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FLAVOR CONVERSIONS OF SUPERNOVA NEUTRINOS

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OUTLINE

Supernovae as neutrino sources

MSW effect in SNe: probing shock-waves and matter turbulences

Self-induced SN ν oscillations: the collective behaviour of a dense ν gas

Open Issues and Conclusions

SUPERNOVA NEUTRINOS

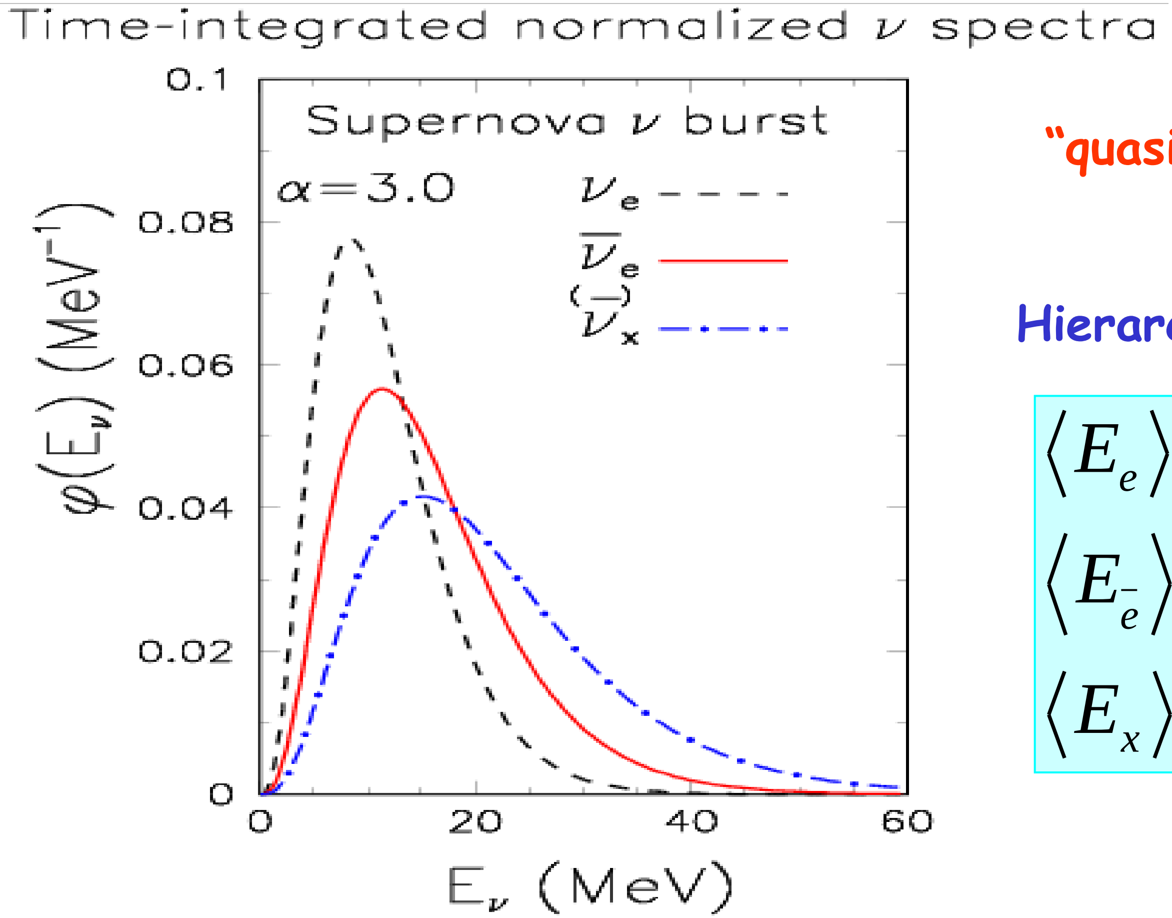
Core collapse SN corresponds to the terminal phase of a massive star [$M \gtrsim 8\ M_\odot$] which becomes unstable at the end of its life. It collapses and ejects its outer mantle in a shock wave driven explosion.

- **ENERGY SCALES:** 99% of the released energy (~ 10^{53} erg) is emitted by ν and $\bar{\nu}$ of all flavors, with typical energies E ~ O(15 MeV).

- **TIME SCALES:** Neutrino emission lasts **~10 s**

- **EXPECTED:** **1-3 SN/century** in our galaxy (d ≈ $\mathcal{O}$(10) kpc).

Neutrino spectra (in energy)



"quasi-thermal" spectra

Hierarchy of the spectra

$$\langle E_e \rangle \approx 9-12 \text{ MeV}$$

$$\langle E_{\bar{e}} \rangle \approx 14-17 \text{ MeV}$$

$$\langle E_x \rangle \approx 18-22 \text{ MeV}$$

These intial fluxes can be strongly modified by the peculiar effects of FLAVOR CONVERSIONS in SN

SN ν FLAVOR TRANSITIONS

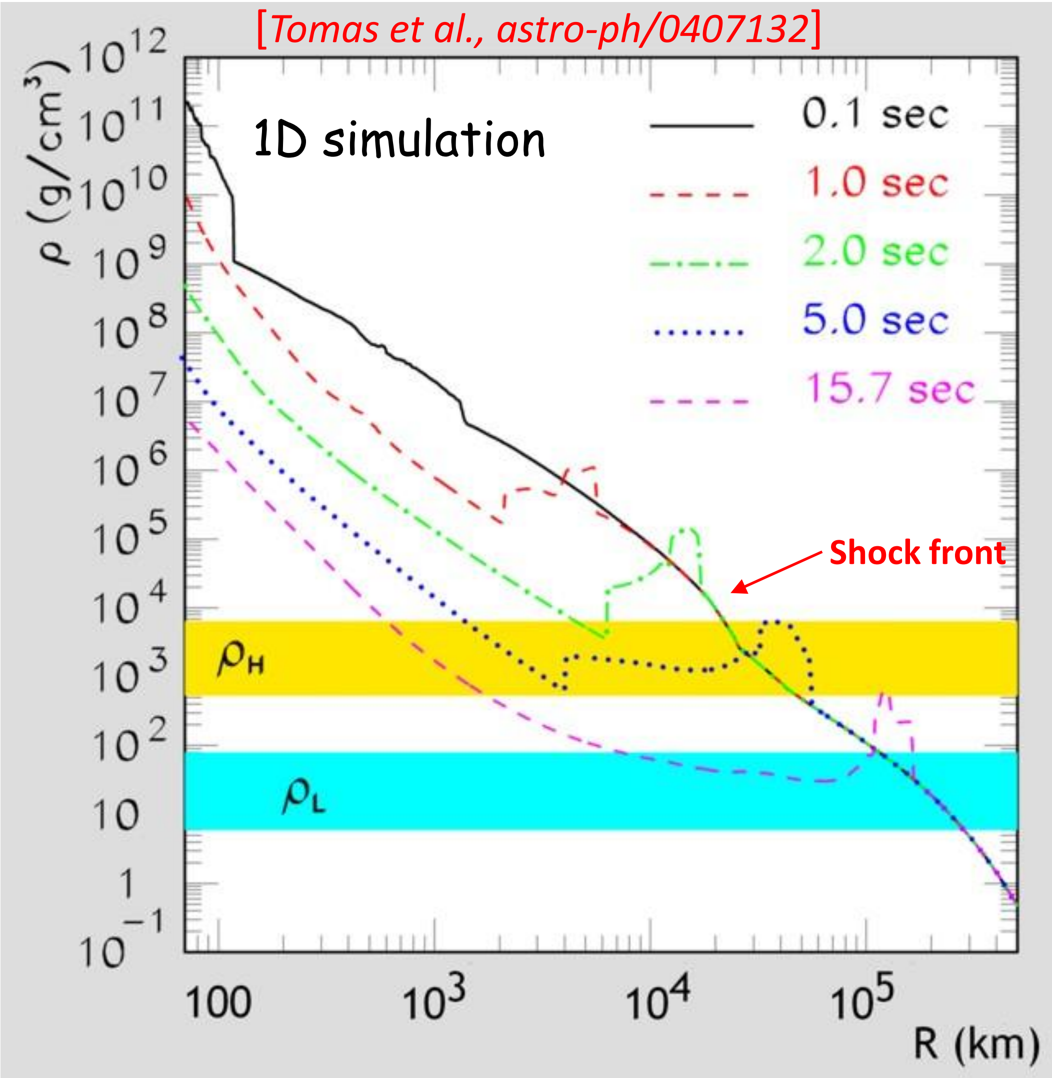
The flavor evolution in matter is described by the non-linear MSW equations:

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

In the standard 3ν framework

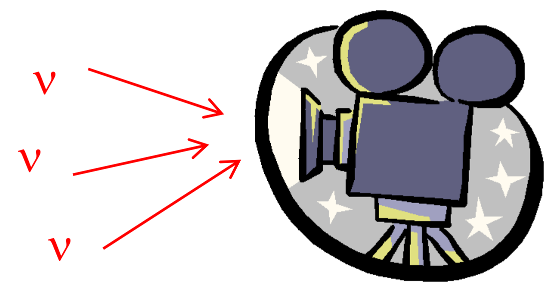
- $$H_{vac} = \frac{U\ M^{2}\ U^{\dagger}}{2E}$$ **Kinematical mass-mixing term**
- $$H_{e} = \sqrt{2}G_{F}\,\mathrm{diag}(N_{e},0,0)$$ **Dynamical MSW term (in matter)**
- $$H_{\nu\nu} = \sqrt{2}G_{F}\int(1-\cos\theta_{pq})\left(\rho_{q}-\bar{\rho}_{q}\right)dq$$ **Neutrino-neutrino interactions term (non-linear)**

MSW MATTER EFFECT IN SN



A few second after the core bounce, shock wave(s) can induce time-dependent matter effects in neutrino oscillations
[R.Schirato, and G. Fuller, astro-ph/0205390]

Neutrino oscillations as a "camera" for shock-wave propagation



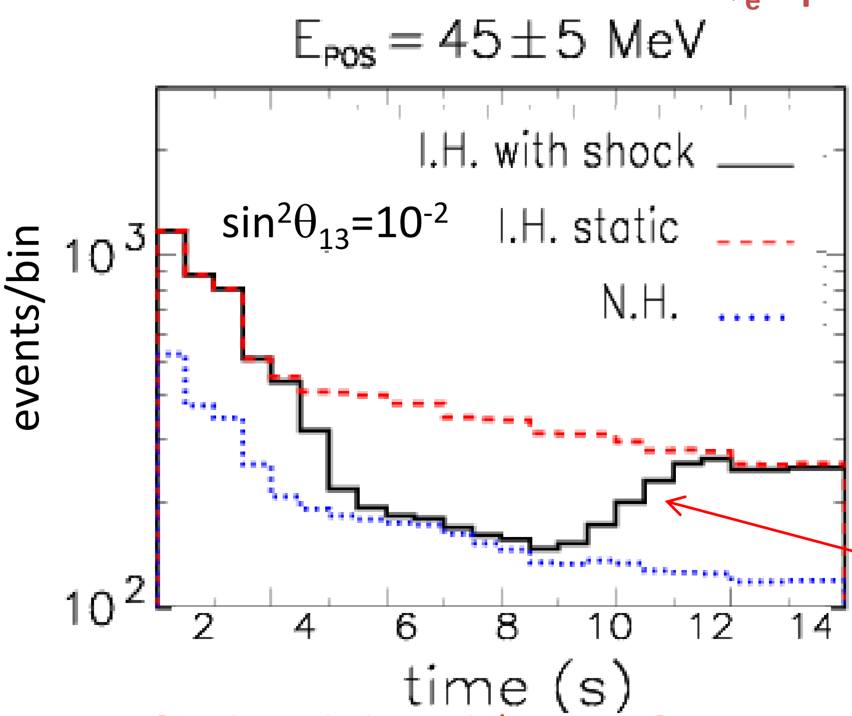
[see, e.g., Fogli, Lisi, A.M., and Montanino, hep-ph/0304056; Fogli, Lisi, A.M., and Montanino, hep-ph/0412046, Tomas et al., astro-ph/0407132, Choubey et al, hep-ph/0605255, Gava et al. 0902.0317,….]

PROBING SHOCK WAVES AND MASS HIERARCHY AT LARGE θ_{13}

0.4 Mton WC

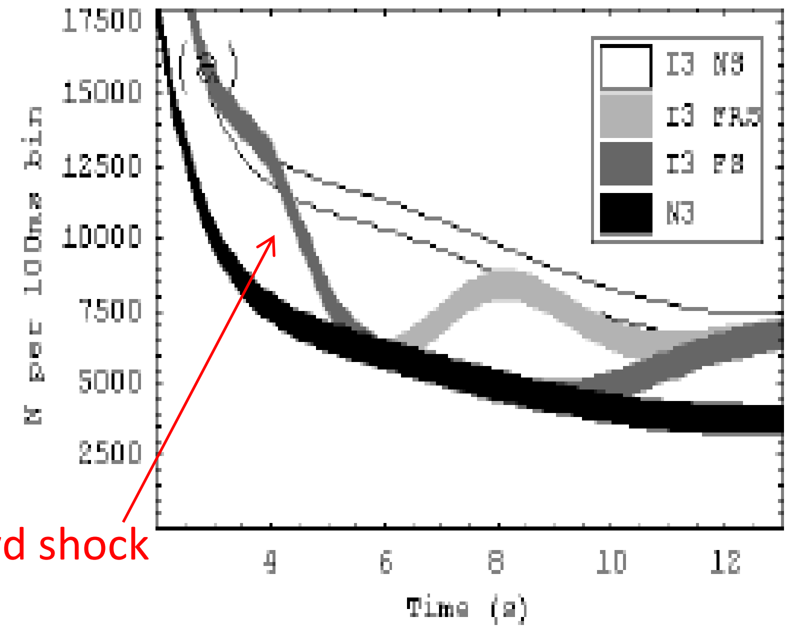
$\bar{\nu}_e + p \rightarrow n + e^+$

Icecube



[Fogli et al., hep-ph/0412046]

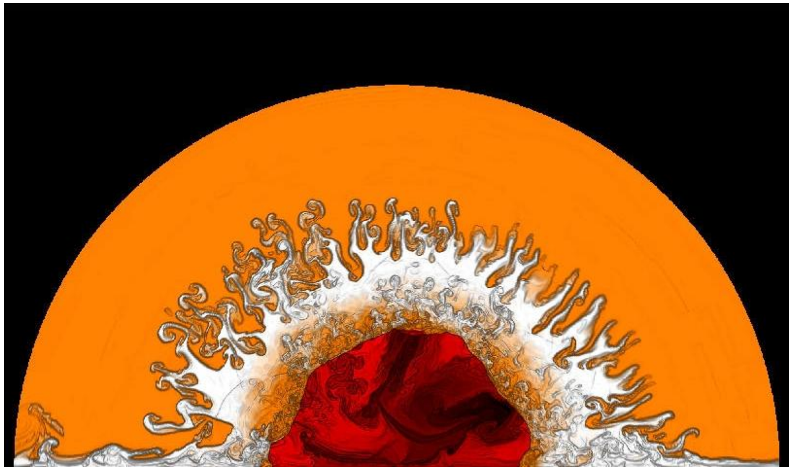
IH fwd shock



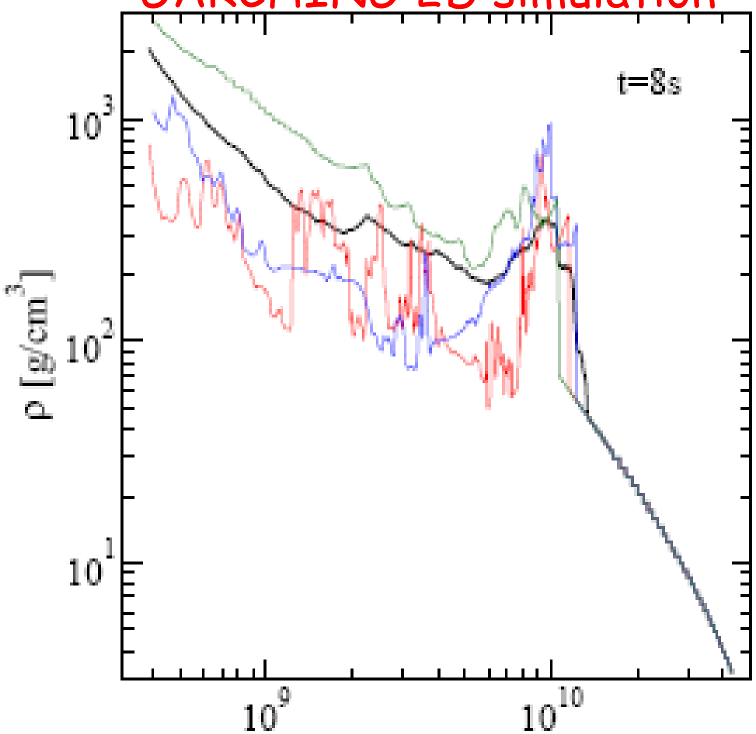
[Choubey et al, hep-ph/0605255]

In inverted hierarchy and for θ_{13} not too small, flavor conversions along the shock-waves induce non-monotonic time spectra.

STOCHASTIC DENSITY FLUCTUATIONS



GARCHING 2D simulation



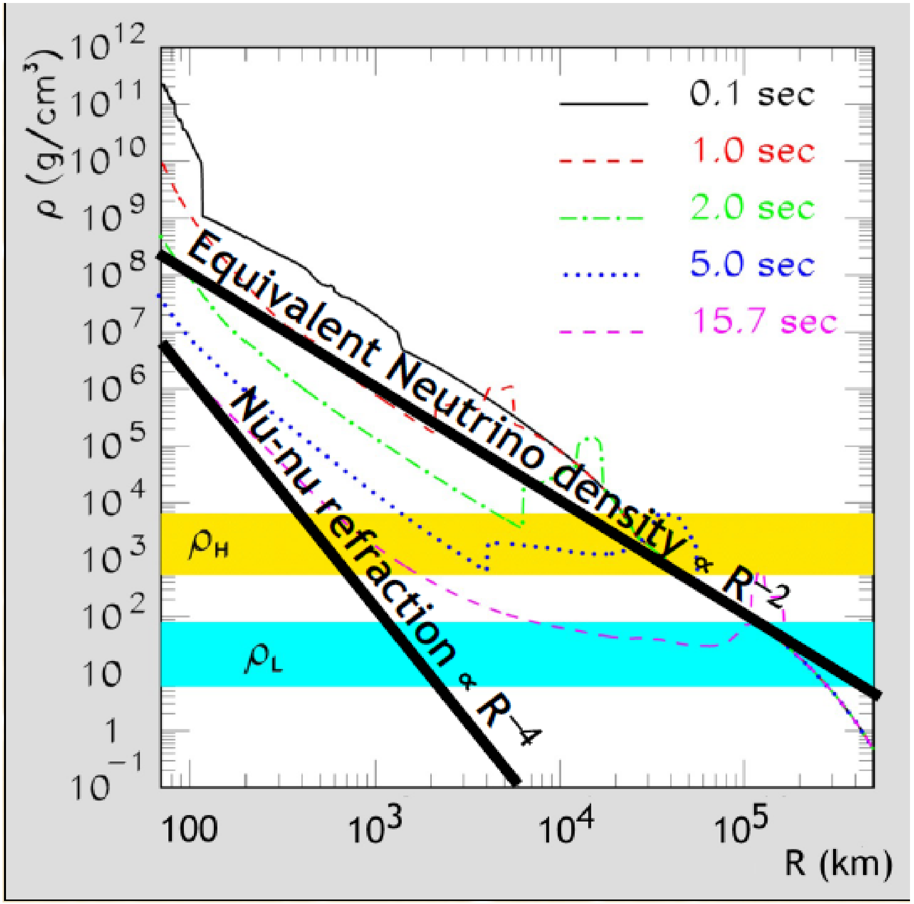
Turbulent convective motions behind the shock front create a fluctuating density field in the post-shock region. A SN neutrino "beam" might thus experience stochastic matter effects while traversing the stellar envelope.

[Fogli, Lisi, A.M. , Montanino, hep-ph/0603033; Friedland, astro-ph/0607244; Choubey, Harries, Ross, hep-ph/0703092, Kneller, 1004.1288, Kneller & Volpe, 1006.0913]

Depolarization ($\langle P_{ee} \rangle \rightarrow \frac{1}{2}$) would replace the shock-signature when turbulence is relevant

NEUTRINO-NEUTRINO INTERACTIONS

In the region just above the neutrino-sphere the neutrino density exceeds the ordinary electron background. Neutrinos themeselves form a background medium



ν–ν NC interactions important!

- Matter bkg potential

$$V = \sqrt{2} G_F N_e \quad \sim R^{-3}$$

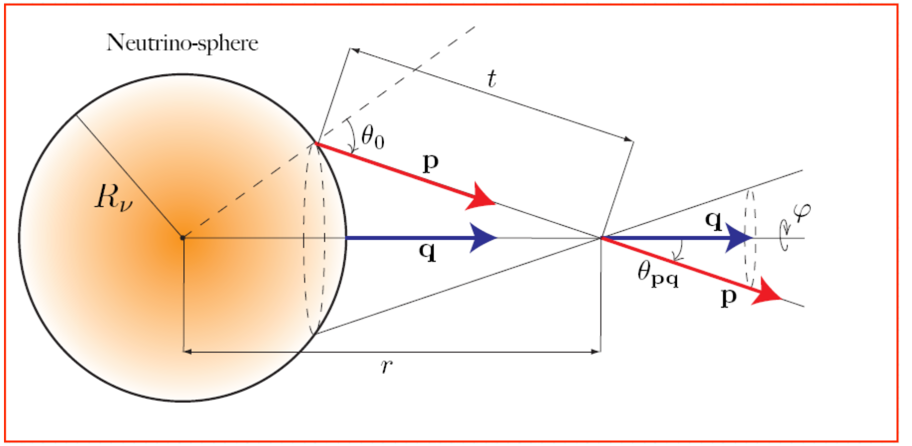
- ν–ν potential ← Multi-angle effects

$$\mu = \sqrt{2} G_F n_\nu (1 - \cos\theta_{pq}) \sim R^{-2} \times R^{-2} = R^{-4}$$

Lesson: self-interactions (μ) can induce large, non-MSW flavor change at small radii, despite large matter density **V**

Two seminal papers in 2006 triggered a torrent of activities
Duan, Fuller, Qian, astro-ph/0511275, Duan et al. astro-ph/0606616

ν-ν INTERACTIONS: SINGLE-ANGLE APPROXIMATION



The structure of neutrino-neutrino interactions contains an angular modulation

"multi-angle case"

$$H_{\nu\nu} = \sqrt{2} G_F \int \frac{d^3\vec{q}}{(2\pi)^3} (1-\cos\theta_{pq})(P_{\vec{q}} - \bar{P}_{\vec{q}})$$

Flavor polarization vectors

This makes very challenging the solution of the equations.

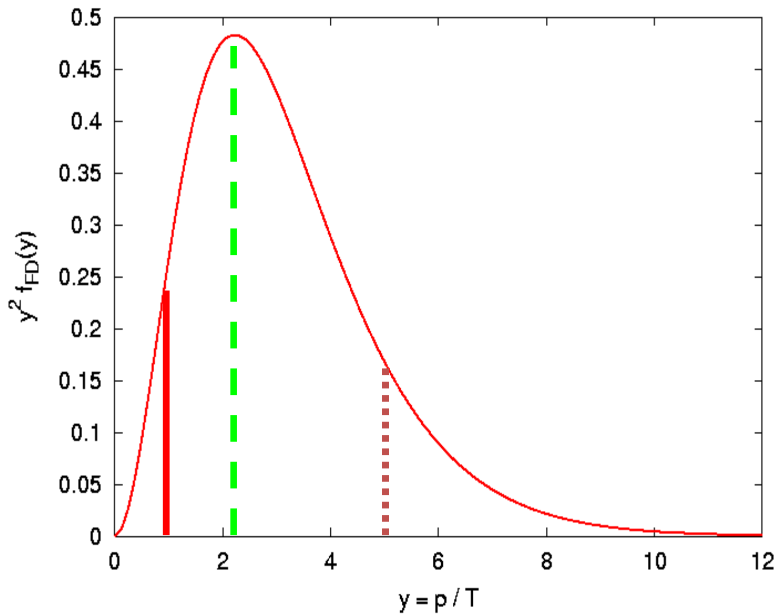
If averaged: single-angle approximation

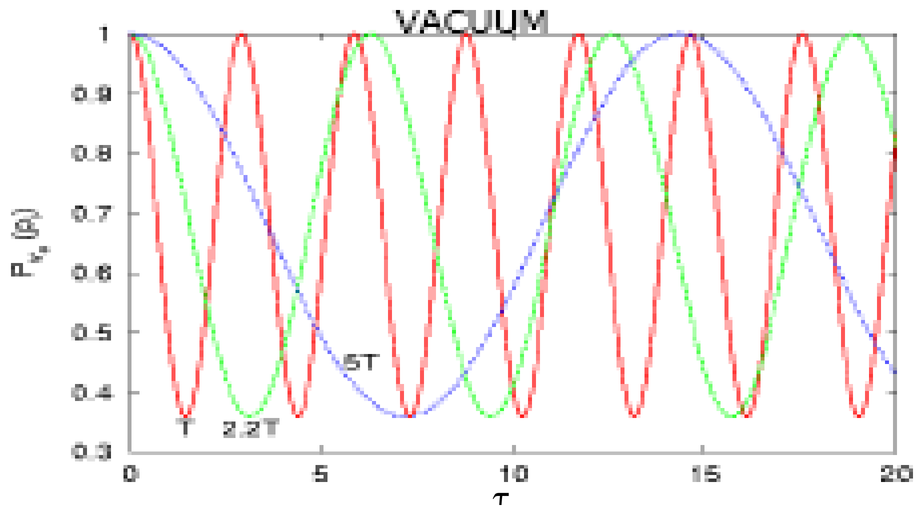
$$H_{\nu\nu} = \mu \int dq (P_q - \bar{P}_q) = \mu (P - \bar{P})$$

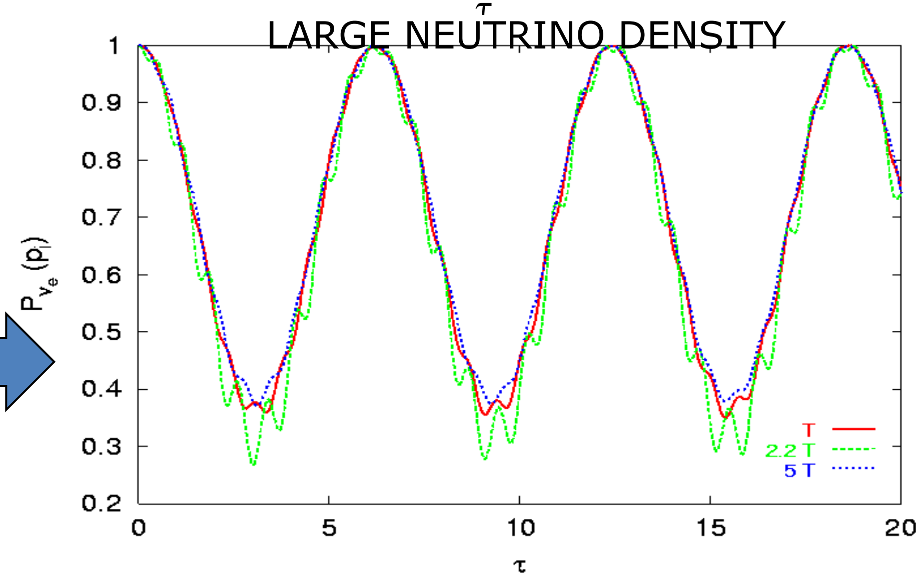
More amenable numerically. It allows for analytical interpretations.

SYNCHRONIZED OSCILLATIONS BY NEUTRINO-NEUTRINO INTERACTIONS

Example: evolution of neutrino momenta with a thermal distribution







If neutrino density dominates, **synchronized oscillations** with a characteristic common oscillation frequency

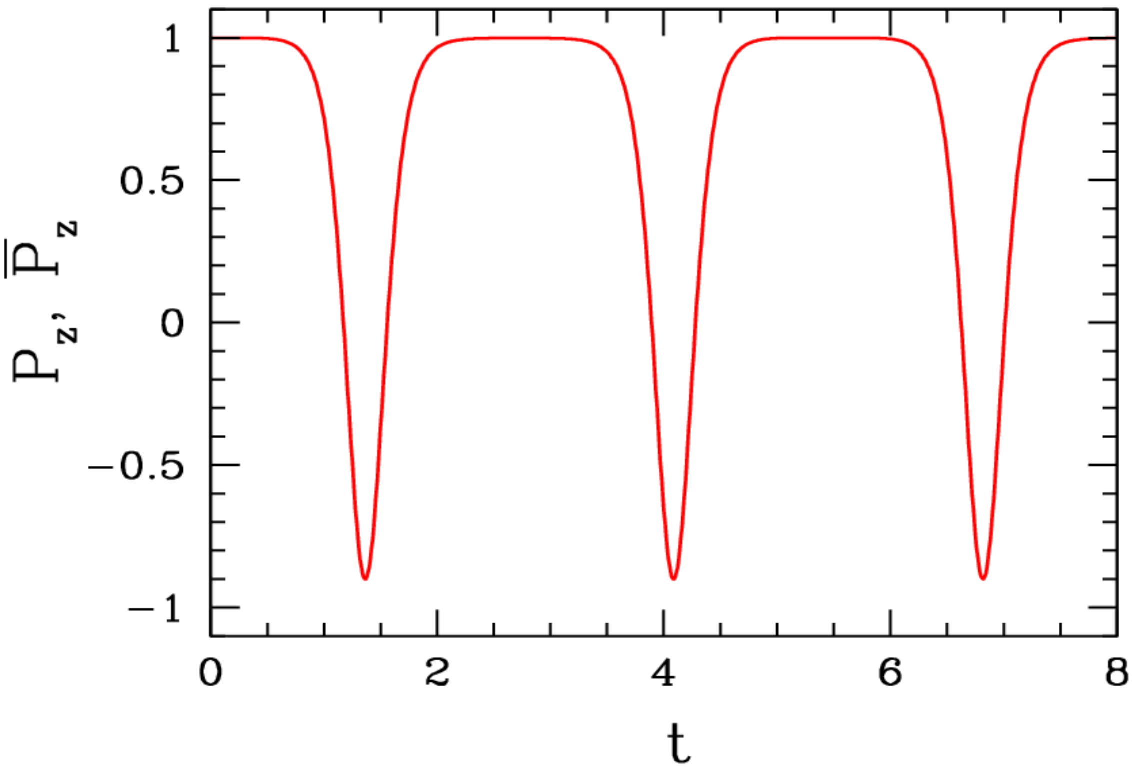
[Pastor, Raffelt, Semikoz, hep-ph/0109033]

PENDULAR OSCILLATIONS

[*Hannestad, Raffelt, Sigl, Wong, astro-ph/0608695*]

Equal densities of ν_e and $\bar{\nu}_e$

INVERTED HIERARCHY + small θ



In inverted hierarchy: coherent "pair conversions" $\nu_e\bar{\nu}_e \longrightarrow \nu_\mu\bar{\nu}_\mu$

With constant μ: periodic behaviour

PENDULUM IN FLAVOR SPACE

[*Hannestad, Raffelt, Sigl, Wong, astro-ph/0608695, Duan, Carlson, Fuller, Qian, astro-ph/0703776*]

Neutrino mass hierarchy (and θ_{13}) set initial condition and fate

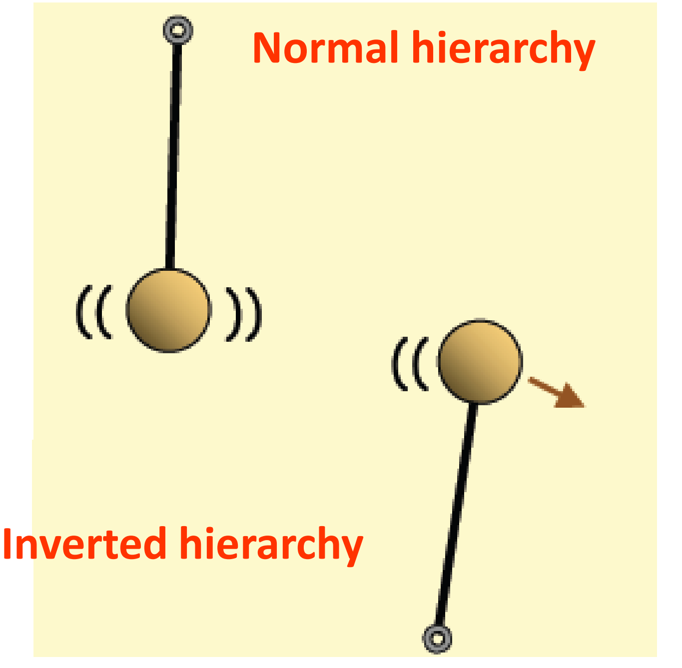
With only initial ν_e and $\overline{\nu}_e$:

- **Normal hierarchy**

  Pendulum starts in ~ downard (stable) positions and stays nearby. No significant flavor change.

- **Inverted hierarchy**

  Pendulum starts in ~ upward (unstable) positions and eventually falls down. Significant flavor changes.



θ_{13} sets initial misalignment with vertical. Specific value not much relevant.

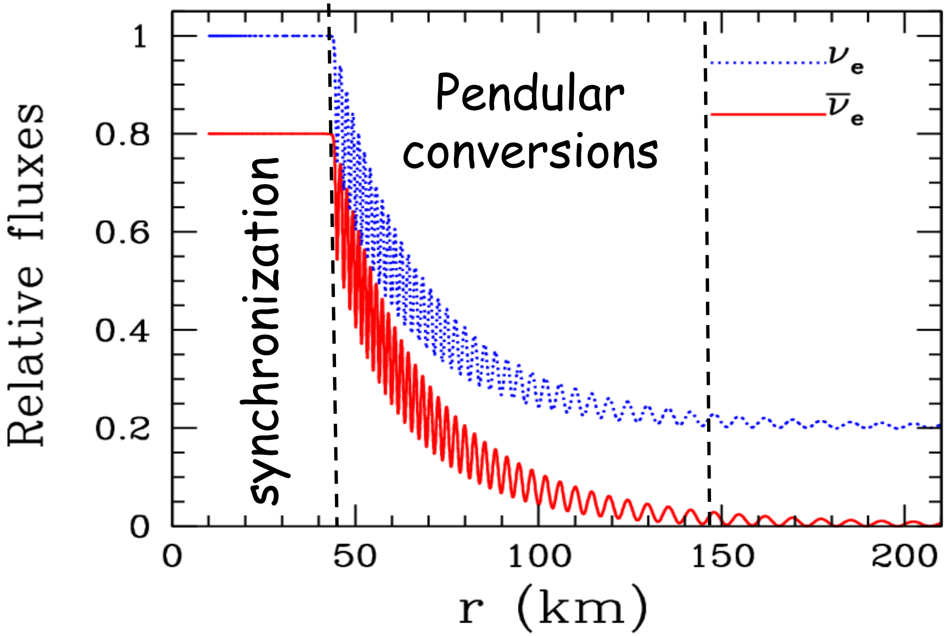
Which mass hierarchy?

With only initial ν_μ and $\overline{\nu}_\mu$ large flavor conversions in NH. The unstable case is when the initial ensemble consists of that flavor which is dominated by the heavier mass eigenstate.

SUPERNOVA TOY-MODEL

[*Hannestad, Raffelt, Sigl, Wong, astro-ph/0608695*]

Only ν_e and $\overline{\nu}_e$



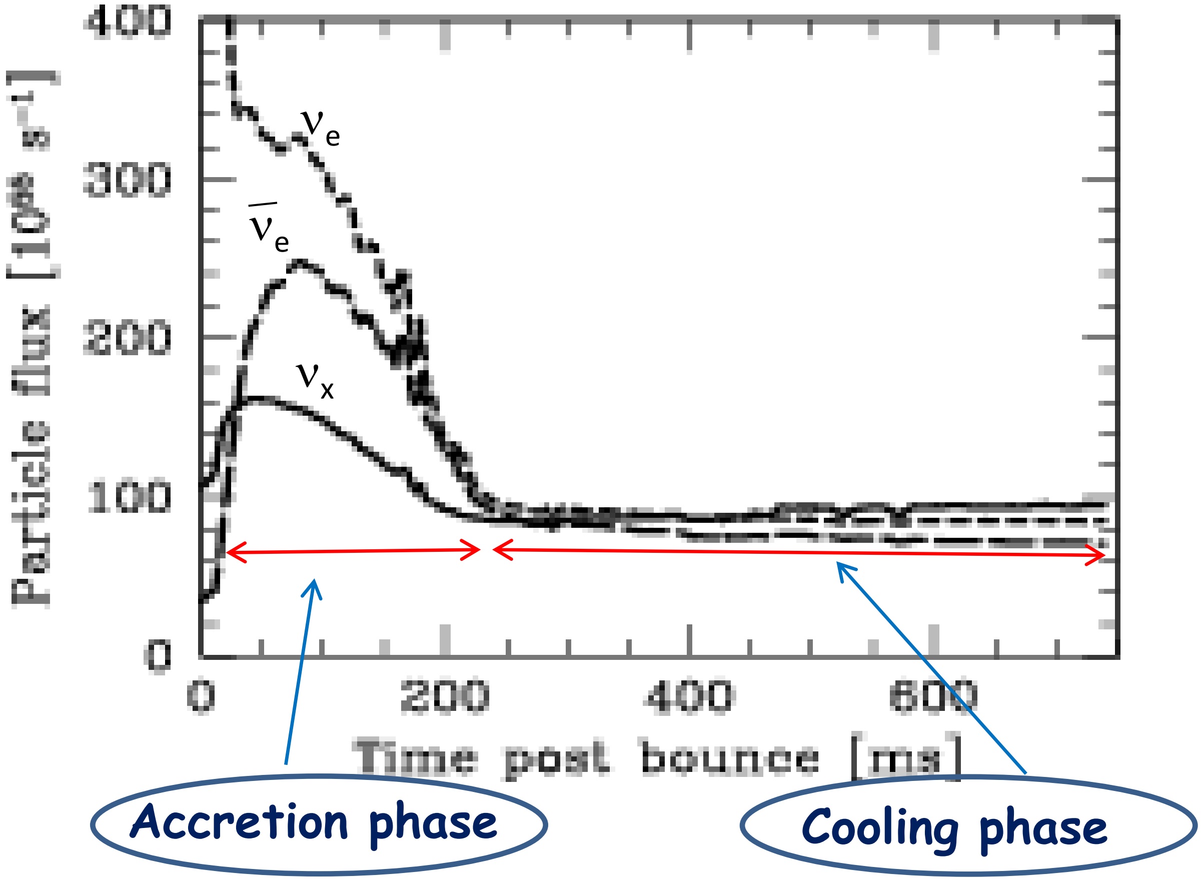
SUPERNOVA: **Non-periodic** since ν density decreases

Complete flavor conversions!

- Occurs for very small mixing angles
- Almost independent of the presence of dense normal matter
- Preserves the initial excess ν_e over $\overline{\nu}_e$ (lepton number conservation)

NEUTRINO FLUX NUMBERS

[*Raffelt et al. (Garching group), astro-ph/0303226*]



$$F_{\nu e} > F_{\bar{\nu} e} > F_{\nu x}$$

Excess of ν_e due to deleponization

$$F_{\nu x} \geq F_{\nu e} \geq F_{\bar{\nu} e}$$

Moderate flavor hierarchy, possible excess of ν_x

LARGE SCALE MULTI-ANGLE SIMULATIONS

$$H_{\nu\nu} = \sqrt{2}G_F \int \frac{d^3\vec{q}}{(2\pi)^3}(1-\cos\theta_{pq})(P_{\vec{q}} - \bar{P}_{\vec{q}})$$

Different coupling strenghts do not average in a non-isotropic medium, like ν streaming off a SN core. Some sort of decoherence could be expected. Is the single-angle approximation a reasonable one?

MULTI-ANGLE SIMULATIONS

- Accretion phase: *Duan, Fuller, Carlson & Qian, astro-ph/0606616, 0608050; Fogli, Lisi, Marrone & A.M., arXiv: 0707.1998, Fogli, Lisi, Marrone, A.M & Tamborra, arXiv:0808.0807; Esteban-Pretel, Pastor, Tomas, Raffelt & Sigl, arXiv:0706.2498.*

- Cooling phase: *Duan & Friedland, arXiv: 1006.2359* → See Friedland's poster

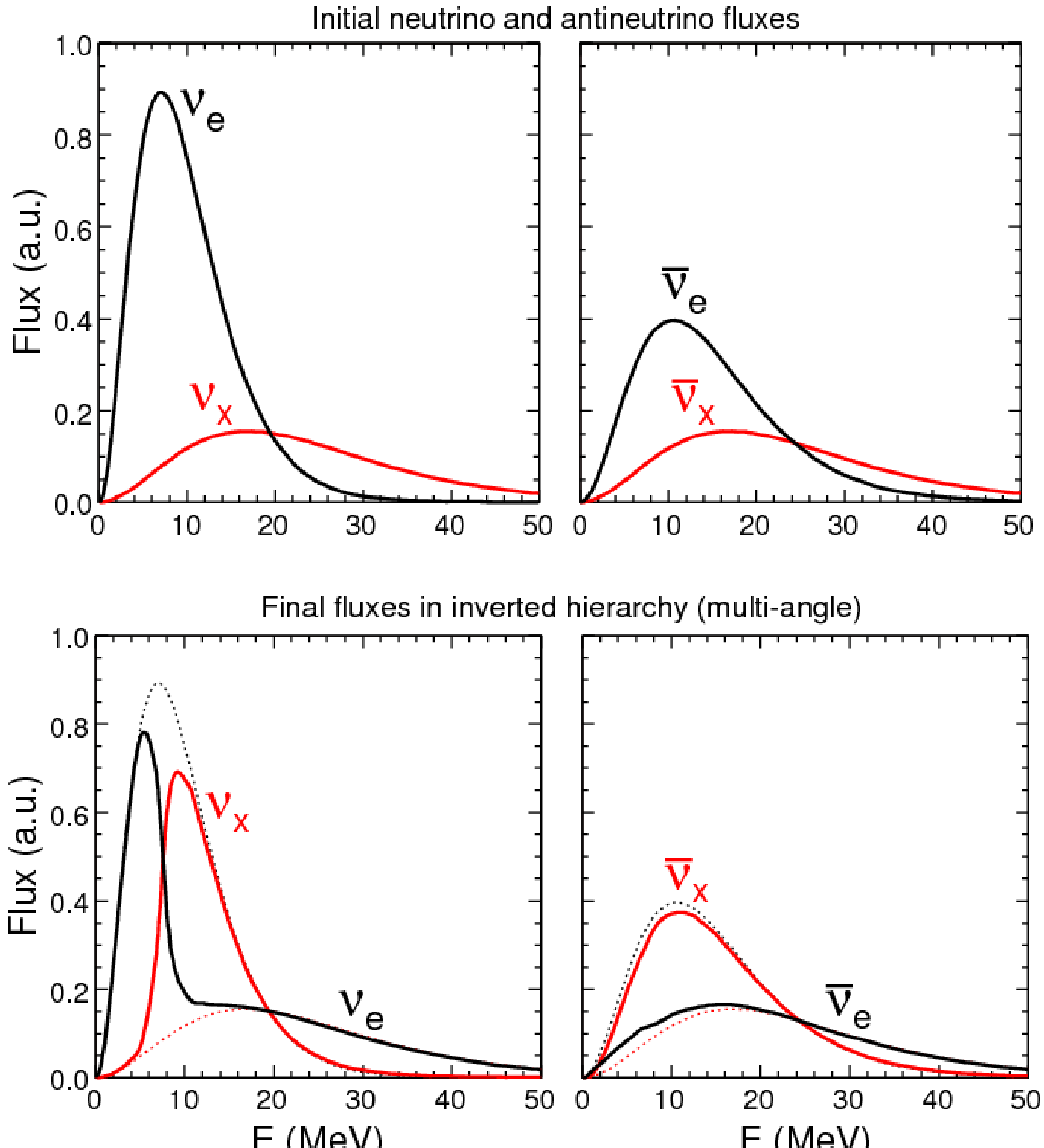
- Neutronization burst O-Ne-Mg SNe: *Cherry et al., arXiv: 1006.2175*

For typical SN ν spectra observed an effective "quasi single-angle" behaviour

However, how generic are these results?

SPECTRAL SPLITS IN THE ACCRETION PHASE

[Fogli, Lisi, Marrone, A.M. , arXiV: 0707.1998 [hep-ph], Duan, Carlson, Fuller, Qian, astro-ph/0703776, Raffelt and Smirnov, 0705.1830 [hep-ph]]



Initial fluxes at neutrinosphere (r ~10 km)

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

(ratio typical of accretion phase)

Inverted mass hierarchy

2ν=(Δm^2, θ_{13})

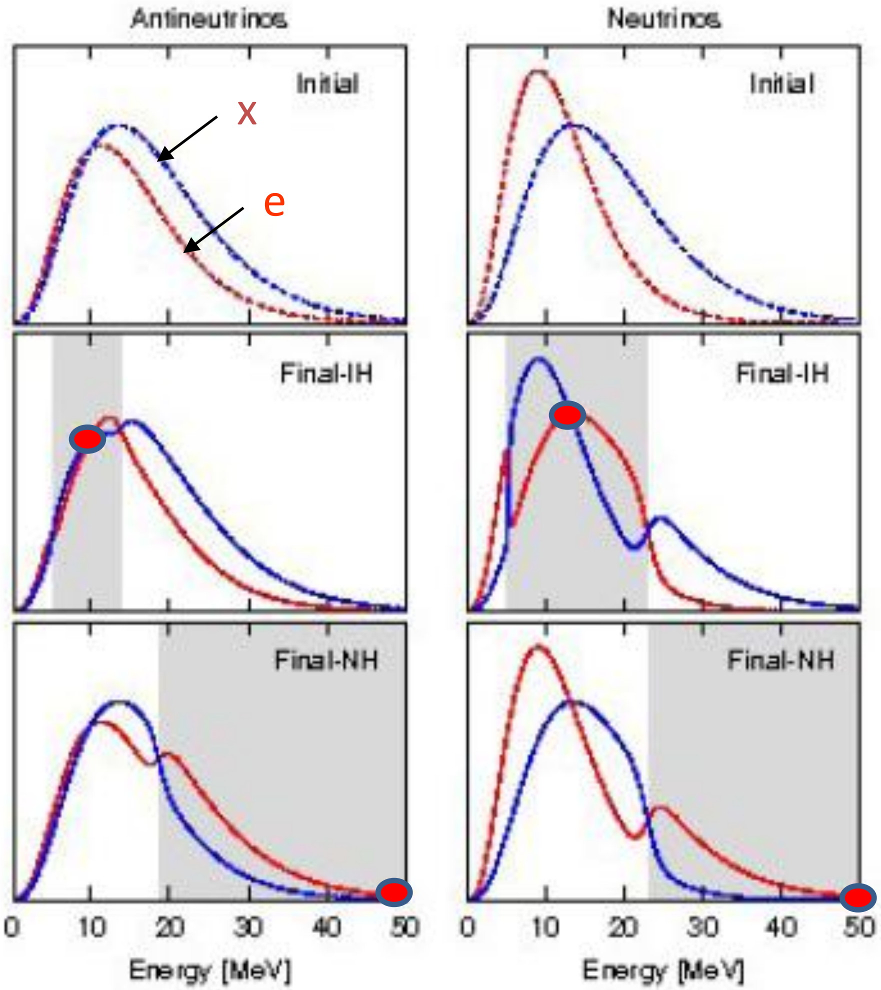
Fluxes at the end of collective effects (r ~200 km)

Nothing happens in NH

MULTIPLE SPECTRAL SPLITS IN THE COOLING PHASE

[Dasgupta, Dighe, Raffelt & Smirnov, arXiv:0904.3542 [hep-ph]]

$2\nu = (\Delta m^2, \theta_{13})$



$$F_{\nu e} : F_{\bar{\nu} e} : F_{\nu x} = 0.85 : 0.75 : 1.00$$

(possible during the cooling phase)

Splits possible in both normal and inverted hierarchy, for ν & $\bar{\nu}$!!

Splits develops around the crossing points of the spectra (expect at E=0)

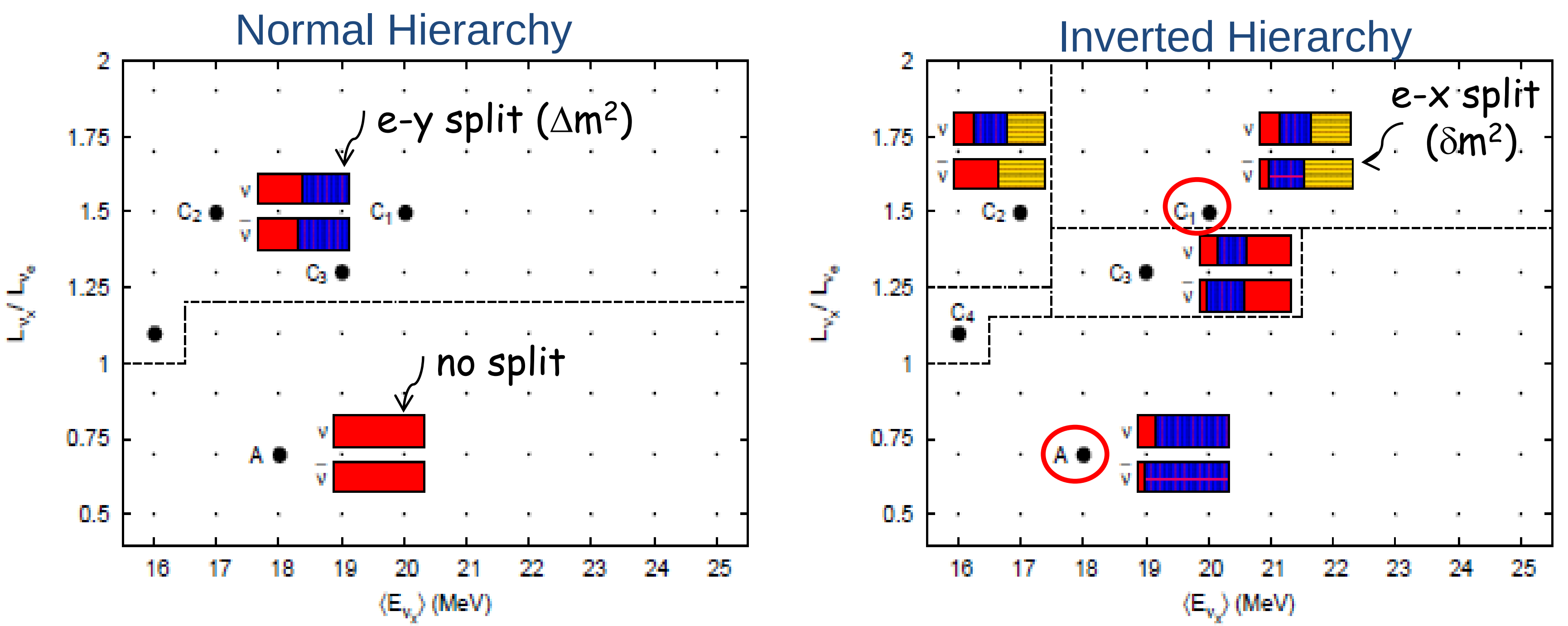
$$F_{\nu e}(E_c) - F_{\nu x}(E_c) = 0$$

THREE FLAVOR EFFECTS RELEVANT IN IH

See posters by Friedland and Tamborra

PHASE DIAGRAM OF SPECTRAL SPLITS

[Choubey, Dasgupta, Dighe, & A.M., to appear soon]



Scan of the parameter space with 3ν simulations (S.A., 80 cases).

Abrupt changes of the split pattern btw different regions of the parameter space (in agreement with *[Fogli, Lisi, Marrone, Tamborra, arXiV:0907.5115]*)

OPEN ISSUES

Theoretical issues

Robustness of the collective behavior vs. multi-angle decoherence effects. Reduced symmetries.

Realistic SN environment

How asphericities, inhomogeneities, turbulence during the SN explosion might influence neutrino-neutrino interaction effects.

Feedback on SN explosion simulations

Collective effects occur in a crucial region for SN dynamics and for nucleosynthesis. SN explosion simulations do not account for neutrino oscillations.

Beyond the SM

Possible new nu-nu interactions beyond SM might profoundly change the current picture.

CONCLUSIONS

Observing SN neutrinos is the next frontiers of low-energy neutrino astronomy

The physics potential of current and next-generation detectors in this context is enormous, both for particle physics and astrophysics.

SNe provide very extreme conditions, where shock-waves, matter turbulences, neutrino-neutrino interactions prove to be surprisingly important for the ν oscillations.

Further investigations needed to better understand neutrino flavor conversions during a stellar collapse.

Therefore, waiting the next galactic SN….

….Still lot of work to decipher the enigma