Extended emission in short GRBs from fallback accretion

Carlo Musolino, Raphaël Duqué, Luciano Rezzolla — Goethe University (in prep.)
EM signals from BNS mergers originate in different components of the outflow…

- circum-merger medium
- (structured) relativistic jet
- jet-driven shock
- jet-ejecta cocoon
- $\nu$- and $\mathbf{B}$-winds (disk and remnant)
- remnant accretion disk
- dynamical ejecta (tidal and merger)
- pre-merger plasmas (e.g., magnetospheric)

(see, e.g., Ascenzi et al. 2019)
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- short GRBs
- BNS (GW170817)
- forward-shock afterglow
- gamma-ray prompt emission
- shock breakout radiation (Matsumoto et al. 2019a,b)
- lanthanide-poor (blue) kilonova
- lanthanide-rich (red) kilonova
- precursor signal
- inspiral signal
A focus on *fallback accretion*: what dynamics and EM signatures?

**Questions:**
- What *dynamics* for the fallback flow?
- What *radiation* from this flow component?
- New explanation for *extended emission* of sGRB?
A focus on *fallback accretion*: what dynamics and EM signatures?

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- New explanation for **extended emission** of sGRB?

**Recent work on fallback accretion:**
- Metzger & Fernandez 2021: focus on excess in GW170817 afterglow (newtonian + neutrinos)
- Ishizaki et al. 2021a,b: effect of intra-fallback nuclear reactions
The relative importance (or existence) of the EM signals is determined by the BNS parameters

\( q = \frac{M_2}{M_1}, \text{EoS, } \vec{B}_{1,2}, \ldots \)
Methodology: Multi-physics high-performance numerical simulations

- neutrino transport
- r-process heating
- GRMHD processes
- strong gravity
- dynamic space-time

initial data → HPC simulations → Einstein Toolkit (Löffler et al. 2012) → post-processing (EM emission models) → EM signals → sGRB phenomenology
**Methodology: Second-moment (M1) neutrino transport**

**Neutrino transport necessary:**
- Effect on post-merger hydrodynamics (through cooling)
- Effect on r-process heating (sets $Y_e$)

**M1 scheme:**
Set the neutrino (grey) flux $F^i$ in the finite-volume evolution as a function of the local fluid fields.

(Musolino et al. 2023)

**Optically thick region:**
- Neutrinos in LTE
- Isotropic flux of black-body neutrinos

**Optically thin region:**
- Neutrinos in free stream

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The material that will fall back is gravitationally bound \((u_t > -1)\).

**First results:**
- **Significant mass** of bound ejecta: \(M_{\text{bound}} \gtrsim 10^{-3} M_\odot\)
- Transition unbound \(\rightarrow\) bound
- Bound ejecta is **nearly isotropic**
- \(q\) and \(EoS\) influence the ejection dynamics
Effect of the EoS on merger remnant and long-term ejection

**Our runbench:**

<table>
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<tr>
<th>Label</th>
<th>$M_1$ [$M_\odot$]</th>
<th>$M_2$ [$M_\odot$]</th>
<th>$q$</th>
<th>EoS</th>
<th>$t_{\text{collapse}}$ [ms]</th>
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<td>1</td>
<td>TNTyst</td>
<td>–</td>
</tr>
<tr>
<td>TNTyst-q.75</td>
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<td>–</td>
</tr>
</tbody>
</table>

**SFHo-q1.0**

(Musolino, Duqué et al., in prep.)

**TNTyst-q1.0**

(post-merger winds)
The fallback accretion rate is determined by the orbital energy distribution

**Rees’ hypothesis for TDEs:**
"uniform mass distribution of orbital energy in the debris"

\[ \frac{dM_{FB}}{d\epsilon} = \text{cst} \iff \dot{M}_{FB} \propto t^{-5/3} \]

(Rees, 1988)

**Result:**
Rees’ hypothesis checked for *tidal and merger ejecta* (SFHo systems) and for *post-merger winds* (TNTyst systems)

(Musolino, Duqué et al. in prep.)
The binary mass-ratio $q$ and EoS influence the ejection dynamics… but the fallback accretion rate is remarkably universal!

**Results:**
- Rees’ universal slope $t^{-5/3}$ recovered
- **Significant accretion** on long timescales: $t_{FB} \gtrsim 100$ s
- Luminosity $L_{FB} > 10^{46}$ erg/s over 100 s potentially

$\Rightarrow$ New explanation for extended emission in sGRBs?

(Musolino, Duqué et al. in prep.)
A new explanation for extended emission in sGRBs?

Extended emission in sGRBs:
- In gamma- and X-rays, $t \gtrsim 100 \text{ s}$
- Can carry more total energy than GRB prompt emission
- Softer spectrum than prompt emission (see, e.g., Kaneko et al. 2015, Kagawa et al. 2015)

Models for extended emission:
- BH launches 2nd jet after disk or fallback accretion (Barkov & Pozanenko 2011, Kisaka & Ioka 2015)
- Radiation originates from post-merger magnetar (Metzger et al. 2008, Murase et al. 2018)
A new picture for $\gamma$-ray and X-ray extended-emission in sGRBs

**Semi-analytical treatment for emission model:**

1. M1 scheme provides $Y_e$, $T$ at $t = 0$
2. r-process heating of the ejecta using SkyNET (Lippuner et al. 2015)
3. Temperature evolution of ejecta $T_\phi(t)$
4. Black-body emission spectrum

(Musolino, Duqué et al., in prep.)
A new picture for $\gamma$-ray and X-ray extended-emission in sGRBs

**Results:**
- Significant luminosity and duration
- Radiation dominates $\gamma$-rays then X-rays

**Key features** of extended-emission:
- Softer than prompt emission (Gehrels et al. 2006, Kaneko et al. 2015)
- Exponential cutoff (Kawaga et al. 2015)

- Emission slope is $t^{-3.5}$, shallower than 2nd-jet models (Kisaka et al. 2015)

**Discussion:**
- Visibility conditions of this radiation?
- Flex level and time-scale determined by initial $Y_e$ and total fallback mass
- Effect on other counterparts, e.g., the kilonova
Effect of fallback radiation on the kilonova signal

Effect on KN:
- The fallback radiation outside the polar region can be reprocessed in the kilonova radiation
- This is a new source of uncertainty in kilonova calorimetry
- Requirement of massive blue ejecta in GW170817? (Metzger et al. 2018)

Order of magnitude of effect:
\[
\frac{\Delta L_{\text{KN}}}{L_{\text{KN}}} \sim \frac{M_{\text{bound}}}{M_{\text{unbound}}} \lesssim 50 \%
\]
+ fallback radiation efficiency
+ reprocessing efficiency
Conclusions

On the method:

- **HPC simulations with semi-analytical post-processing** is a fruitful and resource-efficient method to study the EM counterparts of BNS mergers.
- This bottom-up approach **bridges the (large) gap between binary parameters and astronomical observables.**

On fallback accretion in BNS mergers:

- There is a significant component of the ejecta in BNS mergers that remains bound to the remnant compact object; it should be further studied.
- The fallback material is heated and radiates in the high-energy bands similarly to extended emission in short GRBs.
- The fallback radiation **likely impacts the kilonova signal,** it is a new unknown in KN calorimetry.
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Semi-analytical treatment for the fallback dynamics

**Fallback dynamics:**
- Total mass $M_{FB}$ launched at $t = 0$
- Pure radial motion $\vec{v} = v_r(r, t)\hat{e}_r$
- Pure free-fall dynamics
- $\dot{M}_{FB} \propto t^{-5/3}$

**Emission model:**
r-process heating of the photosphere using SkyNET

**Results:**
- Photosphere is on leading edge
- Temperature evolution of photosphere $T_\phi(t)$

Photosphere position determined with $\kappa = 1 \text{ cm}^2/\text{g}$ (under-estimated)

(Musolino, Duqué et al. in prep.)
A good methodology for the combined study of EM counterparts

- **Bound material** → GRB extended emission
- **Unbound material** → kilonova signal
- **Post-merger disk** → GRB prompt emission
- **(relativistic jet)** → GRB prompt emission and afterglow

A single simulation: ~ 0.5 Mcpuh

Raphaël Duqué