Collective neutrino oscillations in core-collapse supernovae

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Workshop on core-collapse supernova explosions and related physics
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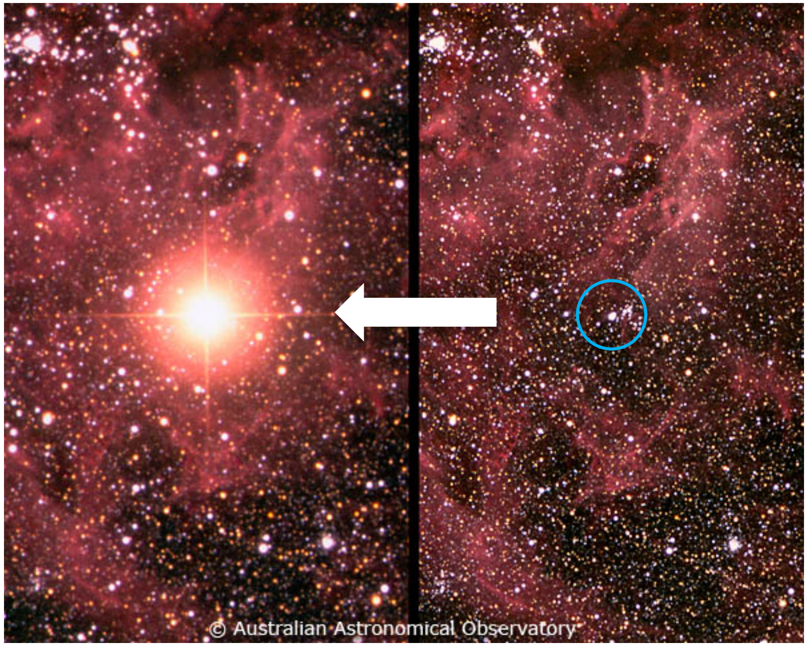
Outlines

- Introduction
    - Collective Neutrino Oscillation (CNO)
    - BULB model
    - Beyond BULB model
        - Recent trials for symmetry breakings

- My recent work
    - Neutrino halo effects in iron-CCSNe

Introduction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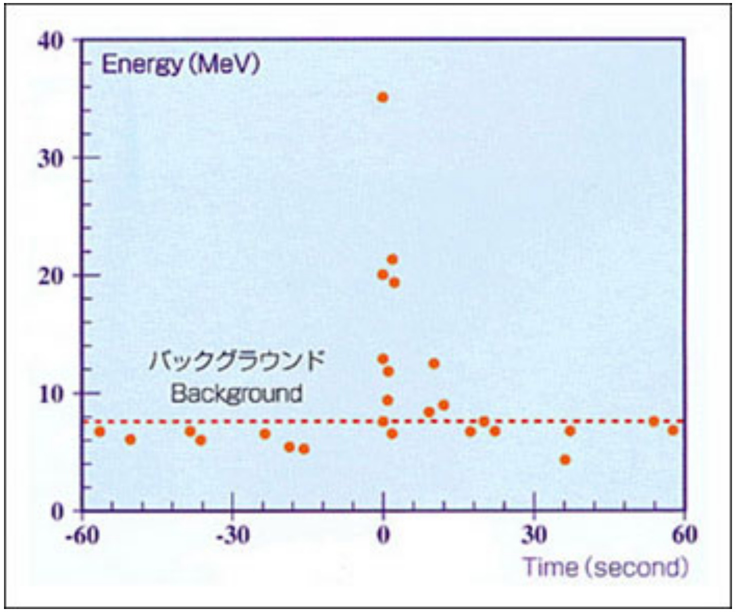


Kamiokande-II and IBM detector observed 20 neutrino events from SN1987A in LMC.

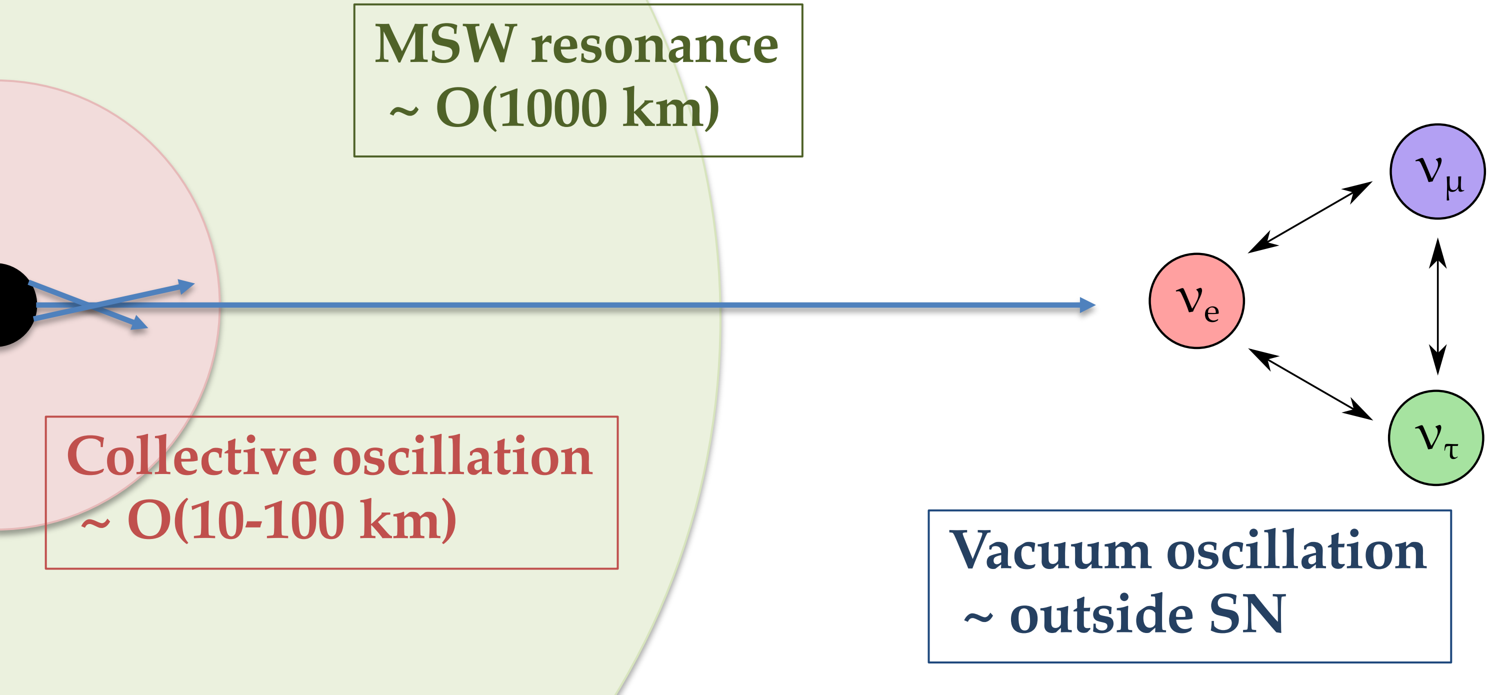
This event taught us much neutrino information.
average energy, luminosity, emission duration.

What will next galactic supernova bring…?

Neutrino oscillations in CCSNe

Neutrino oscillation causes mixing among neutrino flavors, and enable us not to understand detected events easily.

Big problems in neutrino physics.

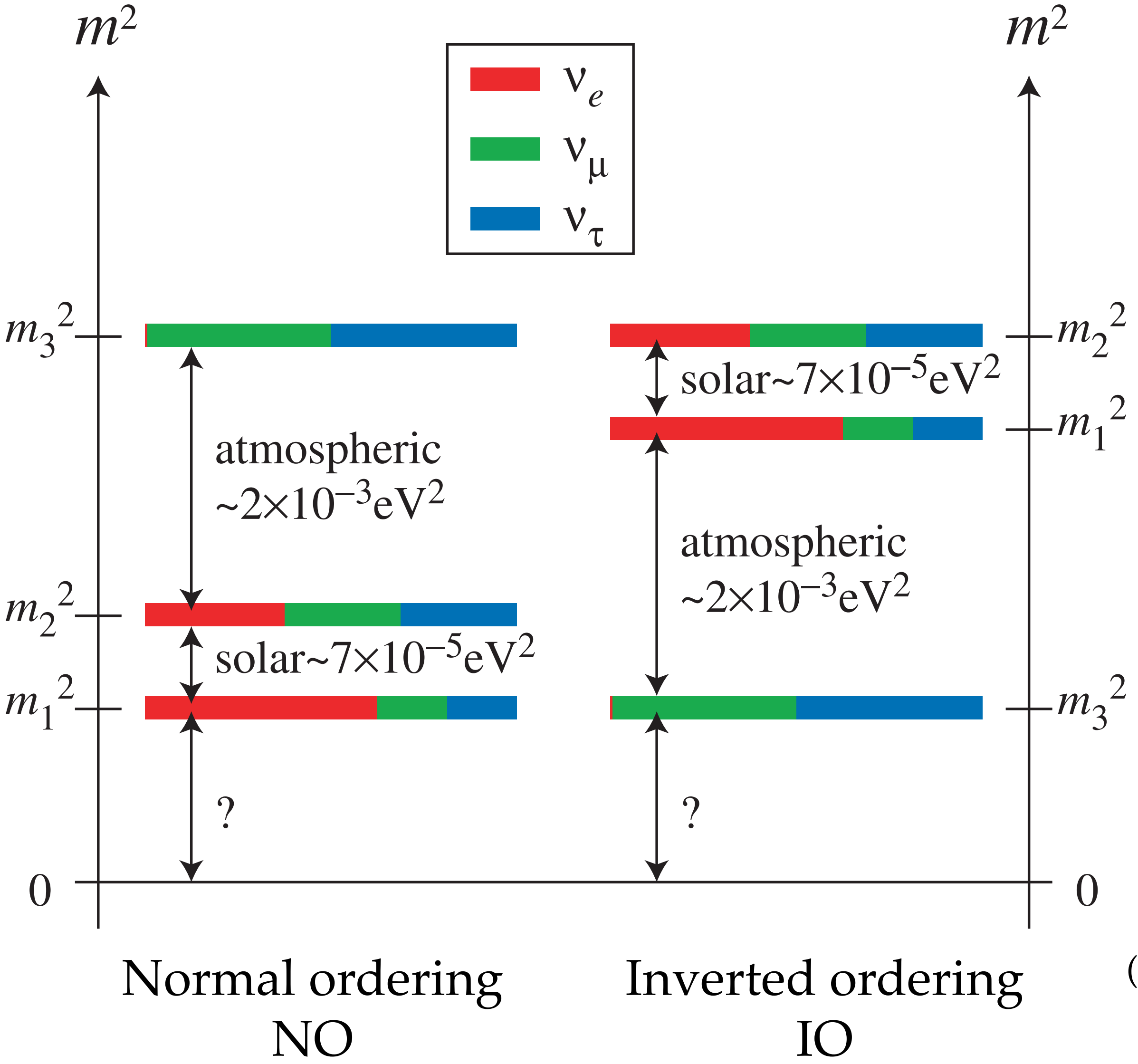


MSW resonance
~ O(1000 km)

Collective oscillation
~ O(10-100 km)

Vacuum oscillation
~ outside SN

Neutrino mass ordering



(©King+ RPPh 2013)

Neutrino oscillation

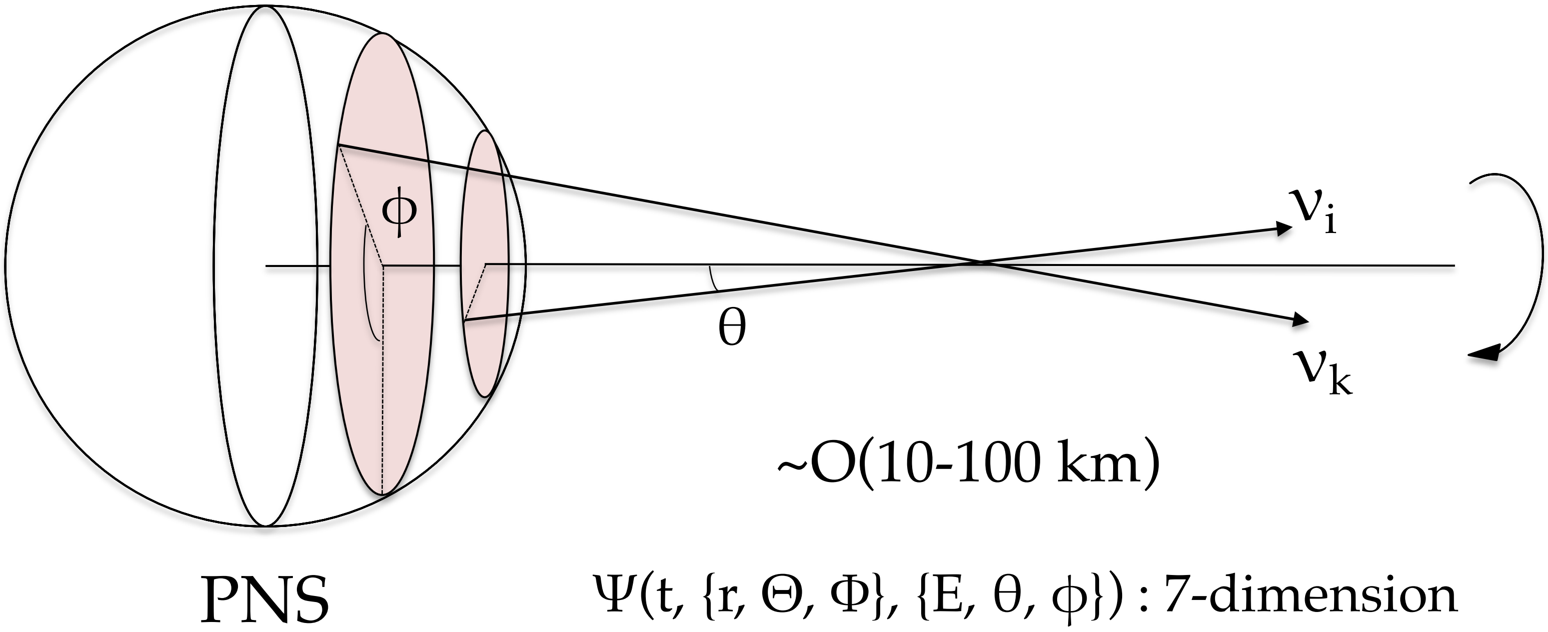
Neutrino oscillations have three types in supernovae.

$$\mathrm{i}\left(\partial_t + \mathbf{v}\cdot\nabla\right)\rho_\nu = \left[H_{\mathrm{tot}},\ \rho_\nu\right]$$

$$\rho_\nu = \begin{pmatrix} f_{\nu_e} & f_{\langle\nu_e\,|\,\nu_x\rangle} \\ f_{\langle\nu_x\,|\,\nu_e\rangle} & f_{\nu_x} \end{pmatrix}$$

$$H_{\mathrm{tot}} = \underbrace{\frac{M^2}{2E}}_{\substack{\text{Vacuum oscillation}\\ \text{(Neutrino mass)}}} + \underbrace{\sqrt{2}G_{\mathrm{F}}n_e}_{\substack{\text{Matter oscillation}\\ \text{(Electron density)}}} + \underbrace{\sqrt{2}G_{\mathrm{F}}\int \mathrm{d}\Gamma'\left(1-\mathbf{v}\cdot\mathbf{v}'\right)\left(\rho_\nu-\bar{\rho}_\nu\right)}_{\substack{\text{Collective neutrino oscillation (CNO)}\\ \text{(ν-ν forward scattering)}}}$$

Collective neutrino oscillation



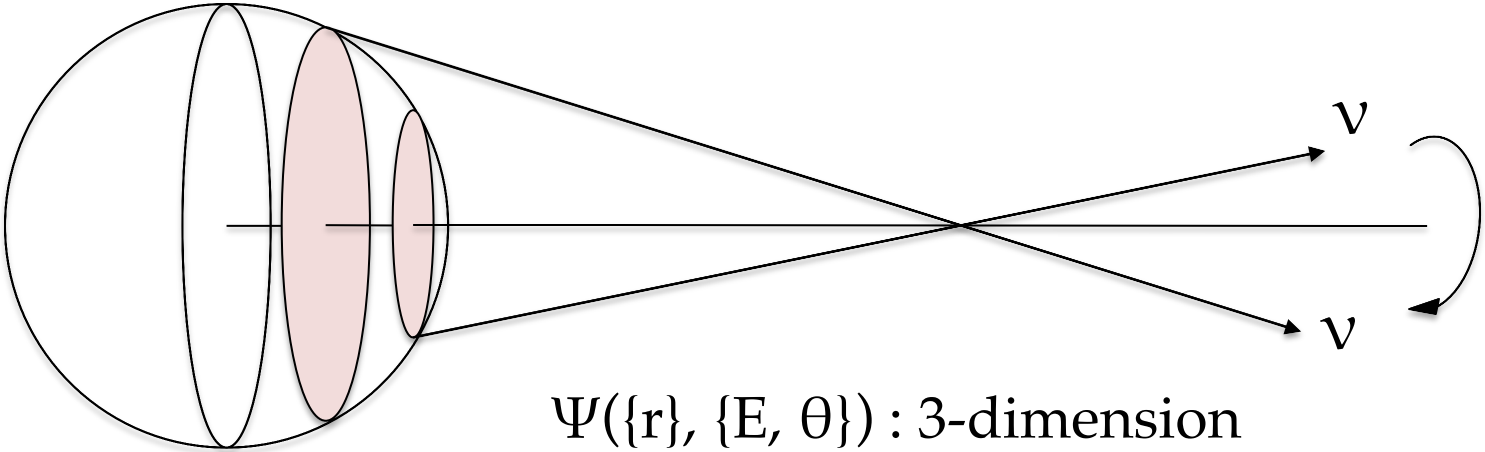
$\Psi(t, \{r, \Theta, \Phi\}, \{E, \theta, \phi\})$: 7-dimension

~10^{58} neutrinos are emitted from a SN in ~10 seconds.

Dense neutrino gas causes neutrino-neutrino interaction near the proto-neutrino star.

Neutrino self-interaction induces collective flavor conversions.

Collective neutrino oscillation



$\Psi(\{r\}, \{E, \theta\})$: 3-dimension

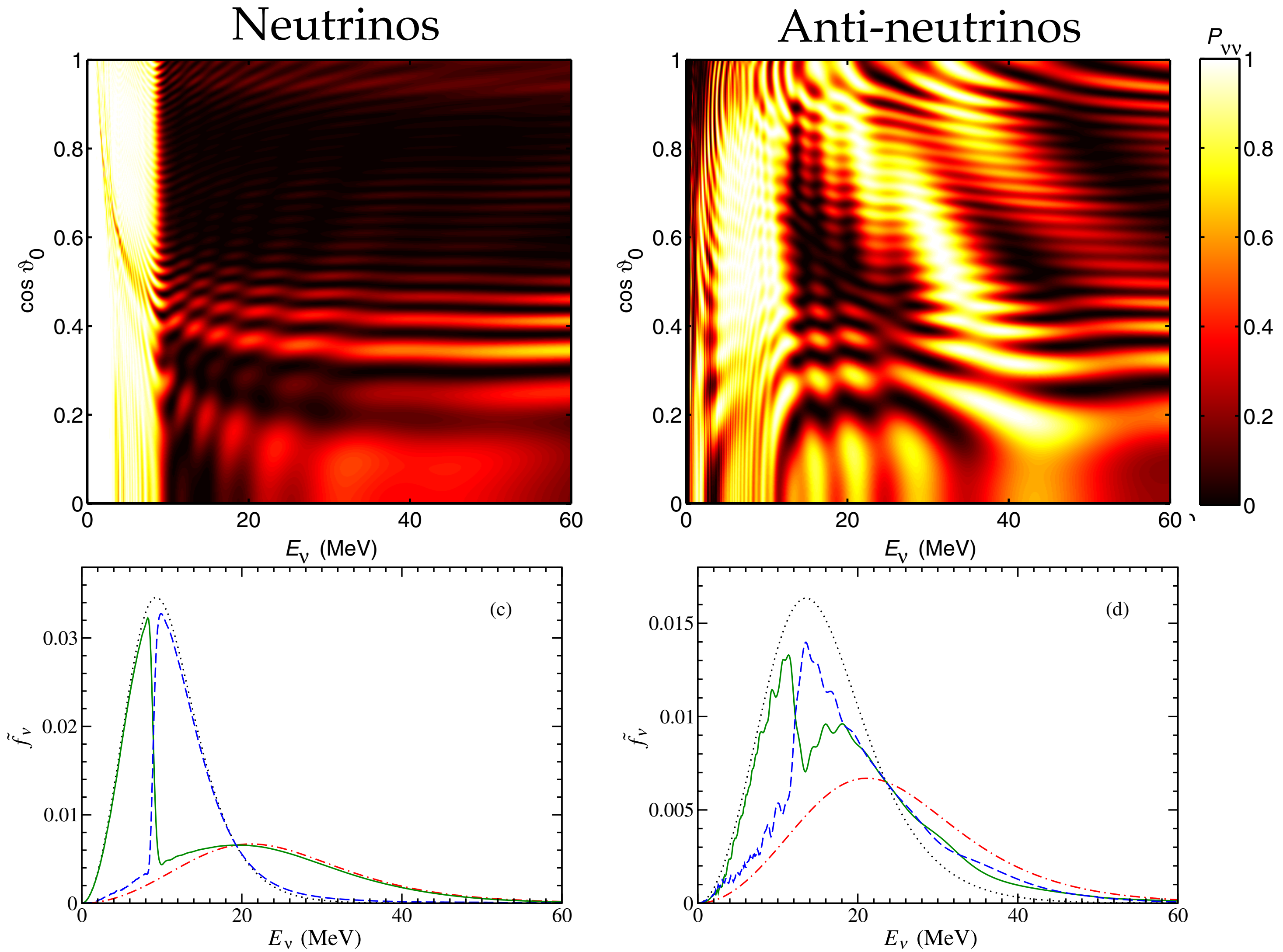
N_flavor × N_E × N_θ = $O(10^7)$ ODE systems

The ``**BULB model**'' to simplify the neutrino self-interaction.

- Homogeneous, Isotropic, Stationary emission
- Axial-symmetry in direction
- 1-dimensional SN model
- Neutrinos propagate free-streamingly.

(Duan+ PRD 2006, Dasgupta+ PRD 2008)

Spectral splits



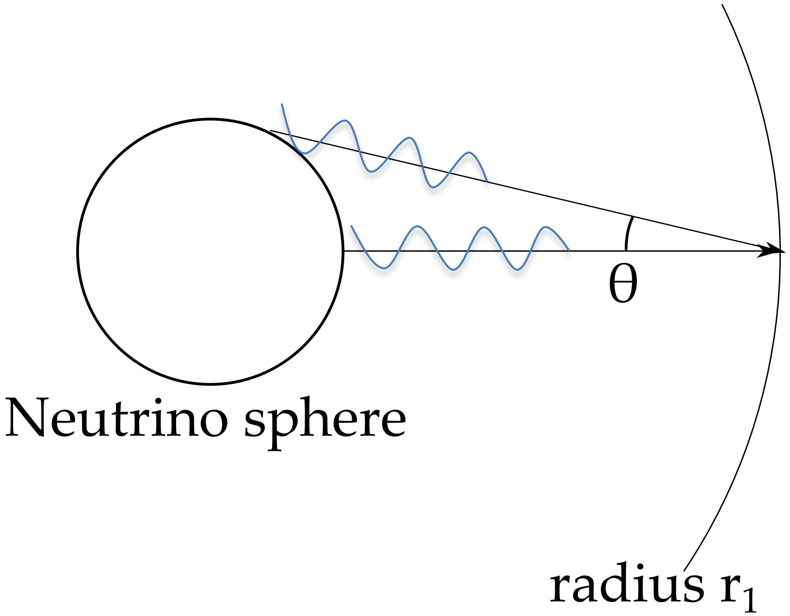
Neutrinos

Anti-neutrinos

(Duan+ PRL, PRD 2006)

Flavor conversions above a critical energy

Collective effects vs. Matter effects



(Esteban-Pretel+ PRD 2008)

Neutrino self-interaction maintains coherence among different neutrino trajectories.

On the other hand,

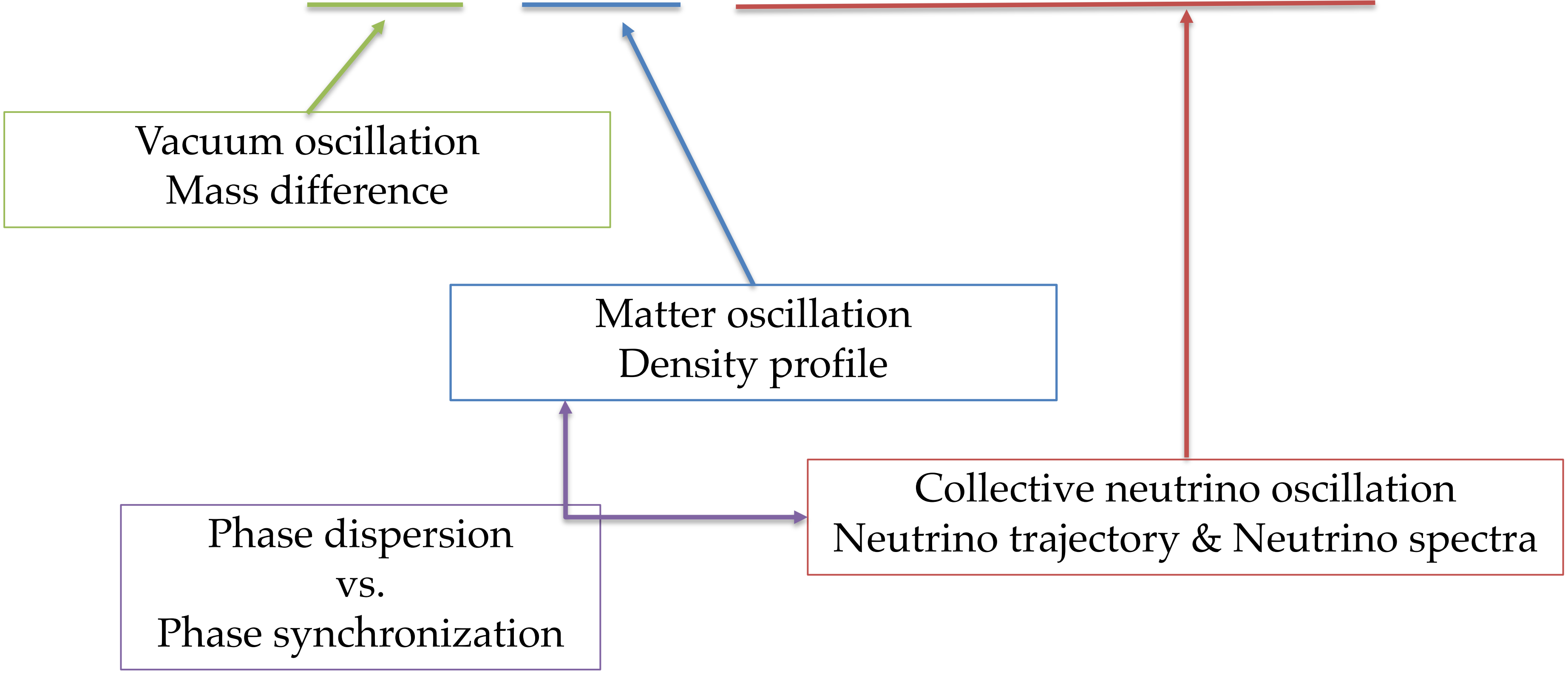
Different neutrino trajectories give the different effective potential from background electrons.
This causes phase dispersion.

- Matter effects > neutrino self-interaction
  → Collective neutrino oscillation can be suppressed.

- Matter effects < neutrino self-interaction
  → Collective flavor transformation occurs.

Equation of motion

$$i\partial_t \rho_i = \left[+U\frac{M^2}{2E_\nu}U^\dagger + \sqrt{2}G_{\mathrm{F}} N_e + \sqrt{2}G_{\mathrm{F}} \int \mathrm{d}\Gamma' \left(1 - \cos\theta_{ik}\right)\left(\rho'_{\nu_k} - \bar{\rho}'_{\nu_k}\right),\ \rho_i \right]$$



Vacuum oscillation
Mass difference

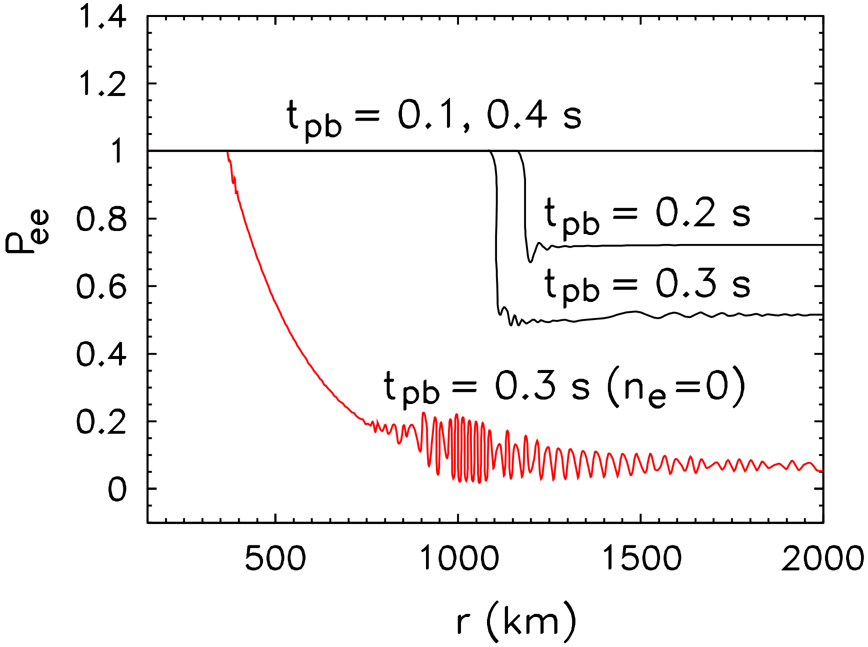
Matter oscillation
Density profile

Collective neutrino oscillation
Neutrino trajectory & Neutrino spectra

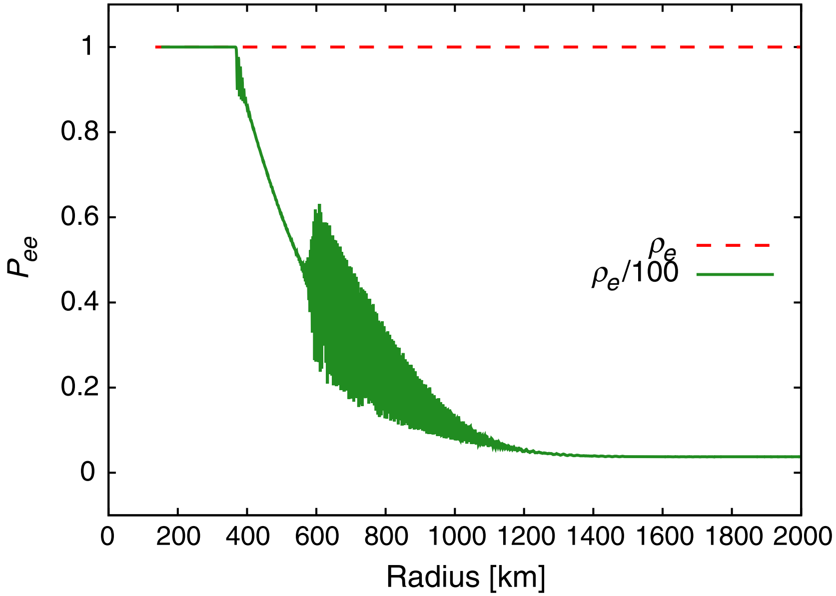
Phase dispersion
vs.
Phase synchronization

Matter suppression

Iron CCSNe with 10.8 $M_\odot$



Failed SNe with 40 $M_\odot$

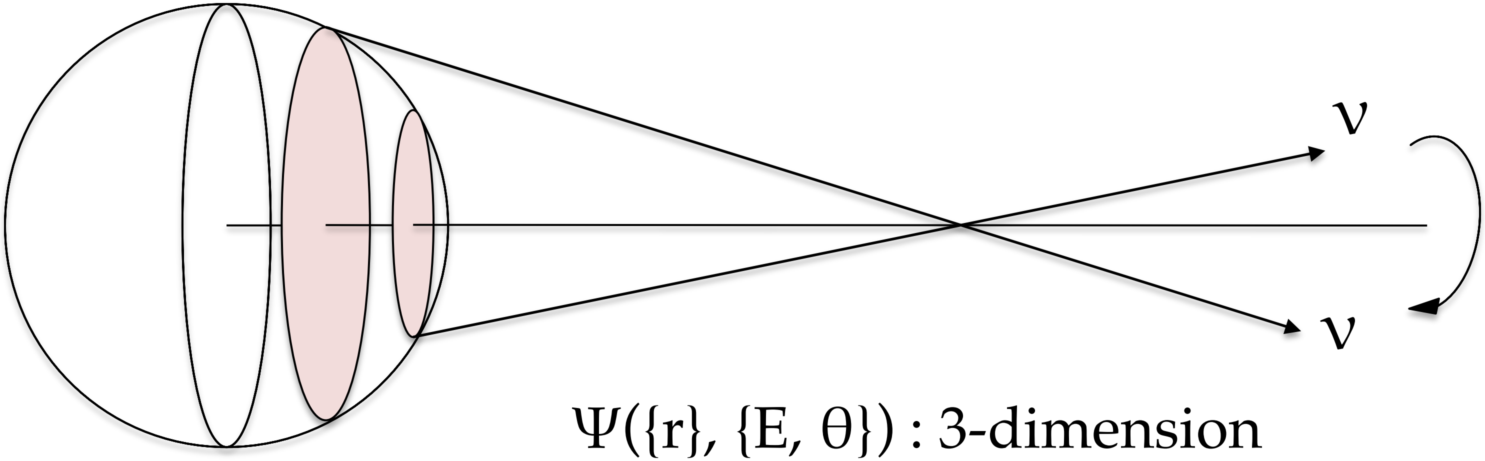


(Chakraborty+ PRD 2011, Zaizen+ PRD 2018)

CNO is suppressed in SNe with low mass progenitor at early time, especially at accretion phase.

CNO is completely suppressed in SNe with heavy progenitor at all time.

Limitation of BULB model?



$\Psi(\{r\}, \{E, \theta\})$: 3-dimension

The BULB model requires many symmetries & assumptions.

- Stationary emission
- 1-dimensional SN model
- Directional axial-symmetry
- Homogeneous, Isotropic emission
- Neutrinos propagate free-streamingly.

Symmetry breaking

3-dimensional EoM --> 7-dimensional EoM

$$\mathrm{i} v_r \partial_r \rho_\nu = [H_{\mathrm{tot}}, \rho_\nu]$$

$$\mathrm{i}(\underline{\partial_t} + v_r \partial_r + \underline{\mathbf{v}_T \cdot \nabla_T})\rho_\nu = [\underline{H_{\mathrm{tot}}}, \rho_\nu]$$

$$\rho_\nu\left(\underline{t}, \{r, \underline{\Theta, \Phi}\}, \{E, \theta, \underline{\varphi}\}\right) : 7 \text{ dimension}$$

The BULB model – three types of symmetries

- Stationary emission → Temporal instability
- 1-dimensional SN model → Homogeneous instability
- Axial-symmetry in direction → Multi-azimuthal angle instability

Stability analysis

$$\mathrm{i}(\partial_t + v_r \partial_r + \mathbf{v}_T \cdot \nabla_T)\rho_\nu = [H_{\mathrm{tot}}, \rho_\nu]$$

$$\rho_\nu = \begin{pmatrix} f_{\nu_e} & f_{\langle \nu_e \mid \nu_x \rangle} \\ f_{\langle \nu_x \mid \nu_e \rangle} & f_{\nu_x} \end{pmatrix}$$

$f_{\langle \nu_e \mid \nu_x \rangle}$ Initially this is zero.
No flavor evolution

Off-diagonal components of density matrix express the transitions from one flavor to another.
We can investigate unstable modes to evaluate the growth rate of transition term.

$$f_{\langle \nu_e \mid \nu_x \rangle} \propto \mathrm{e}^{-\mathrm{i}\Omega r}$$

If Im $\Omega < 0$, we think this is unstable at a radius r.

Stability analysis

$$\mathrm{i}(\partial_t + v_r\partial_r + \mathbf{v}_T\cdot\nabla_T)\rho_\nu = [H_{\mathrm{tot}},\rho_\nu]$$

$$\Big\downarrow$$

Linearize

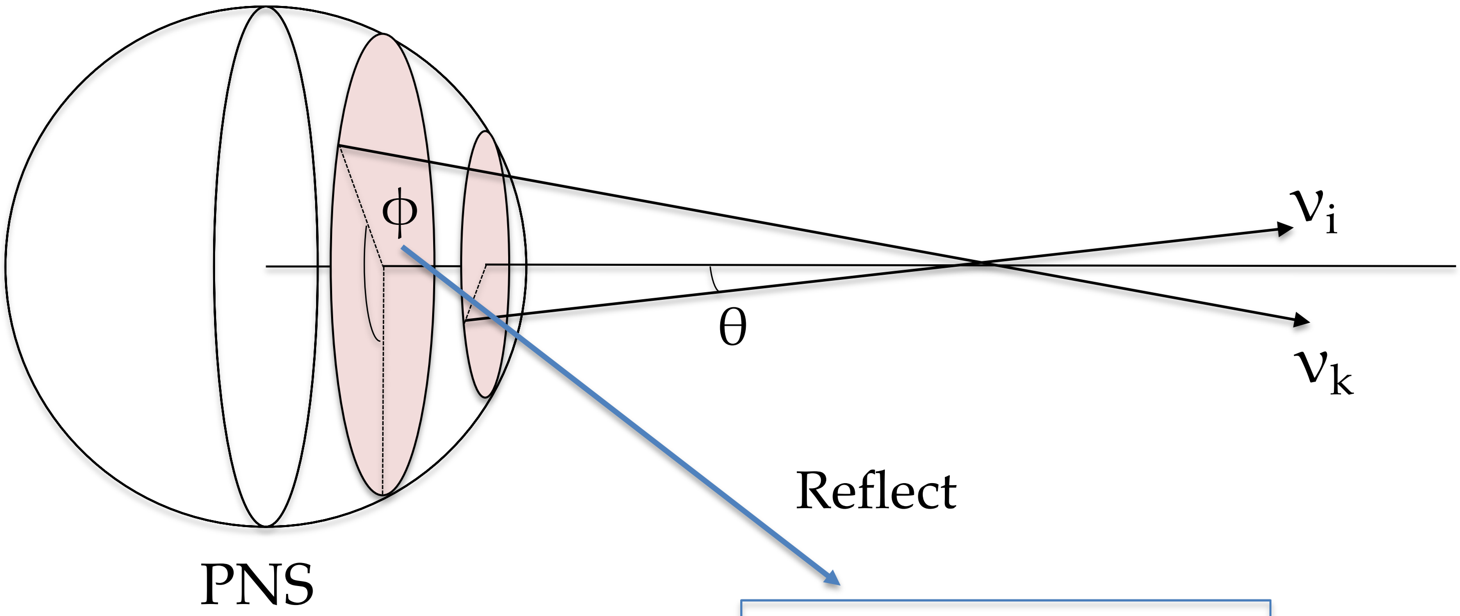
$$\left[\frac{-\omega+\bar{\lambda}-p-\mathbf{v}_T\cdot\mathbf{k}}{v_r}-\Omega_{p,\mathbf{k}}\right]Q_{p,\mathbf{k}} = \frac{\mu}{v_r}\int \mathrm{d}\Gamma'\,(1-\mathbf{v}\cdot\mathbf{v}')\,g'Q'_{p,\mathbf{k}}$$

$$f_{\langle\nu_e\,|\,\nu_x\rangle} = \int \mathrm{d}p\mathrm{d}\mathbf{k}\ \mathrm{e}^{-\mathrm{i}(pt+\mathbf{v}_t\cdot\mathbf{k})}Q_{p,\mathbf{k}}\ \mathrm{e}^{-\mathrm{i}\Omega_{p,\mathbf{k}}r}$$

We solve this linearized equation.

p & v･k arises from derivative term ∂t & v･∇.
BULB model ignores p & v･k terms.

Axial-symmetry breaking

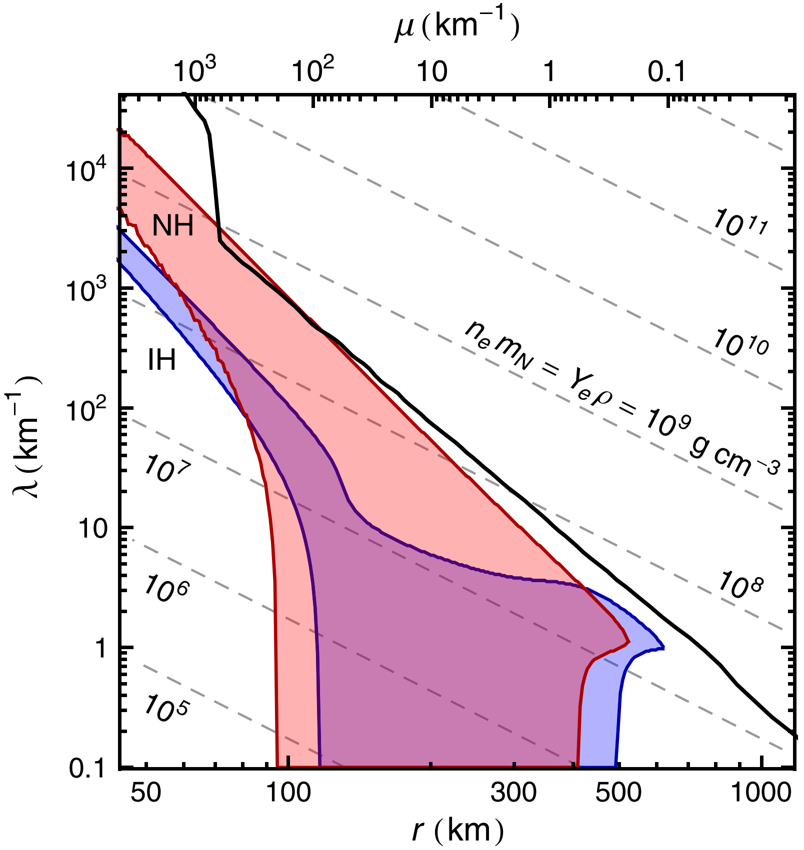


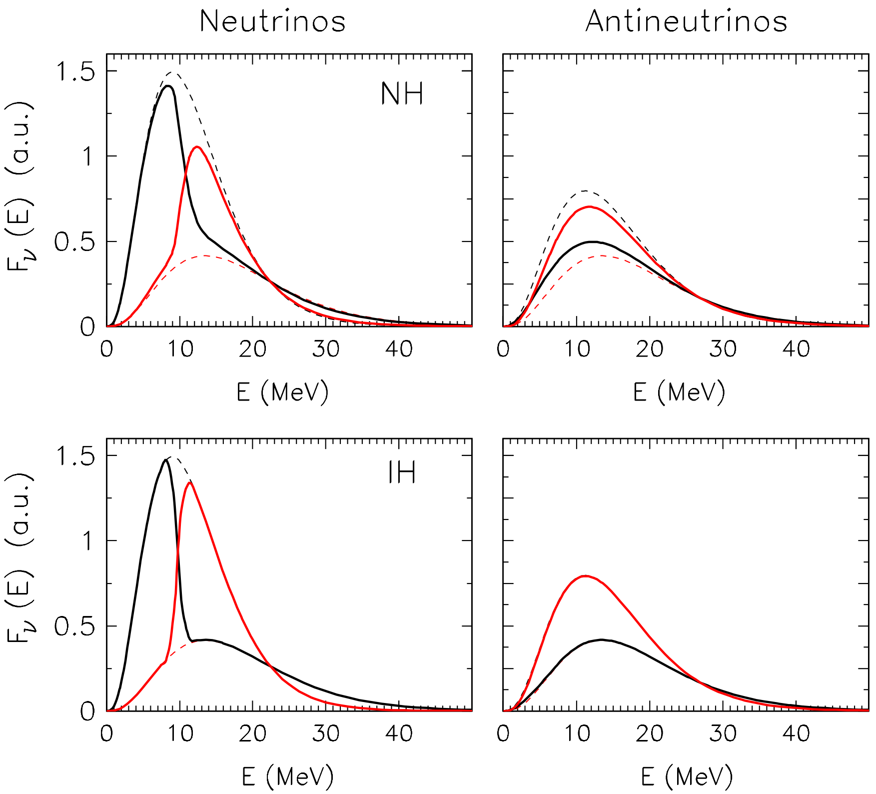
$$H_{\nu\nu} = \int \mathrm{d}\Gamma' \left(\frac{1 - v_{r,u}v_{r,u'} \boxed{- \sqrt{uu'}\frac{R_\nu^2}{r^2}\cos(\varphi - \varphi')}}{v_{r,u}v_{r,u'}} \right) (\rho_\nu - \bar{\rho}_\nu)$$

Add an azimuthal-angle term in neutrino trajectories.

This requires angular binning of $N_\phi \leqq 100$, less than $N_\theta \sim 1000$?

Axial-symmetry breaking



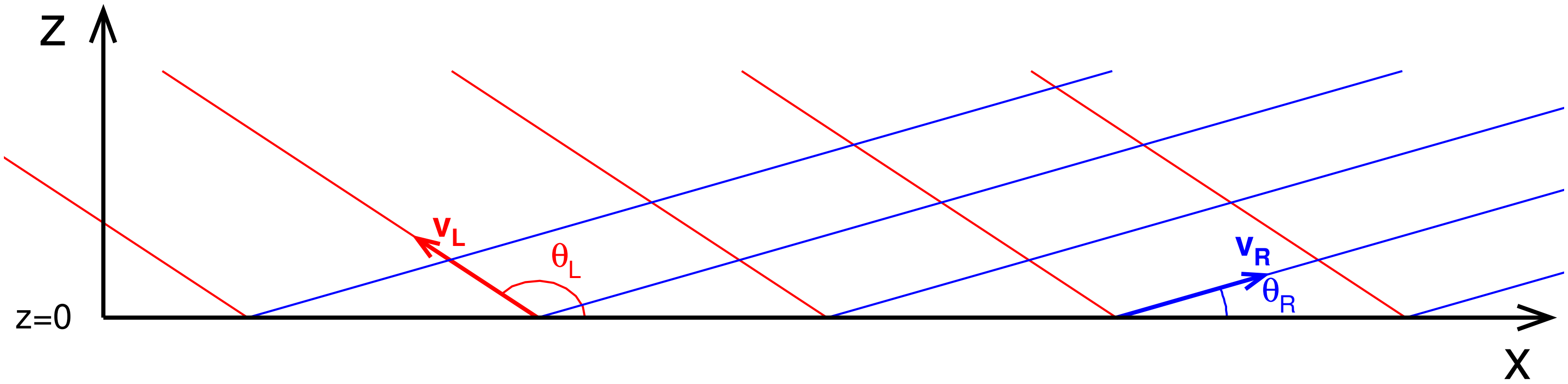


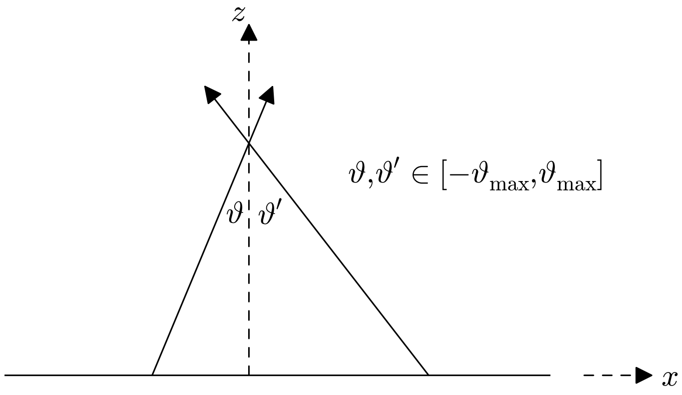
(Raffelt+ PRL 2013, Chakraborty+ PRD 2014)

This axial-symmetry breaking indicates that CNO is more unstable in the normal mass ordering than in the inverted ordering.

This feature is distinct from the BULB model!

Spatial-symmetry breaking





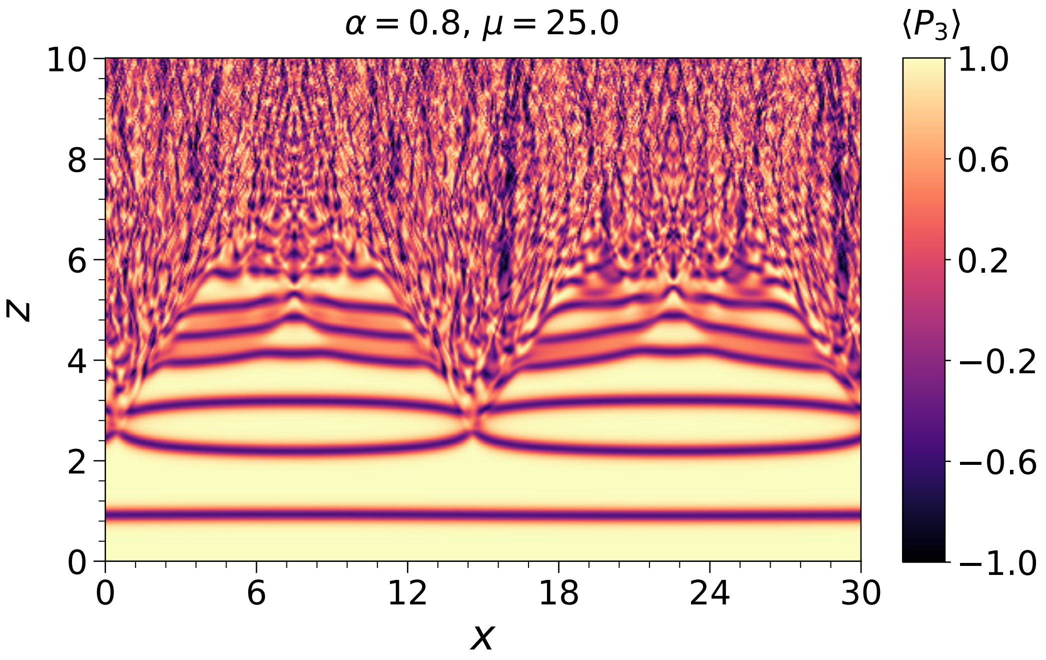
Neutrinos are emitted from the ``**neutrino line**”, not the neutrino sphere.

Simply studies often use a two-beam model, which has a single angle.

(Of course, multi-angle beam model is more realistic.)

Spatial-symmetry breaking

$$\mathrm{i}\left(v_r\partial_r + \underline{\mathbf{v}_T\cdot\nabla_T}\right) f_{\langle\nu_e\,|\,\nu_x\rangle}$$



(Martin+ arXiv 2019)

Two-dimensional, but two-beam line model (θ=π/4).

Large-scale structures along x-direction begin to break down into small-scale structures as z increases.

Small-scale structures require much fine x-binning (Nx = 60,000)…

Temporal instability

$$\mathrm{i}(\partial_t + v_r\partial_r + \mathbf{v}_T\cdot\nabla_T)\rho_\nu = [H_{\mathrm{tot}},\rho_\nu]$$

↓ Linearize $f_{\langle\nu_e\,|\,\nu_x\rangle} \propto \mathrm{e}^{-\mathrm{i}pt-\mathrm{i}\Omega r}$

$$\left[\frac{-\omega + \boxed{\bar{\lambda} - p} - \mathbf{v}_T\cdot\mathbf{k}}{v_r} - \Omega_{p,\mathbf{k}}\right] Q_{p,\mathbf{k}} = \frac{\mu}{v_r}\int \mathrm{d}\Gamma'\,(1-\mathbf{v}\cdot\mathbf{v}')\,g' Q'_{p,\mathbf{k}}$$

p arises from time derivative ∂t. This expresses a pulsating mode.

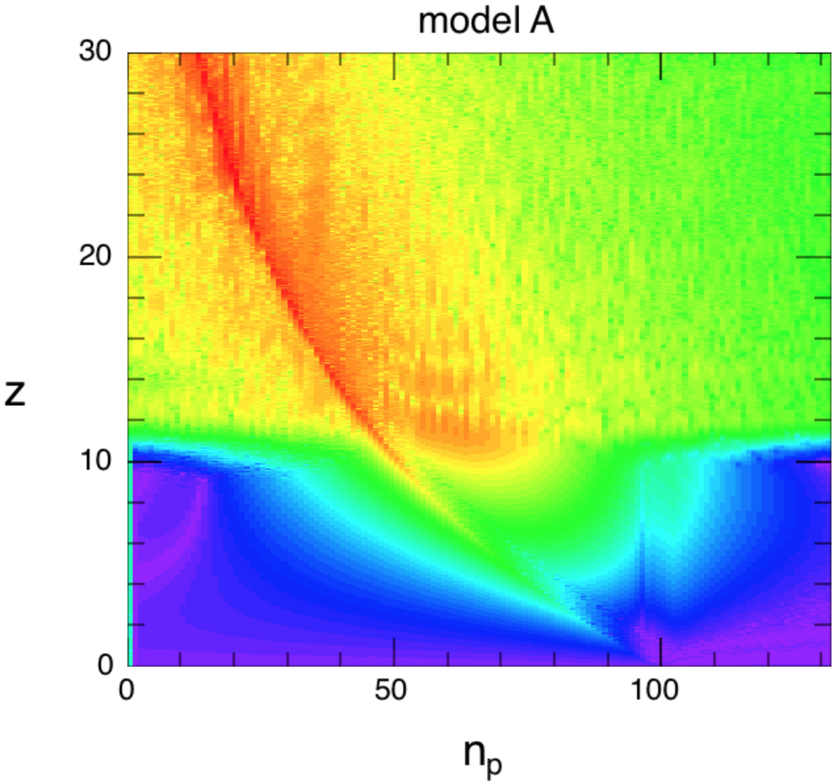
Pulsation mode p can cancel density term λ.
If λ is large enough to suppress CNO completely, instability with pulsation mode p~λ can grow up exponentially.

Temporal instability

$$p = \frac{n_p}{100}\bar{\lambda}$$

$$\bar{\lambda} - p = 0 \to n_p \sim 100$$

$$\lambda = \lambda_0 \times \exp\left(-z/\tau_\lambda\right)$$



(Capozzi+ JCAP 2016)

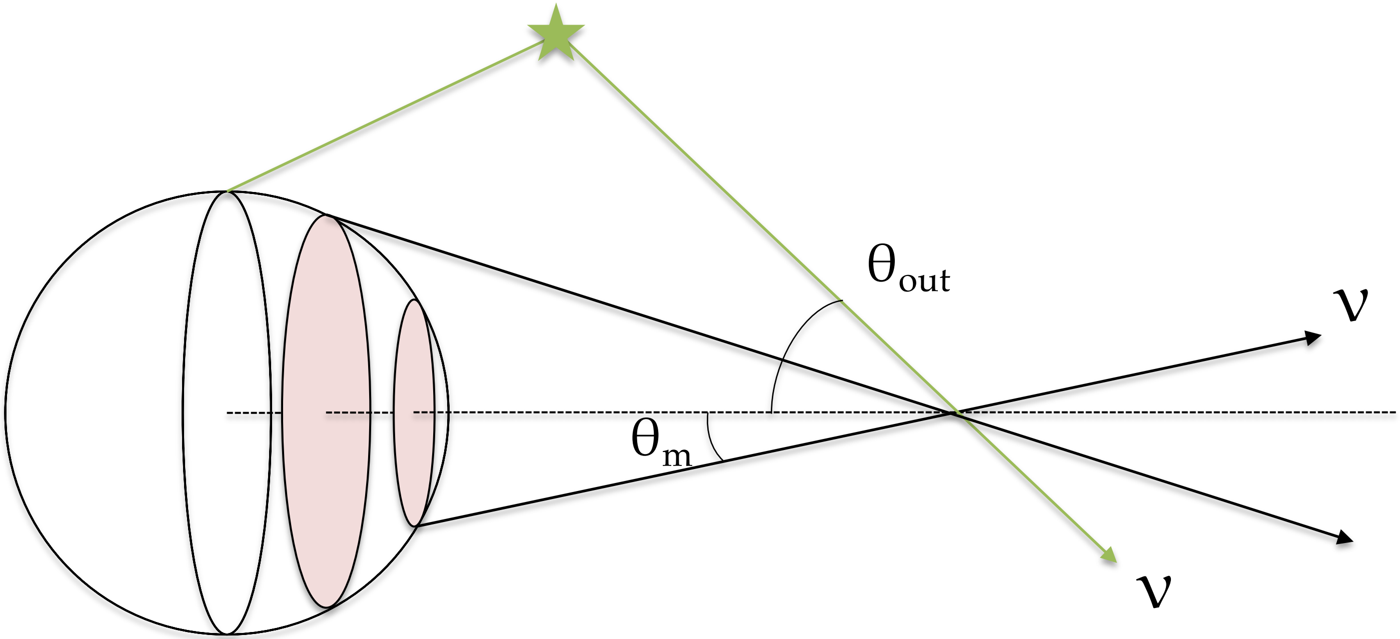
Initially modes at n_p~100 are excited.

Thereafter excited modes are shifted into slower pulsating modes as density declines (z decreases).

Possibility that flavor conversion can occur inside the shock wave at accretion phase?

Neutrino halo effect on collective neutrino oscillation in iron core-collapse supernova

Neutrino halo effect



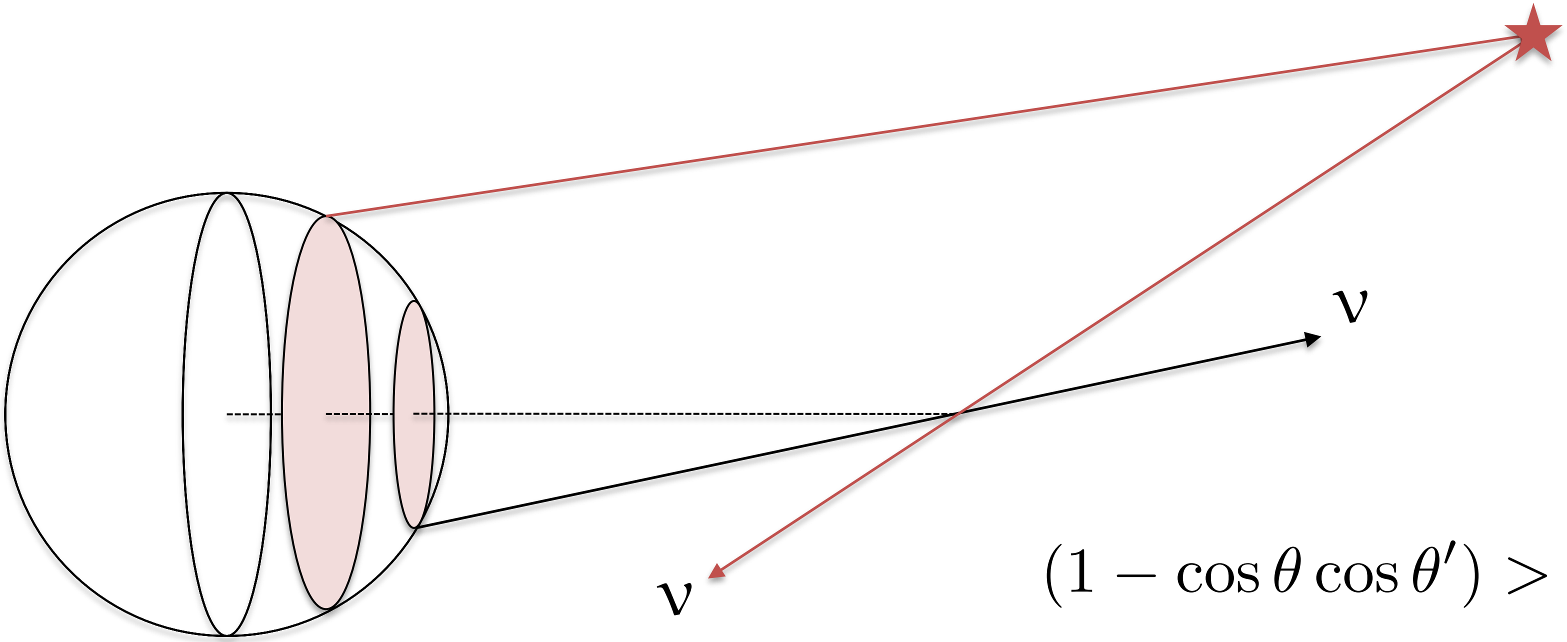
$$(1 - \cos\theta \cos\theta')$$

Some fraction of neutrinos emitted from neutrino sphere can experiences a direction-changing scattering.

These neutrinos have wider-intersection angles, and can have impact on CNO.

(Cherry+ PRL 2012)

Inward neutrino flux



$$(1 - \cos\theta\cos\theta') > 1$$

Inward-scattered neutrinos destroy the bulb model.

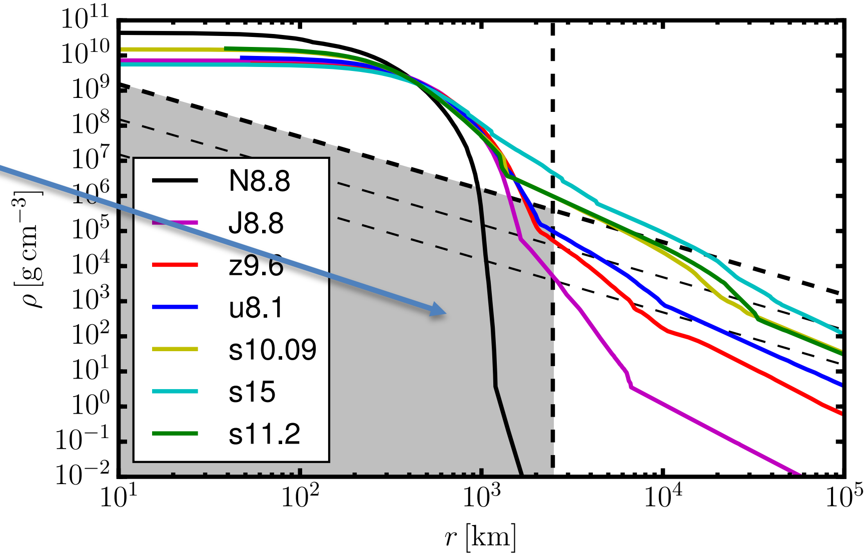
We have to simulate CNO with iteration. But this is still a static case.

In order to calculate CNO within the bulb framework, inward flux needs to be ignored, compared with outward flux.

Inward neutrino flux

Previous study (Cherry+ PRD 2013) employed an O-Ne-Mg SN model.

- It has a steep density gradient.



(Muller 2016)

Neutrino halo is produced by neutrino-nucleon/nucleus scattering.

- After density gradient, scattering becomes much smaller.
- Inward scattering is also much less.

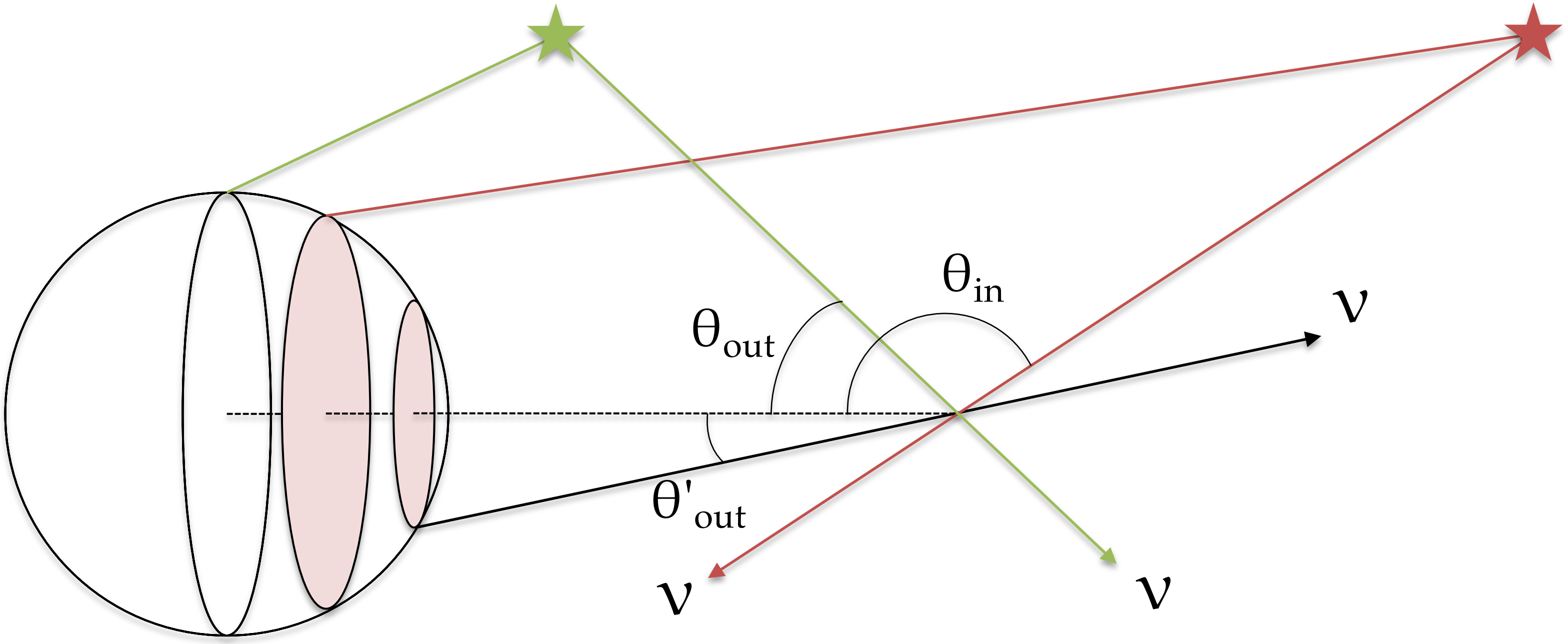
Inward neutrino flux

We employ iron core-collapse SN model with $9.6M_{\odot}$, not O-Ne-Mg SNe.

→ Need to expand neutrino halo effects.
→ What distribution do inward-going neutrinos have?
→ How situation can we ignore them?

We compare inward-going contribution with outward-going one.

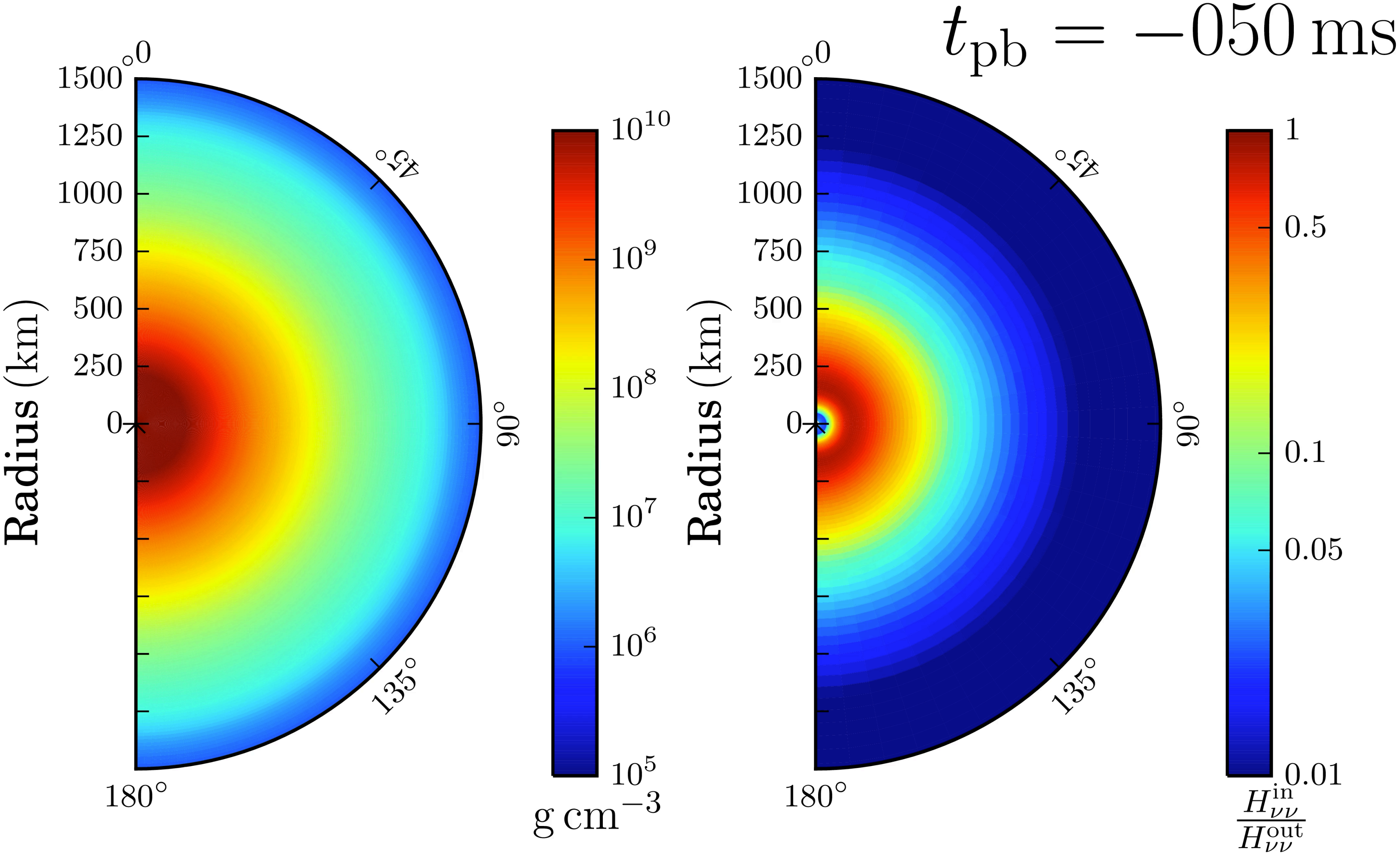
Inward neutrino flux



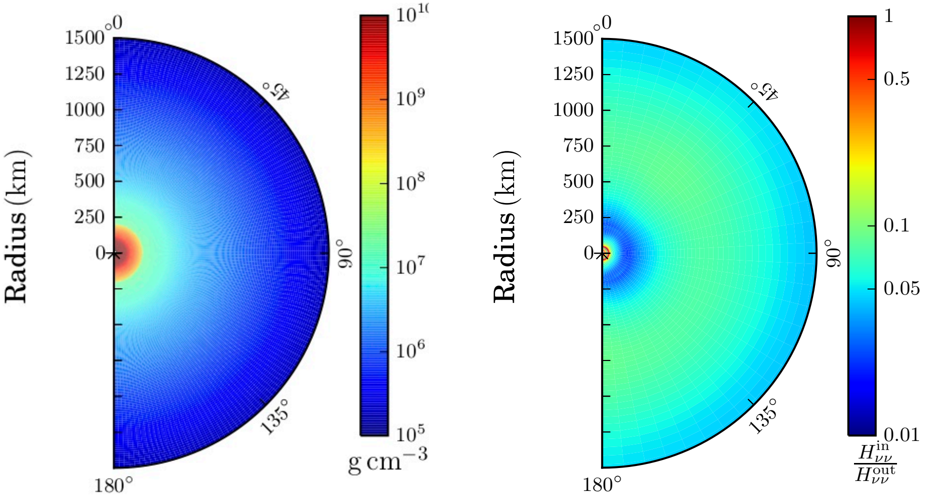
Outward-propagating neutrinos vs. inward-scattered neutrinos

If contribution ratio H_{in}/H_{out} is sufficiently small, we can ignore the inward scattered flux.

$$\langle 1 - \cos\theta_{\rm out}\rangle \Phi_{\nu_{\rm out}} \text{ vs. } \langle 1 - \cos\theta_{\rm in}\rangle \Phi_{\nu_{\rm in}}$$


$t_{\mathrm{pb}} = -050\,\mathrm{ms}$
0°
45°
90°
135°
180°
1500
1250
1000
750
500
250
0
Radius (km)
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
$\mathrm{g\,cm^{-3}}$
0°
45°
90°
135°
180°
1500
1250
1000
750
500
250
0
Radius (km)
1
0.5
0.1
0.05
0.01
$\frac{H^{\mathrm{in}}_{\nu\nu}}{H^{\mathrm{out}}_{\nu\nu}}$

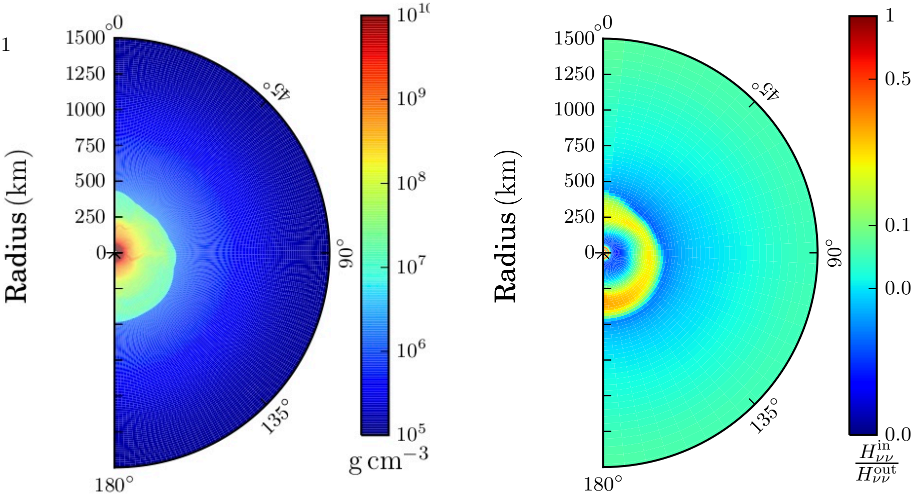
At 86 ms



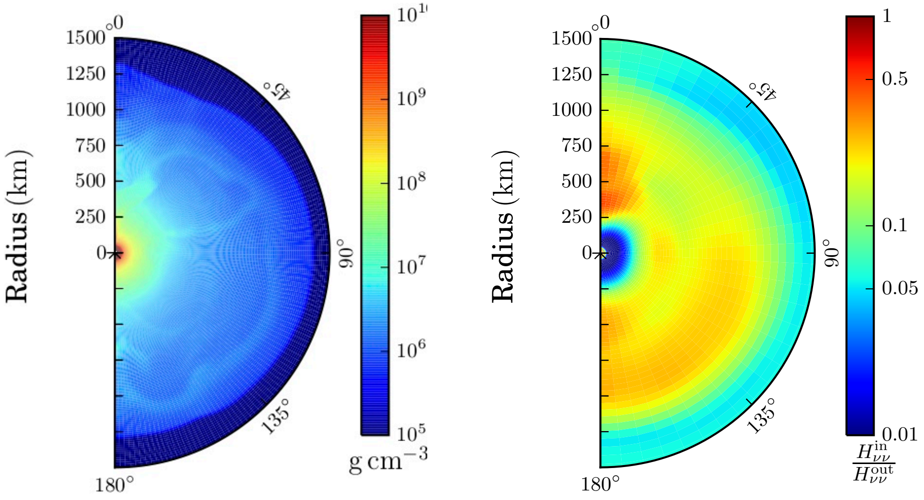
Density profile (left panels)
Halo distribution (right panels)

Inward scattering is stronger inside the shock wave.

At 136 ms

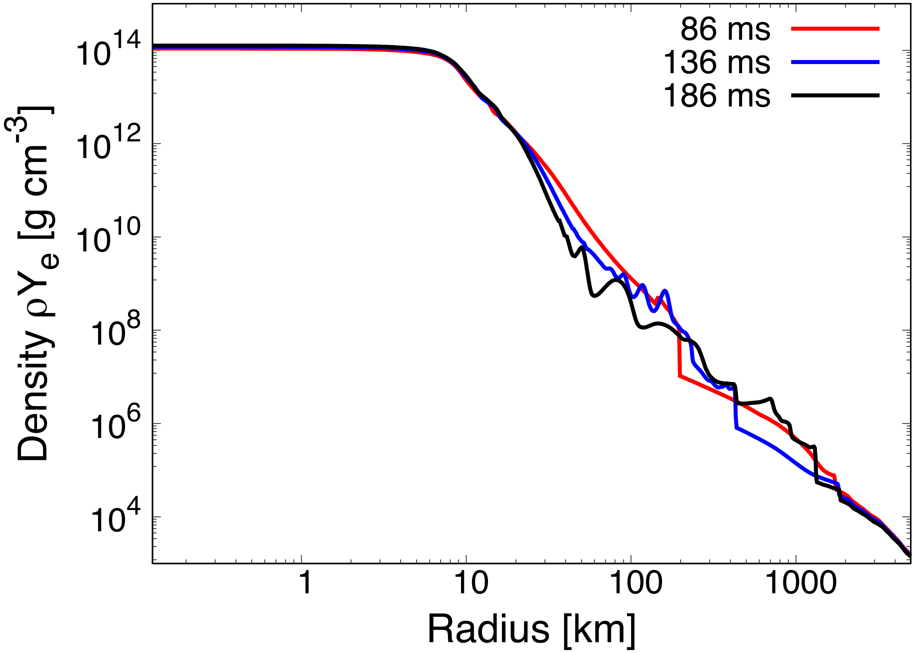


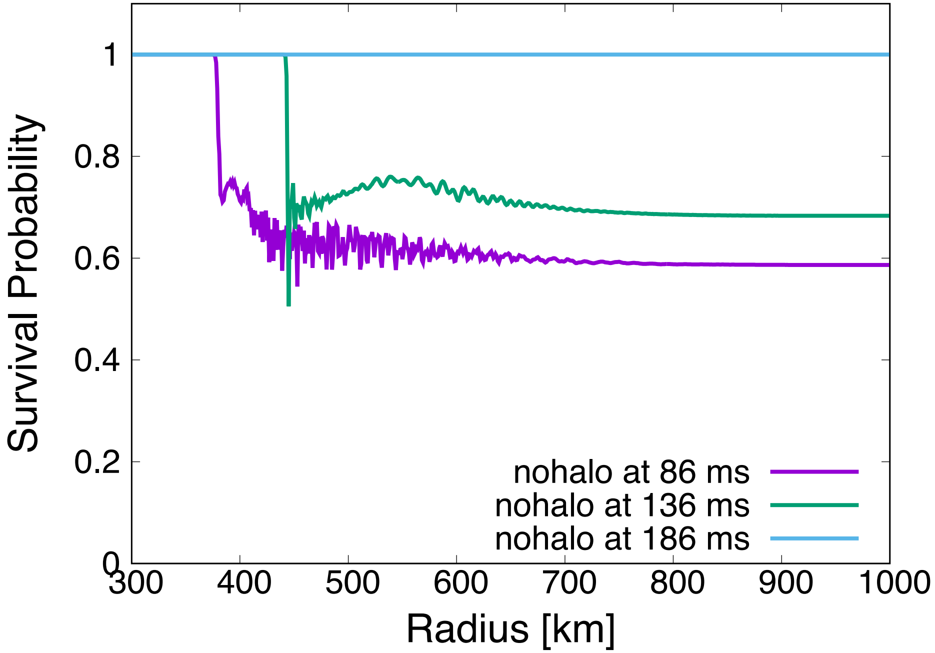
At 186 ms



$$R_{\rm CNO} = \mathcal{O}(10^2)\ \text{km}$$

CNO w/o halo



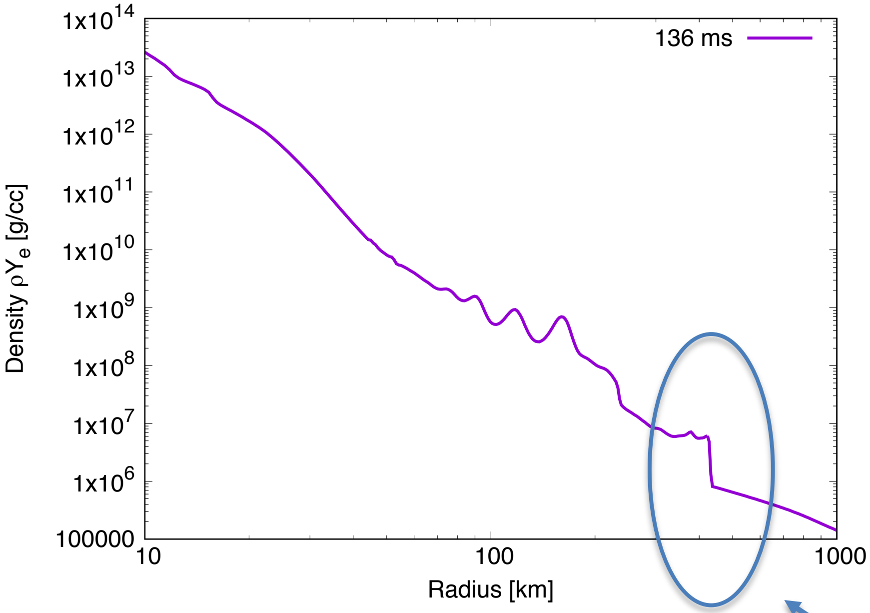


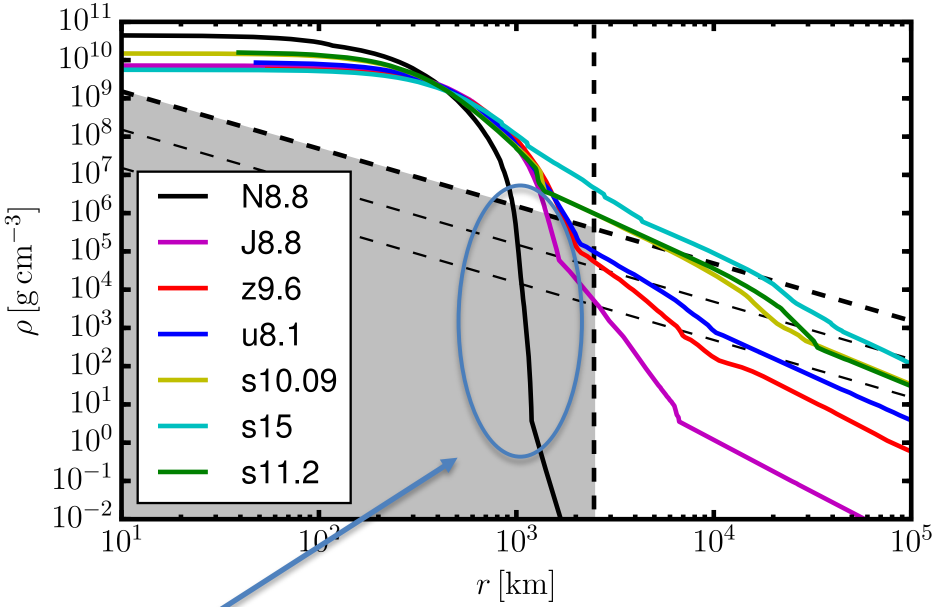
The onset radius of CNO depends strongly on the location of shock wave.

- At 136 ms, CNO starts just after the shock radius.
- At 186 ms, CNO is completely suppressed by high matter density.

Both CNO & halo scattering get free from matter after the shock wave.

CNO w/o halo



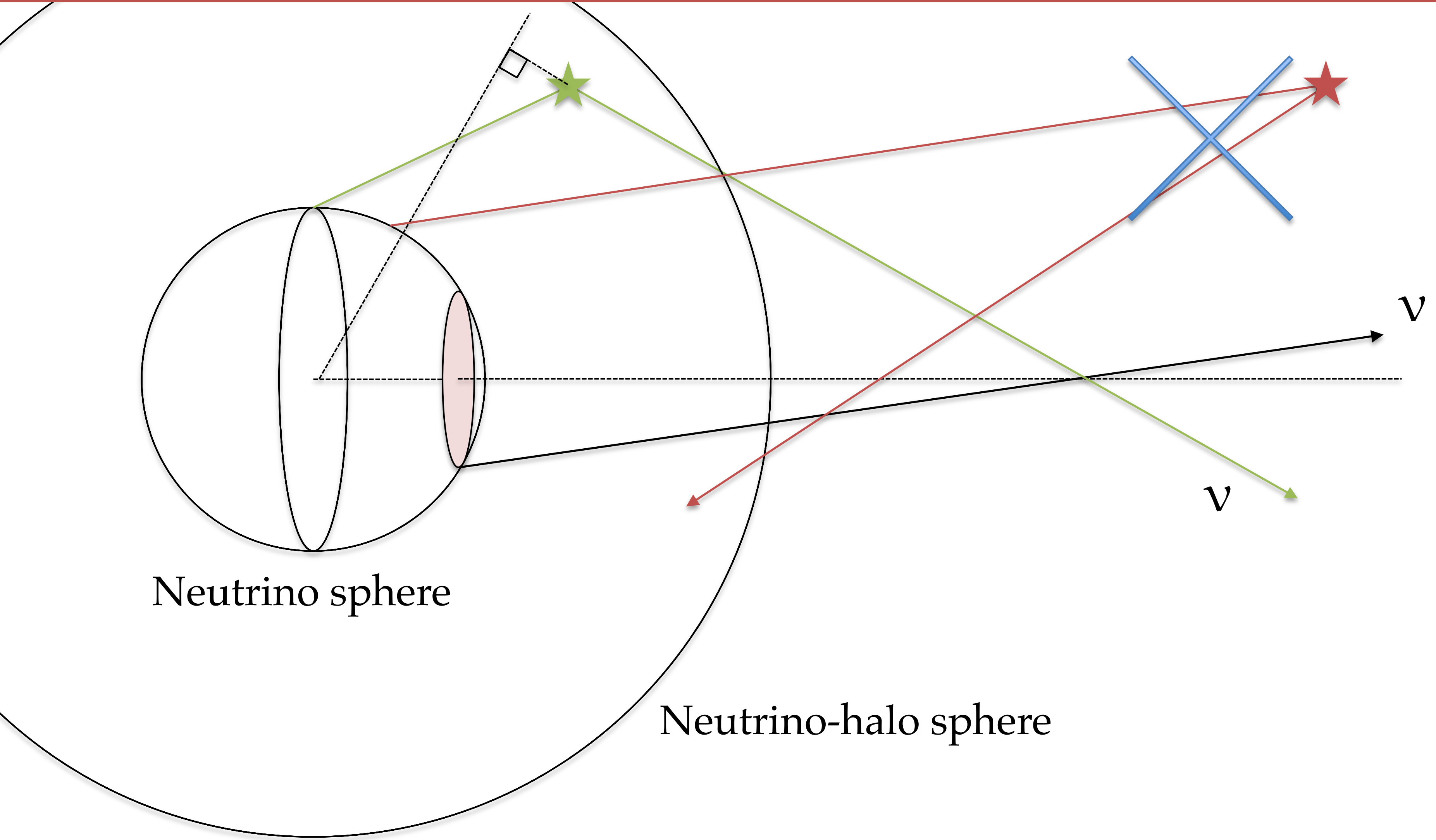


The shock wave in iron-CCSN acts same as

the steep density gradient in O-Ne-Mg SNe!

We can calculate CNO including neutrino halo safely using BULB-like model.

BULB-like model



Neutrinos are newly considered to be emitted from halo sphere.

Survival probability after CNO

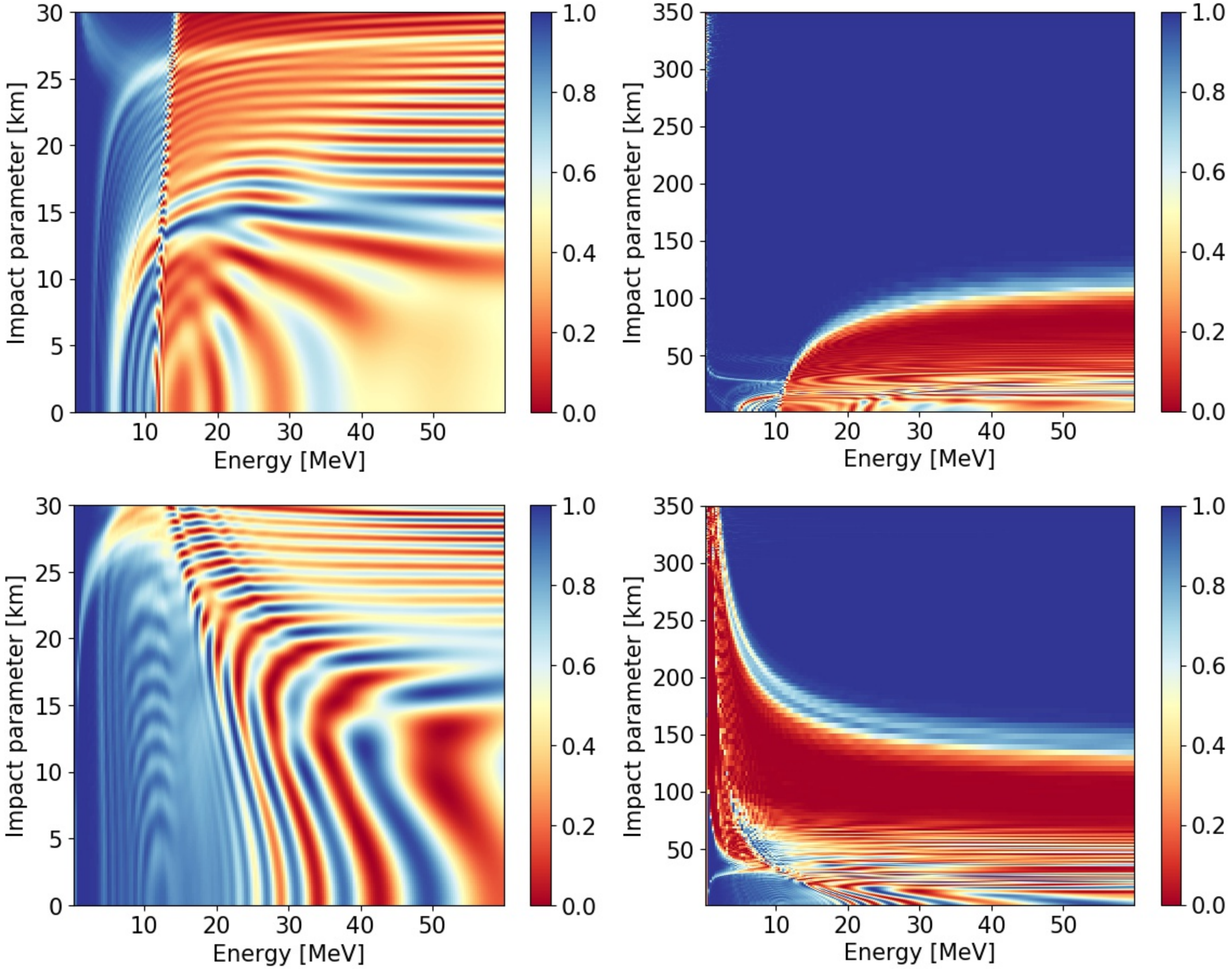
At 136 ms.

No Halo

With Halo

Electron neutrinos

Anti-electron neutrinos



Spectra after CNO

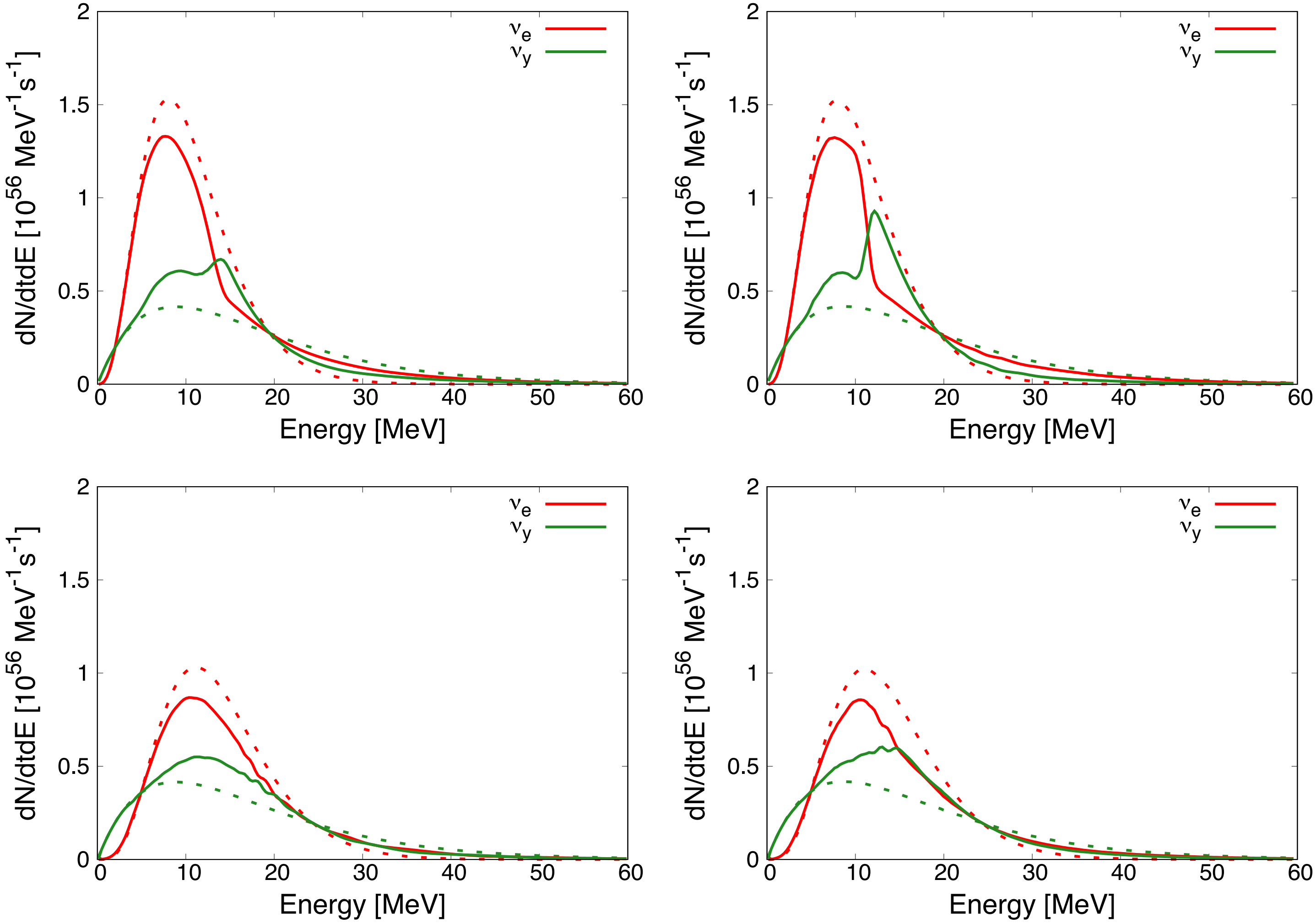
At 136 ms.

No Halo

With Halo

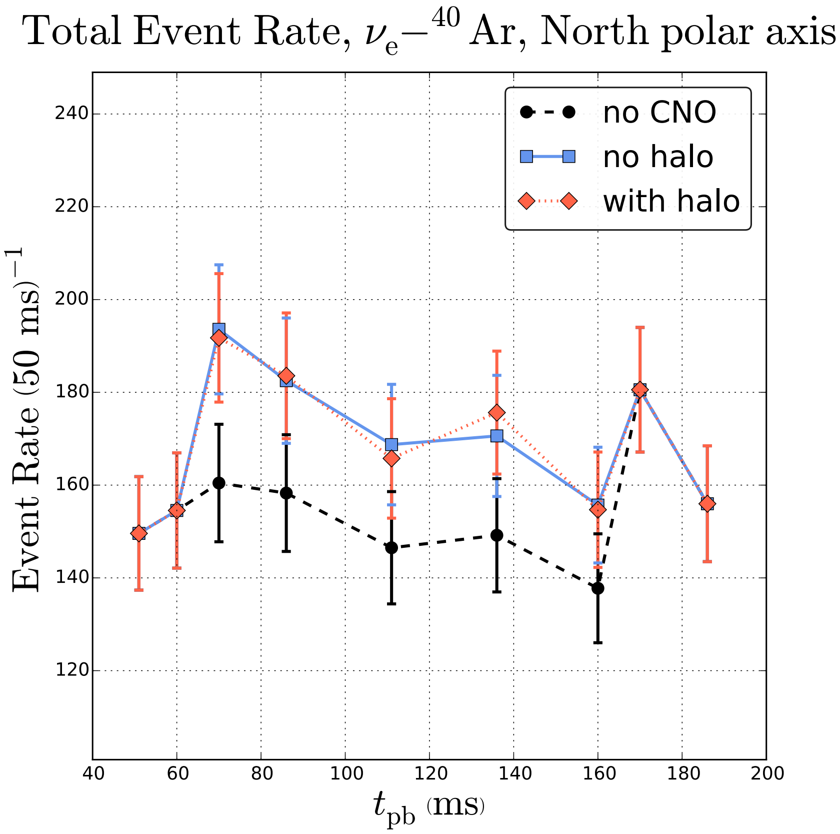
Electron neutrinos

Anti-electron neutrinos

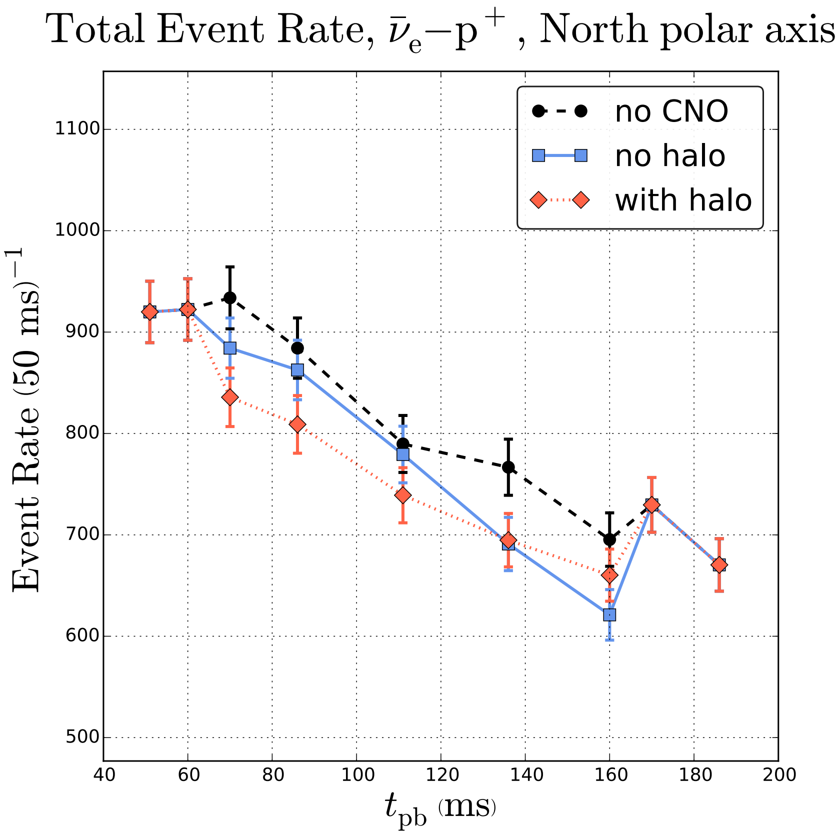


Event rate

DUNE



Super-K



Assume a target at d=10kpc in the Galaxy.

Significant differences between no-CNO and inclusion of CNO.

Maximum difference is ~ 10% between no-halo and with-halo.

Conclusion

- BULB model enables us to calculate CNO, but it is not sufficiently to treat the dimensionality problems.
- Recent studies have investigated the beyond BULB model.
  - Some symmetry breakings overcome matter suppression?
- We calculated CNO w/ halo in iron-CCSNe.
  - Inside the shock wave, inward-going neutrinos can not be ignored, compared with outward ones.
  - Outside the shock, the ratio is less than 10%.
  - CNO starts from outside the shock.
- CNO w/ halo has additional flavor conversions over high energy range.