Neutrinos in neutron star mergers and core-collapse supernovae

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Talk at Theretical Nuclear Physics in Italy 2017

in collaboration with A. Arcones, D. Martin, M. Hempel, C. Frohlich, K. Ebingen, W. Kastaun, O. Korobkin, D. Logoteta, S. Rosswog . . .

Nuclear & neutrino physics in high energy astrophysics

Key role in many high-energy astrophysics environment:

- nuclear equation of state
  - direct dynamical influence (e.g., matter temperature)
  - compact object properties and fate (e.g., compactness)
- neutrino-matter interactions
  - efficient cooling + energy & momentum redistribution
  - set neutron-to-proton ratio ($\mathrm{Y_e}$ or symmetry parameter β)
- explosive nucleosynthesis of heavy elements ($>$ Fe group)
  - extremely sensitive to ejecta properties: entropy, $\mathrm{Y_e}$, peak temeprature, expansion timescale, neutrino irradiation, ...
  - explosive and r-process nucleosynthesis

ν's-matter interactions in hot and dense matter

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

  $p + e^- \rightarrow n + \nu_e$ (EC) $\qquad e^- + e^+ \rightarrow \nu + \bar{\nu}$

  $n + e^+ \rightarrow p + \bar{\nu}_e$ (PC) $\qquad N + N \rightarrow N + N + \nu + \bar{\nu}$
- scattering:

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

Neutrino production rates:

- production boosted by high temperatures & densities:
  - $R_{EC} \propto \rho X_p T^5 F_4(\mu_e/T)$
  - $R_{PC} \propto \rho X_n T^5 F_4(-\mu_e/T)$
  - $R_{BREM} \propto \rho T^6$

e.g. Rosswog & Liebendörfer 03, Hannestad & Raffelt 98

Neutrino opacity in BNS merger remnants

Neutrino absorption/scattering rates:

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

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

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

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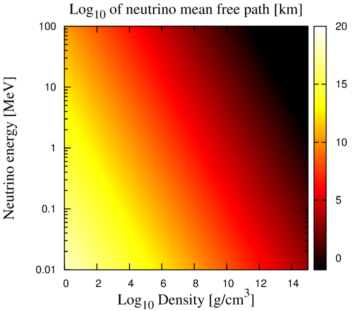

for a system of linear size R, ν absorption and scattering are dynamically relevant if

$$\lambda_\nu \lesssim R$$

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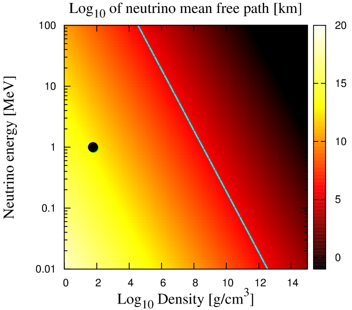

Sun:

- $R = R_\odot \approx 7 \times 10^5\,\mathrm{km}$
- $\rho_{\mathrm{center}} \approx 10^2\,\mathrm{g/cm^3}$
- $E_\nu \approx 1\,\mathrm{MeV}$

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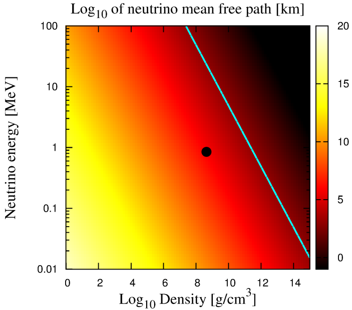

Core massive star:

- $R = R_\odot \approx 10^3\,\mathrm{km}$
- $\rho_{\mathrm{center}} \approx 10^{10}\,\mathrm{g/cm^3}$
- $E_\nu \approx 0.5\,\mathrm{MeV}$

Neutrino opacity in BNS merger remnants

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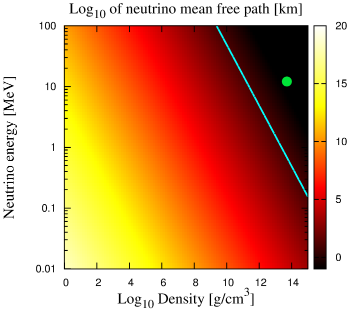


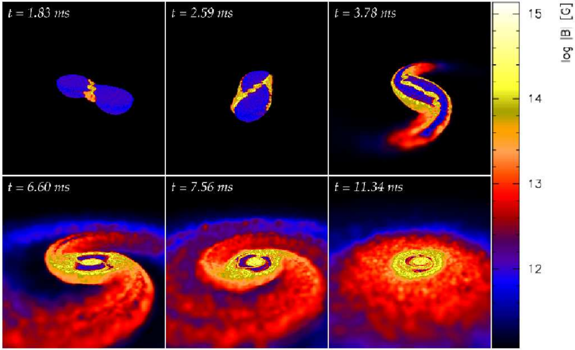
PNS/BNS merger remnant:

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

BNS mergers and their aftermaths

Final stage of a binary NS (BNS) system evolution:

- coalescence phase



B field from a Newtonian SPH simulations of BNS merger (2 x $1.4 M_\odot$)

Credit: Price&Rosswog 2006

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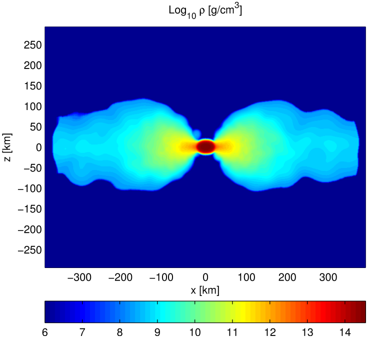
- NS merger aftermath



slice from 3D matter density

- 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
  $M \sim 10^{-3} - 10^{-2} M_\odot$
  $\mathrm{Y_e} \lesssim 0.20$
  $T \sim$ a few MeV
  $\left(\mathrm{Y_e} = \frac{\mathrm{n_e}}{\mathrm{n_B}} \approx \frac{\mathrm{n_p}}{\mathrm{n_p}+\mathrm{n_n}}\right)$
- intense ν emission
  $E_\nu \gtrsim 10\,\mathrm{MeV}$
  $L_{\nu,\mathrm{tot}} \sim 10^{53}\mathrm{erg\,s}^{-1}$

BNS mergers: astrophysical relevance

dynamical encounter of neutron-rich, stellar compact object

- intense emitter of GWs and ν's e.g. Read+13
- ejecta and heavy elements nucleosynthesis

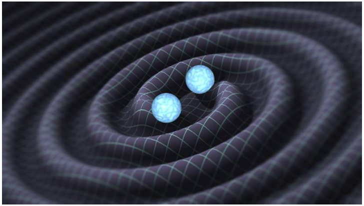
  Lattimer&Schramm74

- short GRBs progenitors

  Paczynski86,Berger 12

- electromagnetic counterpart from radioactive decay

  Li&Paczynski98



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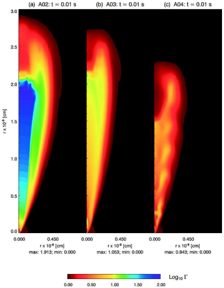

Aloy+05

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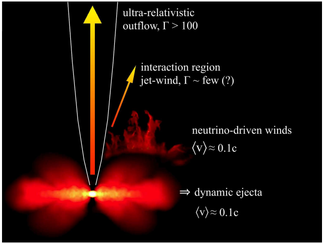
Lattimer&Schramm74



Rosswog 12

- short GRBs progenitors

Paczynski86,Berger 12

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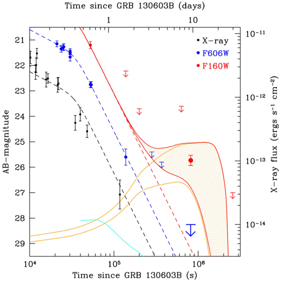
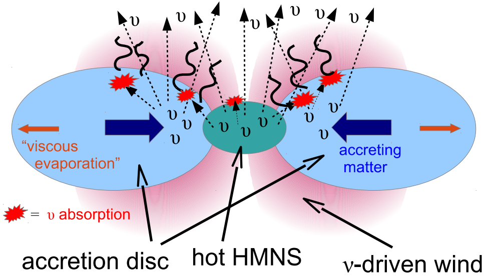


Tanvir+13, Berger+13

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:

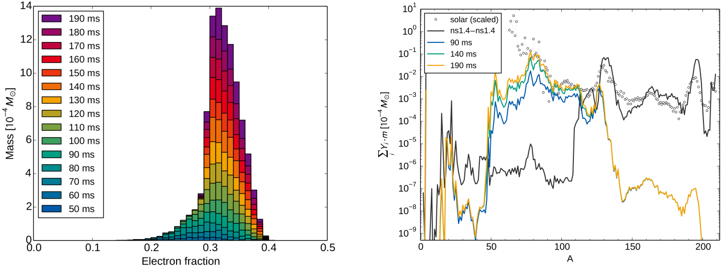
Perego+ 2014, Martin+2015

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

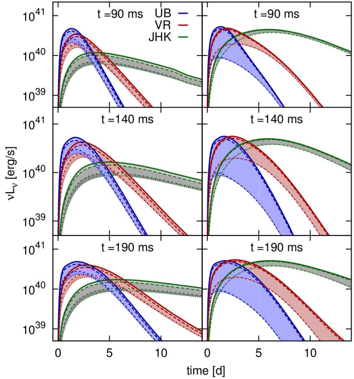
- strong neutrino irradiation: ν's have enough time to change $\mathrm{Y_e}$ towards equilibrium
- broad distribution of (less) n-rich matter ($0.25 \lesssim \mathrm{Y_e} \lesssim 0.4$)
- $10 \lesssim s[\mathrm{k_B/baryon}] \lesssim 20$
- limited r-process nucleosynthesis ($80 \lesssim A \lesssim 130$),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

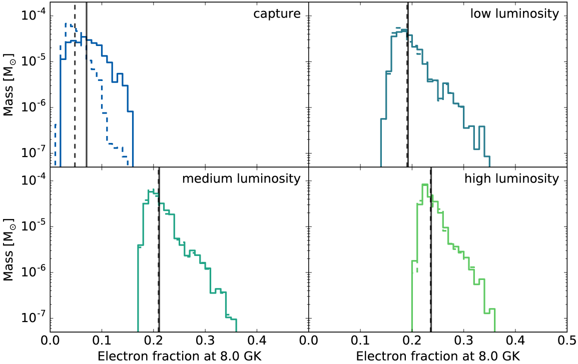
cf Metzger&Fernandez14

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

More on neutrinos in BNS mergers I

- do ν's influence also the dynamic ejecta?
  - Yes!
  - favored by high temperatures (shocked dynamic ejecta)
  - less relevant for cold tidal ejecta

e.g., Sekiguchi+15; Goriely+15, Radice+16, Martin,AP+ submitted



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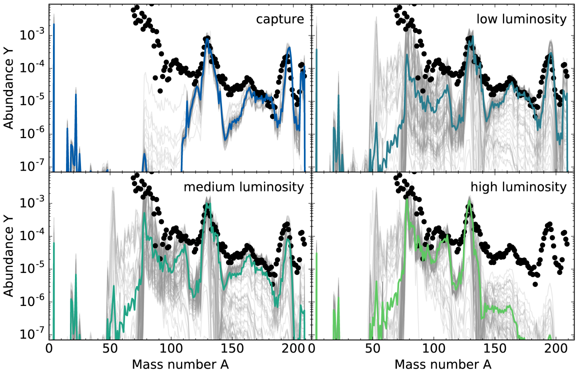
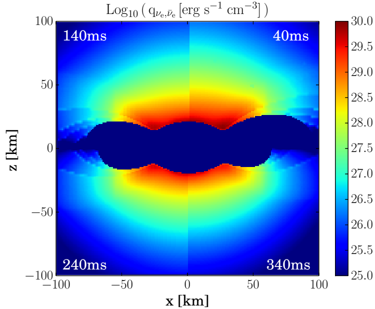


Martin,AP+, submitted

More on neutrinos in BNS mergers II

- Can ν-$\bar{\nu}$ annihilation above a BNS merger remnant launch a relativistic jet?
  - Maybe . . . (→ short GRBs)?
  - energy deposition: 1-2 $\times 10^{49}$ erg in 200ms
  - long lived (H)MNS → $\times 2$
  - enough energy for jets with small opening angles

Richers+16; Perego+17; Fujibayashi+17

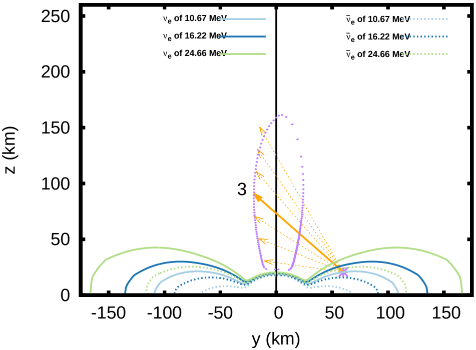


Perego+17

More on neutrinos in BNS mergers III

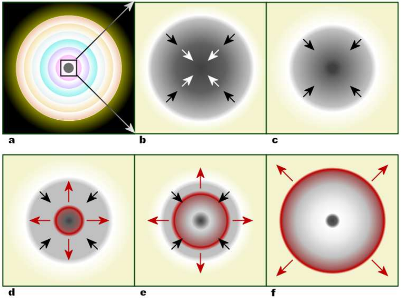
- Do ν's oscillate above BNS merger remnants?
  - Yes!
  - matter-neutrino resonances (MNR)
  - due to excess of $\bar{\nu}_e$ over ν_e and inner $\bar{\nu}_e$ decoupling

Malkus+15;...Zhu,AP,McLaughlin+16; Frensel..AP+17



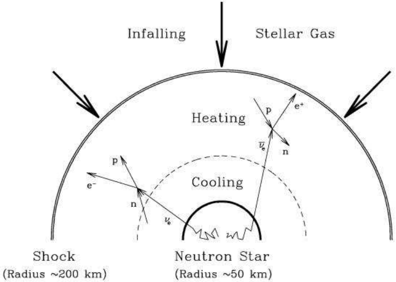
Zhu,AP,McLaughlin 16

CCSNe in a nutshell



- explosive fate of a massive star ($> 8M_\odot$),
- production of a NS/BH + SN remnant

- prompt shock expansion fails to explode the core
- plausible explosion mechanism: delayed ν-driven explosion
- relevance of multi-D



Extensive nucleosynthesis from CCSN models

CCSN are primary actors of Universe chemical enrichment.

Relevant questions:

- conditions for explosive nucleosynthesis in stellar layers?
- prediction for yields as a function of M_{ZAMS} and Z?
- progenitor-remnant connection?

Analysis strategy:

- ideal case:
  ab-initio, self-consistent 3D models in agreement with observables
  However, large uncertainties and too expensive
- realistic strategy: parametrized exploding models
  - (partially) simplified models
  - computationally efficient and physically reliable

Parametrized 1D explosions

1D (spherically symmetric) parametrized, triggered explosions using the PUSH method

Perego+2015

Our requirements:

- to use ν's $\Rightarrow$ to obtain explosion properties ($E_{\rm expl}, M_{\rm cut}, \dots$)
- not to modify $\nu_e, \bar{\nu}_e$ transport $\Rightarrow$ to preserve $\mathrm{Y_e}$ evolution
- to include nuclear EoS and PNS evolution (e.g HS(DD2) EOS)

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PUSH basic idea:

- To tap a fraction of the $\nu_{\mu,\tau}$ luminosity inside the gain region to enhance neutrino absorption

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Our constraints:

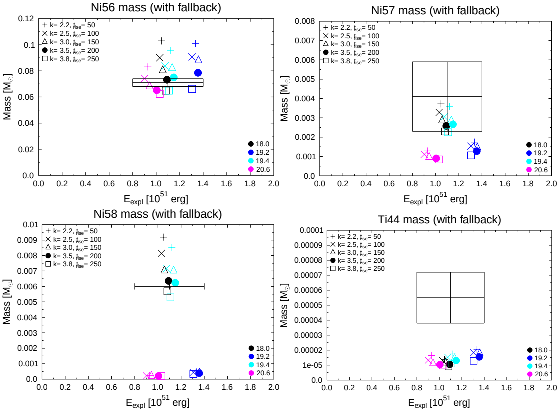
- reproducing observables of nearby CCSNe (e.g. SN1987A)

Blinnikov+00,Seitenzahl+14,Fransson&Kozma 02

Calibration with SN1987A

4 HC progenitors (18.0,19.2,19.4,20.6) + 0.1 $M_\odot$ of late fallback

Abundances: Post-processing of innermost ejecta



Ni56 mass (with fallback)

Ni57 mass (with fallback)

Ni58 mass (with fallback)

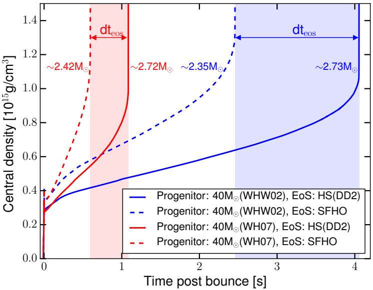
Ti44 mass (with fallback)

calibration set: 18 $M_\odot$, $k_{\rm push} = 3.5$, $t_{\rm rise} = 200\,{\rm ms}$,

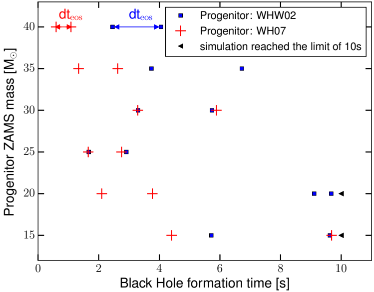
$M_{\rm fallback} = 0.1 M_\odot$

BH formation: EOS and progenitor dependence

Study of BH formation in absence of explosion



dependence on EOS
(2 progenitor series)



dependence on EOS
& progenitor mass
(2 progenitor series)

Preliminary results, courtesy of K. Ebinger (Uni Basel)

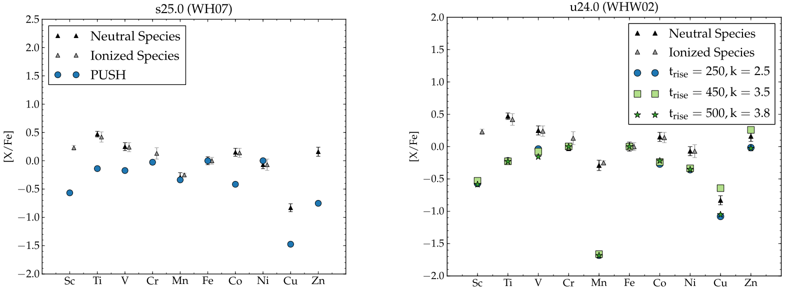
Nucleosynthesis of Fe group nuclei

Comparison with metal poor stars (HD 84937) Sneden+2016

- progenitor: 24 $M_\odot$ with $10^{-4} Z_\odot$ & 25 $M_\odot$ with $Z_\odot$

Woosley 02; Woosley,Heger 07

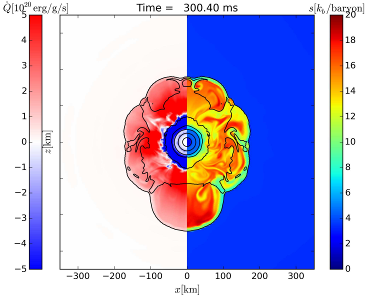
- good agreement, also within model uncertainties
- generally, PUSH results comparable or in better agreement than traditional methods



Preliminary results, courtesy of S. Shina (NCSU)

modelling CCSNe: outlook

- inexpensive multi-D models with ν-treatment
  - multi-D hydro code: `FLASH`
  - microphysical, finite T nucelar EOS
  - ν-treatment: ASL



in collaboration with C.Mattes and A.Arcones (TU-Darmstadt)

Perego+16

- implementation of microphysical nuclear EOS in astrophysical models in collaboration with D. Logoteta and I. Bombaci (INFN-PISA)

Conclusions

- Nuclear and neutrino physics play a key role in high energy astrophysics:
  - core-collapse SNe and NS mergers
  - nuclear matter properties (EOS) and neutrino-matter interactions
  - origin of heavy elements: nucleosynthesis, astrophysical and nuclear input
- nuclear EOS
  - influence on the dynamics
  - decide remnant fate
  - set ejecta properties
- neutrinos and their interactions
  - trigger explosions or eject matter
  - set ejecta properties, mainly neutron abundance
  - set electromagnetic couterparts of GW signals