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Synchrotron and synchrotron-self-Compton mechanisms for VHE emission from GRBs

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GRB Afterglow

Blandford & McKee 1976

Gamma-ray burst - Emission from the jet → Free-coasting phase of the blastwave → Slowing down /deceleration of the blastwave → Self-similar evolution of the blastwave

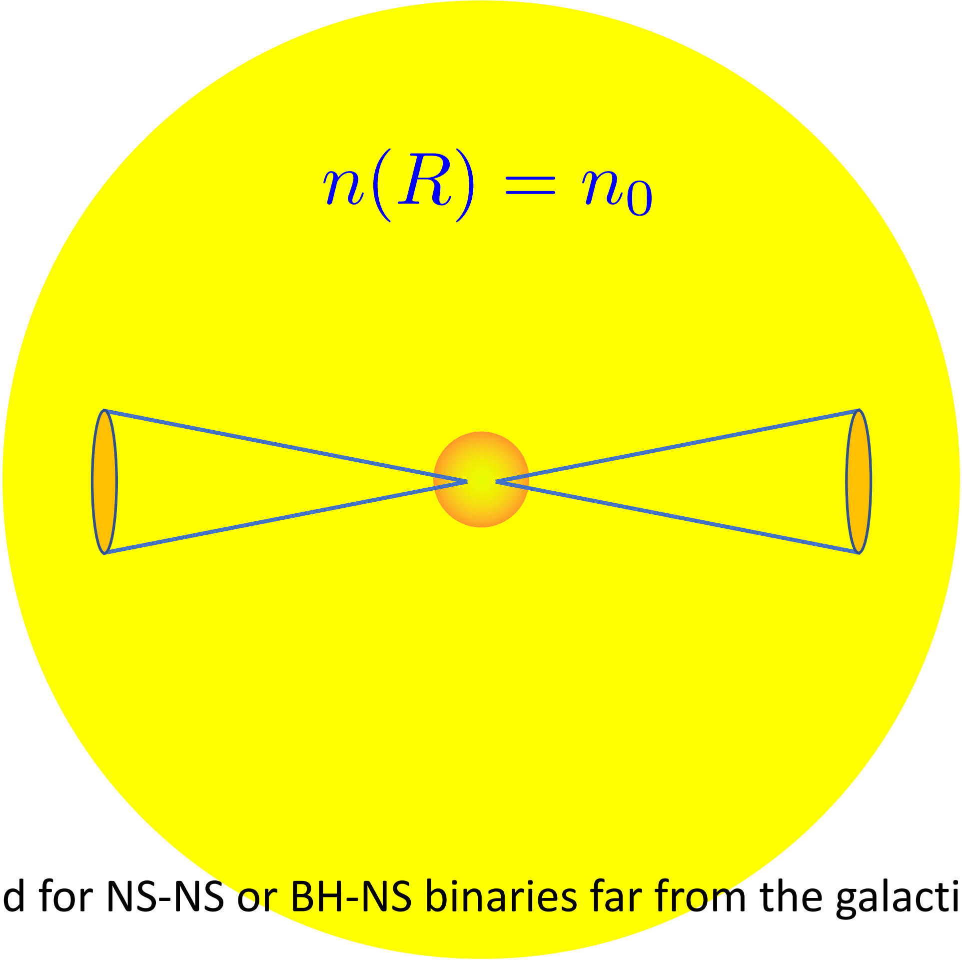
Physical quantities depends on the injected energy and environment

Classical afterglow from the forward shock
Emission process: Synchrotron radiation

Meszaros & Rees 1997; Sari, Piran & Narayan 1998

Chevalier & Li 2000; Granot & Sari 2002

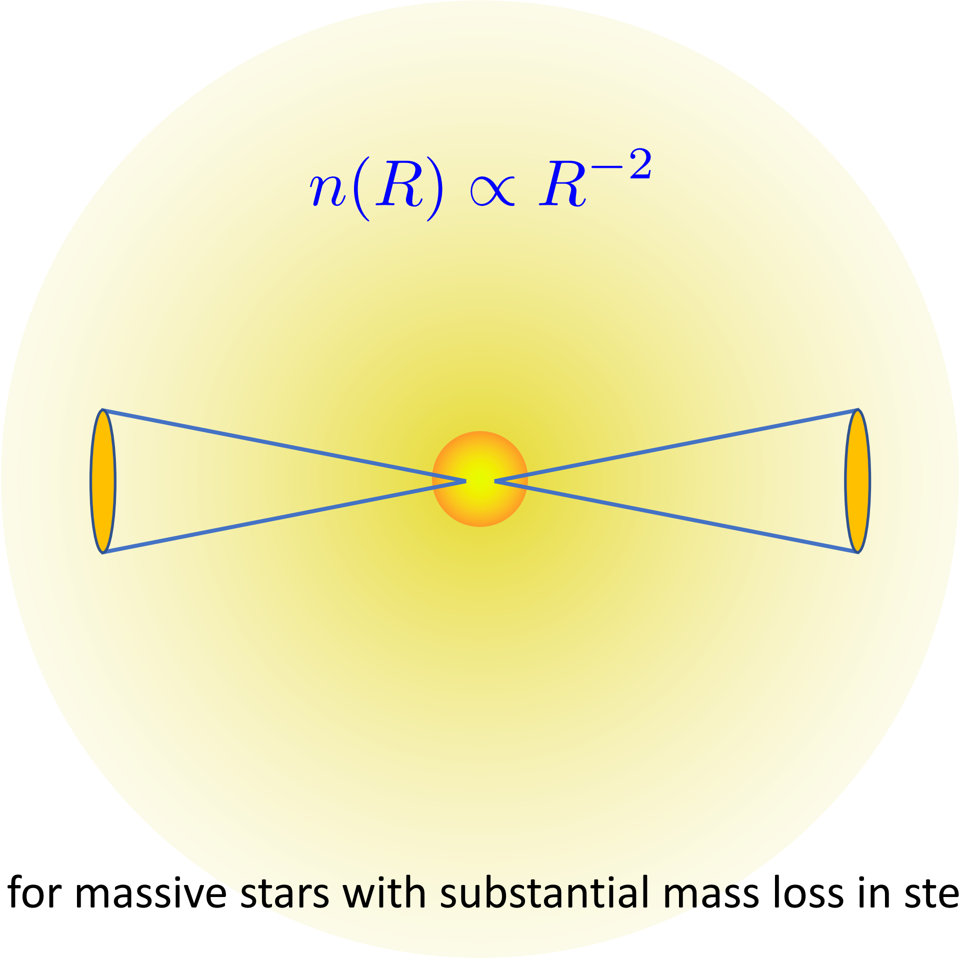
ISM Environment



$$n(R) = n_0$$

Expected for NS-NS or BH-NS binaries far from the galactic plane

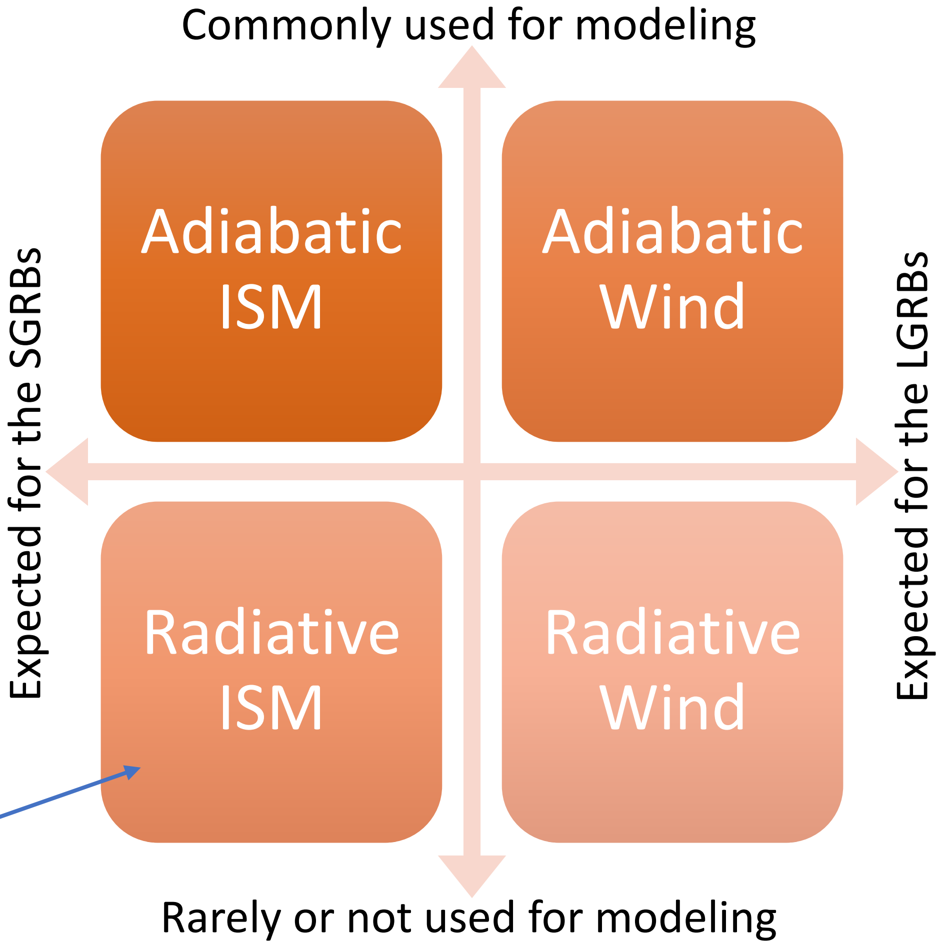
Wind Environment



$$n(R) \propto R^{-2}$$

Expected for massive stars with substantial mass loss in stellar wind

Blastwave Evolution Scenarios



Commonly used for modeling

Expected for the SGRBs

Expected for the LGRBs

Adiabatic ISM

Adiabatic Wind

Radiative ISM

Radiative Wind

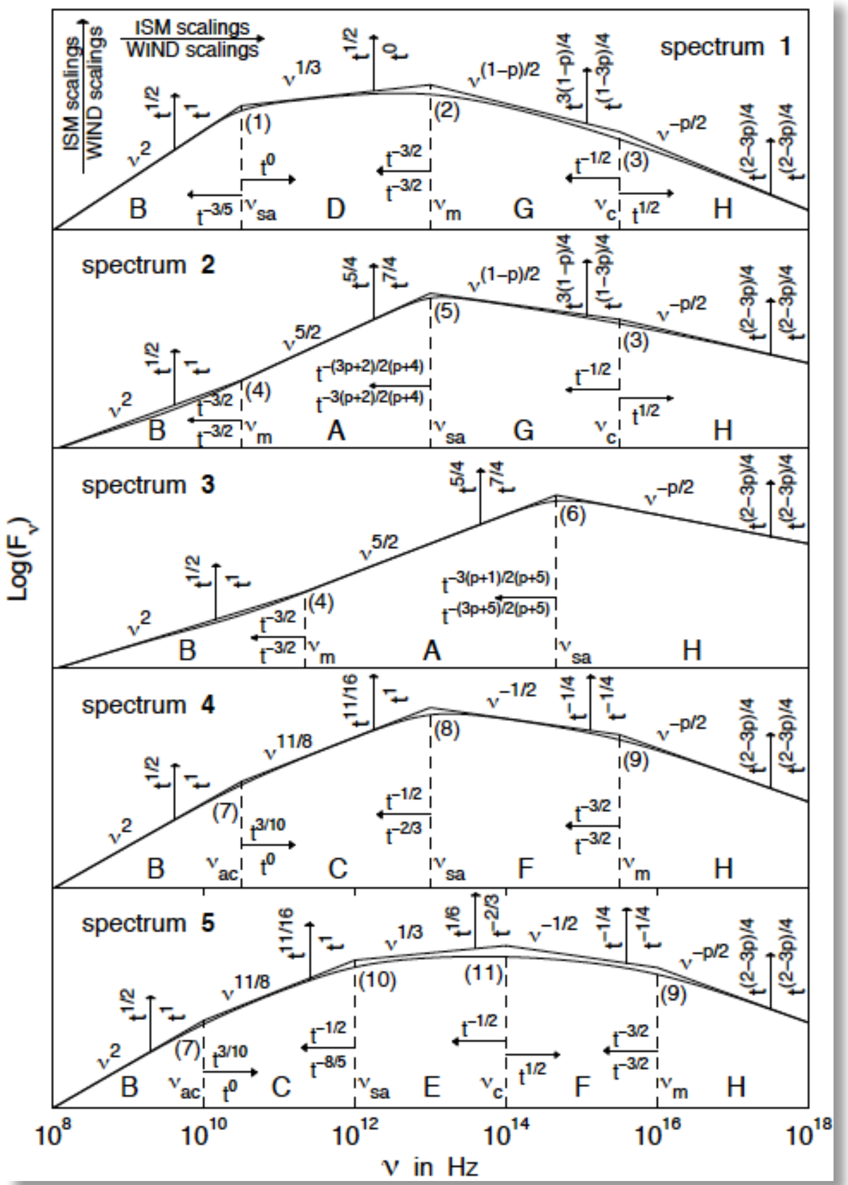
Rarely or not used for modeling

Ghisellini+2010

Afterglow Synchrotron Spectra

- Single power-law electron injection spectrum
- Cooling in the forward-shock magnetic field
- Cooling break in the electron spectrum
- Fast- and slow-cooling synchroton spectra
- Synchrotron self-absorption
- Time evolution of the break frequencies and flux normalization

Reasonably successful in modeling late-time afterglow



Granot & Sari 2002

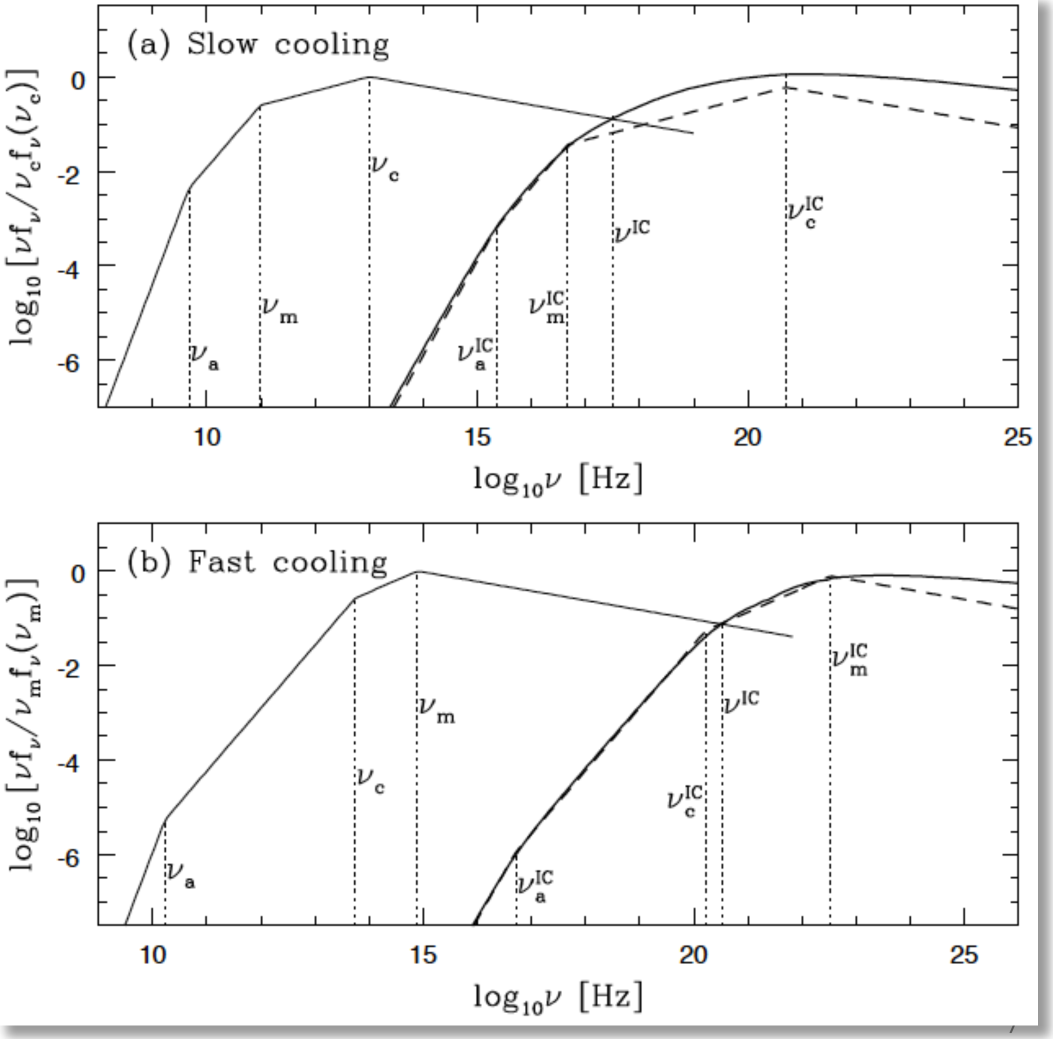
Afterglow inverse-Compton Spectra

- Synchrotron-self-Compton emission from the same electrons
- Simple scaling in the Thomson regime

$$\nu^{\mathrm{IC}} = 2\gamma^2\nu$$

Chiang & Dermer 1999
Sari & Esin 2001
Zhang & Meszaros 2001

We are likely observing now in the VHE regime



Sari & Esin 2001

What is new in this work?

- Four different blastwave evolution scenarios
    - Blastwave evolution parameters
    - Synchrotron break frequencies
    - Inverse-Compton break frequencies
- Detailed calculation of the Compton Y-parameter in the slow-cooling spectra
    - Smooth transition from the fast- to slow-cooling spectra in all scenarios
- Detailed calculation of the synchrotron-self-absorption frequency in all blastwave evolution scenarios and for the fast- and slow-cooling spectra
- Flux closure relations for the synchrotron and inverse-Compton spectra
- Application to two bright GRBs

GRB Afterglow Closure Relations for Synchrotron and inverse-Compton fluxes

$$F_\nu \propto t^\alpha \nu^\beta$$

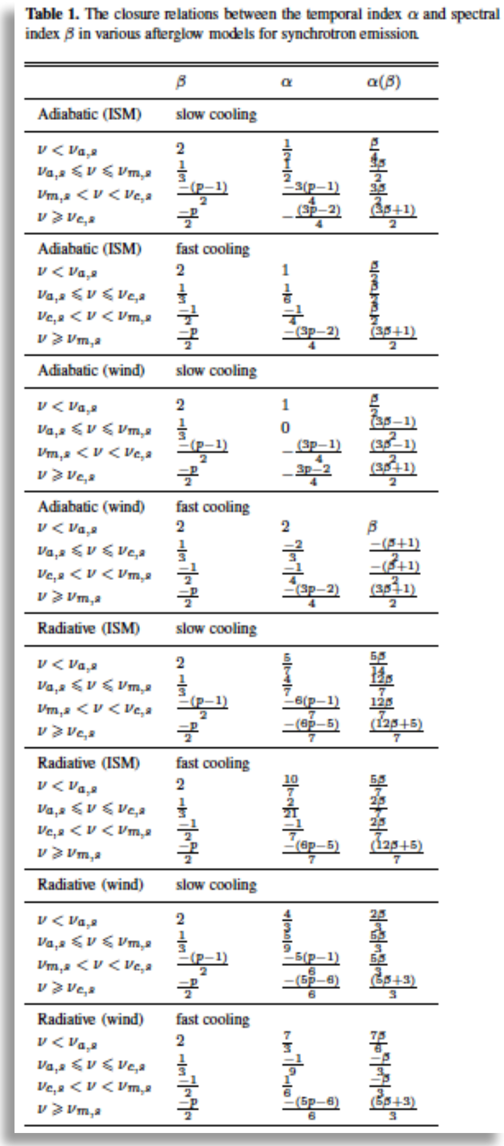


Table 1. The closure relations between the temporal index α and spectral index β in various afterglow models for synchrotron emission.

	β	α	$\alpha(\beta)$
Adiabatic (ISM)	slow cooling		
$\nu < \nu_{a,s}$	2	$\frac{1}{2}$	$\frac{\beta}{4}$
$\nu_{a,s} \leqslant \nu \leqslant \nu_{m,s}$	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{3\beta}{2}$
$\nu_{m,s} < \nu < \nu_{c,s}$	$\frac{-(p-1)}{2}$	$\frac{-3(p-1)}{4}$	$\frac{3\beta}{2}$
$\nu \geqslant \nu_{c,s}$	$\frac{-p}{2}$	$-\frac{(3p-2)}{4}$	$\frac{(3\beta+1)}{2}$
Adiabatic (ISM)	fast cooling		
$\nu < \nu_{a,s}$	2	1	$\frac{\beta}{2}$
$\nu_{a,s} \leqslant \nu \leqslant \nu_{c,s}$	$\frac{1}{3}$	$\frac{1}{6}$	$\frac{\beta}{2}$
$\nu_{c,s} < \nu < \nu_{m,s}$	$\frac{-1}{2}$	$\frac{-1}{4}$	$\frac{\beta}{2}$
$\nu \geqslant \nu_{m,s}$	$\frac{-p}{2}$	$\frac{-(3p-2)}{4}$	$\frac{(3\beta+1)}{2}$
Adiabatic (wind)	slow cooling		
$\nu < \nu_{a,s}$	2	1	$\frac{\beta}{2}$
$\nu_{a,s} \leqslant \nu \leqslant \nu_{m,s}$	$\frac{1}{3}$	0	$\frac{(3\beta-1)}{2}$
$\nu_{m,s} < \nu < \nu_{c,s}$	$\frac{-(p-1)}{2}$	$-\frac{(3p-1)}{4}$	$\frac{(3\beta-1)}{2}$
$\nu \geqslant \nu_{c,s}$	$\frac{-p}{2}$	$-\frac{3p-2}{4}$	$\frac{(3\beta+1)}{2}$
Adiabatic (wind)	fast cooling		
$\nu < \nu_{a,s}$	2	2	β
$\nu_{a,s} \leqslant \nu \leqslant \nu_{c,s}$	$\frac{1}{3}$	$\frac{-2}{3}$	$\frac{-(\beta+1)}{2}$
$\nu_{c,s} < \nu < \nu_{m,s}$	$\frac{-1}{2}$	$\frac{-1}{4}$	$\frac{-(\beta+1)}{2}$
$\nu \geqslant \nu_{m,s}$	$\frac{-p}{2}$	$\frac{-(3p-2)}{4}$	$\frac{(3\beta+1)}{2}$
Radiative (ISM)	slow cooling		
$\nu < \nu_{a,s}$	2	$\frac{5}{7}$	$\frac{5\beta}{14}$
$\nu_{a,s} \leqslant \nu \leqslant \nu_{m,s}$	$\frac{1}{3}$	$\frac{4}{7}$	$\frac{12\beta}{7}$
$\nu_{m,s} < \nu < \nu_{c,s}$	$\frac{-(p-1)}{2}$	$\frac{-6(p-1)}{7}$	$\frac{12\beta}{7}$
$\nu \geqslant \nu_{c,s}$	$\frac{-p}{2}$	$\frac{-(6p-5)}{7}$	$\frac{(12\beta+5)}{7}$
Radiative (ISM)	fast cooling		
$\nu < \nu_{a,s}$	2	$\frac{10}{7}$	$\frac{5\beta}{7}$
$\nu_{a,s} \leqslant \nu \leqslant \nu_{c,s}$	$\frac{1}{3}$	$\frac{2}{21}$	$\frac{2\beta}{7}$
$\nu_{c,s} < \nu < \nu_{m,s}$	$\frac{-1}{2}$	$\frac{-1}{7}$	$\frac{2\beta}{7}$
$\nu \geqslant \nu_{m,s}$	$\frac{-p}{2}$	$\frac{-(6p-5)}{7}$	$\frac{(12\beta+5)}{7}$
Radiative (wind)	slow cooling		
$\nu < \nu_{a,s}$	2	$\frac{4}{3}$	$\frac{2\beta}{3}$
$\nu_{a,s} \leqslant \nu \leqslant \nu_{m,s}$	$\frac{1}{3}$	$\frac{5}{9}$	$\frac{5\beta}{3}$
$\nu_{m,s} < \nu < \nu_{c,s}$	$\frac{-(p-1)}{2}$	$\frac{-5(p-1)}{6}$	$\frac{5\beta}{3}$
$\nu \geqslant \nu_{c,s}$	$\frac{-p}{2}$	$\frac{-(5p-6)}{6}$	$\frac{(5\beta+3)}{3}$
Radiative (wind)	fast cooling		
$\nu < \nu_{a,s}$	2	$\frac{7}{3}$	$\frac{7\beta}{6}$
$\nu_{a,s} \leqslant \nu \leqslant \nu_{c,s}$	$\frac{1}{3}$	$\frac{-1}{9}$	$\frac{-\beta}{3}$
$\nu_{c,s} < \nu < \nu_{m,s}$	$\frac{-1}{2}$	$\frac{1}{6}$	$\frac{-\beta}{3}$
$\nu \geqslant \nu_{m,s}$	$\frac{-p}{2}$	$\frac{-(5p-6)}{6}$	$\frac{(5\beta+3)}{3}$

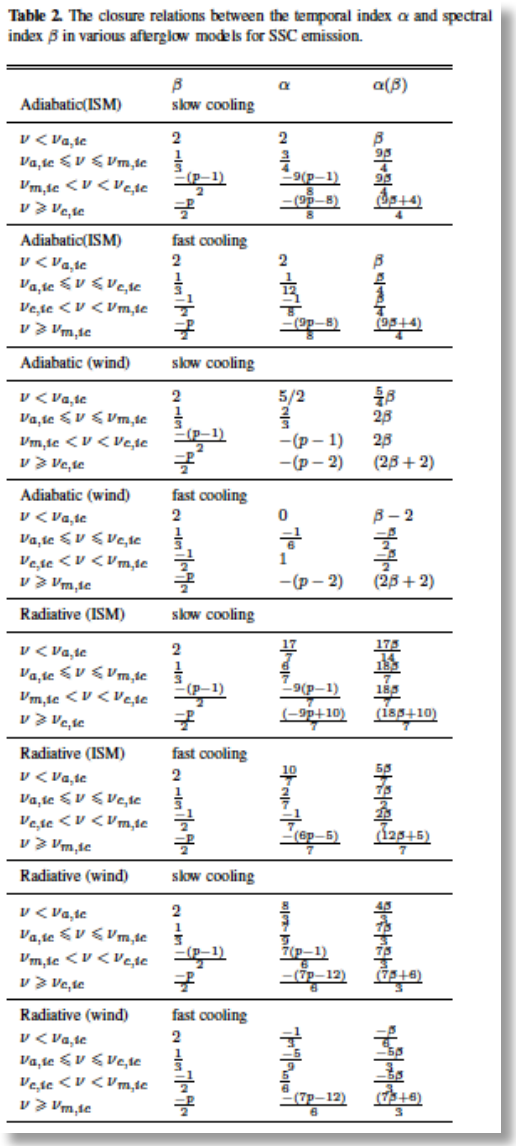
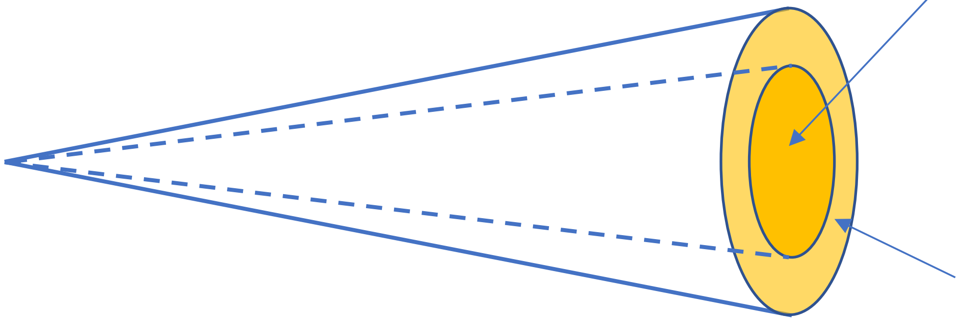


Table 2. The closure relations between the temporal index α and spectral index β in various afterglow models for SSC emission.

	β	α	$\alpha(\beta)$
Adiabatic(ISM)	slow cooling		
$\nu < \nu_{a,ic}$	2	2	β
$\nu_{a,ic} \leqslant \nu \leqslant \nu_{m,ic}$	$\frac{1}{3}$	$\frac{3}{4}$	$\frac{9\beta}{4}$
$\nu_{m,ic} < \nu < \nu_{c,ic}$	$\frac{-(p-1)}{2}$	$\frac{-9(p-1)}{8}$	$\frac{9\beta}{4}$
$\nu \geqslant \nu_{c,ic}$	$\frac{-p}{2}$	$\frac{-(9p-8)}{8}$	$\frac{(9\beta+4)}{4}$
Adiabatic(ISM)	fast cooling		
$\nu < \nu_{a,ic}$	2	2	β
$\nu_{a,ic} \leqslant \nu \leqslant \nu_{c,ic}$	$\frac{1}{3}$	$\frac{1}{12}$	$\frac{\beta}{4}$
$\nu_{c,ic} < \nu < \nu_{m,ic}$	$\frac{-1}{2}$	$\frac{-1}{8}$	$\frac{\beta}{4}$
$\nu \geqslant \nu_{m,ic}$	$\frac{-p}{2}$	$\frac{-(9p-8)}{8}$	$\frac{(9\beta+4)}{4}$
Adiabatic (wind)	slow cooling		
$\nu < \nu_{a,ic}$	2	$5/2$	$\frac{5}{4}\beta$
$\nu_{a,ic} \leqslant \nu \leqslant \nu_{m,ic}$	$\frac{1}{3}$	$\frac{2}{3}$	2β
$\nu_{m,ic} < \nu < \nu_{c,ic}$	$\frac{-(p-1)}{2}$	$-(p-1)$	2β
$\nu \geqslant \nu_{c,ic}$	$\frac{-p}{2}$	$-(p-2)$	$(2\beta+2)$
Adiabatic (wind)	fast cooling		
$\nu < \nu_{a,ic}$	2	0	$\beta-2$
$\nu_{a,ic} \leqslant \nu \leqslant \nu_{c,ic}$	$\frac{1}{3}$	$\frac{-1}{6}$	$\frac{-\beta}{2}$
$\nu_{c,ic} < \nu < \nu_{m,ic}$	$\frac{-1}{2}$	1	$\frac{-\beta}{2}$
$\nu \geqslant \nu_{m,ic}$	$\frac{-p}{2}$	$-(p-2)$	$(2\beta+2)$
Radiative (ISM)	slow cooling		
$\nu < \nu_{a,ic}$	2	$\frac{17}{7}$	$\frac{17\beta}{14}$
$\nu_{a,ic} \leqslant \nu \leqslant \nu_{m,ic}$	$\frac{1}{3}$	$\frac{6}{7}$	$\frac{18\beta}{7}$
$\nu_{m,ic} < \nu < \nu_{c,ic}$	$\frac{-(p-1)}{2}$	$\frac{-9(p-1)}{7}$	$\frac{18\beta}{7}$
$\nu \geqslant \nu_{c,ic}$	$\frac{-p}{2}$	$\frac{(-9p+10)}{7}$	$\frac{(18\beta+10)}{7}$
Radiative (ISM)	fast cooling		
$\nu < \nu_{a,ic}$	2	$\frac{10}{7}$	$\frac{5\beta}{7}$
$\nu_{a,ic} \leqslant \nu \leqslant \nu_{c,ic}$	$\frac{1}{3}$	$\frac{2}{7}$	$\frac{7\beta}{2}$
$\nu_{c,ic} < \nu < \nu_{m,ic}$	$\frac{-1}{2}$	$\frac{-1}{7}$	$\frac{2\beta}{7}$
$\nu \geqslant \nu_{m,ic}$	$\frac{-p}{2}$	$\frac{-(6p-5)}{7}$	$\frac{(12\beta+5)}{7}$
Radiative (wind)	slow cooling		
$\nu < \nu_{a,ic}$	2	$\frac{8}{3}$	$\frac{4\beta}{3}$
$\nu_{a,ic} \leqslant \nu \leqslant \nu_{m,ic}$	$\frac{1}{3}$	$\frac{7}{9}$	$\frac{7\beta}{3}$
$\nu_{m,ic} < \nu < \nu_{c,ic}$	$\frac{-(p-1)}{2}$	$\frac{7(p-1)}{6}$	$\frac{7\beta}{3}$
$\nu \geqslant \nu_{c,ic}$	$\frac{-p}{2}$	$\frac{-(7p-12)}{6}$	$\frac{(7\beta+6)}{3}$
Radiative (wind)	fast cooling		
$\nu < \nu_{a,ic}$	2	$\frac{-1}{3}$	$\frac{-\beta}{6}$
$\nu_{a,ic} \leqslant \nu \leqslant \nu_{c,ic}$	$\frac{1}{3}$	$\frac{-5}{9}$	$\frac{-5\beta}{3}$
$\nu_{c,ic} < \nu < \nu_{m,ic}$	$\frac{-1}{2}$	$\frac{5}{6}$	$\frac{-5\beta}{3}$
$\nu \geqslant \nu_{m,ic}$	$\frac{-p}{2}$	$\frac{-(7p-12)}{6}$	$\frac{(7\beta+6)}{3}$

Jet-inside-Jet / Two Blastwave Model



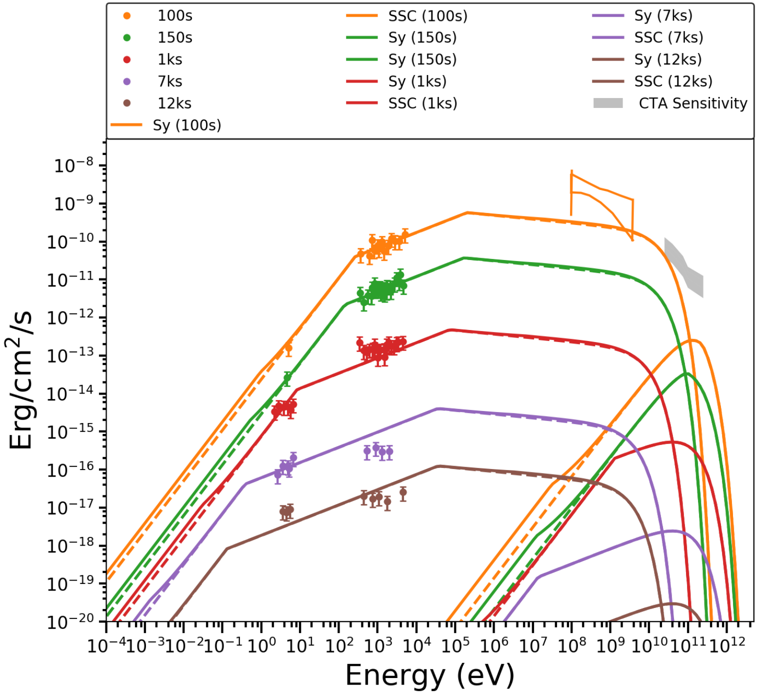
Higher Lorentz factor

Lower Lorentz factor

Zheng & Deng 2010; Corsi+2010; Filgas+2011; Holland+2012, etc.

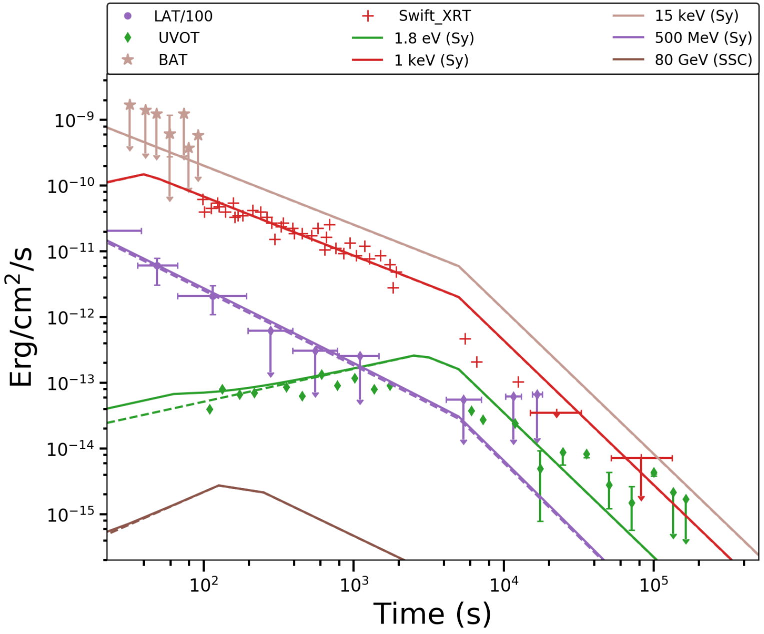
GRB 090510 – SED and Light Curves

Short GRB at z = 0.9, T90 = 0.3 s



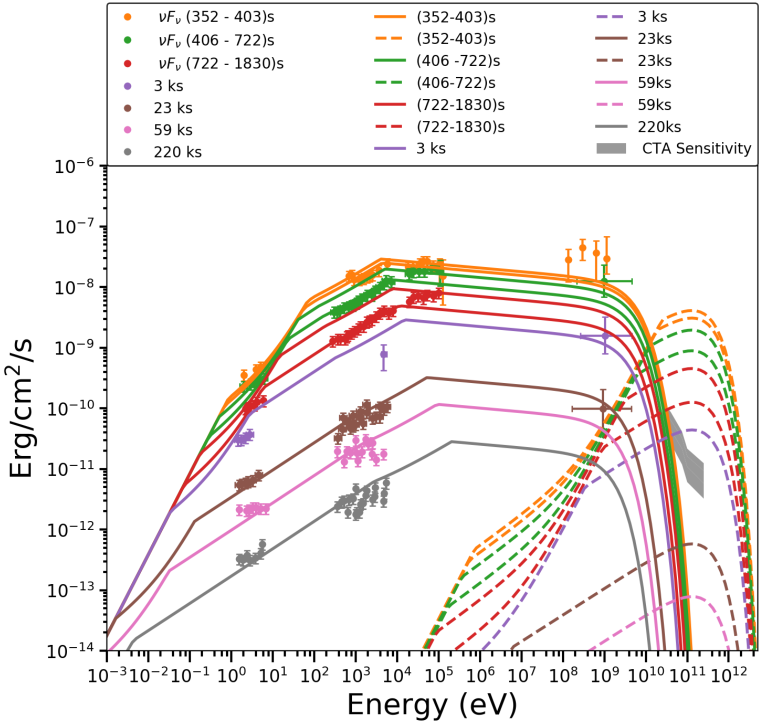
CTA sensitivity for 10s integration

https://www.cta-observatory.org/science/cta-performance



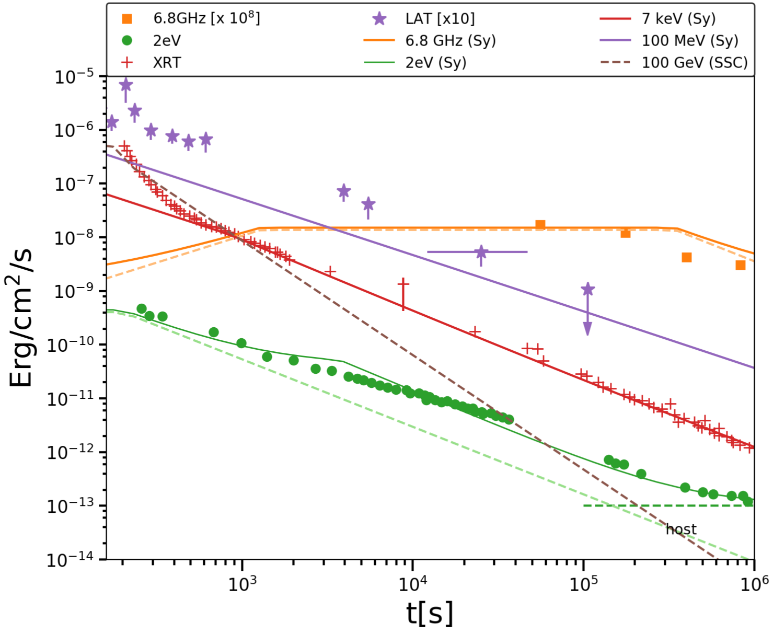
GRB 130427A – SED and Light Curves

Long GRB at z = 0.34, T90 = 276 s



CTA sensitivity for 10s integration

https://www.cta-observatory.org/science/cta-performance



Model Parameters from Afterglow Fits

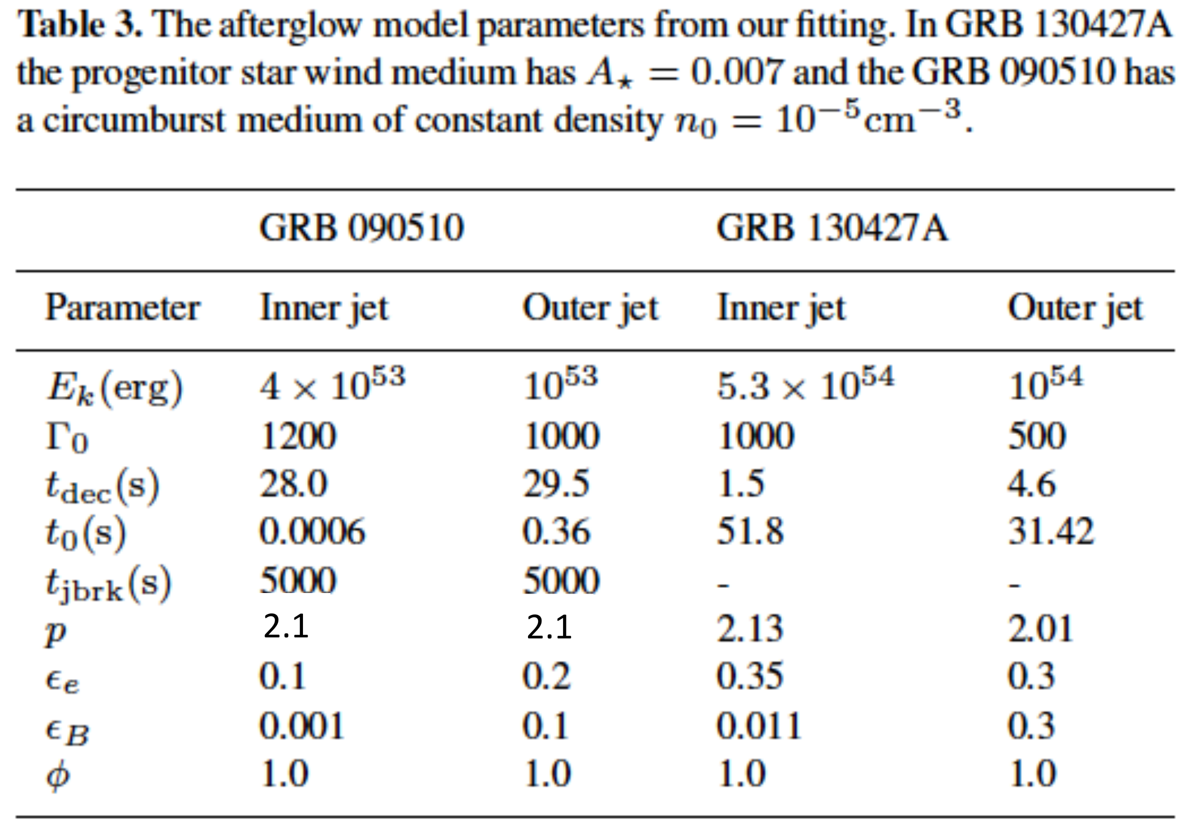


Table 3. The afterglow model parameters from our fitting. In GRB 130427A the progenitor star wind medium has $A_\star = 0.007$ and the GRB 090510 has a circumburst medium of constant density $n_0 = 10^{-5}\mathrm{cm}^{-3}$.

	GRB 090510		GRB 130427A	
Parameter	Inner jet	Outer jet	Inner jet	Outer jet
E_k(erg)	4×10^{53}	10^{53}	5.3×10^{54}	10^{54}
Γ_0	1200	1000	1000	500
t_{dec}(s)	28.0	29.5	1.5	4.6
t_0(s)	0.0006	0.36	51.8	31.42
t_{jbrk}(s)	5000	5000	-	-
p	2.1	2.1	2.13	2.01
ϵ_e	0.1	0.2	0.35	0.3
ϵ_B	0.001	0.1	0.011	0.3
ϕ	1.0	1.0	1.0	1.0

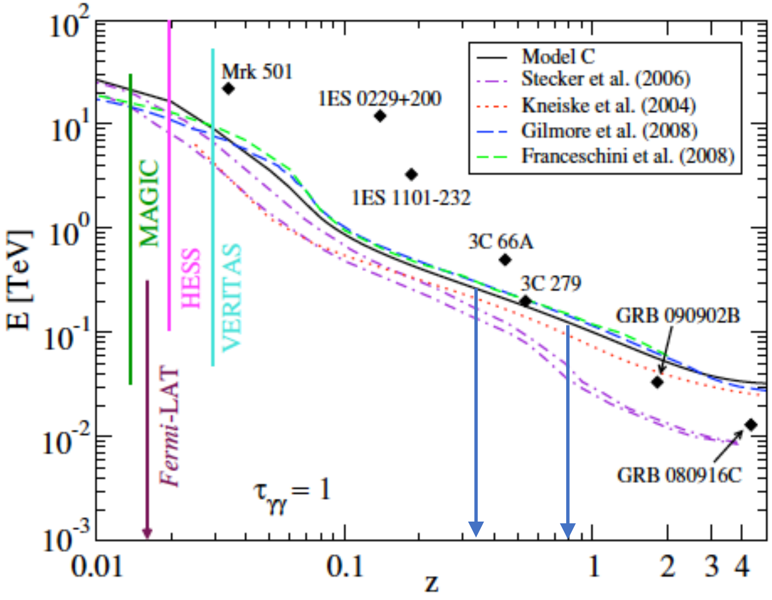
Klein-Nishina and Gamma-Gamma

KN Cutoff fruequency

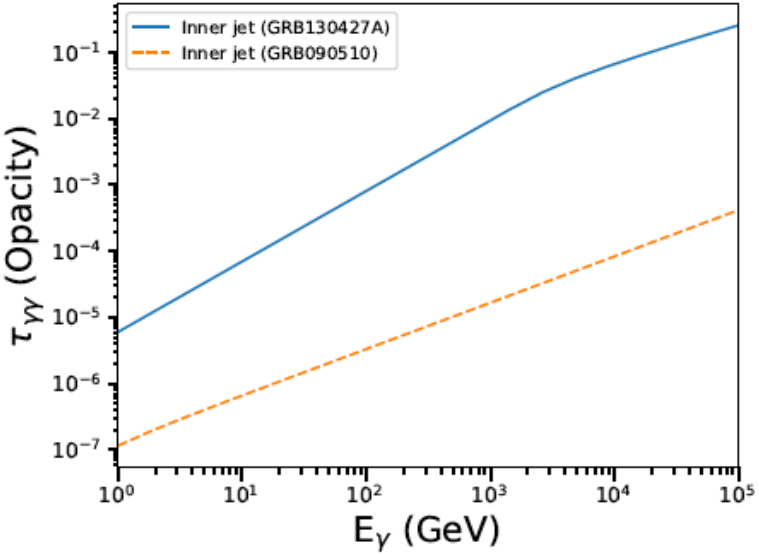
$$\nu^{\mathrm{IC}}_{m/c,\,\mathrm{KN}} = \frac{2m^2c^4}{h^2\nu_{m/c}}\frac{\Gamma^2}{(1+z)^2}$$

> 1 TeV

γγ pair production horizon of the universe



γγ pair production opacities in the blastwaves



EBL attenuation dominates

Conclusions

- A synchro-Compton model for GRB afterglow emission has been developed
  - Some limitations:
    - Klein-Nishina regime has not been included yet
    - Very simple evolution of the electron spectrum
    - No cascade from gamma-gamma pair production
- A numerical code has been developed to fit simultaneously the broadband SEDs and multiwavelength light curves
- Applications to two bright GRBs give reasonable fits and parameter values

GRB 190114C– SED and Light Curves

Long GRB at z = 0.42, T90 ~ 25 s

$E_k = 4 \times 10^{53}\ \mathrm{erg}, \Gamma_0 = 350, n_0 = 0.5\ \mathrm{cm}^{-3}$
$p = 2.5, \epsilon_e = 0.4, \epsilon_B = 0.01$