Weak interactions in BNS mergers: present status and open issues

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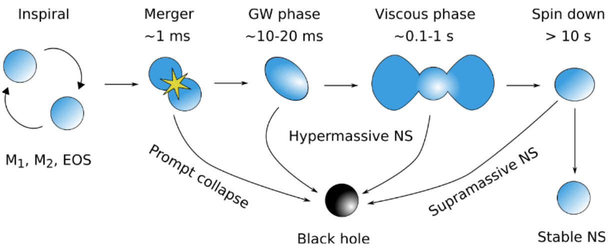
in collaboration with S. Bernuzzi, M. Breschi, M. Cusinato, A. Endrizzi, D. Gizzi, E. Loffredo, D. Radice, S. Rosswog, D. Vescovi, ...

Introduction

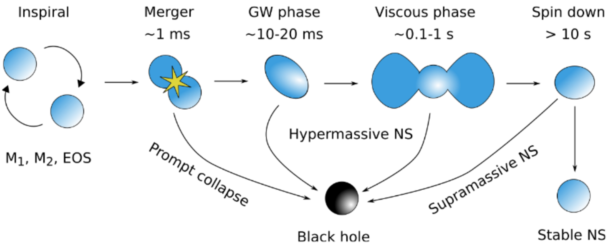
BNS merger in a nutshell



Credit: D. Radice; Radice, Bernuzzi, Perego 2020 ARNPS, Shibata & Hotokezaka 2019 ARNPS for recent reviews

- inspiral: driven by GW emission
- at merger
  - for $q \sim 1$, $v_{\rm orb} \approx \sqrt{\mathcal{C}} \sim 0.39c\,(\mathcal{C}/0.15)^{1/2}$
  - NS collision converts efficiently $E_{\rm kin}$ in $E_{\rm int}$
  - copious ν production: $L_\nu \sim 10^{53}$erg/s $\Rightarrow$ ejecta properties
- GW-dominated phase:
  - $L_{\rm GW} \sim 10^{55}$erg/s — e.g. Zappa *et al* 2018 PRL
- viscous phase: ν's as dominant cooling source $\Rightarrow$ thermal evolution

BNS merger in a nutshell



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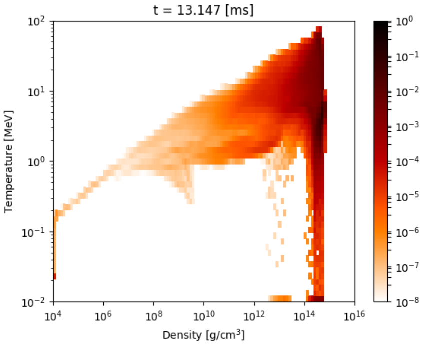
BNS mergers on thermodynamics diagrams

Which are the thermodynamics conditions of matter during the merger?

Perego,Bernuzzi,Radice 2019 EPJ A 2019; see also e.g. Hanauske+ Universe 2019

- NR BNS merger simulations: different NS masses and EOSs
- ν-physics: leakage scheme (optically thick) + M0 transport (opt. thin)
- possibly, turbulent viscosity (GRLES) Radice 2017

at each time, mass weighted histograms in (ρ-T-$\mathrm{Y_e}$) space



WhiskyTHC code

Radice+ 12,14,15

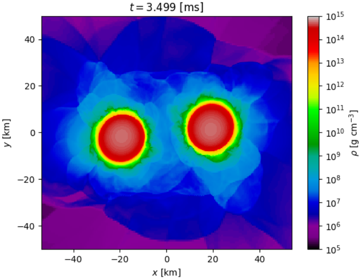
$$M_1 = M_2 = 1.364\, M_\odot$$

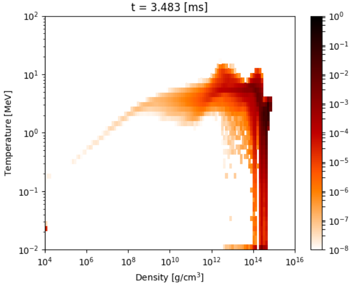
HS(DD2) EOS

movies at www.youtube.com/channel/UChmn-JGNa9mfY5H5938jnig

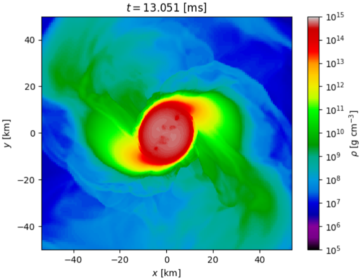
BNS mergers on thermodynamics diagrams II

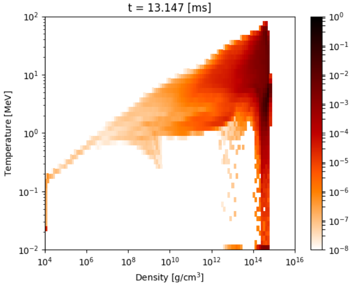
inspiral





$t(T_{peak})$

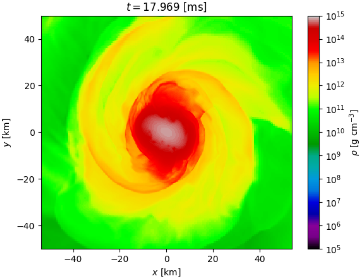


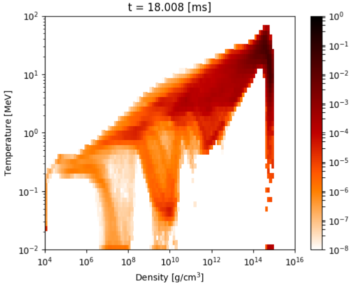


Perego,Bernuzzi,Radice EPJA 2019

BNS mergers on thermodynamics diagrams III

$t \gtrsim t_{\mathrm{dyn}}$





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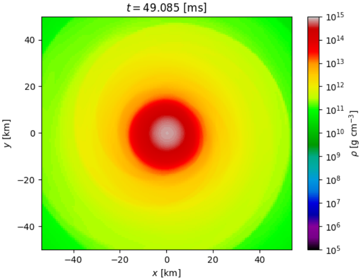
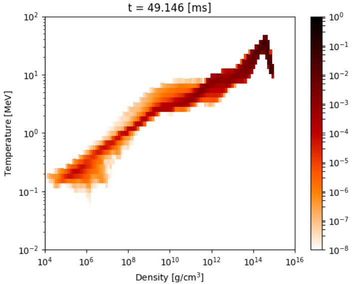




Perego,Bernuzzi,Radice EPJA 2019

Role of neutrinos in BNS mergers

Neutrinos: key players in BNS mergers

- exchange energy and momentum with matter
  - mainly cooling, but also heating
  - ν-$\bar{\nu}$ annihilation and GRBs?

Eichler+ 87

- form trapped gas
  - impact on massive NS stability?

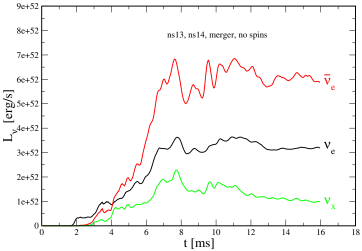
Kaplan+ 14

- set n-to-p ratio $\rightarrow Y_e$
  - $p + e^- \leftrightarrow n + \nu_e$ (EC)
    $n + e^+ \leftrightarrow p + \bar{\nu}_e$ (PC)
- ν luminosities
  - n-richness $\rightarrow L_{\bar{\nu}_e} \gtrsim L_{\nu_e}$
  - EOS dependence

e.g. Sekiguchi+15

- ν oscillations
  - matter-neutrino resonance (MNR)

e.g. Malkus+ 2012, Zhu+ 2017

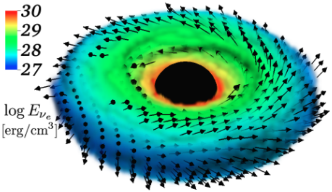


Rosswog+ 2017; First calculations: Ruffert+ 97, Rosswog & Liebendoerfer 03

Present status

Neutrino modelling in BNS mergers

- largely benefitted from ν modelling in CCSNe
- however, less advanced and mature
- prejudices & biases?



Foucart+ 15

microphysics

- opacity calculation
- trapped ν's (part of the EOS?)
- close connection with EOS:
  - finite temperature
  - composition
  - chemical potentials
  - degrees of freedom?
  - consistency with EOS?

transport

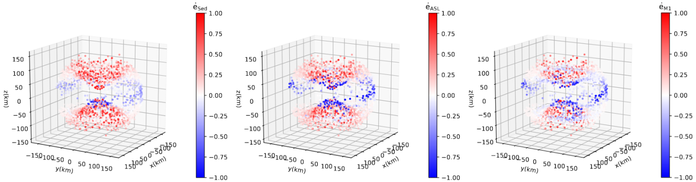
- leakage schemes
- (hybrid) truncated moment schemes
  - leakage+moment scheme
  - gray two-moment schemes with analytic closure
- MC approaches
- Boltzmann Transport?

Leakage schemes

- not really *transport* but effective treatments based on smooth interpolation between emission and diffusion rates
- modern leakage schemes …
  - …evolve Y_l and $u = e + e_\nu$ and model trapped ν's
  - …include ν absorption in optically thin conditions
- pros
  - flexible
  - computationally inexpensive
  - spectral treatment feasible
- cons
  - limited accuracy
  - calibration required
  - not-trustable in diffusive regime

Well suited for both multi-D CCSNe and BNS mergers

e.g. Gizzi *et al* 2019 MNRAS & arXiv:2102.08882 for ASL (Perego *et al* 2016 ApJS)

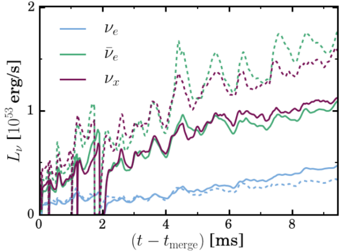


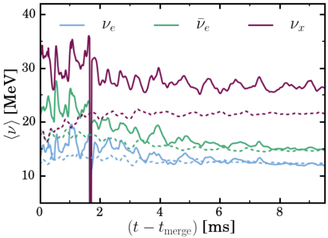
Gizzi *et al* arXiv:2102.08882

Moment schemes

Moment schemes

- approximate solution of transport equation
- reduction of problem dimension by integration over angular variable and truncation at second moment
- pros
  - correct diffusion limit
  - conservative (GR) formulation
  - accurate for ejecta properties
- cons
  - so far, gray
  - possible closure artifacts in funnel



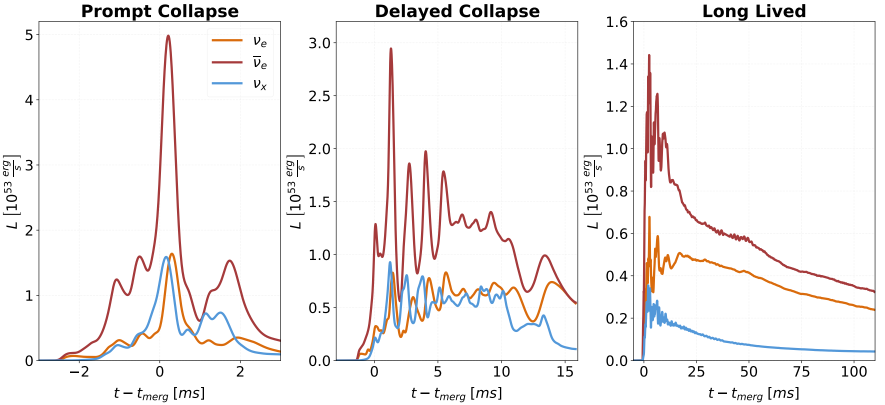


Foucart *et al* PRD 2018

Neutrino luminosities

Qualitative agreement for $L_\nu(t)$ between different groups

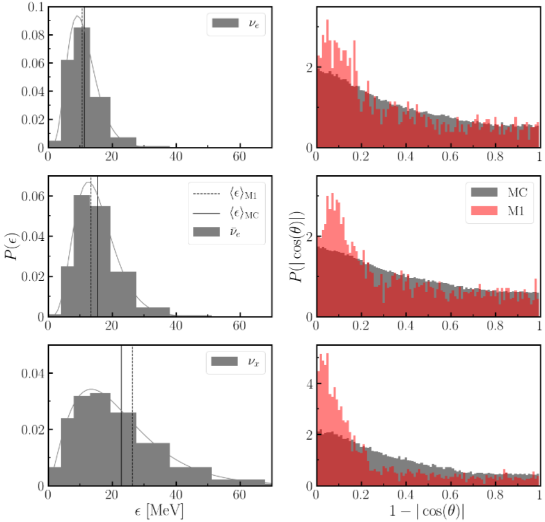
see e.g. Sekiguchi et al PRD 2016, George et al PRD 2020, Foucart et al PRD 93 & 94 2016



Courtesy of M. Cusinato (Master Student, University of Trieste)

above: $L_\nu(t)$ from 3 BNS simulations obtained by `WhiskyTHC`, i.e. with leakage+M0

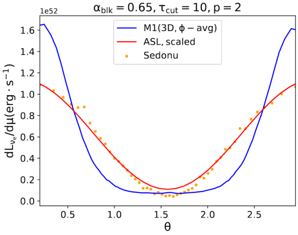
Neutrino spectra and angular distributions



Foucart *et al* PRD 2018

- energy hierarchy: $E_{\nu_e} < E_{\bar{\nu}_e} < E_{\nu_x}$
- disk shadow effect: $L_{\rm pole} > L_{\rm equator}$

Angular distribution: well reproduced by spectral leakage (ASL) + analytic prescription (isotropic + $\cos^2\theta$):



Gizzi *et al* arXiv:2102.08882

Neutrino opacities

- Minimal set of relevant neutrino-matter interactions presently included in simulations:
  - charged-current absorption on nucleons
    - $n + \nu_e \rightarrow p + e^-$
    - $p + \bar{\nu}_e \rightarrow n + e^+$
    - weak magnetism & recoil effects & finite m_e mass — e.g. Horowitz PRD 2001
  - quasi-elastic scattering on nucleons (N) and nuclei (A)
    - $N + \nu \rightarrow N + \nu$
    - $A + \nu \rightarrow A + \nu$
  - neutrino pair processes
    - $\nu + \bar{\nu} \rightarrow e^- + e^+$
    - $N + N + \nu + \bar{\nu} \rightarrow N + N$
    - energy and flavor dependent kernels — Mezzacappa & Bruenn 1993, Hannestadt & Raffelt 1998
- strong ν-energy dependence, e.g.: $\sigma_{N+\nu} \sim E_\nu^2$

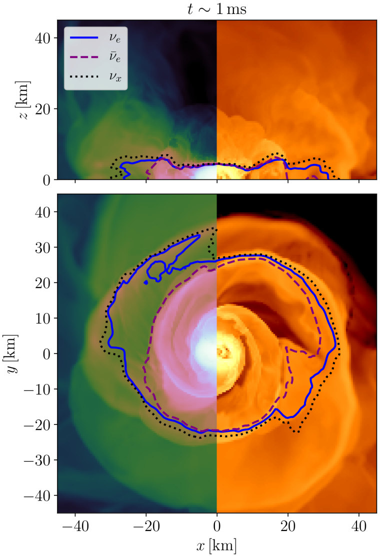
Neutrinos at decoupling surfaces

post-processing outcome of BNS simulations

- WhiskyTHC code Radice *et al* 2012,14,15
- $M_1 = M_2 = 1.364 M_\odot$ (cf $\mathcal{M}_{\rm chirp}$ of GW170817)
- HS(DD2) (stiff) $\rightarrow$ MNS
- calculations of $\tau_{\rm diff}$ and $\tau_{\rm eq}$ for large set of energies:

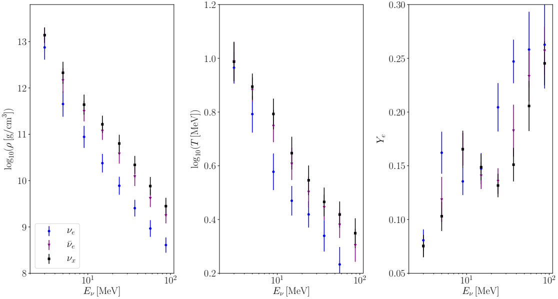
$$1\ \mathrm{MeV} \lesssim E_\nu \lesssim 100\ \mathrm{MeV}$$

- (ρ, T, Y_e) conditions at decoupling surface ($\tau \sim 1$)



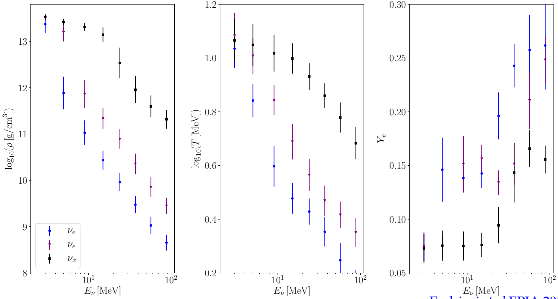
Endrizzi *et al* EPJA 2019

ν surfaces for MNS remnants: energy dependency



- HS(DD2), $\tau_{\mathrm{diff}}(E_\nu) = 2/3$
- dominant $\sigma_\nu \propto \rho E_\nu^2$ contribution
- relevant neutrino decoupling: 10^{9-13}g cm^{-3}

- HS(DD2), $\tau_{\mathrm{eq}}(E_\nu) = 2/3$
- ν_e diffuse & thermalize together
- ν_x: significant T dependence



Endrizzi *et al* EPJA 2019

Some recent applications

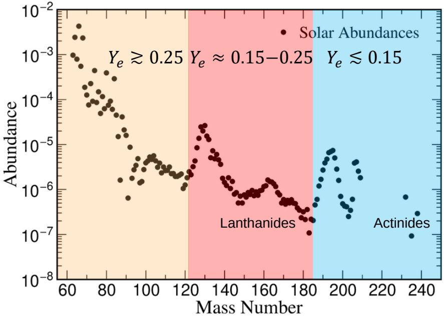
Neutrinos, r-process nucleosynthesis & kilonova

at low entropy ($s \lesssim 50 k_b$/baryon), Y_e dominant parameter for r-process nucleosynthesis

e.g., Hoffman+ ApJ 98

$\Rightarrow$ neutrino-matter interaction essential to predict ejecta composition

e.g., Wanajo *et al* ApJL 2014, Radice *et al* ApJ 2018, Martin *et al* CQG 2018, Bovard *et al* PRD 2017, ...



Courtesy of G. Martinez-Pinedo

Several observables:

- chemical abundances
  - GCE
  - metal poor stars
  - classical & ultra-faint dwarf galaxies
- kilonova
  - slope of bolometric luminosty
  - opacity
  - spectral lines? $\rightarrow$ Sr

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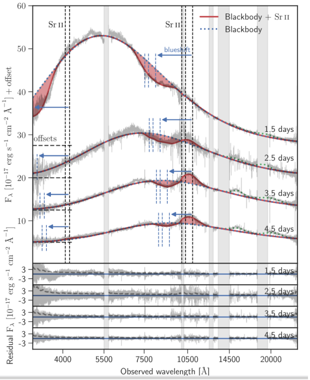

Sr in AT2017gfo spectra: Watson *et al* Nature 2018

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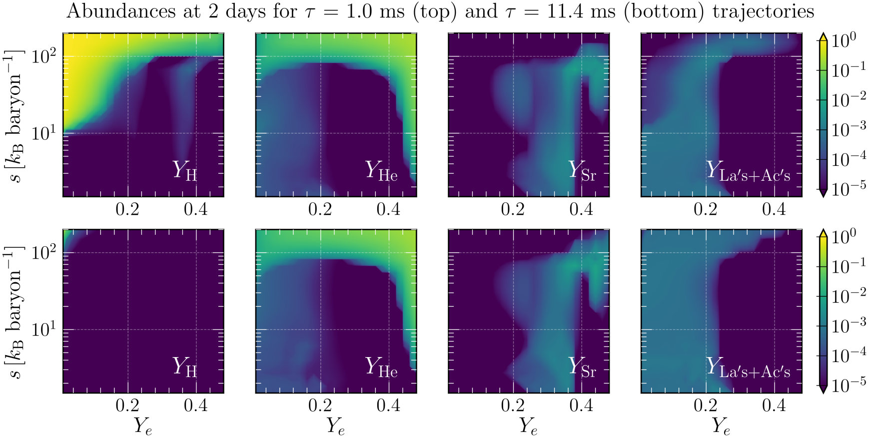
How can Sr be synthesized in BNS mergers?

Under which ejecta conditions can strontium be synthesised?



Perego, Vescovi *et al*, arxiv 2009.08988

Can Sr be synthesized in ejecta?

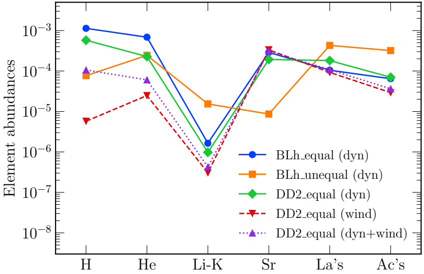
- NR simulations targeted to GW170817 using HS(DD2) and BLh EOS, a new BHF, finite T, composition dependente EOS Logoteta,Perego,Bombaci A&A 2021
- neutrino emission and irradiation included
- calculation of light element abundances in dynamical & spiral-wave wind ejecta
- since $0.7 \lesssim m_{\rm ej}[10^{-3} M_\odot] \lesssim 7$,

$$\Rightarrow 0.2 \lesssim m_{\rm Sr}[10^{-5} M_\odot] \lesssim 2$$

- compatible with observationally required Sr amount:

$$\Rightarrow 1 \lesssim m_{\rm Sr}[10^{-5} M_\odot] \lesssim 5$$

Watson *et al* Nature 2018



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A further constraint on EOS from MM astrophysics

Combination of GW and EM signals from the same event allows to extract more stringent constraints

- inclusion of ν's in NR simulation essential to predict correct ejecta composition, structure and (photon) opacities

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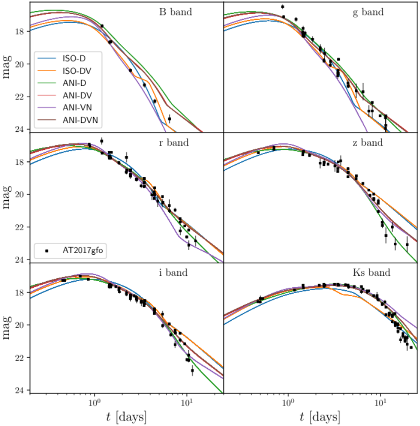
I step

- Bayesian inference on AT2017gfo data using semi-analytical, multi-component kilonova models Perego, Bernuzzi, Radice ApJL 2017
- model selection favors:
  - anisotropic over spherically symmetric models
  - multi-components over single components models



Breschi, Perego, *et al* arXiv:2101.01201

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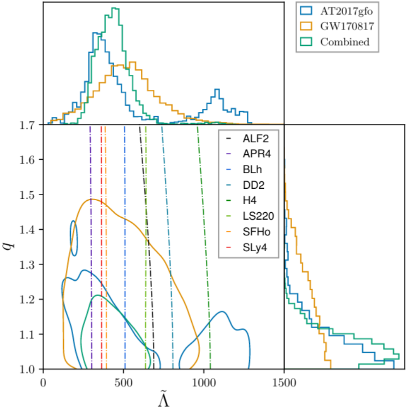
II step

combination of:

- best fit values for ejecta masses, velocities and opacity
- NR-fitting formulae for $m_{\rm ej}$, $Y_{e,\rm ej}$, $v_{\rm ej}$ and $M_{\rm disk}$ (as functions of $\tilde{\Lambda}$ and q) Nedora et al arXiv:2011.11110
- GW posteriors from GW170817

$\Rightarrow$ further constaints on $\tilde{\Lambda}$, q & $R_{1.4M_\odot}$



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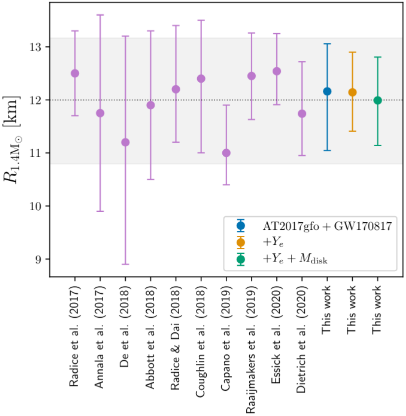

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Some open questions

Influence of trapped neutrinos?

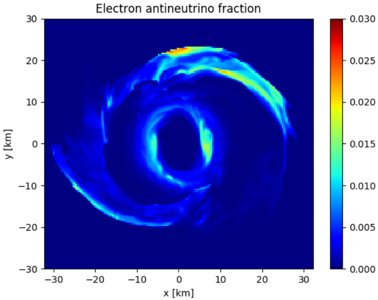
Which are the properties and the influence of trapped neutrinos?

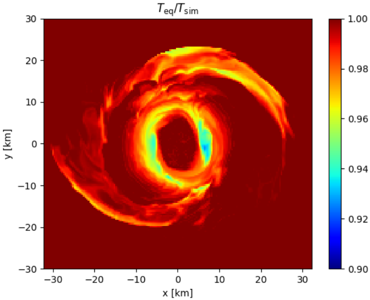
- BNS simulations often do not include trapped neutrinos
- post processing analysis: $Y_e \to Y_l = Y_e + Y_\nu \quad e \to u = e + e_\nu$

$$
\begin{aligned}
Y_l &= Y_{e,\mathrm{eq}} + Y_{\nu_e}(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) - Y_{\bar{\nu}_e}(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) \\
u &= \quad e(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) + \frac{\rho}{m_{\mathrm{b}}}\left[Z_{\nu_e}(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) + \right. \\
&\quad \left. + Z_{\bar{\nu}_e}(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) + 4 Z_{\nu_x}(T_{\mathrm{eq}})\right] \\
0 &= \quad \eta_{\nu_e}(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) - \eta_e(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) + \\
&\quad -\eta_{\mathrm{p}}(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) + \eta_{\mathrm{n}}(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}})\,.
\end{aligned}
$$

- baryon degeneracy favors $\bar{\nu}_e$ over ν_e
- overall, small effect: $\delta T/T \lesssim 8\%$, $\delta P/P \lesssim 5\%$

see also Foucart et al 2016 PRD

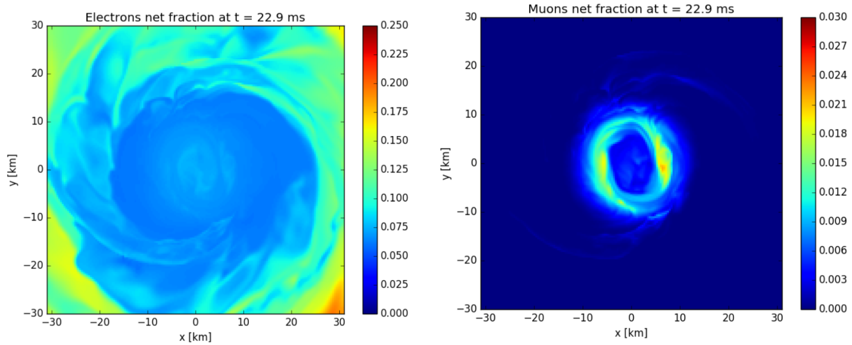




Influence of muon production?

What is the impact of (anti)muons production?

- μ^- expected to be present already at $T = 0$ for $\rho \gtrsim 2\rho_0 \Rightarrow Y_\mu \neq 0$
- $T_{\text{peak}} \sim 50 - 100$MeV comparable to $m_\mu c^2 \approx 105.7$MeV $\Rightarrow Y_\mu \,\&\, Y_{\nu_\mu} \neq 0$
- no BNS simulations include (anti-)muons
- post processing analysis:
  $Y_e \rightarrow Y_{l_e} = Y_e + Y_{\nu_e} - Y_{\bar{\nu}_e} \quad 0 = Y_{l_\mu} = Y_\mu + Y_{\nu_\mu} - Y_{\bar{\nu}_\mu} \quad e \rightarrow u = e + e_\nu$



Courtesy of E. Loffredo (PhD student, GSSI). Master thesis.

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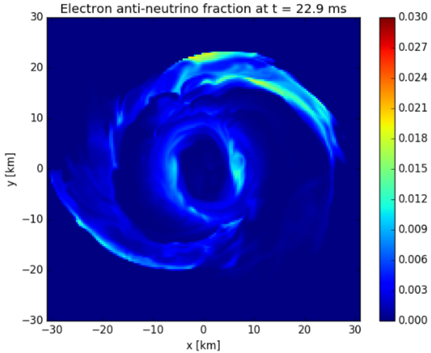

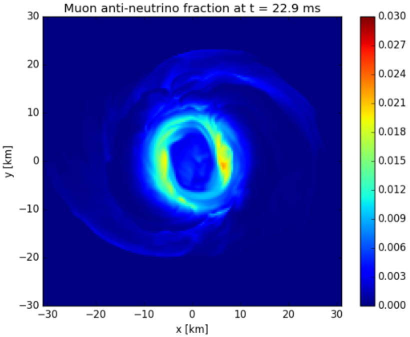

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More accurate neutrino opacities?

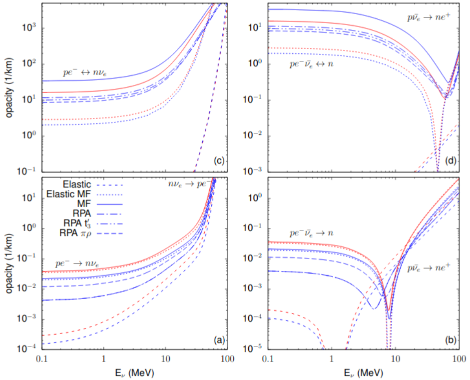
- most (if not all) BNS merger simulations use simple (analytic) expressions for neutrino opacities

Bruenn ApJ 1985; Burrows, Reddy, Thompson 2006; Buras et al 2006, `NuLib` public library, O'Connor PhD thesis 2011

- in-medium effects? more EOS-consistent and accurate opacities?

e.g. Roberts & Reddy 2017 PRC, Oertel *et al* 2020 PRC

- opacity with additional degrees of freedom?



Oertel *et al* 2020 PRC

Conclusions

- weak interactions unavoidable ingredient for accurate BNS merger modelling
- intrinsic connection with nuclear EOS
  - finite temperature effects
  - composition effects
  - additional relevant degrees of freedom (muons, quarks)?
- several open questions...
  - systematic properties of neutrino emission?
  - potential impact of trapped neutrinos?
- ...but many possible observables!