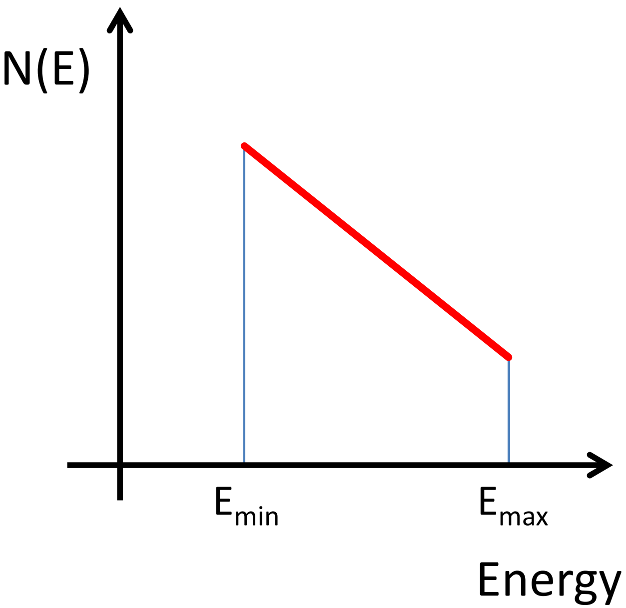
Thermal electrons in GRB afterglows: causes & effects

Don Warren
RIKEN – iTHEMS
RIKEN-RESCEU meeting
19 March 2019

If you remember *one* thing…



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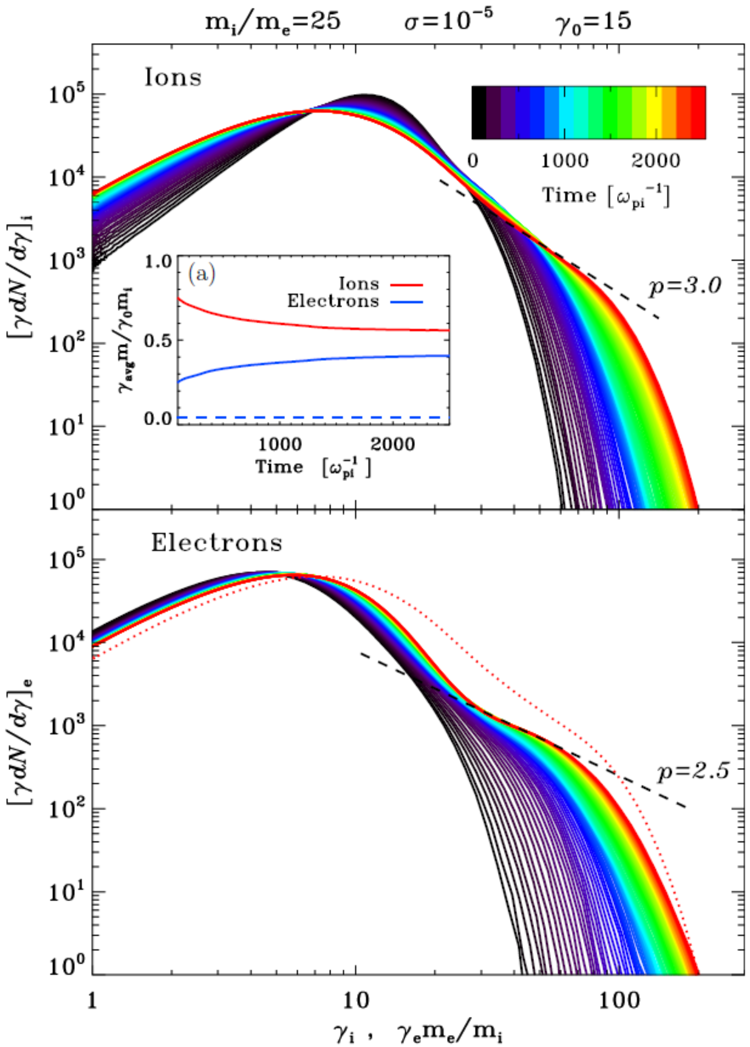


Figure 11. Temporal evolution of the post-shock particle spectrum

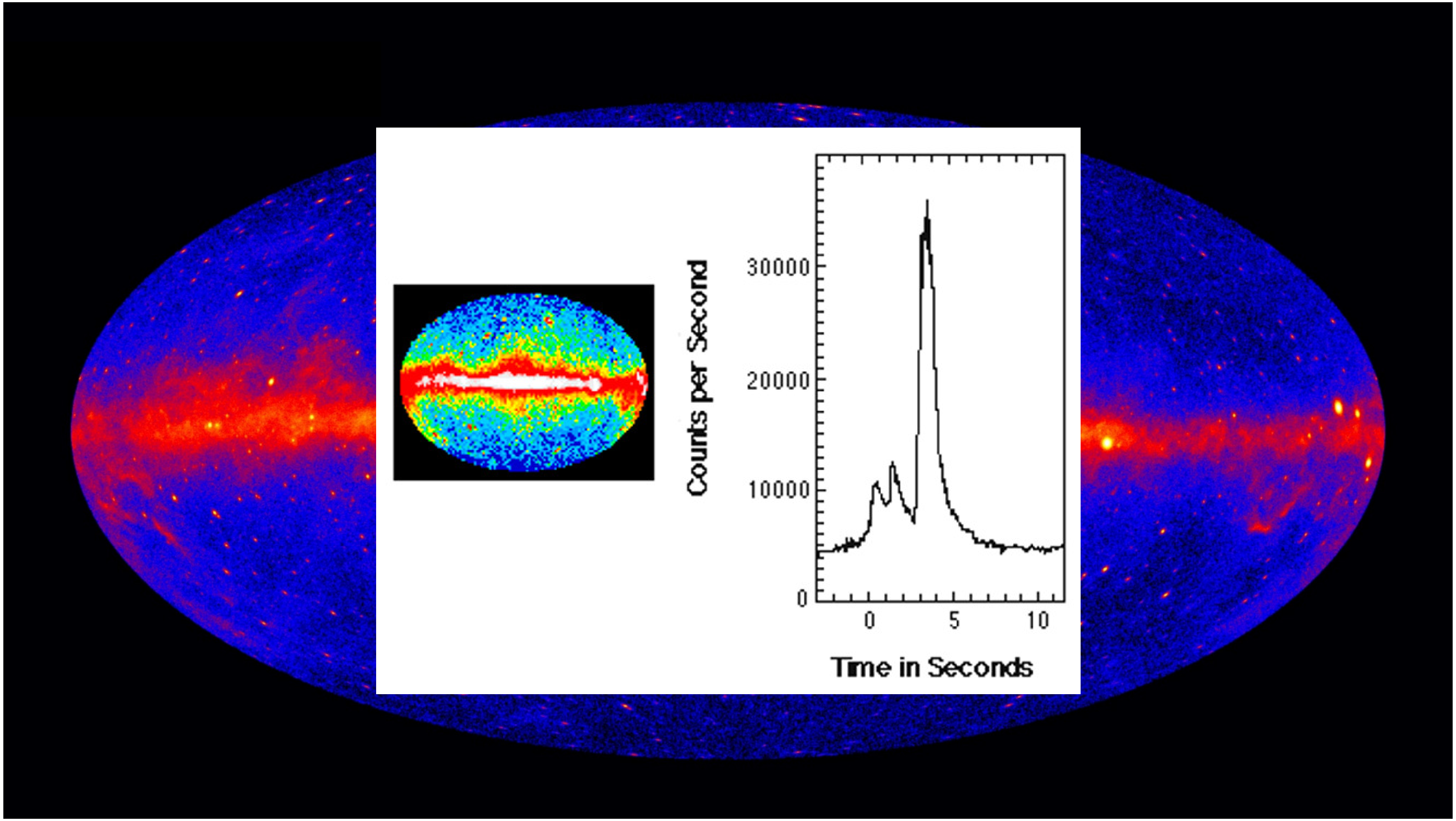
Sironi et al. (2013)
(2013ApJ...771...54S)

Outline

- GRBs and afterglows
- “Thermal” electrons: case for, and consequences of
- A semi-analytic model for GRB afterglows

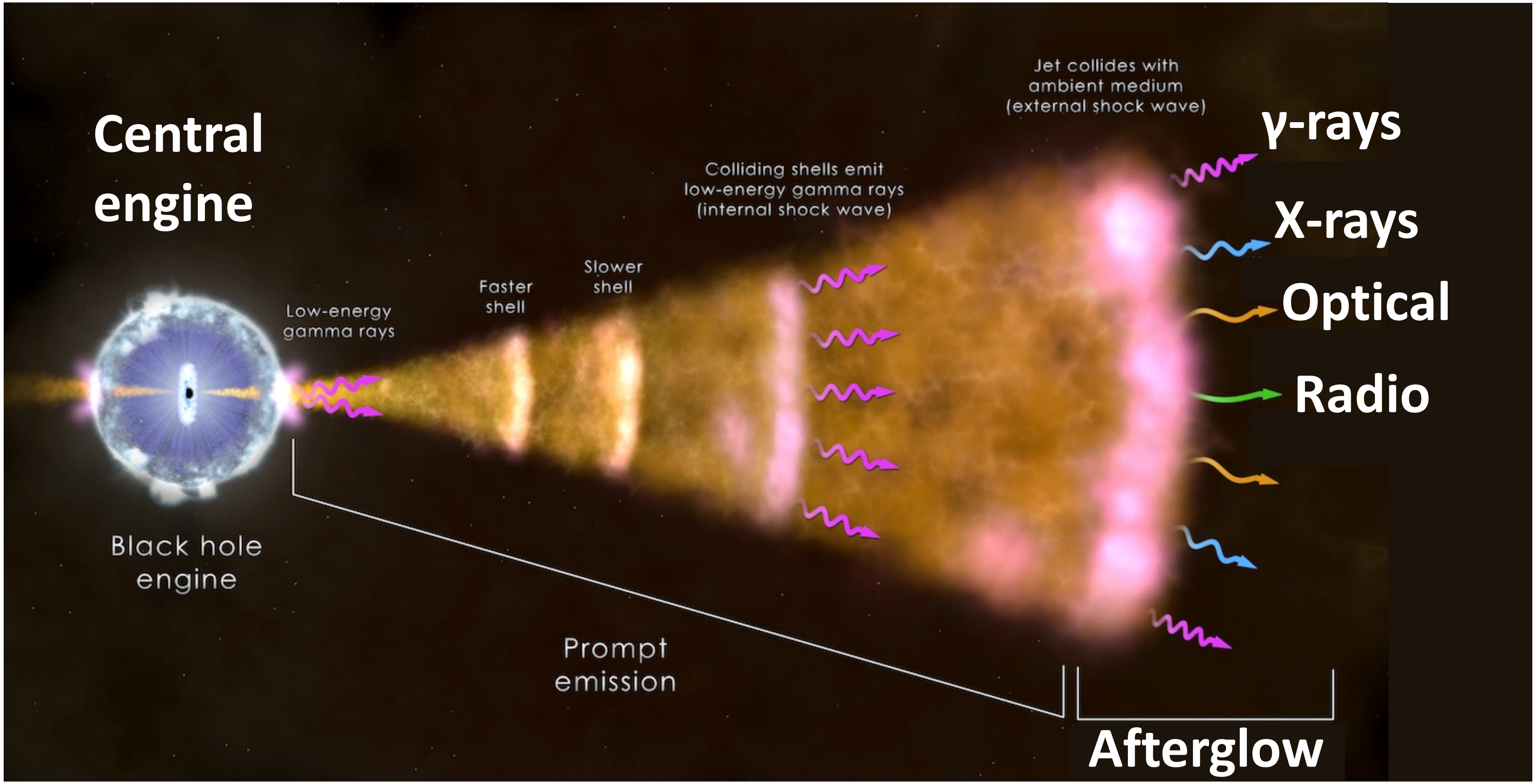
Background

The sky in gamma rays (as seen by Fermi space telescope)



Background

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

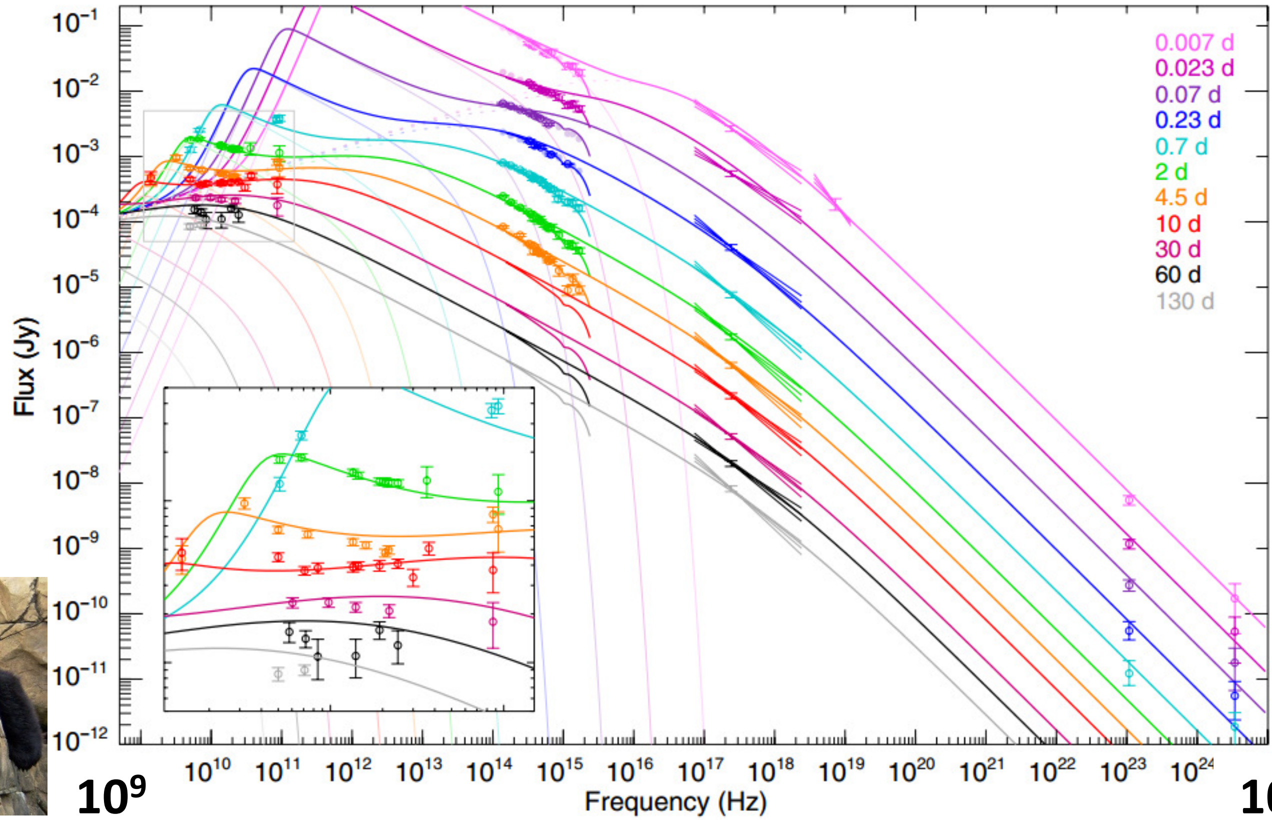


The case for low-energy electrons

Works *really* well most of time, …

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

0.007 d



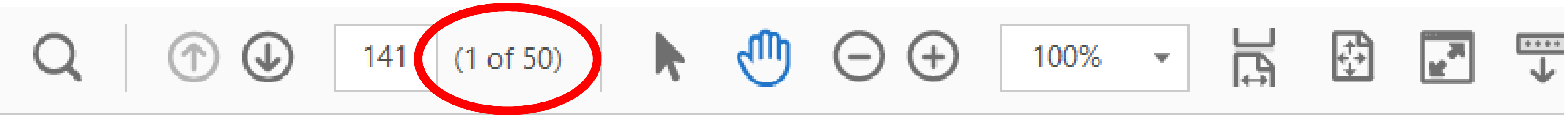
130 d

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



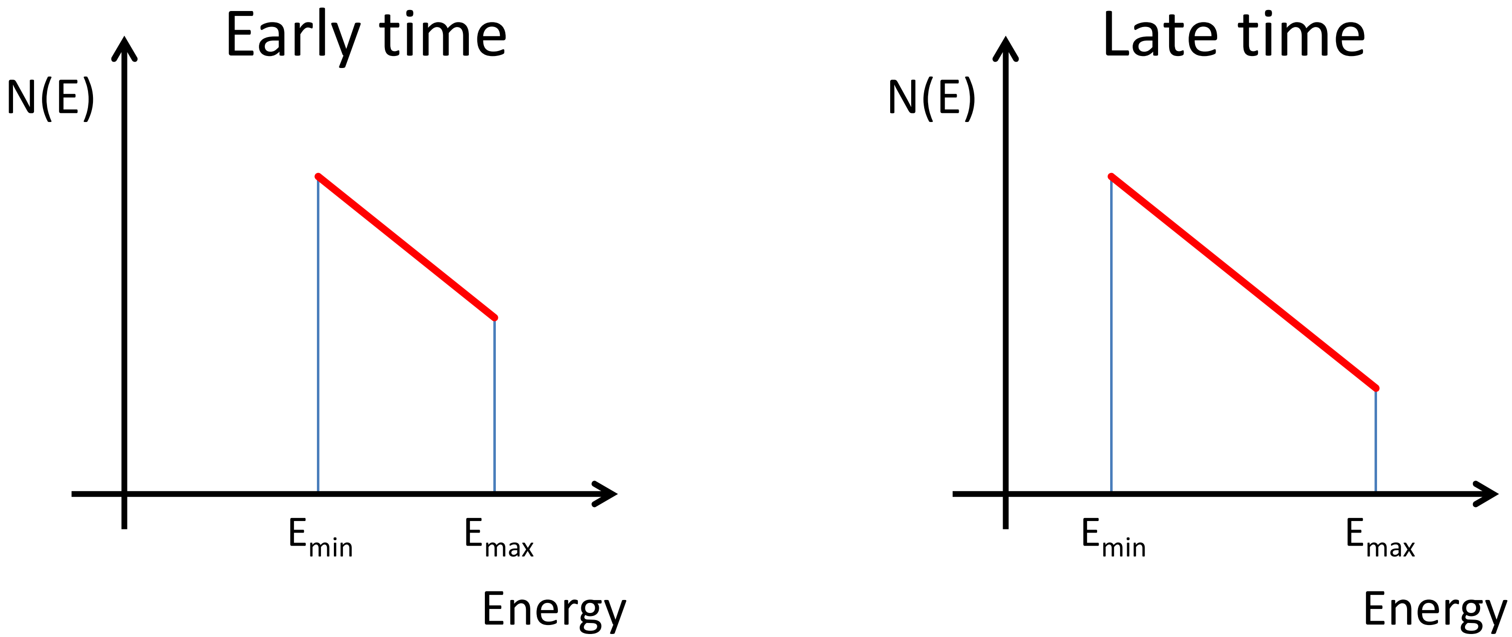
A complete reference of the analytical synchrotron external shock models of gamma-ray bursts

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

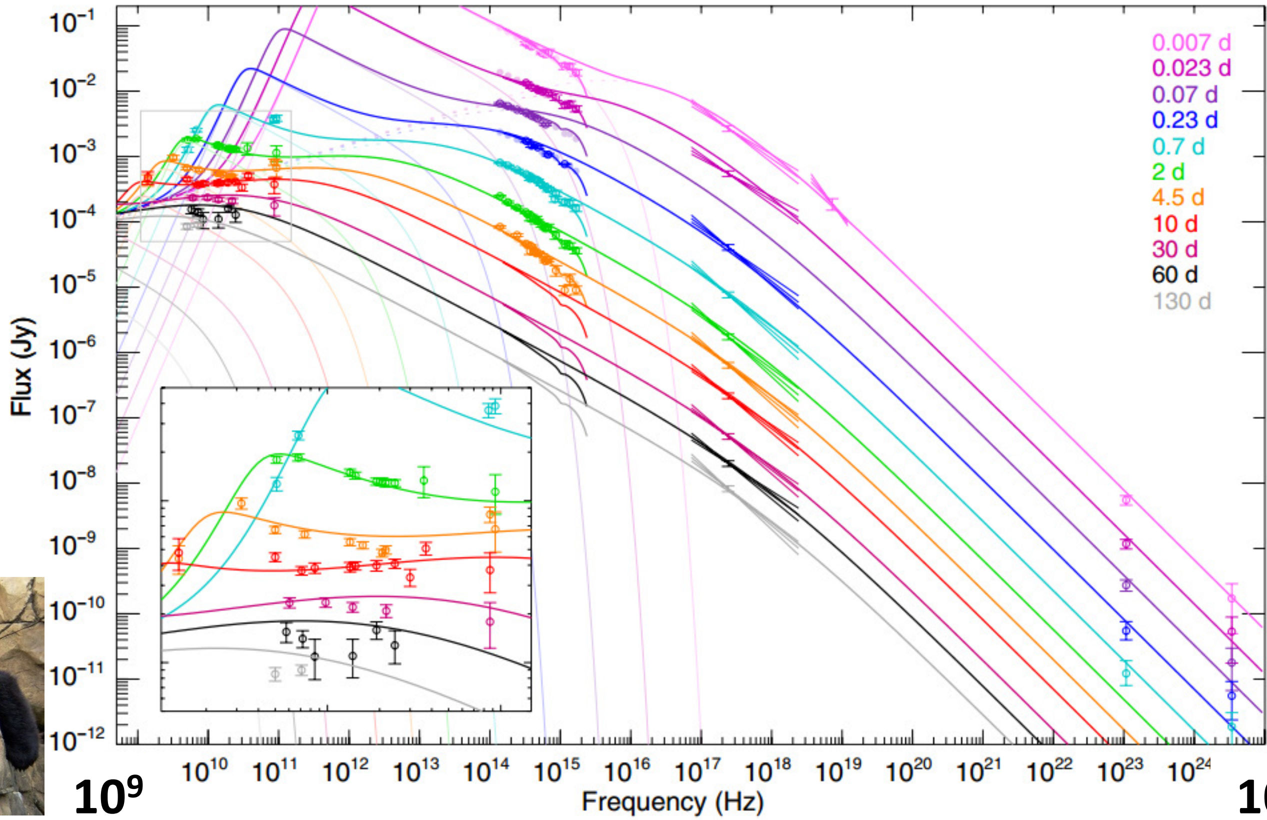


The case for low-energy electrons

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

0.007 d

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



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The case for low-energy electrons

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

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)

The case for low-energy electrons

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

Laskar et al. (2014)
(2014ApJ...781....1L)

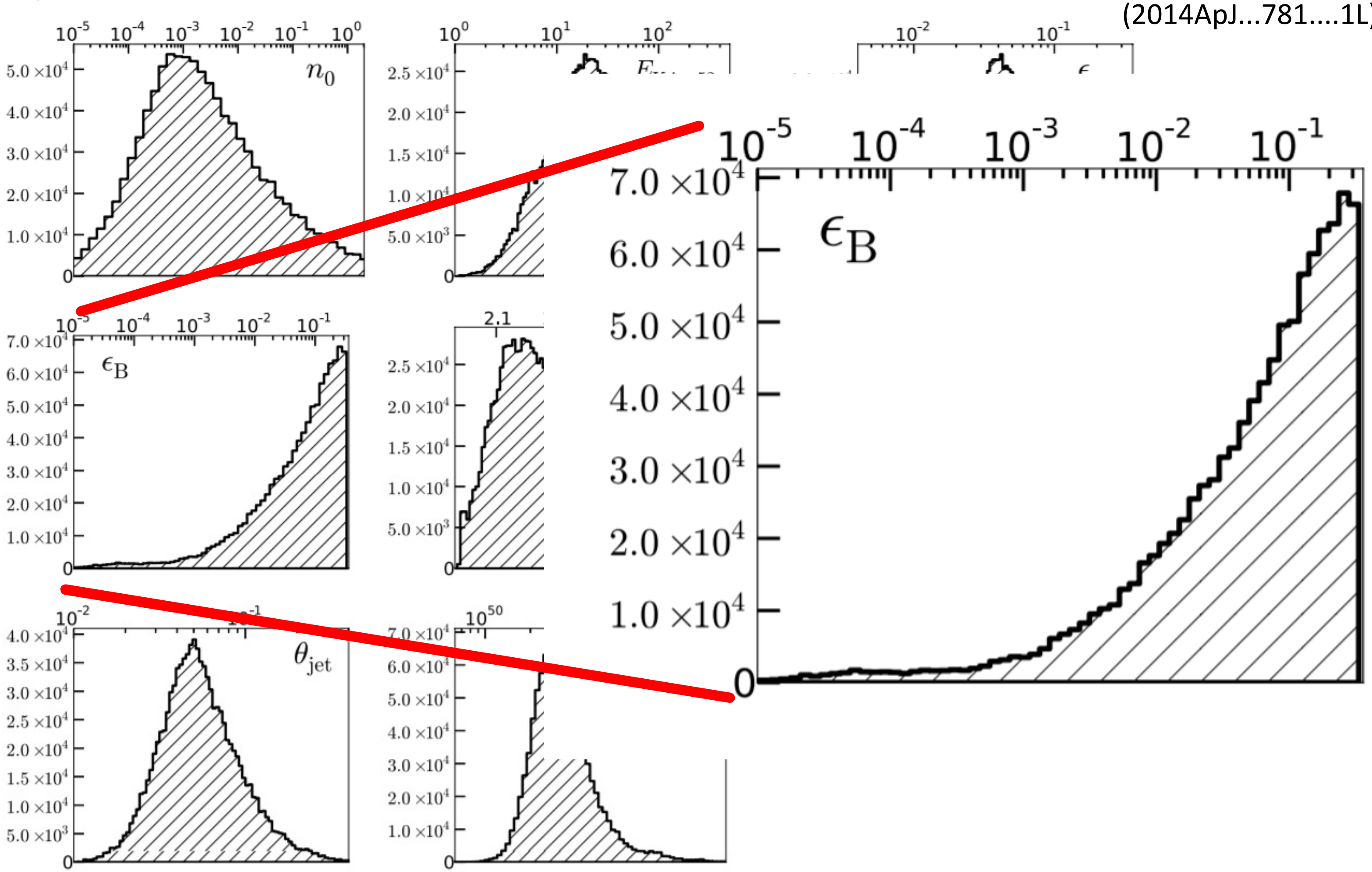


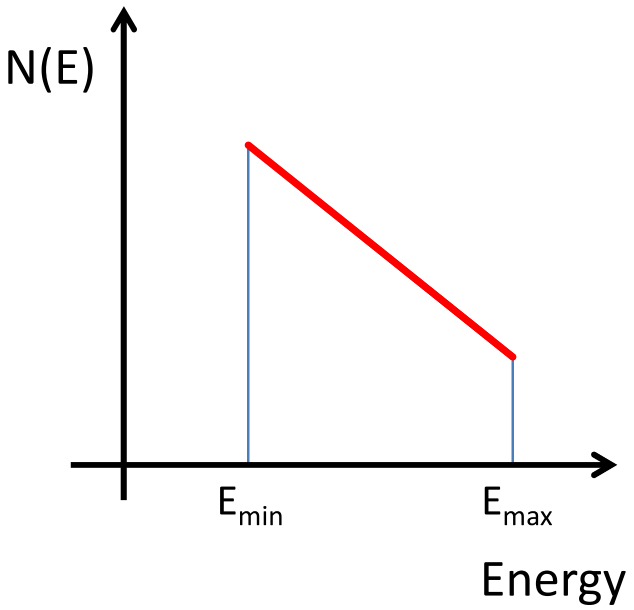
Figure 11. Posterior probability density functions of the physical parameters for GRB 120521C from MCMC simulations. We have restricted $E_{K,iso,52} < 500$, $\epsilon_e < 1/3$, and $\epsilon_B < 1/3$.

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)

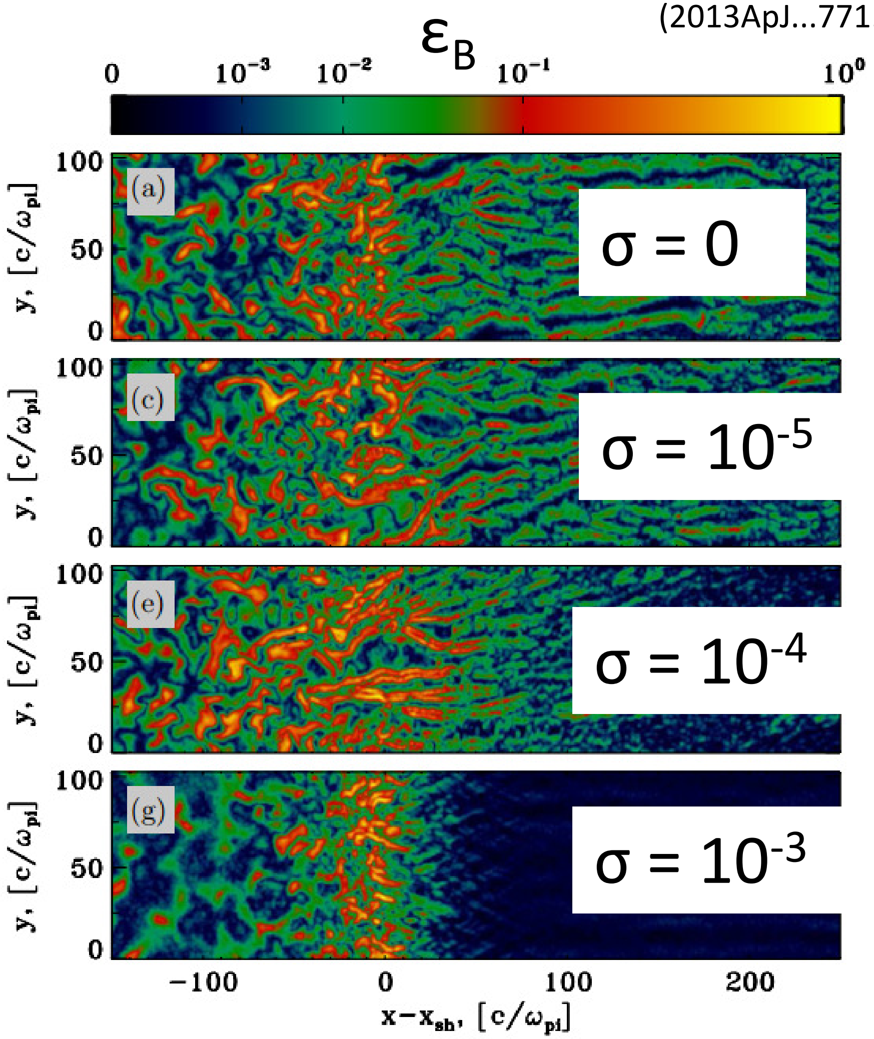
The case for low-energy electrons

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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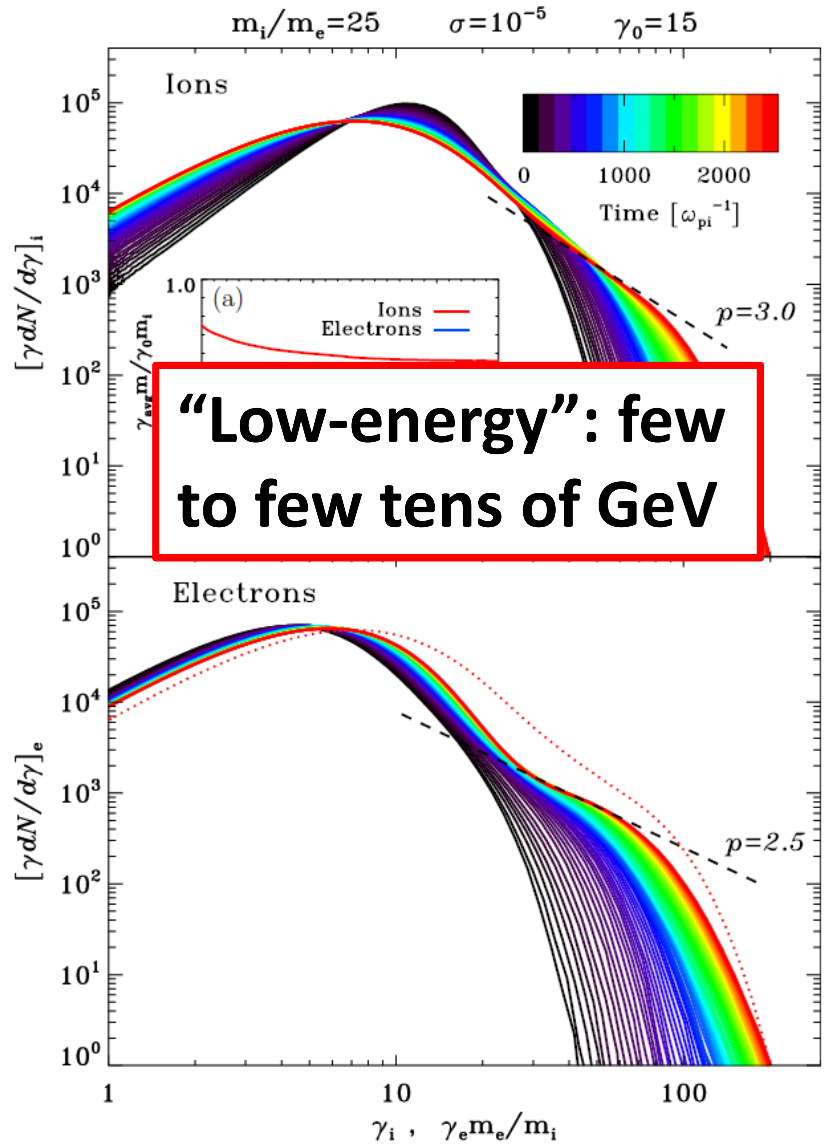
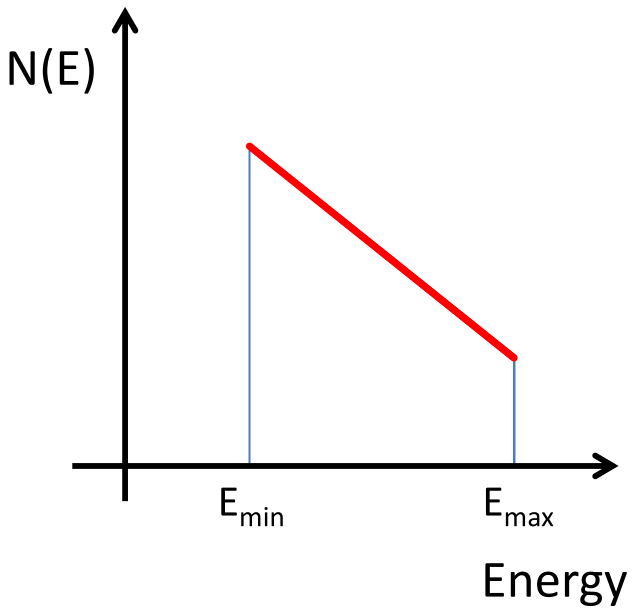


Figure 11. Temporal evolution of the post-shock particle spectrum

The case for low-energy electrons



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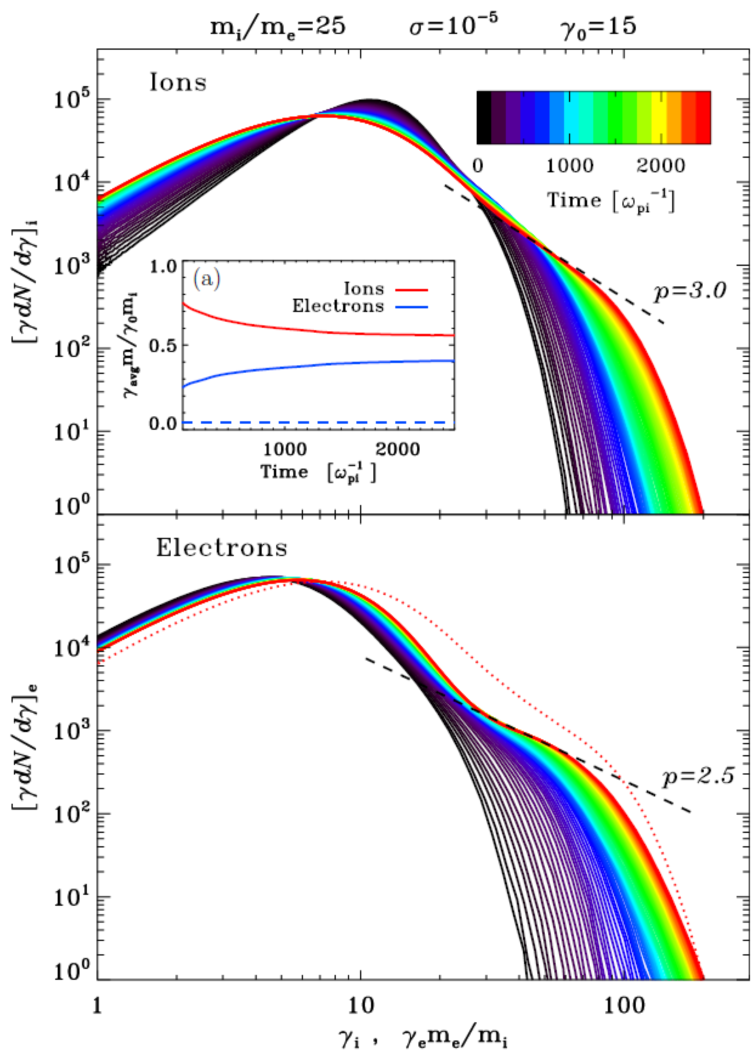

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Sironi et al. (2013)
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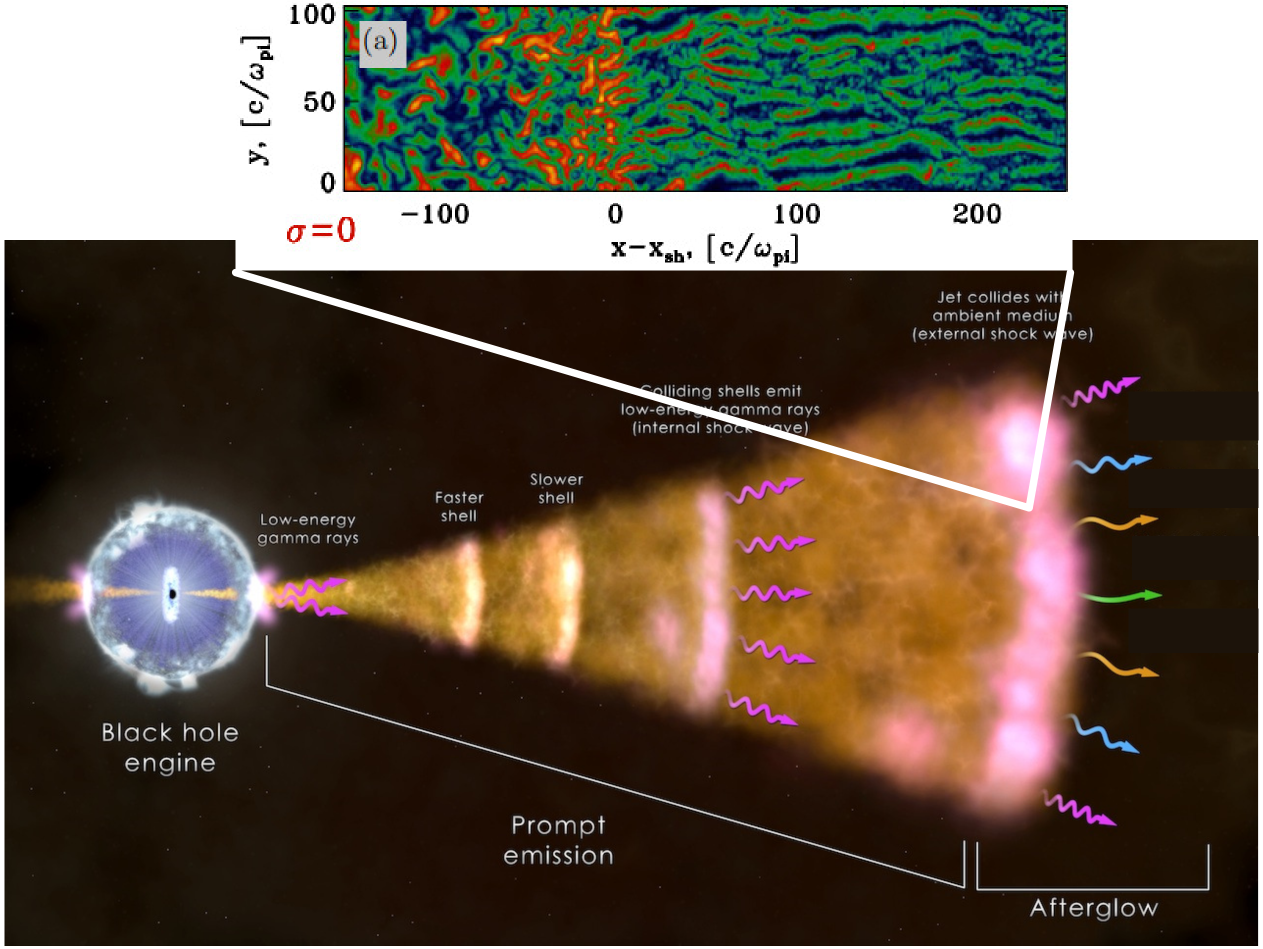
The consequences of low-energy electrons

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

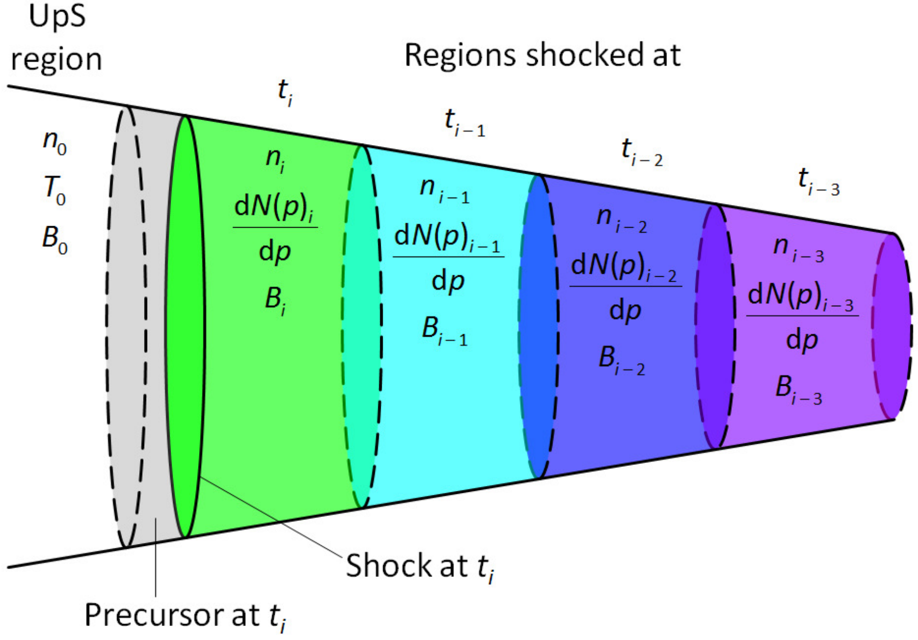


The consequences of low-energy electrons

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

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

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



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Warren et al. (2017)
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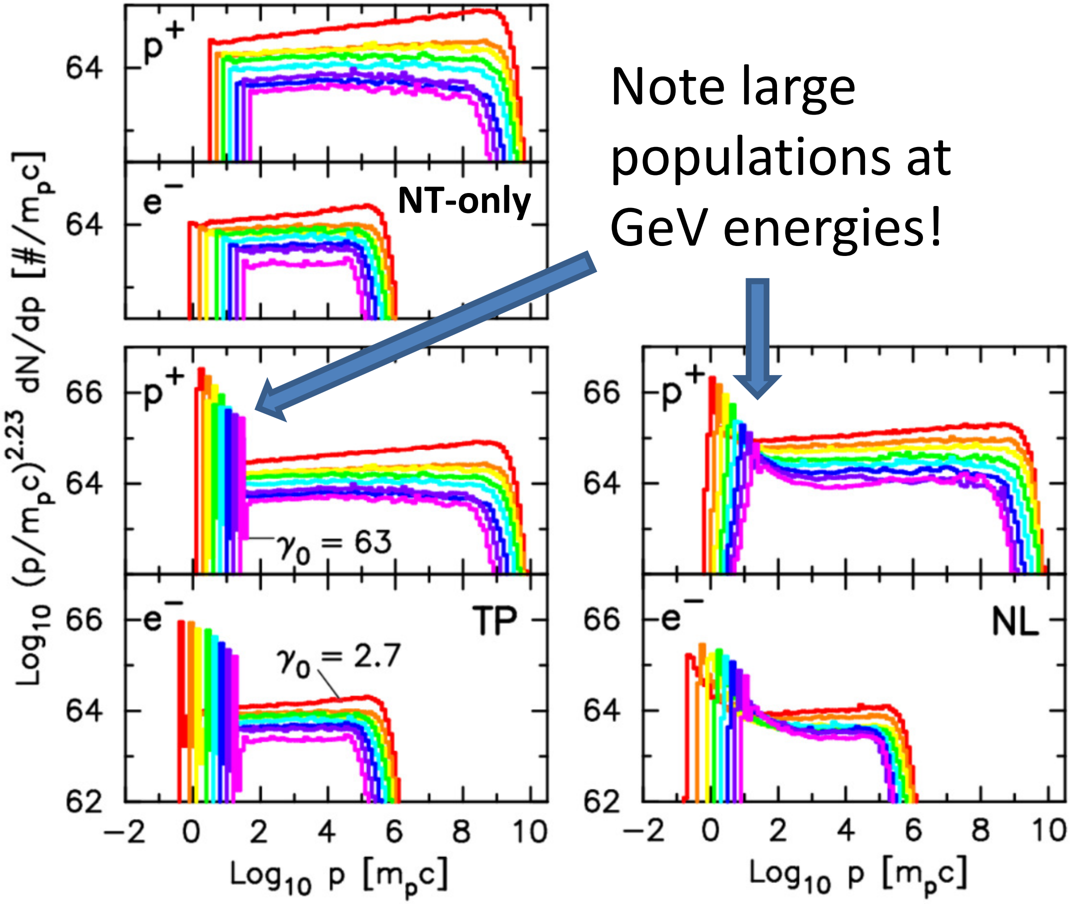
- Retain all shocked plasma, not just material currently interacting with shock

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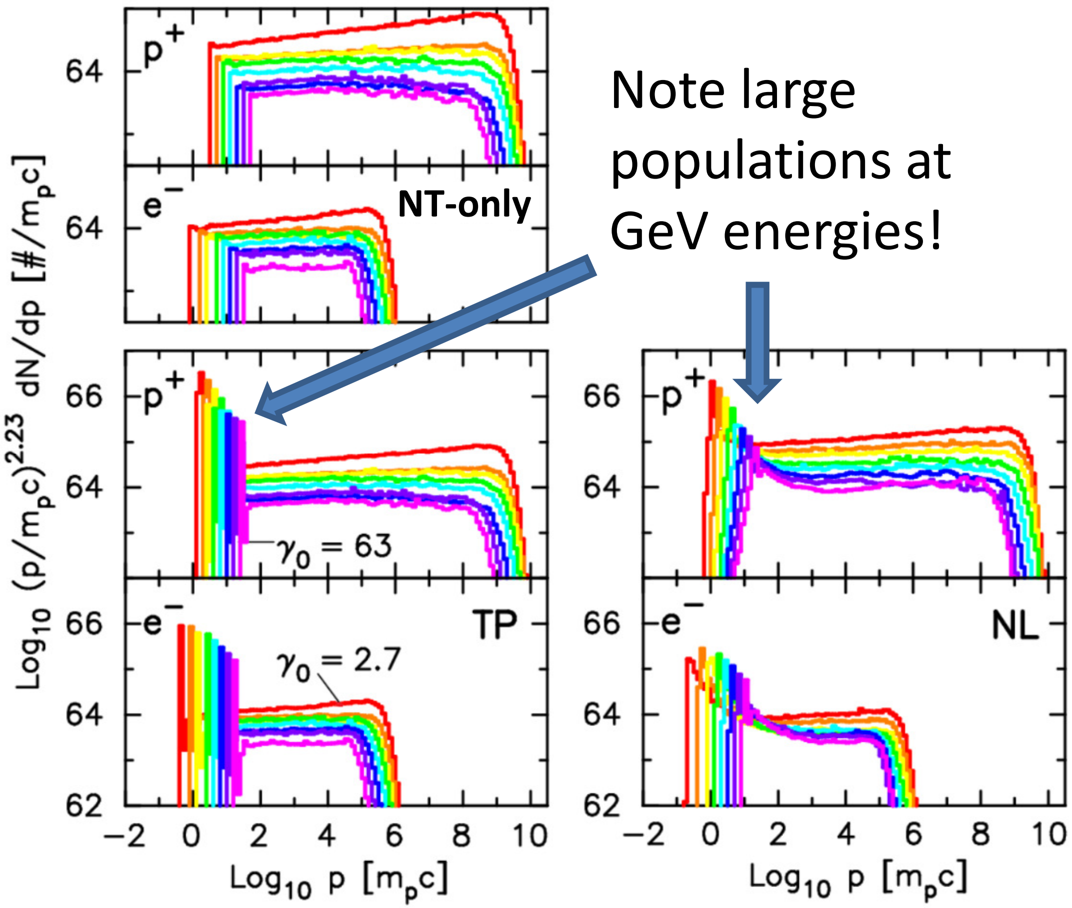
- Photon processes treated:
  - ➢ Synchrotron
  - ➢ Inverse Compton
    - ▪ CMB
    - ▪ Synch. photons
    - ▪ ISRF
  - ➢ (p-p) π production
  - ➢ Absorption
    - ▪ SSA (at radio)
    - ▪ EBL (at GeV+)



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Warren et al. (2017)
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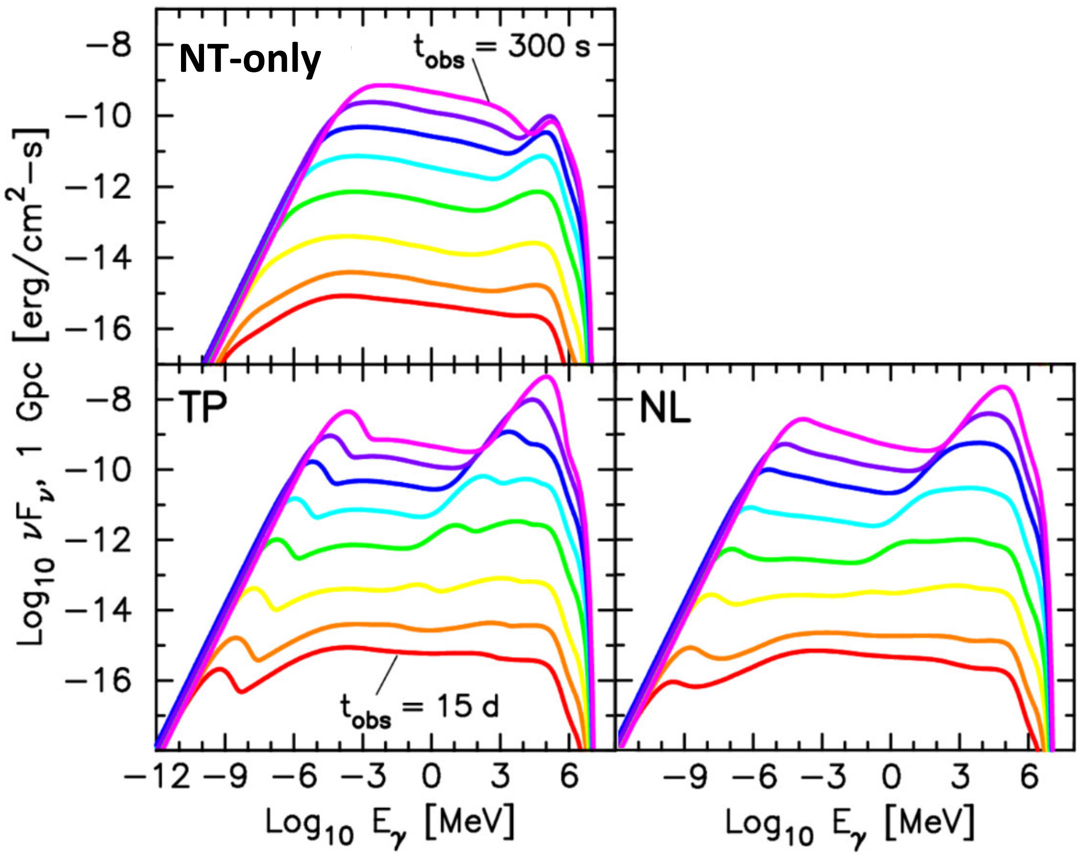
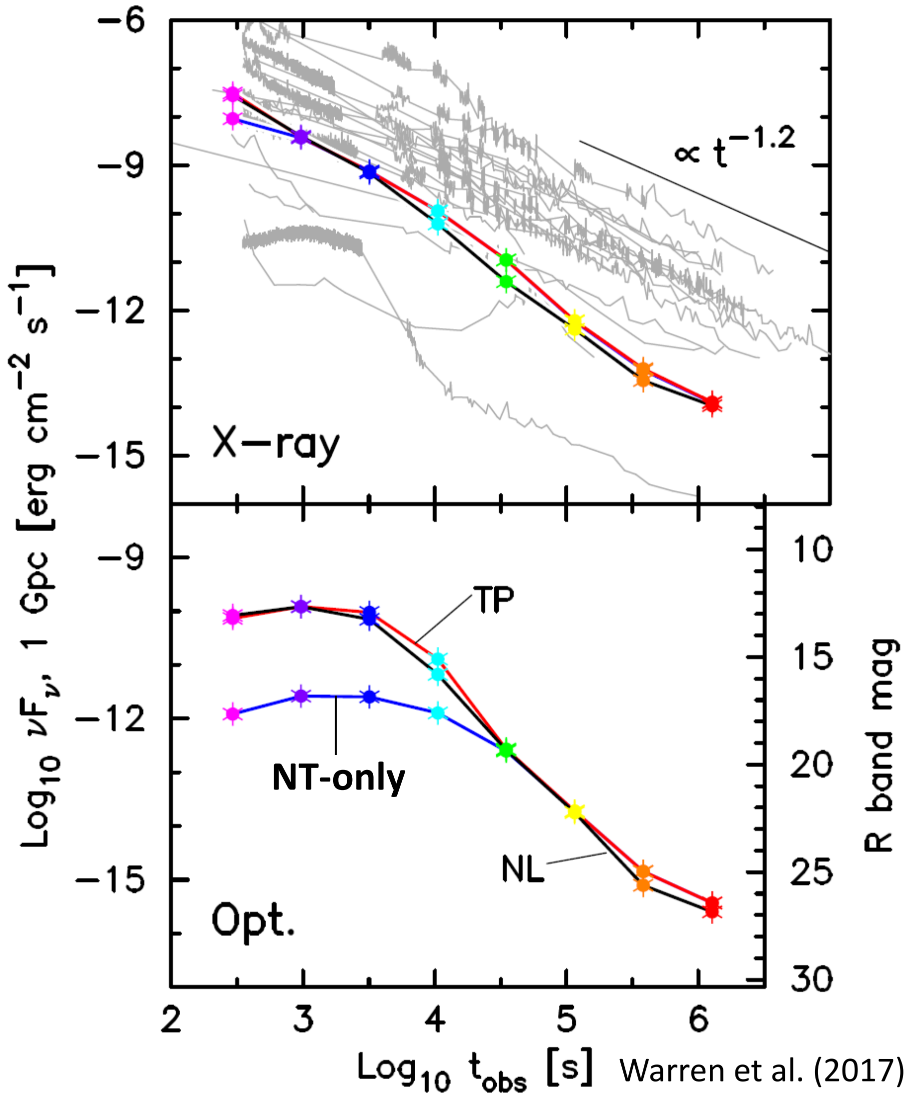


The consequences of low-energy electrons

- 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?



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

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

Warren et al. (2017)
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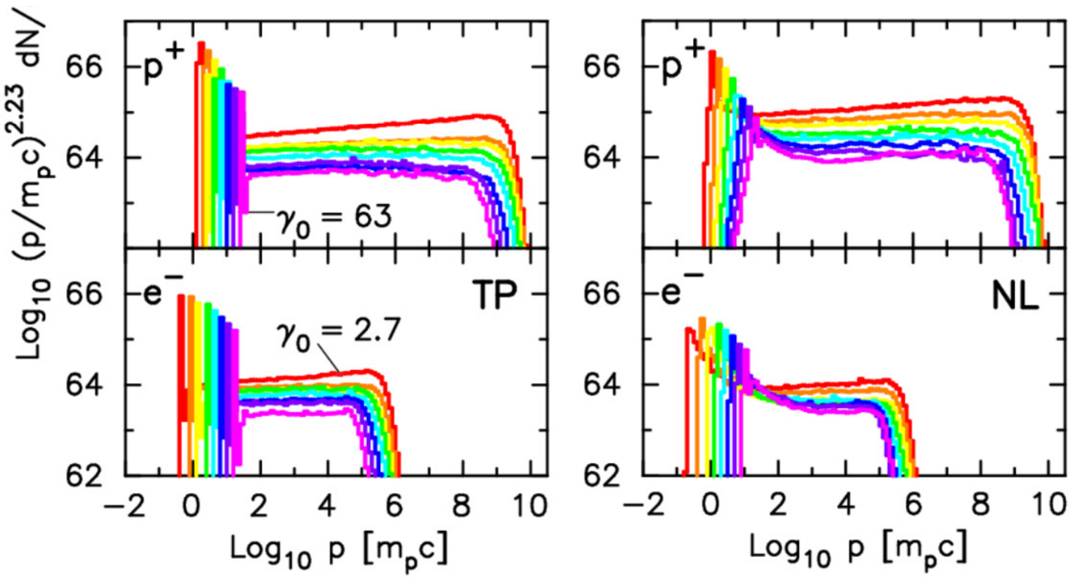

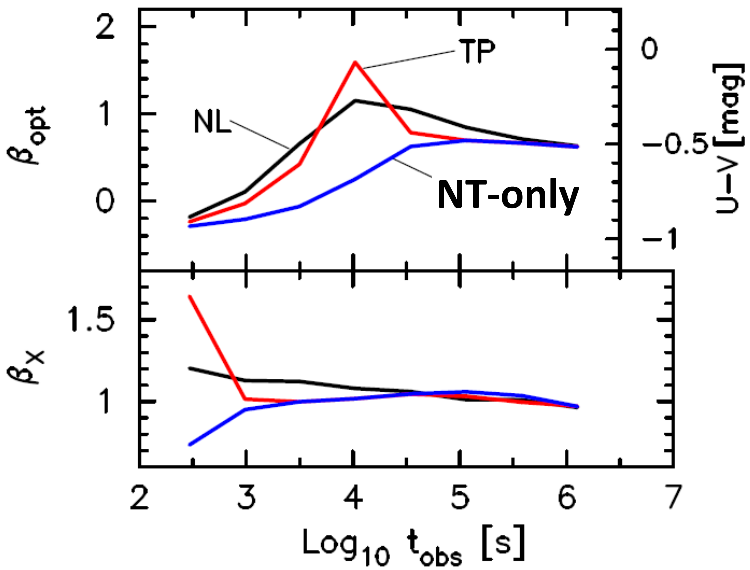

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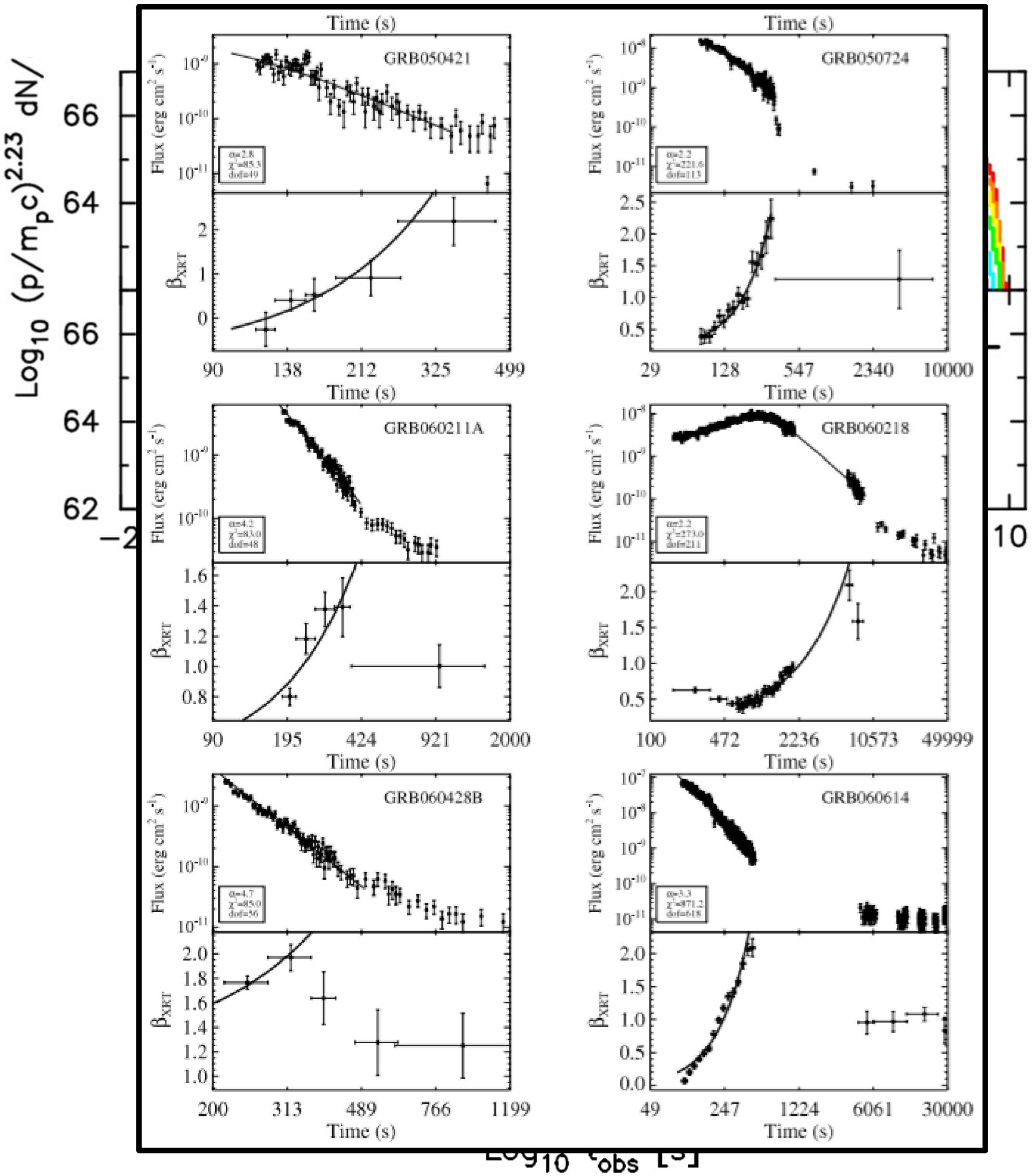
Zhang et al. (2007)
(2007ApJ...666.1002Z)



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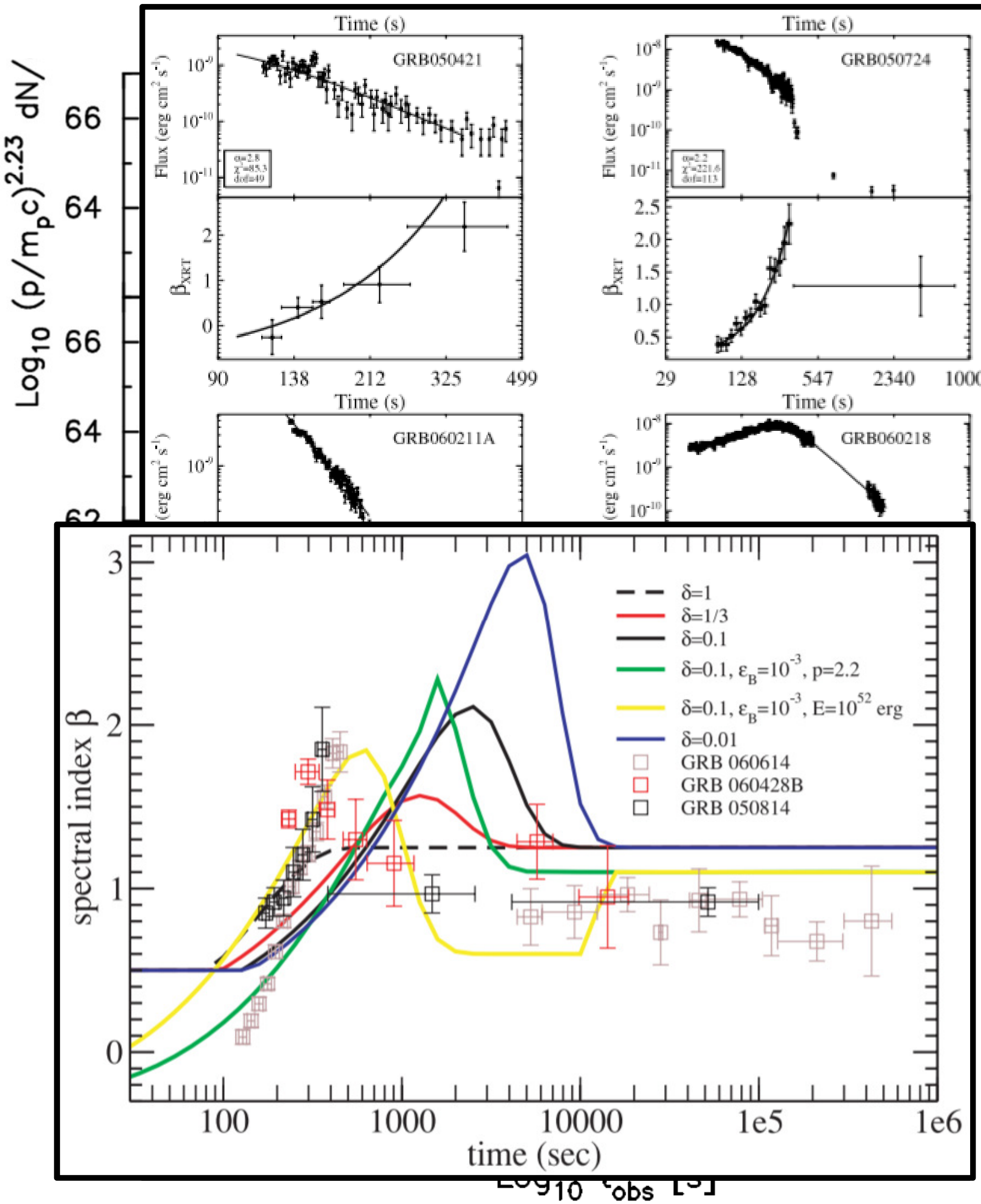
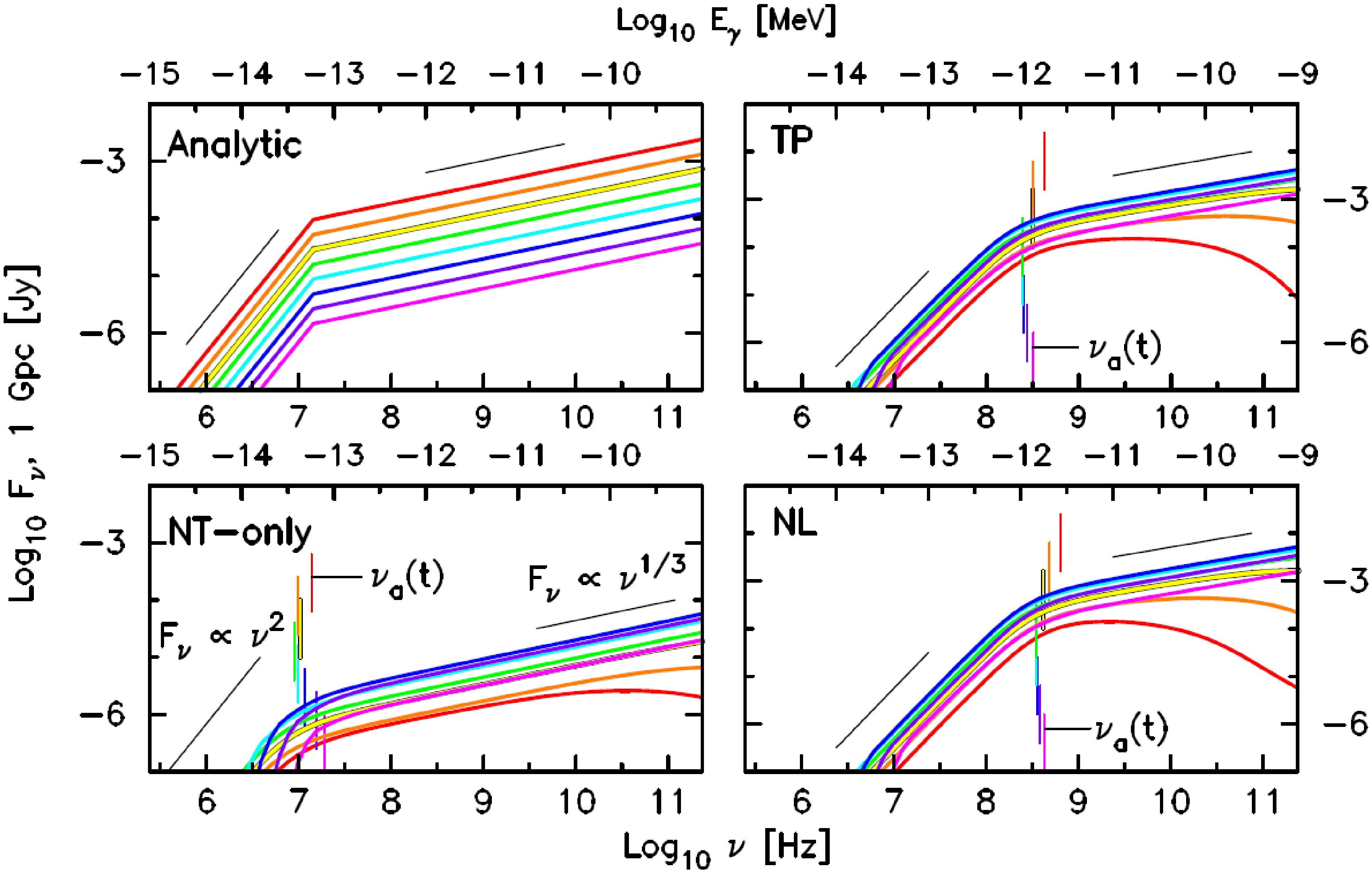


Giannios & Spitkovsky (2009)
(2009MNRAS.400..330G)

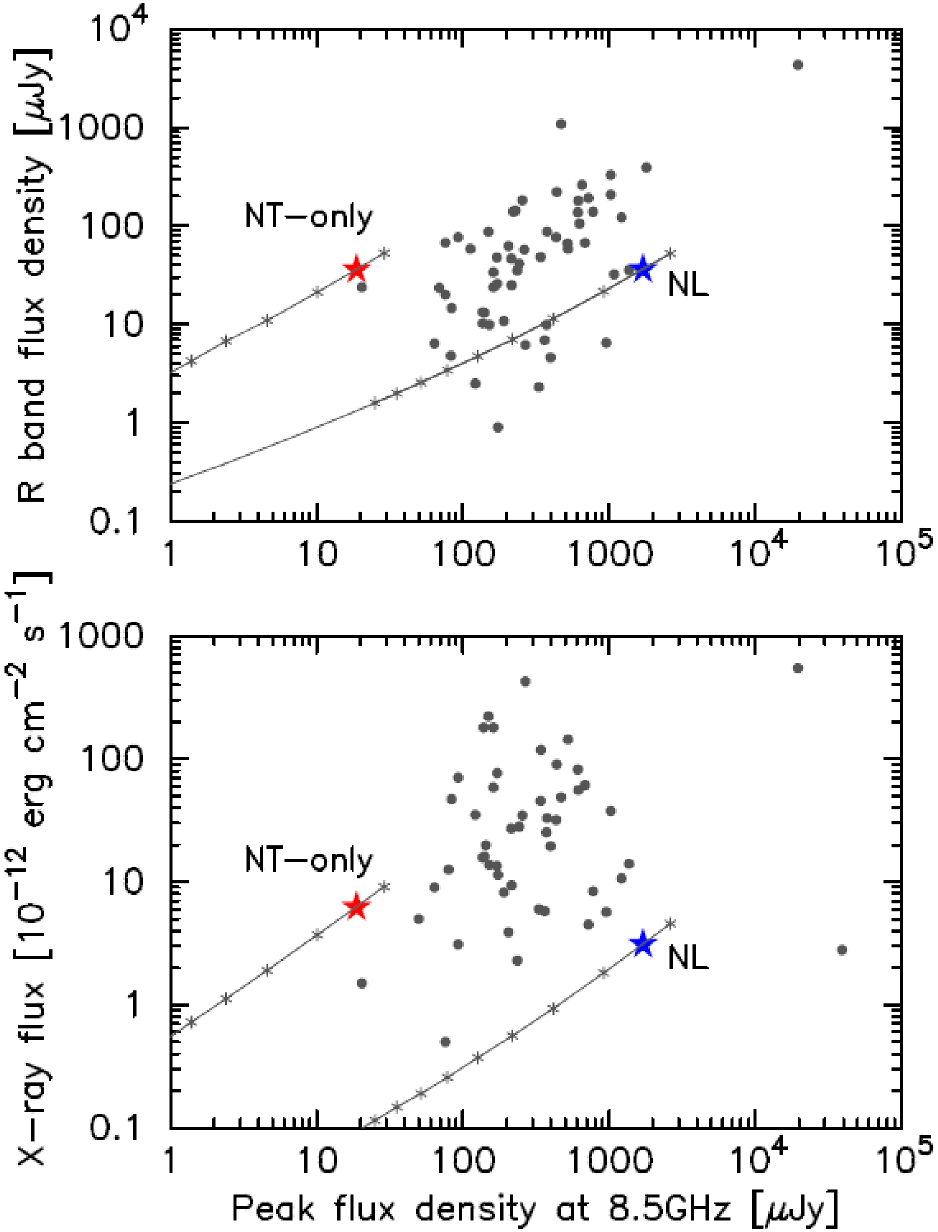
The consequences of low-energy electrons

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



The consequences of low-energy electrons

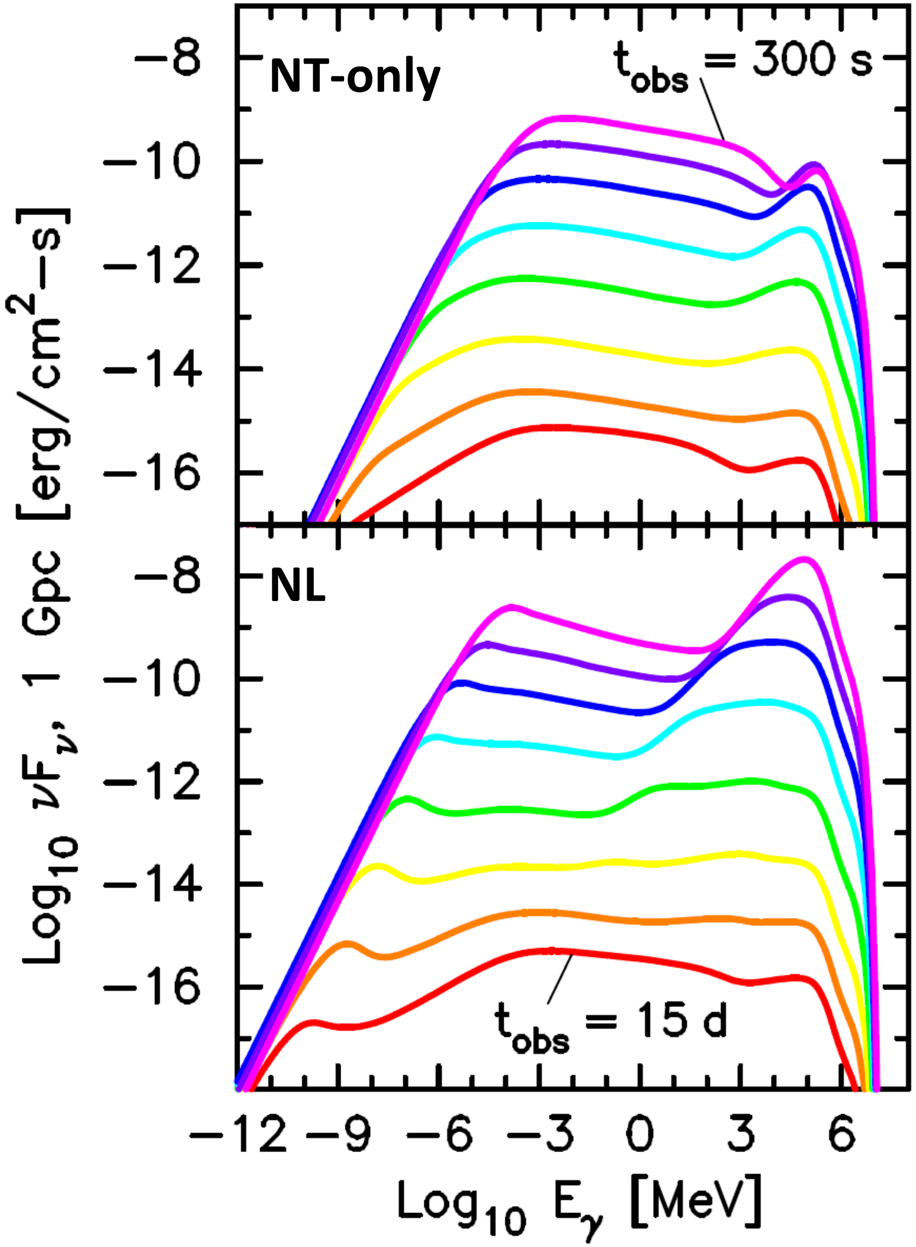
- In radio band, thermal particles very important for both emission and absorption
- For same GRB parameters, huge boost (100x) in radio emission with no change in optical, X-ray
- Fitted GRB parameters will be very different if thermal particles included



The consequences of low-energy electrons

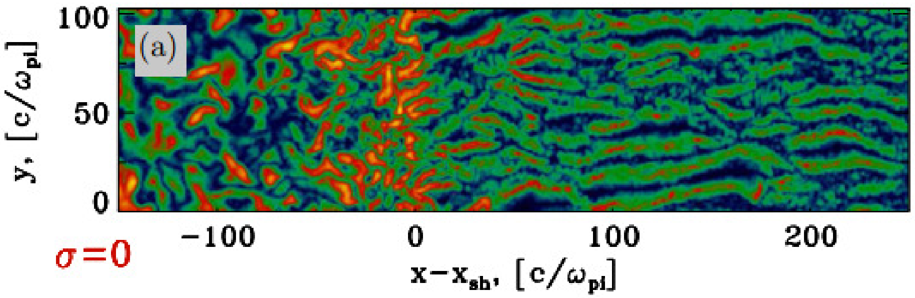
- What about high-energy photons (>100 MeV)?
- Electrons can emit by synchrotron self-Compton process, so adding lots of thermal electrons means adding lots of SSC photons
- SSC production scales with n_{elec}^2, so large gains possible if distribution mostly thermal

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



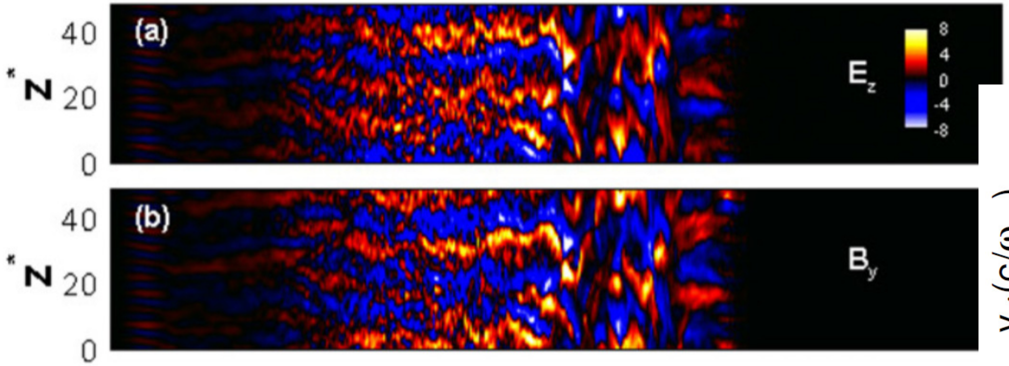
The consequences of low-energy electrons

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

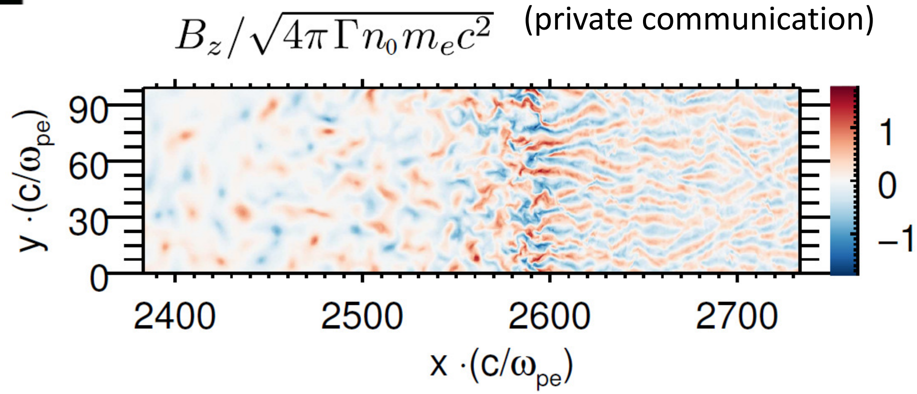


- Presence of hot thermal particles robustly required by plasma physics

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

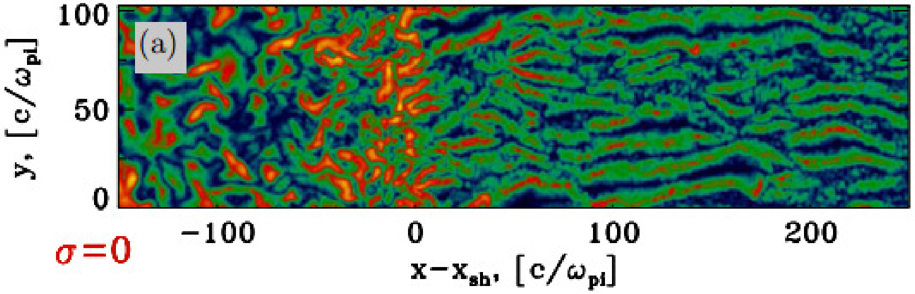
Consequently, their momentum dispersion amounts to $\Delta p_{\rm u}^2 \sim m_{\rm p}{}^2c^2/2$ once the electrons reach the shock front, which corresponds to equipartition with the incoming ions.

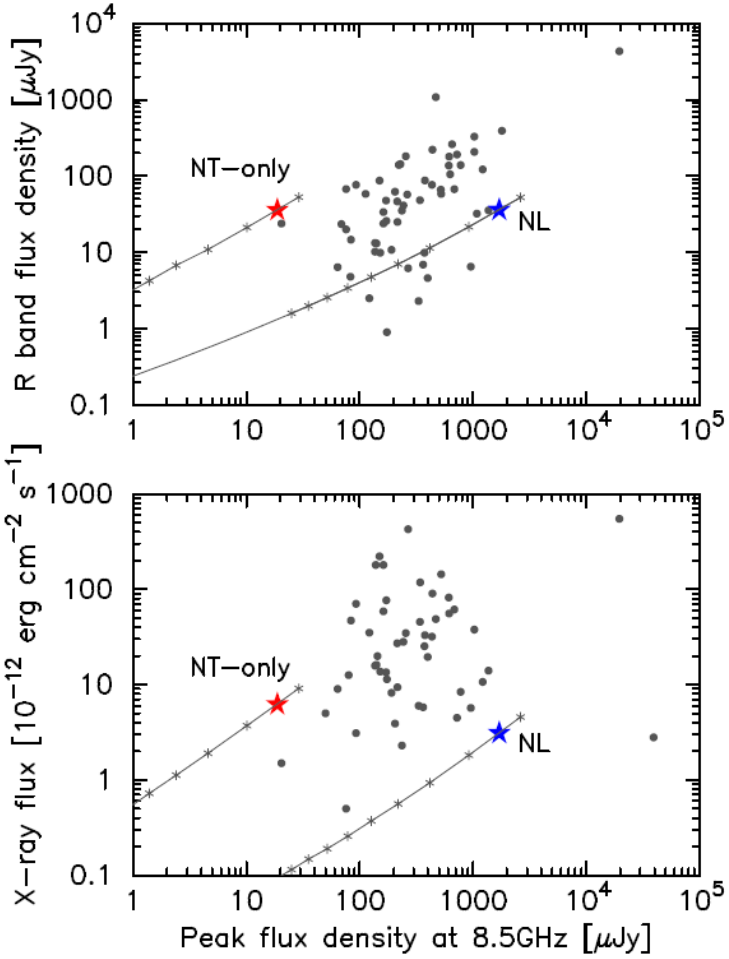
Lemoine & Pelletier (2011)
(2011MNRAS.418L..64L)

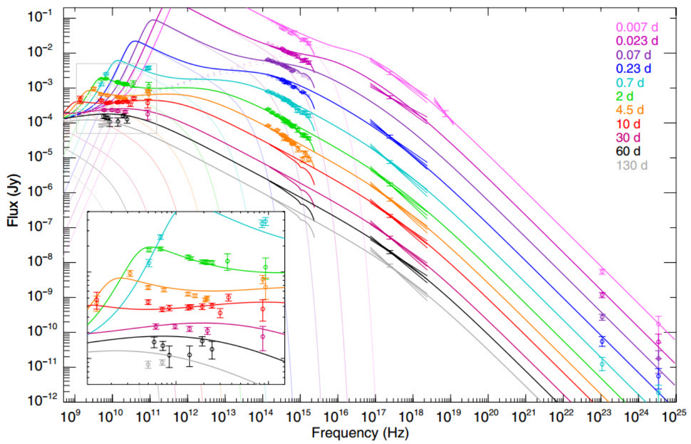
The consequences of low-energy electrons

- 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

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







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

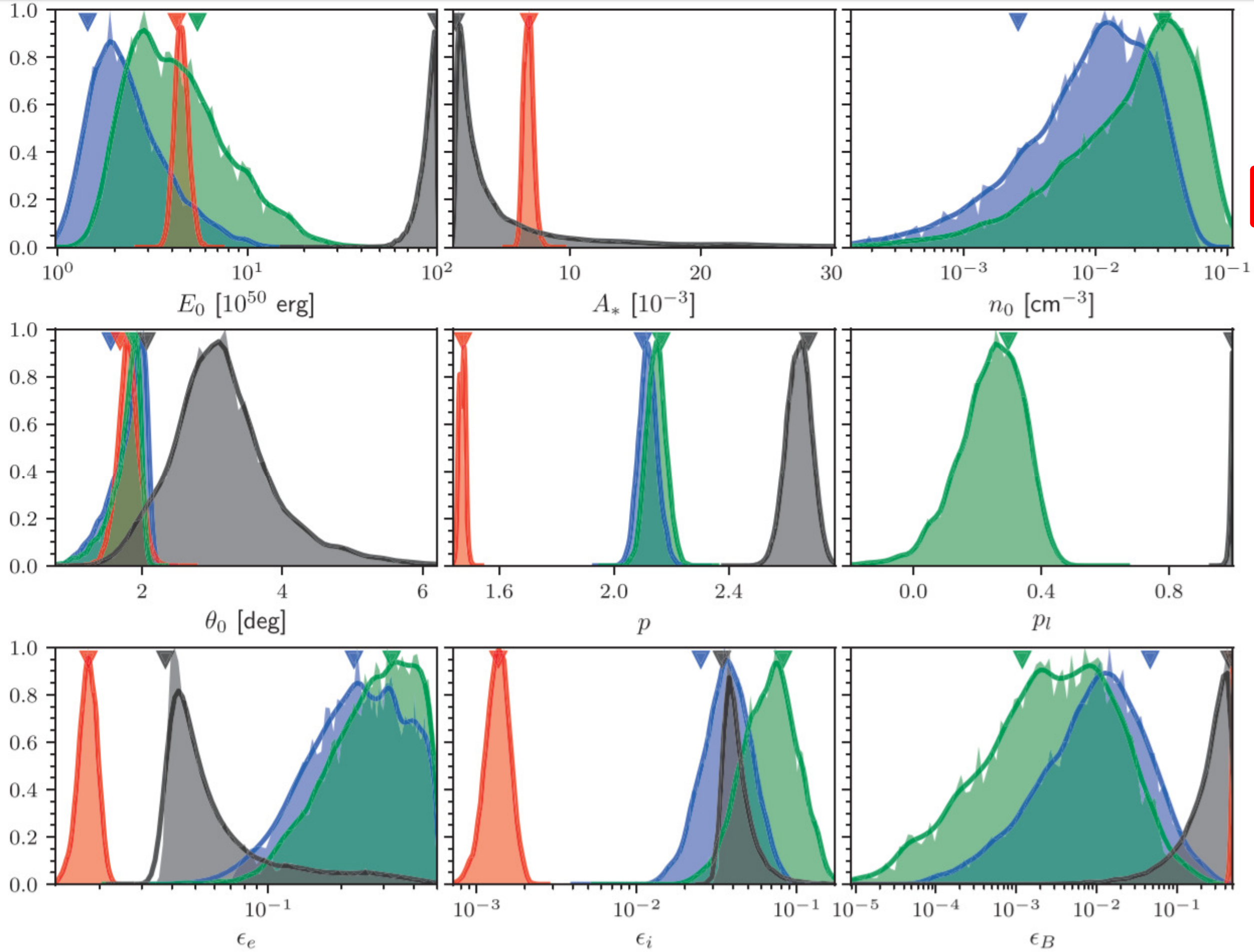
The present of low-energy electrons

- Other people starting to quantify the changes expected

Ressler & Laskar (2017) (2017ApJ...845..150R)

Table 1
MCMC Parameter Fits

Parameter	True	Expected
p	2.5	2.5
ϵ_e	2×10^{-2}	0.1
ϵ_B	2×10^{-3}	0.01
n_0	5.0	1.0
E_{52} [a]	5.0	1.0
f_{NT}	0.2	1.0

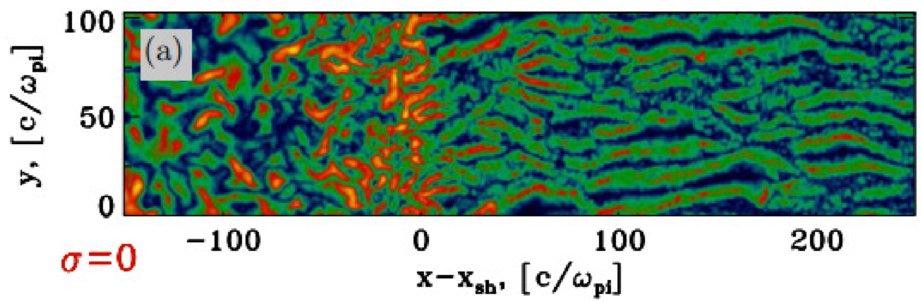


Jóhannesson & Björnsson (2018) (2018ApJ...859L..11J)

The present of low-energy electrons

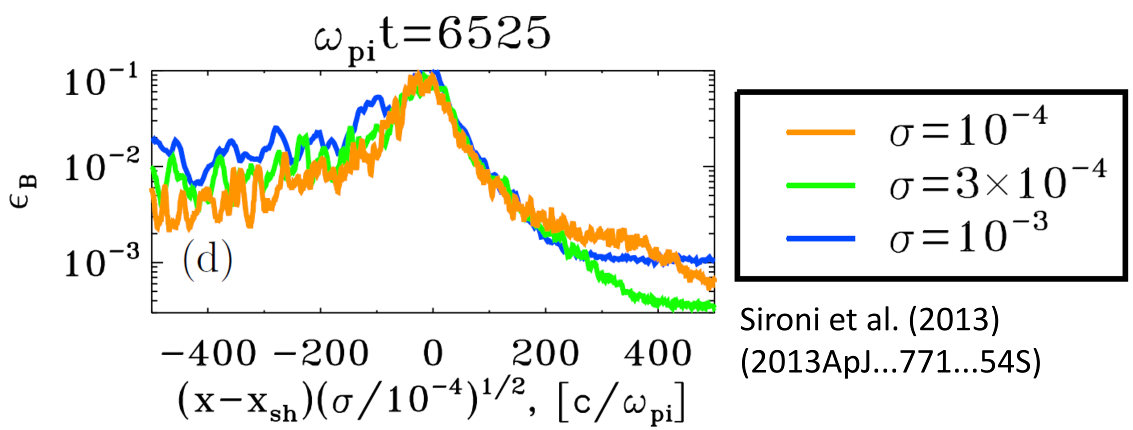
- My current project:
  - Physically-motivated magnetic field structure
  - Analytical approximations

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



- Expect magnetic field to decay downstream from shock

- Specifically, $B \propto t^{-\alpha}$, where $\alpha \approx 0.5$ (Lemoine+ 2013)

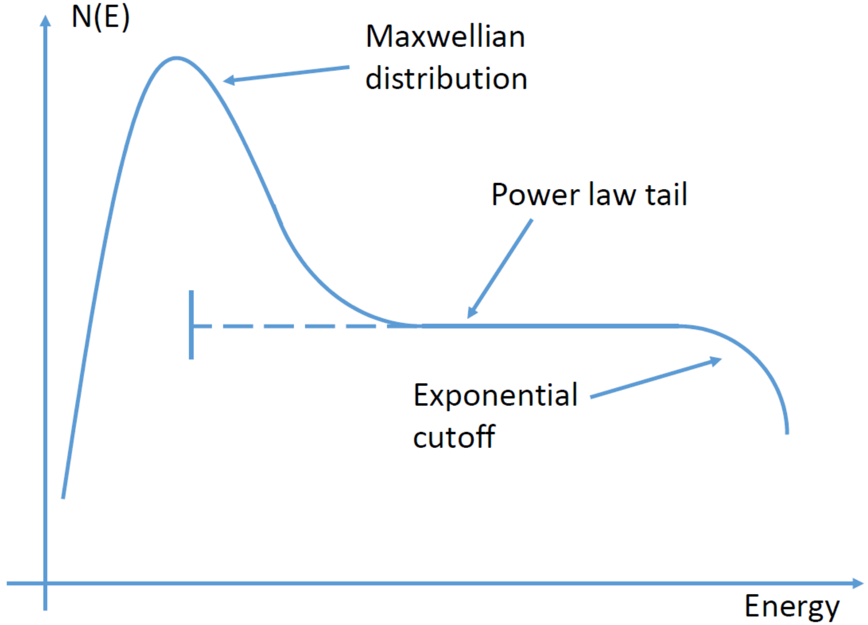


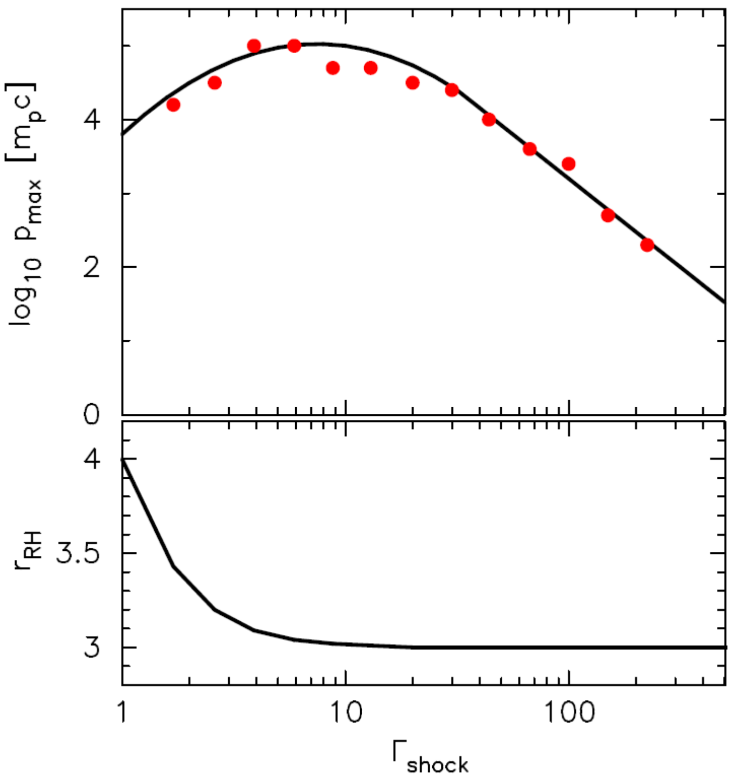
Sironi et al. (2013) (2013ApJ...771...54S)

The present of low-energy electrons

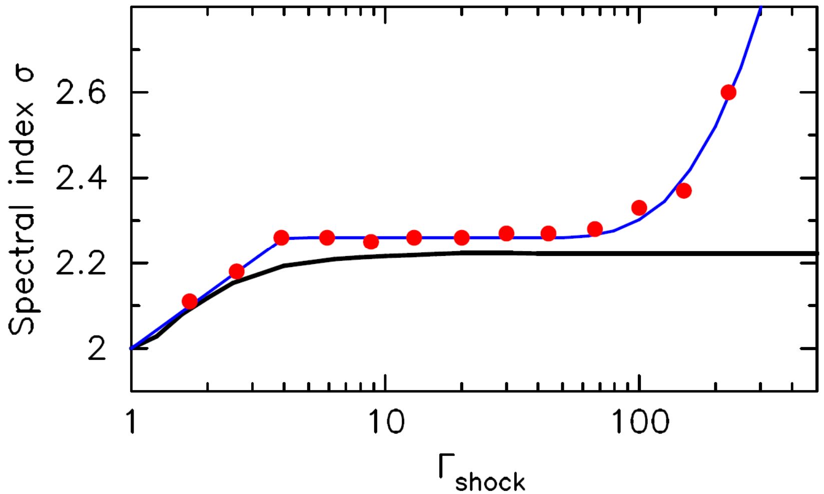
- Want to get electron distribution for any shock without doing 8-80 hours of MC sims

- Do a suite of MC sims & get fitting formulas





PRELIMINARY



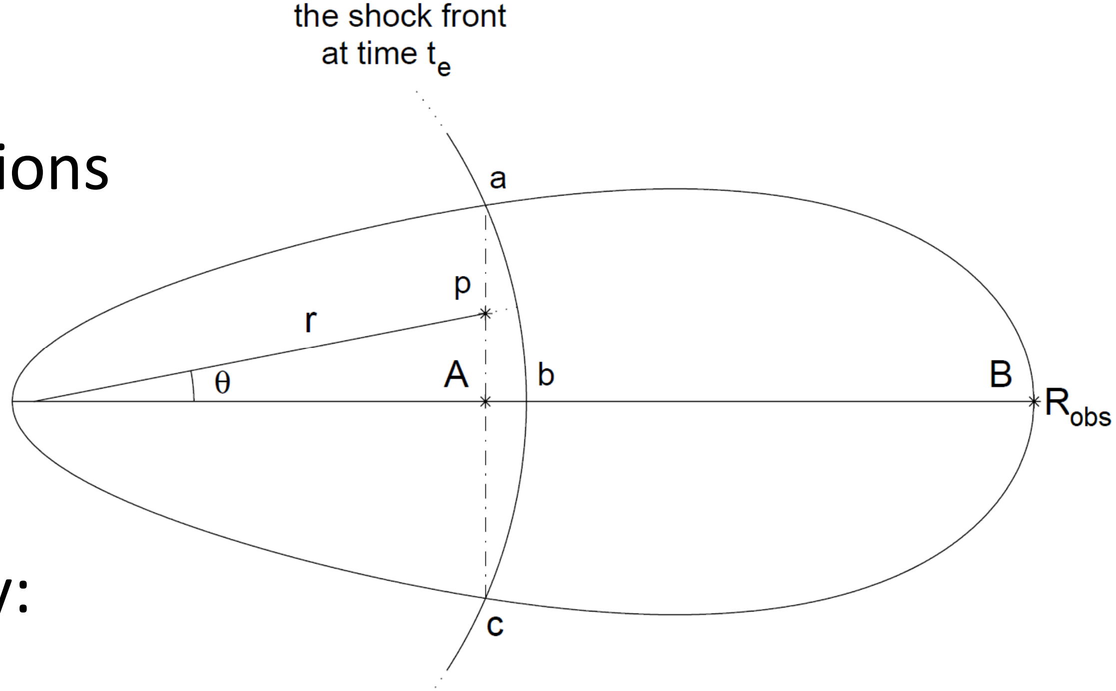
The present of low-energy electrons

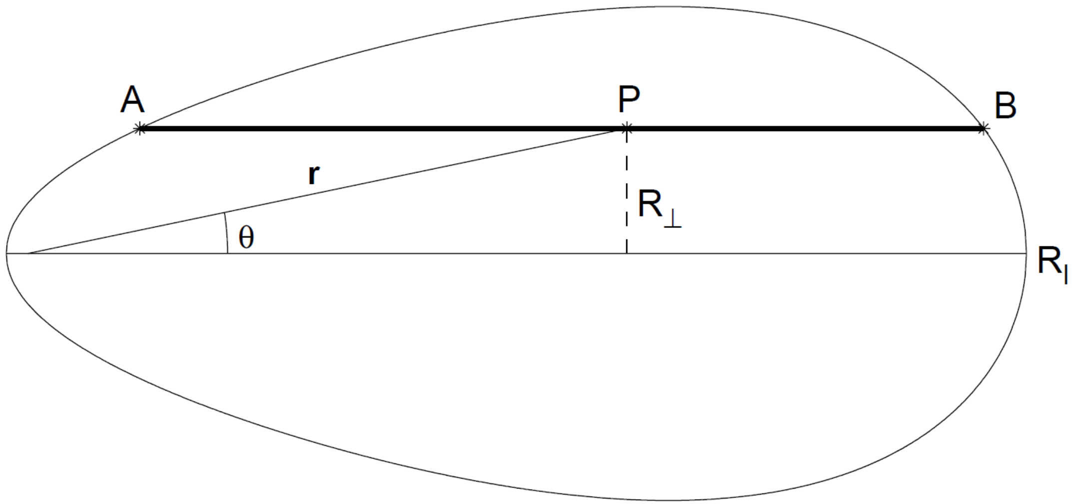
- Throw the decaying B-field and fitted electron distributions into model for shocked plasma of GRB jet

- Integrate along lines of sight to get specific intensity:

$$\frac{dI_\nu}{ds} = j_\nu + \alpha_\nu I_\nu$$

$$F_\nu = \int I_\nu \, d\Omega$$





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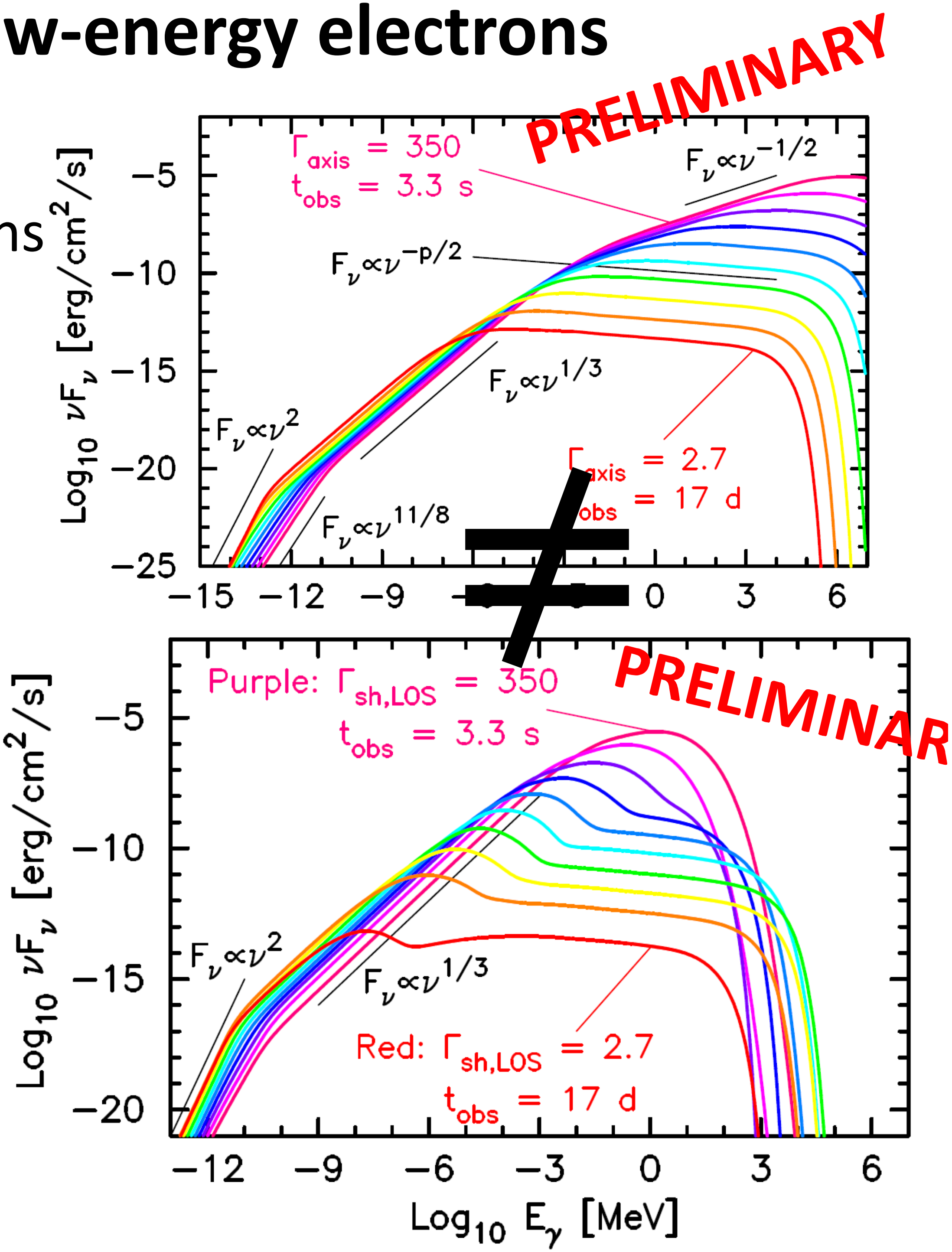

The future of low-energy electrons

- Can now rapidly (seconds-minutes) generate spectra & light curves for huge parameter space of GRBs

- Refit observed GRBs to measure effects of thermal electrons & other physically-motivated changes to standard picture, where ≈97% of electrons are thermal

Ressler & Laskar (2017) (2017ApJ...845..150R)

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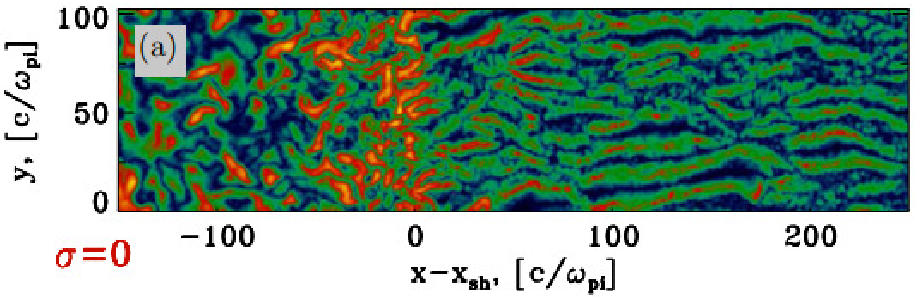
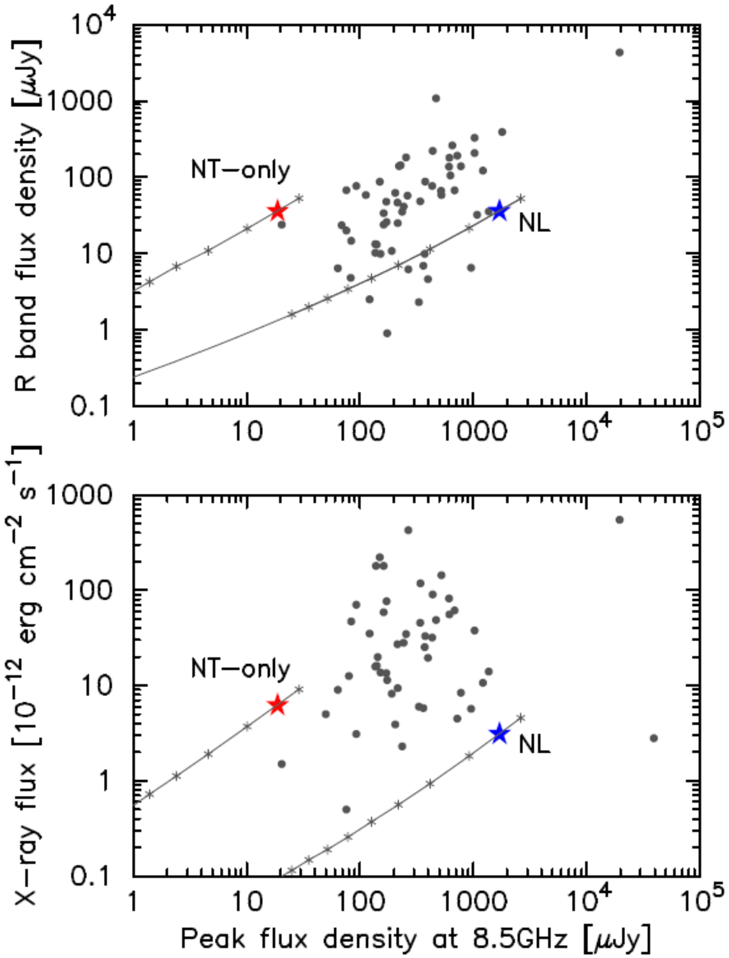
$f_{\rm NT}$	0.2	1.0

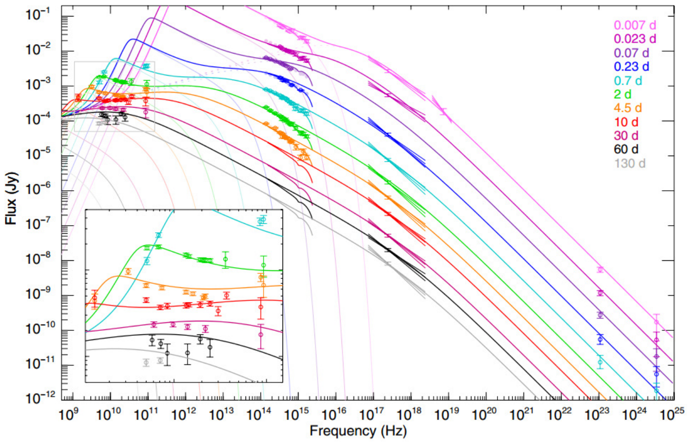
Conclusions

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)