Modelling BNS mergers and their aftermath: the role of neutrinos

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TU-Darmstadt → INFN, Milano-Bicocca & Parma

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

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

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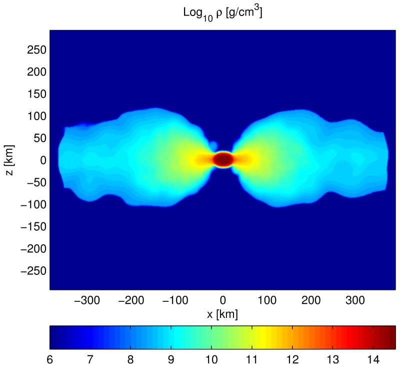
Outline

- Introduction and background
- The role of neutrinos in BNS merger aftermath
  - Neutrino-driven winds
  - Neutrinos and dynamic ejecta
  - Neutrino pair annihilations
- Conclusions and open questions

BNS merger remnant properties

merger remnant: final stages of BNS system evolution



vertical slice of the matter denisty from a 3D simulation

(Perego+ 2014)

- Massive NS ($\rightarrow$ 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
  $E_\nu \gtrsim 10\,\mathrm{MeV}$
  $L_{\nu,\mathrm{tot}} \sim 10^{53} \mathrm{erg\,s^{-1}}$
  $L_{N,\nu,\mathrm{tot}} \sim 10^{57} \mathrm{particles\,s^{-1}}$

Processes in BNS merger remnants

Relevant ingredients and their interplay:

- magnetic field (e.g., MRI) — e.g., Siegel& Metzger17,Ciolfi+2016
  - relevant source of viscosity — e.g. Radice 16, Shibata+16
- viscosity — e.g., works by Just, Fernandez, Metzger
  - accretion
  - angular momentum redistribution
- weak processes — e.g. works by Just, Fernandez, Metzger, Roberts, Radice, Bovard ...
  - neutrino luminosities
  - matter composition (remnant & ejecta)
- remnant fate — e.g., Piro+17
  - BH formation
  - metastable MNS
  - stable MNS

Large variability expected

- dependence on the BNS properties
- influence of EOS

Neutrino-matter interaction in BNS merger remnants

Roberts talk from last week

- ν's are weakly interacting particles:
- both CC and NC channels
- production (and possibly absorption):

  $p + e^- \rightarrow n + \nu_e$ (EC)

  $n + e^+ \rightarrow p + \bar{\nu}_e$ (PC)

  $e^- + e^+ \rightarrow \nu + \bar{\nu}$

  $N + N \rightarrow N + N + \nu + \bar{\nu}$
- scattering:

  $N + \nu \rightarrow N + \nu \qquad e^\pm + \nu \rightarrow e^\pm + \nu$

Neutrino production rates:

- production boosted by high temperatures & densities:
  - $R_{EC} \propto \rho X_p T^5 F_4(\mu_e/T)$
  - $R_{PC} \propto \rho X_n T^5 F_4(-\mu_e/T)$

e.g. Rosswog & Liebendörfer 03

Neutrino opacity in BNS merger remnants

Neutrino absorption/scattering rates:

neutrino opacity $\leftrightarrow$ neutrino mean free path, λ_ν

$$\sigma_\nu \sim \sigma_0 \left(\frac{E_\nu}{m_e c^2} \right)^2 \quad \sigma_0 = \frac{4 G_F^2 (m_e c^2)^2}{\pi (\hbar c)^4} \approx 1.76 \times 10^{-44}\,\mathrm{cm}^2 \approx 2.6 \times 10^{-20} \sigma_t$$

$$\lambda_\nu \approx \frac{1}{n_{\rm target} \sigma_\nu} \sim 2.36 \times 10^{19} \mathrm{cm} \left(\frac{\rho}{1\,\mathrm{g/cm^3}} \right)^{-1} \left(\frac{E_\nu}{1\,\mathrm{MeV}} \right)^{-2}$$

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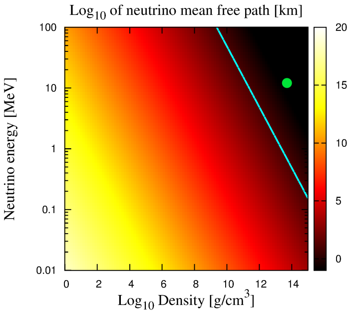


PNS/BNS merger remnant:

- $R \approx 10\,\mathrm{km}$
- $\rho_{\rm center} \approx 10^{14}\,\mathrm{g/cm^3}$
- $E_\nu \approx 10\,\mathrm{MeV}$

Neutrino Surfaces

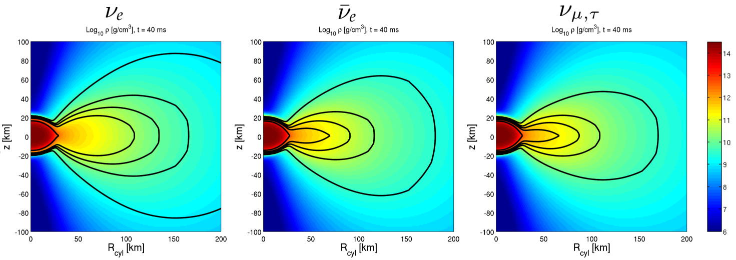
Optical depth:

- $\tau = \int_\gamma \frac{1}{\lambda} \, \mathrm{d}s$
- measure of how optically thin/thick matter is moving along an escaping path γ
- $\lambda_{\rm sc} \approx \sum \lambda_i \rightarrow \tau_{\nu,\rm sc} \sim$ # of ν-matter interaction along γ
- $\lambda_{\rm en} \approx \sqrt{\lambda_{\rm sc}\lambda_{\rm ab}} \rightarrow \tau_{\nu,\rm en} \sim$ # of inelastic ν-matter along γ

$\tau_\nu = 2/3 \quad \Rightarrow \quad \nu$ surfaces, for $E_\nu = 4.6, 10.6, 16.2, 24.6, 57.0\,\mathrm{MeV}$

$\tau_{\nu,\rm sc}$

scatter



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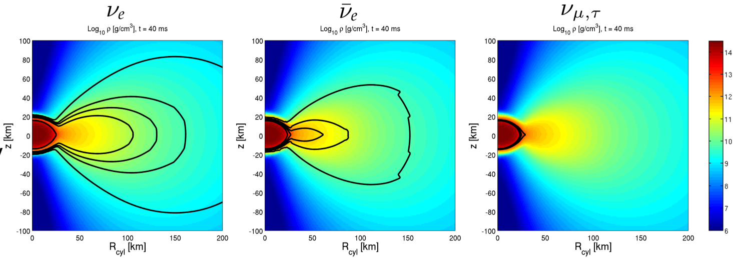
$\tau_{\nu,\rm e}$
energy



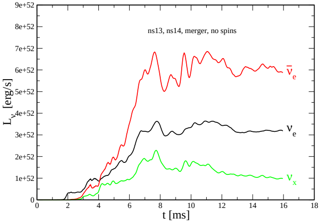
Properties of ν's emission in BNS mergers

evolution of ν luminosities:

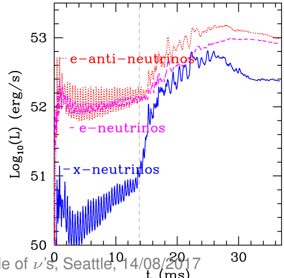
- inspiral phase: negligible
- merger: sudden increase due to T increase
- post merger: powered by accretion and cooling
- possible dependence on nuclear EOS e.g. Sekiguchi+15, Radice+16

properties of ν luminosities:

- ν gas formation and diffusion
- n richness $\rightarrow L_{\bar{\nu}_e} \gtrsim L_{\nu_e}$
- different decoupling depths: $E_{\nu_e} < E_{\bar{\nu}_e} < E_{\nu_{\mu,\tau}}$



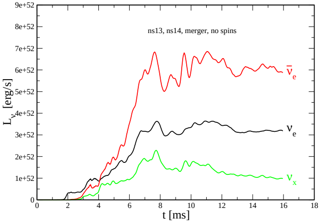
Rosswog+13 (up), Neilsen+15 (down)



Role of ν's in BNS mergers

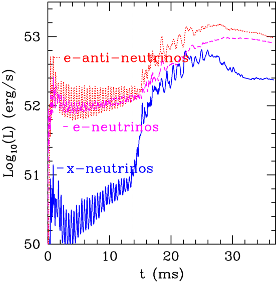
Role of ν's

- 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

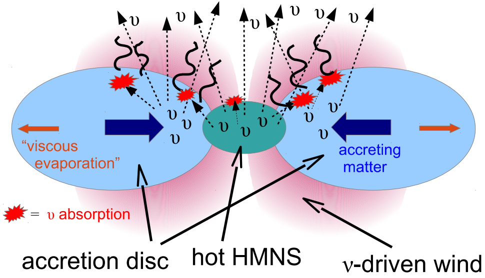


Rosswog+13 (up), Neilsen+15 (down)

- ⇒ relevant to set ejecta properties
- ⇒ relevant to set EM couterpart properties



ν-driven winds from BNS merger remnats: goals



← physical sketch

Perego et al. MNRAS 2014

Martin, Perego et al. ApJ 2015

Goals

- characterize ν emission
- study wind development
- perform nucleosynthesis on ejecta
- compute EM counterparts

see also Dessart+09,Metzger&Fernandez14,Just+14,Sekiguchi+15

Relevant time scales

- disk lifetime:

$$t_{\rm disk} \sim \alpha^{-1} \left(\frac{H}{R}\right)^{-2} \Omega_K^{-1} \sim 0.31\,{\rm s} \left(\frac{\alpha}{0.05}\right)^{-1} \left(\frac{H/R}{1/3}\right)^{-2} \left(\frac{R_{\rm disk}}{100\,{\rm km}}\right)^{3/2} \left(\frac{M_{\rm ns}}{2.5\,M_\odot}\right)^{-1/2}$$

α: viscosity coefficient
$R_{\rm disk}$: disk typical radius
H/R: disk aspect ratio
Ω_K: Keplerian angular velocity

$M_{\rm ns}$: MNS mass

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$$t_{\rm disk} \sim 0.31\,{\rm s} \left(\frac{\alpha}{0.05}\right)^{-1} \left(\frac{H/R}{1/3}\right)^{-2} \left(\frac{R_{\rm disk}}{100\,{\rm km}}\right)^{3/2} \left(\frac{M_{\rm ns}}{2.5\,M_{\odot}}\right)^{-1/2}$$

- disk L:

$$L_{\nu,{\rm disk}} \sim \frac{\Delta E_{\rm grav}}{2\,t_{\rm disk}} \approx 8.35 \times 10^{52}\,{\rm erg\,s^{-1}} \left(\frac{M_{\rm ns}}{2.5\,M_{\odot}}\right)^{3/2} \left(\frac{M_{\rm disk}}{0.2\,M_{\odot}}\right) \left(\frac{R_{\rm disk}}{100\,{\rm km}}\right)^{-3/2} \times \left(\frac{\alpha}{0.05}\right) \left(\frac{R_{\rm ns}}{25\,{\rm km}}\right)^{-1} \left(\frac{H/R}{1/3}\right)^{2}$$

$\Delta E_{\rm grav}$: gravitational energy released during accretion

Relevant time scales

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- MNS L:

$$L_{\nu,{\rm ns}} \sim \frac{\Delta E_{\rm ns}}{t_{\rm cool,ns}} \approx 1.86 \times 10^{52}\,{\rm erg\,s}^{-1} \left(\frac{\Delta E_{\rm ns}}{3.5 \times 10^{52}\,{\rm erg}}\right) \left(\frac{R_{\rm ns}}{25\,{\rm km}}\right)^{-2} \left(\frac{\rho_{\rm ns}}{10^{14}\,{\rm gcm}^{-3}}\right)^{-1} \left(\frac{k_{\rm B} T_{\rm ns}}{15\,{\rm MeV}}\right)^{-2}$$

$\Delta E_{\rm ns}$: thermal energy
$t_{\rm ns,cool} \sim 3\tau_{\nu,{\rm ns}}/\left(R_{\rm ns} c\right)$: diffusion time scale
$\tau_{\nu,{\rm ns}}$: ν optical depth in MNS

Relevant time scales

- disk lifetime:

$$t_{\rm disk} \sim 0.31\,{\rm s} \left(\frac{\alpha}{0.05}\right)^{-1} \left(\frac{H/R}{1/3}\right)^{-2} \left(\frac{R_{\rm disk}}{100\,{\rm km}}\right)^{3/2} \left(\frac{M_{\rm ns}}{2.5\,M_\odot}\right)^{-1/2}$$

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- MNS L:

$$L_{\nu,{\rm ns}} \sim 1.86 \times 10^{52}\,{\rm erg\,s^{-1}} \left(\frac{\Delta E_{\rm ns}}{3.5 \times 10^{52}\,{\rm erg}}\right) \left(\frac{R_{\rm ns}}{25\,{\rm km}}\right)^{-2} \dots$$

- wind time:

$$t_{\rm wind} \sim \frac{e_{\rm grav}}{\dot{e}_{\rm heat}} \approx 0.072\,{\rm s} \left(\frac{M_{\rm ns}}{2.5\,M_\odot}\right) \left(\frac{R_{\rm disk}}{100\,{\rm km}}\right) \left(\frac{E_\nu}{15\,{\rm MeV}}\right)^{-2} \left(\frac{\xi L_{\nu_e}}{4.5 \times 10^{52}\,{\rm erg\,s^{-1}}}\right)^{-1}$$

$e_{\rm grav}$: specific gravitational energy
$\dot{e}_{\rm heat}$: specific heating rate

ξL_{ν_e}: isotropized ν_e luminosity at $\theta \approx \pi/4$, $\xi \sim 1.5$ and $L_{\nu_e} \sim (L_{\rm ns} + L_{\rm disk})/3$

ν-driven winds from BNS merger: the model

- initial conditions:
  - final stage of high resolution BNS merger simulation performed with SPH code — Rosswog&Price07
  - 2 x 1.4 $M_{\odot}$, with Shen EOS
- 3D hydro: `FISH` code — Käppeli+11
- ν treatment: ASL — Perego+16
- nuclear EoS: TM1 — Hempel+12
- tracer particles
- nucleosynthesis network: `Winnet` — e.g. Winteler+12

The ASL scheme

Perego, Cabezon, Käppeli 2016

ASL scheme exploits potentiality of classical gray leakage scheme e.g. Ruffert et al. 1997, Rosswog & Liebendörfer 2003, O'Connor & Ott 2011

What's new:

- inclusion of ν trapped components
- distinction between different ν energies ($\sigma_\nu \propto E_\nu^2$)
- ν-absorption terms in optically thin conditions (ray-tracing)

Strengths:

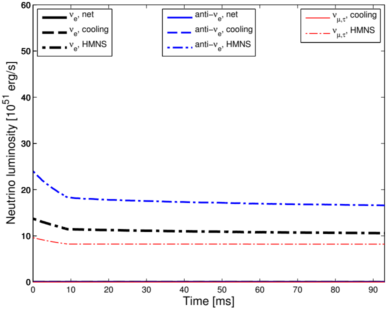
- robust and flexible
- computationally inexpensive
- limited set of free parameters (calibrated with CCSNe)

Caveats:

- effective treatment
- diffusion part: order-of-magnitude

Neutrino luminosities

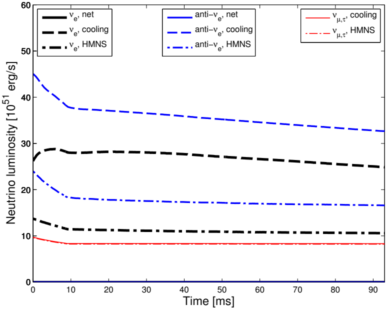
dependence on time



- MNS ($\rho > 5 \times 10^{11} \mathrm{g\,cm^{-3}}$)

Neutrino luminosities

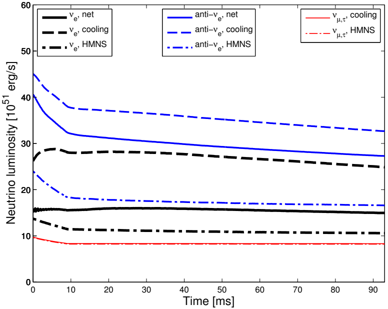
dependence on time



- MNS ($\rho > 5 \times 10^{11}\,\mathrm{g\,cm^{-3}}$)
- MNS ($\rho > 5 \times 10^{11}\,\mathrm{g\,cm^{-3}}$) + disk

Neutrino luminosities

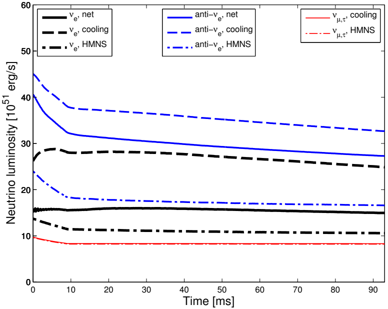
dependence on time



- MNS ($\rho > 5 \times 10^{11} \mathrm{g\,cm^{-3}}$)
- MNS ($\rho > 5 \times 10^{11} \mathrm{g\,cm^{-3}}$) + disk
- luminosity hierarchy: $L_{\bar{\nu}_e} > L_{\nu_e} > L_{\nu_{\mu,\tau}}$
- disk luminosity powered by accretion: $\dot{M} \sim 0.6 - 0.4\, M_\odot\, \mathrm{s}^{-1}$ & $\alpha_{\mathrm{num}} \approx 0.05$

Neutrino luminosities

dependence on time



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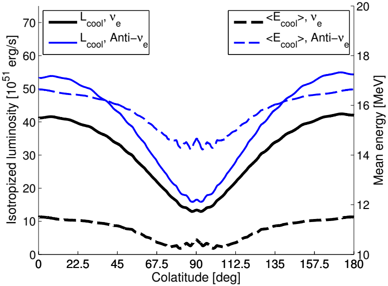
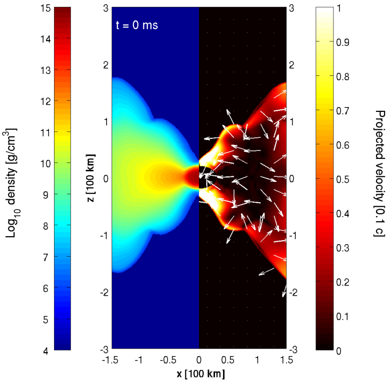
dependence on θ ($t = 40\mathrm{ms}$)



- mean energy hierarchy: $E_{\nu_{\mu,\tau}} > E_{\bar{\nu}_e} > E_{\nu_e}$
- $E_{\nu_e} \approx 11\,\mathrm{MeV}, E_{\bar{\nu}_e} \approx 15\,\mathrm{MeV}$, $E_{\nu_{\mu,\tau}} \approx 18\,\mathrm{MeV}$
- disk-shadow effect

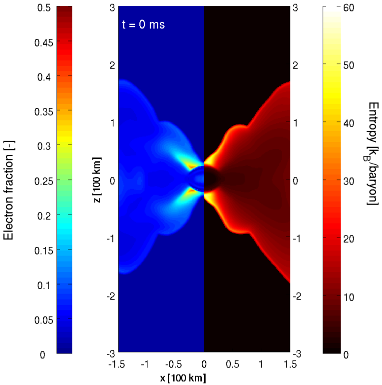
Disk and wind dynamics

t = 0 ms



left: matter density

right: projected velocity

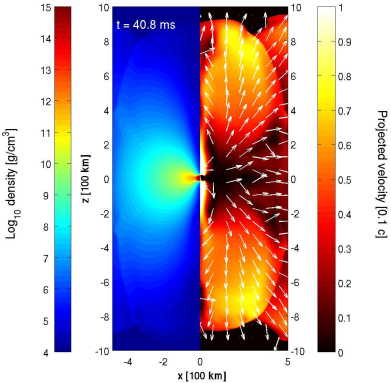


left: electron fraction

right: entropy

Disk and wind dynamics

t = 40 ms



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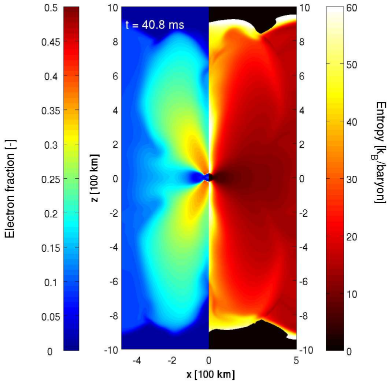
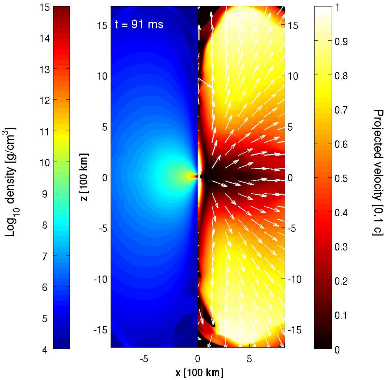


left: electron fraction

right: entropy

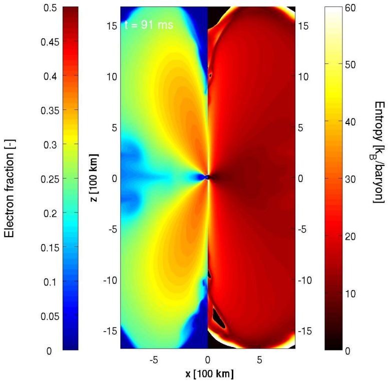
Disk and wind dynamics

t = 90 ms



left: matter density

right: projected velocity

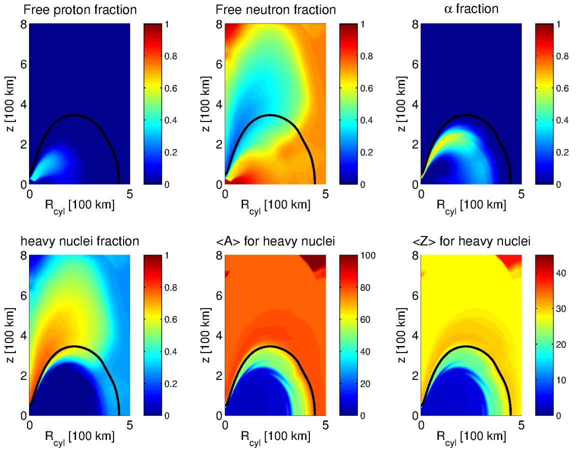


left: electron fraction

right: entropy

Ejection mechanism

- neutrino absorption $\rightarrow e_{\rm tot} \approx 0 \rightarrow$ wind expansion
- nuclear recombination $\rightarrow$ matter ejection



Wind ejecta and nucleosynthesis

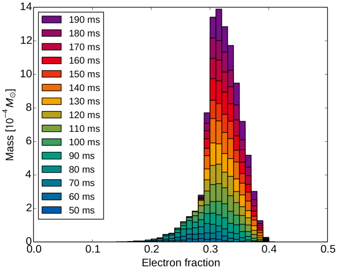
- $m_{\rm ej} \approx 0.05\, M_{\rm disk} @ 200\,{\rm ms}$
- non-equatorial emission: $\theta < 60^o$
- larger $\mathrm{Y_e}$ at small θ

$$\mathrm{Y_{e,eq}} \sim \frac{\lambda_{\nu_e}}{\lambda_{\nu_e}+\lambda_{\bar{\nu}_e}} \approx 0.4$$

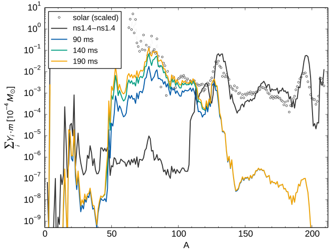
$$t_{\rm wind}^{-1} \lesssim \lambda_{\nu_e} \lesssim \lambda_{\bar{\nu}_e} \approx 30 \text{ s}^{-1}$$

e.g., Qian & Woosley 96

- thermodyn properties as input for nuclear network $\rightarrow$ nucleosynthesis abundances



ejected mass: cumulative histogram



wind ejecta (color lines) + dynamical ejecta (black lines)

from Korobkin+12

Discussion I

- which are the requirements for neutrino treatments in BNS merger?
- how relevant is the modelling of a ν trapped component?
- which are the most relevant weak reactions and under which termodynamical conditions do they occur?

How robust are dynamic ejecta?

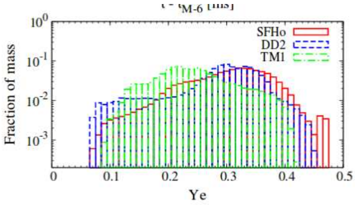
First dynamic ejecta simulations + nucleosynthesis calculations

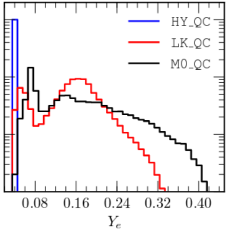
e.g. Korobkin+2012, Bauswein+2013, Hotokezaka+2013

- extremely n-rich, $Y_e \lesssim 0.05$
- 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:

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

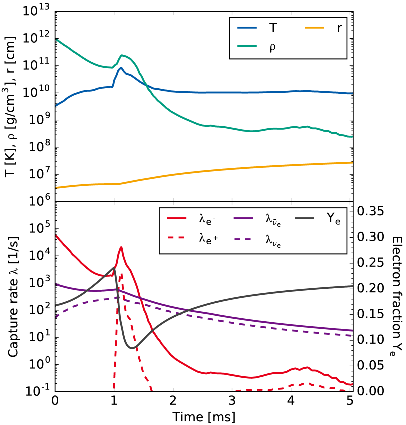
$$\frac{ds}{dt} = \left(\frac{ds}{dt}\right)_{\mathrm{hydro}} + \frac{1}{T}\left[\left(\frac{dQ}{dt}\right)_{\nu} - (\mu_e - \mu_n + \mu_p)\left(\frac{d\mathrm{Y_e}}{dt}\right)_{\nu}\right]$$

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

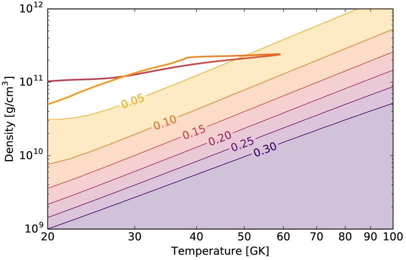
Name	$L_{\nu_e,\mathrm{max}}$ [10^{53} erg/s]	$L_{\bar{\nu}_e,\mathrm{max}}$ [10^{53} erg/s]	$E_{\nu_e,\mathrm{max}}$ [MeV]	$E_{\bar{\nu}_e,\mathrm{max}}$ [MeV]
capture	0.0	0.0	0.0	0.0
low	0.86	1.0	11.5	16.2
medium	1.0	1.5	12.0	16.3
high	1.2	2.4	13.0	16.7

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

Dynamic ejecta: Representative tracer



Profiles from a representative tracer

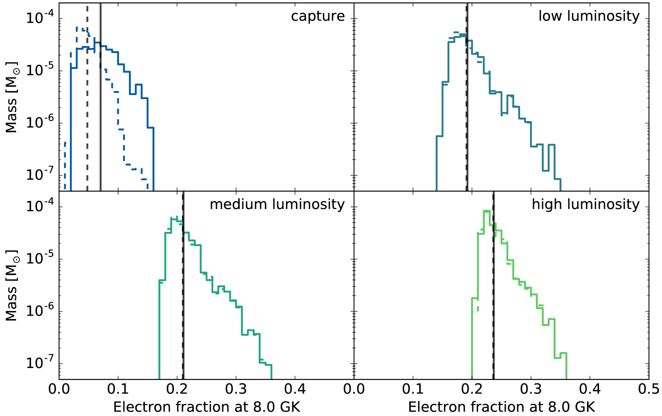


Lines of $Y_p \lambda_e^- / Y_n \lambda_e^+ = 1$

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

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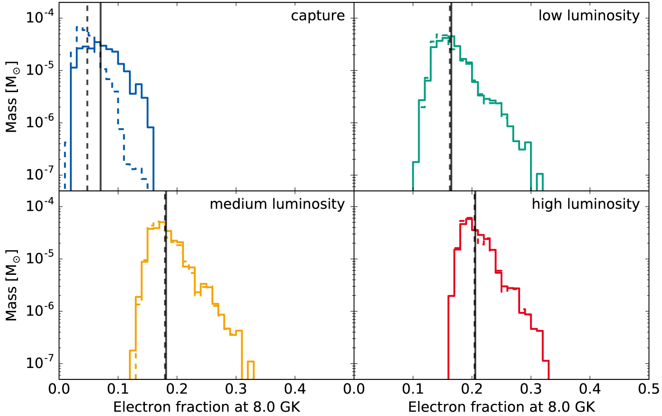


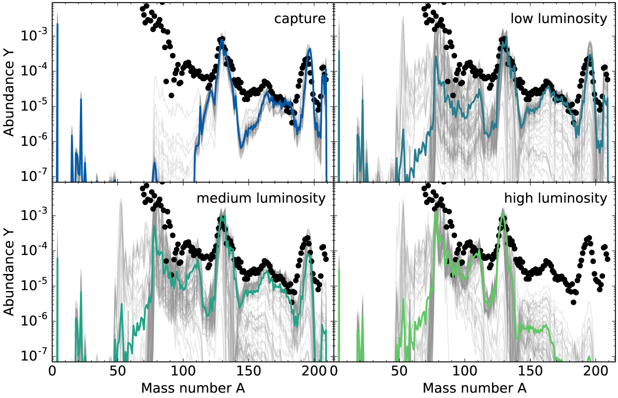
Courtesy of D. Martin

$\alpha = 2$, 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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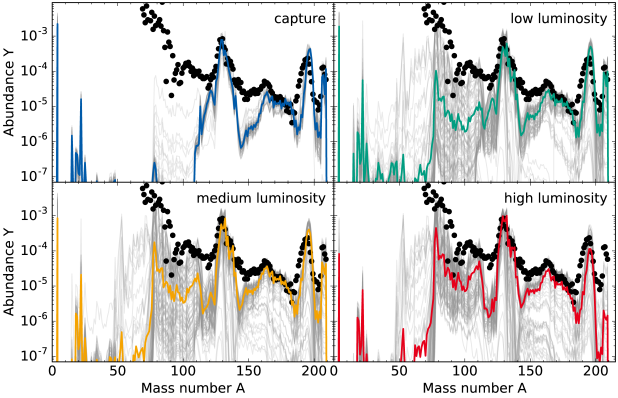


Courtesy of D. Martin

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

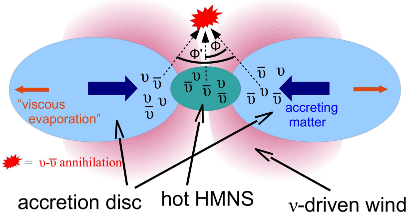
Discussion II

- which are the requirements for neutrino treatments in BNS merger?
- how relevant is the modelling of a ν trapped component?
- which are the most relevant weak reactions and under which termodynamical conditions do they occur?

- how can we understand the change in $\mathrm{Y_e}$ for the dynamic ejecta?
- do we understand the properties of the neutrino emission and its variability?
- which ρ, T and $\mathrm{Y_e}$ conditions occur in and after BNS mergers?

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

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



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

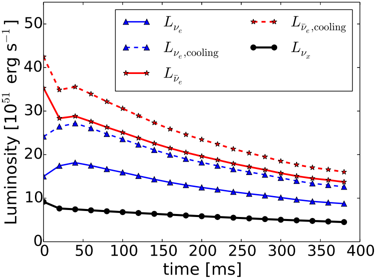
net effect: ν energy and momentum deposition in plasma

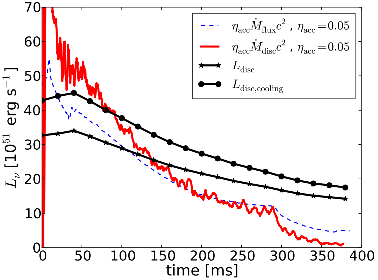
$$q_{\rm ann}(t,\mathbf{x}) \approx \frac{1}{6}\frac{\sigma_0\left(C_A^2+C_V^2\right)}{c\left(m_e c^2\right)} \int I_\nu I_{\bar{\nu}} \left(E_\nu + E_{\bar{\nu}}\right)\left(1-\cos\Phi\right)^2 \, {\rm d}\Omega_\nu {\rm d}\Omega_{\bar{\nu}} {\rm d}E_\nu {\rm d}E_{\bar{\nu}}$$

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 ...

Accretion rate and luminosities

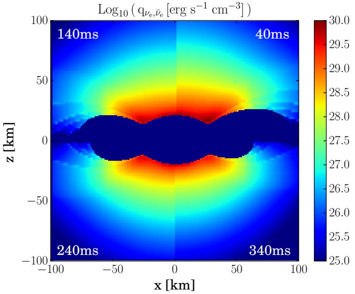




Presence of the MSN VS BH $\rightarrow$ relevant differences

- $L_\nu \not\propto \dot{M}$
- MNS cooling as additional ν source
- structure of the innermost disk
- thick disk cooling

Energy deposition rates



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

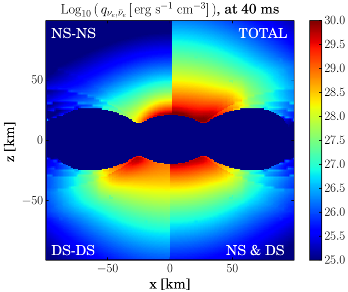
post-processing of previous 3D, long term remnant simulations

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 (e.g., Doppler boost, red/blue shift) cause only a marginal decrease

Energy deposition rates



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

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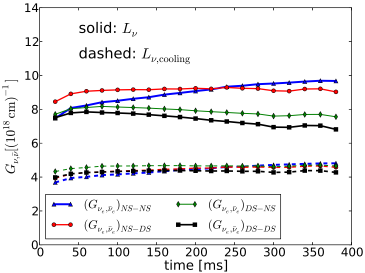
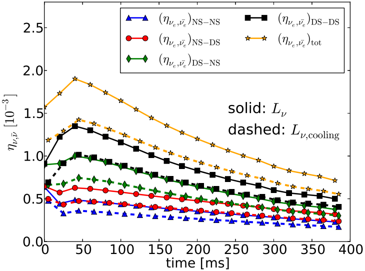
$$I_\nu = (I_\nu)_{\mathrm{NS}} + (I_\nu)_{\mathrm{DS}} \Rightarrow$$

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

- NS & Disk contribution $\approx$ Disk-Disk contribution
- NS & NS contribution locally intense, but globally small

Parametrization and efficiency





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

$$\eta_{\nu,\bar\nu} = \frac{Q_{\nu,\bar\nu}}{L_\nu + L_{\bar\nu}}$$

- $G_{\nu,\bar\nu}$ geometrical factor
- $\sim$ constant during 400ms (remarkably)

- low efficiency, $\eta_{\nu,\bar\nu} \sim 10^{-3}$
- if $L_\nu \approx L_0 \exp -t/\tau_c$ & $L_{\bar\nu}/L_\nu \approx \beta$
  $\eta_{\nu,\bar\nu} \sim G_{\nu,\bar\nu}\, \mathcal{C} L_0\, \beta/(\beta+1) \times \left[\frac{\langle \epsilon_\nu^2 \rangle}{\langle \epsilon_\nu \rangle} + \frac{\langle \epsilon_{\bar\nu}^2 \rangle}{\langle \epsilon_{\bar\nu} \rangle} \right] \exp(-t/\tau)$

Discussion III

- which are the requirements for neutrino treatments in BNS merger?
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- how can we understand the change in $\mathrm{Y_e}$ for the dynamic ejecta?
- do we understand the properties of the neutrino emission and its variability?
- which ρ, T and $\mathrm{Y_e}$ conditions occur in and after BNS mergers?

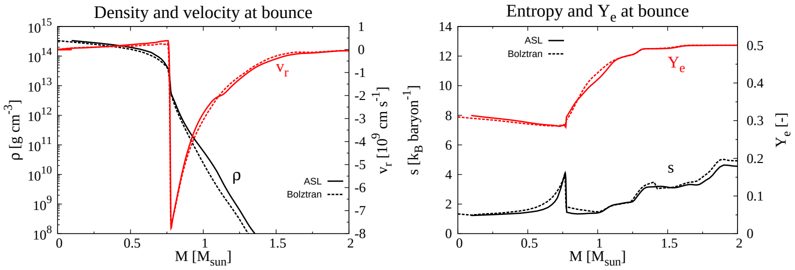
- [ ] can we use parametrized ν annihilation rates?
- [ ] which uncertainties affect ν annihilation process?

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)
- large parameter space exploration still required

AGILE-ASL calibration and tests

- calibrated against 1D models with Boltzmann neutrino transport (AGILE-BOLTZTRAN) e.g. Liebendörfer+2004
- 15 $M_\odot$ progenitor as reference case Woosley+2002
- calibrated parameters tested for two different progenitor (12 $M_\odot$ and 40 $M_\odot$) with satisfactory results



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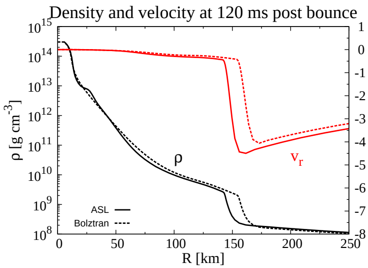

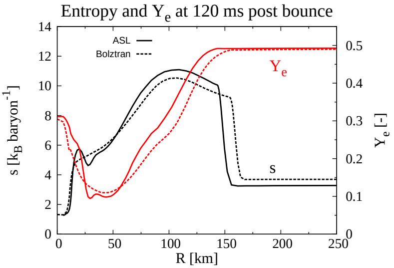

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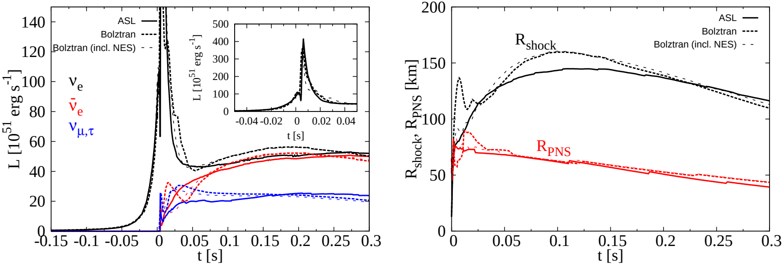

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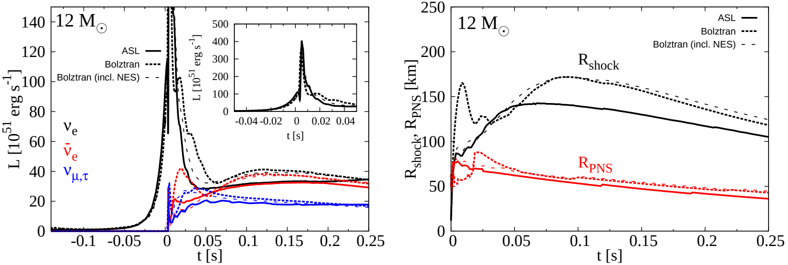

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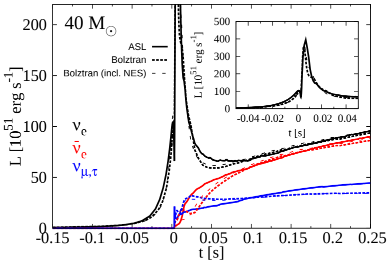
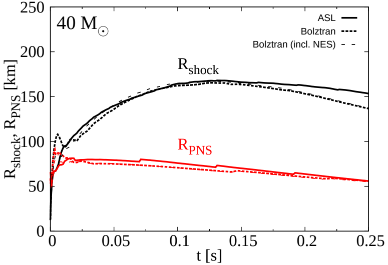
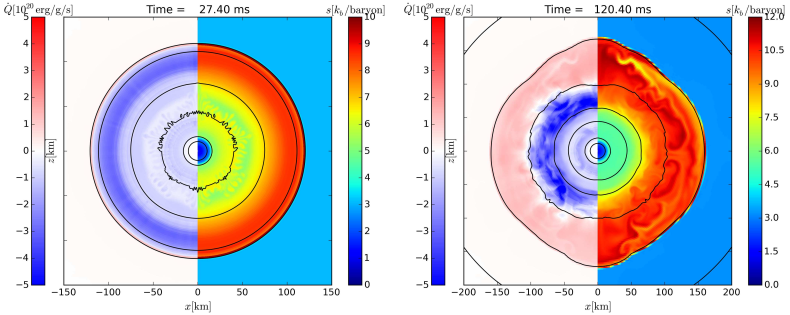




ASL in multi-D tests

Flexibility = successful implementation in different codes

- ASL + 2D Eulerian code
- ASL + 3D SPH code



consistent results within a few hundreds ms after core bounce

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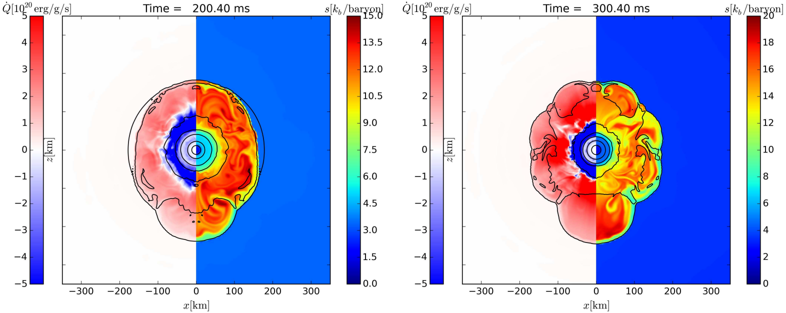

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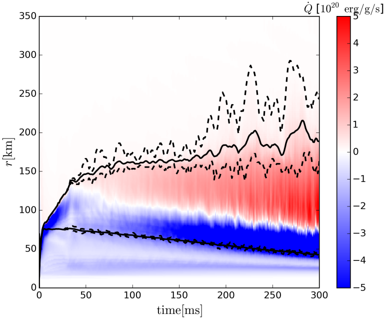

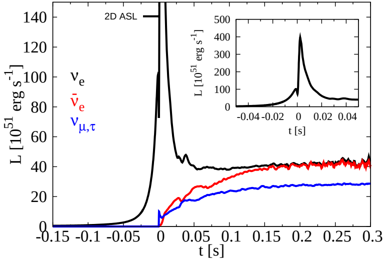

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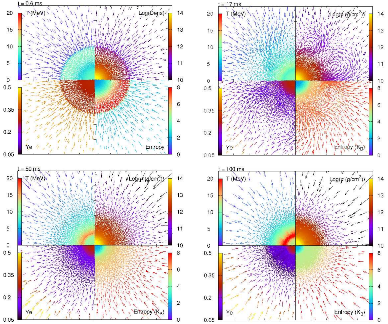
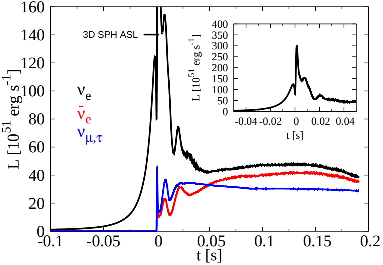
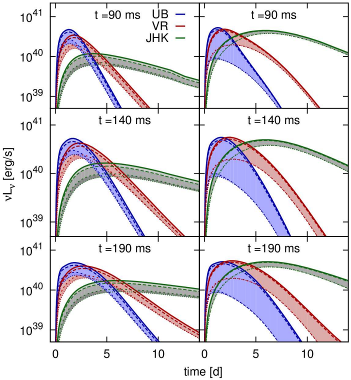




consistent results within a few hundreds ms after core bounce

Electromagnetic transient

γ emission powered by radioactive material in the ejecta



Lanthanides and Actinides mass fraction,

$$\kappa_{A>130} \approx 10\,\mathrm{cm}^2/\mathrm{g} \sim 10\kappa_{Ni}$$

- 1D model for photon propagation and emission

  e.g. Kulkarni 05, Grossman+14

- potentially different from emission coming from dynamical/viscous ejecta
  - earlier and bluer
  - less contaminated by lanthanides and actinides

  cf Metzger&Fernandez14

- possible dependence from viewing angle