Jet propagation and shock breakout emission from neutron star merger simulations

https://arxiv.org/abs/2408.15973 **(out today!)**

Eduardo M. Gutiérrez
IGC Postdoctoral Fellow
Penn State University

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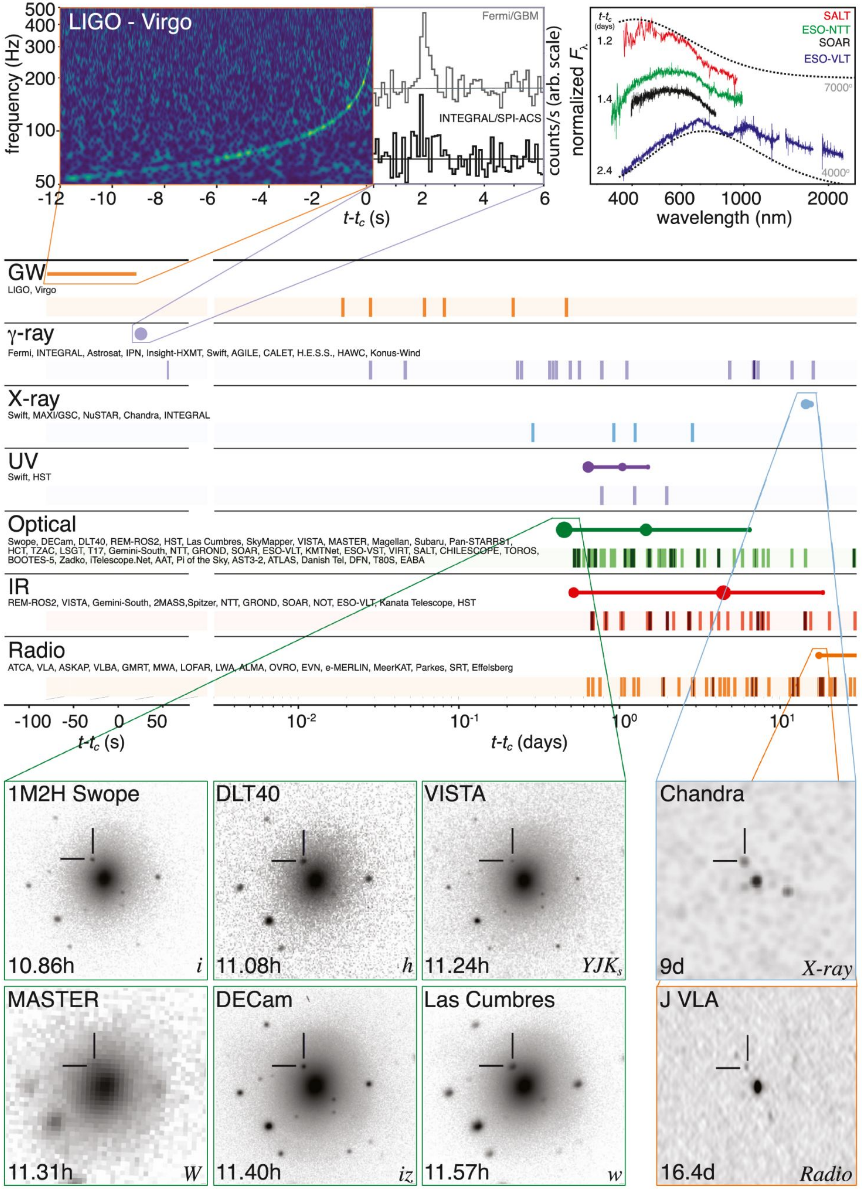
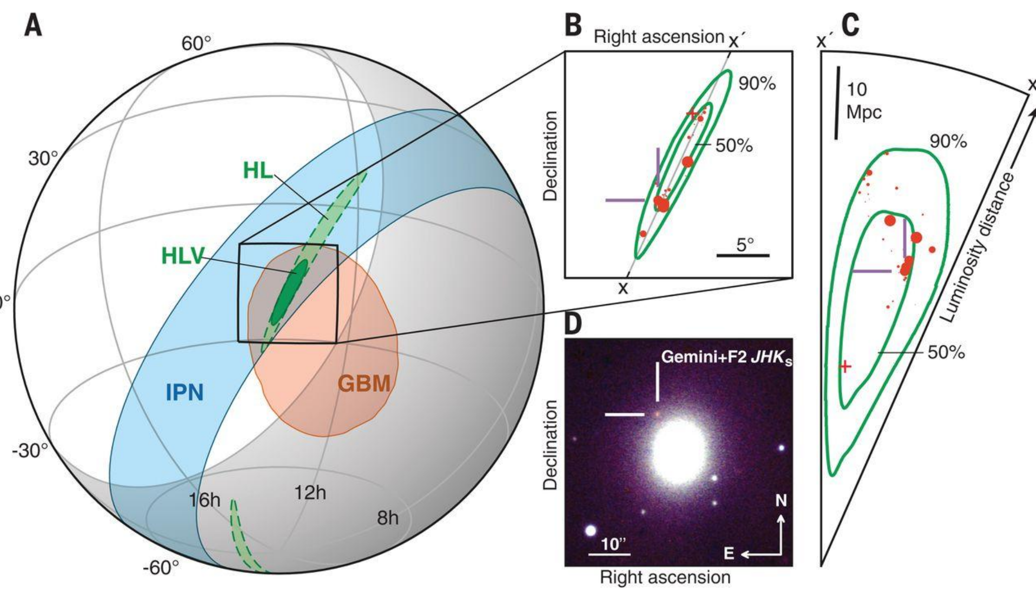
Collab: M. Bhattacharya, D. Radice, K. Murase, S. Bernuzzi

PennState
Eberly College of Science

NSF

GW170817: First multimessenger event of GWs and EM radiation



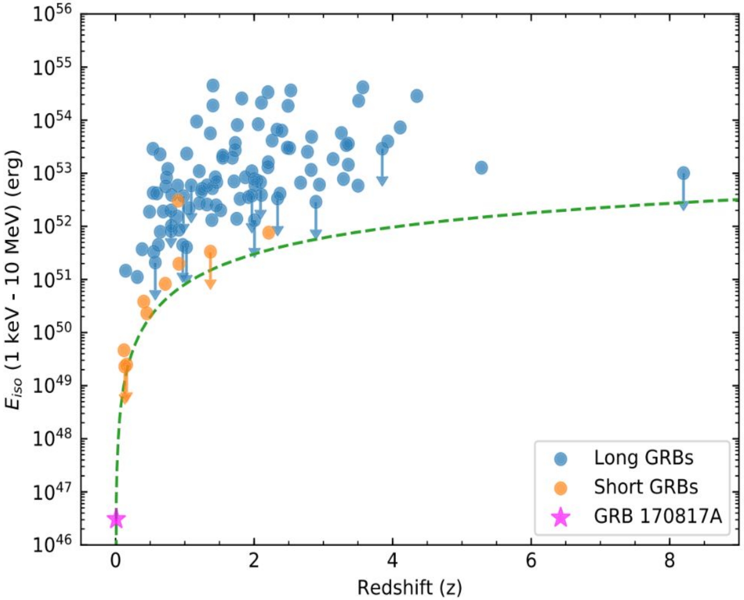


NGC 4993

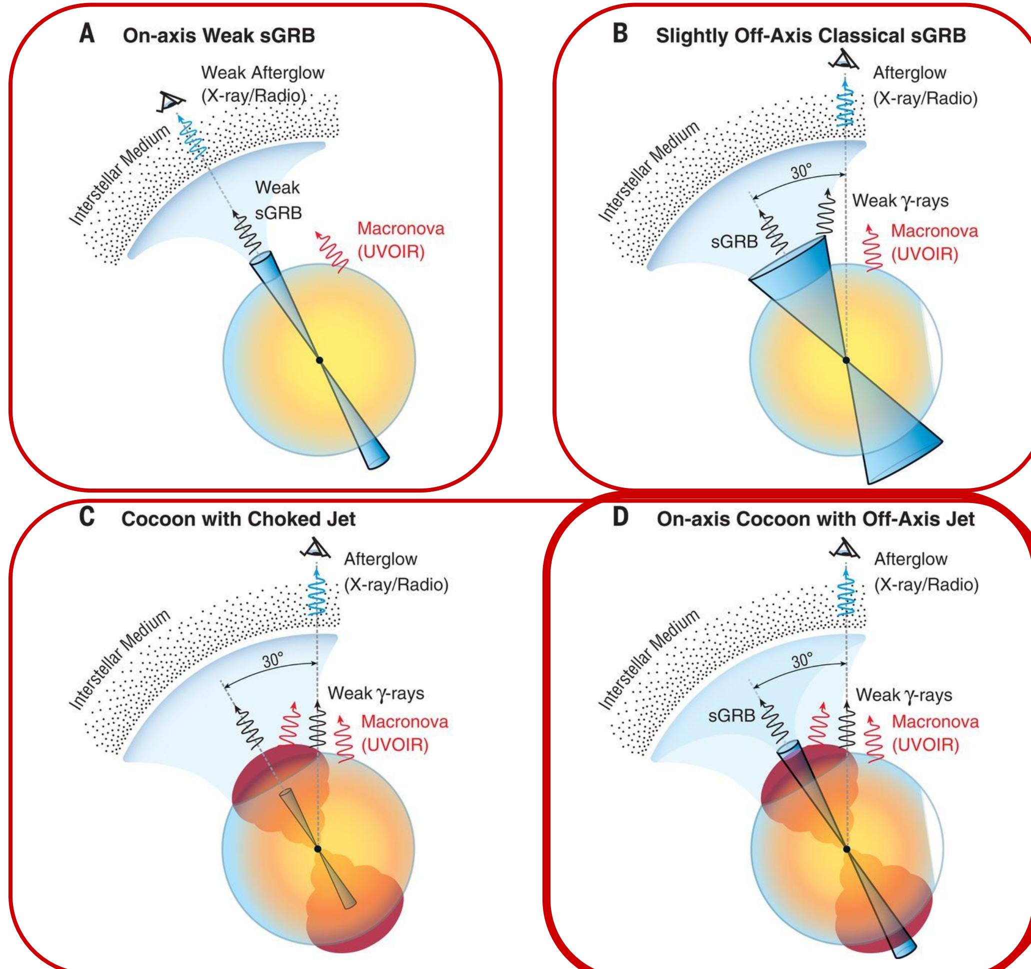
Abbott+ (2017)

GRB 170817A had a very low-luminosity

Why?



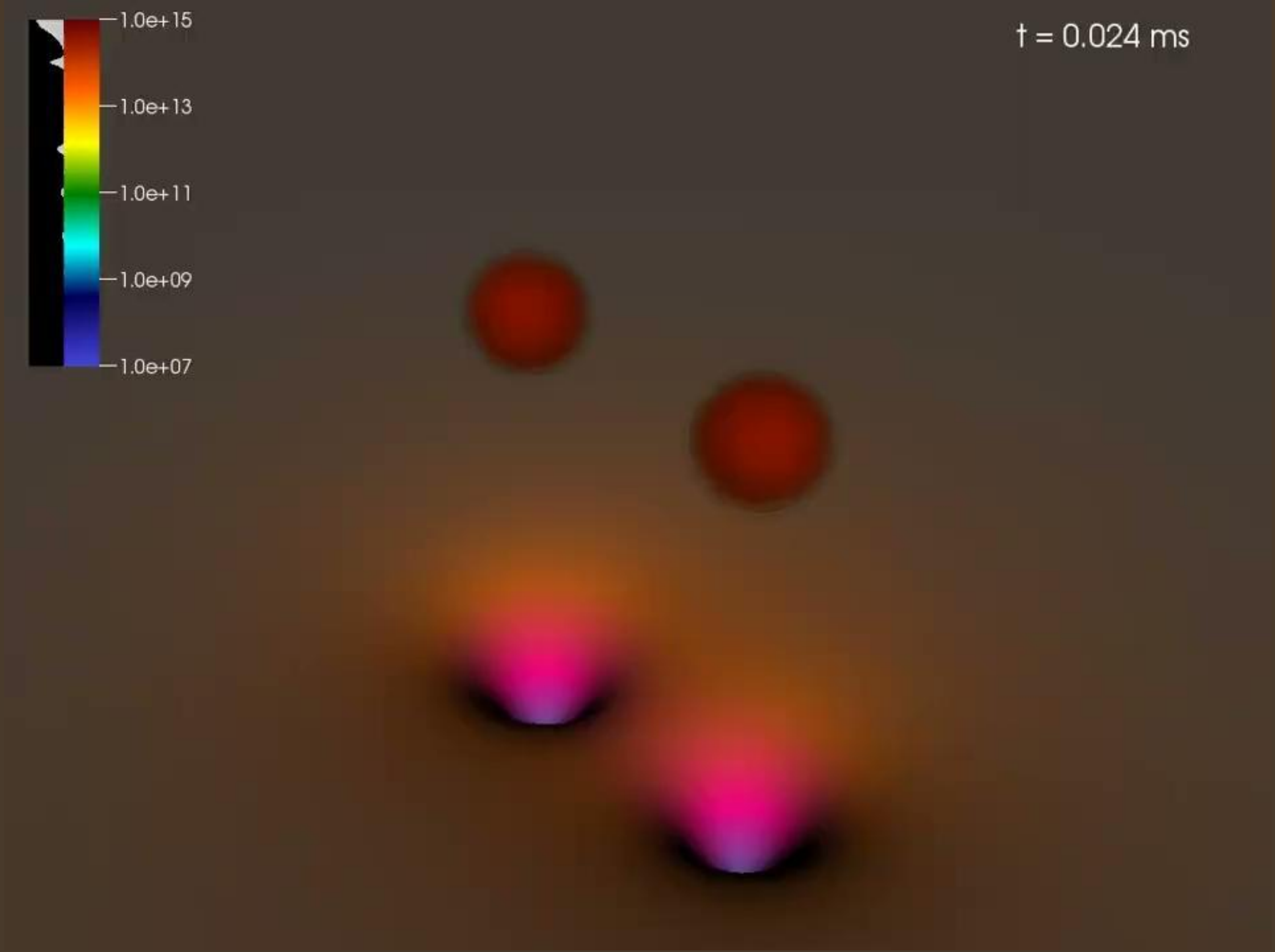
Abbott++, ApJL (2017)



Kasliwal+, Science (2017)

OUR GOALS:

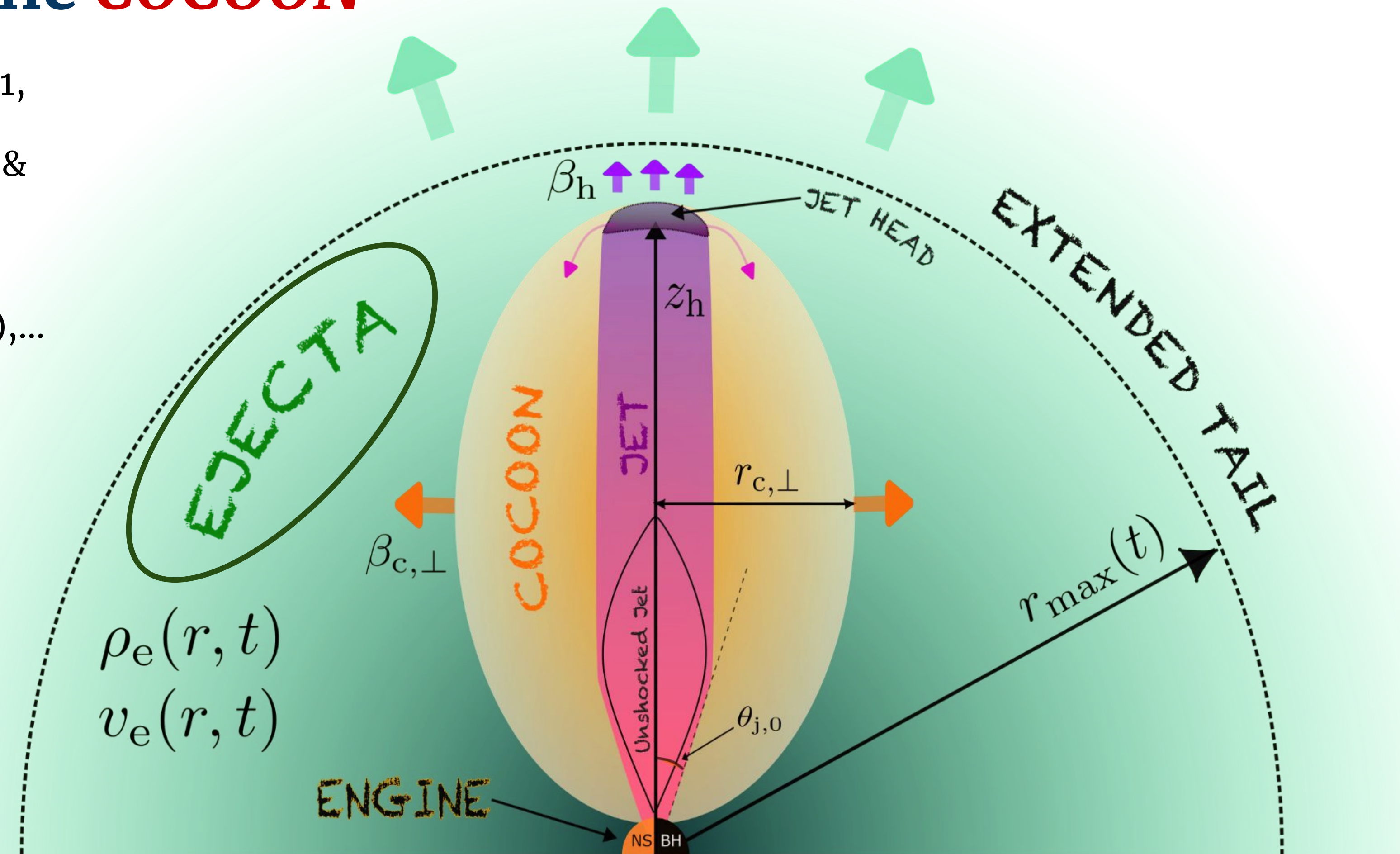
- **Investigate jet propagation in *realistic ejecta from BNS mergers.***
- **Calculate Shock breakout emission ("*first-light*").**
- **Contrast with GRB 170817A and estimate BNS properties: ejecta, engine.**



Courtesy of D. Radice

MODEL: The *JET*, launched by the *ENGINE*, propagates through the merger *EJECTA*, and feeds the *COCOON*

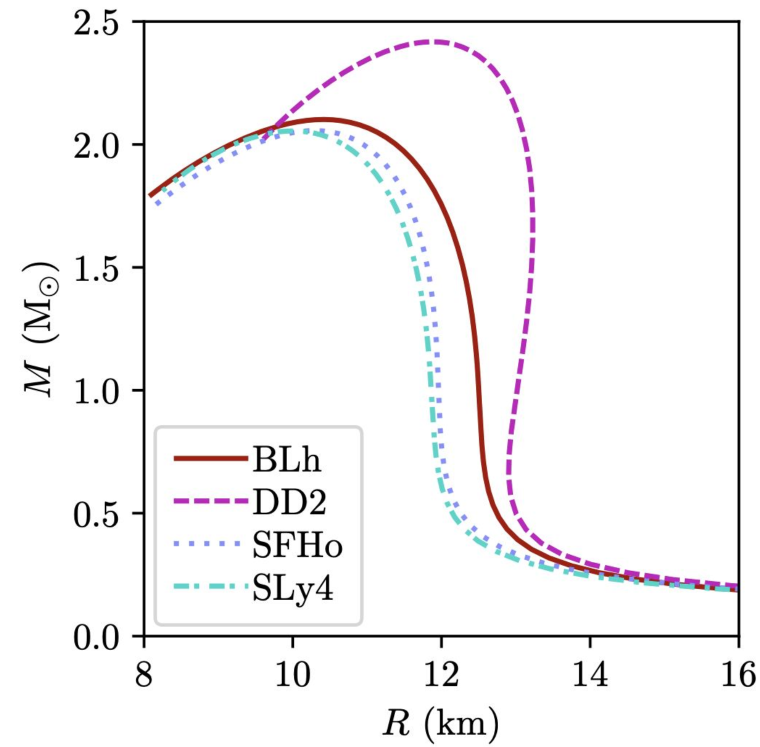
Bromberg++ (2011, 2014), Salafia++ (2020), Levinson & Begelman (2013), Hamidani & Ioka (2020, 2021), Gottlieb++ (2022),...



EJECTA: Long-term simulations with different mass-ratios and Nuclear EOS.
We use the public code *THC_M1*:

(NR)HD + M1 neutrino transport + LES (turbulence)

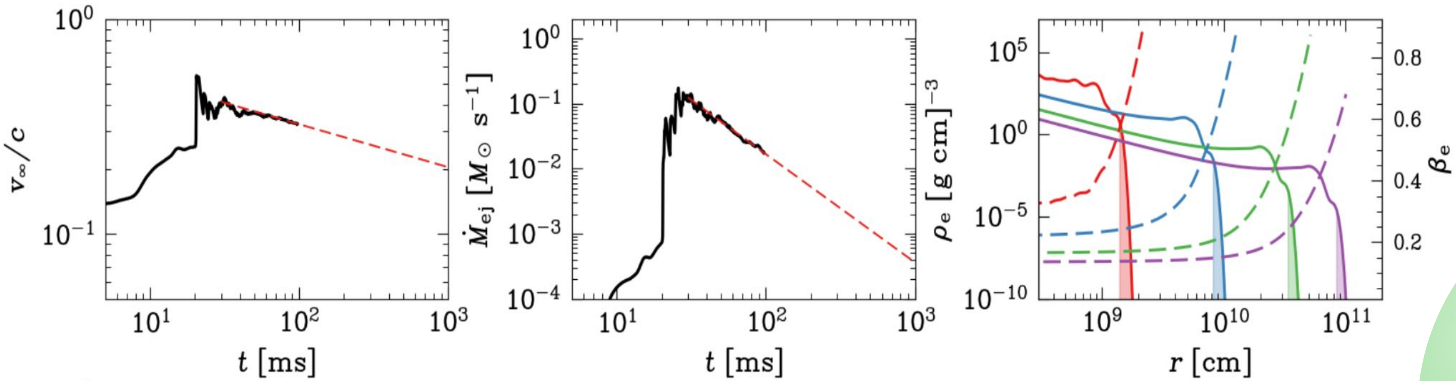
- *DD2_q=1*
- *DD2_q=1.8*
- *BLh_q=1.4*
- *SLy4_q=1.2*
- *SFHo_q=1*

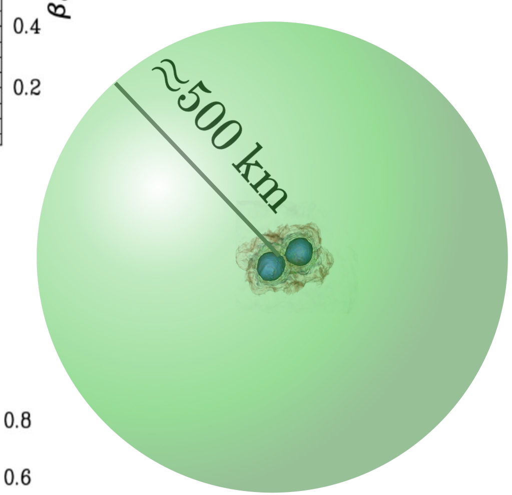


Espino++, arXiv:2311.12923 (2023)

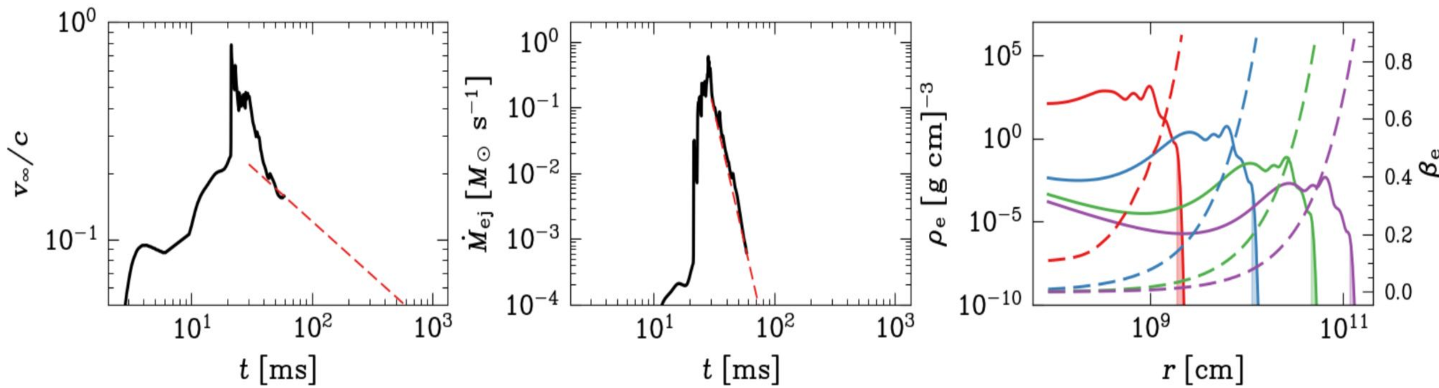
Dynamical ejecta + Neutrino-driven winds

Stiff EOS (DD2): long-lived NS remnant





Soft EOS (SFHo): early collapse to a BH



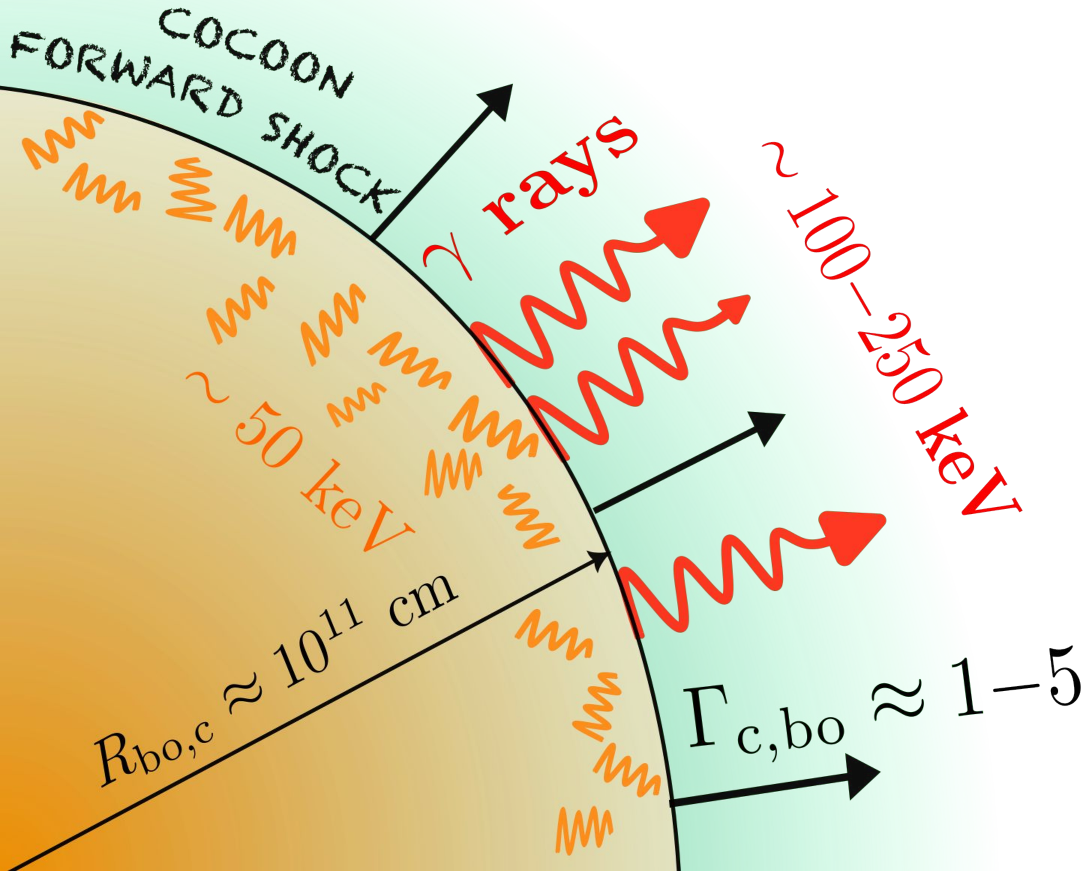
Gutierrez++ (2024),
arXiv:2408.15973

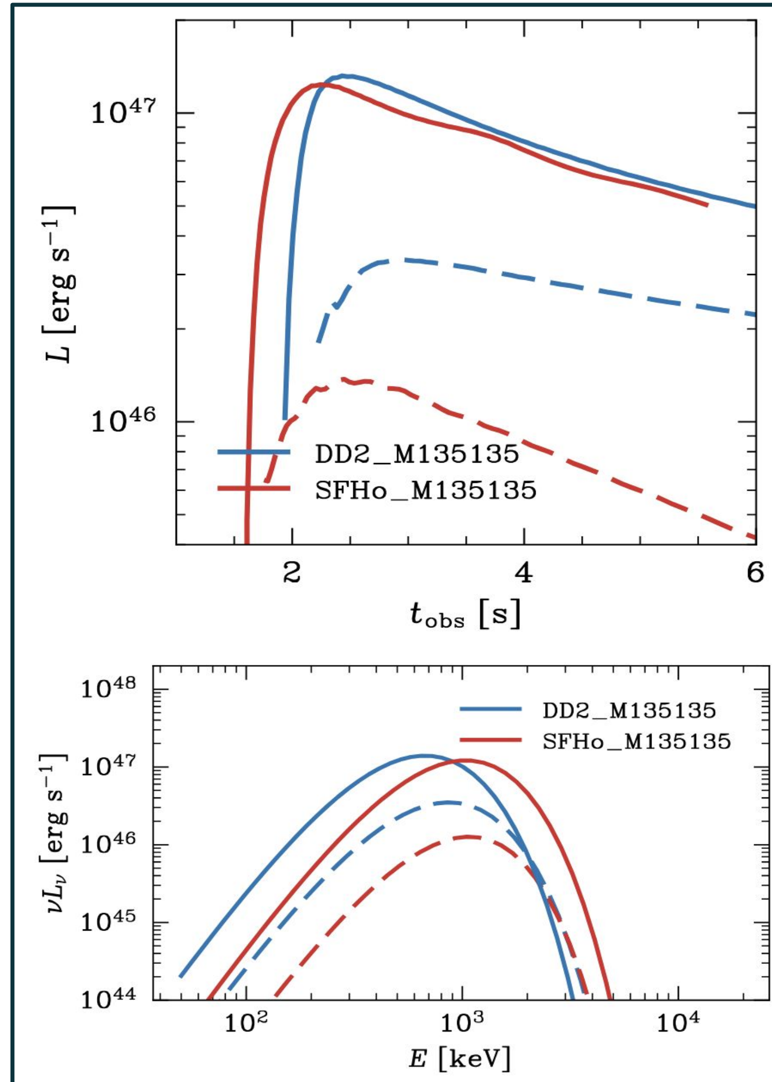
Cocoon breakout emission

Gutierrez++ (2024), arXiv:2408.15973

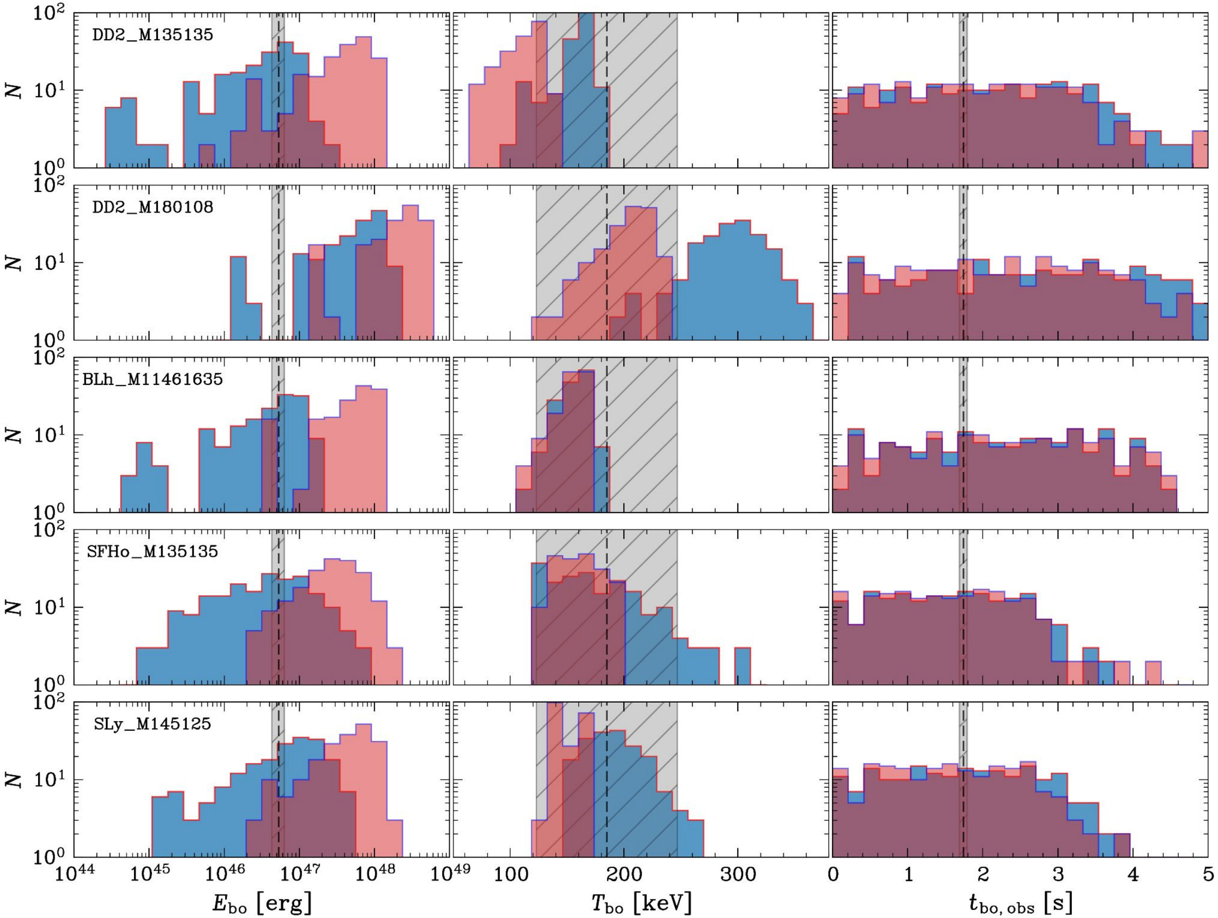
$$t'_{\rm diff} \approx \Delta r'^2 \rho'(\beta)\kappa/c$$

$$t'_{\rm diff} \approx (t - t_{\rm bo})/\Gamma$$





Set of simulations with different engine parameters



$$B_p \in [5 \times 10^{14}, 10^{16}]\ \mathrm{G}$$

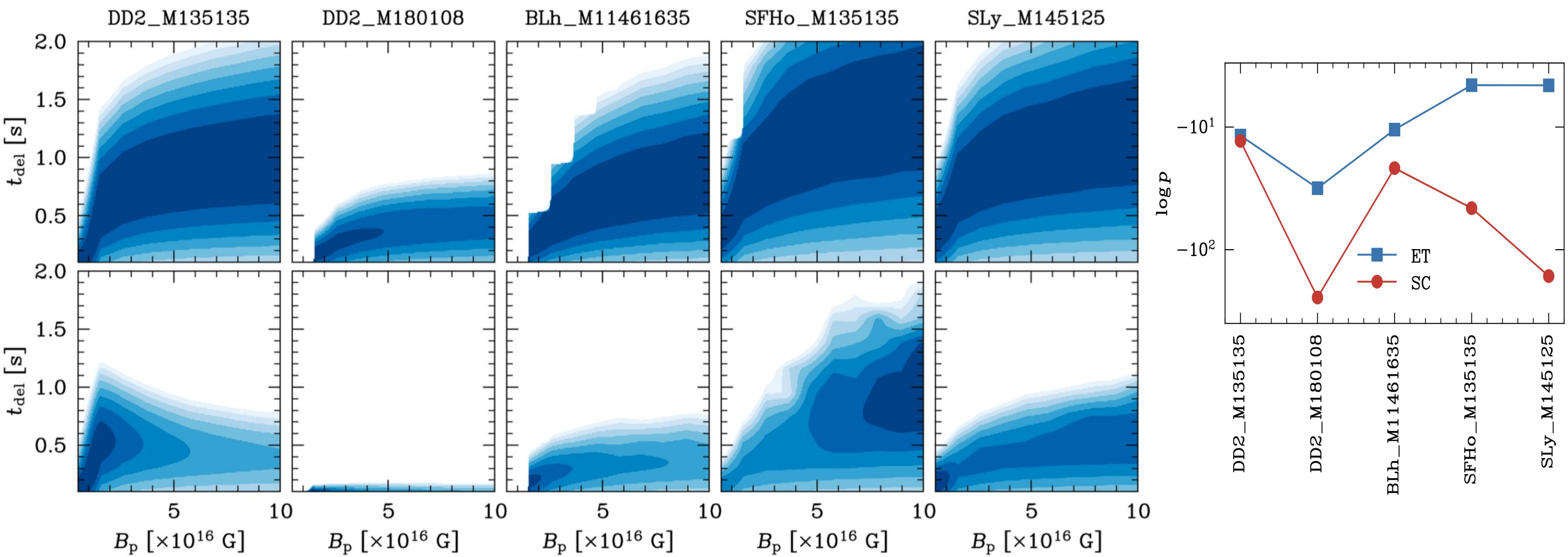
$$t_{del} \in [0.1, 2]\ \mathrm{s}$$

$$\theta_{0,j} = 8^\circ, 16^\circ$$

Profiles with a soft extended tail radiate less energy with higher temperature

Gutierrez++ (2024), arXiv:2408.15973

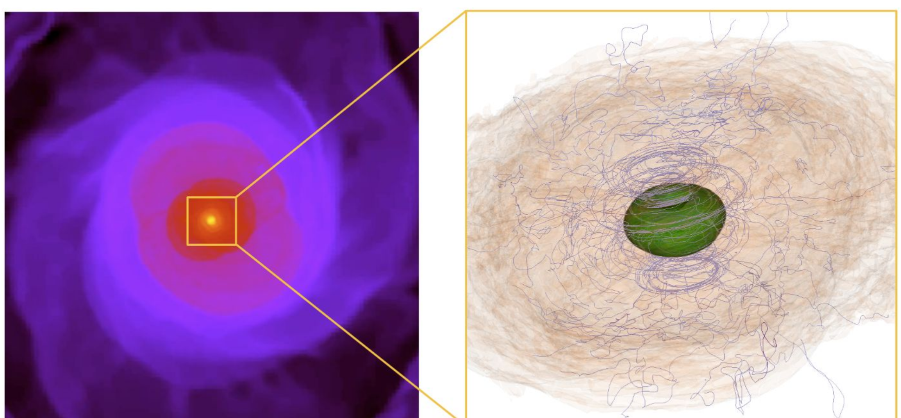
Most likely BNS ejecta scenario and engine parameters?

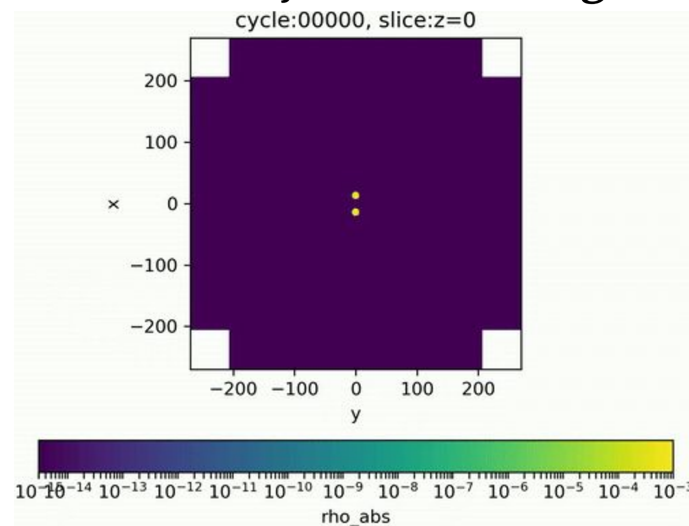


Gutierrez++ (2024), arXiv:2408.15973

Take aways

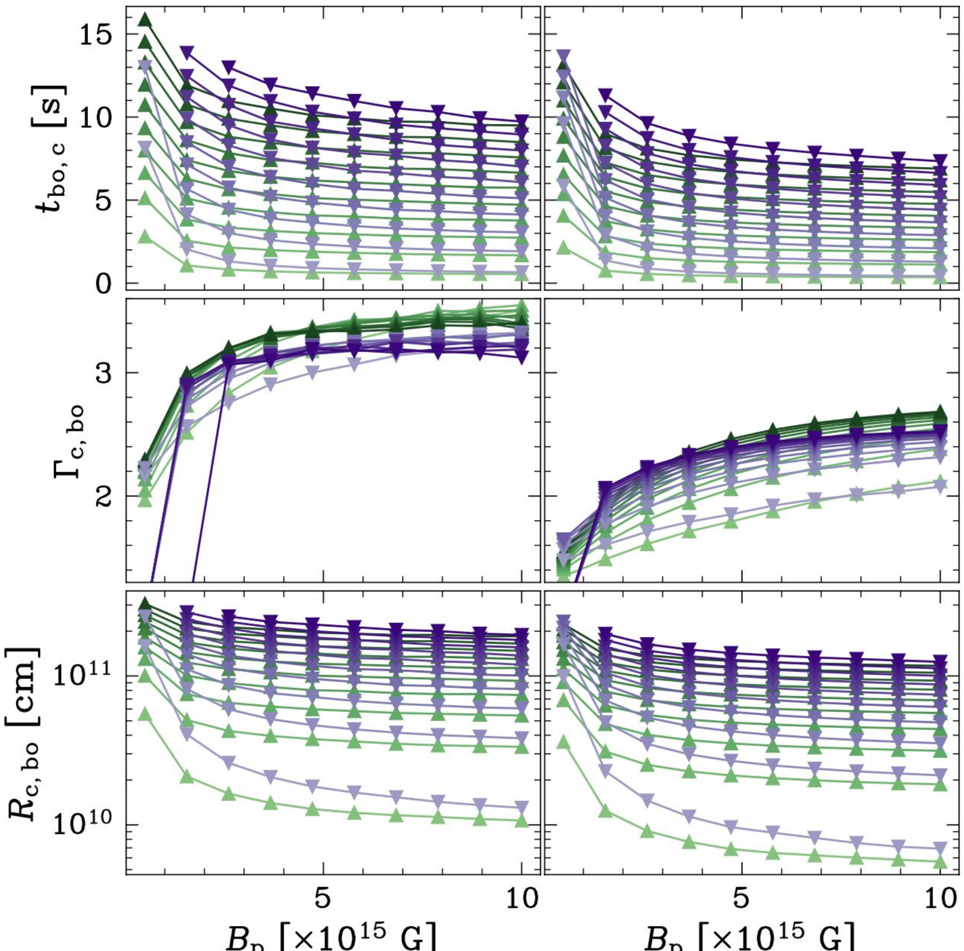
- We investigated ***jet and cocoon evolution*** in BNS mergers for realistic ejecta derived from NR simulations.
- We explored how breakout emission depends on ejecta and engine properties
- Ejecta profiles with an **extended tail** match well the phenomenology associated to GRB 170817A.
- Early collapse slightly favored.
- Future: GRMHD simulations with self-consistent jet launching (GR-Athena++)

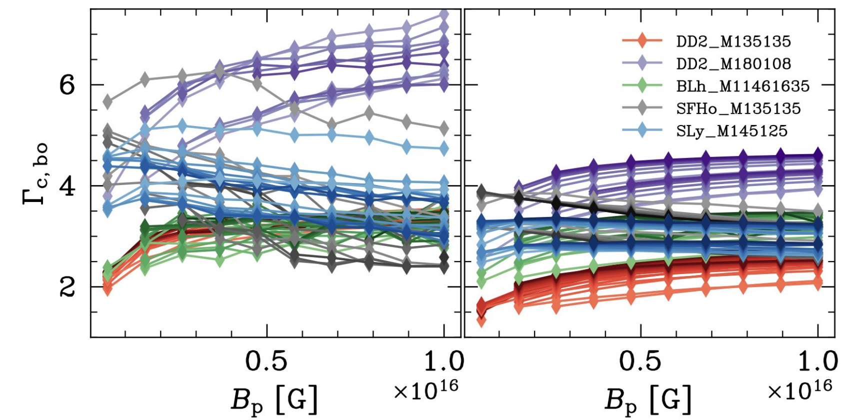




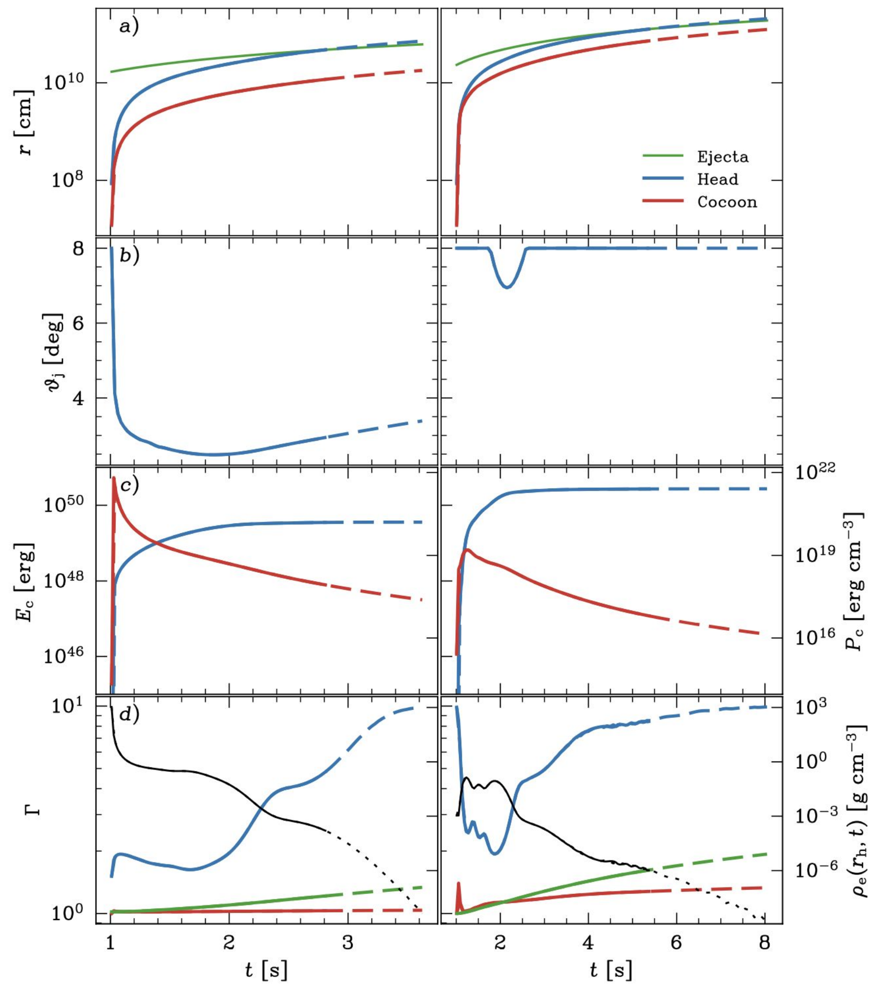
Backup slides

Cocoon breakout

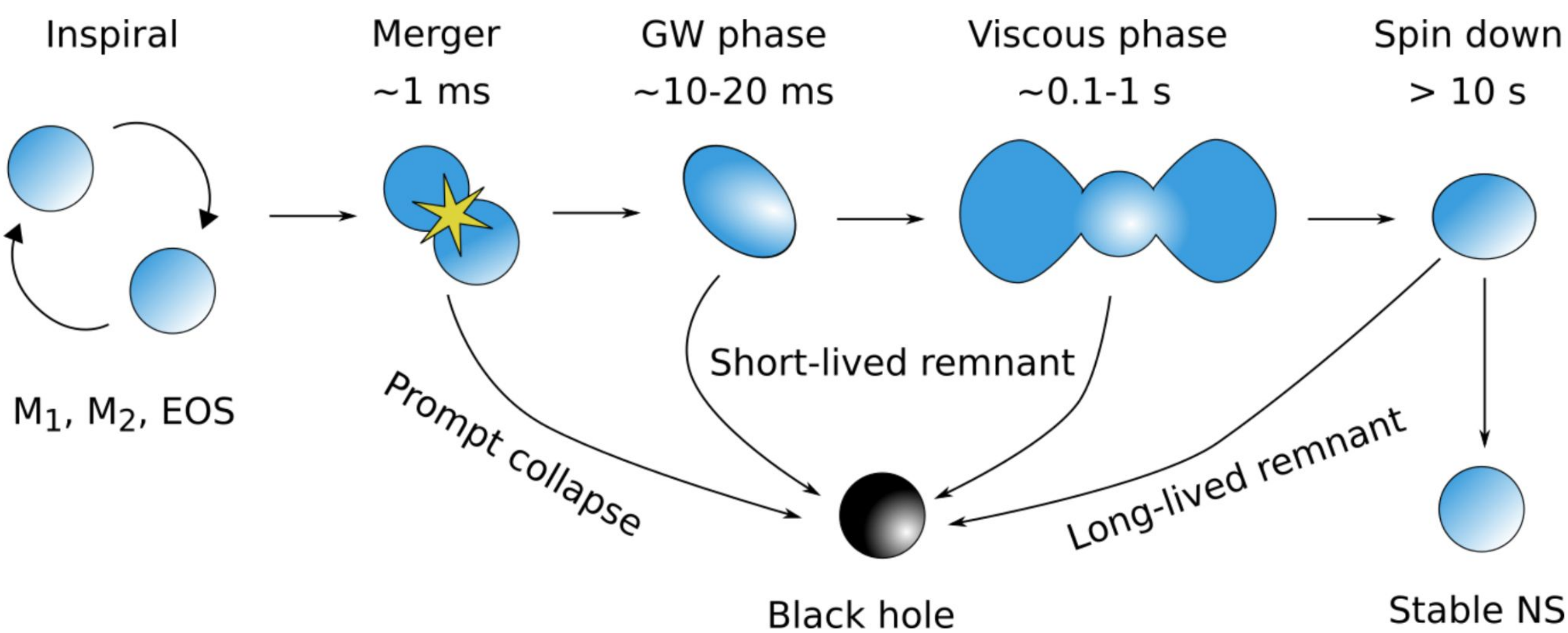




Jet evolution



The merger of two neutron stars may leave different kind of remnants

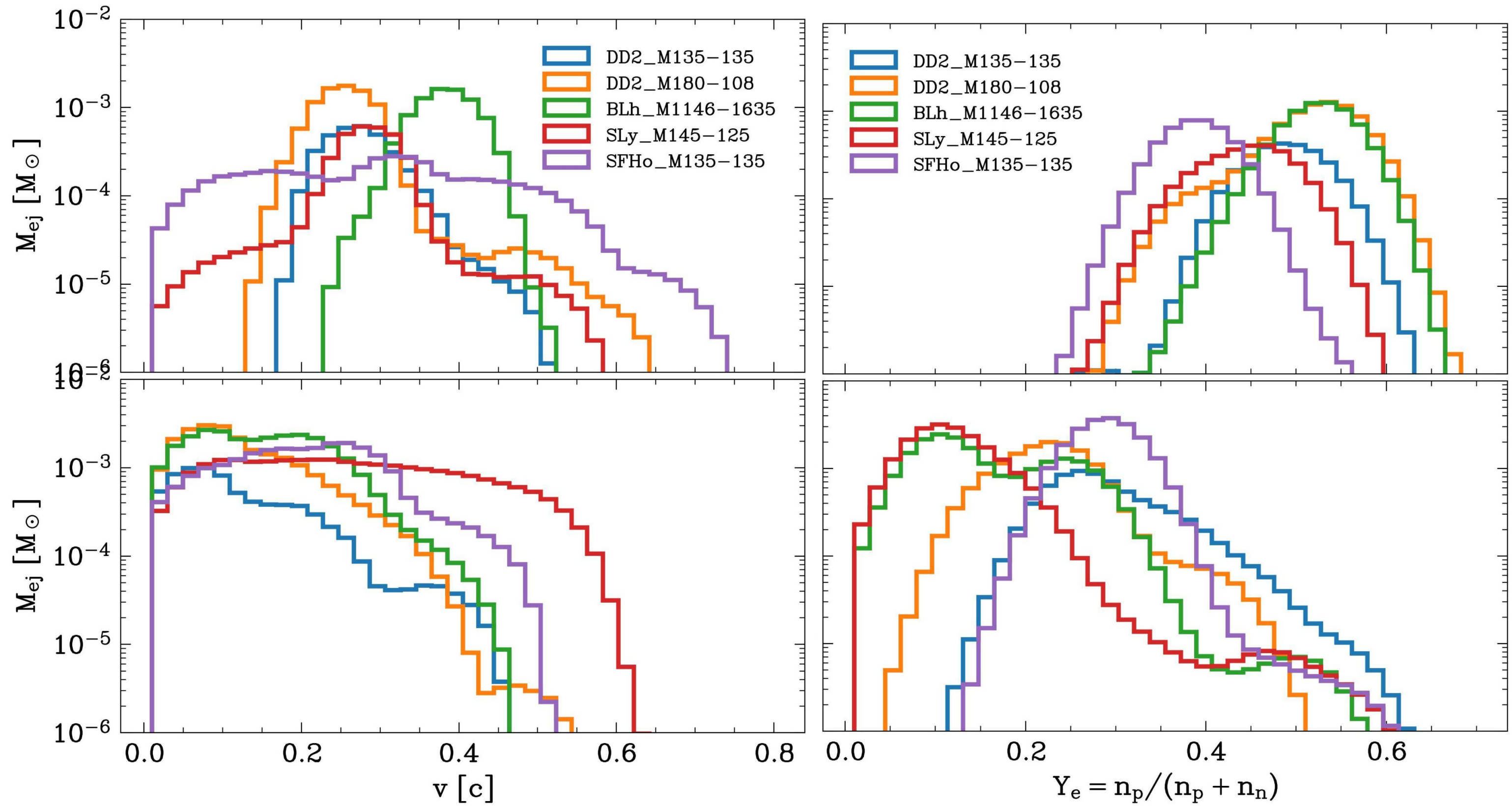


From Radice+, Ann. Rev. Nucl. Part. Sci (2020)

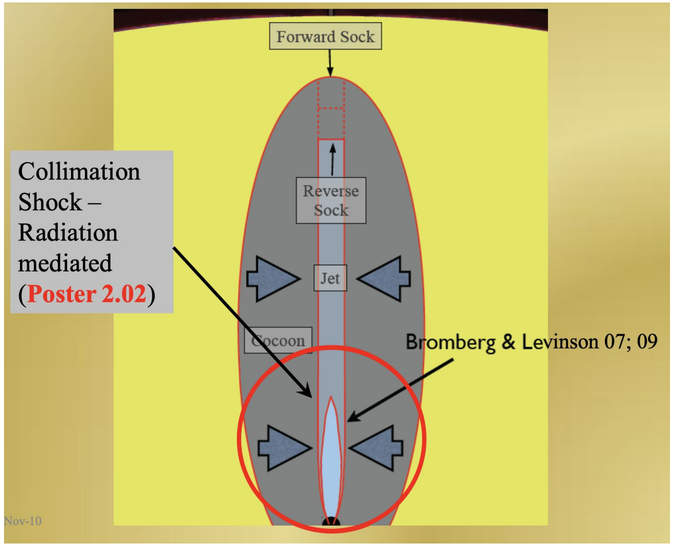
The dynamical ejecta is mostly equatorial; the neutrino-driven wind is mainly polar

$\theta \approx 0^\circ$

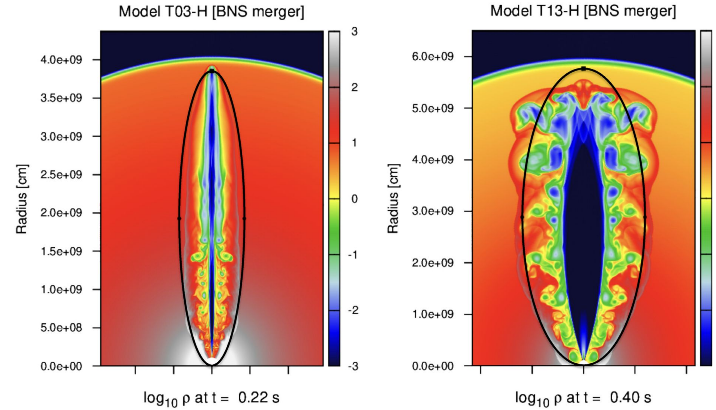
$\theta \approx 90^\circ$



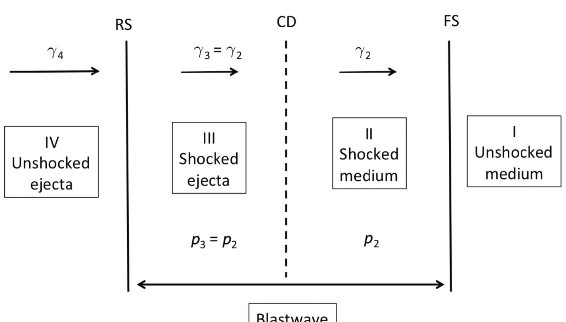
Jet+cocoon propagation



From O. Bromberg presentation



Hamidani & Ioka (2020)



Momentum balance at the forward and reverse shocks gives

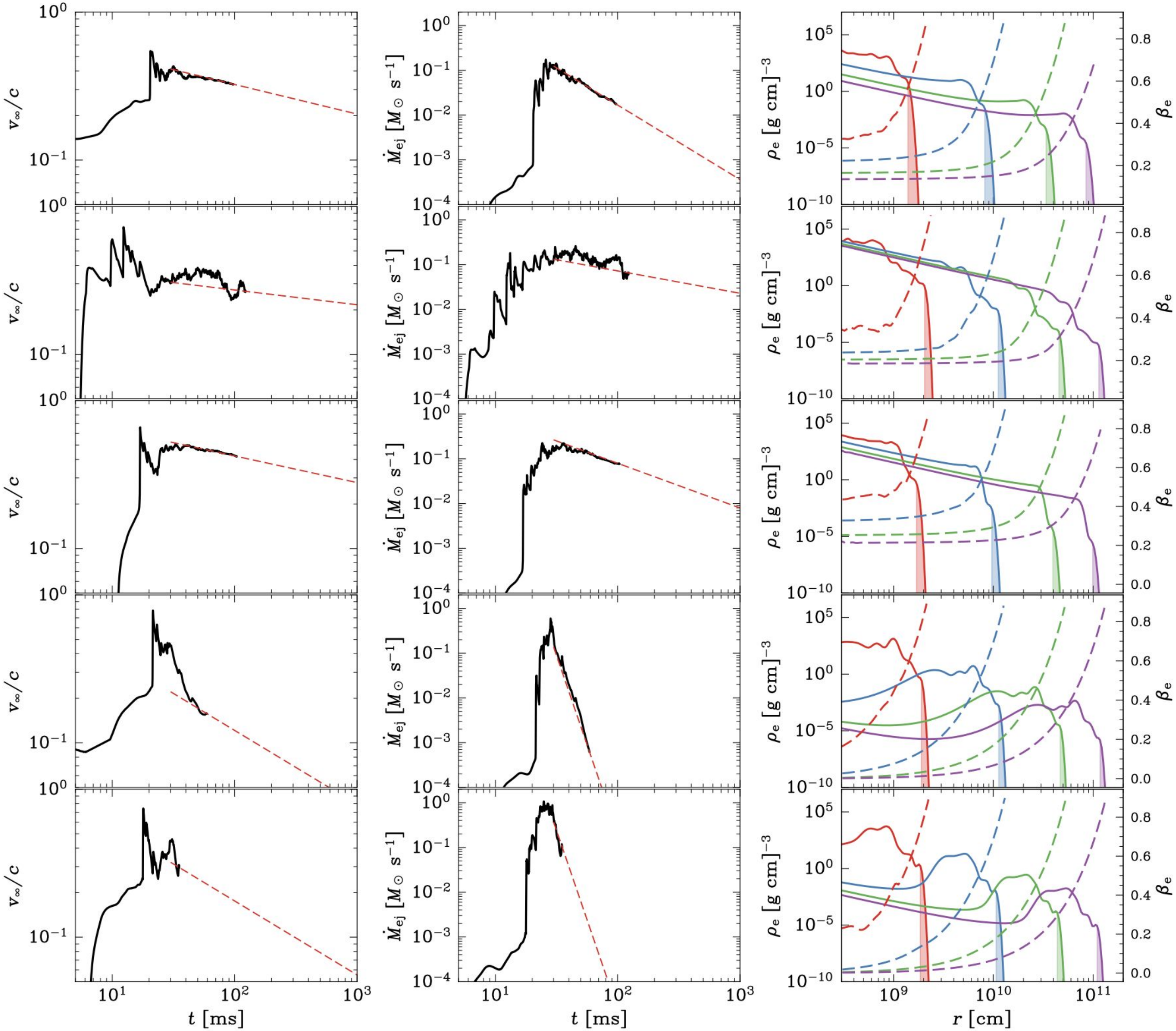
$$(w_\mathrm{j} + b_\mathrm{j}^2)\beta_\mathrm{jh}^2\Gamma_\mathrm{jh}^2 + p_\mathrm{j} + b_\mathrm{j}^2/2 = w_\mathrm{a}\beta_\mathrm{ha}^2\Gamma_\mathrm{ha}^2 + p_\mathrm{a}, \qquad (15)$$

$$\beta_\mathrm{c} = \left(1 + \bar{\rho}_\mathrm{a}c^2/p_\mathrm{c}\right)^{-1/2} + \beta_{\mathrm{a},\perp},$$

$$\frac{dz_\mathrm{h}}{dt} = \beta_\mathrm{h}c,$$

$$\frac{dr_\mathrm{c}}{dt} = \beta_\mathrm{c}c,$$

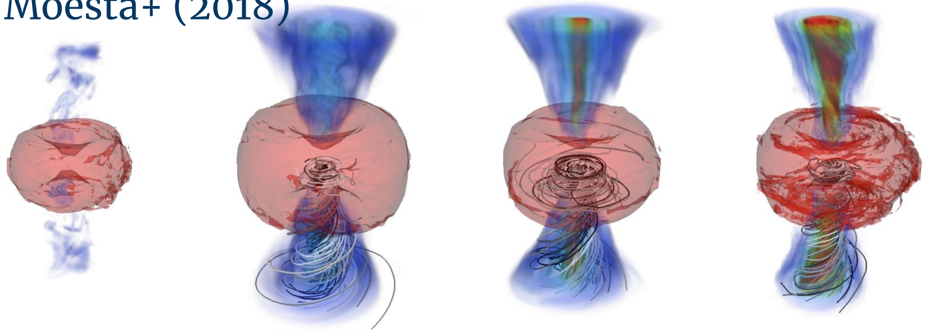
$$\frac{dE_\mathrm{c}}{dt} = \eta L_\mathrm{j}(t_\mathrm{e})\left[\beta_\mathrm{j} - \beta_\mathrm{h}\right].$$



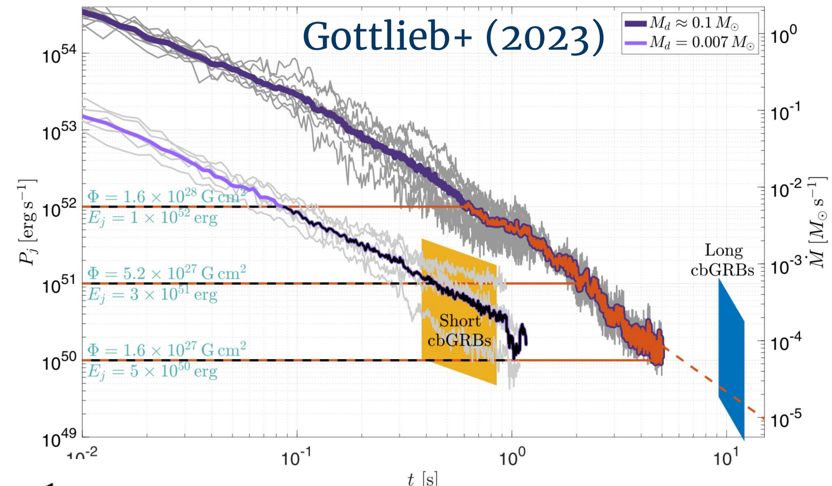
Dynamical ejecta + Neutrino-driven winds

ENGINES: Accreting Kerr black hole (BZ mechanism) / Millisecond Magnetar

Moesta+ (2018)



Moesta+ (2018), Kiuchi+ (2024), Combi+ (2023)



$R_{\rm NS} \sim 10$ km

$P \sim 1$ ms

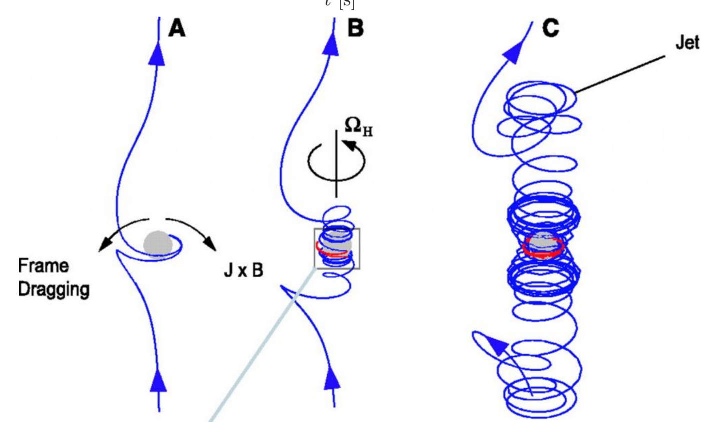
$$L_{\rm em} \simeq (10^{48}\ {\rm erg\ s^{-1}})\, B_{p,14}^2 R_6^3 P_{-4}^{-1},$$

Siegel+ (2014)

$$P_j = \dot{M} \eta_\phi \eta_a c^2$$

$$\eta_\phi = \left(\frac{\phi}{50}\right)^2$$

Gottlieb+ (2023)



Semanov+ (2004)