Neutrino reactions above binary neutron star merger remnants...and more

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Talk at INT: Electromagnetic Signature of r-process Nucleosynthesis in NS Binary Mergers

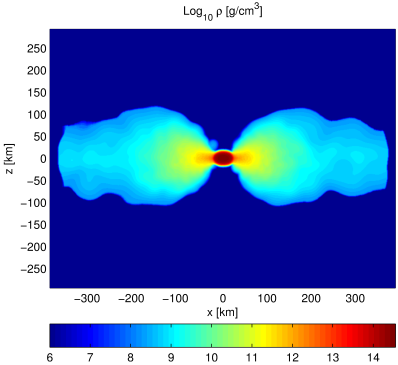
in collaboration with A. Arcones, M. Bonetti, M. Dotti, D. Martin, W. Kastaun, O. Korobkin, S. Rosswog, H. Yasin

Outline

- Neutrino processes above BNS merger remnants
  - Neutrino-driven winds from BNS merger remnants
  - Neutrinos and dynamic ejecta
  - Neutrino pair annihilations above BNS merger remnants
- and more:
  Compact binary merger and the Kozai-Lidov mechanism

BNS merger remnant properties

merger remnant:
final stages of a binary NS (BNS) system evolution



vertical slice of the matter denisty from a 3D simulation

(Perego+ 2014)

- Massive NS (→ BH)
  $M \sim 2.2 - 2.8 M_\odot$,
  $\rho \gtrsim 10^{12}\,\mathrm{g\,cm^{-3}}$
  $T \sim$ a few 10 MeV
- thick accretion disk
  $M \sim 10^{-3} - 10^{-1} M_\odot$
  $\mathrm{Y_e} \lesssim 0.20$
  $T \sim$ a few MeV
  $\left(\mathrm{Y_e} = \frac{\mathrm{n_e}}{\mathrm{n_B}} \approx \frac{\mathrm{n_p}}{\mathrm{n_p+n_n}}\right)$
- intense ν emission
  $E_\nu \gtrsim 10\,\mathrm{MeV}$
  $L_{\nu,\mathrm{tot}} \sim 10^{53}\,\mathrm{erg\,s^{-1}}$
  $L_{N,\nu,\mathrm{tot}} \sim 10^{57}\,\mathrm{particles\,s^{-1}}$

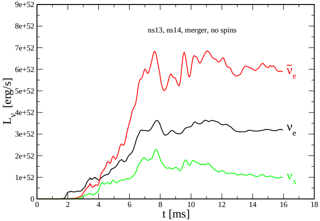
Role of ν's in BNS mergers

Role of ν's

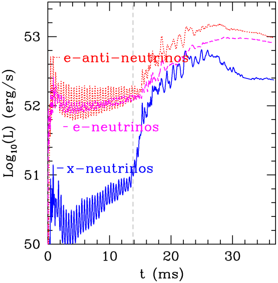
- release energy (cooling effect)
- set n-to-p ratio
  $p + e^- \leftrightarrow n + \nu_e$ & $n + e^+ \leftrightarrow p + \bar{\nu}_e$
- exchange energy and momentum with matter

see talks from Shibata, Foucart, Just, Siegel, Wu, Bovard, ...

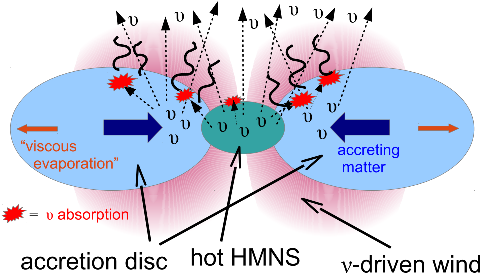
- $\Rightarrow$ relevant to set ejecta properties
- $\Rightarrow$ relevant to set EM couterpart properties



Rosswog+13 (up), Neilsen+15 (down)



Neutrino-driven wind ejecta



energy and momentum deposition by ν_e's and $\bar{\nu}_e$'s in the disk drives matter ejection.

Studied in 3D simulations with spectral leakage scheme and ray tracing algorithm:

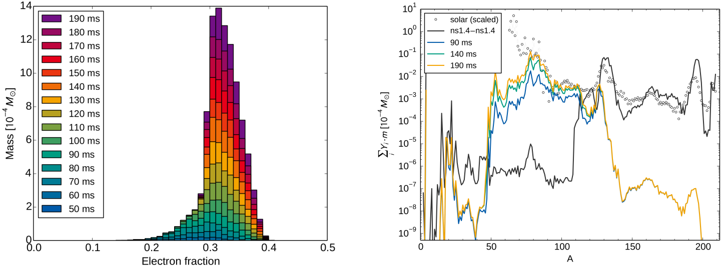
Perego+ 2014, Martin+2015

cfr. Metzger&Fernandez14, Just+2014, Sekiguchi+2015, Fujibayashi+2017

- ejection timescale: tens of ms
- $v_\infty \lesssim 0.1\,c$
- $M_{\nu-\mathrm{wind}}$ depends on L_ν, R_{disk}, MNS lifetime
- $M_{\nu-\mathrm{wind}} \lesssim 0.05\,M_{\mathrm{disk}}$

Properties of ν-driven wind ejecta

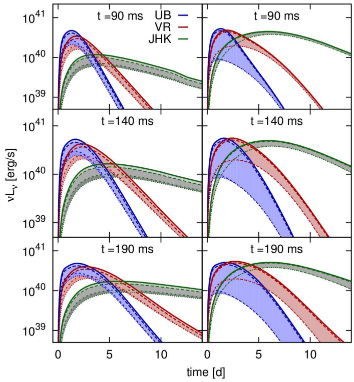
- strong neutrino irradiation: ν's have enough time to change Y_e towards equilibrium
- broad distribution of (less) n-rich matter ($0.25 \lesssim Y_e \lesssim 0.4$)
- $10 \lesssim s[k_B/\mathrm{baryon}] \lesssim 20$
- limited r-process nucleosynthesis ($80 \lesssim A \lesssim 130$), complementary to robust (main) r-process



Martin+15, Perego+14. Right: black line is dynamic ejecta from Korobkin+12

Electromagnetic transient from wind ejecta

γ emission powered by radioactive material in the ejecta



Possible dependence on the viewing angle

- 1D model for photon propagation and emission

  e.g. Kulkarni 05, Grossman+14

- different nucleosynthesis implies different emission properties
  - earlier & bluer (wind) VS later & dimmer & redder (dynamic and viscous)
  - depending on lanthanides and actinides contamination

  cf Metzger&Fernandez14

- imprint of weak interactions
- nuclear and astrophysics uncertainties? cfr. Rosswog+17, Eichler's talk

How robust are dynamic ejecta?

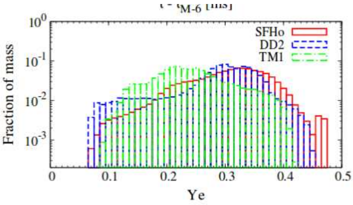
First dynamic ejecta simulations + nucleosynthesis calculations

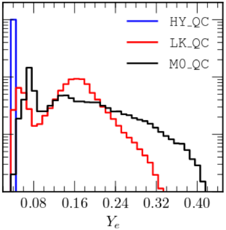
e.g. Korobkin+2012, Bauswein+2013, Hotokezaka+2013

- extremely n-rich, $\mathrm{Y_e} \lesssim 0.05$
- robust r-process nucleosynthesis, $A \gtrsim 120$
- at most, neutrino cooling included

GR simulations + neutrino treatment

e.g. Wanajo+14,Sekiguchi+15 (left figure),Foucart+15,Radice+16 (right figure)





- still robust r-process?
- effect of e^+ capture and/or ν_e absorption?

Parametric study: the input

Perego+, in preparation; cfr. Goriely+2015

shock heated dynamic ejecta from GR simulation Kastaun+17

- 1.4 $M_{\odot}$, equal mass merger, with stiff EOS
- rings of expanding matter:
  disk matter accelerated by shock produced by MNS oscillations
- $\mathrm{Y_e}$: weak equilibrium at $T = 0$, simply advected
- $\langle \mathrm{Y_e} \rangle_{\mathrm{sim}} \sim 0.044$

Parametric study: the model

Perego+, in preparation; cfr. Goriely+2015

Post-processing of tracer particles to include ν's feedback

- coupled $\mathrm{Y_e}$ & entropy evolution:

$$\frac{d\mathrm{Y_e}}{dt} = (\lambda_{\nu_e} + \lambda_{e^+})\,\mathrm{Y_n} - (\lambda_{\bar{\nu}_e} + \lambda_{e^-})\,\mathrm{Y_p}$$

$$\frac{ds}{dt} = \left(\frac{ds}{dt}\right)_{\mathrm{hydro}} + \frac{1}{T}\left[\left(\frac{dQ}{dt}\right)_{\nu} - (\mu_e - \mu_n + \mu_p)\left(\frac{d\mathrm{Y_e}}{dt}\right)_{\nu}\right]$$

- optically thin conditions ($\rho < 10^{12}\,\mathrm{g/cm^3}$)
- consistent ν emission, $\lambda_{\mathrm{e}^\pm}$

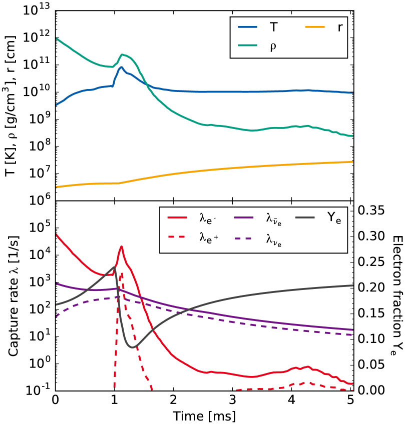
Bruenn 1985 + Horowitz 2002

- parametrized L_ν for ν absorption, $\lambda_\nu \propto \frac{L_\nu}{\langle E_\nu \rangle R^2}\,(\cos\theta)^\alpha$

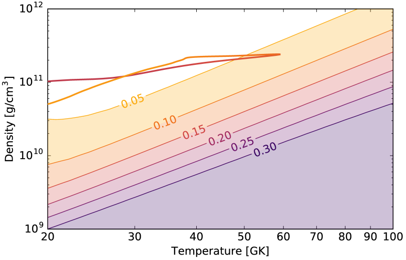
Name	$L_{\nu_e,\mathrm{max}}$ [10^{53} erg/s]	$L_{\bar{\nu}_e,\mathrm{max}}$ [10^{53} erg/s]	$E_{\nu_e,\mathrm{max}}$ [MeV]	$E_{\bar{\nu}_e,\mathrm{max}}$ [MeV]
capture	0.0	0.0	0.0	0.0
low	0.86	1.0	11.5	16.2
medium	1.0	1.5	12.0	16.3
high	1.2	2.4	13.0	16.7

, $+$ $\alpha = 0, 2$

Dynamic ejecta: Representative tracer



Profiles from a representative tracer

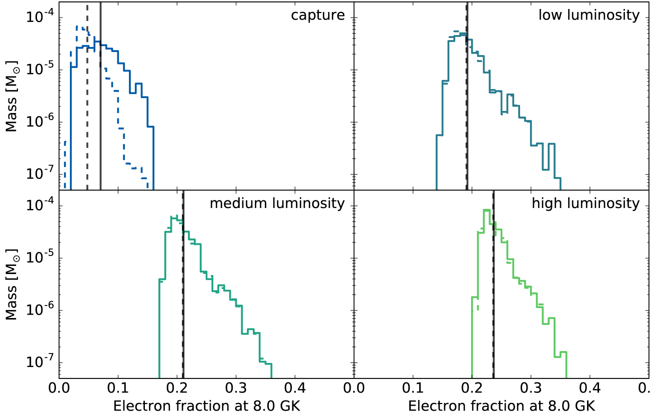


Lines of $Y_p \lambda_e^- / Y_n \lambda_e^+ = 1$

Dynamic ejecta: Distributions

Property distributions at 8 GK (2 different initial conditions):

- weak equilibrim down to $10^{12}\,\mathrm{g/cm^3} \rightarrow$ solid lines
- simulation $\mathrm{Y_e}$ (i.e., $\mathrm{Y_e} = 0.044$) $\rightarrow$ dashed lines



Courtesy of D. Martin

$\alpha = 0$, i.e. isotropic ν emission

Dynamic ejecta: Distributions

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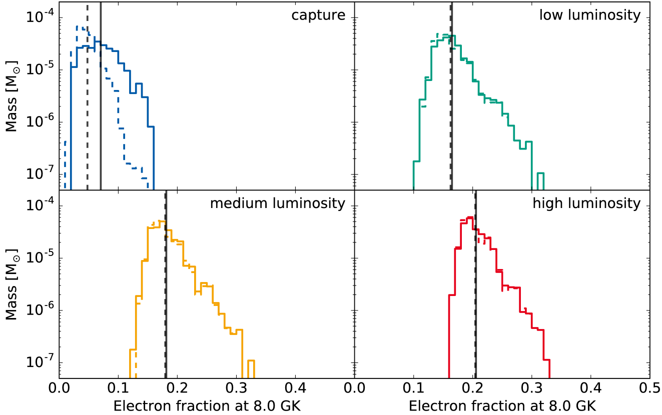


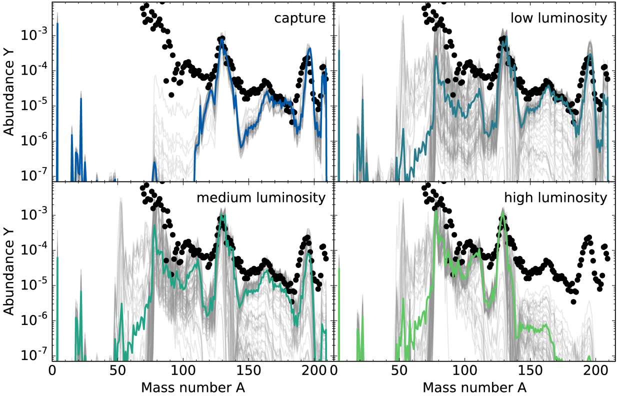
Courtesy of D. Martin

$\alpha = 2$, i.e. unisotropic ν emission

Dynamic ejecta: Nucleosynthesis

Nucleosynthesis from post-processed tracers

- mostly independent from initial conditions
- significant dependence on luminosity spatial distribution



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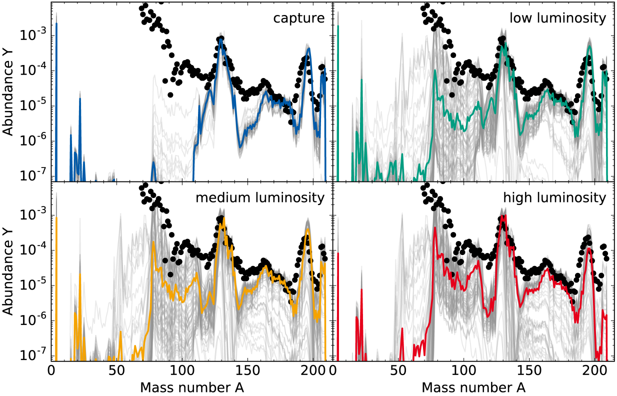

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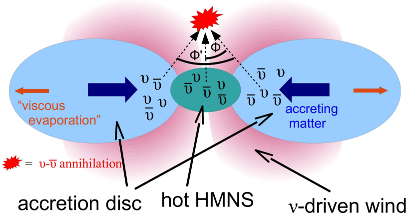
ν-$\bar{\nu}$ annihilation and short GRB engine

ν-$\bar{\nu}$ annihilation rate as sGRB central engine? Eichler et al. 1989



$$\nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau} \rightarrow e^- + e^+$$

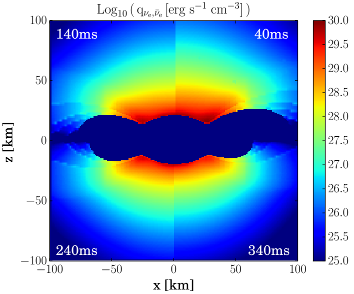
net effect: ν energy and momentum deposition in plasma

$$q_{\rm ann}(t,\mathbf{x}) \approx \frac{1}{6}\frac{\sigma_0\left(C_A^2+C_V^2\right)}{c\left(m_e c^2\right)} \int I_\nu I_{\bar{\nu}} \left(E_\nu + E_{\bar{\nu}}\right)\left(1-\cos\Phi\right)^2 \, \mathrm{d}\Omega_\nu \mathrm{d}\Omega_{\bar{\nu}} \mathrm{d}E_\nu \mathrm{d}E_{\bar{\nu}}$$

why relevant in the funnel?

- high intensity I_ν & good collision angle Φ
- lower baryonic pollution
- open questions: interplay with mag field, MNS VS BH . . . see Talks of Giacomazzo, Siegel, Shibata, Just, Tchekhovskoy

Energy deposition rates



Energy deposition by ν_e-$\bar{\nu}_e$

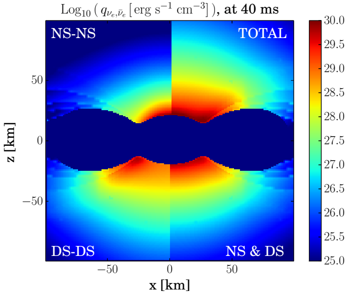
post-processing of previous 3D, long term remnant simulations

Perego, Yasin & Arcones 2017

cfr. Dessart+09,Richers+15,Just+16,Fujibayashi+17

- $Q_{\nu,\bar{\nu}}(t) = \int_V q_{\nu,\bar{\nu}}(\mathbf{x},t)\,\mathrm{d}V \sim 10^{49-50}\,\mathrm{erg/s}$
- $E_{\nu,\bar{\nu}}(t) = \int_t Q_{\nu,\bar{\nu}}(t')\,\mathrm{d}t'$, $E_{\nu,\bar{\nu}}(400\mathrm{ms}) \sim 2\times 10^{49}\,\mathrm{erg}$
- $q_{\nu_x} \sim q_{\nu_e}/60$, due to lower coupling and luminosities
- GR effects cause only a marginal decrease

Energy deposition rates



post-processing of previous 3D, long term remnant simulations

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$$I_\nu = (I_\nu)_{\mathrm{NS}} + (I_\nu)_{\mathrm{DS}} \Rightarrow$$

$$q_{\nu,\bar{\nu}} = (q_{\nu,\bar{\nu}})_{\mathrm{NS,NS}} + (q_{\nu,\bar{\nu}})_{\mathrm{DS,DS}} + (q_{\nu,\bar{\nu}})_{\mathrm{NS\&DS}}$$

- NS & Disk contribution ≈ Disk-Disk contribution
- NS & NS contribution locally intense, but globally small

Parametrization and comparison with observations

- necessary (but not sufficient!) conditions to power a short GRB: $E_{\nu,\bar{\nu}} \gtrsim E_{\mathrm{GRB}}$

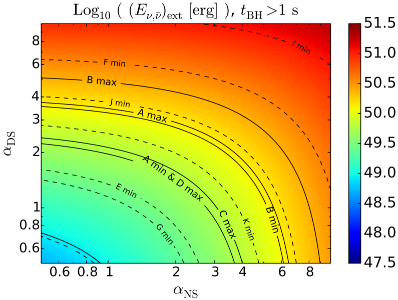
$$E_{\mathrm{GRB}} = (1-\cos\theta_{\mathrm{jet}})(E_{\gamma,\mathrm{iso}}+E_{\mathrm{kin,iso}})$$

- useful & accurate parametrization:

$$Q_{\nu,\bar{\nu}} \propto L_\nu L_{\bar{\nu}} \left[\frac{\langle \epsilon_\nu^2 \rangle}{\langle \epsilon_\nu \rangle} + \frac{\langle \epsilon_{\bar{\nu}}^2 \rangle}{\langle \epsilon_{\bar{\nu}} \rangle} \right]$$

- it allows luminosity scaling to bracket uncertainties e.g., Fujibayashi+17

$$L \rightarrow \alpha L$$



comparison with inferred energy from 11 short GRB observations.

Case I: measured jet opening angle (4) or upper limits (7) from jet non-detection Fong+15

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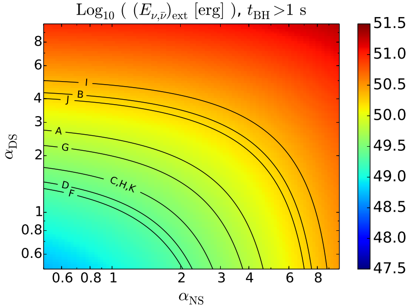
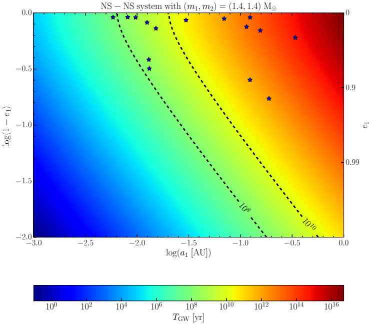


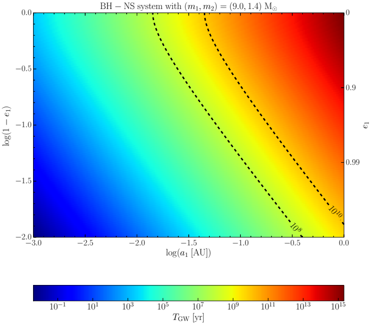
comparison with inferred energy from 11 short GRB observations.

Case II: small opening angle, 6^o, consistent with 4 observed angles Fong+15

Binary merger time scale

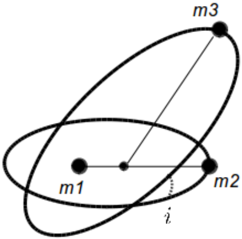
- compact binary (BHNS or NSNS)
- characterized by: m_1, m_2, a_1, e_1
- $t_{\rm merge} \approx t_{\rm GW} \sim 1.11 \times 10^8 {\rm yr} \left(\frac{a}{0.01\,{\rm AU}}\right)^4 \left(\frac{m_{\rm tot}}{5\,M_\odot}\right)^{-2} \left(\frac{\mu}{M_\odot}\right)^{-1} (1-e^2)^{7/2}$





The Kozai-Lidov resonance

- what happens if compact binary is inner binary of a hierarchical triple system?
- Kozai-Lidov resonance: secular exchange of angular momentum between inner and outer binary



- $e_{\max} \approx \sqrt{1 - \frac{5}{3}\cos^2 i}$
- active for $i \lesssim 39^o$ or $i \gtrsim 141^o$

- periodic increase in e_1 ⇒ periodic boost of GW emission ⇒ reduction of t_{merge}
- KL mechanism can modify compact binary rates Thompson 2011
- under which conditions $t_{\mathrm{merge}} < 10^8\mathrm{yr}$?

Preliminary considerations

- 10 parameter problem!

$$(a_1, e_1, m_1, m_2) + (a_2, e_2, m_3, i) + (g_1, g_2)$$

- hierachical system: $a_2 \gg a_1$

$$\frac{a_2}{a_1} > 2.8 \left(1 + \frac{m_3}{m_1 + m_2}\right)^{2/5} \frac{(1+e_2)^{2/5}}{(1-e_2)^{6/5}} \, .$$

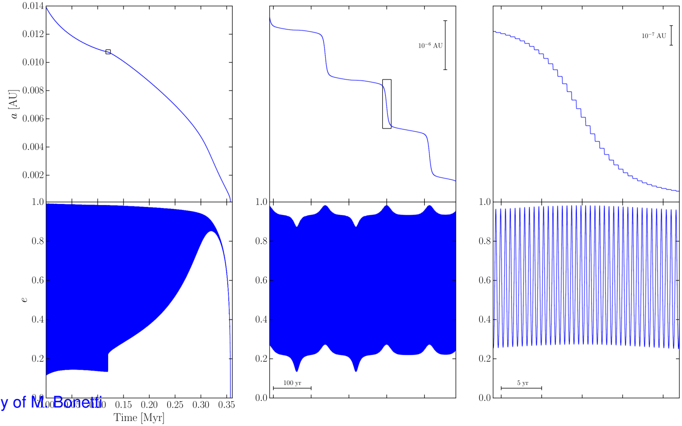
- competition with relativistic precession

$$\frac{a_2}{a_1} < 53\,\mathrm{AU} \left(\frac{a_1}{0.01\,\mathrm{AU}}\right)^{1/3} \left(\frac{m_1 + m_2}{5\,M_\odot}\right)^{-1/3} \left(\frac{m_3}{m_1 + m_2}\right)^{1/3} \left(\frac{1-e_1^2}{1-e_2^2}\right)^{1/2}$$

- integration of equation of motion for $a_1, \; e_1, e_2, g_1, g_2$ and H (total angular momentum) e.g., Ford+2000,Blaes+2002
- large m_3 helps, but massive stars have shorter lifes

A test case

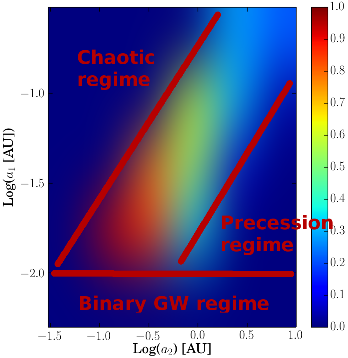
- NS-NS case (1.4-1.4 $M_\odot$)
- $a_1 = 0.014\mathrm{AU}$, $e_1 = 0.15$, $a_2 = 0.306\mathrm{AU}$, $e_2 = 0.6$, $i = 85^o$
- $t_{\mathrm{GW}} \approx 1.8$ Gyr VS $t \approx 0.35$ Myr

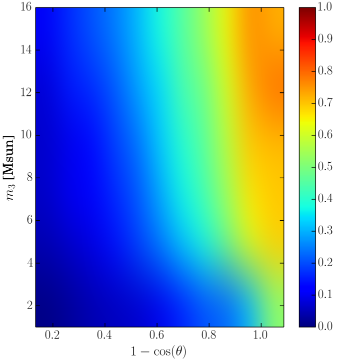


Courtesy of M. Bonetti

Parameter exploration

- generate a large grid for $(a_1, e_1, a_2, e_2, m_3, i)$ parameters
- color-coded quantity: fraction of binary systems that
  - $t_{\mathrm{GW}} > 10^8$ yr
  - merge within 10^8 yr in triple systems
  - varying 2 variable and summing up over all the others
  - $m_1 = 7.5 M_\odot$, $m_2 = 1.2 M_\odot$, $g_1 = 0$ and $g_2 = 180^o$

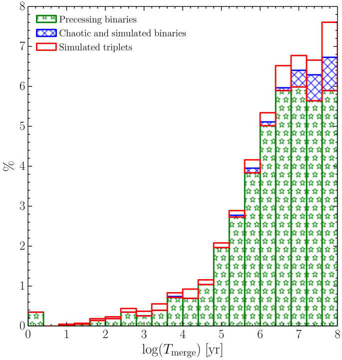




preliminary resuls

Population study

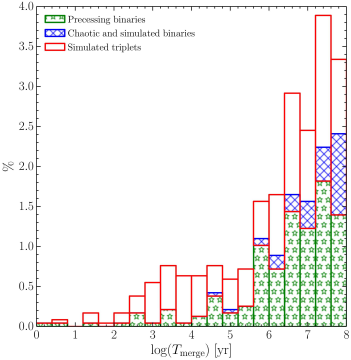
- generate binary and triplet populations according to PDF
- compare $t_{\rm GW}$ with $t_{\rm merge}$



BH-NS case

PDF for a_1: uniform in $\log(a_1)$

preliminary resuls



BH-NS case

PDF for a_1: uniform in a_1

Conclusions

- neutrinos play an important role in BNS mergers
  - they set the properties of the ejecta and potentially of the EM couterparts
  - they can drive an outflow (ν-driven wind)
  - they can extend nucleosynthesis from I to III r-process peak
  - they can inject significant energy in the funnel (MNS can double energy)
  - many improvements to be done (e.g., transport, ν oscillations (McLaughlin, Wu talks))

- dynamical processes (e.g., Kozai-Lidov) in triple systems can decrease $t_{\rm merge}$
  - relevant if the outer body is close enough (but not too close)
  - large inclination angle required
  - it could help if a population of binary with small semi-major axis is not present in nature