Nucleosynthesis and transients in the ν-driven wind from the remnant of binary neutron star mergers

Albino Perego

in collaboration with A. Arcones and D. Martin (TU Darmstadt), O. Korobkin and S. Rosswog (U. Stockholm), R. Cabezon, M. Liebendörfer and F.-K. Thielemann (U. Basel), R. Käppeli (ETH Zürich)

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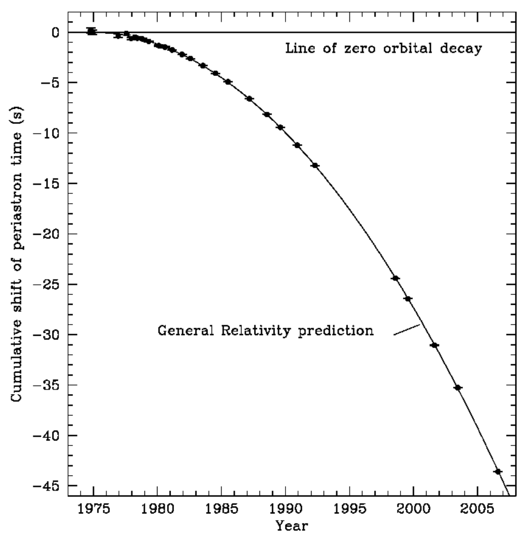
BNS mergers and their aftermaths

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

- double BNS systems do exist
- merger rate: $\sim 10^{-6}\,\mathrm{events\,Myr^{-1}galaxy^{-1}}$



PSR1913+16 periastron shift

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

millisecond pulsars in relativistic binaries

Credit: Weisberg+10, Lorimer 05

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- inspiral phase, driven by GW emission

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

(see, e.g., Lorimer 05)

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

BNS mergers and their aftermaths

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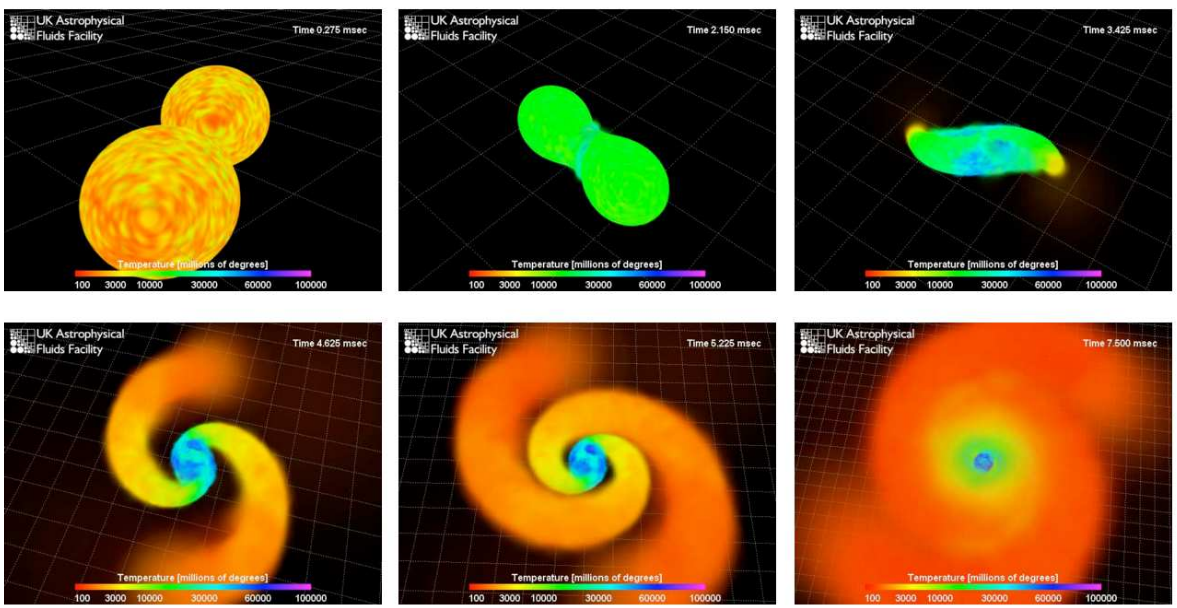
- coalescence phase



Matter temperature from a SPH simulations. Credit: S. Rosswog.

BNS mergers and their aftermaths

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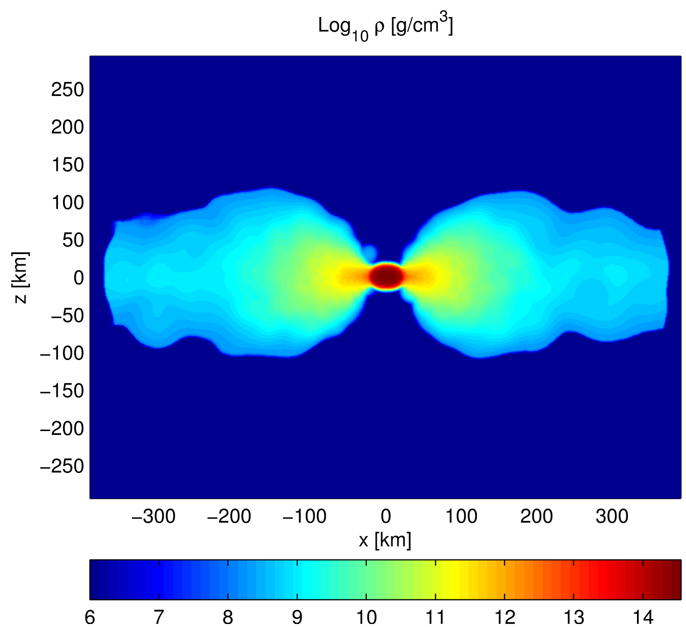
- inspiral phase, driven by GW emission
- coalescence phase
- NS merger aftermath



- (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 GWs and ν's
  e.g. Read+13, Ferrari's talk
- ejecta and nucleosynthesis
  Lattimer&Schramm74, Arcones' talk
- dependence on nuclear EoS
  e.g. Bauswein+14, Burgio's & Andersson's talks
- possible short GRB progenitors
  e.g. Paczynski86, Bernardini's & Debreczeni's talks
- electromagnetic counterpart from radioactive decay   Li&Paczynski98
- ejecta properties depends on ν-matter interaction   e.g. Wanajo+14

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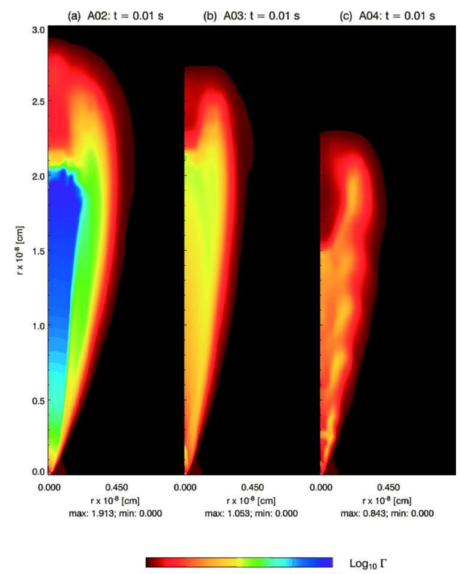

Aloy+05

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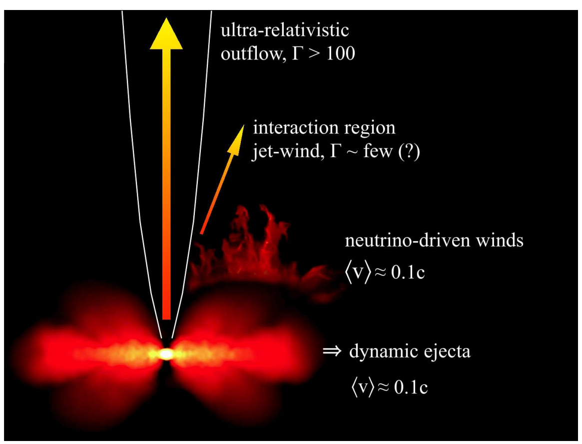
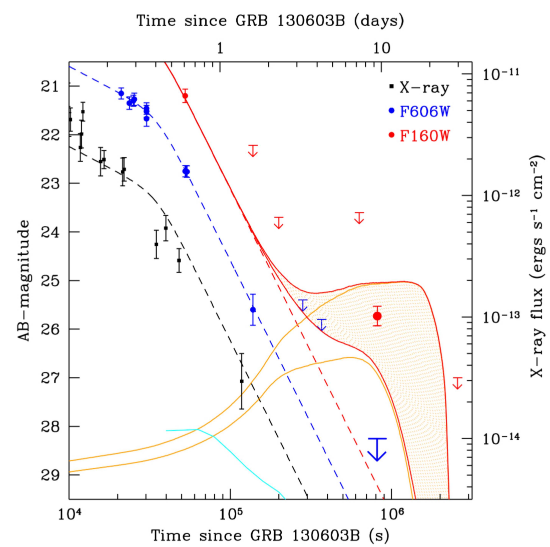


Rosswog 12



Tanvir+13, Berger+13

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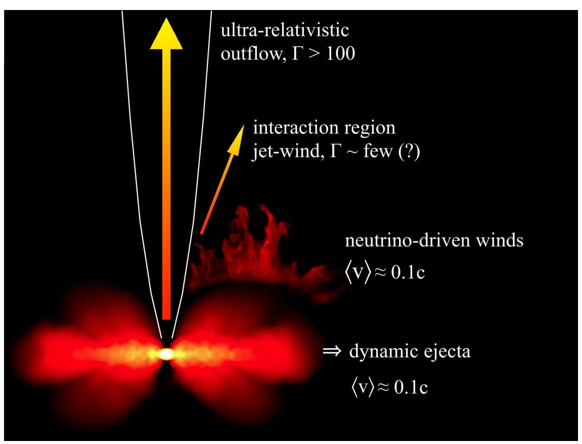

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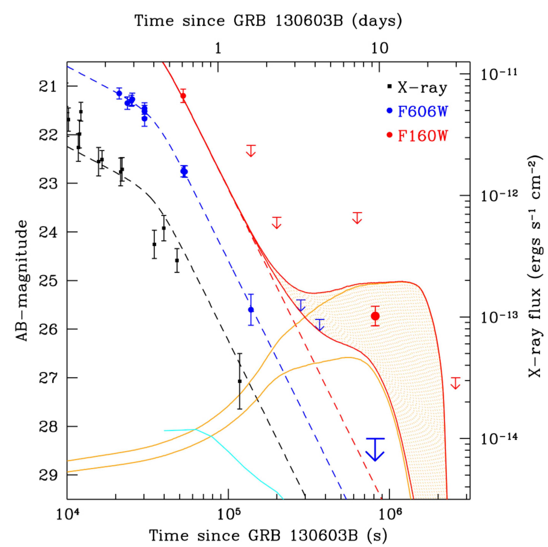
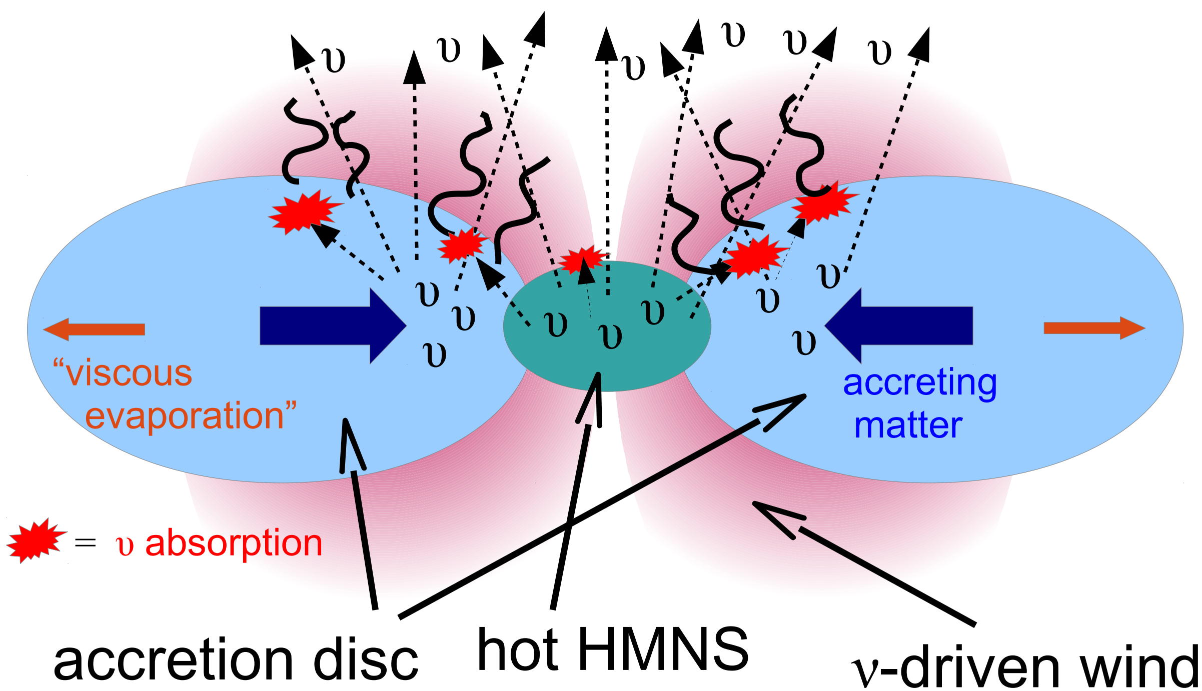


Tanvir+13, Berger+13

Neutrino-driven wind

Physical origin of the ν-driven wind:

- HMNS ($\to$ 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



e.g. Ruffert&Janka 96, Rosswog+03

Goals of this study

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

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

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

what's new/different:

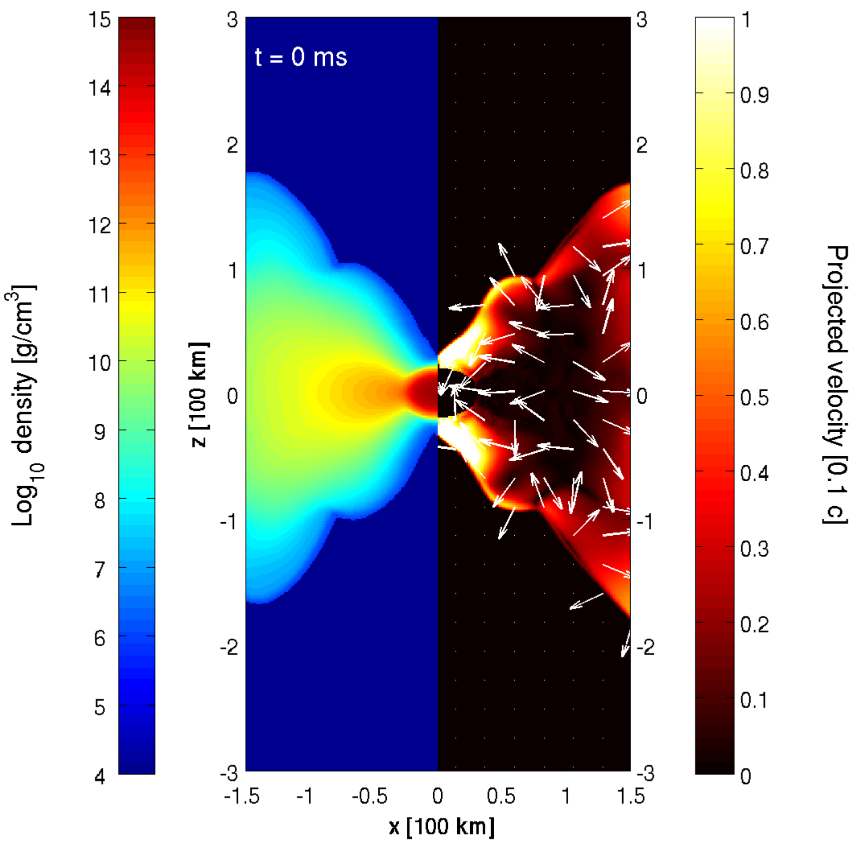
- first wind study in 3D
- disc and wind evolution over ~ 200 ms
- high spatial resolution in the wind $(\Delta x = 1\,\mathrm{km},\ \Delta x/L \sim 5 \times 10^{-4})$

Model ingredients

- initial conditions:
  final stages of high resolution SPH simulation of binary NS merger Rosswog&Price07
- Hydrodynamics:
  `FISH` 3D Grid Cartesian code Käppeli+11
- ν treatment:
  Advanced Spectral Leakage (ASL) scheme
  dominant ν cooling & heating processes
- Nuclear equation of state:
  HS EoS, with TM1 parametrization Hempel+12
- Tracers:
  Lagrangian particles advected in the fluid ($100k$)

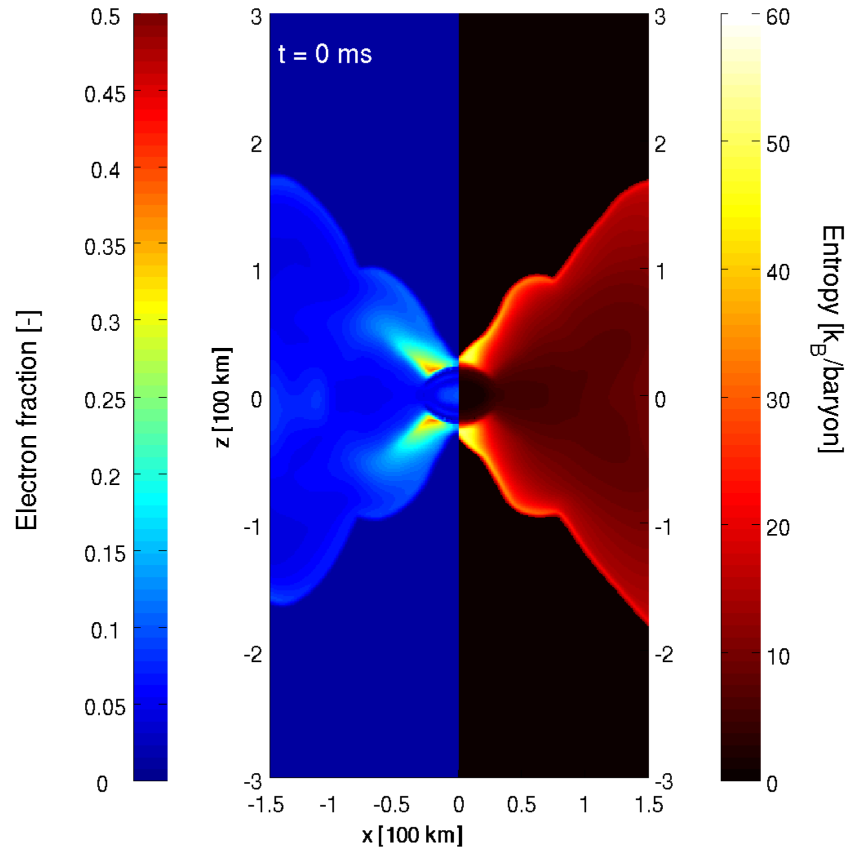
Disc and wind dynamics

t = 0 ms



left: matter density

right: projected velocity



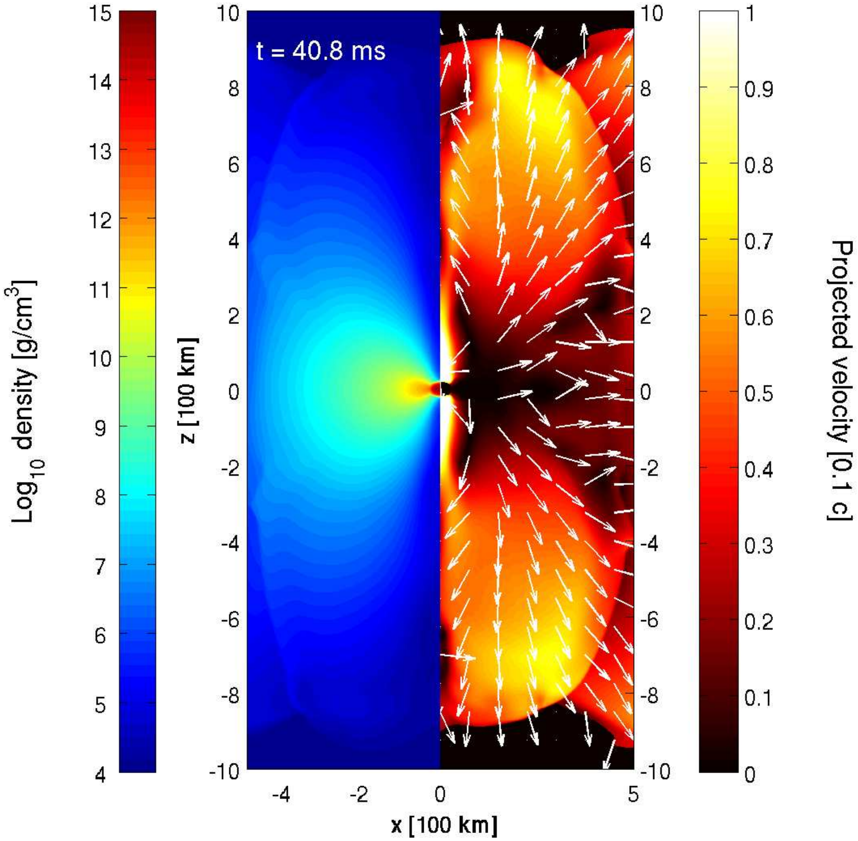
left: electron fraction

right: entropy

✓

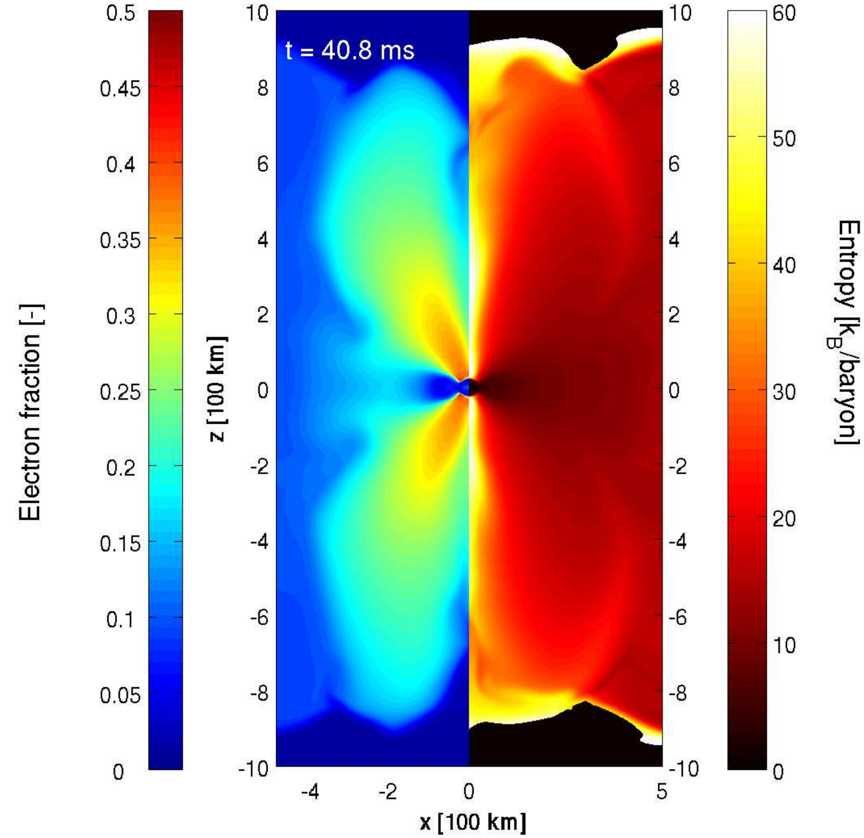
Disc and wind dynamics

t = 40 ms



left: matter density

right: projected velocity

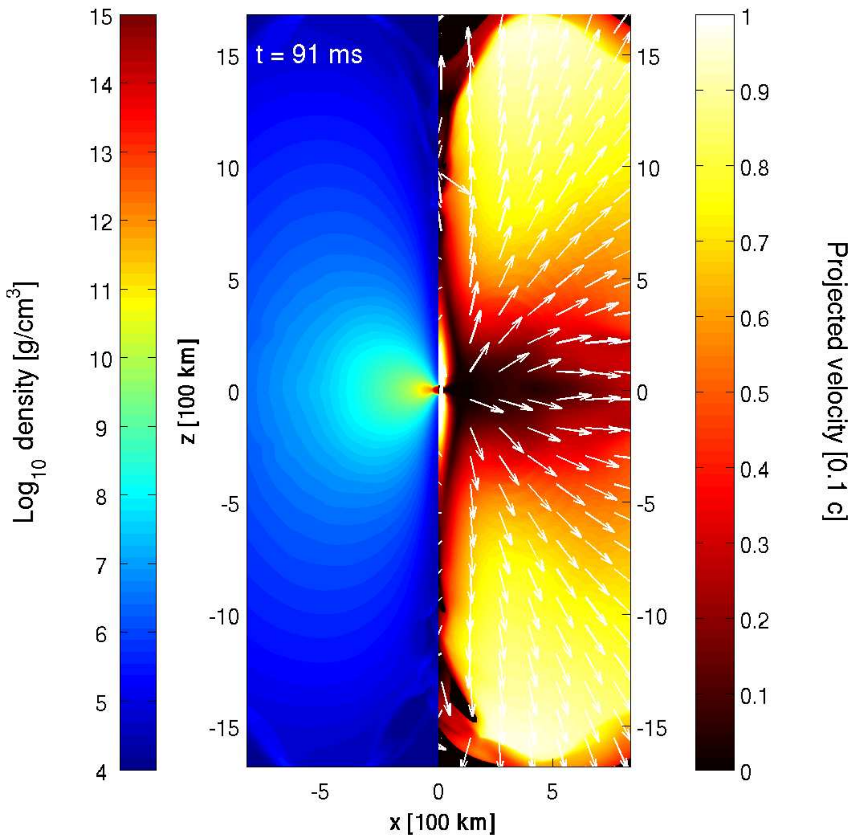


left: electron fraction

right: entropy

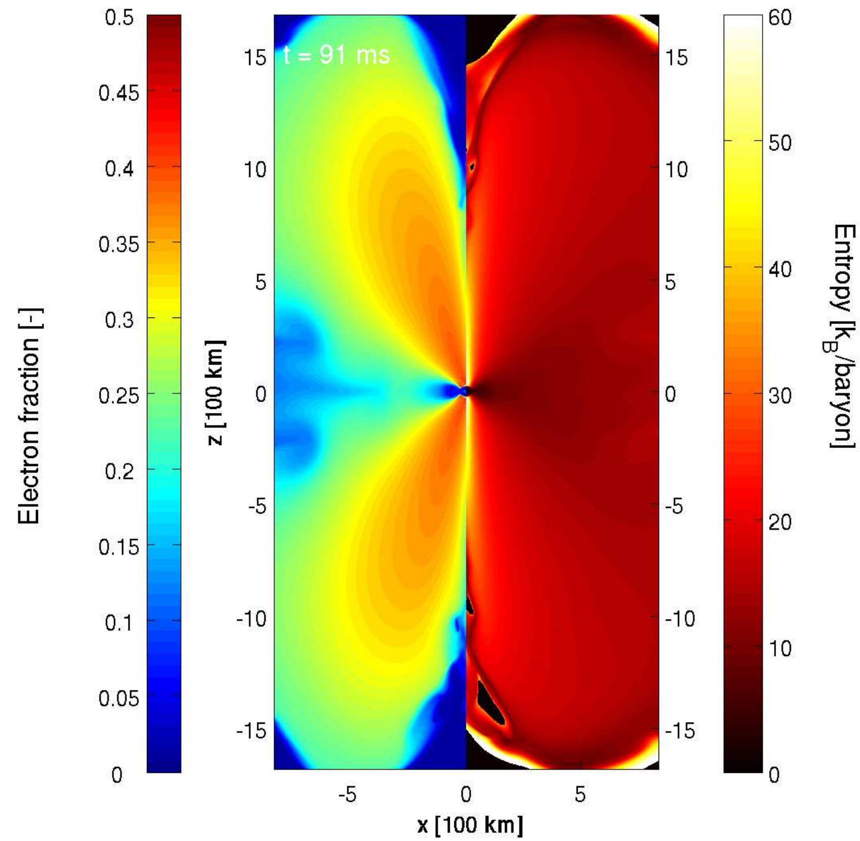
Disc and wind dynamics

t = 90 ms



left: matter density

right: projected velocity



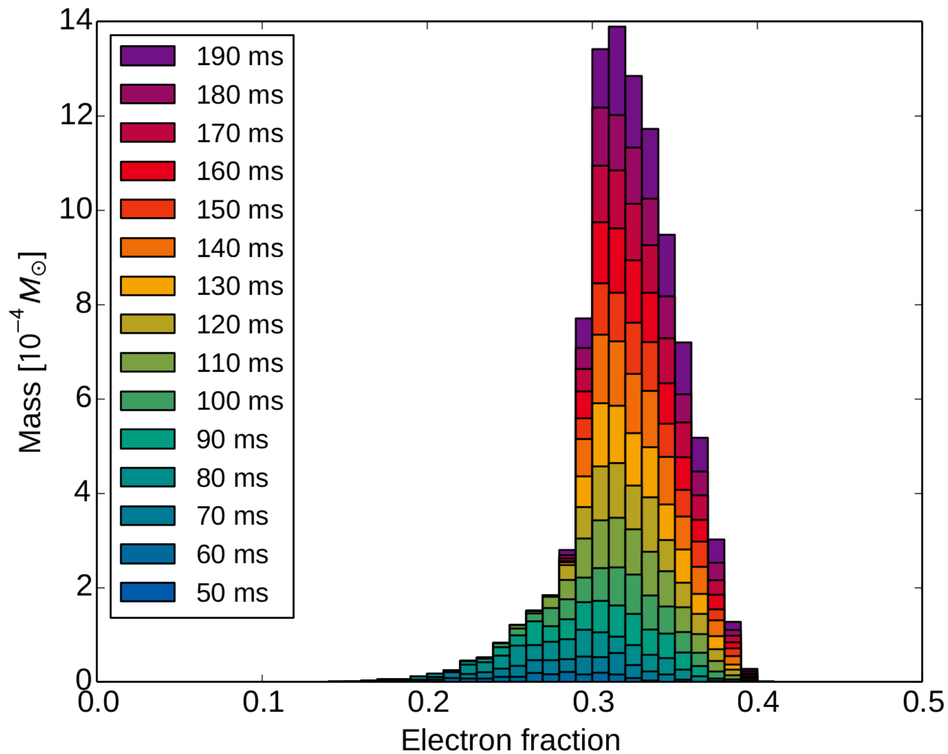
left: electron fraction

right: entropy

✓

Wind ejecta

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



ejected mass: cumulative histogram

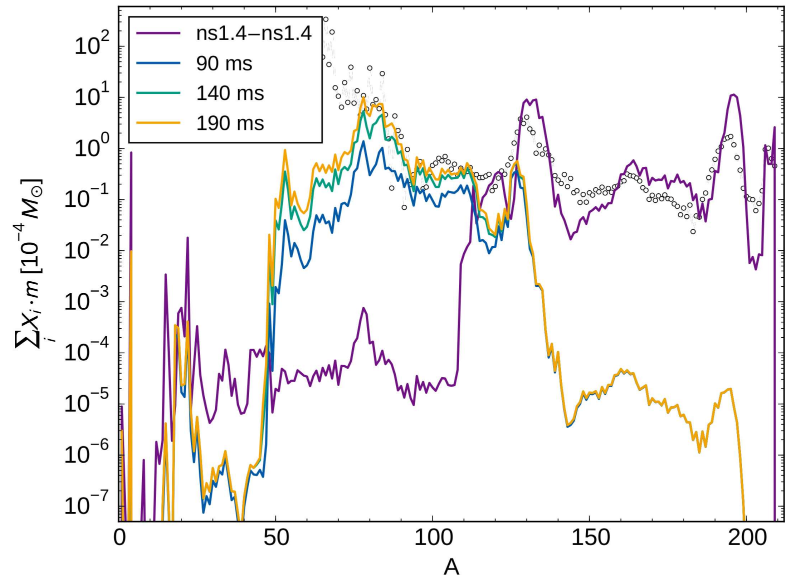
Martin, AP+, in preparation

Nucleosynthesis from the wind

Postprocessing of ejected tracers ($\sim 17k$)

- `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



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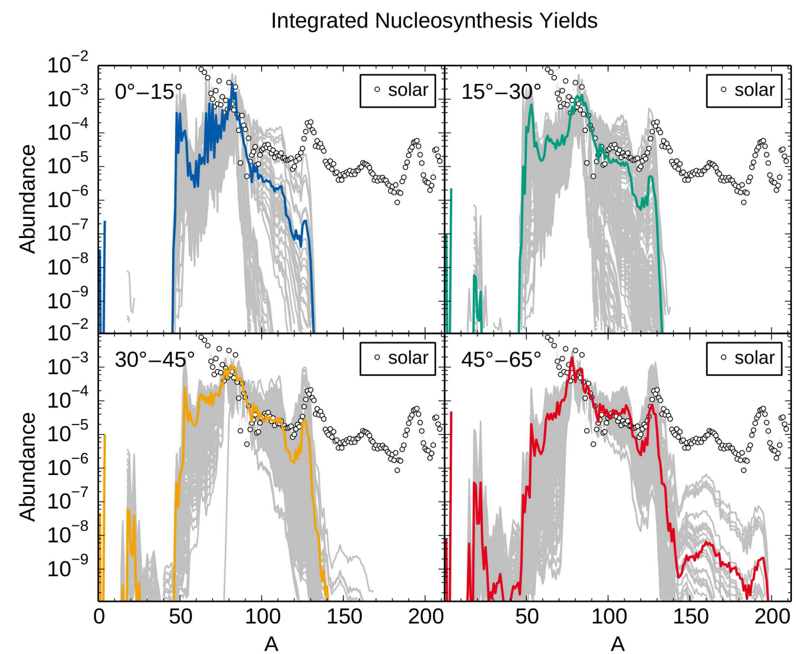
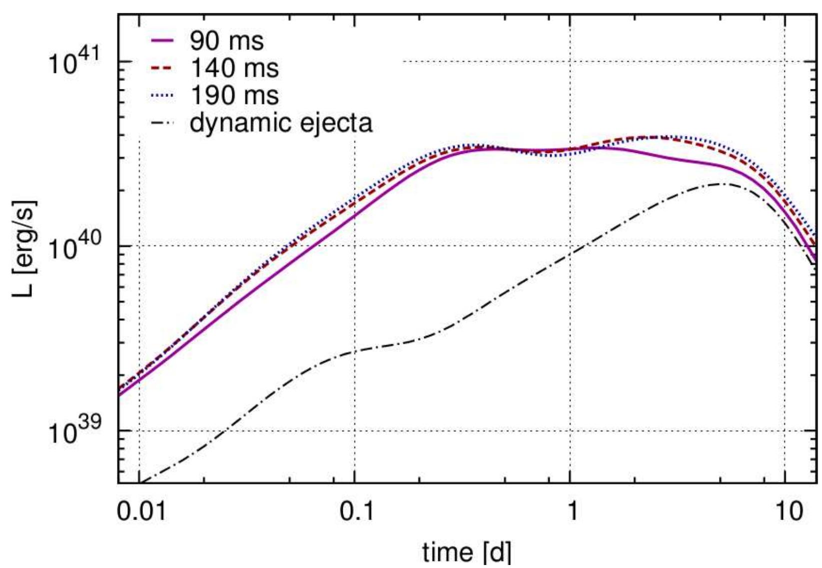
nucleosynthesis at different angles



Martin, AP+, in preparation

Electromagnetic transient

γ emission powered by radioactive material in the ejecta



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

Martin, AP+, in preparation

- model application for photon propagation and emission

  e.g. Kulkarni05,Grossman+13

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

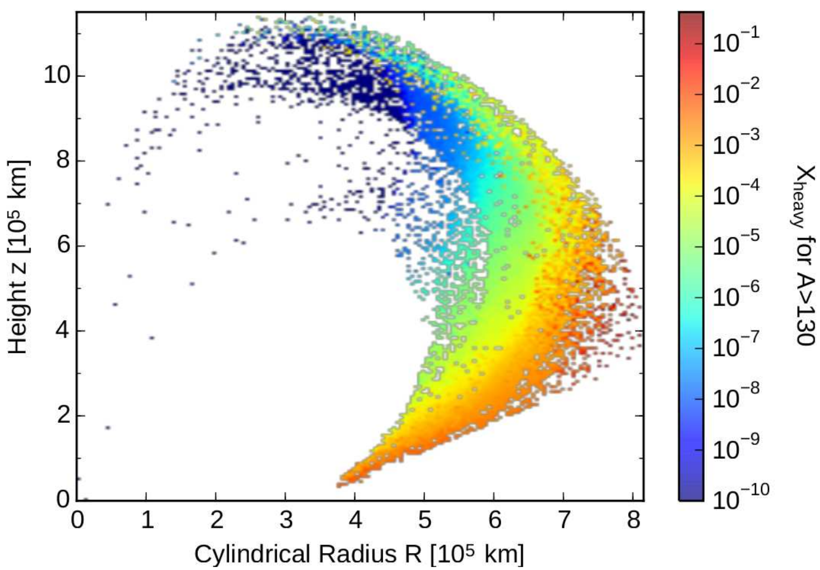
  cf Metzger&Fernandez14

- possible dependence from viewing angle and obscuration effects

  cf Fernandez+15

Electromagnetic transient

γ emission powered by radioactive material in the ejecta



Lanthanides and Actinides mass fraction,

Martin, AP+, in preparation

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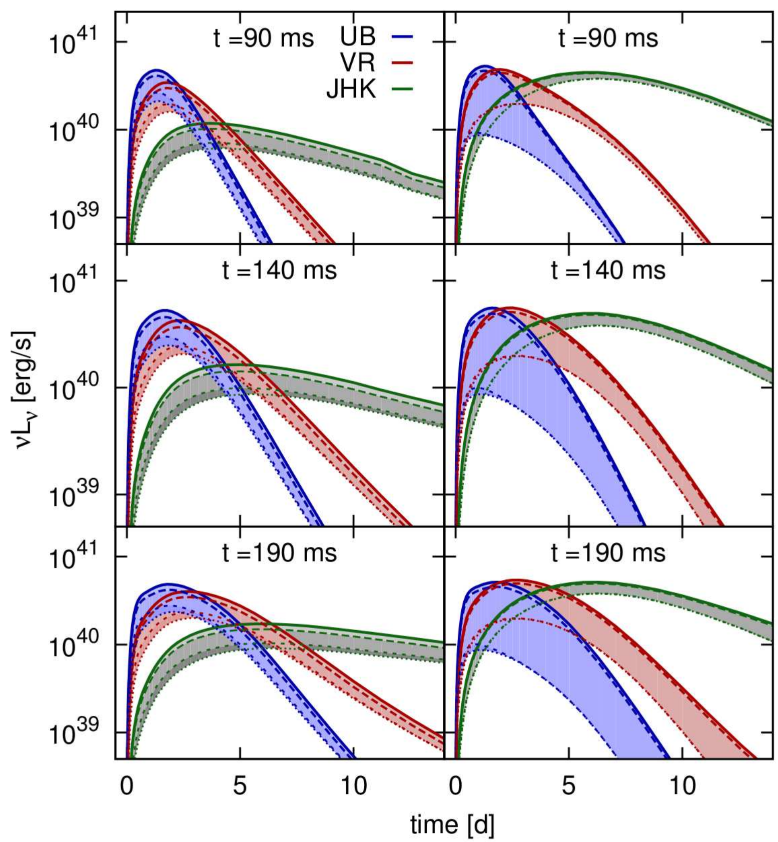
Electromagnetic transient

γ emission powered by radioactive material in the ejecta



broadband curves computed by O. Korobkin

Martin, AP+, in preparation

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  e.g. Kulkarni05,Grossman+13

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  - less contaminated by lanthanides and actinides

  cf Metzger&Fernandez14

- possible dependence from viewing angle and obscuration effects

  cf Fernandez+15

Outlooks

- combination of wind ejecta with viscous ejecta?

  Just+15, Metzger&Fernandez14 (mainly for NS-BH mergers)

- role of neutrinos for dynamical ejecta?

  Wanajo+14,Goriely+15

- GR and EOS effects on dynamics and on neutrinos

  e.g. Rezzolla+10,Kiuchi+12,Deaton+13,Surman+13,Sekiguchi+15,Foucart+15 ...

- ν's and the central engine of GRBs?

  e.g. Rosswog+03, Aloy+05,Paschalidis+14,Murguia-Berthier+14

- ν oscillations in BNS mergers?

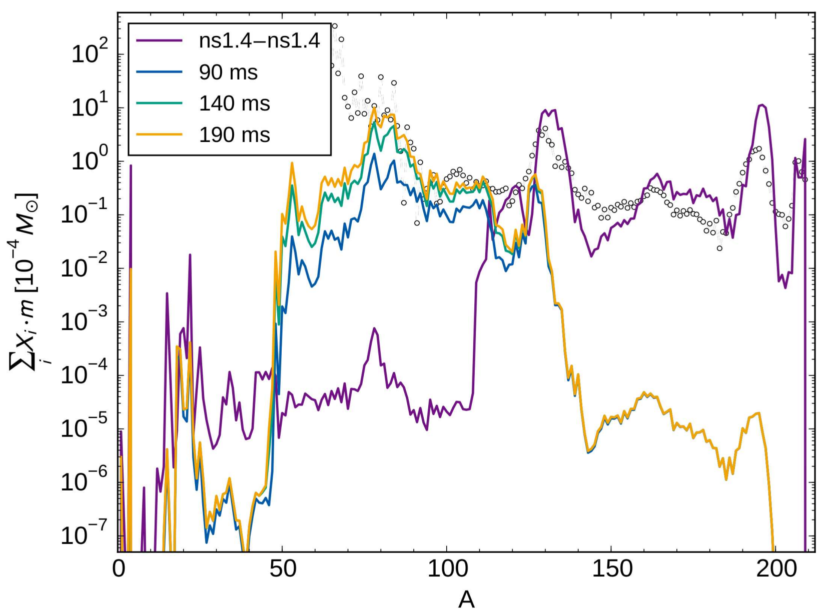
  e.g. Duan+12, Malkus+14

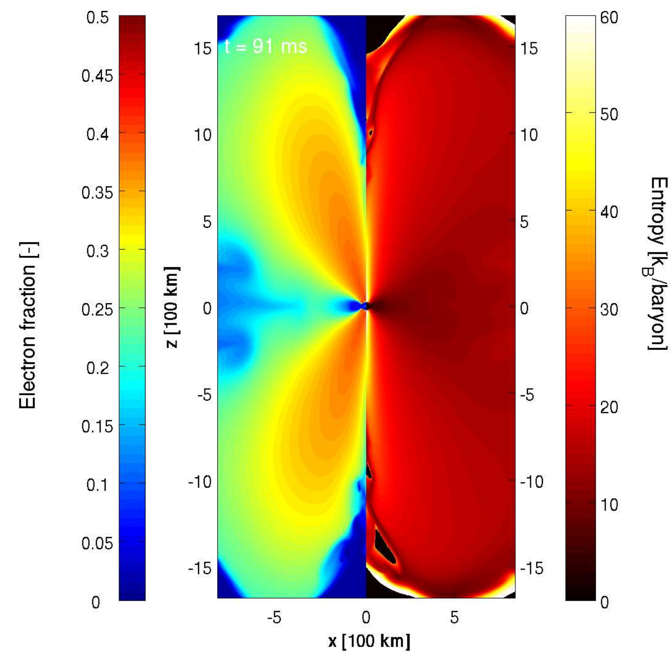
- role of B field?

  Giacomazzo+11

Conclusions

- genuine ν-driven wind from ν heating in the disk
  $t_{\rm wind} \sim$ tens ms
- wind contributes substantially to BNS merger ejecta:
  $\sim 2 \times 10^{-3} M_{\odot}$ @ 100 ms
  $\sim 9 \times 10^{-3} M_{\odot}$ @ 200 ms





- mildly neutron-rich ejecta
  $(0.2 \lesssim Y_{\rm e,ejecta} \lesssim 0.4)$;
  weak r-process nucleosynthesis
  $(A \sim 80 - 130)$
- wind electromagnetic transient
  potentially different from dynamical ejecta transient

BNS mergers as GW sources

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. Duez+10, Read+13
  - constraint on nuclear EoS — e.g. Bauswein+14

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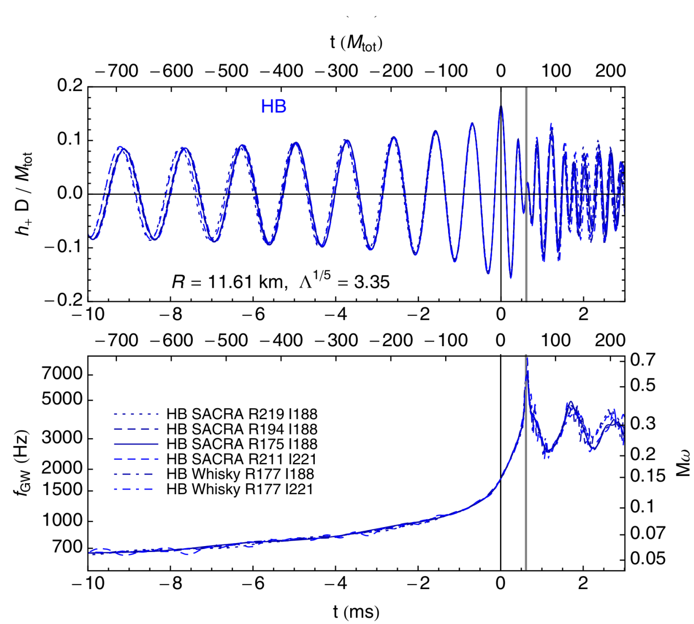
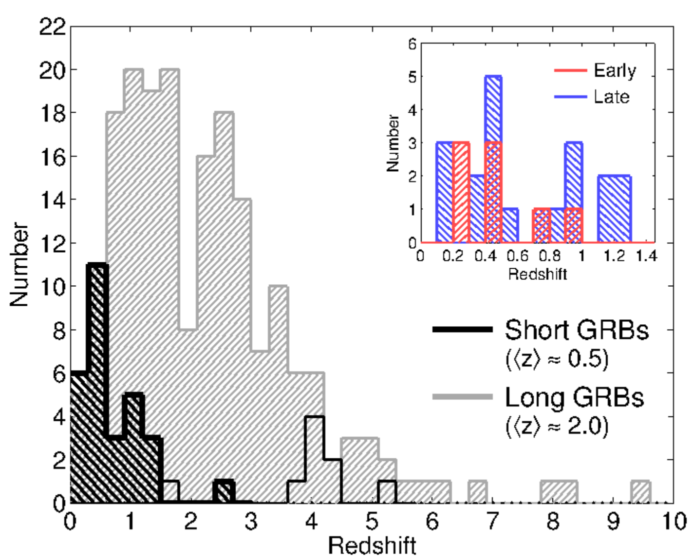


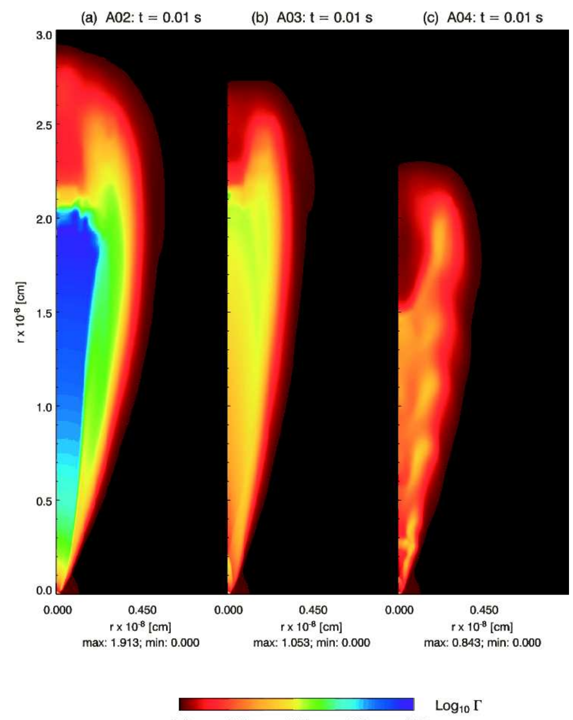
Read+13

BNS mergers & GRBs

- promising progenitors of short/hard GRBs e.g. Paczynski86
  - 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



Berger 14



Aloy+05

BNS mergers & Nucleosynthesis

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

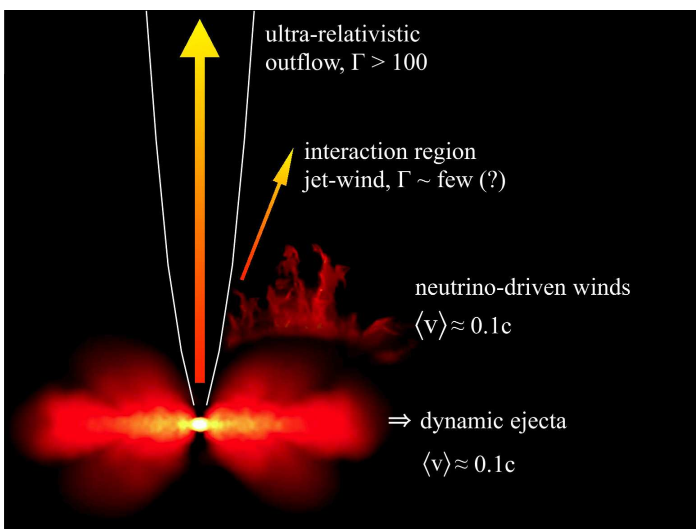
Lattimer&Schramm 74, Eichler+ 89, . . . Surman+08, Just+14 . . .

  - n-rich matter + $L_{\bar{\nu}_e} > L_{\nu_e}$ + fast expansions
  - different ejection channels:

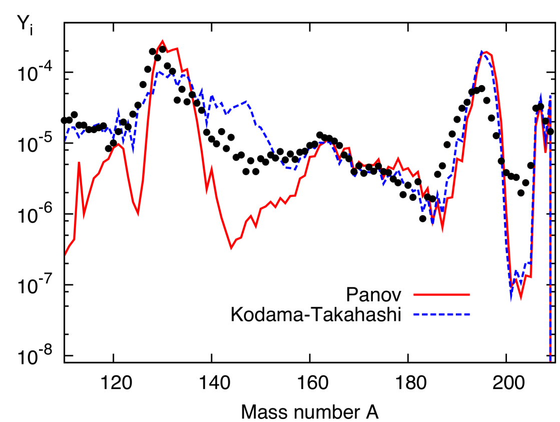
dynamical ejecta — e.g., Korobkin+12, Bauswein+13, Hotokezaka+13

viscous ejecta — e.g., Fernandez&Metzger 13, Just+14

ν-driven wind — e.g. Dessart+09, Metzger&Fernandez 14, Perego+14



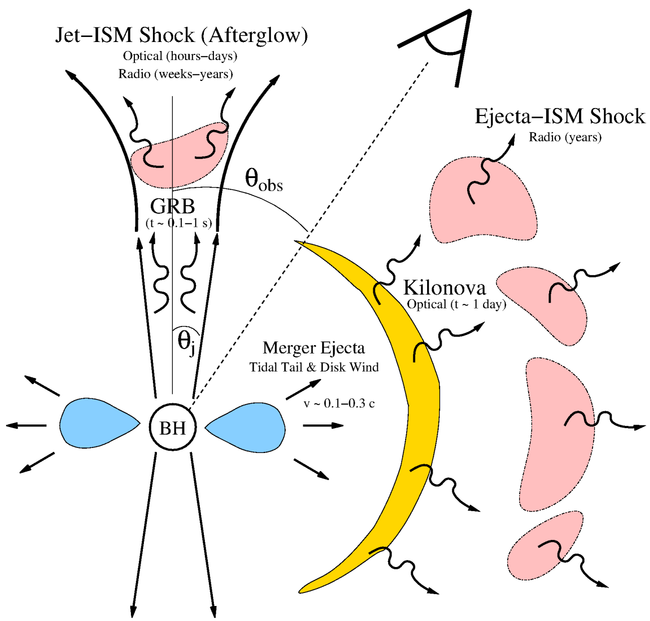
Rosswog2012



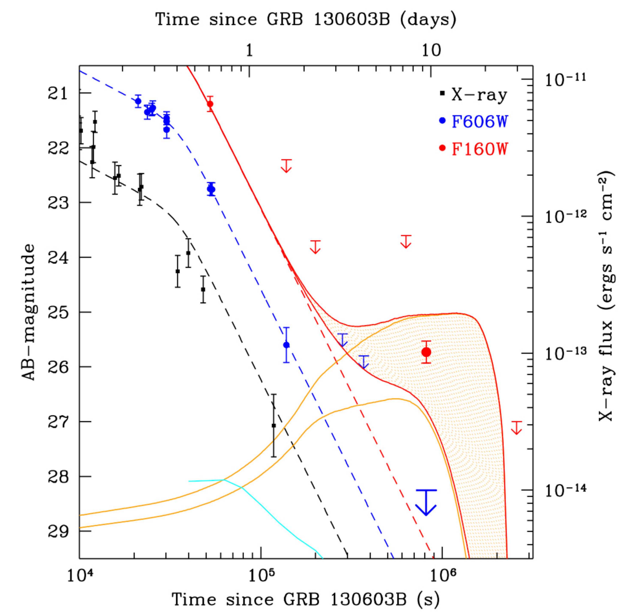
Korobkin+12

BNS mergers & kilonova

- late optical transient 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

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- disk L:

$$L_{\nu,{\rm disk}} \sim \frac{\Delta E_{\rm grav}}{2\,t_{\rm disk}} \approx 8.35\times10^{52}\,{\rm erg\,s^{-1}}\left(\frac{M_{\rm ns}}{2.5\,M_\odot}\right)^{3/2}\left(\frac{M_{\rm disk}}{0.2\,M_\odot}\right)\left(\frac{R_{\rm disk}}{100\,{\rm km}}\right)^{-3/2} \times\left(\frac{\alpha}{0.05}\right)\left(\frac{R_{\rm ns}}{25\,{\rm km}}\right)^{-1}\left(\frac{H/R}{1/3}\right)^{2}$$

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

Relevant time scales

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

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

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

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

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

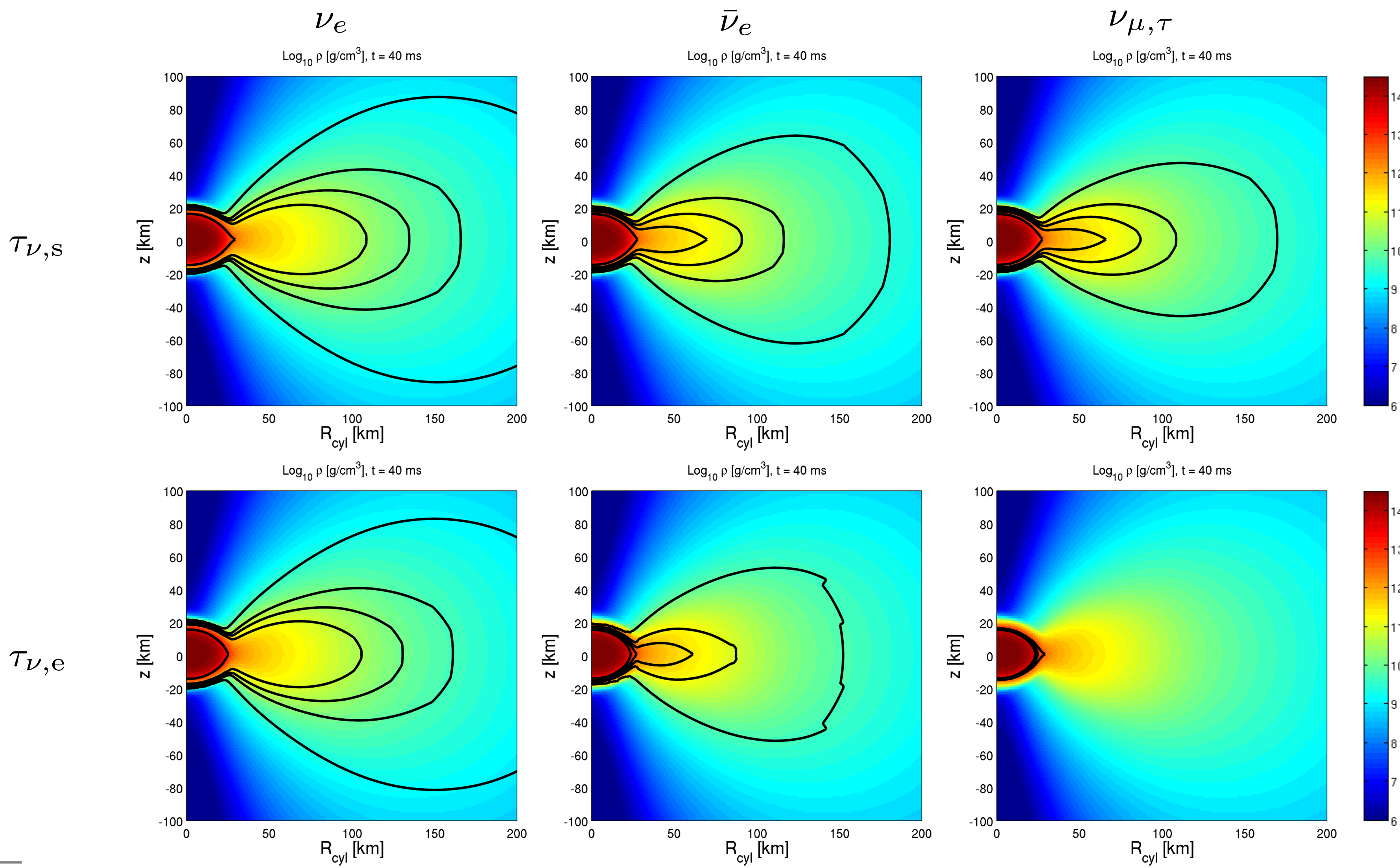
$$t_{\rm bh} \sim 0.01 - 10\,{\rm s}$$

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

e.g. Rezzolla & Kumar 14

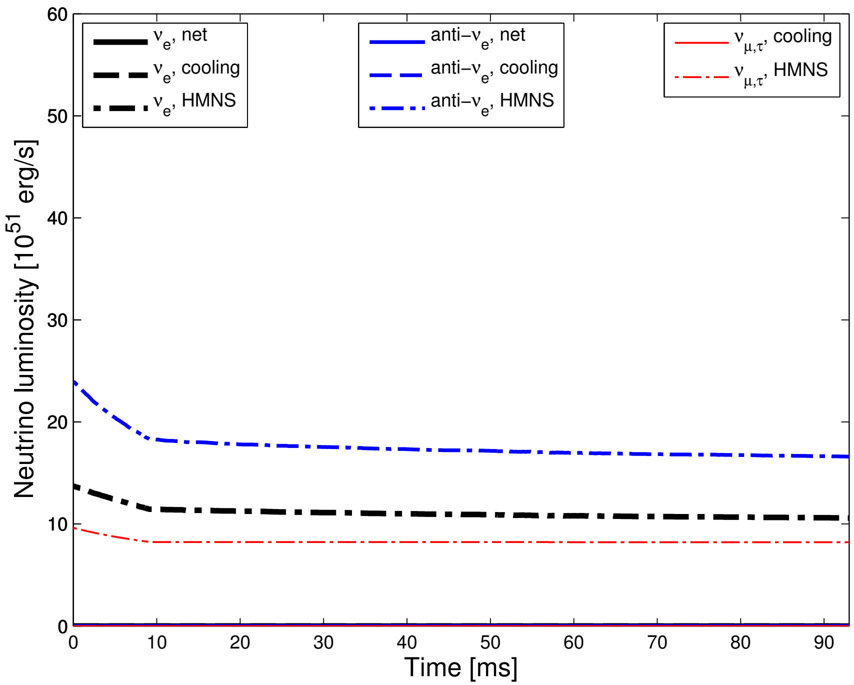
Neutrino Surfaces

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



Neutrino luminosities

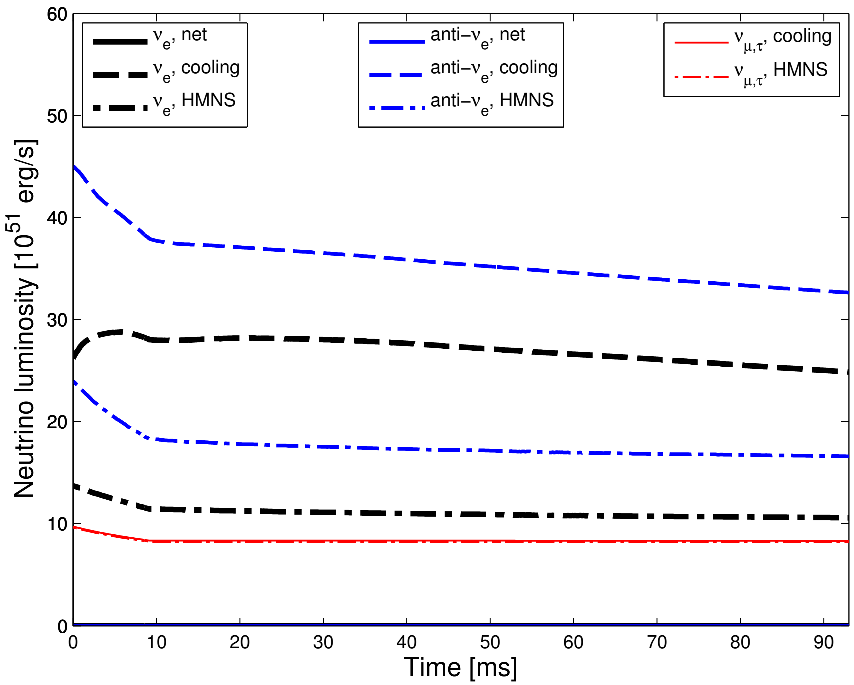
dependence on time



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

Neutrino luminosities

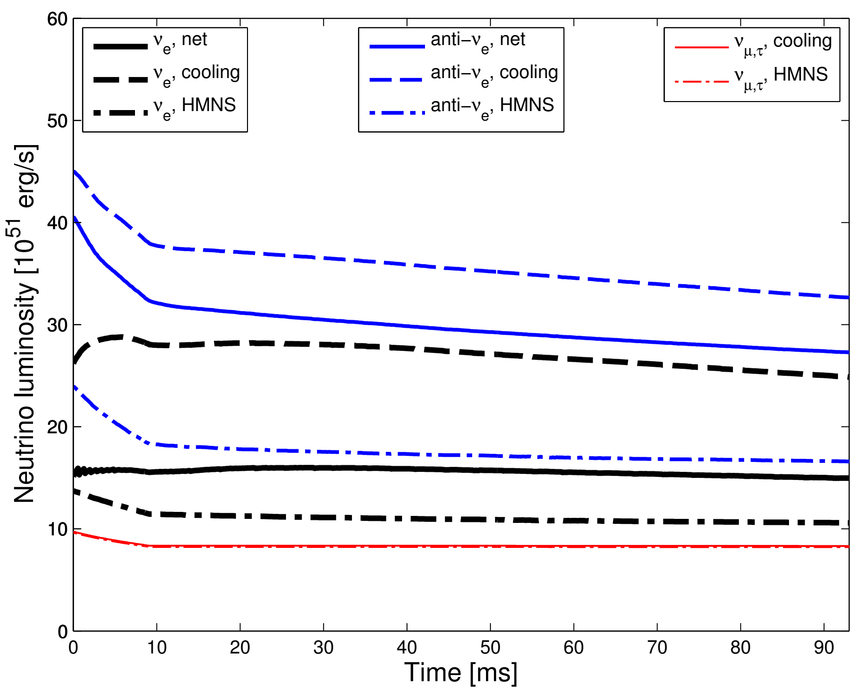
dependence on time



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

Neutrino luminosities

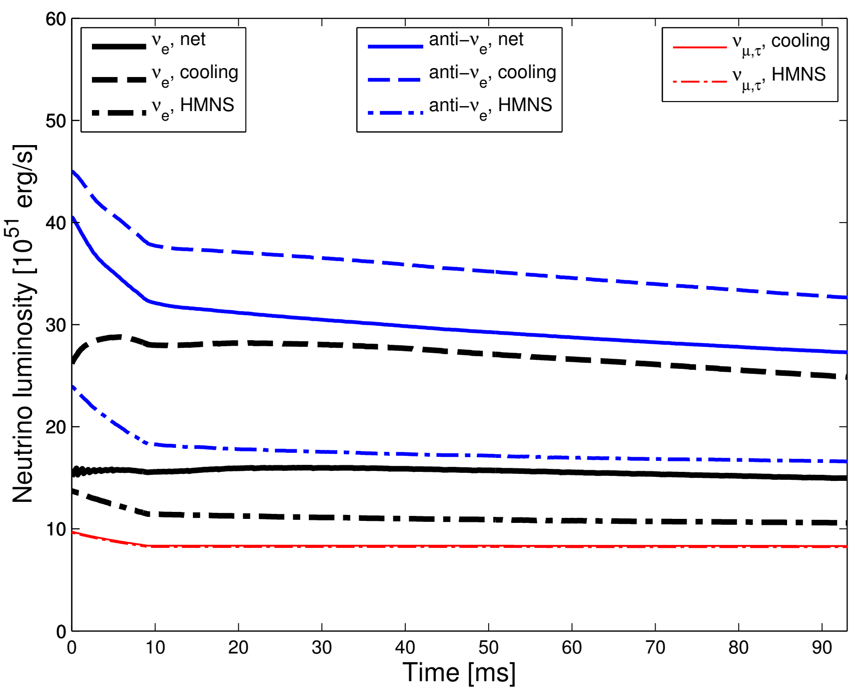
dependence on time



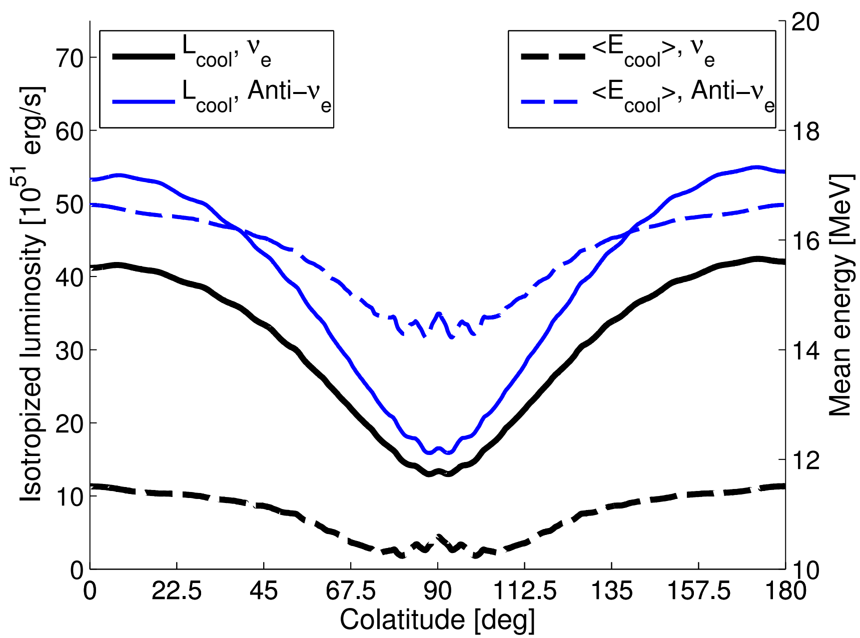
- HMNS ($\rho > 5 \times 10^{11}\,\mathrm{g\,cm^{-3}}$) + disk
- luminosity hierarchy: $L_{\bar{\nu}_e} > L_{\nu_e} > L_{\nu_{\mu,\tau}}$
- disk luminosity powered by accretion: $\dot{M} \sim 0.6-0.4\,M_\odot\,\mathrm{s}^{-1}$ & $\alpha_{\mathrm{num}} \approx 0.05$

Neutrino luminosities

dependence on time

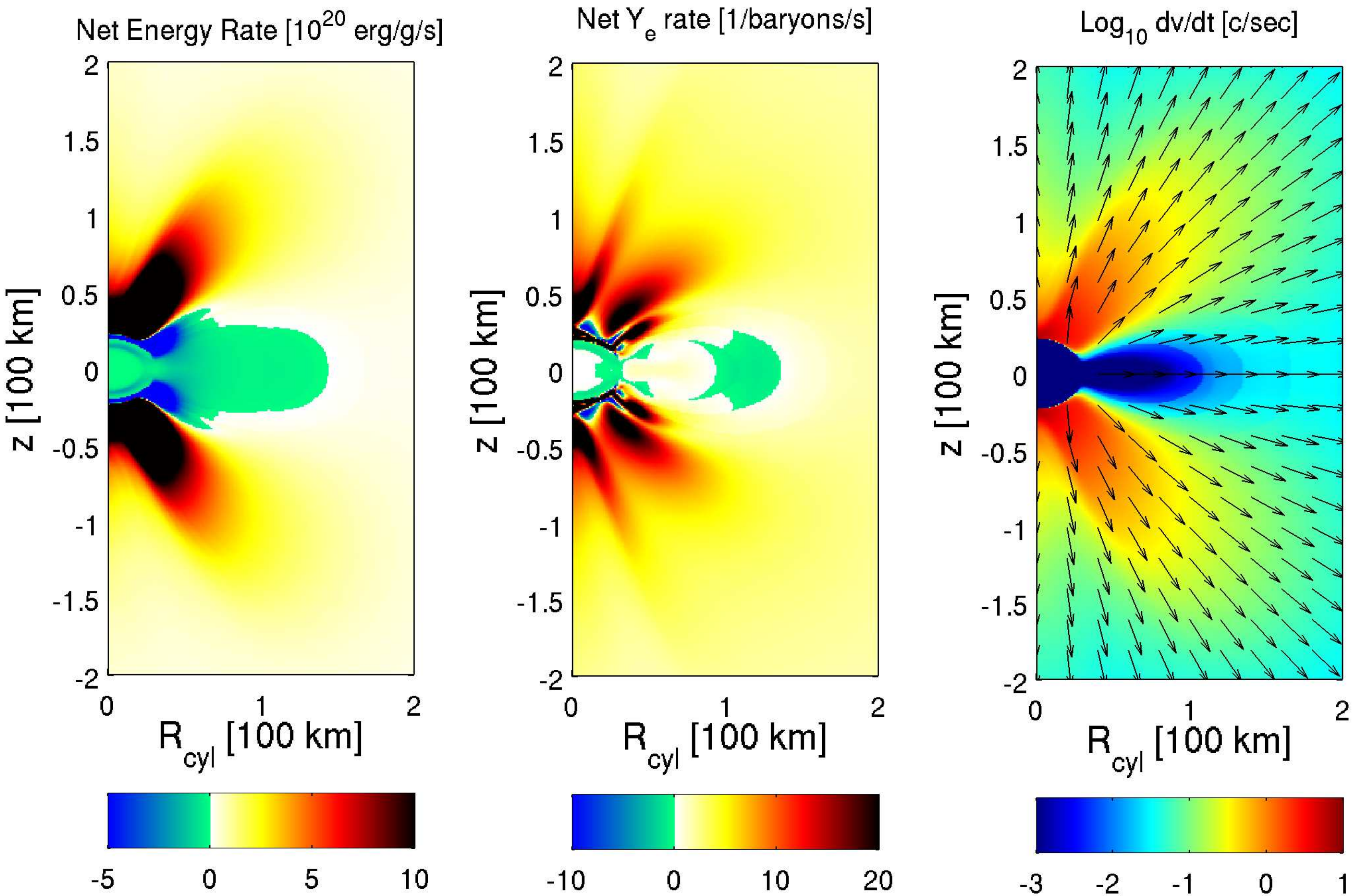


dependence on θ ($t = 40\text{ms}$)

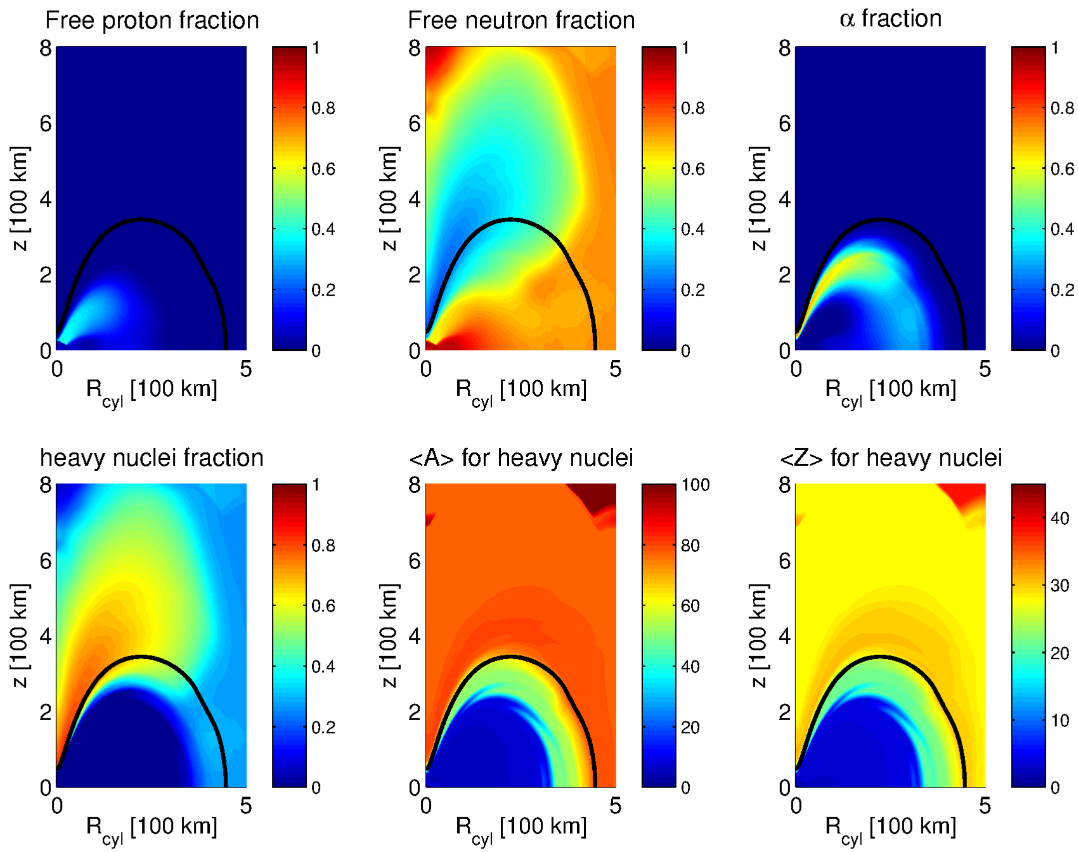


- HMNS ($\rho > 5 \times 10^{11}\,\mathrm{g\,cm^{-3}}$) + disk
- luminosity hierarchy:
  $L_{\bar{\nu}_e} > L_{\nu_e} > L_{\nu_{\mu,\tau}}$
- disk luminosity powered by accretion:
  $\dot{M} \sim 0.6-0.4\,M_\odot\,\mathrm{s}^{-1}$ & $\alpha_{\rm num} \approx 0.05$
- mean energy hierarchy:
  $E_{\nu_{\mu,\tau}} > E_{\bar{\nu}_e} > E_{\nu_e}$
- $E_{\nu_e} \approx 11\,\mathrm{MeV}, E_{\bar{\nu}_e} \approx 15\,\mathrm{MeV}$,
  $E_{\nu_{\mu,\tau}} \approx 18\,\mathrm{MeV}$
- disk-shadow effect

Neutrino net rates



Disc & wind composition



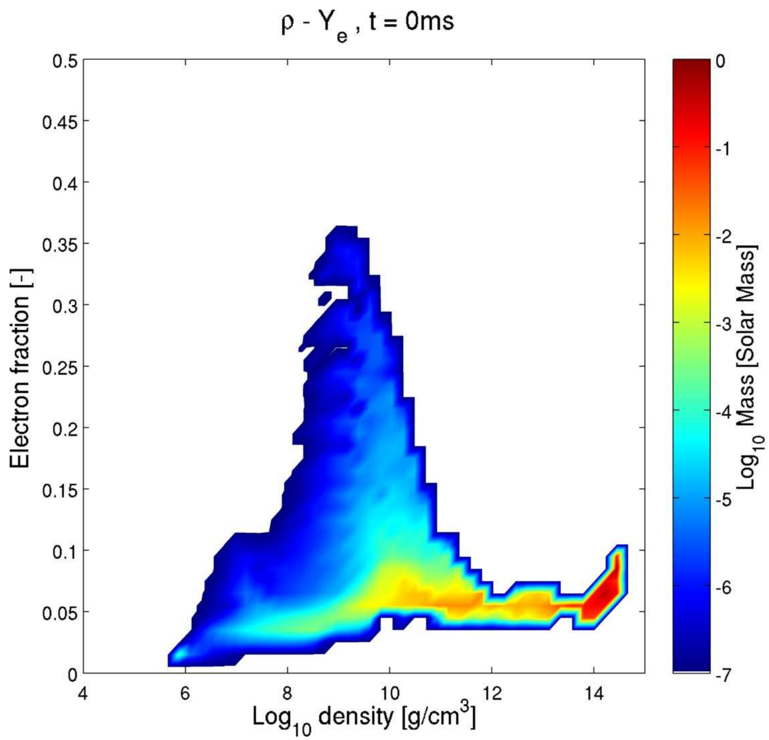
- mass fractions in the disk & wind (as predicted by NSE EOS)
- black line: NSE freeze-out (T=5GK)

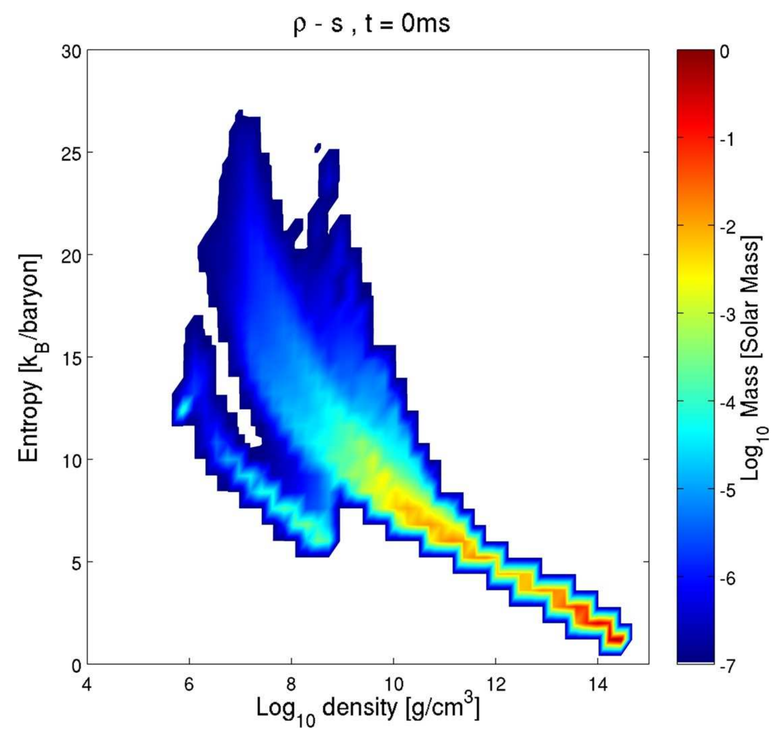
- Relevant changes in nuclear composition:
  - n,p $\rightarrow$ n,α (still within NSE)
  - n,α $\rightarrow$ n,(A,Z) (at NSE-freezout)

Wind properties

2D mass-histograms of (ρ, Y_e) and (ρ, s)

$t \approx 0$ ms

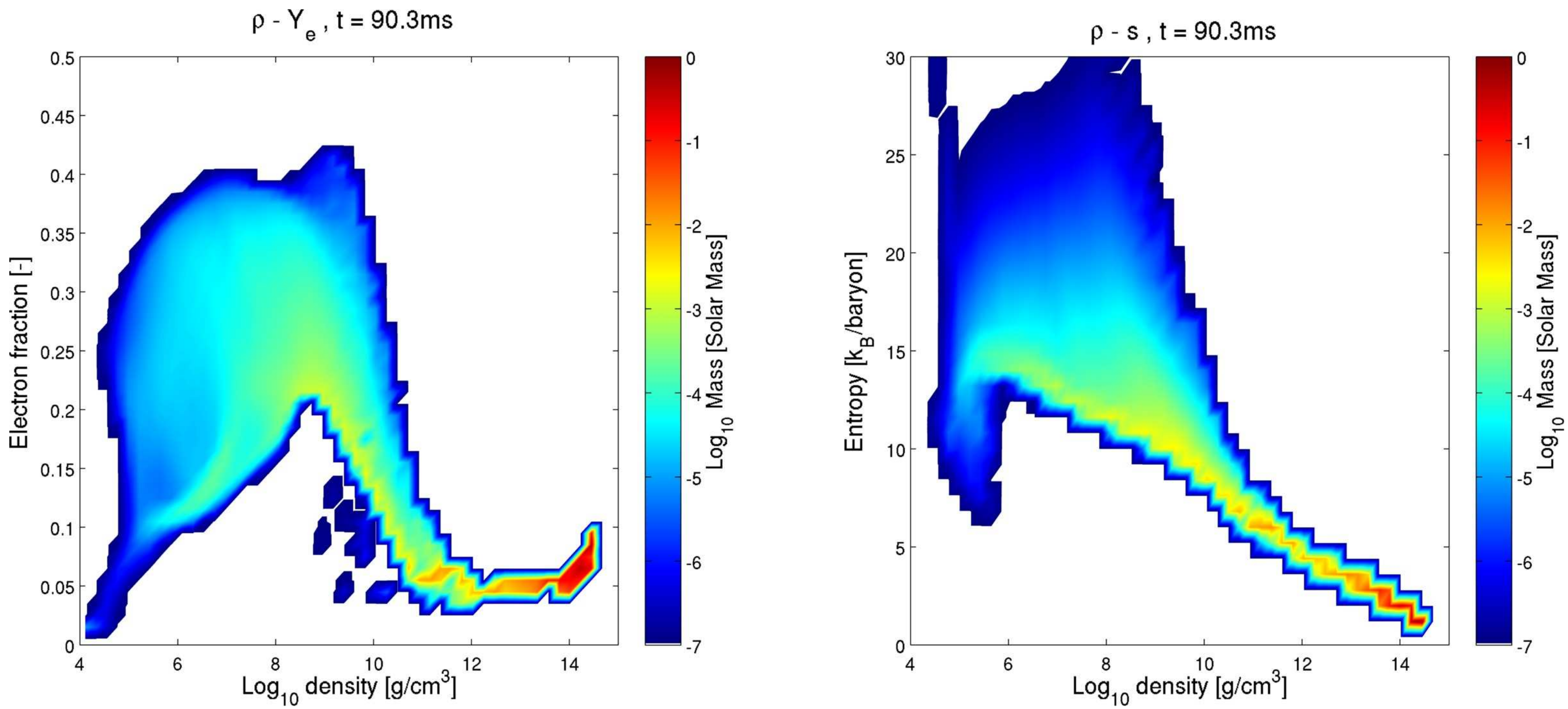




Wind properties

2D mass-histograms of (ρ, Y_e) and (ρ, s)

$t \approx 90$ ms



- large variation for Y_e: $0.1 \lesssim Y_e \lesssim 0.40$
- small variation in entropy: $10 \lesssim s\ [\mathrm{k_B/bar}] \lesssim 22$

Electromagnetic transient