Nonlinear cosmic ray acceleration in GRB afterglows

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RIKEN-RESCEU mtg 2016
27 Jul 2016

Outline

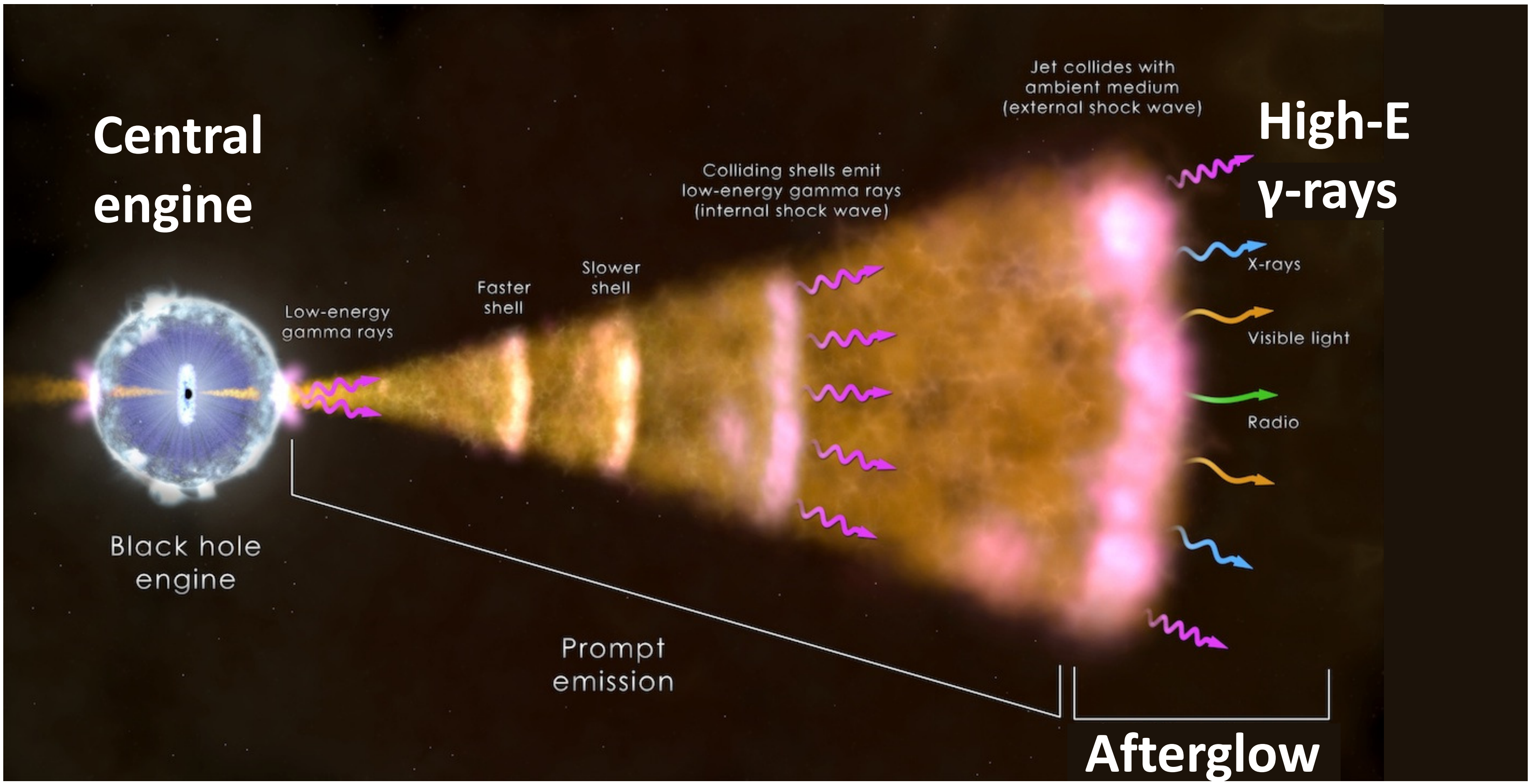
- Background

- Nonlinear diffusive shock acceleration (DSA) in relativistic shocks

- A nonlinear afterglow

Background

Afterglow is long-lived (hours, days, months) multiwavelength relic of GRB



Background

Observations of GRB afterglows cover orders of magnitude in time and energy

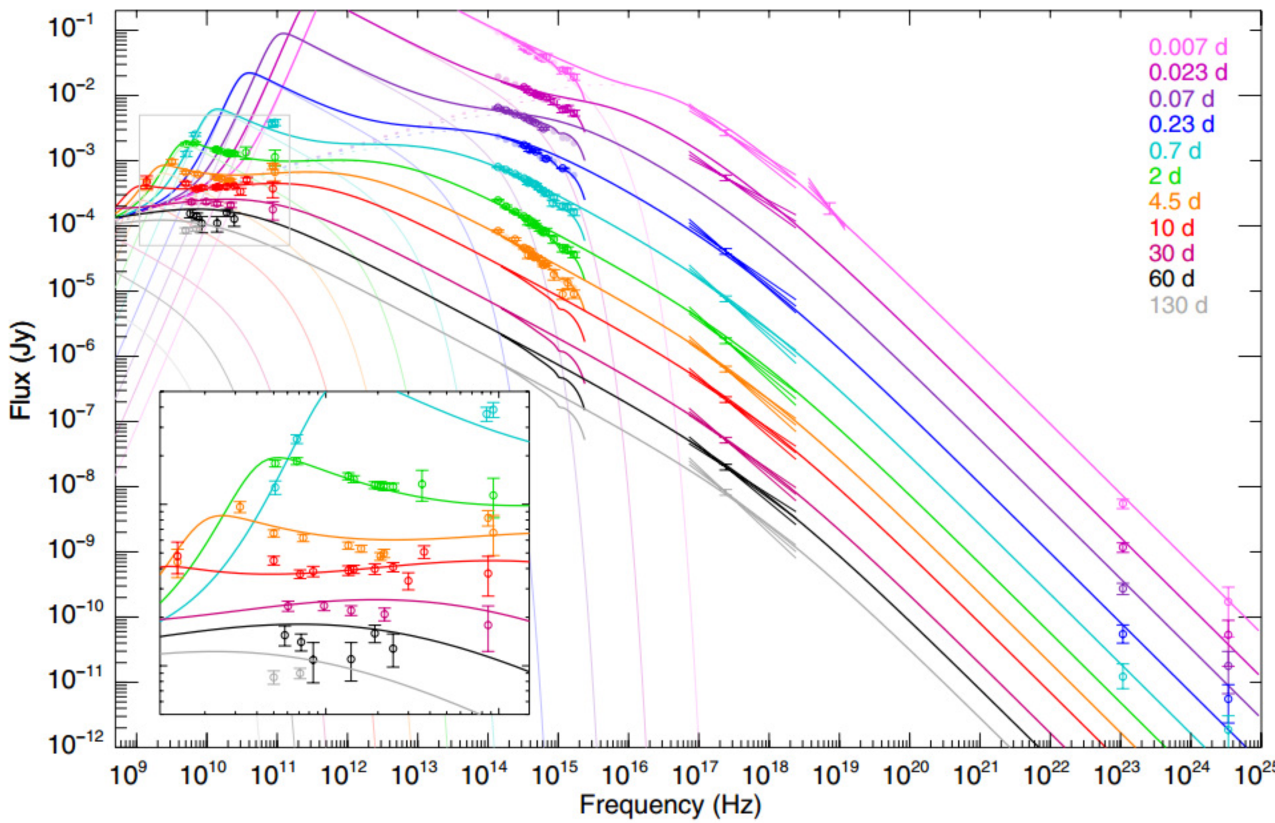


Figure 10. Observations of the afterglow of GRB 130427A spanning from the low-frequency radio to the 100 GeV LAT bands, interpolated to a series of coeval epochs spanning from 0.007 days (10 minutes) to 130 days after the burst. Overplotted over each epoch is our simple forward+reverse shock model from standard synchrotron afterglow theory, which provides an excellent description of the entire data set, a span of 18 orders of magnitude in frequency and 4 orders of magnitude in time. The solid line shows the combined model, with the pale solid line showing the reverse-shock and the pale dotted line showing the forward-shock contribution. The "spur" at $\approx 10^{15}$ Hz shows the effects of host-galaxy extinction on the NIR/optical/UV bands. Open points with error bars are measurements (adjusted to be coeval at each epoch time); pale filled points are model optical fluxes from the empirical fit in Section 3.4. The inset at lower left shows a magnified version of the radio part of the SED (gray box) at $t > 0.7$ days.

Perley et al. (2014)
(2014ApJ...781...37P)

Background

Many different models to explain broadband spectra and light curves

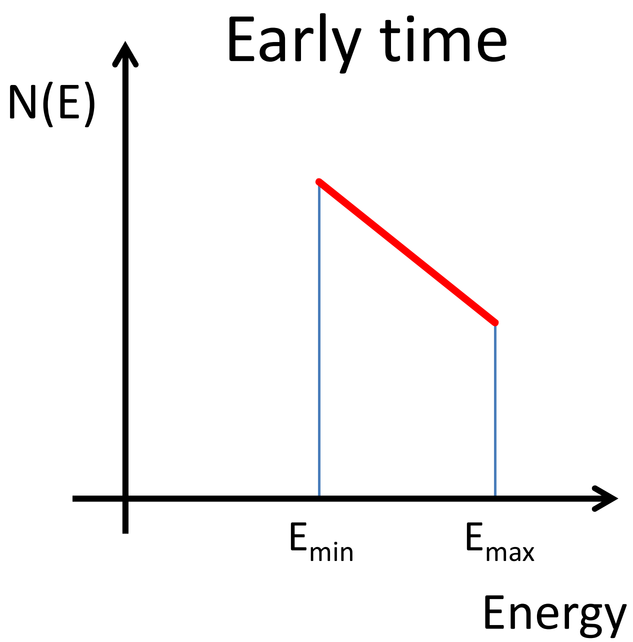
A complete reference of the analytical synchrotron external shock models of gamma-ray bursts

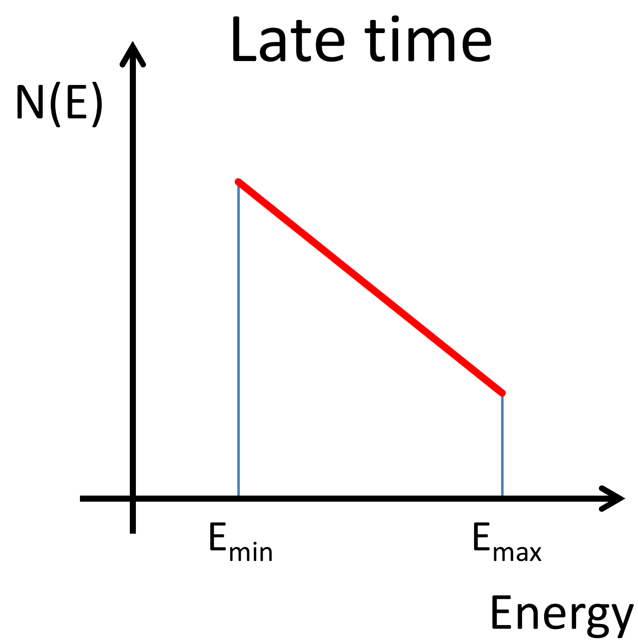
He Gao[a], Wei-Hua Lei[b,a], Yuan-Chuan Zou[b], Xue-Feng Wu[c], Bing Zhang[a,d,e,*]

Background

Many different models to explain broadband spectra and light curves

However, current afterglow studies assume extremely simple model for CR electrons accelerated by shock



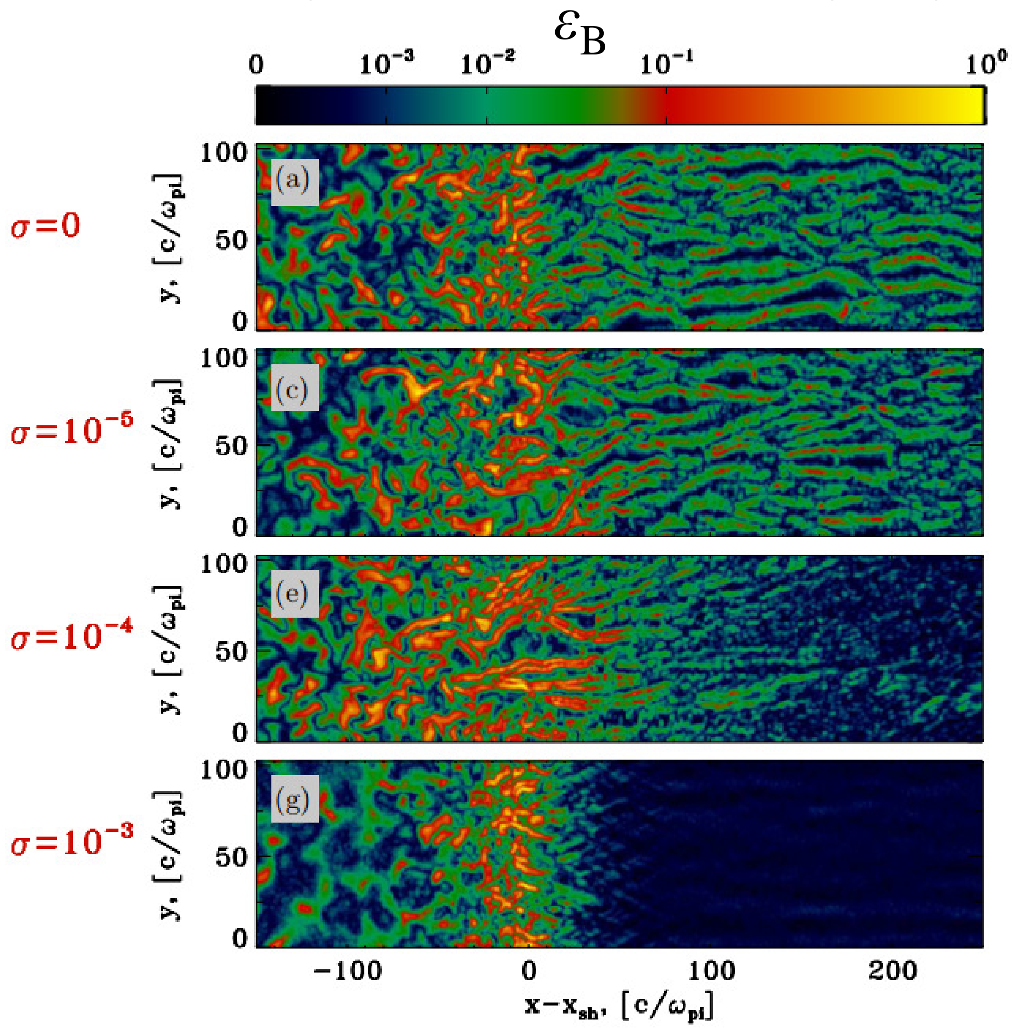


(mostly) Fine if shocks are unaffected by (1) CRs, and (2) B-field

Background

(Particle-in-cell)

Per PIC simulations, magnetic field may not be negligible, and accelerated particles not a simple power law



Sironi et al. (2013) (2013ApJ...771...54S)

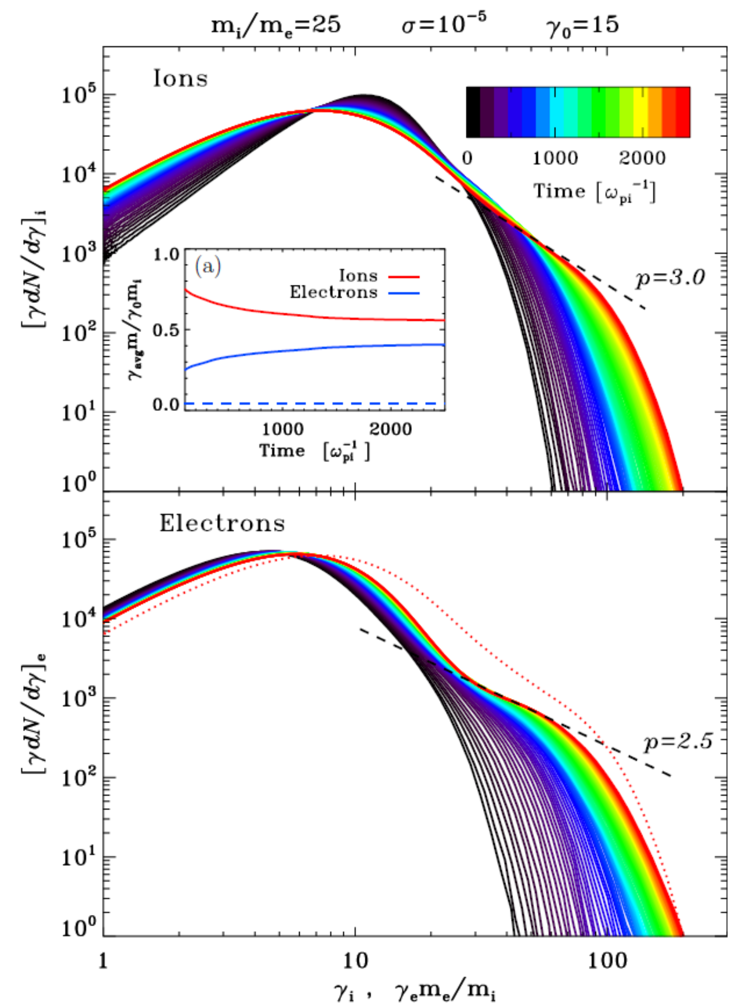
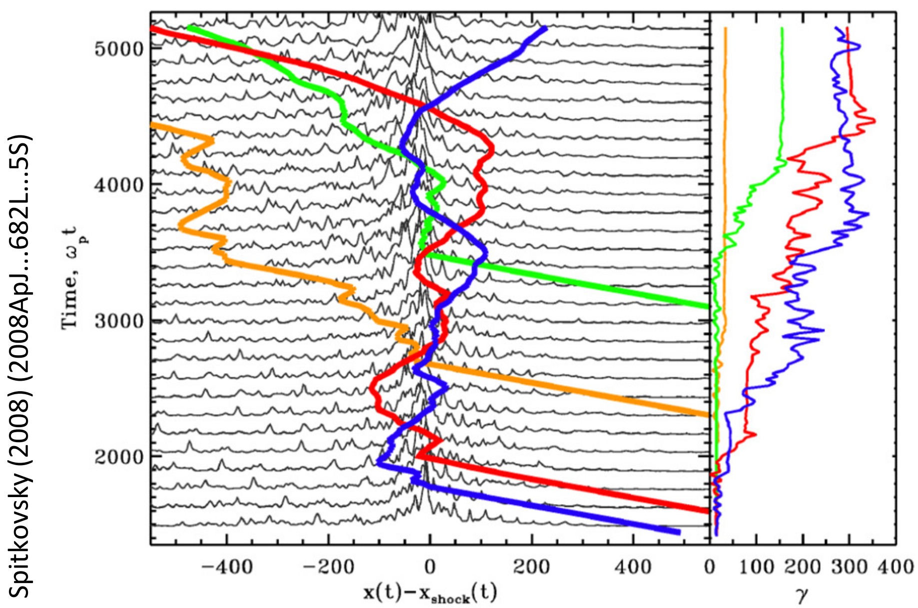
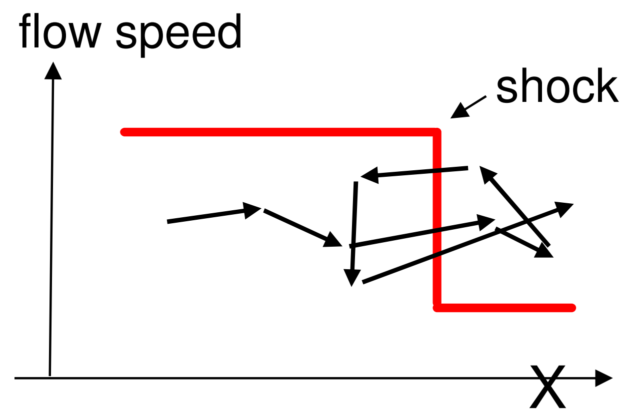


Figure 11. Temporal evolution of the post-shock particle spectrum

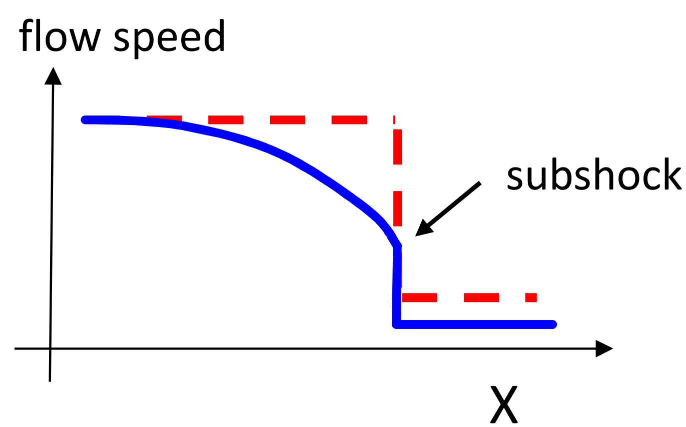
Background

Strong B-field turbulence in vicinity of shock can scatter particles back into upstream region (← diffusive shock acceleration, or **DSA**)





Pressure from UpS particles affects inflow of plasma, which affects shock, which affects acceleration, which affects pressure from UpS particles…



Background

Sironi et al. (2013) (2013ApJ...771...54S)

Interaction between shock, B-field turbulence, and accelerated particles important!

Leads to more complicated CR spectrum than simply E^{-p}

PIC simulations impractical if extended to necessary scales to model GRB afterglows

Monte Carlo code used here balances self-consistency & computation time

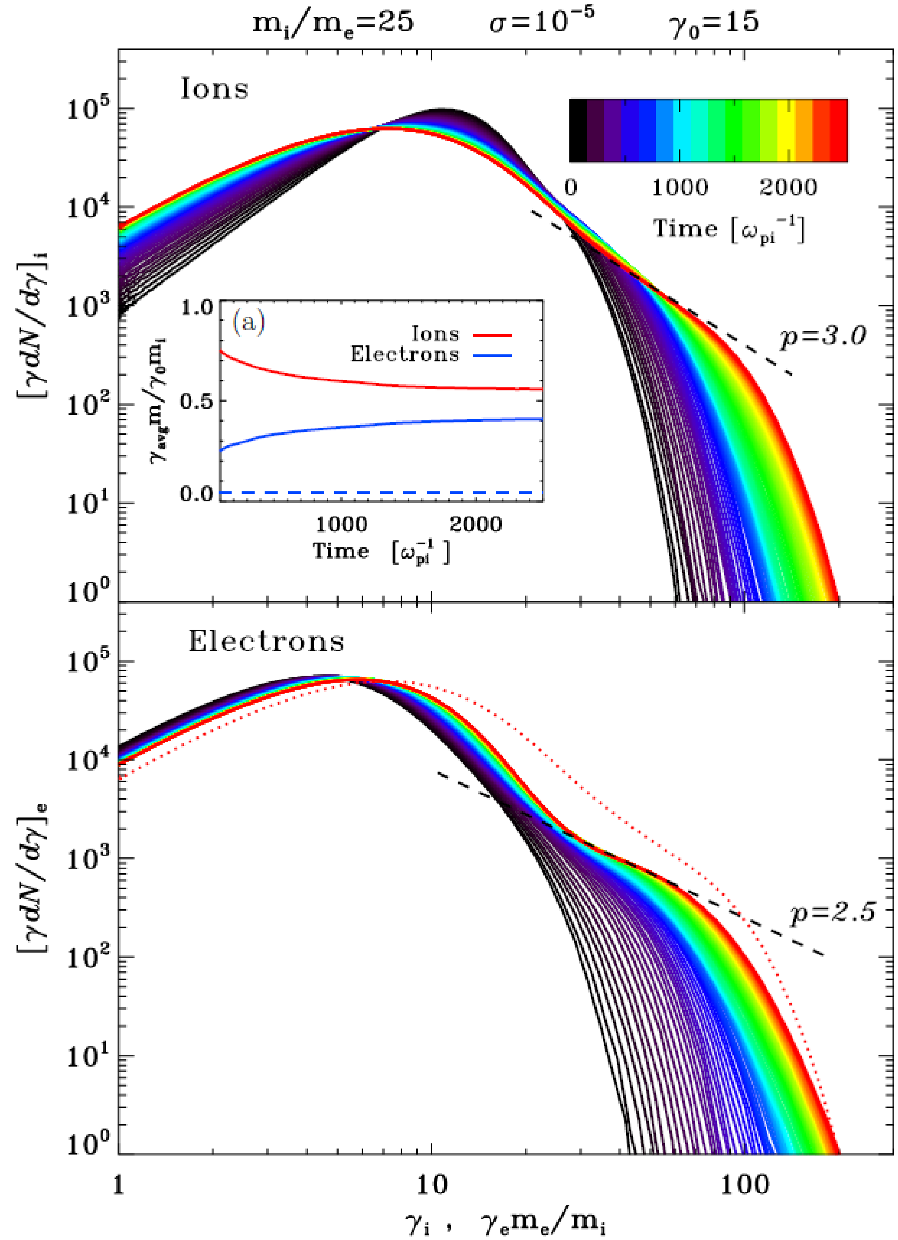


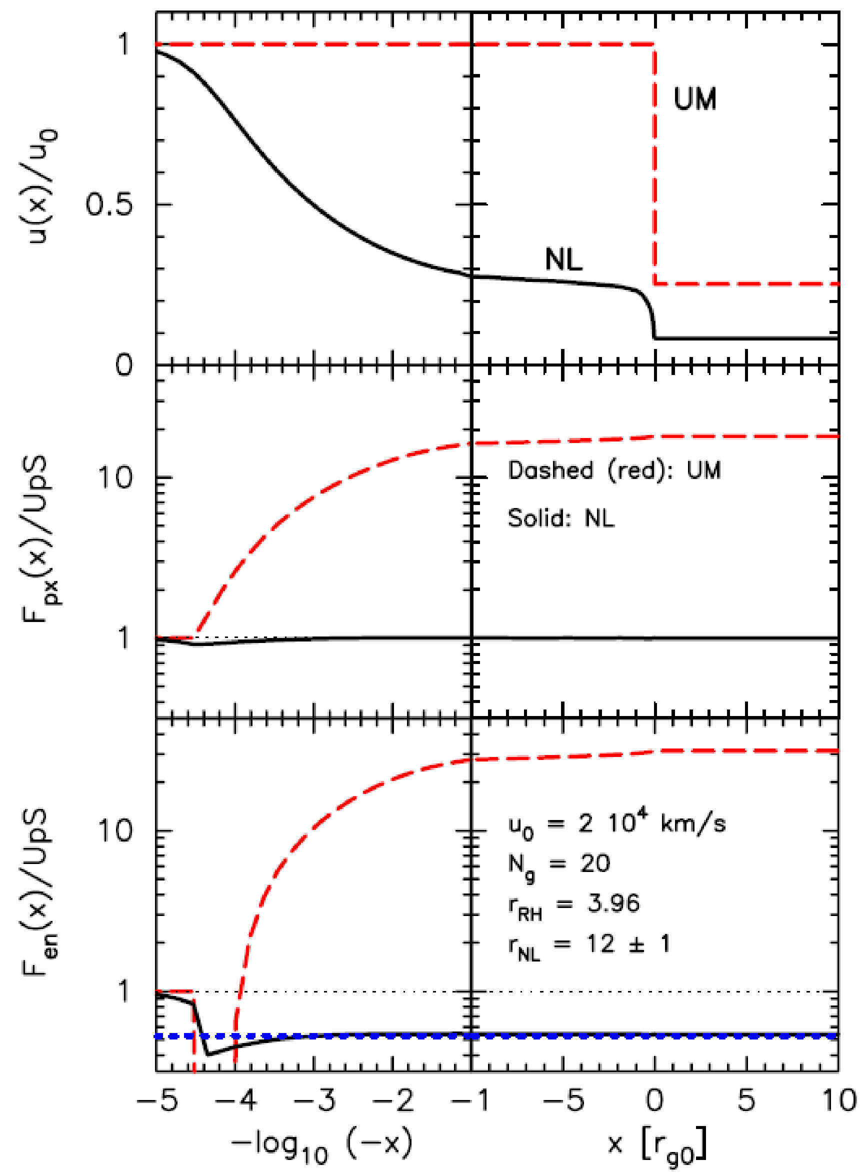
Figure 11. Temporal evolution of the post-shock particle spectrum

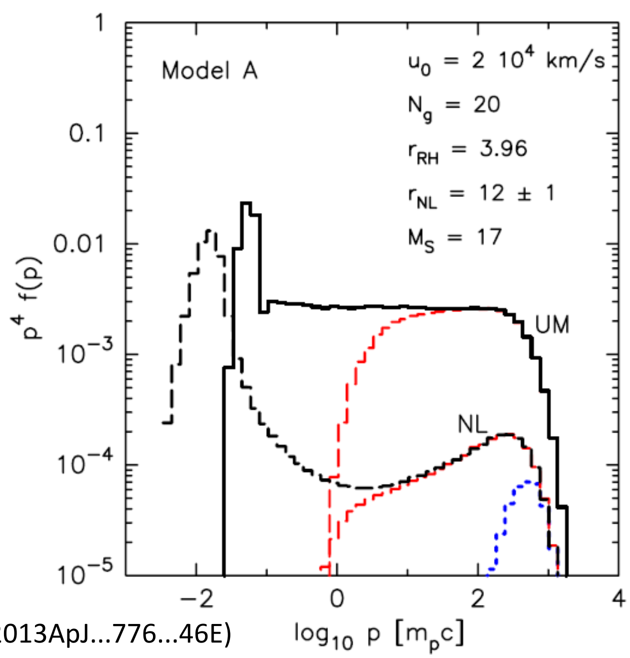
Nonlinear DSA in relativistic shocks

Interaction between shock, B-field turbulence, and accelerated particles important!

Efficient DSA by unmodified shocks does not conserve energy or momentum flux

Ellison et al. (2013) (2013ApJ...776...46E)





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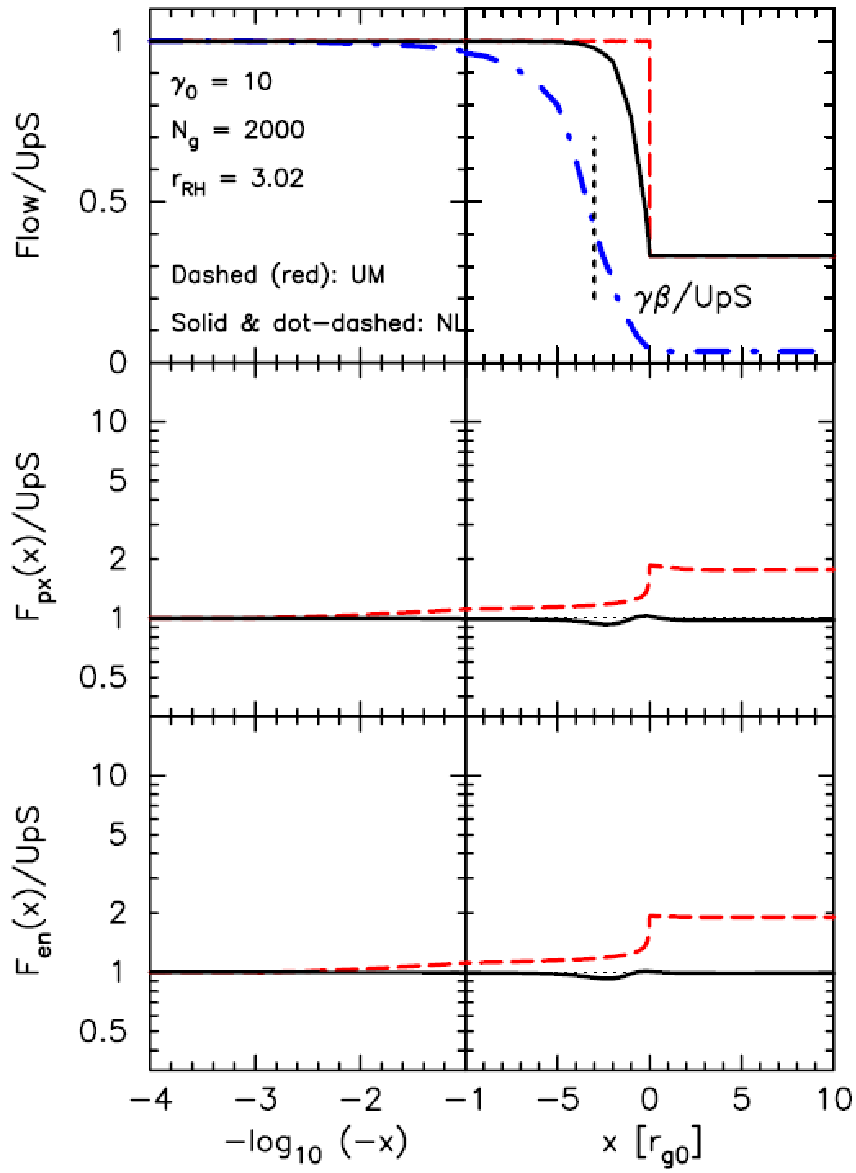
Nonlinear DSA in relativistic shocks

Interaction between shock, B-field turbulence, and accelerated particles important!

Efficient DSA by unmodified shocks does not conserve energy or momentum flux

Even in relativistic shocks, must have precursor & modified velocity profile

Ellison et al. (2013) (2013ApJ...776...46E)



Nonlinear DSA in relativistic shocks

As shock slows, CR spectrum changes too

Single-index approach to CR energy distribution may not hold at any given instant

Very unlikely to hold across extended observations of GRB afterglows

But what about electrons?

Ellison et al. (2013) (2013ApJ...776...46E)

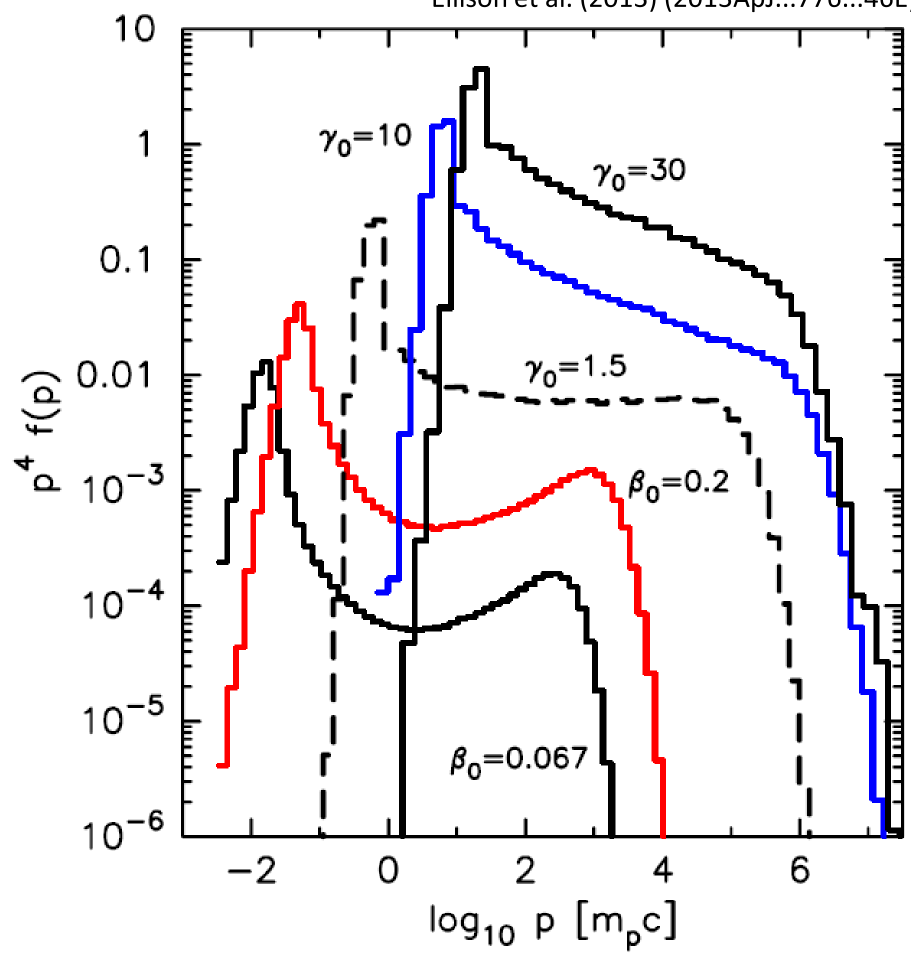


Figure 10. Nonlinear particle distributions calculated downstream from the shock in the shock rest frame for various shock speeds as indicated (Models A–E in Table 1). The spectrum for the $\gamma_0 = 1.5$ shock (dashed black curve) shows the transitional nature of nonlinear DSA.

Electron DSA in relativistic shocks

Sironi et al. (2013) (2013ApJ...771...54S)

Electron acceleration <u>much</u> less efficient than proton acceleration

Without energy transfer from ions, GRB afterglow would be extremely faint

PIC simulations (Sironi+ 2013, Ardaneh+ 2015) show that this transfer does occur

As much as 40% of bulk kinetic energy deposited into electrons

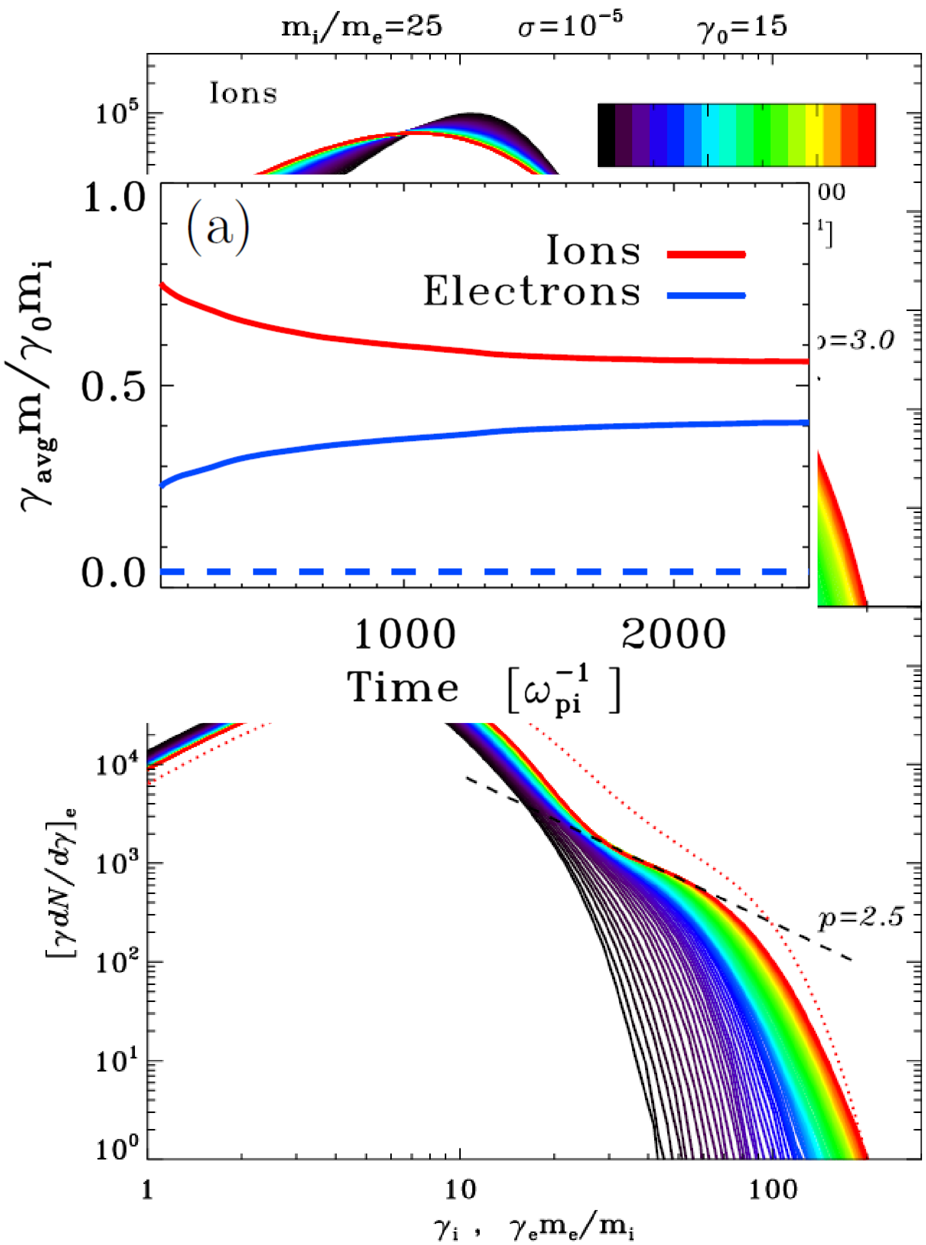


Figure 11. Temporal evolution of the post-shock particle spectrum

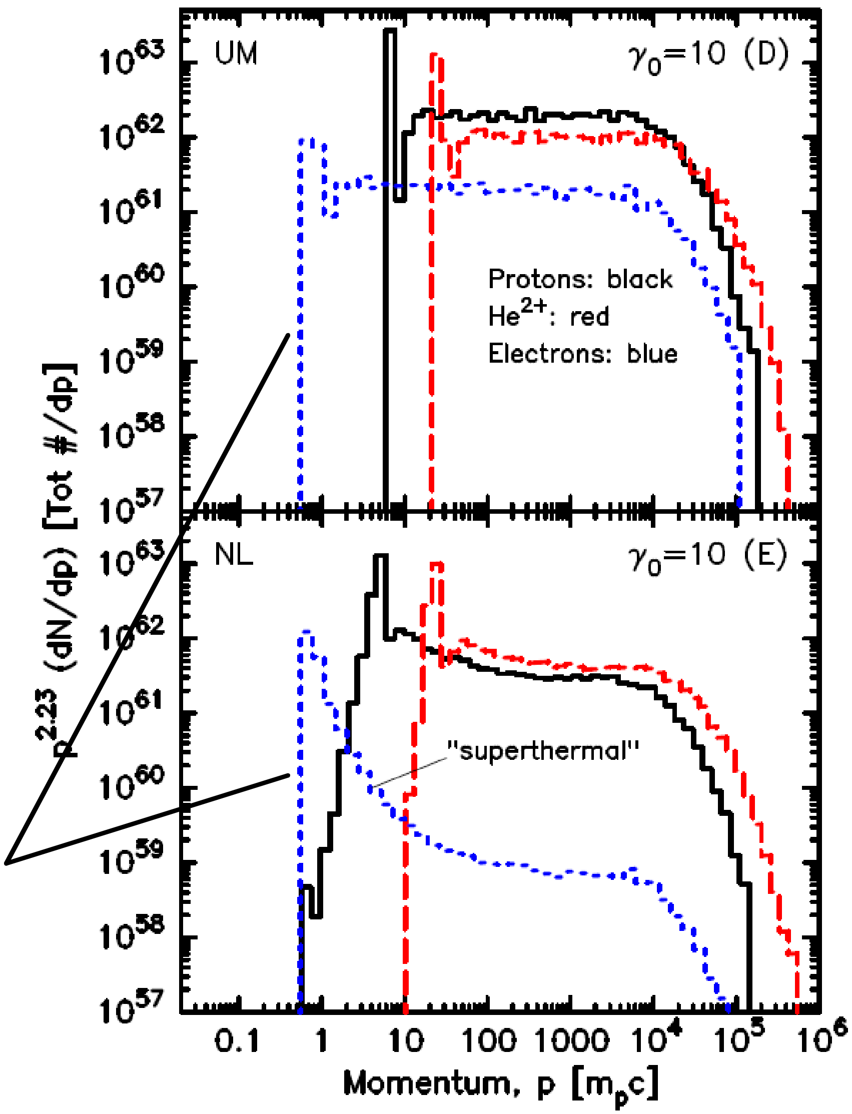
Electron DSA in relativistic shocks

For protons, not much difference between unmodified DSA and nonlinear DSA

For electrons, difference is stark

- Number of high-E electrons depends strongly on energy transfer
- No clear power law in NL electron spectrum

Warren et al. (2015) (2015MNRAS.452..431W)



10% energy transferred

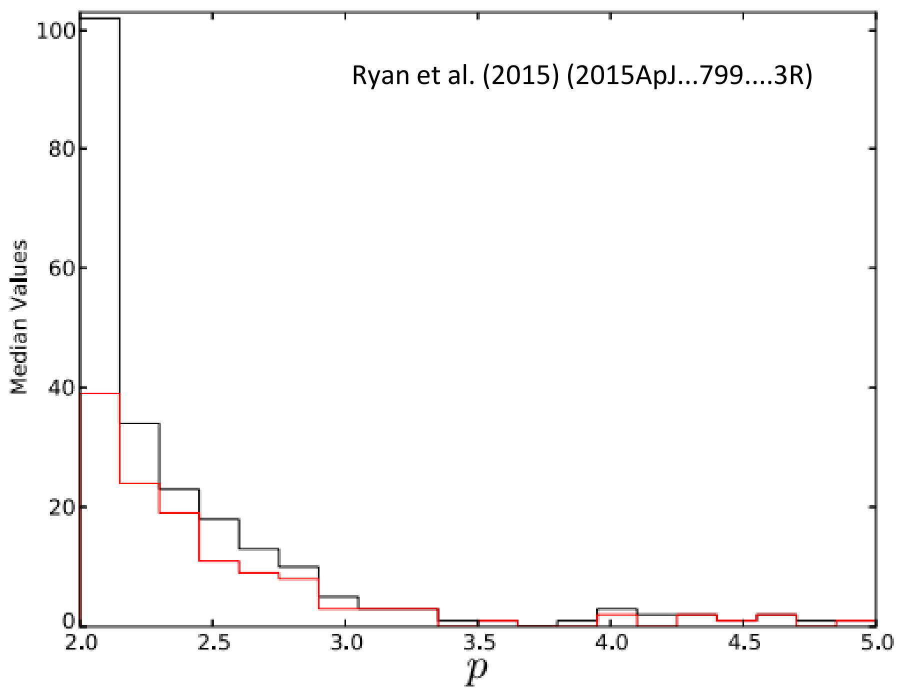
Figure 6. Downstream, LPF spectra for the unmodified shock shown in Fig. 5 (top panel, Model D) and the non-linear shock shown in Fig. 5 (bottom panel, Model E). Note the pronounced 'superthermal' tail on the electron distribution.

Electron DSA in relativistic shocks

Curran et al. (2010) (2010ApJ...716L.135C)

Model	p	σ_p
GDp	2.36	0.590
	(2.40 ± 0.03)	(0.600 ± 0.007)
	$[2.36 \pm 0.05]$	$[0.590 \pm 0.012]$

Notes. The most likely values of electron energy distribution index, p, the related Gaussian scatter, σ_p, the



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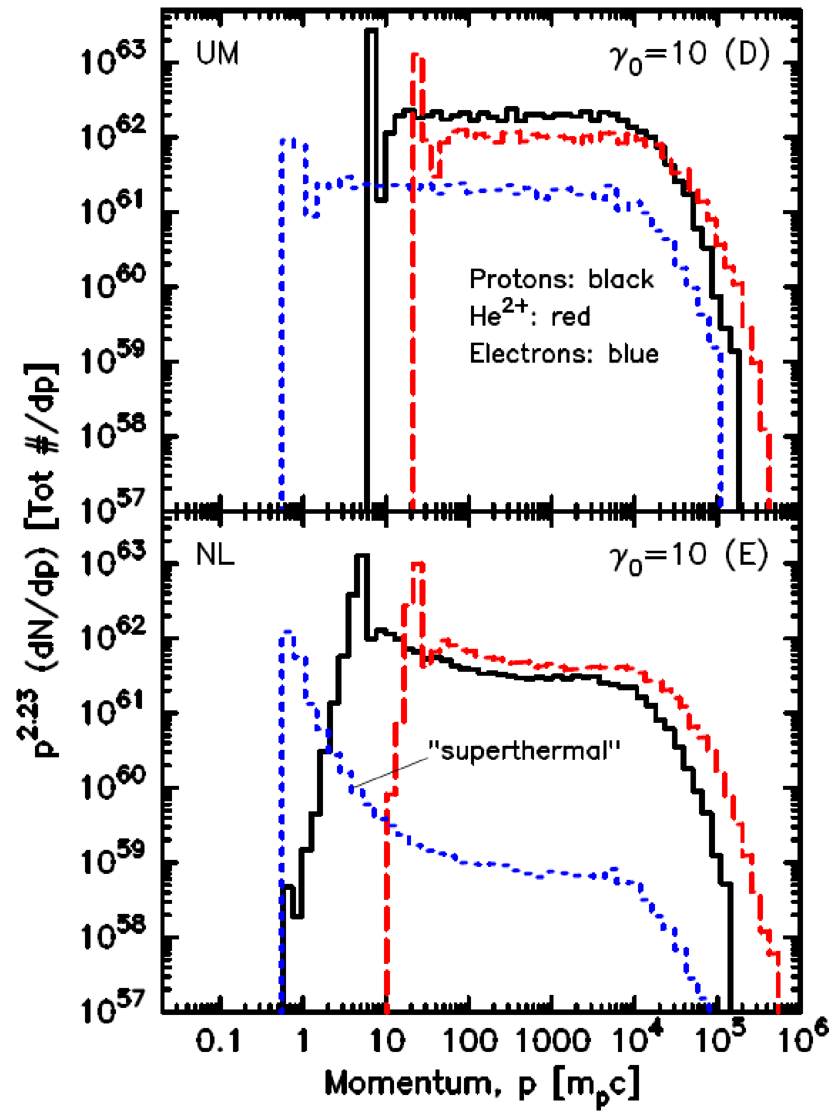
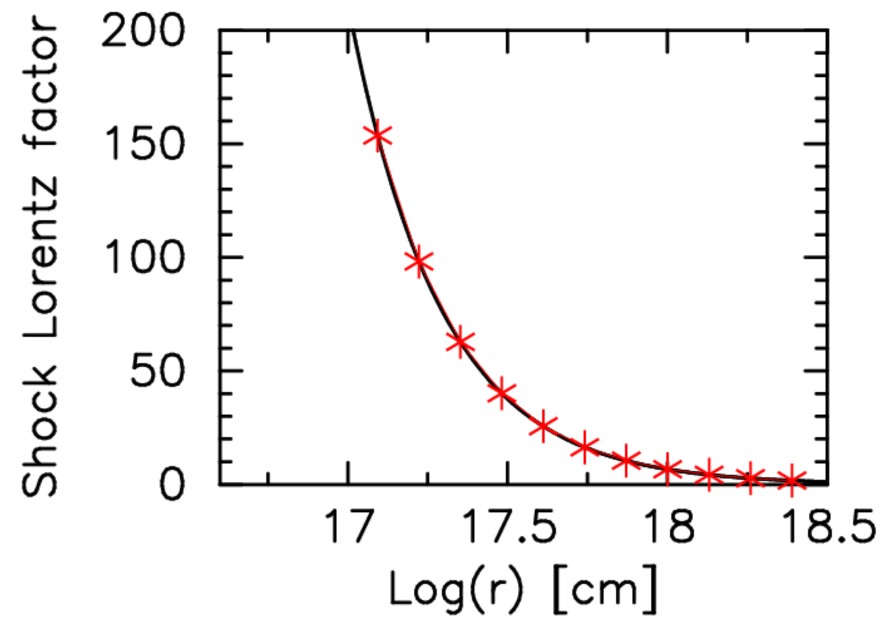


Figure 6. Downstream, LPF spectra for the unmodified shock shown in Fig. 5 (top panel, Model D) and the non-linear shock shown in Fig. 5 (bottom panel, Model E). Note the pronounced 'superthermal' tail on the electron distribution.

Modeling a GRB afterglow

Use Blandford—McKee solution for hydrodynamical base



At select times, model DSA using Monte Carlo code

Calculate photon spectra

Three models discussed here:

- CR-only shocks
- Test particle shocks
- Nonlinear (flux-conserving) shocks

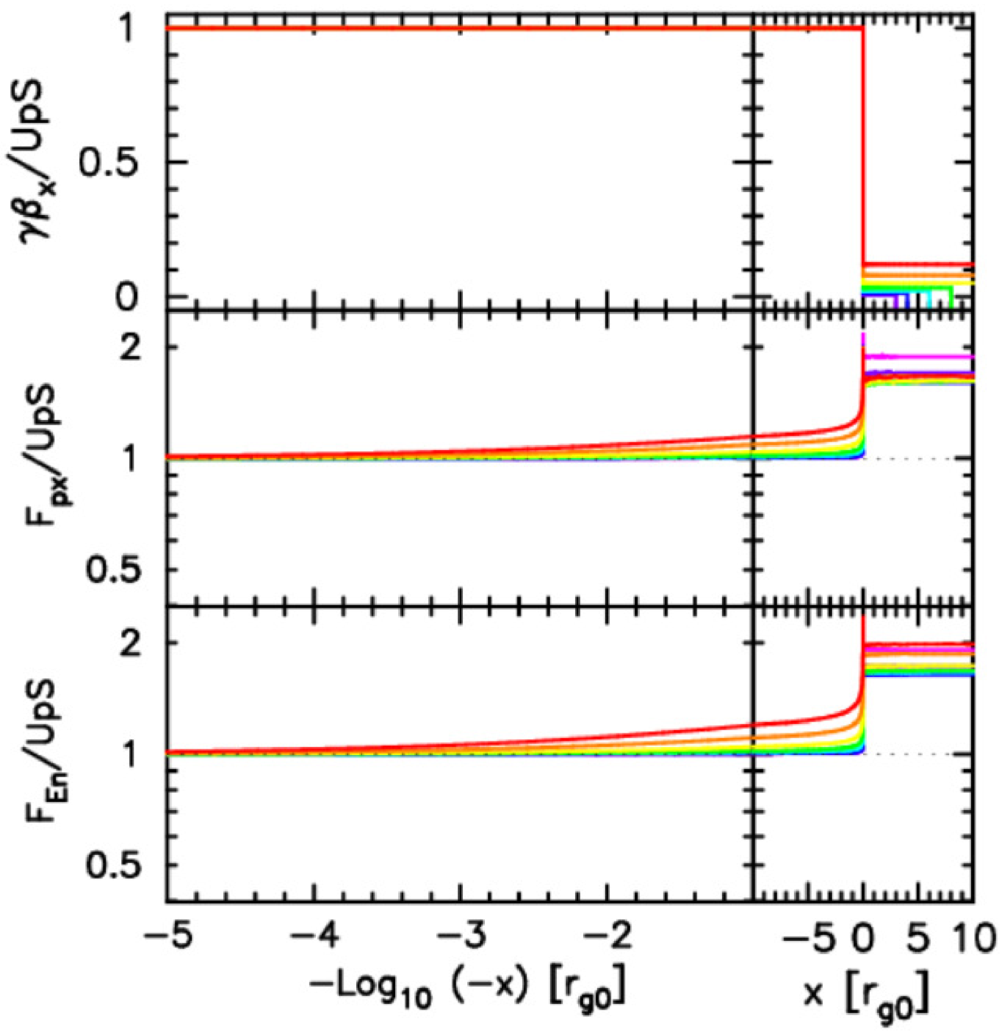
EVERYTHING PRELIMINARY

Key parameters: $E_{iso} = 10^{53}$ erg, $\varepsilon_B \approx 10^{-3}$, $\varepsilon_e \approx 0.3$, 40% energy transfer from protons to electrons

Modeling a GRB afterglow

CR-only & test-particle (TP) shocks use unmodified velocity profiles

Problem: they don't conserve momentum or energy flux

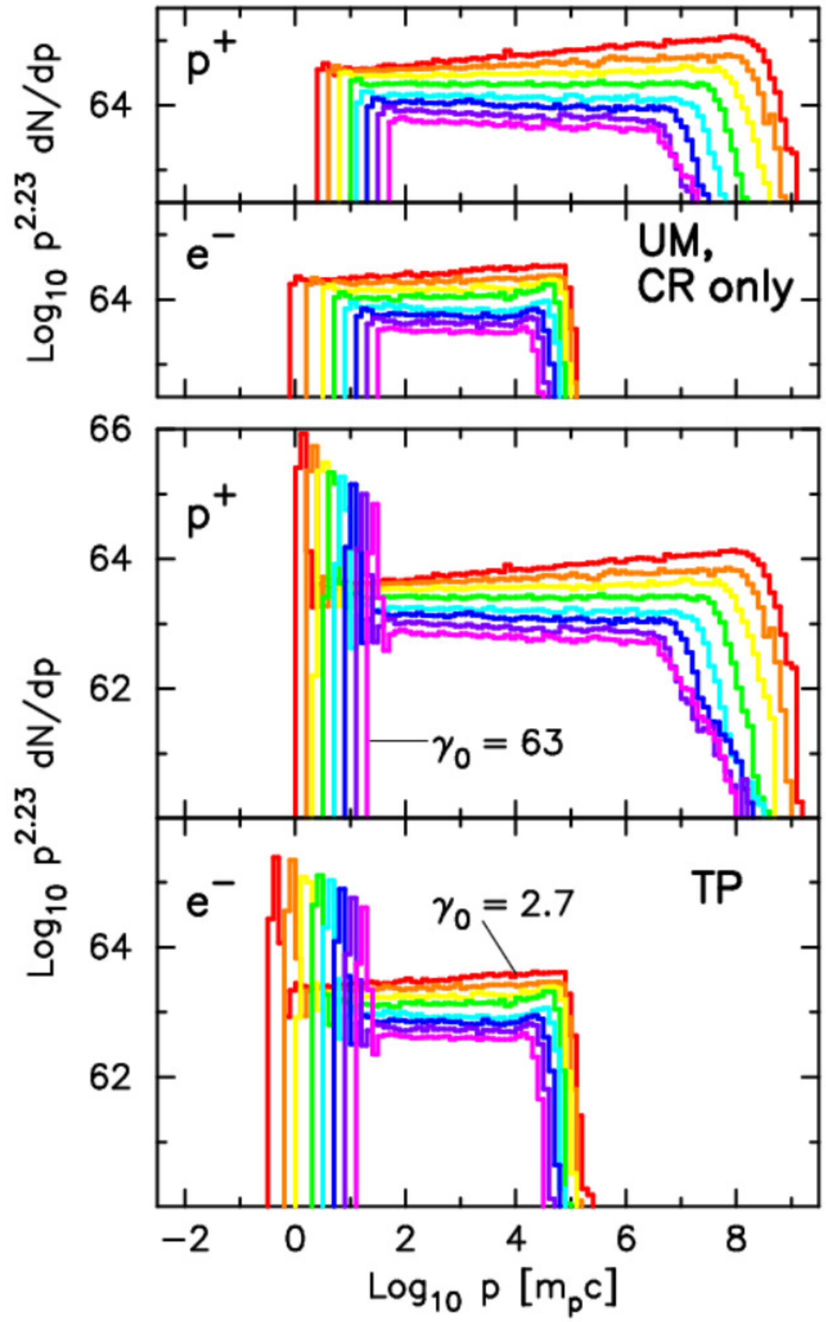


Modeling a GRB afterglow

CR-only & test-particle (TP) shocks use unmodified velocity profiles

Problem: they don't conserve momentum or energy flux

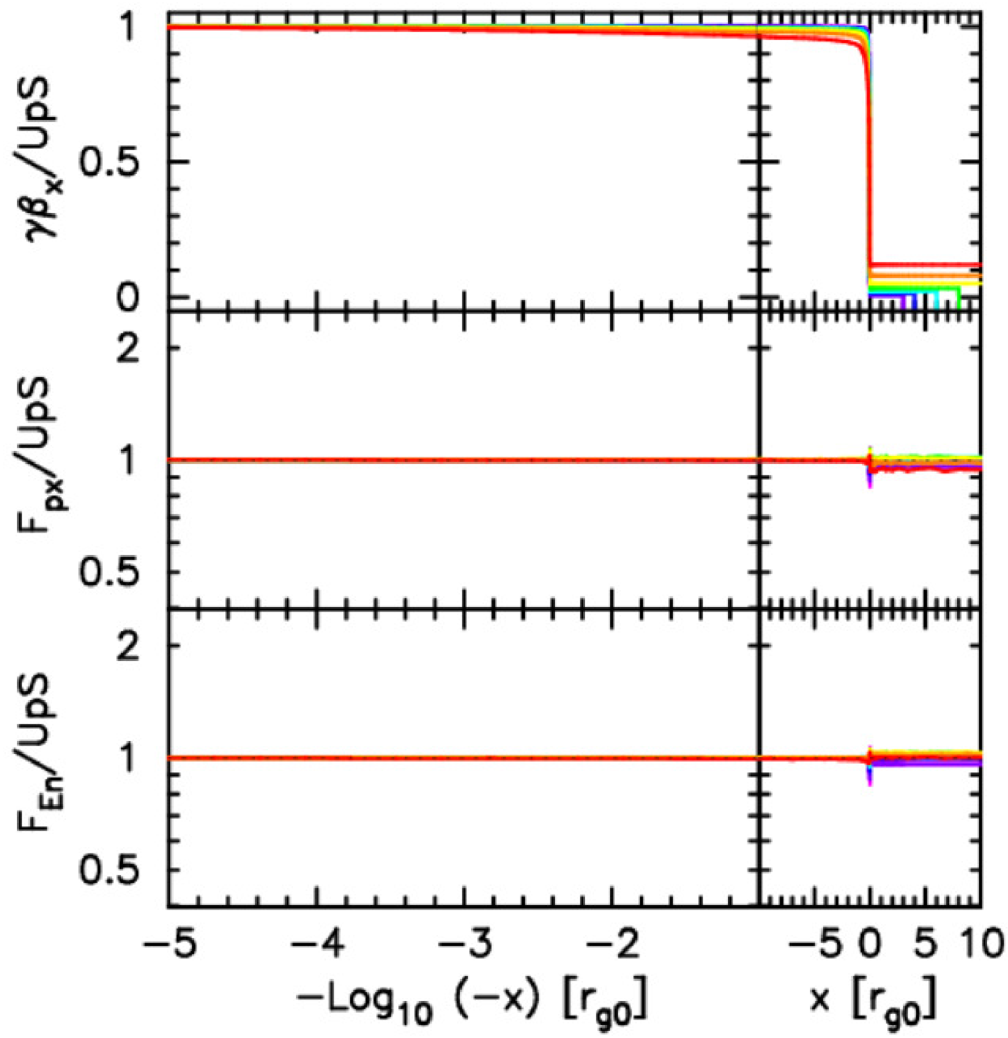
Solution: change number of CRs until they do



Modeling a GRB afterglow

Nonlinear (NL) shocks have a (short) precursor due to CRs upstream of shock

Enough to conserve fluxes (almost) everywhere

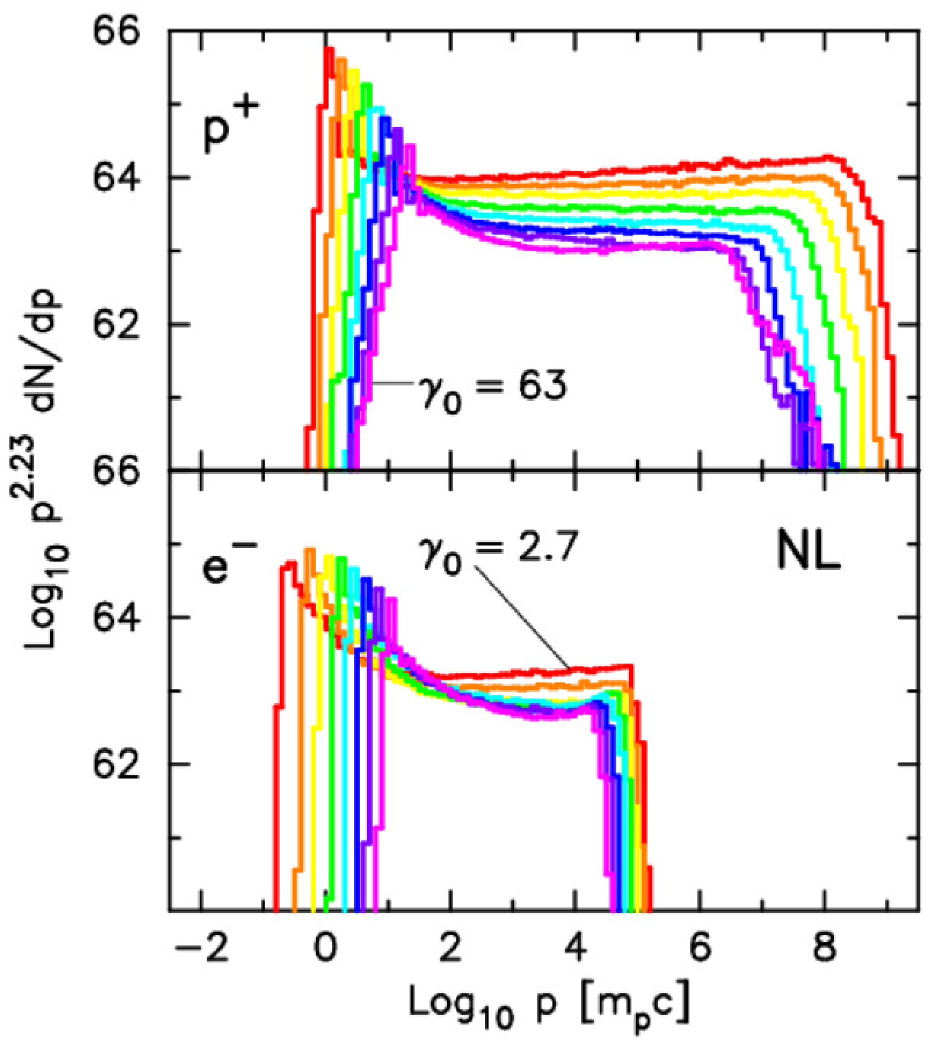


Modeling a GRB afterglow

Nonlinear (NL) shocks have a (short) precursor due to CRs upstream of shock

Enough to conserve fluxes (almost) everywhere

Particle spectra more complex than CR-only or TP



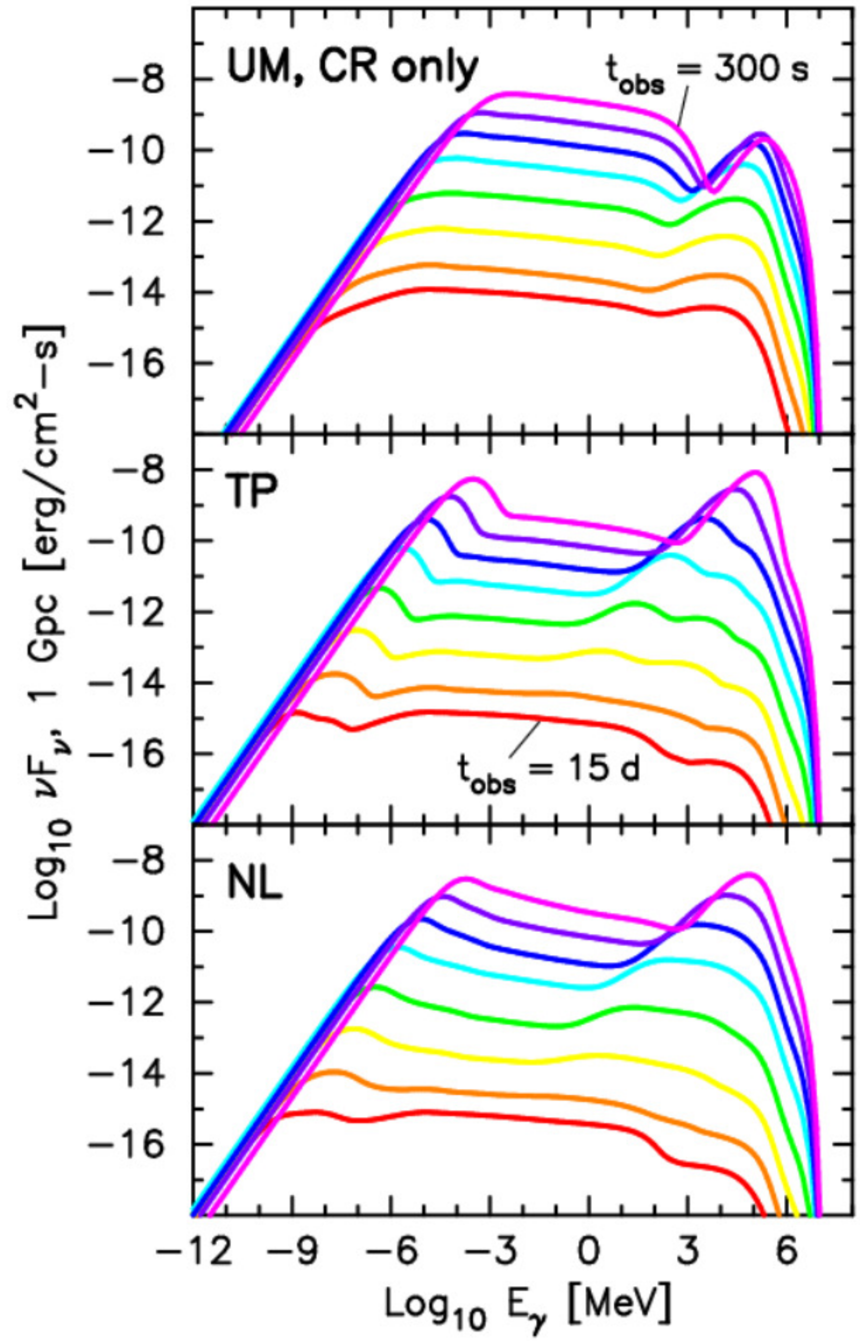
Modeling a GRB afterglow

3 photon processes:

- Synchrotron
- p-p collision
- Inverse Compton (SSC, IC-CMB & IC-ISRF)

Resultant spectra reflect electron spectra

Note how important thermal population is to SSC emission—factor of 30 difference!

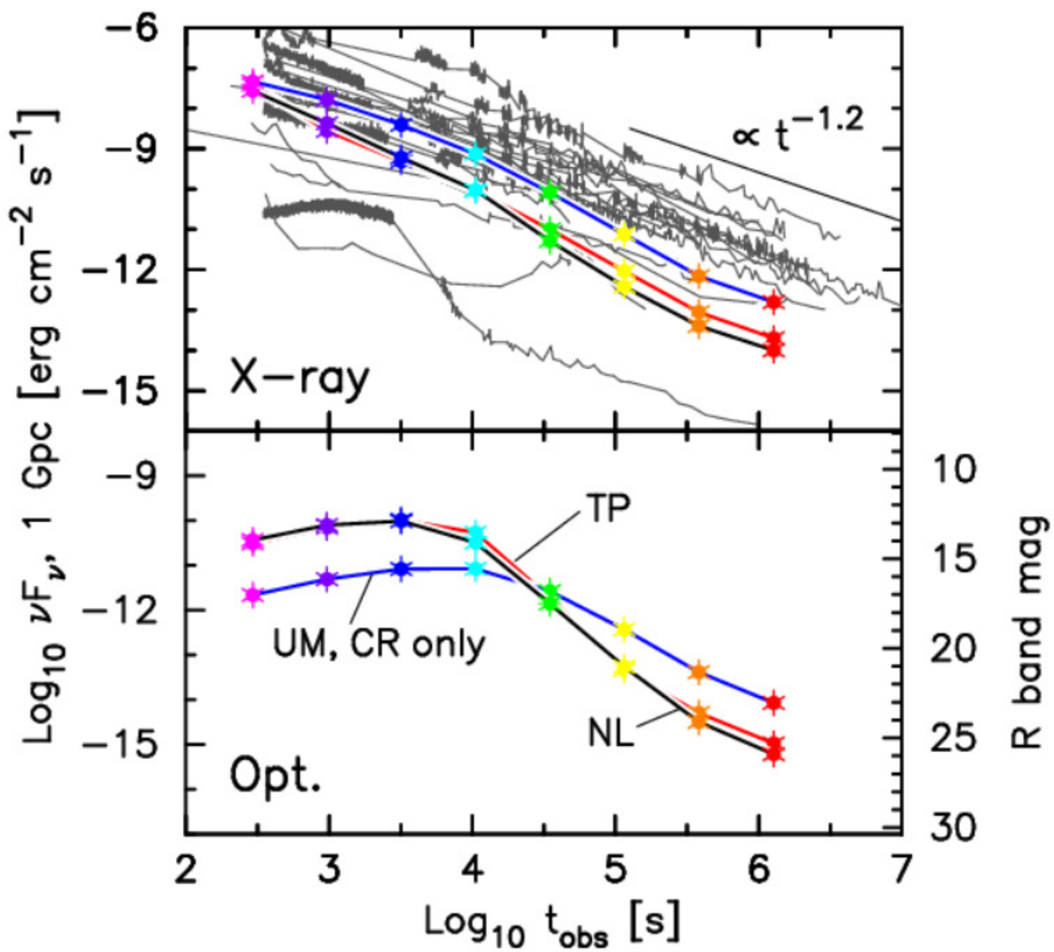


Modeling a GRB afterglow

X-ray light curves in broad agreement with observations

Optical light curves of TP & NL models show steep break from passage of thermal peak—much steeper ($t^{-2.6}$) than predicted by traditional model ($t^{-1.2}$)

Surprising amount of overlap in TP and NL models, given how different particle spectra looked

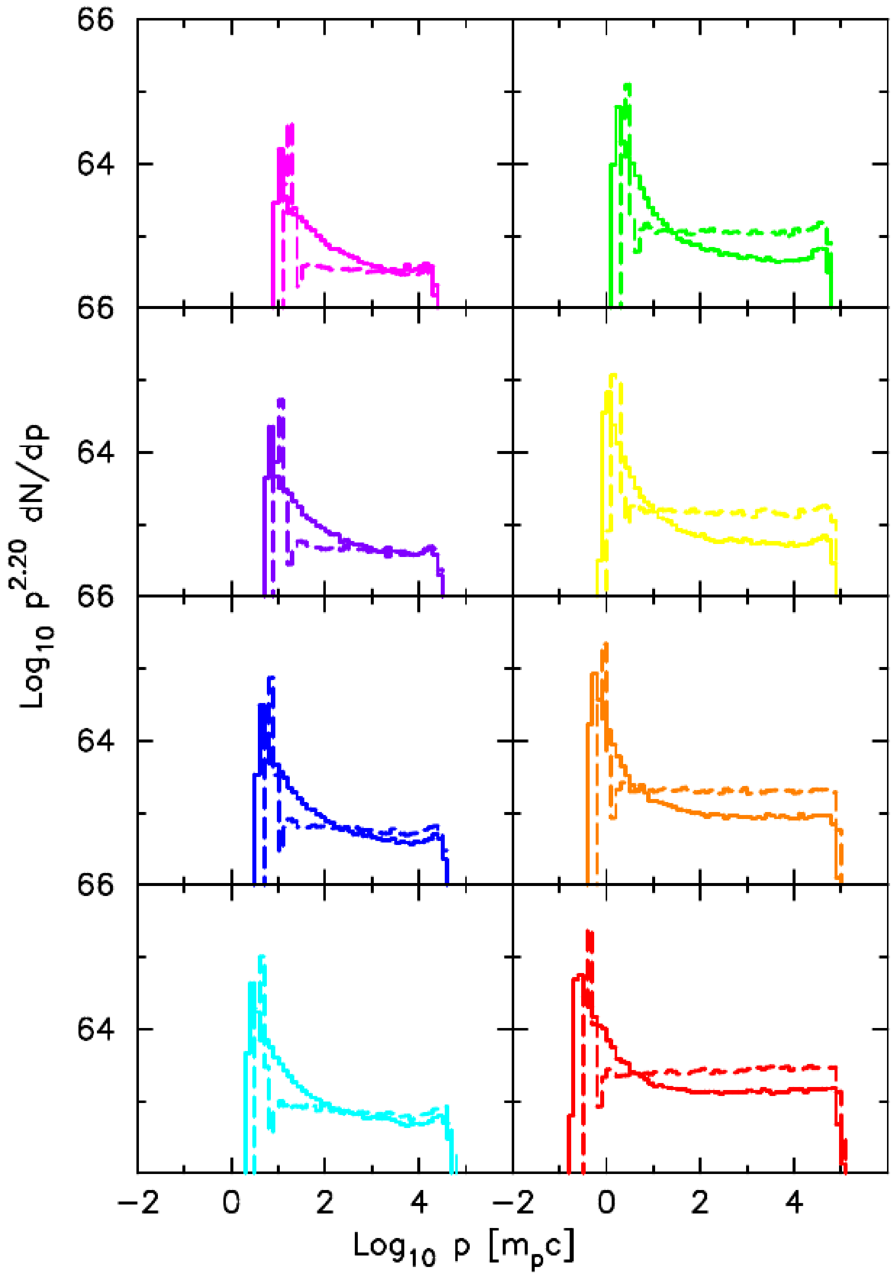


Modeling a GRB afterglow

Reason for overlap is clear when particle spectra are compared

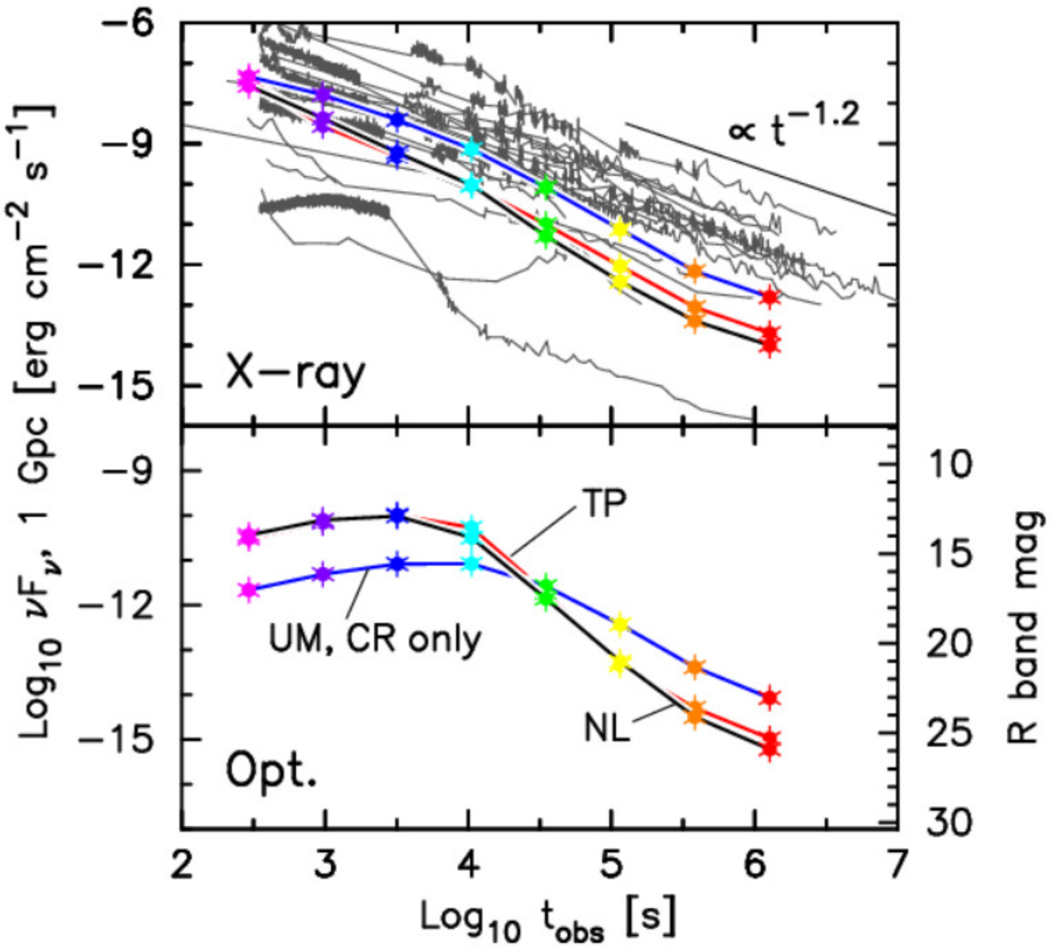
In reducing TP spectra to conserve fluxes, normalization of CR tail winds up almost identical to that of NL shocks

Further investigation planned to explore whether this is coincidence or physically significant



Modeling a GRB afterglow

Can’t use light curves to differentiate between TP and NL models, unfortunately

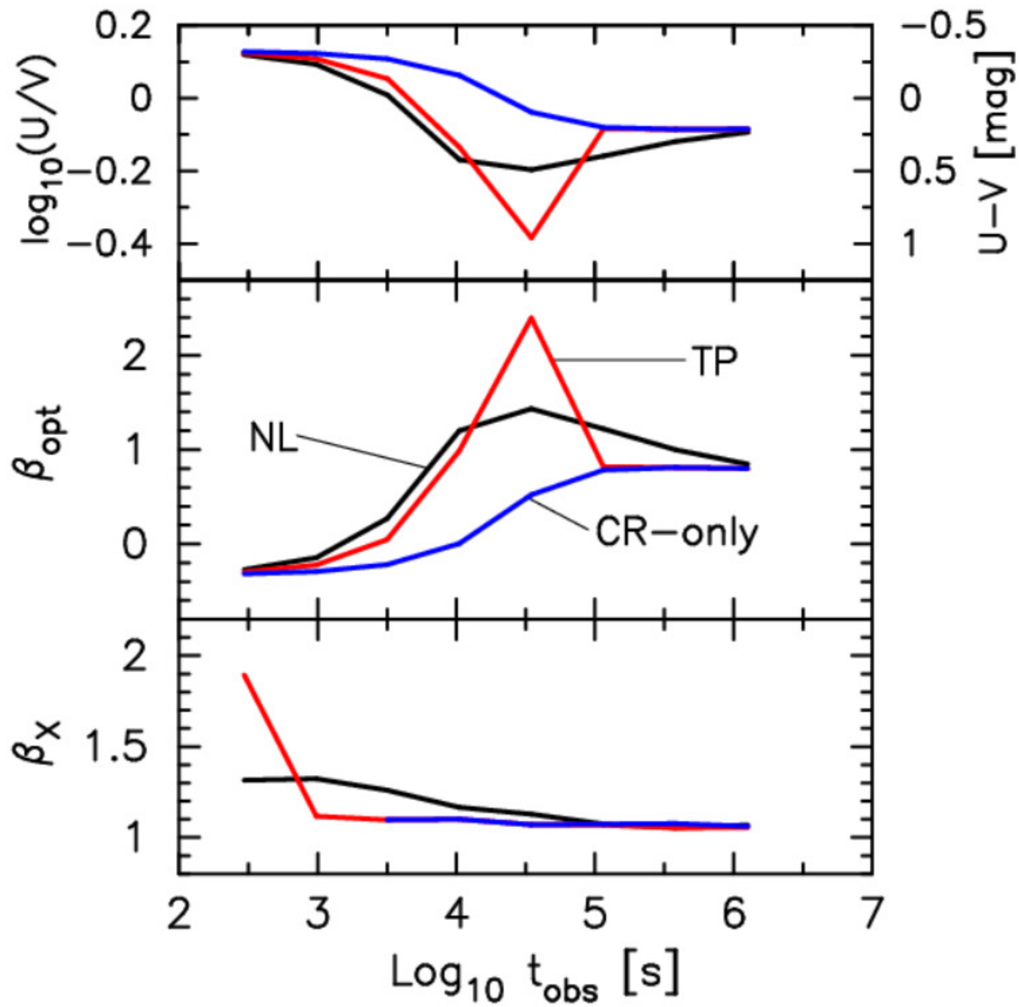


Modeling a GRB afterglow

Can't use light curves to differentiate between TP and NL models, unfortunately

Can use change in spectral index β ($F_\nu \propto \nu^{-\beta}$)

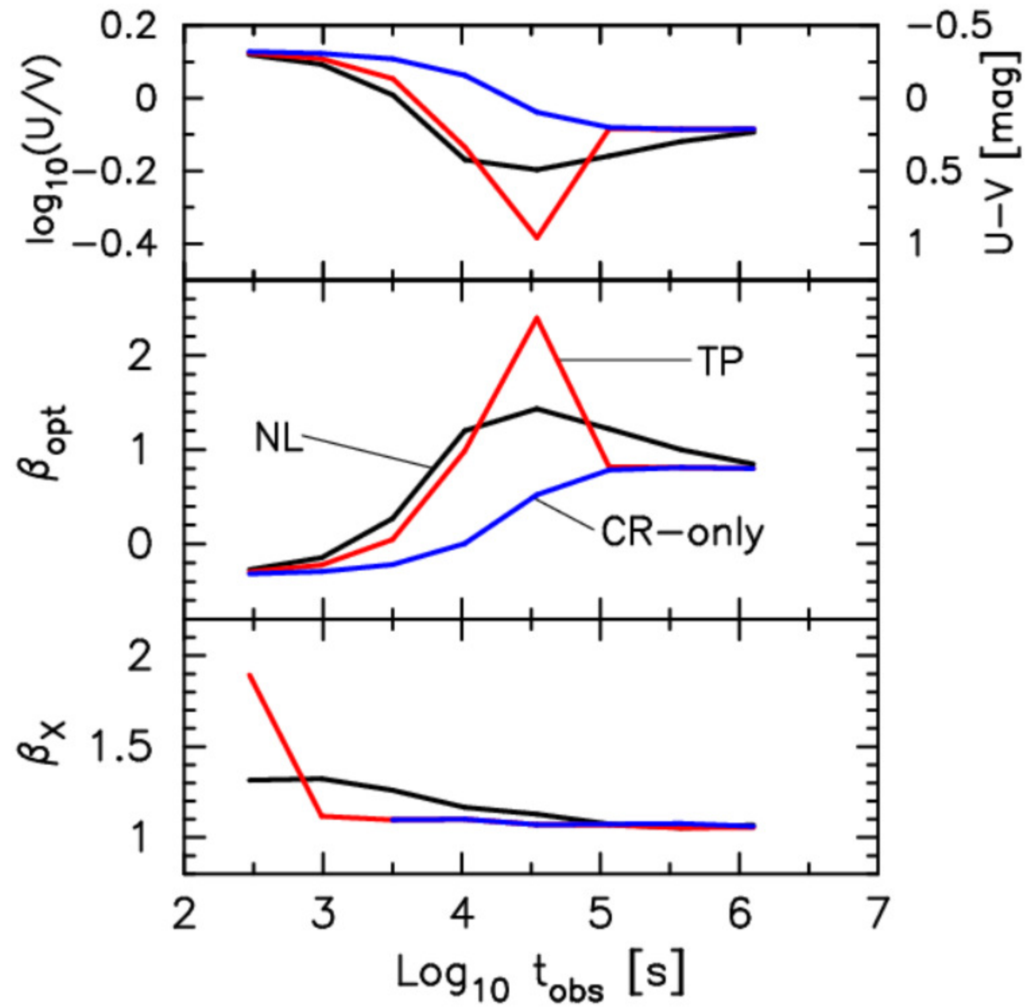
Thermal peak makes β non-monotonic—height/width of peak related to efficiency of acceleration



Modeling a GRB afterglow

X-ray & optical show similar hard-soft-hard shape, but at different times; need to model earlier (i.e. faster) shocks to capture X-ray peak

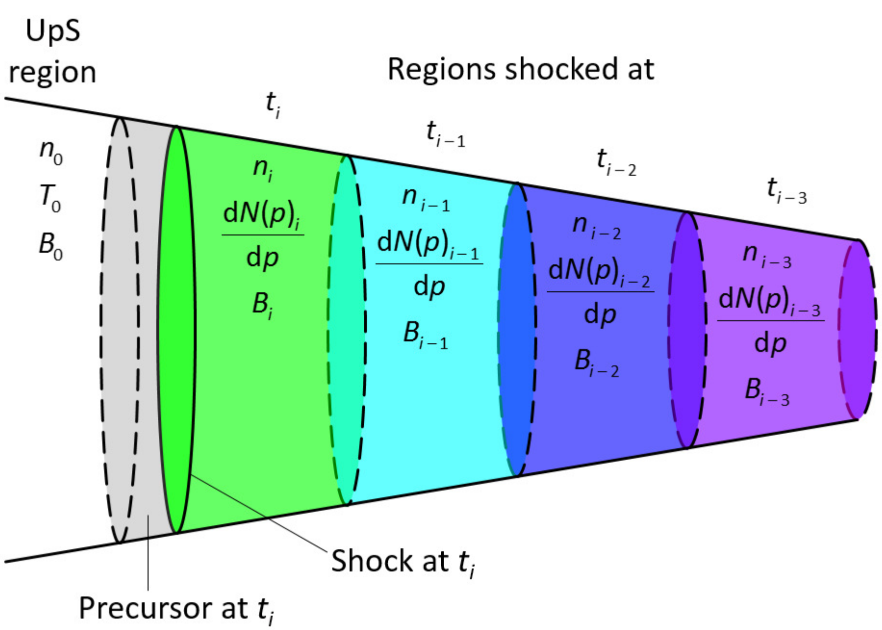
Late-time β not the same for optical & X-ray, despite both coming from CR population

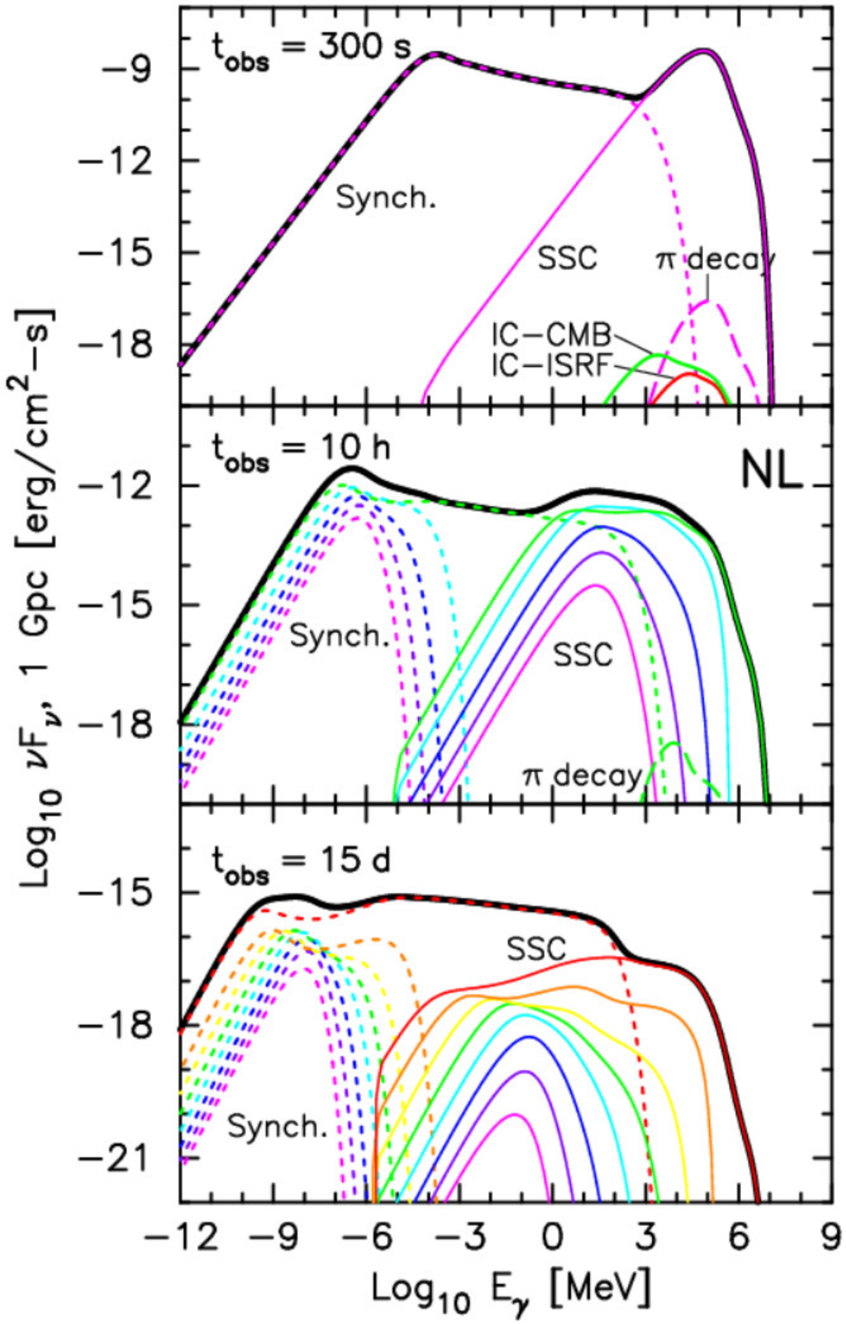


Modeling a GRB afterglow

X-rays always from highest-energy CRs

Optical from more than one zone, including material shocked long ago





Modeling a GRB afterglow

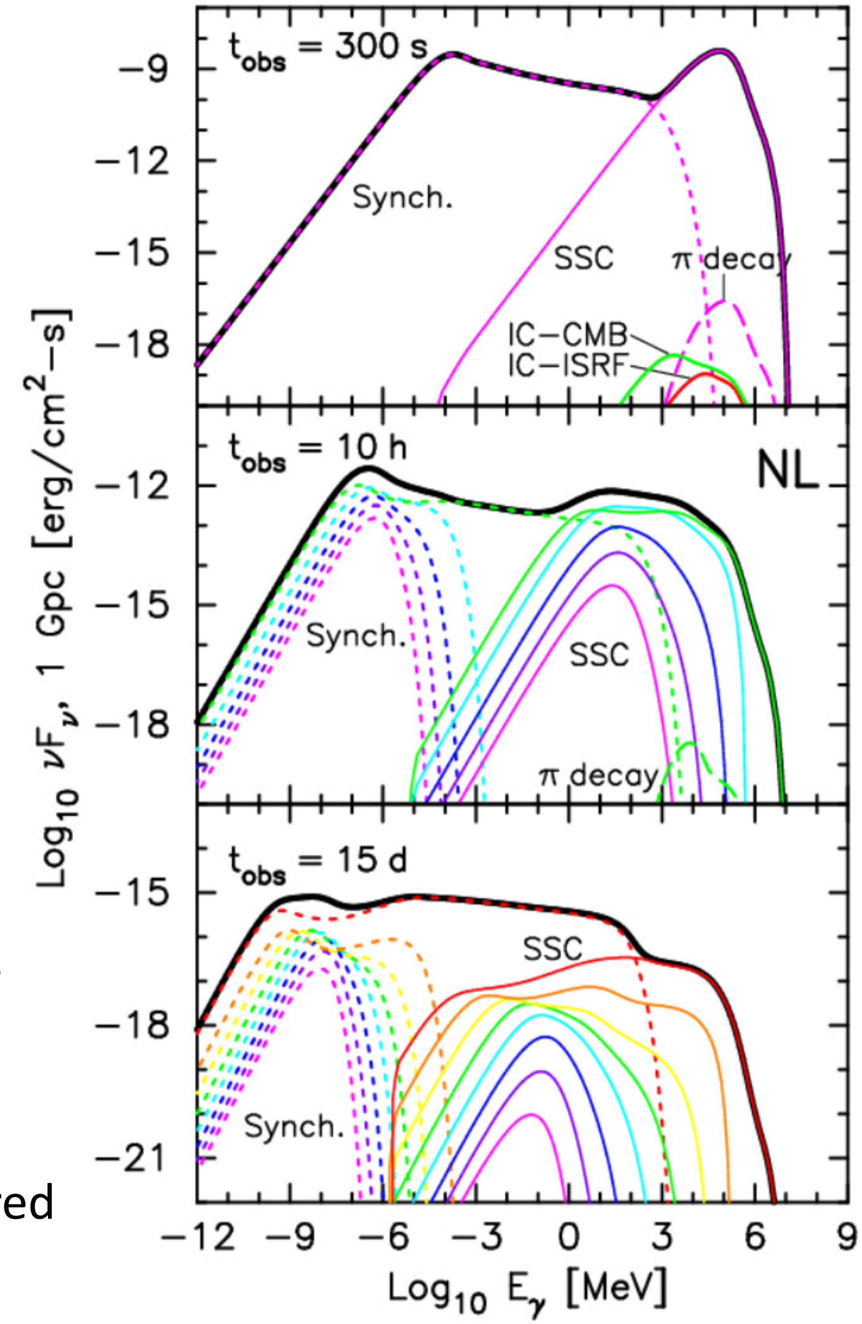
X-rays always from highest-energy CRs

Optical from more than one zone, including material shocked long ago

Later, optical photons come from steep parts of CR spectrum

Different origins can explain "uncoupled" X-ray/optical afterglows

(Note importance of SSC at high energies compared to other processes)



Summary

If CR acceleration by relativistic shocks efficient, **must** consider nonlinear interaction between shock & CRs

Shape of electron, photon spectra strongly affected by thermal particles and by presence of precursor: no longer simple power laws

Expect hard-soft-hard spectral transitions in X-ray & optical

X-ray & optical light curves have different sources, so show different behavior

Bold (premature?) prediction: model proposed here has more explanatory power than standard one-zone synchrotron model