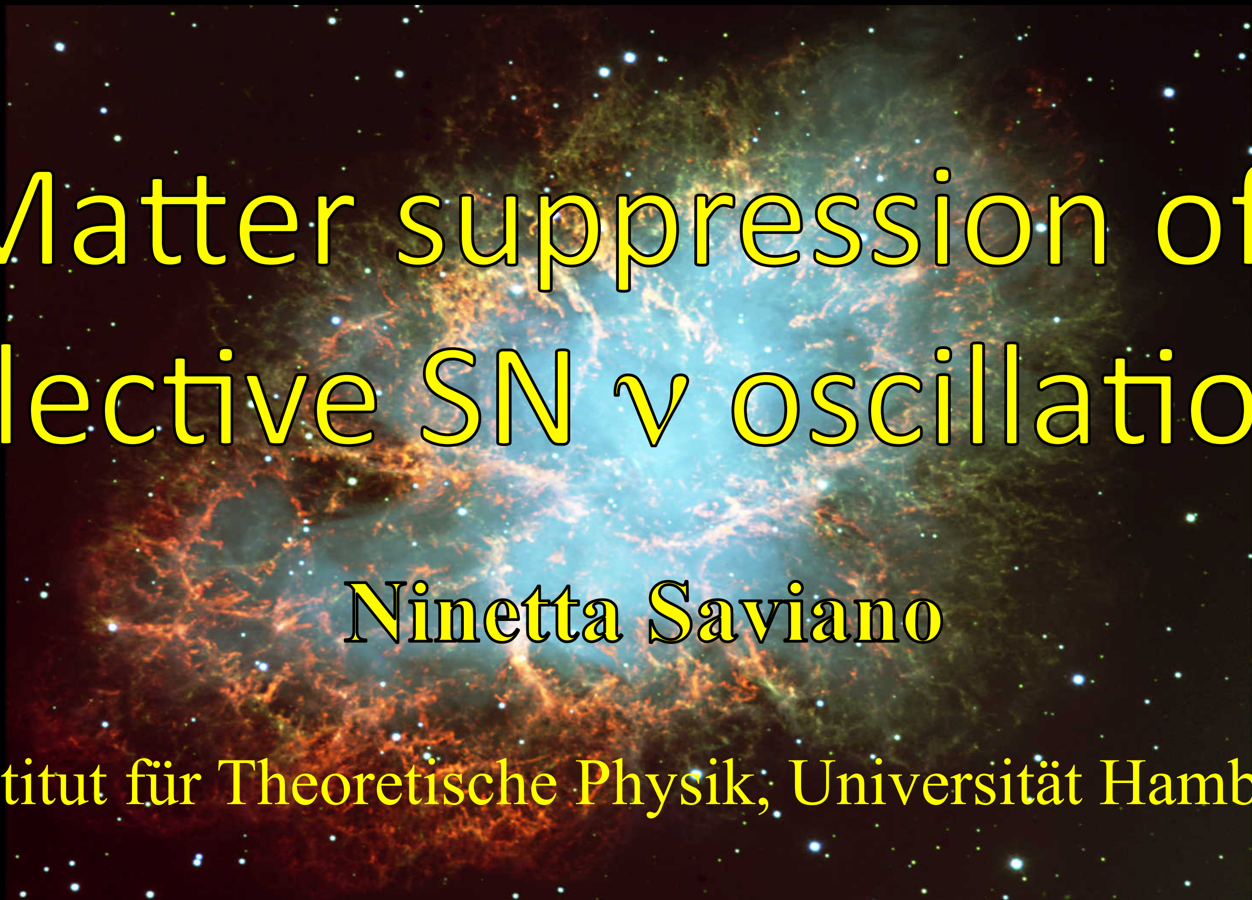
27 May - 1 June

24th Rencontres de Blois



Matter suppression of collective SN ν oscillations

Ninetta Saviano

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based on : Phys.Rev.Lett. 107 (2011) 151101, Phys.Rev. D84 (2011) 025002, arXiv:1203.1484 [hep-ph] (accepted Phys.Rev. D)

in collaboration with S.Chakraborty, T.Fischer, A.Mirizzi, R.Tomas

Supernova is one of the most energetic events in nature.

It is a terminal phase of a massive star ($M>8\div10M_{\odot}$)

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

- ✓ TIME SCALE: The duration of the burst lasts ~10 s
- ✓ EXPECTED RATE: 1-3 SN/century in our galaxy (d≈O(10) kpc).
- ✓ ENERGY SCALES: 99% of the released energy (~10^{53} erg) is emitted by neutrinos and antineutrinos of all flavors with energies O(10 MeV).

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The supernova is one of the most powerful ν source in the Universe → crucial tool to study flavor conversions and to get information about the mixing parameters.

SN ν Flavor Conversions

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

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

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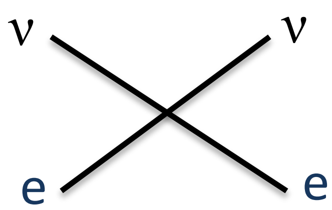
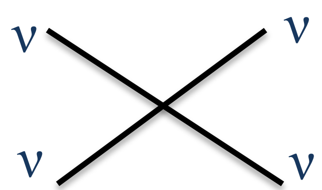
- H_e ~



→ MSW effect (ordinary background medium)

- $H_{\nu\nu}$ ~



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Off- diagonal terms — non-linearity

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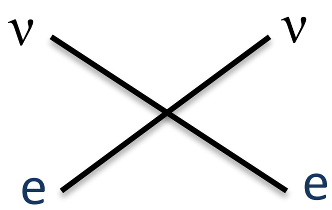
- H_e ~ 

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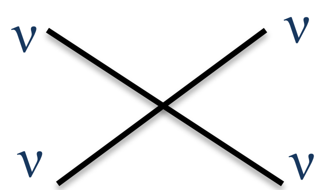
- $H_{\nu\nu}$ ~ 

→ ν background medium (Pantaleone 1992)

Off- diagonal terms — non-linearity

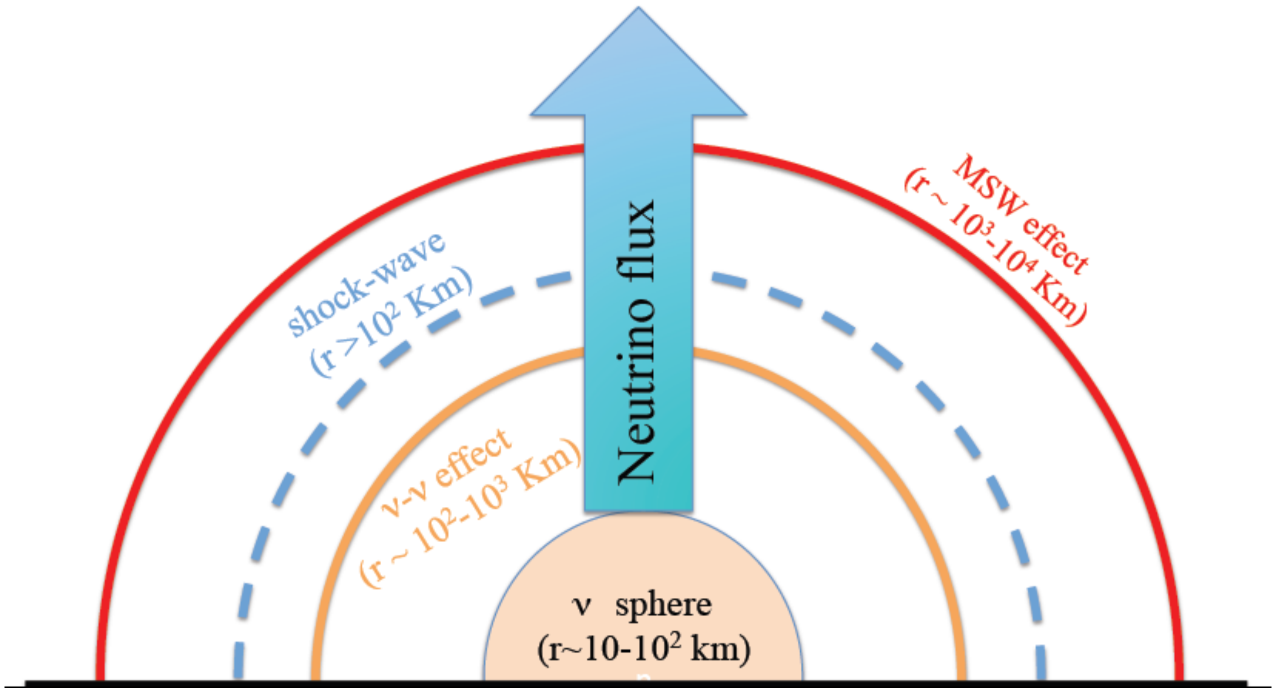
When $H_{\nu\nu} > H_e$ → ***large and rapid*** flavor conversions induced by ν-ν interactions.

They occur in a *coherent* fashion over the entire energy range ↔ ***"collective"***

[see Duan, Fuller and Qian arXiv:1001.2799 [hep-ph]]

Different Oscillation Regimes in SN

Collective oscillations occur between the ν sphere and the MSW region and can modify the neutrino spectra.



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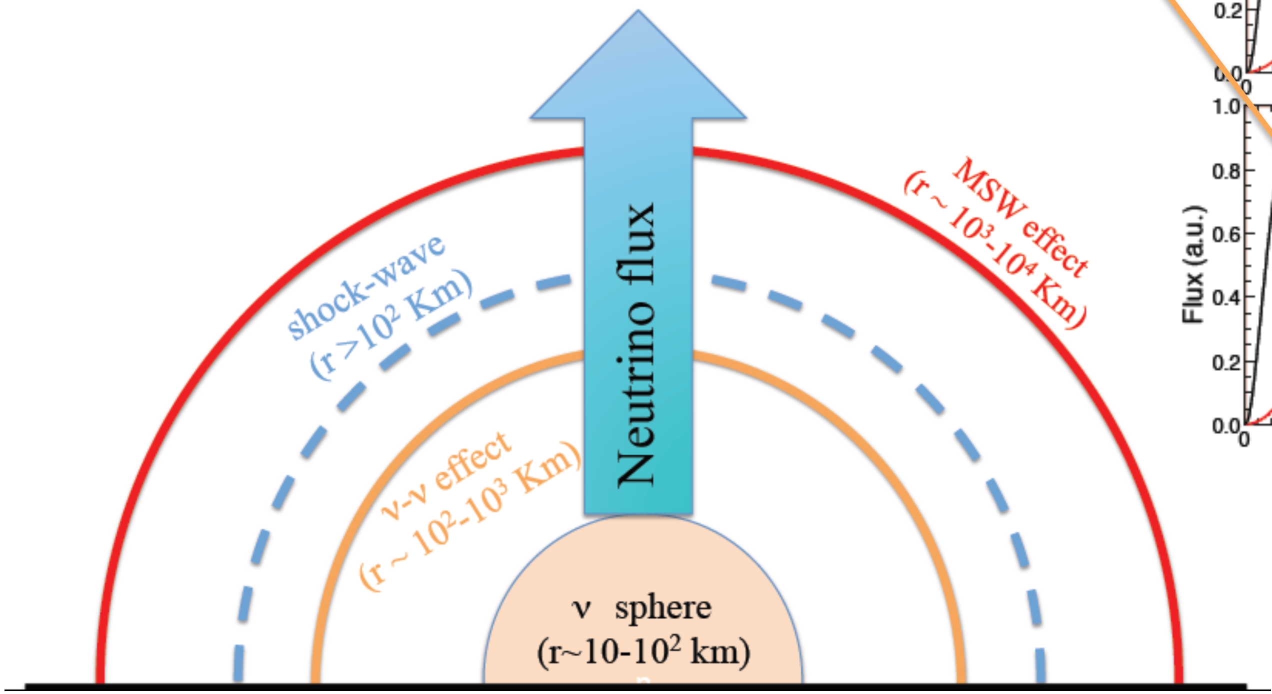
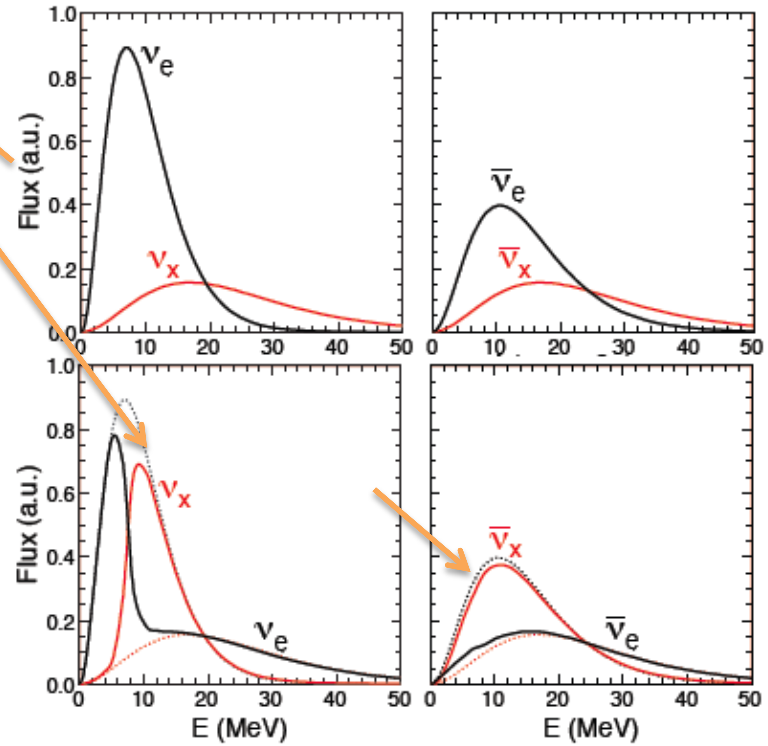
Most important observational consequence: **swap** of the ν_e and $\overline{\nu}_e$ spectra with non-electron ν_x and $\overline{\nu}_x$ spectra

[*Fogli et al., arXiv:0707.1998, 0808.0807 [hep-ph]*]





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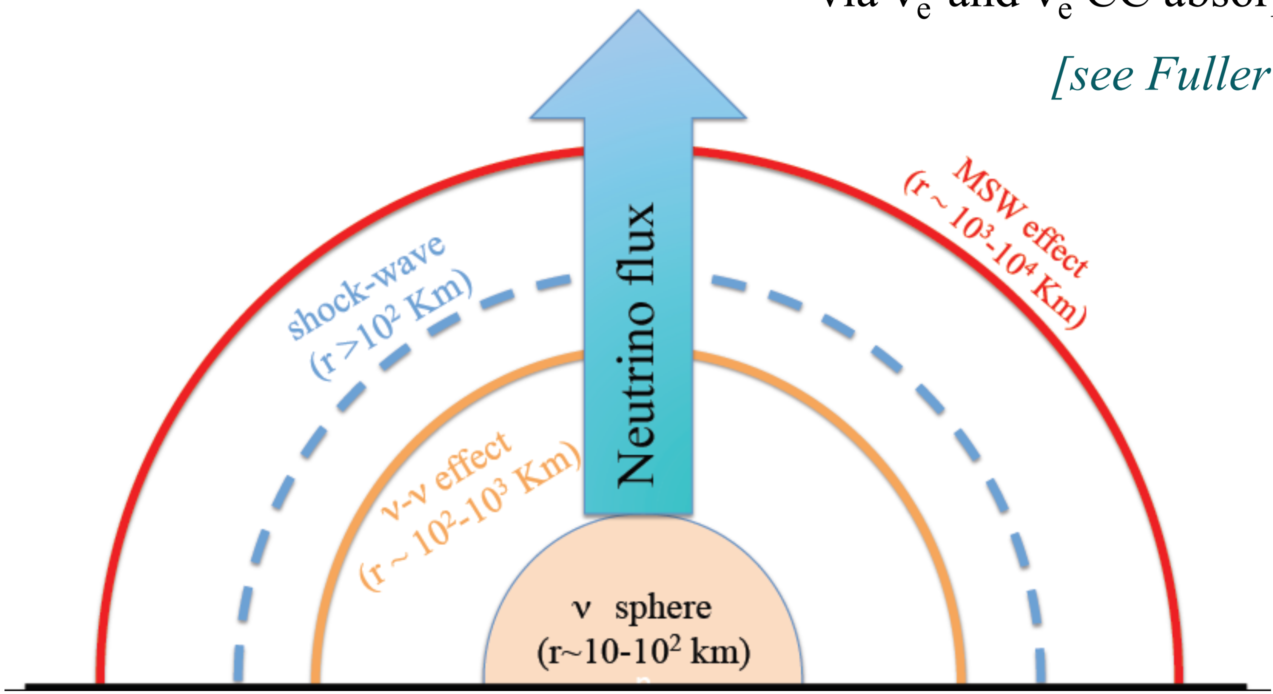

This swap in the region btw the ν sphere and the shock front would increase the heating rate behind the shock via ν_e and $\bar{\nu}_e$ CC absorptions, since $\langle E_x \rangle > \langle E_e \rangle$.

[see Fuller et al., ApJ 389, 517 (1992)]

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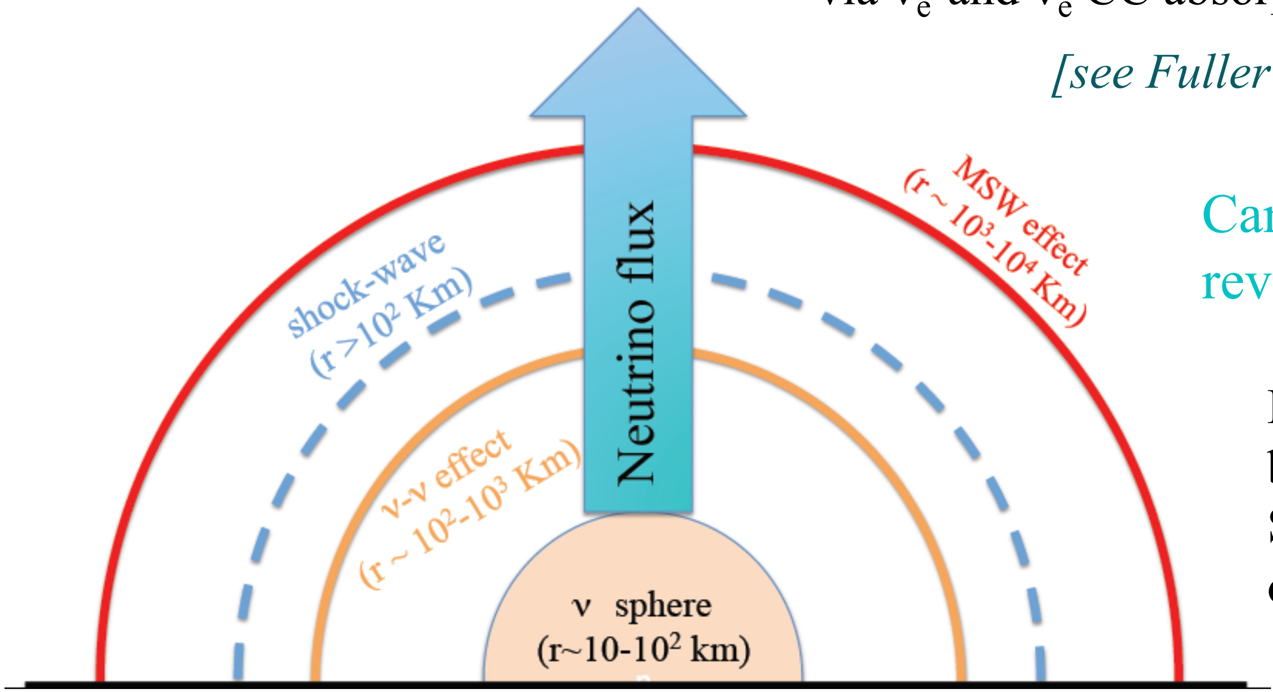

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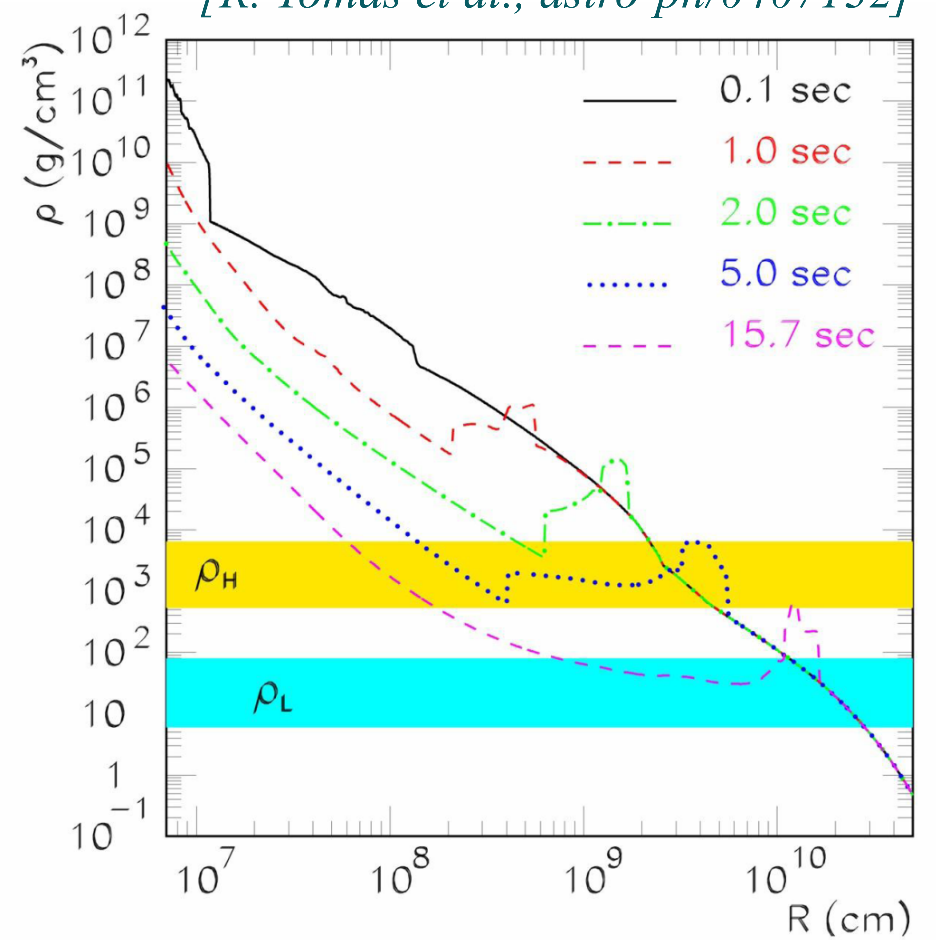
Can collective $\nu_e \bar{\nu}_e \rightarrow \nu_x \bar{\nu}_x$ revitalize the shock wave?

Putting manually a spectral swap before the shock front, strong SN explosions have been obtained for no exploding models

[see Suwa et al., arXiv:1106.5487]

Snap-Shots of SN Density Profile

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



- Matter bkg potential

$$\lambda = \sqrt{2} G_F N_e \quad \sim r^{-3}$$

- ν−ν interaction

$$\mu = \sqrt{2} G_F n_\nu \quad \sim r^{-2}$$

- Vacuum oscillation frequencies

$$\omega = \frac{\Delta m^2}{2E}$$

When **μ>>λ**, SN ν oscillations dominated by ν-ν interactions

➡ Collective flavor transitions at low-radii [*O* ($10^2 - 10^3$ km)]

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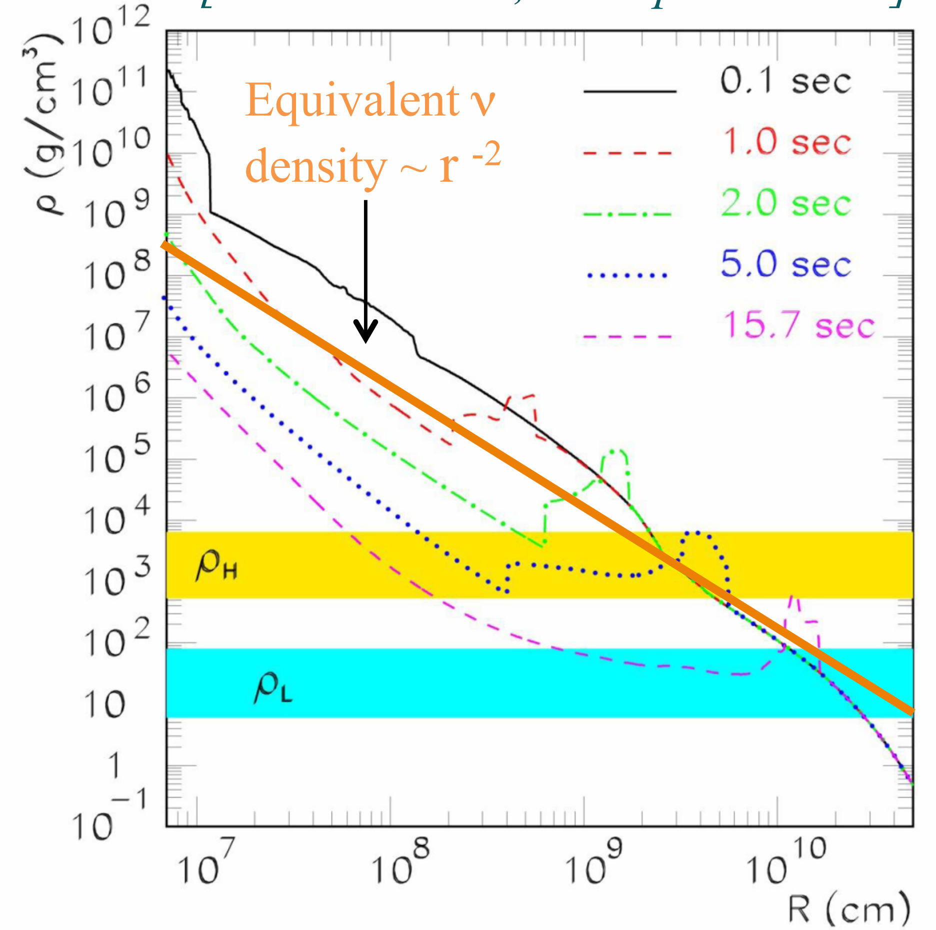

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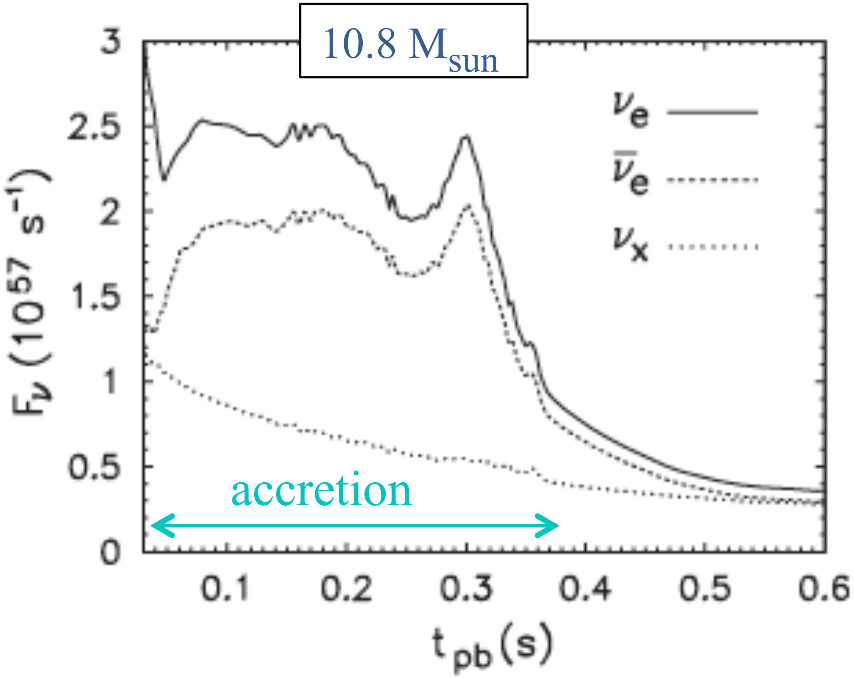
Oscillations during the Accretion Phase

The ***accretion phase*** is the early stage ($t < 0.5$ s) of the SN explosion

New long-term SN simulations [*Fischer et al. (Basel group), arXiv:0908.1871*]



Large ν fluxes with distinct flavor hierarchy

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

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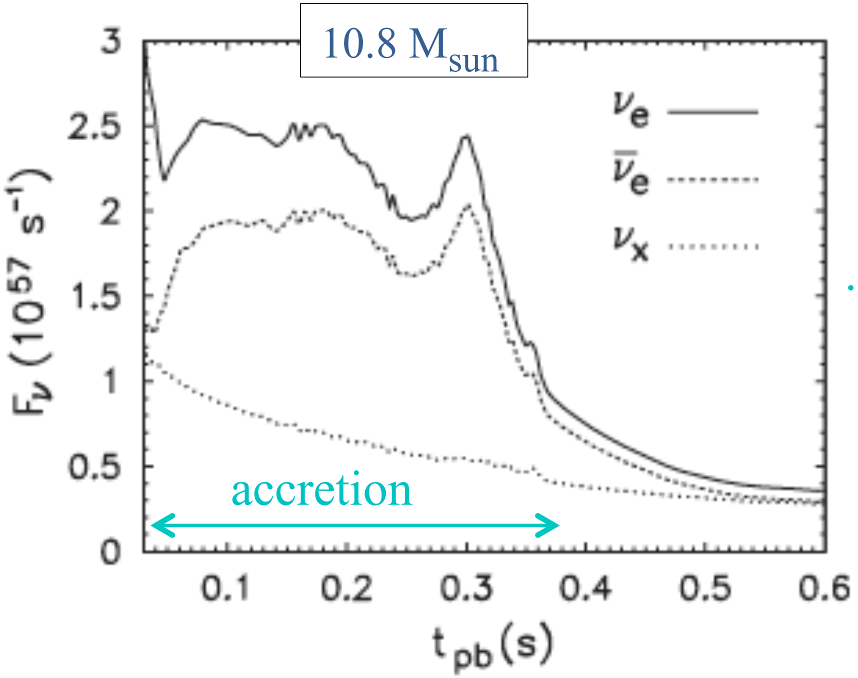

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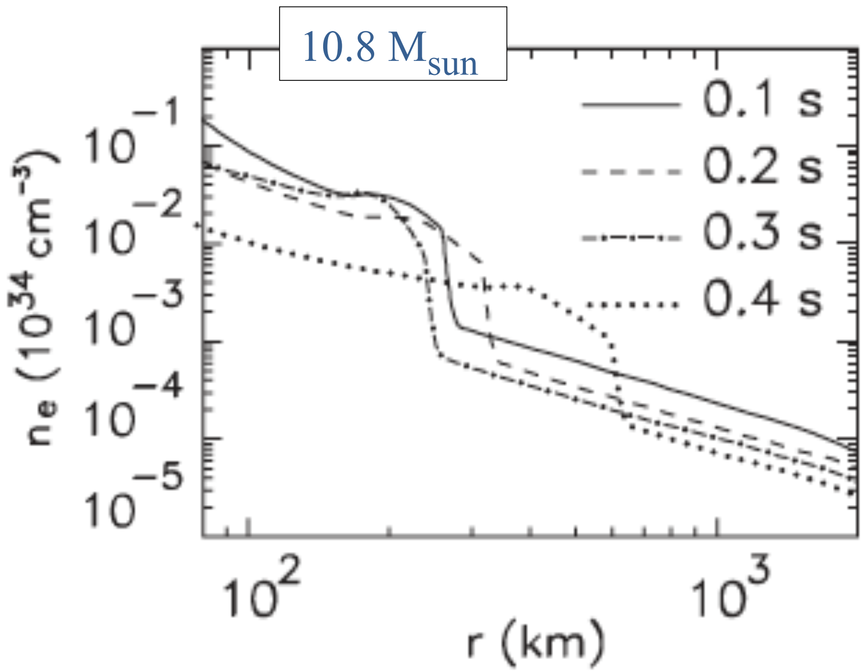

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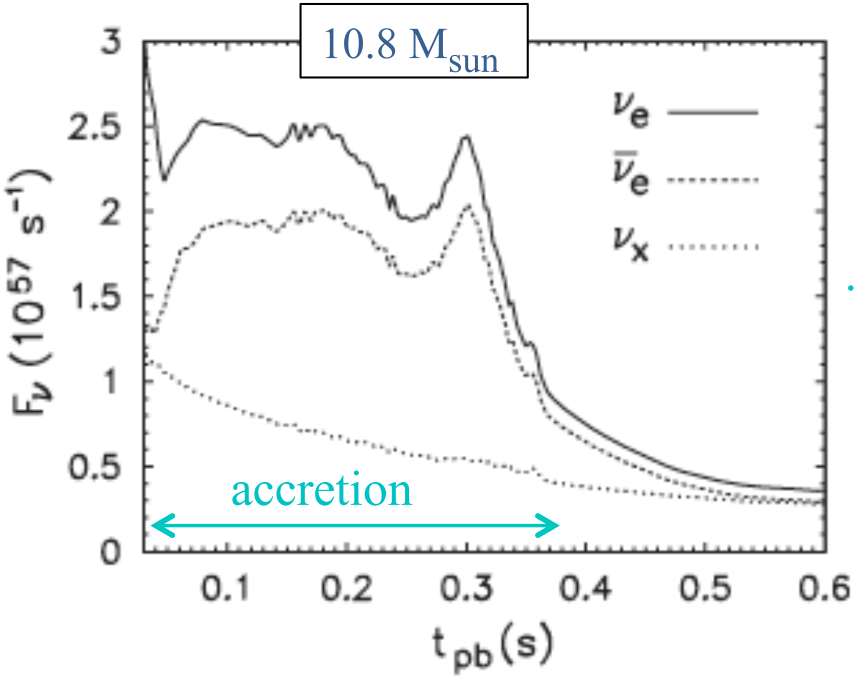

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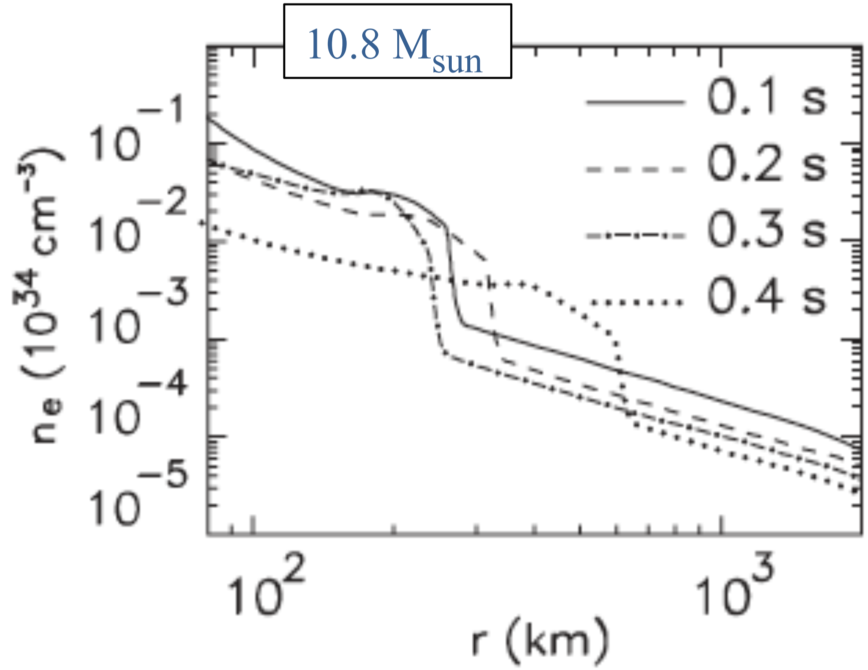

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Neutrinos VS Matter

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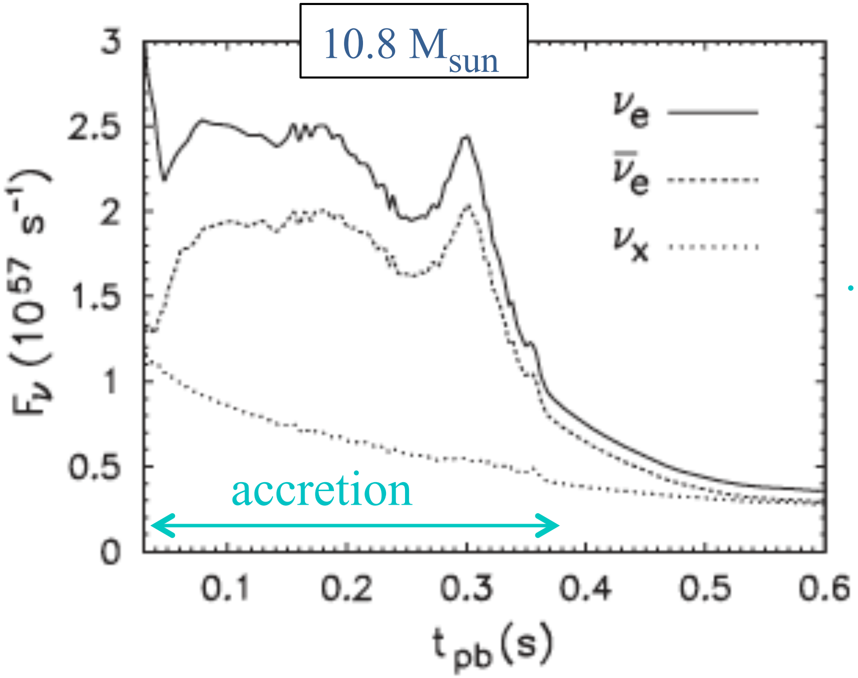

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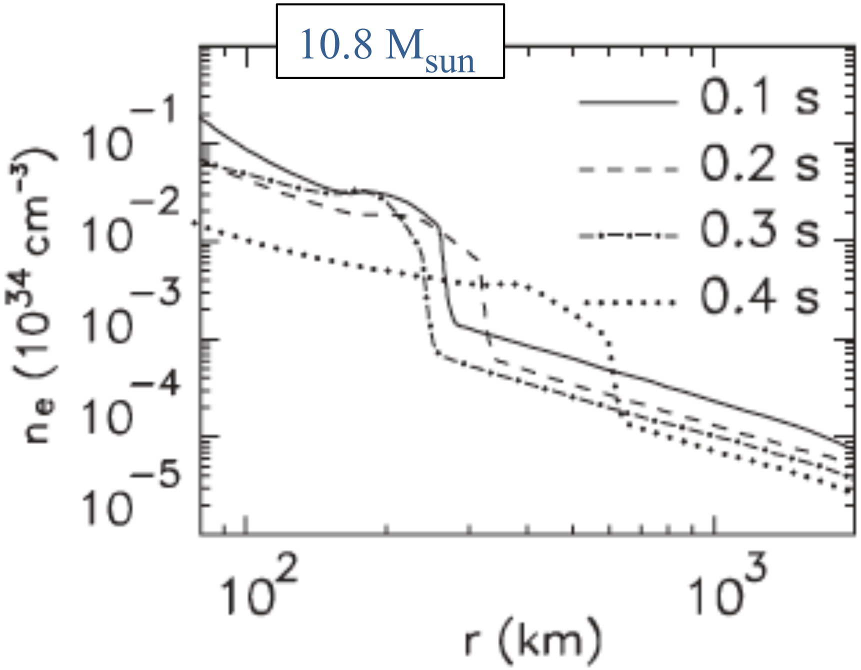

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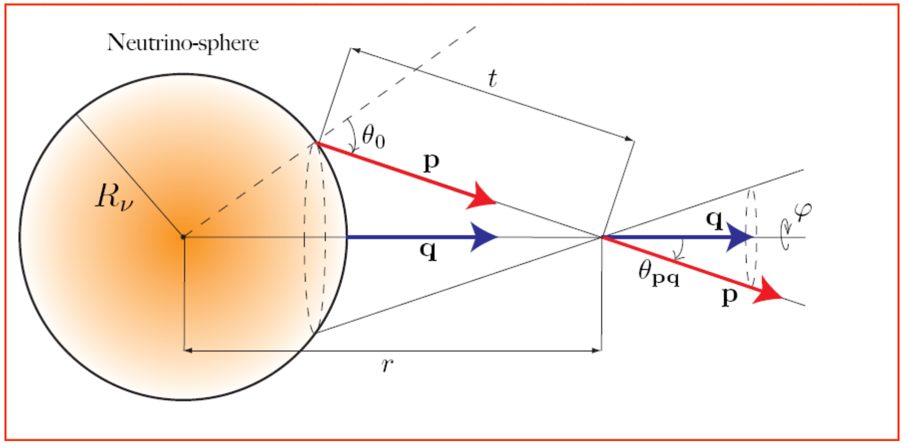
WHAT HAPPENS THEN?

Matter Induced Multi-Angle Effects

✓ Spherical stream

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



- νs emitted from a spherical source acquire different phases at a given radius r.
- Matter effect is not the same for all the modes.
- It would introduce trajectory-dependent multi-angle effects.

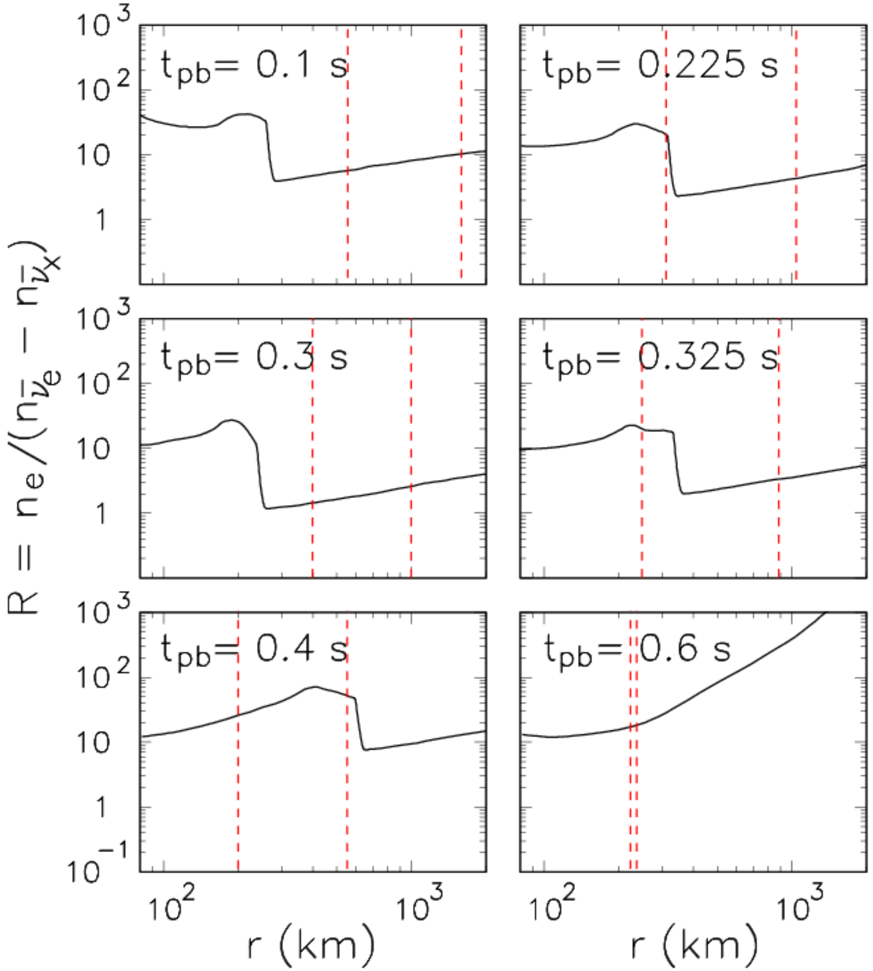
Matter effect can suppress collective conversions unless Ne ≥ Nν

✓ Our model

- monoenergetic ν ensemble
- multi-angle" ν emission [O (10^3) modes]
- "half-isotropic" ν emission (outward-moving angular modes equally occupied)

Matter Suppression of the Collective Oscillations

[*Chakraborthy, Fischer, Mirizzi,* N.S.*& Tomas, arXiv:1105.1130, 1104.4031 [hep-ph]]*



$$R = \frac{n_e}{n_\nu} > 1$$ → Matter effects cannot be neglected

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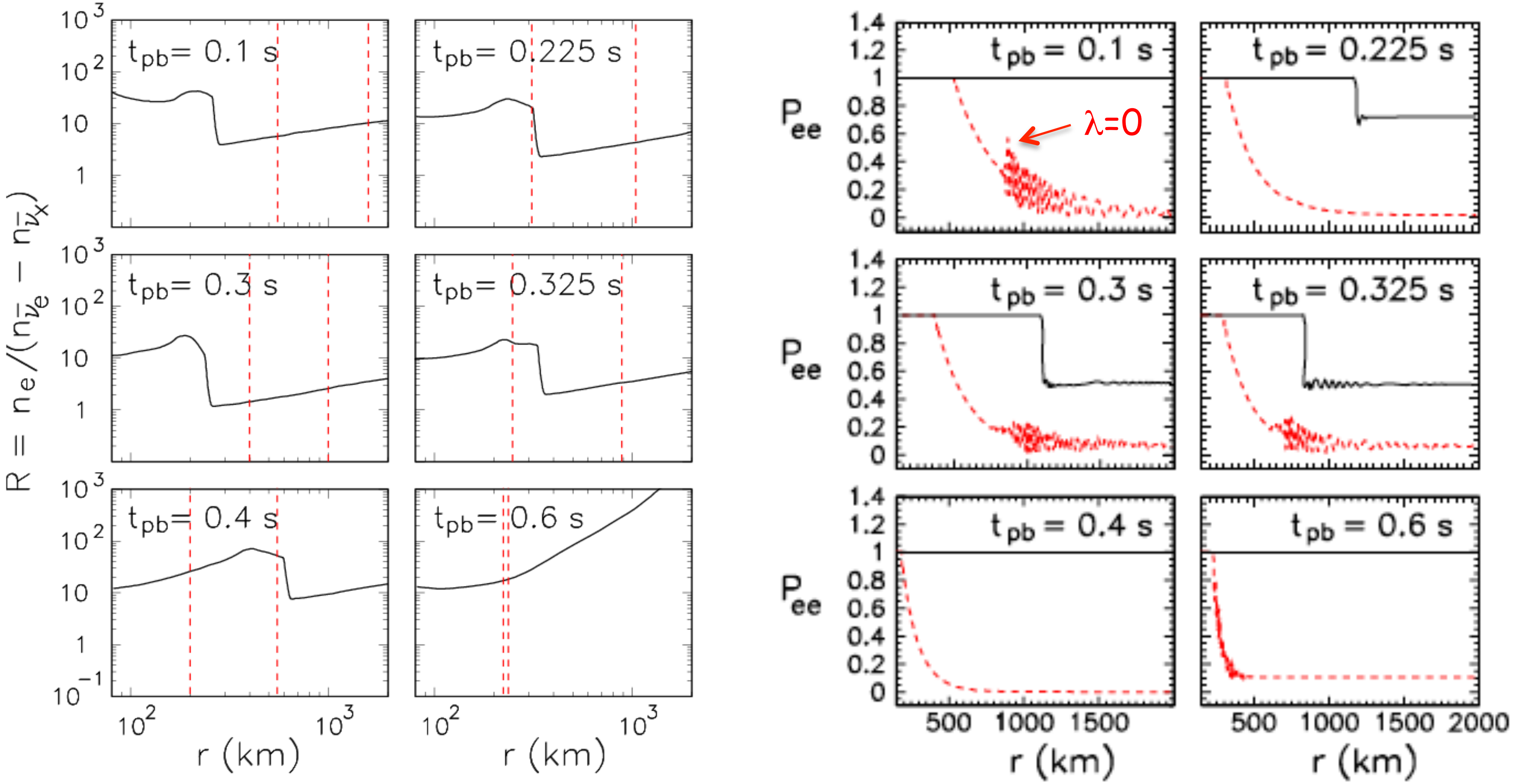


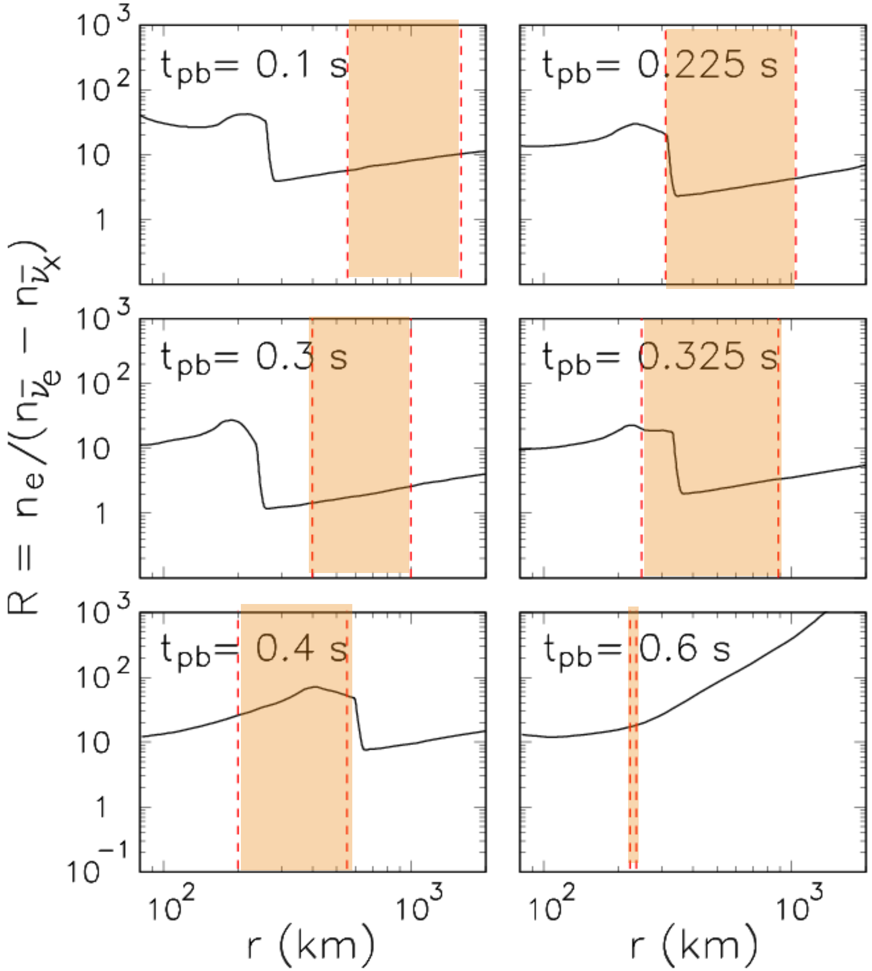
R>>1 → complete suppression (P_{ee} = 1)

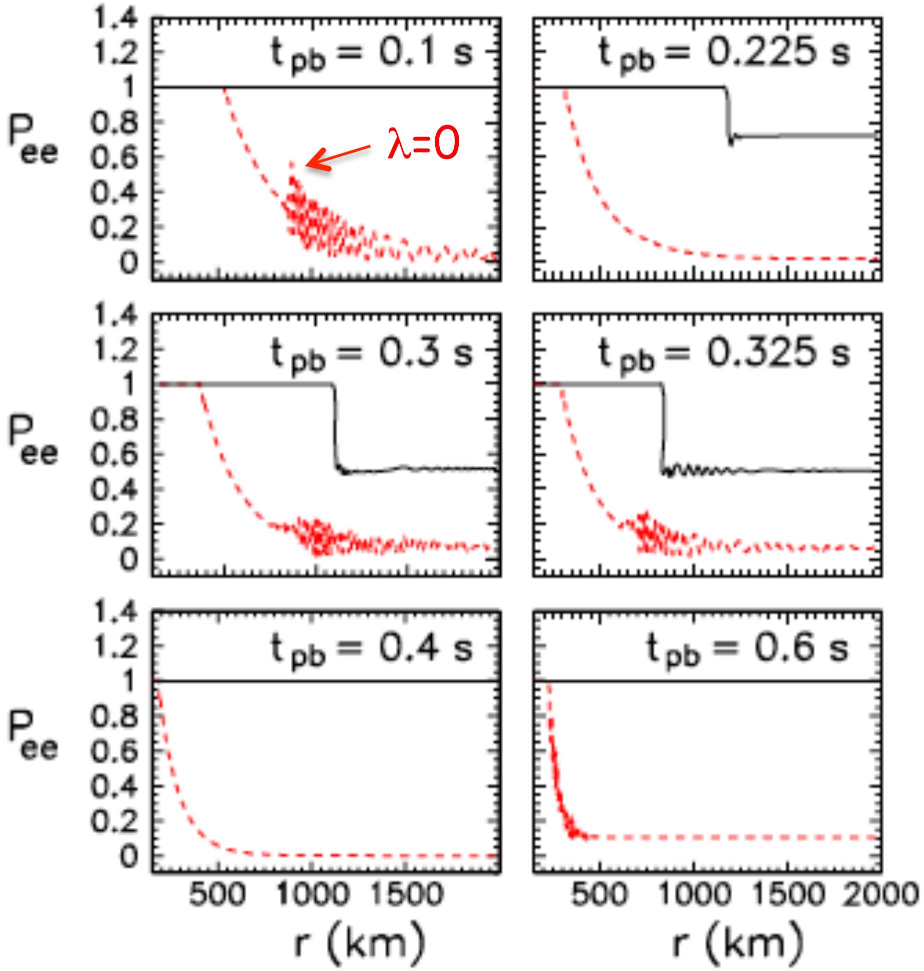
R ~ 1 → decoherence (P_{ee} = 1/2)

Matter Suppression of the Collective Oscillations

[Chakraborthy, Fischer, Mirizzi, N.S.& Tomas, arXiv:1105.1130, 1104.4031 [hep-ph]]

= collective range (λ=0)





Matter suppression implies no oscillation effect on shock-reheating.

Note: already for λ= 0 the oscillation range at t < 0.3 s would be at $r > r_{shock}$

Oscillations via Stability Analysis

[Banerjee, Dighe, Raffelt,1107.2308 [hep-ph]]

$$\mathrm{i}\partial_r \Phi_{E,u} = [H_{E,u}, \Phi_{E,u}]$$

$$H_{E,u} = \frac{1}{v_u}\left(\frac{M^2}{2E} + \sqrt{2}G_F N_l\right) + \frac{\sqrt{2}G_F}{4\pi r^2}\int_{-\infty}^{+\infty} dE' \int_0^1 du' \left(\frac{1 - v_u v_{u'}}{v_u v_{u'}}\right)\Phi_{E',u'}$$

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$$\Phi_{\omega,u} = \frac{\mathrm{Tr}\Phi_{\omega,u}}{2} + \frac{g_{\omega,u}}{2}\begin{pmatrix} s_{\omega,u} & S_{\omega,u} \\ S^*_{\omega,u} & -s_{\omega,u} \end{pmatrix}$$

Swap matrix

small-amplitude limit:

$s_{\omega,u}=1$ and $S_{\omega,u} << 1$

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$$i\partial_r S_{\omega,u} = [\omega + u(\lambda + \epsilon\mu)]S_{\omega,u} - \mu \int du' d\omega' (u + u') g_{\omega',u'} S_{\omega',u'}$$

Linearized evolution equations for $S_{\omega,\, u}$

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→ Linearized evolution equations for $S_{\omega,u}$

- Look for solutions of the form $S_{\omega,u} = Q_{\omega,u} e^{-i\Omega r}$
- A complex solution $\Omega = \gamma + i\,k$, with $k > 0$ indicates an exponentially increasing $S_{\omega,u}$

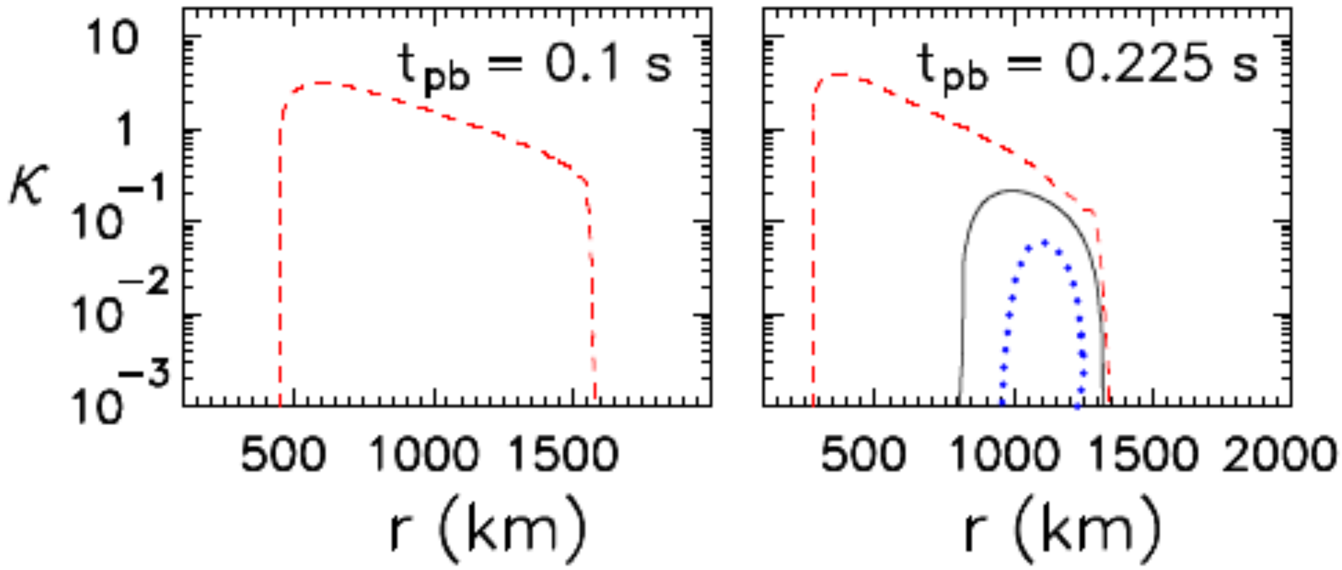
⟶ **Instability**

The stability analysis determines only if flavor conversions occur or not, i.e. the ***onset*** of conversions

Stability Analysis Results

✓ multi-energy distribution

[N.S., Chakraborthy, Fischer, Mirizzi arXiv:1203.1484 [hep-ph]]



10.8 M_{sun}

$\lambda = 0$, half-isotropic

$\lambda \neq 0$, half-isotropic

$\lambda \neq 0$, angular distribution

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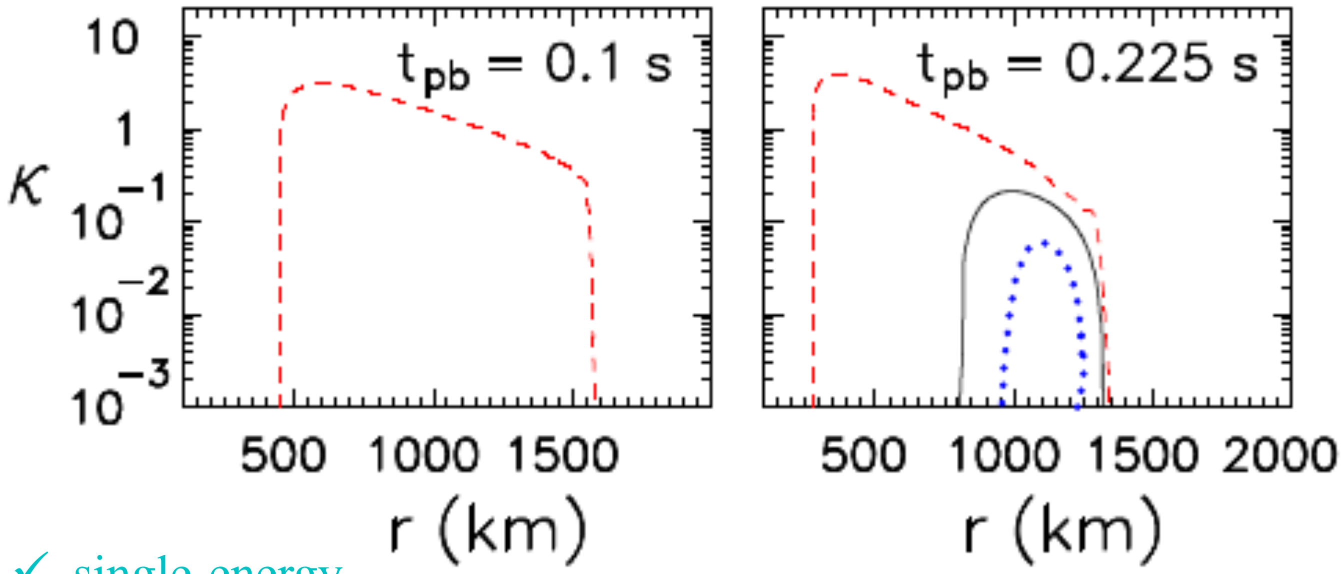

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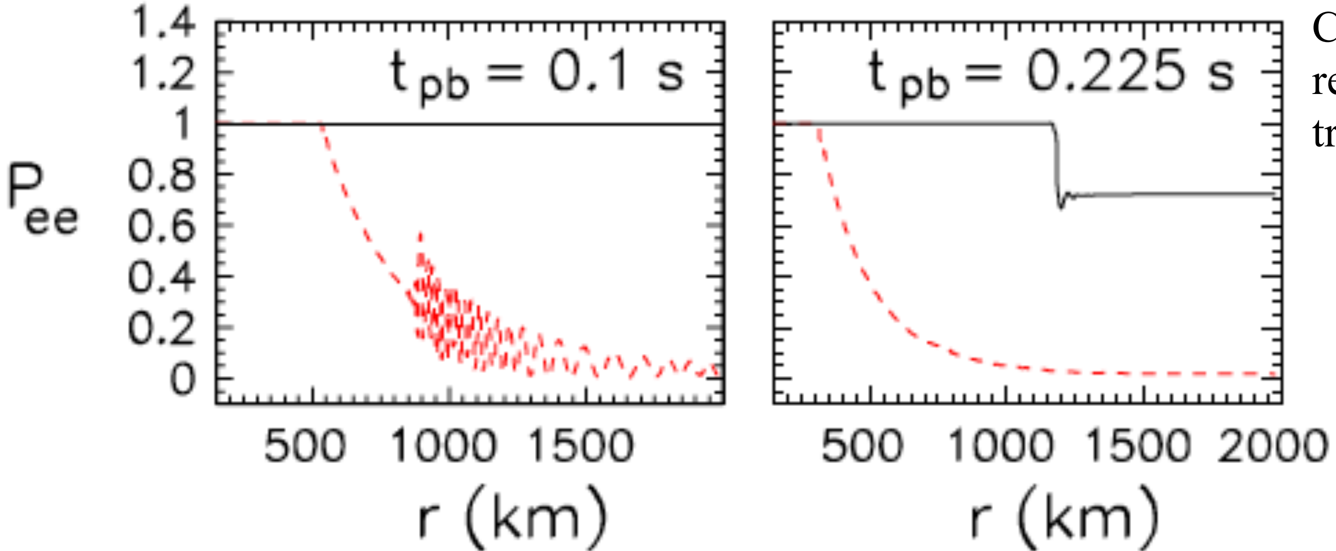
✓ single-energy



Comparison with our previous results with full numerical treatment of EoM

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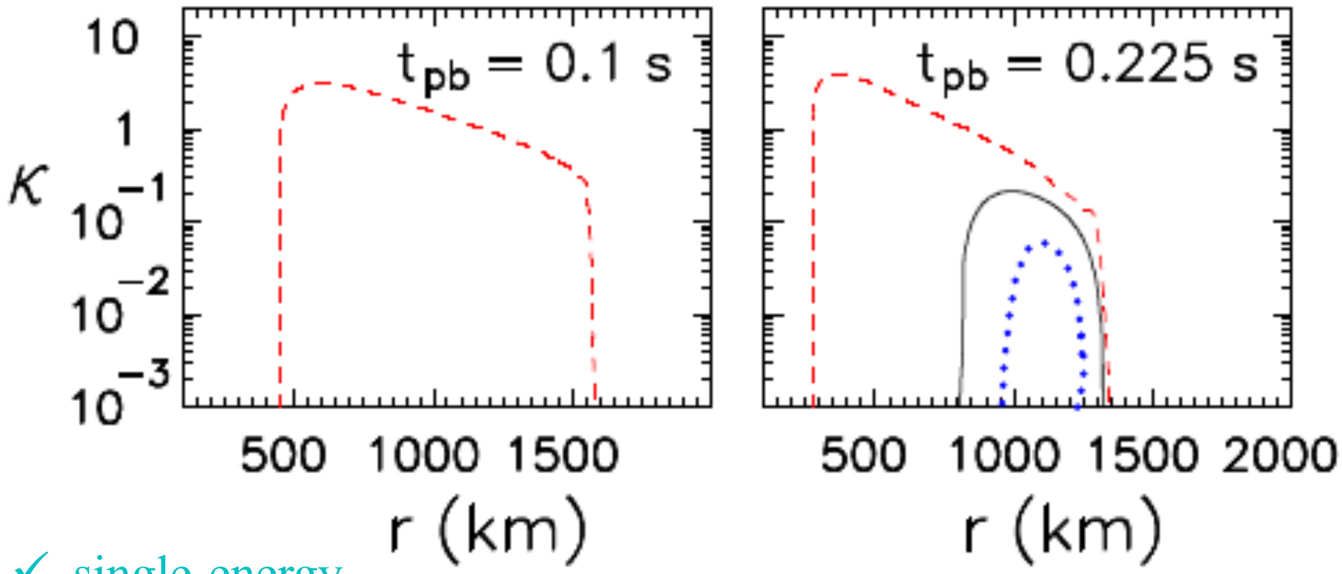

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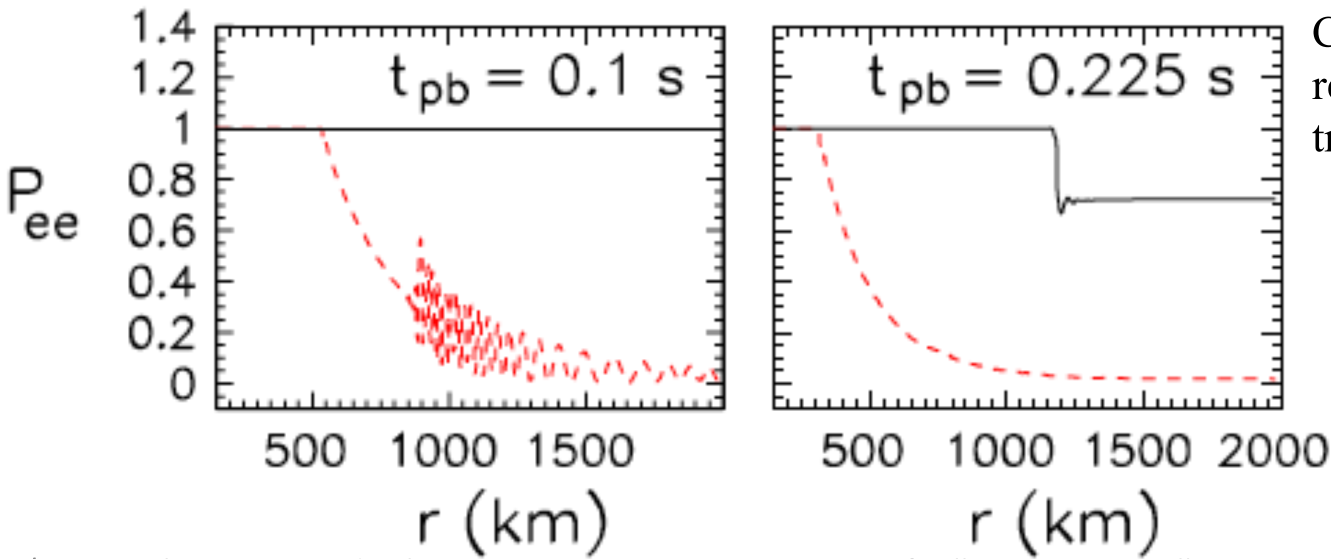

Comparison with our previous results with full numerical treatment of EoM

agreement with the onset of the oscillations
(also in the case of multi-energy distribution)

Stability Analysis Results

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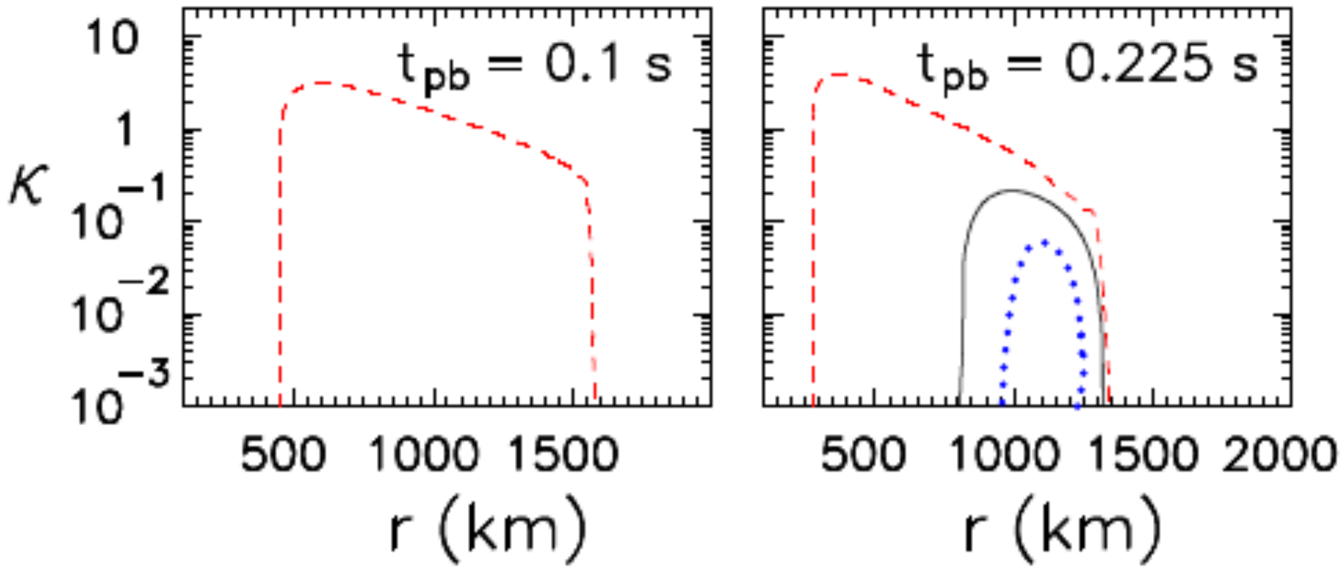
[N.S., Chakraborthy, Fischer, Mirizzi arXiv:1203.1484 [hep-ph]]



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$\lambda \neq 0$, angular distribution

The stability analysis confirms the collective suppression induced by the multi-angle matter effect.

Similar results found with Garching models in [Sarikas et al. arXiv:1109.3601 [astro-ph.SR]]

Conclusions

The perspectives for the detection of signatures of self-induced flavor conversions in SNe change once more.

✓ Multi-angle effects associated to the dense matter do suppress collective ν oscillations during the accretion phase.

- Full numerical treatment of the non linear EoMs.
- stability analysis of linearized EoMs.

✗ No impact of ν flavor conversions on the SN shock revival.

✓ Possibility to probe the neutrino mass hierarchy at large θ_{13} with ordinary matter effects


Thank you

back up slide

SN Explosion Mechanism

Equilibrium between gravitational force and thermal pressure kept by several nuclear burning stage

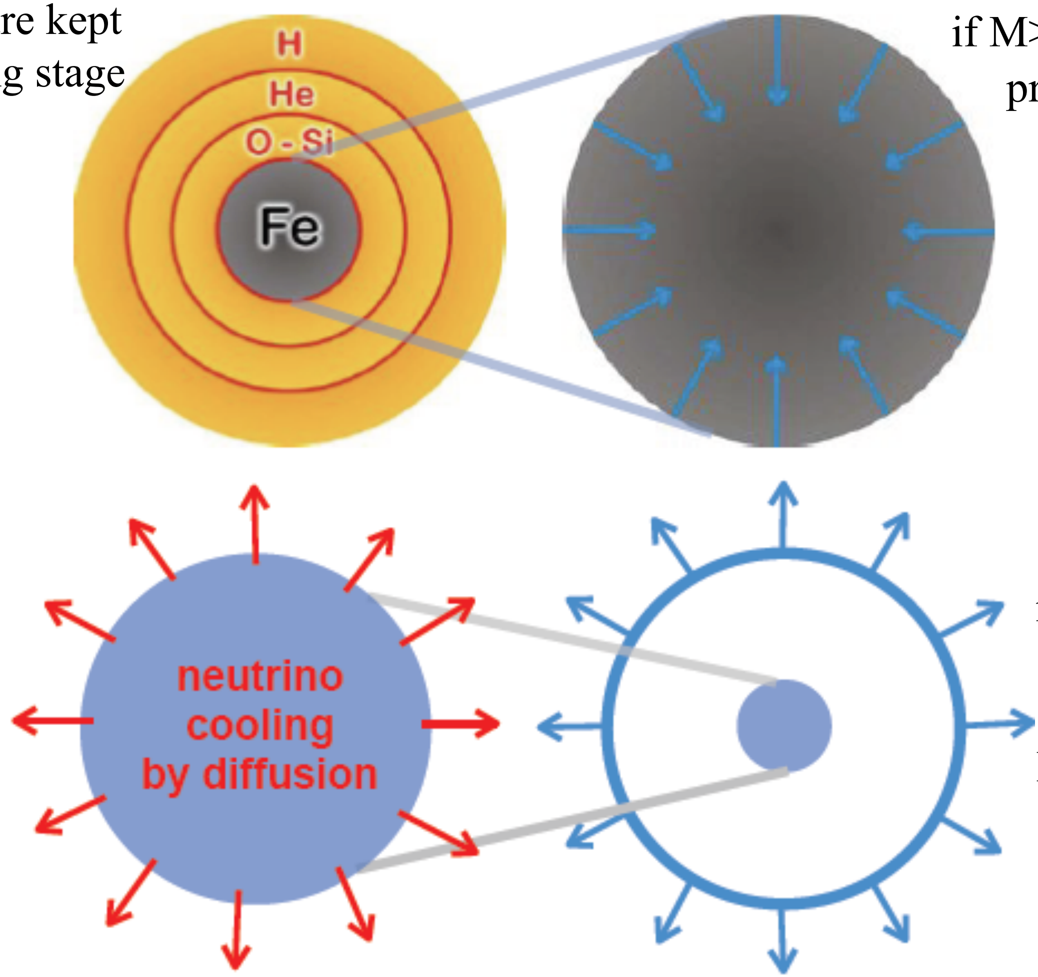
↓

Onion structure until one reaches the Fe

The fate of the star is marked if M> $M_{Ch.}$. The gravitational pressure is not compensated anymore

↓

Implosion and collapse



nuclear matter density is reached→rise in pression.

Inner core incompressible
→ reboundes
→ Shock wave

Explosion

Proto- Neutron star

3) Cooling

2) Accretion

1)Neutronization burst

Effective mixing Hamiltonian

$$H = \frac{M^2}{2E} + \sqrt{2}G_F \begin{pmatrix} N_e - \frac{N_n}{2} & 0 \\ 0 & -\frac{N_n}{2} \end{pmatrix} + \sqrt{2}G_F \begin{pmatrix} N_{\nu e} & N_{\langle \nu e|\nu\mu \rangle} \\ N_{\langle \nu\mu|\nu e \rangle} & N_{\nu\mu} \end{pmatrix}$$

Mass term in flavor basis: vacuum oscillations

Wolfenstein's weak potential: MSW "resonant" conversion together with vacuum term

Flavor-off-diagonal potential, caused by flavor oscillations. (J.Pantaleone,)

Writing in terms of the density matrix ρ in flavor space: $(\varrho_{\mathbf{p}})_{ij} = \langle a_i^\dagger a_j \rangle_{\mathbf{p}}$

(generalized occupation number)

$$\mathsf{H}_{\mathbf{p}} = \Omega_{\mathbf{p}} + \mathsf{V} + \sqrt{2}\,G_{\rm F} \int \frac{{\rm d}^3\mathbf{q}}{(2\pi)^3} \left(\varrho_{\mathbf{q}} - \bar\varrho_{\mathbf{q}}\right) \left(1 - \mathbf{v}_{\mathbf{q}} \cdot \mathbf{v}_{\mathbf{p}}\right)$$

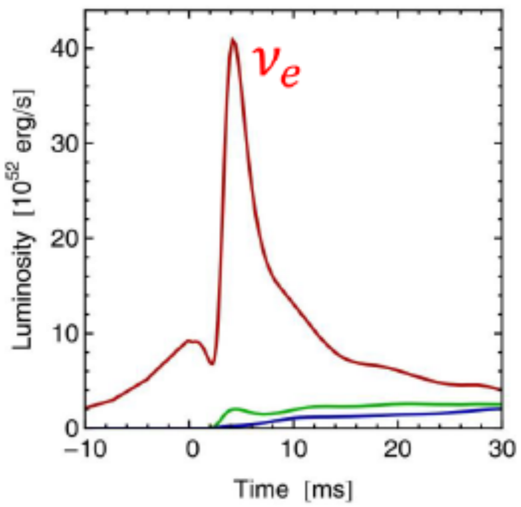
$$\mathbf{v}_{\mathbf{p}} = \mathbf{p}/p$$

$$= (1 - \cos\theta_{\mathbf{pq}})$$

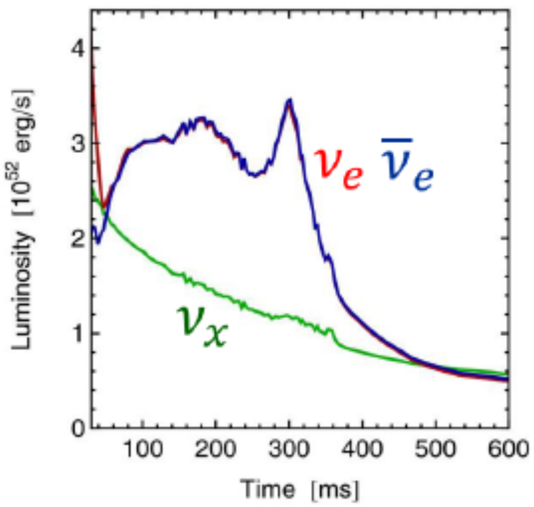
Current-current nature of weak interaction

Characteristic of Neutrino Signal

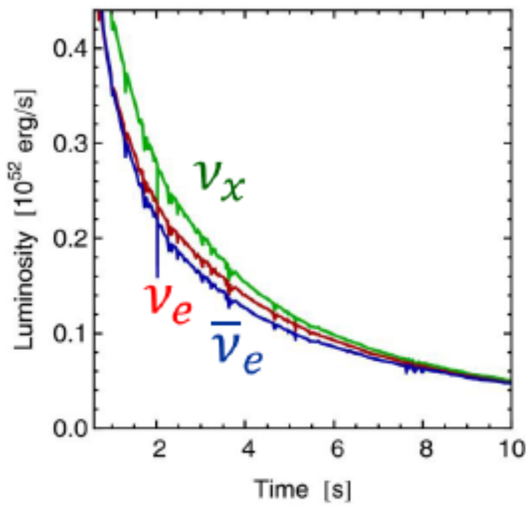
Prompt ν_e burst



Accretion



Cooling



De-leptonization burst
(large ν_e luminosity peak)
$(e^- + p \rightarrow n + \nu_e)$

Nuclei dissociation and
ν emission → energy loss
in the shock wave
→ it stalls

The signal is independent on the
SN mass. Could be adopted
as standard candles

large fluxes and significant
flux differences

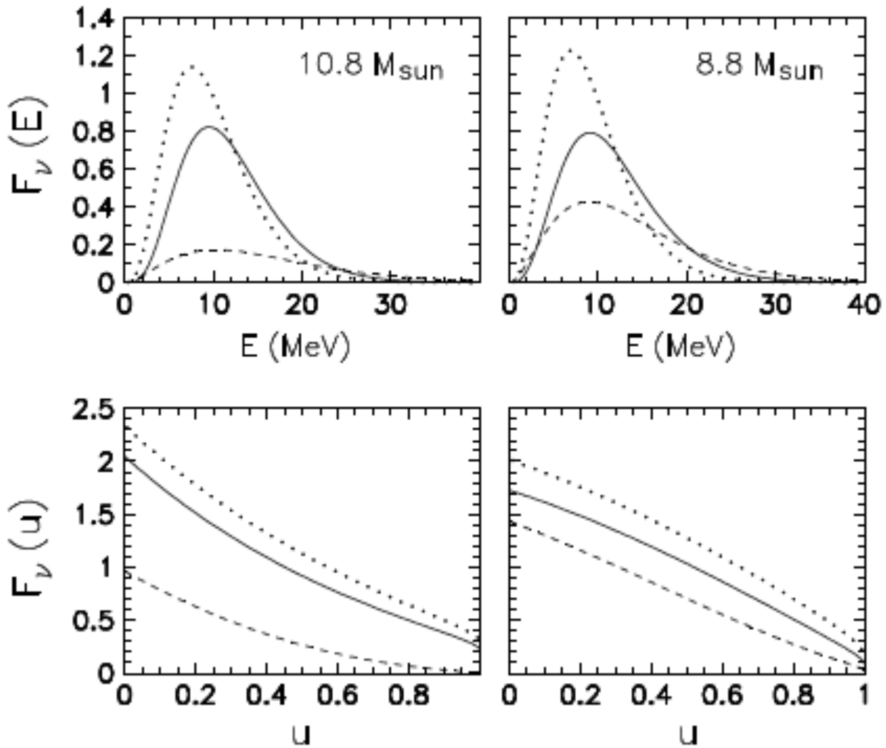
$$\begin{pmatrix} e^+ + n \rightarrow \bar{\nu}_e + p \\ e^+ + e^- \rightarrow \nu + \bar{\nu} \end{pmatrix}$$

small fluxes and small
flux differences

Neutron rich → suppresion
CC reactions for anti ν_e

The part not ejected
evolve to a cold neutro star

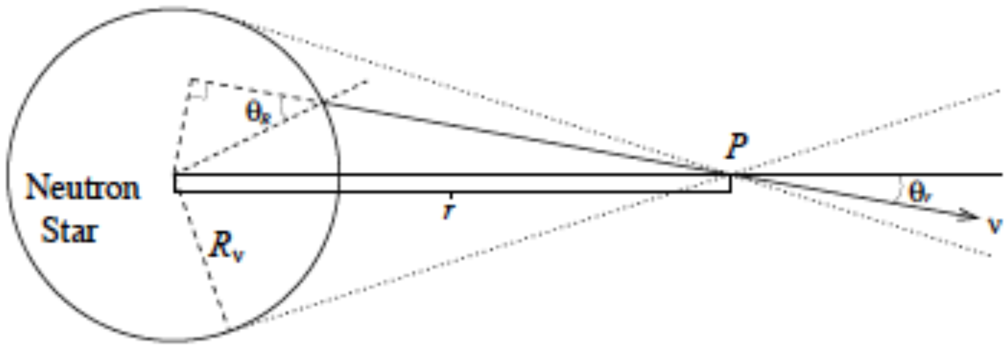
Realistic Energy and Angular Distribution



ν_x spectra less suppressed, since in low-mass core the duration of the accretion is very short

Angular spectra significantly forward enhanced (peaked at small u)

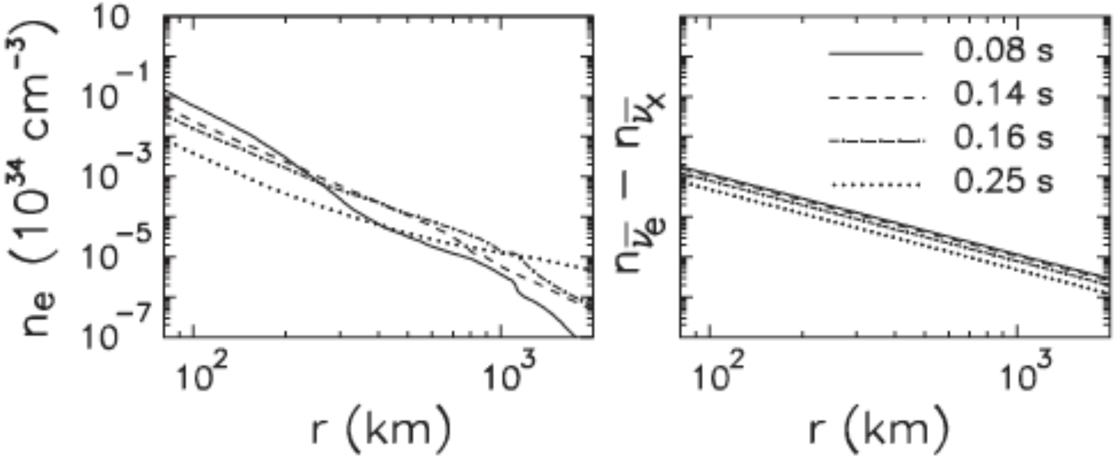
Angular spectra for e-specie less forward enhanced and less pronounced difference between the flavors.
Also this effect is due to the dominant role of NC processes



$$u = \sin^2 \vartheta_R$$ → to label the different angular modes

- u=0 → radial modes
- u=1 → tangential modes

8.8 Msun Progenitor Mass (O-Ne-Mg core)



- The matter density of the envelope is very low compared to the iron-core, → the n_e density is very steep declining faster than the neutrino density.

- Also the neutrino densities are smaller than in the iron-core case

→ Absence of an extended accretion phase for this low- mass star

Time evolution of the neutrino oscillation probability during the accretion phase is significantly different

Matter suppression effect much reduced

Possible distinction of a O-Ne-Mg core SN from iron-core one, in a detection of a future galactic event.