# NEUTRINOS IN VACUUM AND MATTER WITH ASTROPHYSICAL APPLICATIONS

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UNIVERSITY OF JYVÄSKYLÄ

2005-2010

- Bachelor of Science (3 months)
- Research Training (during 4th year)
- Master of Science (during 5th year)
  (under supervision of Prof. J. Maalampi)
- Cyclotron operator (during 3rd and 4th year )


March 2010

- Professional Training (5 months)
  (under supervision of Prof. M.C. Volpe)

# Bachelor of Science Thesis

(under supervision of Prof. J. Maalampi)

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- Basic concepts of neutrino oscillations in vacuum
  - Massive and mixed neutrinos: $\nu_l = \sum_{i=1}^{3} U_{li}\nu_i \ (l = e, \mu, \tau)$
  - Unitary rotation matrix describing how the different bases are related:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}c_{13}e^{-i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{-i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{-i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{-i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \times \begin{pmatrix} e^{-i\alpha_1} & 0 & 0 \\ 0 & e^{-i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \text{ where } c_{ij} \equiv \cos\theta_{ij}, \ s_{ij} \equiv \sin\theta_{ij} \quad (i, j = 1, 2, 3)$$

# Bachelor of Science Thesis

(under supervision of Prof. J. Maalampi)

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- Flavor lepton numbers are not conserved:

  Neutrinos are allowed to change from one type to another
- Certain probability for such transitions:

$$P(\nu_l \to \nu_{l'}) = \sum_i |U_{l'i}|^2 \, |U_{li}|^2 + 2\mathcal{R}\mathrm{e}\left[\sum_{i>j} U_{l'i} U_{li}^* U_{lj} U_{l'j}^* e^{-\mathrm{i}\left(\frac{\Delta m_{ij}^2}{2E}\right)L}\right] \quad \begin{matrix}(l = e, \mu, \tau) \\ (i, j = 1, 2, 3)\end{matrix}$$

- Observed phenomenon (terrestrial, atmospheric and solar neutrinos): $\Delta m_{21}^2 \sim 10^{-5}\ \mathrm{eV}^2\ , |\Delta m_{32}^2| \sim 10^{-3}\ \mathrm{eV}^2 \sim |\Delta m_{13}^2|$
- Neutrinos indeed are massive and mixed!

$$\Delta m_{32}^2 = m_3^2 - m_2^2 > 0 \quad \mathrm{NMH}$$
$$\Delta m_{32}^2 = m_3^2 - m_2^2 < 0 \quad \mathrm{IMH}$$

$$0.538 < \theta_{23} < 0.659$$
$$0.613 < \theta_{12} < 0.931$$
$$0 < \theta_{13} < 0.2$$

# Bachelor of Science Thesis

(under supervision of Prof. J. Maalampi)

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- UltraHigh-Energy Cosmic Ray (UHECR) neutrinos

$$\begin{cases} p + \gamma \rightarrow p + \pi^0 + \pi^{\pm} \\ p + N \rightarrow \pi^+ + X \end{cases}$$

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

  - Expected initial UHECR neutrino fluxes:

$$\begin{pmatrix} F^0(\nu_e) \\ F^0(\nu_\mu) \\ F^0(\nu_\tau) \end{pmatrix} = \begin{pmatrix} 1 \\ 2 \\ 0 \end{pmatrix} F^0(\nu_e)$$

  - Effects of neutrino oscillations

$$\begin{pmatrix} F(\nu_e) \\ F(\nu_\mu) \\ F(\nu_\tau) \end{pmatrix} = \begin{pmatrix} P_{ee} & P_{\mu e} & P_{\tau e} \\ P_{e\mu} & P_{\mu\mu} & P_{\tau\mu} \\ P_{e\tau} & P_{\mu\tau} & P_{\tau\tau} \end{pmatrix} \begin{pmatrix} F^0(\nu_e) \\ F^0(\nu_\mu) \\ F^0(\nu_\tau) \end{pmatrix} \approx \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} F^0(\nu_e)$$

  - Uncertainties on the mixing parameters:

$$0.77 \lesssim F(\nu_e) : F(\nu_\mu) \lesssim 1.19$$

# Research Training

(under supervision of Prof. J. Maalampi)

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- Neutrino mass generation mechanisms

  (beyond the Standard Model (SM)):
  - Dirac neutrinos (distinguished antiparticles) $\nu = \nu_L + \nu_R$
  - Majorana neutrinos $\nu = \nu_{L,R} + \nu_{L,R}^C \Leftrightarrow \nu = \nu^C$
  - Dirac-Majorana neutrinos $M = \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} \qquad m_1 \propto \frac{m_D^2}{m_2}$
    - See-saw mechanism
    - plausible explanation for the smallness of neutrino masses
- Only left-handed take part in the SM weak interactions
- Possibility of sterile neutrinos (which lack the SM interactions)

# Research Training

(under supervision of Prof. J. Maalampi)

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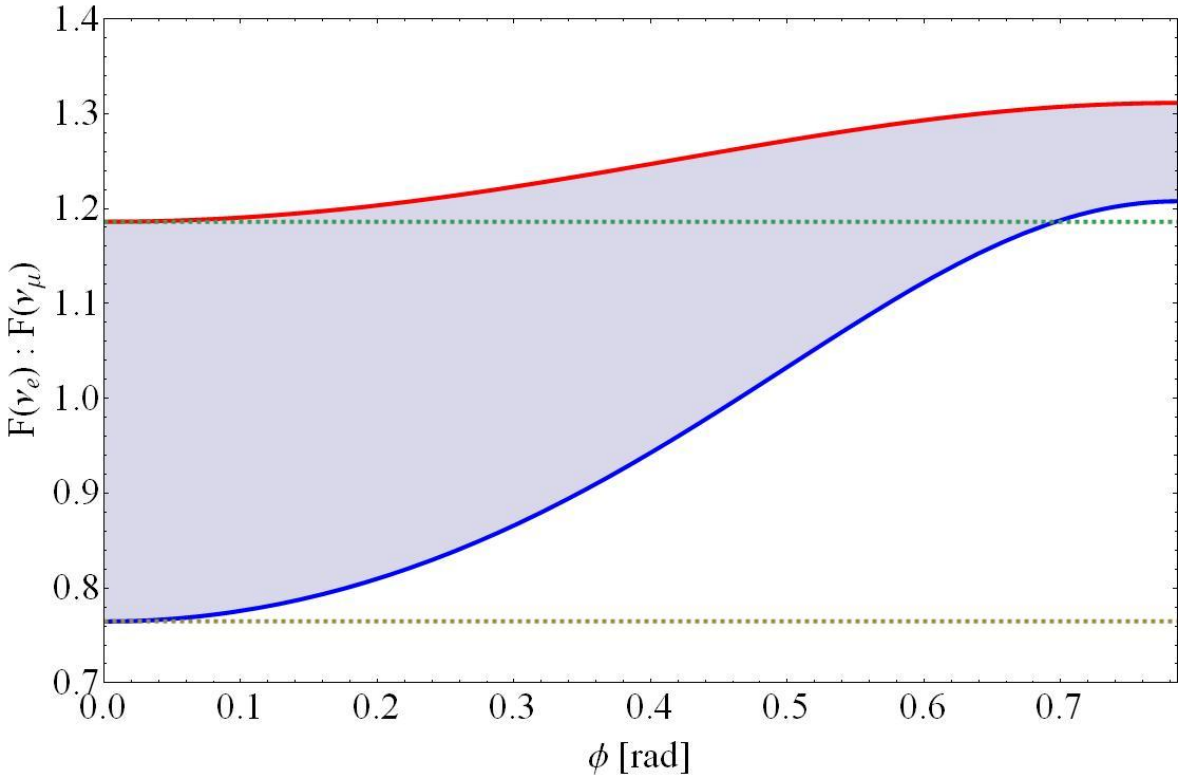
- Active-sterile mixing:

$$\nu_3 = \cos\phi\hat{\nu}_3 - \sin\phi\nu_s$$
$$\nu_4 = \sin\phi\hat{\nu}_3 + \cos\phi\nu_s$$

- Effects on the UHECR neutrino fluxes



# Master of Science Thesis

(under supervision of Prof. J. Maalampi)

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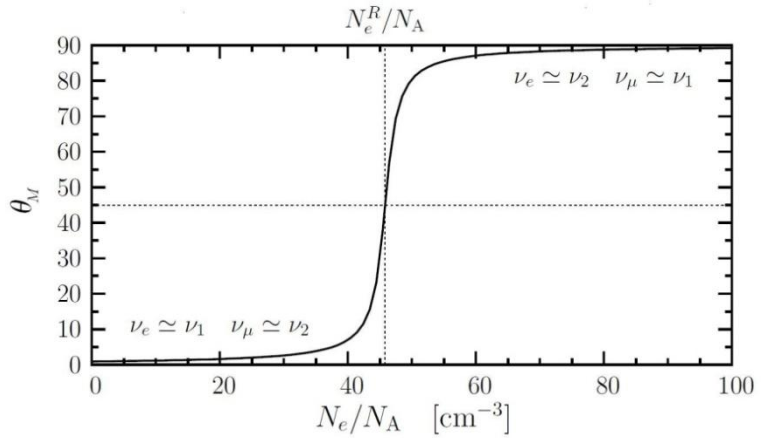
- Neutrino oscillations in matter (the MSW effect)
  - Additional potentials due to the interactions with particles in the medium
  - Effective mixing angle:

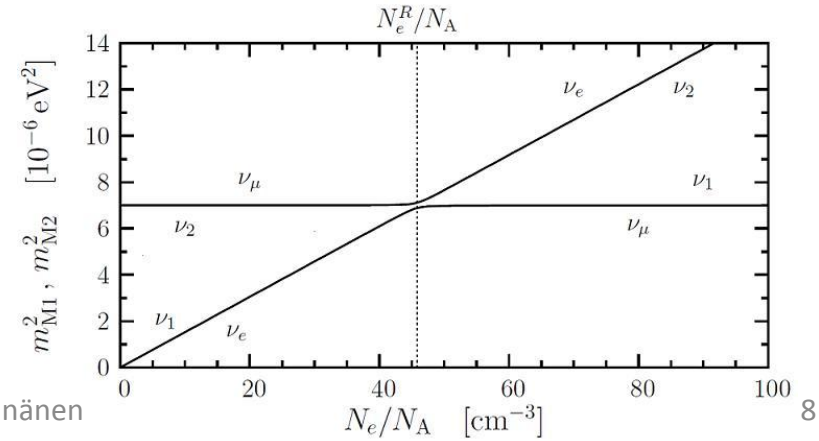
$$A_{CC} \equiv 2EV_{CC} = 2\sqrt{2}EG_F N_e$$

$$\tan(2\theta_M) = \frac{\tan(2\theta)}{1 - \frac{A_{CC}}{\Delta m^2 \cos(2\theta)}}$$

$$A_{CC}^R = \Delta m^2 \cos(2\theta)$$




  - Effective squared-masses:



# Master of Science Thesis

(under supervision of Prof. J. Maalampi)

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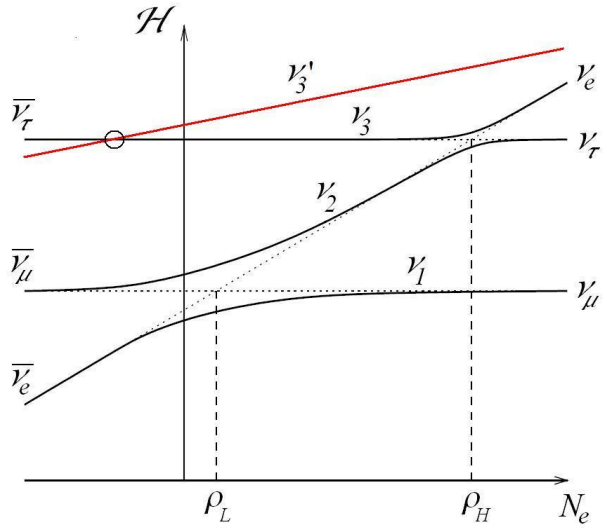
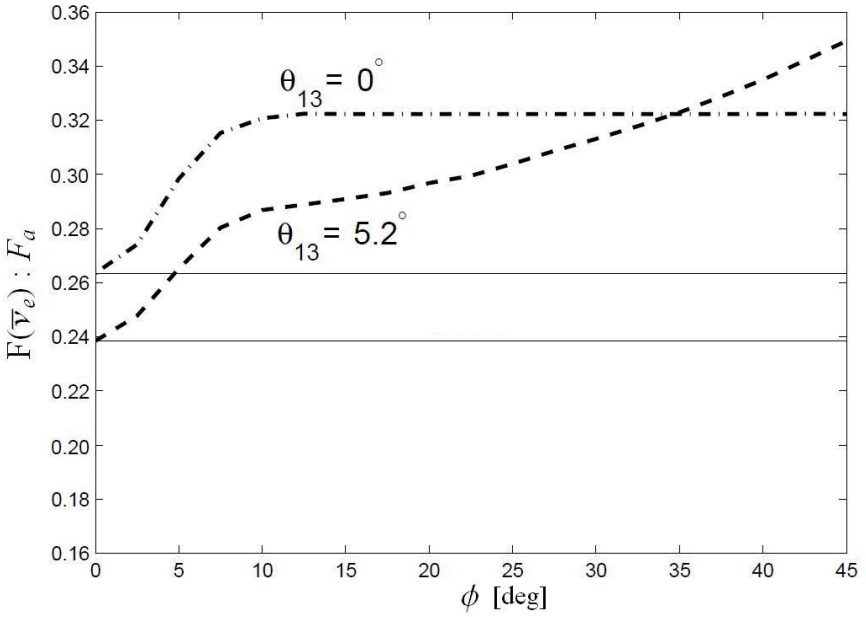
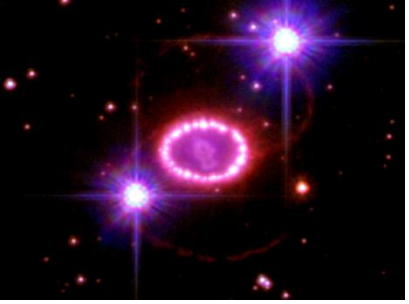
- Effects of neutrino oscillations on supernova (SN) neutrinos
  - Matter effects play crucial role in neutrino propagation
  - Factorization of SN dynamics and addition of possible sterile neutrinos:





# Professional Training

(under supervision of Prof. M.C. Volpe)

- New predictions for the HALO – project
- Helium And Lead Observatory at SNOlab:
  - A dedicated supernova neutrino detector
  - 80t of Pb (HALO-2: 1kt)

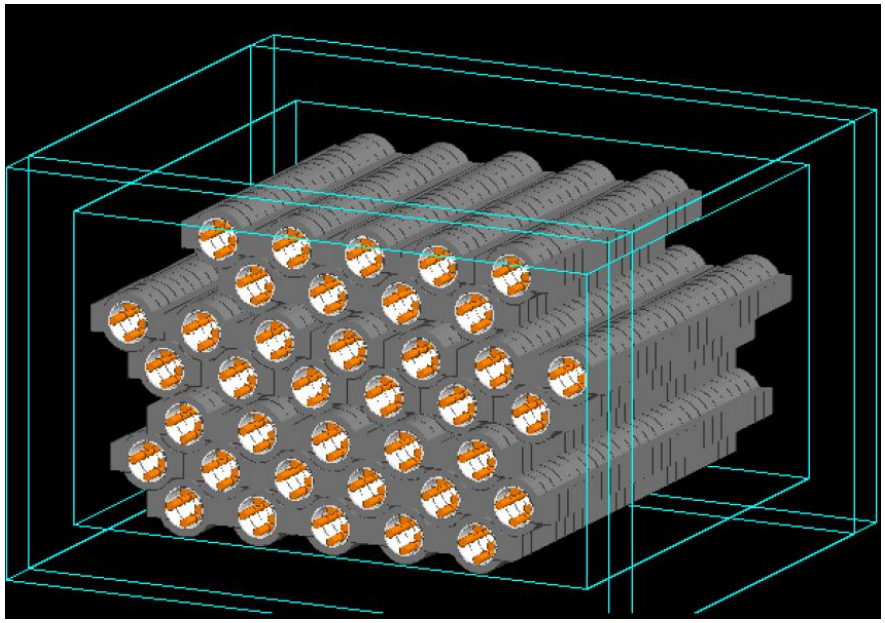
$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + \mathrm{n} + \mathrm{e}^-$$

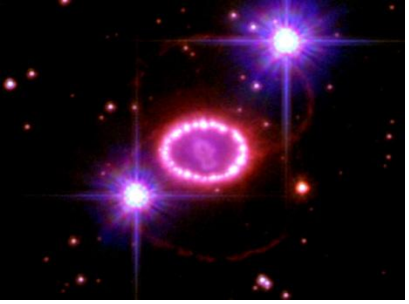
$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2\mathrm{n} + \mathrm{e}^-$$

$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + \mathrm{n}$$

$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2\mathrm{n}$$

  - Inside $^3$He gas detectors for neutron detection





# Professional Training

(under supervision of Prof. M.C. Volpe)

- Collective flavor transformations due to high neutrino density close to neutrinospheres – observed in the simulations
- Fluxes to be detected:

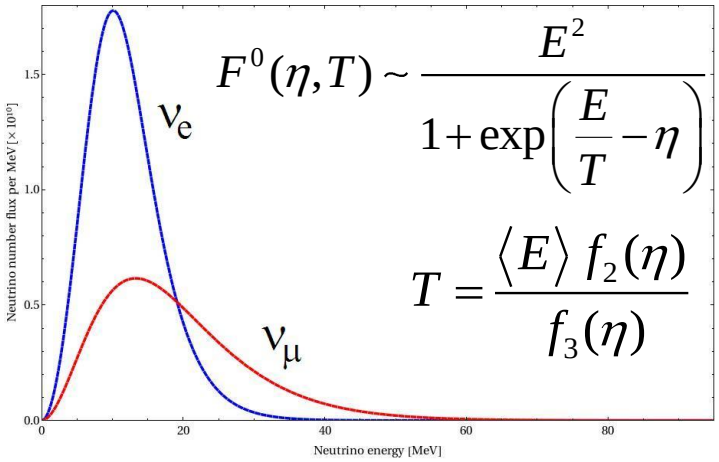
  (Core-collapse SNe, factorized dynamics)

$$\begin{pmatrix} F(\nu_e) \\ F(\nu_\mu) \\ F(\nu_\tau) \end{pmatrix} = P \begin{pmatrix} F^0(\nu_e) \\ F^0(\nu_\mu) \\ F^0(\nu_\tau) \end{pmatrix}, \quad P = D\, P_{MSW}\, P_{\upsilon\upsilon}$$

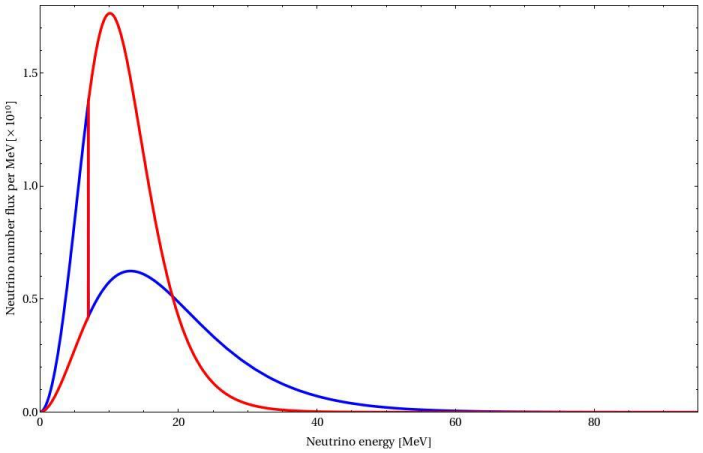
- Initial fluxes: "pinched" Fermi-Dirac distributions (or Power law)

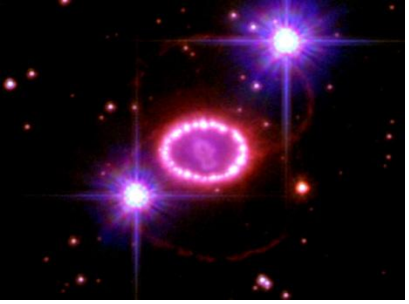
$$F^0(\eta, T) \sim \frac{E^2}{1+\exp\left(\frac{E}{T}-\eta\right)}$$

$$T = \frac{\langle E \rangle\, f_2(\eta)}{f_3(\eta)}$$




Collective Effects (IMH)





# Professional Training

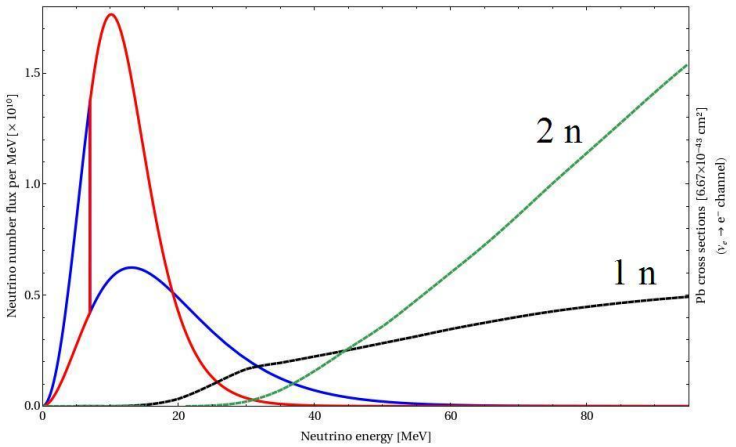
(under supervision of Prof. M.C. Volpe)

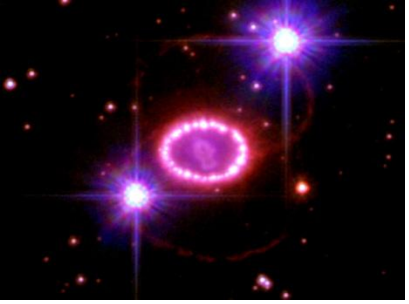
- Signatures of the unknown neutrino properties ($\theta_{13}$ and the mass hierarchy) and collective flavor conversion effects

| | Numbers of events IMH (NMH) | |
|---|---|---|
| | No collective effects ($\theta_{13}$ small) | With collective effects ($\theta_{13}$ large) |
| $\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + \mathrm{n} + \mathrm{e}^-$ | 259 | 335 |
| $\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2\mathrm{n} + \mathrm{e}^-$ | 88 | 126 |

- Comparison with other detectors sensitive to $\bar{\nu}_e$ 's (e.g SuperK)

- However, large uncertainties on initial fluxes





# Professional Training

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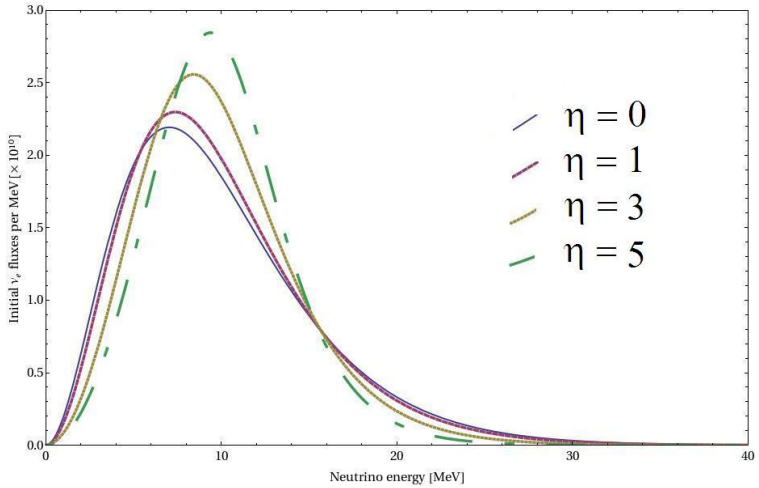
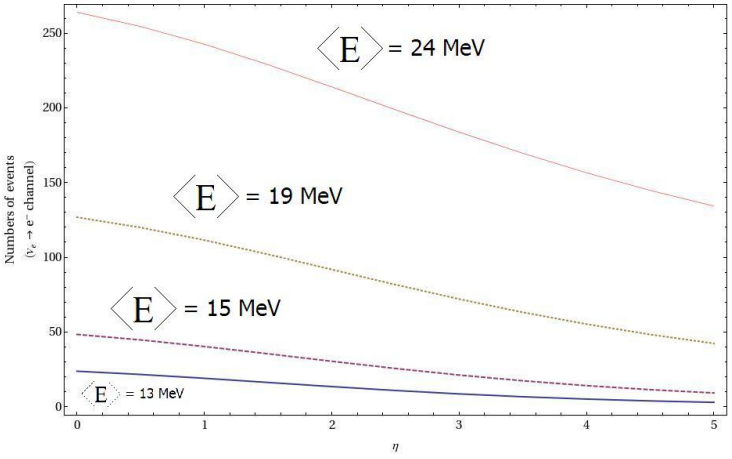
- HALO sensitive to parametrization of the initial fluxes
- Same average neutrino energies, different numbers of events depending on parameter values
- Different average energies possible




- In addition, time resolution sufficient to have information from different phases of the explosion
- Results to be published this summer

# Some Fundamental Open Questions in Physics

- Contents of the Universe?
  - Dark energy?
  - Dark matter ?

→ Sterile neutrinos?

- Matter-antimatter-asymmetry?

→ Leptonic CP violation (non-zero $\theta_{13}$ / $\delta_{CP}$)?

- Physics beyond the SM?
  - Extra dimensions?
  - Mass hierarchy?
  - Generations of matter?

→ Massive and mixed neutrinos! Nature of neutrinos (Dirac, Majorana, D-M, …)?

- More?

→ More studies at  ?


VIELEN
DANK!
Giant Hubble Mosaic of the Crab Nebula
HUBBLESITE.org