Neutrinos and nucleosynthesis in binary neutron star mergers

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

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

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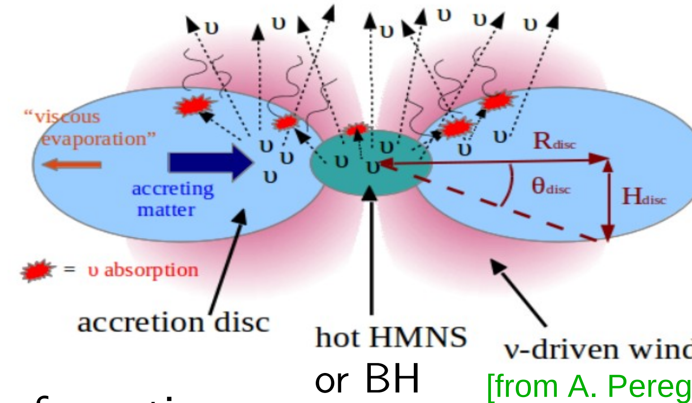
Neutrinos from the merger remnants

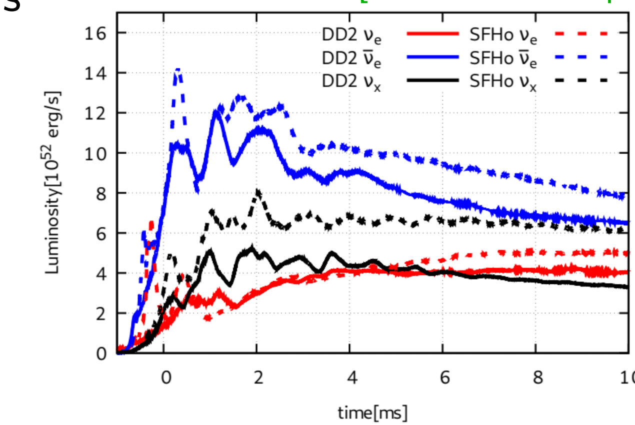


[from A. Perego]

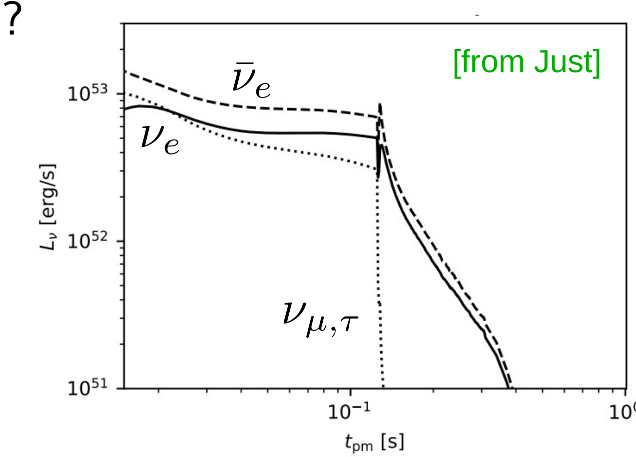
Neutrinos play key roles in:

- merger remnant dynamics
  - cooling of the hypermassive neutron star / black hole formation
  - cooling of the accretion disk / launch of the disk winds
  - driving the neutrino-driven winds
  - contributing to jet-launching?

[from Ardevol-Pulpillo]



- composition evolution
  - affecting Y_e in the remnants and in outflows ($\nu_e + n \leftrightarrow p + e^-$, $\bar{\nu}_e + p \leftrightarrow n + e^+$)
  - altering nucleosynthesis paths by ν-nucleus interaction?



→ accurate merger modeling requires solving ν transport:

$$(\partial_t + \mathbf{v}\cdot\partial_{\mathbf{x}} + \mathbf{F}\cdot\partial_{\mathbf{p}}) f_{\nu_\alpha}(\mathbf{x},\mathbf{p},t) = \mathcal{C}$$

their flavor oscillations (conversions of $\nu_e \leftrightarrow \nu_{\mu/\tau}$)?

The oscillation "problem"

Oscillations (quantum nature of ν) $\rightarrow$ density matrix $\varrho(t, \mathbf{x}, \mathbf{p}) = \begin{bmatrix} f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho^*_{e\mu} & f_{\nu_\mu} & \varrho_{\mu\tau} \\ \varrho^*_{e\tau} & \varrho^*_{\mu\tau} & f_{\nu_\tau} \end{bmatrix}$

$\rightarrow$ requires solving (at least) the neutrino quantum kinetic equation (νQKE):

sourced by medium correction to neutrino's dispersion relation

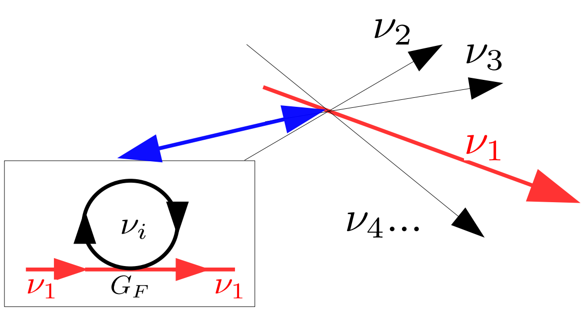
$$(\partial_t + \mathbf{v} \cdot \partial_\mathbf{x} + \mathbf{F} \cdot \partial_\mathbf{p})\varrho(\mathbf{x}, \mathbf{p}, t) = -i[\underbrace{H_{\text{vac}} + \overbrace{H_{\text{m}}}^{}}_{} + H_{\nu\nu}, \varrho(\mathbf{x}, \mathbf{p}, t)] + \mathcal{C}(\varrho)$$

function of $|\mathbf{p}|$ and n_e, no non-linearity, nearly diagonal

Neutrino-neutrino forward scattering:

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

- non-linear (depends on the integral of ρ of all momenta)
- carries strong directional dependence
- introduce a scale $L_{\text{SI}}^{-1} \sim G_F n_\nu \gg |H_{\text{vac}}|$



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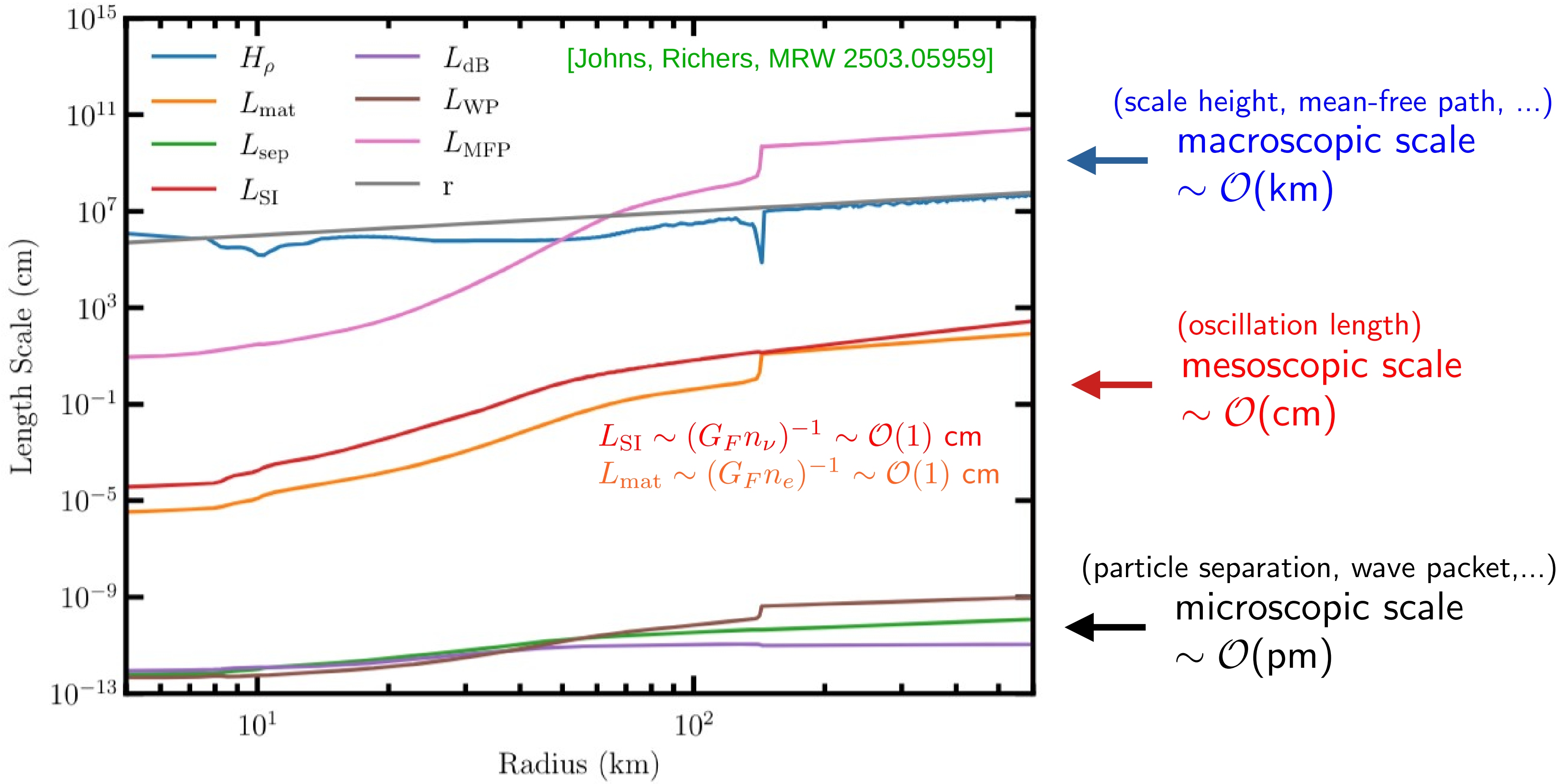


A "complete" modeling of neutrino flavor oscillations in SNe & mergers requires resolving the mesoscopic oscillations at length scale of $L_{\rm SI} \sim (\sqrt{2} G_F n_\nu)^{-1} \sim \mathcal{O}(1)$ cm

Collective neutrino flavor oscillations

Assuming $|\rho_{\alpha\beta}|/f_{\nu_\alpha} \ll 1$, linearization of the EoM allows to find the dispersion relation of collective modes:

[Banerjee+ 2011, Raffelt+ 2013, Izaguirre+ 2017...]

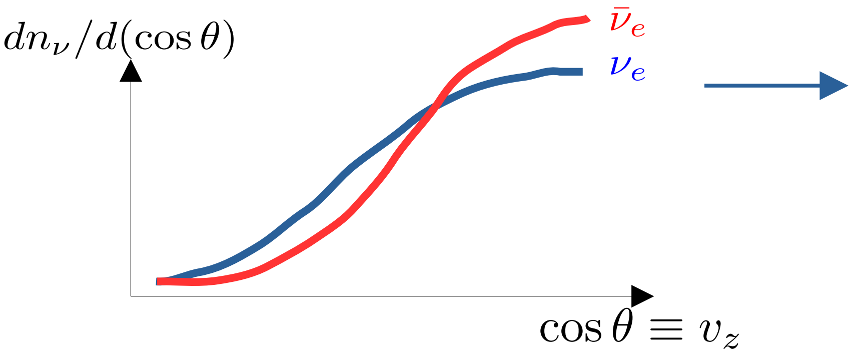
$$|\varrho_{\alpha\beta}| \propto \exp(ik^\mu x_\mu) \longrightarrow \text{EoM} \longrightarrow \mathcal{D}(\omega, \vec{k}) = 0$$

complex frequency $\leftrightarrow$ unstable collective modes

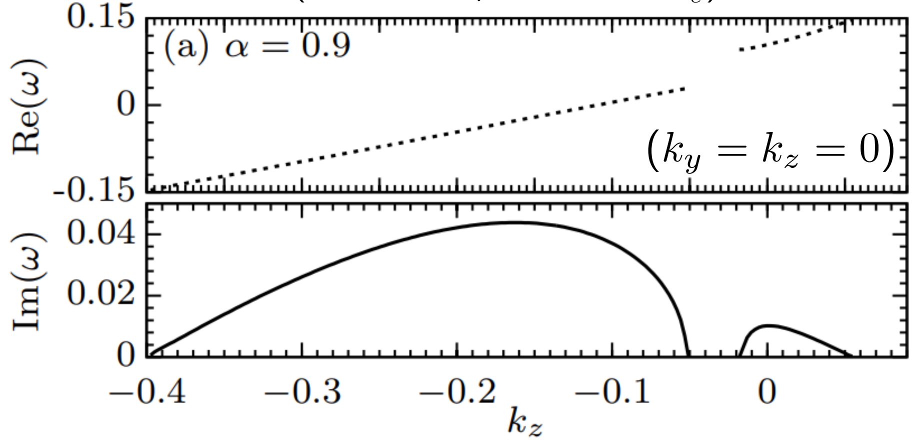
[MRW, George, Lin, Xiong 2108.09886]

An example: existence of a "crossing" in neutrino angular distributions

(fast flavor instabilities / conversions)



(in units of $\mu \equiv \sqrt{2}G_F n_{\nu_e}$)



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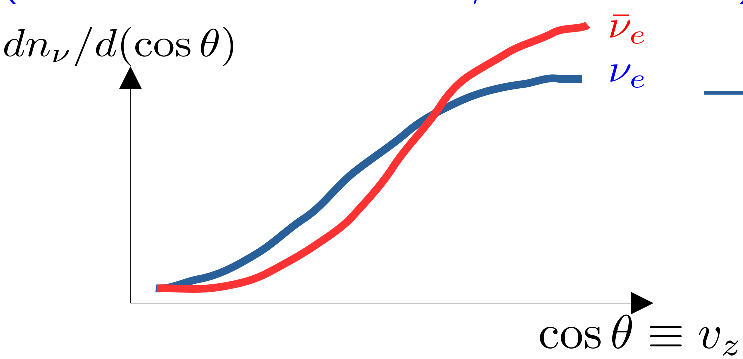

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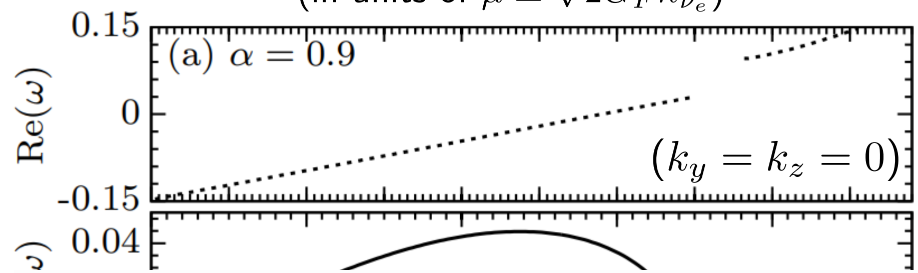
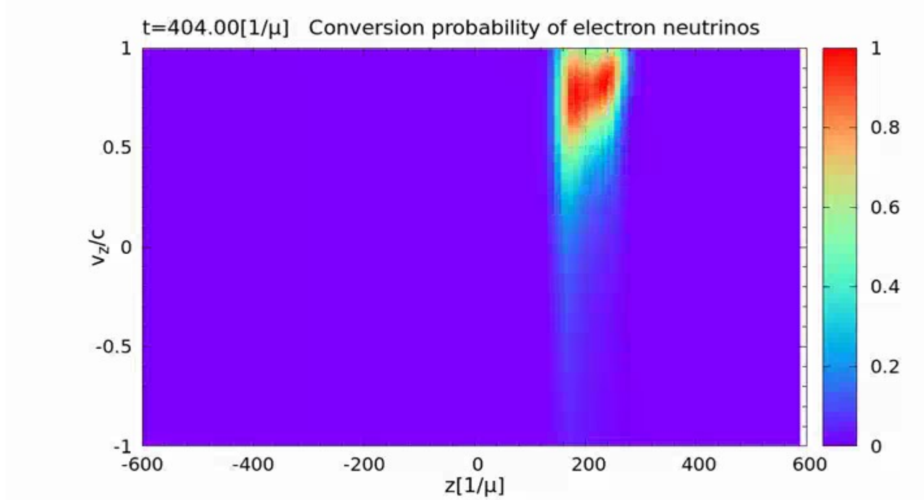




these collective unstable modes can grow in nanoseconds and lead to "flavor waves" of centimeter wavelengths (mesoscopic scale!)

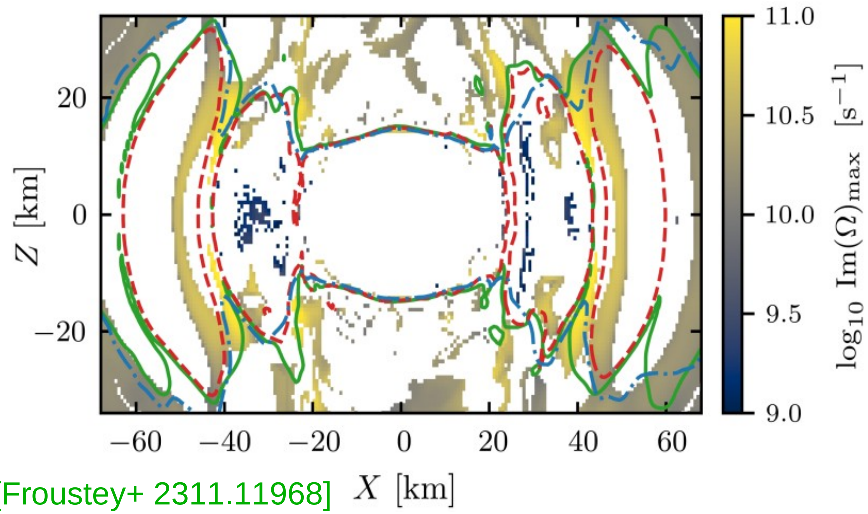
[See Fiorillo & Raffelt, 2502.06935 for the language of "flavomon" + a very nice series of papers using plasma physics approach]

Fast flavor instabilties in NSM

Analyses indicate that fast flavor instabilities exist very robustly in NSM remnants, related to their “protonization”

[MRW+, Abbar+, Richers+, Froustey+, Nagakura+,...]

dynamical phase ~ 5 ms post merger

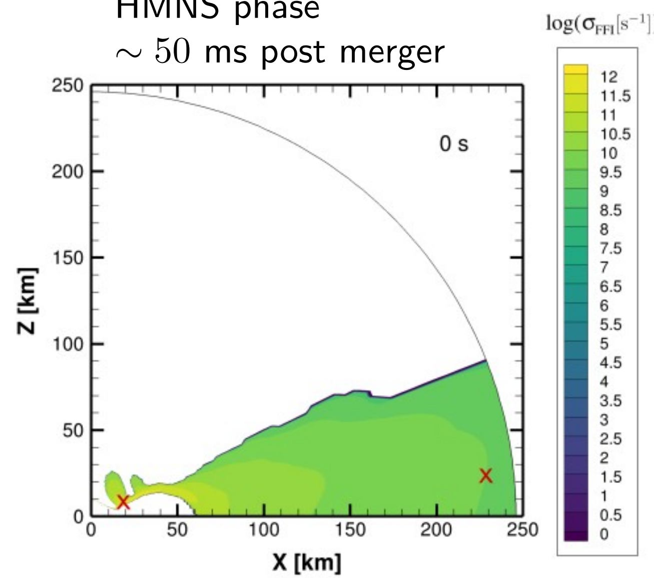


[Froustey+ 2311.11968]

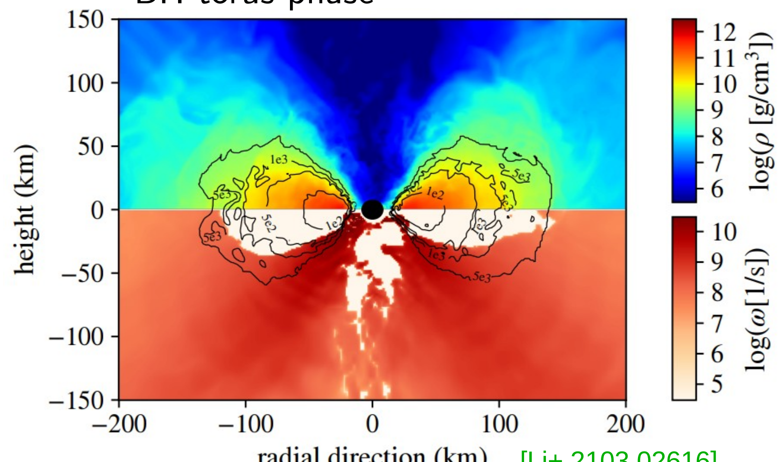
[Nagakura+ 2504.20143]

HMNS phase

~ 50 ms post merger



BH-torus phase



[Li+ 2103.02616]

instability growth rate $\gtrsim \mathcal{O}(10^9)$ s^{-1}

$\rightarrow$ expects very rapid flavor conversions

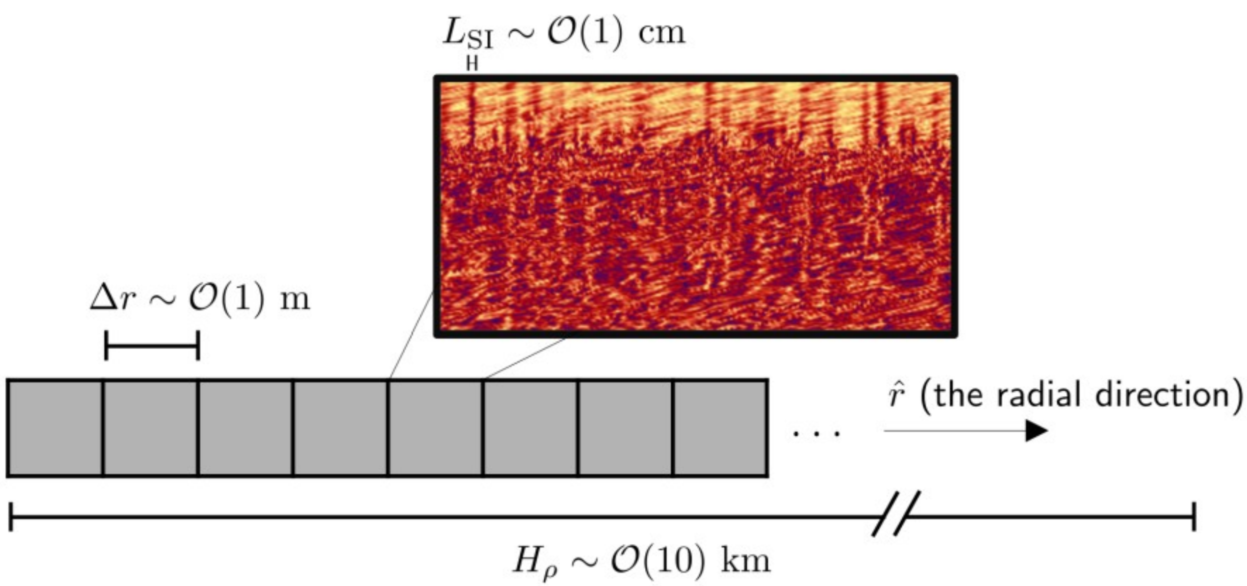
what is the outcome of flavor conversion?

what are the possible impacts?

Approaches to resolve the “oscillation problem”

Q: Obviously it’s not possible to directly solve the νQKE in SN or NSM simulations, can one construct surrogate models that incorporate oscillation physics in a satisfactory way?

$\rightarrow$ likely will involve the development of **subgrid-scale** models.



Local quasi-equilibrium state of fast flavor conversion

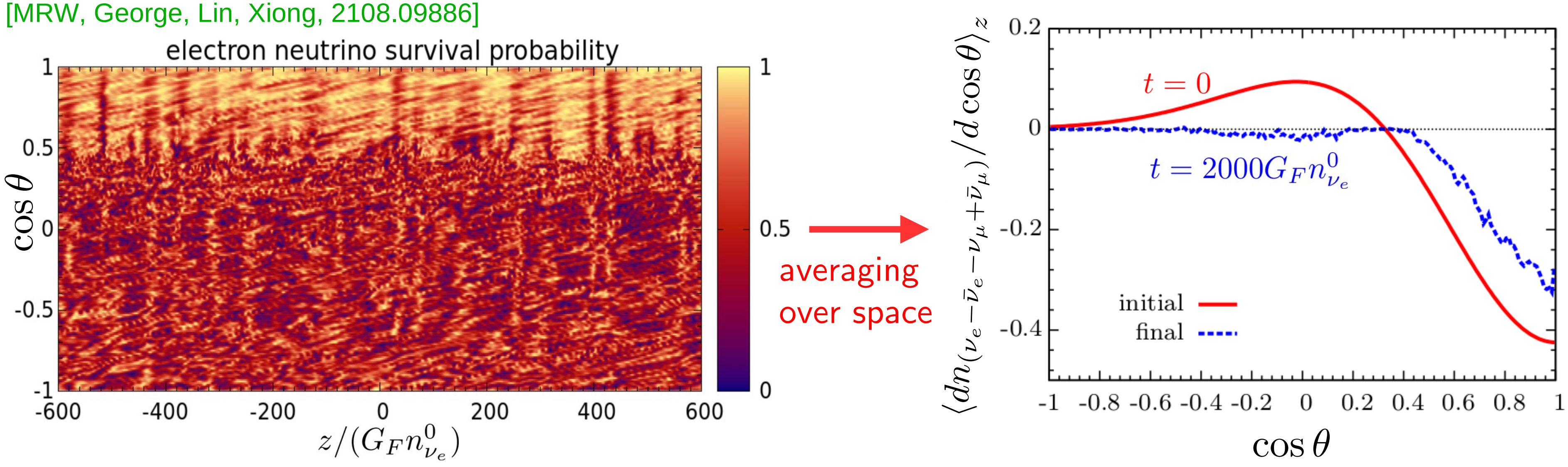
Simulations of fast flavor conversions in "local" periodic boxes found:

[see also Bhattacharyya+, Richers+, Nagakura+, Cornelius+, Delfan Azari+, ...]

nonlinear flavor wave interaction
$\rightarrow$ kinematic decoherence
$\rightarrow$ coarse-grained equilibrium
$\rightarrow$ near flavor equipartition in one side of the angular domain

$$\langle \frac{dn_{\nu_e}}{d\cos\theta} \rangle_z \simeq \langle \frac{dn_{\nu_\mu}}{d\cos\theta} \rangle_z, \ \langle \frac{dn_{\bar\nu_e}}{d\cos\theta} \rangle_z \simeq \langle \frac{dn_{\bar\nu_\mu}}{d\cos\theta} \rangle_z \text{ for } \cos\theta \lesssim 0.35$$

[MRW, George, Lin, Xiong, 2108.09886]



The form of the quasi-equilibrium state can be approximately parametrized by analytical formulas that map the initial $\langle f^0_{\nu_\alpha} \rangle$ to $\langle f^{\rm eq}_{\nu_\alpha} \rangle$

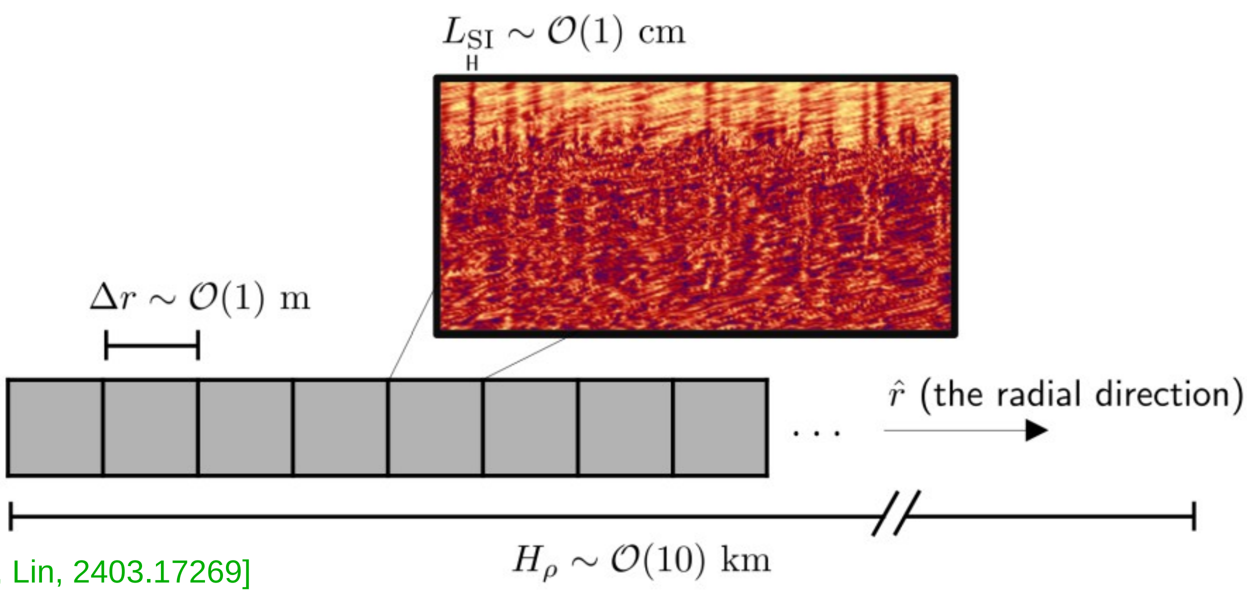
Sub-grid model for fast flavor conversions

- Full νQKE: solves $(\partial_t + v_r\partial_r + \frac{1-v_r^2}{r}\partial_{v_r})\varrho_\nu = -i[H_{\rm vac} + H_{\rm m} + H_{\nu\nu}, \varrho_\nu] + \mathcal{C}$

$$H_{\nu\nu}(\mathbf{x},\mathbf{p},t) = \frac{\sqrt{2}G_F}{(2\pi)^3}\int d^3q(1-\hat{\mathbf{p}}\cdot\hat{\mathbf{q}})[\varrho - \bar{\varrho}^*], \quad \varrho(t,\mathbf{x},\mathbf{p}) = \begin{bmatrix} f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho^*_{e\mu} & f_{\nu_\mu} & \varrho_{\mu\tau} \\ \varrho^*_{e\tau} & \varrho^*_{\mu\tau} & f_{\nu_\tau} \end{bmatrix}$$

- Effective transport: solves $(\partial_t + v_r\partial_r + \frac{1-v_r^2}{r}\partial_{v_r})f_\nu = \mathcal{C}$ with:

  f_ν replaced by $f_\nu^{\rm eq}$ computed using the analytical formula at each time and location where $e-\mu$ crossing is found



[Xiong, MRW, George, Lin, 2403.17269]

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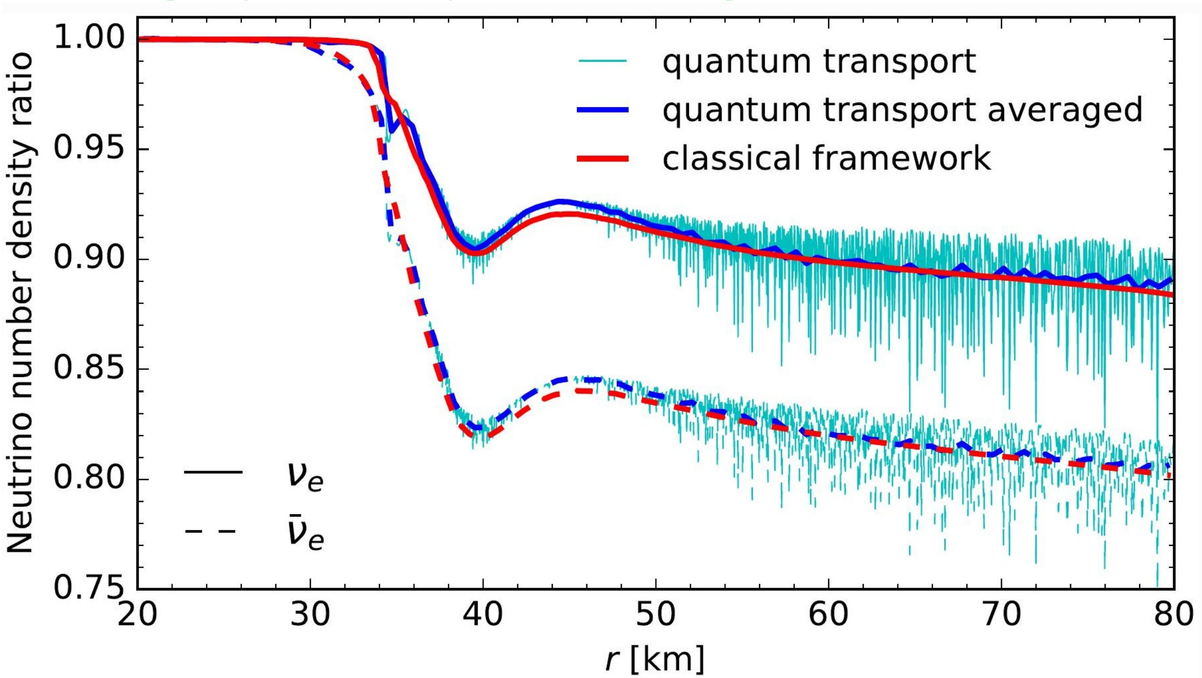


if one keeps the full ν angular information in transport, FFC may be treated rather well by subgrid models

Impact of fast flavor conversions?

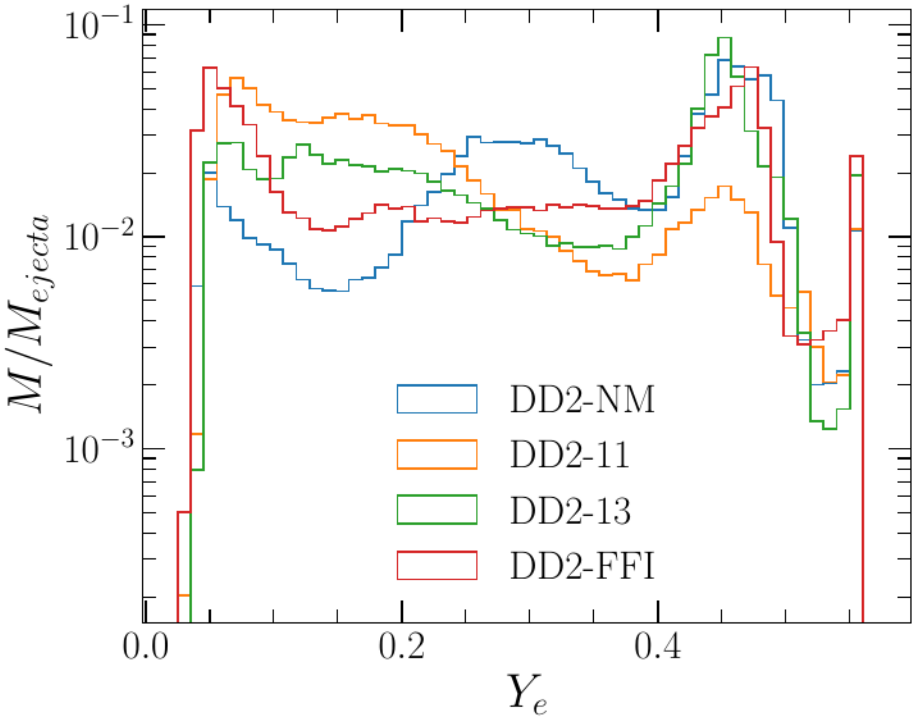
No merger simulations can keep full ν angular distributions

$\rightarrow$ various simplified treatments to investigate the potential impact of FFCs

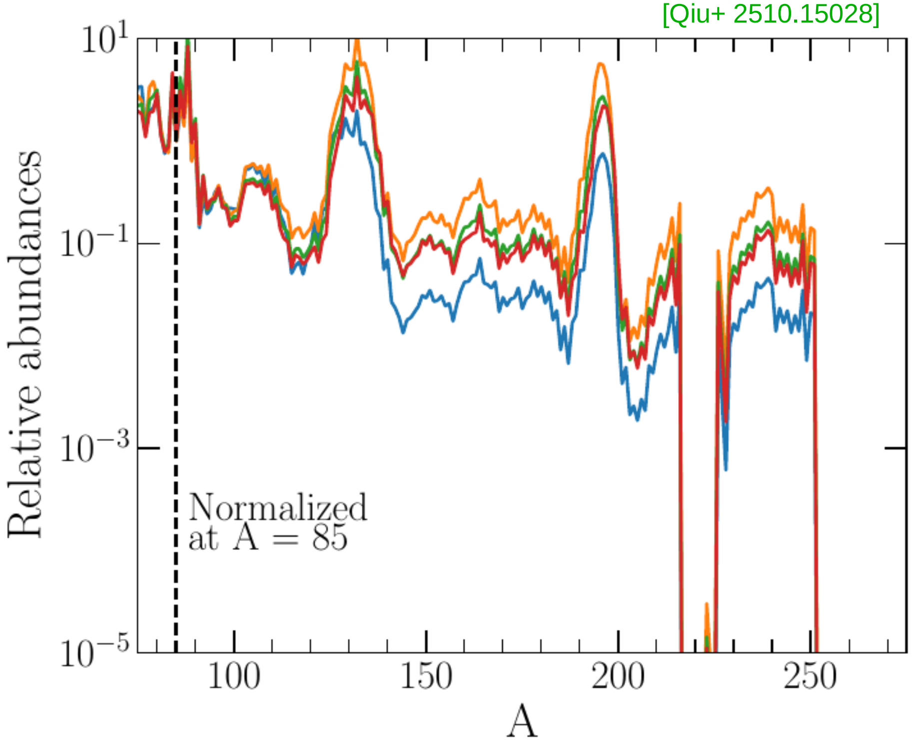
(density/flux factor/optical depth threshold, supercell averaging, ...)

[MRW+, Li+, Just+, Fernandez+, Lund+, Qiu+, ...]

dynamical ejecta (up to 35 ms)



[Qiu+ 2510.15028]



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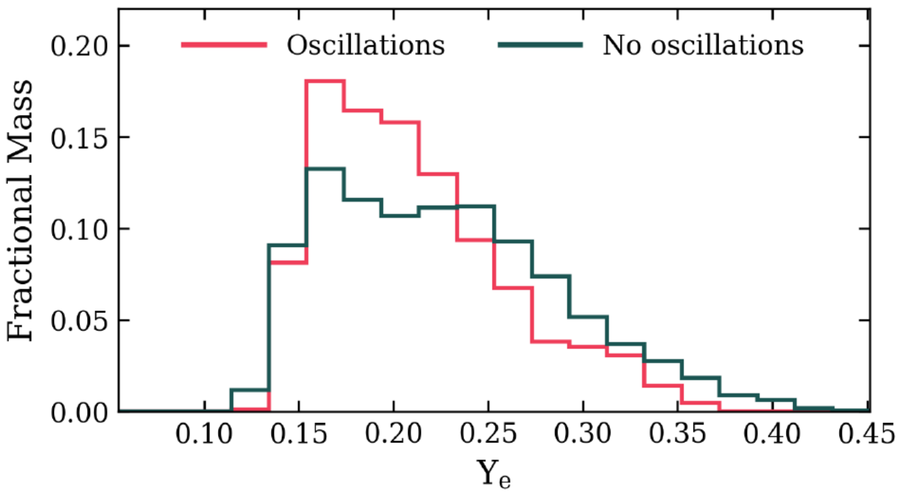
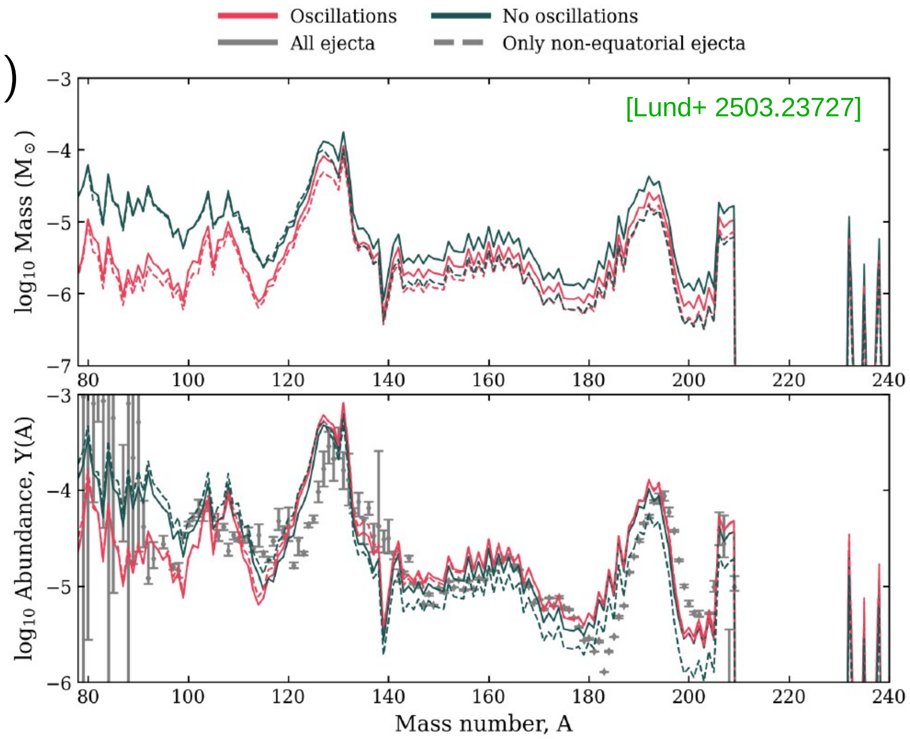
[MRW+, Li+, Just+, Fernandez+, Lund+, Qiu+, ...]

early BH-disk ejecta (GRMHD+MC transport)





general finding:

– relatively enhanced low Y_e materials due to reduced ν_e and $\bar{\nu}_e$ exposure

– reduced outflow mass due to enhanced cooling

Challenges going forward...

- self-consistent sub-grid model for M1 scheme without full angular information?
- does strong matter density gradient affects fast flavor conversions in mergers?
- do collisional flavor instability and/or slow flavor conversions matter?
- flavor swap effect? matter-neutrino resonances? B-field?
- collective pairing/helicity oscillations?
- any “many-body” effect?

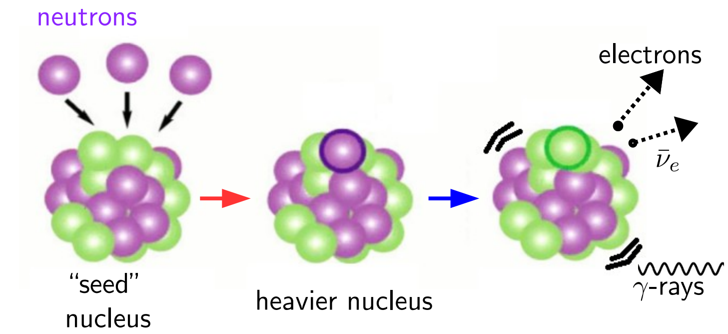
neutrinos from decay of r-process nuclei

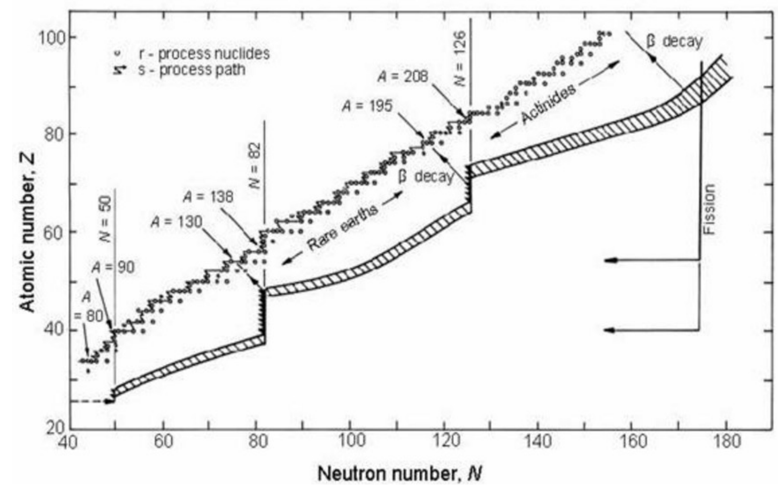
Antineutrinos from r-process nuclei?

The beta decays during and after r process naturally produce $\bar{\nu}_e$

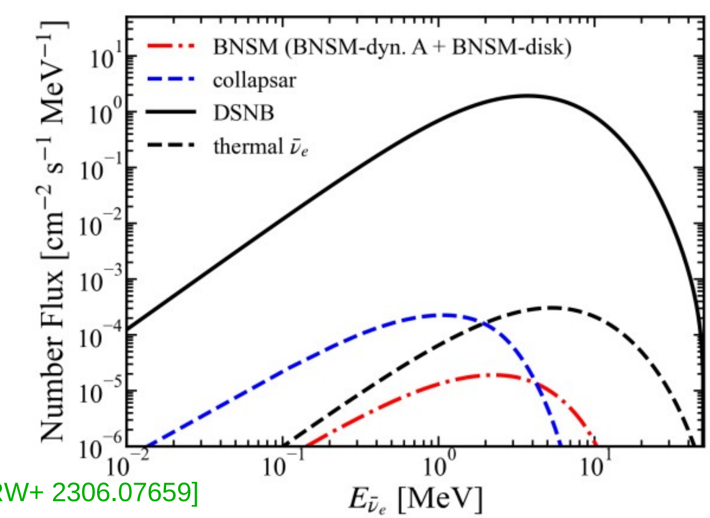
$$N_{\bar{\nu}_e} \sim 10^{55-56} \text{ for } M_{\rm ej} \sim 0.1 M_\odot$$

$$\langle E_{\bar{\nu}_e} \rangle \sim 3 - 10 \text{ MeV}$$





Unlikely for direct detection unless a merger happens within $\mathcal{O}(1)$Mpc.
The diffuse component is also buried under the diffuse supernova neutrino background



Can they affect anything else?

[An, MRW+ 2306.07659]

Annihilation of low- and high-energy neutrinos?

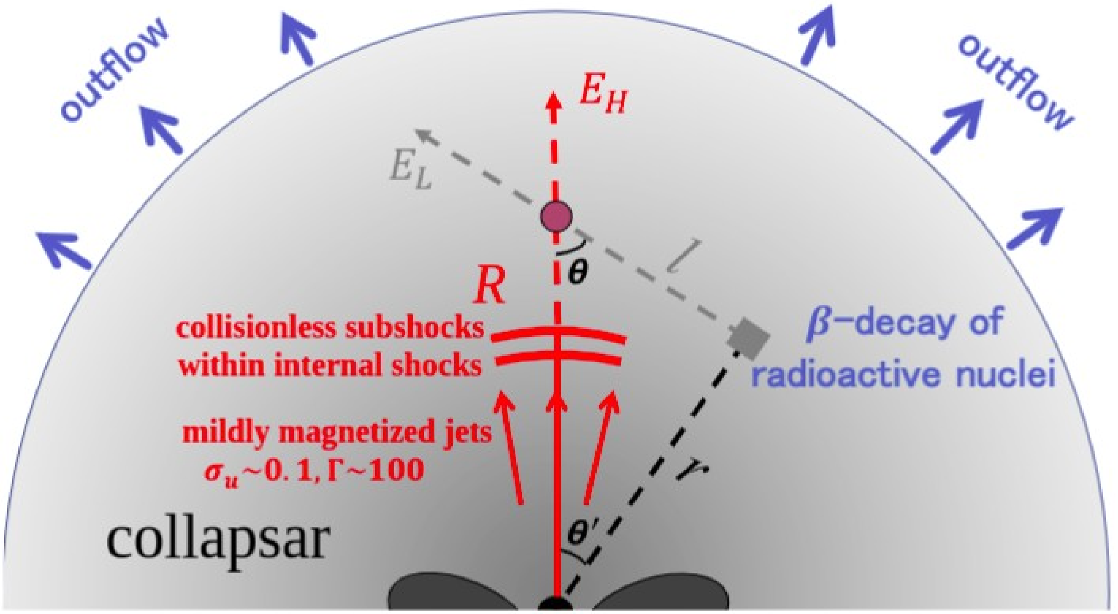
If high energy neutrinos ($E_H \sim 100 - 1000$ TeV) can be produced at $\sim 10^{10}$ cm at r-process sites, the decay $\bar{\nu}_e$ may resonantly annihilate with them

At $R \sim 10^{10}$ cm, $\quad n_{\bar{\nu},\mathrm{LE}} \sim 10^{23}\ \mathrm{cm}^{-3} \left(\frac{\dot{M}}{0.02 M_\odot/\mathrm{s}}\right)\left(\frac{0.05c}{v_{\mathrm{ej}}}\right)\left(\frac{10^{10}\ \mathrm{cm}}{R}\right)^2$

With $\sigma_{\mathrm{res}} \sim 10^{-31}$ cm^2 for $2E_H E_L \simeq m_Z^2$

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

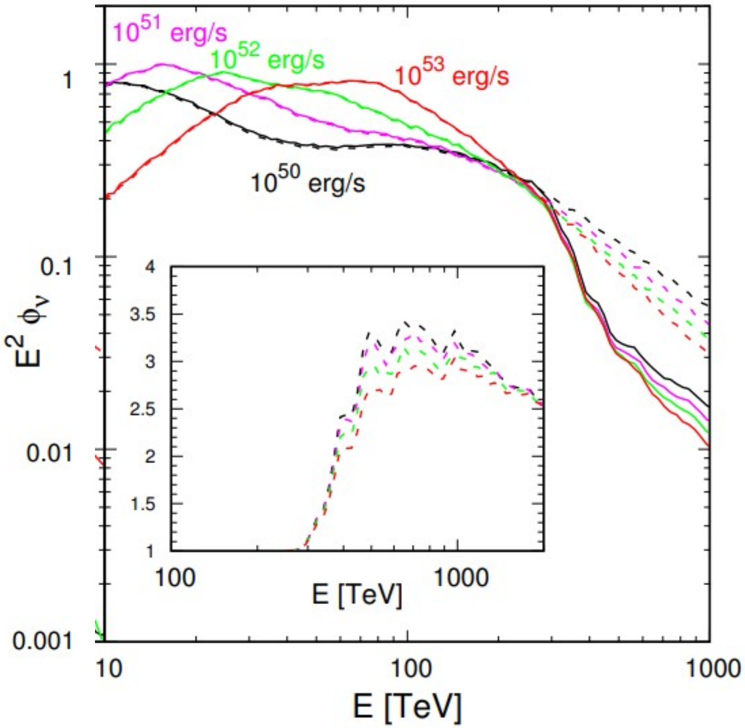
efficient annihiliation



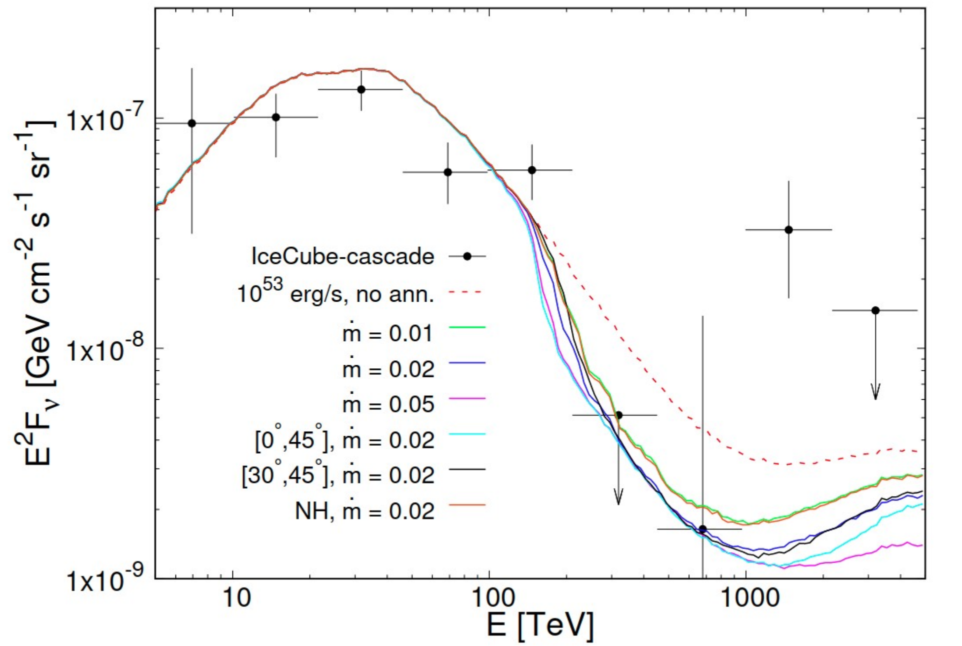
[Guo, Qian, MRW, 2212.08266]

Annihilation of low- and high-energy neutrinos?

For a wide range of jet power or different $\dot{M}_{\rm ej}$, annihilation can suppress the HEν flux substantially above $\sim 200 - 300$ TeV



[Guo, Qian, MRW, 2212.08266]

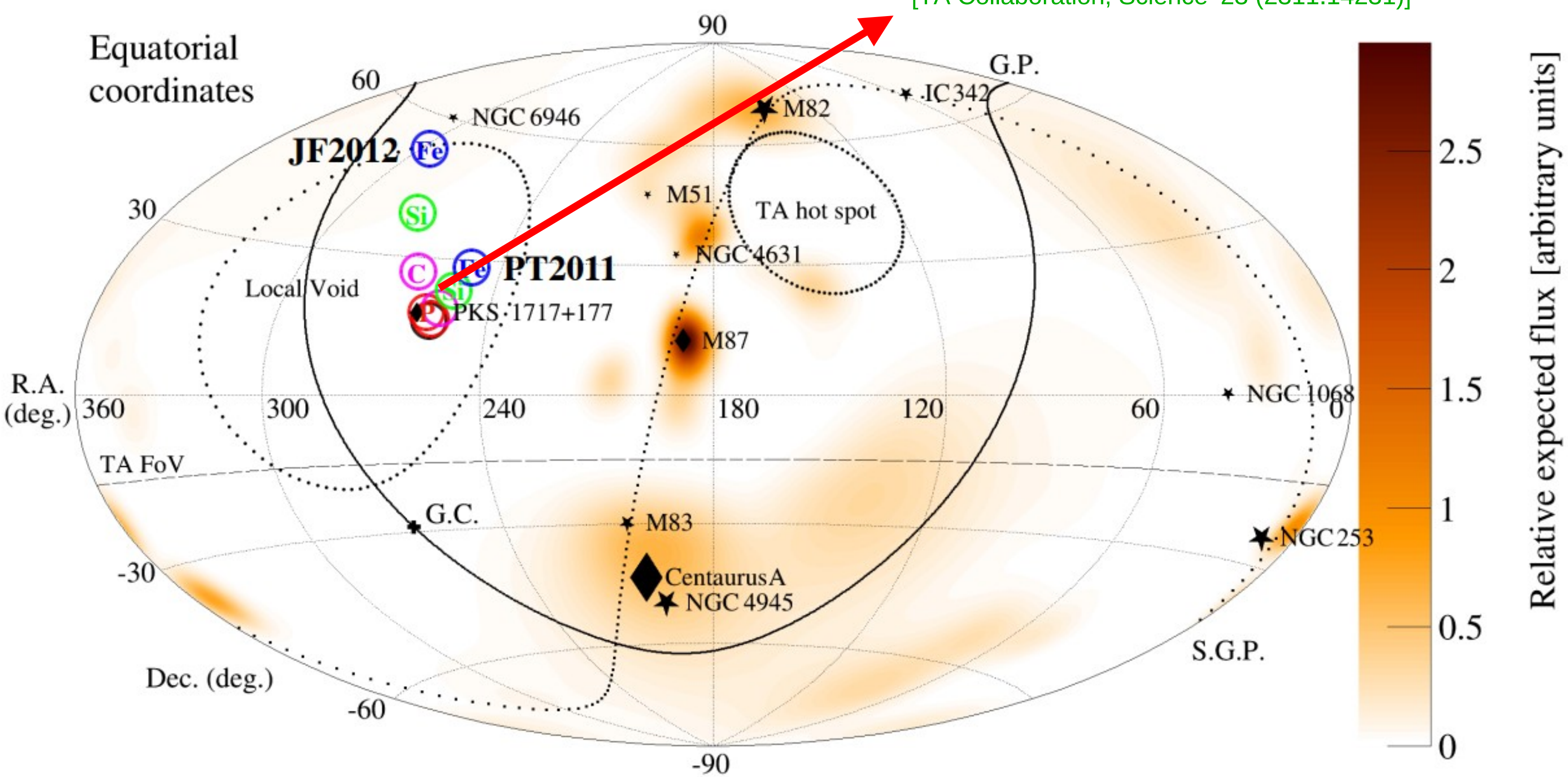


Can this be relevant for potential HE neutrino productions associated with mergers or other scenarios?

r-process nuclei as ultra-high-energy cosmic rays?

"Amaterasu" event (~ 244 EeV) by Telescope Array

[TA Collaboration, Science '23 (2311.14231)]



– produced by transient sources? [Bartos+]

– can they be nuclei heavier than iron? [Farrar, Zhang+,]

– can typical sGRB conditions allow r-process nuclei be accelerated to $\gtrsim 100$ EeV? [Guo+]

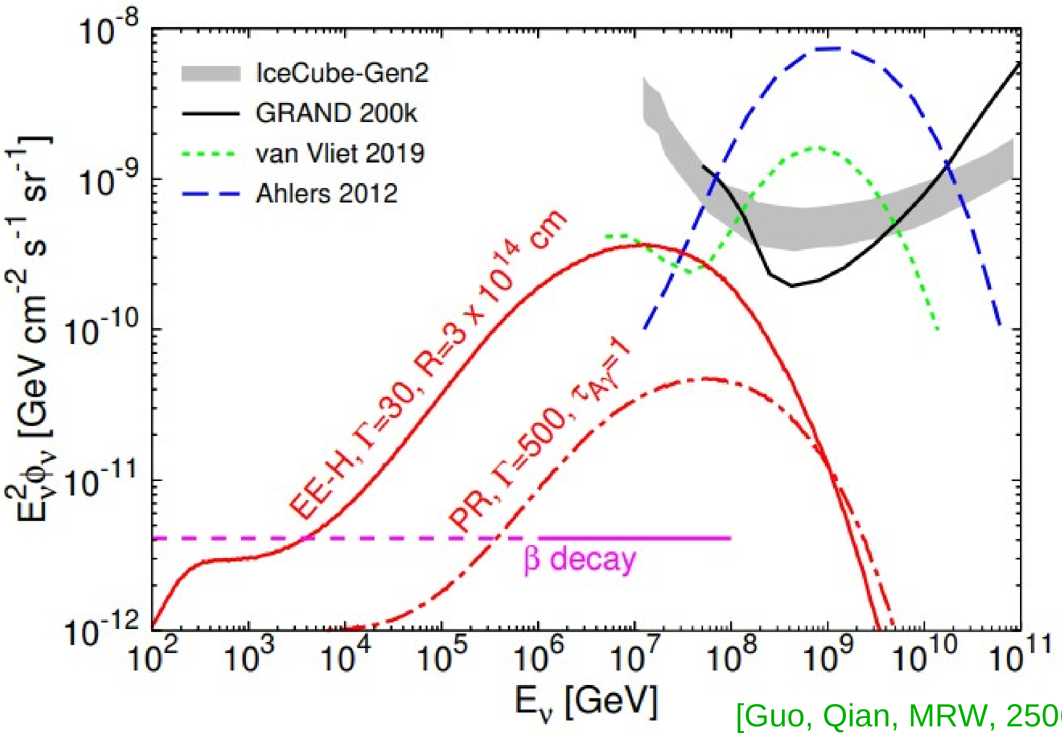
HE neutrinos from decay of UHE r-nuclei?

Taking 1) energy generation rate denisty $\sim 10^{43}$ erg/Mpc^3/yr above 100 EeV
2) sGRB rate ~ 300/Gpc^3/yr

$\rightarrow$ each sGRB produces UHE r-nuclei that carry $\sim 3 \times 10^{49}$ erg

$\rightarrow$ fix the normalization factor for UHE r-nuclei energy spectra $\frac{dN_h}{dE_h} \propto E_h^{-2}$

$\rightarrow E_\nu^2 \frac{dN_\nu}{dE_\nu} \simeq 10 \times (10^{-4}) \times E_h^2 \frac{dN_h}{dE_h}$, assuming each UHE r-nucleus produce ~ 10 decay neutrinos and each neutrino carries $E_\nu \sim 10^{-4} E_h$



[Guo, Qian, MRW, 2506.17581]

diffuse flux $\sim \mathcal{O}(10 - 100)$ below next-generation experiments

Take-home messages

- Collective fast neutrino flavor conversions (FFCs) that occur in nanosecond/centimeter scales need to be considered in accurate neutron star merger models.
- Succesful sub-grid models for FFCs utilizing the scale-separation nature are being developed and seriously tested.
- Merger simulations that approximately included FFC effects found broadly-consistent impact: reduced outflow mass with increased neutron richness.
- Direct detection of antineutrinos from the decay of r-process nuclei is unlikely, but they may leave imprints on high-energy neutrinos produced in the same site, or show up as high-energy neutrinos if ultra-high-energy neutrinos are dominated by r-process nuclei.