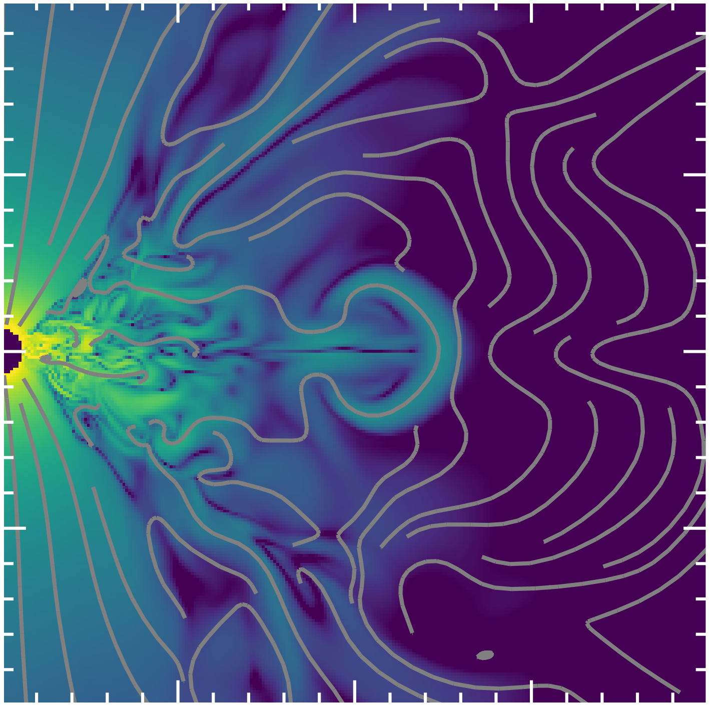
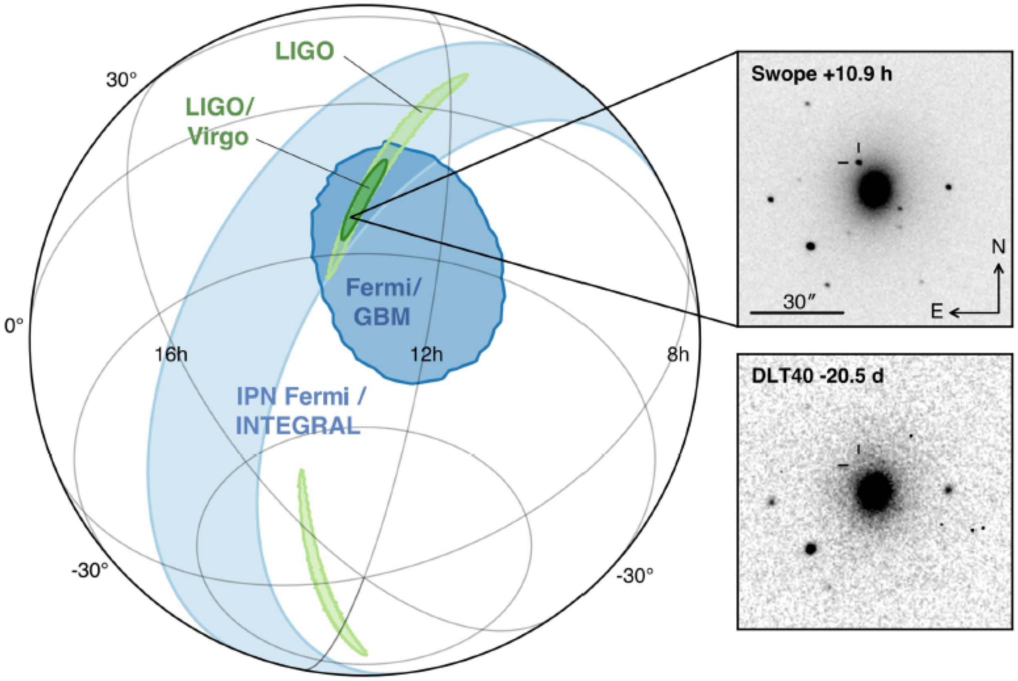


RF et al. (2019)



Abbott et al. (2017) [LVC]: GW170817

# The fast flavor instability in HMNS disk outflows

Rodrigo Fernández (University of Alberta)

Sherwood Richers (UTK), Nicole Mulyk (McMaster), Steven Fahlman (UAlberta)

# Overview

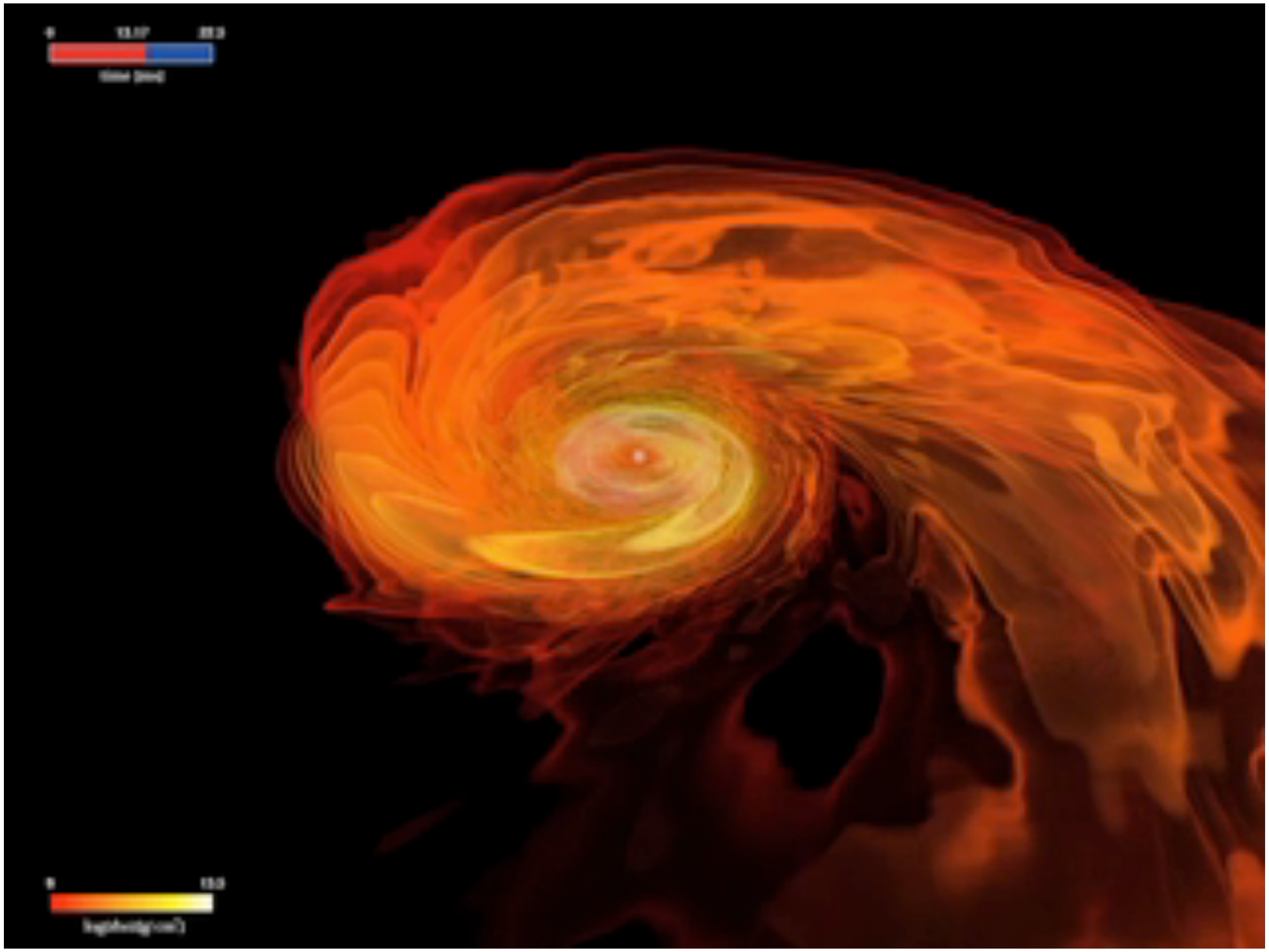
1) Neutron star mergers

2) Accretion disk outflow & neutrinos

2) Effect of Fast Flavor Instability

# Neutron Star Mergers

Unequal mass NS-NS merger:



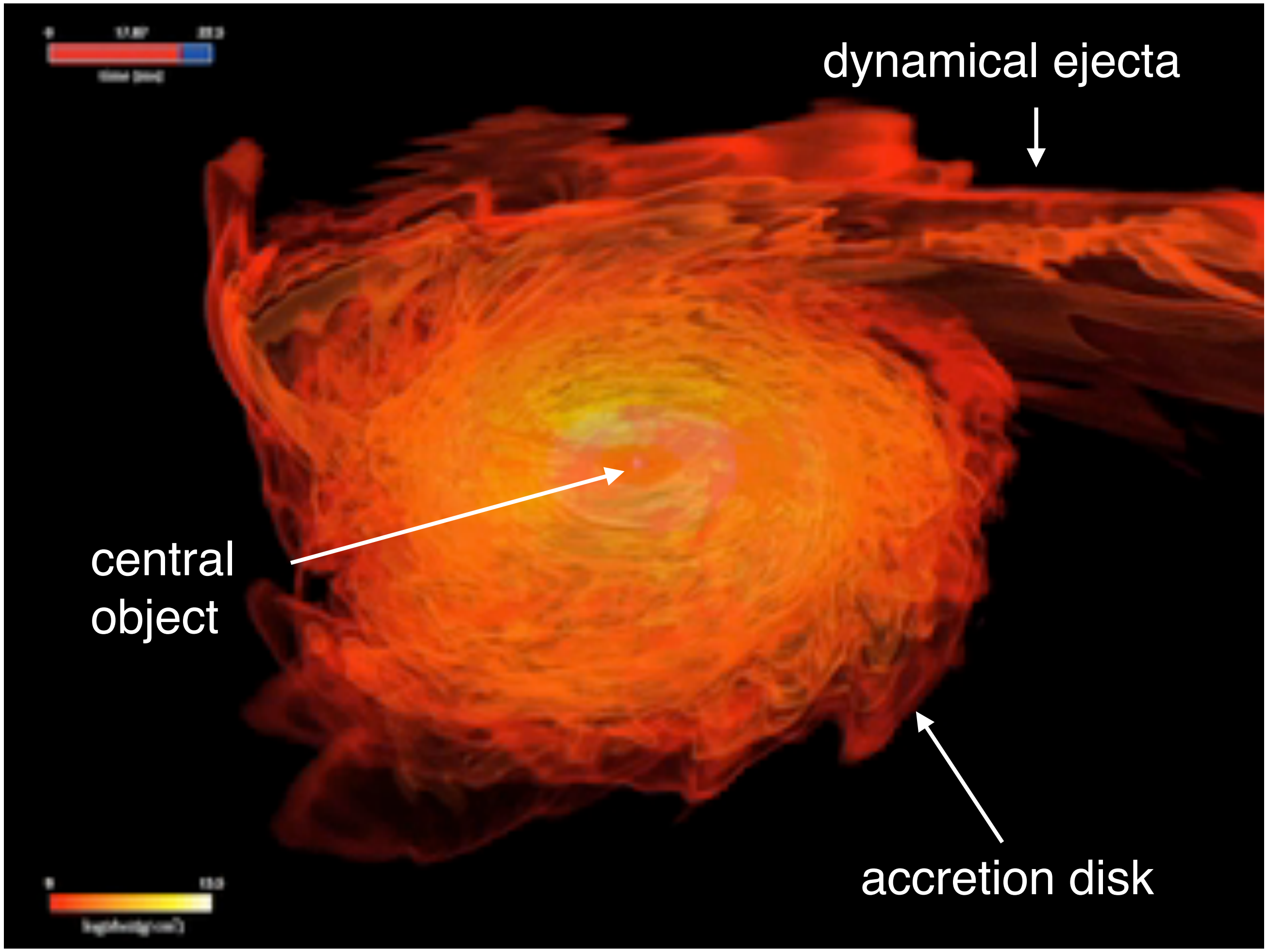
Rezzolla+ (2010)

Phases:

- inspiral
- merger
- remnant + ejecta

# Neutron Star Mergers

Unequal mass NS-NS merger:



Rezzolla+ (2010)

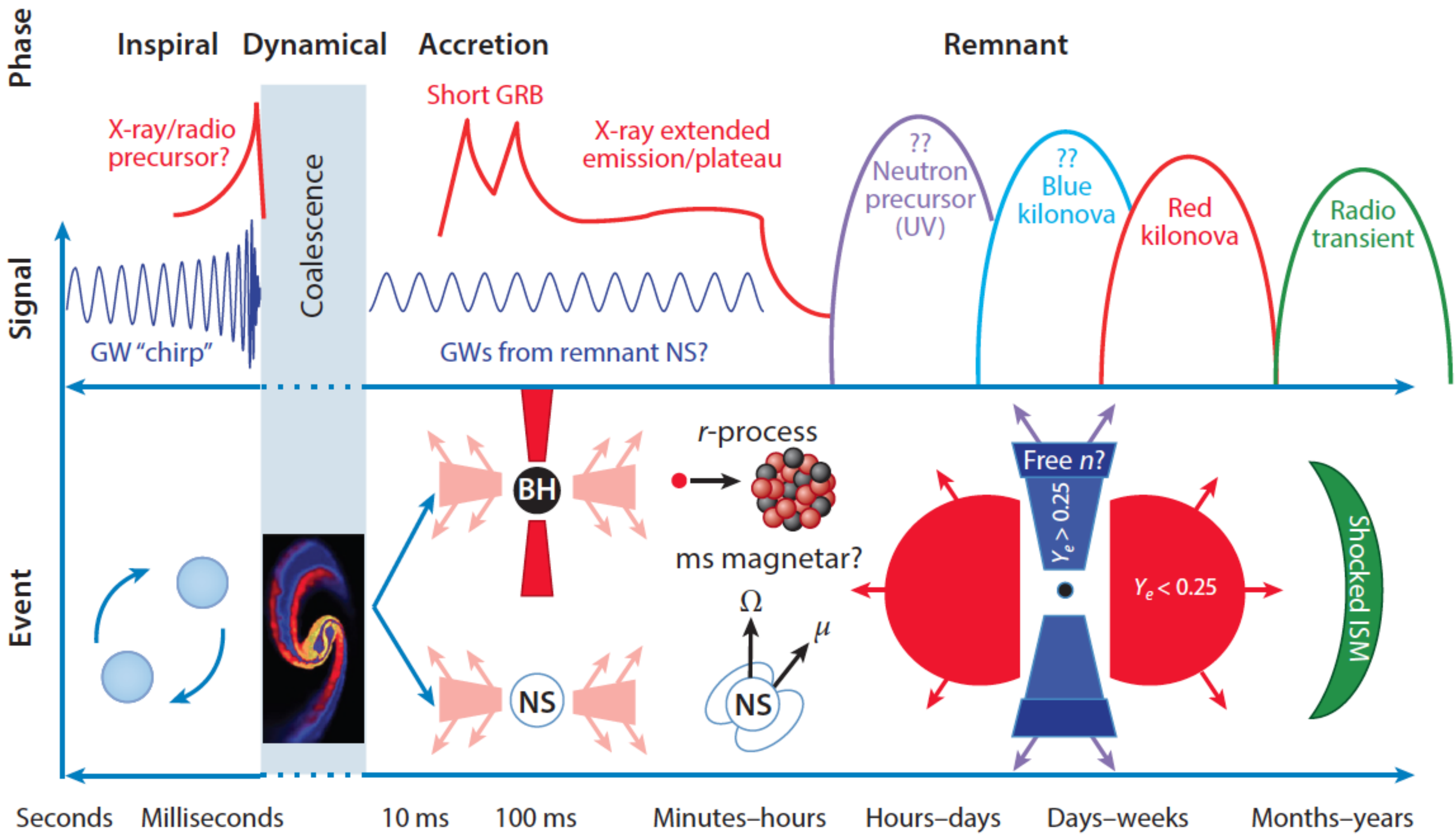
Phases:

- inspiral
- merger
- remnant + ejecta
- relativistic jet (?)

Large body of work:

MPA, Kyoto, Caltech-Cornell-CITA
Princeton, Frankfurt, Trento,
Stockholm, Illinois, Perimeter, etc.

# Neutron Star Mergers



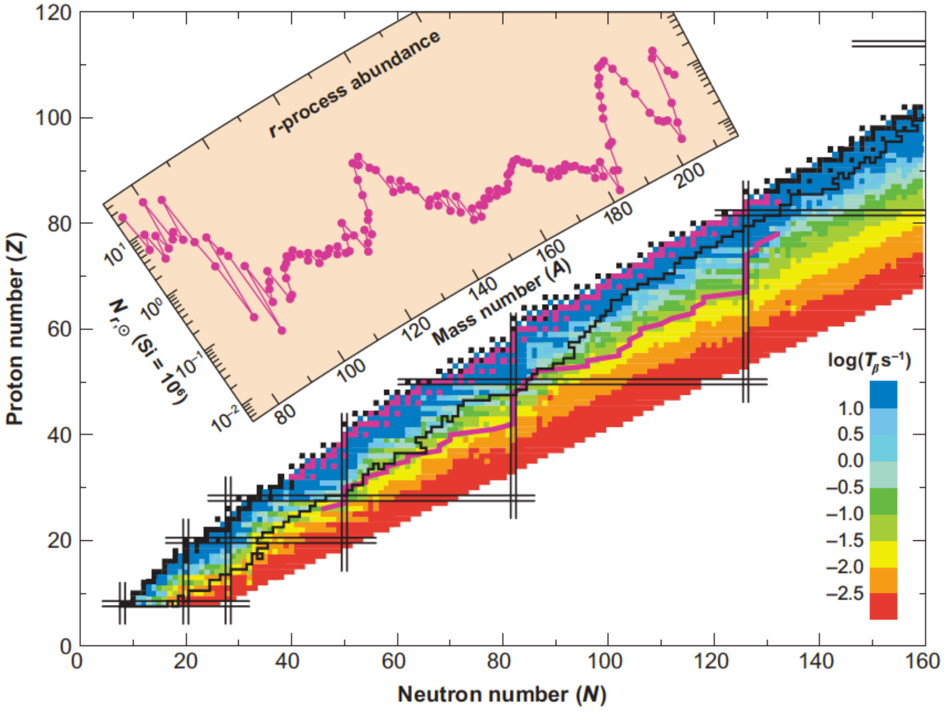
RF & Metzger (2016)

# r-Process Nucleosynthesis

~50% of elements heavier than Zinc (Z=30) require formation by 'rapid' neutron capture (r-process)

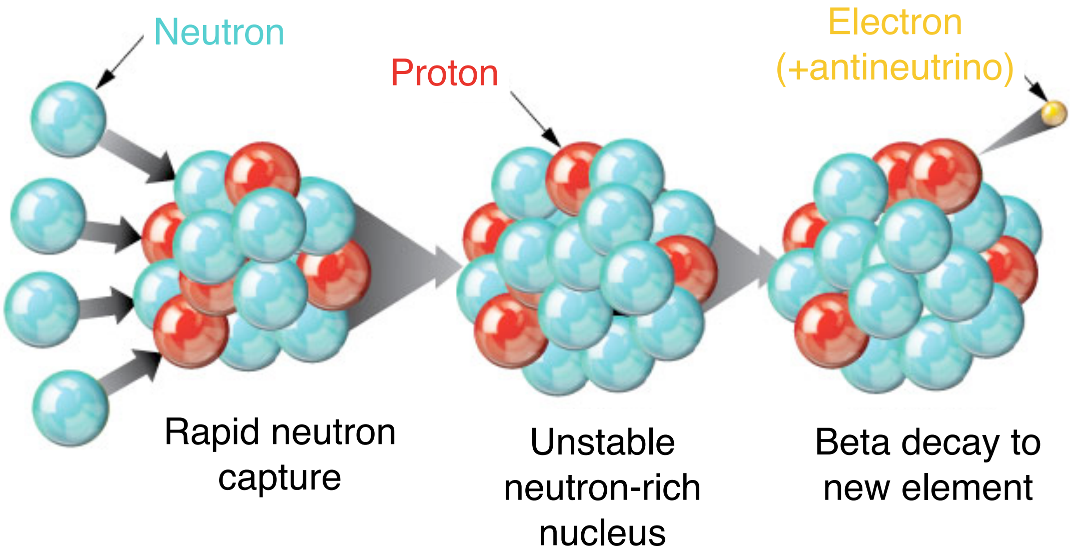
Burbidge et al. (1957), Cameron (1957)

Nuclear Chart & Solar System abundances:



Möller, Nix, & Kratz (1997)

$$t_{\mathrm{n-capture}} \ll t_{\beta-\mathrm{decay}}$$



Rapid neutron capture

Unstable neutron-rich nucleus

Beta decay to new element

llnl.gov

Astrophysical sites that meet the conditions:

1) Neutron Star Mergers

2) Core-Collapse Supernovae

# Accretion Disk

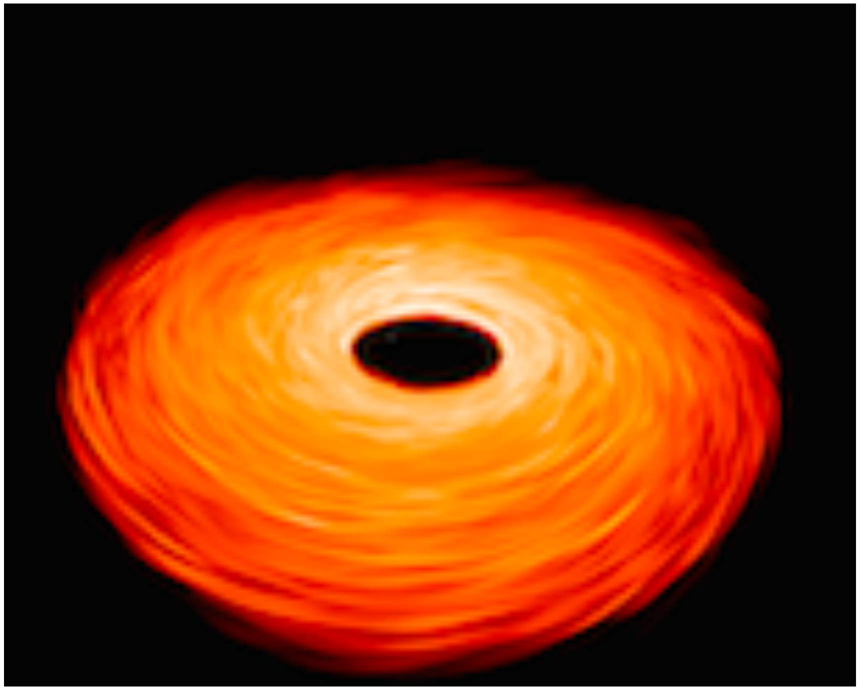
Structure formed by gas orbiting a central object. Gravity balanced mostly by centrifugal acceleration (angular momentum). Matter is (initially) bound gravitationally.

Thermal pressure provides partial support, determines vertical extent of disk ("puffiness").

Settling of mass onto central object ("accretion") requires gas to lose angular momentum and thermal energy.

- angular momentum transport mechanism
- neutrino cooling (for NS mergers)

**Mass can be unbound** from the accretion disk by a variety of mechanisms: disk outflow

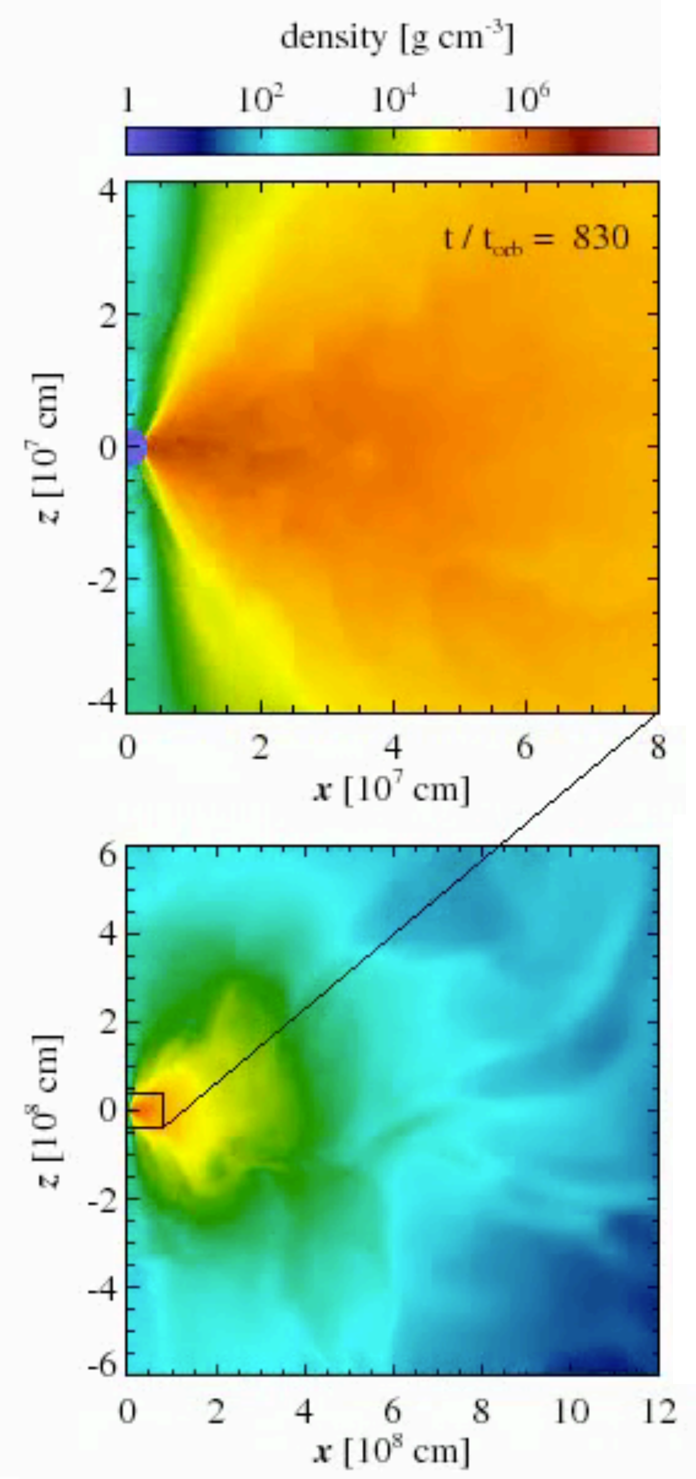


Mario Flock / KITP

**Q1**: outflow mass, properties

**Q2**: r-process contribution

**Q3**: observational EM signature (contribution to kilonova, jet, etc.)



# Outflow from accretion disk

- Neutrino cooling shuts down as disk spreads on accretion timescale (~300ms)
- Viscous heating & nuclear recombination are unbalanced
- Fraction ~10-20% of initial disk mass ejected, ~1E-3 to 1E-2 solar masses
- Material is neutron-rich (Ye ~ 0.2-0.4)
- Wind speed (~0.05c) is slower than dynamical ejecta (~0.1-0.3c)

RF & Metzger (2013)

Just et al. (2015, 2021)

Fujibayashi et al. (2020)

Haddadi et al. (2022)

Setiawan et al. (2005)

Lee, Ramirez-Ruiz, & Lopez-Camara (2009)

Metzger (2009)

# GRMHD: poloidal, toroidal & hydro

| | Model | $M_{\rm ejec}$ | | $\langle v_r \rangle$ | $\langle Y_{\rm e} \rangle$ |
|---|---|---|---|---|---|
| | Name | (%) | ($10^{-2}\,M_\odot$) | | |
| GRMHD | BPS | 40 | 1.3 | 0.18 | 0.16 |
| | BPW | 30 | 0.99 | 0.08 | 0.19 |
| | BT | 27 | 0.89 | 0.05 | 0.18 |
| Hydro | $\alpha = 0.1$ | 22 | 0.67 | 0.05 | 0.17 |
| | $\alpha = 0.03$ | 21 | 0.63 | 0.03 | 0.20 |
| | $\alpha = 0.01$ | 16 | 0.48 | 0.03 | 0.26 |

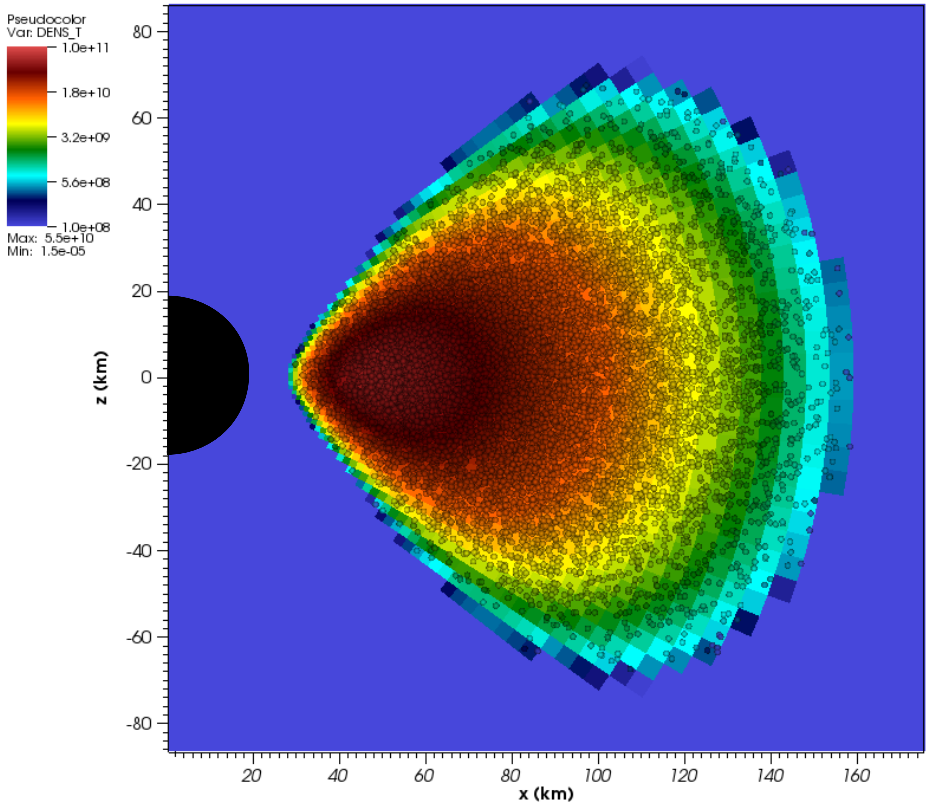
Main caveat: Ye set only by neutrino cooling

RF et al. (2019)

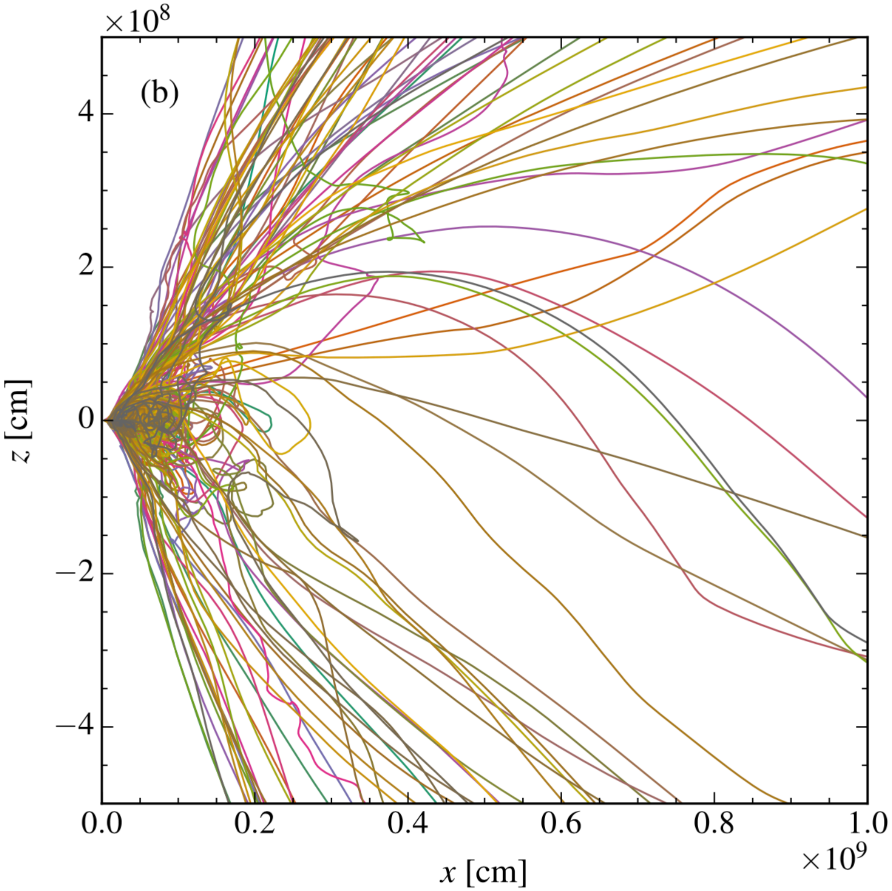
Christie, Lalakos, Tchekhovsoy, RF+ (2019)

# Nucleosynthesis with Tracer Particles

Passive tracers follow density distribution



Disk is convective



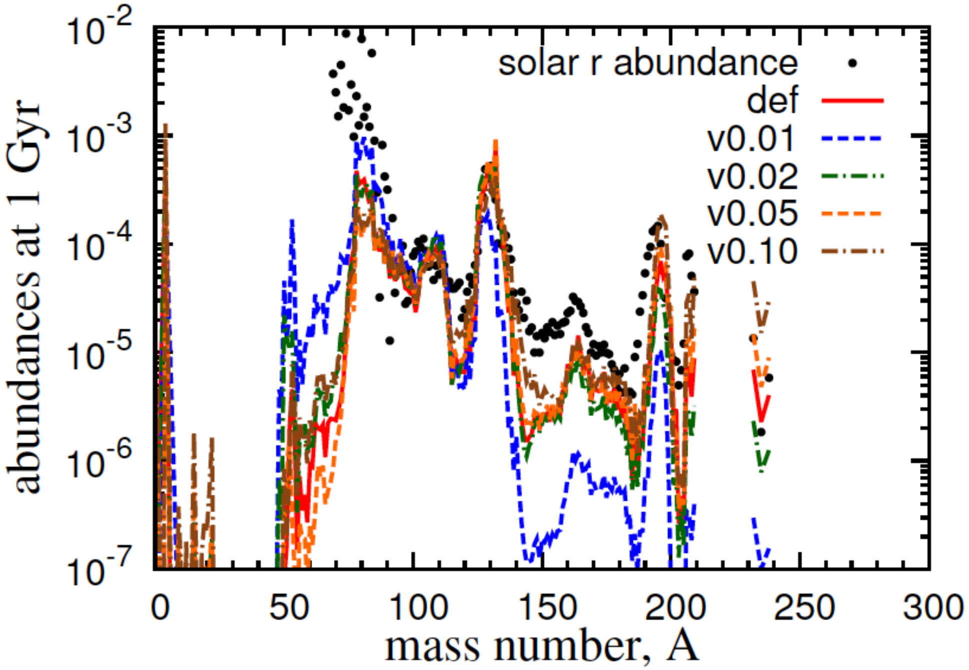
M-R Wu, RF, Martinez-Pinedo & Metzger (2016)

- Nuclear network: ~7000 isotopes,
  include neutrino effects

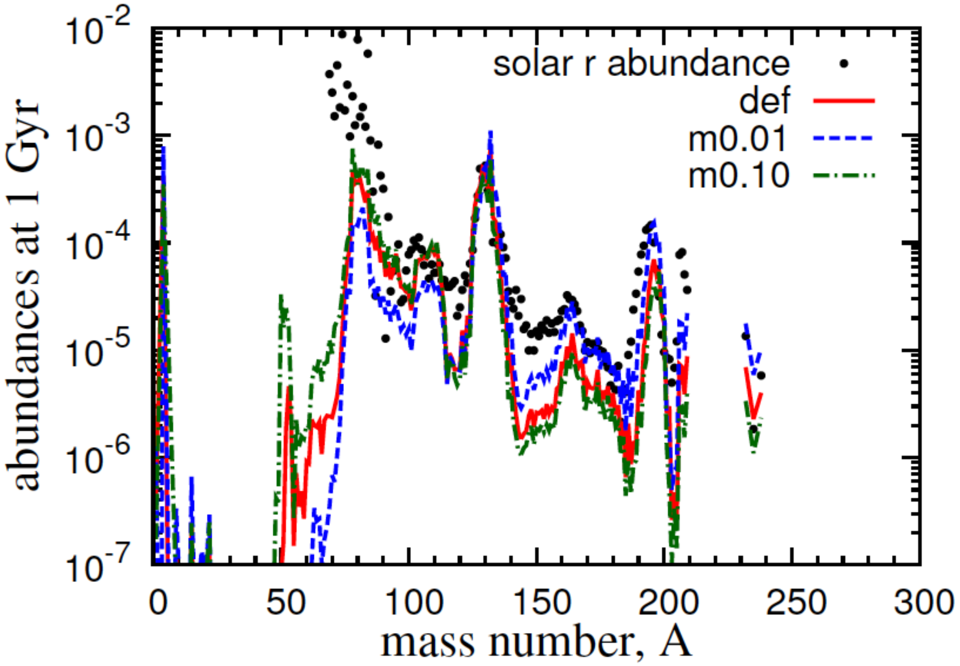
- Non-spinning BH, parameter dependencies

# Black Hole Accretion Disks

Varying disk viscosity:



Varying disk mass:

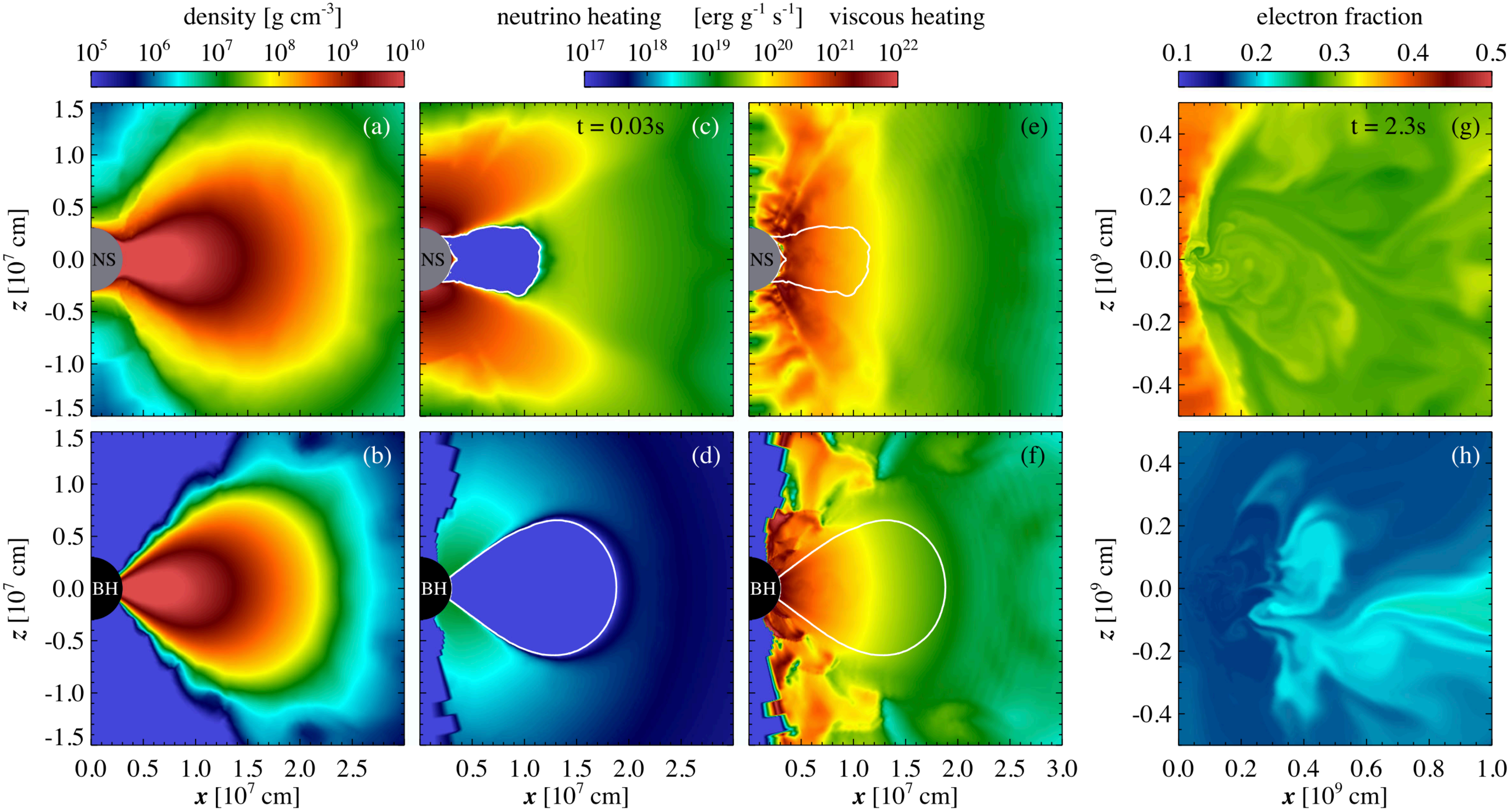


M-R Wu, RF, Martinez-Pinedo & Metzger (2016)

- Most sensitive to viscosity: expansion time vs weak interaction time
- Also sensitive to disk mass and degeneracy: neutrinos & equilibrium Ye

- Not very sensitive to initial Ye
- See also Just et al. 2015

# Hypermassive NS versus BH

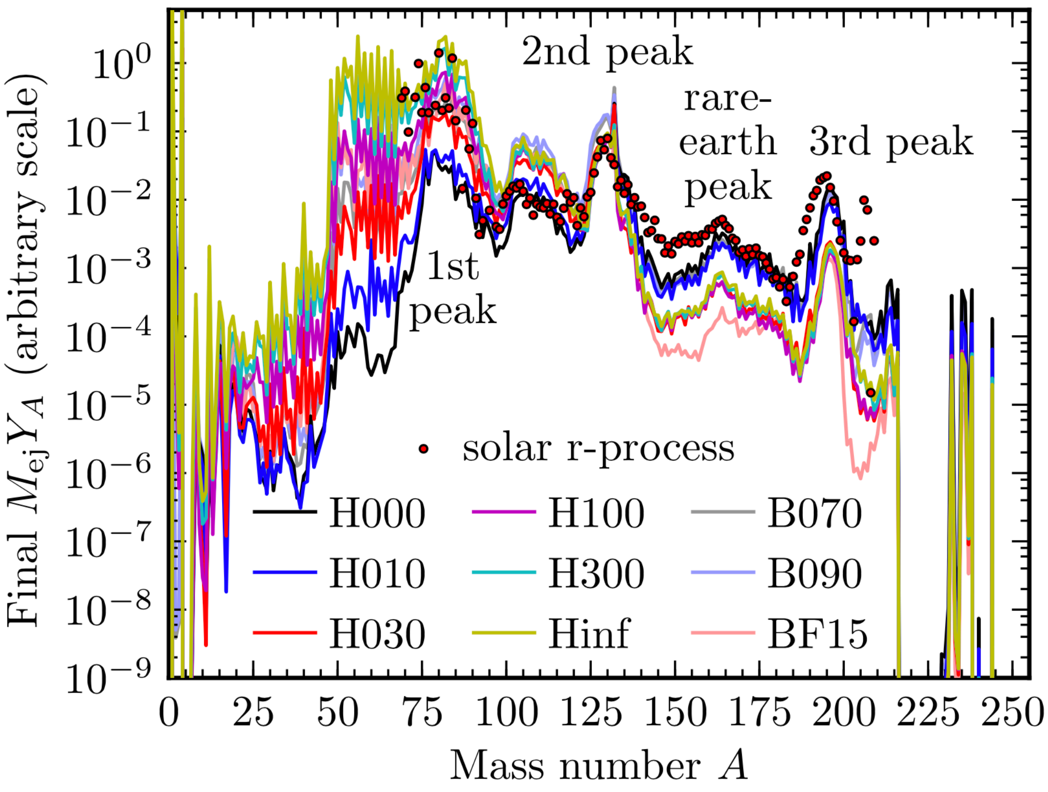


Metzger & RF (2014)

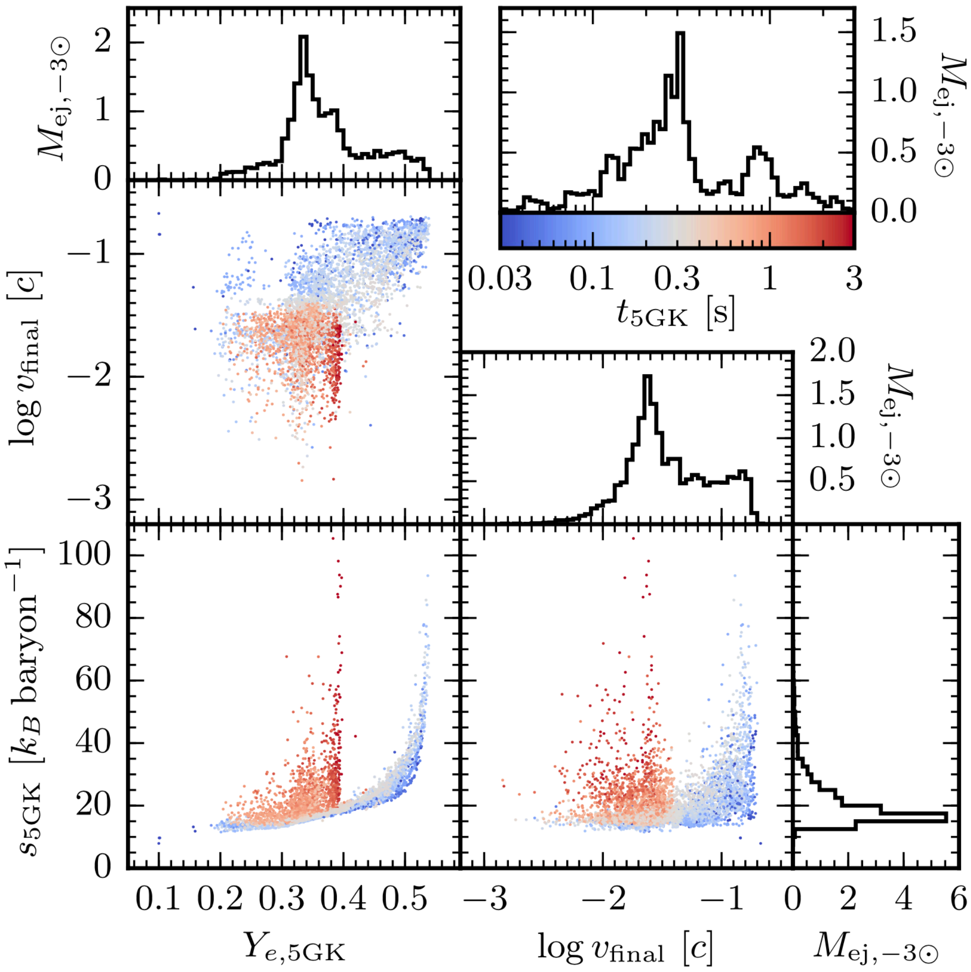
See also: Dessart+ (2009) Martin+ (2015) Moesta+ (2020)
Perego+ (2014) Fujibayashi+ (2017a,b) Ciolfi+ (2020)

# HMNS disks

Varying HMNS lifetime & BH spin



Outflow components (lifetime 300ms)



Lippuner, RF, Roberts, et al. (2017)

# Fast Flavor Instability

Quantum Kinetic equation ($f^{ab}$ : occupation number matrix)

$$p^{\alpha}\frac{\partial f}{\partial x^{\alpha}}+\frac{dp^{\alpha}}{d\lambda}\frac{\partial f}{\partial p^{\alpha}}=\boldsymbol{\varepsilon}\left(\mathscr{C}-\boldsymbol{i}\left[\mathscr{H},f\right]\right)$$

(e.g., Sigl & Raffelt 1993)

Hamiltonian matrix:

$$\mathscr{H}^{ab}(\mathbf{x},\mathbf{p}):=\mathscr{H}_{\text{vac}}(\boldsymbol{\varepsilon})+\mathscr{H}_{\text{matter}}(\mathbf{x})+\mathscr{H}_{\nu\nu}(\mathbf{x},\mathbf{v})$$

Self-interaction Hamiltonian

$$H_{\nu\nu}=\frac{\sqrt{2}G_{\mathrm{F}}}{(2\pi)^3}\int d^3p\ \left(f_{\nu}-\bar{f}_{\nu}^{*}\right)(1-\cos\theta)$$

Angular asymmetry in neutrino fluxes can result in rapid (~ns) oscillations over small (~cm) distances. Conditions fulfilled in NS merger remnants.

(e.g., Wu & Tamborra 2017)

+ large body of recent work (Richers, Duan, Dasgupta, Xiong, George, etc.)

# Global Prescription for Leakage Schemes

Simple implementation in a leakage+lightbulb scheme: neutrinos undergo flavor transformation upon emission, so effect applies only to **absorption**.

$$\eta_{\rm osc} = \exp(-\tau_{\bar{\nu}_e})$$

luminosity for absorption: $L^*_{\nu_i} \to L^{\rm eff}_{\nu_i} = (1-\eta_{\rm osc})L^*_{\nu_i} + \eta_{\rm osc}L^{\rm osc}_{\nu_i}$

“oscillated” luminosities:

$$\begin{aligned} L^{\rm osc}_{\nu_e} &= (1-a_{\rm osc})L^*_{\nu_e} + a_{\rm osc}L_{\nu_x} \\ L^{\rm osc}_{\bar{\nu}_e} &= (1-b_{\rm osc})L^*_{\bar{\nu}_e} + b_{\rm osc}L_{\bar{\nu}_x} \end{aligned}$$

“oscillated” temperatures:

$$\begin{aligned} kT^{\rm eff}_{\nu_e} &= (1-\eta_{\rm osc}a_{\rm osc})\; kT_{\nu_e} + \eta_{\rm osc}a_{\rm osc}\, kT_{\nu_x} \\ kT^{\rm eff}_{\bar{\nu}_e} &= (1-\eta_{\rm osc}b_{\rm osc})\; kT_{\bar{\nu}_e} + \eta_{\rm osc}b_{\rm osc}\, kT_{\bar{\nu}_x} \end{aligned}$$

flavor equilibration: $a_{\rm osc} = b_{\rm osc} = 2/3$

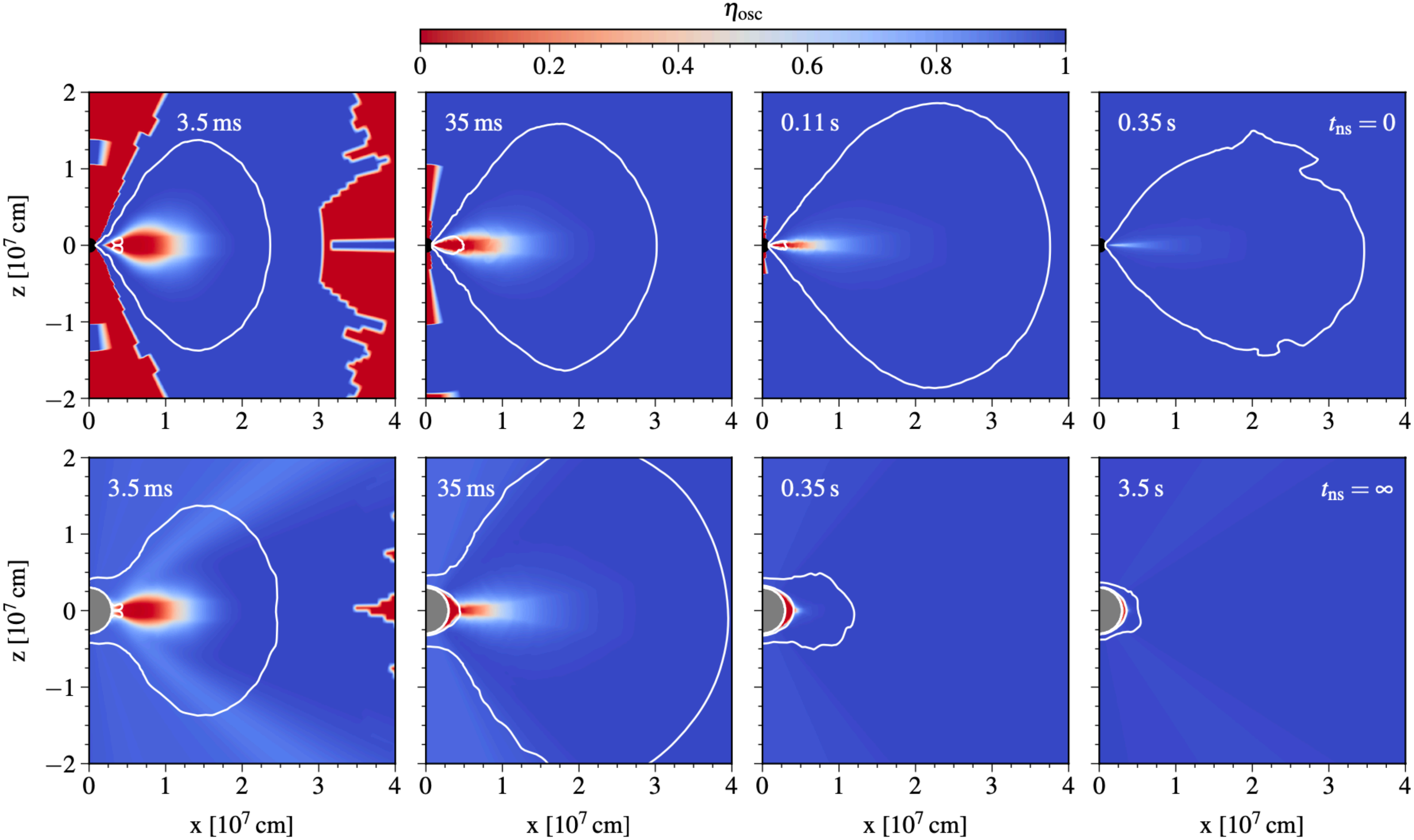
lepton number conservation: $a_{\rm osc}\,(n_{\nu_e} - n_{\nu_x}) = b_{\rm osc}\,(n_{\bar{\nu}_e} - n_{\bar{\nu}_x})$

Carry out a sequence of simulations, varying oscillation coefficients and HMNS lifetime

(previous work by Li & Siegel 2021 and Just et al. 2022)

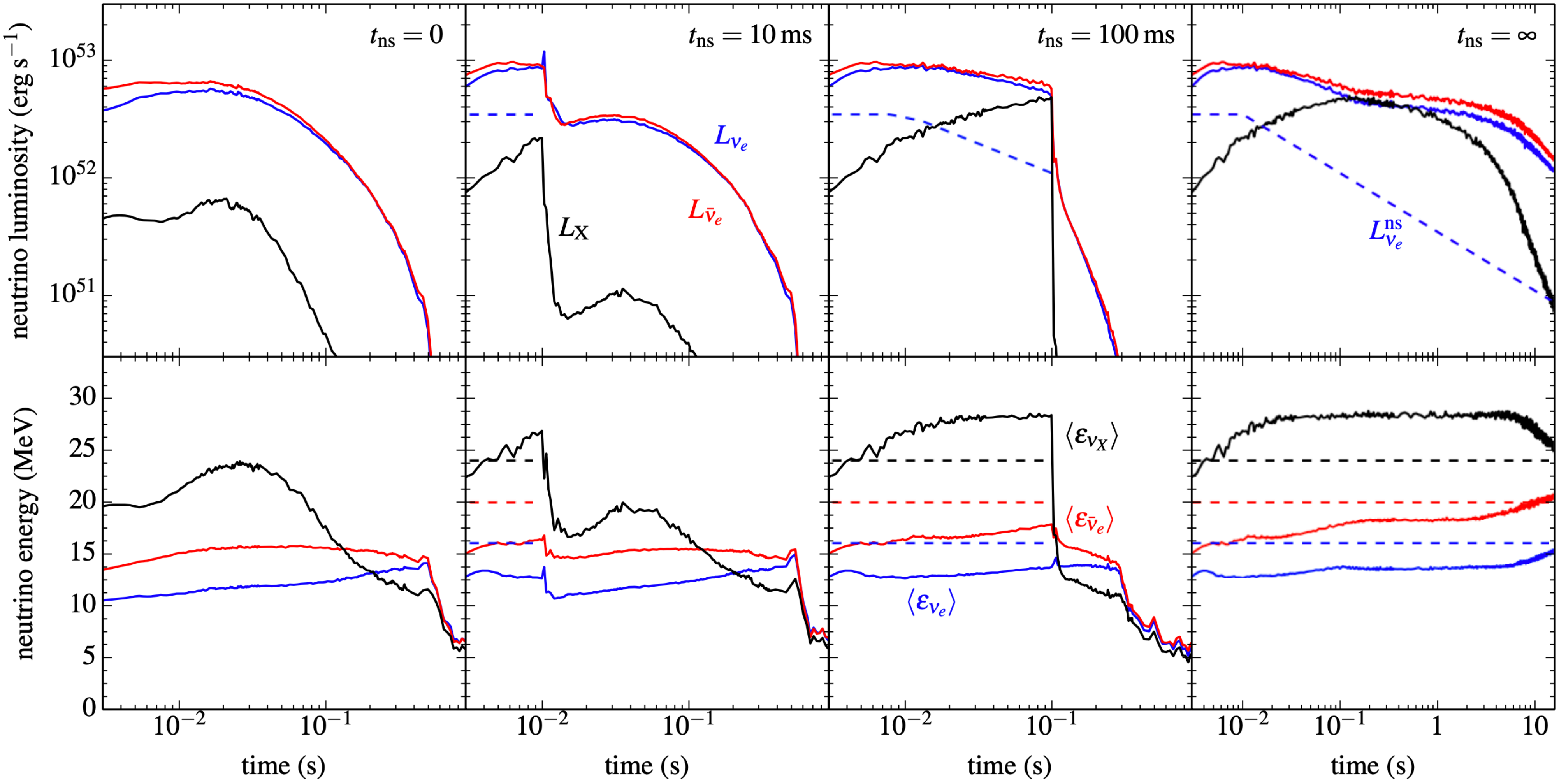
# Onset of the FFI

Activation Parameter: $\eta_{\rm osc} = \exp(-\tau_{\bar{\nu}_e})$



RF, Richers, Mulyk, & Fahlman (2022) arXiv:2207.10680

# Hierarchy of Luminosities & Energies

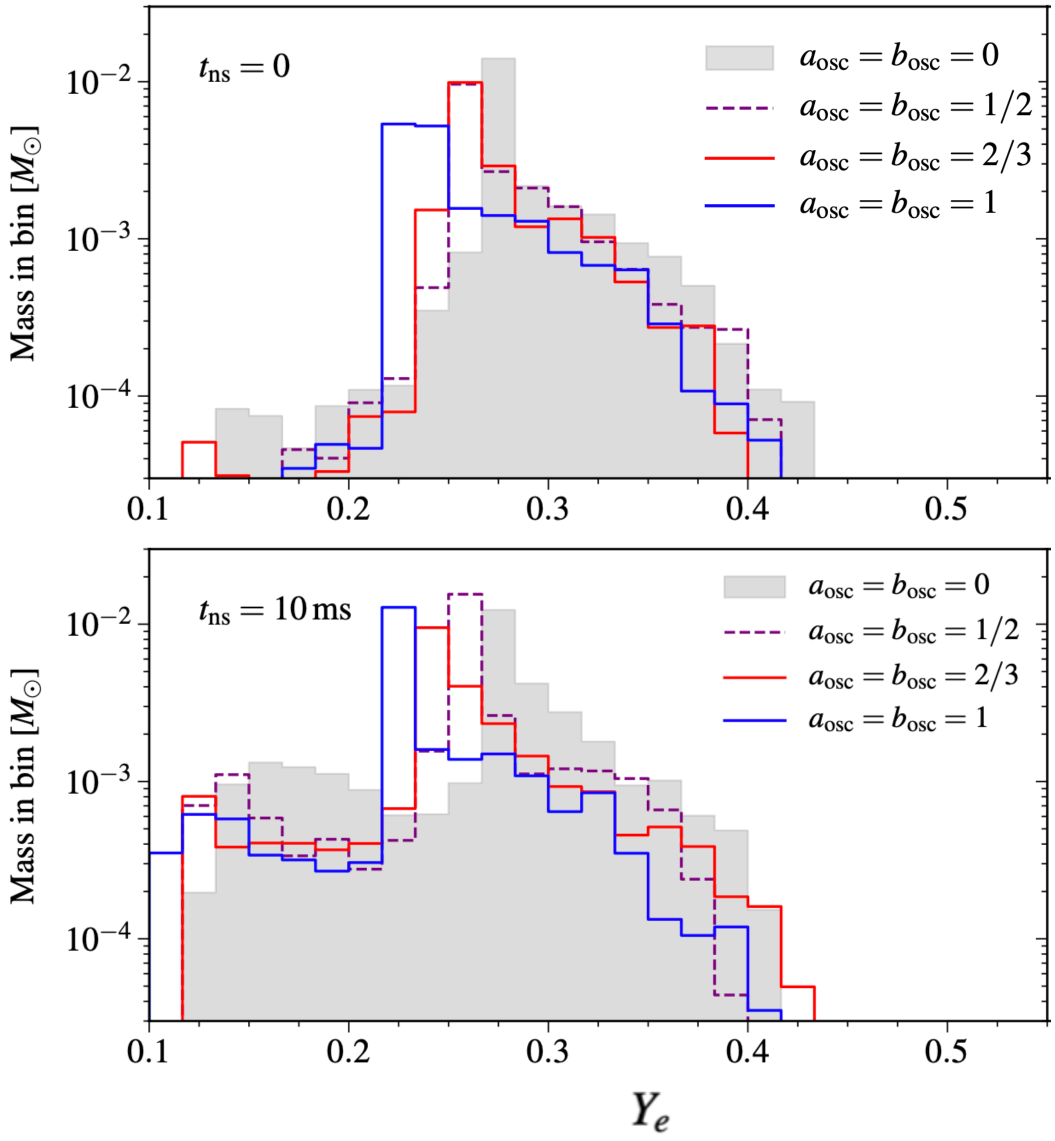


RF, Richers, Mulyk, & Fahlman (2022) arXiv:2207.10680

# Effect on Ye distribution: BH

Increasing the strength of flavor transformation makes the outflow more neutron rich: electron fraction distribution shifts

A short-lived HMNS preserves the trend: more neutron rich outflow (a neutrino-driven component emerges)

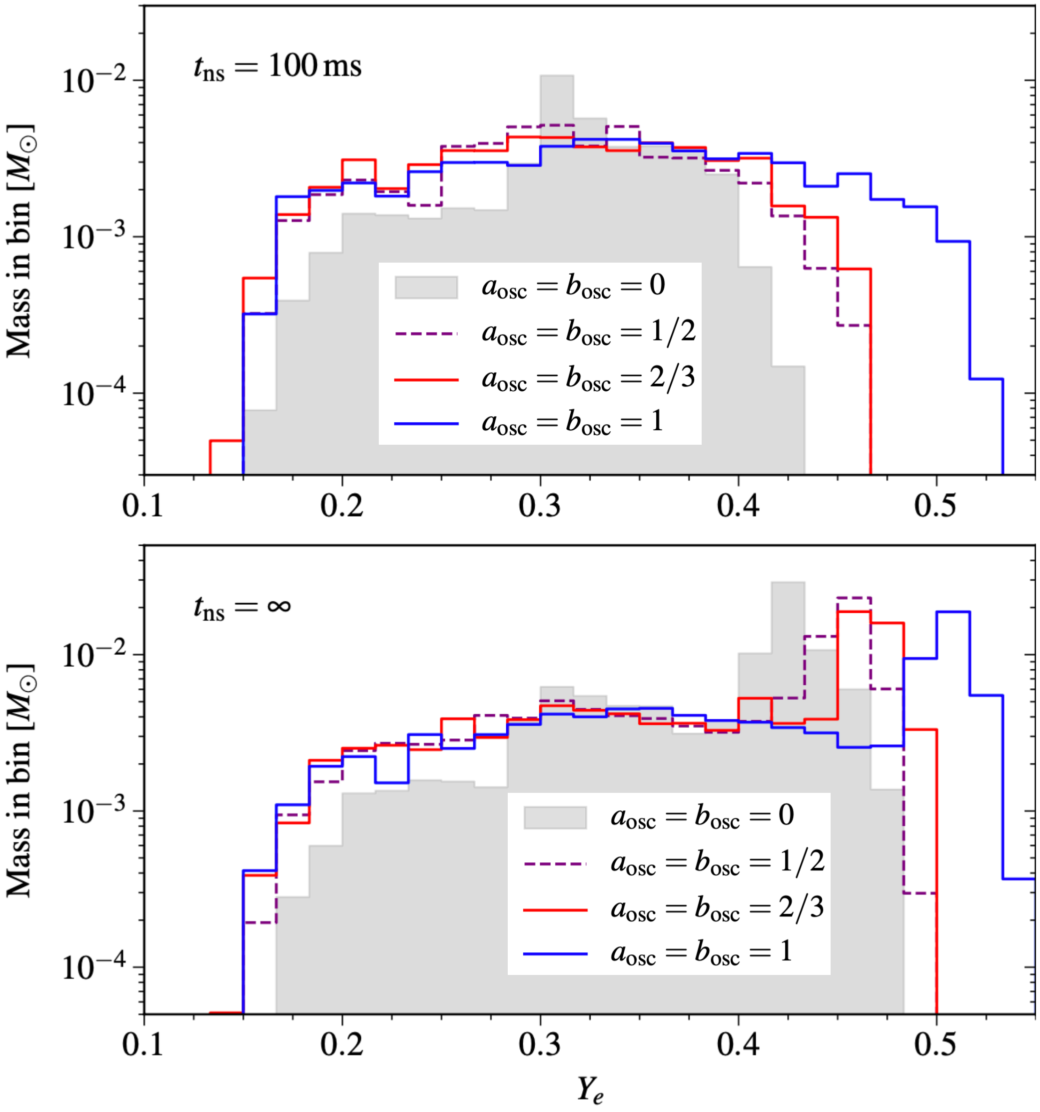


RF, Richers, Mulyk, & Fahlman (2022) arXiv:2207.10680

# Effect on Ye distribution: HMNS

For longer lived HMNS disks, the strength of flavor transformation also introduces a less neutron rich component

The effect is strongest for very long-lived HMNS (until the end of the simulation)

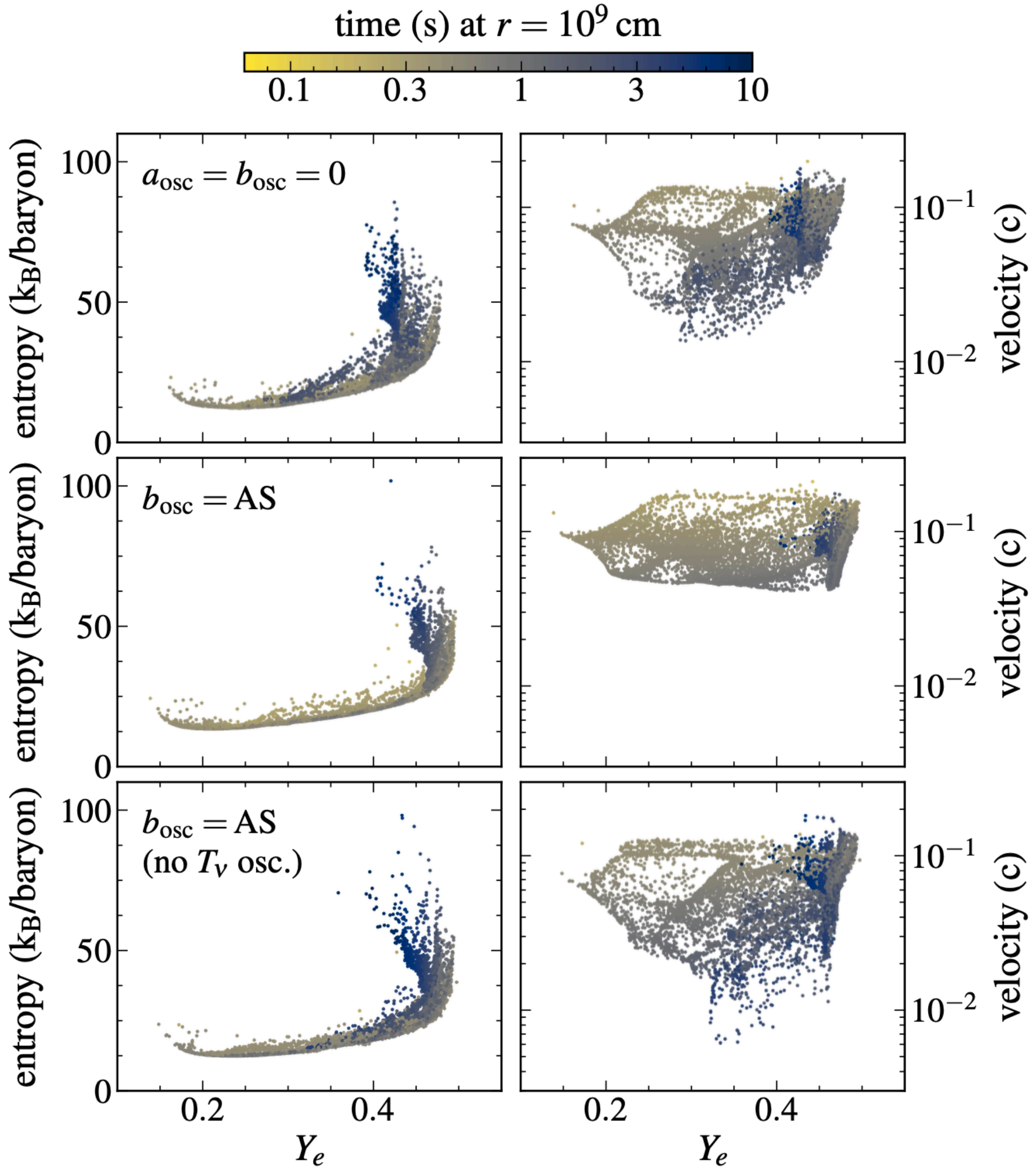


RF, Richers, Mulyk, & Fahlman (2022)
arXiv:2207.10680

# FFI and Radiative Driving

For long-lived HMNS, flavor transformation increases radiative driving: low velocity outflow is removed.

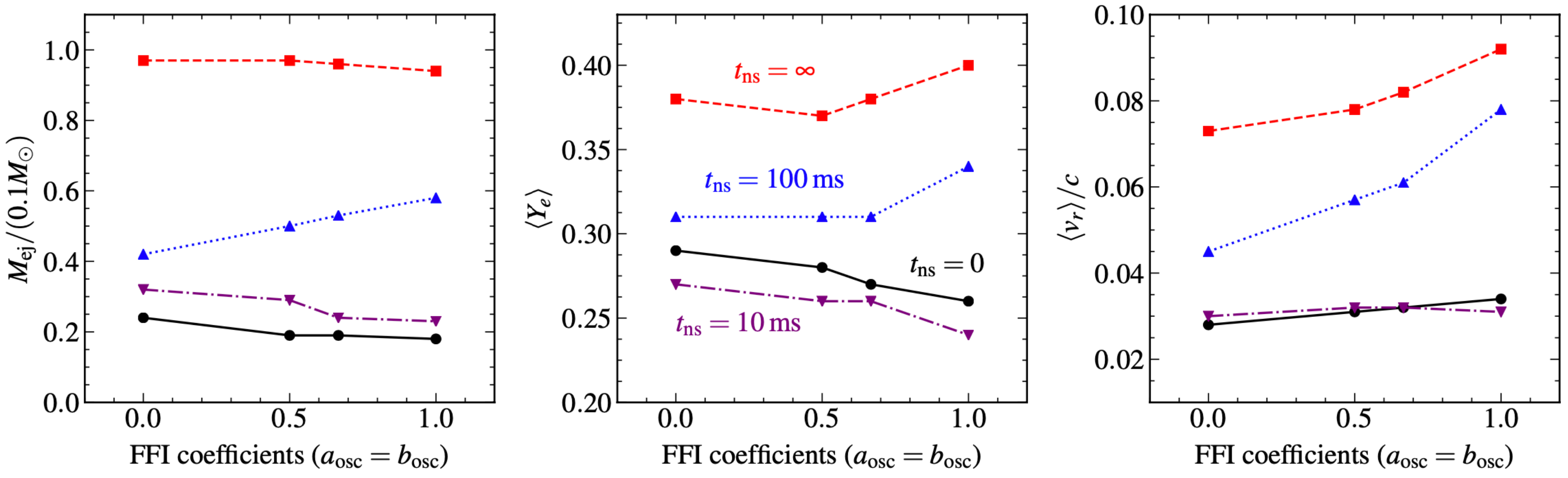
Effect of temperature swapping is most important for radiative driving. Keeping swapping of fluxes but not of temperature yields similar results to unoscillated case.



RF, Richers, Mulyk, & Fahlman (2022)

arXiv:2207.10680

# Trends with Flavor Swap



Short-lived HMNS: lower Ye, mass ejection decreases

Long-lived HMNS: higher Ye, mass ejection can increase

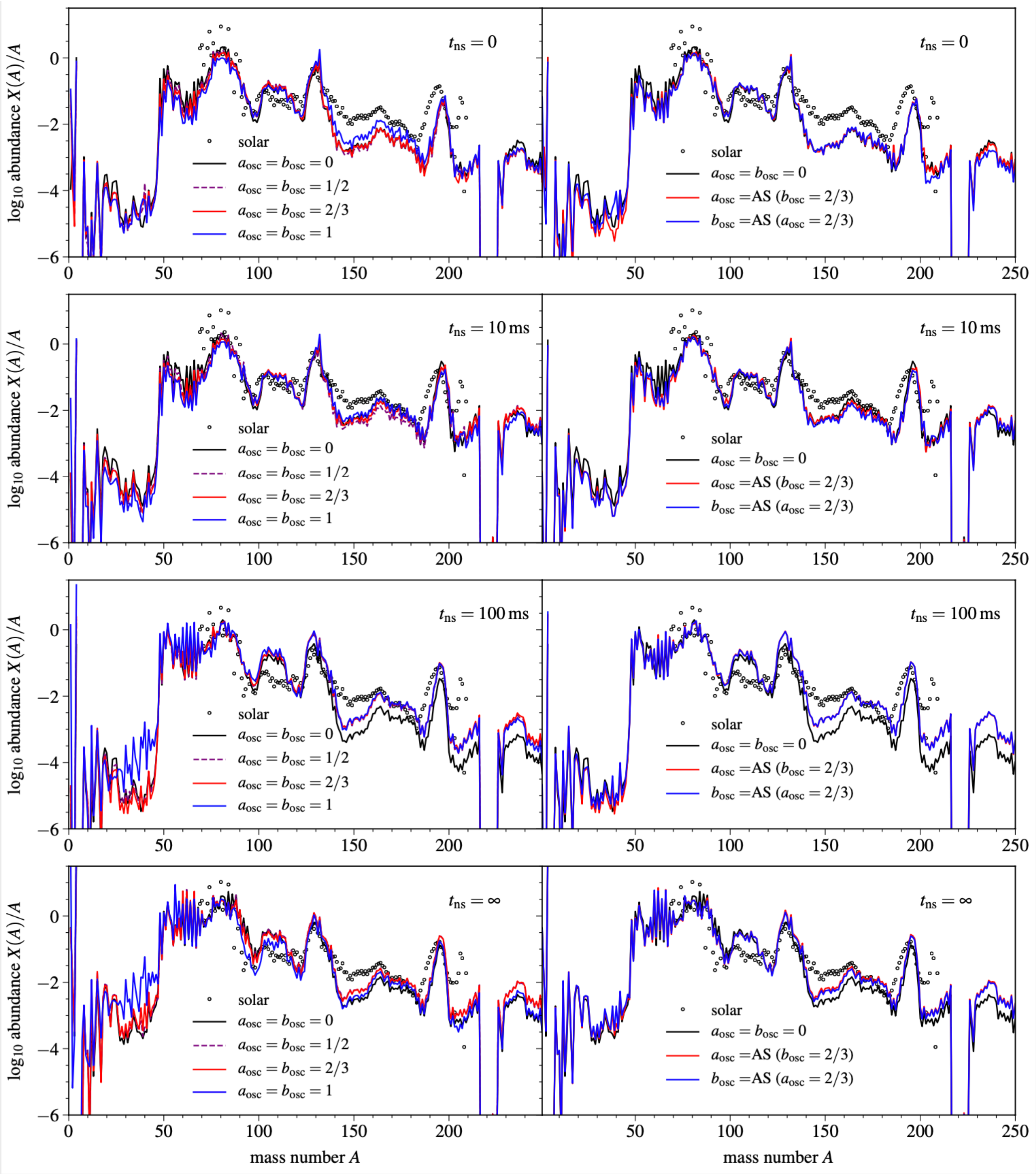
faster outflow in all cases (lower amount of  marginally bound ejecta)

RF, Richers, Mulyk, & Fahlman (2022)
arXiv:2207.10680

# Nucleosynthesis Effects

Overall, minor impact on the composition of the outflow.

Mass fraction of lanthanides can change by a factor ~ 2



RF, Richers, Mulyk, & Fahlman (2022) arXiv:2207.10680

# Summary

1. Global prescription for the FFI applicable to neutrino leakage schemes, using flavor equilibration at varying levels, or conservation of lepton number. Applied to accretion disks.

2. Effects controlled by swapping of neutrino fluxes and mean energies.

3. Prompt BH: lower electron neutrino absorption and higher cooling, less ejecta and more neutron rich

4. Long-lived HMNS: broader Ye distribution, more ejecta moving faster, stronger neutrino driven wind component

**PRD, 2022, v. 106, 103003** **arXiv:2207.10680**

Thanks to: