Nonlinear cosmic ray acceleration in GRB afterglows

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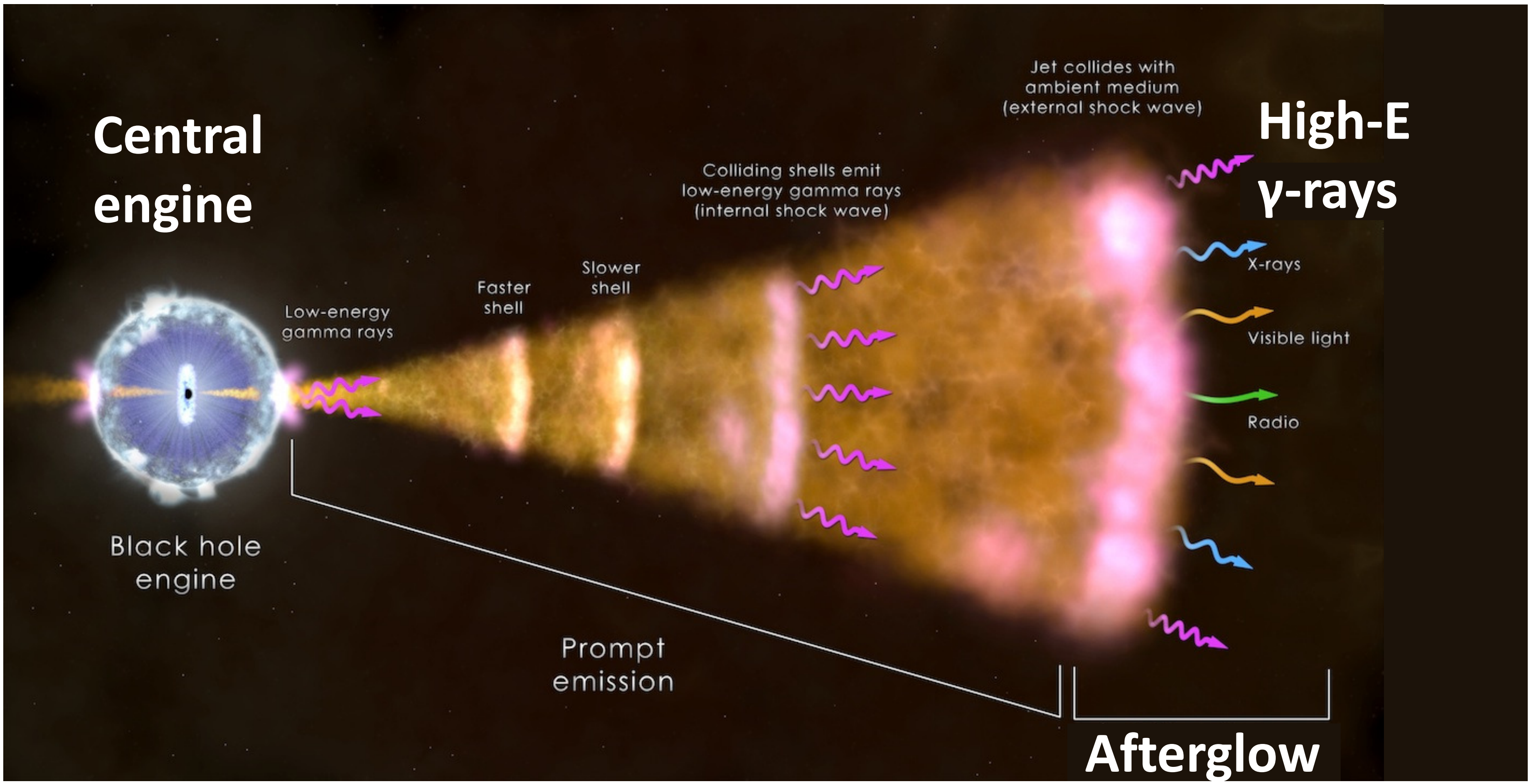
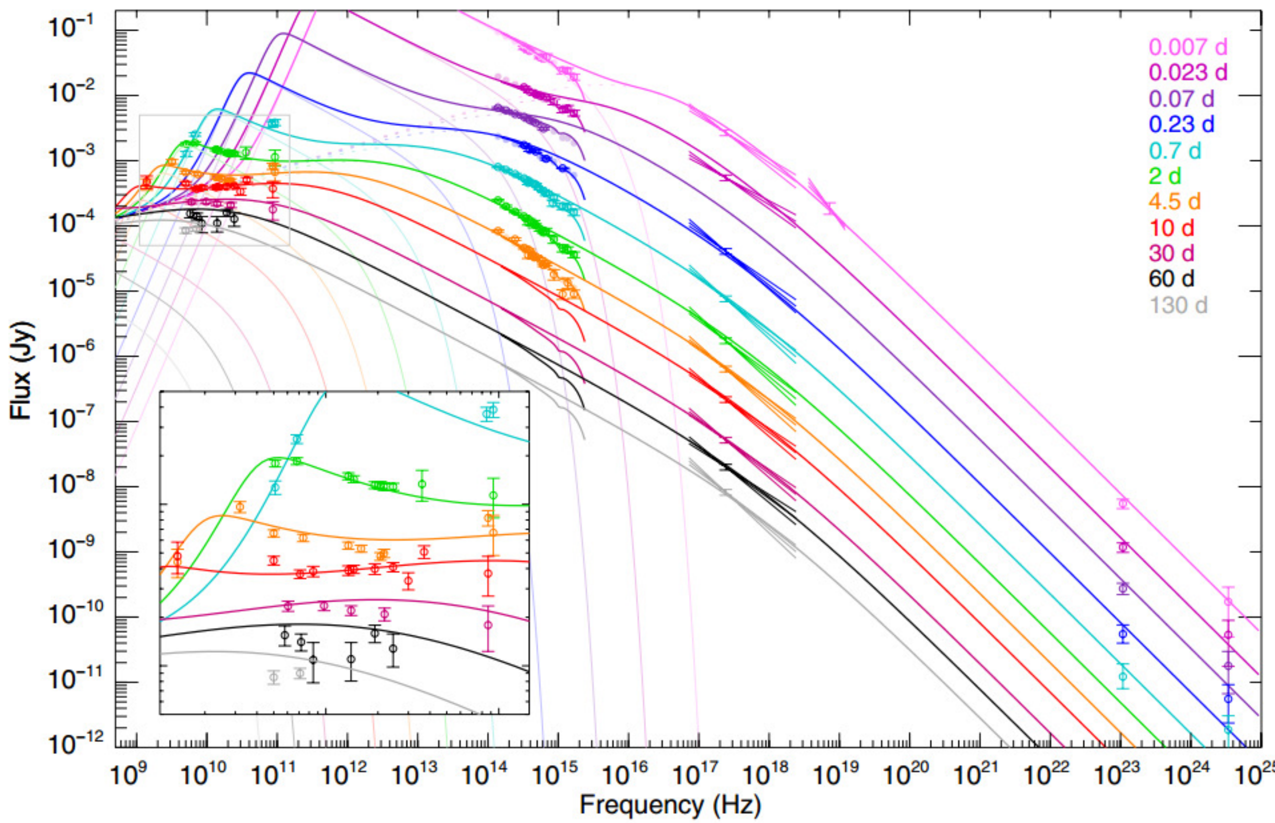
Background

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



Background

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

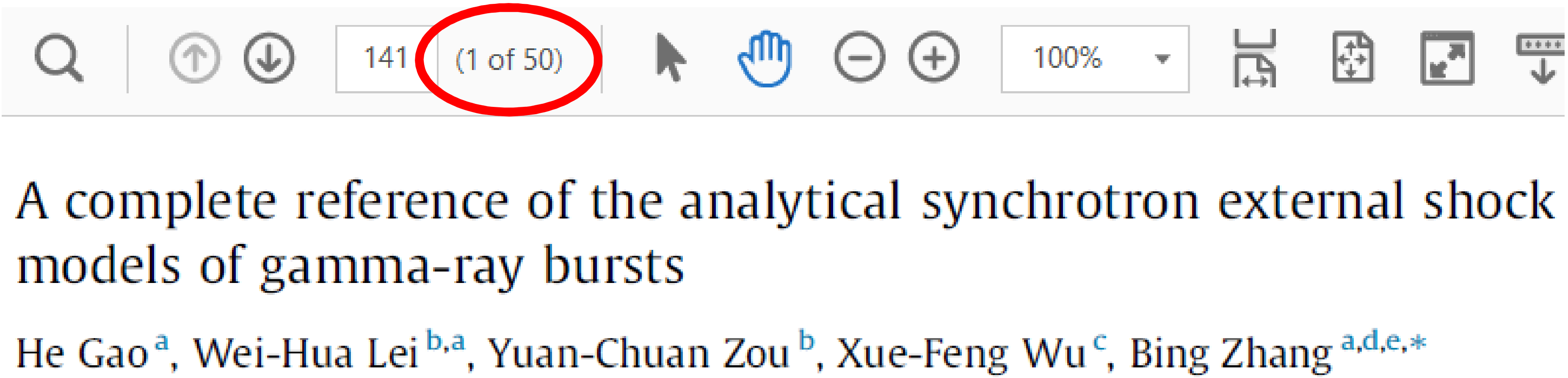


Perley et al. (2014)
(2014ApJ...781...37P)

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.

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,*]

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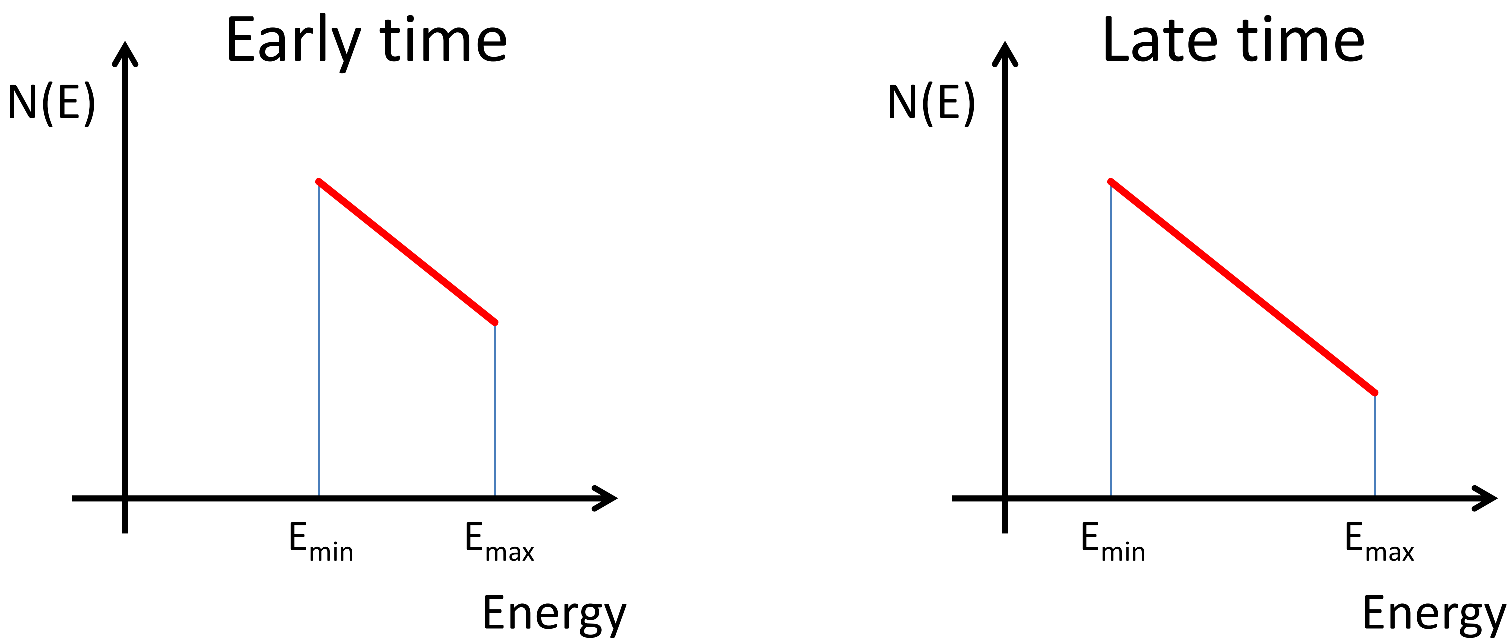
Many different models to explain broadband spectra and light curves

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



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Many different models to explain broadband spectra and light curves

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

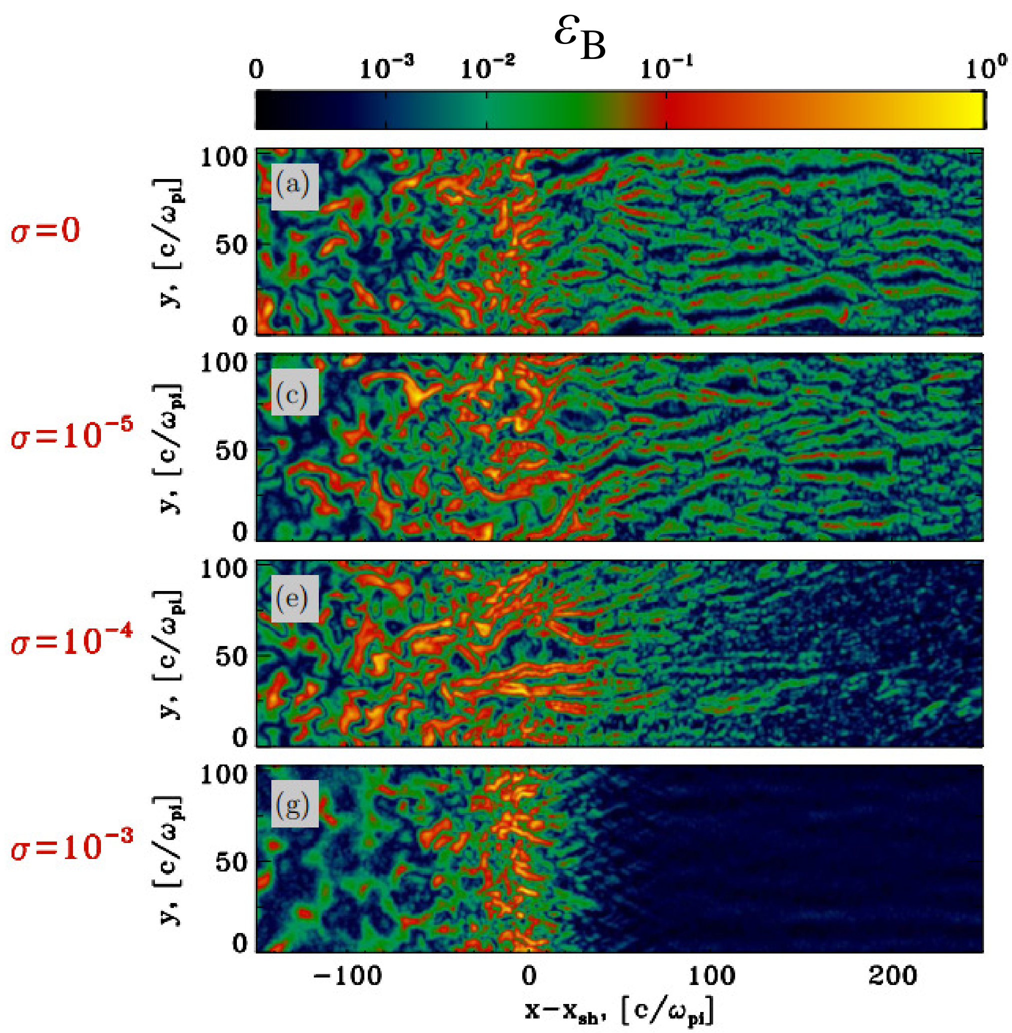
(Protons not even considered by afterglow community)

Mostly fine if (1) all relativistic particles are CRs, (2) acceleration inefficient, (3) magnetic field is neglible

Background

(Particle-in-cell)

Per PIC simulations, this is not true



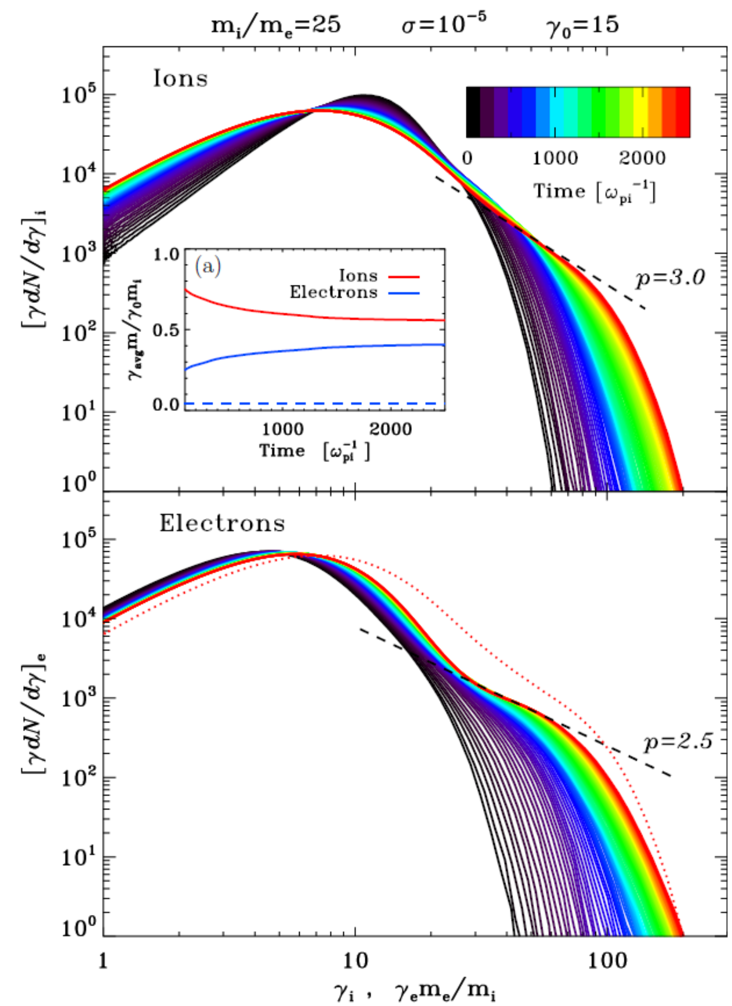
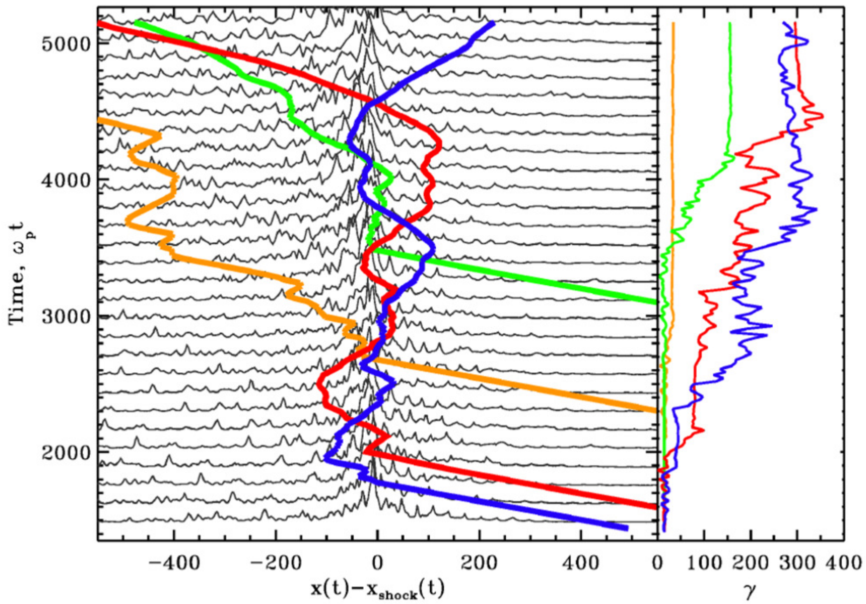


Figure 11. Temporal evolution of the post-shock particle spectrum

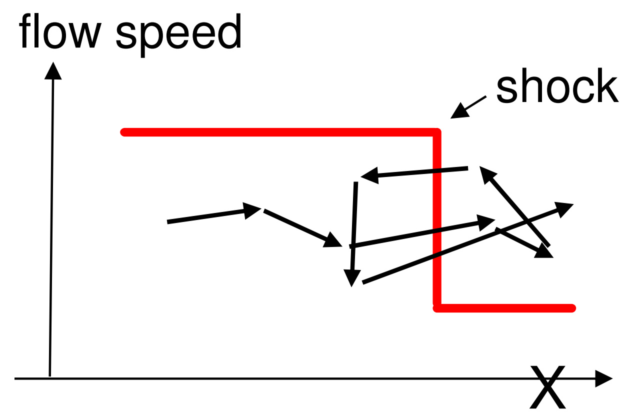
Sironi et al. (2013) (2013ApJ...771...54S)

Background

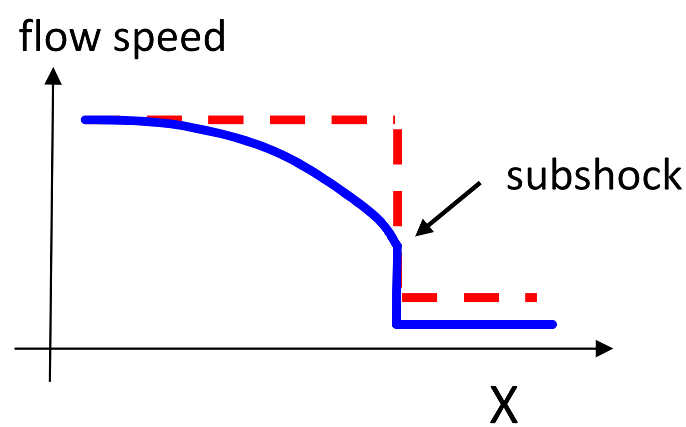
Strong B-field turbulence in vicinity of shock can scatter particles back into upstream region (← diffusive shock acceleration, or **DSA**)



Spitkovsky (2008) (2008ApJ...682L...5S)



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



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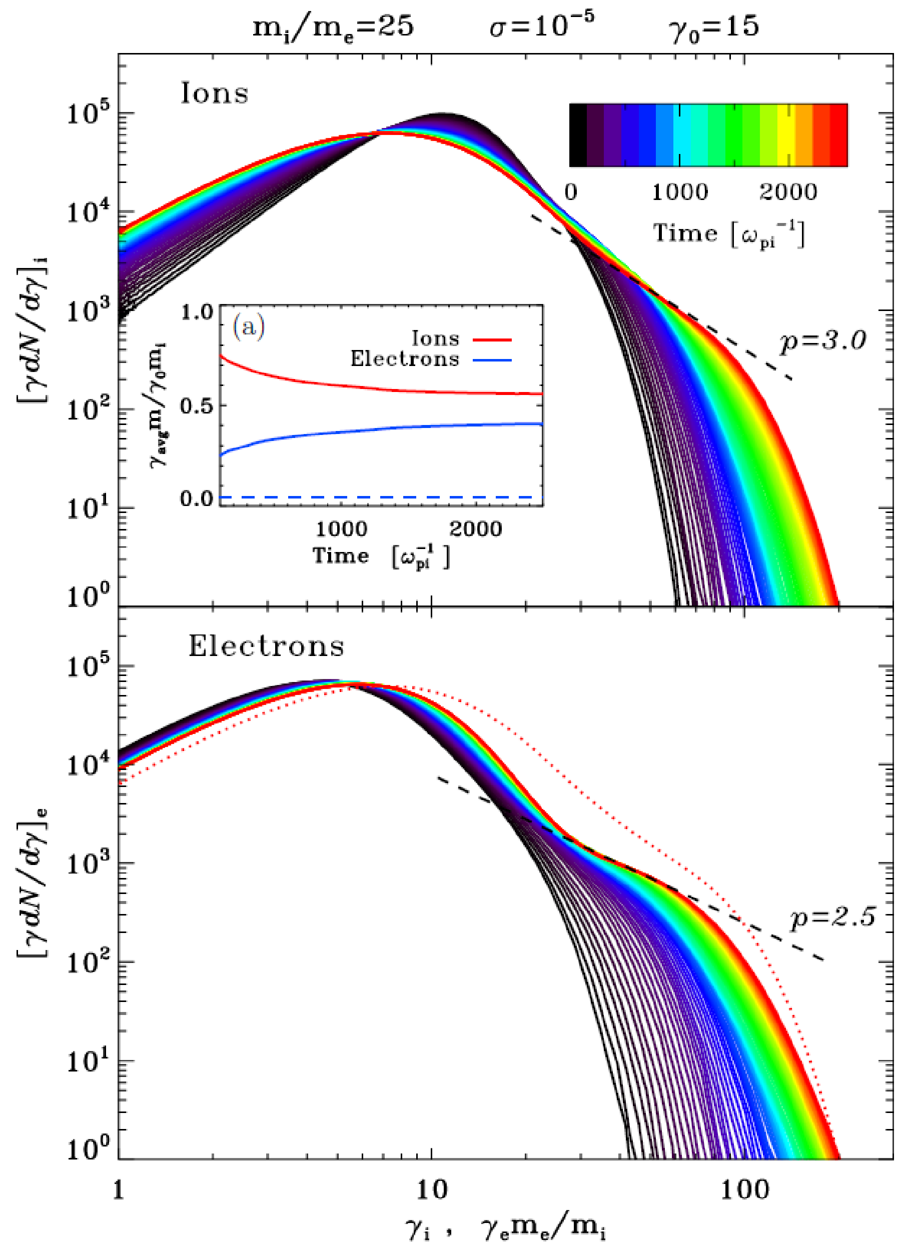
Interaction between shock, B-field turbulence, and accelerated particles important!

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



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

Additionally, ≈40% of UpS kinetic energy transferred into electrons crossing shock

All particles, in all species, are relativistic & can enter acceleration process

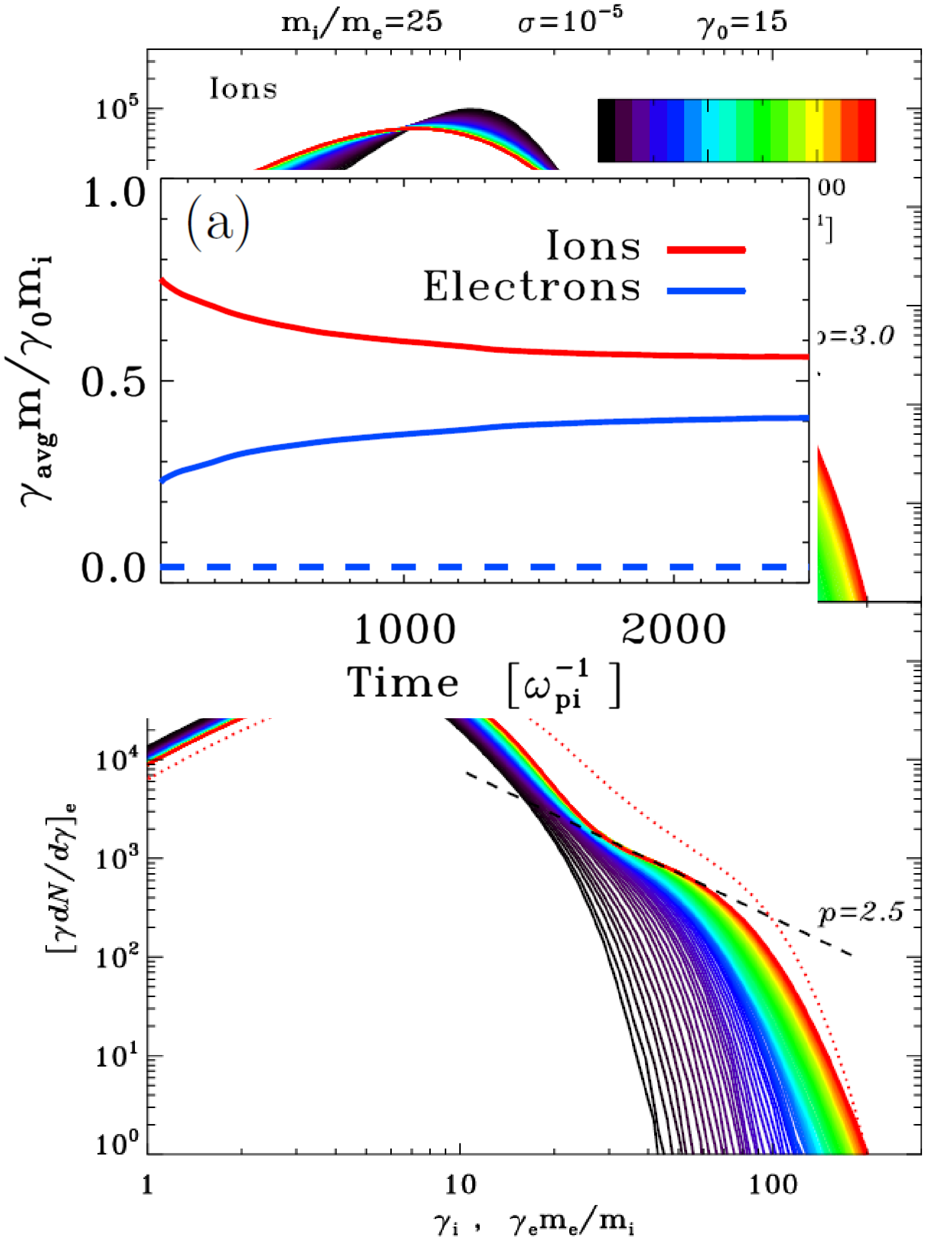


Figure 11. Temporal evolution of the post-shock particle spectrum

Monte Carlo approach

Problem: PIC simulations can't explore UHECR production

- Too much physics to model large volumes/times

Solution: parametrize microphysics with a Monte Carlo code

- Assume scattering prescription, & diffusion coefficient

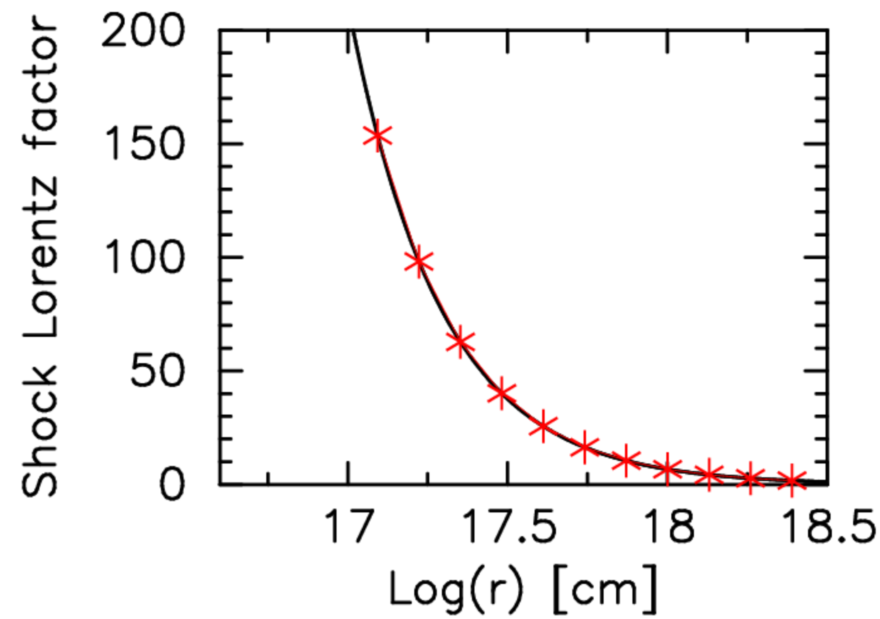
Key assumptions of MC code used here:

- Bohm diffusion: particles accumulate 90° of deflection in one gyroradius ($\lambda_{mfp} \propto$ momentum)
- Magnetic turbulence: present, self-generated, able to ensure above scattering

Can compute to arbitrary energies using personal computer, since PIC simulations tell us how injection occurs

Modeling a GRB afterglow

Use Blandford–McKee solution for hydrodynamical base



At select times (i.e. shock ages), model DSA using Monte Carlo code

Calculate photon spectra

Three models discussed here:

- CR-only shocks (not a serious contender)
- Test particle shocks (inefficient CR acceleration)
- Nonlinear shocks (efficient CR acceleration)

Key parameters: $E_{iso} = 10^{53}$ erg, $\varepsilon_B \approx 10^{-3}$, $\varepsilon_e \approx 0.3$, 40% energy transfer from protons to electrons, $\sigma_0 \approx 0$

Modeling a GRB afterglow

Only protons/electrons (could do He/Fe, but haven't yet)

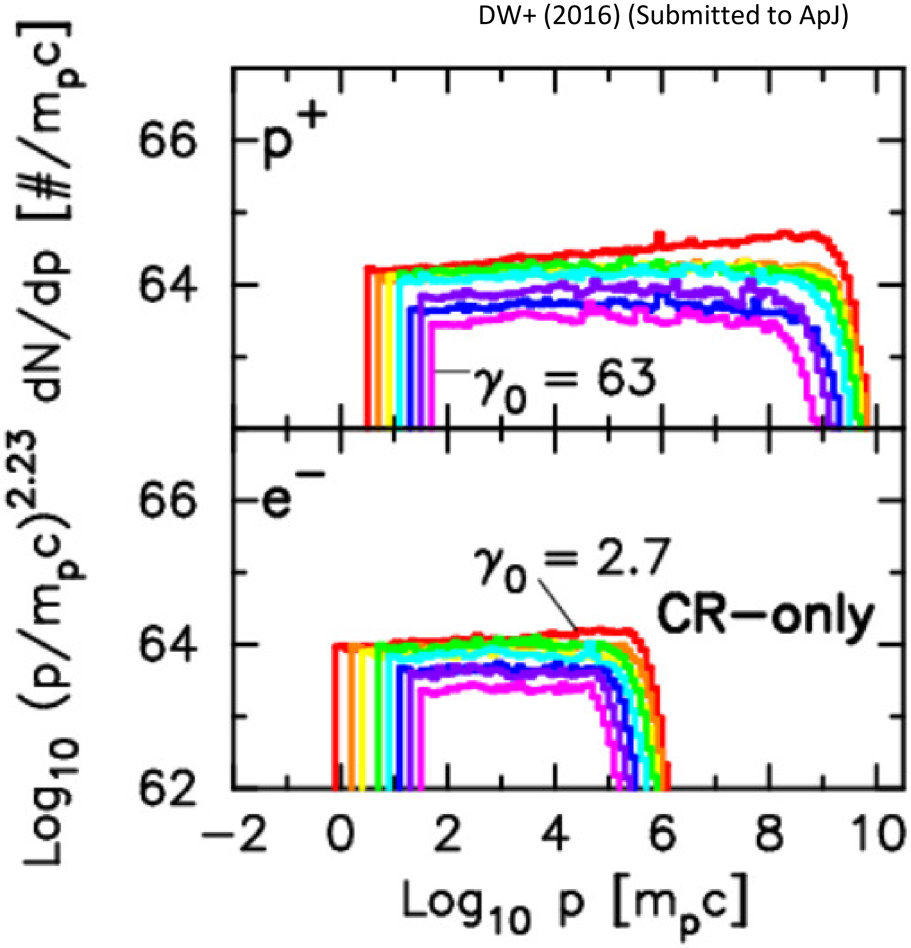
Protons time-limited

Electrons loss-limited

Proton $E_{max} \approx 10^{17}$-10^{19} eV, regardless of accel efficiency

If E_{iso} increases or Γ_{max} decreases, E_{max} of protons increases; 10^{20} eV plausible but (as yet) unconfirmed

DW+ (2016) (Submitted to ApJ)



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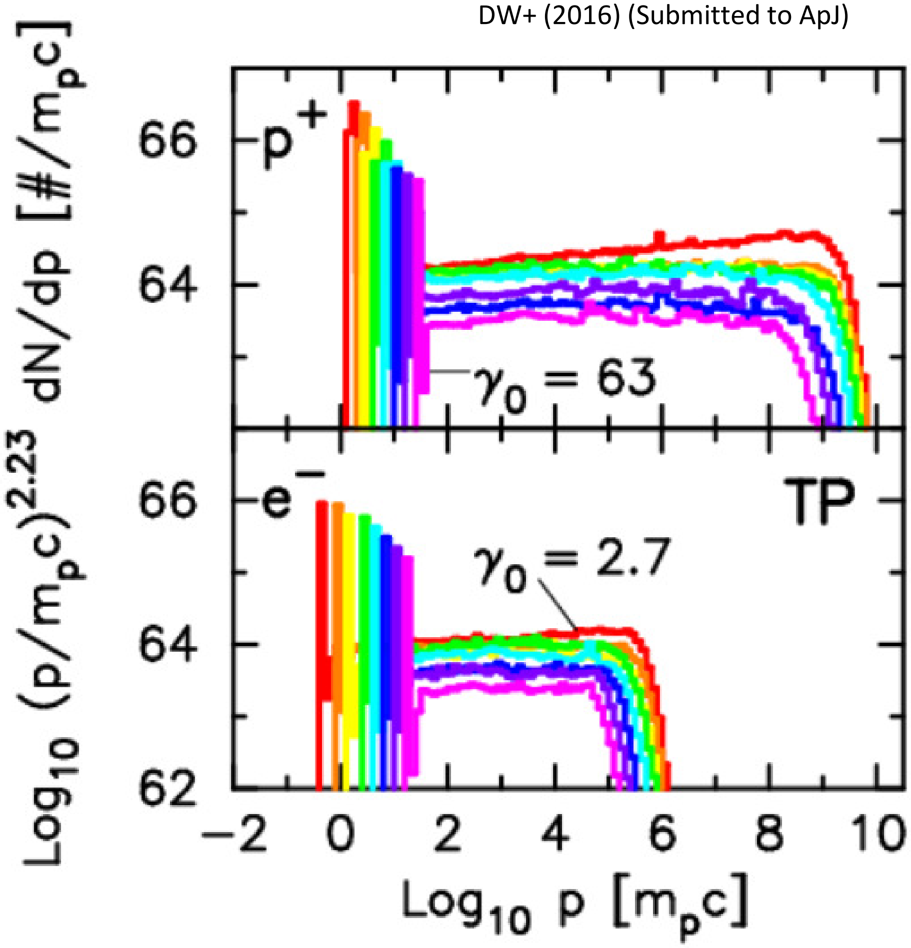

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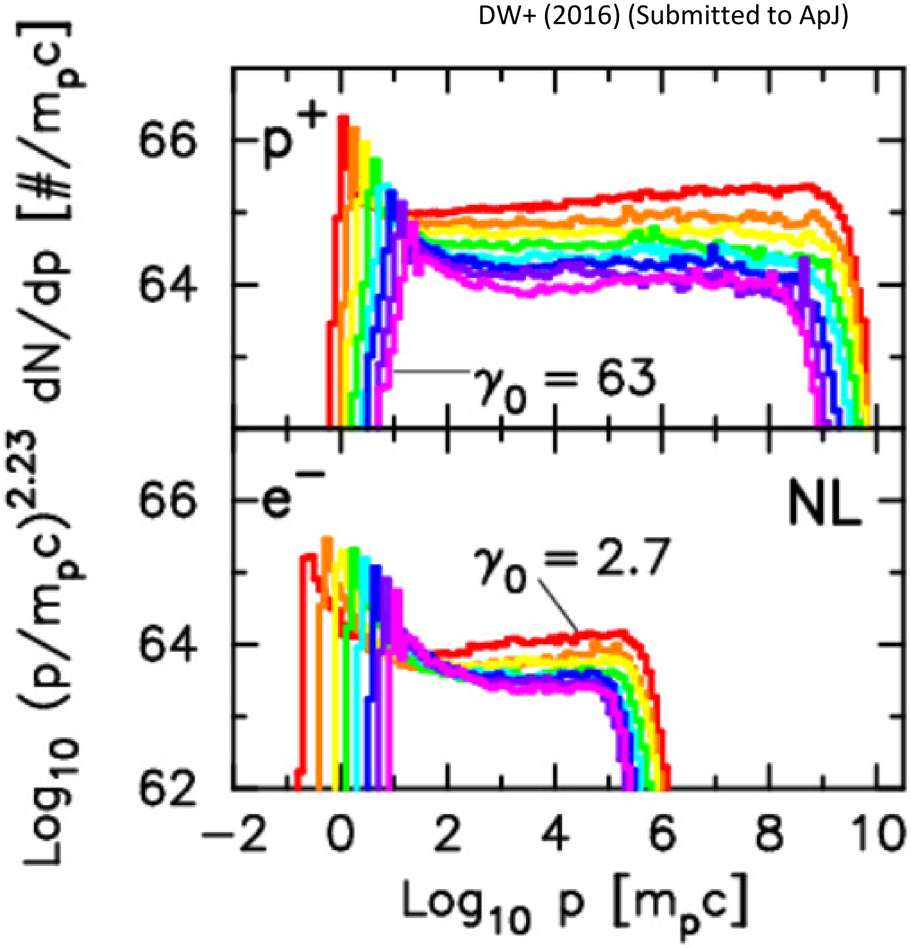

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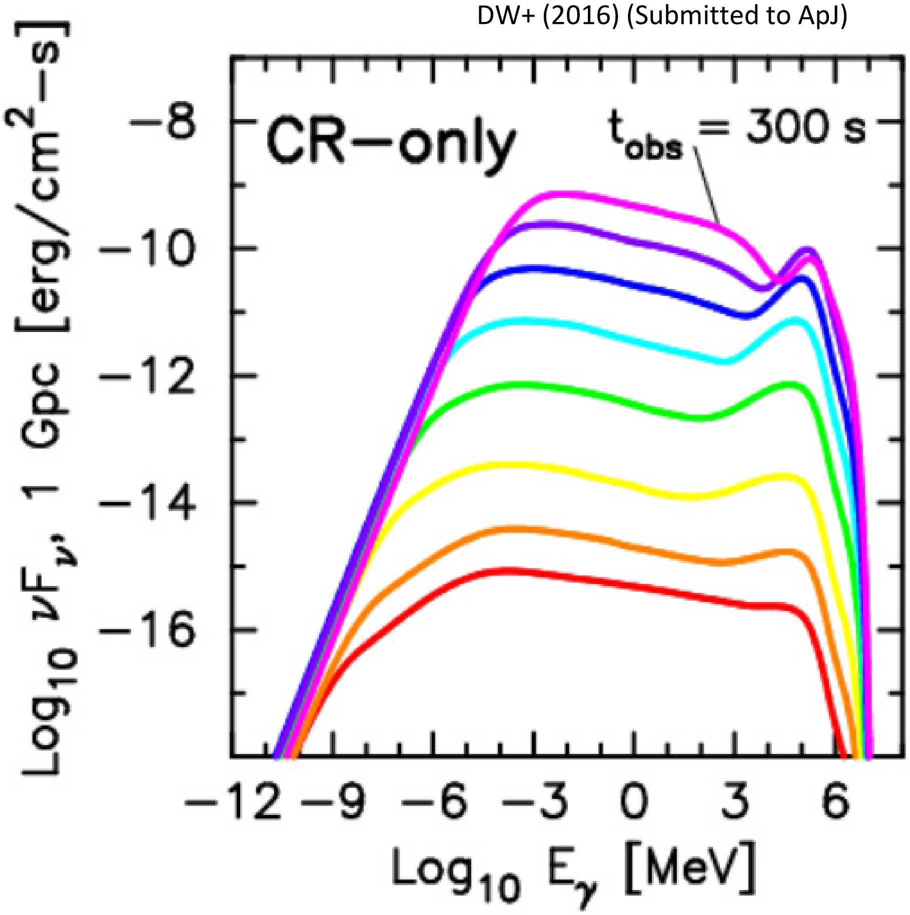

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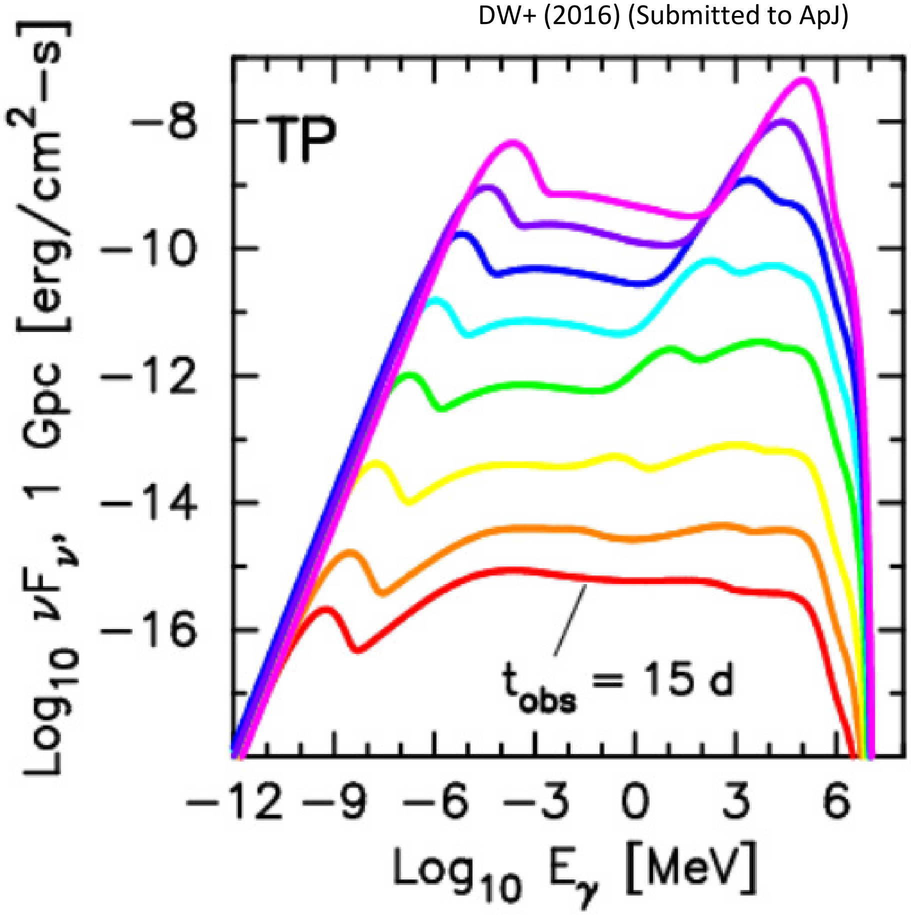

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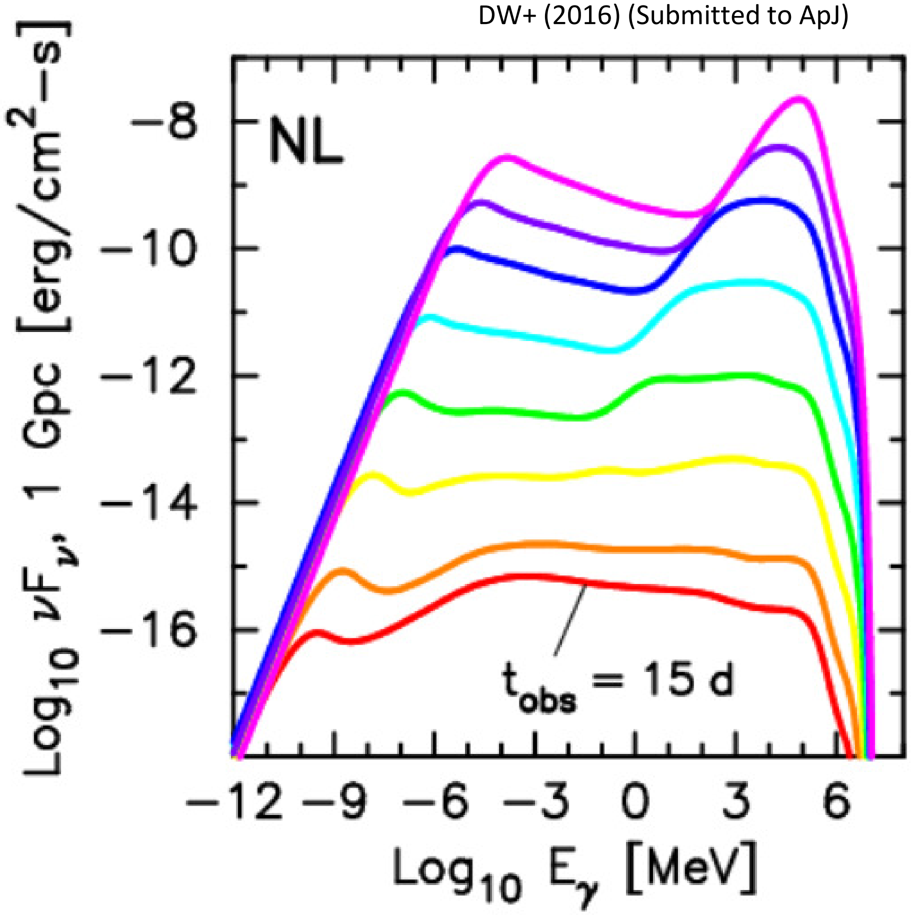


Summary

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

Time-limited proton acceleration reaches 10^{19} eV, with hope for 10^{20} eV if GRB parameters are right

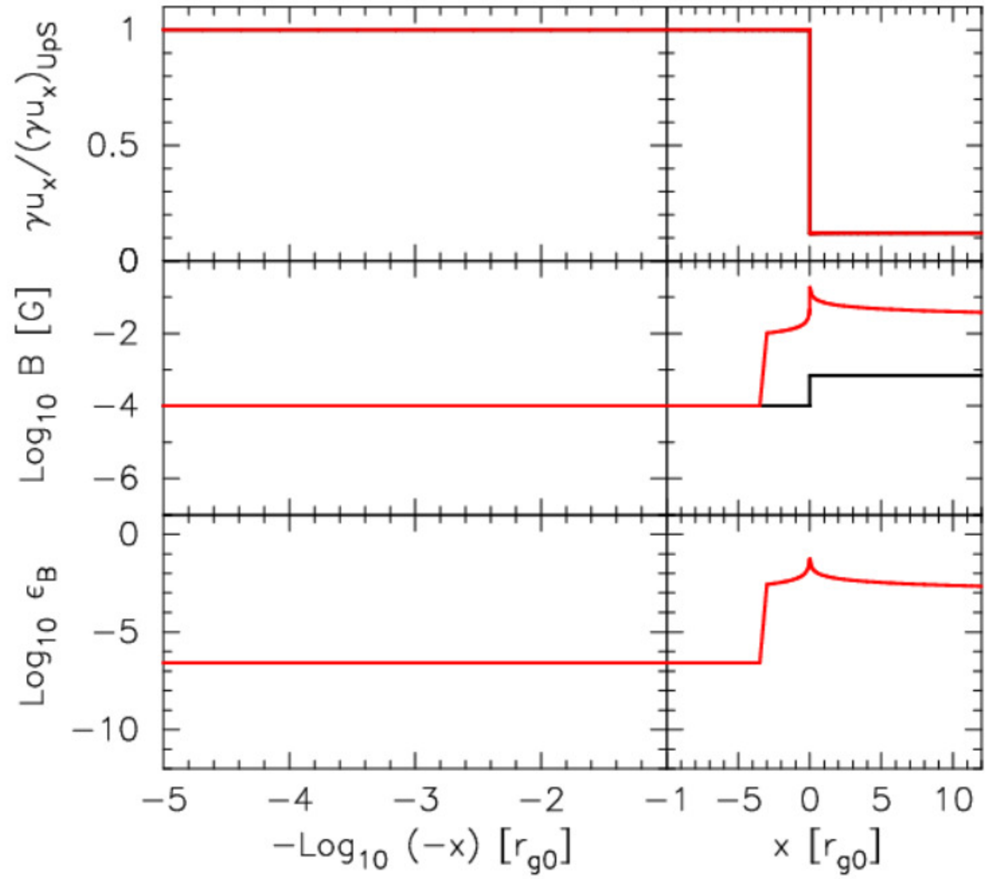
Don't forget low-energy particles. They're interesting, too!

Extension

PIC simulations, analytical work suggest magnetic field depends on position in shock frame:

- $\varepsilon_{max} \approx 0.1$
- $\varepsilon_B \propto (-x)^{-0.6}$ UpS from shock
- $\varepsilon_B \propto x^{-0.5}$ DwS from shock

Computation times increased by 50x (!)



Early results suggest E_{max} of protons unaffected (factor < 2)