Neutrinos in supernova evolution and nucleosynthesis

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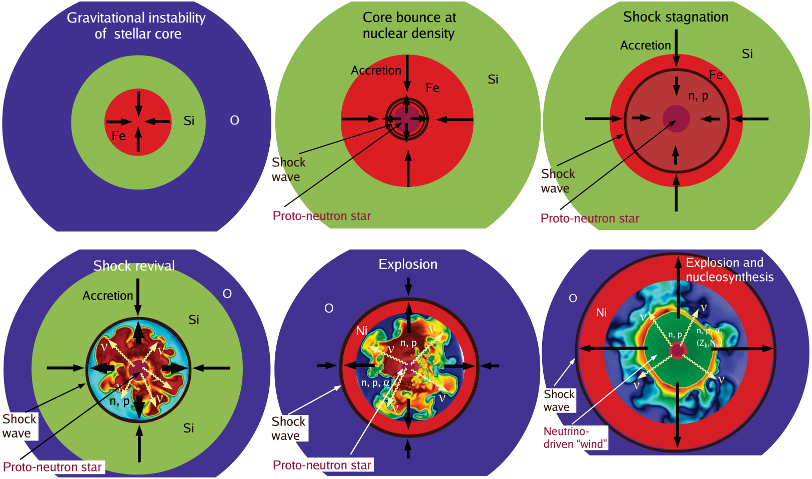
   - Nucleosynthesis in neutrino-driven winds
   - Neutrino nucleosynthesis
3. Neutrinos and neutron star mergers
   - Impact on electromagnetic transients
4. Summary

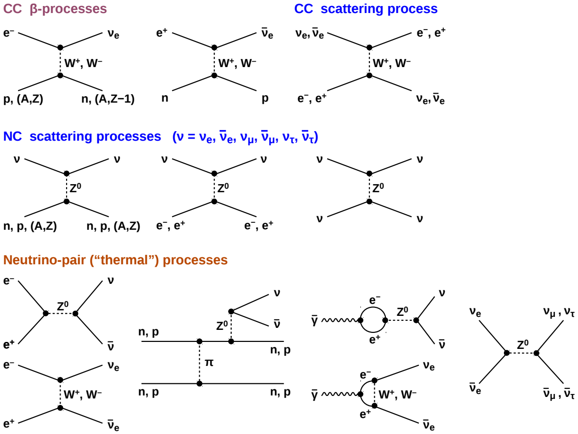
Core-collapse supernova

H.-Th. Janka, *et al*, PTEP 01A309 (2012)



Relevant neutrino processes

Many different neutrino processes need to be modelled within Boltzmann radiation transport.



From H.-Th. Janka, arXiv:1702.08713 [astro-ph.HE]

Microphysics vs multidimensional supernova

- Three dimensional supernova simulations are very sensitive to variations of 10-20% in neutrino opacities (Melson+, 2015)
- Most studies focus on neutral current neutrino-nucleon scattering:

$$\frac{1}{V}\frac{d\sigma}{d\Omega} \approx \frac{G_F^2 E_\nu^2}{16\pi^2}\left[c_a^2(3-\cos\theta)S_A + c_v^2(1+\cos\theta)S_V\right]$$

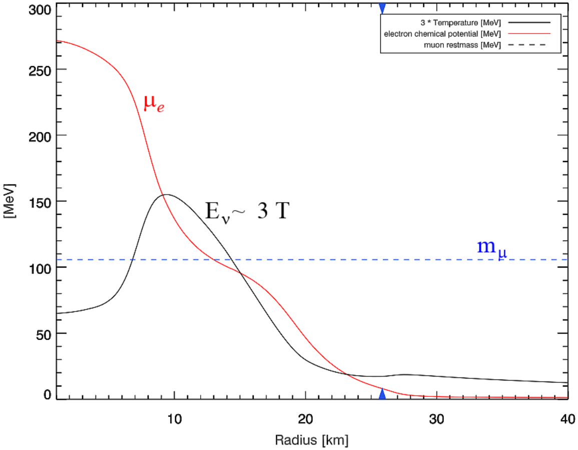
  - Reduction due to strangeness contribution to axial-vector coupling constant (Melson+, 2015, Hobbs+, 2016):

$$c_a = \pm g_A - g_s, \quad g_s = -0.103 \pm 0.013$$

  - Reduction structure factor due to correlations at low densities (Virial expansion Horowitz+, 2017)
- What about additional degrees of freedom: muons, pions, hyperons, …

Muons in core-collapse supernova

Muons are routinely considered in cold neutron stars but so far have been neglected in supernova modeling.



Muons can be produced both by thermal (electromagnetic) processes and by weak processes.

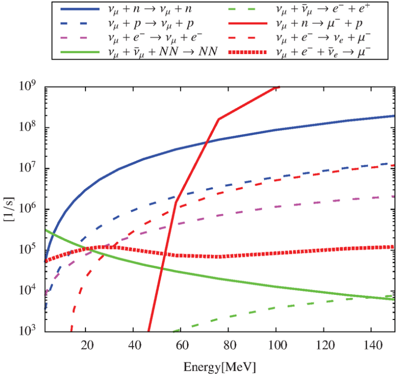
Description of muon opacities

- Thermal processes (subdominant)

$$\gamma + \gamma \rightarrow \mu^+ + \mu^-$$
$$e^+ + e^- \rightarrow \mu^+ + \mu^-$$

- weak processes: produce a net muonic number.
- Requires six flavor Boltzmann neutrino transport.

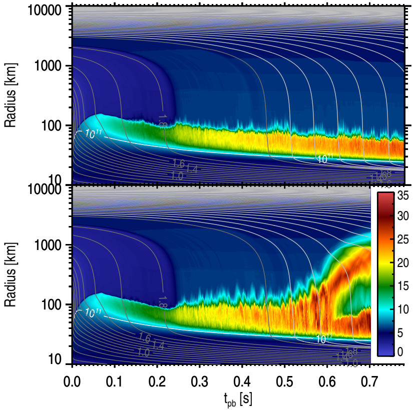
$\nu + \mu^- \rightleftarrows \nu' + \mu^{-\prime}$	$\nu + \mu^+ \rightleftarrows \nu' + \mu^{+\prime}$
$\nu_\mu + e^- \rightleftarrows \nu_e + \mu^-$	$\bar{\nu}_\mu + e^+ \rightleftarrows \bar{\nu}_e + \mu^+$
$\nu_\mu + \bar{\nu}_e + e^- \rightleftarrows \mu^-$	$\bar{\nu}_\mu + \nu_e + e^+ \rightleftarrows \mu^+$
$\bar{\nu}_e + e^- \rightleftarrows \bar{\nu}_\mu + \mu^-$	$\nu_e + e^+ \rightleftarrows \nu_\mu + \mu^+$
$\nu_\mu + n \rightleftarrows p + \mu^-$	$\bar{\nu}_\mu + p \rightleftarrows n + \mu^+$



A. Lohs, 2015

2D simulations

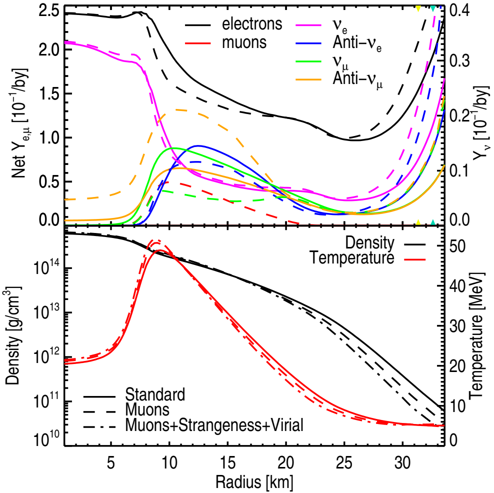
Inclusion of muons can lead to explosions in models that otherwise do not explode



Bollig, Janka,Lohs, GMP, Horowitz, and Melson, arXiv:1706.04630 [astro-ph.HE]

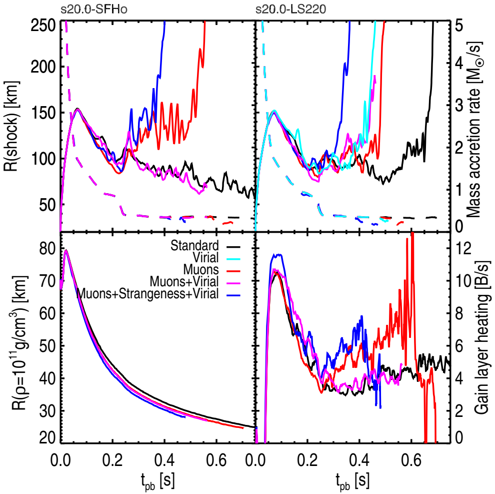
Composition around 400 ms

- Thermal energy is converted into muon rest mass energy
- Electron degeneracy pressure reduced



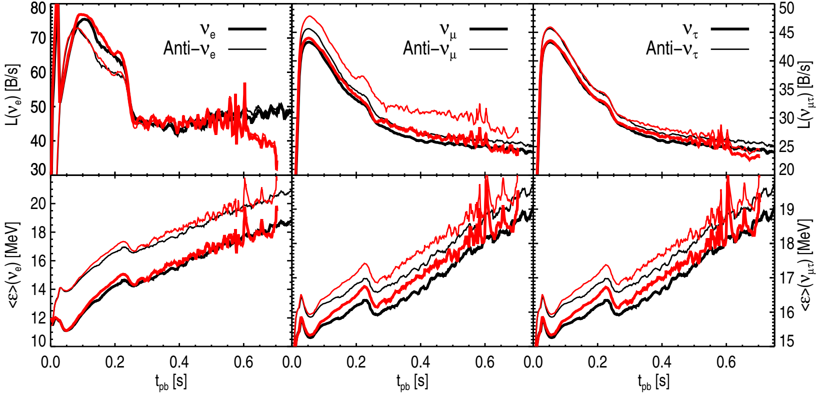
2D simulations: shock evolution

- Inclusion of muons favors the explosion
- Protoneutron star shrinks faster
- Strangeness corrections also favor explosions
- Role of virial correlations uncertain.

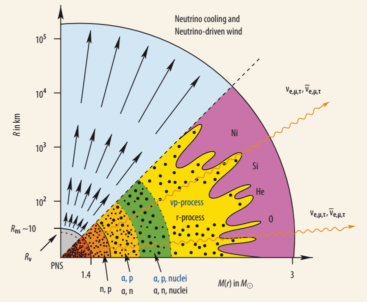


2D simulations: neutrino spectral properties

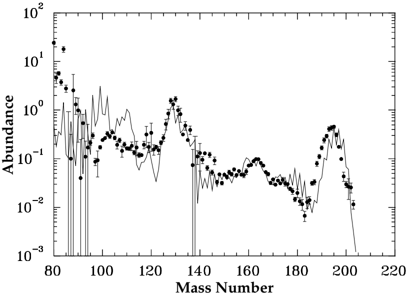
Hotter neutrino emission with distinct neutrino spectra for all flavors.

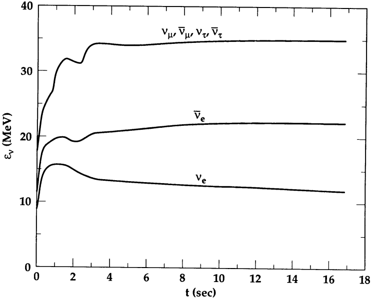


Neutrino-driven winds and r process



Woosley *et al*, ApJ **433**, 229 (1994), suggested neutrino-driven winds as the r-process site.





Nucleosynthesis in neutrino-driven winds

Neutrino interactions determine Y_e

$$\nu_e + n \rightleftarrows p + e^-$$
$$\bar{\nu}_e + p \rightleftarrows n + e^+$$

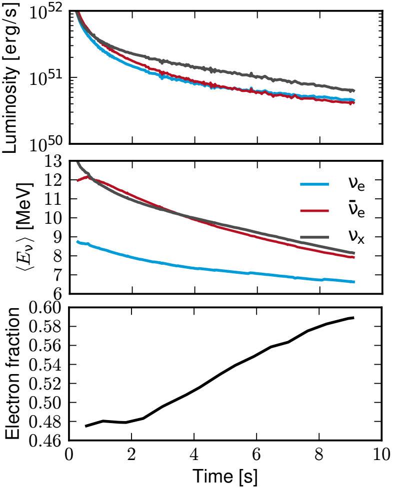
Neutron-rich ejecta:

$$\langle E_{\bar{\nu}_e}\rangle - \langle E_{\nu_e}\rangle > 4\Delta_{np} - \left[\frac{L_{\bar{\nu}_e}}{L_{\nu_e}} - 1\right]\left[\langle E_{\bar{\nu}_e}\rangle - 2\Delta_{np}\right]$$

- neutron-rich ejecta: weak r-process
- proton-rich ejecta: νp-process

Energy difference related to symmetry energy (GMP+ 2012, Roberts+ 2012)

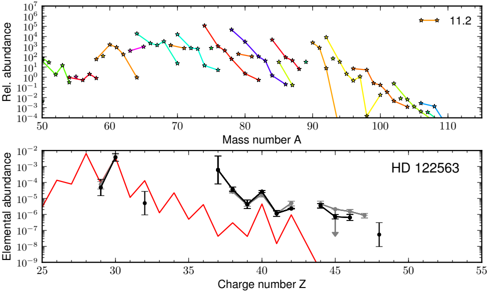
1D Boltzmann transport simulation (DD2 EoS)



GMP+ 2013

Nucleosynthesis

Neutron-deficient isotopes of elements between Zn and Mo



Can heavier elements be produced?

- Improved treatment opacities: no, increases Y_e.
- Explosions lighter stars (ONeMg cores): yes, reduced exposure to neutrino fluxes.
- Flavor oscillations:
  - Collective: minor impact (Wu+ 2015)
  - Active-sterile ($\Delta m_{as} \sim 1$ eV): important impact on nucleosynthesis, detrimental for the explosion (Nunokawa+ 1997, Wu+ 2013)

MSW mechanism for sterile neutrinos

For the case of active (electron neutrinos)-sterille flavor conversions. The ν_e effective potential is:

$$V_{\nu_e}^{\text{eff}} = \frac{\sqrt{2}}{2} G_F \frac{\rho}{m_u} (c_v^e Y_e + c_v^p Y_p + c_v^n Y_n) = \frac{3\sqrt{2}}{2} G_F \frac{\rho}{m_u} \left(Y_e - \frac{1}{3} \right)$$

The MSW resonance for neutrinos will appear when:

$$\frac{\Delta m^2}{2E_\nu} \cos 2\theta = \frac{3\sqrt{2}}{2} G_F \frac{\rho}{m_u} \left(Y_e - \frac{1}{3} \right) \equiv V_{\nu_e}^{\text{eff}} \Rightarrow Y_e = \frac{1}{3} + \epsilon$$

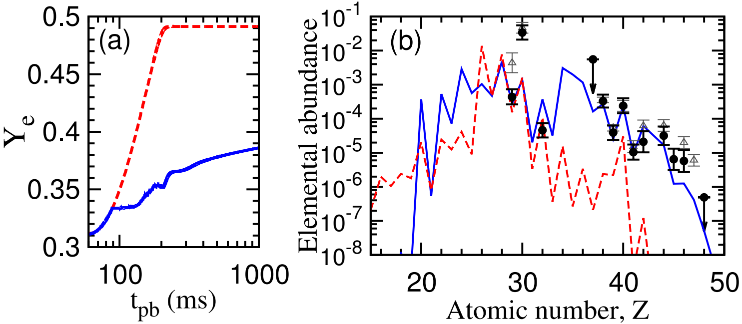
and for antineutrinos:

$$\frac{\Delta m^2}{2E_\nu} \cos 2\theta = -\frac{3\sqrt{2}}{2} G_F \frac{\rho}{m_u} \left(Y_e - \frac{1}{3} \right) \equiv V_{\bar{\nu}_e}^{\text{eff}} \Rightarrow Y_e = \frac{1}{3} - \epsilon$$

- Oscillations depend on Y_e-profile that is itself affected by the oscillations. A fully self-consistent approach is necessary to account for feedback effects
- Feedback effects enhance oscillations and reduce Y_e of ejected matter.

Impact on nucleosynthesis

M.-R. Wu, T. Fischer, GMP, Y.-Z. Qian, PRD 89, 061303(R), 2014



- Active-sterile flavor conversion increases the neutron richness of the ejected material
- This allows for the production of elements between Sr and Cd in agreement with metal-poor star observations.

Neutrino nucleosynthesis: ν process

Neutrino-nucleus interactions in the outer layers produce several key isotopes (Woosley+ 1990, Heger+ 2005, Suzuki+ 2013)

Product	Parent	Reaction
^{7}Li	^{4}He	$^{4}\mathrm{He}(\nu,\nu' p)^{3}\mathrm{H}(\alpha,\gamma)^{7}\mathrm{Li}$ $^{4}\mathrm{He}(\nu,\nu' n)^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}(e^{-},\nu_e)^{7}\mathrm{Li}$
^{11}B	^{12}C	$^{12}\mathrm{C}(\nu,\nu' n)^{11}\mathrm{C}(\beta^{+})^{11}\mathrm{B}$, $^{12}\mathrm{C}(\nu,\nu' p)^{11}\mathrm{B}$
^{15}N	^{16}O	$^{16}\mathrm{O}(\nu,\nu' n)^{15}\mathrm{O}(\beta^{+})^{15}\mathrm{N}$, $^{16}\mathrm{O}(\nu,\nu' p)^{15}\mathrm{N}$
^{19}F	^{20}Ne	$^{20}\mathrm{Ne}(\nu,\nu' n)^{19}\mathrm{Ne}(\beta^{+})^{19}\mathrm{F}$, $^{20}\mathrm{Ne}(\nu,\nu' p)^{19}\mathrm{F}$
^{138}La	^{138}Ba	$^{138}\mathrm{Ba}(\nu_e,e^{-})^{138}\mathrm{La}$, $^{138}\mathrm{Ba}(\nu_e,e^{-}n)^{137}\mathrm{La}(n,\gamma)^{138}\mathrm{La}$
^{180}Ta	^{180}Hf	$^{180}\mathrm{Hf}(\nu_e,e^{-})^{180}\mathrm{Ta}$

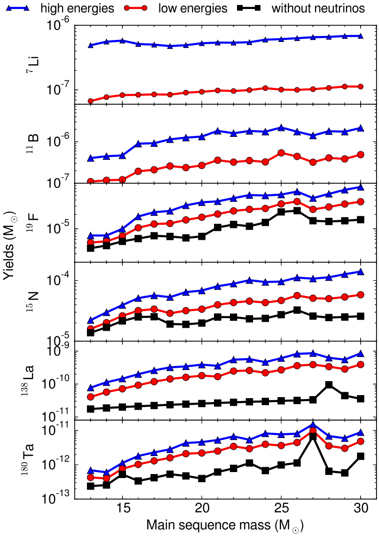
- So far studies have assumed large average neutrino energies: $\langle E_{\nu_e}\rangle = 12$ MeV, $\langle E_{\bar{\nu}_e}\rangle = 15.8$ MeV, $\langle E_{\nu_{\mu,\tau}}\rangle = 19$ MeV (high energies)
- Modern supernova simulations predict lower average energies: $\langle E_{\nu_e}\rangle = 9$ MeV, $\langle E_{\bar{\nu}_e}\rangle = 12$ MeV, $\langle E_{\nu_{\mu,\tau}}\rangle = 12$ MeV (low energies)

Nucleosynthesis yields

Yields normalized to ^{16}O and averaged over initial mass function.

Nucleus	no ν	Low energies	High energies
^{7}Li	0.002	0.07	0.45
^{11}B	0.008	0.36	1.54
^{15}N	0.05	0.07	0.13
^{19}F	0.12	0.19	0.33
^{138}La	0.12	0.59	1.29
^{180}Ta	0.19	0.49	0.88

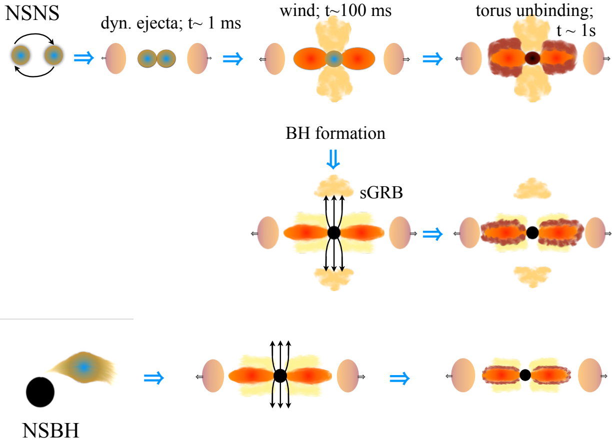
- ^{7}Li and ^{15}N varely produced by the ν process
- ^{11}B consistent with expected yields from cosmic rays (Austin+ 2011)
- ^{19}F is expected to be produced mainly in AGB stars
- ^{138}La and ^{180}Ta have also contributions from s process.



Sieverding+, in preparation

Merger channels and ejection mechanism

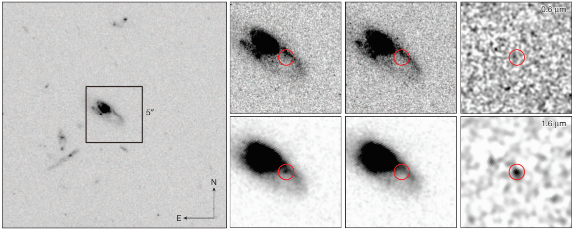
In mergers we deal with a variety of initial configurations (netron-star neutron-star vs neutron-star black-hole) with additional variations in the mass-ratio. The evolution after the merger also allows for further variations.

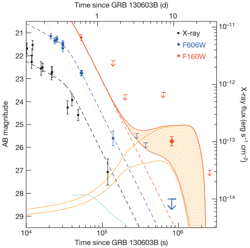


Rosswog, *et al*, Class. Quantum Gravity **34**, 104001 (2017)

Kilonova/Macronova electromagnetic transient

- Electromagnetic transitent from radioactive decay r-process ejecta [Li & Paczyński 1998]
- Luminosities ~ 1000 times those of a nova at timescales of a day in the blue [Metzger *et al*, 2010]
- Large optical opacities of Lanthanides delay the peak to timescales of a week in the red/infrared [Kasen *et al*, 2013]
- Probably observed associated to GRB 130603B



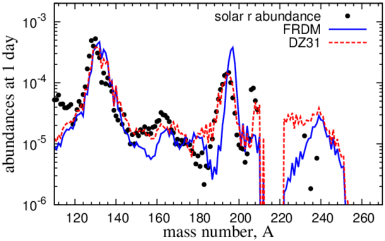


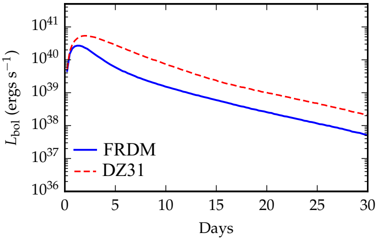
First direct observation of an r-process event?

Tanvir+, Nature **500**, 457 (2013)

r process and electromagnetic transient

Provided sufficiently neutron rich matter is ejected $Y_e \lesssim 0.1$ (merger neutron star black hole) a robust r process takes place



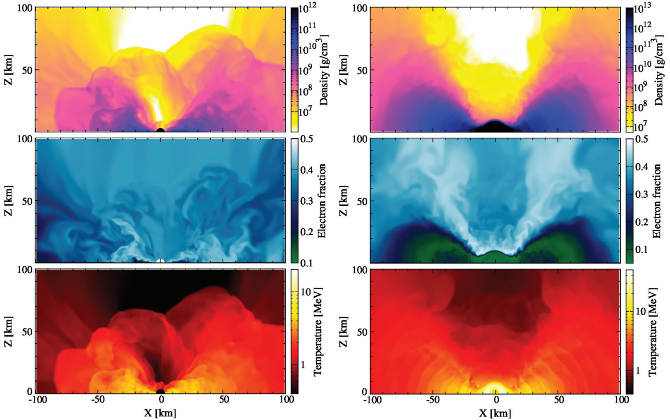


Luminosity is mainly sensitive to abundances of long-live actinides that release energy by alpha-decay.

Mendoza-Temis, Wu, Langanke, GMP, Bauswein, Janka, PRC **92**, 055805 (2015)
Barnes, Kasen, Wu, GMP, ApJ **829**, 110 (2016); Rosswog et al, CQG **34**, 104001 (2017)

neutrinos in NS-NS mergers

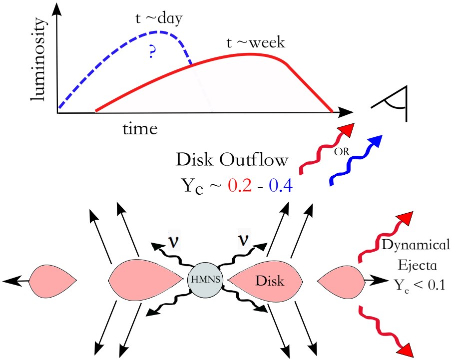
- For NS-NS mergers the central hypermassive neutron star will produce large neutrino fluxes $L_\nu \sim 10^{53}$ erg s^{-1} (Sekiguchi+ 2015, 2016).
- Mildly neutron-rich ejecta in the polar region ($Y_e \lesssim 0.5$). Lanthanide free ejecta.



From Y. Sekiguchi *et al*, PRD **93**, 124046 (2016).

Observational consequences

- An observation of a light curve from a NS-NS from the polar region it is expected to produce a blue kilonova on timescales of a day.
- At later times red/infrared emission from neutron-rich ejecta may dominate.
- We may even see a signature of the collapse of the hypermassive neutron star to a black hole.



From Metzger & Fernández, MNRAS **441**, 3444 (2014)

Summary

- Muon production in supernova matter facilitates neutrino-driven explosions.
- Heavy element nucleosynthesis in core-collapse supernova is limited to elements between Zn and Mo ($A \sim 90$).
- Neutron star mergers are likely the site where the “main r process” takes place.
- Radioactive decay of r-process ejecta produces an electromagnetic transient known as kilonova.
- The observation of a kilonova transient will confirm that r process occurs in mergers and provide information about the dynamics and the role of neutrinos.