GRB afterglows with hard spectrum

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GRB afterglow evolution

Dynamics: $E, n \;\Rightarrow\; \Gamma(t), R(t)$

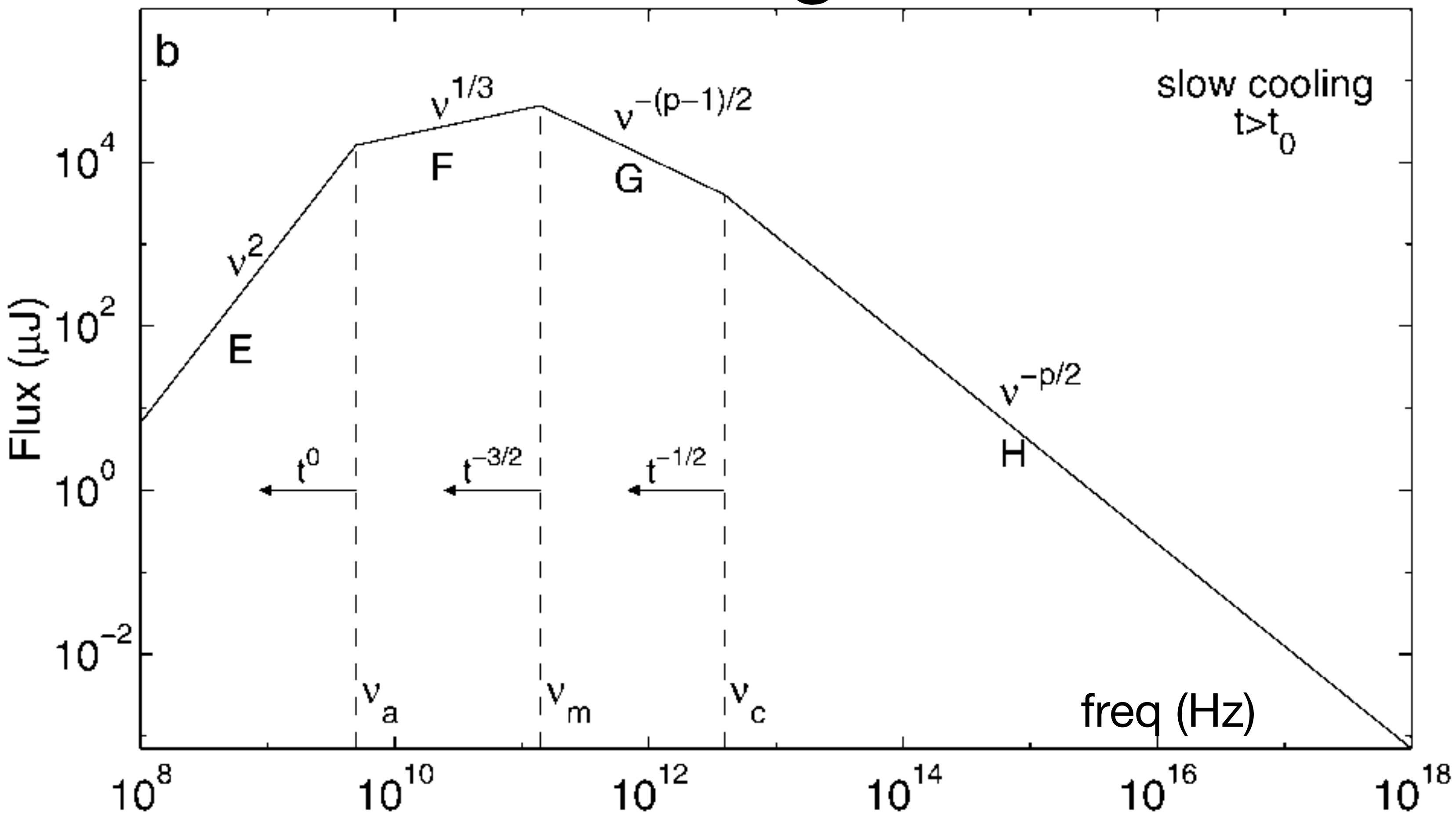
Magnetic field $B(t)$**: assume** $B^2/8\pi = \epsilon_B u_{\rm th} = \epsilon_B 4\Gamma^2 n m_p c^2$

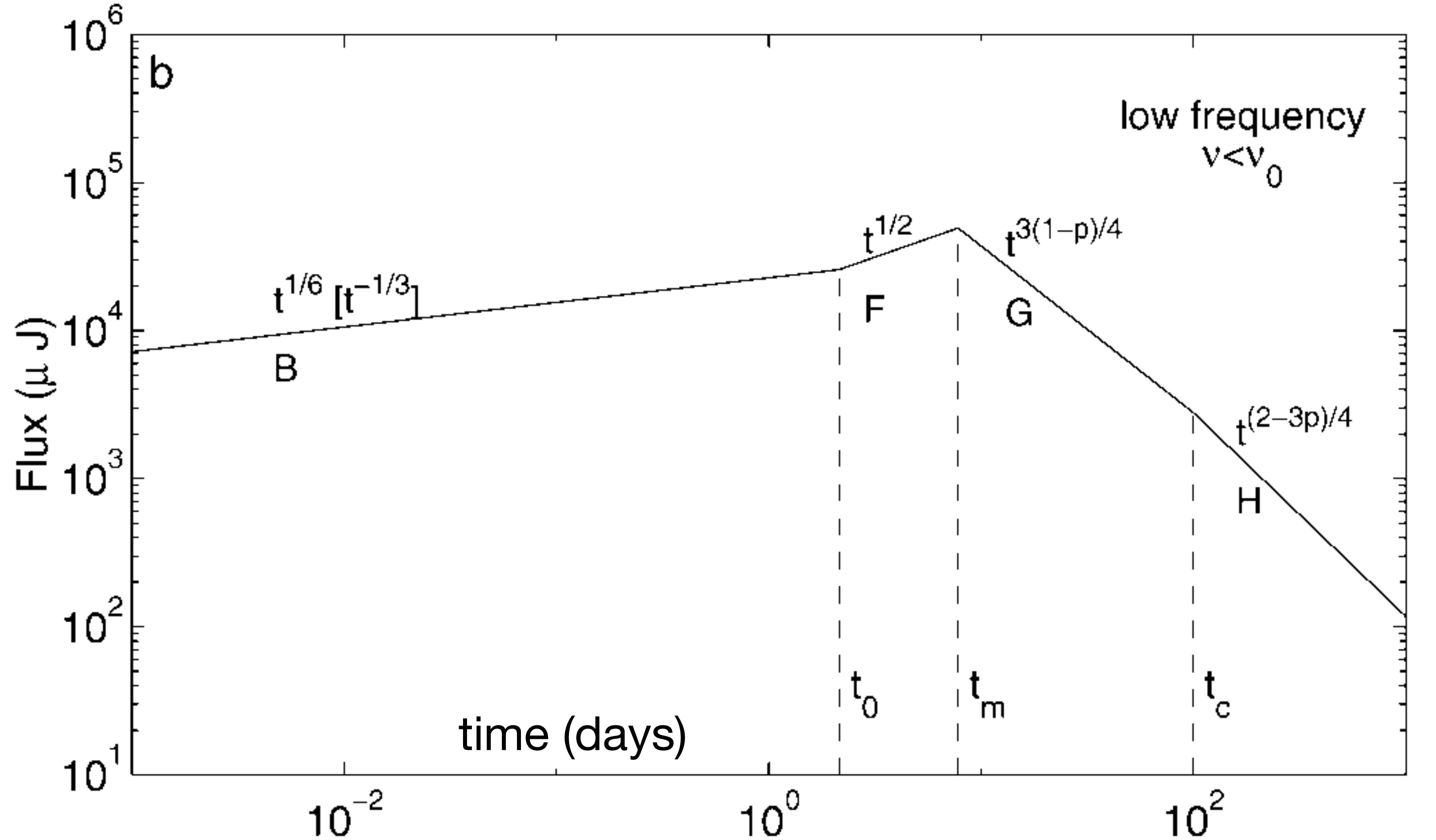
Electrons: $N_e(\gamma_e)d\gamma_e = K\gamma_e^{-p}d\gamma_e$

$$\int_{\gamma_m}^{\gamma_u} N_e(\gamma_e)d\gamma_e = 4\Gamma n$$

$$\int_{\gamma_m}^{\gamma_u} \gamma_e m_e c^2 N_e(\gamma_e)d\gamma_e = \epsilon_e 4\Gamma^2 n m_p c^2$$

Standard afterglow evolution





$p > 2$

$\gamma_u \to \infty$

Sari et al 1998

If $p < 2$ then γ_u cannot be ignored

$p > 2$

$$\gamma_m = \epsilon_e \left(\frac{p-2}{p-1}\right) \frac{m_p}{m_e} \Gamma$$

Panaitescu 2000:

Hard spectrum in GRB000301c

Keep $\gamma_m \propto \Gamma$

Allow ϵ_e **to determine** γ_***, the upper cutoff**

[*equivalent to* $q = 1$]

$1 < p < 2$

$$\gamma_m = \left[\epsilon_e \left(\frac{2-p}{p-1}\right) \frac{m_p}{m_e} \Gamma \gamma_u^{p-2}\right]^{1/(p-1)}$$

$$\gamma_u \propto \Gamma^q$$

DB 2001

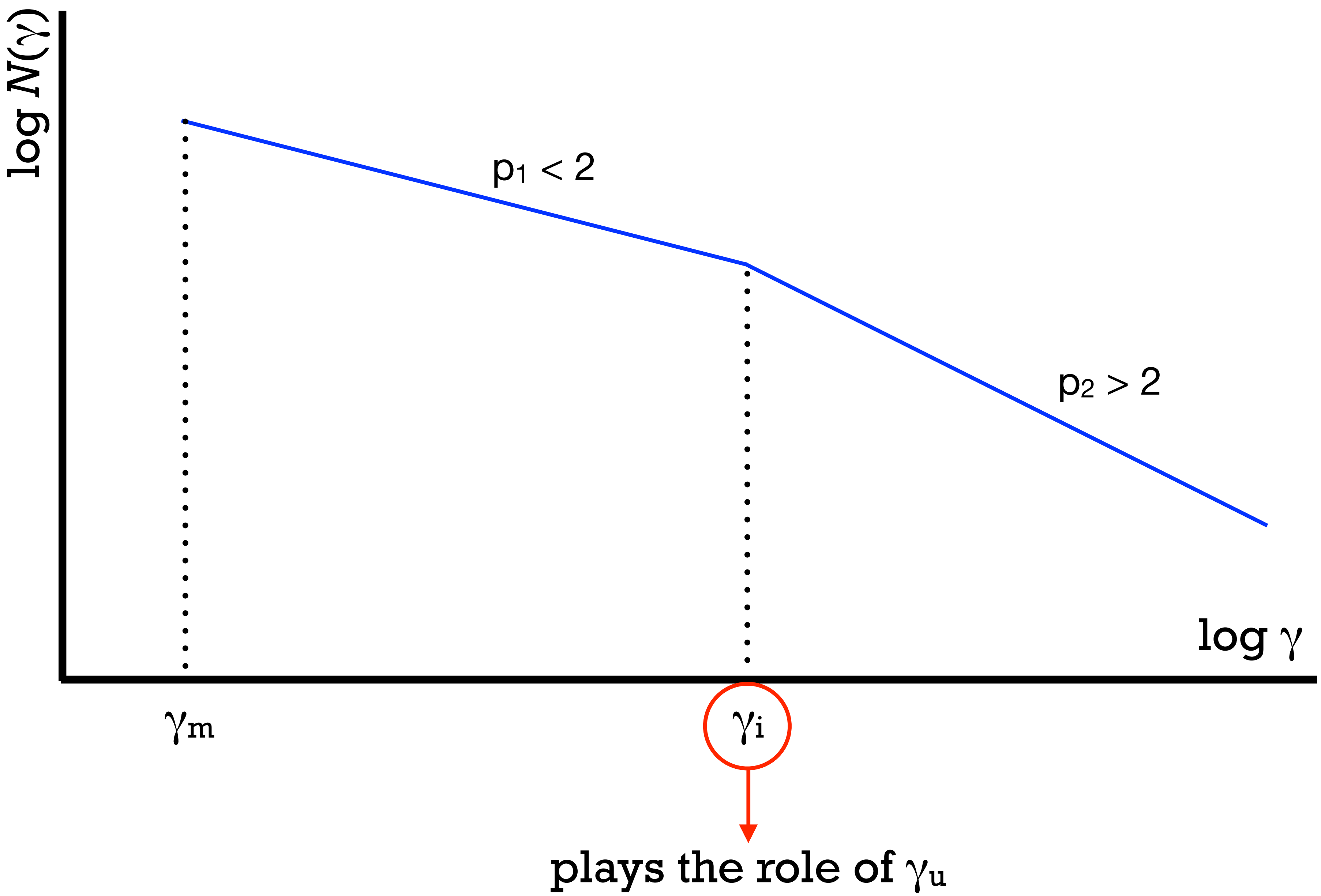
$$\gamma_u = \gamma_c \propto \Gamma^{-1/2}$$

Dai & Cheng 2001

Application to GRB 010222

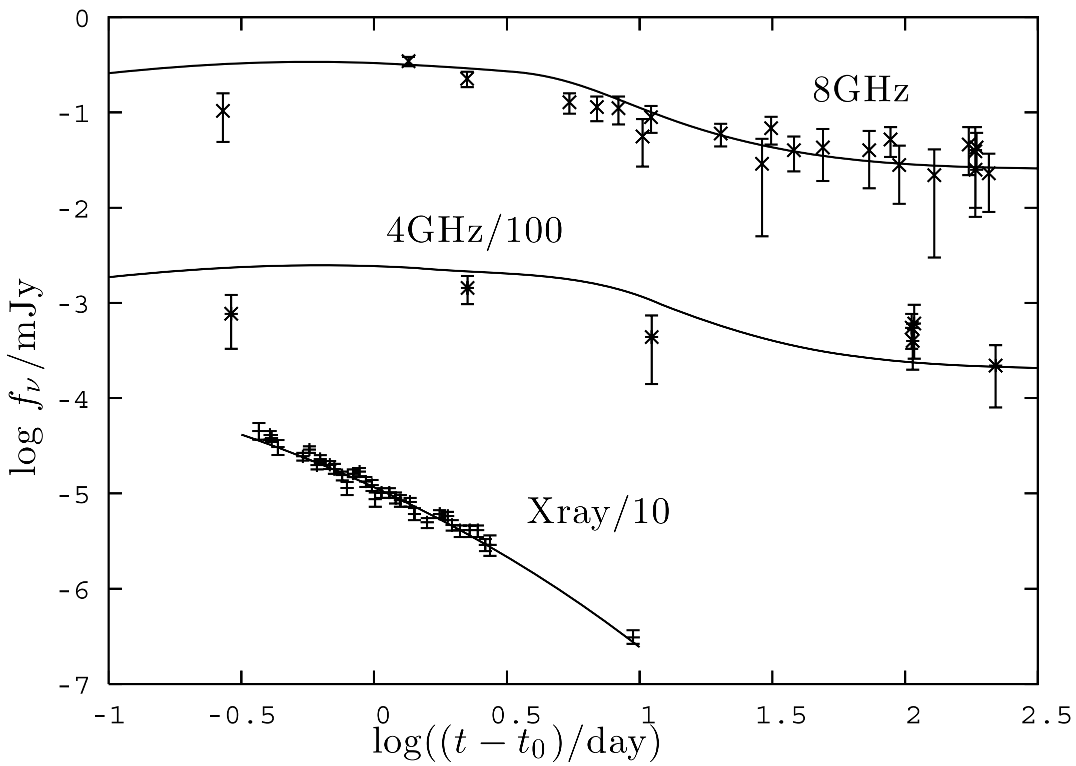
Sagar et al 2001, Cowsik et al 2001, Dai & Cheng 2001
Stanek et al 2001, Jha et al 2001

Injection Break

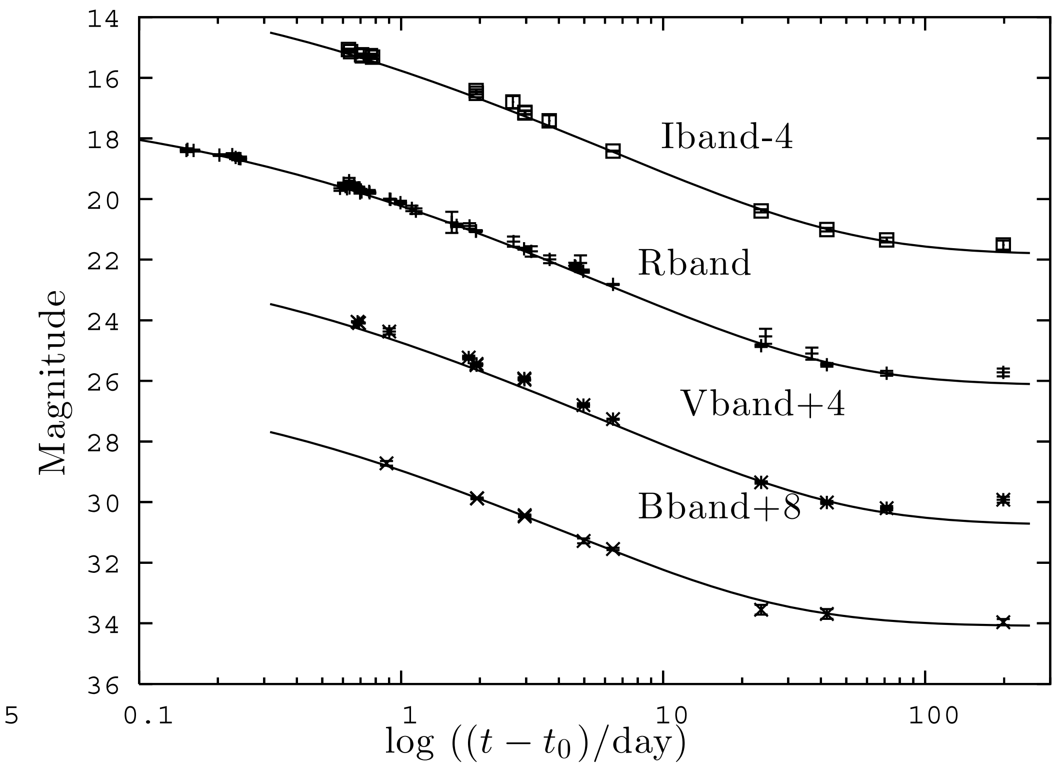


Panaitescu 2000
Panaitescu & Kumar 2001
Resmi & DB 2008

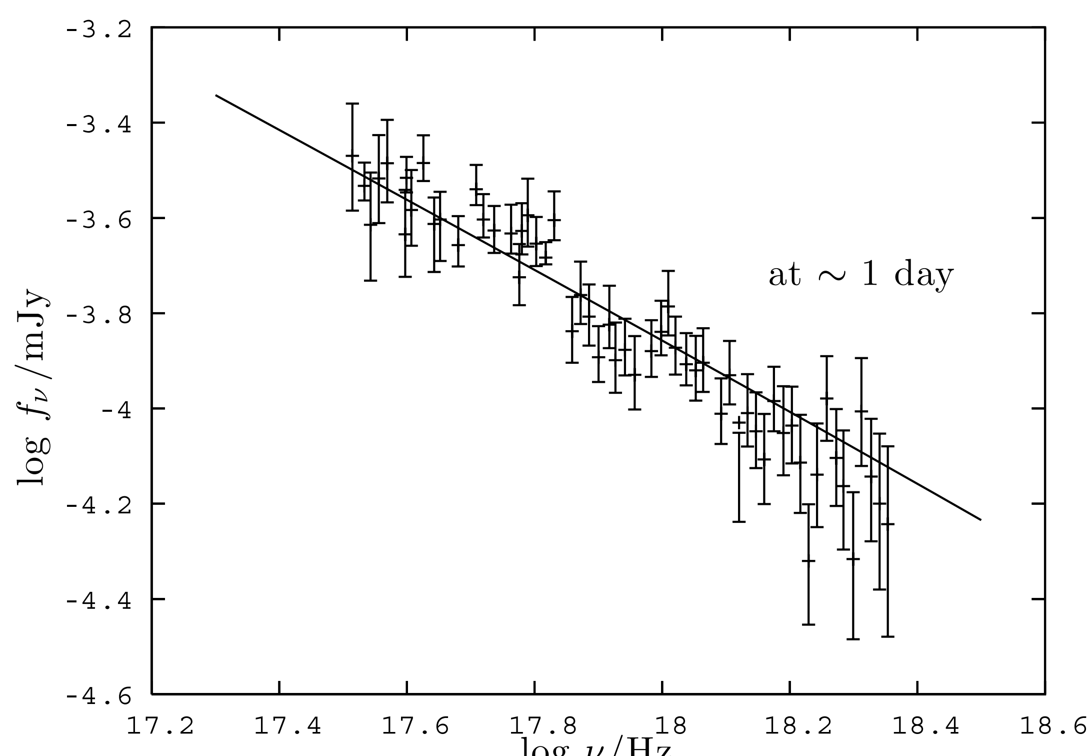
GRB 010222



(a)



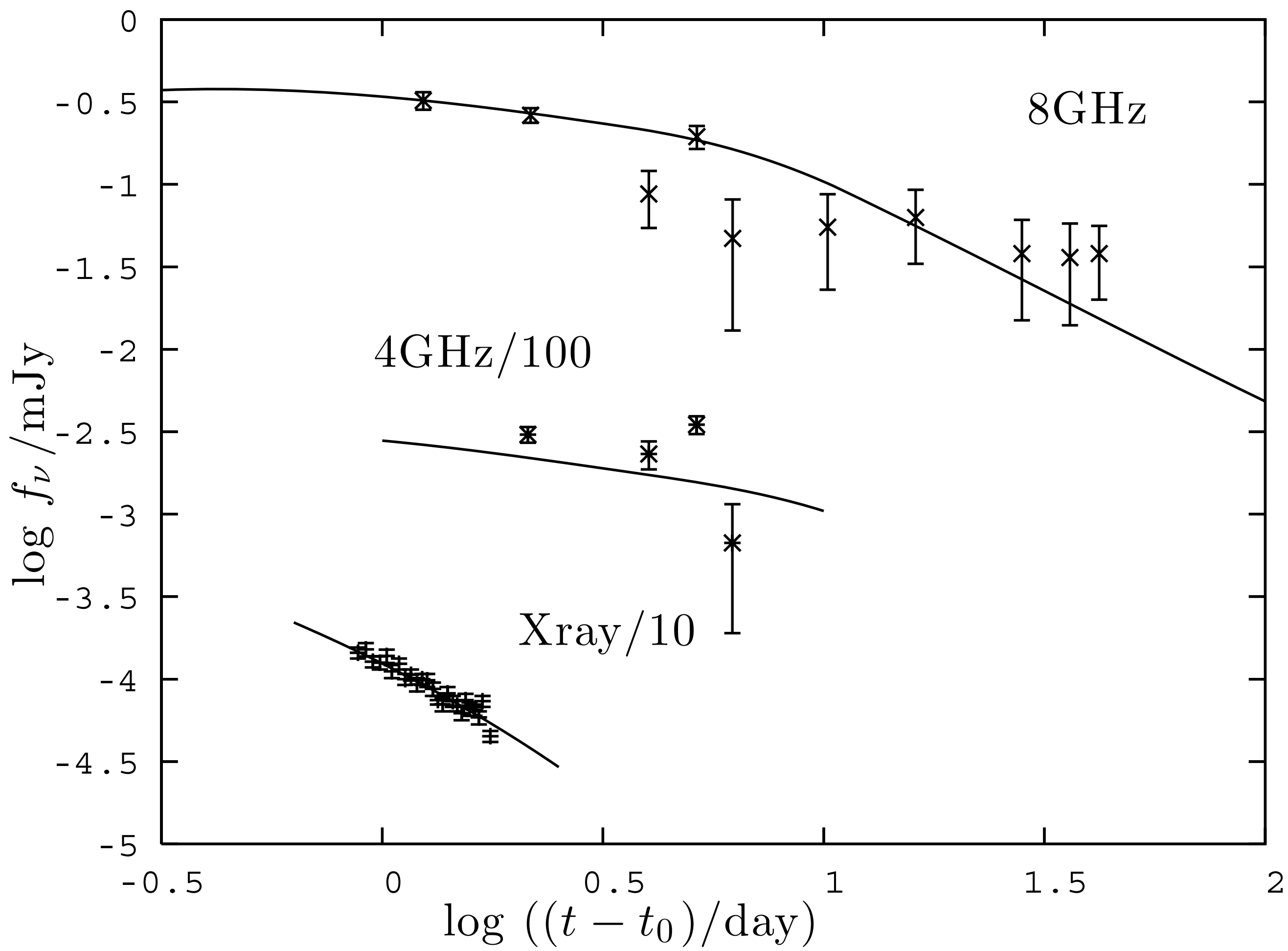
(b)

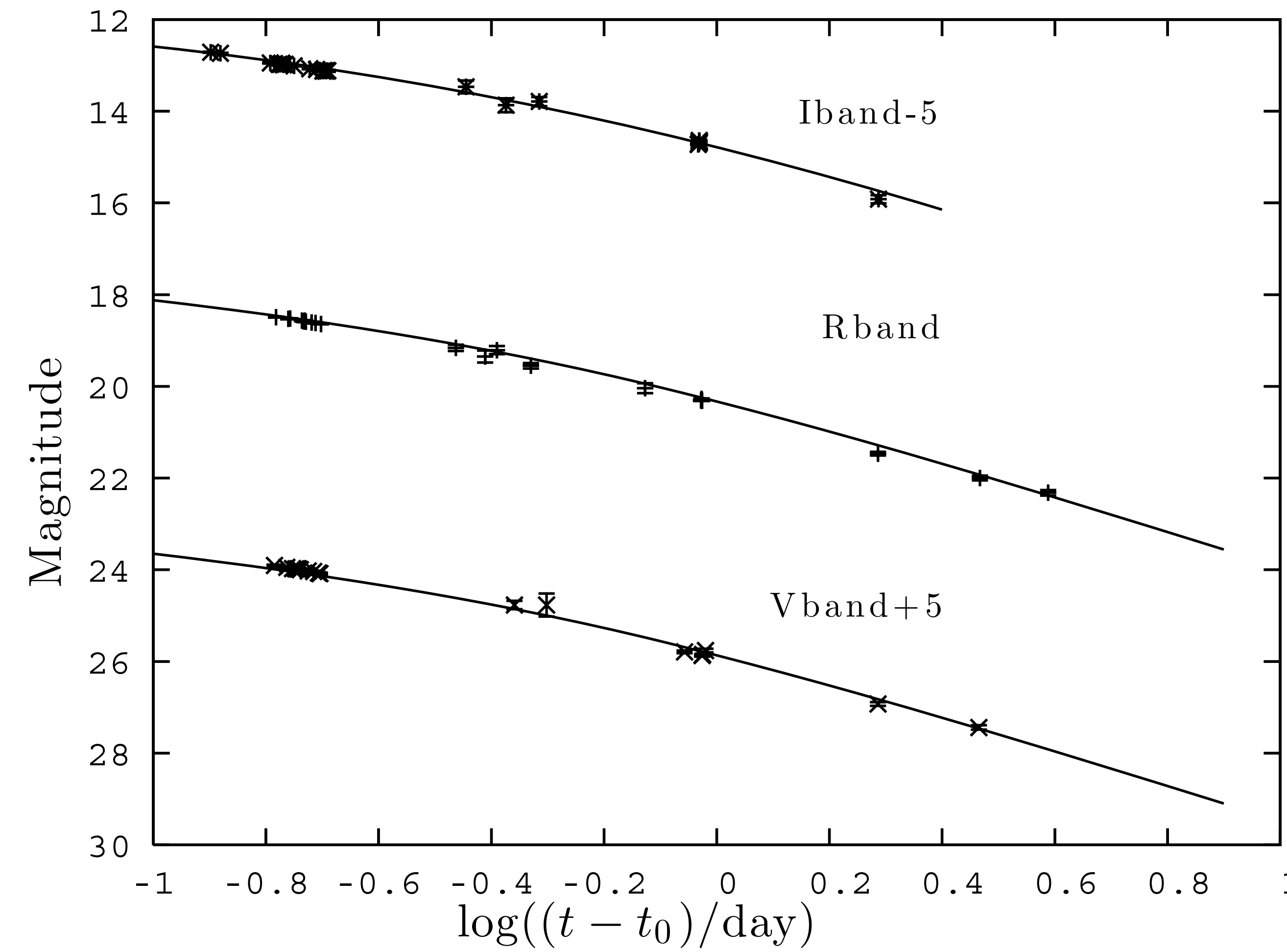


(c)

Resmi & DB 2008

GRB 041006





Misra et al 2004
Resmi & DB 2008

Fit parameters	GRB010222	GRB020813	GRB041006
p_1	$1.47^{+0.004}_{-0.003}$	$1.40^{+0.007}_{-0.004}$	1.29–1.32
p_2	$2.04^{-0.01}_{+1.76}$	~ 2.1	>2.2
q	1.3 ± 0.06	1.3 ± 0.05	0.95–1.14

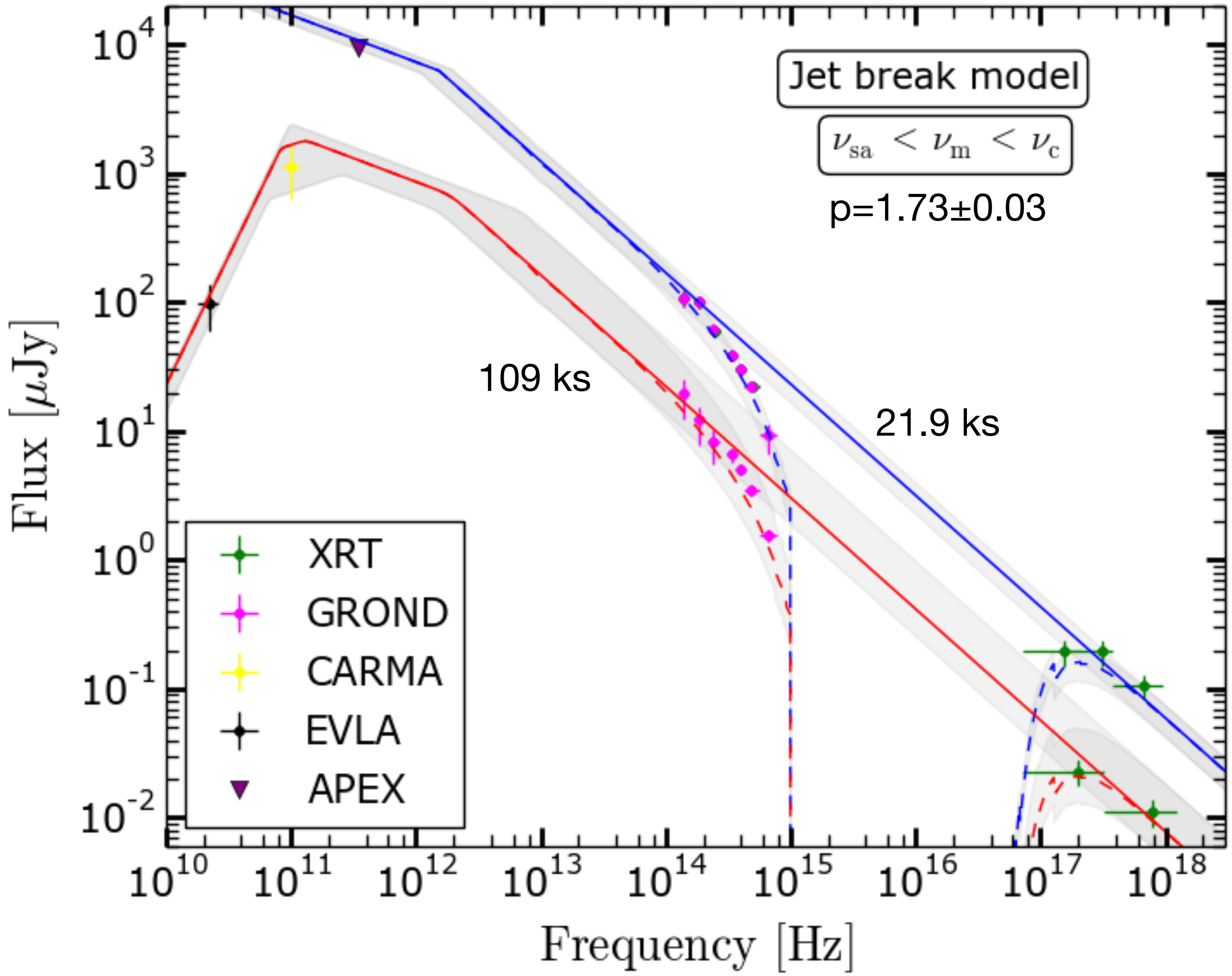
Compilation of observationally derived microphysical parameters of GRBs

GRB	Density (cm^{-3})	p	ϵ_e	ϵ_B
970228		2.44[8]		
970508	0.75[2]	2.29[2, 3, 8]	0.19[1, 2, 3]	0.1685[1, 2, 3, 6]
971214		2.2[8]		
980329		2.69[3, 8]	0.12[3]	0.17[3]
980519	0.14[2]	2.87[2, 8]	0.11[2]	0.000 035[2]
980703		2.64[3, 8]	0.27[3]	0.0018[3]
990123	0.0019[4]	2.135[2, 8]	0.13[2]	0.000 74[2]
990510	0.29[4]	1.945[2, 8]	0.025[2]	0.0052[2]
991208	18[2]	1.53[2]	0.056[2]	0.035[2]
991216	4.7[2]	1.36[2]	0.014[2]	0.018[2]
000301C	27[4]	1.43[2]	0.062[2]	0.072[2]
000418	27[2]	2.04[2]	0.076[2]	0.0066[2]
000926	22[4]	2.58[2, 3, 8]	0.125[2, 3]	0.0435[2, 3]
010222	1.7[2]	1.695[2, 8]	0.43[2]	0.000 067[2]
011121		2.5[5]		0.5[5]
011211	3[5]	2.4[5]	0.0025[5]	0.01[5]
050801		2.64[9]		
050802		2.62[9]		
050904			0.0309[7]	
051109A		2.08[9]		
060124		2.02[9]		
060729		2.22[9]		
061121		1.88[9]		
090323			0.07[10]	0.0089[10]
090328		2.26[10]	0.11[10]	0.0019[10]
090902B	0.000 56[10]	2.21[10]	0.13[10]	0.33[10]
090926A		2.13[10]	0.33[10]	0.081[10]

1: Wijers & Galama (1999)
2: Panaitescu & Kumar (2002)
3: Yost et al. (2003)
4: Chevalier & Li (2004)
5: Piro et al. (2005)
6: van der Horst, Wijers & Rol (2005)
7: Gou, Fox & Mészáros (2007)
8: Starling et al. (2008)
9: Curran et al. (2009)
10: Cenko et al. (2011)

Macpherson & Coward 2015

GRB121024A



Varela et al 2016

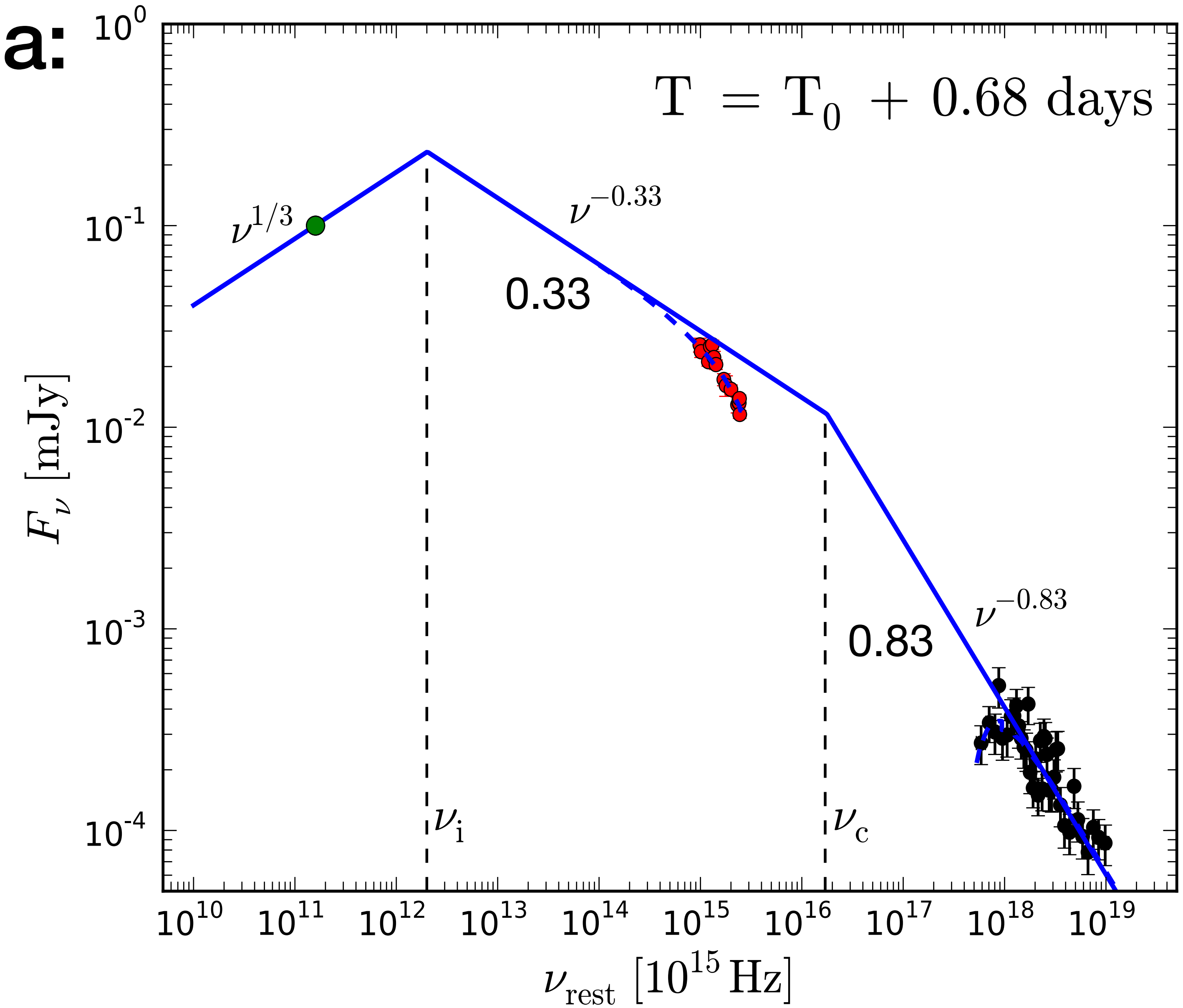
Shallow SED slope

GRB 060908: $\beta_{\rm opt} = 0.33$ Covino et al 2010

GRB 091127: $\beta_{\rm opt} = 0.25, \beta_X = 0.75$

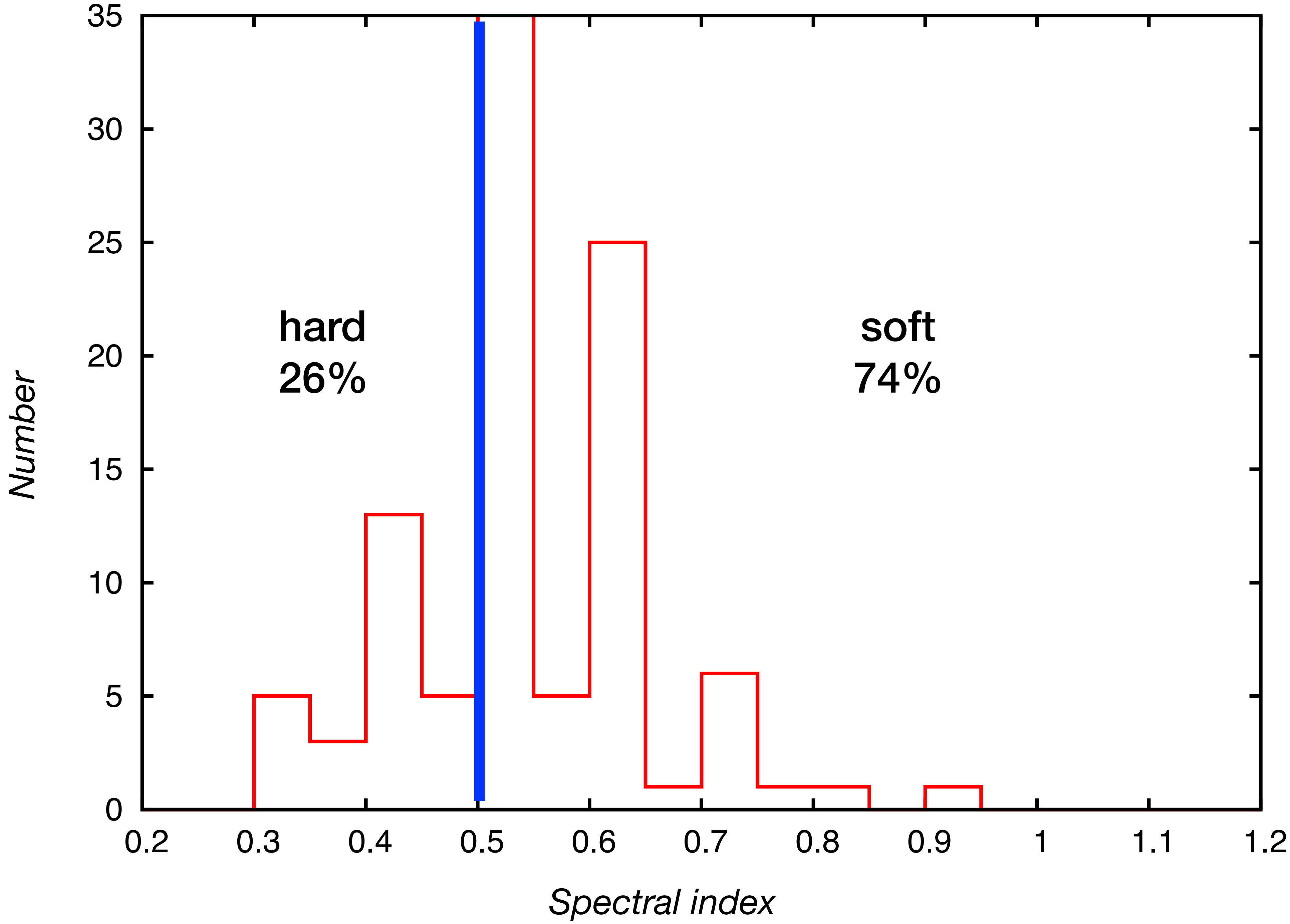
$p = 1.5, q = 0.64$ Zhang et al 2015

GRB 140515a:



Melandri et al 2015

Distribution of β of shell-type radio SNRs



Particle energy distribution generated by Shock Acceleration

Data from Cambridge SNR catalogue, D. Green

Summary

- Electron energy spectrum in GRB afterglows typically have $p \sim 2.2 - 2.5$, but in a minority of cases $p < 2$ have been inferred
- In case of hard energy spectrum the evolution of the upper cutoff energy affects the light curve
- Originally motivated to obtain consistency between spectral and temporal slopes of a few GRBs, the models required strong synchrotron cooling.
- More recently, cases of SED with flat spectrum below cooling frequency have been found
- What caused the diversity in energy distribution is unclear, shock acceleration theory tends to predict universal slope
- Even in shell SNRs a distribution of p is observed, with some fraction below 2