ν-matter interaction in CCSNe and NS mergers and the role of the nuclear EOS

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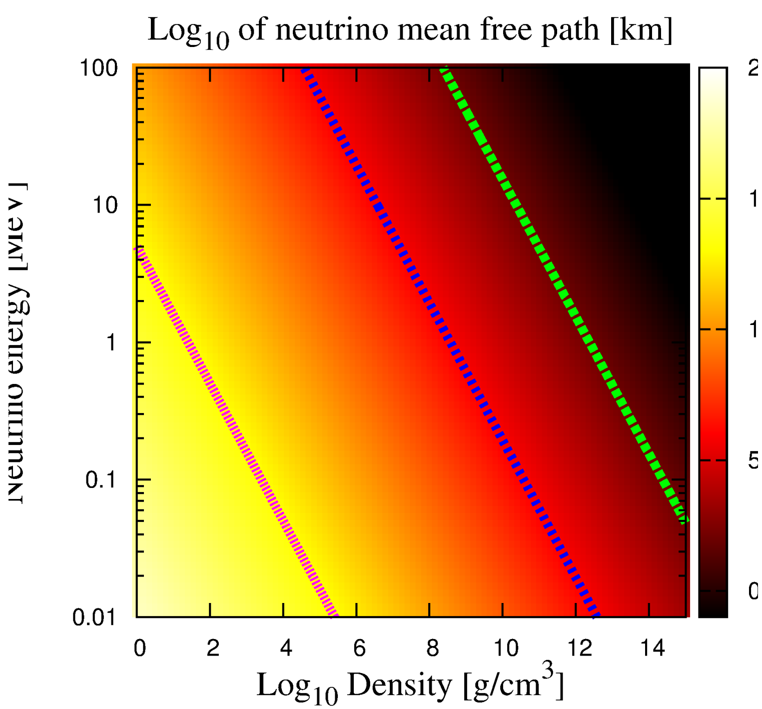
TU-Darmstadt, IKP-Theory

Neutrino matter interaction

ν's are weakly interacting particles:

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

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



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

$$\lambda_\nu \lesssim R$$

dashed lines: $\lambda_\nu = 1$ ly , $R_\odot$, 100 km

Astrophysical scenarios

- CCSN supernovae
  - ν's have a crucial cooling role and can potentially trigger explosion
  - ν's set properties of ejected matter
  - effective 1D model for CCSN explosions: PUSH

Perego, Hempel, Fröhlich et al, ApJ, 806, 275

- Binary NS mergers
  - ν's trigger matter ejection and set ejecta properties
  - 3D model of ν-driven wind in binary NS merger

Perego et al., MNRAS, V. 443, p. 3134-3156

Martin, AP et al., arXiv:1506.05048

What is the role of finite temperature, nuclear EOS on the dynamics and on the ν role/observables?

Nuclear EOS influence

Available nuclear EOS at finite T:

- LS (LDP: $K = 180, 220\mathrm{MeV}$ + Skyrme-like interact. + excluded V) Lattimer&Swesty 91
- STOS (RMF: TM1 + excluded V) Shen 98
- HS (RMF: DD2,TMA, . . . + excluded V + internal part. func.) Hempel, Schaffner-Bielich 10
- SHT/SHO (RMF: NL3,FSU + virial expansion) G. Shen 12
- . . .

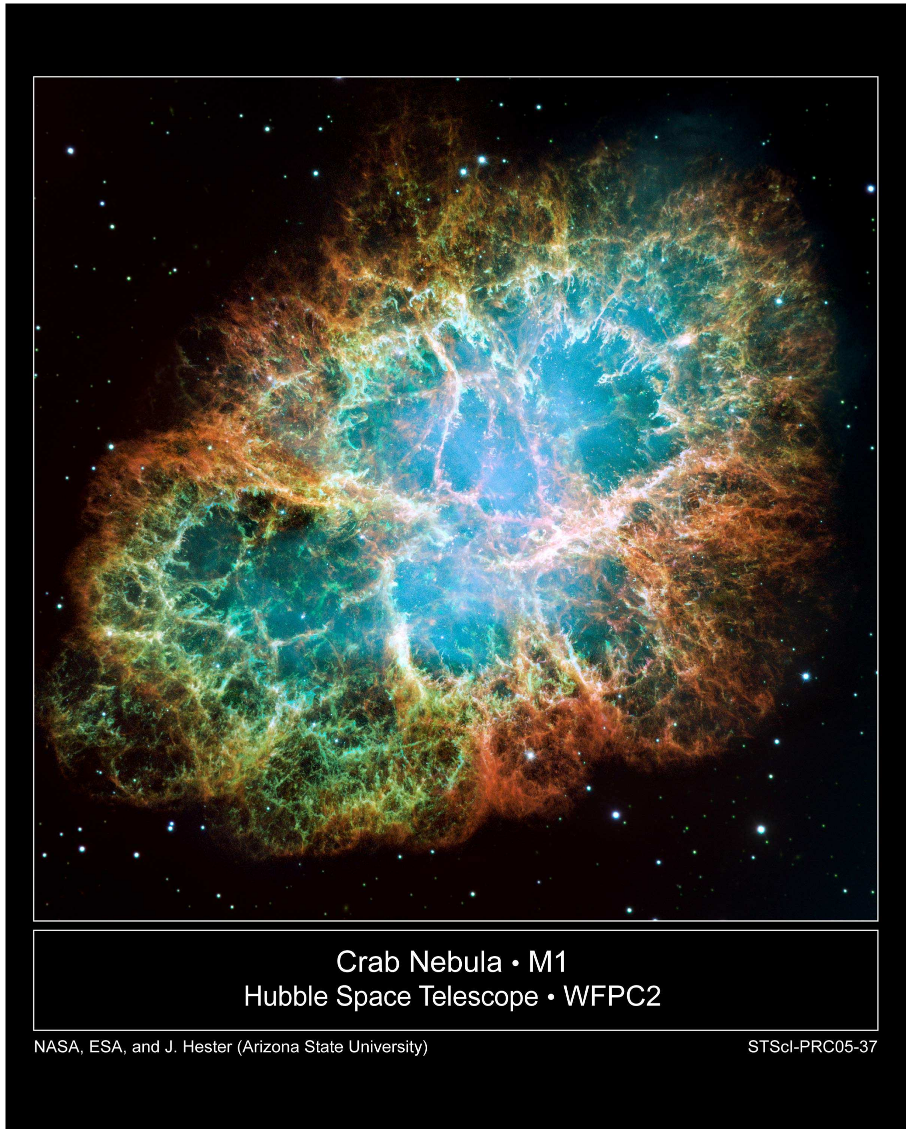
Different EOS result in:

- different matter properties: β-equilibrium, chemical potentials, compositions . . .
- different neutrino interaction: emissivity & opacities
  - inclusion of nucleon self-energy

  Roberts+12,Martinez-Pinedo+12,Hempel+15
- different PNS/NS properties: compactness (M/R) and structure

CCSN: basic picture

end of the life of massive stars (ZAMS $M \gtrsim 8 M_\odot$)



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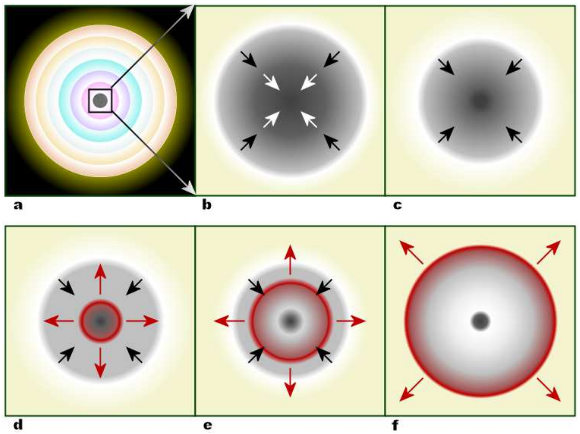
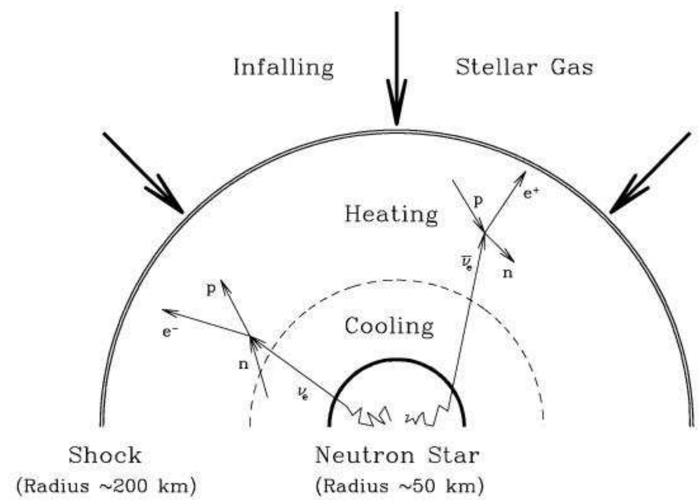


CCSN scenario (R.J. Hall, Wikipedia)

- robust picture e.g. Janka 12, Burrows 13
- $\Delta E_{\rm grav} \sim G\frac{3M_{\rm NS}^2}{5R_{\rm NS}} \sim \text{a few } 10^{53}\text{erg}$
- ν diffusion time scale: $\sim 10\,\text{s}$
- intense ν-emission ($L \sim 10^{53}\text{erg/s}$)

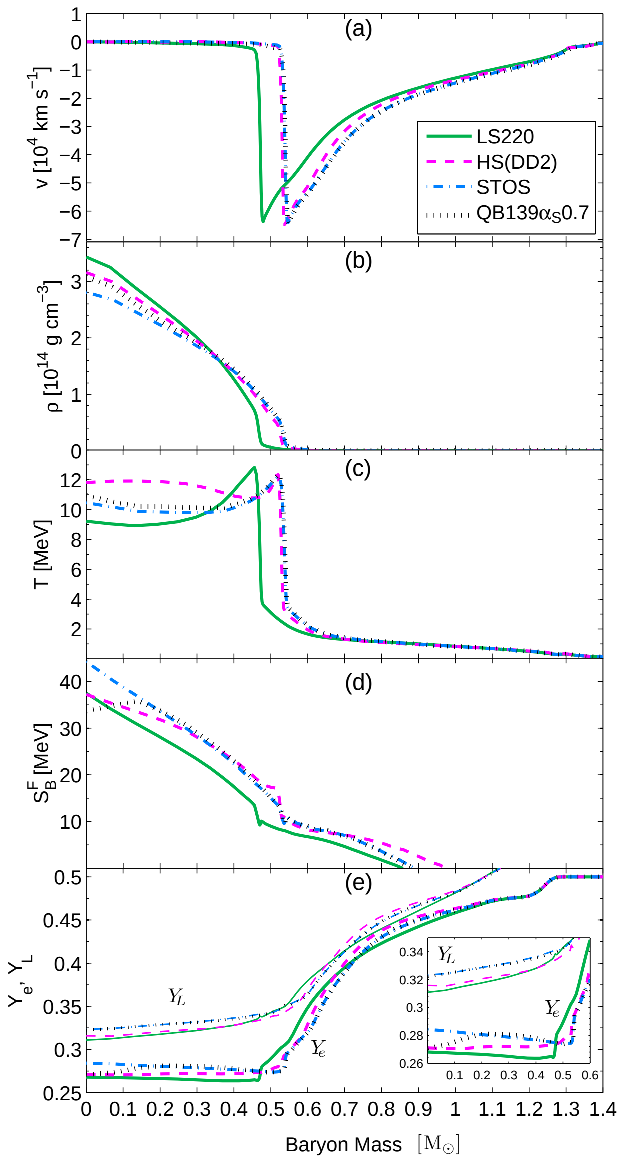
- still uncertainties in the explosion mechanism
- plausible mechanism: delayed ν-driven explosion, enhanced by convection and multi-D instabilities Wilson 85



Janka 01

EOS influence in CCSN

- collapse duration and profiles at bounce e.g. Couch 12, Fischer+14



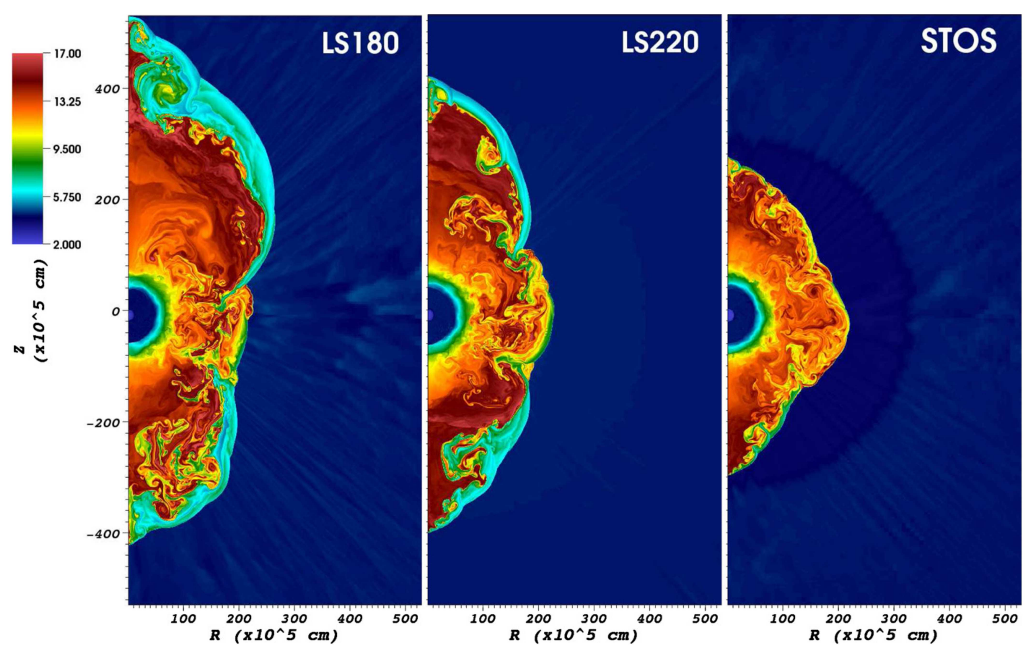
Profiles at bounce for 11.2 $M_{\odot}$, Fischer+14

EOS influence in CCSN

- collapse duration and profiles at bounce e.g. Couch 12, Fischer+14
- development of multi-D instabilities and structure of the CCSN mantle

e.g. Marek&Janka 09, Couch 12, Suwa+13

softer EOS lead to a more compact PNS, stronger instabilities, earlier explosions



2D entropy for 15 $M_\odot$

at 600ms post bounce, Couch 12

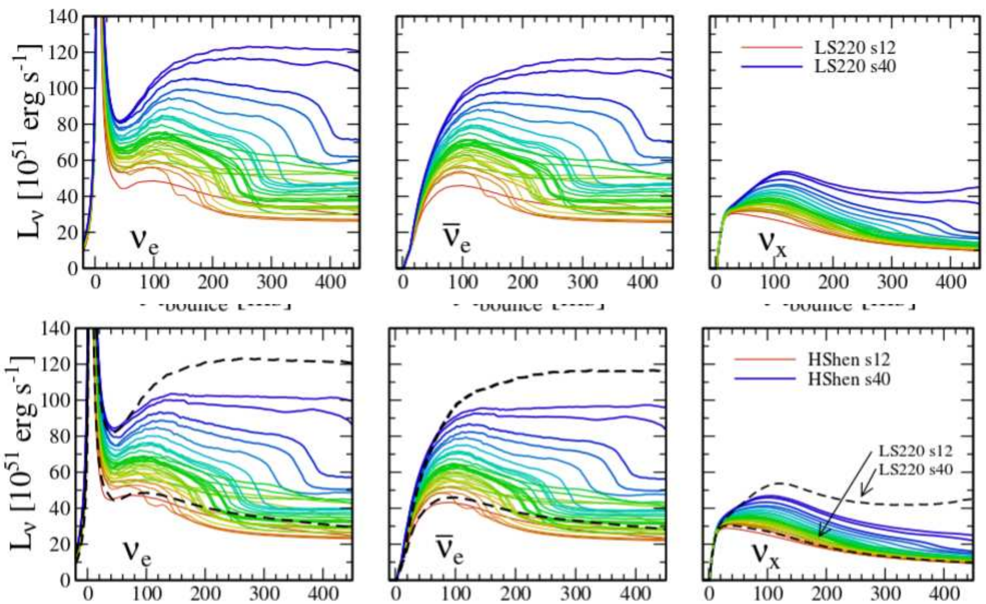
EOS influence in CCSN

- collapse duration and profiles at bounce e.g. Couch 12, Fischer+14
- development of multi-D instabilities and structure of the CCSN mantle

  e.g. Marek&Janka 09, Couch 12, Suwa+13
- neutrino luminosities and spectra

  e.g. O'Connor&Ott 13, Fischer+14

softer EOS lead to higher luminosities and spectra, due to the more compact PNS



O'Connor&Ott 13

EOS influence in CCSN

- collapse duration and profiles at bounce e.g. Couch 12, Fischer+14
- development of multi-D instabilities and structure of the CCSN mantle

  e.g. Marek&Janka 09, Couch 12, Suwa+13
- neutrino luminosities and spectra

  e.g. O'Connor&Ott 13, Fischer+14
- PNS collapse to a BH

  e.g. Fischer+ 09, O'Connor&Ott 11

  softer EOS lead to higher densities and quicker BH collapse

EOS influence in CCSN

- collapse duration and profiles at bounce e.g. Couch 12, Fischer+14
- development of multi-D instabilities and structure of the CCSN mantle

  e.g. Marek&Janka 09, Couch 12, Suwa+13
- neutrino luminosities and spectra

  e.g. O'Connor&Ott 13, Fischer+14
- PNS collapse to a BH

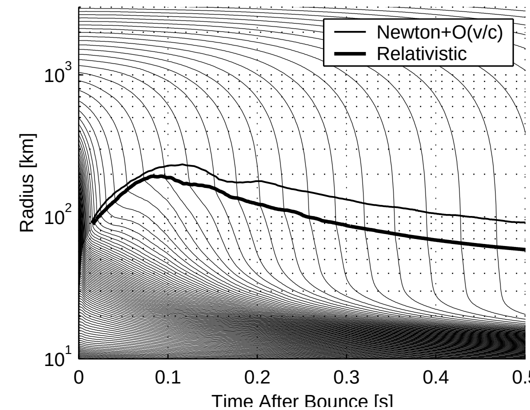
  e.g. Fischer+ 09, O'Connor&Ott 11
- electron fraction in ejecta and ν-driven wind

  e.g. Arcones+07,Fischer+ 10, Hüdepohl+10, Roberts+12,Martinez-Pinedo+12

  p-rich or (weakly) n-rich?

CCSN: modeling

- spherically symmetric (1D) models with detailed input physics fail (in general) to explode Liebendörfer+04, Thompson+03, Rampp & Janka 02, Sumyioshi+05



mass trajecory and shock position from 1D simulation, Liebendörfer+01

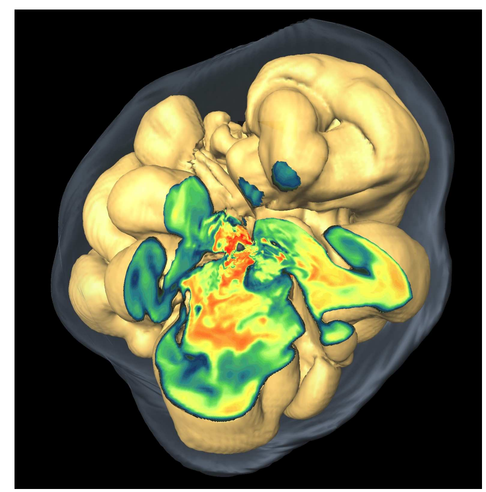
- multi-D hydro instabilities can play a crucial role, enhancing ν heating

  Nordhaus+10,Hanke+12,Couch+13,Dolence+13, . . .

- however, no consensus (so far) on multi-D results

  Müller+12,13; Bruenn+13,14; Melson+15, Dolence+15...

- multi-D + detailed input physics increase computational costs



entropy contours from 3D simulation, www.rzg.mpg.de

PUSH basic idea

Our goal:

To provide 1D exploding models of CCSN with ν's + employing $\nu_e, \bar{\nu}_e$ transport (IDSA) + nuclear EoS (HS(DD2))

Basic idea:

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

What's it good for?

- broad parameter studies (e.g., progenitor masses and metallicity)
- explosive nucleosynthesis and explosion properties

Strengths

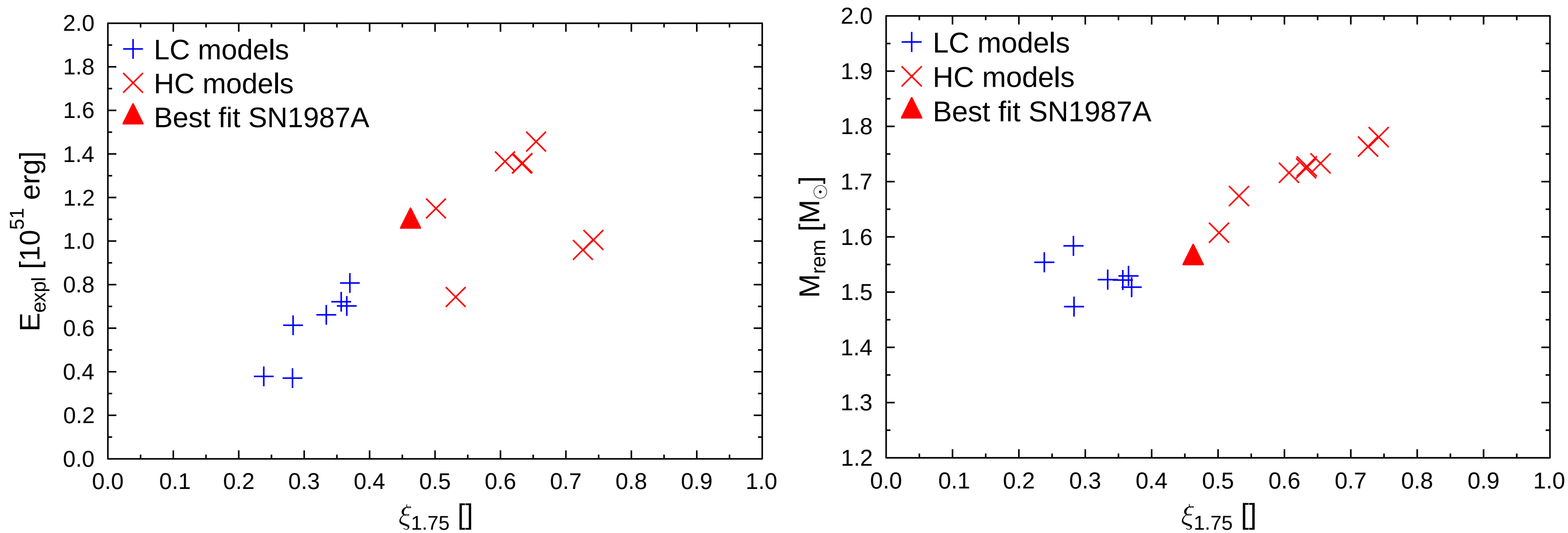
- preservation of ν_e and $\bar{\nu}_e$ properties
- inclusion of nucleon self-energy
- evolution of Y_e and of the proto-NS

Caveats

- effective 1D model
- usage of $\nu_{\mu,\tau}$ (however, averages $\nu_{\mu,\tau}$ properties correlate with ν_e and $\bar{\nu}_e$'s one)

First results with PUSH

Effective model: calibration of free parameters, using SN1987A data



Perego+ 15

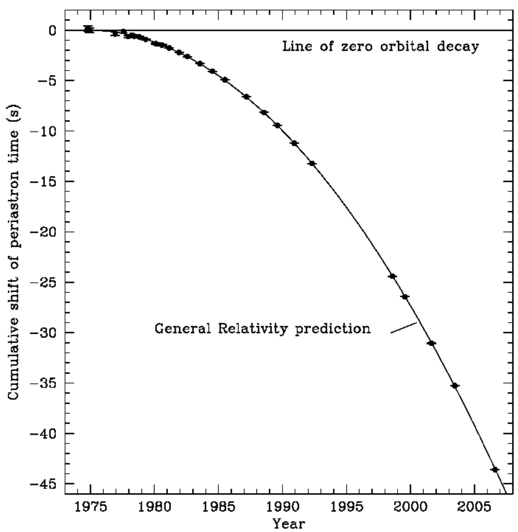
- 18-21 $M_\odot$ exploration
- todo: progenitor exploration + explosive nucleosynth.
- todo: EOS influence and im-medium effects

let’s assume that two CCSNe explode in a stellar binary system, leaving behind 2 NSs in a binary system ...

BNS mergers and their aftermaths

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

- double BNS systems do exist



PSR	P ms	P_b days	a sin i lt-s	e	$\dot{\omega}$ deg yr^{-1}	M $M_\odot$	$\tau_{\rm GW}$ Gyr
Double neutron star binaries							
B1913+16	59.0	0.323	2.34	0.617	4.227	2.83	0.31
B1534+12	37.9	0.421	3.73	0.274	1.756	2.75	2.69
B2127+11C	30.5	0.335	2.52	0.681	4.457	2.71	0.22
J1518+4904	40.9	8.634	20.04	0.249	0.011	2.62	9600
J1811−1736	104.2	18.779	34.78	0.828	0.009	2.6	1700
J0737−3039A	22.7	0.102	1.42	0.088	16.88	2.58	0.087
J0737−3039B	2773.5	0.102	1.51	0.088	.	2.58	0.087
J1829+2456	41.0	1.17	7.24	0.14	0.28	2.53	60
J1756−2251	28.5	0.319	2.75	0.18	2.59	2.57	1.7
Neutron star–white dwarf binaries							
B2303+46	1066.4	12.34	32.69	0.66	0.010	2.53	4500
J1141−6545	393.9	0.20	1.86	0.17	5.33	2.30	0.59

PSR1913+16 periastron shift

millisecond pulsars in relativistic binaries

Credit: Weisberg+10, Lorimer 05

BNS mergers and their aftermaths

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

- double BNS systems do exist
- inspiral phase, driven by GW emission

$$t_{\rm insp} \approx 4.56\,{\rm Gyr}\left(\frac{T_{\rm orb}}{10{\rm h}}\right)^{8/3}\left(\frac{M}{M_\odot}\right)^{-2/3}\left(\frac{\mu}{M_\odot}\right)^{-1}\left(1-e^2\right)^{7/2}.$$

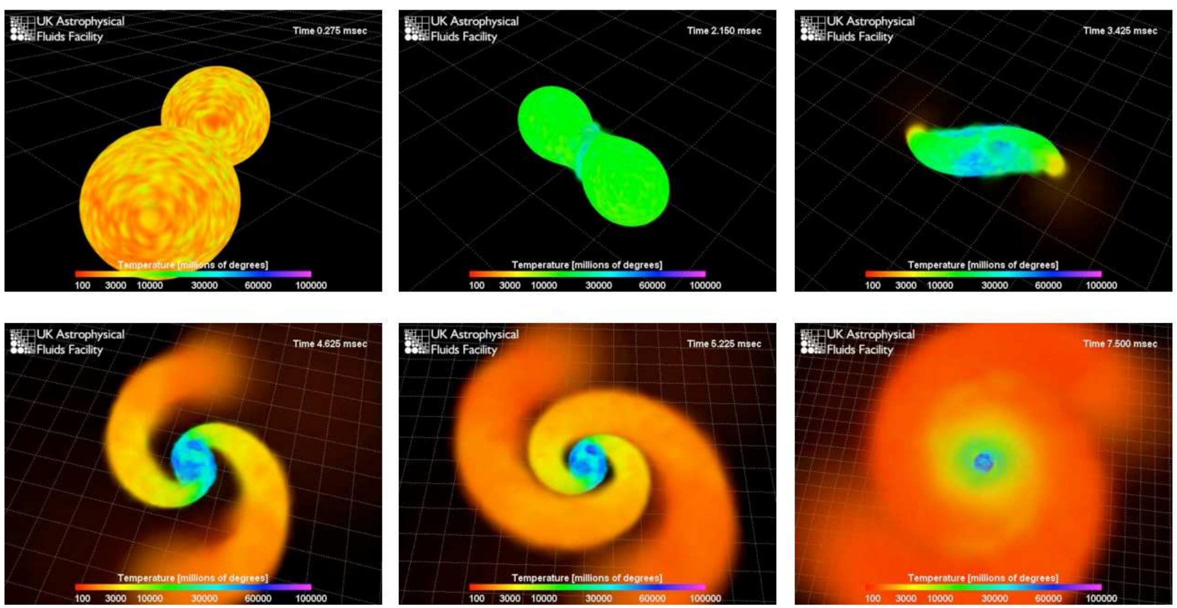
(see, e.g., Lorimer 05)

- $T_{\rm orb}$ orbital period
- M total mass
- μ reduced mass
- e eccentricity

BNS mergers and their aftermaths

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

- double BNS systems do exist
- inspiral phase, driven by GW emission
- coalescence phase

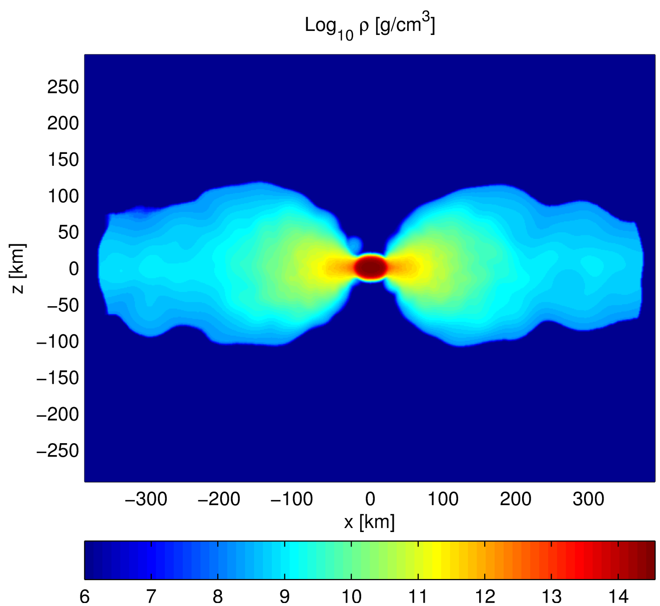


Temperature from a SPH simulations. Credit: S. Rosswog.

BNS mergers and their aftermaths

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

- double BNS systems do exist
- inspiral phase, driven by GW emission
- coalescence phase
- NS merger aftermath



- Hyper Massive NS ($\rightarrow$ BH) $\sim 2.6 M_\odot$, $\rho \gtrsim 10^{12}\mathrm{g\,cm^{-3}}$
- thick accreting disk $\sim 0.15 M_\odot$, $Y_e \lesssim 0.05$
- intense ν emission $L_{\nu,\mathrm{tot}} \sim 10^{53}\mathrm{erg\,s^{-1}}$

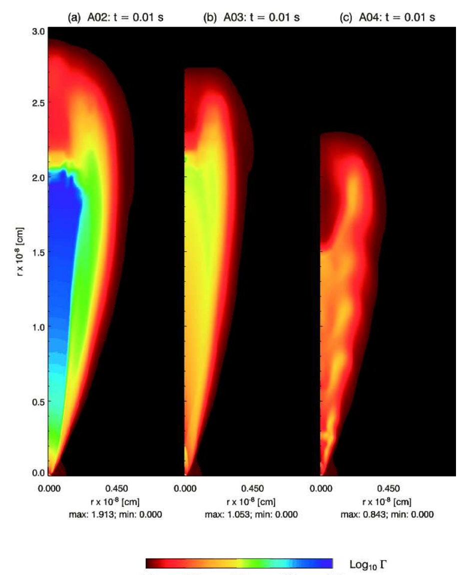
$\leftarrow$ figure: matter density

Nuclear & Astro relevance

dynamical encounter of neutron-rich, stellar compact object

- intense emitter of gravitational waves and neutrinos e.g. Read+13
- ejecta and heavy elements nucleosynthesis Lattimer&Schramm74
- significant dependence on nuclear EoS properties e.g. Bauswein+14
- possible short gamma-ray burst progenitors e.g. Paczynski86
- electromagnetic counterpart from radioactive decay Li&Paczynski98
- ejecta properties depends on ν-matter interaction e.g. Wanajo+14

www.ligo.caltech.edu



Aloy+05

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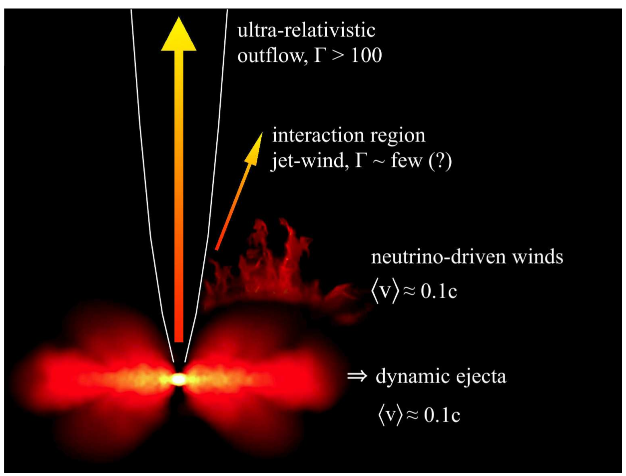
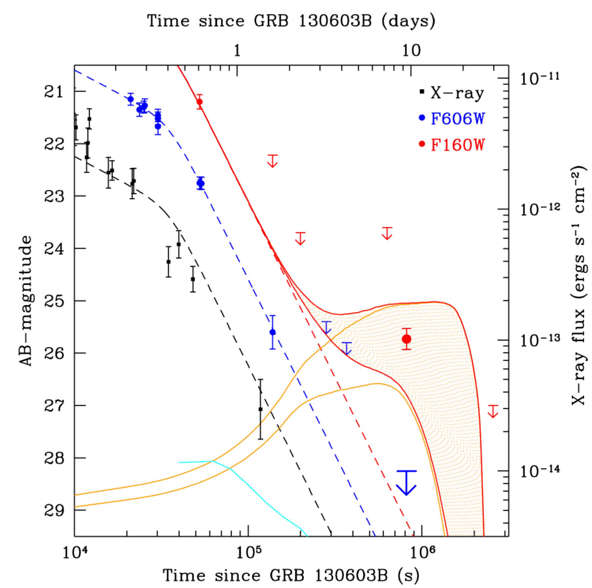


Rosswog 12



Tanvir+13, Berger+13

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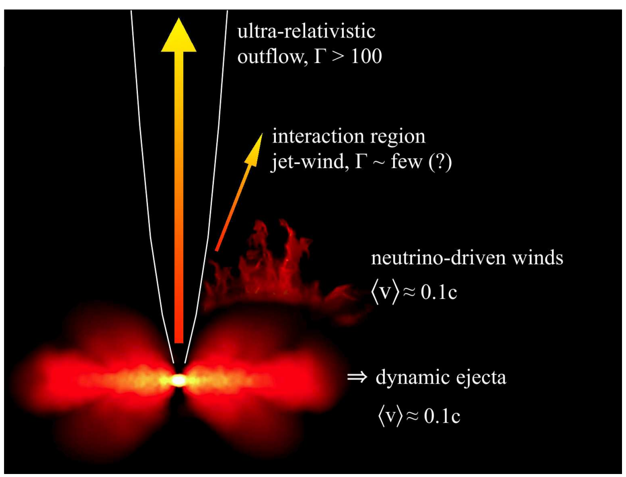

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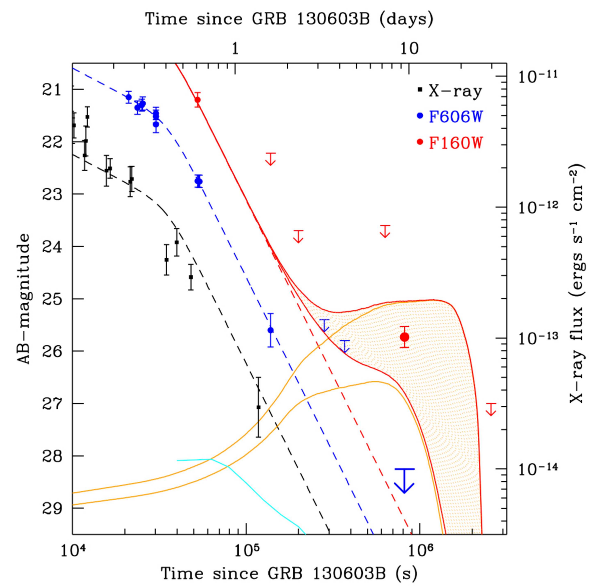
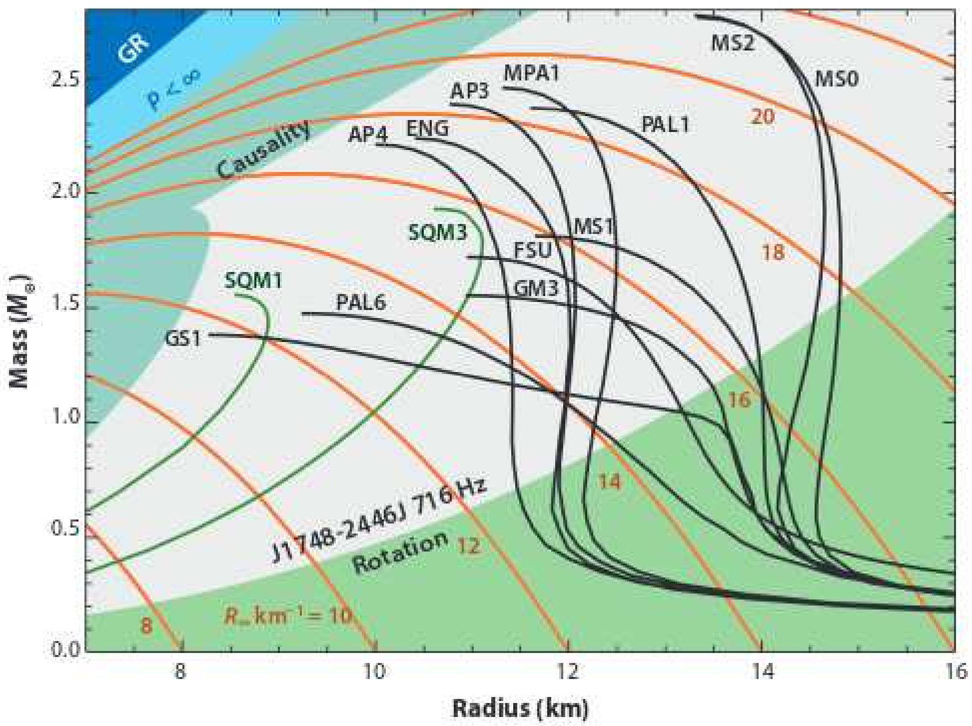


Tanvir+13, Berger+13

EOS influence in BNS mergers

Nuclear EOS influence the NS compactness:
(softer EOS $\rightarrow$ smaller R_{NS})



e.g. Lattimer+12,Lattimer&Steiner 14

EOS influence in BNS mergers

Nuclear EOS influence the NS compactness:
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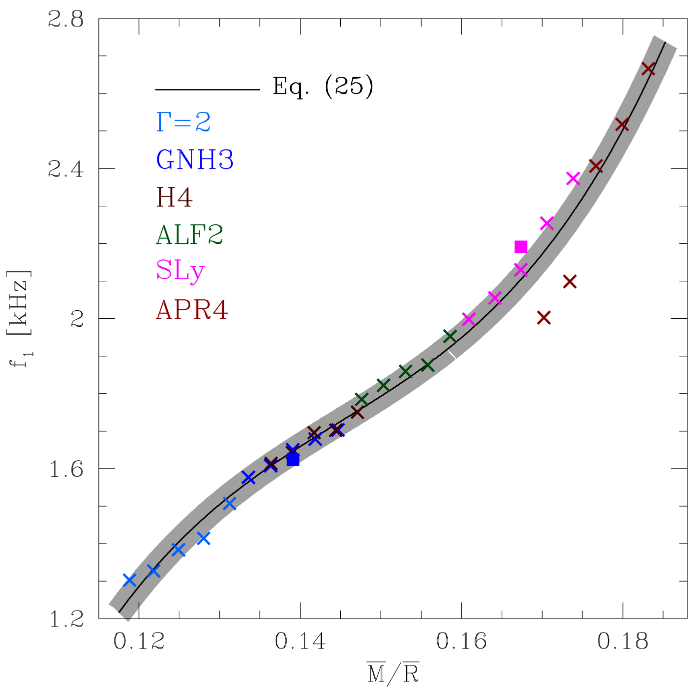
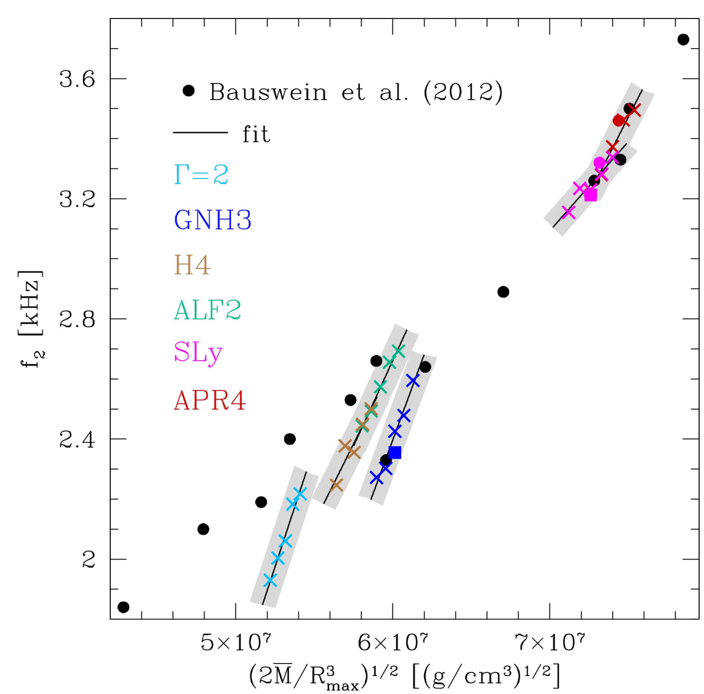
- GW signal

e.g. Read+13, Hotokezaka+13, Bauswein+13, Takami+15

more compact NS' produce higher frequencies





Takami+15

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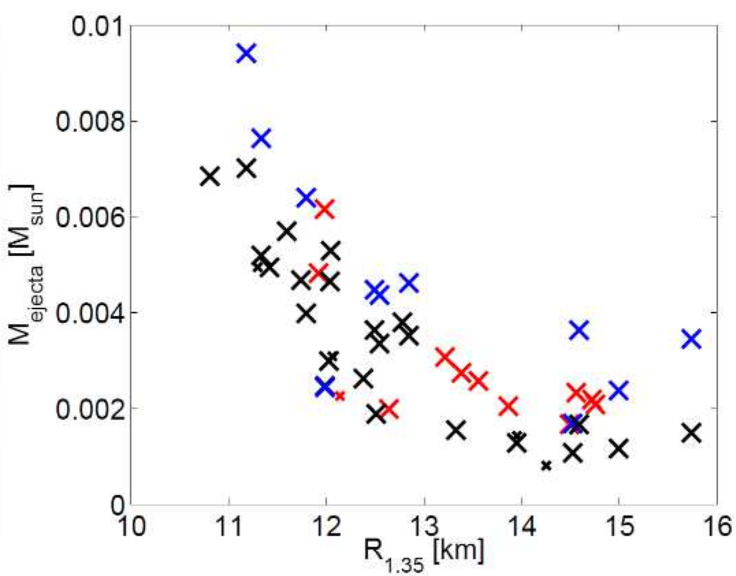
- GW signal

e.g. Read+13, Hotokezaka+13, Bauswein+13, Takami+15

- amount of ejecta and mass of the disc

e.g. Ruffer+98, Rosswog+ 03,Rosswog+12, Hotokezaka+13, Bauswein+13

more compact NS' eject more mass, less compact have tidal contribution



Bauswein+13

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- GW signal

  e.g. Read+13, Hotokezaka+13, Bauswein+13, Takami+15

- amount of ejecta and mass of the disc

  e.g. Ruffer+98, Rosswog+ 03,Rosswog+12, Hotokezaka+13, Bauswein+13

- velocity of the ejecta e.g. Rosswog+12, Hotokezaka+13, Bauswein+13

  more compact NS' produce larger velocities

EOS influence in BNS mergers

Nuclear EOS influence the NS compactness:
(softer EOS $\rightarrow$ smaller $R_{\rm NS}$)

- GW signal

  e.g. Read+13, Hotokezaka+13, Bauswein+13, Takami+15

- amount of ejecta and mass of the disc

  e.g. Ruffer+98, Rosswog+ 03,Rosswog+12, Hotokezaka+13, Bauswein+13

- velocity of the ejecta e.g. Rosswog+12, Hotokezaka+13, Bauswein+13
- intensity of ν emission e.g. Sekiguchi+15, Rosswog+14

  more compact NS' have larger temperatures and larger ν luminosities

EOS influence in BNS mergers

Nuclear EOS influence the NS compactness:
(softer EOS $\rightarrow$ smaller R_{NS})

- GW signal

  e.g. Read+13, Hotokezaka+13, Bauswein+13, Takami+15

- amount of ejecta and mass of the disc

  e.g. Ruffer+98, Rosswog+ 03,Rosswog+12, Hotokezaka+13, Bauswein+13

- velocity of the ejecta — e.g. Rosswog+12, Hotokezaka+13, Bauswein+13
- intensity of ν emission — e.g. Sekiguchi+15, Rosswog+14
- destiny of the remnant:

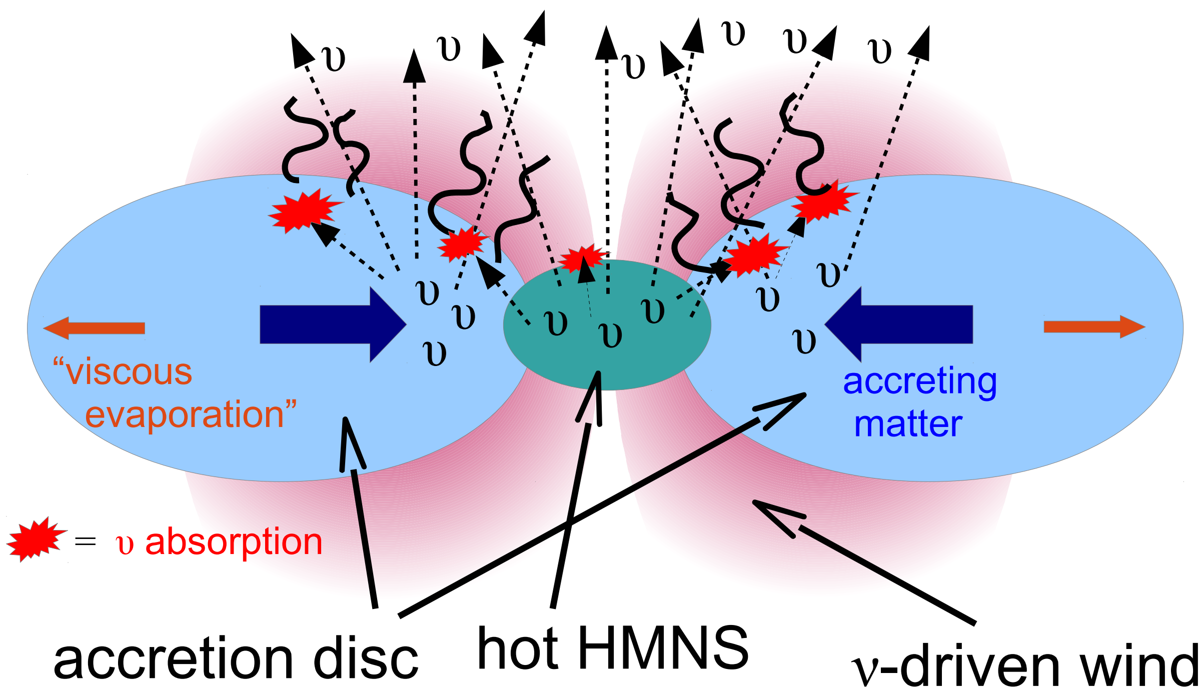
  e.g. Hotokezaka+13, Bauswein+14

  SMNS, HMNS $\rightarrow$ BH (time scale?), BH

Neutrino-driven wind

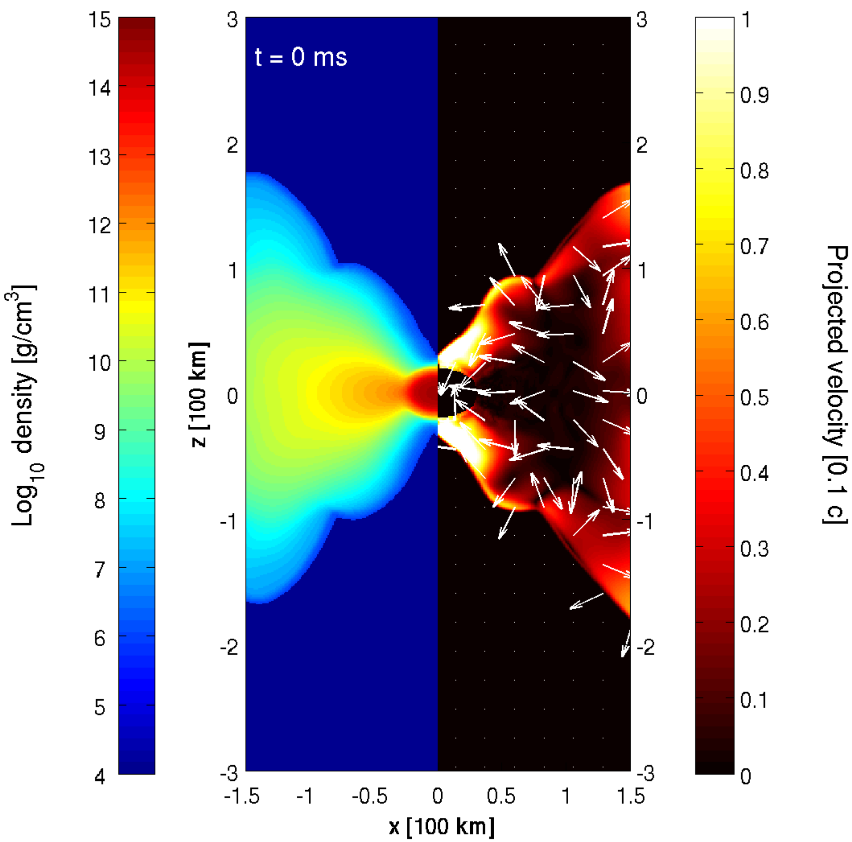
Physical origin of the ν-driven wind:

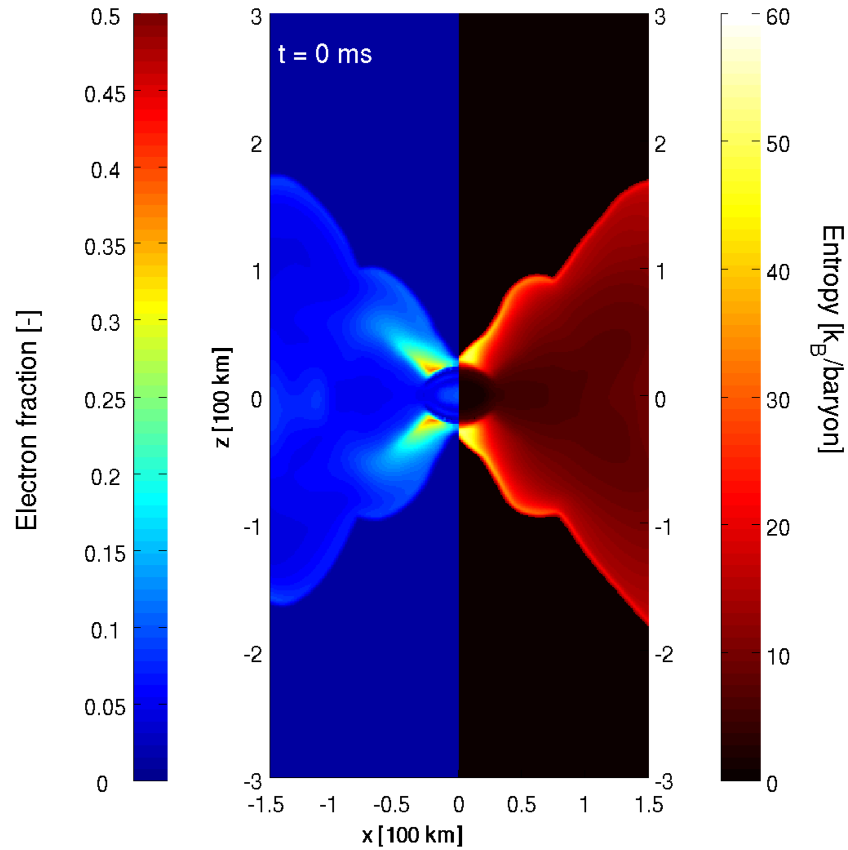
- HMNS ($\rightarrow$ BH)
  $\sim 2.60 M_\odot$
- thick accreting disk
  $\sim 0.17 M_\odot$, $Y_e \lesssim 0.05$
- intense neutrino (ν) emission
  $L_{\nu,\mathrm{tot}} \sim 10^{53} \mathrm{erg\,s^{-1}}$
- ν-disk interaction: wind formation



Disc and wind dynamics

t = 0 ms





left: matter density

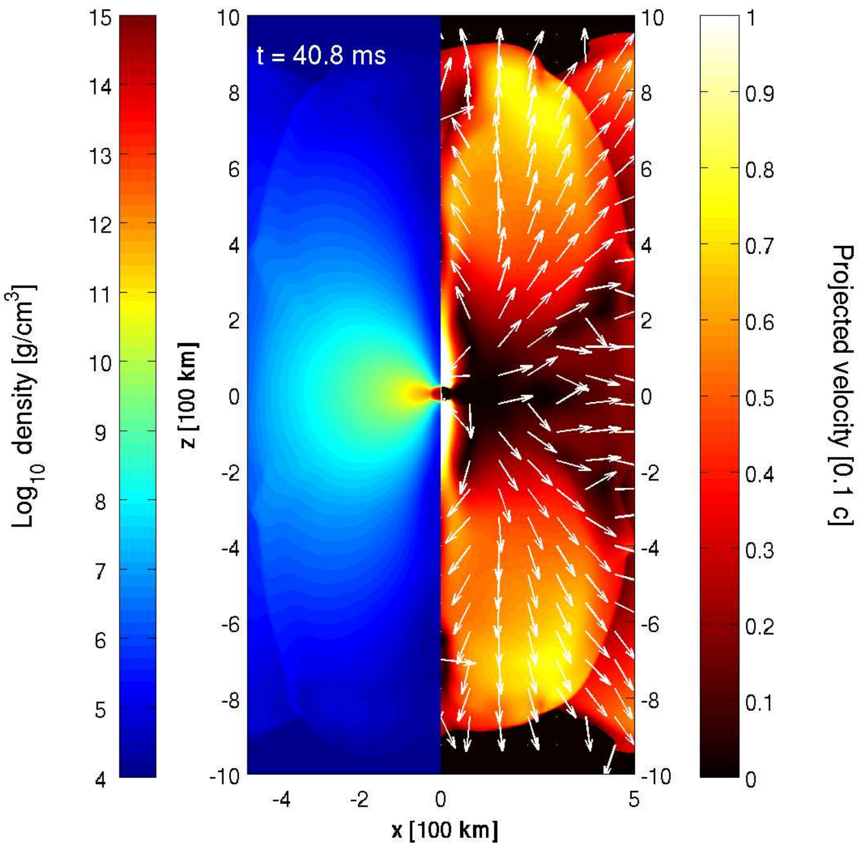
right: projected velocity

left: electron fraction

right: entropy

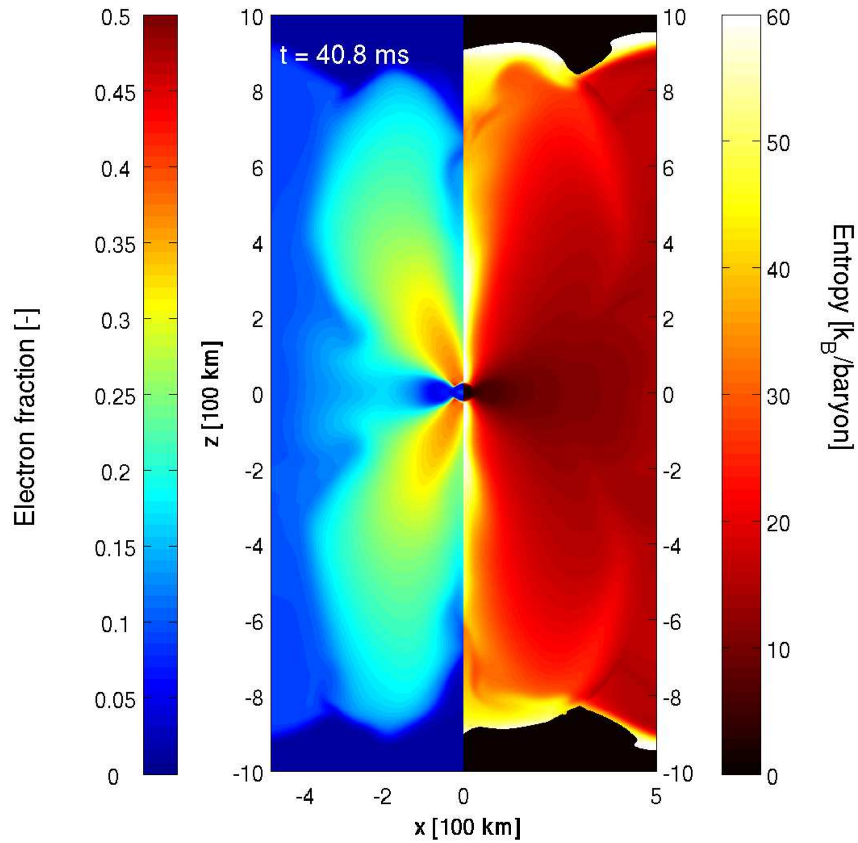
Disc and wind dynamics

t = 40 ms



left: matter density

right: projected velocity

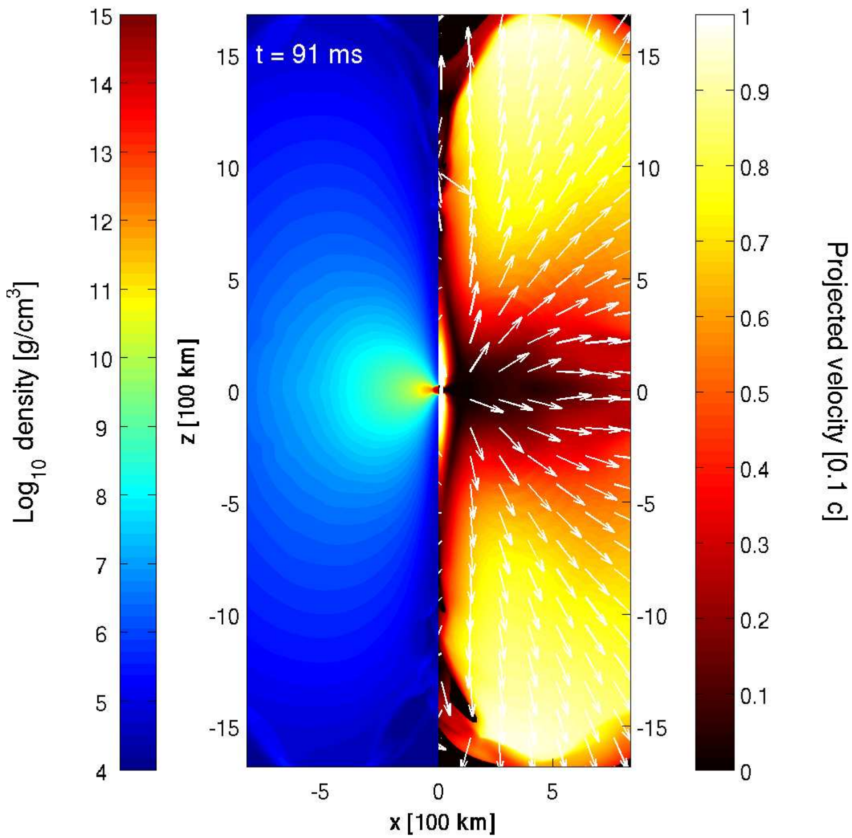


left: electron fraction

right: entropy

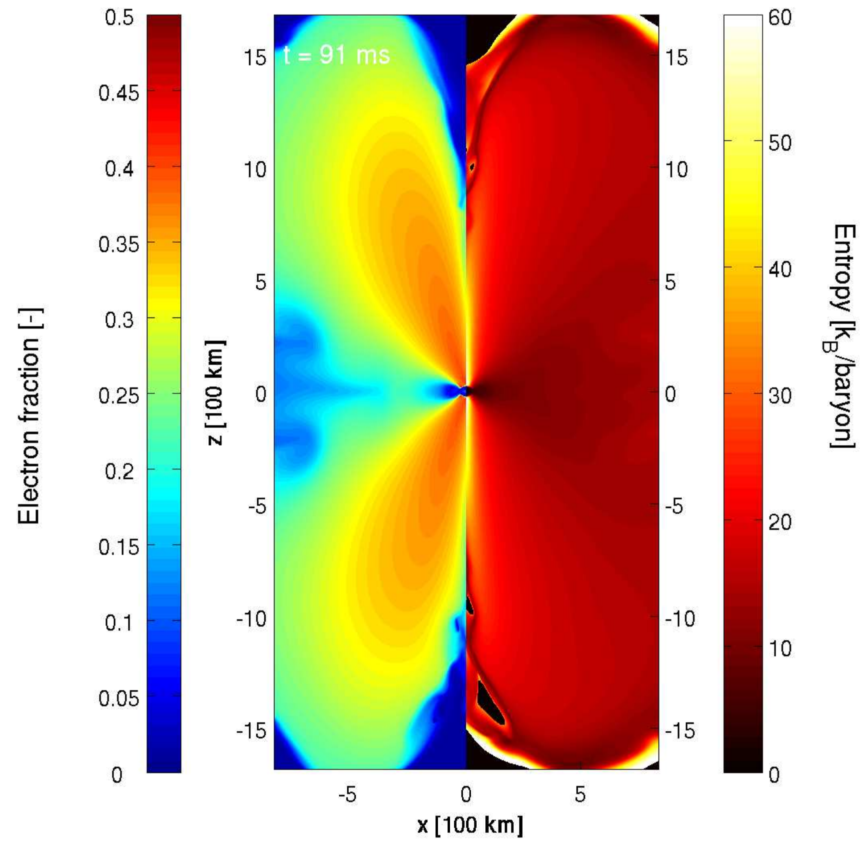
Disc and wind dynamics

t = 90 ms



left: matter density

right: projected velocity



left: electron fraction

right: entropy

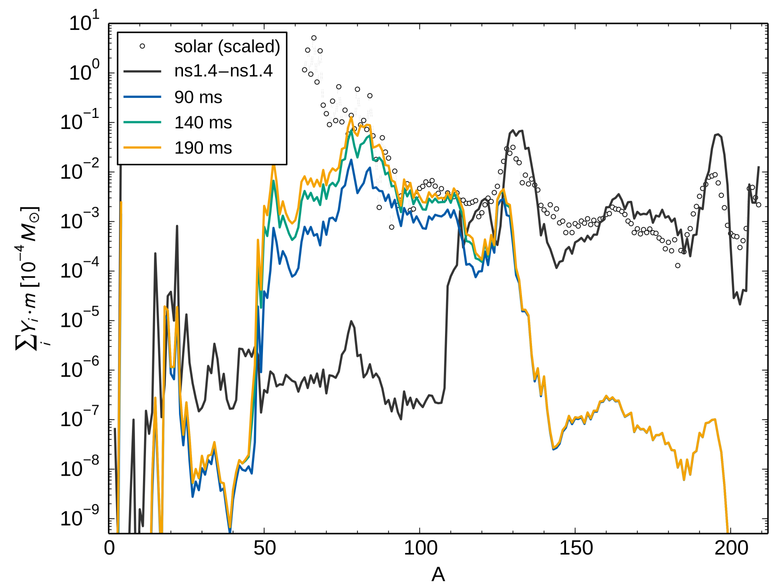
Nucleosynthesis from the wind

Postprocessing of ejected tracers $(\sim 17k \rightarrow 9 \times 10^{-3} M_\odot)$

- `Winnet` nuclear network
- weak r-process: 80<A<130
- complementary to robust r-process nucleosynthesis from dynamic ejecta
- possible differences between high and low latitude ejecta

our wind ejecta + dynamical ejecta

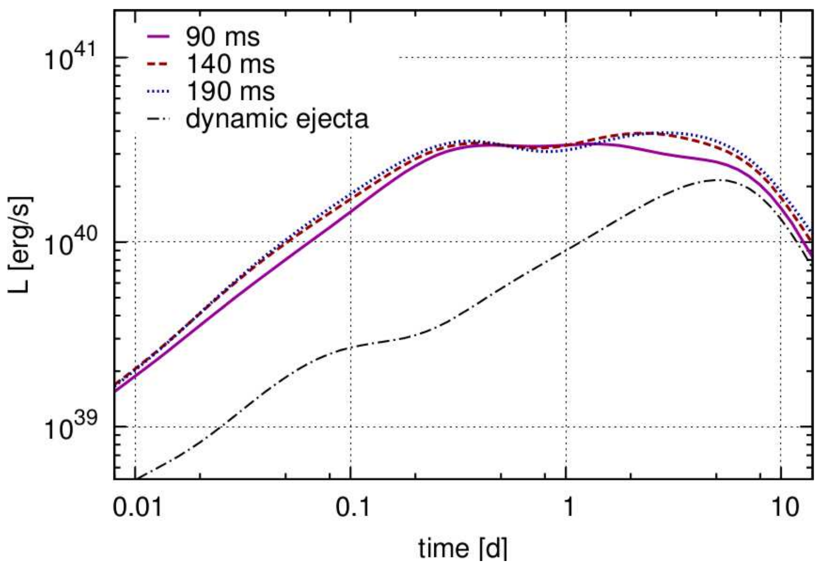
$(m_{\rm dyn} \approx 10^{-2} M_\odot)$ from Korobkin+12



Martin,AP et al., arXiv:1506.05048

Electromagnetic transient

γ emission powered by radioactive material in the ejecta



bolometric luminosity (dynamic + wind), computed by O. Korobkin

Martin,AP et al, arXiv:1506.05048

- model application for photon propagation and emission

  e.g. Kulkarni 05,Grossman+13

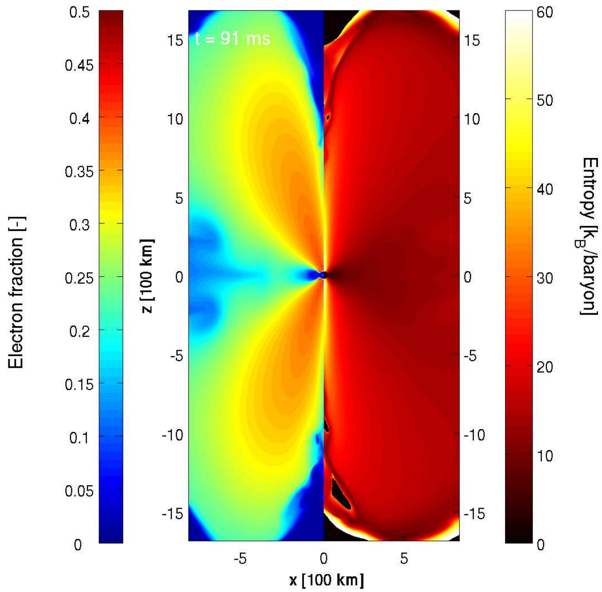
- potentially different from emission coming from dynamical/viscous ejecta
  - earlier and bluer
  - less contaminated by lanthanides and actinides

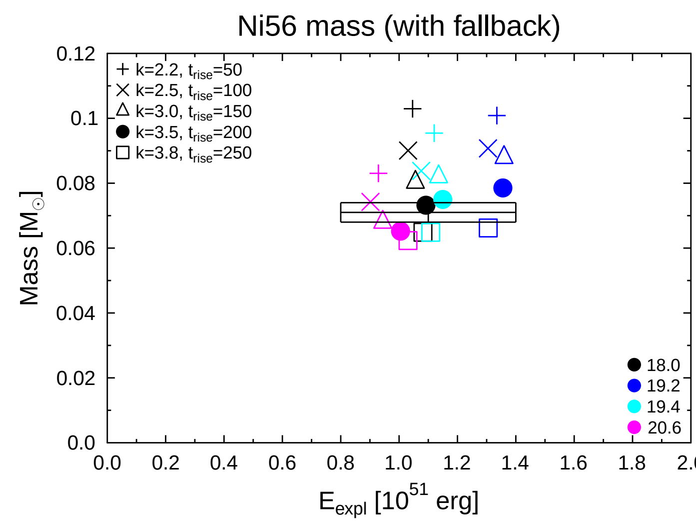
  cf Metzger&Fernandez14

- impact of different EOS on the wind and its Y_e?

Conclusions

- ν's are crucial ingredients of CCSN and BNS merger modeling
- nuclear EOS impacts on dynamics and ν properties
- still large uncertanties due to nuclear input physics
- large impact on ejecta properties





- PUSH: 1D effective model to explode stars using ν's
- tool to compute nucleosynthesis yields & test EOS impact
- ν-driven wind from BNS merger
- effect of EOS still unknown