Neutrino Oscillations in Core-Collapse Supernovae

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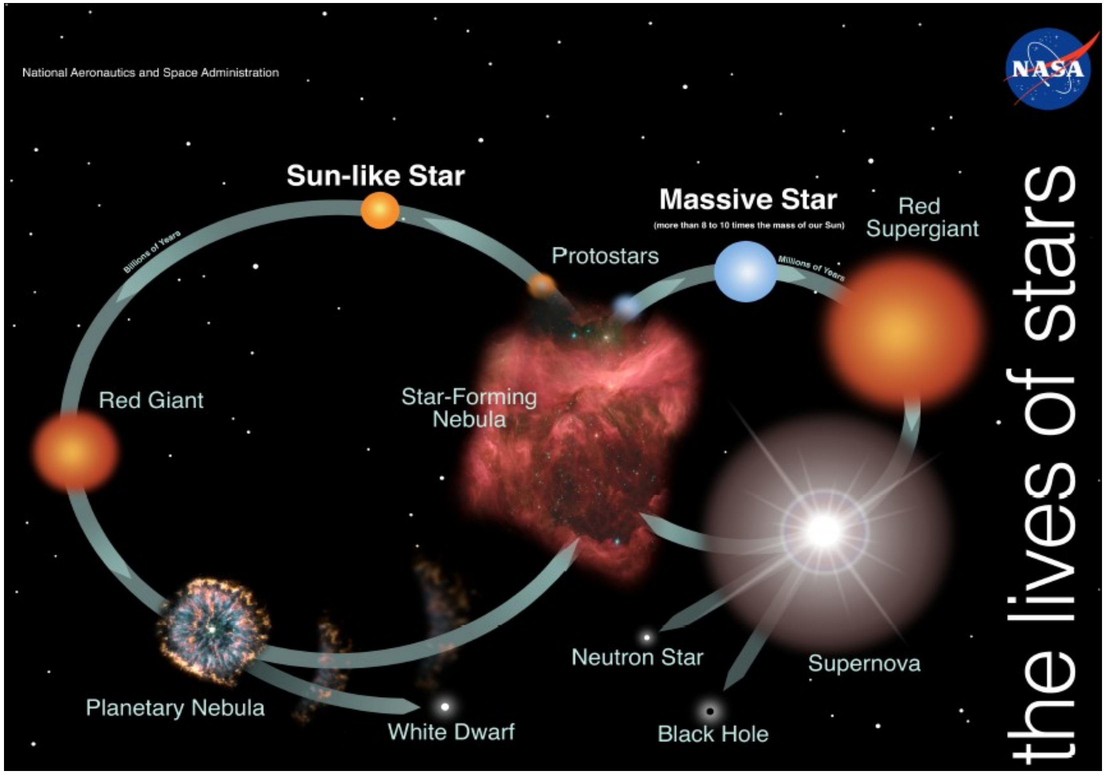
Neutrino Oscillations in Core-Collapse Supernovae

- Core-collapse supernovae & neutrinos
- Active-active neutrino oscillations
- Active-sterile neutrino oscillations

Supernova explosion – the death of massive stars



(From NASA website)

The Tarantula Nebula and supernova 1987a in the LMC

(From AAO website)

energy of the emitted light ~ 10^{49}-10^{50} ergs
peak luminosity may be as bright as an entire galaxy!

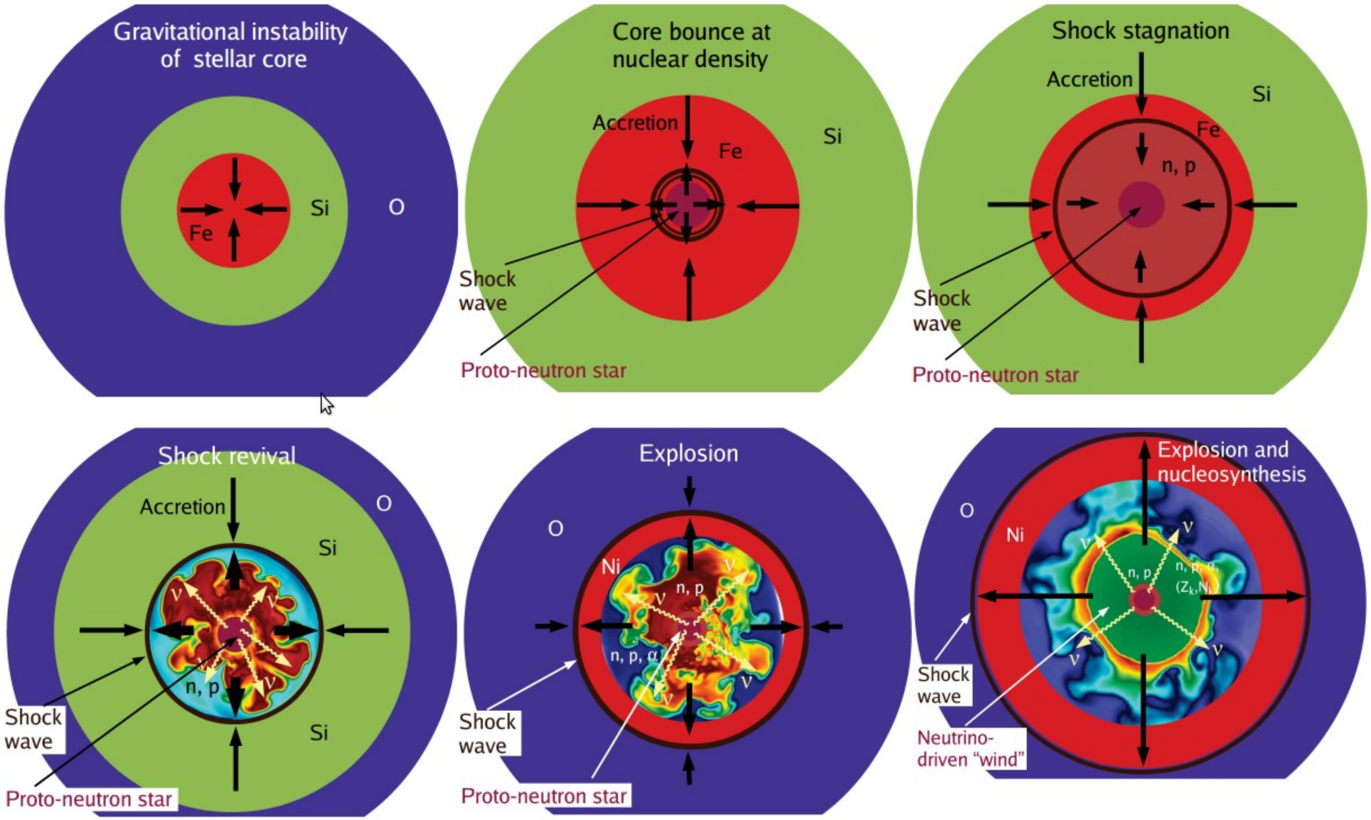
- produce elements after BBN
- star formation & galaxy formation
- galactic chemical enrichment

Neutrinos in supernovae

Over 99 percent of gravitational energy is carried away by ~10^{58} different kind of neutrinos in a time scale of 10 seconds.

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

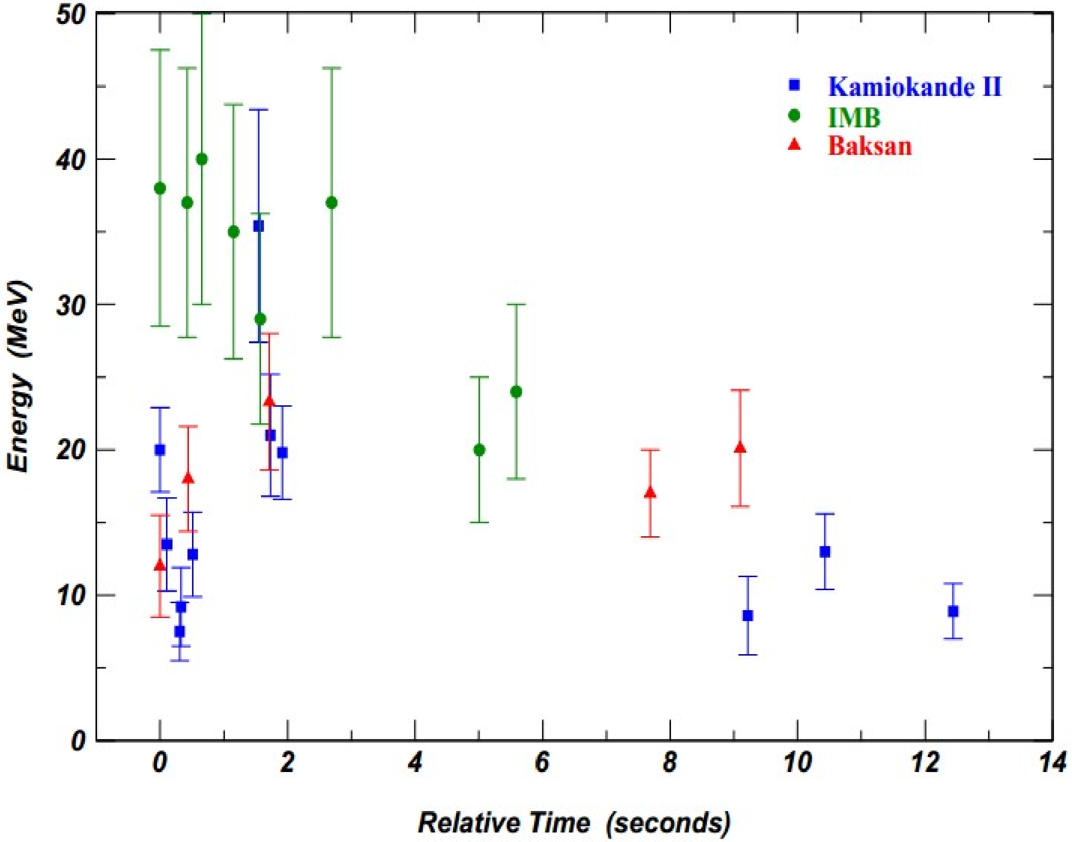
(H.-Th. Janka, et al, PTEP 01A309 (2012))



→ Delayed neutrino-heating mechanism for explosion
→ Neutrino-driven winds as a site of heavy element formation
→ Neutrino-induced nucleosynthesis in supernova envelopes

Neutrino signals

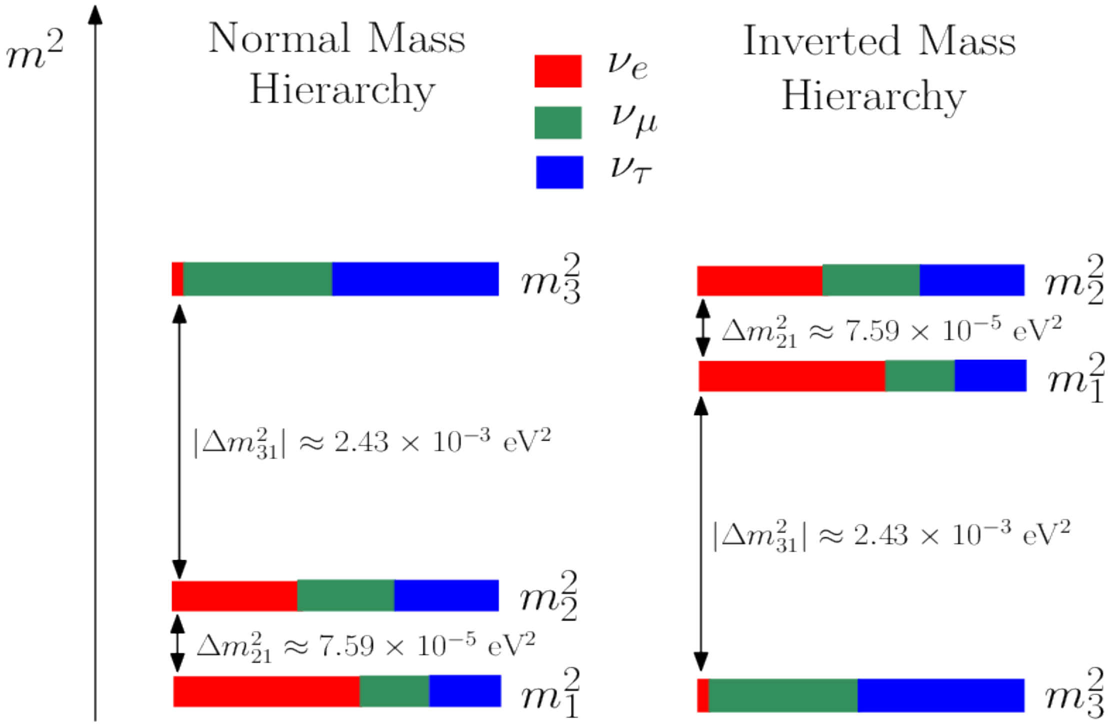
We have ~ 20 SN neutrinos detected from SN1987a



- Confirms the basic picture of core-collapse SN model
- Set limit on the absolute neutrino mass from the time-of-flight

Neutrino mixing among active flavors

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



$$\theta_{12} \approx 45^\circ$$

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

$$\theta_{23} \approx 34^\circ$$

Energy hierarchy of supernova neutrinos

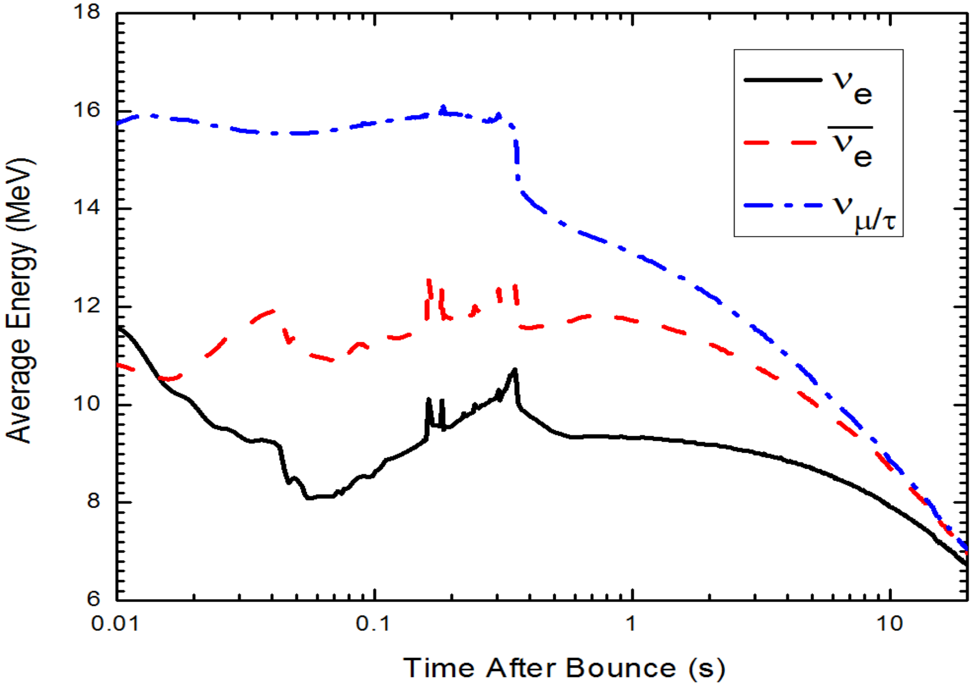
There exists an energy hierarchy between the emitted neutrinos :

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

because of (a) muon and tau abundances are suppressed
(b) more neutrons than protons

Neutrino flavor oscillations might affect supernova physics!

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



The next galactic supernova?

(Kate Scholberg., Ann.Rev.Nucl.Part.Sci, 62, 2012)

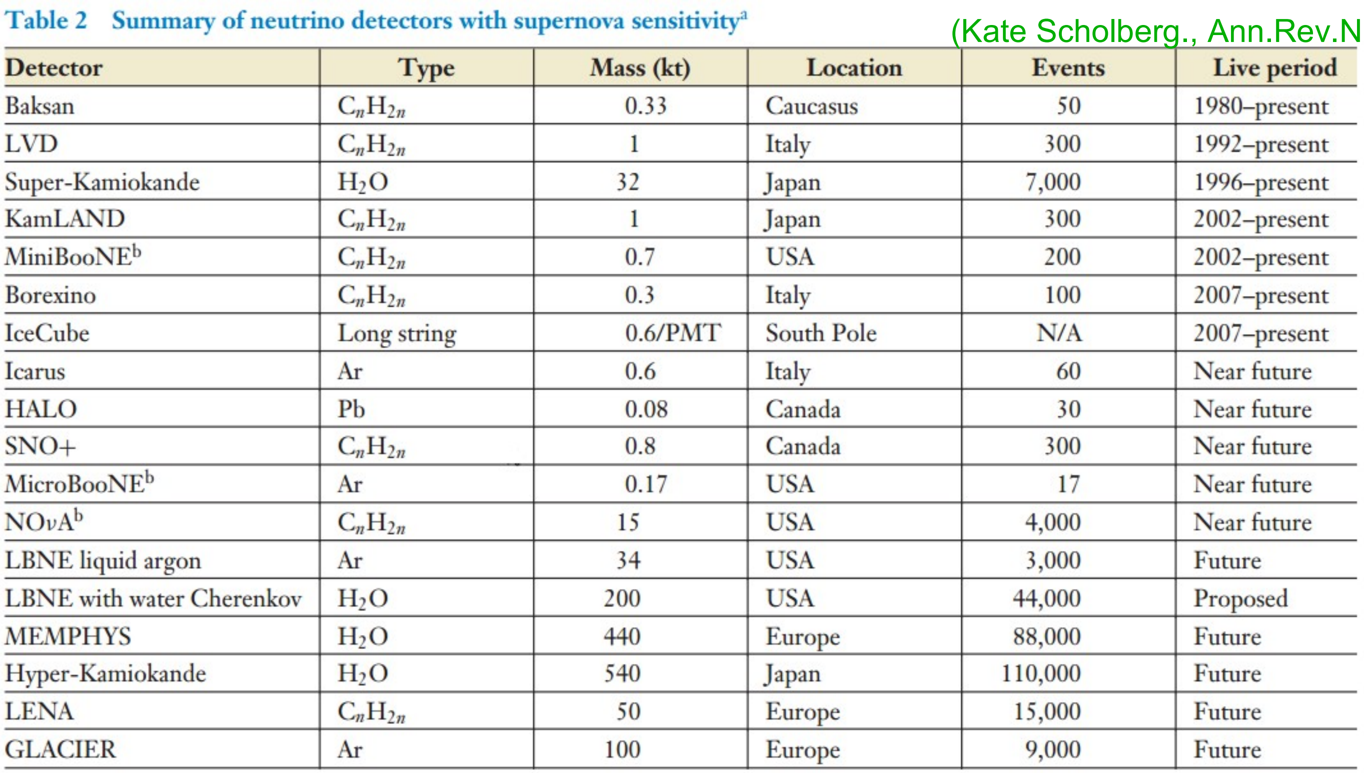


Table 2 Summary of neutrino detectors with supernova sensitivity[a]

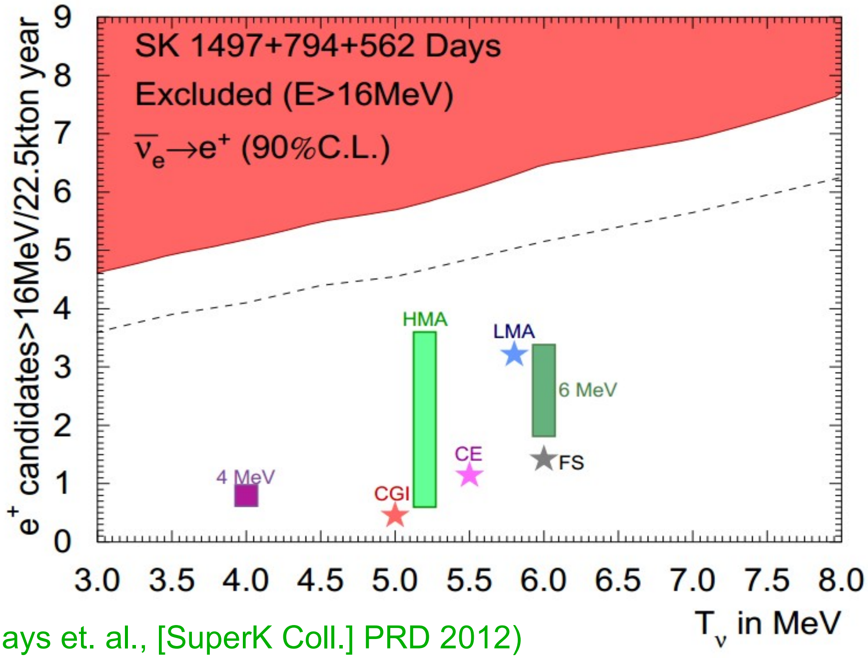
Detector	Type	Mass (kt)	Location	Events	Live period
Baksan	C_nH_{2n}	0.33	Caucasus	50	1980–present
LVD	C_nH_{2n}	1	Italy	300	1992–present
Super-Kamiokande	H_2O	32	Japan	7,000	1996–present
KamLAND	C_nH_{2n}	1	Japan	300	2002–present
MiniBooNE[b]	C_nH_{2n}	0.7	USA	200	2002–present
Borexino	C_nH_{2n}	0.3	Italy	100	2007–present
IceCube	Long string	0.6/PMT	South Pole	N/A	2007–present
Icarus	Ar	0.6	Italy	60	Near future
HALO	Pb	0.08	Canada	30	Near future
SNO+	C_nH_{2n}	0.8	Canada	300	Near future
MicroBooNE[b]	Ar	0.17	USA	17	Near future
NOνA[b]	C_nH_{2n}	15	USA	4,000	Near future
LBNE liquid argon	Ar	34	USA	3,000	Future
LBNE with water Cherenkov	H_2O	200	USA	44,000	Proposed
MEMPHYS	H_2O	440	Europe	88,000	Future
Hyper-Kamiokande	H_2O	540	Japan	110,000	Future
LENA	C_nH_{2n}	50	Europe	15,000	Future
GLACIER	Ar	100	Europe	9,000	Future

(d=10 kpc)

- Supernova explosion : Explosion mechanism, shock propagation, progenitor structure, NS or BH?...
- Properties of proto-neutron star : Nuclear equation of state, hadron-quark phase transition....
- Properties of neutrinos : Neutrino mass hierarchy, absolute neutrino mass, non-standard interaction? sterile neutrinos?...

Diffusive supernova neutrino background

$$\frac{d\phi}{dE_\nu} = c \int R_{\rm CCSN}(z, M) \frac{dN_\nu(\bar{E}_\nu, M)}{d\bar{E}_\nu dM} (1+z) \left| \frac{dt}{dz} \right| dz dM$$



(Bays et. al., [SuperK Coll.] PRD 2012)

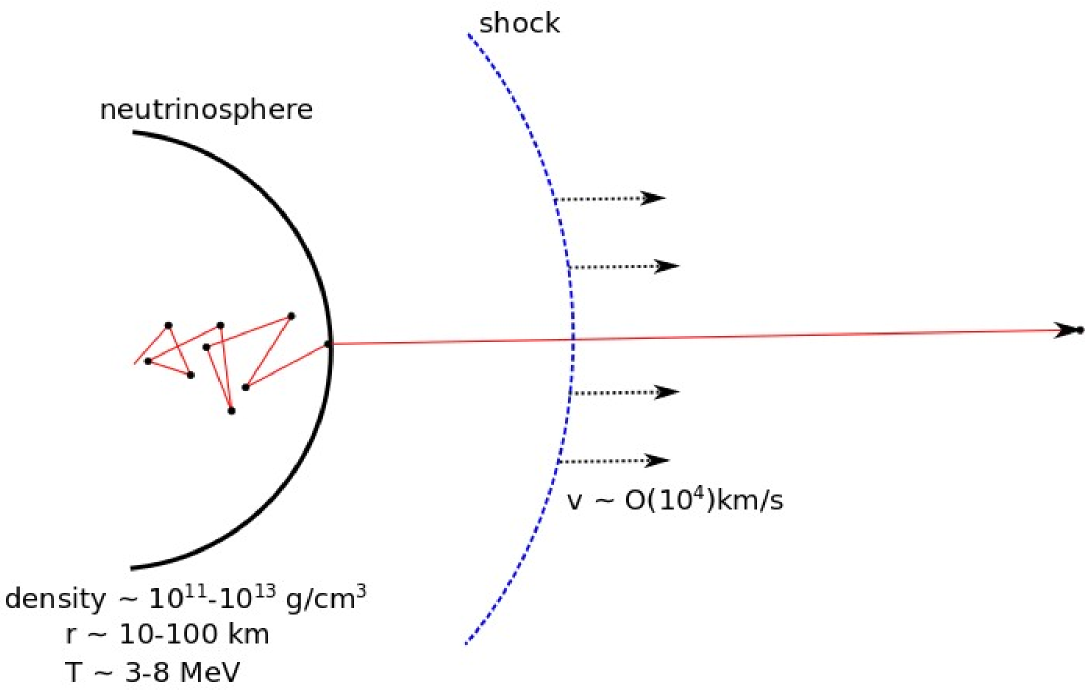
Better understanding of neutrino oscillations in supernovae allows us to extract more information!

Active-active Neutrino Oscillations in Supernovae

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 in flavor space



Neutrino flavor evolution :

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

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

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

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

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

Neutrino flavor evolution :

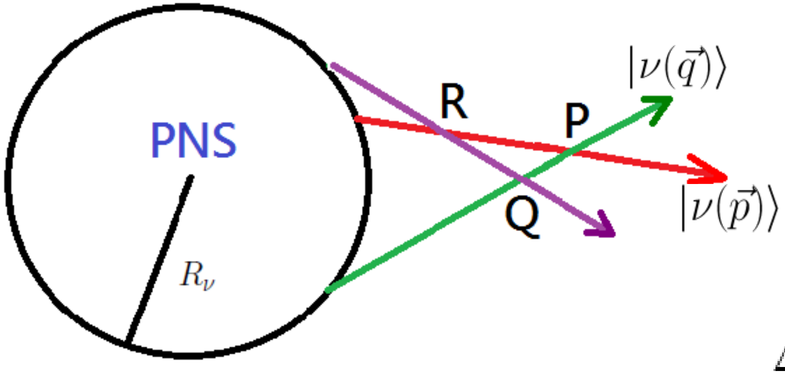
$$i\frac{d}{dt}|\nu\rangle = \left(H_{\rm vac} + H_m + H_\nu\right)|\nu\rangle \quad , \; |\nu\rangle = \left[a_e, a'_\mu, a'_\tau\right]^\dagger$$

neutrino-neutrino term :

(Fuller, et. al., 1987; Pantaleone, 1992;
Sigl & Raffelt, 1992; Pehlivan & Balantekin 2006)

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

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



=> coupled non-linear equation

=> collective neutrino oscillations
would occur closer to the PNS

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

Why “collective”?

Two flavor, pure isotropic neutrino gas :

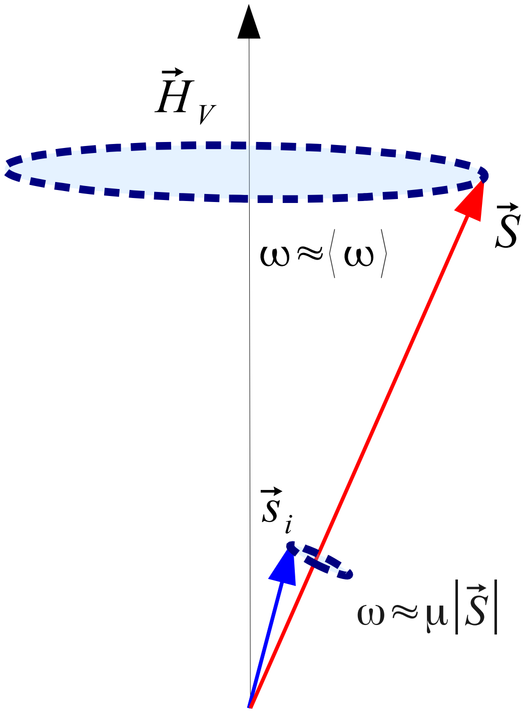
Neutrino “spin” : $\vec{s}_\nu \equiv \langle \nu | \vec{\sigma}/2 | \nu \rangle = \frac{1}{2}\begin{pmatrix} 2\Re(a_e^* a_x) \\ 2\Im(a_e^* a_x) \\ |a_e^2| - |a_x^2| \end{pmatrix}$

$$\frac{d\vec{s}_i}{dt} = \vec{s}_i \times \left(\omega_i \vec{H}_V - \mu \sum_j \vec{s}_j \right) \qquad \omega_i \equiv \frac{|\delta m^2|}{2E_i} \qquad \mu \equiv 2\sqrt{2} G_F n_\nu$$

$$when \ \ \mu \gg \omega_i, \ \frac{d\vec{s}_i}{dt} \approx -\mu \vec{s}_i \times \vec{S}$$

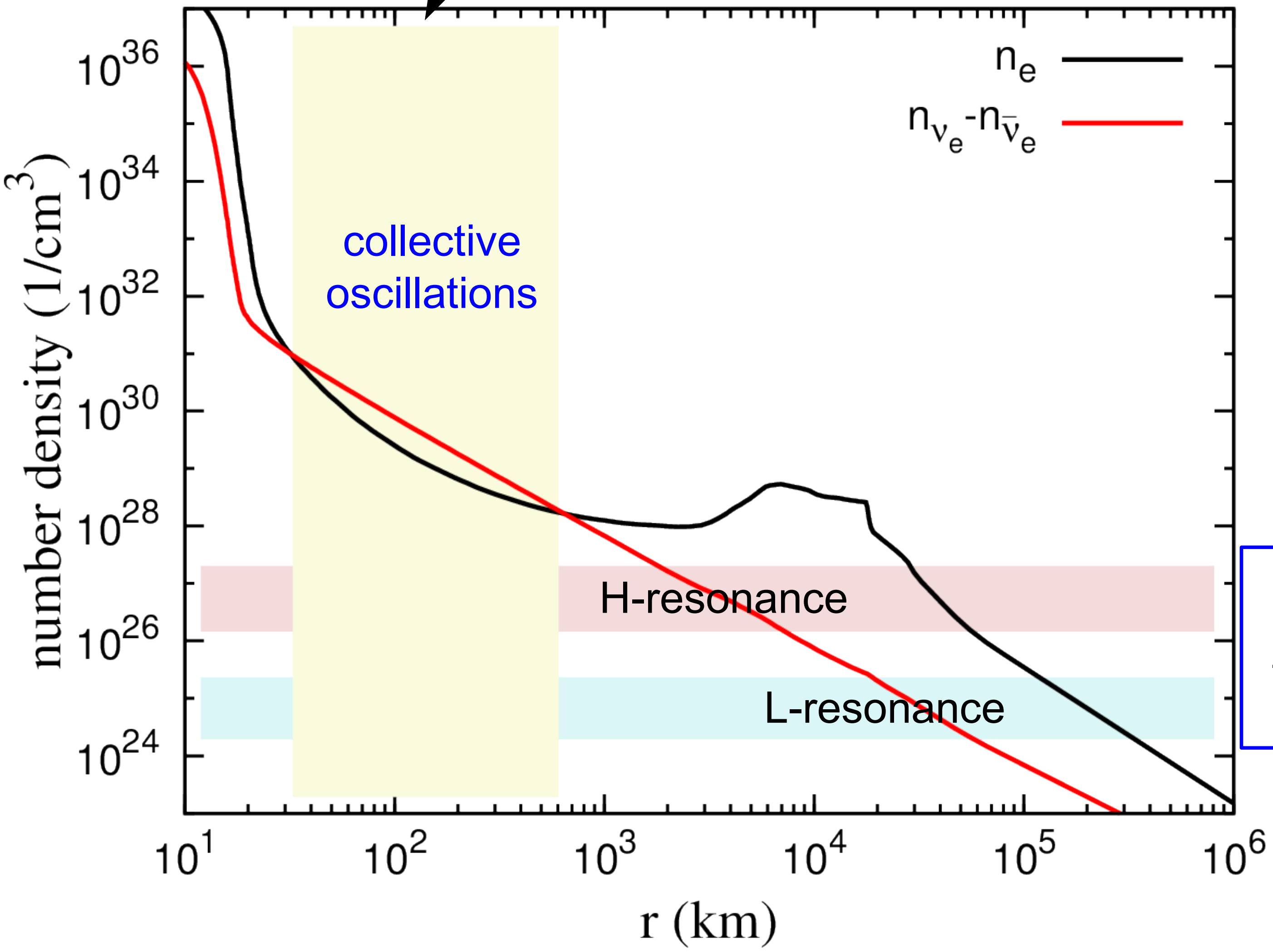
→ every neutrino “spin” essentially aligns with $\vec{S}$

$$\Rightarrow \frac{d\vec{S}}{dt} \approx \langle\omega\rangle \vec{S} \times \vec{H}_V$$



All neutrino “spins” precess (oscillate) around $\vec{H}_V$ with a collective frequency $\langle\omega\rangle$.

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

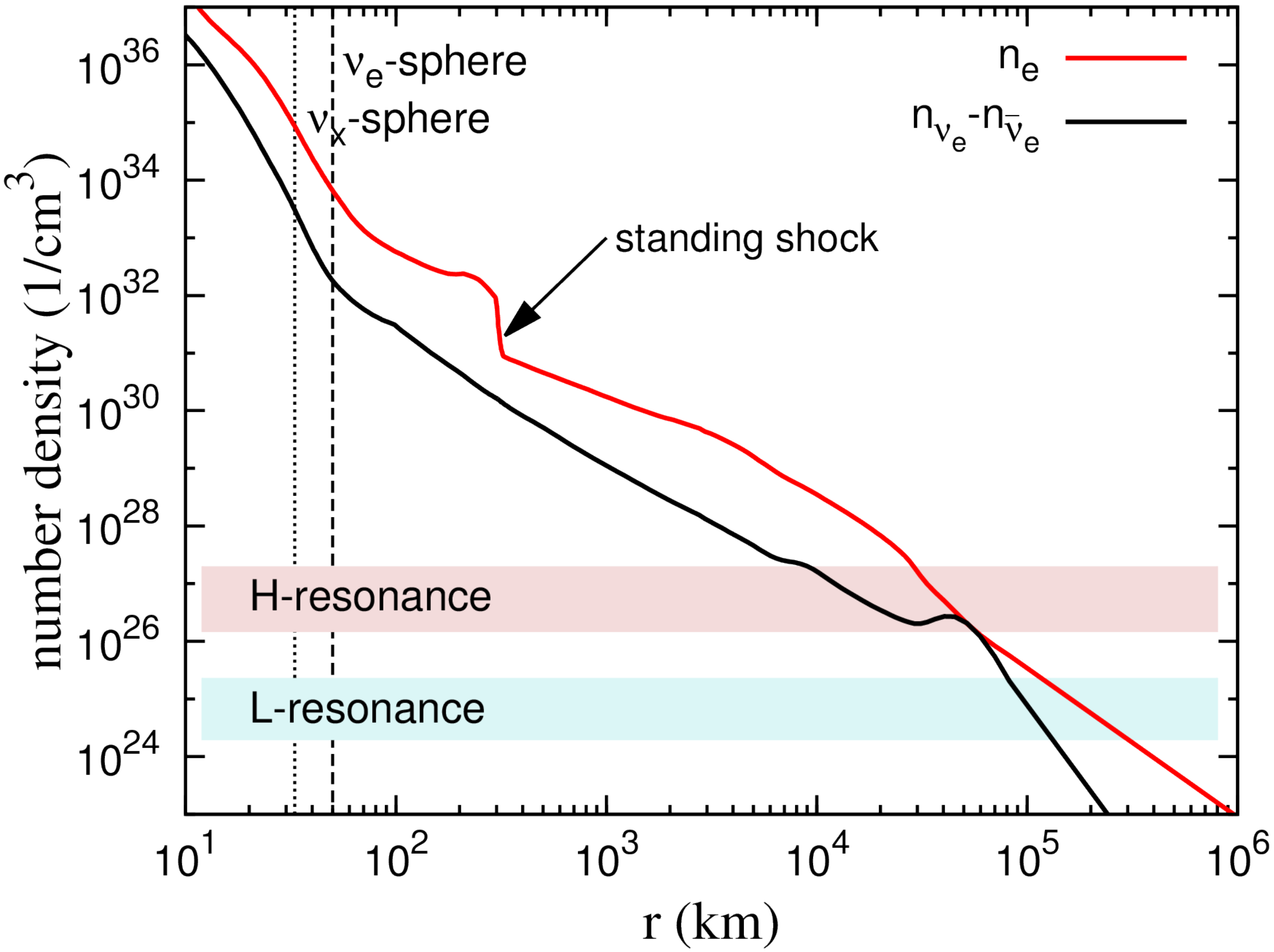


$$\frac{\Delta m^2_{ij}}{2E_\nu} \approx \sqrt{2}G_F n_e$$

	Shock Revival ~O(10^2 km)	v-driven Wind ~O(10^3 km)	v-induced nucleosynthesis in He shell ~O(10^5 km)	Neutrino signals
Collective Oscillations	No(?)	Maybe	Yes	Yes
MSW H-resonance	No	No	Yes	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.

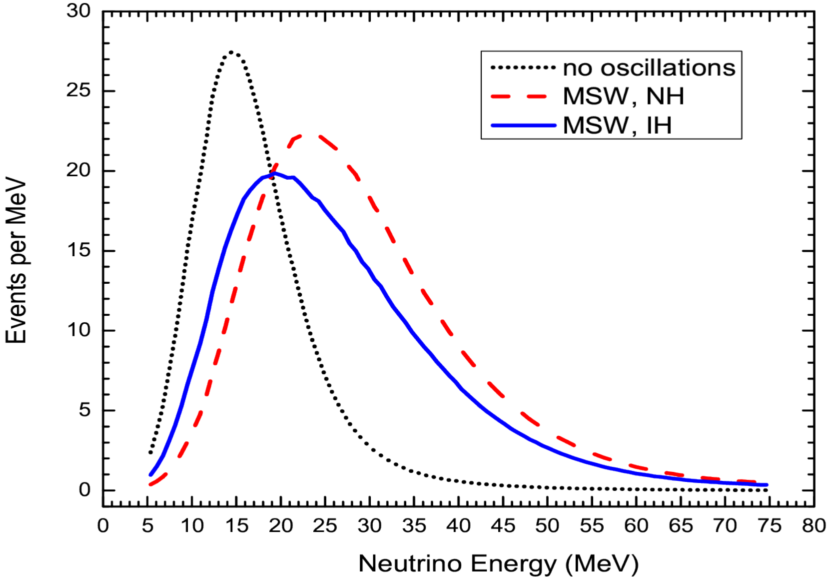


Neutrino signals and mass hierarchy

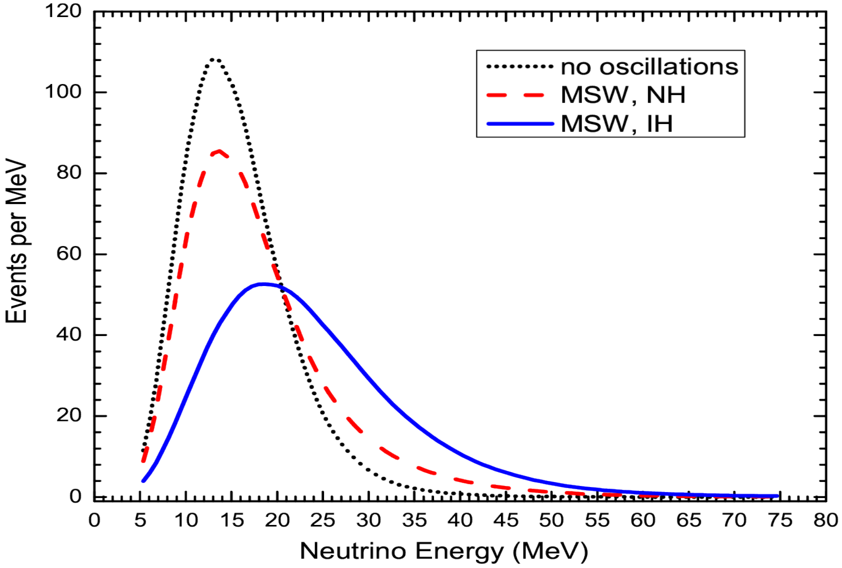
In the accretion phase of Fe-core SN, collective oscillations are expected to be suppressed by the large matter potential.

→ possibility of using SN signal to distinguish the neutrino mass hierarchy by comparing the event rates and spectra using multiple detection channels.

ν_e signal @ 34k-ton LAr detector



$\bar{\nu}_e$ signal @ Super-K



(MRW, Qian, Martinez-Pinedo, Fischer, in preparation)

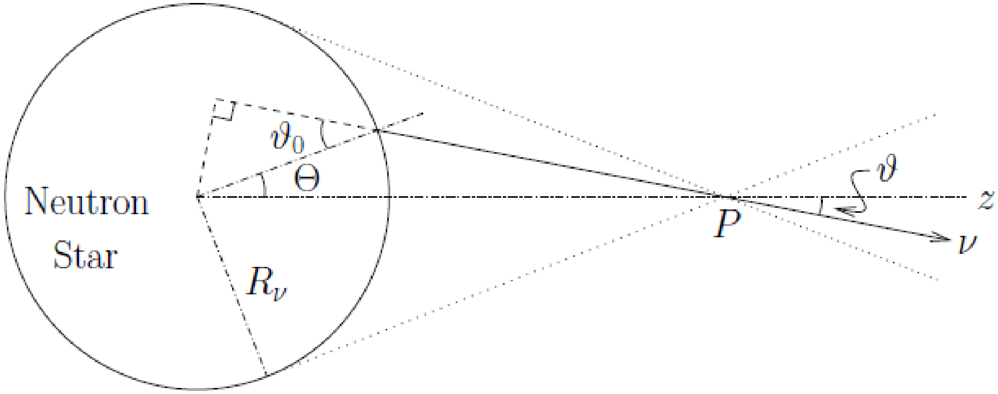
Neutrino-bulb model for collective oscillations

(Duan et. al., PRD 74, 105014, 2006)

- Supernova environment is spherically symmetric.
- All neutrinos are emitted from a sharp neutrinosphere.
- All neutrinos are in pure flavor states at the neutrino sphere.

→ ray-tracing neutrinos with different energy E_ν and emission angle *θ*.

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



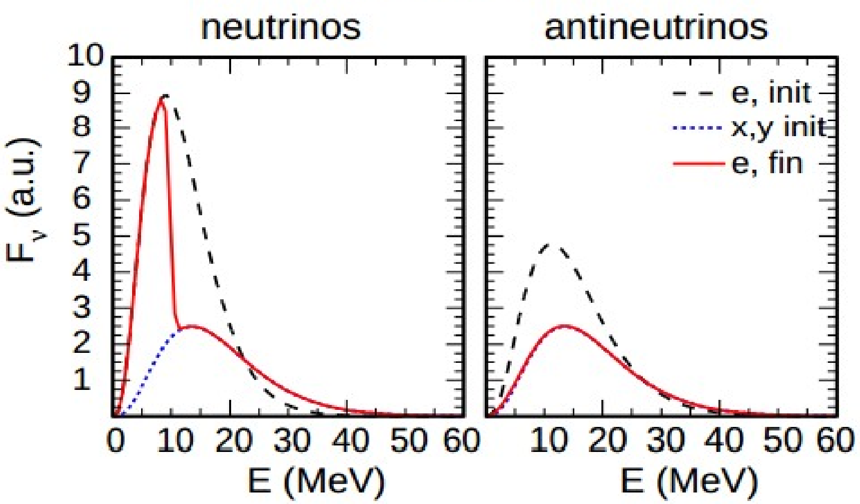
Spectral splits (swaps) :

The collective frequency

$$\langle \omega \rangle = \int \frac{\delta m^2}{2E_\nu} f_\nu(E_\nu, \mu) dE_\nu d\mu$$

gives rise to the “spectral splits” (“spectral swaps”)

(Raffelt 2007, 2011. Duan et. al. 2007. Dasupta et. al., 2009. MRW & Qian 2011, Volpe et. al., 2011)



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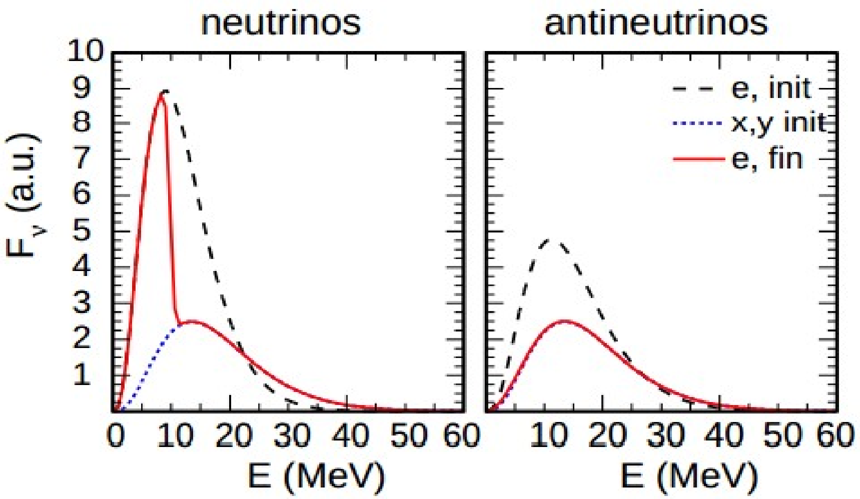


Warning :

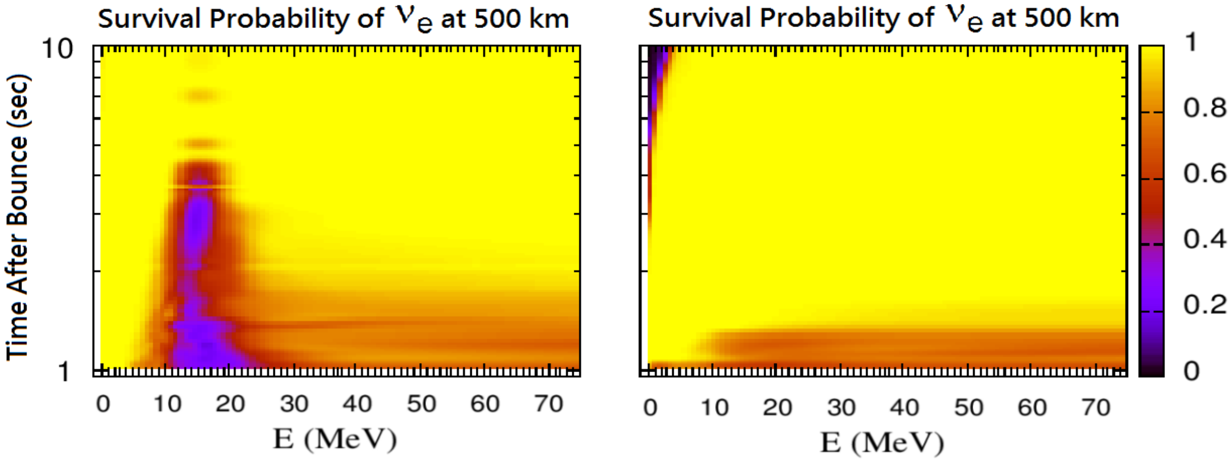
The results sensitively depend on :

(a) relative spectra of electron (anti)neutrinos and mu/tau (anti)neutrinos.

(b) competition of matter potential and neutrino-neutrino potential.

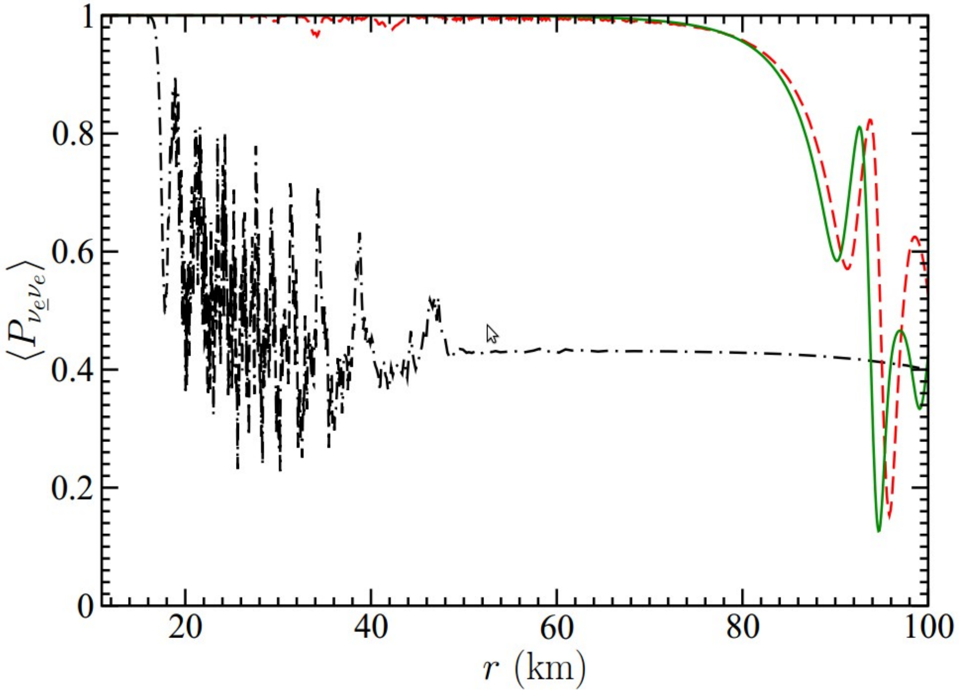
(MRW, Qian, Martinez-Pinedo, Fischer, in preparation)

→ possibility to explore the micro-physics that determines the neutrino spectra.



Problems of the neutrino-bulb model :

- Numerically, requires a large numbers of angular bins/modes (~10^2-10^4) to prevent spurious flavor instability.



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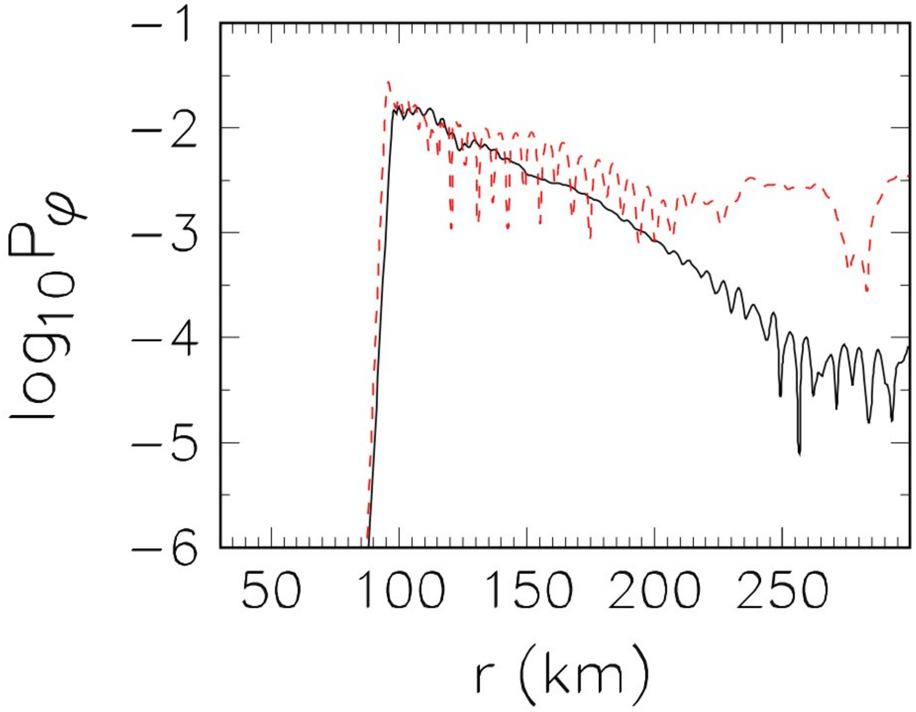
- Numerically, requires a large numbers of angular bins/modes (~10^2-10^4) to prevent spurious flavor instability.

- Break down of spherical symmetry from the azimuthal-angle induced instability → ultimate need of reduced 6-D problem? (Raffelt et. al, PRL, 2013)



$$\bar{P}_\phi \propto \int_0^{2\pi} d\phi (\cos\phi) |a_e^* a_x|^2$$

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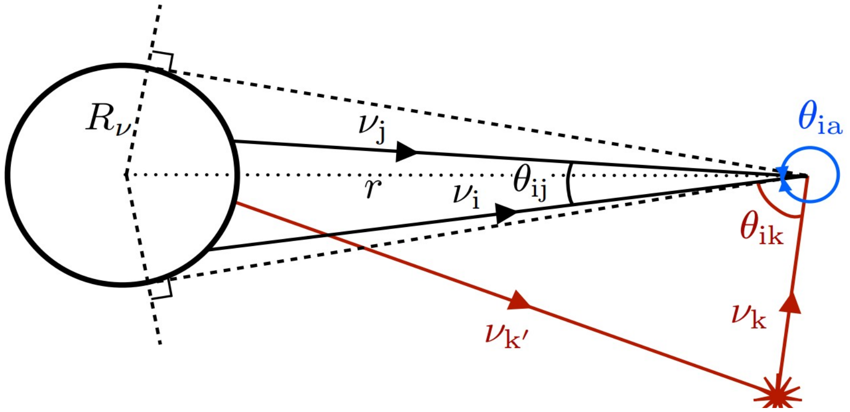
- Are the two regimes (Boltzmann & Schrodinger-like) really separable?

(Cherry et. al, PRL, 2012)



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- Break down of spherical symmetry from the azimuthal-angle induced instability → ultimate need of reduced 6-D problem?

- Are the two regimes (Boltzmann & Schrodinger-like) really separable?

- Is there any neutrino-antineutrino coherent flavor transformation near the neutrinosphere? (Volpe et. al, PRD, 2013, Vlasenko et. al., 2013)

More works to be done both analytically and numerically!

Summary (I)

- Neutrinos play essential roles in core-collapse supernovae. To really understand their effects in supernovae and to extract more information from SN neutrino signals, it is important to understand their flavor transformation.

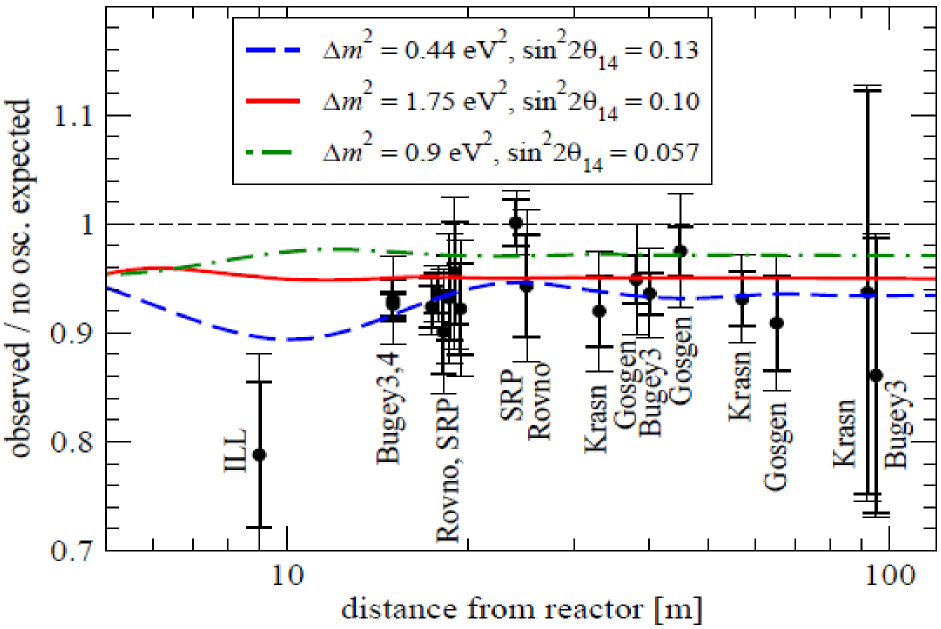
- If collective neutrino oscillations are suppressed during the accretion phase of Fe-CCSNe. There is a possibility of using the neutrino signals to identify the neutrino mass hierarchy.

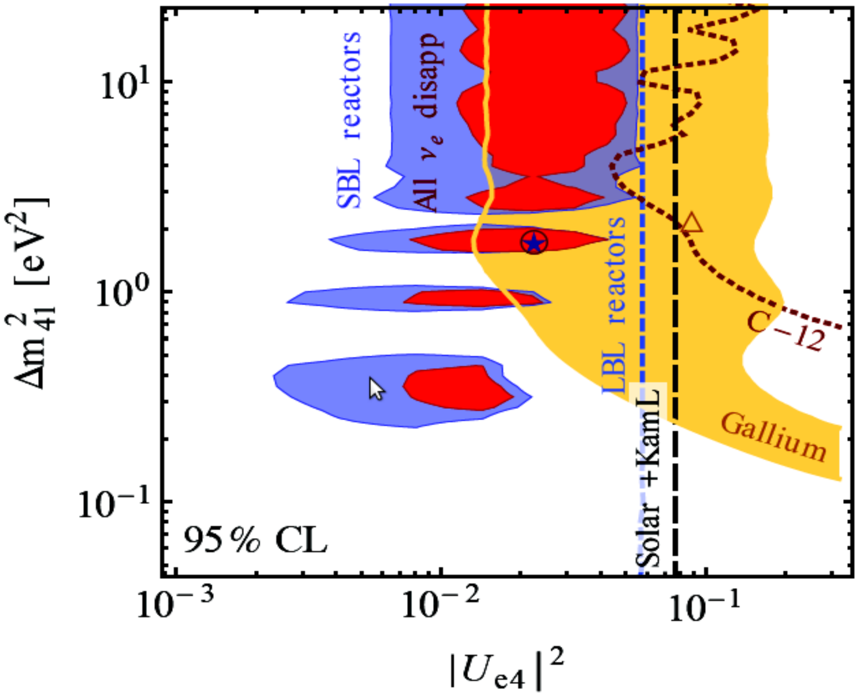
- Collective neutrino oscillations among active flavors typically produce spectral splits/swaps. However, many more challenges are still ahead of us.

Active-sterile Neutrino Oscillations in Supernovae

eV sterile neutrinos?

(Kopp, Machado, Maltoni, Schwertz, JHEP05 (2013) 050)





The anomaly of electron antineutrino disappearance experiments from short-baseline reactors & Gallium solar neutrino experiments may be accounted for by introducing eV scale sterile neutrinos.

In 3+1 scheme : $P_{ee}^{\rm SBL,3+1} = 1 - 4|U_{e4}|^2(1-|U_{e4}|^2)\sin^2\frac{\Delta m_{41}^2 L}{4E} = 1-\sin^2 2\theta_{ee}\sin^2\frac{\Delta m_{41}^2 L}{4E}$

$$\delta m_{14}^2 \sim O(\mathrm{eV}^2), \quad \sin^2 2\theta_{14} = \sin^2 2\theta_{ee} \sim 0.1$$

Hints from different experiments/observations

- LSND, MiniBooNE

- Long-base line accelerator experiments

- Cosmology/BBN

- Solar Neutrinos

Role of eV sterile neutrinos in supernovae?

First pointed out in [Nunokawa, Peltoniemi, Rossi & Valle, PRD 56, 1704(1997)]
that eV sterile neutrinos might have effects on shock-revival and electron fraction
In the ejecta.

However, the feedback on the electron-to-baryon ratio (Ye) was not treated
in a consistent manner.

Neutrino oscillations in medium

With two-flavor approximation and in the free-streaming regime, the neutrino flavor evolution is governed by the vacuum Hamiltonian + matter-induced Hamiltonian :

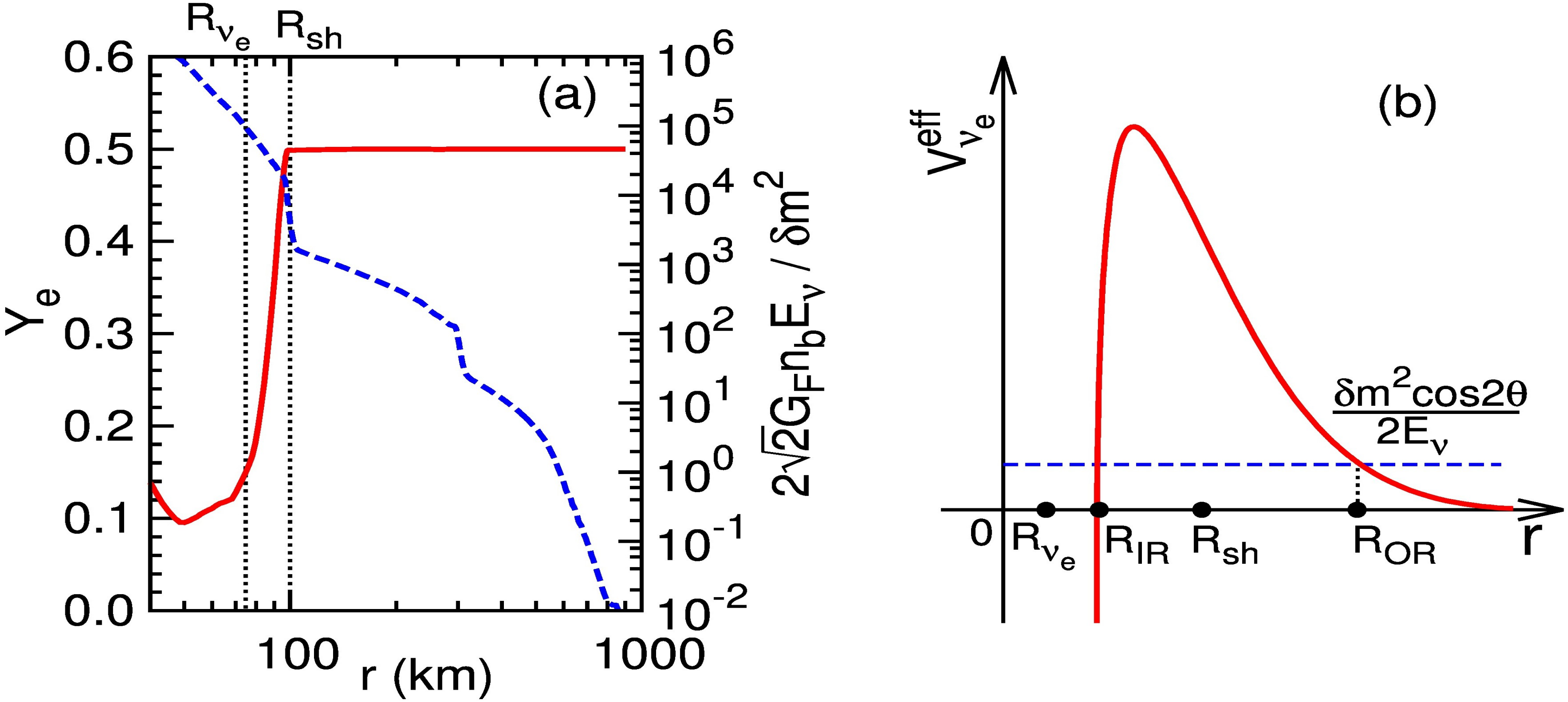
$$H_{\rm vac} = \frac{\delta m^2_{14}}{4E_\nu}\begin{bmatrix} -\cos 2\theta_{14} & \sin 2\theta_{14} \\ \sin 2\theta_{14} & \cos 2\theta_{14} \end{bmatrix}$$

$$\begin{aligned} H_{\rm m} &= \pm\frac{\sqrt{2}}{2}G_F n_b\left(Y_e - \frac{Y_n}{2}\right)\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \\ &= \pm\frac{3\sqrt{2}}{4}G_F n_b\left(Y_e - \frac{1}{3}\right)\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \end{aligned}$$

different from the MSW potential that for active flavors because of the neutral-current

=> MSW resonance : $\frac{\delta m^2_{14}}{4E_\nu}\cos 2\theta_{14} = \pm\frac{3\sqrt{2}}{4}G_F n_b\left(Y_e - \frac{1}{3}\right)$

Supernova profiles



- Because of the deleptoniztion that occurs during the collapse and the shock break-out, the electron-to-baryon ratio Ye ~ 0.1 around the neutrinosphere such that active-sterile MSW resonance could occur between the neutrinosphere and the shock.

- Collective neutrino oscillations are suppressed because at IR in bulb model, $\rho \sim 10^9 - 10^{11}\,\mathrm{g/cm^3}$ and $Y_e \gg Y_{\nu_e}$

MSW flavor transformation at the inner resonance

For neutrinos :

$$Y_e < \frac{1}{3}^{+}, \nu_L = \nu_e, \ \nu_H = \nu_s, \qquad Y_e > \frac{1}{3}^{+}, \nu_L = \nu_s, \ \nu_H = \nu_e$$

For antineutrinos :

$$Y_e < \frac{1}{3}^{-}, \bar{\nu}_L = \bar{\nu}_s, \ \bar{\nu}_H = \bar{\nu}_e, \qquad Y_e > \frac{1}{3}^{-}, \bar{\nu}_L = \bar{\nu}_e, \ \bar{\nu}_H = \bar{\nu}_s,$$

Electron (anti)neutrinos may be transformed to sterile (anti)neutrinos when they cross Ye~1/3.

MSW flavor transformation at the inner resonance

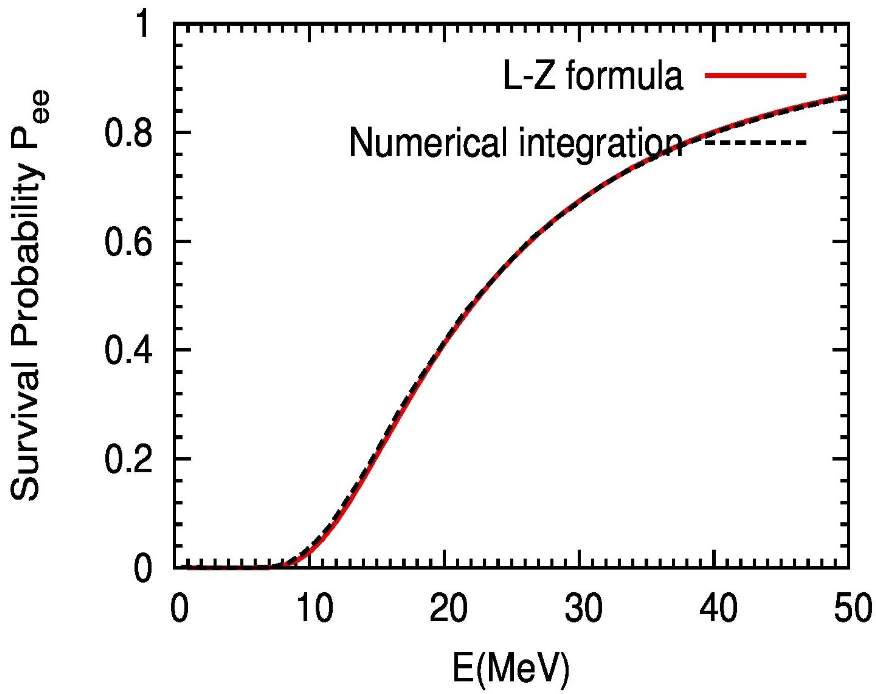
Landau-Zener survival probability :

$$P_{ee} = \exp\left(-\frac{\pi^2}{2}\frac{\Delta r}{L_{\rm osc}}\right)$$

The oscillation length at resonance :

$$L_{\rm osc} = \frac{4\pi E_\nu}{\delta m_s^2 \sin 2\theta_{14}},$$

$$\approx 45\ {\rm m}\left(\frac{E_\nu}{10{\rm MeV}}\right)\left(\frac{1.75{\rm eV}^2}{\delta m_s^2}\right)\left(\frac{0.1^{1/2}}{\sin 2\theta}\right)$$



The resonant width :

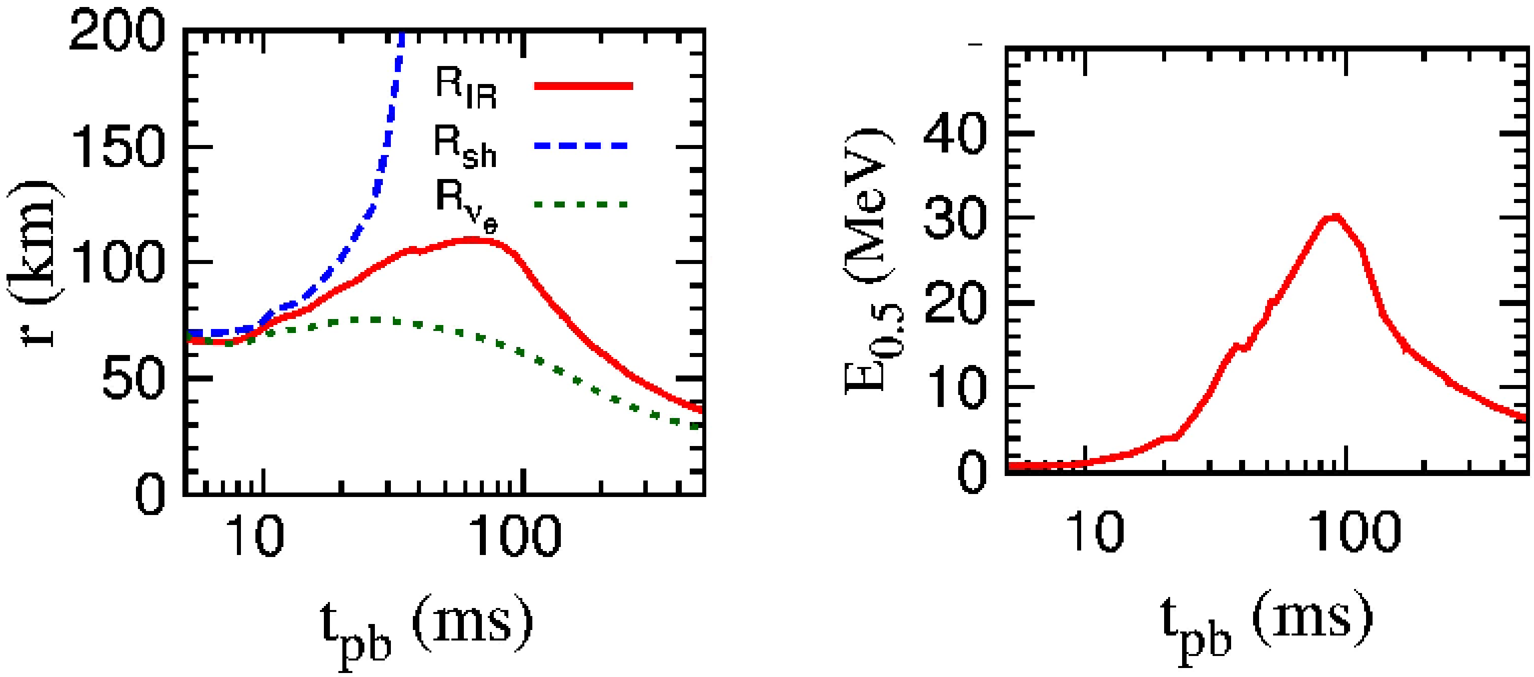
$$\Delta r \approx 2\tan 2\theta_{14}\left|\frac{Y_e - 1/3}{dY_e/dr}\right|_{\rm res}$$

$$\approx 50\ {\rm m}\left(\frac{0.1/10{\rm km}}{dY_e/dr}\right)\left(\frac{10^9 g/cm^3}{\rho}\right)\left(\frac{10{\rm MeV}}{E_\nu}\right)\left(\frac{\delta m_{14}^2}{1.75{\rm eV}^2}\right)\left(\frac{\sin 2\theta_{14}}{0.1^{1/2}}\right)$$

Time evolution of R_{IR} and $E_{0.5}$ with Ye from an 8.8 SN Model

- The inner resonance happens at radius that increases with shock expansion initially, and then retreats with PNS cooling later.

- $E_{0.5}$ follows the change of R_{IR}, exceeding the average neutrino energy ~ 10 MeV for substantial amount of time.



(MRW, Fischer, Martinez-Pinedo, Qian, arXiv:1305.2382)

Feedback on Ye profile?

Since (1) Ye is determined by the competition of rates of electron/positron and electron (anti)neutrino captures :

$$\nu_e + n \rightleftharpoons p + e^-$$

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

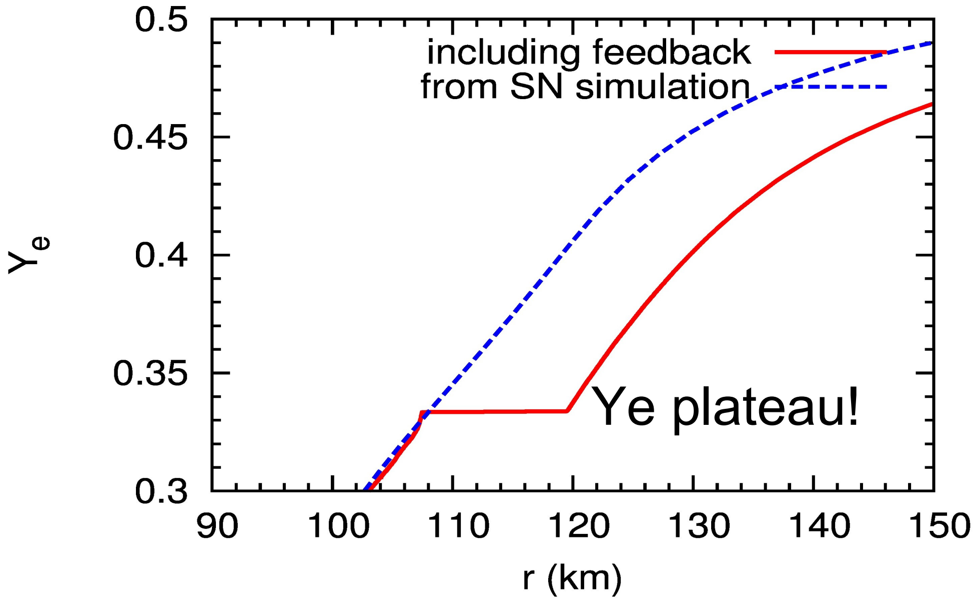
(2) electron (anti)neutrino capture rates are affected by the flavor oscillations which depends on Ye profiles

→ Need to evolve the Ye along with the active-sterile flavor transformation!

Feedback on Ye profile:

We follow the evolution of Ye for relevant mass shells, assuming the hydrodynamics are not affected.

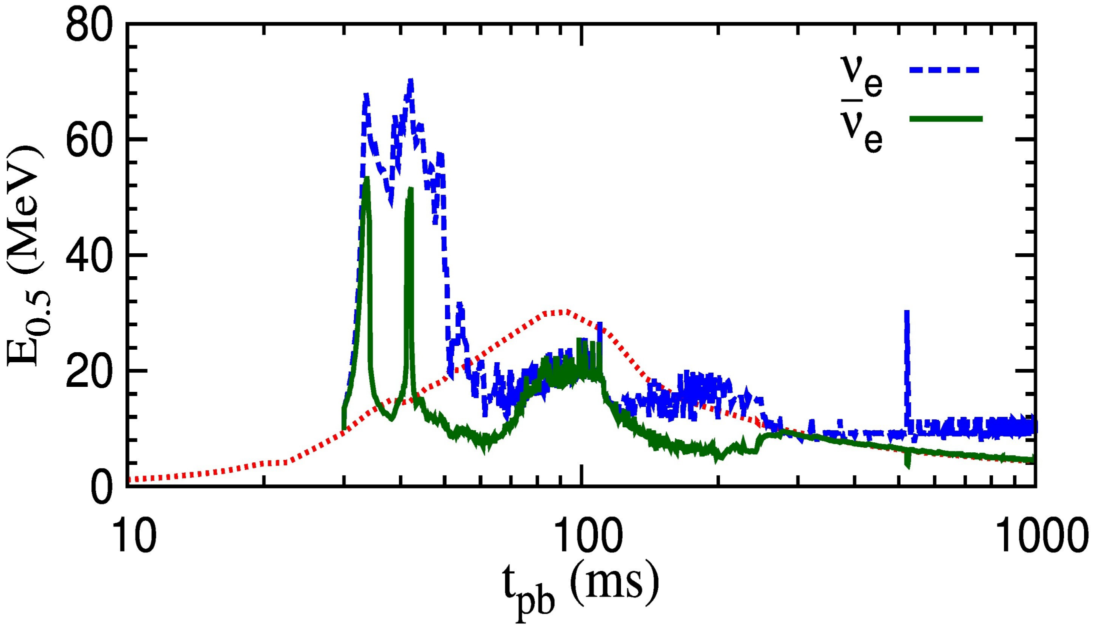
$$\frac{dY_e}{dt} = (\lambda_{\nu_e n} + \lambda_{e^+ n})Y_n - (\lambda_{\bar{\nu}_e p} + \lambda_{e^- p})Y_p$$



$$(-\dot{Y}_e)|_{R_{\mathrm{IR},\bar{\nu}_e} < r < R_{\mathrm{IR},\nu_e}} < (-\dot{Y}_e)|_{r < R_{\mathrm{IR},\bar{\nu}_e}} < (-\dot{Y}_e)|_{r > R_{\mathrm{IR},\nu_e}}$$

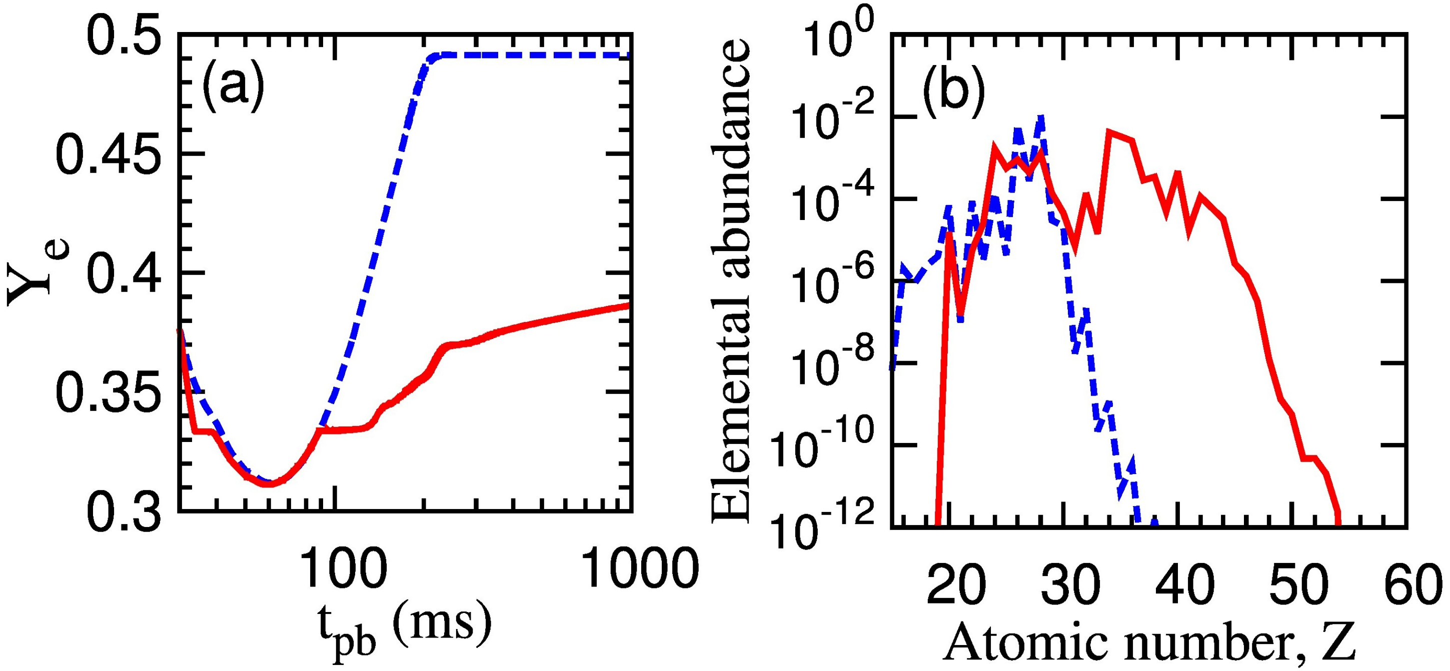
Effect on the oscillations

The formation of the Ye plateau breaks the degeneracy between neutrinos and antineutrinos and induces more flavor transformation in the shock expansion phase.



- Reduce the capture rates of electron neutrinos more than that of electron antineutrinos.
- Greatly reduce the *ν*-heating rates around the phase of shock break-out.

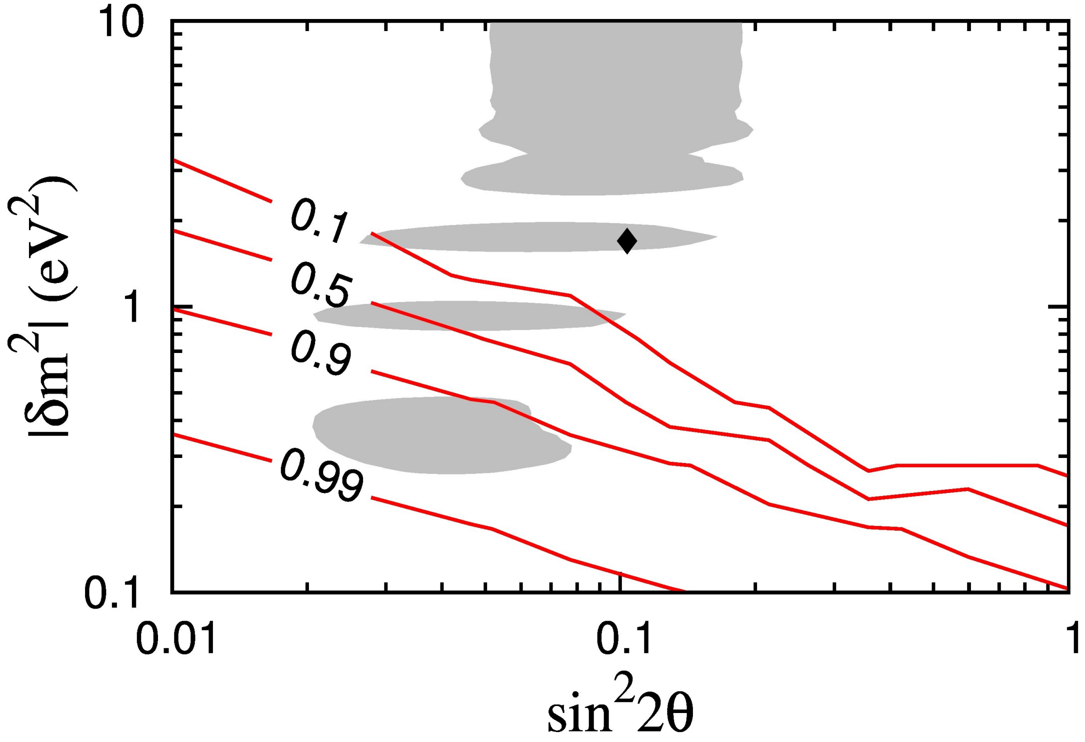
Effect on nucleosynthesis



- Ye at alpha freeze-out in the ejecta is reduced from ~0.5 to ~0.4.
- For the 8.8M⊙ SN model, the main products of nucleosynthesis shift from the iron peak to Sr-Ru.

Effect on ν-heating rates

The reduction of heating rate around the shock break-out :



Possibility of using SN models to constrain the parameter space of sterile neutrinos?

Summary (II)

- If light eV sterile neutrinos exist, active-sterile MSW flavor conversion in supernovae might happen between the neutrinosphere and the shock.

- The flavor conversion reduces the neutrino heating rates (dynamics) substantially and change the ratio of electron neutrino capture and electron antineutrino capture rates (nucleosynthesis).

- Including the feedback on Ye creates a plateau around Ye~1/3 and furthers enhance the effects.

- It would be interesting to include it in a supernova simulation to see if it could provide firm constraints on the parameter space of sterile neutrinos and study the signature in neutrino signals.

Thanks for your attention!