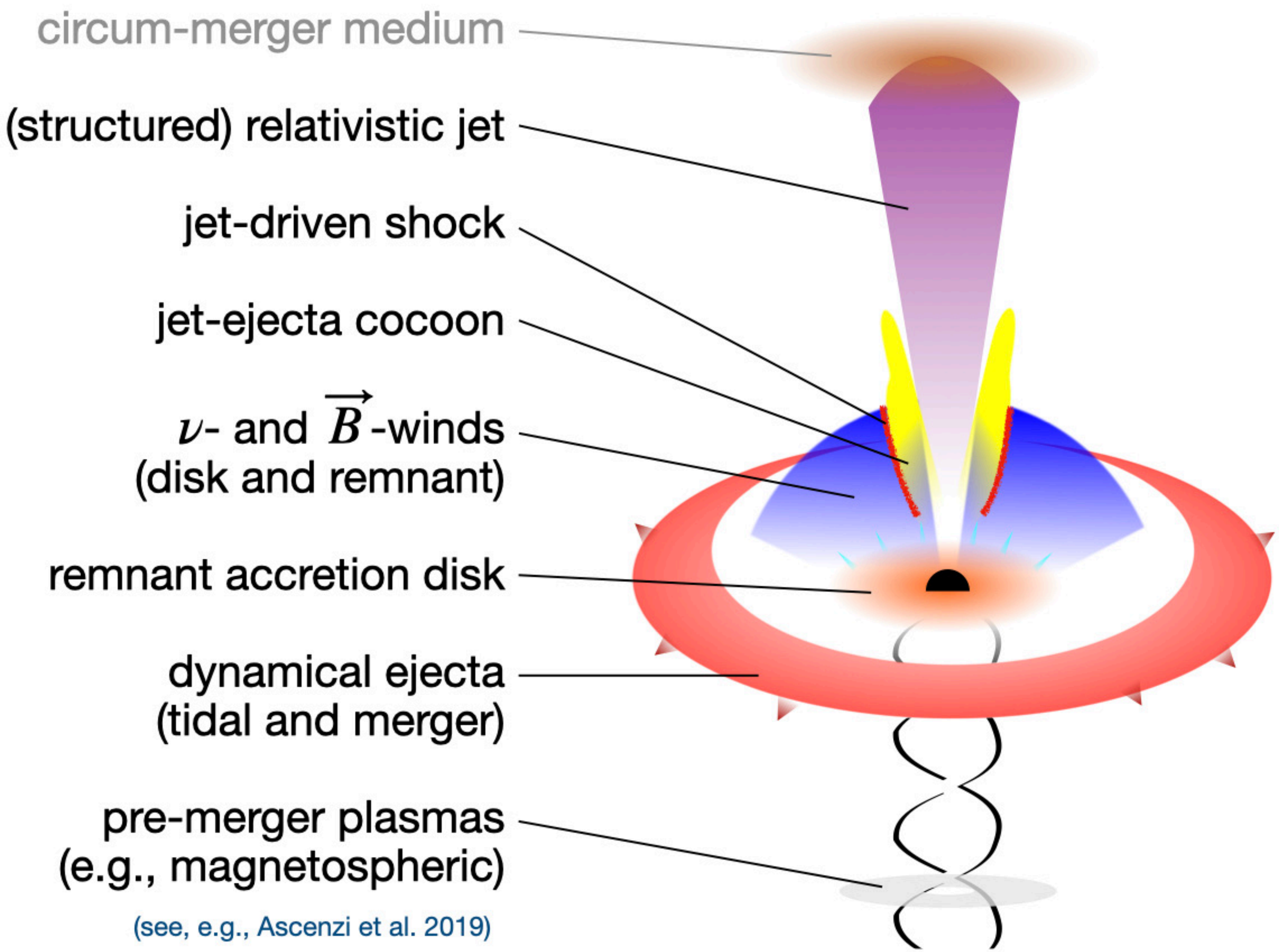
Extended emission in short GRBs from fallback accretion

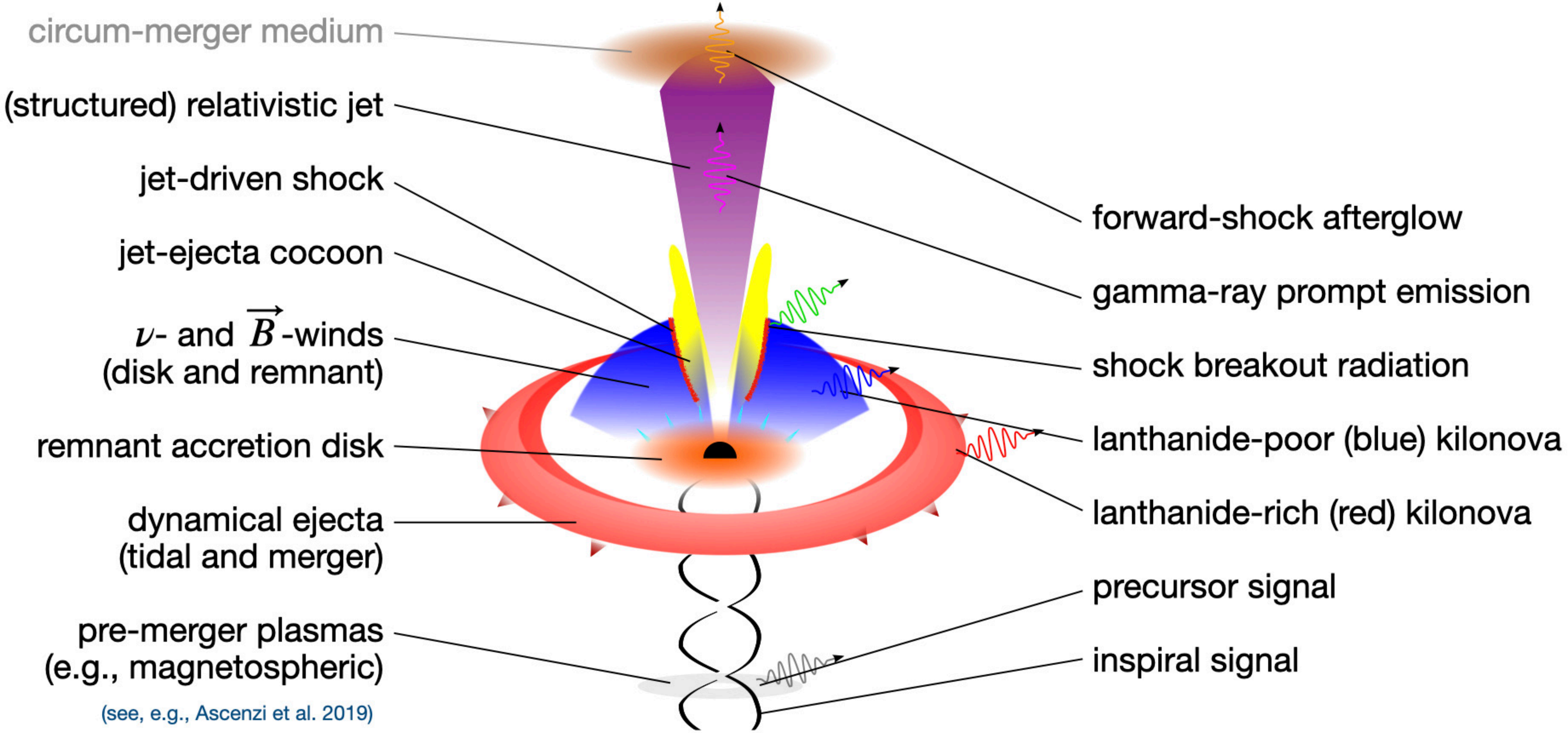
Carlo Musolino, Raphaël Duqué, Luciano Rezzolla — Goethe University
(in prep.)

EM signals from BNS mergers originate in different components of the outflow…



(see, e.g., Ascenzi et al. 2019)

EM signals from BNS mergers originate in different components of the outflow…
… and make up their multi-messenger phenomenology



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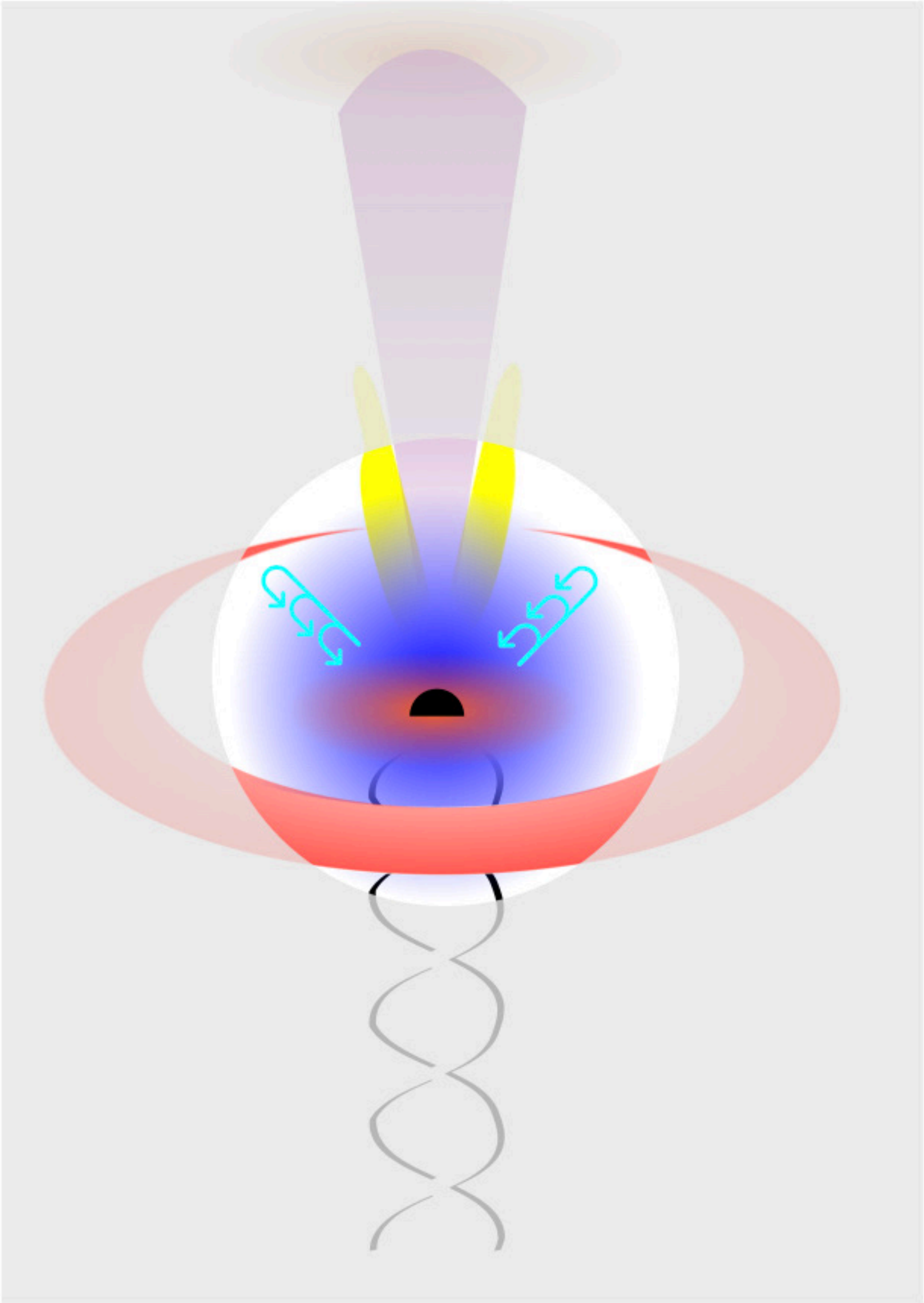
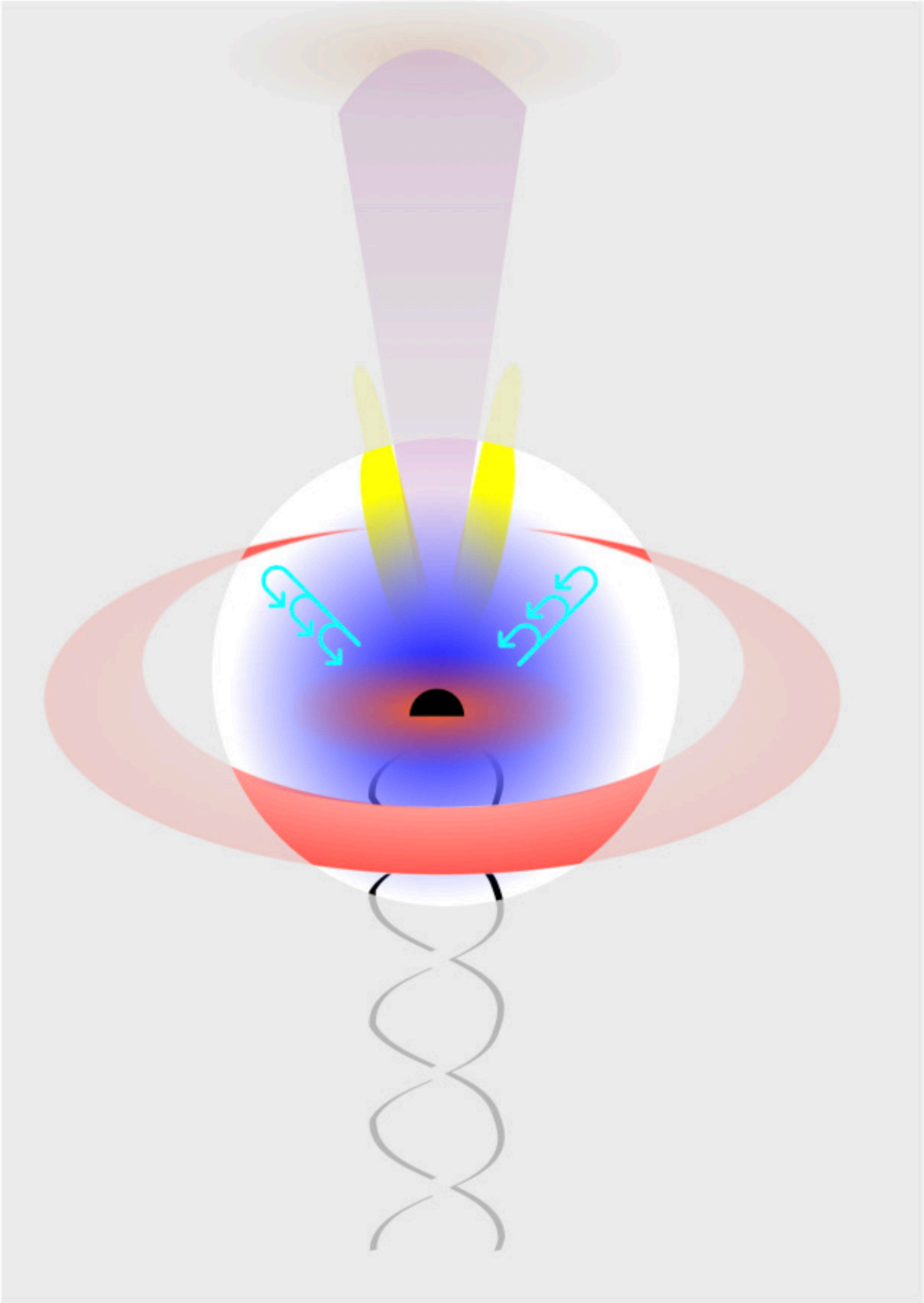
A focus on *fallback accretion*: what dynamics and EM signatures?



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?



Questions:

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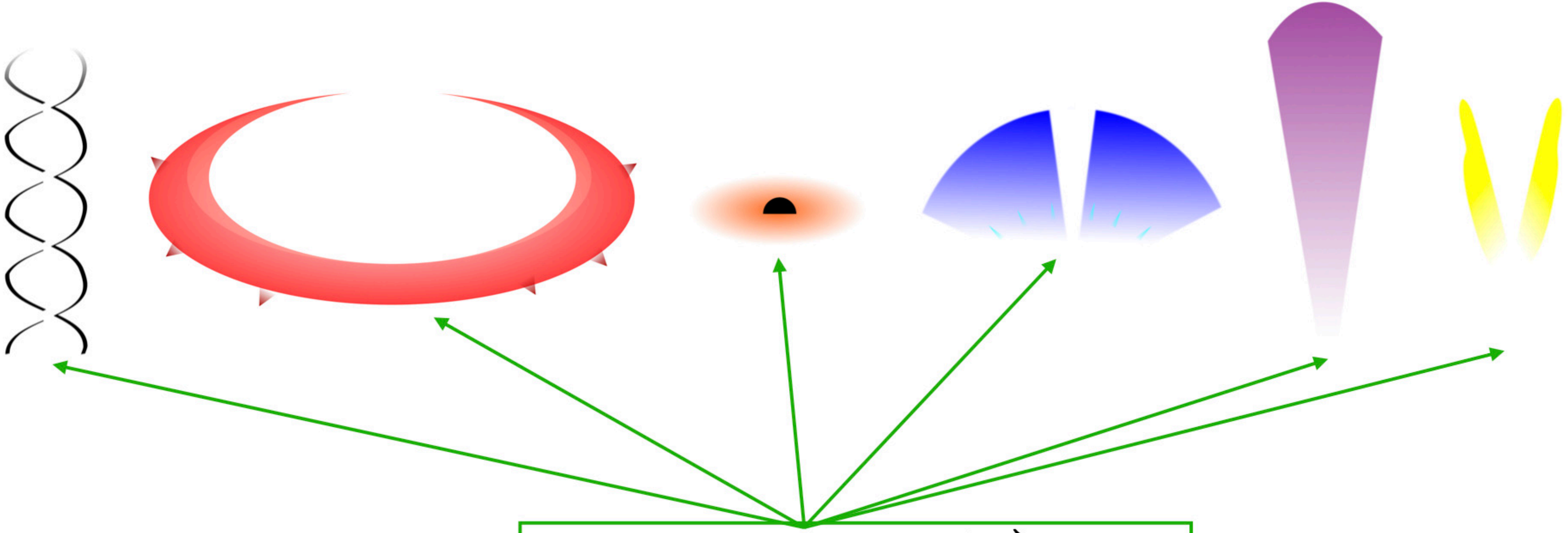
Recent work on fallback accretion:

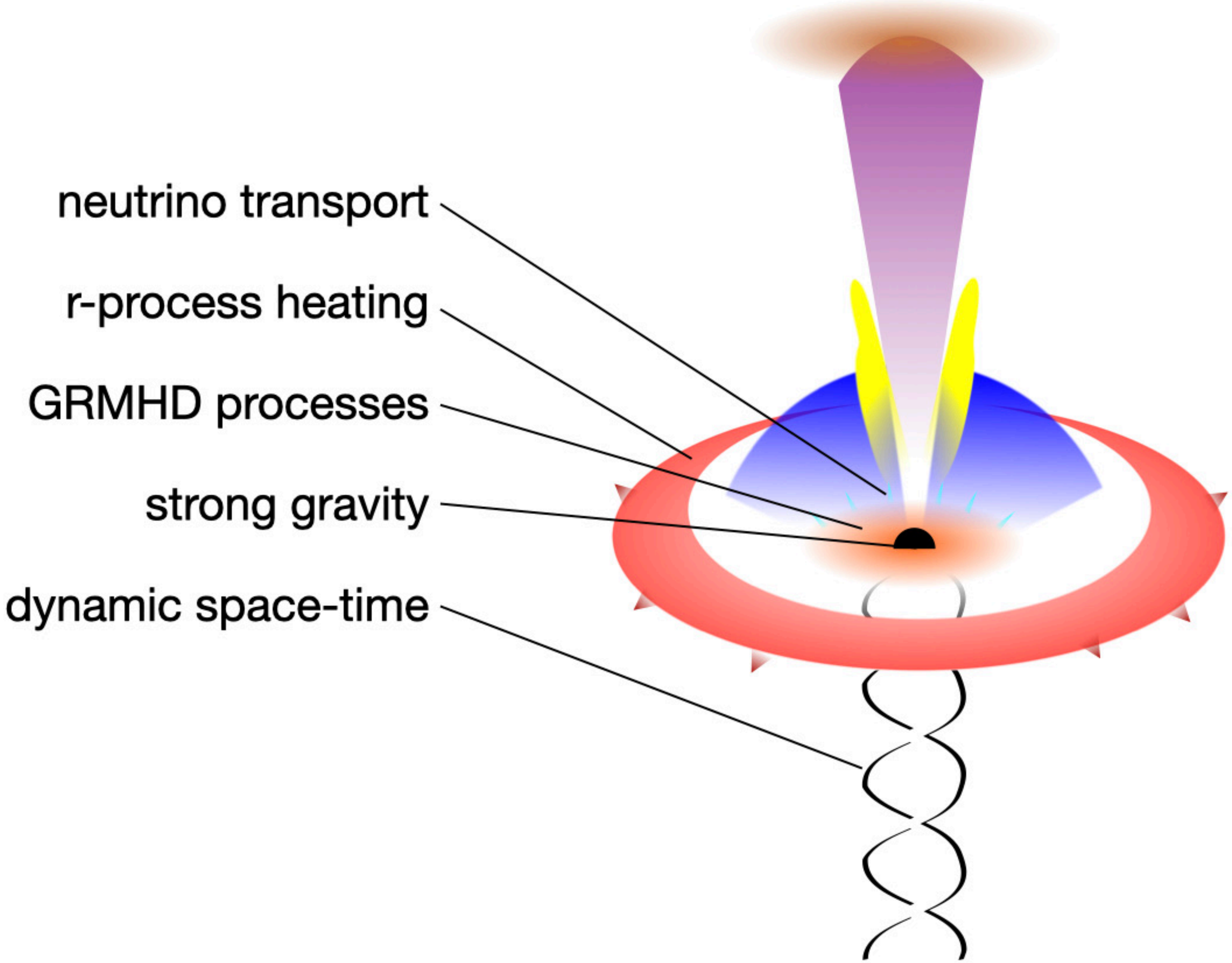
- Metzger & Fernandez 2021: focus on excess in GW170817 afterglow (newtonian + neutrinos)
- Ishizaki et al. 2021a,b: effect of intra-fallback nuclear reactions

The relative importance (or existence) of the EM signals is determined by the BNS parameters



$$(q = M_2/M_1, \text{EoS}, \overrightarrow{B}_{1,2}, \ldots)$$

Methodology: Multi-physics high-performance numerical simulations



initial data

↓ *HPC simulations*

einstein toolkit (Löffler et al. 2012)

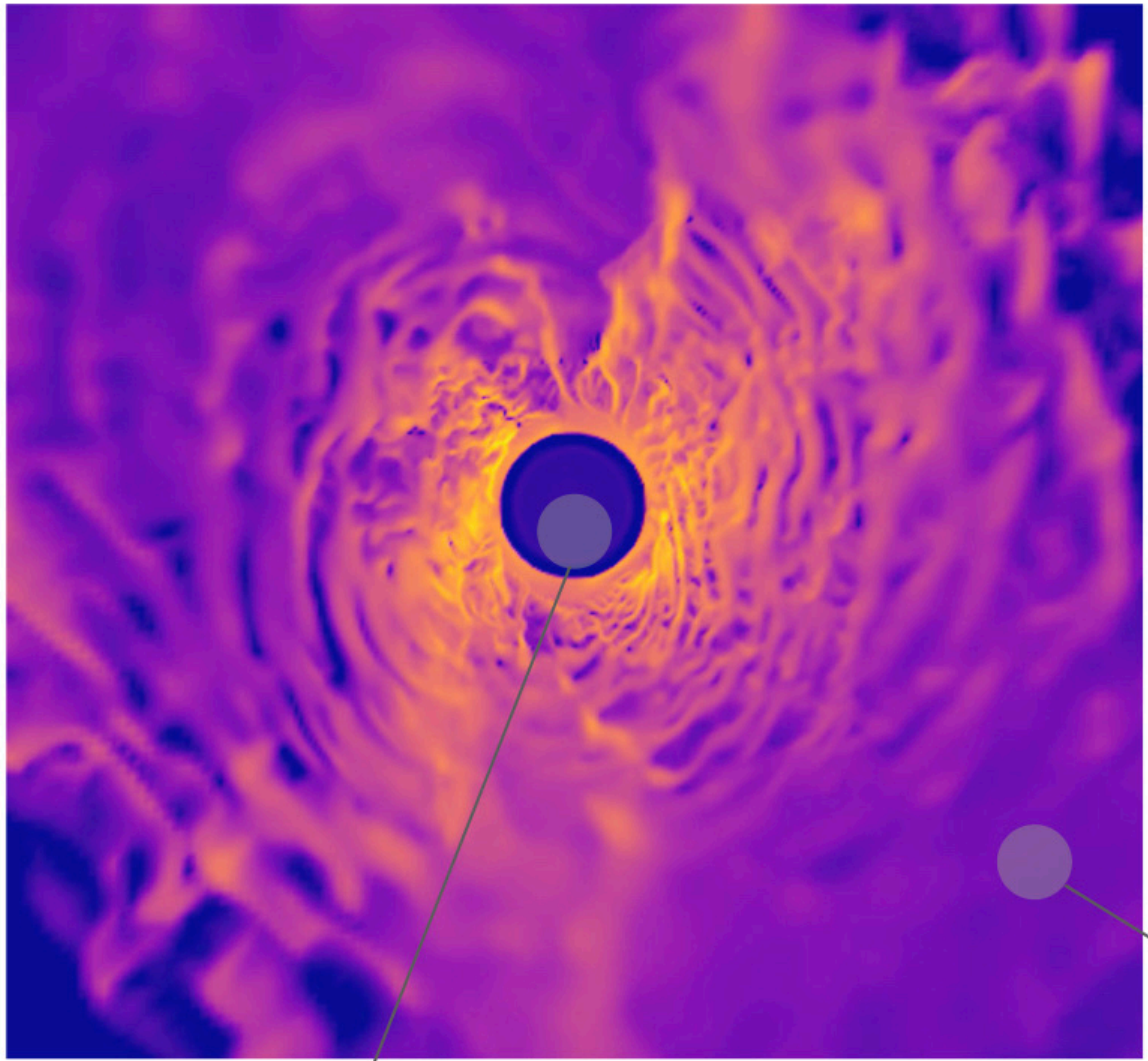
↓ *post-processing (EM emission models)*

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_ν in the finite-volume evolution as a function of the local fluid fields.

(Musolino et al. 2023)

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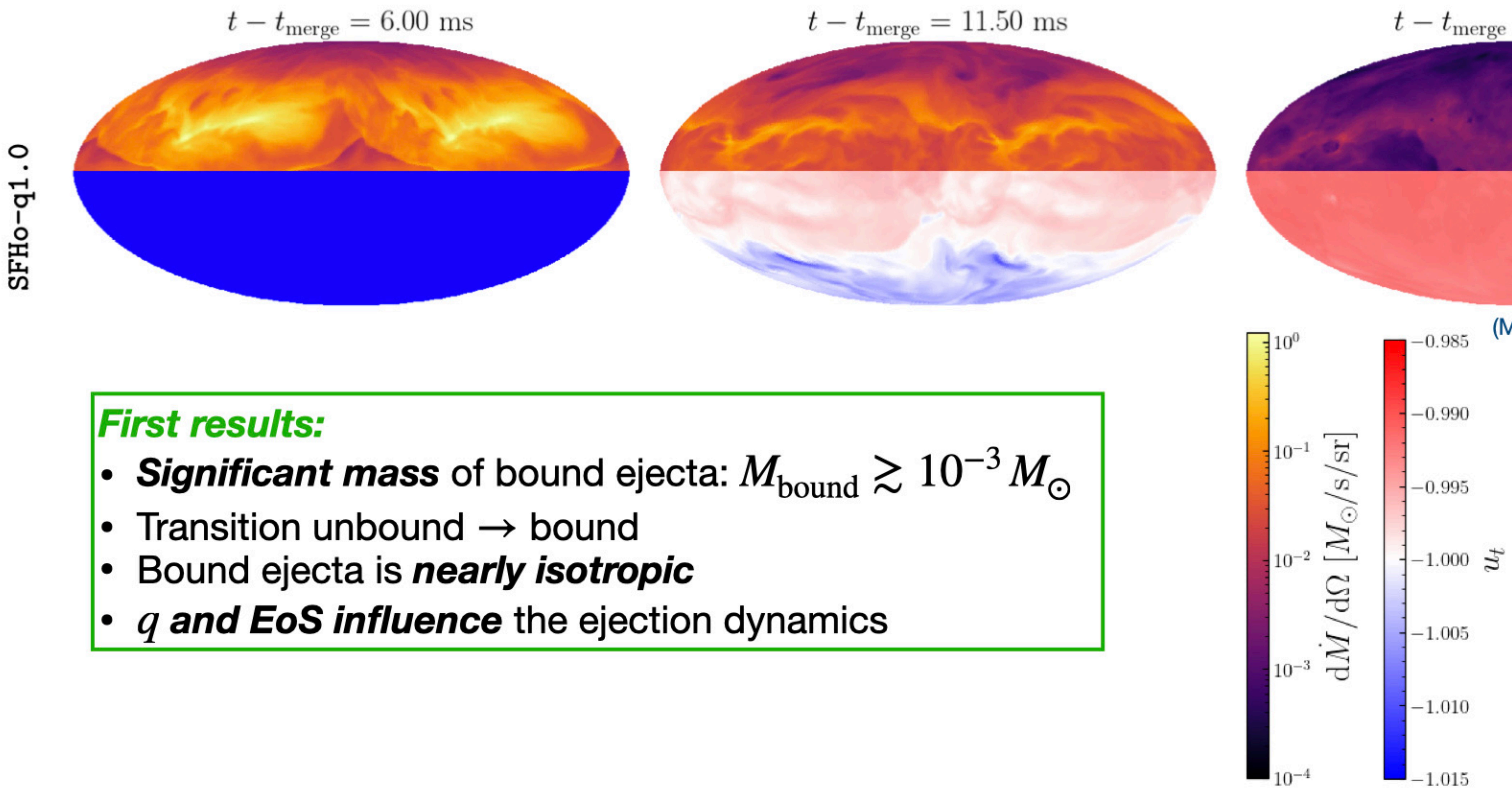
The material that will fall back is gravitationally bound ($u_t > -1$)



(Musolino, Duqué et al. in prep.)

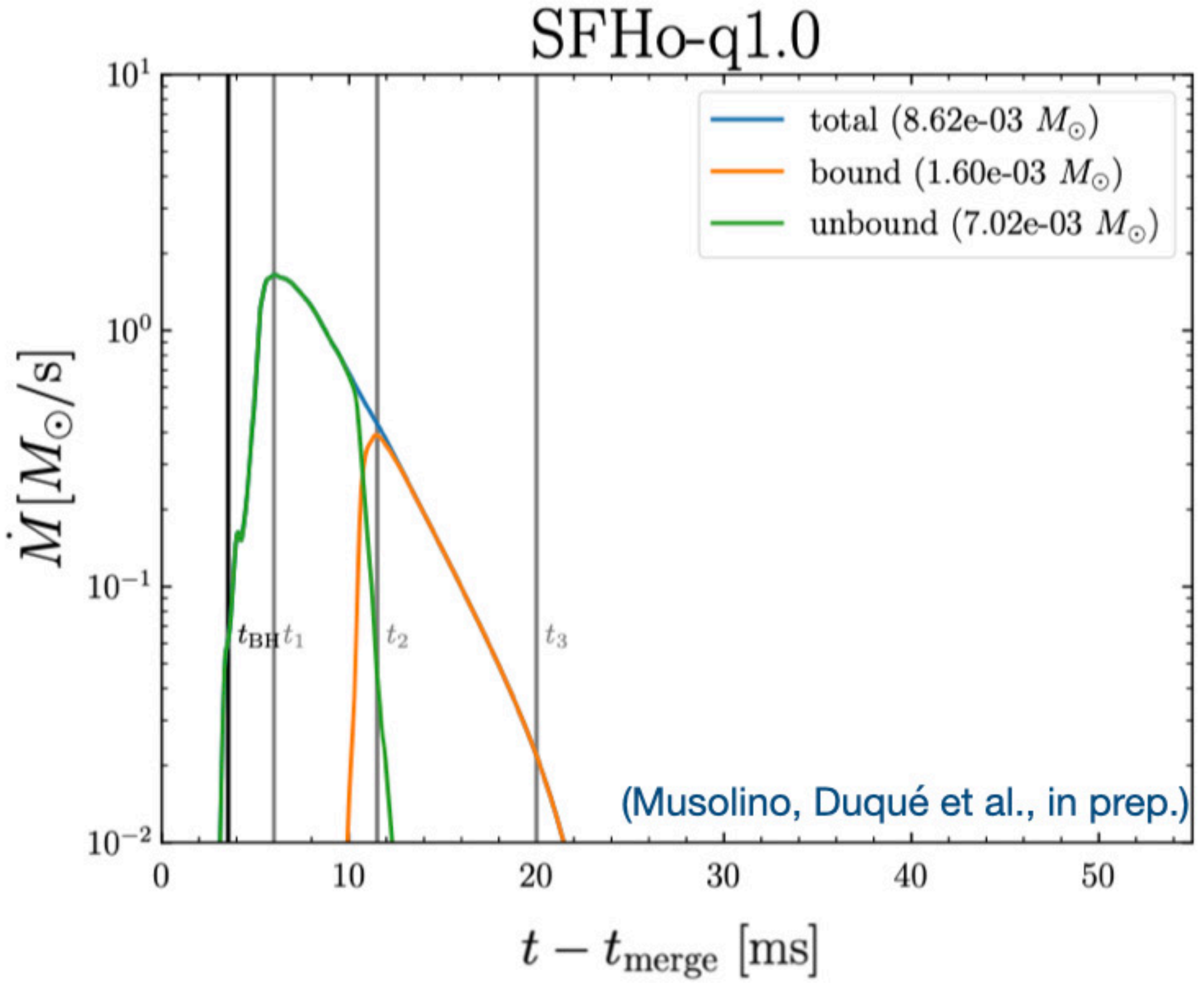
First results:

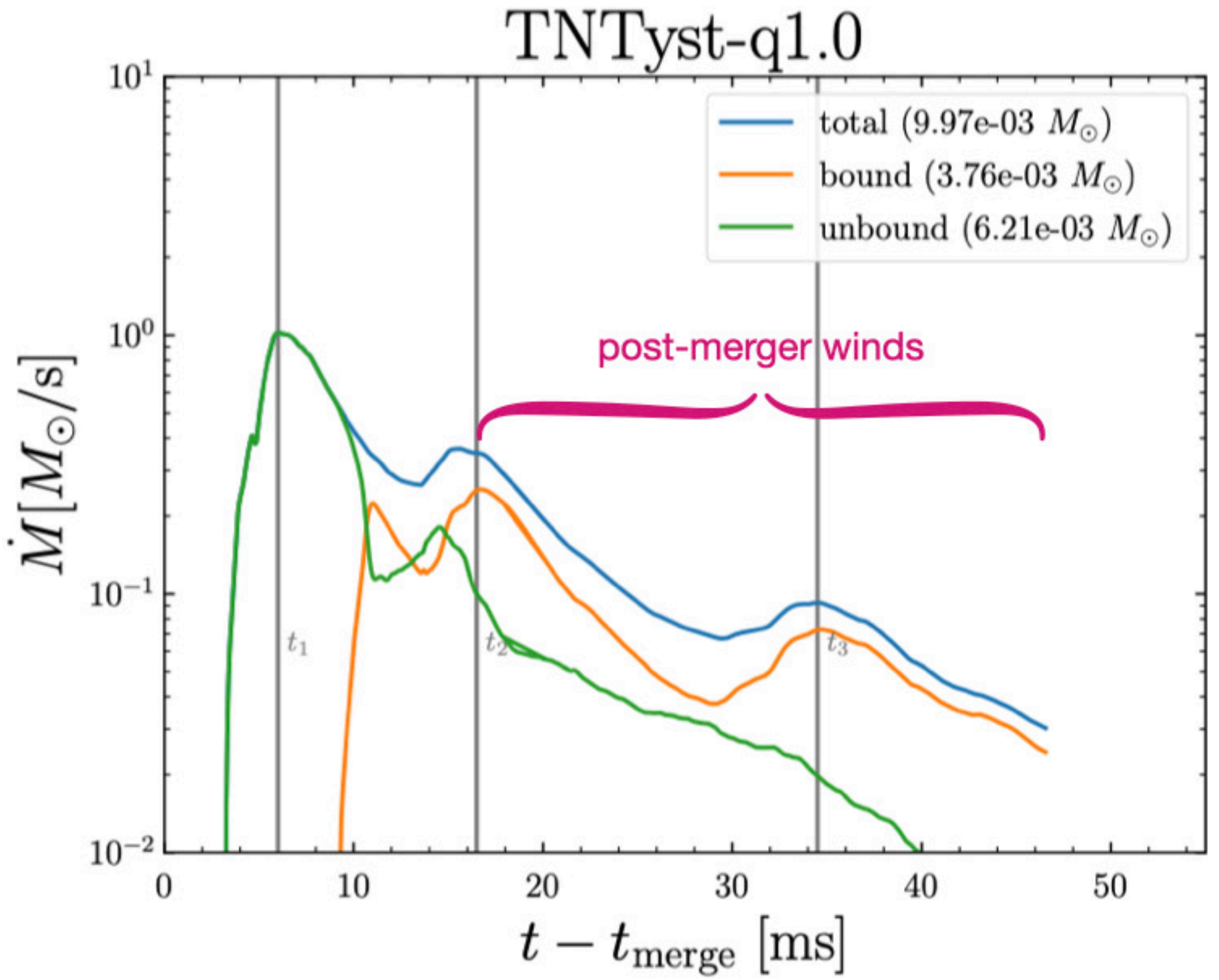
- ***Significant mass*** of bound ejecta: $M_{\rm bound} \gtrsim 10^{-3}\, M_\odot$
- Transition unbound → bound
- Bound ejecta is ***nearly isotropic***
- q ***and EoS influence*** the ejection dynamics

Effect of the EoS on merger remnant and long-term ejection

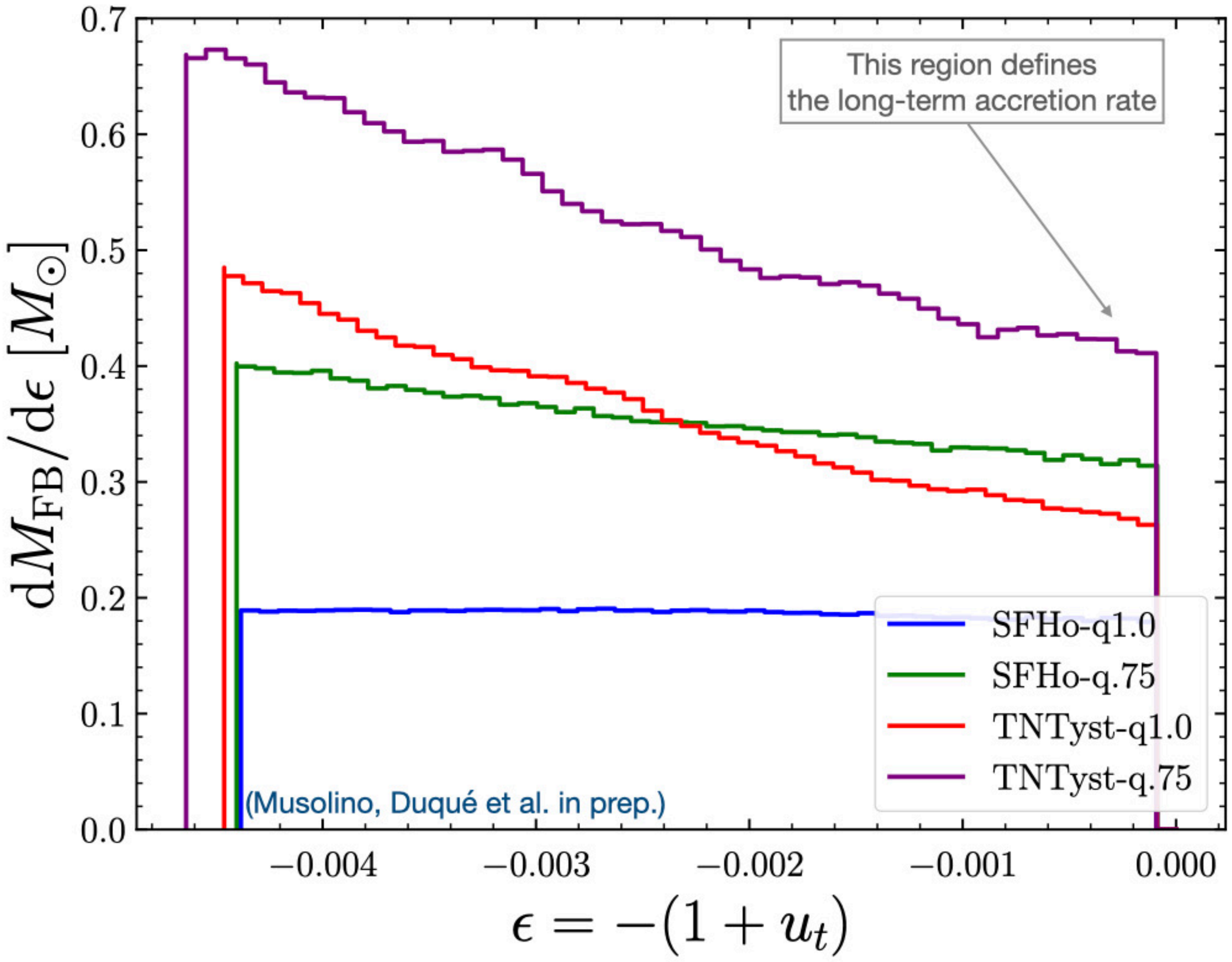
Our runbench:

	Label	M_1 [$M_\odot$]	M_2 [$M_\odot$]	q	EoS	$t_{\rm collapse}$ [ms]
softer EoS	SFHo-q1.0	1.36	1.36	1	SFHo	3.7
	SFHo-q.75	1.18	1.57	0.75	SFHo	4.0
stiffer EoS	TNTyst-q1.0	1.36	1.36	1	TNTyst	–
	TNTyst-q.75	1.18	1.57	0.75	TNTyst	–





The fallback accretion rate is determined by the orbital energy distribution



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

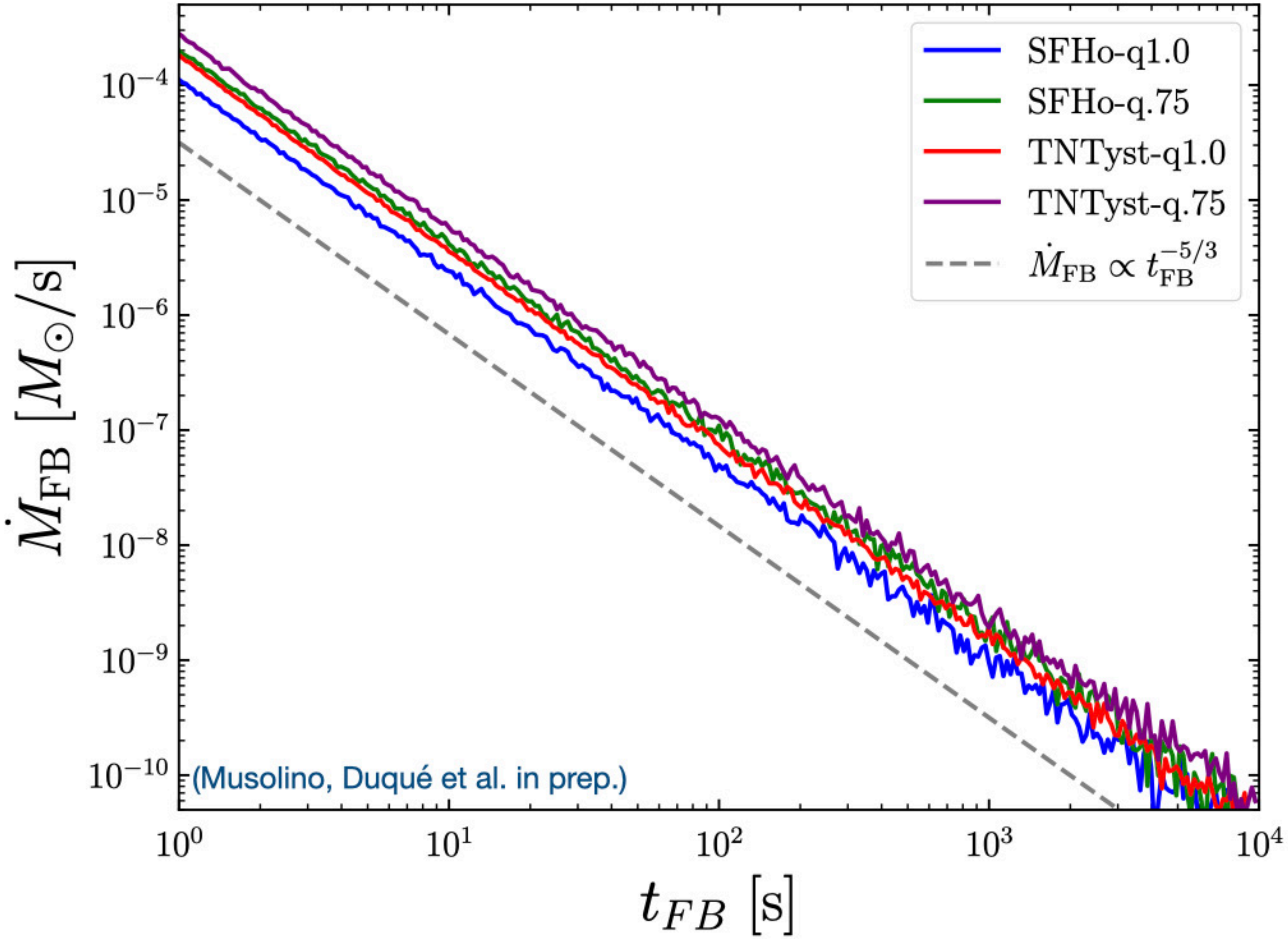
$$\mathrm{d}M_{\mathrm{FB}}/\mathrm{d}\epsilon = \mathrm{cst} \;\Leftrightarrow\; \dot{M}_{\mathrm{FB}} \propto t^{-5/3}$$

(Rees, 1988)

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

The binary mass-ratio q and EoS influence the ejection dynamics…

but the fallback accretion rate is remarkably universal!

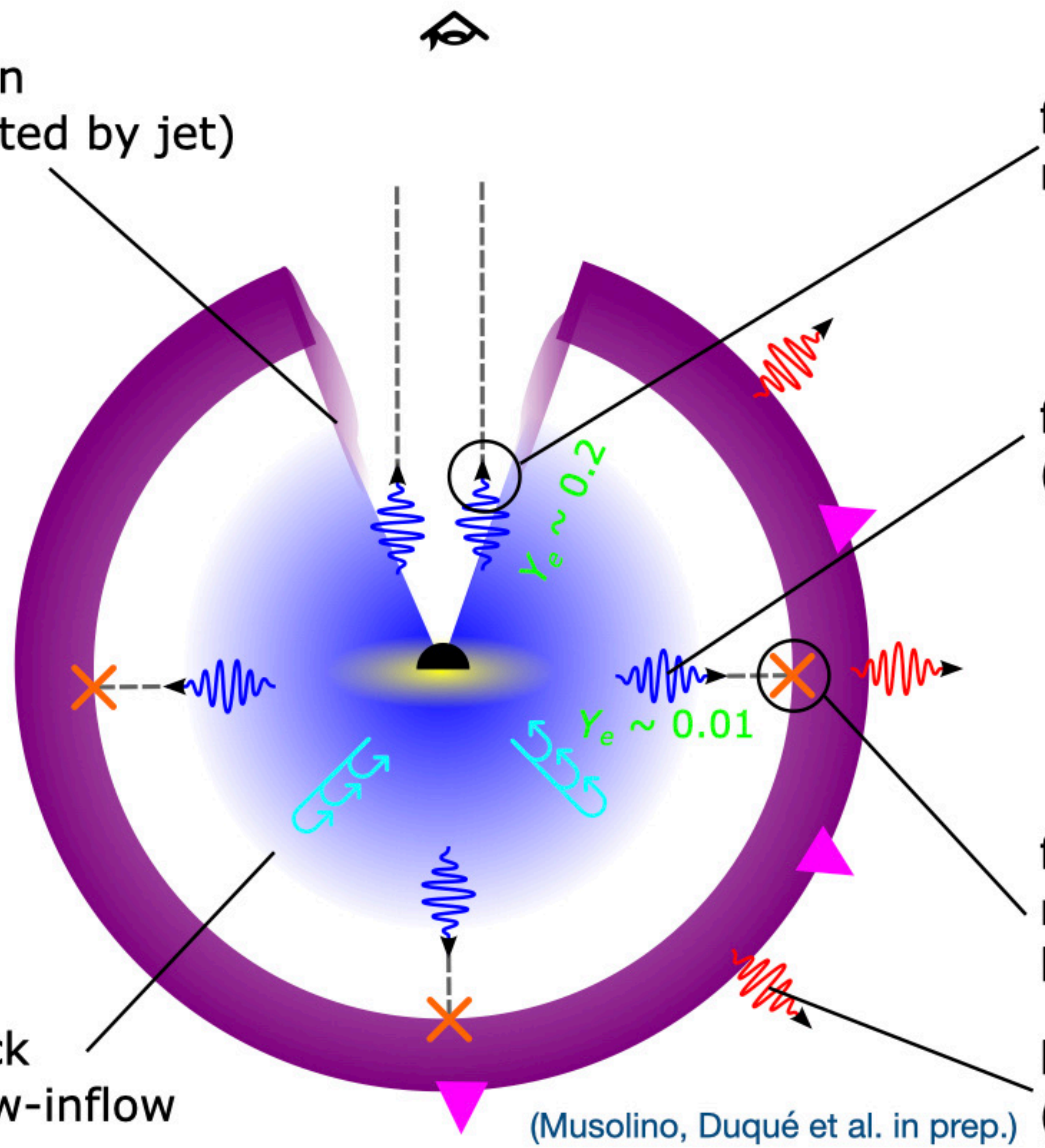


Results:

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

⇒ New explanation for extended emission in sGRBs?

A new explanation for extended emission in sGRBs?



(Musolino, Duqué et al. in prep.)

Extended emission in sGRBs:

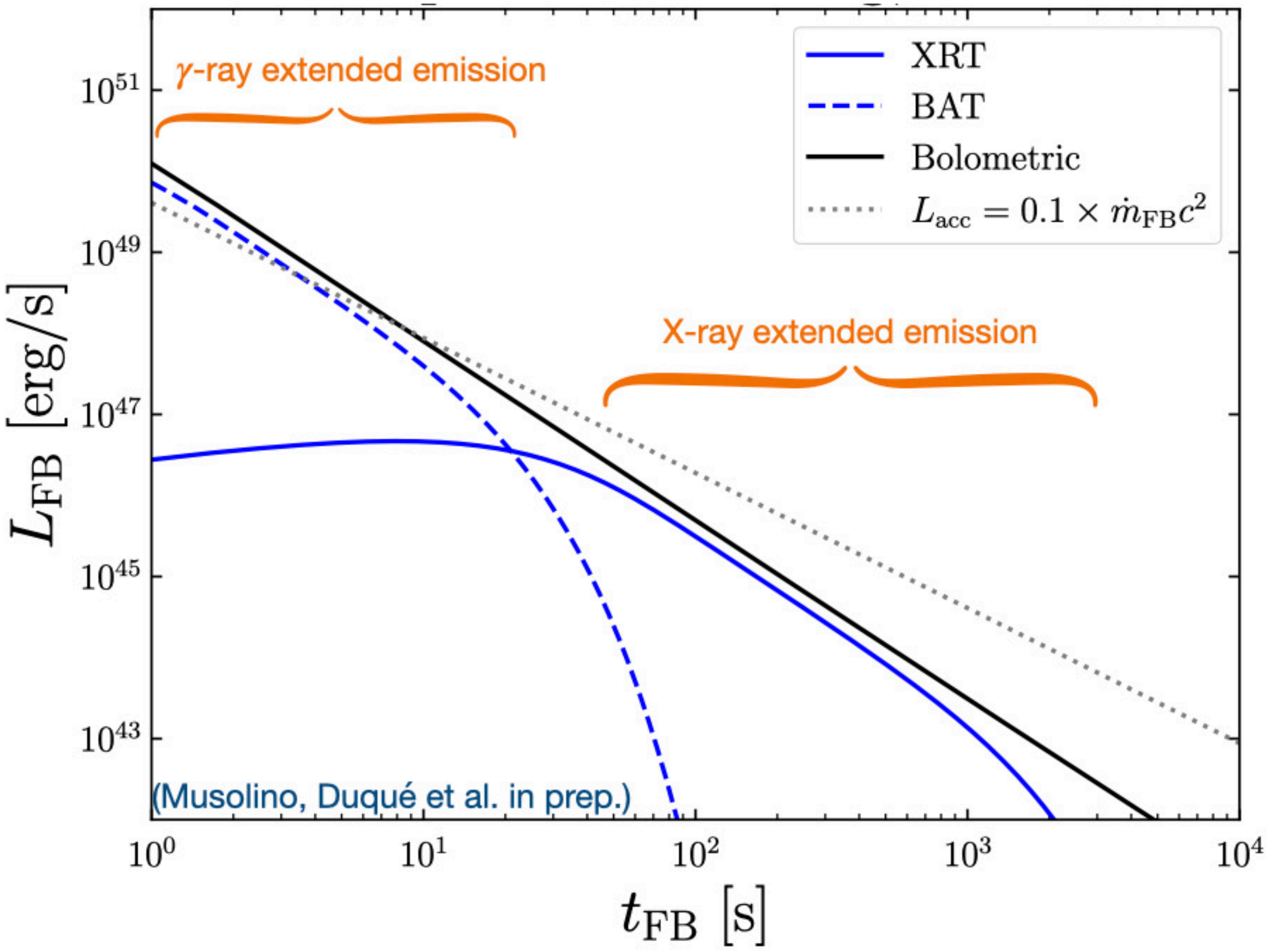
- In gamma- and X-rays, $t \gtrsim 100\,\mathrm{s}$
- Can carry **more total energy** than GRB prompt emission
- **Softer** spectrum than prompt emission

(see, e.g., Kaneko et al. 2015, Kagawa et al. 2015)

Models for extended emission:

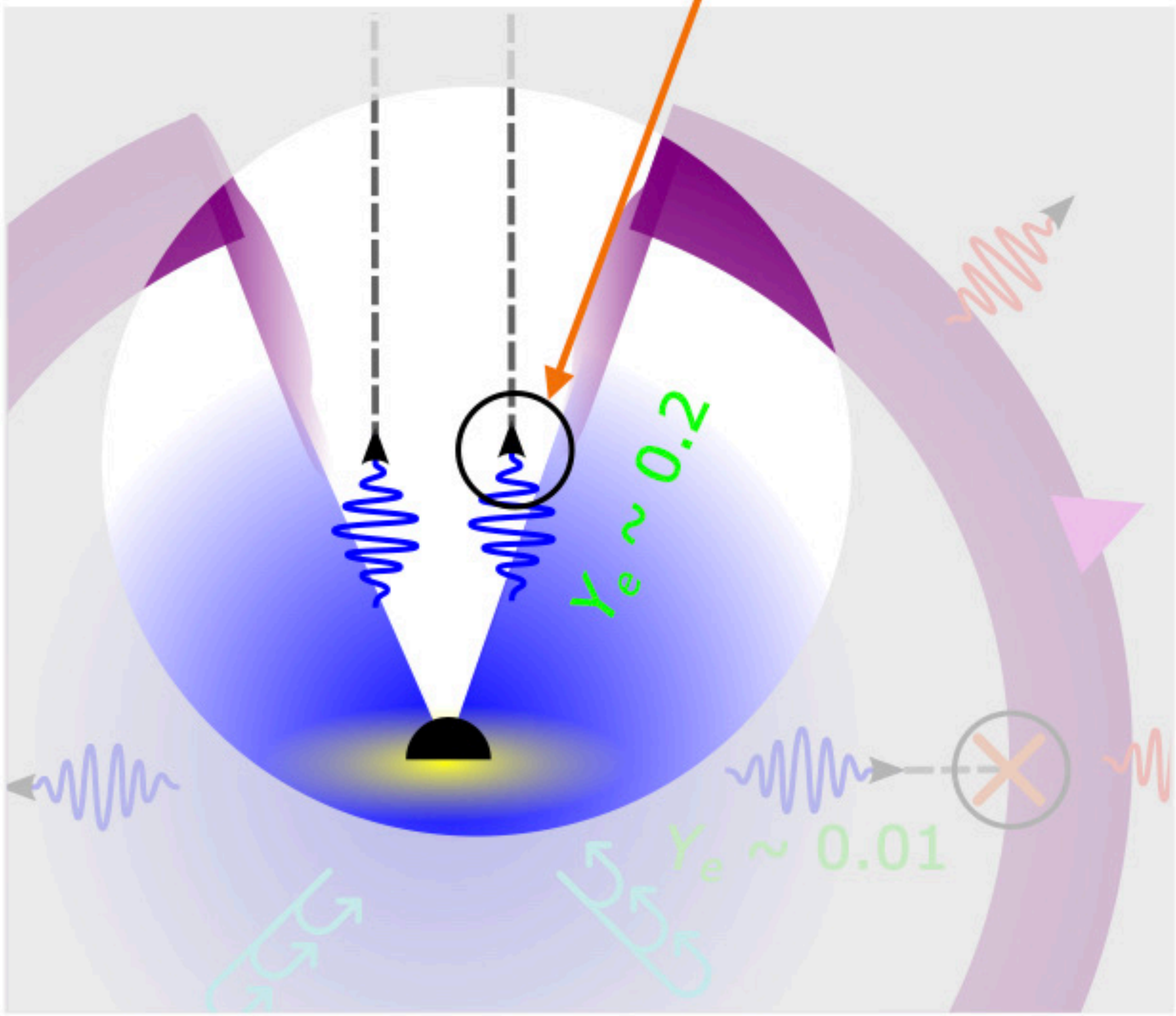
- BH launches 2nd jet after disk or fallback accretion (Barkov & Pozanenko 2011, Kisaka & Ioka 2015)
- Radiation originates from post-merger magnetar (Metzger et al. 2008, Murase et al. 2018)

A new picture for γ-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



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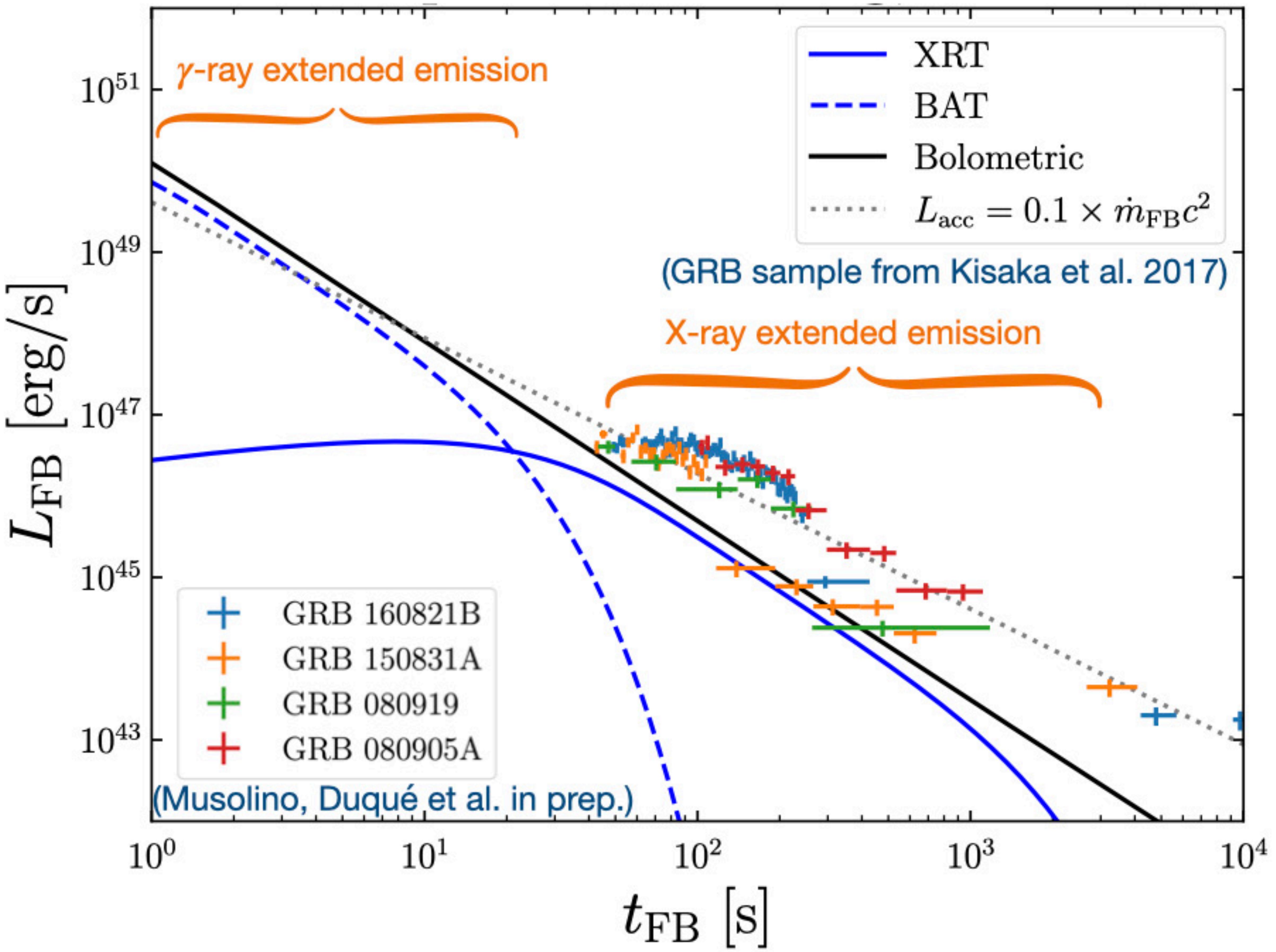


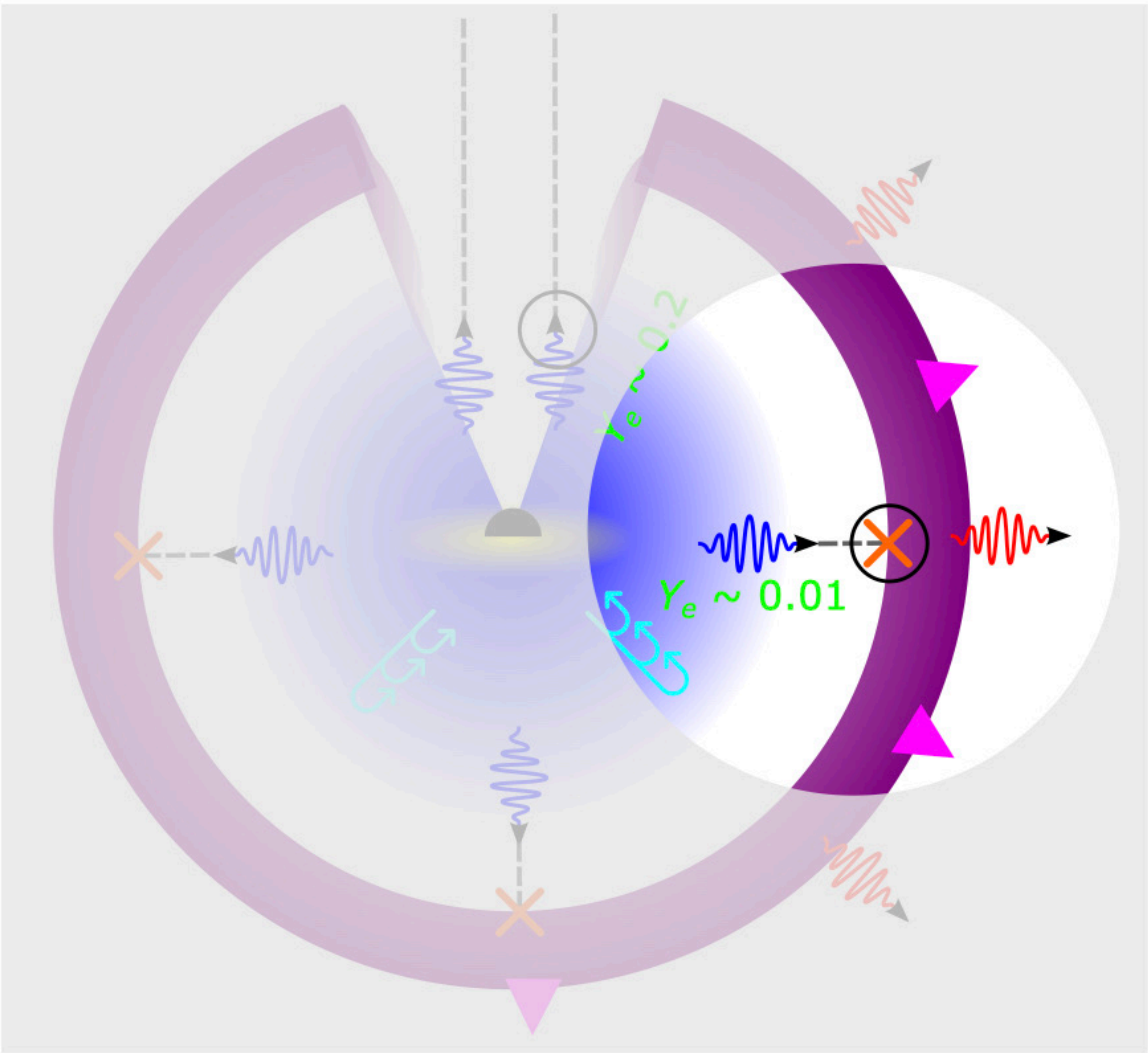
Results:

- Significant luminosity and duration
- Radiation dominates γ-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:

$$\frac{\Delta L_{\mathrm{KN}}}{L_{\mathrm{KN}}} \sim \frac{M_{\mathrm{bound}}}{M_{\mathrm{unbound}}} \lesssim 50\,\%$$

+ 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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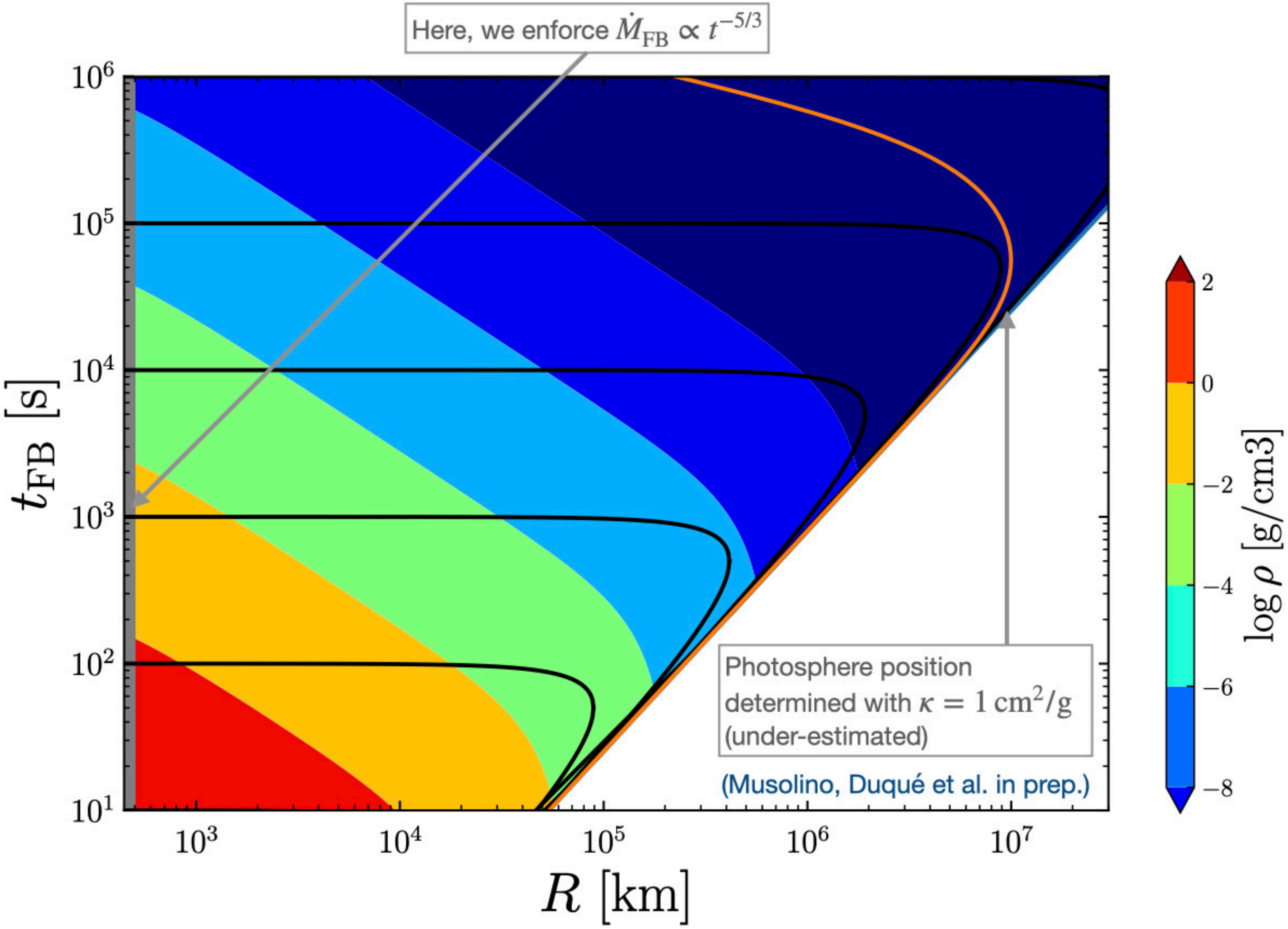
Semi-analytical treatment for the fallback dynamics



Fallback dynamics:

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

Emission model:

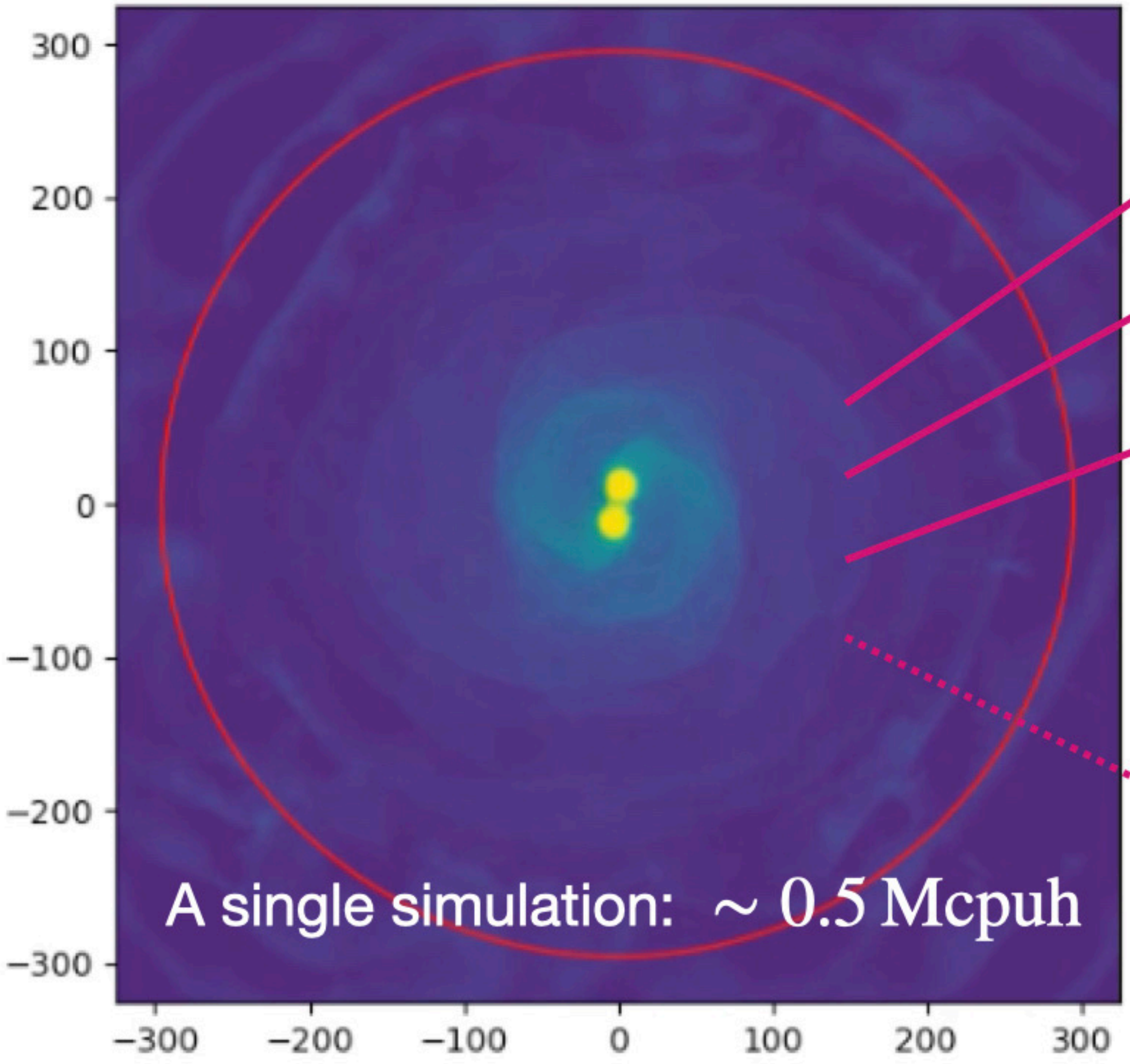
r-process heating of the (Lippuner et al. 2015) photosphere using `SkyNET`

M1 scheme provides Y_e, $T(t=0)$

Results:

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

A good methodology for the combined study of EM counterparts



Bound material $\longrightarrow$ GRB extended emission

Unbound material $\longrightarrow$ kilonova signal

Post-merger disk $\longrightarrow$ GRB prompt emission

(relativistic jet) $\longrightarrow$ GRB prompt emission and afterglow

fixed space-time simulation