New understanding in neutrino flavor oscillations and annhiliations in astrophysical explosions

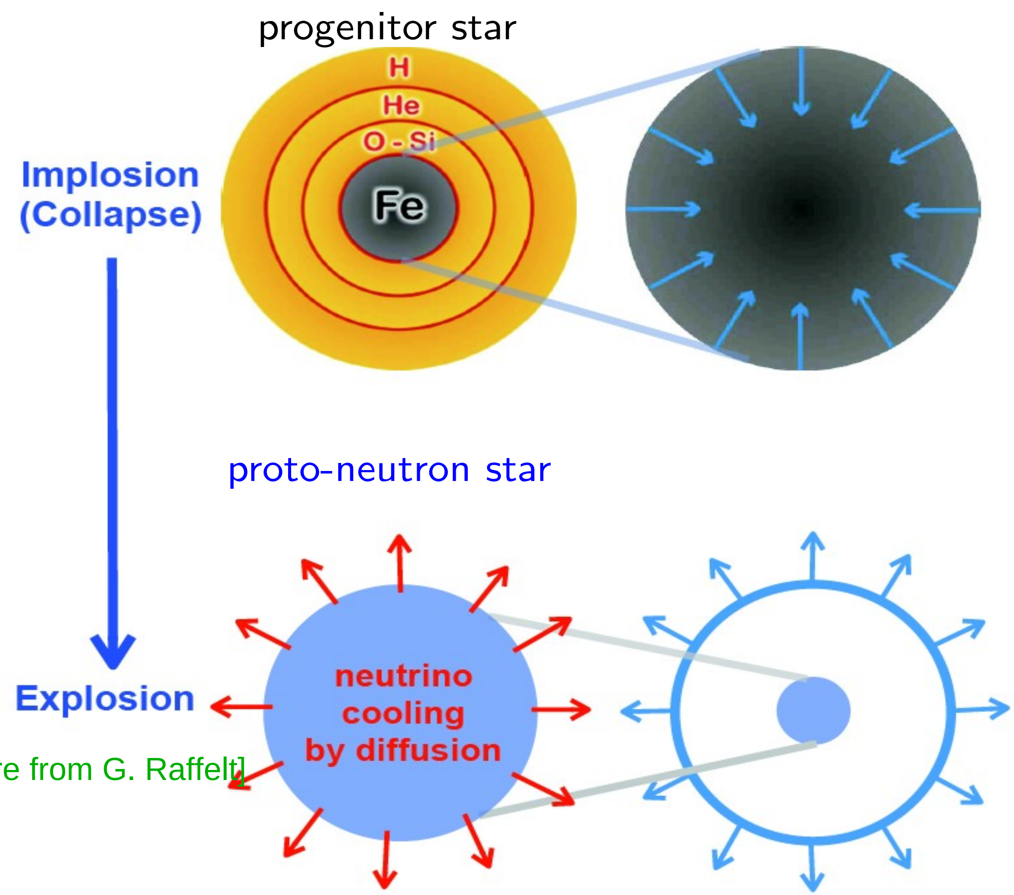
Meng-Ru Wu (Institute of Physics, Academia Sinica)

Mini-Workshop on Highlights of 2022
NCTS, NTU, Taipei, Taiwan, December 29, 2022

中央研究院物理研究所
INSTITUTE OF PHYSICS, ACADEMIA SINICA

NSTC 國家科學及技術委員會
National Science and Technology Council

Core-collapse supernovae – turning implosion into explosion



[Figure from G. Raffelt]

$M_{\mathrm{Fe,core}} \approx 1.4 M_\odot$

$R_{\mathrm{Fe,core}} \approx 3000$ km

$\rho_c \approx 10^9$ g cm^{-3}

$T_c \approx 10^{10}$ K~ 1 MeV

$M_{\mathrm{PNS}} \approx 1.4 M_\odot$

$R_{\mathrm{PNS}} \approx 15$–$50$ km

$\rho_c \approx 3 \times 10^{14}$ g cm^{-3}

$T_c \approx 30$ MeV

$E_{\mathrm{grav}} \sim \frac{G M_{\mathrm{PNS}}^2}{R_{\mathrm{PNS}}} \sim 10^{53}$ erg, radiated mostly by $\sim 10^{58}$ ν's in ~ 10 seconds

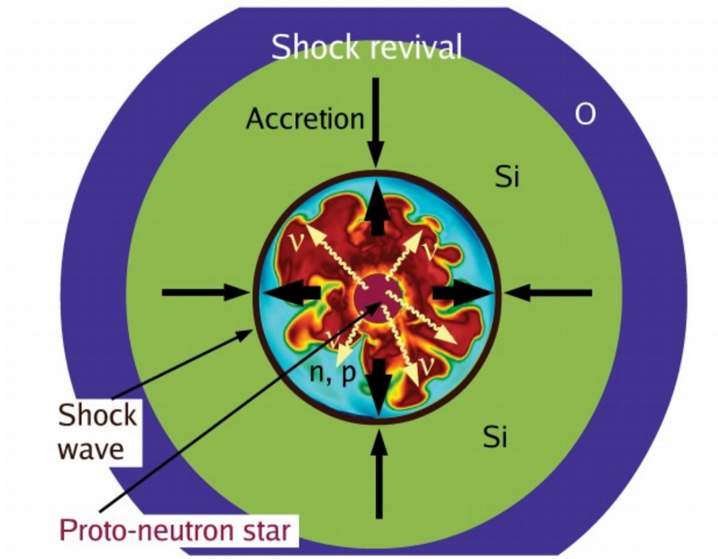
$\rightarrow \sim 20$ $\bar{\nu}_e$ events (inverse β decay) from SN1987a at LMC

thousands of events in ALL FLAVORs expected from the next Galactic SN

Core-collapse supernovae

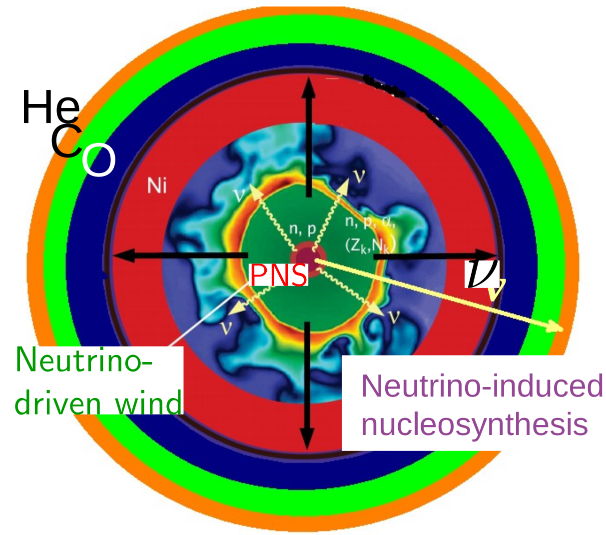
Neutrinos play key roles in

shock revival



[Janka+, PTEP 01A309, 2012]

Nucleosynthesis



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

Detection of the next galactic SN's neutrinos would offer unprecedented opportunity to probe supernova interior, neutrino physics, and physics beyond the Standard Model

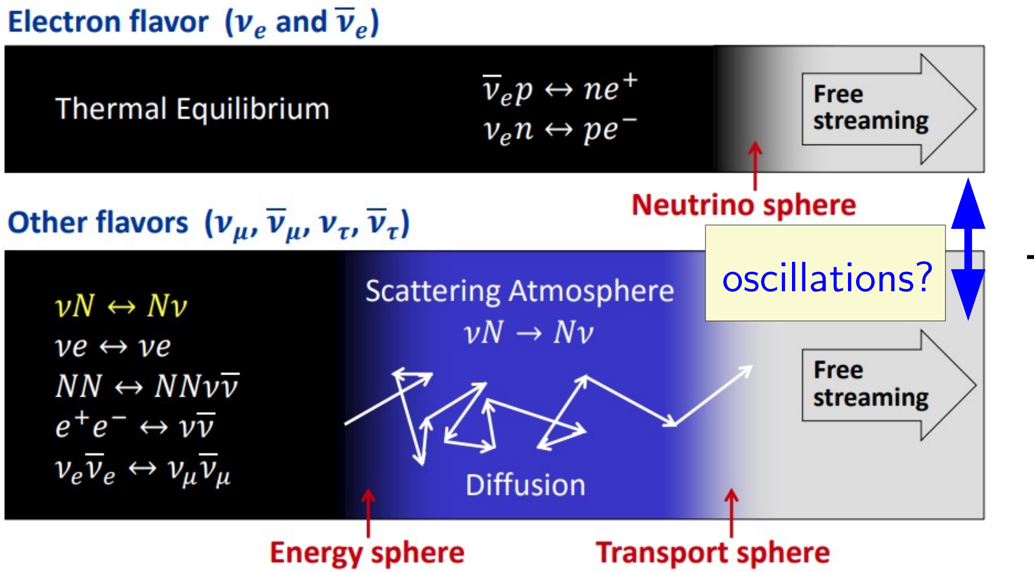
However, probing physics within SM requires high precision. Some of those can sensitively depend on uncertain factors in modeling SNν emission

Fore-front (neutrino-related) theory issues in supernovae

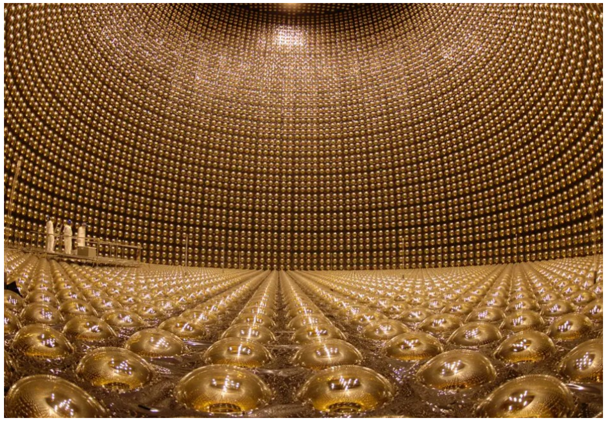
• neutrino nuclear matter interaction: uncertainty can be large (a factor of a few) at high densities; impacts the neutrino luminosities at level of $\sim$ tens percents; affects shock revival dynamics and nucleosynthesis [Burrows+, Fischer+, Guo+, Horowitz+, Lin+, Martinez-Pinedo+, Oertel+ Reddy+, Roberts+, Schwenk+,...]

• neutrino flavor oscillations: new and exciting effects every few years, but no consistent and trustable global impact yet;

[Abbar+, Balantekin+, Capozzi+, Cervia+, Chakraborty+, Dasgupta+, Duan+, Fuller+, Friedland+, Johns+, Kato+, Kajino+, Kneller+, Martin+, Manibrata+, Mclaughlin+, Mirizzi+, Morigana+, Nagakura+, Raffelt+, Richers+, Rogerro+, Rrapaj+, Sawyer+, Shalgar+, Tamborra+, Volpe+, MRW+, Xiong+, Yamada+...]

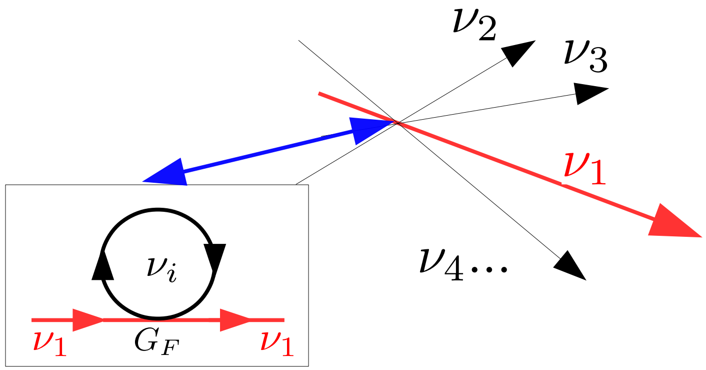


[Janka 1702.08713, Raffelt 2012]



[from Super-K]

Collective neutrino oscillations



[Fuller+ 1987, Pantaleone 1992, Sigl & Raffelt, 1992]

flavor evolution for ν with different momenta are coupled through the forward scattering contribution of ν-ν interaction

$$(\partial_t + \mathbf{v} \cdot \partial_{\mathbf{x}} + \mathbf{F} \cdot \partial_{\mathbf{p}}) \varrho(\mathbf{x}, \mathbf{p}, t) = -i[H_{\rm vac} + H_{\rm m} + H_{\nu\nu}, \varrho(\mathbf{x}, \mathbf{p}, t)] + \mathcal{C}(\varrho)$$

$$H_{\rm vac}(p) = U M^2 U^\dagger / (2|\mathbf{p}|),$$

$$H_{\rm MSW}(\mathbf{x}, t) = \sqrt{2} G_F n_e \times {\rm diag}(1, 0, 0)$$

$$H_{\nu\nu}(\mathbf{x}, \mathbf{p}, t) = \frac{\sqrt{2} G_F}{(2\pi)^3} \int d^3q (1 - \hat{\mathbf{p}} \cdot \hat{\mathbf{q}}) [\varrho - \bar{\varrho}^*]$$

$$\varrho(t, \mathbf{x}, \mathbf{p}) = \begin{bmatrix} f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho^*_{e\mu} & f_{\nu_\mu} & \varrho_{\mu\tau} \\ \varrho^*_{e\tau} & \varrho^*_{\mu\tau} & f_{\nu_\tau} \end{bmatrix}$$

flavor density matrix of the neutrino ensemble

- for $E_\nu \sim 10$ MeV:

$$\omega_{\rm vac} \sim \frac{\delta m^2_{13}}{2E_\nu} \sim 0.6 \ {\rm km}^{-1}$$

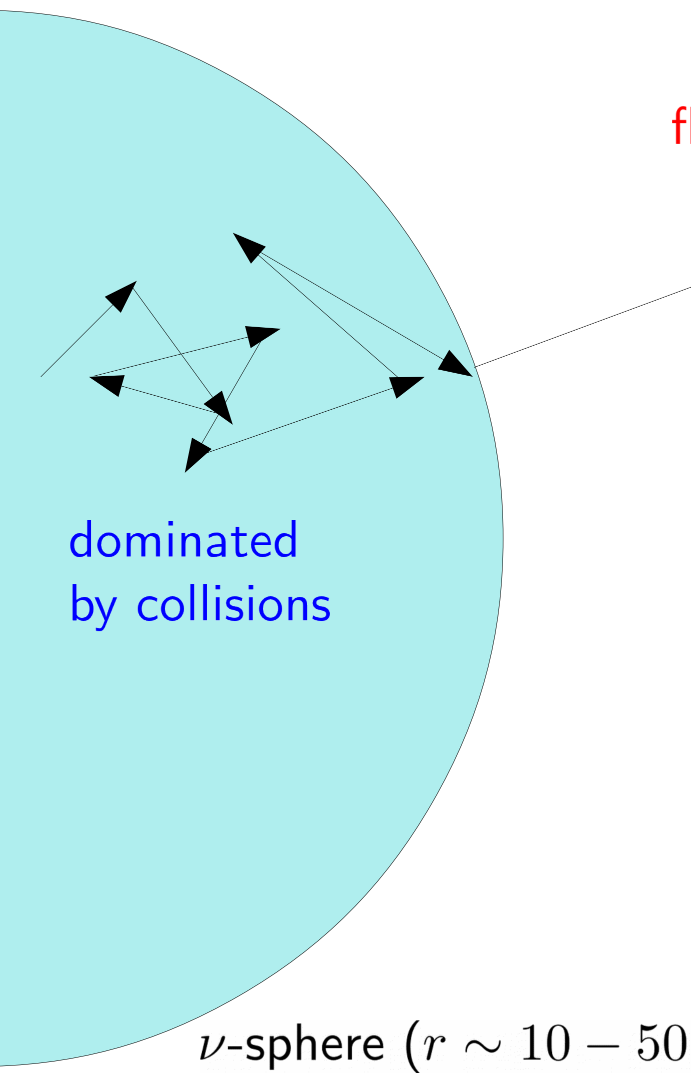
- for $n_\nu \sim 10^{33}$ cm^{-1}:

$$\mu \sim \sqrt{2} G_F n_\nu \sim 6 \times 10^5 \ {\rm km}^{-1}$$

$\rightarrow$ strong coupling in flavor space leading to collective modes!

Separation of two regimes?

$$(\partial_t + \mathbf{v}\cdot\partial_\mathbf{x} + \mathbf{F}\cdot\partial_\mathbf{p})\varrho(\mathbf{x},\mathbf{p},t) = -i[H_{\rm vac} + H_{\rm m} + H_{\nu\nu}, \varrho(\mathbf{x},\mathbf{p},t)] + \mathcal{C}(\varrho)$$



Earlier studies on collective oscillation found that it only starts to develop at $\mathcal{O}(10^2$ km), due to decoherence effect, with

$$\omega_{\rm col} \sim (\omega_{\rm vac}\mu)^{1/2} \sim \mathcal{O}(1)\ {\rm km}^{-1} \qquad \text{(slow mode)}$$

[Duan+, Raffelt+, Mirizzi+,... many others]

$\rightarrow$ no impact on supernova dynamics, but can affect nucleosynthesis and neutrino signals

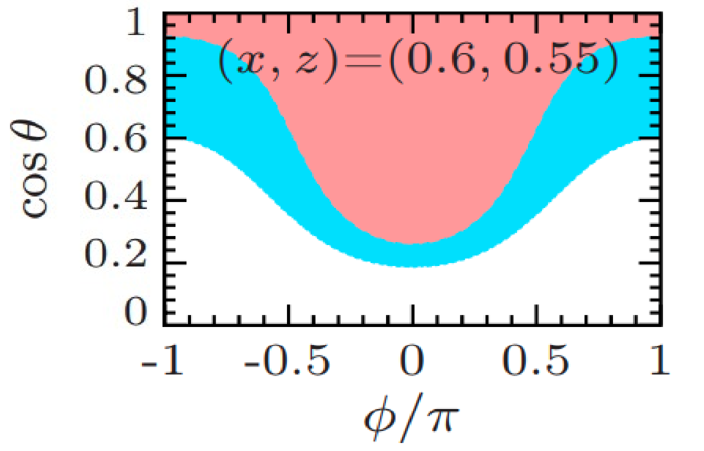
Fast neutrino oscillations

Recent studies revealed that a novel kind of "fast collective mode" can happen when there exist a "crossing" in the $e-\mu$ neutrino angular distribution

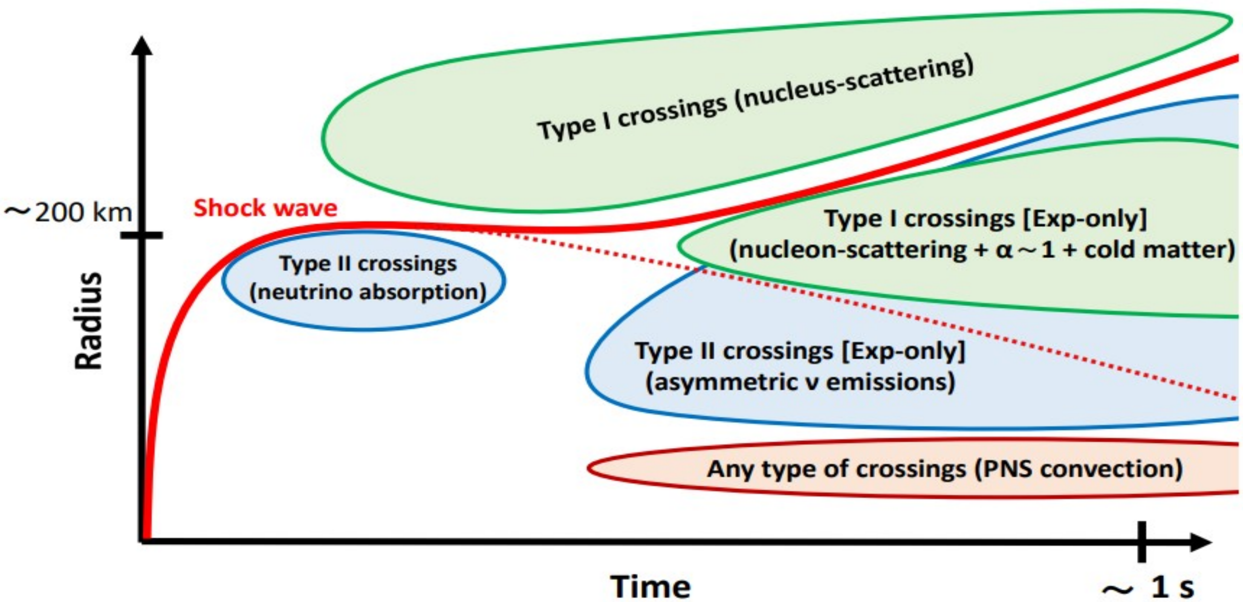
[Sawyer+, Izaguirre+, Dasgupta+,...many others]

$$\to \omega_{\rm col} \sim \mu \sim \mathcal{O}(1){\rm cm}^{-1}$$

$$G(\theta,\phi) \propto \int dE_\nu E_\nu^2 (f_{\nu_e} - f_{\nu_\mu} - f_{\bar{\nu}_e} + f_{\bar{\nu}_\mu})$$



Space-time diagram of ELN-angular crossings in CCSNe



can exist in different regions and epochs of SN evolution, even inside the ν-sphere

$\to$ need to include this effect in SN simulations!

[Nagakura+ 2108.07281]

[See also Morigana+ 1909.13131, Nagakura+ 1910.04288, Johns+ 1910.05682, Delfan Azari+ 1910.06176, Glas+ 1912.00274, Abbar+ 2003.00969, Capozzi+ 2005.14204, Abbar+ 2012.06594, Capozzi+ 2012.08525, Johns+ 2104.04106, Nagakura+ 2106.02650, Harada+ 2110.08291,...]

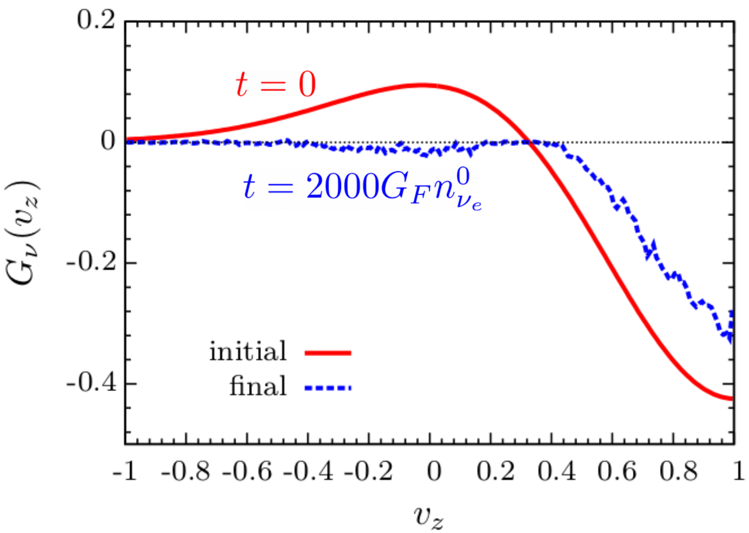
(code available at https://github.com/cosenu/cosenu)

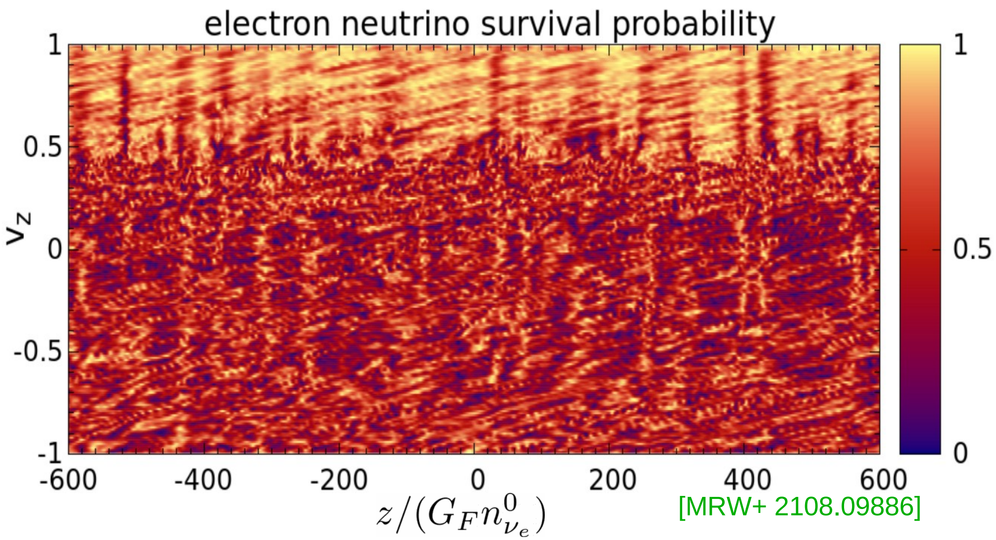
Fast neutrino oscillations

Several groups started to develop multidimensional simulation code to compute the outcome of fast oscillations in a perodic box

[See Richers+ 2205.06282 for detailed comparison of simulation results]

$\rightarrow$ fast oscillations that tend to erase the ELN crossing [Bhattacharyya+, Richers+, MRW+]





[MRW+ 2108.09886]

These local simulations motivate the formulations of analytical approximation of final state of neutrino distribution, which may allow SN modelers to include this effect in their simulations

[Bhattacharyya+2020, 2022, Zaizen 2022]

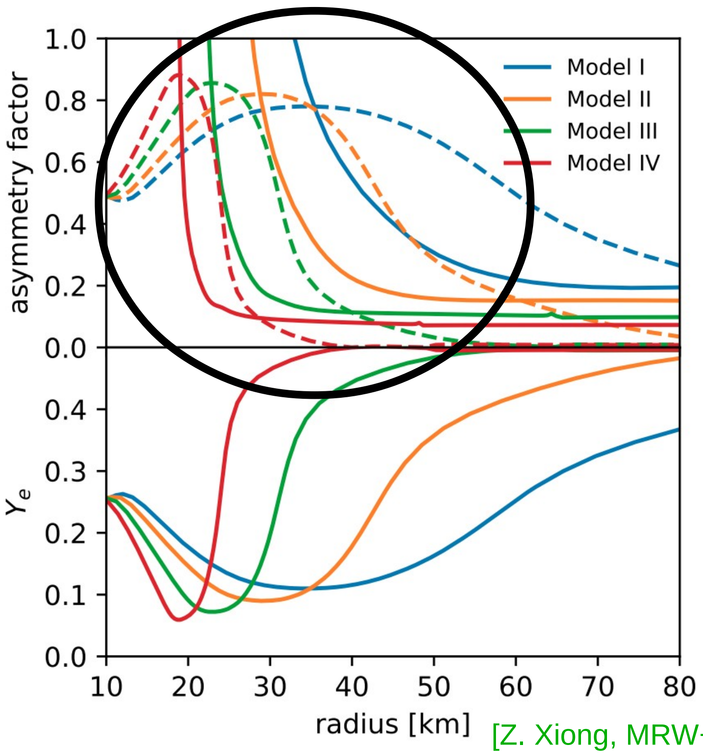
Even more...collision-induced collective oscillation mode

L. Johns (2021) discovered that another kind of collective mode can be induced when one considers both collision term and the forward-scattering term

$\rightarrow \omega_{\rm col} \sim \Gamma$ (collision rates)$\sim \mathcal{O}(1)$ km^{-1}

needs asymmetric $\bar{\nu}_e$ and ν_e collision rates

$$\mathcal{R} \equiv \frac{n_{\bar{\nu}_e} - n_{\bar{\nu}_x}}{n_{\nu_e} - n_{\nu_x}} \gtrsim \frac{\bar{\Gamma}}{\Gamma} \equiv \mathcal{R}_{\rm crit}$$



[Z. Xiong, MRW+ 2210.08254]

Even more...collision-induced collective oscillation mode

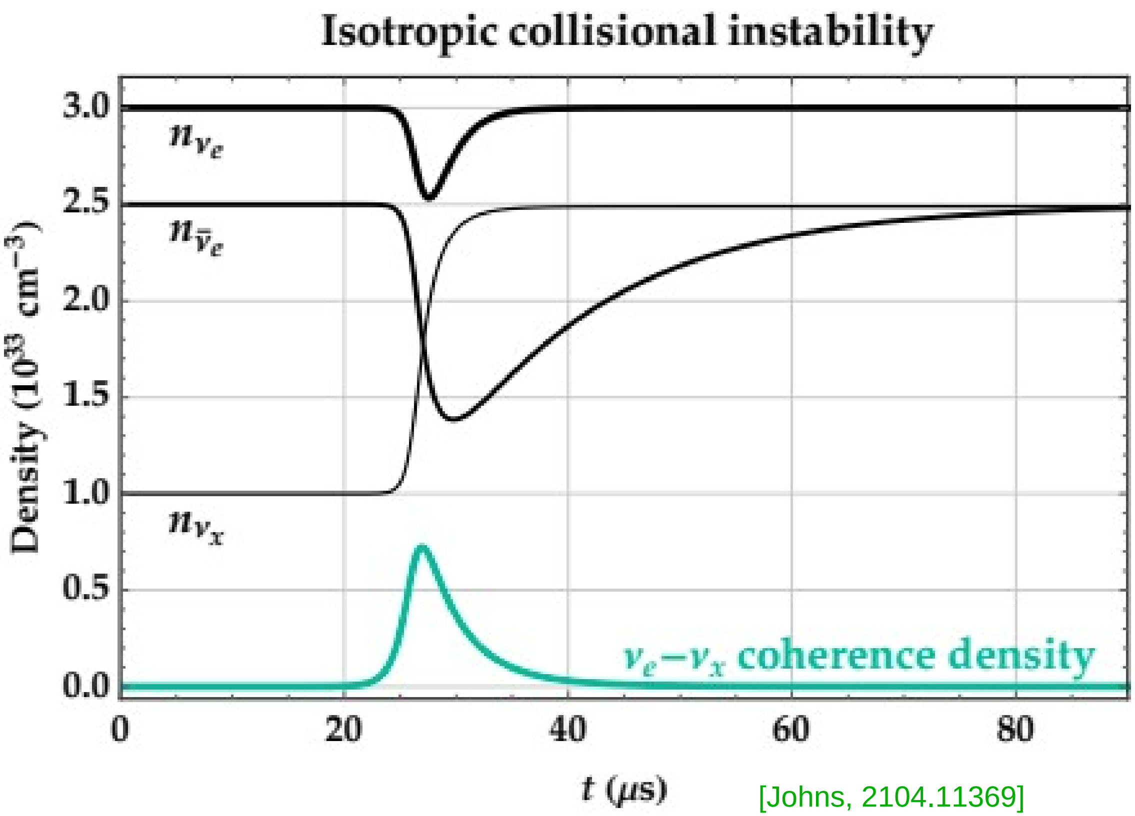
L. Johns (2021) discovered that another kind of collective mode can be induced when one considers both collision term and the forward-scattering term

$\rightarrow \omega_{\rm col} \sim \Gamma$ (collision rates)$\sim \mathcal{O}(1)$ km^{-1}

needs asymmetric $\bar{\nu}_e$ and ν_e collision rates

$$\mathcal{R} \equiv \frac{n_{\bar{\nu}_e} - n_{\bar{\nu}_x}}{n_{\nu_e} - n_{\nu_x}} \gtrsim \frac{\bar{\Gamma}}{\Gamma} \equiv \mathcal{R}_{\rm crit}$$

$\rightarrow$ can lead to large production of heavy-lepton flavor neutrinos



[Johns, 2104.11369]

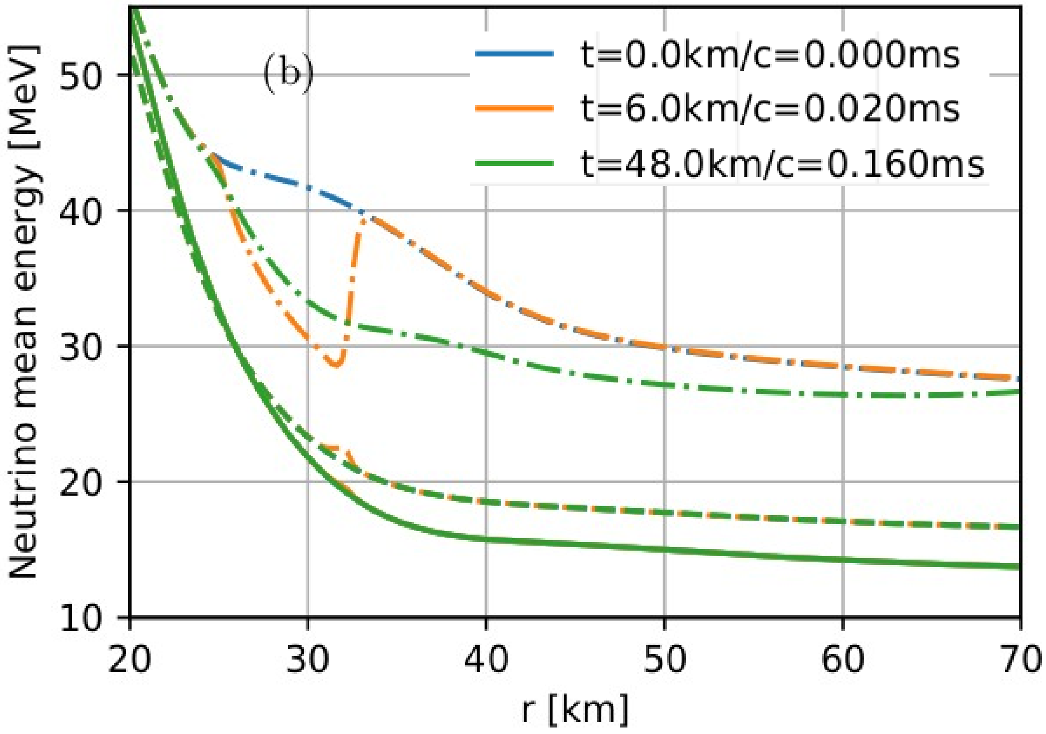
Global simulations of collision-induced oscillations

We recently solve the neutrino flavor evolution equation with collision terms over spherically symmetric background obtained by 1D SN simulation, where the fast modes are absent

[Z. Xiong, MRW+ 2210.08254]

– collisional instability exists generically around the neutrino sphere

– affects the local properties of neutrinos

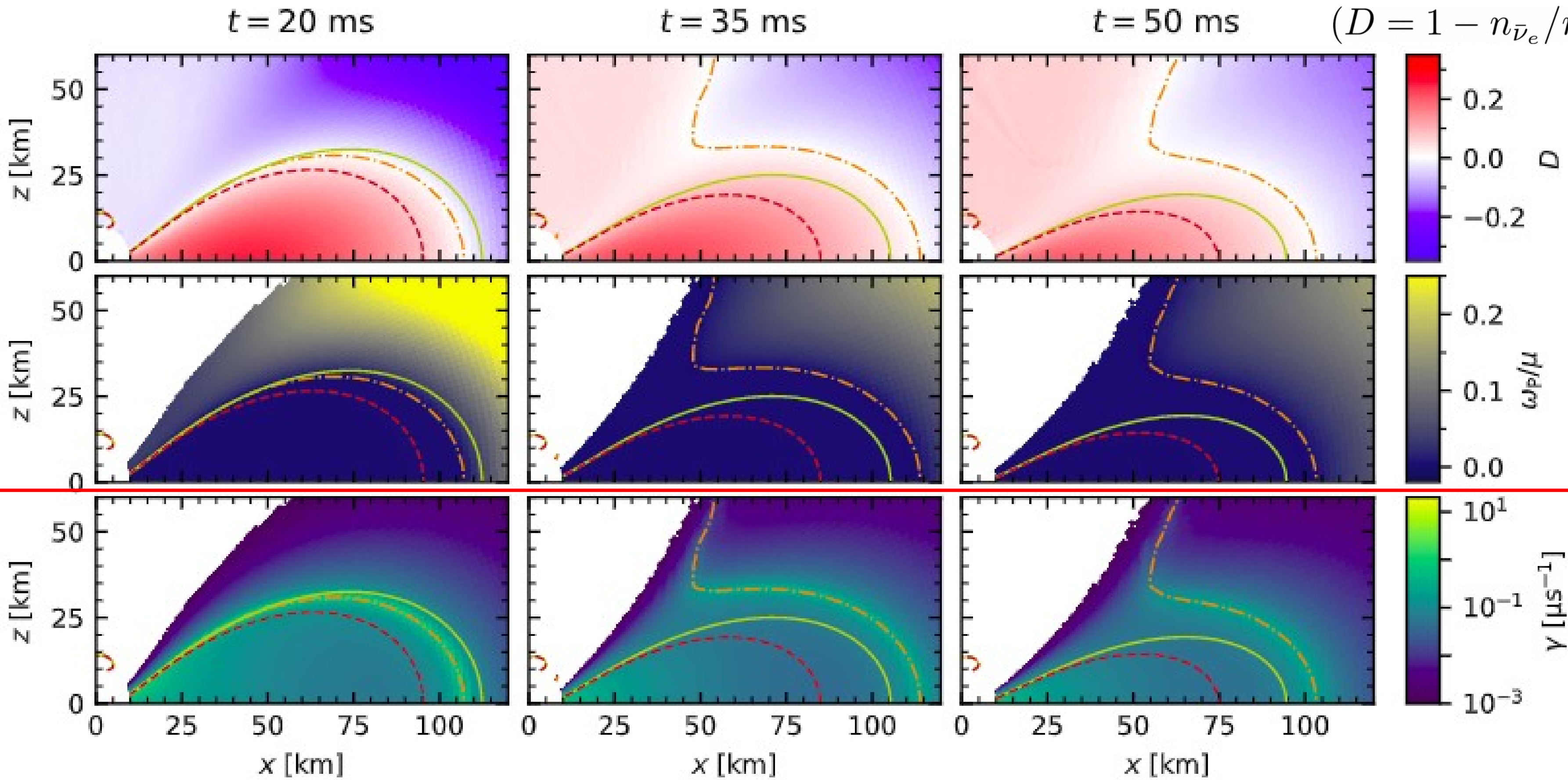


→ definitely needs to be implemented in SN simulations together with fast oscillations

Collision-induced instabilities in BH disks

In the BH-disk remnants from neutron star mergers, collision-induced flavor instabilities can be present universally inside the disk

$(D = 1 - n_{\bar{\nu}_e}/n_{\nu_e})$



[Xiong, Johns, MRW, Duan, 2212.03750]

peaks at where $n_{\nu_e} \simeq n_{\bar{\nu}_e}$

Focus workshop on collective oscillations and chiral transport of neutrinos

14–17 Mar 2023
Institute of Physics, Academia Sinica, Taiwan
Asia/Taipei timezone

Enter your search term

- Overview
- Timetable
- Invited speakers
- Registration
- Participant List
- Visa
- Venue
- Accommodation
- Transportation

Contact

mwu@gate.sinica.edu…
dlyang@gate.sinica.e…

This workshop will be devoted to recent development in understanding the collective flavor oscillations of neutrinos, their quantum kinetic and chiral transport in astrophysics and/or cosmology, the aspect of the many-body nature of the problem, and the possibility of integrating with hydrodynamical simulations. The meeting shall bring together experts from these fields to discuss progresses and future directions.

The program will consist of invited overview talks for different research areas by senior scientists, invited presentations from young researchers on their recent work, as well as some contributed talks from participants. Ample time for discussions will be allocated on each day of the workshop to promote collaborations.

Starts 14 Mar 2023, 09:00
Ends 17 Mar 2023, 17:00
Asia/Taipei

Institute of Physics, Academia Sinica, Taiwan

No. 128, Sec. 2, Academia Rd., Nangang Dist.,
Taipei City 115201, Taiwan (R.O.C.)

Di-Lun Yang
Huaiyu Duan
Meng-Ru Wu
Naoki Yamamoto

There are no materials yet.

Connecting r-process and high-energy neutrinos in collapsars via their annhiliation

Collapsars

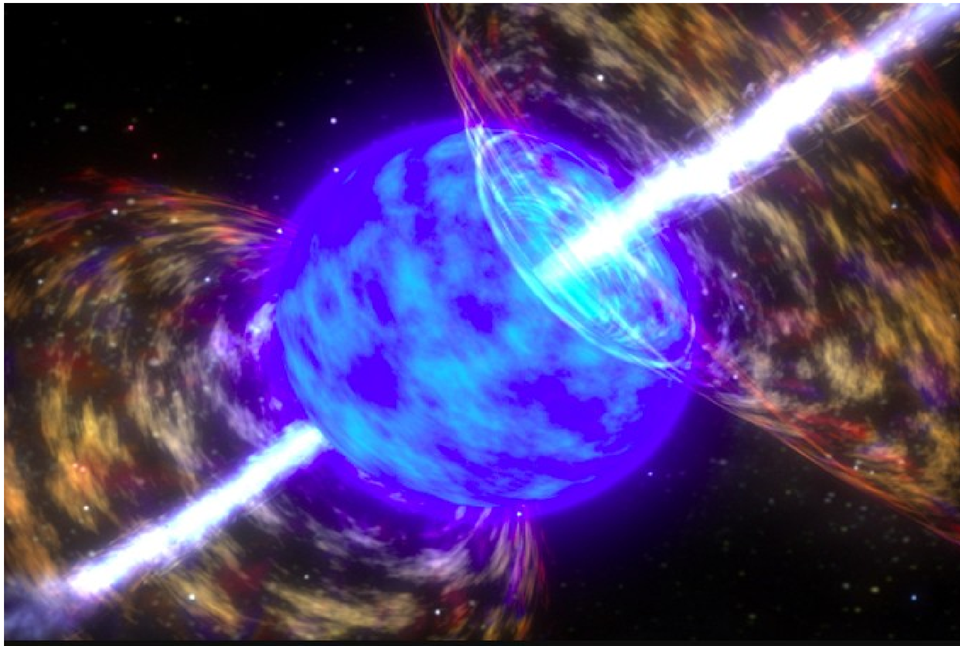
- Remnants of rapidly rotating massive stars, with a black hole surrounded by an accretion disk

- May be associated with long gamma-ray bursts, and can possibly be the production sites of high-energy neutrinos detected by IceCube

[Woosley 1993, Woosley & MacFadyen 1999,...; Mesaros+, Murase+, Razzaque+, Tamborra+, ...]

- May also produce r-process nuclei in the outflow driven from the accretion disk

[Siegel+ 2019; but see also Just+2022, Fujibayashi+2022,...]



Collapsars

r-process produces a lot of neutron-rich unstable nuclei that β decay

$\rightarrow$ produce low-energy neutrinos ($\bar{\nu}_e$) of $E_L \sim 5$ MeV

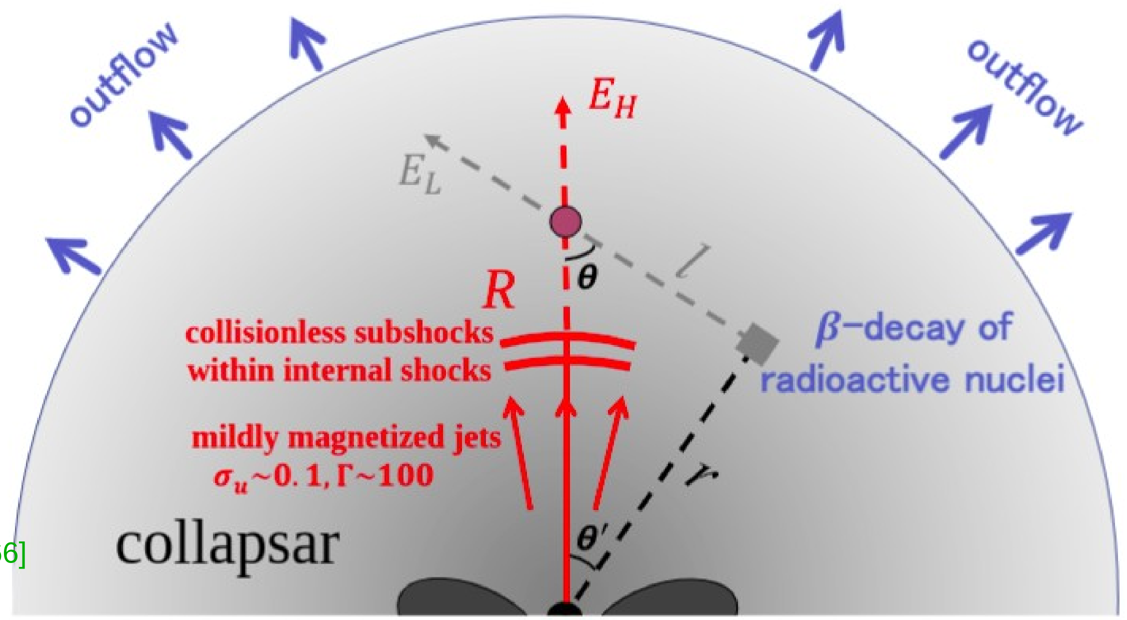
$\rightarrow$ oscillate to different flavors and annihilate with high-energy neutrinos with $E_H \sim 100 - 1000$ TeV via Z-resonance

$$\text{At } R \sim 10^{10} \text{ cm}, \quad n_{\bar{\nu},\mathrm{LE}} \sim 10^{24}\ \mathrm{cm}^{-3} \left(\frac{\dot{M}}{0.1 M_\odot/\mathrm{s}}\right) \left(\frac{0.1c}{v_{\mathrm{ej}}}\right) \left(\frac{10^{10}\ \mathrm{cm}}{R}\right)^2$$

With $\sigma_{\mathrm{res}} \sim 10^{-31}$ cm^2

$\rightarrow \sigma_{\mathrm{res}} n_{\bar{\nu},\mathrm{LE}} R \gg \mathcal{O}(1)$

efficient annihilation



[G. Guo, Y.-Q. Qian, MRW, 2212.08266]

High-energy neutrino production and effect of annihiliation

[Gottlieb & Globus 2021, Beloborodov+ 2015, 2017]

We consider protons accelerated at mildly-magnetized internal sub-shocks with:

$$\phi_p(E_p) \propto E_p^{-2} \exp\left(-E_p/E_{p,\max}\right) \qquad (E_{p,\max} \sim 10^6 \text{ GeV})$$

The accelerated HE protons collide with target protons and gamma-rays, produce mesons which decay and give rise to neutrinos

$$p + p(\text{and } \gamma) \to p, n, \pi^0, \pi^\pm, K^{\pm,0}, \ldots$$

(computed by PYTHIA and SOPHIA)

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

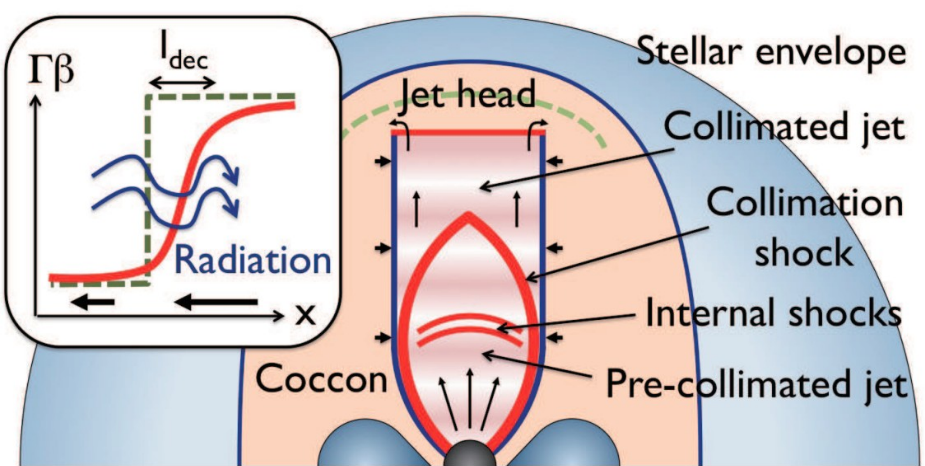
$$\pi^- \to \mu^- + \bar{\nu}_\mu$$

$$\mu^+ \to e^- + \bar{\nu}_e + \nu_\mu$$

$$\pi^0 \to 2\gamma$$

$$K^{\pm,0} \to \pi^{\pm,0}, \mu^\pm, \ldots$$

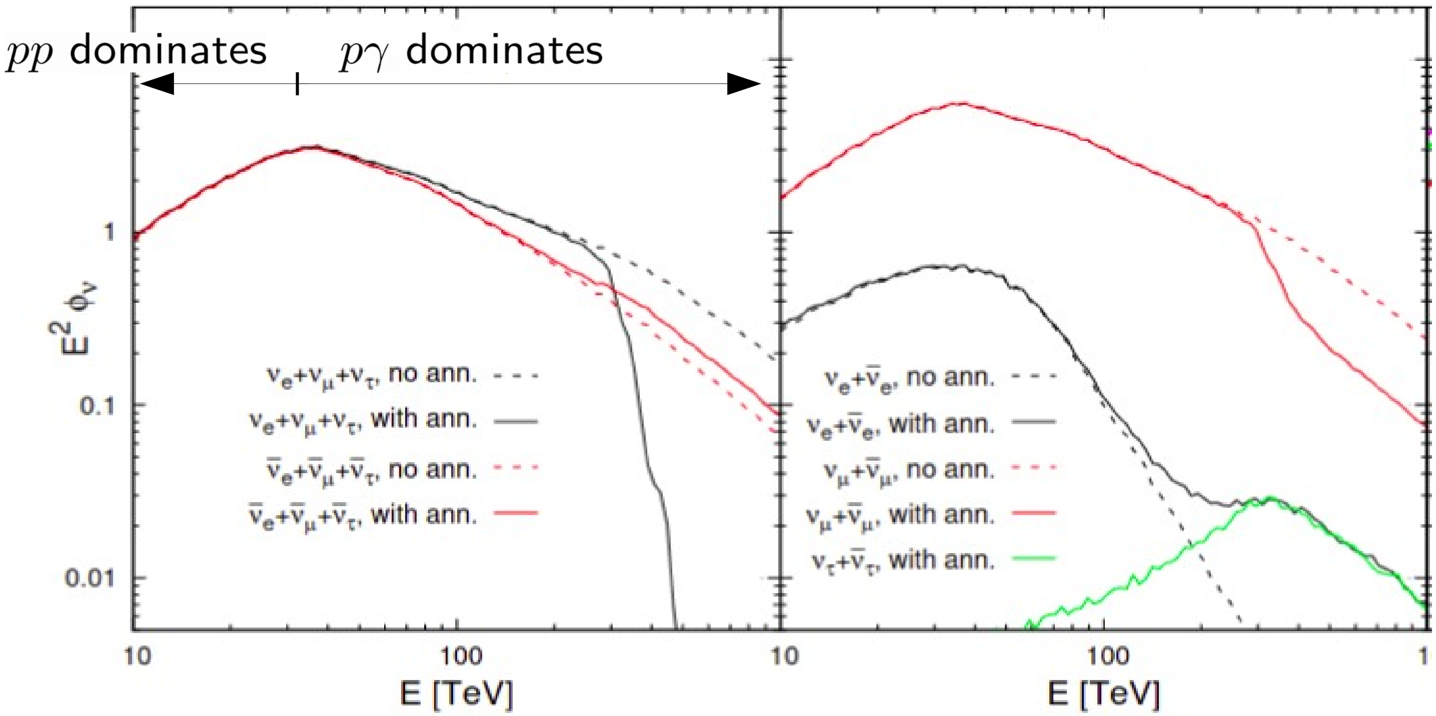
(particle coolings due to synchrotron, Bethe-Heitler, inverse Compton, adiabatic expansion are taken into account)



High-energy neutrino production and effect of annhiliation

For $L_{\rm iso} = 10^{53}$ erg, $\Gamma_r = 2\Gamma \sim 450$, $\epsilon_{B,u} = B_u^2/(8\pi\rho_u c^2) = 0.05$:

[G. Guo, Y.-Q. Qian, MRW, 2212.08266]

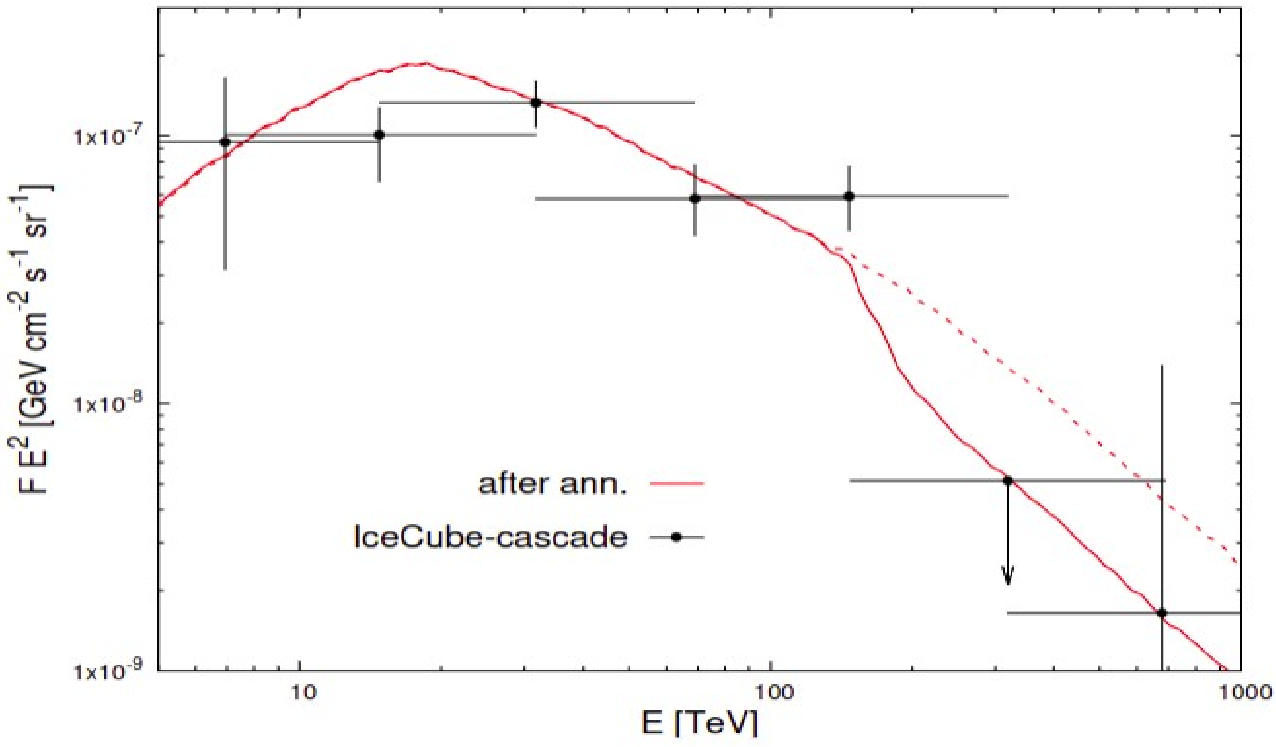


- μ flavor neutrinos dominate due to efficient cooling of $\mu^\pm$
- strong cutoff of ν above ~ 300 TeV due to efficient annhilation
- annhiliation lead to $\sim$ amount of $e-$ and $\tau-$ flavor neutrinos
- similar results hold for $L_{\rm iso}$ and $\epsilon_{B,u}$ that are 10 times smaller

Diffuse flux v.s. IceCube detection

Assuming that such sources are ~ 4 times more frequent than the bright GRB and integrate over redshift, the resulting diffuse flux is

[G. Guo, Y.-Q. Qian, MRW, 2212.08266]



May be further tested with improved statistics on diffuse flux or from point-source measurement

Summary

- Neutrino flavor oscillations can happen collectively in supernova interior and can potentially affect their dynamics and composition

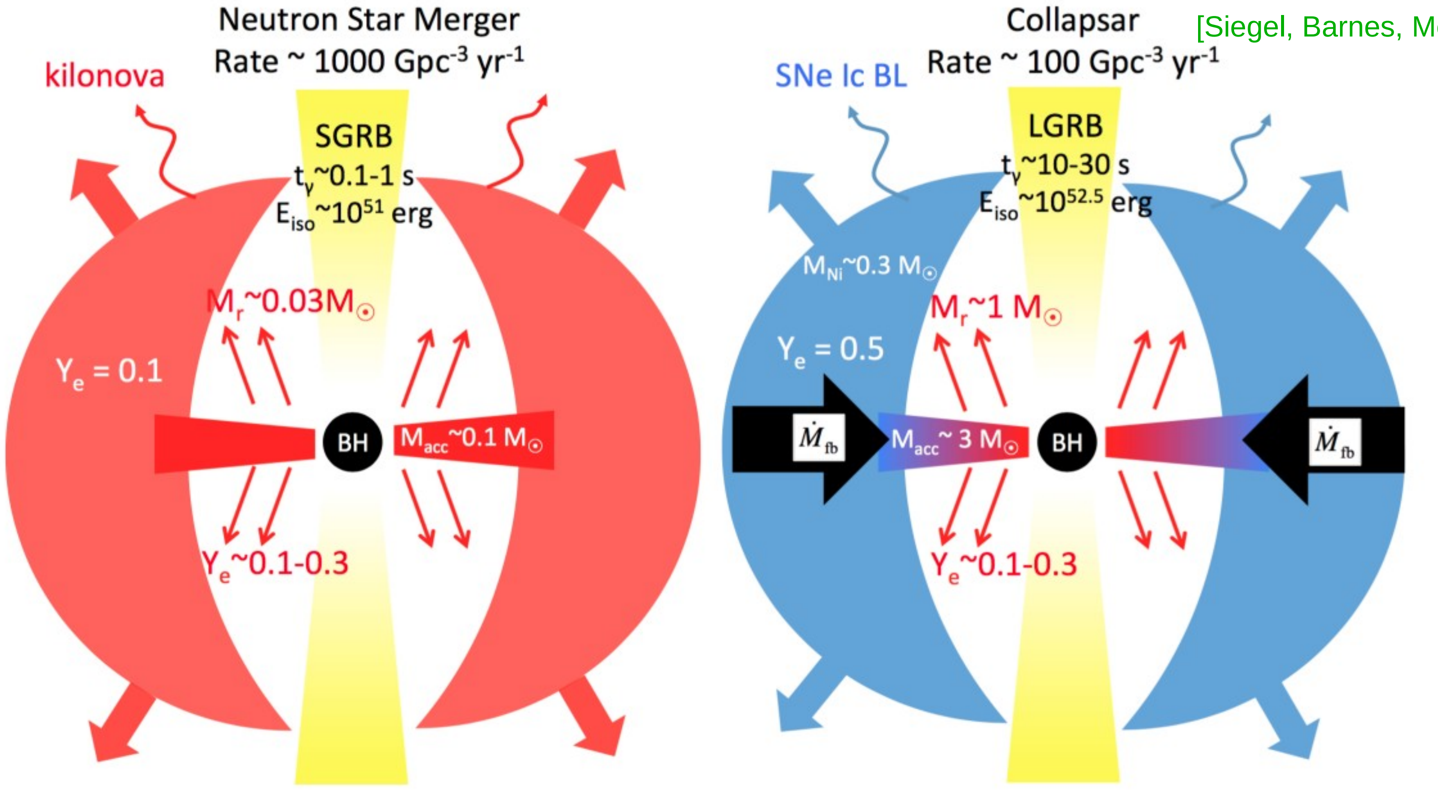
- Multidimensional transport codes solving the quantum kinetic equation of neutrinos are being actively developed. Preliminary local simulations for fast oscillations and global simulations with collision-induced oscillations are performed.

- If collapsars are both the production site of high-energy neutrinos and r-process nuclei, the low-energy antineutrinos prodiuced via the β-decay of unstable nuclei can annhiliate with the HE neutrinos and produce interesting signature in the HE neutrino spectrum

r-process in collapsar outflow?

Siegel+ (2019) suggested that the accretion disk of collapsars can result in neutron-rich outflow due to viscos heating, in a way similar to the BH-disk system from binary neutron star mergers

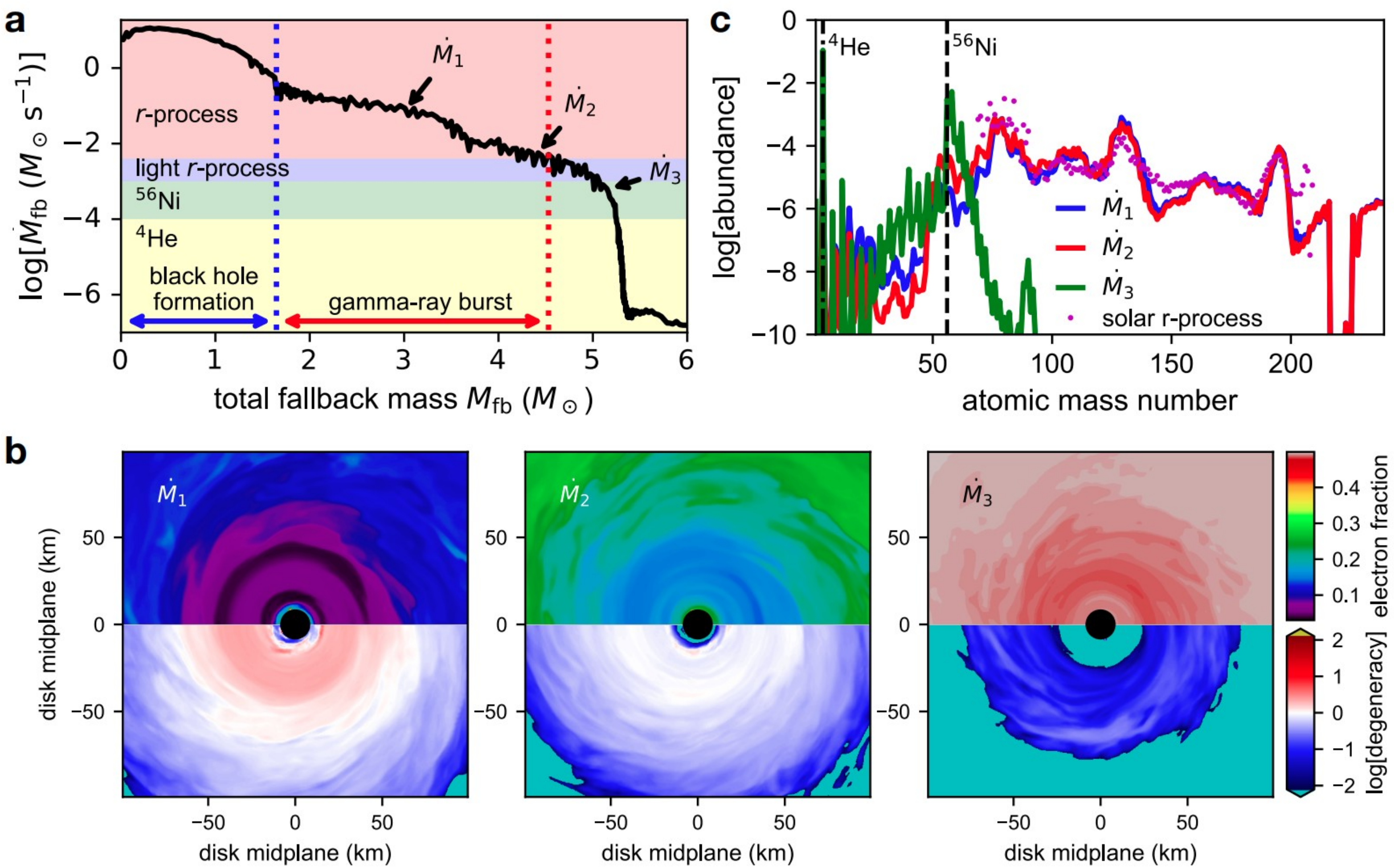
[Siegel, Barnes, Metzger, 1810.00098]



$$(Y_e \equiv n_e/n_{\rm baryon})$$

r-process in collapsar outflow?

[Siegel, Barnes, Metzger, 1810.00098]

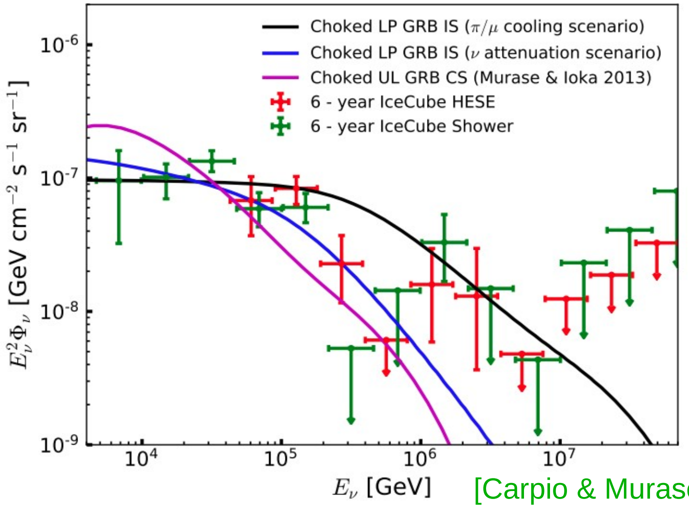


Can this really happen in nature? requires more advanced simulations as well as observation confirmation

Collapsars as HE neutrino sources?

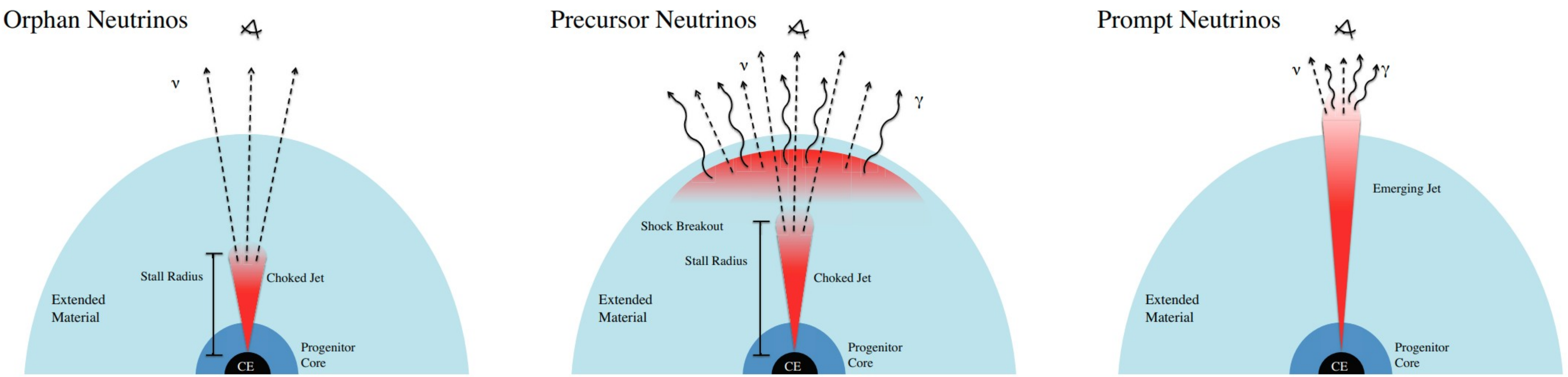
Non-association of diffuse HE neutrinos with GRBs put stringent bound on their overall contribution to those detected by IceCube ($\lesssim 1\%$) [IceCube 2017]

However, low-luminsoity GRBs (LLGRBs) or choked GRBs are still viable options of HE neutrinos, and may share similar collapsar origin as bright GRBs

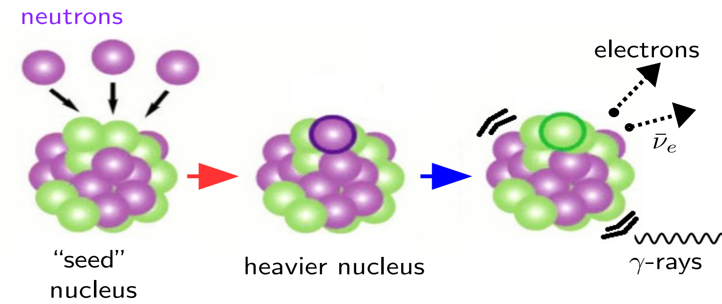


[Carpio & Murase 2020]

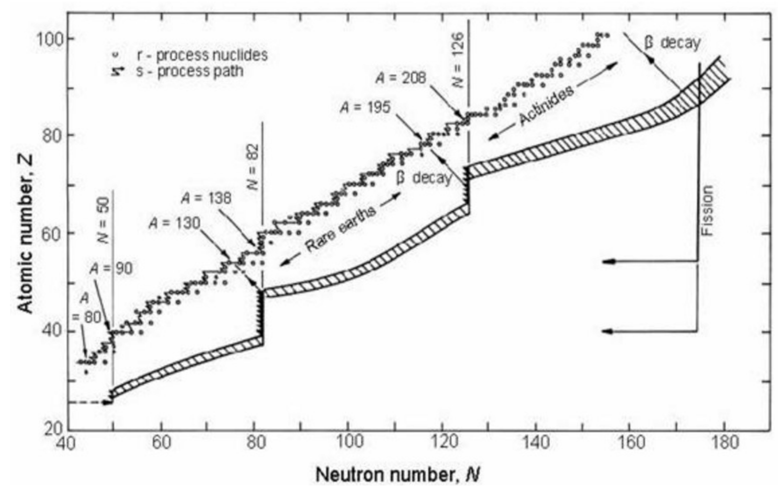
[Senno, Murase, Meszaros, 1512.08513]



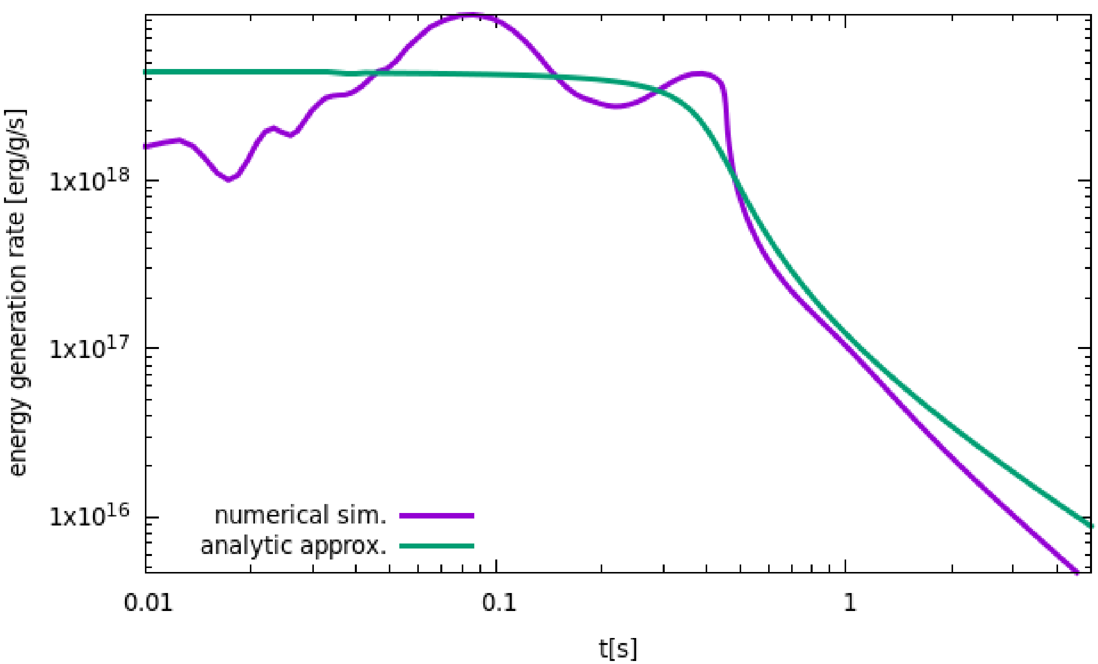
Low-energy antineutrinos from r-process



r-process produces a lot of neutron-rich unstable nuclei that β decay



→ produce low-energy neutrinos ($\bar{\nu}_e$) of $E_L \sim 5$ MeV



→ for $M_{\rm ej} \sim 1\ M_{\odot}$, about 10^{57} antineutrinos are emitted