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#### Extreme matter

# in core-collapse supernovae and neutron star mergers



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# Extreme matter in neutron star mergers

Ejecta:

extreme neutron-rich conditions —> successful r-process kilonova observation after GW170817: weak and strong r-process



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#### Ejecta

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# Equation of state and neutrinos

#### GR simulations: different EoS (Bovard et al. 2017) impact of neutrinos (Martin et al. 2018)



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## Core-collapse supernovae: ejecta



Standard **neutrino-driven supernova**: Weak r-process and vp-process Elements up to ~Ag

#### **Magneto-rotational supernovae**

Neutron-rich matter ejected by strong magnetic field (Cameron 2003, Nishimura et al. 2006)

2D and 3D + parametric neutrino treatment :

- jet-like explosion: heavy r-process
- magnetic field vs. neutrinos: weak r-process

Nishimura et al. 2015, 2017, Winteler et al. 2012, Mösta et al. 2018



## Impact of astrophysical uncertainties

Steady-state model to explore possible nucleosynthesis patterns in supernova neutrino-driven ejecta



Input parameters: M<sub>ns</sub>, R<sub>ns</sub>, Y<sub>e</sub>

Nucleosynthesis ~3000 trajectories

Bliss, Witt, Arcones, Montes, Pereira (2018)

## Characteristic nucleosynthesis patterns



Bliss, Witt, Arcones, Montes, Pereira (2018)

#### Classification of nucleosynthesis patterns



# Reactions in neutrino-driven supernova ejecta

- Important reactions: α-, n-, p-capture reactions, β-decays
- $\tau_{expansion} \ll \tau_{\beta} \rightarrow (\alpha, n)$  are key reactions
- α-process (Hoffman & Woosley 1992)
- Absence of relevant experiments
  - → theoretical reaction rates based on Hauser-Feshbach model

time : 9.936e-03 s, T : 4.193e+00 GK,  $\rho$  : 2.481e+05 g/cm<sup>3</sup>



J. Bliss, A. Arcones, F. Montes, and J. Pereira (2017)

# Equation of State



# Core-collapse supernovae: Equation of State

There are several studies based on different EoS

- different underlying theory or
- all nuclear physics inputs changed simultaneously



Janka (2012)

# Core-collapse supernovae: Equation of State

Spherically symmetric supernova simulations with FLASH, M1 neutrino treatment, enhanced neutrino energy deposition (Couch & O'Connor, 2018)



Yasin, Schäfer, Arcones, Schwenk (in prep.)

#### Figure 3

igure 5								
Typical <i>M</i> — <i>I</i> curves for h EOSs ( <i>green urves</i> ) The Figure 2. Regions of the <i>I</i> ndicated. The orange cur oounded by the realistic m 1748-2446J (14). Sgurea	adminic equations EOS names are giv M-R plane exclude ves show contours ass-shedding limit aspect for Ree	offstate (EOSs) (black current en in Reference II, and ed by general relativity (Co of $R_{\infty} = R(1 - 2 GM / R)$ for the highest known p ence II.	beir $P=r$ relation GR), finite pressur $c^2)^{-1/2}$ . The regination Ulsar frequency. 7 The regination of the second secon	uark matter (SQM) are displayed in e, and causality are on marked rotation is 16 Hz, for PSR ar PNSSICS	input			
Skyrme functional: Lattimer & Swesty (1991)								
$p(u, x) = u^2 n_s \left(\frac{\partial}{\partial x}\right)$	$\left(\frac{e}{u}\right)_{r} \simeq u^2 n_s \left[\frac{K_o}{9}\right]$	$(u-1) + \frac{K'_o}{54}(u-1)^2$	$+\frac{dS_2}{du}(1-2x)^2$	$+p_{\ell}+\cdots,$ 5.				
where $p_{\ell}$ <b>EOS</b> lepton p lmost completely deter are discussed in Section	pressurg <sub><math>\eta_s</math></sub> In the vi rmined by <sub>3</sub> dS <sub>2</sub> /di fm <sup>-3</sup>	cinity of <i>u</i> <b>B</b> 1, with <i>x</i> <i>u</i> . Laboratory constrain [MeV]	$\ll 1$ , $M$ is small its on the nuclea [MeV]	and the pressure is ar symmetry energy [MeV]	L [MeV]	<i>m</i> *	$M_{ m NS}$ $[M_{\odot}]$	R <sub>1.4M<sub>NS</sub> [km]</sub>
LS220	0.155	16.00	220.0	28.61	73.7	1	2.06	12.2
2.2. The Maximally Shen	Compact Equ	uation of State	281.2	36.89	110.8	0.634	2.22	14.6
Koranda et al. (16) suggested that absolute limits to neutron star structure could be found by considering a soft low-density EOS coupled with a stiff high-density EOS, which would maximize								
he comparties $M/R$ . The 57 mitting lease of $15$ , $220916$ , $43=0$ . The lime 25 dig carries at 35 EDS is $2.4 - 69.8 \sim 0.8$ 9.7								9.7 - 13.9
$\frac{(p/d\varepsilon)^2}{(p/d\varepsilon)^2} = \frac{(c_L/2)^2}{13} = \frac{1}{1000}, \text{ where } c_s \text{ is the adiabatic speed of sound that should not exceed the speed of 40.5 - 61.9}{29.0 - 32.7} = 40.5 - 61.9$ $10.7 - 13$ $Exp. \qquad p = \frac{1}{2} = 5 - p_0 + \frac{1}{2} = \frac{1}{2} $								
This EOS has a single parameter, $\varepsilon_0$ , and therefore the structure equations (Equation 2) can be								
xpressed in Friend and the free way: at al 2010, Hebeler et al 2013, Drischler et al 2017								
Lattimer & $\frac{dw}{dx}$ im, $\frac{20133}{x(x-2x)}$ ; $\frac{dy}{dx} = 4\pi x^2 w.$ 7.								
Exp: Shlomo et al 2006 Here, $w = \varepsilon/\varepsilon_0$ , $x = r\sqrt{G\varepsilon_0/c^2}$ , and $y = m\sqrt{G^3\varepsilon_0/c^4}$ . Varying the value of w at the origin $w_0$ ) gives rise to a family of solutions described by dimensionless radius X and total mass Y. The								

attimer

# Conclusions

#### Neutron star mergers

r-process and kilonova microphysics in simulations (EoS and neutrinos): improvement necessary

#### Core-collapse supernovae

Nucleosynthesis of lighter heavy elements: astro and nuclear uncertainties

EoS: First exploration of individual nuclear physics input Effective mass determines PNS contraction

