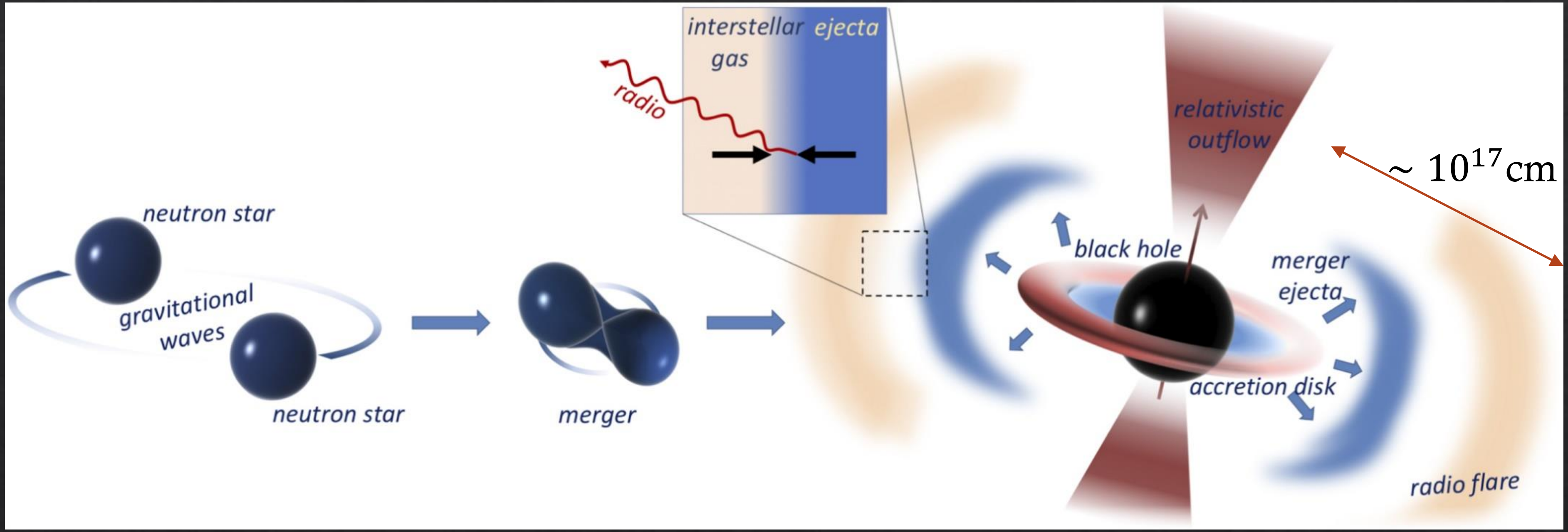
WEIZMANN INSTITUTE OF SCIENCE

Sadeh, Gilad; Guttman, Or; Waxman, Eli

Non-thermal emission from mildly relativistic dynamical ejecta of BNS merger

Overview



Credit: AAS Nova

- BNS mergers are expected to eject mass dynamically at mildly relativistic velocities, $\beta > 0.6$
- A collisionless shock driven by this ejecta will accelerate electrons and produce synchrotron radiation
- Previous models are based on extrapolation of results valid for $\gamma\beta \gg 1$ & $\gamma\beta \ll 1$ to $\gamma\beta \sim 1$

WEIZMANN INSTITUTE OF SCIENCE
מכון ויצמן למדע

Why Kilonova ejecta?

Properties	Kilonova ejecta	Relativistic jet
Mass	$10^{-2} - 10^{-3}\ M_{\odot}$	$\sim 10^{-8}\ M_{\odot}$
Velocity	$0.1 < \gamma\beta < 4$	$\gamma \gg 10$
Geometry	Quasi-spherical	Cone, opening angle of ~ 0.1

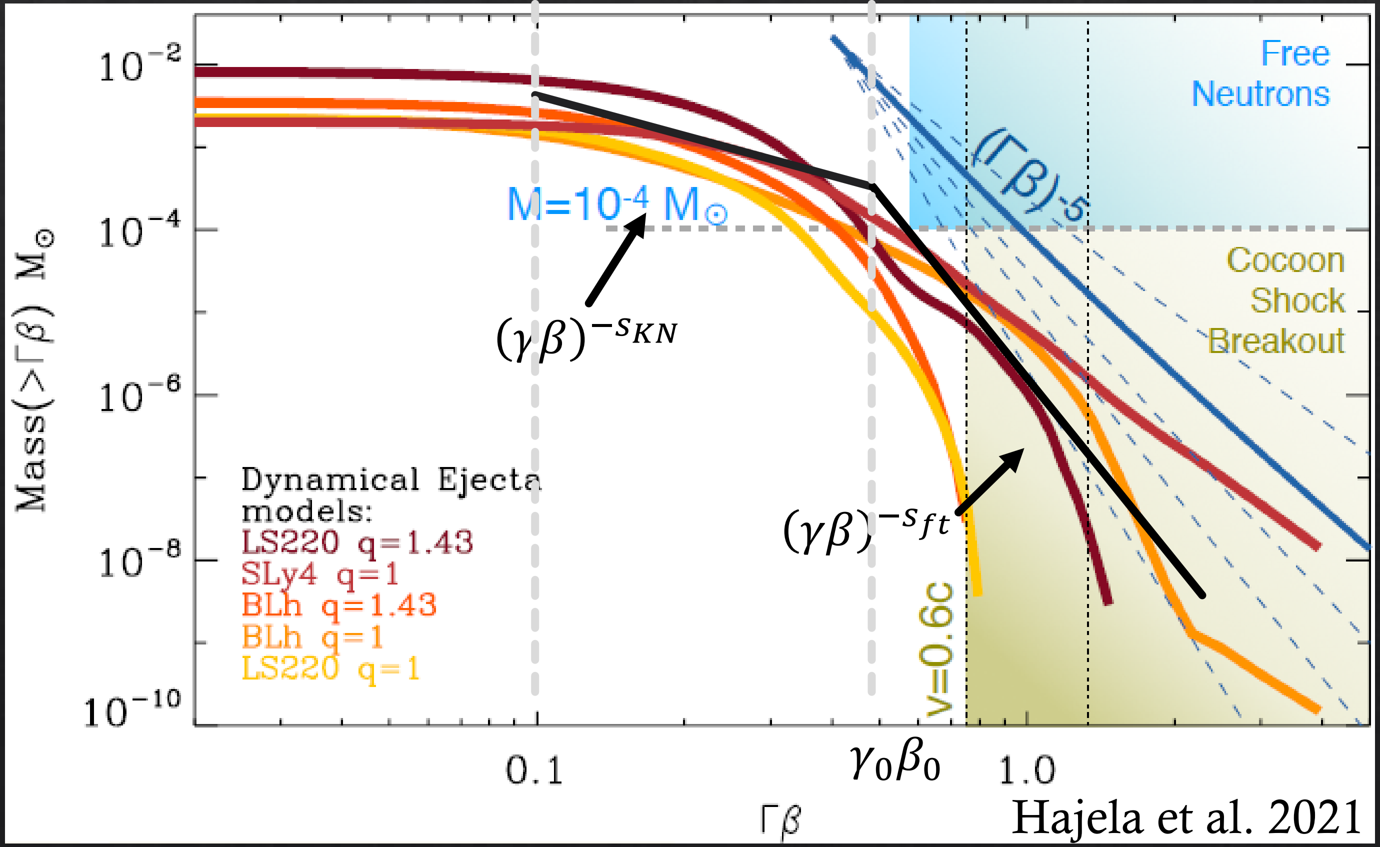
- Large numerical uncertainty, especially for $\gamma\beta > 1$
- Dominate emission at late time
- Constrain the properties of Kilonova ejecta → binary system parameters + EoS + merger dynamics

Published work: spherical ejecta

- $$M(>\gamma\beta) = M_0 \begin{cases} \left(\frac{\gamma\beta}{\gamma_0\beta_0}\right)^{-s_{ft}}, & \gamma_0\beta_0 < \gamma\beta \\ \left(\frac{\gamma\beta}{\gamma_0\beta_0}\right)^{-s_{KN}}, & 0.1 < \gamma\beta < \gamma_0\beta_0 \end{cases}$$

$s_{ft} > 5$,
$1 < s_{KN} < 3$,
$0.3 < \gamma_0\beta_0 < 1$

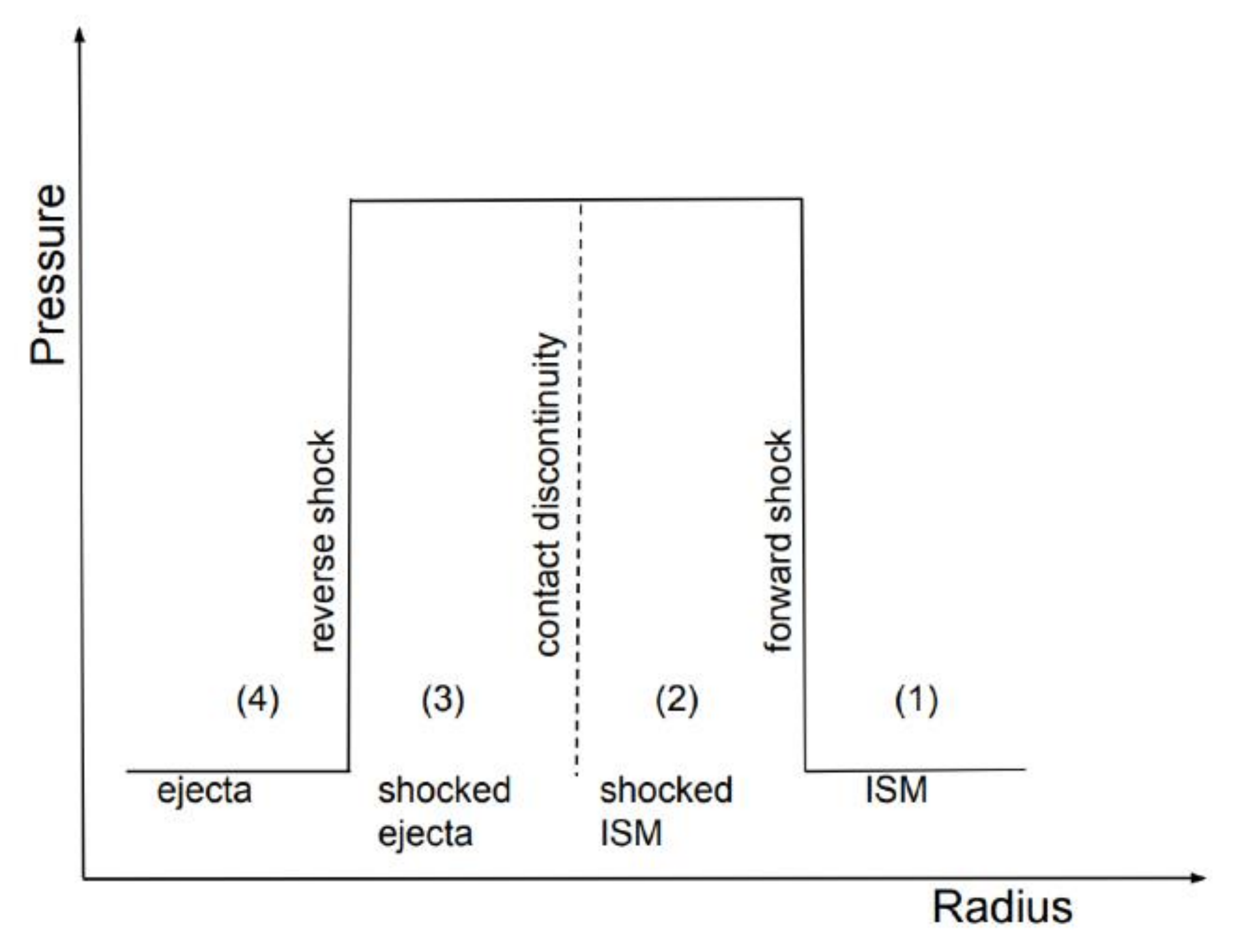
Ejected mass: BNS merger simulation



Hajela et al. 2021

Non-thermal emission

- Assumptions:
  - Fractions ε_e and ε_B of the post shock internal energy carried by non-thermal electrons and magnetic fields.
  - Electrons follow energy power-law distribution $\frac{dn_e}{d\gamma_e} \propto \gamma_e^{-p}$
- Two competing effects:
  - Increase of the shocked mass
  - Deceleration



Solution methods

- Analytic, based on an approximate solution for the dynamics
  - Including emission from forward shock only
- Numeric, relativistic hydrodynamic calculation of the dynamics
  - Integrating over the emissivity, properly accounting for relativistic effects and radiation arrival time
  - Including both forward & reverse shock emission

The analytic solution provides an excellent approximation to the numeric results

WEIZMANN INSTITUTE OF SCIENCE

Key analytic results

Peak flux obtained when the reverse shock crosses the fast tail ($s_{ft} > 5$), reaching the "break" in the ejecta profile at β_0

$t < t_{peak}$

Reverse shock in the steep ejecta ($s_{ft} > 5,\ \beta > \beta_0$)

Rising flux $F_\nu \propto t^{q_{ft}}$

→

$t_{peak} < t < t_{ST}$

Reverse shock in the moderate ejecta

($1 < s_{KN} < 3,\ \beta < \beta_0$)

Deceleration is faster for a shallow mass distribution

Declining flux $F_\nu \propto t^{q_{KN}}$

→

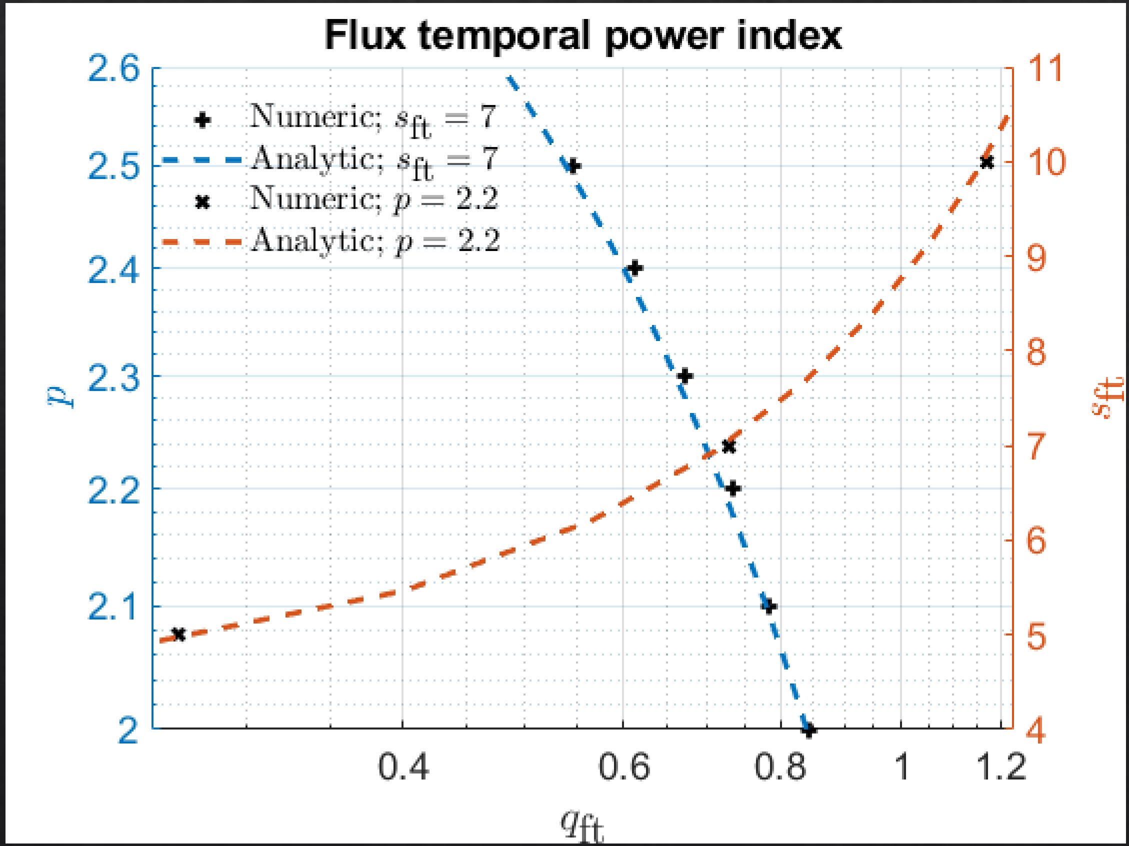
$t_{ST} < t$

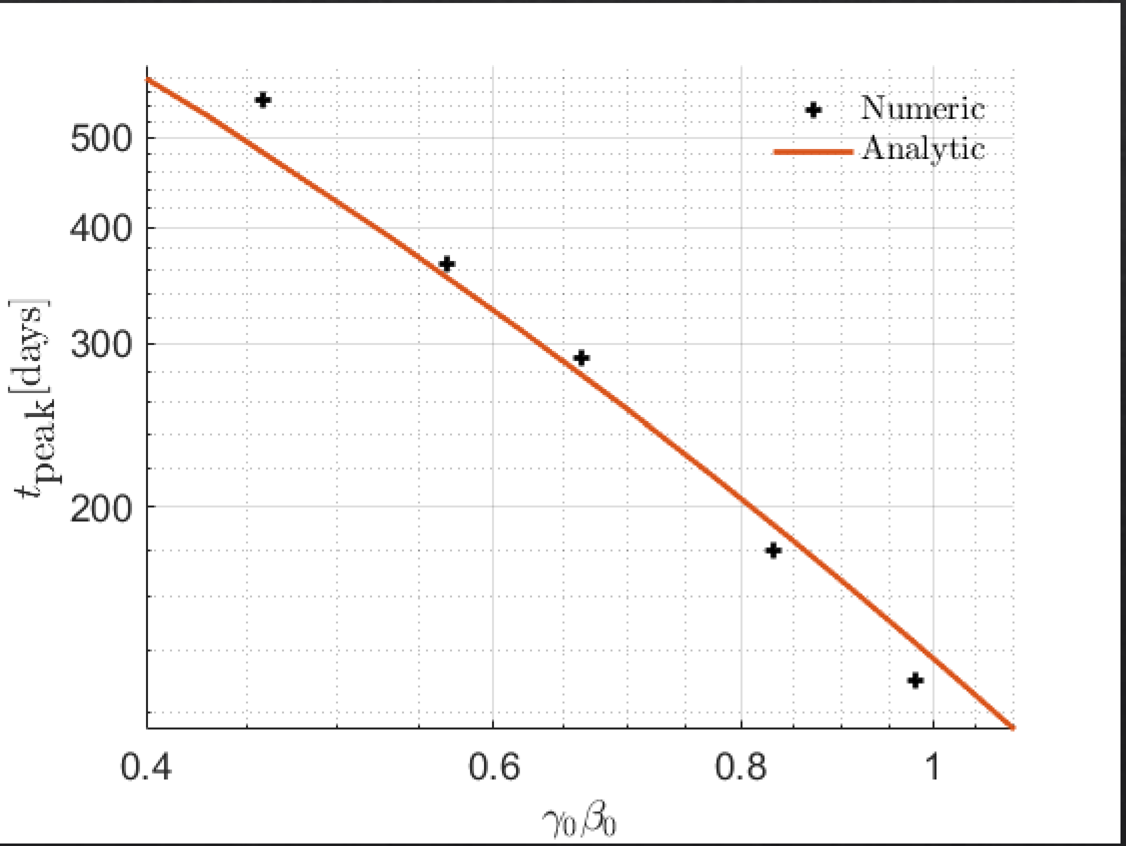
Non-relativistic

Sedov-Taylor flow, $F_\nu \propto t^{q_{ST}}$

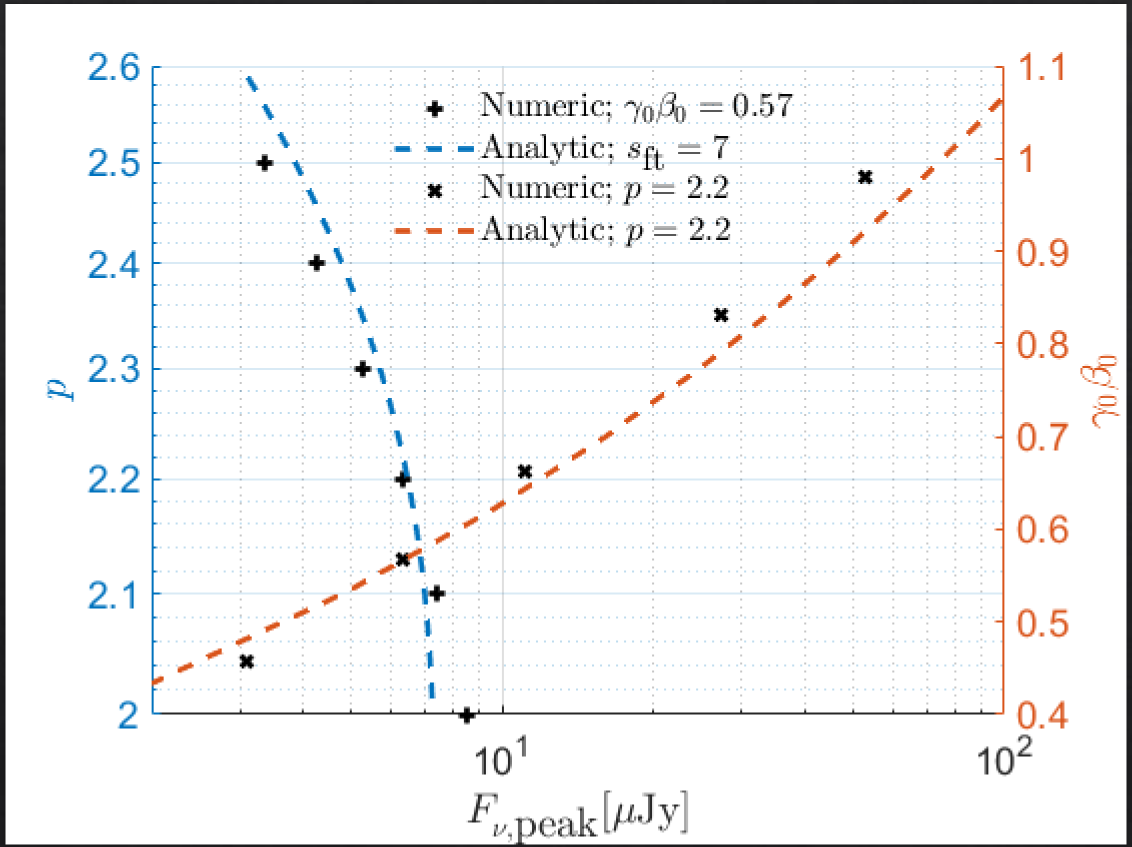
- $F_{\nu,peak} \approx 12 D_{26.5}^{-2} \varepsilon_{e,-1}^{p-1} \varepsilon_{B,-2}^{\frac{p+1}{4}} n_{-2}^{\frac{p+1}{4}} M_{0,-4} \nu_{9.5}^{\frac{1-p}{2}} (\gamma_0\beta_0)^{2.2p-0.5} \mu\text{Jy}$ $\quad (\nu < \nu_c)$
- $t_{peak} = 550 \left(\frac{M_{0,-4}}{n_{-2}}\right)^{\frac{1}{3}} g(\beta_0) \text{days}, \qquad g(\beta_0) = \frac{1.5 - \sqrt{0.25 + 2\beta_0^2}}{\gamma_0^{\frac{1}{3}} \beta_0}$

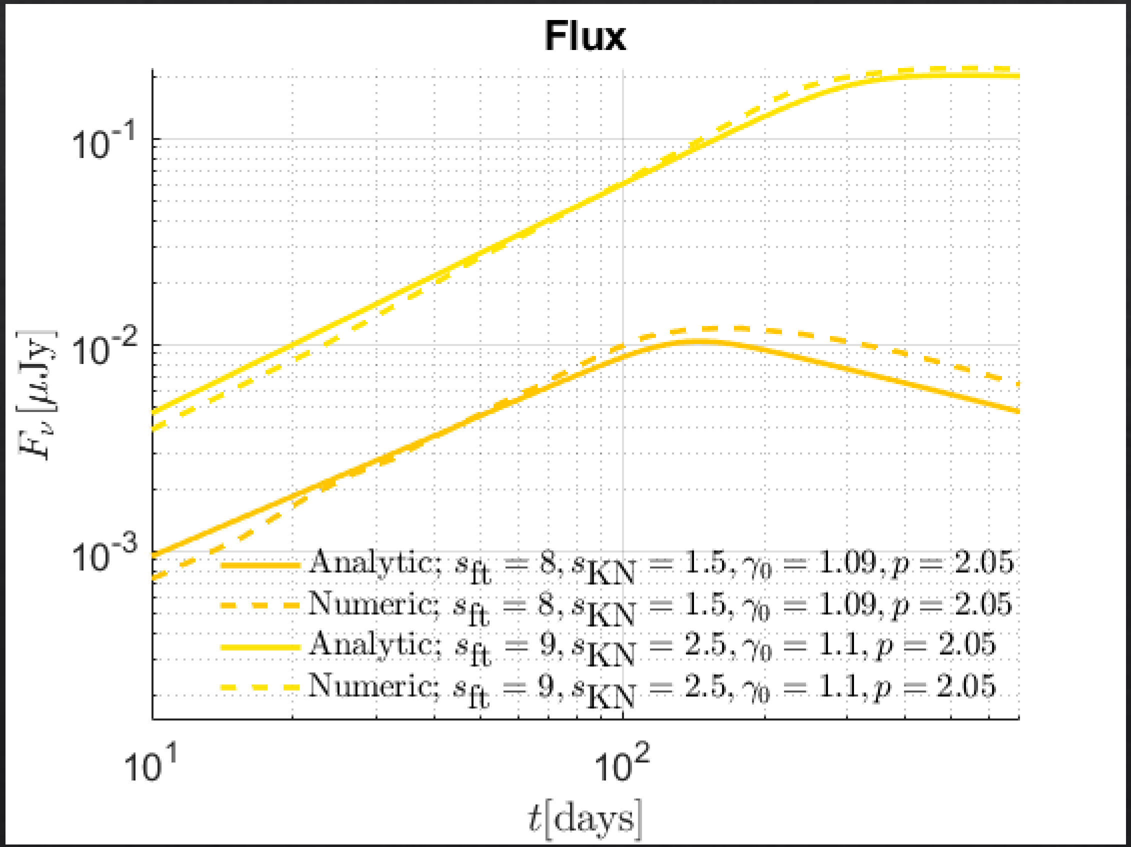
Excellent agreement with full numeric results





Excellent agreement with full numeric results

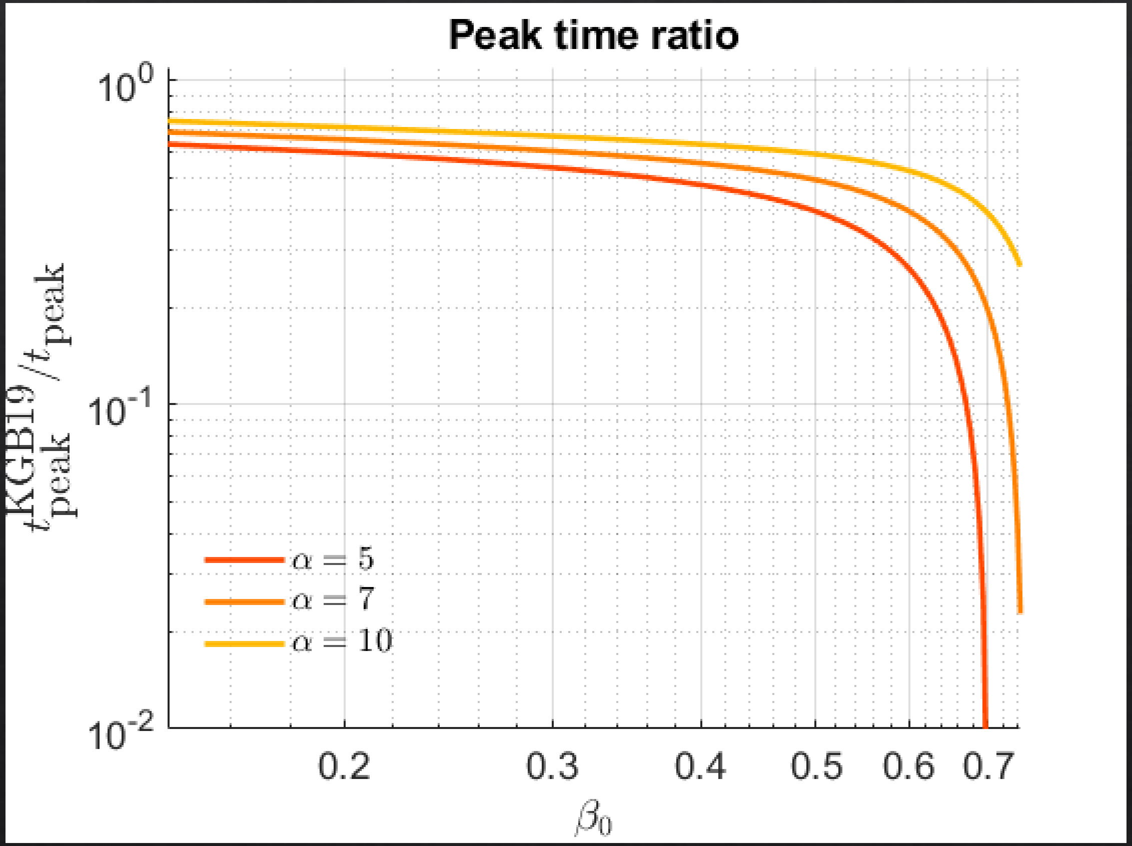




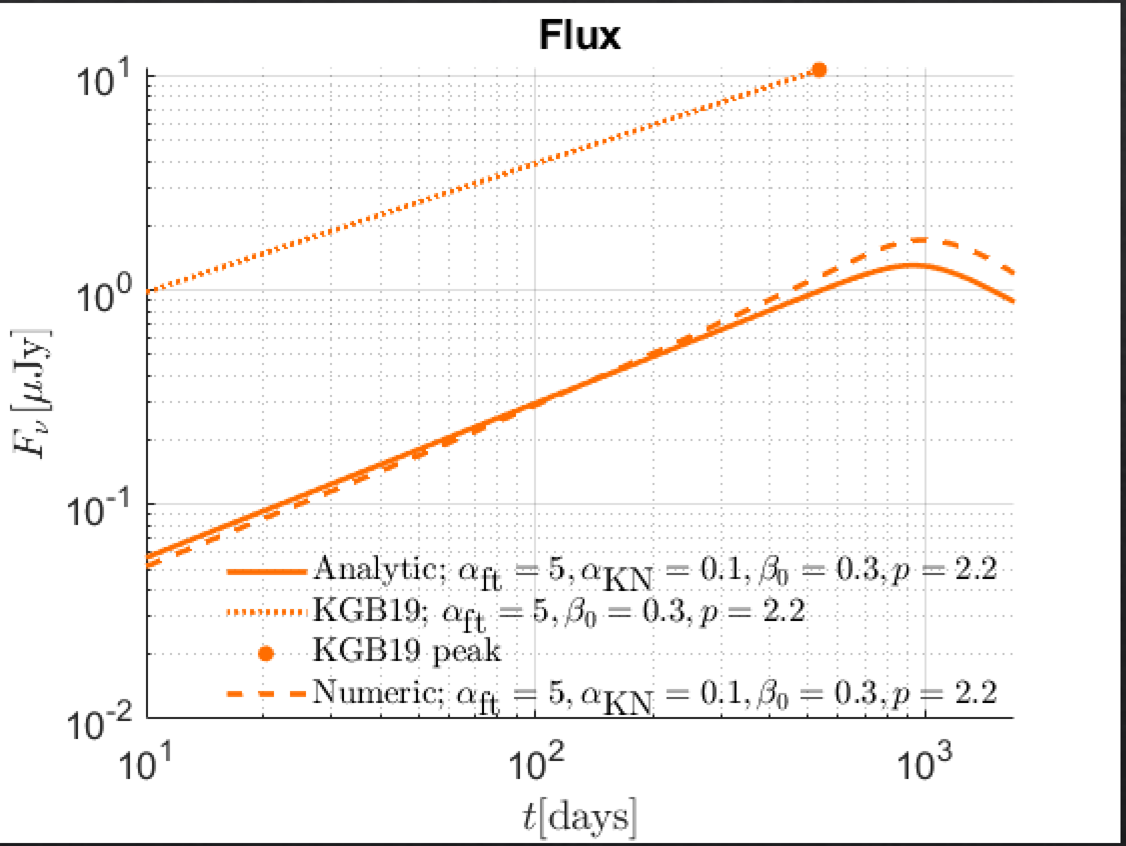
Comparison with earlier work

- Earlier analytic work by Kathigamaraju et al (2019), based on Nakar and Piran (2011)
- A single power-law for $t < t_{peak}$, not including the deceleration to $\beta_0 \ll 1$
- Valid for $\beta_0 < 0.5$
- The peak flux obtained in their work is typically an order of magnitude larger than our result, $\frac{F_{\nu,peak}}{F_{\nu,peak}^{our}} \approx 6\gamma_0^{2.5-2.2p}\beta_0^{0.3p-1}$

Comparison with earlier work



As expected, large deviations for $\beta_0 > 0.5$



$\beta_0 = 0.3$

GW170817

- The early ($t < 1000$ days) non-thermal emission following GW170817 is consistent with a jet
- A late ($t > 1000$ days) non-thermal emission may indicate a new component, due to a “fast tail” of the KN ejecta
- Using GW170817 ejecta parameters inferred from the radioactive emission for $\beta < 0.3$,

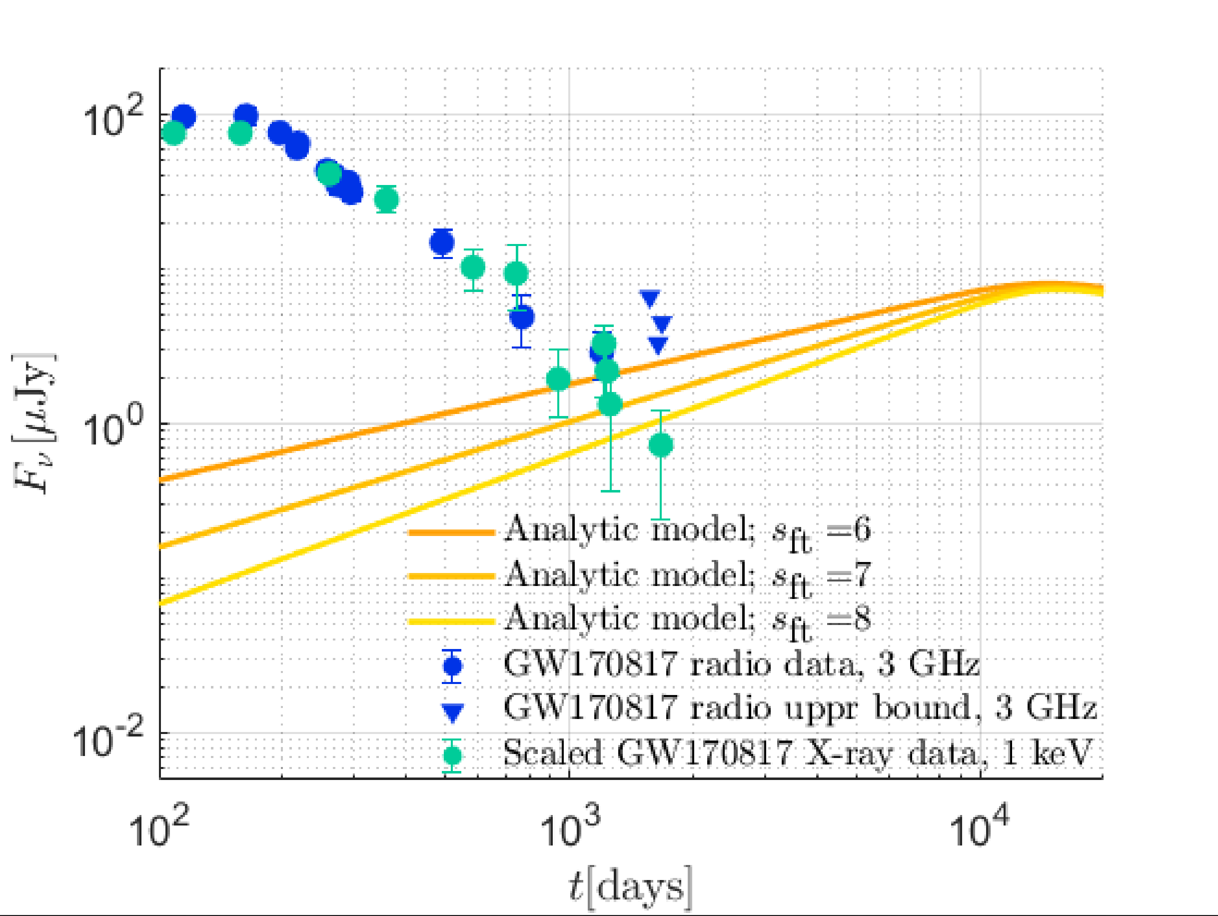
$$M = 0.05M_{\odot},\ \beta_0 = 0.3,\ s_{KN} = 1.6$$

[Waxman et al. 2018)]

We infer from the late time observations

$$\varepsilon_{B,-2}^{-1.5}\, n_{-2}^{-1.17} > 6.7,$$

$$\varepsilon_{e,-1}^{1.05}\, \varepsilon_{B,-2}^{0.76}\, n_{-2}^{1.03} < 0.12$$



Summary

- We derived an analytic model for the non-thermal emission from a mildly relativistic ejecta with a broken power-law mass distribution
- The model provides an excellent approximation to the results of numeric calculations for a wide range of ejecta parameter values, that represent the mass profiles produced in merger simulations
- The analytic model

  - Expands the validity range of existing models, $\gamma\beta \gg 1, \gamma\beta \ll 1$, to $\gamma\beta \sim 1$

  - Includes a description of the phase of deceleration to sub-relativistic expansion

  - Is accurate to 10's of percent, a significant improvement over previous work, which overestimate the flux by ~an order of magnitude for relevant parameter values
- An analytic description is highly valuable for the "inverse problem", inferring model parameters from observations: It does not require resource consuming numeric calculations for the derivation of model predictions for each point in the parameter space.

WEIZMANN INSTITUTE OF SCIENCE

Sadeh, Gilad; Guttman, Or; Waxman, Eli

Thank you