Multi-Messenger Astrophysics in the Gravitational Wave Era
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Effects of R-Process Heating on Fall-Back Accretion in Neutron Star/Black Hole Mergers

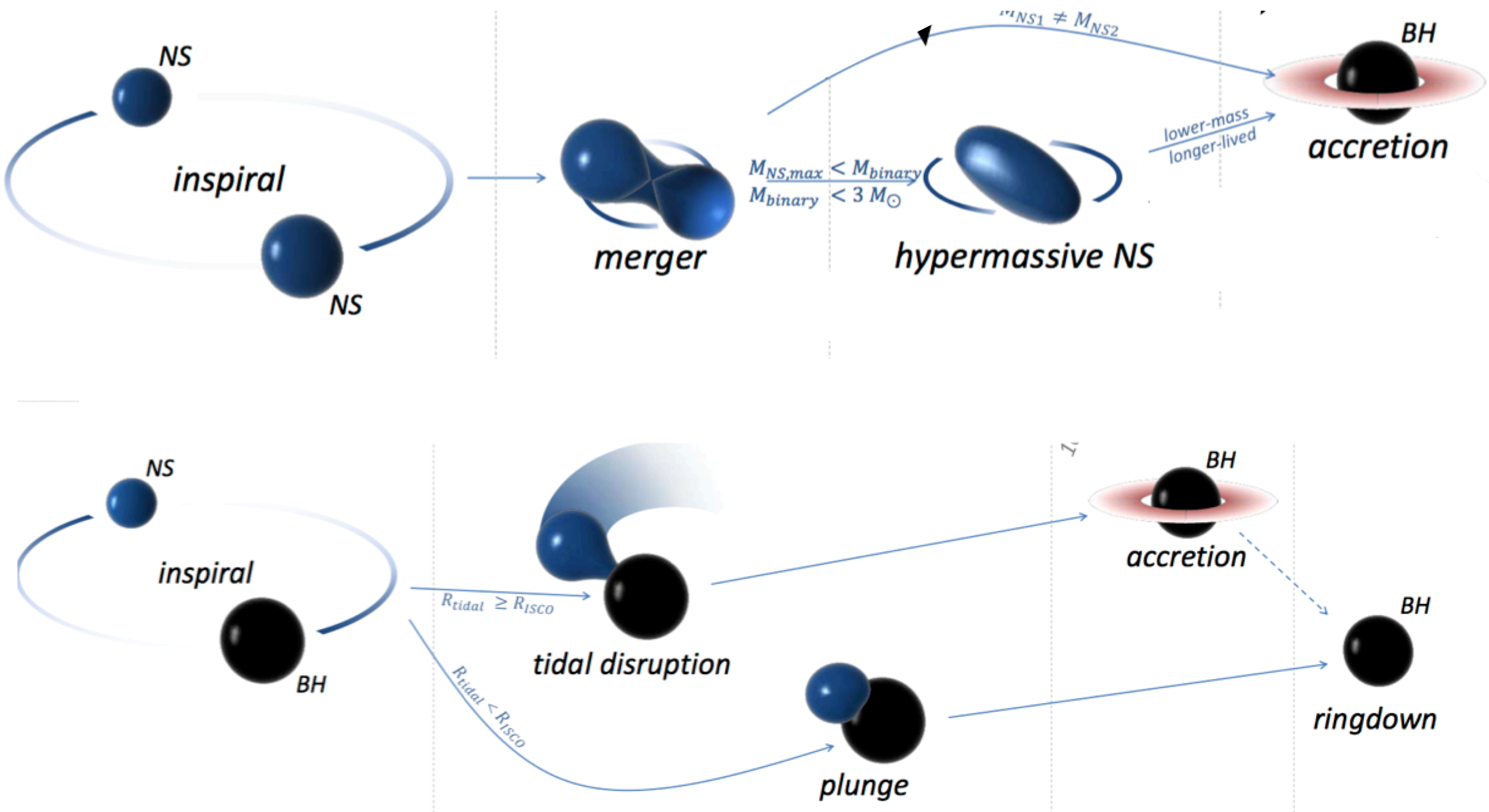
Dhruv Desai
Columbia University
Advisors: Brian Metzger (Columbia), Francois Foucart (UNH)

Overview

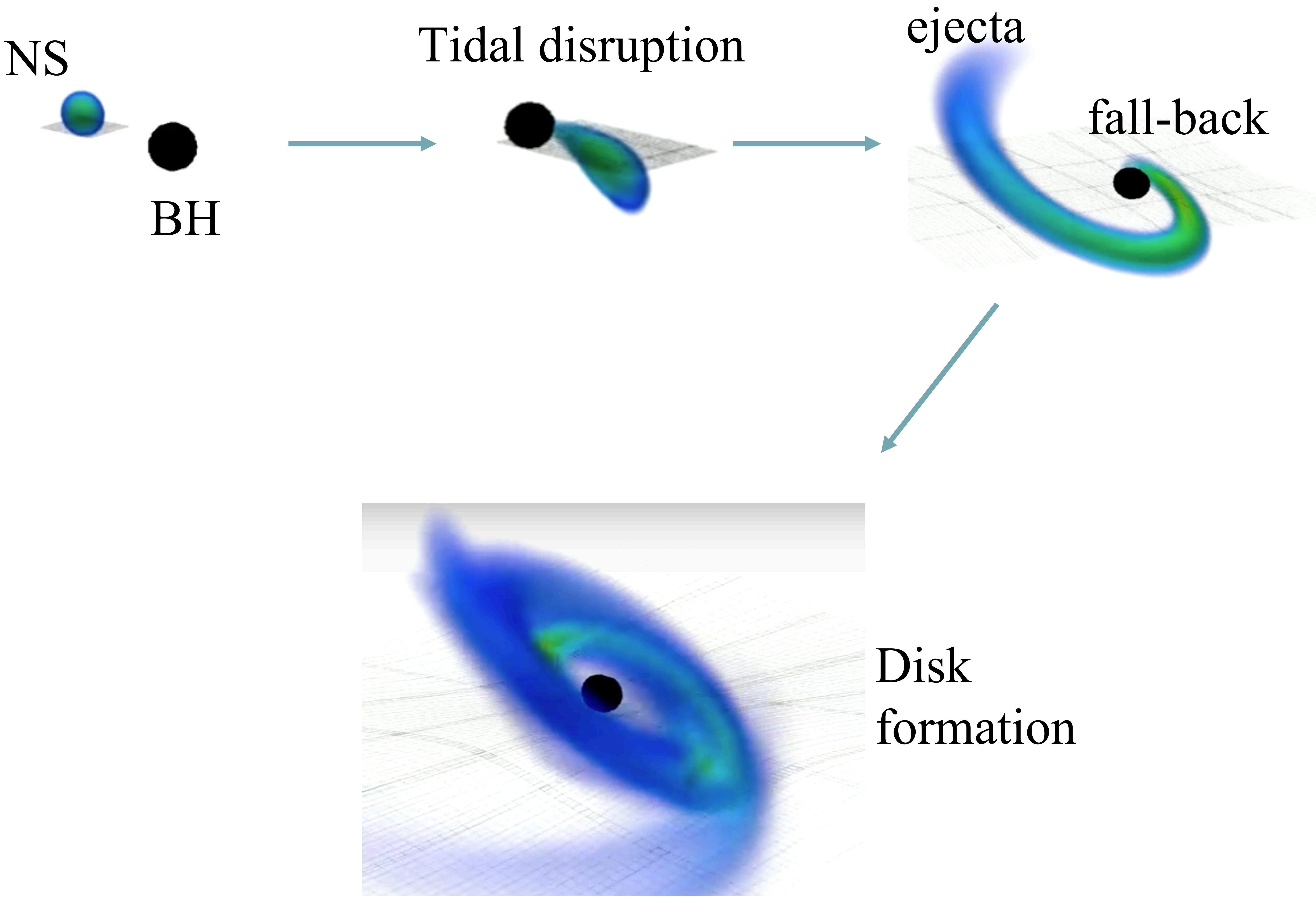
- Intro to mergers
- Intro to Short Gamma-Ray Bursts & temporally Extended X-ray Emission
- Fall-back Accretion Model
- Importance of r-process heating on dynamics
- Our Fall-back model
- Different Outcomes of the model
- Implications for distinguishing BH-NS from NS-NS mergers

The Picture

Bartos, Brady, Marka 2013

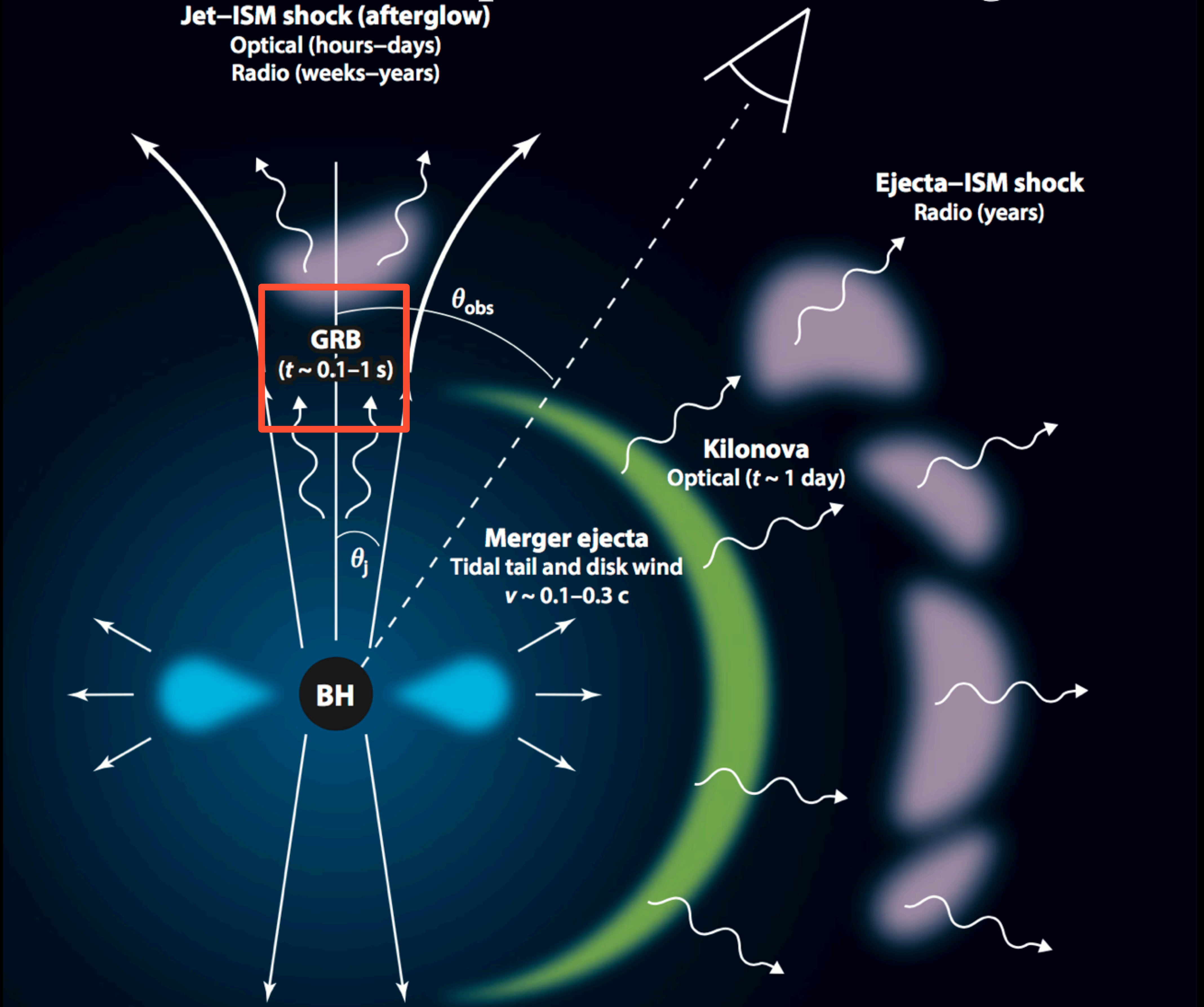


NS-BH mergers tend to eject more neutron rich material



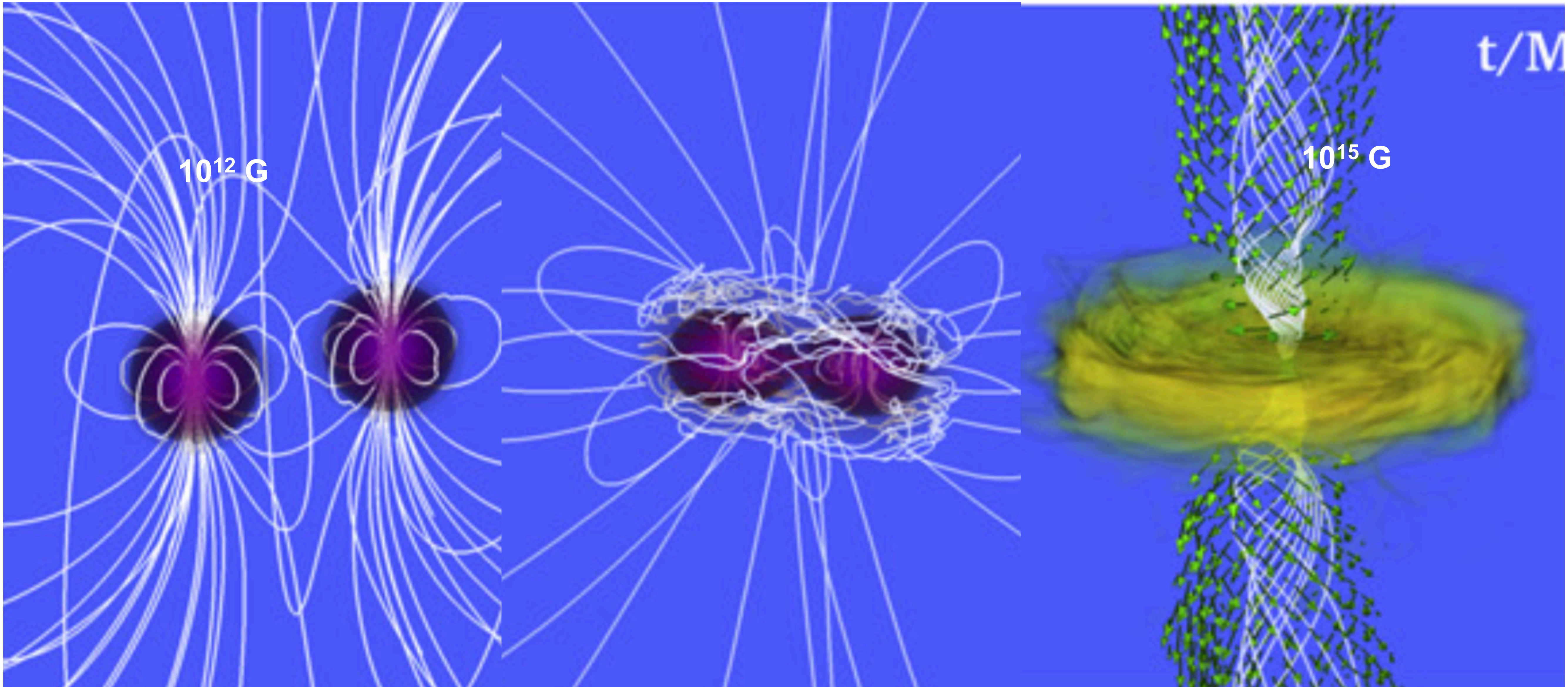
Images provided from SpEC simulations, courtesy of Francois Foucart

EM Counterparts of BNS Mergers



BDM & Berger 12

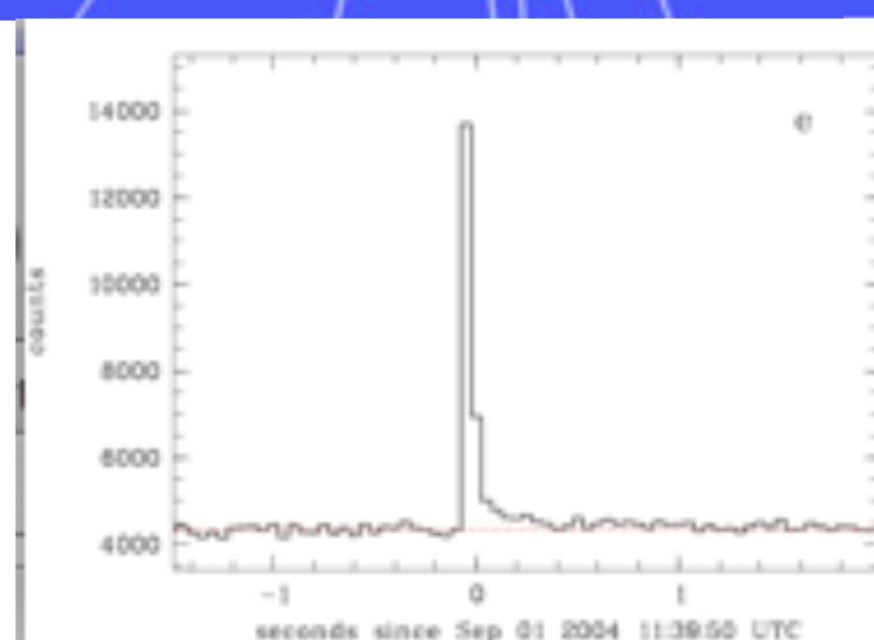
GRB Jets Powered by Black Hole Accretion

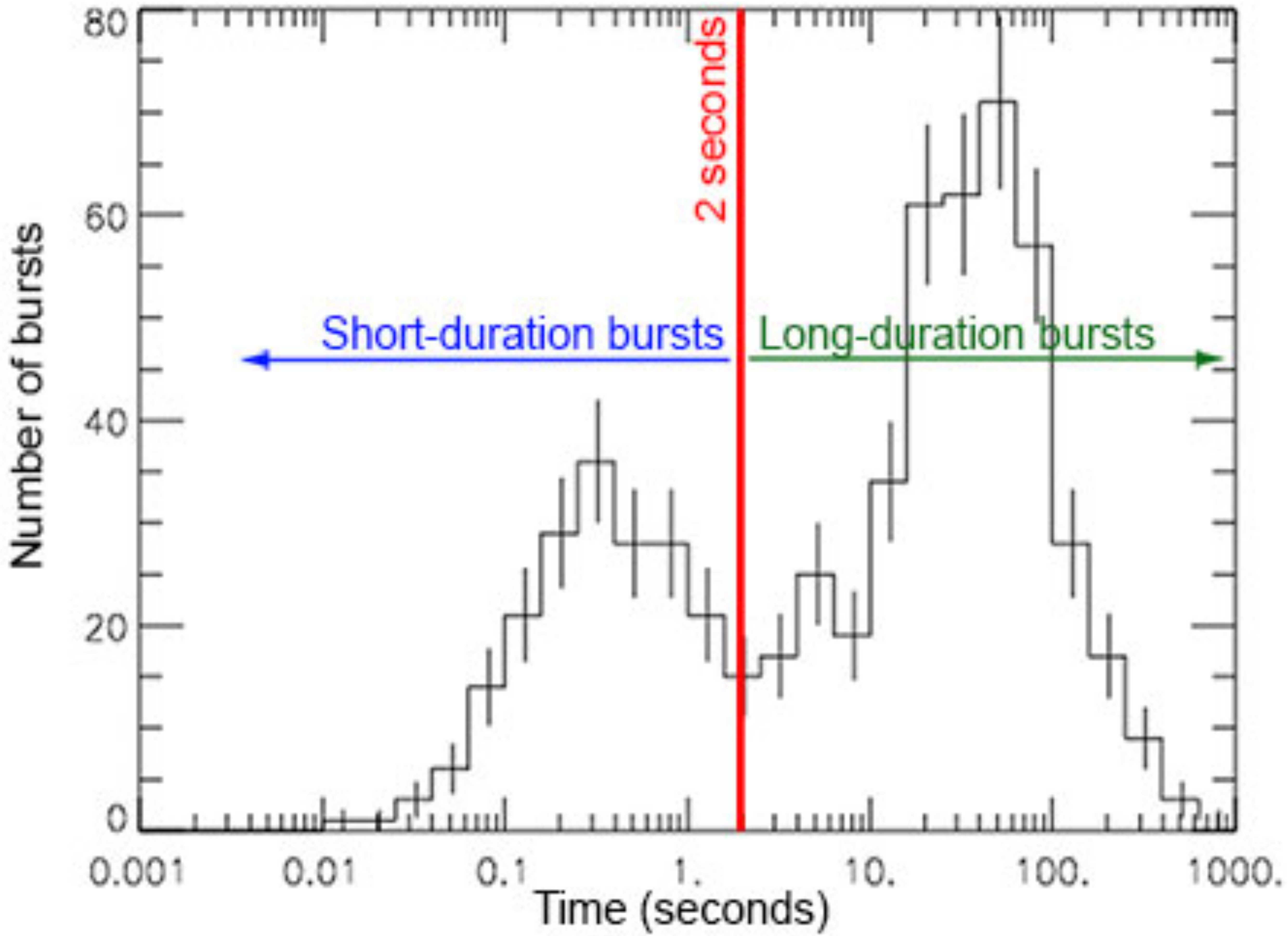


Ruiz et al. 2016

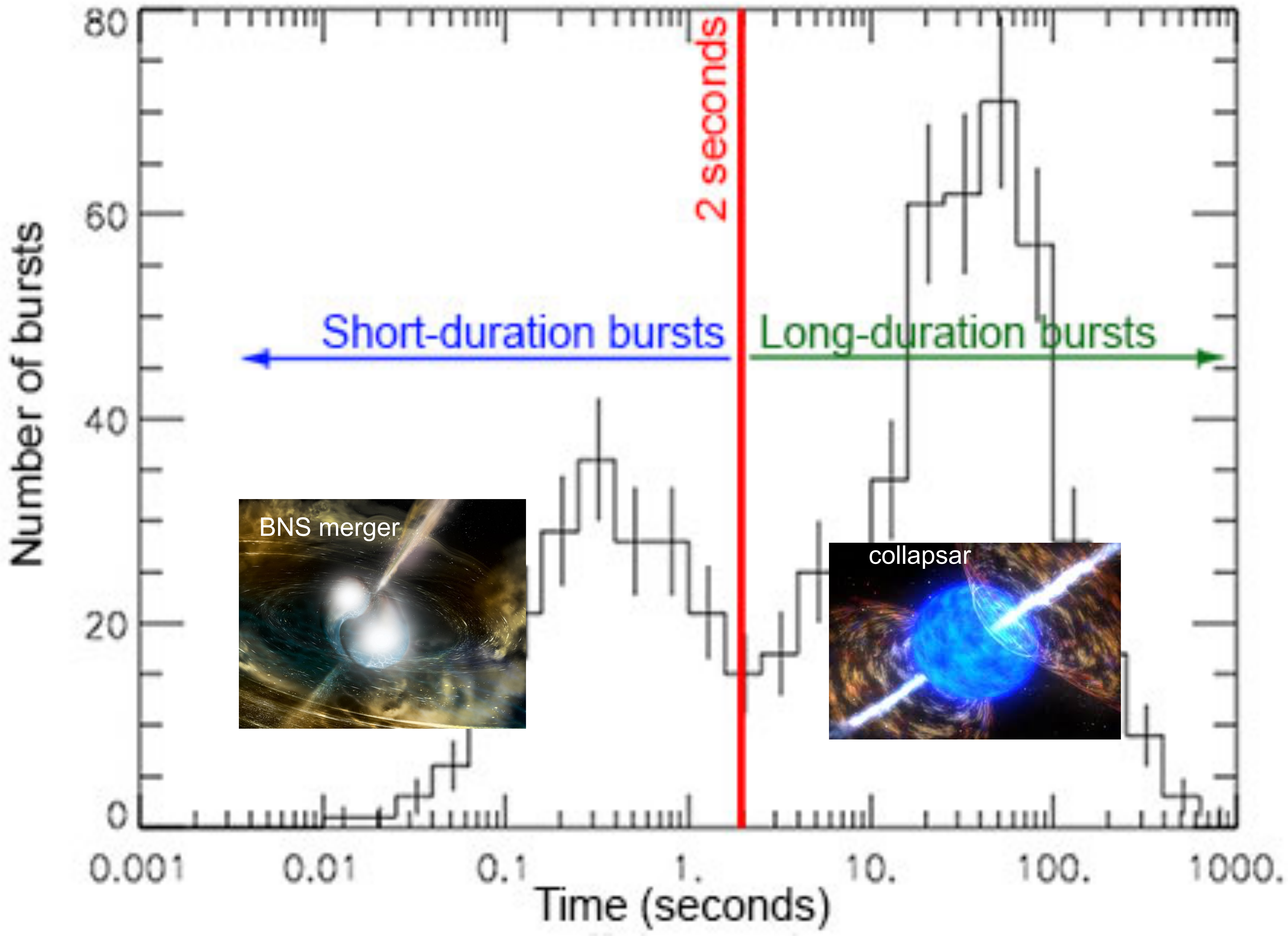
Short GRB

$$L = \epsilon \dot{M} c^2$$



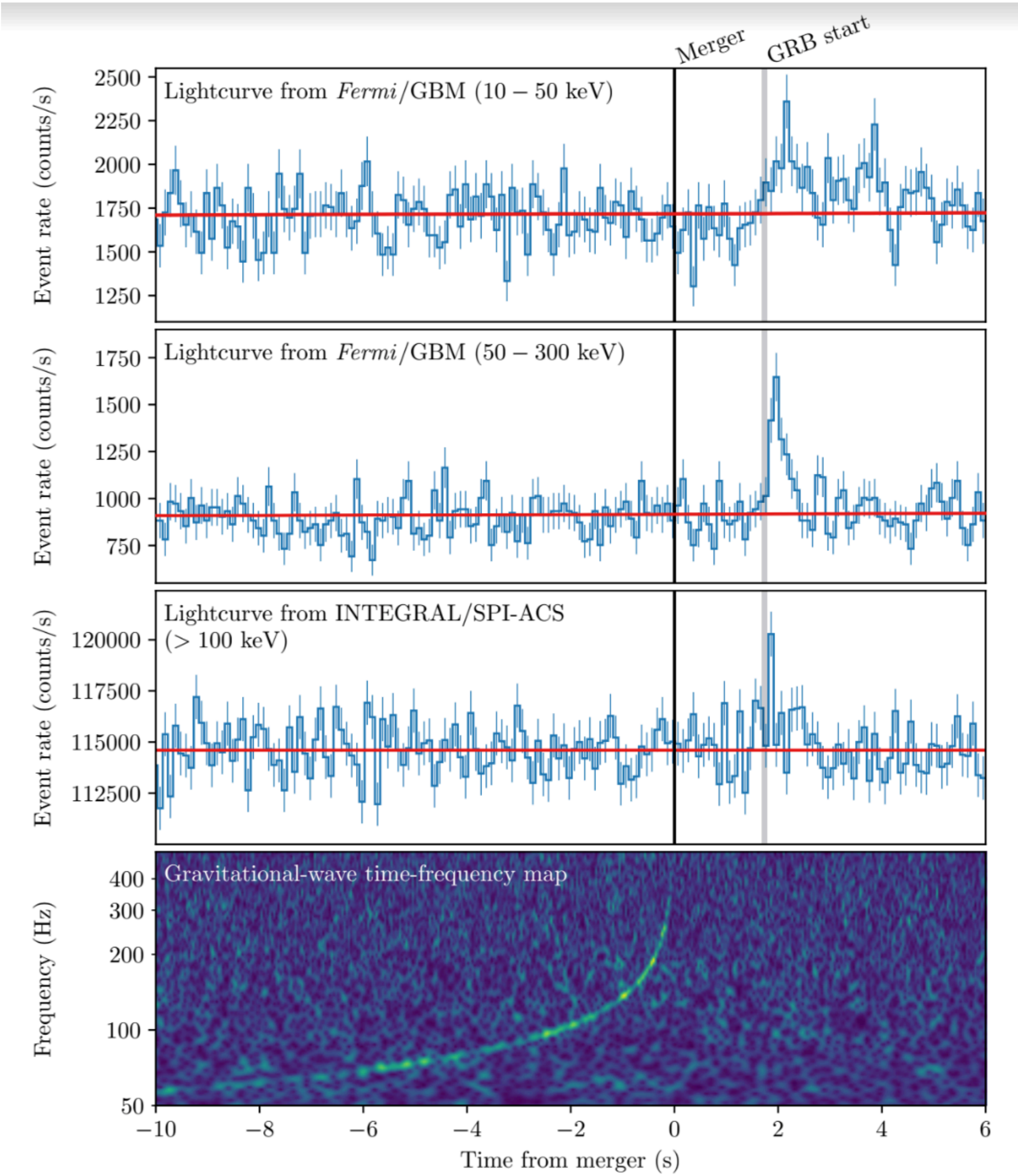


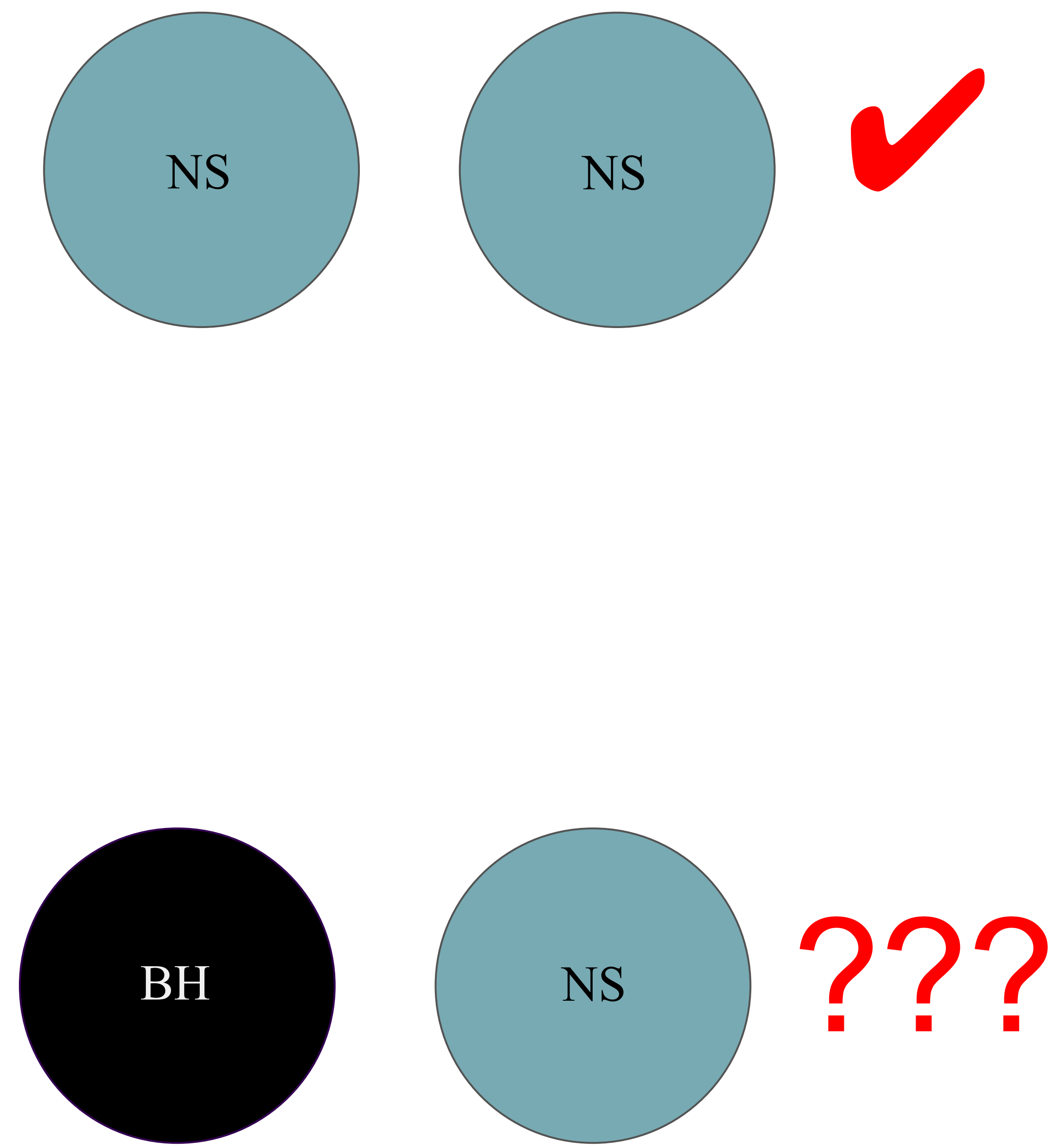
Number of bursts
80
60
40
20
0
2 seconds
Short-duration bursts
Long-duration bursts
0.001
0.01
0.1
1.
10.
100.
1000.
Time (seconds)



80
60
40
20
0
Number of bursts
2 seconds
Short-duration bursts
Long-duration bursts
BNS merger
collapsar
0.001
0.01
0.1
1.
10.
100.
1000.
Time (seconds)

Binary NS mergers can produce short GRB

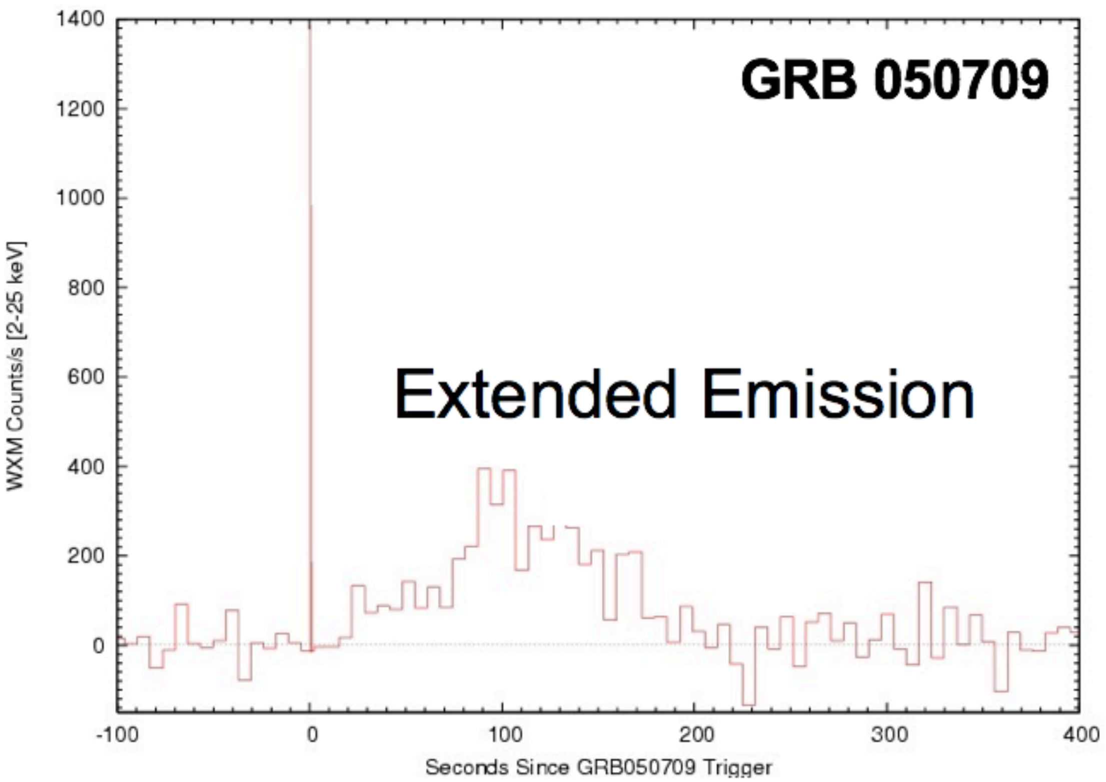


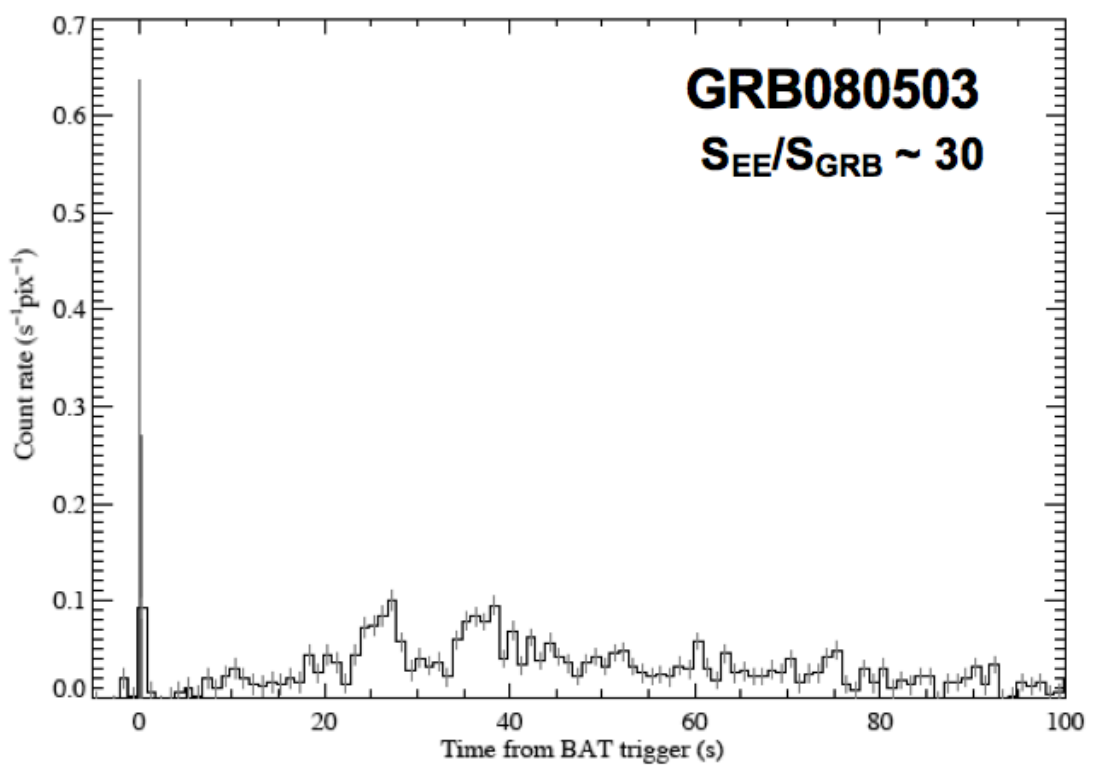


The physics is the same

LVC + Fermi GBM + Integral 2017

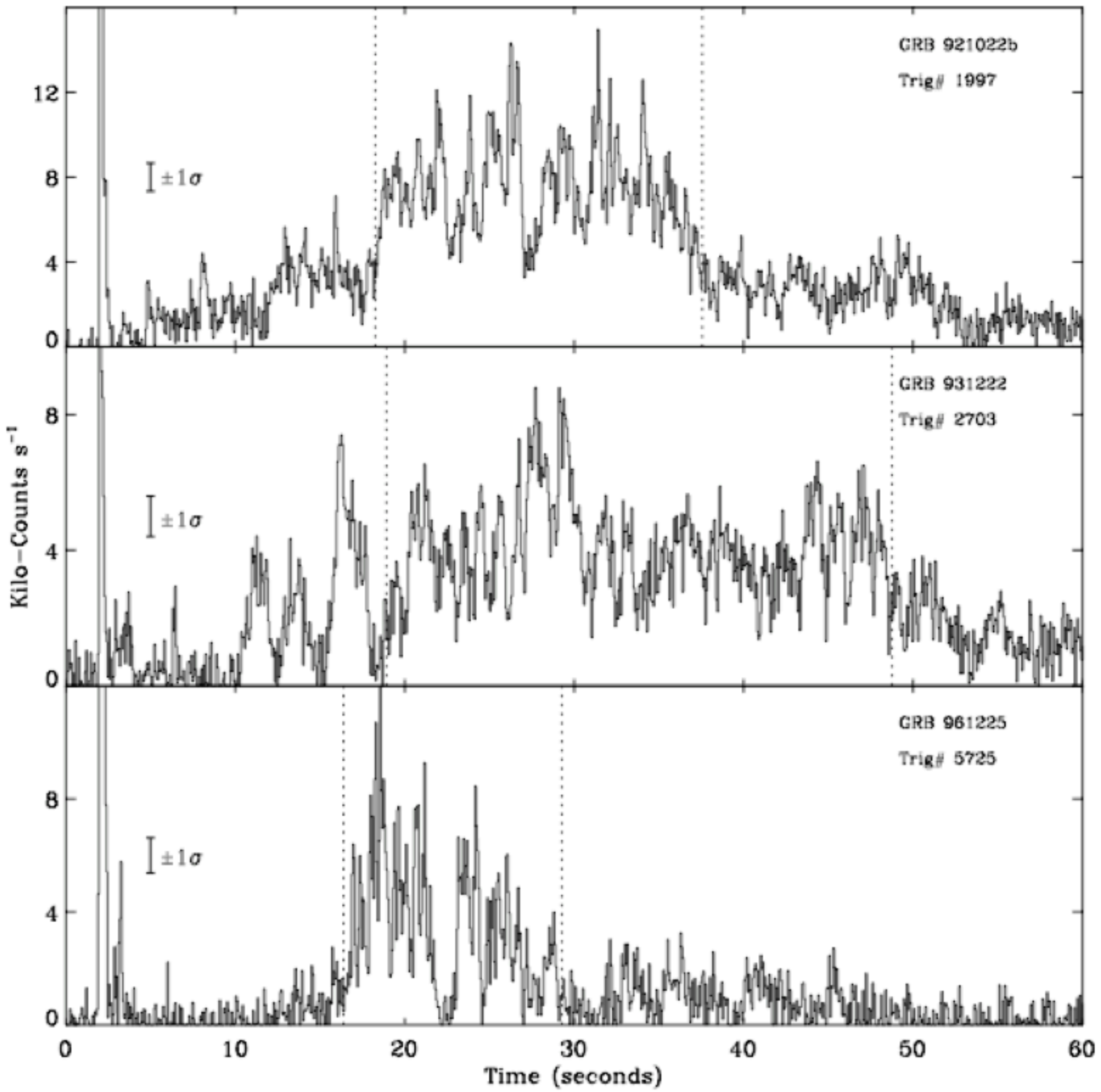
Short GRBs with Extended Emission





Perley, BDM et al. 2009

- 20% short GRBs have X−ray tails
- Rapid variability ⇒ ongoing engine activity
- Energy up to ~30 times prompt burst Itself!



BATSE Examples (Norris & Bonnell 2006)

Potential Candidates?

- Long-Lived Magnetar Model

  Disfavored by lack of radio emission at late times

  (Bower & Metzger 14, Horesh+16, Fong+16)

- Fall-back Accretion Model (Rosswog 2007)
  - Idea: Accretion powers a jet; jet produces X-rays

Fall-back Accretion Model

Begin with Kepler's Law:

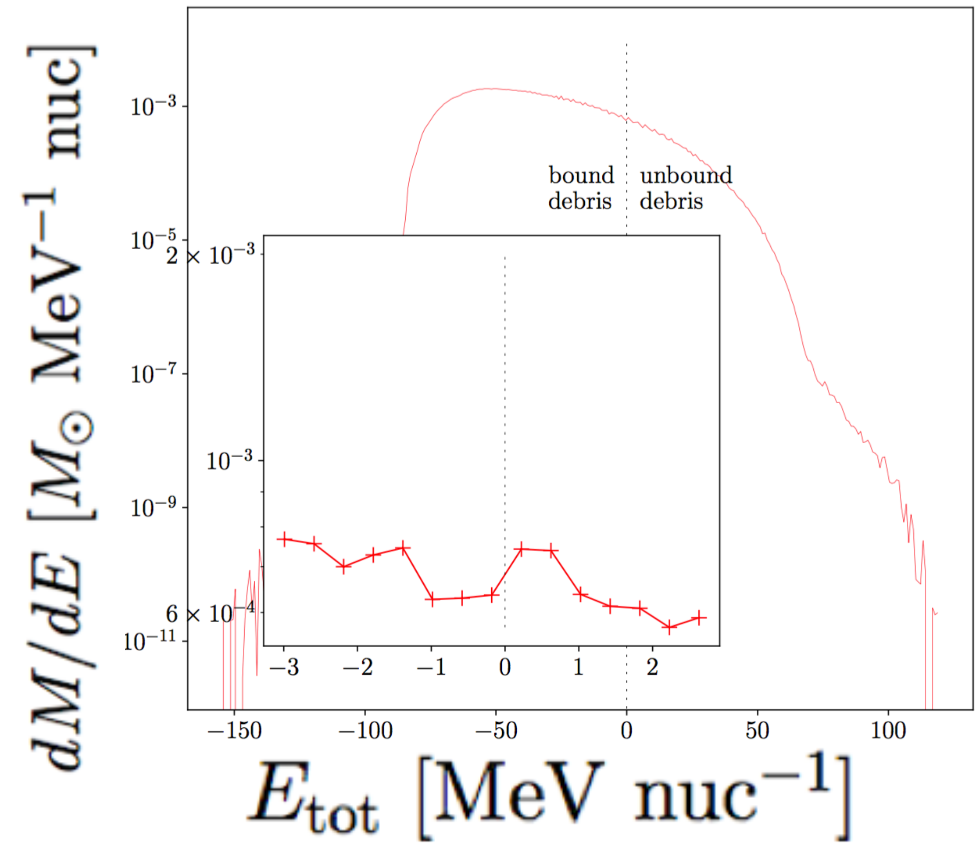
$$a^3 \propto t^2$$

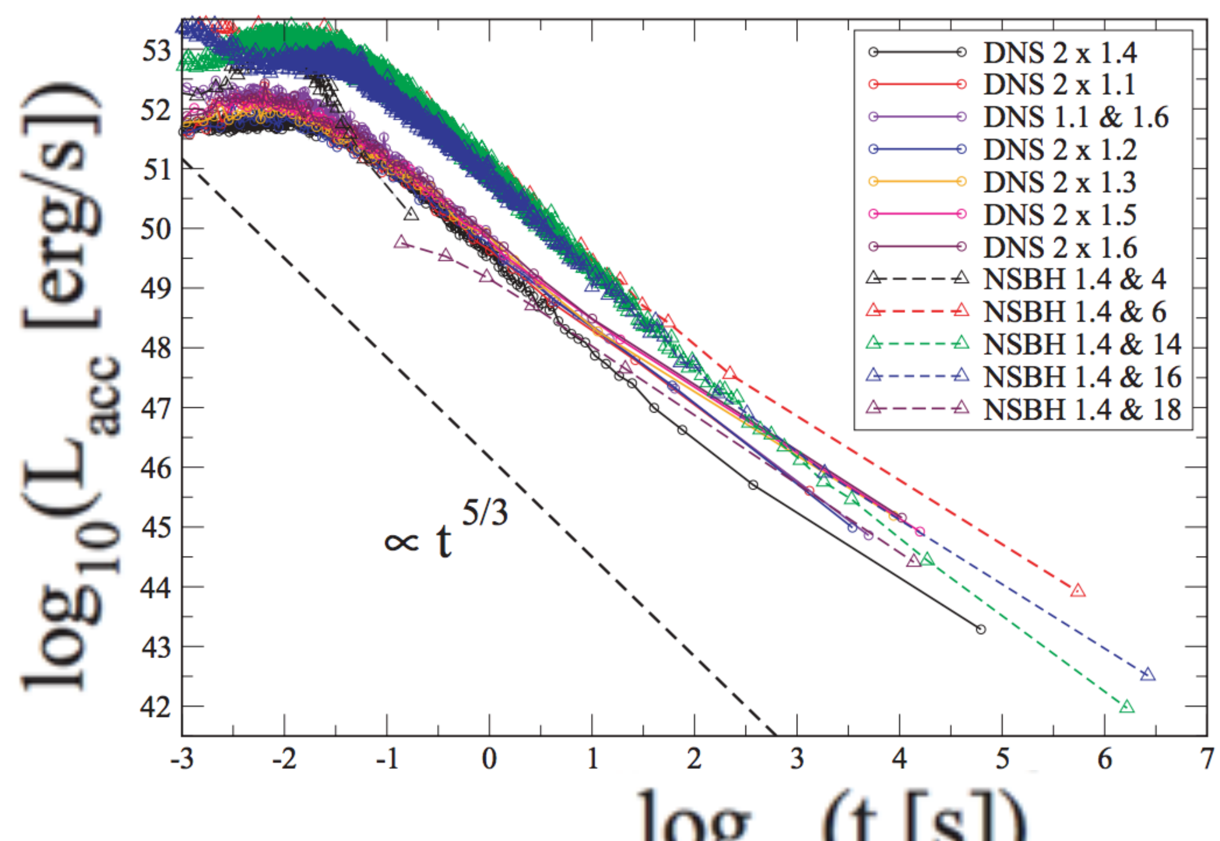
$$E \sim \frac{GMm_p}{a} \propto \frac{1}{a}$$

Fall-back rate:

$$\frac{dM}{dt} = \frac{dM}{dE}\frac{dE}{dt} \propto t^{-5/3}$$

(dM/dE is ~ constant near E=0)





Rosswog 2007

Problems with the Fall-back Accretion Model

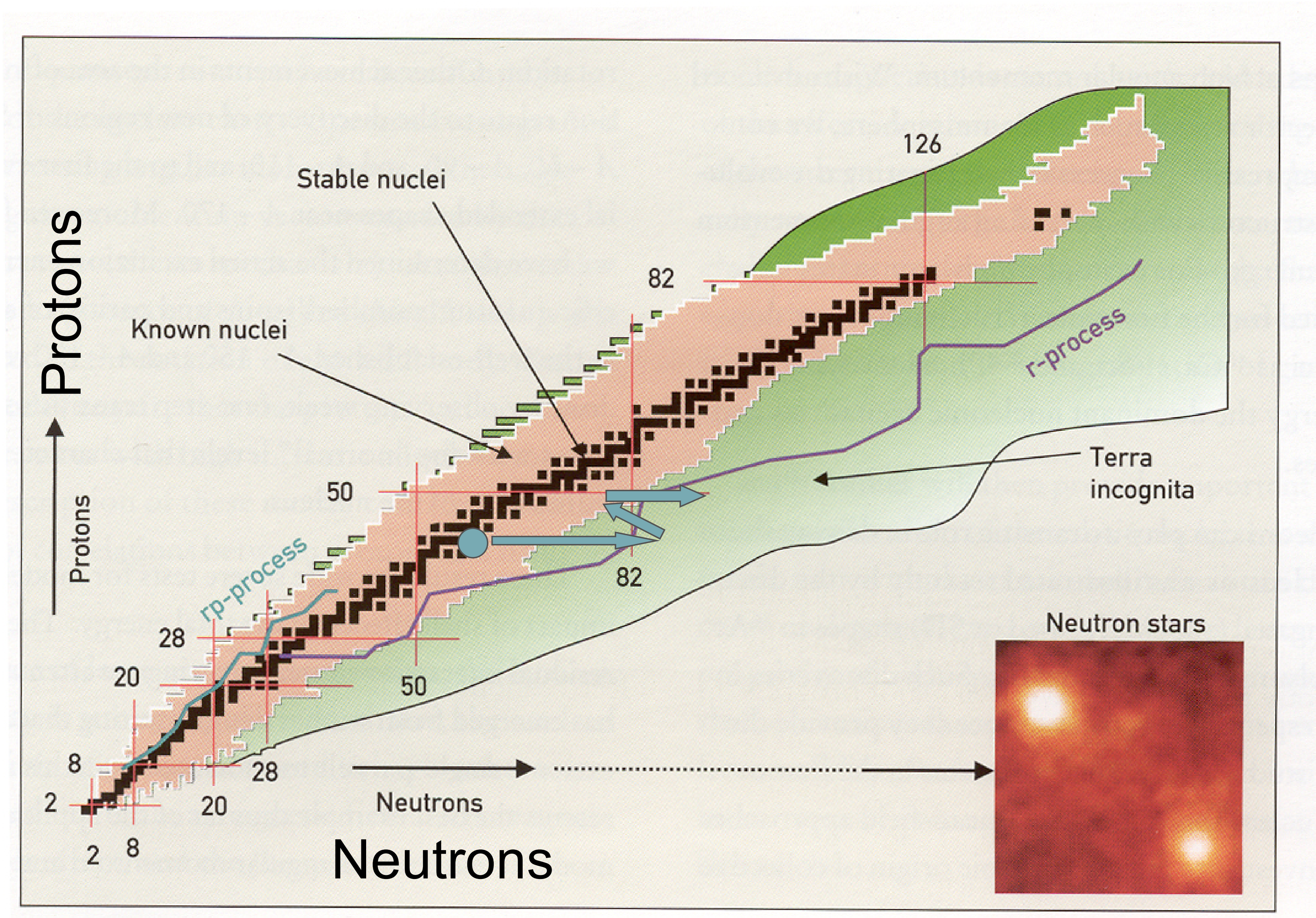
Gap between SGRB and Extended Emission unexplained.

Only ~ 20% of SGRBs are accompanied by Extended Emission. Why don't they all?

Possible solution: R-Process Heating!

Rapid Neutron Capture (R - Process) Heating
(not included in present simulations!)

Decompressing NS Matter ⇒ A ~ 100 Nuclei + Free Neutrons (Lattimer et al. 1977; Meyer 1989; Freiburghaus et al. 1999):



Neutron Fuel: $\Delta E_r \sim$ 1-3 MeV nucleon^{-1} released over $\Delta t_{heat} \sim 1$ second

Energy Released by R-Process (~few MeV)

$$\Delta E_{\rm r} \simeq (1 - f_\nu)\left[\left(\frac{B}{A}\right)_r - X_{\rm s}\left(\frac{B}{A}\right)_s - X_{\rm n}\Delta_{\rm n}\right]$$

Energy lost to neutrinos

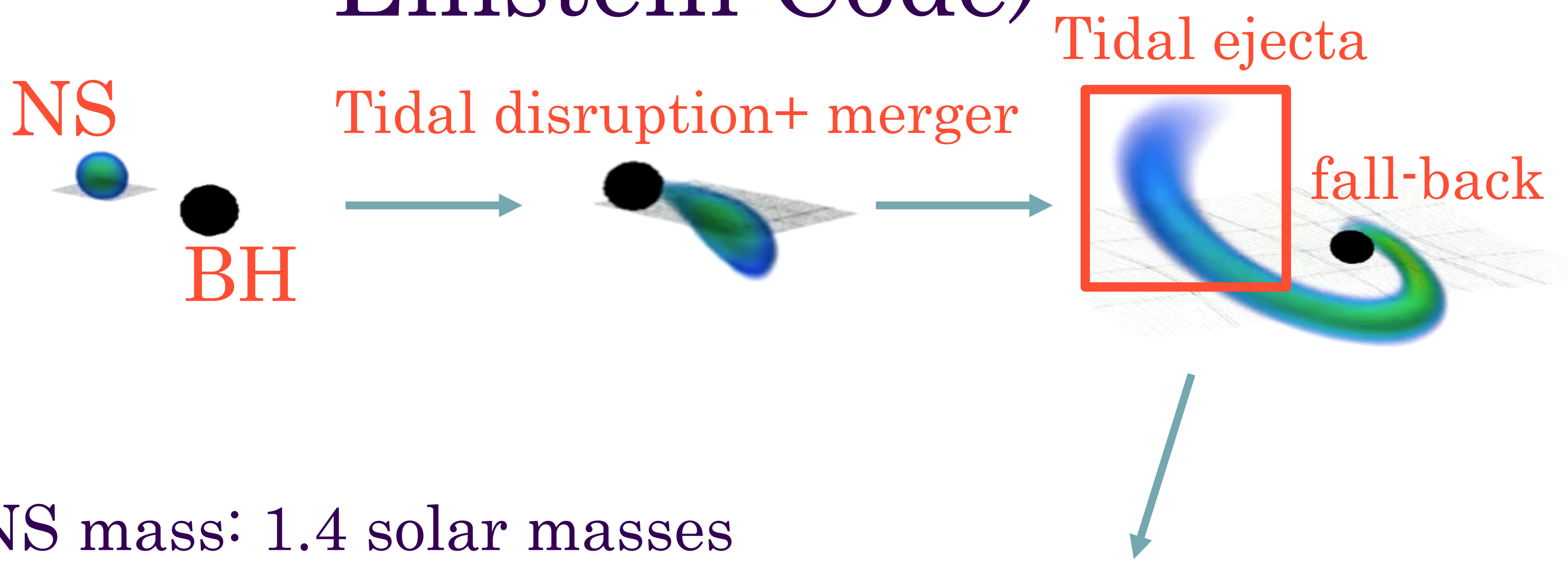
Rest-mass energy of newly formed r-process nuclei

Rest-mass energy of seed nuclei

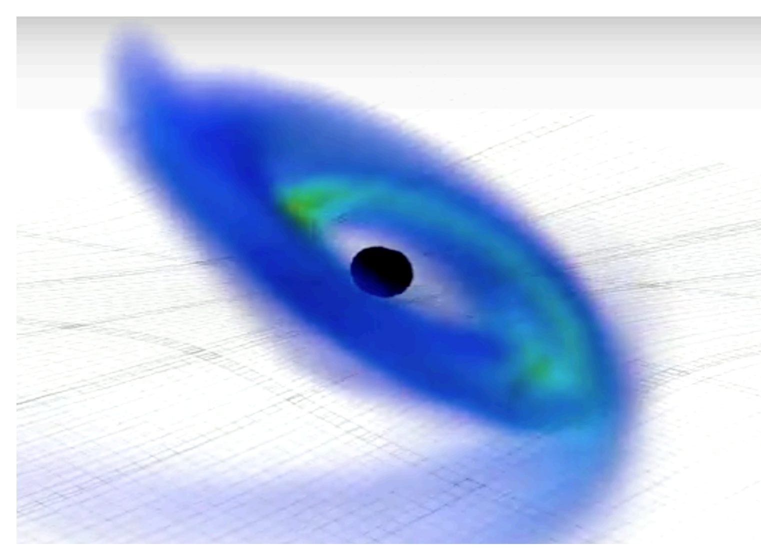
Rest-mass energy of neutron

How does r-process heating alter fall-back accretion rate?

Output of GR simulation (Spectral Einstein Code)



- Initial NS mass: 1.4 solar masses
- Initial BH mass: 5 solar masses
- Precessing system
- Final BH mass ~ 6 solar masses
- Data taken at $t = 15$ms after merger

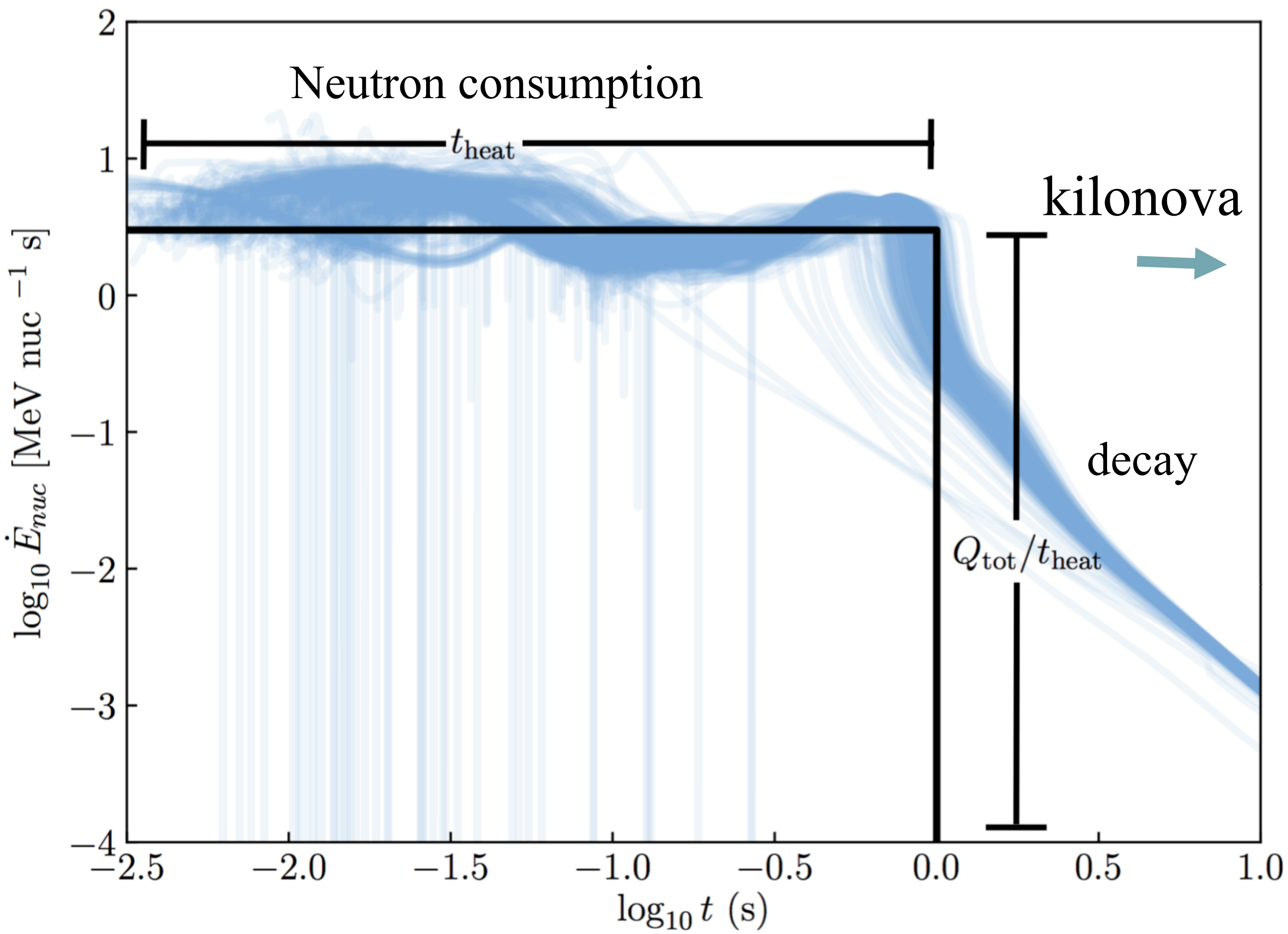


Disk formation

Images provided from SpEC simulations, courtesy of Francois Foucart

R-Process Heating Curves of Ejecta

- constant for first ~ 1 s of evolution, and decreases as a power law ($t^{-1.3}$)
- Heating released on timescale comparable to SGRB X-ray Emission



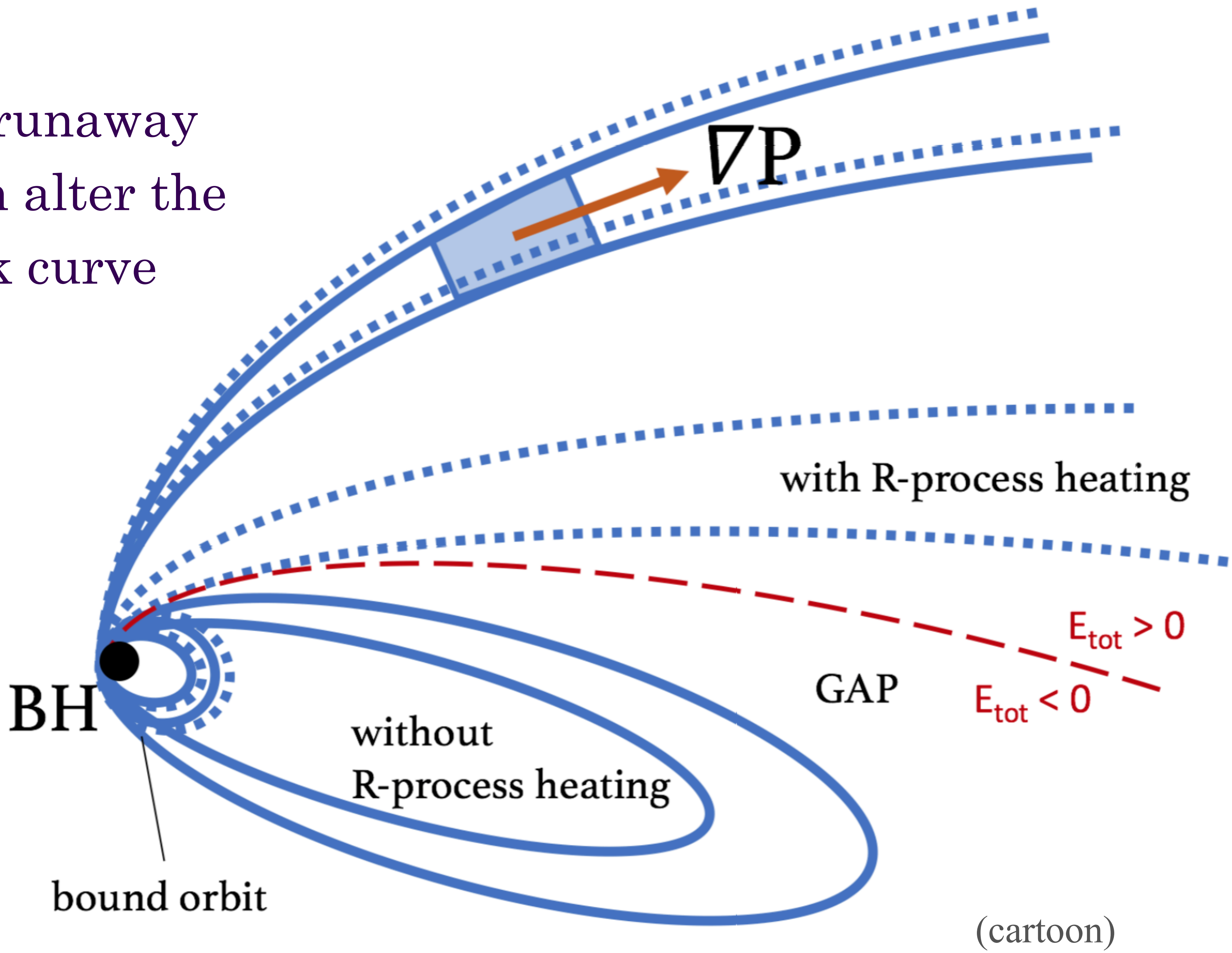
Calculated using SkyNet (Lippuner & Roberts 2014)

R-process heating

- Radiation dominated, but optically thick ejecta → adiabatic expansion
- Pressure gradient directed outwards
- Thermal energy → Kinetic energy along orbital direction

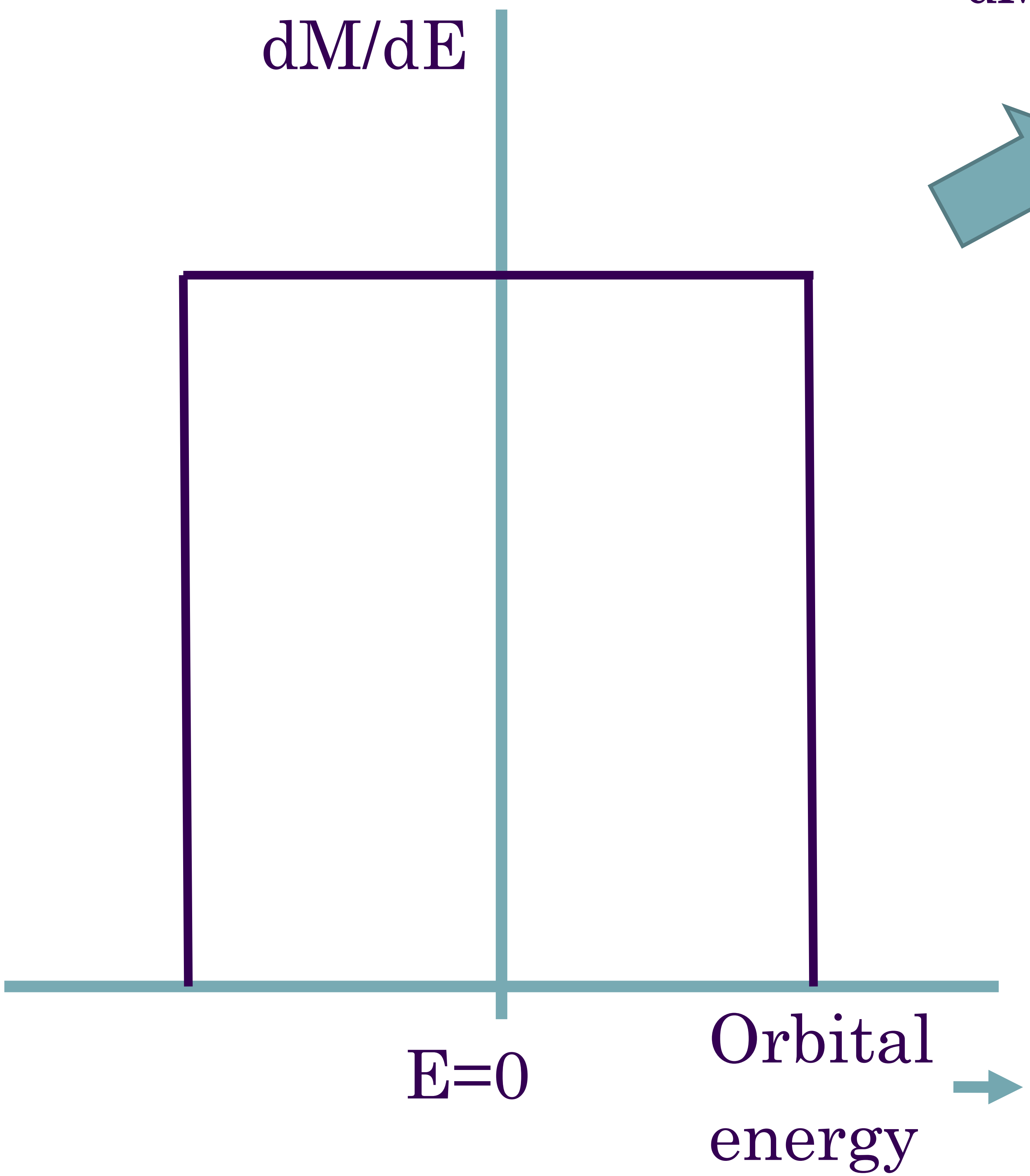
R-process heating alters fluid trajectories!

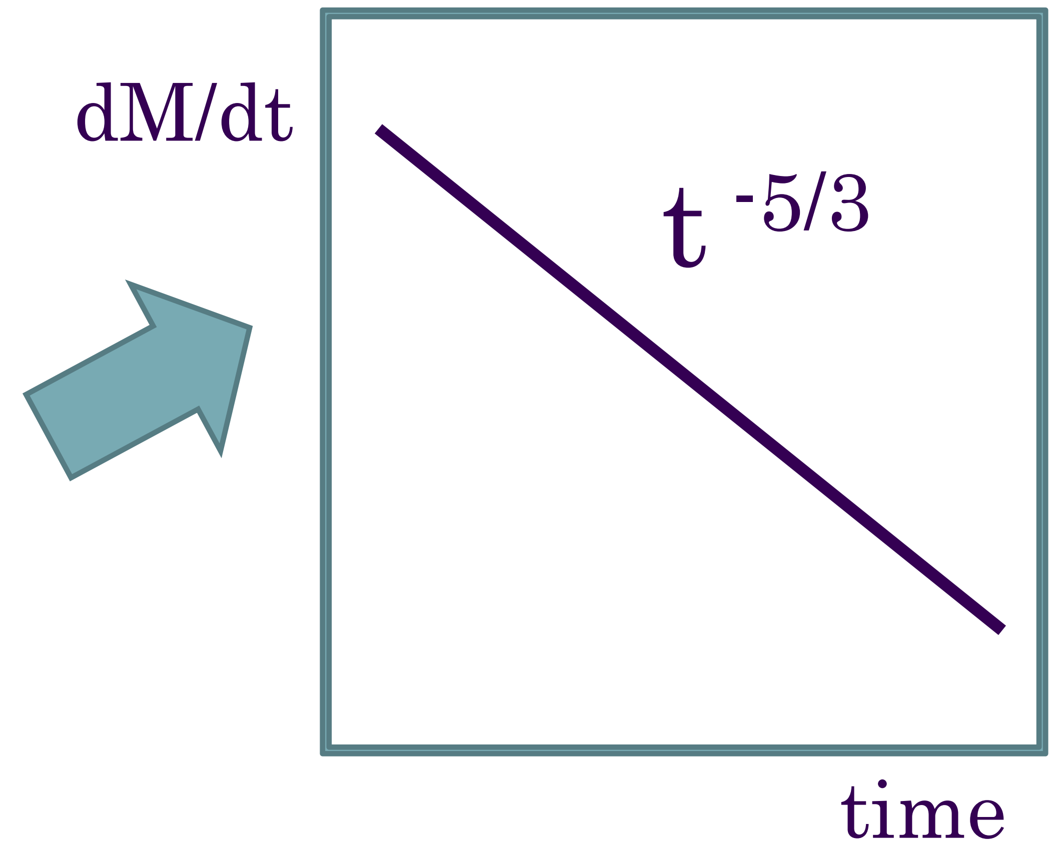
A simple runaway process can alter the fall-back curve



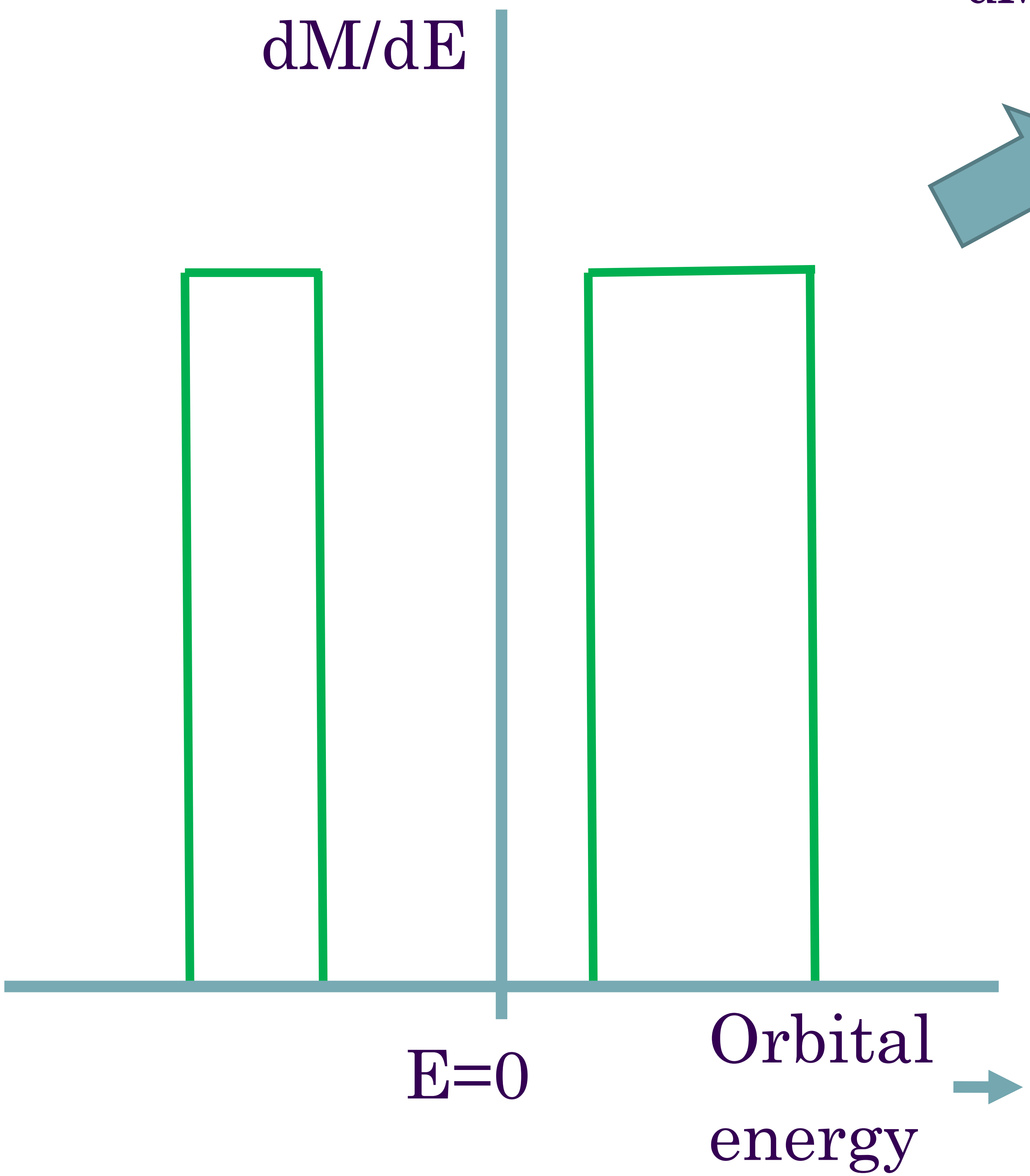
arXiv:1812.04641v2

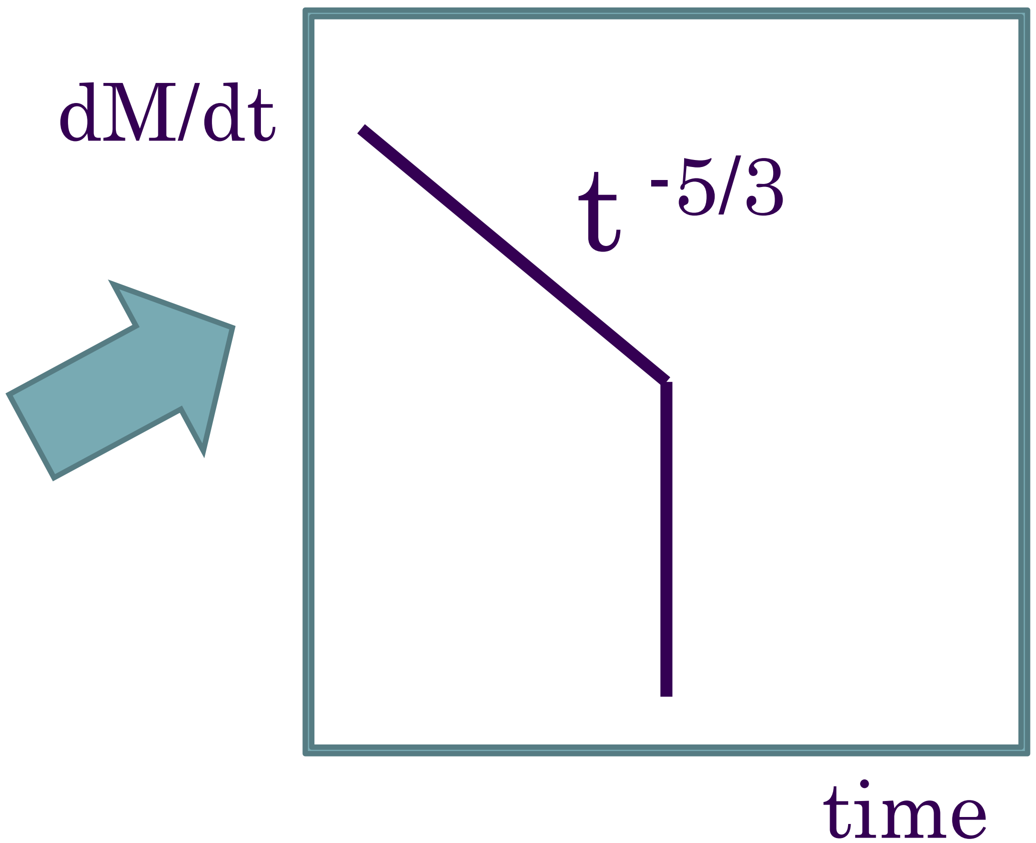
D. Desai et al. 2019



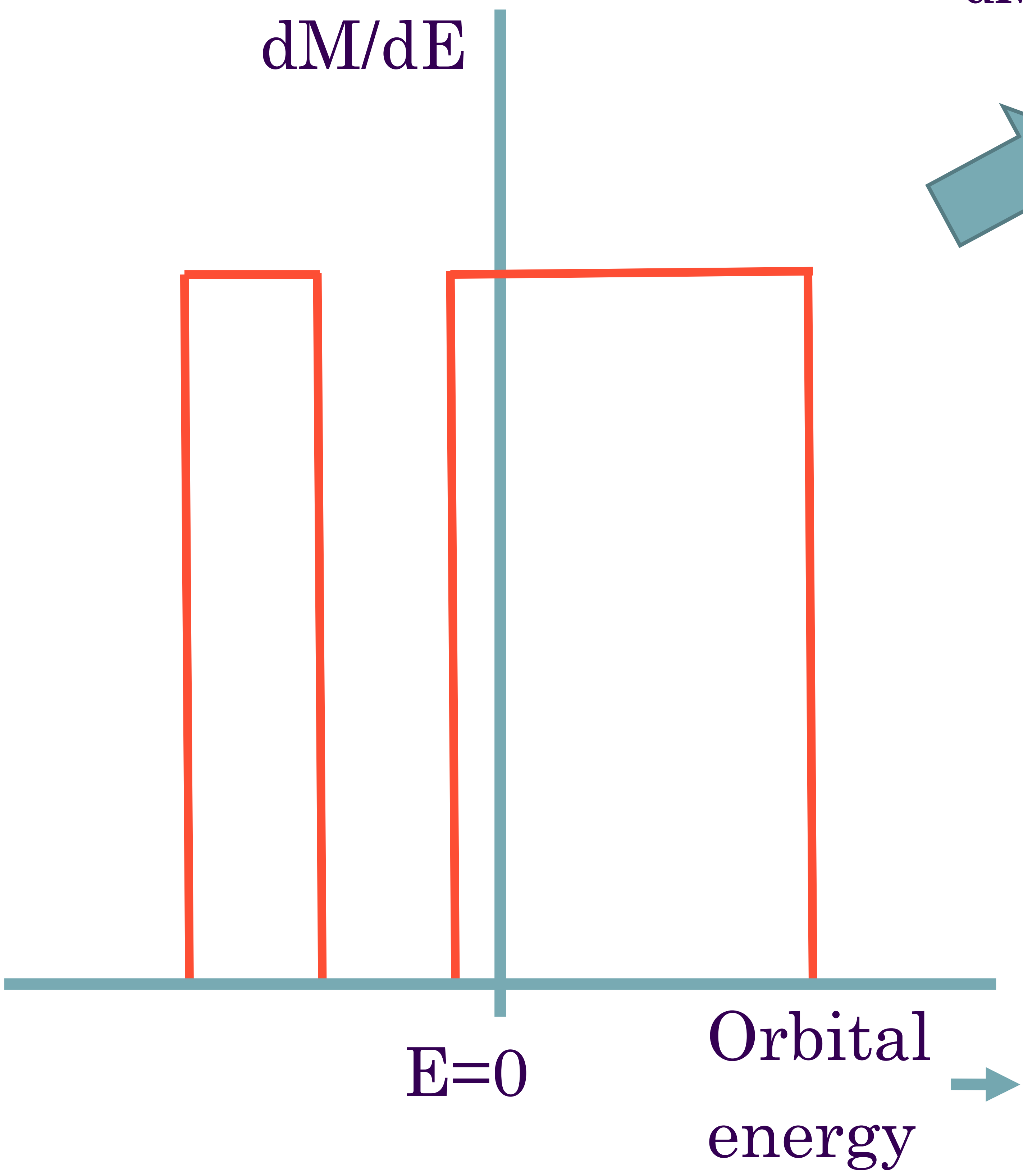


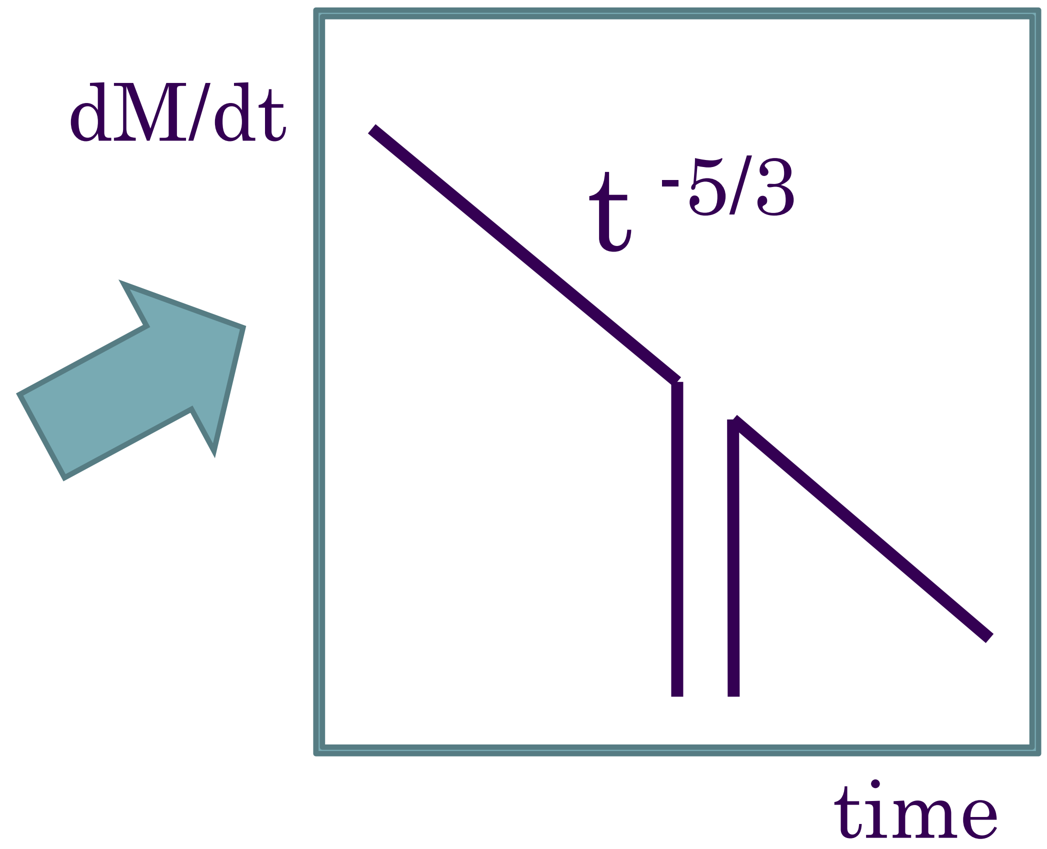
Energy distribution of matter determines fall-back curve!





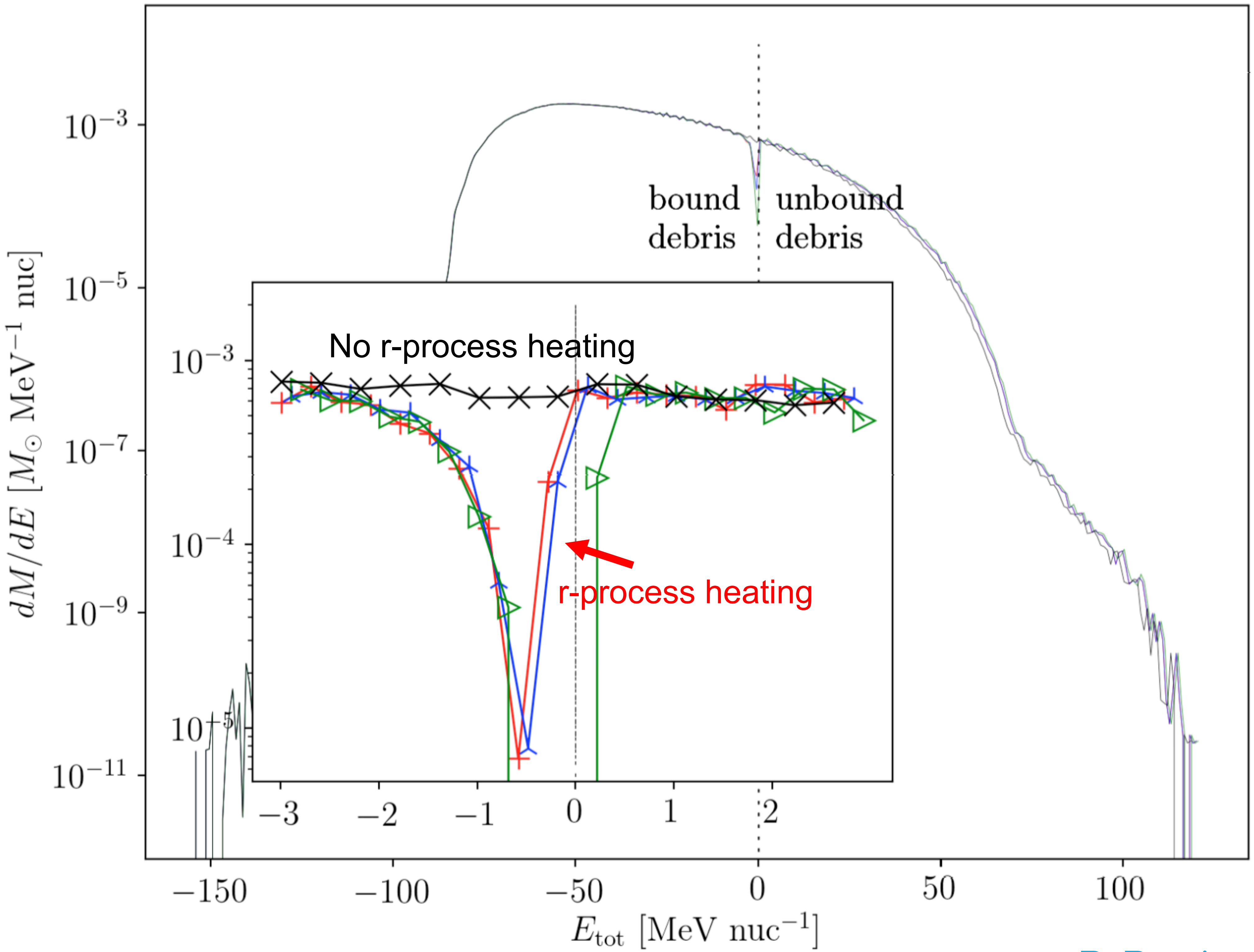
Energy distribution of matter determines fall-back curve!





Energy distribution of matter determines fall-back curve!

Energy Distribution With R-Process Heating



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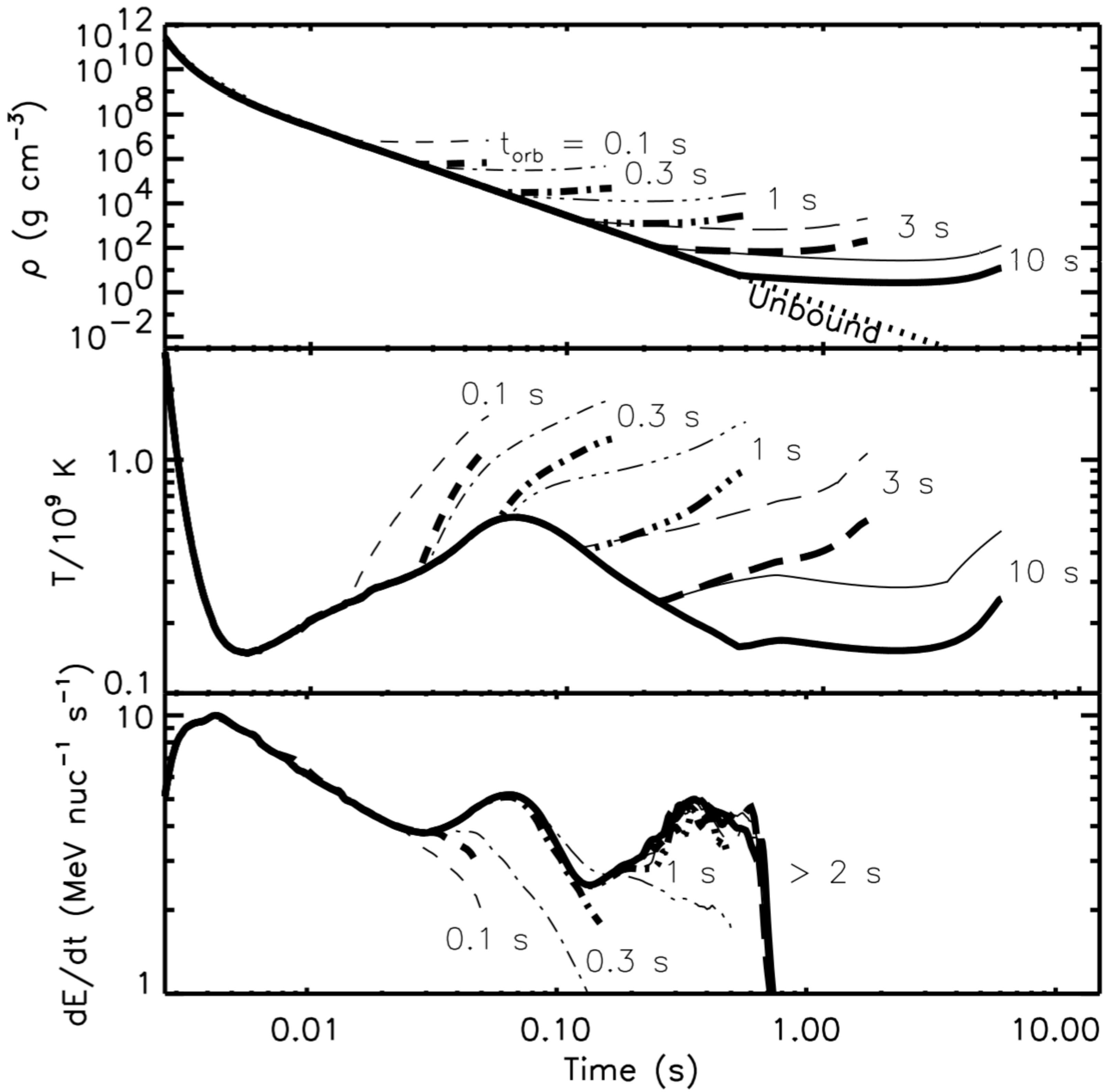
Details of our model

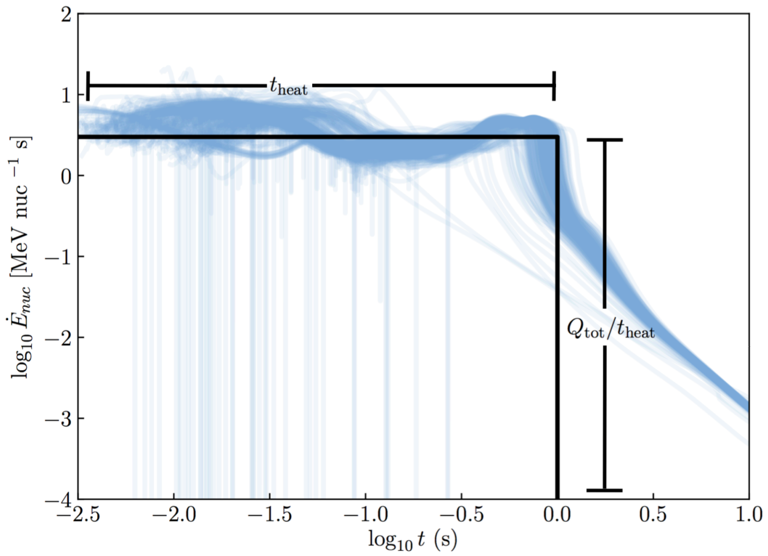
SkyNet simulation results show heating is cut off for negative radial velocities (r-process shuts off)

Metzger et al. 2010a



Details of our model

1. Q_{tot}, t_{heat} specified at initial time (uniform heating across all fluid elements)



2. Heating rate prescribed to each fluid element with:

$$\dot{q} = \begin{cases} Q_{tot}/t_{heat}, & \text{if } t \le t_{heat} \text{ and } v_r > 0 \\ 0, & \text{if } t > t_{heat} \text{ or } v_r < 0, \end{cases}$$

Note: some fluid elements (those with $t_{orb} < t_{heat}$) will receive less heat than Q_{tot}

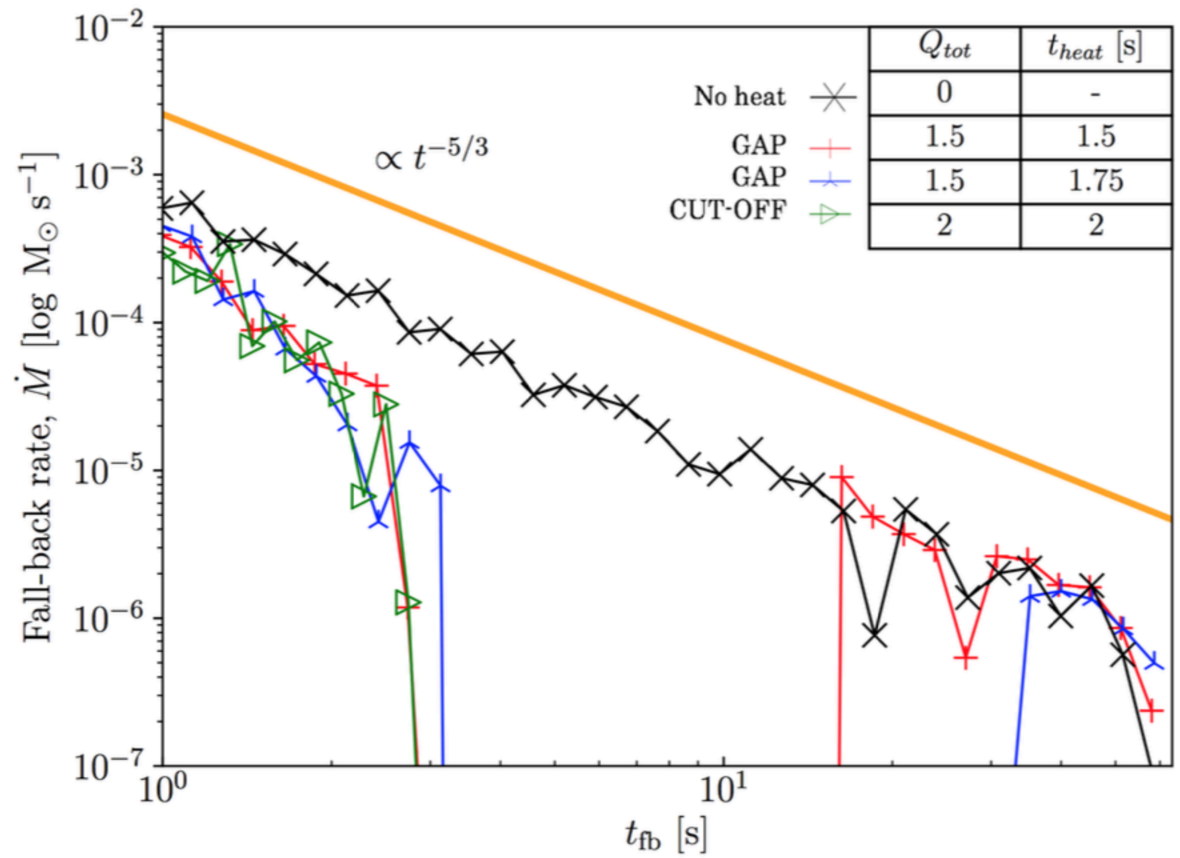
3. Kinetic energy directly increased according to:

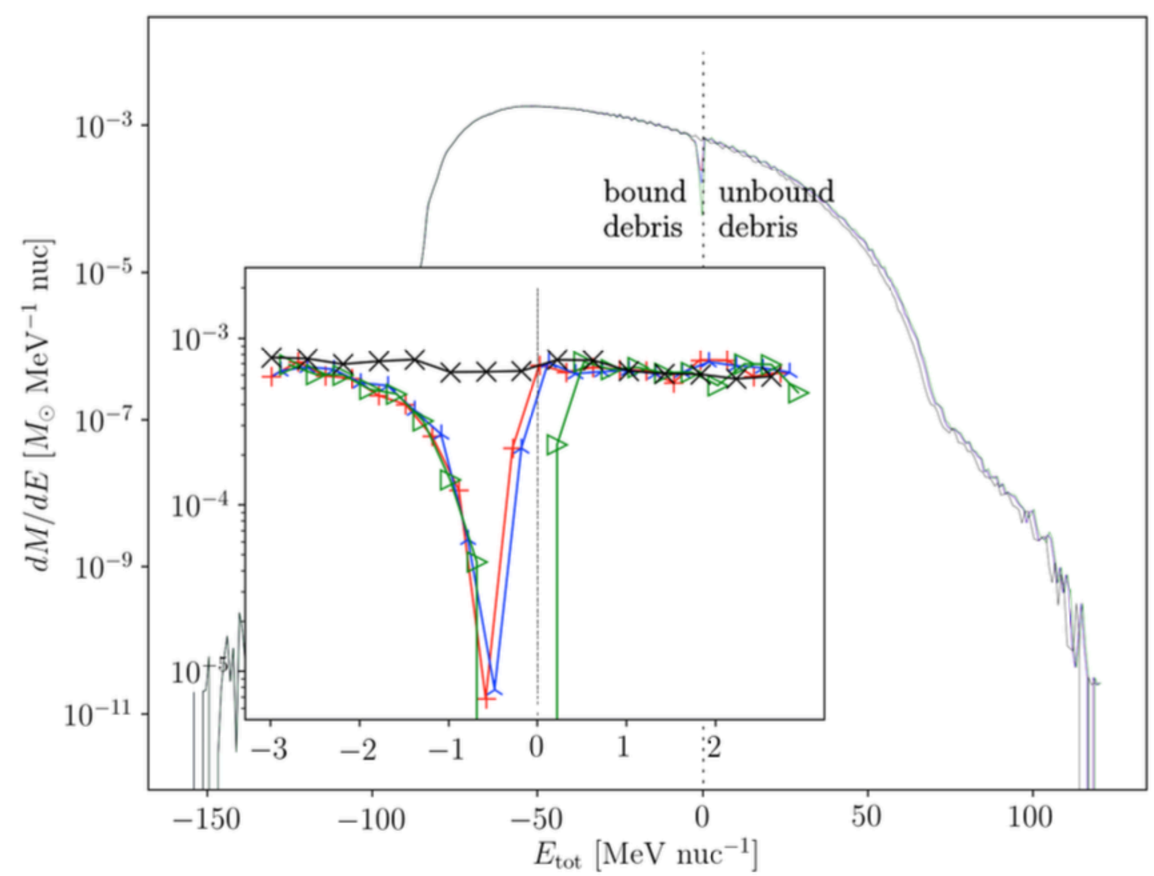
$$\frac{d}{dt}\left(\frac{1}{2} m_n v_{r,i}^2\right) = \dot{q}_i,$$

Results of our model

- With heating, we see gap in energy distribution of ejecta

- Depending on Q_{tot}, t_{heat}, this results in either a gap, or cutoff in fall-back





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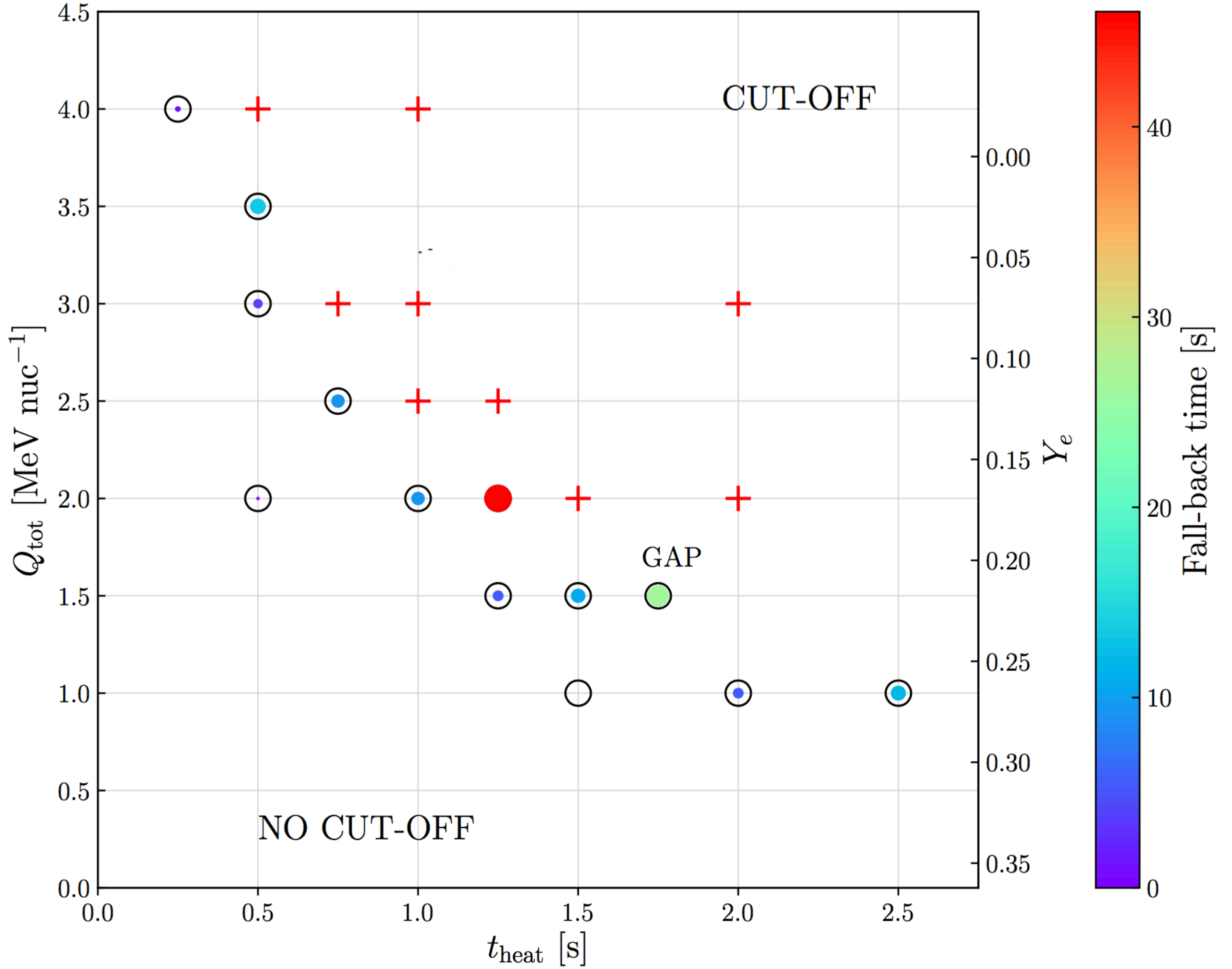
Fall-back results for a suite of simulations with varying Q_{tot}, t_{heat}



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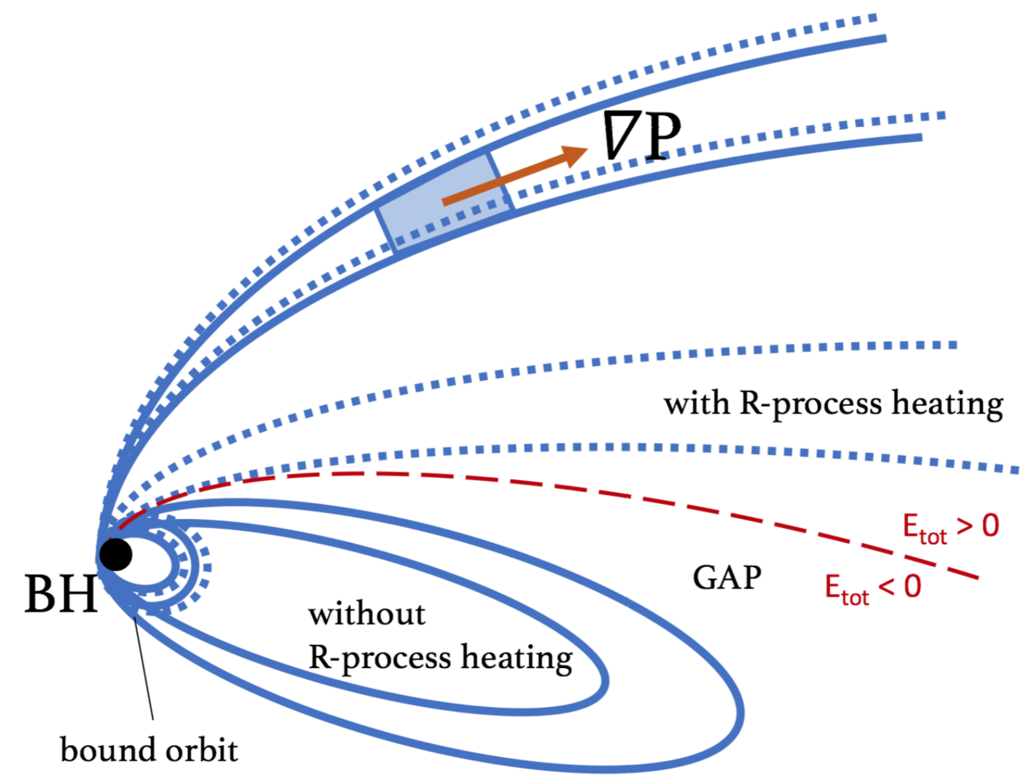
Energy required to unbind material (when $t_{orb} < t_{heat}$):

$$|E_{\rm tot,c}| \approx Q_{\rm tot}\frac{t_{\rm orb,c}}{t_{\rm heat}}$$

$$t_{\rm orb} = 2\pi\left(\frac{a^3}{GM}\right)^{1/2} \approx 1.6\,{\rm s}\left(\frac{|E_{\rm tot}|}{1\,{\rm MeV}}\right)^{-3/2}\left(\frac{M}{5M_\odot}\right)$$



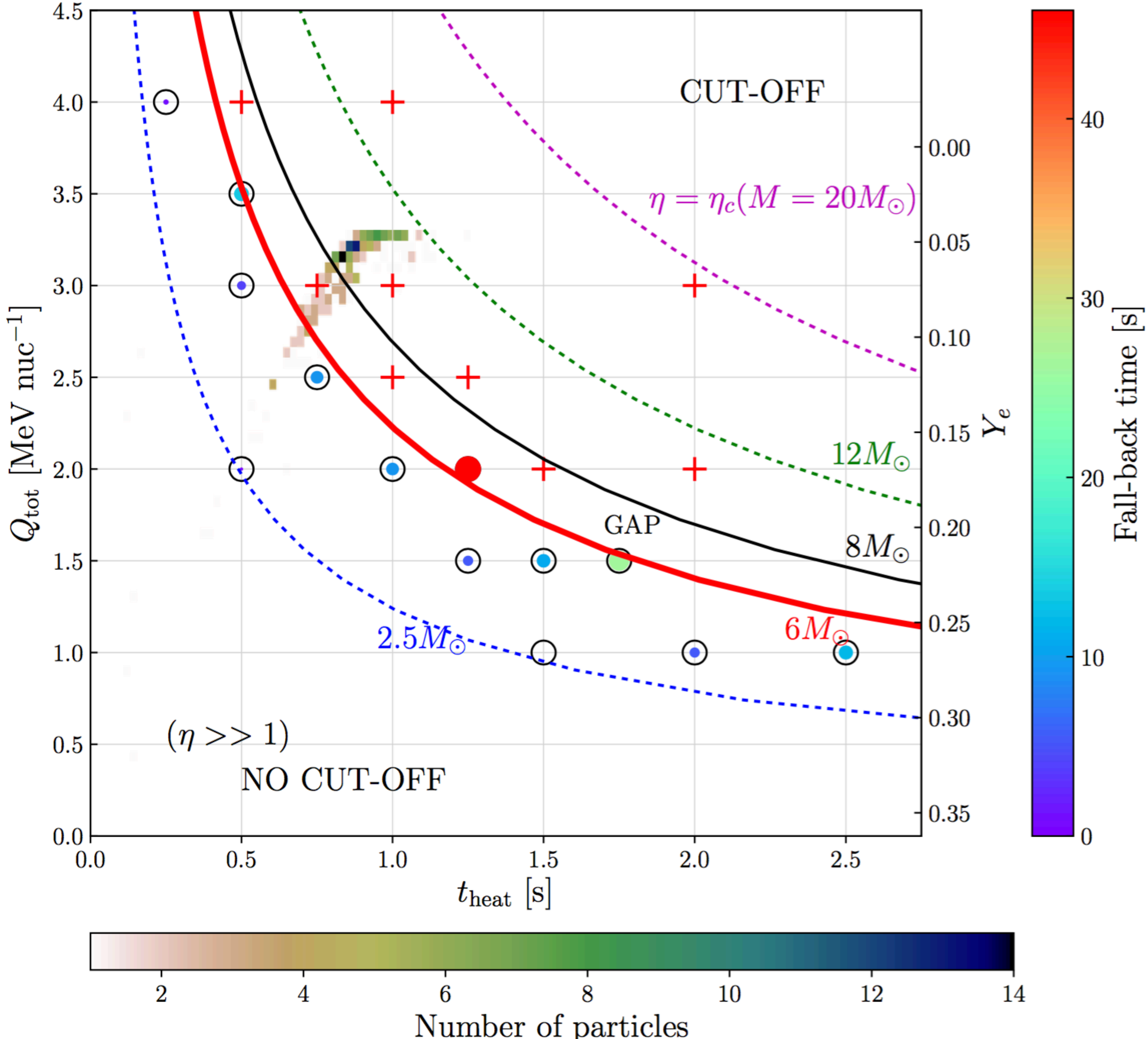
Critical Dimensionless Ratio

$$\eta \equiv \frac{t_{\rm heat}}{t_{\rm orb,c}} \approx 1.6\left(\frac{M}{5M_\odot}\right)^{-2/5}\left(\frac{Q_{\rm tot}}{3\,{\rm MeV}}\right)^{3/5}\left(\frac{t_{\rm heat}}{1{\rm s}}\right)^{2/5}$$

Ratio determines shape of fall-back curve!

$\eta \gg 1 \rightarrow$ Uninterrupted Fall-Back

$\eta \ll 1 \rightarrow$ Gap in Fall-Back Rate



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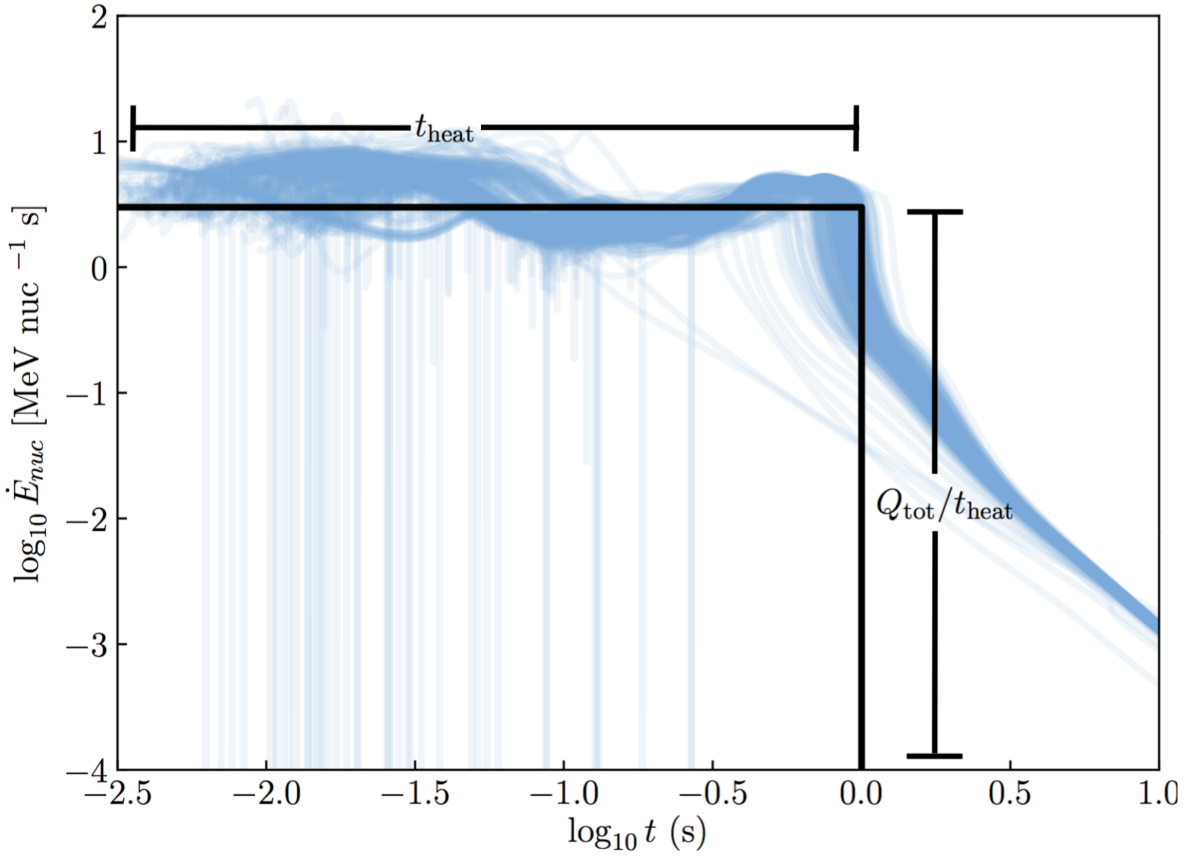
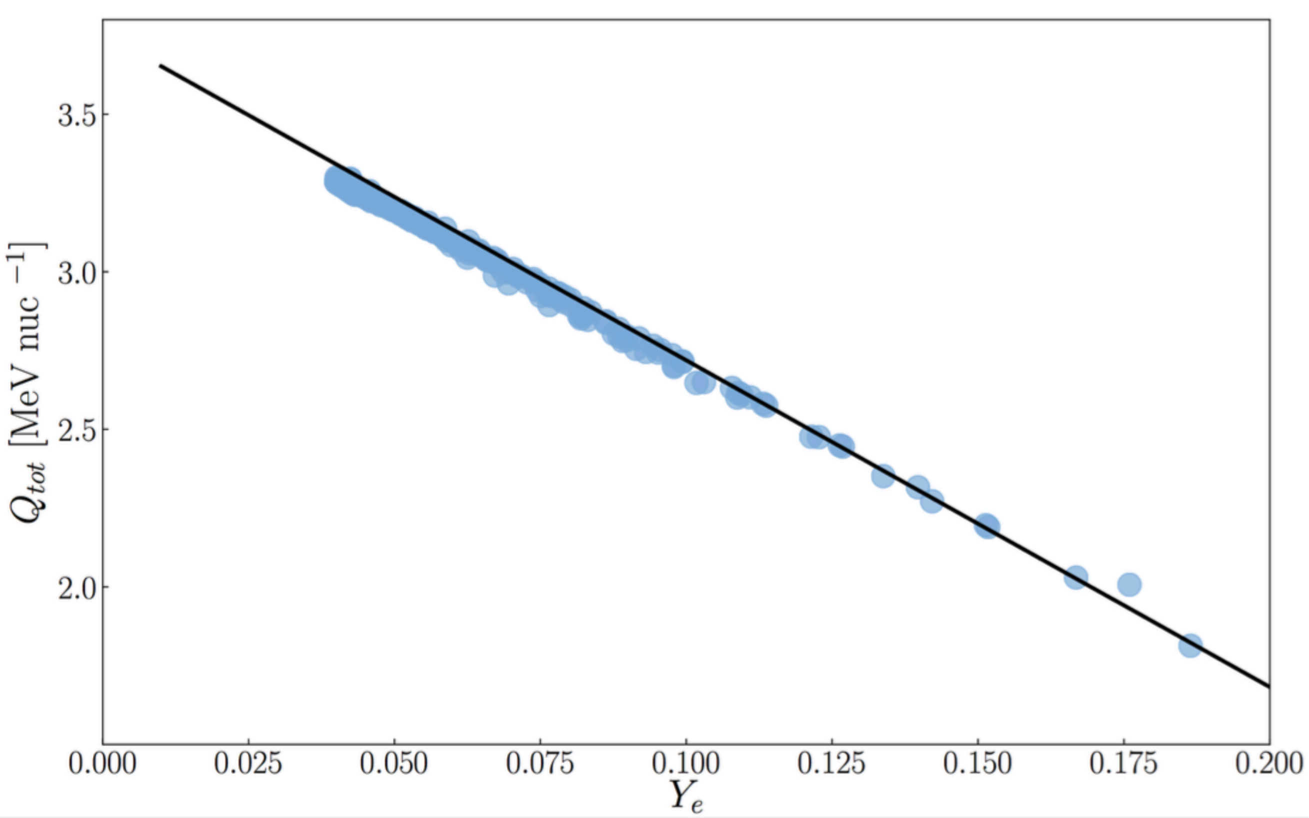
Does gap still arise with a more realistic heating distribution?





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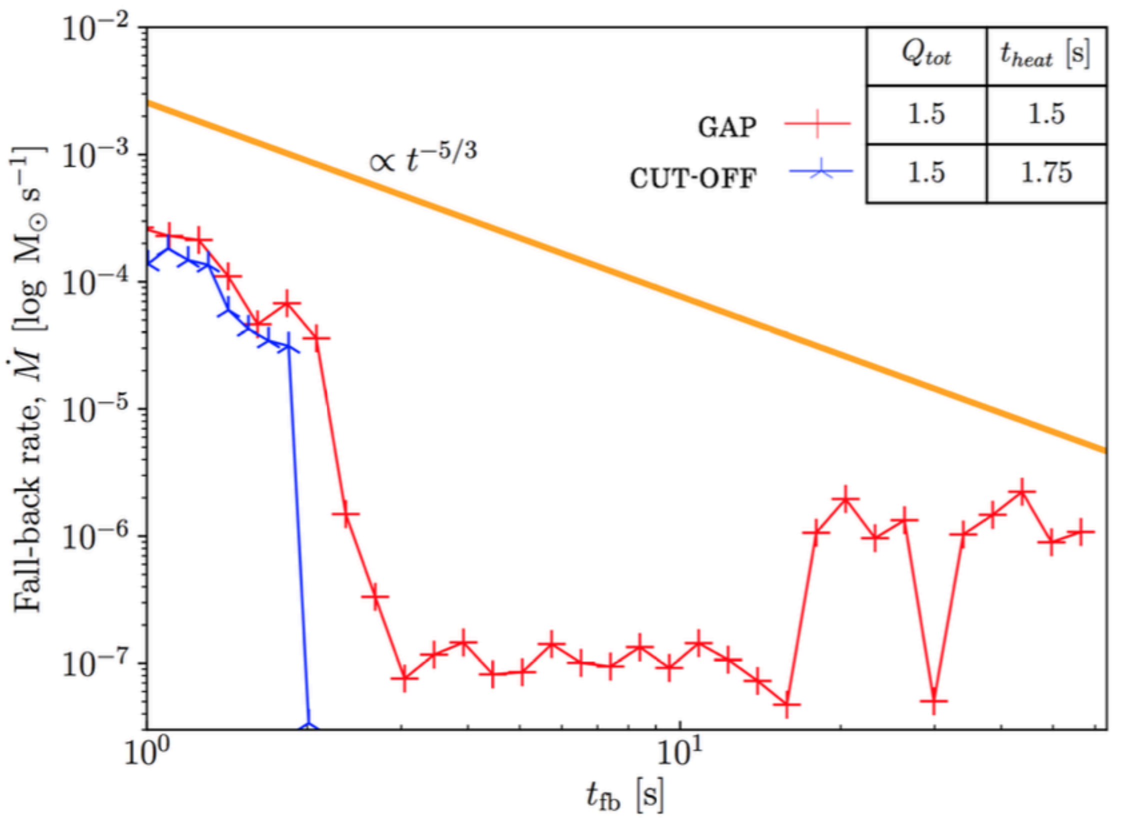
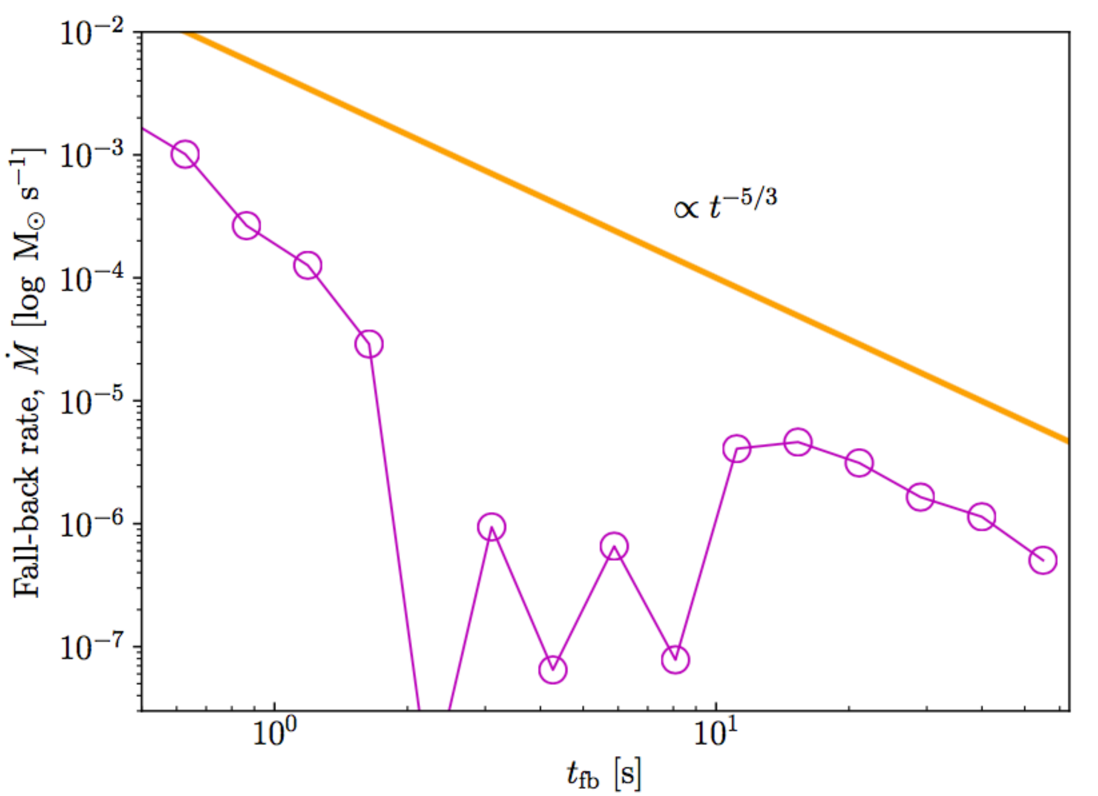
More realistic heating distributions

A. Chosen based on Ye distribution, centered on chosen mean values of Q_{tot}, t_{heat}

B. Heating rates directly mapped from SkyNet to fluid elements based on Ye





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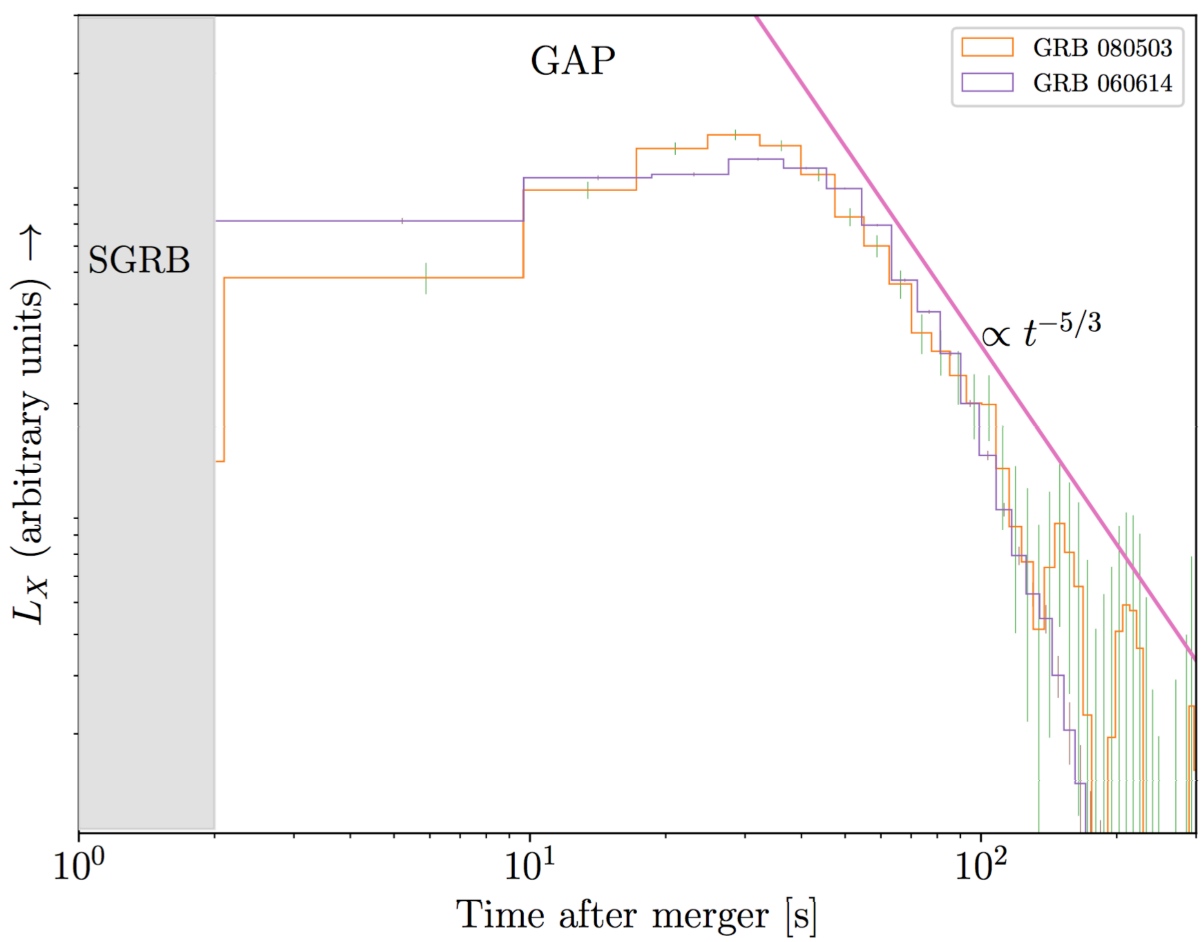
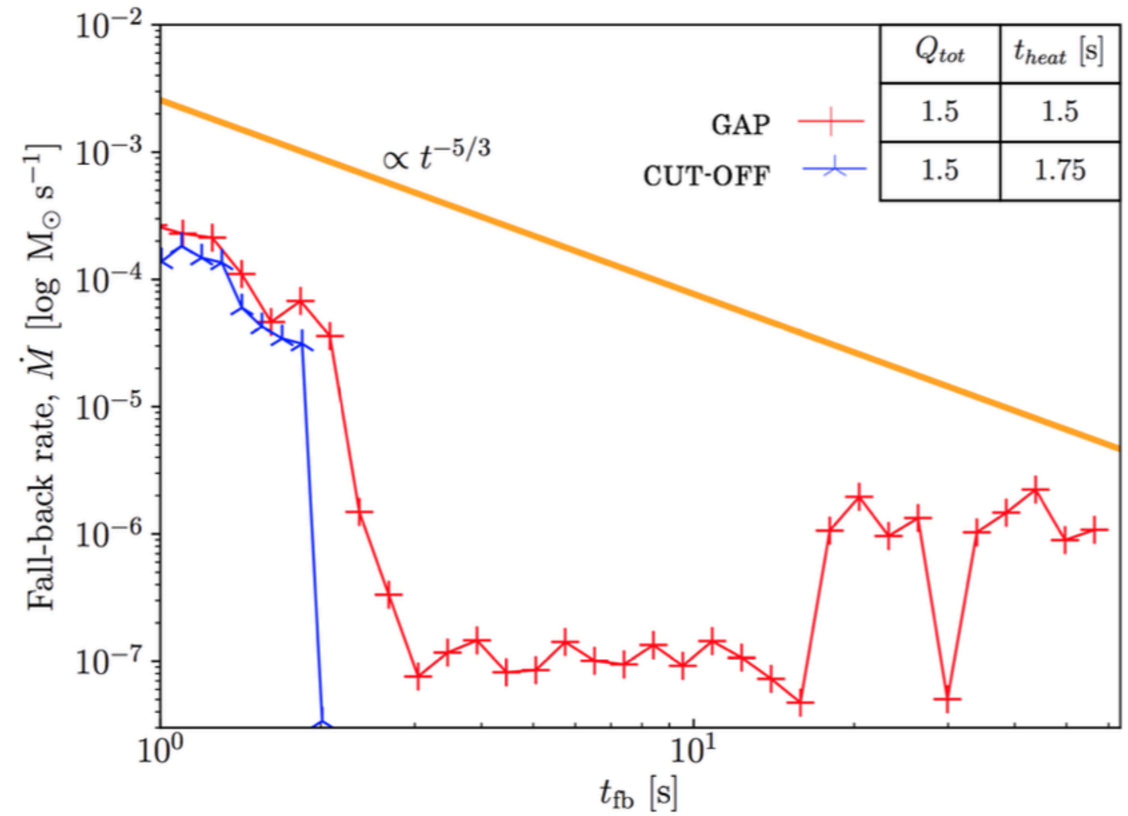
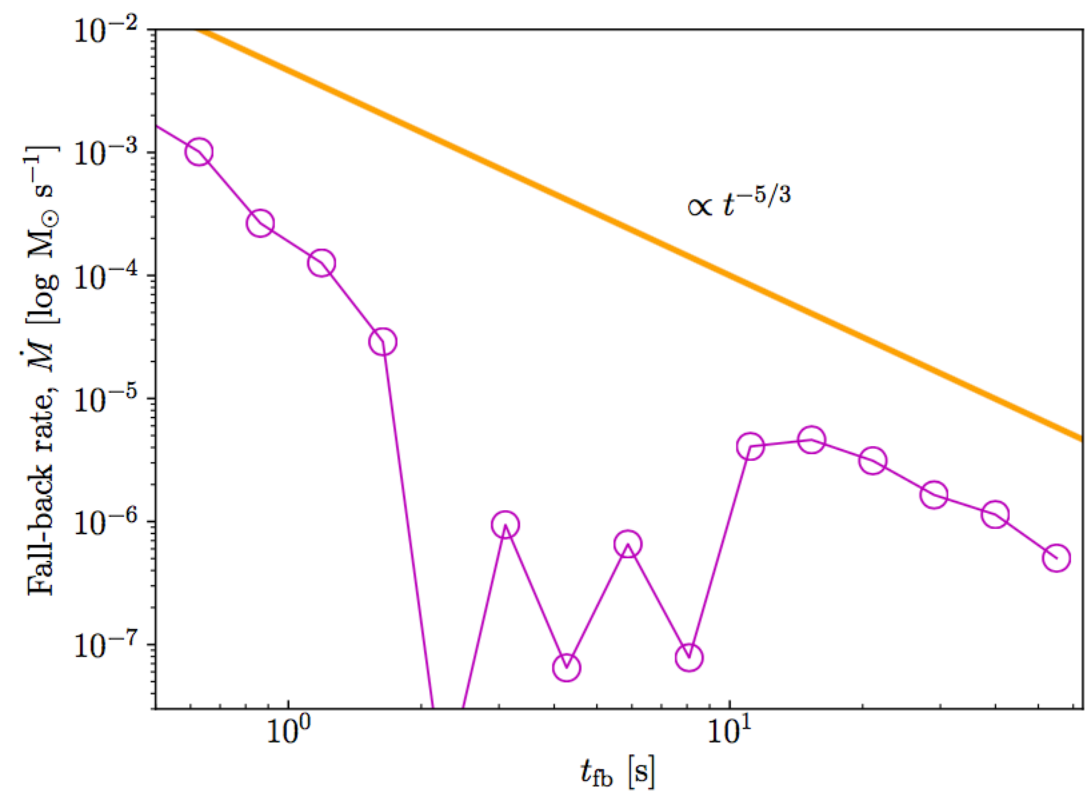
These occur on similar timescales!







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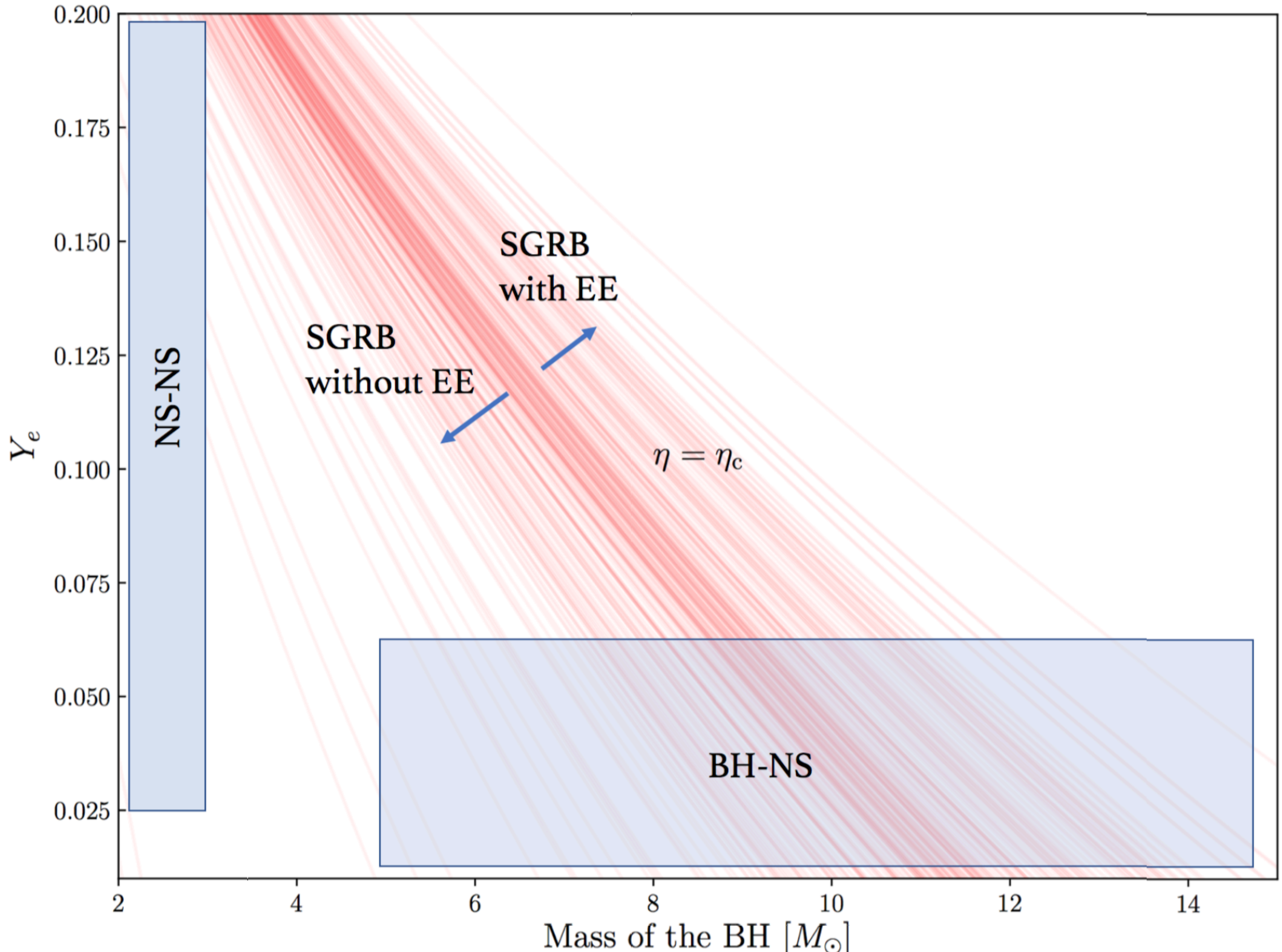
Distinguishing BH-NS & NS-NS mergers



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Event rates

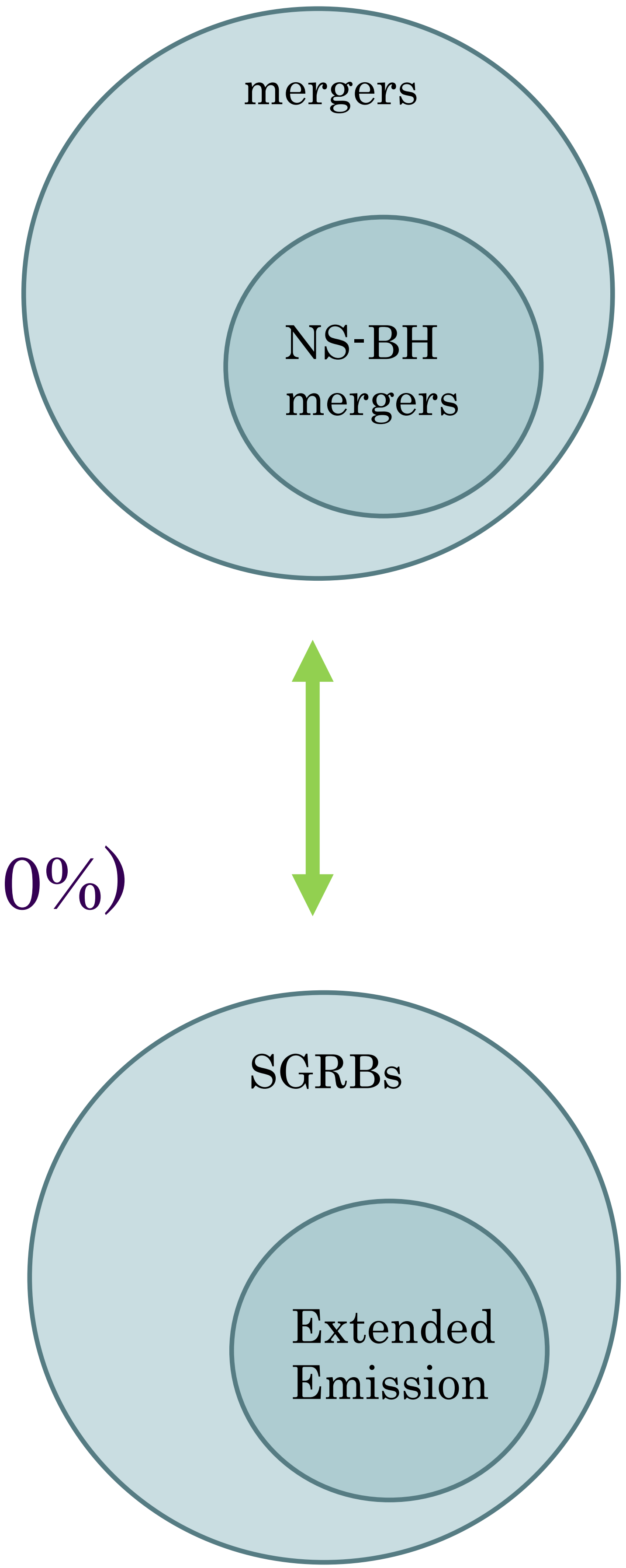
Assumptions:

1. All NS-NS mergers produce SGRBs
2. All NS-BH mergers produce SGRBs,
3. and are followed by EE

fraction of mergers which are NS-BH
= fraction of SGRBs followed by EE (~30%)

But, not every NS-BH merger will produce SGRB/EE → fraction of NS-BH mergers must be ≳30%

Current LIGO detection rates are consistent with these rate predictions!



Conclusions

- R-process heating significantly alters fall-back behavior, resulting in gap or cut-off
- Higher central mass favors gap in fall-back

→ EE more likely to originate from NS-BH mergers?

- Hydrodynamic simulations to check consistency
- Check robustness of heating by assuming different theoretical models for nuclear masses
- At steady state, LIGO should detect more NS-BH mergers than NS-NS mergers due to higher sensitivity