Neutrino Fast Flavor Oscillations in Neutron Star Merger Disks

Kelsey Lund [1,2,†]

with P. Mukhopadhyay [1], G.C. McLaughlin [3], J.M. Miller [4]

[1] UC Berkeley [2] Institute for Nuclear Theory, Seattle, WA, USA [3] Department of Physics, North Carolina State University, Raleigh, NC, USA [4] Los Alamos National Laboratory, Los Alamos, NM, USA [†] N3AS Fellow

Kelsey's Website

Context

Neutron star mergers are a preferred site for the synthesis of heavy elements via the rapid neutron capture **(r-) process**.
The black hole-accretion disk system that remains after the merger can provide the necessary conditions for r-process nucleosynthesis.

Neutrinos play an important role in setting the conditions in the merger ejecta by setting the ratio of neutrons to protons (Y_e):

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

Fast flavor instabilities occur when there is a *crossing* in the angular distributions of neutrinos and antineutrinos.
Fast flavor instabilities drive fast flavor conversions (FFCs):

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

Magnetohydrodynamics → Nucleosynthesis

nubhlight [1]: 3D General relativistic Radiation magnetohydrodynamics (GRMHD) simulation for black hole + accretion disk systems

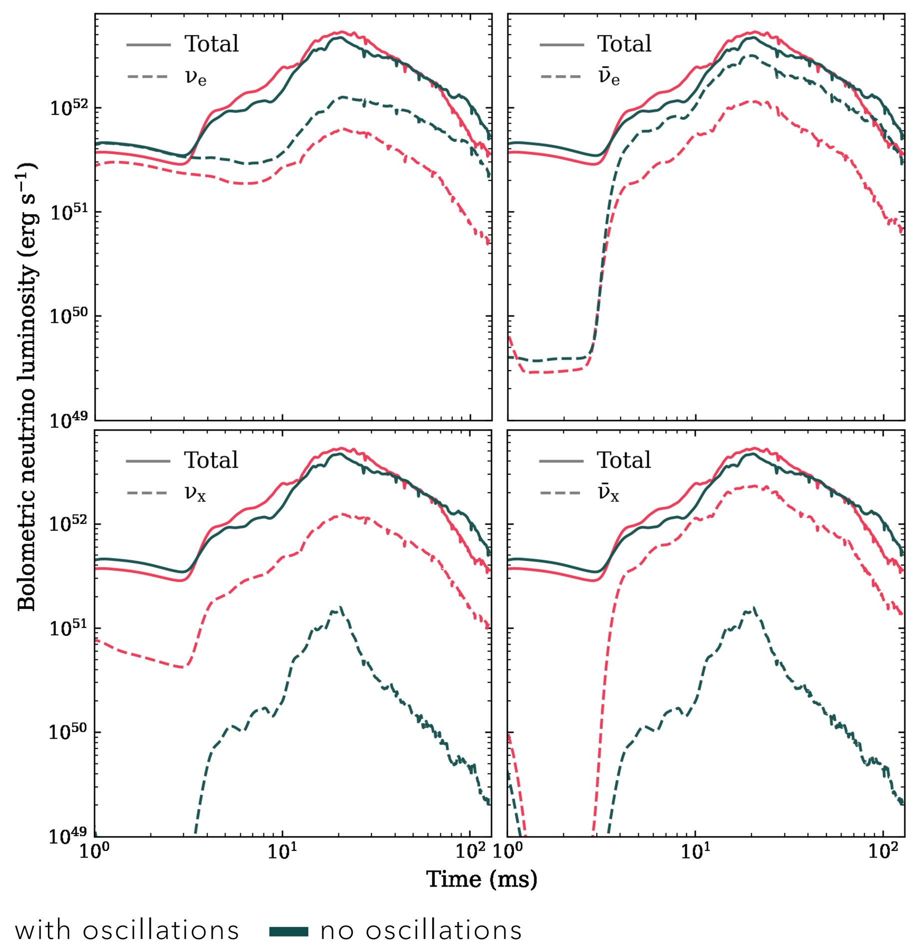
disk mass	black hole mass	initial Y_e
0.12 $M_\odot$	2.58 $M_\odot$	0.1

Nucleosynthesis using PRISM [2] via Lagrangian tracer particles from nubhlight

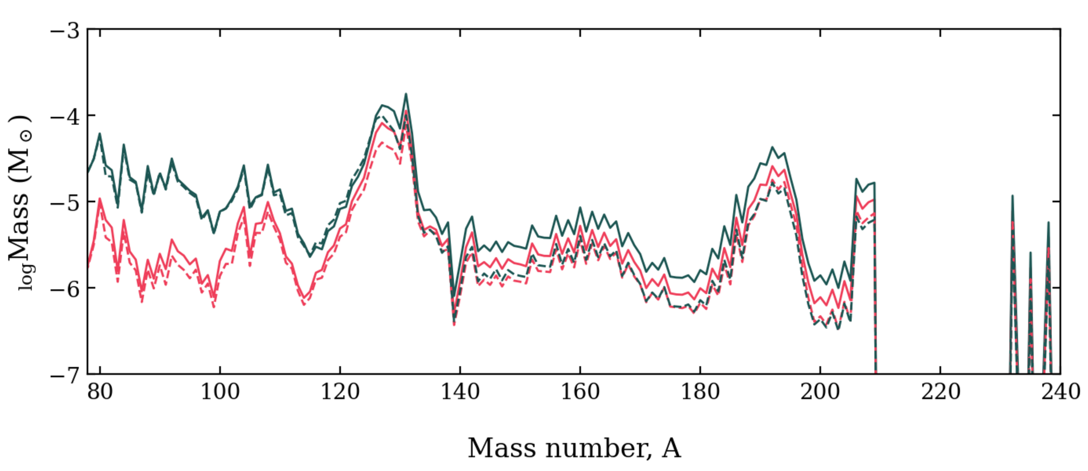
Neutrino Luminosity

FFCs enhance heavy flavor neutrino luminosity, decrease electron flavor neutrino luminosity.

More energy is lost when oscillations are included – decreased temperatures (center figure), weakened thermal wind

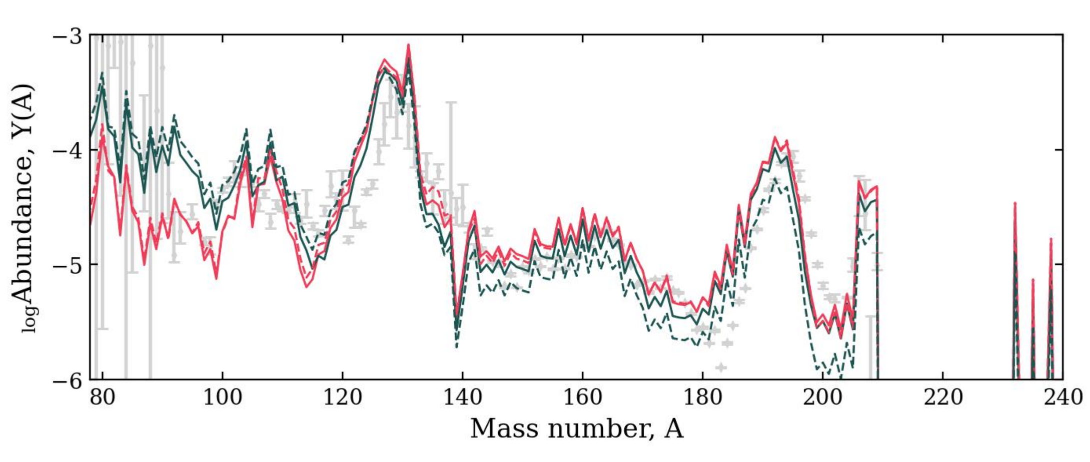


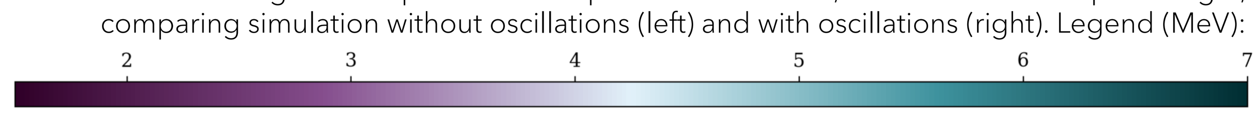
Nucleosynthesis: Mass abundances



Comparison of *total* abundances (in $M_\odot$) shows FFCs reduce total ejecta mass *and* total r-process mass (especially weak r-process)

Comparison of scaled (relative) abundances: fast flavor oscillations make non-equatorial ejecta (dashed) more neutron rich- dominates r-process pattern





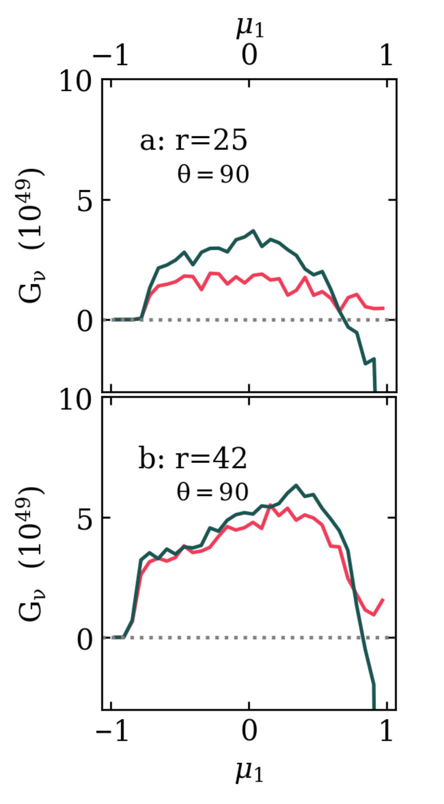
Combining MC Neutrino Transport & FFCs

We incorporate FFCs into a classical 3D-GRMHD disk simulation with Monte Carlo neutrino transport by implementing a prescription[3] to modify the neutrino field given an ELN-XLN crossing using the *crossing indicator function*:

$$G_\nu = (f_{\nu_e} - f_{\bar{\nu}_e}) - \frac{1}{2}(f_{\nu_x} - f_{\bar{\nu}_x}) = 0$$

FF transformation eliminates crossing, while conserving:

$$\int d\varepsilon d\Omega G_\nu(t, x, y, z, \varepsilon, \Omega)$$

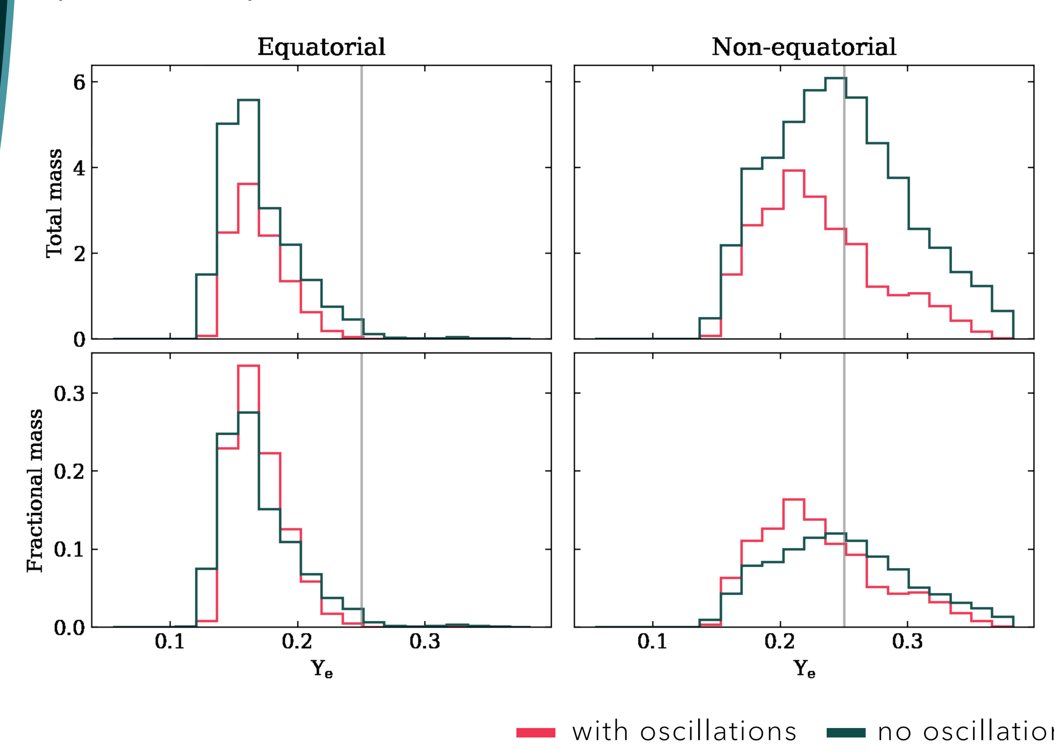


Ejecta Properties

Disk with oscillations has weakened thermal wind, decreased total ejected mass:

without oscillations:	with oscillations:
$M_{ej} = 2.2 \cdot 10^{-3}$ $M_\odot$	$M_{ej} = 1.1 \cdot 10^{-3}$ $M_\odot$

FFCs result in more non-equatorial material with lower Y_e: better conditions for robust r-process production.



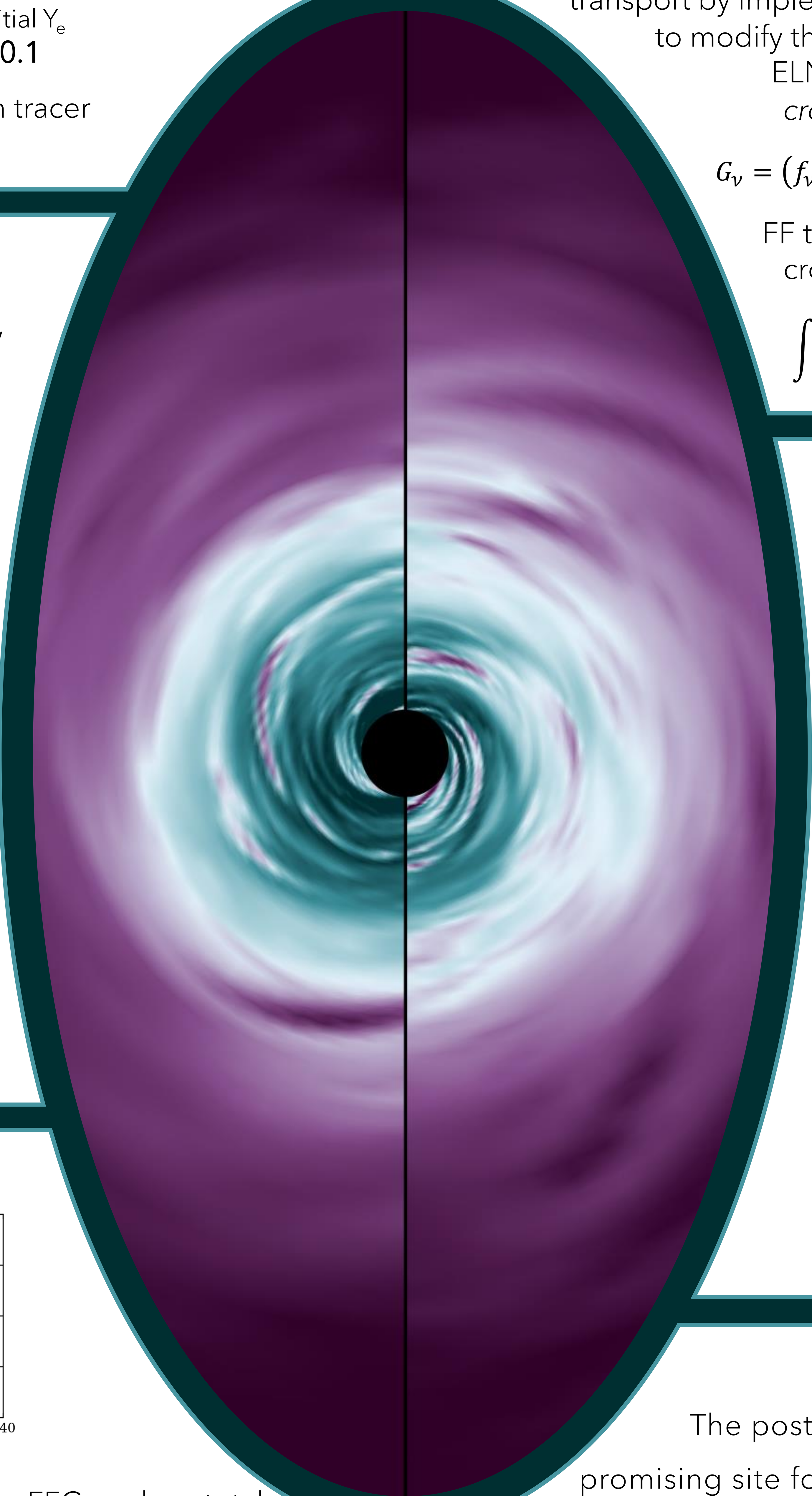
Concluding Observations

The post-neutron star merger disk system remains a promising site for the production of a full r-process pattern.

Fast flavor oscillations can *decrease* ejecta mass but *increase* the fraction of main r-process material produced in the ejecta.

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

Center figure: comparison of temperature in the disk, measured at 25ms postmerger, comparing simulation without oscillations (left) and with oscillations (right). Legend (MeV):



[1] Miller+ 2019 : 10.3847/1538-4365/ab09fc
[2] Mumpower+ 2017 : 10.1088/1361-6471/44/3/034003
This work: Lund+2025: 10.3847/2041-8213/add0a7

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