Radio Afterglow from Kilonova Ejecta of GW170817

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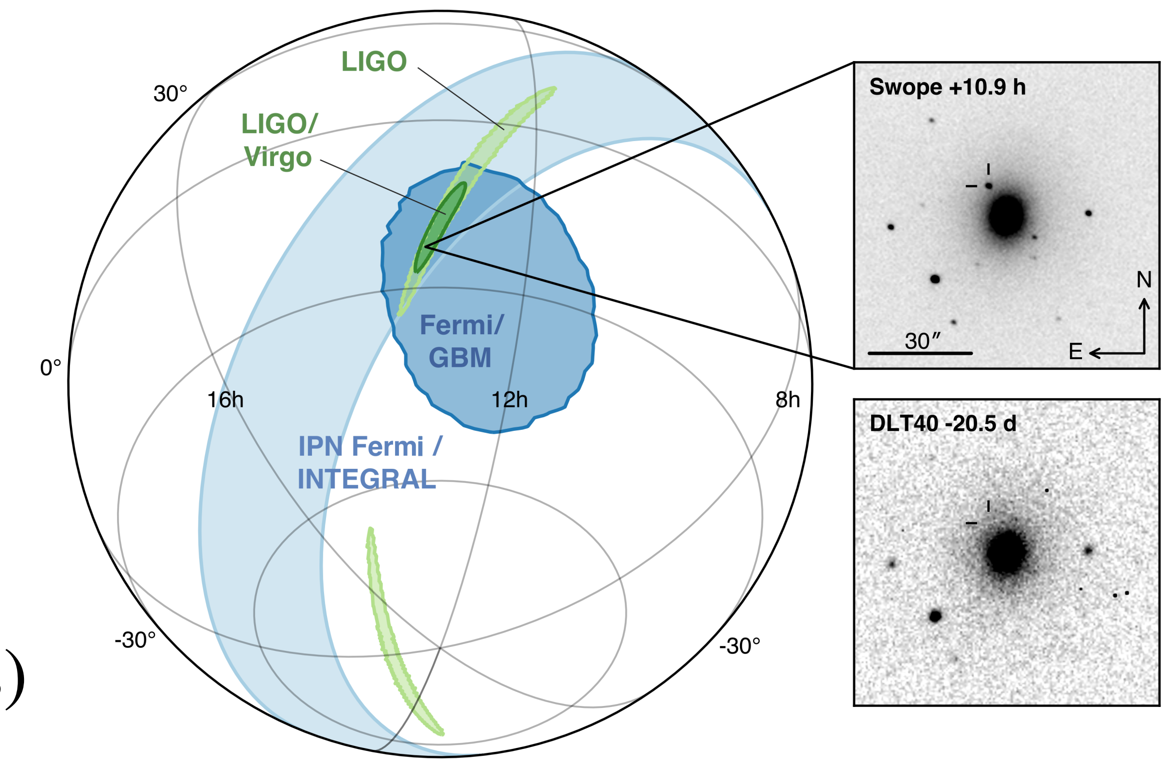
Outlines

- **Backgrounds**
  - **GW170817**
  - **Radio monitoring in the first 100 days**
- **Formalism to predict radio afterglow**
- **Fittings to the current data**
- **Predictions for future radio light curve**

GW170817

- A binary neutron star (BNS) merger event on 2017 August 17
- Luminosity distance ~ 40 Mpc
- Total binary masses ~ 2.74 $M_\odot$
- Confirmed by EM follow-up
  - GRB 170817A (+1.7 s)
  - Optical transient AT 2017gfo (+11 hours)
  - X-ray (+9 days) & radio (+15 days)



Abbott et al. (2017)

- X-ray/radio monitoring revealed continued rising light curves (+100 days)

Radio emission from ejecta-ISM interaction

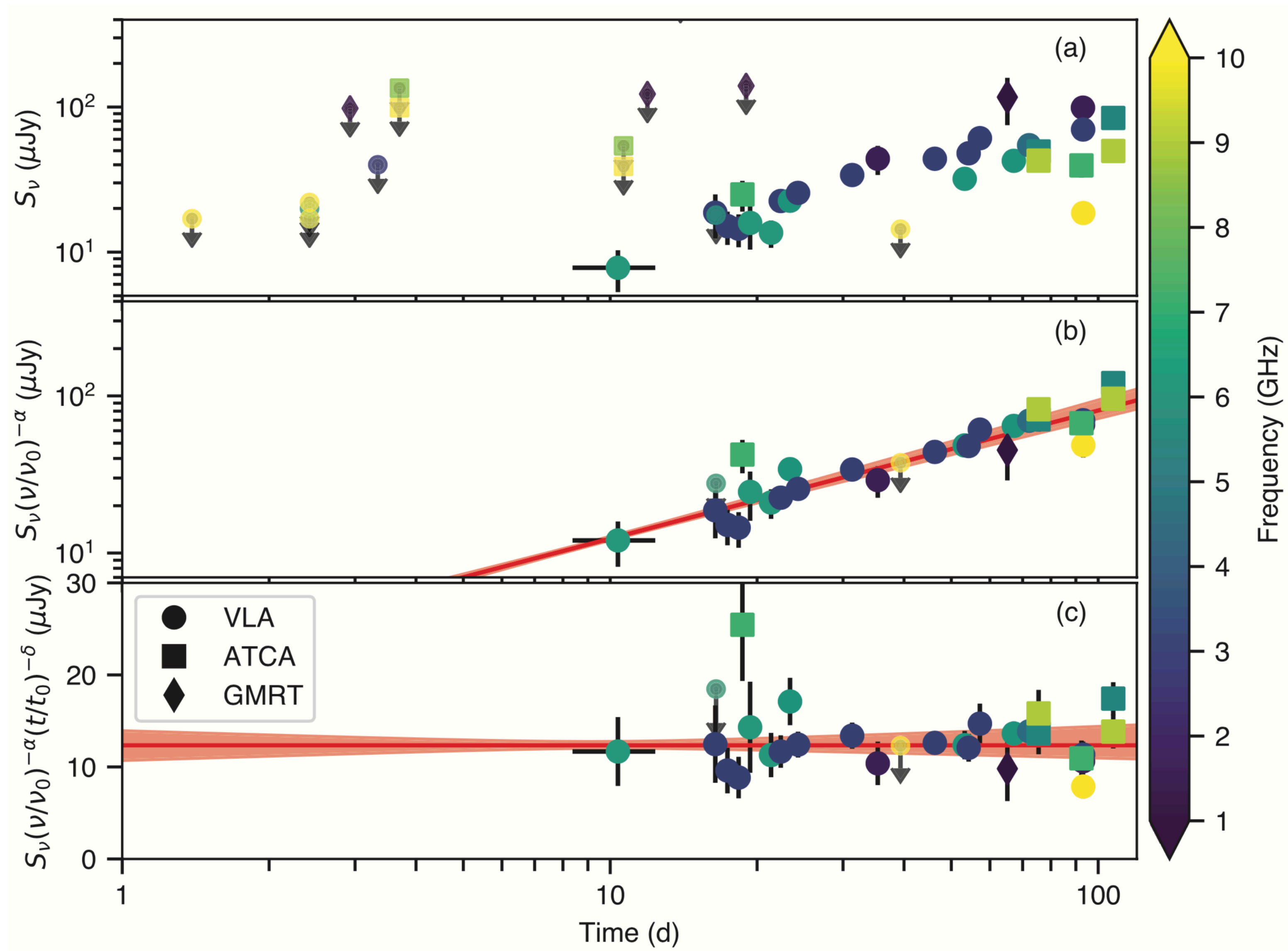
- **Nakar E. & Piran T., 2011, Nature, 478, 82**
  - Merger launches mildly relativistic ejecta (~ 0.3c) into ISM
  - Ejecta-ISM interaction generates a blast wave
  - Magnetic field accelerates electrons to emit synchrotron radiation, peaks at radio band (SNR, GRB)
  - Detectable radio flares
    - Reaches peak flux when ejecta swept up comparable ISM mass (~ years)
    - Radio flux ~ sub-mJy up to d = 40 Mpc
    - Detectable by current (VLA, ATCA, uGMRT) & next-generation radio facilities (ngVLA, SKA1-MID)

Previous work on radio afterglow

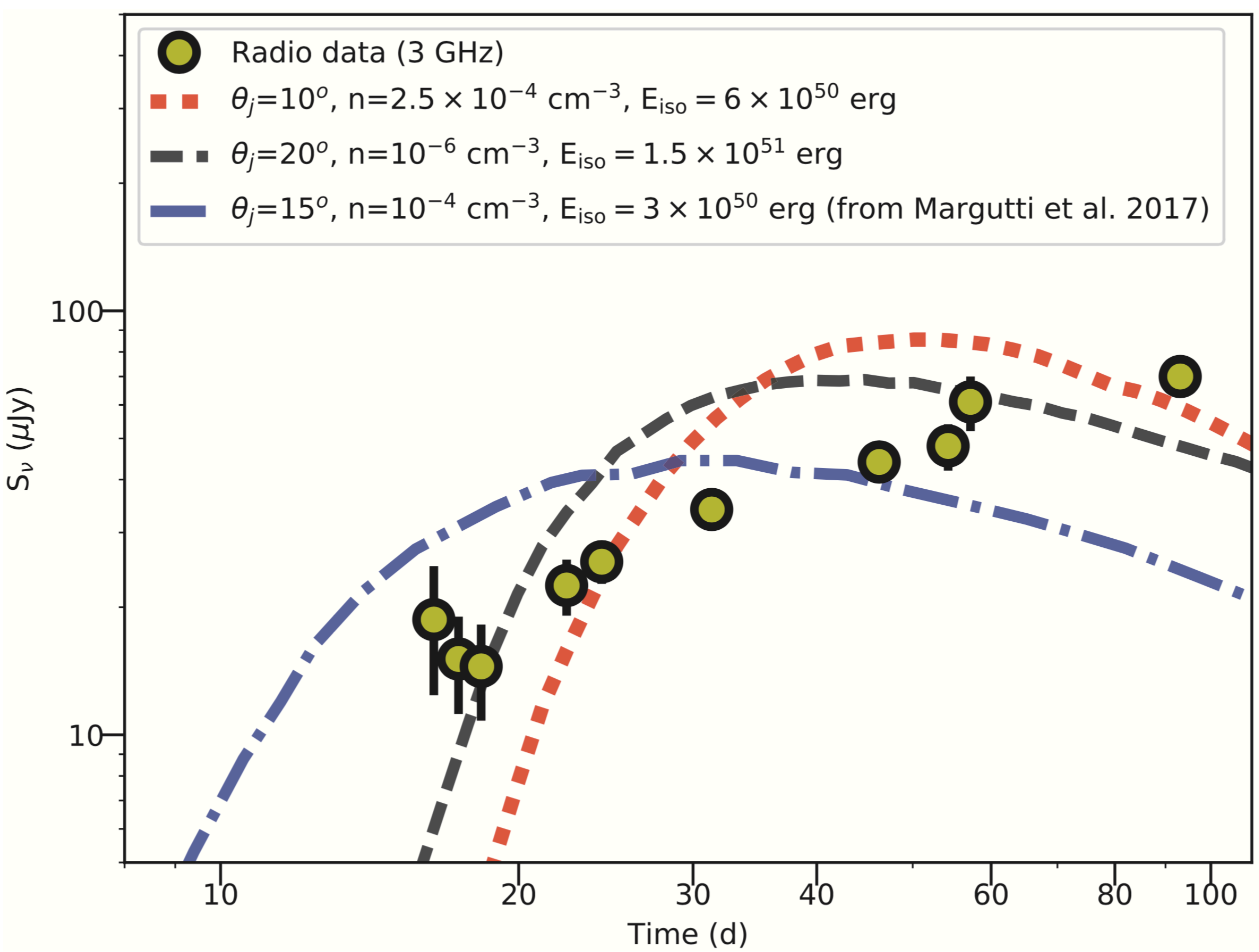
- **Piran, Nakar & Rosswog (2013)**
  - Radio light curves computed with numerical simulations
- **Hotokezaka & Piran (2015)**
  - Radio signals from different components: ejecta, jet, wind, cocoon
- **Margalit & Piran (2015)**
  - Effect of ejecta anisotropy: increases timescale but weakens signals
- **Hallinan et al. (2017)**
  - Detection of radio counterpart to GW170817: off-axis jet or cocoon emission?
- **Alexander et al. (2017)**
  - First prediction for future radio afterglow of GW170817, detectable on a timescale of 5-10 years
- **Mooley et al. (2017)**
  - Radio monitoring of GW170817 in the first 100 days
  - Radio data rules out off-axis ultra-relativistic jet, but favors mildly-relativistic outflow
  - Common synchrotron origin for X-ray & radio? (confirmed by Ruan et al. 2017)

Radio monitoring of GW170817 (Mooley et al. 2017)

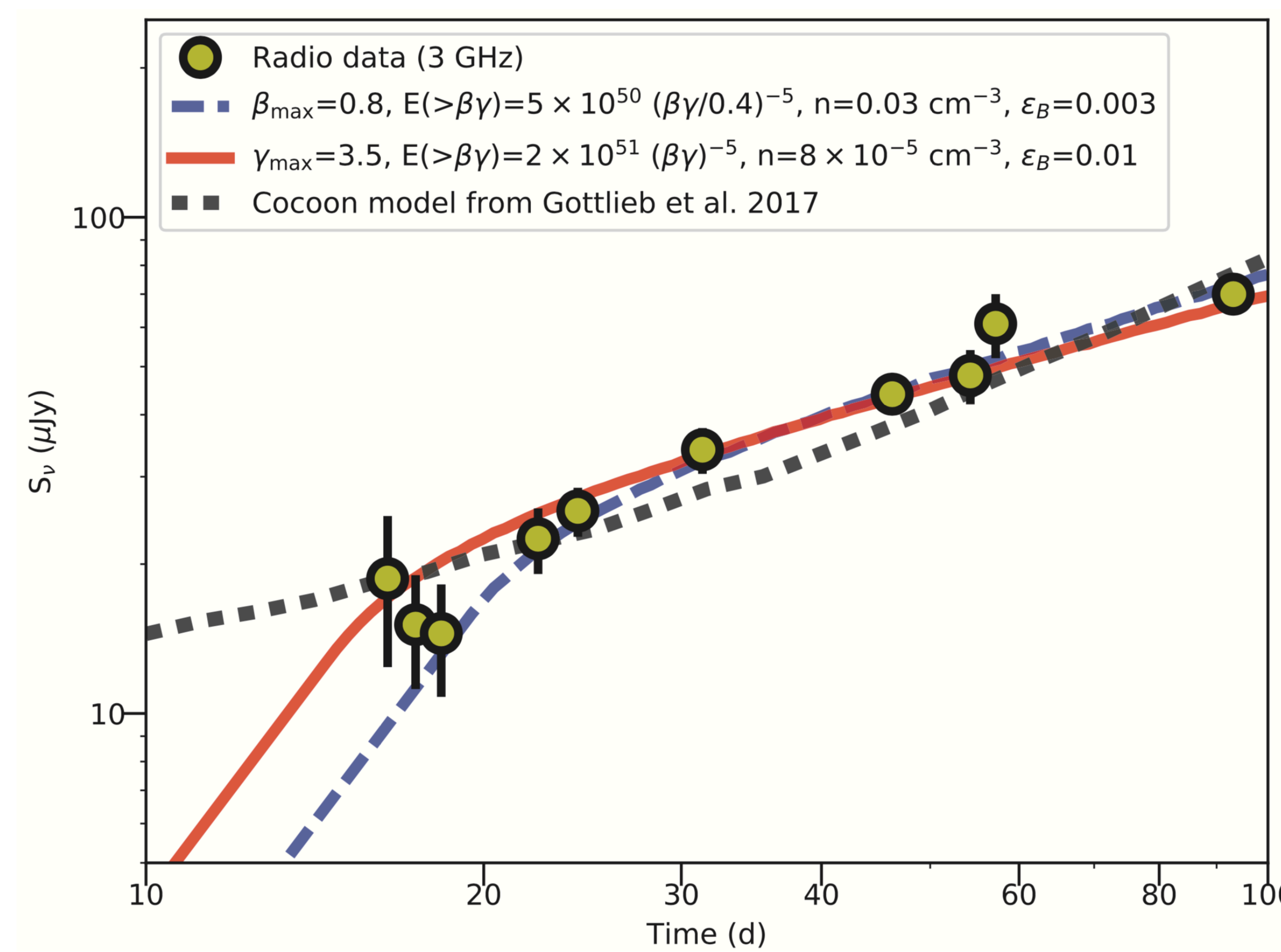
- Timespan
  ~ +16 - 107 days
- Radio band range
  ~ 0.6 - 15 GHz
- Flux level
  ~ 10^1 - 10^2 μJy
- Temporal index
  ~ +0.78
- Spectral index
  ~ -0.61



Fittings to the 3 GHz radio data (Mooley et al. 2017)



Off-axis jet models: RULED OUT



Cocoon & Fast ejecta models

Our research

- Motivation of this study
  - To make precise prediction for future radio light curves of GW170817 with numerical simulations
  - Modeling of the radio data may shed lights on the unknown remnant of GW170817
- What is done in this study
  - Formulations for the radio emission from ejecta-ISM blast wave
  - A different treatment for non-thermal electron spectrum from previous work
  - Realistic ejecta profile taken from high-resolution numerical simulations (Kiuchi et al. 2014)

Ejecta-ISM blast wave dynamics

- Energy injection

$$E(>\beta_{\rm inj}) = (\Gamma - 1)M(>\beta_{\rm inj})c^2 + (\Gamma^2 - 1)mc^2$$

Energy that catches up with the blast wave

Kinetic energy of catch-up ejecta

Kinetic energy of swept-up ISM

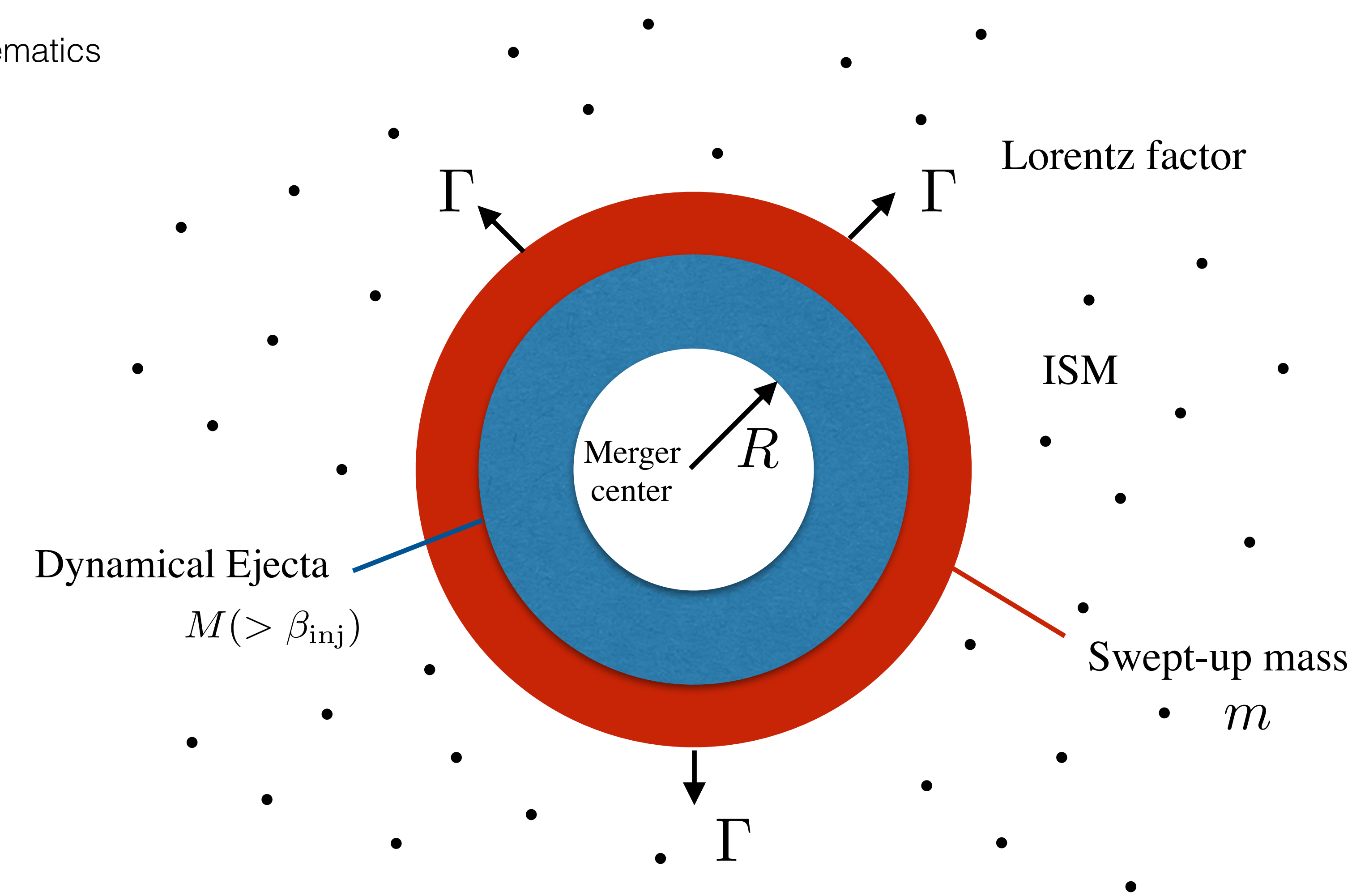
$$\beta_{\rm inj}ct = R$$ Chasing-up kinematics

- Swept-up mass

$$m = \frac{4}{3}nm_pR^3$$

- Blast wave kinematics

$$\dot{R} = (1 - \Gamma^{-2})^{1/2}c$$



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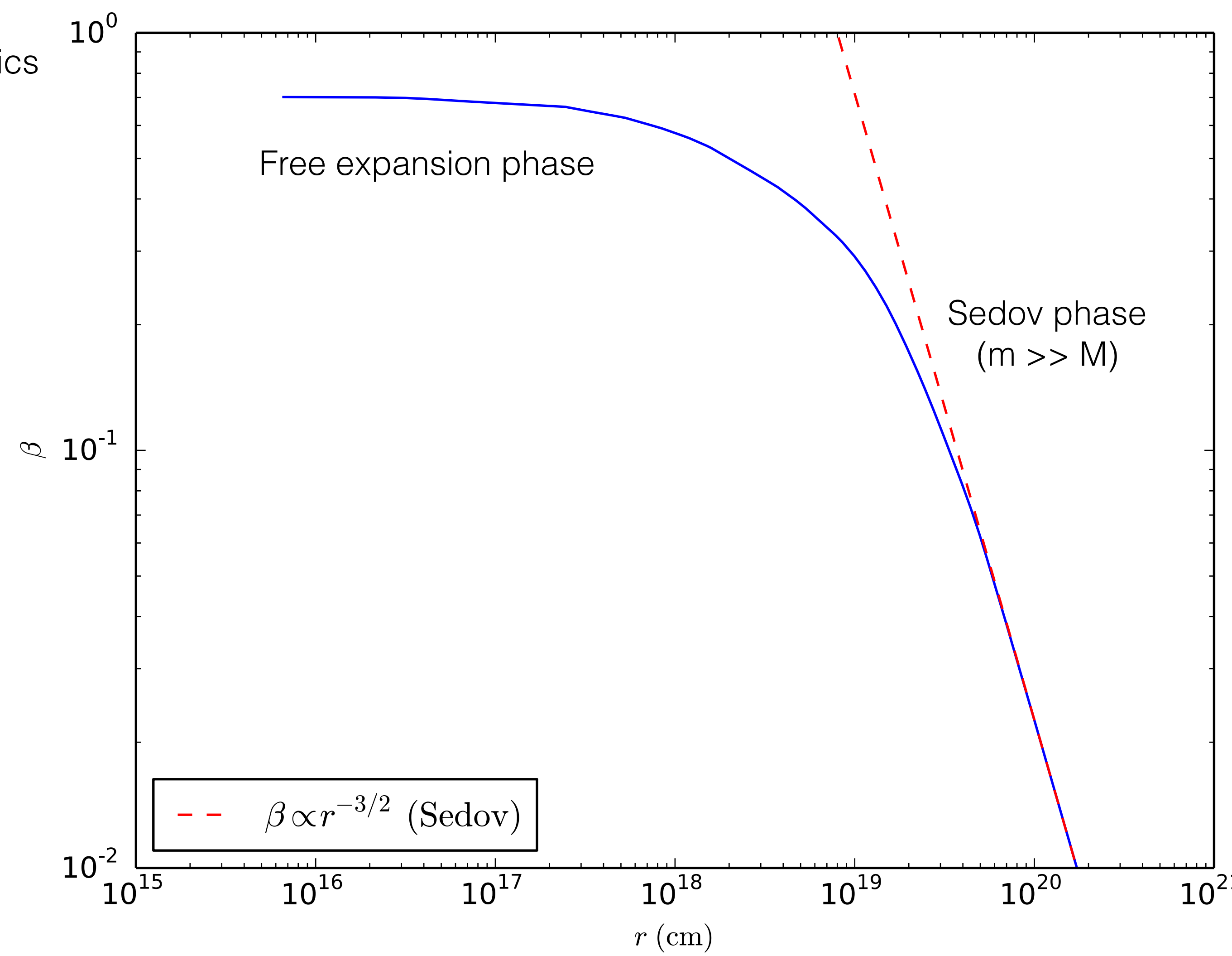


Radio light curves formulations

- Microphysical parameters: magnetic field, non-thermal electrons carries a fraction ϵ_B, ϵ_e of the shocked internal energy

$$\frac{B^2}{8\pi} = \epsilon_B (\Gamma - 1) \frac{\hat{\gamma}\Gamma + 1}{\hat{\gamma} - 1} n m_p c^2$$

$$\int_{\gamma_m}^{\infty} (\gamma_e - 1) m_e c^2 \frac{dN_e}{d\gamma_e} d\gamma_e = \epsilon_e (\Gamma - 1) m c^2$$

Shocked Lorentz factor $\Gamma - 1$

Density compression ratio $\frac{\hat{\gamma}\Gamma + 1}{\hat{\gamma} - 1}$

Electron energy distribution $\frac{dN_e}{d\gamma_e} \propto \gamma_e^{-p}$

Minimum Lorentz factor $\gamma_m = \frac{m_p}{m_e}(\Gamma - 1) + 1$

- These give estimations

$$B = \left[8\pi \epsilon_B \frac{\hat{\gamma}\Gamma + 1}{\hat{\gamma} - 1} n m_p c^2 (\Gamma - 1) \right]^{1/2}$$

$$N_e = \frac{\epsilon_e (\Gamma - 1) m}{\left[\frac{p-1}{p-2} \frac{m_p}{m_e} (\Gamma - 1) + \frac{1}{p-2} \right] m_e} \propto \begin{cases} R^3 & \text{(free expansion phase)} \\ \text{constant} & \text{(Sedov phase)} \end{cases}$$

$$\gamma_m = \epsilon_e \frac{p-2}{p-1} \frac{m_p}{m_e} \beta^2$$

$$N_e \propto R^3$$

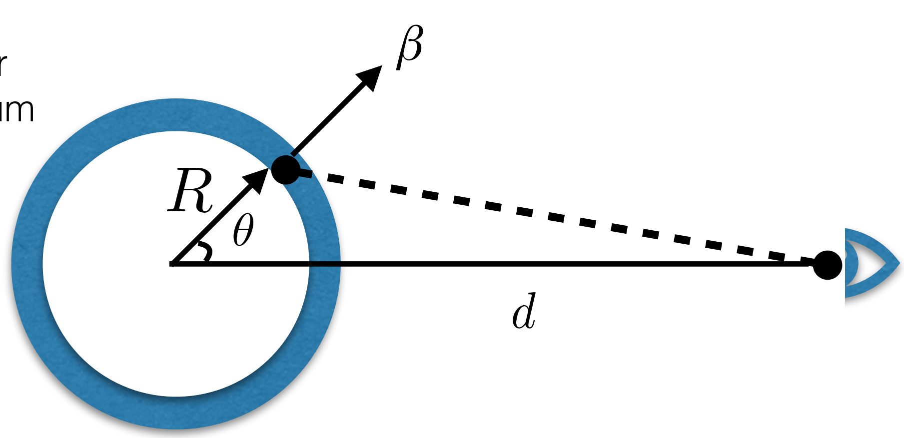
Nakar & Piran (2011)

Radio light curves formulations

- Synchrotron flux received at distance *d*, integrated over all directions

$$F_{\nu_{\rm obs}}(T) = \frac{1}{4\pi d^2}\int \frac{1}{\Gamma(t)^3(1-\beta(t)\cos\theta)^3}\frac{dP'_{\nu'}}{d\Omega'}(t)\sin\theta d\theta d\phi$$

receiving area — relativistic+ direction correction — Power spectrum



- Power spectrum emitted by electrons (rest-frame)

$$\frac{dP'_{\nu'}}{d\Omega'} = \frac{\sqrt{3}}{4\pi}\frac{e^3 B}{m_e c^2}\int_{\gamma_m}^{\infty} F\left(\frac{\nu'}{\nu'_c(\gamma_e)}\right)\frac{dN_e}{d\gamma_e}d\gamma_e \quad \propto \left(\frac{\nu'}{\nu'_m}\right)^{-\frac{p-1}{2}}$$

peaks at $\nu'_m \equiv \frac{1}{2\pi}\frac{eB}{m_e c}\gamma_m^2 \propto \begin{cases}\beta^5 & (\gamma_m \gg 1)\\ \beta & (\gamma_m \simeq 1)\end{cases}$

- Doppler effect: $\nu' = \Gamma(1-\beta\cos\theta)\nu_{\rm obs}$

Rest-frame frequency — Observed frequency

$$\nu'_m \equiv \frac{1}{2\pi}\frac{eB}{m_e c}\gamma_m^2 \propto \beta^5$$

Nakar & Piran (2011)

- Equal arrival time surface: $t = T + R(t)\cos\theta/c$

Rest-frame time — Received time

Radio light curves formulations

- Synchrotron self-absorption coefficient

$$\alpha'_{\nu'} = \frac{(p+2)}{8\pi m_e \nu'^2} \int_{\gamma_m}^{\gamma_M} \sqrt{3}\frac{e^3 B}{m_e c^2} F\left(\frac{\nu'}{\nu'_c(\gamma_e)}\right) \frac{dn_e}{d\gamma_e}\frac{d\gamma_e}{\gamma_e}$$

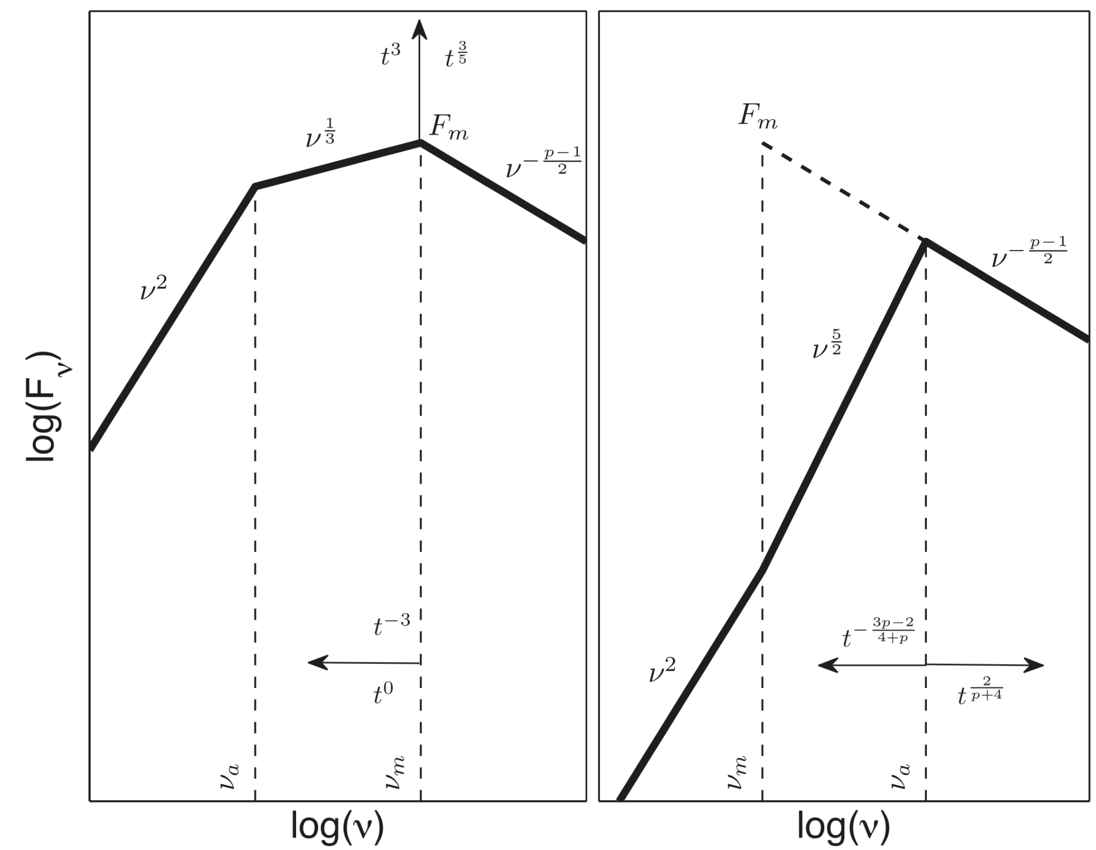
absorption frequency determined by optical depth

$$\alpha'_{\nu'_a}\delta r' = 1$$

- Absorbed spectra

$$F_\nu = F_m \begin{cases} (\nu_a/\nu_m)^{1/3}(\nu/\nu_a)^2 & (\nu < \nu_a) \\ (\nu/\nu_m)^{1/3} & (\nu_a < \nu < \nu_m) \\ (\nu/\nu_m)^{-\frac{p-1}{2}} & (\nu_m < \nu) \end{cases} \qquad \nu_a < \nu_m$$

$$F_\nu = F_m \begin{cases} (\nu_a/\nu_m)^{-\frac{p-1}{2}}(\nu_m/\nu_a)^{5/2}(\nu/\nu_m)^2 & (\nu < \nu_m) \\ (\nu_a/\nu_m)^{-\frac{p-1}{2}}(\nu/\nu_a)^{5/2} & (\nu_m < \nu < \nu_a) \\ (\nu/\nu_m)^{-\frac{p-1}{2}} & (\nu_a < \nu) \end{cases} \qquad \nu_m < \nu_a$$



Two possible spectra

Piran, Nakar & Rosswog (2013)

Overview of the formulations

Blast wave dynamics

Ejecta profile

$E(>\beta)\quad M(>\beta)$

↓

Blast wave dynamics

$$E(>\beta_{\rm inj}) = (\Gamma-1)M(>\beta_{\rm inj})c^2 + (\Gamma^2-1)mc^2$$

$$\beta_{\rm inj}ct = R$$

$$m = \frac{4}{3}nm_pR^3$$

$$\dot{R} = (1-\Gamma^{-2})^{1/2}c$$

↑

Circumburst density n

→

Velocity

$\Gamma(t)$

Radius

$R(t)$

→

Synchrotron emission

Circumburst density n

Microphysical parameters ϵ_B, ϵ_e

Electron spectrum index p

↓

Minimum synchrotron frequency

ν_m

Self-absorption frequency

ν_a

↓ Distance $d = 40$ Mpc

Radio light curve

$F_\nu(T)$ ✔

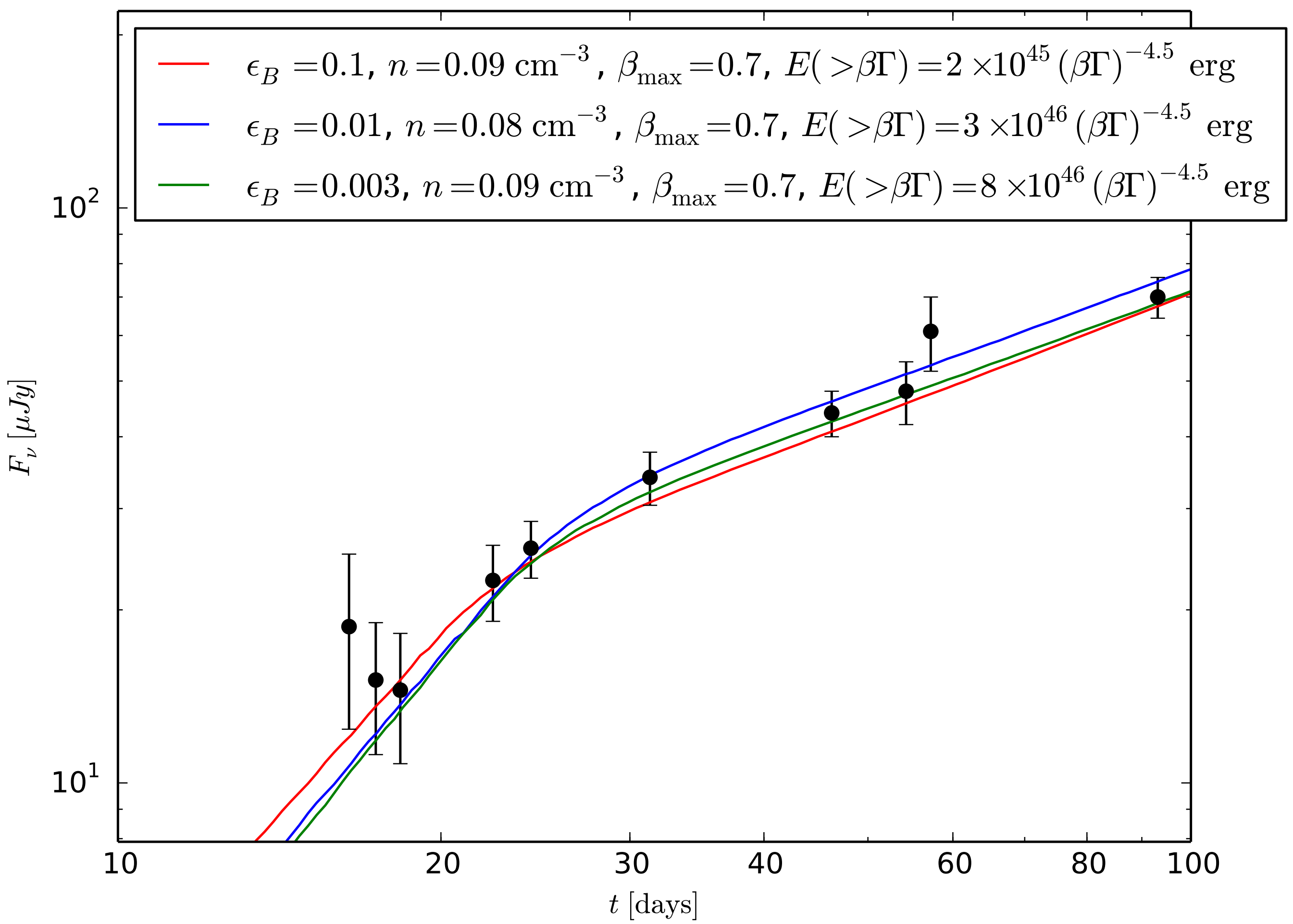
Fitting to the radio data

- A simple power-law ejecta profile is assumed:

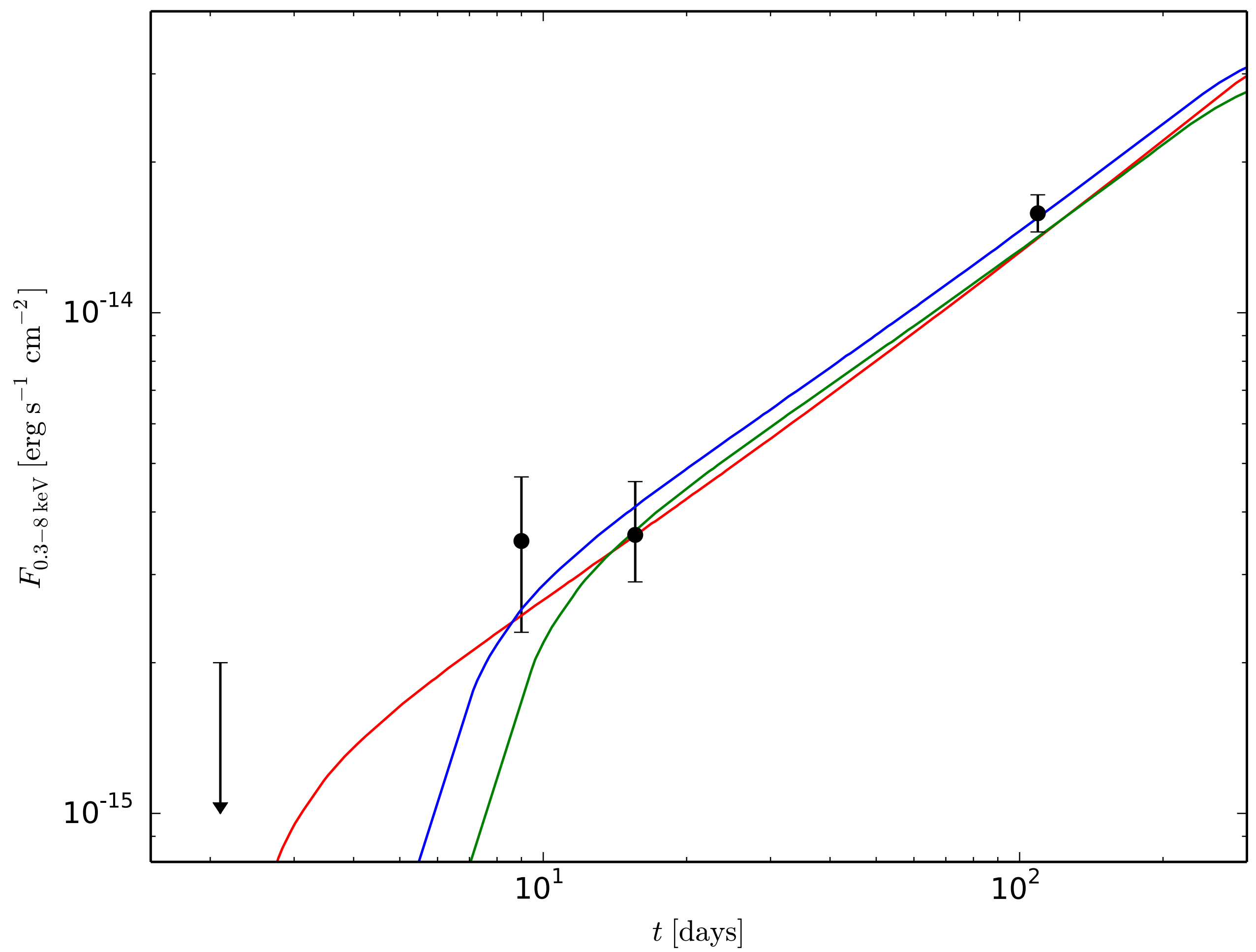
$$E(>\beta\Gamma) = E_0 \left(\frac{\beta\Gamma}{\beta_{\min}\Gamma_{\min}}\right)^{-k} \quad (\beta_{\min} < \beta < \beta_{\max})$$

- $\beta_{\rm min}$ is irrelevant with current radio data (< 100 days)
- Direct constraints from radio data:
  - Temporal index ~ +0.78 → $k = 4.5$
  - Spectral index ~ -0.61 → $p = 2.2$
- Canonical microphysical parameters $\epsilon_e = 0.1$, $\epsilon_B = 0.003$-0.1
- Parameter space to search: $(n, E_0, \beta_{\rm max})$

Fittings to radio & X-ray data



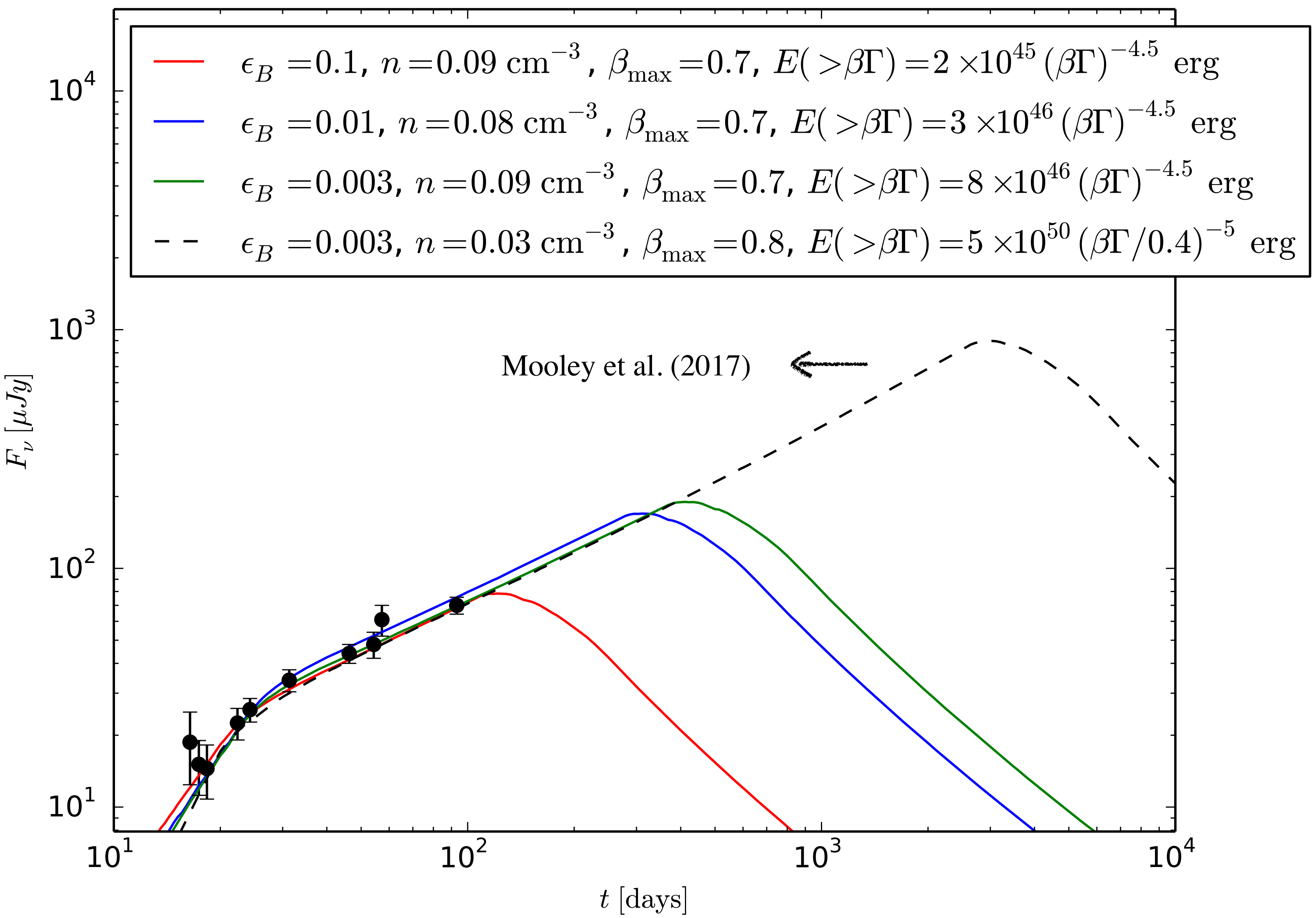
3 GHz radio light curve



0.3-8 keV X-ray light curve

$n \sim 0.1\ \mathrm{cm}^{-3}$; $\beta_{max} \sim 0.7$; ϵ_B is degenerate with E_0

Predictions for future radio light curve



Predictions for future 3 GHz radio light curves with reasonable range of ϵ_B, compared with Mooley et al. (2017)

- $\beta_{min}\Gamma_{min} = 0.3$ as suggested from kilonova observations/numerical simulations
- Compared with Mooley et al. (2017)
  - Lower injected energy ~ $10^{47\text{-}49}$ erg
  - Earlier peak time with lower peak flux

Summary

- Formalism of ejecta-ISM blast wave dynamics is made
- A different treatment for non-thermal electron spectrum is considered
- Preliminary fitting results to the radio data:
    - Circumburst density n ~ 0.1 cm^{-3}
    - Maximum ejecta velocity β_{max} ~ 0.7
    - Lower inject energy ~ 10^{47-49} erg compared with Mooley et al. (2017)
    - Earlier peak time & lower peak flux compared with Mooley et al. (2017)

Future work

- Compare fitted profile with high-res numerical simulations

- Determine low-velocity profile with numerical simulations to predict a precise radio light curve

- Energy injection from merger remnant (long-lived spinnin neutron star, black hole with remnant disk):

$$E_{\rm remnant}(t) + E(>\beta_{\rm inj}) = (\Gamma - 1)M(>\beta_{\rm inj})c^2 + (\Gamma^2 - 1)mc^2$$

- Reverse shock emission