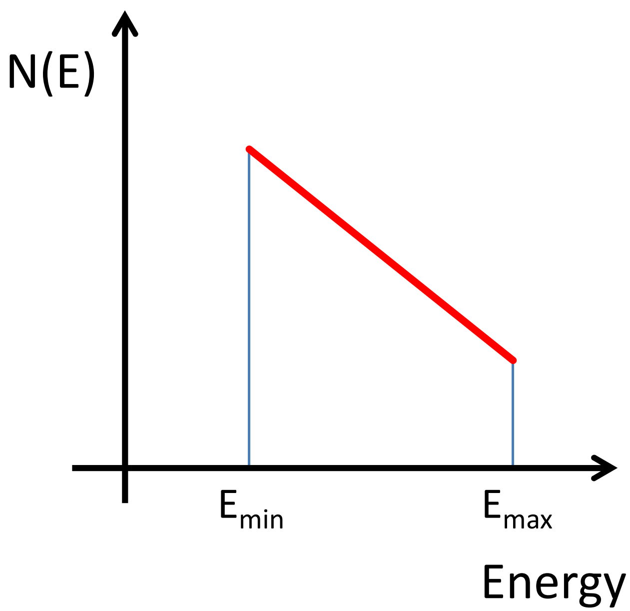
Thermal electron production and consequences for GRB afterglows

Don Warren
RIKEN – ABBL
PACIFIC meeting
16 Feb 2018

If you remember *one* thing…



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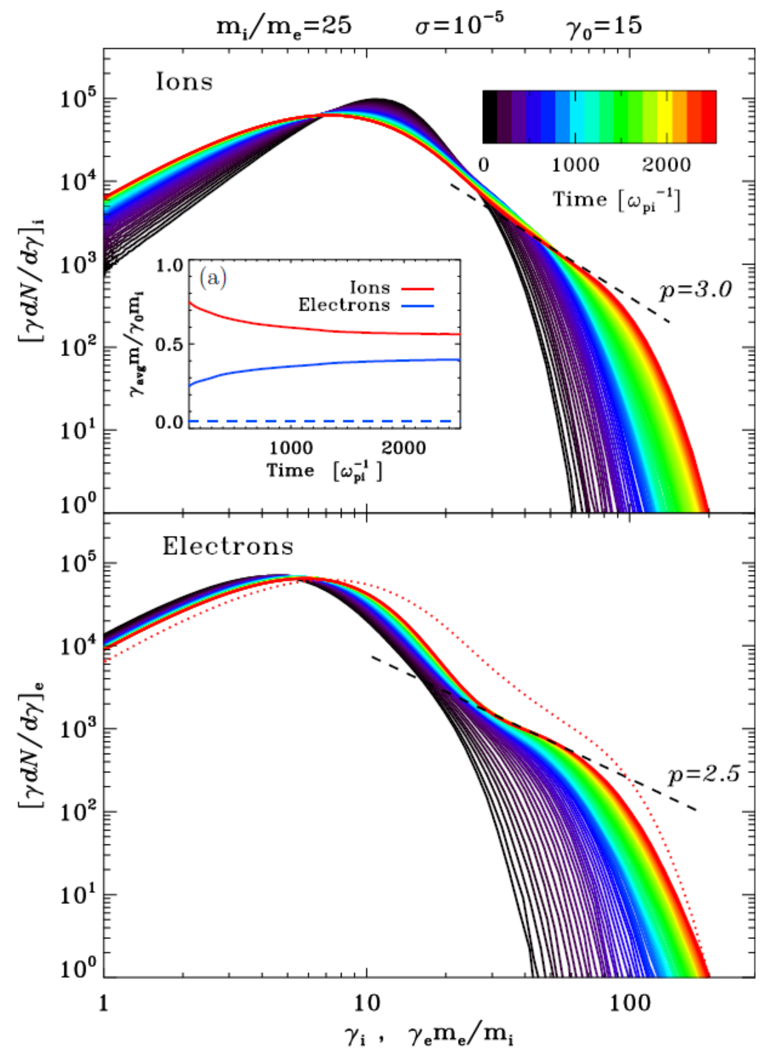
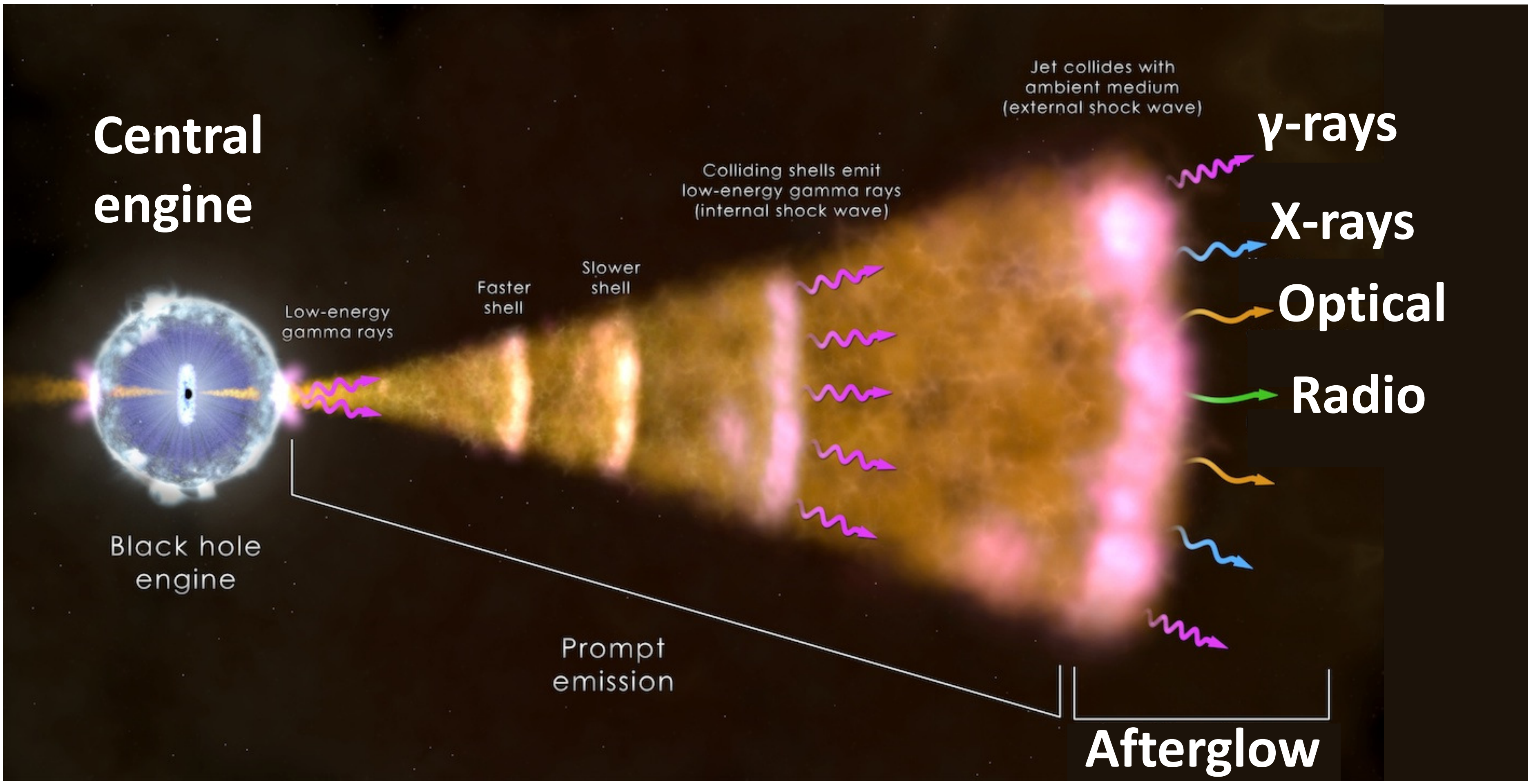


Figure 11. Temporal evolution of the post-shock particle spectrum

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

Background

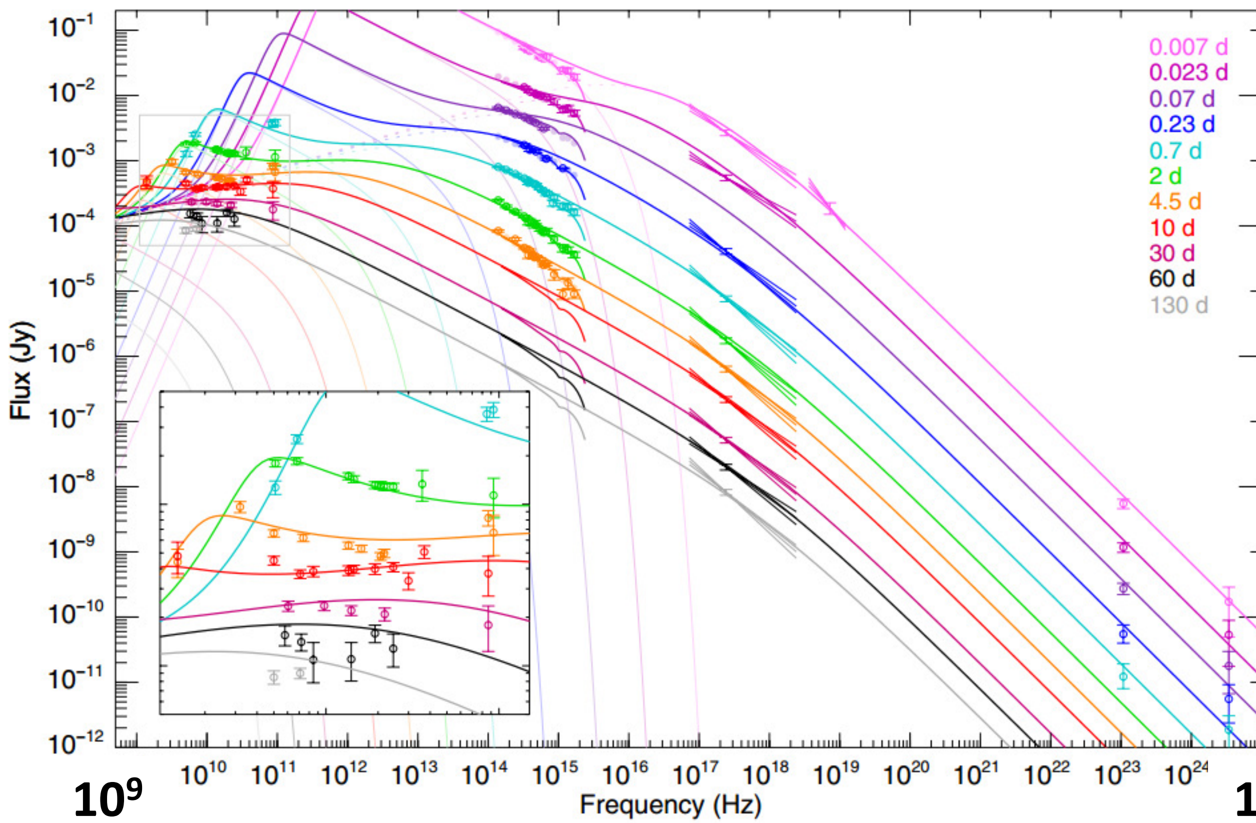
Afterglow is long-lived (hours, days, months) multiwavelength relic of a gamma-ray burst (GRB)



Background

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

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



0.007 d

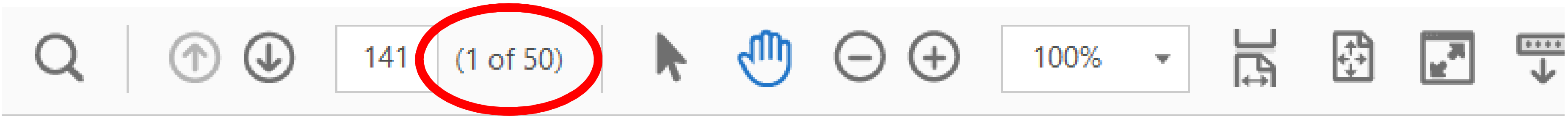
130 d

10^9 10^{25}

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



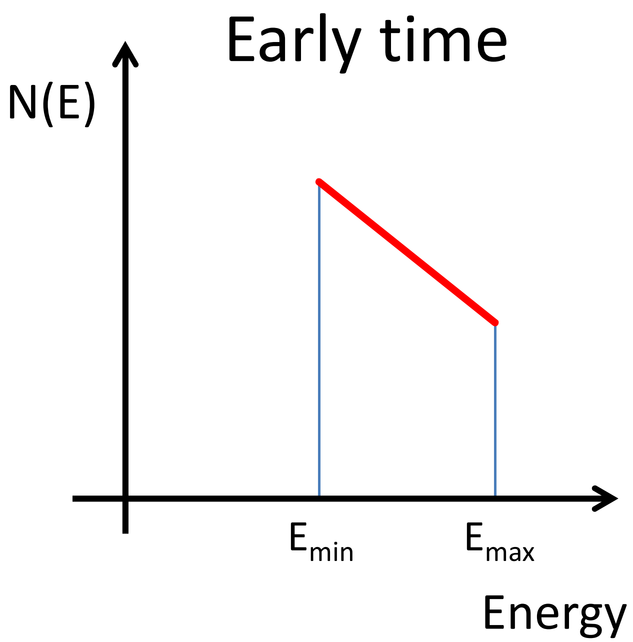
A complete reference of the analytical synchrotron external shock models of gamma-ray bursts

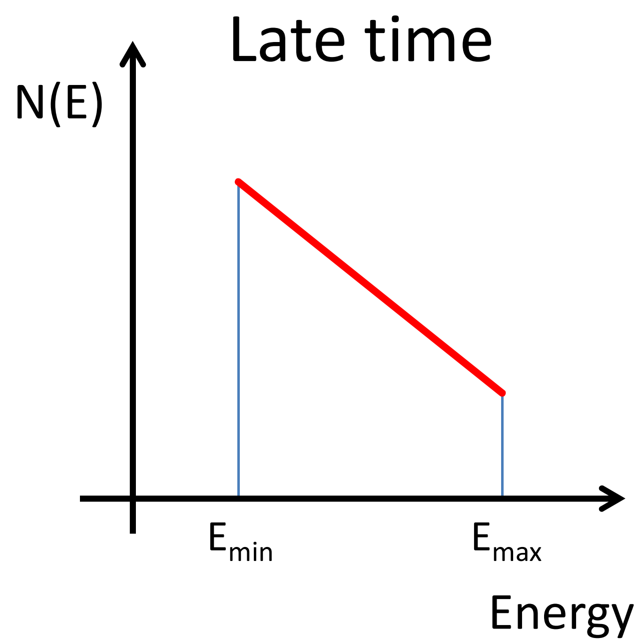
He Gao[a], Wei-Hua Lei[b,a], Yuan-Chuan Zou[b], Xue-Feng Wu[c], Bing Zhang[a,d,e,*]

Background

Many different models to explain broadband spectra and light curves

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





The case for low-energy electrons

Works *really* well most of time, but sometimes runs into difficulty

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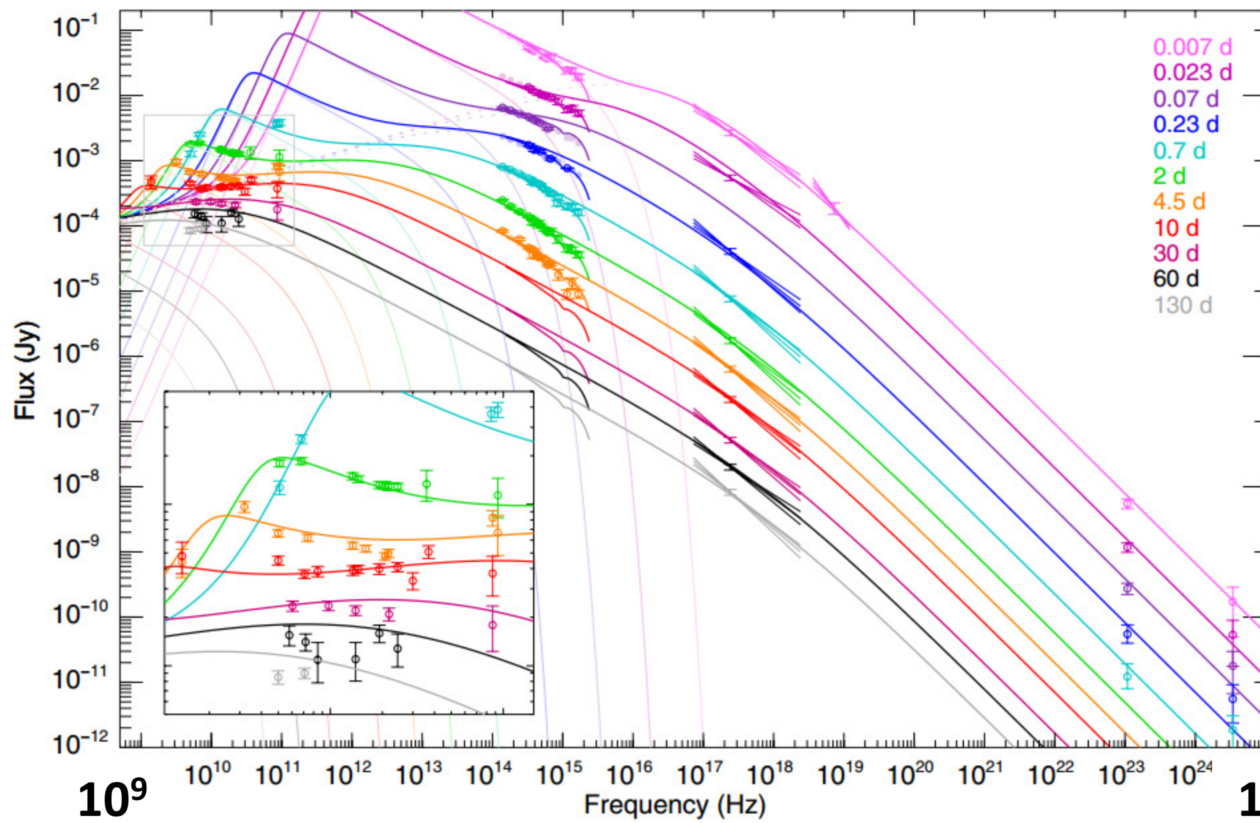

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Frail et al. (2000) (2000ApJ...537..191F)

Furthermore, we find that the electrons and magnetic field are close to equipartition with $\epsilon_e \sim \epsilon_B \sim 0.5$.

TABLE 2
MODEL PARAMETERS

Parameter	Value
Forward Shock (ISM)	
ϵ_e	$0.84^{+0.06}_{-0.08}$
ϵ_B	$0.11^{+0.07}_{-0.05}$
Forward Shock (wind)	
ϵ_e	0.60
ϵ_B	0.40

Laskar et al. (2016) (2016ApJ...833...88L)

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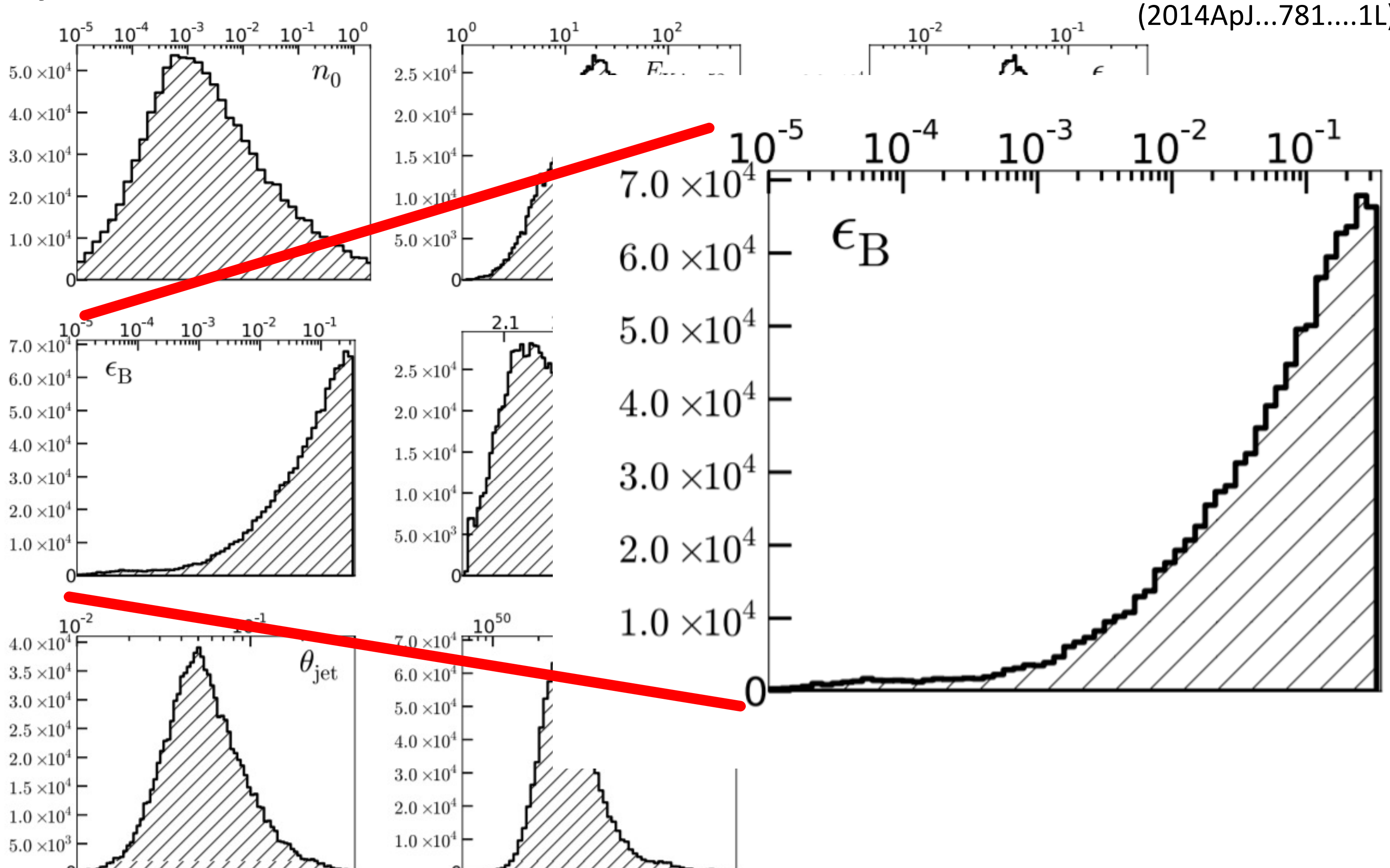


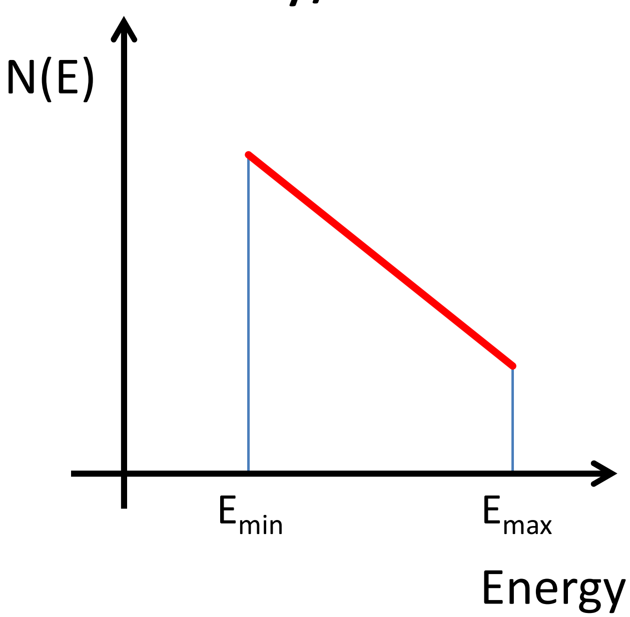
Figure 11. Posterior probability density functions of the physical parameters for GRB 120521C from MCMC simulations. We have restricted $E_{K,iso,52} < 500$, $\epsilon_e < 1/3$, and $\epsilon_B < 1/3$.

The case for low-energy electrons

All these numbers relied on radio observations.

Why is radio leading to suspicious results? Look at the model:

Early/late time



(Electrons assumed to form power law with index constant in time)

But, with shock acceleration,

- Have "non-nonthermal" particles: crossed shock but didn't enter acceleration process
- Spectral index varies with Lorentz factor (will not be constant in time)

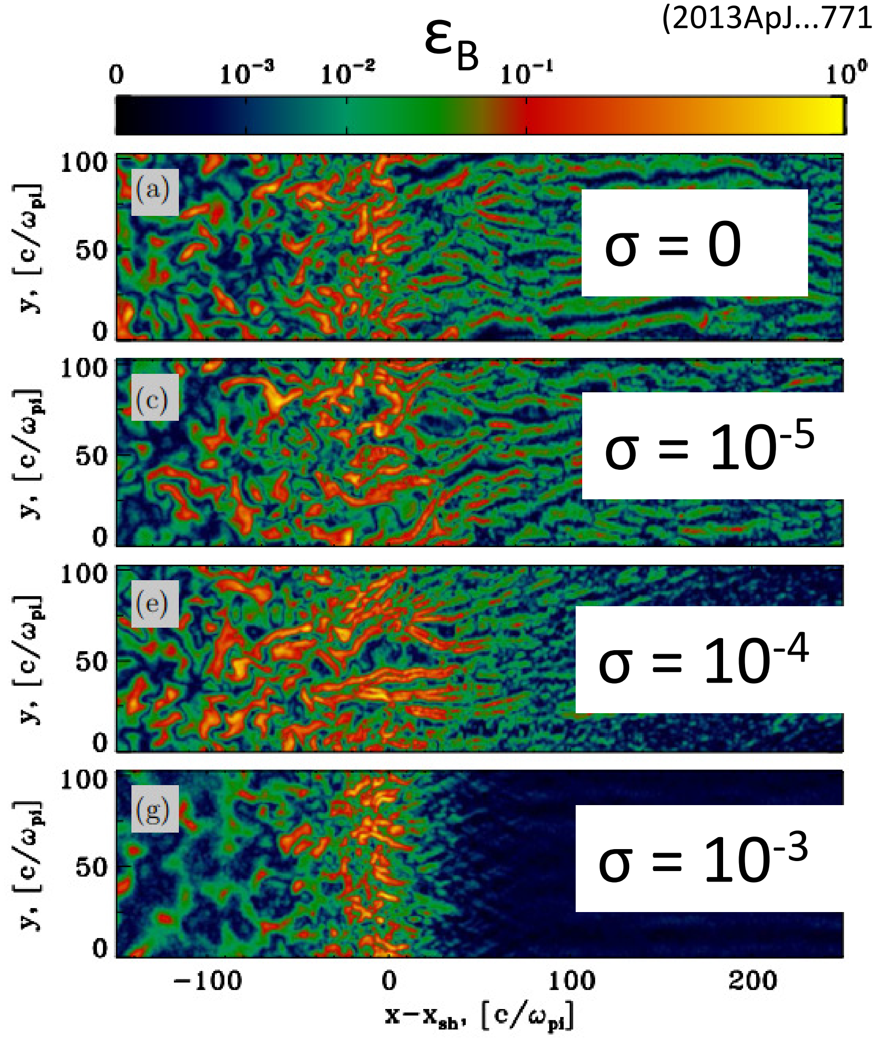
The case for low-energy electrons

Know this from particle-in-cell (PIC) simulations of relativistic low-magnetization shocks

Critical results:

- Plasma instabilities UpS from shock transfer energy from ions to electrons
- Electrons, ions both cross shock at $E \sim \gamma_0 m_p c^2$
- Only small fraction (few %) enter shock accel process & become cosmic rays

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



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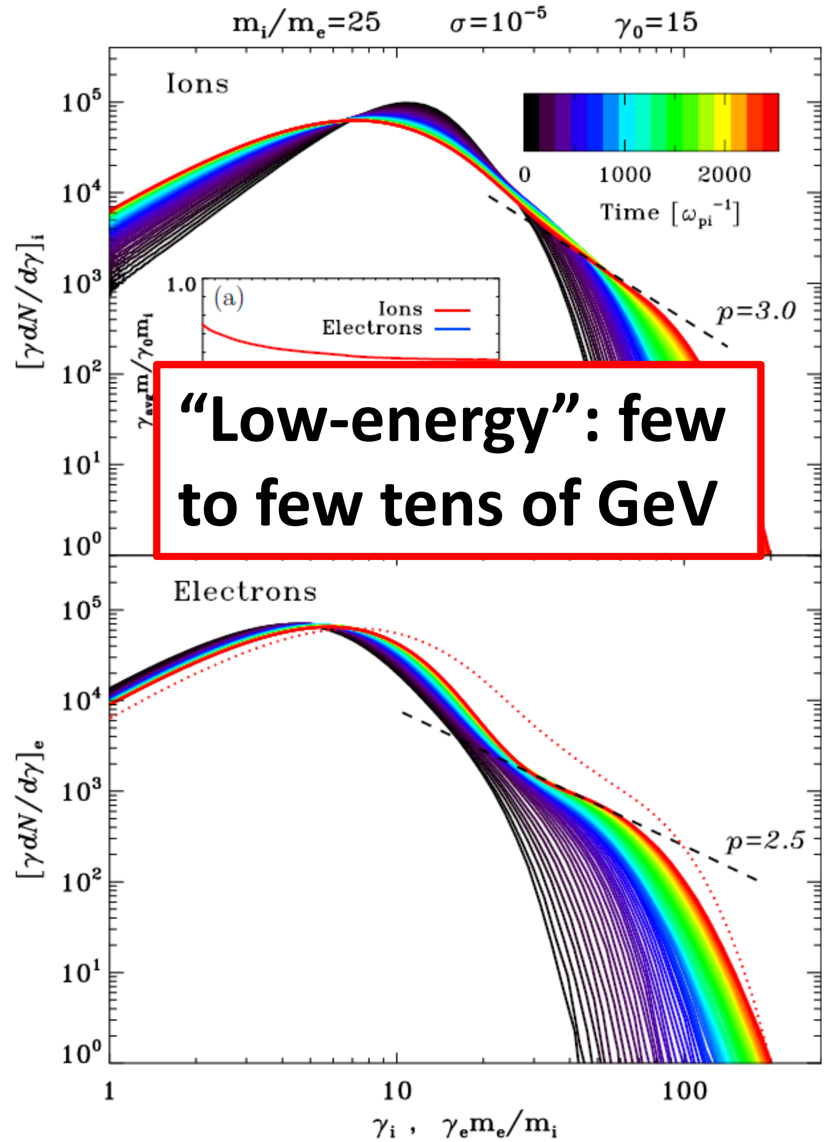

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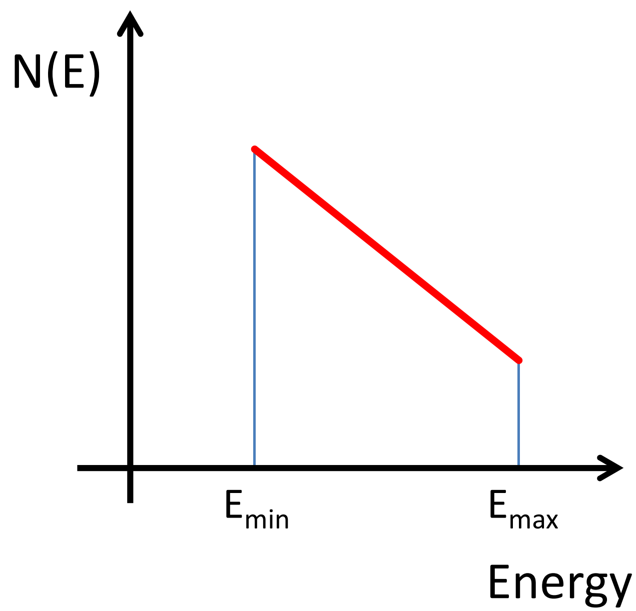

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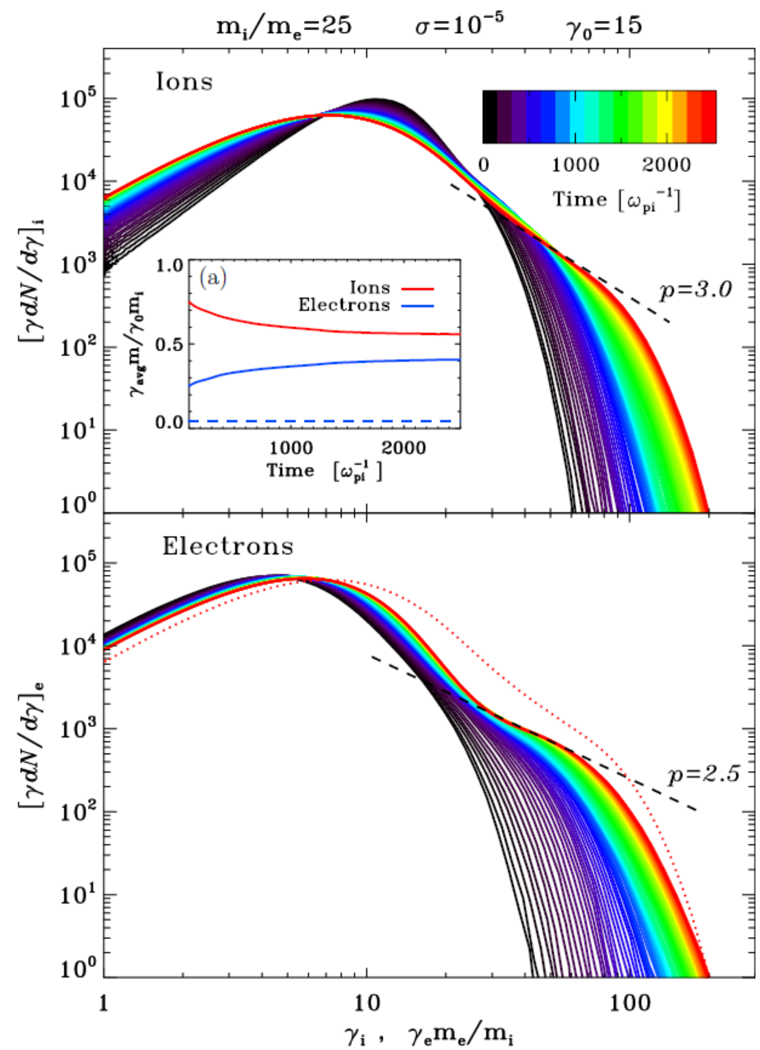

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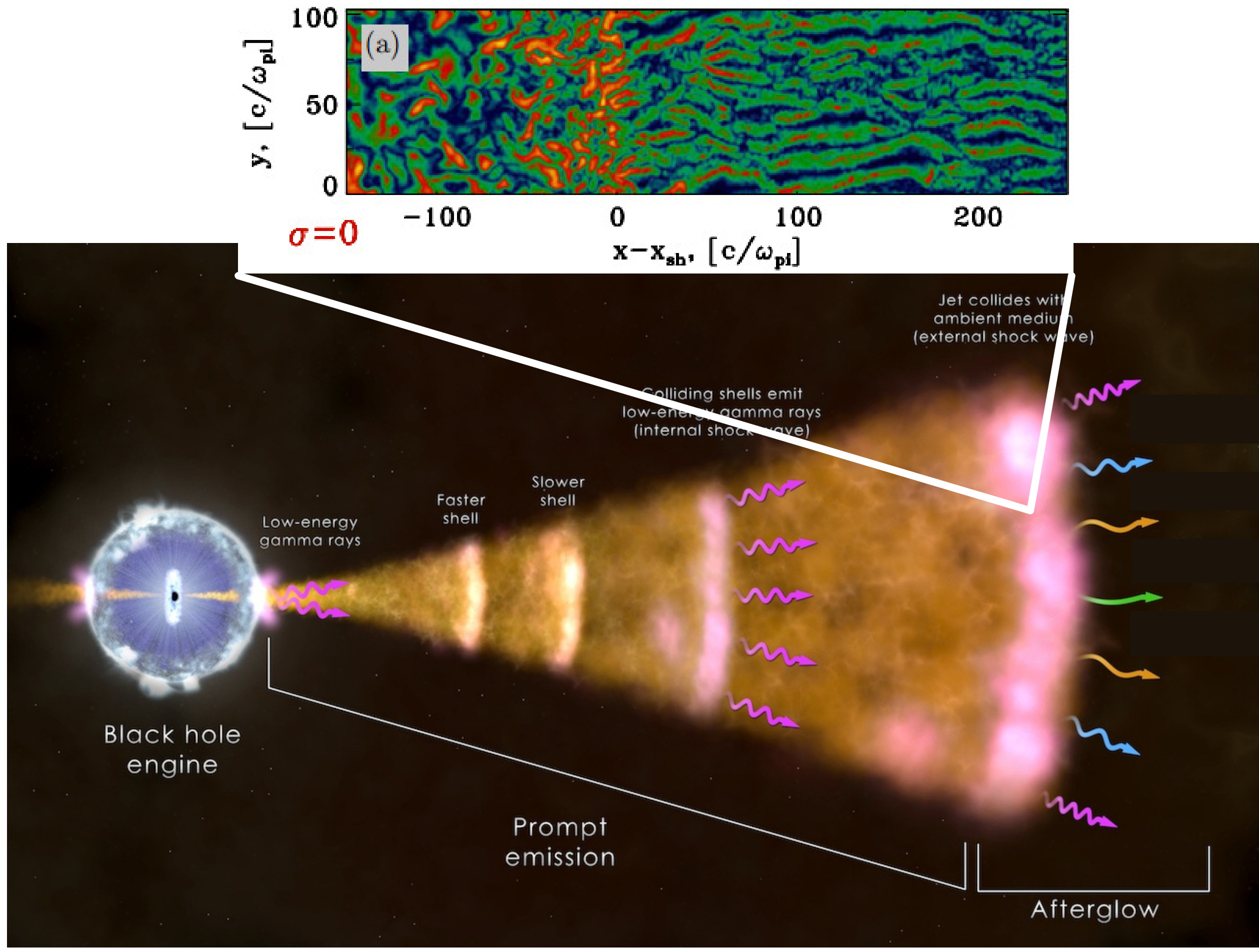
The consequences of low-energy electrons

Use PIC results to guide Monte Carlo simulations of shock accel process in GRB afterglow

Why MC?

- PIC sims ~10^9 cm across, forward shock >10^{13} cm. Too large space/time domain for computation
- MC approach balances versatility with simplicity: computable on desktop

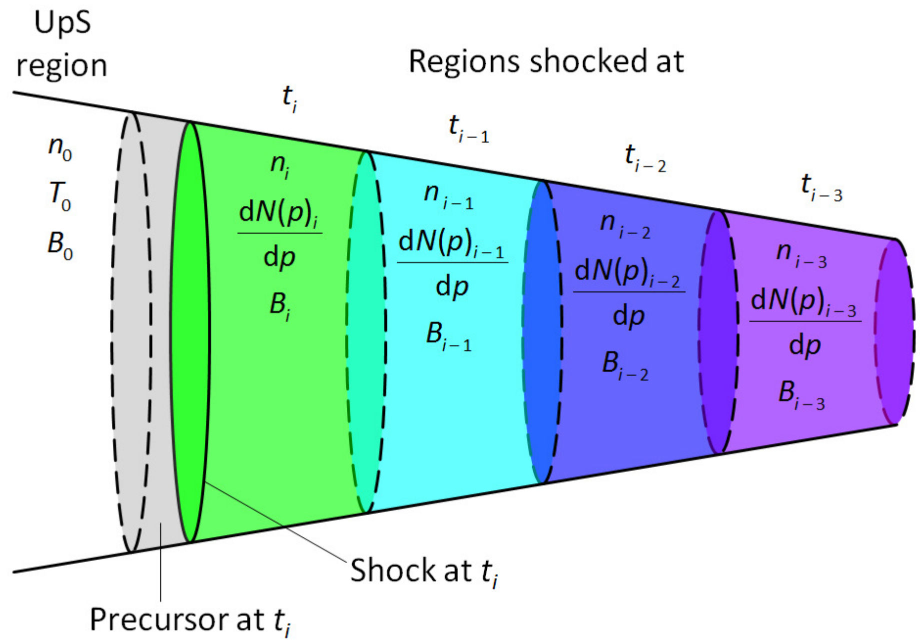


The consequences of low-energy electrons

- Model shock acceleration process at select points in afterglow, then compute photon production

Warren et al. (2017)
(2017ApJ...835..248W)

- Retain all shocked plasma, not just material currently interacting with shock



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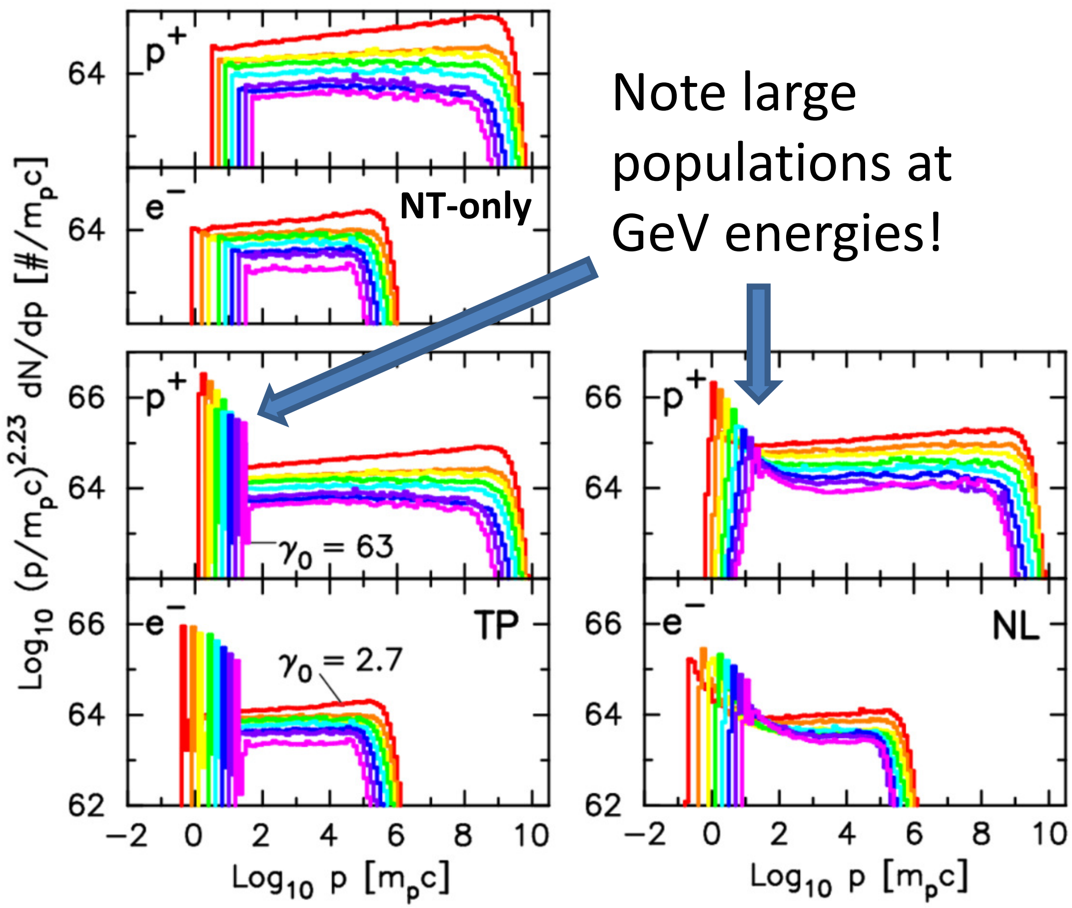
- Consider 3 cases:
  - NT-only: ignore thermal population
  - TP (test particle): assume inefficient injection to shock accel process
  - NL (nonlinear): assume efficient injection, & all consequences



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Warren et al. (2017)
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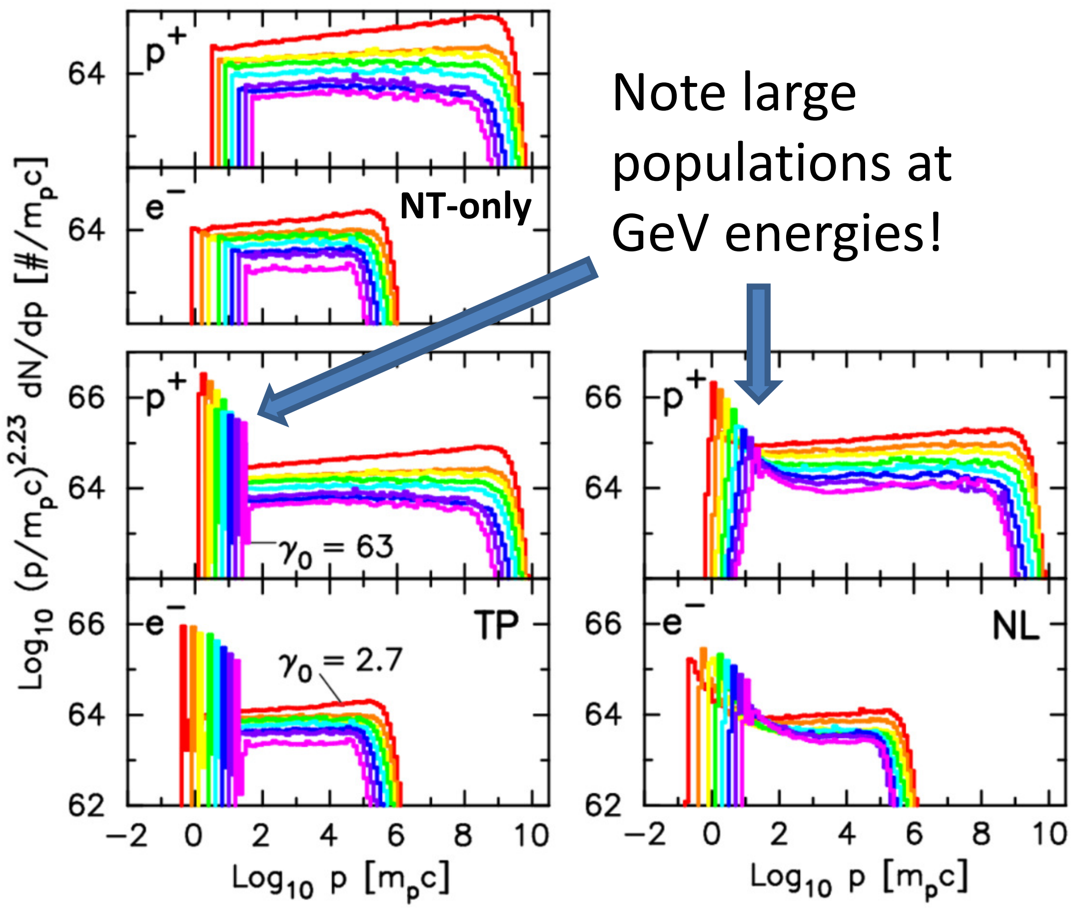
- Photon processes treated:
  - ➢ Synchrotron
  - ➢ Inverse Compton
    - CMB
    - Synch. photons
    - ISRF
  - ➢ (p-p) π production
  - ➢ Absorption
    - SSA (at radio)
    - EBL (at GeV+)



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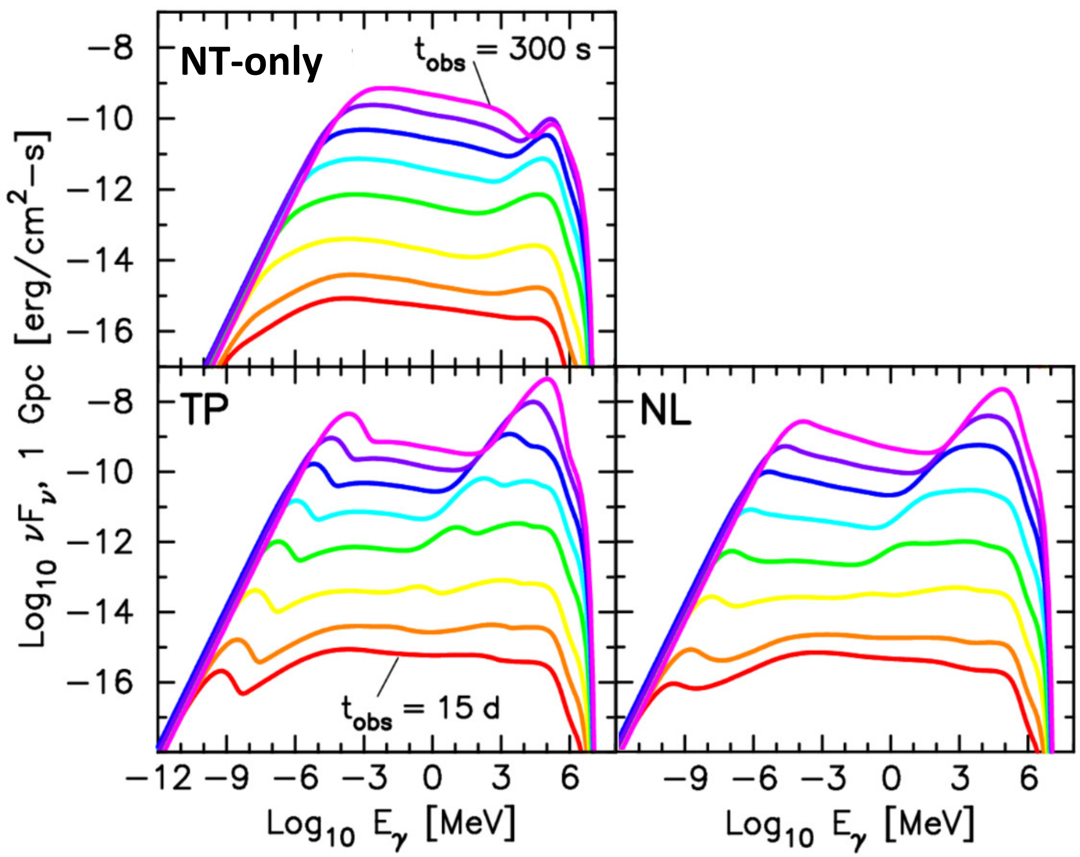
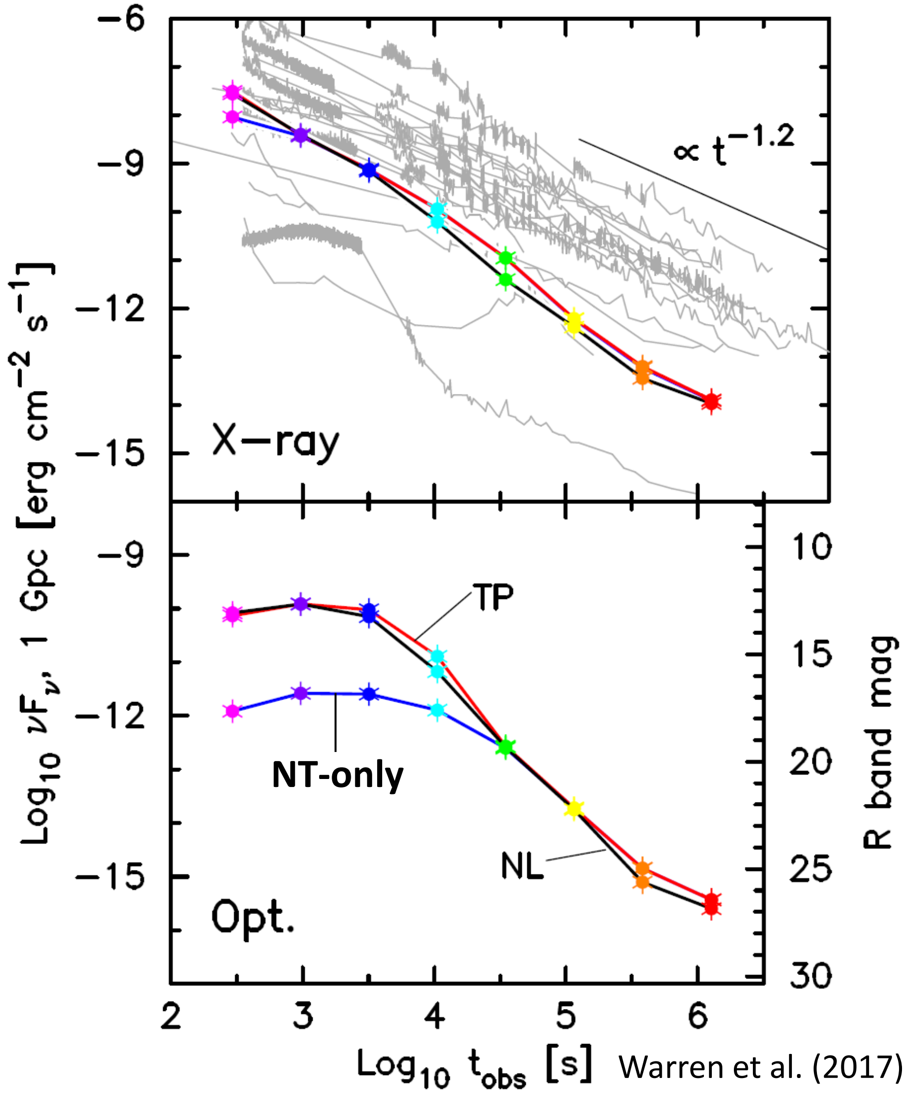


The consequences of low-energy electrons

- In X-ray & optical, all photons are synchrotron
- Just produced by different parts of electron distribution
- Huge (100x) difference in emission when thermal particles included
- Later, all three models similar since non-thermal tails almost identical
- How to distinguish TP and NL?



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The consequences of low-energy electrons

- How to distinguish TP and NL? Look at spectral index
- Transition from thermal to non-thermal is smoother for NL model than for TP model
- Thermal particles produce hard-soft-hard variation in spectral index
- Height, width affected by efficiency of injection

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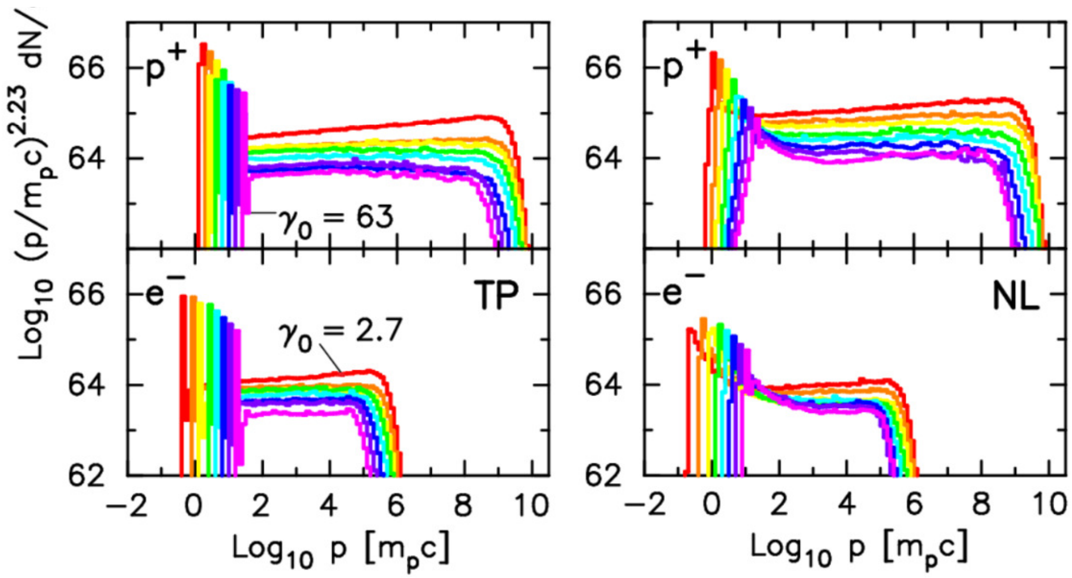

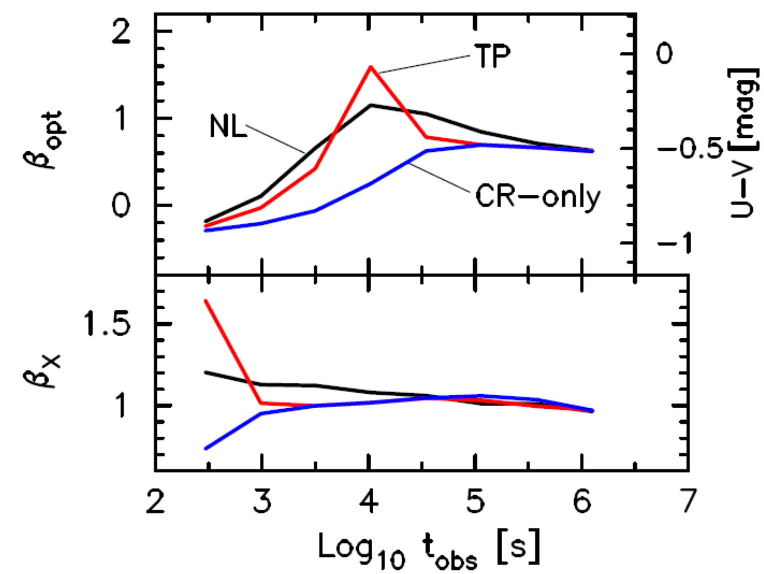

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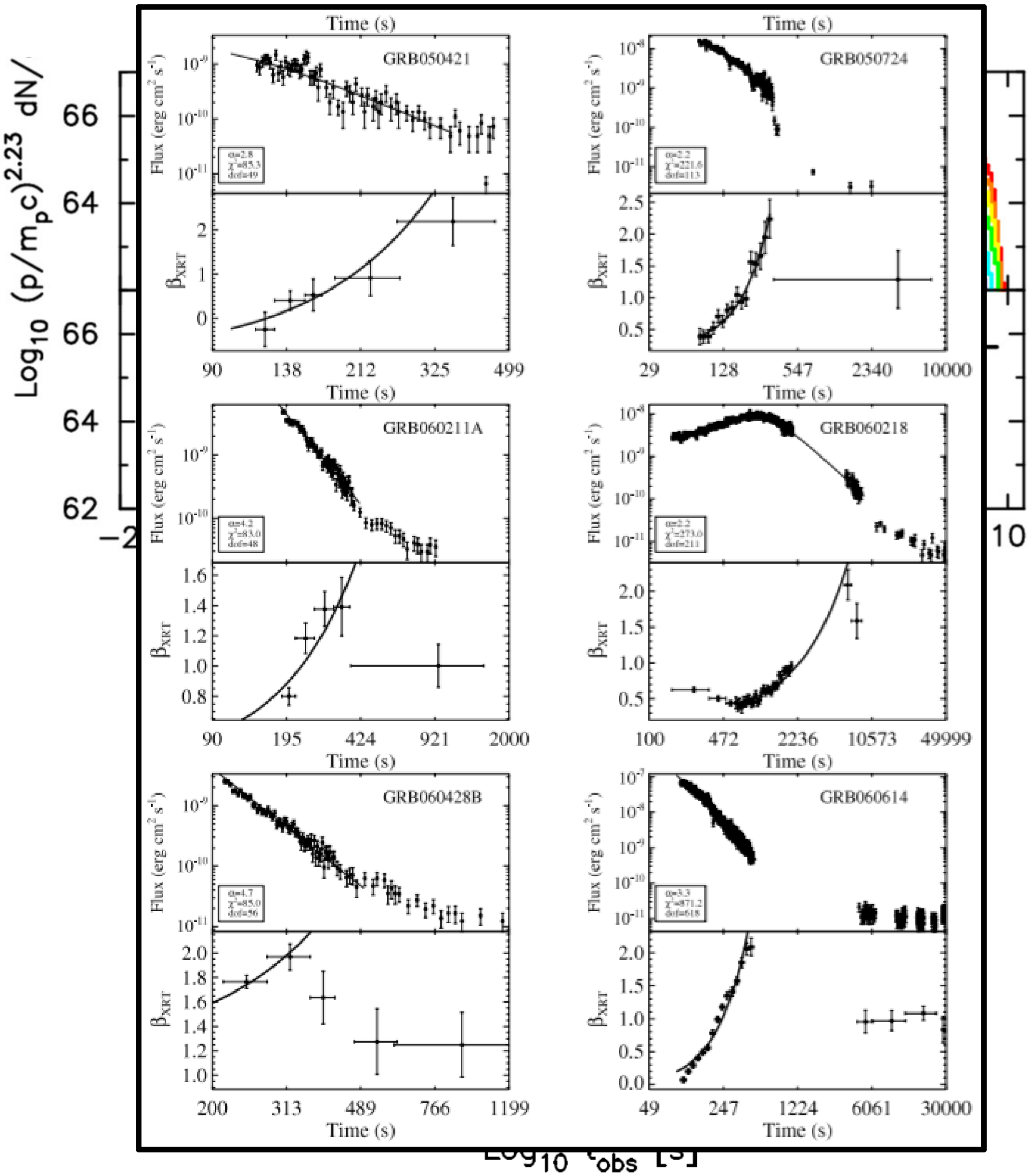
Zhang et al. (2007)
(2007ApJ...666.1002Z)



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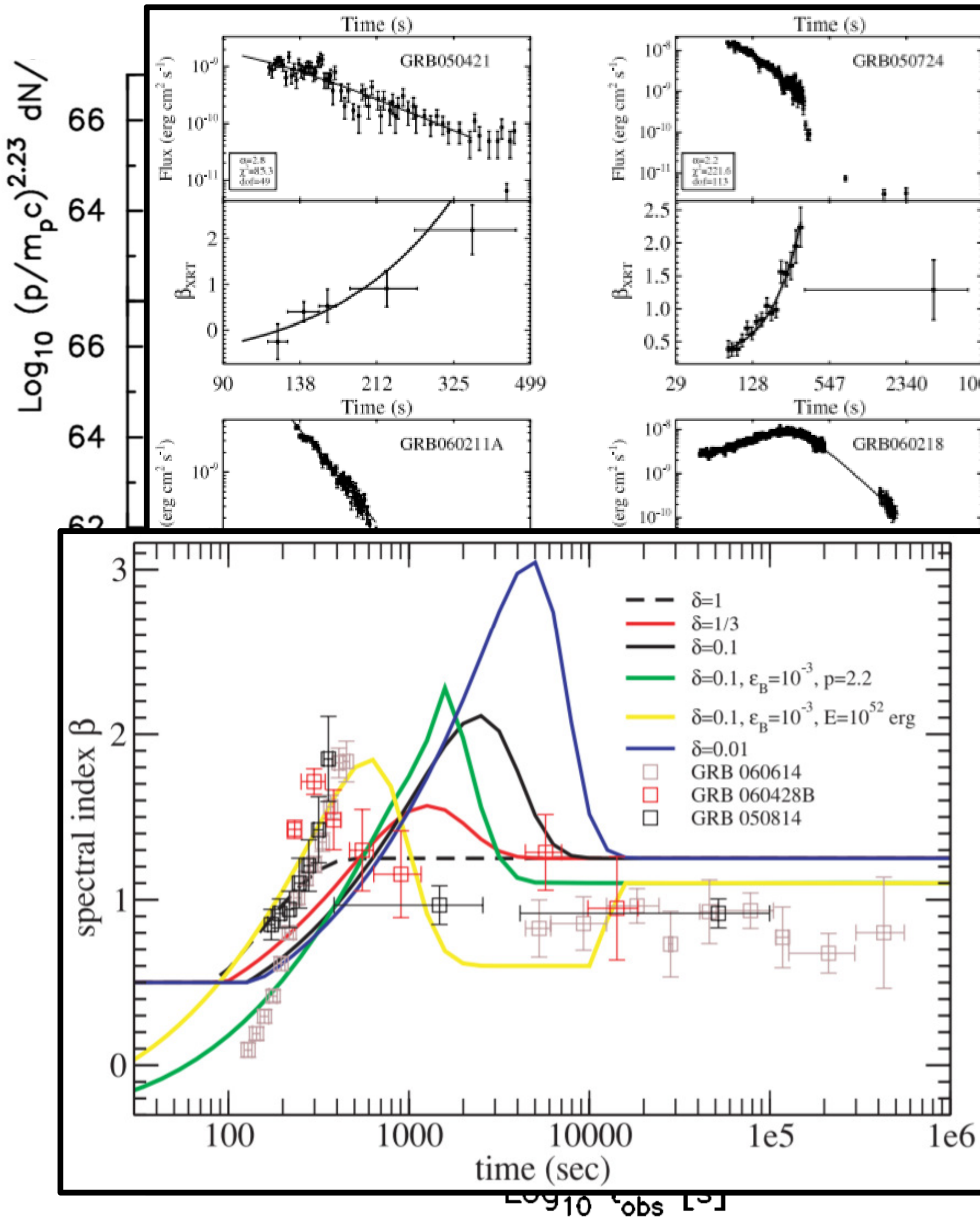
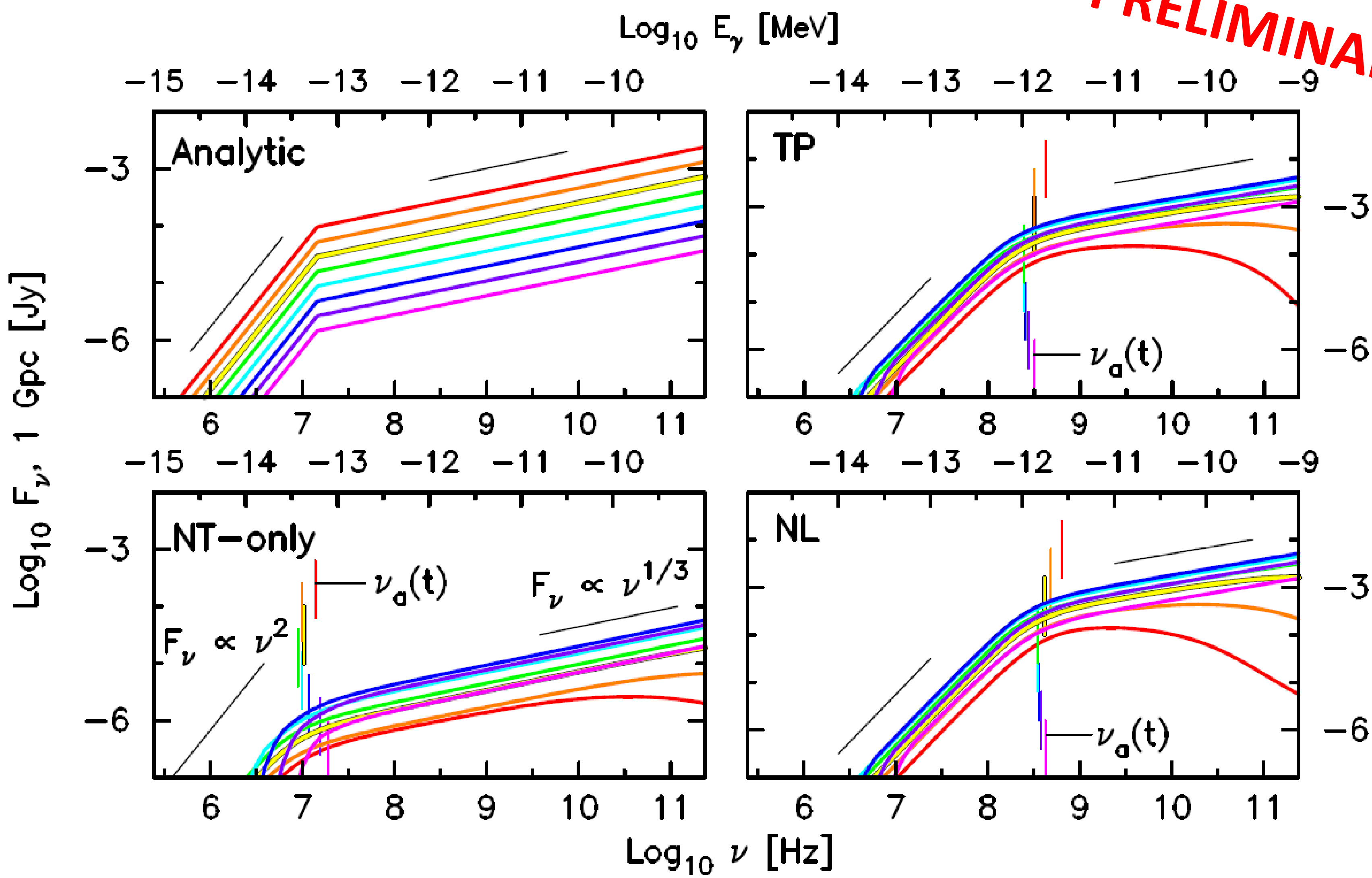


Giannios & Spitkovsky (2009)
(2009MNRAS.400..330G)

The consequences of low-energy electrons

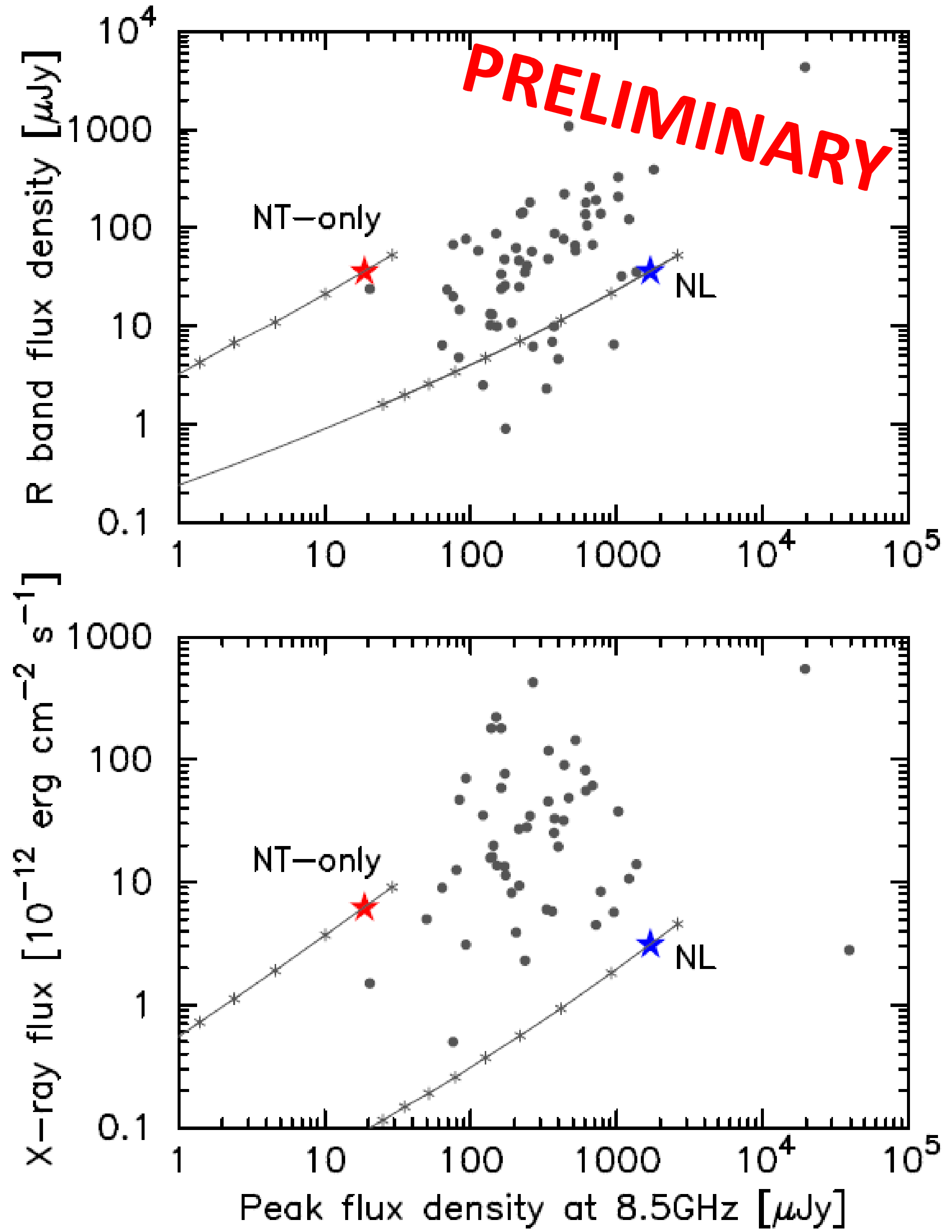
- In radio band, thermal particles very important for both emission and absorption

PRELIMINARY



The consequences of low-energy electrons

- In radio band, thermal particles very important for both emission and absorption
- For same GRB parameters, huge boost (100x) in radio emission with no change in optical, X-ray
- Fitted GRB parameters will be very different if thermal particles included



The consequences of low-energy electrons

- Presence of hot thermal particles robustly required by plasma physics

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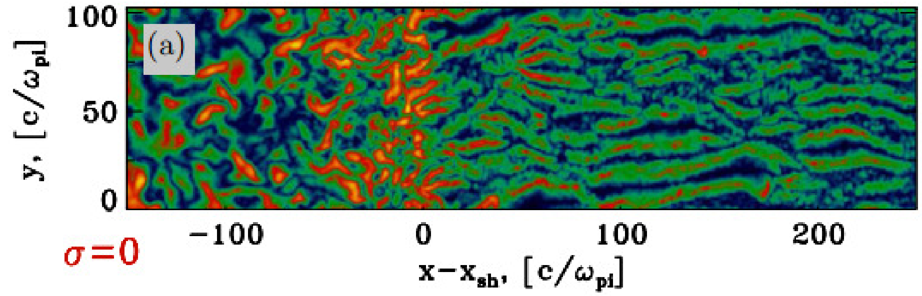
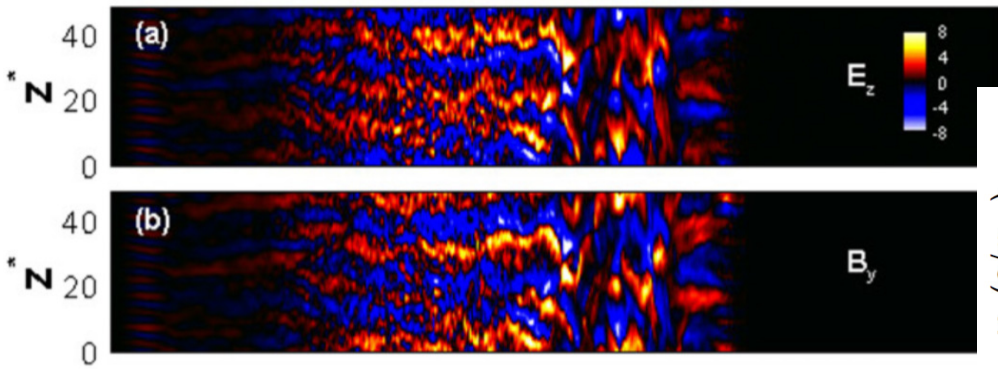
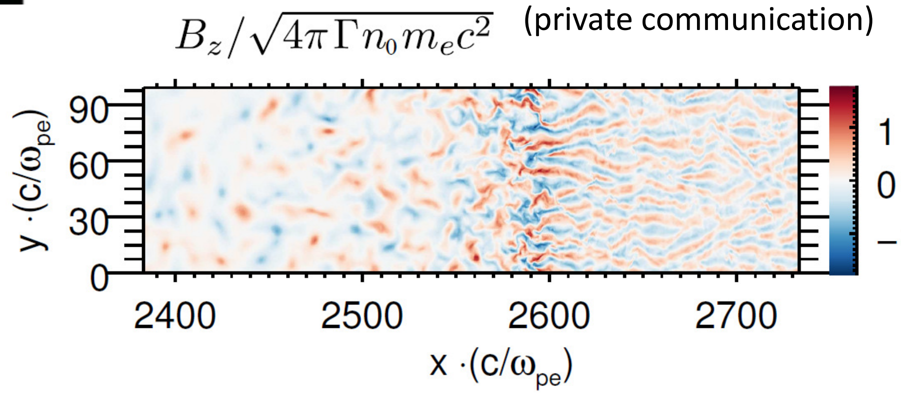


Ardaneh et al. (2015)
(2015ApJ...811...57A)



Ikeya, Matsumoto et al.
(private communication)



This equation can be cast in the form

Medvedev (2006)
(2006ApJ...651L...9M)

$$\epsilon_e \simeq \lambda\sqrt{\epsilon_B}.$$

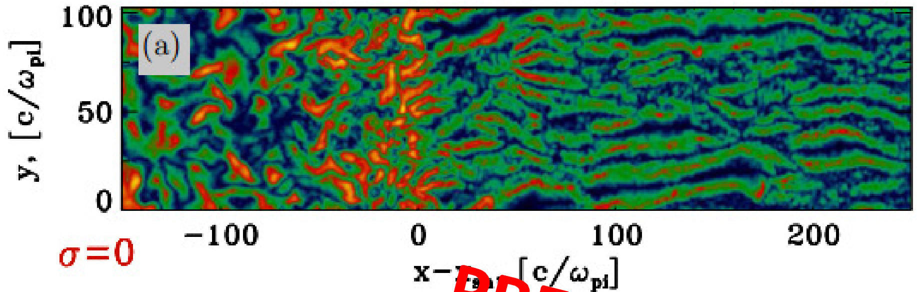
Note that we made no assumptions h
compression has already occurred (
we are). We only used the fact that
are due to proton currents, which a
fields. These electrostatic fields local

Consequently, their momentum dispersion amounts to $\Delta p_{\rm u}^2 \sim m_{\rm p}{}^2c^2/2$ once the electrons reach the shock front, which corresponds to equipartition with the incoming ions.

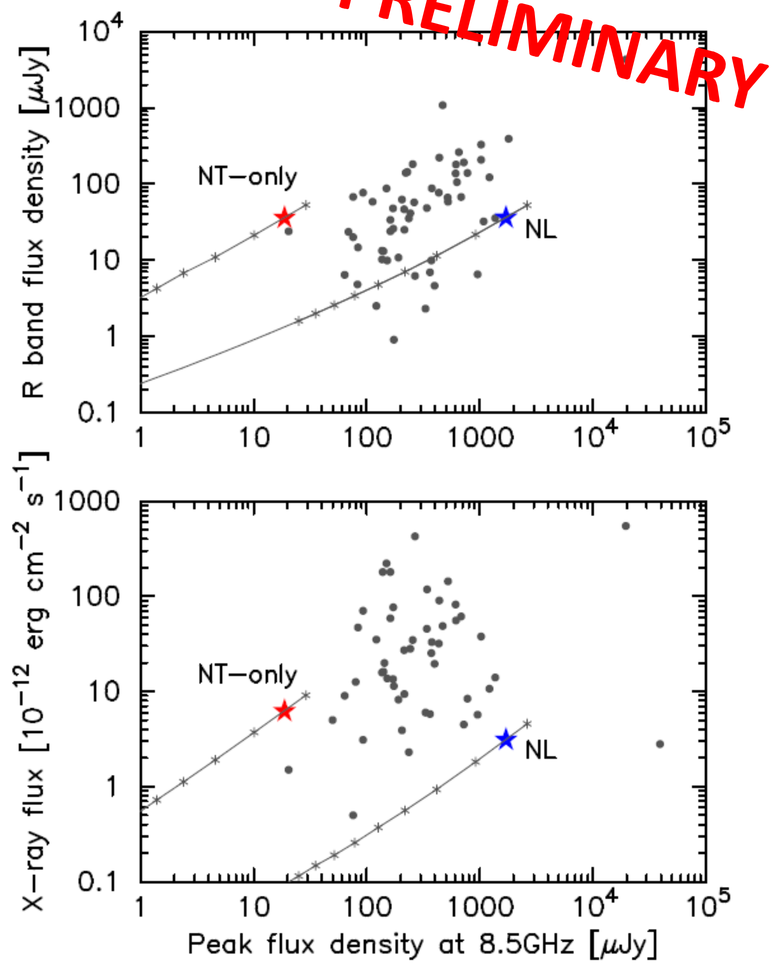
Lemoine & Pelletier (2011)
(2011MNRAS.418L..64L)

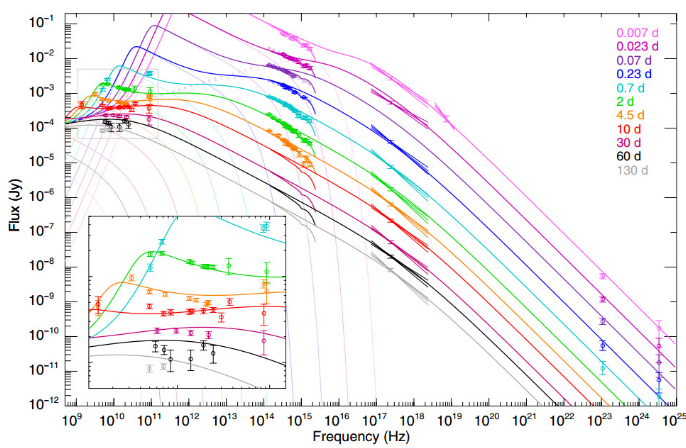
The consequences of low-energy electrons

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



- Presence of hot thermal particles robustly required by plasma physics
- Thermal particles have large impact on photon production & absorption processes
- Expect “standard model” for afterglow to change dramatically





Perley+ (2014) (2014ApJ...781...37P)

The future of low-energy electrons

- Problem: can't precisely predict yet how standard afterglow model will change

- Many additional steps needed
  - Energy transfer at late times
  - Physically-motivated magnetic field structure
  - Analytical approximations
  - Spanning GRB-environment parameter space
  - (Neutrinos & multimessenger astronomy?)
  - (Heavy nuclei?)
  - (Ultra-high energy cosmic rays?)

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The future of low-energy electrons

- With no plasma insta-bilities, no energy transfer
- With no energy transfer, thermal electrons too cold to radiate significantly
- Key filamentation instability quenches around $\gamma_0 = 10$
- What happens after? Nobody knows

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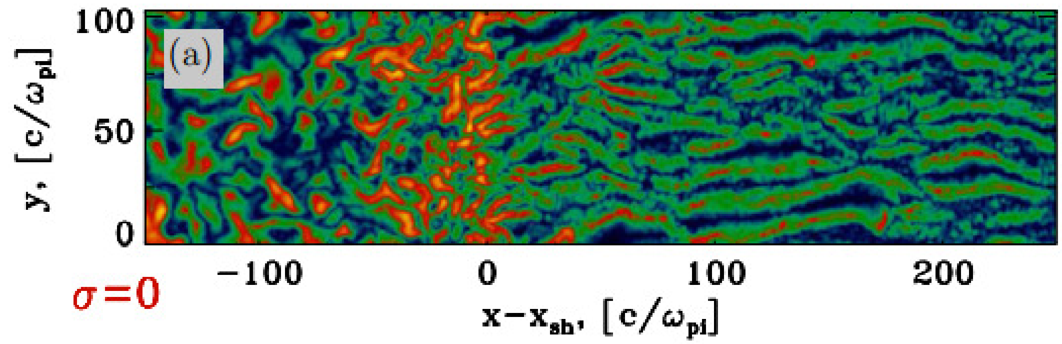

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$$\gamma_{\rm sh} \gg \xi_{\rm b}^{-1/3}\left(\frac{m_{\rm e}}{m_{\rm p}}\right)^{-1/3}\left(\frac{k_\perp c}{\omega_{\rm p}}\right)^{1/3} \qquad \left(\frac{\omega_{\rm p}}{\gamma_{\rm b}} \ll k_\perp c \ll \omega_{\rm p}\right). \tag{7}$$

One can thus check that, indeed, for $\gamma_{\rm sh} = 10$ (corresponding to $\gamma_{\rm b} \simeq 100$), the above condition is violated

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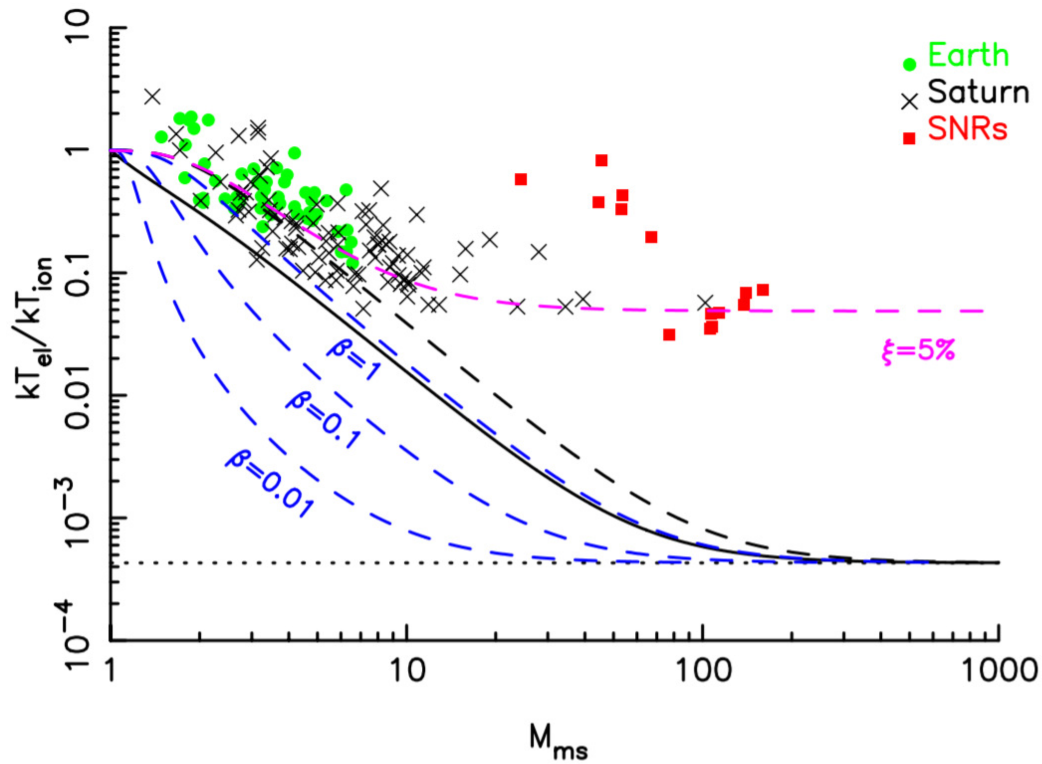
Vink et al. (2015) (2015A%26A...579A..13V)



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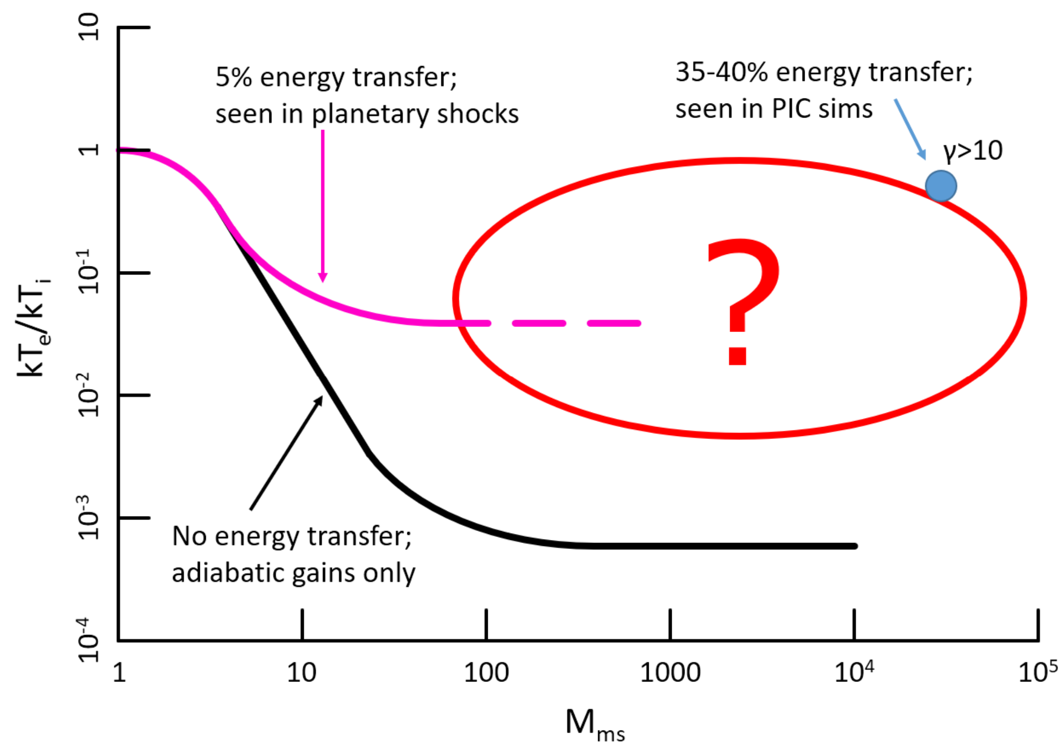

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- Need PIC simulations to determine behavior of instability, but have to beg others to do them for me

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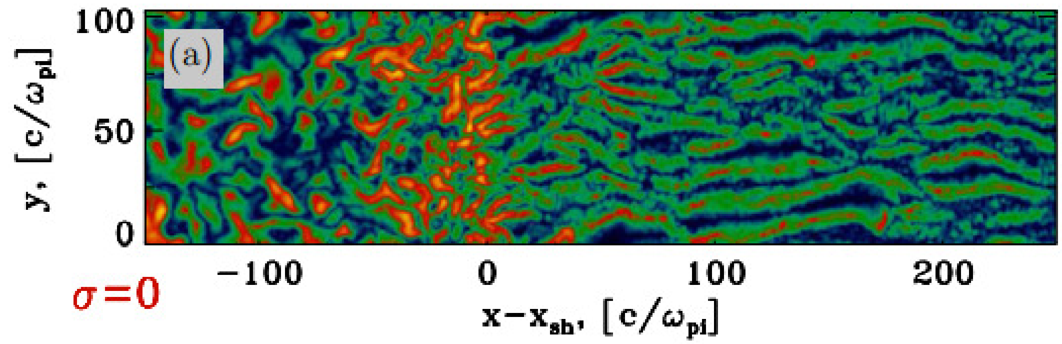

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Conclusions

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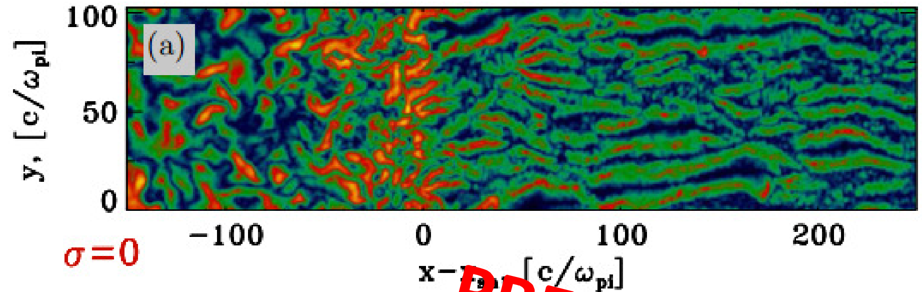

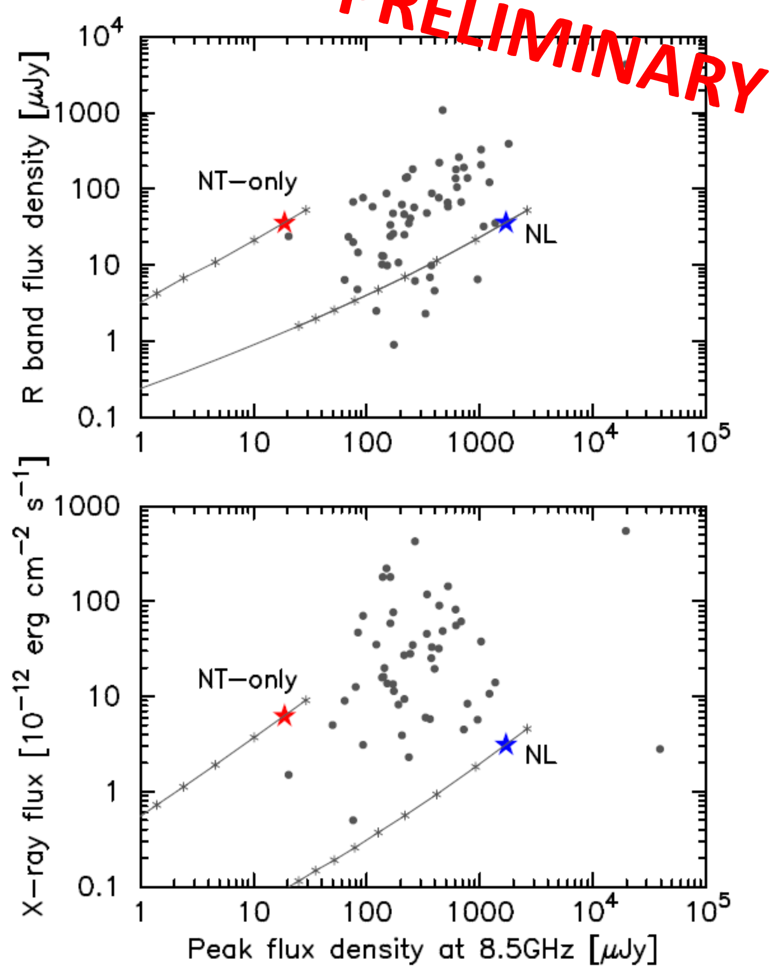

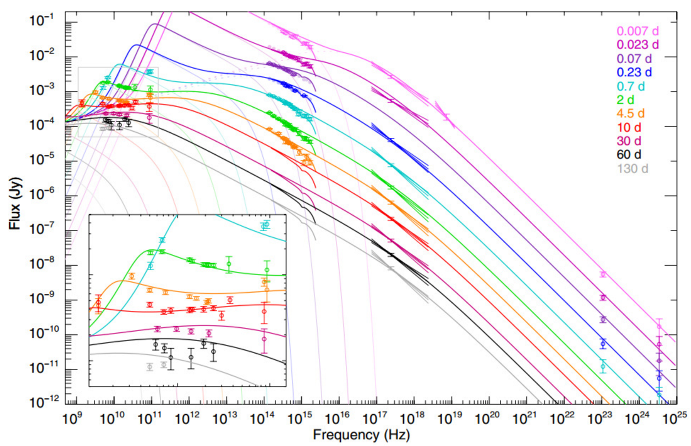

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