Neutrinos and Explosive Nucleosynthesis in Core-collapse Supernovae

Meng-Ru Wu (TU Darmstadt)

Tobias Fischer (U of Wroclaw), Lutz Huther (TU Darmstadt),
Gabriel Martinez-Pinedo (TU Darmstadt & GSI), Yong-Zhong Qian (U of Minnesota)

NAVI Meeting, 12/17/2013, GSI, Darmstadt, Germany

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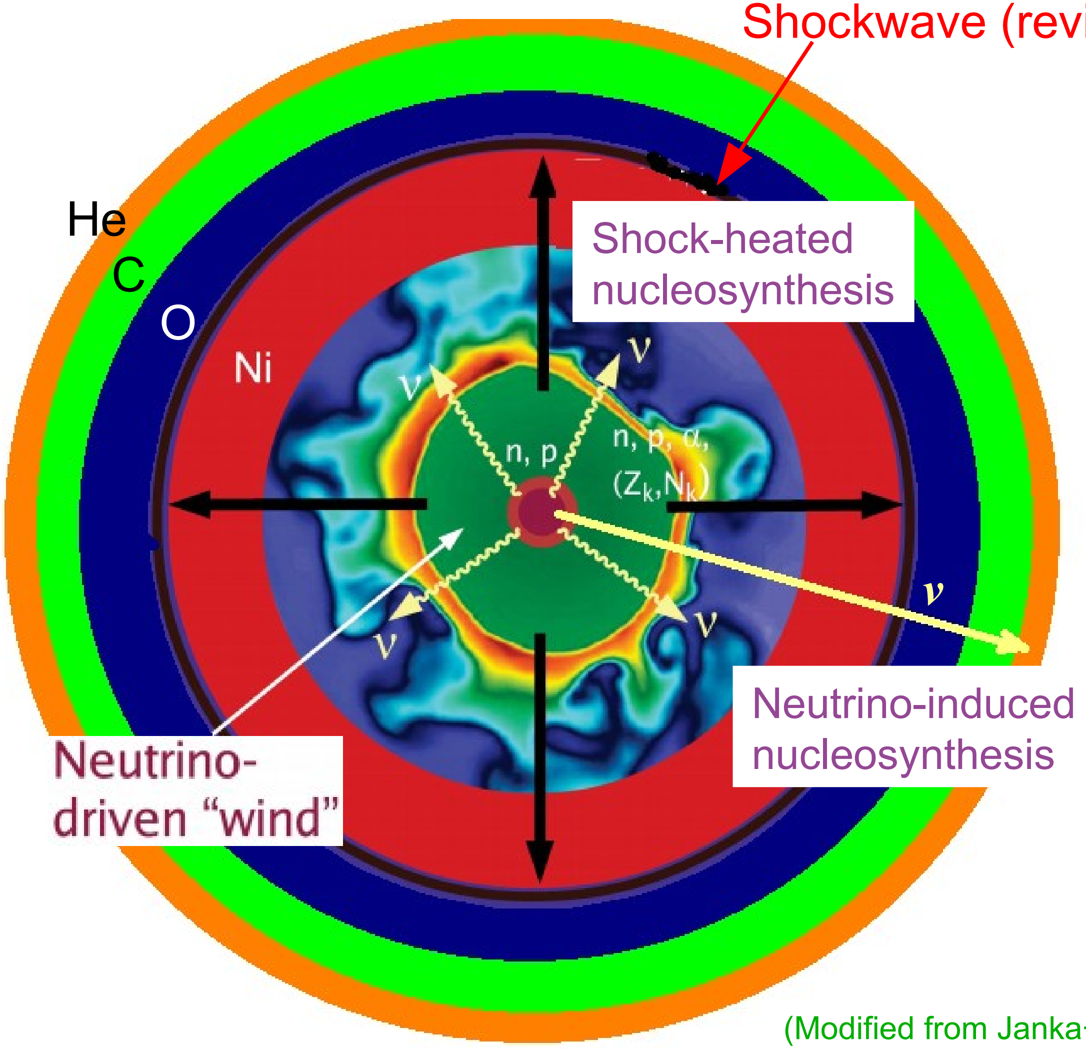
Neutrinos and nucleosynthesis in core-collapse supernovae

Energy source : gravity

$$E_G \approx \frac{3GM_{NS}^2}{5R_{NS}} \approx 3\times 10^{53}\ ergs\,!$$

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

Shockwave (revived mainly by neutrino-heating)



- Shock-heated nucleosynthesis
  → Elements below Fe group from nuclear burning.

- Neutrino-driven wind
  → nuclei with A $\lesssim$120.

- Neutrino nucleosynthesis
  → Light elements : Li, Be, B.
  r-process in He shell.

(see talks by Qian and Arcones)

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

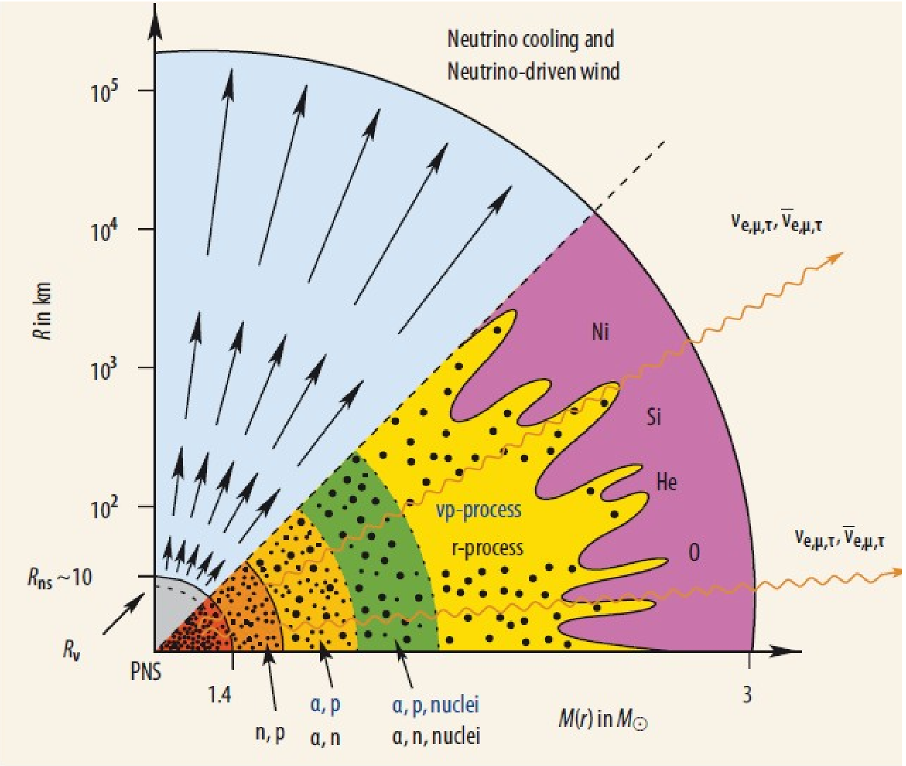
Explosive nucleosynthesis in CCSNe

The proton-to-neutron ratio is determined by neutrino interactions :

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

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

Assume (1) sub-dominant electron & positron capture rates and, (2) luminosities of electron neutrinos and electron antineutrinos being similar :



$$\langle E_{\bar{\nu}_e}\rangle - \langle E_{\nu_e}\rangle \gtrsim 4(m_n - m_p)$$ → neutron-rich ejecta, (weak) r process.

$$\langle E_{\bar{\nu}_e}\rangle - \langle E_{\nu_e}\rangle \lesssim 4(m_n - m_p)$$ → proton-rich ejecta, *ν*p process.

Results sensitive to the neutrino spectra → need models with detailed neutrino transport.

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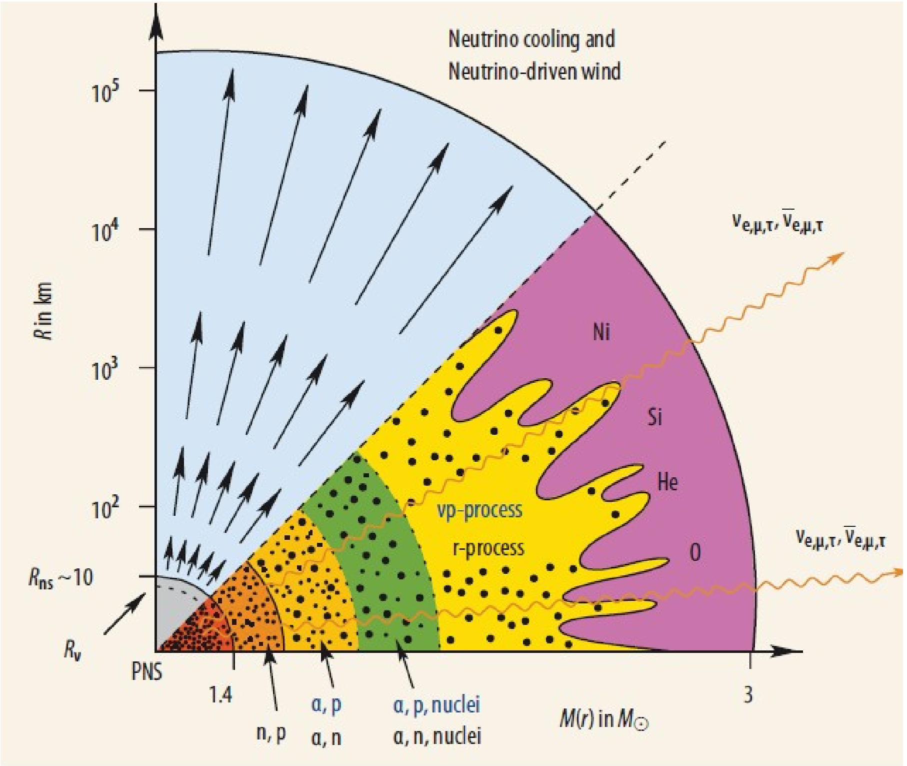

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Results sensitive to the neutrino spectra → need models with detailed neutrino transport.

- micro-physics in PNS determining the neutrino spectra at neutrinosphere.
- neutrino oscillations outside neutrinospheres.

Supernova models

- spherically symmetric hydrodynamics + 3 flavor Boltzmann neutrino transport.
- explosion triggered by enhanced neutrino absorption rates for Fe-core progenitors.

(Fischer+, A&A 517, 2010)

Supernova models with improved micro-physics

- spherically symmetric hydrodynamics + 3 flavor Boltzmann neutrino transport.
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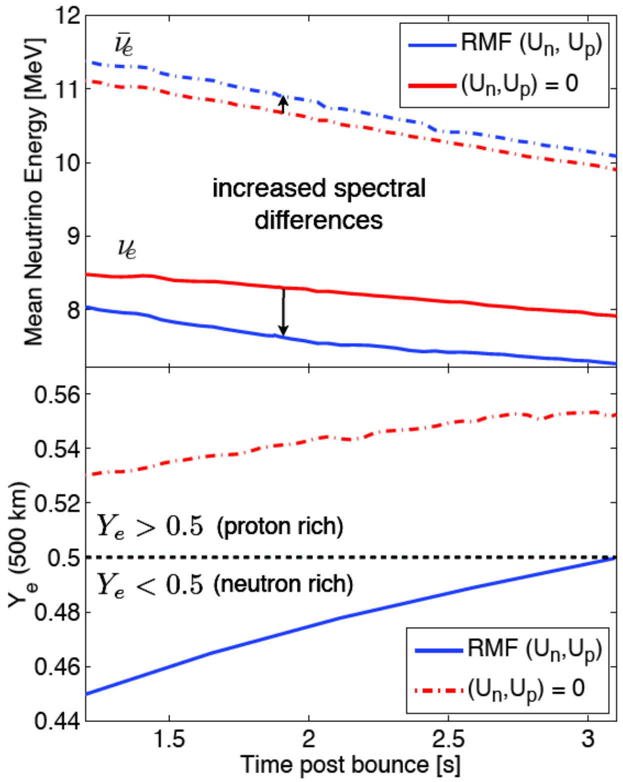
- weak interaction rates consistent with the nuclear equation of state.

(Martinez-Pinedo+ PRL 109, 2012; Roberts+ PRC 86, 2012)



With the inclusion of the mean field potential U_n and U_p of nucleons,
→ the neutrino opacity increases for electron neutrinos, but decreases for electron antineutrinos.

$$\chi(E_{\nu_e}) \propto (E_{\nu_e} + \Delta m^* + \Delta U)^2 \exp\left(\frac{E_{\nu_e} + \Delta m^* + \Delta U - \mu_e}{T}\right)$$

$$\chi(E_{\bar{\nu}_e}) \propto (E_{\bar{\nu}_e} - \Delta m^* - \Delta U)^2$$

$$\Delta U \equiv U_n - U_p > 0$$

With larger ΔU (i.e. larger nuclear symmetry energy)
→ larger energy difference between ν_e and $\bar{\nu}_e$.
→ lower Ye.
→ smaller neutrino luminosity.

Supernova models with improved micro-physics

- spherically symmetric hydrodynamics + 3 flavor Boltzmann neutrino transport.
- explosion triggered by enhanced neutrino absorption rates for Fe-core progenitors.
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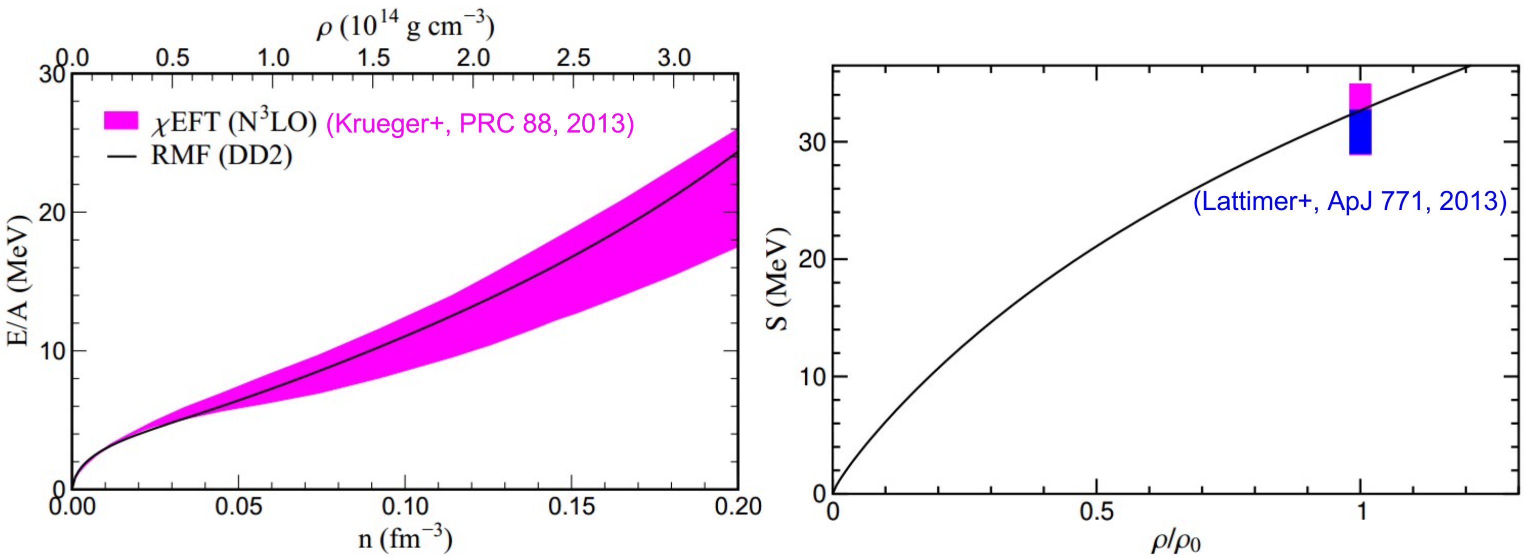
- nuclear equation of state consistent with theoretical and experimental constraints.

(Typel+, PRC 81, 2010; Hempel+, ApJ 748, 2012)



[Martinez-Pinedo, Fischer & Huther, arXiv:1309.5477, 2013]

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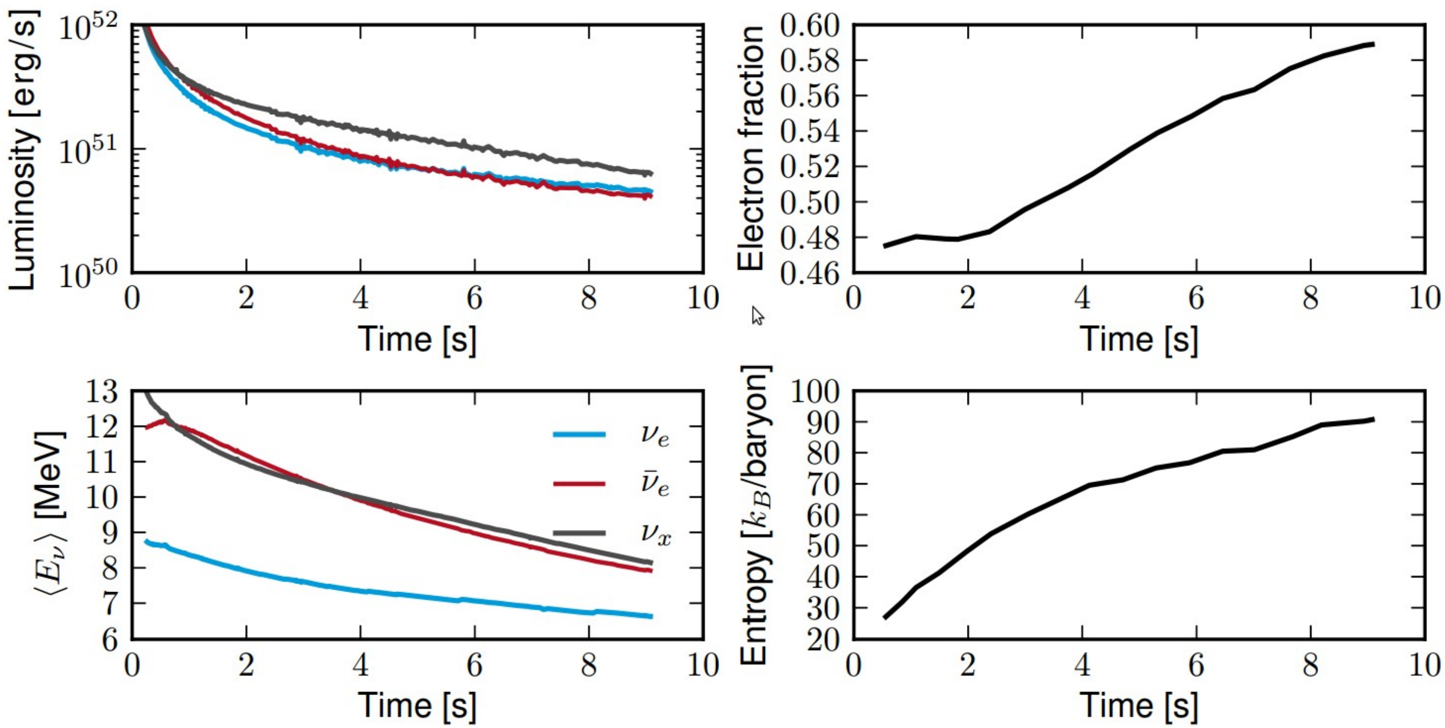
Long-term evolution of neutrino & wind characteristics for an 11.2 $M_{\odot}$ model :

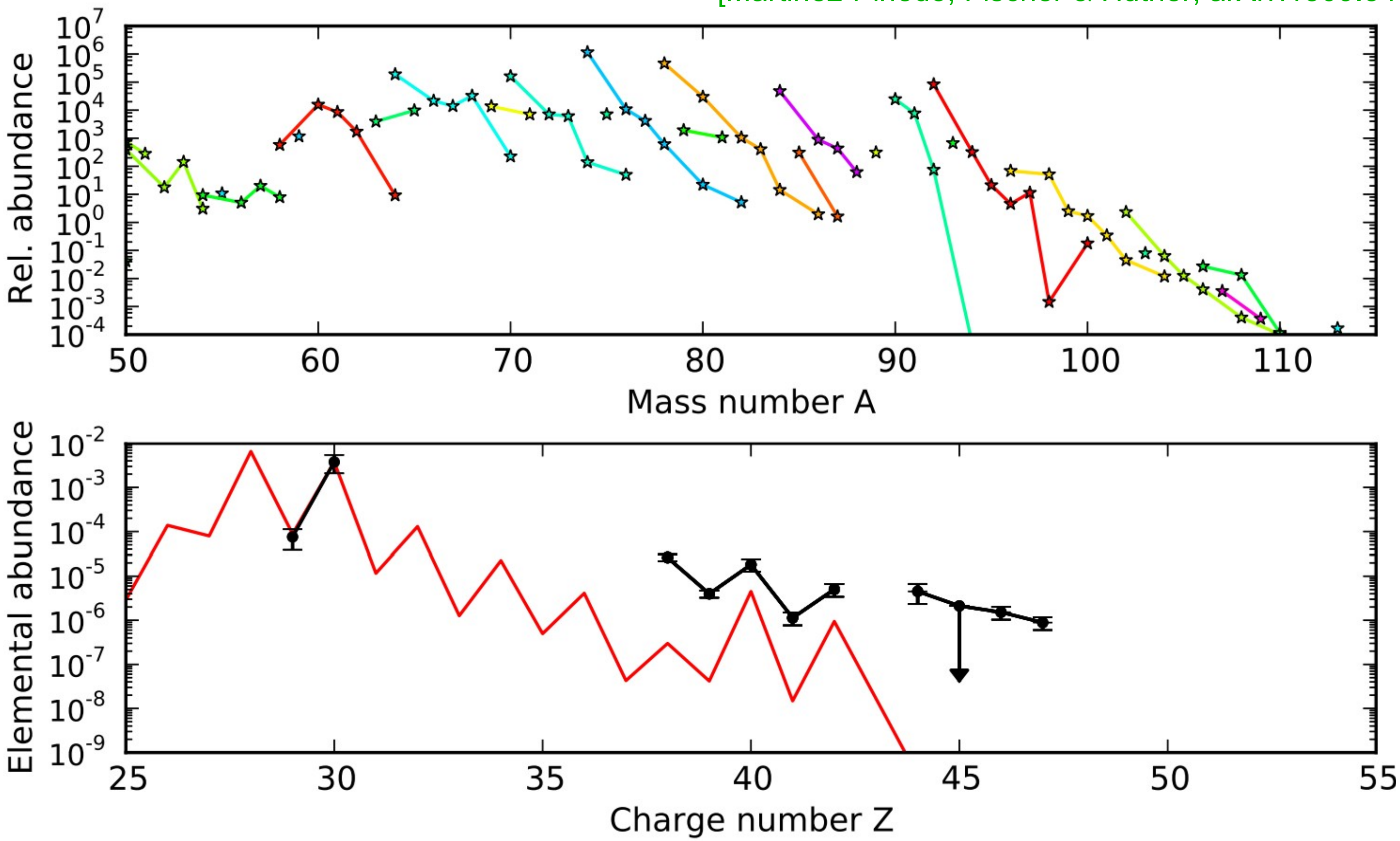


[Martinez-Pinedo, Fischer & Huther, arXiv:1309.5477, 2013]

Integrated nucleosynthesis

- produce elements around Z=40 such as Sr, Y, Zr, but not beyond Mo (Z=42).
- neutron-deficient isotopes are produced (ex: ^{92}Mo).
- production is dominated by the slightly neutron-rich ejecta at earlier time.

[Martinez-Pinedo, Fischer & Huther, arXiv:1309.5477, 2013]



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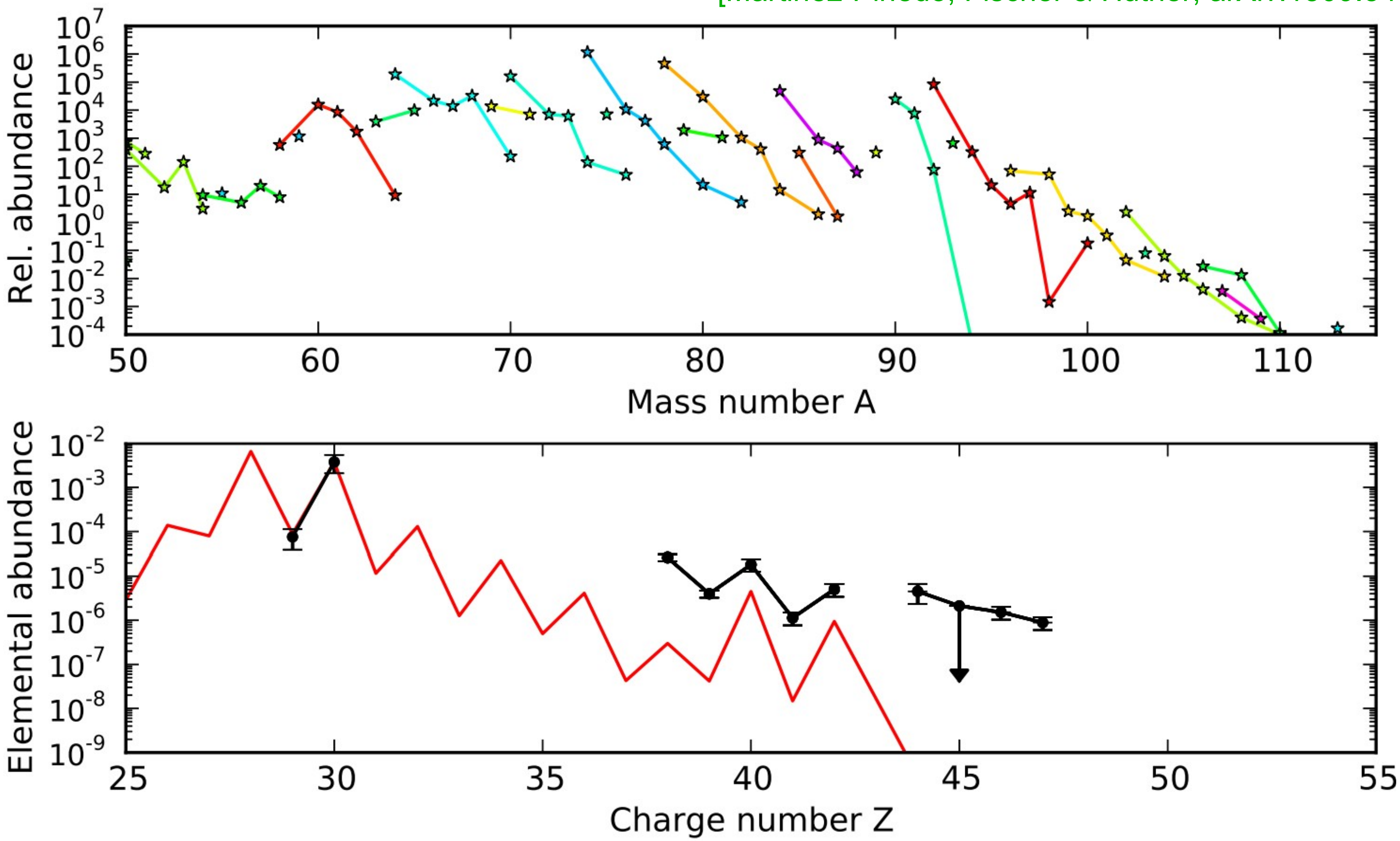
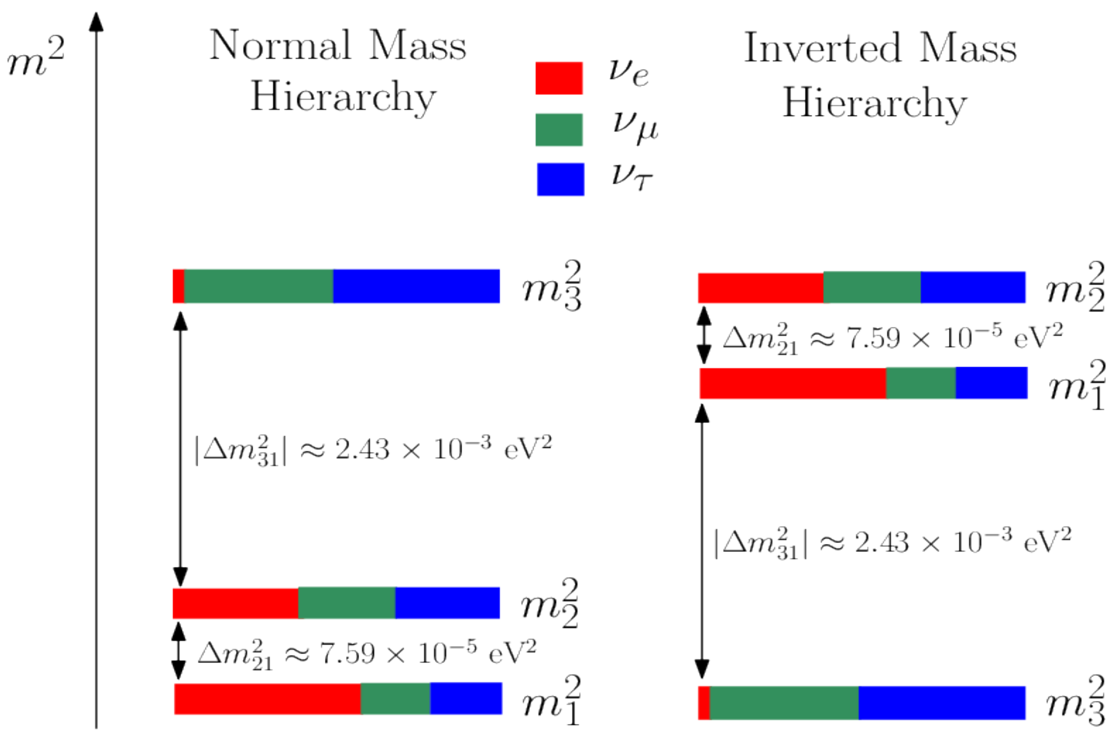


similar results in models with different progenitor mass?
something missing or produced in other sites?

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 :

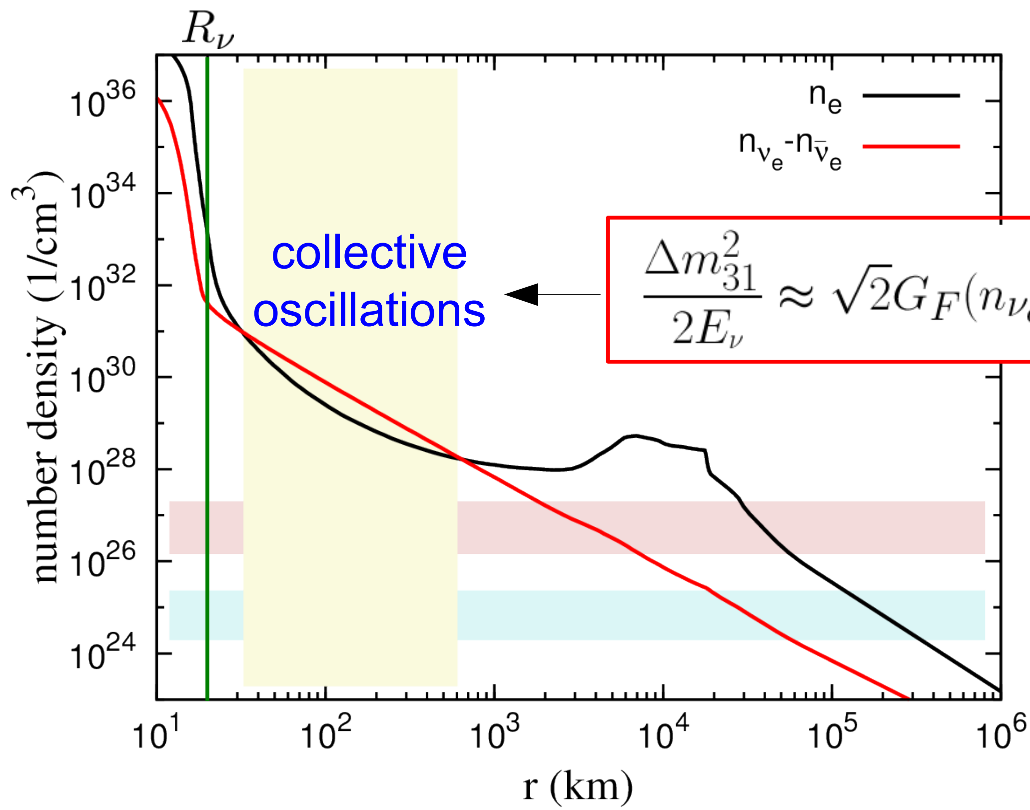
$\theta_{12} \approx 34^\circ$

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

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

unknowns :
mass hierarchy, CP phases
absolute neutrino mass

Active neutrino oscillations in supernovae



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

Collective oscillations : (Duan, et. al, 2006-2013, Raffelt, et. al., 2006-2013, ...)

- large neutrino flux above the neutrinosphere.
- dominant neutrino-neutrino forward-scattering potential.
- neutrino flavor evolution of different energy and trajectory couple with each other.
- sensitive to the neutrino spectra.

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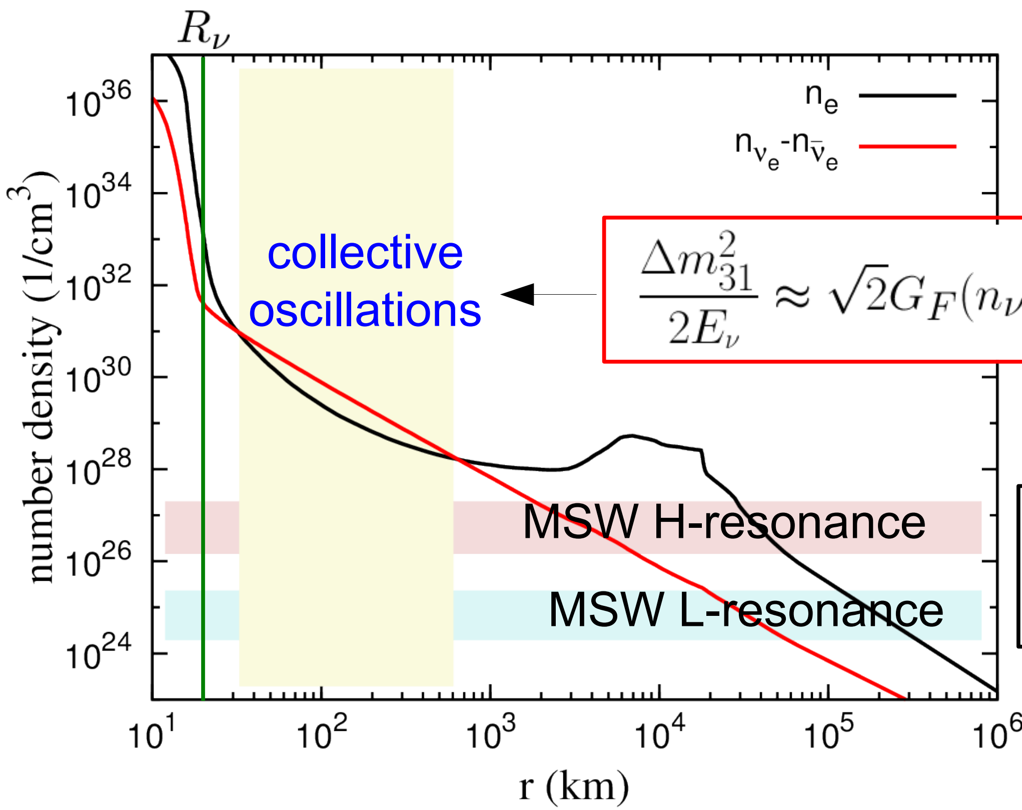

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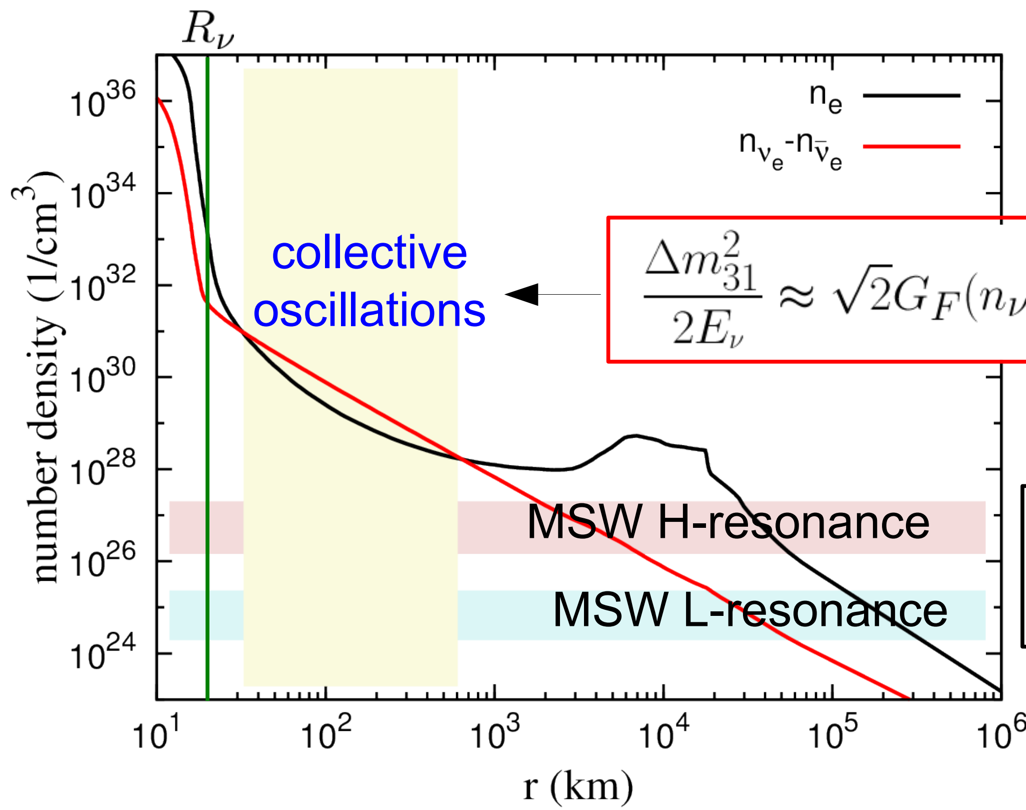
MSW oscillations :

- mostly adiabatic, might be affected by the passing of the supernova shock.

Active neutrino oscillations in supernovae



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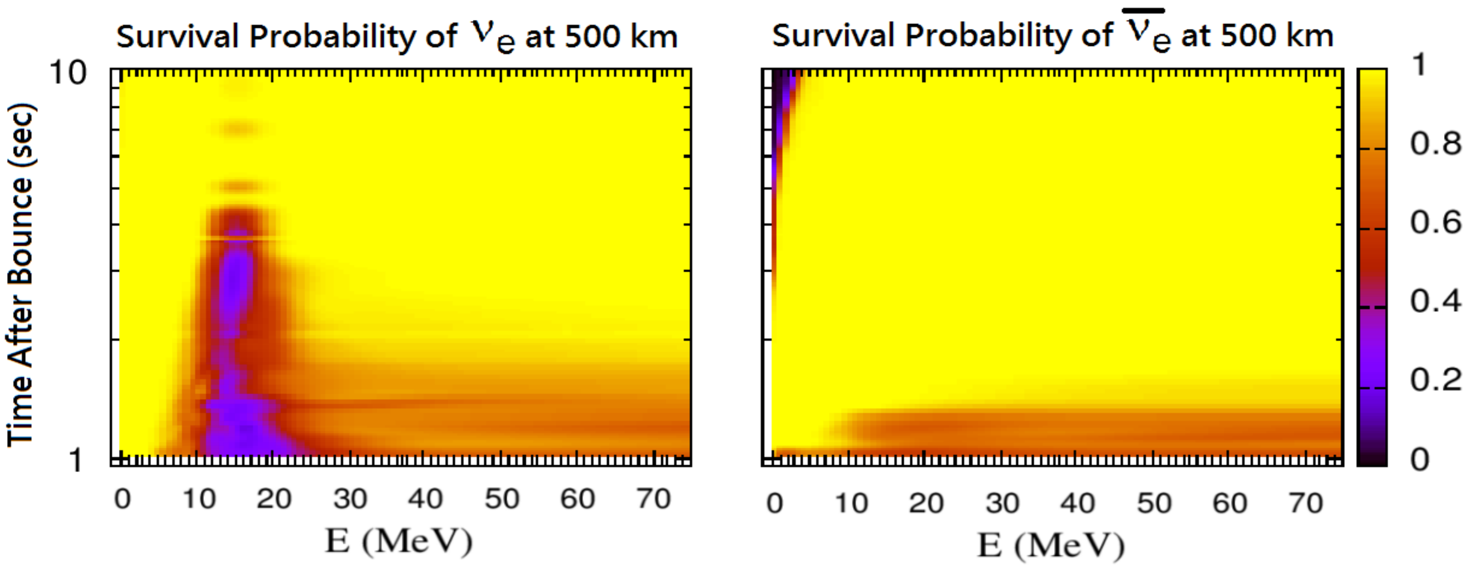
	Shock Revival ~O(10^2 km)	ν-driven Wind ~O(10^3 km)	ν-induced nucleosynthesis in outer shells ~O(10^5 km)	Neutrino signals
Collective Oscillations	No(?) (Chakraborty + 2011 Dasgupta + 2012)	Maybe (GMP + 2011, Duan + 2012)	Yes	Yes (Gava + 2009 Dighe + 2000 Tomas+ 2004 ……… ………)
MSW H-resonance	No	No	Yes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

Collective neutrino oscillations

- 18 $M_\odot$, spherically symmetric, without mean-field potential.
- Time-dependent neutrino spectra, luminosity and matter density from the SN model.
- Ray-tracing neutrino flavor evolution with different energies and emission angles.
- map out the neutrino spectra including oscillations for the whole wind-phase.

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



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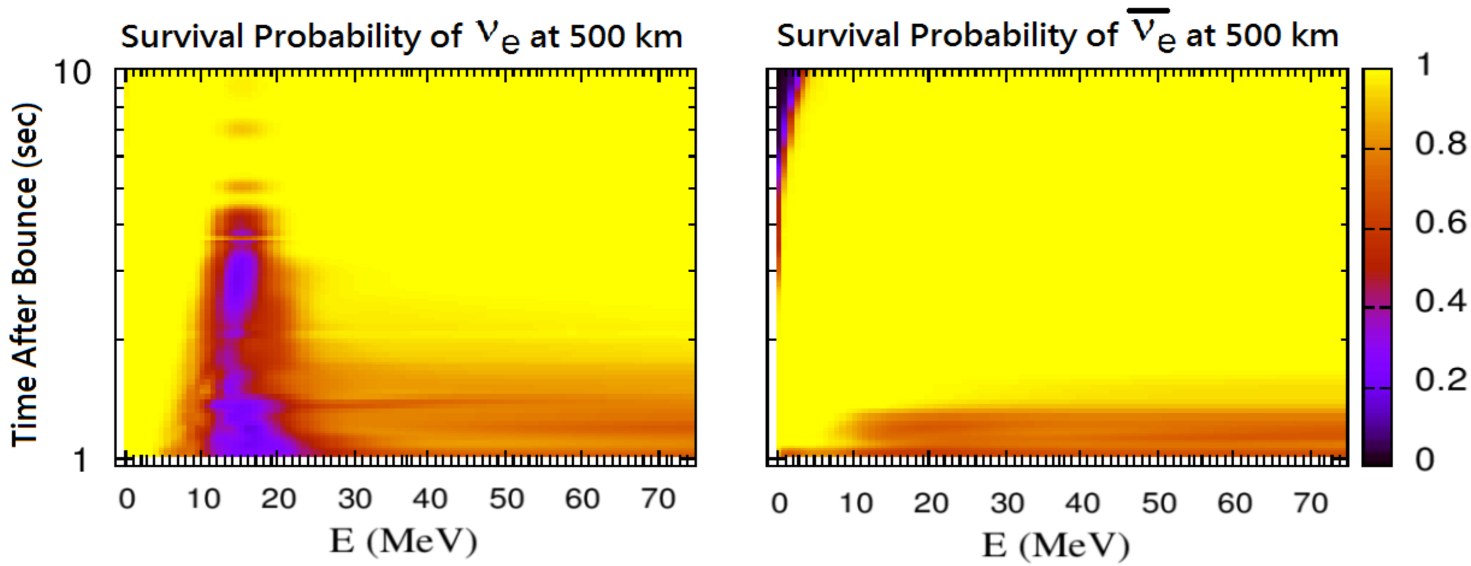

- results sensitive to the neutrino spectra, mean-field potential effect? Muons?
- azimuthal symmetry breaking of neutrino flavor evolution?

Neutrino signals in IceCube

$$\text{photon count rate} = \frac{n_p L_n}{4\pi d^2} \int dE_{\bar{\nu}_e} \sigma_{\bar{\nu}_e p}(E_{\bar{\nu}_e}) N_\gamma(E_e) V_\gamma^{\text{eff}} \tilde{f}_{\bar{\nu}_e}^{(\text{f})}(E_{\bar{\nu}_e}) \times (\text{number of digital optical modules})$$

(Abbasi et. al., A&A 535, A109, 2011)

for $d \approx 10\ kpc$

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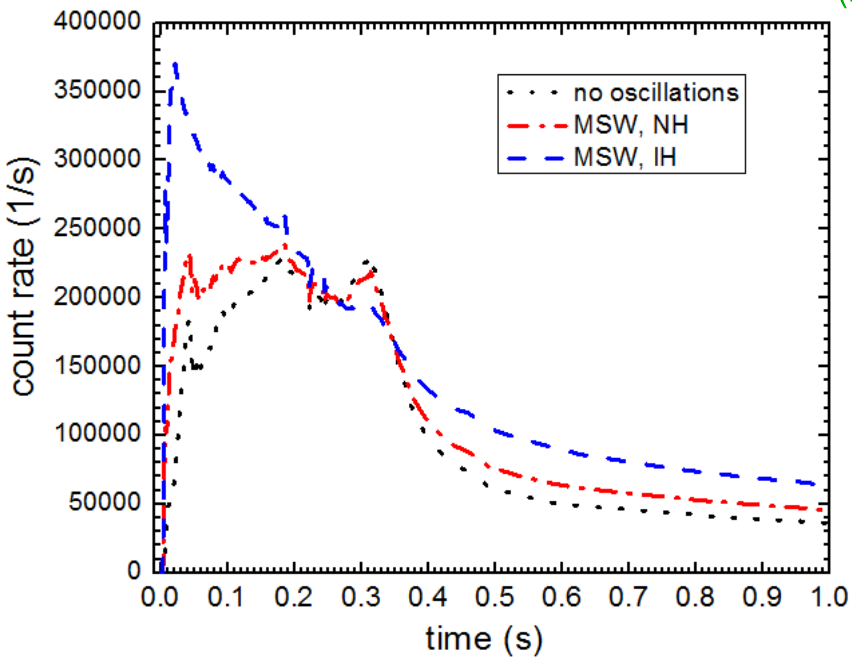

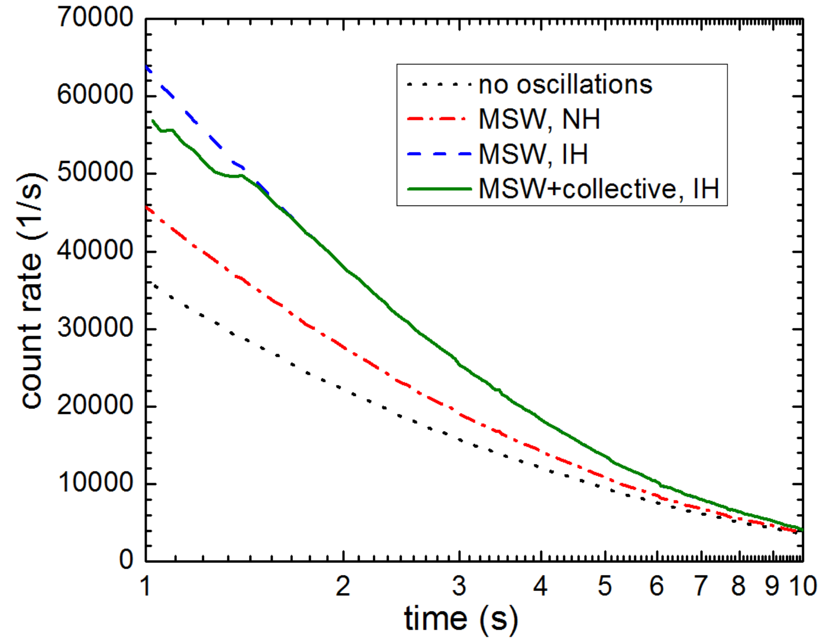

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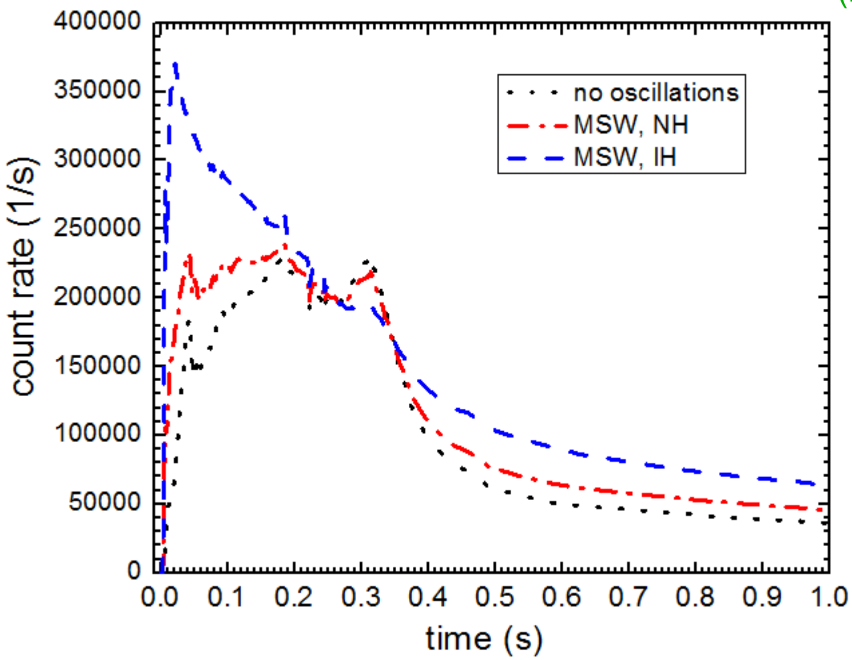
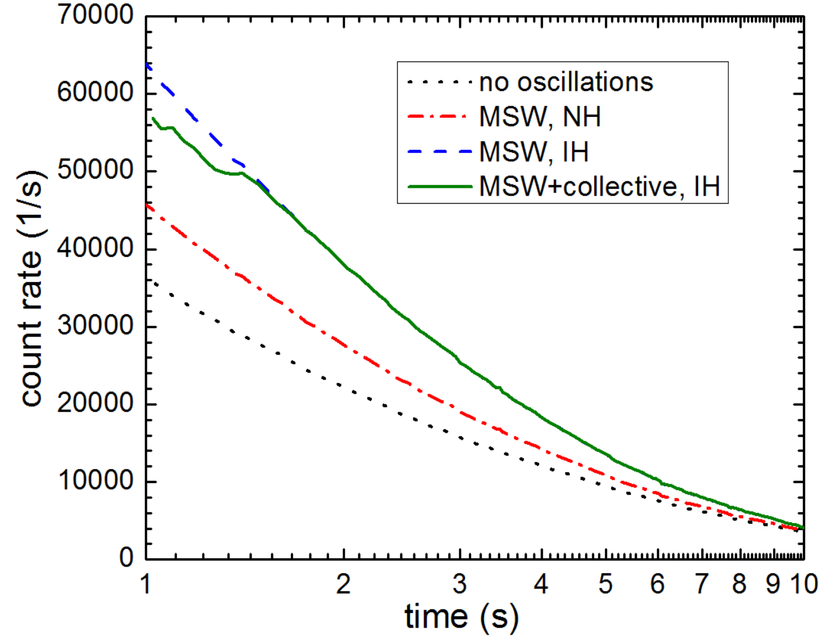


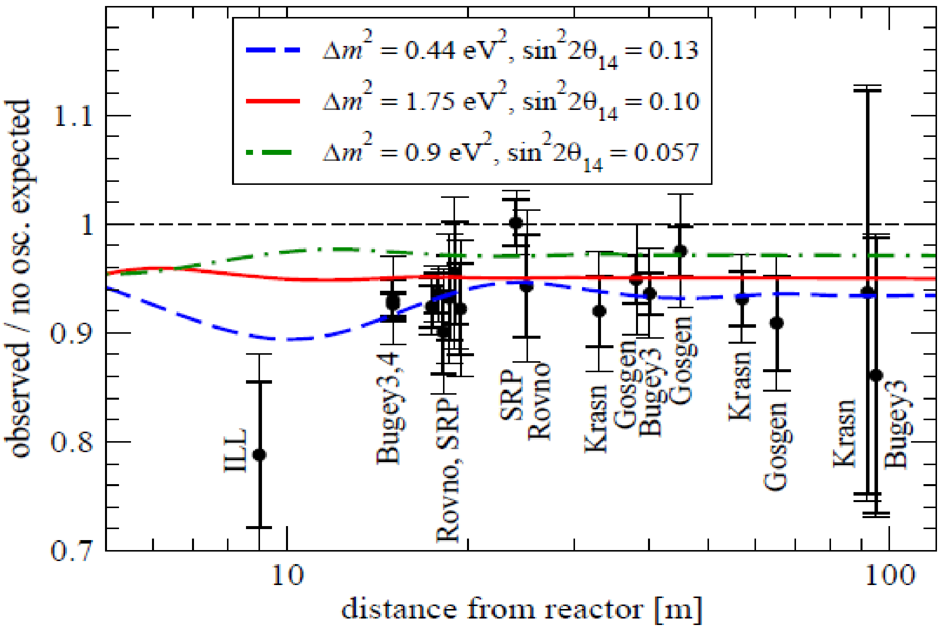


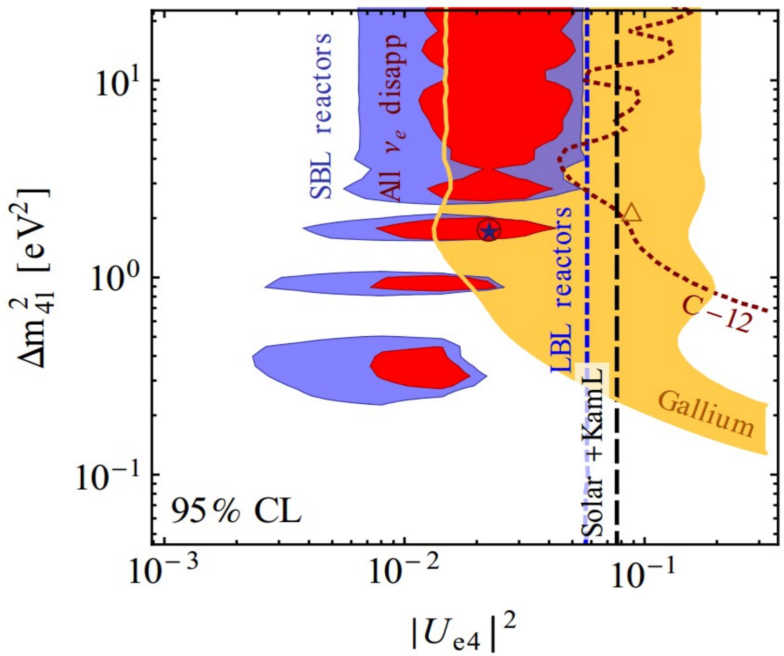
- possible to extract the shock-revival time?

- possible to identify the neutrino mass hierarchy?

eV sterile neutrinos?

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





The anomaly of neutrino (dis)appearance in short-baseline experiments may hint for the possible existence of eV scale sterile neutrinos :

- Reactor neutrino anomaly. (Mention + PRD 2011)
- Gallium anomaly. (Acero + PRD 2008; Giunti + PRC 2011)
- LSND. (Aguilar-Arevalo + PRD 2001)
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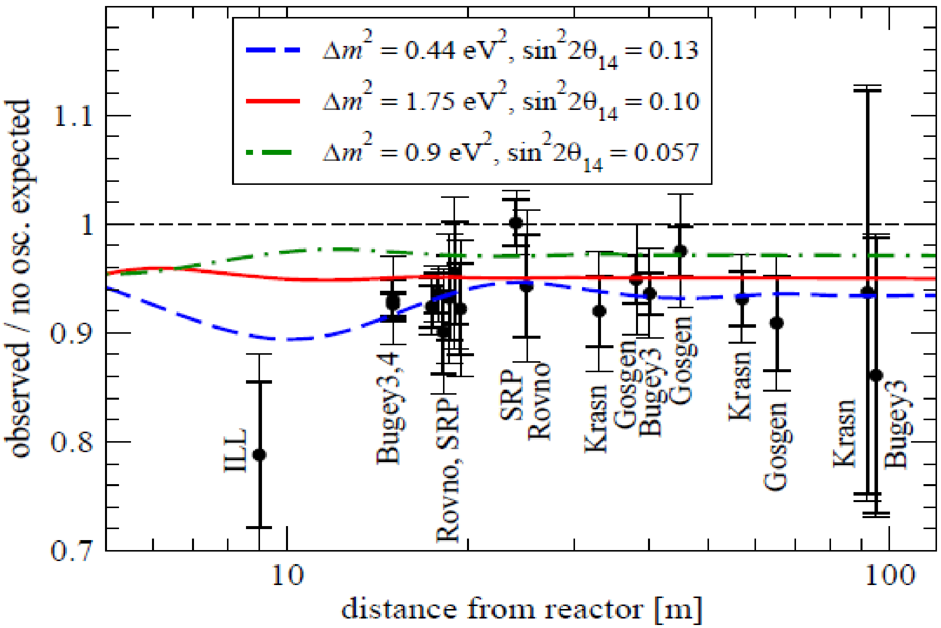

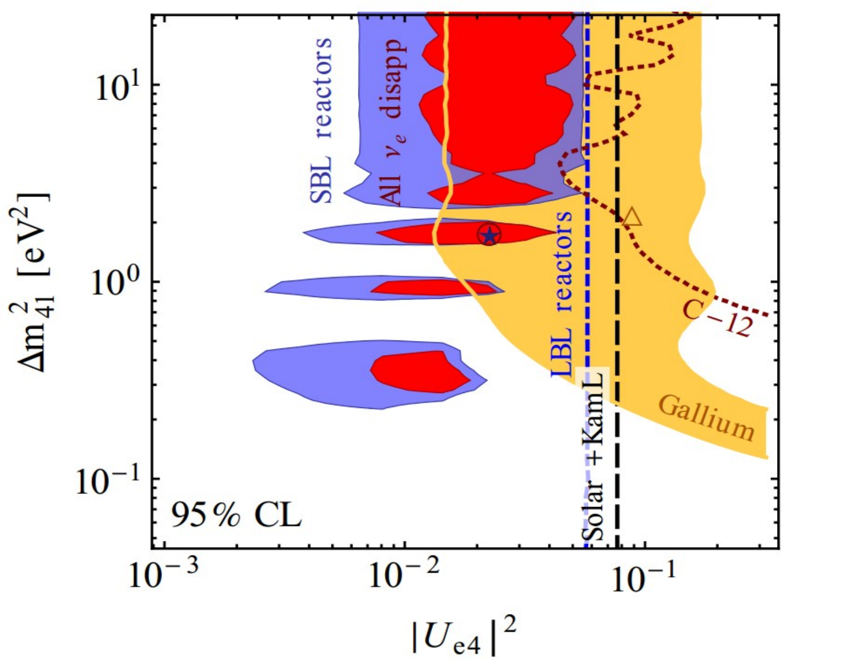

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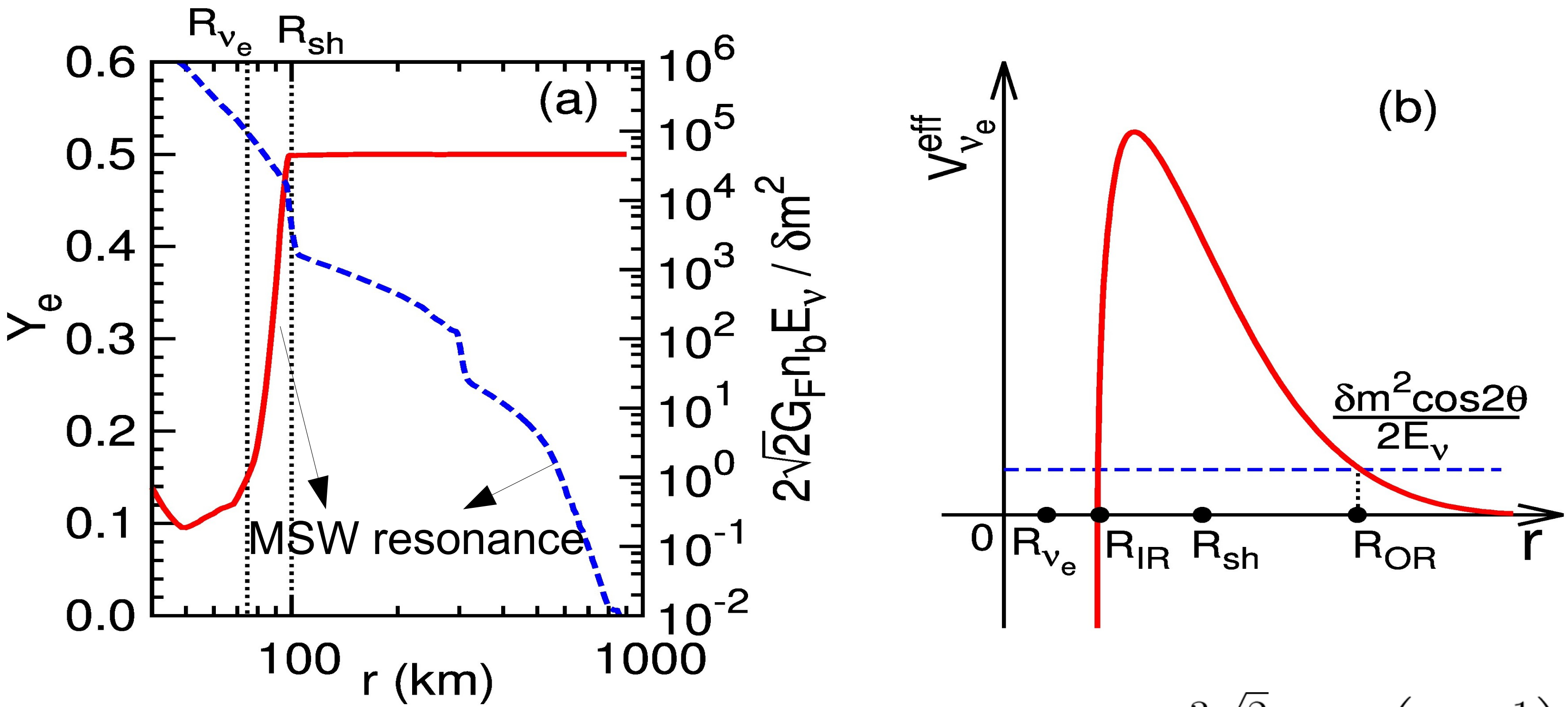
Global fit in phenomenological 3+1 scheme : (Kopp + JHEP 2013; Guinti + PRD 2013)

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

Active-sterile MSW flavor conversion

In supernovae, (anti-)ν_e - (anti-)ν_s MSW flavor conversion occurs at $Y_e \approx 1/3$, where $\rho \sim 10^9 - 10^{11}\mathrm{g/cm}^3$. (Nunokawa + 1997; Fetter + 2003; Tamborra + 2012 ...)



$$V^{\mathrm{eff}}_{\nu_e} = \frac{3\sqrt{2}}{2} G_F n_b \left(Y_e - \frac{1}{3} \right)$$

Active-sterile MSW flavor conversion

For an 8.8 $M_{\odot}$ electron-capture supernova :

- consistently treat the convolution of flavor conversion with evolution of Ye(r,t).

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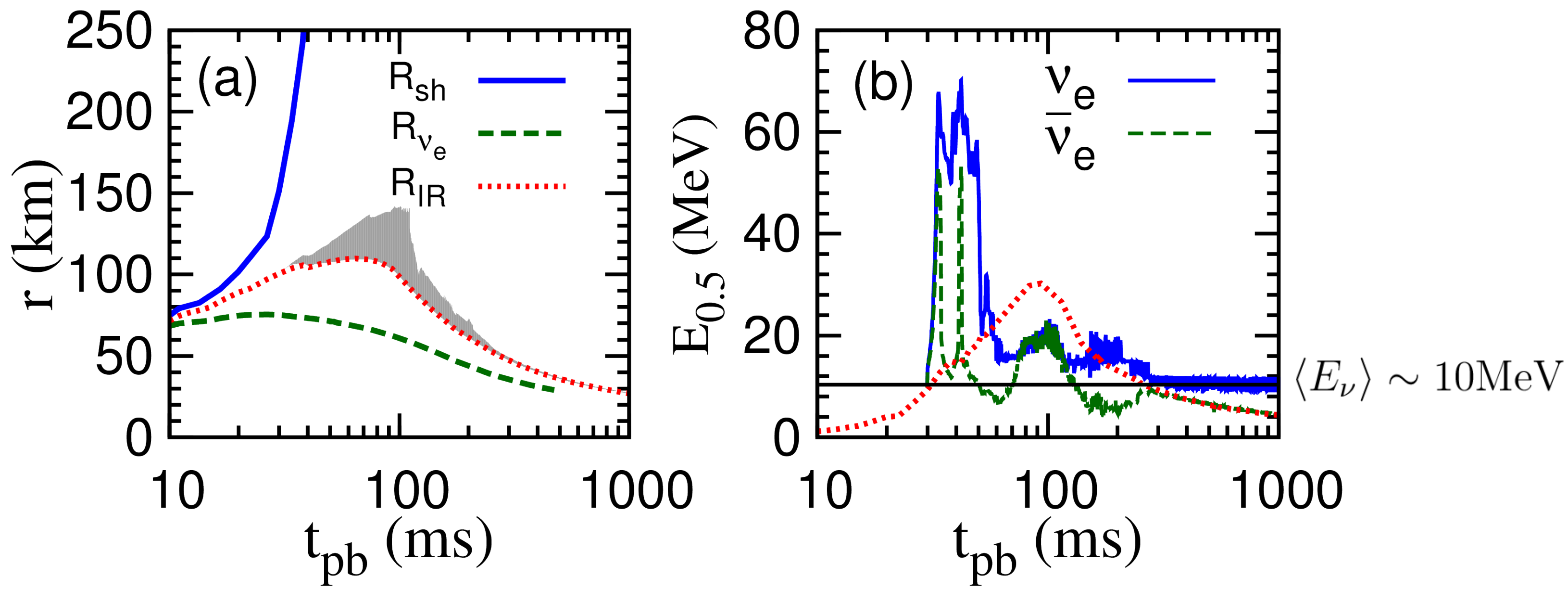

- significantly lower Ye for region above the resonance region (Ye~1/3).
- large amount of electron (anti)neutrinos are converted to sterile type.
- convert more electron neutrinos than electron antineutrinos.

Impact on nucleosynthesis

For an 8.8 $M_\odot$ electron-capture supernova :

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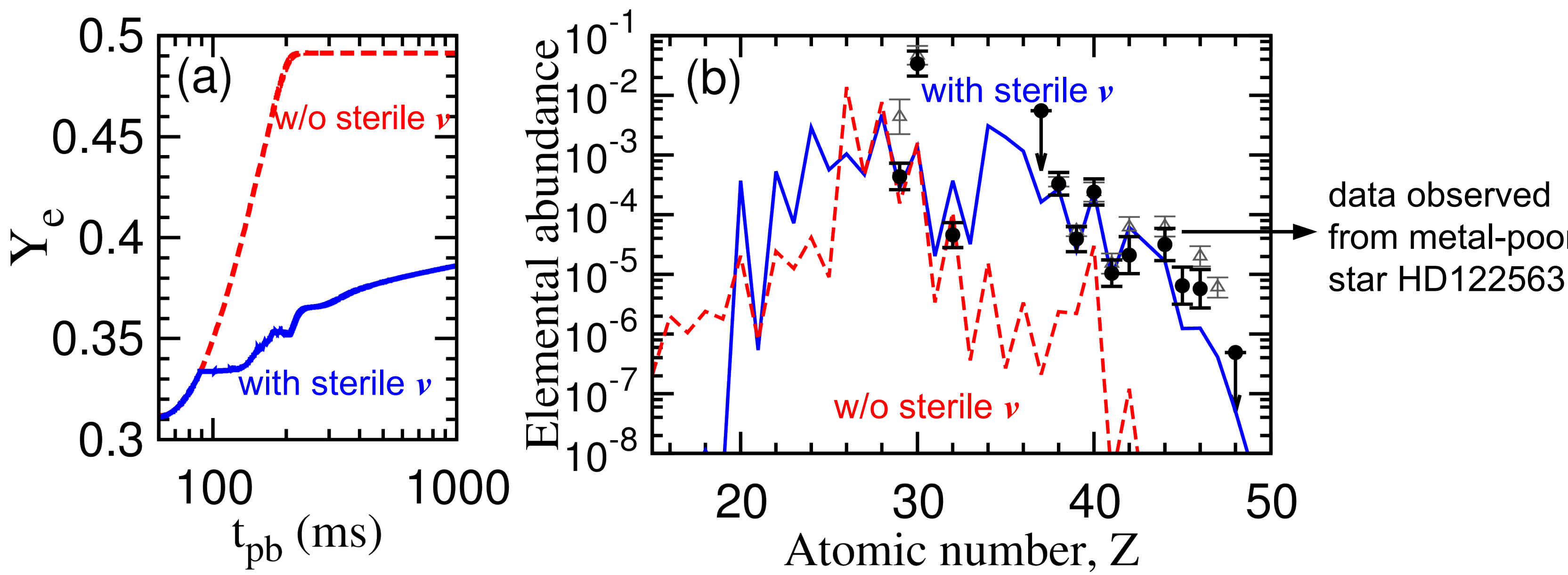

- Ye is lowered from ~0.48 to ~0.37 for a significant part of the ejecta.
- produce elements between Sr-Cd, with consistent pattern compared to the observation from the r-process deficient metal-poor star HD122563.
- produce mainly neutron-rich isotopes.

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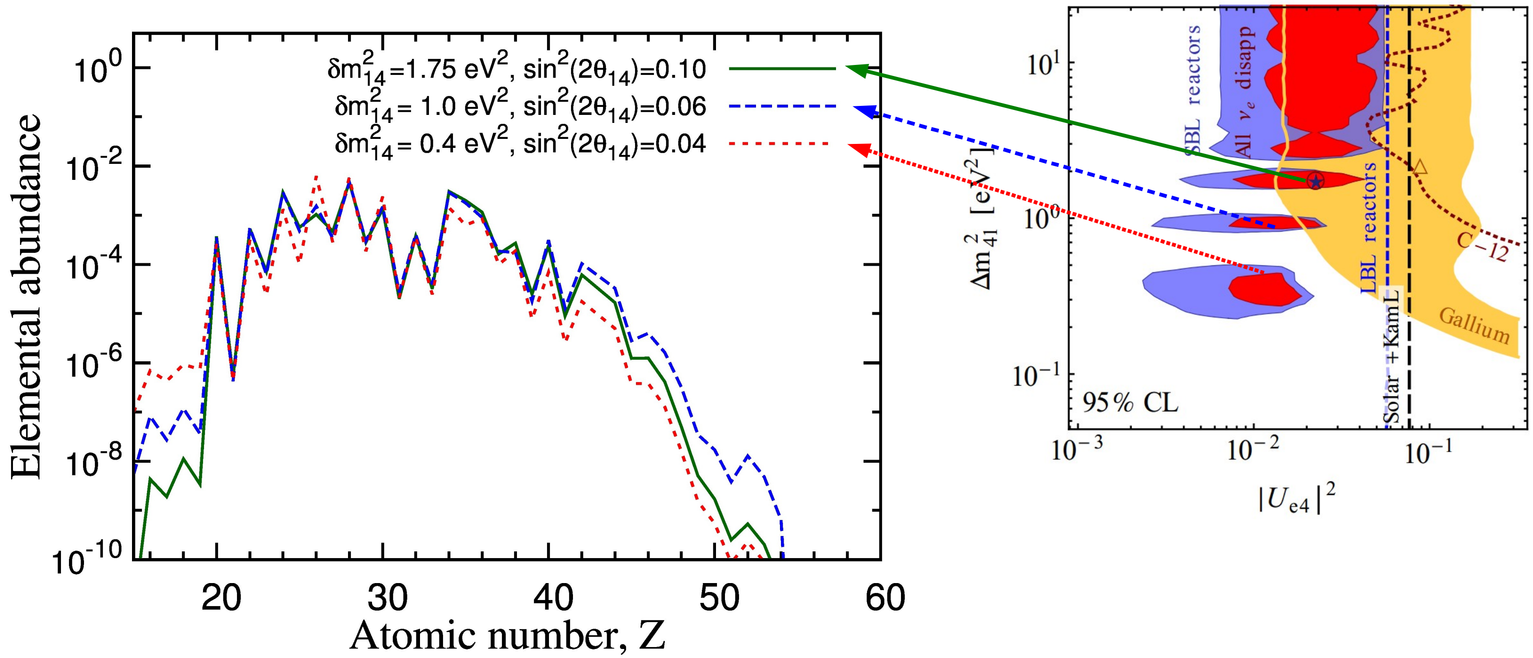

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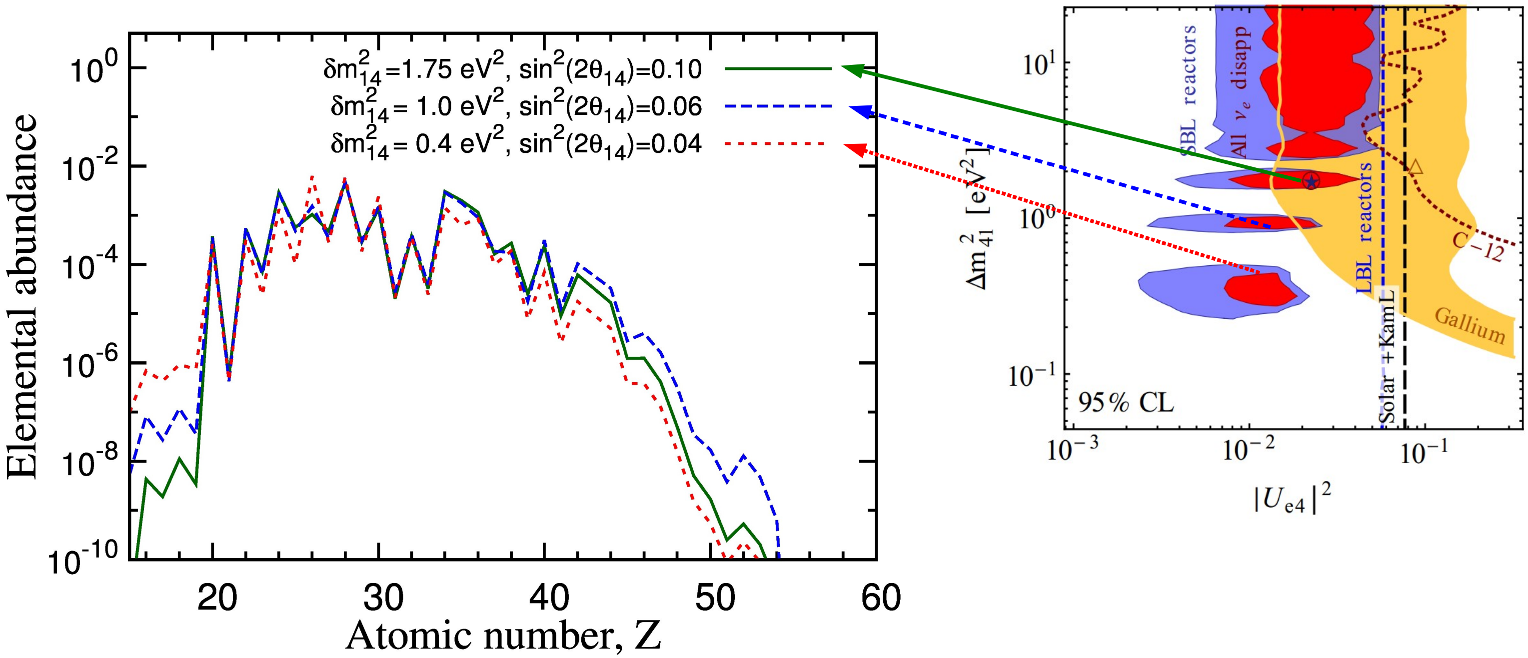


- more massive progenitors?
- change of thermal-dynamical quantities and dynamics?

Summary

- Nucleosynthesis outcome of explosive nucleosynthesis in CCSNe may sensitively depends on the nuclear physics inside PNS and neutrino oscillations above PNS.

- Sr, Y, Zr and p-rich isotopes such as ^{92}Mo are produced in a wind model using data from spherically symmetric supernova simulation with updated nuclear equation of state, weak interaction rates, and detailed neutrino transport.

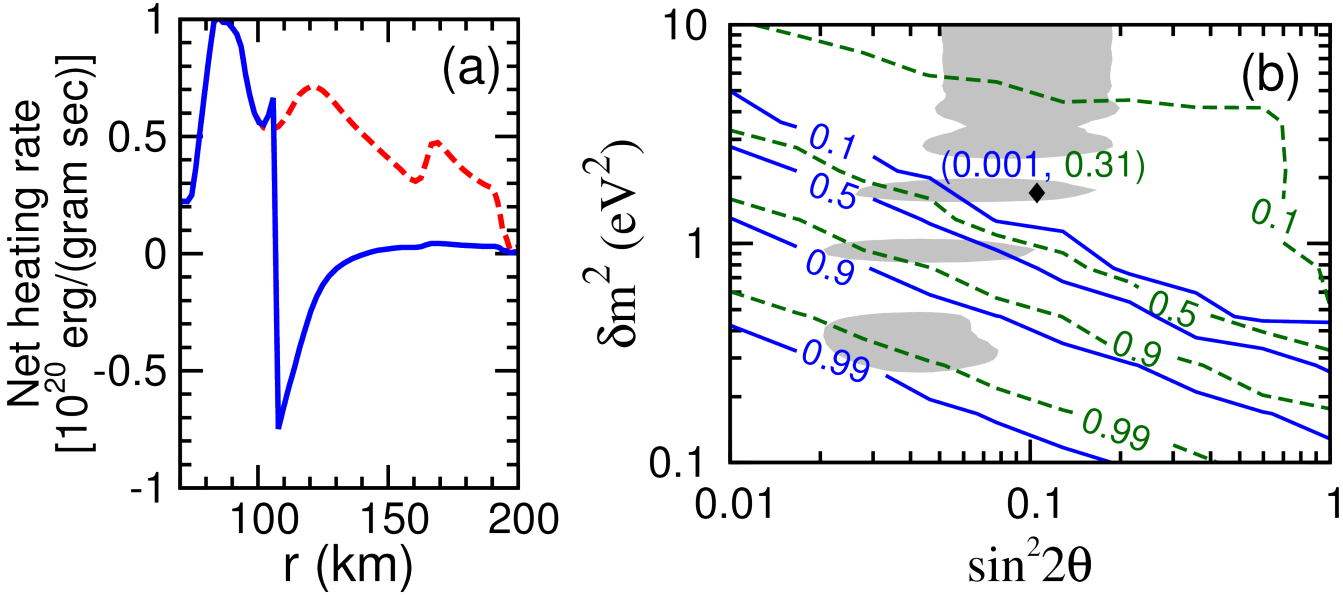
- Active neutrino oscillations potentially have impact on supernova nucleosynthesis and neutrino signals. Detailed & improved modeling for collective oscillations is required.

- With eV sterile neutrinos, elements between Sr-Cd may be produced in electron-capture supernovae, with consistent pattern compared to the metal-poor star observation.

Can supernova model explode?

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

[MRW, Fischer, Huther, Martinez-Pinedo, Qian, arXiv:1305.2382, 2013]



Possibility of using SN models to constrain the parameter space of sterile neutrinos?...remains to be explored.