# Neutrino pair annihilation above neutron star merger remnants

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*(Credit: NASA/ University of Copenhagen)*

# Outline

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- Gamma ray bursts (GRB)
- Neutron star (NS) merger
- Neutrinos
- Results
- Comparison to observations

# Gamma ray bursts (GRB)

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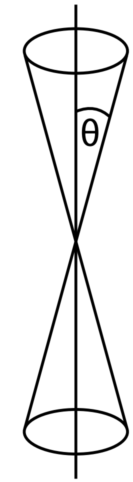
- Intense flashes of electromagnetic radiation

*Review: e.g. Berger 2014*

- Two classes: **short** (t < 2s) and long GRB (t ~ 30s)




- Nonthermal spectrum, observed energies: $E_{iso} \sim 10^{51}$ erg
- Collimated Outflows: source emitting into two cones

$$E_{\mathrm{true}} = E_{\mathrm{iso}} \cdot \frac{\Delta\Omega}{4\pi} \approx \frac{E_{\mathrm{iso}}}{65} \cdot \left(\frac{\theta^{\circ}}{10^{\circ}}\right)^2$$

*Rosswog, Brüggen 2007*

- $E_{true} \sim 10^{48}$ - $10^{49}$ erg *Lee & Ramirez-Ruiz 2007*

# Gamma ray bursts (GRB)

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- GRB are distributed isotropically → extragalactical
- Possible progenitor candidate: NS merger *e. g. Paczynski 1986, Eichler et al. 1989*
- Fireball model *e. g. Piran 1999, Nakar 2007*

➜ Central engine needs to provide a large enough energy reservoir and account for relativistic acceleration

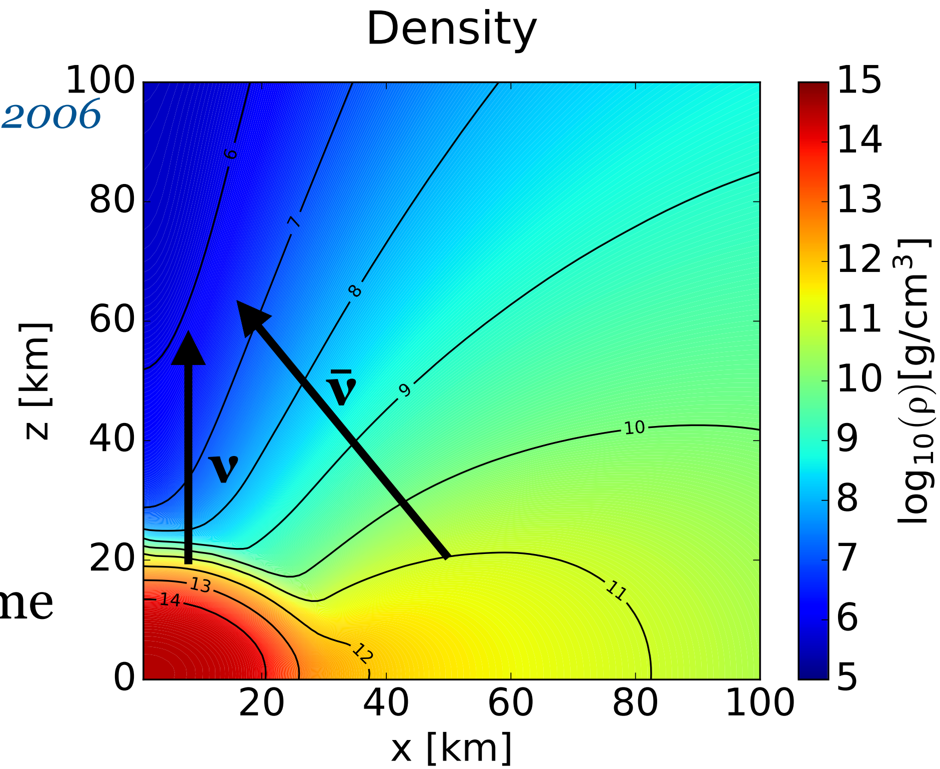
- Other mechanisms (e.g. magnetic fields) also possible

*e.g Metzger 2008*

# NS merger simulation *Perego et al. 2014*



- 3D, Newtonian, based on SPH merger simulation *Price & Rosswog 2006*
- $M_{NS} \sim 2.6\, M_{\odot}$, $M_{disk} \sim 0.18\, M_{\odot}$
- TM1 EOS
- Neutrino treatment: Energy dependent, spectral leakage scheme
- Three neutrino species: $\nu_e$, $\bar{\nu}_e$, $\nu_x$




*Snapshot at t ≈ 40 ms*

➜ Neutrinos from the NS and disk can deposit energy and momentum via pair annihilation *Eichler et al. 1989*

# Neutrino-antineutrino annihilation

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- Possibility for energy deposition: $\nu + \bar{\nu} \rightarrow e^{+} + e^{-}$

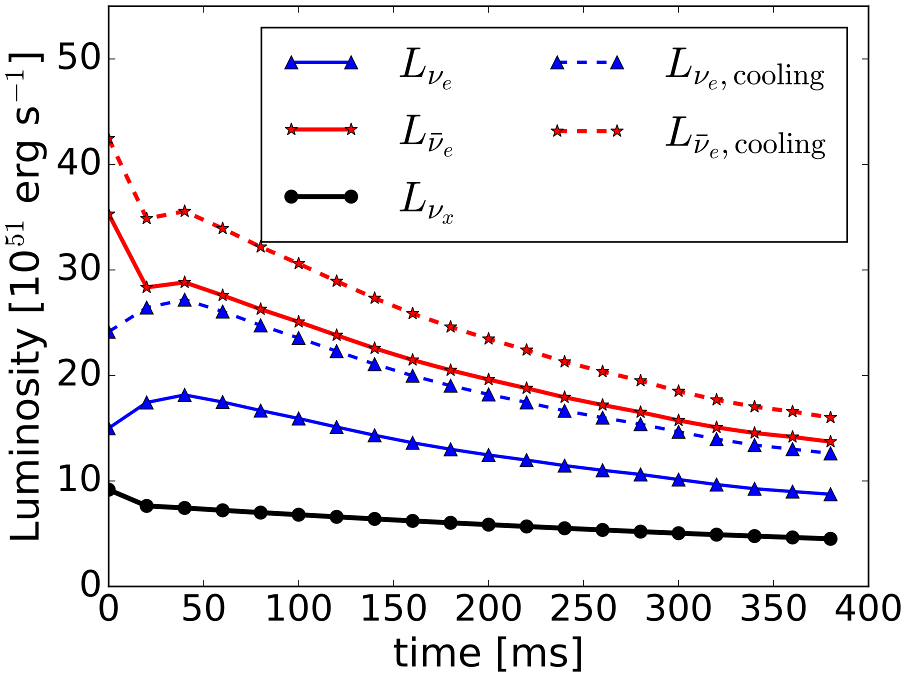
$$q_{\nu,\bar{\nu}} = \frac{1}{6} \frac{\sigma_0 \, (c_A^2 + c_V^2)}{c \, (m_e c^2)^2} \int d\Omega_\nu \int d\Omega_{\bar{\nu}} \int d\epsilon_\nu \int d\epsilon_{\bar{\nu}} \, (\epsilon_\nu + \epsilon_{\bar{\nu}}) \, I_\nu \, I_{\bar{\nu}} \, (1 - \cos\Phi)^2$$

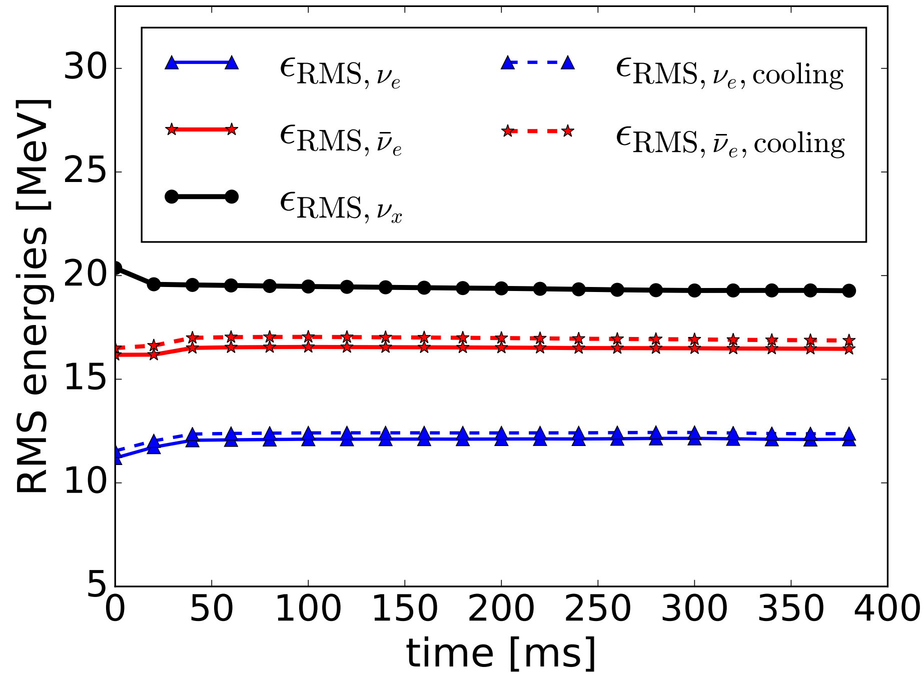
*Dessart et al. 2009*

- $\sigma_0 \simeq 1.71 \cdot 10^{-44}$ cm$^2$

- Energy deposition rate *q* depends on:
  - ⋆ Neutrino intensities (luminosities)
  - ⋆ Angle between the neutrinos Φ
  - ⋆ Neutrino energies

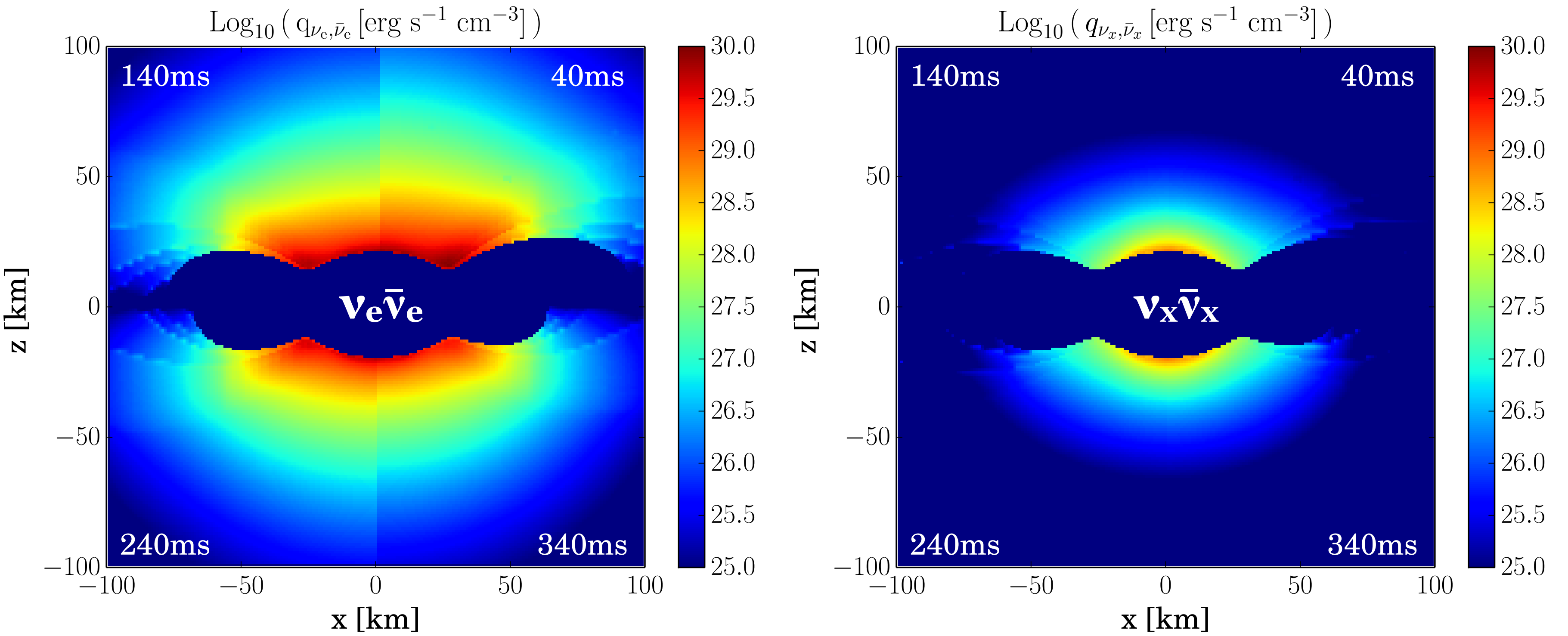
# Neutrino luminosities and energies




- Cooling: No absorption processes outside last scattering surfaces included
- NS luminosity from cooling/diffusion, disk luminosity from accretion

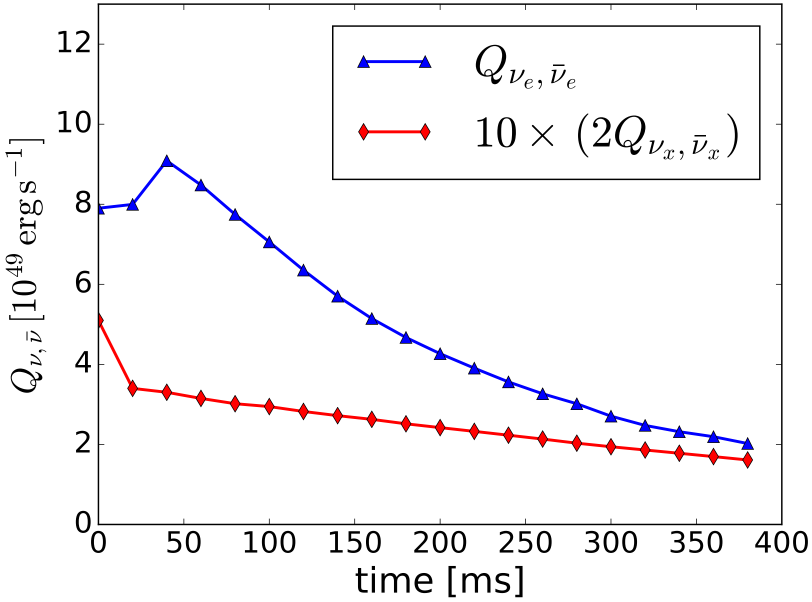
# Results

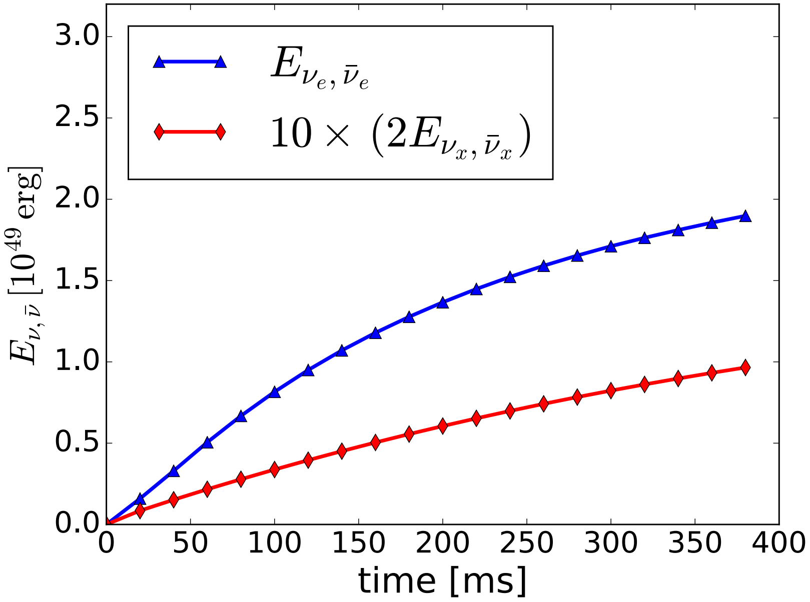



- Energy deposition rate for $\nu_e\bar{\nu}_e$ larger compared to $\nu_x\bar{\nu}_x$:

$$( c_A^2 + c_V^2 )_{\nu_e\bar{\nu}_e} / ( c_A^2 + c_V^2 )_{\nu_x\bar{\nu}_x} \approx 4.6 \qquad L_{\nu_e}L_{\bar{\nu}_e} / ( L_{\nu_x}L_{\bar{\nu}_x} ) \approx 12$$

# Results




- Volume integrated energy deposition rates: $Q_\nu(t) = \int_V q_\nu(t,x)\, dV$
- Time integrated energy deposition rates: $E_\nu(t) = \int_t Q_\nu(t')\, dt'$
- At t = 380 ms: $\mathbf{E_{tot} = 1.95 \cdot 10^{49}}$ **erg**

# Role of the hypermassive NS

- Split neutrinos into two groups: NS and disk (DS)

- Intensity calculated via:

  $I_\nu = I_{\nu,\,NS} + I_{\nu,\,DS}$

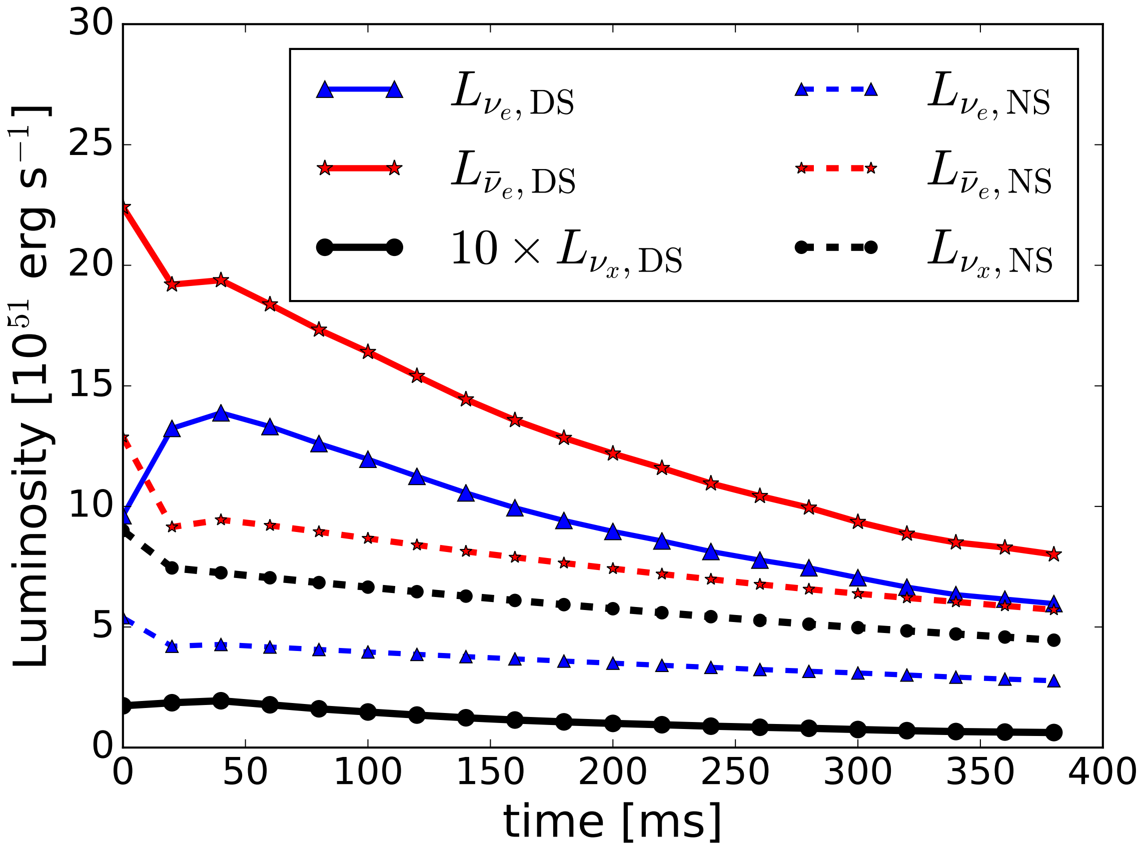
- Deposition rate:

  $q_\nu = q_{\nu,\,NS\text{-}NS} +$

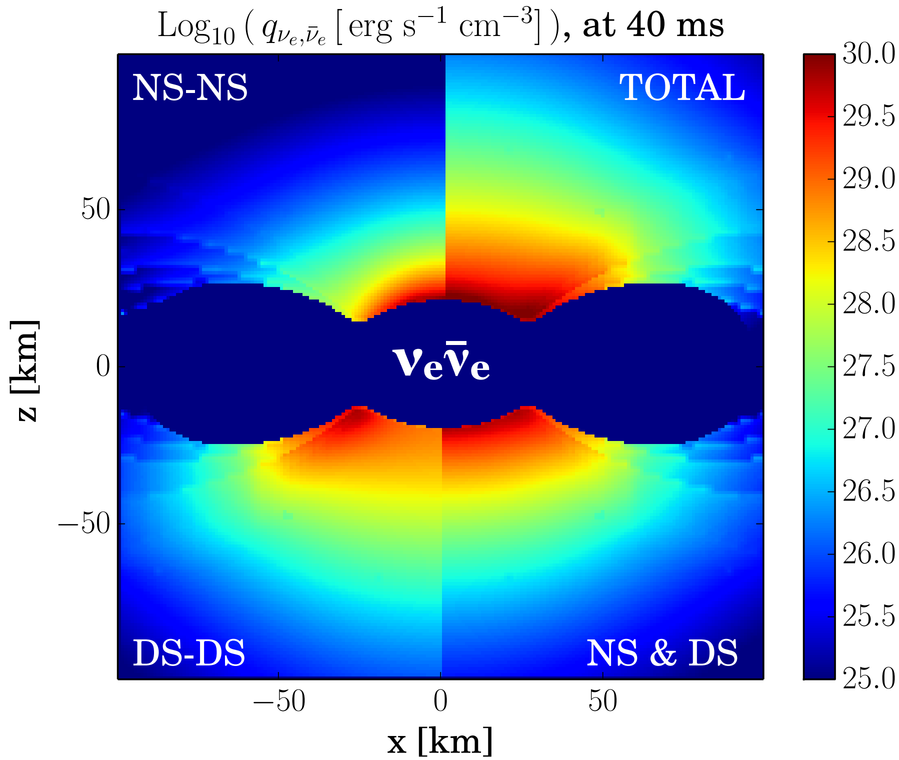
  $q_{\nu,\,NS\text{-}DS} +$

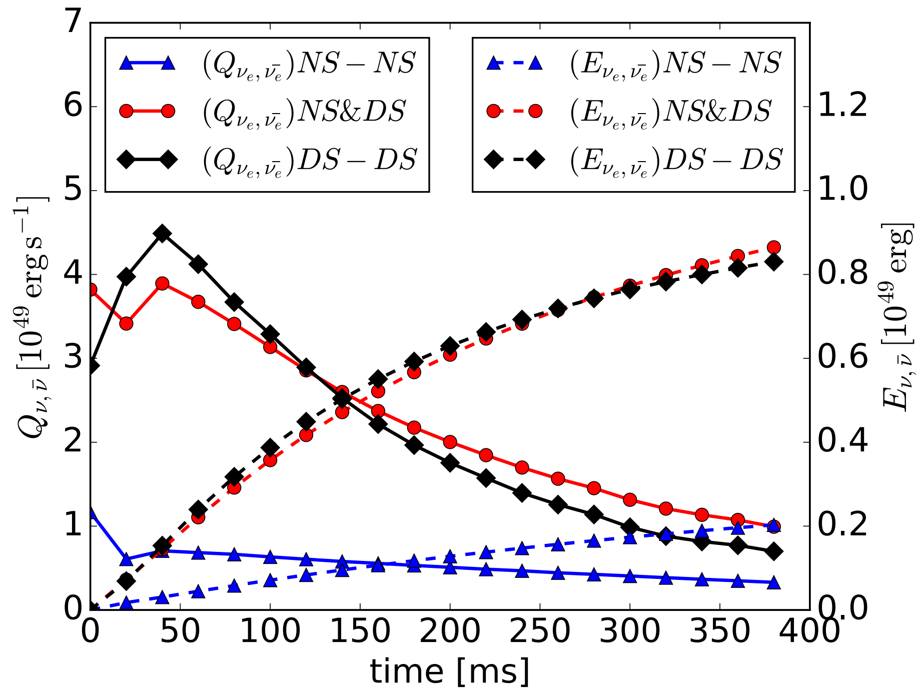
  $q_{\nu,\,DS\text{-}NS} +$

  $q_{\nu,\,DS\text{-}DS}$



# Role of the hypermassive NS

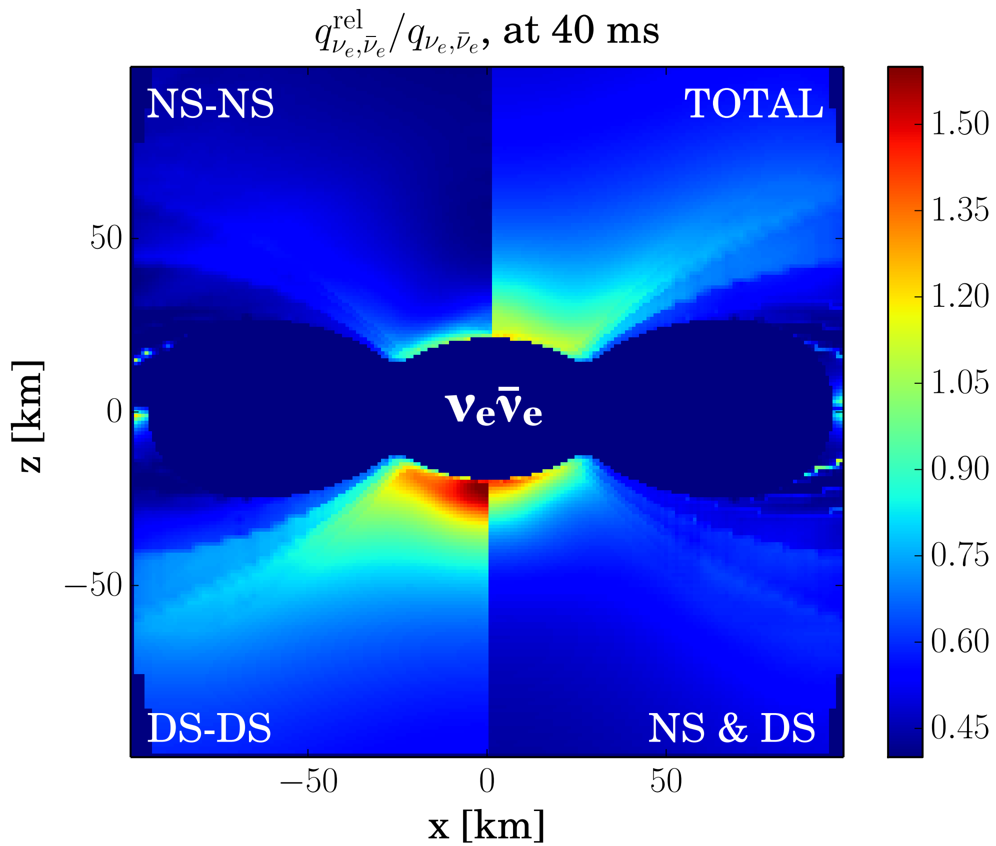



- Contribution from NS not negligible
- Contributions from NS-DS and DS-DS comparable

# Relativistic effects

- Include relativistic effects in the ν propagation:
  - Doppler effect ↑
  - Beaming effects ↓
  - Redshift ↓, blueshift ↑
  - Light bending ↑
- Local changes up ~ 50%
- Effects do not change behavior qualitatively

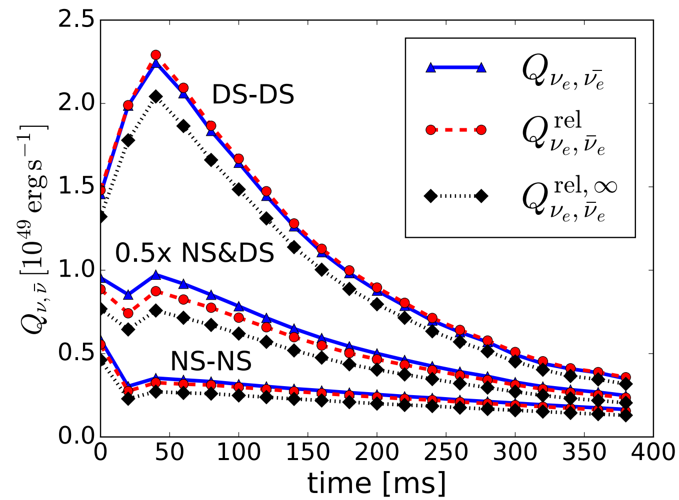


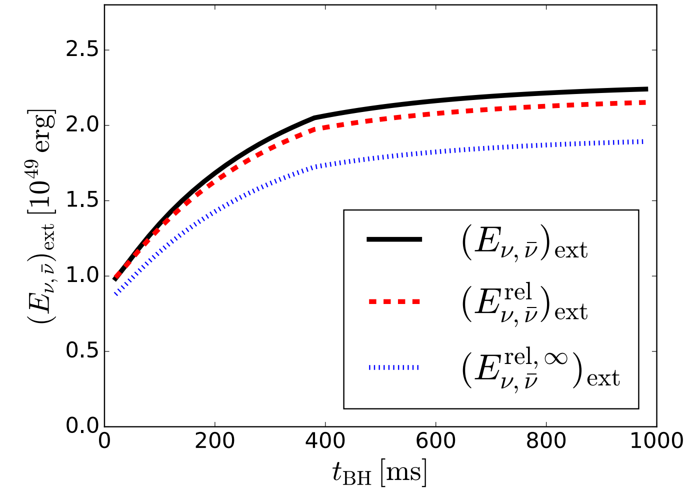
# Comparison, NS collapse

- Differentiate energy deposition in the local frames $Q^{rel}$ and measured by an infinitely distant observer $Q^{rel,\infty}$

- Impact of a possible NS collapse (at $t_{BH}$) and black hole (BH) formation (only DS-DS contribution) can be investigated

| | $E_{\nu,\,nrel}$ [$10^{49}$ erg] | $E_{\nu,\,rel}$ [$10^{49}$ erg] | $E_{\nu,\,rel\infty}$ [$10^{49}$ erg] |
|---|---|---|---|
| 380 ms | 1.95 | 1.88 | 1.64 |
| 1000 ms | 2.24 | 2.15 | 1.89 |



# Geometrical factor

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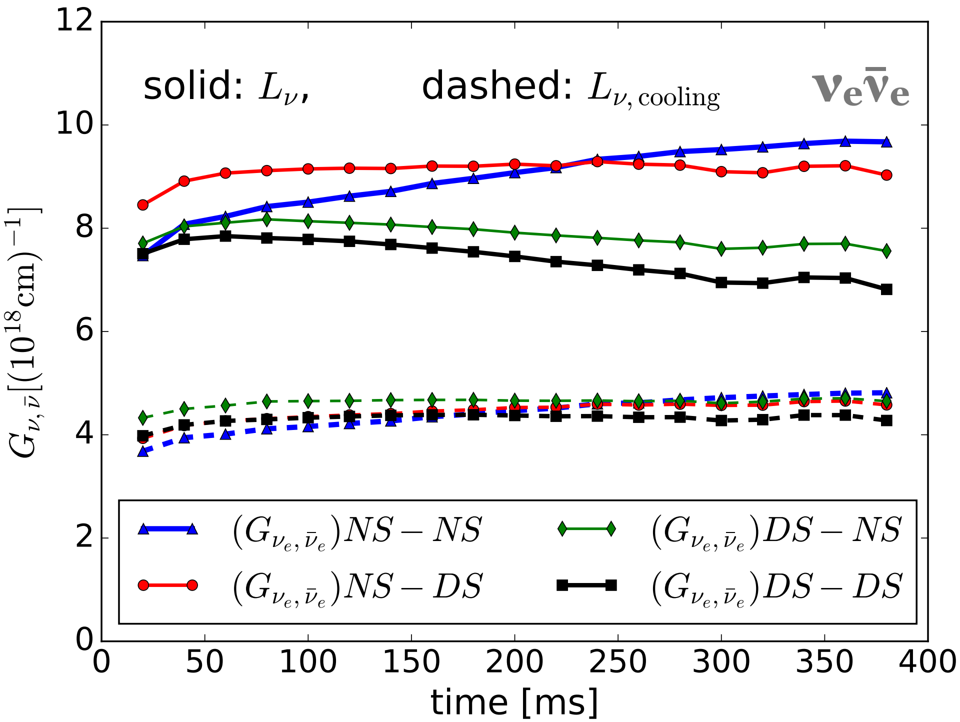
- Investigation of a possible parametrization for the deposition rates $Q_\nu$

$$(Q_{\nu,\bar{\nu}})_{i,j} \approx \text{const.} \cdot \; L_{\nu,i} \; L_{\bar{\nu},j} \; (G_{\nu,\bar{\nu}})_{i,j} \left[ \frac{\langle \epsilon^2_{\nu,i} \rangle}{\langle \epsilon_{\nu,i} \rangle} + \frac{\langle \epsilon^2_{\bar{\nu},j} \rangle}{\langle \epsilon_{\bar{\nu},j} \rangle} \right]$$

*i, j* = {NS; DS}

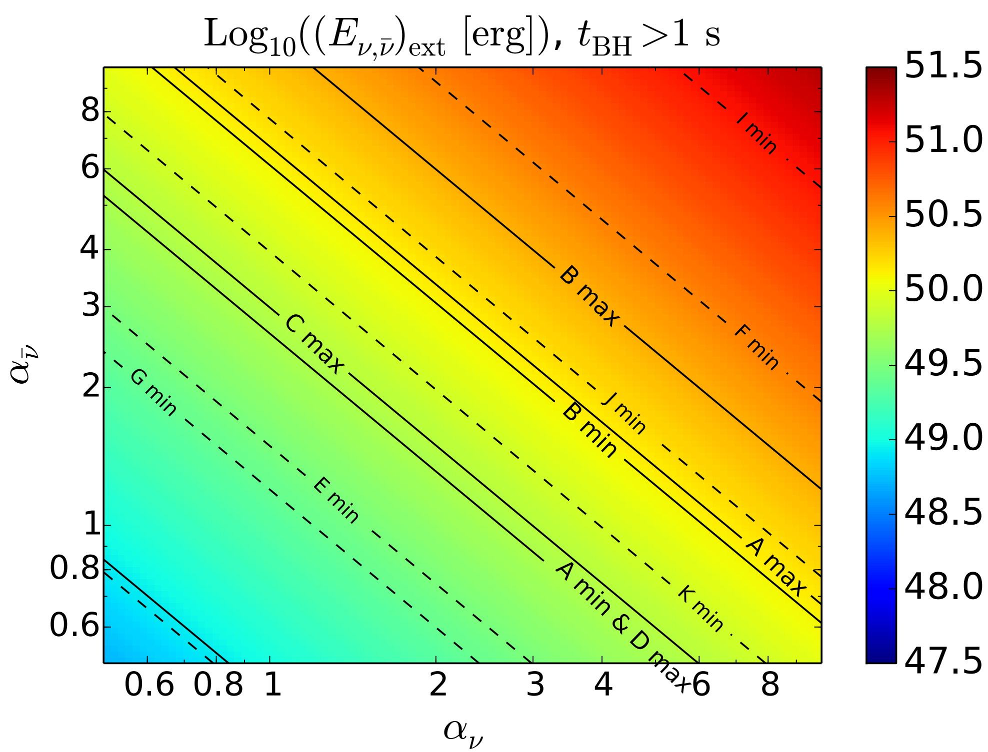
*e.g. Goodman 87, Janka 91*




- Provide global information about $Q_\nu$ based on neutrino emission ($L_\nu$) and on geometry of the system ($G_\nu$)
- Cooling luminosities more const.
- Similar for $\nu_x$

# Comparison with observations

- Comparison of extrapolated $E_{\nu\bar{\nu}}$ with energetics of observed short GRBs




- Rescale: $L_\nu \rightarrow \alpha_\nu L_\nu$
- $\alpha_\nu = \alpha_{\bar{\nu}} = 1$ corresponds to our simulation
- Solid lines: values for opening angle available
- Dashed lines: only lower estimates
- NS ↔ DS also possible

# Conclusions

*arXiv:1701.02017*

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- Energy deposition at 380 ms of $E_{tot} = 1.95 \cdot 10^{49}$ erg
- The hypermassive NS adds important contribution (factor of $\sim 2$), relativistic effects affect $E$ by at most 20%
- Possible parametrization introduced
- Comparison to observations require higher luminosities (GR simulations?)
- BH formation + energy extraction from accreting BH also possible (baryonic pollution problem) *e.g Just et al. 2016*
- Other mechanisms (e.g. magnetic fields) are also likely to contribute *e.g Metzger 2008*