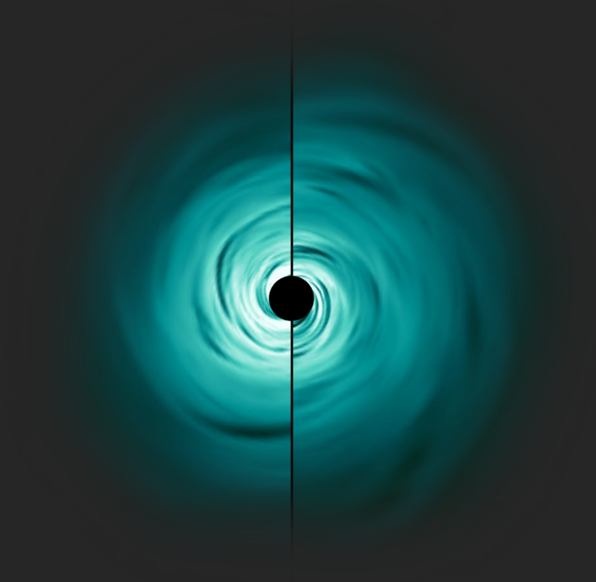
Neutrino Oscillations in Post-Merger Disks



Kelsey Lund

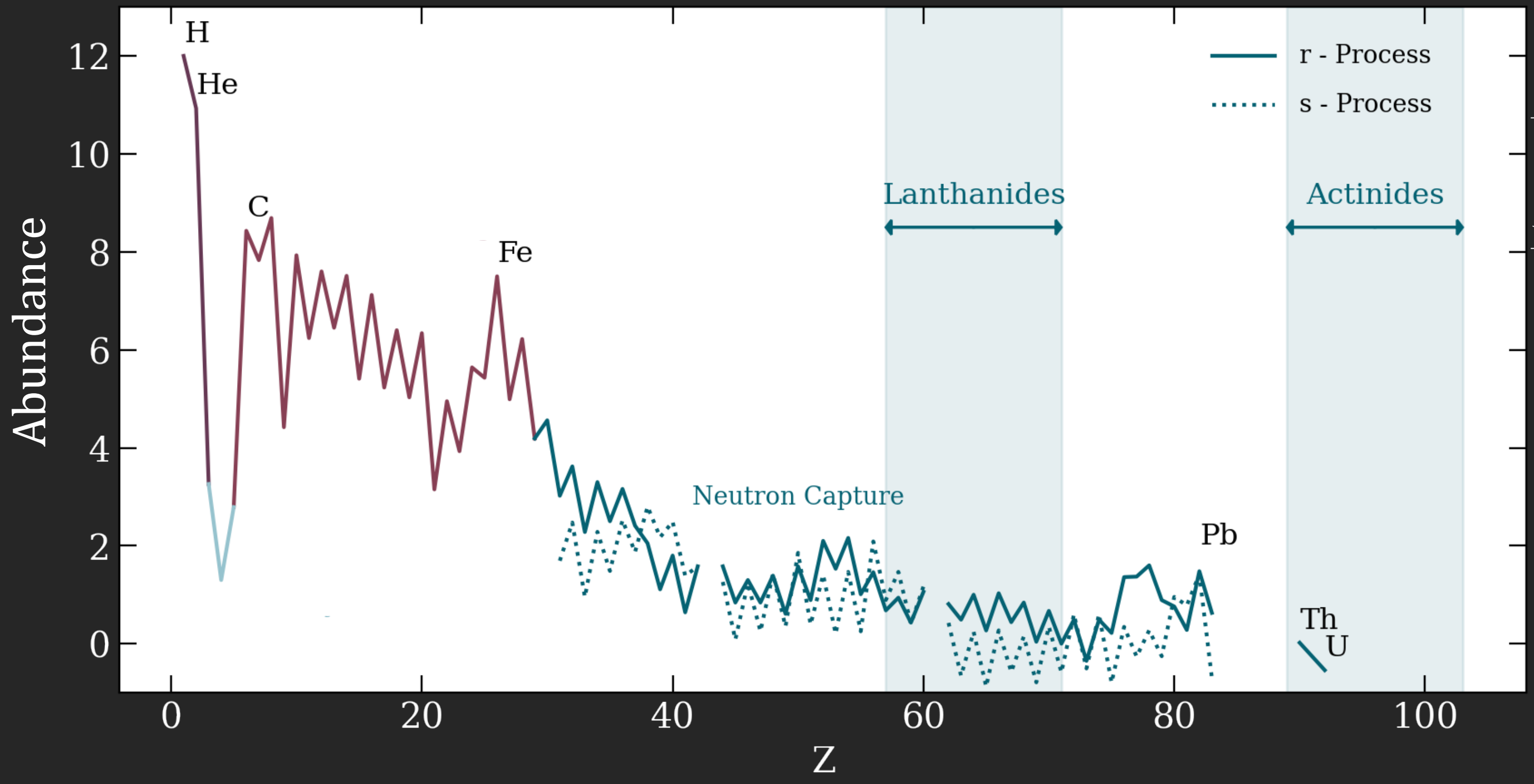
with Payel Mukhopadhyay, Jonah Miller, Gail McLaughlin

Nuclei in the Cosmos XVIII

19 · June · 2025with

A Big Question

Where can we find the conditions that facilitate the r-process?



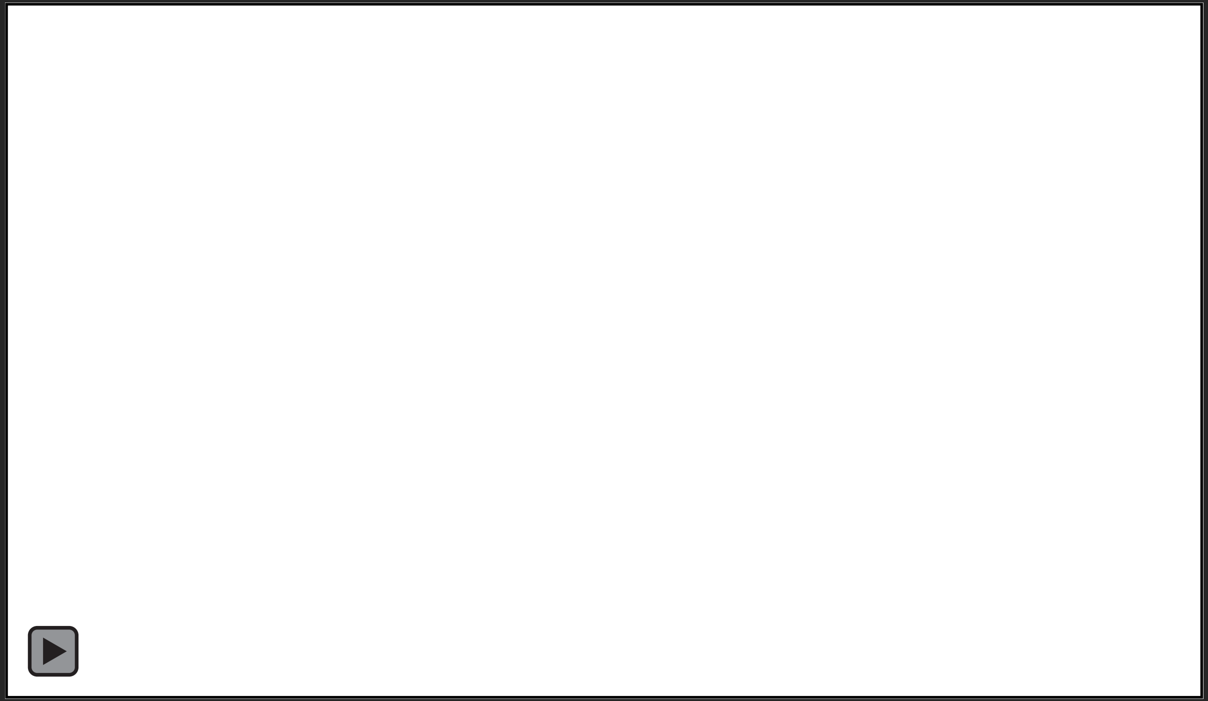
An inventory of the elements in the Solar System

Data from Asplund+ 2009, r-process residuals from Arlandini+ 1999

The synthesis of the heaviest elements is facilitated largely by a large number of free neutrons: Y_e is a key value!

Why mergers?

The merging of two neutron stars, as well as the aftermath, harbor conditions friendly to the r-process.



Timelapse of kilonova imaging (L) and spectra (R)

ESO/E. Pian/S. Smartt & ePESSTO/N. Tanvir/VIN-ROUGE

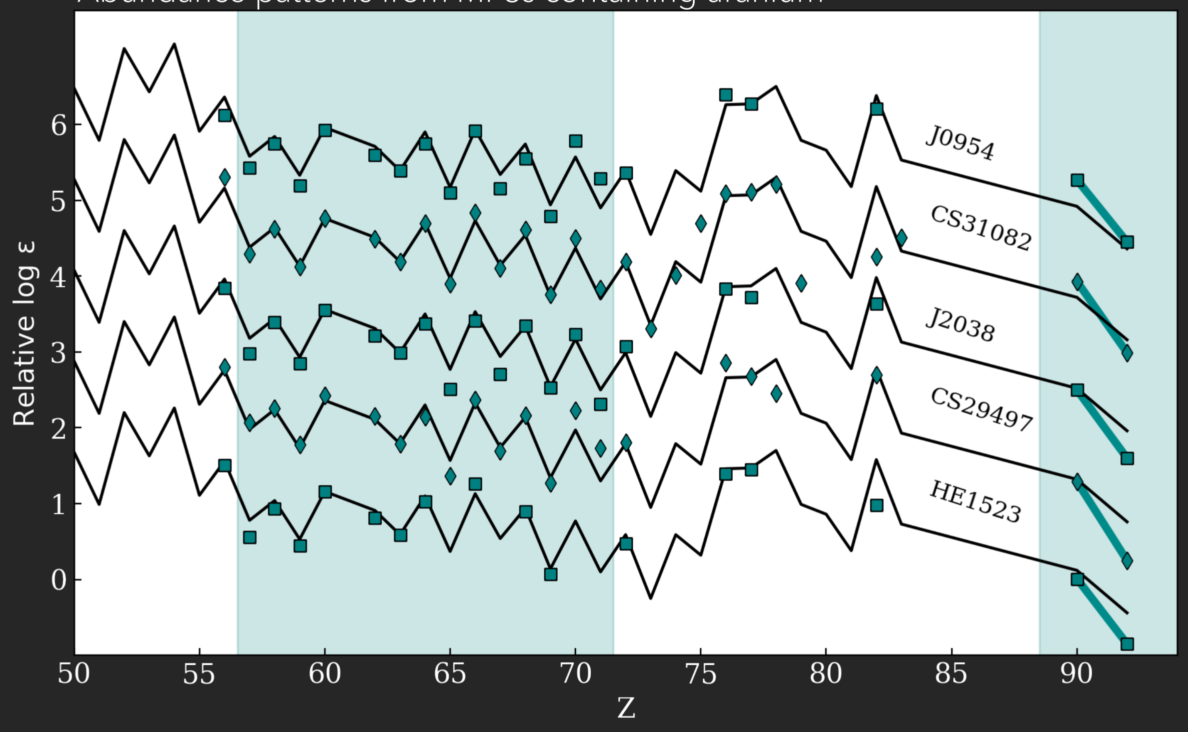
Late-time, long-wavelength electromagnetic signal indicates lanthanide production and decay in merger ejecta

Metal Poor Stars as Probes of r-Process

Metal poor, r-process enhanced stars:

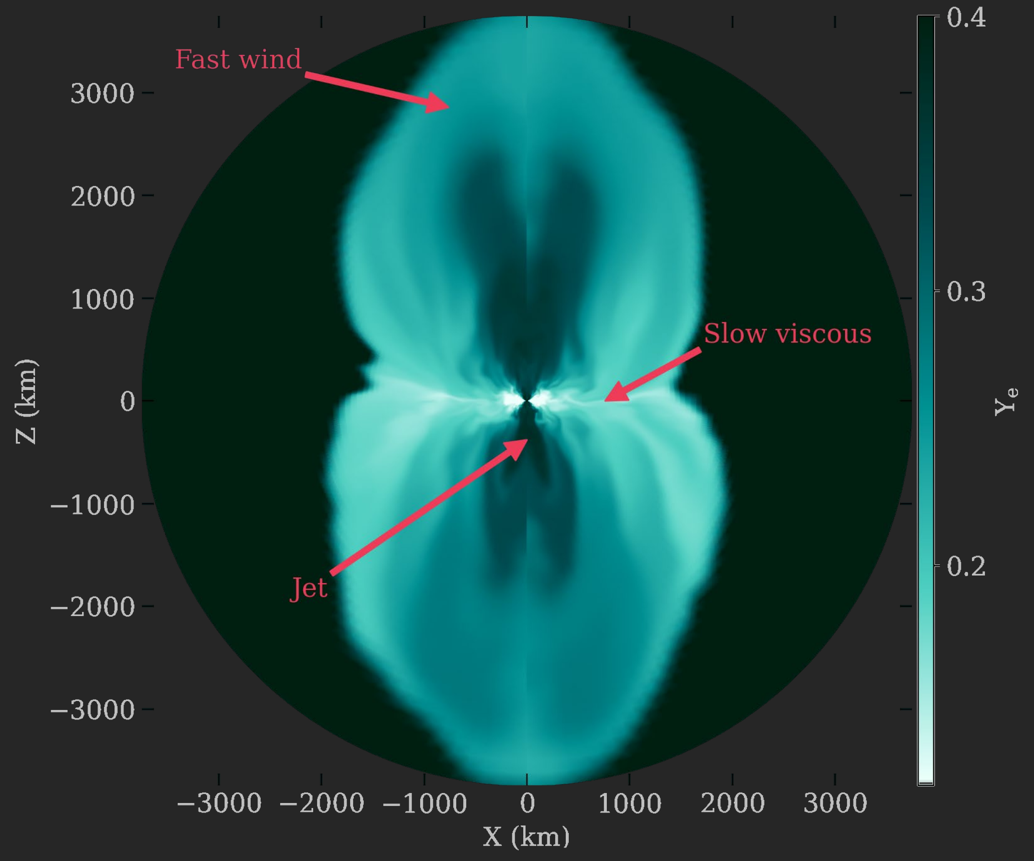
- Enriched by few r-process producing events
- Probe wider range of elemental abundance patterns (compared to transient observations)

Abundance patterns from MPSs containing uranium



Post-Merger Disks as r-Process Sites

Sprouse, **KAL**, Miller + 2024: 2309.07966



Magnetically driven accretion disk forms *after* the two neutron stars merge

Variety of conditions in different "sites" within post-merger remnant:

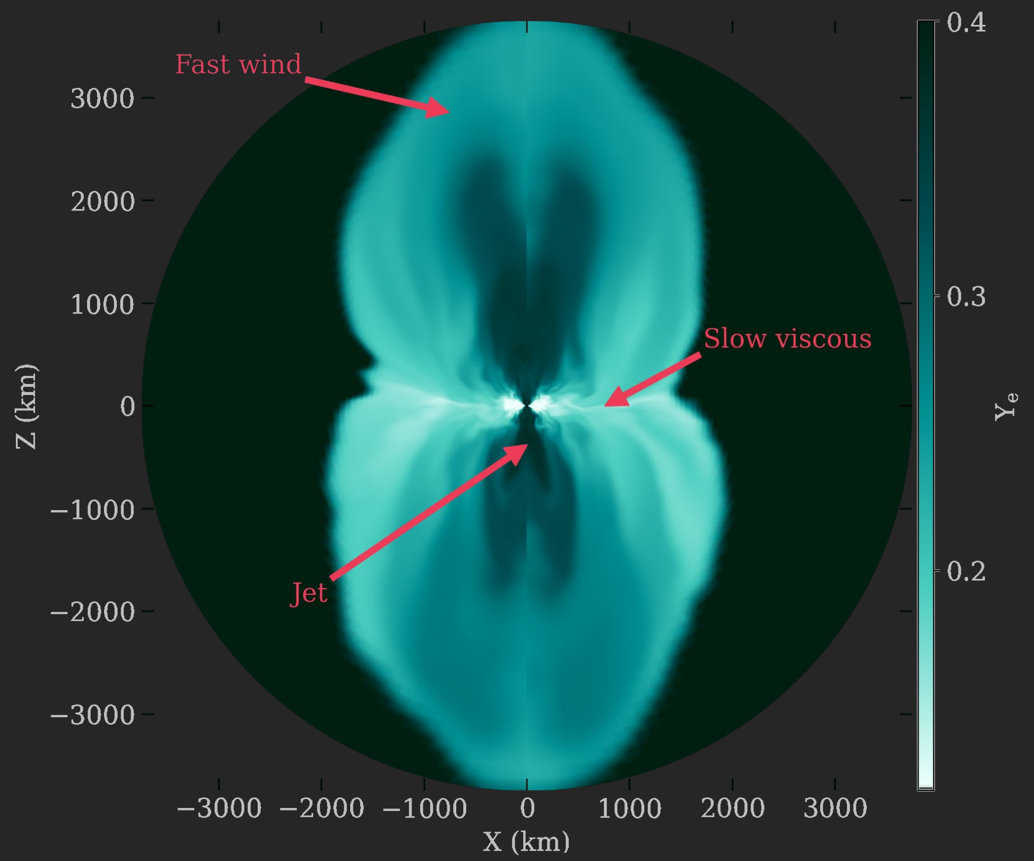
- Fast wind driven off material in mid-plane
- Slow, viscous disk
- Material entrained in semi-relativistic jet

nubhlight!*

Miller + 2019: 1903.09273

3D General Relativistic Radiation Magnetohydrodynamics simulation for black hole accretion disk systems

* Description borrowed heavily from J. Miller



Magnetized gas via finite volume methods

- Standard second-order Gudonov scheme
- Cell-centered constrained transport for magnetic fields
- WENO5 reconstruction
- Local Lax-Friedrichs Riemann solver

Neutrinos via Monte Carlo methods

- Explicit integration along geodesics
- Probabilistic emissivity, absorption, and scattering
- Coupled via operator splitting

Built on top of: HARM (Gammie2003), grmonty (Dolence 2009), and bhlight (Ryan 2015)

github.com
lanl/nubhlight

Neutrinos Matter for Nucleosynthesis

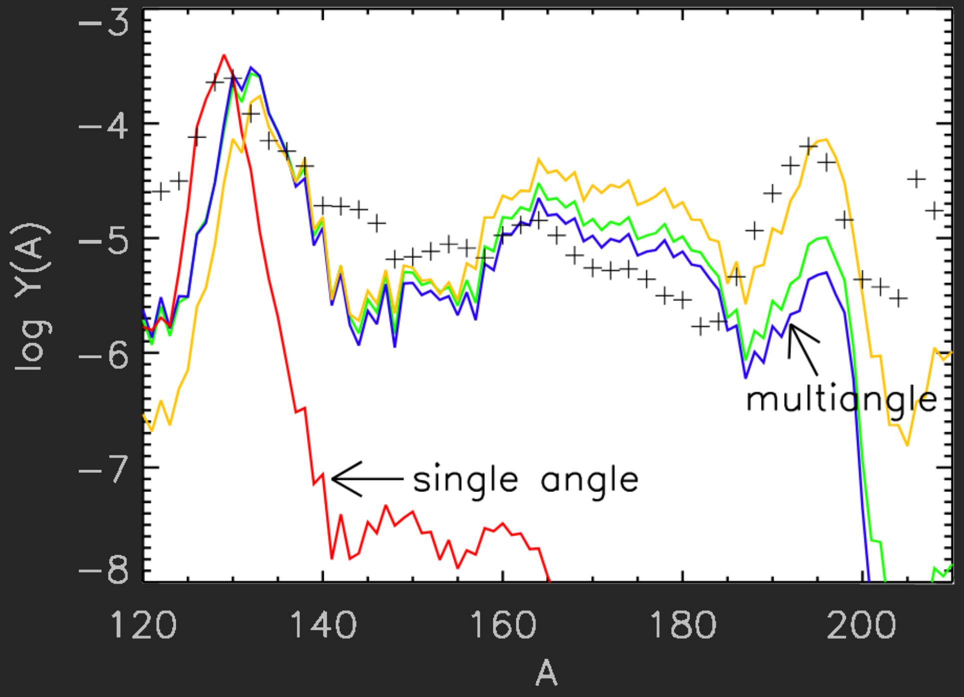
Neutrinos change the Y_e of the ejecta:

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

Neutrinos in ejecta are mostly electron flavor, BUT neutrinos change flavor:

$$\nu_e \leftrightarrow \nu_\mu, \nu_\tau \qquad \bar{\nu}_e \leftrightarrow \bar{\nu}_\mu, \bar{\nu}_\tau$$

Abundance patterns produced from
different neutrino treatments
Adapted from Duan+ 2011



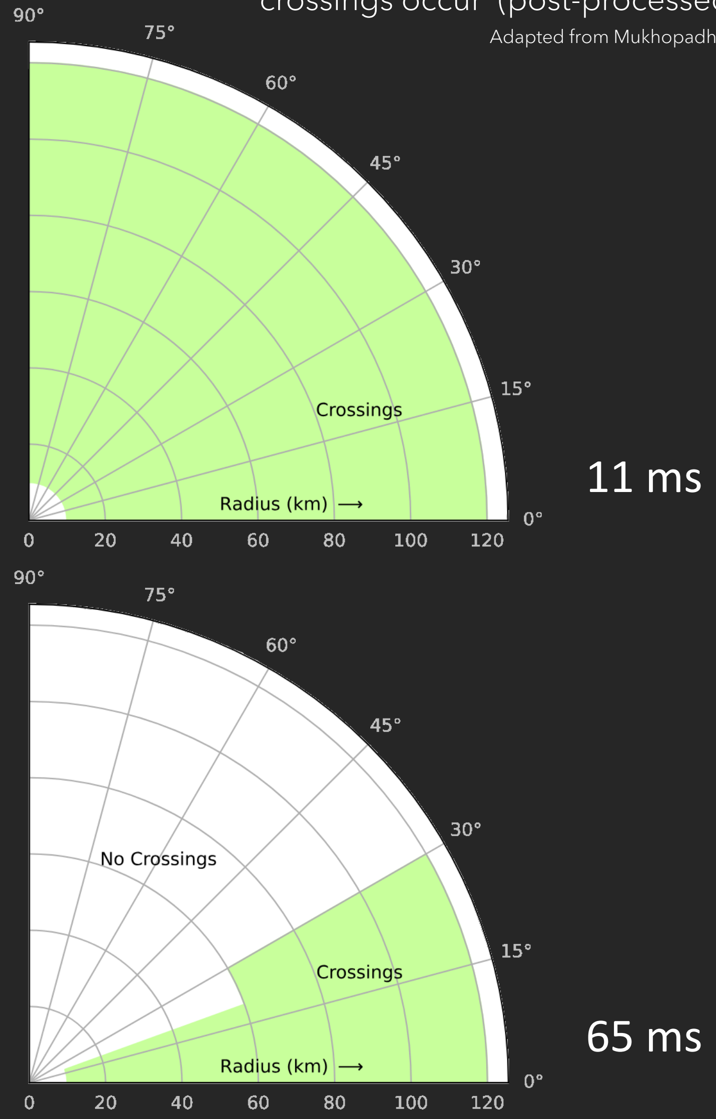
Oscillations are Time and Space Dependent

Fast flavor instabilities will occur wherever the angular distributions of neutrinos and antineutrinos cross each other at a given point in space.

This criterion is termed the presence of an electron lepton number–heavy lepton number (ELN-XLN) crossing.

r-θ map showing snapshots of where crossings occur (post-processed disk)

Adapted from Mukhopadhyay+ 2024



Combining MC Neutrino Transport and FFCs

We incorporate FFCs into a classical 3D GRMHD disk simulation with MC neutrino transport by implementing a prescription to modify the neutrino field given a *crossing* following Zaizen+Nagakura (2023)

Crossing indicator function: $G_\nu = 0$

$$G_\nu = \left(f_{\nu_e} - f_{\bar{\nu}_e}\right) - \frac{1}{2}\left(f_{\nu_x} - f_{\bar{\nu}_x}\right)$$

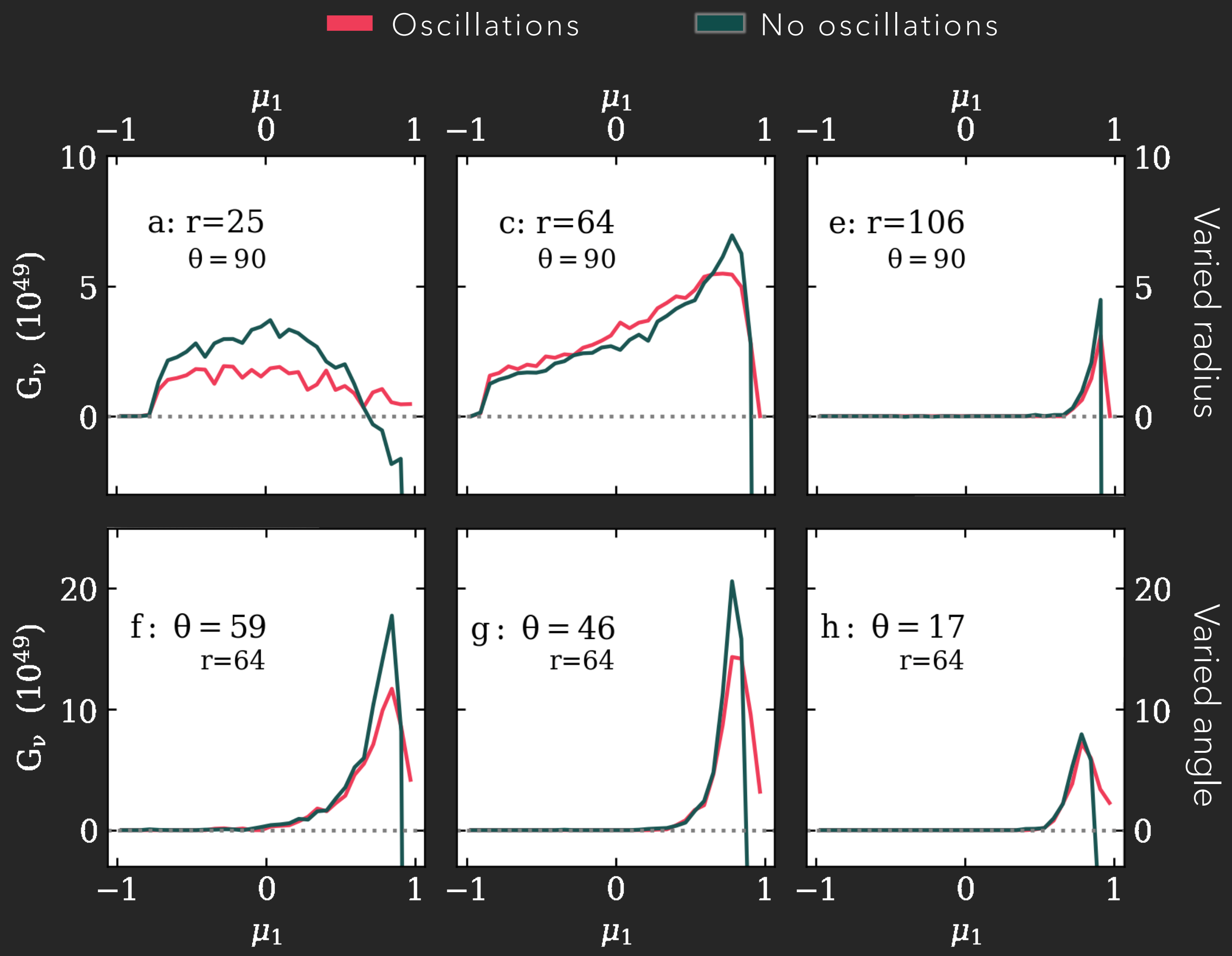
ν_x separate from $\bar{\nu}_x$!

FF transformation eliminates crossing, conserves $\int d\varepsilon d\Omega G_\nu(t, x, y, z, \varepsilon, \Omega)$

Our test case: a 0.12 $M_\odot$ accretion disk around a 2.58 $M_\odot$ black hole

Crossings are Eliminated

$$\mu_1 = \frac{\hat{r} \cdot k}{|\hat{r}||k|}$$

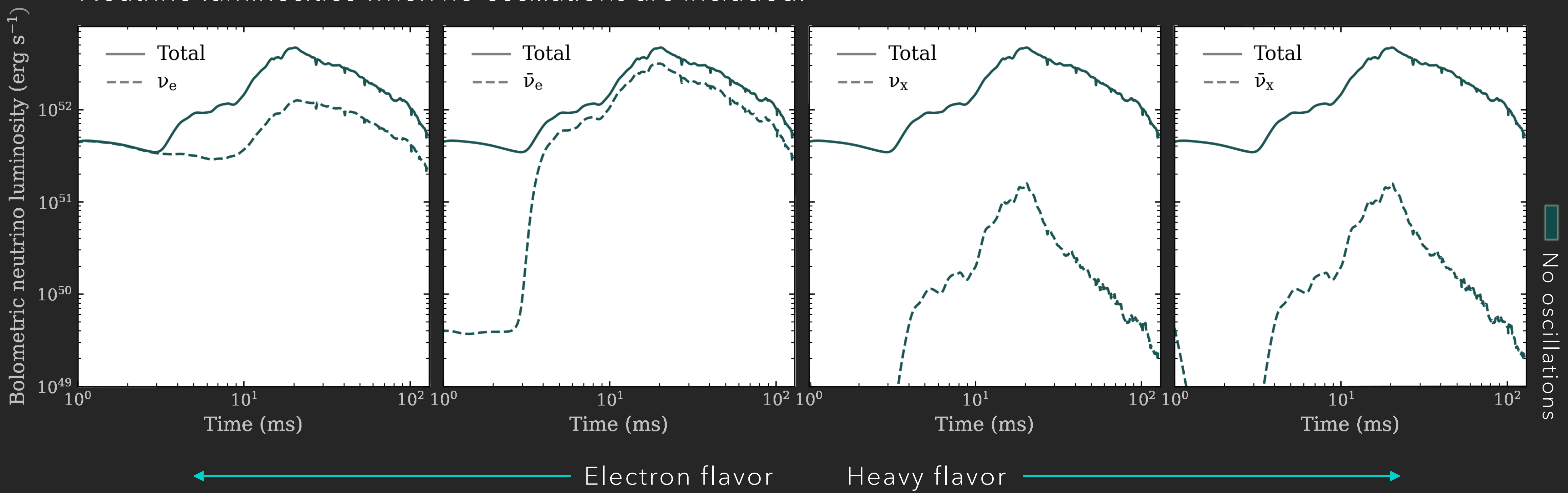


Blue lines: simulation *without* oscillations. Crossings are present across the disk

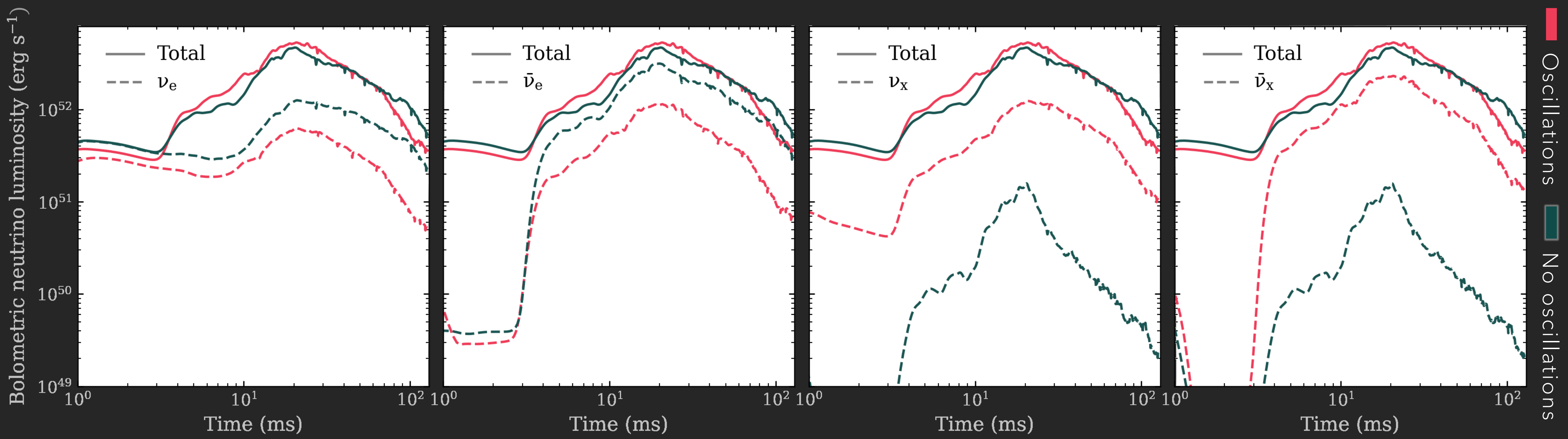
Pink lines: simulation *with* oscillations eliminate crossings by FFC

Neutrino Luminosities are Affected

Neutrino luminosities when *no* oscillations are included:



Neutrino Luminosities are Affected



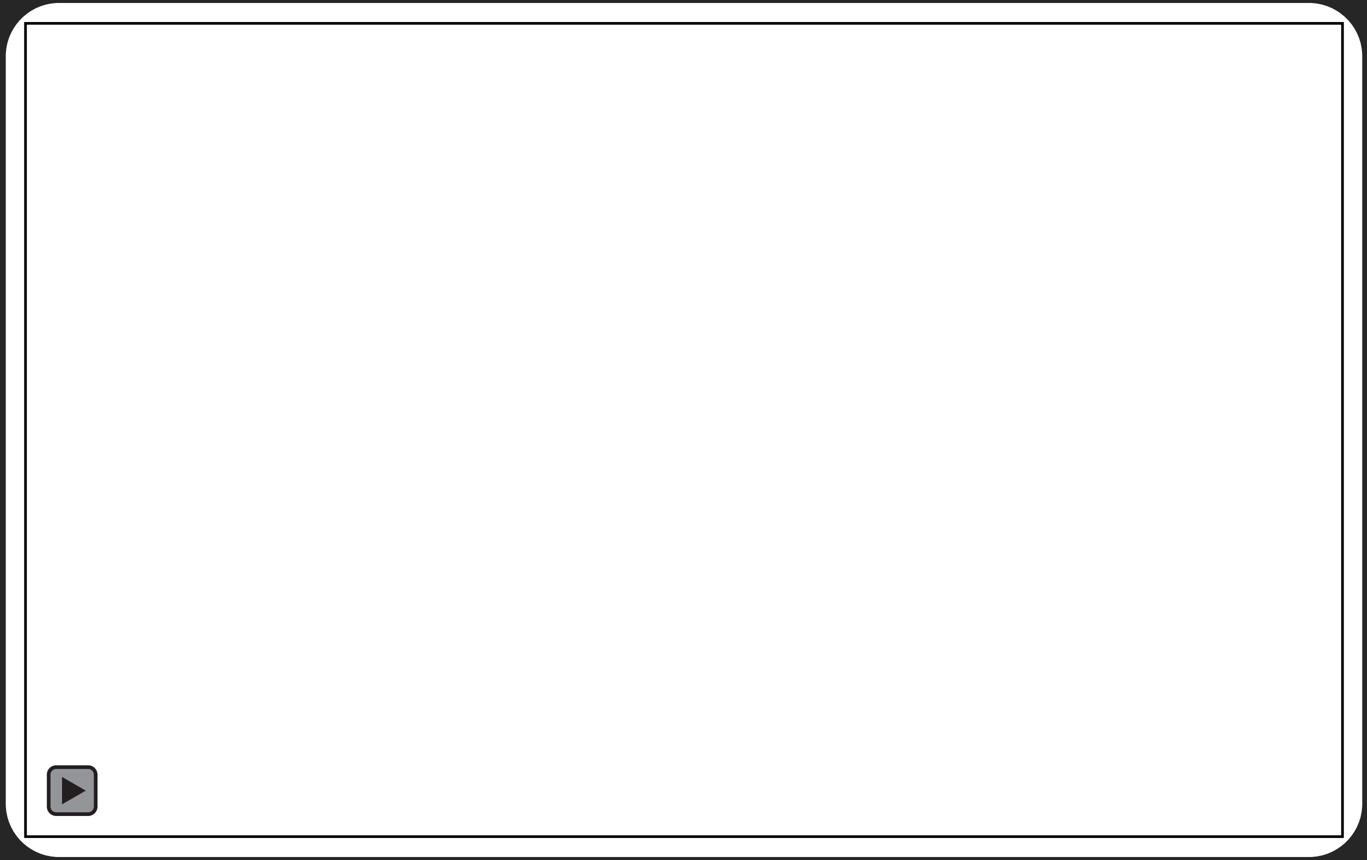
Electron flavor

Heavy flavor

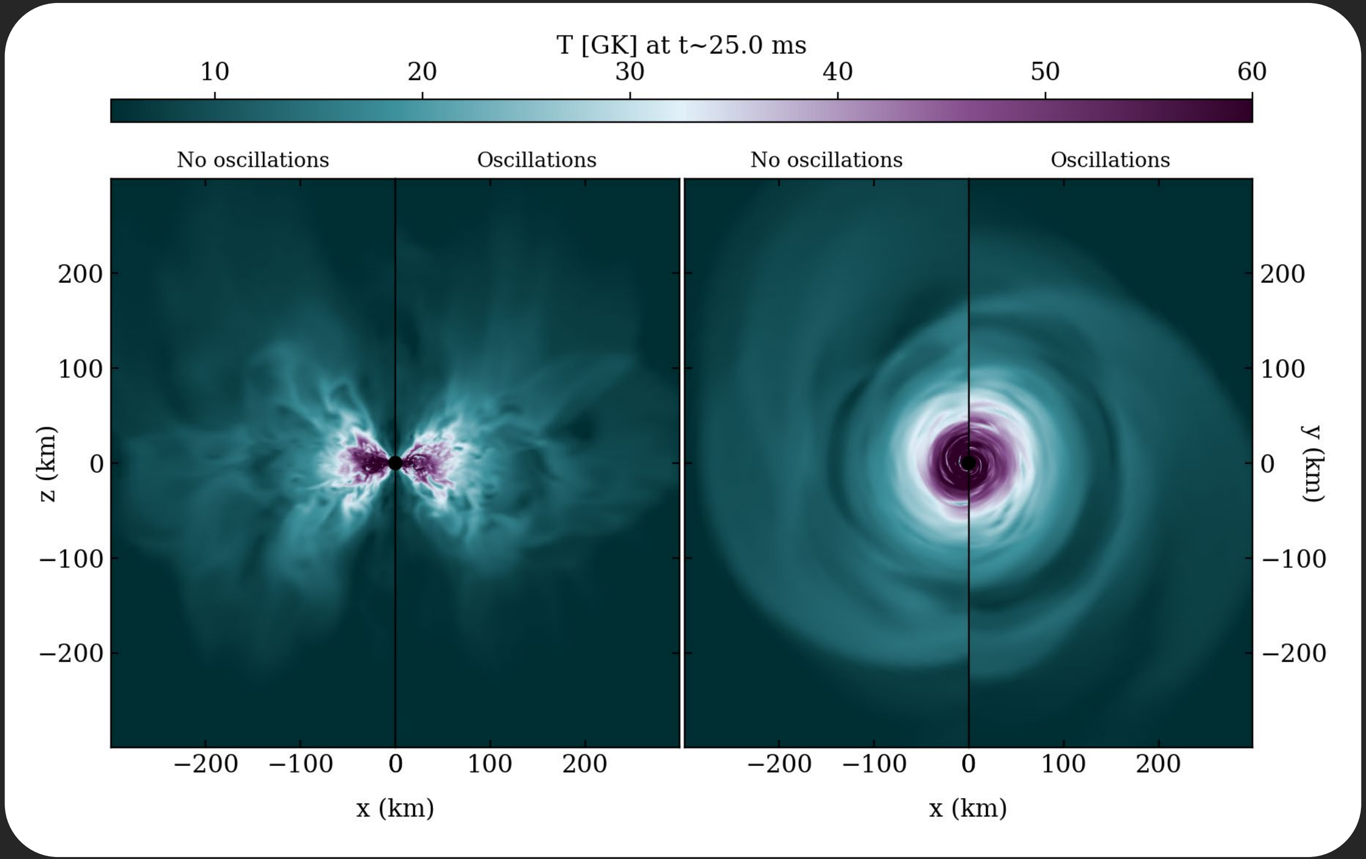
Decreased ν_e and $\bar{\nu}_e$ luminosities

Increased ν_x and $\bar{\nu}_x$ luminosities

Energetics of the Disk Depends on FFCs



Energetics of the Disk Depends on FFCs



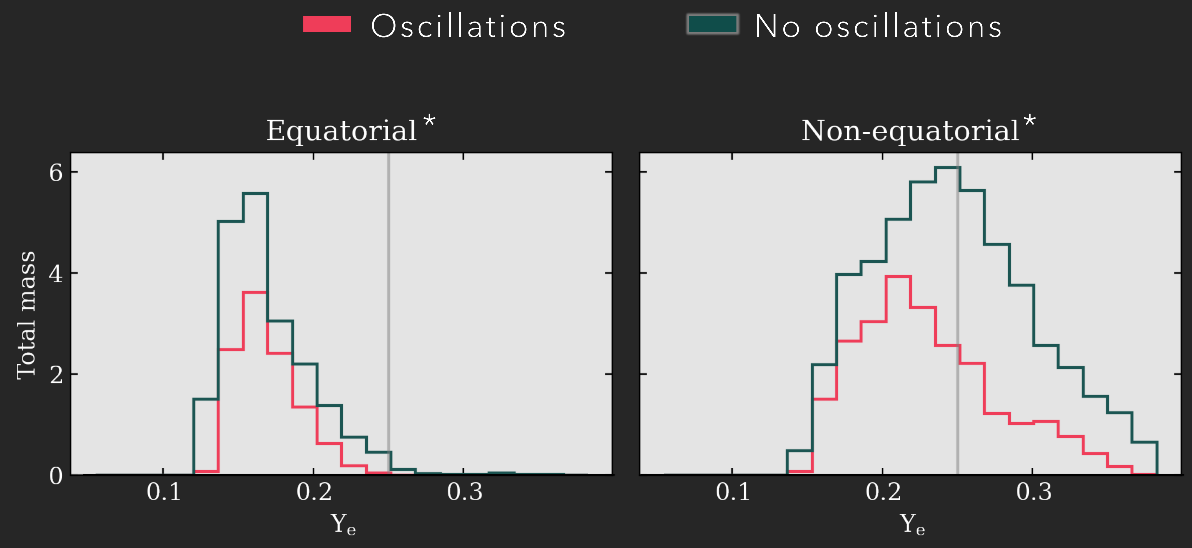
Disk is more efficiently cooled when oscillations are included, weakened thermal wind

Effect on Y_e Angular Structure…

Two ways to look at the mass distribution of Y_e:

If we compare the total ejecta mass:

Oscillations reduce total ejecta mass by a factor of ~2



*Cutoff is 30° above mid-plane

Effect on Y_e Angular Structure...

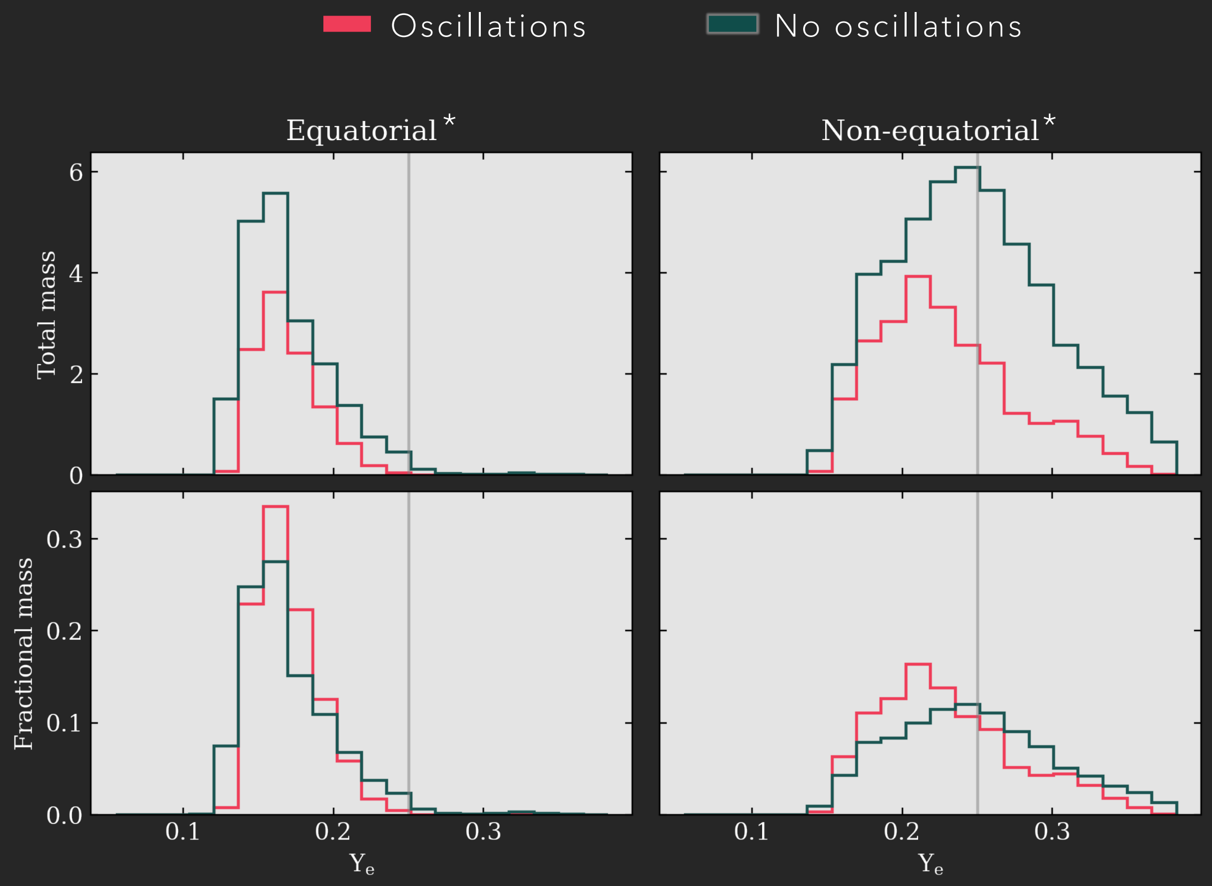
Two ways to look at the mass distribution of Y_e:

If we compare the total ejecta mass:

Oscillations reduce total ejecta mass by a factor of ~2

If we compare the fractional ejecta mass:

Oscillations shift Y_e distribution of non-equatorial material to lower values, steeper cutoff past Y_e=0.25

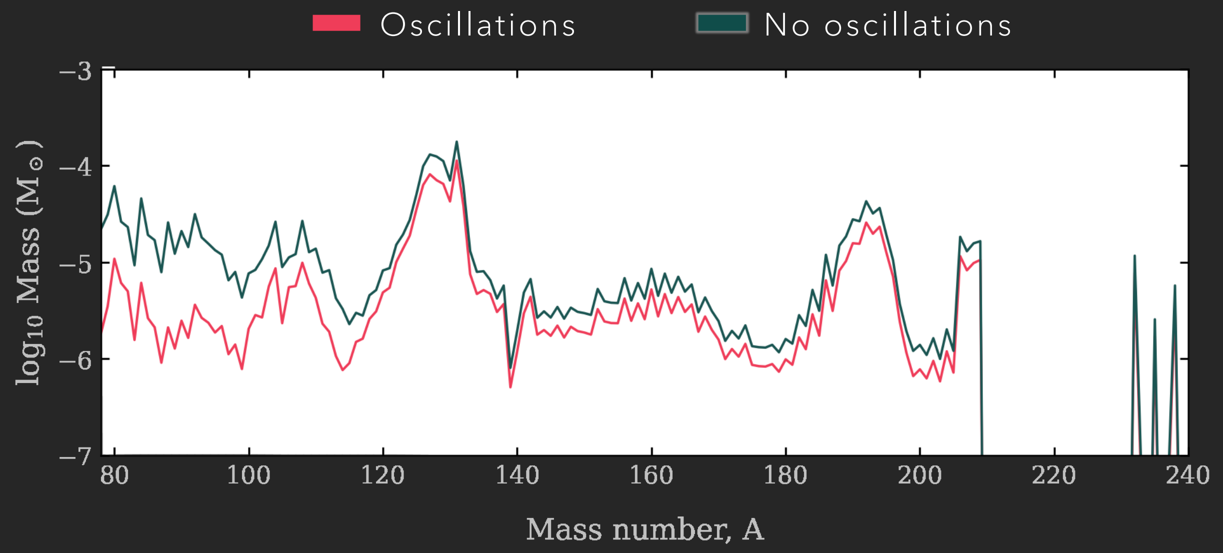


*Cutoff is 30° above mid-plane

...Affect the Nucleosynthesis

If we compare the total abundances:

Oscillations reduce total ejecta mass and total r-process (especially weak) mass



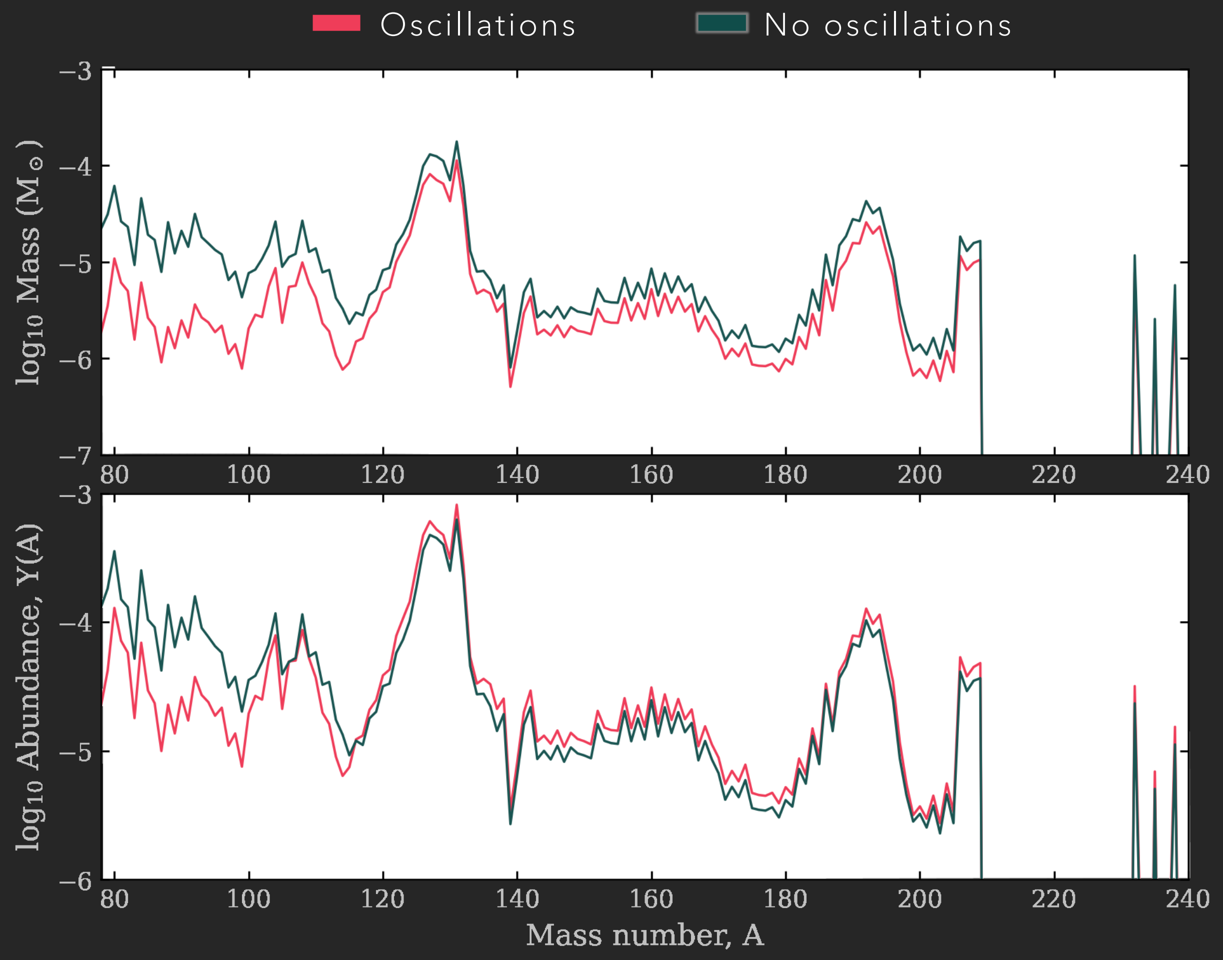
...Affect the Nucleosynthesis

If we compare the total abundances:

Oscillations reduce total ejecta mass and total r-process (especially weak) mass

If we compare the log-scaled abundances:

Oscillations make equatorial ejecta more neutron rich, dominates r-process pattern (compare pink solid to pink dashed)

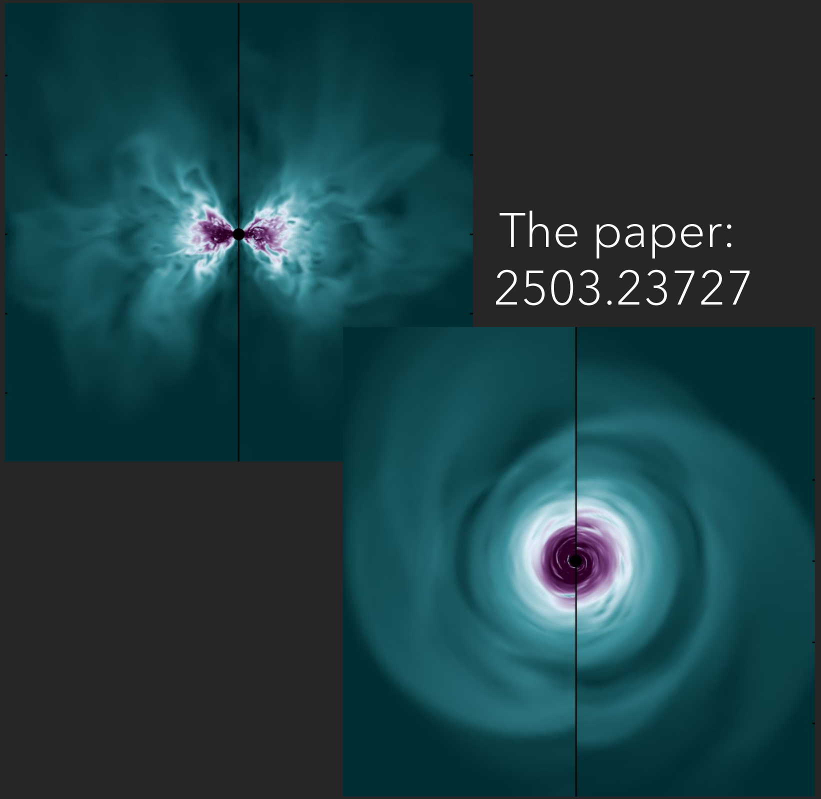


Thank you!

The post-neutron star merger disk system remains a promising site for r-process production

Neutrinos and their transport are key ingredients for our understanding of heavy element nucleosynthesis

- Fast flavor oscillations can *decrease* ejecta mass but *increase* fraction of main r-process



The paper:
2503.23727

The rich physics needed to get an accurate picture of the disk evolution and nucleosynthetic outcomes represents both challenge and opportunity

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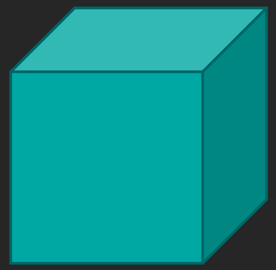
Appendix

Appendix: GRRMHD with MC Neutrino Transport

Miller+ 2019: 1903.09273

For each time step:

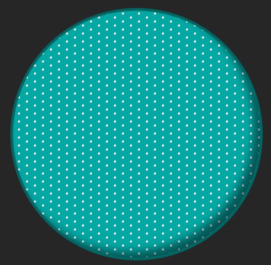
Deterministically solve GRMHD equations for full finite-volume grid



Finite volume (3D)

Radiation (G_ν), lepton (G_{Ye}) source terms

Emissivity, absorption opacity, scattering cross sections



Radiation packet (6D)

Use MC methods to solve full kinetic Boltzmann equation

Appendix: The GRMHD+Transport Equations

Conservation of baryon number

$$\partial_t(\sqrt{-g}\rho_0 u^t) + \partial_i\left(\sqrt{-g}\rho_0 u^i\right) = 0$$

Magnetic flux conservation

$$\partial_t\left(\sqrt{-g}B^i\right) + \partial_j\left[\sqrt{-g}\left(b^j u^i - b^i u^j\right)\right] = 0$$

Conservation of energy-momentum

$$\partial_t[\sqrt{-g}(T^t_\nu + \rho_0 u^t \delta^t_\nu)] + \partial_i\left[\sqrt{-g}\left(T^i_\nu + \rho_0 u^i \delta^t_\nu\right)\right] = \sqrt{-g}\left(T^\kappa_\lambda \Gamma^\lambda_{\nu\kappa} + G_\nu\right)$$

Conservation of lepton number

$$\partial_t(\sqrt{-g}\rho_0 Y_e u^t) + \partial_i\left(\sqrt{-g}\rho_0 Y_e u^i\right) = \sqrt{-g}G_{ye}$$

Transport equation

$$\frac{D}{d\lambda}\left({\nu_\epsilon}^3 I_{\epsilon,f}\right) = \left({\nu_\epsilon}^2 \eta_{\epsilon,f}\right) - \left(\nu_\epsilon \chi_{\epsilon,f}\right)\left({\nu_\epsilon}^2 I_{\epsilon,f}\right)$$

Appendix: Neutrino Quantities

Scattering interaction (p,n,A,α)

Extinction coefficient: $\chi_{\epsilon,f} = \alpha_{\epsilon,f} + \sigma^{a}_{\epsilon,f}$

Absorption coefficient

Scattering cross section

Emissivity: $\eta_{\epsilon,f} = j_{\epsilon,f} + \eta^{s}_{\epsilon,f}(I_{\epsilon,f})$

Fluid emissivity

Scattering emission