Role of Neutrinos
in Extreme Astrophysical Environments

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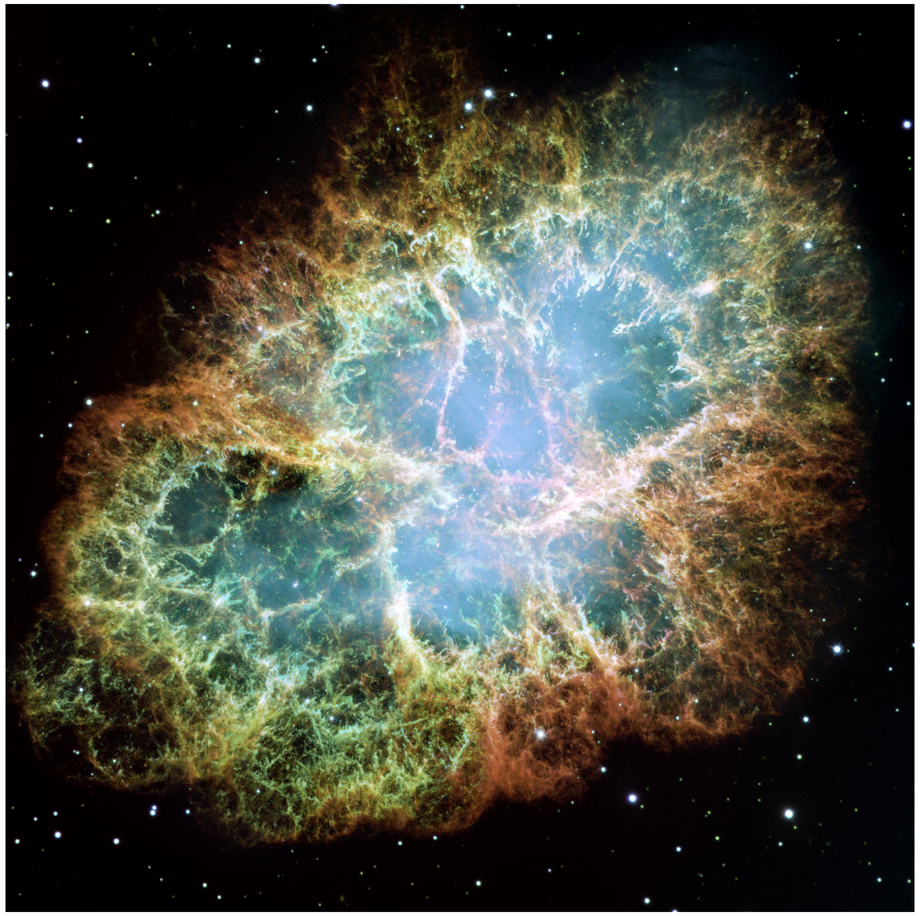
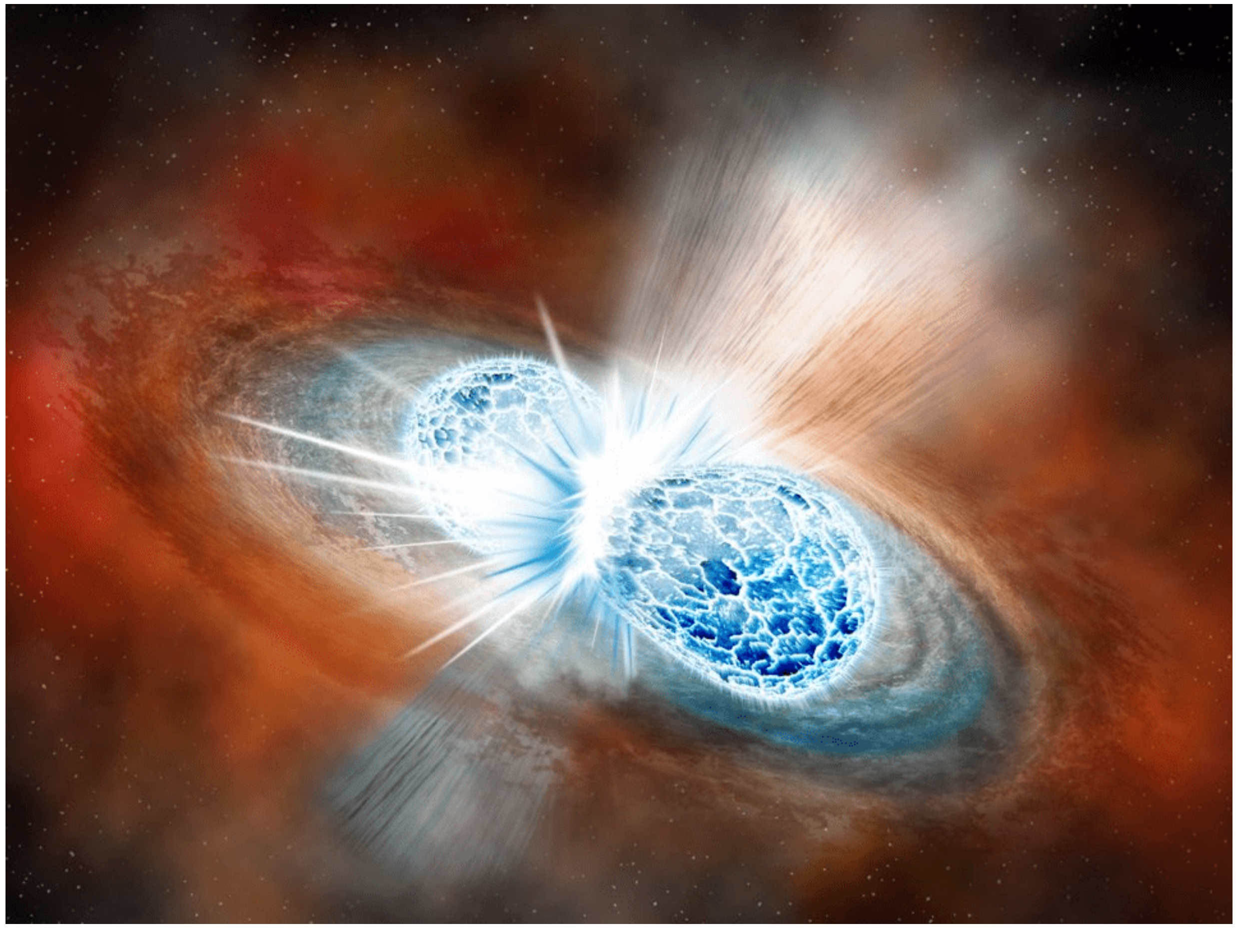
Extreme astrophysical environments

Core-collapse supernova
(CCSN)



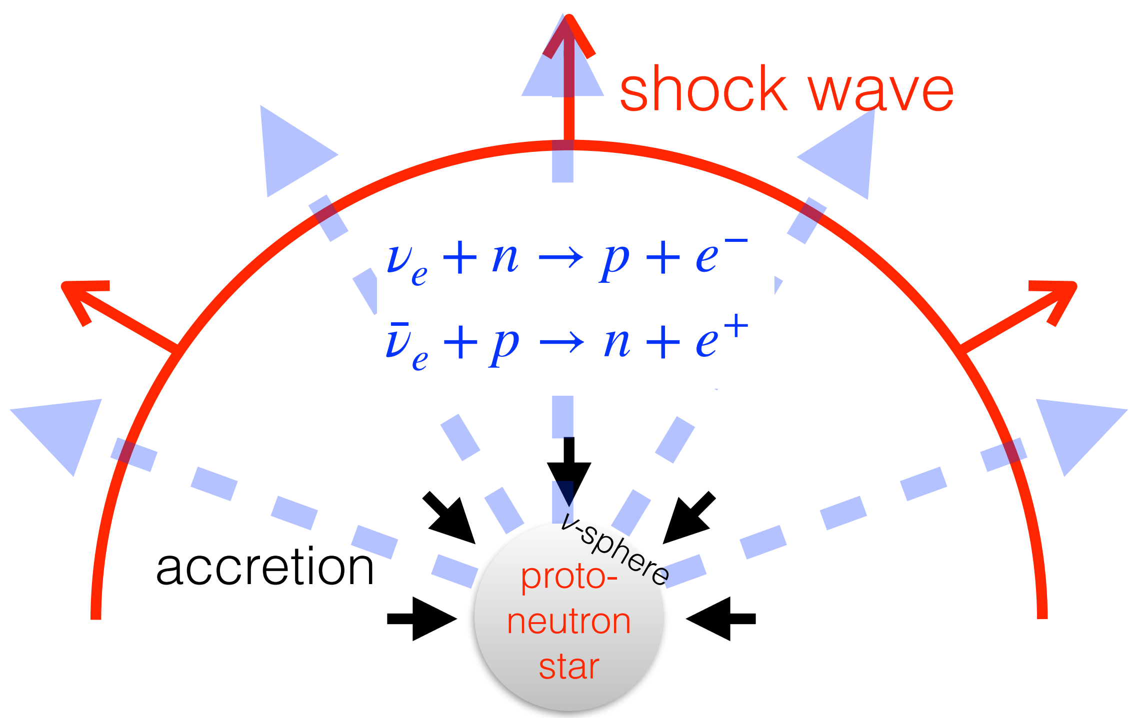
Neutron star merger
(NSM)



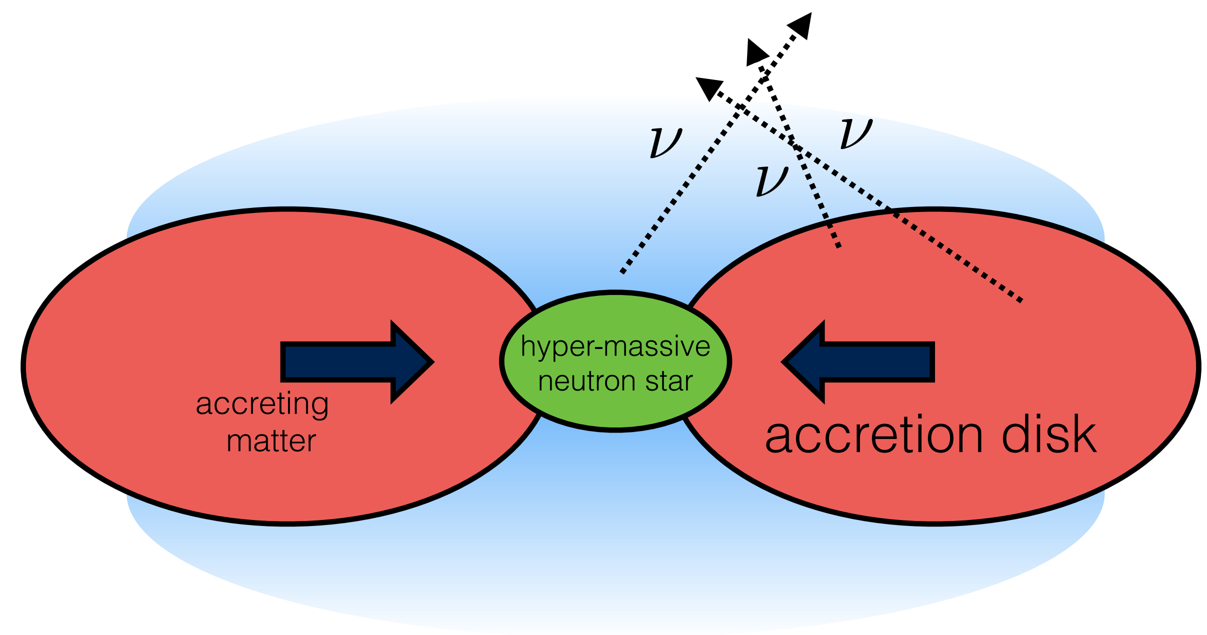
Credit: NASA

Prolific sources of neutrinos

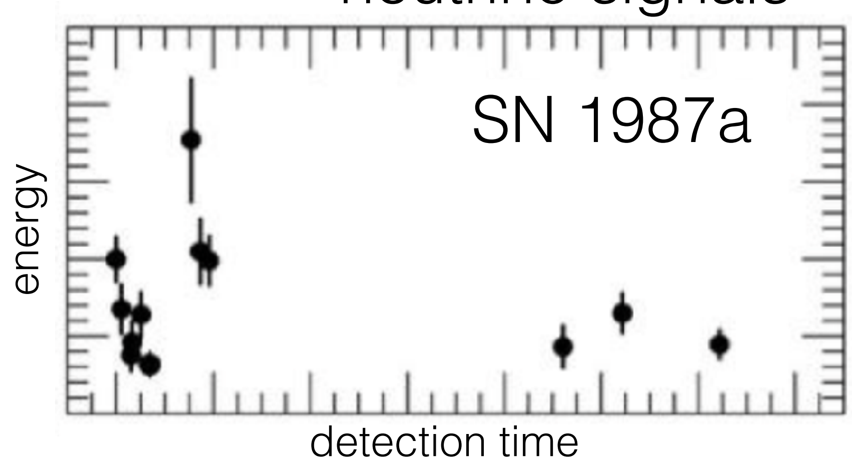
CCSN



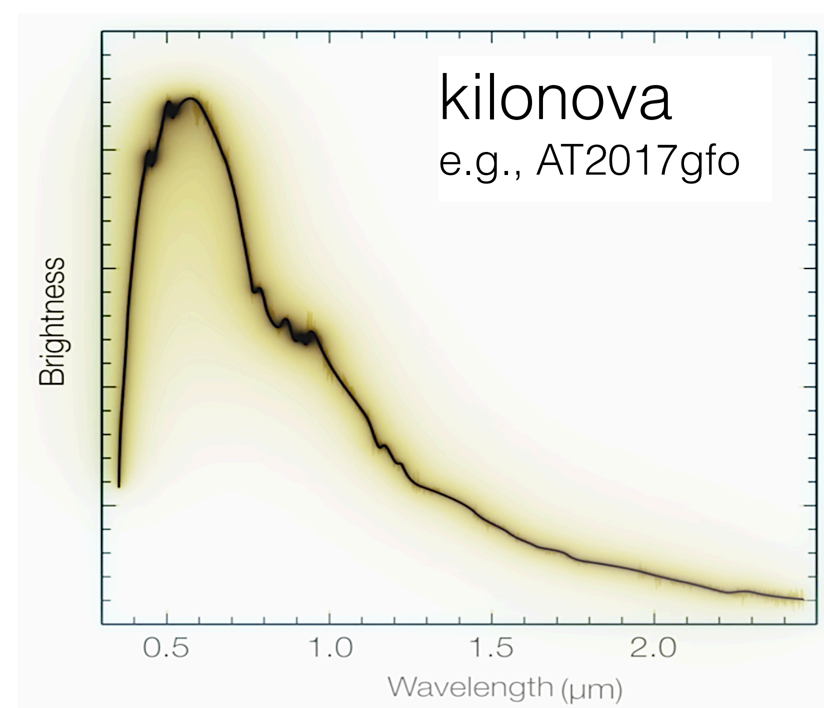
NSM



neutrino signals



origin of heavy elements



Neutrino interactions

[see, e.g., A. Mezzacappa et al, Living Reviews in Computational Astrophysics Reports 6, 1-174 (2020)]

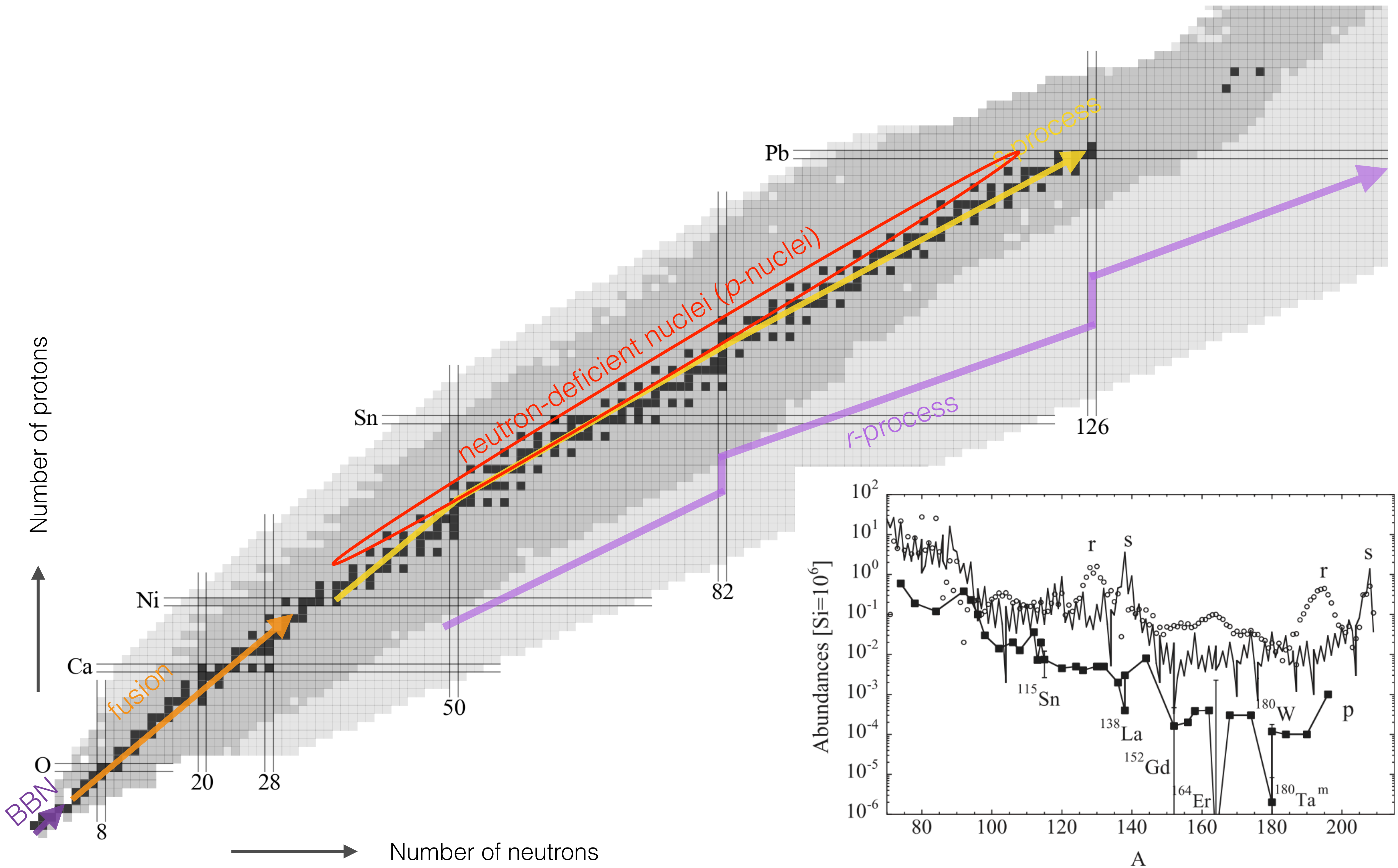
emission and absorption	$\nu_e + n \leftrightarrows p + e^-$
	$\bar{\nu}_e + p \leftrightarrows n + e^+$
	$\bar{\nu}_e + p + e^- \leftrightarrows n$
ν-nucleon scatterings	$\nu + N \leftrightarrows \nu + N$
	$\bar{\nu} + N \leftrightarrows \bar{\nu} + N$
ν-electron scatterings	$\nu + e^\pm \leftrightarrows \nu + e^\pm$
Pair reactions	$\nu + \bar{\nu} \leftrightarrows e^- + e^+$
	$\nu + \bar{\nu} + N + N \leftrightarrows N + N$
...	...
ν-nucleus interactions	$\nu_e + (A,Z) \leftrightarrows (A,Z+1) + e^-$
	$\bar{\nu}_e + (A,Z) \leftrightarrows (A,Z-1) + e^+$
	$\nu + (A,Z) \leftrightarrows \nu + (A,Z)$
Collective neutrino oscillations	$''\nu_e(p) + \nu_x(p') \leftrightarrows \nu_x(p) + \nu_e(p')''$
	$''\nu_e(p) + \bar{\nu}_e(p') \leftrightarrows \nu_x(p) + \bar{\nu}_x(p')''$

Production of *p*-nuclei from *r*-process seeds: *νr*-process

Quantum kinetics

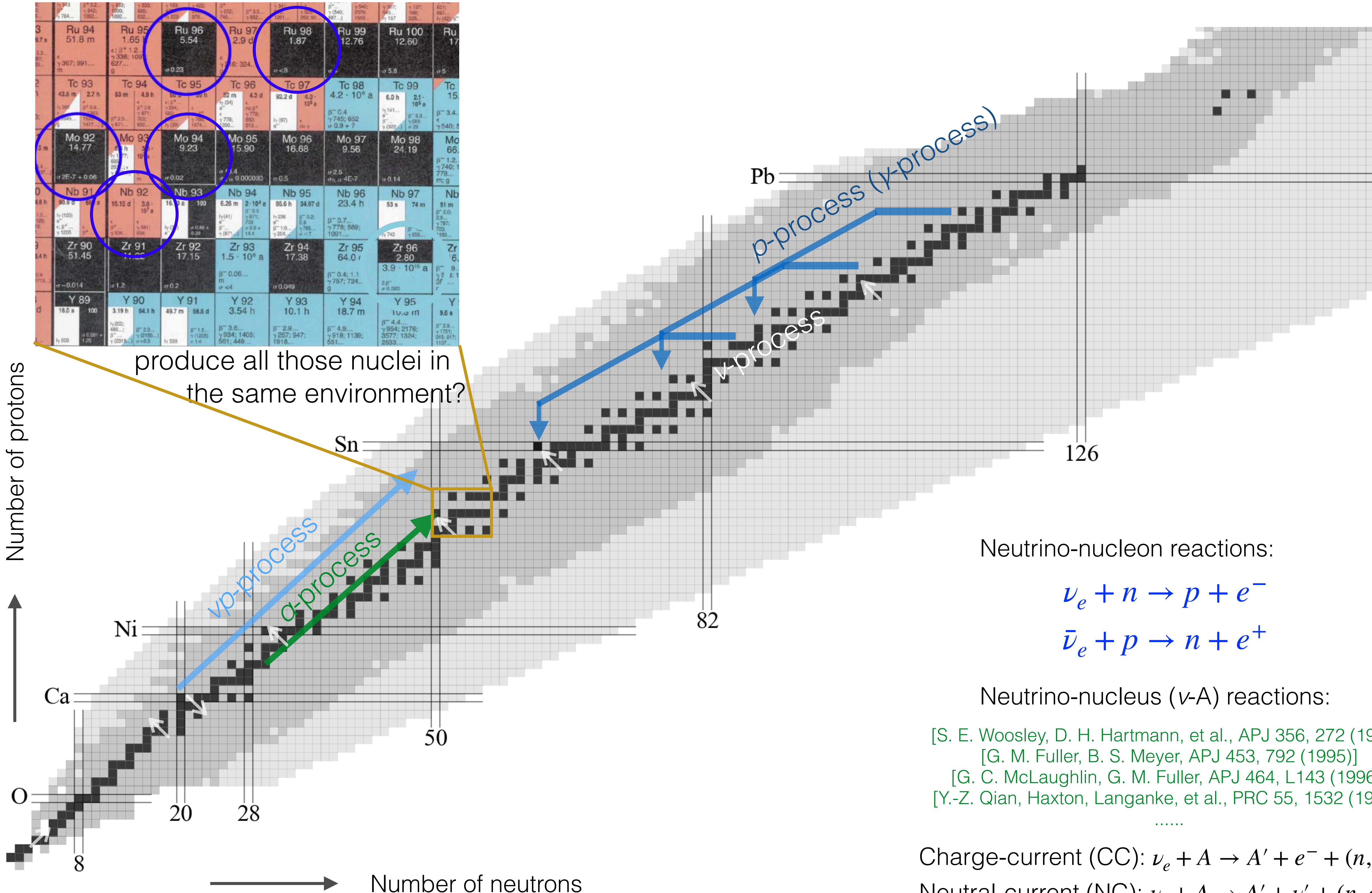
Production of *p*-nuclei from *r*-process seeds: *νr*-process

Origin of heavy elements



[M. Arnould, S. Goriely, Physics Reports 384, 1 (2003)]

Neutrinos & nucleosynthesis



Neutrino-nucleon reactions:

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

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

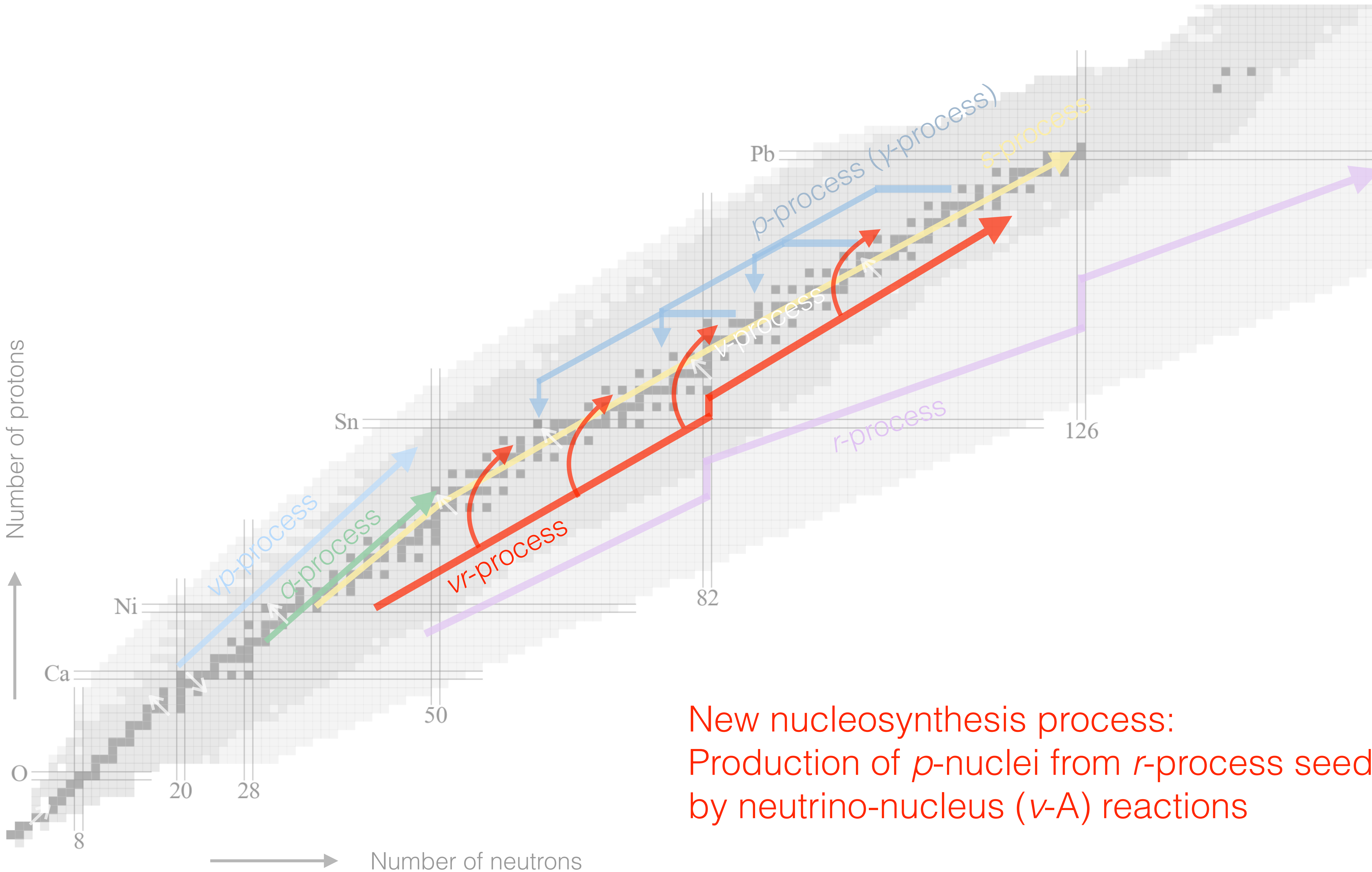
Neutrino-nucleus (ν-A) reactions:

[S. E. Woosley, D. H. Hartmann, et al., APJ 356, 272 (1990)]
[G. M. Fuller, B. S. Meyer, APJ 453, 792 (1995)]
[G. C. McLaughlin, G. M. Fuller, APJ 464, L143 (1996)]
[Y.-Z. Qian, Haxton, Langanke, et al., PRC 55, 1532 (1997)]
......

Charge-current (CC): $\nu_e + A \rightarrow A' + e^- + (n, \alpha, p)$

Neutral-current (NC): $\nu_e + A \rightarrow A' + \nu_e' + (n, \alpha, p)$

νr-process



New nucleosynthesis process:
Production of *p*-nuclei from *r*-process seeds
by neutrino-nucleus (*ν*-A) reactions

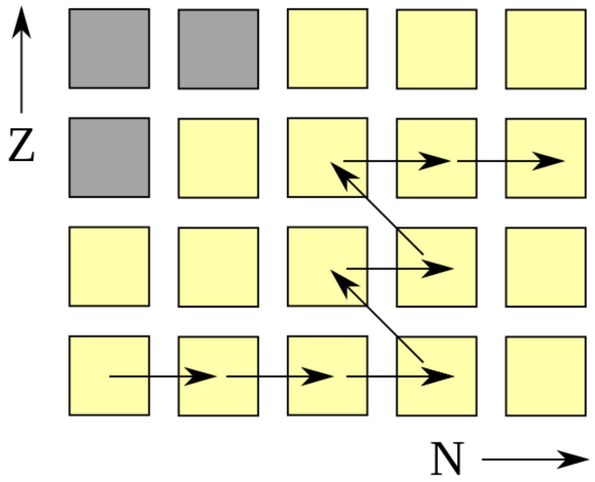
[ZX, G. Martínez-Pinedo, O. Just, A. Sieverding, PRL 132, 192701 (2024)]

Phases of the *r*-process

- **Weak freeze-out:** proton-to-nucleon ratio (or electron fraction Y_e) determined by neutrino-nucleon reactions

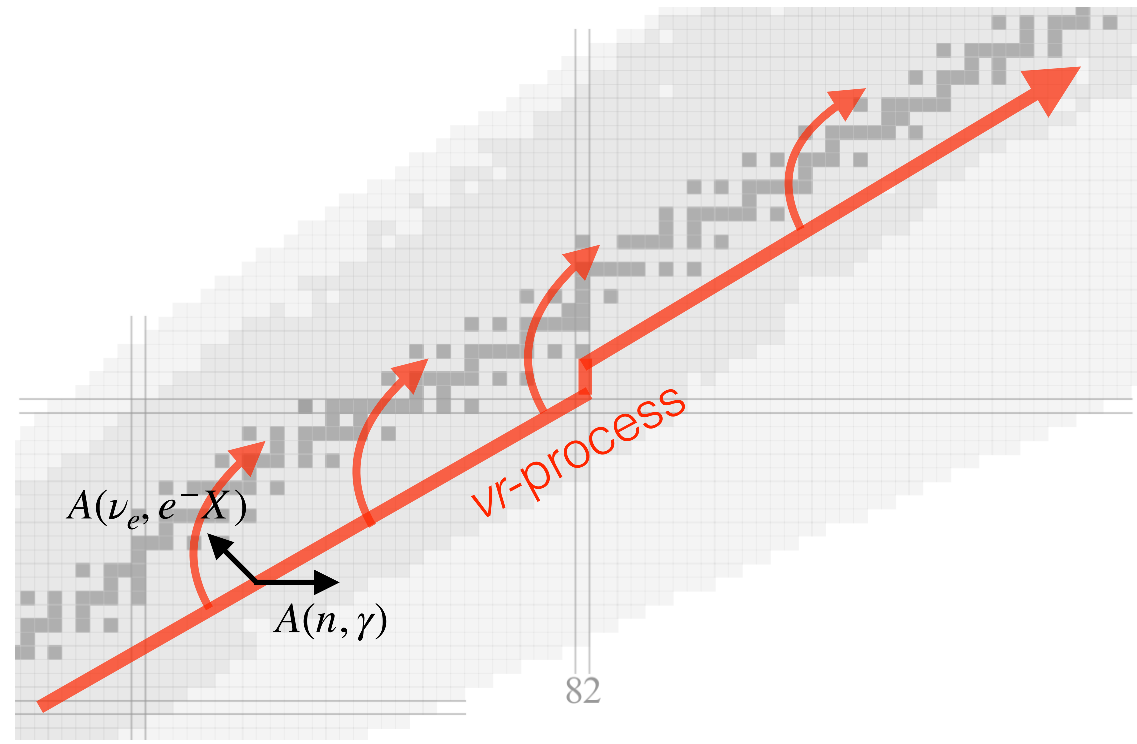
- **Seed production:** Charged particle reactions operating for $T \gtrsim 2$ GK produce the seed nuclei

- **Neutron-capture phase:** neutrons are captured on the available seed nuclei
  - $(n,\gamma) \leftrightarrows (\gamma,n)$ equilibrium
  - Beta-flow equilibrium



- **Freeze-out and decay to stability:** fully dynamical phase in which competition between neutron-captures, beta-decay (and fission) determines the final abundance pattern

Phases of the νr-process

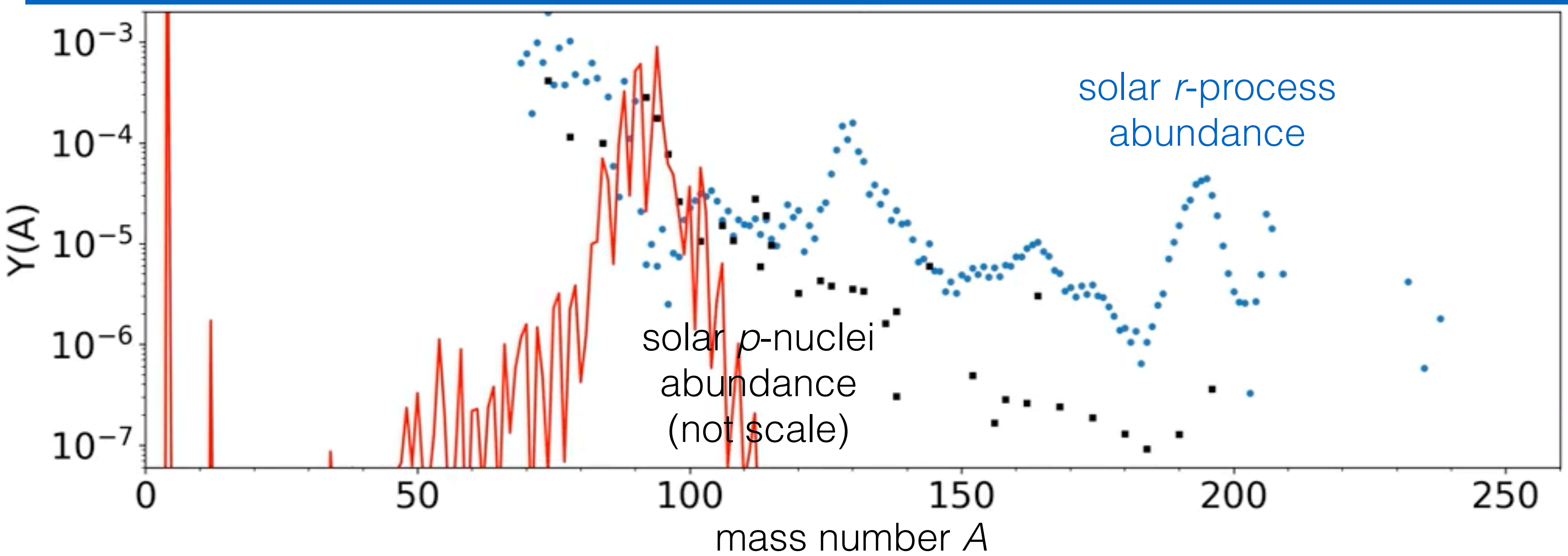


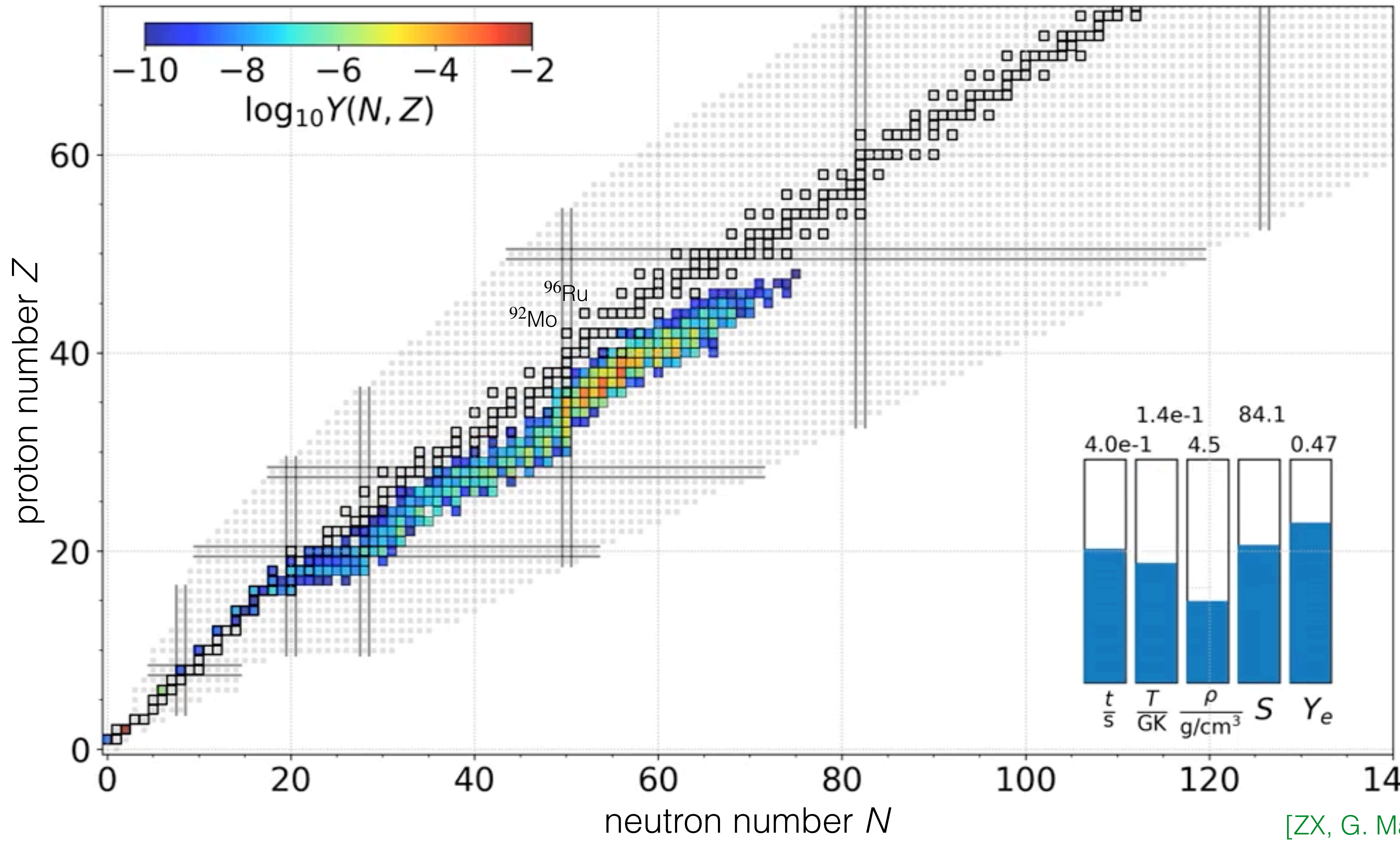
- **Seed production:** Strong neutrino fluxes drive material to $Y_e \sim 0.4 - 0.5$

- **Neutron-capture phase:** neutrons are used relatively fast by two competing mechanisms:
  - $n(\nu_e, e^-)p$ converts neutrons into protons that are captured in medium mass nuclei
  - $A(\nu_e, e^- X)$ speeds up the increase of Z and the build-up of heavy nuclei ($X = n, p, \alpha$)

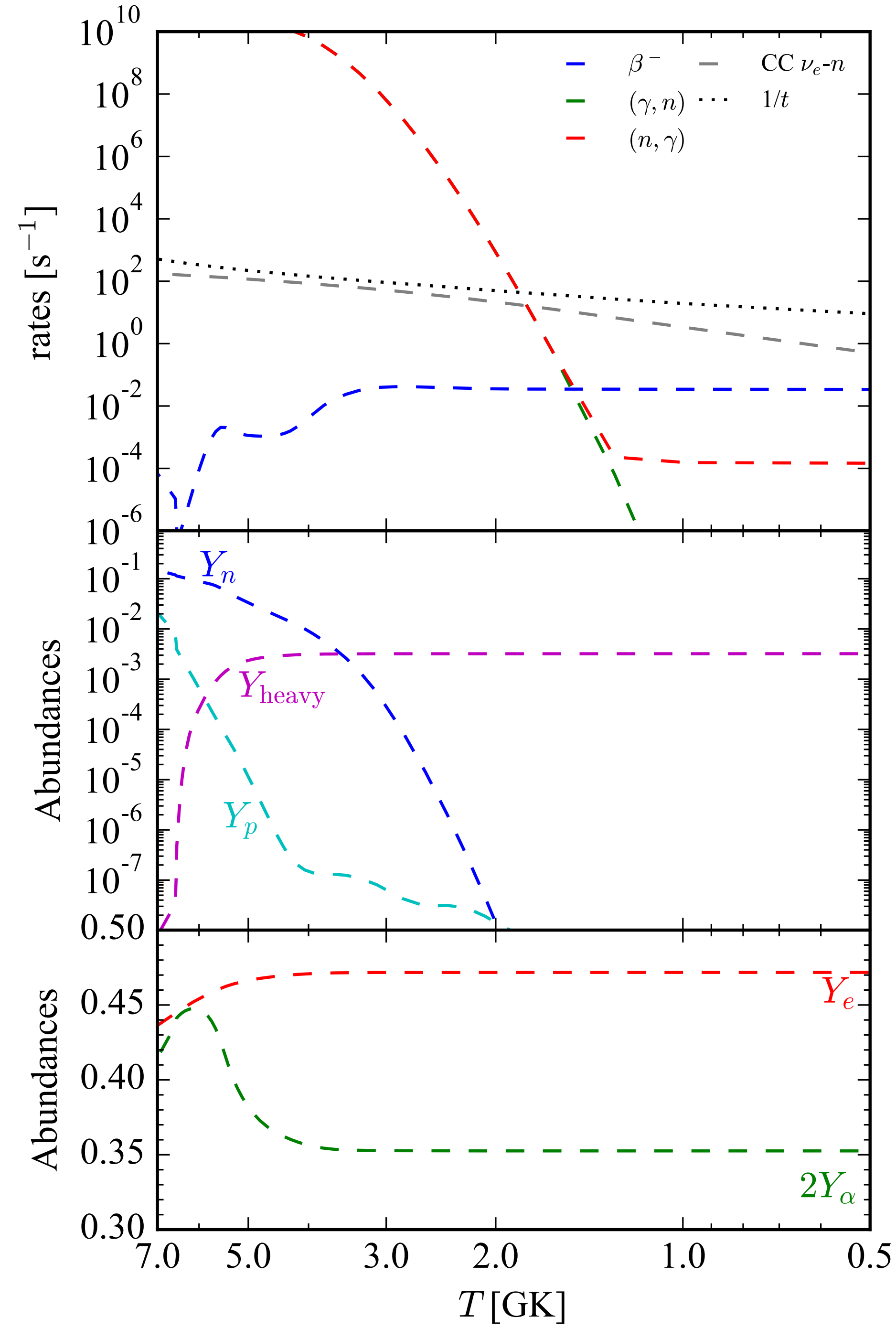
- **Fast transition towards stability and beyond:** $A(\nu_e, e^- X)$ reactions drive material to β-stability line and beyond
  - Neutrons, protons and alphas produced by both charged- and neutral-current spallation reactions
  - Protons and alphas captured mainly in light nuclei
  - Equilibrium between $A(\nu_e, e^- X)$ and $A(n, \gamma)$ determines final abundance

Nucleosynthesis (no neutrino-nucleus reaction)



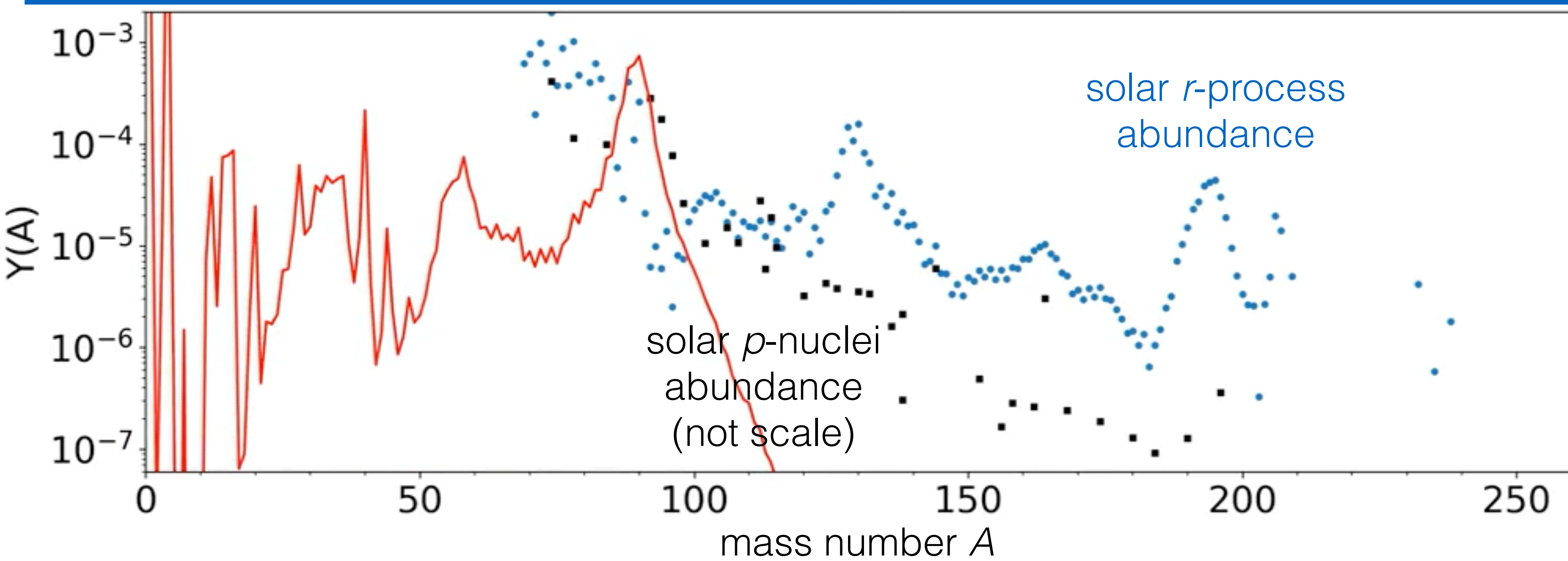


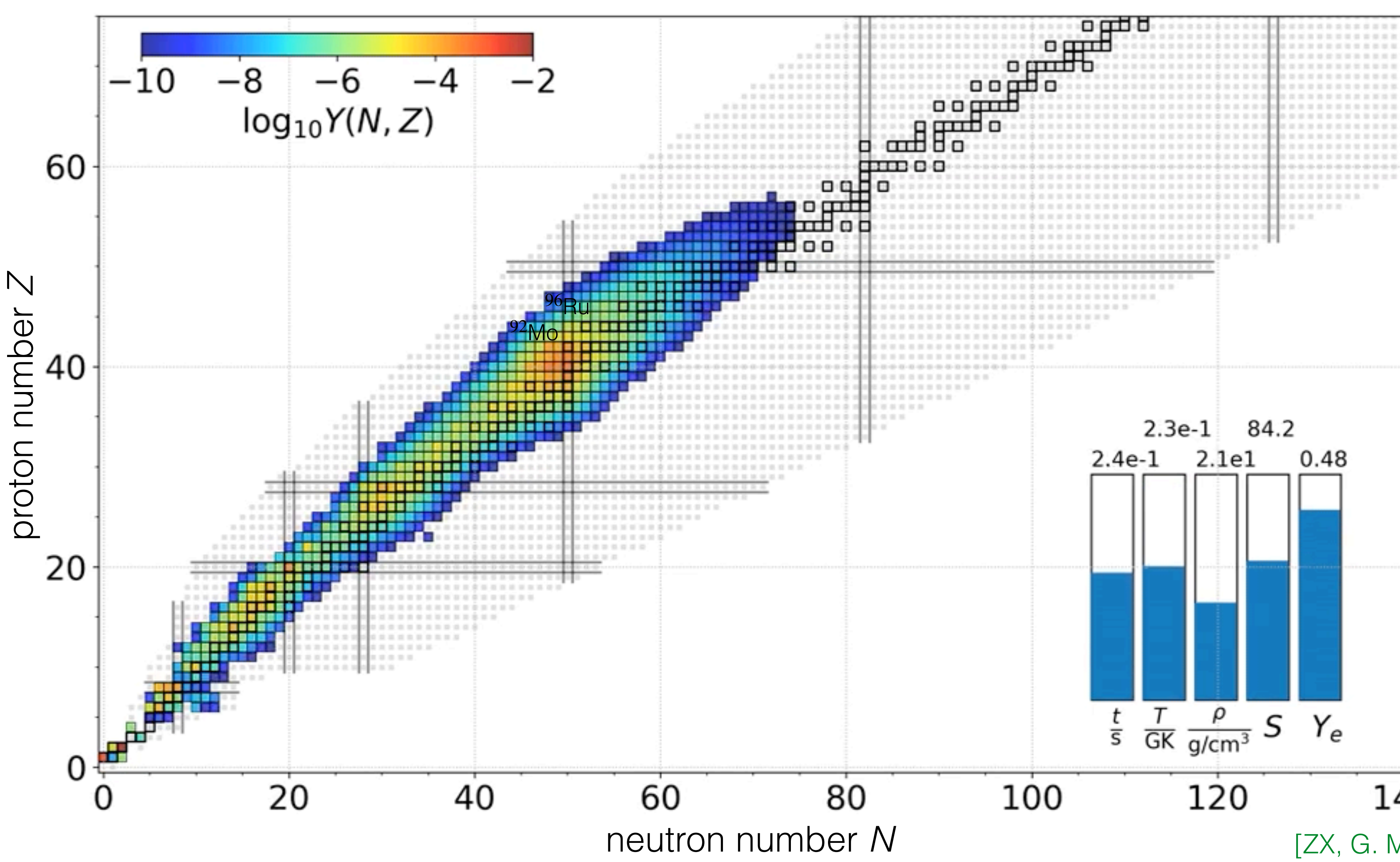
CC: charged-current

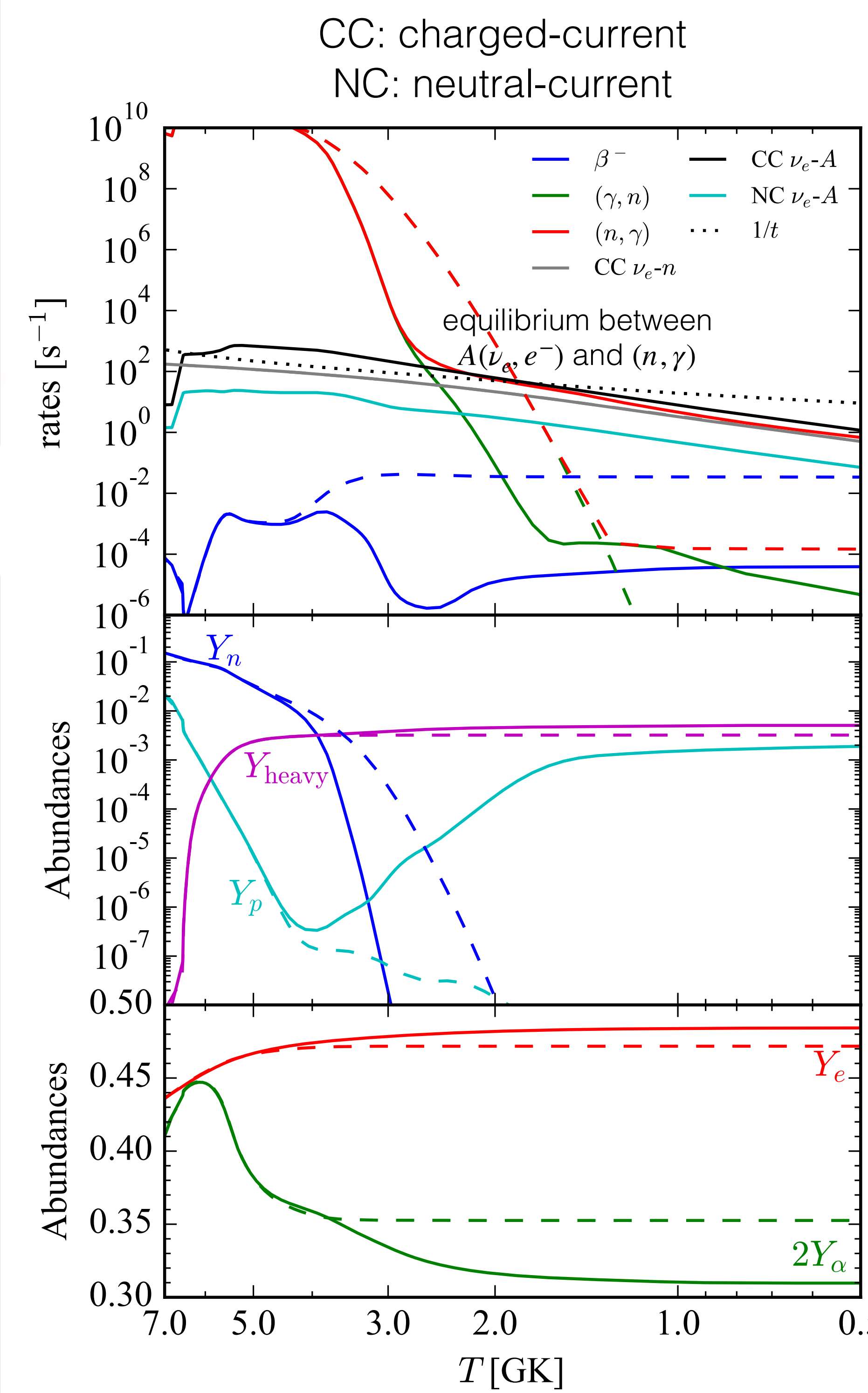


[ZX, G. Martínez-Pinedo, O. Just, A. Sieverding, PRL 132, 192701 (2024)]

Nucleosynthesis (with neutrino-nucleus reaction)

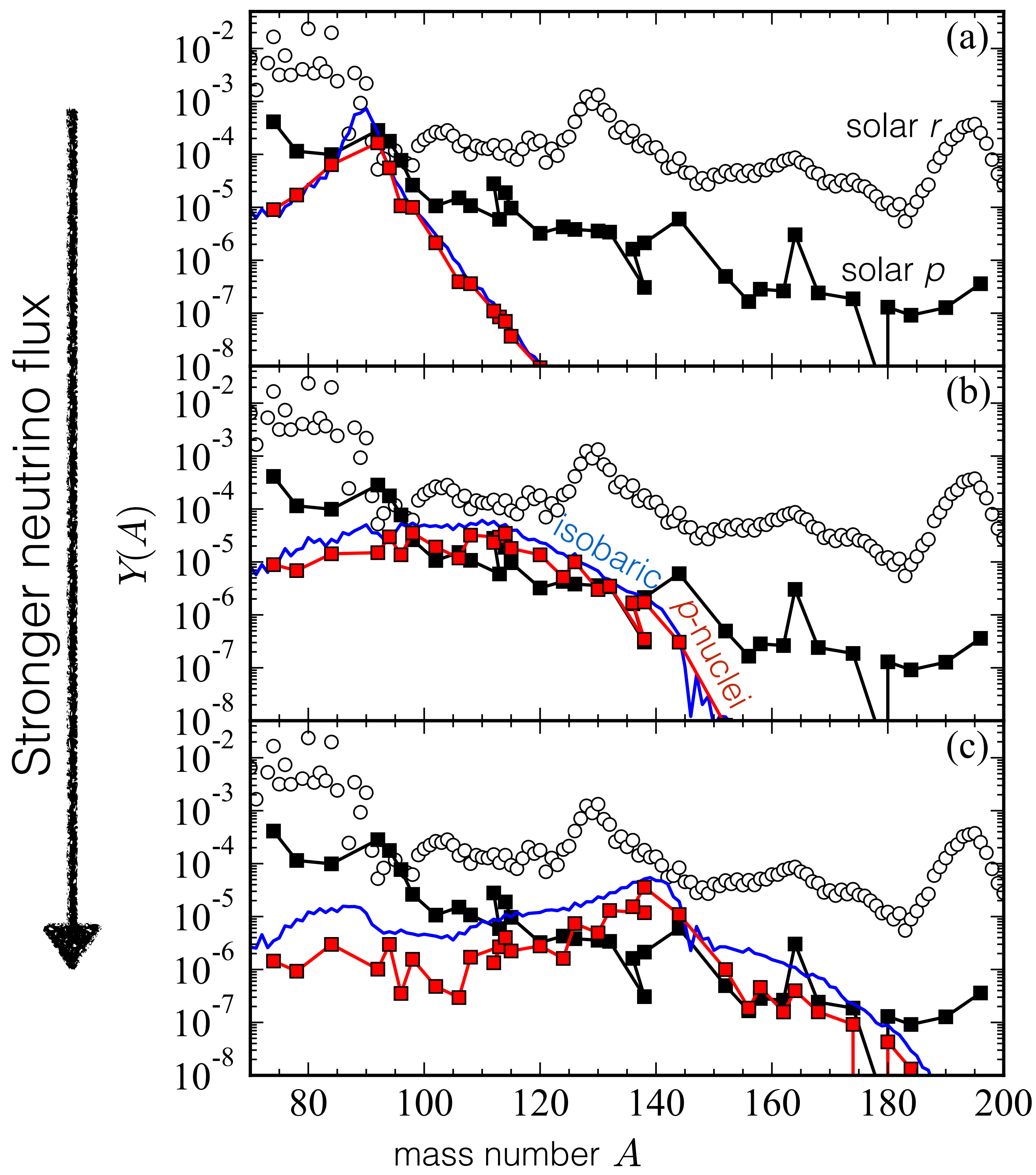






[ZX, G. Martínez-Pinedo, O. Just, A. Sieverding, PRL 132, 192701 (2024)]

Dependence on neutrino fluxes



- Increasing neutrino fluxes can produce heavier *p*-nuclei
- Assuming the same astrophysical site produces both *r*-process and *p*-nuclei, around 1% of the ejecta should reach *νr*-process conditions

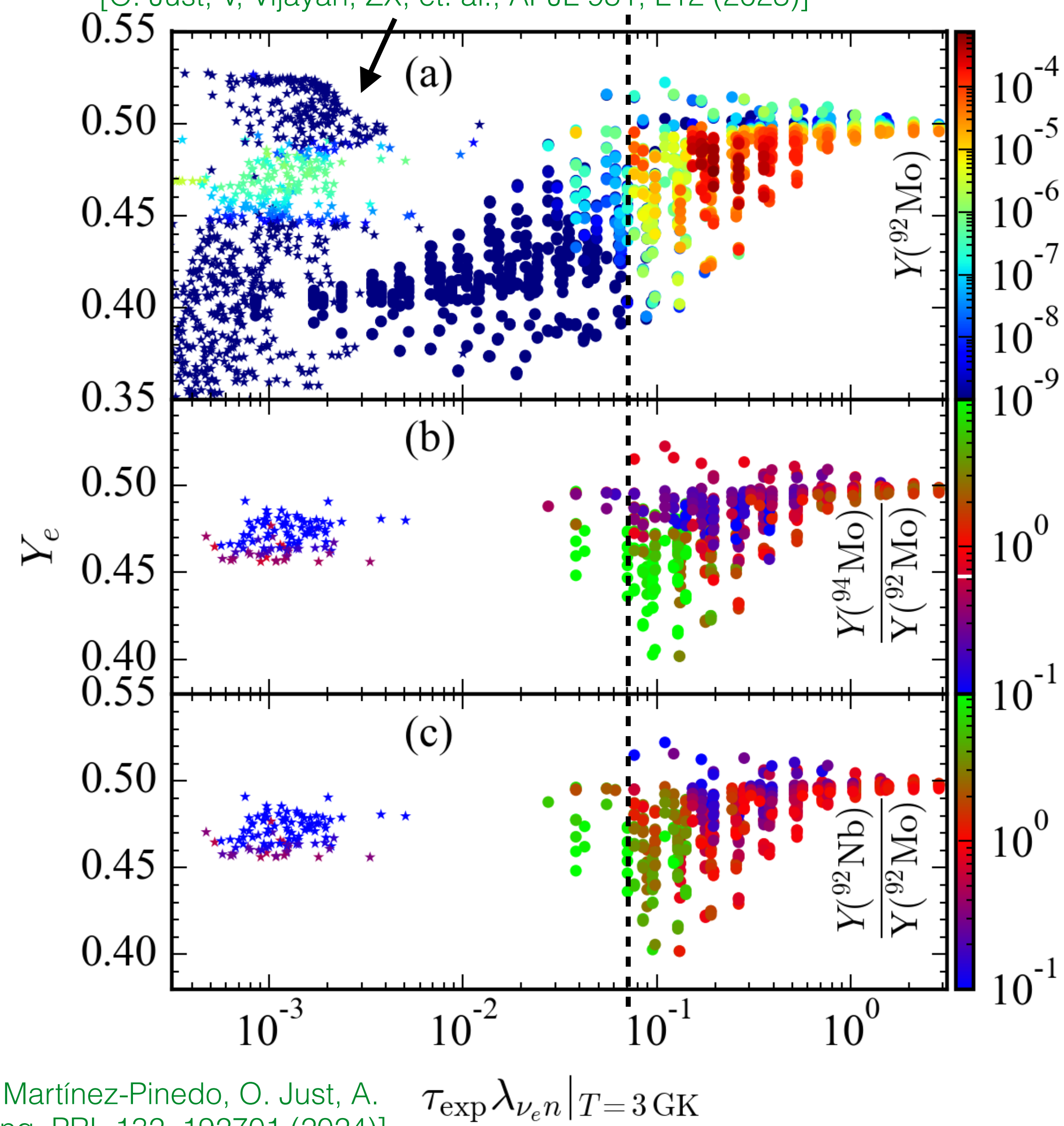
[ZX, G. Martínez-Pinedo, O. Just, A. Sieverding, PRL 132, 192701 (2024)]

Dependence on Y_e and neutrino exposure

- Significant amounts are produced when $Y_e < 0.5$ and the neutrino exposure is great than 0.1.

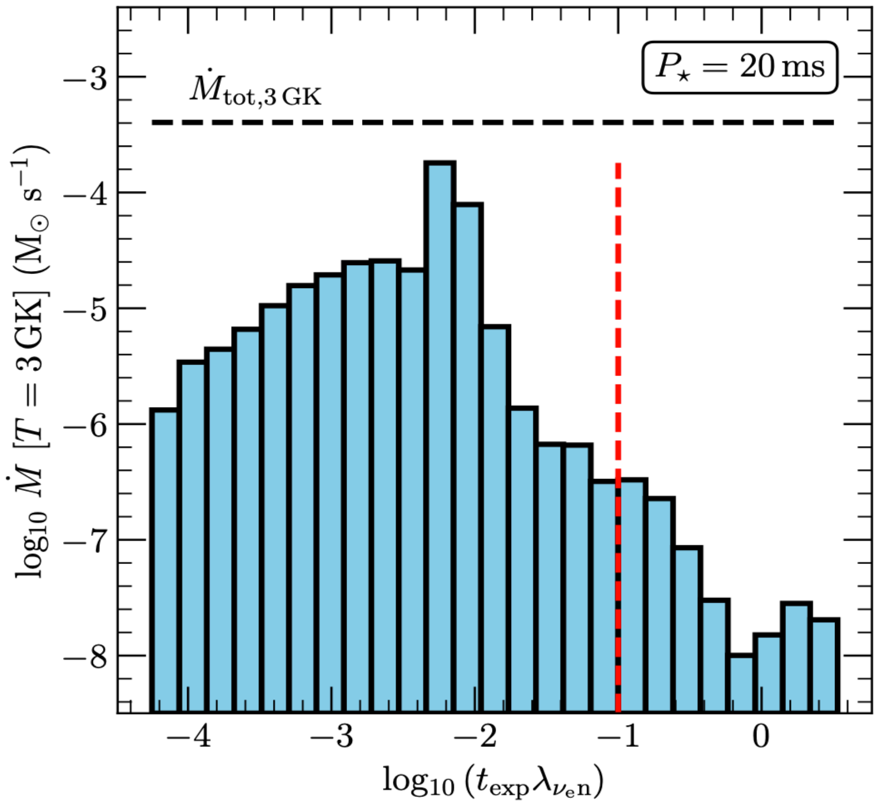
binary neutron-star merger simulation

[O. Just, V, Vijayan, ZX, et. al., APJL 951, L12 (2023)]



[ZX, G. Martínez-Pinedo, O. Just, A. Sieverding, PRL 132, 192701 (2024)]

- Current neutrino-hydrodynamical NSM model shows conditions deficient by ~1 order of magnitude.
  - The polar wind ejecta cool down to 3 GK at radii $\gtrsim 2000$ km.
  - A non-thermal ejection mechanism is necessary (magnetic fields? e.g., proto-magnetar winds?)



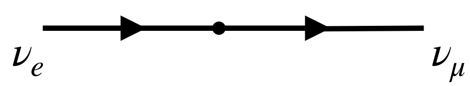
[T. Prasanna, M. Coleman, T. Thompson, arXiv:2402.06003]

Simulations of fast neutrino flavor conversions in spherically symmetric supernova models

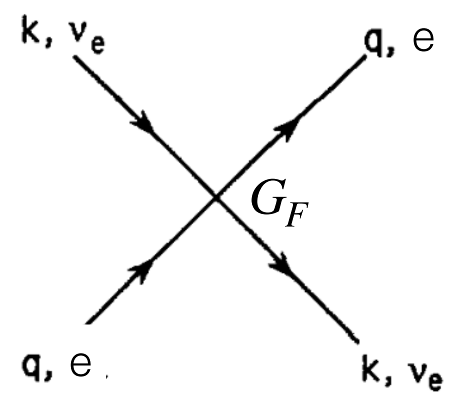
Collective neutrino oscillations

Flavor mixing in vacuum

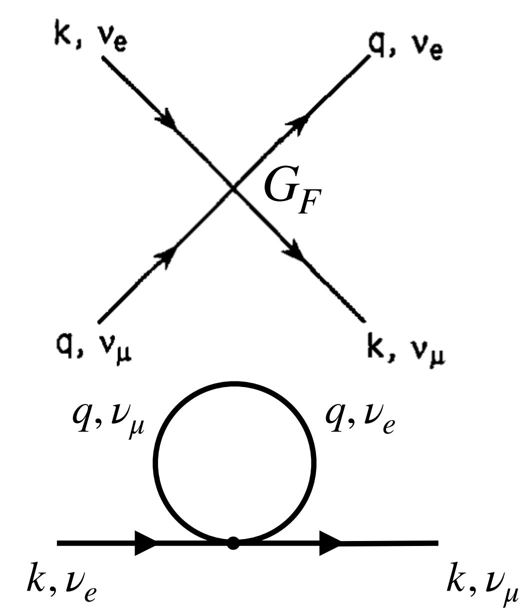
flavor eigenstate $\nu_\alpha = U_{\alpha l} \nu_l$ mass eigenstate



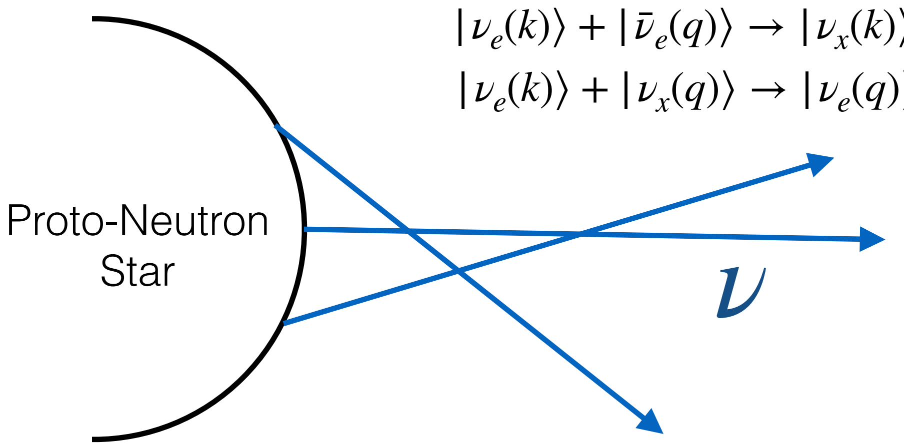
Matter effect



Neutrino-neutrino coherent forward scattering



$$|\nu_e(k)\rangle + |\bar{\nu}_e(q)\rangle \rightarrow |\nu_x(k)\rangle + |\bar{\nu}_x(q)\rangle$$
$$|\nu_e(k)\rangle + |\nu_x(q)\rangle \rightarrow |\nu_e(q)\rangle + |\nu_x(k)\rangle$$
$$(x = \mu, \tau)$$



- Collective phenomena:
  - Matter-neutrino resonance
  - Slow flavor instability, energy spectrum swapping/splitting
  - Collisional flavor instability
  - Fast flavor instability

Fast flavor instability (FFI)

non-trivial neutrino angular distributions

A "very fast" time scale $(G_F n_\nu)^{-1}$, where n_ν is the neutrino number density $n_e \sim T^3$. In our domain this time is of order 10^{-3} cm in units in which $c = 1$.

[redacted] the "very fast" rate mentioned in the introduction. This situation only arises when the angular distributions in the initial state are somewhat complex. [R. F. Sawyer, PRD 79, 105003 (2009)]

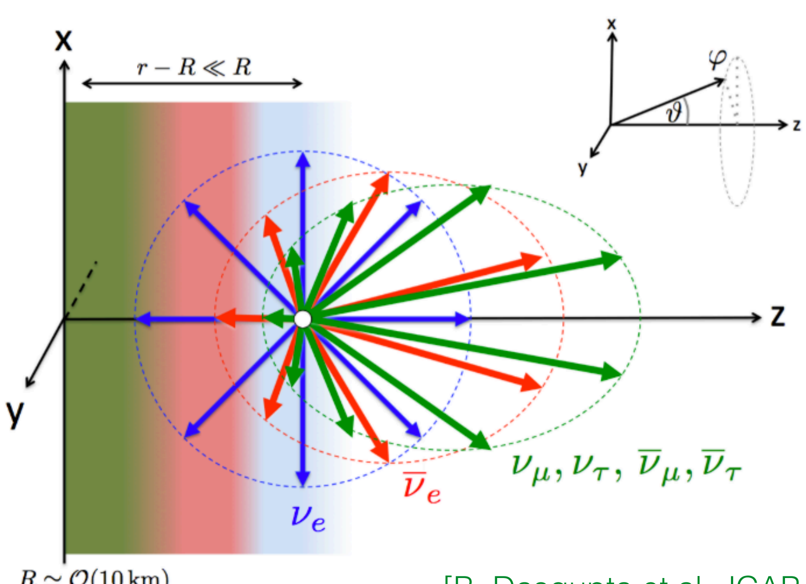
Occurrence of FFI in supernova:

- ahead of the shock wave,
- near the neutrinosphere,
- deep inside neutrinosphere

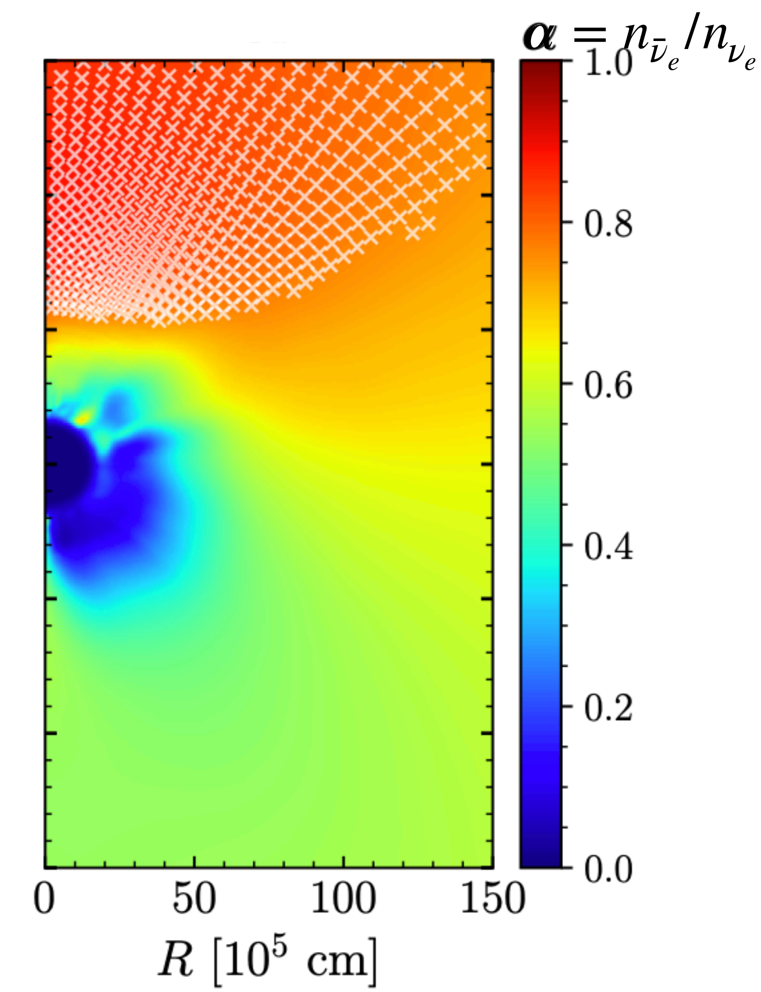
[S. Abbar, H. Duan, et al., PRD 100, 043004 (2019);
M. Azari, S. Yamada et al. PRD 99 103011 (2019);
R. Glas, H.-T. Janka et al., PRD 101, 063001 (2020);
H. Nagakura, A. Burrows et al., PRD 104, 083025 (2021);
...]

Fast flavor instability is present if and only if the angular distributions of neutrino lepton number of two flavors cross each other. [T. Morinaga, PRD 105, L101301 (2022)]

$$G \equiv f_{\nu_e}(\mathbf{v}) - f_{\bar{\nu}_e}(\mathbf{v}) - f_{\nu_x}(\mathbf{v}) + f_{\bar{\nu}_x}(\mathbf{v})$$ (ELN, or E-XLN)



[B. Dasgupta et al, JCAP 02 (2017) 019]



Neutrino quantum kinetic equation (νQKE)

$$(\partial_t + \mathbf{v}\cdot\nabla_{\mathbf{r}})\varrho = -i[\mathbf{H}_{\rm vac} + \mathbf{H}_{\rm mat} + \mathbf{H}_{\nu\nu}, \varrho] + \mathbf{C}(\varrho)$$

advection — vacuum mixing — coherent forward scatterings (matter, self-induced) — collisional weak processes

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

$$\mathbf{H}_{\rm vac}(E) = \mathbf{U}\mathbf{M}^2\mathbf{U}^\dagger$$

$$\mathbf{H}_{\rm mat} = \sqrt{2}G_F {\rm diag}[n_e, 0, 0]$$

$$\mathbf{H}_{\nu\nu}(\hat{\mathbf{p}}) = \sqrt{2}G_F \int d\mathbf{p}'(1-\hat{\mathbf{p}}\cdot\hat{\mathbf{p}}')[\varrho(\mathbf{p}') - \bar{\varrho}^*(\mathbf{p}')]$$

$$df_{\nu_e}/dt = j_e(1-f_{\nu_e}) - \chi_e f_{\nu_e}$$

emissivity — opacity

$$\mathbf{C} \sim \begin{pmatrix} j_e(1-f_{\nu_e}) - \chi_e f_{\nu_e} & -(j_e+\chi_e)\varrho_{e\mu}/2 \\ -(j_e+\chi_e)\varrho_{e\mu}^*/2 & 0 \end{pmatrix}$$

Challenging problem:

- Nonlinearity!
- High dimensions! $\varrho(t,\mathbf{r},\mathbf{p})$
- Scale separation! $\mathbf{H}_{\nu\nu} \sim G_F n_\nu \sim \mathcal{O}(\rm cm)$

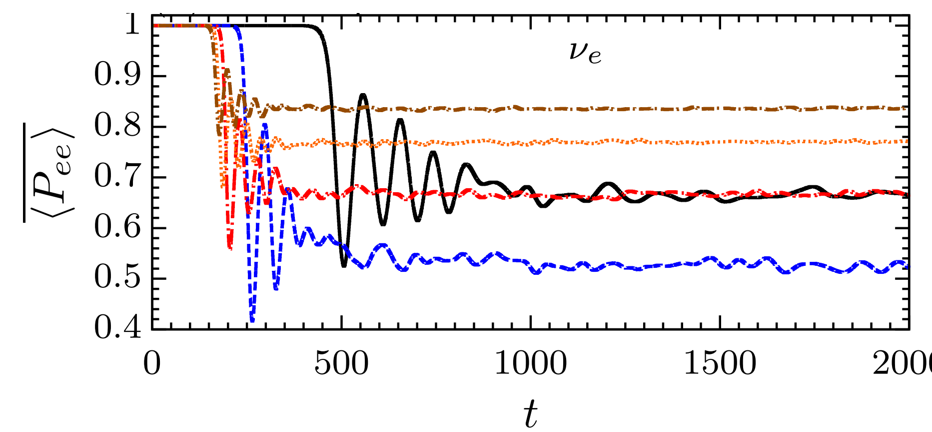
  $\mathbf{C} \sim \chi_e \sim G_F^2 E^2 n_{\rm N} \sim \mathcal{O}(\rm km)$

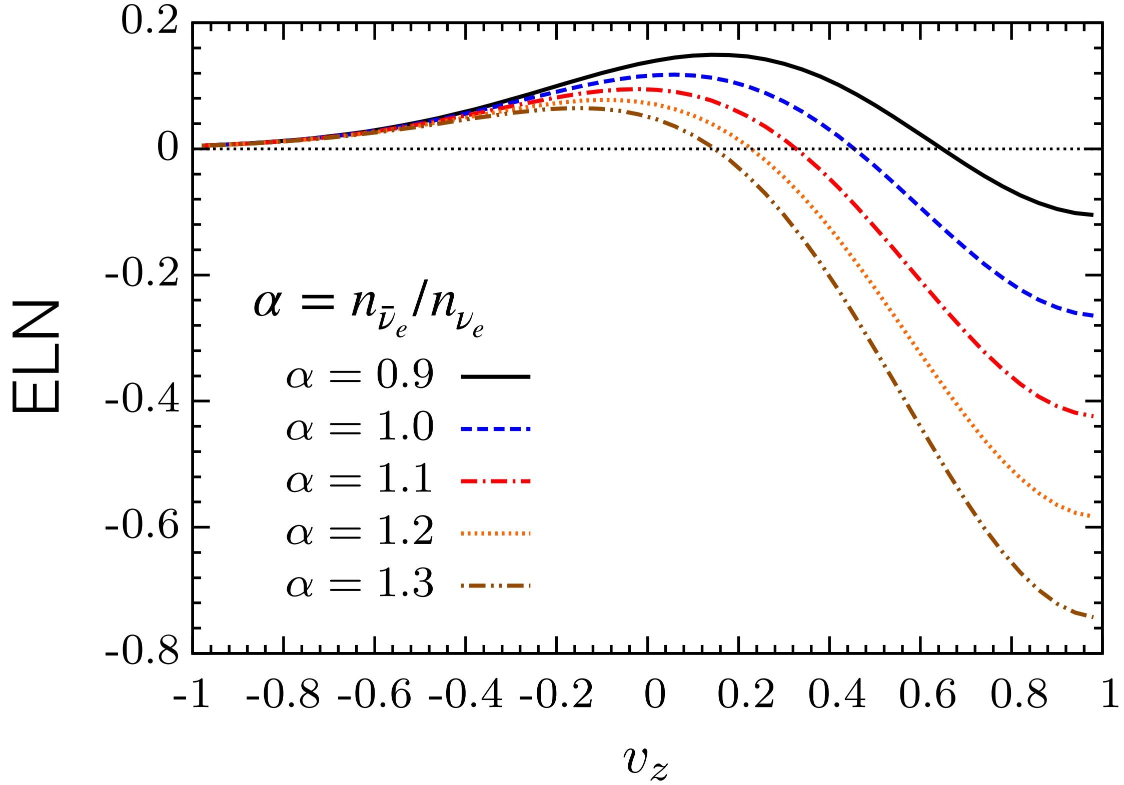
- Local box $\sim \mathcal{O}(\rm m)$:
  periodic boundary condition
  without collisions

- Global advection $\sim \mathcal{O}(100\ \rm km)$:
  attenuation on $\mathbf{H}_{\nu\nu}$
  keeping the same hierarchy

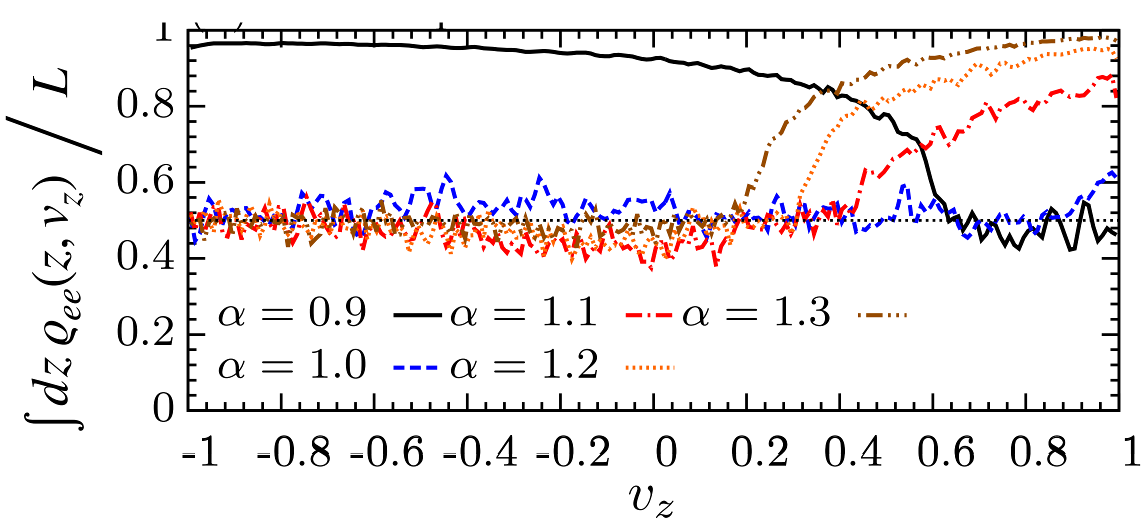
Local-box simulation

$$(\partial_t + v_z\partial_z)\varrho(v_z) = -i[\mathbf{H}_{\nu\nu}(v_z), \varrho(v_z)]$$

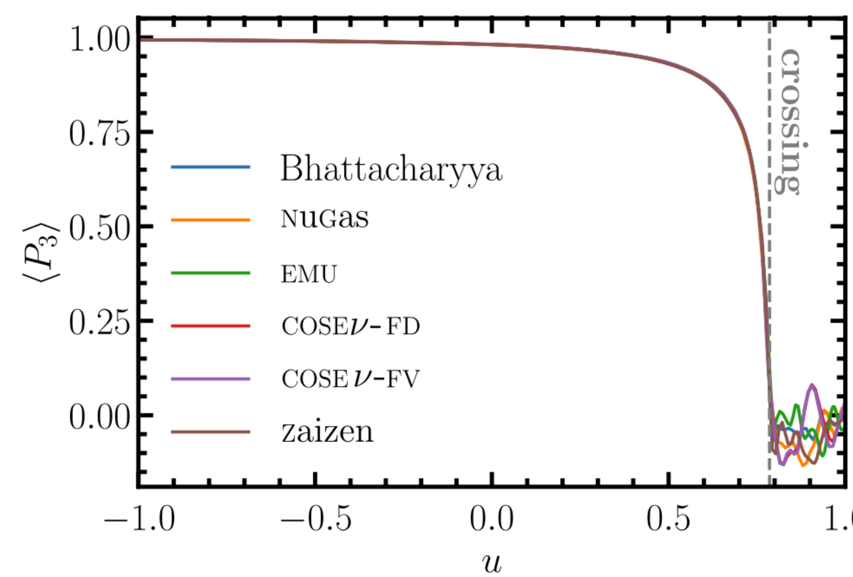




- COSEν code (Collective Oscillation Simulation Engine for Neutrinos) [M. George et al., Comput. Phys. Commun. (2023)]
- Reach asymptotic state in coarse-grained level
- Complete flavor equilibration when α=1
- Strong angle-dependence when $\alpha \neq 1$



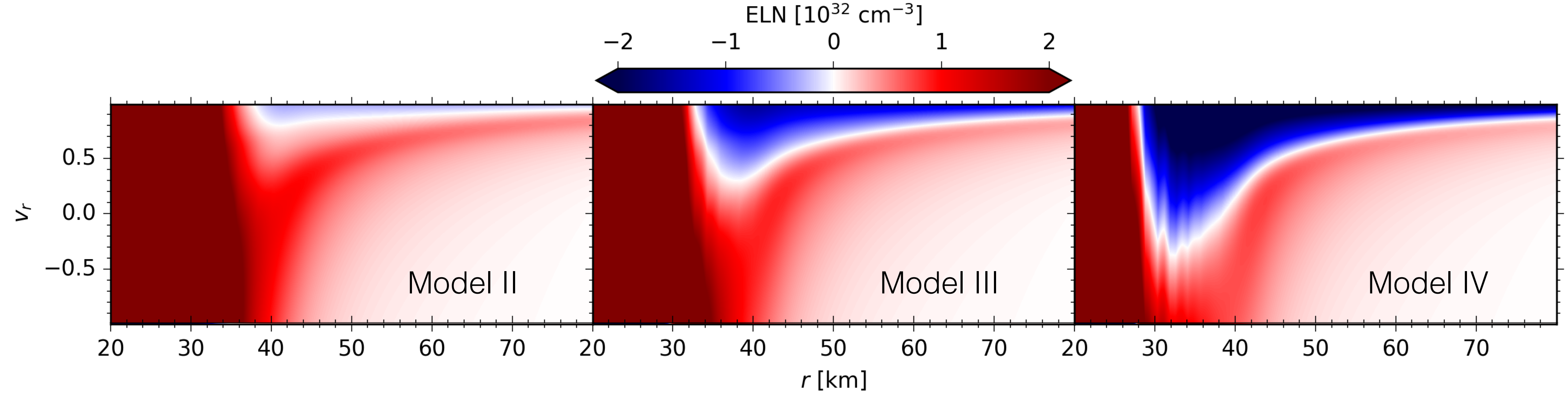
[M.-R. Wu, M. George, C.-Y. Lin, ZX, PRD 104, 103003 (2021)]



[S. Richers et al, PRD 106, 043011 (2022)]

Global simulation set-up

- CCSN background matter profile from `AGILE-BOLTZTRAN`, $25M_\odot$ progenitor

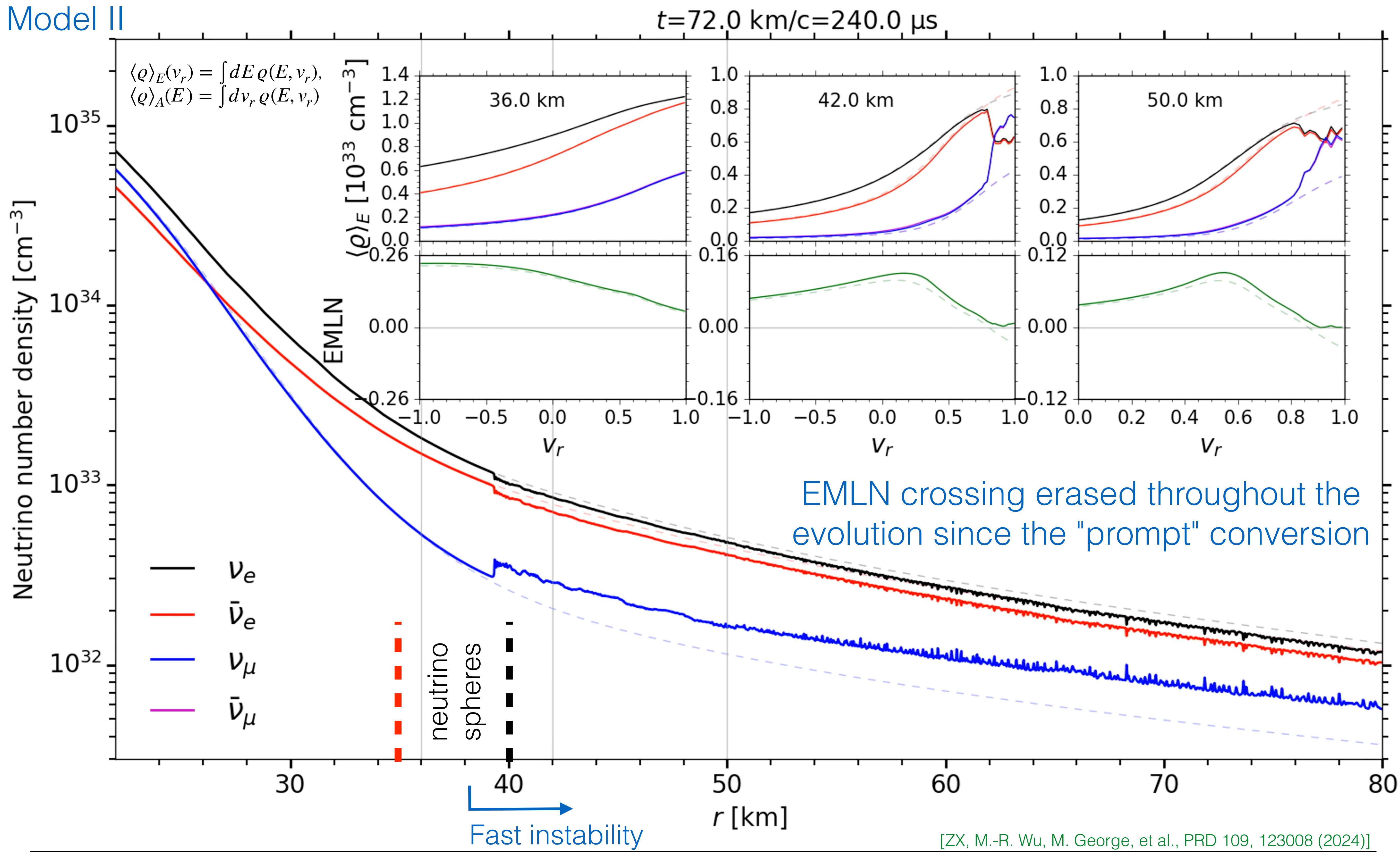


- $$(\partial_t + v_r\partial_r + \frac{1-v_r^2}{r}\partial_{v_r})\varrho(E, v_r) = -i[\mathbf{H}_{\rm vac} + a_{\nu\nu}\mathbf{H}_{\nu\nu}, \varrho(E, v_r)] + \mathbf{C}$$
  - COSEν code: multi-energy & multi-angle
  - $a = 4 \times 10^{-3}$, $N_r = 50{,}000$, $N_{v_r} = 100$, $N_E = 15$
  - *Collisional weak processes:* emission & absorption, iso-energetic neutrino-nucleon scattering, inelastic neutrino-electron scatterings, & pair reactions
  - *Inner boundary (20km):* thermal equilibrium at the boundary, collisional weak processes determine neutrino spheres
  - *Outer boundary (80km):* freely stream out, no injection for incoming neutrinos

[ZX, M.-R. Wu, M. George, et al., PRD 109, 123008 (2024)]

Global simulation: instability beyond neutrino-sphere

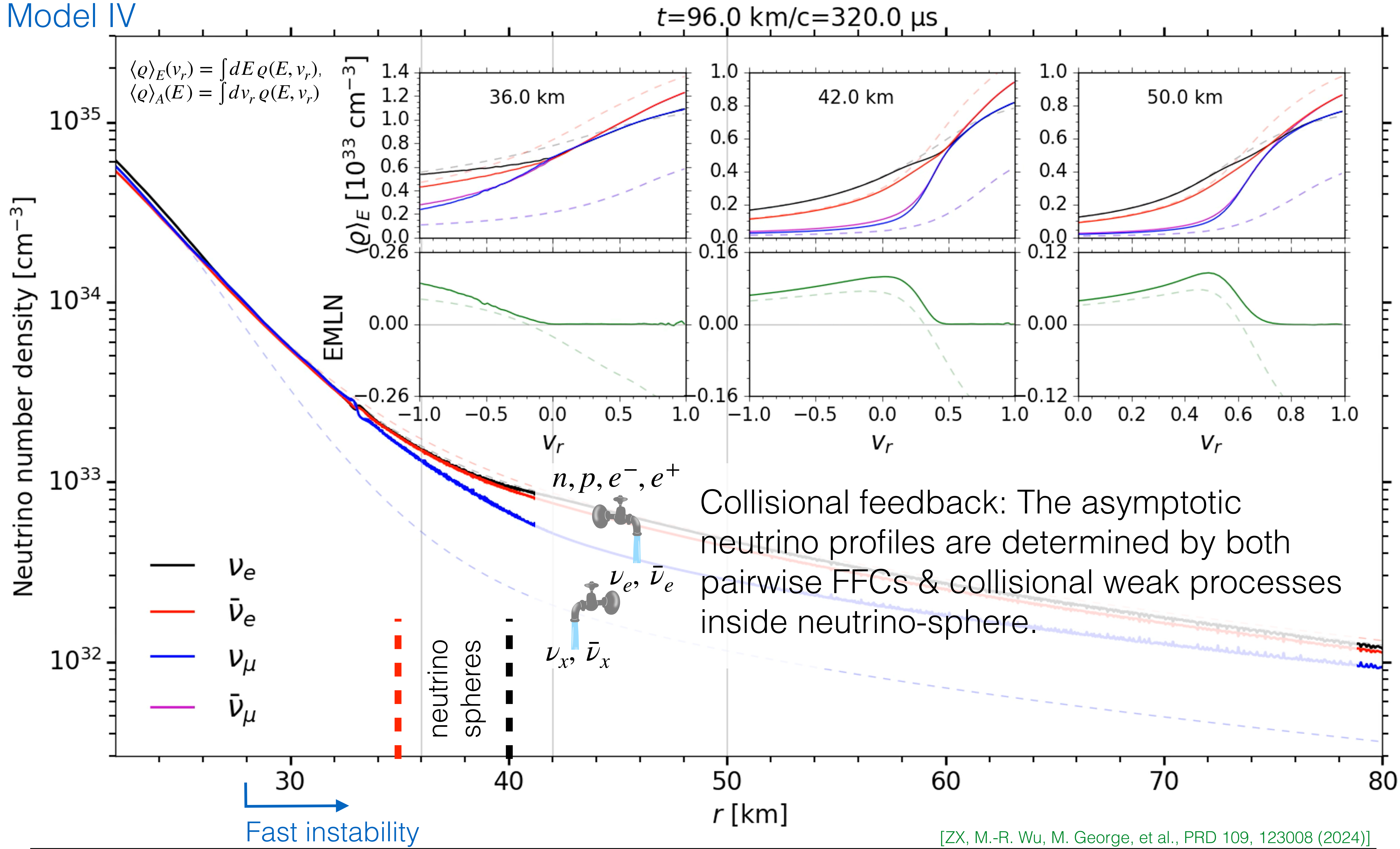
Model II



[ZX, M.-R. Wu, M. George, et al., PRD 109, 123008 (2024)]

Global simulation: instability from inside neutrino-sphere

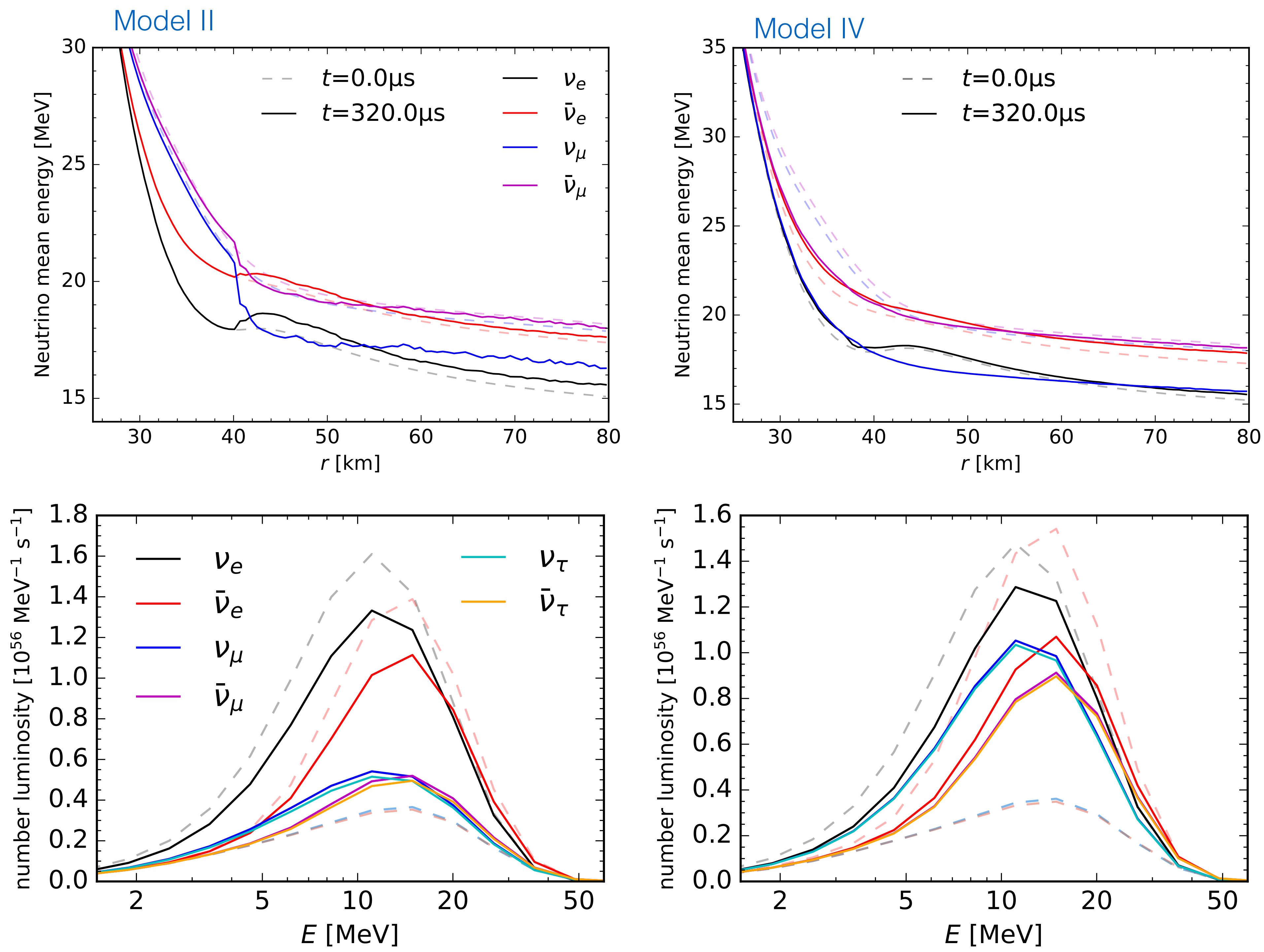
Model IV



Collisional feedback: The asymptotic neutrino profiles are determined by both pairwise FFCs & collisional weak processes inside neutrino-sphere.

[ZX, M.-R. Wu, M. George, et al., PRD 109, 123008 (2024)]

Neutrino mean-energy & free-streaming energy spectra

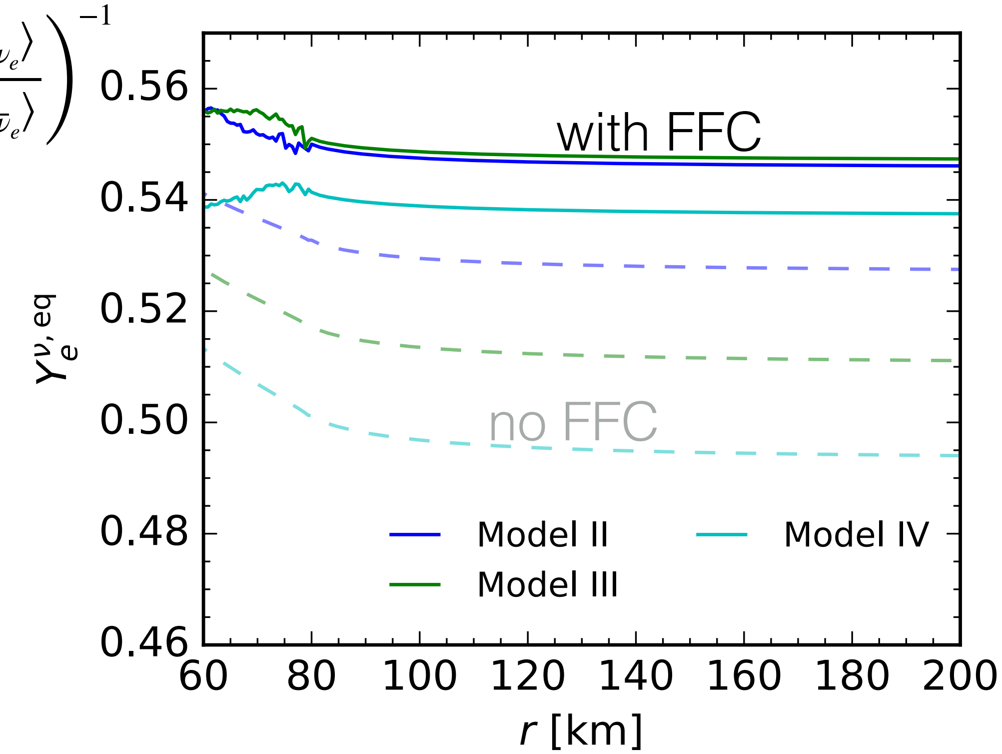


[ZX, M.-R. Wu, M. George, et al., PRD 109, 123008 (2024)]

Effects in neutrino heating & nucleosynthesis

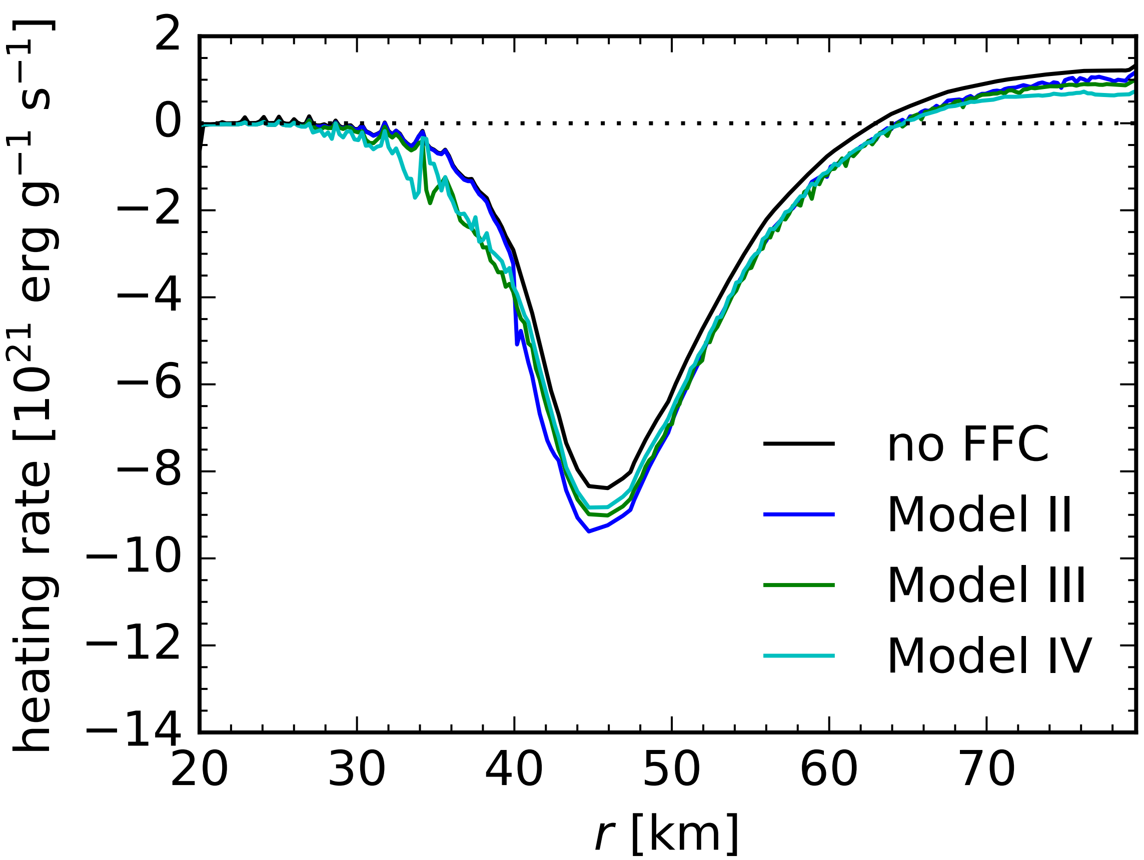
$$\nu_e + n \leftrightarrows p + e^-$$
$$\bar{\nu}_e + p \leftrightarrows n + e^+$$

$$Y_e^{\nu,\mathrm{eq}} \sim \left(1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \frac{\langle E_{\nu_e}\rangle}{\langle E_{\bar{\nu}_e}\rangle}\right)^{-1}$$



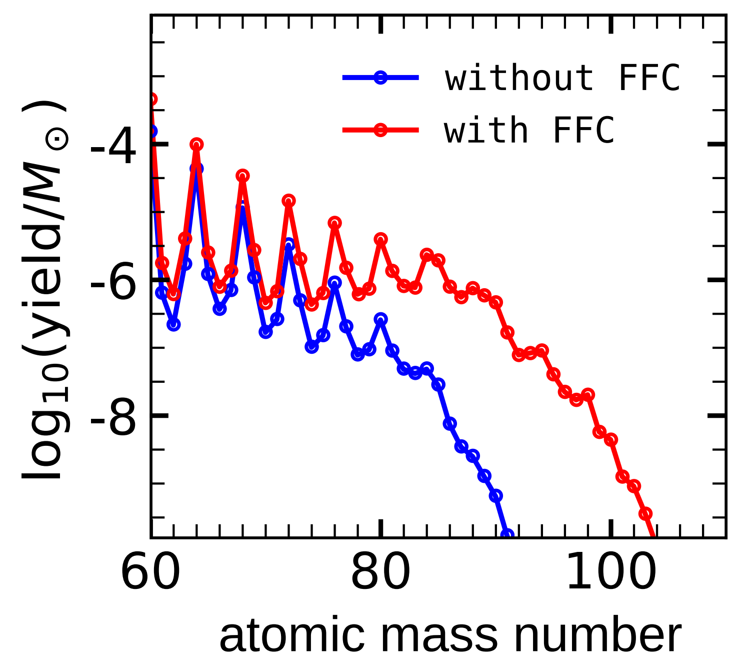
can increase cooling & reduce heating

[see also H. Nagakura, PRL 130, 211401 (2023);
J. Ehring, S. Abbar, H.-T. Janka et al, PRL, (2023)]



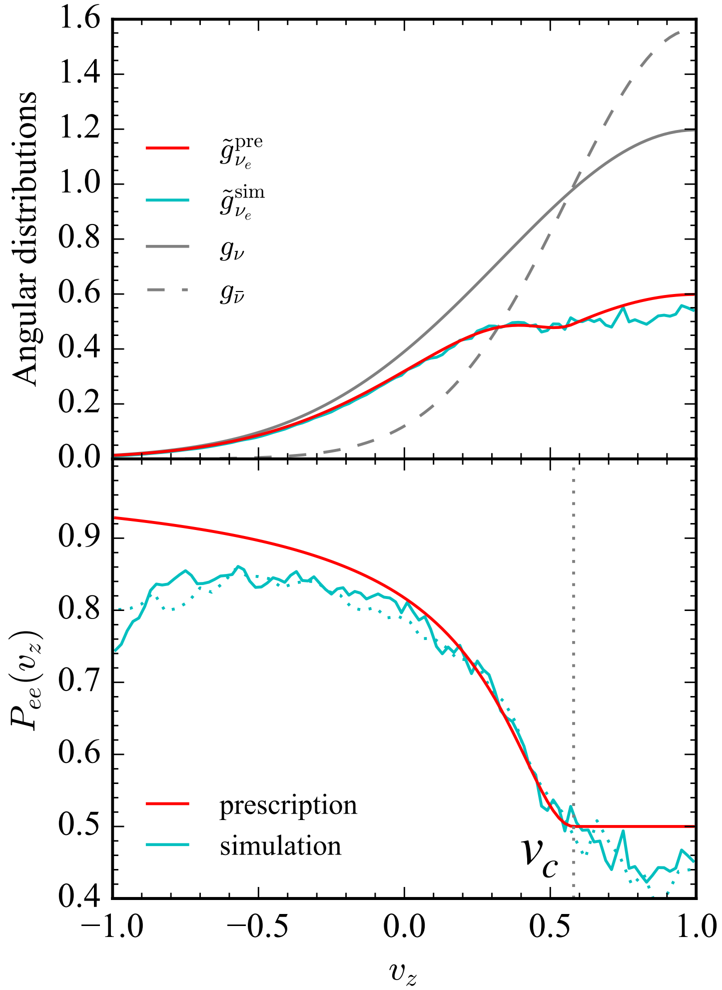
[ZX, M.-R. Wu, M. George, et al., PRD 109, 123008 (2024)]

can enhance *vp*-process



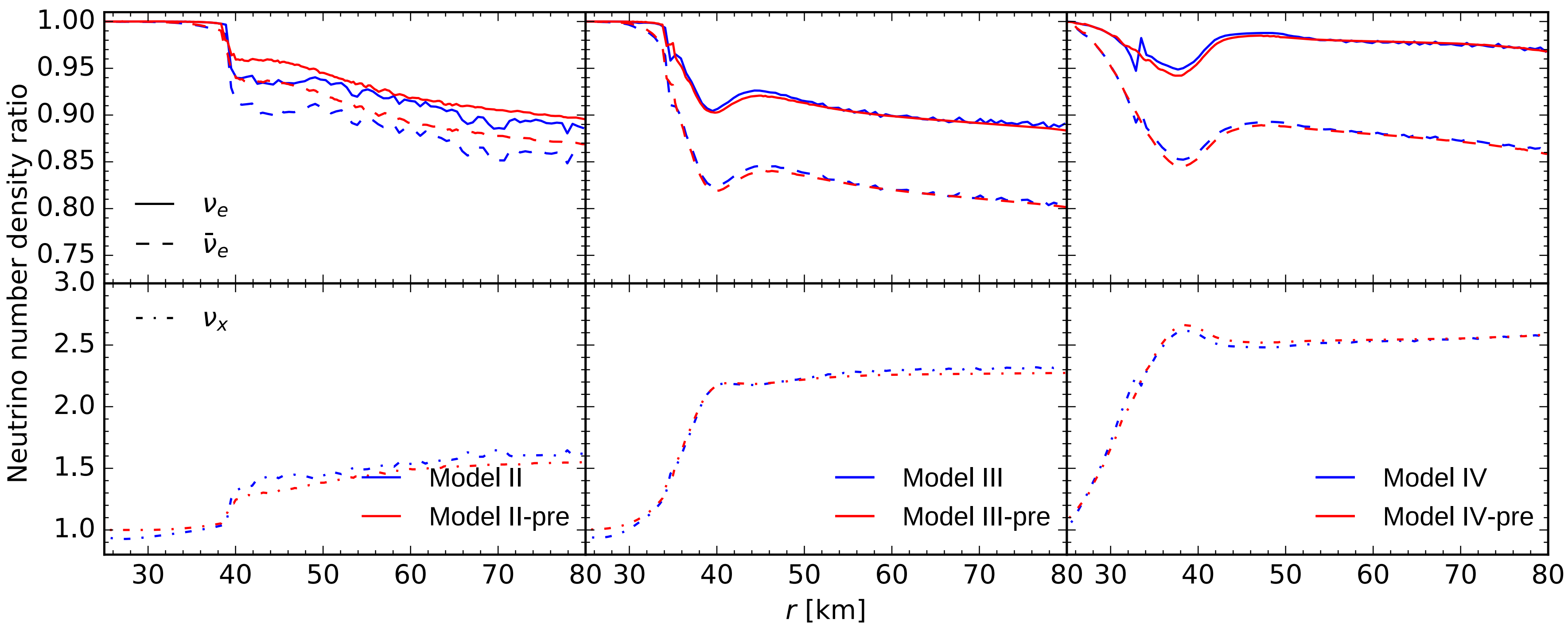
[ZX, A. Sieverding et al., APJ 900, 2 (2020)]

Analytical prescription



[ZX, M.-R. Wu, S. Abbar, et al., PRD (2023)]

- approximate the survival probability after FFC in local-box simulations as
  $P_{ee} = 1 - \frac{1}{2}h(|v_z - v_c|/a)$ with $h(x) = (x^2+1)^{-1/2}$
- effectively describe the pairwise flavor conversions $\nu_e, \bar\nu_e \to \nu_x, \bar\nu_x$ by
  $F^{\rm FFC}_{\nu_e} = P_{ee}F^0_{\nu_e} + (1-P_{ee})F^0_{\nu_x}$
  $F^{\rm FFC}_{\nu_x} = (1-P_{ee})F^0_{\nu_e} + P_{ee}F^0_{\nu_x}$
- apply the above prescription in the global simulations as a source term or instantaneously updating after every hydro time step
- to avoid explicitly including the oscillation term that requires fast time and length scales

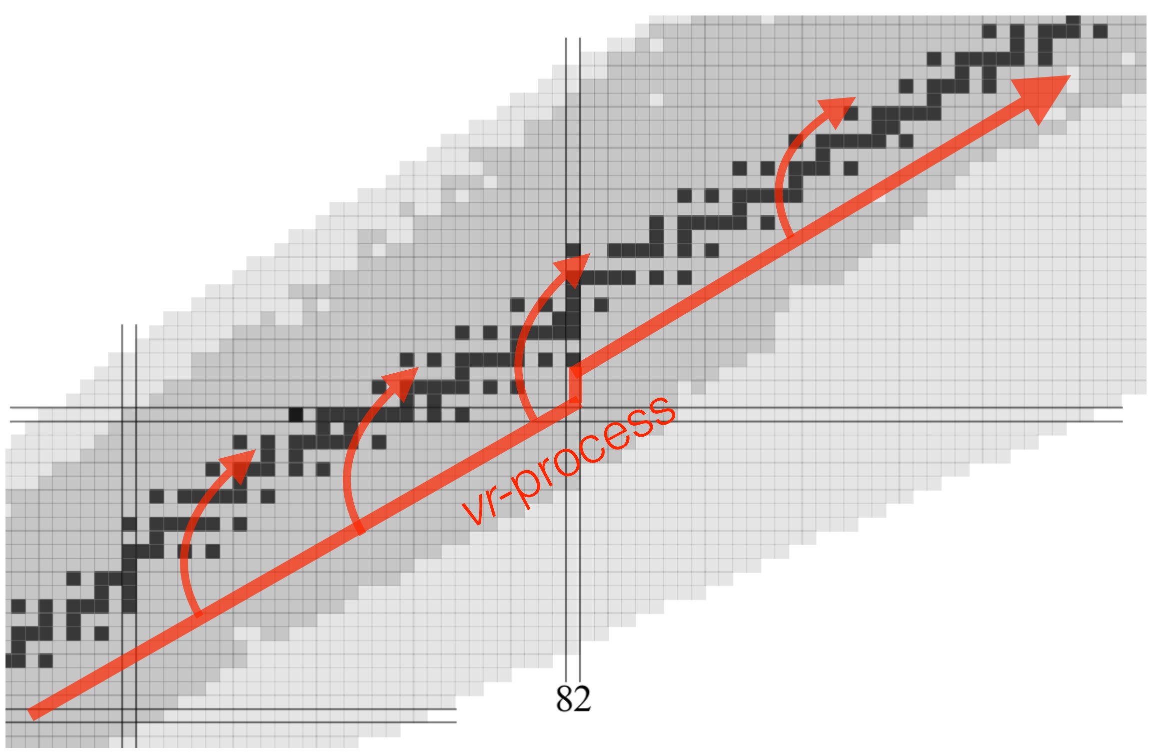


Prescription excellently captures the asymptotic solution from vQKE.

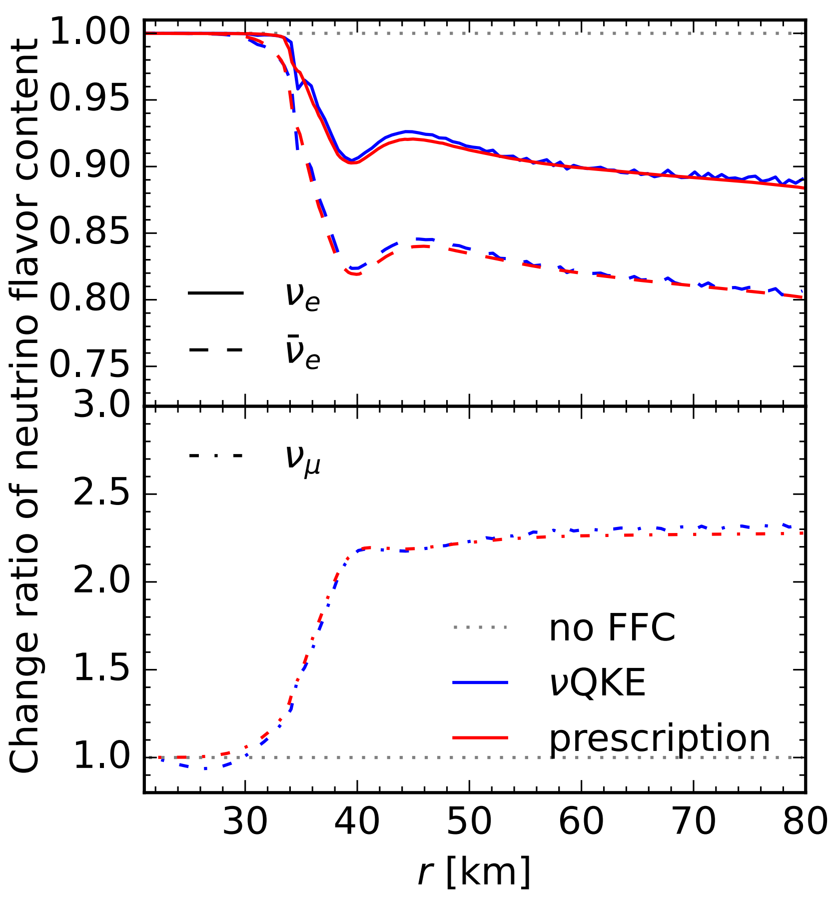
[ZX, M.-R. Wu, et al., arXiv:2403.17269, submitted to PRL]

Summary & outlook

- We propose the vr-process as driven by neutrino-nucleus reactions
  - may take place on neutron-rich ejecta experiencing an intensive neutrino flux
  - final abundance is determined by the equilibrium between $A(\nu_e, e^- X)$ and $A(n, \gamma)$ reactions
  - allows a consistent co-production of ^{92,94}Mo, ^{92}Nb, ^{96,98}Ru, and heavier *p*-nuclei
  - more complicated physics? magnetic fields?



- We perform both local-box and global simulations for self-induced fast oscillations
  - asymptotic state at the coarse-grained level
  - co-determined by both collisions & pairwise FFCs when FFIs are inside the neutrinosphere
  - affect the net neutrino heating rate & equilibrium Y_e
  - excellent reproduction of vQKE solutions using prescription: incorporated in hydro simulations?
  - multi-dimensional geometry? feedback on matter?



NeuTrAE project

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ERC Starting Grant for neutrino research awarded to Dr. Zewei Xiong

05.09.2024 | Dr. Zewei Xiong has received a prestigious ERC Starting Grant from the European Research Council (ERC). The funding is one of Europe's most important research awards, aimed at talented young scientists at an early career stage to show their potential as a research leader. Dr. Zewei Xiong is currently working as a postdoctoral researcher in the Nuclear Astrophysics and Structure Department at the GSI Helmholtzzentrum für Schwerionenforschung.

- NeuTrAE: Neutrino flavor Transformations in dense Astrophysical Environments.
- Scientific goals:
  - performing quantum kinetic simulations for collective neutrino flavor oscillations
  - developing numerically effective schemes that can be incorporated in state-of-the art hydrodynamical simulations
  - assessing quantitatively the impact of neutrino flavor transformations on heavy element nucleosynthesis and its electromagnetic signatures
- Total duration of the project: five years
- will open a PhD position soon, which will start next year with a duration of three years.

European Research Council
Established by the European Commission