High energy radiation from *Fermi* GRBs: Electrons acceleration in the external forward shock

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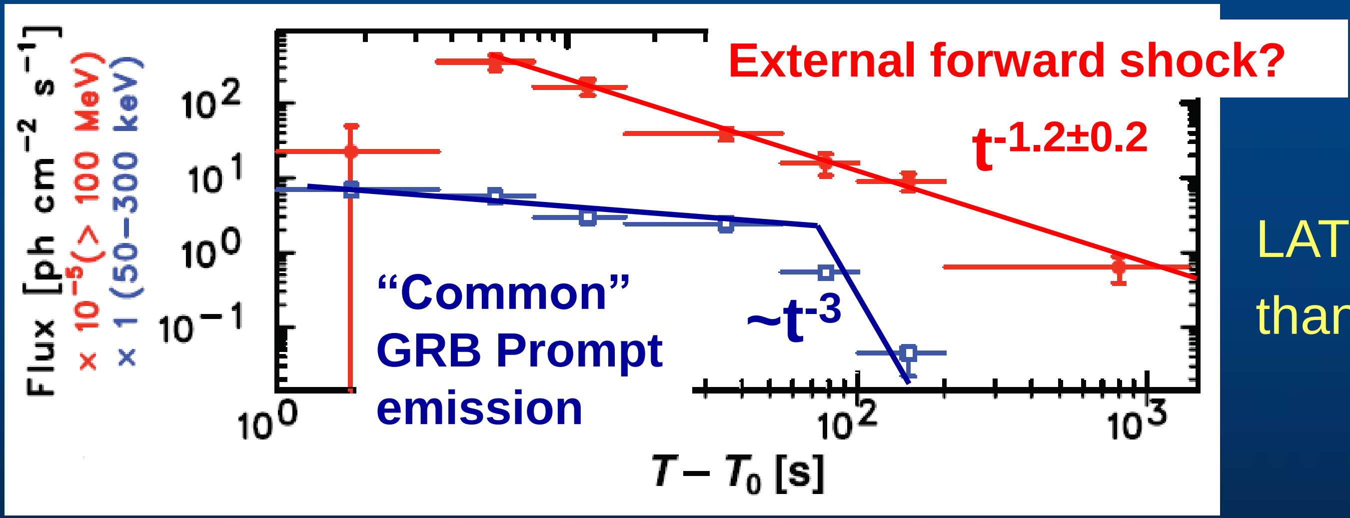
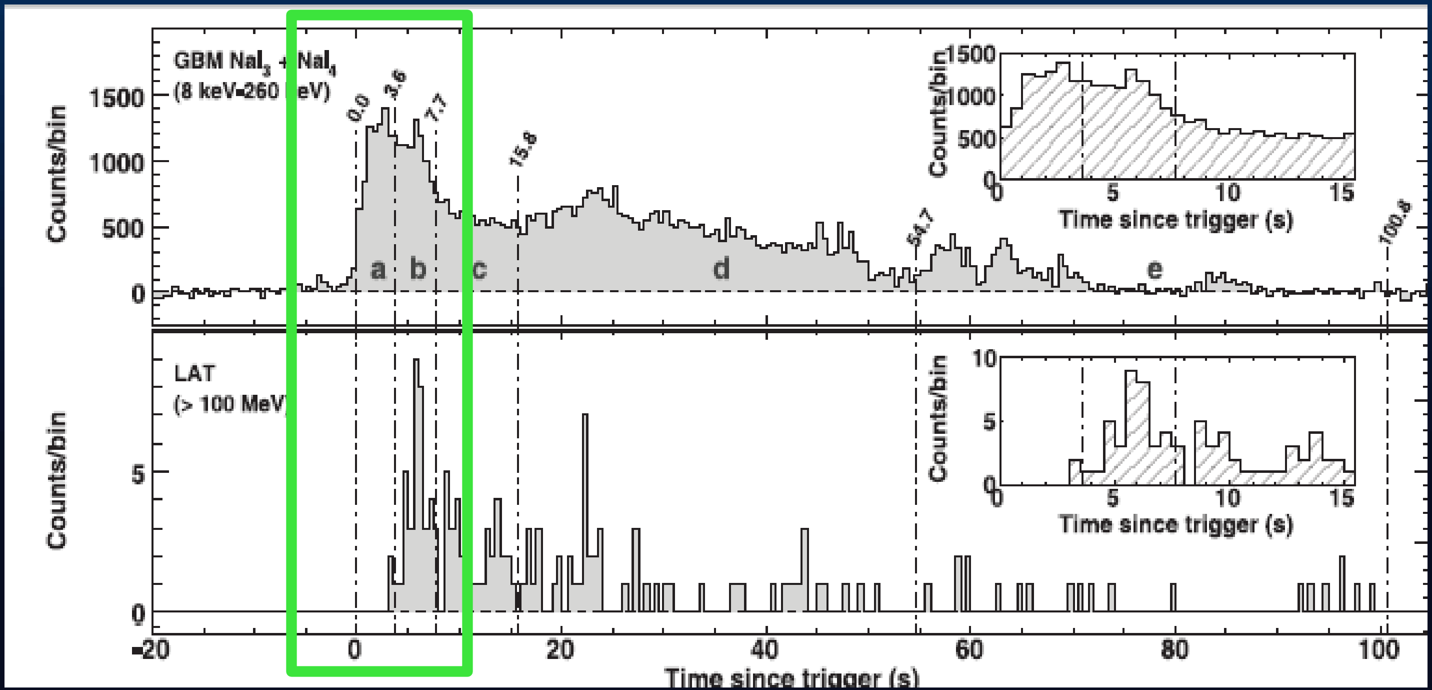
Main puzzles of *Fermi* GRBs



LAT emission lasts longer than GBM emission

LAT emission is delayed compared to GBM emission



GRB 0809016C: Abdo et al. 2009

External forward shock origin of Fermi/LAT emission

(Kumar & Barniol Duran 2009, 2010)

(See also, e.g., Gao et al. 2009, Ghirlanda et al. 2010, Ghisellini et al. 2010, De Pasquale et al. 2010, Corsi et al. 2010, …)

Why external forward shock?

Emission in the LAT band from the external forward shock is **unavoidable** if:

1. Energy in external shock (E_{iso}) ≥ energy radiated in gamma-rays ($E_{\gamma,iso}$)
   → Otherwise radiation efficiency ≥ 50%.
2. Electrons are accelerated in the shock
   → I will address this shortly

Magnitude of flux and time decay index for, e.g., GRB080916C:

Flux at 150 s and 100MeV:

$$f_\nu = (11n\mathrm{Jy})(E_{KE,55}^{iso})^{1.1}\varepsilon_{e,-1}^{1.4}\boxed{\varepsilon_{B,-2}^{0.1}} = 60n\mathrm{Jy}$$

vs.

Observed value:

$$f_\nu = 70n\mathrm{Jy}$$

Weak dependence on magnetic field, no dependence on density

LAT expected temporal decay (β_{LAT} = 1.2):

$$\alpha_{ES} = (3\beta - 1)/2 = 1.3$$

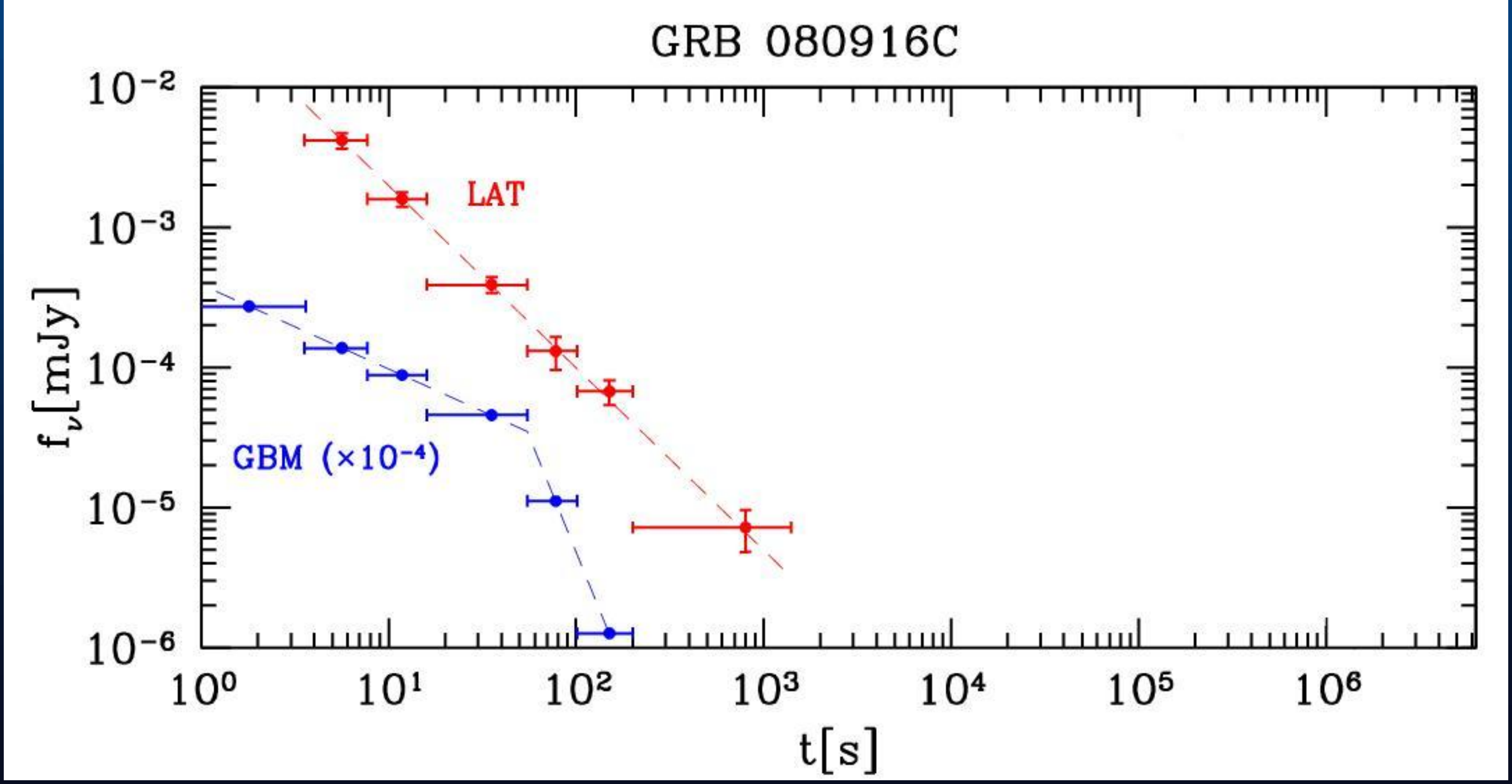
vs.

Observed value:

$$\alpha_{LAT} = 1.2 \pm 0.1$$

Expected data from ES at late times: GRB 080916C

- Using the parameter space determined from the LAT data: What is the expected ES flux in the X-ray and optical band?



Abdo et al. 2009

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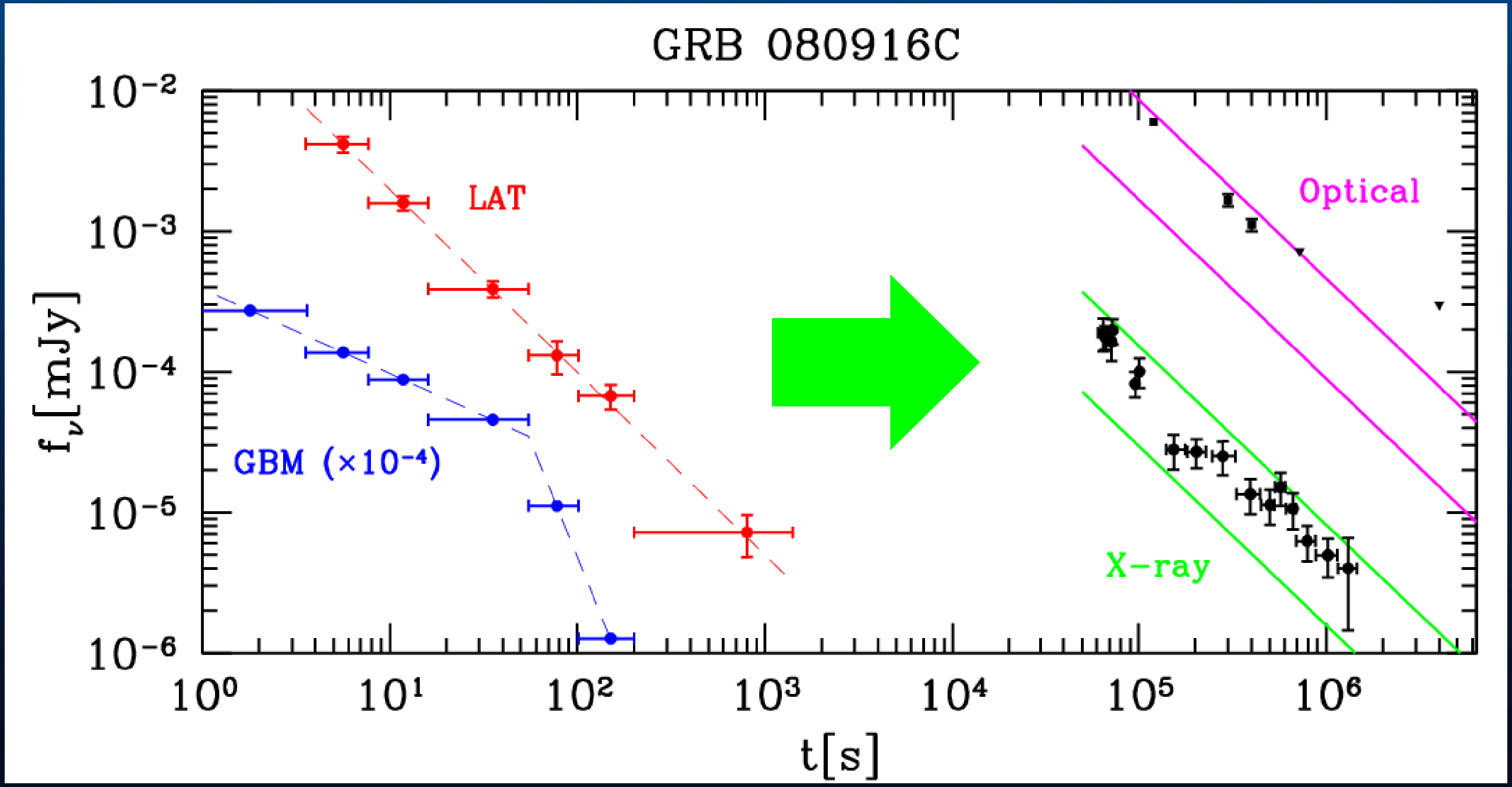
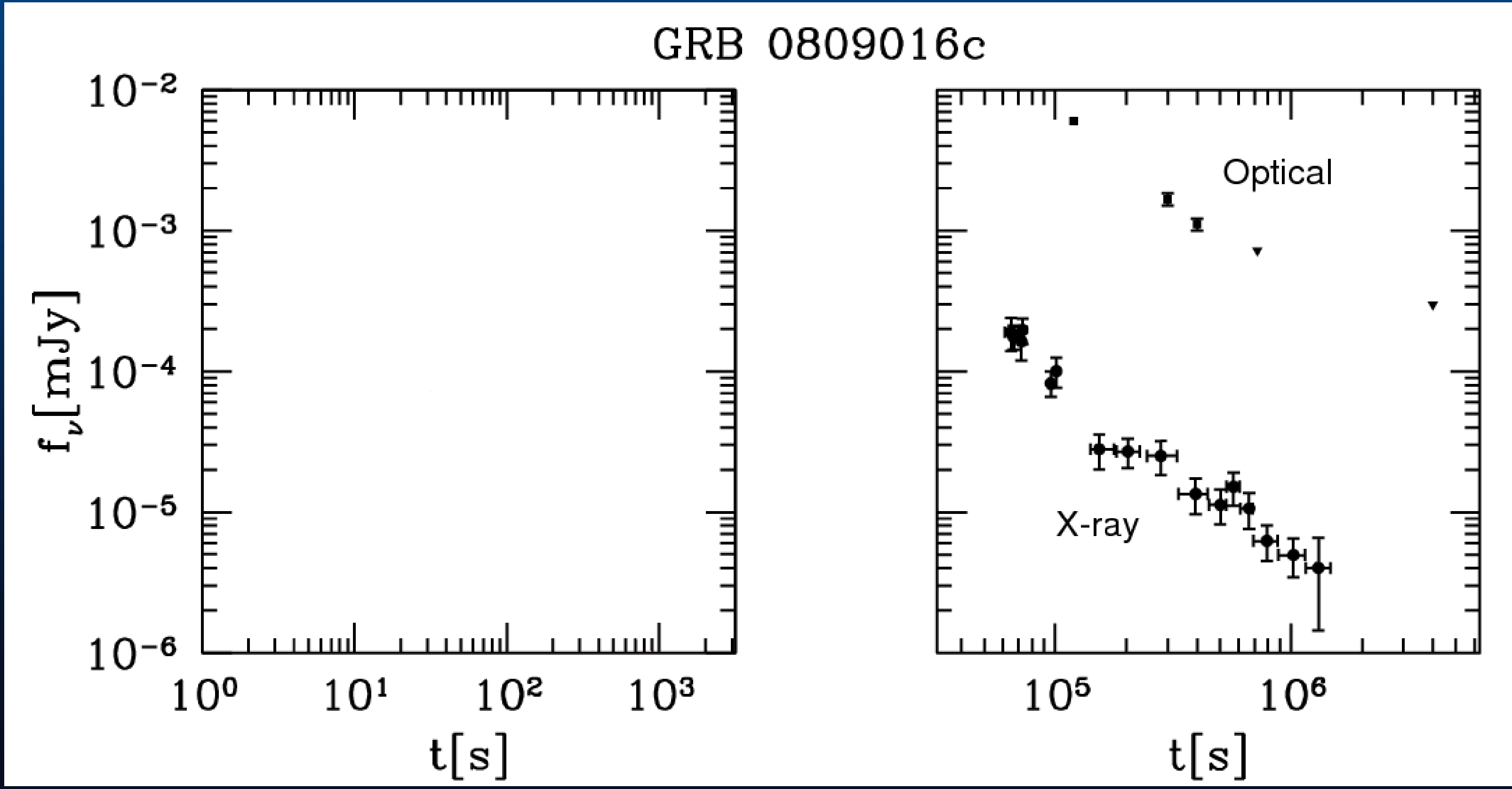


Abdo et al. 2009; Greiner et al. 2009; Evans et al. 2007, 2009

- We can then compare it with the available X-ray and optical data.

Expected data from ES at early times: GRB 080916C

- Assuming the X-ray and optical flux are from ES: What is the expected flux at > 100 MeV at early time?



Greiner et al. 2009; Evans et al. 2007, 2009

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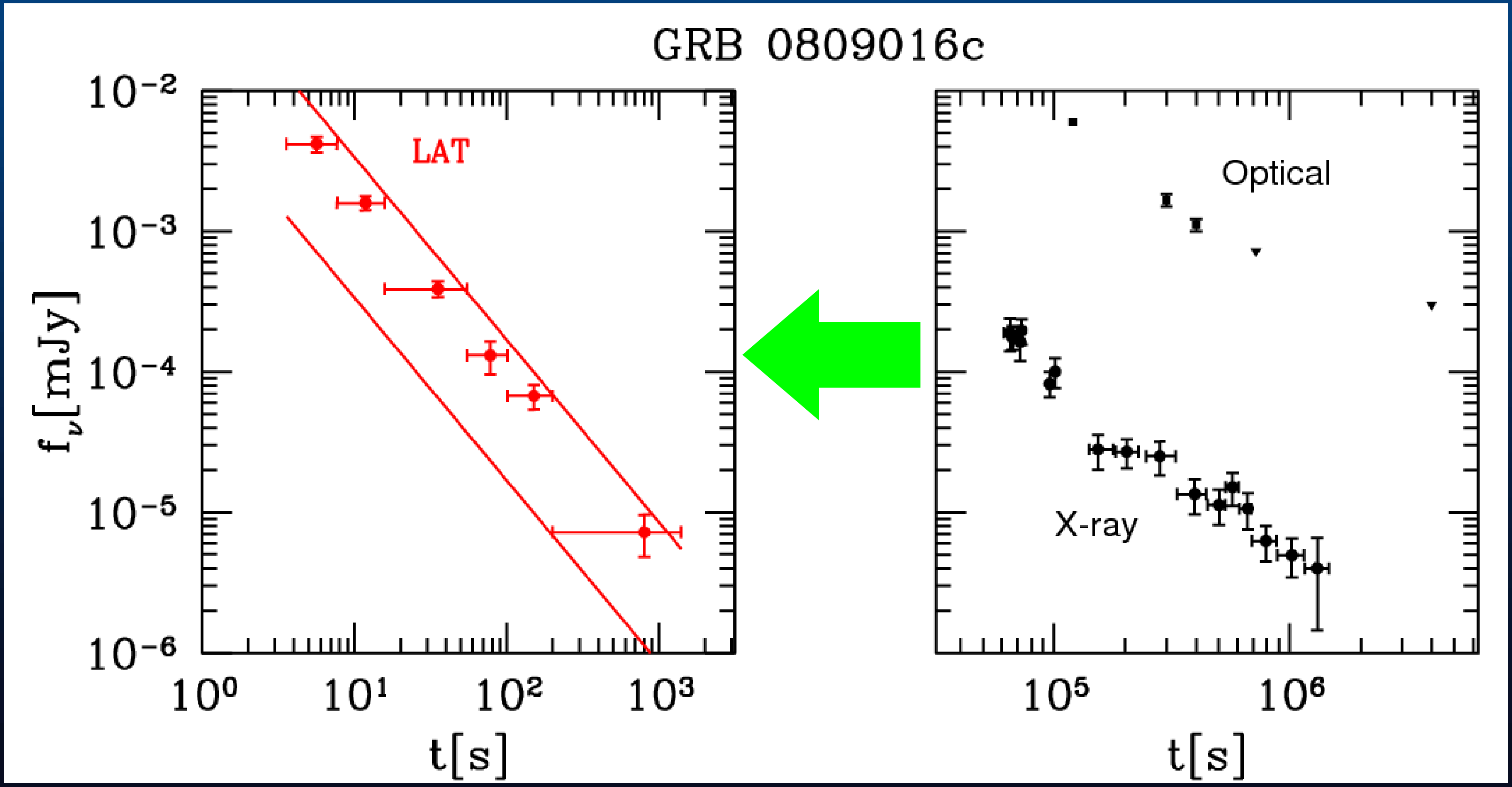


Abdo et al. 2009; Greiner et al. 2009; Evans et al. 2007, 2009

- We can then compare it with the available Fermi data.

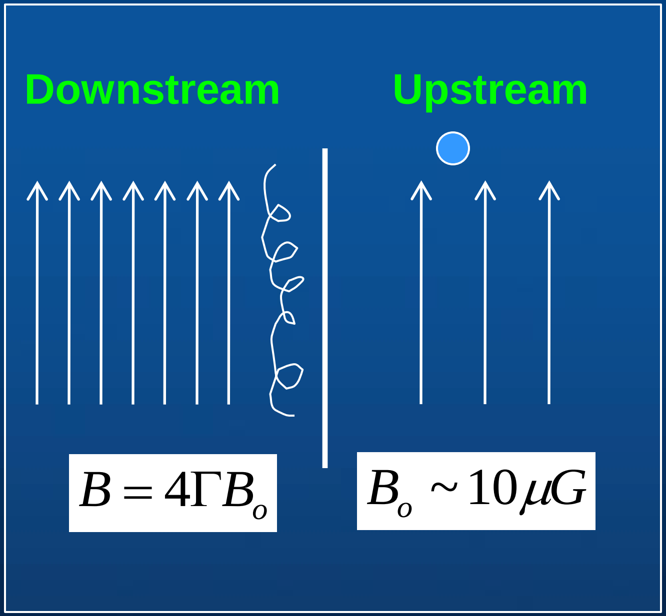
Taking a closer view:

Can electrons be accelerated in the external shock?

To high energies so they can radiate at ~10GeV?

(Barniol Duran & Kumar 2010, see also Piran & Nakar 2010)

Electrons acceleration in the external shock



Can electrons be accelerated to ~10GeV?

1. Can they be confined?

$$R_L \propto B^{-1}$$

← Low B, Larmor radius is large

For electrons radiating at 10GeV with upstream field of 10μG:

$$\gamma_e \approx 10^8$$

An electron upstream of the shock travels only a distance R_L/Γ before returning to downstream (Achterberg et al. 2001), therefore, we compare:

$$\frac{R_L}{\Gamma} \approx 10^{16}\,cm \quad < \quad R \approx 10^{17}\,cm$$

Size of the system!

Electrons acceleration in the external shock

Can electrons be accelerated to ~10GeV?

2. Will they lose to much energy via radiation?

$$t_s \approx \frac{R_L}{c\Gamma^2} \approx 10^3 s$$

← Residency time for electrons radiating at 10GeV

Need to compare with Cooling time-scales:

a. Synchrotron cooling
b. Inverse Compton Cooling. Seed photons are:
   -- Prompt *MeV* photons
   -- External forward shock photons
   -- External reverse shock photons

$$\nu_{p,RS} \approx \nu_{KN} \approx 5eV$$

$$t_{IC,RS} \approx 400s\left(\frac{f_{RS}}{1Jy}\right)^{-1}\left(\frac{\gamma_e}{10^8}\right)^{-1}$$

→ Lower energy electrons *can* be accelerated:

100MeV → f_{RS} = 1Jy
1GeV → f_{RS} ~ 0.1Jy
10 GeV → When f_{RS} decreases

Note: Li (2010) finds a larger upstream field due to an error in Compton Y calculation. When fixing this error, Li's result agrees exactly with our B field.

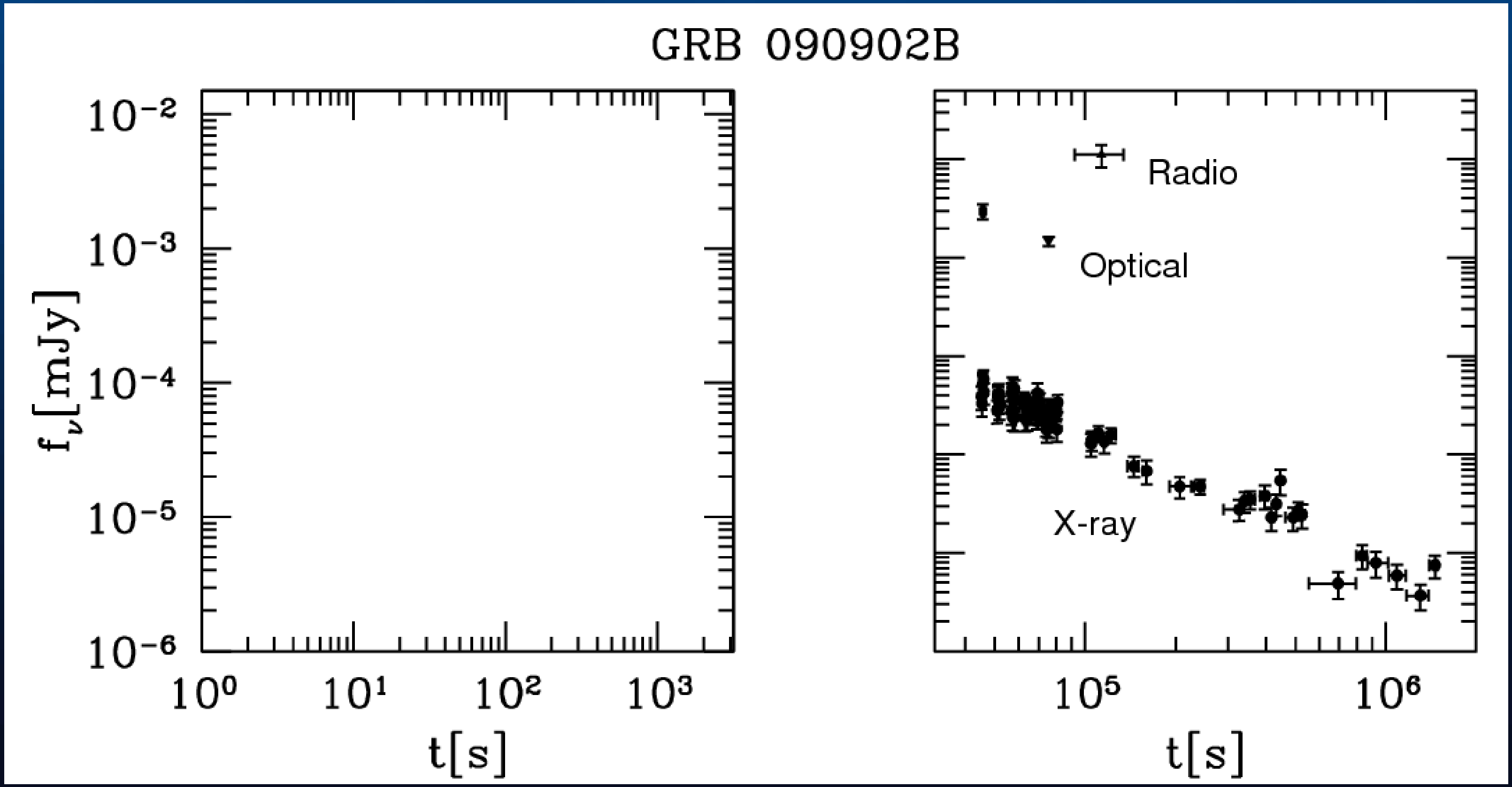
GRB090902B: Global properties

From Radio to GeV, from days to 50 s

(Barniol Duran & Kumar, in preparation)

Expected data from ES at early times: GRB 090902B

- Assuming the X-ray, optical and radio flux are from ES: What is the expected flux at > 100 MeV at early time?



Swenson et al. 2009; Guidorzi et al. 2009; Evans et al. 2007, 2009

Expected data from ES at early times: GRB 090902B

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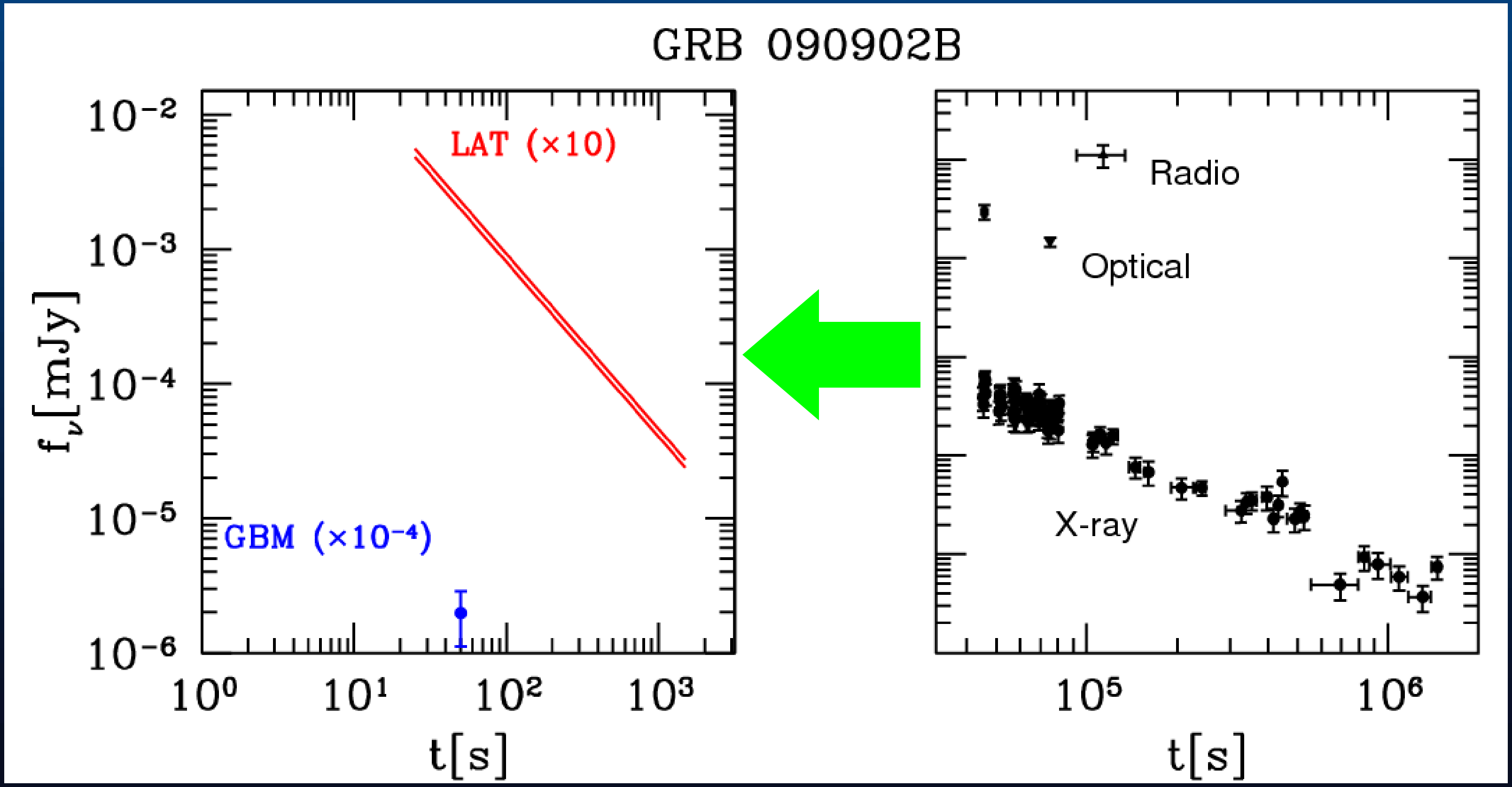
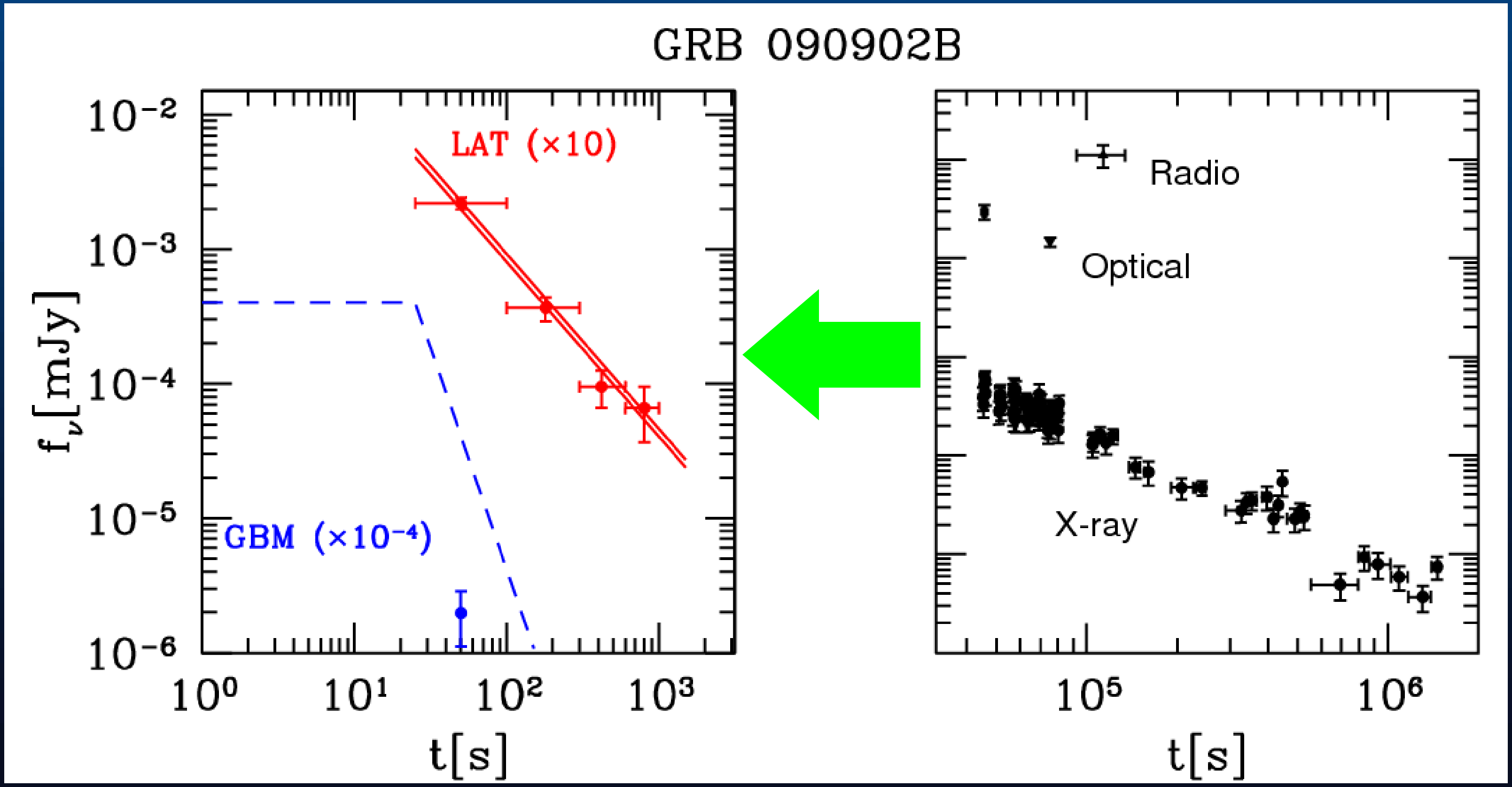


Swenson et al. 2009; Guidorzi et al. 2009; Evans et al. 2007, 2009

- We have used: $E_{KE}^{iso} > E_{\gamma}^{iso}$ and $\epsilon_e > 0.2$

Expected data from ES at early times: GRB 090902B

- Assuming the X-ray, optical and radio flux are from ES: What is the expected flux at > 100 MeV at early time?



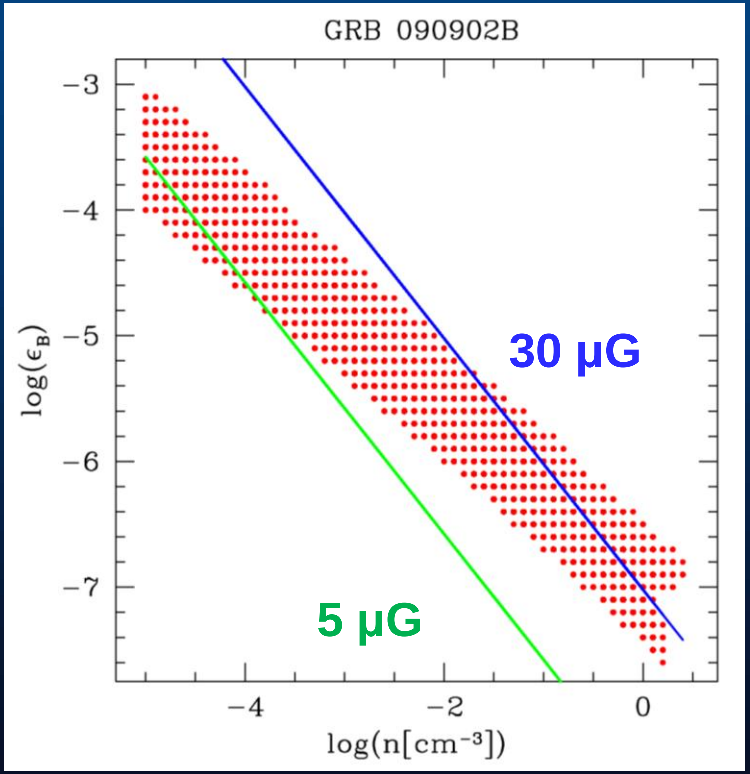
Abdo et al. 2009; Swenson et al. 2009; Guidorzi et al. 2009; Evans et al. 2007, 2009

- Cenko et al. (2010) find a smaller value of LAT flux due to their smaller $E_{KE}^{iso}=E_{\gamma}^{iso}/5$.

External shock parameters: GRB 090902B

Using ONLY early time >100MeV *Fermi* data:

Parameter search at t = 50 sec.



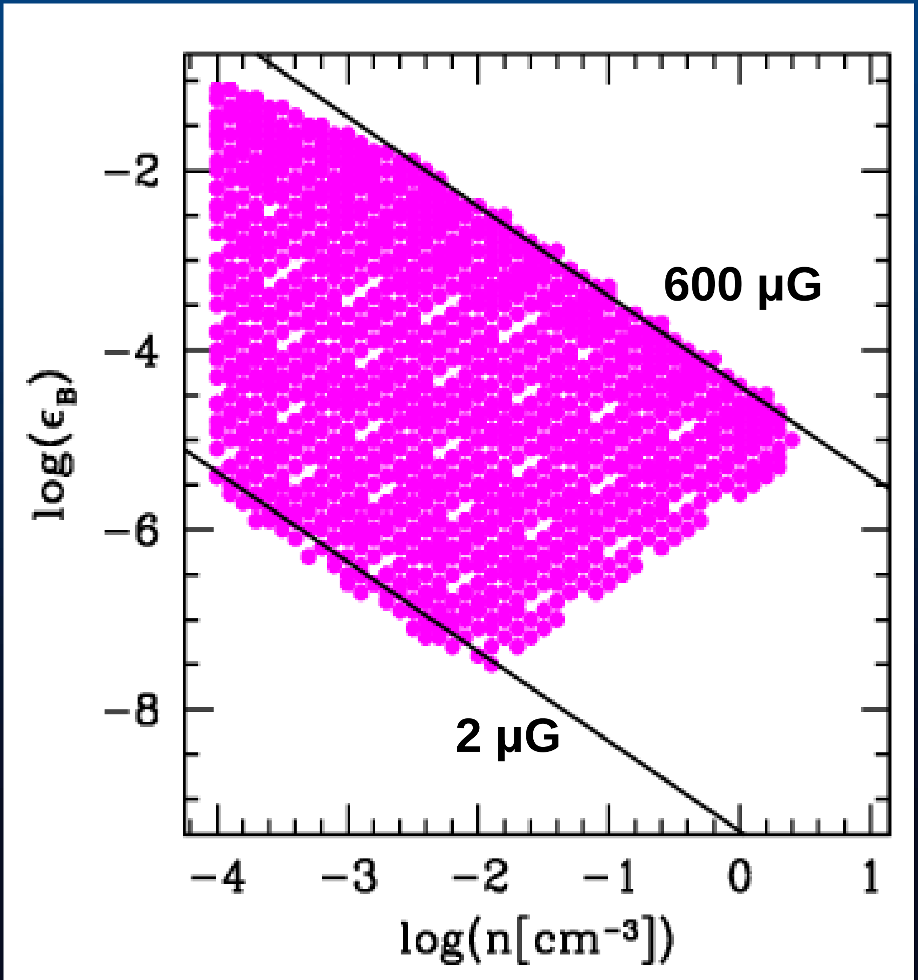
→ Magnetic field is consistent with shock-compressed magnetic field of CSM of a few tens of micro-Gauss.

→ Similar results apply also for the case of GRB 080916C and GRB 090510.

External shock parameters: GRB 090902B

Using ONLY late time X-ray, optical and radio data:

X-ray, optical, radio fluxes within the uncertainty of their measurements.



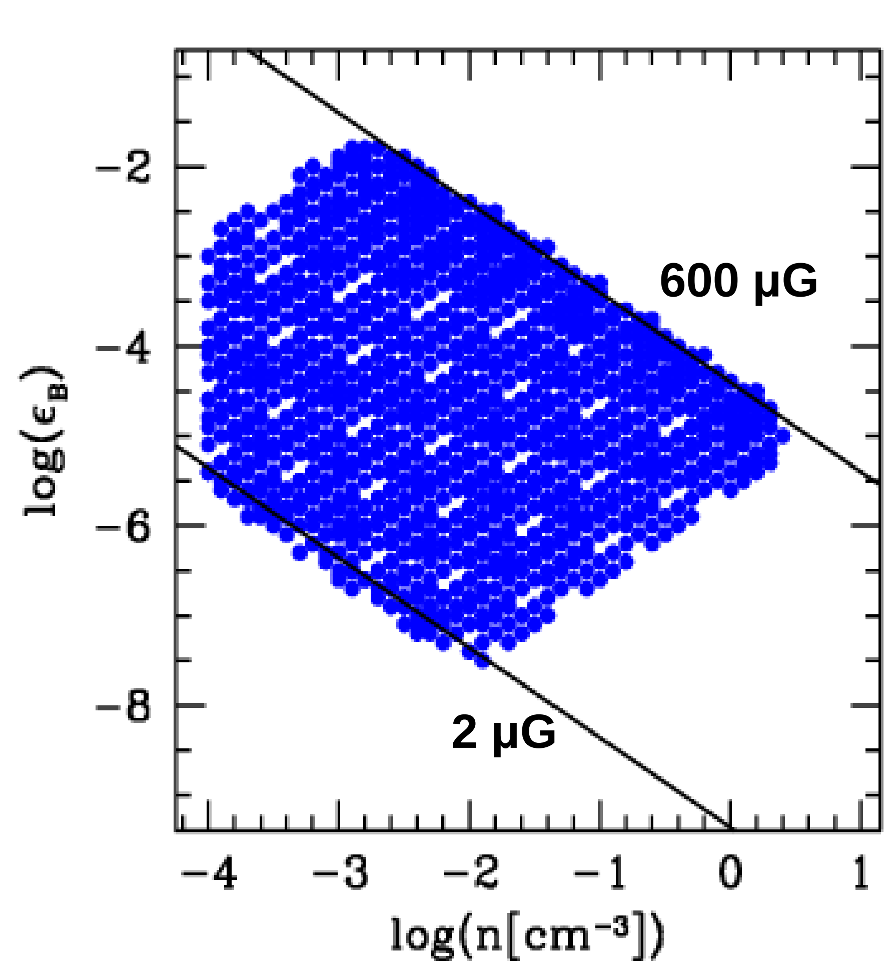
External shock parameters: GRB 090902B

Using ONLY late time X-ray, optical and radio data:

X-ray, optical, radio fluxes within the uncertainty of their measurements.

In addition:

$\varepsilon_e > 0.1$



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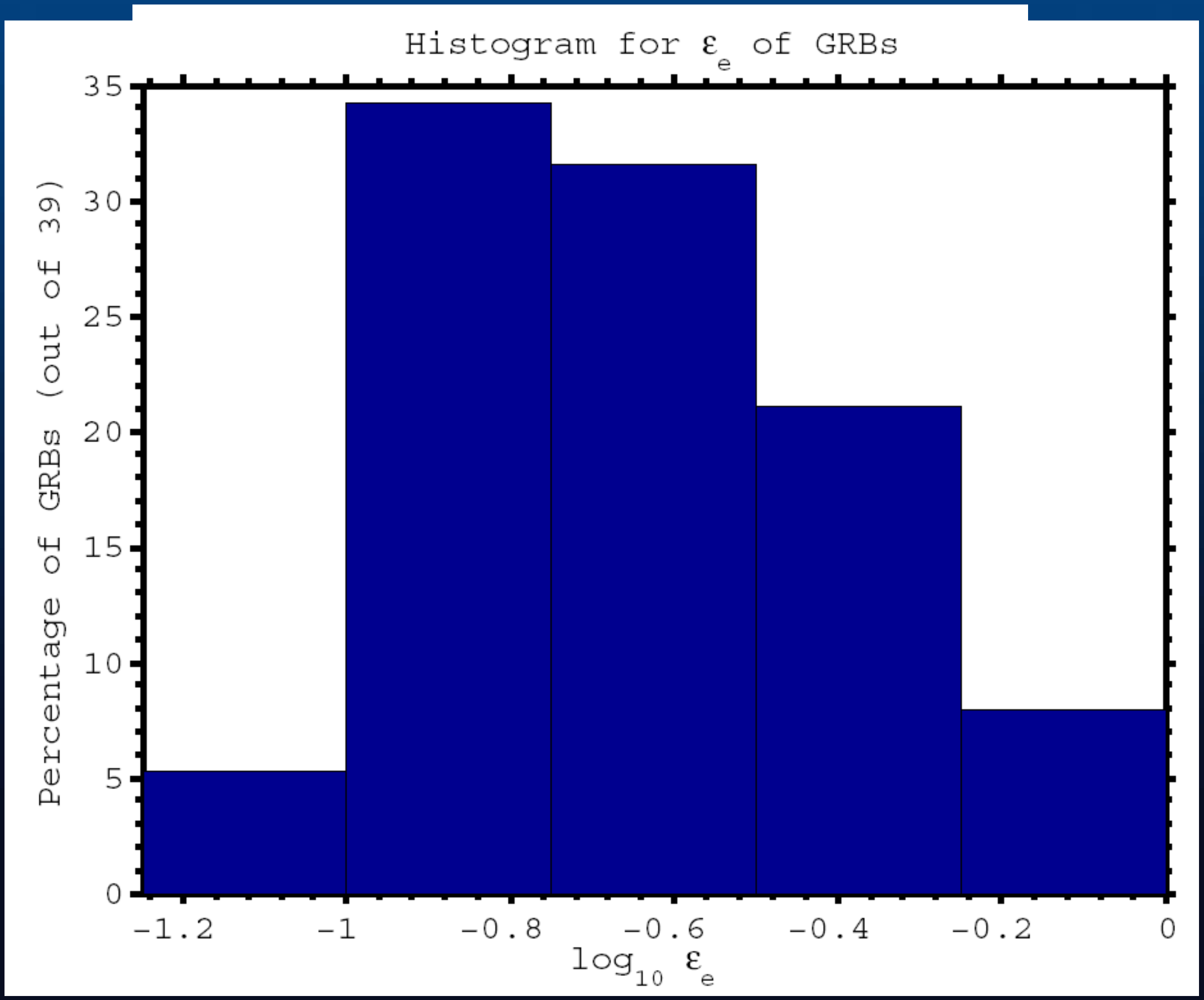


External shock parameters: GRB 090902B

Using ONLY late time X-ray, optical and radio data:

X-ray, optical, radio fluxes within the uncertainty of their measurements.

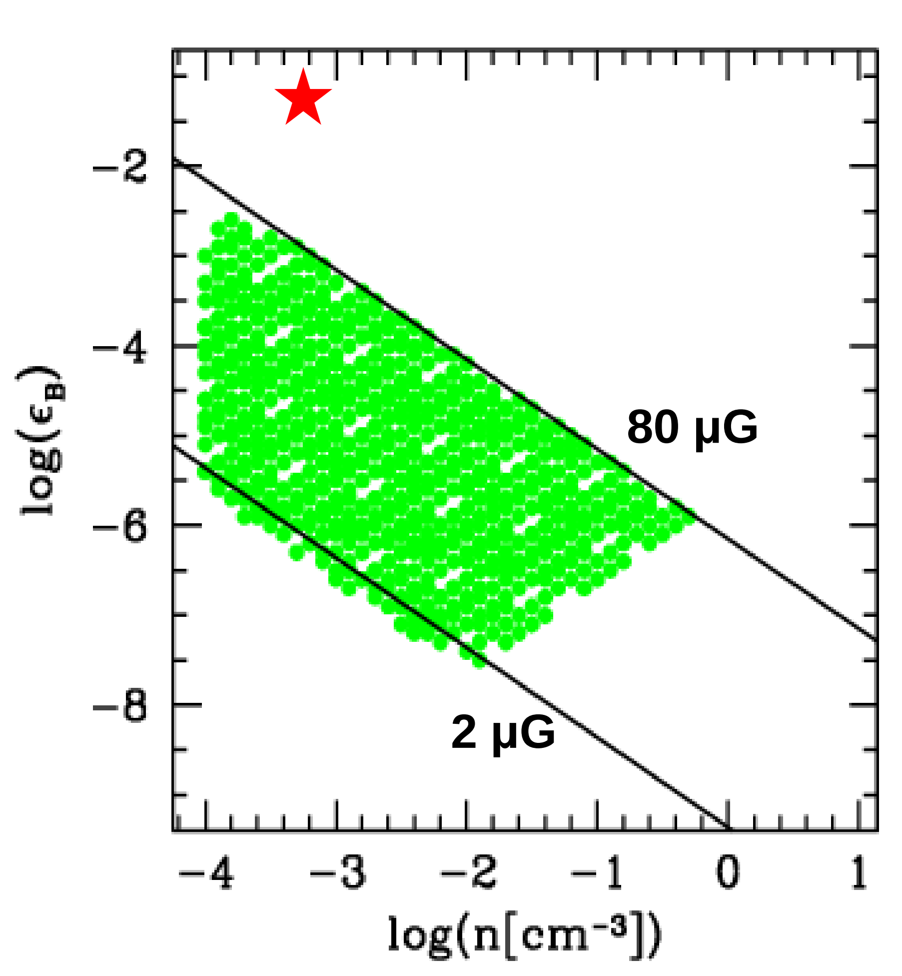
In addition:

$\varepsilon_e > 0.1$

$E_{KE}^{iso} \geq E_{\gamma}^{iso}/5$

$\eta \leq 83\ \%$

(Cenko et al.)



Red star marks Cenko et al. (2010) solution.

External shock parameters: GRB 090902B

Using ONLY late time X-ray, optical and radio data:

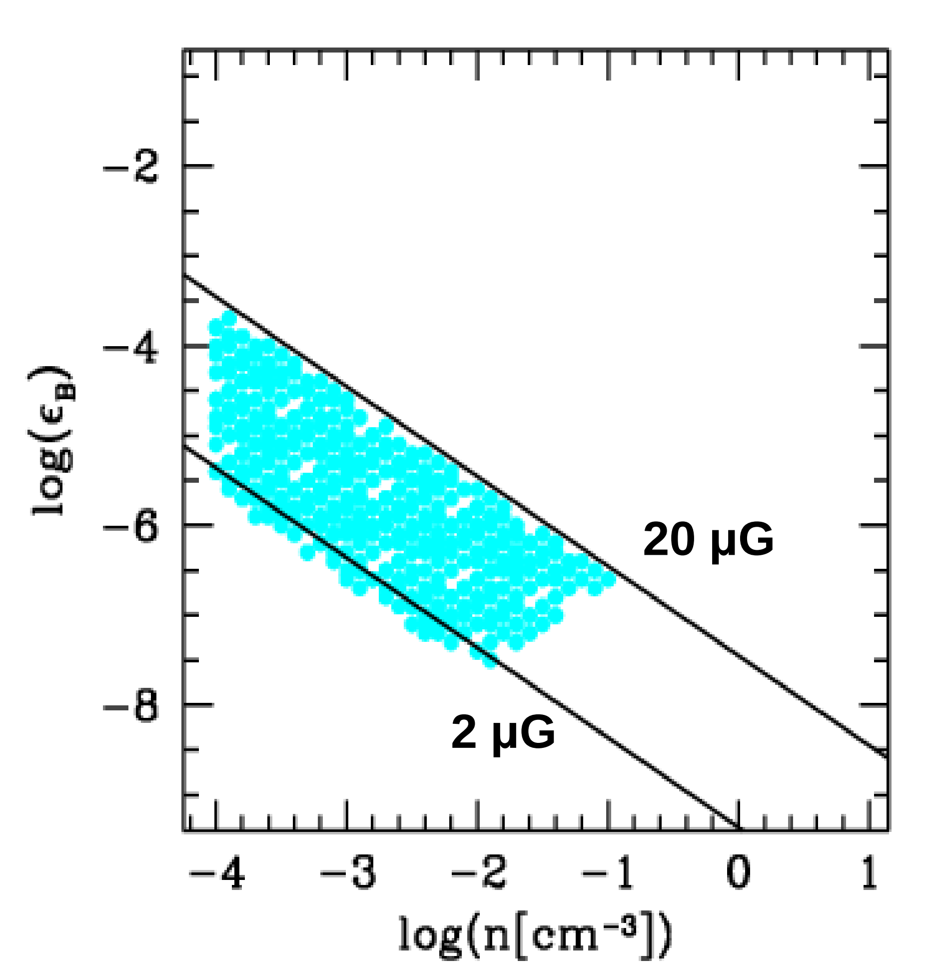
X-ray, optical, radio fluxes within the uncertainty of their measurements.

In addition:

$\epsilon_e > 0.1$

$E_{KE}^{iso} \geq E_{\gamma}^{iso}$

$\eta \leq 50$ %



Consistent with solution using *ONLY* LAT data.

Late time afterglow of GRB090902B

Temporal decay index and spectrum of X-ray and optical data:

$$-\begin{array}{l}\alpha_X = 1.36 \pm 0.03 \\ \alpha_{opt} = 0.89 \pm 0.05\end{array} \qquad -\begin{array}{l}\beta_X = 0.90 \pm 0.13 \\ \beta_{opt} = 0.76 \pm 0.07\end{array}$$

(Pandey et al. 2010, Cenko et al. 2010)

$$\Delta\alpha = 0.47 \pm 0.08 \qquad \Delta\beta = 0.14 \pm 0.20$$

Expected in the external shock for: $\nu_i < \nu_{opt} < \nu_c < \nu_X$ ✖

$\Delta\alpha = 0.25$ ✖ & $\Delta\beta = 0.5$ ✖

→ The X-ray decay must be steepened by $\sim t^{0.2}$

$$f_\nu \propto \begin{cases} (E_{KE}^{iso})^{1.4}\varepsilon_e^{1.4}\varepsilon_B^{0.9}n^{0.5} & ; \quad \nu_i < \nu_{opt} < \nu_c \\ (E_{KE}^{iso})^{1.1}\varepsilon_e^{1.4}\varepsilon_B^{0.1}(1+Y)^{-1} & ; \quad \nu_c < \nu_X \end{cases}$$

→ Radiative losses and varying microphysical parameters doesn't work: They affect also the optical light curve.

→ **Very** careful calculation shows that *at most* $(1+Y) \sim t^{0.03}$!

Late time afterglow of GRB090902B

Temporal decay index and spectrum of X-ray and optical data:

$$
\begin{array}{rl}
- & \alpha_X = 1.36 \pm 0.03 \\
 & \alpha_{opt} = 0.89 \pm 0.05 \\
\hline
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\end{array}
\qquad
\begin{array}{rl}
- & \beta_X = 0.90 \pm 0.13 \\
 & \beta_{opt} = 0.76 \pm 0.07 \\
\hline
 & \Delta\beta = 0.14 \pm 0.20
\end{array}
$$

(Pandey et al. 2010, Cenko et al. 2010)

Expected in the external shock for: $\nu_i < \nu_{opt} < \nu_X < \nu_c$ ✓

$\Delta\alpha = 0$ ✗ & $\Delta\beta = 0$ ✓

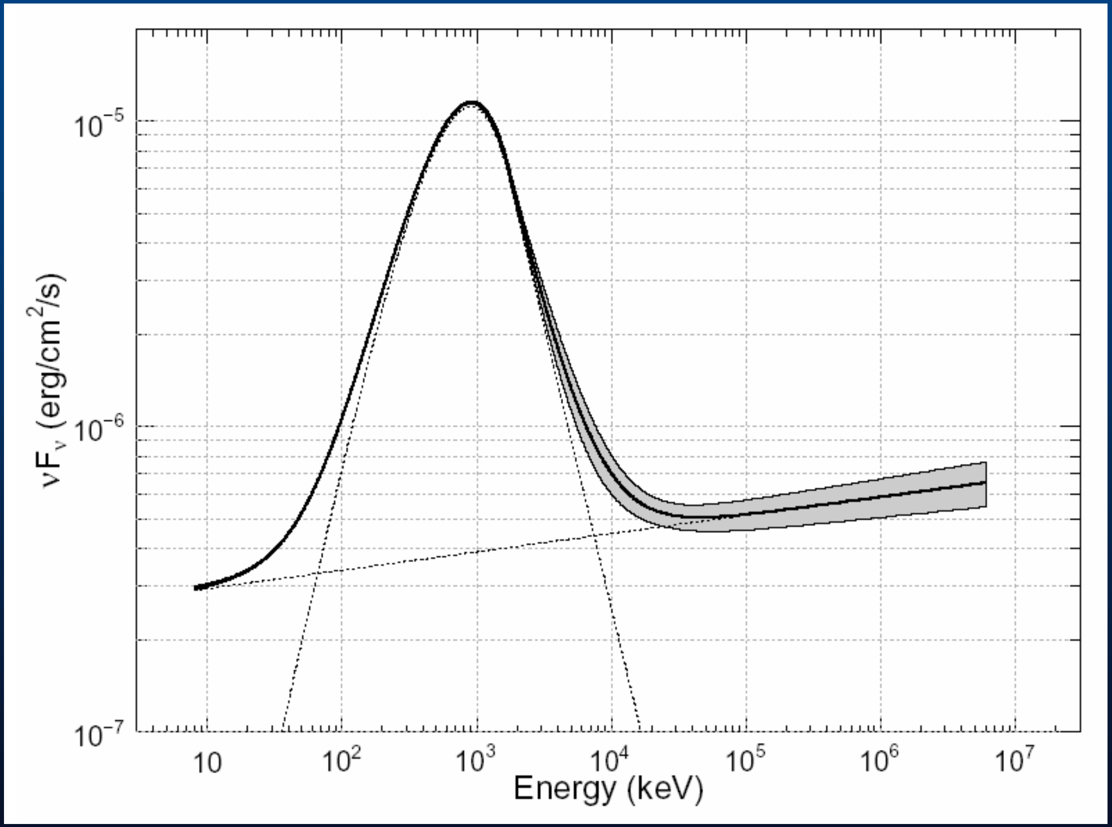
→ ONLY way to steepen X-ray and NOT optical is by having:

$p_{opt} < p_X$ Slight curvature in the power-law distribution of electrons!

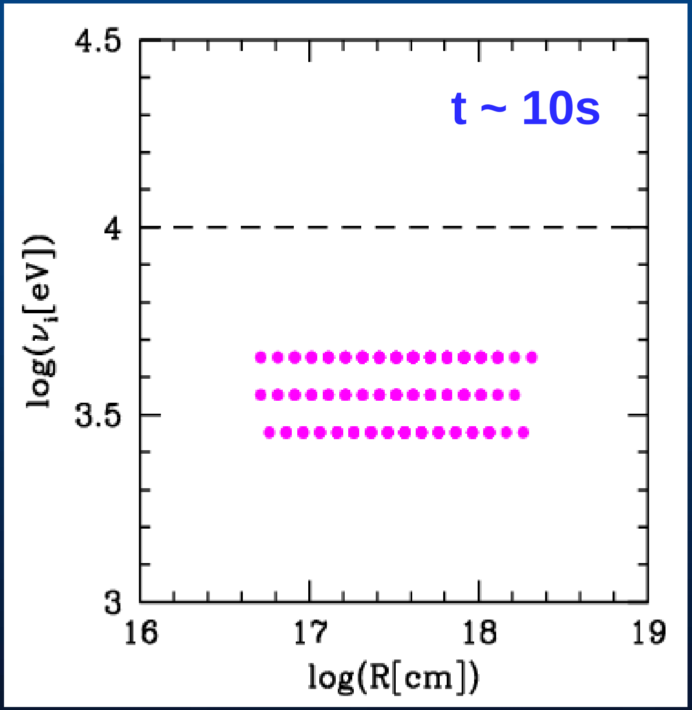
(More details to come in BD&K, *in prep*)

New issues of GRB090902B

In addition to Band spectrum: Single Power-Law found for GRB090902B



GRB 090902B: Abdo et al. 2009



GRB 090902B: Injection frequency at 10s.
Radio/Optical/X-ray constraints applied

→ It is possible that this power-law ALSO is produced by the external shock.

→ This works for GRB090902B, however, for GRB090510, the injection frequency is too large at early times (something else is going on).

Conclusions

•The high energy emission (> 100 MeV) detected in Fermi GRBs is consistent with being produced in the external forward shock via synchrotron emission.

•The magnetic field in the region where high-energy photons were produced (and also the late time afterglow emission region) is found to be consistent with shock compressed magnetic field of the circum-stellar medium.

•Extra power-law component extending to ~10 keV in GRB090902B might be also produced by the external forward shock.

•Late time X-ray optical observations, if produced by the external forward shock, can only be explained if there is slight curvature in the power-law distribution of electrons.