Nucleosynthesis and Kilonova from BNS mergers: impact of nuclear matter properties

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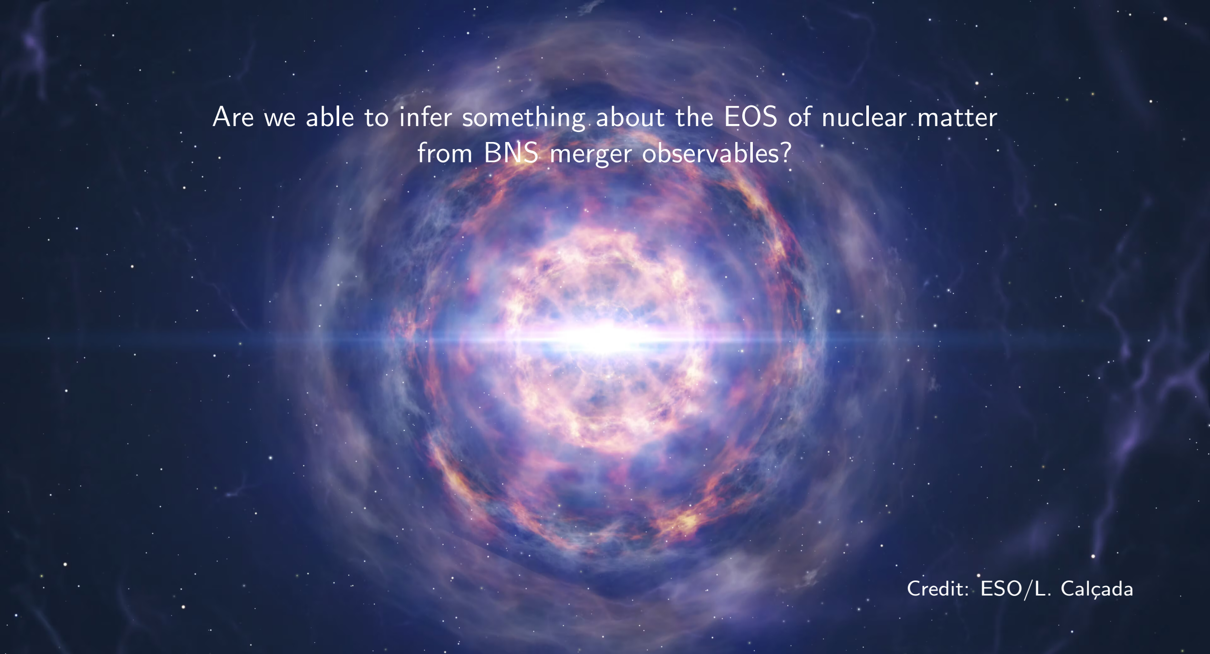
SFB 1245

Are we able to infer something about the EOS of nuclear matter from BNS merger observables?

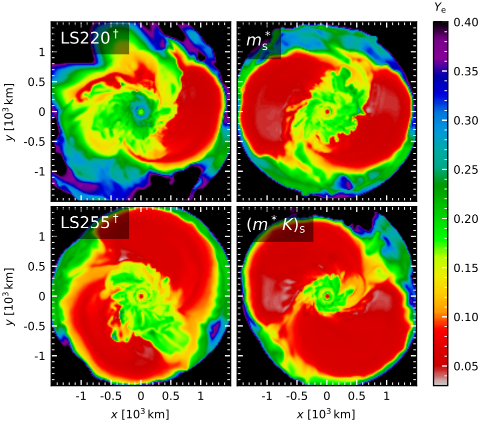


Credit: ESO/L. Calçada

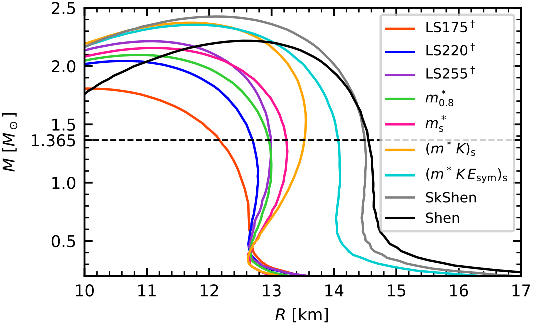
Merger simulations with parametrized EOSs

Simulations of symmetric BNS merger with $M_{\rm NS} = 1.365\ M_\odot$ ($M_{\rm chirp} = 1.188\ M_\odot$)

$\Rightarrow$ Jacobi et al. (in prep.)



- GRHD with `Whisky THC` (Radice & Rezzolla 2012)
- ν emission/absorption with leakage + M0 scheme (Galeazzi et al.2013, Radice et al. 2018)
- Skyrme-type EOS models tabulated with `SROEOS` (Schneider et al. 2017):



Merger simulations with parametrized EOSs

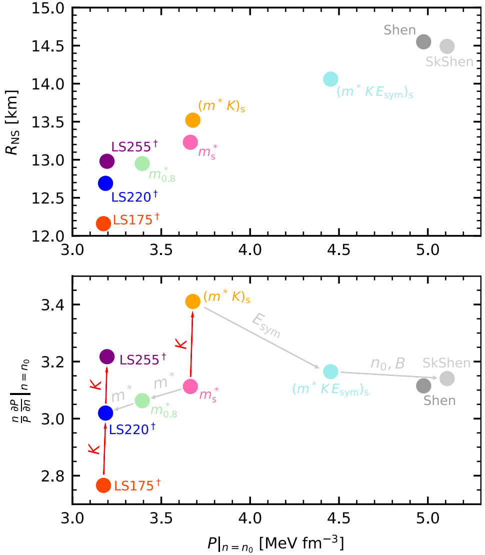
Skyrme-type EOS models tabulated with SROEOS:
(Schneider et al. 2017)

EOS	m^* [m_n]	K [MeV]	$\tilde{\Lambda}$	$R_{1.4}$ [km]
LS175†	1.0	175	358.9	12.1
LS220†	1.0	220	606.2	12.7
LS255†	1.0	255	661.1	13.0
$m^*_{0.8}$	0.8	220	698.4	12.9
m^*_S	0.634	220	765.4	13.2
$(m^*K)_S$	0.634	281	975.0	13.5
SkShen	0.634	281	1295.5	14.5
Shen	0.634	281	1220.8	14.5

Energy per particle expansion around $n = n_0$, $Y_e = 0.5$:

$$\left.\frac{E}{A}\right|_{T=0} = -B + \frac{1}{2}K\chi^2 + S(\chi)\beta^2 + \mathcal{O}(\chi^3) + \mathcal{O}(\beta^4)$$

with $\chi = \frac{(n-n_0)}{3n_0}$ and $\beta = 1 - 2Y_e$



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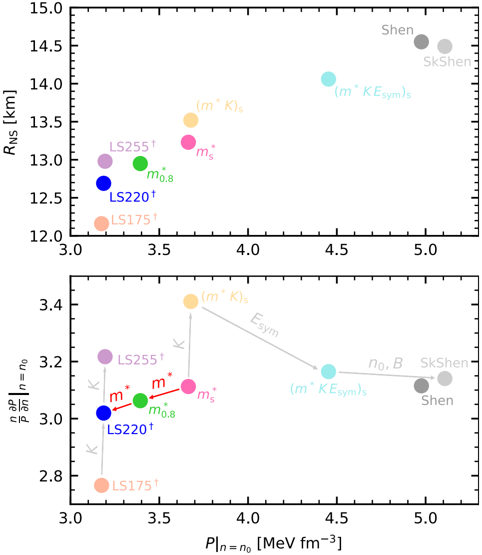
Skyrme energy density functional:

$$P|_{T=0} = \sum_t \left(\frac{5}{3}\frac{1}{2m^*} - \frac{1}{2m}\right)\frac{(3\pi n_t)^{5/3}}{5\pi^2}$$

Thermal index: $\Gamma_{\rm th} := 1 + \frac{P_{\rm th}}{\epsilon_{\rm th}} \sim \frac{5}{3} - \frac{n}{m^*}\frac{\partial m^*}{\partial n}$



Ejecta structure

Classification at 300 km:

- Dynamical ejecta

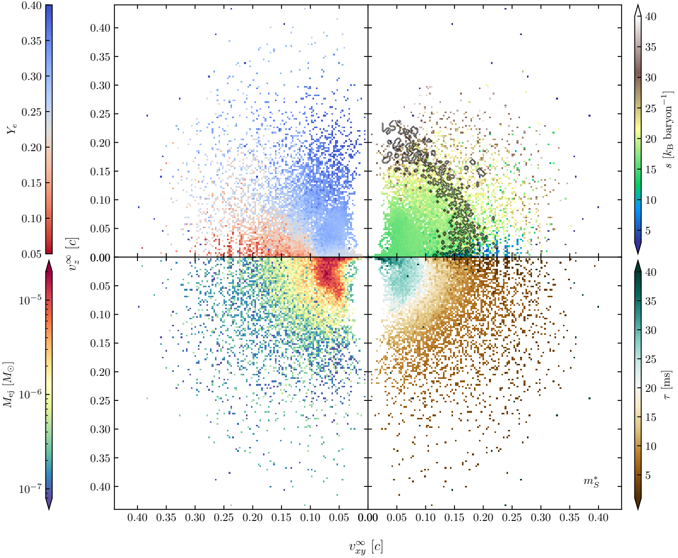
$\rightarrow$ geodesic criterion: $-u_t > 1$

  - Tidal component: $Y_e \lesssim 0.1$, $s \lesssim 10\ \mathrm{k_B/baryon}$, $\tau \lesssim 5$ ms
  - Shock heated component: $0.2 \lesssim Y_e \lesssim 0.4$, $s \gtrsim 10\ \mathrm{k_B/baryon}$

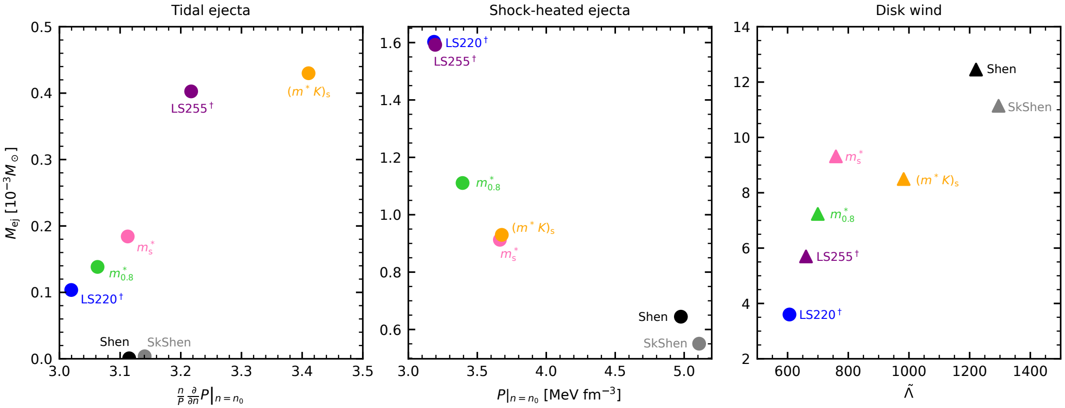
- Disk wind

$\rightarrow$ only Bernoulli criterion: $-hu_t > h_\infty$

  - Spiral wave wind: $t \gtrsim 10$ ms, $Y_e \lesssim 0.25$
  - ν-irradiated wind: $40^\circ \lesssim \theta \lesssim 80^\circ$, $Y_e \sim 0.3$



Ejecta correlations

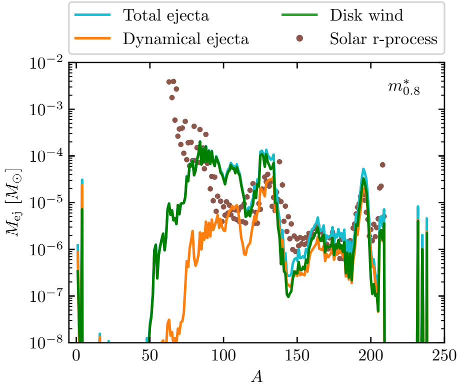


→ Mass values at simulation end (∼ 40 ms)

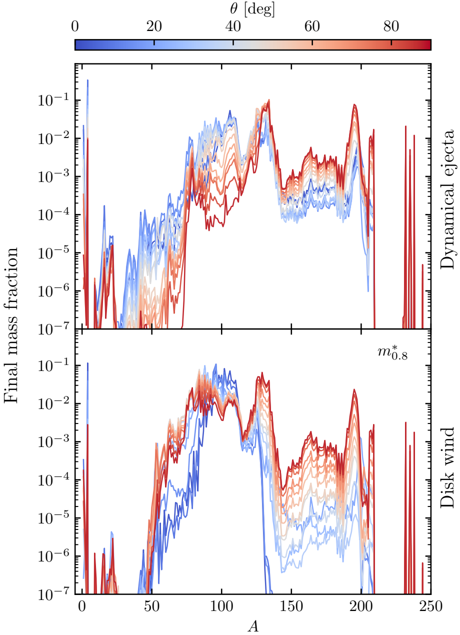
Nucleosynthesis calculations

Reaction network `WinNet` (Reichert et al. 2023):

- $\sim$ 15000 tracer particles per model
- NSE freeze-out at 7 GK



$\rightarrow$ Disk ejecta dominate the yields



Models for Kilonova light curves

- Semi-analytic models

E.g. Metzger et al. (2010), Chatzopoulos et al. (2012), Grossman et al. (2014)...

Inexpensive solution of simplified problem
$\Rightarrow$ Useful for large number of runs

- Radiative transfer simulations

E.g. Kasen et al. (2006), Sim (2007), Wollaeger et al. (2013), Tanaka & Hotokezaka (2013), Kerzendorf et al. (2018)...

Detailed photon transport with atomic data
$\Rightarrow$ Useful for accurate targeted predictions

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Examples:

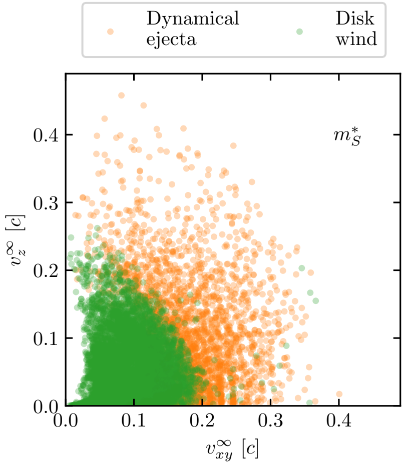
KN1) $$\frac{dE_i}{dt} + \frac{E_i}{t} = \dot{Q}_i - L_i \quad \Rightarrow \quad L(t) = \sum_{\text{shell } i} \operatorname{erfc}\left(\sqrt{\frac{t_{\mathrm{diff,i}}}{2t}}\right) \frac{E_{\mathrm{i}}}{\min(t_{\mathrm{diff,i}}, t) + \frac{v_{\mathrm{i}} t}{c}}$$

Hotokezaka & Nakar (2019)

KN2) $$\frac{DE}{Dt} - \frac{c}{3r^2}\frac{\partial}{\partial r}\left(\frac{r^2}{\chi}\frac{\partial E}{\partial r}\right) + \frac{4\dot{R}}{R}E = \dot{Q}_i \quad \Rightarrow \quad L(t) \propto \frac{(v_{\max} t_0 T_0)^4}{\kappa M_{\mathrm{ej}}} \sum_{n=1}^{\infty} (-1)^{n+1} n\pi \phi_n(t)$$

Ricigliano et al. (2023), Wollaeger et al. (2017)

Anisotropic Kilonova scheme



Ray-by-ray approach

Symmetries:

- Rotational axis
- Equatorial plane

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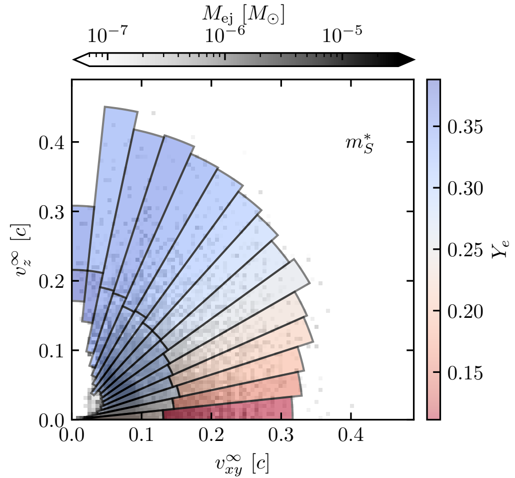


Ray-by-ray approach

Symmetries:

- Rotational axis
- Equatorial plane

Inputs:

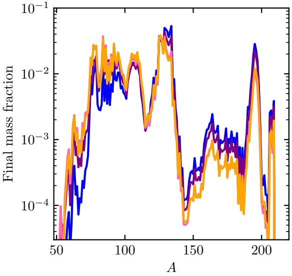
- Masses $M_{\rm ej}(\theta)$
- Characteristic velocities $v_{ej}(\theta)$
- Average grey opacities $\kappa(\theta)$
- Energy deposition rates $\dot{\epsilon}(t, \theta)$

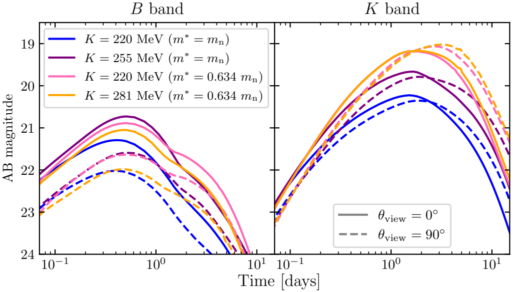
Distributions can be imported from NR and nucleosynthesis simulations or be parametric.

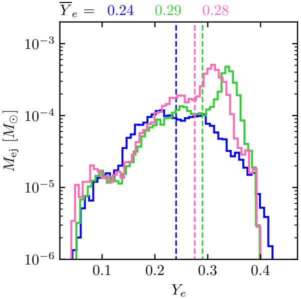
EOS effects

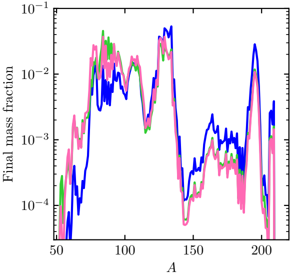
Network with detailed thermalization treatment and `KN1` model

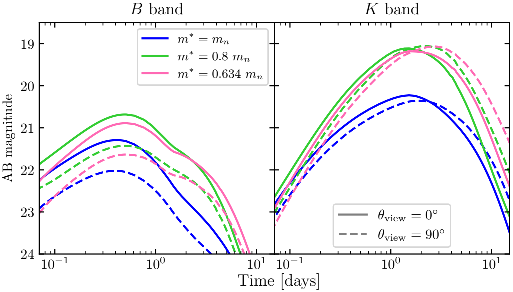
- Indirect impact through collapse
- Red bands mostly affected by EOS stiffness
- Blue bands also specifically by m^*







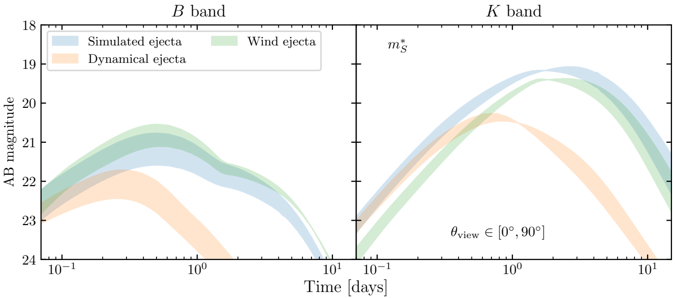




Trends reliability

⇒ Dynamical ejecta more important for $t \lesssim 1$ day:

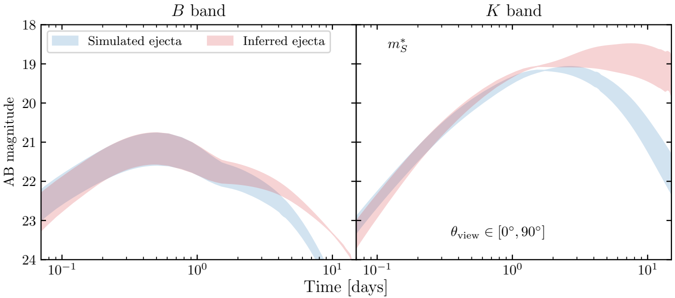
- Tidal ejecta has curtain effect
- Shock-heated ejecta relevant very early (a few hours)



Model secular ejecta:

- $M_{\rm sec}^{\rm ej} \sim 20\%$ of $M_{\rm disk}$
- properties from last few ms of disk wind ejection

⇒ Effects only for $t \gtrsim 1$ day while hierarchy preserved



Case of study: GW190425

GRHD BNS simulations
(leakage+M0 for νs, finite T EOSs)
+ Skynet + KN2 model
(Camilletti et al. 2022)

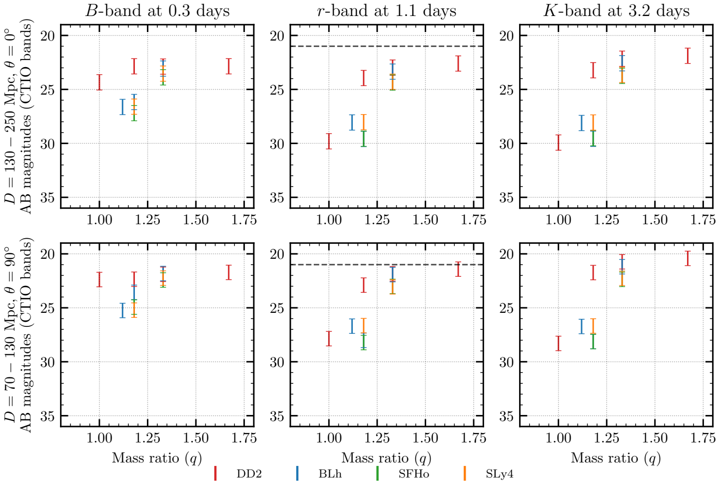
Dynamical ejecta:

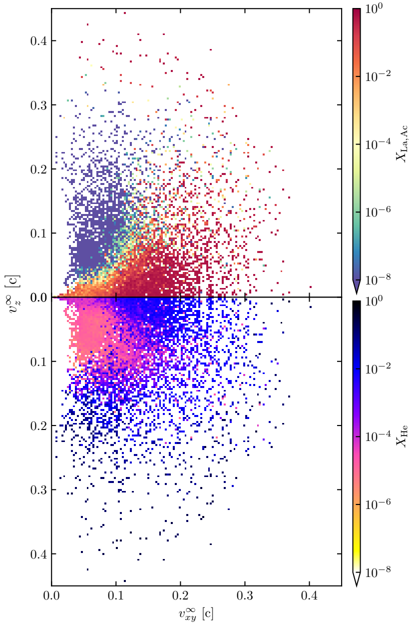
- anisotropic (from simulation)
- $M_{\rm dyn} \sim 10^{-6} - 10^{-4}\ M_\odot$
- $v_{\rm dyn} \sim 0.2 - 0.3\ c$
- $Y_{\rm e,dyn} \sim 0.10 - 0.25$

Disk wind:

- isotropic (modeled from disk)
- $M_{\rm wind} \sim 10^{-4} - 10^{-2}\ M_\odot$
- $v_{\rm wind} \sim 0.06\ c$
- $\kappa_{\rm wind} \sim 5\ {\rm cm^2 g^{-1}}$

Limit: 21 mag r,g at $\sim$ 1 day (ZTF)





- Simulations suggest correlations between nuclear matter properties and dynamical ejecta in particular

- K, m^* variations affect observables (final yields, KN light curves), although not easy to disentangle

- m^* connection to disk wind has implications on light elements production and blue KN bands

... however to fully assess the impact, further evolution of the system is necessary!