Neutrino oscillations in core-collapse supernovae, nucleosynthesis, and the neutrino signals

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INT Program : Nucleosynthesis and Chemical Evolution
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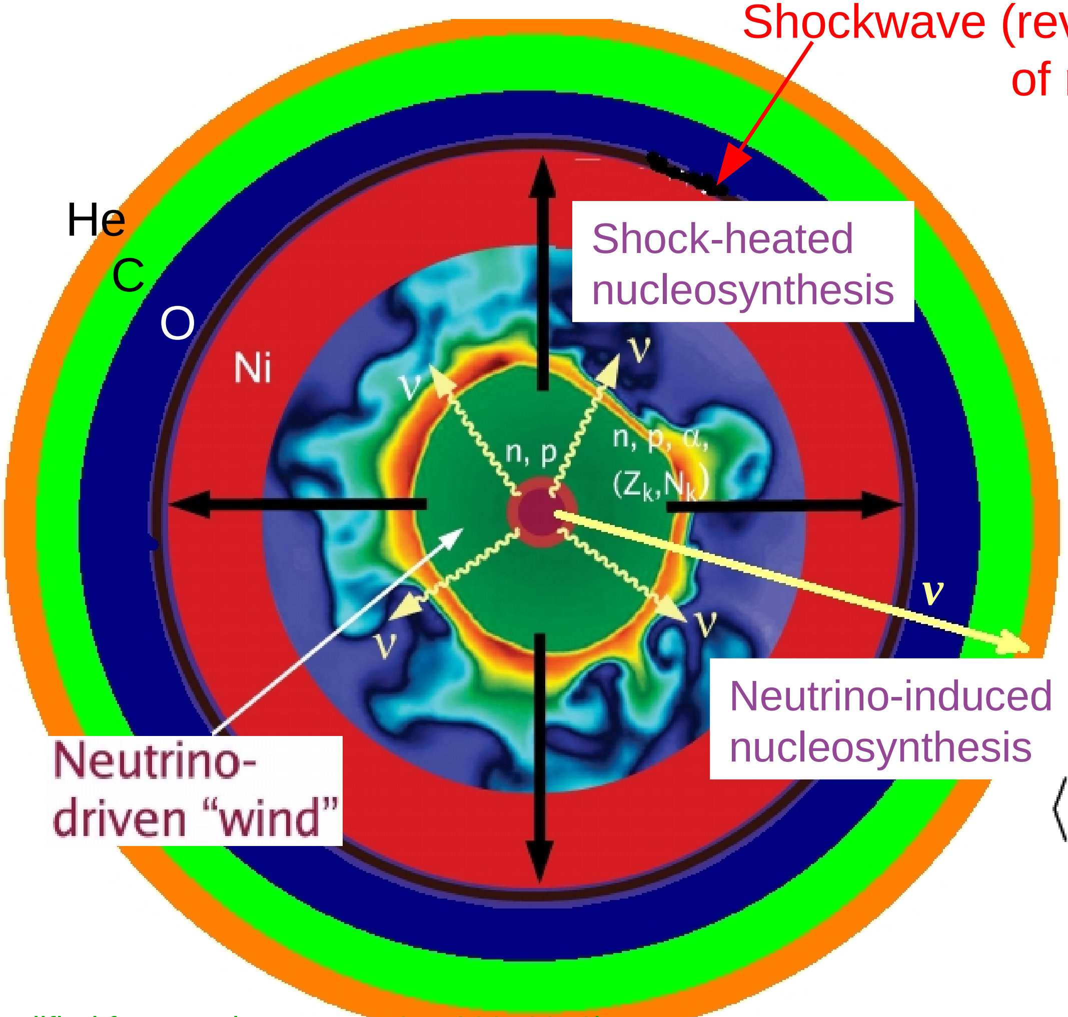
Neutrinos in core-collapse supernovae

Energy source : gravity

$$E_G \approx \frac{3GM_{NS}^2}{5\,R_{NS}} \approx 3\times10^{53}\,ergs\,!$$

carried away by ~10^{58} neutrinos of all flavors in a time scale of 10 seconds.

Shockwave (revived mainly by the energy deposition of neutrino-heating)

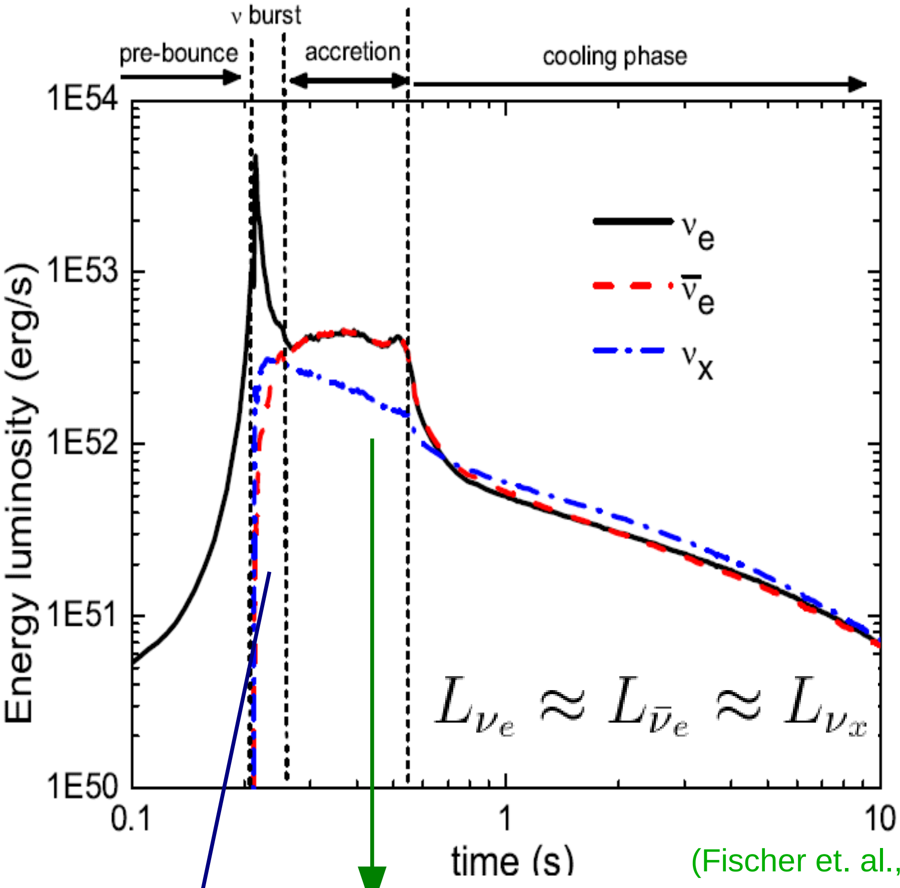


(Modified from Janka+, PTEP 01A309, 2012)

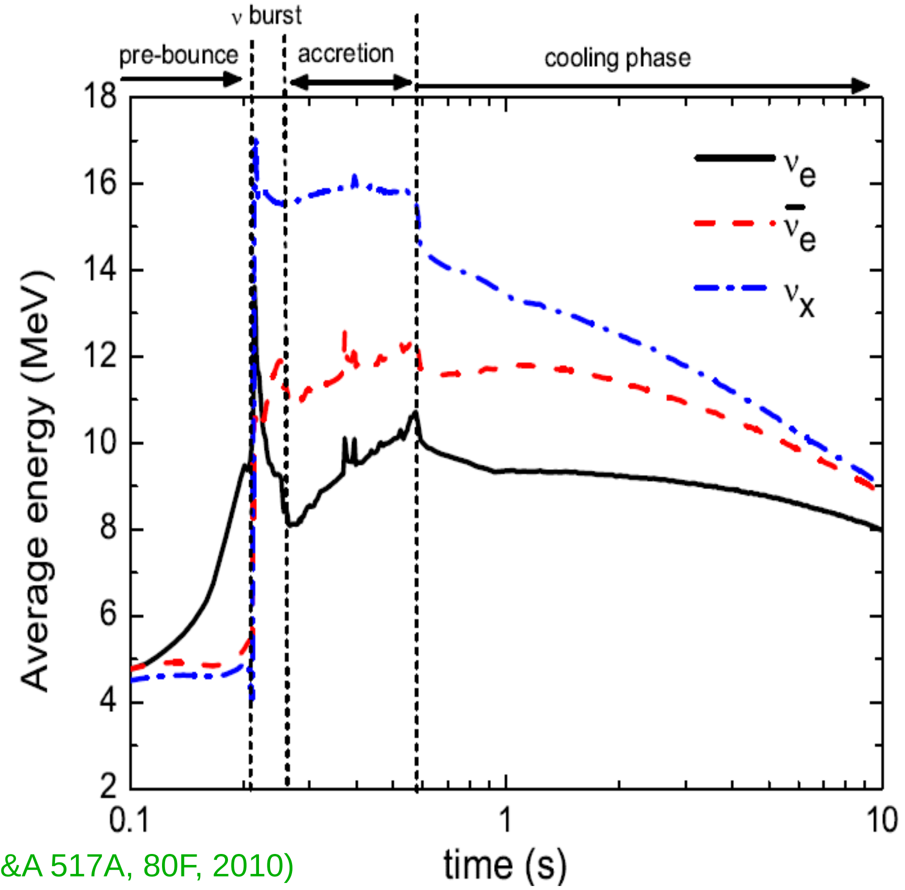
Nucleosynthesis:
- shock-heated nucleosynthesis
  → Elements below Fe group from nuclear burning.
- neutrino-driven wind
  → nuclei with A<120.
- neutrino nucleosynthesis
  → Light elements : Li, Be, B. r-process in He shell.

$$\langle E_{\nu_e}\rangle < \langle E_{\bar{\nu}_e}\rangle < \{\langle E_{\nu_\mu}\rangle, \langle E_{\nu_\tau}\rangle\}$$

→ important to know how neutrino spectra are affected by oscillations on their way of propagation.



$L_{\nu_e} \approx L_{\bar{\nu}_e} \approx L_{\nu_x}$



(Fischer et. al., A&A 517A, 80F, 2010)

$L_{\nu_e} \approx L_{\bar{\nu}_e} > L_{\nu_x}$

$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$

$L_{\nu_e} \gg \{L_{\bar{\nu}_e}, L_{\nu_x}\}$

Supernova neutrino signals

So far we have only ~ 20 SN neutrinos detected from SN1987a,
- confirms the basic picture of core-collapse SN model.
- set limit on the absolute neutrino mass from the time-of-flight.

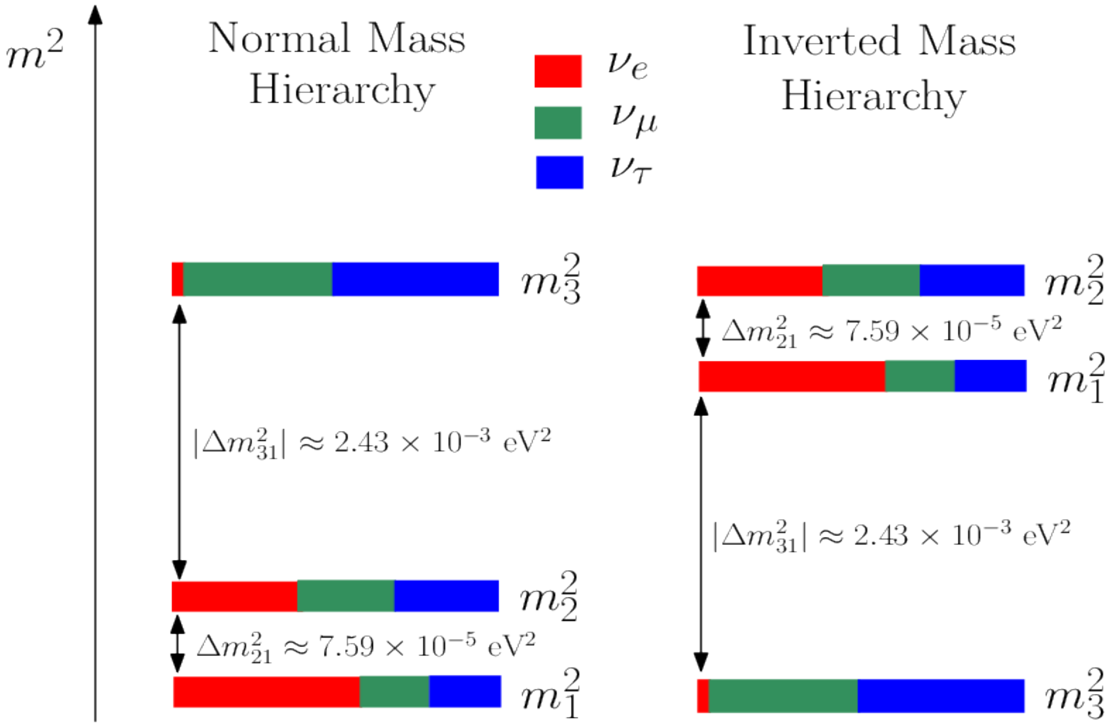
Large amount of events from the next Galactic supernova are expected,
- supernova explosion : explosion mechanism, shock propagation,
  progenitor structure, NS or BH?...
- properties of the PNS : nuclear equation of state,
  hadron-quark phase transition....
- properties of neutrinos : neutrino mass hierarchy, absolute neutrino mass,
  non-standard interaction? sterile neutrinos?...

Diffusive SN neutrino background (SN relic neutrinos).

Again, it is important to know how neutrino spectra are affected by oscillations in order to extract as much information as possible!

Neutrino mixing among active flavors

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2}|\nu_1\rangle \\ e^{i\alpha_2/2}|\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$



mixing angles :

$$\theta_{12} \approx 34^\circ$$

$$\theta_{13} \approx 9^\circ$$

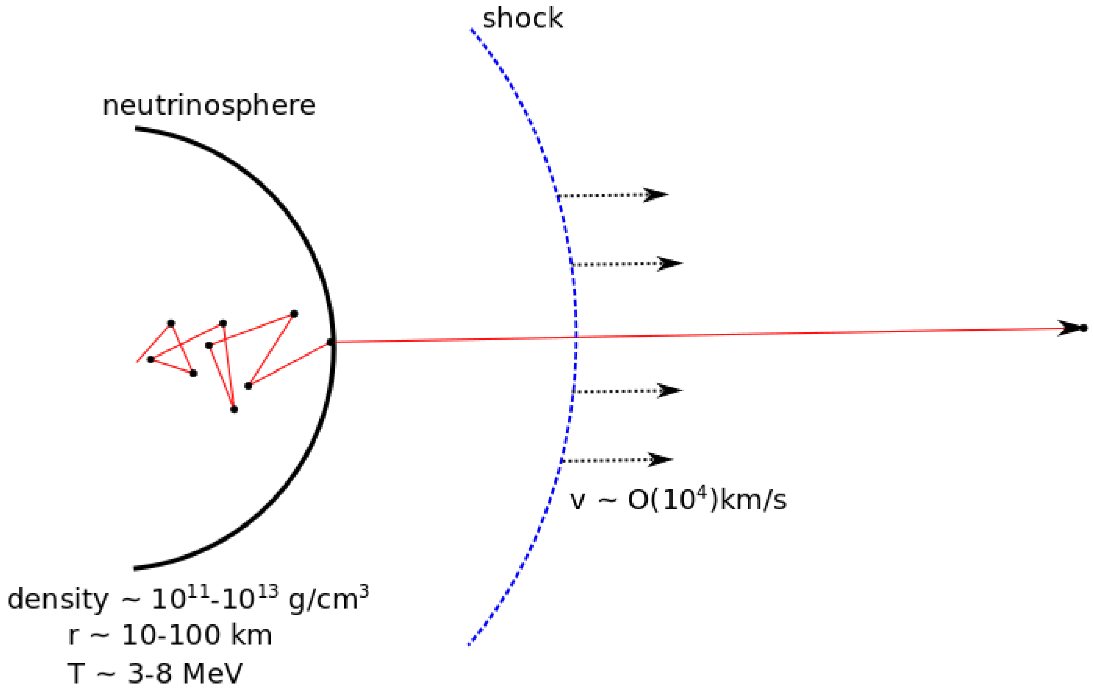
$$\theta_{23} \approx 45^\circ$$

unknowns :
mass hierarchy, CP phases
absolute neutrino mass

Separation of two regimes :

Inside the neutrinospheres → neutrinos are trapped, no flavor oscillations, described by Boltzmann transport.

Outside the neutrinospheres → free-streaming, flavor oscillations described by one-particle Schrödinger-like equation.

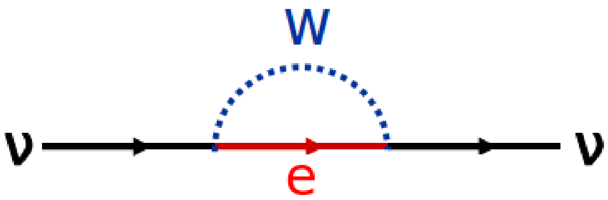


Neutrino flavor evolution :

$$i\frac{d}{dt}|\nu\rangle = (H_{\rm vac} + H_m + H_\nu)\,|\nu\rangle \quad , \quad |\nu\rangle = [a_e, a'_\mu, a'_\tau]^\dagger$$

vacuum term : $H_{\rm vac} \approx \frac{\Delta m^2_{31}}{4E_\nu}\begin{bmatrix} -\cos 2\theta_{13} & 0 & \sin 2\theta_{13} \\ 0 & 1 & 0 \\ \sin 2\theta_{13} & 0 & \cos 2\theta_{13} \end{bmatrix} + \frac{\Delta m^2_{21}}{4E_\nu}\begin{bmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} & 0 \\ \sin 2\theta_{12} & \cos 2\theta_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$

MSW term : $H_m = \pm\sqrt{2}\, G_F\, n_e\, diag(1,0,0)$ (Wolfenstein 1978; Mikheyev & Smirnov, 1985)



=> MSW resonance : $\pm\sqrt{2}\, G_F\, n_e = \frac{\Delta m^2_{ij}}{2E_\nu}\cos 2\theta_{ji}$

$$\text{for } \delta m^2_{31}, \ \rho_{\rm res} \sim O(10^3)\ \mathrm{g/cm^3}$$

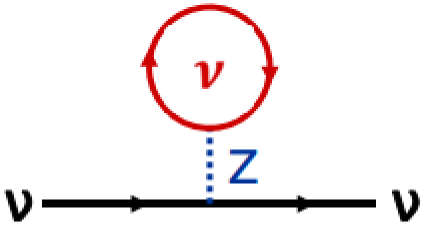
$$\text{for } \delta m^2_{21}, \ \rho_{\rm res} \sim O(10)\ \mathrm{g/cm^3}$$

Mostly adiabatic, but may be disturbed by the passing of supernova shock

Neutrino flavor evolution :

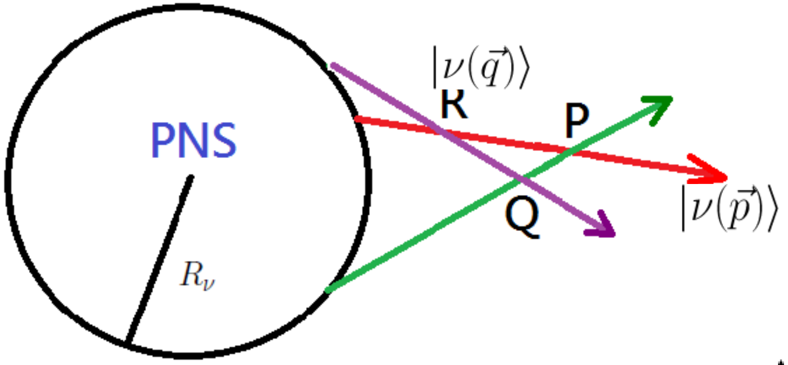
$$i\frac{d}{dt}|\nu\rangle = (H_{\rm vac} + H_m + H_\nu)\,|\nu\rangle \quad , \; |\nu\rangle = [a_e, a'_\mu, a'_\tau]^\dagger$$

neutrino-neutrino term : (Fuller, et. al., 1987; Pantaleone, 1992; Sigl & Raffelt, 1992; Pehlivan & Balantekin 200



$$H_\nu = \sqrt{2}G_F \int \underbrace{(1-\cos\theta_{\vec{p}\vec{q}})}_{\propto \left(\frac{R_\nu}{r}\right)^2}[\rho_\nu(\vec{q}) - \bar{\rho}^*_\nu(\vec{q})]\,dn_\nu(\vec{q})$$

$$\rho_\nu = |\nu\rangle\langle\nu| = \begin{bmatrix} |a_e|^2 & a_e a^*_{\mu'} & a_e a^*_{\tau'} \\ a^*_e a_{\mu'} & |a_{\mu'}|^2 & a_{\mu'} a^*_{\tau'} \\ a^*_e a_{\tau'} & a^*_{\mu'} a_{\tau'} & |a_{\tau'}|^2 \end{bmatrix}$$

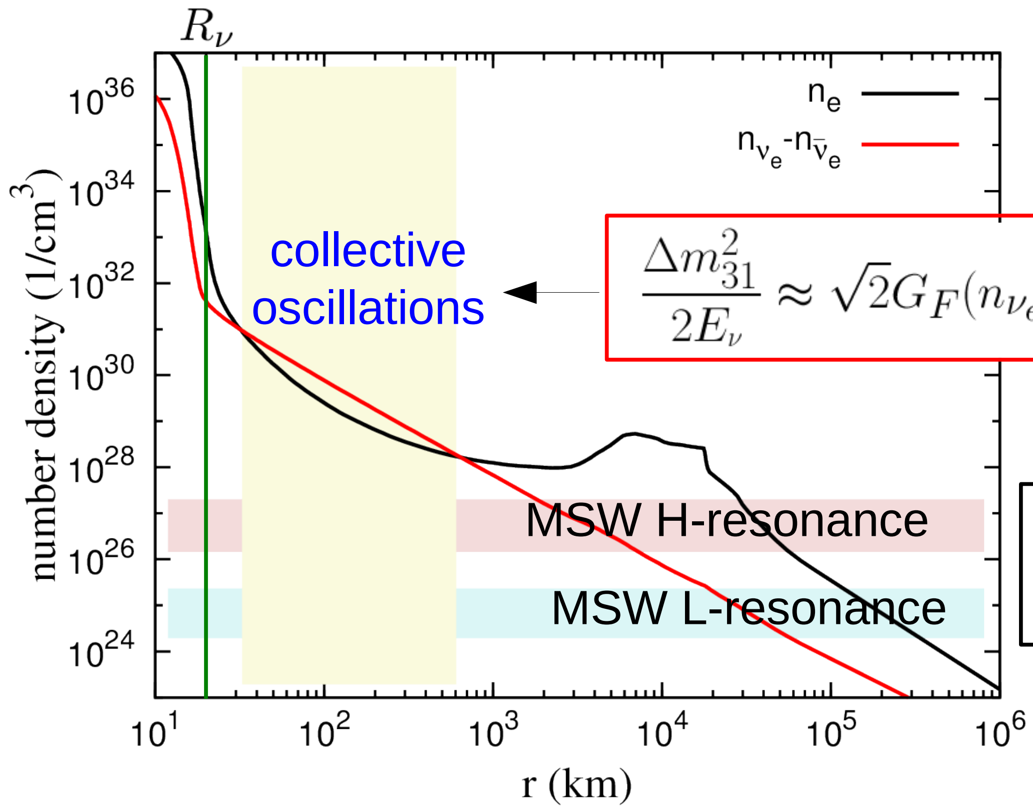


=> coupled non-linear flavor evolution for neutrinos with different energy and trajectory

=> collective neutrino oscillations might occur closer to the PNS

$$\frac{\Delta m^2_{31}}{2E_\nu} \approx \sqrt{2}G_F(n_{\nu_e} - n_{\bar{\nu}_e})\frac{R^2_\nu}{r^2}$$

Regions of neutrino oscillations in supernovae



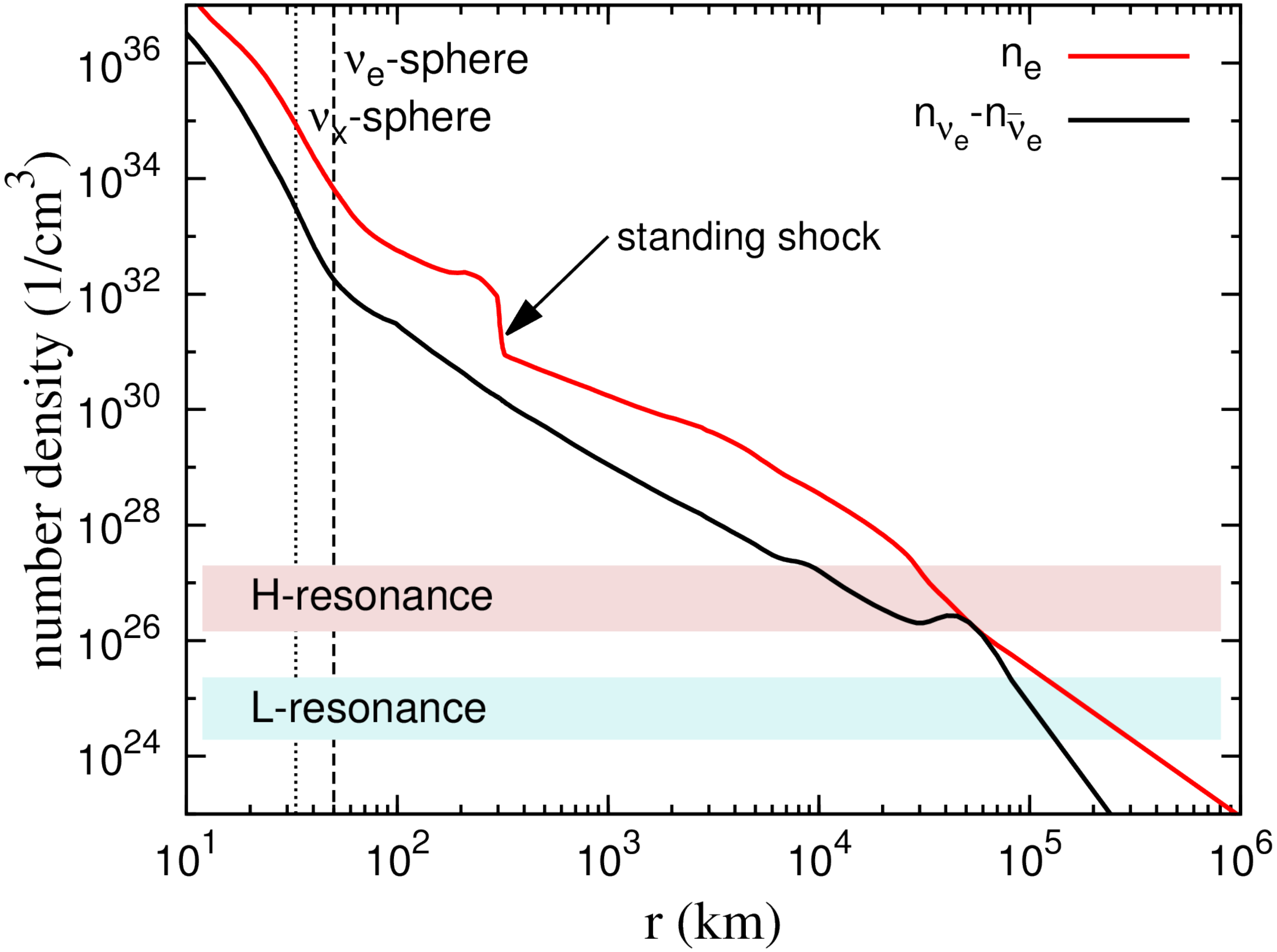
$$\frac{\Delta m_{31}^2}{2E_\nu} \approx \sqrt{2}G_F(n_{\nu_e} - n_{\bar{\nu}_e})\frac{R_\nu^2}{r^2} \quad , n_e \lesssim n_{\nu_e} - n_{\bar{\nu}_e}$$

$$\frac{\Delta m_{ij}^2}{2E_\nu} \approx \sqrt{2}G_F n_e$$

	Shock Revival ~O(10^2 km)	*v*-driven Wind ~O(10^3 km)	*v*-induced nucleosynthesis in outer shells ~O(10^5 km)	Neutrino signals
Collective Oscillations	No(?) (Chakraborty + 2011 Dasgupta + 2012)	Maybe (GMP + 2011, Duan + 2012)	?	Yes(?) (Gava + 2009 Dighe + 2000 Tomas+ 2004 ……… ……..)
MSW H-resonance	No	No	Yes (Yoshida + 2006, Banerjee + 2011, 2012)	Yes
MSW L-resonance	No	No	No	Yes

Neutrino signals and mass hierarchy

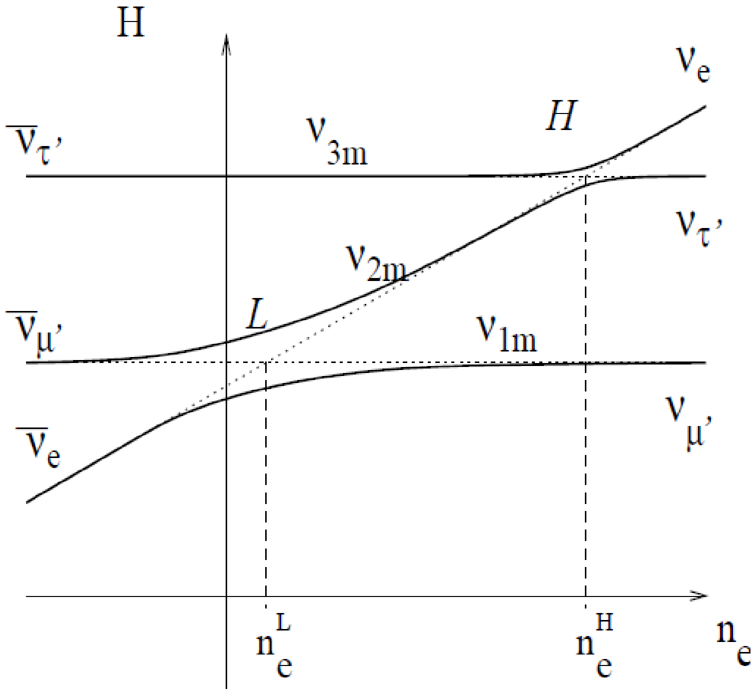
In the accretion phase of Fe-core SN, collective oscillations are expected to be suppressed by the large matter potential.



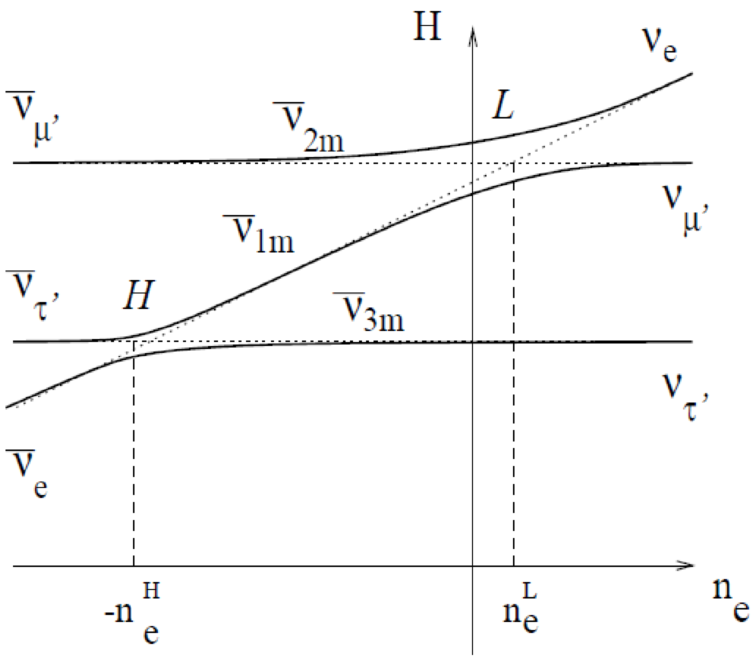
Adiabatic MSW flavor evolution

	$f^{(\mathrm{f})}_{\nu_e}$	$f^{(\mathrm{f})}_{\bar{\nu}_e}$
Normal mass hierarchy	$\approx f^{(\mathrm{i})}_{\nu_x}$	$\approx 0.7 f^{(\mathrm{i})}_{\bar{\nu}_e} + 0.3 f^{(\mathrm{i})}_{\bar{\nu}_x}$
Inverted mass hierarchy	$\approx 0.3 f^{(\mathrm{i})}_{\nu_e} + 0.7 f^{(\mathrm{i})}_{\nu_x}$	$\approx f^{(\mathrm{i})}_{\bar{\nu}_x}$

Normal mass hierarchy

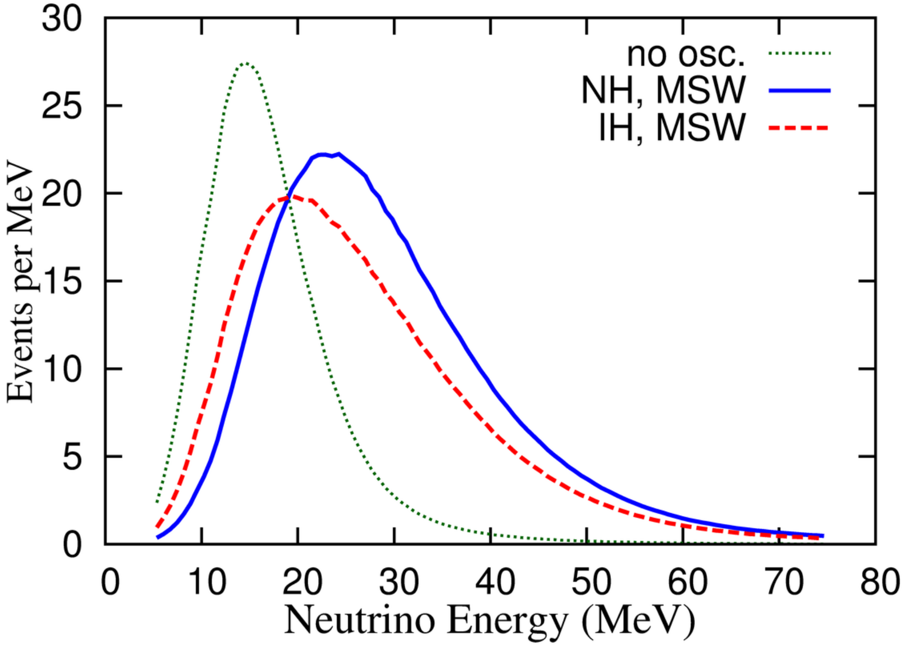


Inverted mass hierarchy

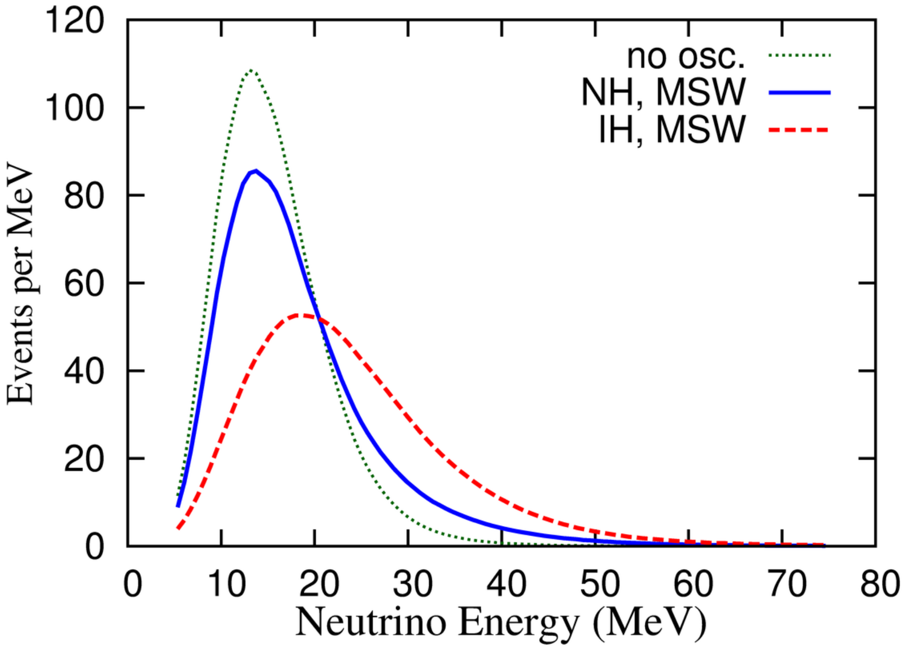


Neutrino signals

ν_e signal in a 40k ton liquid argon detector



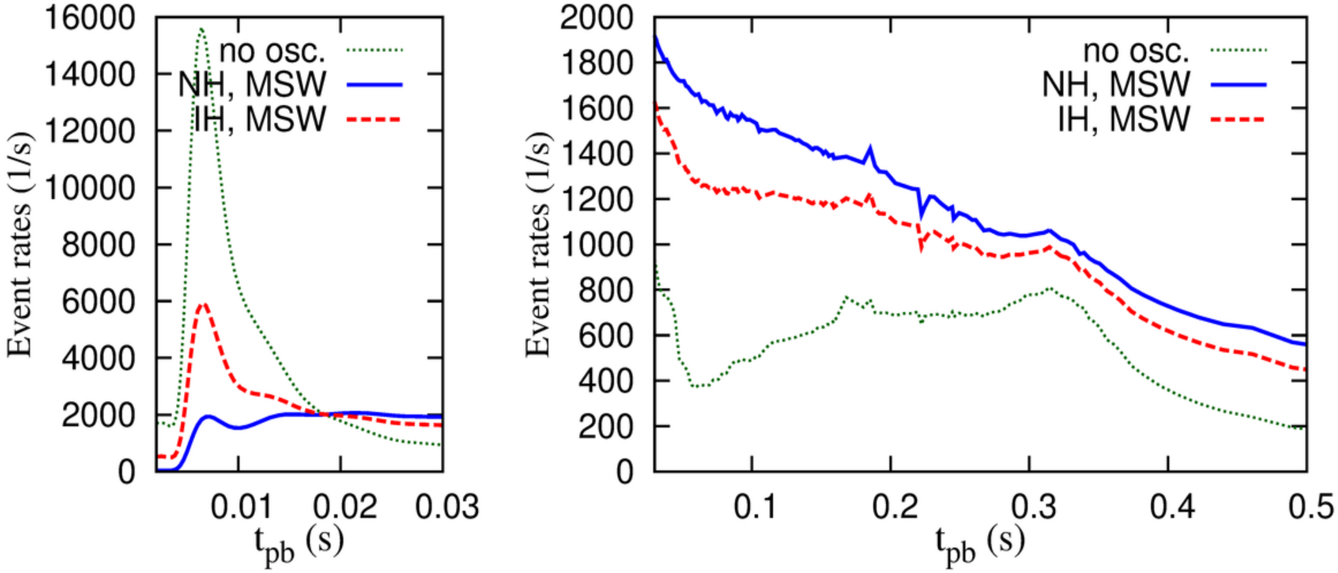
Anti-ν_e signal in Super-K



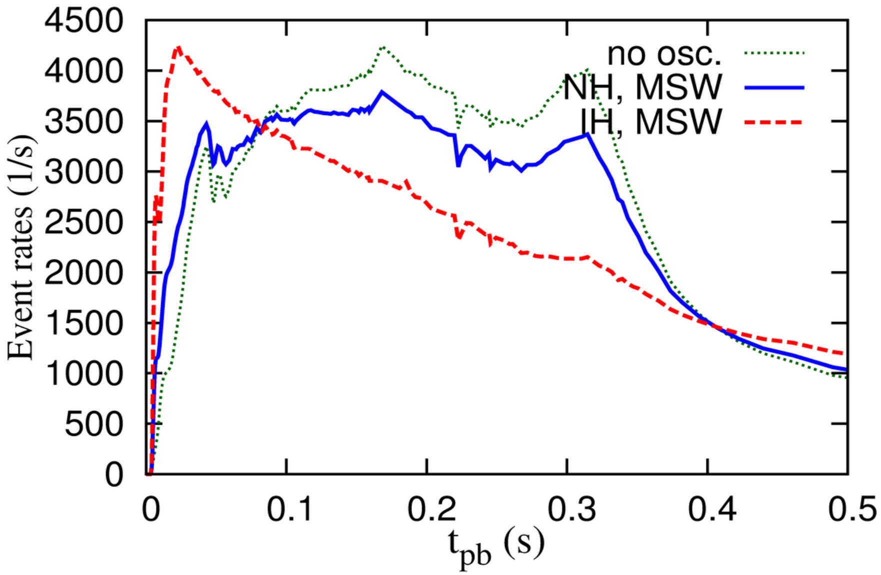
Neutrino signals

$$\text{event rate} = N_{\text{target}} \frac{L_{n,\nu}}{4\pi d^2} \int dE_\nu \sigma(E_\nu) f_\nu^{(\text{f})}(E_\nu)$$

ν_e signal in a 40k ton liquid argon detector

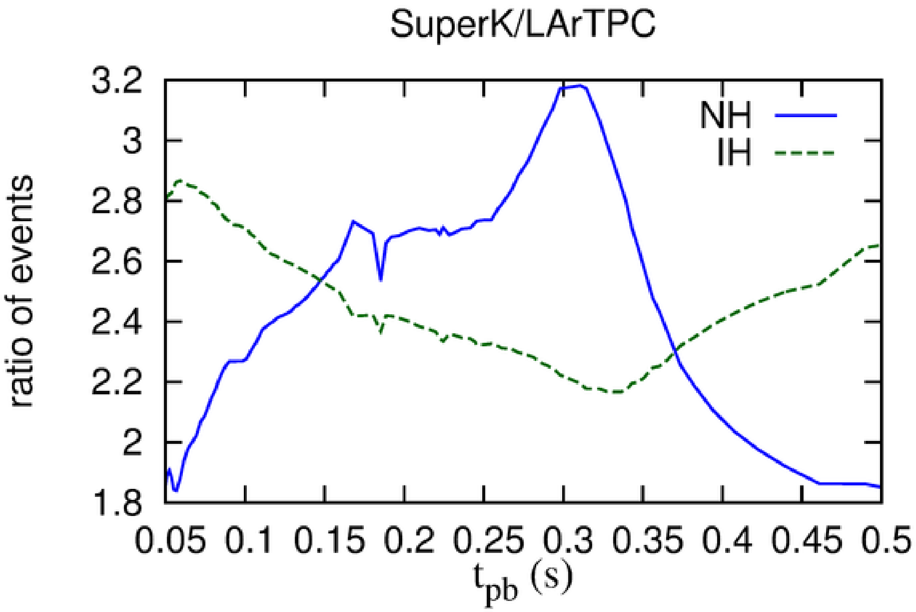


Anti-ν_e signal in Super-K

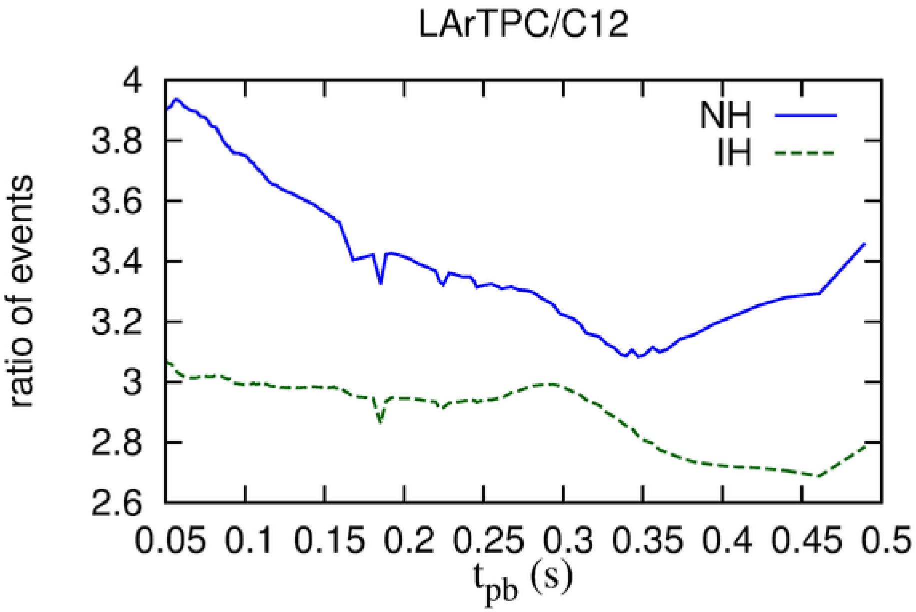


(d=10 kpc)

Neutrino signals

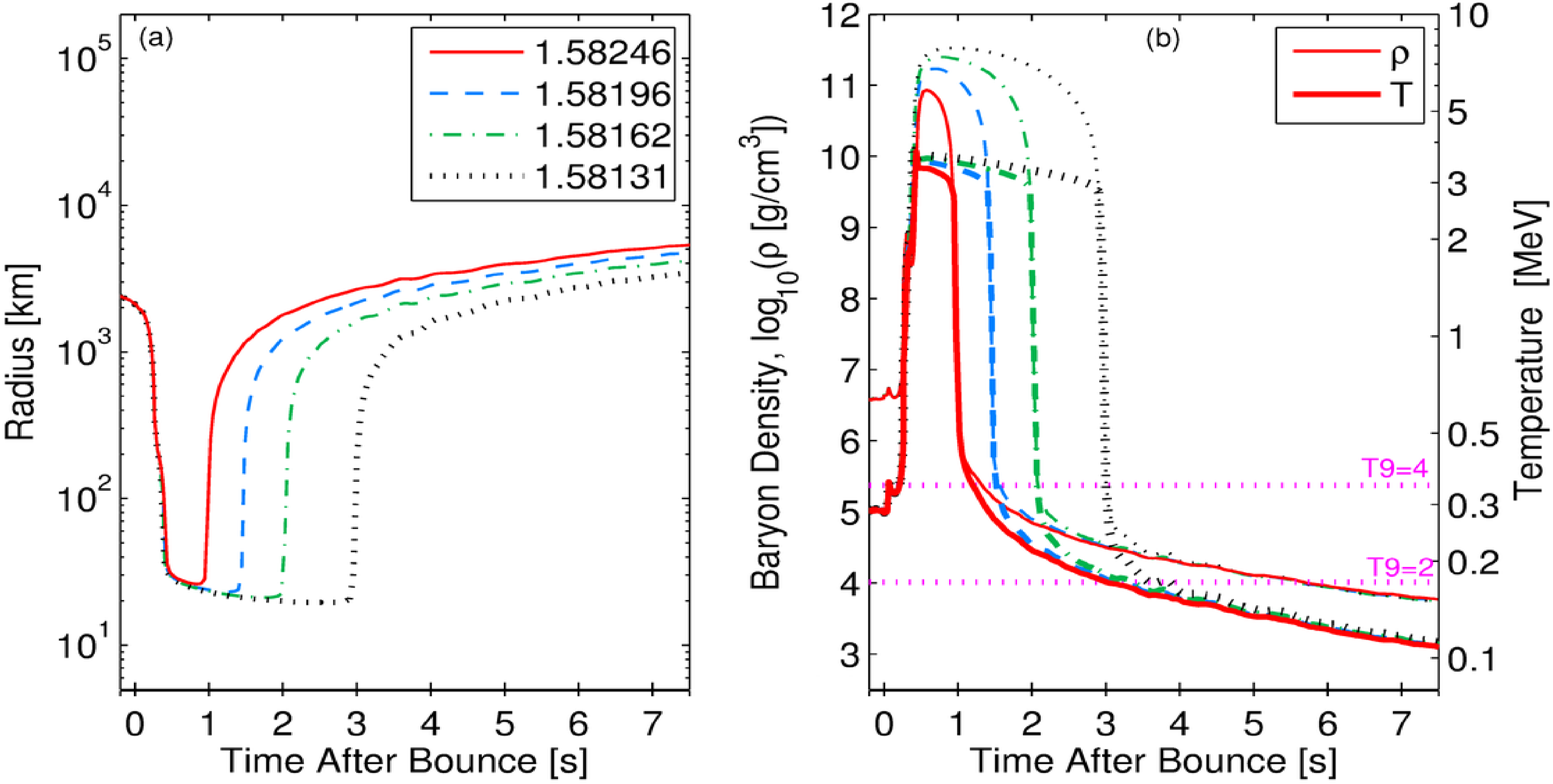


SuperK/LArTPC



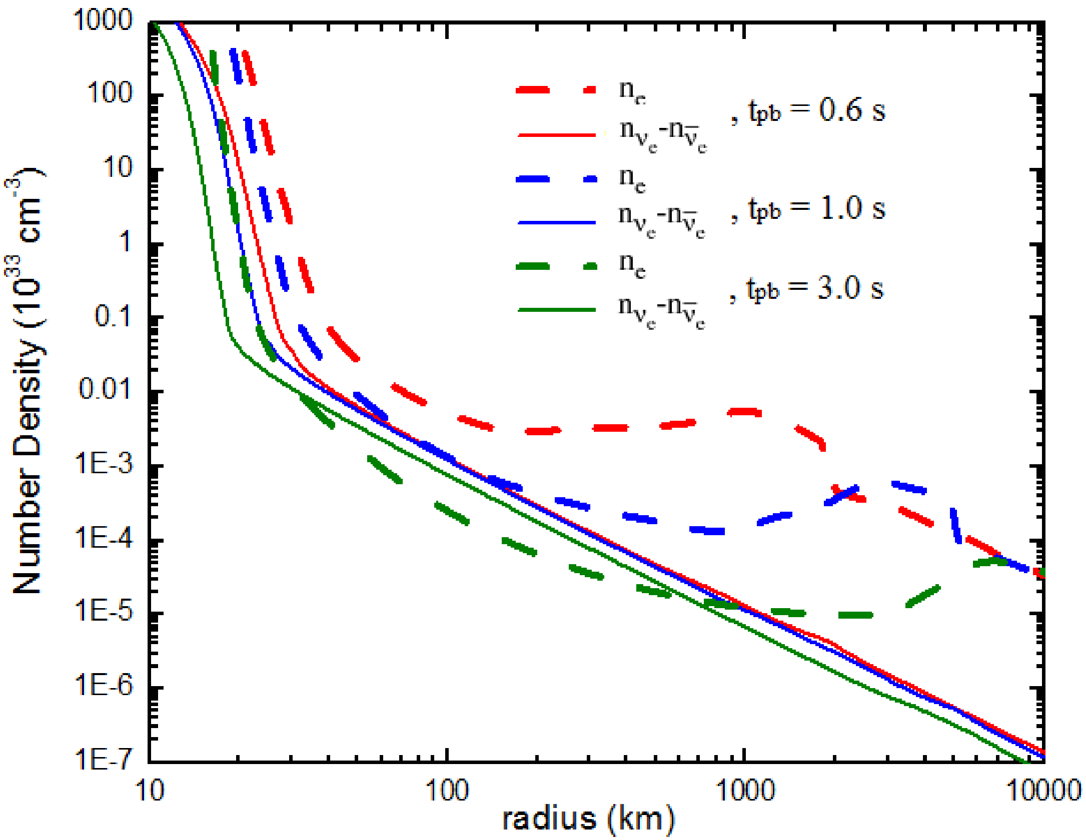
LArTPC/C12

Nucleosynthesis in the neutrino-driven wind



Y_e ~ 0.53, site for vp process,
produce nuclei of A < 110

Nucleosynthesis in the neutrino-driven wind



Collective neutrino oscillations may be sensitive to

(a) the time-evolving neutrino spectra
(b) the time-evolving matter density profiles

→ need to calculate the flavor evolution history for different time grids in order to study its effect on nucleosynthesis or signals

Collective oscillations with inputs from supernova model

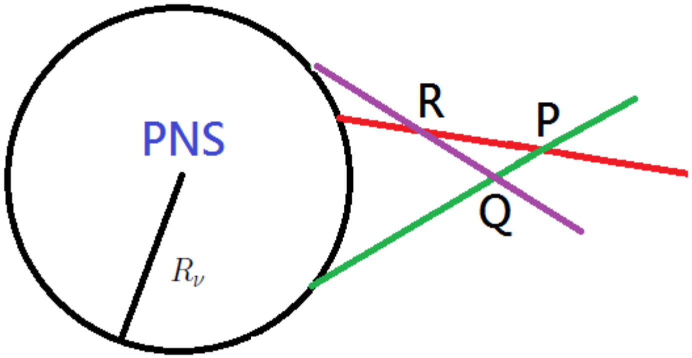
Supernova Model

(Fischer et. al., A&A 517A, 80F, 2010)

- 18 $M_\odot$, 1D hydro + 2D neutrino transport
- Artificially enhanced neutrino heating above the neutrino-spheres
- Neutrino-driven winds are proton-rich, possible νp process site

Model of Neutrino Oscillations

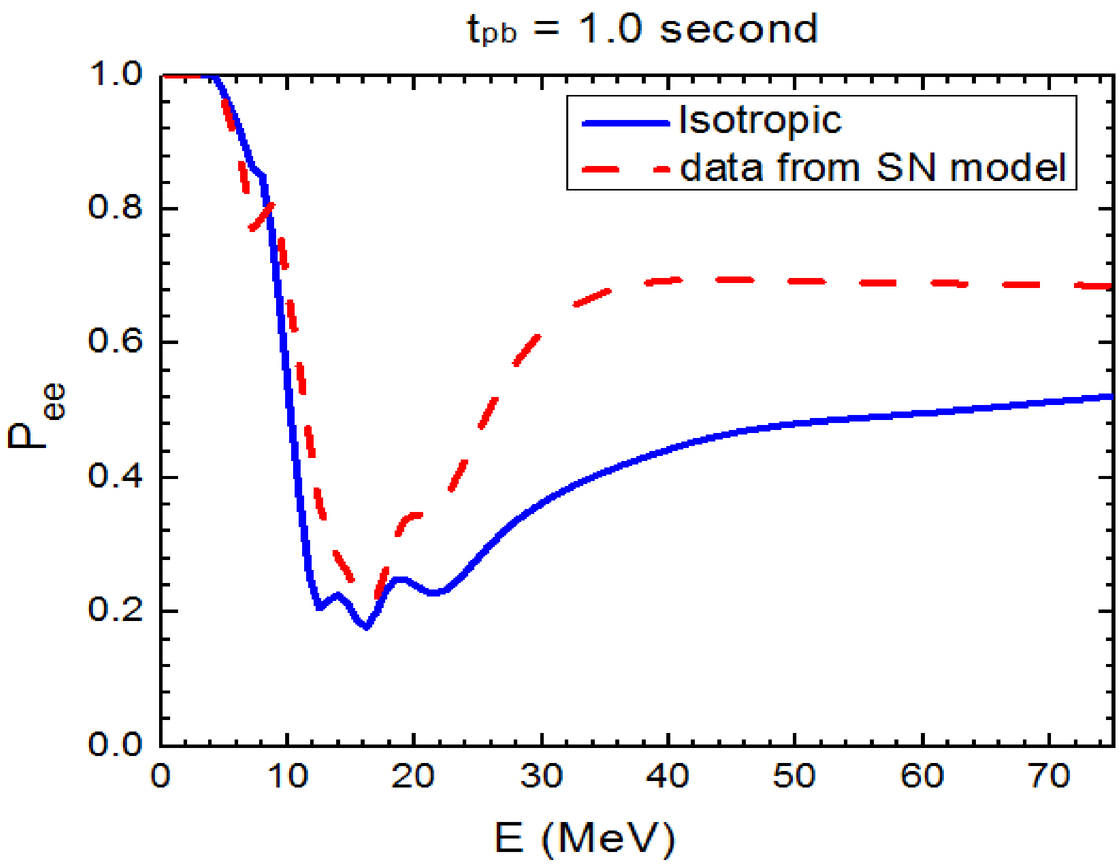
- A sharp neutrino decoupling spheres
- Forward-peaked angular distribution
- Ray-tracing neutrinos with different energies and emission angles



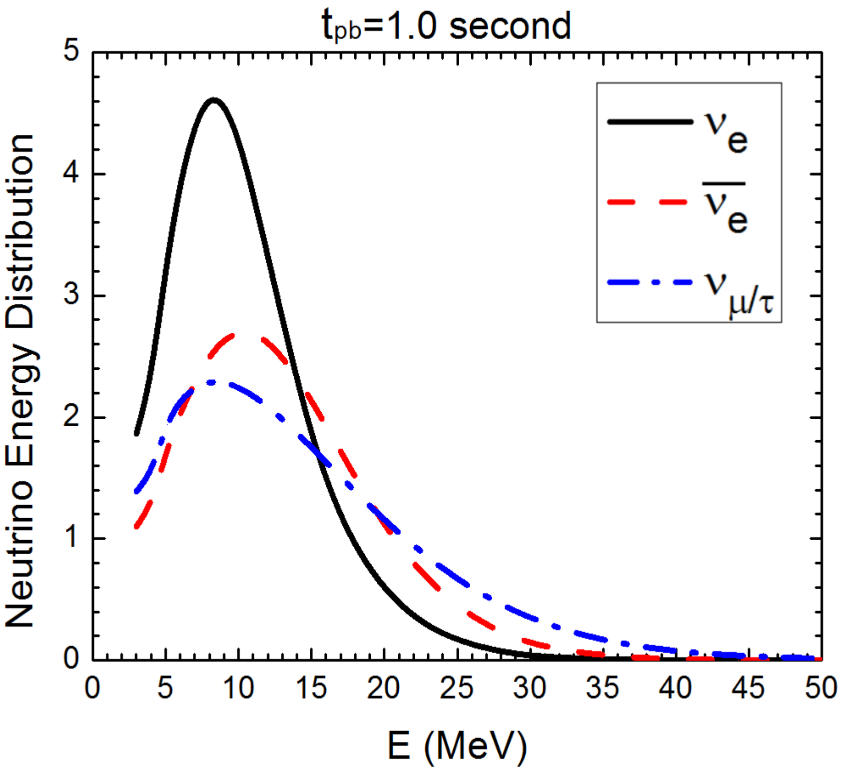
Require ~ O(10^3) energy bins
x O(10^3) angular bins
to reach convergence

$$i\frac{d}{dr}\psi(E_\nu,\theta,r) = \left[\frac{H_v(E_\nu)+H_m(r)}{D(\theta,r)} + H_\nu(\theta,r)\right]\psi(E_\nu,\theta,r)$$

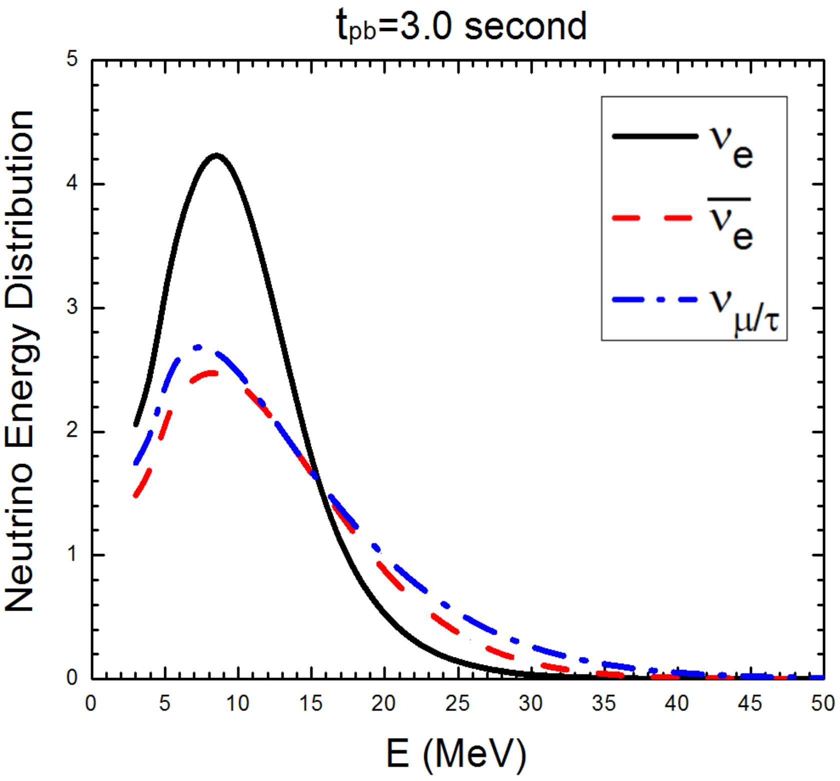
Neutrino angular distribution



Neutrino spectra in different post-bounce time

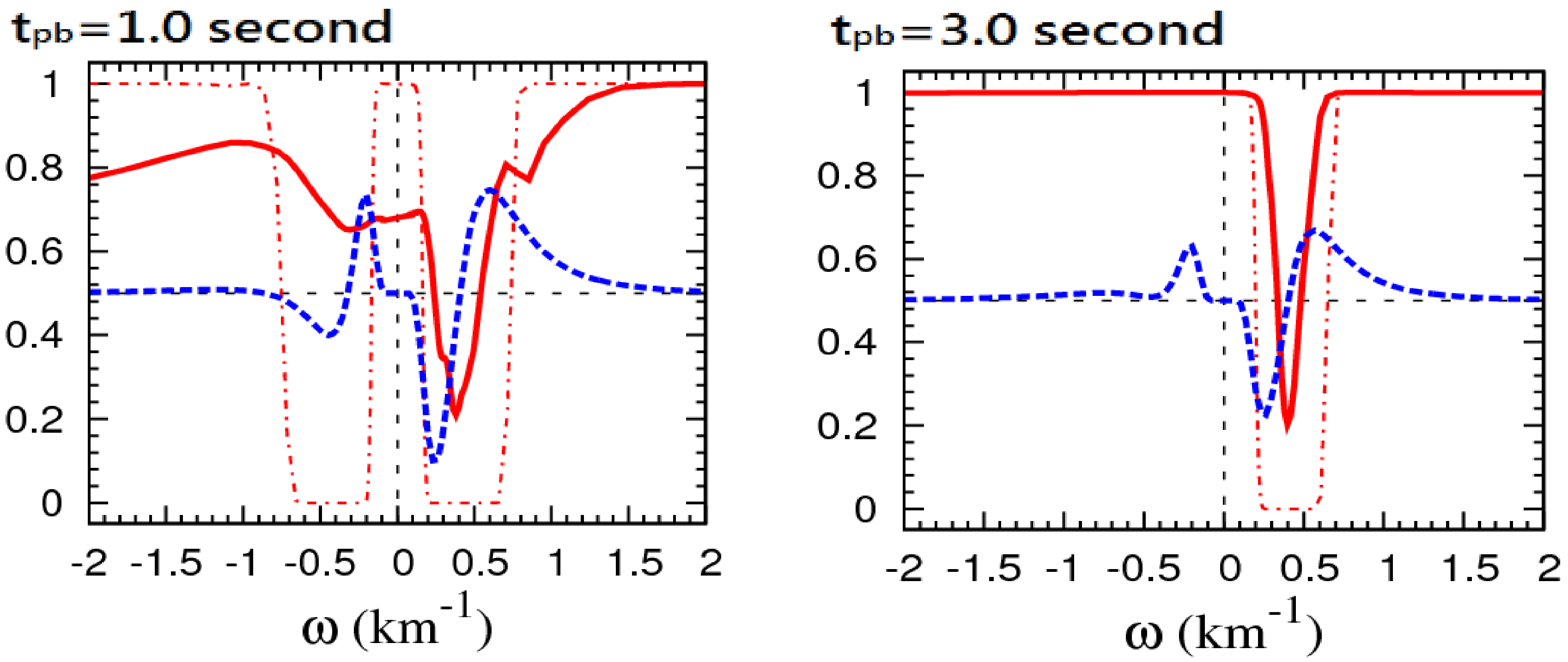


t_{pb}=1.0 second



t_{pb}=3.0 second

Neutrino spectra in different post-bounce time



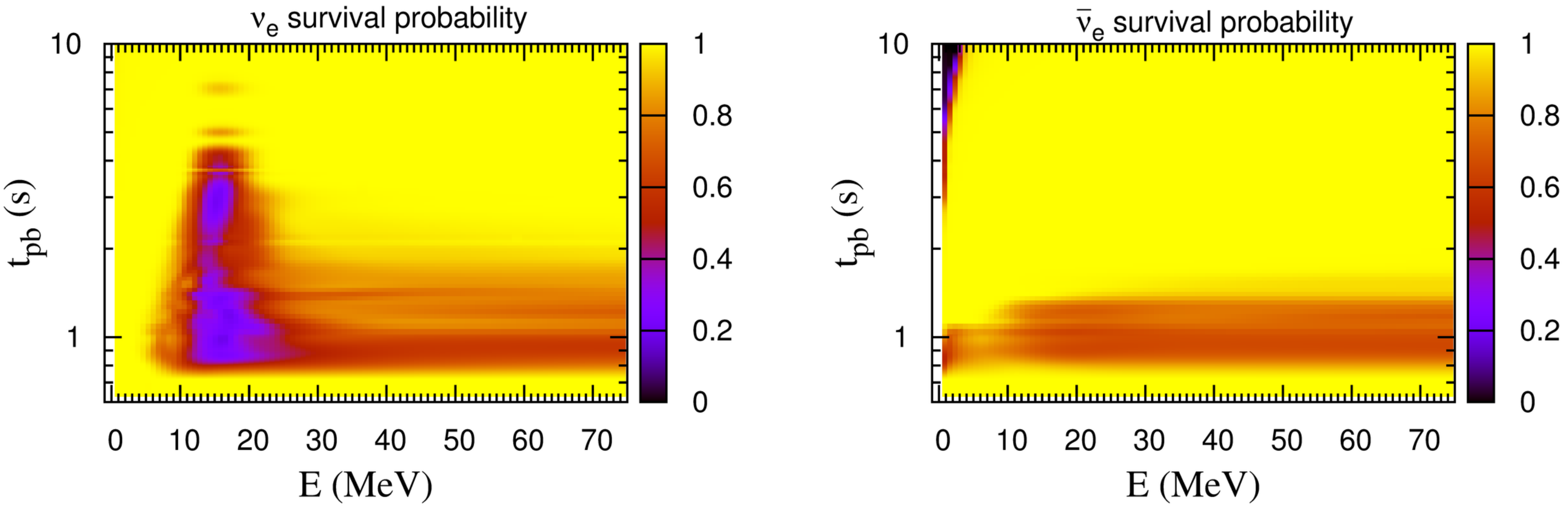
$$\omega = \pm\frac{|\delta m^2_{31}|}{2E} = \pm 0.616 \times \left(\frac{10\mathrm{MeV}}{E}\right)\mathrm{km}^{-1}$$

$$g(\omega) \propto \omega^{-2}\begin{cases} f_{\nu_e}(E) - f_{\nu_x}(E), & \omega > 0 \\ f_{\bar{\nu}_x}(E) - f_{\bar{\nu}_x}(E), & \omega < 0 \end{cases}$$

— $\langle P_{\nu_e\nu_e}\rangle$

- - - $g(\omega)$

Collective oscillations with inputs from supernova model



Partial flavor conversion for the inverted mass hierarchy :

$0.8\text{s} < t_{pb} \leq 1.5$ s, ν_e and anti-ν_e with E > 10 MeV

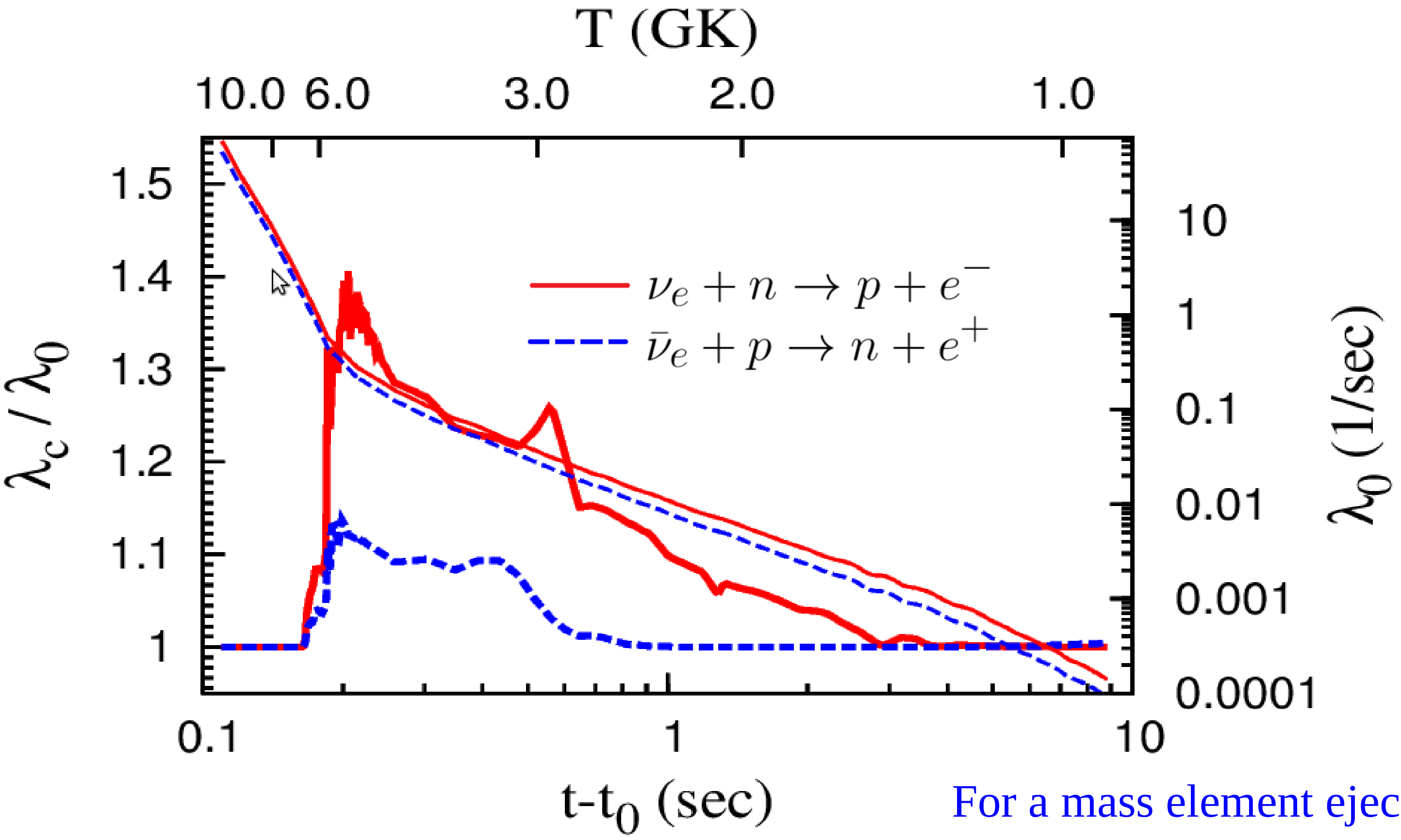
$1.5\text{s} < t_{pb} \leq 5.0$ s, only ν_e with 10 < E < 20 MeV

after 5.0 s, no collective oscillations

No collective oscillations in the normal mass hierarchy!

(similar results in the 10.8 solar mass SN model with the same settings)

Effect on nucleosynthesis?

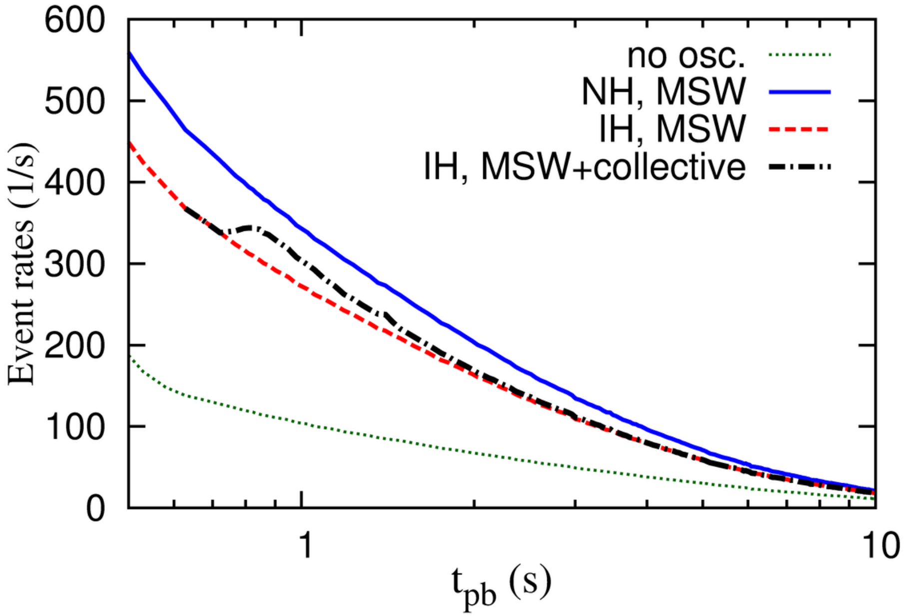


For a mass element ejected
~ 0.85 second post bounce

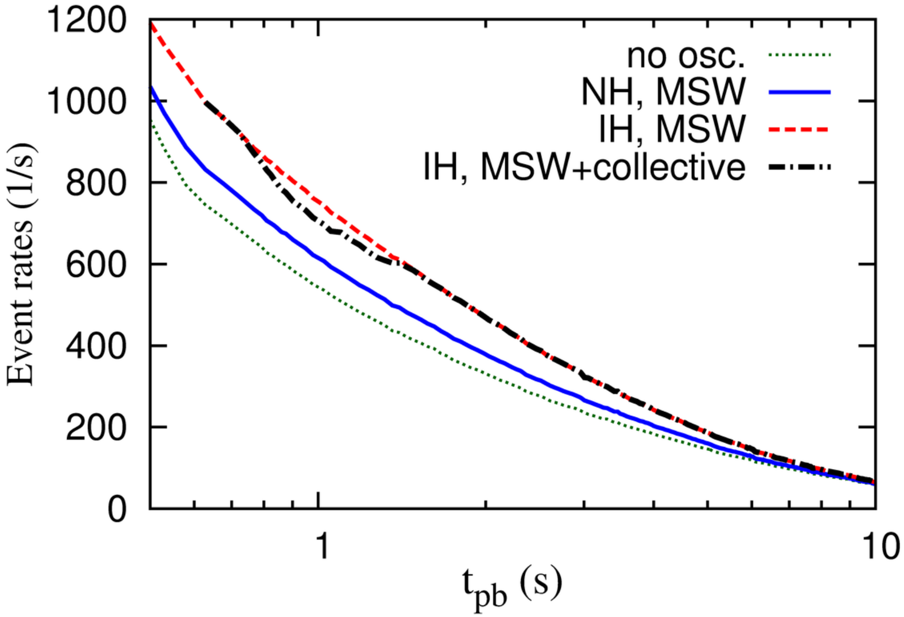
Little impact on *ν*p process associated with the SN model.

Neutrino signals again

ν_e signal in a 40k ton liquid argon detector



Anti-ν_e signal in Super-K



Summary

- Neutrinos play significant roles in different aspects in supernovae. Understand how flavor oscillations happen in supernova is a necessity for supernova nucleosynthesis and neutrino signals.

- Neutrino signals of different detection channel during the supernova accretion phase may give indication about the neutrino mass hierarchy.

- To access the impact of neutrino oscillations on supernova nucleosynthesis, it is important to use the correspondingly time-evolving neutrino spectra and supernova density profiles, with a careful treatment of the inner boundary condition.