Nucleosynthesis in Neutron Star Mergers: Dynamic vs. Wind Ejecta*

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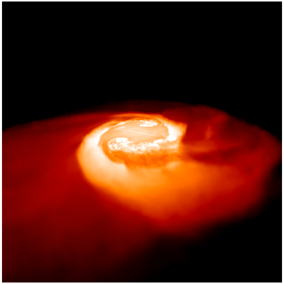

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Neutron Star Mergers

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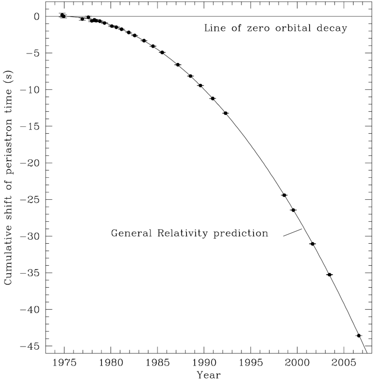
- Binary system of neutron stars
- Inspiral time: 1 Myr to 1 Gyr
- Orbital decay: emission of gravitational waves (GWs)
- Agreement with general relativity
- Estimated rate:

$$\sim \ 10^{-5} - 10^{-4} \ (\text{yr galaxy})^{-1}$$

[Kalogera et al. (2004)]



[Weisberg et al. (2010)]

Astrophysical relevance of neutron star mergers

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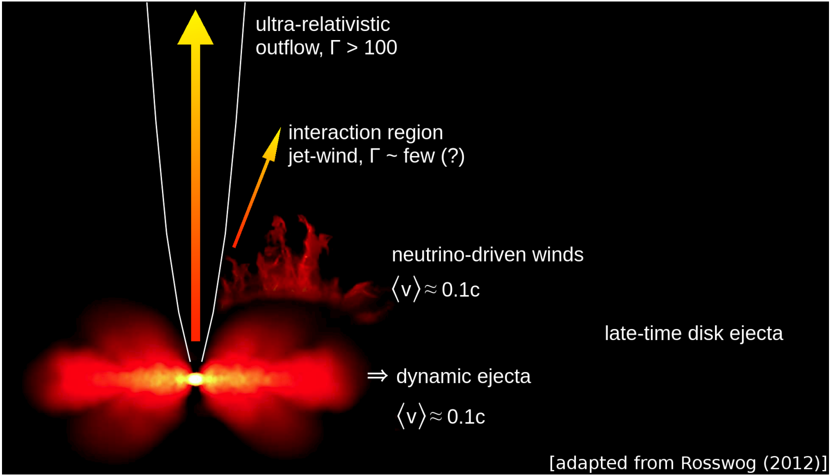
- Emission of **gravitational waves**
- Involve all fundamental forces in nature
- Best candidate to explain **short gamma-ray bursts**
- Scenario for the main **rapid neutron capture process (r-process)** (*Freiburghaus et al. (1999)*)
- Long-term decay heating of ejected material
- Light curve in agreement with recent **kilonova** detection (see *Tanvir et al. (2013)*)
- Electromagnetic counterpart for detection of GW

Recent review: *Rosswog (2015)*

Channels of matter ejection



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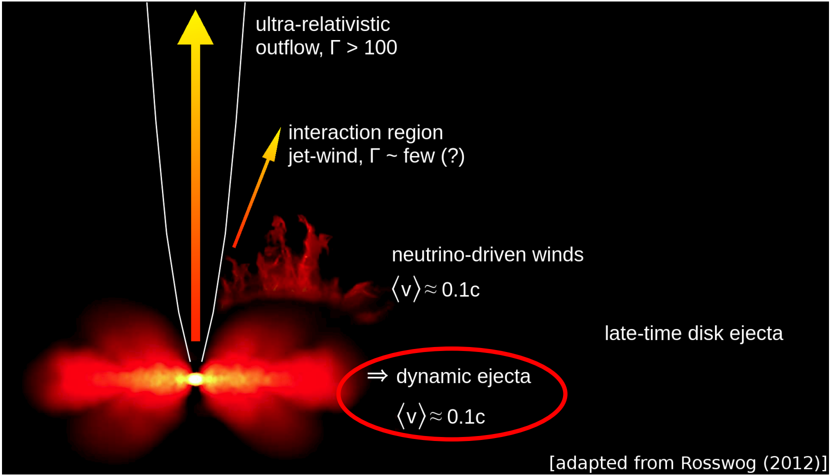

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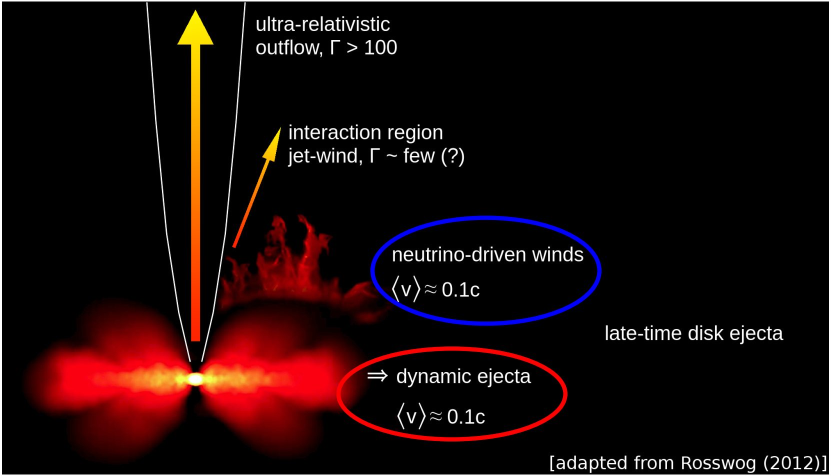

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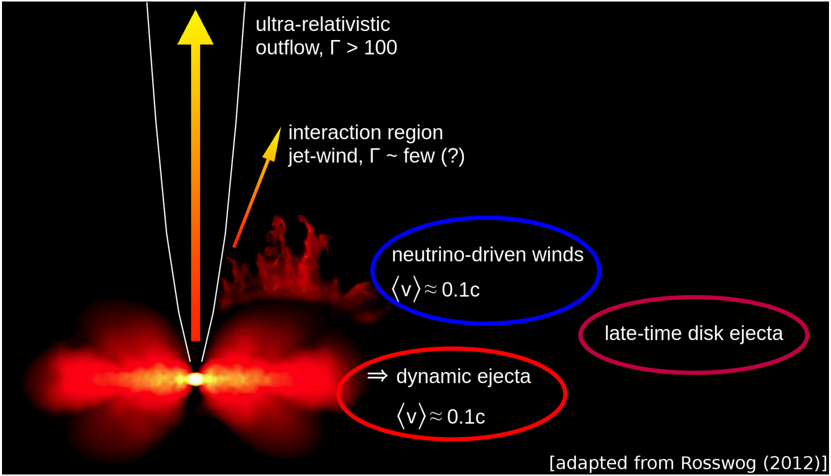

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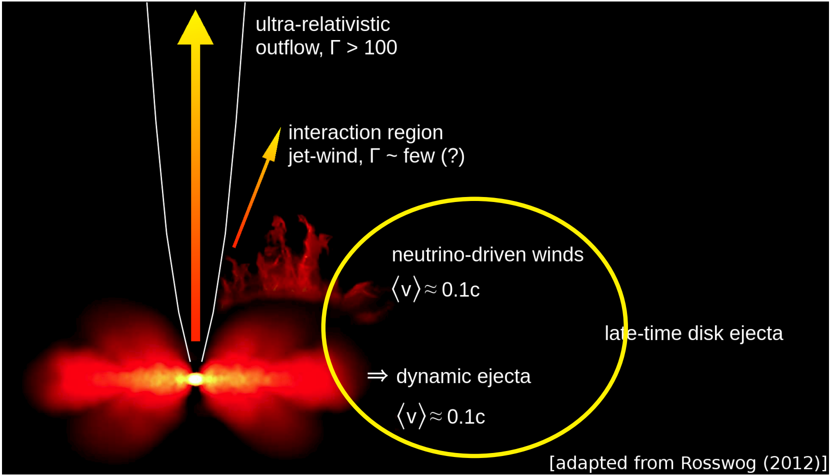
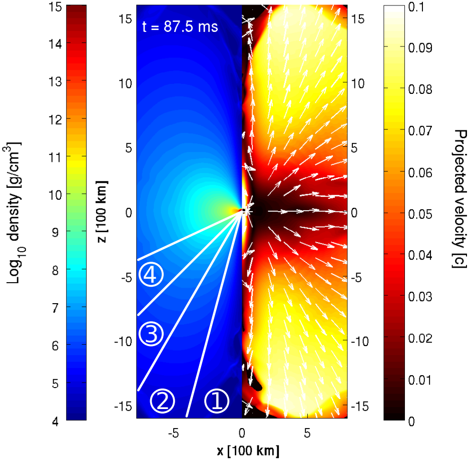


Neutrino-driven wind from a NSM

Perego et al. (2014):

- Initial conditions from *Rosswog et al. (2013)*
- 3D, Newtonian simulation
- Hypermassive NS with a mass of $2.5M_\odot$
- Accretion disk of $0.2M_\odot$
- Spectral neutrino leakage scheme



Tracers in the simulation

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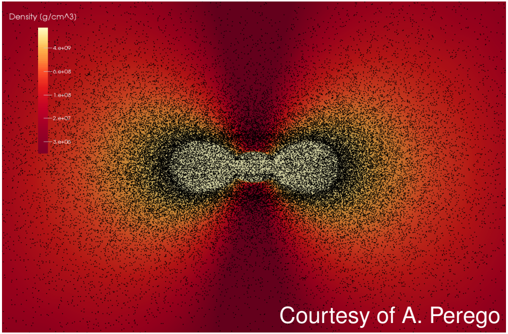
- 100 000 Lagrangian particles, passively advected
- Equal mass $m = 5.42 \cdot 10^{-7} M_{\odot}$
- Distributed prop. to initial density ($\rho_{\mathrm{tr,g\cdot cm^{-3}}} \in [2 \cdot 10^{6}, 2 \cdot 10^{10}]$)
- Ejection criteria:
  1. Positive radial velocity
  2. Positive total energy
  3. Within a cone of 60° opening angle



Properties of the ejecta of the neutrino-driven wind

- Low electron fraction:

$$Y_e = 0.20 - 0.35$$

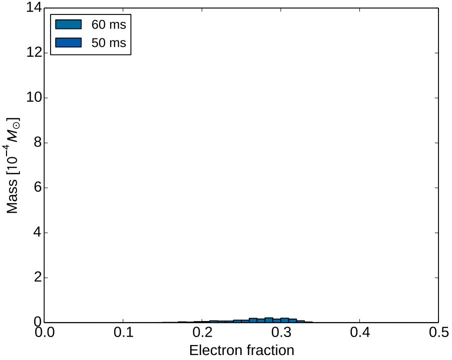
- Low matter entropy:

$$S = 10 - 25 k_B / \text{baryon}$$

- Fast expansion velocity:

$$v = 0.04c - 0.08c$$

- Up to $9 \cdot 10^{-3} M_\odot$ unbound



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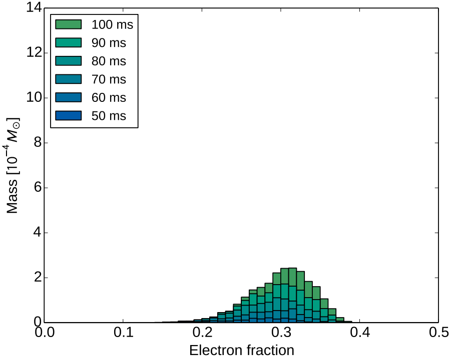

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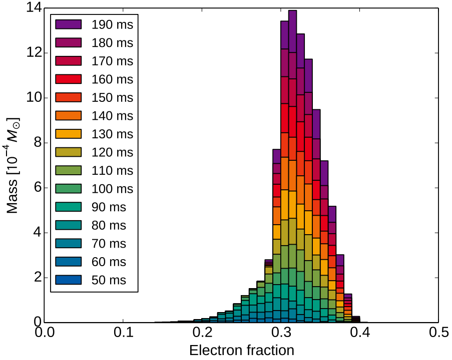

Nucleosynthesis calculations

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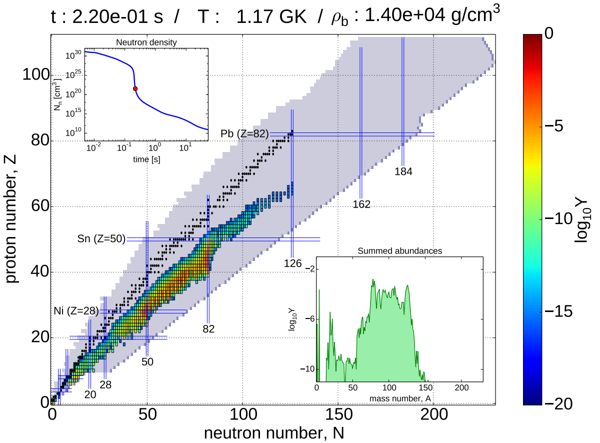
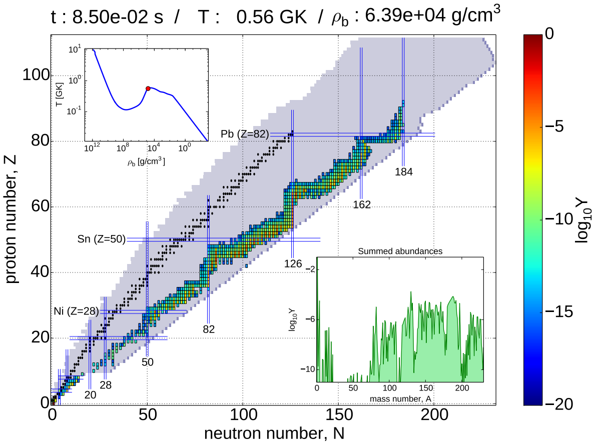
- Post-processing with `WINNET` (*Winteler et al. (2012)*)
- Over 5800 nuclei up to $Z = 111$
- Nuclear physics input:
  - Reaction rates from *Rauscher & Thielemann (2000)*
  - Neutrino absorption on nucleons
  - Fission (spontaneous, β-delayed, n-induced)
  - Heating from nuclear reactions (β-decays dominate)
- NSE for $T \geq 8$ GK
- Trajectories followed until $t_{\mathrm{sim}} \approx 200$ ms
- Adiabatic expansion with $\rho = \rho_0 \cdot (t_0/t)^3$
- More than 17000 trajectories analyzed

Example: neutrino-driven wind



Example: dynamic ejecta



(adapted from *Korobkin et al. (2012)*)

Mass-weighted final abundances

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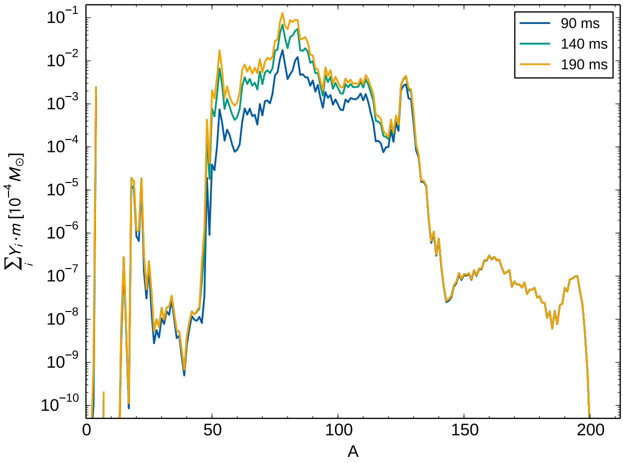
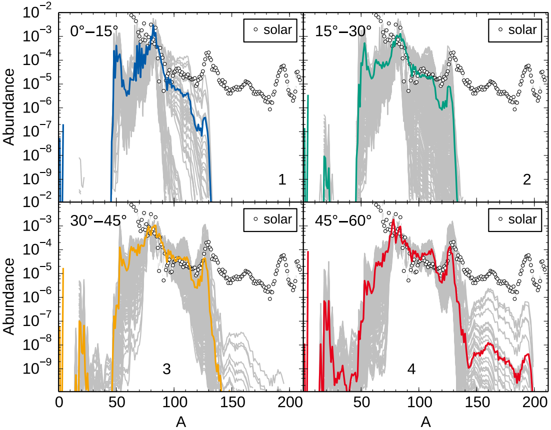
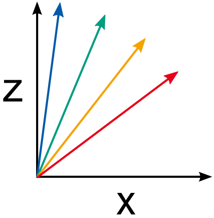


- Heavy nuclei produced early
- Then: Nuclei with $A \lesssim 120$
- Consequence of Y_e evolution

Integrated nucleosynthesis





- Solar system abundances from *Lodders (2003)*
- Nucleosynthesis depends on latitude

Mixing: dynamic vs. wind ejecta

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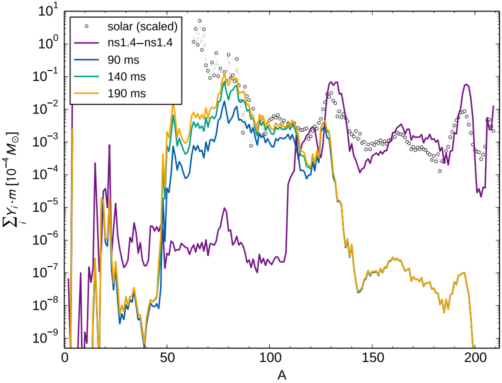

- Dynamic ejecta from a $1.4 M_\odot - 1.4 M_\odot$ merger (*Korobkin et al. (2012)*)
- $M_{\mathrm{ej,dyn.}} = 1.28 \cdot 10^{-2} M_\odot$
- Assumption: complete mixing
- Complementary nucleosynthesis
- Late-time ejecta? (cf. *Fernández & Metzger (2013)*, *Just et al. (2014)*)

Mixing: dynamic vs. wind ejecta

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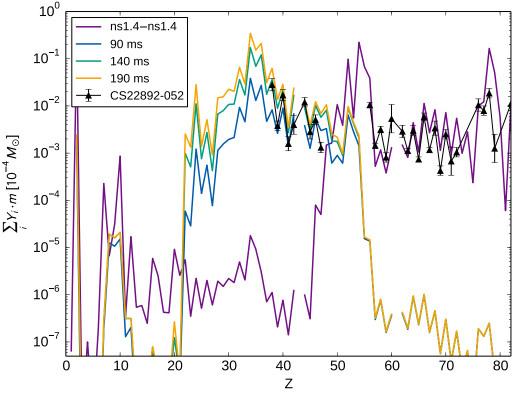

- CS22892-052: r-process enriched, metal-poor star
- Lighter heavy elements in neutrino-driven wind
- Observed pattern fairly well reproduced
- Deviations also due to nuclear physics input!

Light curves

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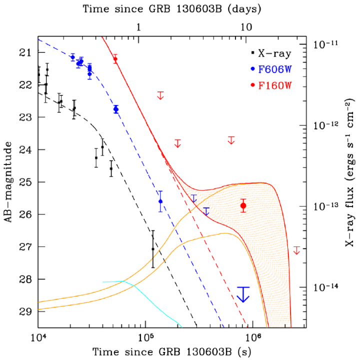
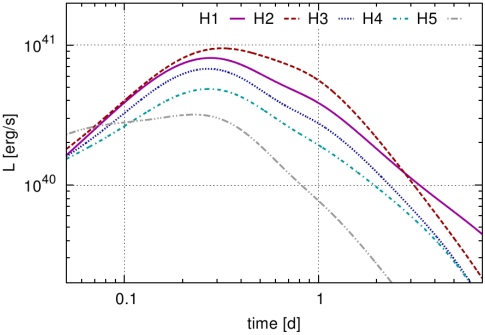
- Decay of radioactive nuclei produces EM transient
- Infrared data point explainable with dynamic ejecta
- Opacity depends on composition (*Kasen et al. (2013)*)
- Distinguish (*Kasen et al. (2014)*):
  - Ejecta with $Y_e \gtrsim 0.25$: blue component
  - Ejecta with $Y_e \lesssim 0.25$: red component



[Tanvir et al. (2013)]

Light curves

- Simple, spherical symmetry
- $M_{\text{ej,wind}} \approx 2 \cdot 10^{-3} M_\odot$
- Opacity κ = 1 cm^2/g
- Peak $\lesssim$ 1 day after merger
- Mixing with dynamic ejecta: increased opacity (cf. *Kasen et al. (2014)*)
- Angular dependence important



[Perego et al. (2014)]

Summary and outlook

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- NSMs plausible candidates for main r-process
- Different components of ejecta
- Time and angle dependence
- Neutrino-driven wind complements dynamic ejecta

- Nucleosynthesis yields from all ejecta need to be combined
- Total amount of ejecta still unclear
- Calculate light curves
- Chemical evolution $\rightarrow$ only/main r-process site?

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Thank you for your attention!

Backup: distribution of tracers

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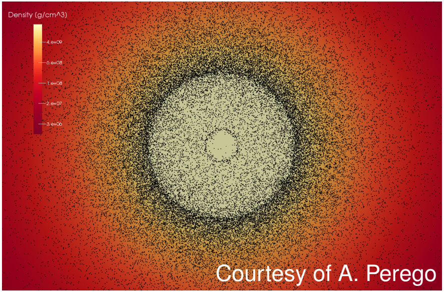
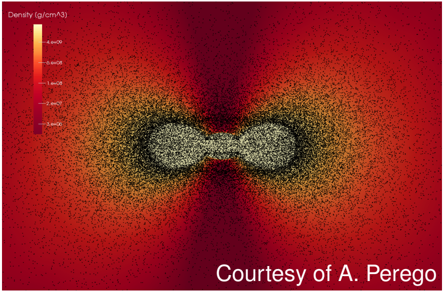


top view



side view

Backup: analytical estimates

Dynamical time-scale of the disk

$$t_{\text{dyn}} \sim 2\pi\Omega_K^{-1} \approx 0.011 \text{ s}$$

Lifetime of the accretion disk

$$t_{\text{disk}} \sim \alpha^{-1} \, (H/R)^{-2} \, \Omega_K^{-1} \approx 0.3 \text{ s}$$

Cooling time-scales

$$t_{\text{cool,ns}} \sim 3\frac{\tau_{\nu,\text{ns}} R_{\text{ns}}}{c} \approx 1.88 \text{ s}$$

$$t_{\text{cool,disk}} \sim 3\frac{\tau_{\nu,\text{disk}} H_{\text{disk}}}{c} \approx 1.68 \text{ ms}$$

Backup: analytical estimates

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Cooling luminosities

$$L_{\nu,\text{ns}} \sim \frac{\Delta E_{\text{ns}}}{t_{\text{diff,ns}}} \approx 1.86 \cdot 10^{52}\ \text{erg/s}$$

$$L_{\nu,\text{disk}} \sim 0.5\,\frac{\Delta E_{\text{grav}}}{t_{\text{disk}}} \approx 8.35 \cdot 10^{52}\ \text{erg/s}$$

Wind time-scale

$$t_{\text{wind}} \sim 0.07\ \text{s}\ \left(\frac{M_{\text{ns}}}{2.5 M_{\odot}}\right)\left(\frac{R_{\text{disk}}}{100\ \text{km}}\right)\left(\frac{L_{\nu_e}}{3 \cdot 10^{52}\ \text{erg/s}}\right)^{-1} \times \left(\frac{\xi}{1.5}\right)^{-1}\left(\frac{E_{\nu,\text{disk}}}{15\ \text{MeV}}\right)^{-2}$$