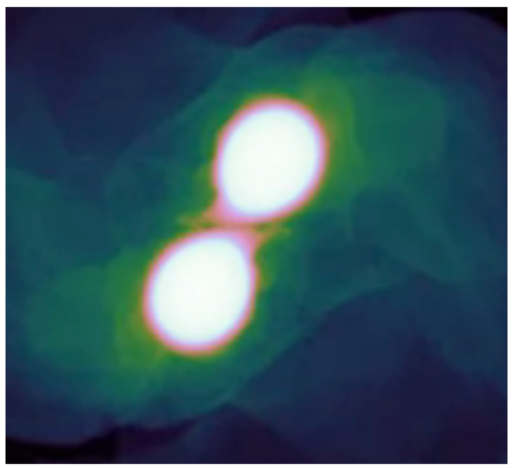
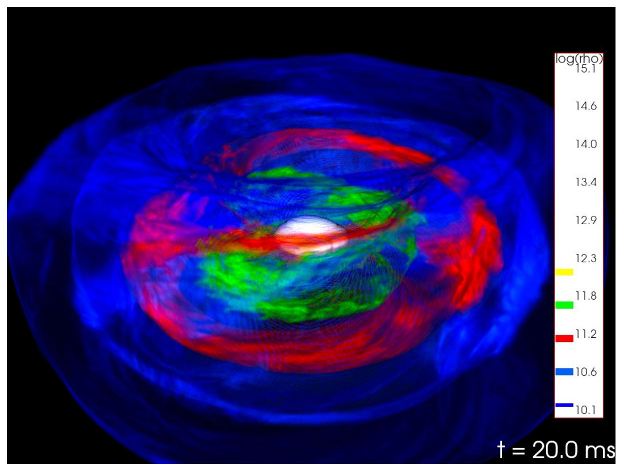
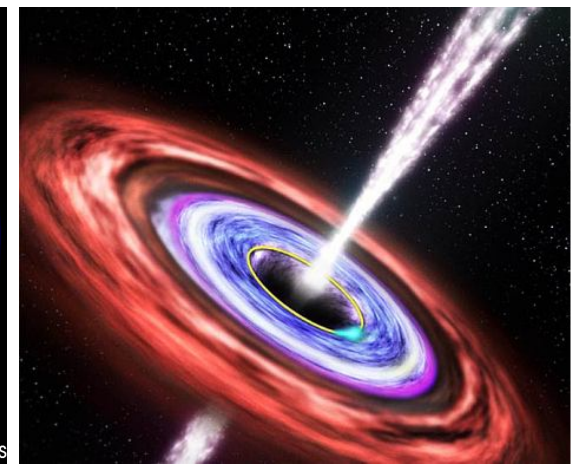
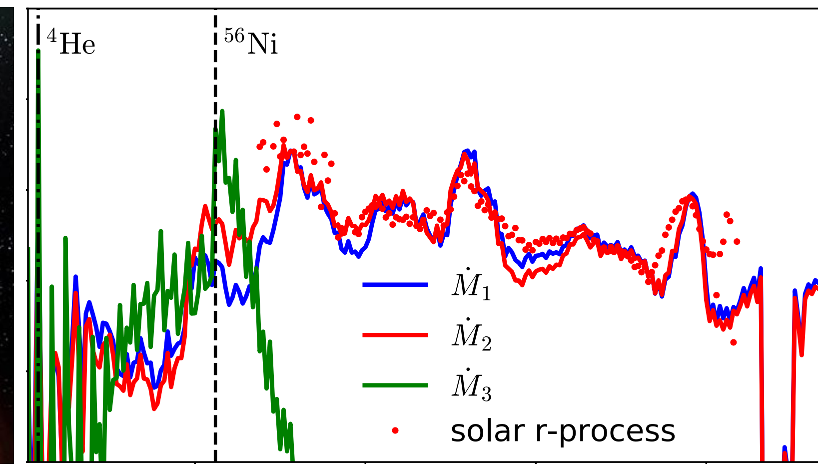
Post-merger evolution and nucleosynthesis









Daniel M. Siegel

Perimeter Institute for Theoretical Physics

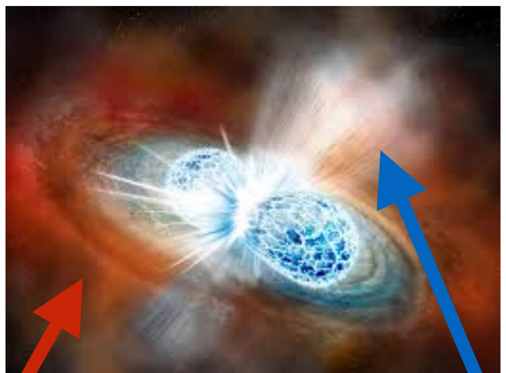
and University of Guelph, Ontario, Canada

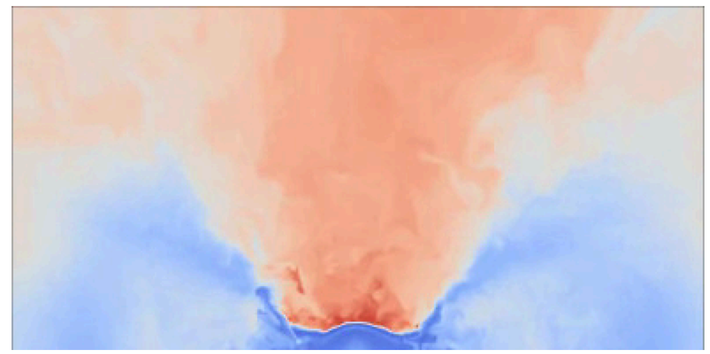
TCAN meeting, July12-15, 2021

Neutron-star mergers

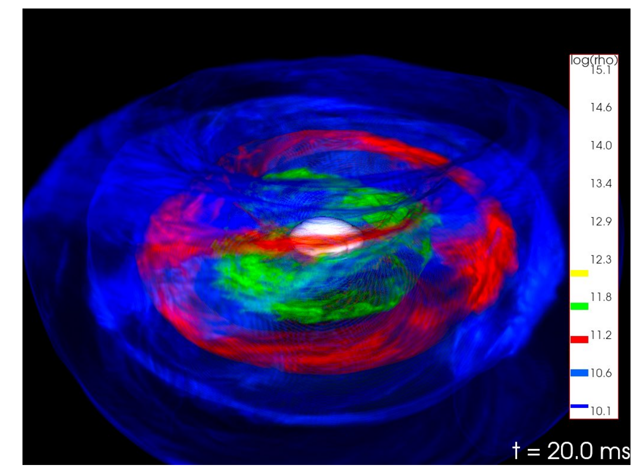
dynamical ejecta (~ms) | wind ejecta (~10-100ms) | accretion disk ejecta (~0.1-1s)

NS-NS





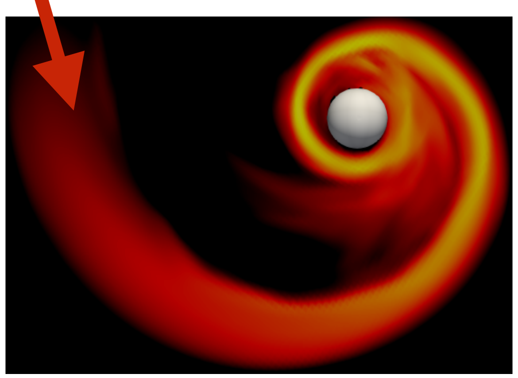
remnant NS



tidal ejecta

shock-heated ejecta

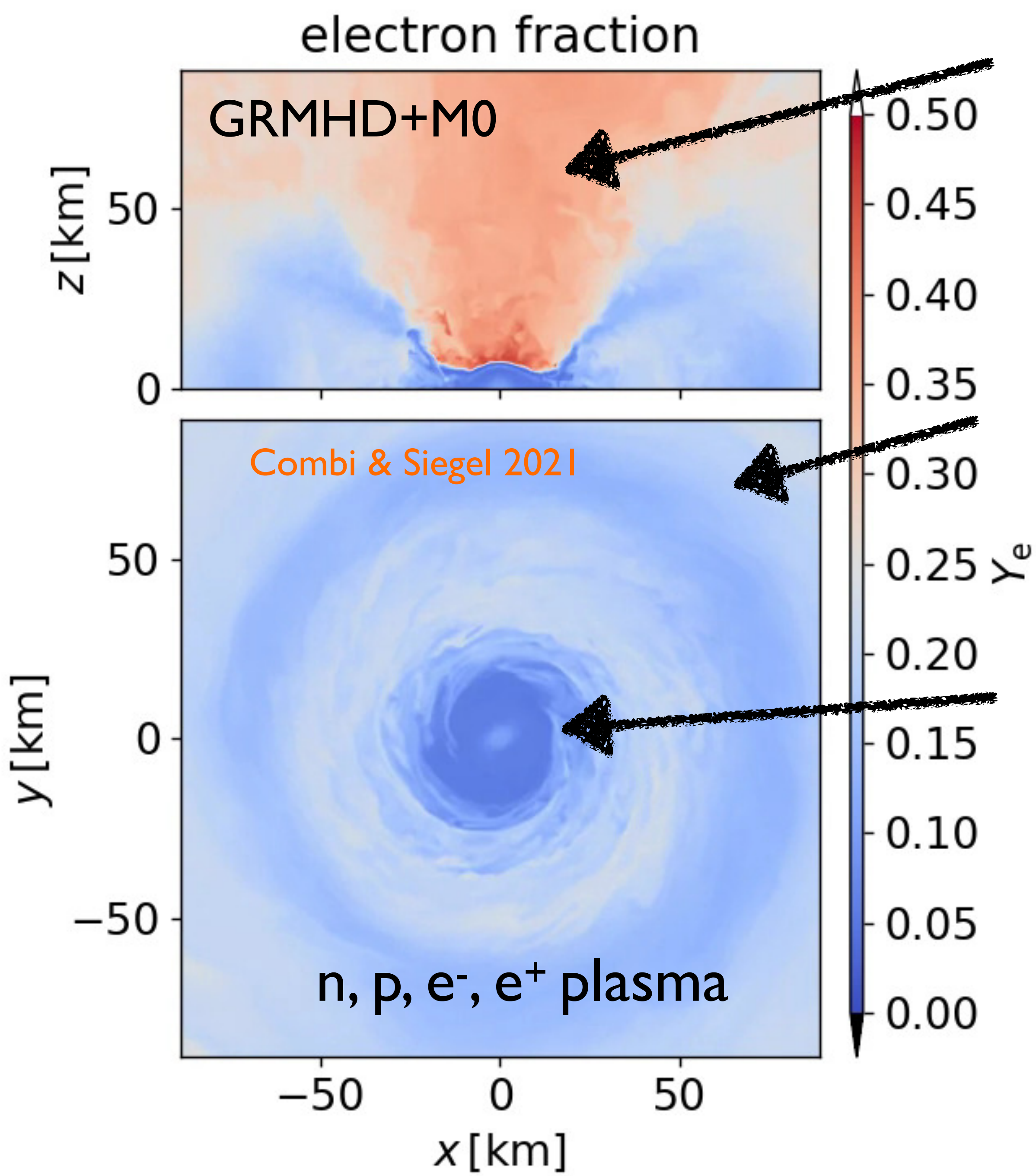
NS-BH



Some complications for NS-NS:

- magnetically driven winds
- neutrino-driven winds
- GWs, non-linear (magneto-)hydrodynamics

Early post-merger phase



neutrino irradiation changes plasma composition:
high proton fraction ($Y_e > 0.25$), hot wind ejecta

medium proton fraction (Y_e), hot (>10 MeV) disk wind

hot (>30 MeV) neutron star

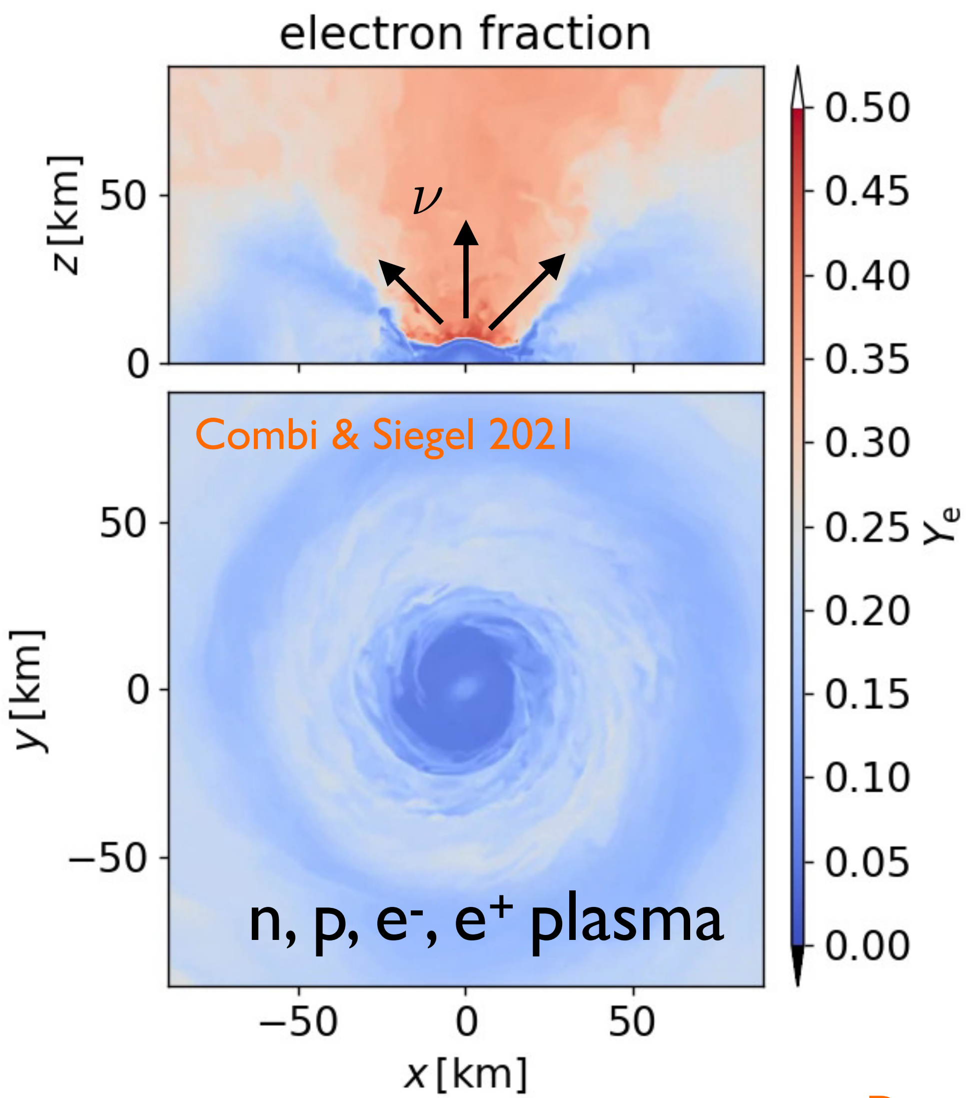
- neutrino-driven winds
- magnetically driven winds
- GWs, non-linear hydrodynamics

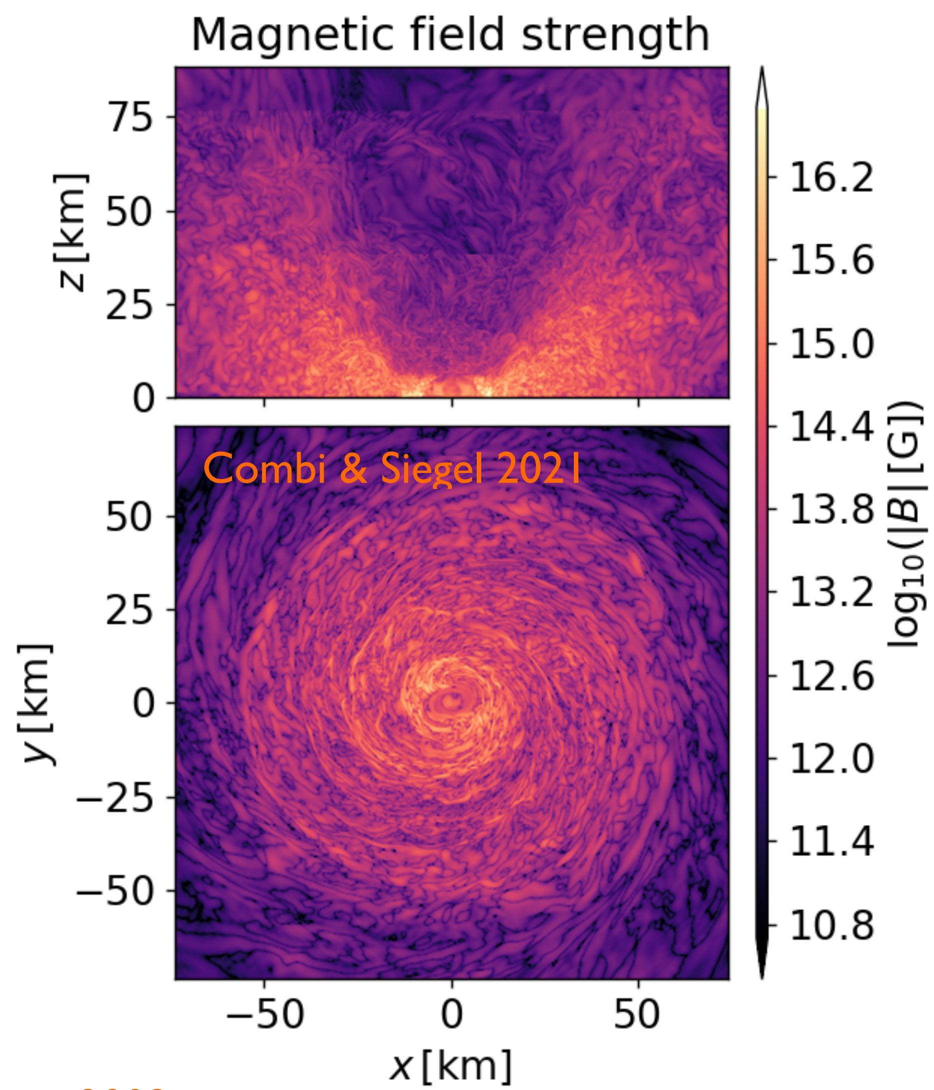
Dessart+ 2009
Siegel+ 2014
Ciolfi & Kalinani 2020
Metzger+ 2018

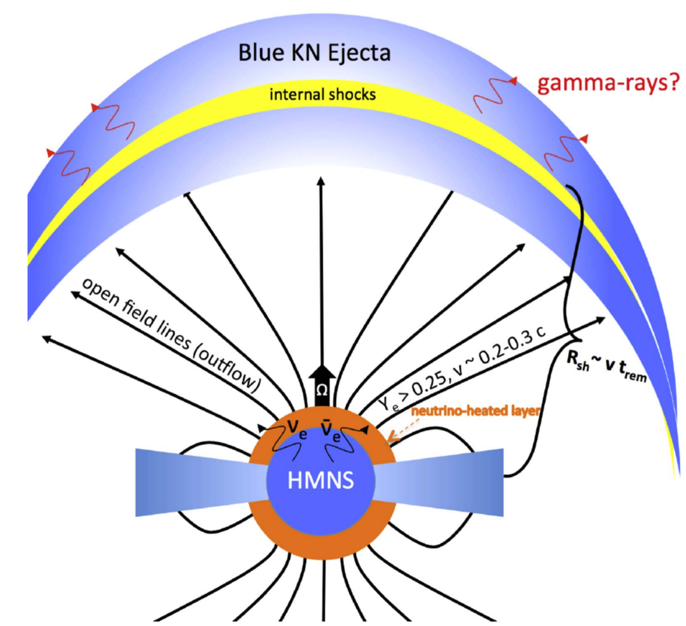
Nedora+ 2019, 2021
Kastaun & Ohme 2021
Shibata+ 2021

Early post-merger phase

Mass ejection: neutrino- and magnetically driven winds







Metzger+ 2018

- neutrino-driven winds
- magnetically driven winds
- GWs, non-linear hydrodynamics

Dessart+ 2009
Siegel+ 2014
Ciolfi & Kalinani 2020
Metzger+ 2018

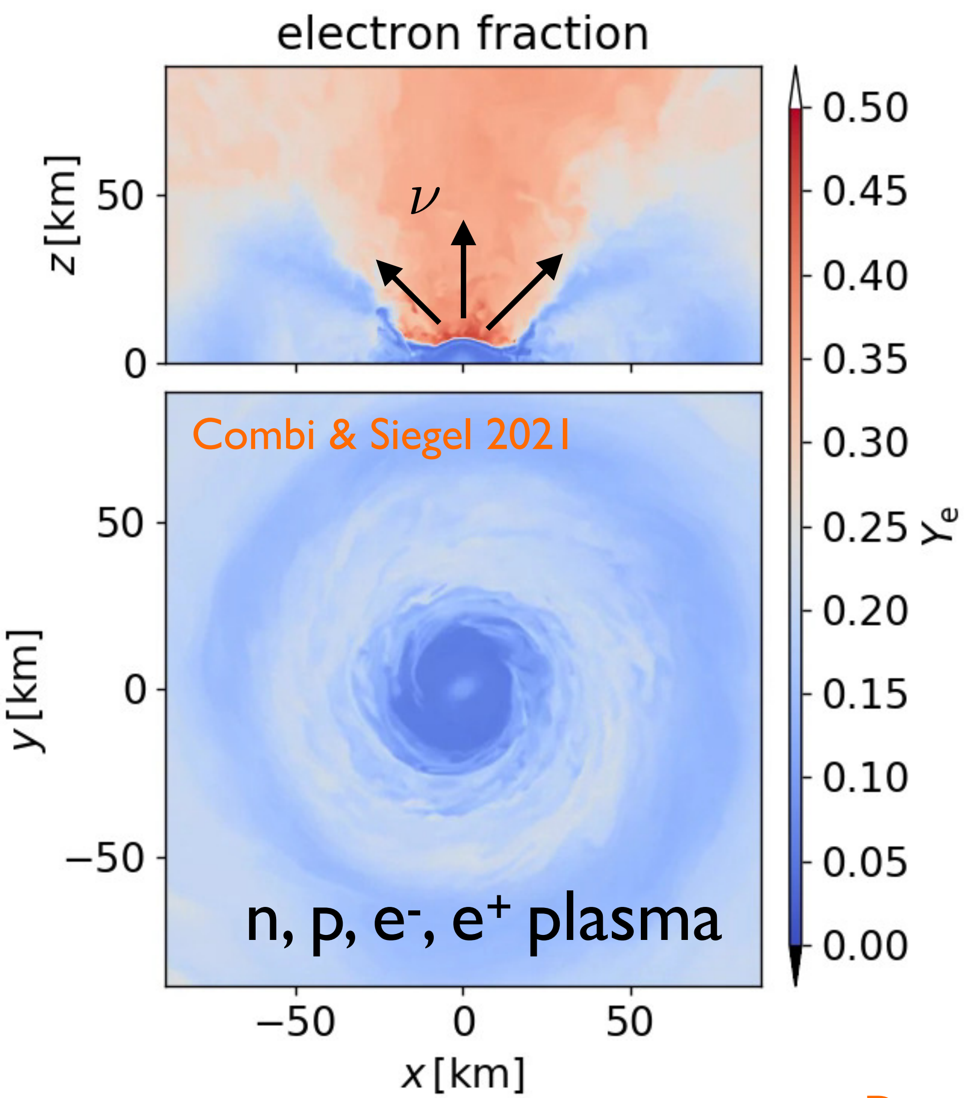
Nedora+ 2019, 2021
Kastaun & Ohme 2021
Shibata+ 2021

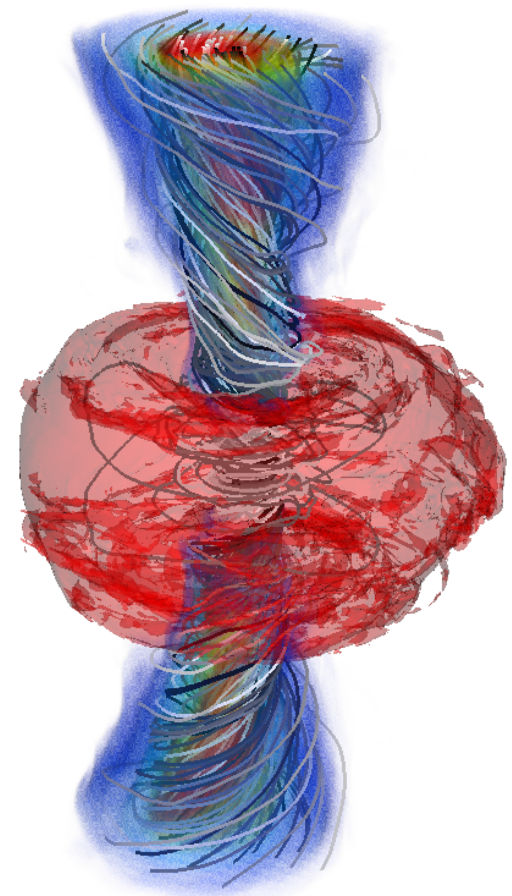
Estimated ejecta mass:

$$M_{\rm ej} \sim (10^{-4} - 10^{-2}) M_\odot \left(\frac{t_{\rm rem}}{0.1{\rm s}}\right)$$

Early post-merger phase

Mass ejection: neutrino- and magnetically driven winds





Mösta+ 2020

Start with 10^{15}G poloidal B-field after merger, short lived remnant (~20ms)

$$\dot{M} \sim 10^{-1} M_{\odot}\,\mathrm{s}^{-1}$$

$$v \sim 0.05 - 0.4c$$

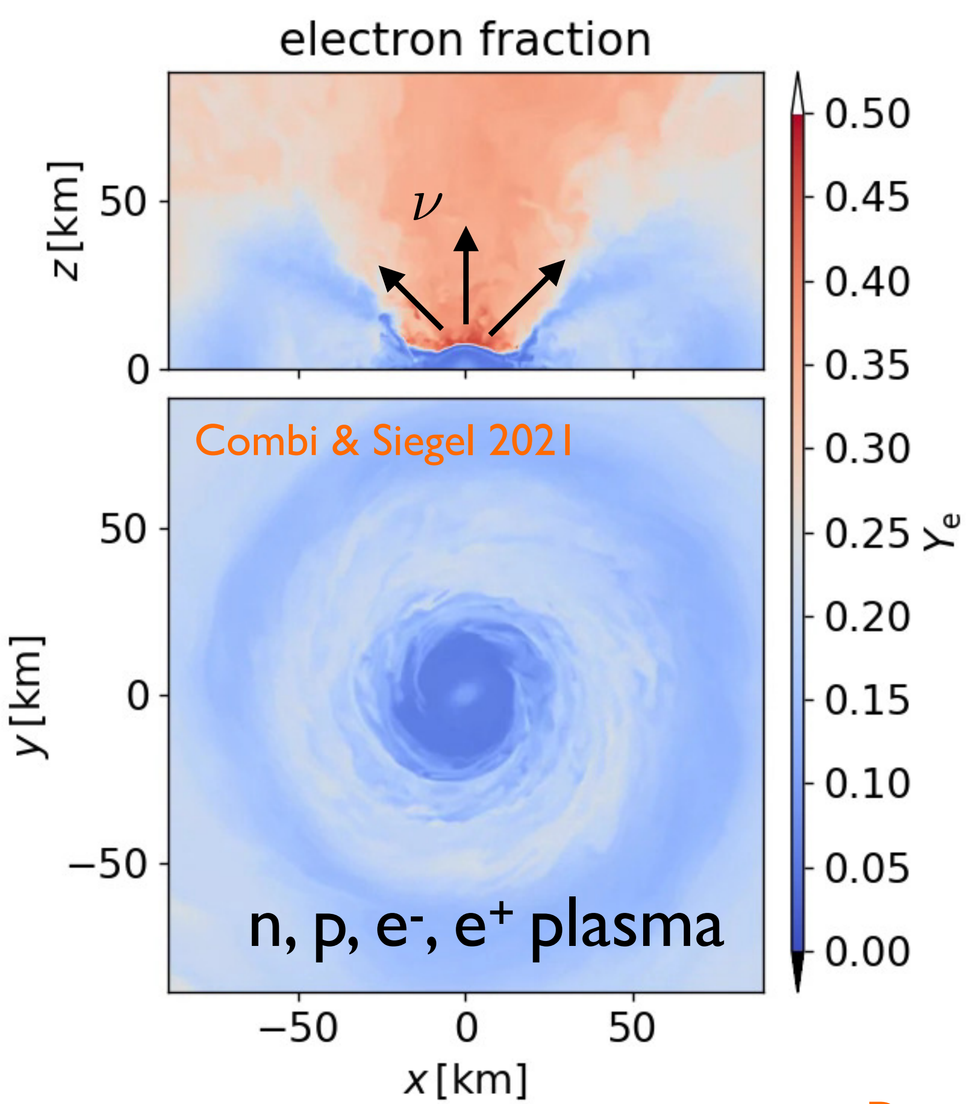
- neutrino-driven winds
- magnetically driven winds
- GWs, non-linear hydrodynamics

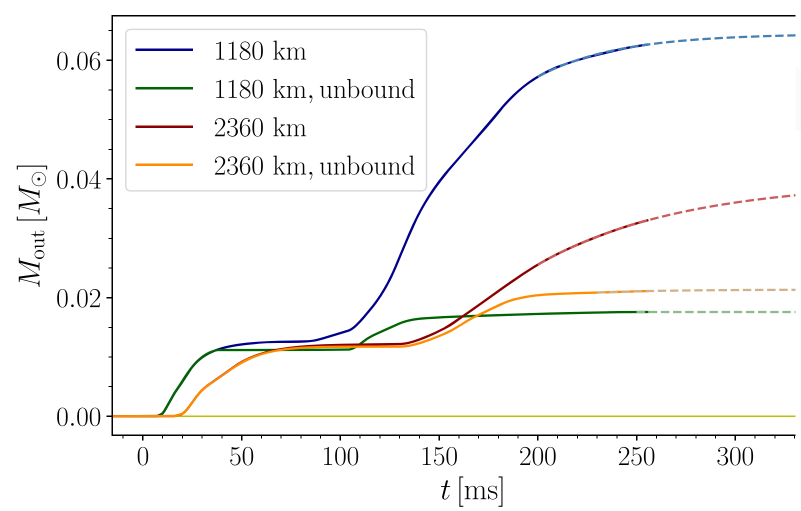
Dessart+ 2009
Siegel+ 2014
Ciolfi & Kalinani 2020
Metzger+ 2018

Lehner+ 2016, Nedora+ 2019, 2021
Kastaun & Ohme 2021
Shibata+ 2021

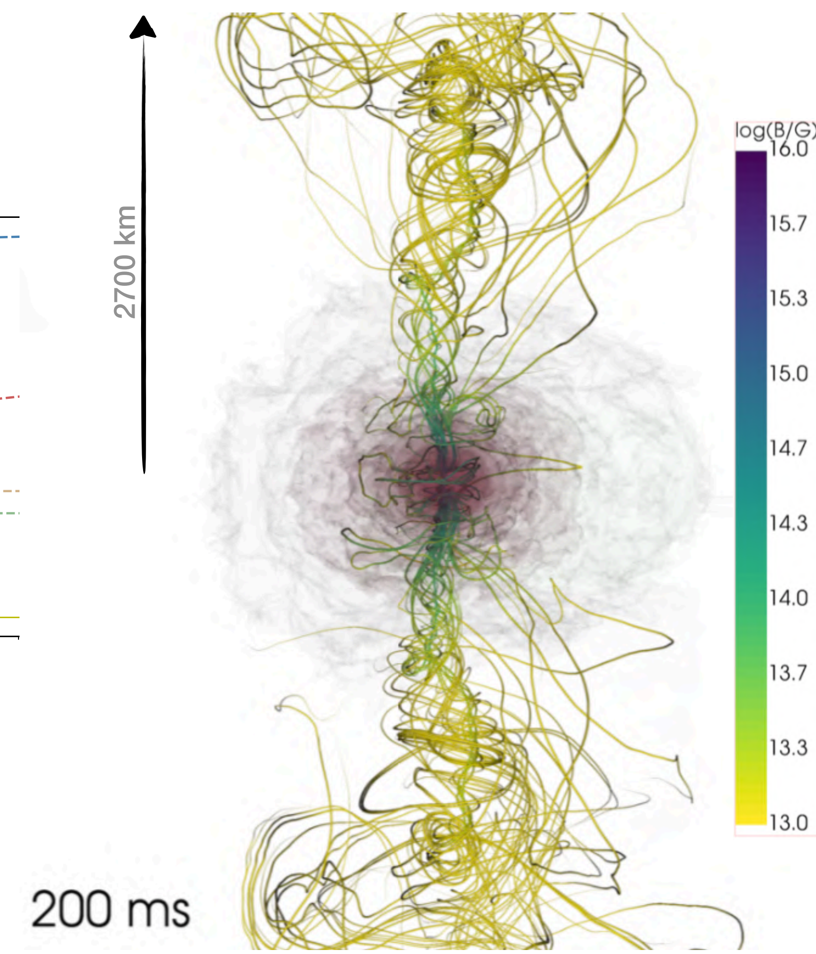
Early post-merger phase

Mass ejection: neutrino- and magnetically driven winds





Ciolfi & Kalinani 2020



- neutrino-driven winds
- magnetically driven winds
- GWs, non-linear hydrodynamics

Dessart+ 2009
Siegel+ 2014
Ciolfi & Kalinani 2020
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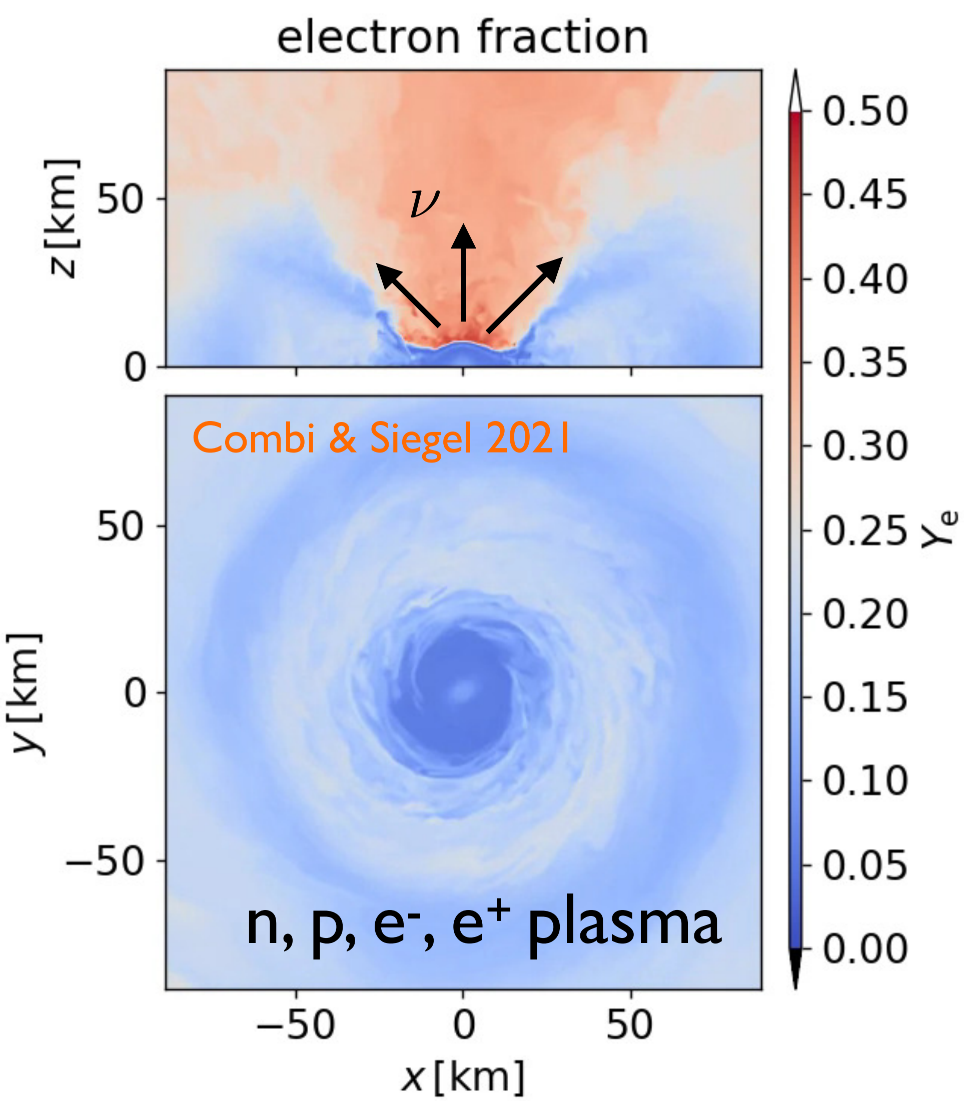
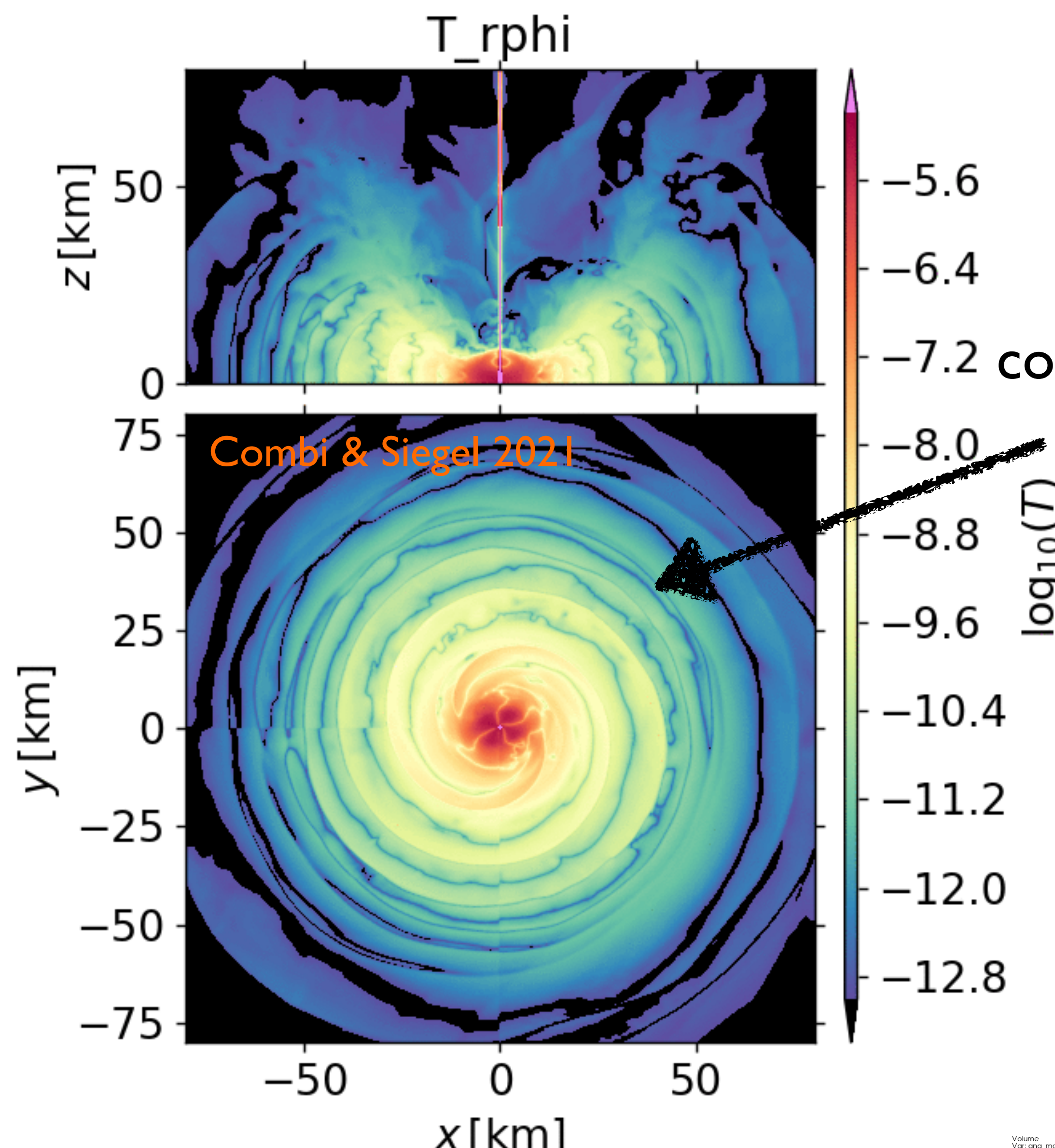
Lehner+ 2016, Nedora+ 2019, 2021
Kastaun & Ohme 2021
Shibata+ 2021

Early post-merger phase

Mass ejection: disk winds & spiral waves



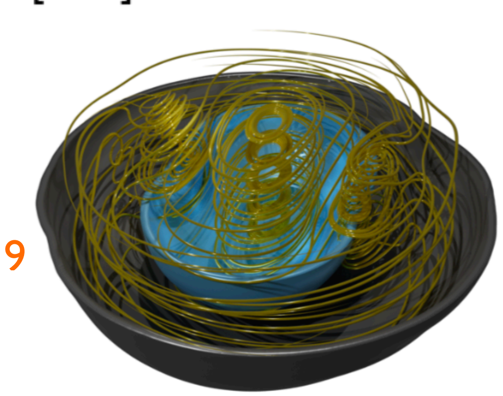


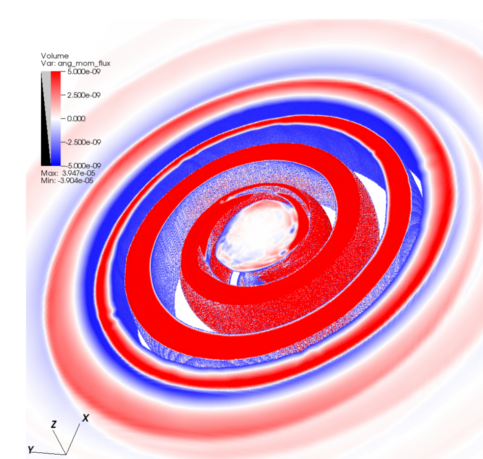
competition btw. MRI and spiral waves

- neutrino-driven winds
- magnetically driven winds
- GWs, non-linear hydrodynamics

Dessart+ 2009
Siegel+ 2014
Ciolfi & Kalinani 2020
Metzger+ 2018

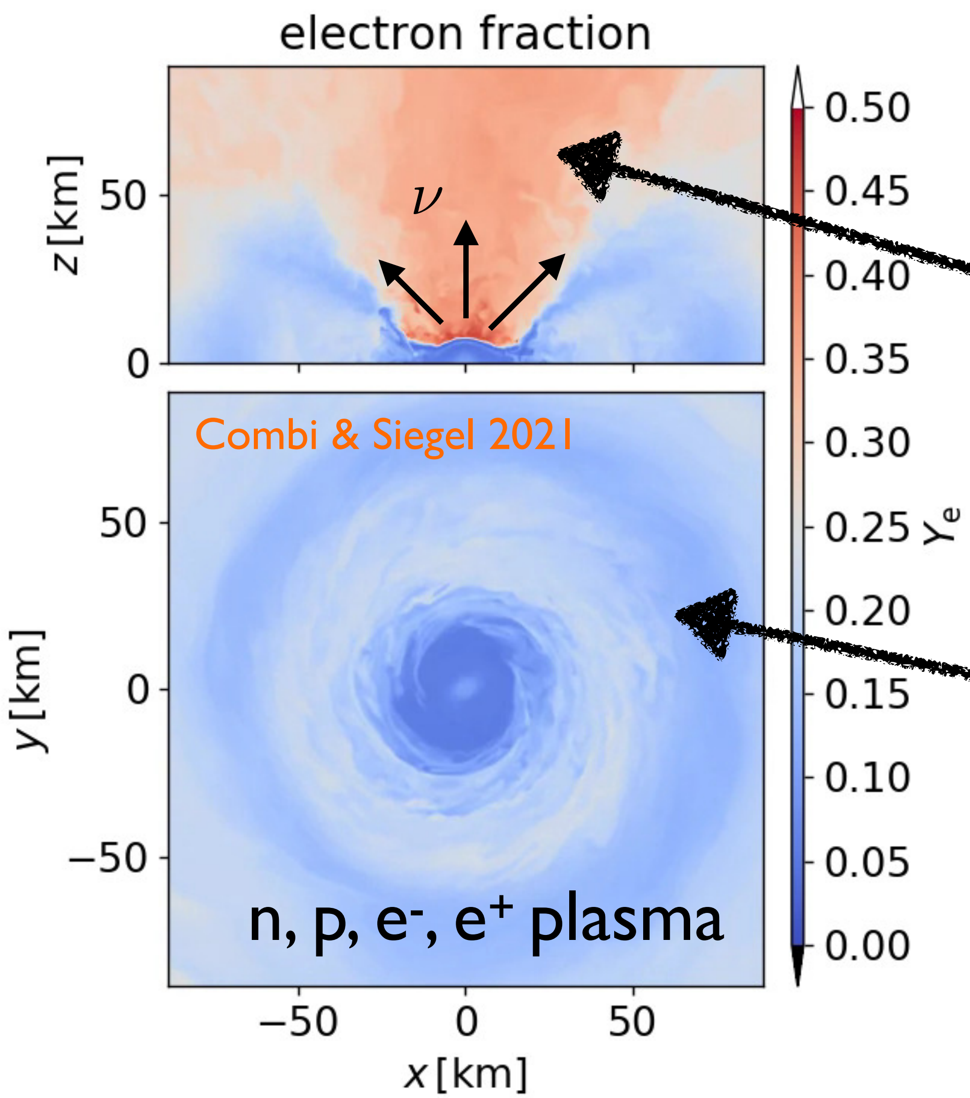
Lehner+ 2016. Nedora+ 2019
Kastaun & Ohme 2021
Shibata+ 2021





Early post-merger phase

Mass ejection: composition



Chiefly determined by: (radiation transport!)

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

absorption dominated, non-degenerate: Qian & Woosley 1996

$$Y_e^{\rm eq} \simeq \left[1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \frac{\epsilon_{\bar{\nu}_e} - 2\Delta + 1.2\Delta^2/\epsilon_{\bar{\nu}_e}}{\epsilon_{\nu_e} + 2\Delta + 1.2\Delta^2/\epsilon_{\nu_e}}\right]^{-1} \sim 0.4 - 0.5$$

absorption and emission important, degenerate

→ typically low Y_e: $Y_e \simeq Y_e^{\rm eq} \sim 0.1 - 0.2$ Beloborodov 2001

final Y_e of disk outflow strongly depends on ejection path and timescale as it traverses different regimes (details of accretion disk evolution matter):

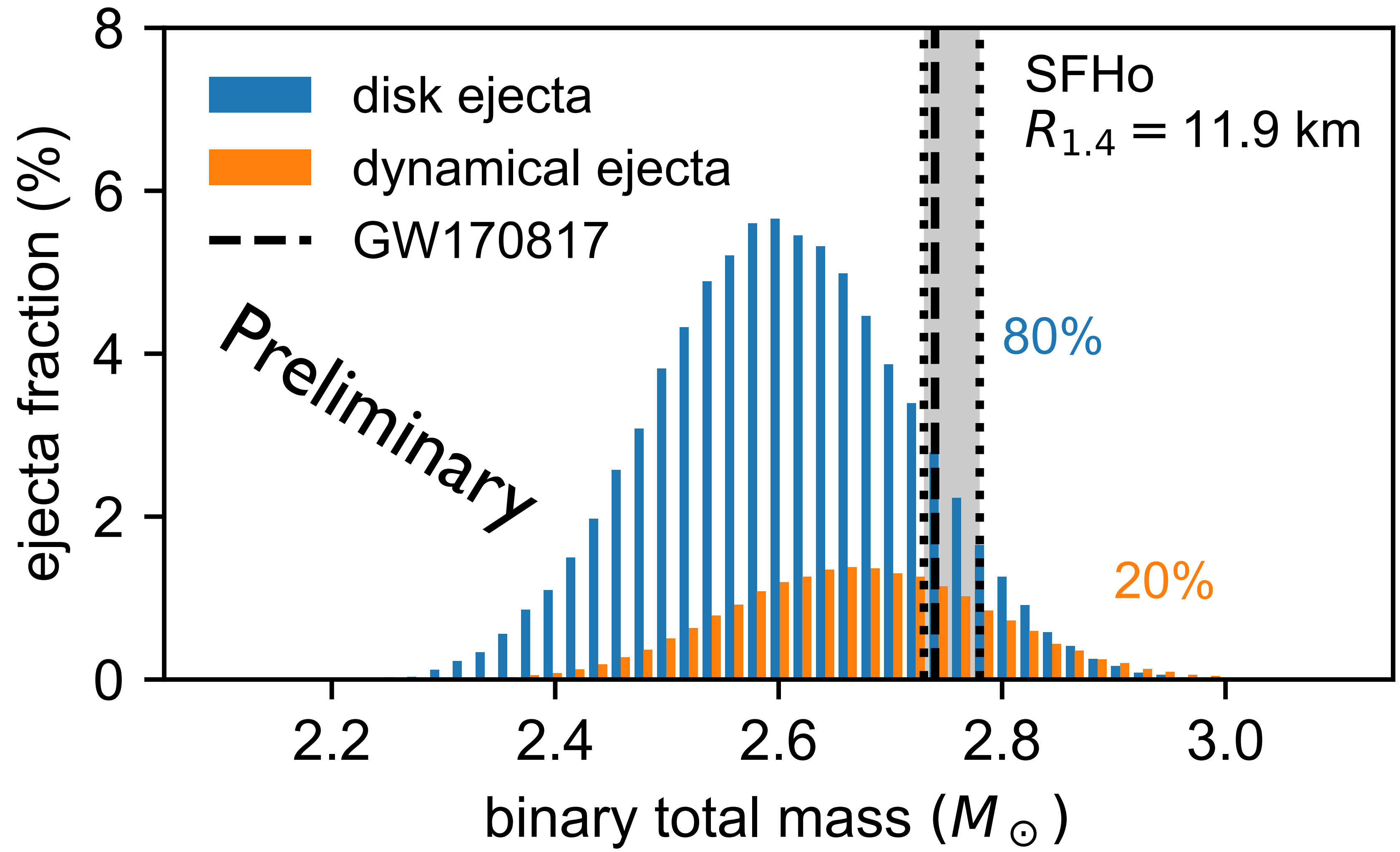
trapped, emission+absorption → mostly emission → mostly absorption → Y_e freeze out

decreasing density, temperature ⟶

disk viscous evolution, disk radius ⟶

Post-merger disks: exploring BNS parameter space

Siegel 2021, Nature Rev. Phys.

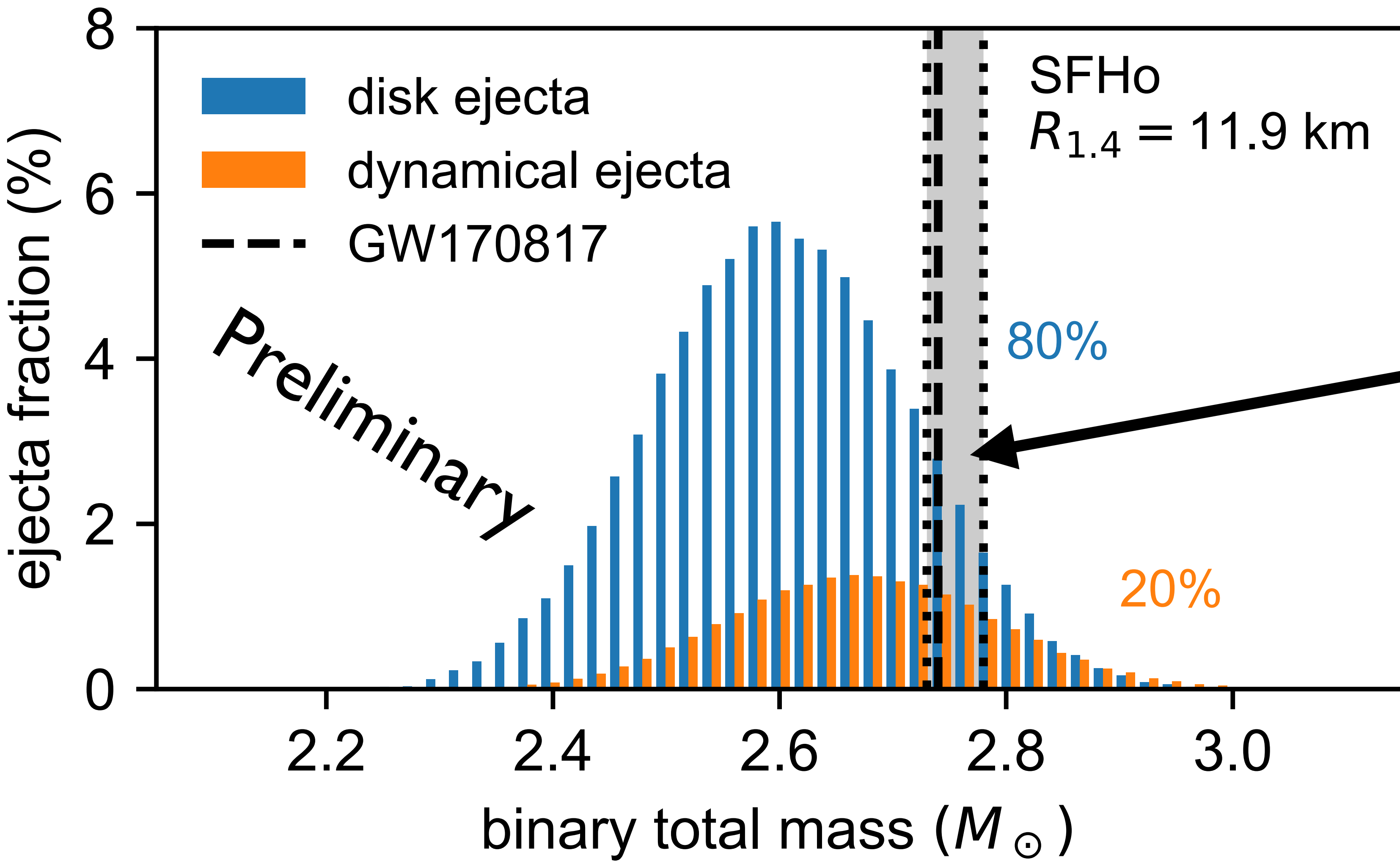


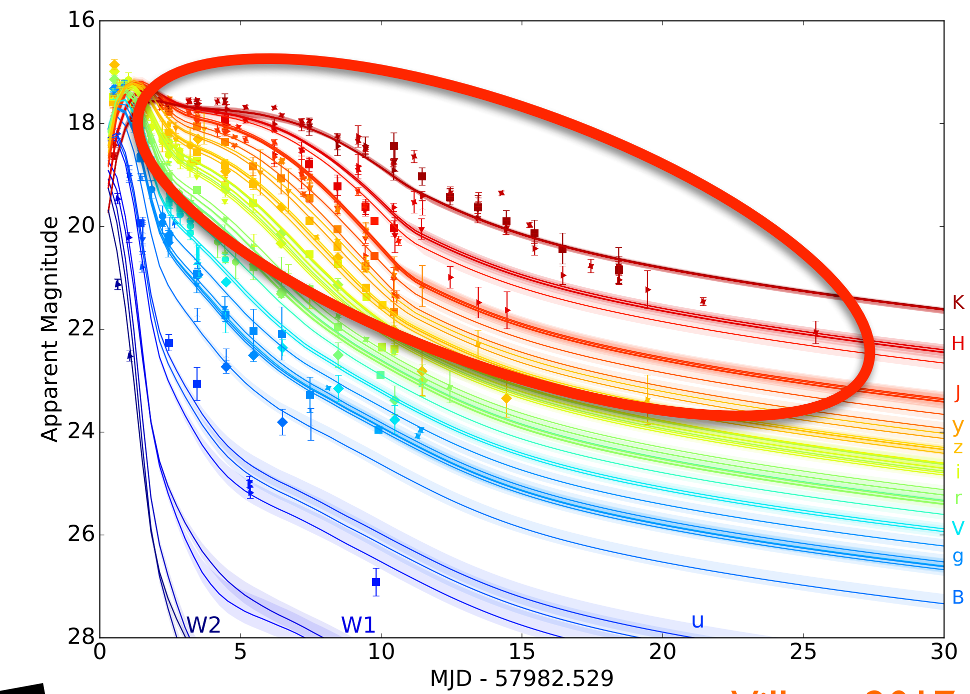
Fitting formulae: Krüger & Foucart 2020

Conjecture: *Outflows from compact (neutrino-cooled) accretion disks synthesize most of the (heavy) r-process elements in the Universe.*

Post-merger disks: exploring BNS parameter space

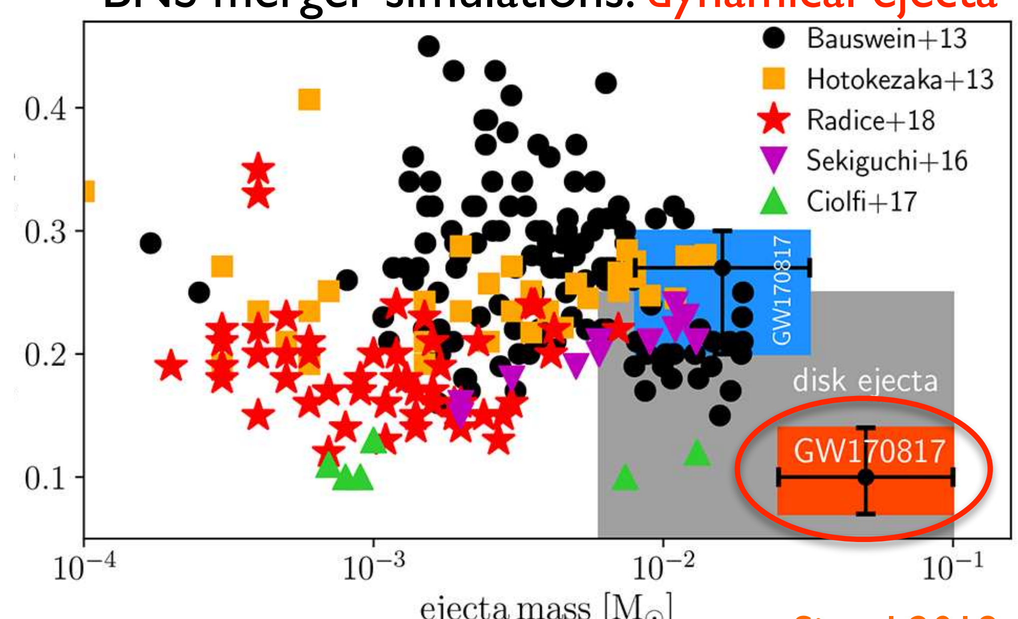
Siegel 2021, Nature Rev. Phys.





Villar+ 2017

BNS merger simulations: dynamical ejecta

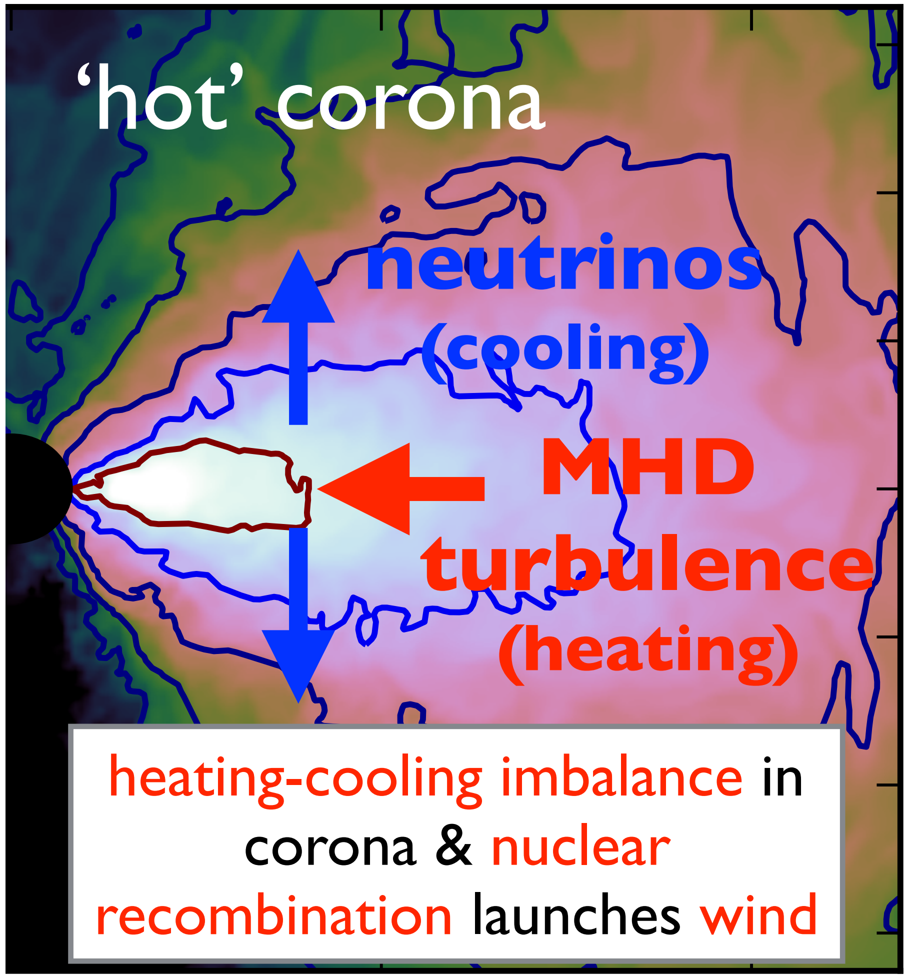


Siegel 2019

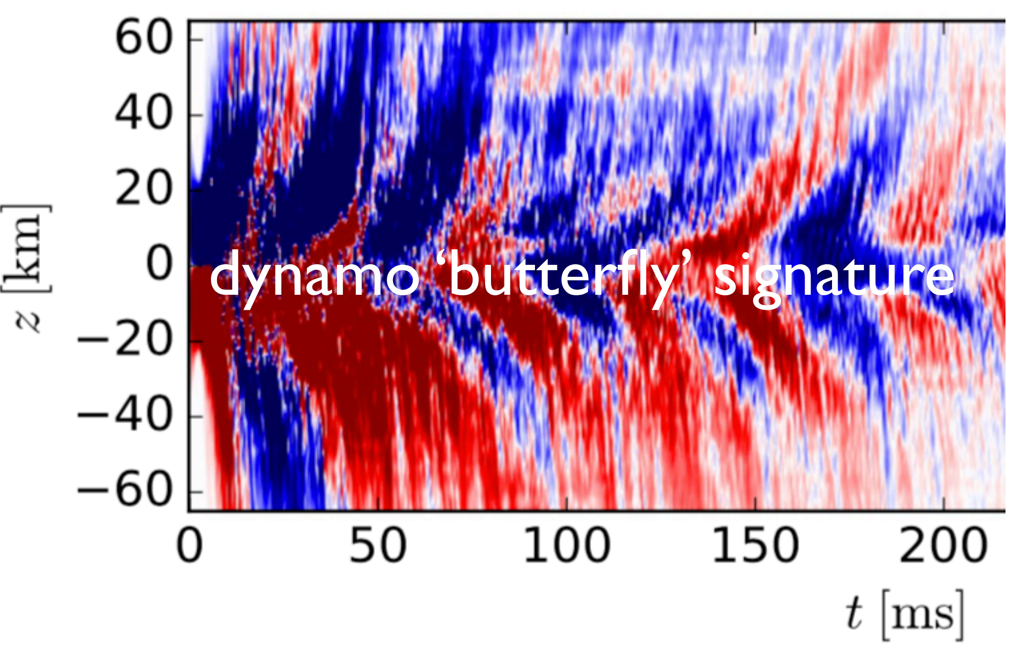
Fitting formulae: Krüger & Foucart 2020

Conjecture: *Outflows from compact (neutrino-cooled) accretion disks synthesize most of the (heavy) r-process elements in the Universe.*

Weak interactions in post-merger disks



Siegel & Metzger, PRL 2017



Weak interactions are key for composition, nucleosynthesis, kilonova

Importance of weak interactions:

$$\mathcal{R} = \frac{Q_\nu^-}{Q^+} \sim \frac{1}{2}$$

neutrino emission

viscous heating (MRI)

1D alpha-disk model

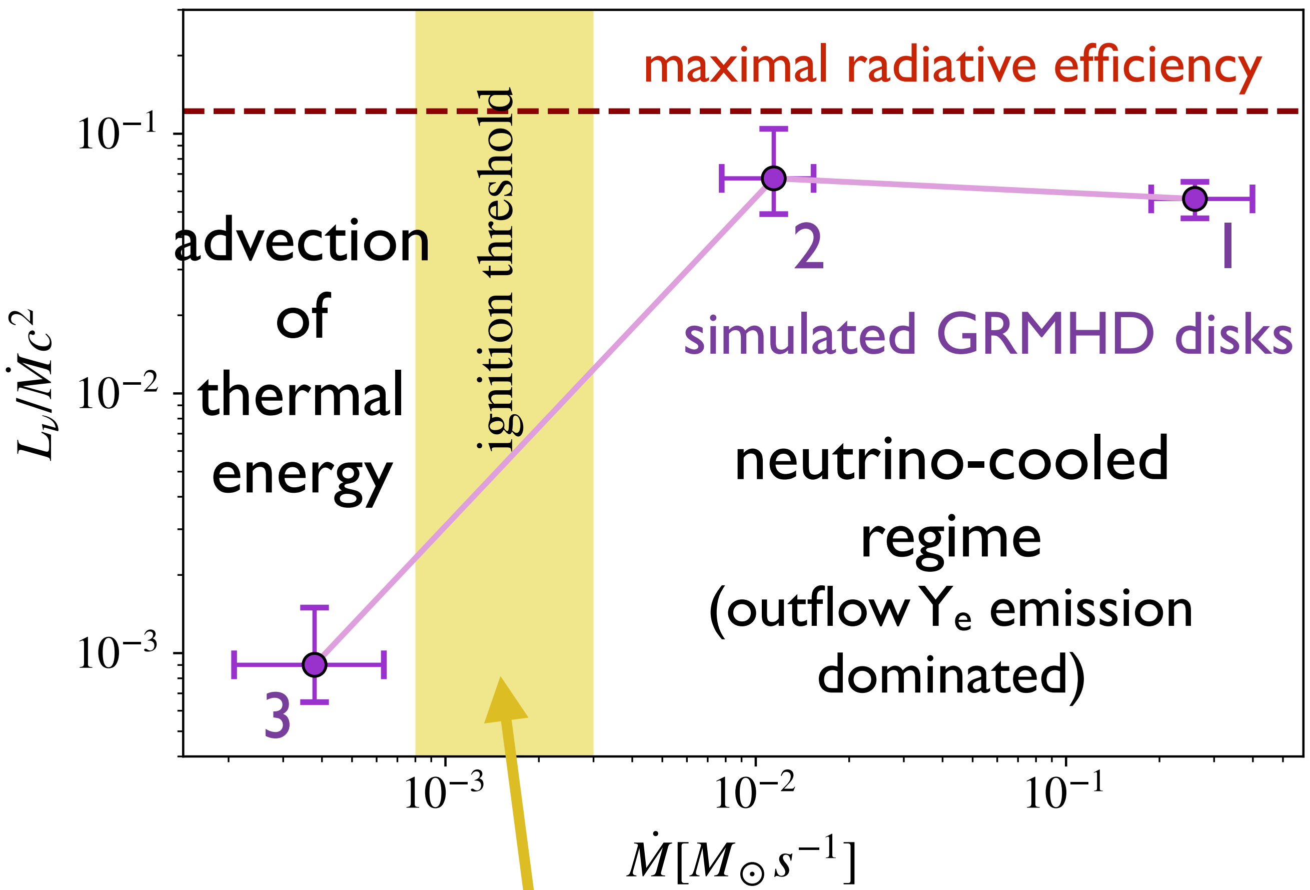
Ignition threshold: De & Siegel 2021

$$\dot{M}_{\rm ign} = 2\times 10^{-3} M_\odot {\rm s}^{-1} \left(\frac{M_{\rm BH}}{3M_\odot}\right)^{\frac{4}{3}} \left(\frac{\alpha_{\rm eff}}{0.02}\right)^{\frac{5}{3}}$$

Accretion rate parametrizes importance of weak interactions

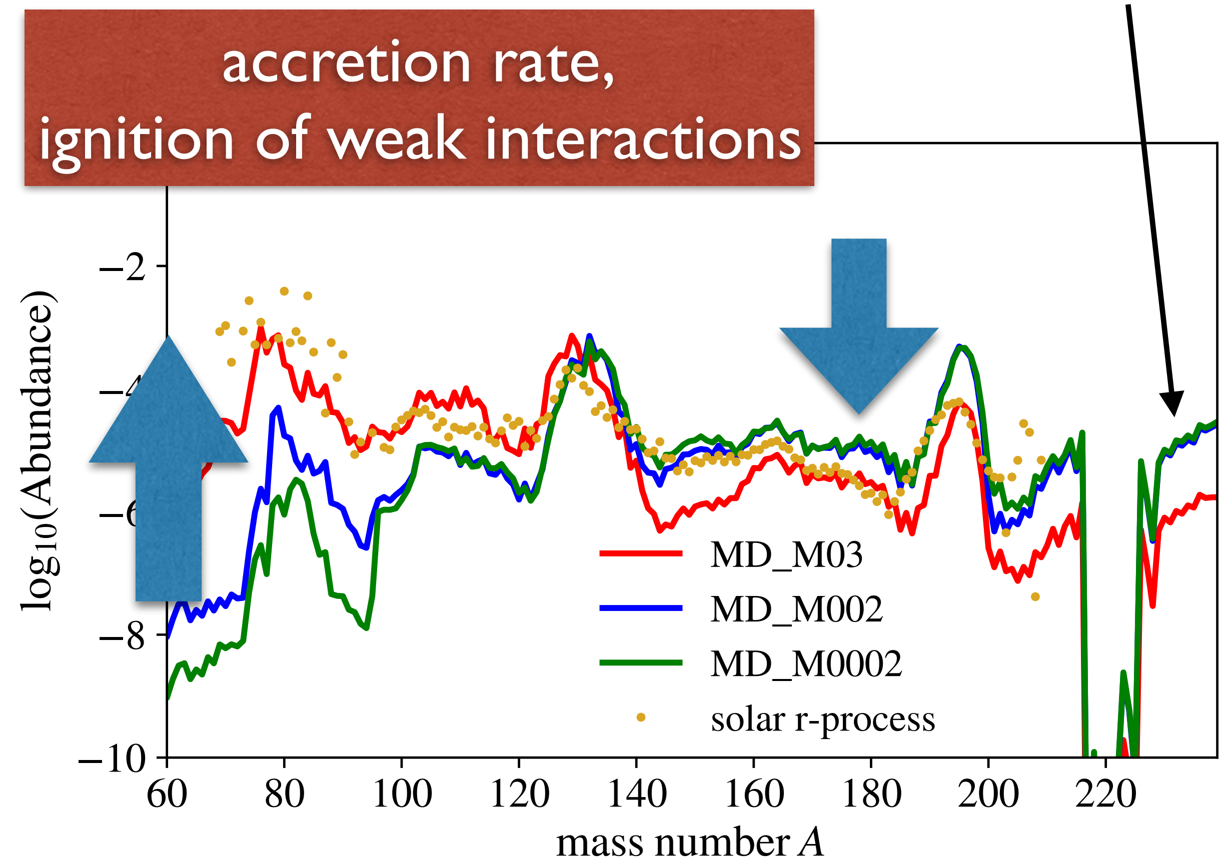
Ignition of weak interactions

De & Siegel 2021



analytic estimate

actinide abundances



Ejected disk mass:

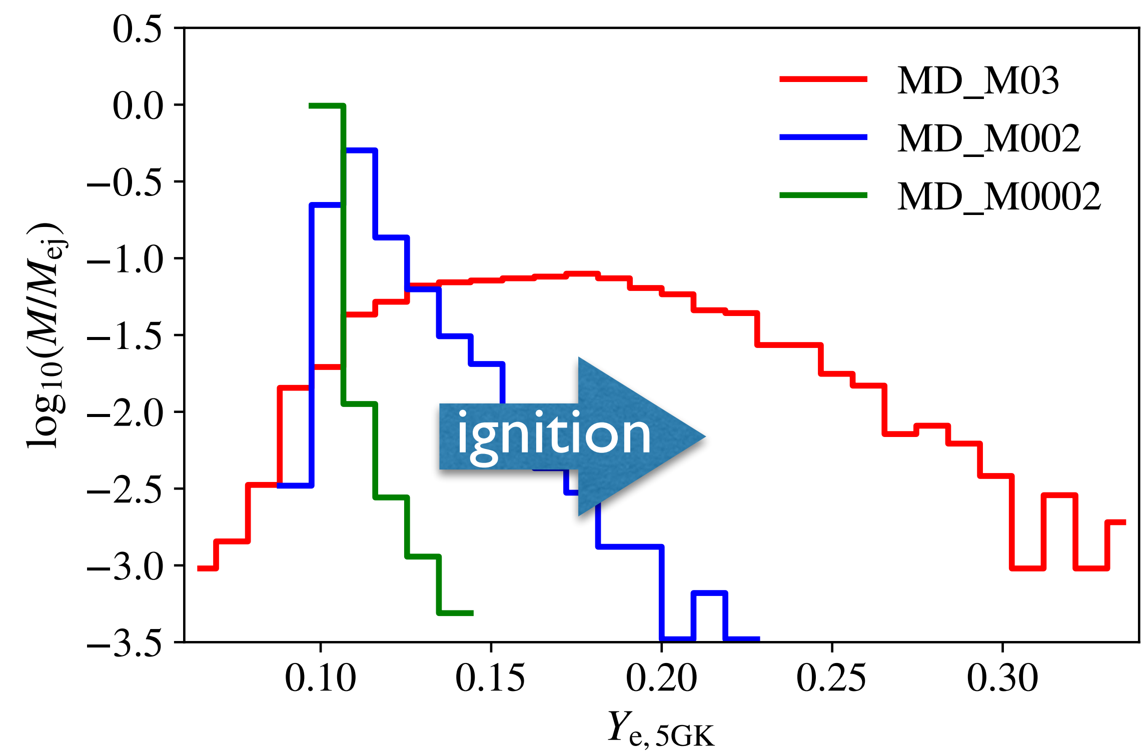
1 ~ 35%

2 ~ 35%

3 ~ 60%

see also:
Siegel & Metzger 2018
Fernandez+ 2019, 2020
Christie+ 2019

more effective evaporation in the absence of cooling



Nucleosynthesis regimes

ejecta Y_e absorption dominated

Miller+ 2019
Li & Siegel, PRL 2021

$$\dot{M} = \begin{cases} > \dot{M}_\nu & \text{lanthanide suppression} \\ \in [\dot{M}_{\rm ign}, \dot{M}_\nu] & \text{'full' r-process} \\ < \dot{M}_{\rm ign} & Y_e \text{ frozen} \end{cases}$$

ejecta Y_e emission dominated

$$\dot{M}_\nu \simeq 0.1 M_\odot \mathrm{s}^{-1} \left(\frac{M_{\rm BH}}{3M_\odot}\right)^{\frac{4}{3}} \left(\frac{\alpha_{\rm eff}}{0.02}\right)$$

$$\dot{M}_{\rm ign} \simeq 2\times 10^{-3} M_\odot \mathrm{s}^{-1} \left(\frac{M_{\rm BH}}{3M_\odot}\right)^{\frac{4}{3}} \left(\frac{\alpha_{\rm eff}}{0.02}\right)^{\frac{5}{3}}$$

Post-merger accretion disk can 'sweep through' one or more regimes while viscously spreading

Nucleosynthesis regimes

$$\dot{M} = \begin{cases} > \dot{M}_\nu & \text{lanthanide suppression} \\ \in [\dot{M}_{\rm ign}, \dot{M}_\nu] & \text{'full' r-process} \\ < \dot{M}_{\rm ign} & Y_e \text{ frozen} \end{cases}$$

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Li & Siegel, PRL 2021

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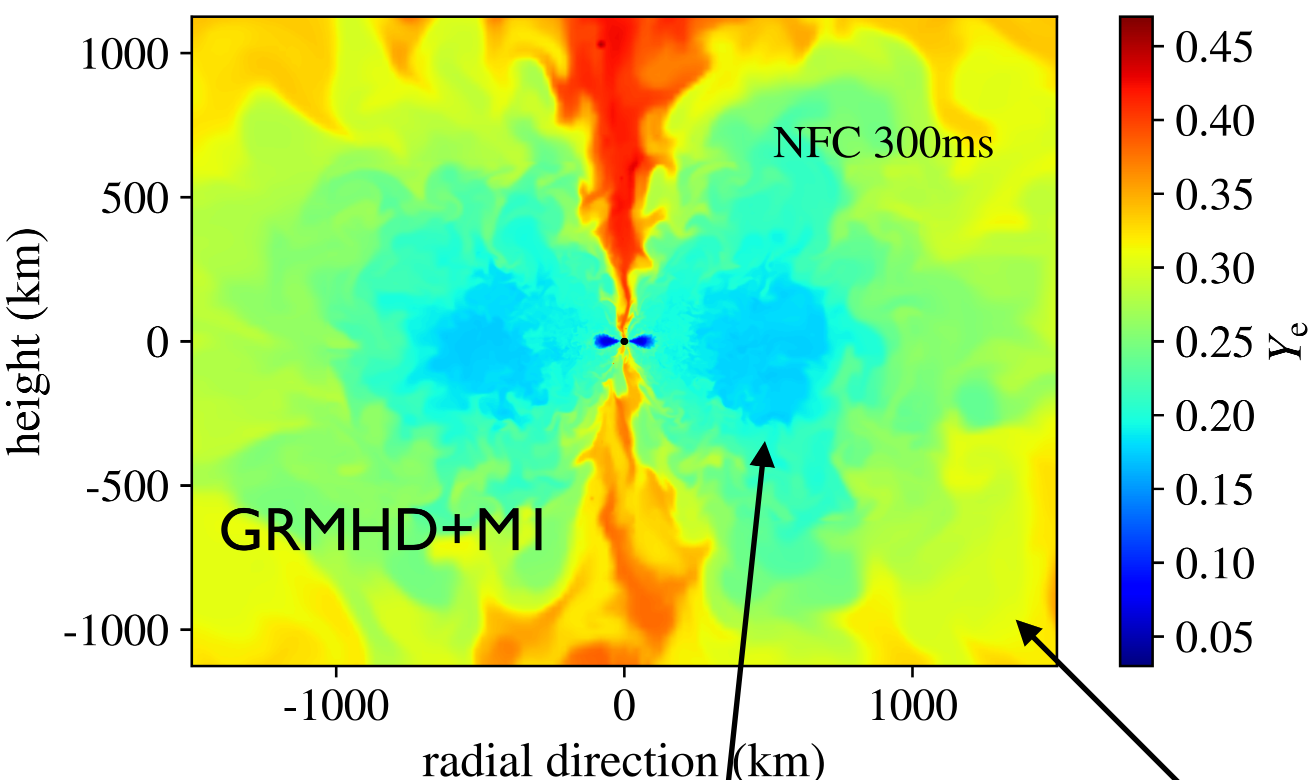
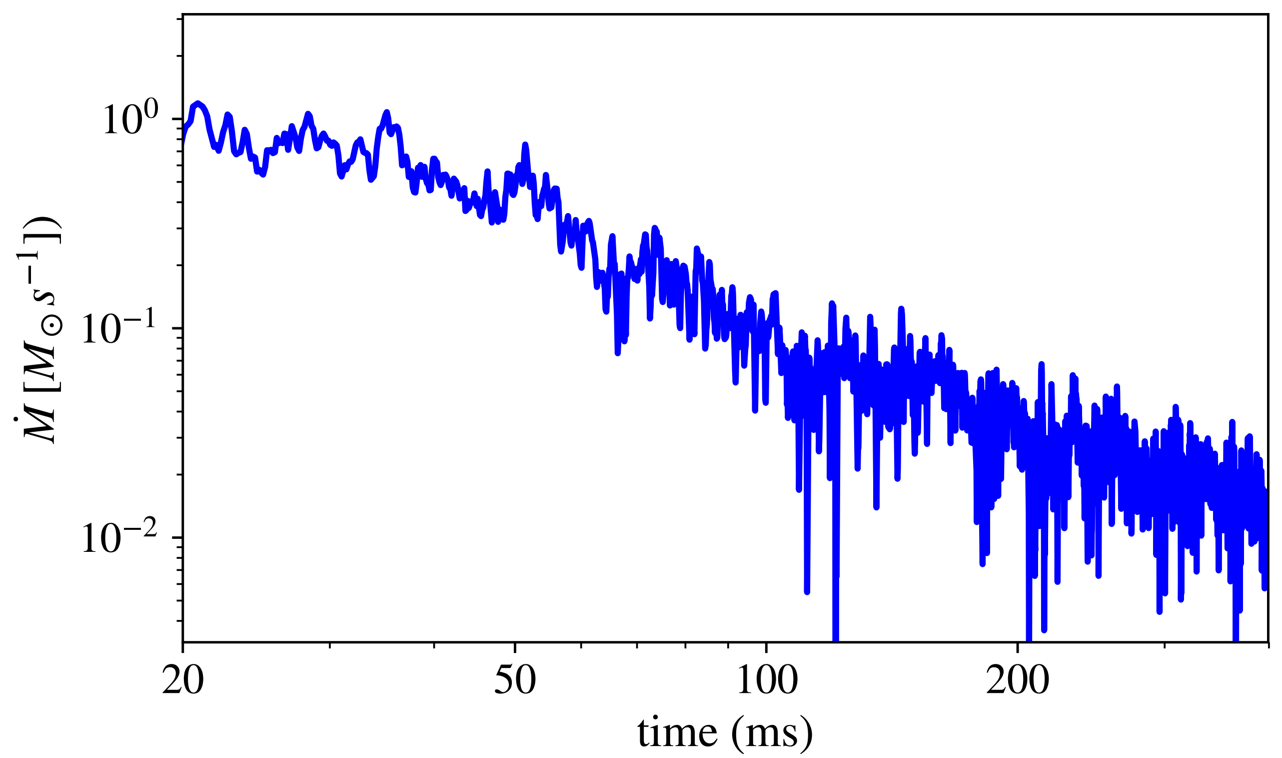
Li & Siegel, PRL 2021





medium $\dot{M}$

high $\dot{M} \approx 1 M_\odot \mathrm{s}^{-1}$

Nucleosynthesis regimes

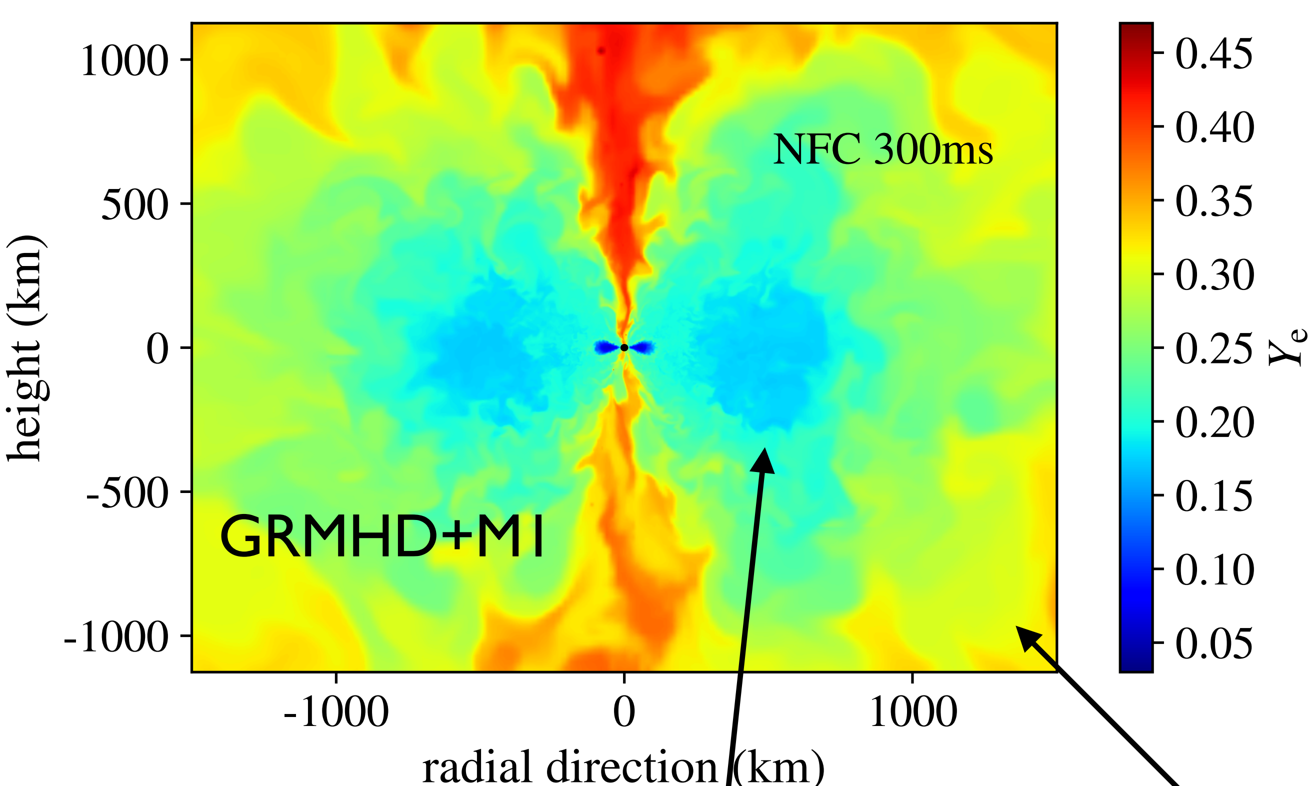
ejecta Y_e absorption dominated

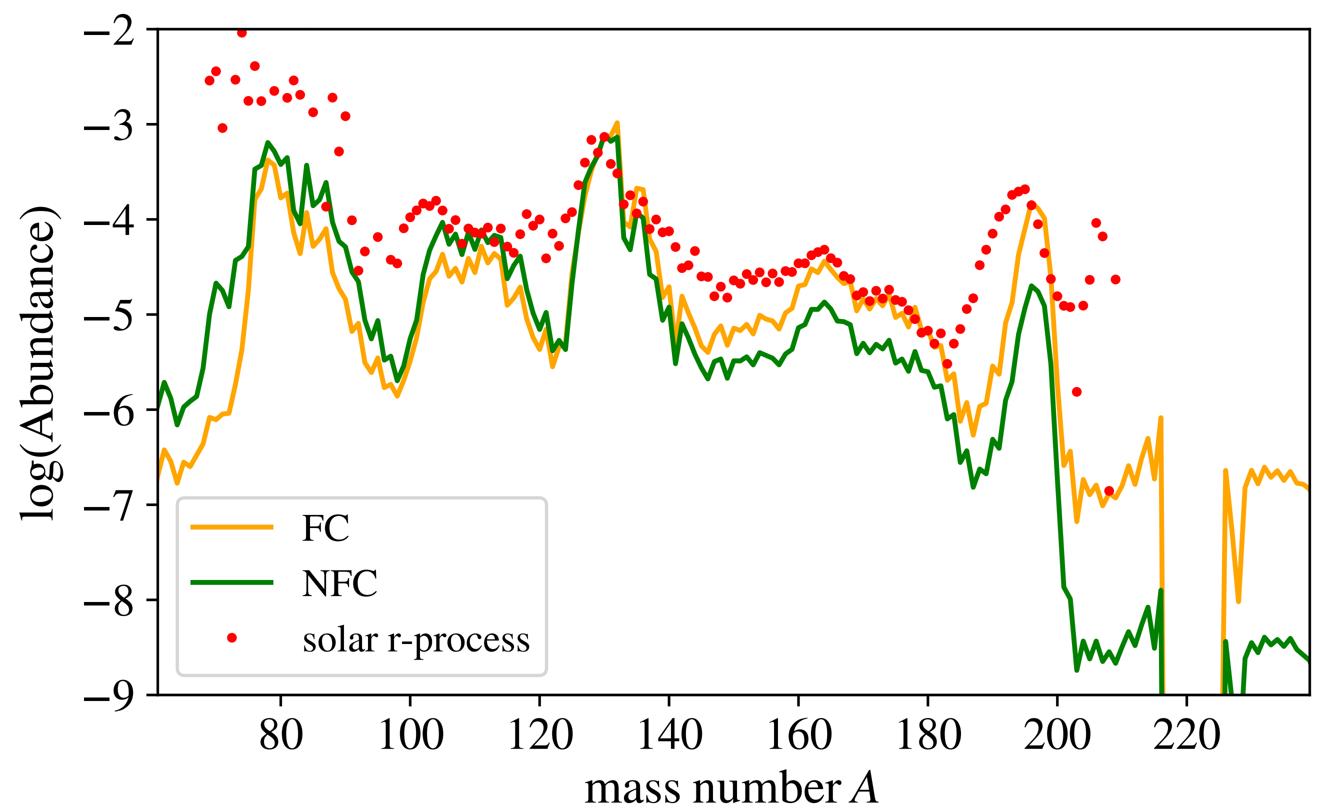
Miller+ 2019
Li & Siegel, PRL 2021

$$\dot{M} = \begin{cases} > \dot{M}_\nu & \text{lanthanide suppression} \\ \in [\dot{M}_{\rm ign}, \dot{M}_\nu] & \text{'full' r-process} \\ < \dot{M}_{\rm ign} & Y_e \text{ frozen} \end{cases}$$

ejecta Y_e emission dominated

Li & Siegel, PRL 2021



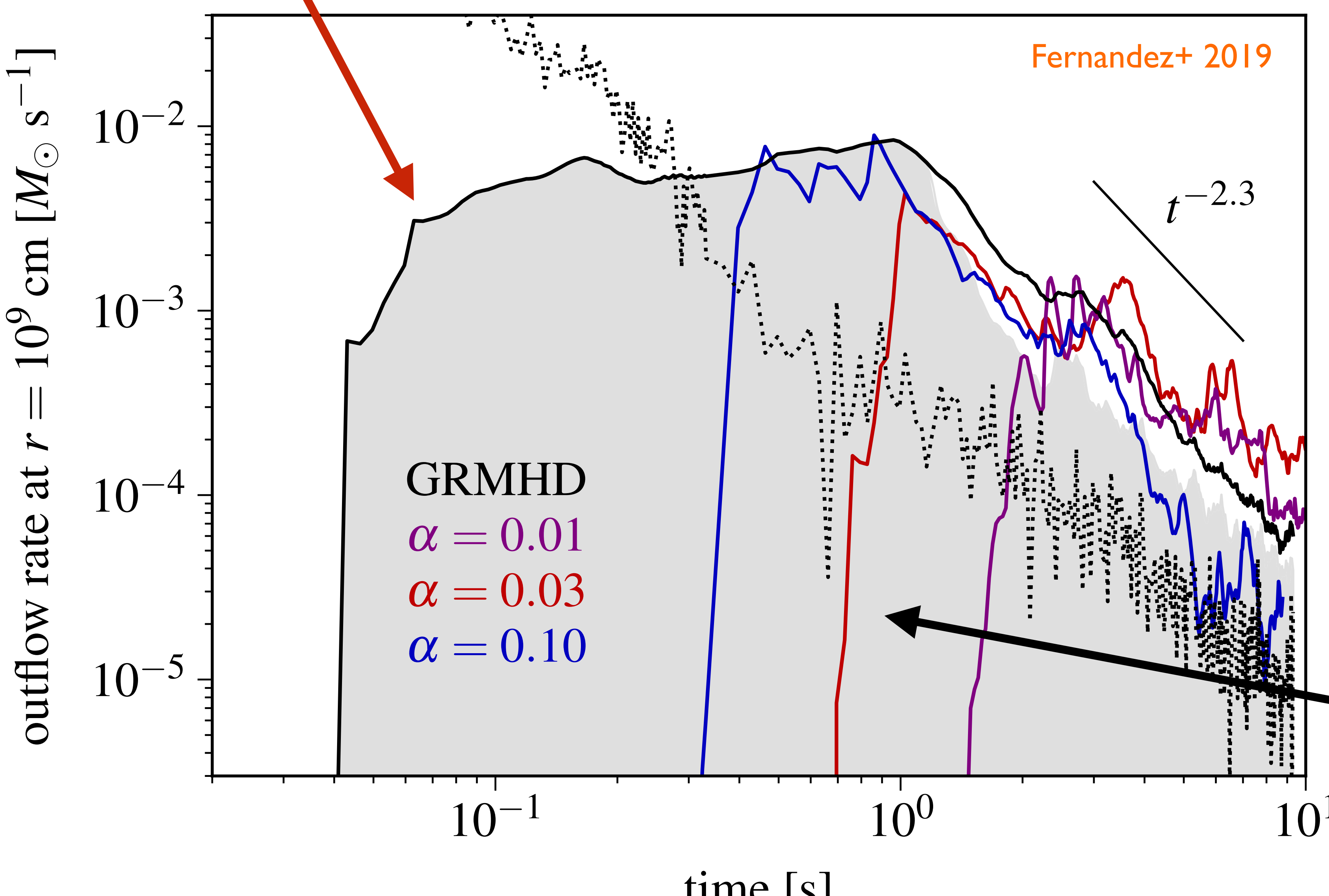


medium $\dot{M}$

high $\dot{M} \approx 1 M_\odot \mathrm{s}^{-1}$

MHD vs. α-disks

GRMHD outflows are early!



α-disk outflows starting at $\sim t_{visc}$

- α-disks: viscous outflows, ejected late $t > t_{visc}$, Y_e set by freeze-out in disk relative to t_{visc}

  Fernandez+ 2013, 2020, Just+ 2015, 2021, Fujibayashi+ 2018, 2020

- MHD-disks: outflows arise early (heating-cooling imbalance) $t < t_{visc}$, Y_e set by weak physics early on

  Siegel & Metzger 2017, 2018, Fernandez+ 2019, Miller+ 2019, Just 2021

Neutrino fast flavour conversions

Li & Siegel 2021, PRL

Kinetic equation for neutrino transport (similar for $\bar{\nu}$):

$$iv^\mu \partial_\mu \rho_\nu = [H, \rho_\nu] + \mathcal{C} \qquad H = H_V + H_M + H_\nu \qquad \rho_\nu = \begin{pmatrix} f_{\nu_e} & f_{\langle \nu_e | \nu_\mu \rangle} & f_{\langle \nu_e | \nu_\tau \rangle} \\ f_{\langle \nu_\mu | \nu_e \rangle} & f_{\nu_\mu} & f_{\langle \nu_\mu | \nu_\tau \rangle} \\ f_{\langle \nu_\tau | \nu_e \rangle} & f_{\langle \nu_\tau | \nu_\mu \rangle} & f_{\nu_\tau} \end{pmatrix}$$

"Collisions": emission, absorption

$$H_V \equiv \frac{M^2}{2E}, \qquad \text{vacuum oscillations}$$

$$H_M \equiv -v^\mu \Lambda_\mu \frac{\sigma_3}{2}, \qquad \text{matter interaction ("MSW")}$$

$$H_\nu \equiv -\sqrt{2} G_F \int \frac{E'^2 dE'}{2\pi^2} d\Gamma' v^\mu v'_\mu \rho'_\nu \qquad \text{self-interaction}$$

Diagonal: usual occupation number
Off-diagonal: flavour coherence

Flavor evolution due to off-diagonal terms in H; H_ν can cause run-away modes (non-linearity)

Conditions for fast conversions:

$$\Phi_0 = \sqrt{2} G_F \hbar^{-1} n_\nu = 1.92 \times 10^9 \mathrm{s}^{-1} \left(\frac{n_\nu}{10^{31} \mathrm{cm}^{-3}} \right)$$

Neutrino oscillations in post-merger disks

Li & Siegel 2021, PRL

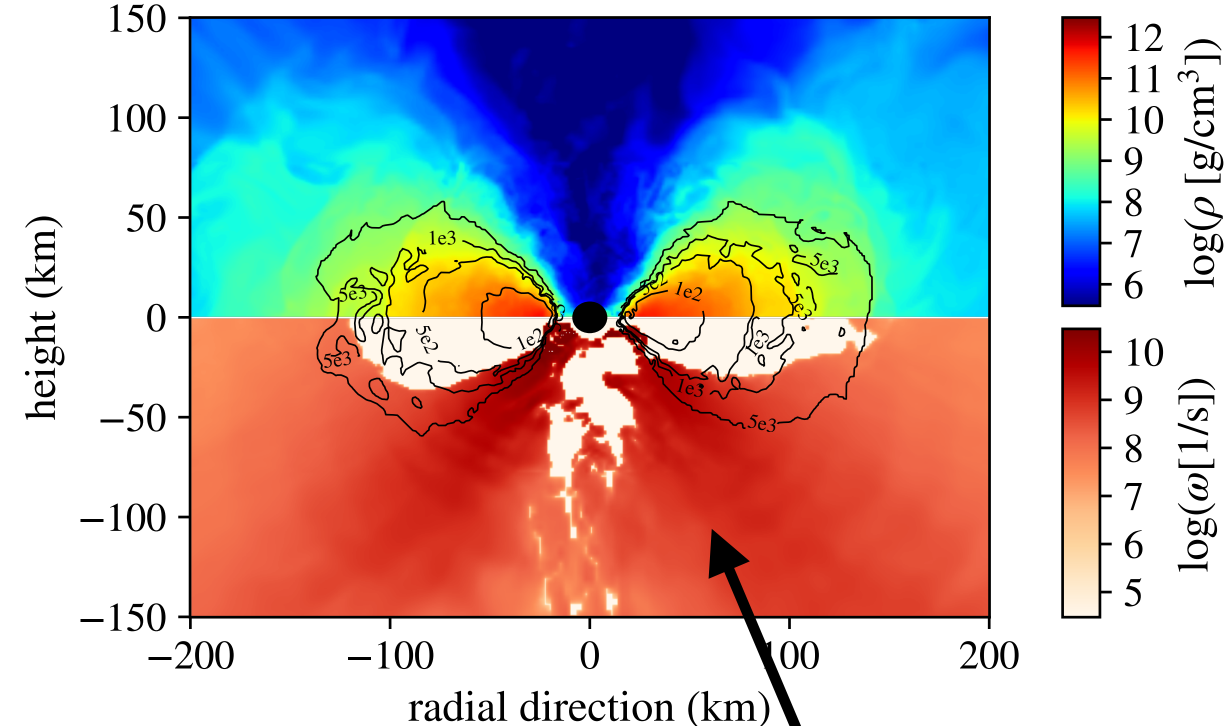
Kinetic equation for neutrino transport:

$$iv^{\mu}\partial_{\mu}\rho_{\nu} = [H, \rho_{\nu}] + \mathcal{C} \qquad H = H_V + H_M + H_\nu$$

vacuum oscillations

matter interaction (MSW effect)

self-interaction



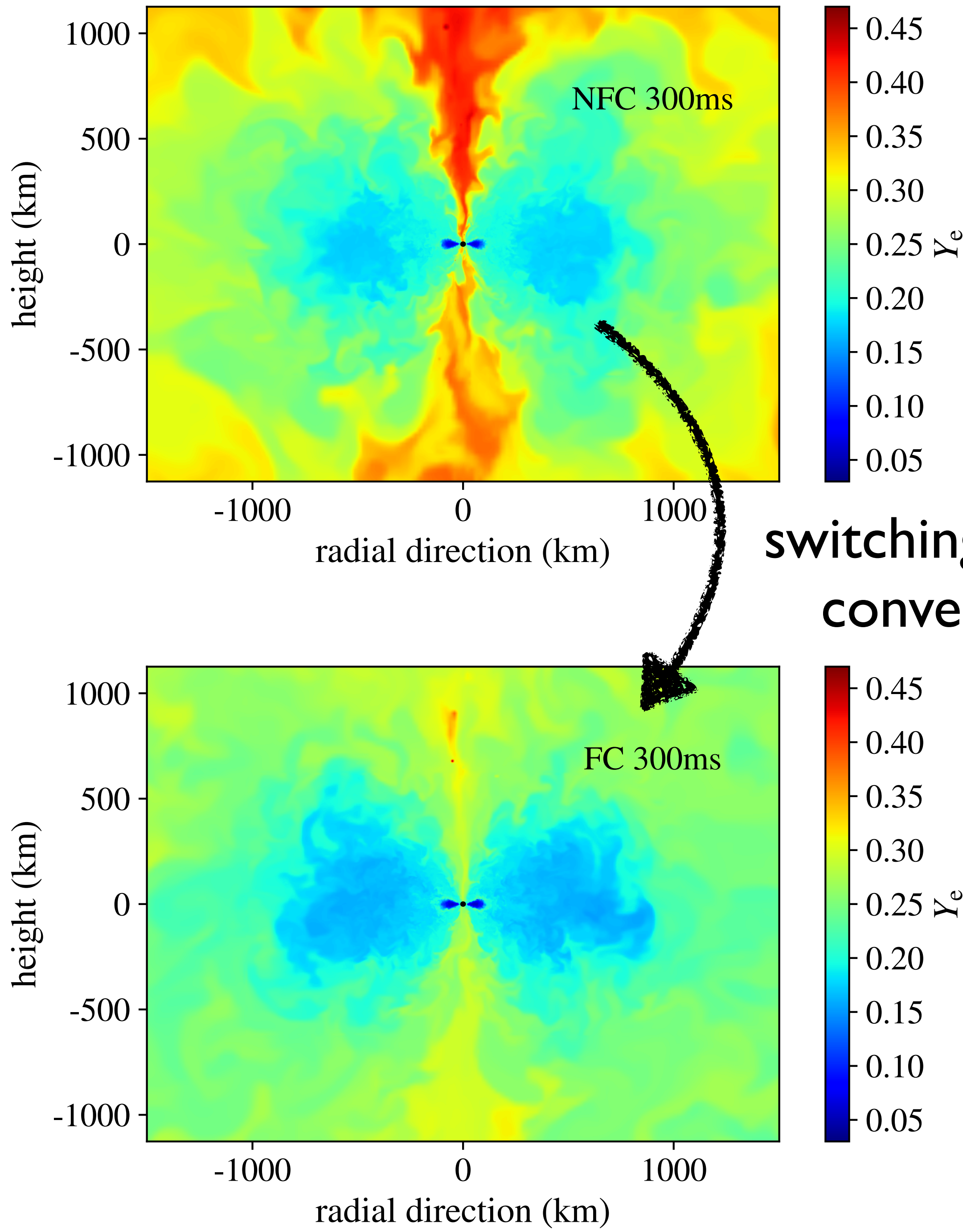
ubiquitous flavor conversions ~ns timescales

- GRMHD + M1 neutrino radiation transport
- First simulation with fast conversions included dynamically Wu+ 2017 George+ 2020
- Dispersion relation approach Izaguirre+ 2017
- Use equivalence principle in GRMHD+M1 formalism to compute dispersion relation locally
- Outcome of non-linear regime of instability still uncertain, assume approximate equipartition Richers+ 2021

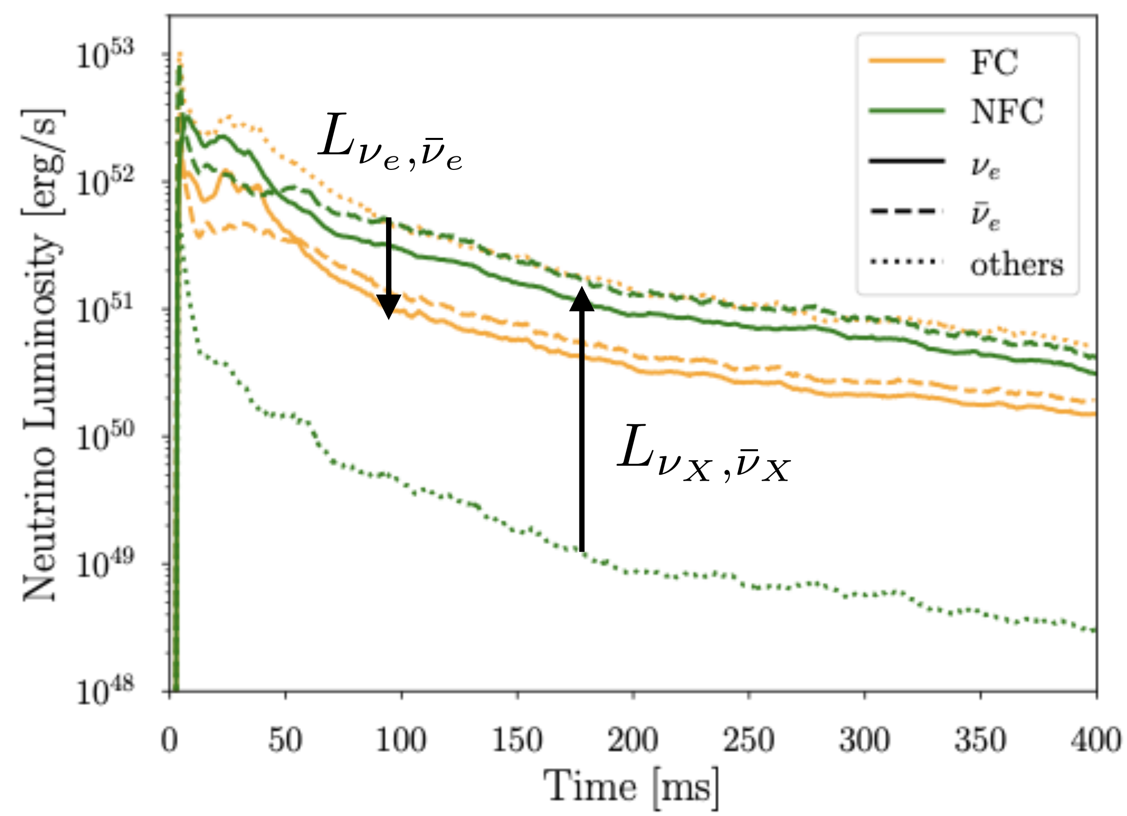
First astrophysical simulation with fast conversions, also relevant to core-collapse supernovae Nagakura+ 2019

Neutrinos & r-process: fast flavour conversions

Li & Siegel 2021, PRL



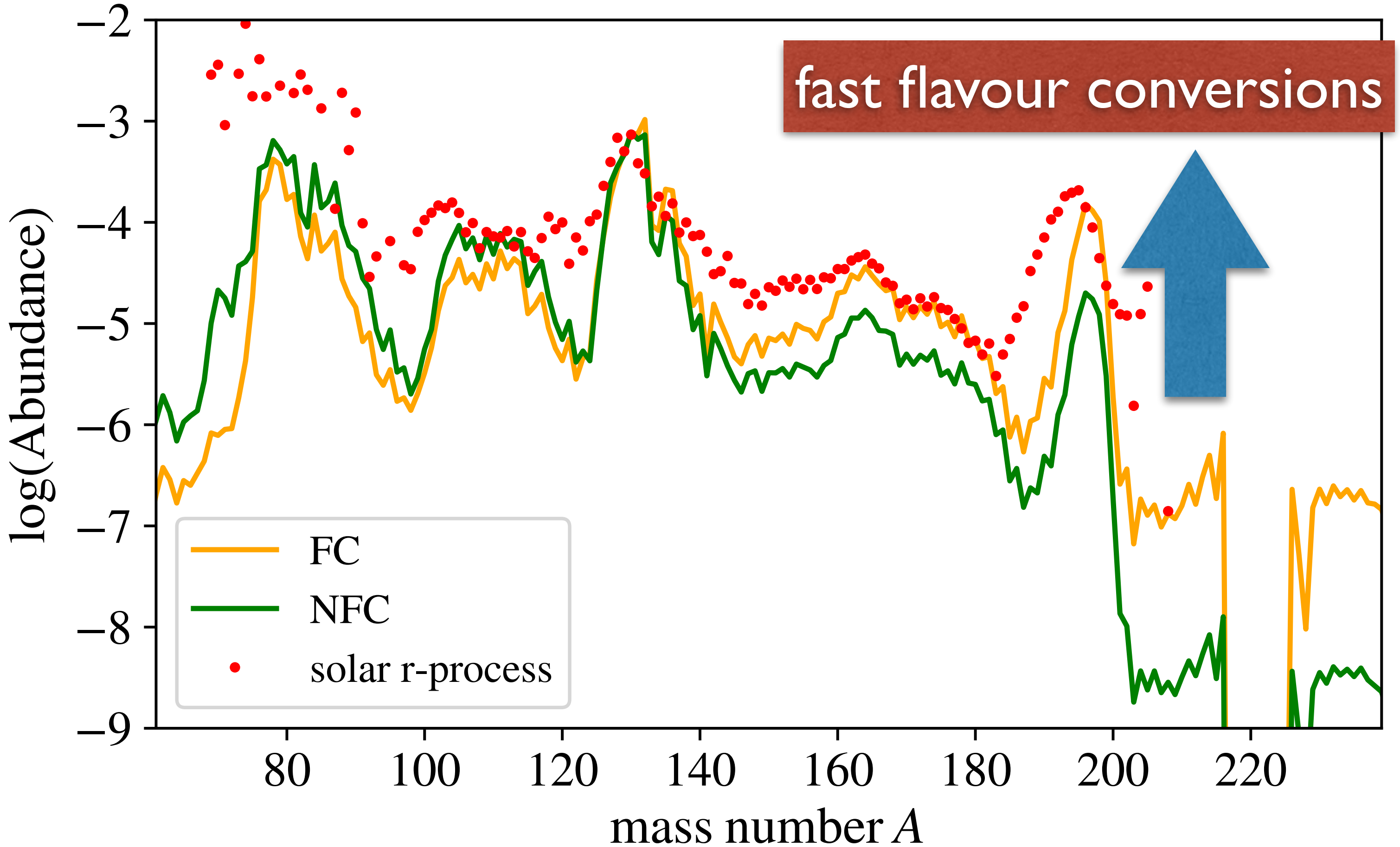
switching on fast conversions

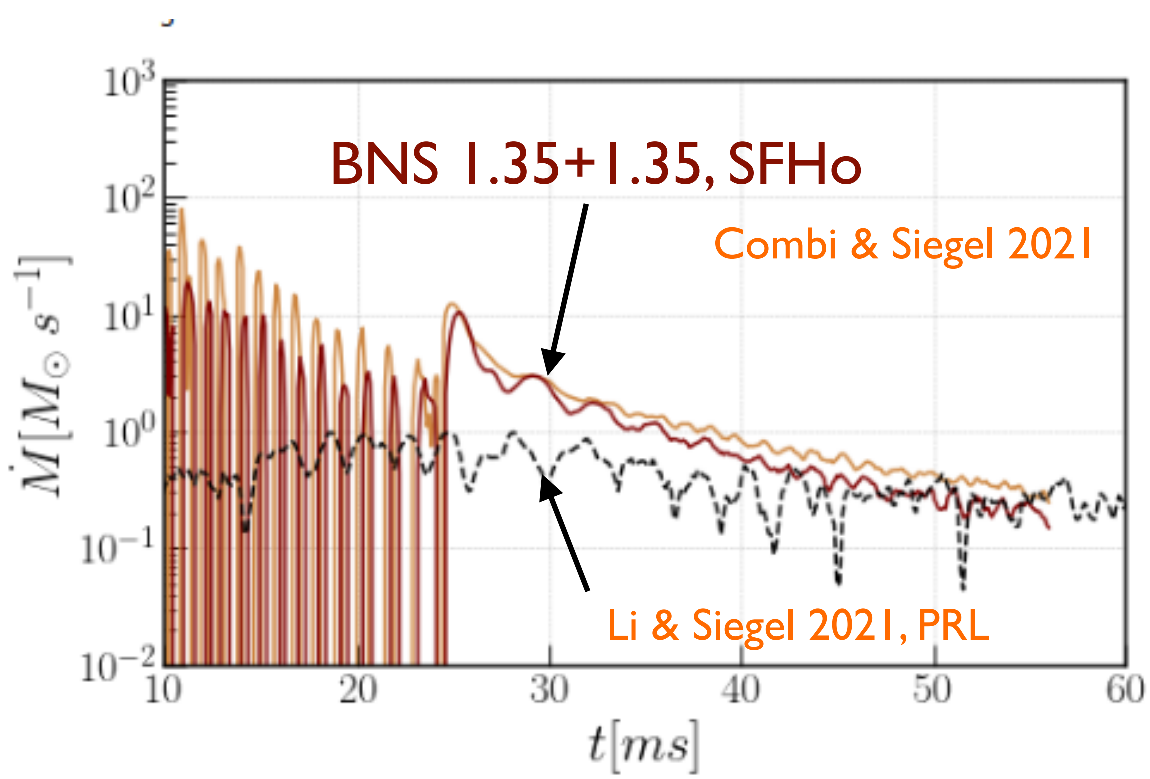


ejecta becomes more neutron rich

Neutrinos & r-process: fast flavour conversions

Li & Siegel 2021, PRL





- boost lanthanide mass fraction by factor ~2-few
- boost 3rd peak r-process elements by factor ~10

→ can convert a kilonova from 'blue' to 'red'

→ massive disks ($\dot{M} \sim 1 M_\odot \mathrm{s}^{-1}$) can produce heavy r-process similar to solar

Conclusions

- NS mergers give rise to various ejecta components with a broad range of properties

  → multi-component kilonovae, relative strength determined by binary parameters

  → ejecta expected to be dominated by disk outflows

  → much of post-merger phenomenology still poorly understood

- post-merger BH-accretion disk parameter space mostly determined by single parameter: accretion rate

  → various nucleosynthesis regimes

  → GRMHD & 3D crucial for nature of outflows, composition, r-process, kilonovae

- first simulations with neutrino fast flavour conversions suggest observable imprint: boost in heavy elements and opacity

  → red kilonova possible even for very massive disks

  → r-process abundances can be similar to solar

  → also important for early post-merger phase, much to be explored