Neutrinos and nucleosynthesis in supernovae

Meng-Ru Wu (TU Darmstadt)

NAVI Physics Days, 02/27/2015, GSI, Darmstadt, Germany

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Neutrino (oscillations), nucleosynthesis, (and a little bit of neutrino signals) in supernovae

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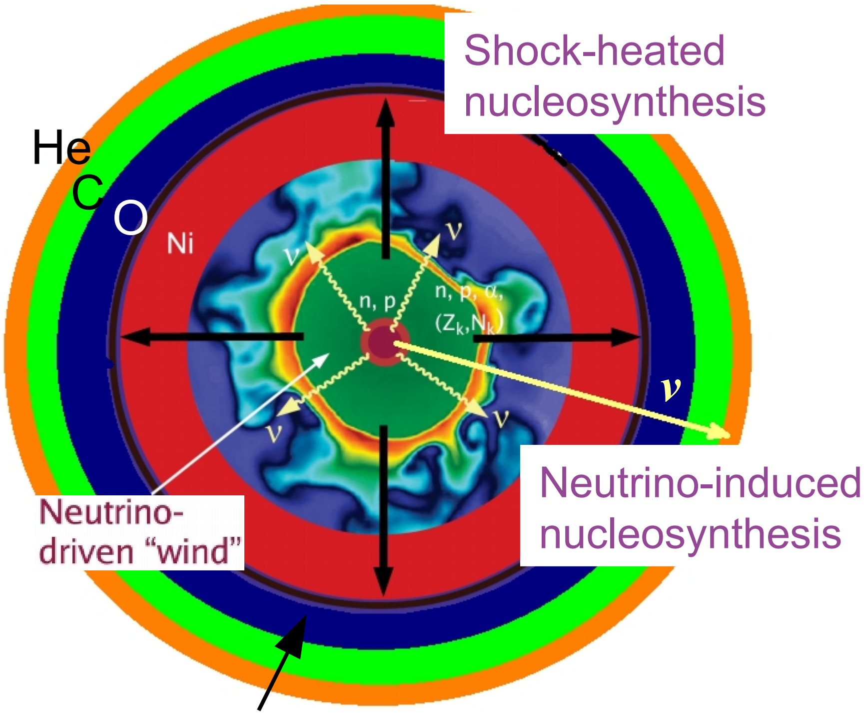
[Modified from Janka+, PTEP 01A309, 2012]



shockwave (revived mainly by ν-heating)

- neutrino (induced) nucleosynthesis
  - $\rightarrow$ light elements : Li, Be, B, F
  - $\rightarrow$ radioactive nuclei : ^{22}Na, ^{26}Al
    rare isotopes : ^{138}La, ^{180}Ta

- neutrino-driven wind

$$\nu_e + n \rightarrow p + e^-$$
$$\bar{\nu}_e + p \rightarrow n + e^+$$

$\rightarrow$ determine the neutron-to-proton ratio (or equivalently, the electron number fraction per baryon, Y_e) of the ejecta

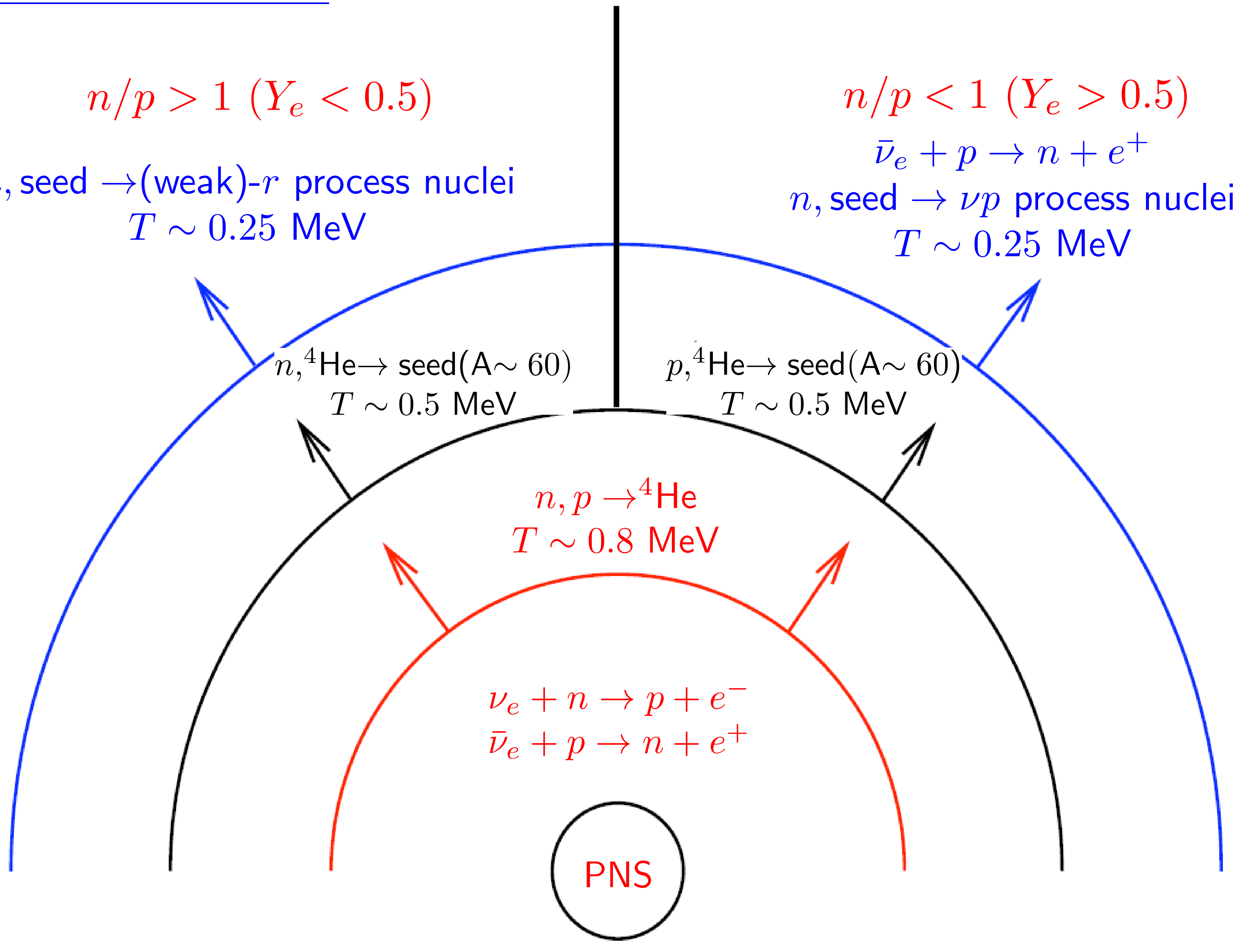
$\rightarrow$ interact with nuclei formed at larger radius as an additional neutron source

$\sim 10^{58}$ neutrinos of different flavors in $\sim$ 10 seconds

$$\langle E_\nu \rangle \sim 7 - 20 \text{ MeV}$$

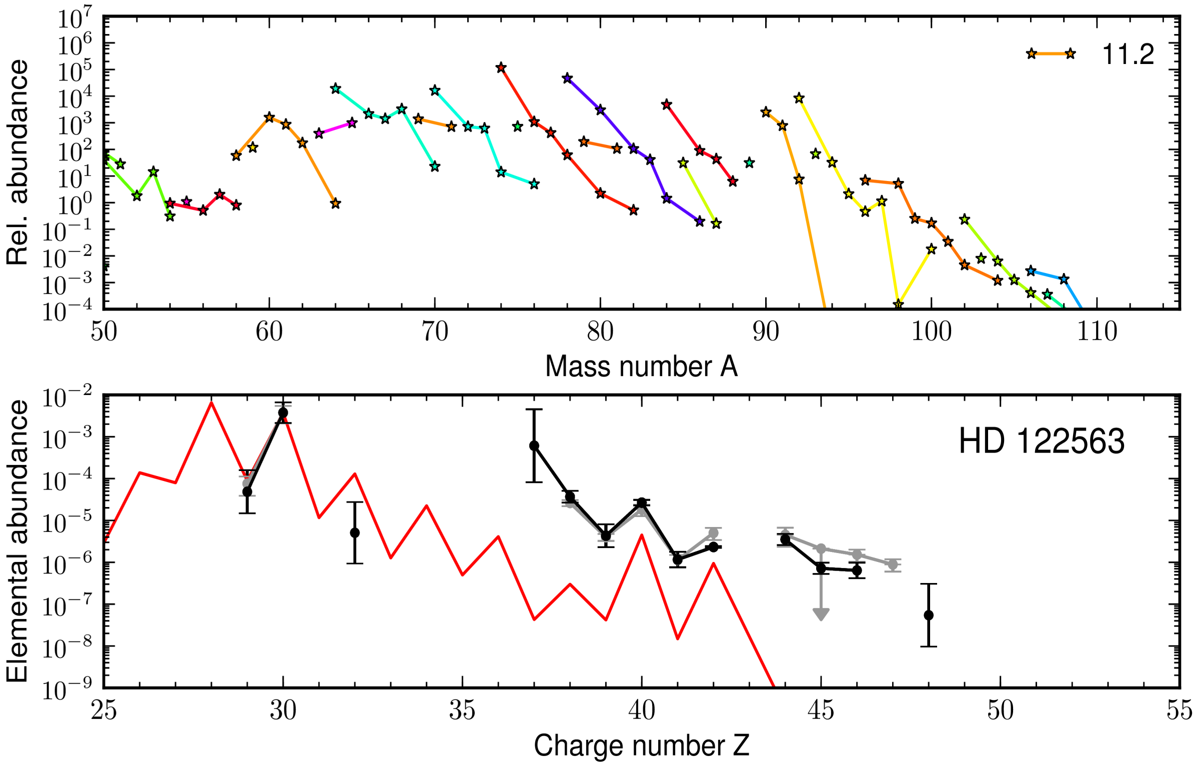
$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_{\mu,\tau}} \rangle$$

Neutrino-drive wind



Nucleosyntesis yield from the ν-driven wind

- long-term supernova simulation with 3 flavor Boltzmann neutrino transport
- consistent weak interaction rates and the nuclear equation of state



[Martinez-Pinedo, Fischer & Huther, J.Phys.G 41, 044008, 2014]

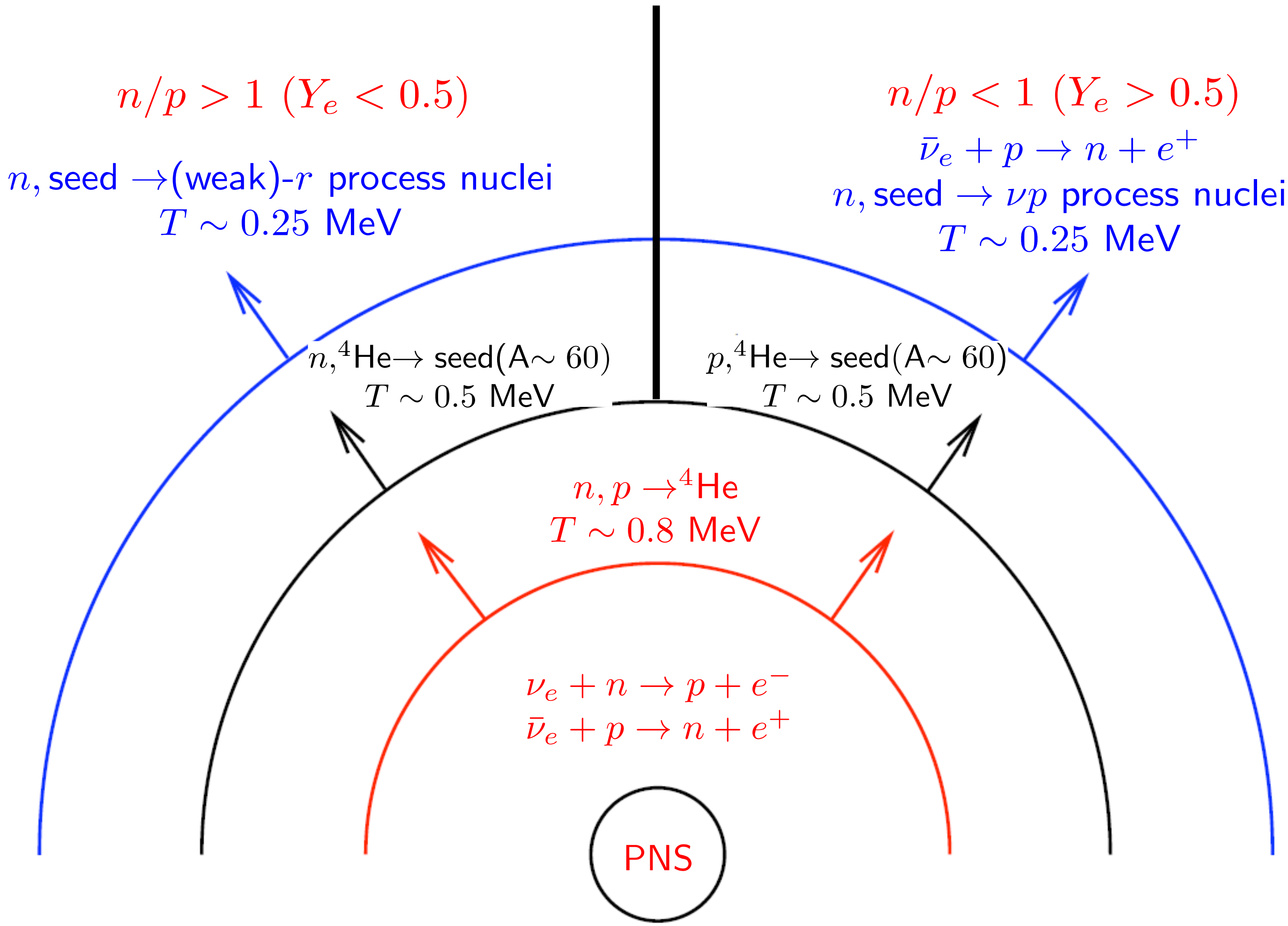
- produce elements around $Z = 40$ such as Sr, Y, Zr, but not beyond Mo ($Z = 42$)
- neutron-deficient isotopes are produced (ex: ^{92}Mo)

$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_{\mu,\tau}} \rangle$ at the surface of PNS

neutrino flavor oscillations $\nu_e \leftrightarrow \nu_{\mu,\tau}$ & $\bar{\nu}_e \leftrightarrow \bar{\nu}_{\mu,\tau}$

$\nu_e \leftrightarrow \nu_s$ & $\bar{\nu}_e \leftrightarrow \bar{\nu}_s$

when? where? how (much)?

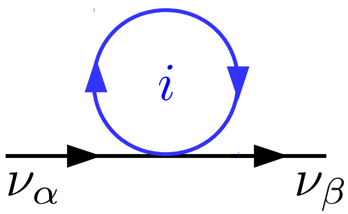


Simulating neutrino flavor oscillations in supernovae

In collisionless limit, time evolution of the reduced density matrix in the flavor space, normalized by the ν phase space distribution function: [Sigl+ 1992, Volpe+ 2014, Vlashenko+ 2014]

$$i\frac{d}{dt}\varrho_{\nu,\vec{p},\vec{r}} = [H_{\rm vac} + H_{\rm int}, \varrho_{\nu,\vec{p},\vec{r}}], \qquad \varrho_{\nu,\vec{p},\vec{r}} = \begin{pmatrix} |a_e|^2 & a_e a_x^* \\ a_e^* a_x & |a_x|^2 \end{pmatrix}$$

$$H_{\rm vac} = \frac{\delta m^2}{4E_\nu}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} \qquad H_{{\rm int},\alpha\beta} = (\sum_i \Gamma_i)_{\alpha\beta} - \frac{1}{2} tr(\sum_i \Gamma_i)\delta_{\alpha\beta}$$



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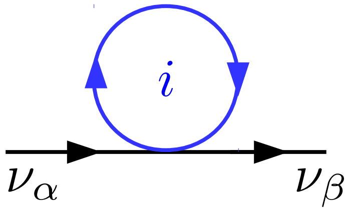
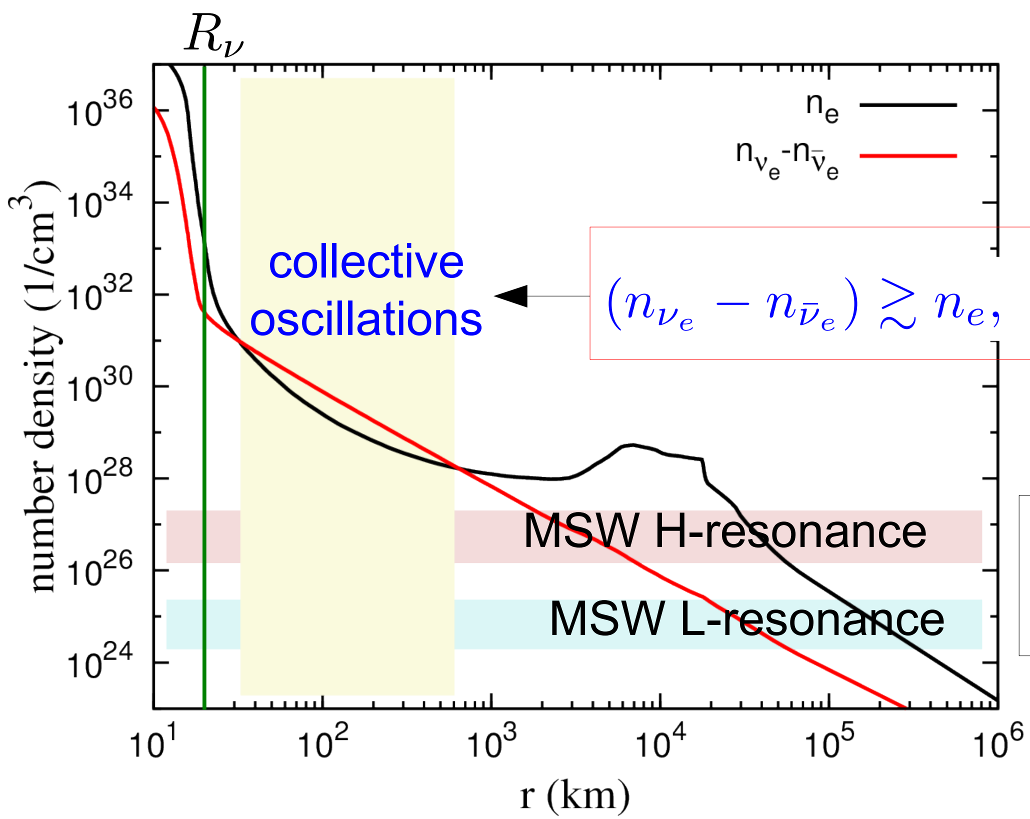


For mixing between active neutrinos emitted from a source with size $\sim R$, without any flavor oscillations:

$$H_{\rm int} \sim \pm\frac{1}{2}\left[\sqrt{2}G_F n_e + \sqrt{2}G_F(n_{\nu_e} - n_{\bar{\nu}_e}) \times \frac{R^2}{2r^2}\right]\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

in general, $H_{{\rm int},\nu} \propto \int d^3\vec{p}(f_{\nu,\vec{p},\vec{r}}\varrho_{\nu,\vec{p},\vec{r}} - f_{\bar{\nu},\vec{p},\vec{r}}\varrho^*_{\bar{\nu},\vec{p},\vec{r}})$ couples the flavor evolution of neutrinos with different phase space indices and give rise to the collective behavior that may trigger unexpected large scale of flavor oscillations supernova profile during the wind phase:



$$(n_{\nu_e} - n_{\bar{\nu}_e}) \gtrsim n_e, \quad \sqrt{2} G_F n_{\nu_e} \times \frac{R_\nu^2}{r^2} \gtrsim \frac{\delta m^2}{2E_\nu}$$

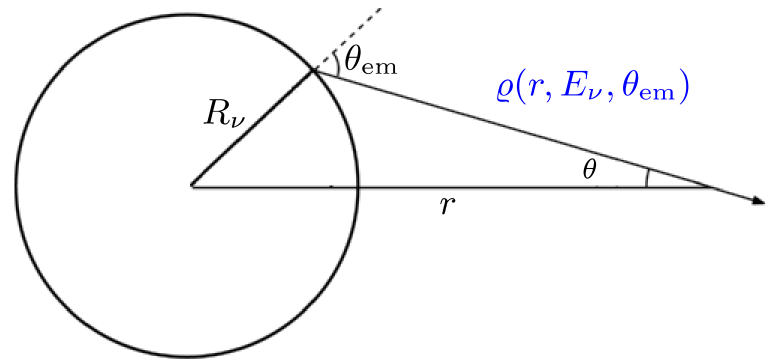
$$\sqrt{2} G_F n_e \approx \frac{\delta m^2}{2E_\nu}$$

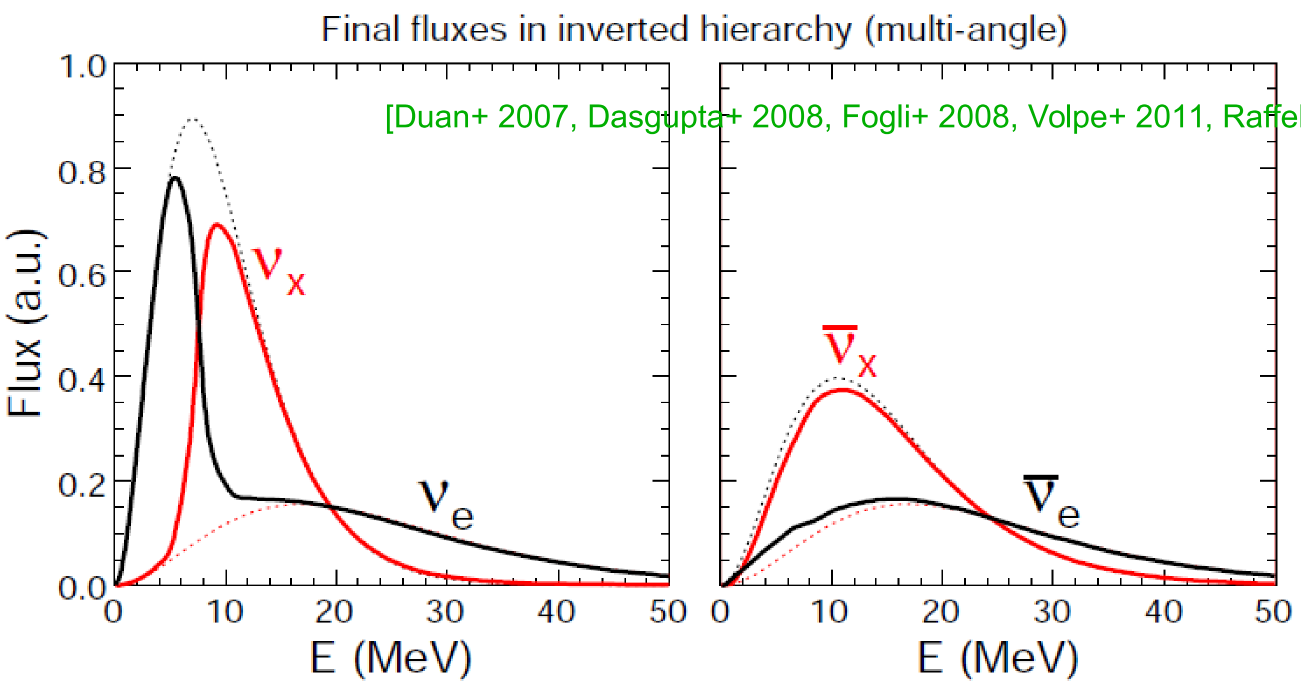
prior to the wind phase, collective ν oscillations are likely to be suppressed by larger matter density [Chakraborty+ 2011, 2014]

Neutrino bulb model: [Duan, Fuller, Carlson, Qian, PRD 74, 105014, 2006]

- spherically symmetric stationary environment
- a sharp ν-emitting spheres, R_ν
- all neutrinos in pure flavor states at R_ν
- axial-symmetry of ν flavor evolution

$\rightarrow$ numerically ray-tracing $\sim$ thousands to millions of coupled ODEs, from the strong coupling regime to the vacuum regime





Possible impact on nucleosynthesis in the ν-driven wind have been studied in Duan et. al., 2011 (r-process) and Martínez-Pinedo et. al., 2011 (νp process)

However, detailed modelling is required for the application to nucleosynthesis, why?

Possible impact on nucleosynthesis in the ν-driven wind have been studied in Duan et. al., 2011 (r-process) and Martínez-Pinedo et. al., 2011 (νp process)

However, detailed modelling is required for the application to nucleosynthesis, why?

(i) matter suppression of collective oscillations

at the temperature of ^{4}He formation (i.e. n/p ratio) of $T \approx 0.8$ MeV:

$$n_e \sim 1.6 \times 10^{30}\ \mathrm{cm}^{-3} \left(\frac{T}{0.8\mathrm{MeV}}\right)^3 \left(\frac{50}{S/k_B}\right)$$

$$n_{\nu_e} - n_{\bar{\nu}_e} \sim 1.5 \times 10^{30}\ \mathrm{cm}^{-3} \left(\frac{L_\nu}{10^{51}\mathrm{erg/s}}\right) \left(\frac{50\mathrm{km}}{r}\right)^2$$

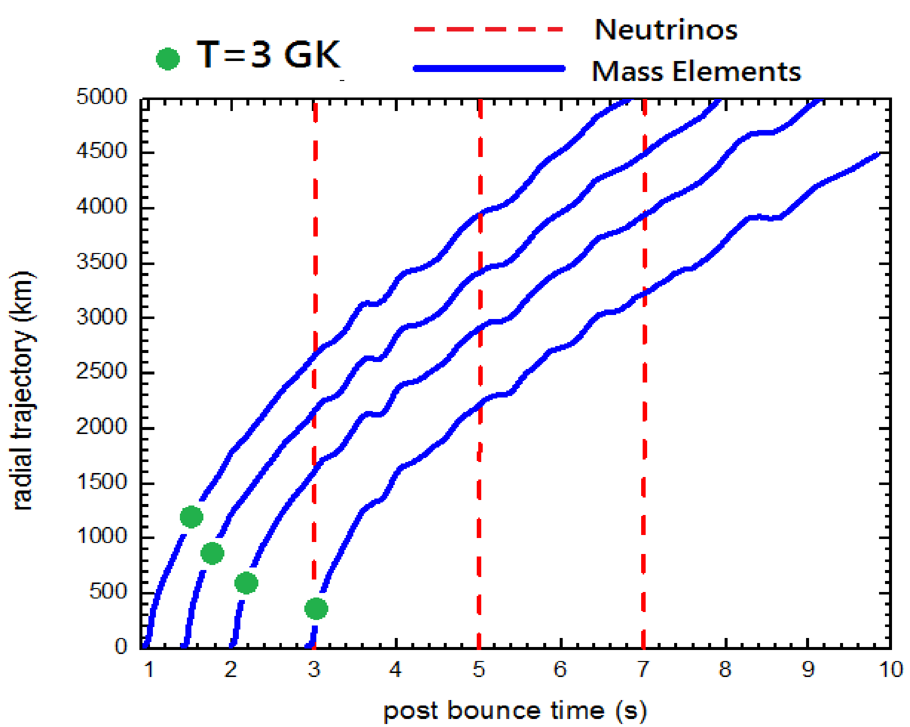
(ii) sensitive to the ν emission spectra

In a dynamical supernova environment, both the ν emission characteristics and the density profiles can change significantly in the time scale of the nucleosynthetic process of seconds

$\rightarrow$ an approach consistent with the underlying SN model is needed

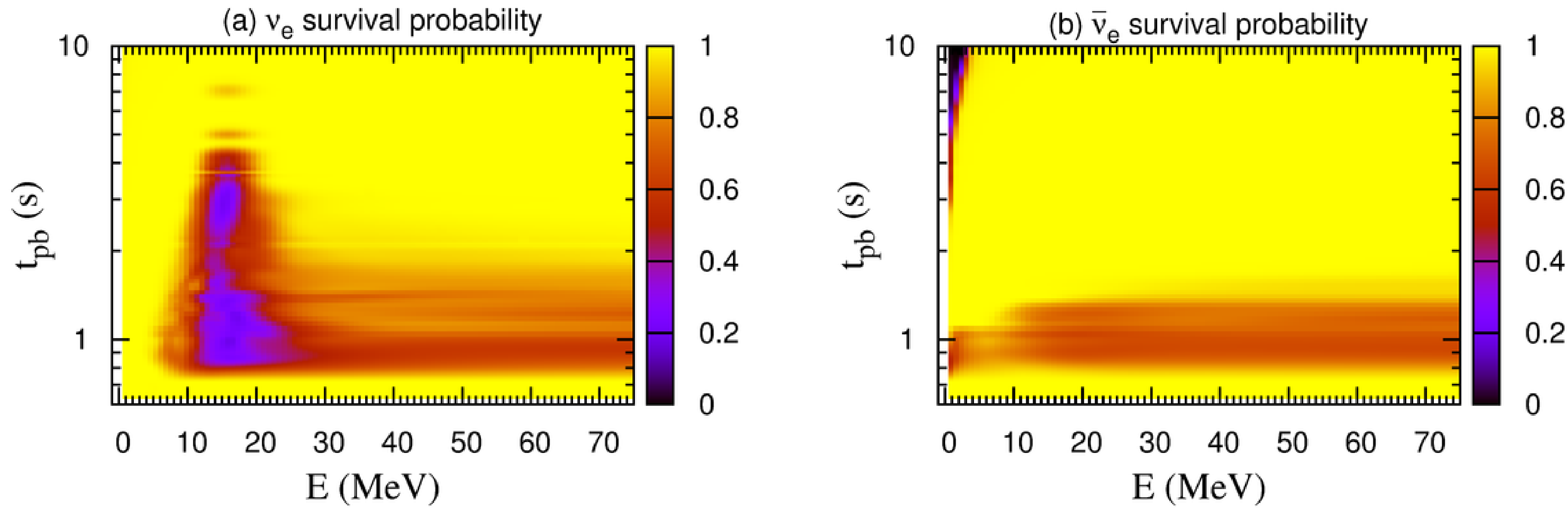
Approach consistent with the underlying astrophysical model

(i) post-processing data from the SN simulation
(ii) construct the time-dependent ν decoupling spheres
$\rightarrow$ energy and angular dependent ν distribution
(iii) construct time-dependent density profiles seen in ν propagation
(iv) calculate flavor evolution for the whole SN evolution phase
(v) evaluate the impact on nucleosynthesis and ν signals



Approach consistent with the underlying astrophysical model

for an 18 $M_\odot$ spherically-symmetric supernova model:
at $r = 500$ km



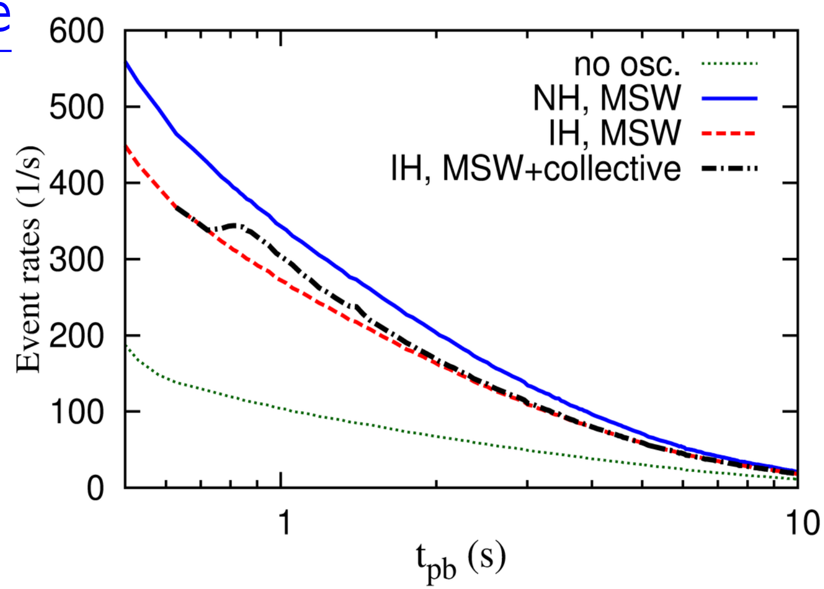
[MRW, Qian, Martinez-Pinedo, Fischer, Huther, arXiv:1412.8587]

- collective ν oscillations only occur for the inverted ν mass hierarchy
- no effect on the ν-driven wind nucleosynthesis
- enhance the production of ^{138}La, ^{180}Ta
- affect the ^{7}Li and ^{11}B production combined with MSW oscillations

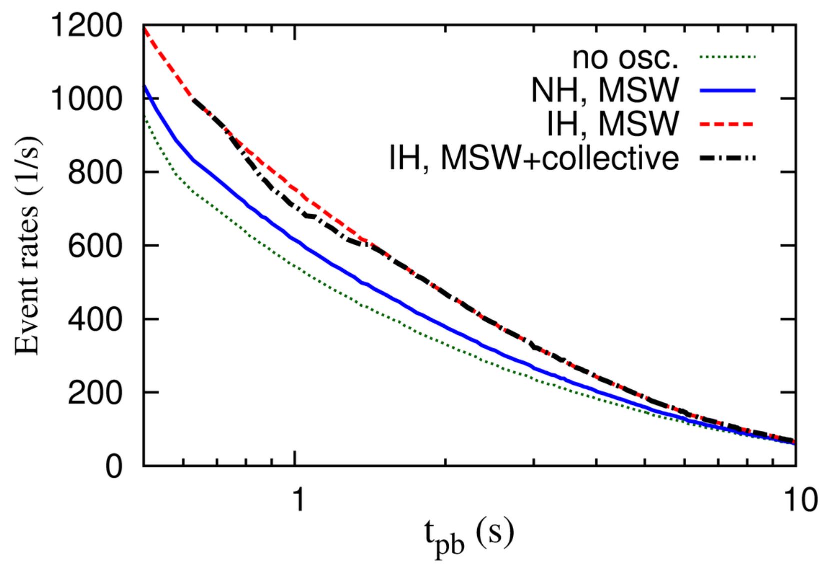
Neutrino signals in wind phase

for a SN at 10 kpc away

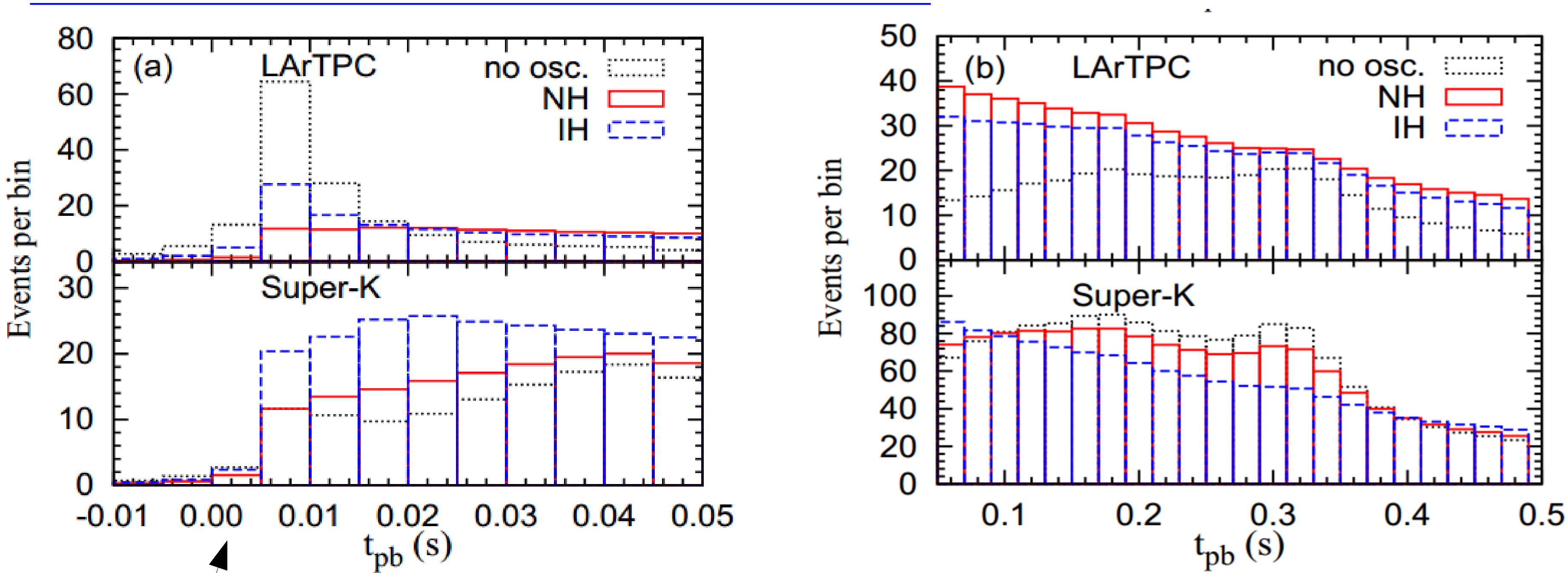
ν_e signal in a 34k-ton liquid argon detector



$\bar{\nu}_e$ signal in Super-Kamiokande detector



Neutrino signals prior to the wind phase



with very large events, the rise time of $\bar{\nu}_e$ signal may be used to infer the mass hierarcy

[Serpico+ 2012]

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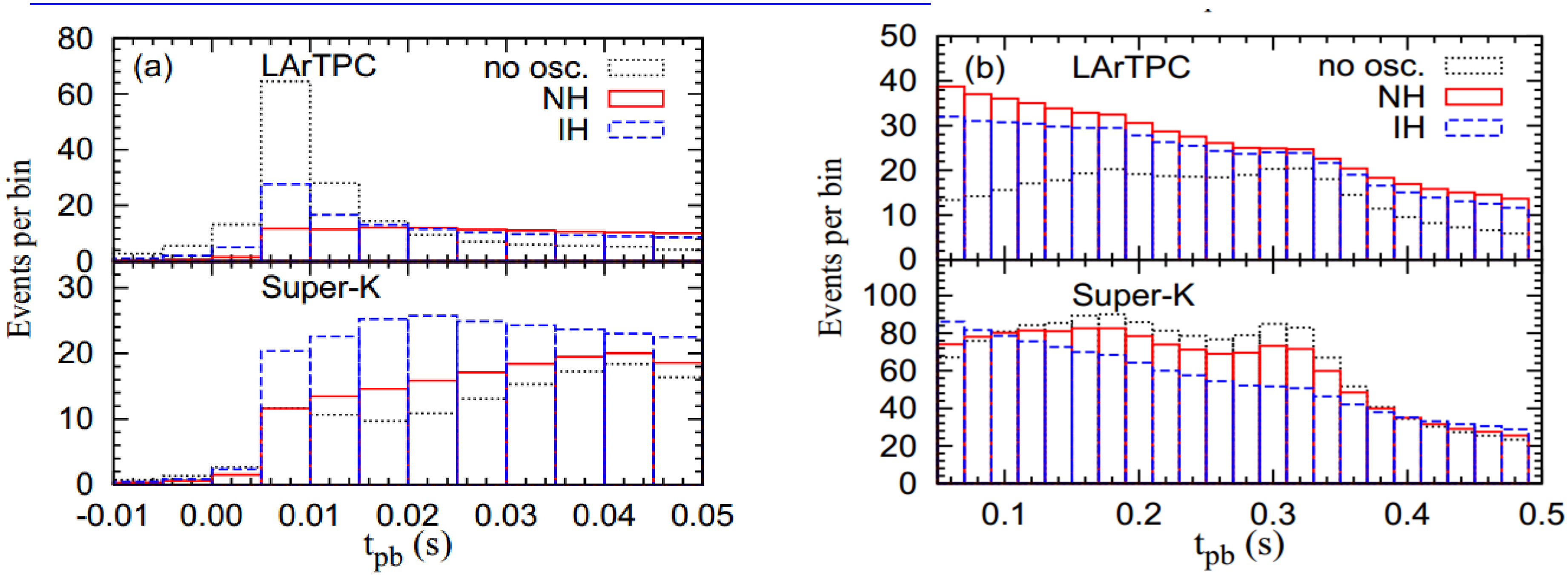
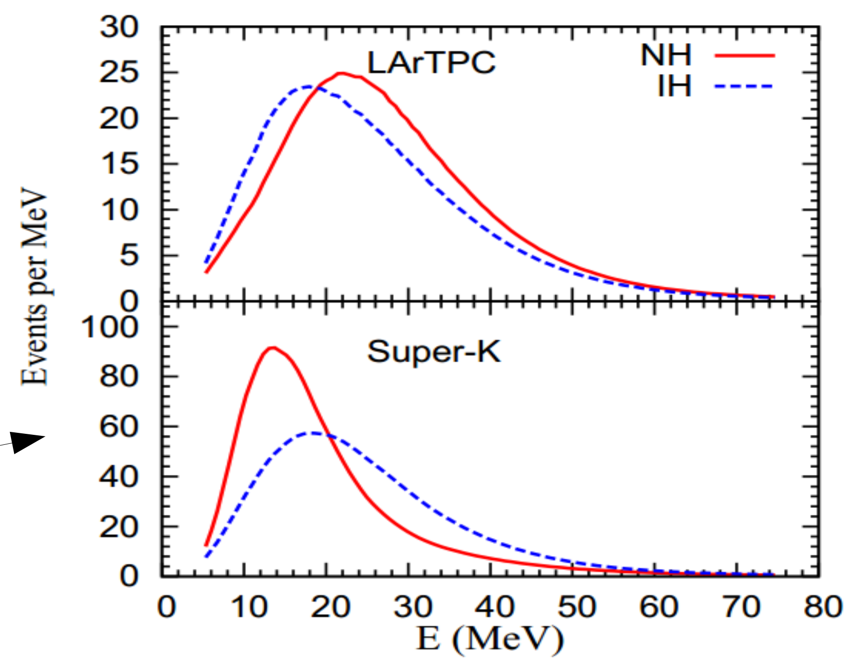


with very large events, the rise time of $\bar{\nu}_e$ signal may be used to infer the mass hierarcy

with multi-detection channel the detected neutrino spectra may also be used to infer the mass hierarcy



above discussions are based on the assumption that the change of composition and/or hydrodynamics has negligible feedback effect on ν oscillations itself

If ν oscillations happen at a region where the ν interaction rates are large, eg., close to PNS where $Y_e \approx 1/3$ (eV mass sterile ν, ν-$\bar{\nu}$ coherence)

or above the disk of merger where $n_e + (n_{\nu_e} - n_{\bar{\nu}_e})\frac{R^2}{2r^2} \sim 0$

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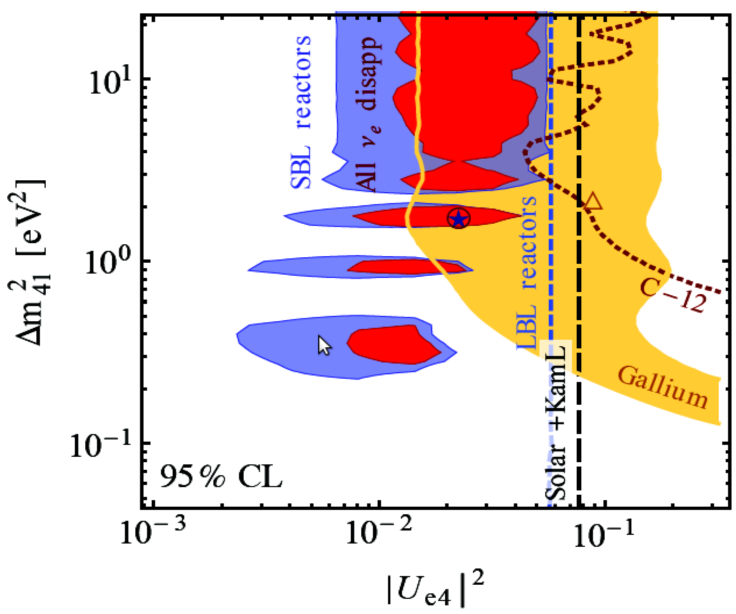
or above the disk of merger where $n_e + (n_{\nu_e} - n_{\bar{\nu}_e})\frac{R^2}{2r^2} \sim 0$

Reactor ν anomaly + Gallium anomaly:
(Mention+ 2011) (Giunti+ 2011-2013)

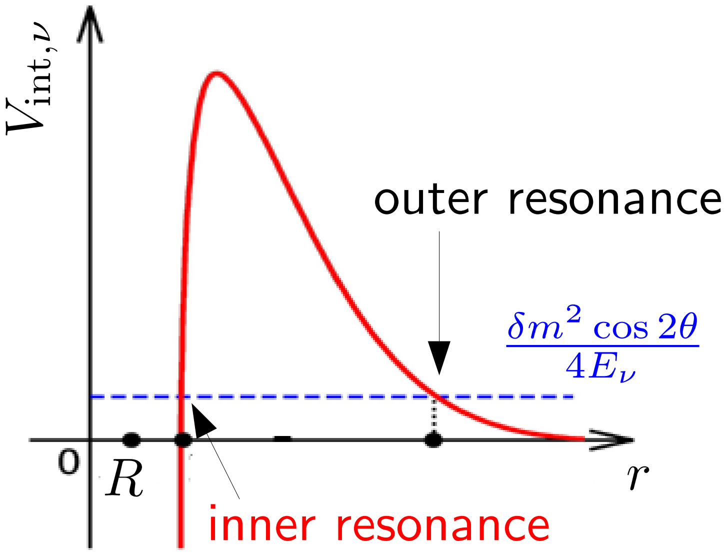
$$\delta m^2_{41} \sim O(\mathrm{eV}^2)$$
$$\sin^2 2\theta_{14} = \sin^2 2\theta_{ee} \sim 0.1$$

(Kopp et.al, JHEP05 (2013) 050)



Active-sterile ν oscillations

$$H_{\rm int} \sim \underbrace{\pm\frac{3\sqrt{2}}{4}\left[G_F n_b\left(Y_e-\frac{1}{3}\right)+\frac{4}{3}G_F(n_{\nu_e}-n_{\bar\nu_e})\times\frac{R^2}{2r^2}\right]}_{V_{{\rm int},\nu}}\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}$$

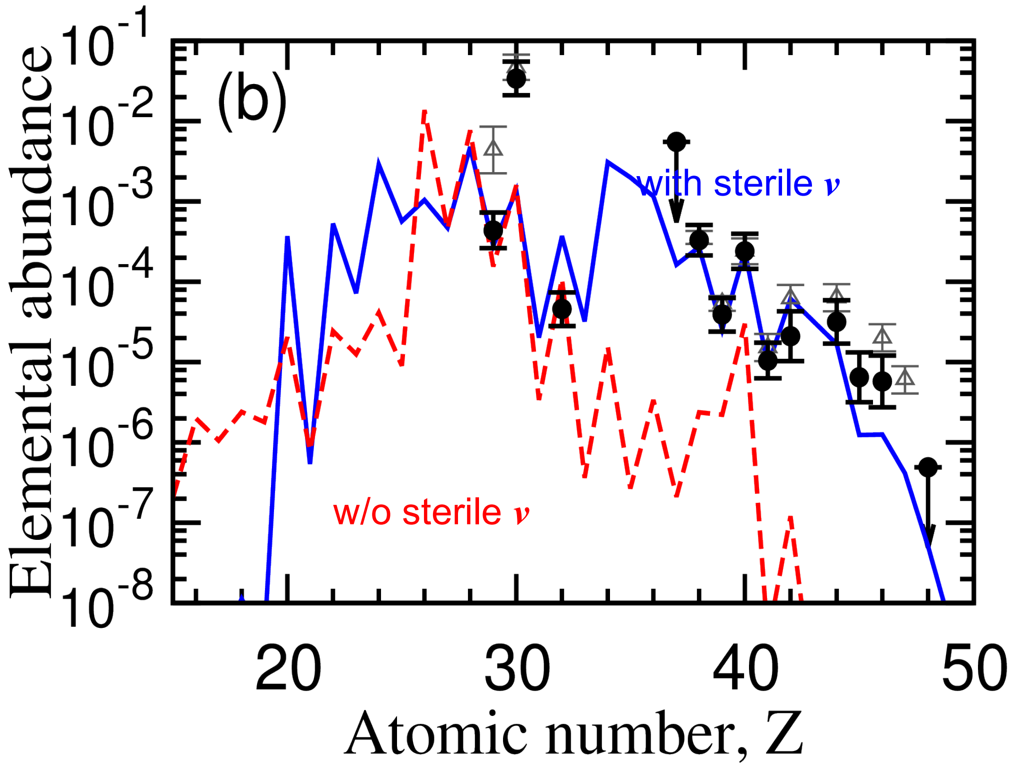


inner resonance:
- $Y_e \approx 1/3$, $\rho \sim 10^9$ g/cm^3, $n_b \gg n_\nu$
- resonance for both ν and $\bar\nu$

outer resonance:
- $Y_e \approx 0.5$, $\rho \sim 10^6$ g/cm^3
- mostly $\nu_e \leftrightarrow \nu_s$,

inner resonance was often neglected due to the very steep $V_{{\rm int},\nu}$

when feedback on Y_e is included, for the early phase of SN ejecta



[MRW, Fischer, Huther, Martinez-Pinedo, Qian, PRD 89, 061303, 2014]

viable weak-r process?
consistent with SN explosion?

feedback on hydrodynamics? ν-ν contribution?

steady-state ν-driven wind model [Qian+ 1996, Otsuki+2000, Thompson+2001]

- general relativistic spherically symmetric constant mass outflow
- solution exists given L_{ν_α}, $\langle E_\alpha \rangle$, proto-neutron mass M, and radius R
- ν heating sets the hydrodynamic properties of the ejecta:
  larger heating rates $\rightarrow$ shorter dynamical time-scale and larger entropy
- competition between ν_e and $\bar{\nu}_e$ absorption rates determines Y_e

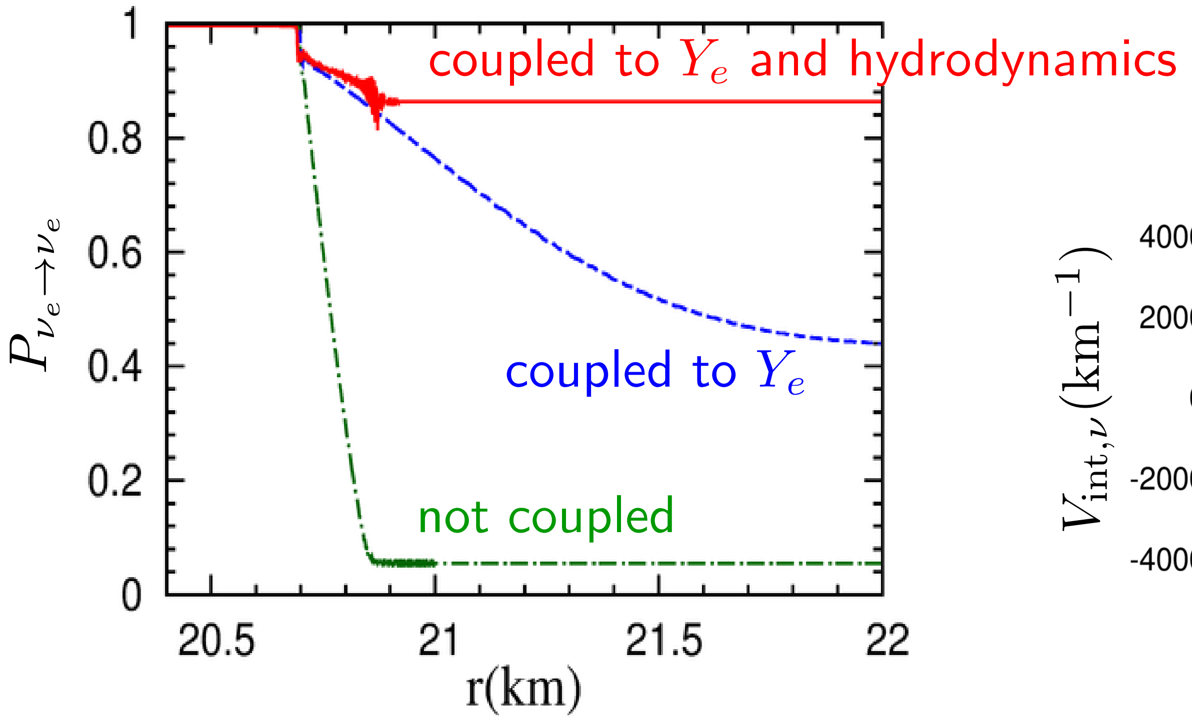
coupled with ν flavor evolution

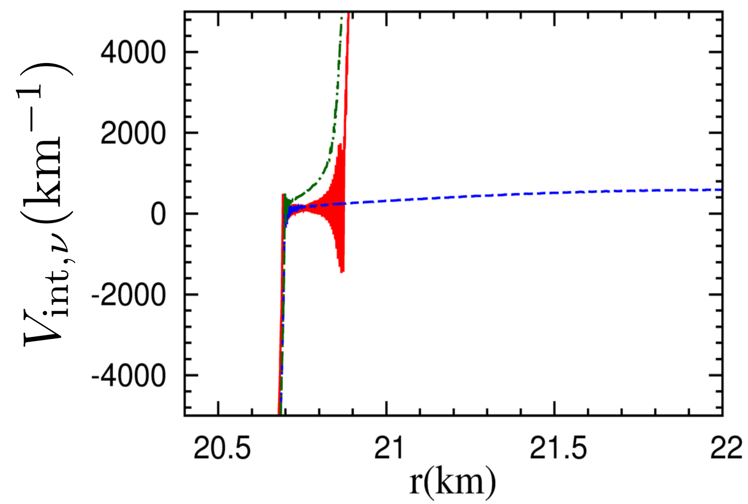
- co-evolve both hydrodynamic equations and flavor evolution equation
- access the convoluted feedback between the change of hydrodynamic properties, composition, and flavor oscillations
- explore different input parameter space
- applicable to different oscillation scenario

$M = 1.282\ M_\odot,\ R = 18.07$ km, $T_b = 0.12$ MeV
$(L_{\nu_e}, L_{\bar{\nu}_e}, L_{\nu_x}) = (1.67, 2.01, 2.58) \times 10^{51}$ erg/s
$(\langle E_{\nu_e}\rangle, \langle E_{\bar{\nu}_e}\rangle, \langle E_{\nu_x}\rangle) = (8.43, 11.9, 11.7)$ MeV

for active-sterile ν oscillations

at the inner resonance :





the change of the wind velocity may alter the behavior of flavor oscillations drastically!

Impact on nucleosynthesis

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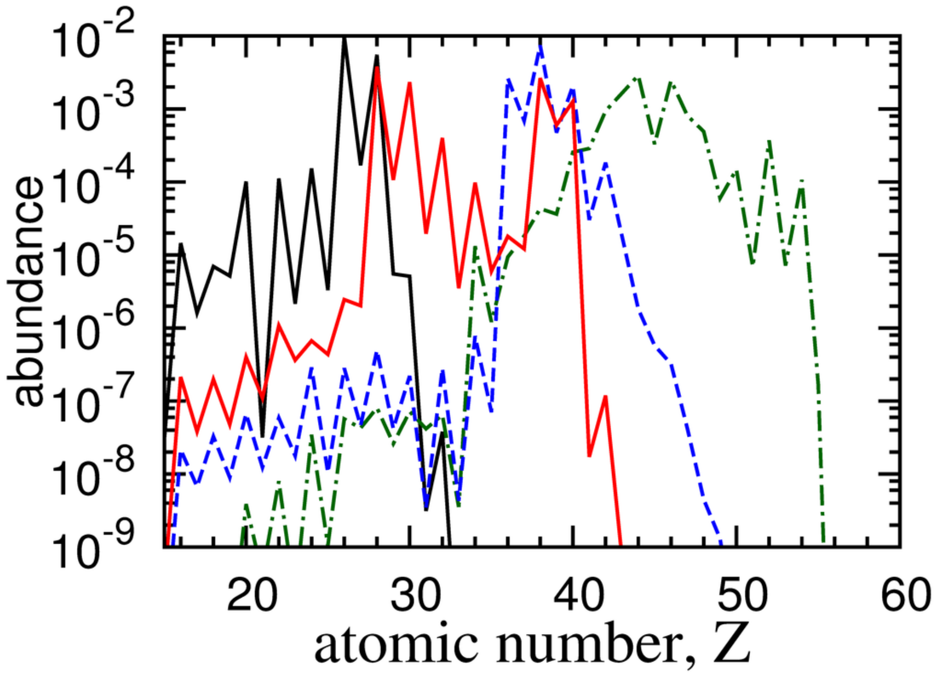
$(\langle E_{\nu_e}\rangle, \langle E_{\bar{\nu}_e}\rangle, \langle E_{\nu_x}\rangle) = (8.43, 11.9, 11.7)$ MeV

without oscillations: $Y_e \approx 0.49$ at $T = 0.8$ MeV

coupled to Y_e and hydrodynamics: $Y_e \approx 0.45$ ($\tau_{\rm dyn}$ increased by $\sim 25\%$)

coupled to Y_e only: $Y_e \approx 0.40$

not coupled at all: $Y_e \approx 0.31$



Summary and outlook

- For collective ν oscillations, an approach consistent with the underlying supernova model is essential to understand the effect on nucleosynthesis and on the ν signals
- When flavor oscillations happen at the region that can largely affect the neutron-to-proton ratio, one may have to couple flavor oscillations to the evolution of composition and hydrodynamics

Summary and outlook

- For collective ν oscillations, an approach consistent with the underlying supernova model is essential to understand the effect on nucleosynthesis and on the ν signals
- When flavor oscillations happen at the region that can largely affect the neutron-to-proton ratio, one may have to couple flavor oscillations to the evolution of composition and hydrodynamics

---

- beyond spherical symmetry? contribution from scattered ν? ν wave-packet size?
- ν-$\bar{\nu}$ oscillations? merger of compact object?

Thanks to my collaborators:

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

and thanks for your attention