Neutrino Mass Hierarchy with Supernova Neutrinos

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Universität Hamburg

NOW, September 09-16, 2012

Plan of the talk

Supernova (SN) Neutrinos

Oscillation of SN Neutrinos

Signatures of Neutrino Mass Hierarchy

Conclusions

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23 February 1987 SN 1987A

Supernova one of the most energetic events in nature.

Terminal phase of a massive star ($M > 8\sim10\ M_\odot$)

Collapses and ejects the outer mantle in a shock wave driven explosion.

ENERGY SCALES: ~ 10^{53} erg : 99% energy is emitted by Neutrinos (Energy ~ 10 MeV).

TIME SCALE: The duration of the burst lasts ~10 s.

Neutrino Emission Phases

[Fischer et al. (Basel Simulations), A&A 517:A80,2010, 10. 8 M_{sun} progenitor mass]

Neutronization burst

- Shock breakout
- De-leptonization of outer core layers
- **Duration ~ 25 ms**

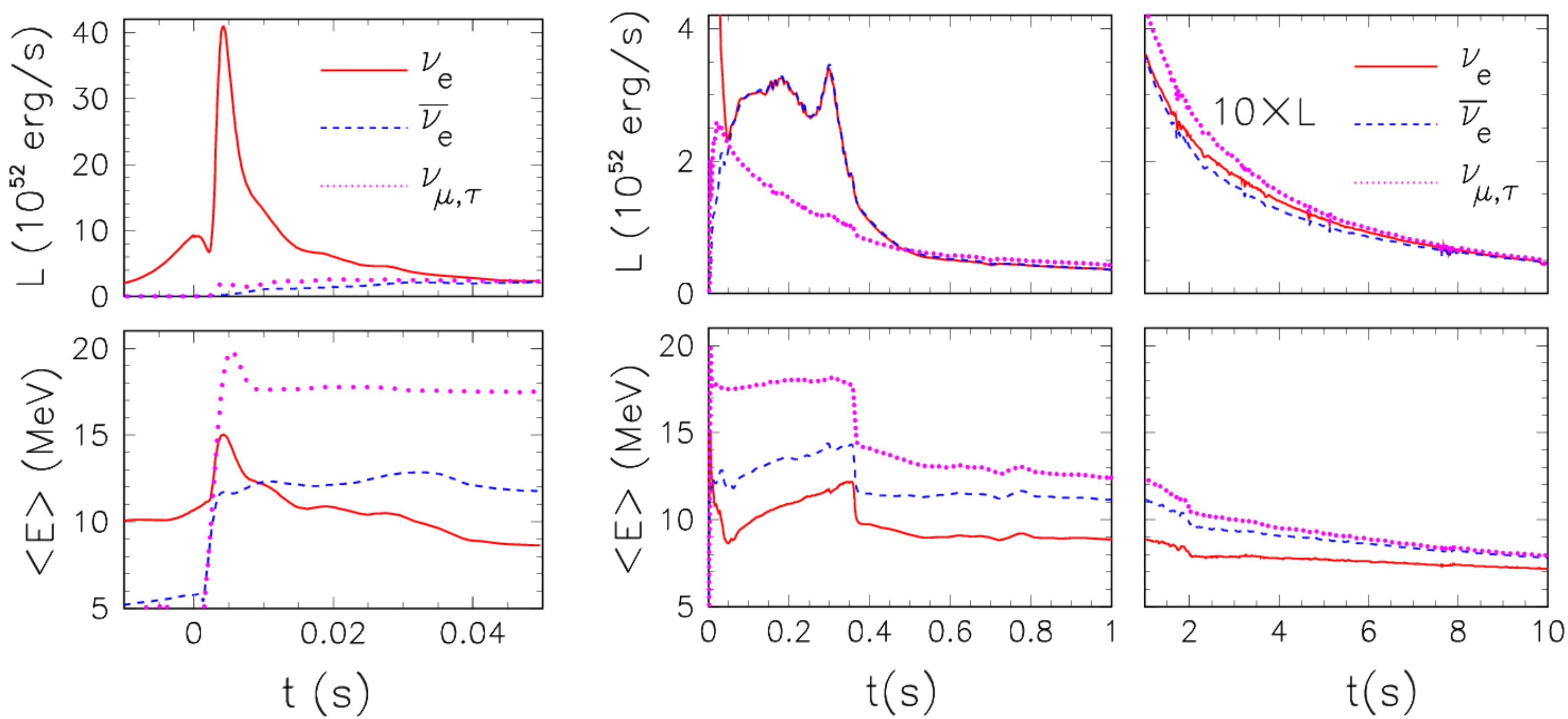
Accretion

- powered by infalling matter
- Stalled shock

Cooling

- Cooling by ν diffusion

Accretion: ~ 0.5 s ; Cooling: ~ 10 s



Neutrino Emission Phases

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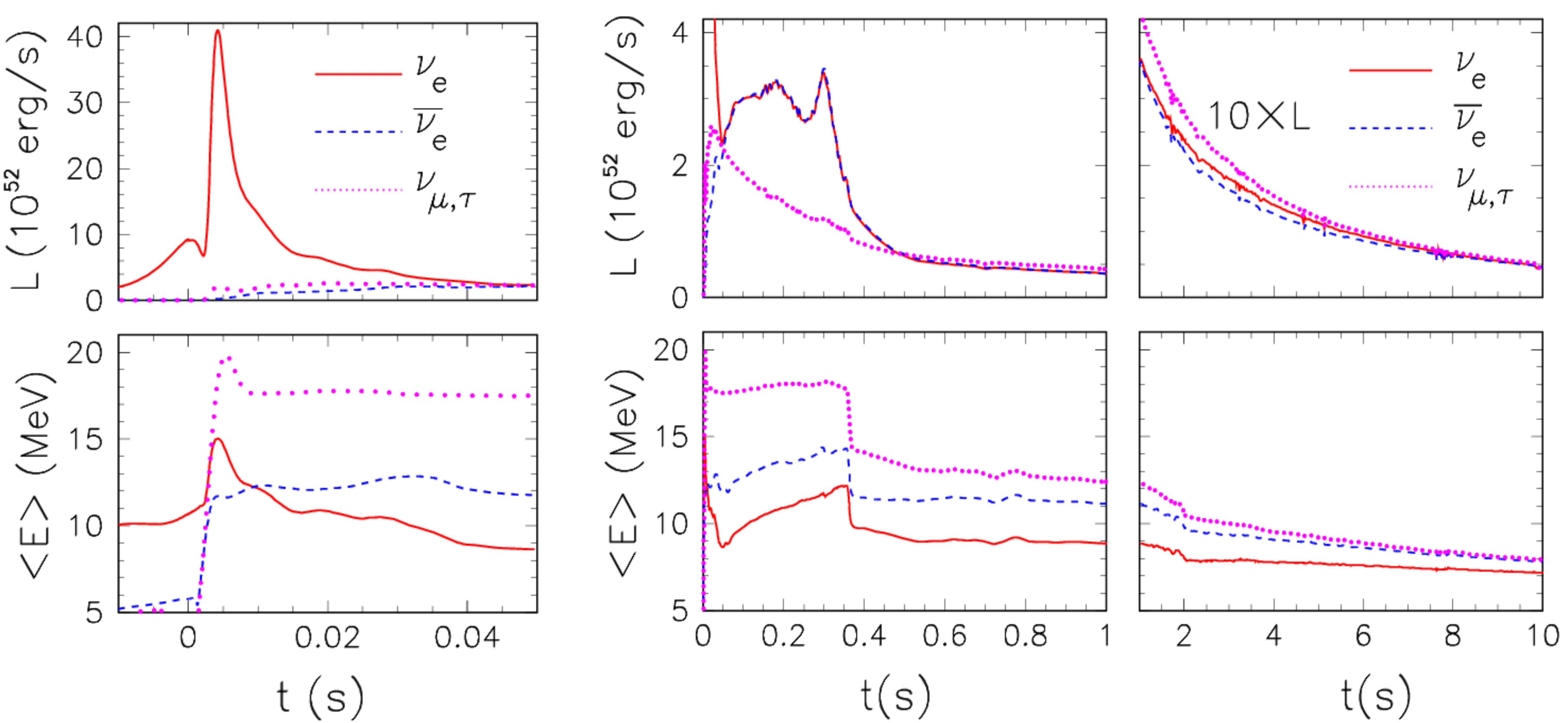
Neutronization burst | **Accretion** | **Cooling**

Large flux differences in Accretion Phase (best for oscillation effects!)

Cooling Phase : Equipartition of luminosity + Mild flavor hiearchy in <E>



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SN ν Flavor Transitions

The flavor evolution in matter is described by the non-linear MSW equations:

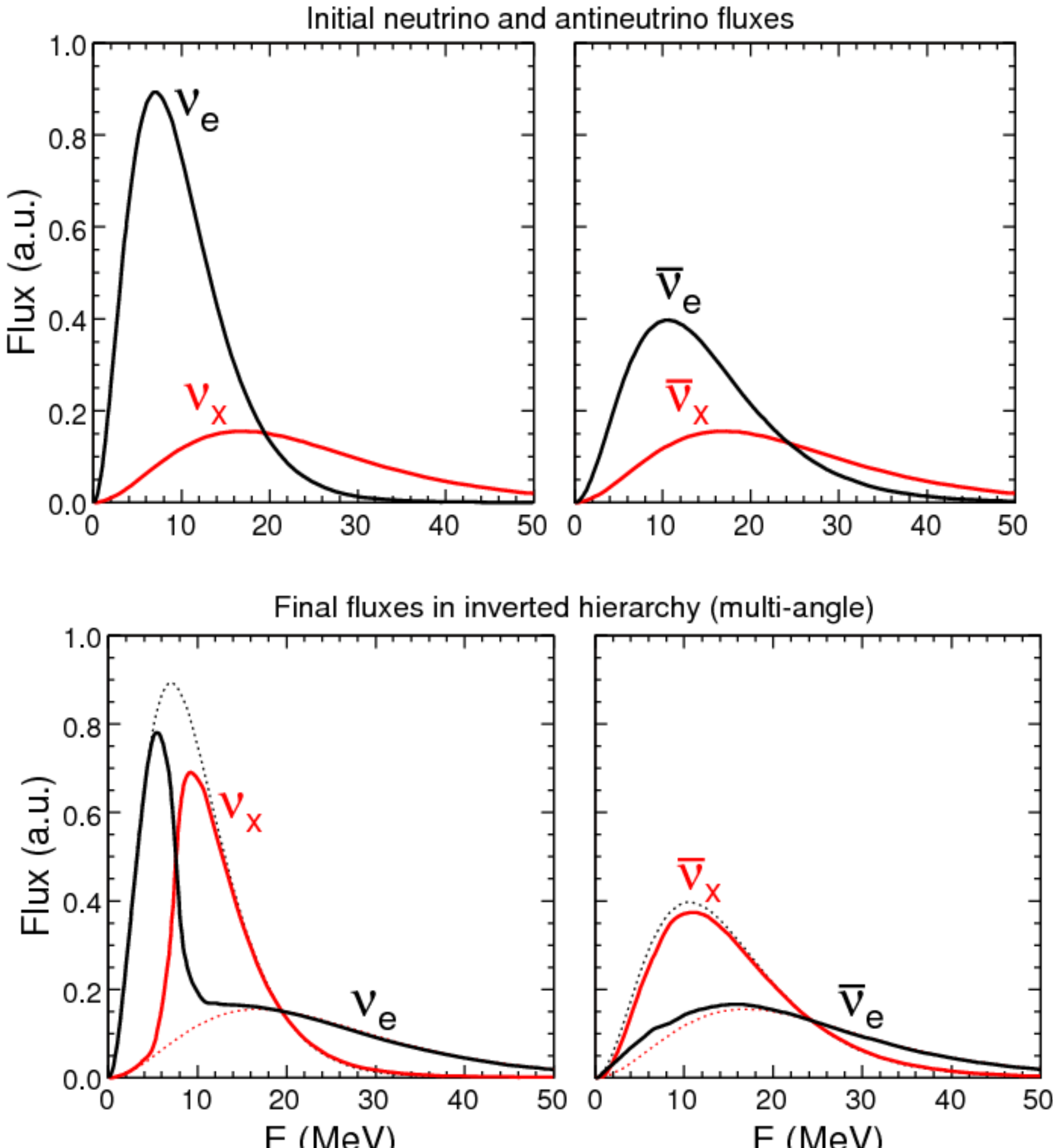
$$i\frac{d}{dx}\psi_\nu = \left(H_{vac} + H_e + H_{\nu\nu}\right)\psi_\nu$$

In the standard 3ν framework

- $$H_{vac} = \frac{U\ M^2\ U^\dagger}{2E}$$ **Kinematical mass-mixing term**
- $$H_e = \sqrt{2}G_F \,\mathrm{diag}(N_e, 0, 0)$$ **Dynamical MSW term (in matter)**
- $$H_{\nu\nu} = \sqrt{2}G_F \int (1-\cos\theta_{pq})\left(\rho_q - \bar{\rho}_q\right) dq$$ **Neutrino-neutrino interactions term (non-linear)**

Spectral Splits in the Accretion Phase

[Fogli, Lisi, Marrone, Mirizzi, arXiV: 0707.1998 [hep-ph]]



Initial fluxes typical of accretion phase at neutrinosphere (r ~10 km)

$$F_{\nu e} : F_{\bar{\nu} e} : F_{\nu x} = 2.4 : 1.6 : 1.0$$

Inverted mass hierarchy (IH)

Fluxes at the end of collective effects (r ~200 km)

Nothing happens in Normal Hierarchy (NH)

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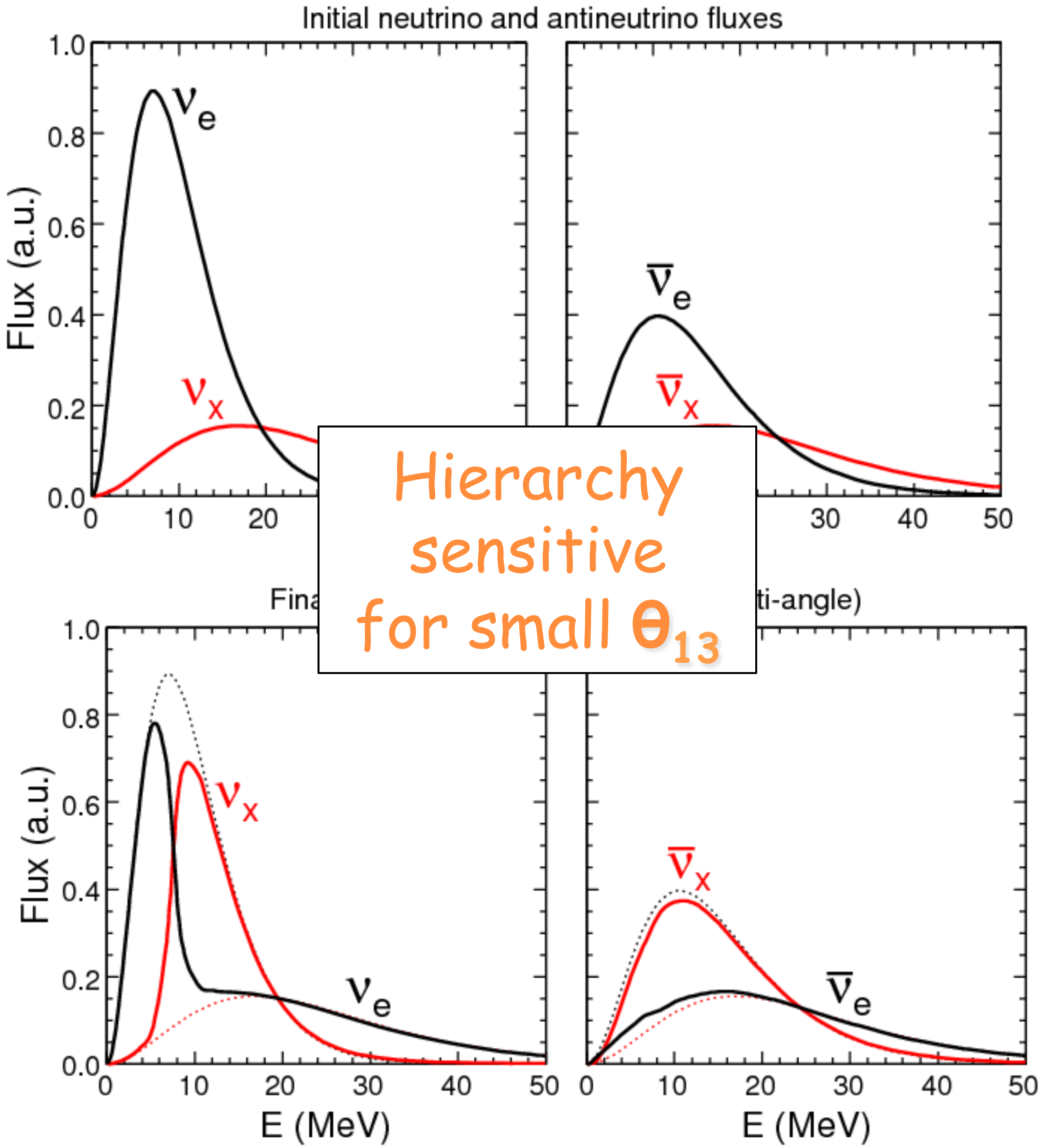

Hierarchy sensitive for small θ_{13}

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Suppression of Collective effects

Predictions are robust when collective effects are suppressed, i.e.:

1) Neutronization burst (t < 20 ms)

large ν_e excess and ν_x deficit

[Hannestad et al., astro-ph/0608695]

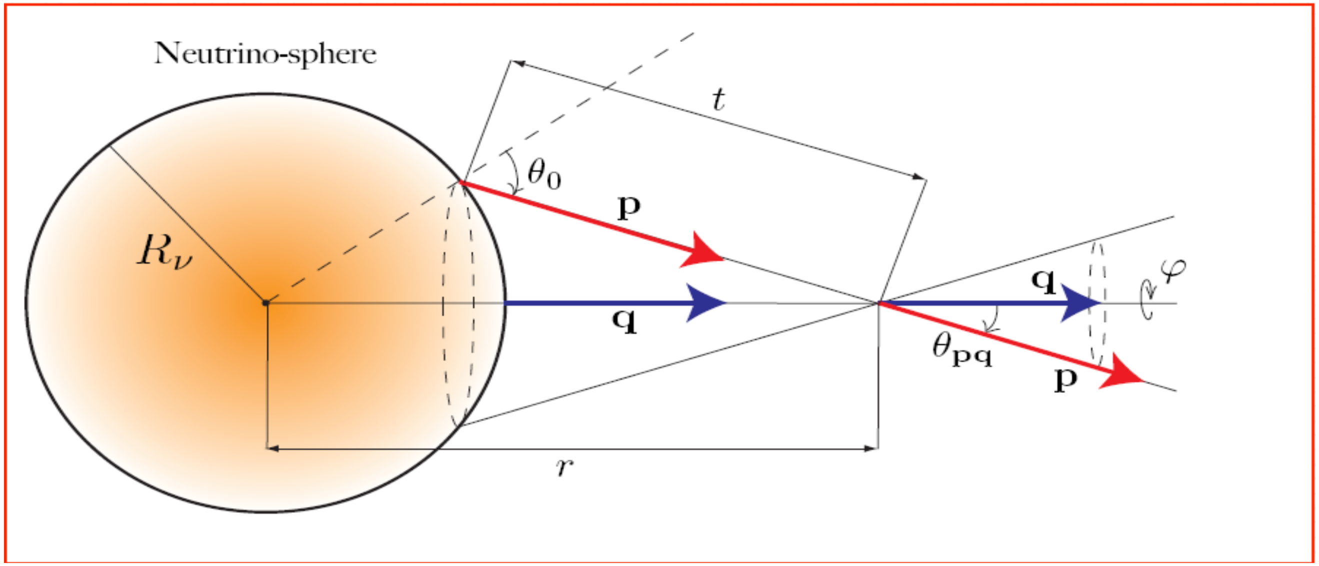
2) Accretion phase (t < 500 ms)

Dense matter term dominates over nu-nu interaction term.

[**S.C**, Fischer, Mirizzi, Saviano &Tomas

PRL 107:151101, 2011
PRD 84:025002, 2011]

Matter Suppression



- Neutrinos emitted from spherical source, travel on different trajectories.
- Different oscillation phases for neutrinos traveling in different paths.
- Strong $\nu-\nu$ interaction can overcome trajectory dependent dispersion.

Collective conversion requires : $n_e \ll n_\nu$

Collective conversion is matter Suppressed : $n_e \gtrsim n_\nu$

[Esteban-Pretel, Mirizzi, Pastor, Tomas, Raffelt, Serpico & Sigl, arxiv: 0807.0659]

Suppression of Collective effects

Dense matter (**n_e**) dominates over nu-nu interaction (**n_ν**).

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Sarikas, Raffelt, Hüdepohl &
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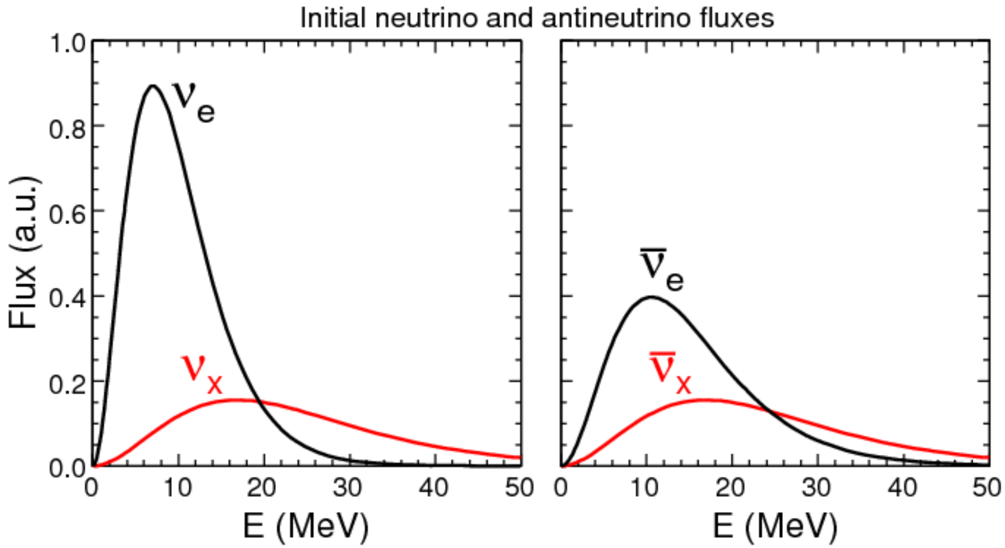

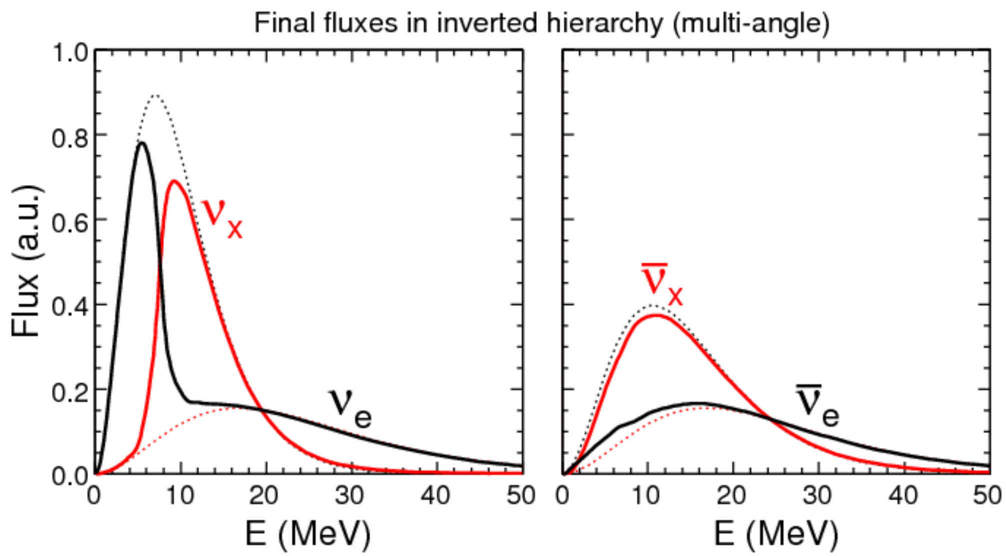

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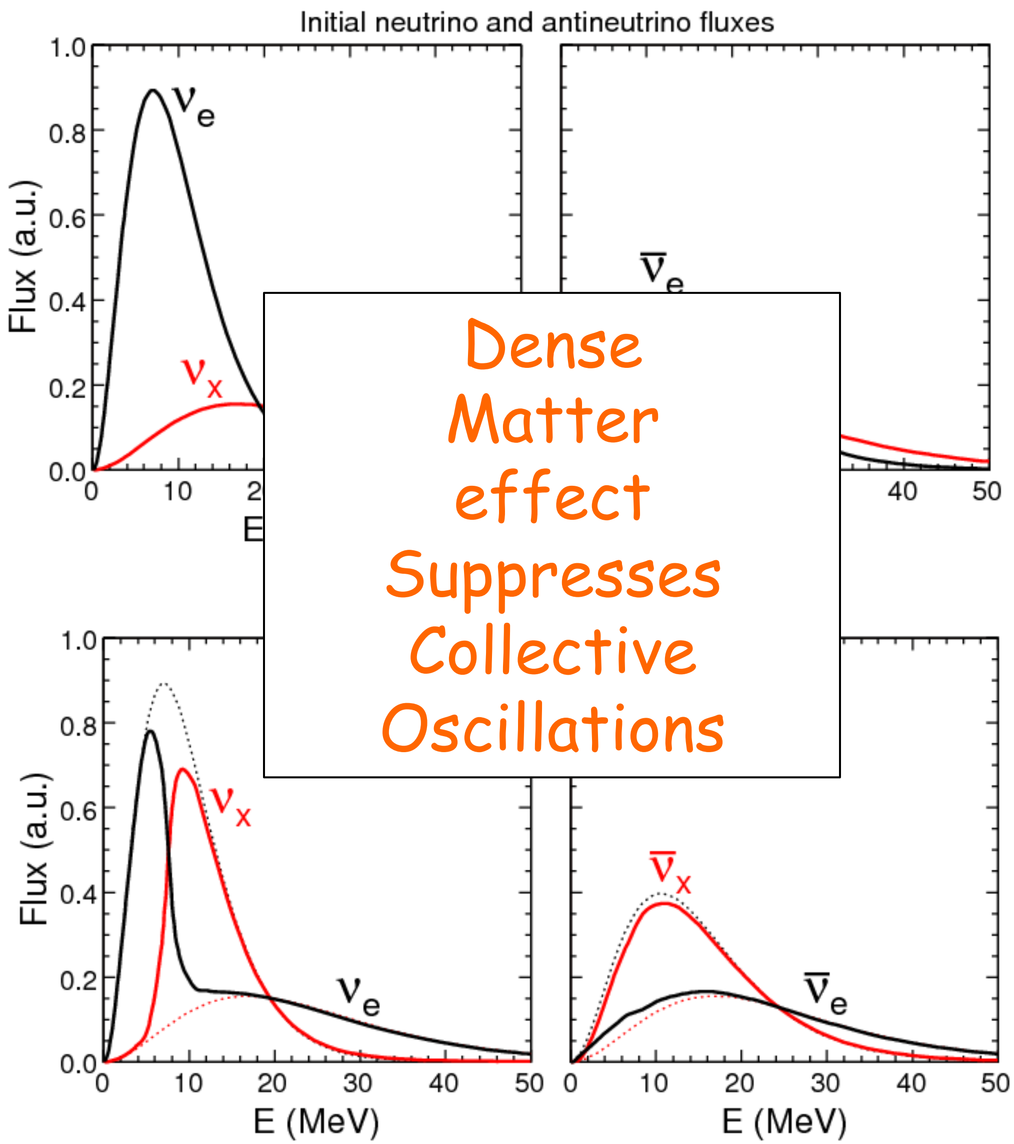

Dense Matter effect Suppresses Collective Oscillations

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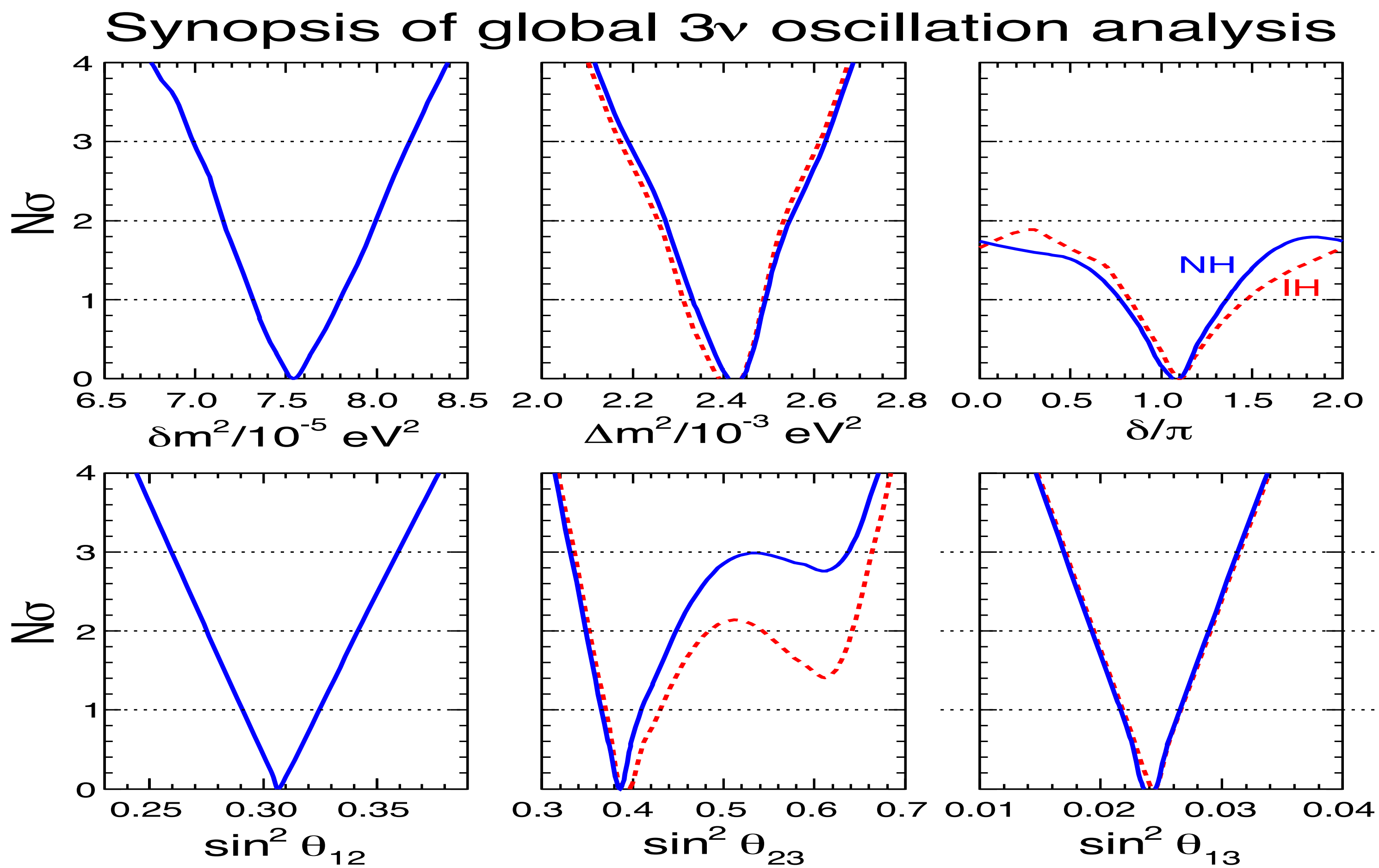
Discovery of large θ_{13}

T2K; MINOS; Double Chooz -> Large θ_{13}

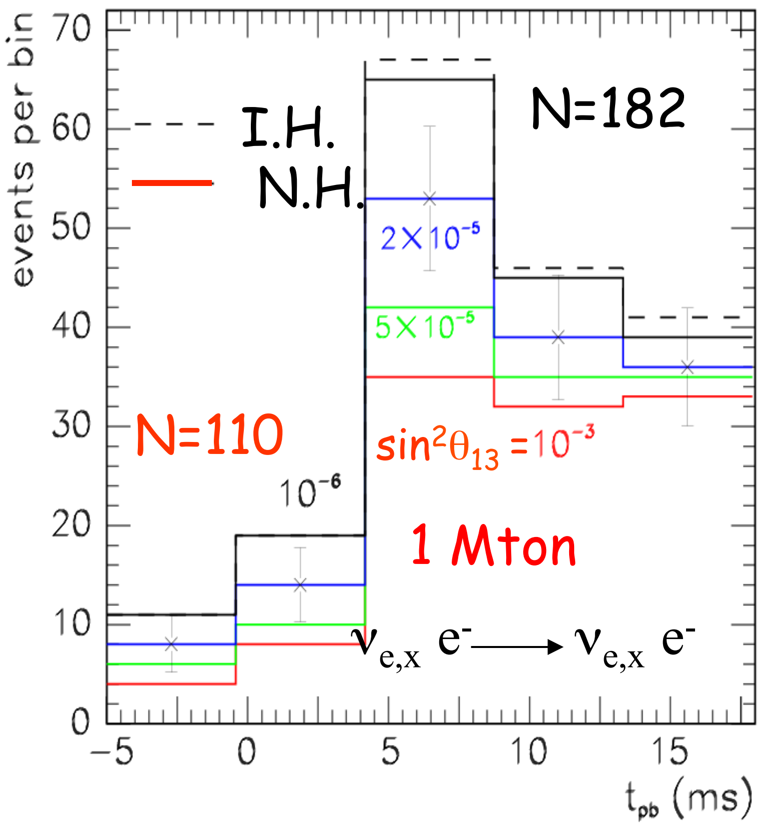
Daya Bay-> $\sin^2 2\theta_{13} = 0.092 \pm 0.017$



[Fogli, Lisi, Marrone, Montanino, Palazzo & Rotunno, PRD 86:013012, 2012]

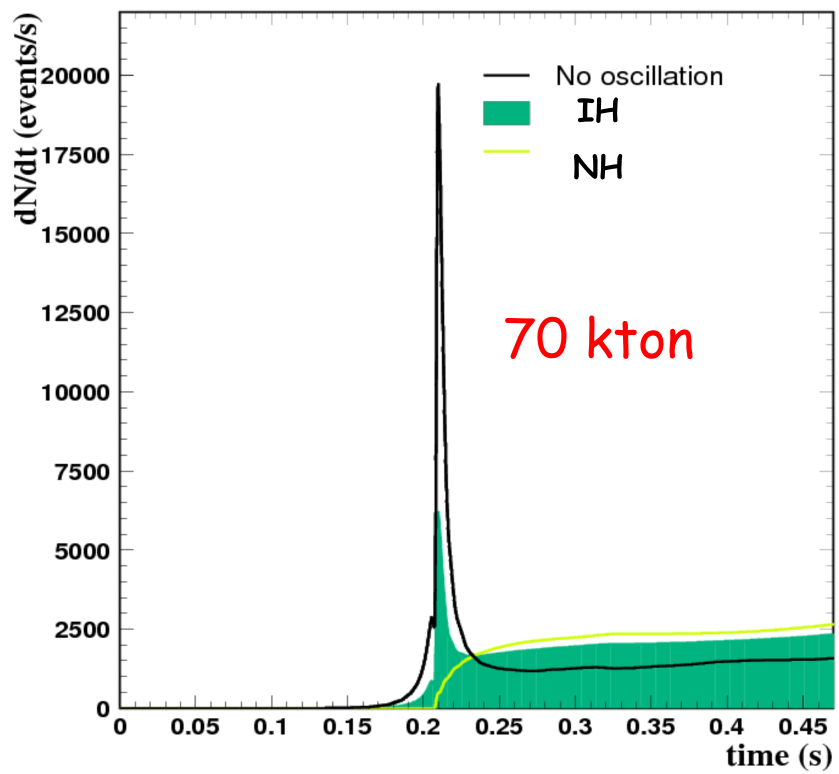
Oscillations in the Neutronization Burst

Water Cherencov



[M.Kachelriess & R. Tomas, hep-ph/0412082]

Liq Ar TPC $\nu_e\,^{40}$Ar CC



[I.Gil-Botella & A.Rubbia, hep-ph/0307244]

- The peak <u>is not seen</u> ⟶ The hierarchy is normal
- The peak <u>is seen</u> ⟶ The hierarchy is inverted

SN antineutrino Flux at Earth

Accretion Phase:

Complete Suppression

- Normal mass hierarchy

$$F^D_{\bar{\nu}_e} = \cos^2\theta_{12} F_{\bar{\nu}_e} + \sin^2\theta_{12} F_{\bar{\nu}_x}$$

- Inverted mass hierarchy
  - $\sin^2\theta_{13} \geq 10^{-3}$

$$F^D_{\bar{\nu}_e} = F_{\bar{\nu}_x}$$

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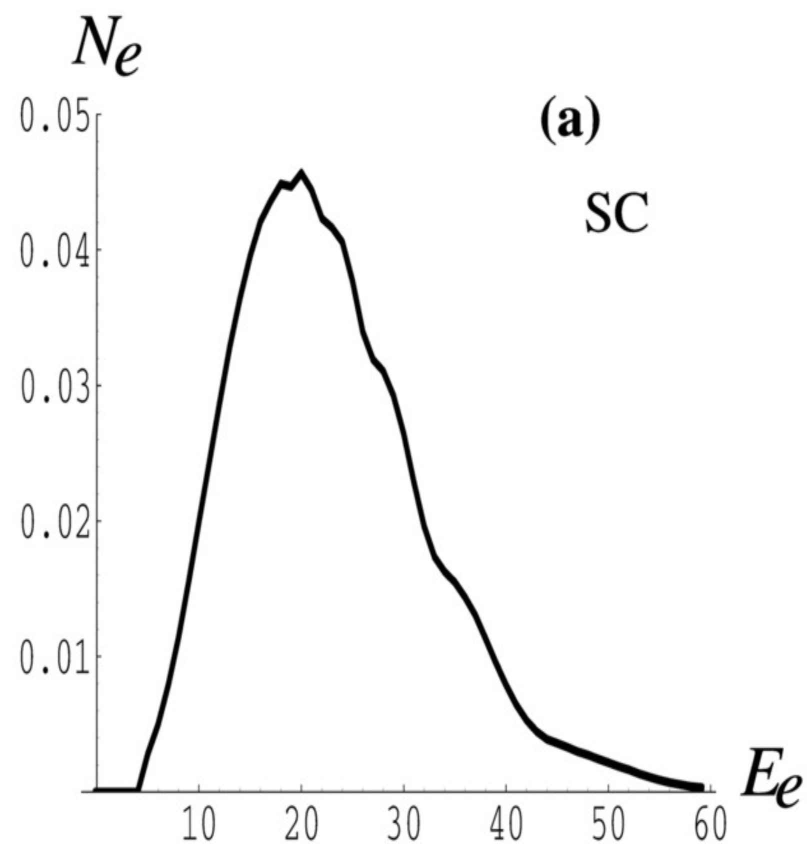
Earth Matter Effect:



Identify “wiggles” in a signal (but good E-resolution & high statistics required): Liquid scintillators like LENA?

[Dighe, Keil & Raffelt, hep-ph/0304150]

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No E.M

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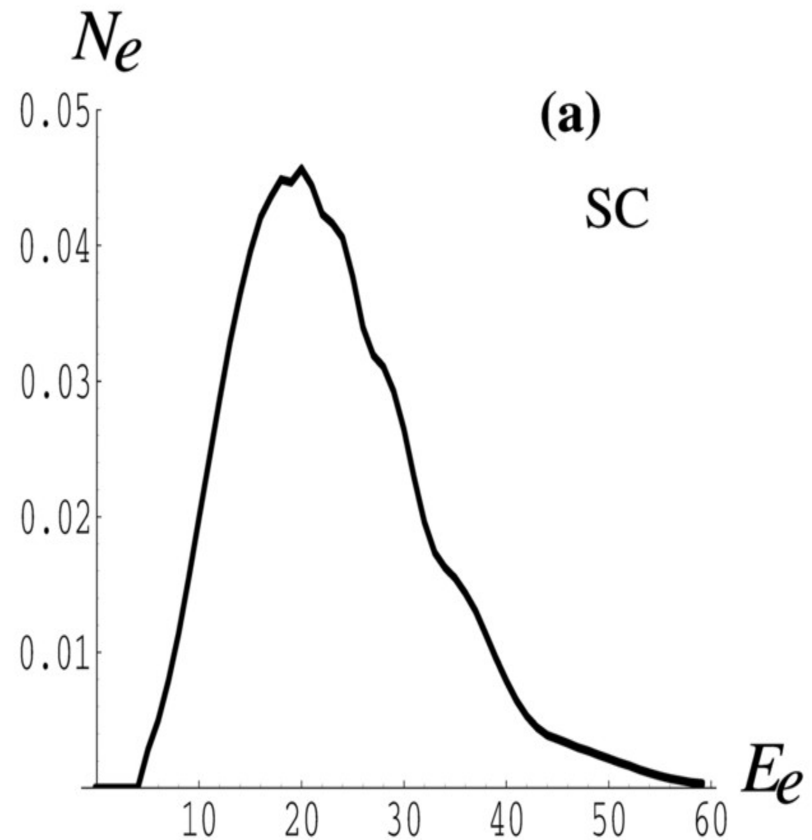

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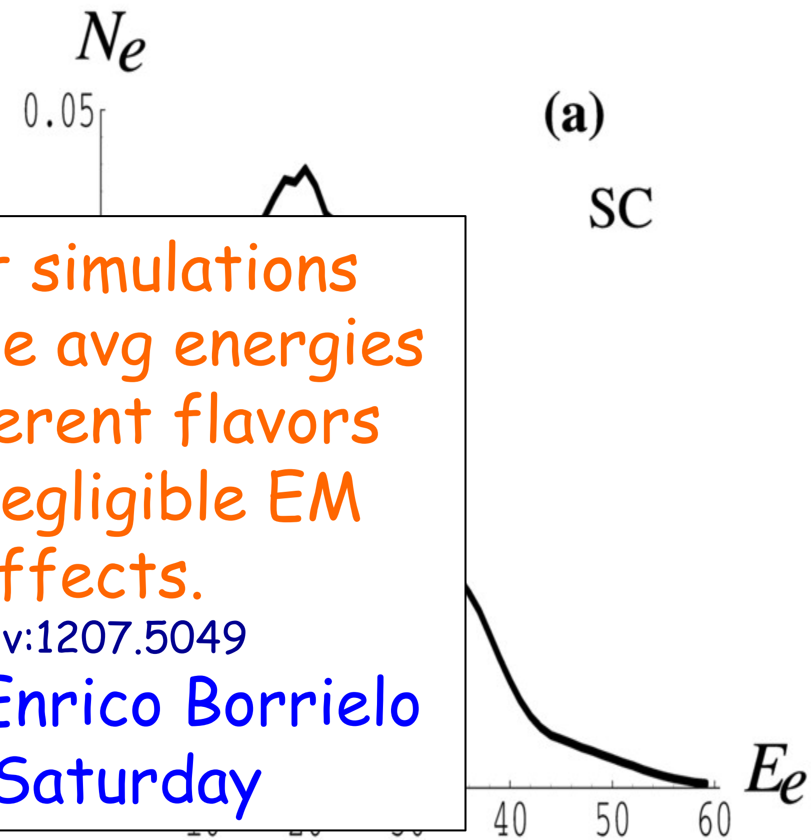


Recent simulations with close avg energies of different flavors show negligible EM effects.

arXiv:1207.5049

Talk of Enrico Borrielo on Saturday

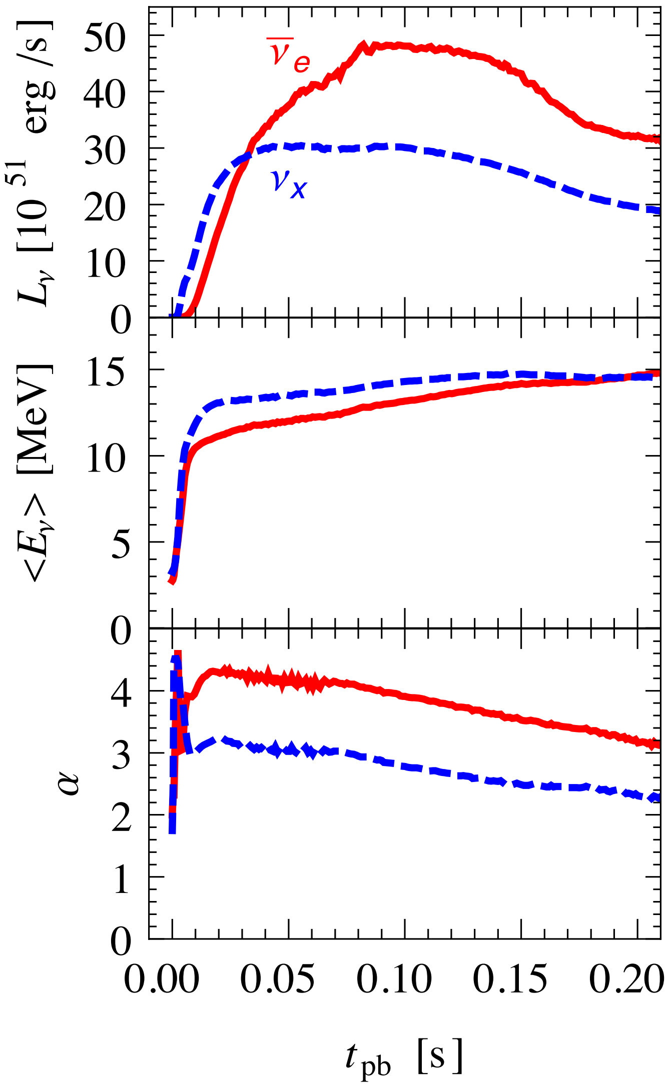
Identify "wiggles" in a signal (but good E-resolution & high statistics required): Liquid scintillators like LENA?

[Dighe, Keil & Raffelt, hep-ph/0304150]

Rise time Analysis: Hierarchy Determination

15 Solar Mass

Garching



ν_x has only NC, $\bar{\nu}_e$ has both CC+NC.

$\bar{\nu}_e$ more in equilibrium with environment than ν_x

Flux of ν_x rises faster than $\bar{\nu}_e$

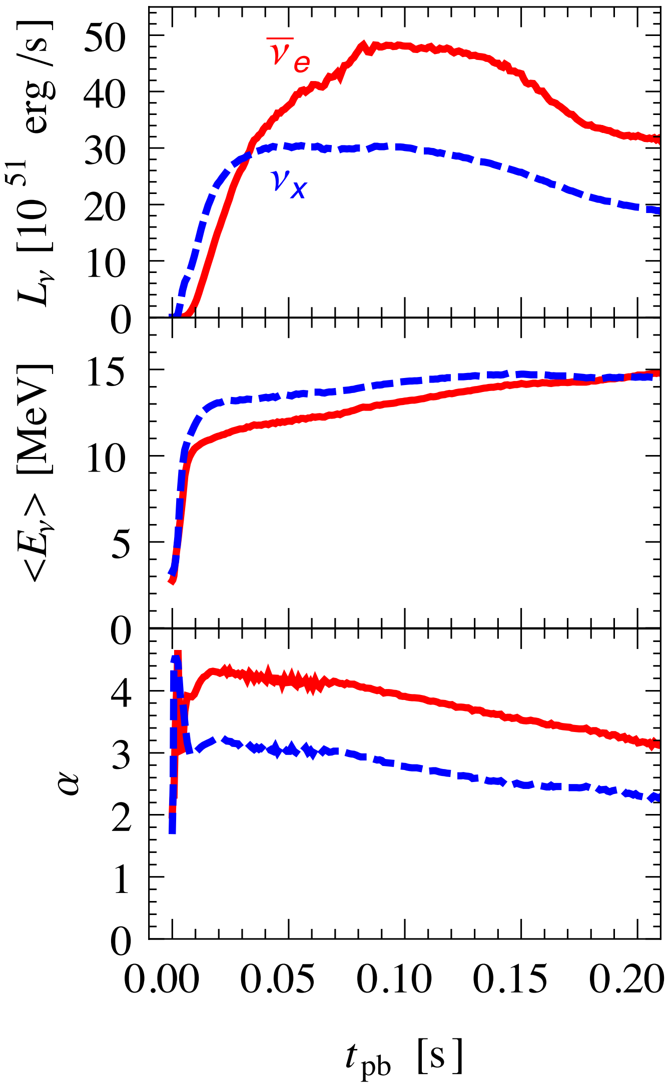
Flux in IH (ν_x) rises faster than NH (ν_x, $\bar{\nu}_e$)

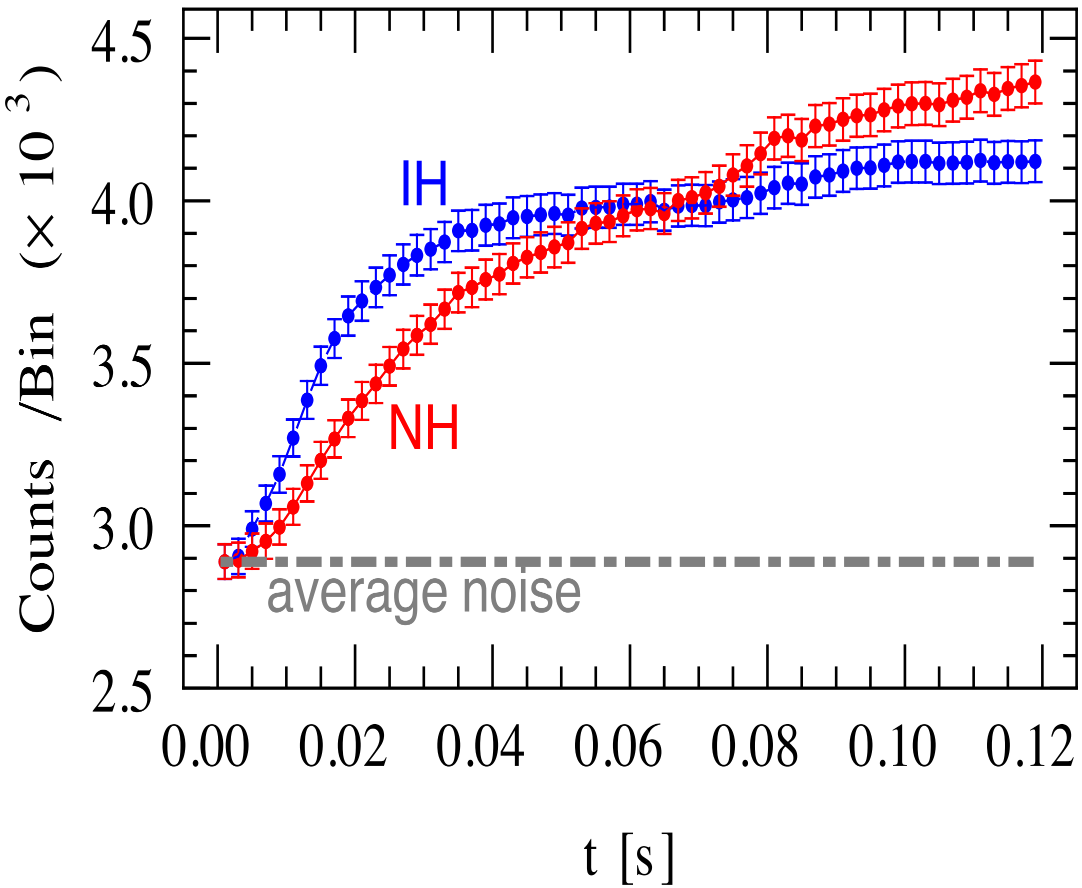
[Serpico, **S.C**, Fischer, Hüdepohl, Janka & Mirizzi
PRD 85:085031,2012]

Rise time Analysis: Hierarchy Determination

Garching

15 Solar Mass
in Ice-Cube





Flux in IH rises faster than NH

[Serpico, **S.C**, Fischer, Hüdepohl, Janka & Mirizzi
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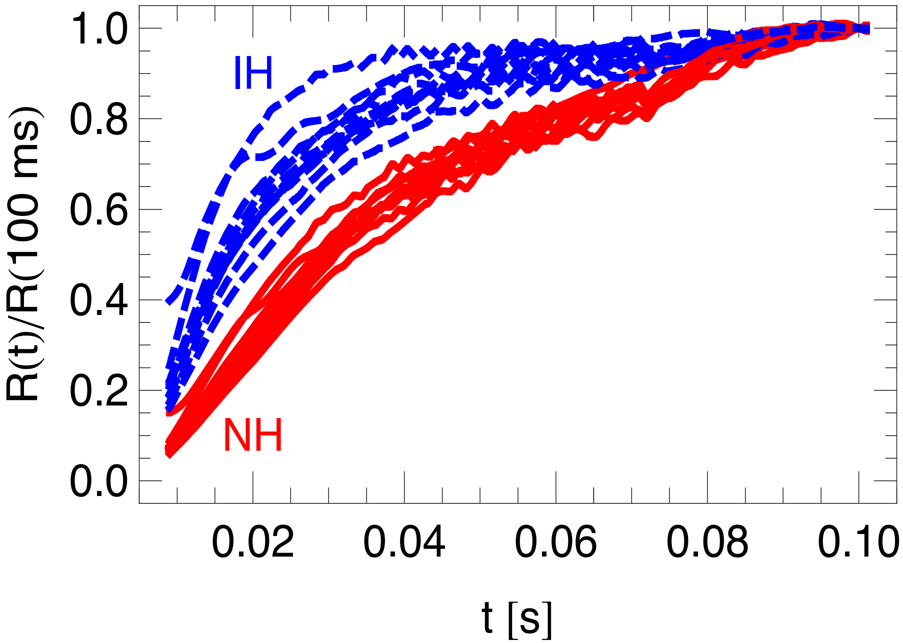

Count rate (normalized to value at 100 ms)
10 different models, masses 12 to 40 Msun
[Blue: IH ; Red: NH]

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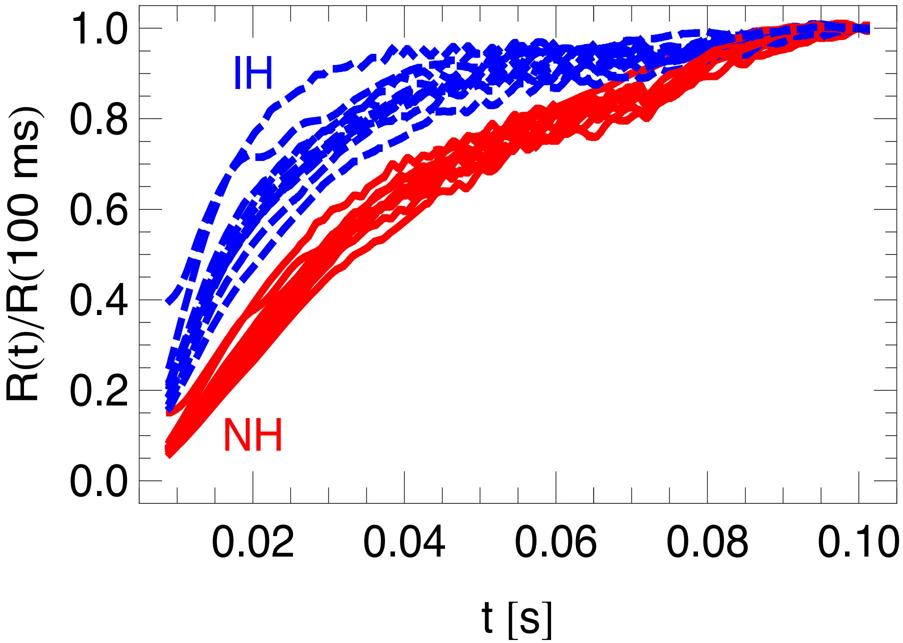

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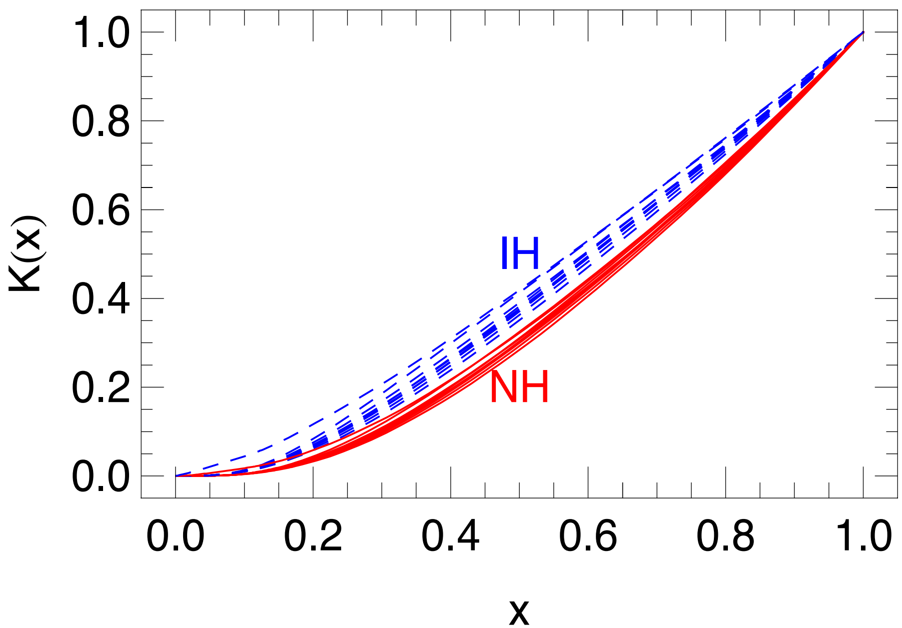
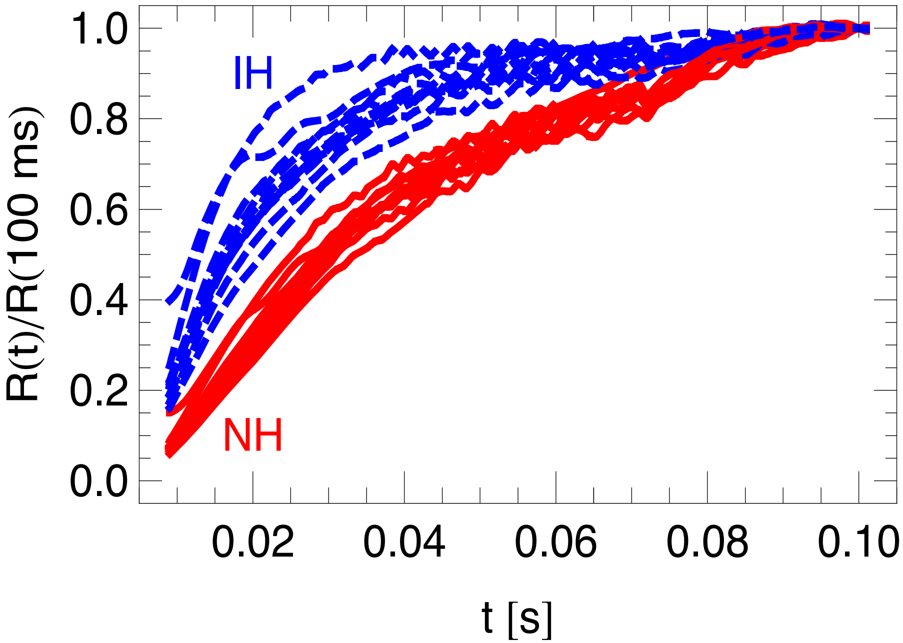


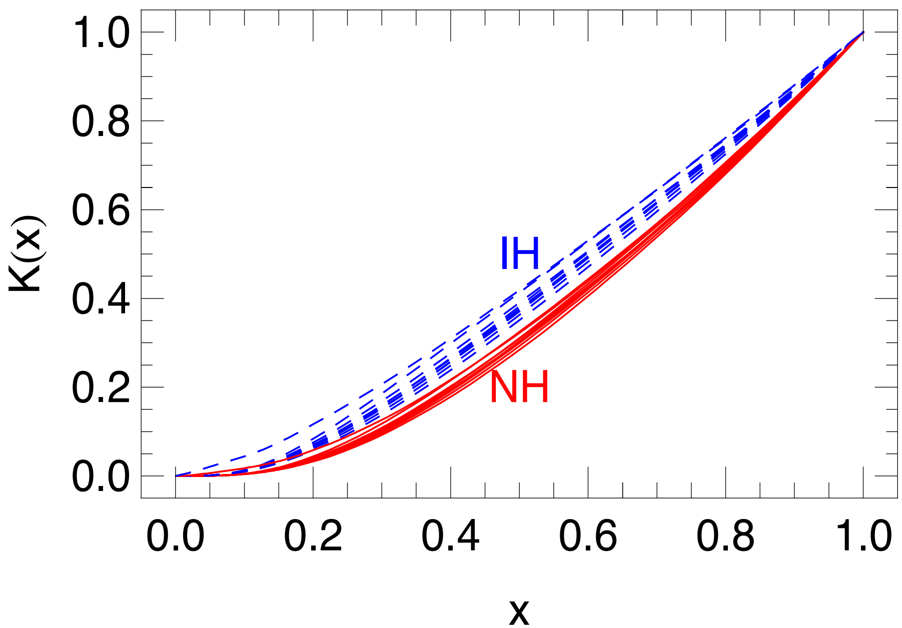
For Statistical analysis introduce
Cumulative Time Distribution K(x)

$$x = R(t)/R(t_{\mathrm{end}})$$

$$K(x) = \frac{\int_0^{x\, t_{\mathrm{end}}} dt\, R(t)}{\int_0^{t_{\mathrm{end}}} dt\, R(t)}$$

Rise time Analysis: Hierarchy Determination





Kolmogorov-Smirnov Statistics :

$$\mathcal{D}_\infty(K_i^A, K_j^B) = \max_{x\in[0;1]} \left|K_i^A(x) - K_j^B(x)\right|$$

Distance between any randomly picked NH "model" from average IH one is significantly above the one from average NH ones and well expected statistical errors.

Assessing "theory/numerical" error requires detailed study over other simulations with comparable sophistication.

Conclusions

- SNe provide very extreme conditions like neutrino-neutrino interactions which prove to be surprisingly important for the ν oscillations.
- Neutronization burst phase: No collective due to large lepton asymmetry.
- Accretion phase: Multi angle effects from large matter suppress the collective oscillations and sensitive to neutrino mass hierarchy at large θ_{13}.
- Rise time of SNe signal contains information of Hierarchy.

Thank You !

Rise time Analysis: Hierarchy Determination

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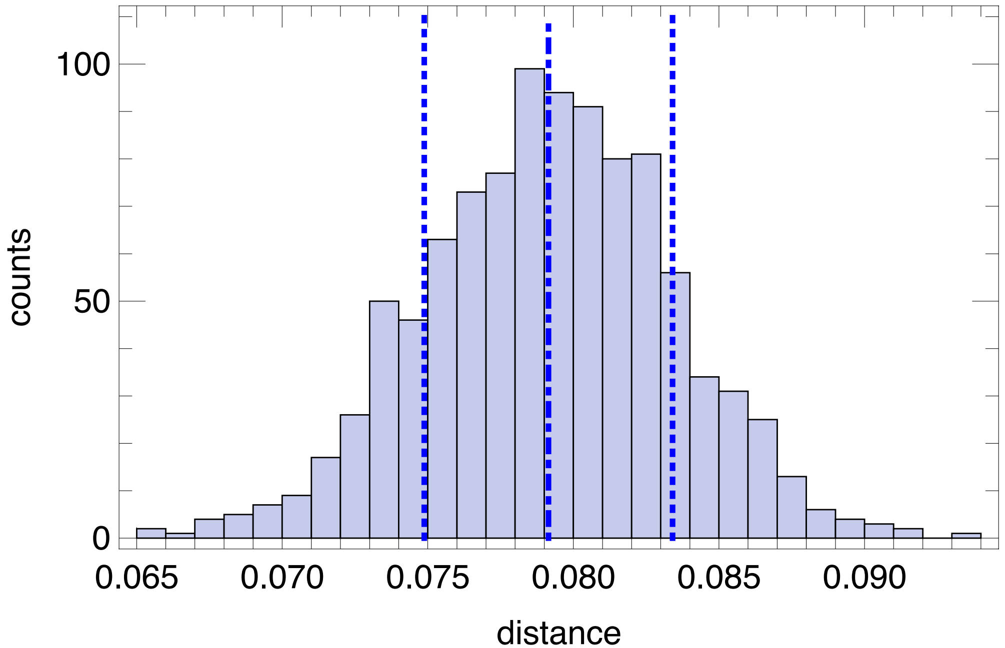

Distribution of distances between ``theoretical'' NH and 1000 Monte Carlo Simulations in IH for the 15 $M_\odot$ model.