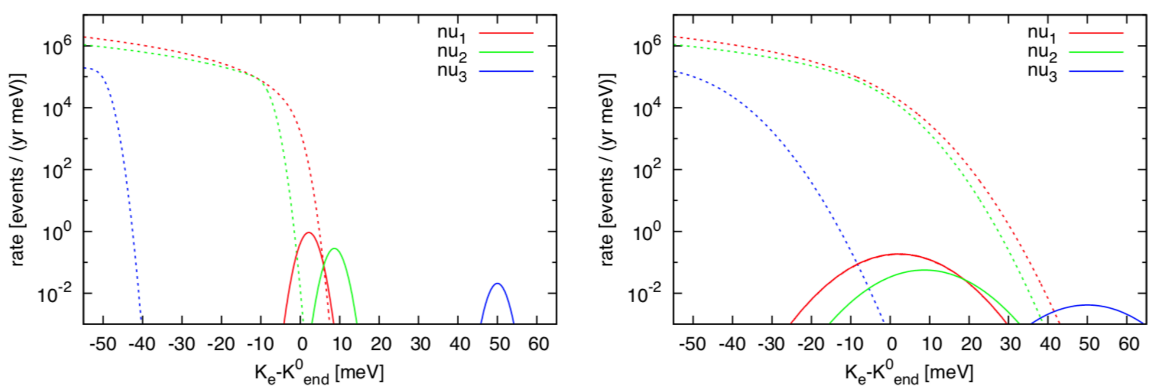


Figure 3: Rate of beta decay (dashed lines) and CνB capture for Dirac neutrinos (solid lines) and for a target with 100 g of tritium. We assume the normal hierarchy and show separately the contributions associated to each of the three neutrino mass eigenstates, adopting $m_1 = 1$ meV. The left panel considers an energy resolution $\Delta = 4$ meV. The right panel has instead $\Delta = 20$ meV.

summary

- capture rate of CνB depends upon neutrino mass type and spectra, i.e., mass hierarchy and lightest mass value: stay tuned on oscillation and CMB neutrino studies
- Dirac rate twice less (Lunardini et al) except if m_1 very small (Roulet et al)
- normal mass hierarchy could in principle allow to measure m_1 (even if small m_1 doesn't make detection of CνB easier)
- (I know you know, still) need very good resolution & enough mass

for discussion & details, see JCAP10(2018)049

Thanks & good luck!

appendix

Consider one Dirac neutrino with mass m_i produced in the big-bang, whose momentum is subject to adiabatic expansion of the Universe, and consider helicity states. We need to evaluate the polarized density matrix bracketed between two chirality projectors,

$$P_L \; u_i\overline{u_i} \; P_R = P_L \; (\not{p}_i + m_i)\frac{1+\gamma_5 \not{\xi}_i}{2} P_R = P_L \frac{\not{p}_i - m_i \not{\xi}_i}{2} P_R \tag{1}$$

Thus the usual calculations have to be modified trivially: we should include systematically a factor 1/2 in the calculation of the interaction rate, and moreover we should replace the 4-momentum

$$p_i \to p_i - m_i \, \xi_i$$

Considering helicity $\lambda = \pm 1$, we have $p_i = (E_i, \vec{n}\, p)$ and $m_i \, \xi_i = \lambda(p, \vec{n}\, E_i)$, where E_i is the energy and $\vec{n}$ the direction of the motion of the neutrino, $\vec{p} = p\, \vec{n}$. We get,

$$\frac{p_i - m_i \, \xi_i}{2} = \frac{1 \mp \lambda \beta_i}{2} \times p_i \text{ where } \beta_i = \frac{p}{E_i} \tag{2}$$

The overall factor on the right-hand side is the one in which we are interested. The unpolarized neutrino density matrix $\rho_i(\nu) \equiv \not{p}_i$ has to be modified trivially

$$\rho_i(\nu) \to \frac{1 \mp \lambda \beta_i}{2} \times \rho_i(\nu)$$