Modelling GRB and kilonova ejecta afterglows

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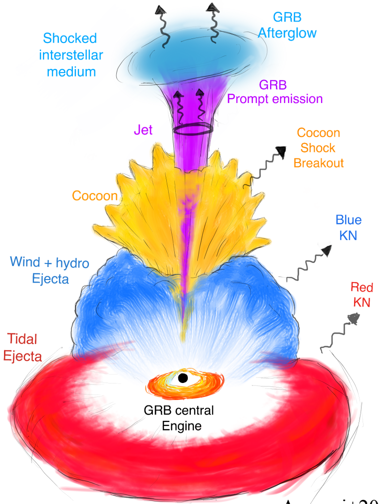
January 11, 2022

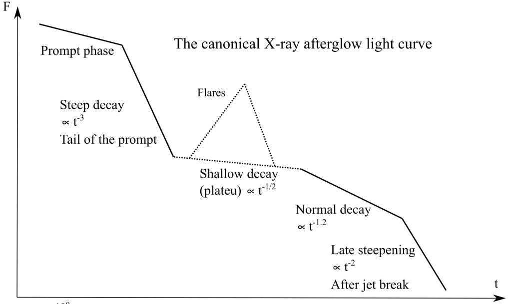
- One of the ways to understand the properties of matter at supernuclear densities is to study EM signatures of BNS, NSBH mergers and CCSNe.
- Non-thermal EM signatures: GRBs, kN afterglows, ...
- Origin: interaction between transrelativistic ejecta and ISM.
- Thus study of GRBs, kN probe the ejecta properties and by extension, the properties of the postmerger/post-SNe remnant.
- NR simulations + observations show



Ascenzi+20

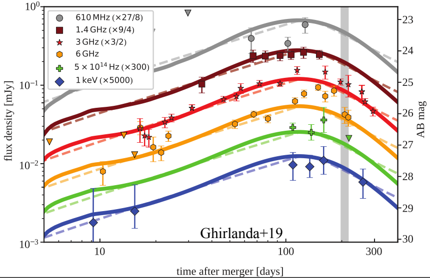
Main Features:

- Short & Long
- Three main stages: thermal/photosphere, prompt, **afterglow** (flares, shallow rise, rebrightening(*))
- Display plateus, flares, rebrightening(*)
- Afterglow: synchrotron emission from (and forward shock).



Key observables:

- $F_{\nu;p} \propto E_{\rm iso} n_{\rm ISM}^{(p+1)/4} \theta_{\rm obs}^{-2p} \varepsilon_e^{p-1} \varepsilon_B^{(p+1)/4} D_L \nu^{(1-p)/2}$
- $t_p \propto E_{\rm iso}^{1/3} n_{\rm ISM}^{-1/3} \theta_{\rm obs}^2$
- Jet composition (Baryonic vs Poyniting flux)
- Late-time engine activity

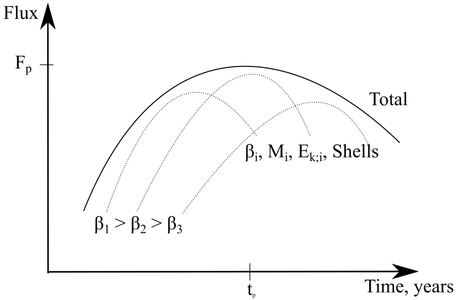


Main Features:

- Synchrotron emission from mildly relativistic ejecta (similar to GRB afterglow and SNe remnants)
- Expected in sGRBs but have not observed(*)
- Complex ejecta structure/geometry → non-trivial EM signature

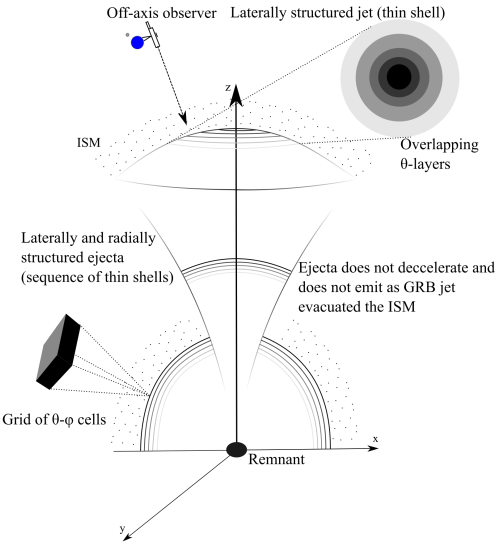
Key Observables:

- $F_{\nu,p} \propto E n^{(p+1)/4} \beta^{(5p-7)/2} \varepsilon_e^{p-1} \varepsilon_B^{(p+1)/4} D_L^{-2} \nu^{(-p-1)/2}$
- $t_p \propto E^{1/3} n^{-1/3} \beta^{-5/3}$
- Timescale of years.
- Trace the properties of the fastest ejecta



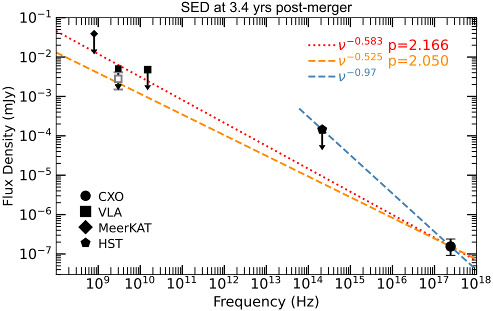
Goal: combine structured GRB and kilonova afterglows.
Key features:

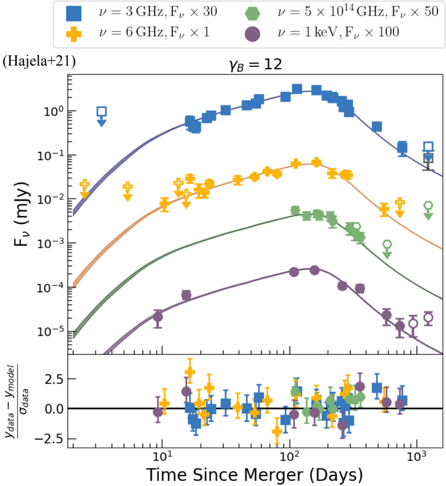
- lateral structure & lateral spreading of GRB ejecta
- lateral & velocity structure of kilonova ejecta
- GRB jet evacuates ISM in front of ejecta
- thermal electrons contribute to synchrotron emission from kilonova ejecta



GRB170817 from [Hajela et al 2021]:

- Statistical fit indicates *harder radio-to-X-ray spectrum* (lower p)
- Radio obs. $\rightarrow$ optically thin spectrum
- Lower $p = 2$ *is expected* in non-relativistic shocks (but with lower ε_e as well)





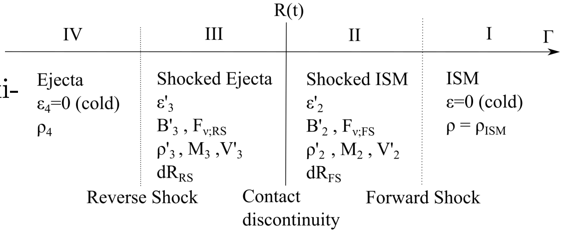
Blast wave dynamics under "thin-shell" approximation.

- jet/ejection duration is short (ejecta thickness is small)
- $E_{\mathrm{kin}} \gg e_{\mathrm{th}}, P$
- 4 region system

$$E = \Gamma M_0 c^2 + T^{00} V, \;\; T^{00} = (\epsilon' + P')\Gamma - P'$$

$$P' = (4/3)(\Gamma^2 - 1)\rho c^2, \;\; \rho' = 4\Gamma\rho, \;\; \epsilon' = 4\Gamma\rho c^2$$

After dt, blast-wave sweeps up dm from ISM, and energy conservation gives $d\Gamma$. Separate inclusion of $d\theta/dt$.



Shock downstream:

- fluid compression;
- magnetic field amplification (ε_B)
- first order Fermi acceleration (ε_e)

Fokker-Plank type equation:

$$\frac{\partial N(\gamma,t')}{\partial t'} = -\frac{\partial}{\partial\gamma}\left[\left(\dot{\gamma}_{\rm syn}+\dot{\gamma}_{\rm adi}N(\gamma,t')\right)\right]+Q(\gamma,t')$$

$$\dot{\gamma}_{\rm syn} = -\frac{4}{3}\frac{\sigma_T c}{m_e c^2}\gamma^2, \quad \dot{\gamma}_{\rm adi} = -\frac{\gamma\beta_e^2}{3}\frac{d\ln V'}{dt'},$$

$$Q(\gamma,t) = \begin{cases} Q_0(\gamma_m,t)\left(\frac{\gamma}{\gamma_m}\right)^{-p} & \gamma\in(\gamma_m,\gamma_M), \\ 0 & \text{elswhere.} \end{cases}$$

Is $Q_0 = f(B)$ – YES!
Steady state solution $\partial/\partial t' = 0$ and $\dot{\gamma}_{\rm adi} = 0$. Cooling $\gamma_c = 6\pi m_e c/(\sigma_T B^2 t)$.
Electron cooling modifies distribution

Electrons $\gamma > \gamma_c$ occupy $(\gamma/\gamma_c)^{-1} \ll 1$ fractional depth. Effective line-of-sight electron distribution

$$\left\langle\frac{\partial N}{\partial\gamma}\right\rangle \propto \frac{\partial N}{\partial\gamma}\min\left(1,\frac{\gamma_c}{\gamma}\right)$$

$$\left\langle\frac{\partial N}{\partial\gamma}\right\rangle_{\rm fc} \propto \begin{cases}\gamma^{-p} & \gamma_m<\gamma<\gamma_c; \\ \gamma^{-p-1} & \gamma>\gamma_c\end{cases}$$

$$\left\langle\frac{\partial N}{\partial\gamma}\right\rangle_{\rm sc} \propto \begin{cases}\gamma^{2} & \gamma_c<\gamma<\gamma_m; \\ \gamma^{-p-1} & \gamma>\gamma_m\end{cases}$$

Afterglow spectrum is defined by γ_m and γ_c

$$\boldsymbol{\eta}(\boldsymbol{\beta},\theta)d\omega = \frac{e^2\omega^2}{2\pi c}\left[\sum_{m=1}^{\infty}\left(\frac{\cos\theta-\beta_{||}}{\sin\theta}\right)^2 J_m^2(x) + \beta_\perp^2 J_m'^2(x)\right]\delta(y)d\omega$$

where $x=(\omega/\omega_0)\beta_\perp\sin\theta$ $y=m\omega_0-\omega(1-\beta_{||}\cos\theta)$, $\delta(y)$ is the delta function $J_m(x)$ is the Bessel function, $\beta_{||}=\beta\cos\theta_p$, $\beta_\perp=\beta\sin\theta_p$, with $\theta_p=\angle(\boldsymbol{\beta},\boldsymbol{B})$.

- Cyclotron, $m\beta \ll 1$: Expand $J(x)$ to lowest x, for successive harminics.
- Synchrotron $\gamma_e \gg 1$: $J(x)$ approximated by modified Bessel function

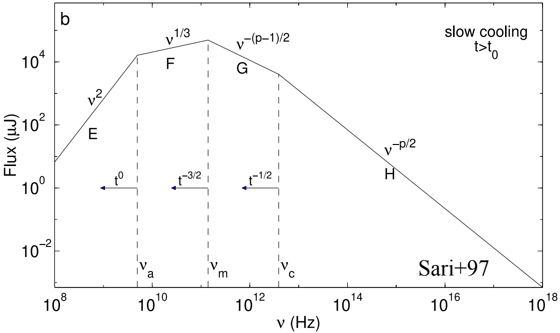
$$\frac{dE}{d\omega} = \frac{\sqrt{3}e^3 B\sin\theta_p}{2\pi m_e c^2}\frac{\omega}{\omega_c}\int_{\omega/\omega_c}^{\infty} F_{5/3}(\xi)d\xi,$$

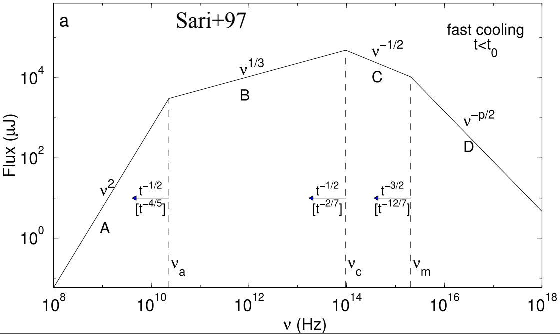
where $\omega_c=(3/2)\gamma^2\omega_b\sin\theta_p$

$$L_\omega = 2\pi\int_0^1 \frac{\partial N}{\partial\gamma_e}d\gamma_e\int_0^1 d(\cos\theta_p)\int_{-1}^1 d(\cos\theta)\boldsymbol{\eta}_{\boldsymbol{\beta},\theta}.$$

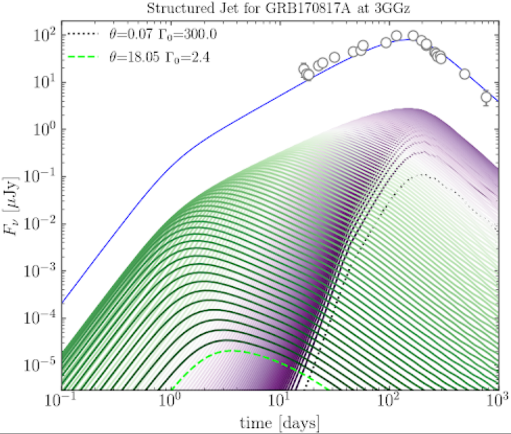
Consider $dN/d\gamma_e \propto \gamma^{-p}$, with min. γ_m and cool. γ_c.
Spectrum is determined by the location of $\nu_c = \gamma_c^2 \nu_g$, $\nu_g = q_e B/(2\pi m_e c)$ is a gyrofrequency. $F_\nu = N_e P_{\nu;\max}/4\pi D^2$ where $P_\nu \approx \Gamma B m_e c^2 \sigma_T / 3 q_e$

- (i) low-energy tail $\nu < \min(\nu_m, \nu_c)$,
- (ii) power-law segment $\nu \in (\nu_m, \nu_c)$
- (iii) exponential cut-off

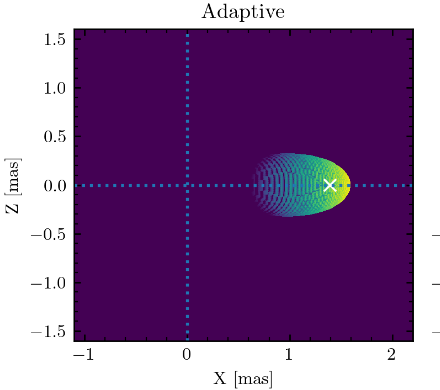




- Gaussian jet $E(\theta) \propto e^{(\theta/\theta_c)^2}$
- Off-axis $\theta_{\rm obs} > \theta_c$
- Relativistic core, $\Gamma_c \sim 10^2$; low ISM density.



Flux centroid motion, 4.5 GGz; Color is $I/I_{\rm max}$

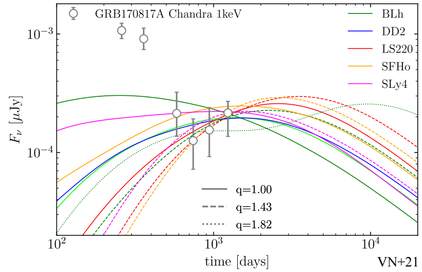


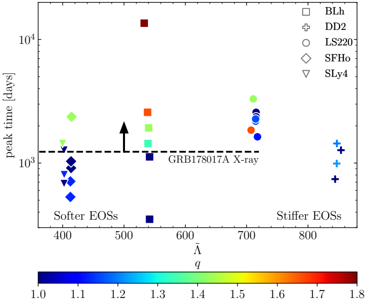
Kilonova afterglow for NR ejecta profiles

- Set of NS BNS simulations targeted to GW170817.
- BNS model $(q, \tilde{\Lambda})$ $q = M_A/M_B$ is the mass ratio, $\tilde{\Lambda}$ tidal deformability parameter (Depends in EOS of NS)
- Ejecta $M, \beta, E_k = f(q, \tilde{\Lambda})$

Assuming that GRB170817A change in afterglow is due to the emergence of a new component:

- New way to constrain binary parameters, EOS
- Additional information on ISM
- Information on shock physics

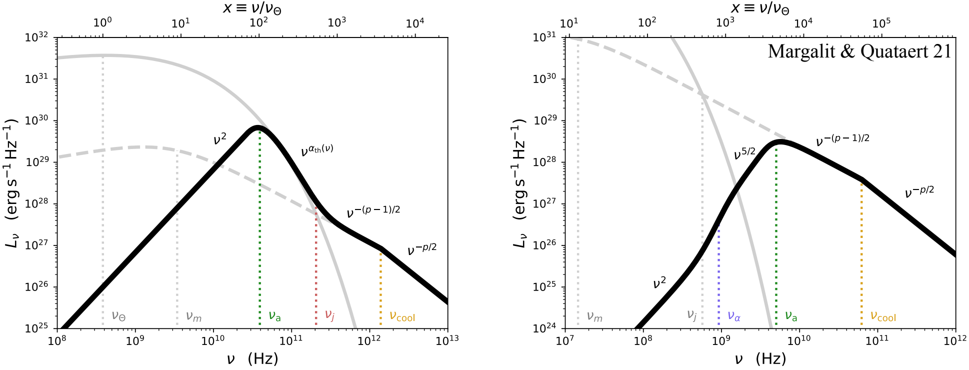




- "Thermal spectrum" (left)
- "Non-thermal spectrum" (right)

$\beta_{\rm sh} = 0.1,\ n_{\rm ISM} = 10^4\ {\rm cm}^{-3},\ t = 200\,{\rm d},$
$\delta = 0.1,\ p = 3,\ B = 0.1\,{\rm G},\ \varepsilon_T = 0.1$

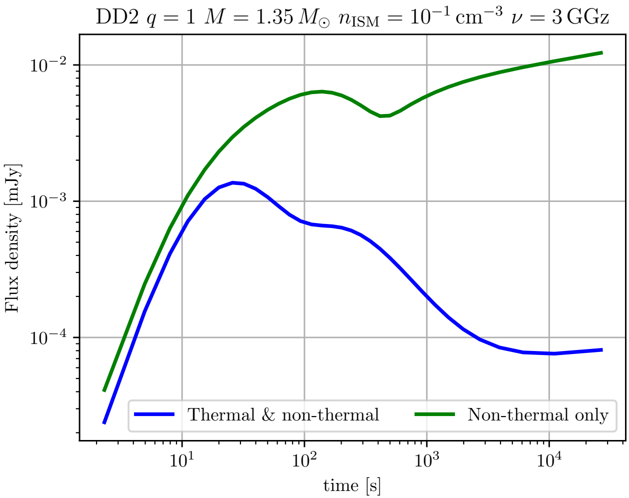
$$\left.\frac{\partial N}{\partial \gamma}\right|_{\rm th} = n_e \frac{\gamma^2\sqrt{1-\gamma^{-2}}}{K_2(1/\Theta)\Theta} e^{-\gamma/\Theta},$$
$$\left.\frac{\partial N}{\partial \gamma}\right|_{\rm pl} = n_e g(\Theta)\delta \frac{p-2}{3\Theta}\left(\frac{\gamma}{3\Theta}\right)^{-p}$$



Comparison between two optically thin ight cruves:

- "Thermal" (blue)
- "Non-thermal" (green)

Further investigations required!



Extracting kilonova ejecta profile

- $E_{\rm k} = f(\theta, \beta)$
- $E_{\rm k;max}$ at $\theta \to 0$ and $\beta \to 0.2$.
- $\log_{10}(E_k) = b_0 + (b_1\theta) + (b_2\beta) + (b_3\theta^2) + (b_4\theta\beta) + (b_5\beta^{1/4})$