ν-matter interaction in CCSNe and NS mergers

Albino Perego

in collaboration with

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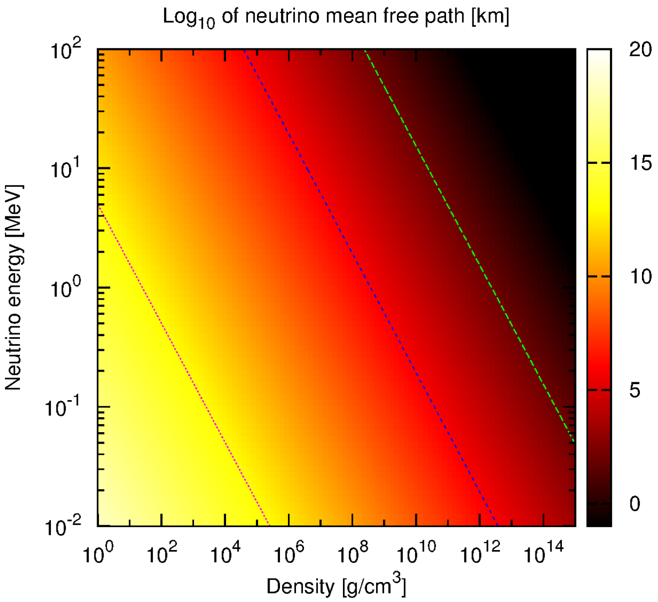
TU-Darmstadt, IKP-Theory

Neutrino matter interaction

ν's are weakly interacting particles:

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

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



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 role and can potentially trigger explosion
  - effective spherically symmetric model for CCSN explosions: PUSH

Perego, Hempel, Frölich, Ebinger, Eichler, Casanova, Liebendörfer, Thielemann

arXiv150102845P

- Binary NS mergers
  - ν's can trigger matter ejection
  - 3D model of ν-driven wind in binary NS merger aftermath

Perego, Rosswog, Cabezon, Korobkin, Käppeli, Arcones, Liebenörfer

MNRAS, V. 443, p. 3134-3156

CCSN: a brief overview

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

e.g., Bethe 90

- enrich the host galaxy with nucleosynthetic yields

Bliss', Wu's, Sievering's talks

- inject $E_{\rm kin} \sim 10^{51} {\rm erg/event}$ in the interstellar medium
- produce compact remnants (NS or BH)
- present large variety of properties (connections with progenitor properties?)


Crab Nebula • M1
Hubble Space Telescope • WFPC2

NASA, ESA, and J. Hester (Arizona State University)

STScI-PRC05-37

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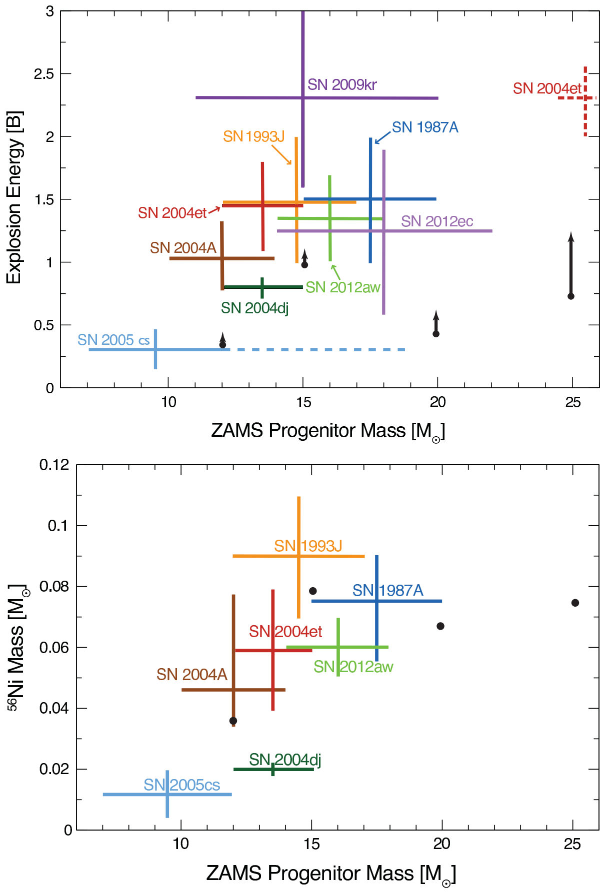
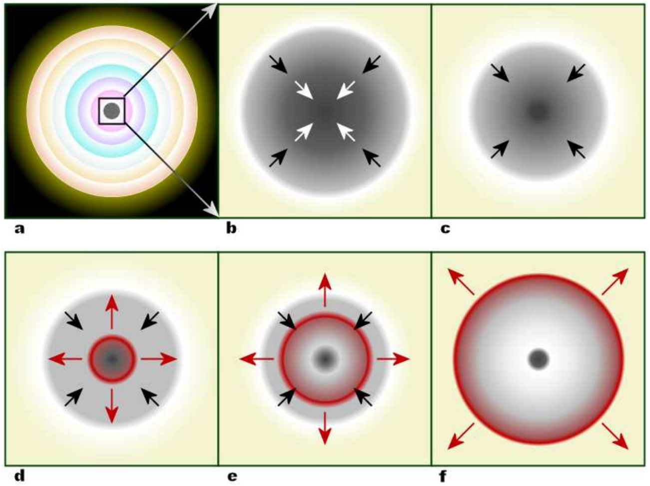


Bruenn+14

CCSN modeling

e.g. Burrows 13, Janka 12, Fischer's talk



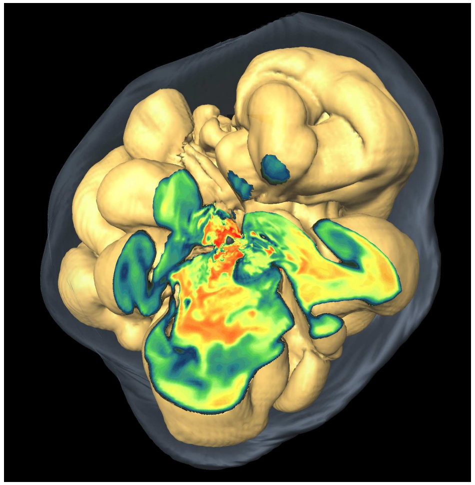
- robust basic picture
- intense ν emission ($L \lesssim 10^{53}\mathrm{erg/s}$)
- still uncertainties in the explosion mechanism
- plausible mechanism: delayed ν-driven explosion Wilson 85

Core Collapse scenario by R.J. Hall, Wikipedia

- spherically symmetric (1D) models with detailed ν-transport fail (in general) to explode

  Liebendörfer+04, Thompson+03, Rampp & Janka 02
- 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
- multi-D + detailed ν-transport increase computational costs



www.rzg.mpg.de

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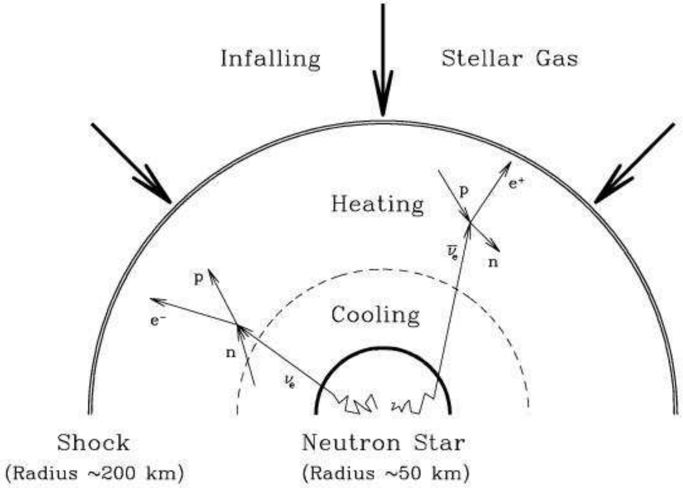

Janka 01

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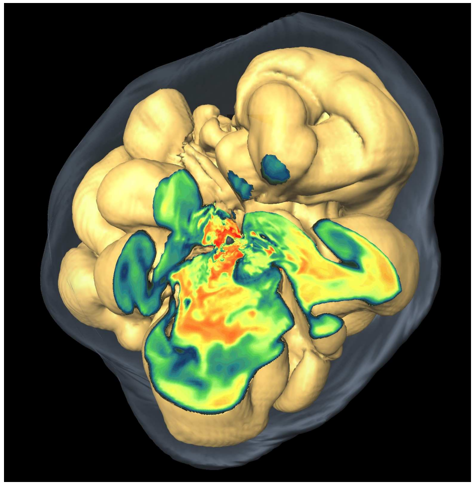

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PUSH basic idea

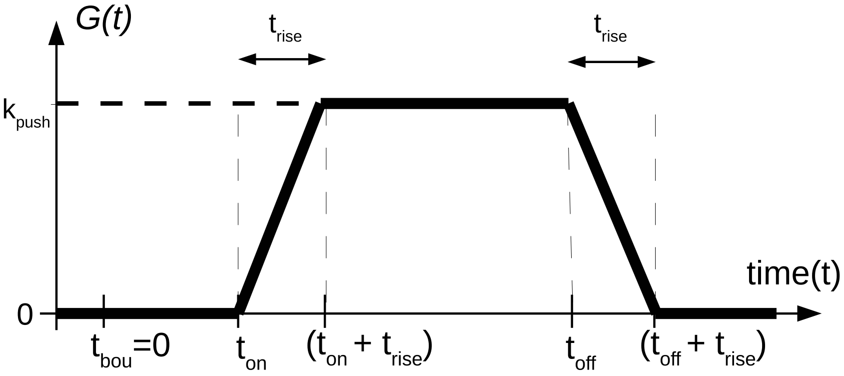
Our goal: To provide a 1D model to trigger CCSN explosions, following ν-driven explosion paradigm and employing $\nu_e, \bar{\nu}_e$ transport + nuclear EoS

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?

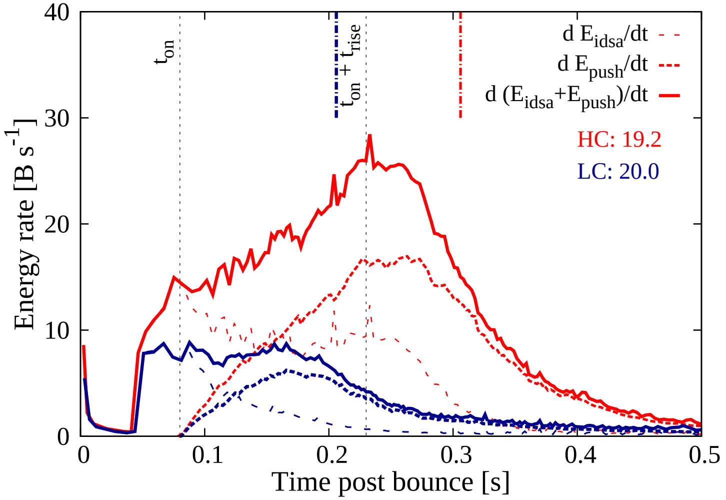
- to perform broad parameter studies (e.g., progenitor masses and metallicity)
- to study explosive nucleosynthesis, based on detailed ν transport
- to explore explosion properties and their connection with progenitor properties

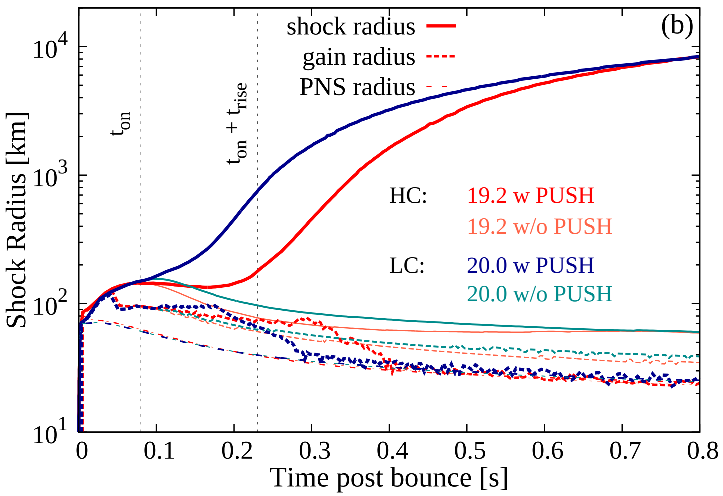
PUSH at work



free parameters:

- $t_{\text{on}} = 80\,\text{ms}$
- $t_{\text{off}} = 1\,\text{sec} \gg t_{\text{expl}}$
- $k_{\text{push}} \sim 1$
- $50\,\text{ms} \lesssim t_{\text{rise}} \lesssim 250\,\text{ms}$



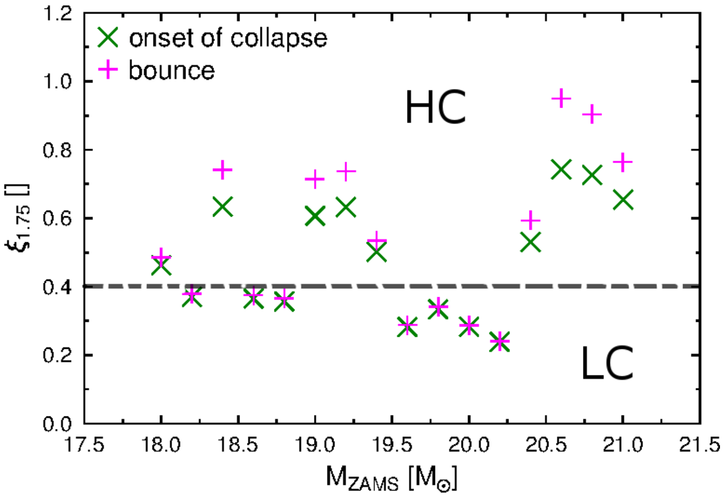


Calibration strategy

search for $(k_{\rm push}, t_{\rm rise})$ and $M_{\rm prog}$ that reproduces SN1987A observables

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

$E_{\rm expl}$	$(1.1 \pm 0.3) \times 10^{51}$ erg
$M_{\rm prog}$	$18 - 21 M_\odot$
$m(\,^{56}$Ni$)$	$(0.071 \pm 0.003) M_\odot$
$m(\,^{57}$Ni$)$	$(0.0041 \pm 0.0018) M_\odot$
$m(\,^{58}$Ni$)$	$0.006 M_\odot$
$m(\,^{44}$Ti$)$	$(0.55 \pm 0.17) \times 10^{-5} M_\odot$



exploration of 16 progenitors (18-21 $M_\odot$), at solar metallicity

WHW 02

compactness parameter:

$$\xi_{1.75} = \frac{1.75}{R(1.75 M_\odot)/1000\,{\rm km}}$$

O'Connor & Ott 11

$E_{\rm expl} \gtrsim 1.0 \times 10^{51}\,{\rm erg}$ for $\xi_{1.75} > 0.4$ (HC)

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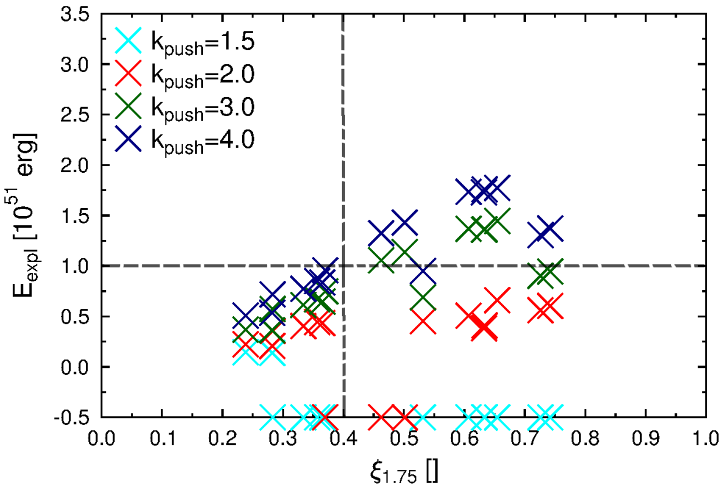

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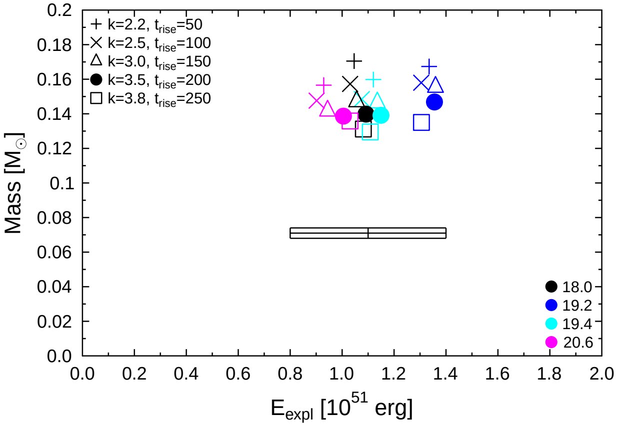
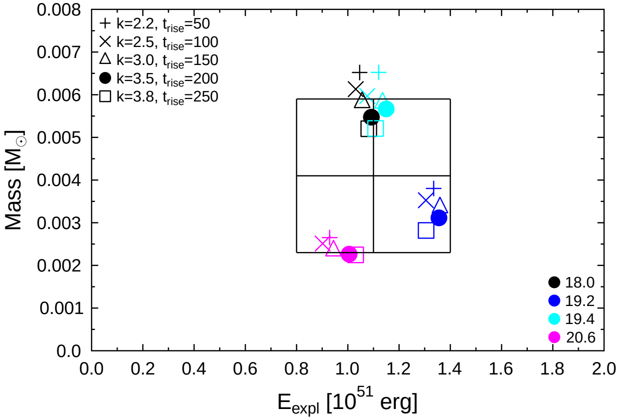
Results without fallback

4 HC progenitors (18.0,19.2,19.4,20.6)

Abundances: Post-processing of innermost ejecta with WinNet (full nuclear network)


Ni56 mass (without fallback)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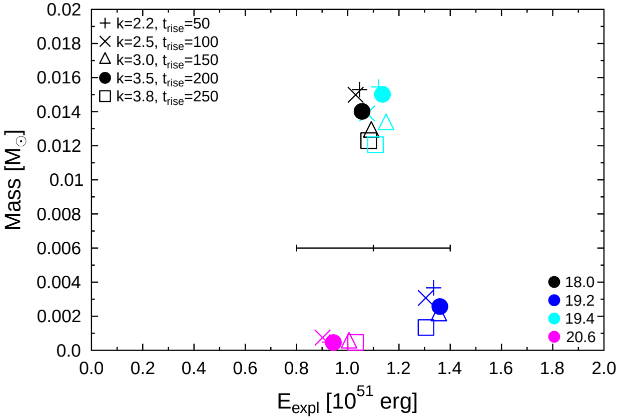
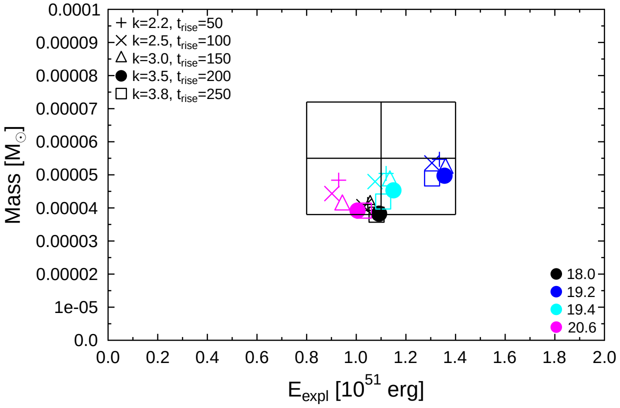

Ni58 mass (without fallback)

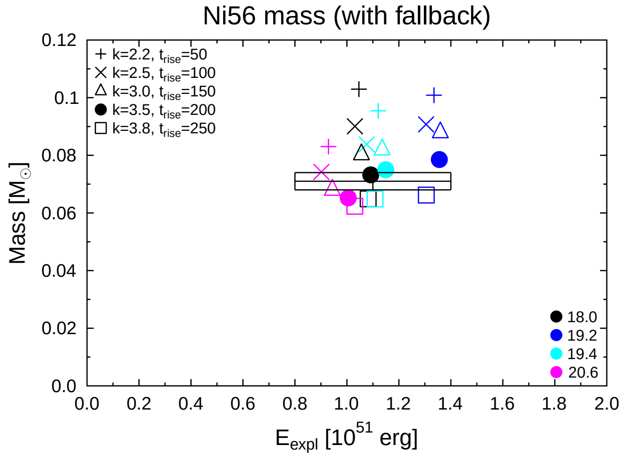

Ti44 mass (without fallback)

calibration set: X

Results with fallback

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

Abundances: Post-processing of innermost ejecta with WinNet (full nuclear network)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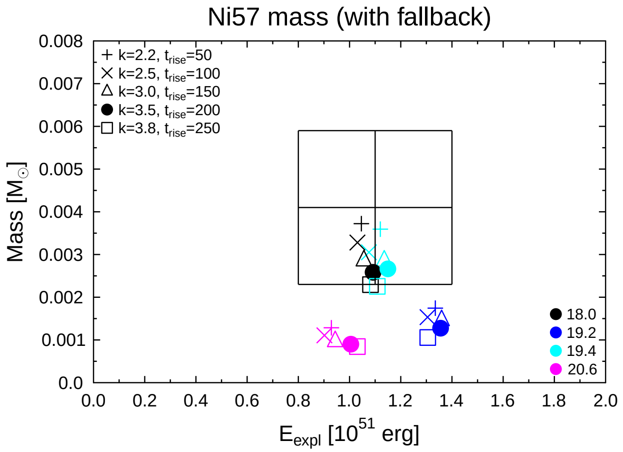
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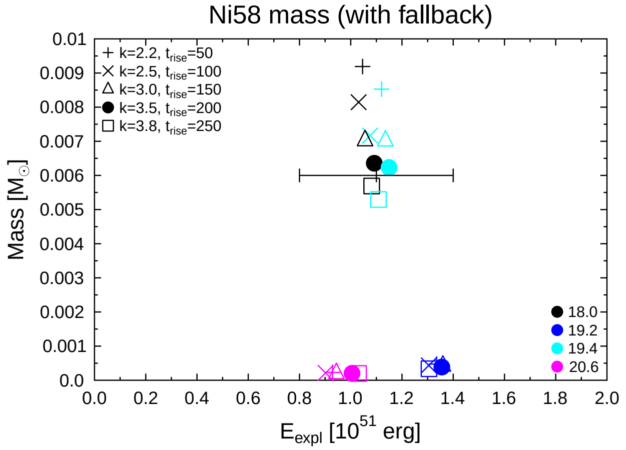
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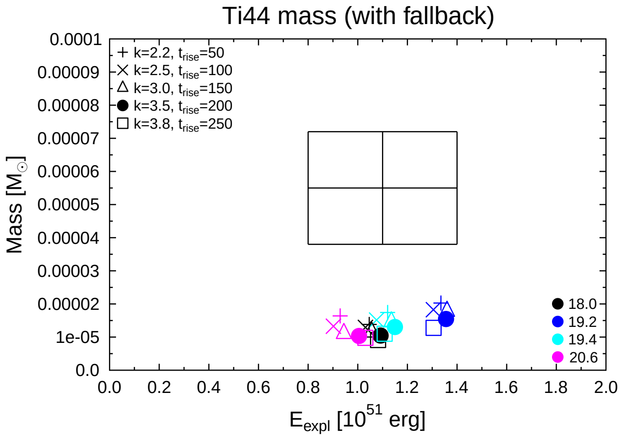

Ti44 mass (with fallback)

calibration set: 18 $M_\odot$, $k_{\text{push}} = 3.5$, $t_{\text{rise}} = 200\,\text{ms}$, $M_{\text{fallback}} = 0.1 M_\odot$

Calibration discussion

Fallback

$M_{\text{fallback}} \approx 0.1 M_{\odot}$ in agreement with

- long term simulations of 1D explosions Ugliano+12
- requirement of a large fallback to sub-merge the B field and hide the NS Chevalier98

Compact remnant

- $M_{\text{remn,grav}} = 1.50 M_{\odot}$
- $M_{\text{remn,bar}} = 1.66 M_{\odot}$ $< M_{\text{max,DD2}} = 2.92 M_{\odot}$
- BH formation would require $\approx 1.3 M_{\odot}$ additional fallback

$^{57-58}$Ni abundances

- significant production of $^{57-58}$Ni requires slightly n-rich ejecta
- this requires mass-cut inside the Si shell
- possible constraint on progenitors and t_{expl}

^{44}Ti abundance

All models with fallback underproduce ^{44}Ti. Uncertainties in

- ejecta mixing
- nuclear physics (^{44}Ti(α, p) ^{47}V)

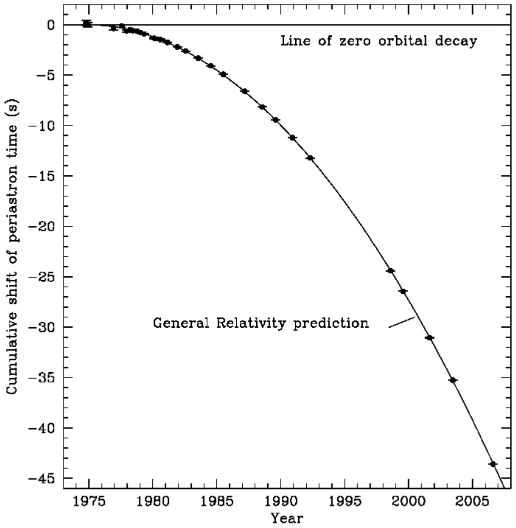
can increase abundance up to ×4, reducing the discrepancy let’s assume that two CCSNe explode in a stellar binary system, leaving behind 2 NSs in a binary system . . .

BNS mergers and their aftermaths

e.g. Rosswog 15, Bauswein's talk

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+2010, Lorimer

BNS mergers and their aftermaths

e.g. Rosswog 15, Bauswein's talk

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

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

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

(see, e.g., Lorimer 2005)

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

BNS mergers and their aftermaths

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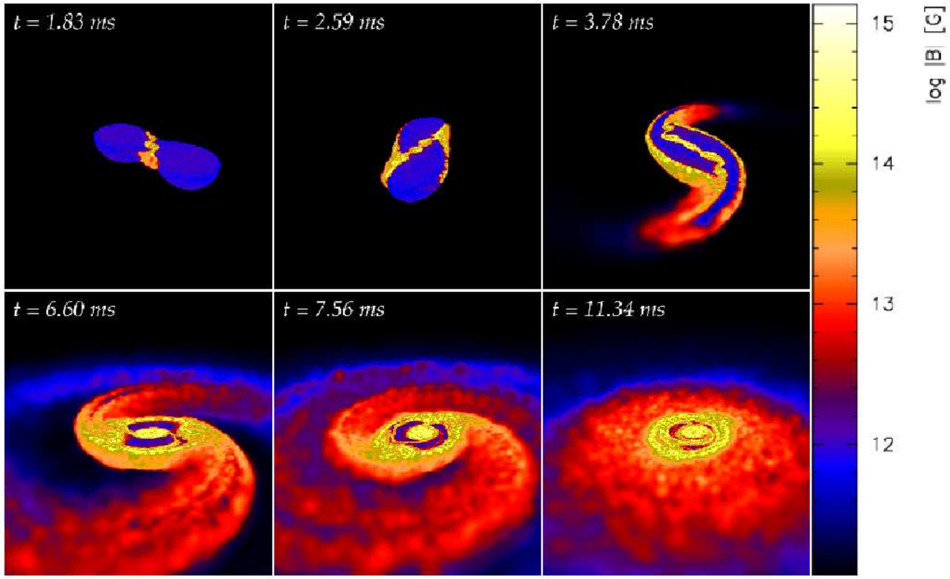
- inspiral phase, driven by GW emission
- coalescence phase



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

Credit: Price&Rosswog 2006

BNS mergers and their aftermaths

e.g. Rosswog 15, Bauswein's talk

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

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- inspiral phase, driven by GW emission
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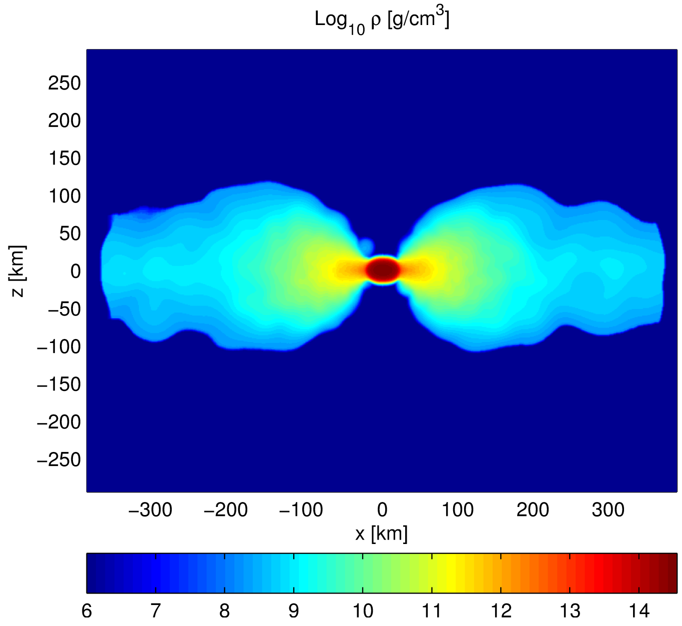
- NS merger aftermath



- 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 $L_{\nu,\mathrm{tot}} \sim 10^{53} \mathrm{erg\,s^{-1}}$

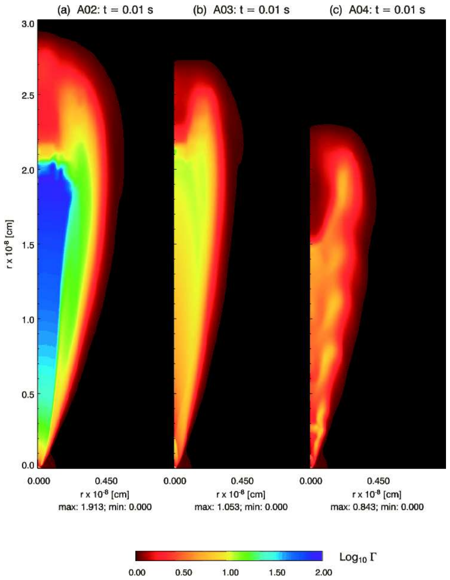
Nuclear & Astro relevance

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

www.ligo.caltech.edu

- possible short gamma-ray burst progenitors e.g. Paczynski86
- electromagnetic counterpart from ejecta radioactive decay Li&Paczynski98
- ejecta properties depends on ν-matter interaction e.g. Wanajo+14



Aloy+05

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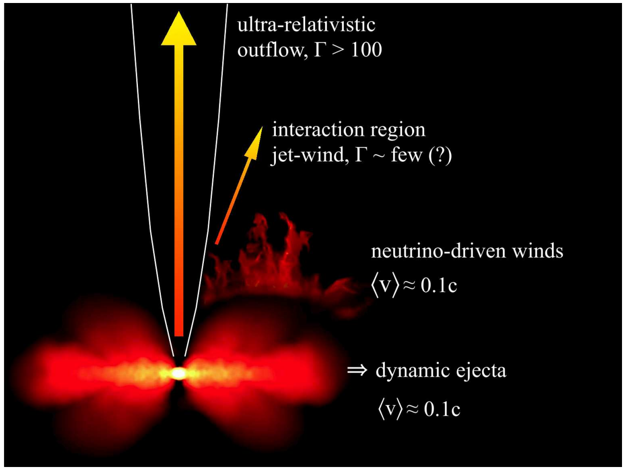
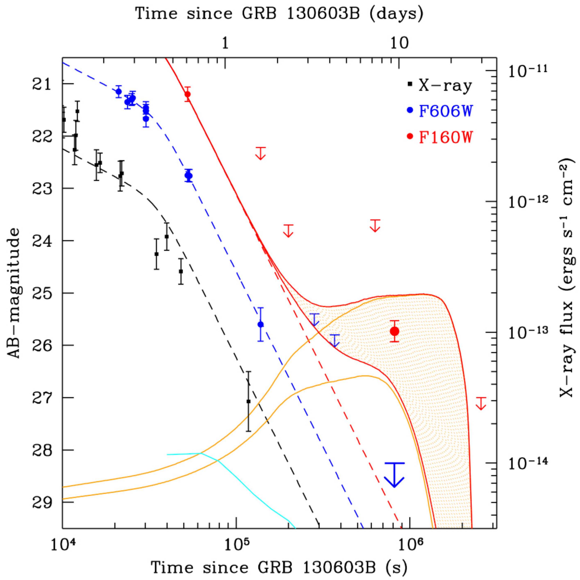


Rosswog 12



Tanvir+13, Berger+13

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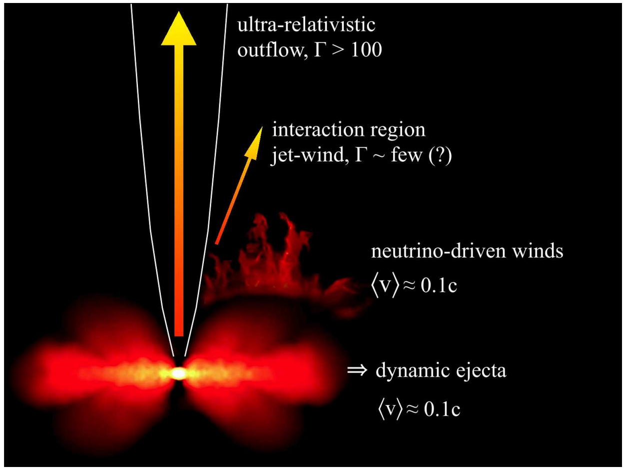

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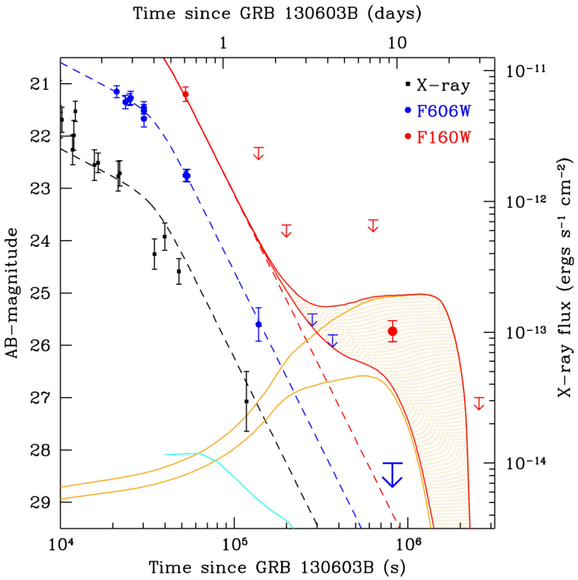
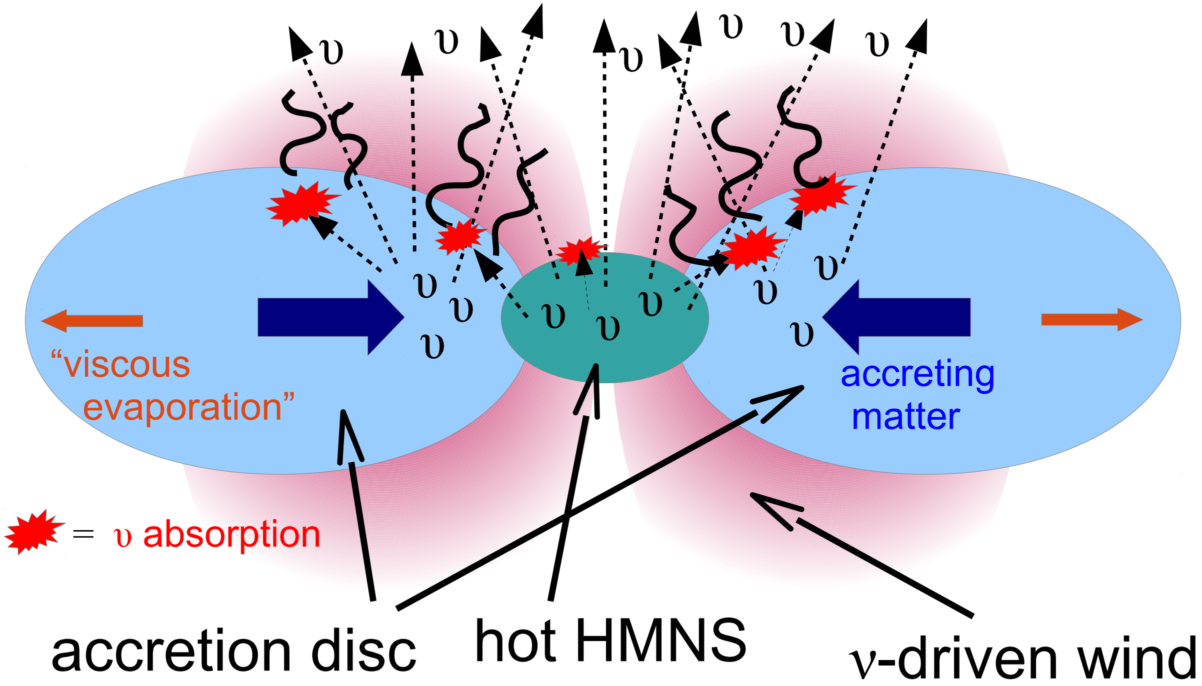


Tanvir+13, Berger+13

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



Goals of this study

- to characterize the neutrino emission
- to study the wind development
- to analyze the ejecta and to perform nucleosynthesis calculations

Martin's talk

- to compute electromagnetic counterparts

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

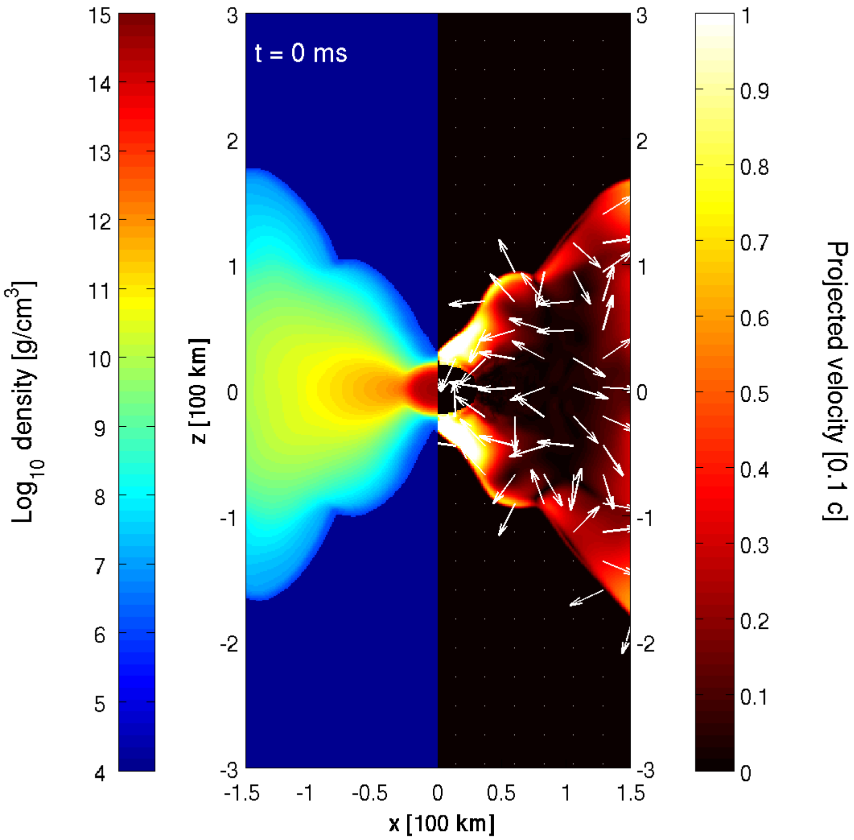
what's new/different:

- first wind study in 3D
- disc and wind evolution over a few 100 ms
- high spatial resolution in the wind

Perego et al, MNRAS 2014; Martin et al, in preparation

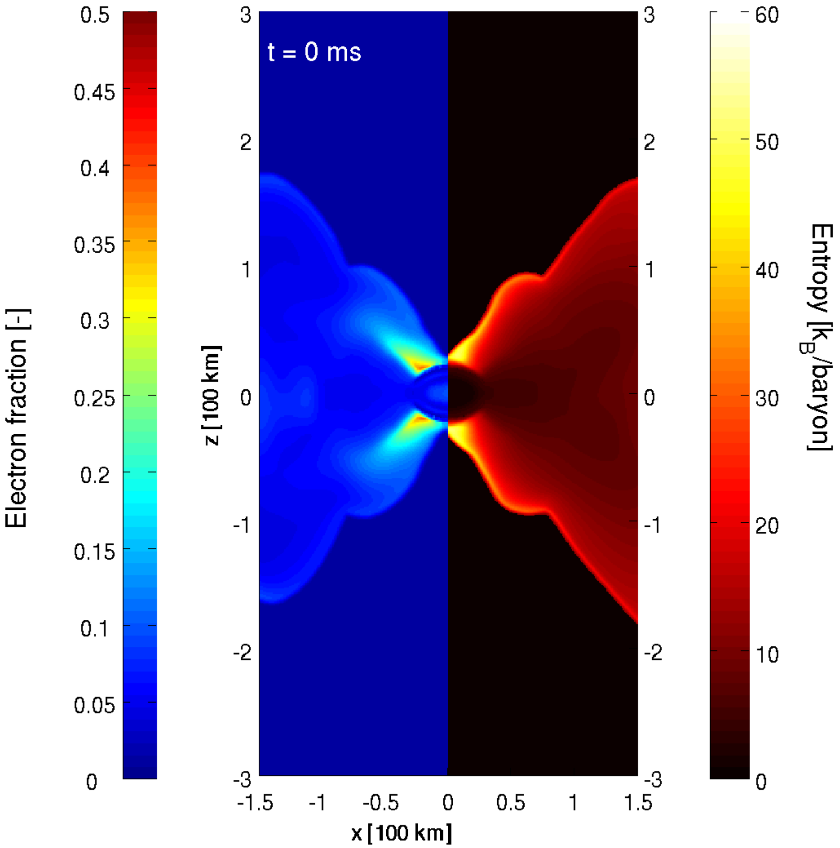
Disc and wind dynamics

t = 0 ms



left: matter density

right: projected velocity

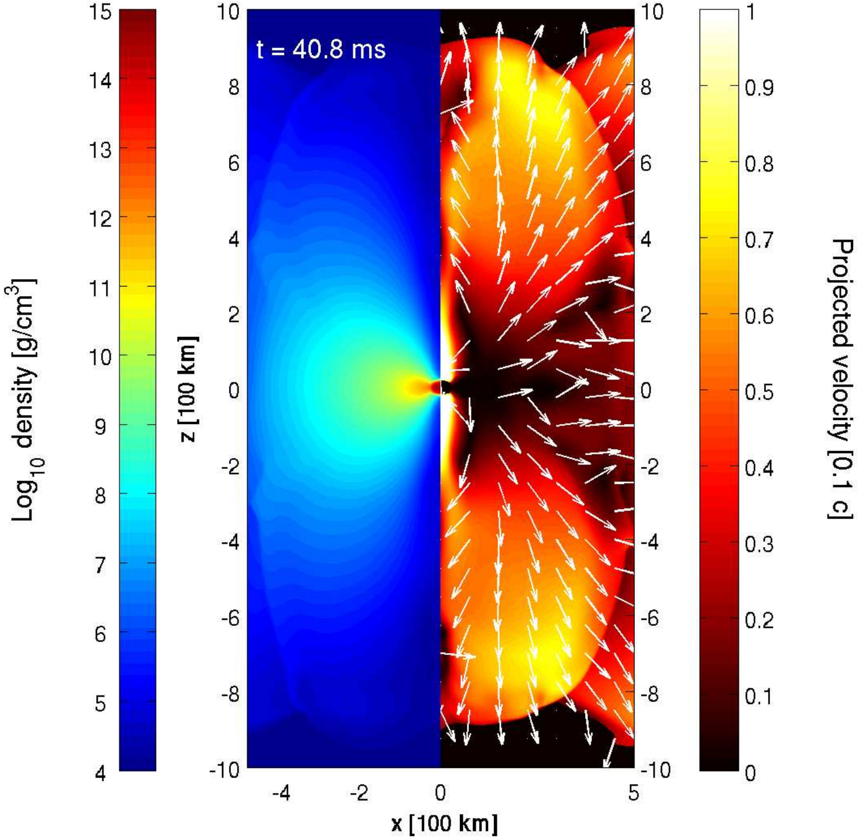


left: electron fraction

right: entropy

Disc and wind dynamics

t = 40 ms



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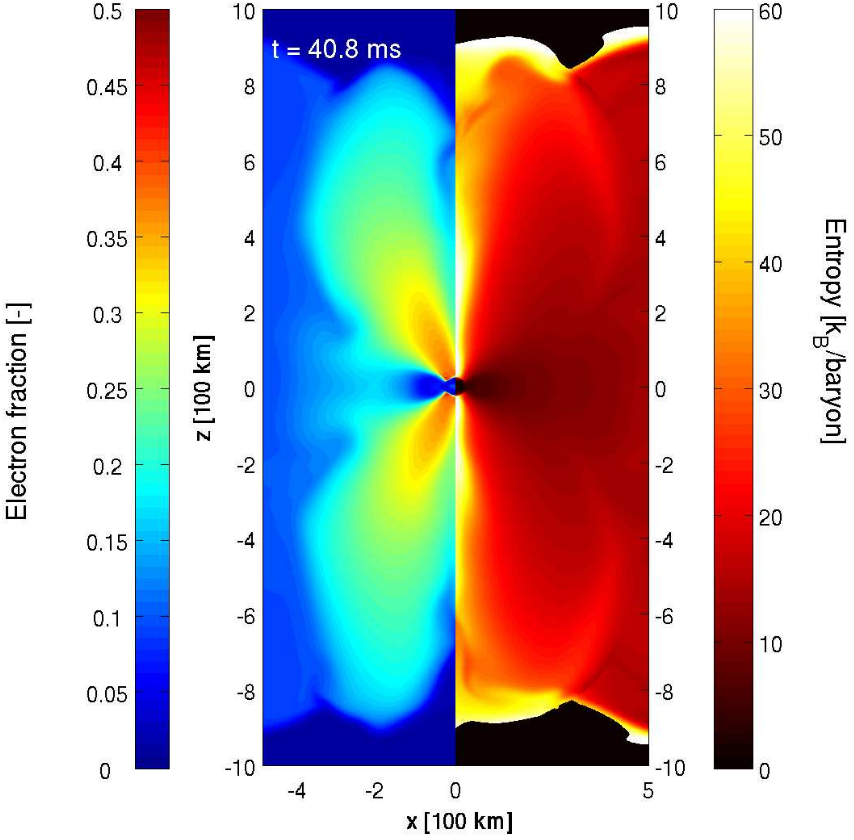

left: electron fraction

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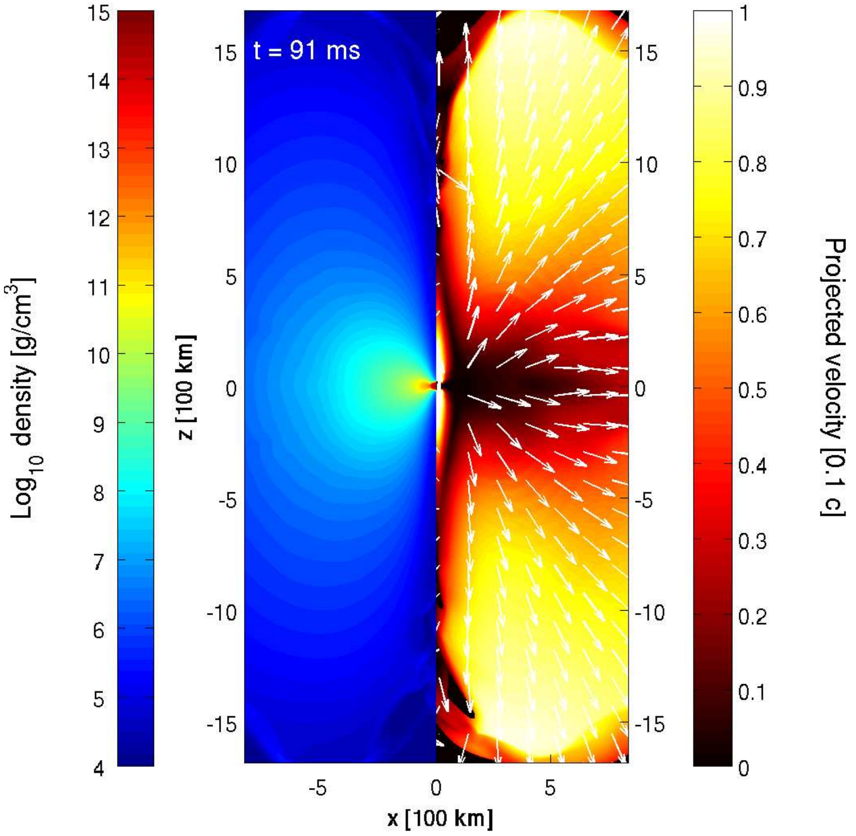
Disc and wind dynamics

t = 90 ms



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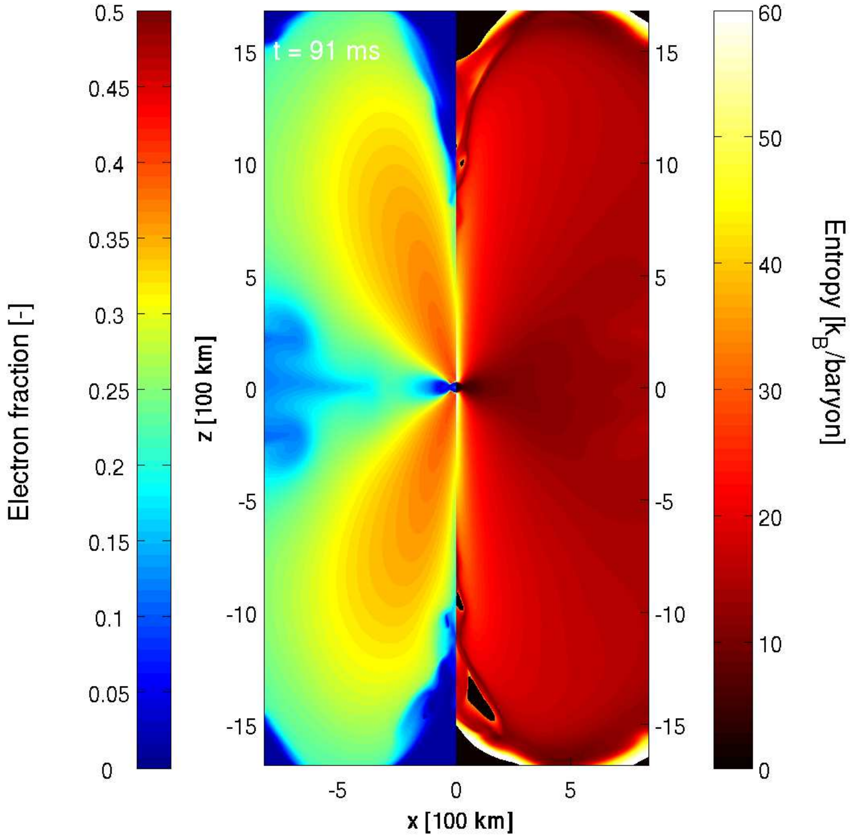
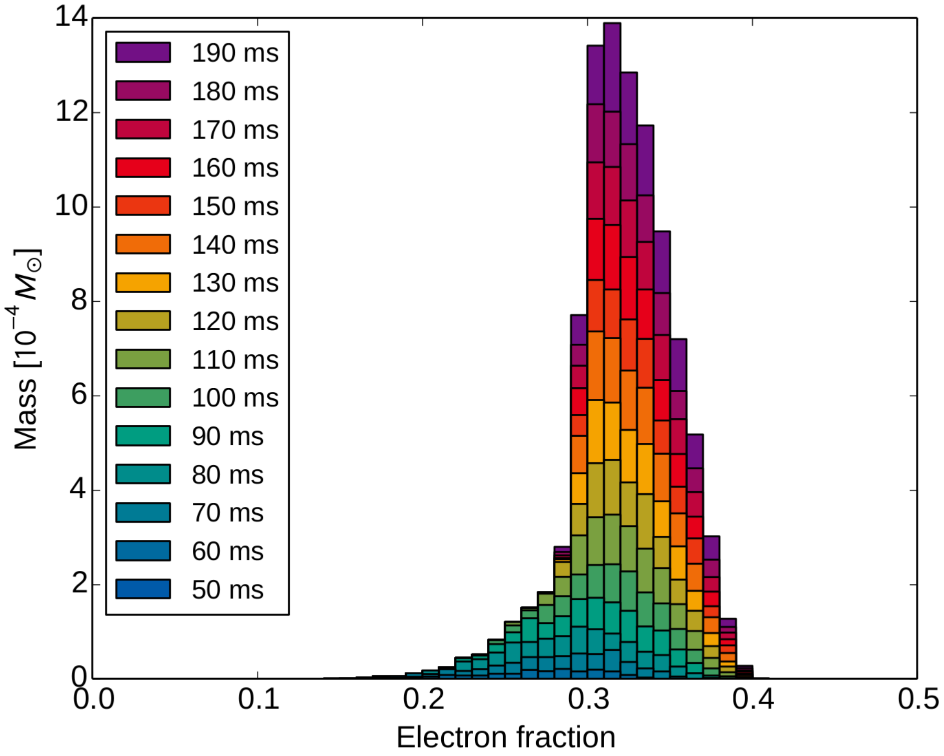


left: electron fraction

right: entropy

Wind ejecta

- non-equatorial emission: $\theta < 60^o$
- $m_{\rm ej}(t \approx 100\,{\rm ms}) \approx 1.7 \times 10^{-3} M_\odot$
  $m_{\rm ej}(t \approx 200\,{\rm ms}) \approx 9.6 \times 10^{-3} M_\odot$
- $0.2 \lesssim Y_e \lesssim 0.4$, increasing with time
- s: 15-20 $k_{\rm B}/{\rm baryon}$
- v_r: 0.06-0.09 c



ejected mass: cumulative histogram

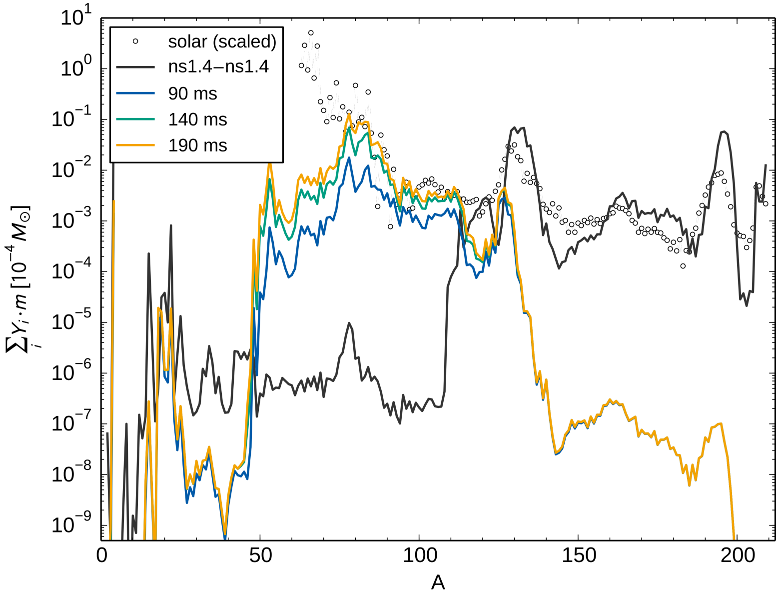
Preliminary, courtesy of D. Martin

Nucleosynthesis from the wind

Postprocessing of ejected tracers:

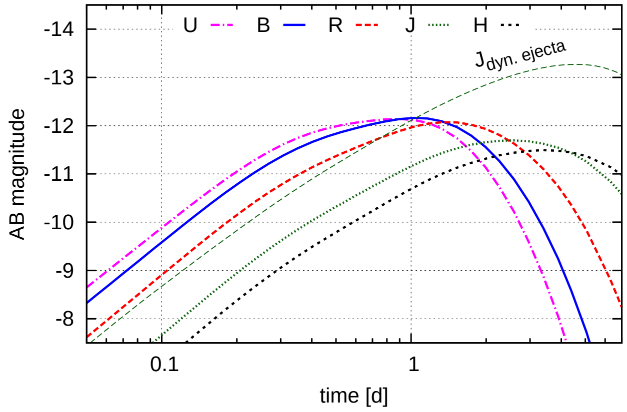
- `Winnet` nuclear network
- weak r-process
- complementary to robust r-process nucleosynthesis from dynamical ejecta
- possible differences between high and low latitude ejecta

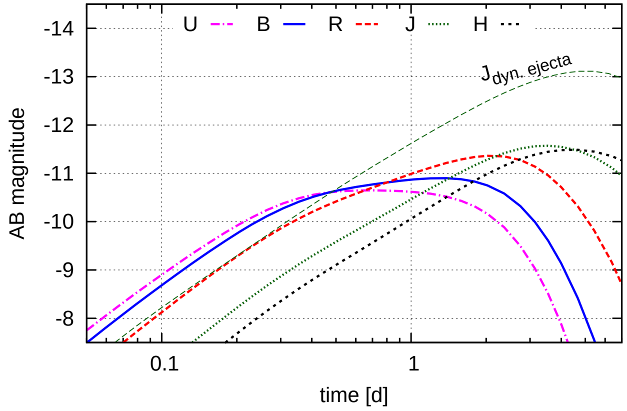
our wind ejecta + dynamical ejecta ($m_{\rm dyn} \approx 10^{-2} M_\odot$) from Korobkin+12



Preliminary, courtesy of D. Martin

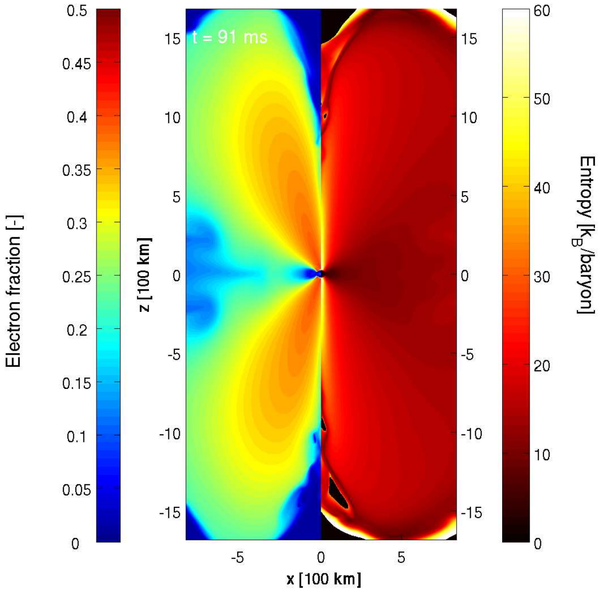
Electromagnetic transient





- photon emission powered by radioactive material in the wind
- different from emission coming from dynamical and viscous ejecta
    - earlier and bluer
    - less contaminated by lanthanides and actinides
- possible dependence from viewing angle

Conclusions

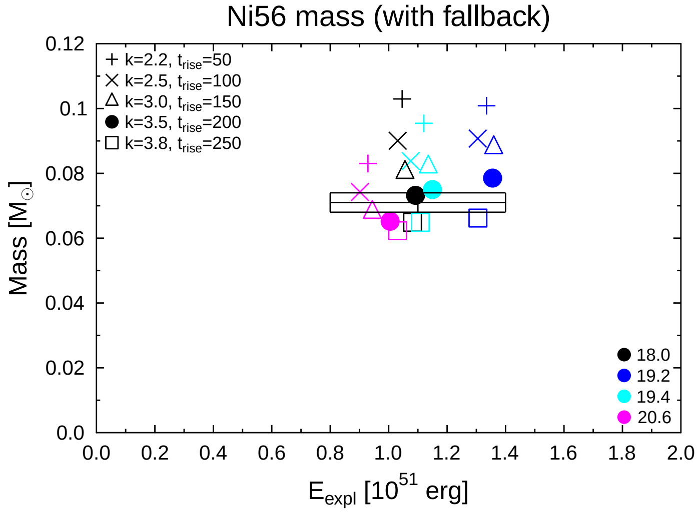


ν-driven CCSNe

- PUSH, effective and efficient 1D, ν-driven explosion models
- calibrated with SN1987A
- inclusion of spectral ν-transport
- suitable to study explosion properties and nucleosynthesis

binary NS merger aftermath

- genuine ν-driven wind from ν heating in the disk
- wind contributes substantially to BNS merger ejecta
- weak r-process nucleosynthesis
- wind electromagnetic transient



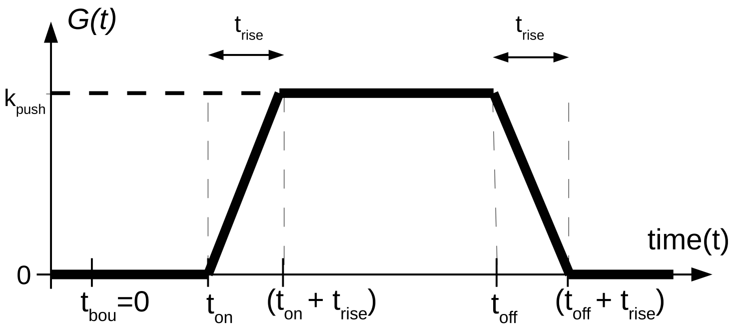
PUSH: the basic idea

Basic PUSH's idea:

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

$$\dot{E}^{+}_{\mathrm{push}}(t,r) \propto \left(\int_0^{+\infty} \sigma_0 \left(\frac{E}{m_e c^2} \right)^2 \left(\frac{1}{4\pi r^2} \frac{\mathrm{d}L_{\nu_{\mu,\tau}}}{\mathrm{d}E} \right) \mathcal{F}(t,r,E)\, \mathrm{d}E \right) \mathcal{G}(t)$$

- typical neutrino cross section
- space location function
  - outside the ν_e neutrinosphere
  - $E_{\nu_e,\bar{\nu}_e} > 0$
  - $\mathrm{d}s/\mathrm{d}r < 0$ (convection)
- spectral $\nu_{\mu,\tau}$ energy flux
- temporal function



$t_{\mathrm{on}} = 80\,\mathrm{ms}$ $\quad t_{\mathrm{off}} = 1\,\mathrm{sec} \gg t_{\mathrm{expl}}$ $\quad k_{\mathrm{push}} \sim 1$ $\quad 50\,\mathrm{ms} \lesssim t_{\mathrm{rise}} \lesssim 250\,\mathrm{ms}$

Implementation & Strategy

- Hydro: AGILE (spherically symmetric, GR Lagrangian) Liebendörfer+02
- $\nu_e, \bar{\nu}_e$ transport: IDSA Liebendörfer+09
  (with mean-field interaction effects) Reddy+98,Roberts+12,Martinez-Pinedo+12,Hempel 14
- $\nu_{\mu,\tau}$ treatment: ASL Perego+2014
- NSE EOS: HS EOS, with DD2 parametrization Hempel & Schaffner-Bielich 10, Fischer+14
- non-NSE EOS: ideal gas (25 nuclei, $e^{\pm}$, γ)

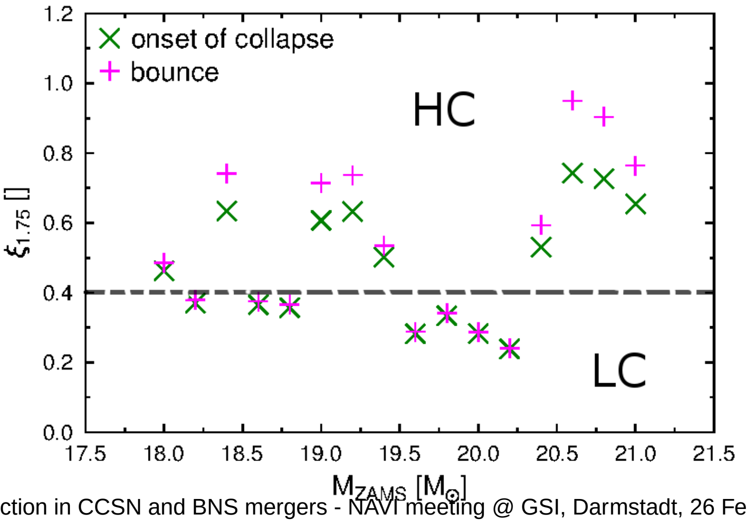
Strategy:

- calibration of PUSH using SN1987A observables
- exploration of 16 progenitors (18-21 $M_\odot$), at solar metallicity WHW 02

$$\xi_{1.75} = \frac{1.75}{R(1.75 M_\odot)/1000\,\mathrm{km}}$$ O'Connor & Ott 11

E_{expl}	$(1.1 \pm 0.3) \times 10^{51}$ erg
M_{prog}	$18 - 21 M_\odot$
$m(^{56}$Ni$)$	$(0.071 \pm 0.003) M_\odot$
$m(^{57}$Ni$)$	$(0.0041 \pm 0.0018) M_\odot$
$m(^{58}$Ni$)$	$0.006 M_\odot$
$m(^{44}$Ti$)$	$(0.55 \pm 0.17) \times 10^{-5} M_\odot$

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



Previous models

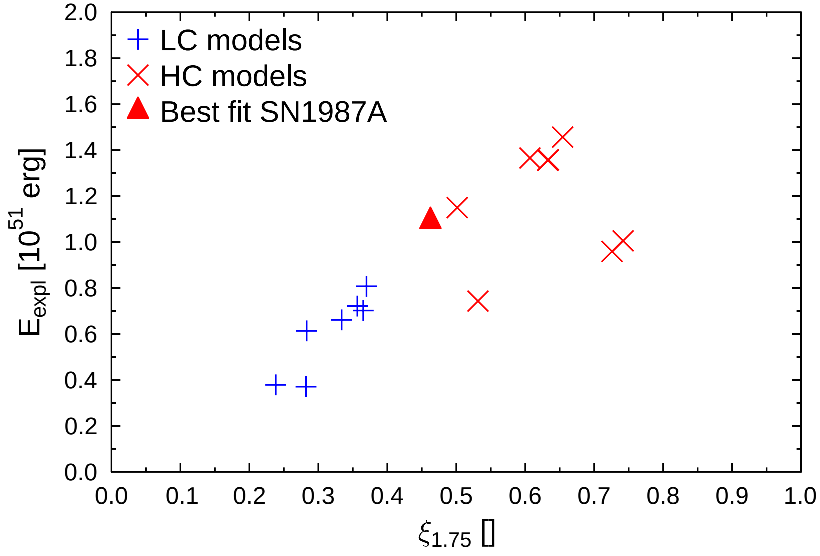
Large variety of triggered explosions in 1D models:

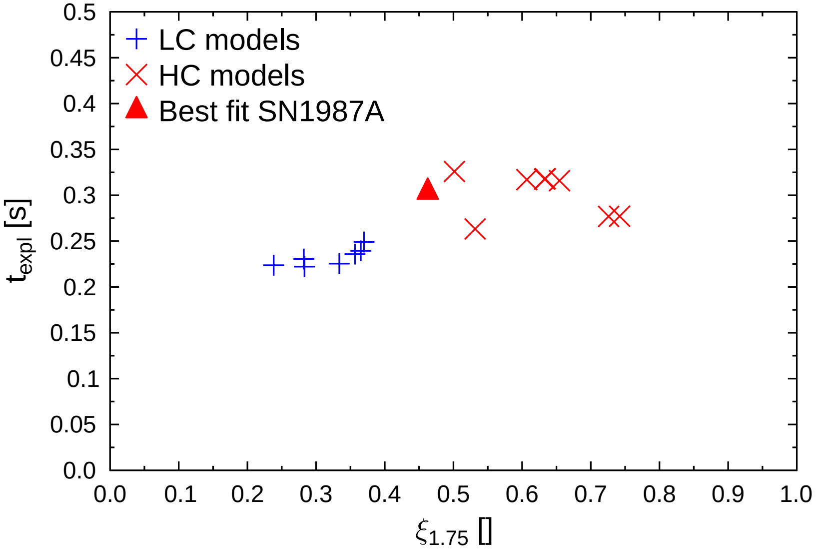
- piston — e.g. Woosley & Weaver 95, Limongi & Chieffi 13
- therma bomb — e.g. Umeda & Nomoto 08
- light-bulb method (LBM) — e.g. Yamamoto+13
- core-contraction method (CCM) — Ugliano+12
- modified ν-transport (MνT) — e.g. Frölich+06, Fischer+10

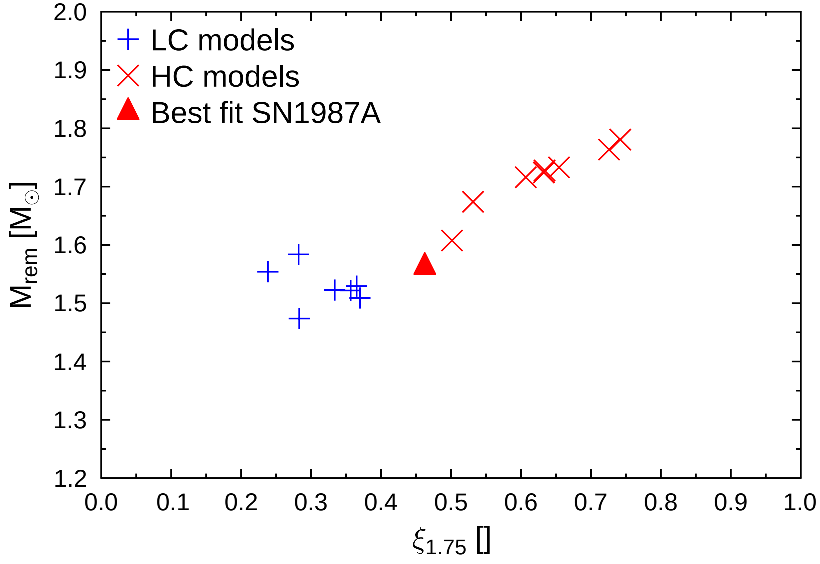
	Piston	Bombs	LBM	MνT	CCM	PUSH
ν-driven explosion	X	X	✓	✓	✓	✓
E and lepton number conservation	X	X	X	✓	✓	✓
PNS self-consistent evolution	X	X	X	✓	X	✓
tunable explosion observables	✓	✓	✓	X	✓	✓
$\nu_e, \bar{\nu}_e$ spectral transport	X	X	X	✓	X	✓
Preserve ν CC reactions	X	X	✓	X	✓	✓
nucleon mean field interaction	X	X	X	X	X	✓

Correlations

Full 18-21 $M_\odot$ sample with calibration set







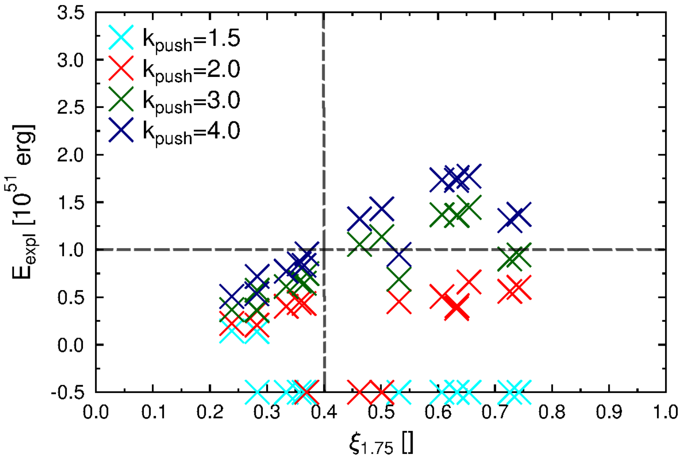
Hints for a possible correlation with $\xi_{1.75}$

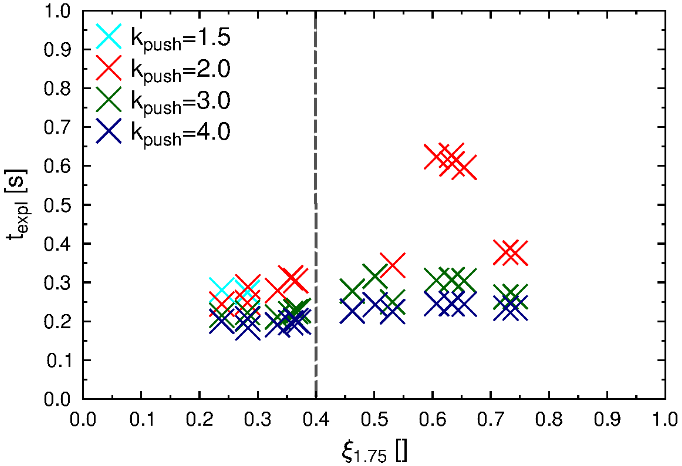
Warning: limited sample!

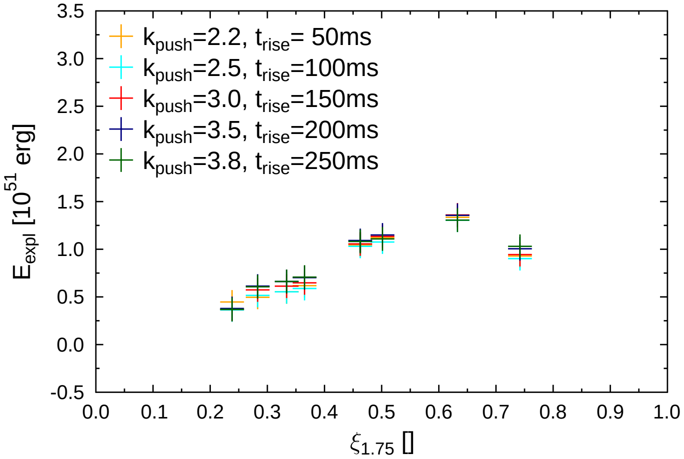
Free parameter analysis

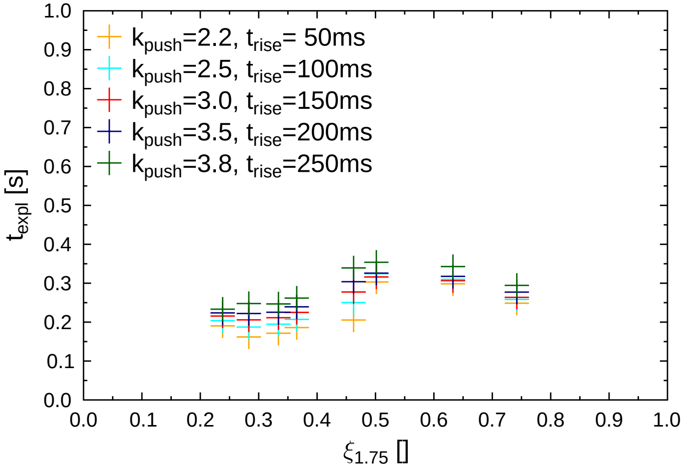
$t_{\mathrm{rise}} = 150\,\mathrm{ms}$

$k_{\mathrm{push}} = 1.5 - 4.0$









$E_{\mathrm{expl}} \approx \mathrm{const.}$

$(k_{\mathrm{push}}, t_{\mathrm{rise}})$

$t_{\mathrm{rise}} = 50 - 250\,\mathrm{ms}$

$k_{\mathrm{push}} = 1.5 - 4.0$

Model ingredients

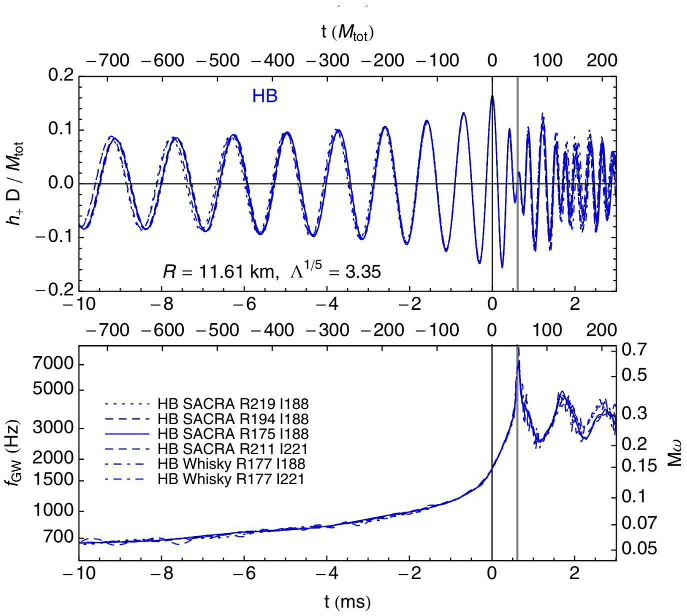
- initial conditions:
  - final stage of 1.4-1.4 $M_\odot$ no-spin NS merger
  - high resolution Newtonian SPH simulation, including ν cooling and nuclear EoS Rosswog&Price 06
- Hydrodynamics:
  `FISH` 3D Newtonian Cartesian code Käppeli+11
- ν treatment:
  ASL scheme Perego+14
- Nuclear equation of state:
  HS EoS, with TM1 parametrization Hempel & Schaffner-Bielich 12

Astrophysical relevance

BNS mergers (together with BH-NS mergers) are . . .

- . . . primary target of ground based GW detectors
  - aLIGO (next year!), VIRGO e.g. Acernese+08, Abbott+09
  - calculation of GW signal from inspiral/merger/post-merger phases e.g. Read+13
  - constraint on nuclear EoS e.g. Bauswein+14

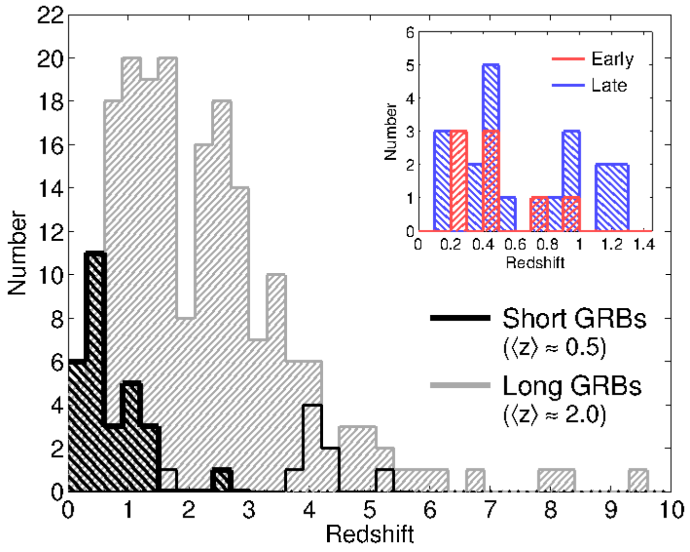
www.ligo.caltech.edu



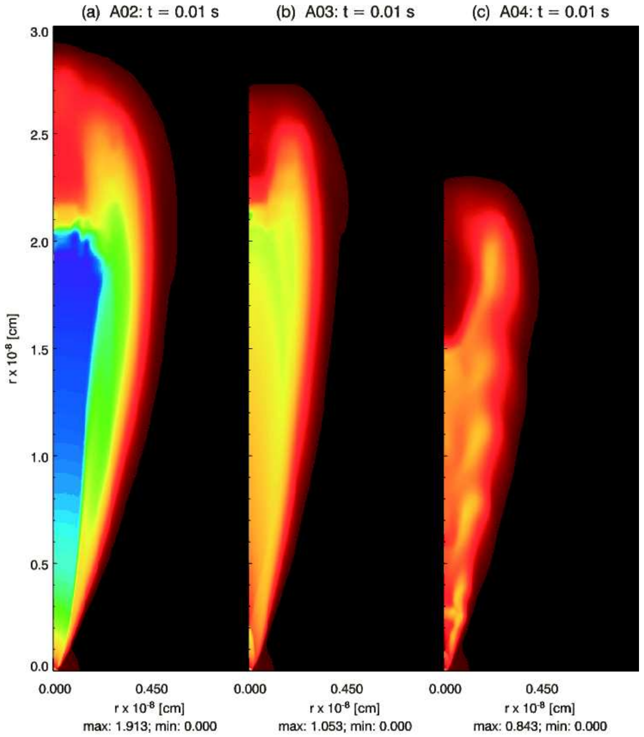
Read+13

Astrophysical relevance

- . . . promising progenitors of short/hard GRBs
  - compatibility with observation constraints e.g. Berger 14
  - mass accretion on BH/NS: large energy reservoir
  - ν's and B field: intense energy deposition rates



Berger2014



Aloy+05

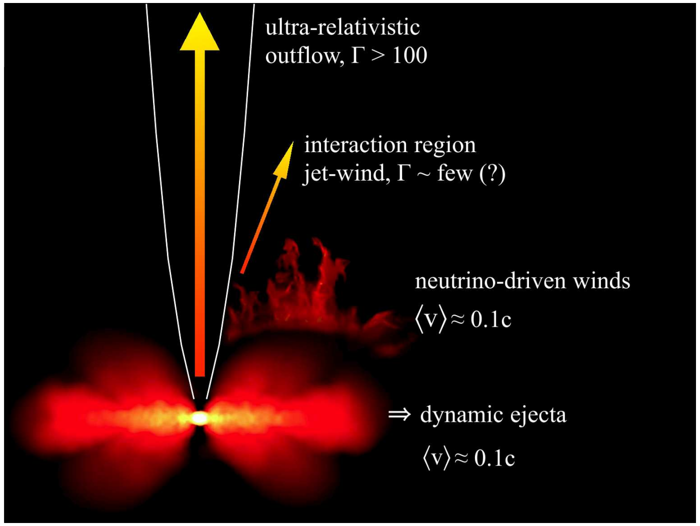
Astrophysical relevance

- . . . site for heavy-elements (r-process) production

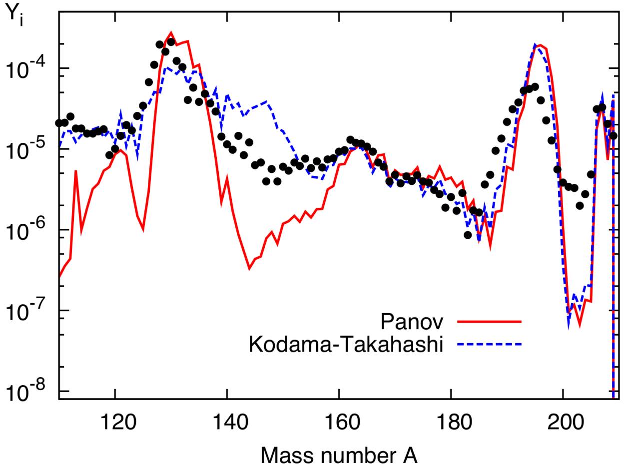
Lattimer&Schramm 74, Eichler+ 89

  - n-rich matter + $L_{\bar{\nu}_\mathrm{e}} > L_{\nu_\mathrm{e}}$ + fast expansions
  - different ejection channels:

dynamical ejecta	e.g., Korobkin+12, Bauswein+13, Hotokezaka+13
viscous ejecta	e.g., Fernandez&Metzger 13, Just+14
ν-driven wind	e.g. Dessart+09, Metzger&Fernandez 14, Perego+14, Just+14



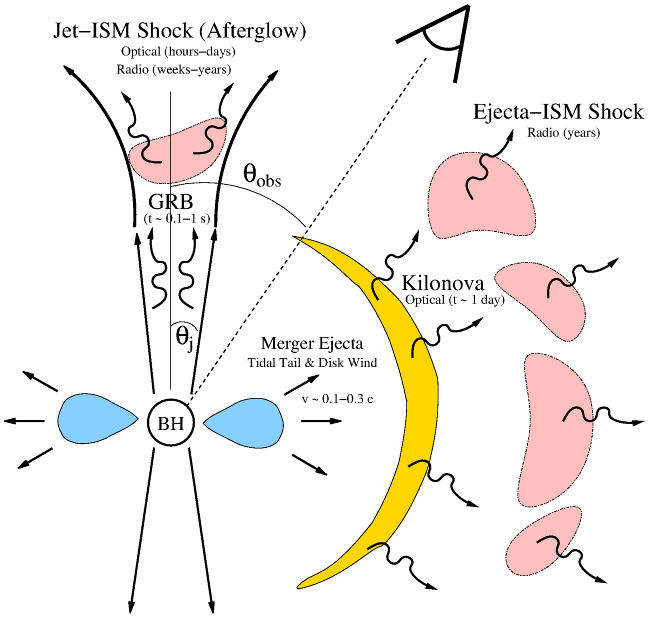
Rosswog2012



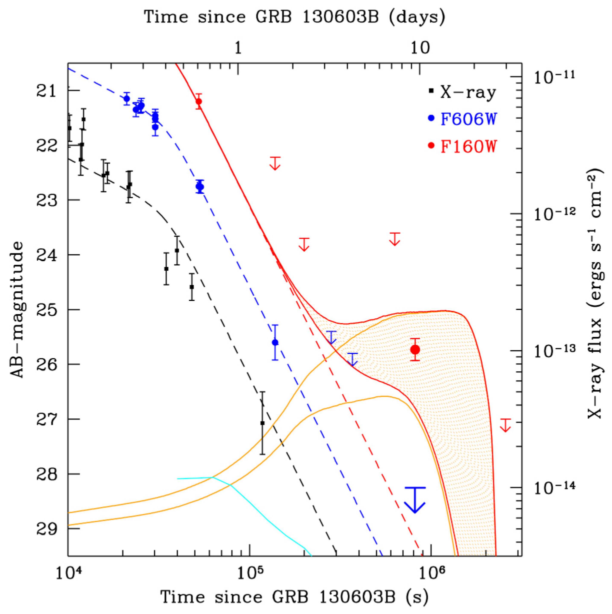
Korobkin+12

Astrophysical relevance

- e.m. counterparts associated with short GRBs
  - radioactively-powered transient — e.g. Li&Paczynski98
  - first kilo/macro-nova observation, associated with GRB130603B



Metzger&Berger 12



Tanvir+13, Berger+13

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
$M_{\rm ns}$: HMNS mass

Relevant time scales

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

- 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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- HMNS 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 HMNS

Relevant time scales

- disk lifetime: $t_{\rm disk} \sim 0.31\,{\rm s}\,\left(\frac{\alpha}{0.05}\right)^{-1}\left(\frac{H/R}{1/3}\right)^{-2}\left(\frac{R_{\rm disk}}{100\,{\rm km}}\right)^{3/2}\left(\frac{M_{\rm ns}}{2.5\,M_\odot}\right)^{-1/2}$
- disk L: $L_{\nu,{\rm disk}} \sim 8.35 \times 10^{52}\,{\rm erg\,s^{-1}}\left(\frac{M_{\rm ns}}{2.5\,M_\odot}\right)^{3/2}\left(\frac{M_{\rm disk}}{0.2\,M_\odot}\right)\dots$
- HMNS L: $L_{\nu,{\rm ns}} \sim 1.86 \times 10^{52}\,{\rm erg\,s^{-1}}\left(\frac{\Delta E_{\rm ns}}{3.5\times10^{52}\,{\rm erg}}\right)\left(\frac{R_{\rm ns}}{25\,{\rm km}}\right)^{-2}\dots$
- wind time:

$$t_{\rm wind} \sim \frac{e_{\rm grav}}{\dot{e}_{\rm heat}} \approx 0.072\,{\rm s}\left(\frac{M_{\rm ns}}{2.5\,M_\odot}\right)\left(\frac{R_{\rm disk}}{100\,{\rm km}}\right)\left(\frac{E_\nu}{15\,{\rm MeV}}\right)^{-2}\left(\frac{\xi L_{\nu_e}}{4.5\times10^{52}\,{\rm erg\,s^{-1}}}\right)^{-1}$$

$e_{\rm grav}$: 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 $L_{\nu_e} \sim (L_{\rm ns} + L_{\rm disk})/3$

Relevant time scales

- disk lifetime: $t_{\rm disk} \sim 0.31\,{\rm s}\,\left(\frac{\alpha}{0.05}\right)^{-1}\left(\frac{H/R}{1/3}\right)^{-2}\left(\frac{R_{\rm disk}}{100\,{\rm km}}\right)^{3/2}\left(\frac{M_{\rm ns}}{2.5\,M_\odot}\right)^{-1/2}$
- disk L: $L_{\nu,{\rm disk}} \sim 8.35 \times 10^{52}\,{\rm erg\,s^{-1}}\left(\frac{M_{\rm ns}}{2.5\,M_\odot}\right)^{3/2}\left(\frac{M_{\rm disk}}{0.2\,M_\odot}\right)\dots$
- HMNS 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: $t_{\rm wind} \sim 0.072\,{\rm s}\,\left(\frac{M_{\rm ns}}{2.5 M_\odot}\right)\left(\frac{R_{\rm disk}}{100\,{\rm km}}\right)\left(\frac{E_\nu}{15\,{\rm MeV}}\right)^{-2}\left(\frac{\xi L_{\nu_e}}{4.5\times 10^{52}\,{\rm erg\,s^{-1}}}\right)^{-1}$

$$t_{\rm wind} < t_{\rm disk}$$

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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- HMNS L: $L_{\nu,{\rm ns}} \sim 1.86 \times 10^{52}\,{\rm erg\,s^{-1}} \left(\frac{\Delta E_{\rm ns}}{3.5\times10^{52}\,{\rm erg}}\right) \left(\frac{R_{\rm ns}}{25\,{\rm km}}\right)^{-2} \ldots$
- wind: $t_{\rm wind} \sim 0.072\,{\rm s} \left(\frac{M_{\rm ns}}{2.5 M_\odot}\right) \left(\frac{R_{\rm disk}}{100\,{\rm km}}\right) \left(\frac{E_\nu}{15\,{\rm MeV}}\right)^{-2} \left(\frac{\xi L_{\nu_e}}{4.5\times10^{52}\,{\rm erg\,s^{-1}}}\right)^{-1}$

$$t_{\rm wind} < t_{\rm disk}$$

- HMNS → BH: EoS, $M_{\rm ns}$, $B_{\rm ns}$, ang. mom. transport, etc.

$$t_{\rm bh} \sim 0.01 - 10\,{\rm s}$$

our assumption: $t_{\rm bh} \gtrsim 0.1 - 0.2\,{\rm s}$

ASL: overview

- based on previous grey leakage schemes

  (Ruffert et al. 1997, Rosswog & Liebendörfer 2003)

- spectral scheme (12 bins, $2 - 200\,\mathrm{MeV}$)
- 3 flavors: ν_e,$\bar{\nu}_e$, $\nu_{\mu,\tau}$ ($\nu_{\mu,\tau} \equiv \nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$)
- ν reactions: ($\nu \equiv \nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$)

$e^- + p \to n + \nu_e$	O,T,P	$(A,Z) + \nu \to (A,Z) + \nu$	O
$e^+ + n \to p + \bar{\nu}_e$	O,T,P	$e^+ + e^- \to \nu + \bar{\nu}$	T,P
$e^- + (A,Z) \to \nu_e + (A, Z-1)$	T,P	$N + N \to N + N + \nu + \bar{\nu}$	T,P
$N + \nu \to N + \nu$	O		

major roles: O → opacity, T → thermalization, P → production

Bruenn 1985, Mezzacappa & Bruenn 1993, Hannestad & Raffelt 1998

- treatment developed and tested in Core Collapse Supernova context

ν optical depth

- optical depth: average number of interactions for a ν, before leaving the system

$$\tau_\nu = \int_\gamma \frac{1}{\lambda}\,\mathrm{d}s \qquad \lambda = \frac{1}{n_{\rm target}\ \sigma_{\nu-{\rm target}}} \propto E_\nu^2$$

- scattering optical depth, $\tau_{\nu,\rm s}$:
  - $\lambda_{\rm s}^{-1} = \lambda_{\rm scat}^{-1} + \lambda_{\rm abs}^{-1}$ (all possible reactions)
  - $\tau_{\nu,\rm s} \gg 1$: diffusive regime
- energy optical depths, $\tau_{\nu,\rm e}$:
  - $\lambda_{\rm e}^{-1} = \sqrt{\left(\lambda_{\rm scat}^{-1} + \lambda_{\rm abs}^{-1}\right)\lambda_{\rm abs}^{-1}}$ (geometrical mean)
  - $\tau_{\nu,\rm e} \leq \tau_{\nu,s}$
  - $\tau_{\nu,\rm e} \gg 1$: diffusive regime & thermal equilibrium

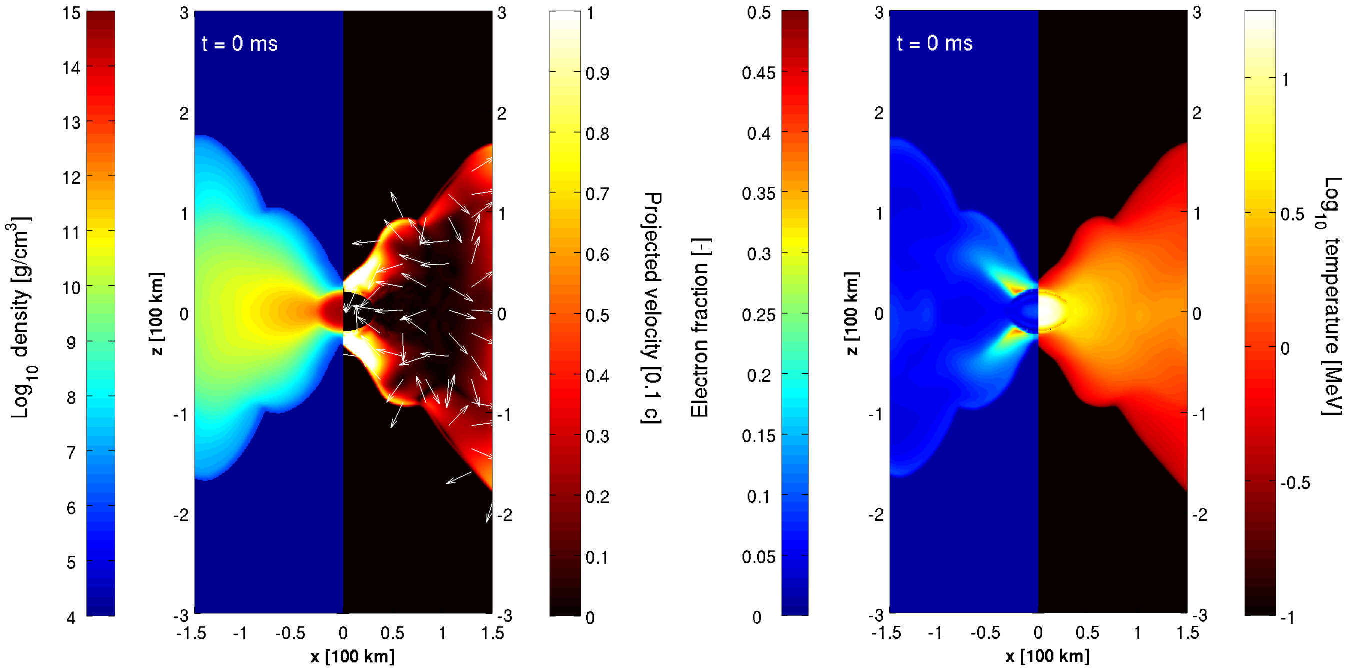
ASL: basics

- effective scheme: ASL mimics known solutions of radiative transfert
- cooling part:
  - smooth interpolation between diffusion and production (spectral) rates
  - reproduction of the correct limits: diffusive ($\tau_\nu \gg 1$) and free streaming ($\tau_\nu \lesssim 1$)

    (τ_ν neutrino optical depth)
- heating part (for $\tau_\nu \lesssim 1$):
  - n_ν (neutrino density) calculated by ray-tracing algorithm; input: emission rates at ν-surfaces
  - $r_{\mathrm{heat}} \propto \chi_{\mathrm{ab}} \cdot n_\nu$ $\quad$ (χ_{ab} absorptivity)

Initial conditions

- 3D SPH data mapped on 3D `FISH` grid
- 1 km resolution: HMNS treated as stationary object
- data relaxation: $\Delta t \approx 10\mathrm{ms}$, hydro + ν emission

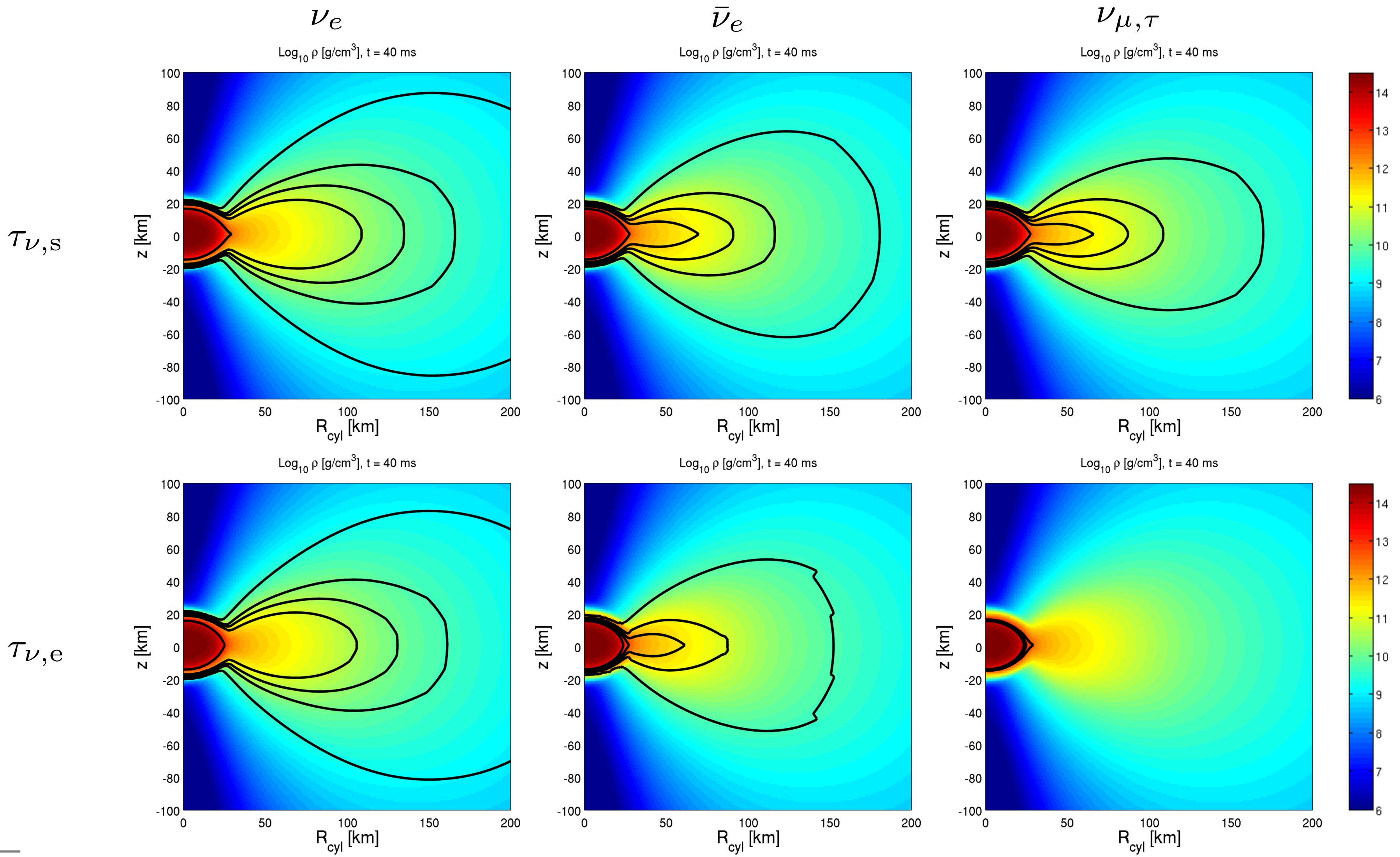


density, velocity, Y_e, temperature

2D slice of 3D domain, at $t = 0$

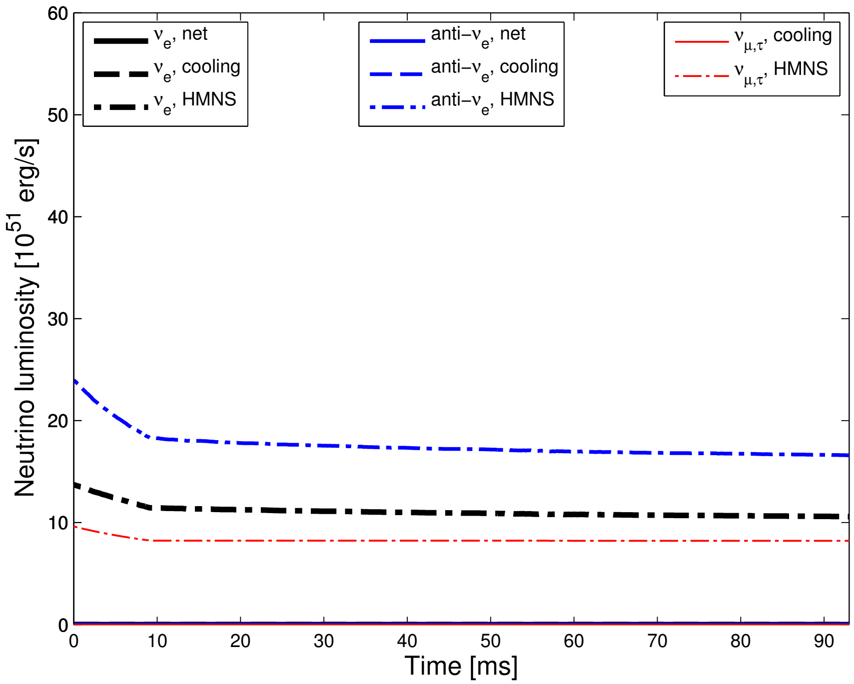
Neutrino Surfaces

$\tau_\nu = 2/3 \quad \Rightarrow \quad \nu$ surfaces, for $E_\nu = 4.6, 10.6, 16.2, 24.6, 57.0\,\mathrm{MeV}$, at 40 ms



Neutrino luminosities

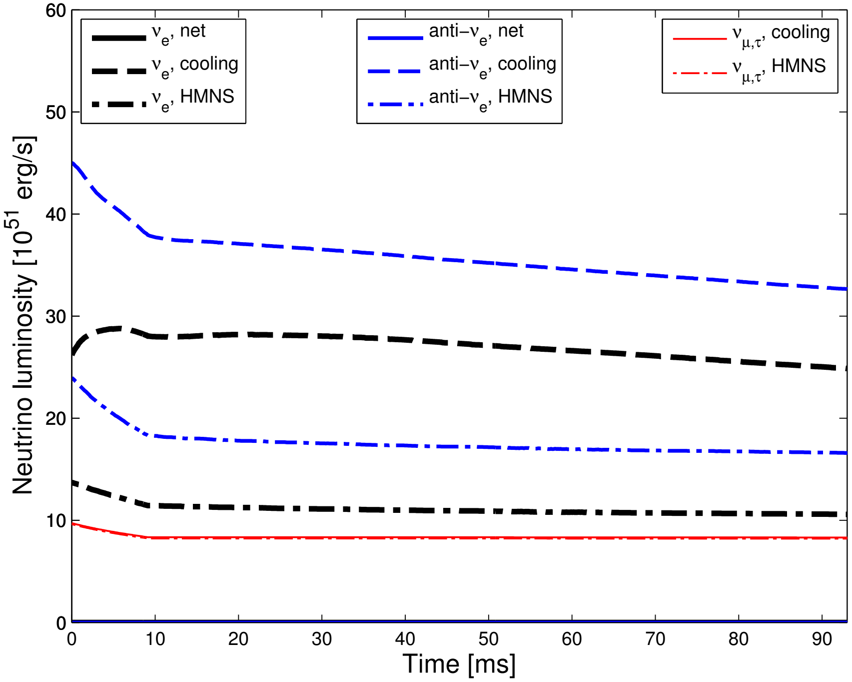
dependence on time



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

Neutrino luminosities

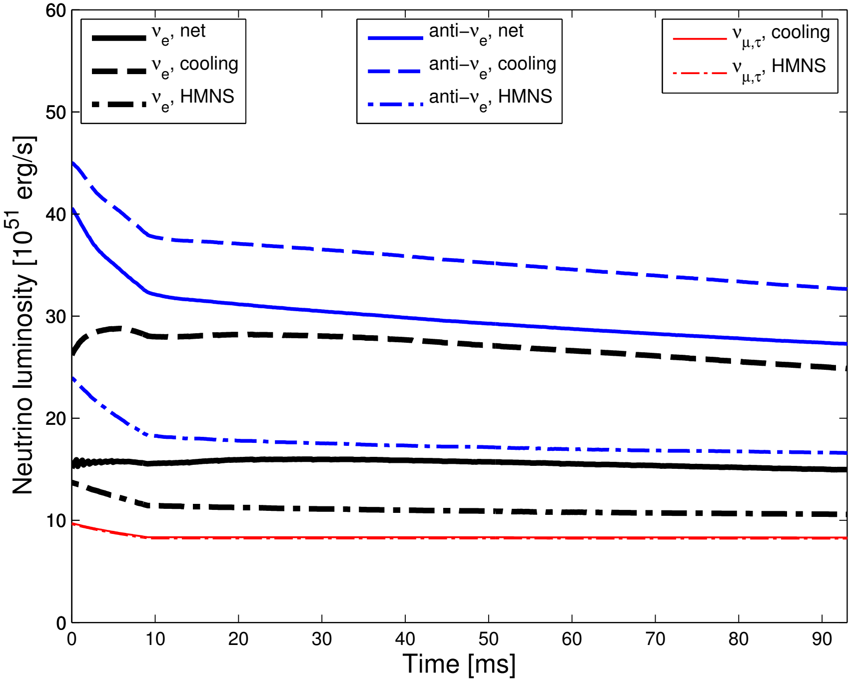
dependence on time



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

Neutrino luminosities

dependence on time



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

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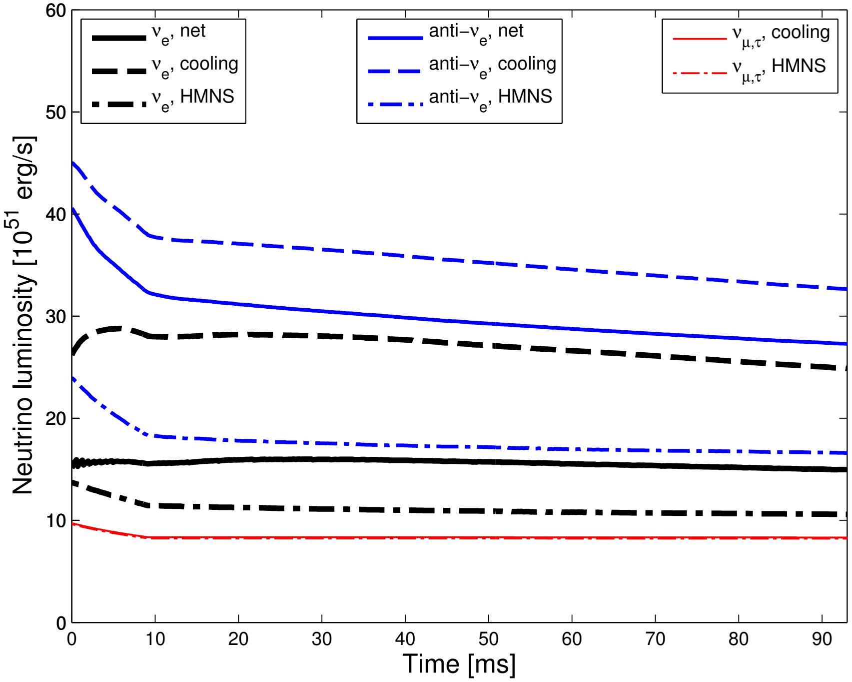
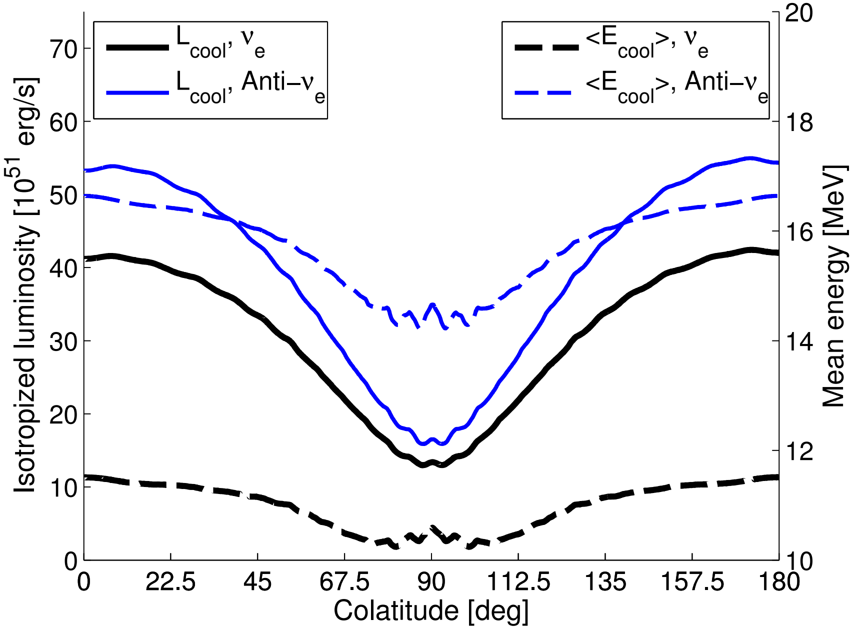


dependence on θ $(t = 40\mathrm{ms})$



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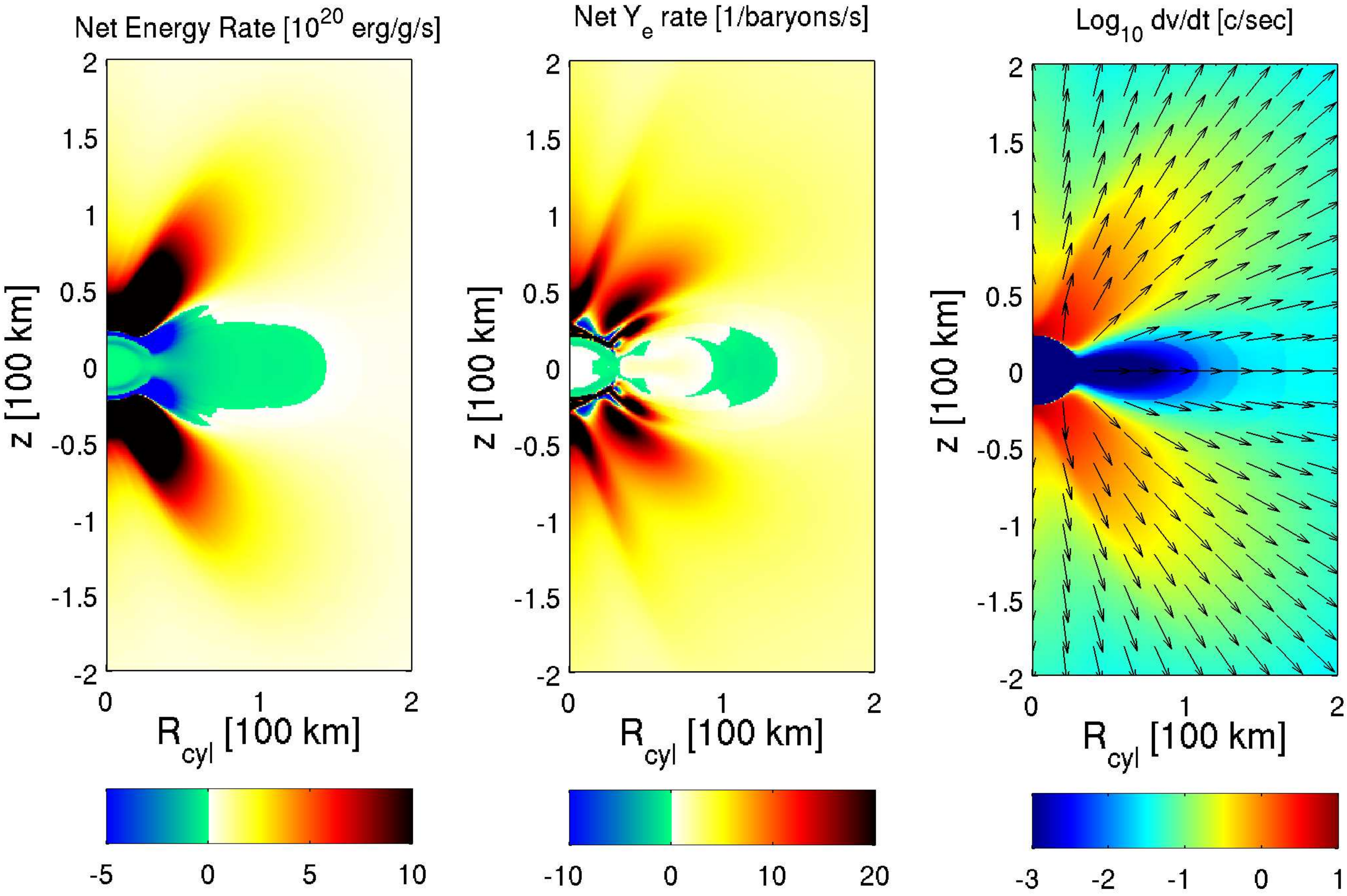
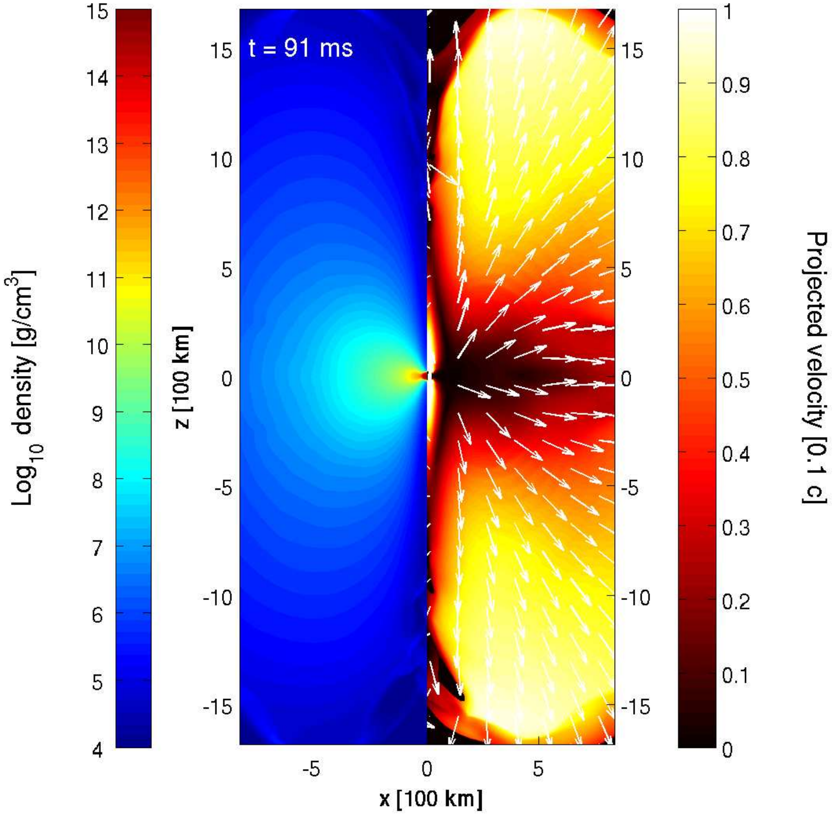
- luminosity hierarchy:
  $L_{\bar{\nu}_e} > L_{\nu_e} > L_{\nu_{\mu,\tau}}$
- disk luminosity powered by accretion:
  $\dot{M} \sim 0.6 - 0.4\,M_\odot\,\mathrm{s}^{-1}$ & $\alpha_{\mathrm{num}} \approx 0.05$
- mean energy hierarchy:
  $E_{\nu_{\mu,\tau}} > E_{\bar{\nu}_e} > E_{\nu_e}$
- $E_{\nu_e} \approx 11\,\mathrm{MeV}, E_{\bar{\nu}_e} \approx 15\,\mathrm{MeV},$
  $E_{\nu_{\mu,\tau}} \approx 18\,\mathrm{MeV}$
- disk-shadow effect

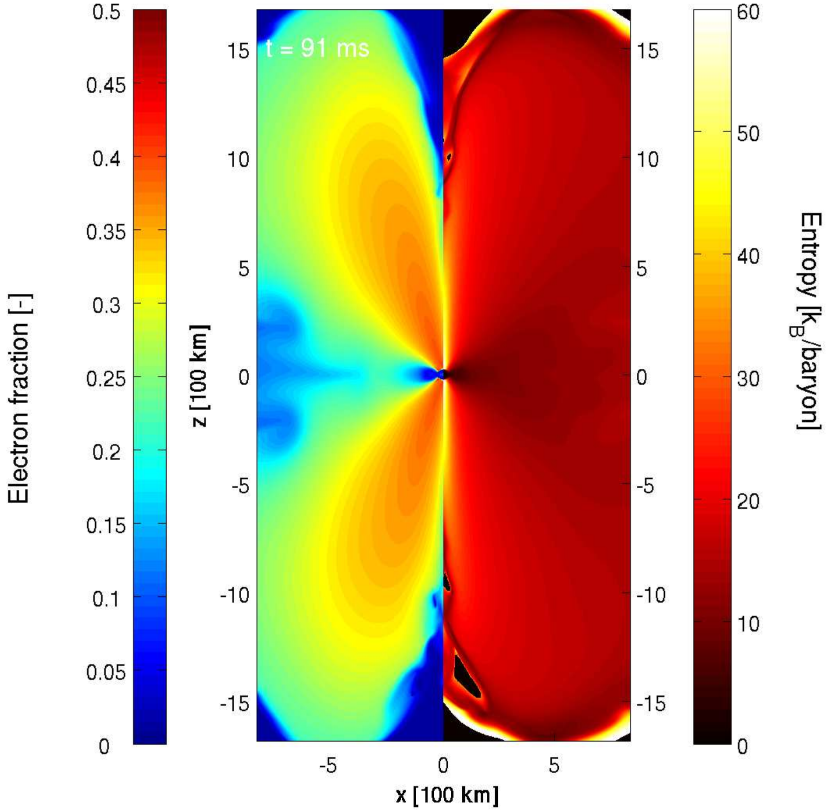
Neutrino net rates



Disc and wind dynamics



Picture I
left: matter density
right: projected velocity

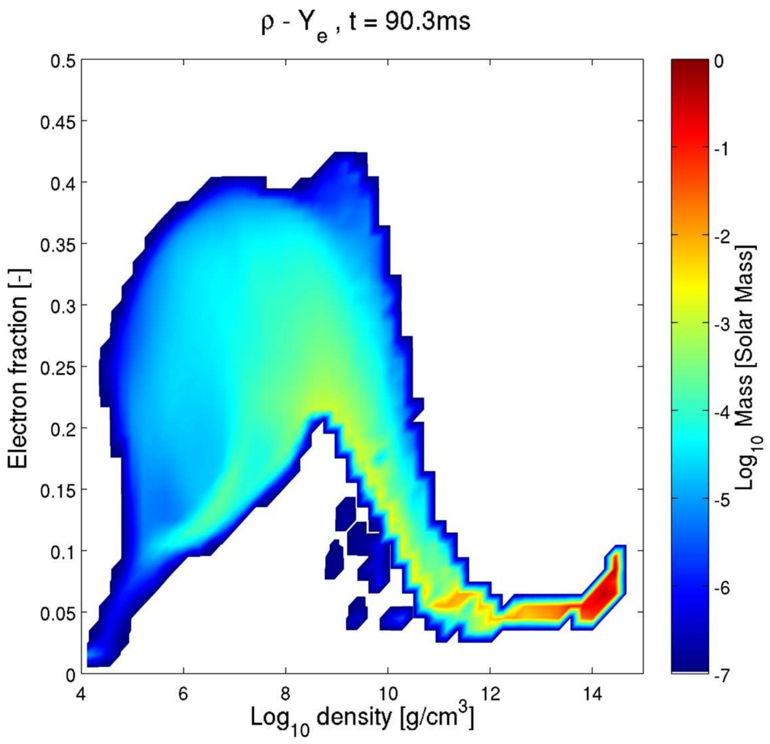


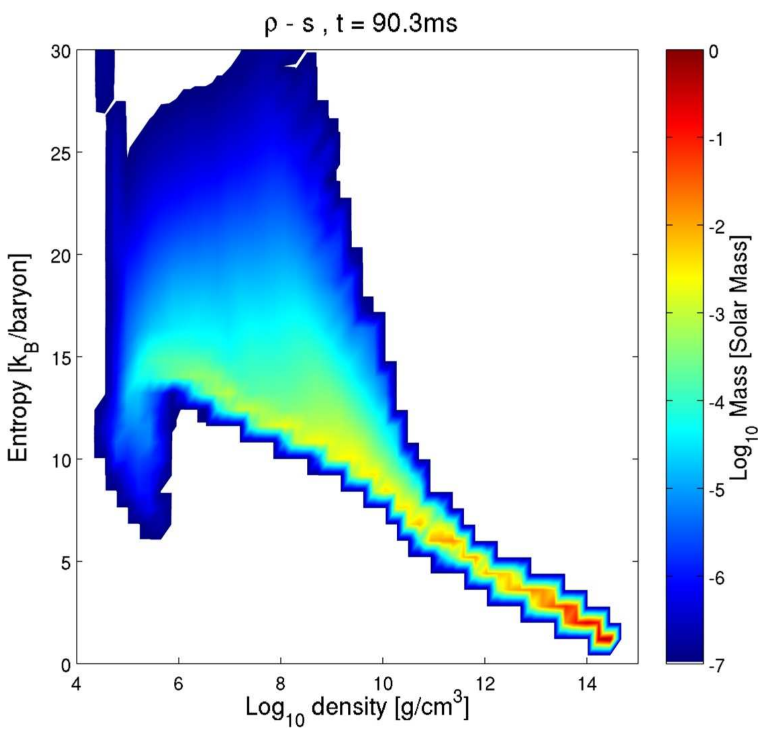
Picture II
left: electron fraction
right: entropy

Click here for the video

Wind properties

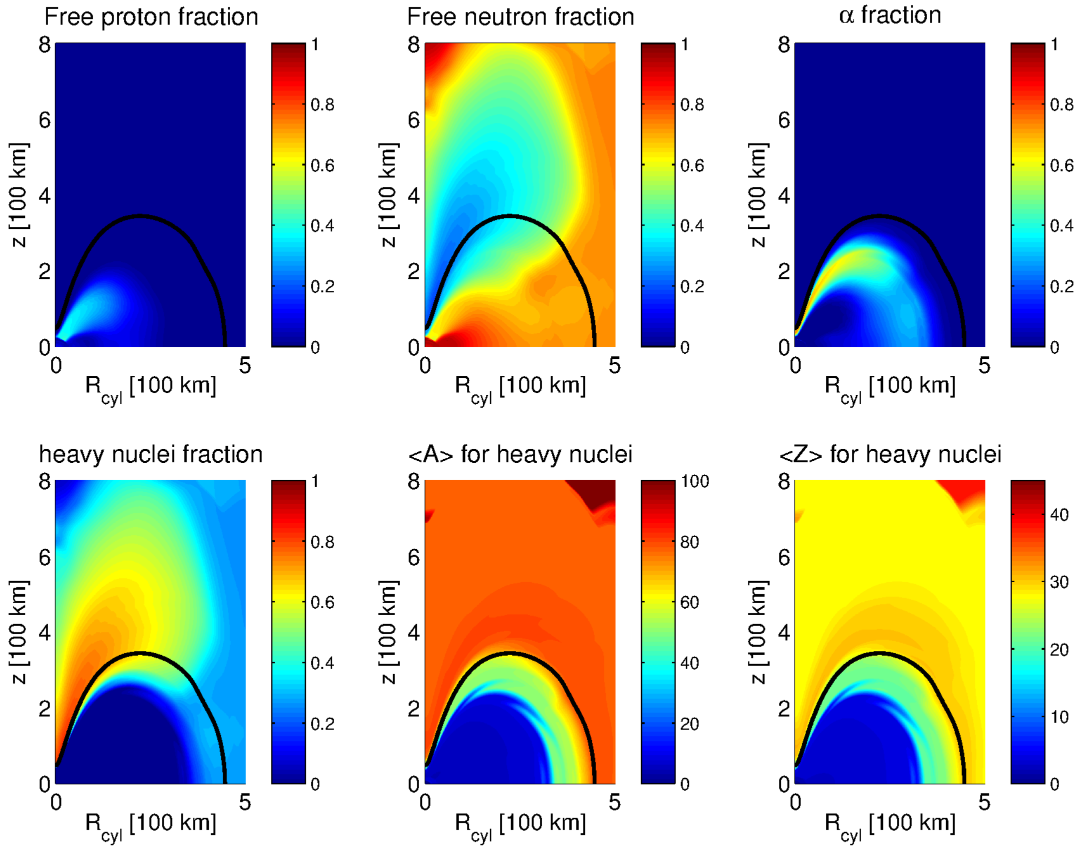
- 2D mass-histograms of (ρ, Y_e) and (ρ, s)
- large variation for Y_e: $0.1 \lesssim Y_e \lesssim 0.40$
- small variation in entropy: $10 \lesssim s\ [\mathrm{k_B/bar}] \lesssim 22$





Click here for the video

Disc & wind composition



- mass fractions in the disk & wind

  (as predicted by NSE EOS)
- black line:
  NSE freeze-out
  (T=5GK)

- Relevant changes in nuclear composition:
  - n,p $\rightarrow$ n,α (still within NSE)
  - n,α $\rightarrow$ n,(A,Z) (at NSE-freezout)

Wind ejecta

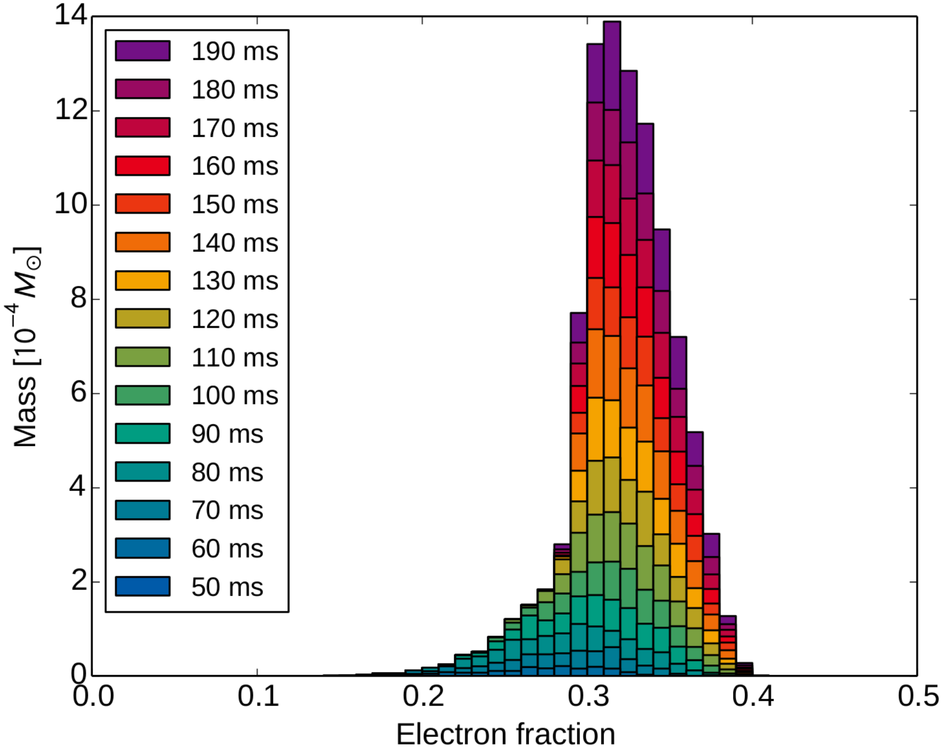
- criteria: I) $e_{\rm tot} = e_{\rm kin} + e_{\rm th} + e_{\rm pot} > 0$ & II) $v_r > 0$ & III) $\theta < 60^o$
- nuclear recombination energy included

high latitudes ($0^o < \theta < 45^o$)

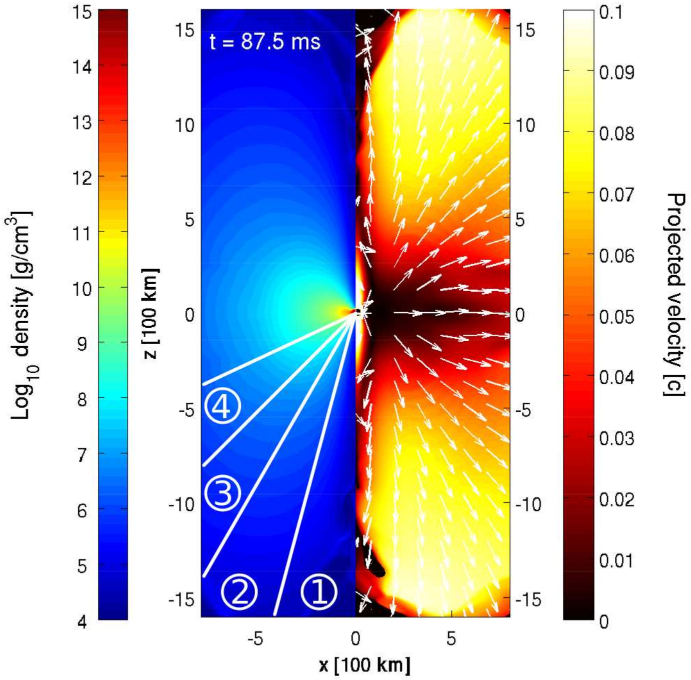
- $m_{\rm ej}(t = 91\,{\rm ms}) \approx 1.3 \times 10^{-3} M_\odot$
  $m_{\rm ej}(t = 190\,{\rm ms}) \approx 5.0 \times 10^{-3} M_\odot$
- $0.3 \lesssim Y_e \lesssim 0.4$
  s: 15-20 $k_{\rm B}/{\rm baryon}$, v_r: 0.08-0.09 c
- more genuine ν-driven wind

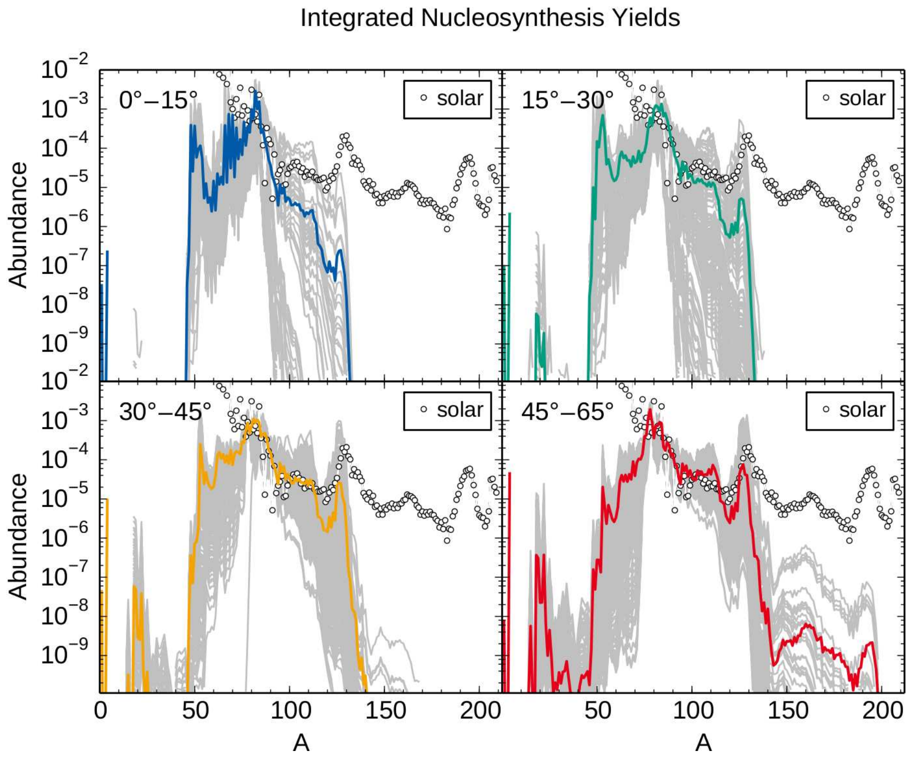
low latitudes ($45^o < \theta < 60^o$)

- $m_{\rm ej}(t = 91\,{\rm ms}) \approx 0.42 \times 10^{-3} M_\odot$
  $m_{\rm ej}(t = 190\,{\rm ms}) \approx 4.6 \times 10^{-3} M_\odot$
- $0.2 \lesssim Y_e \lesssim 0.3$
  s: 14-15 $k_{\rm B}/{\rm baryon}$, v_r: 0.06-0.07 c
- ν-driven wind + viscous ejecta



Nucleosyntheis from wind





Selected angular sections

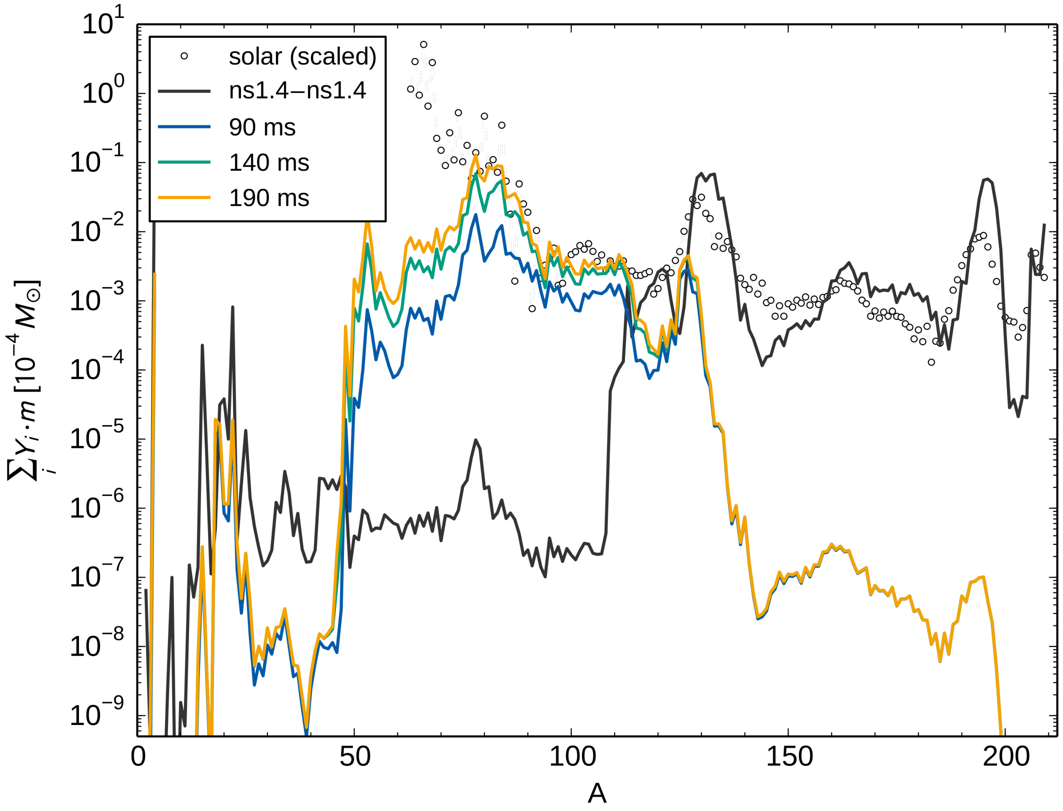
Integrated nucleosynthesis @ 190ms

Martin+, in preparation

- tracers post-processed with *WinNet* e.g. Winteler+2012
- no robust r-process, but weak r-process
- possible differences between high and low latitude ejecta

Dynamical + wind nucleosyntheis

Combination of dynamical and wind nucleosynthesis (missing viscous component)



$m_{\rm dyn} \approx 10^{-2} M_\odot$

Korobkin+12

e.m. transient: the model

- L_γ powered by radioactive material in the wind
- spherically symmetric model with $m_{\rm ej} \approx 2 \times 10^{-3} M_\odot$, $v_{\rm ej} \approx 0.08\, c$

Kulkarni 05, see also Tanaka&Hotokezaka 13, Grossmann+14

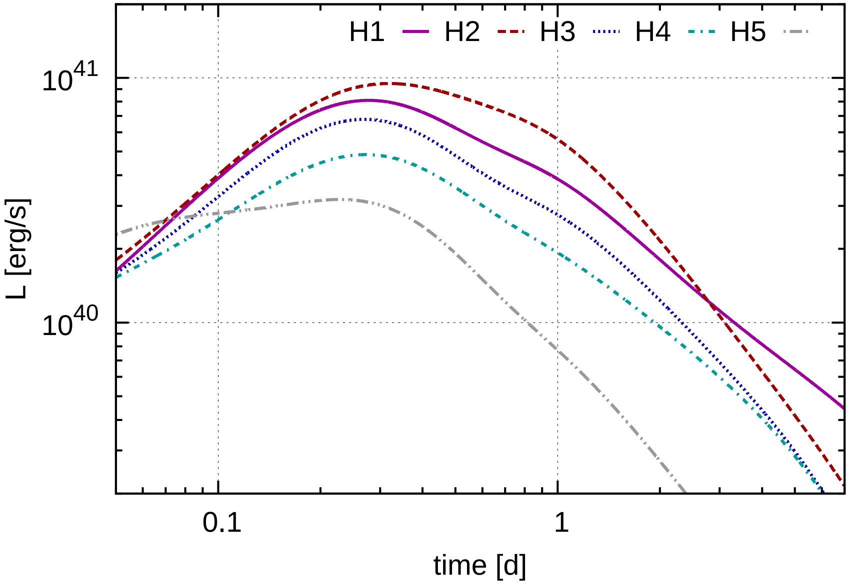
- 10 representative tracers
- high (H) and low (L) latitudes tracers
- uniform grey opacity: $\kappa_H = 1\,{\rm cm}^2\,{\rm g}^{-1}$, $\kappa_L = 10\,{\rm cm}^2\,{\rm g}^{-1}$

Tracer	Y_e	s [k_B/baryon]	$\langle A \rangle_{\rm final}$	$\langle Z \rangle_{\rm final}$	$X_{\rm La,Ac}$
L1	0.213	12.46	118.0	46.2	0.04
L2	0.232	11.84	107.1	42.5	0.009
L3	0.253	12.68	98.0	39.2	$7 \cdot 10^{-5}$
L4	0.275	12.73	90.2	36.4	$1 \cdot 10^{-7}$
L5	0.315	13.68	81.7	33.0	$3 \cdot 10^{-12}$
H1	0.273	13.57	93.0	37.4	$8 \cdot 10^{-7}$
H2	0.308	14.69	83.3	33.7	$6 \cdot 10^{-11}$
H3	0.338	15.36	79.4	32.1	$< 10^{-12}$
H4	0.353	16.40	78.4	31.7	$< 10^{-12}$
H5	0.373	18.35	76.8	31.0	$< 10^{-12}$

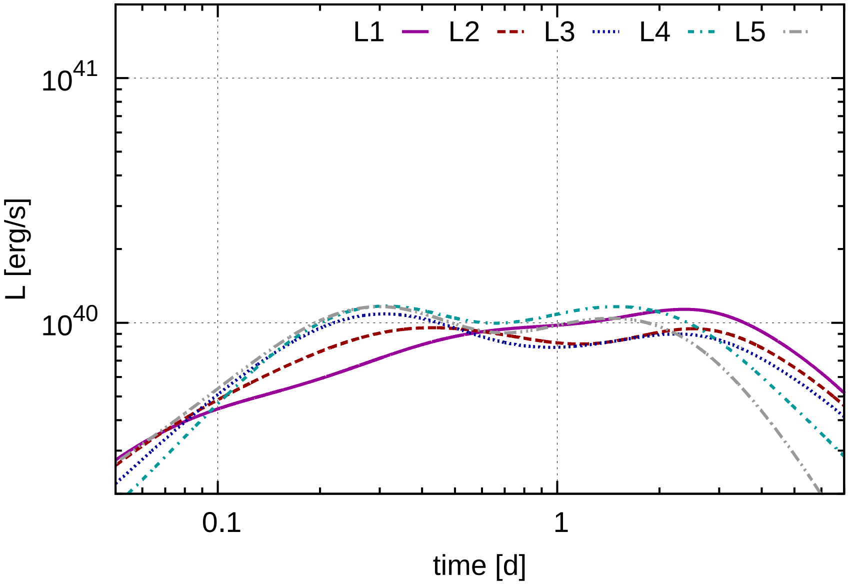
- computation of bolometric luminosities and broadband lightcurves

e.m. transient: the results

bolometric luminosities



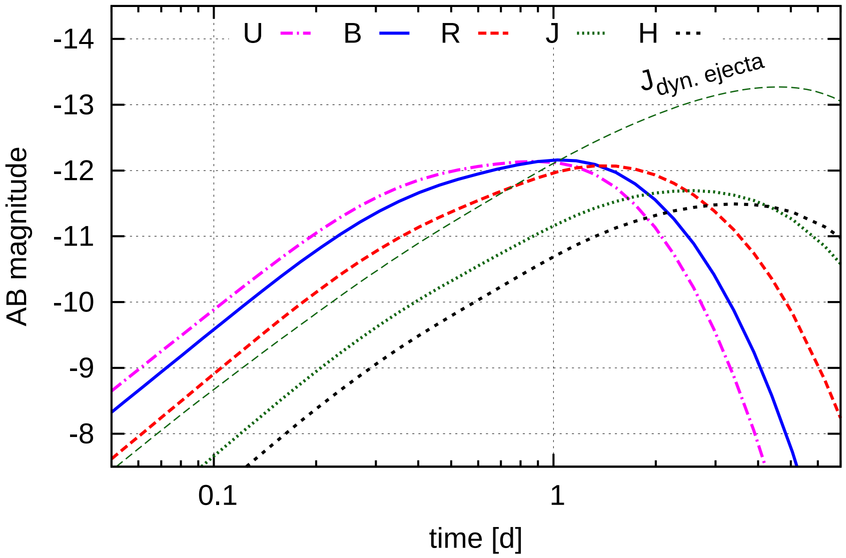
high latitude tracers



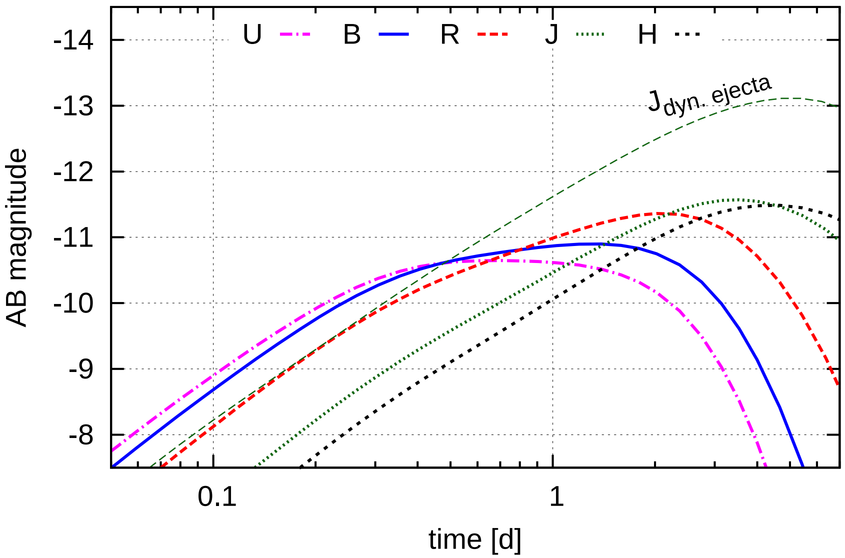
low latitude tracers

e.m. transient: the results

broadband lightcurves



top/on-axis view



side/off-axis view