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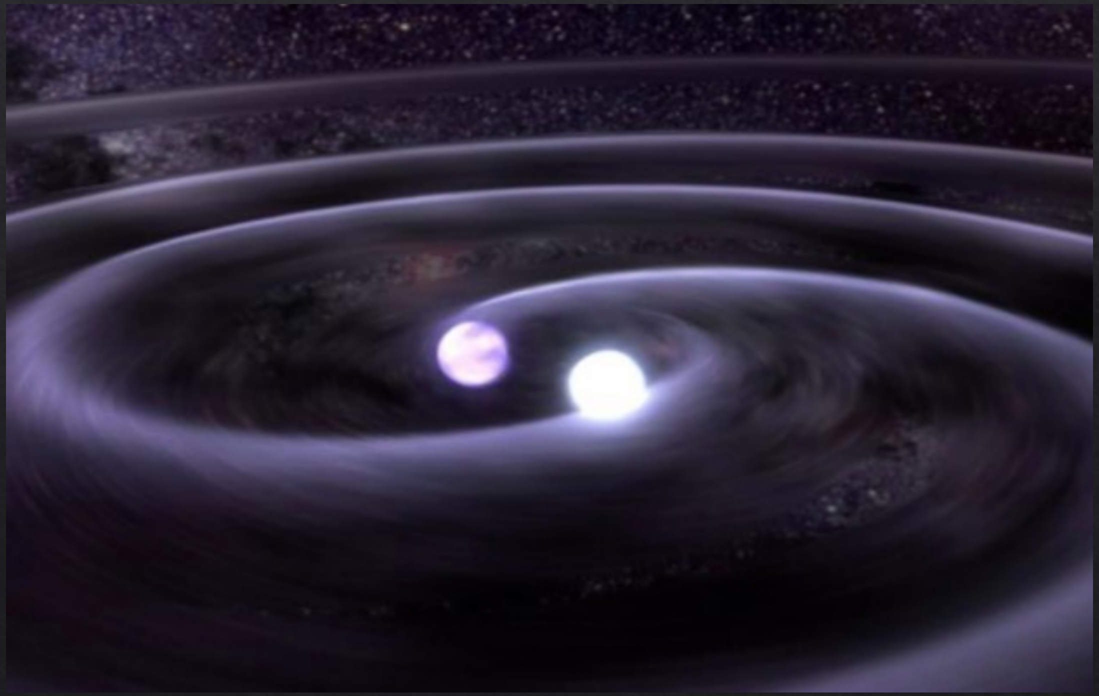
Late synchrotron signal following compact objects merger

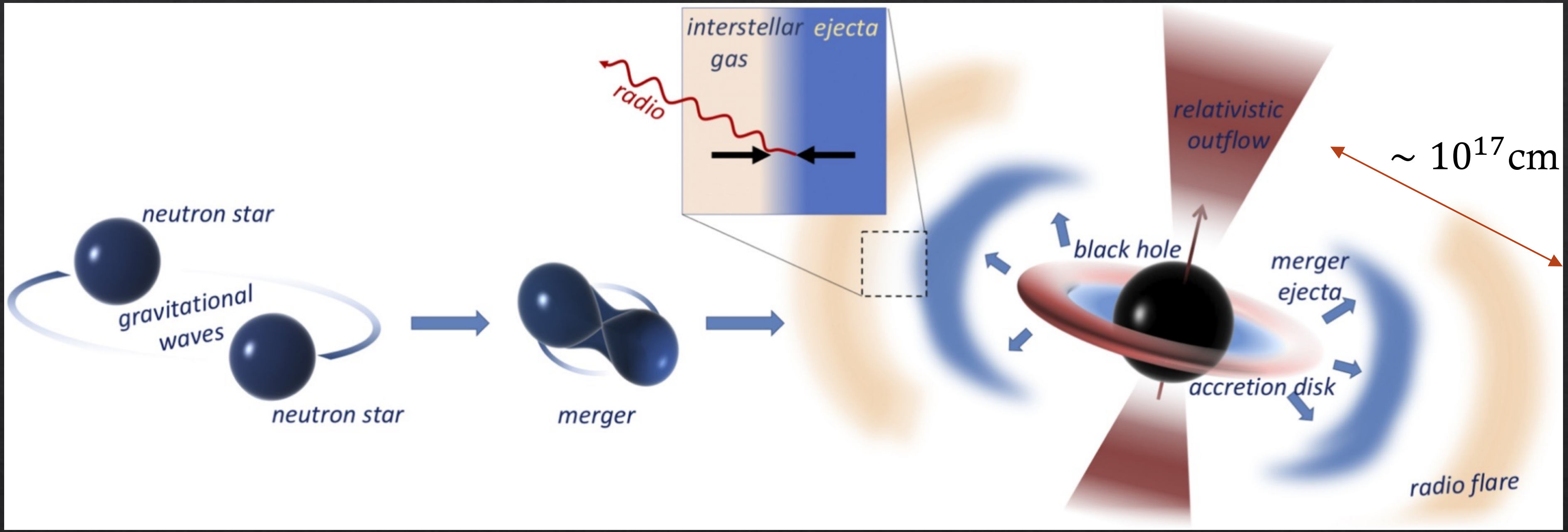
Papers:
https://arxiv.org/abs/2406.01338
https://academic.oup.com/mnras/article/531/3/3279/7679126
https://academic.oup.com/mnras/article/518/2/2102/6824444

Compact objects mergers (BNS, NSBH)

- Binary systems of massive stars may end up as BNS or NSBH systems
- If close enough (< 1Mkm), the rotating compact objects may "lose" their energy in favor of emitting gravitational waves and merge
- GW170817 provided a rich set of observations, both thermal and non-thermal EM emission



Compact objects mergers (BNS, NSBH)

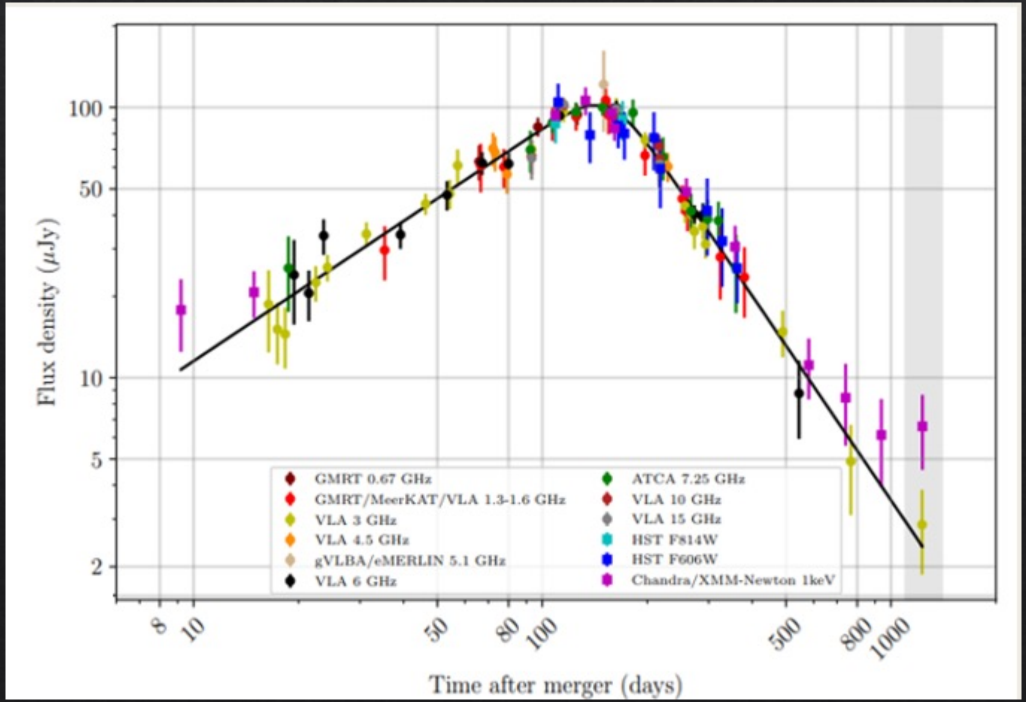


Credit: AAS Nova

- A highly relativistic, highly non-spherical component is ejected from the poles (jet)
- These mergers are expected to eject mass dynamically at mildly relativistic velocities, $\beta > 0.6$
- A collisionless shock driven by these different components will accelerate electrons and produce synchrotron radiation: a possible way to constrain the ejecta structure

GW170817- jet component

- Consistent with synchrotron emission from a power-law distribution of electrons
- Consistent with a highly relativistic, $\gamma < 10$, non-spherical outflow
- No synchrotron signal observed from the mildly-relativistic ejecta- should we wait?



Makhathini et al. 2021

Why dynamical ejecta?

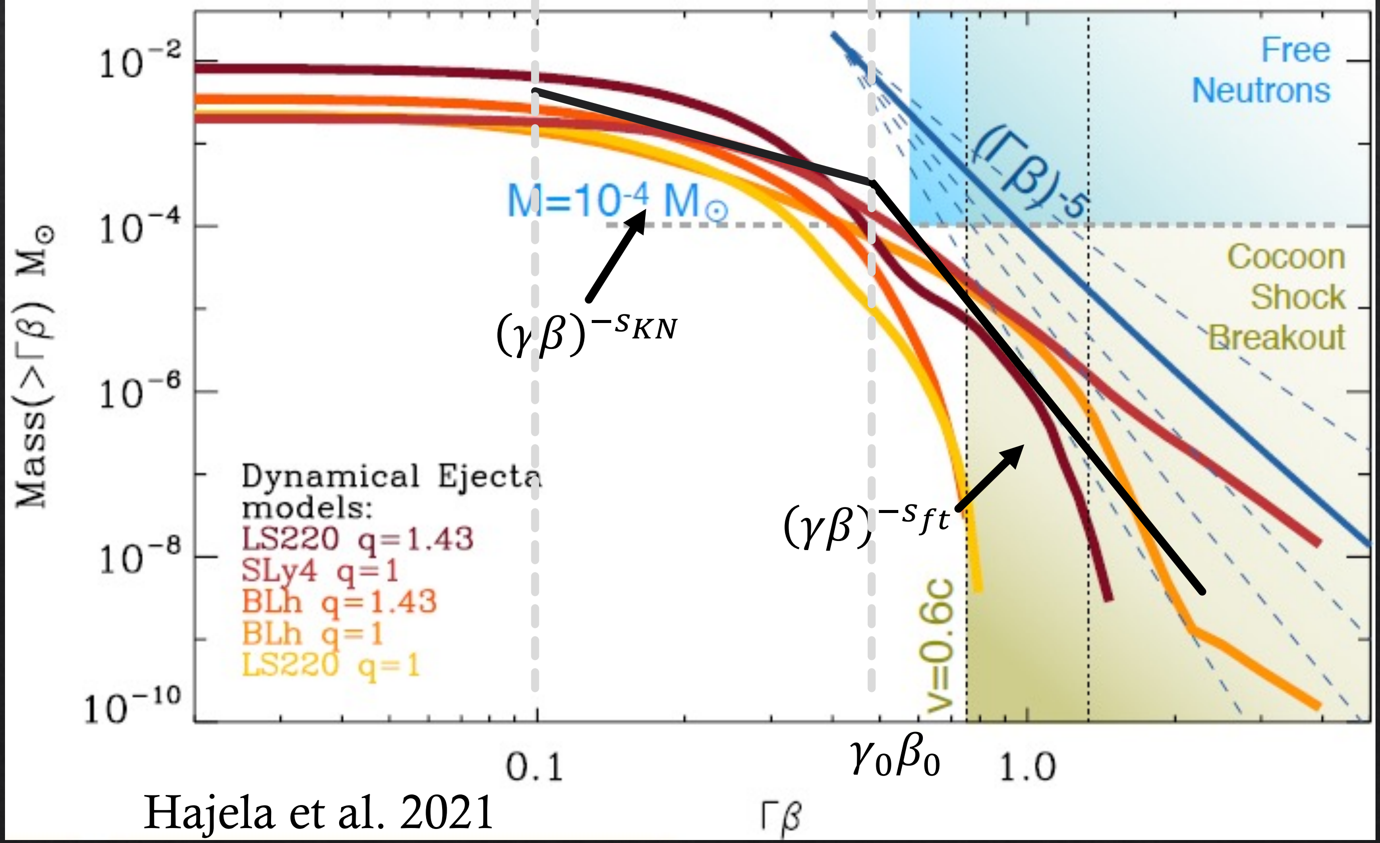
Properties	**Dynamical ejecta**	**Relativistic jet**
Mass	$10^{-1} - 10^{-3}\ M_\odot$	$\sim 10^{-8}\ \ M_\odot$
Velocity	$0.1 < \gamma\beta < 4$	$\gamma \gg 10$
Geometry	Quasi-spherical/Toroid	Cone, opening angle of ~ 0.1

- Significant numerical uncertainty in the ejecta structure and mass, especially for $\gamma\beta > 1$
- Ejection mechanism: Shocks due to the collision and tidal forces
- Non-thermal emission: dominates at late time
- Previous models are based on extrapolation of results valid for $\gamma\beta \gg 1$ & $\gamma\beta \ll 1$ to $\gamma\beta \sim 1$ (hard to compute)
- Constrain the properties of dynamical ejecta → binary system parameters + EoS + merger dynamics

Ejecta profile

- Significant numerical uncertainty- observations can provide bounds over the ejecta structure
- Simple analytic formula

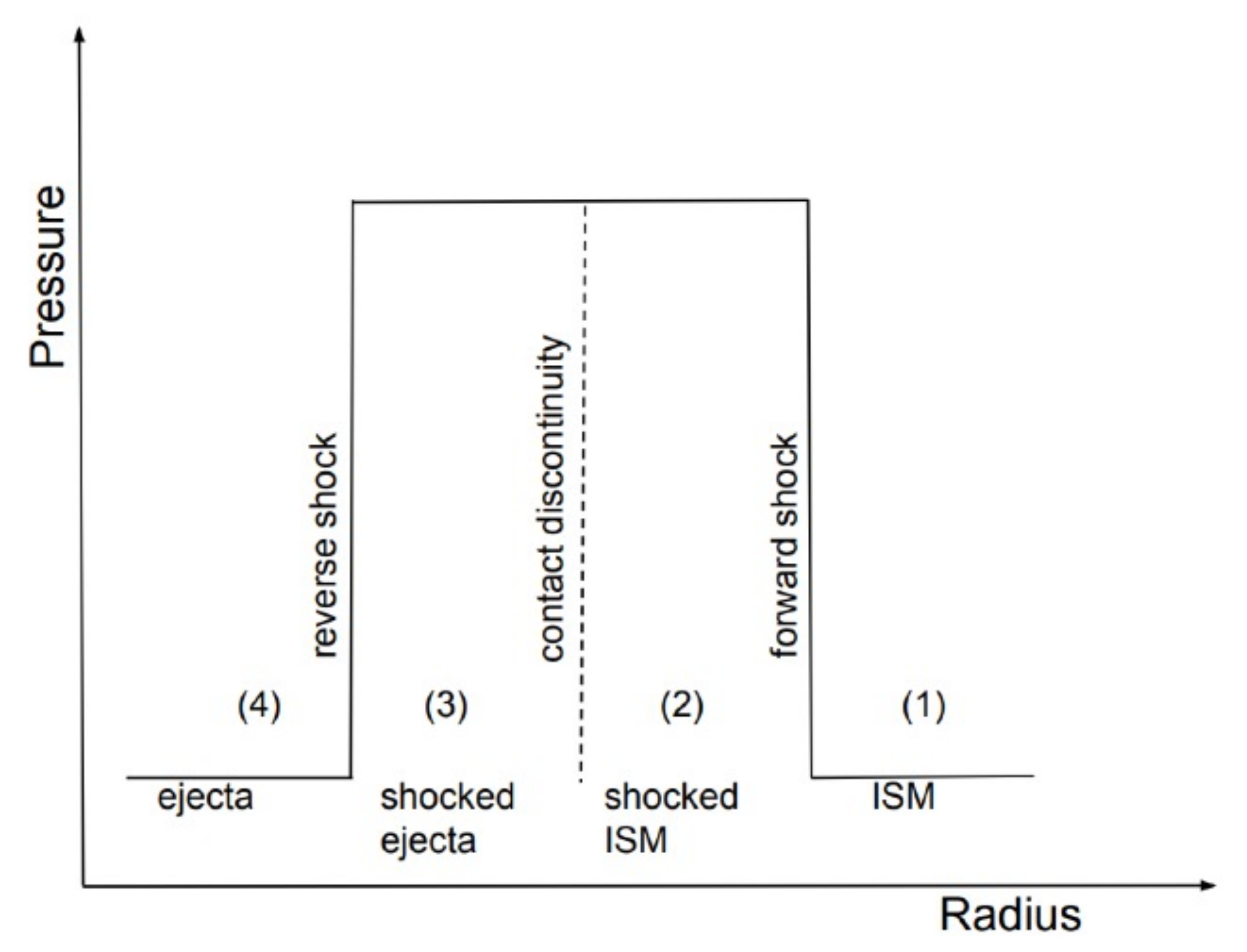
Ejected mass: BNS merger simulations



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
  - Adiabatic cooling + deceleration
- 5 observables at the peak



Solution methods- summary

Solution method	**Advantage**	**Disadvantage**
Analytic	Simple expressions- parameter dependence	Accuracy must be tested, only spherical
Semi-analytic	More accurate, can be used for non-spherical	Valid only for the fast tail
Numerical	Most Accurate	Long time, computing resources

Key analytic results: Spherical ejecta

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

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

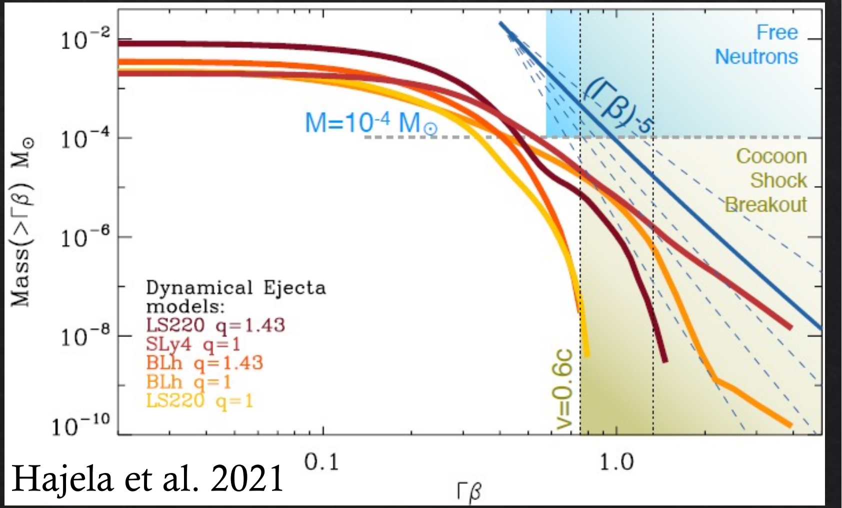
Deceleration is faster for a shallow mass distribution

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

$t_{ST} < t$

Non-relativistic

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



Hajela et al. 2021

Key analytic results: Spherical ejecta

- Model parameters: $M_0, s_{ft}, s_{KN}, \gamma_0\beta_0, n, \varepsilon_e, \varepsilon_B, p$
- Analytic expressions for:

- Flux temporal dependence

- $F_{\nu,peak} \approx 15 D_{26.5}^{-2} \varepsilon_{e,-1}^{p-1} \varepsilon_{B,-2}^{\frac{p+1}{4}} n_{-2}^{\frac{p+1}{4}} M_{0,-4} \nu_{9.5}^{\frac{1-p}{2}} (\gamma_0\beta_0)^{2.2p-0.5} \mu\mathrm{Jy} \qquad (\nu < \nu_c)$

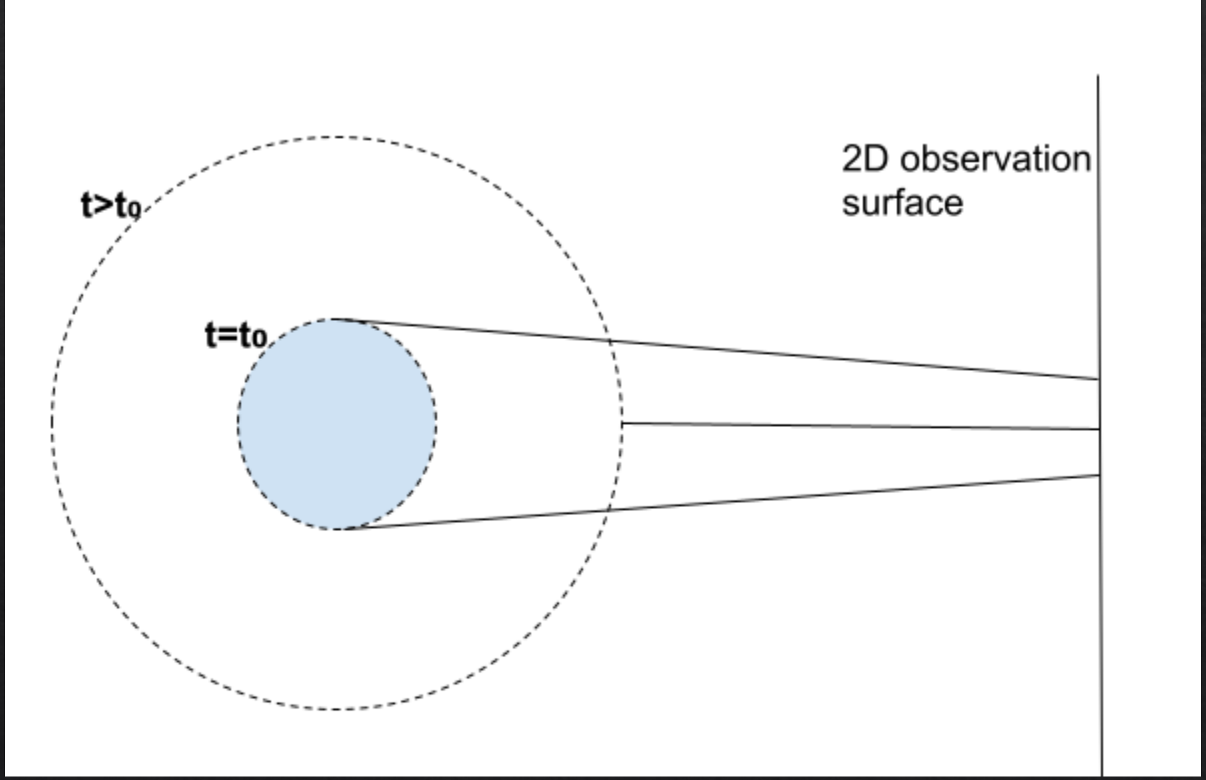
- $t_{peak} = 550 \left(\frac{M_{0,-4}}{n_{-2}}\right)^{\frac{1}{3}} g(\beta_0)\mathrm{days}, \qquad g(\beta_0) = \frac{1.5 - \sqrt{0.25 + 2\beta_0^2}}{\gamma_0^{\frac{1}{3}} \beta_0}$

- Angular size on the sky (at $t < t_{peak}$)

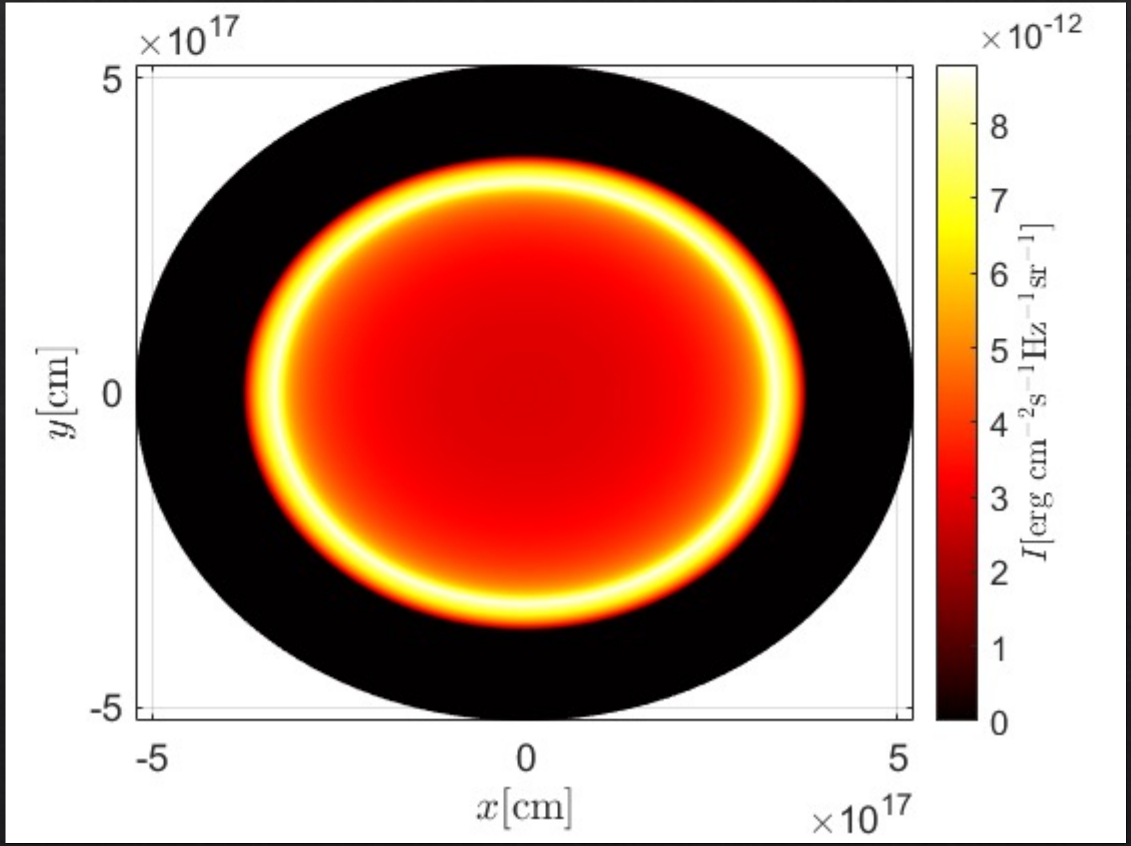
- Break frequencies (at $t < t_{peak}$)

- For a "well observed" event each of the model parameters can be deduced

Spherical intensity map

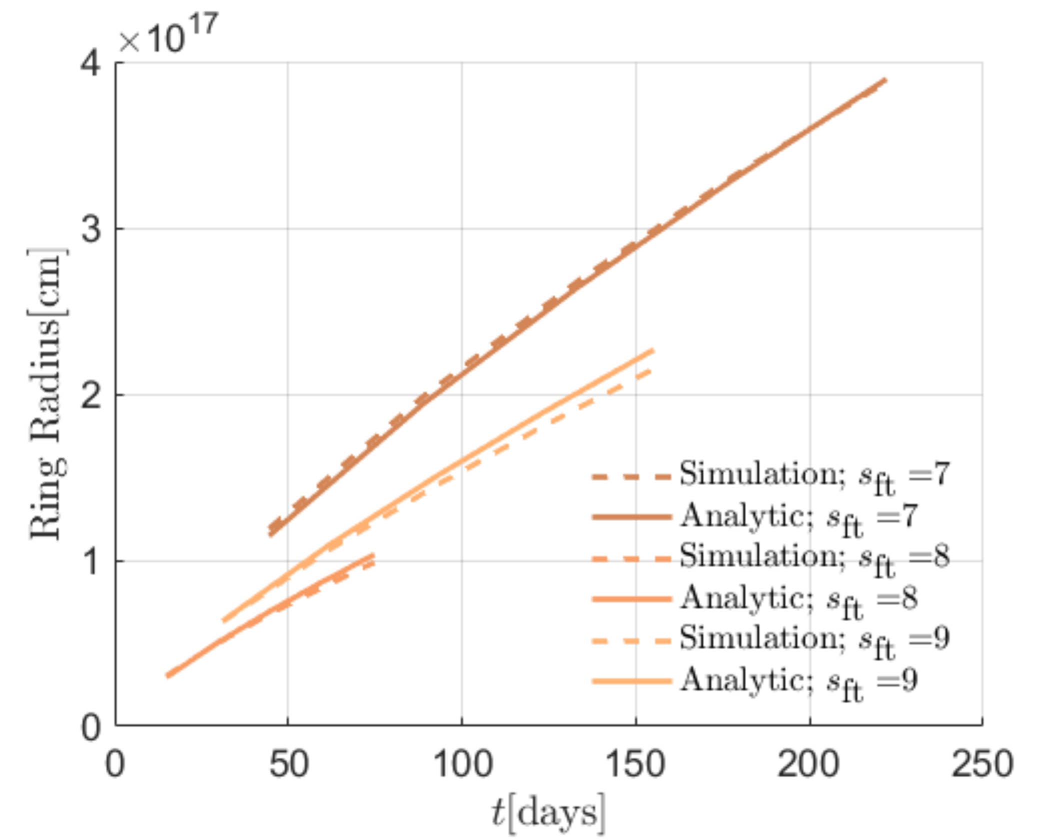


Intensity map

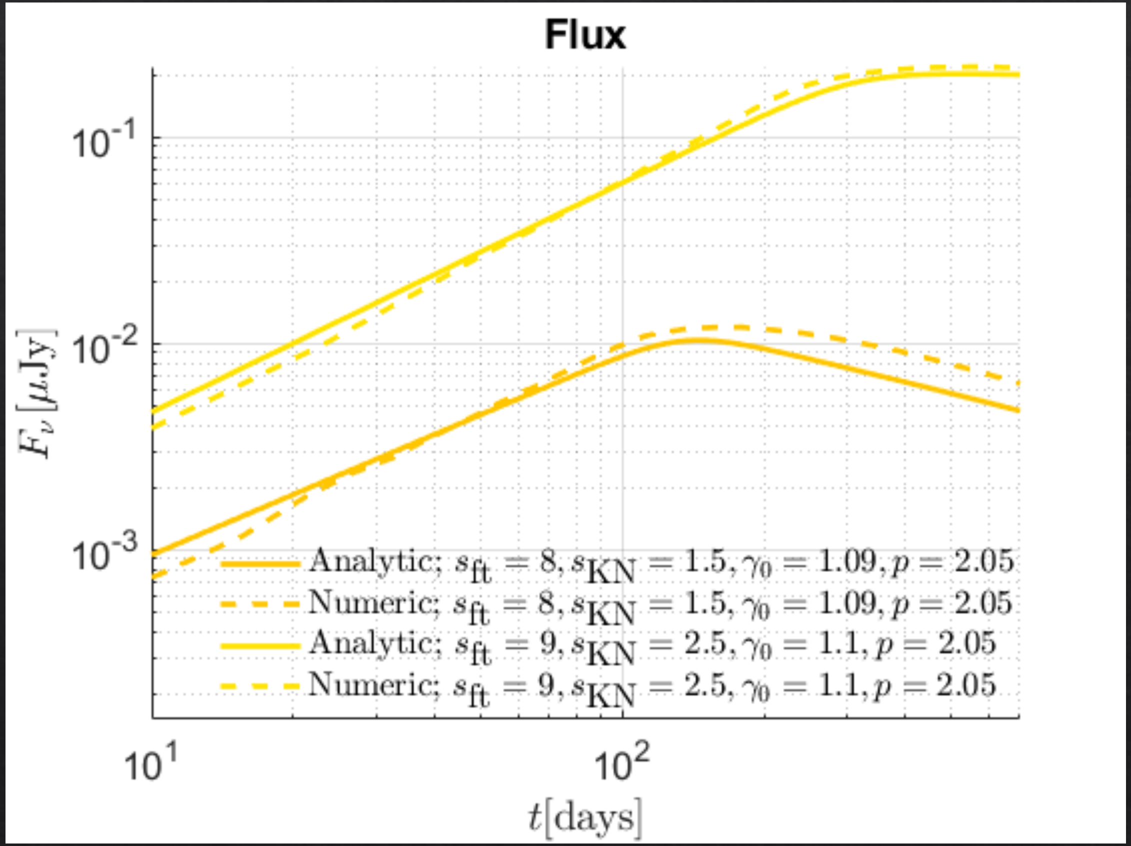


Excellent agreement with full numeric results rescale results formulae

Ring radius

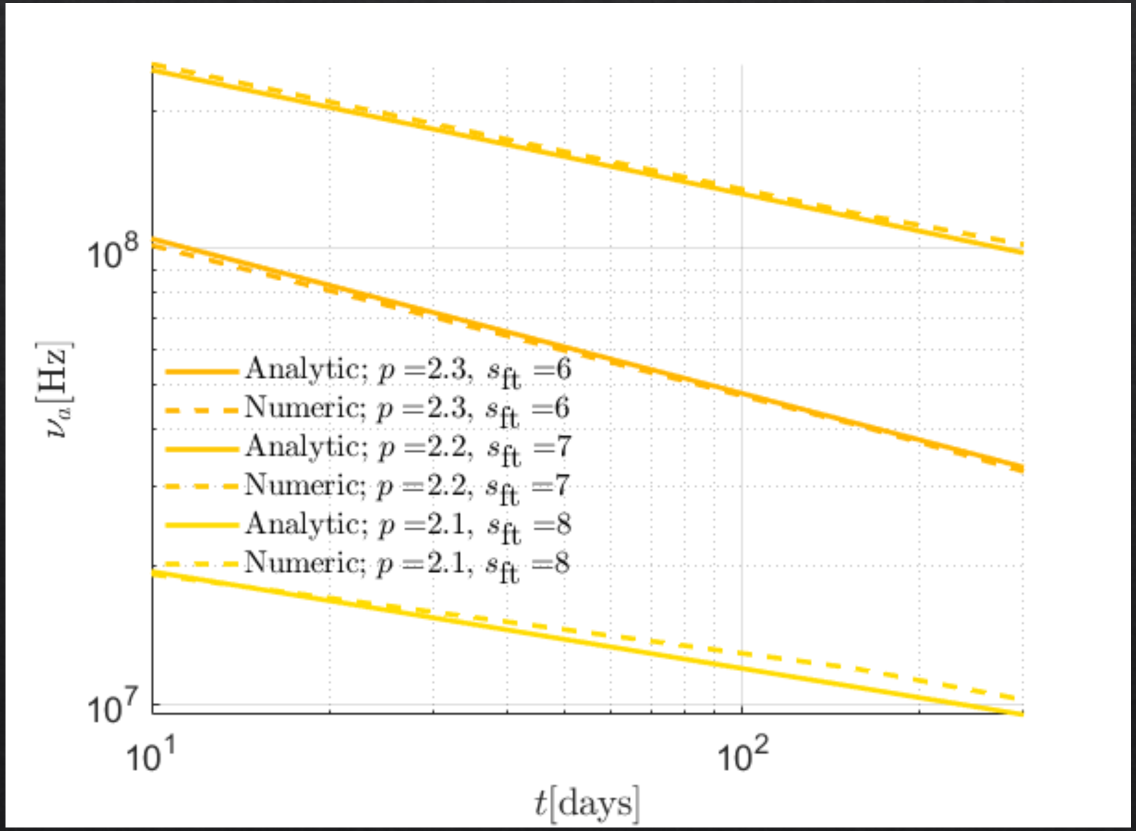


Light curves- 3GHz

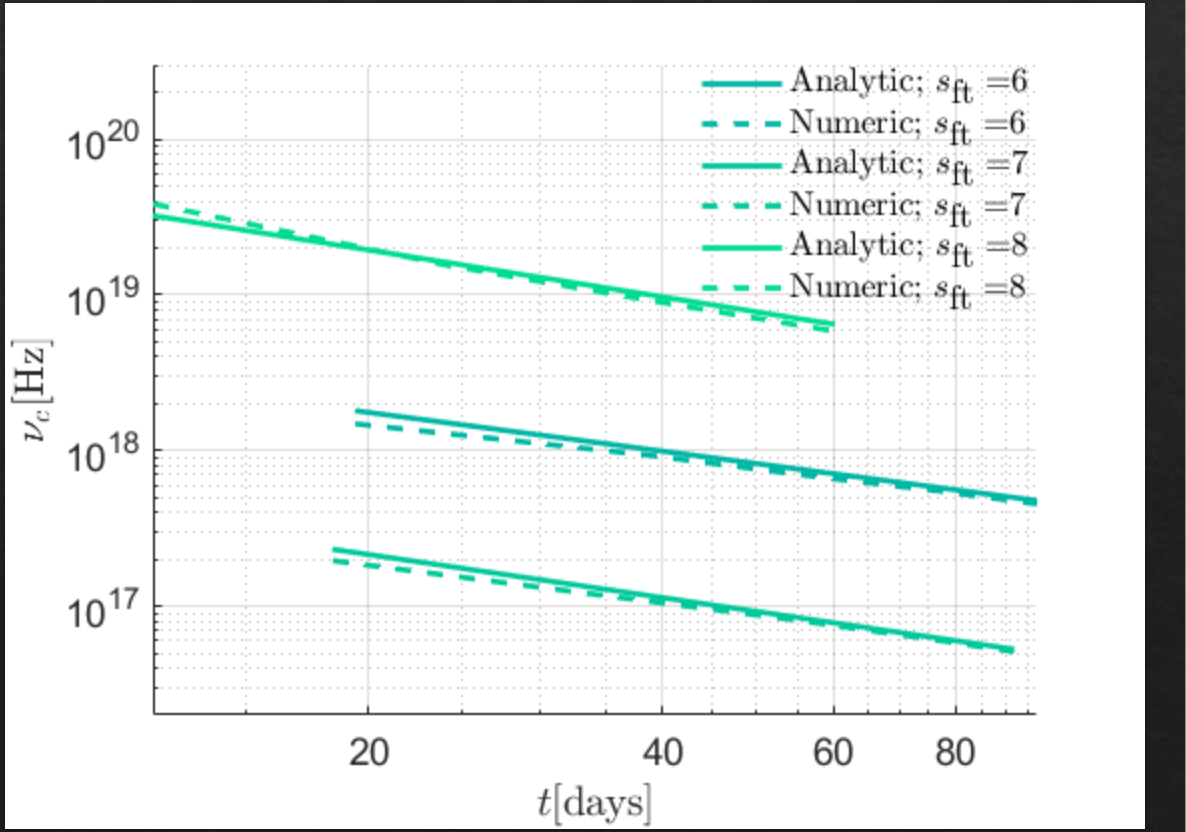


Excellent agreement with full numeric results:

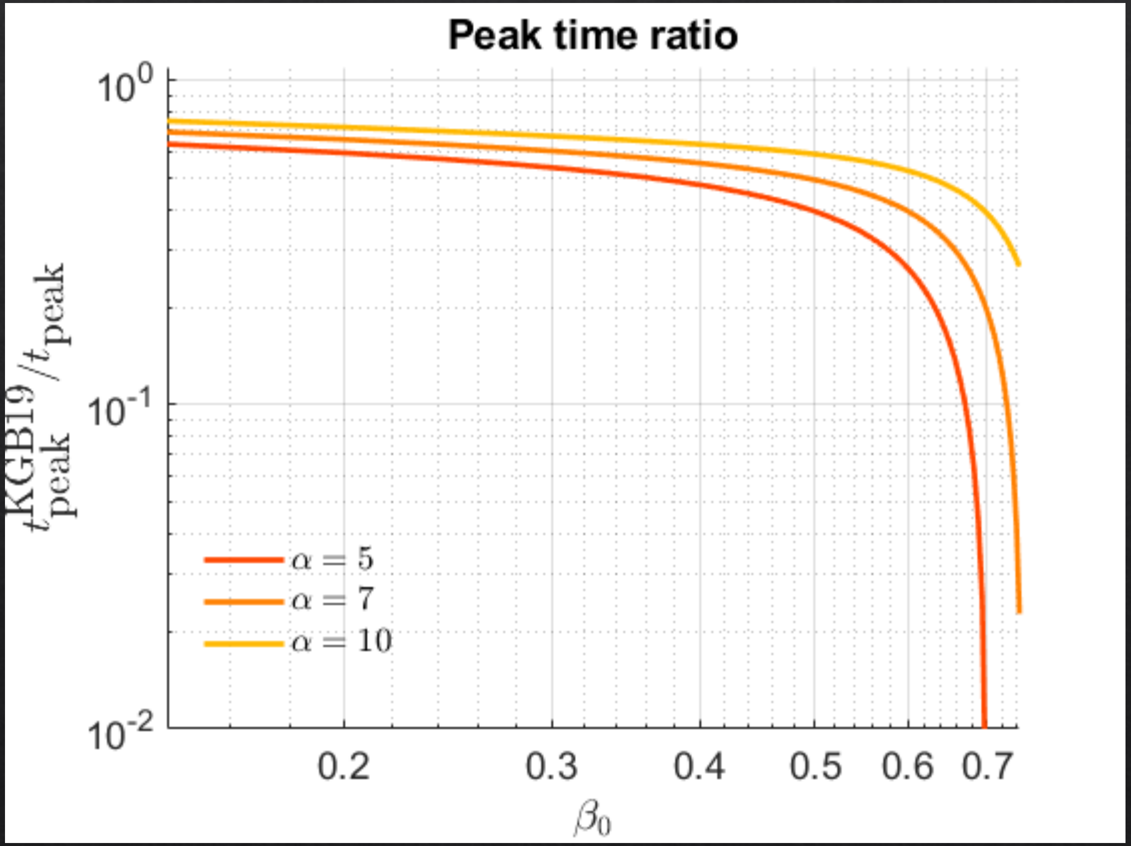
Self-absorption frequency



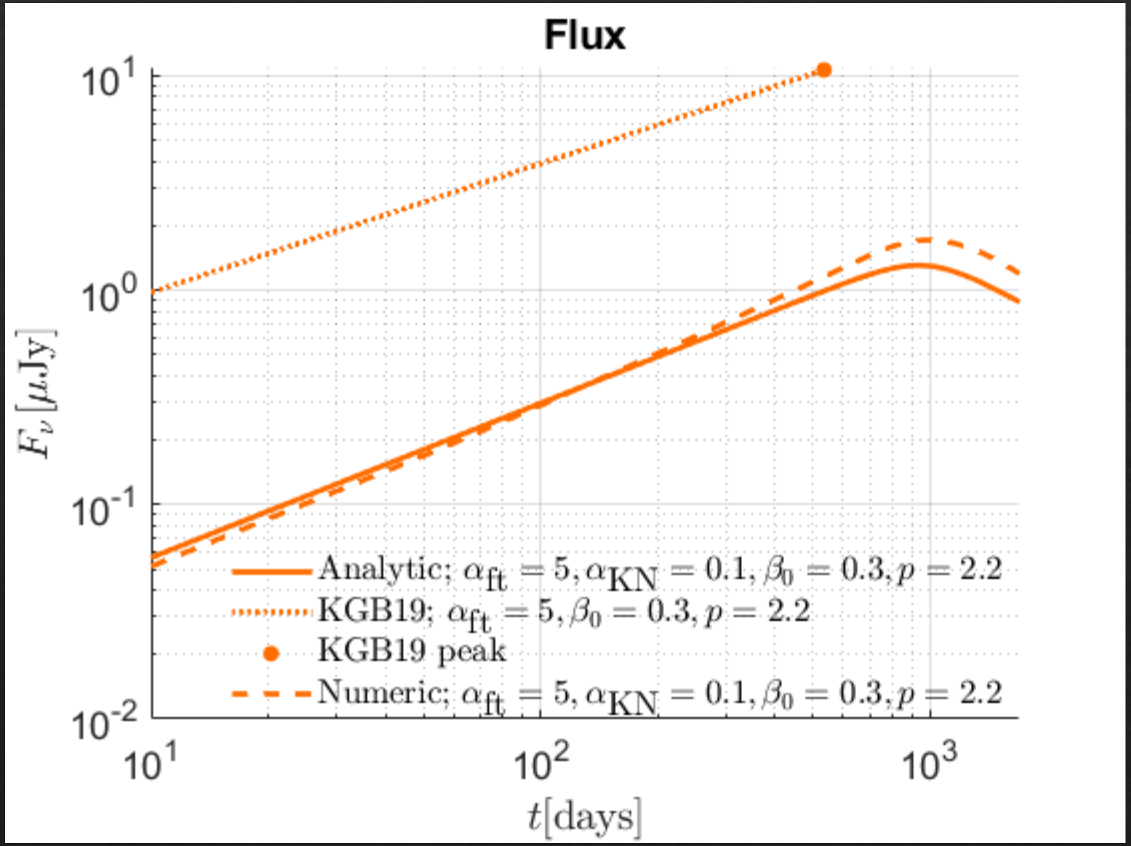
Cooling frequency



Comparison with earlier work



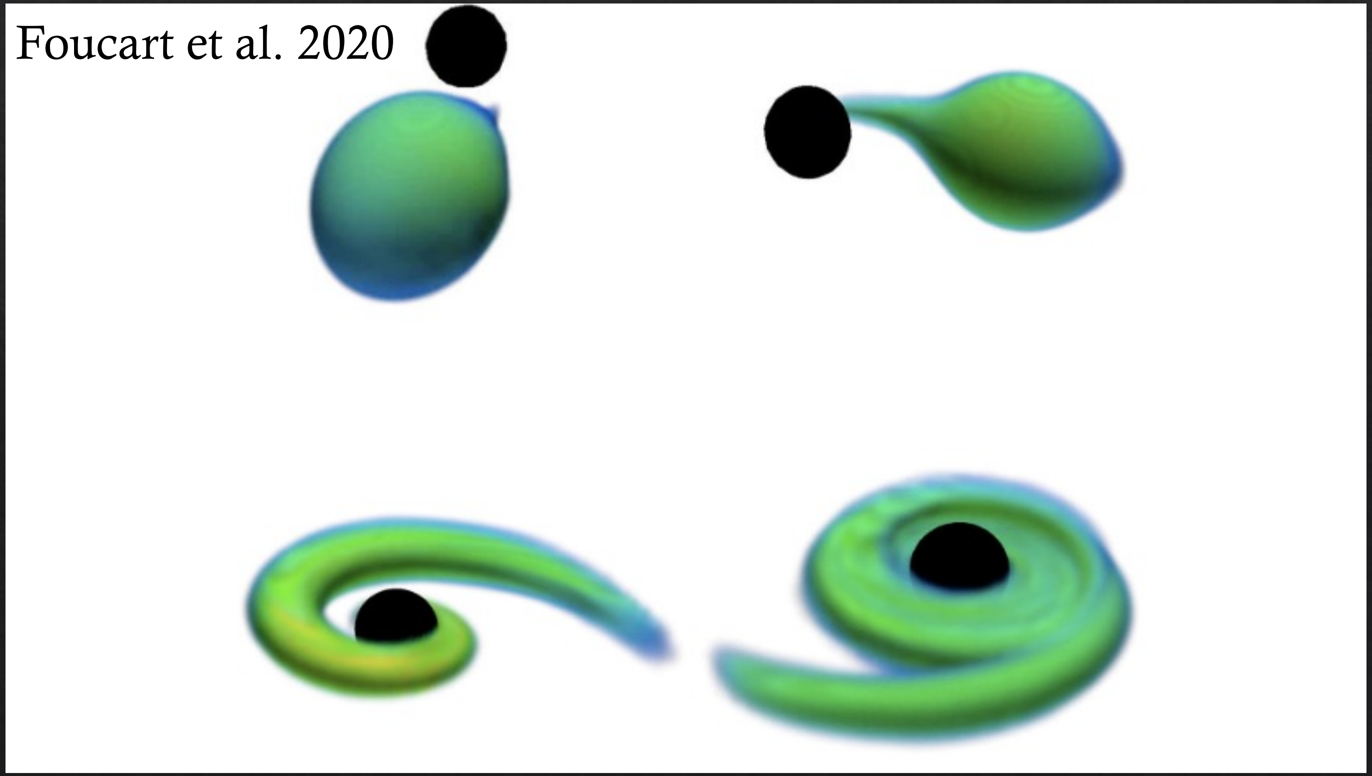
As expected, large deviations for $\beta_0 > 0.5$



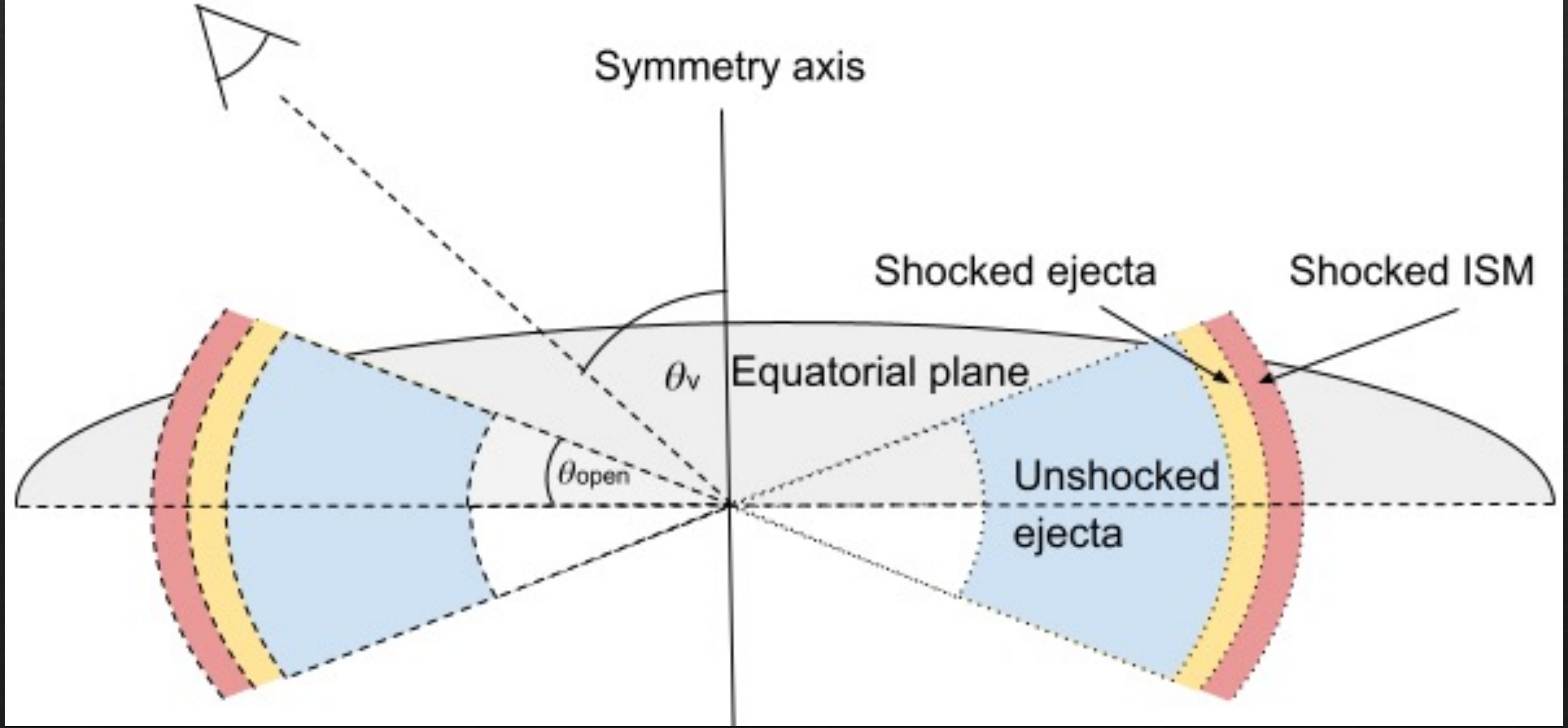
$\beta_0 = 0.3$

Merger with a large mass ratio ($q > 1.5$)

- Mergers of compact objects with mass ratio $q > 1.5$ eject mass mostly within ~ 20° from the orbital plane
- Tidal forces are the main ejection mechanism


Foucart et al. 2020

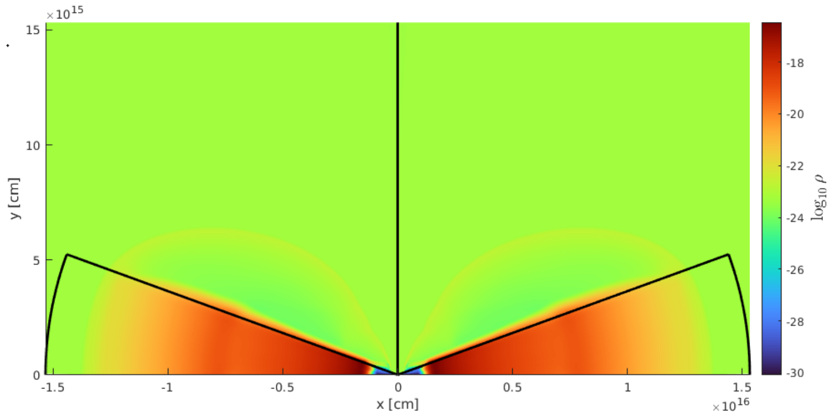
Toroid ejecta ($q > 1.5$)



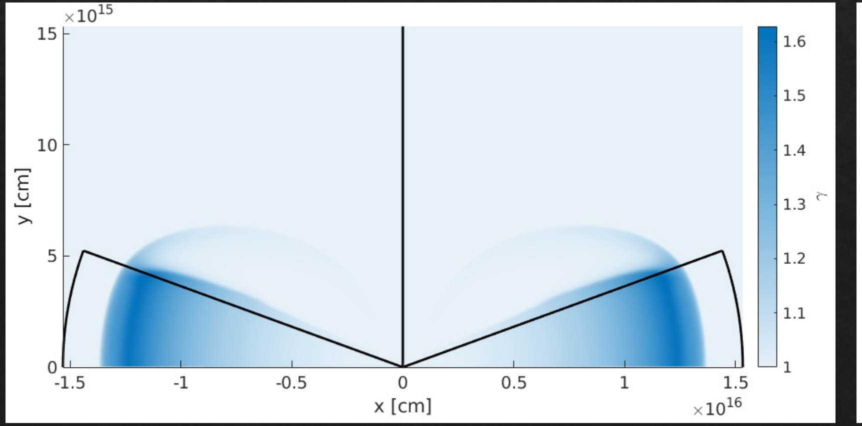
Dynamics 2D: Toroid ejecta

- Lateral expansion is negligible due to the unshocked ejecta and the steep mass profile
- Dynamics can be approximated by $M_{iso} = \frac{M}{\sin\theta_{open}}$
- Full 2D relativistic numerical calculation

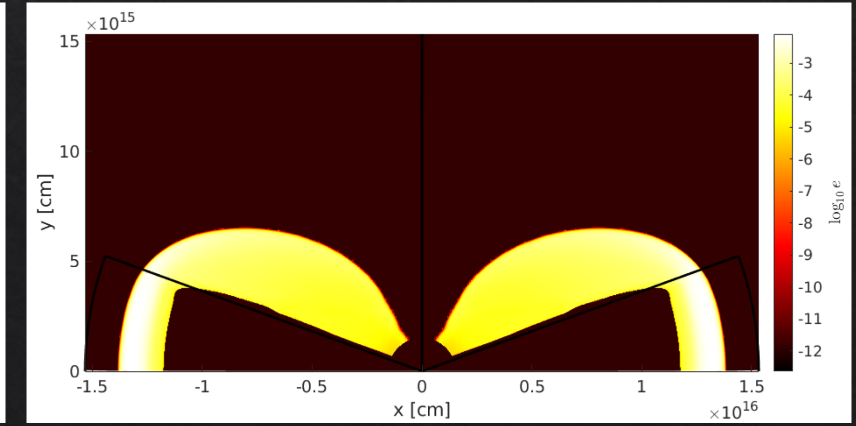
Mass density



Lorentz factor

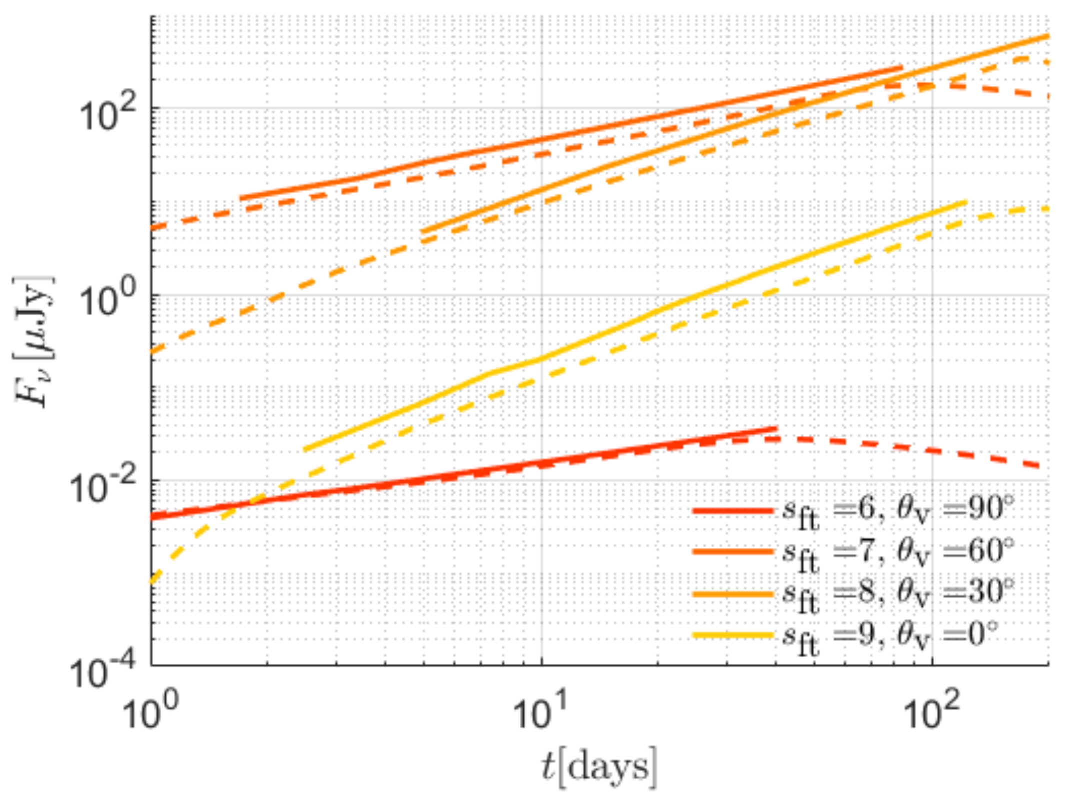


Internal energy density



Excellent agreement with full numeric results- similar peak time and flux

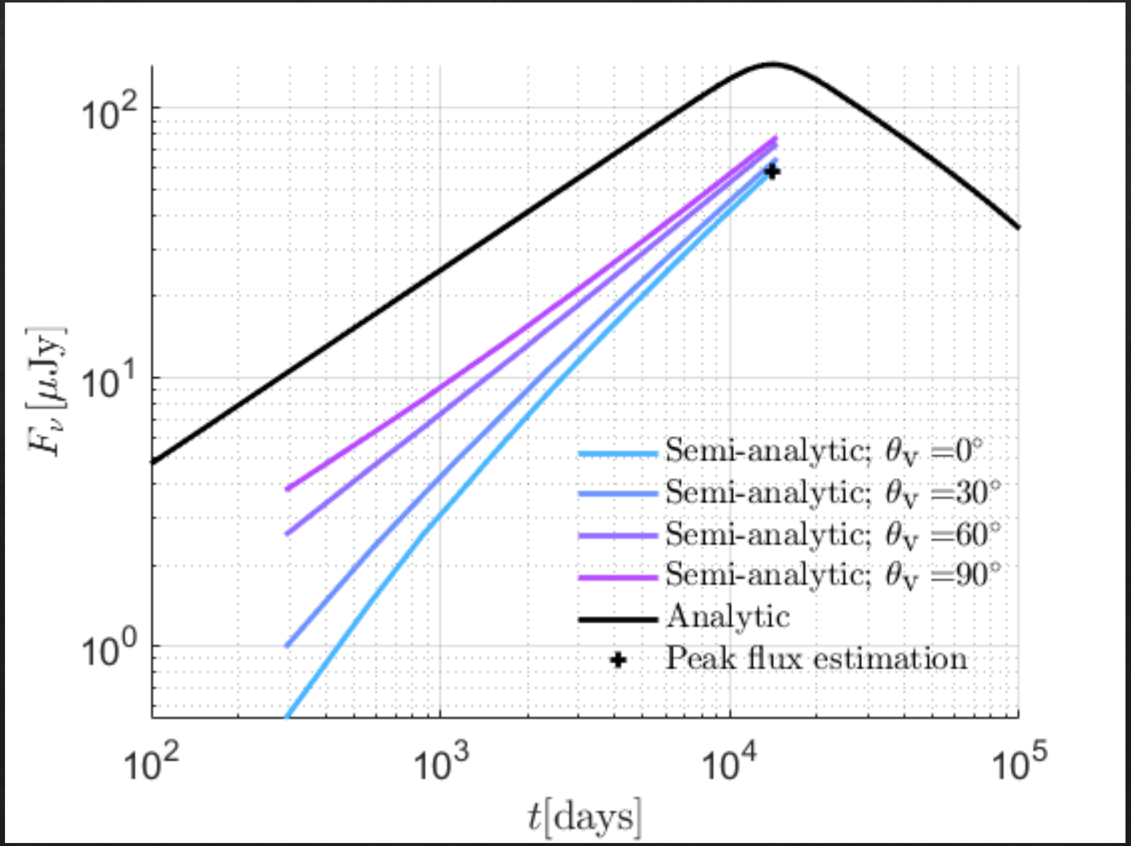
Light curves- simulations and semi-analytic



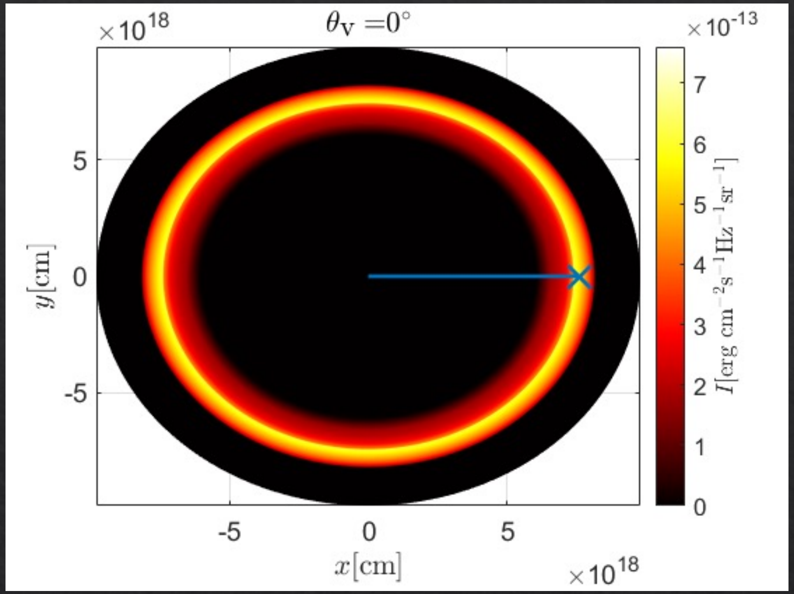
NSBH Typical parameters

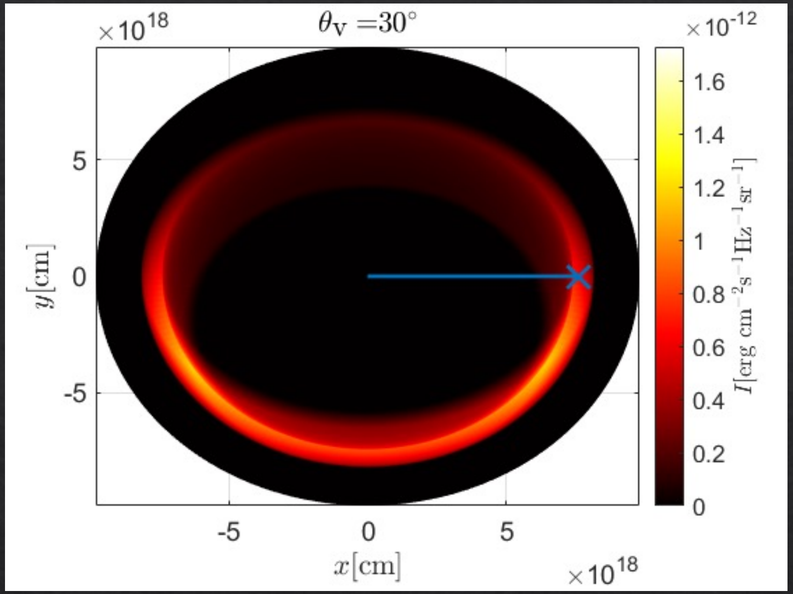
- Among the ejecta parameters, the peak flux primarily relies on the total mass of the fast tail

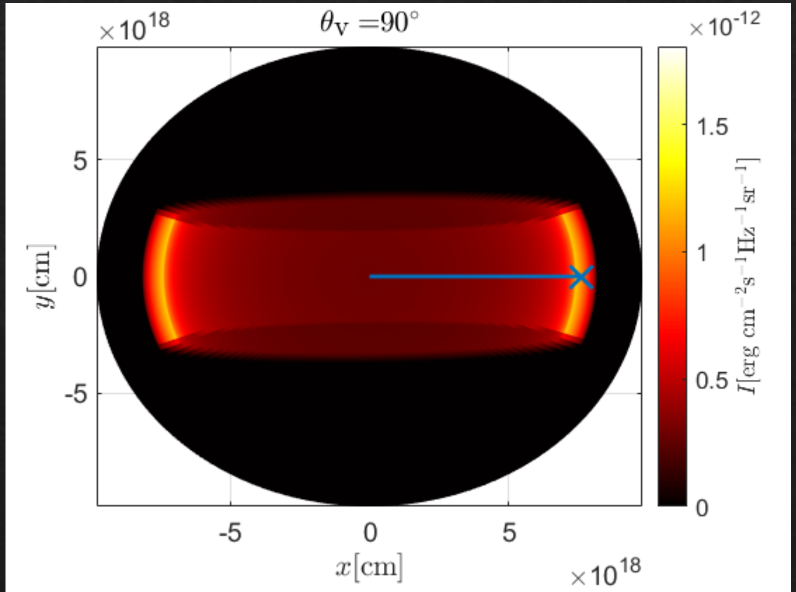
Light curves

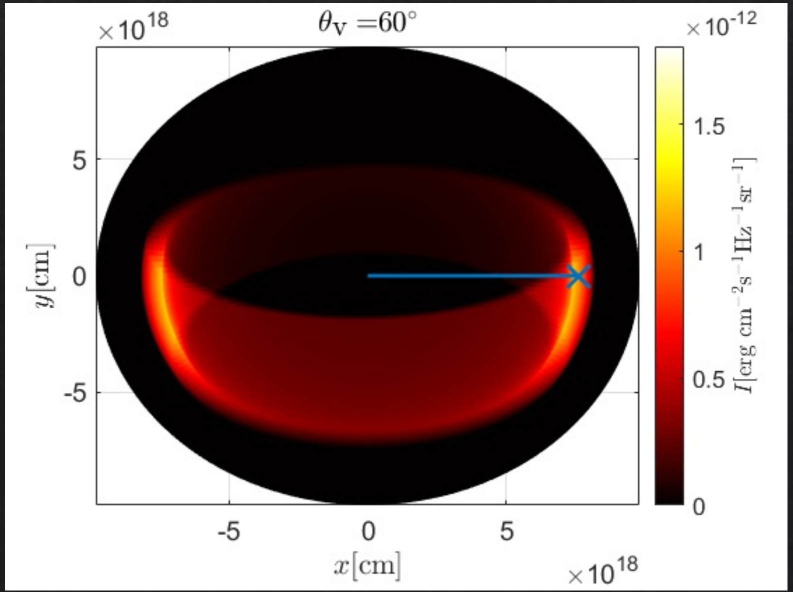


Radio maps


$\theta_V = 0°$
$\times 10^{18}$
$\times 10^{-13}$
5
0
-5
y[cm]
-5
0
5
x[cm]
$\times 10^{18}$
7
6
5
4
3
2
1
0
I[erg cm^{-2}s^{-1}Hz^{-1}sr^{-1}]


$\theta_V = 30°$
$\times 10^{18}$
$\times 10^{-12}$
5
0
-5
y[cm]
-5
0
5
x[cm]
$\times 10^{18}$
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
I[erg cm^{-2}s^{-1}Hz^{-1}sr^{-1}]


$\theta_V = 90°$
$\times 10^{18}$
$\times 10^{-12}$
5
0
-5
y[cm]
-5
0
5
x[cm]
$\times 10^{18}$
1.5
1
0.5
0
I[erg cm^{-2}s^{-1}Hz^{-1}sr^{-1}]


$\theta_V = 60°$
$\times 10^{18}$
$\times 10^{-12}$
5
0
-5
y[cm]
-5
0
5
x[cm]
$\times 10^{18}$
1.5
1
0.5
0
I[erg cm^{-2}s^{-1}Hz^{-1}sr^{-1}]

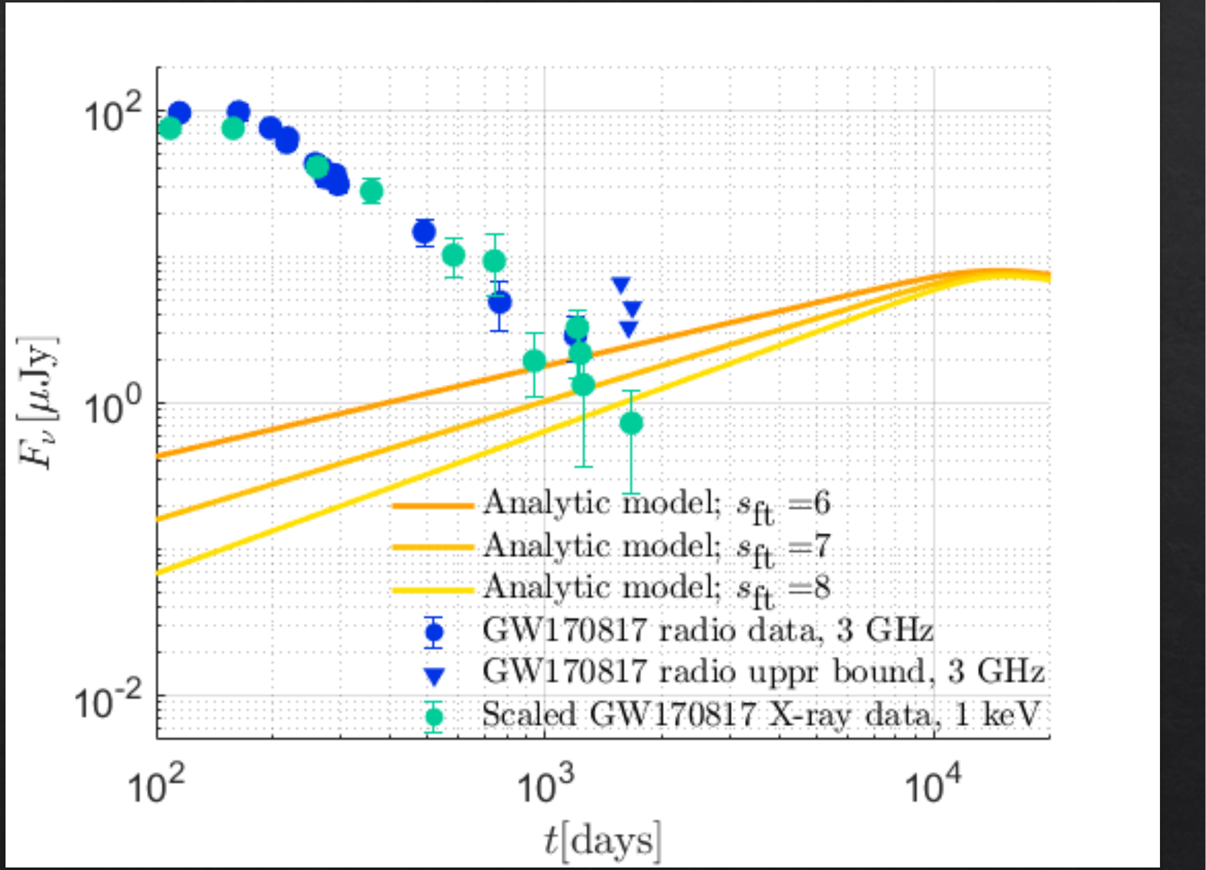
Back to GW170817

- The early ($t < 1000$ days) non-thermal emission following GW170817 is consistent with a highly relativistic, highly non-spherical component
- Observation of non-thermal emission in the future may indicate a new component due to a “fast tail” of the KN ejecta
- GW170817 ejecta parameters inferred from the radioactive emission,

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

[Waxman et al. 2018)]

- Angular size on the sky: 45 mas
- Break frequencies: 3MHz, 0.25keV



Summary

- Mergers of compact objects, such as BNS and NSBH systems, are expected to produce mildly relativistic ejecta with velocities extending to $\beta \sim 0.6$
- We derived both analytic and semi-analytic calculations for the synchrotron emission from such ejecta that can be used to deduce model parameters from future observations
- The analytic results are accurate to 10's of percent, a significant improvement over previous work, which overestimate the flux and self-absorption frequency by ~an order of magnitude for the relevant parameter values
- For typical parameter values ($\beta_0 = 0.3, n = 10^{-2}\mathrm{cm}^{-3}, \mathrm{M}_0 = 10^{-2}\mathrm{M}_\odot$):
  -This signal can be observed to distances of $100 - 200$ Mpc
  -The peak time is ≥ 10 years
  -The observed image on the sky is expected to reach an angular size of 10 mas at a distance of 100 Mpc, resolvable by the VLBI

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Thank you