Nucleosynthesis of light and iron-group elements in the ejecta of binary neutron star mergers

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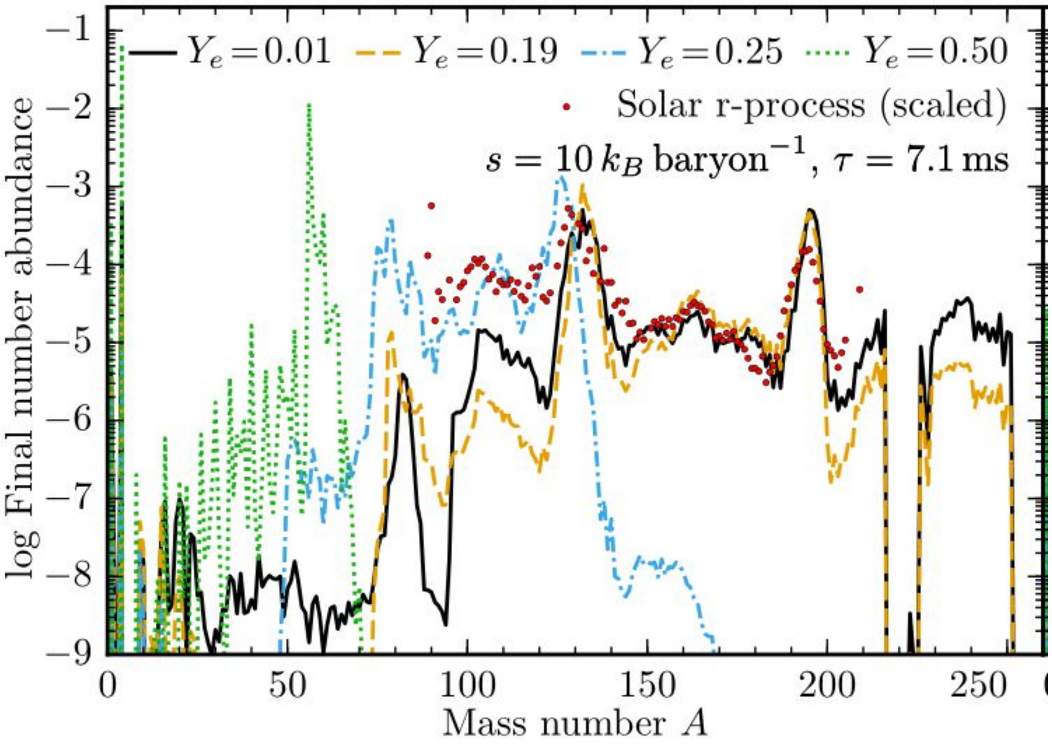
r-process nucleosynthesis

- Neutron-rich environment ⇒ sequence of rapid neutron captures

credit: Lippuner & Roberts (2015)



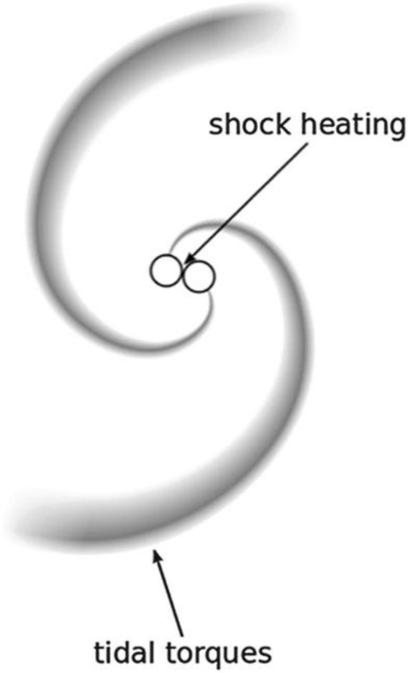
$$Y_\mathrm{e} \equiv \frac{n_{\mathrm{e}^-} - n_{\mathrm{e}^+}}{n_\mathrm{b}}$$

BNS mergers as r-process sites

- GW170817 + AT2017gfo ⇨ BNS mergers as sites for r-process nucleosynthesis

- BNS ejecta:
  - ➢ Dynamical ejecta (tidal + shock-heated)
  - ➢ Disk-wind ejecta (e.g. spiral-wave wind)

$$\boxed{0.05 \lesssim Y_\mathrm{e} \lesssim 0.4}$$



- **Production of light elements (Z $\lesssim$ 38) in BNS ejecta** (see also [Perego et al. 2022])

➔ nucleosynthesis pattern is more sensitive to binary parameters

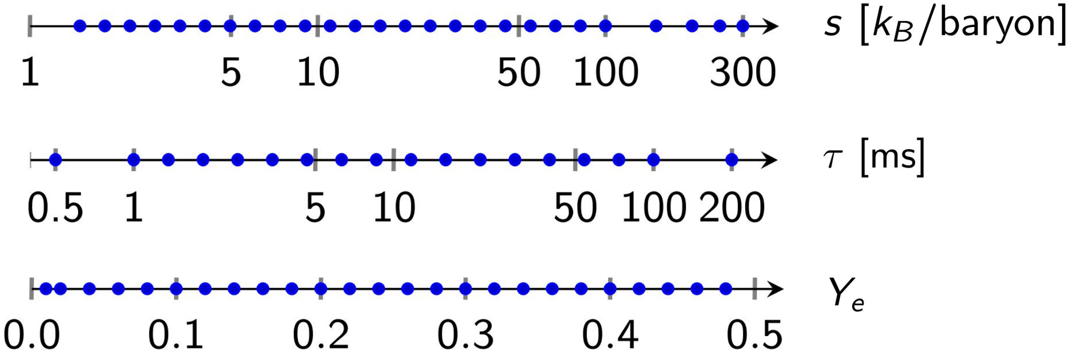
➔ kilonova spectral identification (e.g. Strontium, [Watson et al. 2019])

Methods

1. Parametric study wrt specific entropy (s), electron fraction (Y_e), expansion timescale (τ)

bitbucket.org/jlippuner/skynet

Lippuner & Roberts (2015)



$$\rho(t) = \begin{cases} \rho_0 \, e^{-t/\tau} & t \le 3\tau, \\ \rho_0 \left(\dfrac{3\tau}{et}\right)^3 & t \ge 3\tau \end{cases}$$

$$\boxed{\rho_0 = \mathrm{NSE}(s, Y_e, T_0) \qquad T_0 = 8.0\ \mathrm{GK}}$$

2. Compute final yields in BNS ejecta ⇨ 38 numerical BNS simulations targeted to GW170817 (WhiskyTHC)

$$Y_i(t) = \frac{\sum_\alpha \overbrace{Y_i^{(\alpha)}(t)}^{\text{from SkyNet}} \times \mathrm{dm}(\alpha)}{\sum_\alpha \mathrm{dm}(\alpha)}$$

$$\alpha \equiv (s, \tau, Y_e)$$

- ★ EOS ⇒ DD2, LS220. BLh, SFHo, SLy4
- ★ mass ratio ⇒ 0.55 ≤ q ≤ 1.00
- ★ neutrinos ⇒ LK + M0 scheme

Results - parametric nucleosynthesis study

- Underproduction in the range $3 \leq Z \leq 19$: $Y \lesssim 10^{-5}$
- Iron-group elements ($24 \lesssim Z \lesssim 28$):

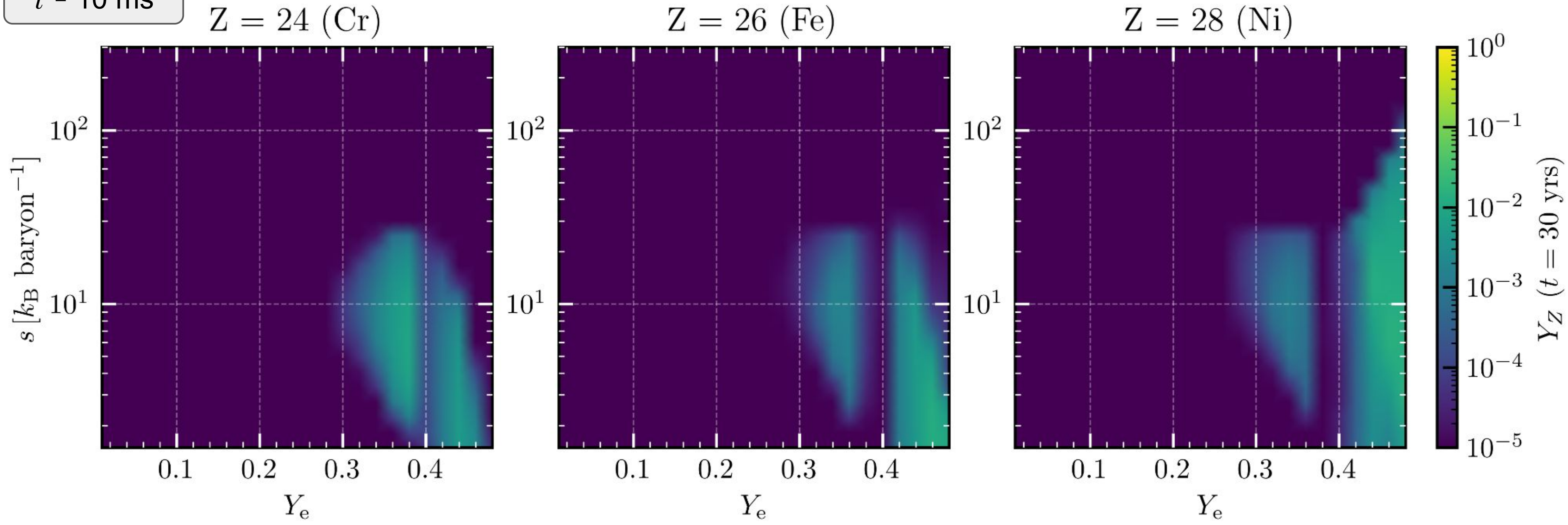
} cf. [Perego et al. 2022]

➔ $Y_e \gtrsim 0.3$ and $s \lesssim$ a few tens of k_B/baryon ⇒ $Y \sim 10^{-3} - 10^{-2}$

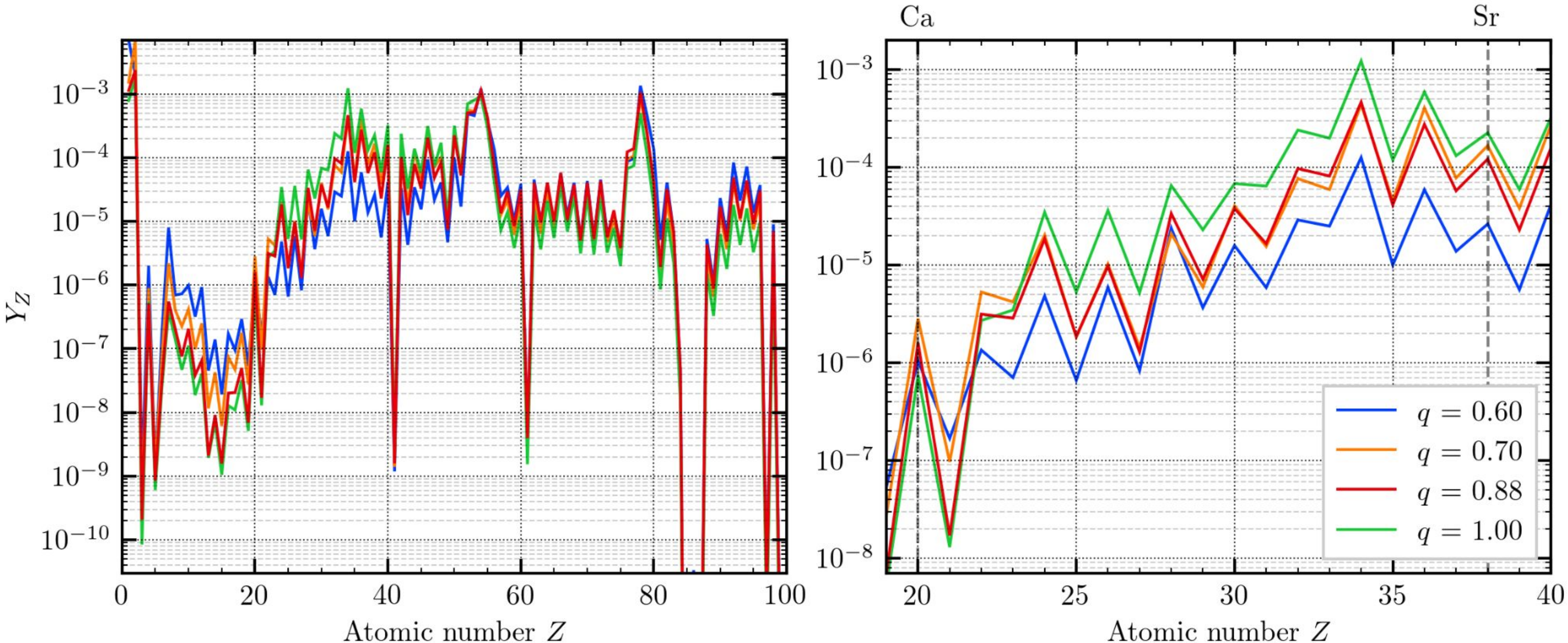
➔ gap around $Y_e \sim 0.4$ ⇨ $Y_e < 0.4$: weak *r*-process

$Y_e > 0.4$: synthesis at NSE

$\tau \simeq 10$ ms



Results - yields in dynamical ejecta



EOS = SFHo

- Iron-group elements favoured by equal-mass binaries (q → 1) and soft EOS

⇨ shock-heated contribution (violent collision, high temperatures increase Y_e in the ejecta)

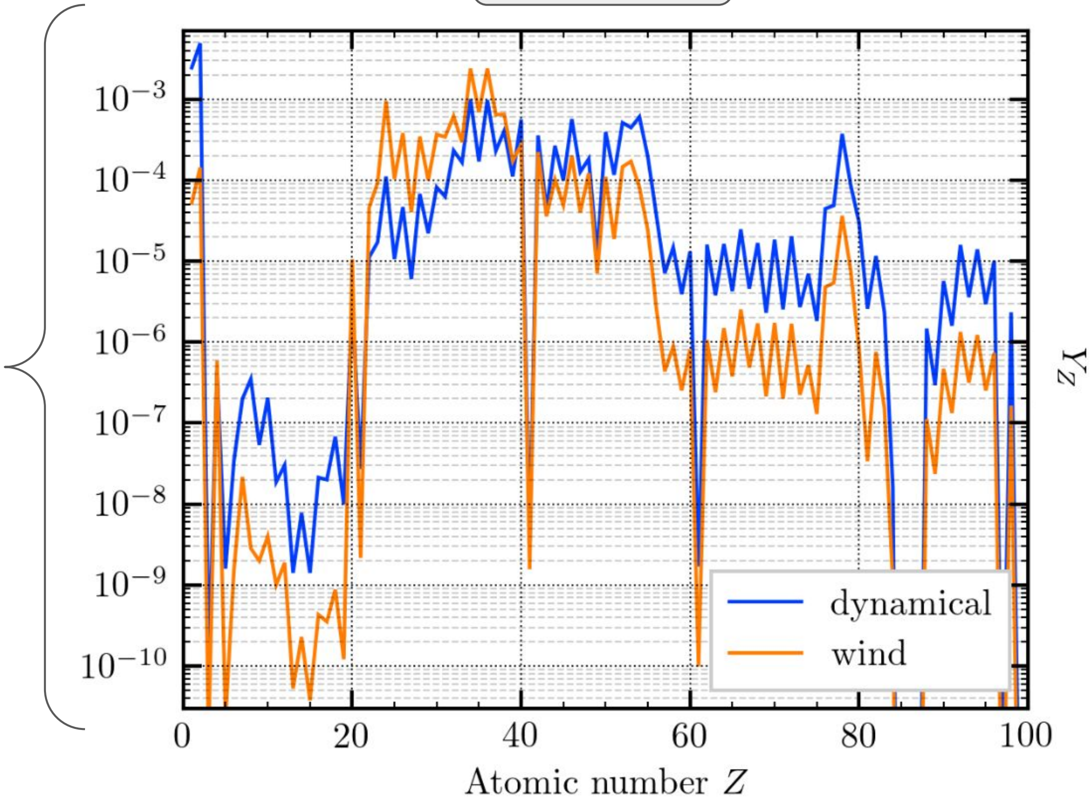
Results - dynamical vs spiral-wave

- Nucleosynthesis in spiral-wave wind:

BLh (q = 1)

Iron-group + 1st peak

Heavy ($\gtrsim 2^{nd}$ peak)



- Iron-group elements ($Y \gtrsim 10^{-4}$) comparable to or even higher than 2nd and 3rd *r*-process peaks in disk ejecta!

Summary and conclusions

- Light elements important to constrain our understanding of BNS mergers

- Negligible production for $Z < 20$ (except H and He)

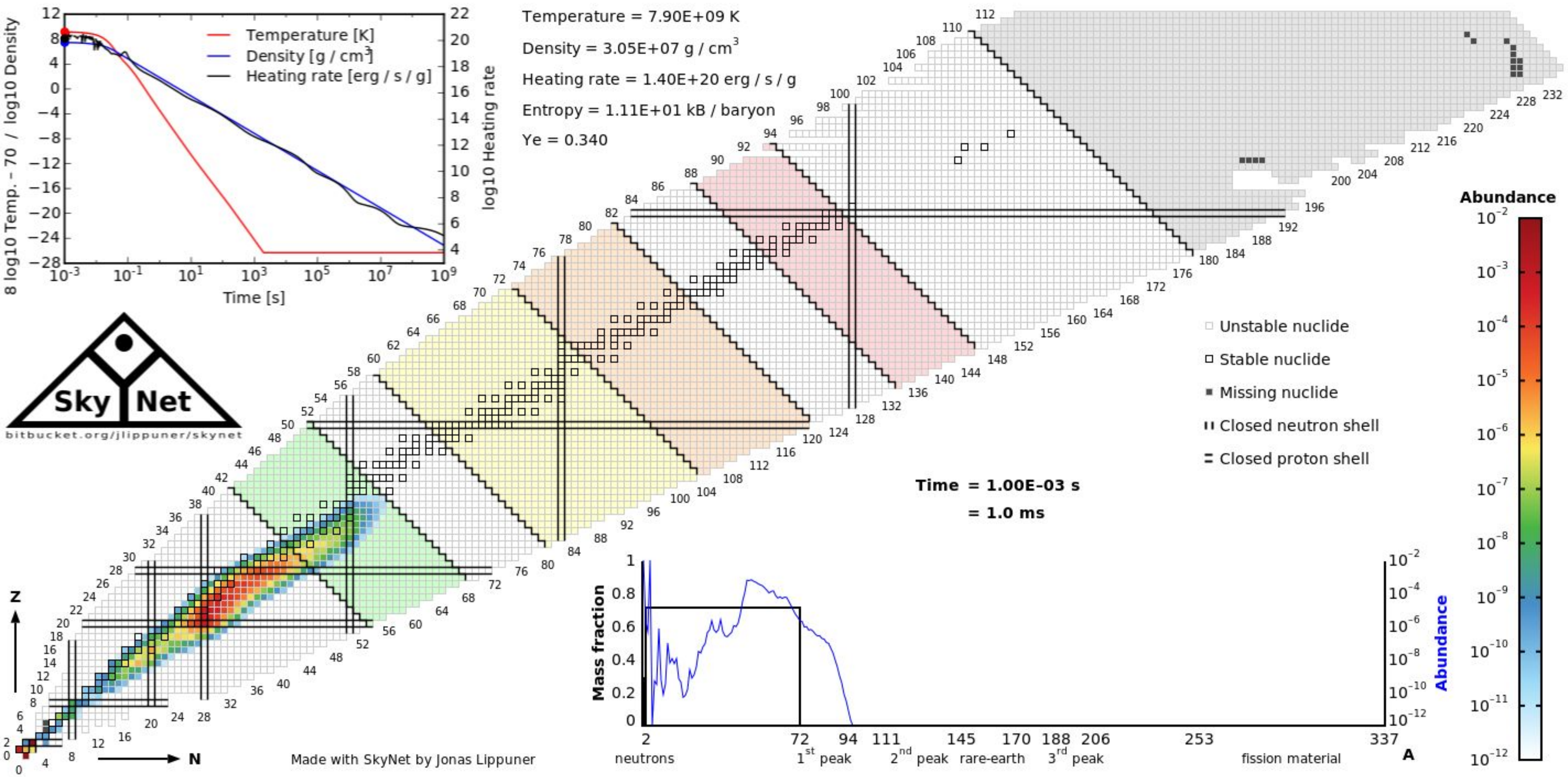
- Iron-group elements produced for $Y_e \gtrsim 0.3$ and low/moderate s

  ⇨
  - ❑ favoured in equal-mass mergers with soft EOS
  - ❑ in disk-wind ejecta, comparable with abundances of 2nd and 3rd r-process peaks

- Possibile improvements ⇒
  1. more detailed information (e.g. single isotopes, angular distribution)
  2. more accurate neutrino treatment

Backup slides

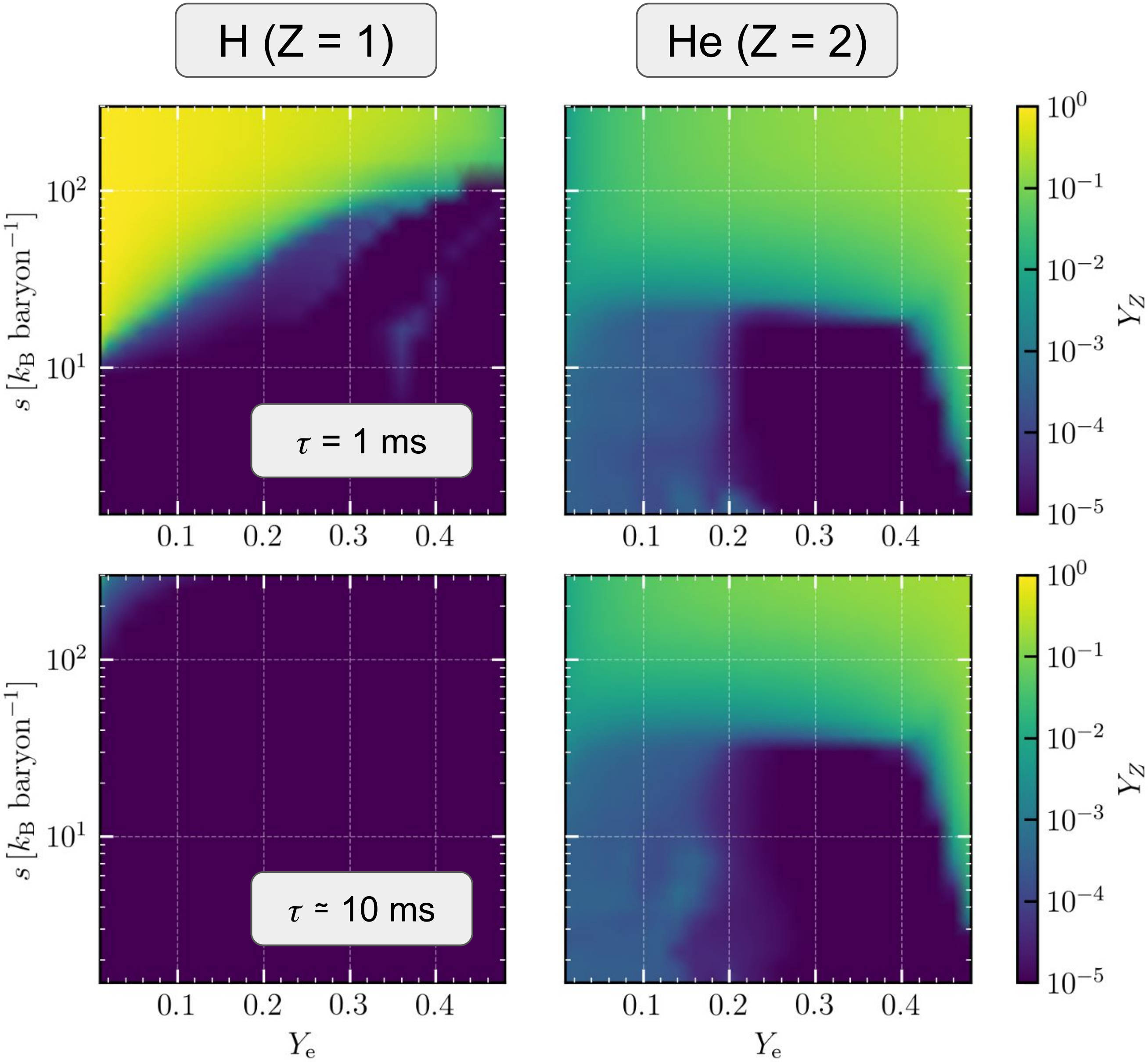
Nuclear-chart distribution



$s \simeq 10\ k_B$/baryon, $Y_e = 0.34$, $\tau \simeq 10$ ms

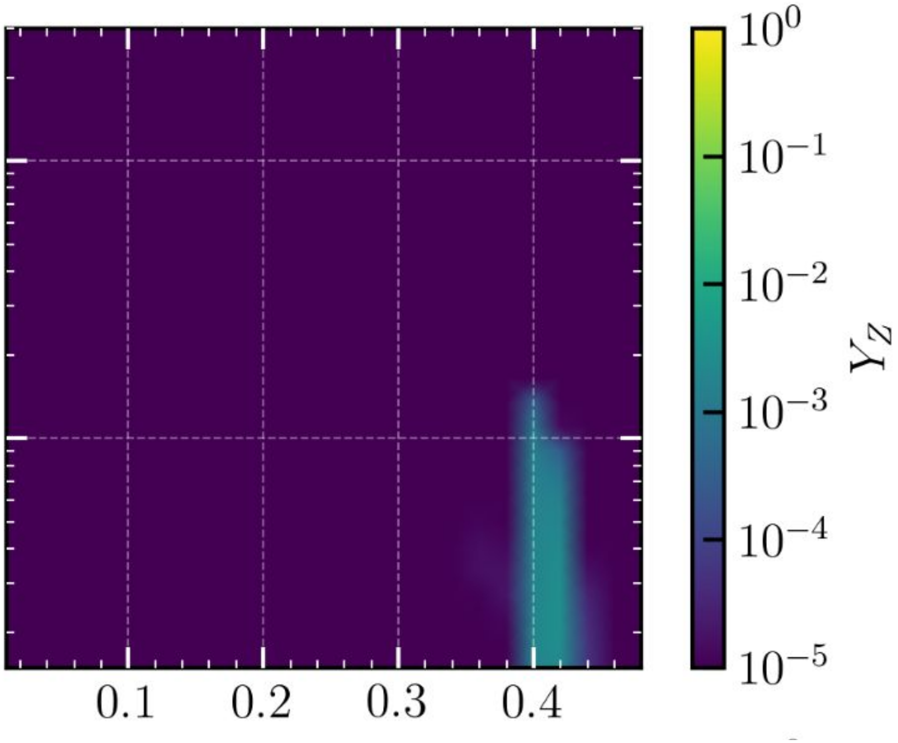
Hydrogen and Helium production

- H ⇒ β-decay of free n for fast expanding ejecta
- He ⇒ α-rich freeze-out at high entropies
- Qualitative agreement with [Perego et al. 2022]



Calcium production

Ca ($\tau \simeq 10$ ms)



- Ca potentially observable in kilonova spectra for lanthanide-poor ejecta [Domoto et al. 2021]

- Very specific conditions

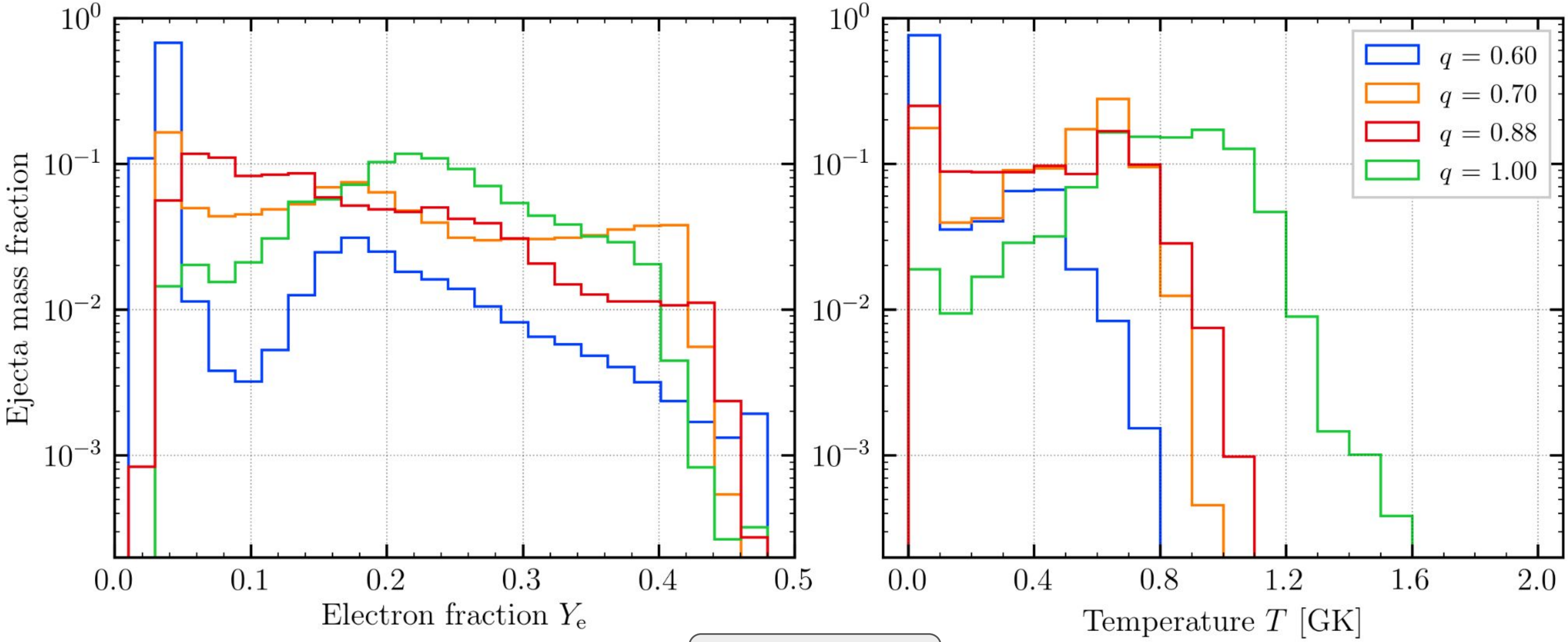
⇩

$Y_e \sim 0.4$ and $s \lesssim 10\ k_B$/baryon

- Negligible dependence on τ

- Abundance dominated by doubly-magic ^{48}Ca, synthesized during initial NSE conditions

Thermodynamics conditions in BNS ejecta



EOS = SFHo

- Distribution peak moves towards higher values for increasing mass ratio

BNS simulation sample