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FUTURE DETECTION OF SUPERNOVA NEUTRINO BURST:

A PROBE FOR FLAVOR TRANSITIONS AND EXPLOSION MECHANISM

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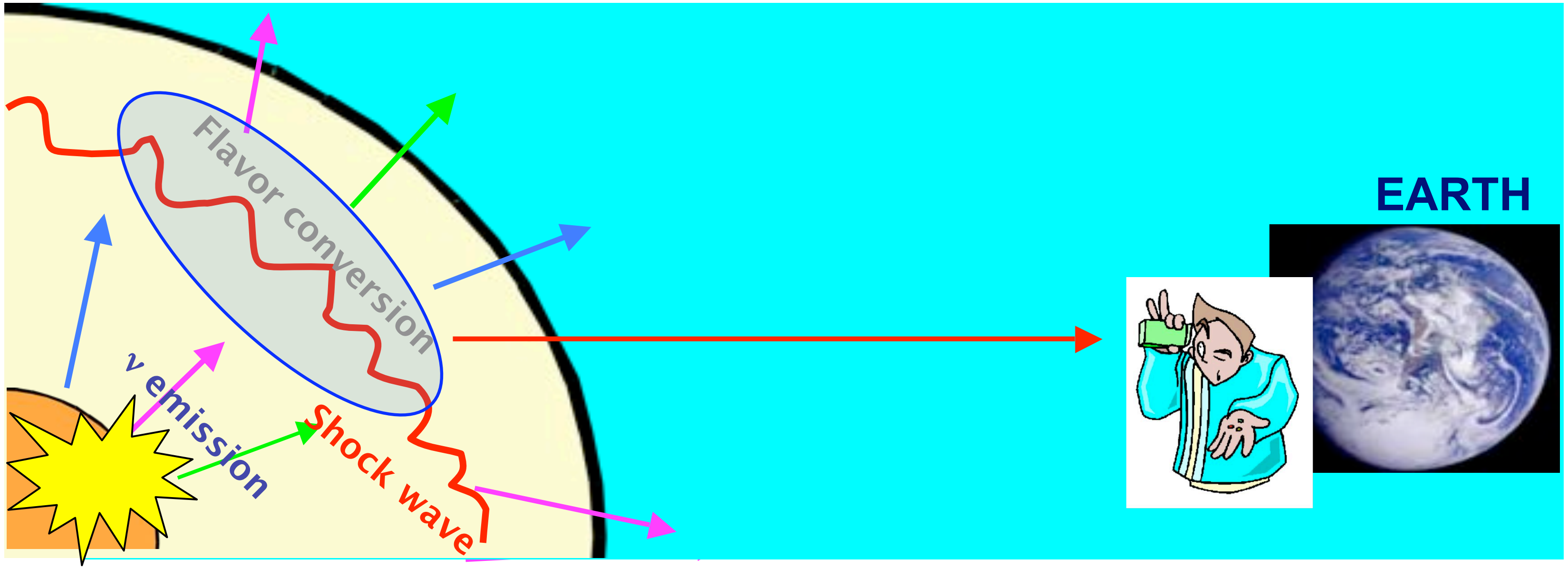
CORE-COLLAPSE SUPERNOVAE

Core collapse SN corresponds to the terminal phase of a massive star [$M \gtrsim 8\ M_{\odot}$] which becomes instable 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 ($\sim 10^{53}$ erg) is emitted by ν and $\bar{\nu}$ of all flavors with $E \sim O(10\ \mathrm{MeV})$
- **TIME SCALES:** Neutrino emission lasts **~10 s**
- **EXPECTED: 1-3 SN/century** in our galaxy ($d \approx \mathcal{O}(10)$ kpc).

OBSERVING SN NEUTRINOS

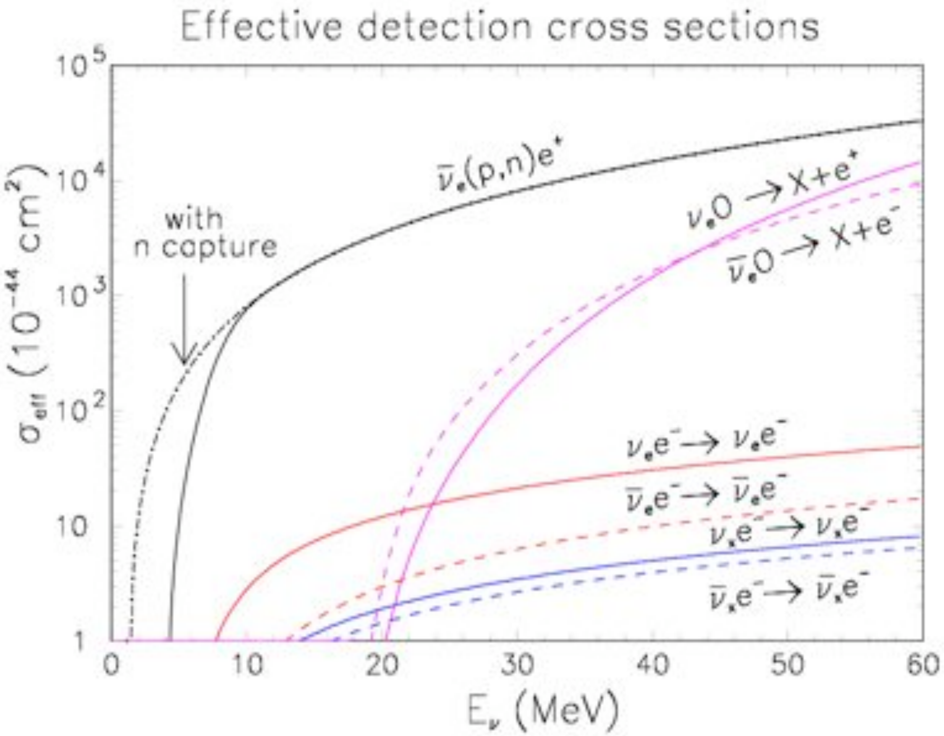


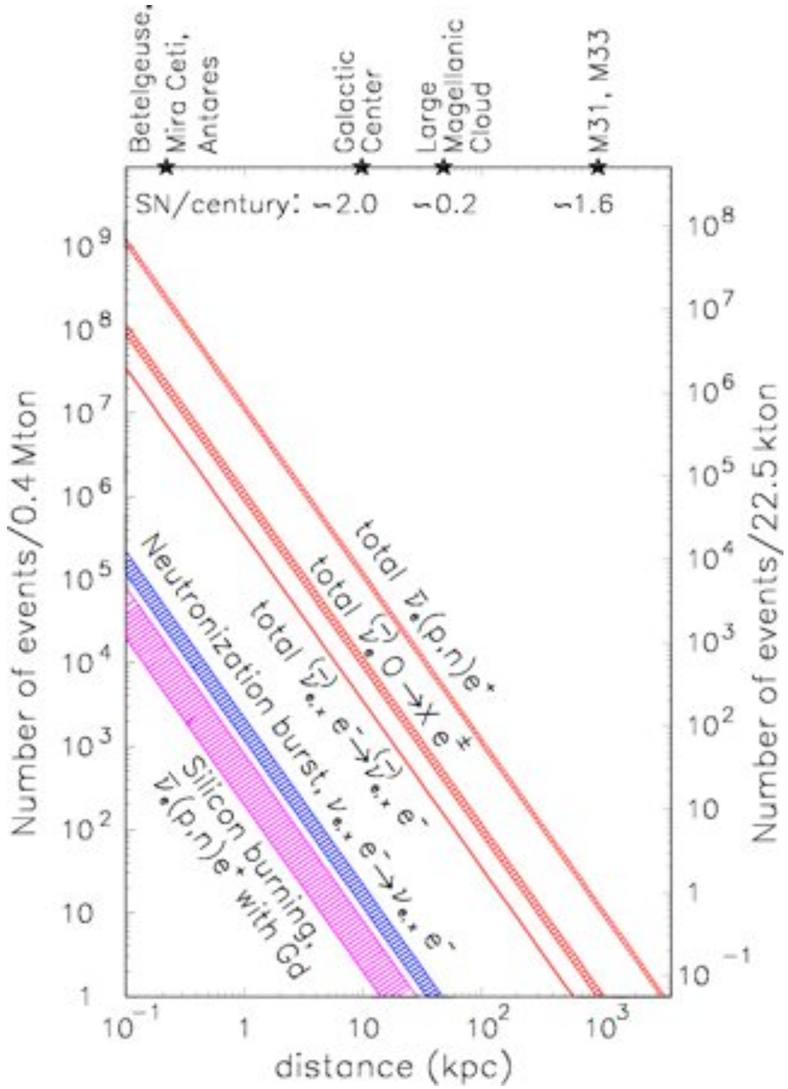
Core Collapse

Event rate spectra ➡ $$\int \phi(\nu_\alpha) P\left(\nu_\alpha \to \nu_\beta\right) \sigma\left(\nu_\beta\right) \varepsilon_\beta$$

- ϕ : **from simulations of SN explosions**
- ***P*** **: from** ν **oscillations + simulations (density profile)**
- σ : **(well) known**
- ε : **under control**

0.4 Mton WATER CHERENKOV DETECTOR





Golden channel: Inverse beta decay (IBD) of $\overline{\nu}_e$

~2.5×10^5 events @ 10 kpc

Mton Cherenkov detectors detectors would assure a high-statistics measurement of galactic SN neutrinos.

This would allow spectral studies

- **in time**
- **in energy**
- **in different interaction channels**

We will mainly focus on the possibility to detect the signatures in the ν signal for a typical galactic SN explosion (d=10 kpc) associated to:

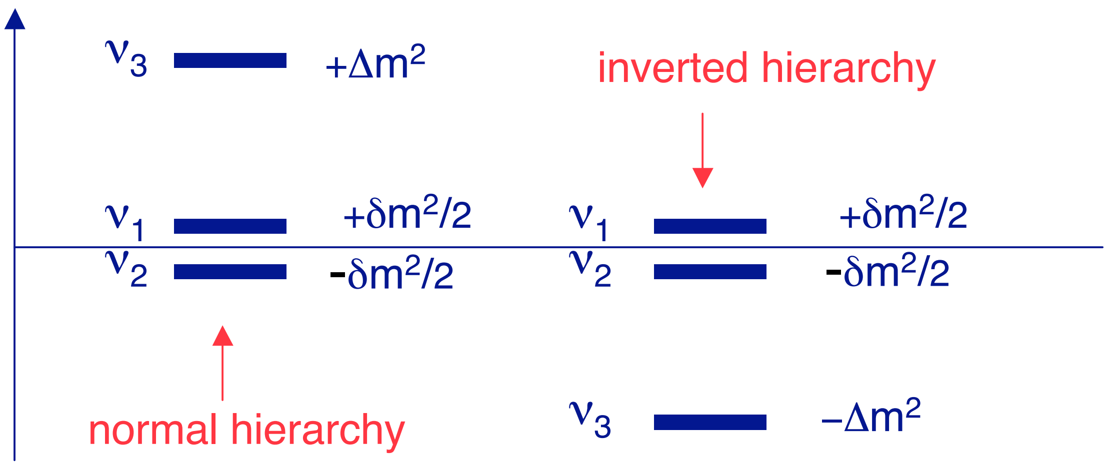
- **Shock wave propagation**
- **Turbulent density fluctuations**

through peculiar modulation of the MSW ν flavor conversions.

3 ν framework

- **Mixing parameters:** $U = U(\theta_{12}, \theta_{13}, \theta_{23})$ as for CKM matrix

- **Mass-gap parameters:** $M^2 = \left(\underbrace{-\frac{\delta m^2}{2}, +\frac{\delta m^2}{2}}_{\text{“solar”}}, \underbrace{\pm \Delta m^2}_{\text{“atmospheric”}} \right)$



$\delta m^2 \approx 7.92\,(1 \pm 0.09) \times 10^{-5}\ \text{eV}^2$

$\sin^2\theta_{12} \approx 0.314\,(1^{+0.18}_{-0.15})$

$\Delta m^2 \approx 2.6\,(1^{+0.14}_{-0.15}) \times 10^{-3}\ \text{eV}^2$

$\sin^2\theta_{23} \approx 0.45(1^{+0.35}_{-0.20})$

$\sin^2\theta_{13} = 0.8^{+2.3}_{-0.8} \times 10^{-2}$

[Fogli et al., hep-ph/0608060]

- **Neutrino potential in matter:** $V(x) = \sqrt{2} G_F N_e(x)$

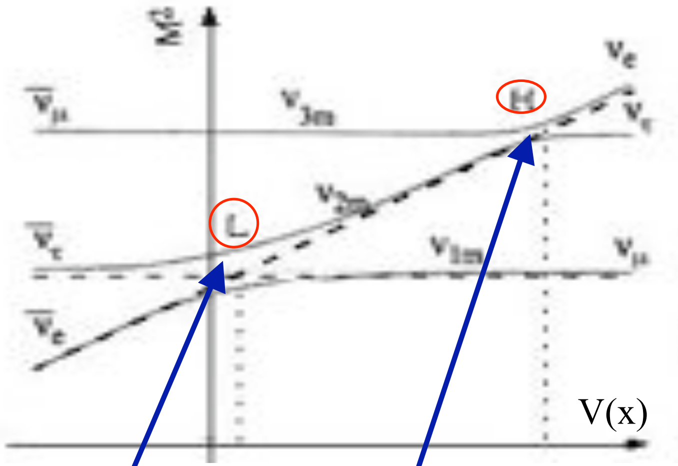
Collective effects from ν-ν interactions important just above the ν-sphere

[Pastor & Raffelt, astro-ph/0207281; Duan, Fuller, Carlson & Qian, astro-ph/0606616; Hannestad, Raffelt, Sigl & Wong, astro-ph/0608695]

SUPERNOVA NEUTRINO OSCILLATIONS

Neutrino flavor evolution equations must be solved to obtain the relevant

$$P_{ee} = P(\overset{(-)}{\nu}_e \rightarrow \overset{(-)}{\nu}_e) < 1$$



Final rotation to the flavor eigenstates in vacuum

Rotation to eigenstates in matter (at the neutrinosphere)

$$P_{ee} \cong \overbrace{\left(U_{e1}^2 \quad U_{e2}^2 \quad U_{e3}^2\right)}\underbrace{\begin{pmatrix} 1-P_L & P_L & 0 \\ P_L & 1-P_L & 0 \\ 0 & 0 & 1 \end{pmatrix}} \cdot \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1-P_H & P_H \\ 0 & P_H & 1-P_H \end{pmatrix}} \cdot \overbrace{\begin{pmatrix} U_{m,e1}^2 \\ U_{m,e2}^2 \\ U_{m,e3}^2 \end{pmatrix}}$$

Lower level crossing transition. $P_L \approx 0$ (adiabatic) since θ_{12} large and δm^2 small

Higher level crossing transition. $0 \leq P_H \leq 1$ depending on θ_{13}

SUPERNOVA NEUTRINO SURVIVAL PROBABILITY

$$P_{ee} \approx \begin{cases} \sin^2\theta_{12} P_H & (\nu, \text{normal}) \\ \cos^2\theta_{12} & (\bar{\nu}, \text{normal}) \\ \sin^2\theta_{12} & (\nu, \text{inverted}) \\ \cos^2\theta_{12} P_H & (\bar{\nu}, \text{inverted}) \end{cases}$$

P_H modulates P_{ee}

[See A.Dighe & A.Smirnov, hep-ph/9907423; G.L.Fogli et al., hep-ph/0111199]

Given the smallness of θ_{13}, $P_H = P_{ee}^{2\nu,\,H}(\Delta m^2, \theta_{13}, V)$.

Matter effects encoded in $P_H = P_H^{2\nu,\,H}(\Delta m^2, \theta_{13}, V)$ strongly dependent on: energy, potential profile V, and unknown mixing angle θ_{13} .

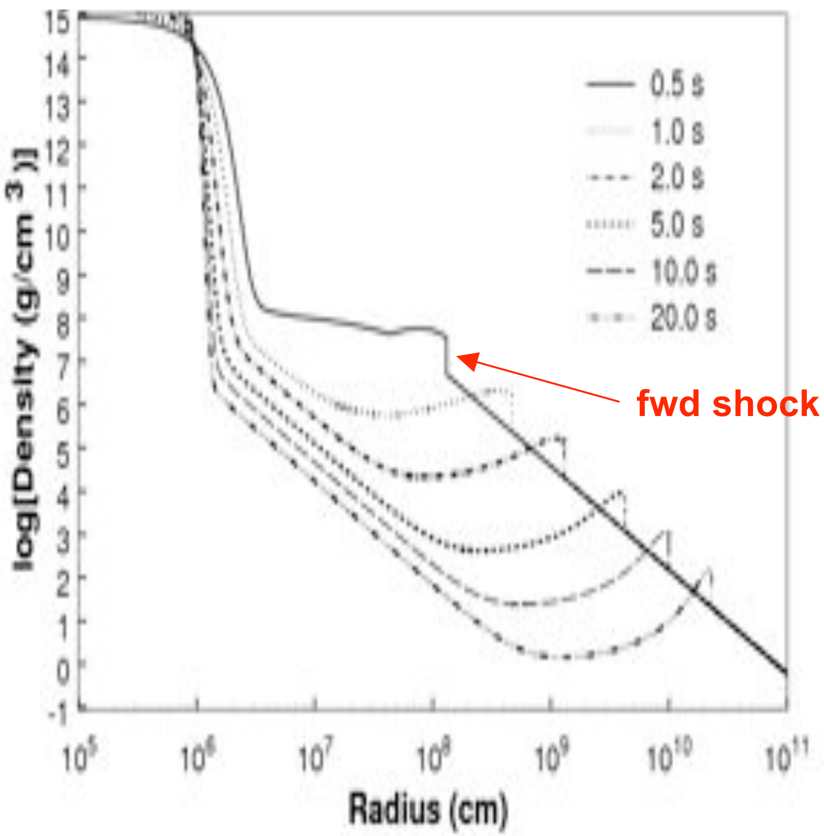
A time dependent potential $V=V(t)$ modulates the survival probability P_H and thus leaves an "imprint" on the time spectrum of the neutrino burst.

SHOCK-WAVE PROPAGATION

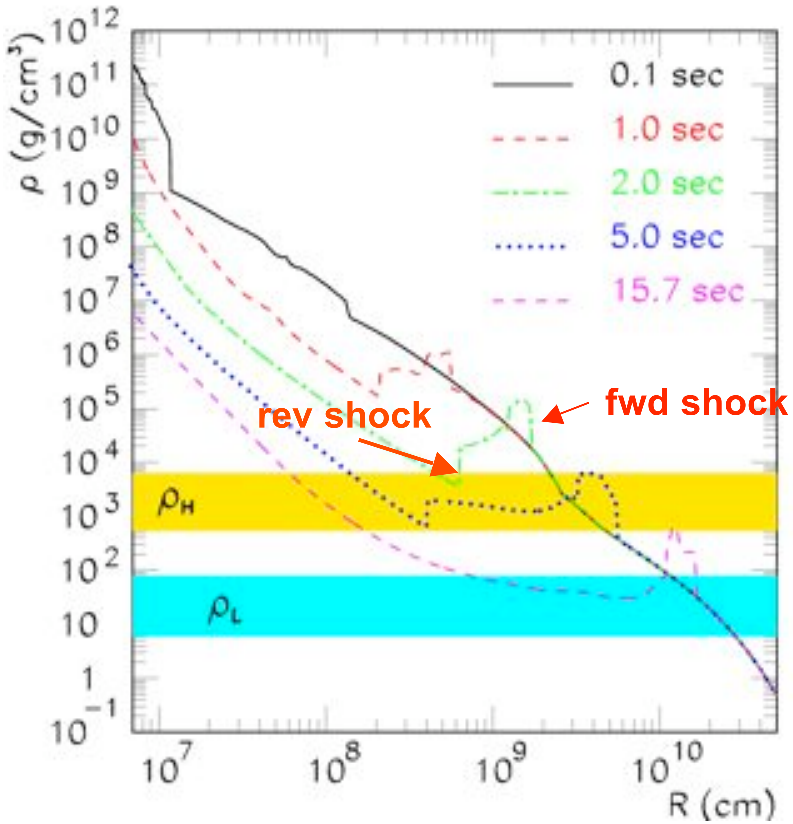
Recent core-collapse SN simulations have obtained the propagation of the shock-wave in a range of time of ~ 20 s after the core bounce.

The main feature of the shock-wave physics is that the matter density profile is:
1) nonmonotonic and time dependent; 2) step-like at the shock front.

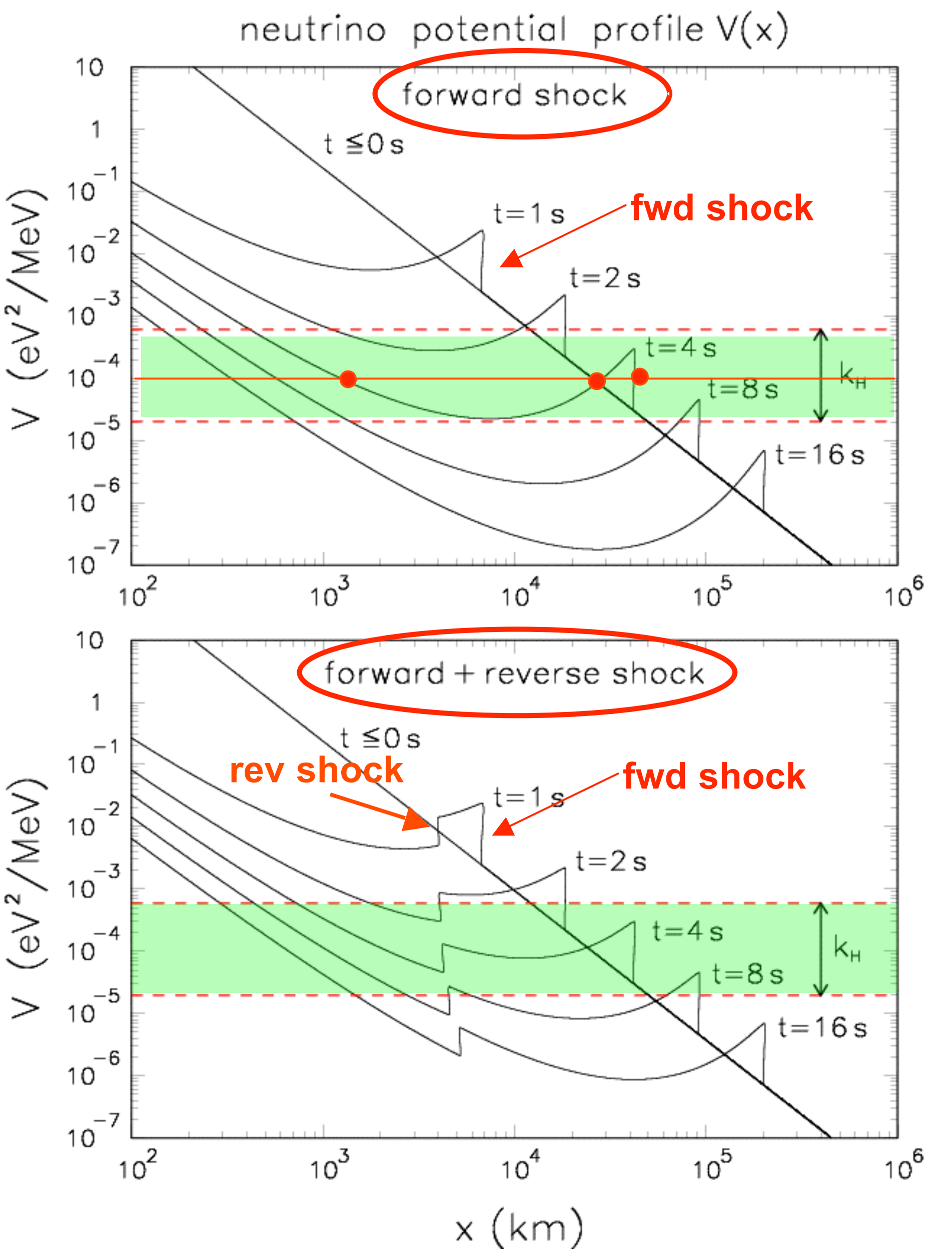
R.Schirato, and G. Fuller, astro-ph/0205390



R.Tomas et al., astro-ph/0407132



NEUTRINO OSCILLATIONS AND SHOCK WAVE



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]

The probability P_H is expected to play a significant role when

$$V(x) \sim k_H = \Delta m^2/2E$$

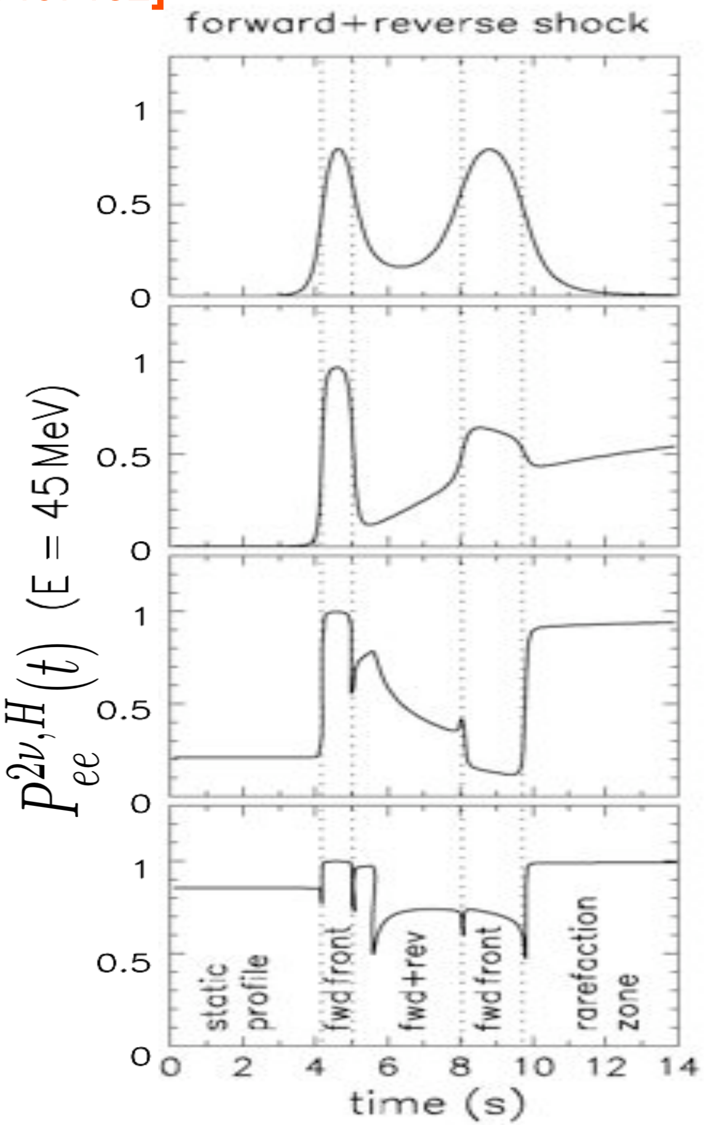
For t ~ 2-10 s : multiple crossings

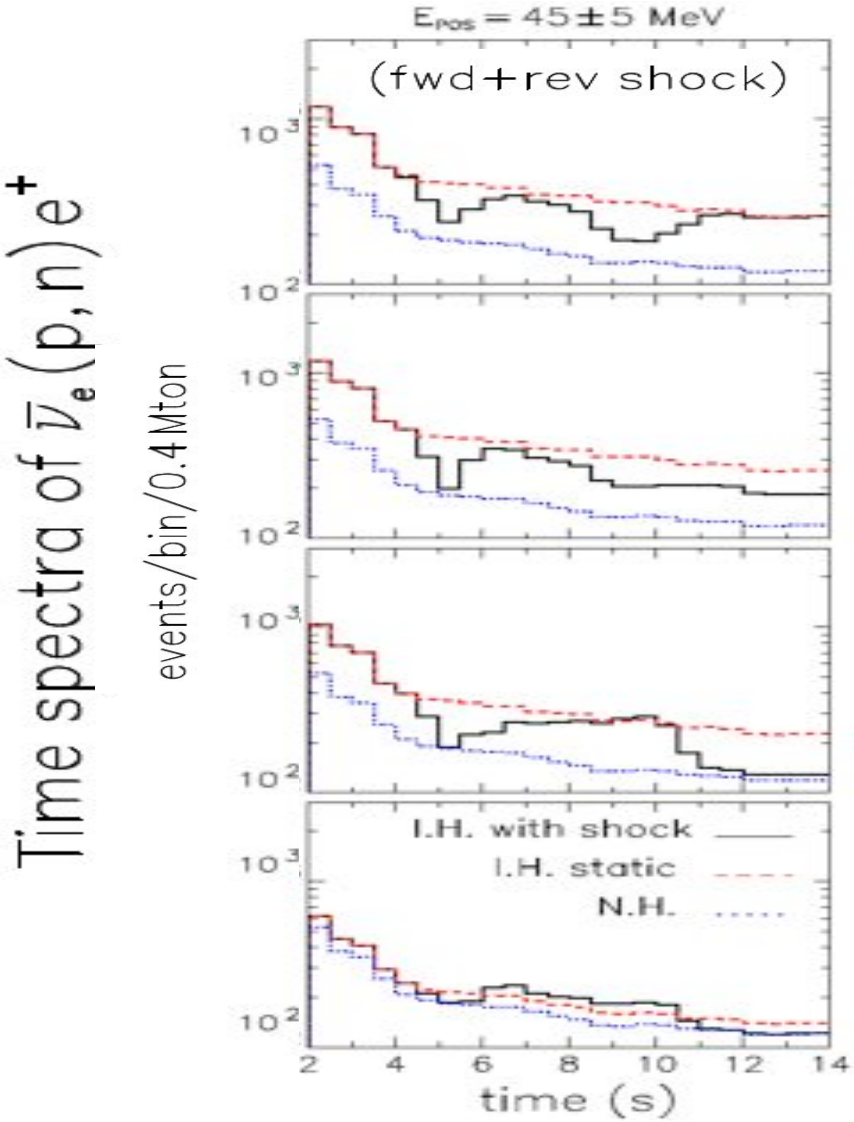
Peculiar modifications of P_H , w.r.t. to the case of a static matter density profile

(see [G.L. Fogli, E.Lisi, **A.M.**, and D. Montanino, hep-ph/0304056])

● **How to extract a model-independent signature of shock-wave propagation?**

[G.L. Fogli, E. Lisi, **A.M.**, and D. Montanino, hep-ph/0412046, see also R.Tomas et al., astro-ph/0407132**]**





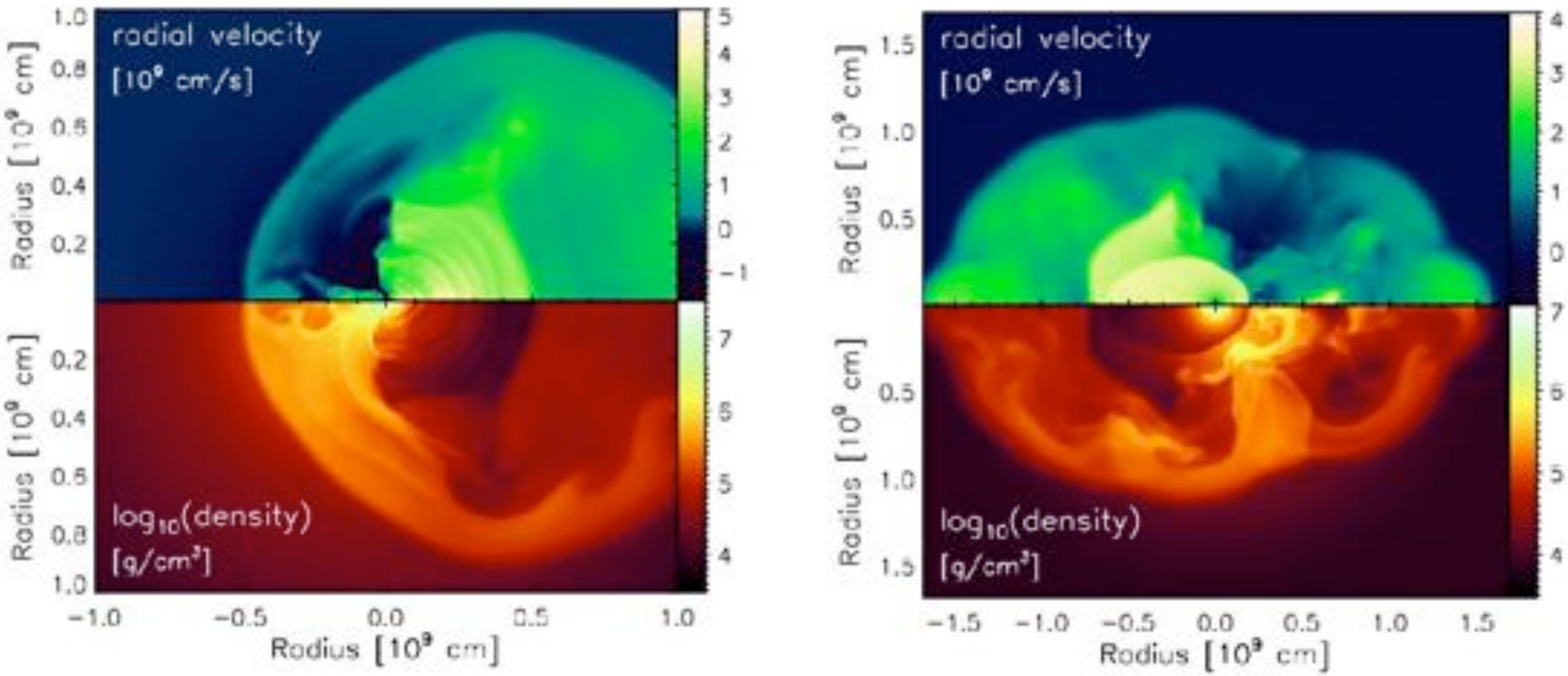
In IH and for θ_{13} not too small, SN shock wave(s) induce non-monotonic time spectra at "sufficiently high" energy.

Correct cartoon?

- Nothing close to "standard supernova model"; must use a correct cartoon of the explosion for neutrino calculations hoping that the cartoon captures essential physics features for neutrino propagation
- Are the cartoon used so far the right cartoons? What features are important for neutrinos?

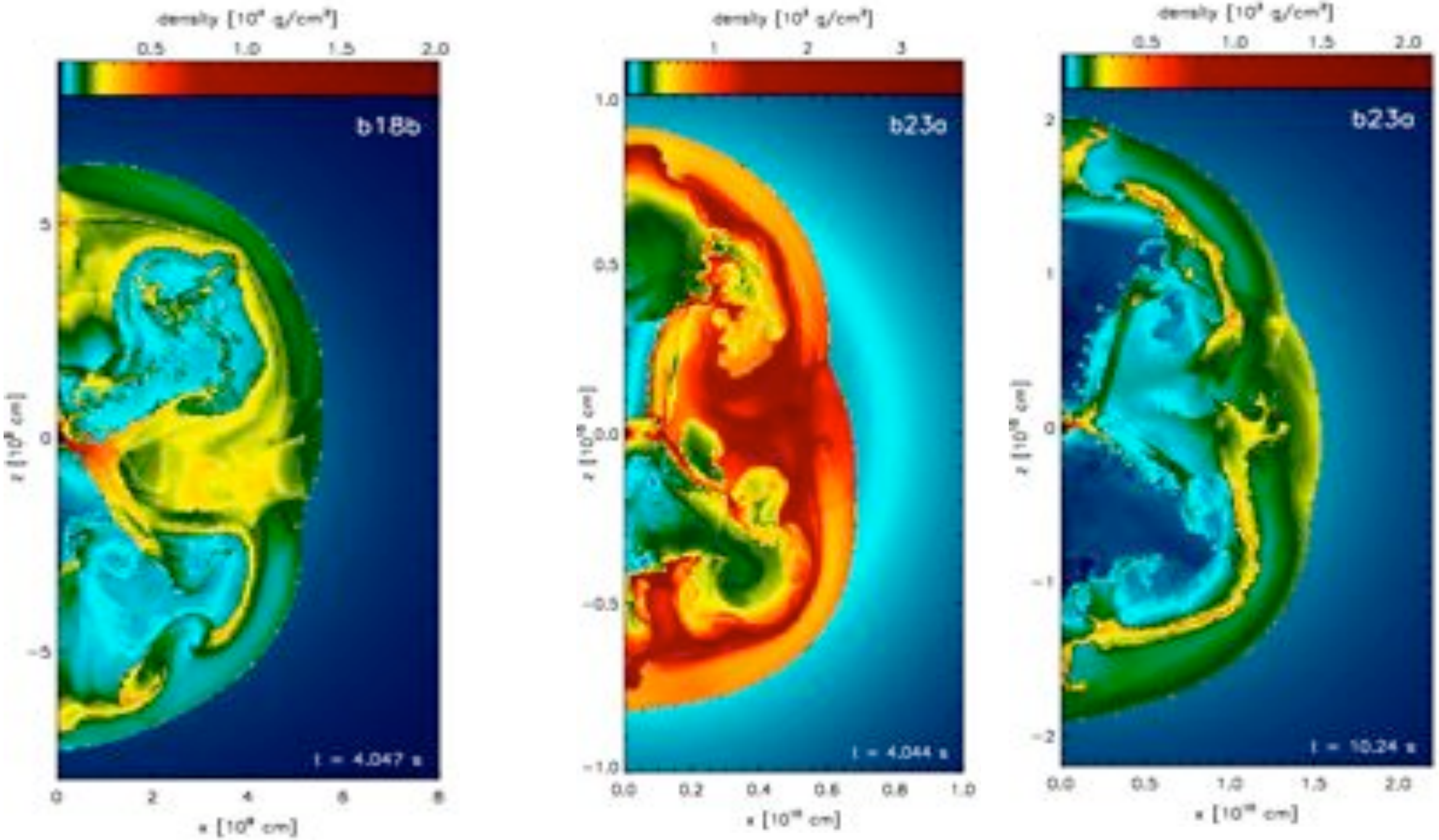
SUPERNOVA TURBULENCE

Latest state of art simulations show vigorous turbulence behind the shock front at early times ….

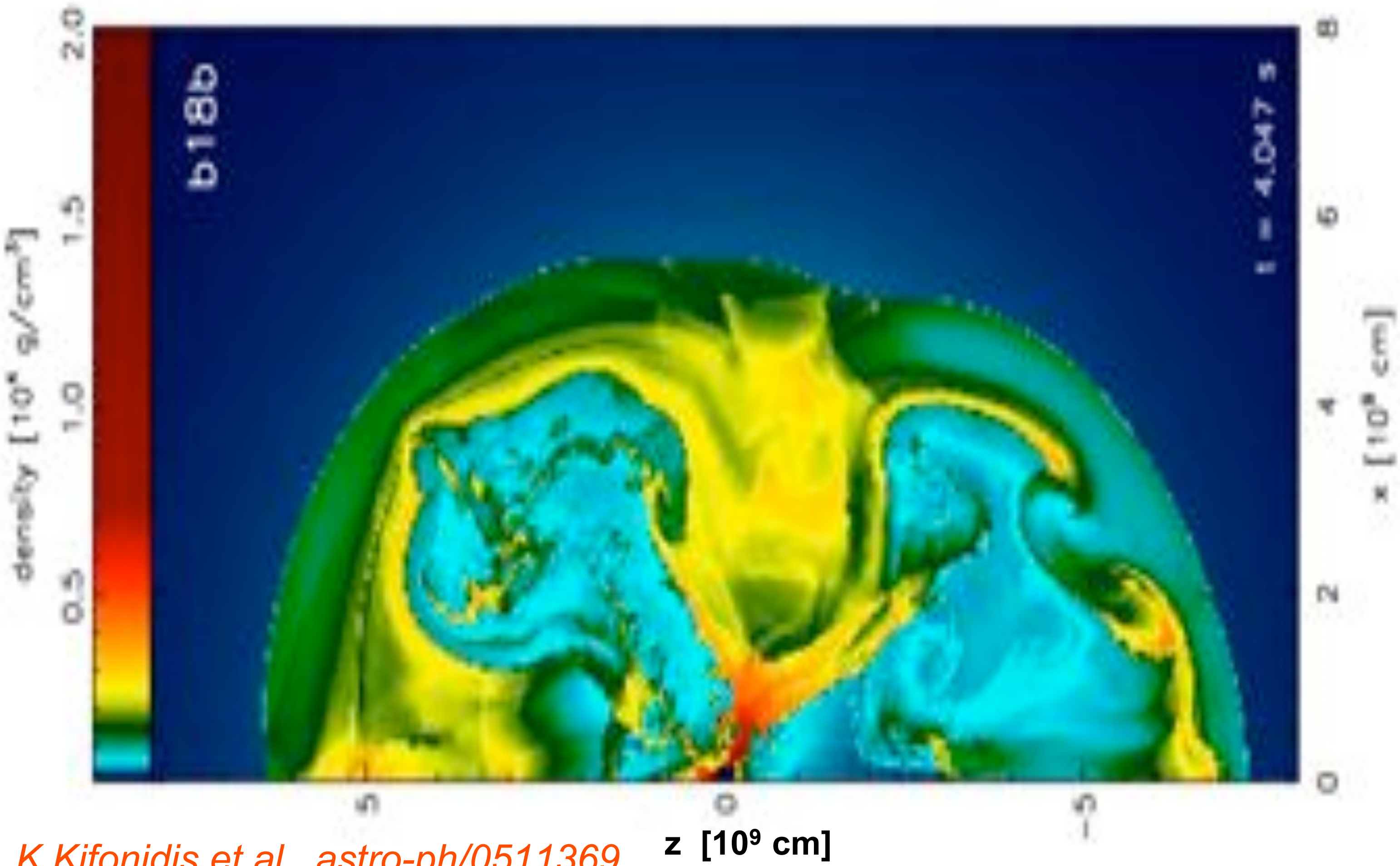


[*L.Scheck et al., astro-ph/0307352*]

… Turbulence persists to later times



K.Kifonidis et al., astro-ph/0511369



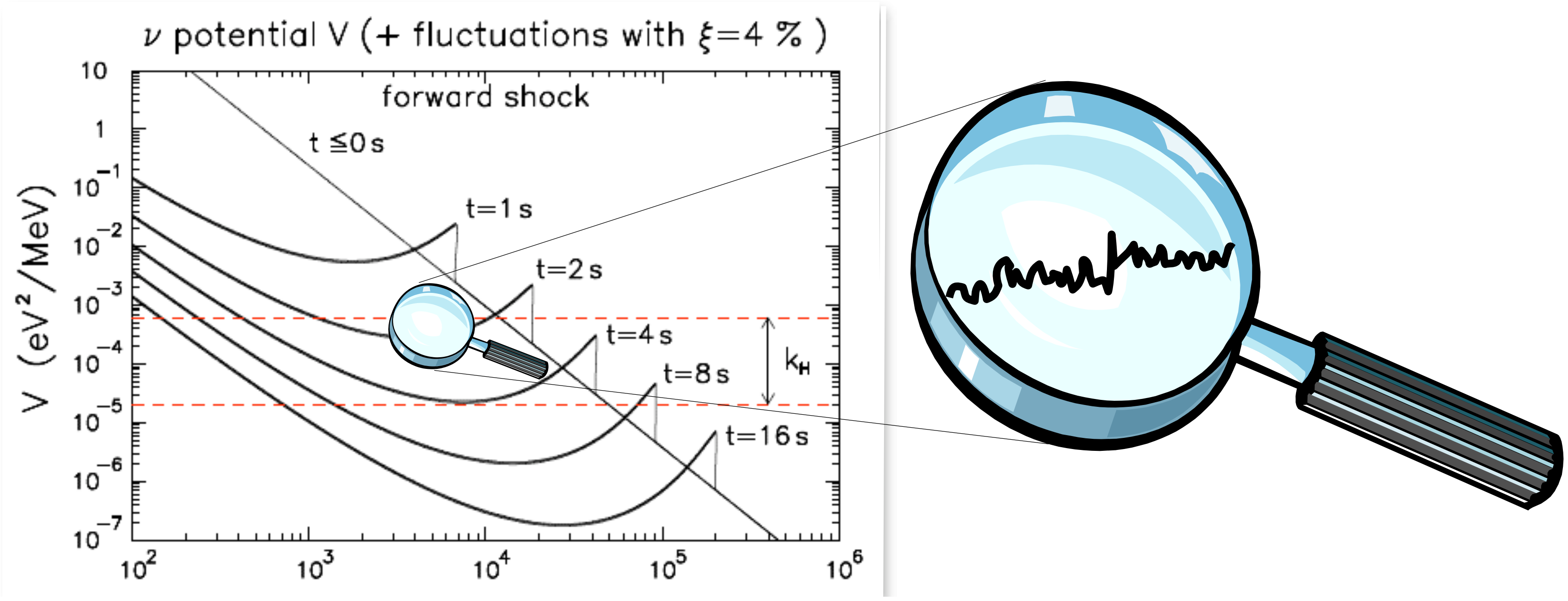
K.Kifonidis et al., astro-ph/0511369

Turbulent convective motions 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.

See the talk by Timur Rashba for a general review

STOCHASTIC SN MATTER DENSITY FLUCTUATIONS

[G.L. Fogli, E. Lisi, **A.M.**, and D. Montanino, hep-ph/0603033]



We will consider only "small" scale fluctuations, whose correlation length L_0 is smaller than the typical oscillation wavelength in matter. With this hypothesis the density fluctuations can be considered "δ-correlated", i.e.:

$$V(r) = \overline{V}(r) + \delta V(r)$$

$$\langle \delta V(r) \rangle = 0$$

$$\langle \delta V(r) \delta V(r') \rangle = 2 L_0 \xi^2 \overline{V}^2(r) \delta(r - r')$$

$$\xi = 4\%$$

$$L_0 = 10 \text{ km}$$

DAMPING OF OSCILLATIONS

$$P = \begin{pmatrix} 2\,\mathrm{Re}(\nu_e^* \nu_a) \\ 2\,\mathrm{Im}(\nu_e^* \nu_a) \\ 2|\nu_e|^2 - 1 \end{pmatrix}$$

Polarization vector

$$\begin{cases} |P|=1 \longrightarrow \text{pure state} \\ |P|=0 \longrightarrow \text{completely mixed state} \end{cases}$$

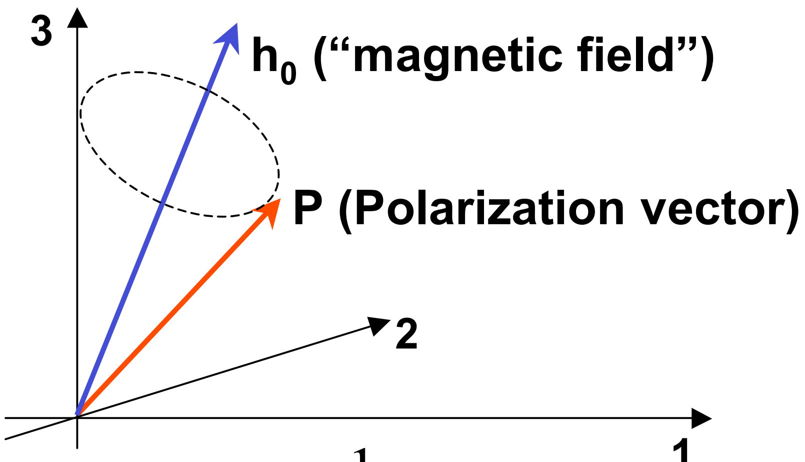
BLOCH EQUATION

$$\boxed{\frac{d}{dx} P = h_0 \times P - D P_T}$$

*[L.Stodolsky, PRD **36**, 2273 (1987)]*

Coherent MSW precession

Damping



$$H = \frac{1}{2} h \cdot \sigma$$

$$P_T = P - P_3$$

It produces a shrinking of P

$$\frac{dP^2}{dt} = -2D\, P \cdot P_T < 0$$

$$|P| = 0$$

Flavor depolarization

SURVIVAL PROBABILITY

The (fluctuation-averaged) survival probability for electron neutrinos is then given by:

$$P_{ee} = \frac{1 + P_3}{2}$$

We suppose that the fluctuations are sufficiently small to affect only the “high” subsector.
After some calculations, the probability $P^{2\nu,H}_{ee}$ in presence of random noise can be recast as

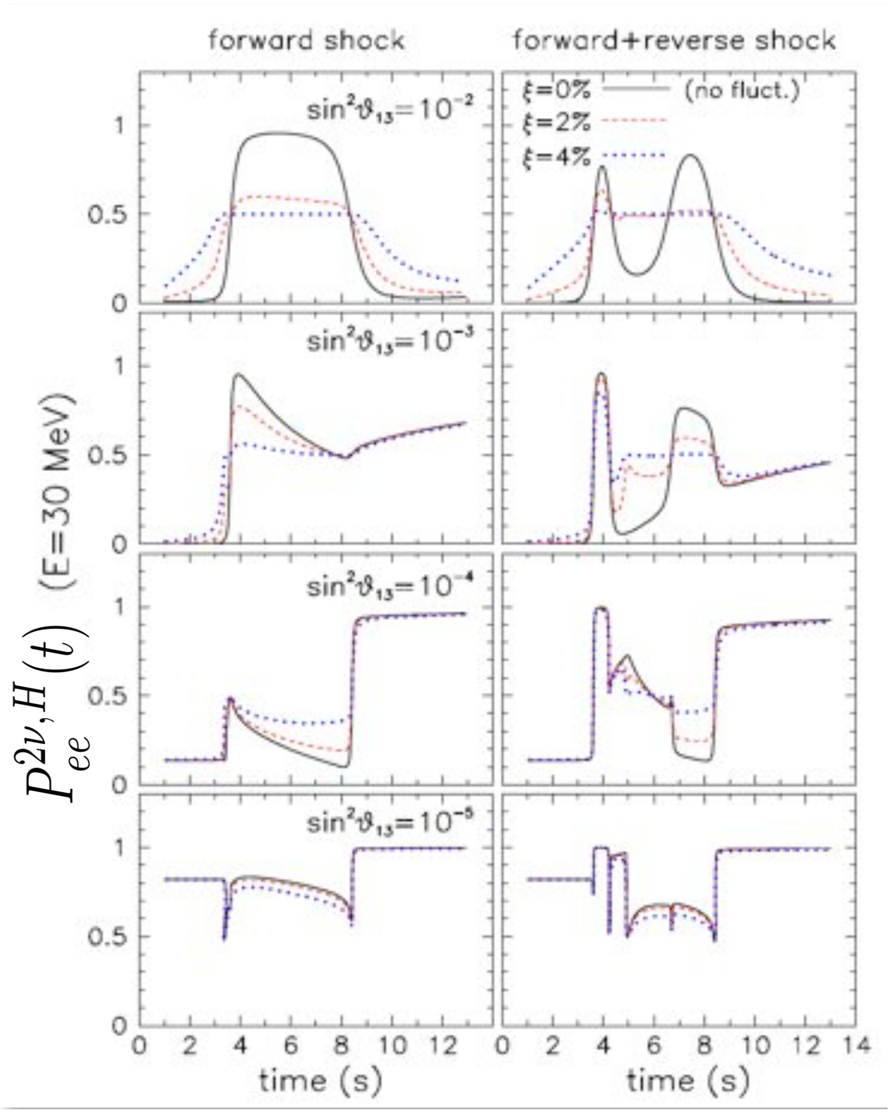
$$\boxed{P_{ee}^{2\nu,H}(\xi) \simeq e^{-\Gamma(\xi)} P_{ee}^{2\nu,H}(\xi = 0) + \frac{1 - e^{-\Gamma(\xi)}}{2}}$$

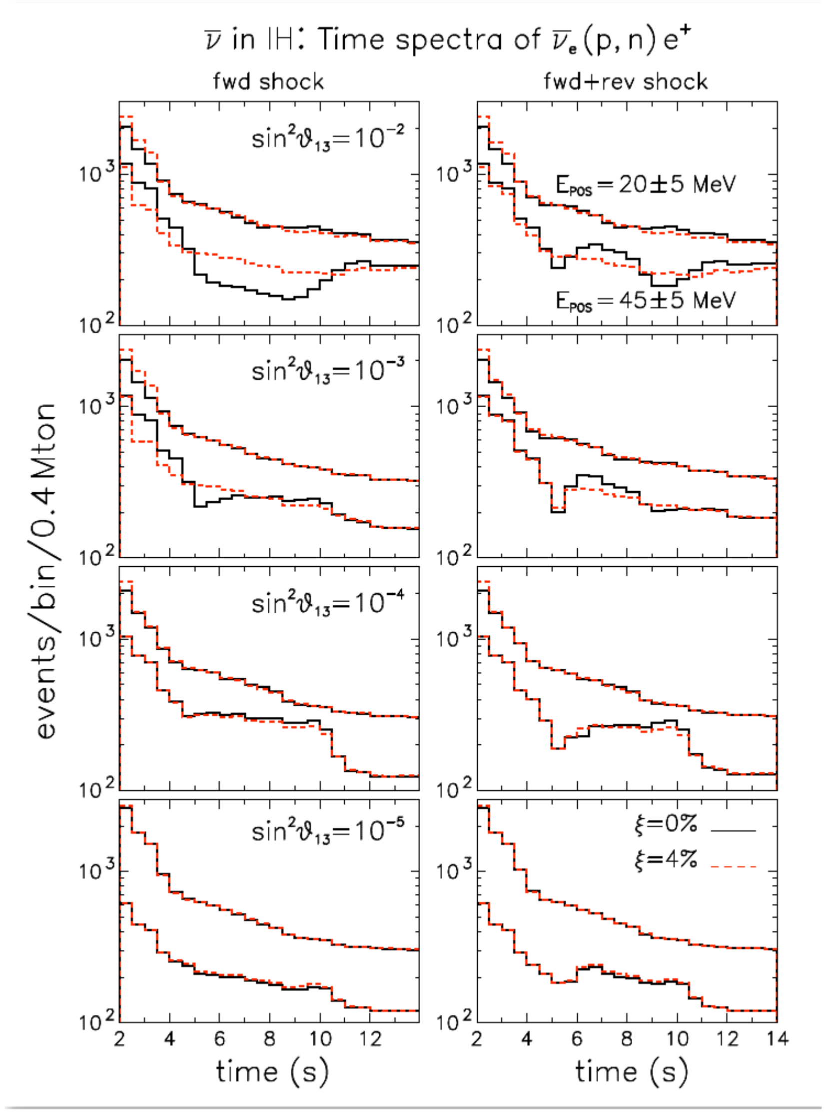
with

$$\Gamma(\xi) = \xi^2 L_0 \times \int_0^{r_{shock}} dy \; \overline{V}^2(y) \sin^2 2\tilde{\theta}_{13}(y)$$

where θ_{13} is the effective “1-3” mixing angle in matter

The effect of noise is thus to suppress the MSW effect into the stellar medium. In the limit of large fluctuations, one gets $P^{2\nu,H}_{ee} \rightarrow 1/2$, which corresponds to a sort of complete “flavor depolarization” for the effective ν states in the H subsystem.





Small-scale fluctuations with an amplitude ξ~ few % of the local density might potentially suppress shock-wave effects on ν time spectra for large values of θ_{13}. [*See also A. Friedland and A. Gruzinov, astro-ph/0607244*]

CONCLUSIONS

Future observations of SN neutrino burst might be an useful probe of neutrino flavor transitions and explosion mechanism:

- **The modulation in the survival probability caused by the passage of the shock wave can give us valuable information on the unknown oscillation parameters (mass hierarchy, θ_{13}) as well as on the internal structure of the exploding star.**

- **Small-scale fluctuations with an amplitude ξ~ few % of the local density might potentially suppress shock-wave effects on ν time spectra for large values of θ_{13}.**

- **A better theoretical understanding of stochastic density fluctuations behind the shock front would be of great benefit for future interpretation of SN neutrino events**