Neutrino flavor conversion impact on r-process nucleosynthesis from mergers

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The r-process and the nuclear EOS after LIGO-Virgo's third observing run
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Outline

- Collective fast neutrino oscillations in BH-torus simulation

  [Just, Abbar, MRW, Tamborra, Janka, Capozzi, 2203.16559]

  – collective fast oscillations

  – new implementation

  – impact on nucleosynthesis and kilonova

Collective neutrino oscillations

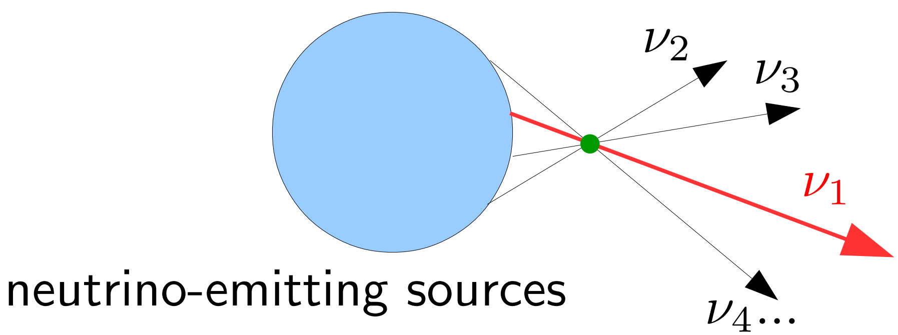
In a neutrino-dense environment, multi-dimensional quantum transport of neutrinos is needed when flavor oscillations are involved

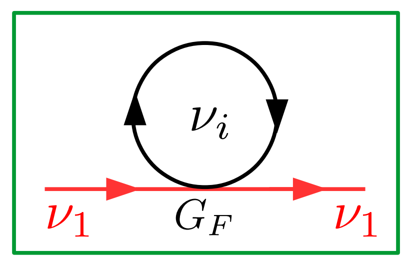
$$(\partial_t + \mathbf{v}\cdot\partial_{\mathbf{x}} + \mathbf{F}\cdot\partial_{\mathbf{p}})\varrho(\mathbf{x},\mathbf{p},t) = -i[H_{\rm vac} + H_{\rm m} + H_{\nu\nu}, \varrho(\mathbf{x},\mathbf{p},t)] + \mathcal{C}(\varrho)$$

ϱ: Wigner-transformed flavor density matrix, $= \begin{pmatrix} f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho^*_{e\mu} & f_{\nu_\mu} & \varrho_{\mu\tau} \\ \varrho^*_{e\tau} & \varrho^*_{\mu\tau} & f_{\nu_\tau} \end{pmatrix}$

$H_{\nu\nu} \sim G_F \sum_{\mathbf{p}'} (\varrho(\mathbf{x},\mathbf{p}',t) - \bar{\varrho}^*(\mathbf{x},\mathbf{p}',t))(1 - \mathbf{v}\cdot\mathbf{v}') \rightarrow$ non-linear coupling

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





$H_{\rm vac} \sim \delta m^2/(4E_\nu)$
$H_m \sim G_F n_e$

When the magnitude of elements in $H_{\nu\nu}$ dominates that of $H_{\rm vac}$, H_m, and $\mathcal{C}$, collective behavior can emerge; neutrinos with different momenta can oscillate *collectively*

[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+...]

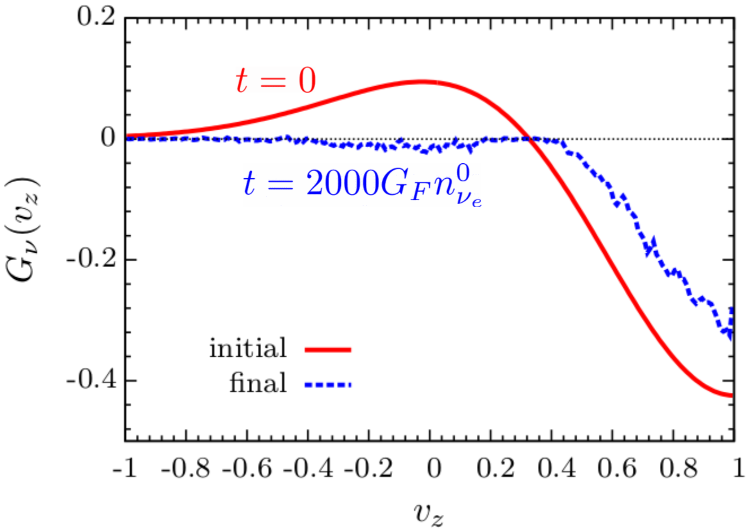
Fast collective neutrino flavor conversion

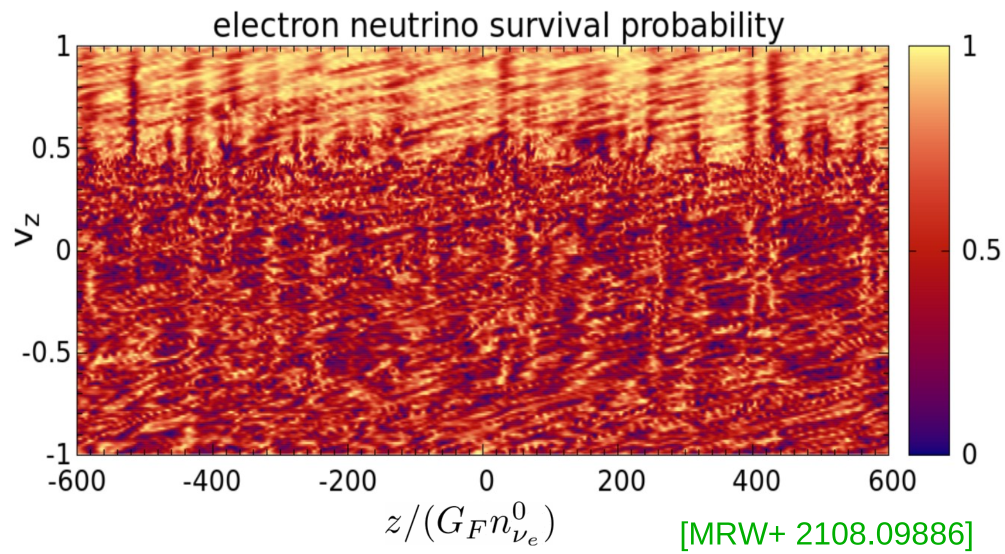
The angular crossing of electron-neutrino lepton number (ELN crossing)

(the ELN function $G^0_{\mathbf{v}_\nu} \propto \int E_\nu^2 dE_\nu [f^0_{\nu_e}(\mathbf{p}_\nu) - f^0_{\bar{\nu}_e}(\mathbf{p}_\nu)]$ has + and − values)

$\rightarrow$ flavor instability with growth rate $\sim G_F n_\nu \sim \mathcal{O}(\text{ns}^{-1})$ [Sawyer+, Izaguirre+, Dasgupta+, Morinaga+...]

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





[MRW+ 2108.09886]

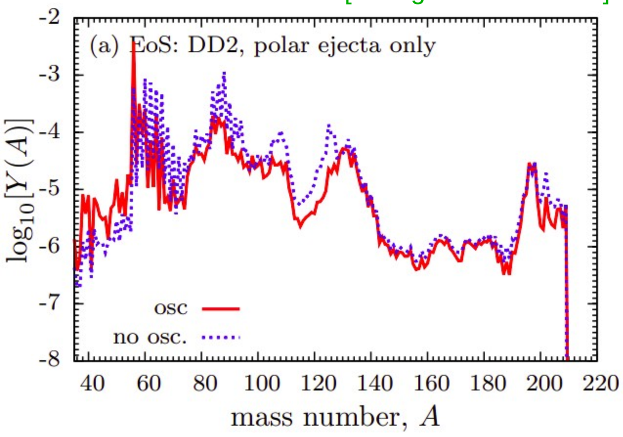
The net ELN number $= \int dV \int d^2\mathbf{v}_\nu G_{\mathbf{v}_\nu}$ is conserved with fast conversions

$\rightarrow$ the amount of converted ν_e equals that of $\bar{\nu}_e$

Earlier works on fast conversions in mergers

- MRW+ 1701.06580, MRW+1711.00477, George+2009.04046
  - – ELN crossings above artificially assumed sharp neutrino decoupling surfaces in BH–disk and early post-merger simulation data
  - – Impacts on nucleosynthesis in neutrino-driven or polar part of the ejecta

[George+ 2009.04046]



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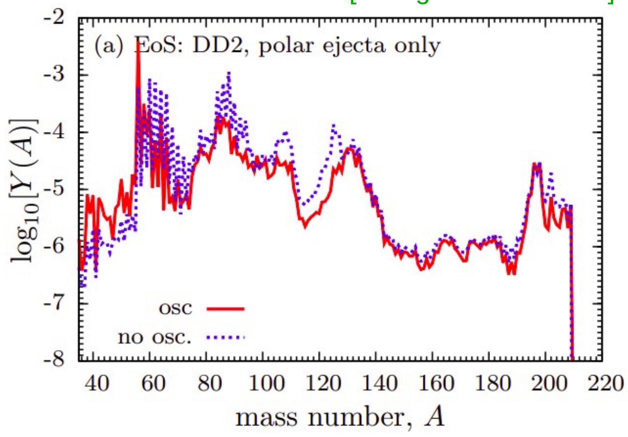
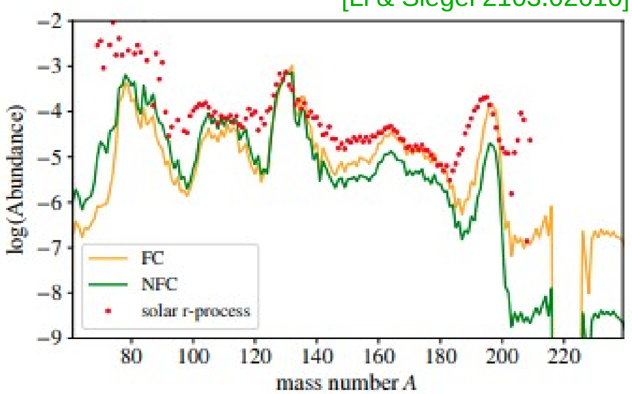


- Li & Siegel 2103.02616 *(see Xinyu Li's talk)*
  - – Identifiy flavor instability for the homogenous ($\mathbf{k} = 0$) mode directly in GRMHD simulations with M1 transport
  - – Impacts on nucleosynthesis in BH–disk ejecta launched within ~ 400 ms

[Li & Siegel 2103.02616]



Full flavor equipartition ($f_{\nu_e} = f_{\nu_\mu} = f_{\nu_\tau}$ and same for antineutrinos) after fast conversions were assumed

What's new (different) in our work

- examine BH-disk simulation data using a more general scheme searching for instabilities

for moments of ϕ-integrated ELN function

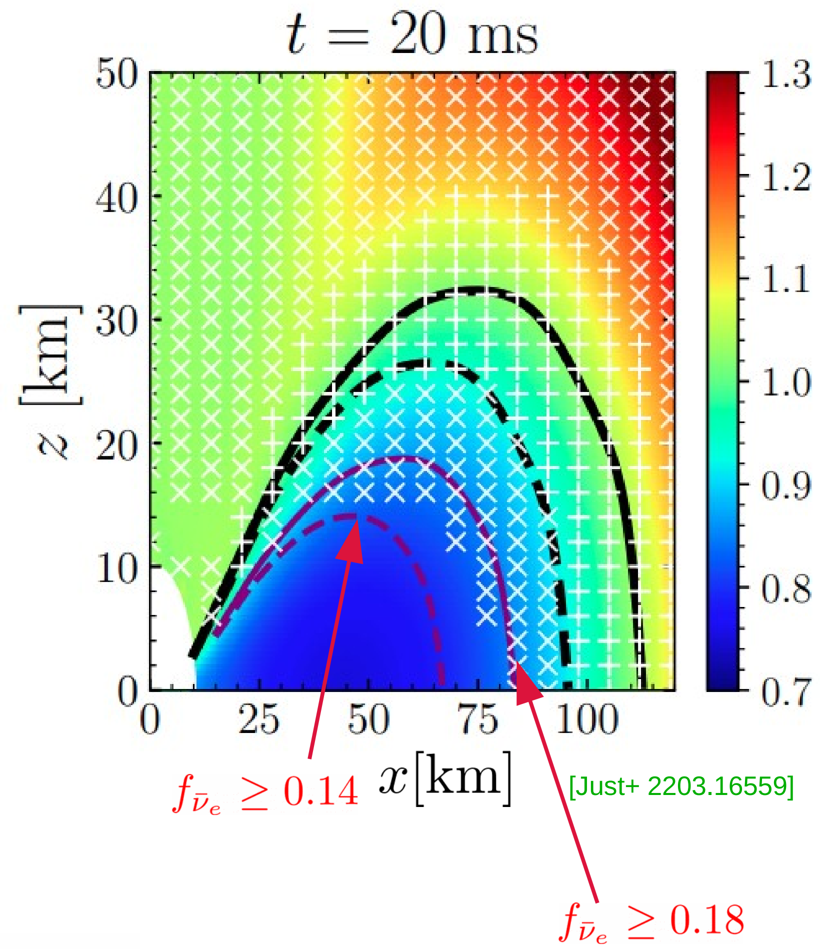
$$I_n = \int d\mu \mu^n G(\mu),\ \mu = \cos\theta$$

if there exists a $\mathcal{F}(\mu) = \sum_{n=0}^{N} a_n \mu^n > 0$,

such that $I_0 \left(\sum_{n=0}^{N} a_n I_n \right) < 0$,

$\rightarrow$ ELN crossing exists [Abbar 2003.00969]

(x: up to I_2, $+$: up to I_3)



- locations with instability can be largely covered by the criterion $f_{\bar{\nu}_e} = |\mathbf{F}_{\bar{\nu}_e}|/n_{\bar{\nu}_e} \gtrsim 0.175$

What's new (different) in our work

- explore different parametrized outcomes of flavor conversion:

  (i) mix1: conserves net ELN number for all energy bins

  (ii) mix2: $f_{\nu_e} = f_{\nu_\mu} = f_{\nu_\tau}$ and the same for antineutrinos

  (iii) mix3: $f_{\nu_e} = f_{\nu_\mu} = f_{\nu_\tau} = f_{\bar{\nu}_e} = f_{\bar{\nu}_\mu} = f_{\bar{\nu}_\tau}$

  (*) mix1f: number density same as mix1, but keep flux factors unchanged

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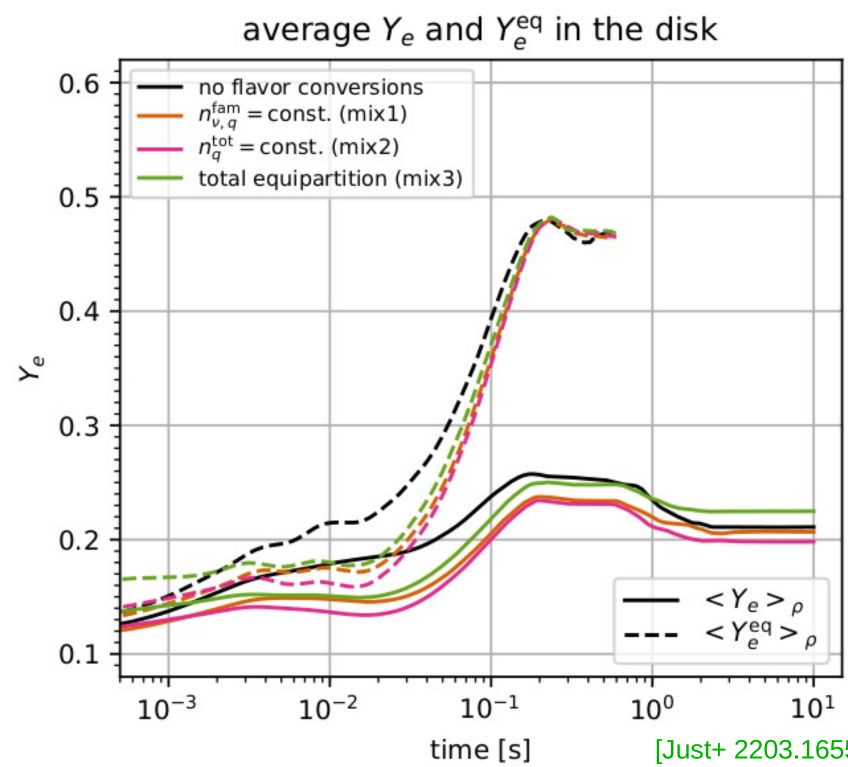
flavor oscillations lead to

- faster disk cooling & higher e^- degeneracy
- lower ν_e and $\bar{\nu}_e$ abundances

→ lower disk Y_e by $\sim 0.03 - 0.06$

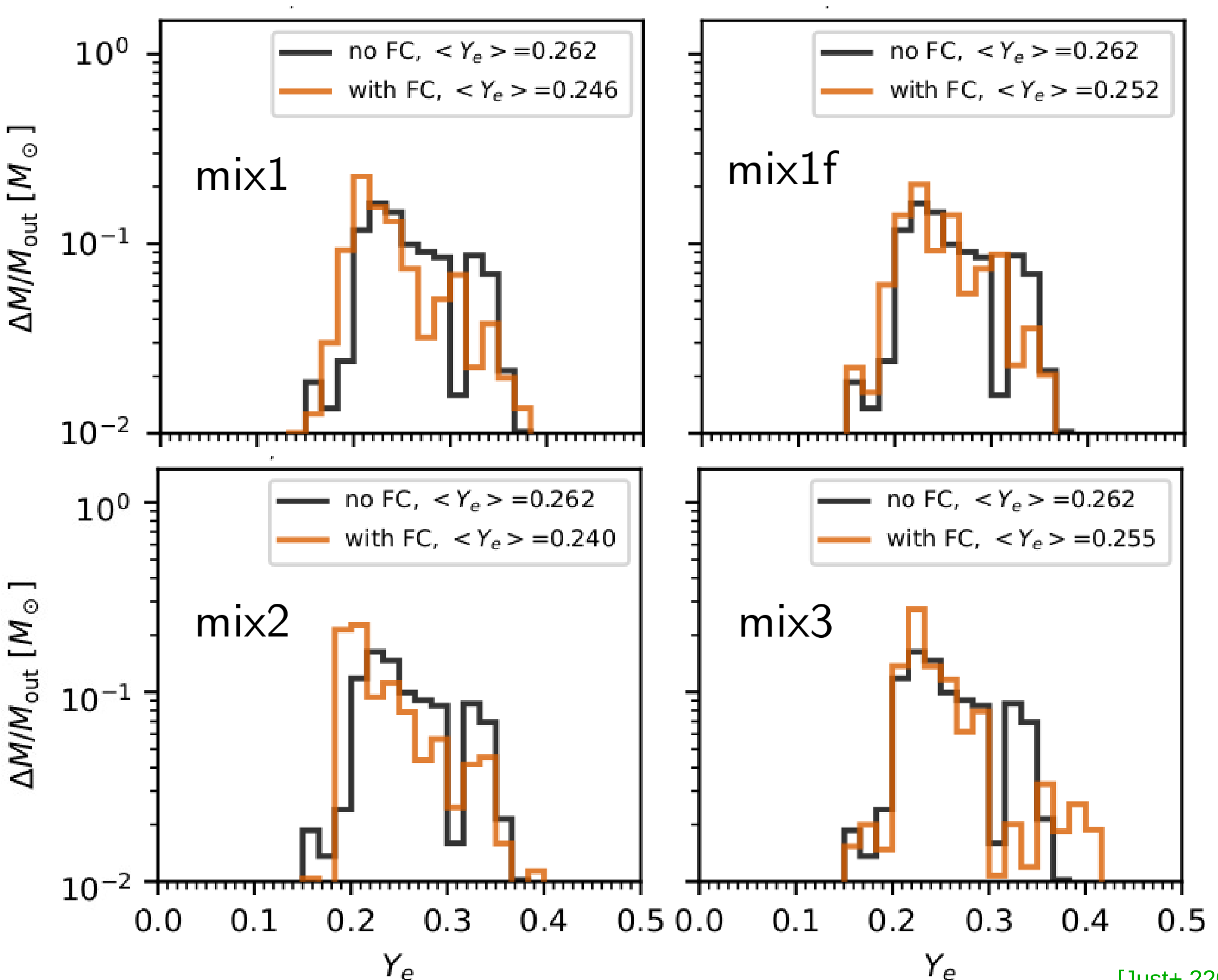
(see also Oliver Just's talk)



[Just+ 2203.16559]

Outflow Y_e distribution

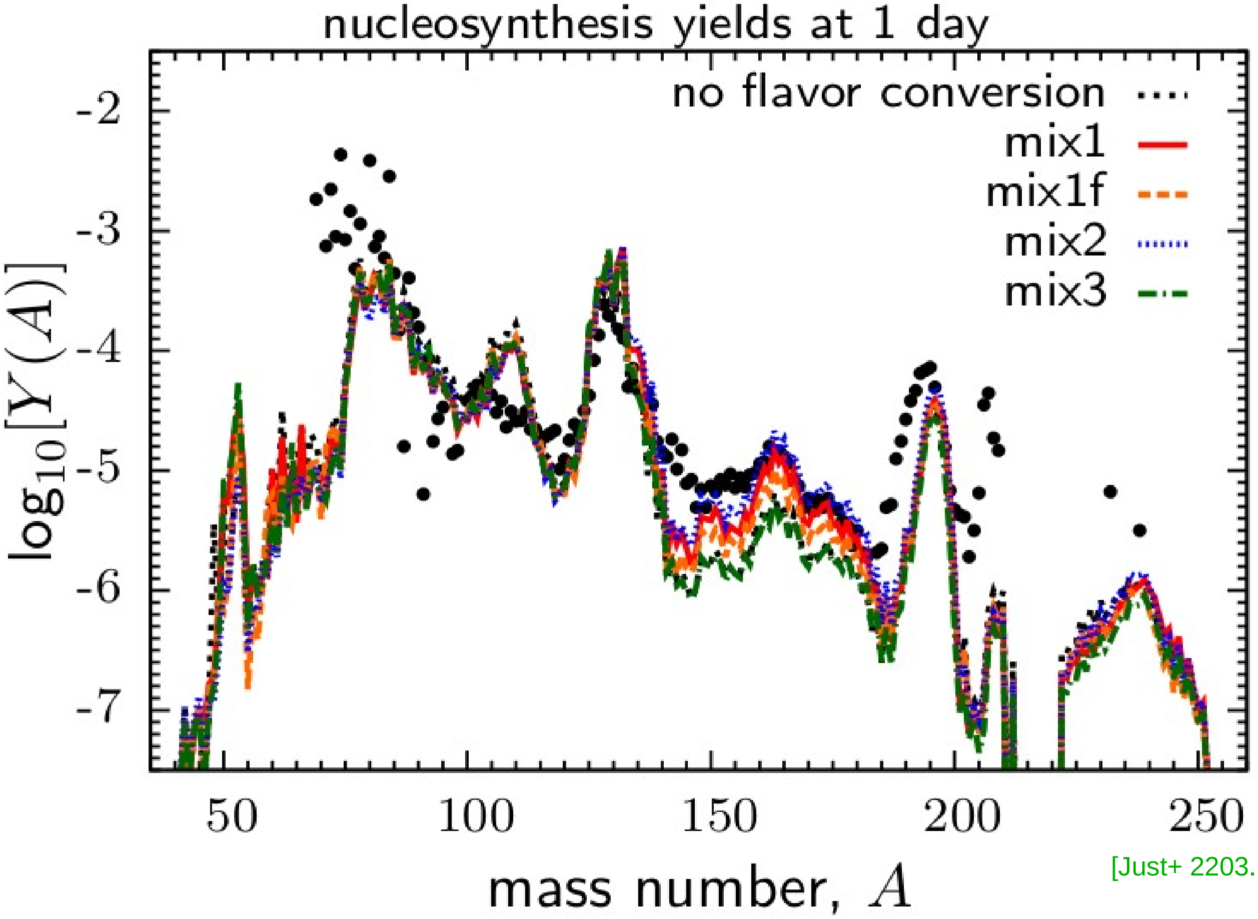
outflow Y_e reduced by $\sim 0.01 - 0.03$, ejecta mass and velocity reduced by $\sim 10\%$



[Just+ 2203.16559]

Impact on nucleosynthesis

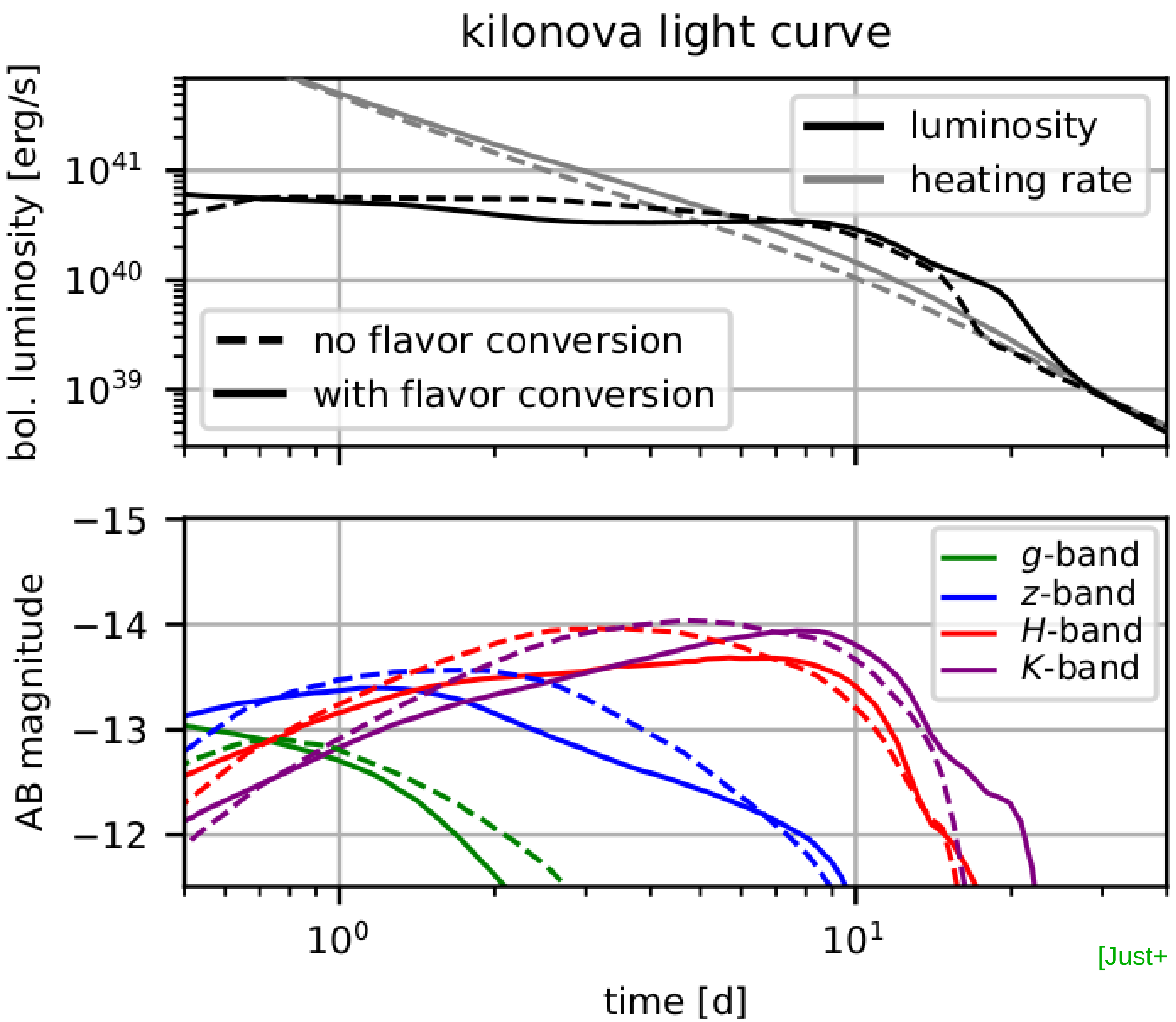
Enhance the mass fraction of lanthanides + actinides by $\sim$ a factor of $2-3$



[Just+ 2203.16559]

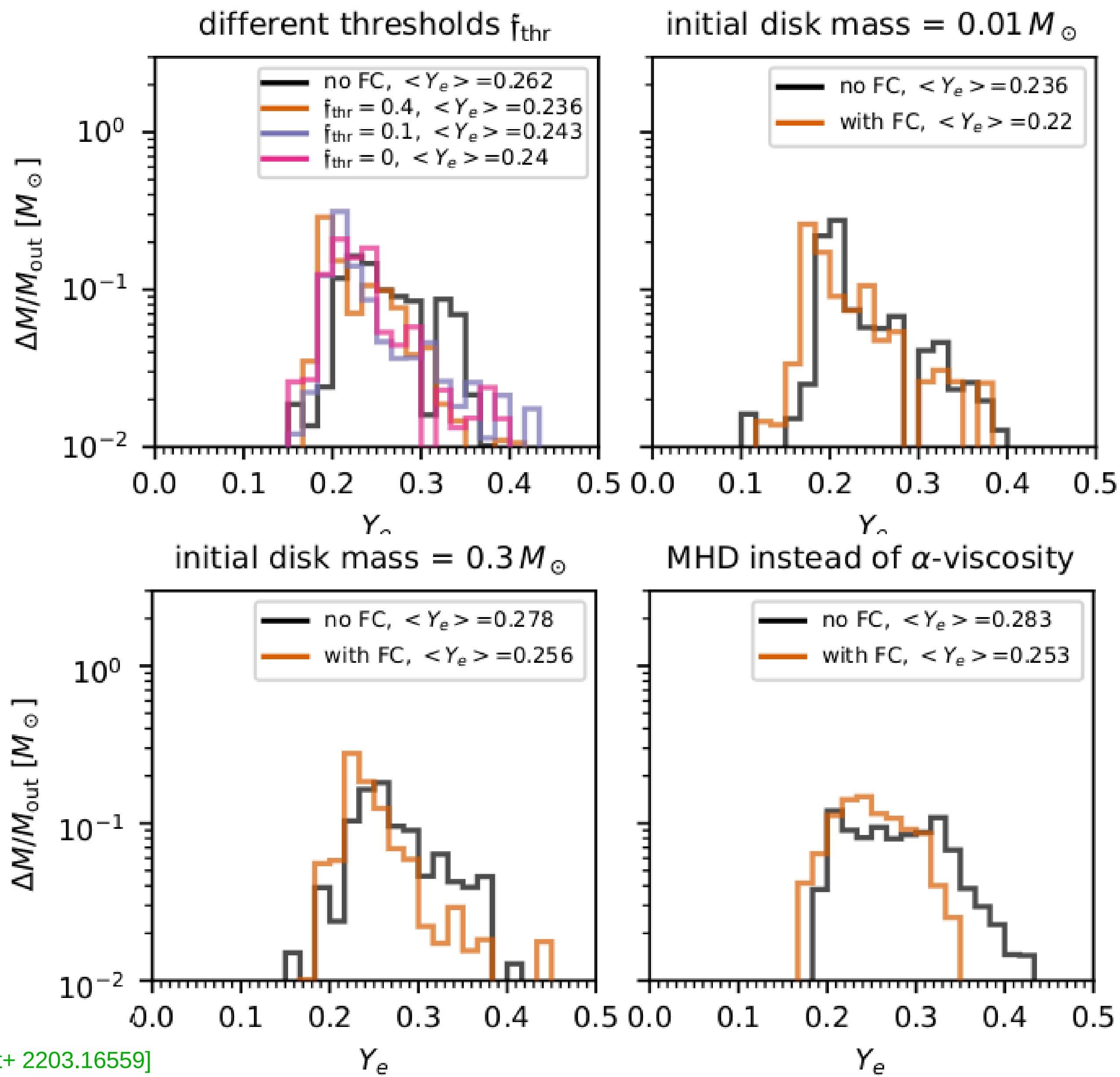
Impact on kilonova lightcurve

slightly dimmer at peak with prolonged diffusion bump due to enhanced opacity



[Just+ 2203.16559]

Model dependence



qualitatively similar results for different model parameters

[Just+ 2203.16559]

Summary

- Improved the modeling of including fast neutrino flavor conversions in BH–disk simulations

- some non-negligible impact on disk cooling and composition, neutrino emission, and ejecta Y_e

- lanthanide and actinide mass fraction affected by a factor of $2 - 3$, leading to changes in kilonova lightcurves